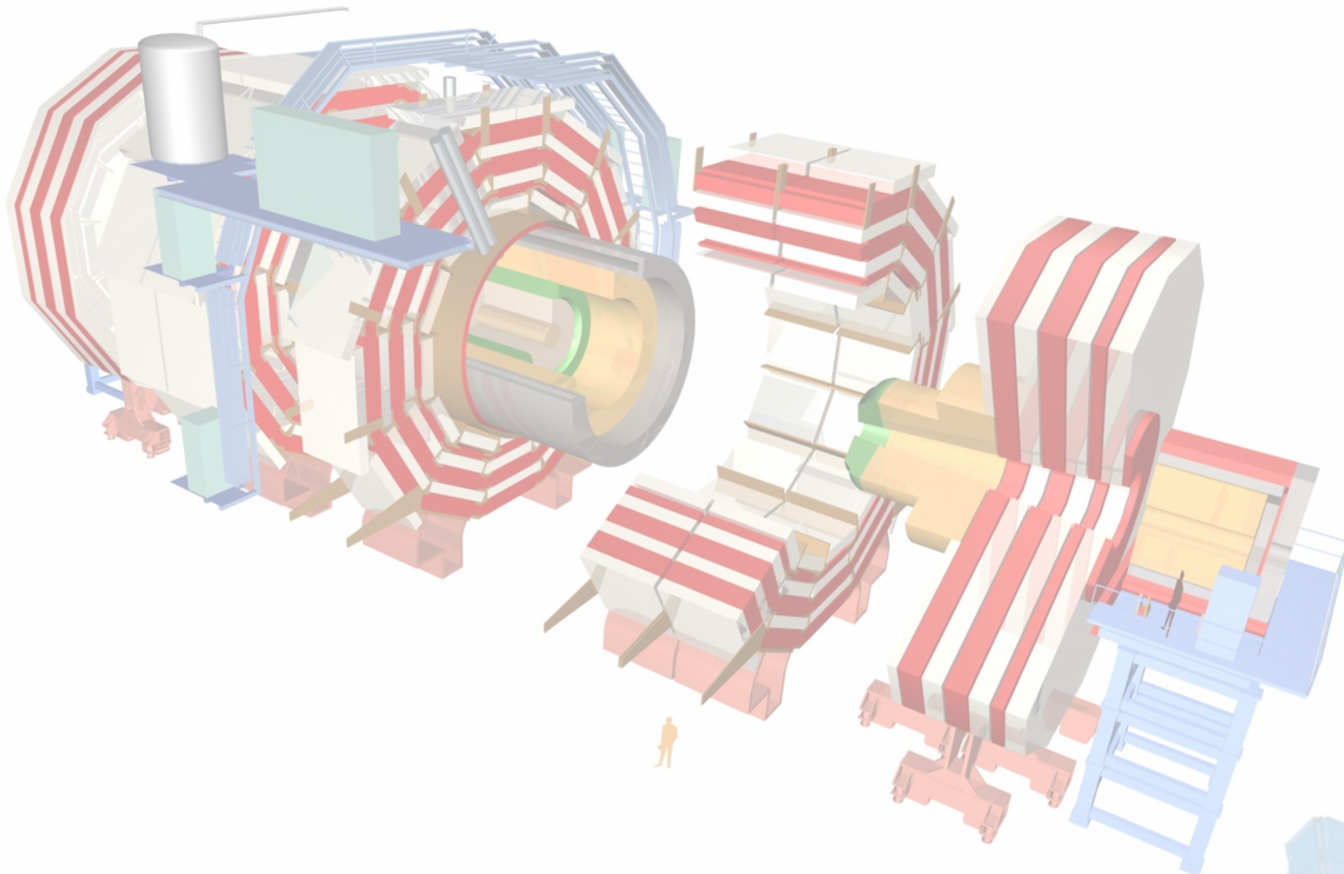
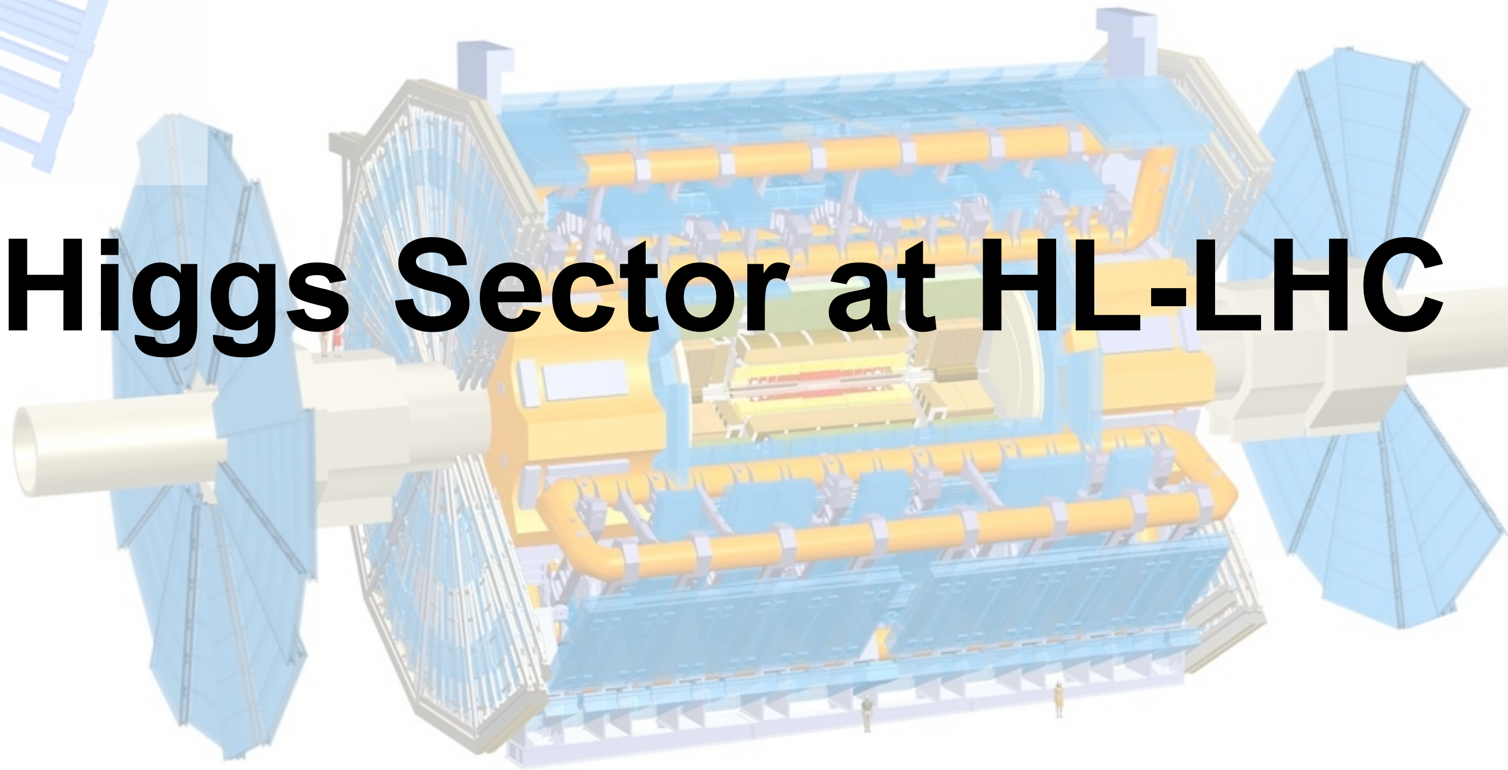
EU-Italy-Russia@Dubna Round Table



Prospects of the Higgs Sector at HL-LHC



High Luminosity LHC

Paolo Giacomelli (INFN Bologna)

What Next ?, JINR, Dubna

Monday, March 3rd, 2014

Outline

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- Where we stand today

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- LHC and HL-LHC luminosity projections

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Important Caveat

In this talk *Higgs boson* stands for the scalar boson predicted independently by
R. Brout, F. Englert and P.W. Higgs,
a more appropriate name would be *BEH boson*

Integrated luminosity in 2012

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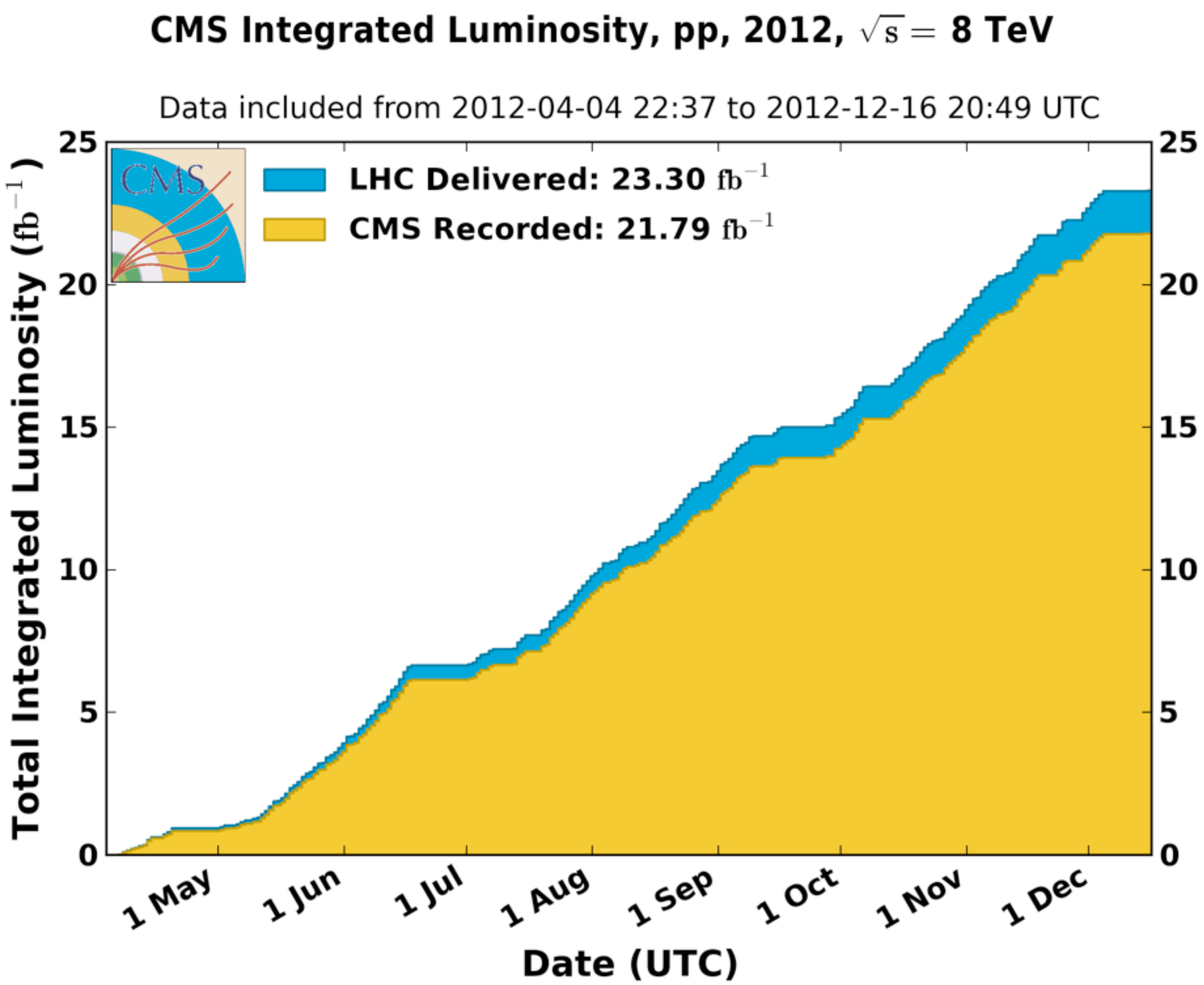

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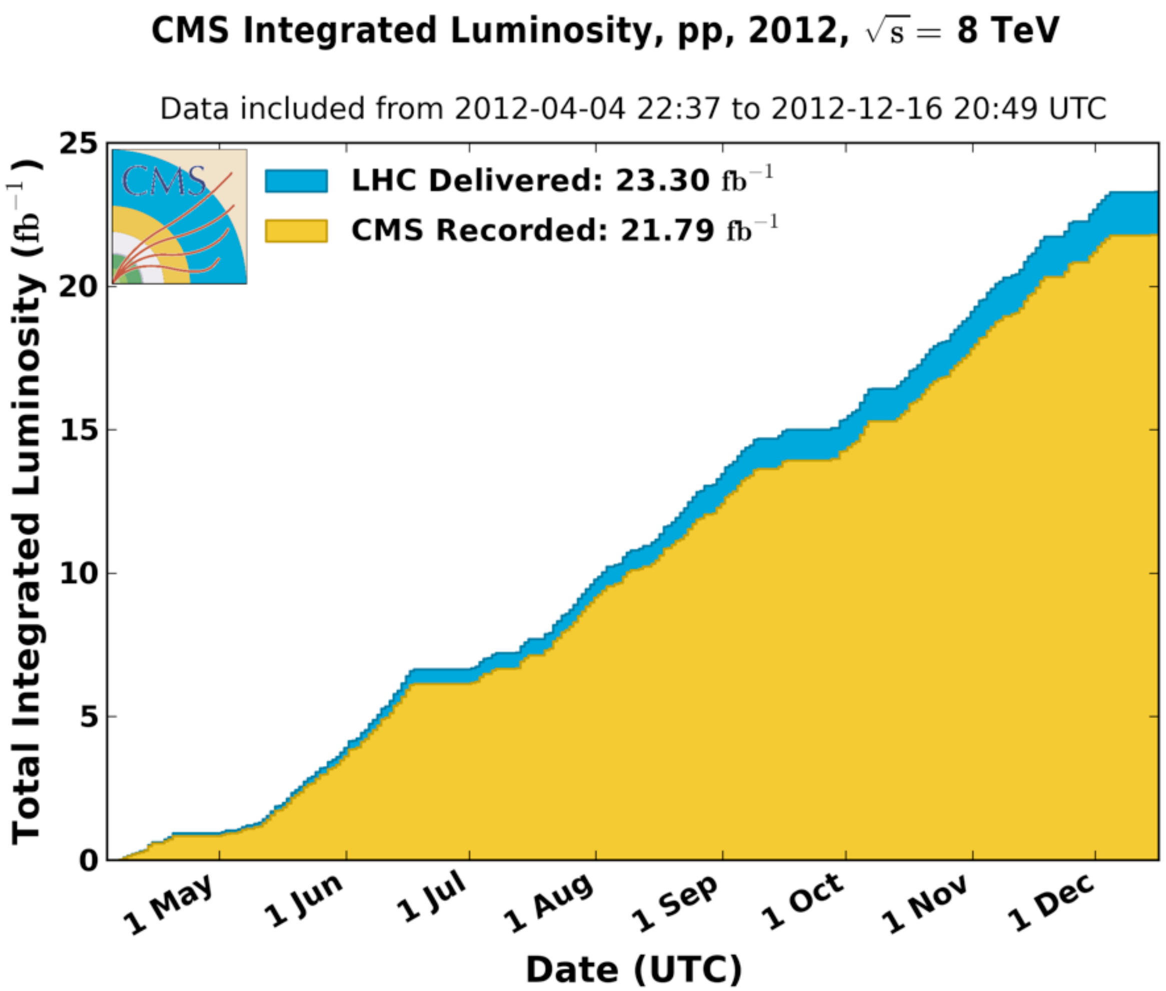
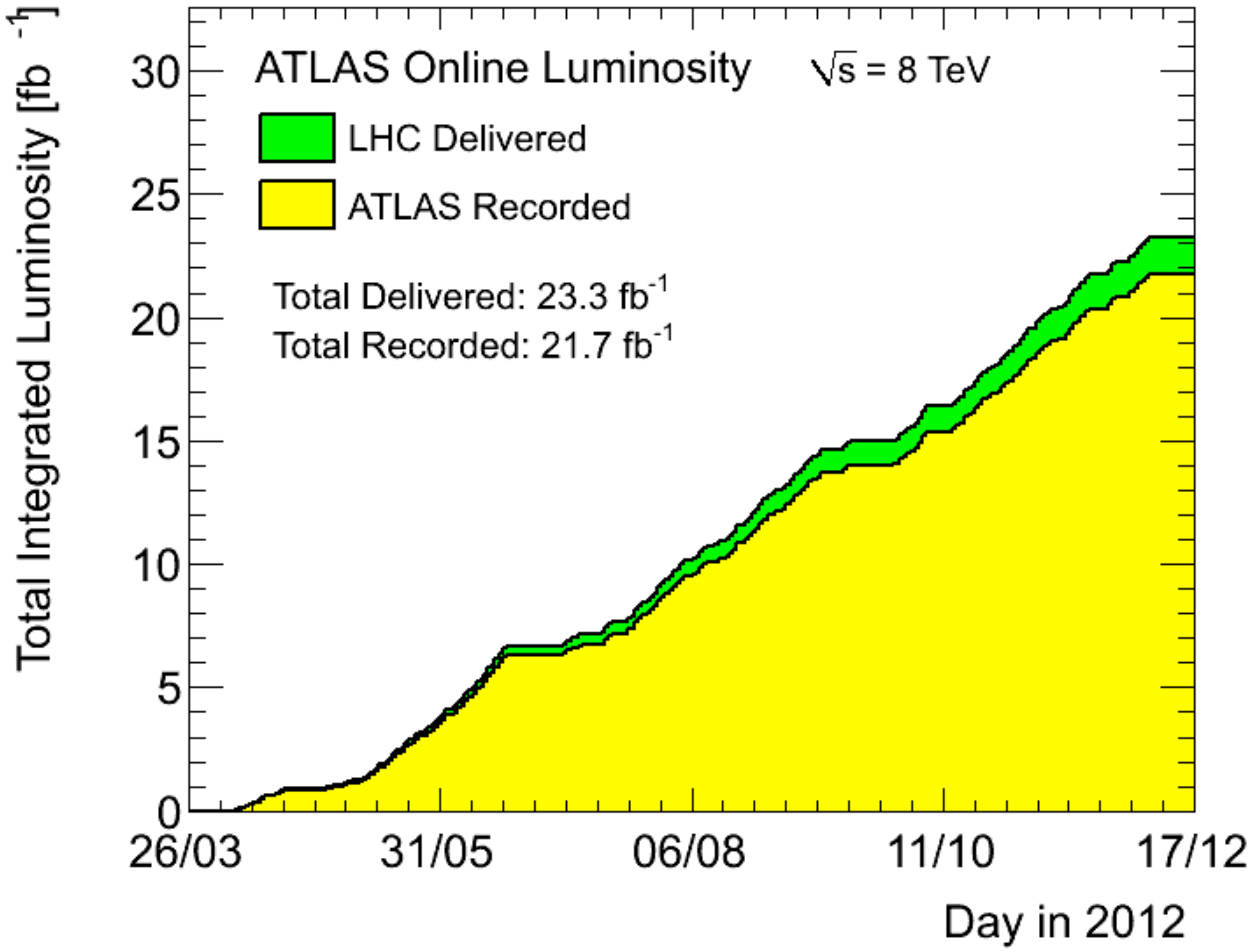
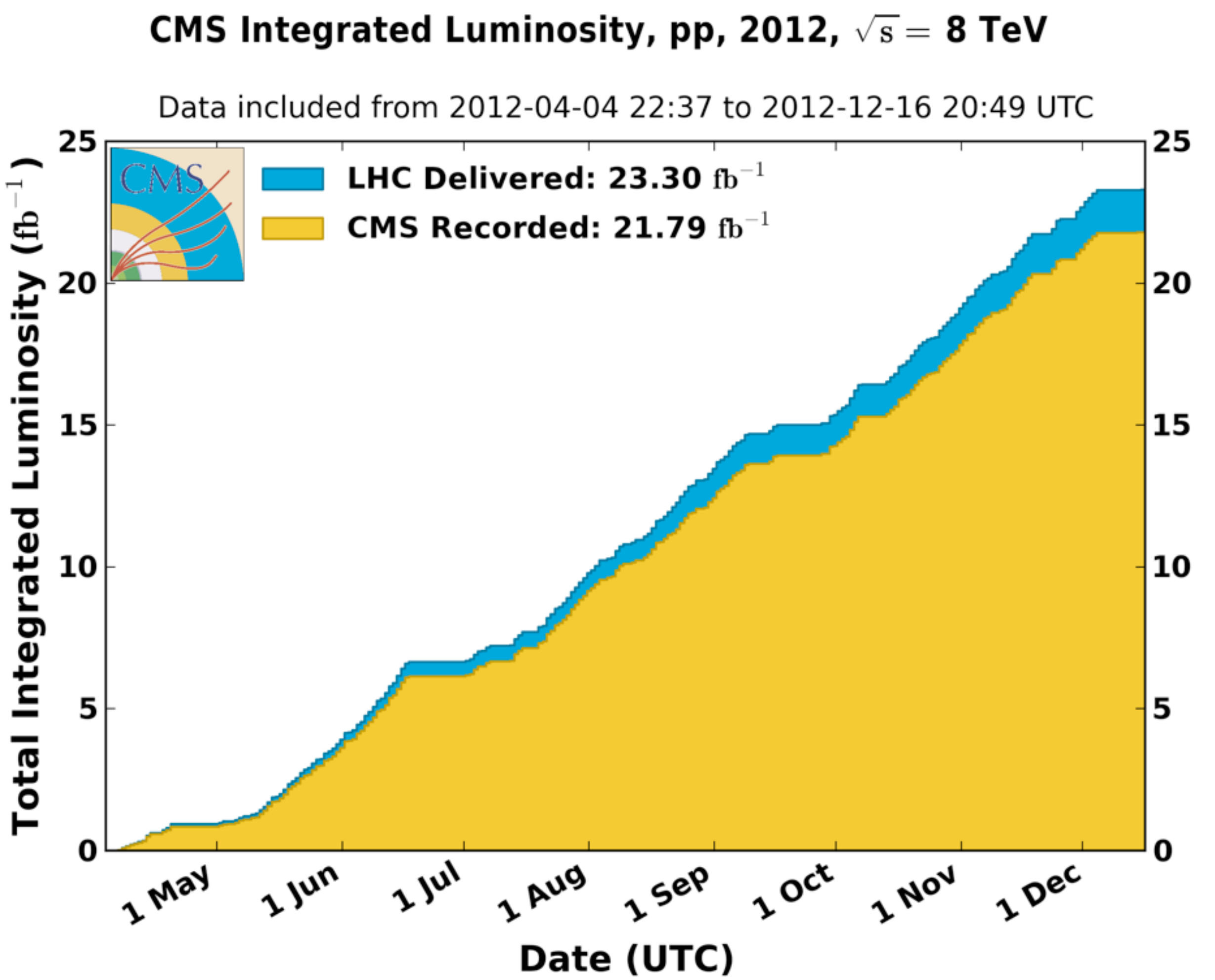
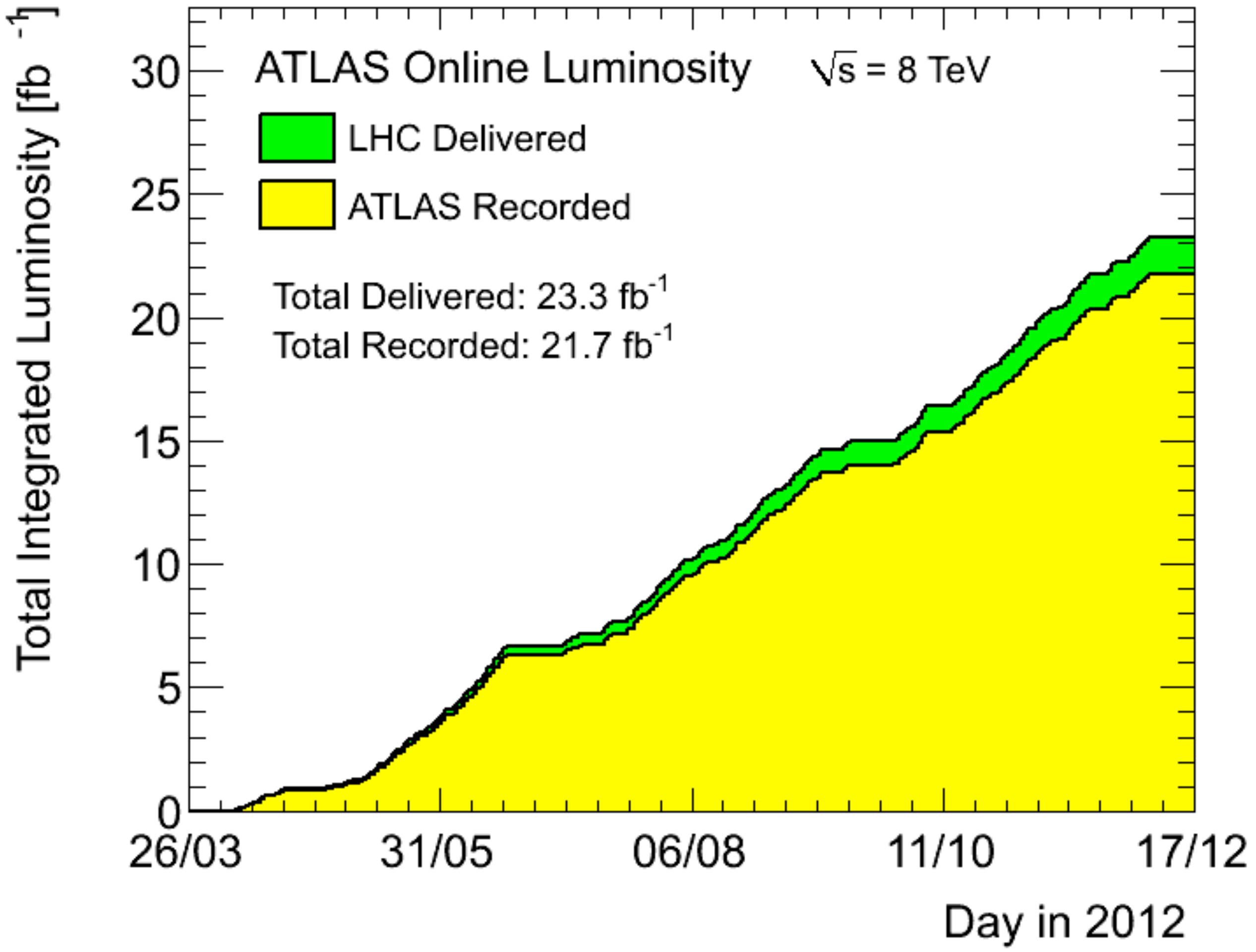




Integrated luminosity in 2012

Integrated luminosity recorded in 2012: **~22 fb^{-1}**





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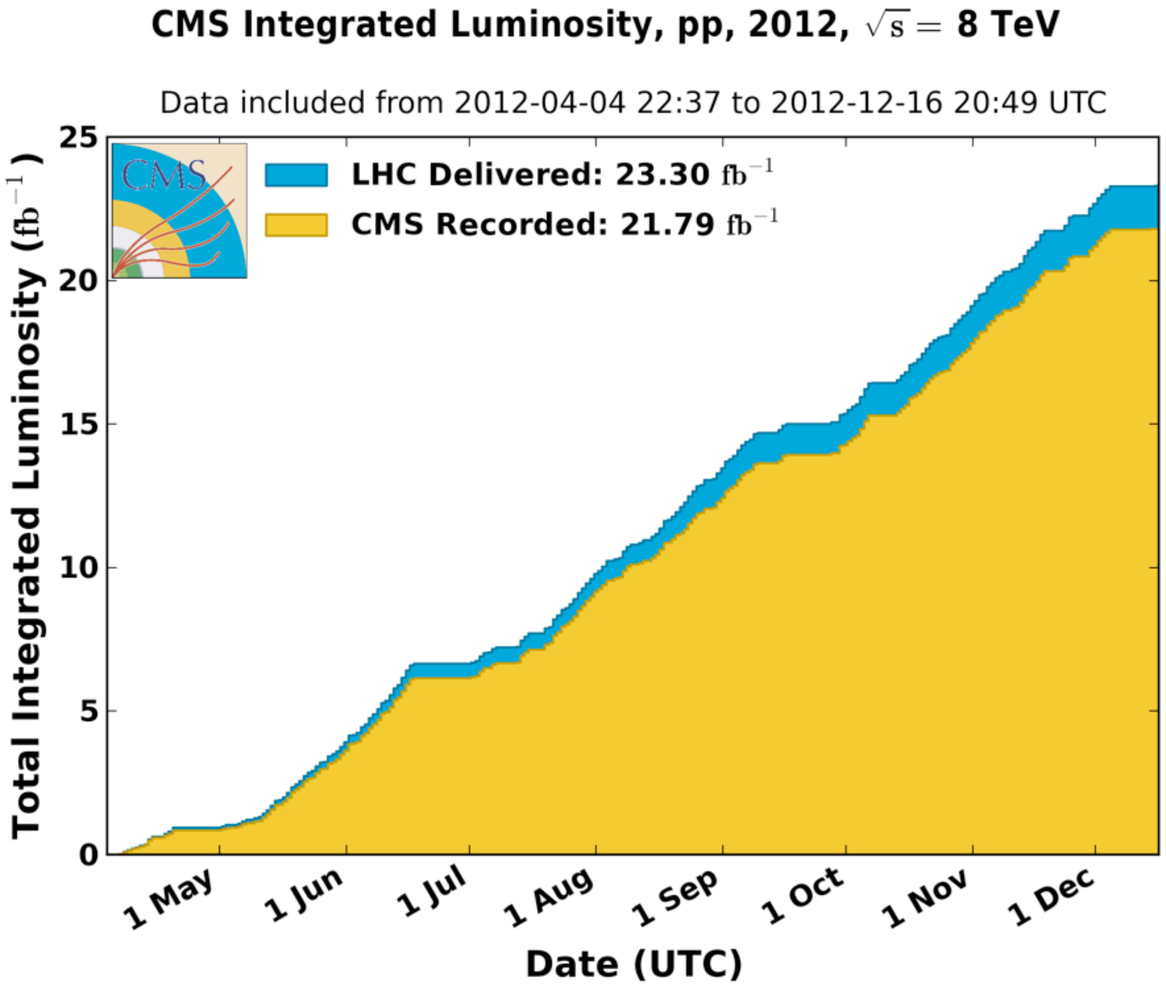

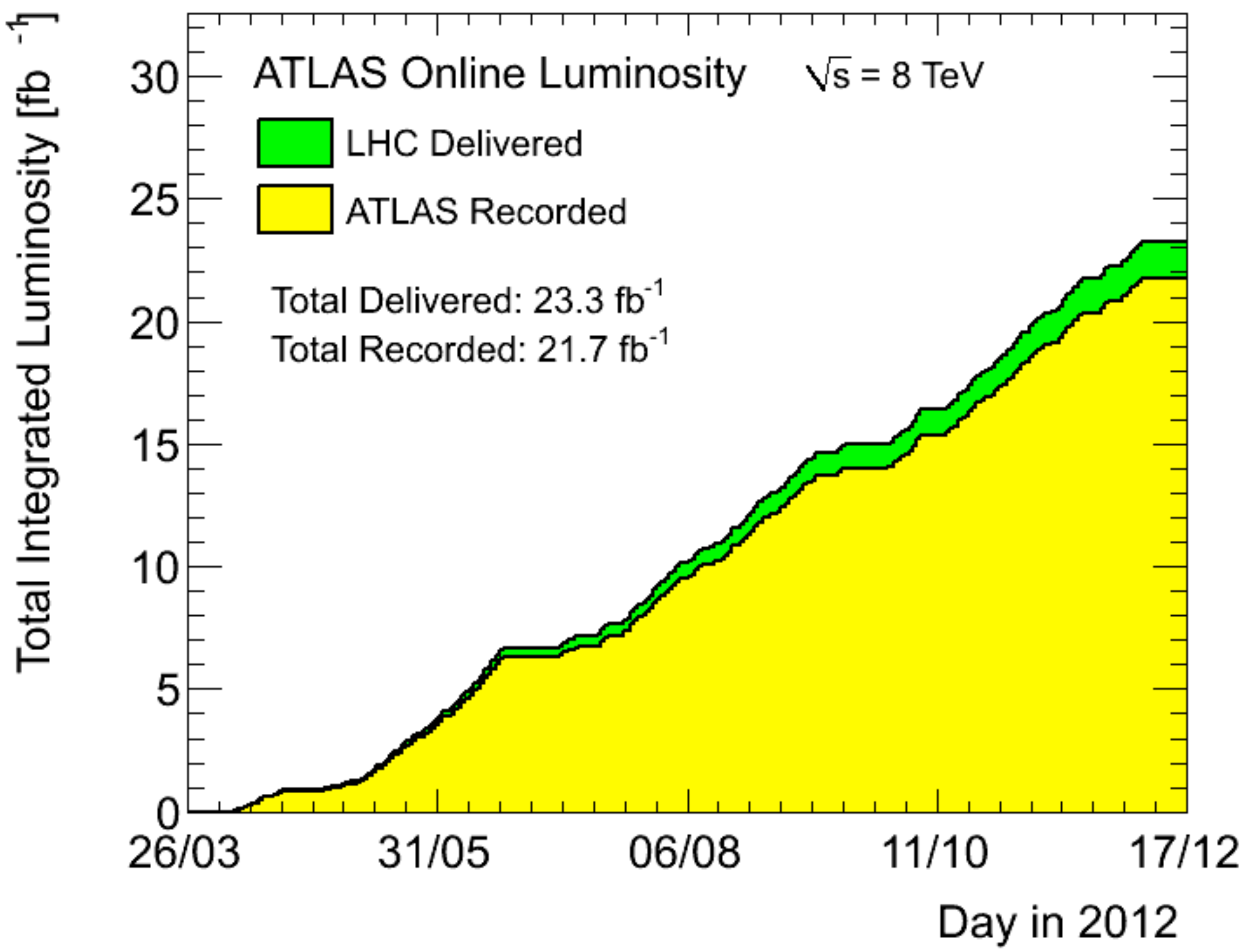

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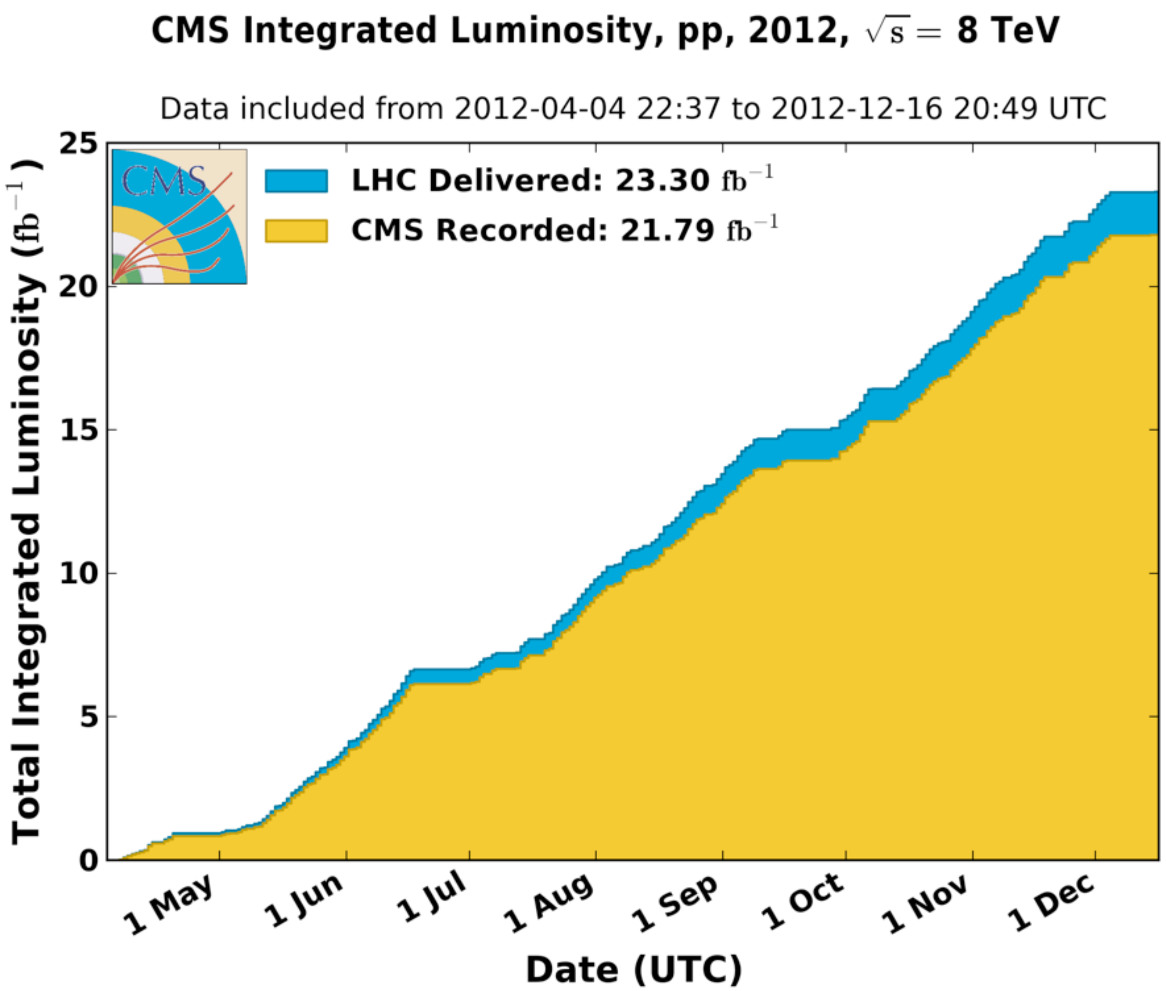

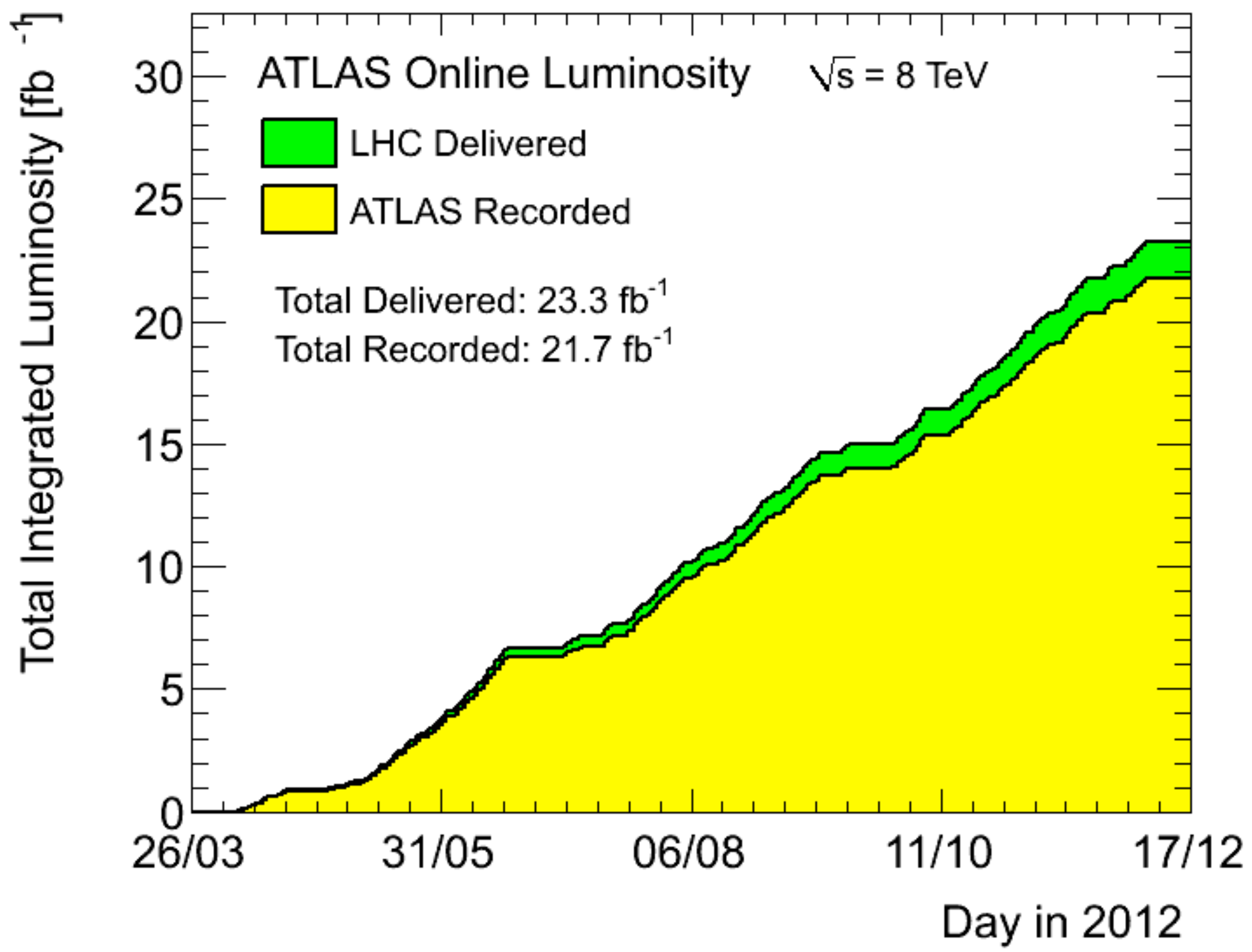

Total delivered luminosity: **~30 fb^{-1}**

Total recorded luminosity: **~27 fb^{-1}**

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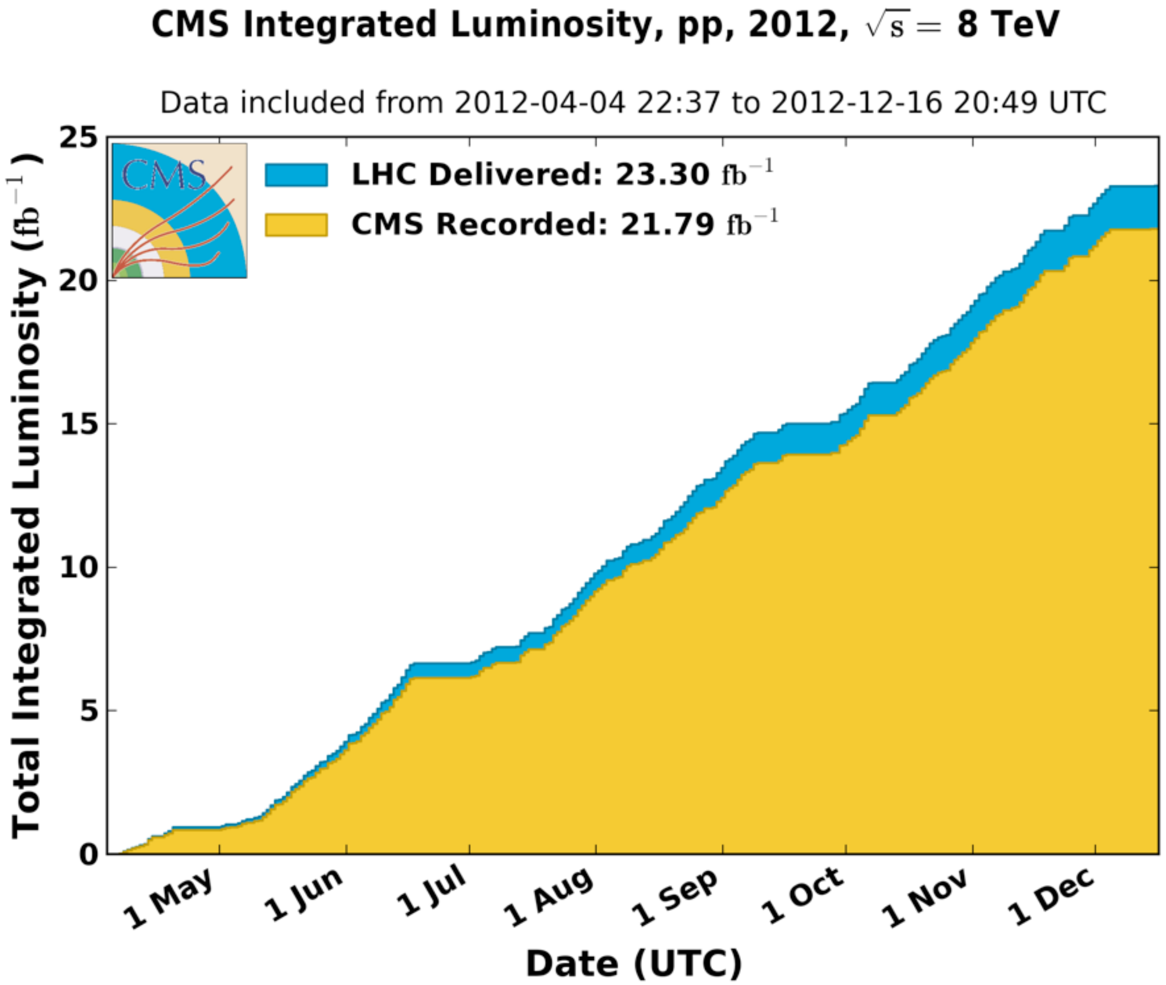

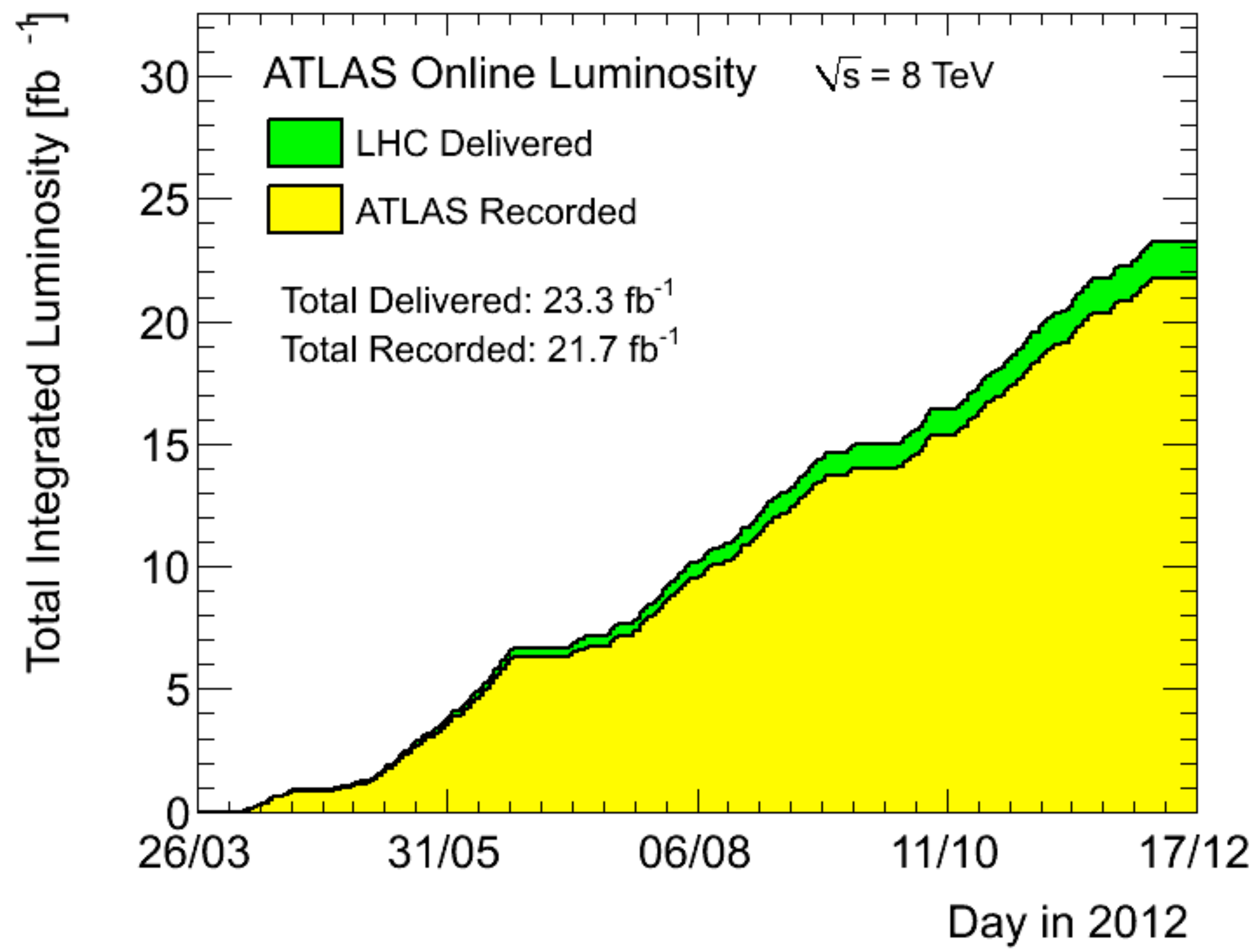

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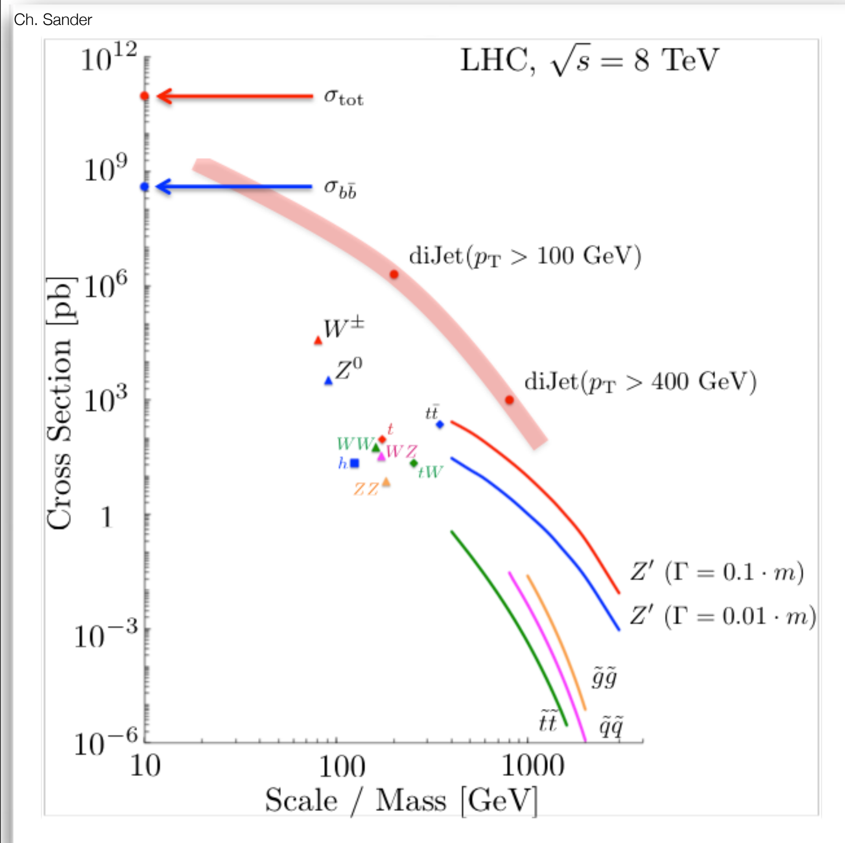
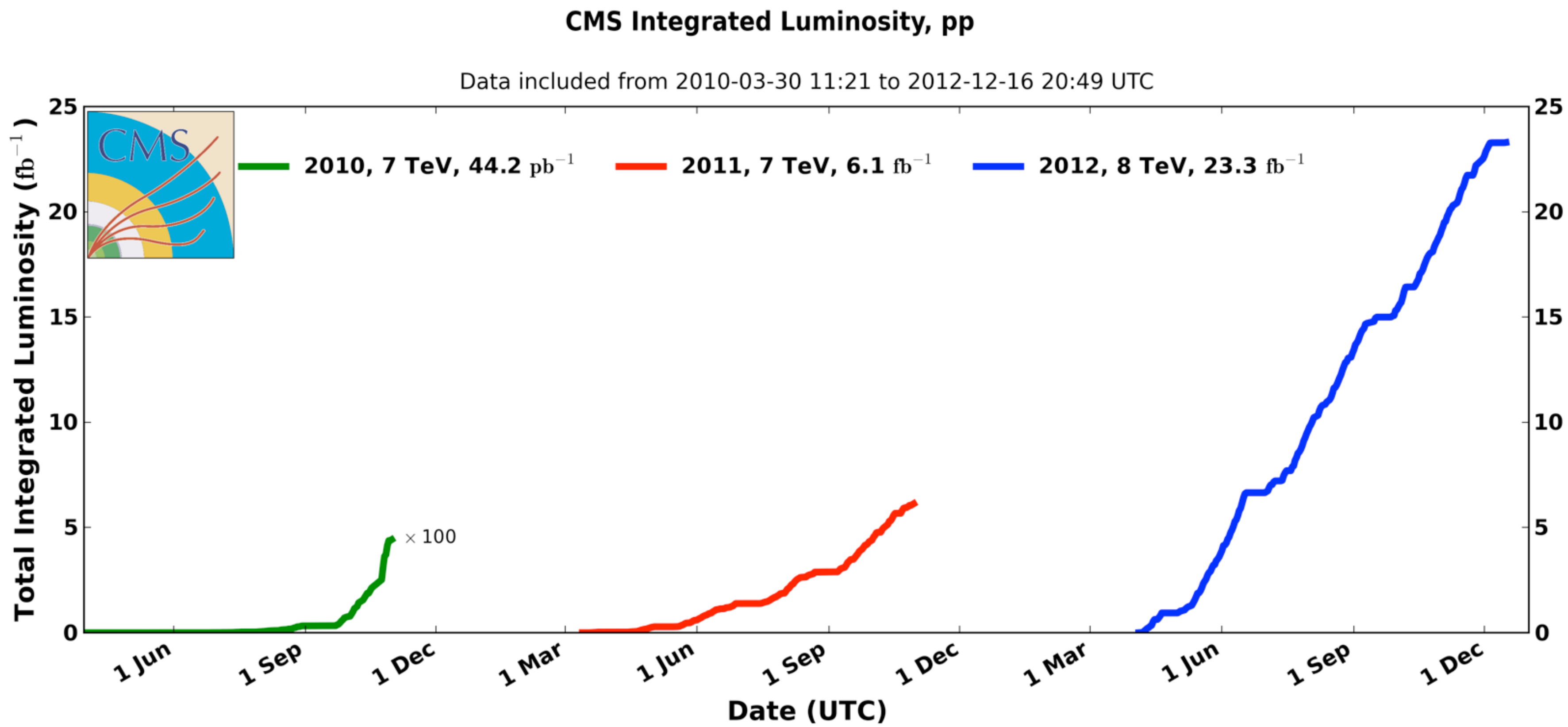
Excellent LHC peformance and very high data-taking efficiency of the two detectors

A 3-year long sprint....

CMS as example ...





From G. Dissertori (ETH)

δ .. relative uncert.
Δ .. absolute uncert.

A 3-year long sprint….

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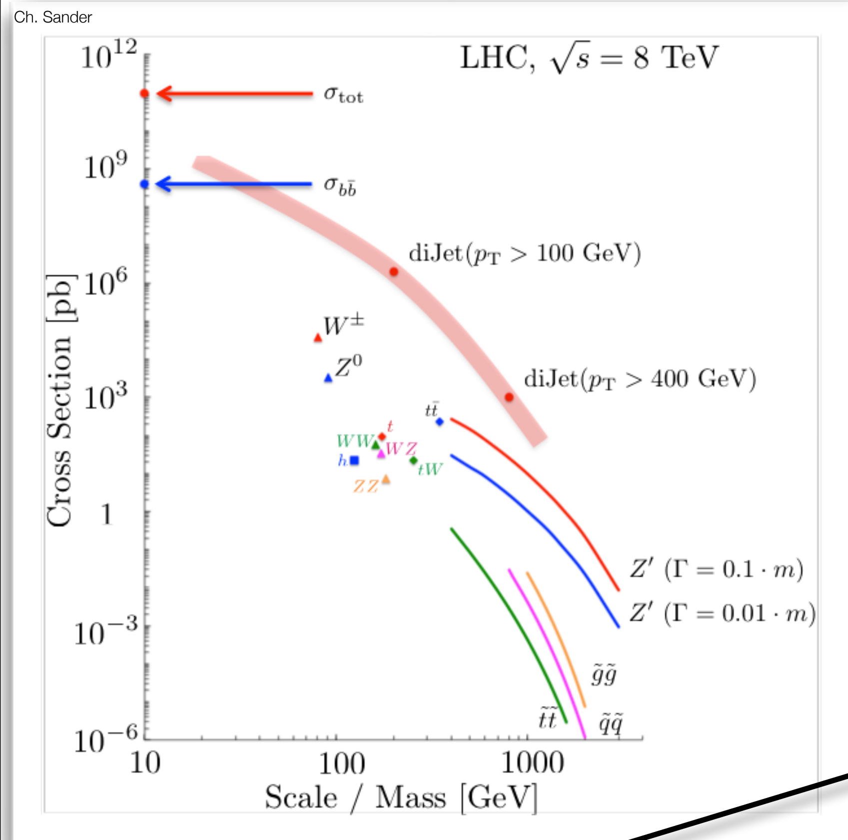

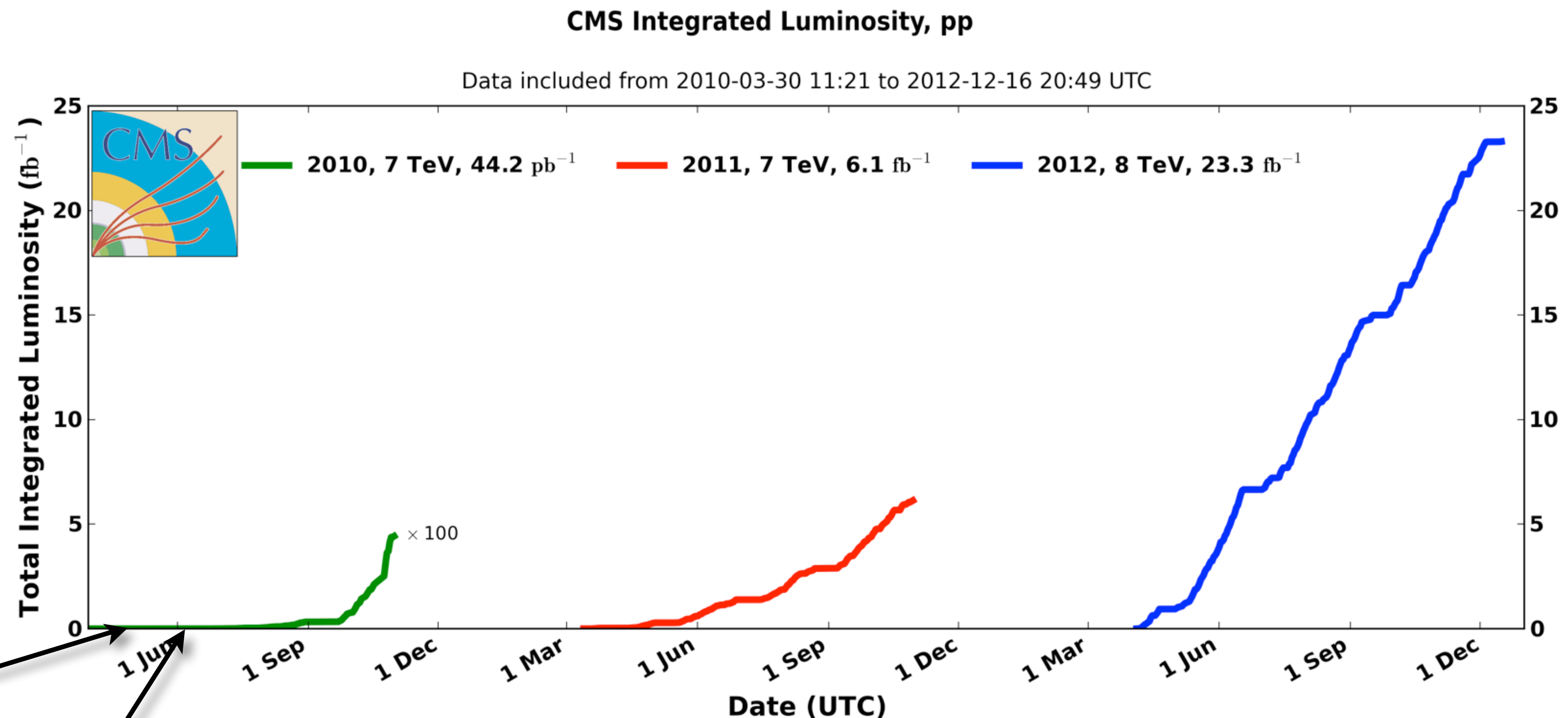

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first incl. jet x-section, PF jets
60/nb δ ~ 20-30%

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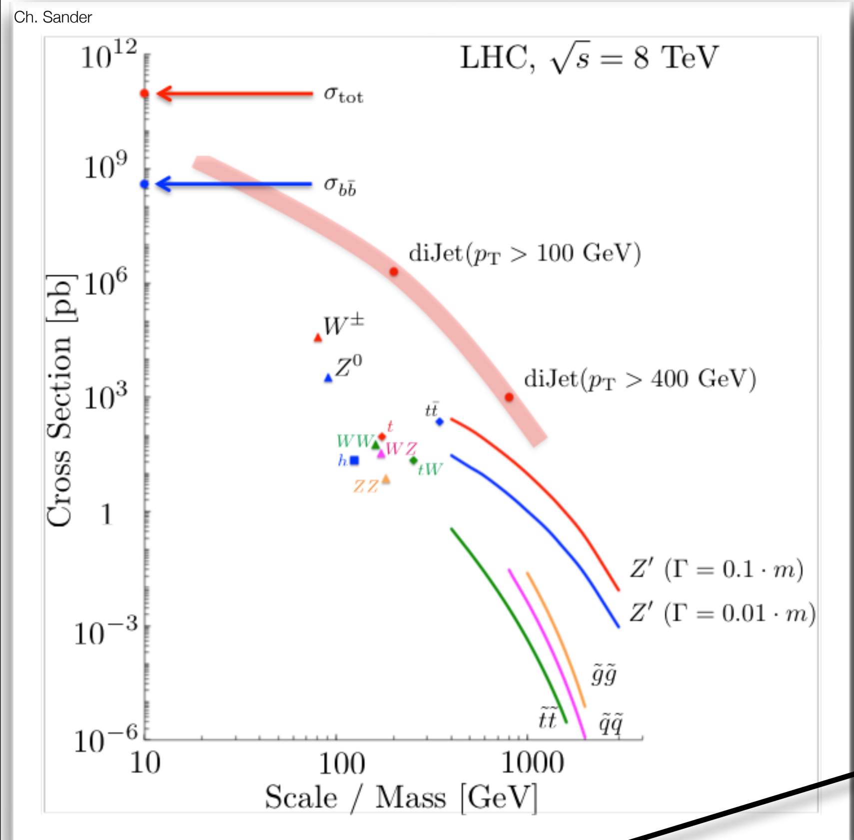

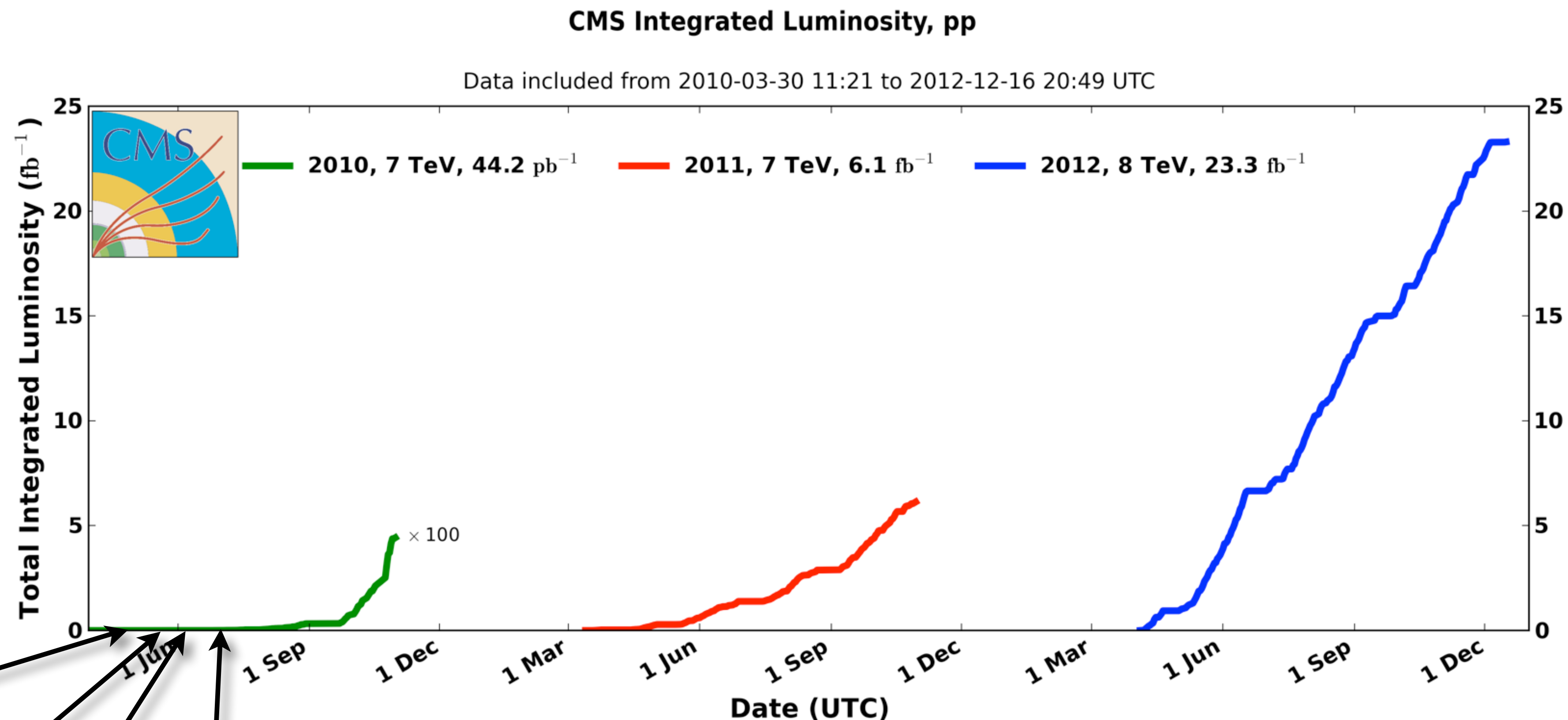

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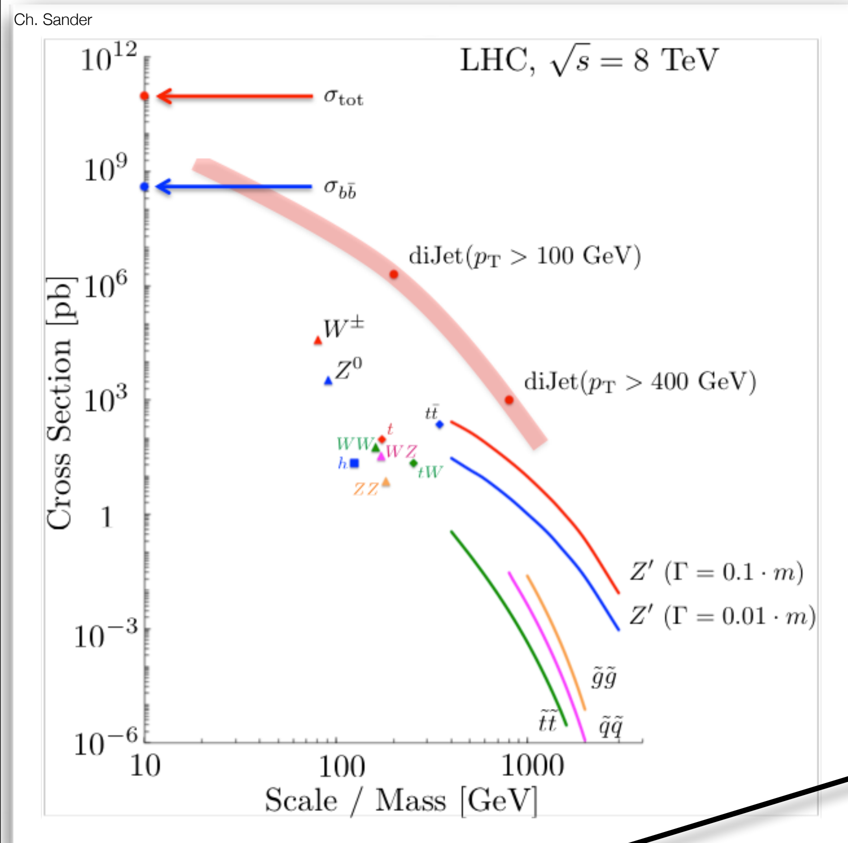

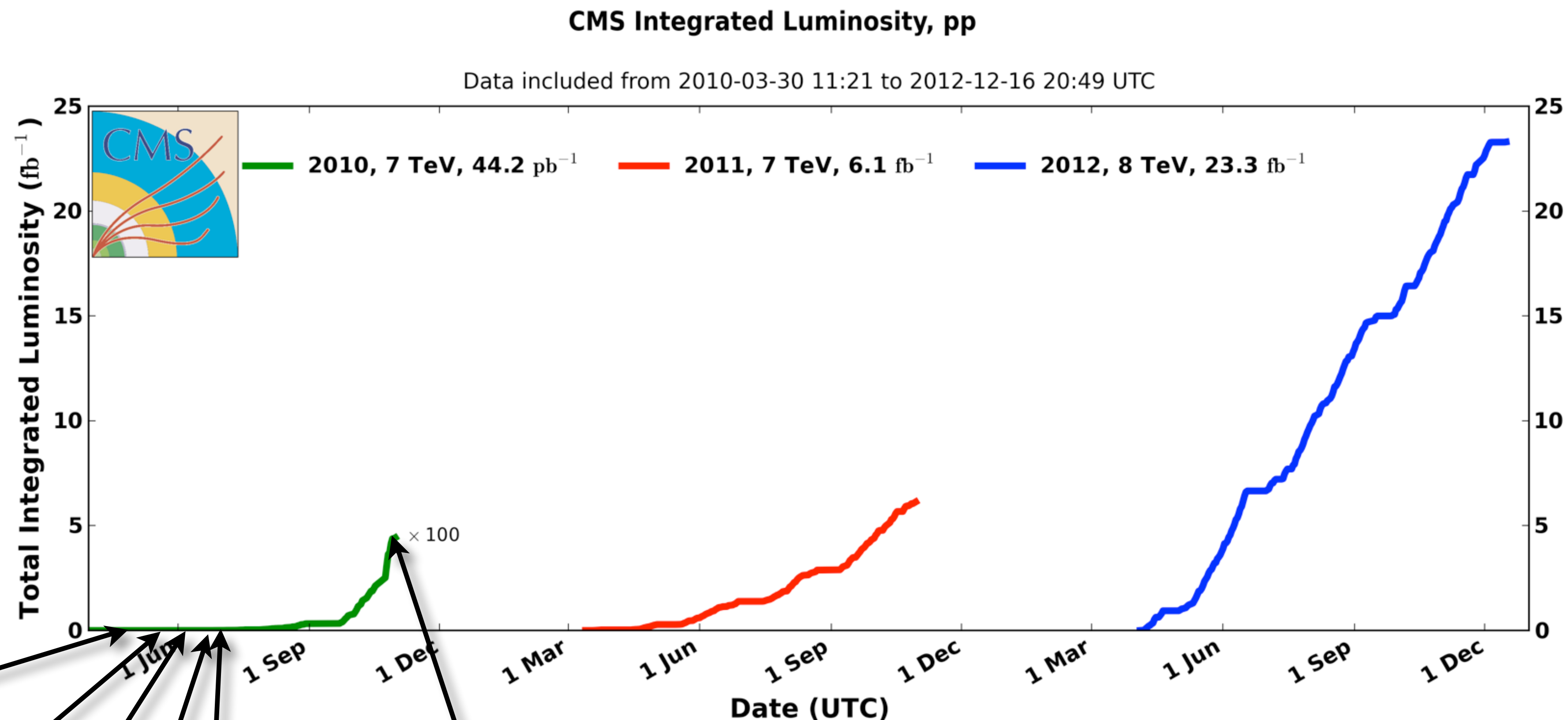

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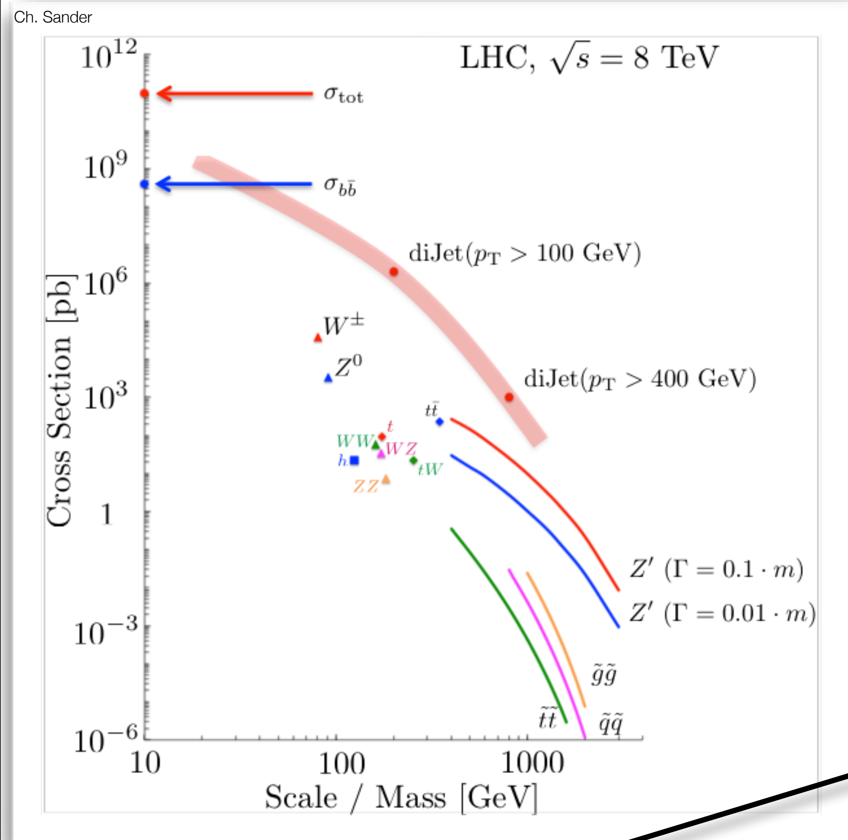

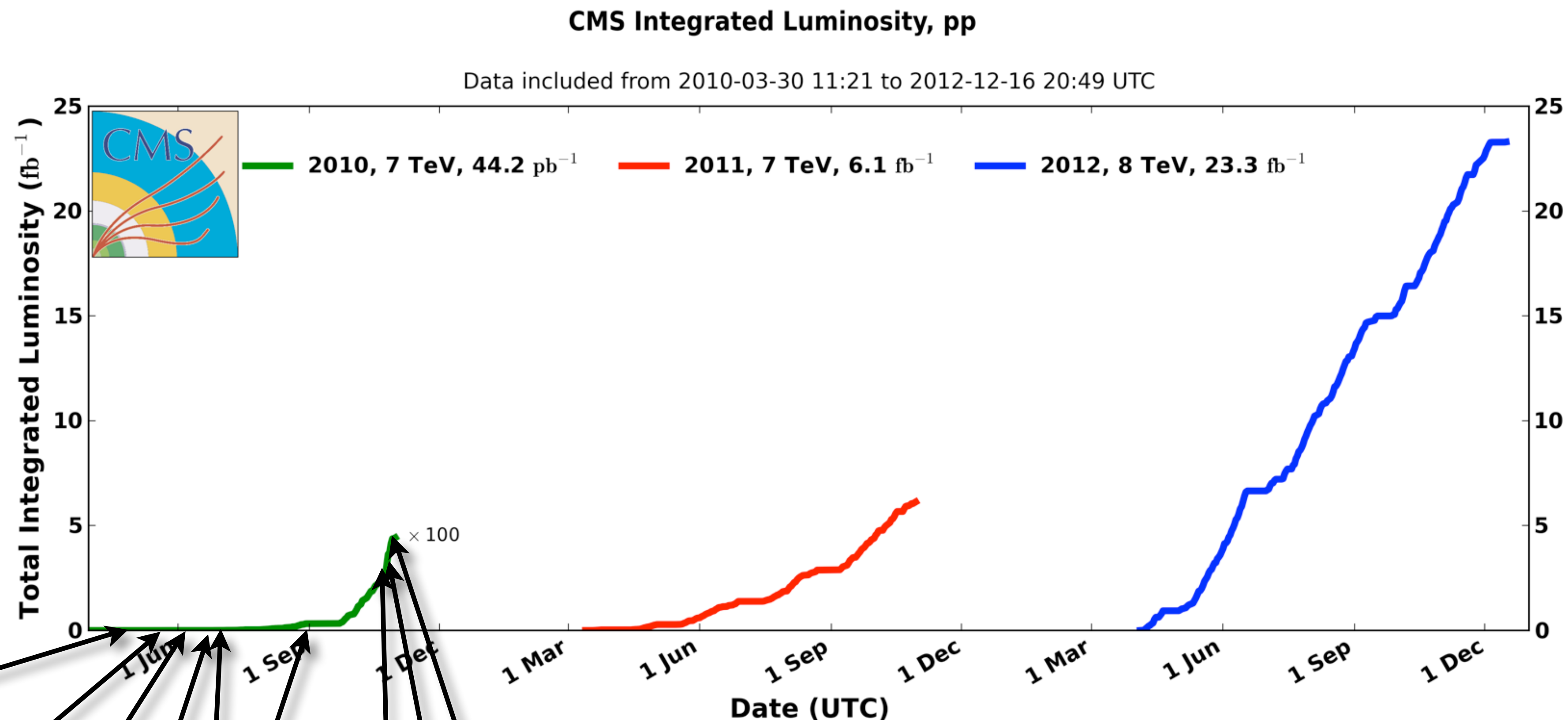

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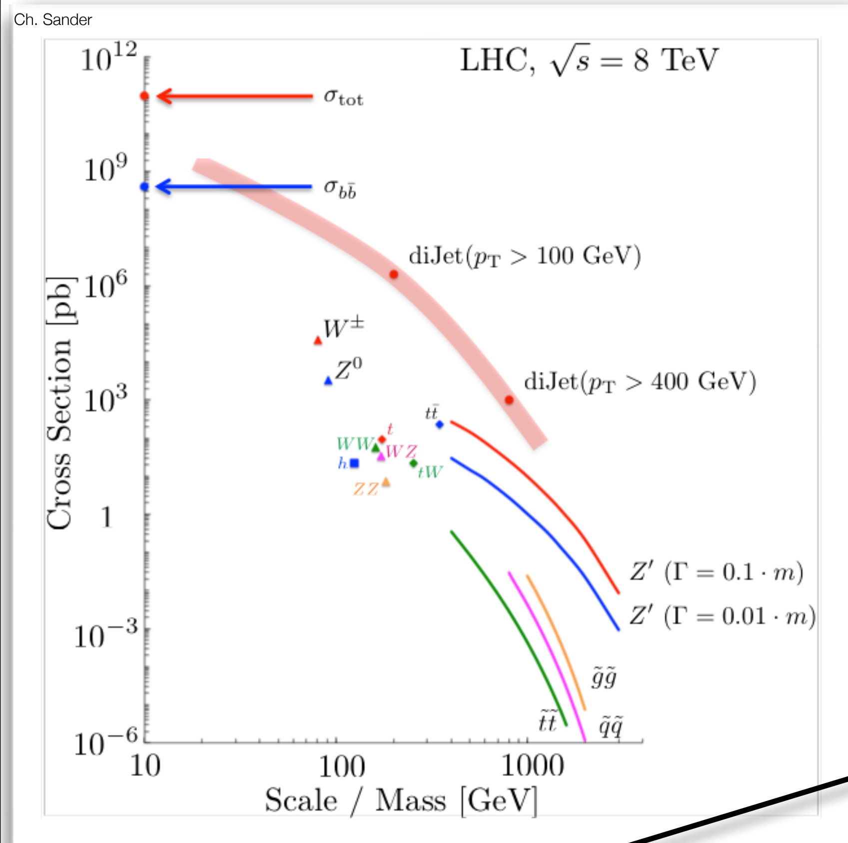

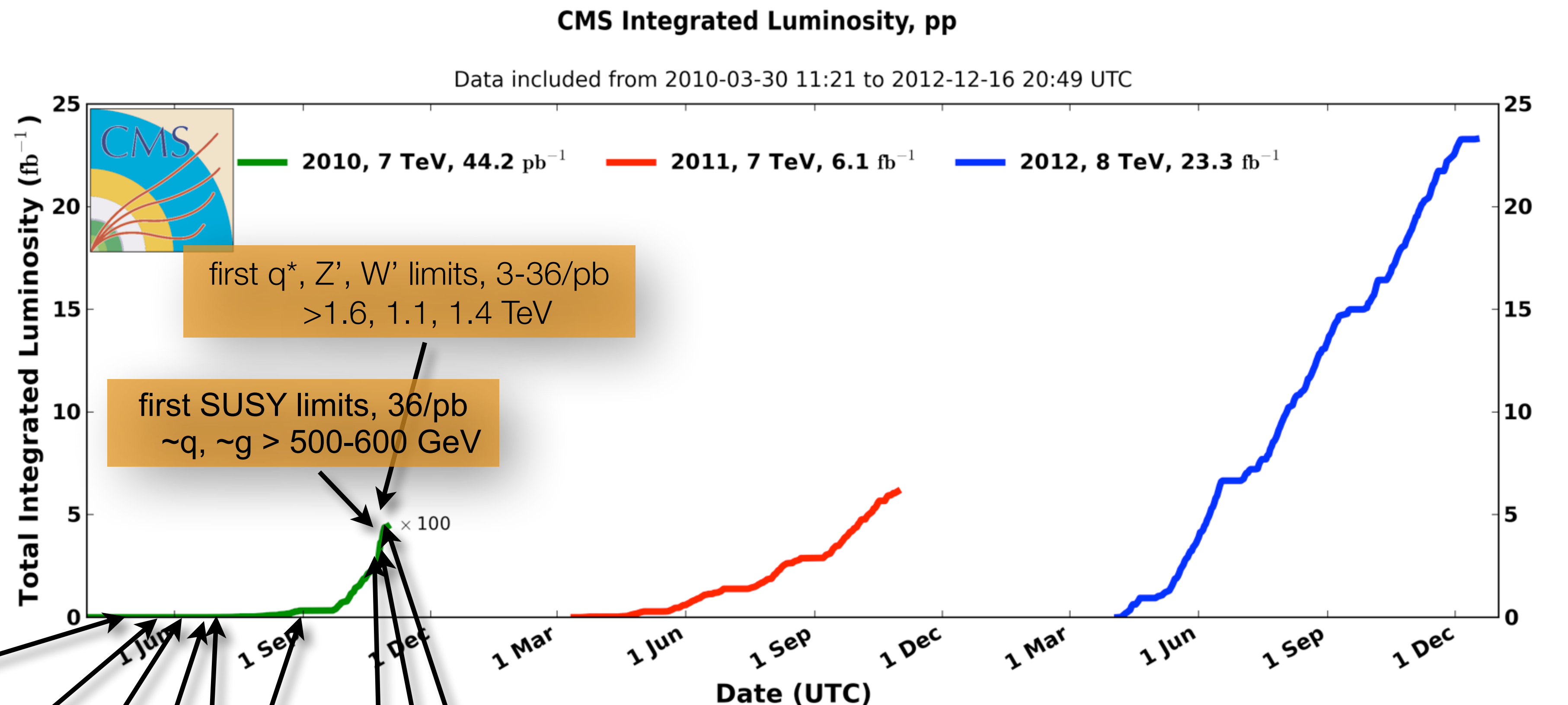

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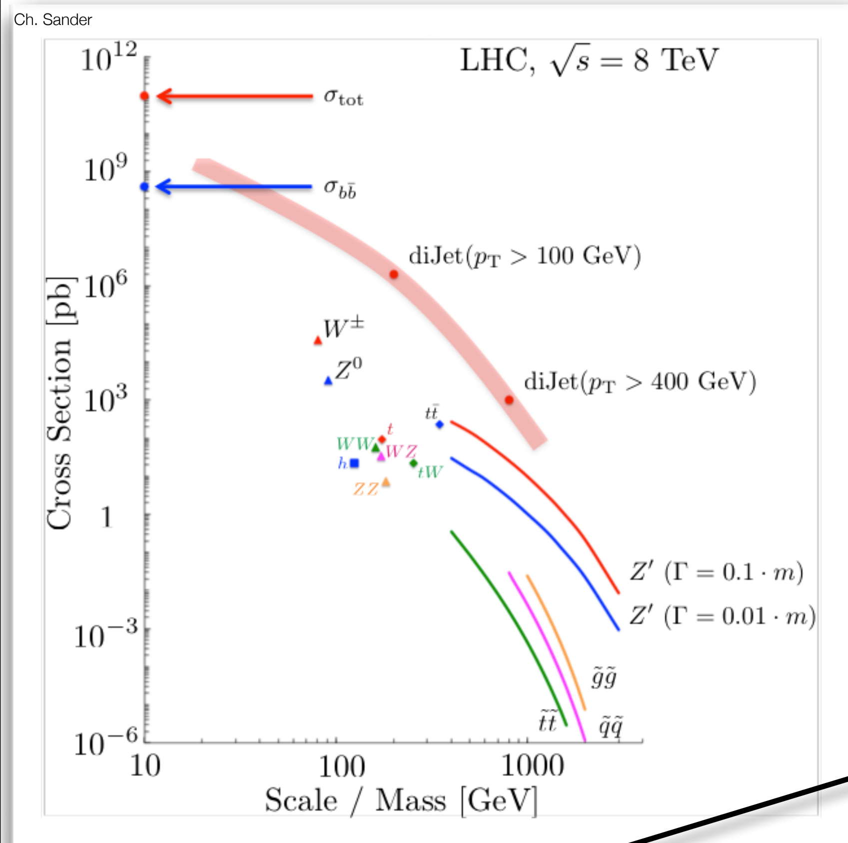

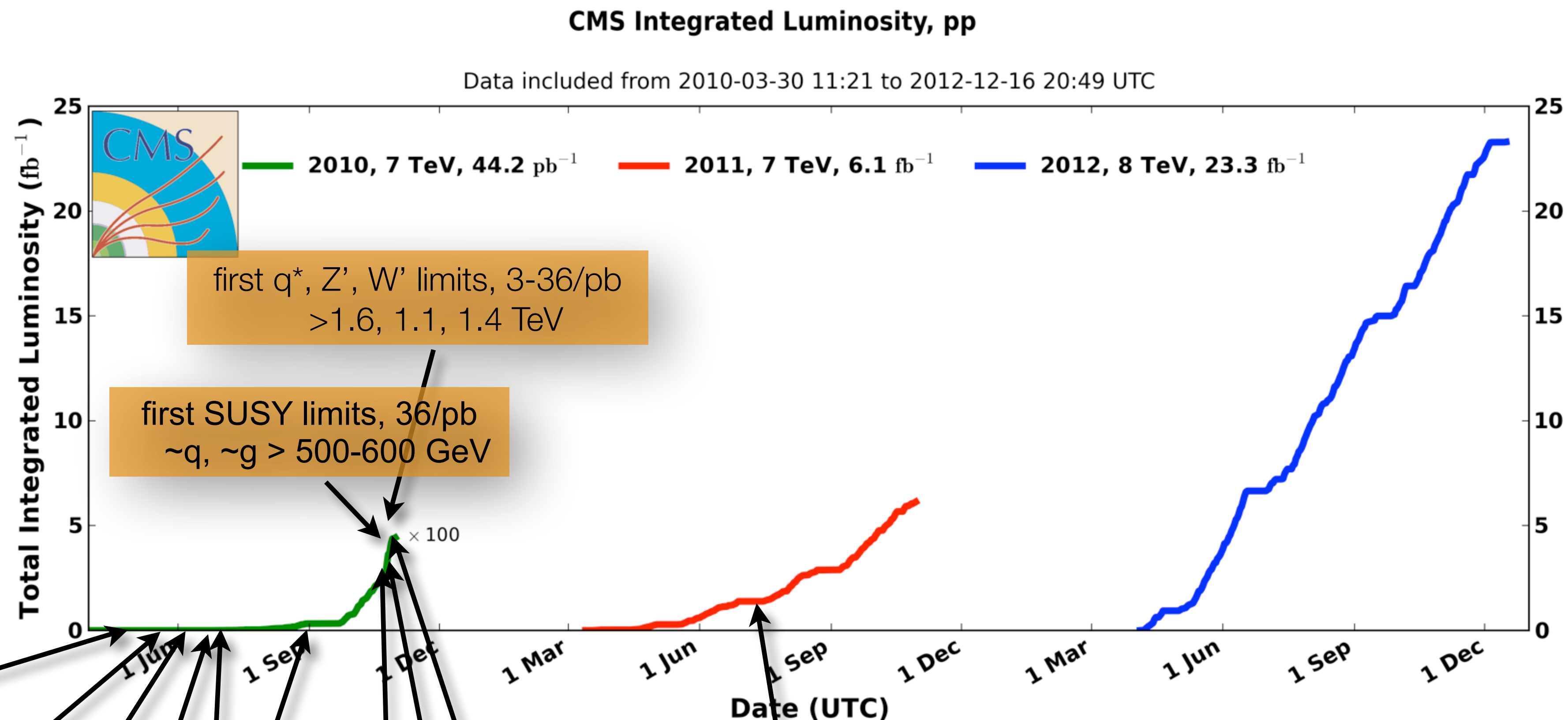

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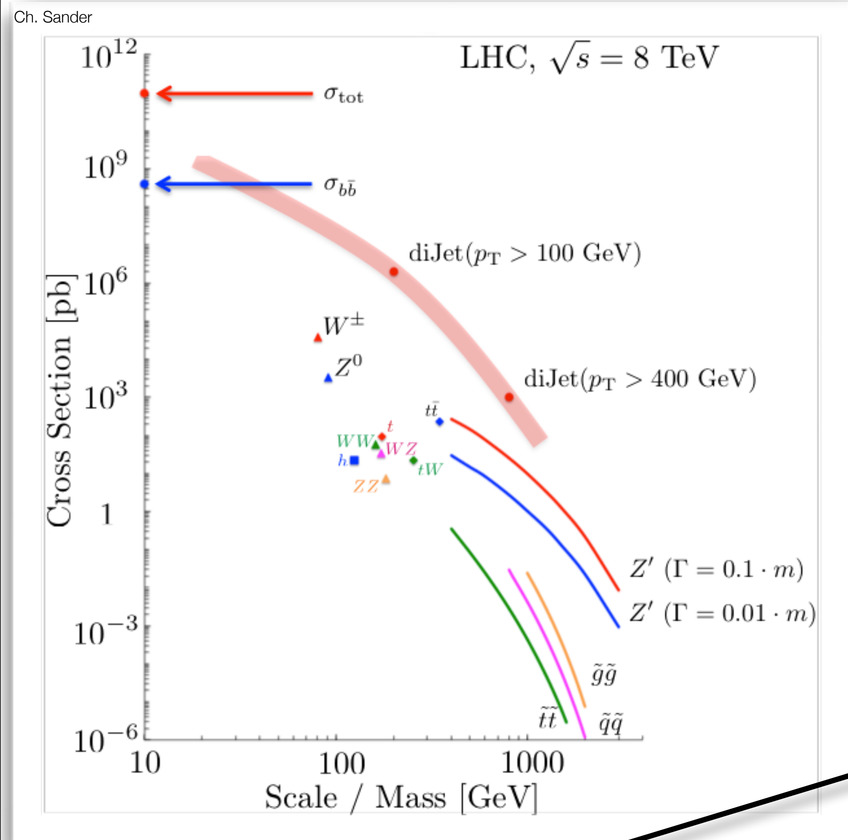

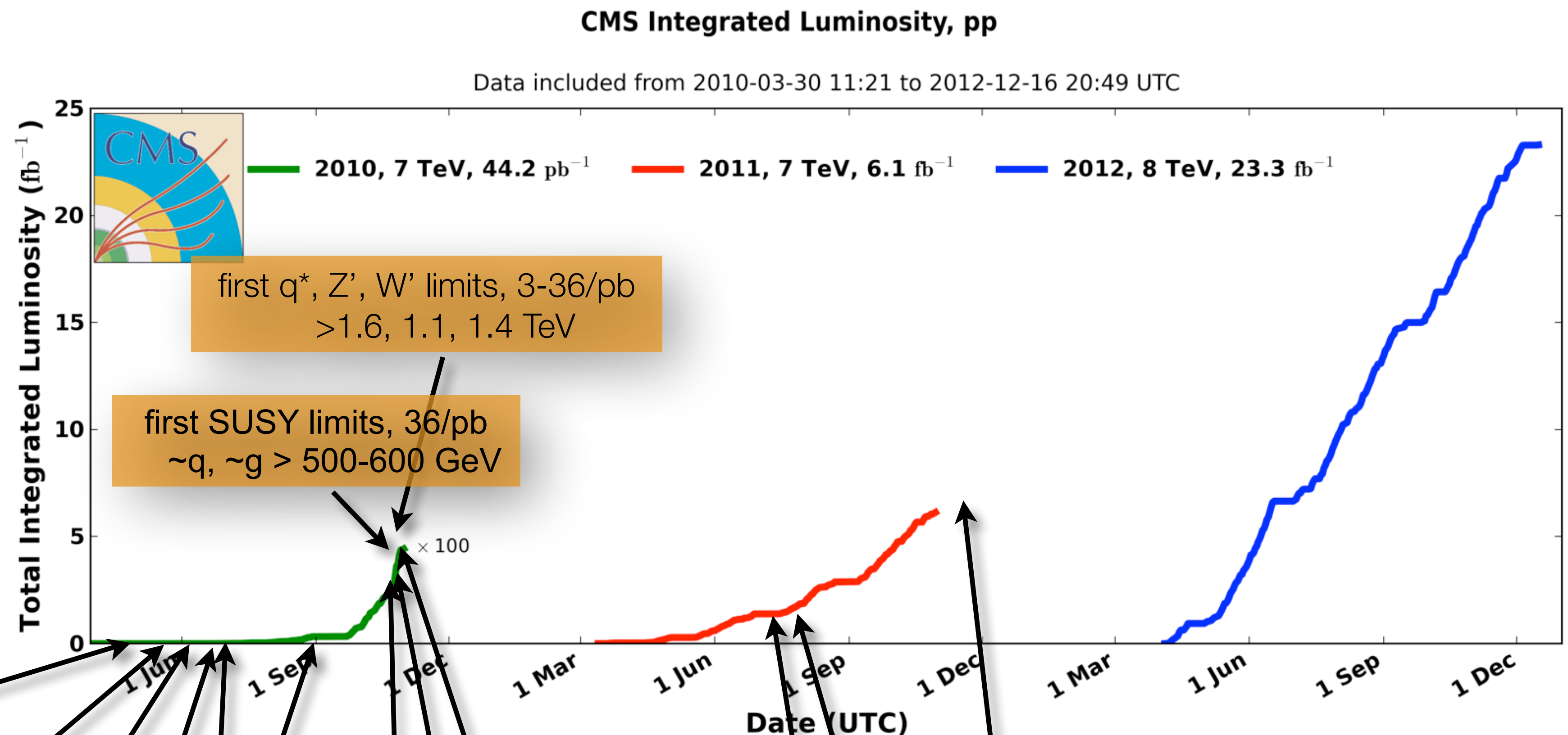

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by CMS: Ξ_b

From G. Dissertori (ETH)

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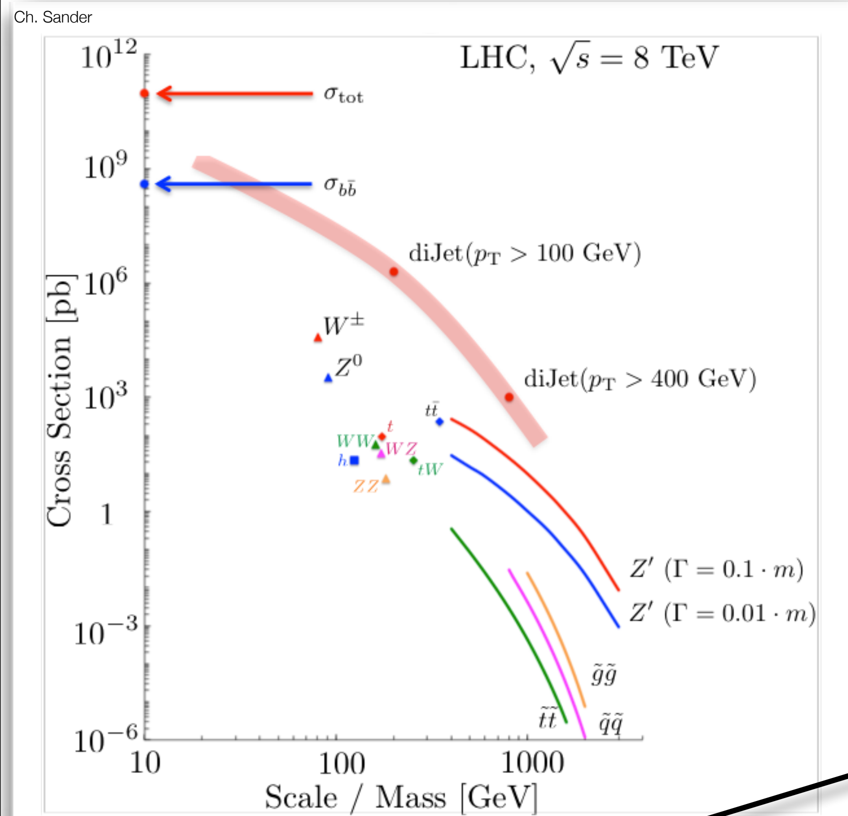

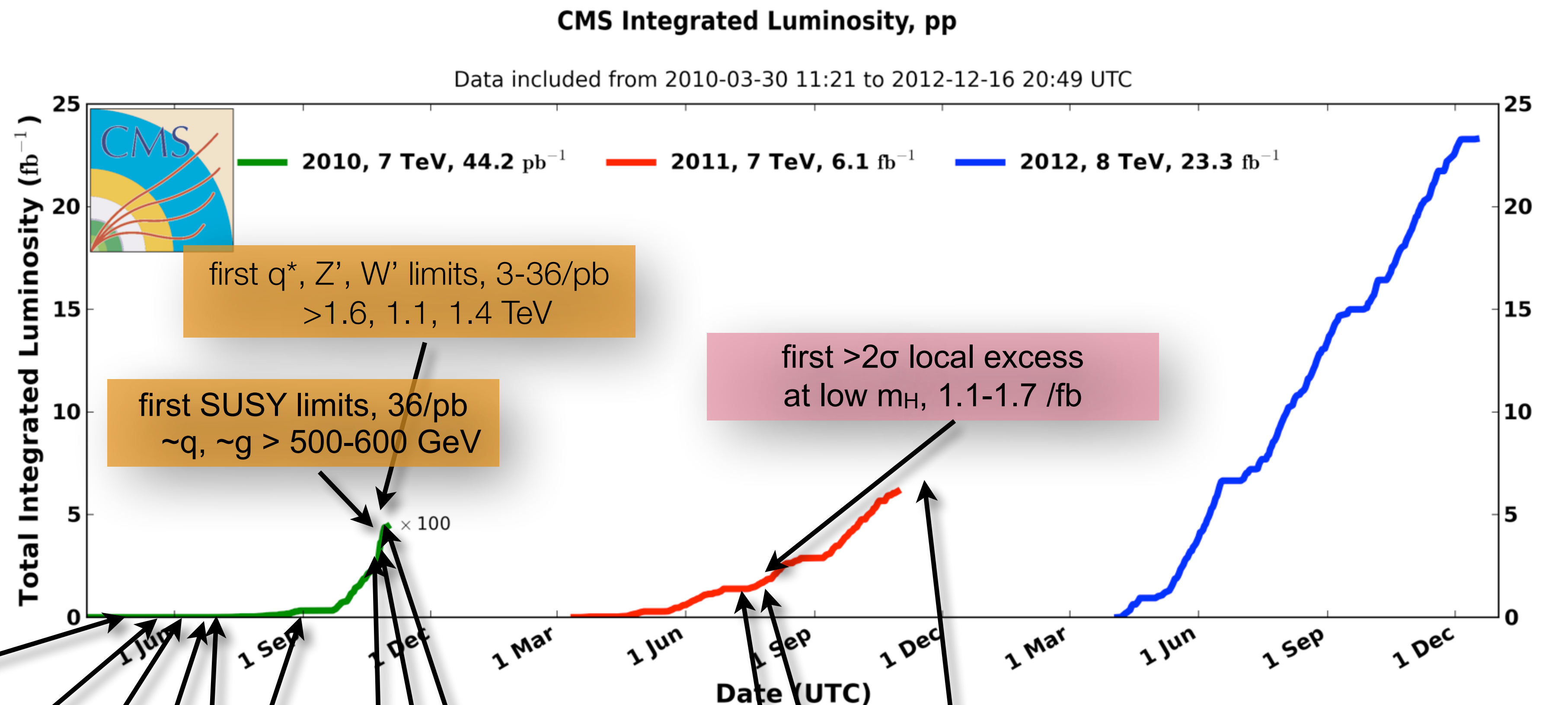

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first >2σ local excess
at low m_H, 1.1-1.7 /fb

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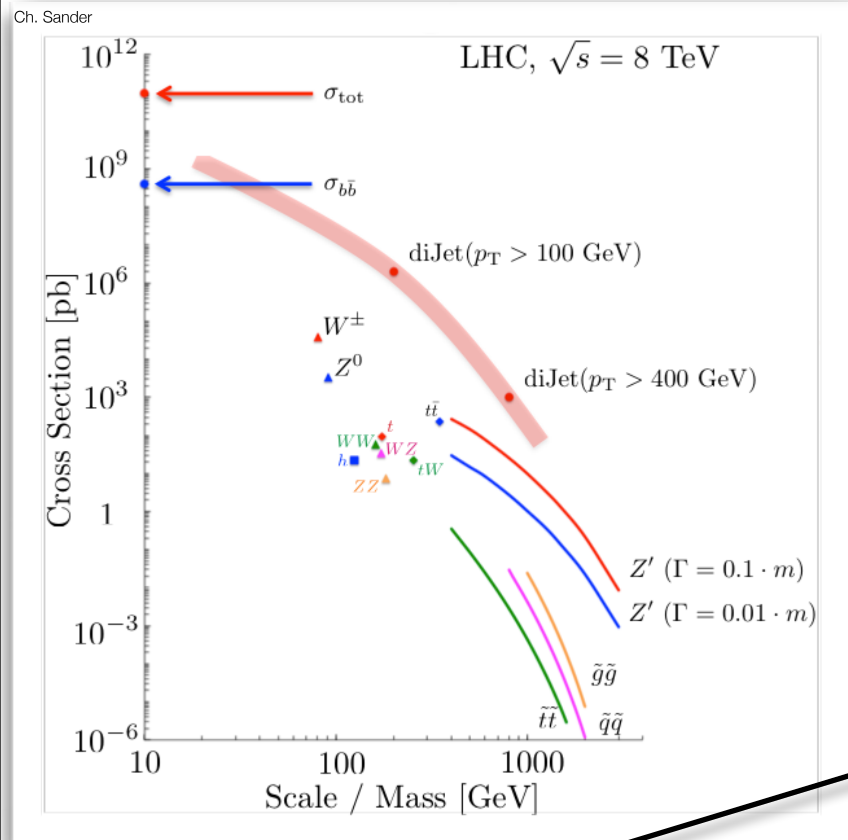

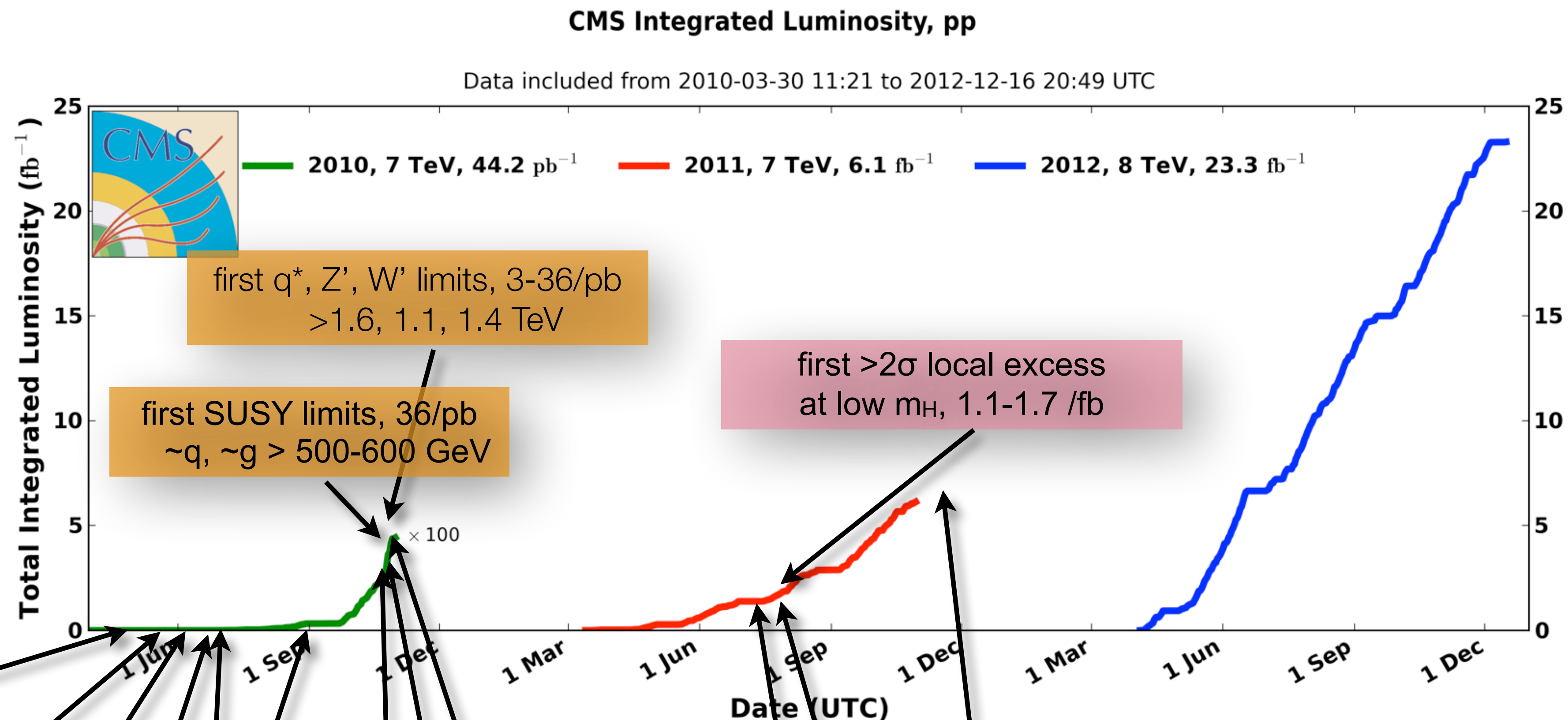

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BSM searches continue, limits pushed

From G. Dissertori (ETH)

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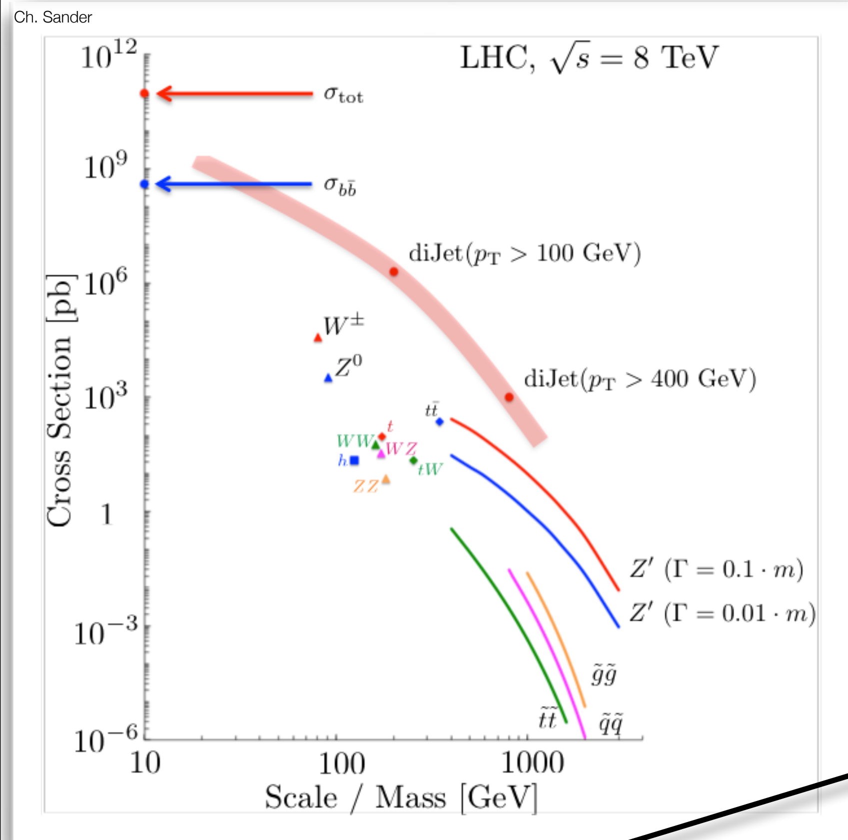

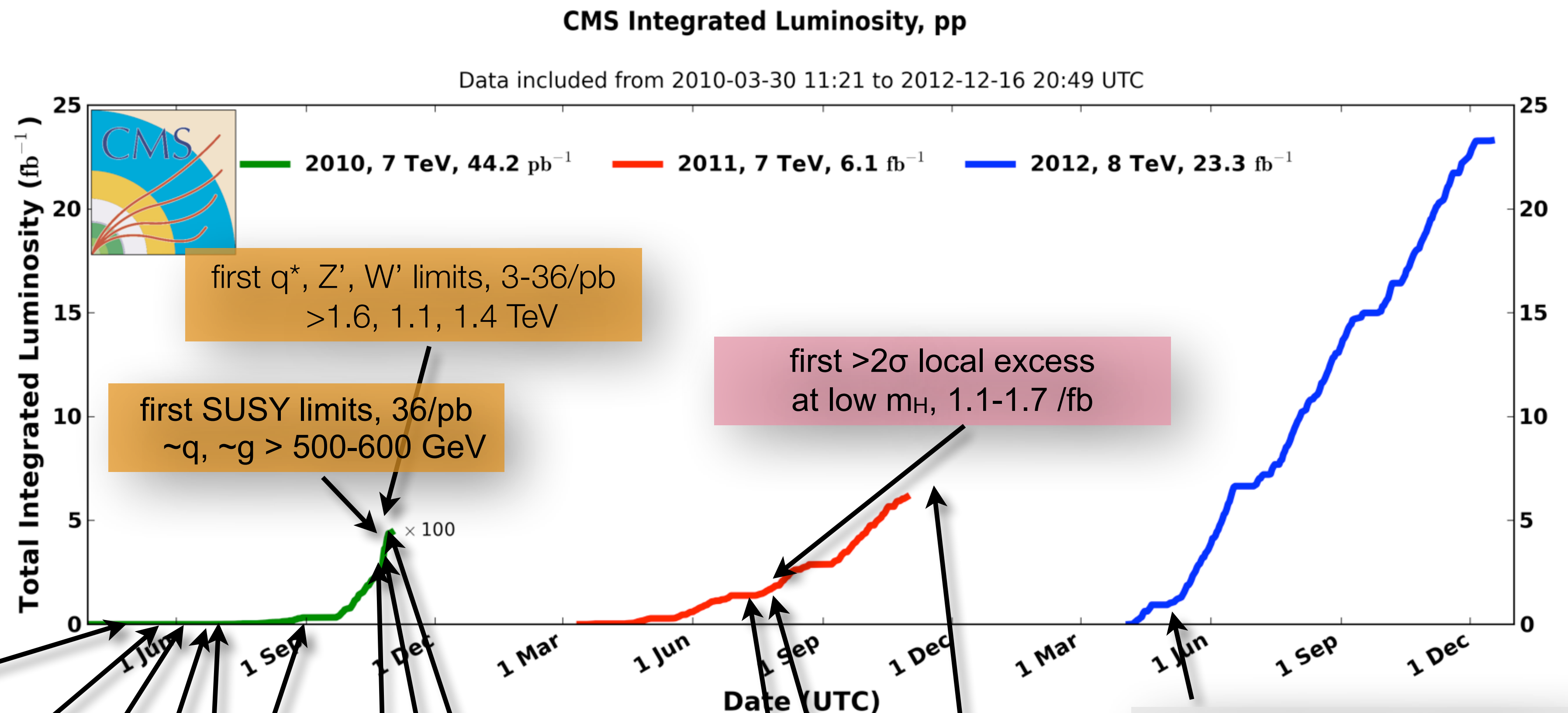

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repeating the program
at 8 TeV

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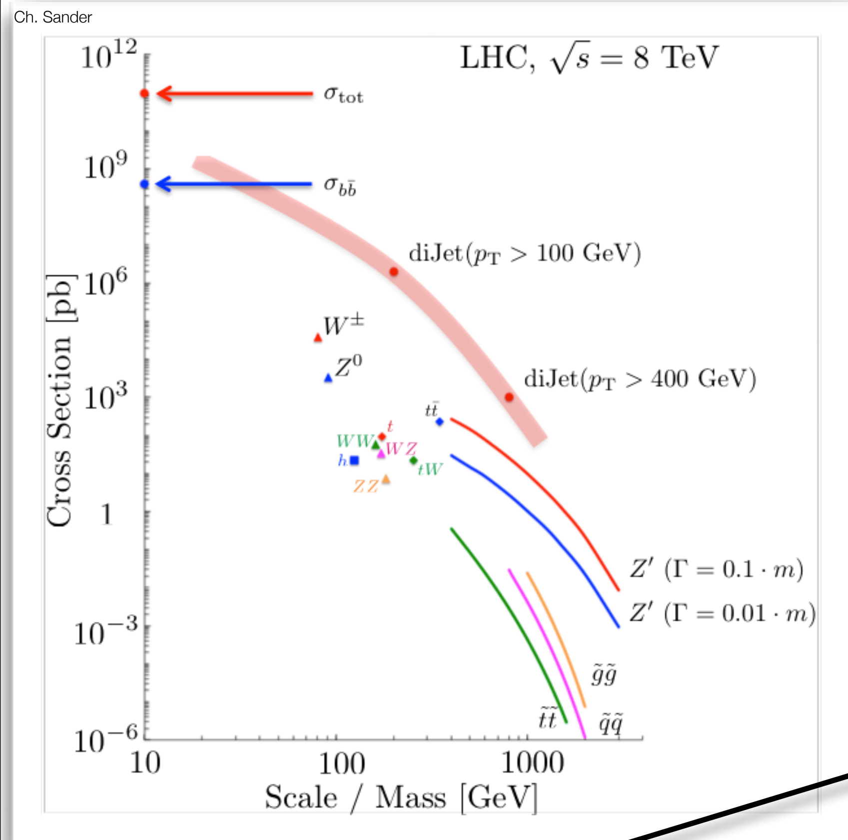

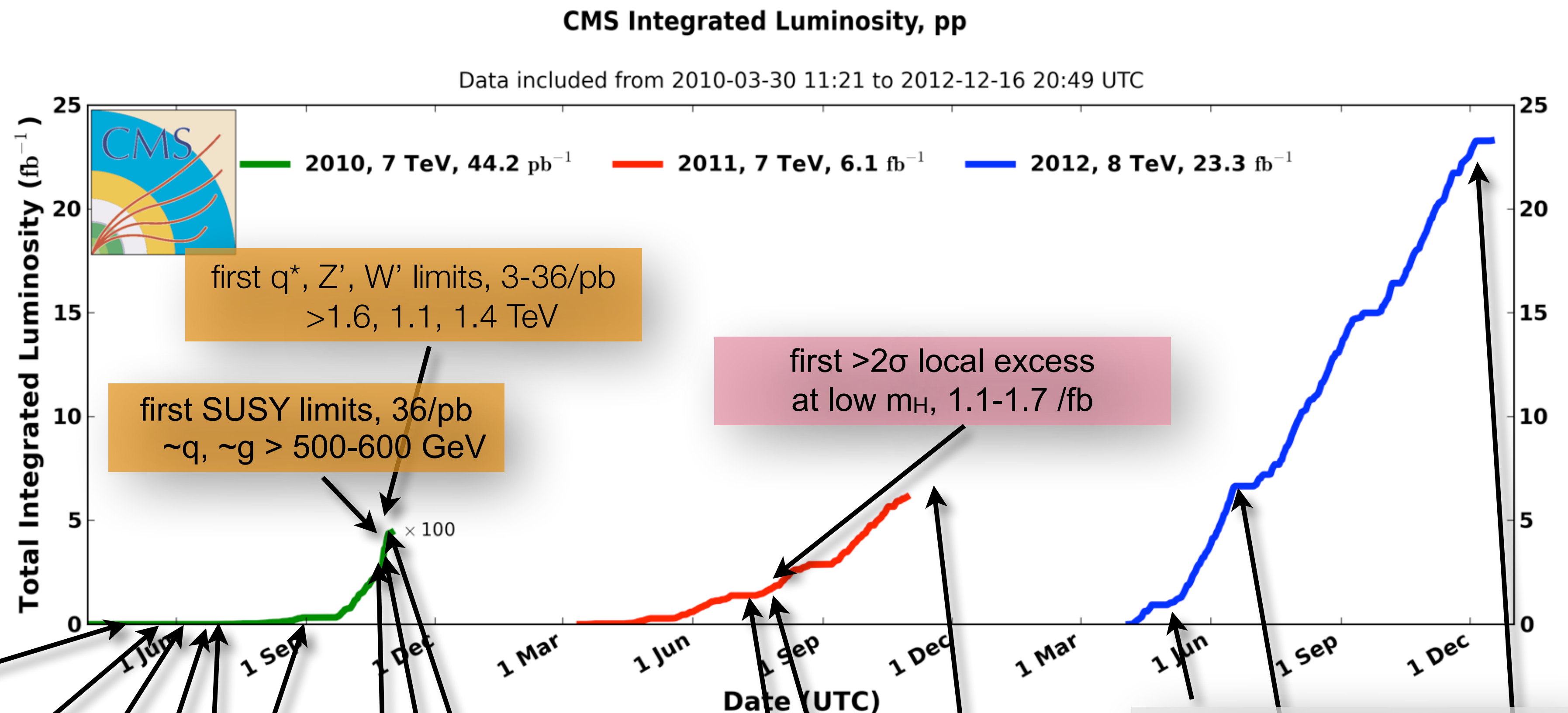

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repeating the program
at 8 TeV

a new boson is
announced, 5 /fb

first spin parity analysis
of the boson, 17 /fb

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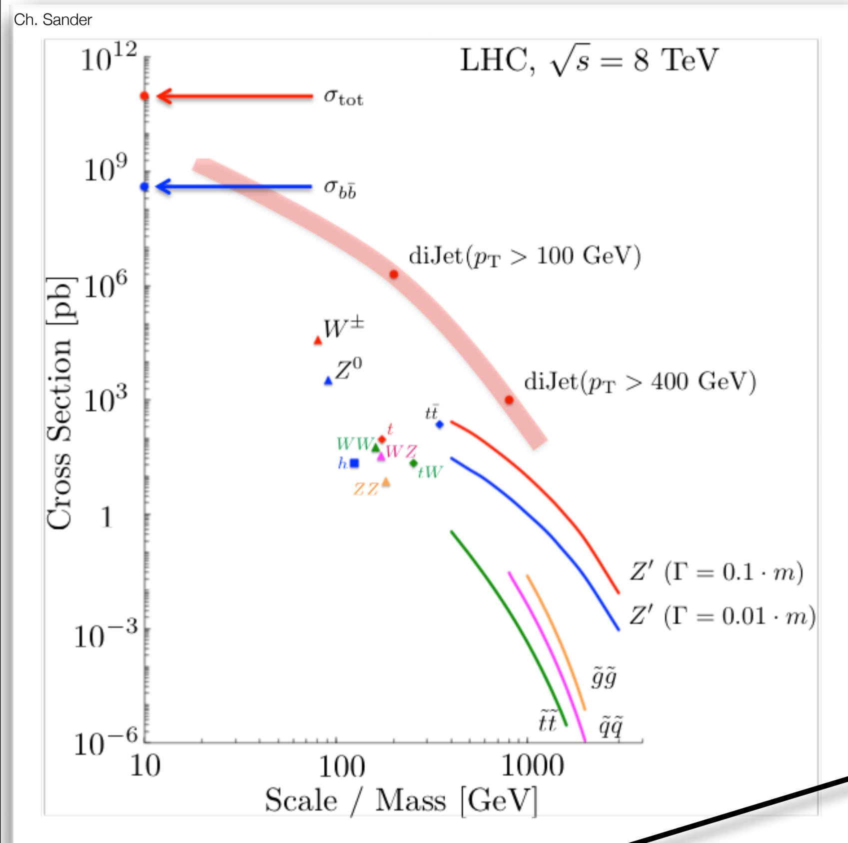

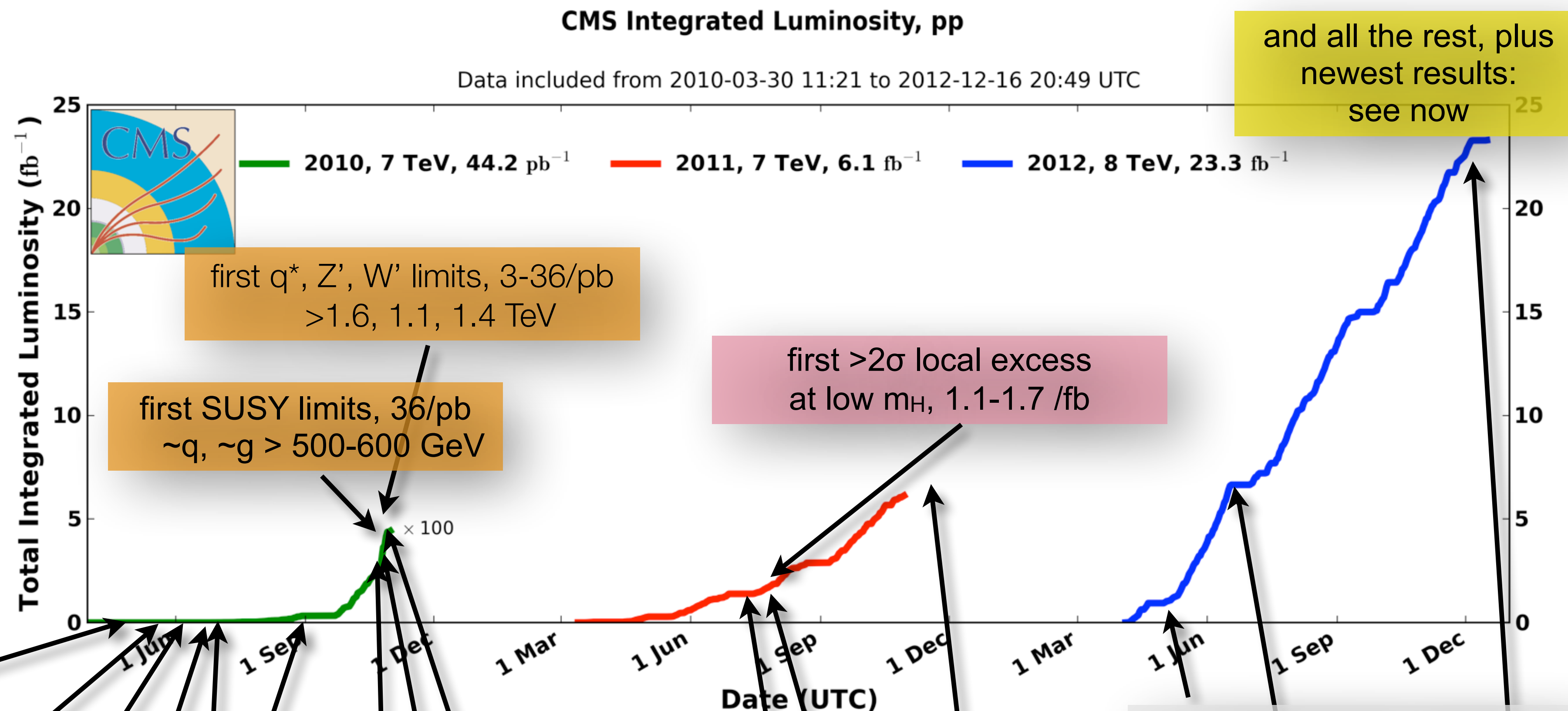

and all the rest, plus newest results: see now

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first SUSY limits, 36/pb ~q, ~g > 500-600 GeV

first >2σ local excess at low m_H, 1.1-1.7 /fb

repeating the program at 8 TeV

first MinBias / UE studies, particle multiplicities

first incl. b x-section, 8/nb δ ~ 15 %

first incl. jet x-section, PF jets 60/nb δ ~ 20-30%

first incl. W/Z x-sections, 200/nb δ ~ 4-6%, +11% lumi

first incl. J/Ψ x-section, 100/nb δ ~ 20%

first top xsec, 3/pb δ ~ 40%

first single top xsec, t-chan., 36/pb δ ~ 36%

first m_{top}, 36/pb Δ ~ 6.5 GeV

first WW xsec, 36/pb δ ~ 40% first limit on HWW

first ZZ xsec, 1.1 /fb δ ~ 40%

going more differential, e.g. Z/W + j,b,c

first significant limit on $B_s \to \mu\mu$, BR<1.9×10^{-8}

first particle discovered by CMS: Ξ_b

BSM searches continue, limits pushed

a new boson is announced, 5 /fb

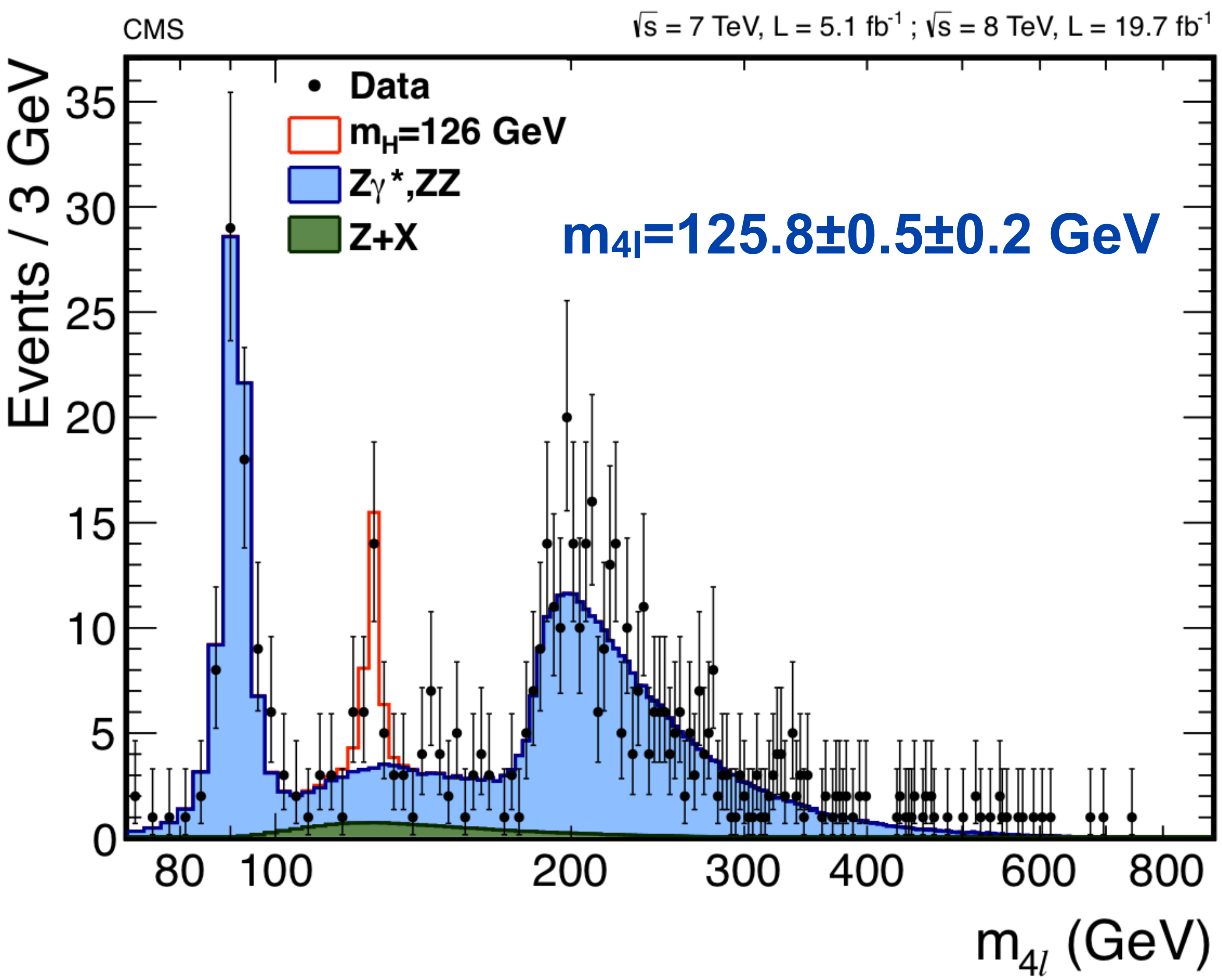
first spin parity analysis of the boson, 17 /fb

δ .. relative uncert.
Δ .. absolute uncert.

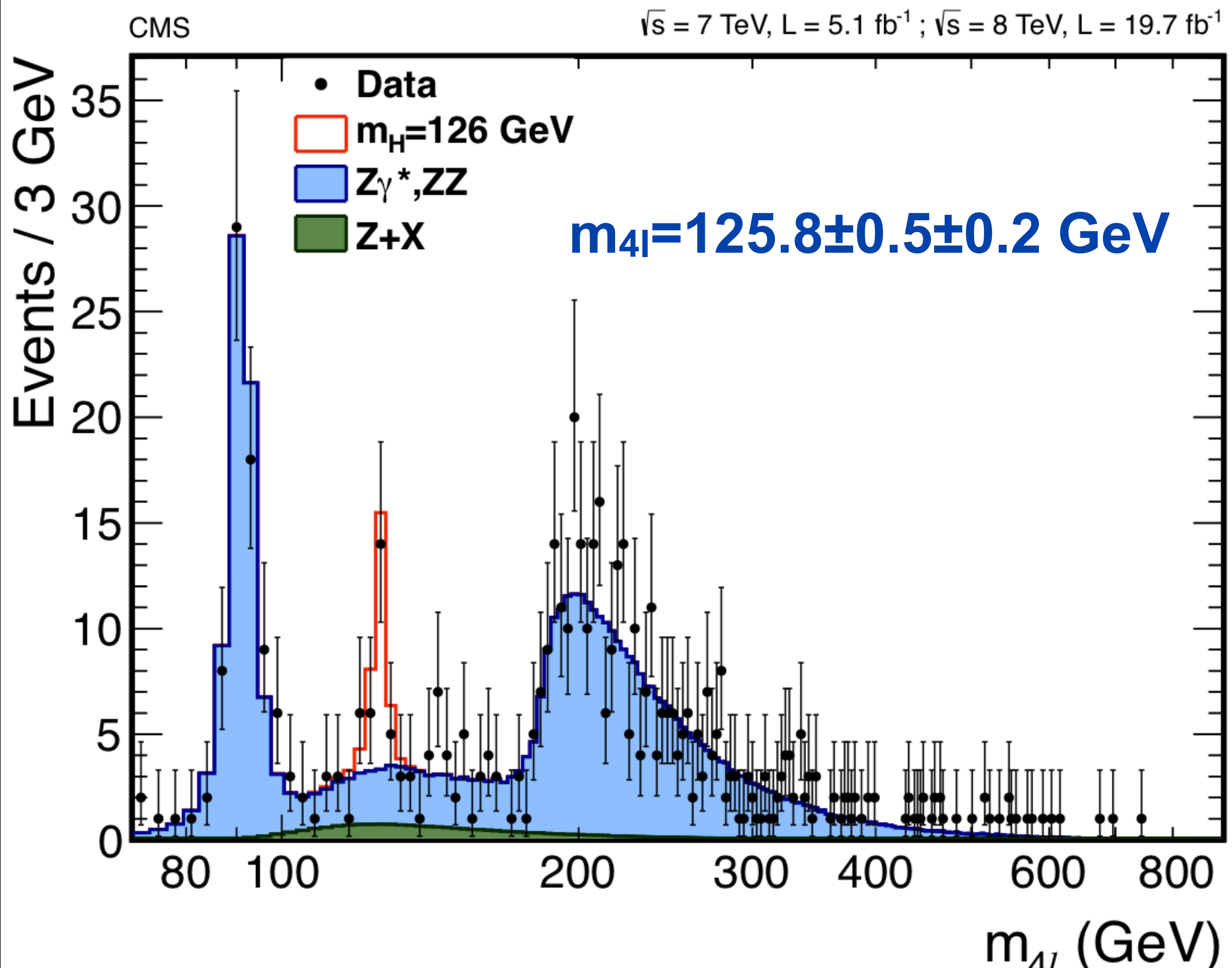
From G. Dissertori (ETH)

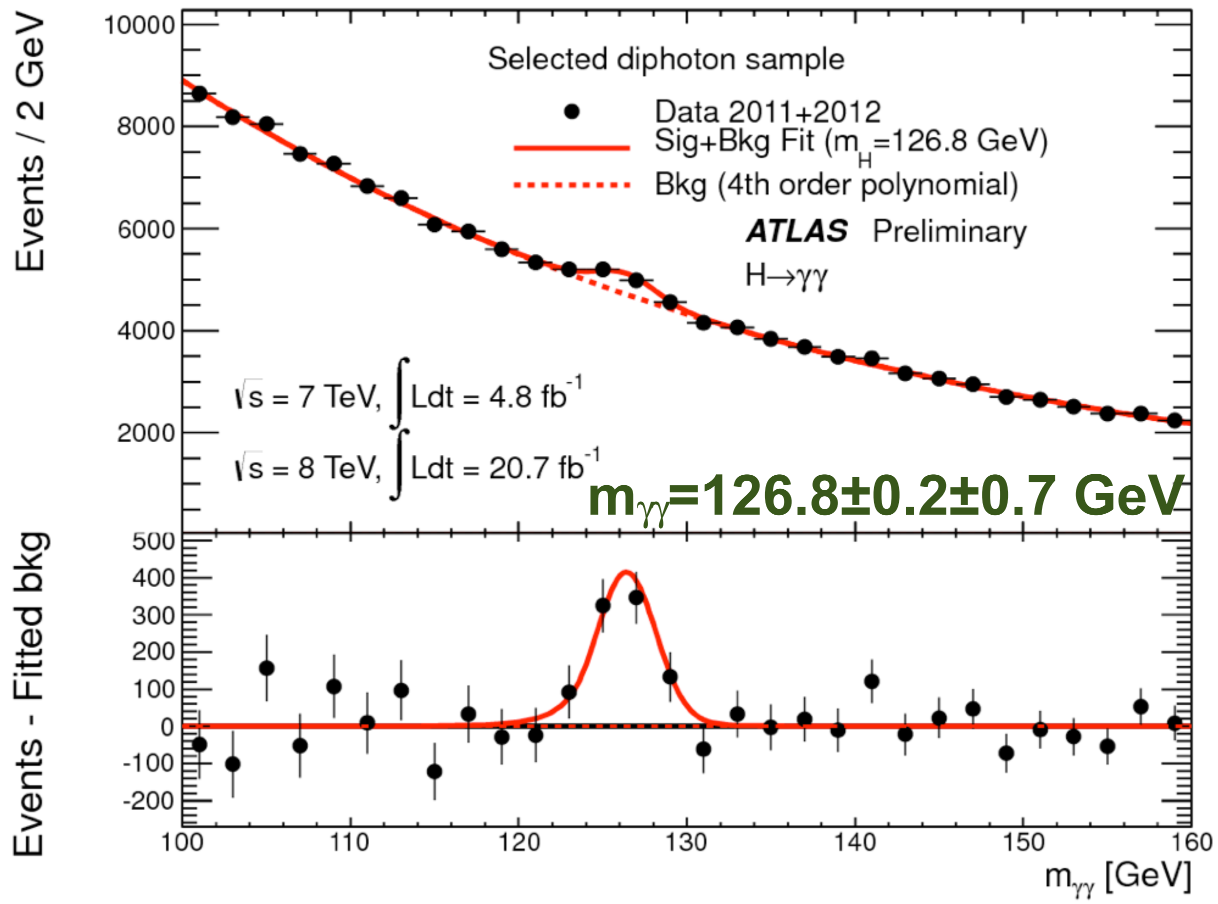
New boson with a mass of ~125 GeV

New boson with a mass of ~125 GeV



New boson with a mass of ~125 GeV





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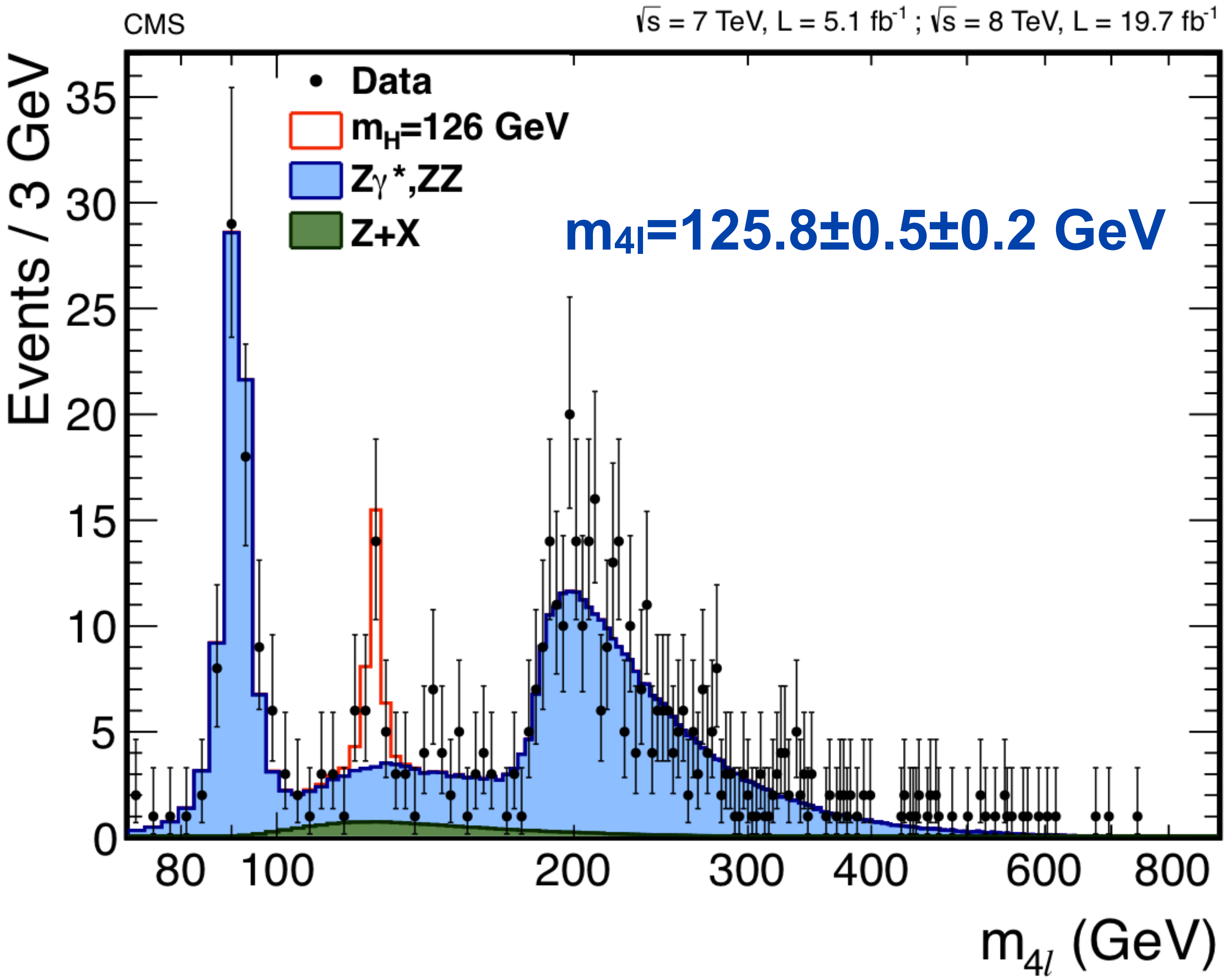
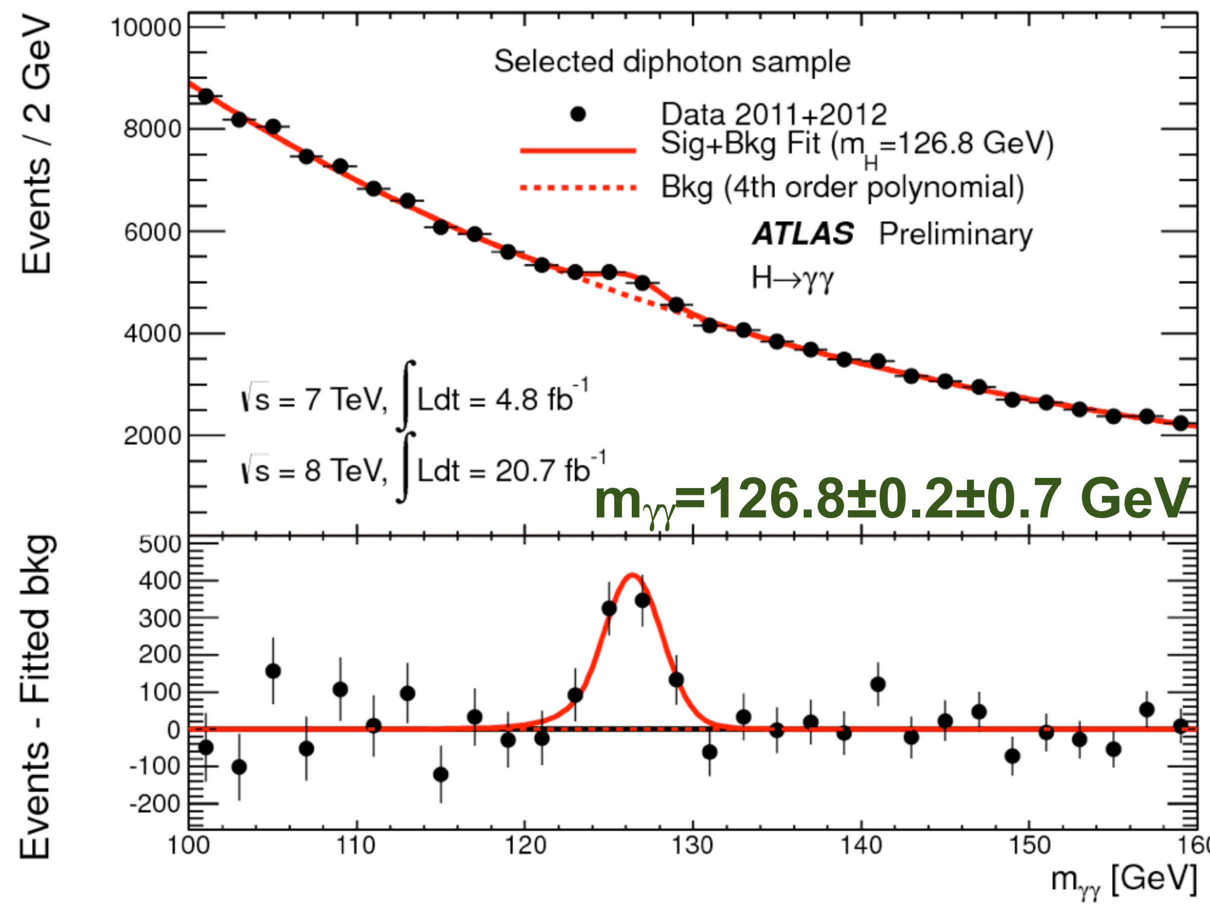
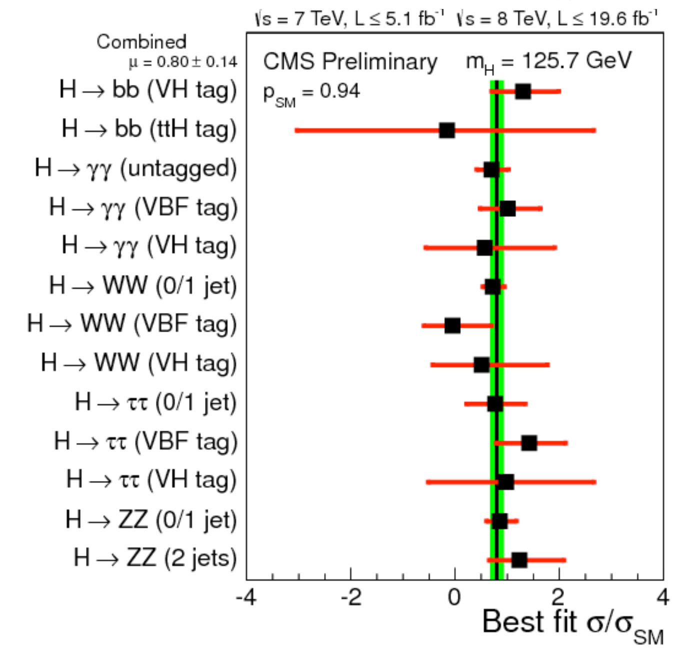


m_{4l}=125.8±0.5±0.2 GeV

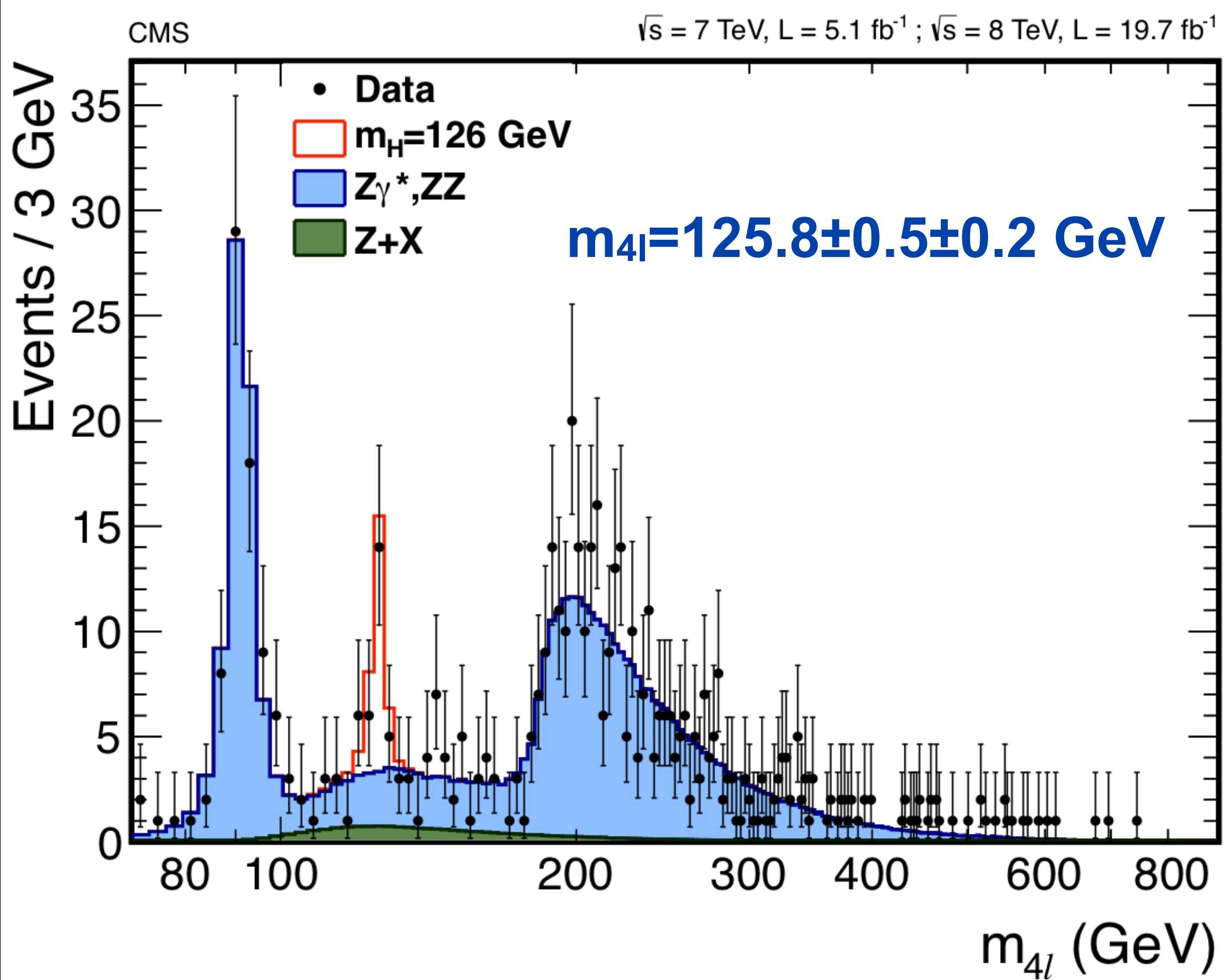


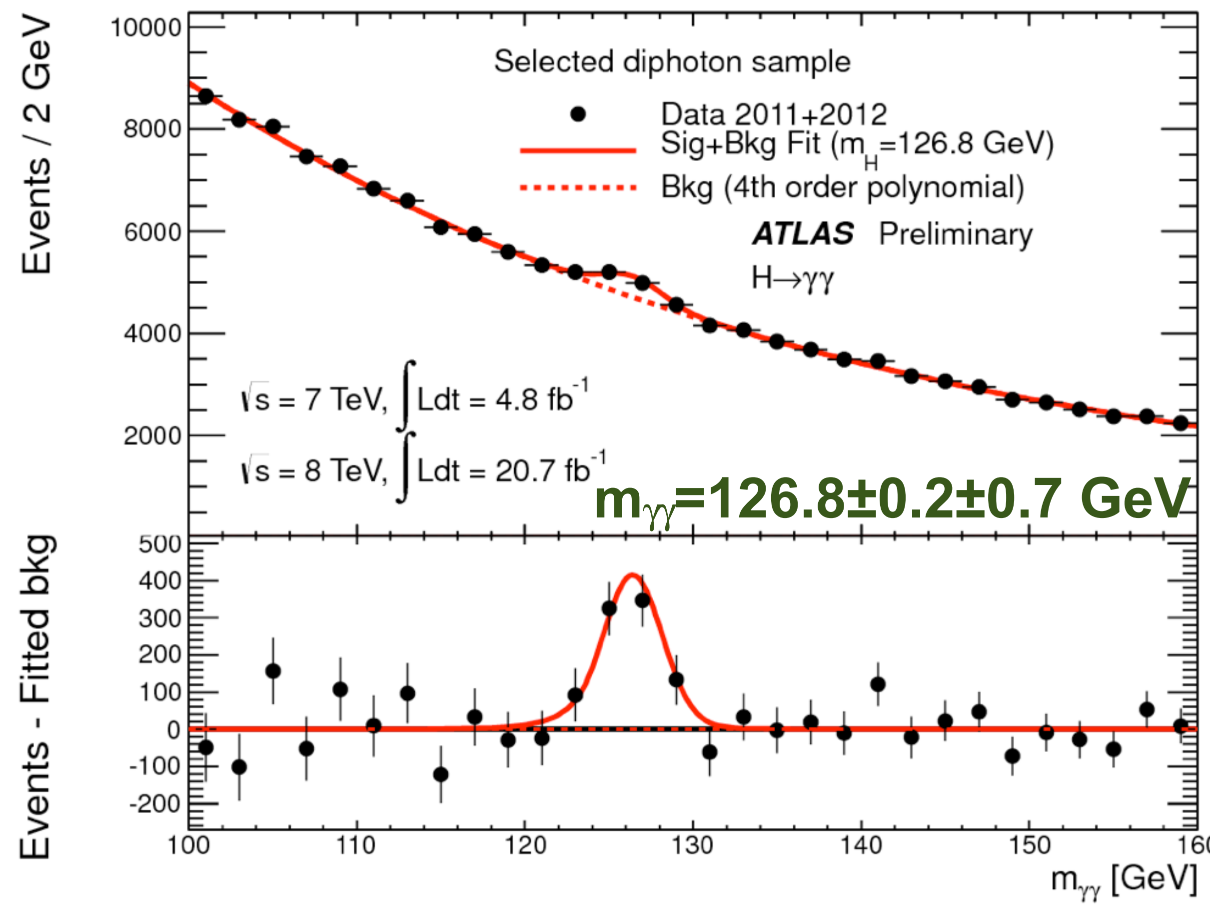
$m_{\gamma\gamma}$=126.8±0.2±0.7 GeV

$\mu = \sigma/\sigma_{SM}$ = 0.80±0.14



New boson with a mass of ~125 GeV





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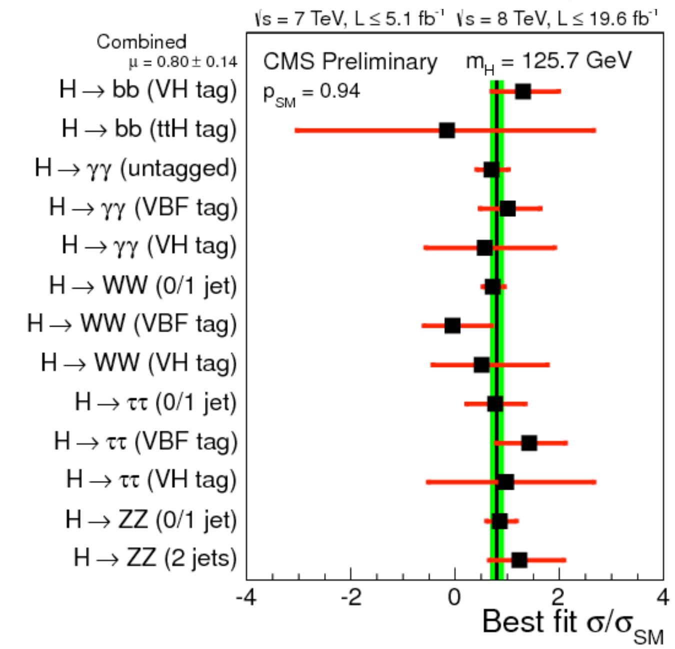
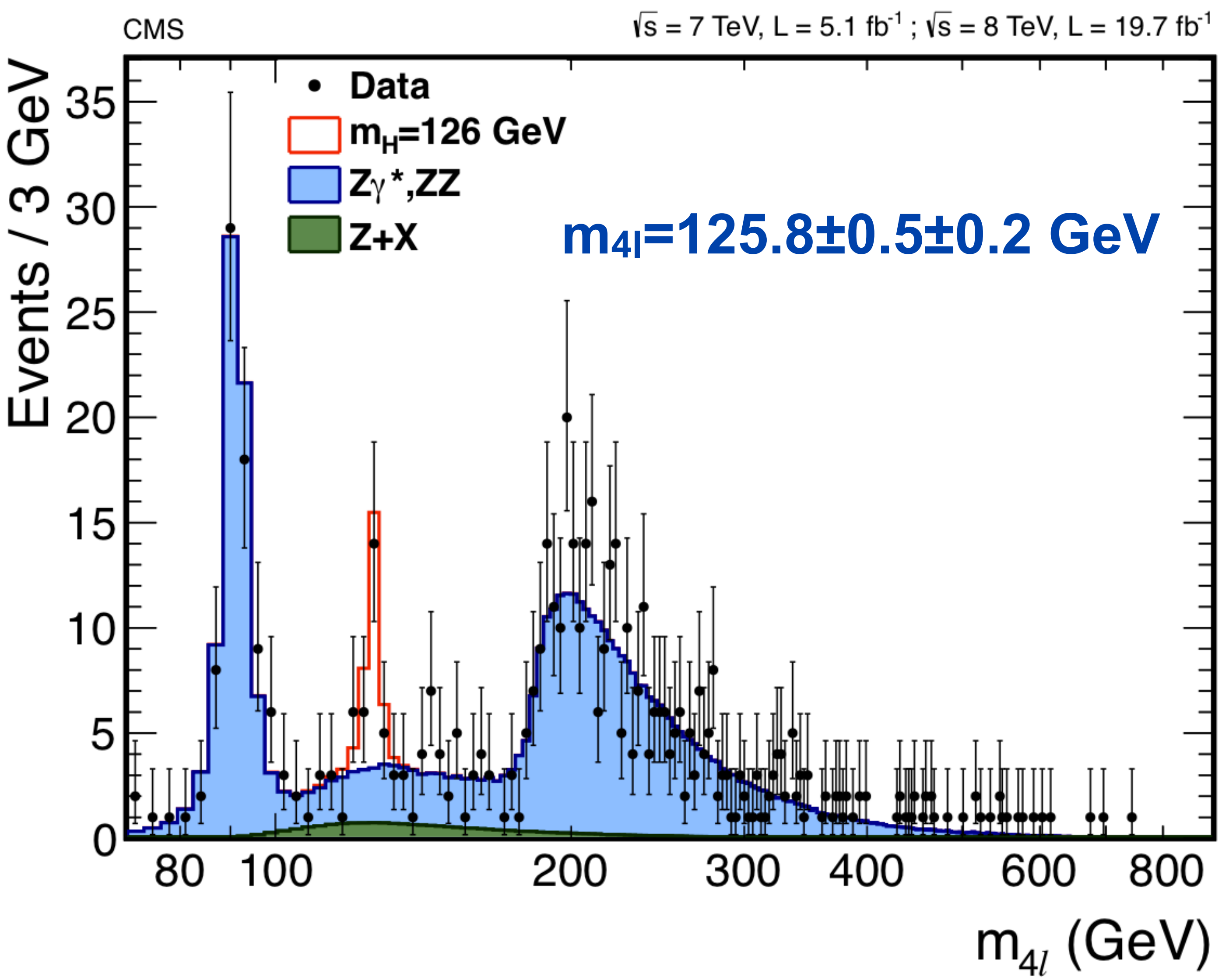
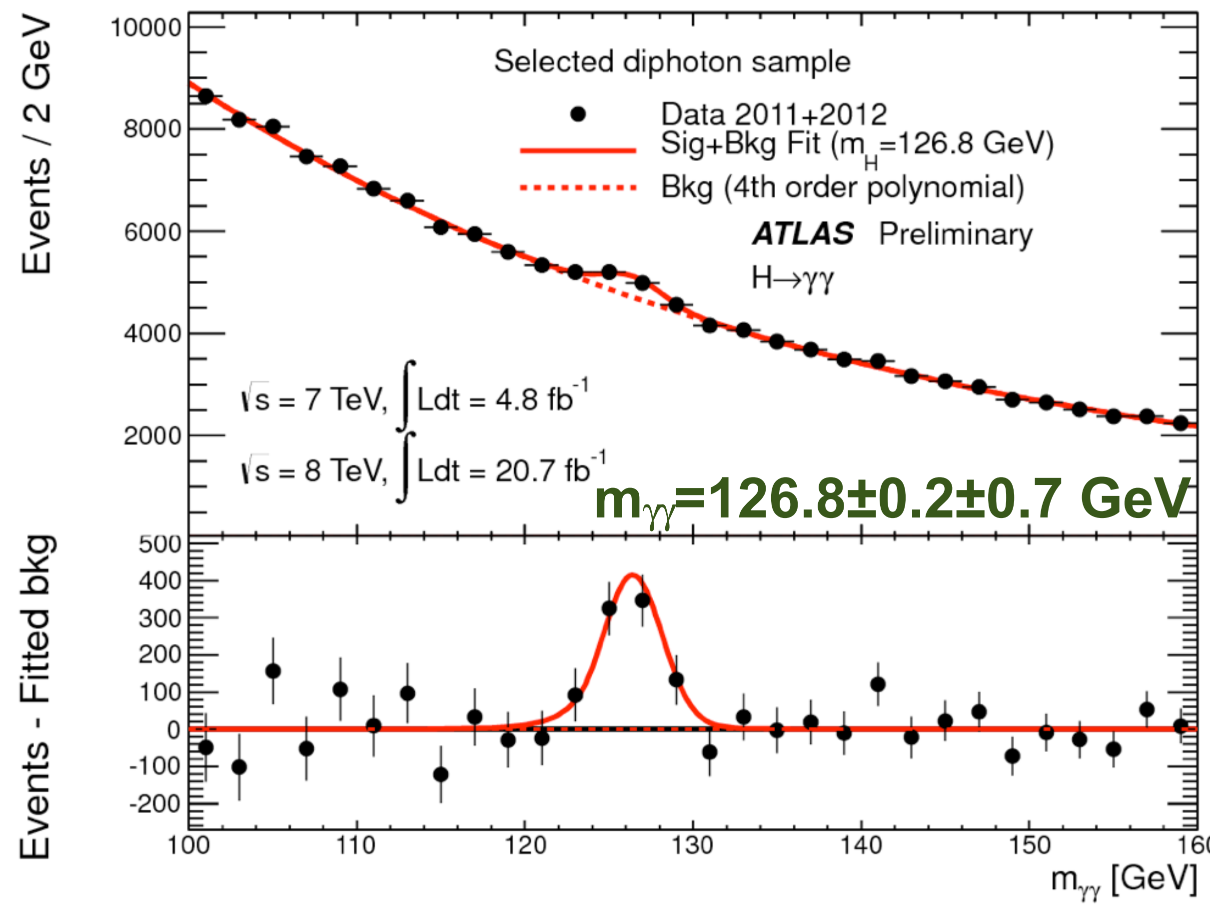


The new boson is consistent with being the SM Higgs boson

New boson with a mass of ~125 GeV

- We have discovered a SM-like scalar boson with a mass of ~125 GeV.
- J^{PC}, consistent with SM scalar boson, couplings will need more data.





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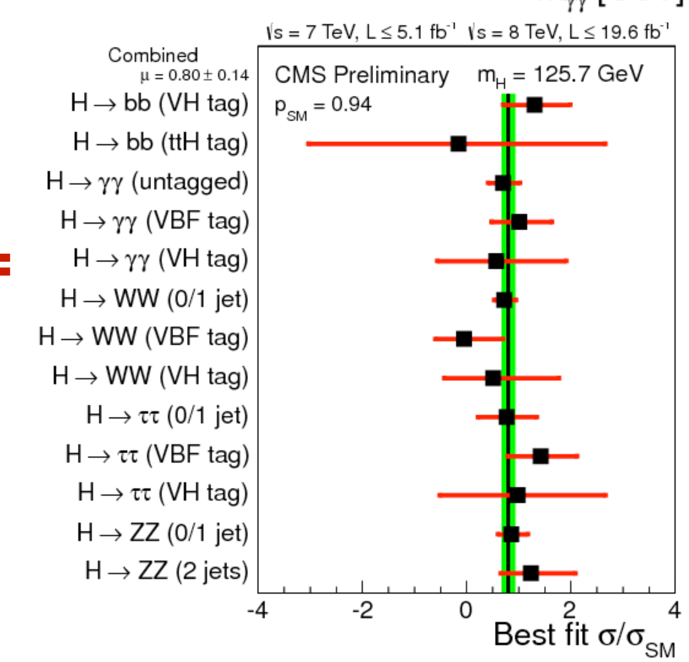


The new boson is consistent with being the SM Higgs boson

LHC and HL-LHC

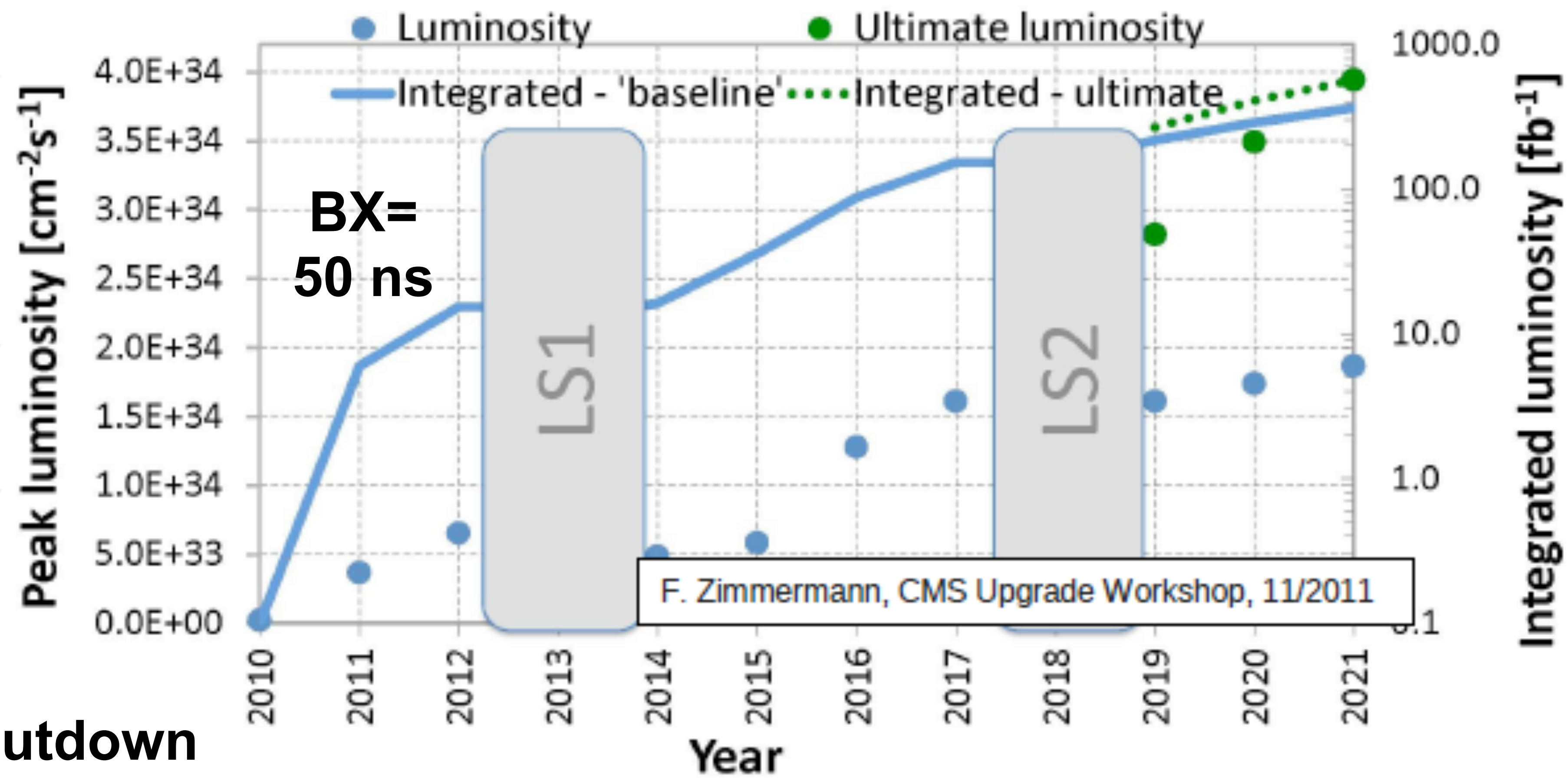
LHC

HL-LHC

$PU = \begin{cases} 100@25ns \\ 200@50ns \end{cases}$

$PU = \begin{cases} 50@25ns \\ 100@50ns \end{cases}$

$PU = \begin{cases} 25@25ns \\ 50@50ns \end{cases}$



Luminosity-leveled at 5×10^{34} $cm^{-2}s^{-1}$ in HL-LHC

LS= Long Shutdown

$L_{instantaneous}$

$L_{integrated}$

Pile Up

LS1

LS3

LHC and HL-LHC

LHC

Energy increase
8 TeV to 13/14 TeV

HL-LHC

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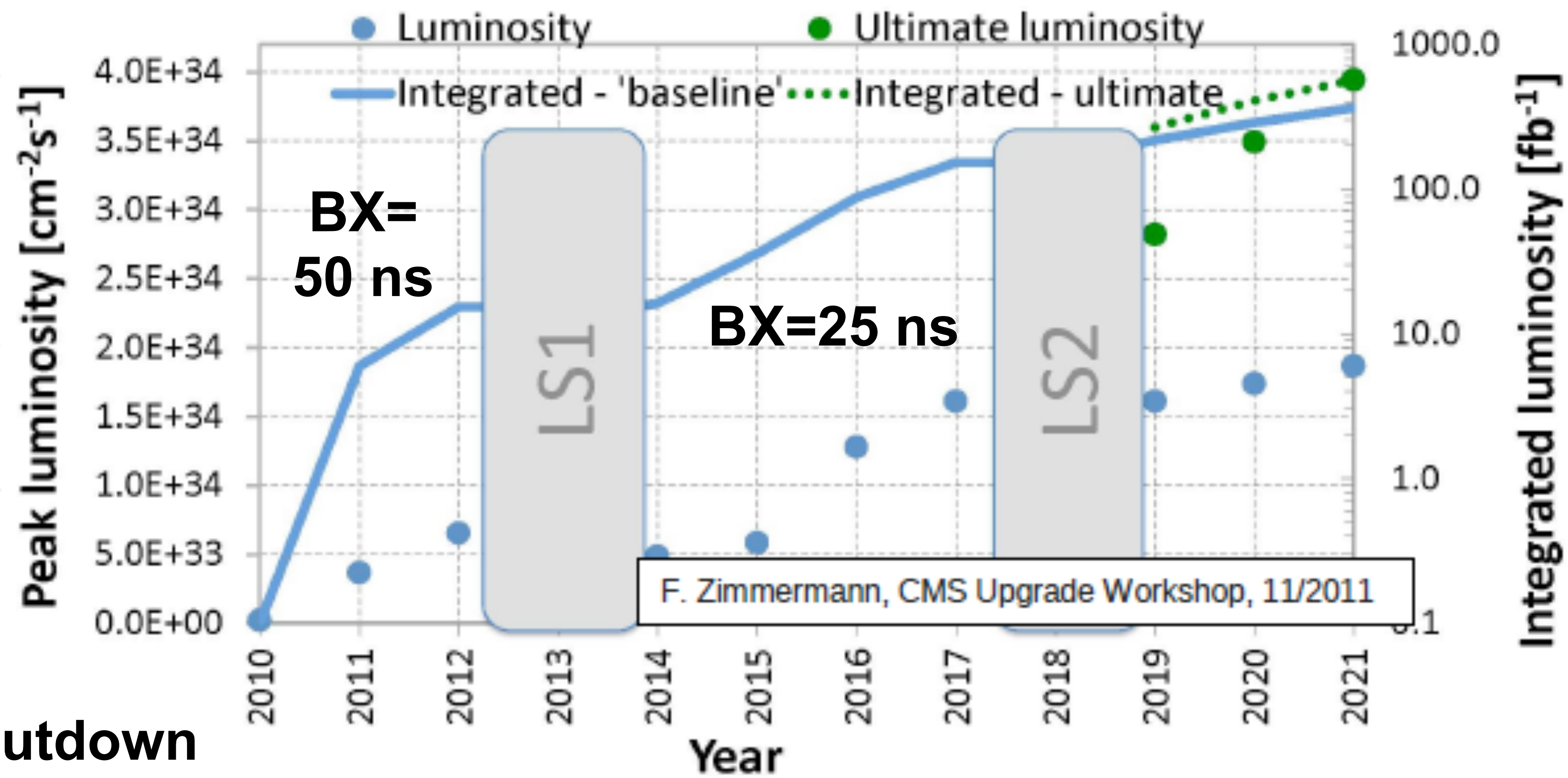

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LS= Long Shutdown

$L_{instantaneous}$
$L_{integrated}$
Pile Up

LHC and HL-LHC

LHC | **Energy increase 8 TeV to 13/14 TeV** | **Injection upgrade** | **HL-LHC**

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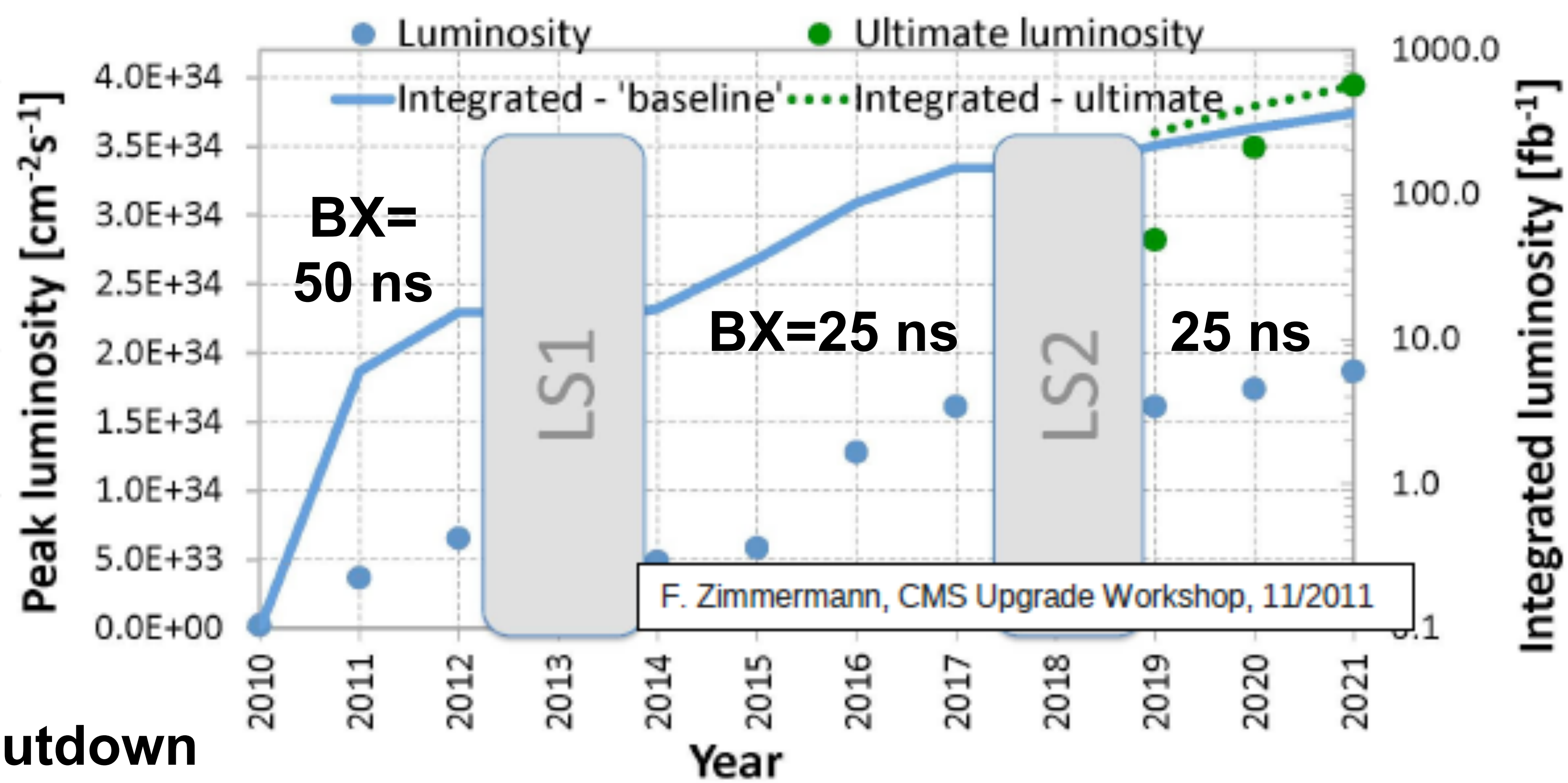

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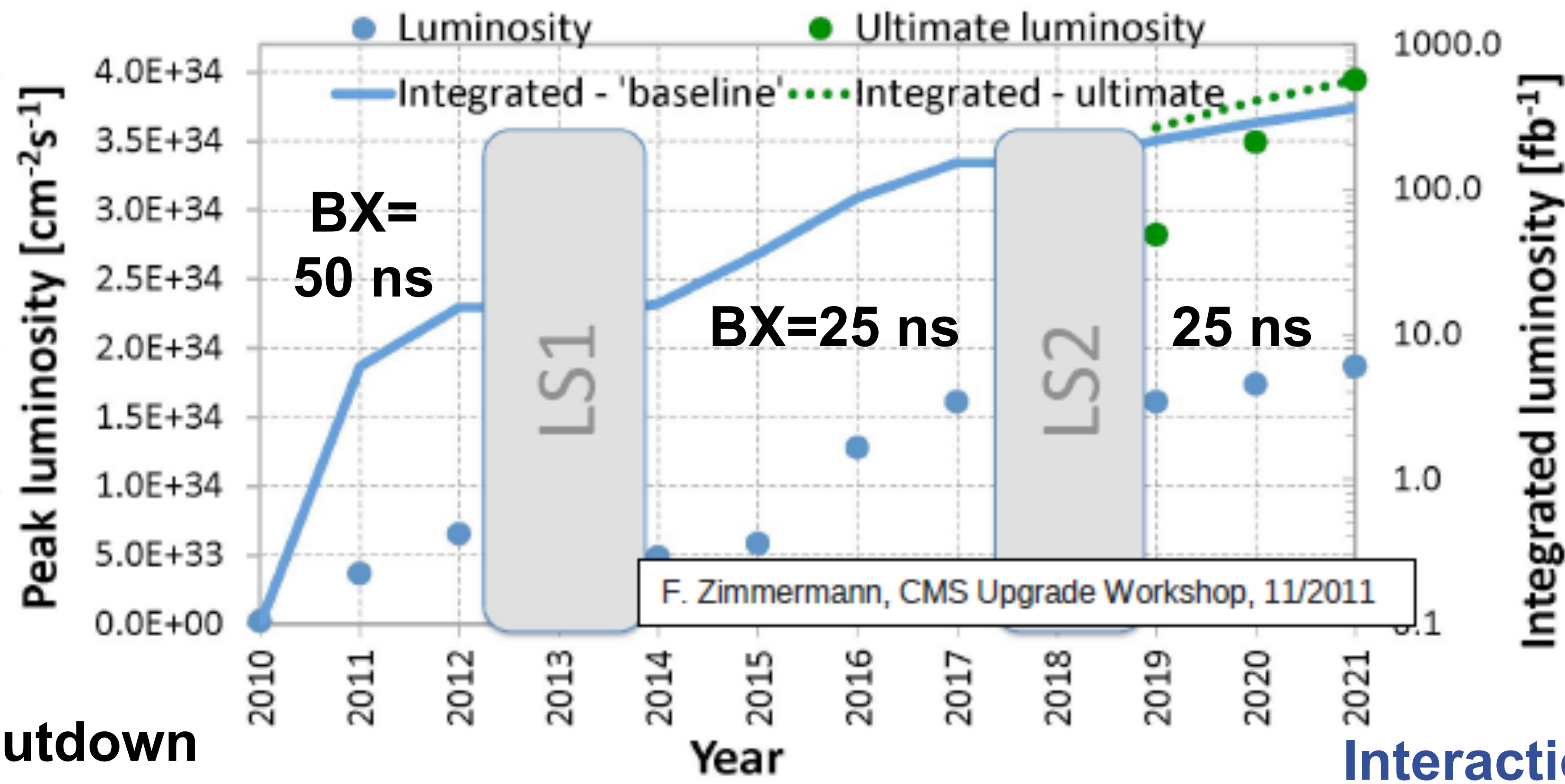

Luminosity-leveled at 5×10^{34} $cm^{-2}s^{-1}$ in HL-LHC

LS= Long Shutdown

Interaction region upgrade

$L_{instantaneous}$

$L_{integrated}$

Pile Up

LS1 → LS3 →

LHC and HL-LHC

LHC	Energy increase 8 TeV to 13/14 TeV	Injection upgrade	HL-LHC

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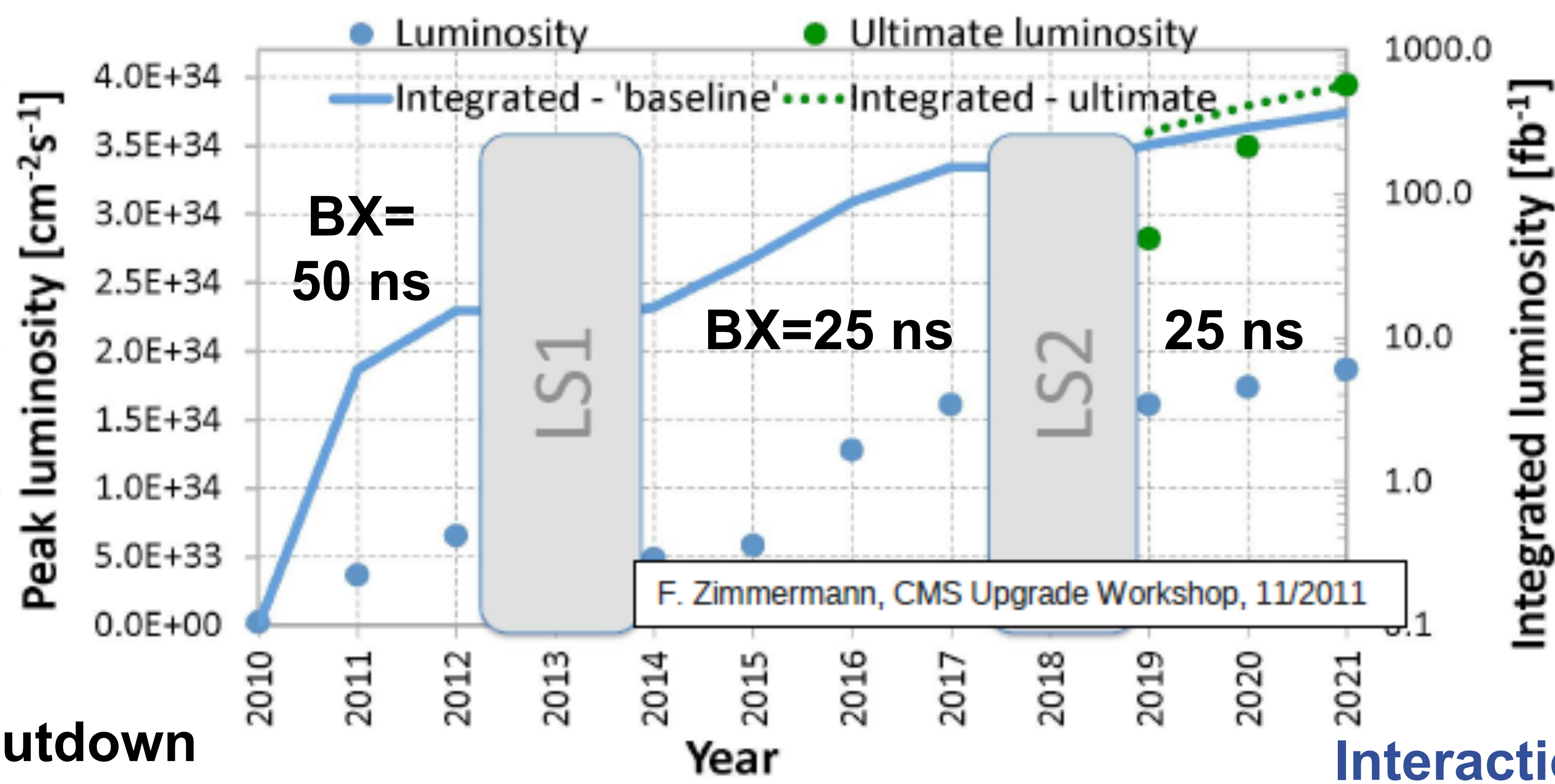

Luminosity-leveled at 5×10^{34} $cm^{-2}s^{-1}$ in HL-LHC

LS= Long Shutdown

Interaction region upgrade

$L_{instantaneous}$	8×10^{33} Hz/cm^2
$L_{integrated}$	30 fb^{-1}
Pile Up	PU ~40

→ LS1 → LS3 →

LHC and HL-LHC

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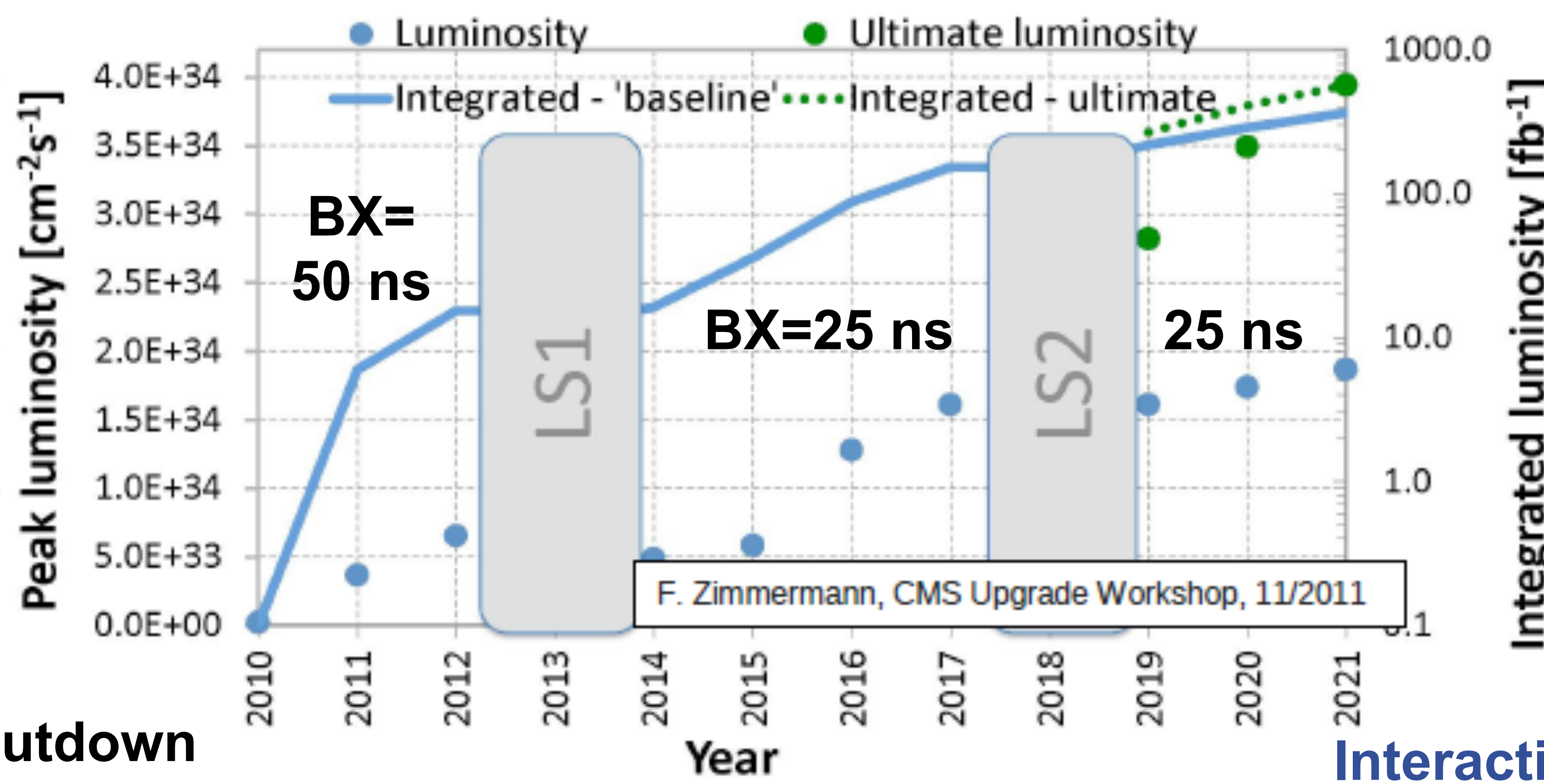

Luminosity-leveled at 5×10^{34} cm^{-2}s^{-1} in HL-LHC

LS= Long Shutdown

Interaction region upgrade

$L_{\text{instantaneous}}$
$L_{\text{integrated}}$
Pile Up

8×10^{33} Hz/cm^2
30 fb^{-1}
PU ~40

LS1

2×10^{34} Hz/cm^2
300 fb^{-1}
PU ~50

LS3

LHC and HL-LHC

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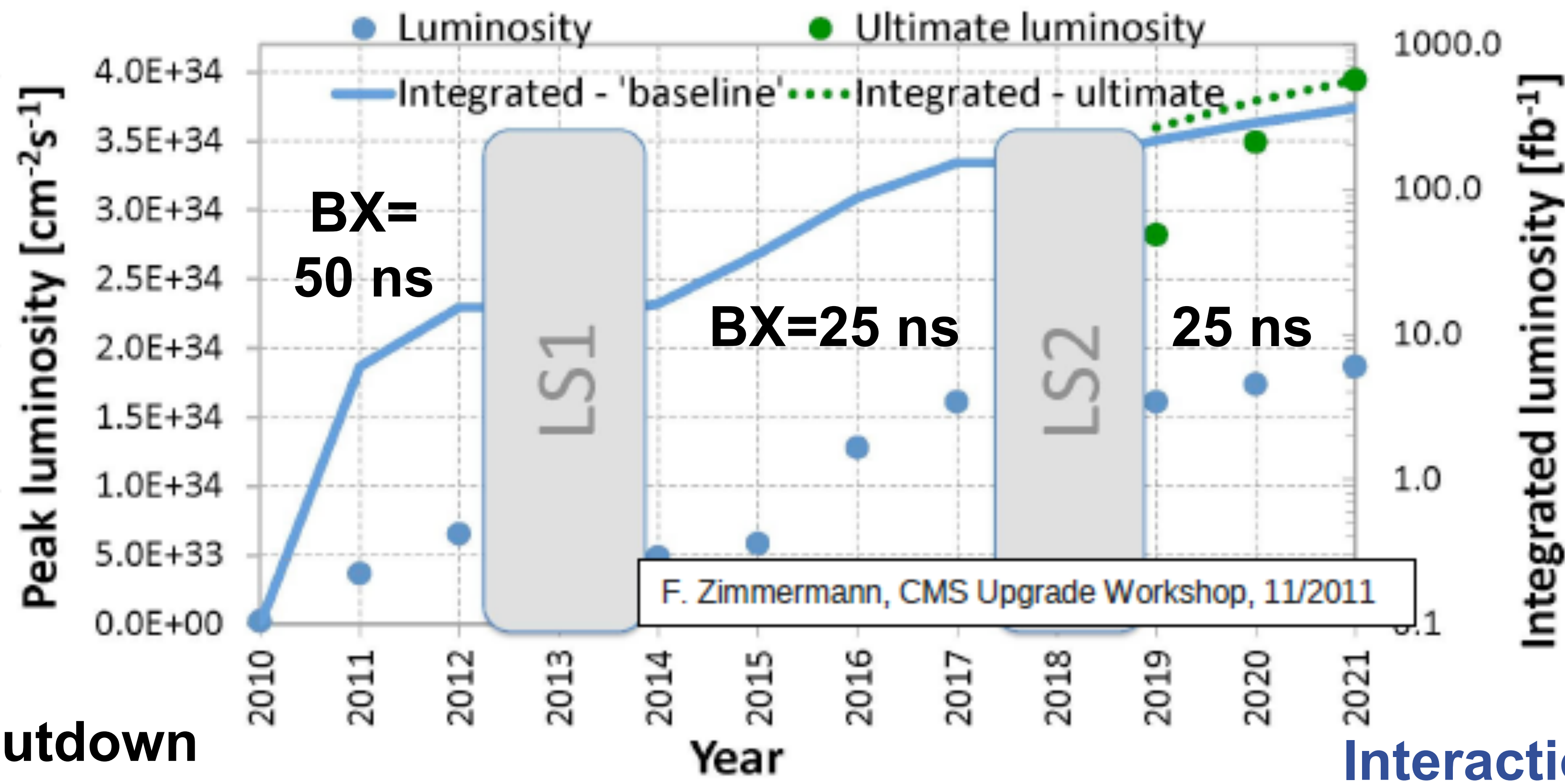

Luminosity-leveled at 5×10^{34} cm^{-2}s^{-1} in HL-LHC

LS= Long Shutdown

Interaction region upgrade

	LHC (before LS1)	after LS1	after LS3
$L_{instantaneous}$	8×10^{33} Hz/cm^2	2×10^{34} Hz/cm^2	5×10^{34} Hz/cm^2
$L_{integrated}$	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
Pile Up	PU ~40	PU ~50	PU ~140

→ LS1 → LS3 →

LHC and HL-LHC

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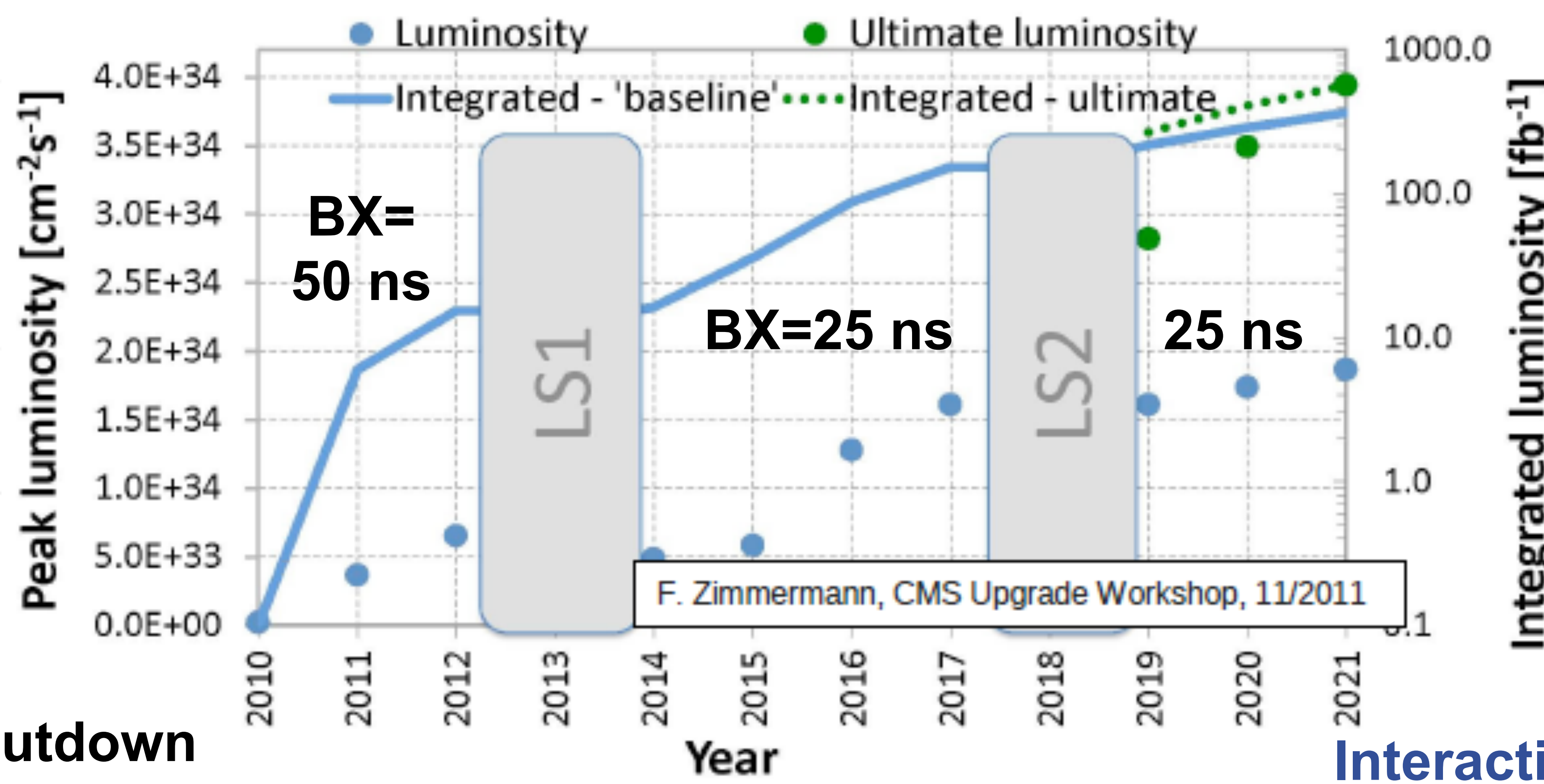

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Pile Up	PU ~40	LS1	PU ~50	LS3	PU ~140

ATLAS, CMS Upgrade plan

LHC and HL-LHC

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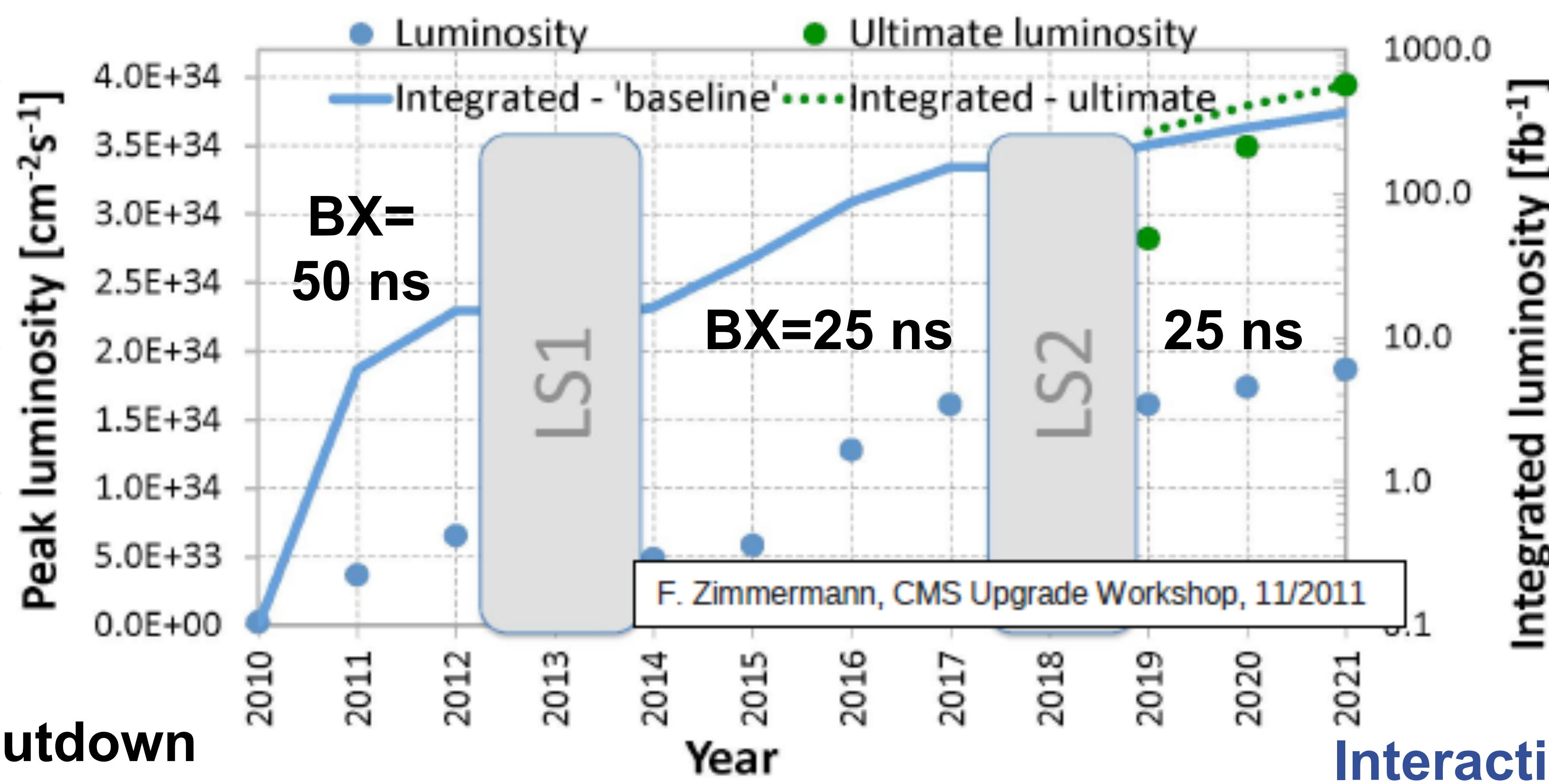

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Phase 1 Upgrade

ATLAS, CMS Upgrade plan

LHC and HL-LHC

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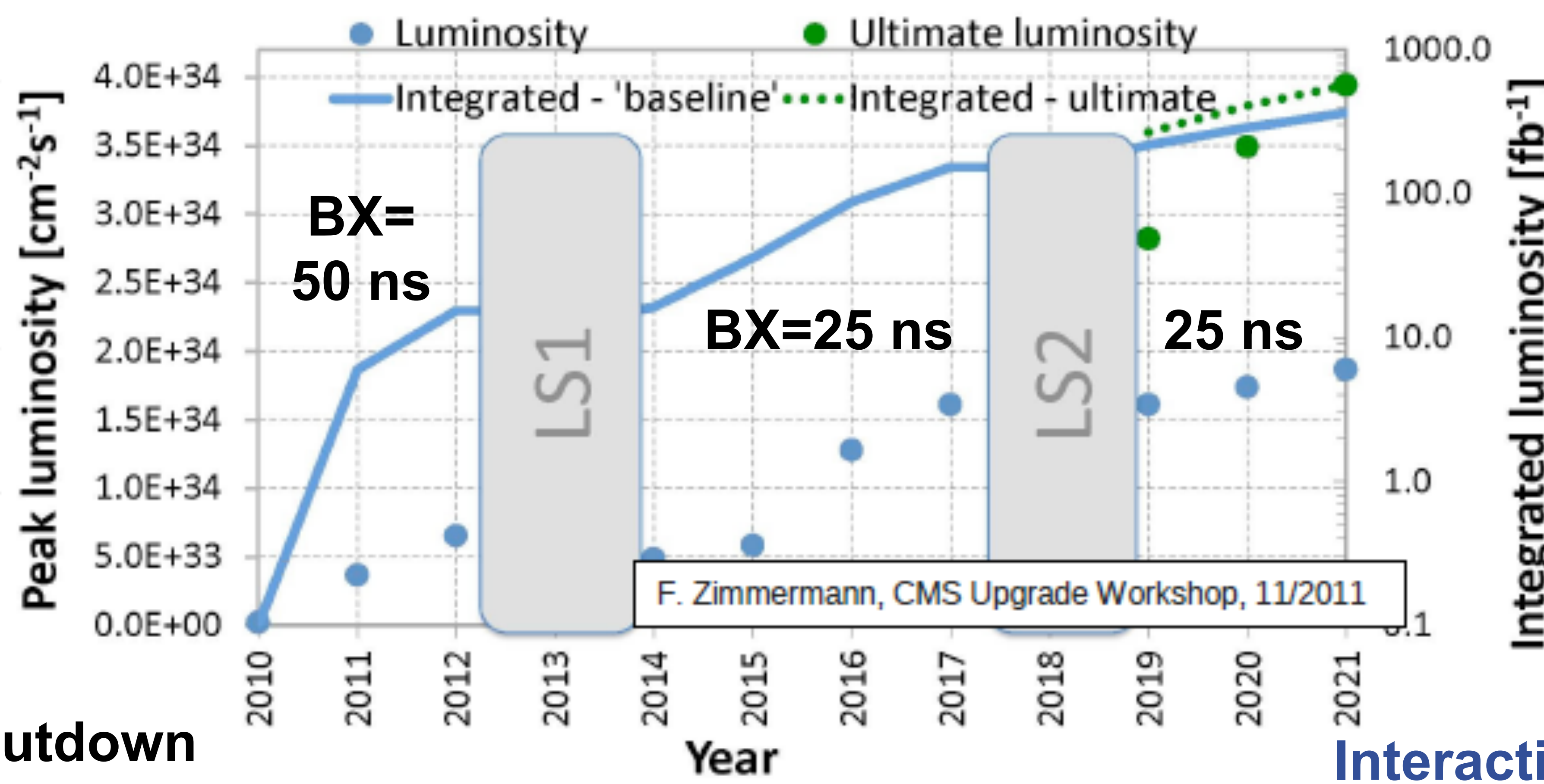


Luminosity-leveled at $5x10^{34}$ cm^{-2}s^{-1} in HL-LHC

LS= Long Shutdown

Interaction region upgrade

		LS1		LS3	
$L_{instantaneous}$	$8x10^{33}$ Hz/cm^2		$2x10^{34}$ Hz/cm^2		$5x10^{34}$ Hz/cm^2
$L_{integrated}$	30 fb^{-1}		300 fb^{-1}		3000 fb^{-1}
Pile Up	PU ~40		PU ~50		PU ~140

ATLAS, CMS Upgrade plan

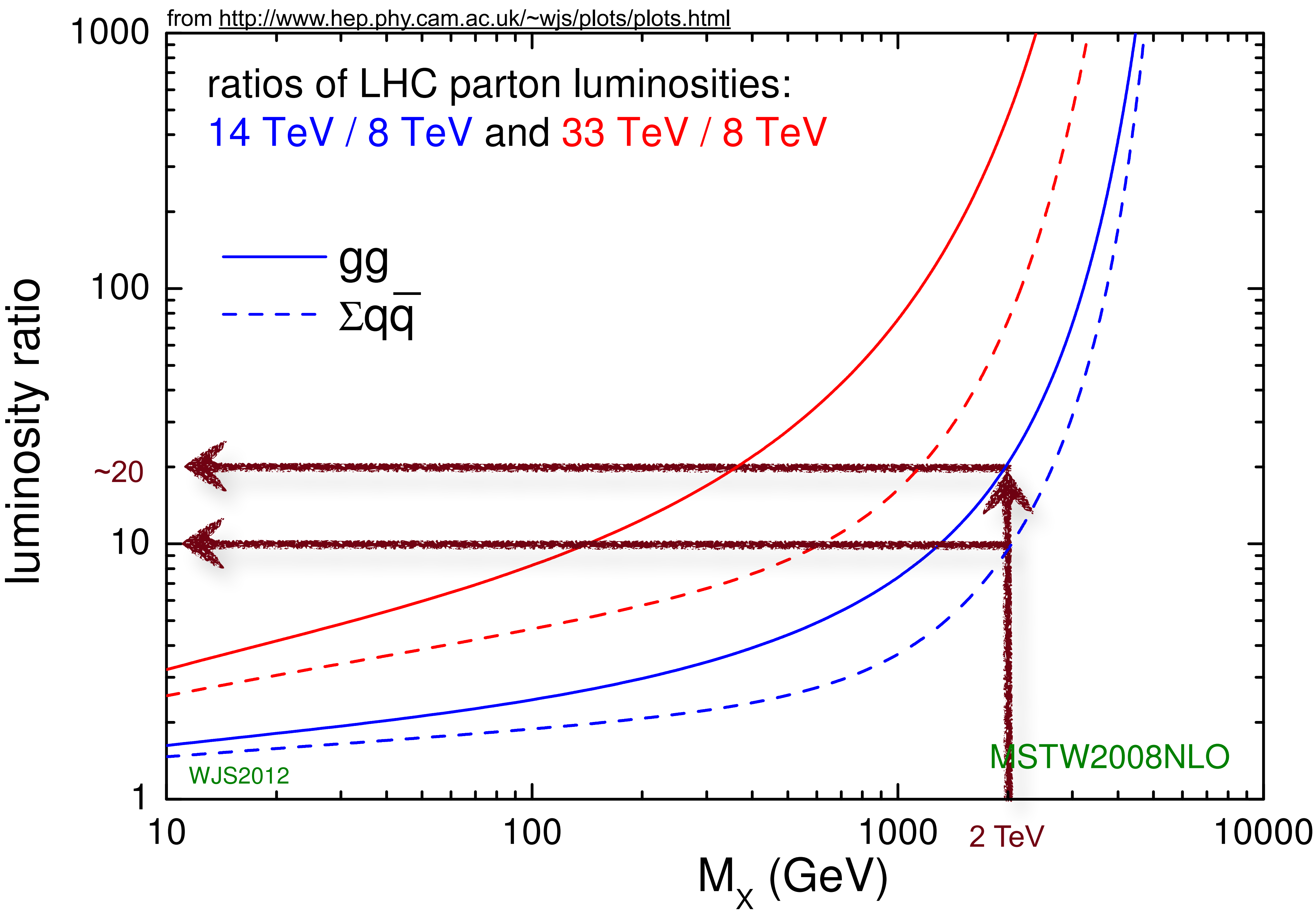
Phase 1 Upgrade

Phase 2 Upgrade

LHC after LS1

From G. Dissertori (ETH)

LHC after LS1



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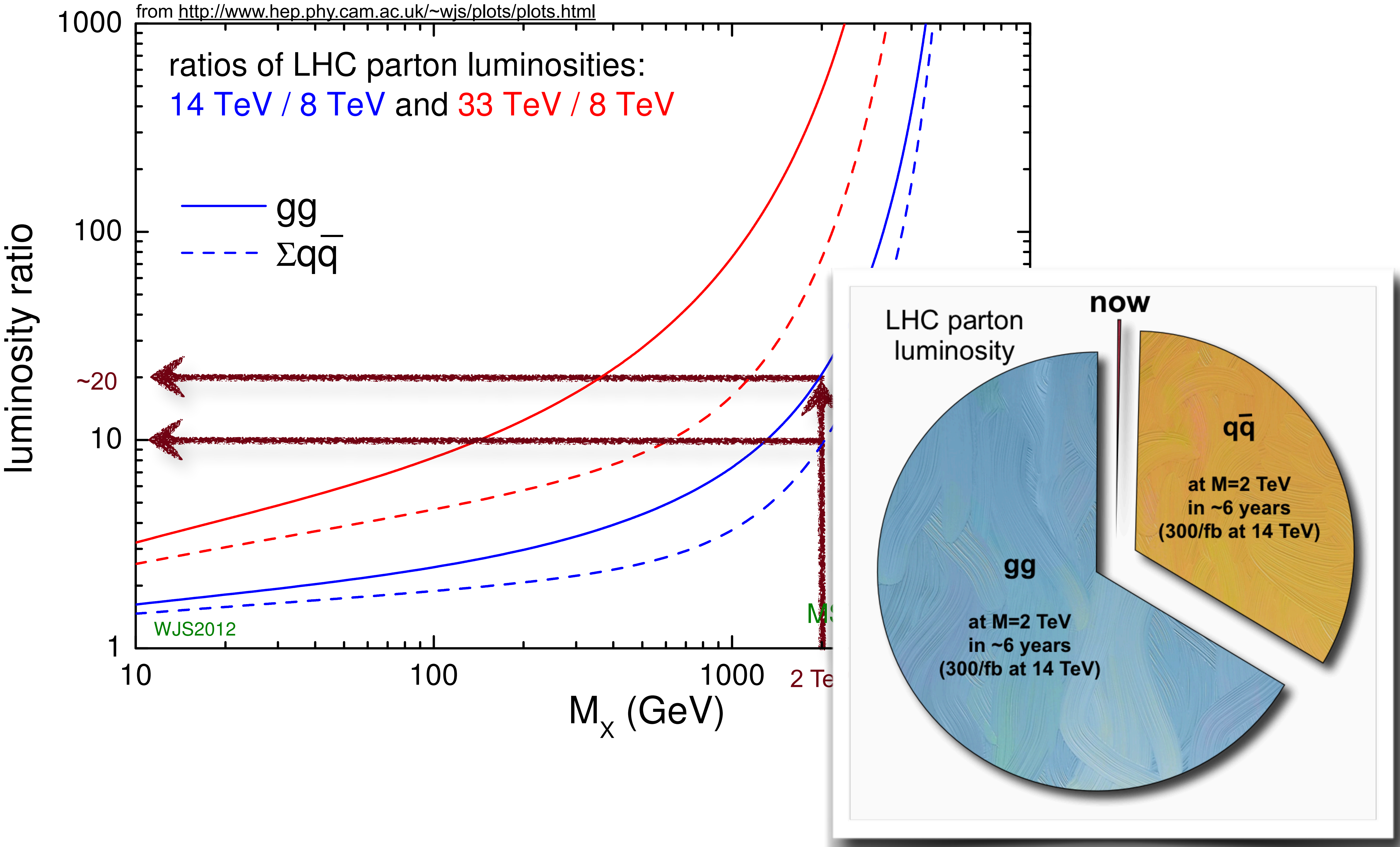
LHC after LS1



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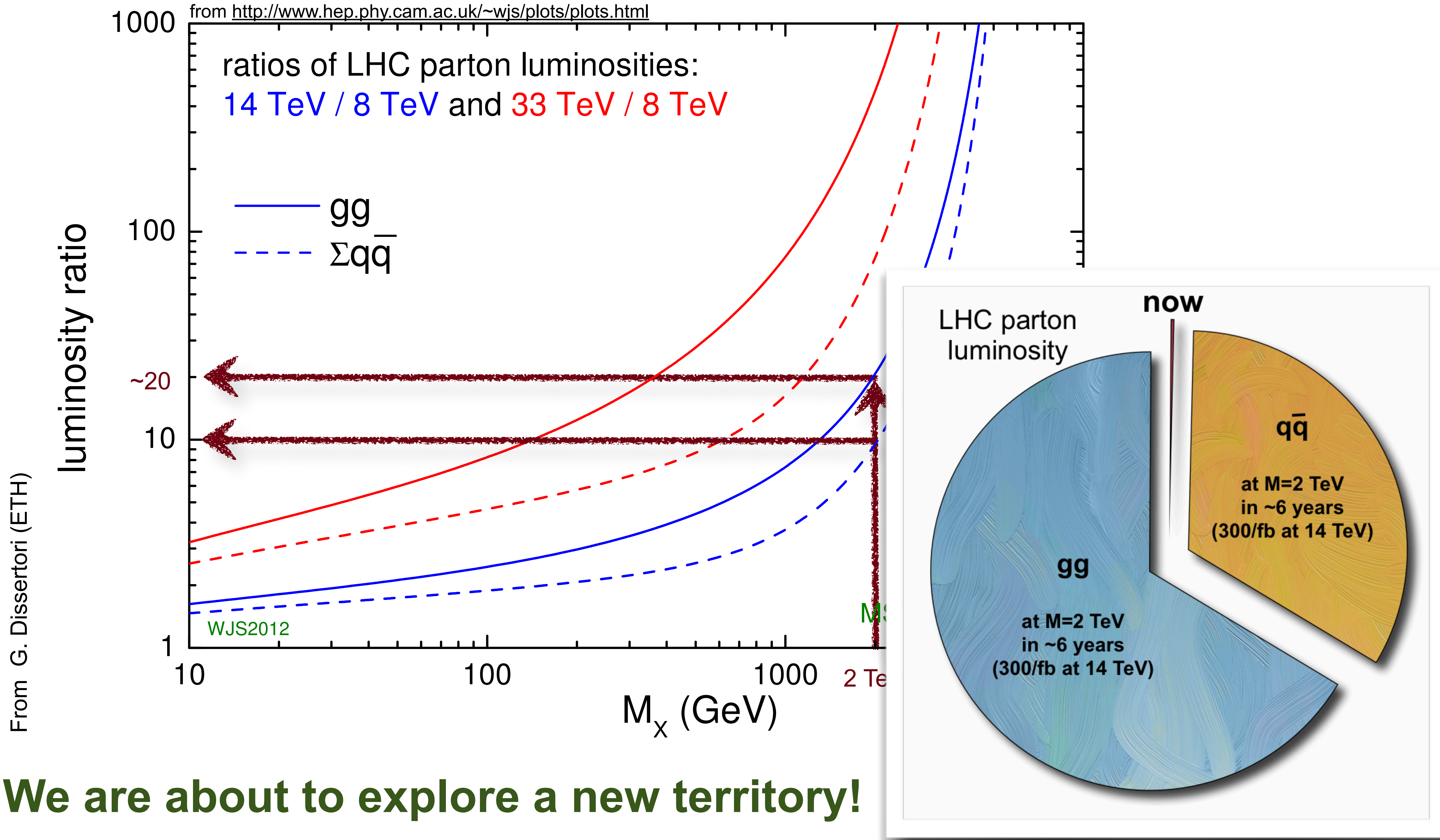
LHC after LS1



We are about to explore a new territory!

Detector and trigger challenges

Detector and trigger challenges

- Need detectors and trigger with high performances from low to high energy scales

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  - Event pileup reaches ~140 collisions per beam crossing (@ 25 ns)

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- Phase 2 Upgrade: 5x LHC design luminosity
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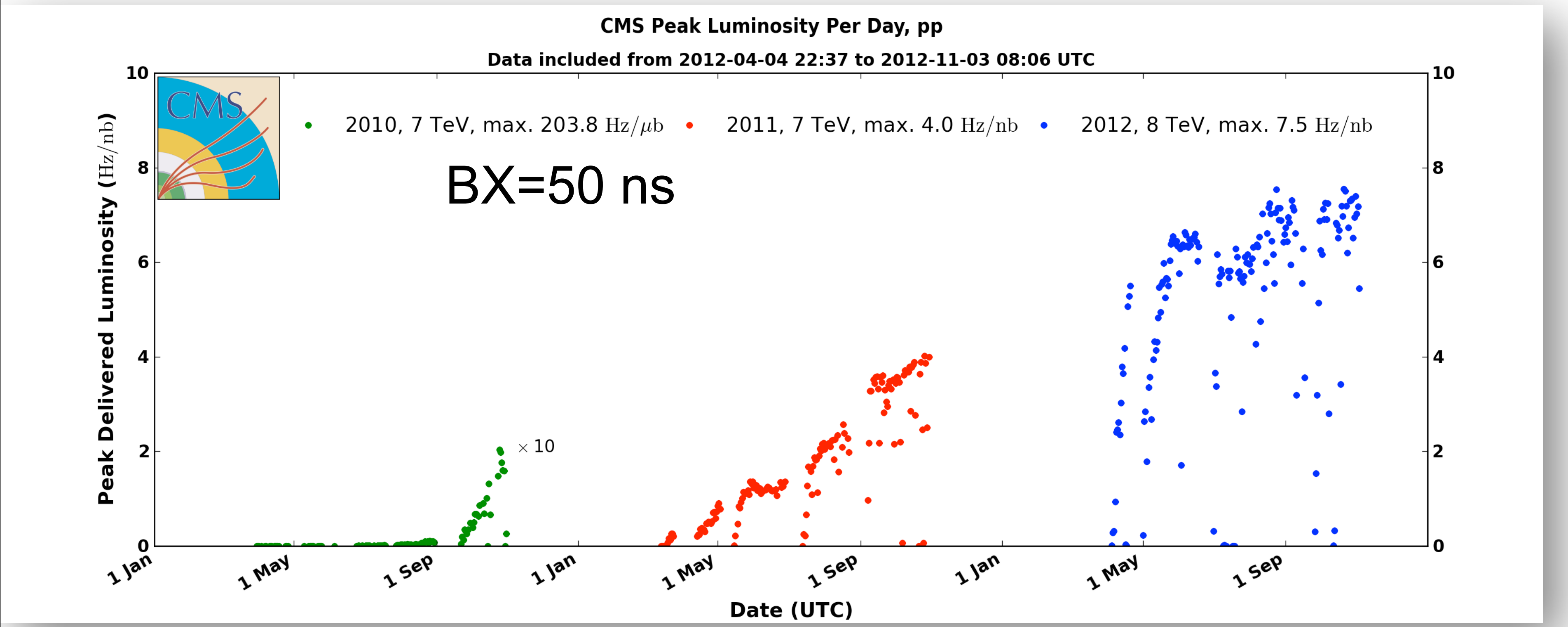
  - Need solutions to cope with very high rates (10-15 x 2012), radiation and pileup

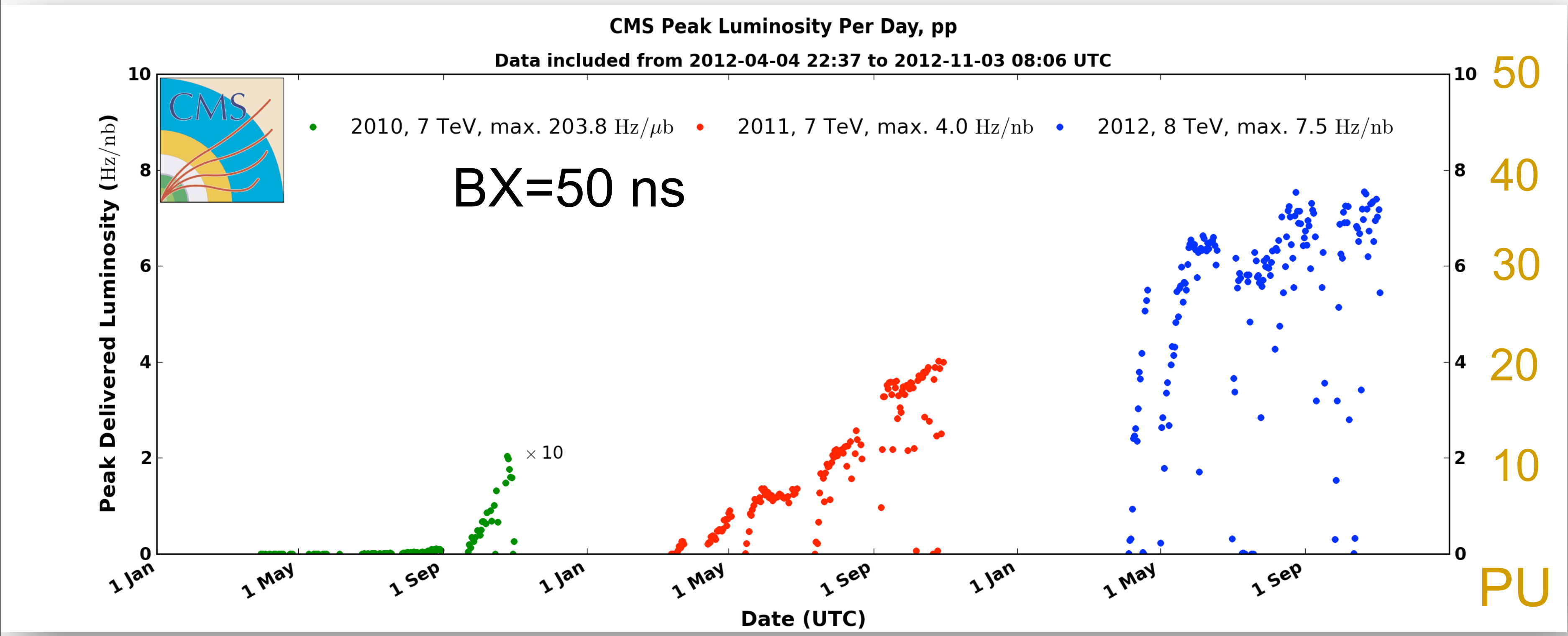
ATLAS and CMS were designed to cope with L= 1-2 x10^{34} $cm^{-2}s^{-1}$

Pileup in 2012

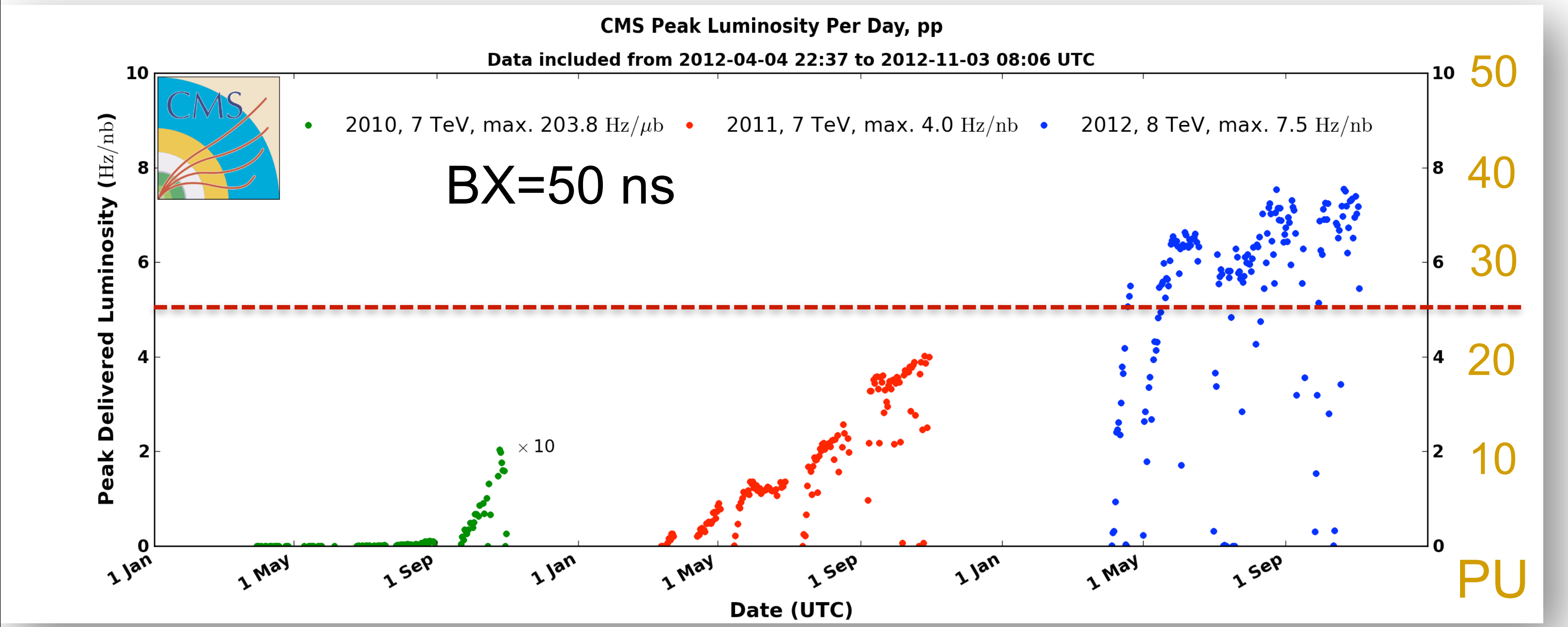
Pileup in 2012



Pileup in 2012

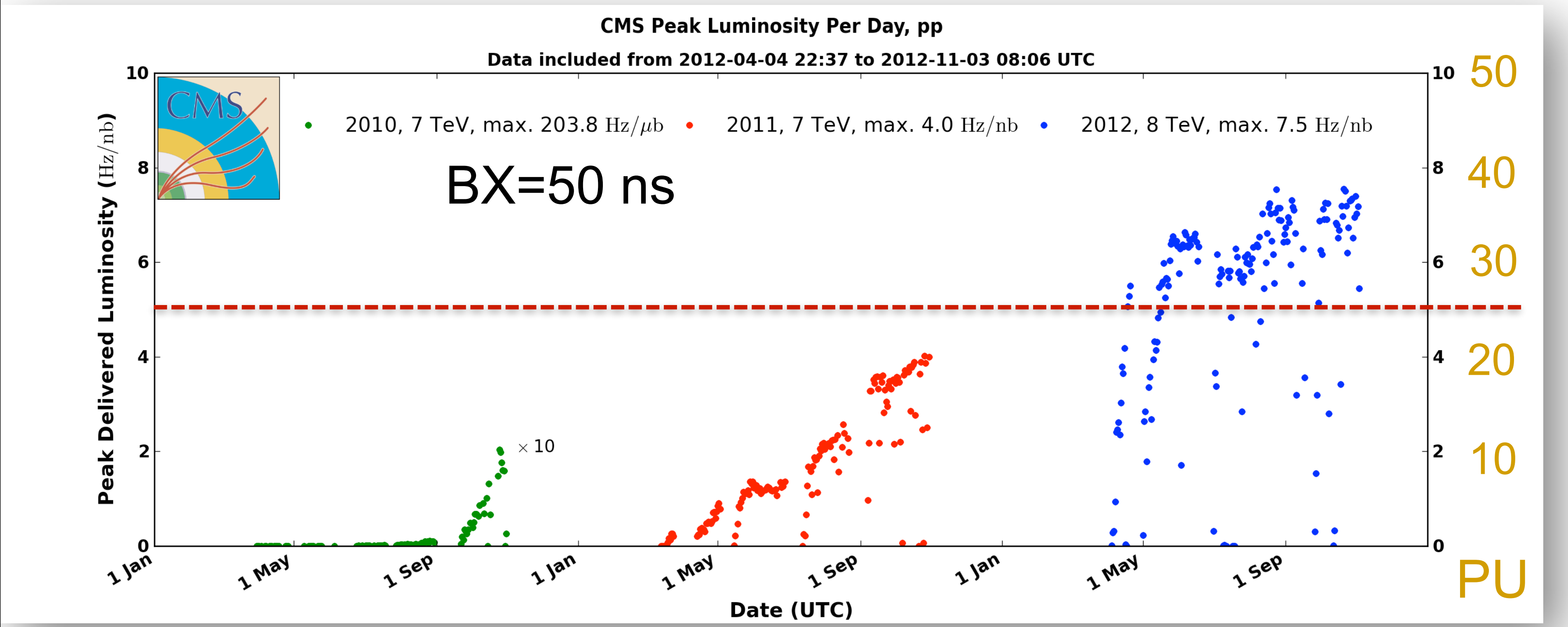


Pileup in 2012



Design value
25 pileup events
($L=10^{34}$, BX=25 ns)

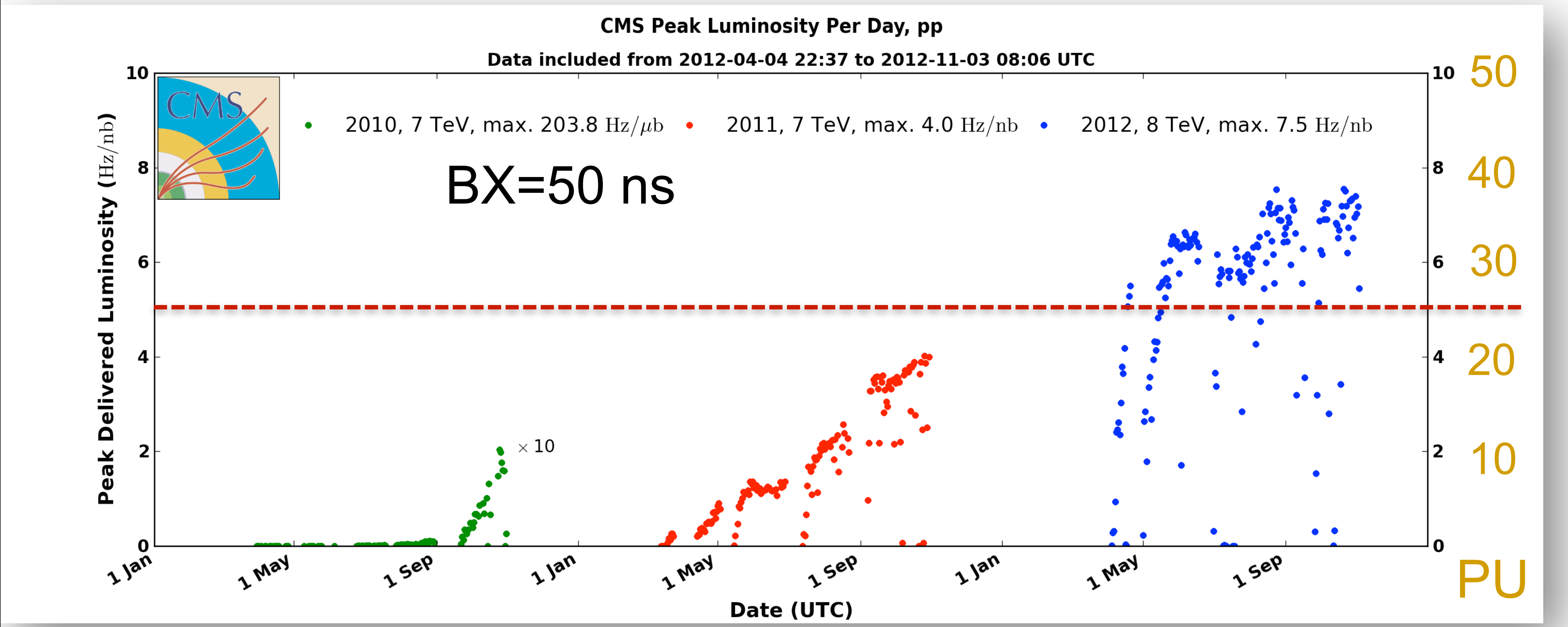
Pileup in 2012



Peak: 37 pileup events

Design value
25 pileup events
(L=10^{34}, BX=25 ns)

Pileup in 2012



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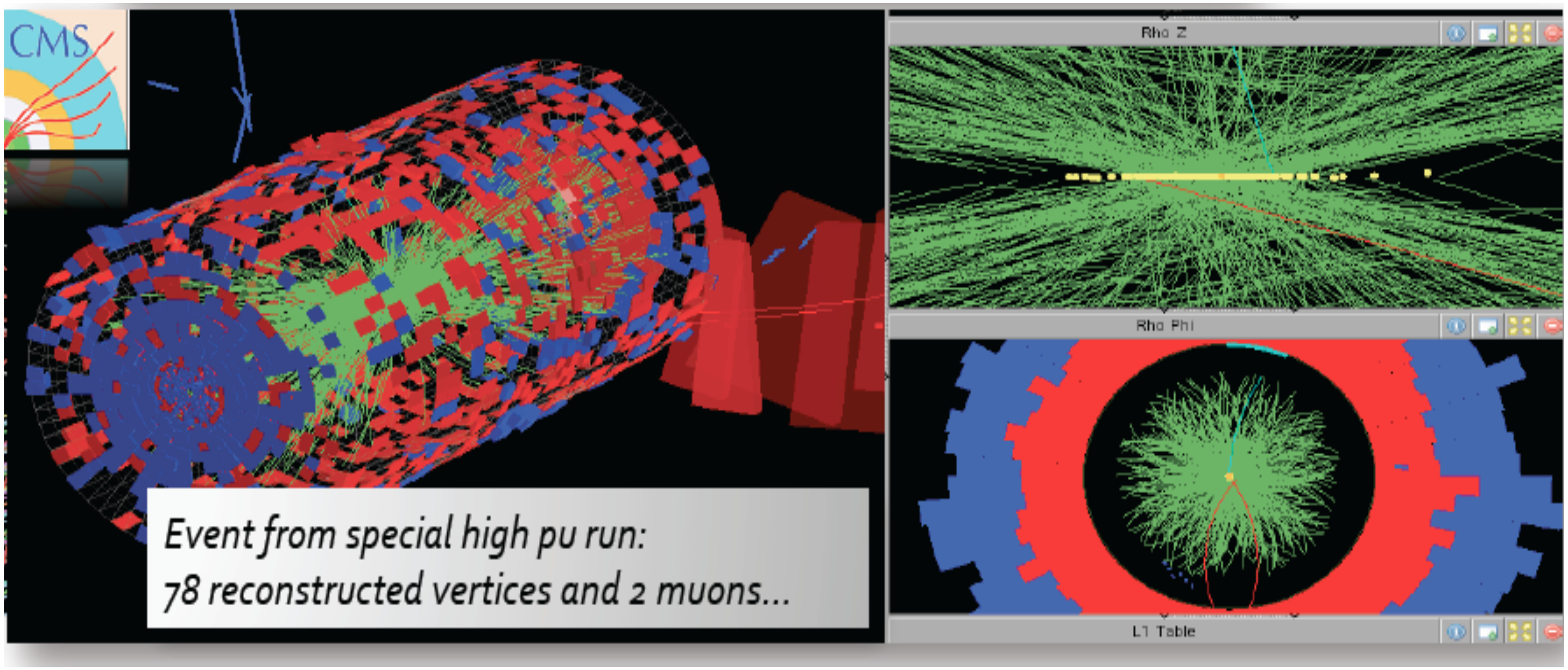
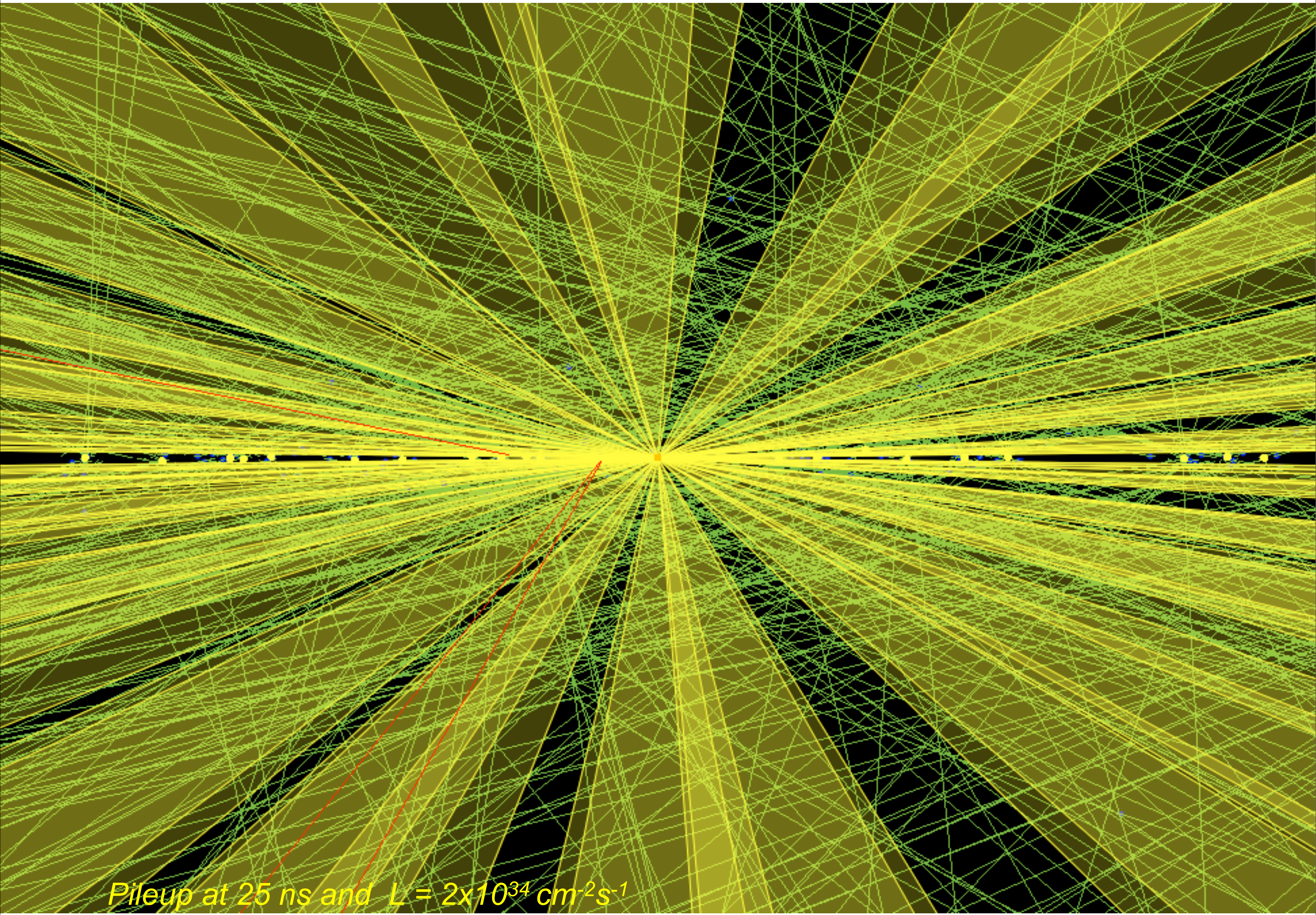
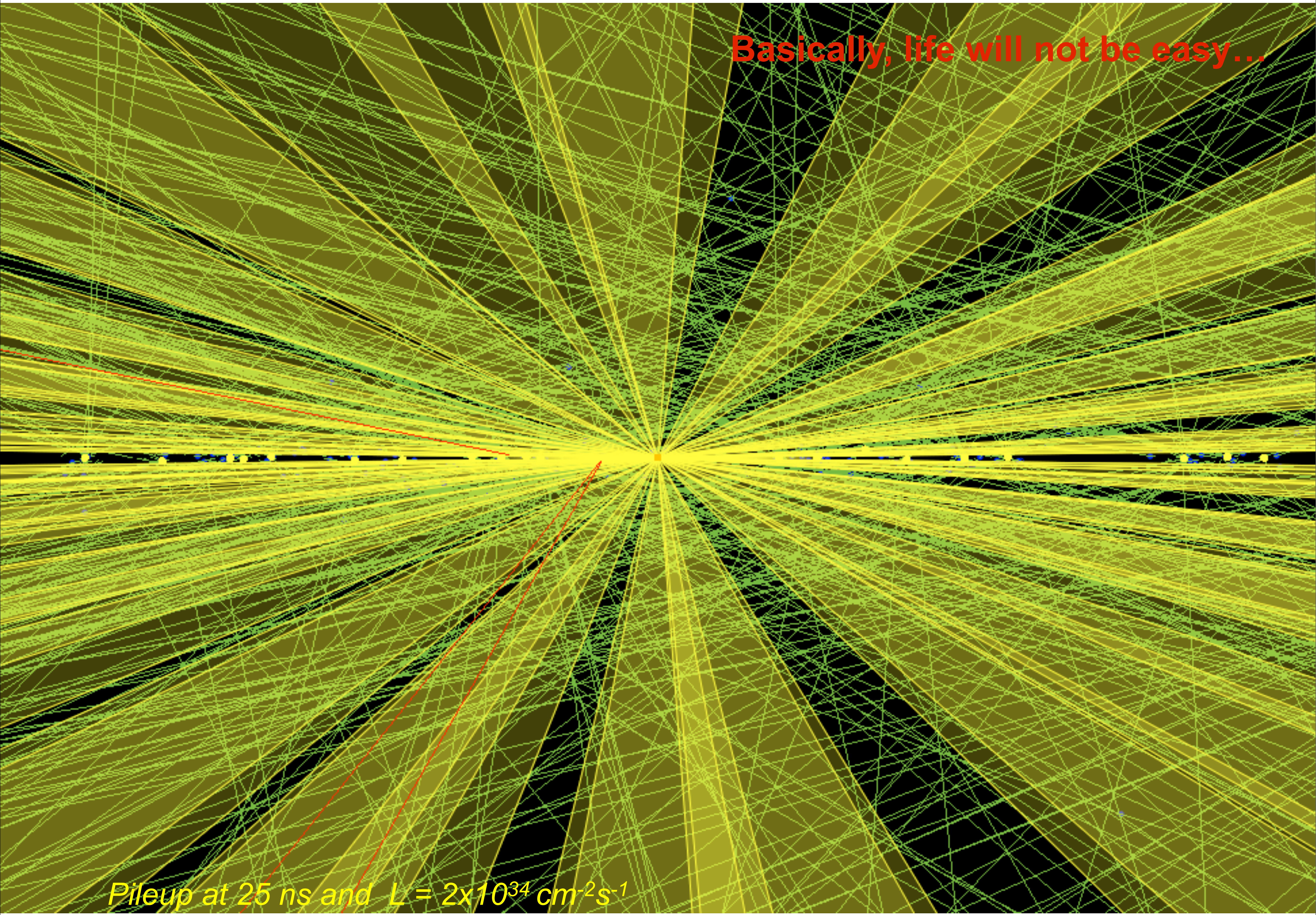
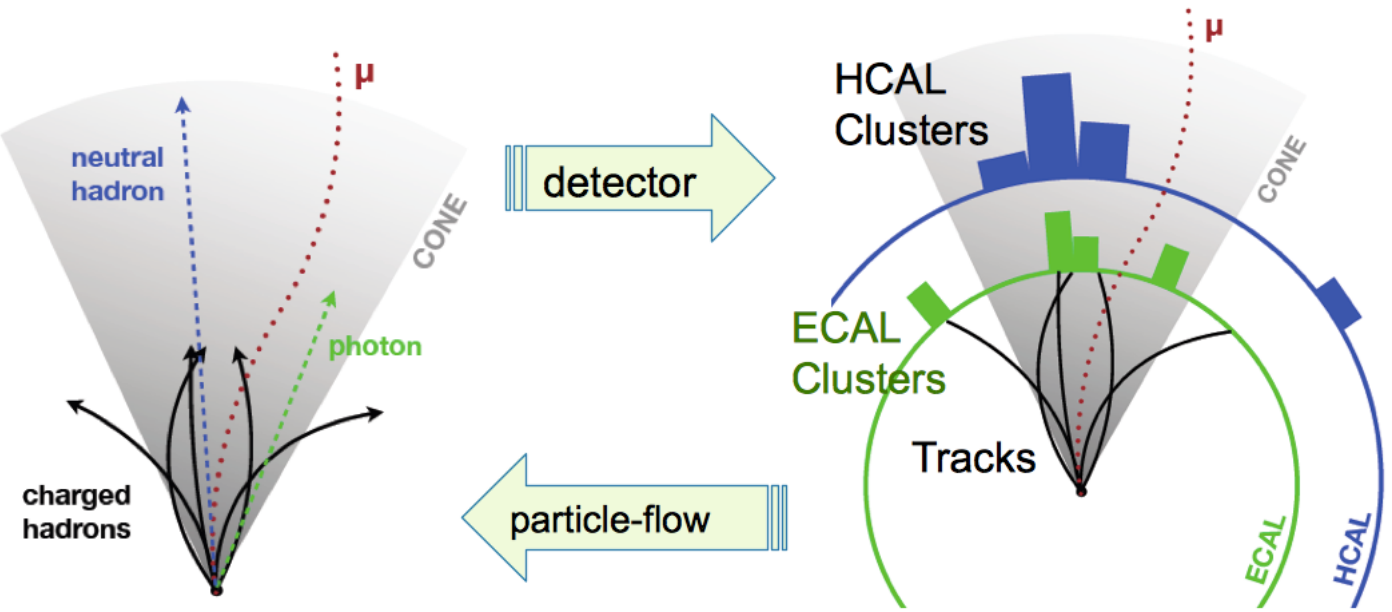
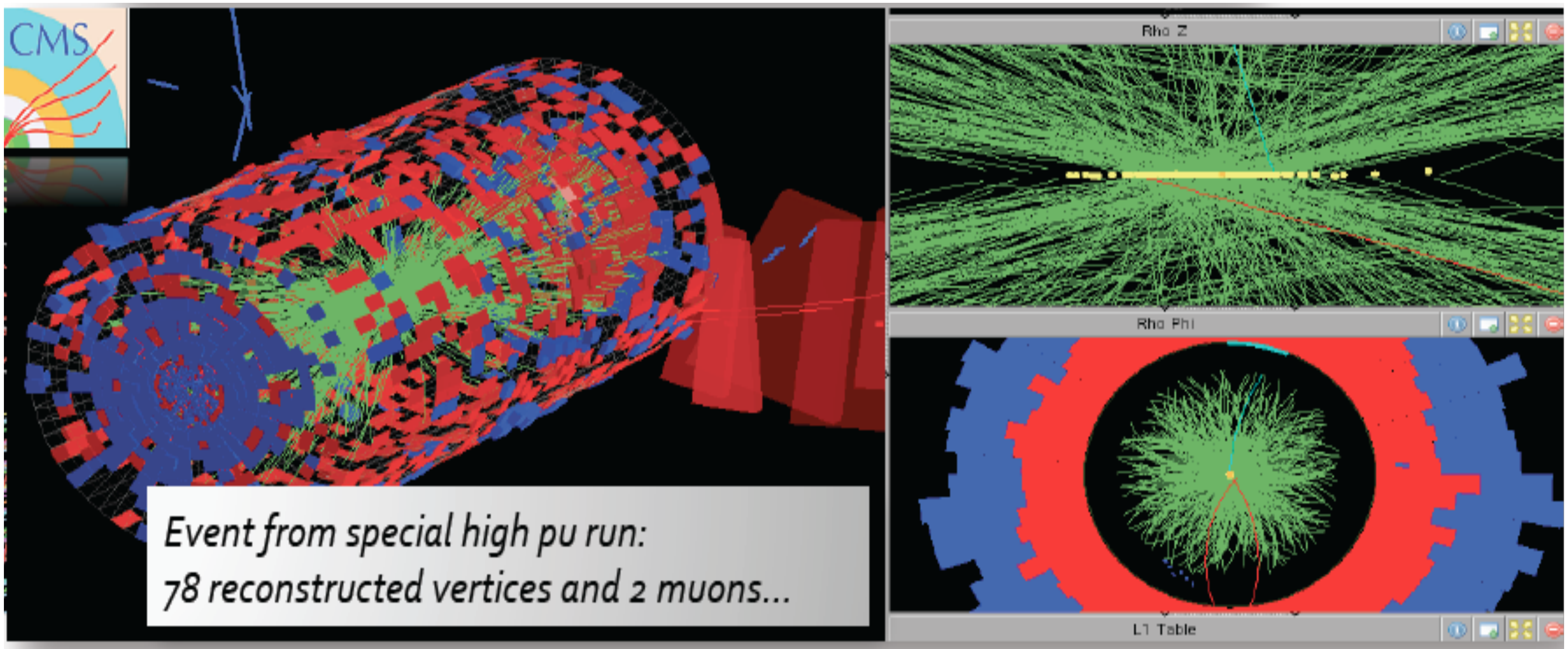



Pileup at 25 ns and L = 2x10^{34} cm^{-2}s^{-1}


Basically, life will not be easy…
Pileup at 25 ns and L = 2x10^34 cm^-2 s^-1

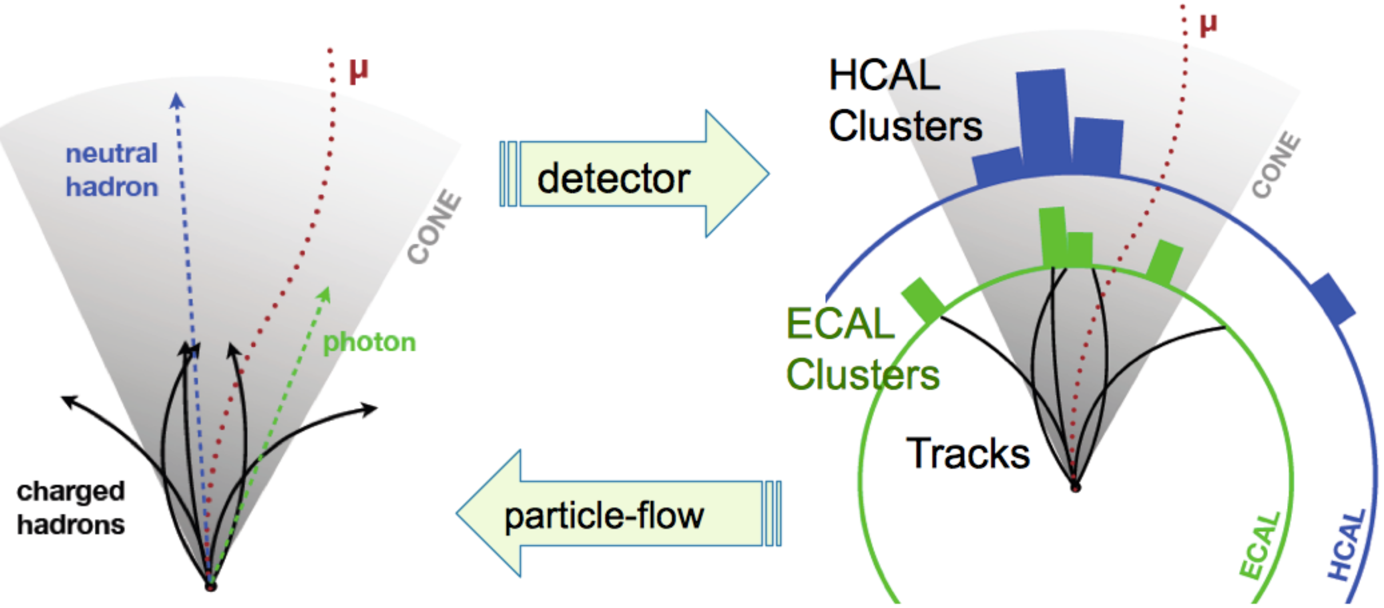
Upgrade challenges and recipe

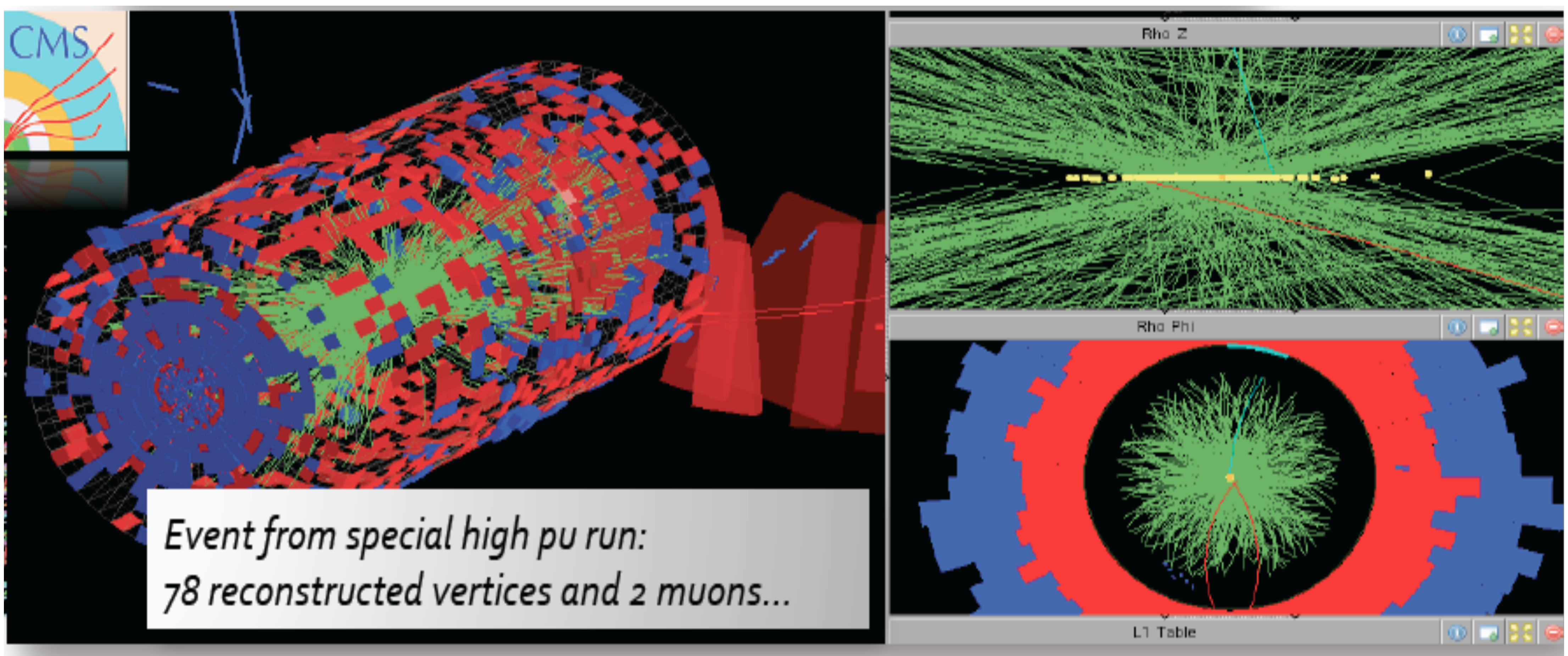




Upgrade challenges and recipe

Maintain low trigger thresholds, efficient particle and physics object reconstruction at high rate and pile-up





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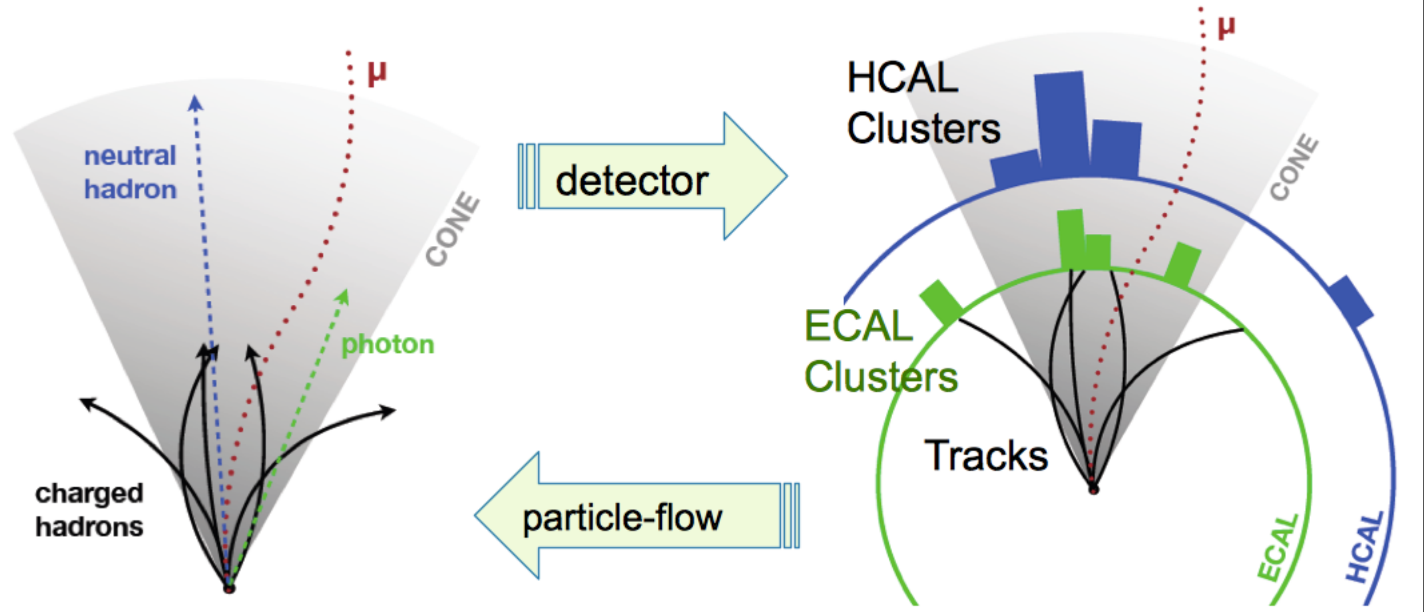
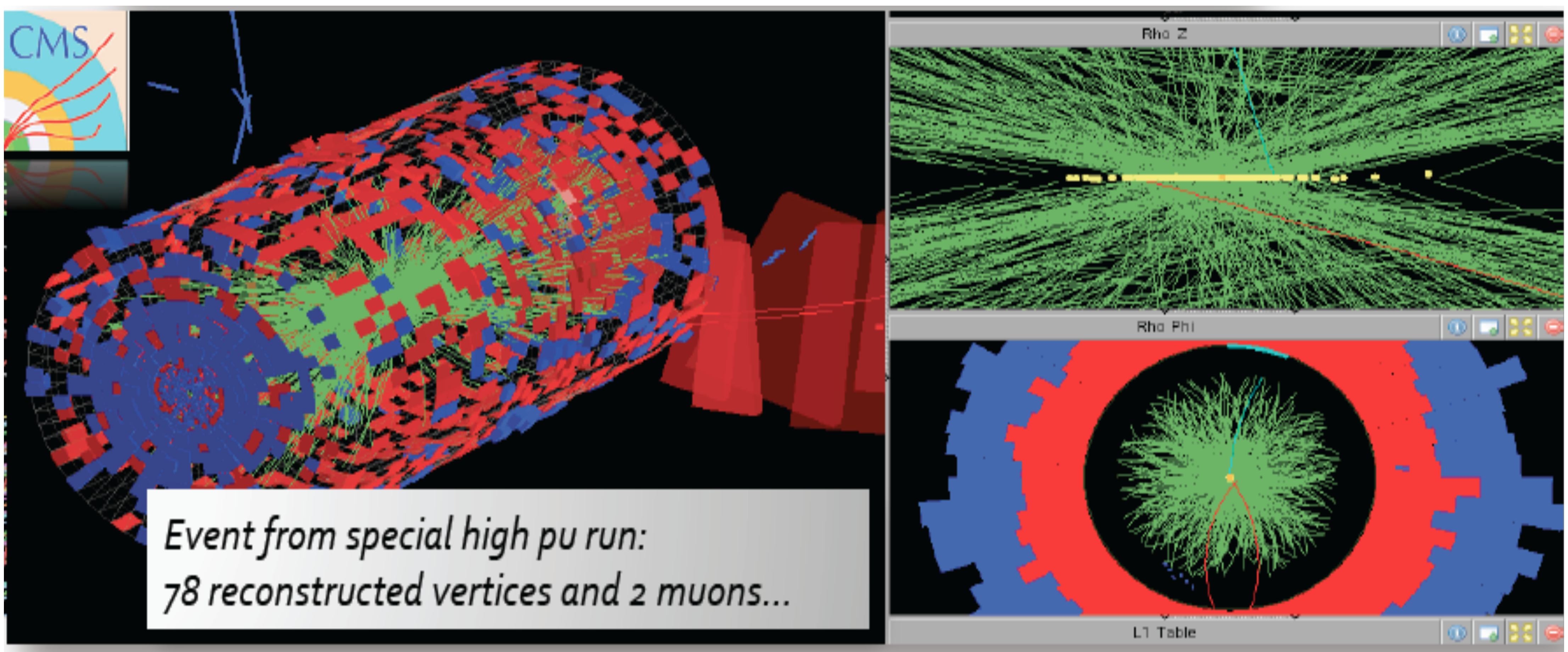
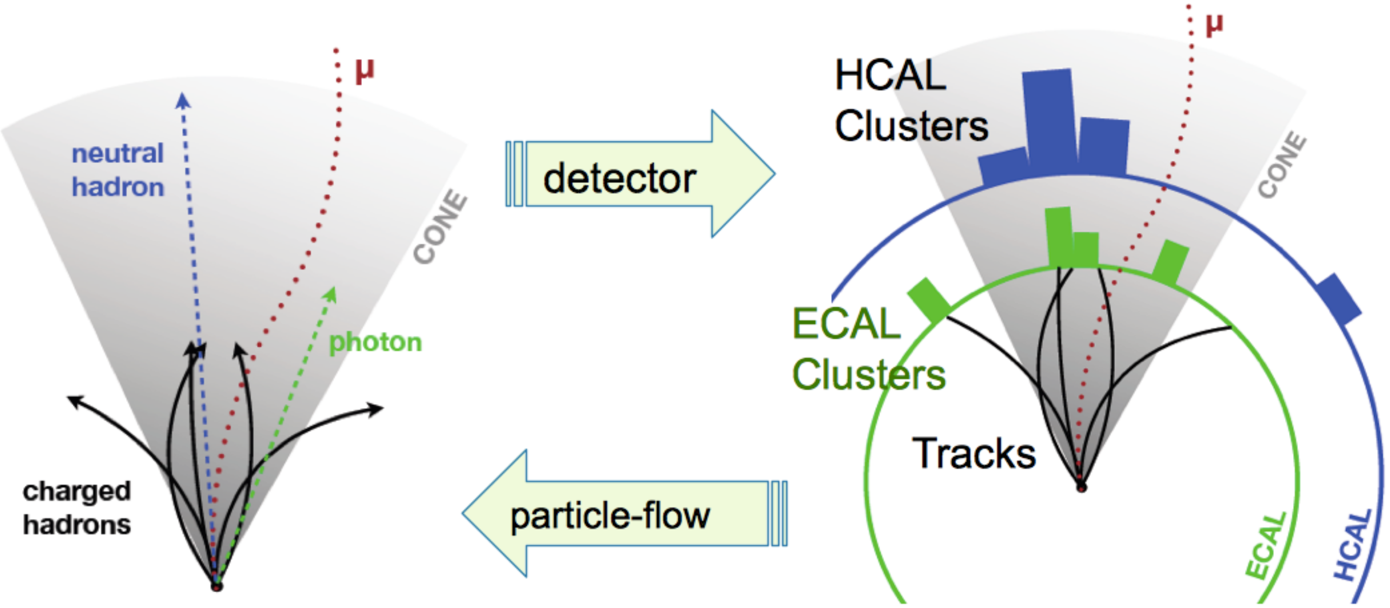


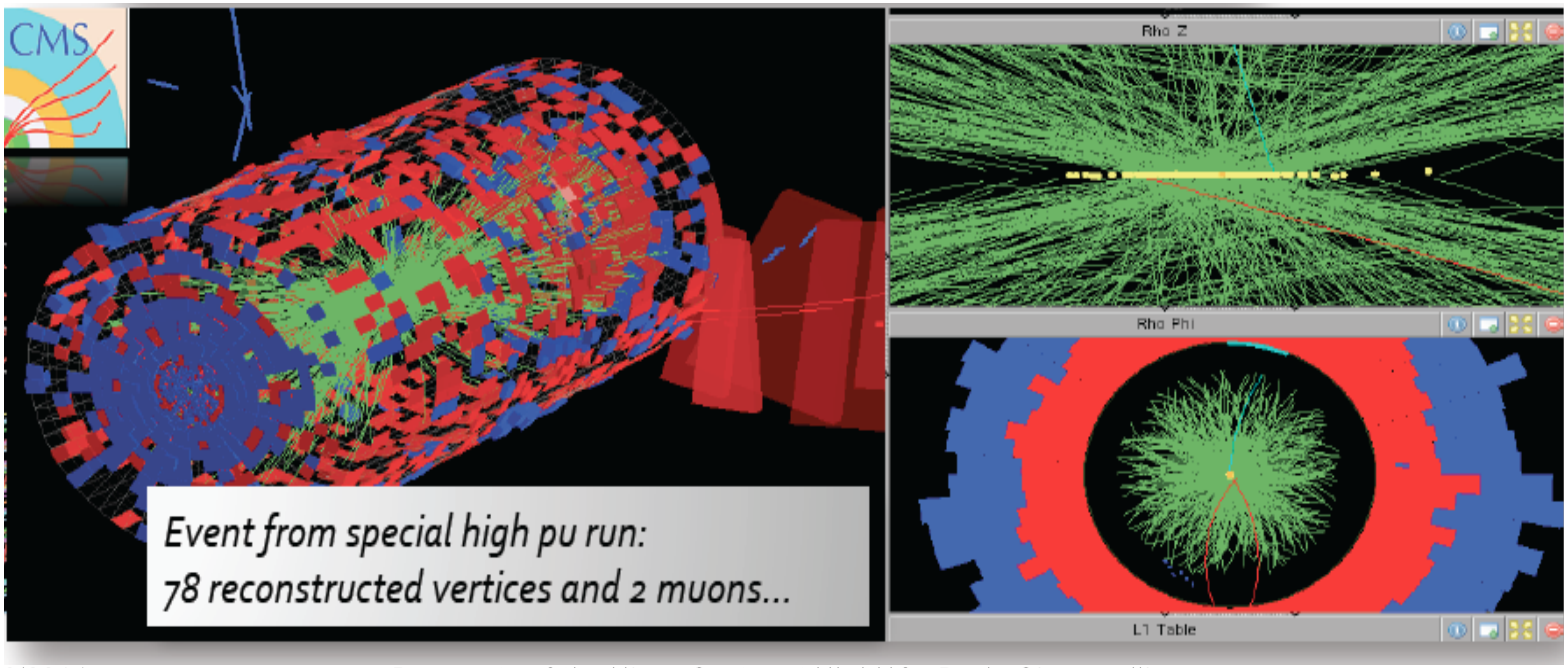


Upgrade challenges and recipe

Maintain low trigger thresholds, efficient particle and physics object reconstruction at high rate and pile-up

Need new technology R&Ds to:





Upgrade challenges and recipe

Maintain low trigger thresholds, efficient particle and physics object reconstruction at high rate and pile-up

Need new technology R&Ds to:

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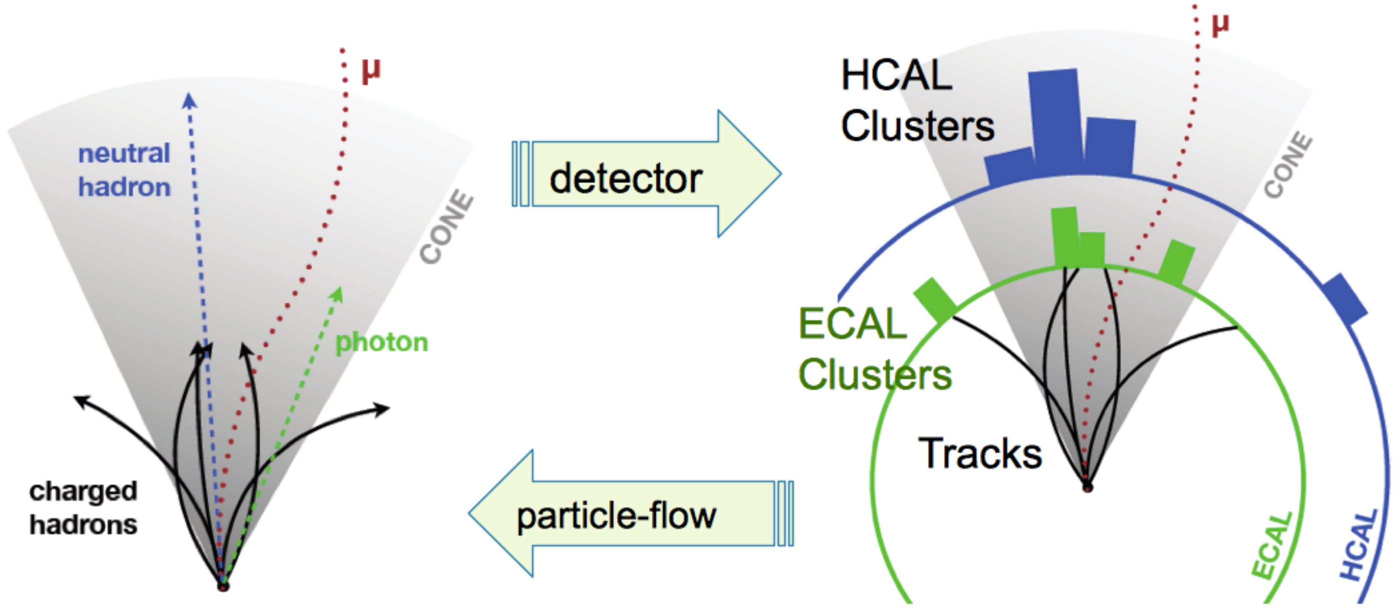

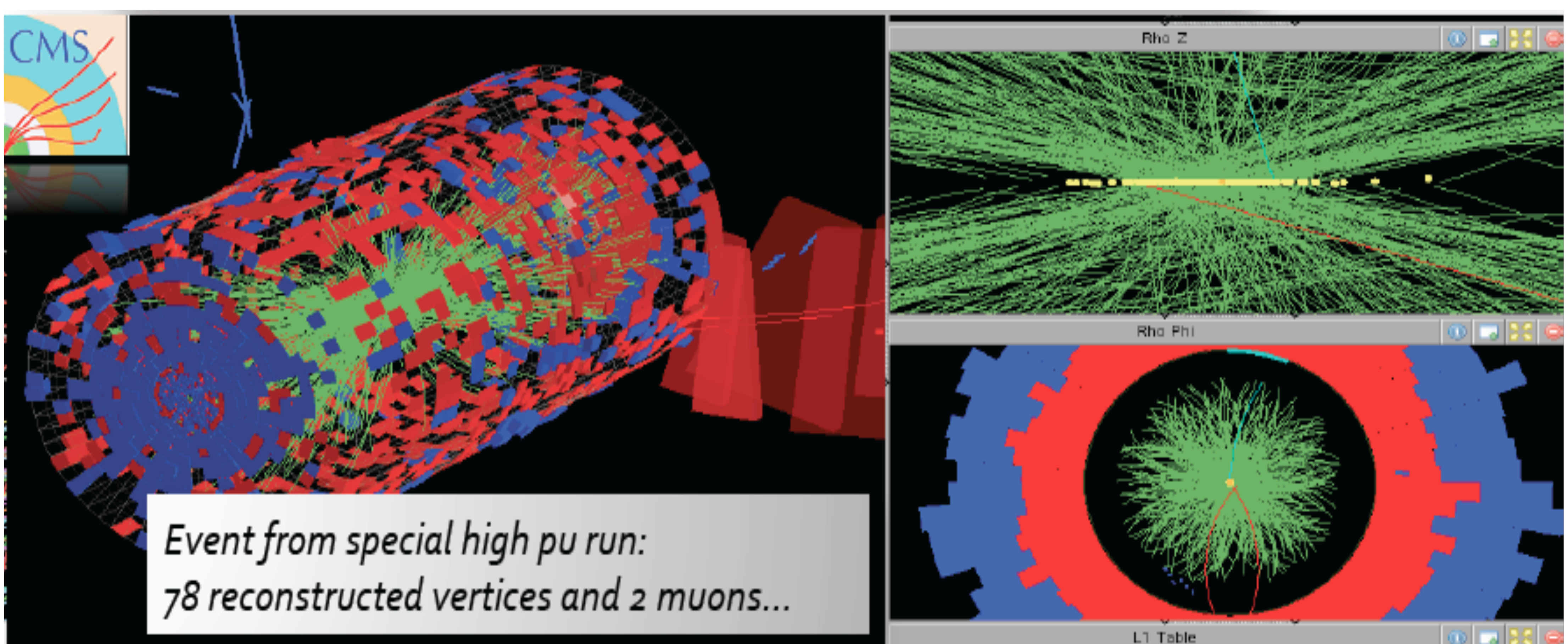

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Need new technology R&Ds to:

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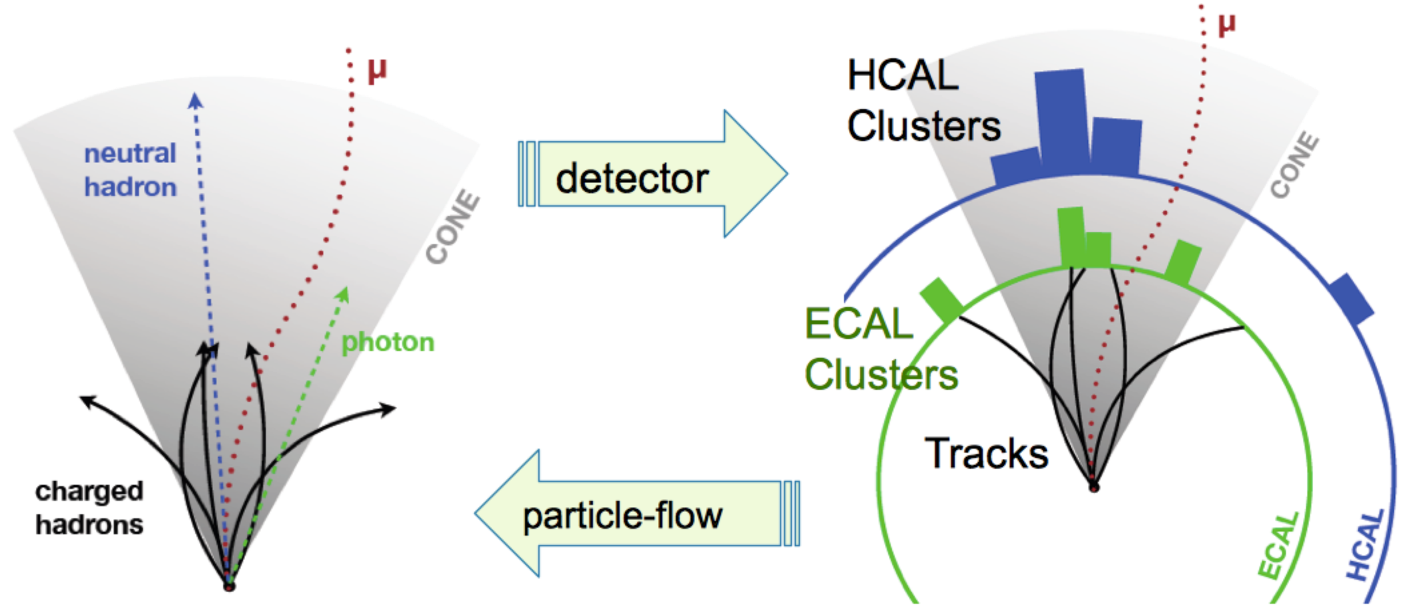

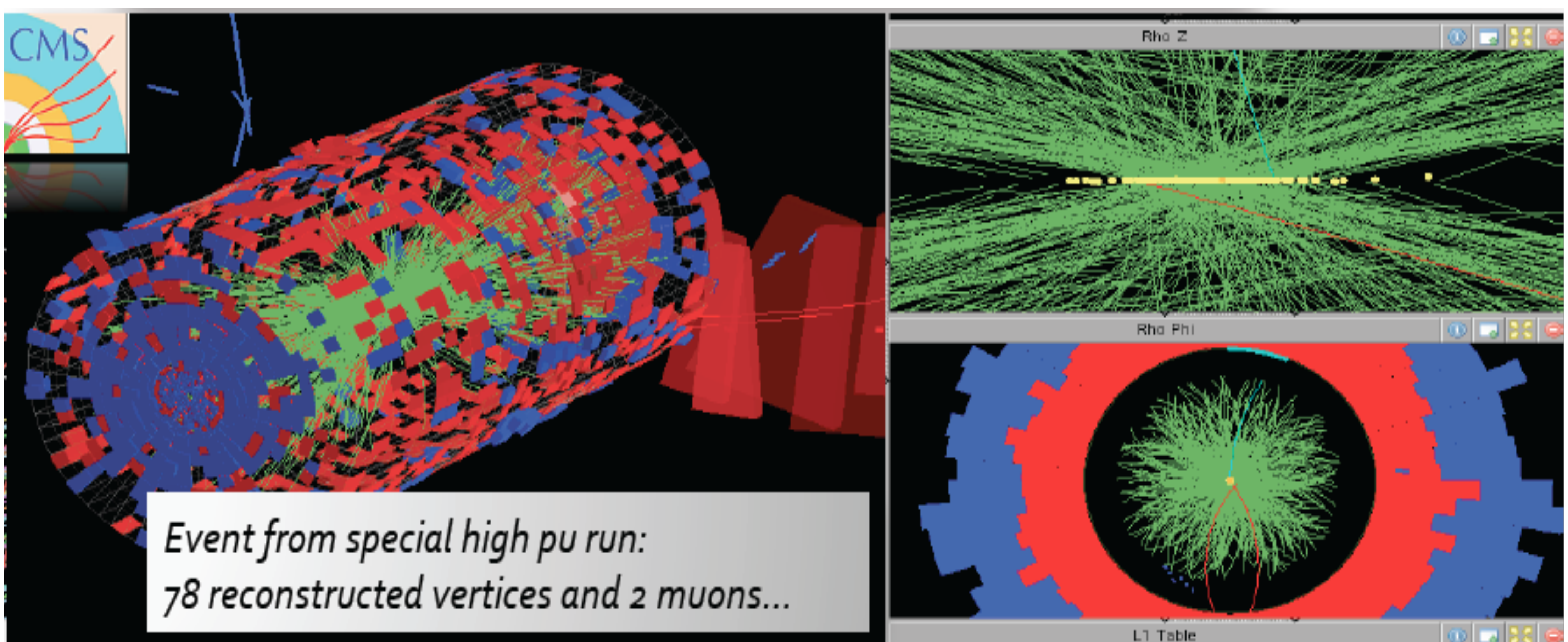

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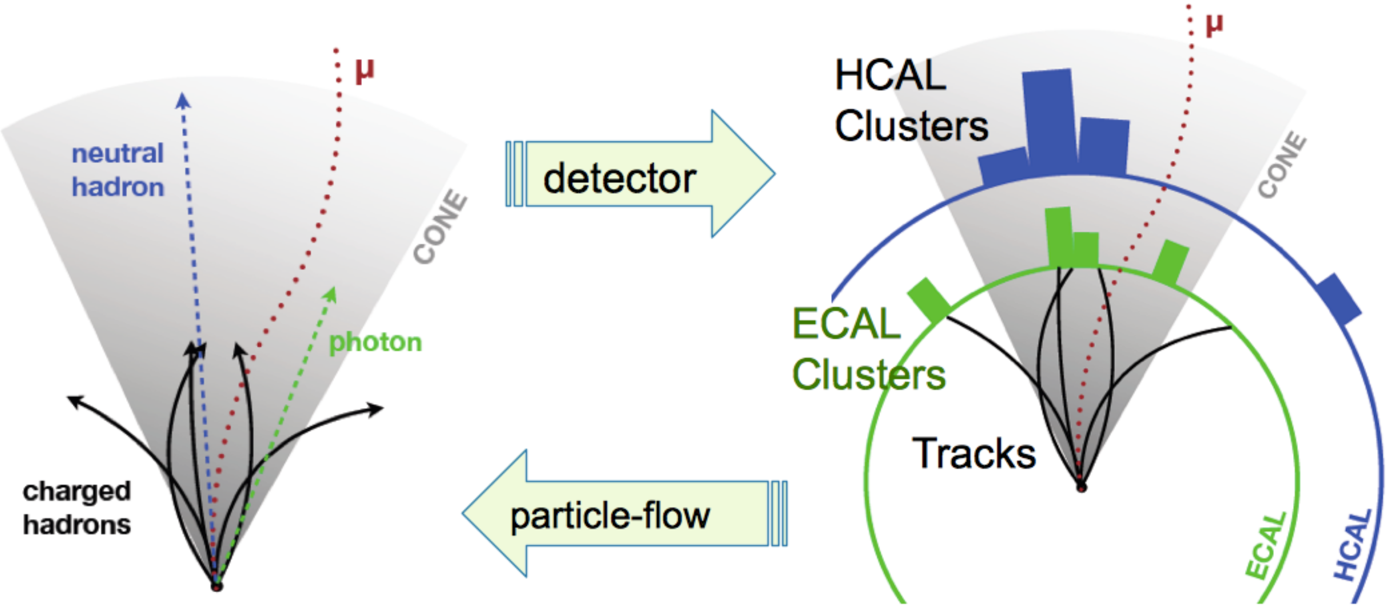

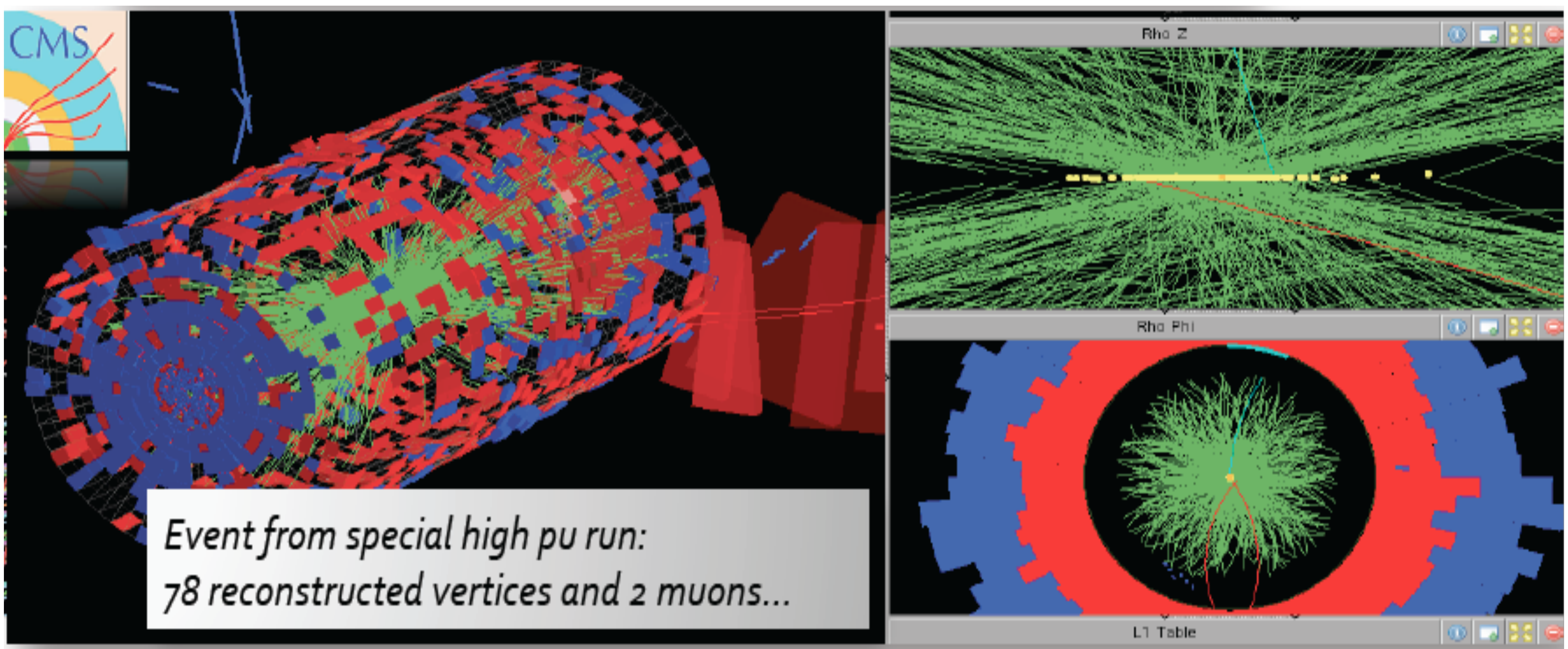

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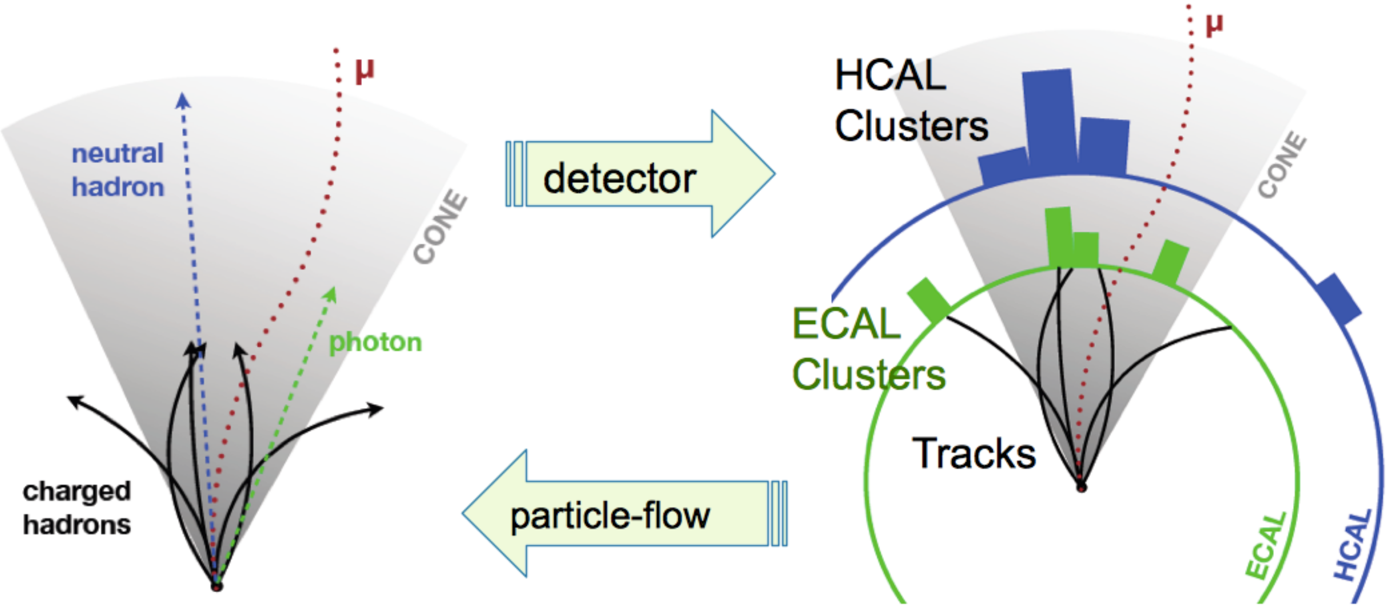

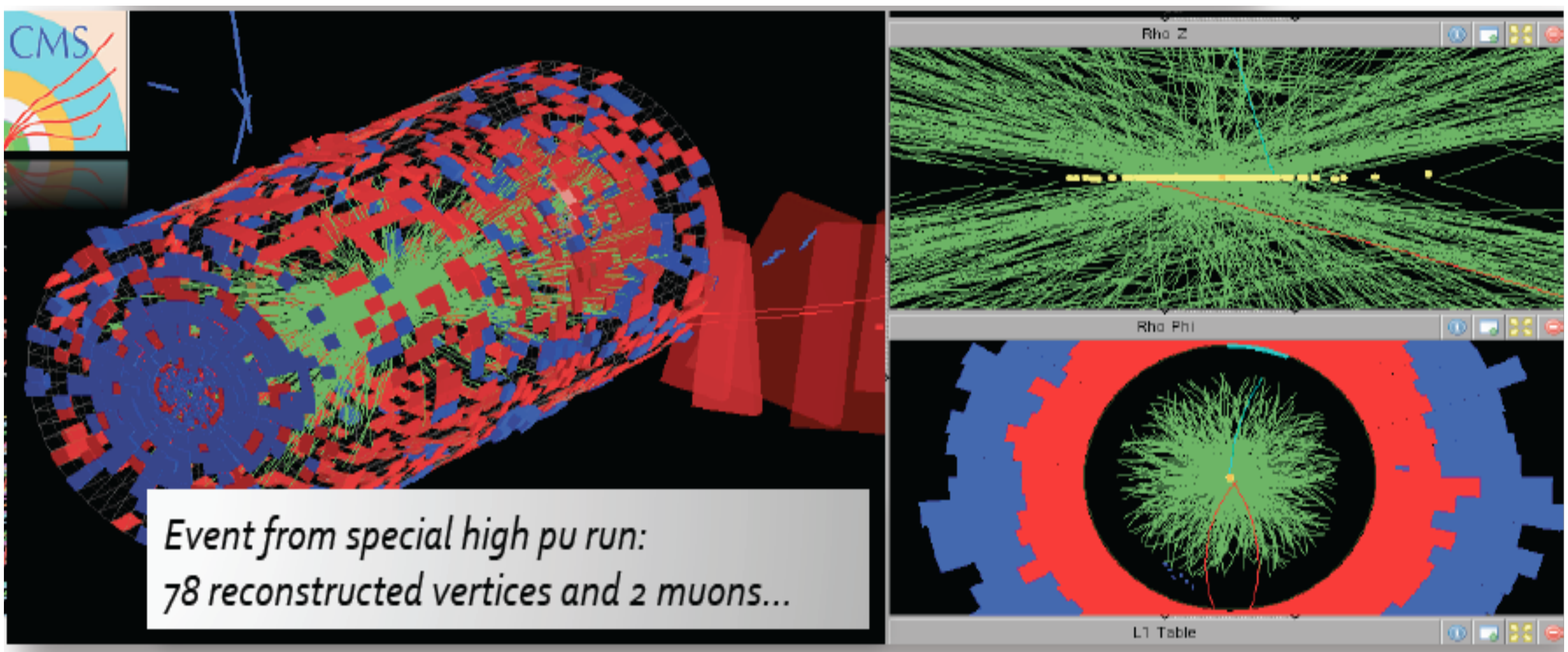

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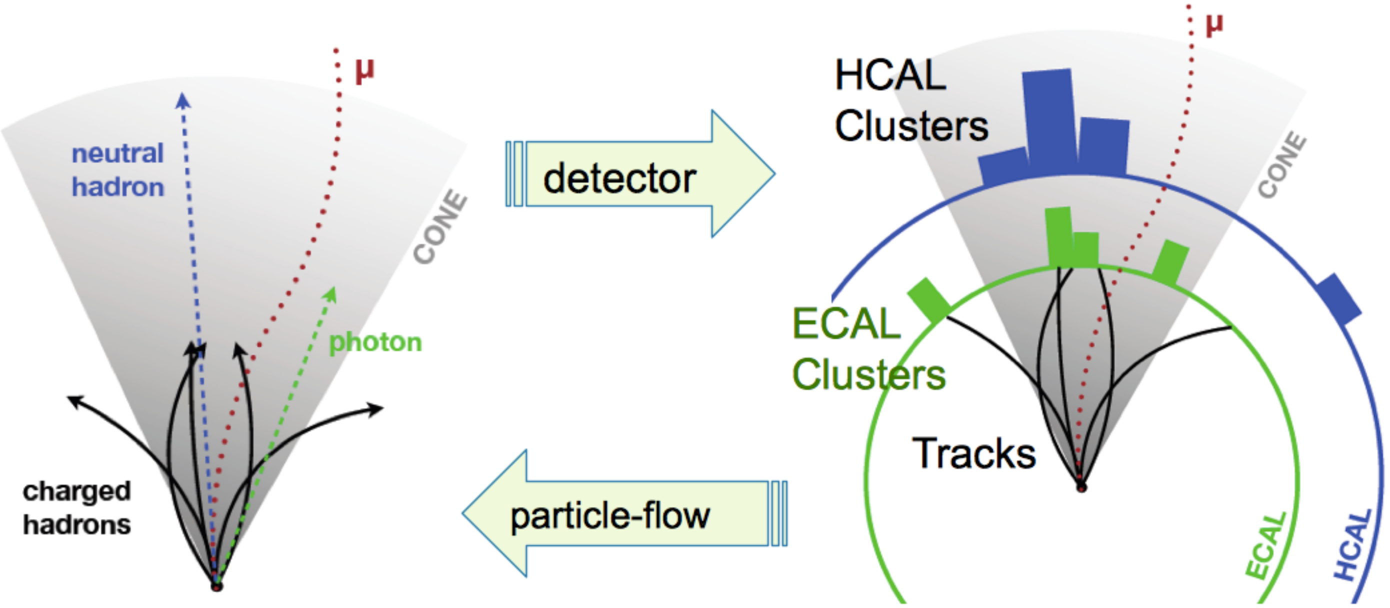
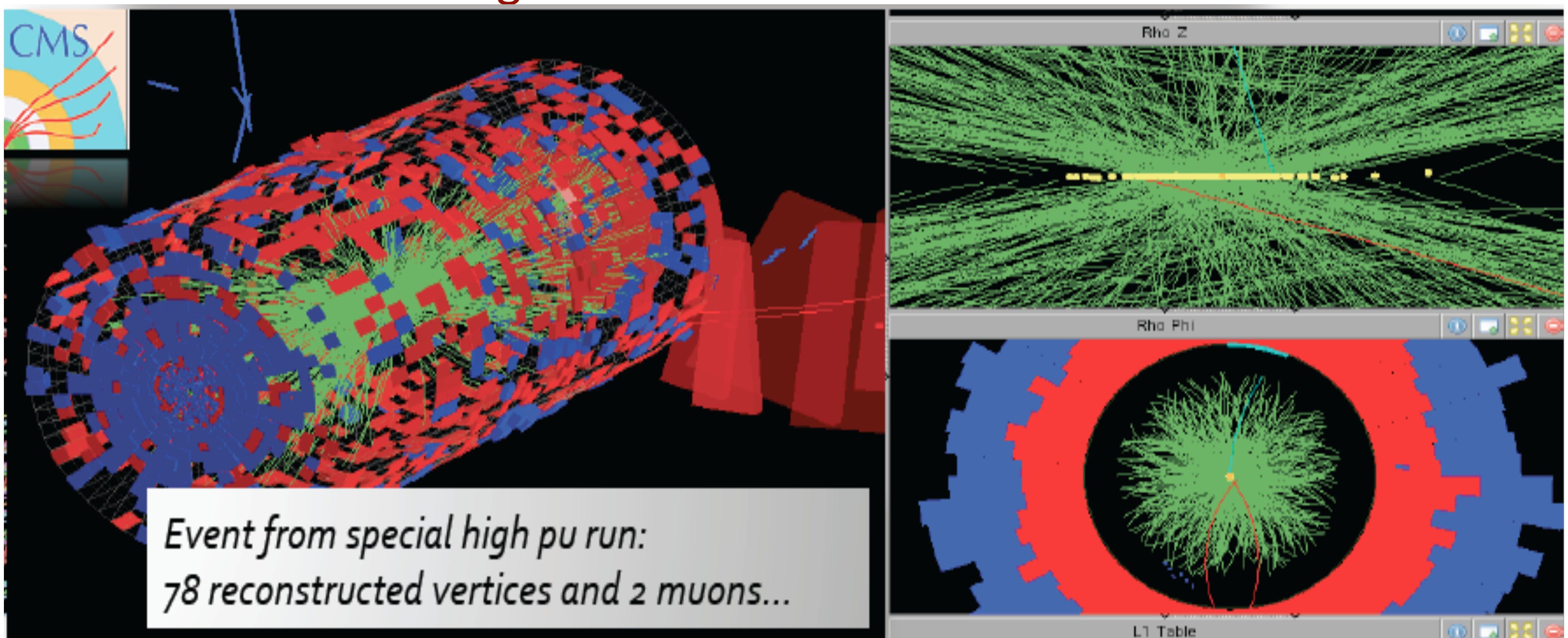


Need new technology R&Ds to:

– Increase granularity
– Increase data bandwidth
– Increase processing power
– Improve radiation hardness
– Minimize material in tracking devices



Physics program priorities

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Higgs Physics at HL-LHC

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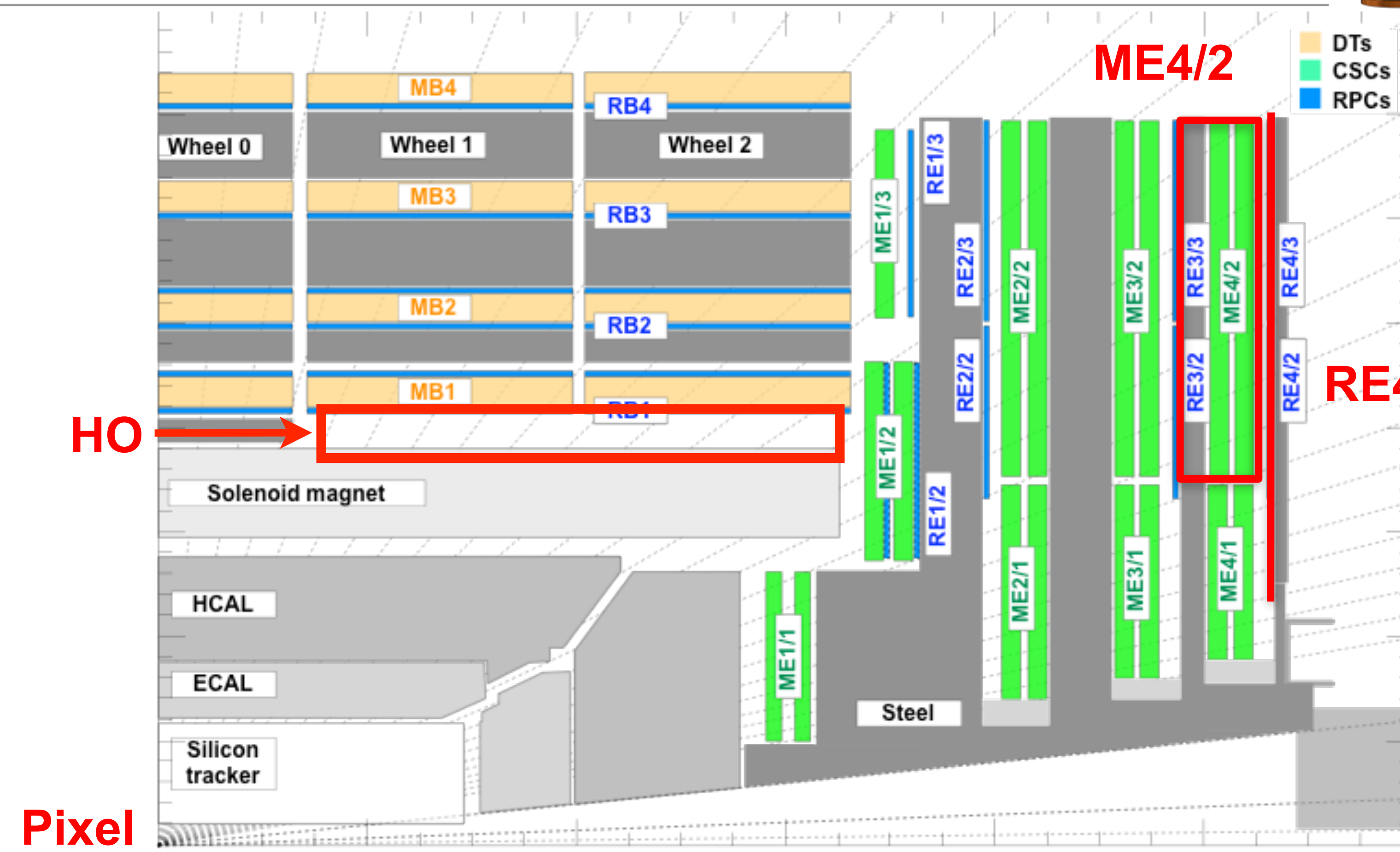
  - Look for small deviations from SM predictions

CMS upgrade program



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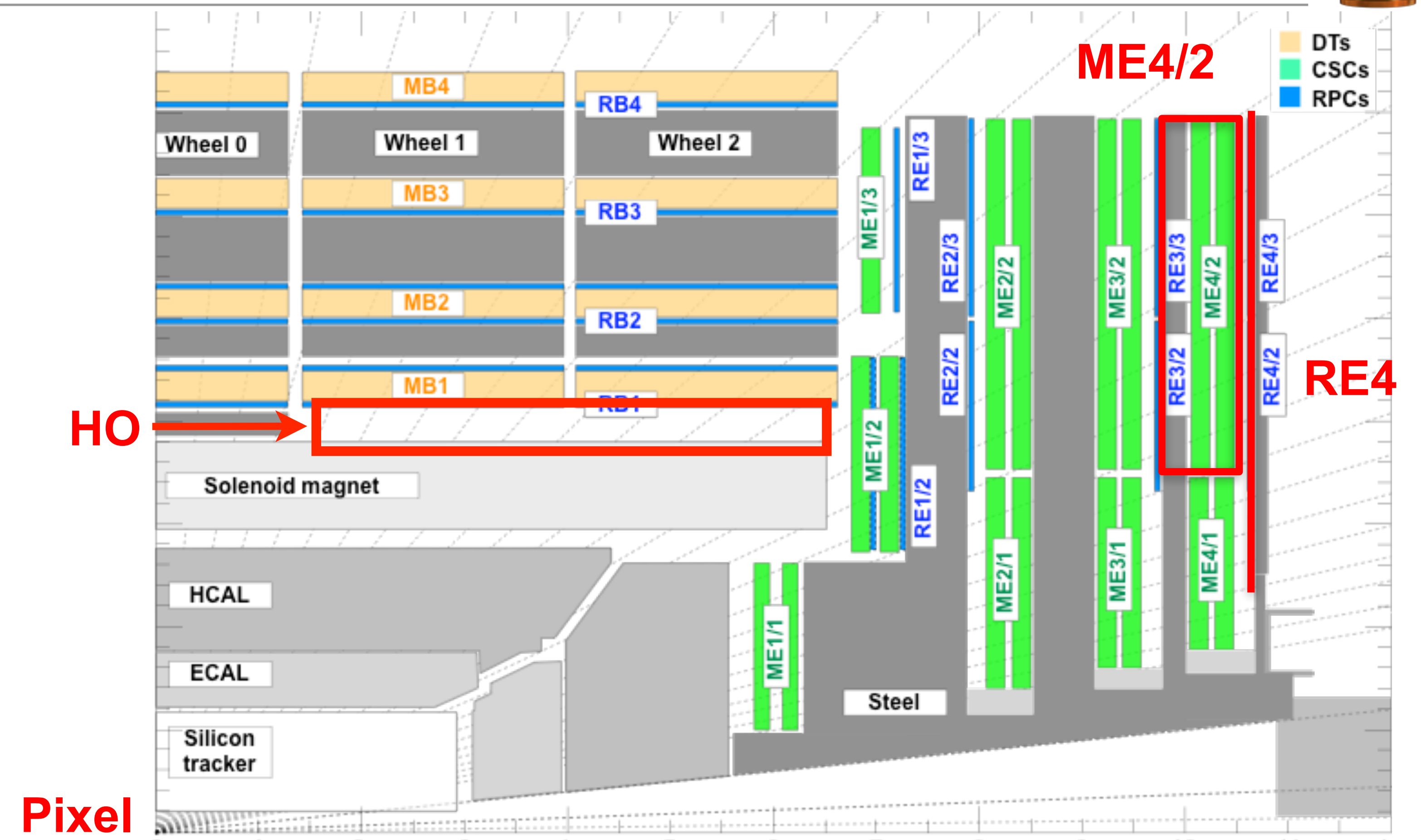

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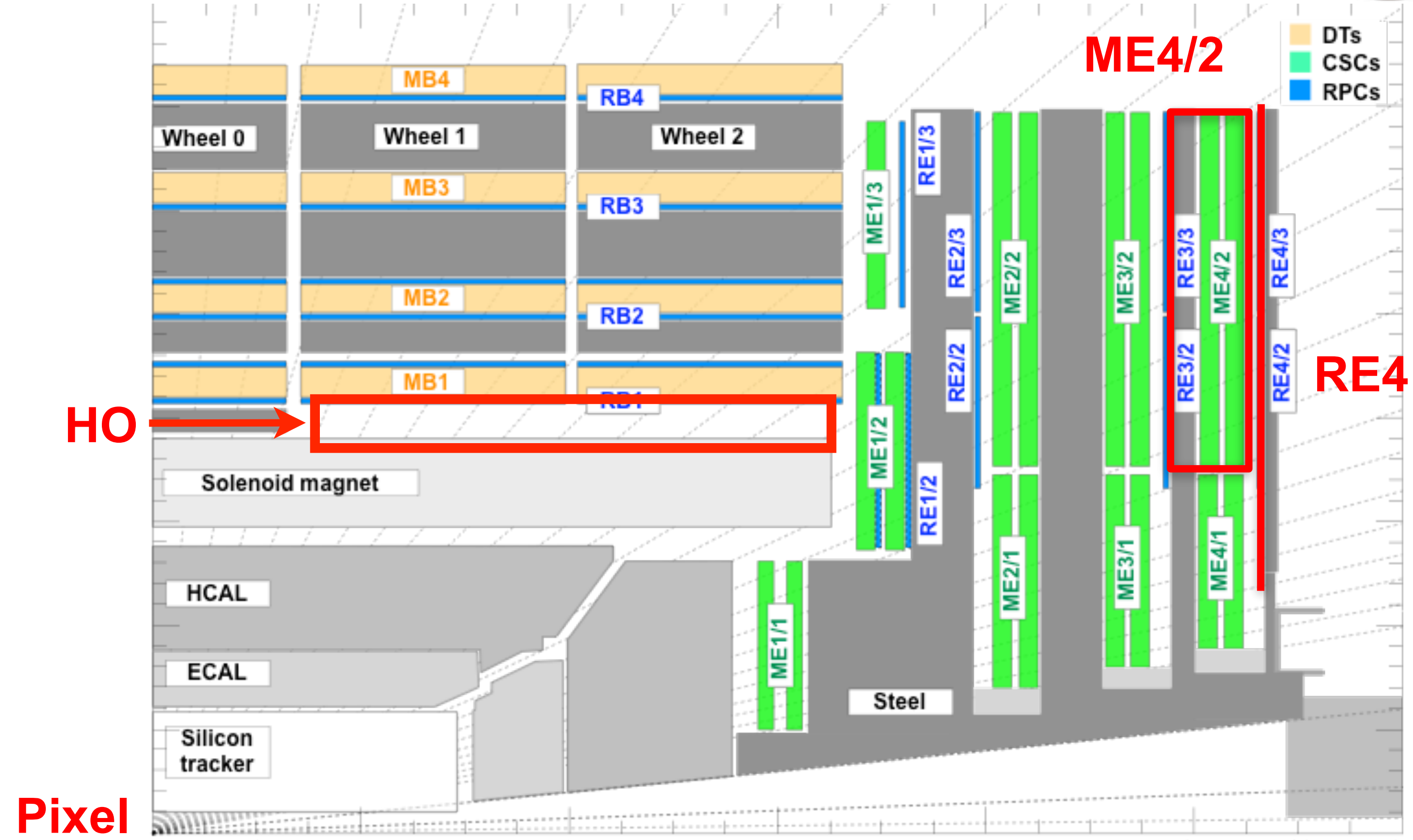
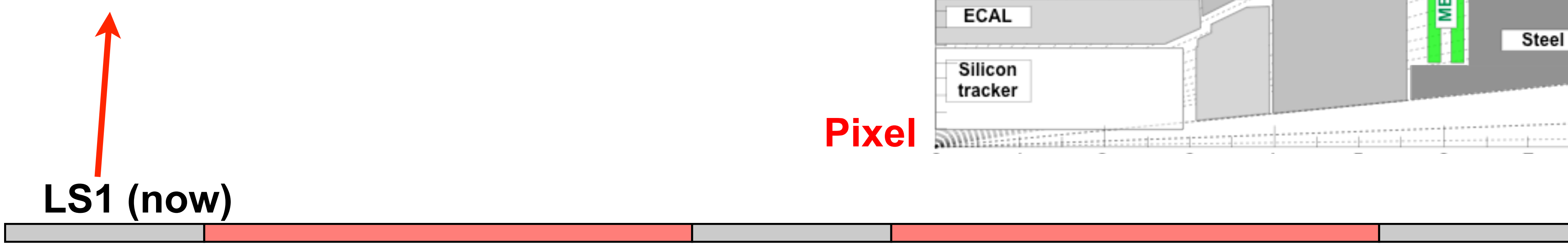
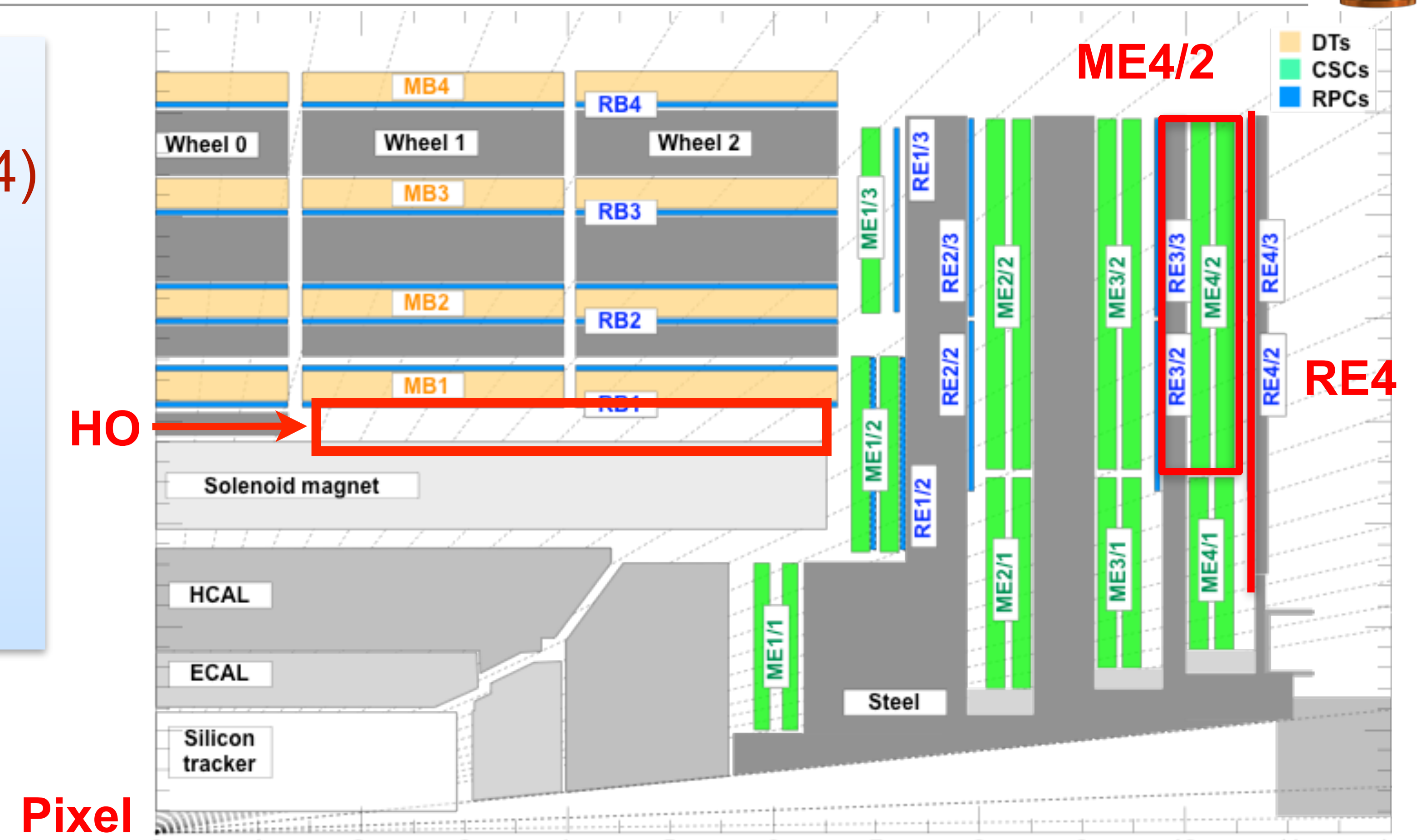




CMS upgrade program

LS1 Projects

- Complete Muon coverage (ME,RE4)
- Improve muon operation, DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD→SiPMs)
- DAQ1→DAQ2



LS1 (now)

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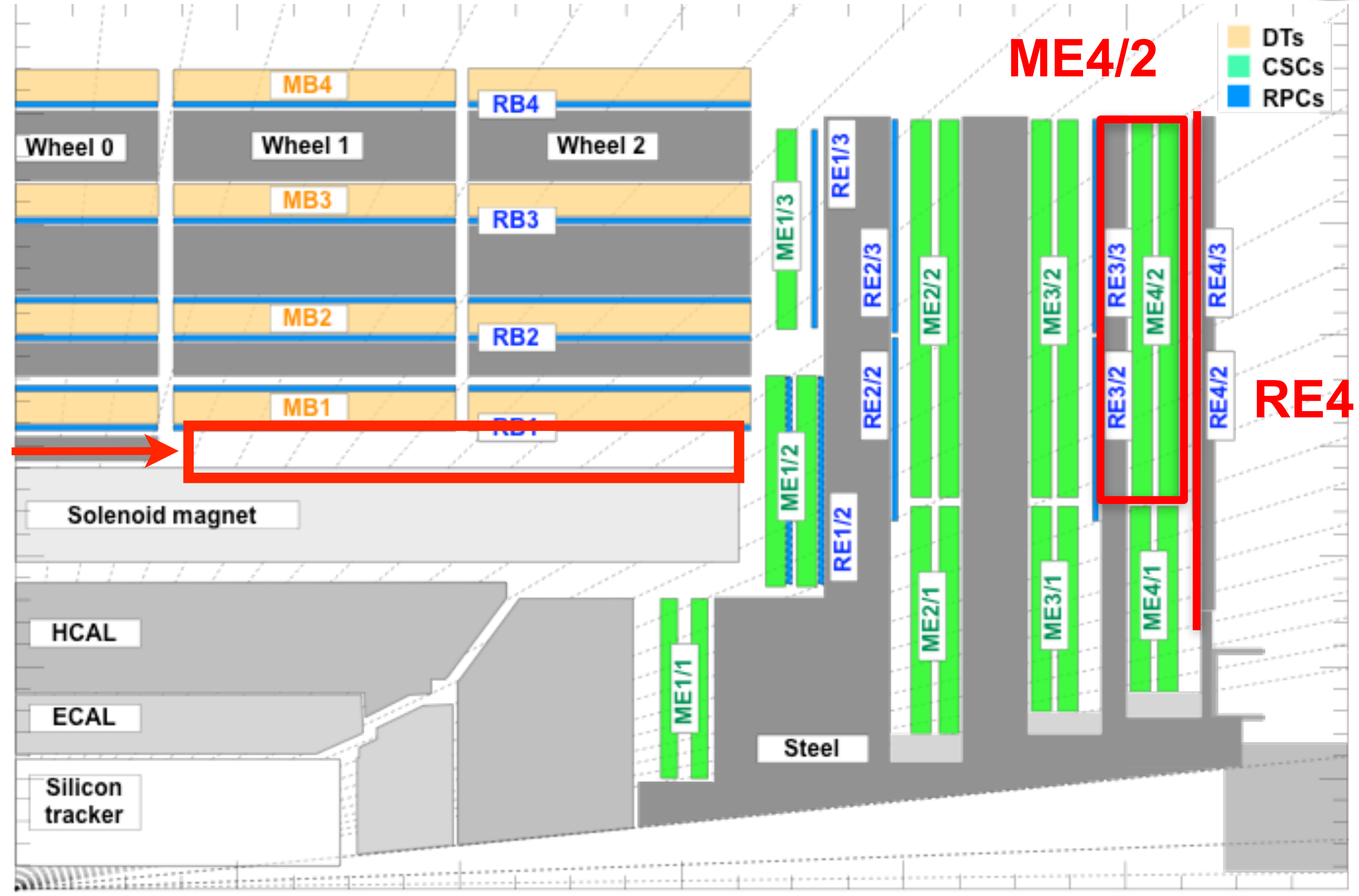
HO



Pixel

LS1 (now)

LS2 (2018)

Phase 1 Upgrades

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- GEMs for forward muon det. under review
- Preparatory work during LS1
  - New beam pipe for pixel upgrade
  - Install test slices of pixel, HCAL, L1-trigger
  - Install ECAL optical splitters for L1-trigger

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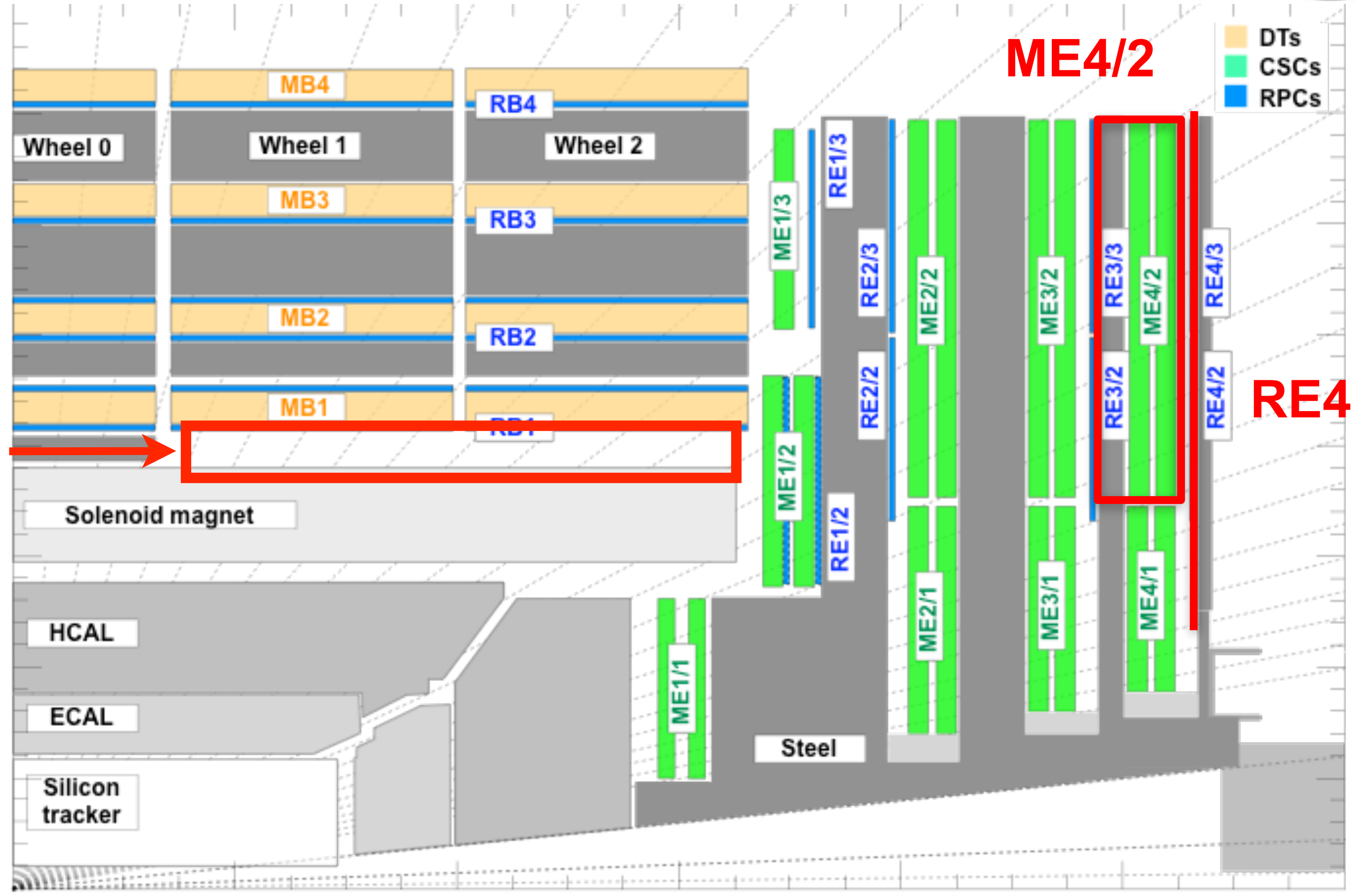

LS1 (now) LS2 (2018) LS3 (~2023)

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Phase 2: being defined now

- Tracker replacement, L1 Track-Trigger
- Forward: calorimetry, muons and tracking
- High precision timing for PU mitigation
- Further Trigger upgrade
- Further DAQ upgrade

Expected Phase 1 improvements

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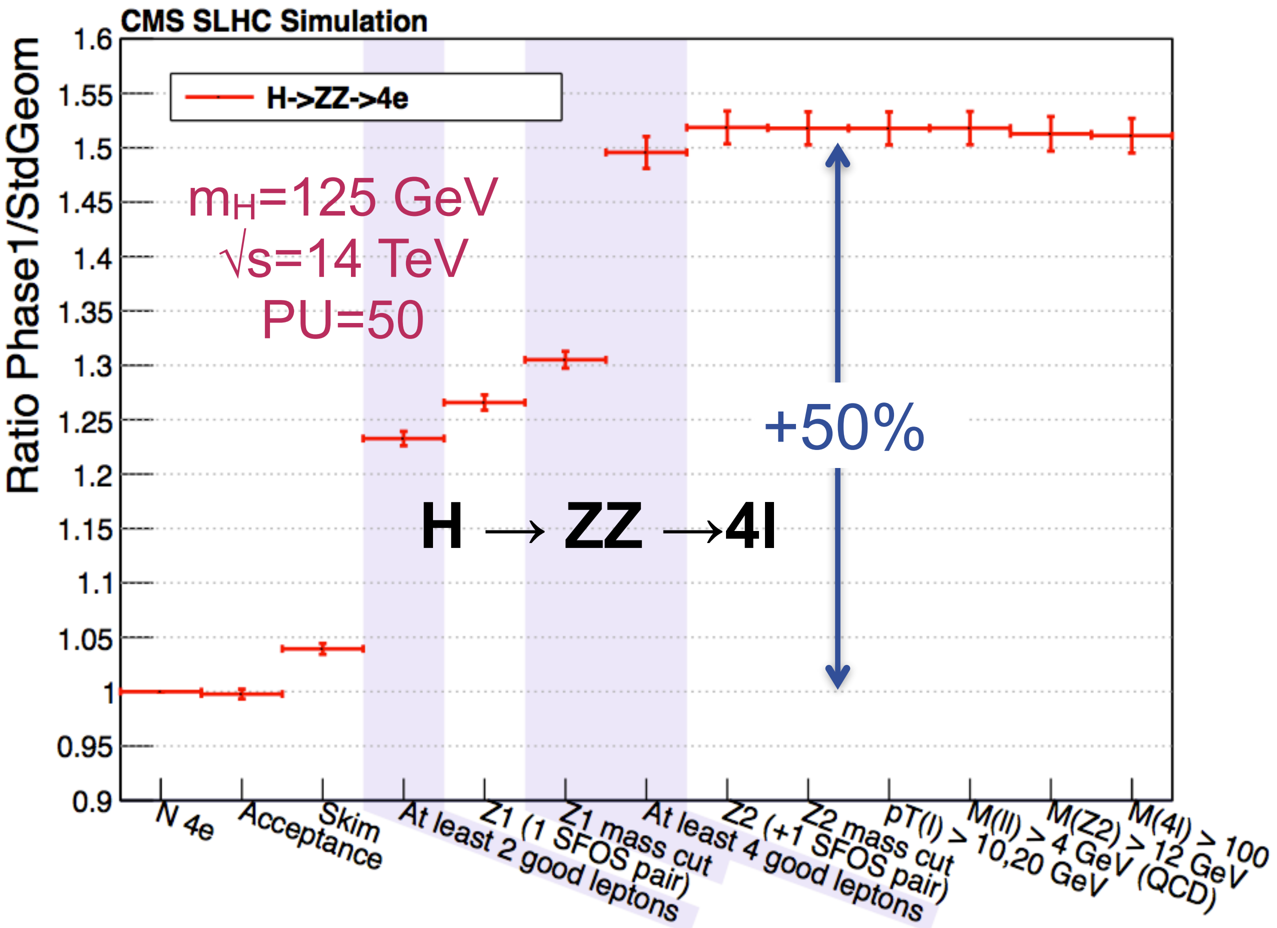

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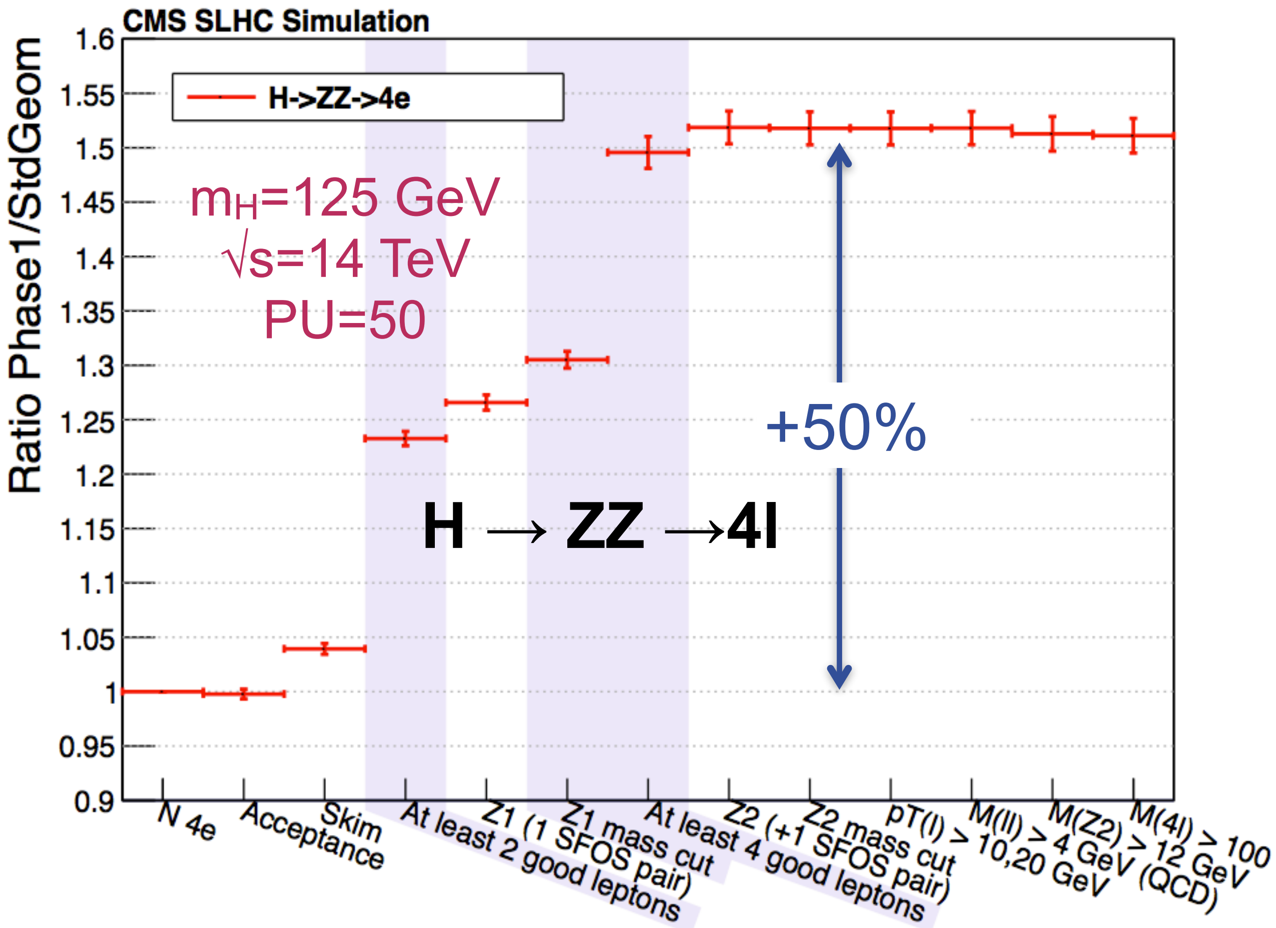

Significant gain in signal reconstruction efficiency:

H→ 4μ	+41%
H→ 2μ2e	+48%
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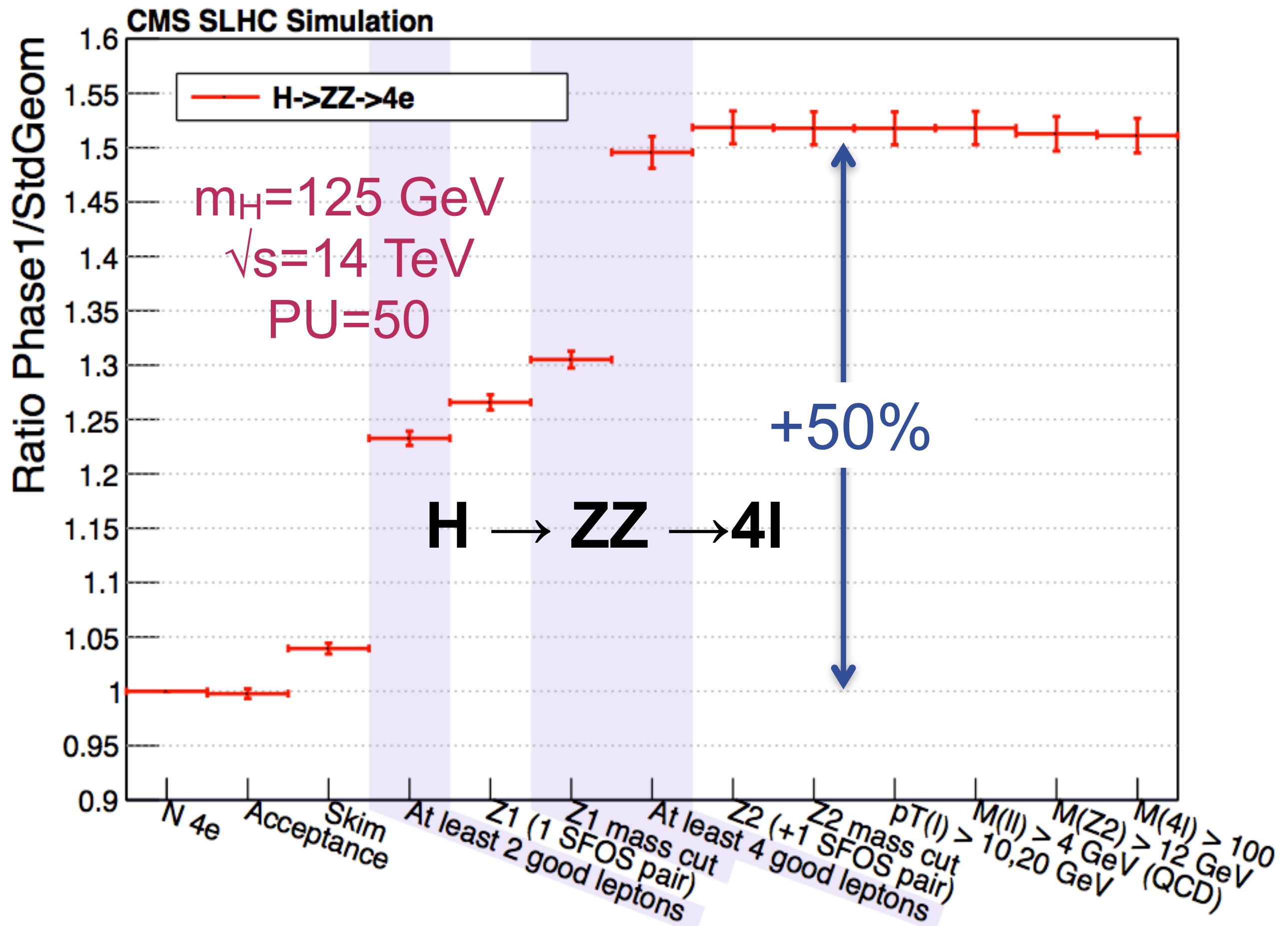

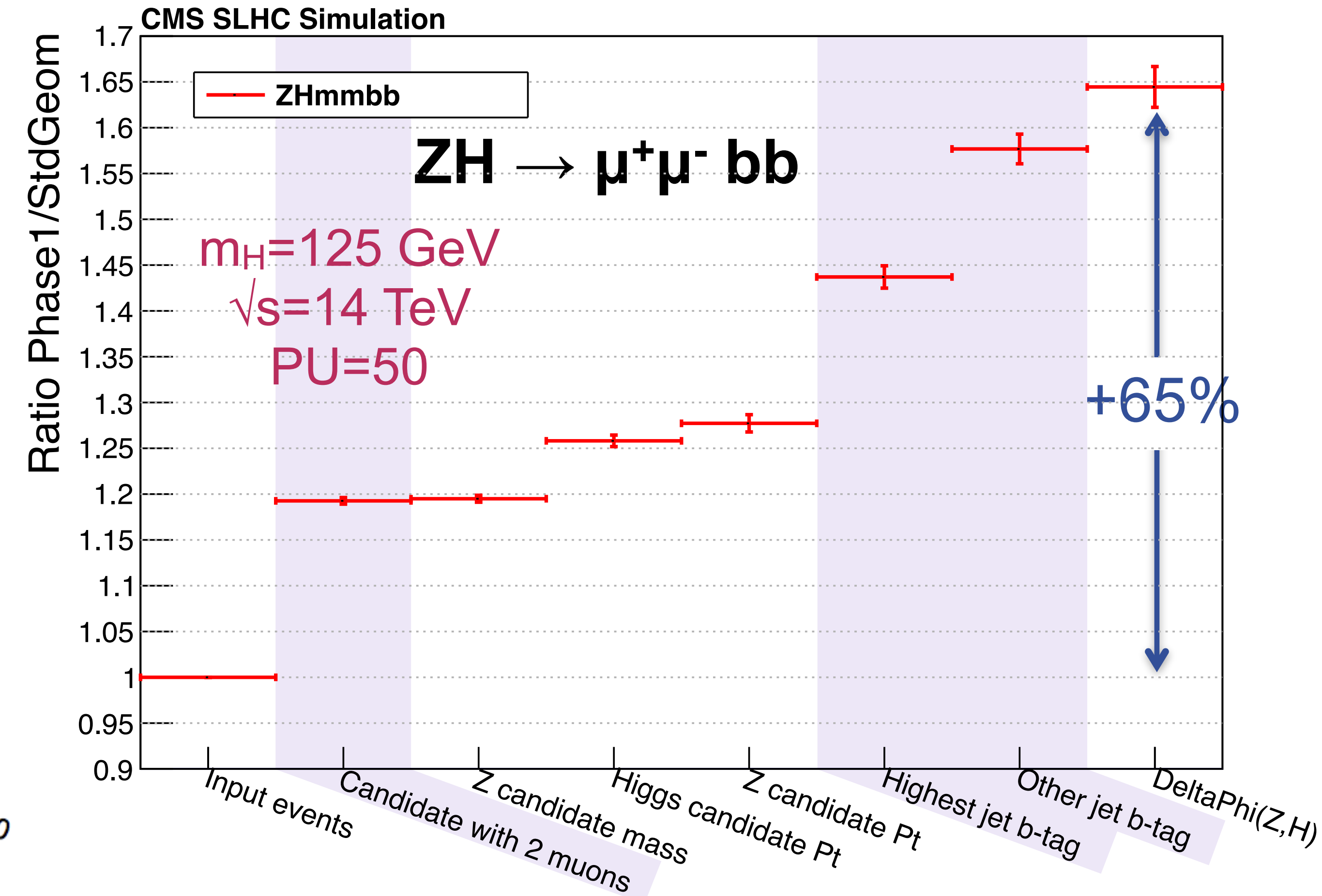

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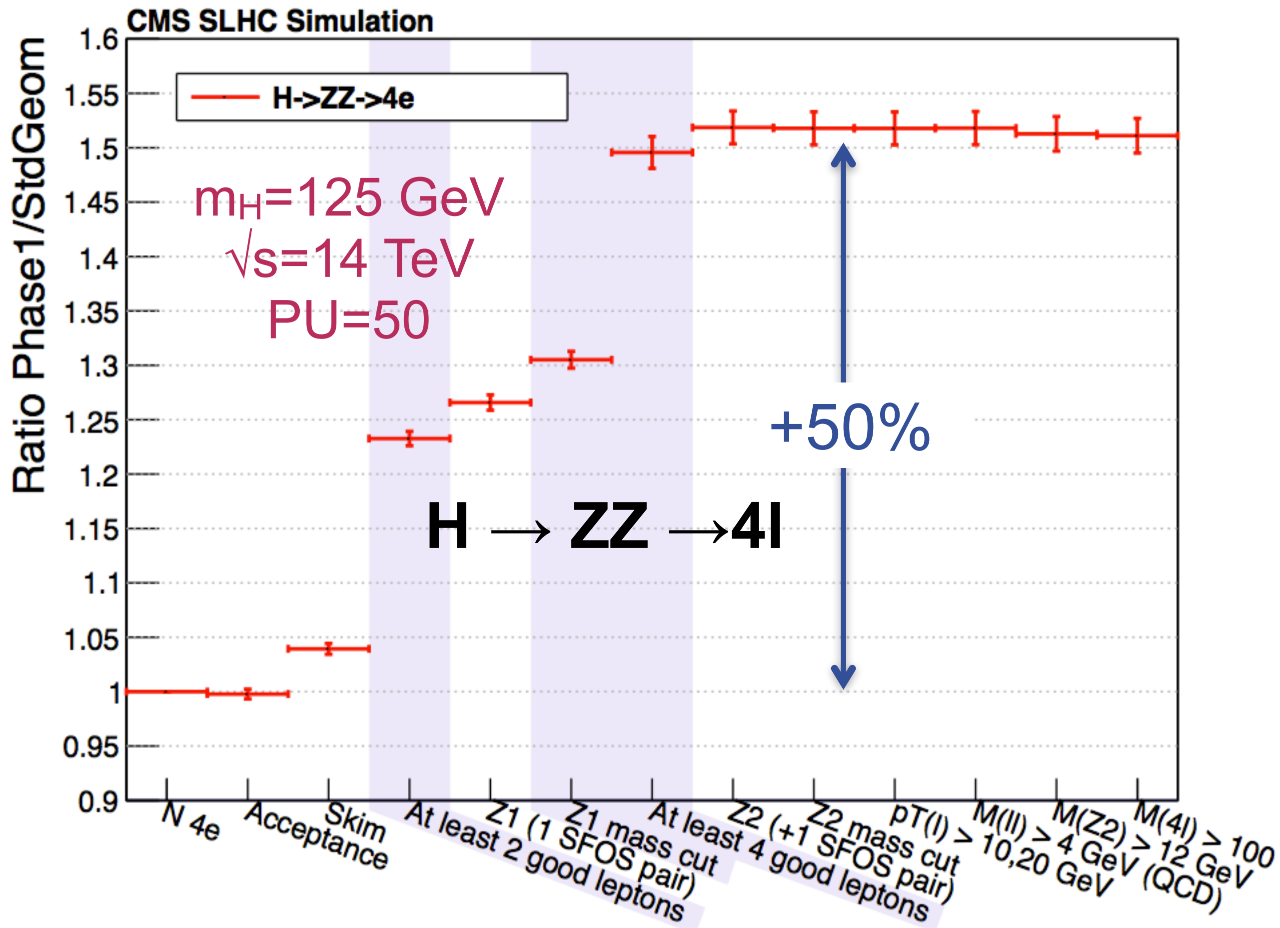

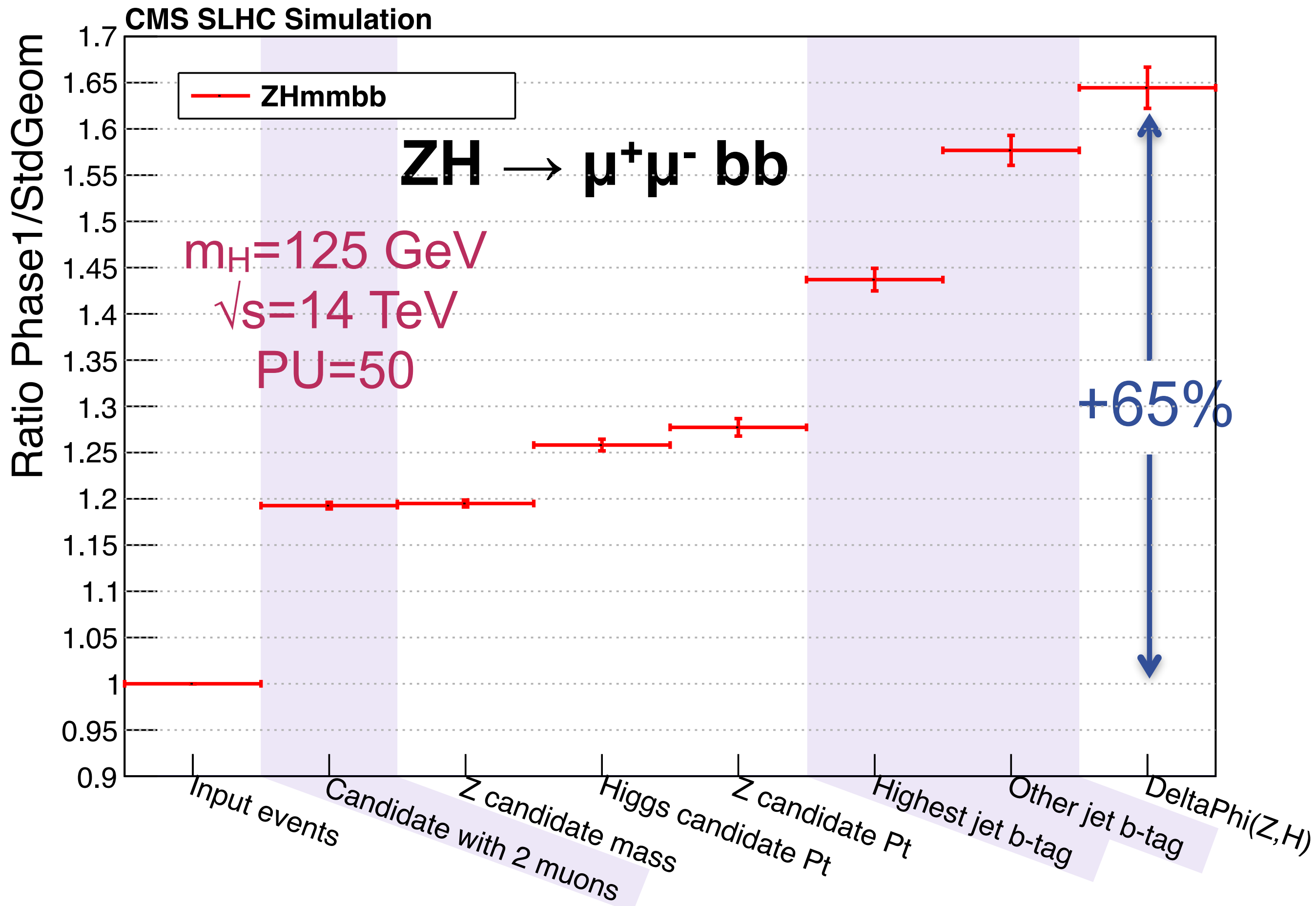

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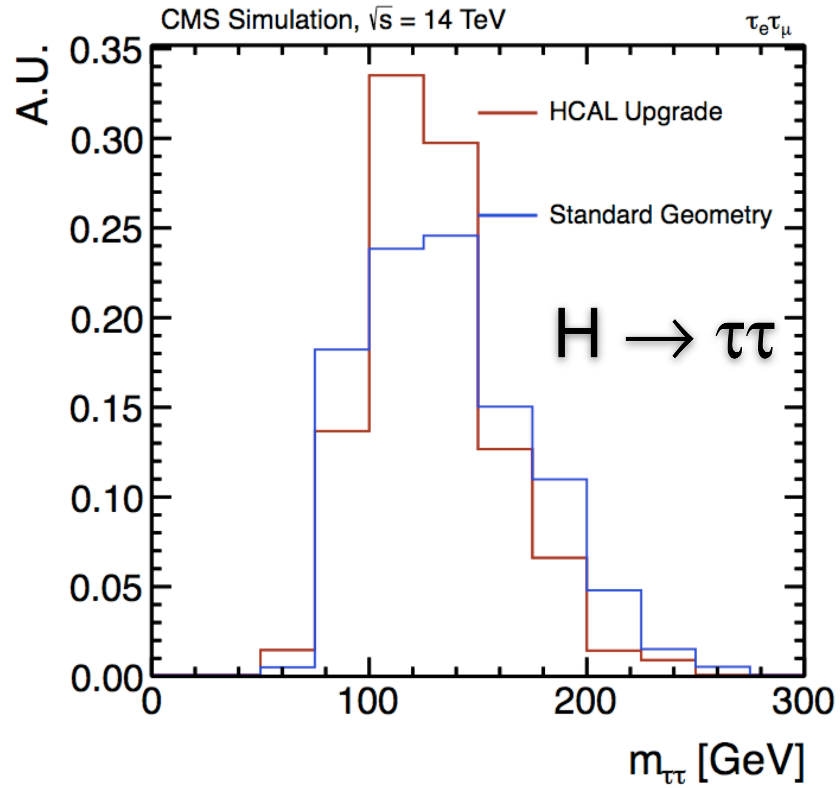

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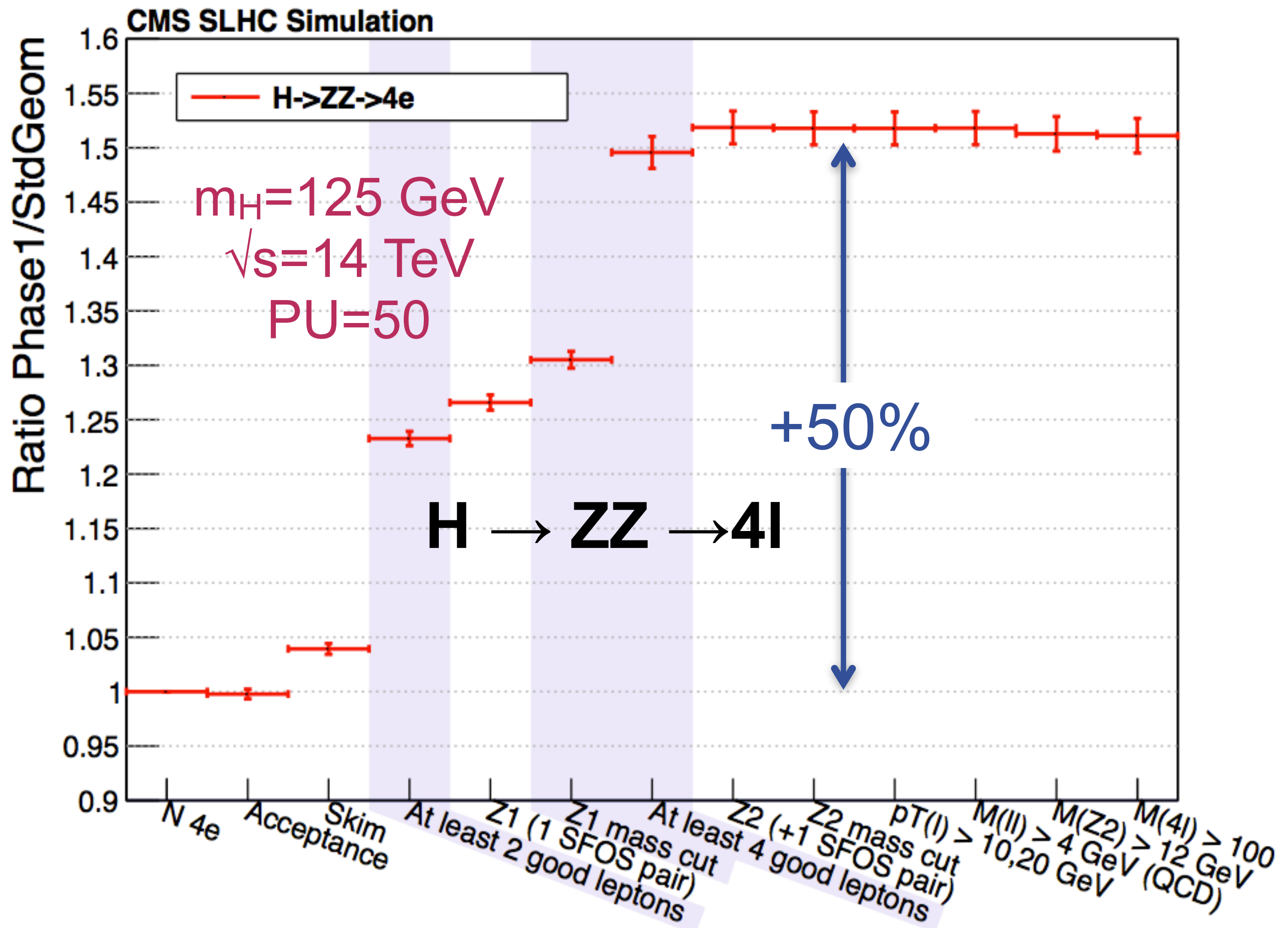

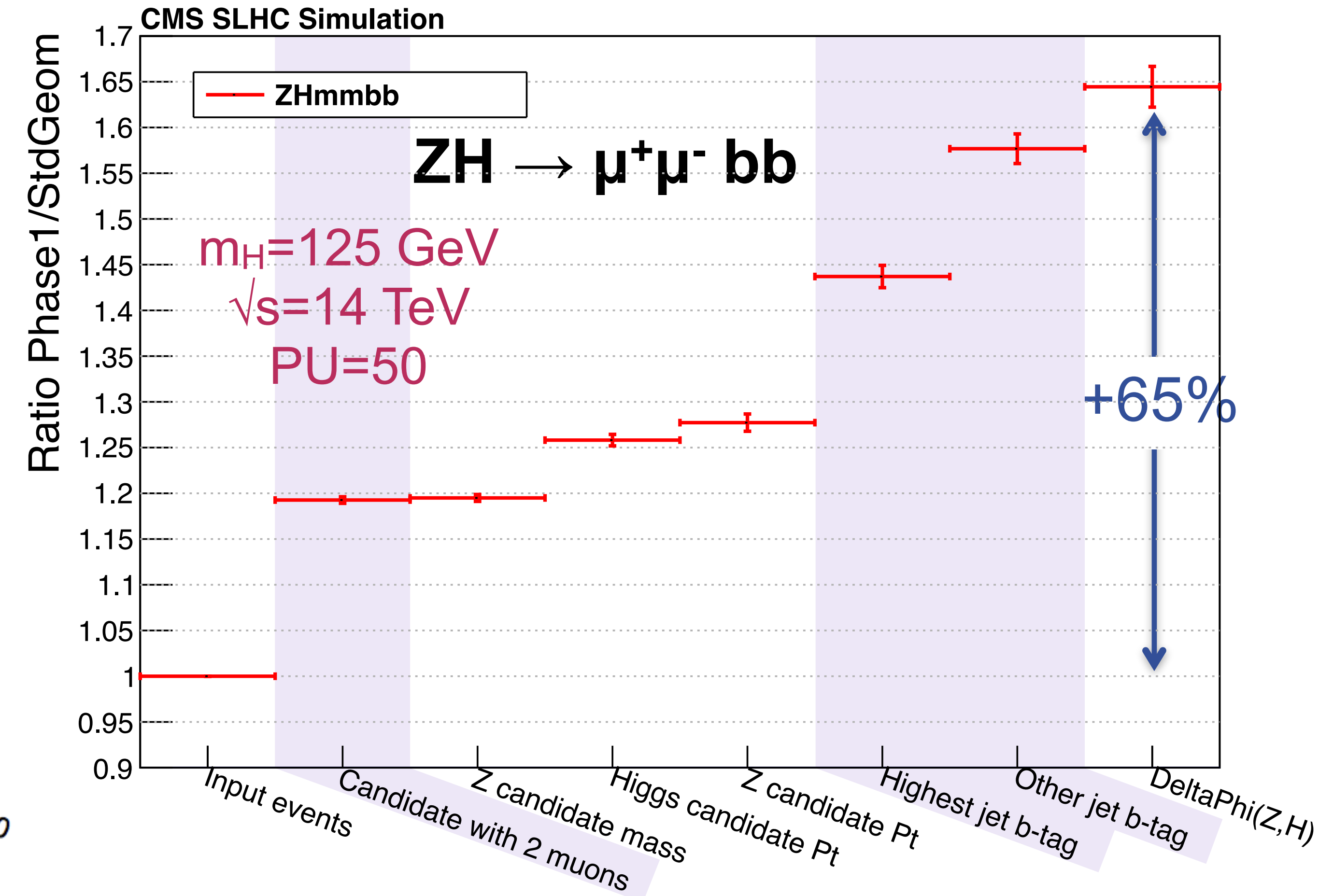

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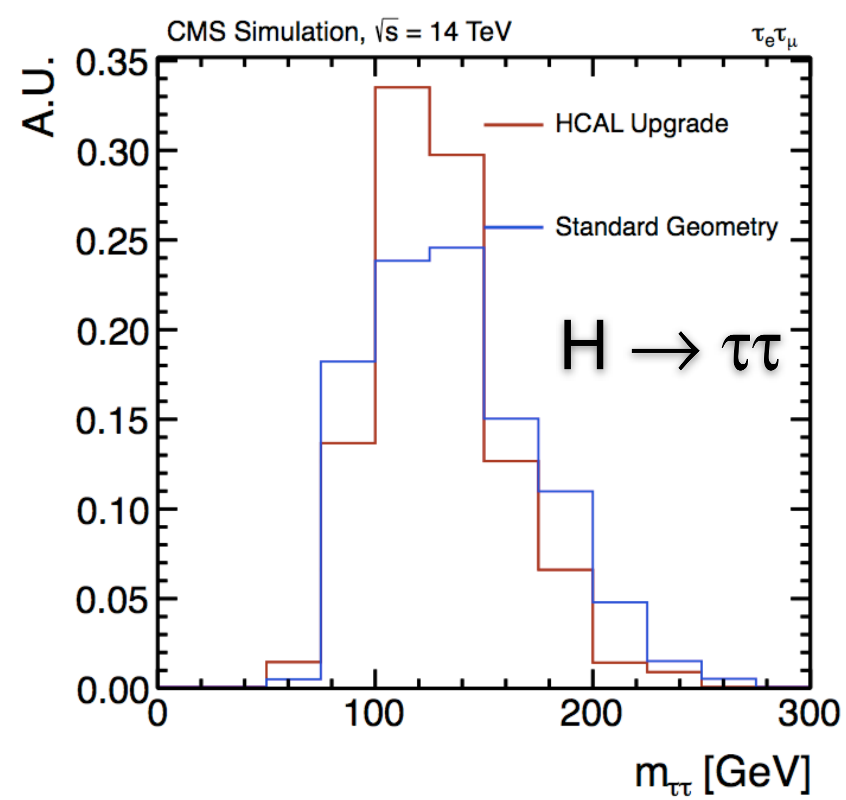

Total efficiency improvement: factor of 2.5 (4.5% → 11%)

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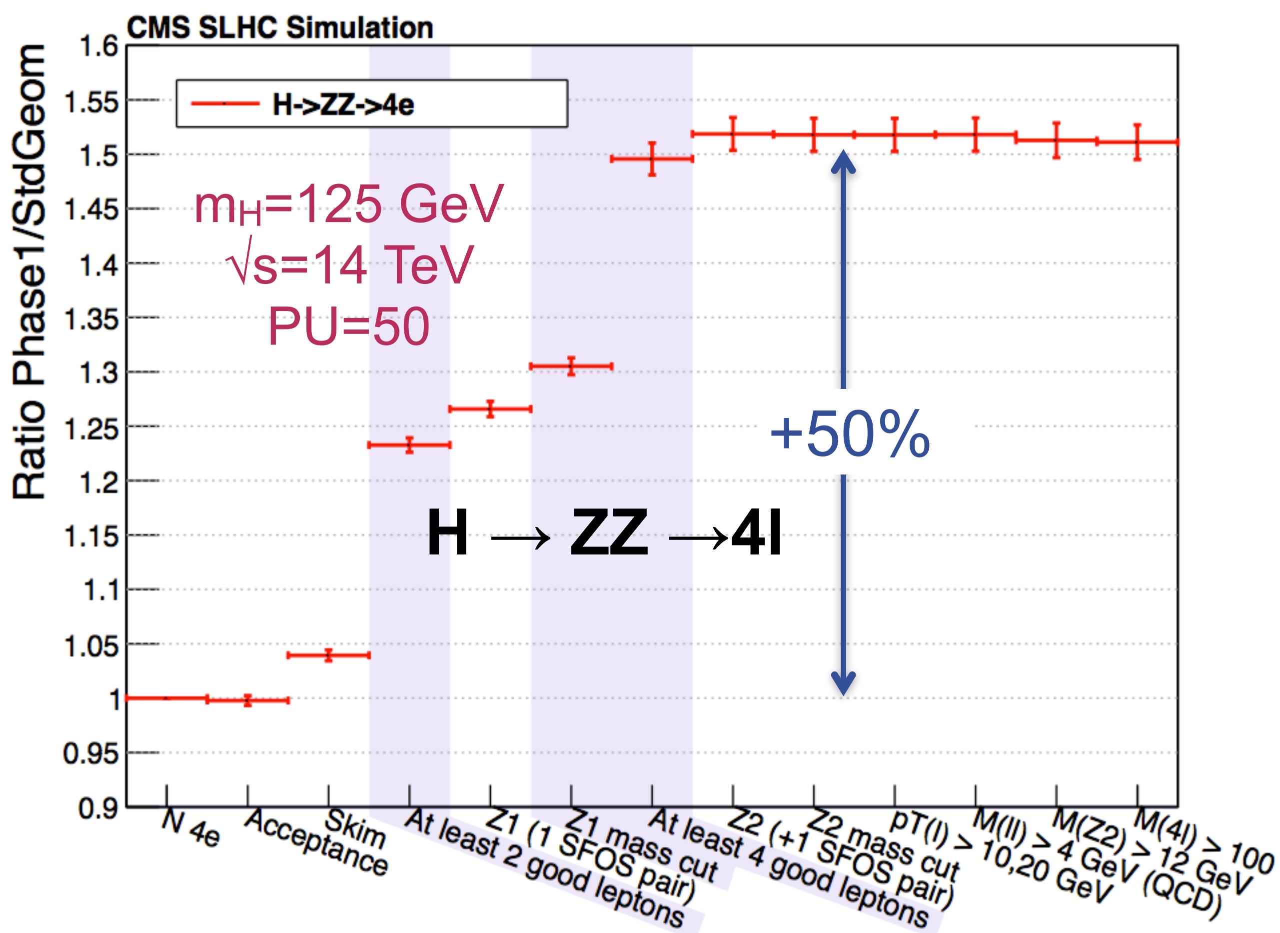

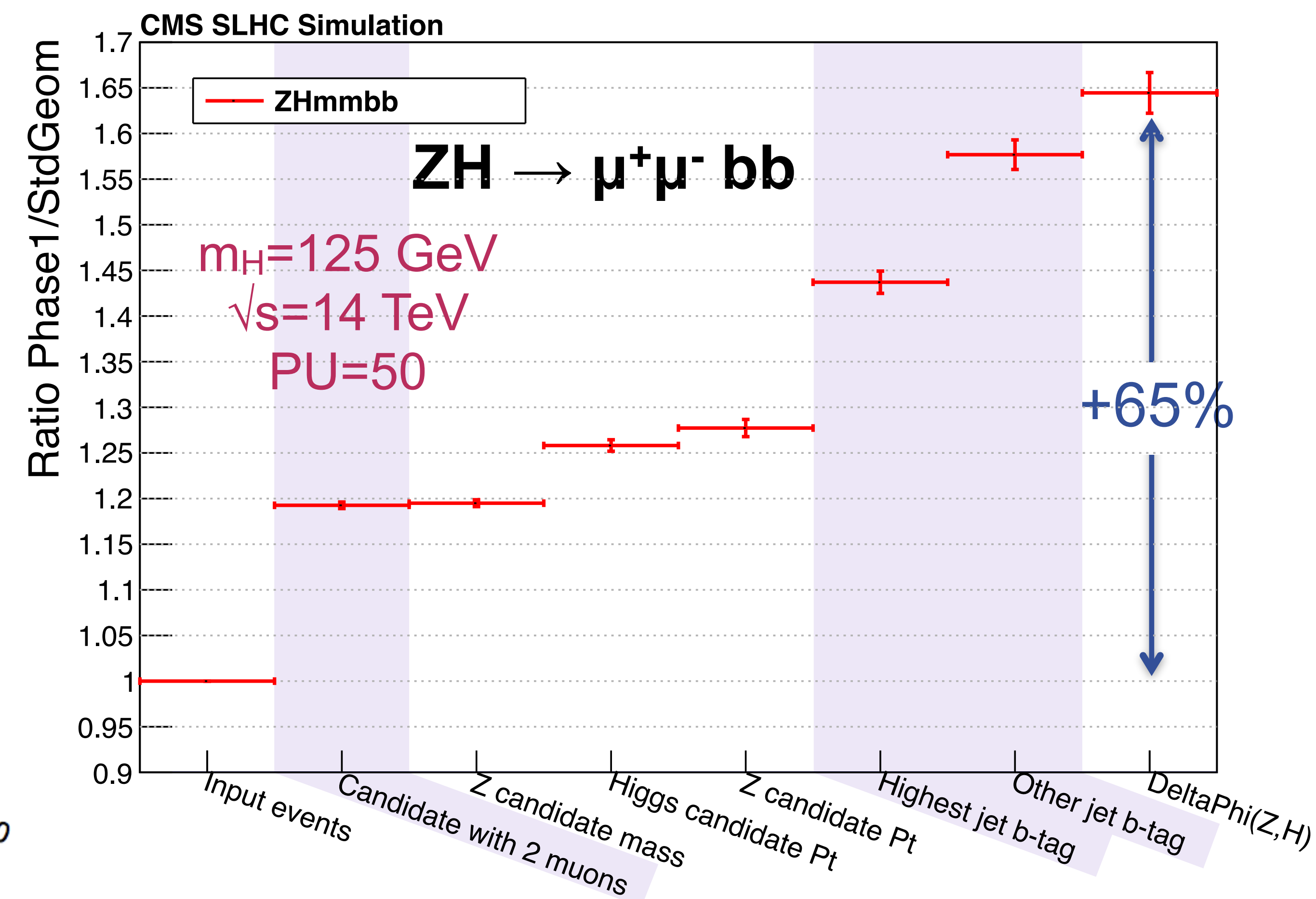

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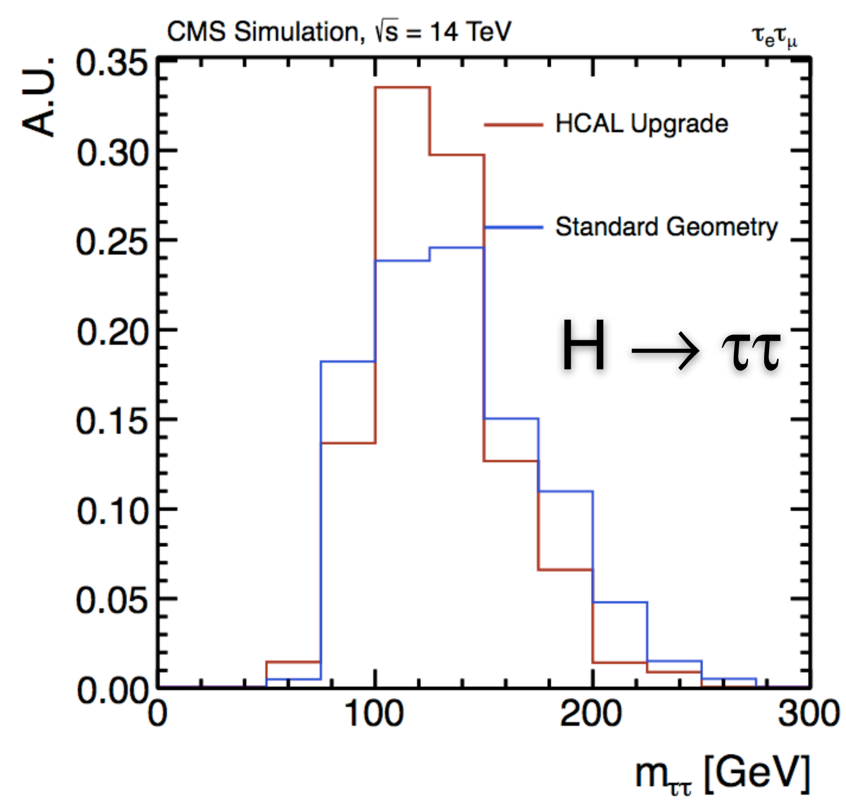

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Improved jet and MET → 25% improvement in $m_{\tau\tau}$ resolution

CMS Phase II Muon detector

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Increase det. acceptance up to $|\eta|$=4.0

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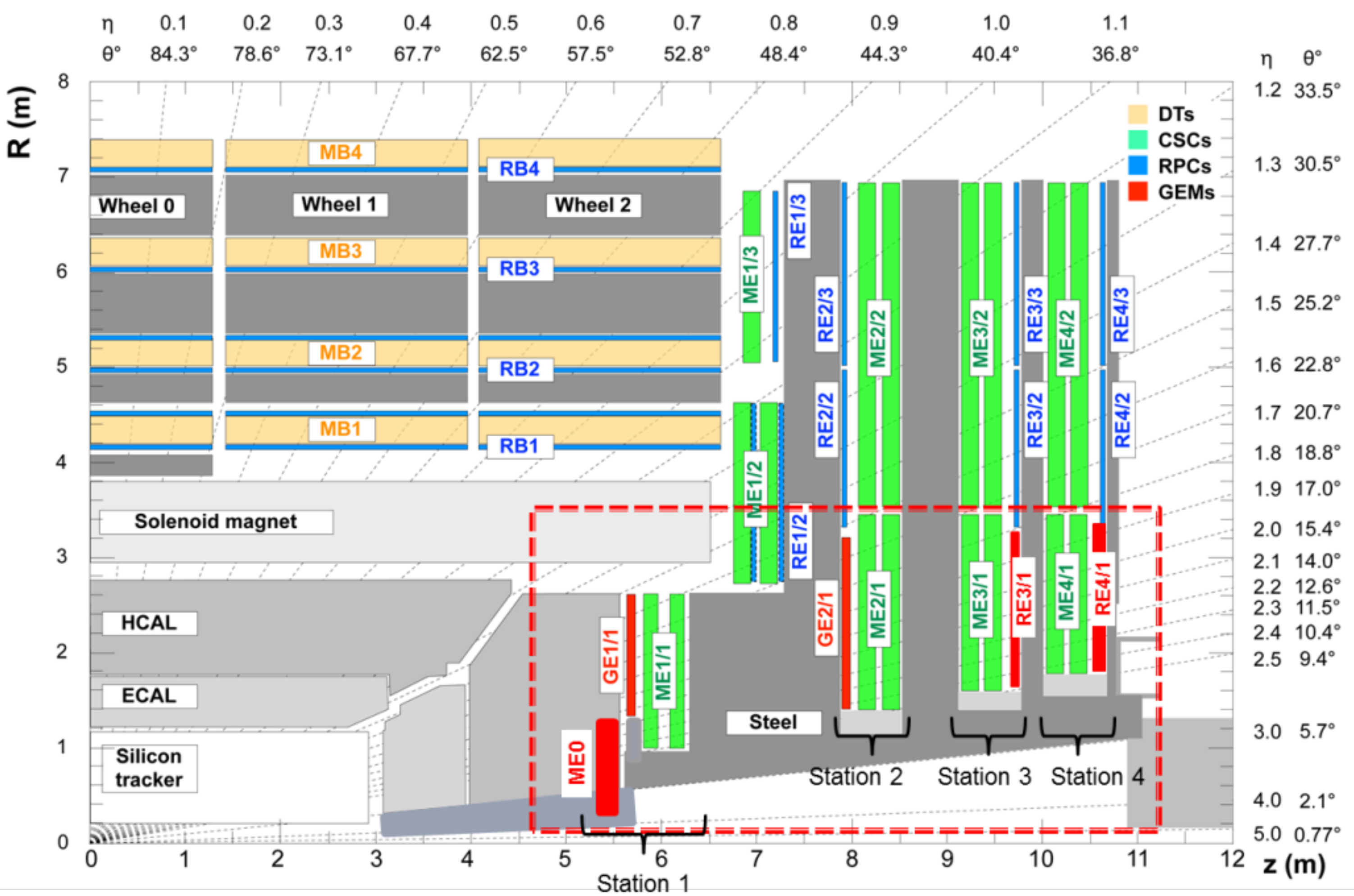

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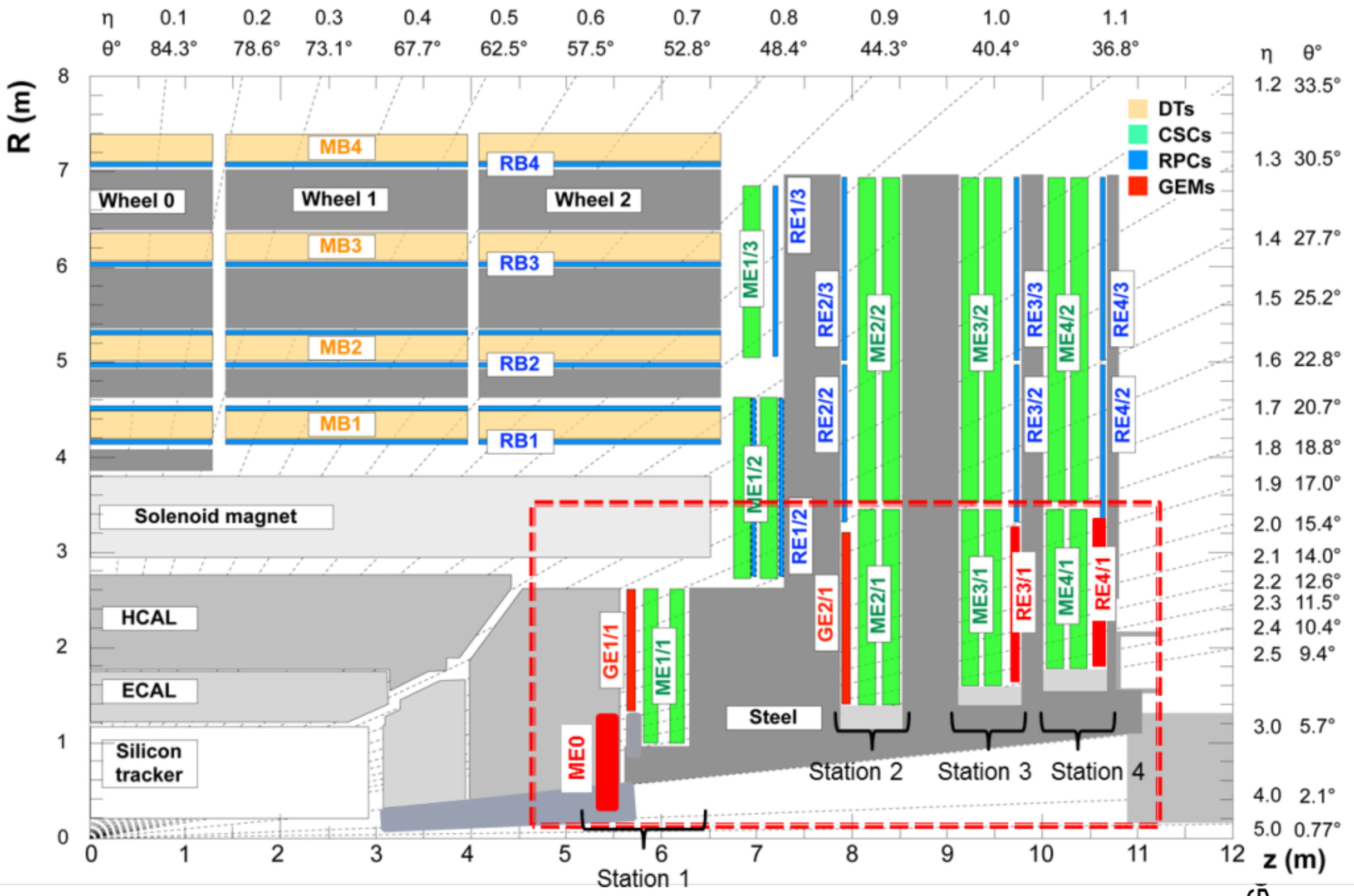

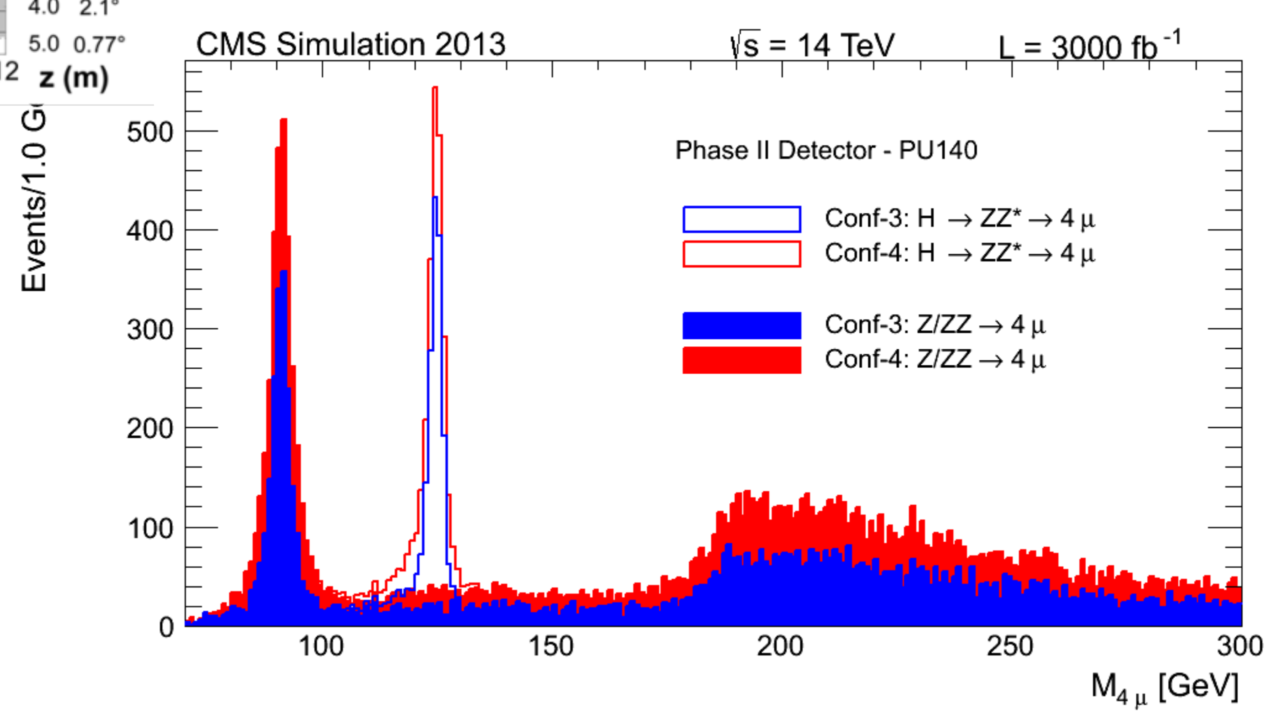

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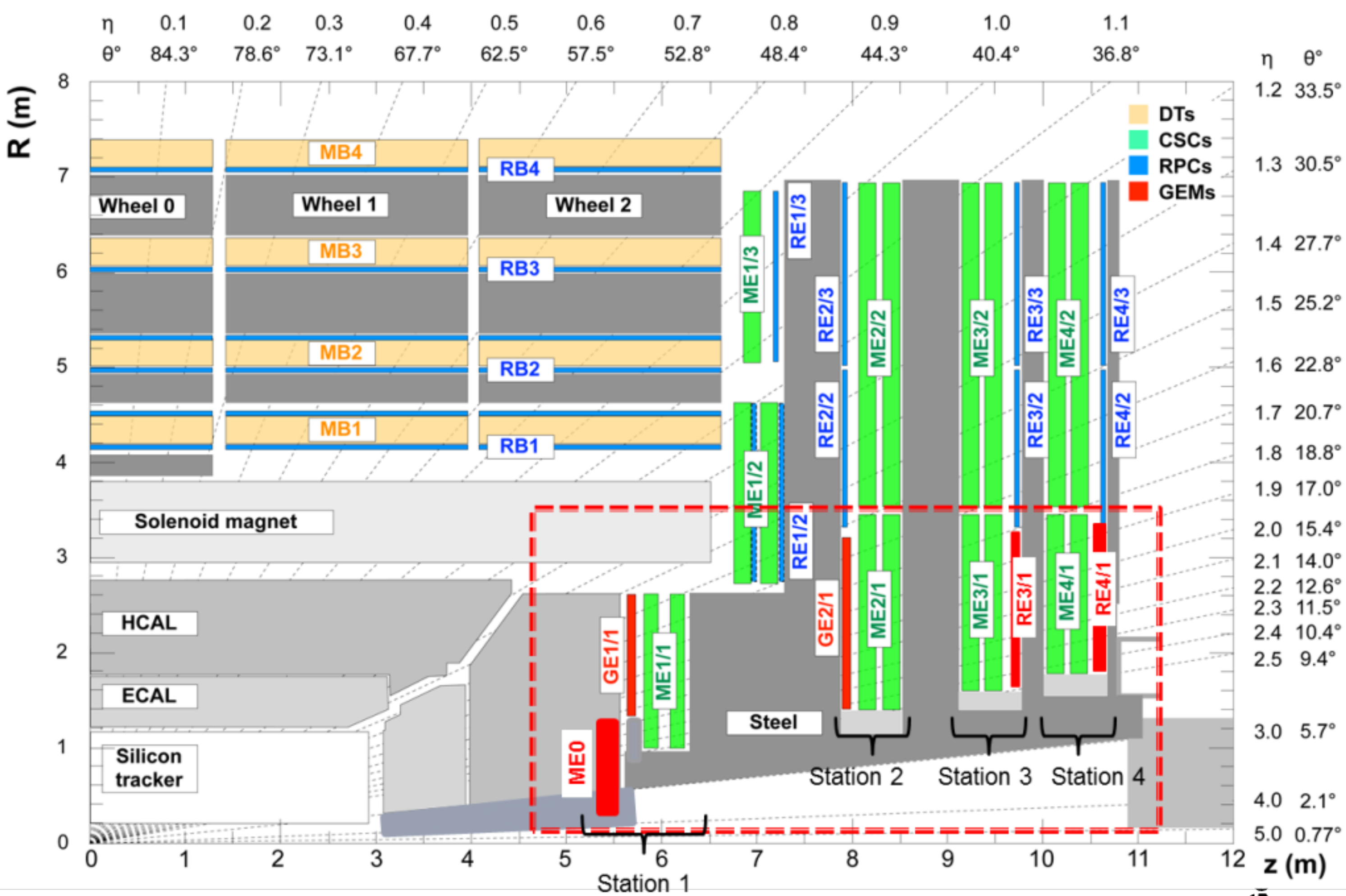

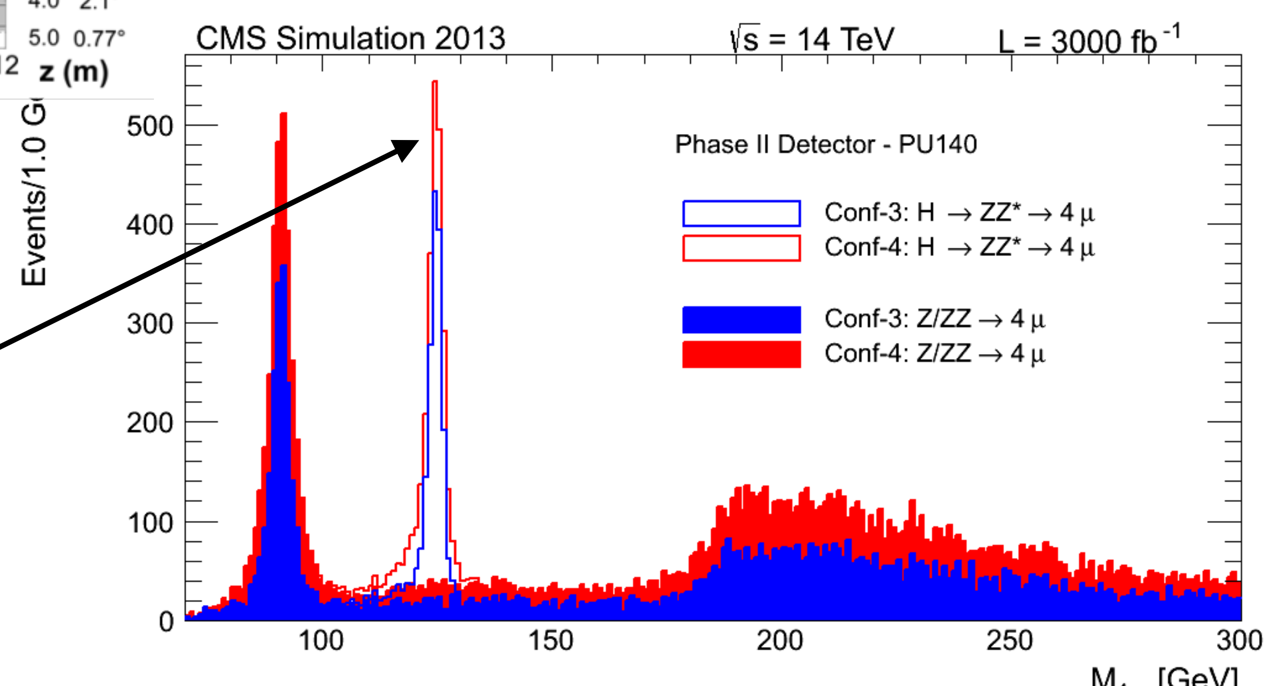

>40% more H→4μ events

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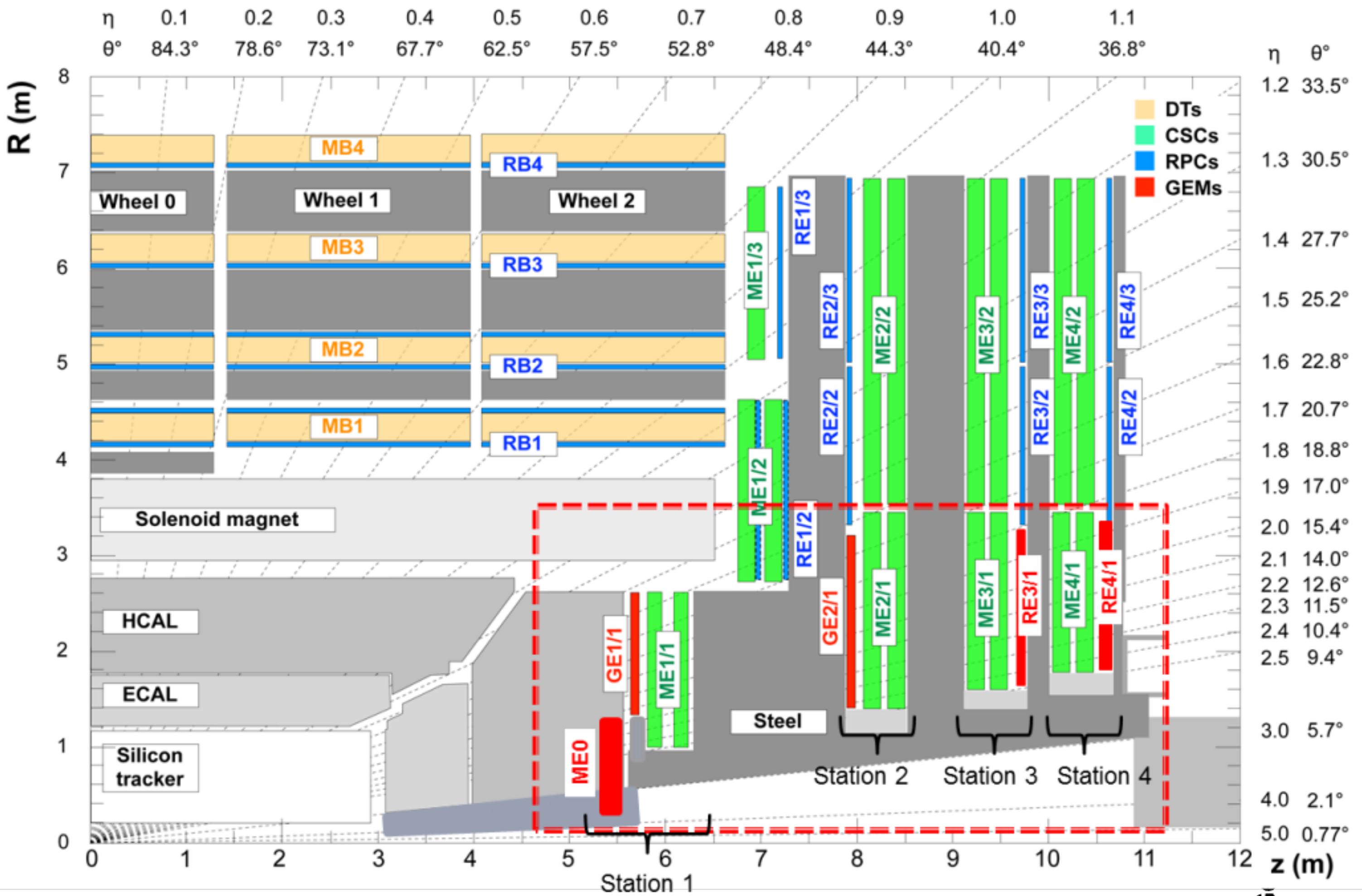

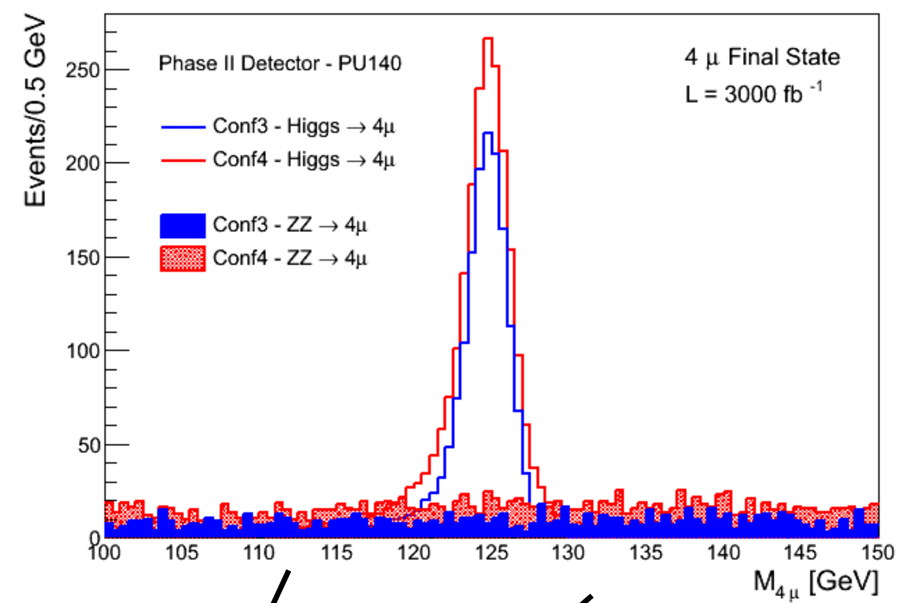

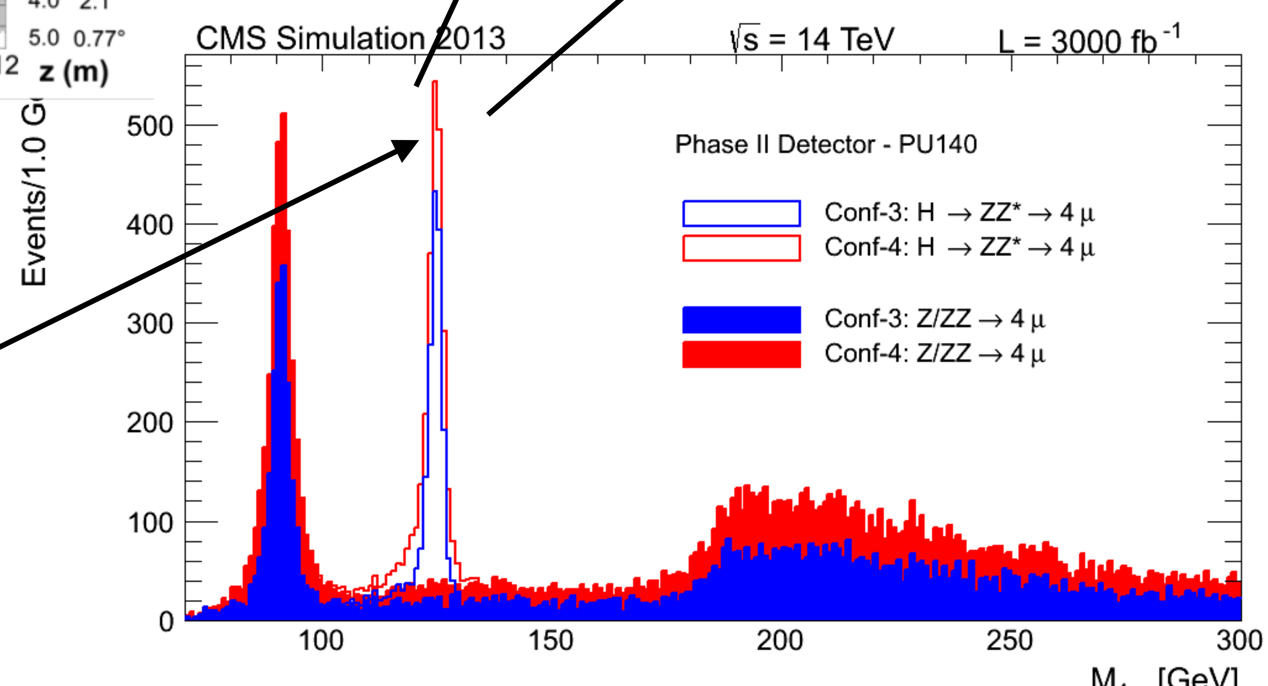

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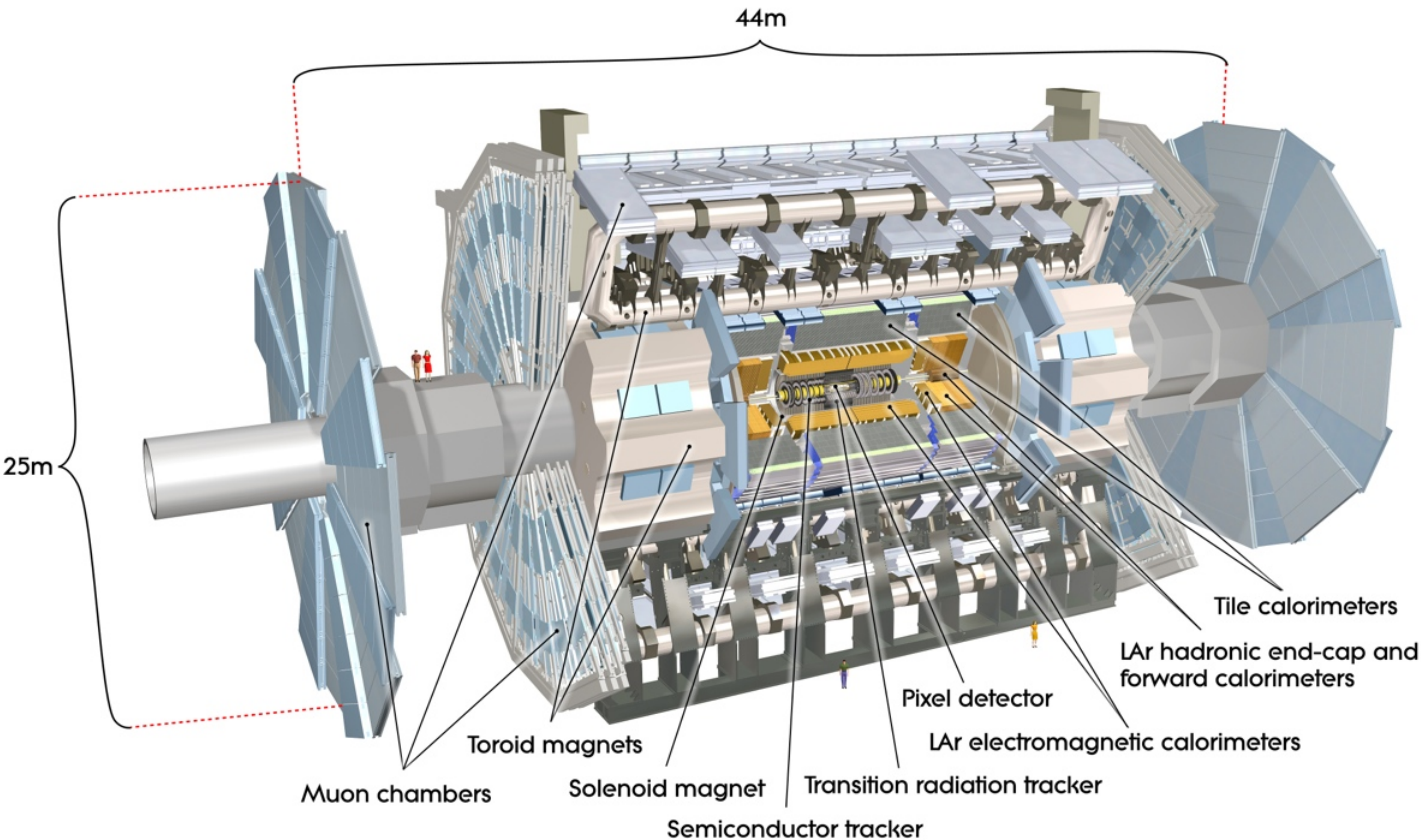
ATLAS detector



ATLAS upgrade program

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	...	2030
Prepare for:		Phase 0,I		LS1				Phase I,II	LS2			Phase II	LS3			

"Phase-0" upgrade: consolidation
$\sqrt{s}$ = 13~14 TeV, 25ns bunch spacing
$L_{inst} \simeq 1 \times 10^{34}$ $cm^{-2}s^{-1}$ ($\mu \simeq 27.5$)
$\int L_{inst} \simeq 50$ fb^{-1}

"Phase-I" upgrades:
ultimate luminosity
$L_{inst} \simeq 2\text{-}3 \times 10^{34}$ $cm^{-2}s^{-1}$ ($\mu \simeq 55\text{-}81$)
$\int L_{inst} \gtrsim 350$ fb^{-1}

"Phase-II" upgrades:
$L_{inst} \simeq 5 \times 10^{34}$ $cm^{-2}s^{-1}$ ($\mu \simeq 140$) w. leveling
$\simeq 6\text{-}7 \times 10^{34}$ $cm^{-2}s^{-1}$ ($\mu \simeq 192$) no level.
$\int L_{inst} \simeq 3000$ fb^{-1}

ATLAS has devised a 3 stage upgrade program

From M. Diemoz

ATLAS upgrade program

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	...	2030

Prepare for: Phase 0,I **LS1** Phase I,II **LS2** Phase II **LS3**

"Phase-0" upgrade: consolidation
$\sqrt{s}$ = 13~14 TeV, 25ns bunch spacing
$L_{inst} \simeq 1 \times 10^{34}$ cm^{-2}s^{-1} ($\mu \simeq 27.5$)
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"Phase-I" upgrades:
ultimate luminosity
$L_{inst} \simeq 2\text{-}3 \times 10^{34}$ cm^{-2}s^{-1} ($\mu \simeq 55\text{-}81$)
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"Phase-II" upgrades:
$L_{inst} \simeq 5 \times 10^{34}$ cm^{-2}s^{-1} ($\mu \simeq 140$) w. leveling
$\simeq 6\text{-}7 \times 10^{34}$ cm^{-2}s^{-1} ($\mu \simeq 192$) no level.
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ATLAS has devised a 3 stage upgrade program

- New insertable pixel b-layer (IBL)
- New Al beam pipe
- New pixel services
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- New evaporative cooling plant
- Consolidation of detector services
- Specific neutron shielding
- Upgrade magnet cryogenics

From M. Diemoz

ATLAS upgrade program

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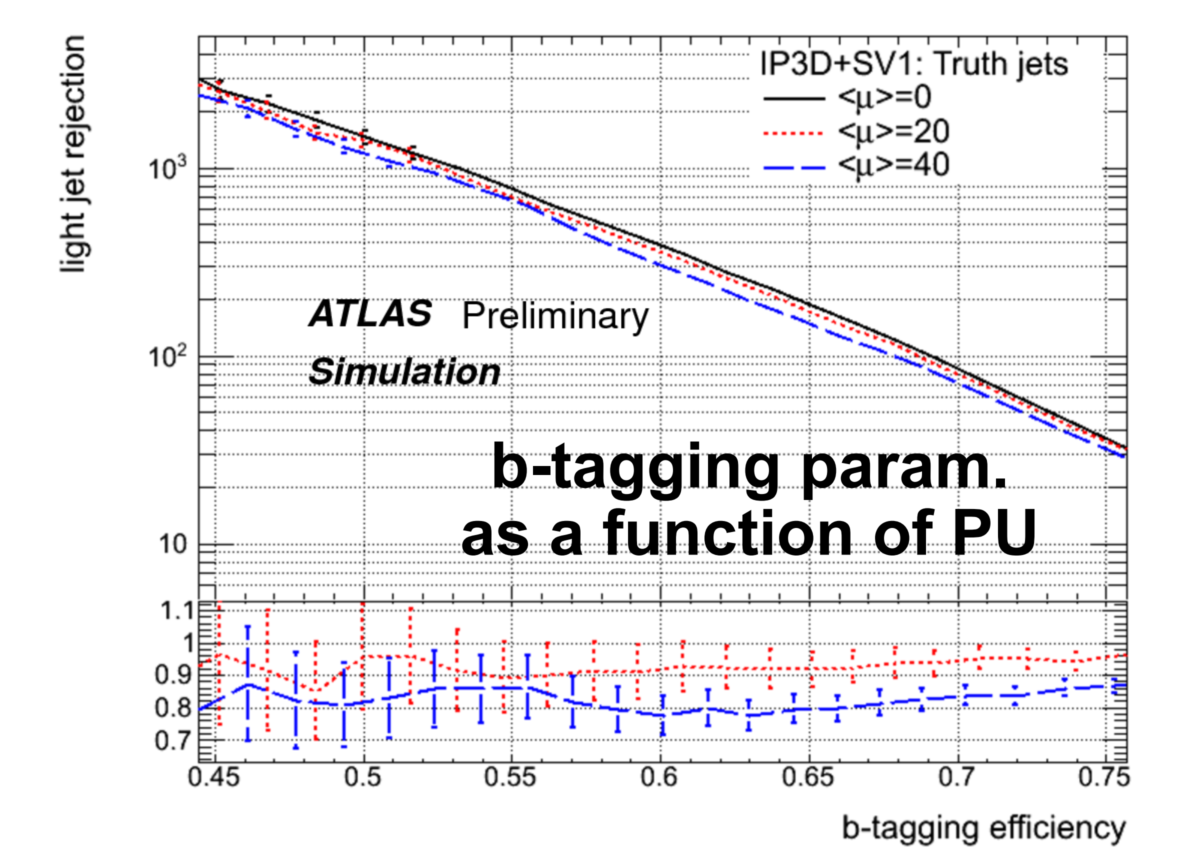
- Completely new tracking detector
- Calorimeter electronics upgrades
- Upgrade part of the muon system
- Possible L1-trigger track trigger
- Possible changes to the forward calorimeters

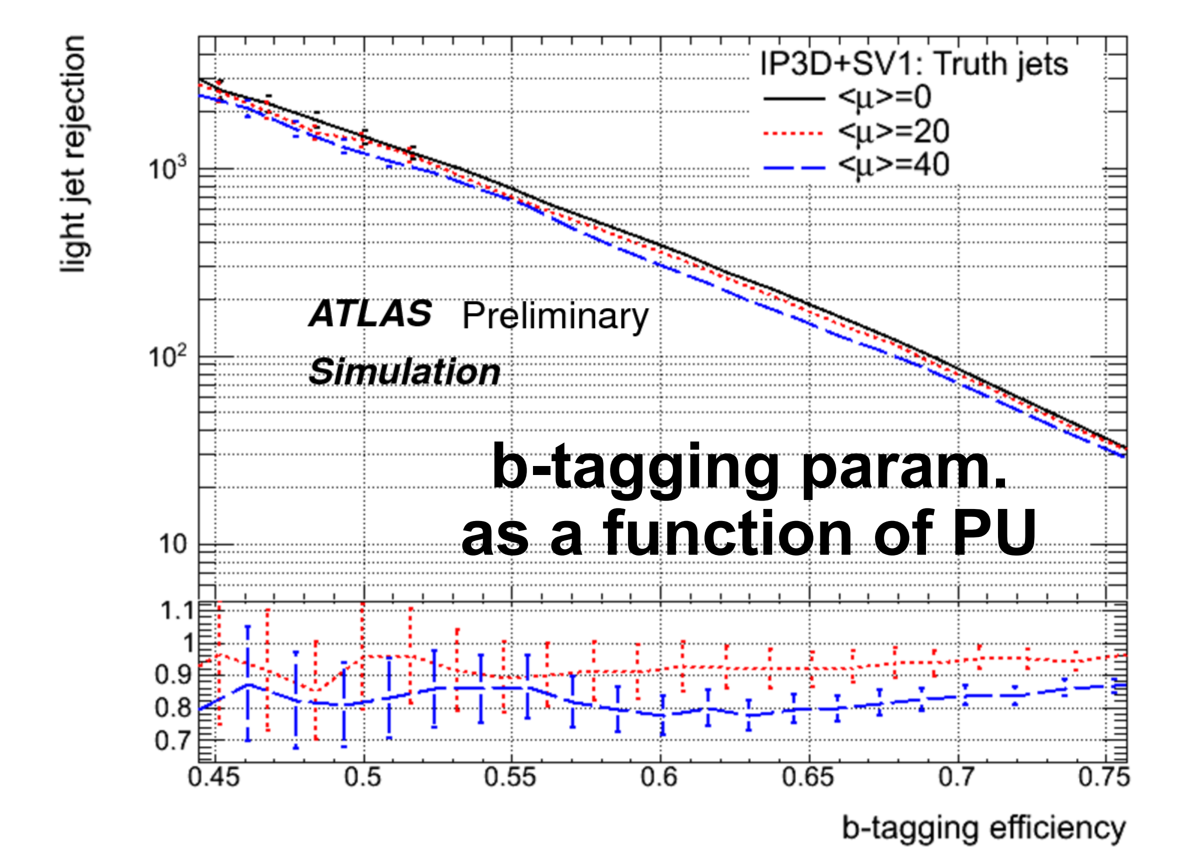
From M. Diemoz

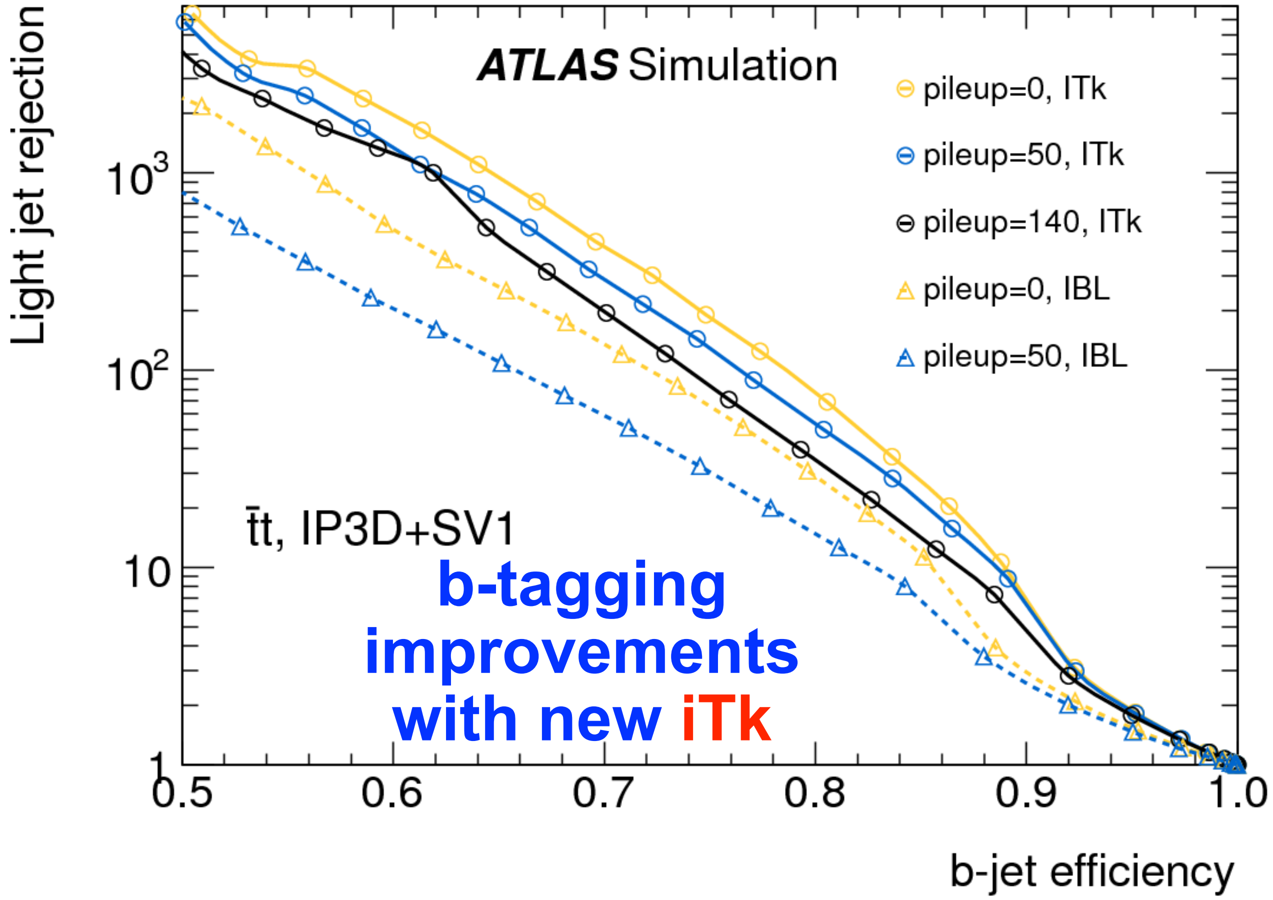
ATLAS upgrade performances

ATLAS upgrade performances



ATLAS upgrade performances





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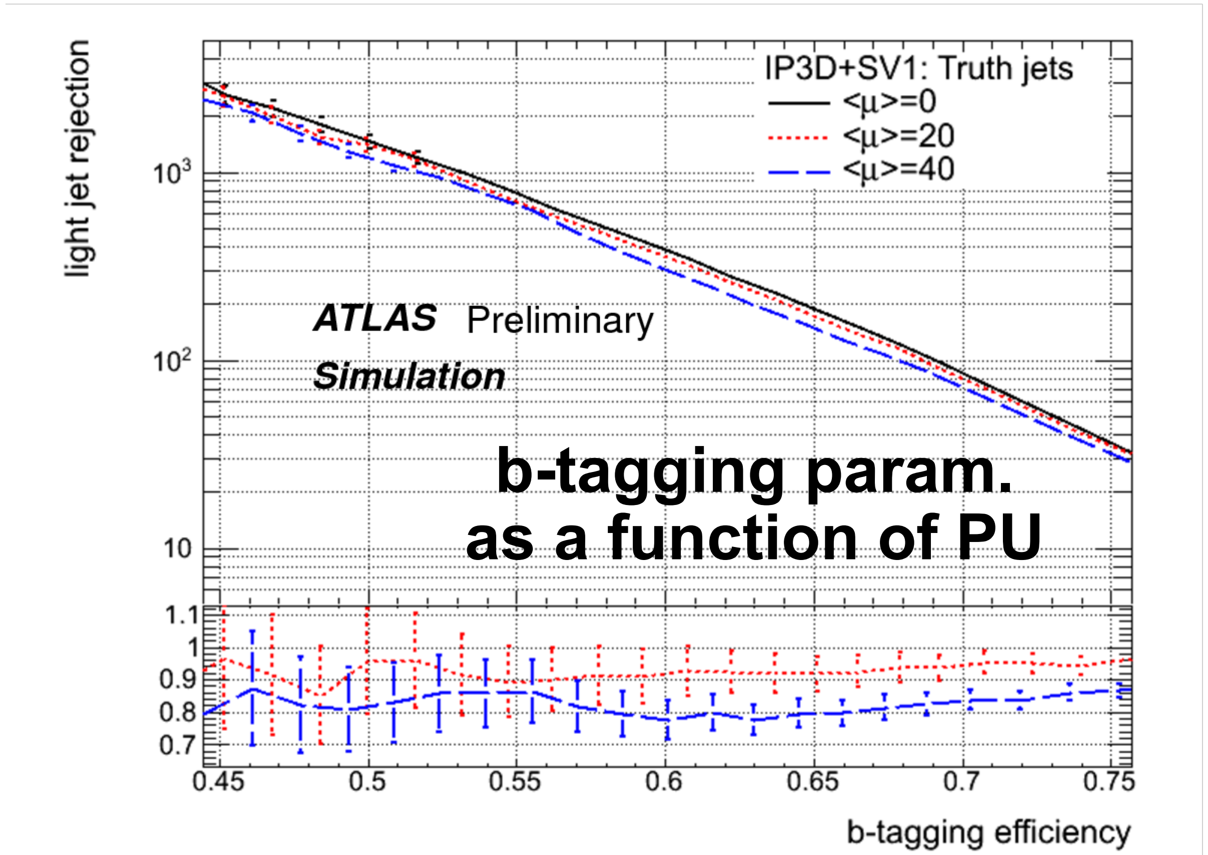
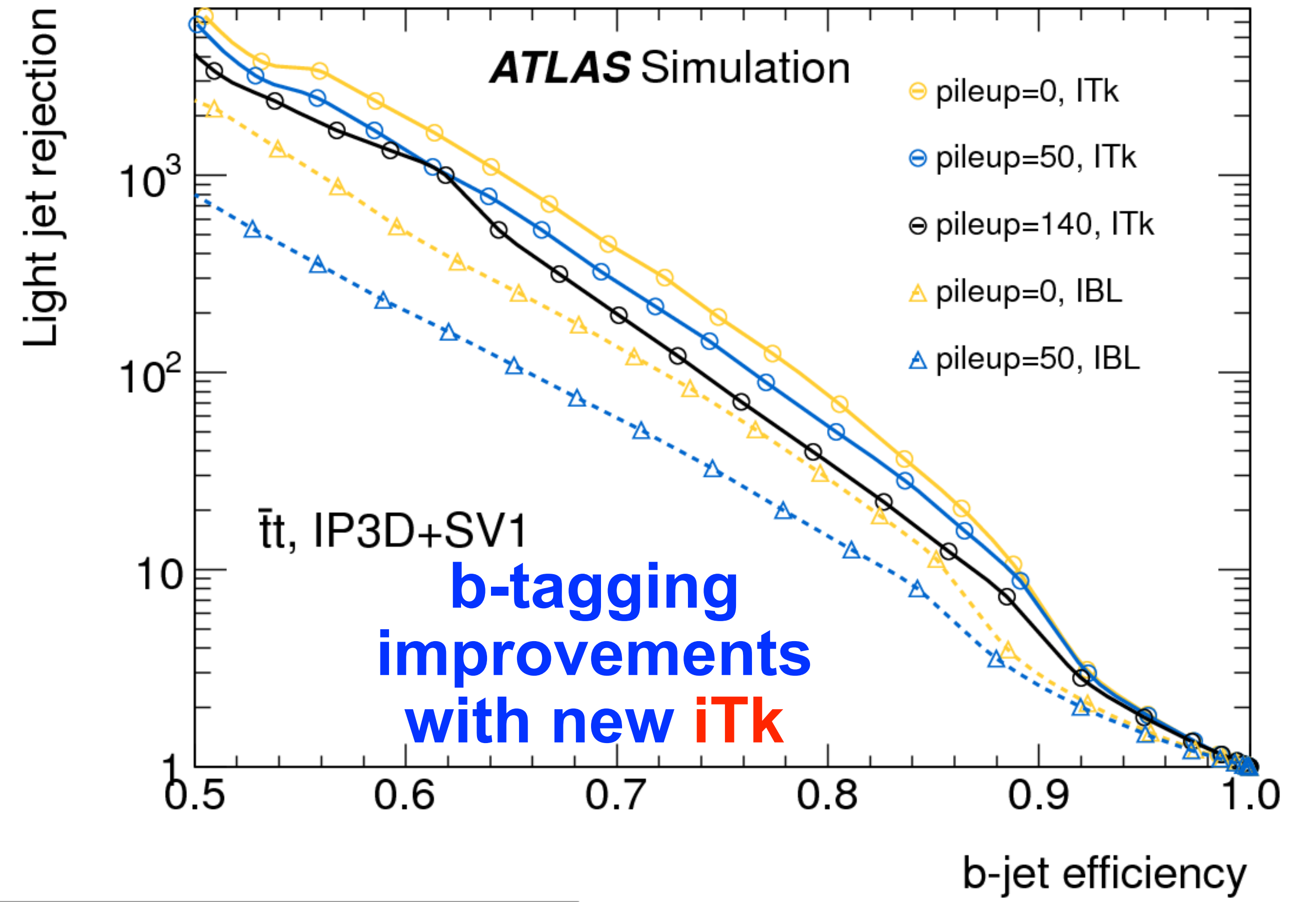
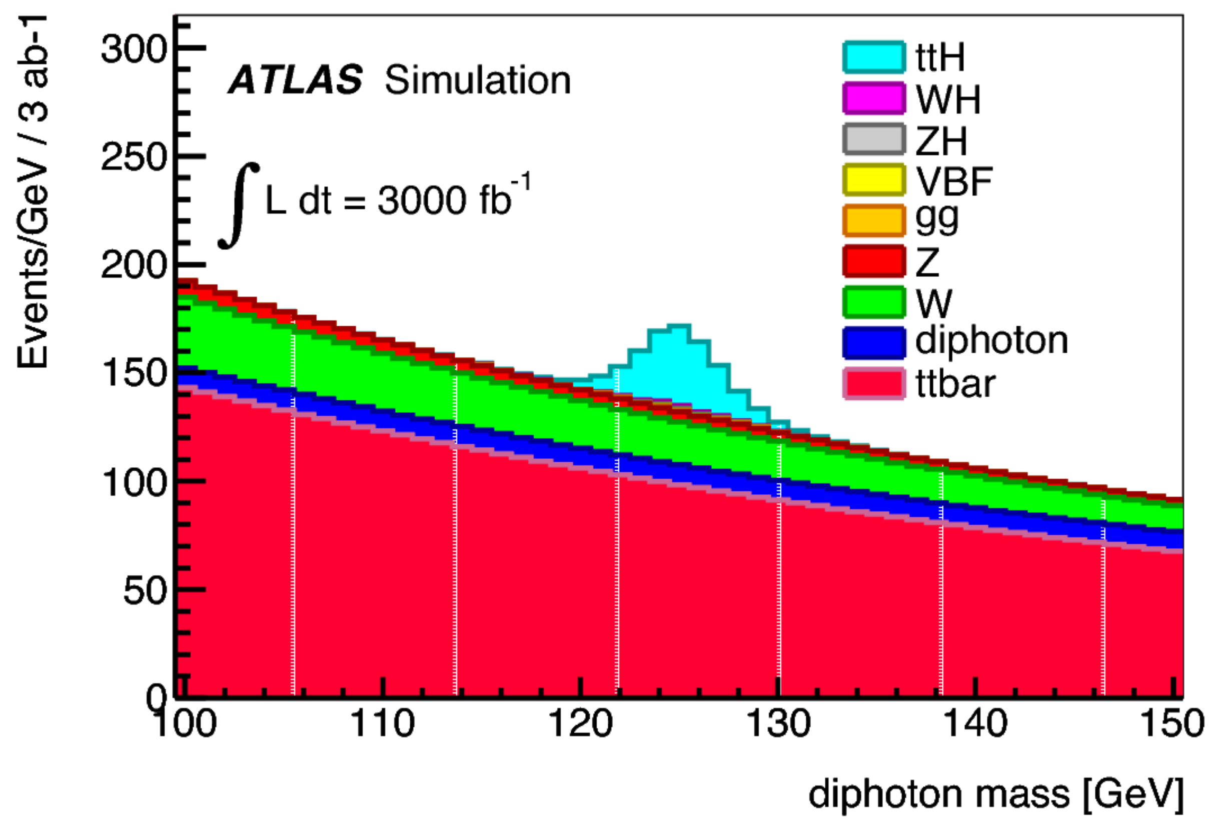


b-tagging param. as a function of PU



b-tagging improvements with new iTk

di-photon mass resolution in ttH channel



From 2012 to HL-LHC

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Need upgraded detectors to offset the much harsher LHC conditions and radiation damage

ATLAS and CMS have launched a comprehensive upgrade program

Higgs boson projections after LS1

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Approaches adopted for physics projections

Higgs boson projections after LS1

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Higgs signal strength with 300 fb^{-1}

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  - is subject to large uncertainties
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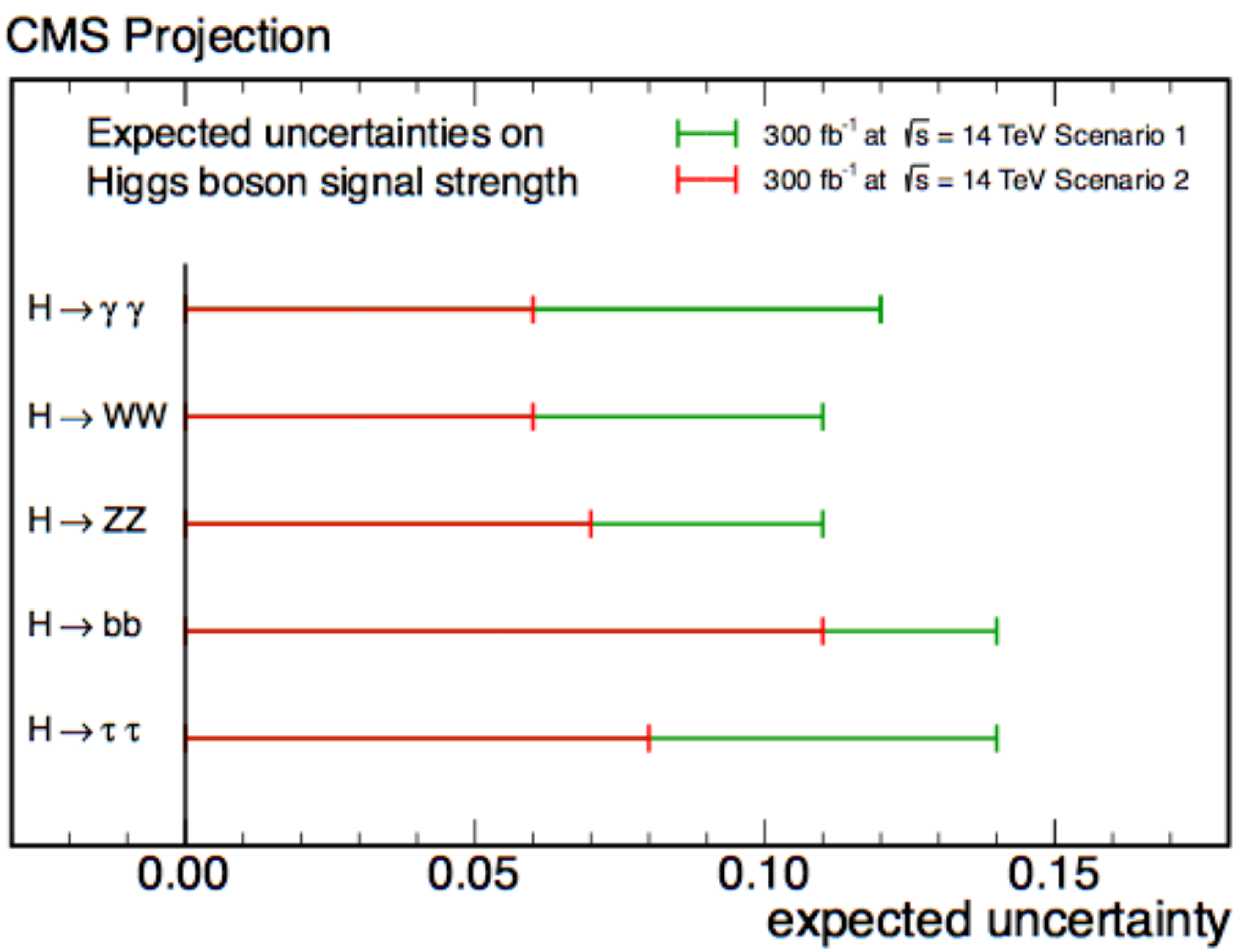

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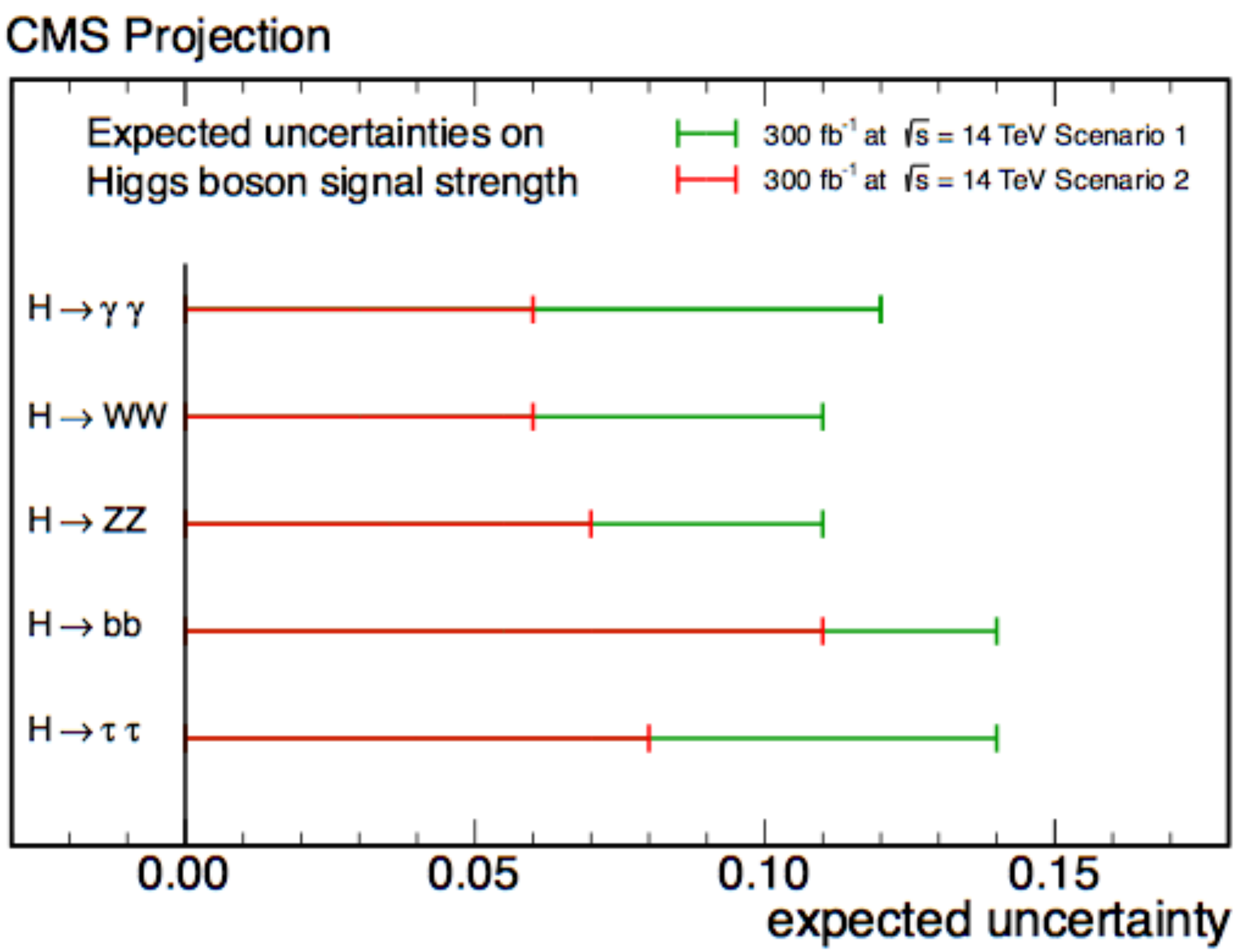

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With 300 fb^{-1} the precision on the signal strength, $\mu = \sigma/\sigma_{SM}$, is expected to be 10-15% per channel

Higgs signal strength with 3000 fb^{-1}

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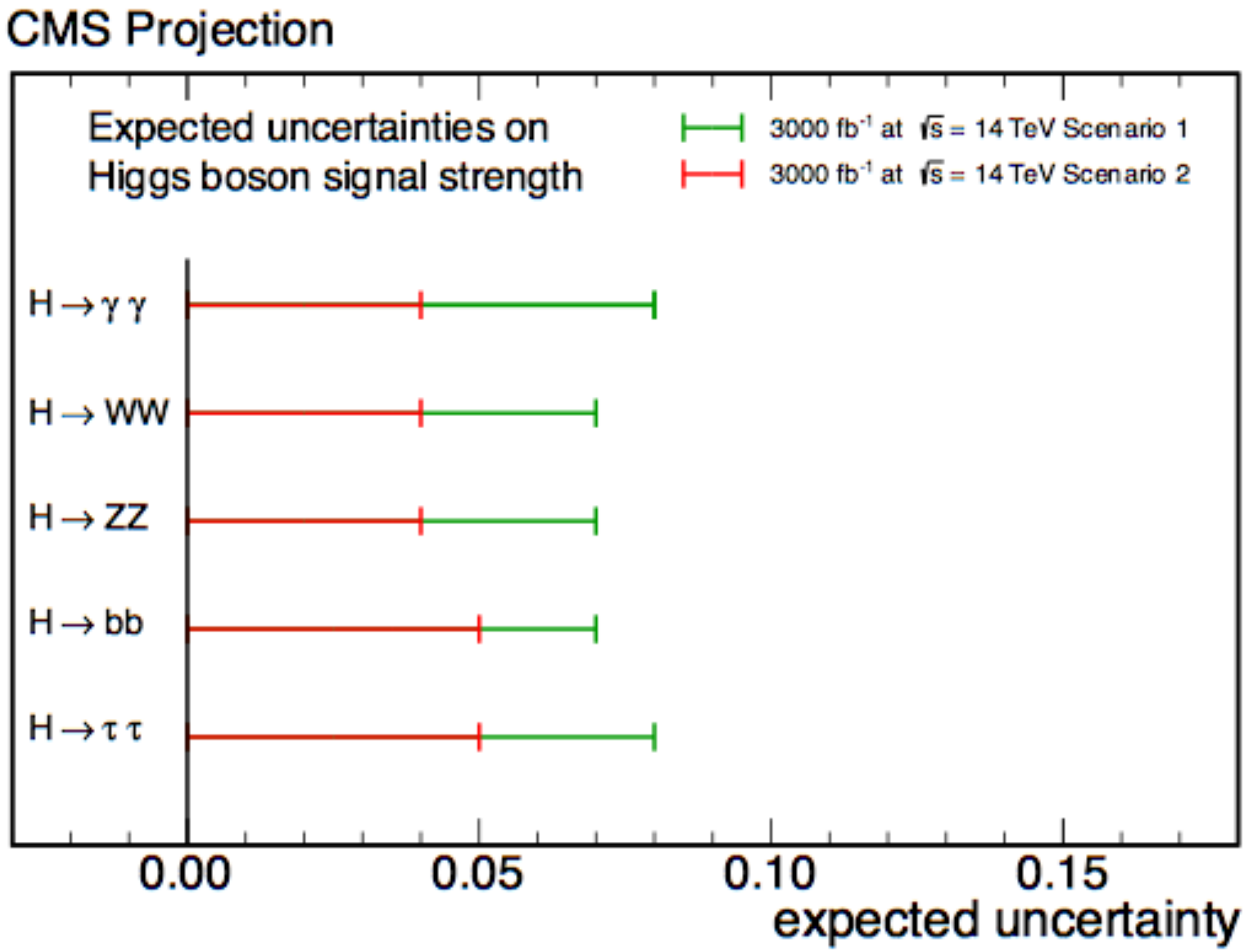

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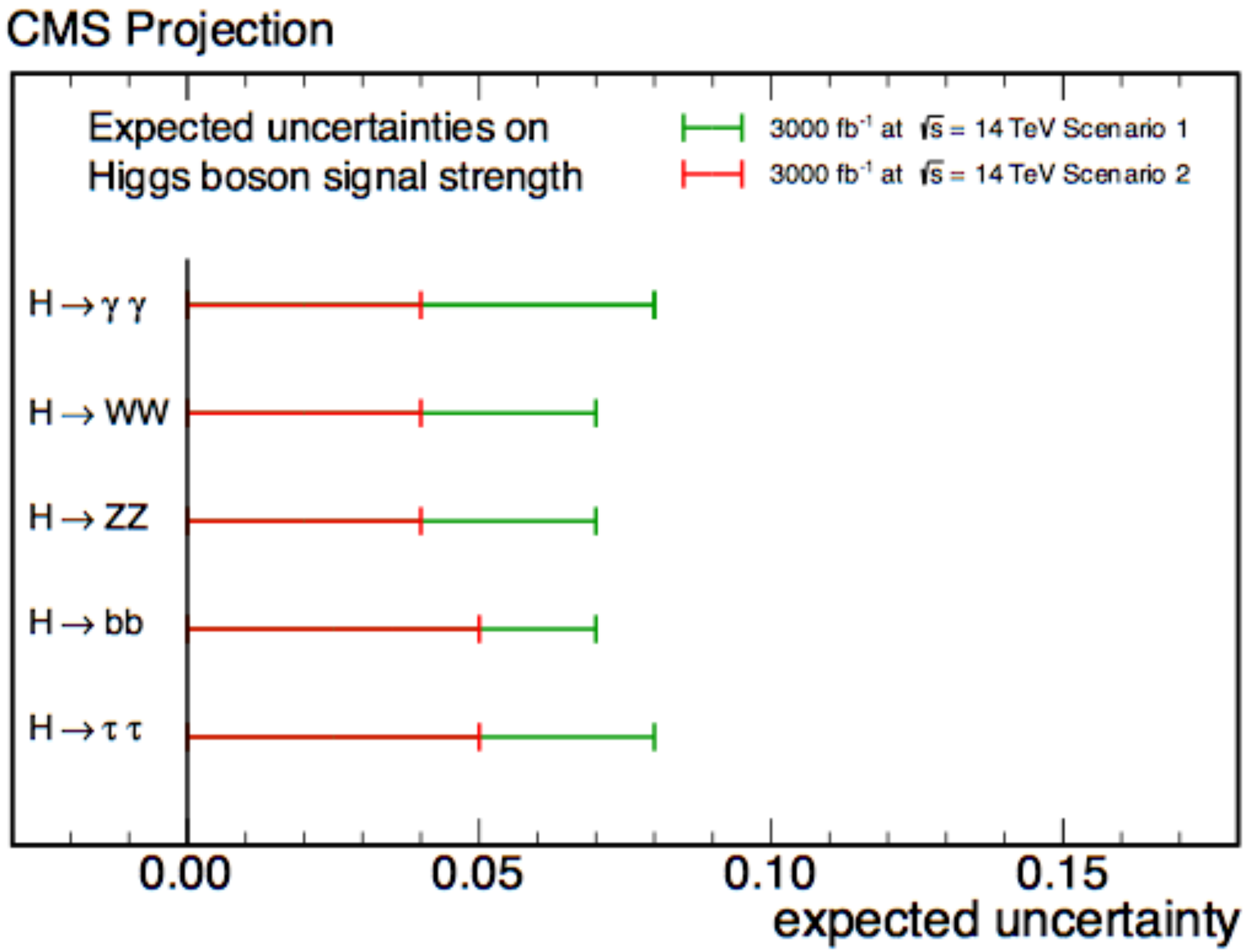

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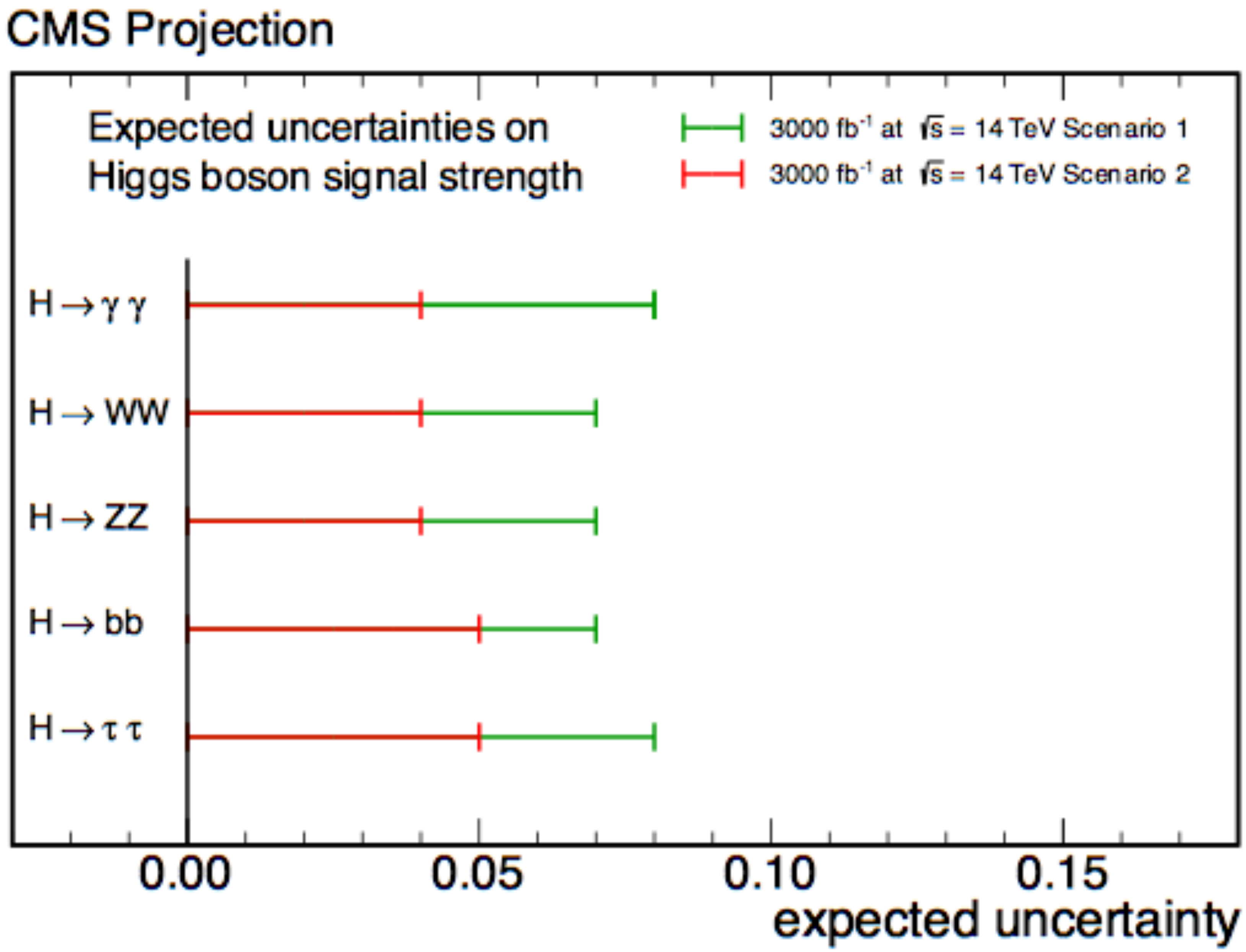
L (fb	H→γγ	H→WW	H→ZZ	H→bb	H→ττ	H→Zγ	H→μμ	H→inv.
300	[6,12]	[6,11]	[7,11]	[11,14]	[8,14]	[62,62]	[40,42]	[17,28]
3000	[4,8]	[4,7]	[4,7]	[5,7]	[5,8]	[20,24]	[20,24]	[6,17]

Higgs signal strength with 3000 fb^{-1}



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With 3000 fb^{-1} the precision on μ is expected to be 4-8% per channel

Higgs boson couplings @300 fb^{-1}

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- Two scenarios:
  - Scenario 1: same systematics as in 2012
  - Scenario 2: theory systematics scaled by a factor ½, other systematics scaled by $1/\sqrt{L}$

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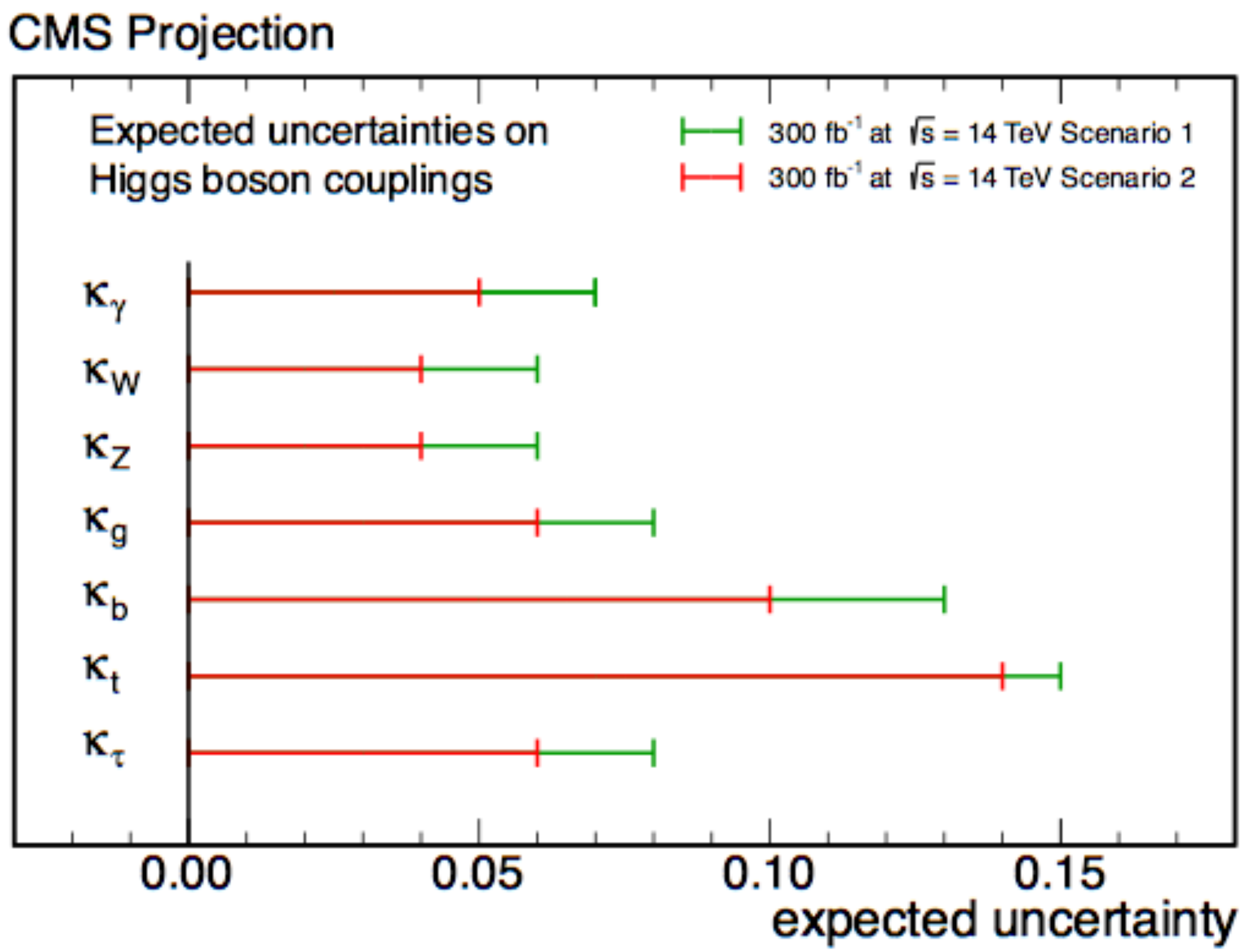

300 fb^{-1} 14 TeV, Scenario 1
300 fb^{-1} 14 TeV, Scenario 2

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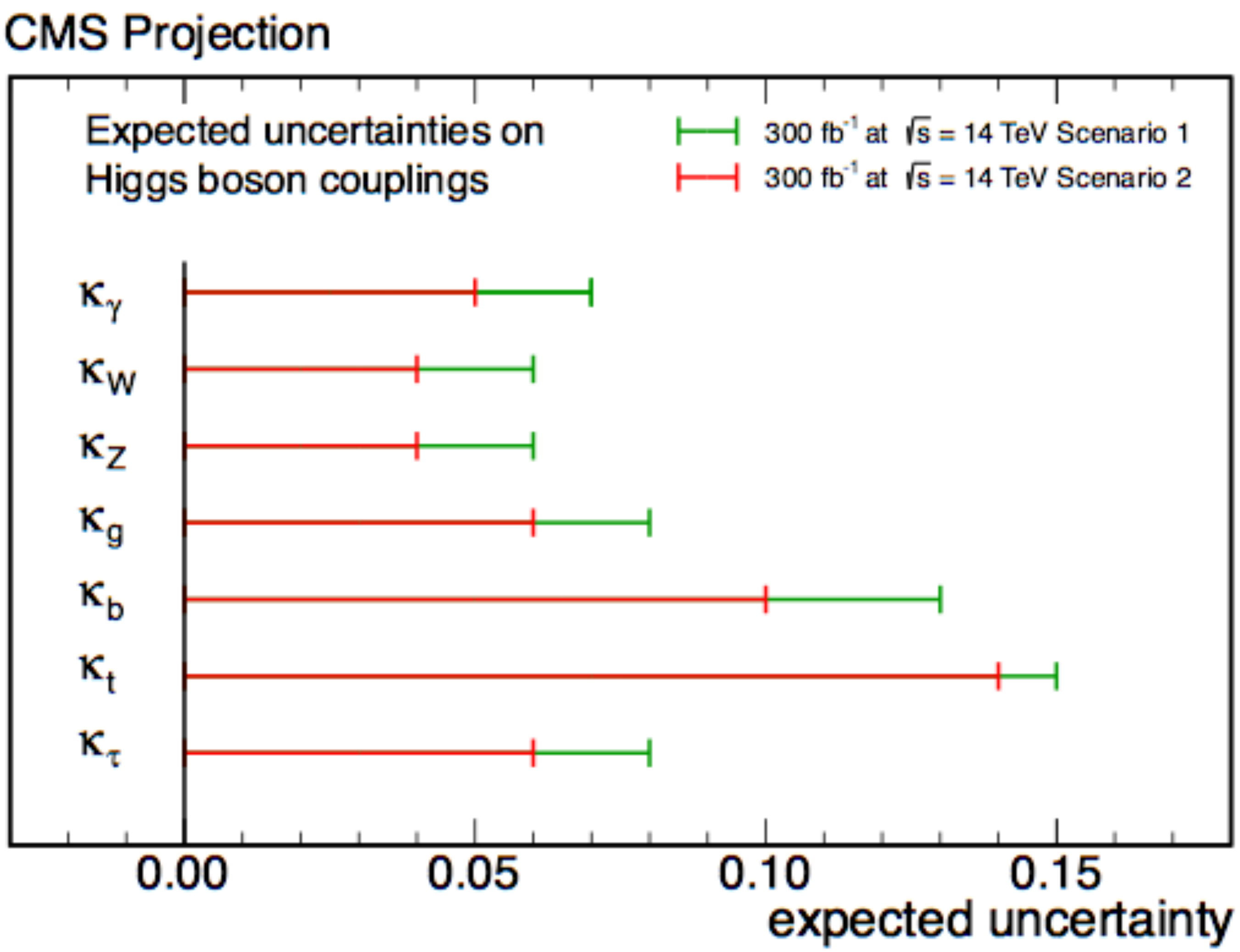


300 fb^{-1} 14 TeV, Scenario 1

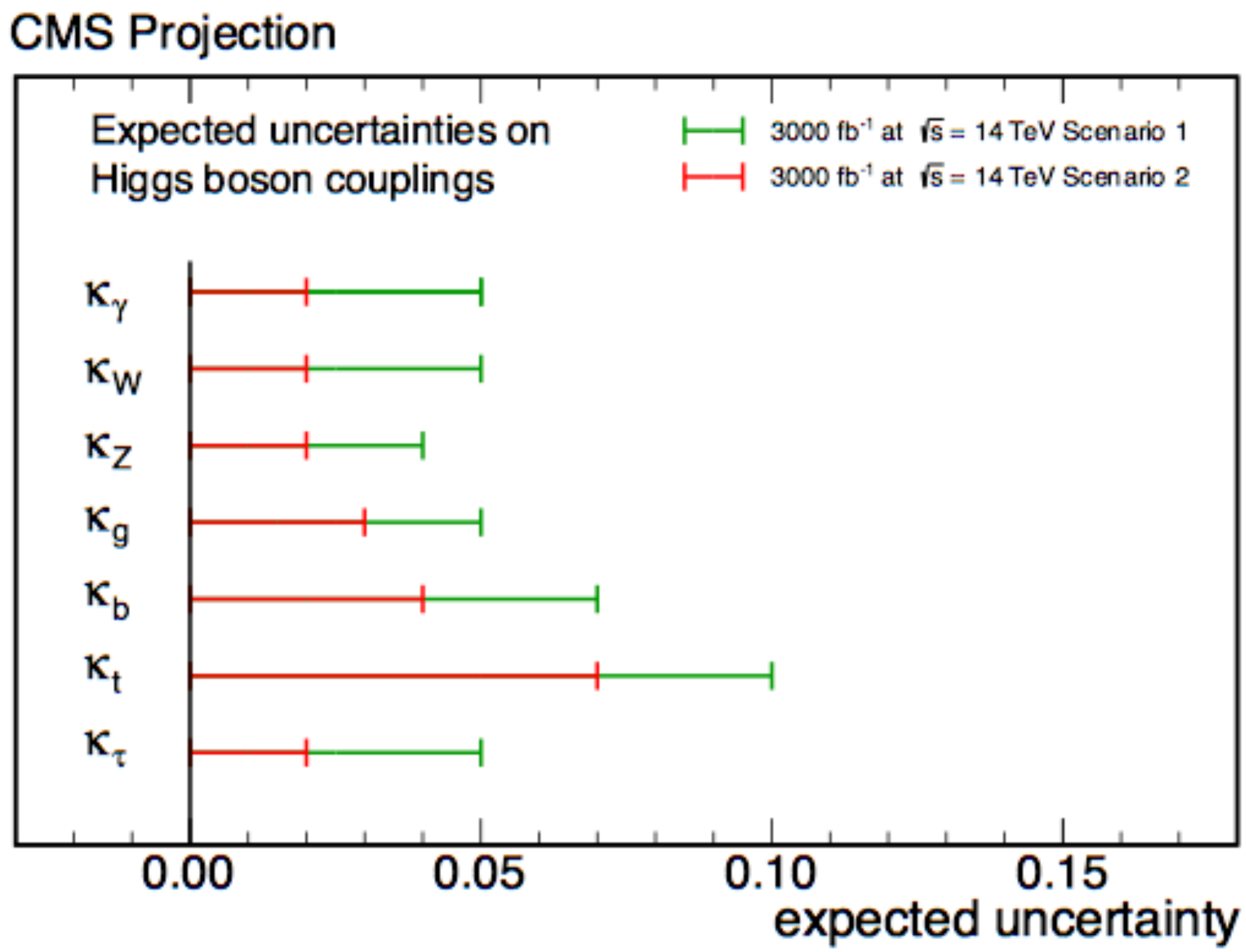
300 fb^{-1} 14 TeV, Scenario 2

With 300 fb^{-1} the uncertainties on the Higgs couplings are expected in the range $\sigma(\kappa_V) \sim$ 4-7%

$\sigma(\kappa_f) \sim$ 6-15%

Higgs boson couplings @3000 fb^{-1}

Higgs boson couplings @3000 fb^{-1}



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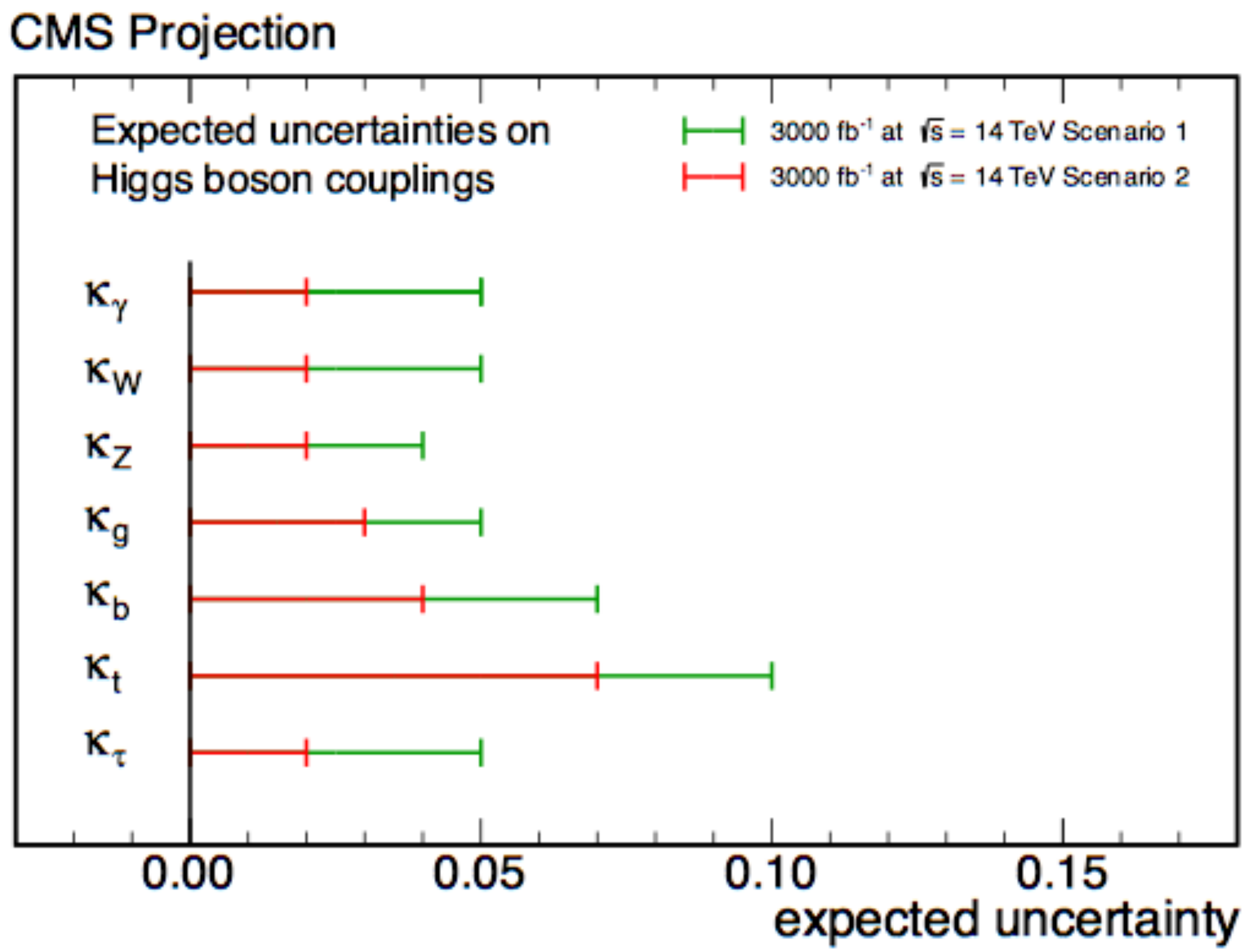
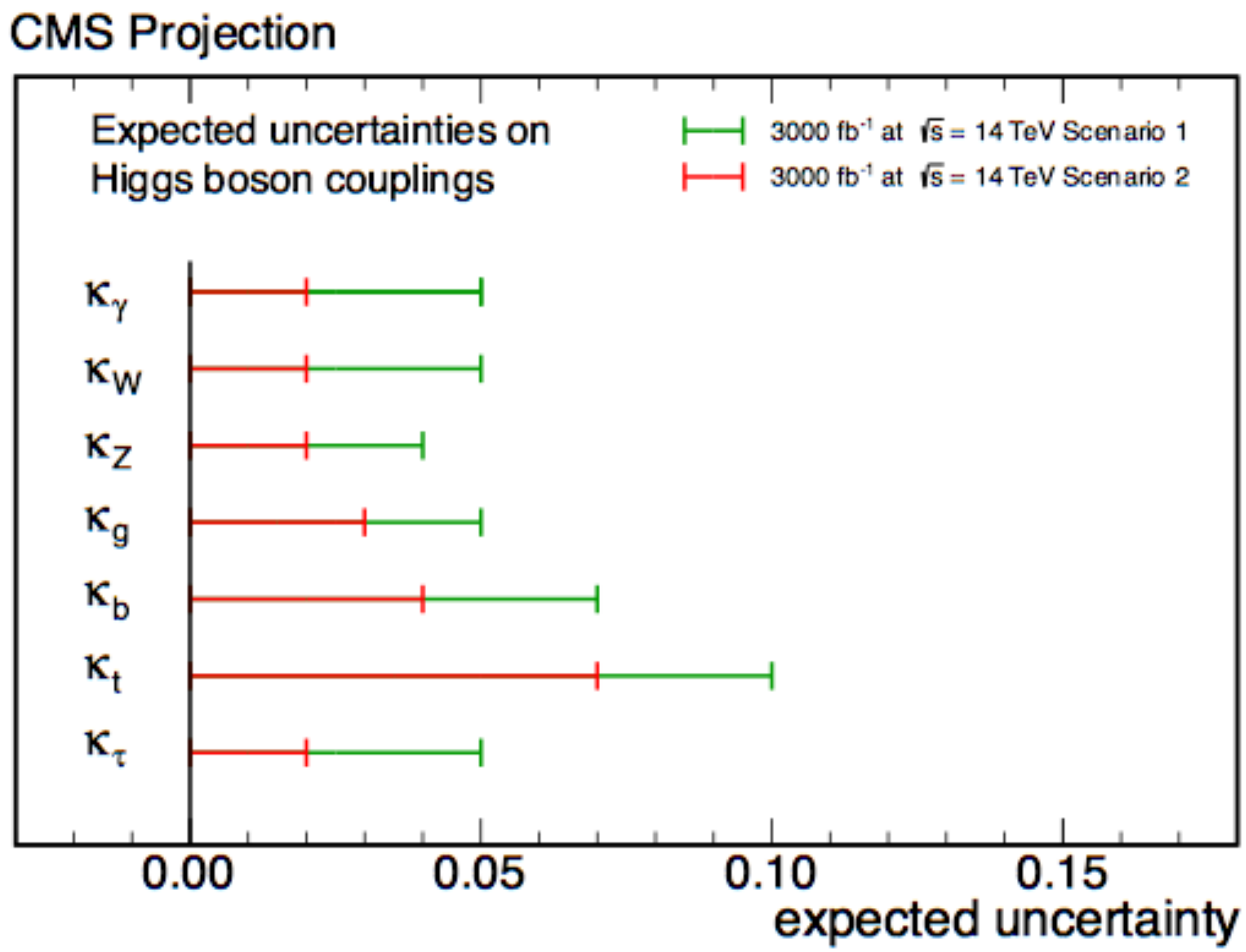


L (fb	K	K	K	K	K	K	K	K	K	BR
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]	[14,18]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]	[7,11]

Higgs boson couplings @3000 fb^{-1}



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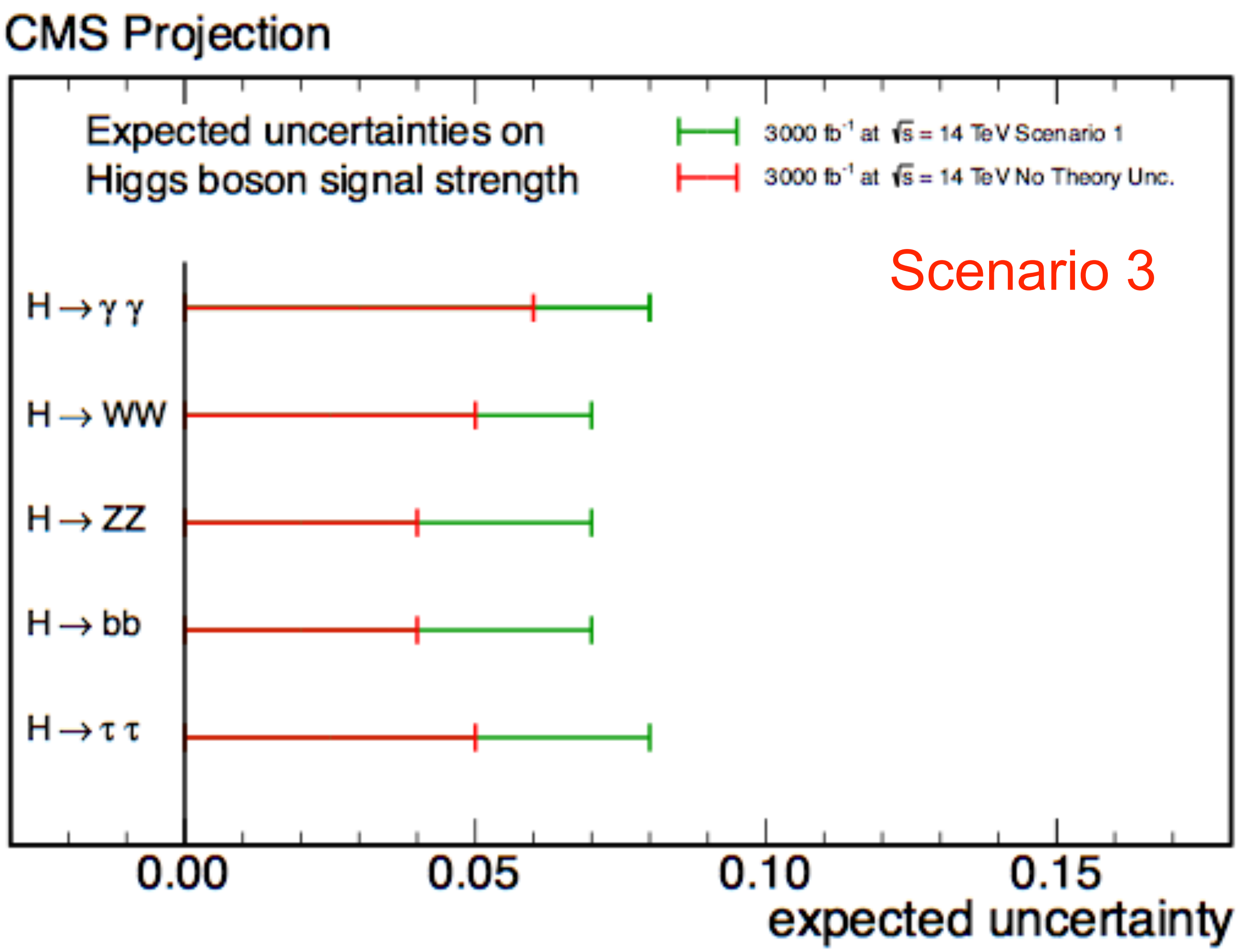
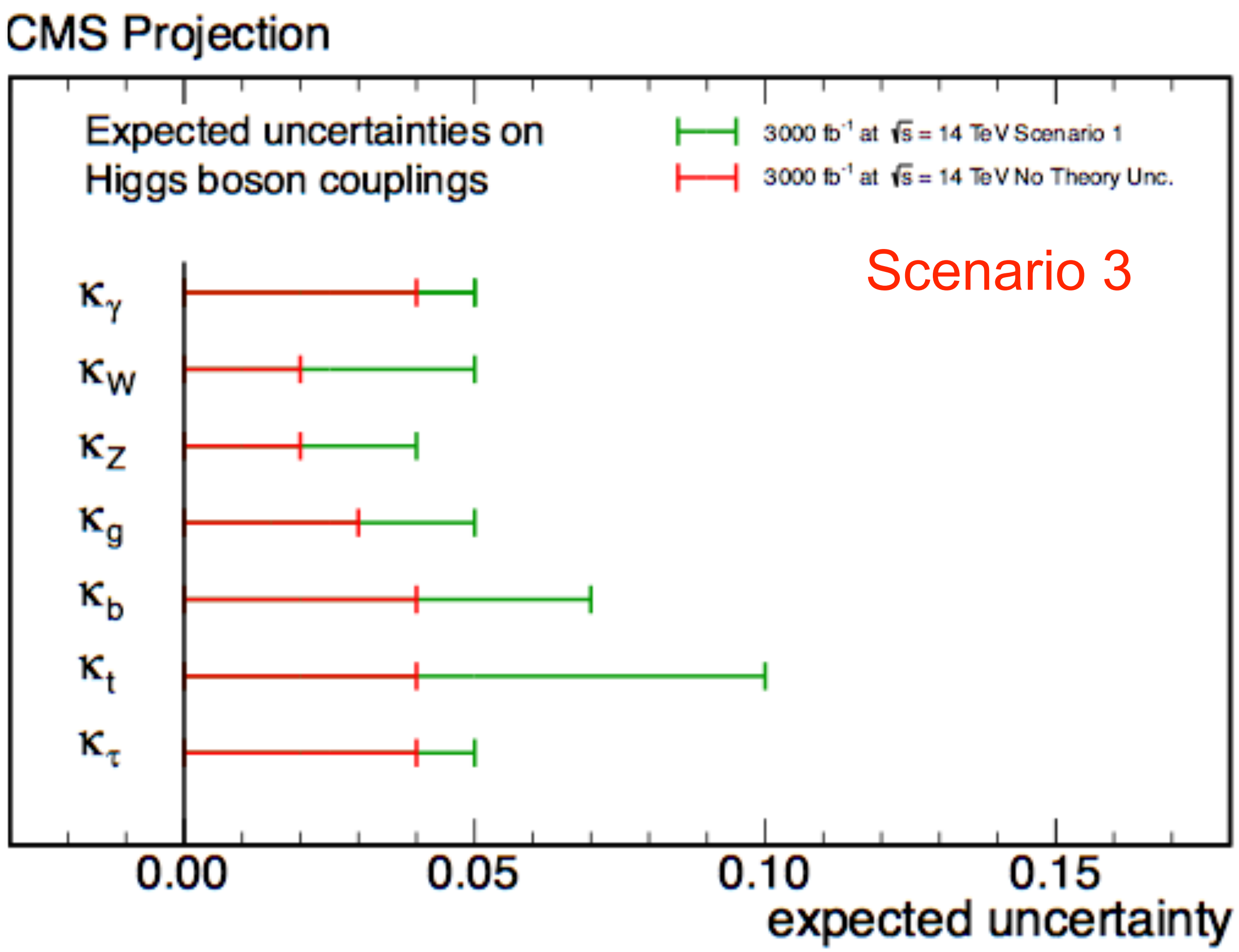
- With 3000 fb^{-1} the Higgs couplings can be determined with high precision (2-7%)

Higgs projections @3000 fb^{-1}





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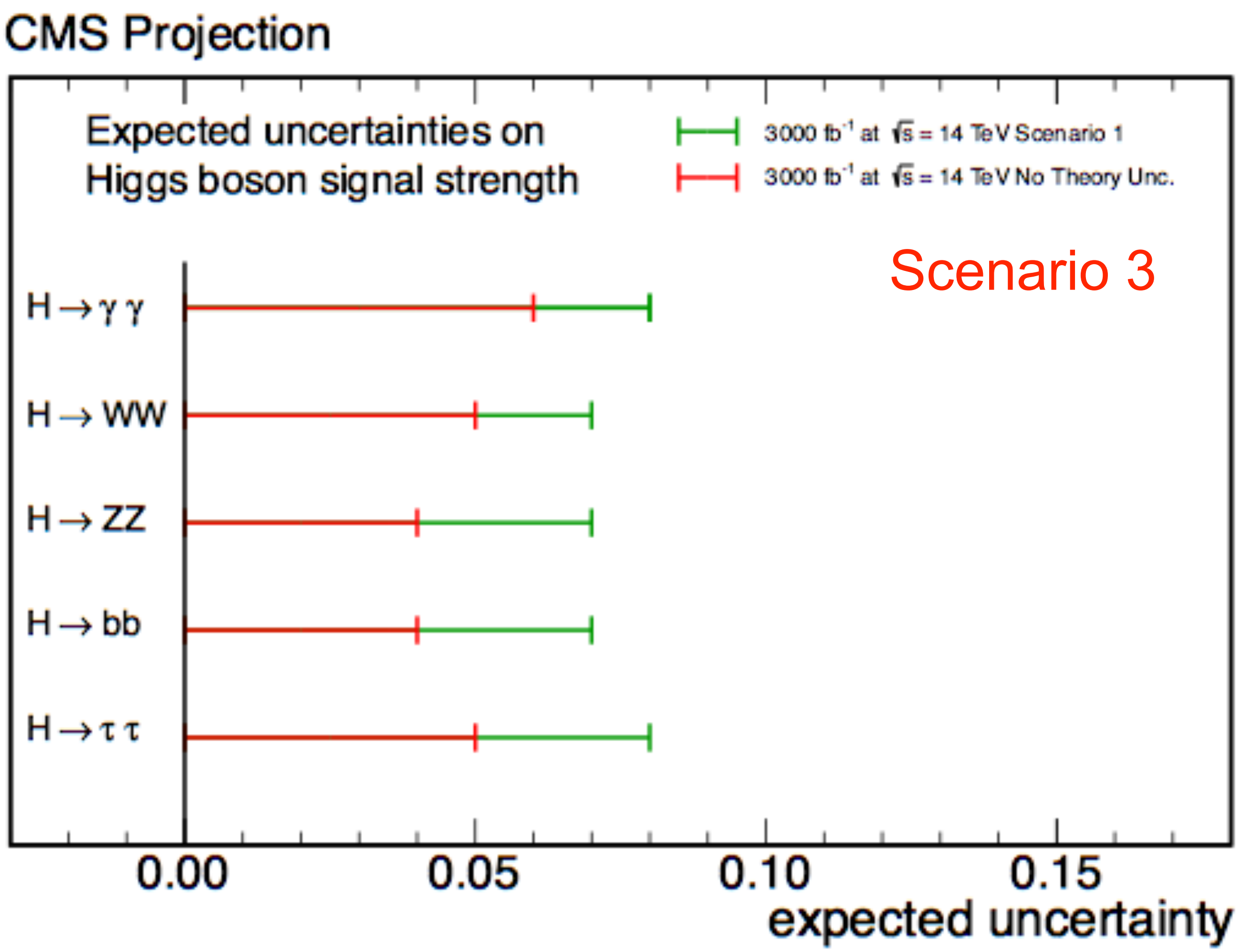

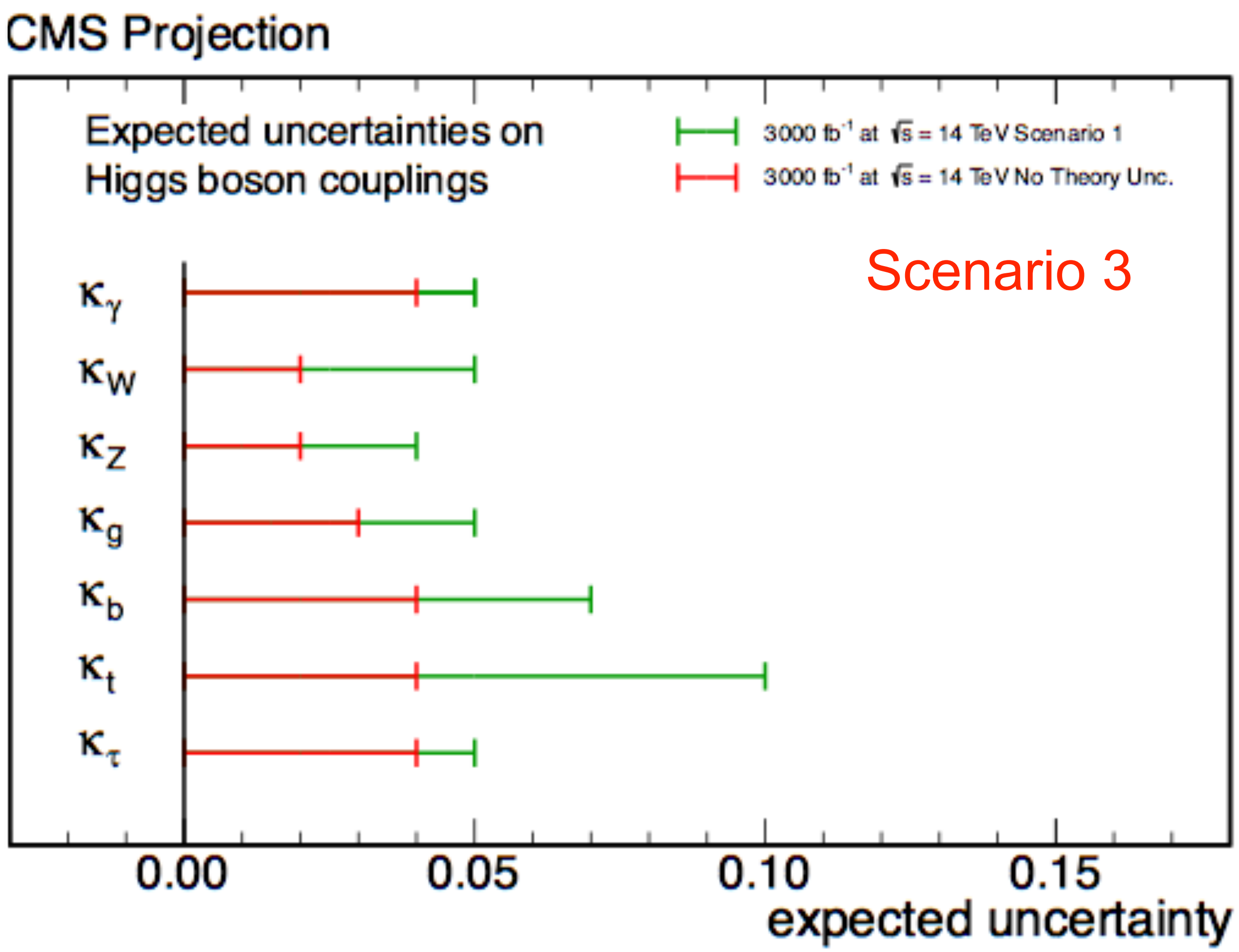

- Extrapolation by two orders of magnitude to higher luminosity
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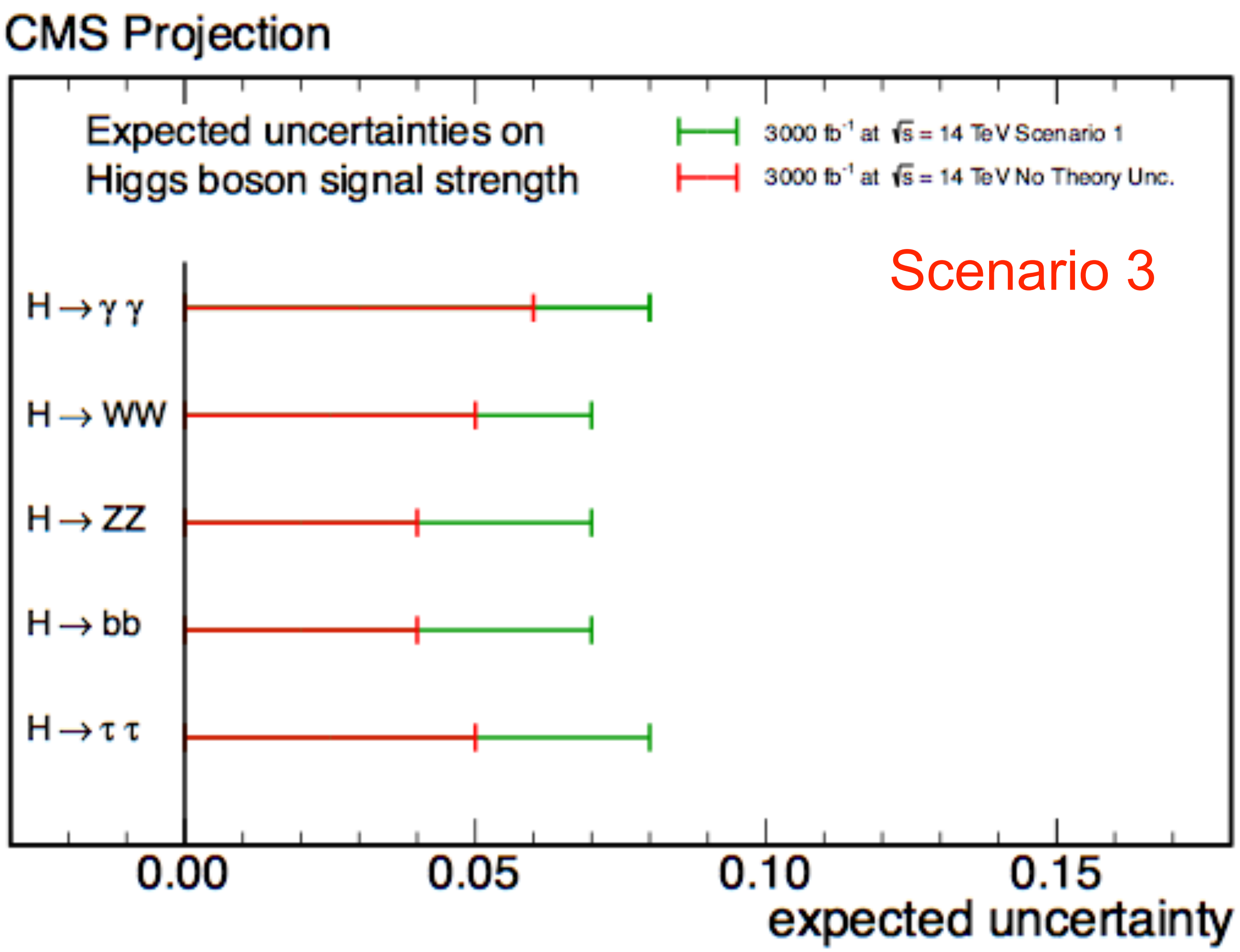

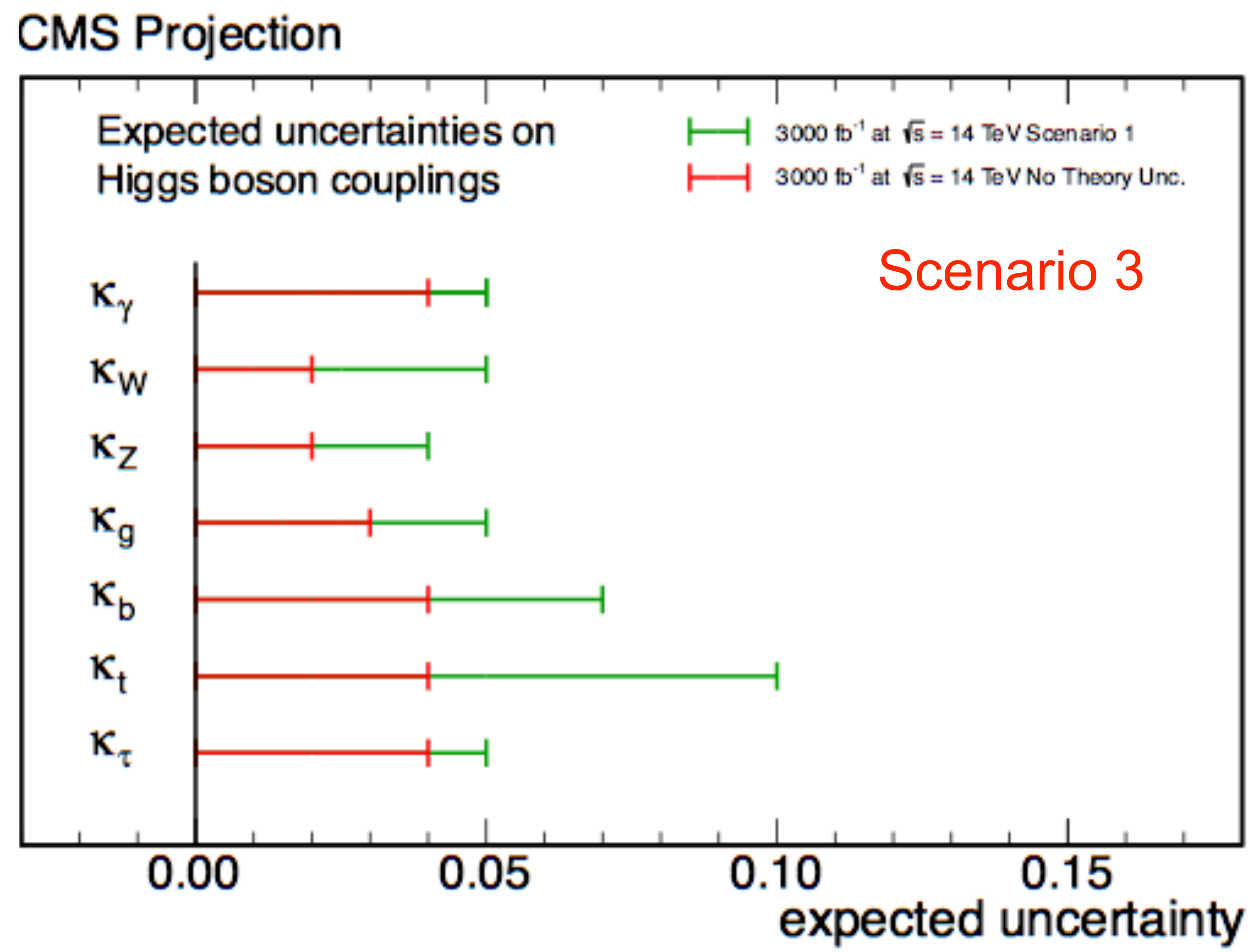

- Extrapolation by two orders of magnitude to higher luminosity
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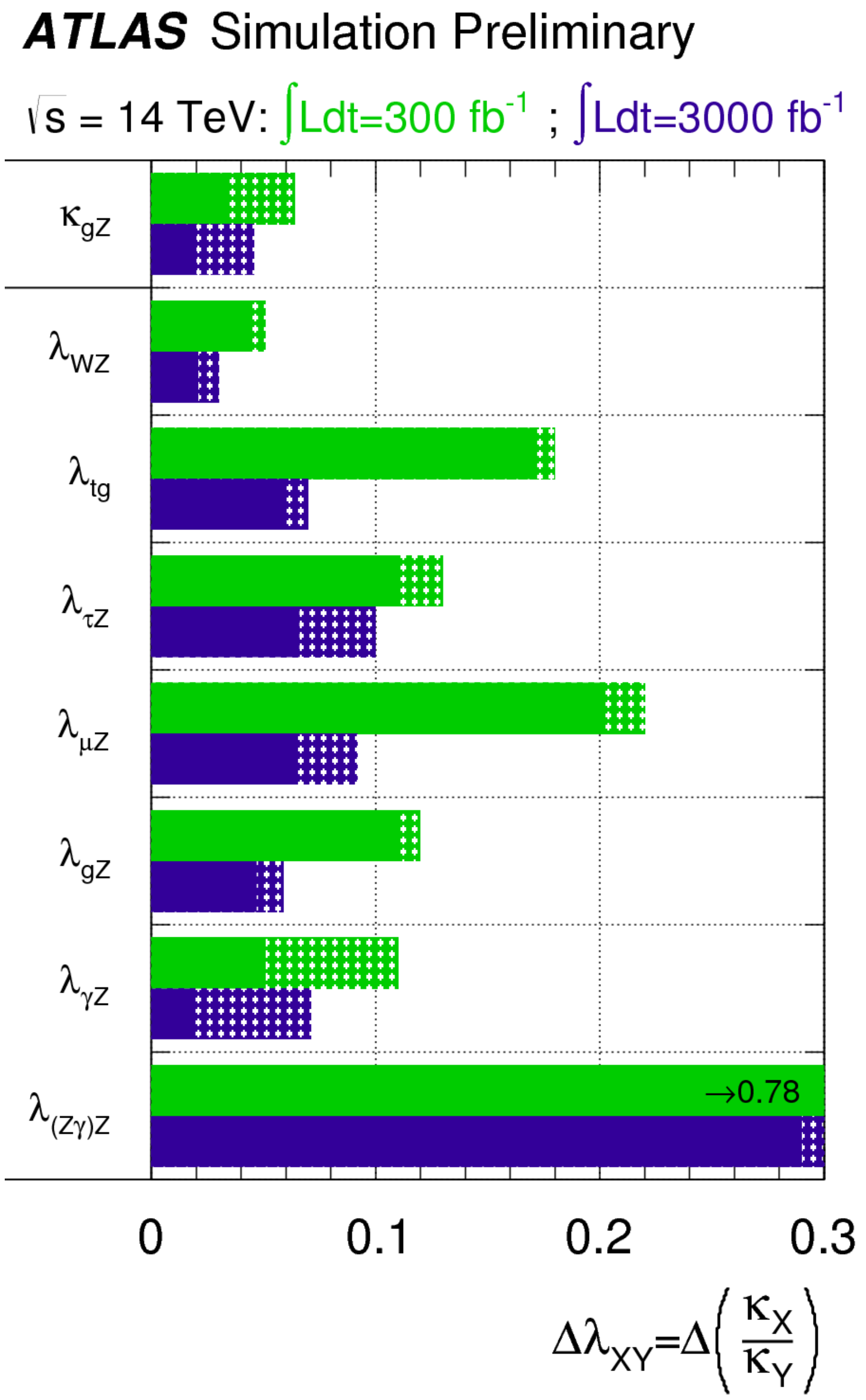
- Results will become syst. limited due to theory uncertainties. We must encourage our theoretical friends to improve their calculations!

Higgs couplings @3000 fb^{-1}



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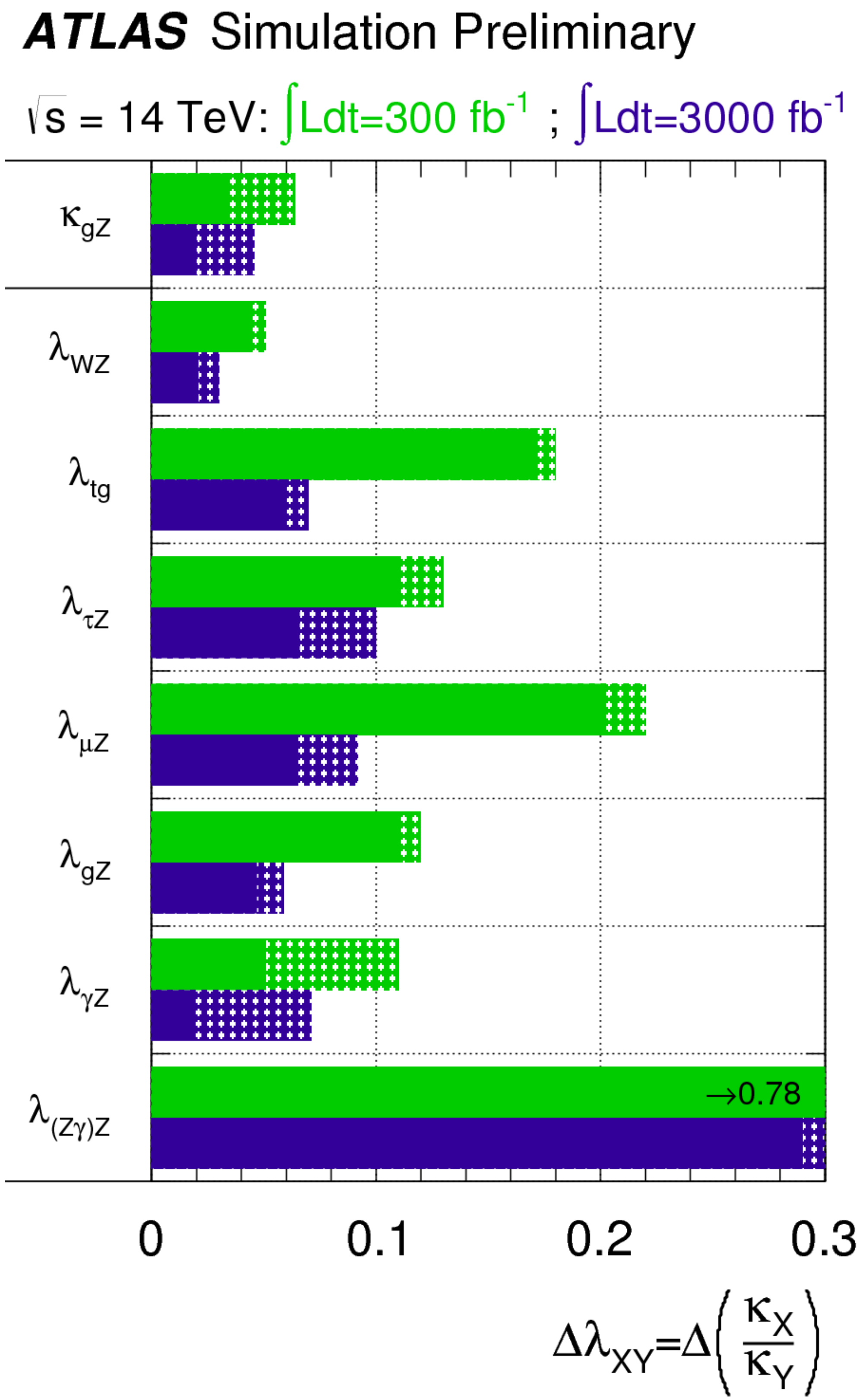
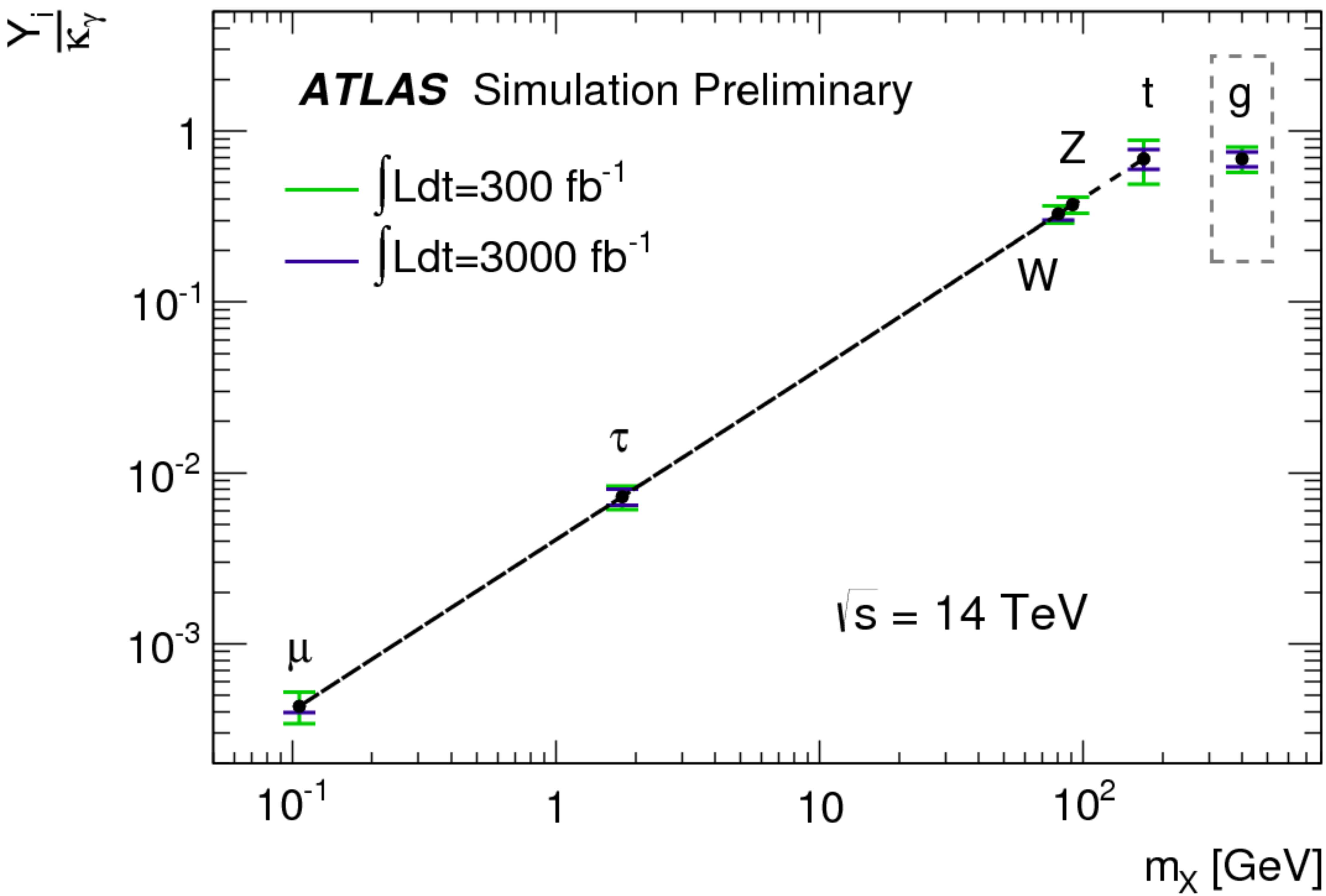


- With 3000 fb^{-1} the couplings can be determined with high precision (up to a few %)

Higgs coupling ratios vs. mass

Mass-scaled coupling ratios vs. particle mass



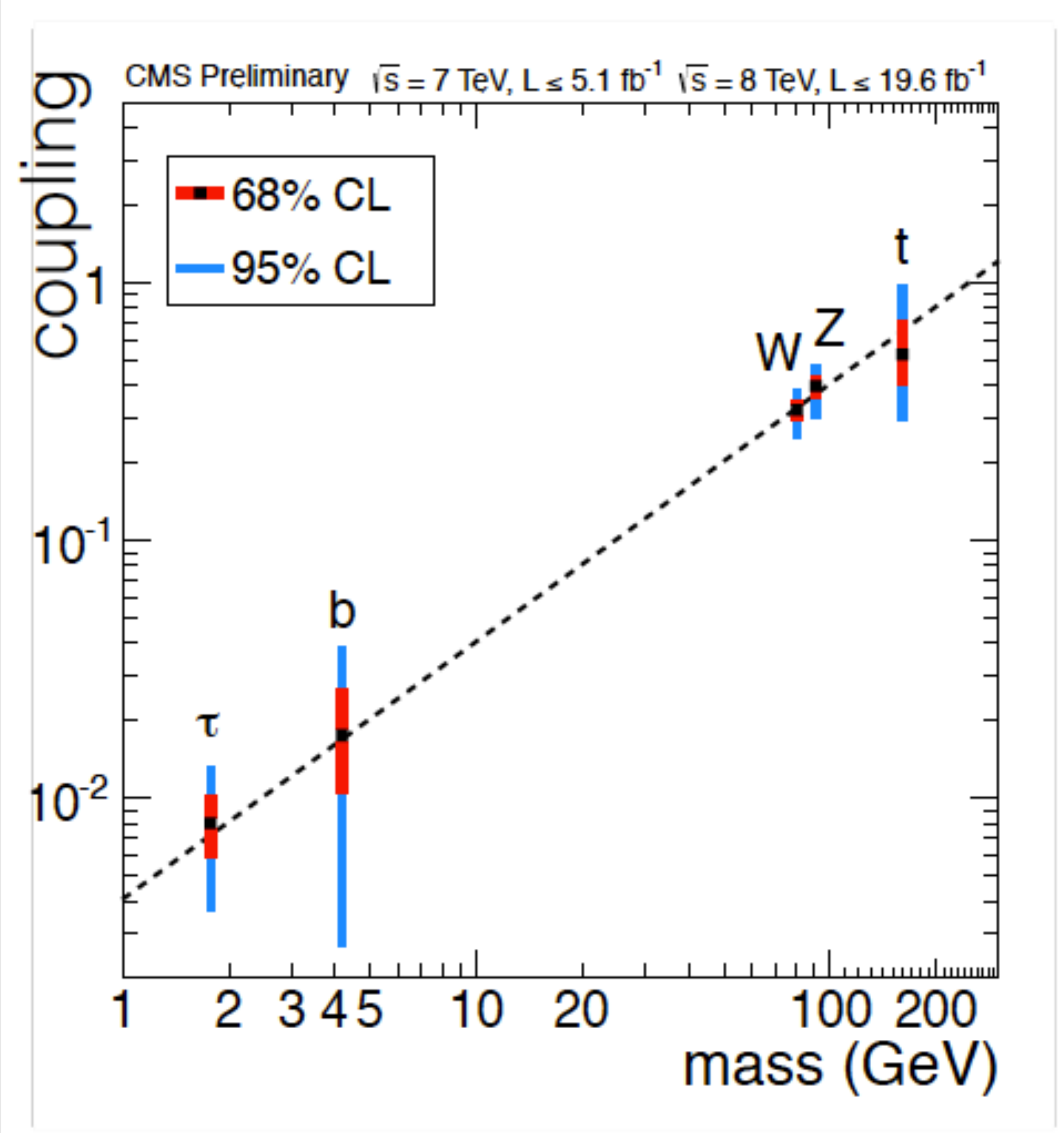
H→μμ

G. Salam, A. Weiler

- By LHC14@300, we'll have probed all 3rd generation fermion couplings to O(10–20%)
- H → μ⁺μ⁻ gives us access to 2nd lepton generation, i.e. is the mass-generation mechanism same for all generations, for quarks and leptons?

mass ∝ coupling to Higgs ?

$$Br(H \to \mu^+\mu^-)_{\rm SM} = 2.2 \cdot 10^{-4}$$



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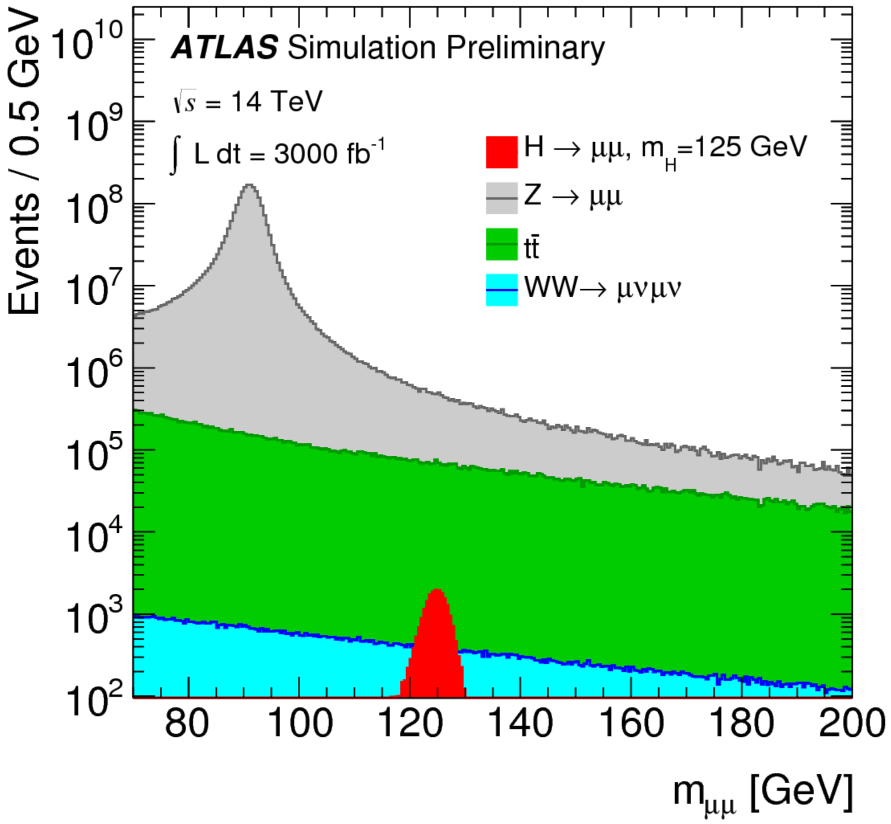
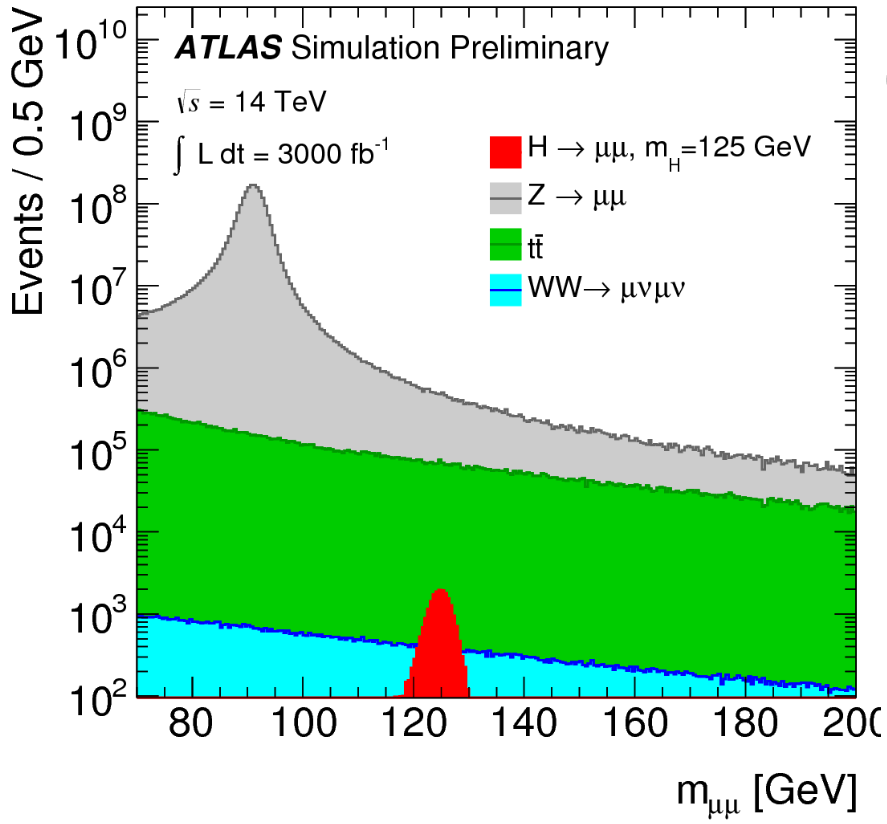

ATLAS Simulation Preliminary
√s = 14 TeV
∫ L dt = 3000 fb-1
H → μμ, mH=125 GeV
Z → μμ
tt̄
WW→ μνμν
Events / 0.5 GeV
m μμ [GeV]
80
100
120
140
160
180
200

H→μμ



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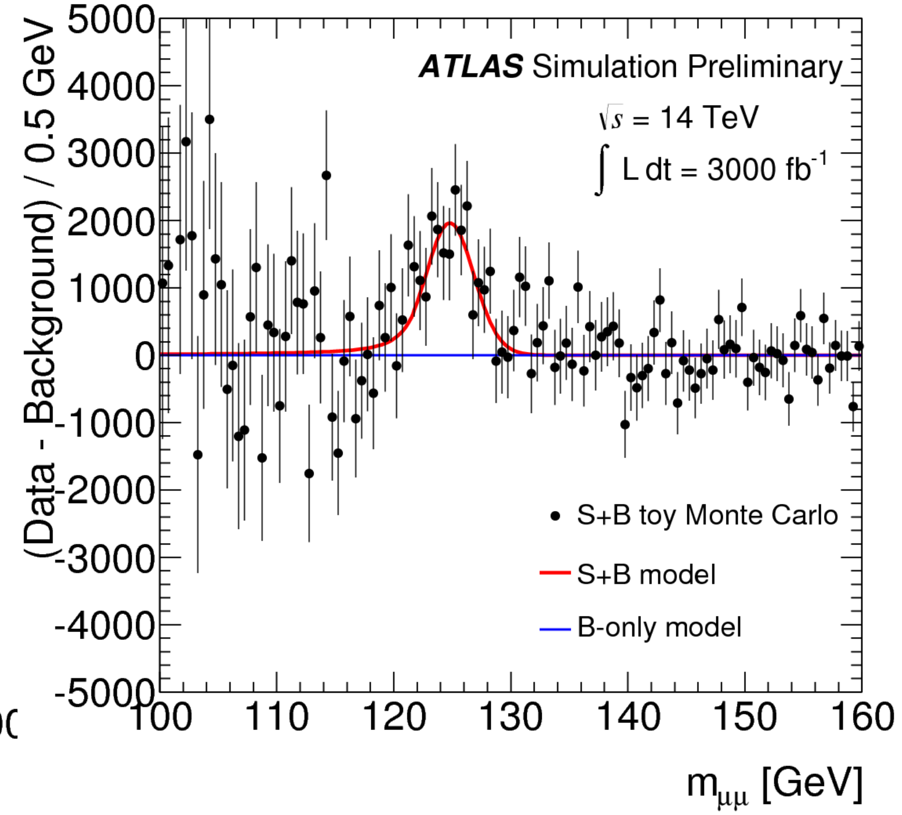

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S+B toy Monte Carlo
S+B model
B-only model
(Data - Background) / 0.5 GeV
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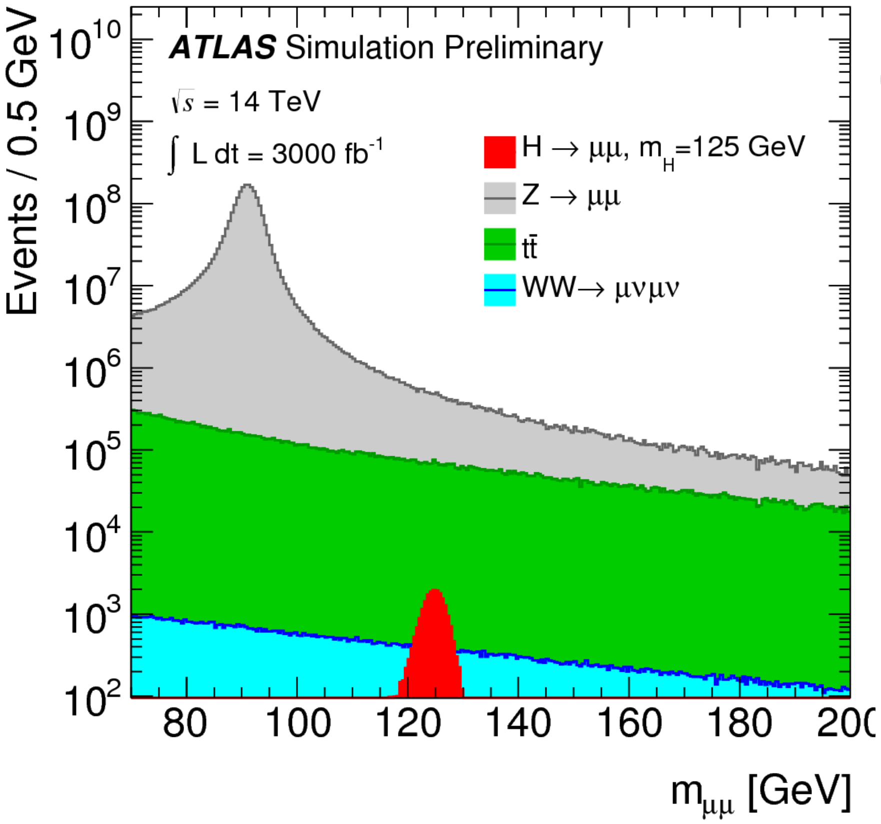

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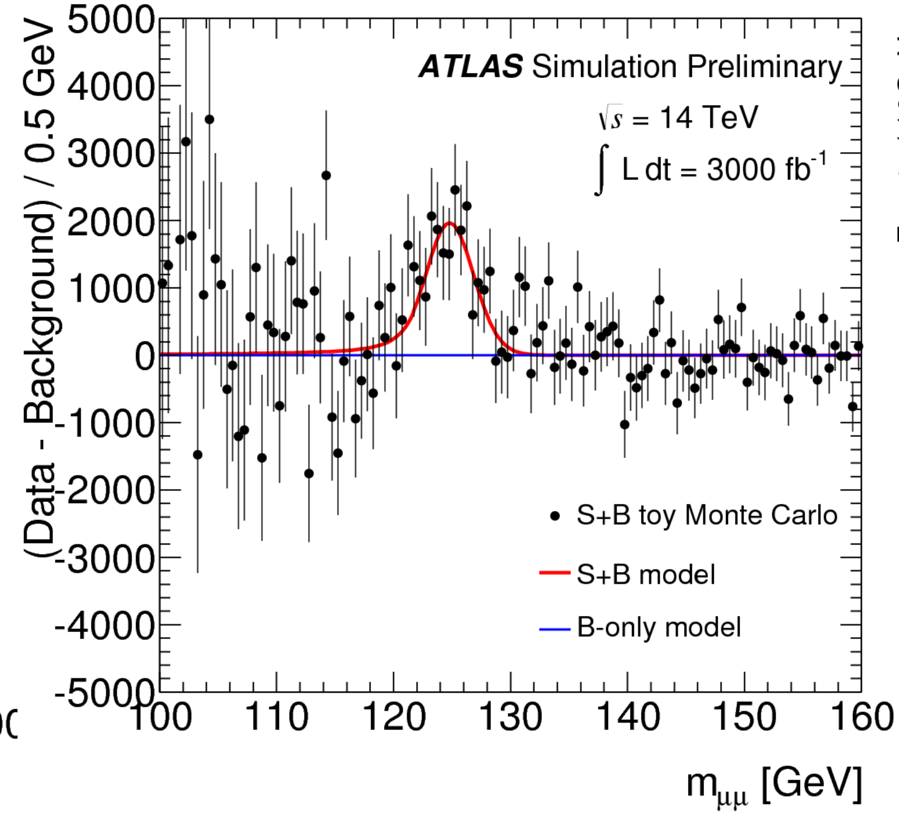

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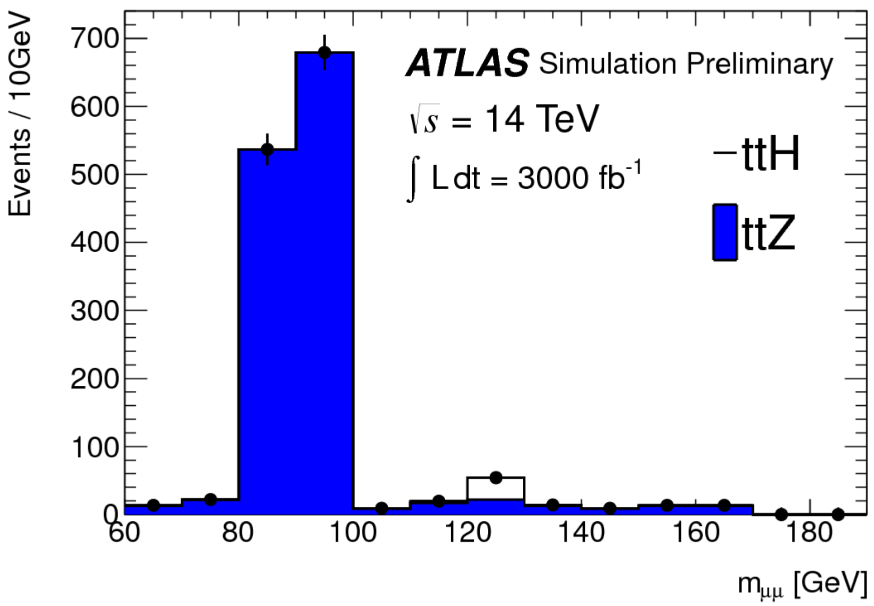

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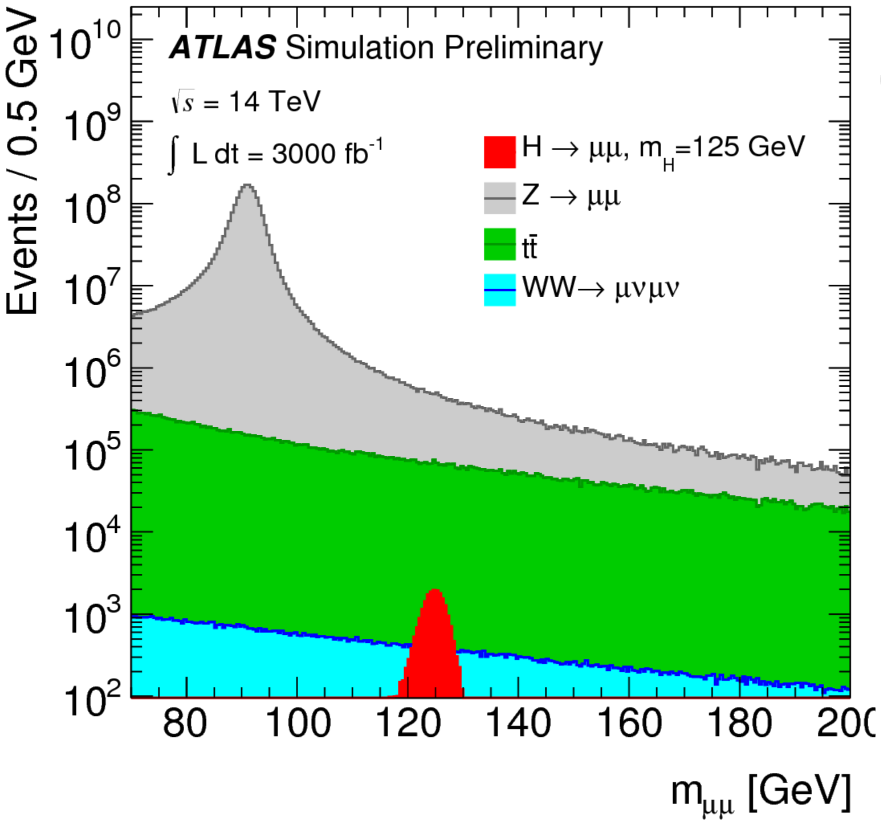
ttH
ttZ
Events / 10GeV
mμμ [GeV]

H→μμ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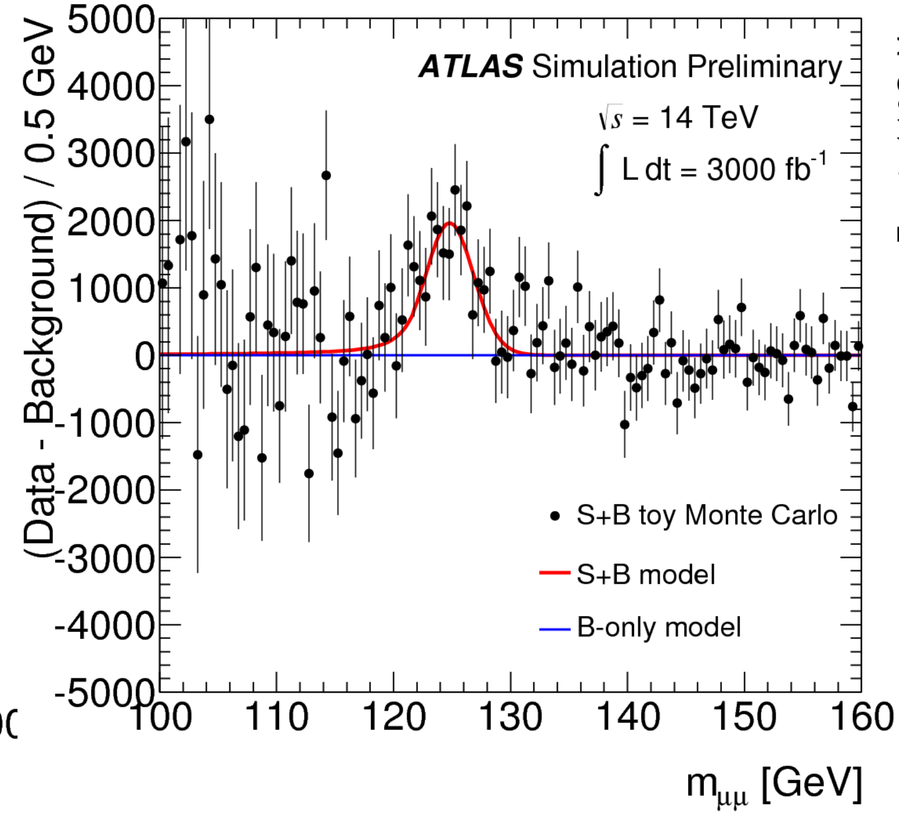
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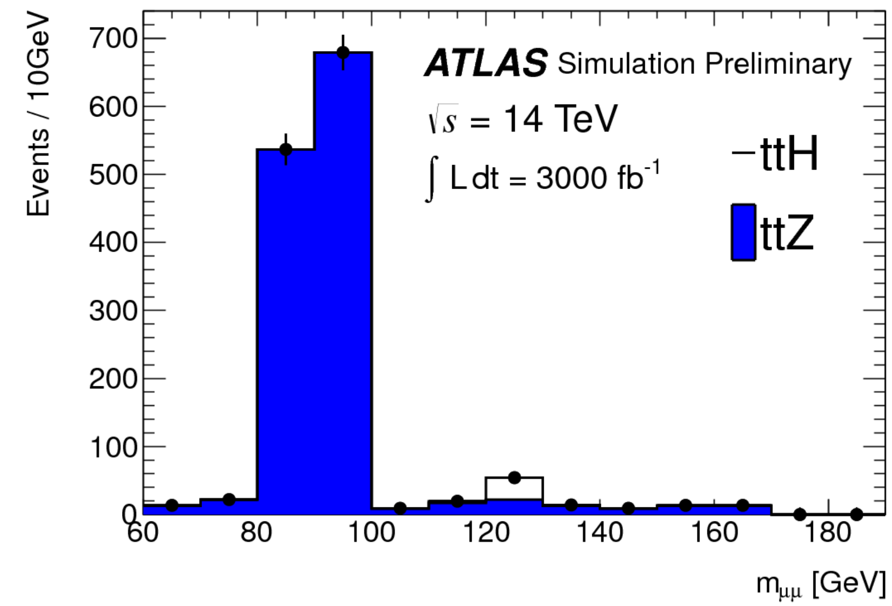
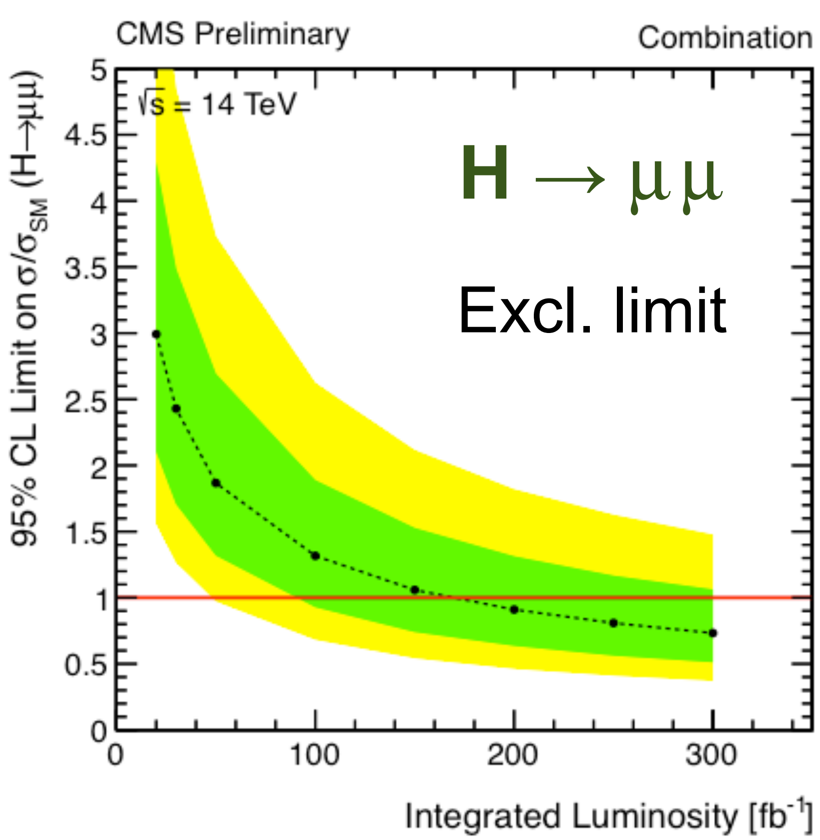
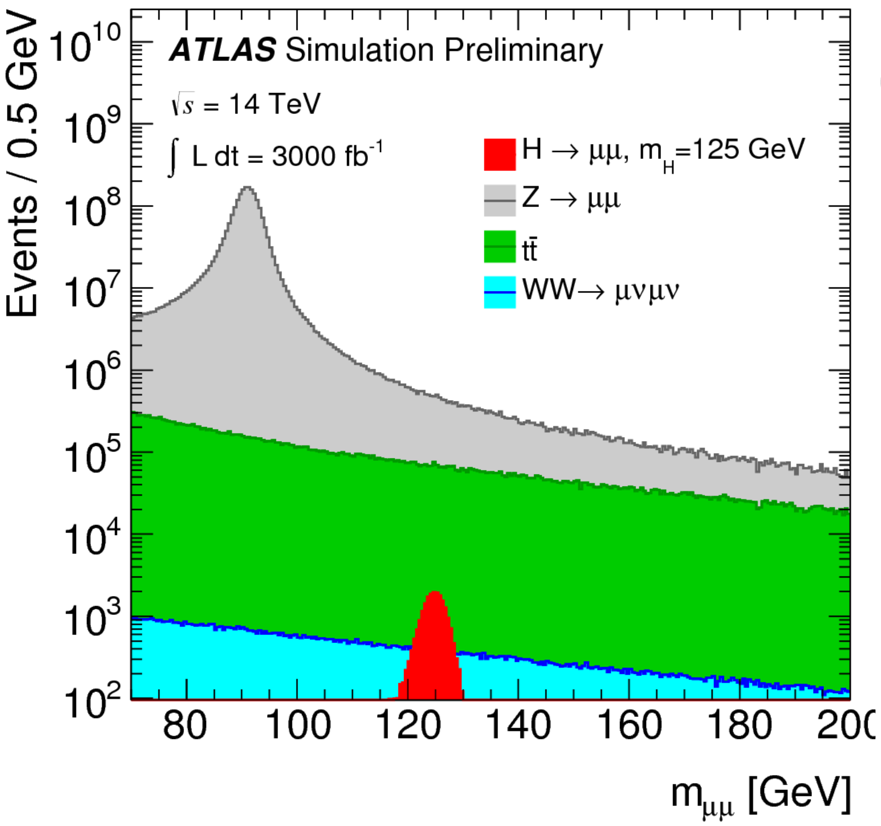
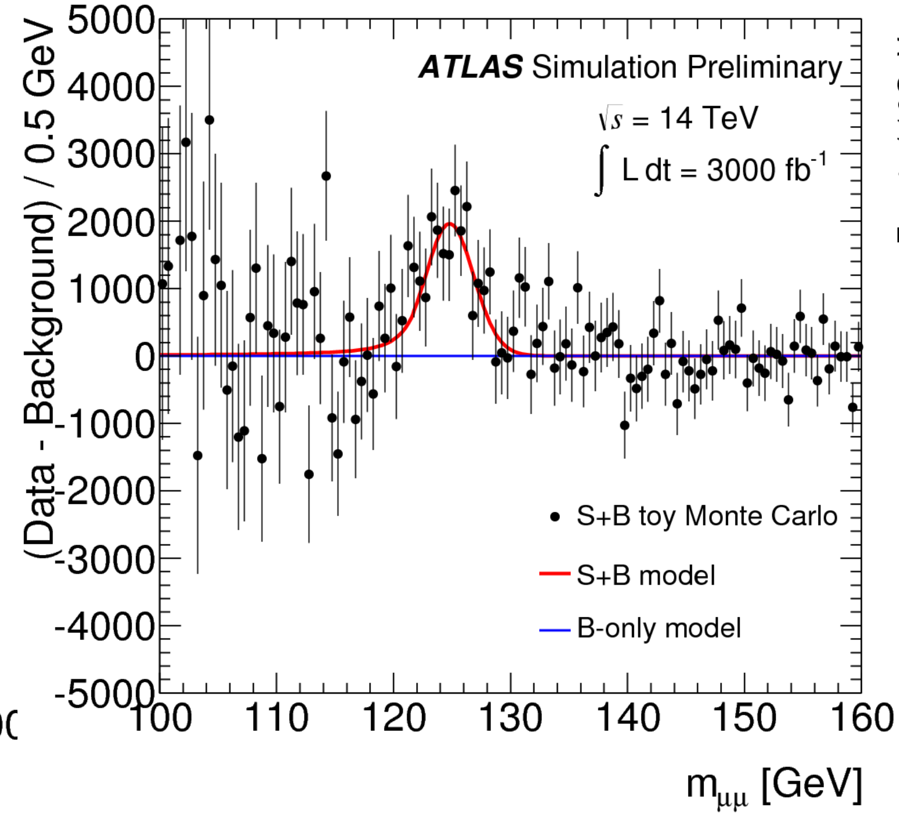
(Data - Background) / 0.5 GeV
m_μμ [GeV]

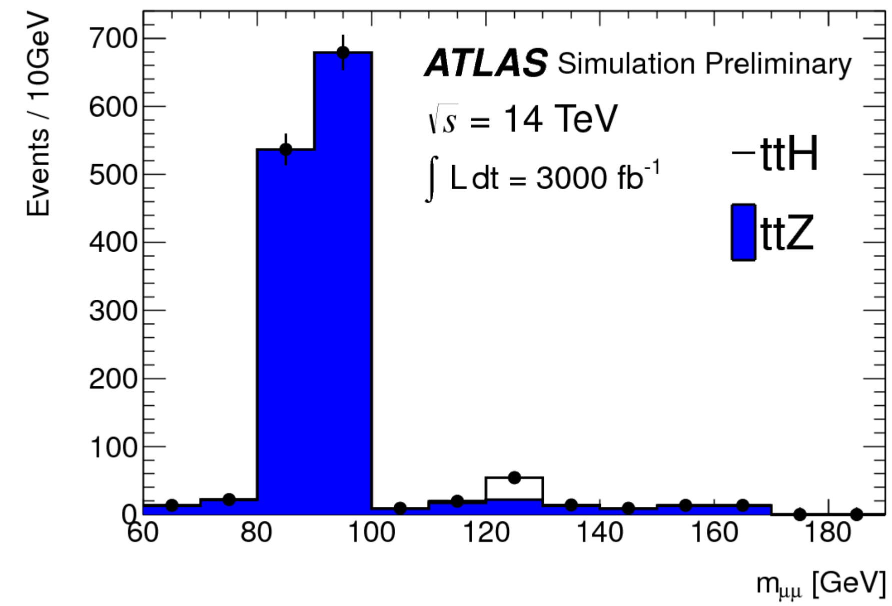

ATLAS Simulation Preliminary
√s = 14 TeV
∫ L dt = 3000 fb⁻¹
ttH
ttZ
Events / 10GeV
m_μμ [GeV]

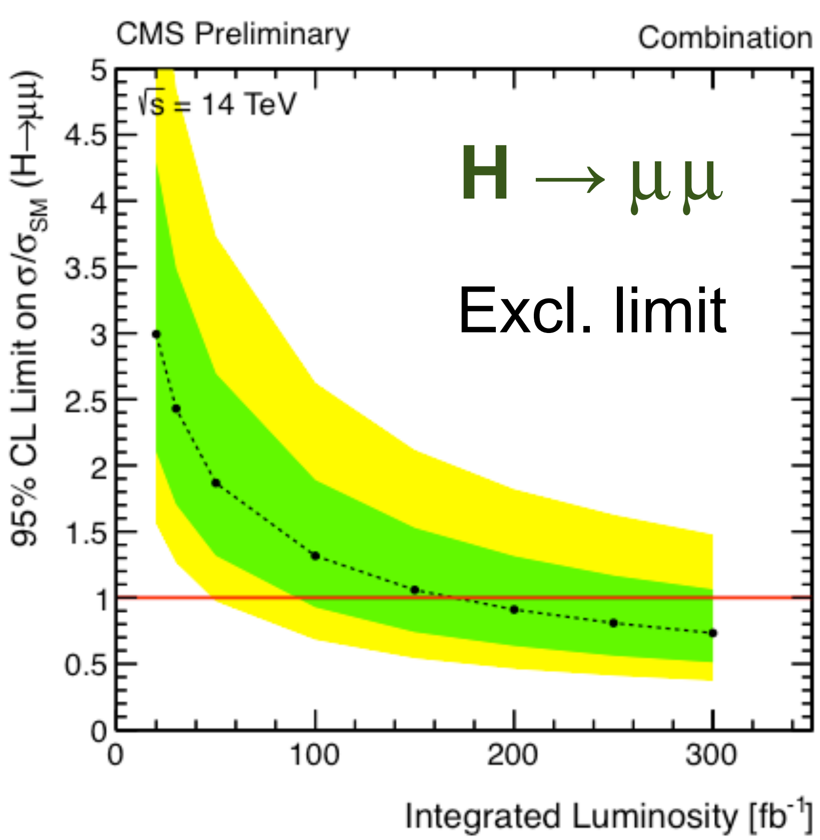

CMS Preliminary
Combination
√s = 14 TeV
H → μμ
Excl. limit
95% CL Limit on σ/σ_SM (H→μμ)
Integrated Luminosity [fb⁻¹]

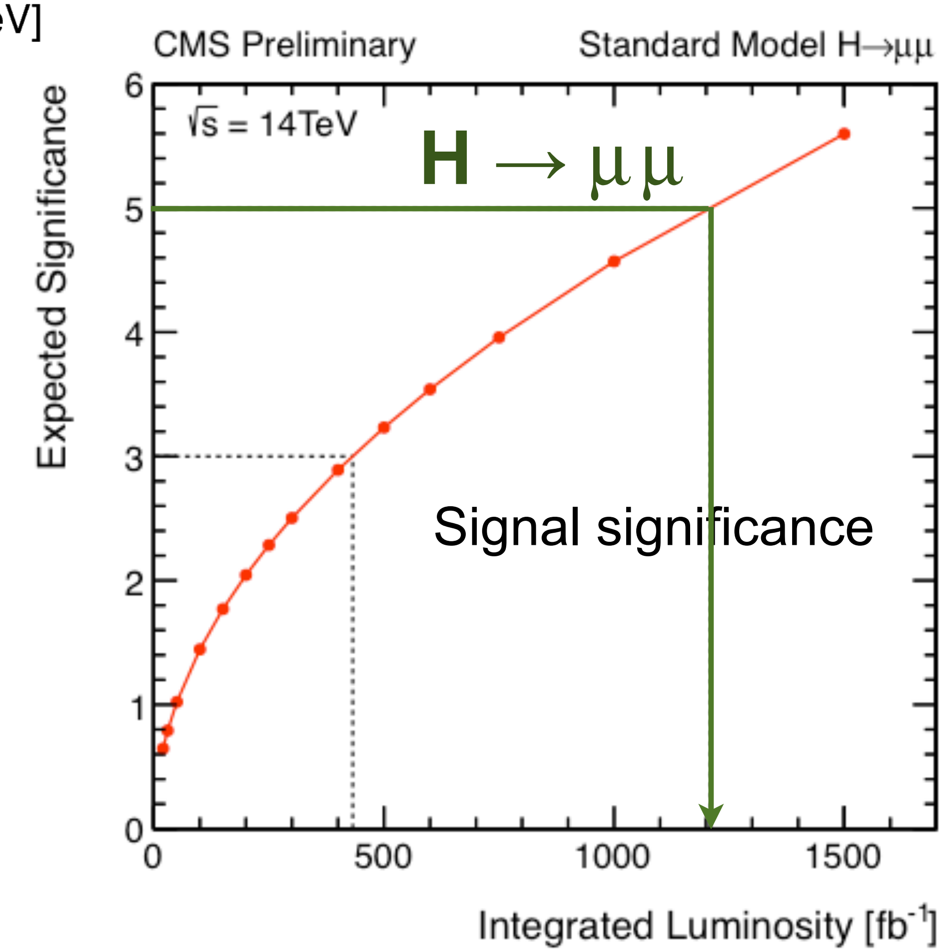
H→μμ


ATLAS Simulation Preliminary
√s = 14 TeV
∫ L dt = 3000 fb⁻¹
H → μμ, m_H=125 GeV
Z → μμ
tt̄
WW→ μνμν
Events / 0.5 GeV
m_μμ [GeV]

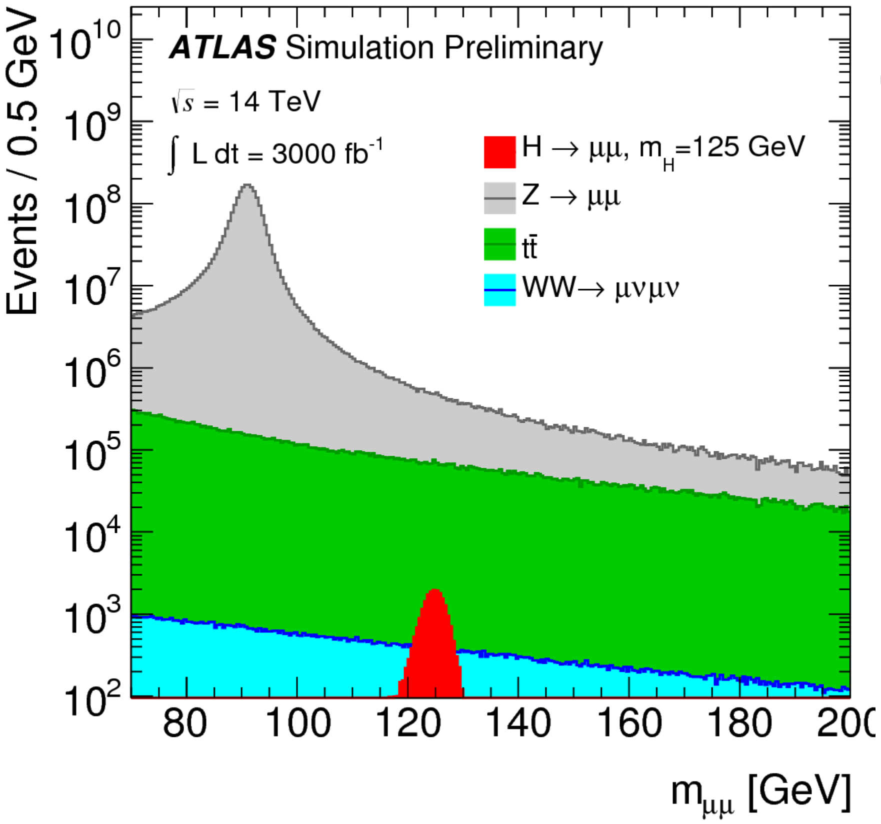

ATLAS Simulation Preliminary
√s = 14 TeV
∫ L dt = 3000 fb⁻¹
S+B toy Monte Carlo
S+B model
B-only model
(Data - Background) / 0.5 GeV
m_μμ [GeV]

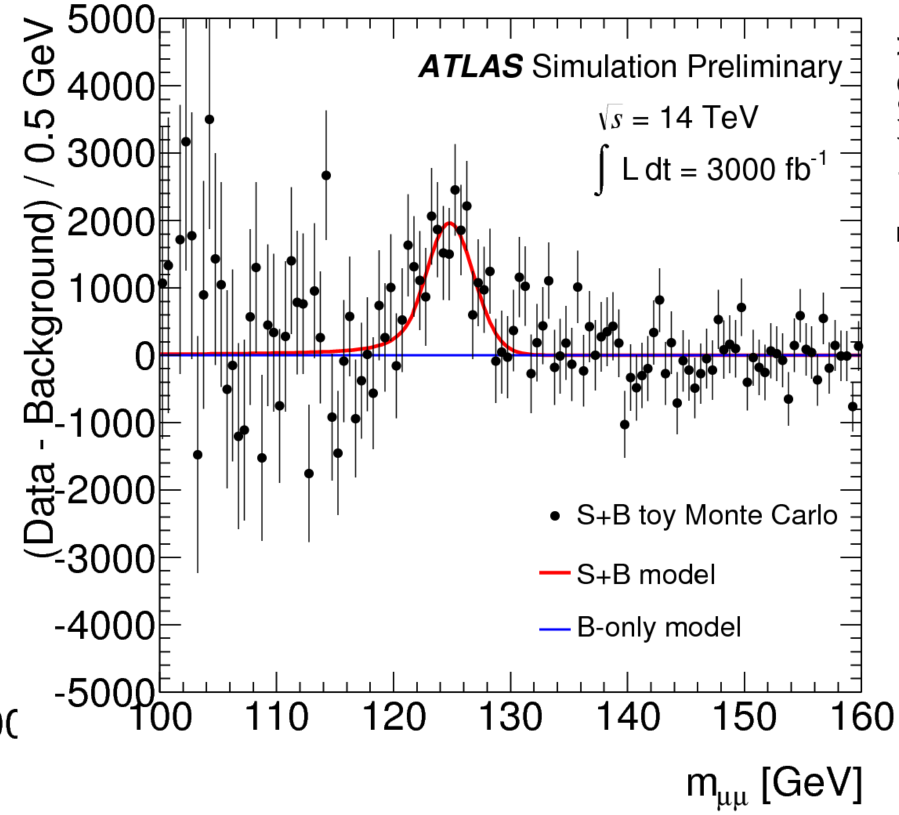

ATLAS Simulation Preliminary
√s = 14 TeV
∫ L dt = 3000 fb⁻¹
ttH
ttZ
Events / 10GeV
m_μμ [GeV]

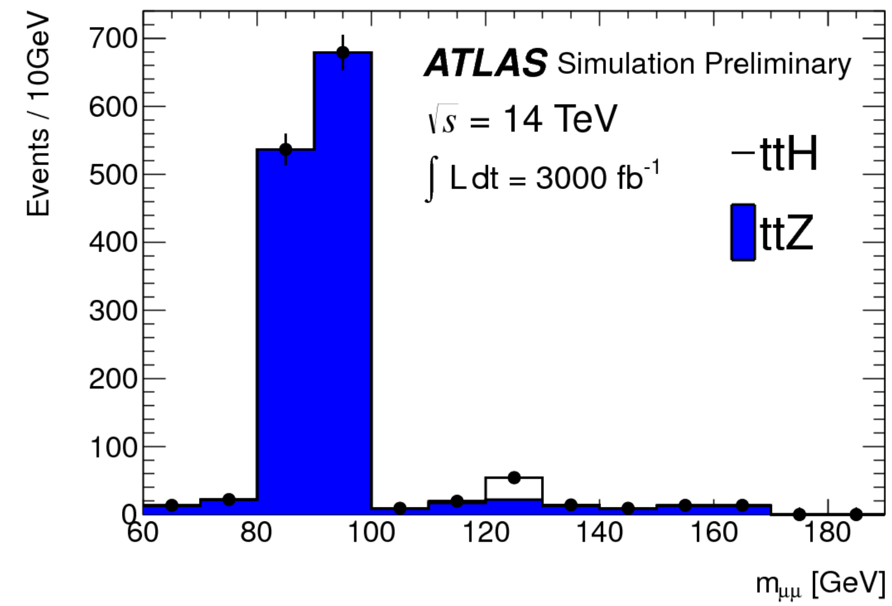

CMS Preliminary
Combination
√s = 14 TeV
H → μ μ
Excl. limit
95% CL Limit on σ/σ_SM (H→μμ)
Integrated Luminosity [fb⁻¹]

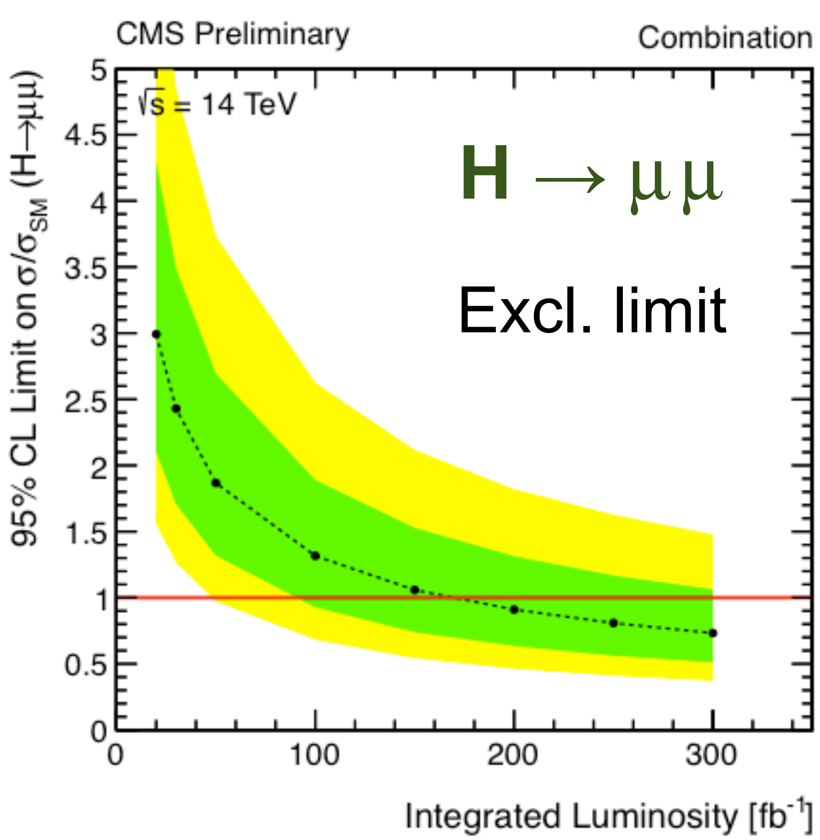

CMS Preliminary
Standard Model H→μμ
√s = 14TeV
H → μ μ
Signal significance
Expected Significance
Integrated Luminosity [fb⁻¹]

H→μμ

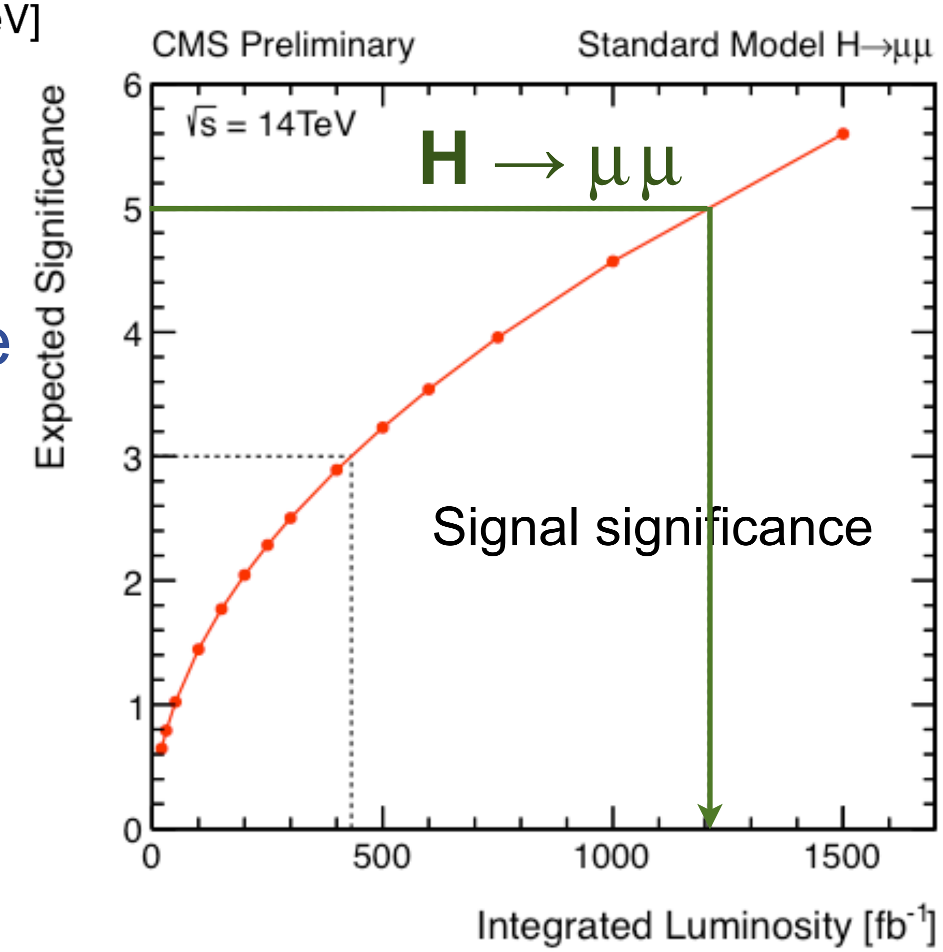








- The decay H→μμ can be observed with a significance of 5 sigma
  - measurement of the Hμμ coupling with a precision of ~10%



$H \rightarrow Z\gamma$

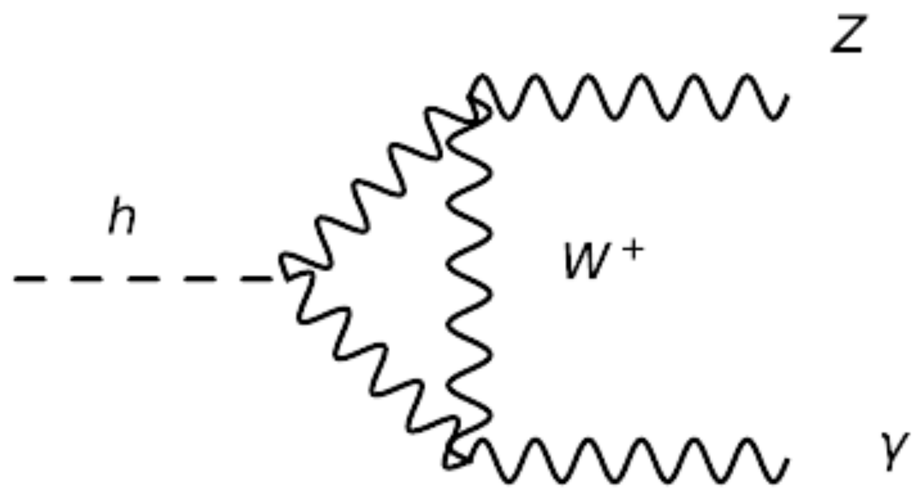
$H\to Z\gamma$

- γZ like γγ and gg loop induced, but sensitive to effects invisible in γγ and gg (because of chiral couplings)

G. Salam, A. Weiler

- In composite Higgs: Not protected by Goldstone symmetry, large γZ while γγ and gg small

SM



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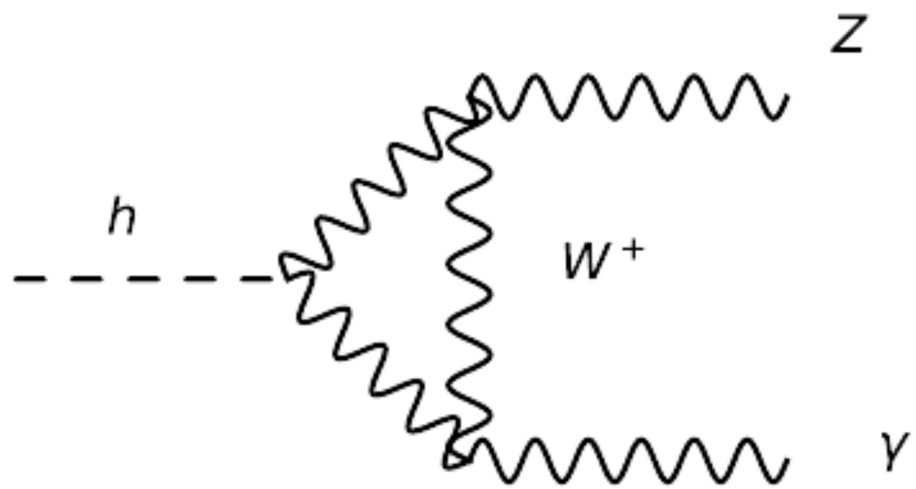
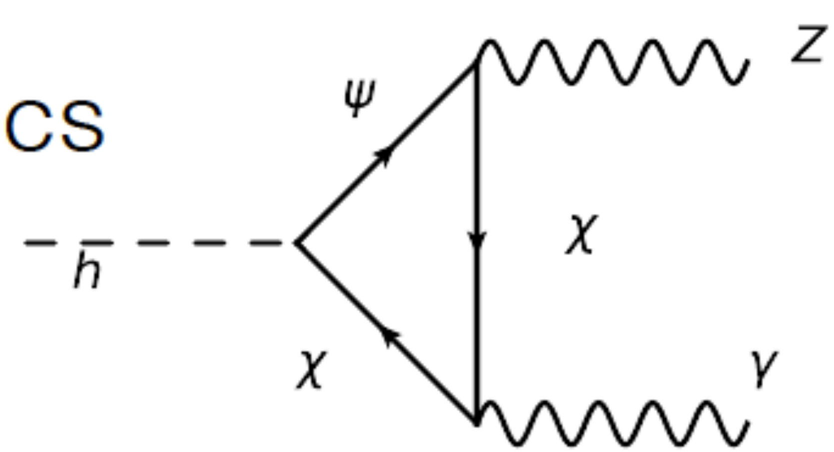


New physics



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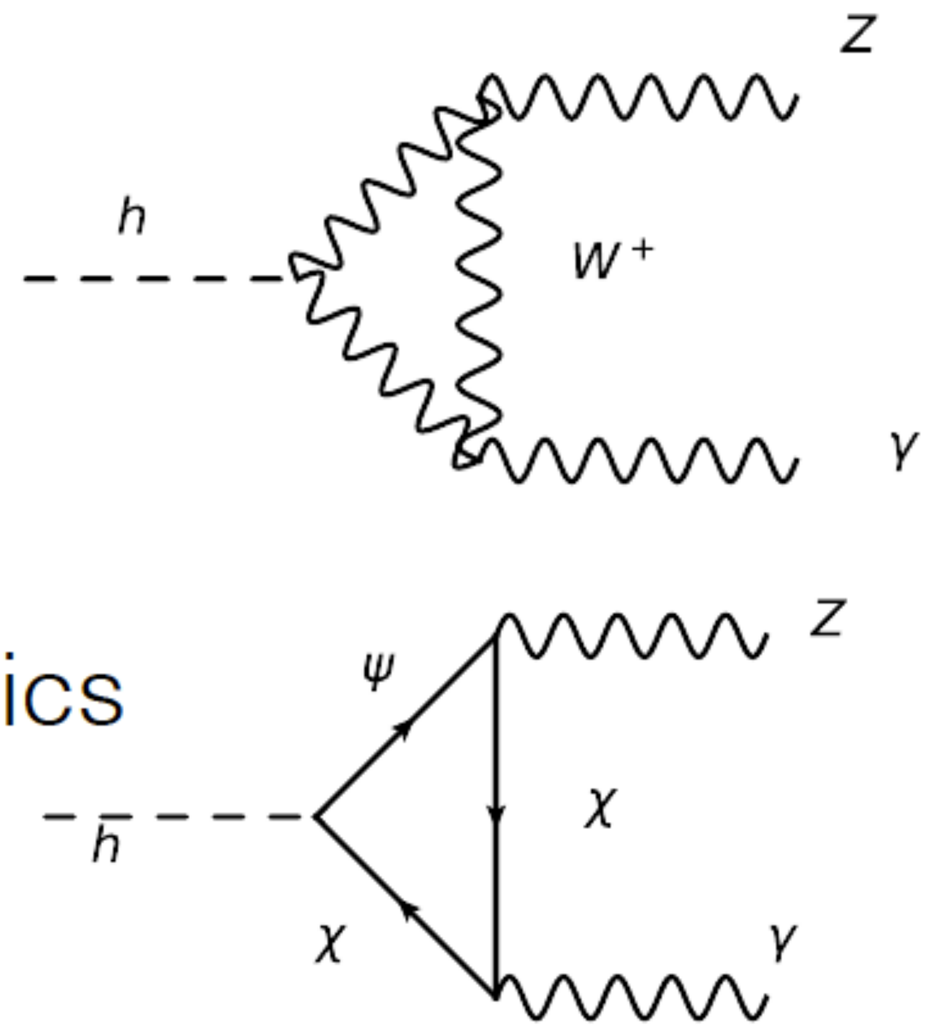
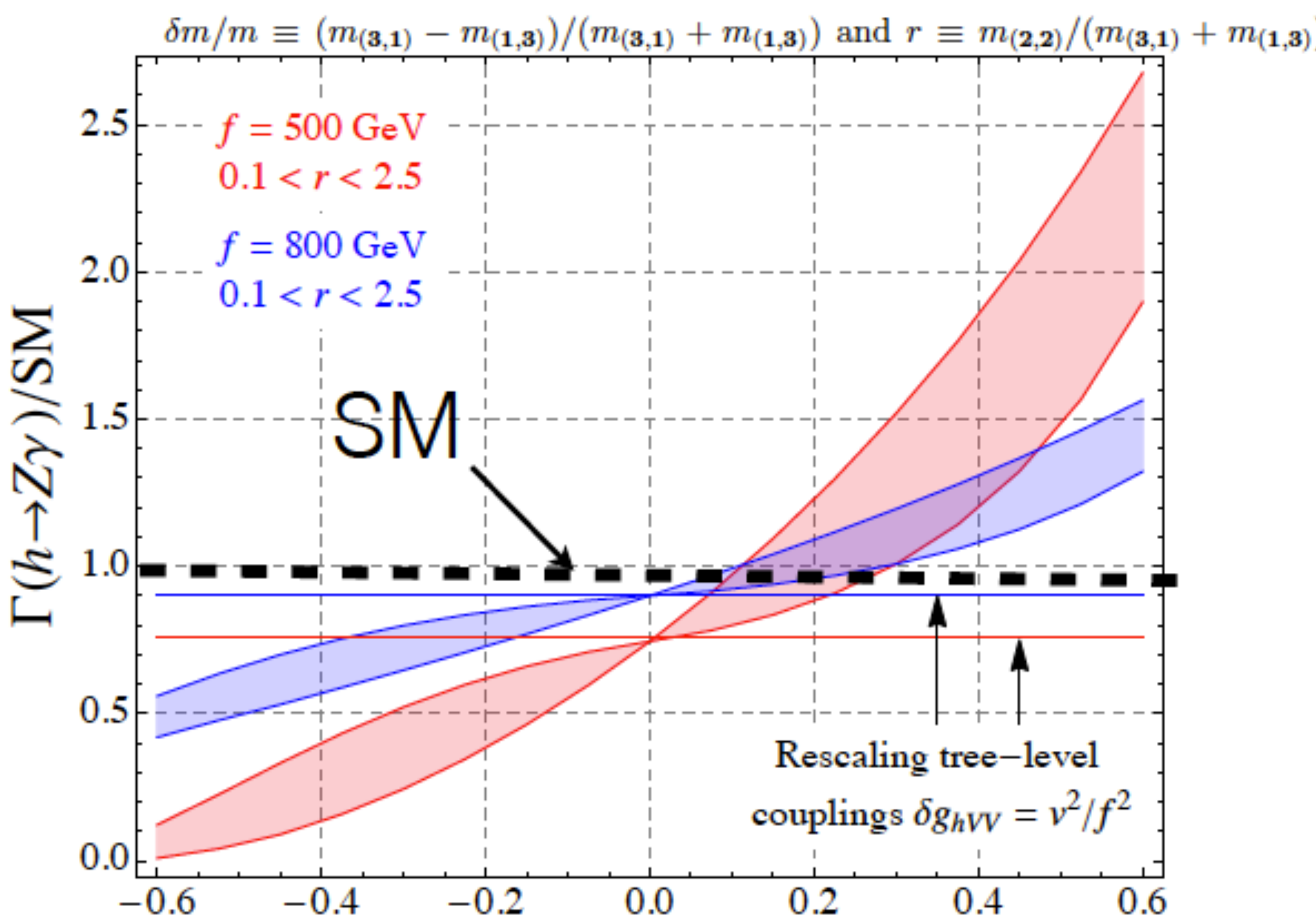
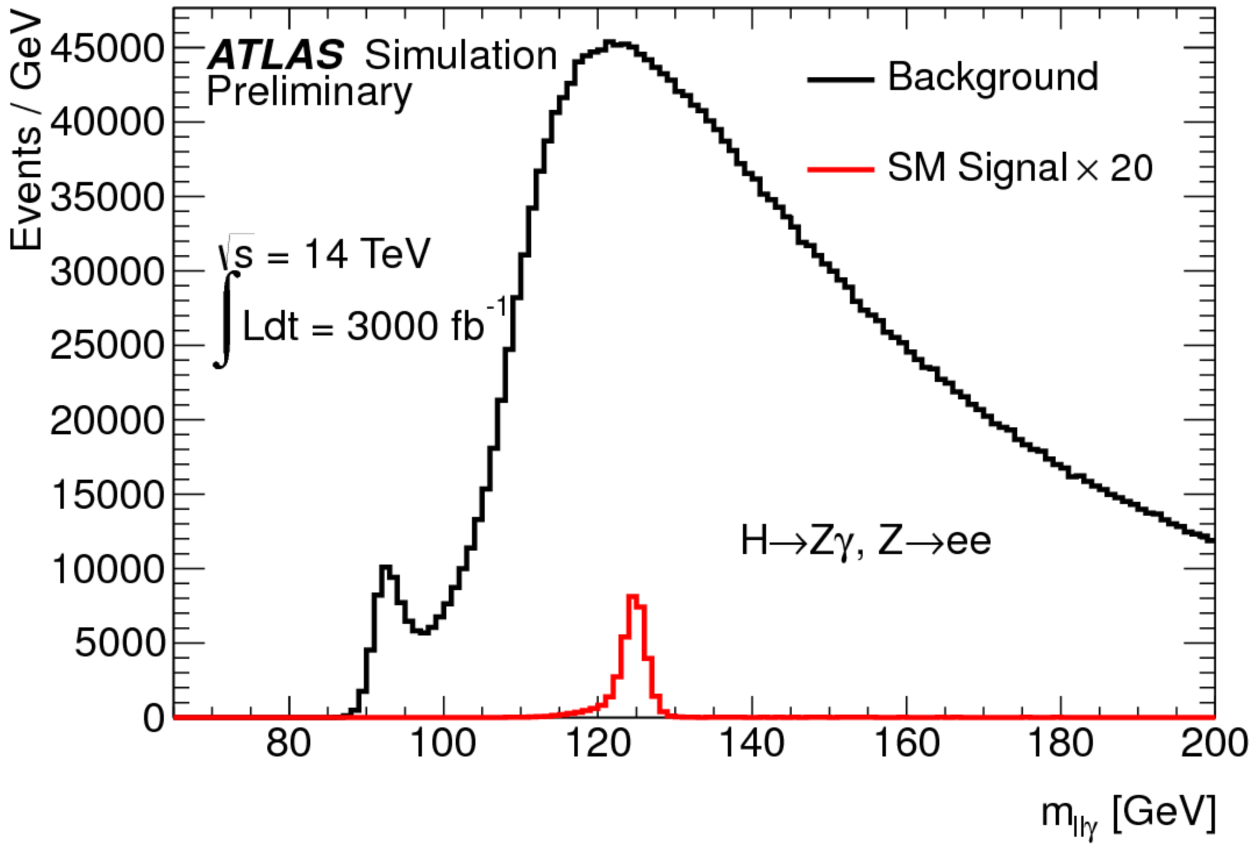




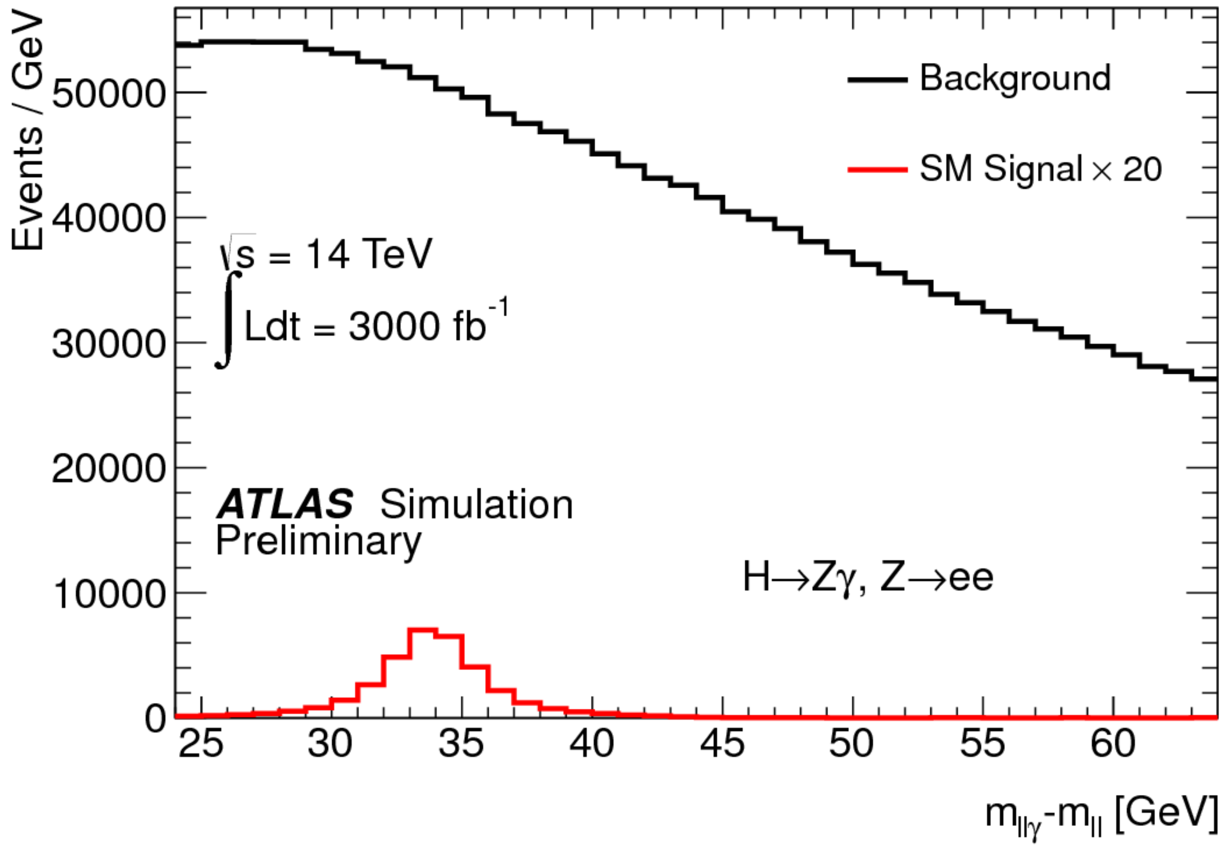
1308.2676

H→Zγ

H→Zγ

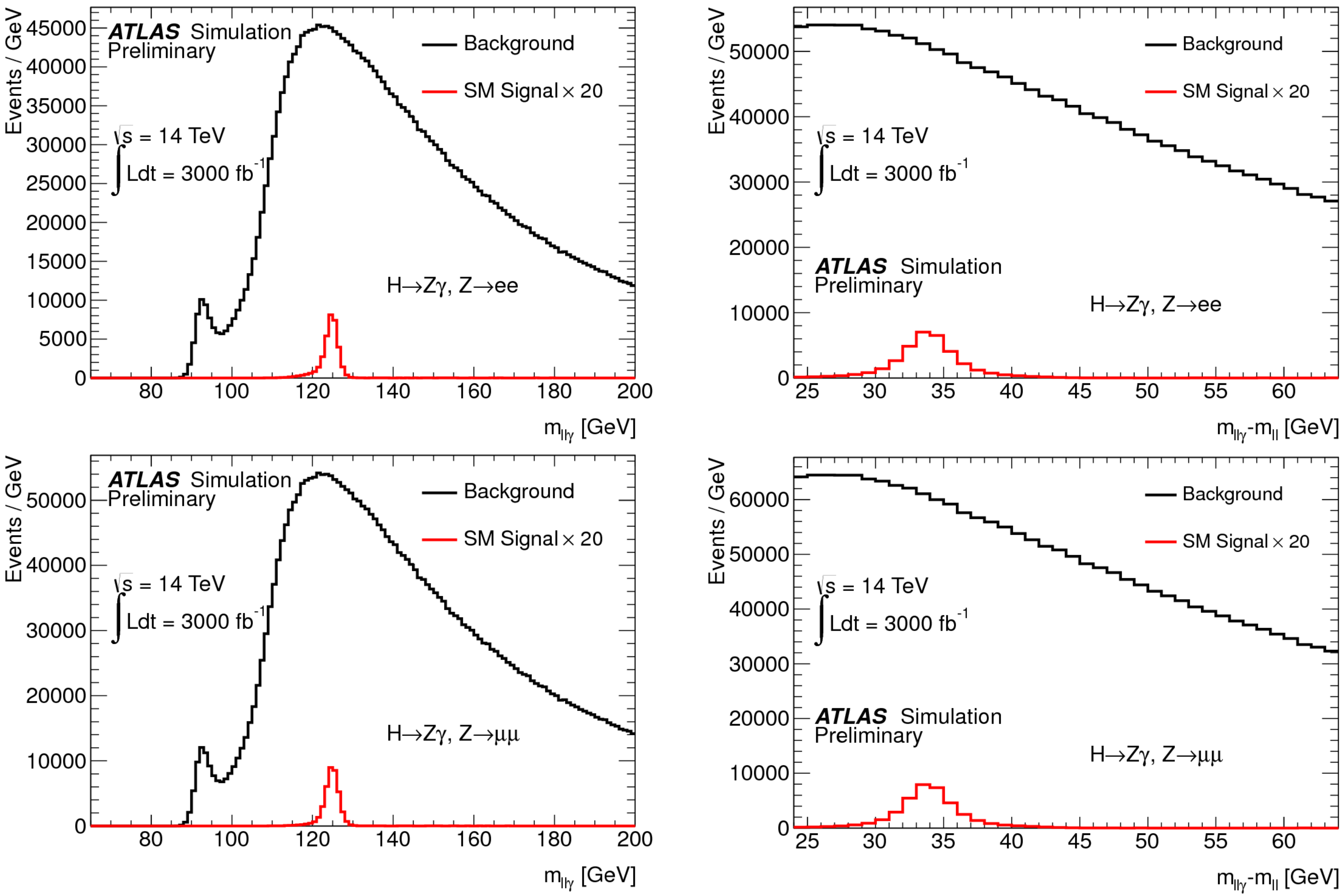


ATLAS Simulation
Preliminary
Background
SM Signal × 20
√s = 14 TeV
∫Ldt = 3000 fb^-1
H→Zγ, Z→ee
Events / GeV
m_llγ [GeV]



ATLAS Simulation
Preliminary
Background
SM Signal × 20
√s = 14 TeV
∫Ldt = 3000 fb^-1
H→Zγ, Z→ee
Events / GeV
m_llγ-m_ll [GeV]

H→Zγ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Background
SM Signal × 20
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H→Zγ, Z→ee
H→Zγ, Z→μμ
Events / GeV
m_llγ [GeV]
m_llγ-m_ll [GeV]

H→cc

H→cc

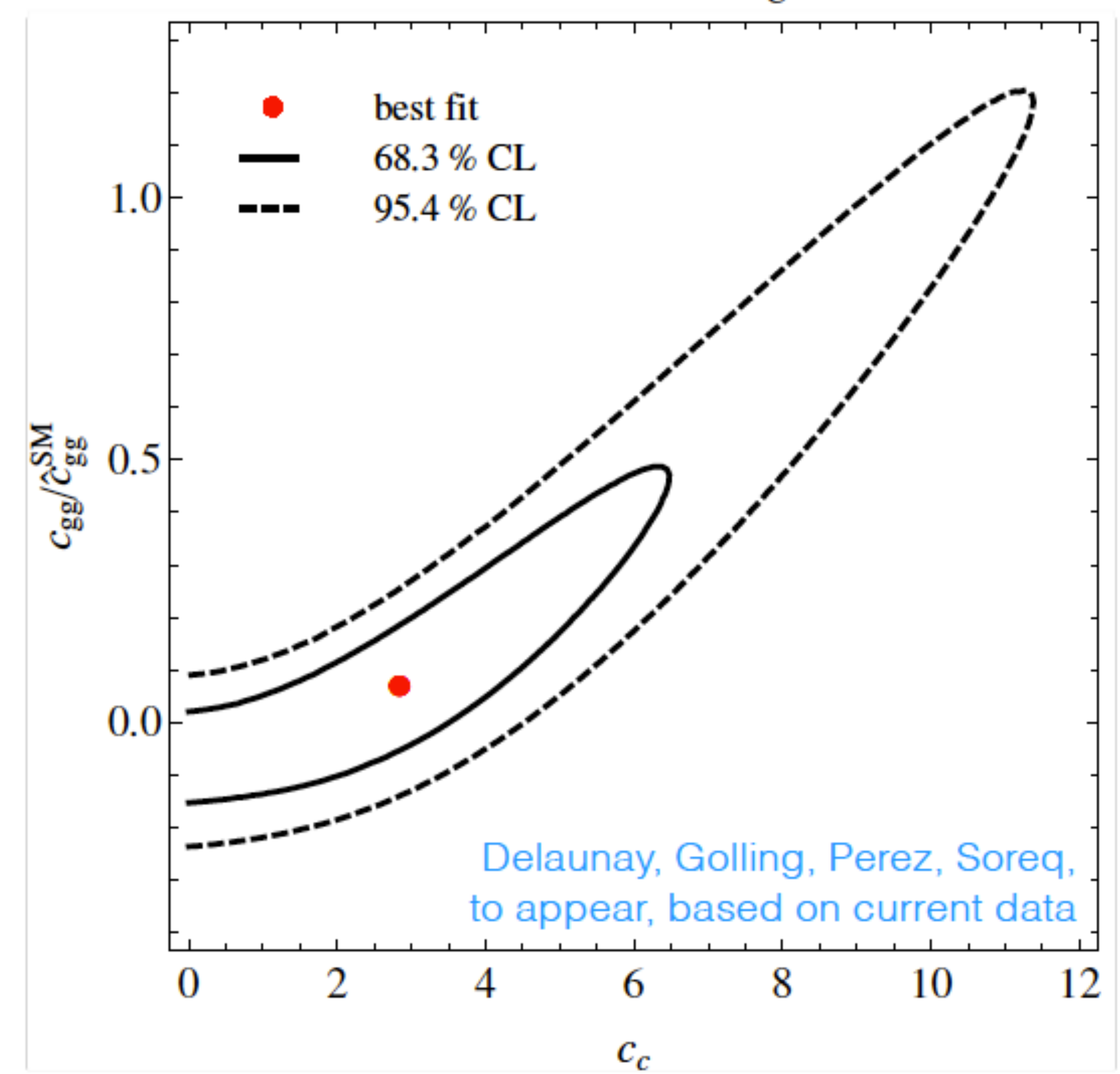
- Hcc coupling can still be 4-8 x SM

$$\mathcal{L} = c_c\, h \frac{m_c}{v} \bar{c}c + \ldots$$

- In composite Higgs

$$c_c \simeq 1 + \mathcal{O}\left(\frac{v^2}{f^2}\right) + \mathcal{O}\left(\epsilon_c^2 \frac{g_\psi^2 v^2}{m_\psi^2}\right)$$

large for composite charm and light charm partners



G. Salam, A. Weiler

H→cc

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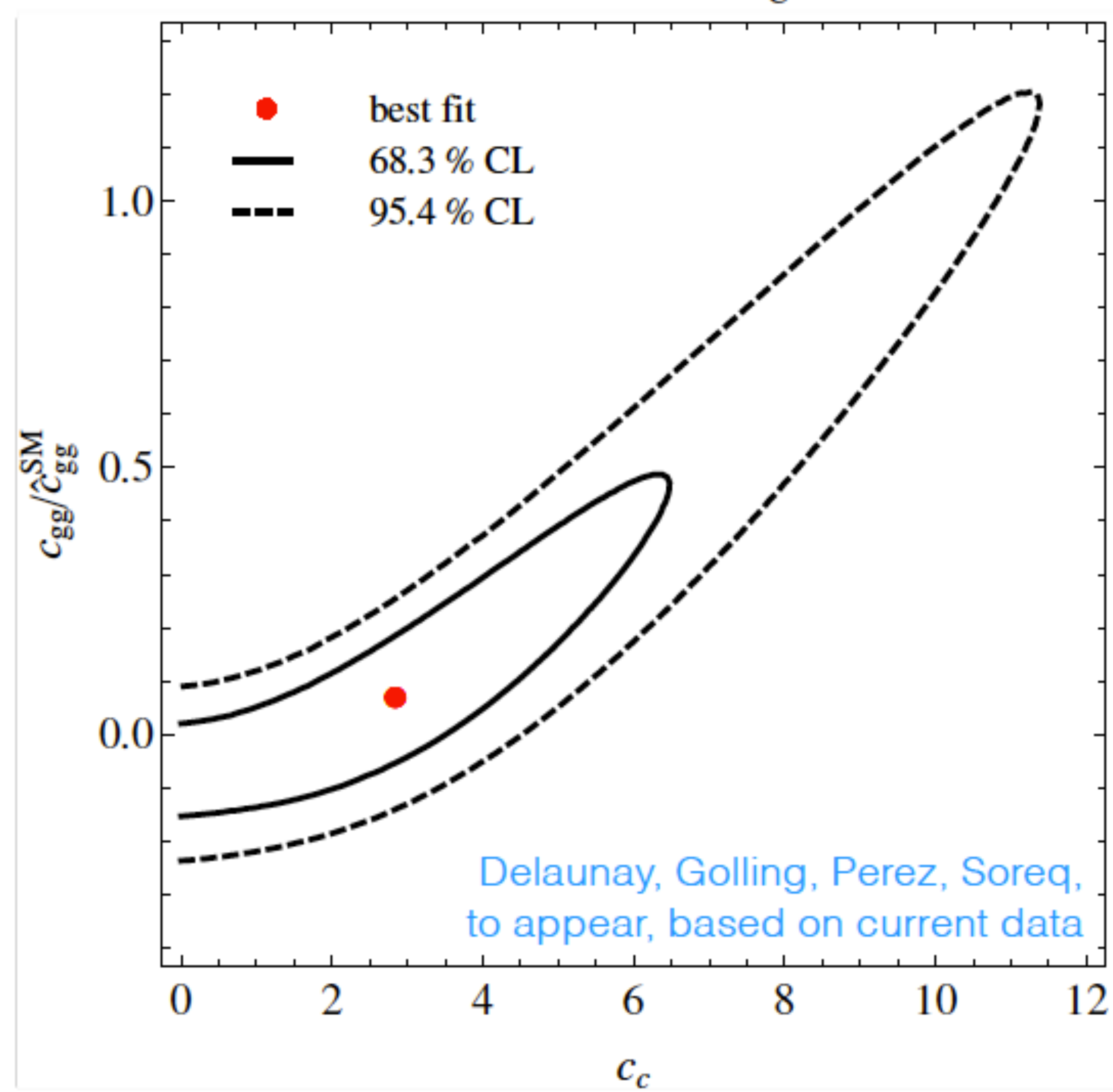


Measuring it?

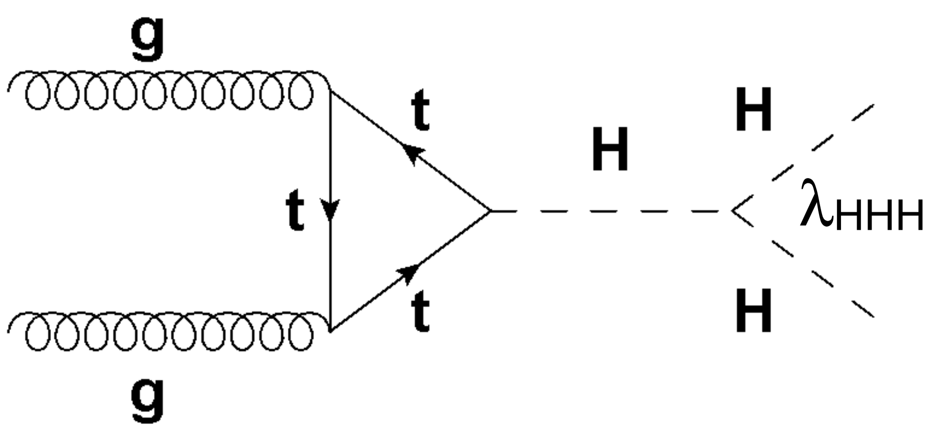
Like H→bb, but with charm tagging?

Or via H→ J/ψ γ ? 1306.5770

G. Salam, A. Weiler

Higgs boson pair-production

Higgs boson pair-production



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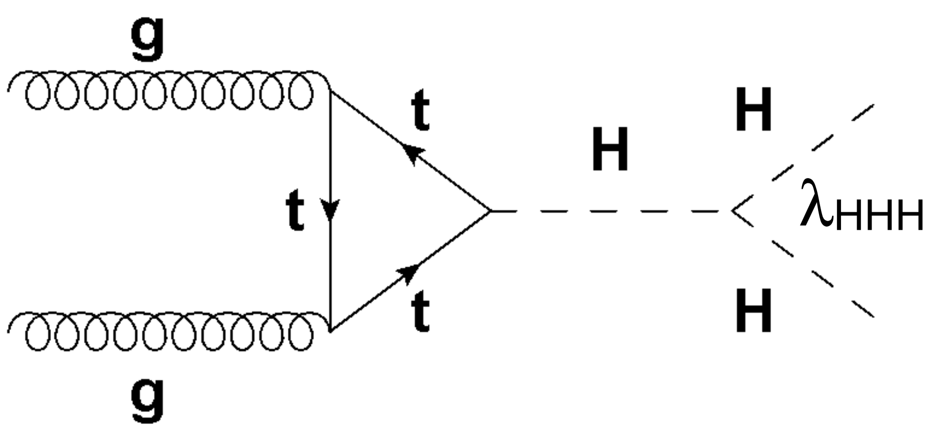
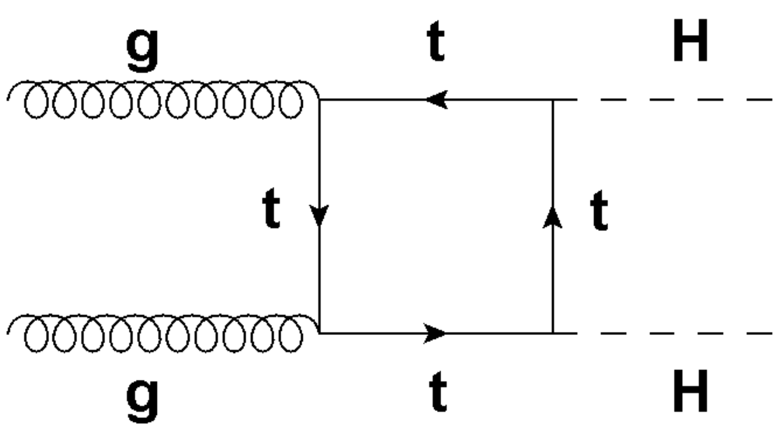
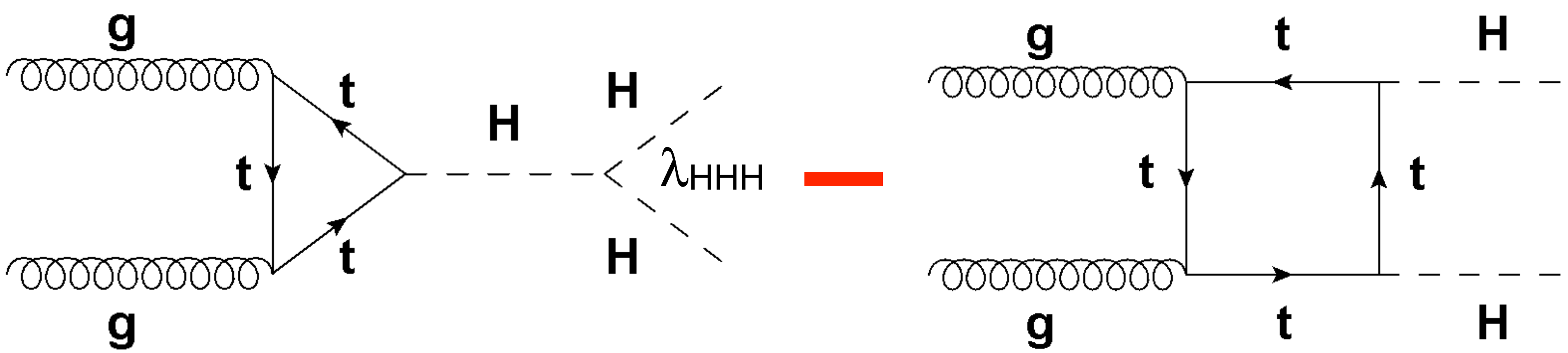




Higgs boson pair-production

Destructive interference between the two diagrams



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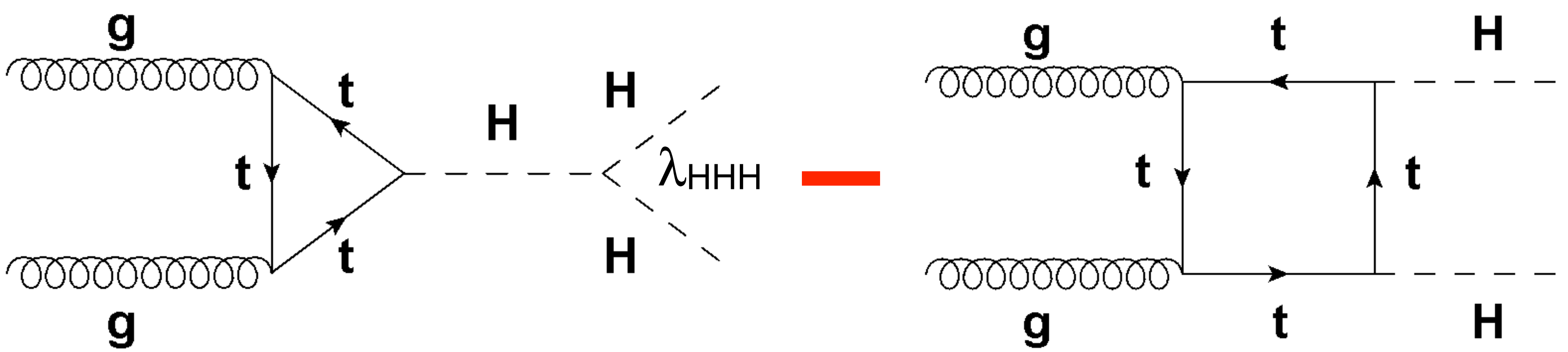
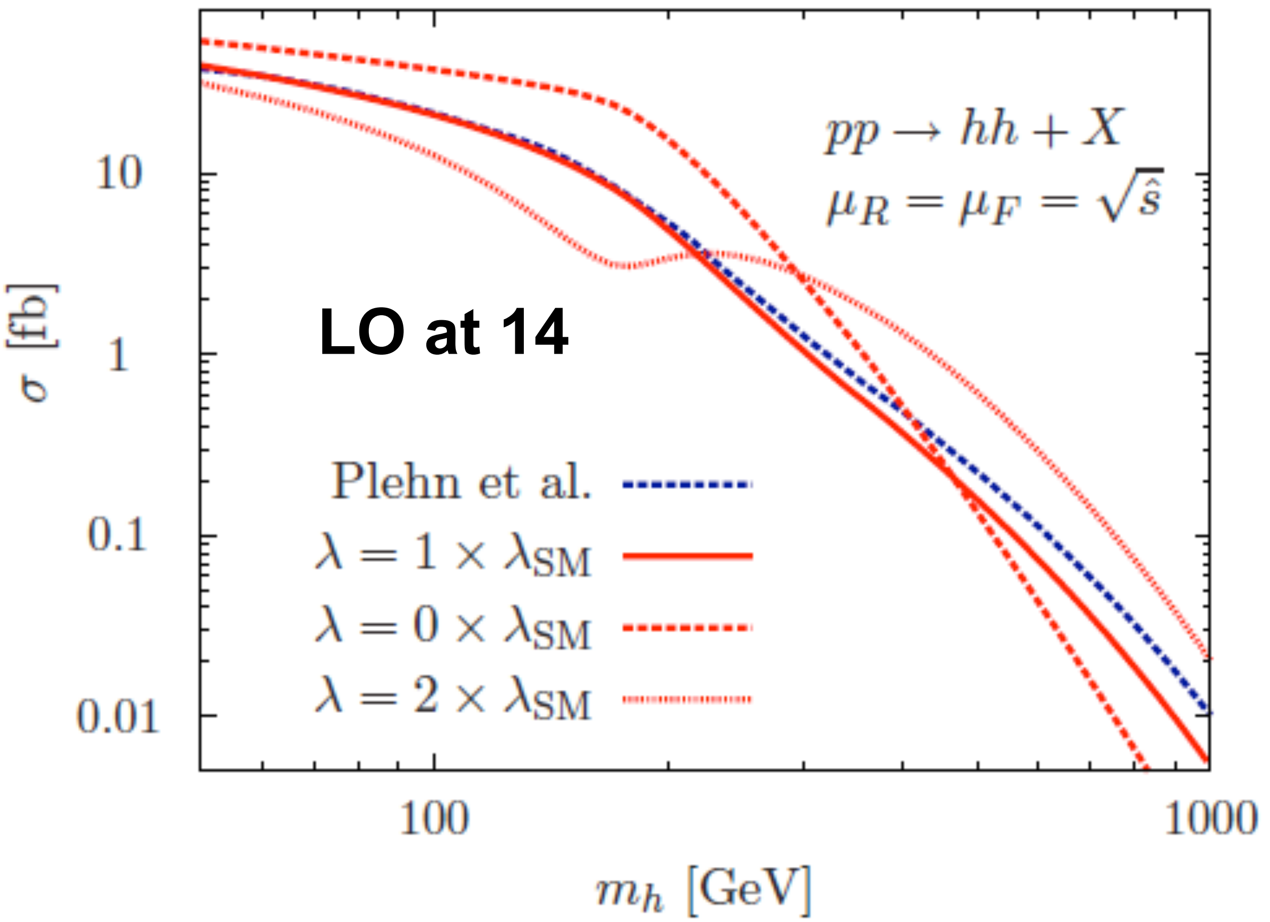


Taken from **"Higgs self-coupling measurements at the LHC"** by M. J. Dolan, C. Englert and M. Spannowsky, JHEP 10 (2012 112.



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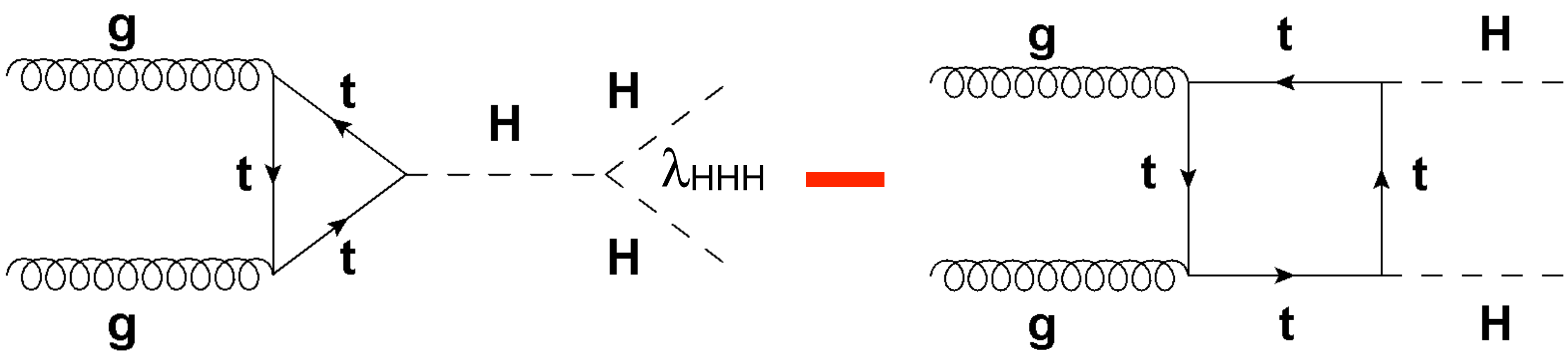

Many channels to investigate. Most promising ones:

$b\bar{b}W^+W^-$ (large BR but large bkg.)

$b\bar{b}\gamma\gamma$ (clean but small BR)

$b\bar{b}\tau^+\tau^-$

$b\bar{b}\mu^+\mu^-$ also being considered

$b\bar{b}b\bar{b}$

$b\bar{b}2l2\nu$

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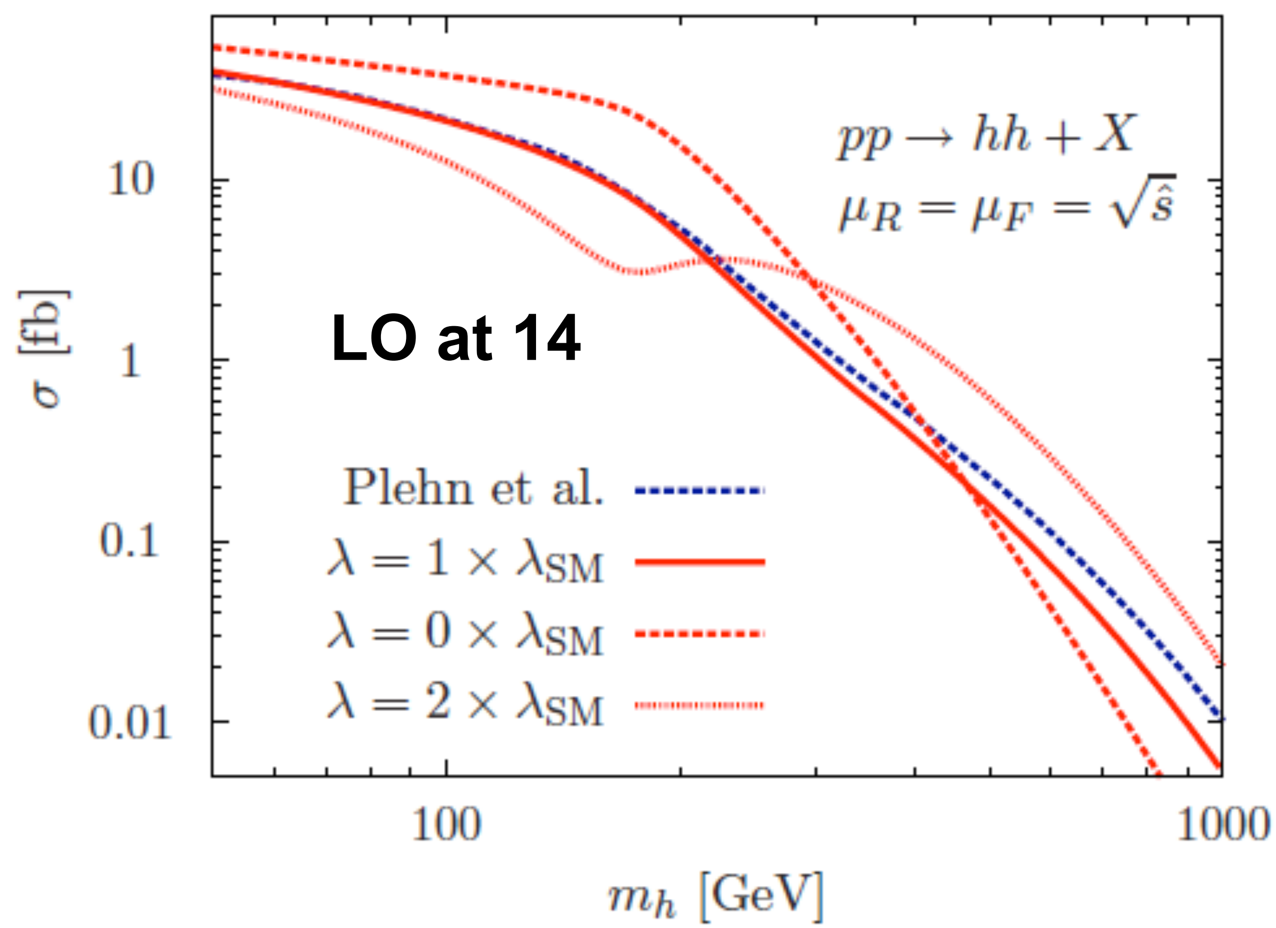

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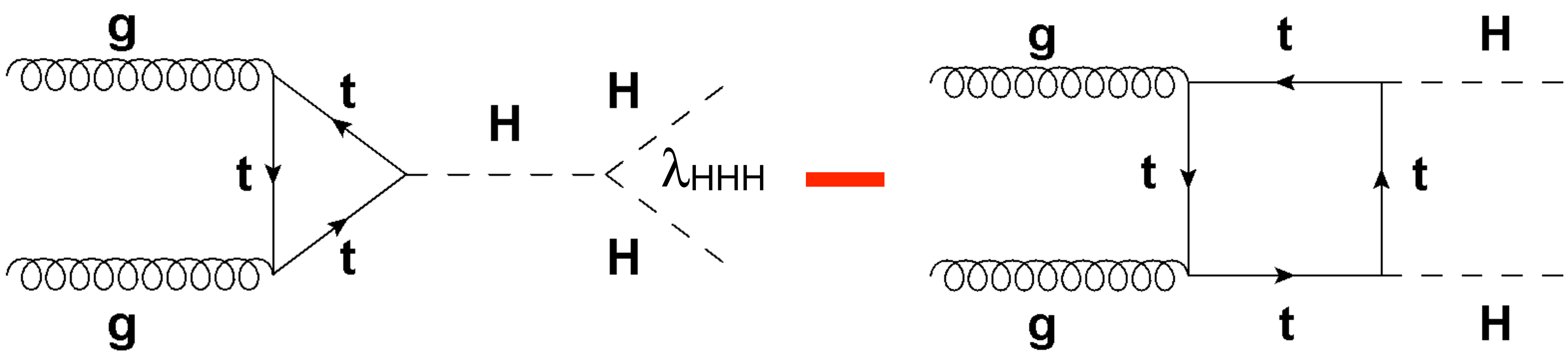

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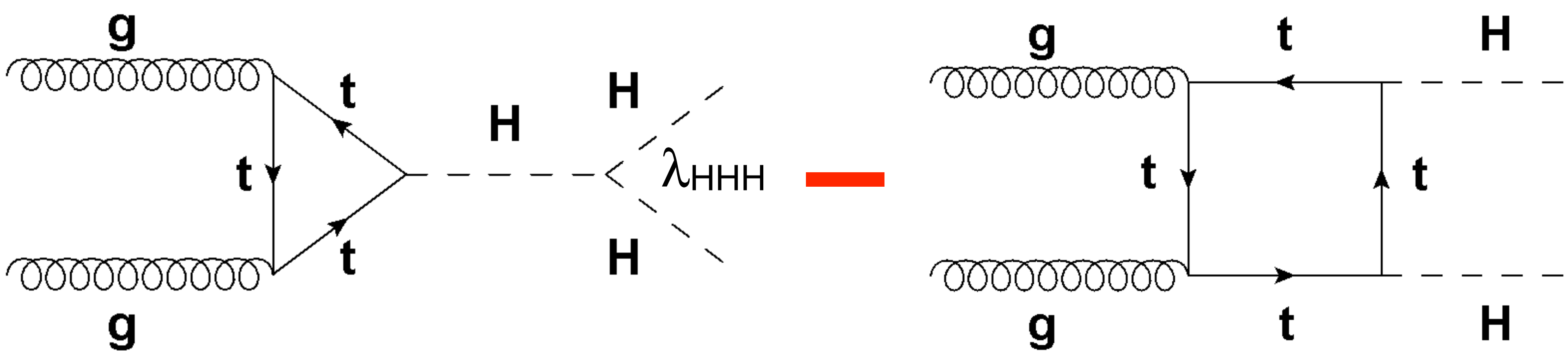

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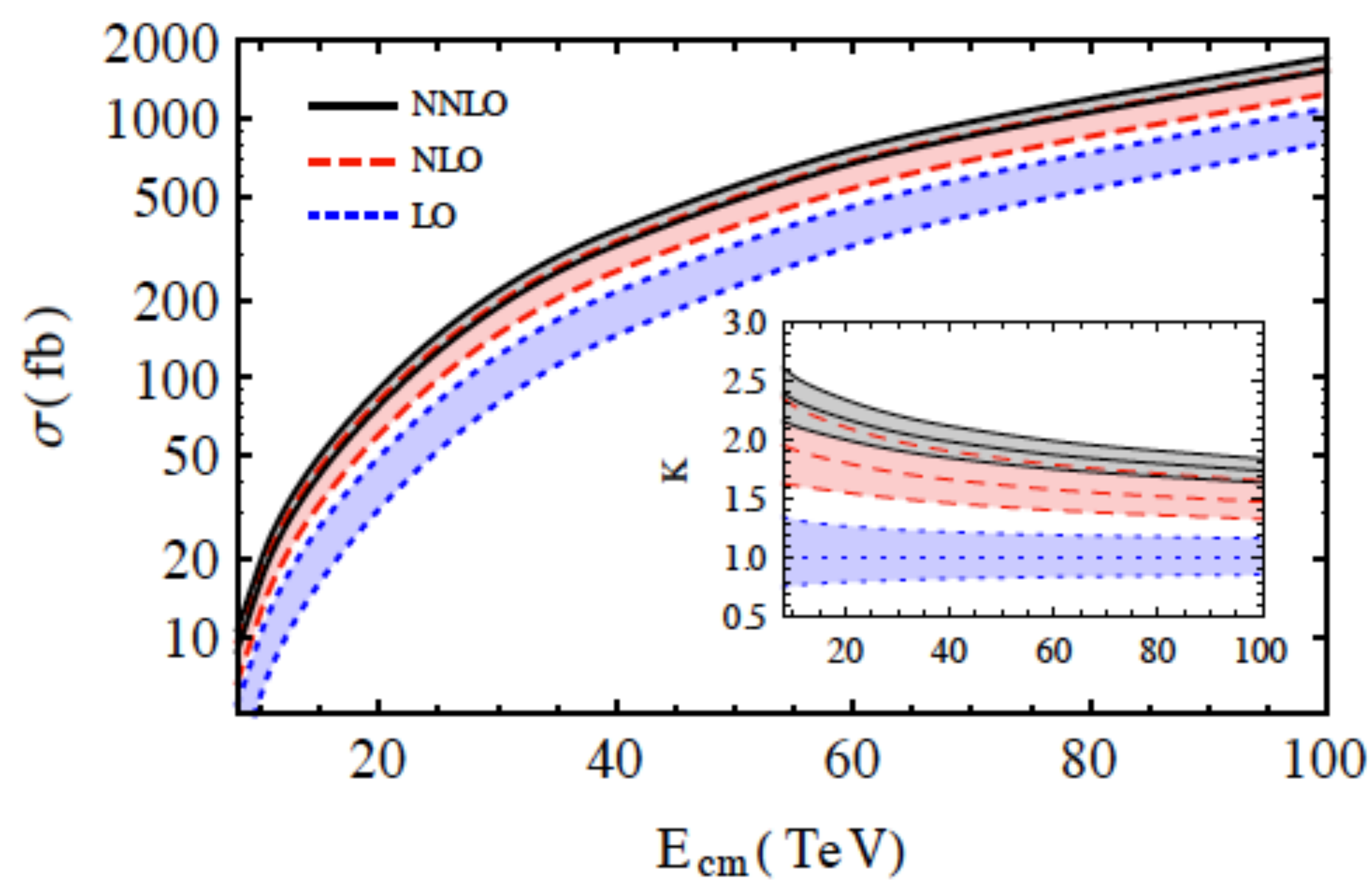

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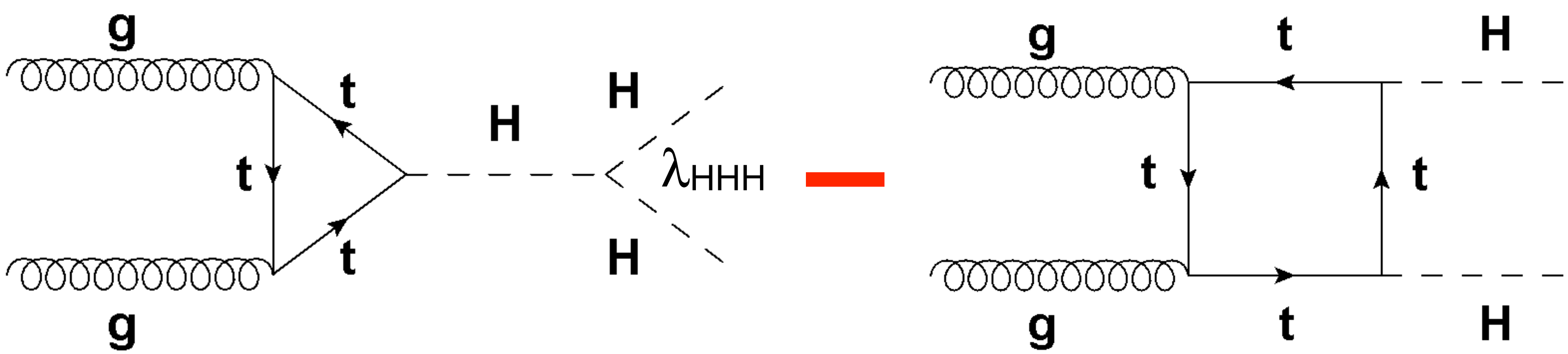

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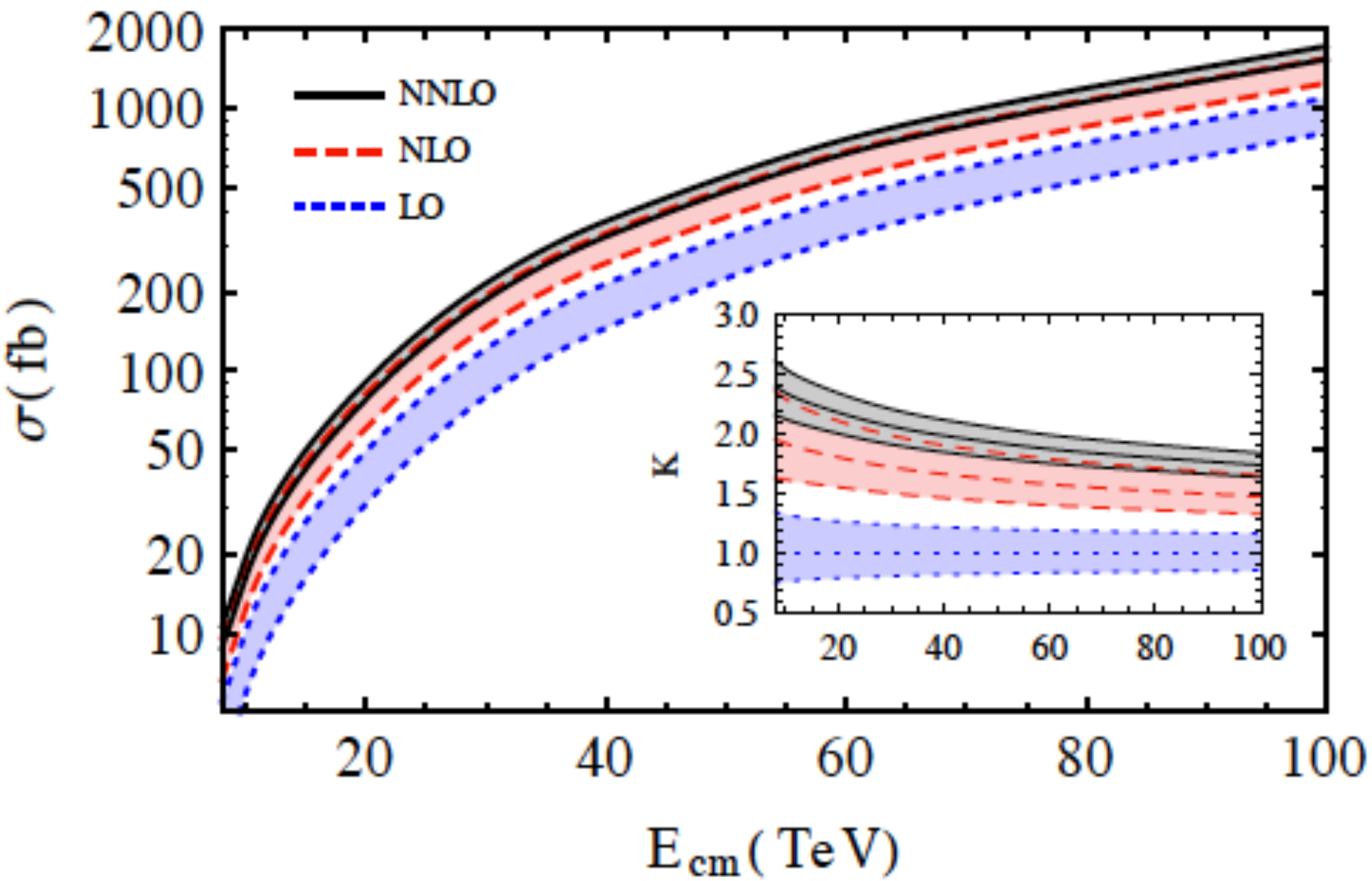

NNLO cross-section at m_H=125 GeV:

σ = 40 ± 3 fb

G. de Florian, J. Mazzitelli, 1309.6594

di-Higgs production

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At HL-LHC with L=3000 fb^{-1} we will produce ~120000 HH events

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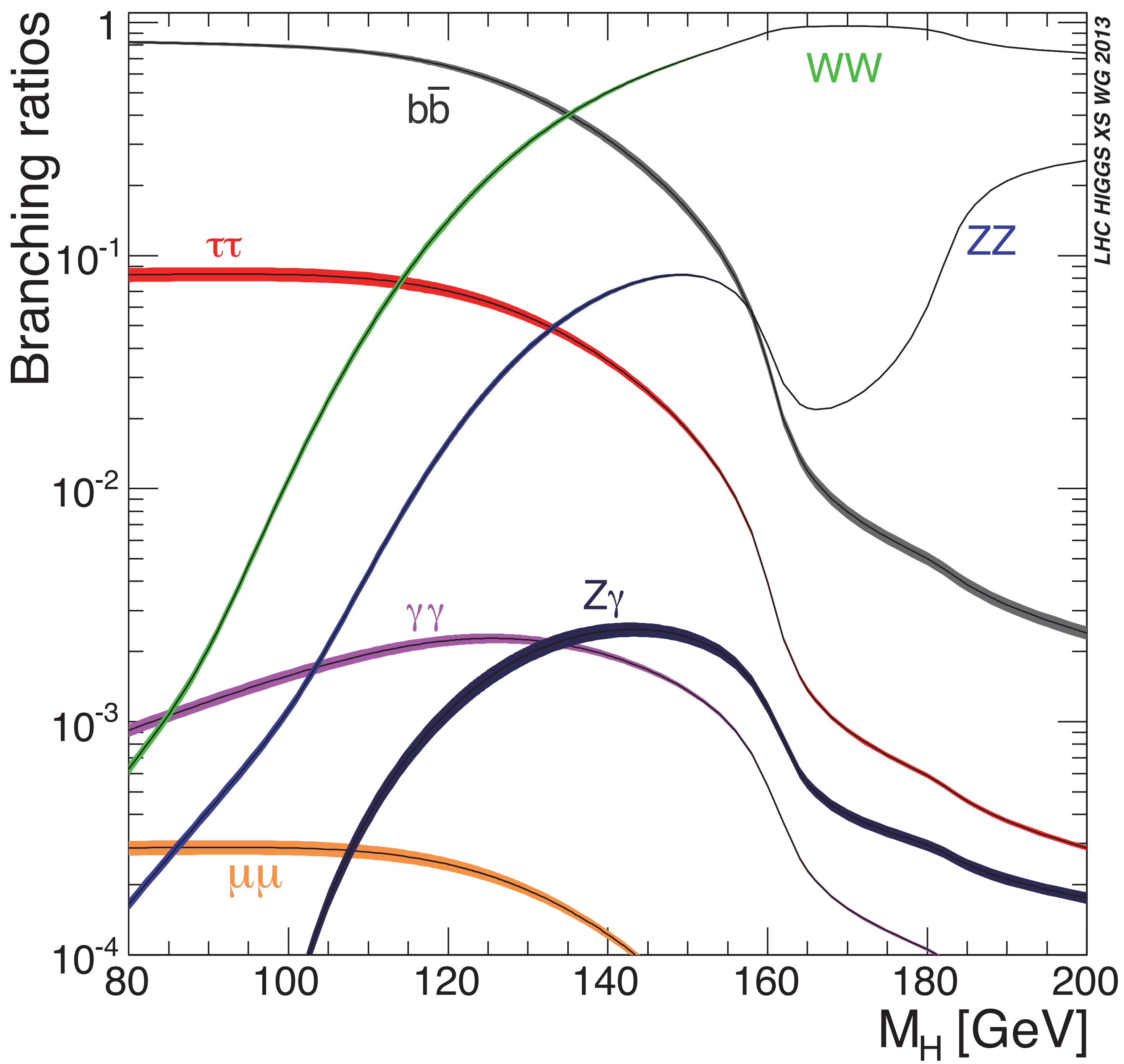
However we pay a big price in BR's …



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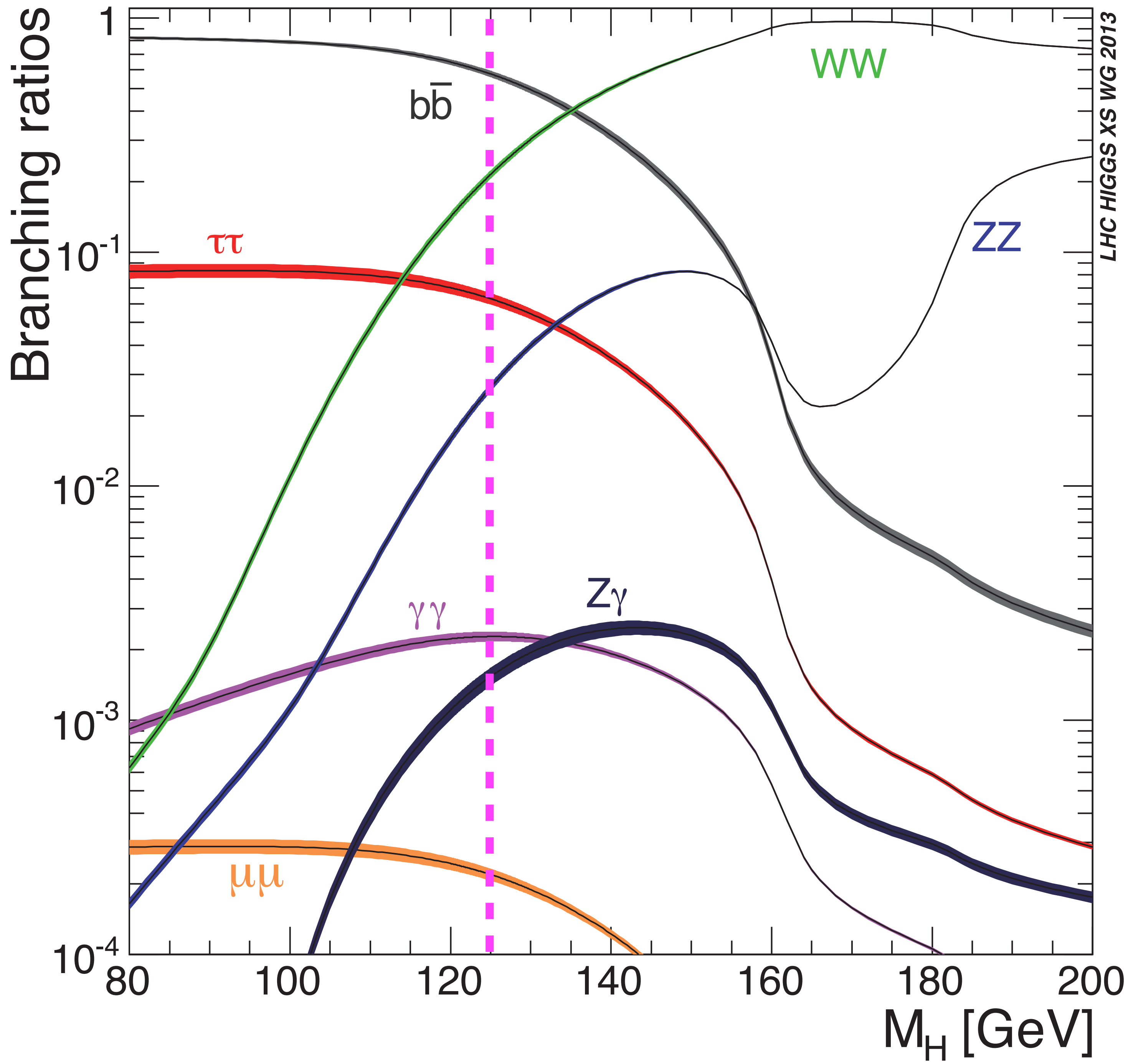

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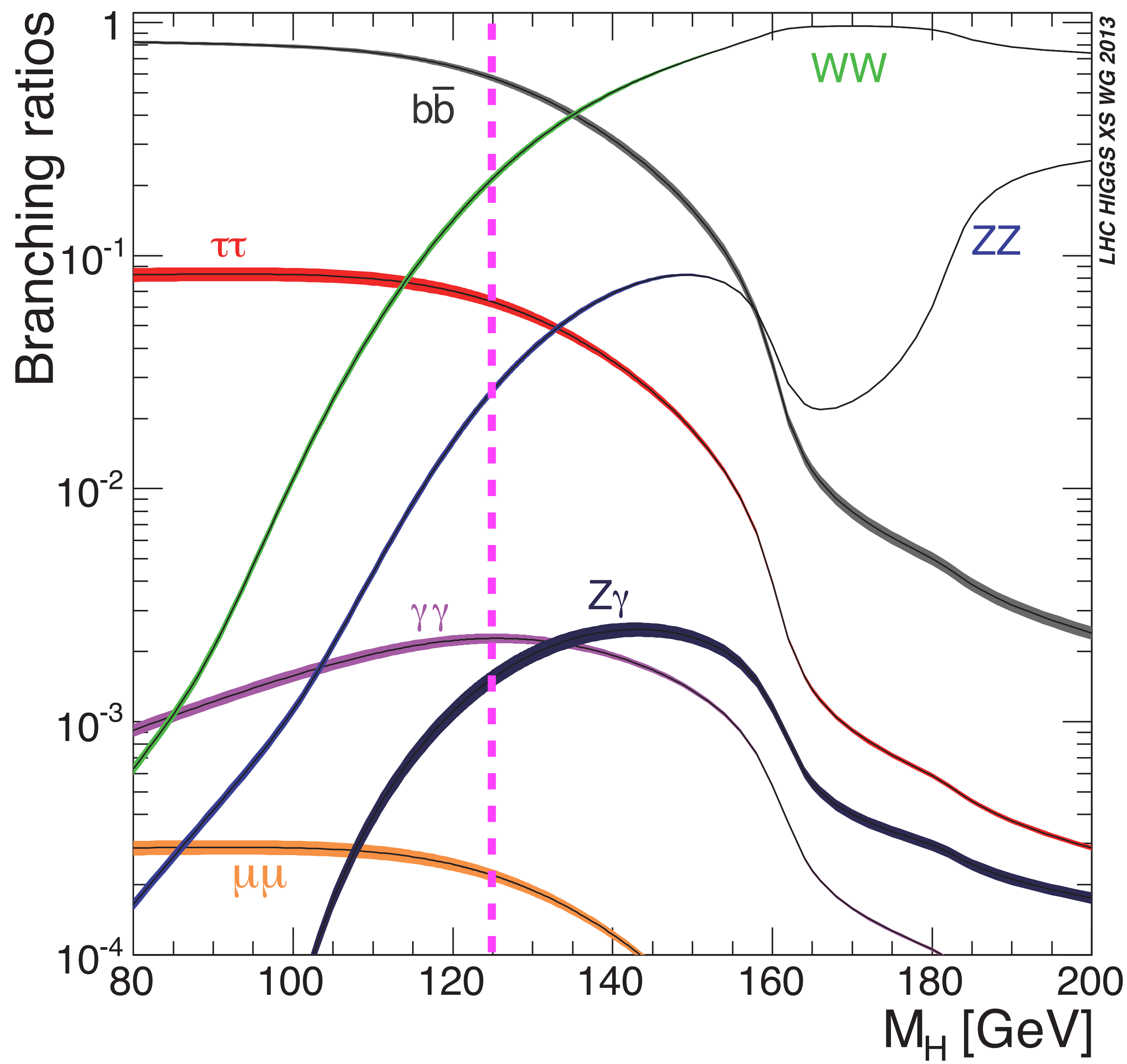

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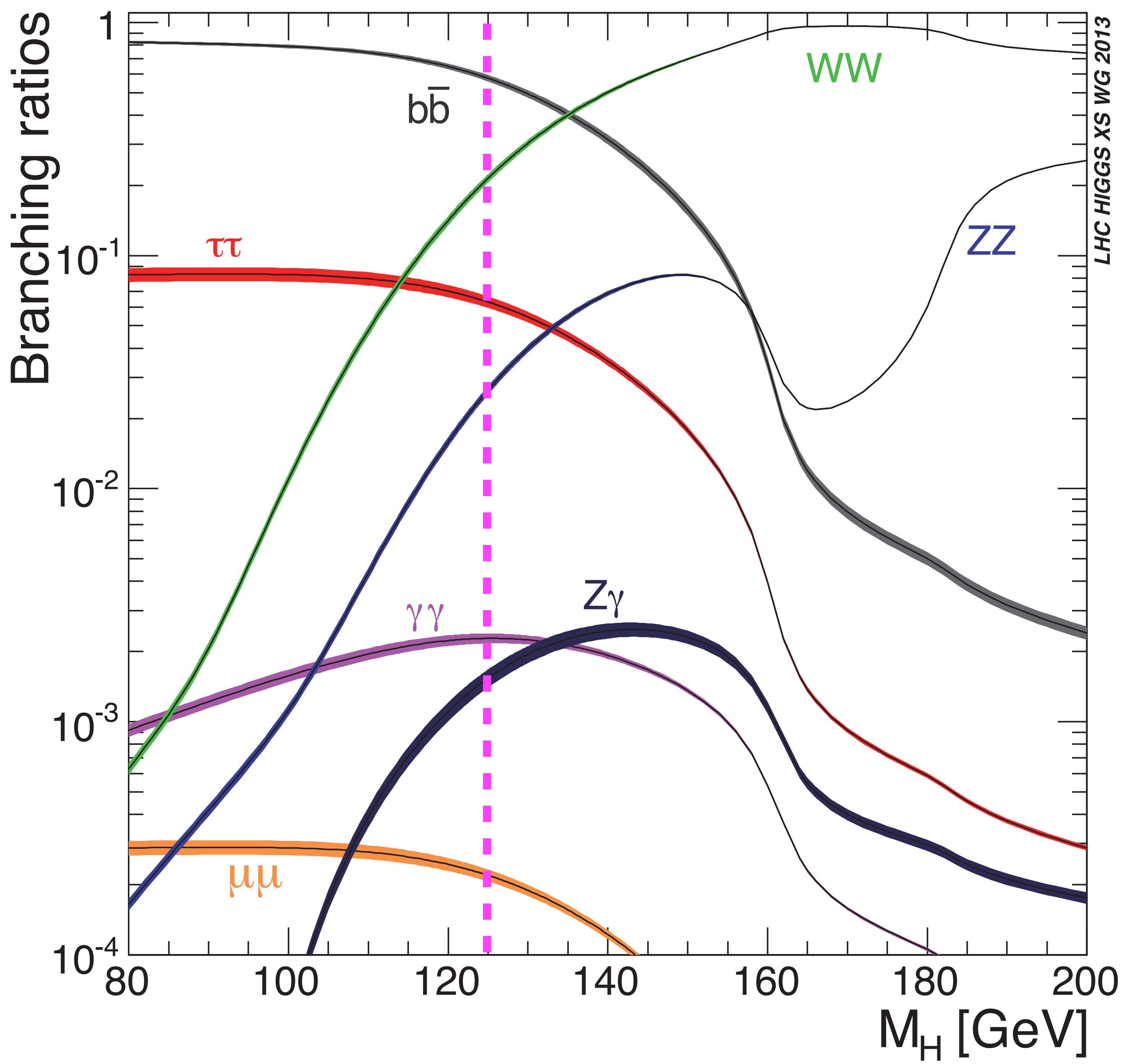

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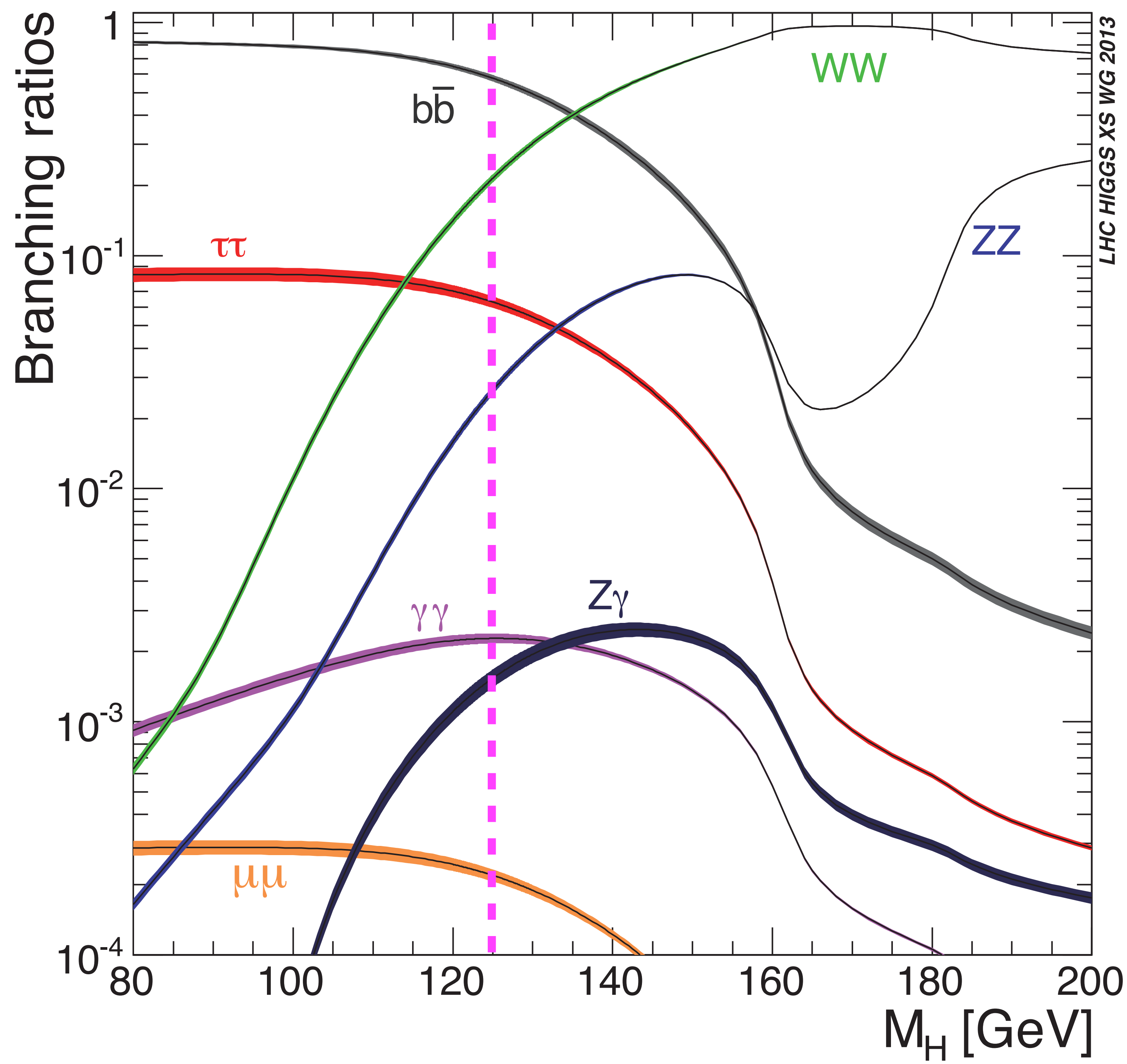

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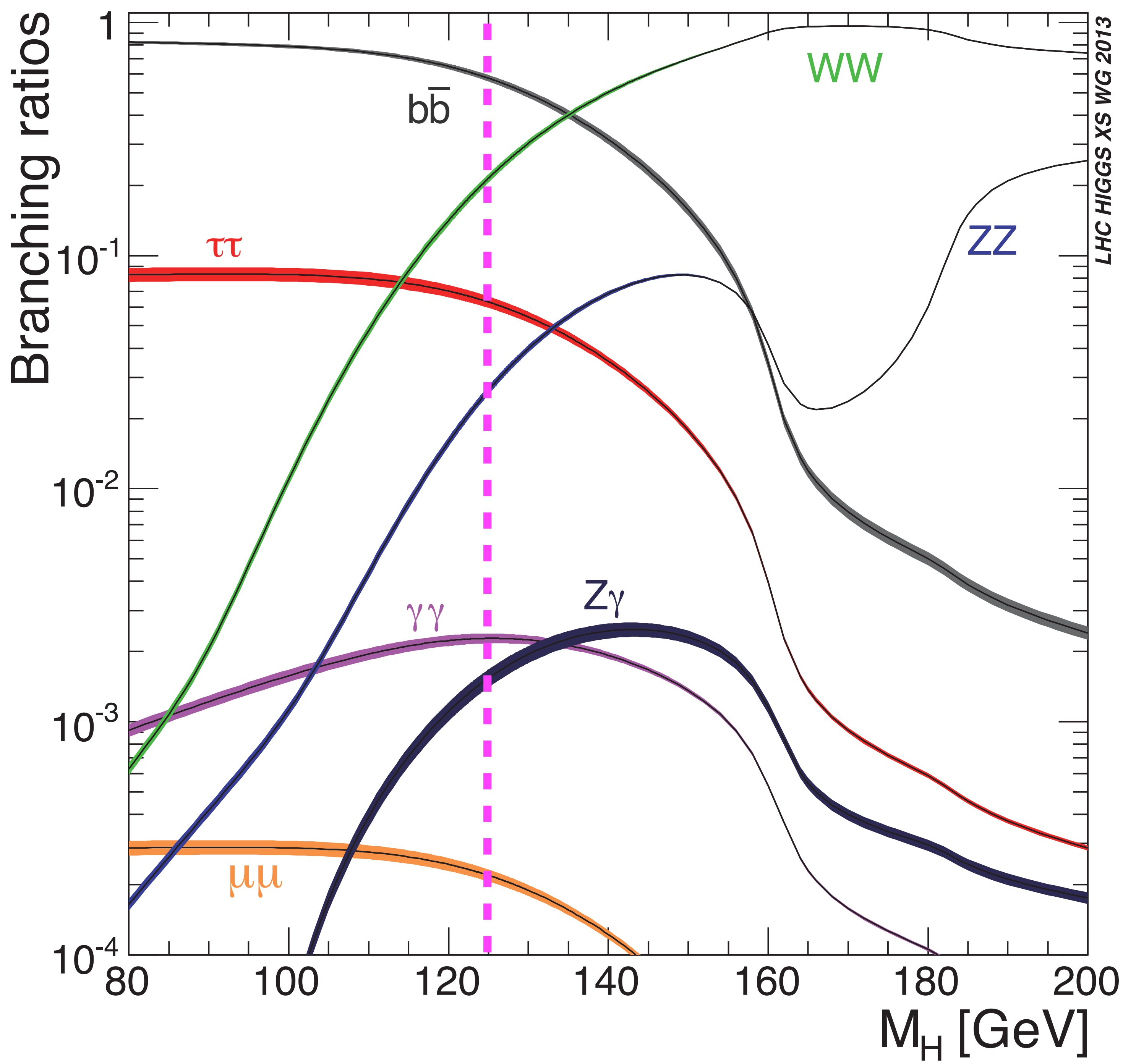
$b\bar{b}2l2\nu$ ~ 730 events



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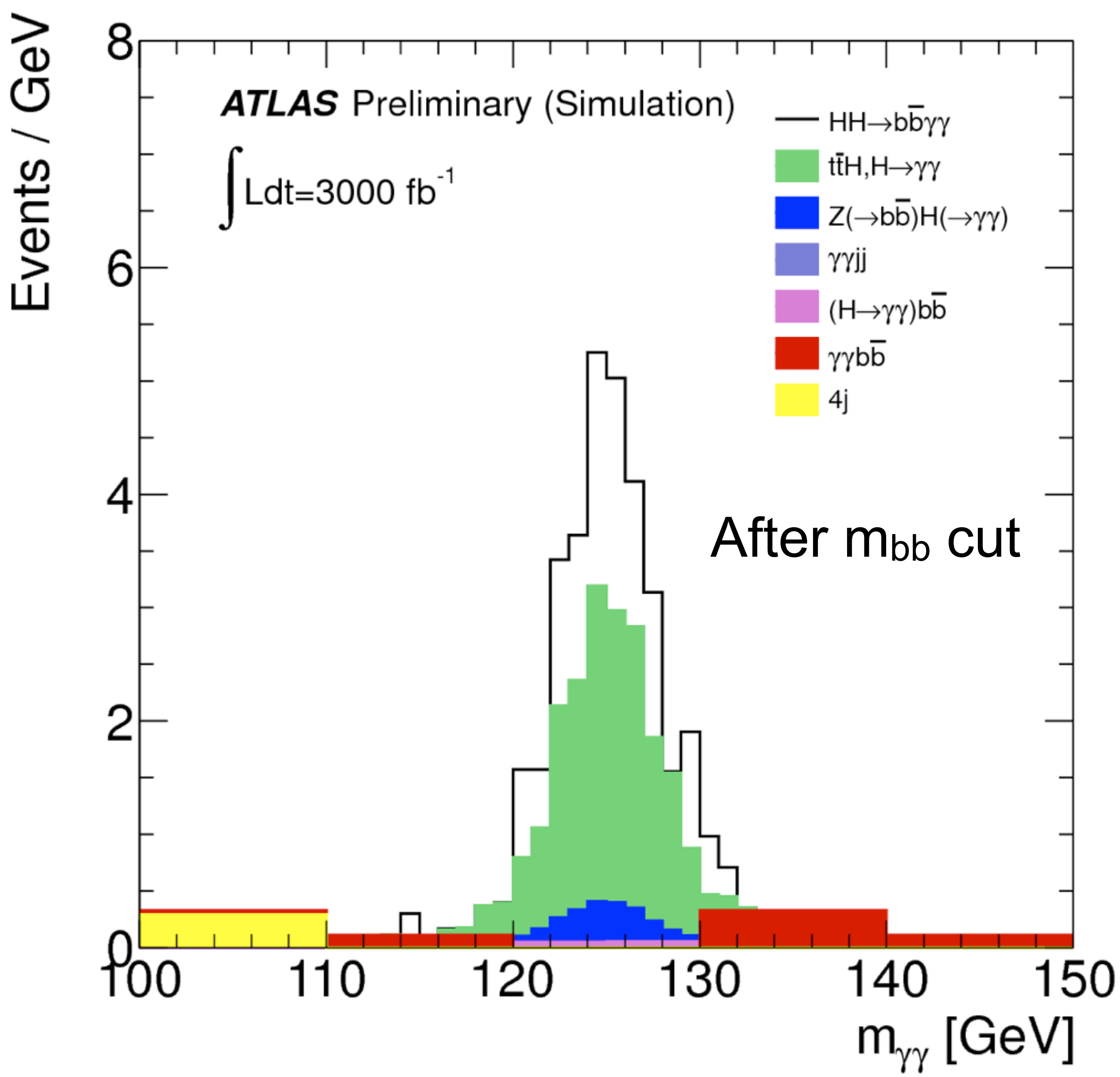
HH→$b\bar{b}\gamma\gamma$

di-Higgs production

HH→bb̄γγ



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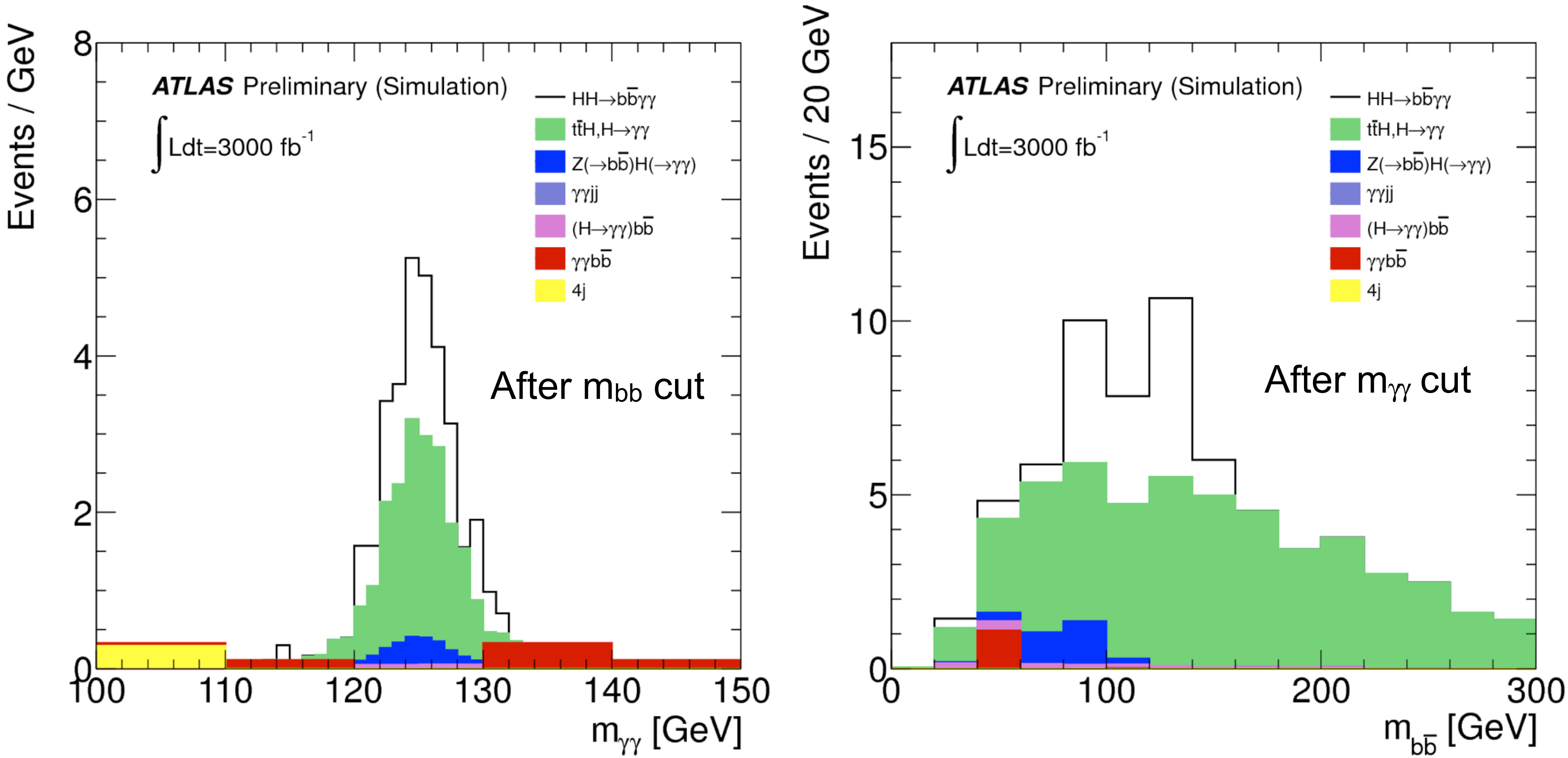
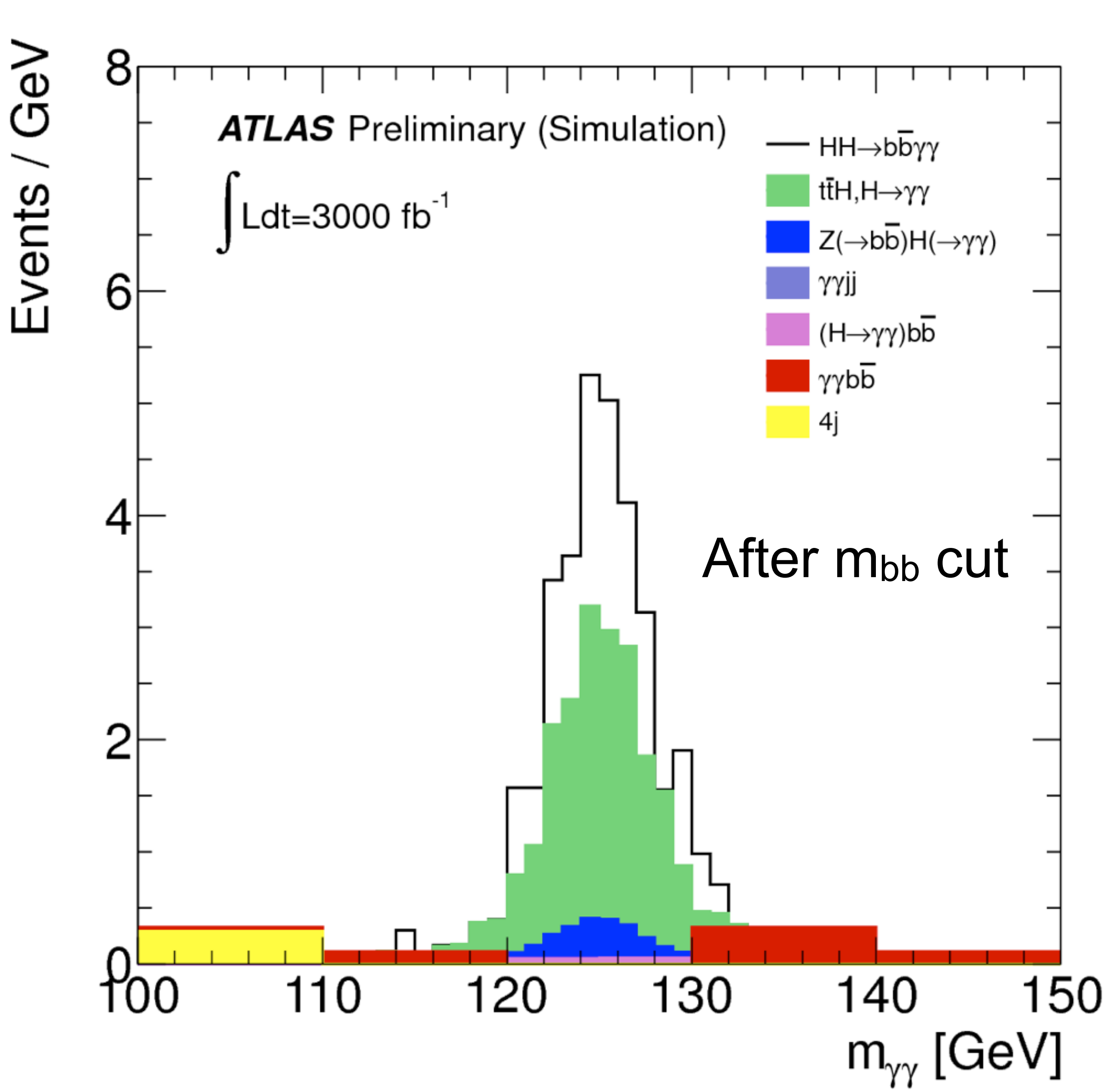
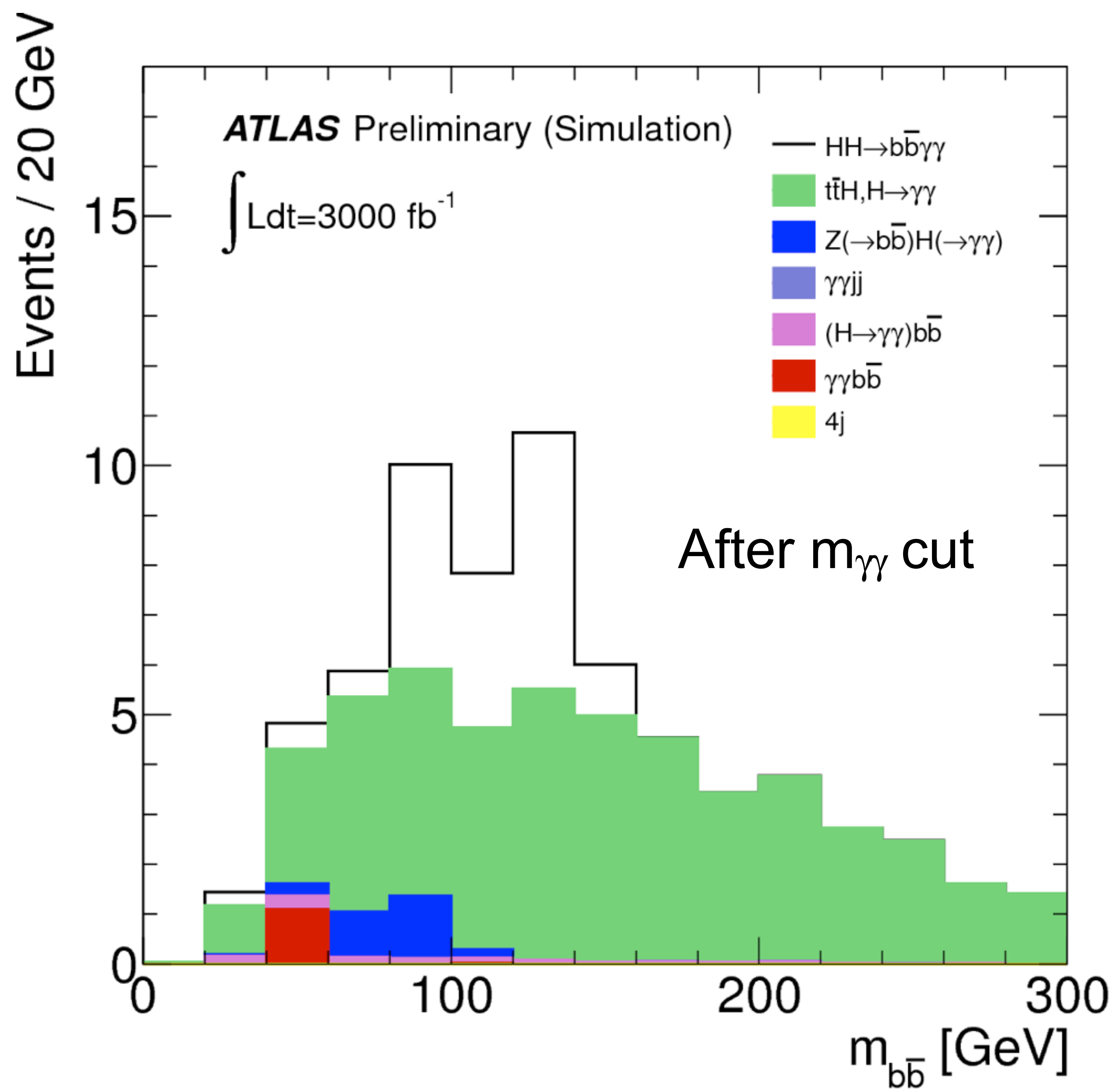


di-Higgs production

HH→b$\bar{b}$γγ





Preliminary results with L=3000 fb^{-1}

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Personal opinion

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<u>Personal opinion</u>

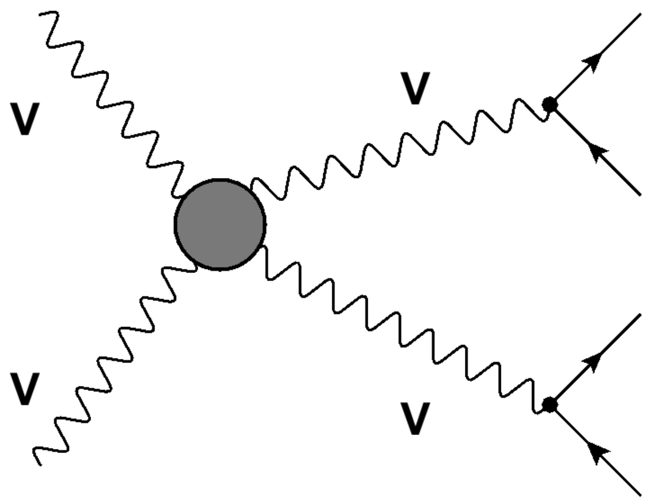
There is good hope to reach a sensitivity of ~3σ per experiment with L=3000 fb^{-1}

VV scattering: unitarity violation

Taken from **“Prospects for VV scattering: latest news”** by S. Bolognesi (JHU)
talk at Implications of LHC results for TeV-Scale physics (March 2012)

VV scattering: unitarity violation

VV→VV



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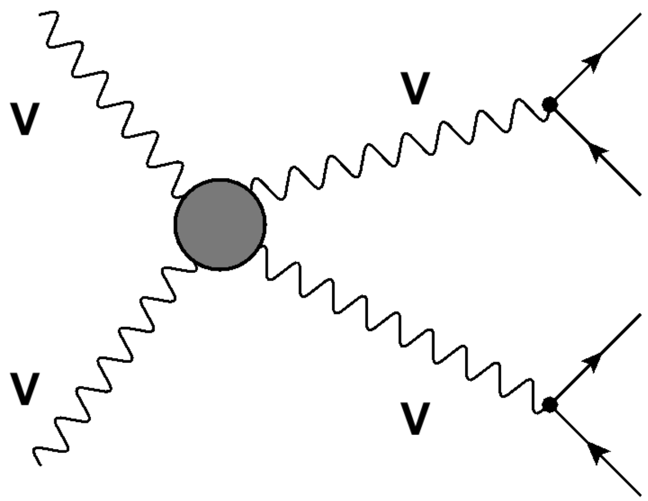

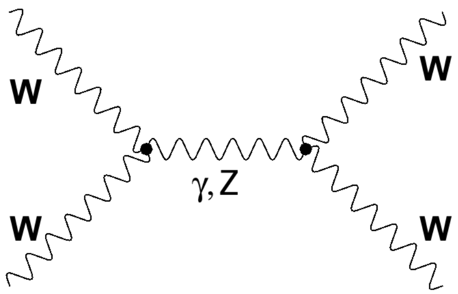

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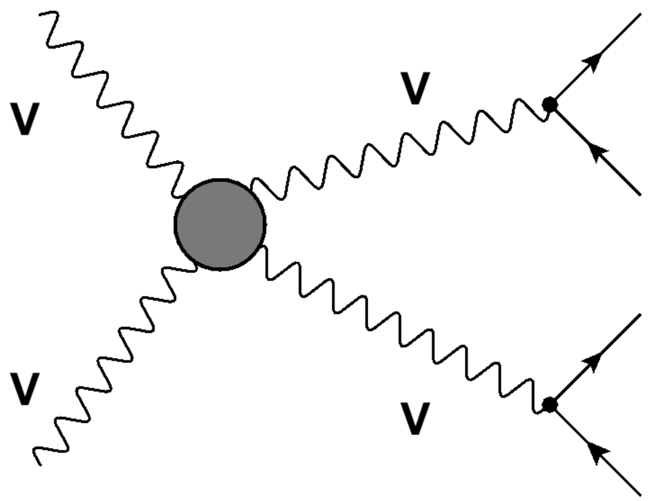

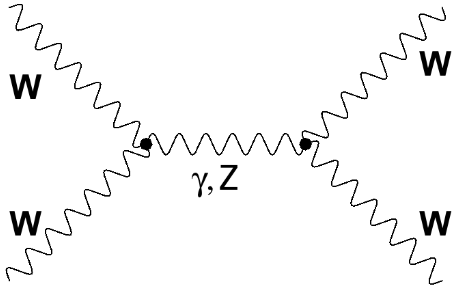

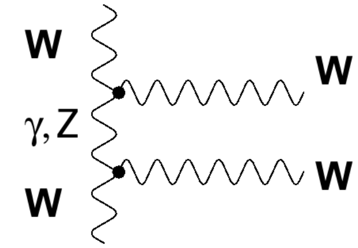

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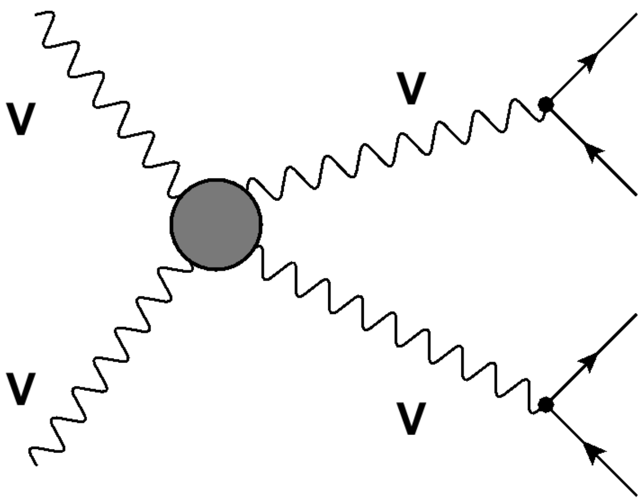

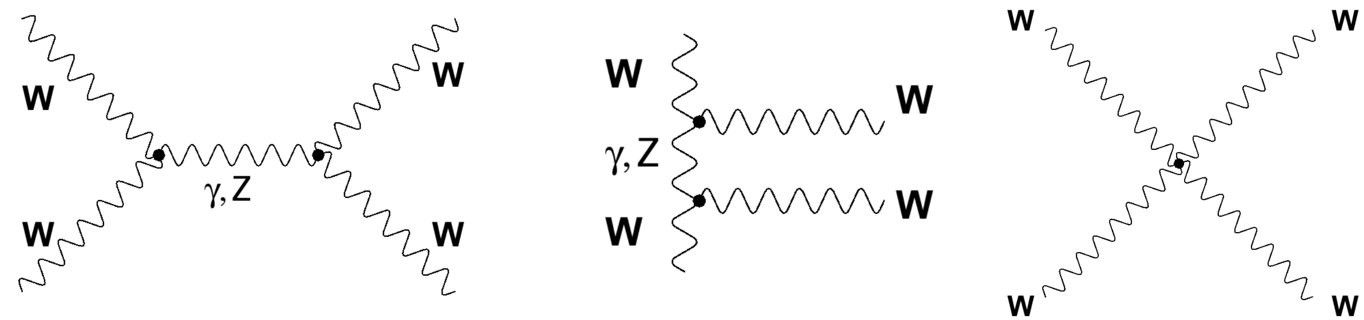

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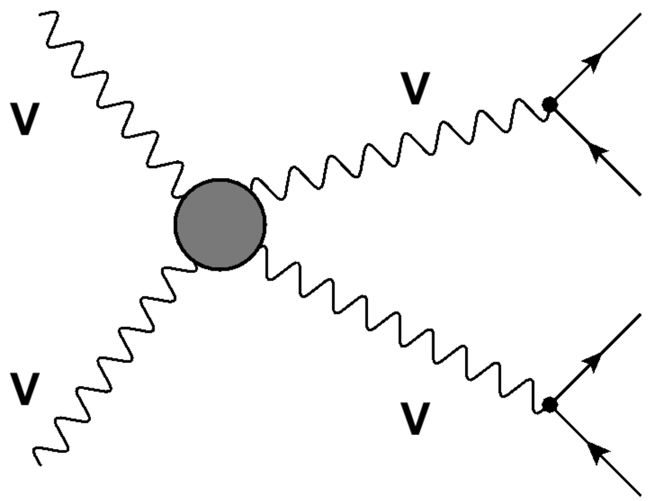

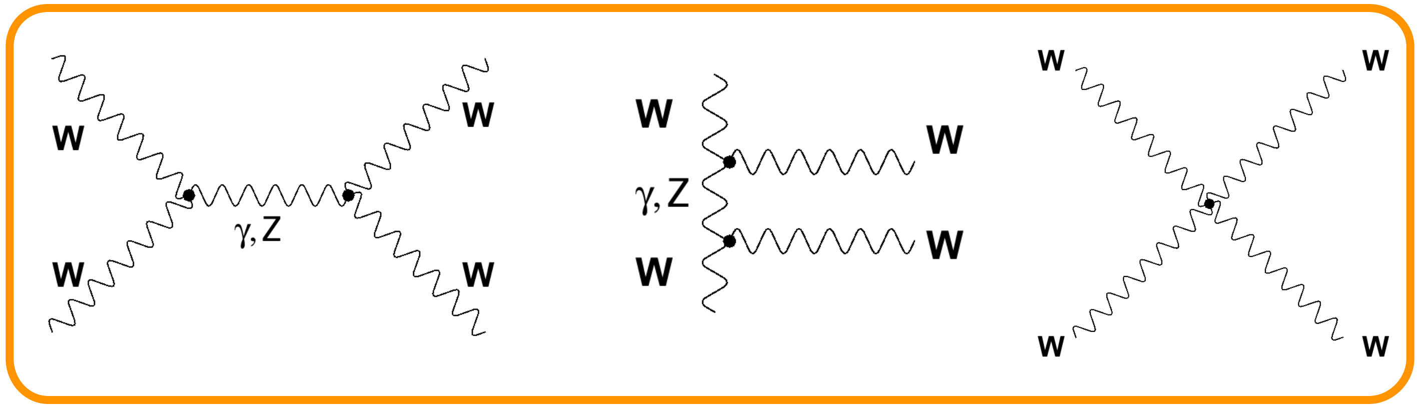

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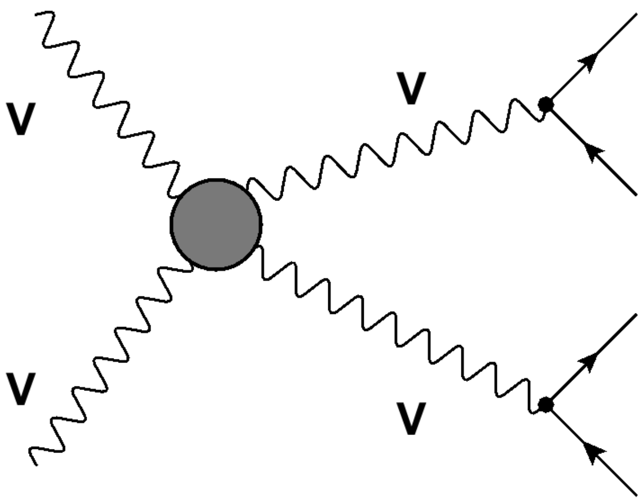

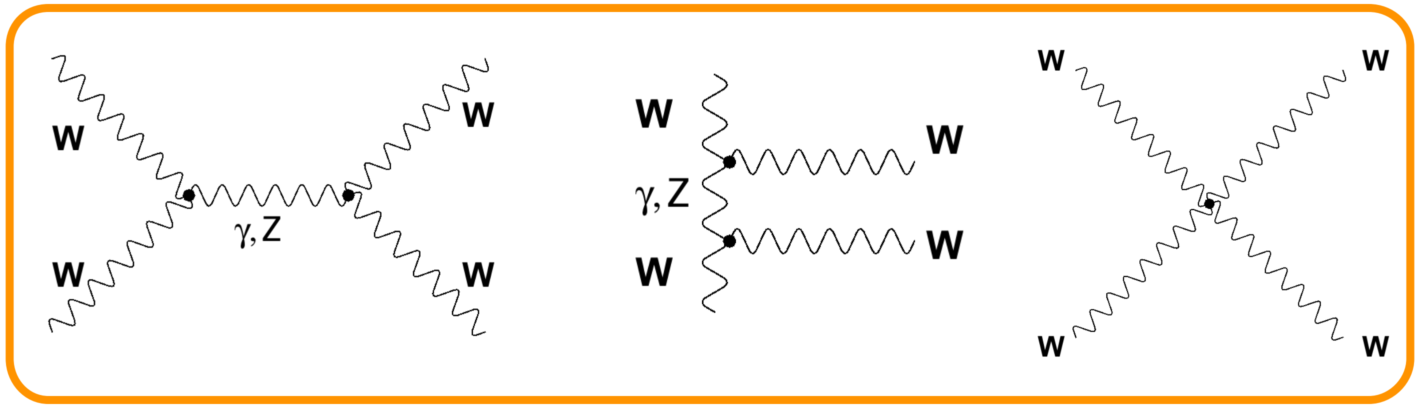

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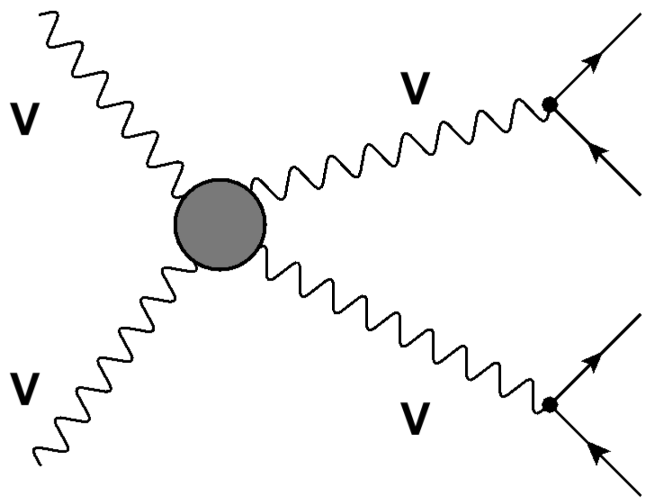

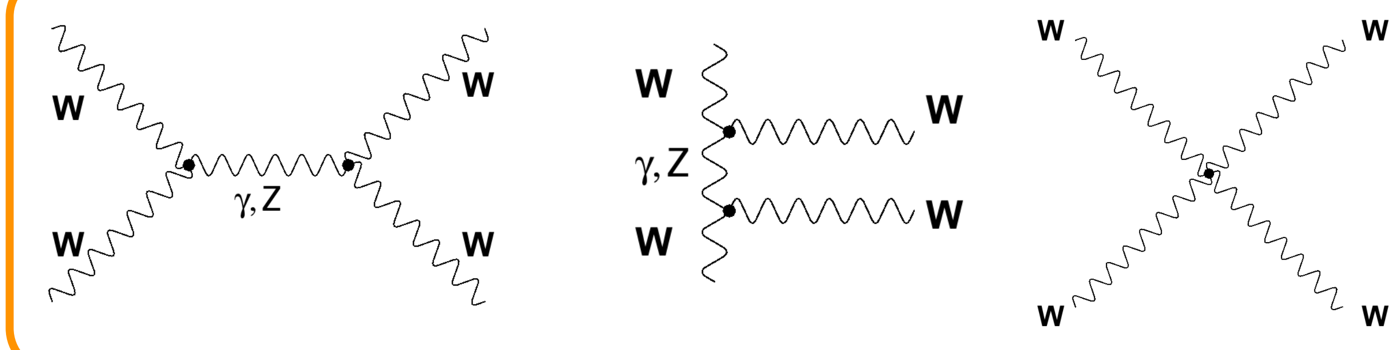

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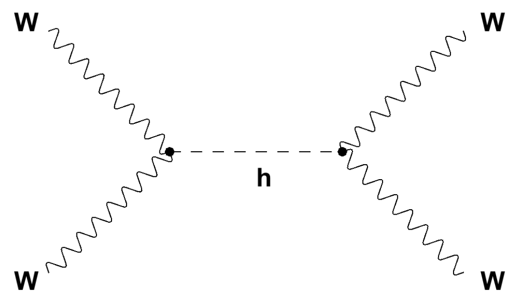

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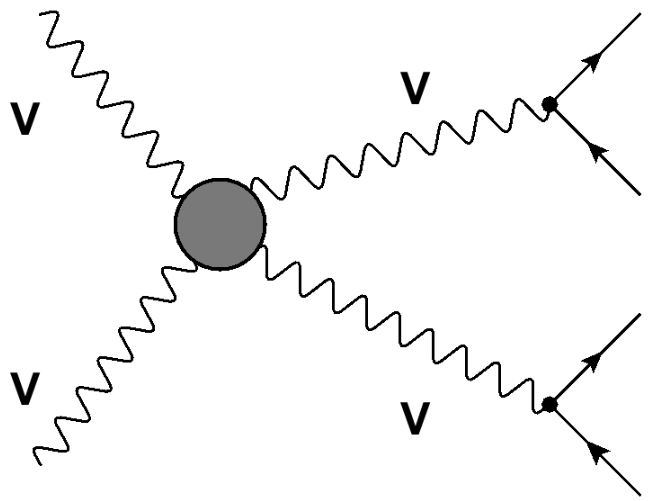

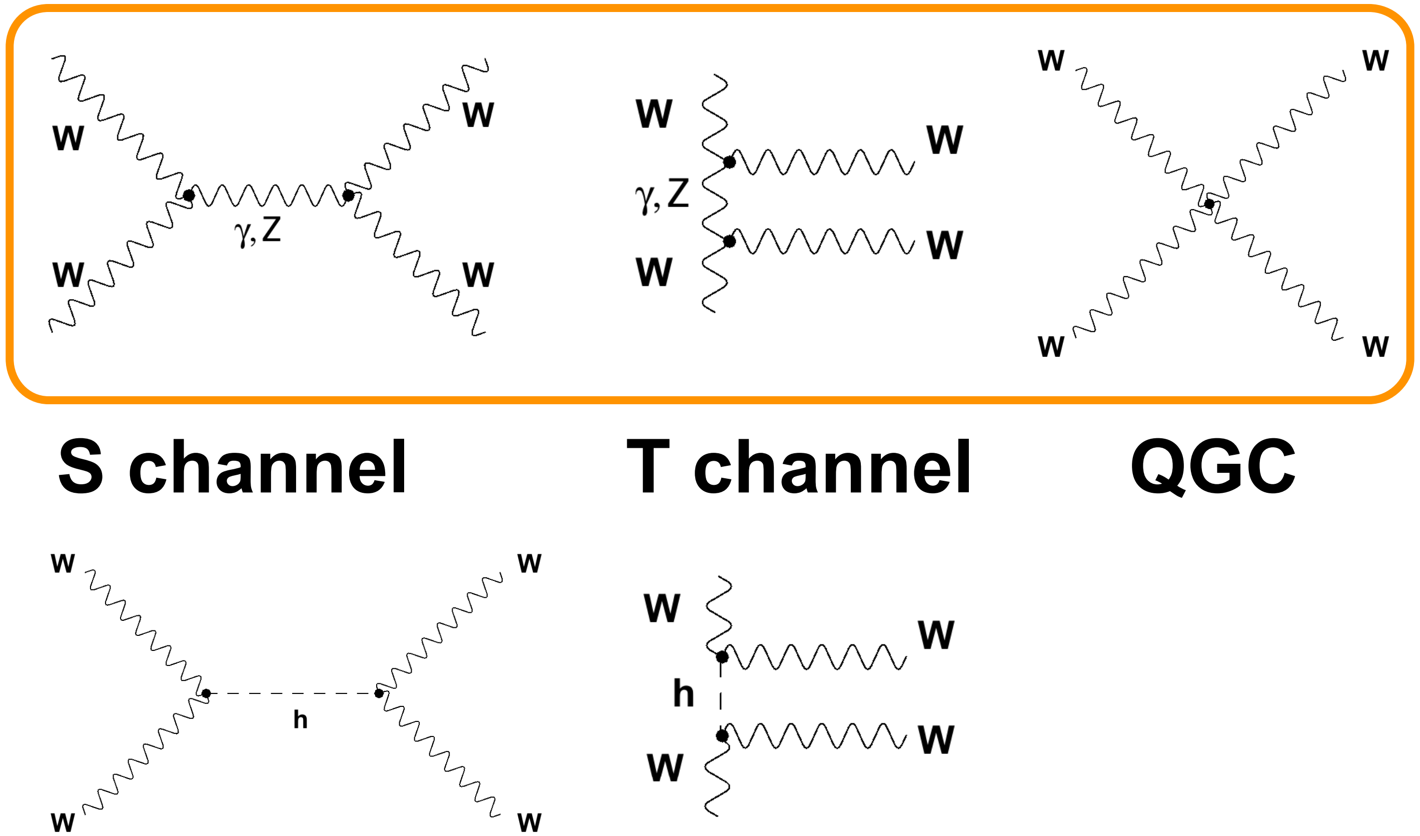

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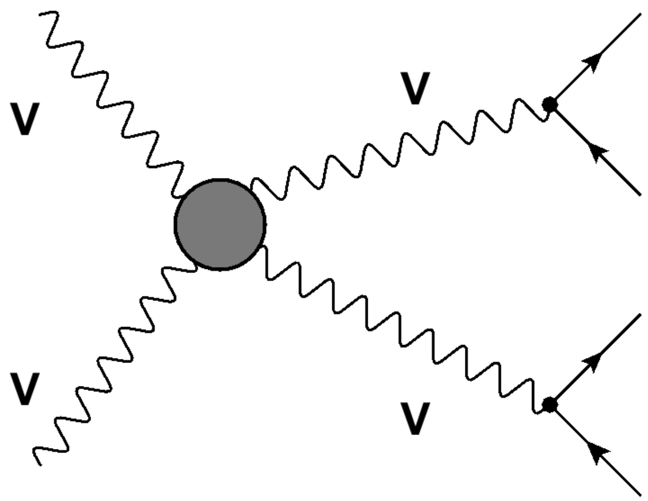

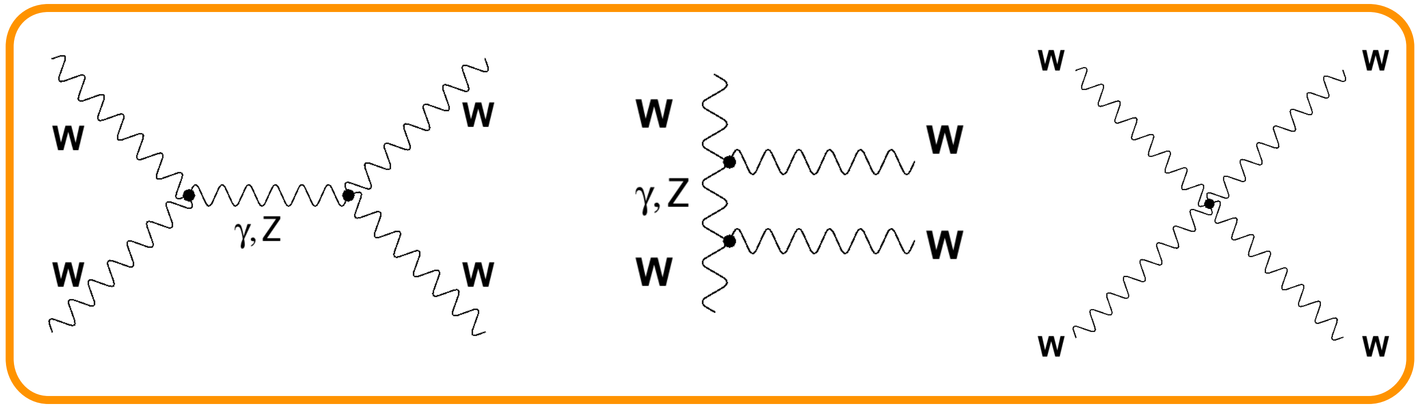

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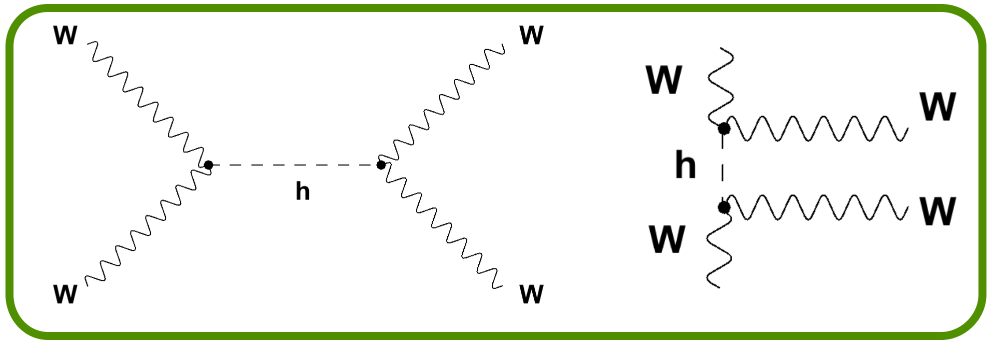

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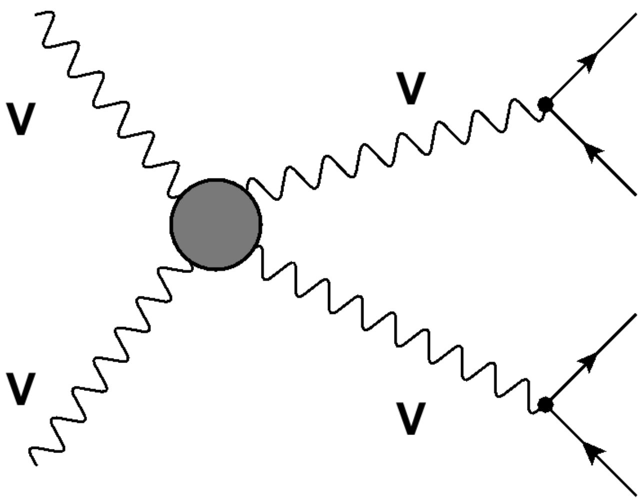

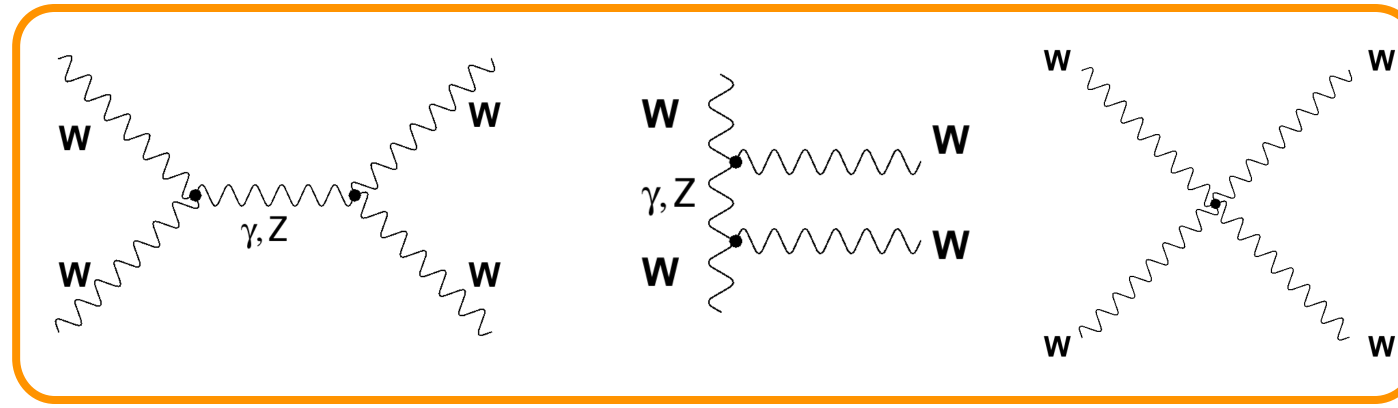

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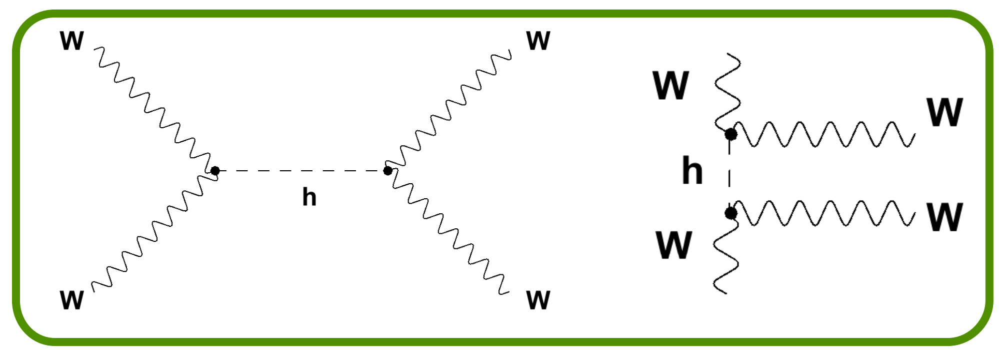

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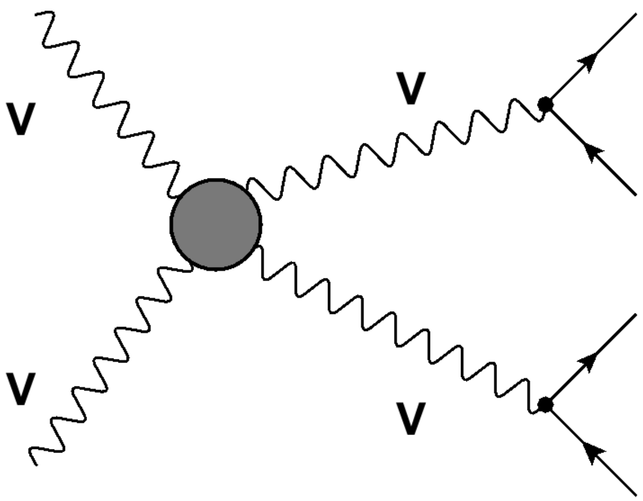

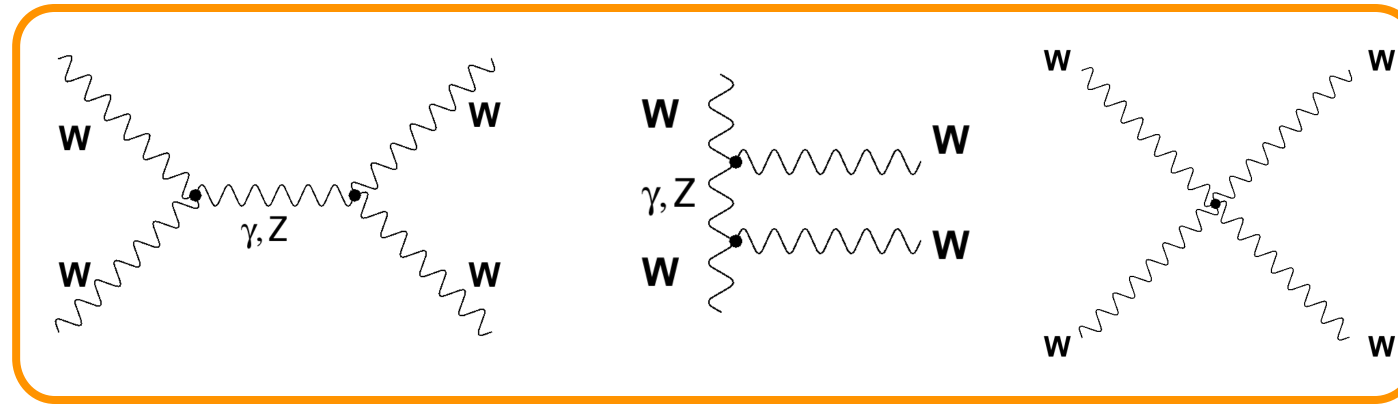

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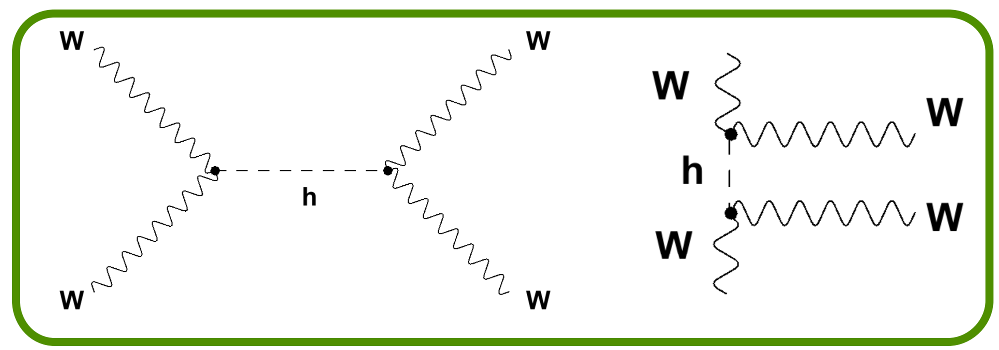

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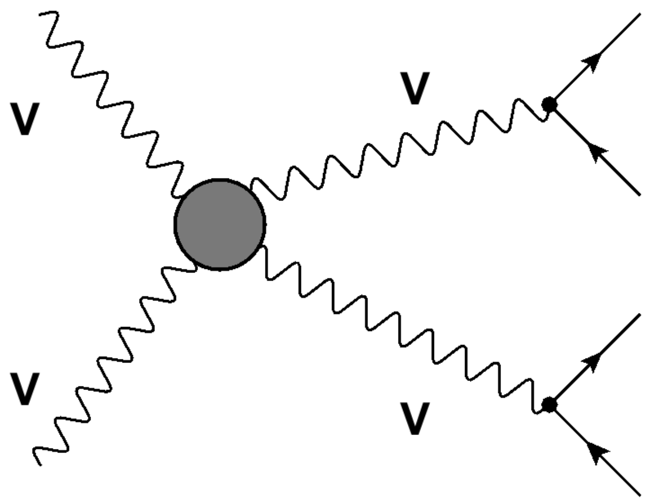

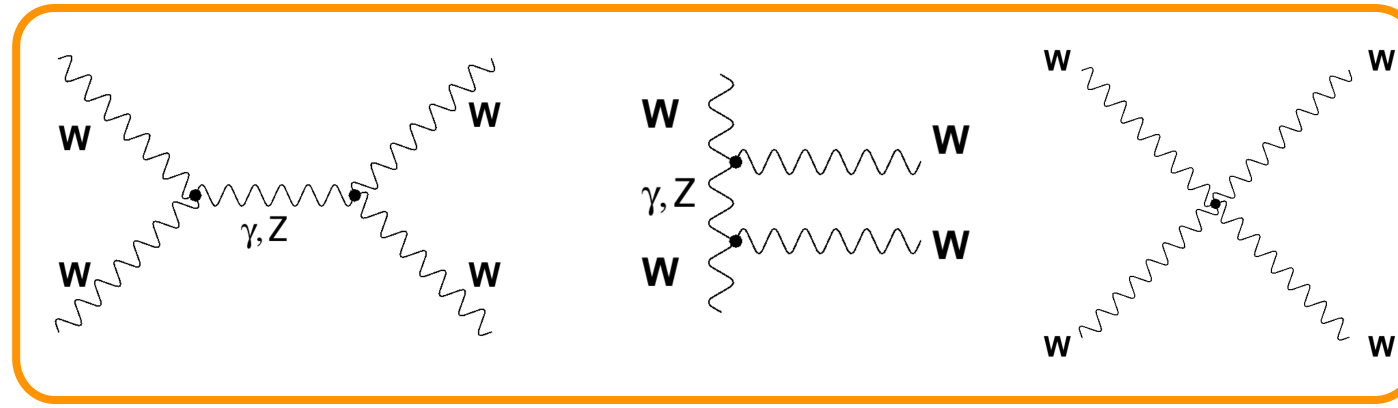

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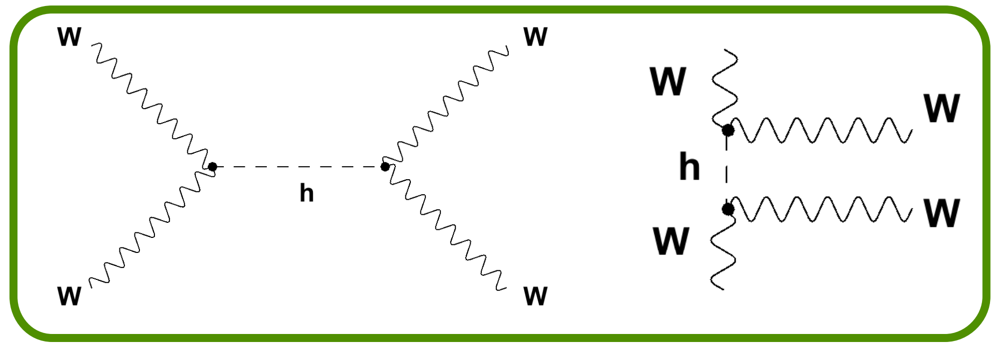

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VV scattering is the smoking gun for EWSB!

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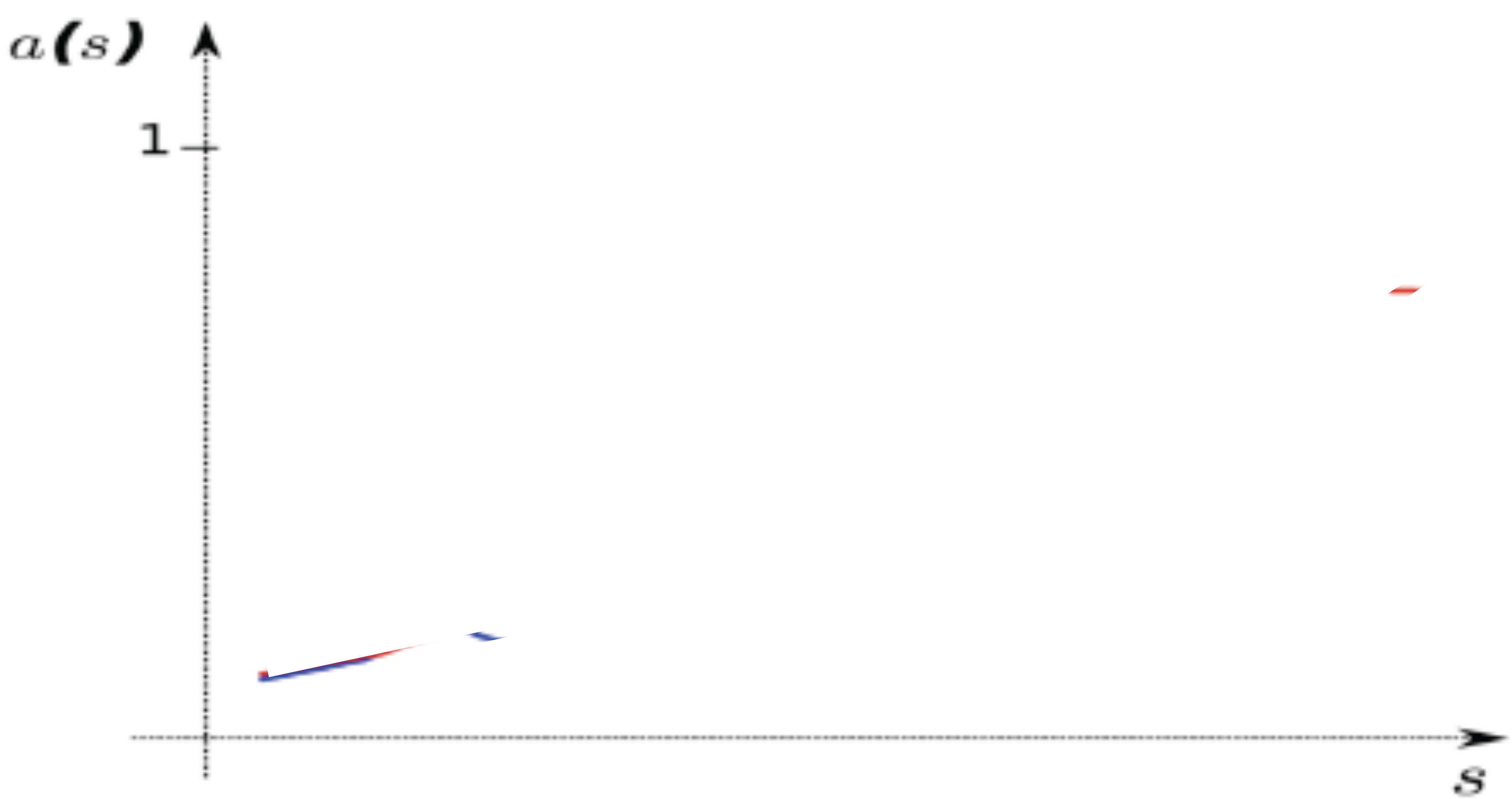
VV Scattering spectrum, σ(VV→VV) vs M(VV)

is the fundamental probe to test the nature of the BEH boson or to find an alternative EWSB mechanism



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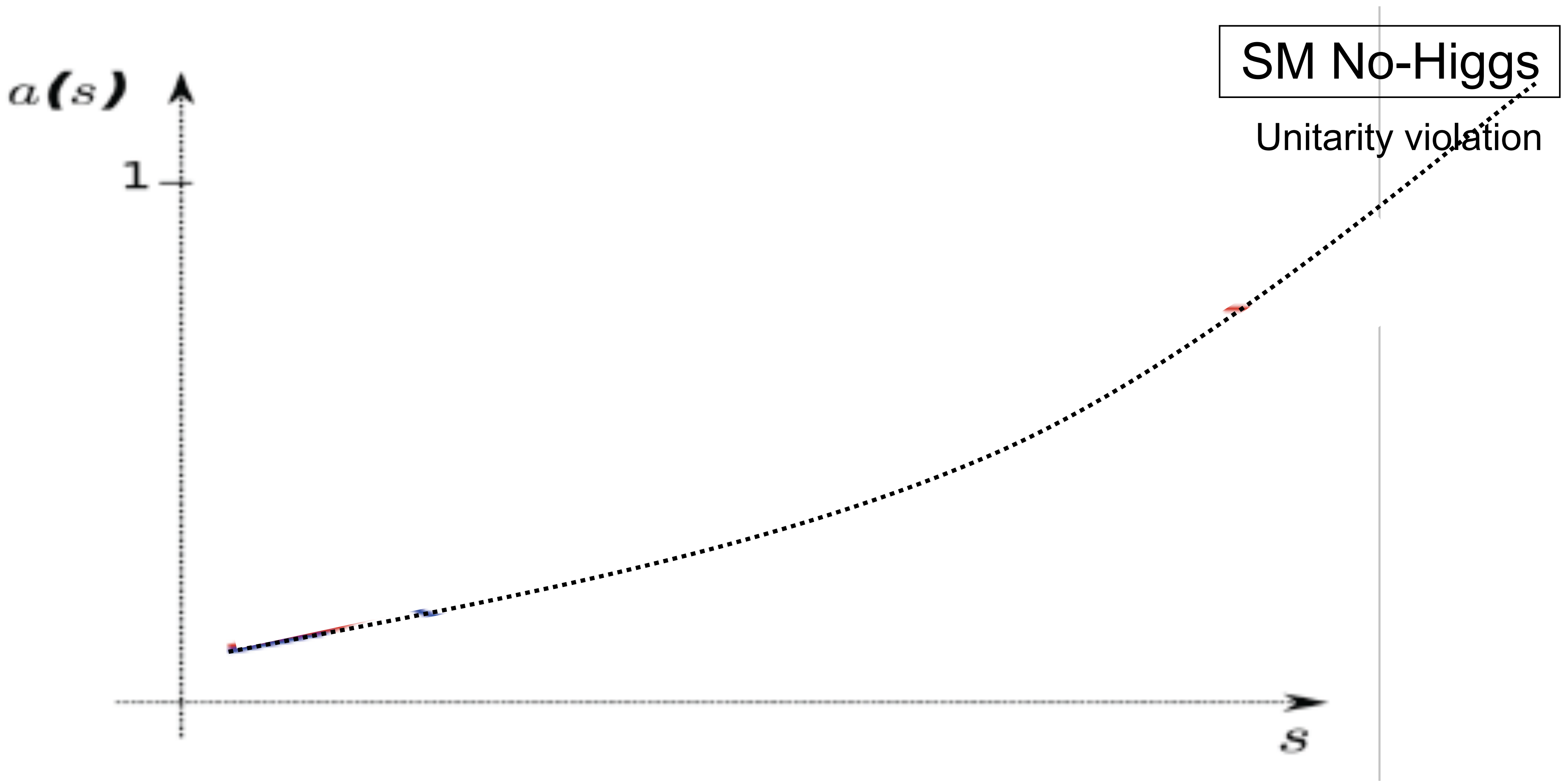

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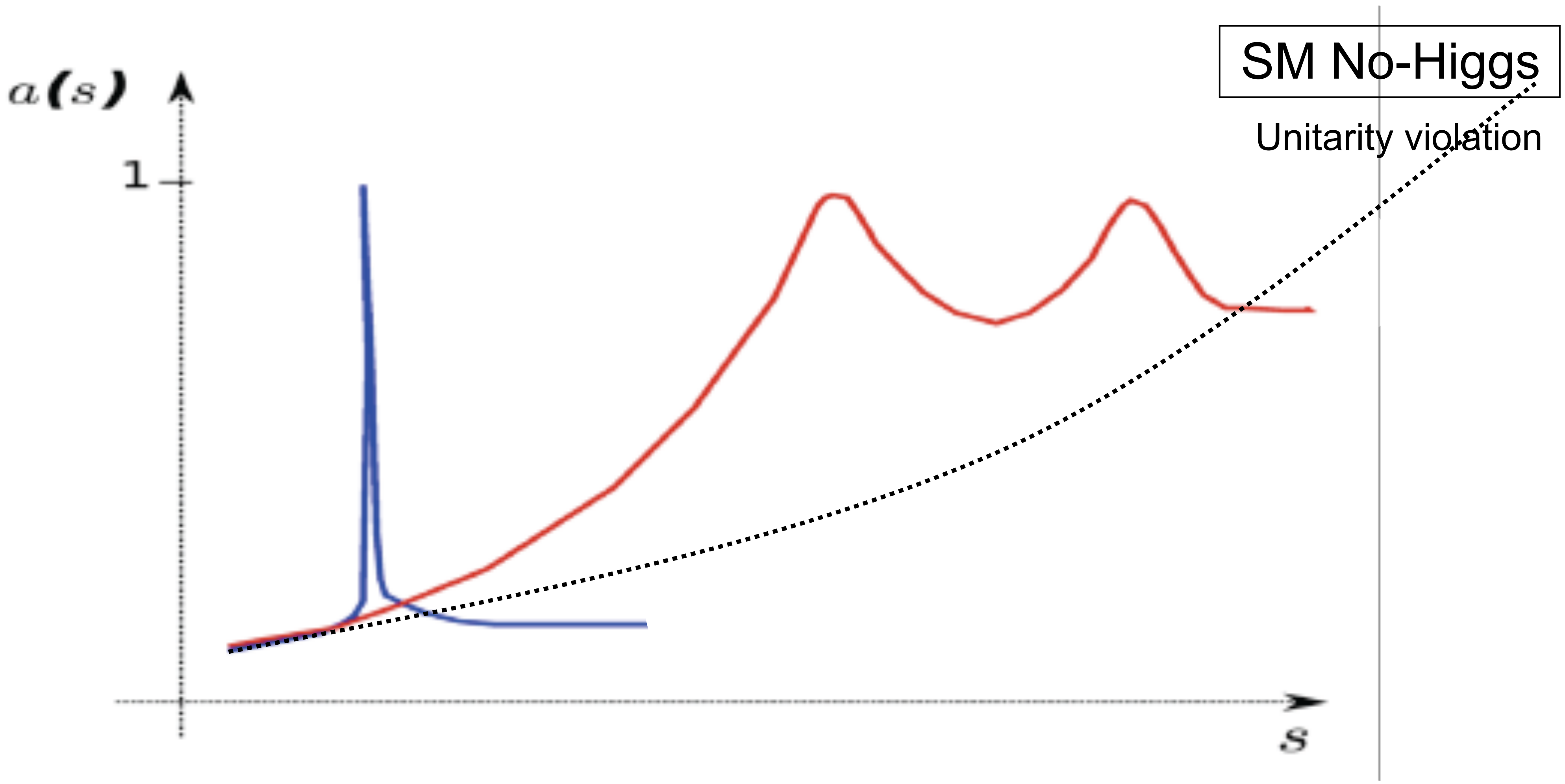

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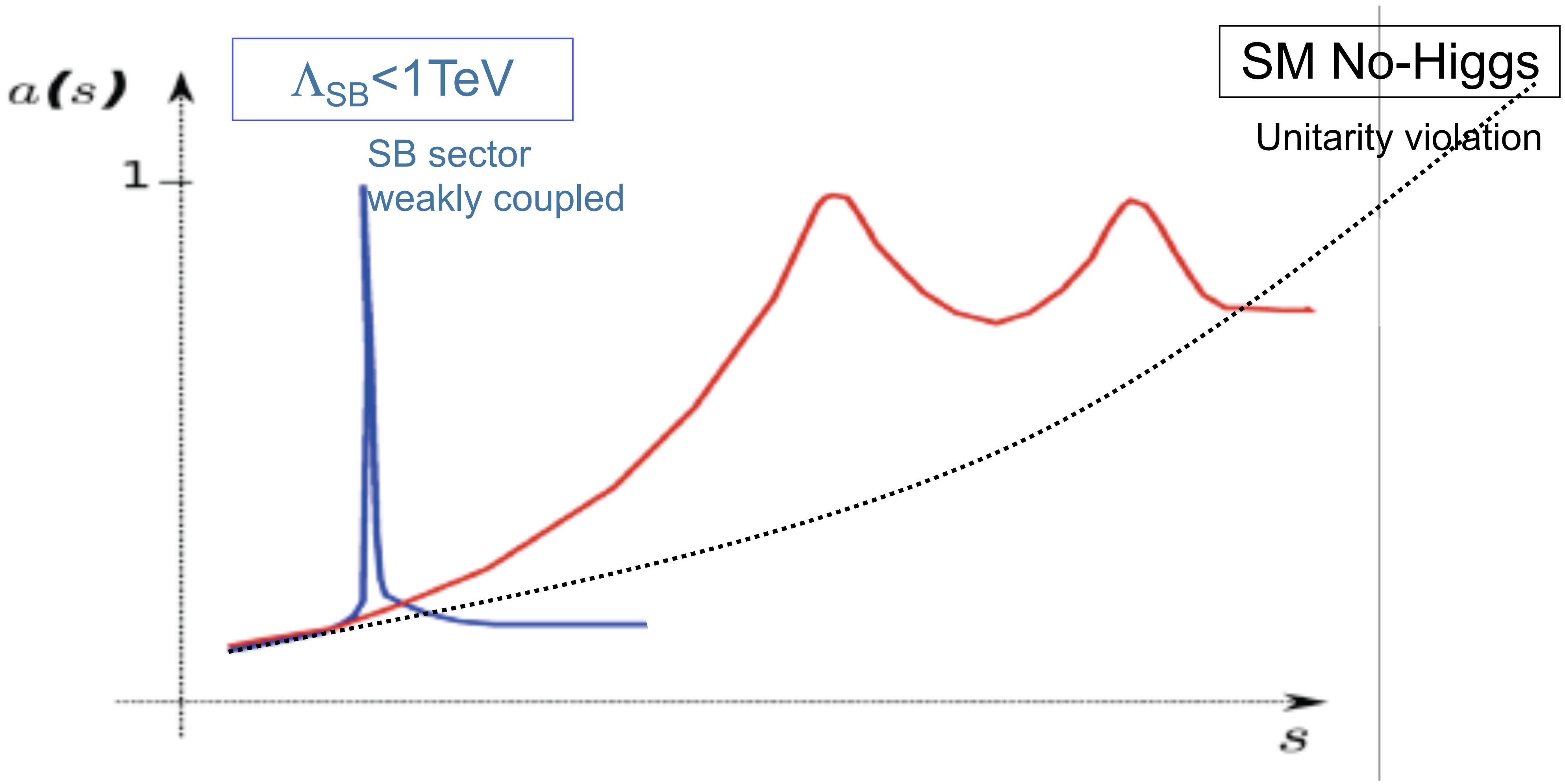

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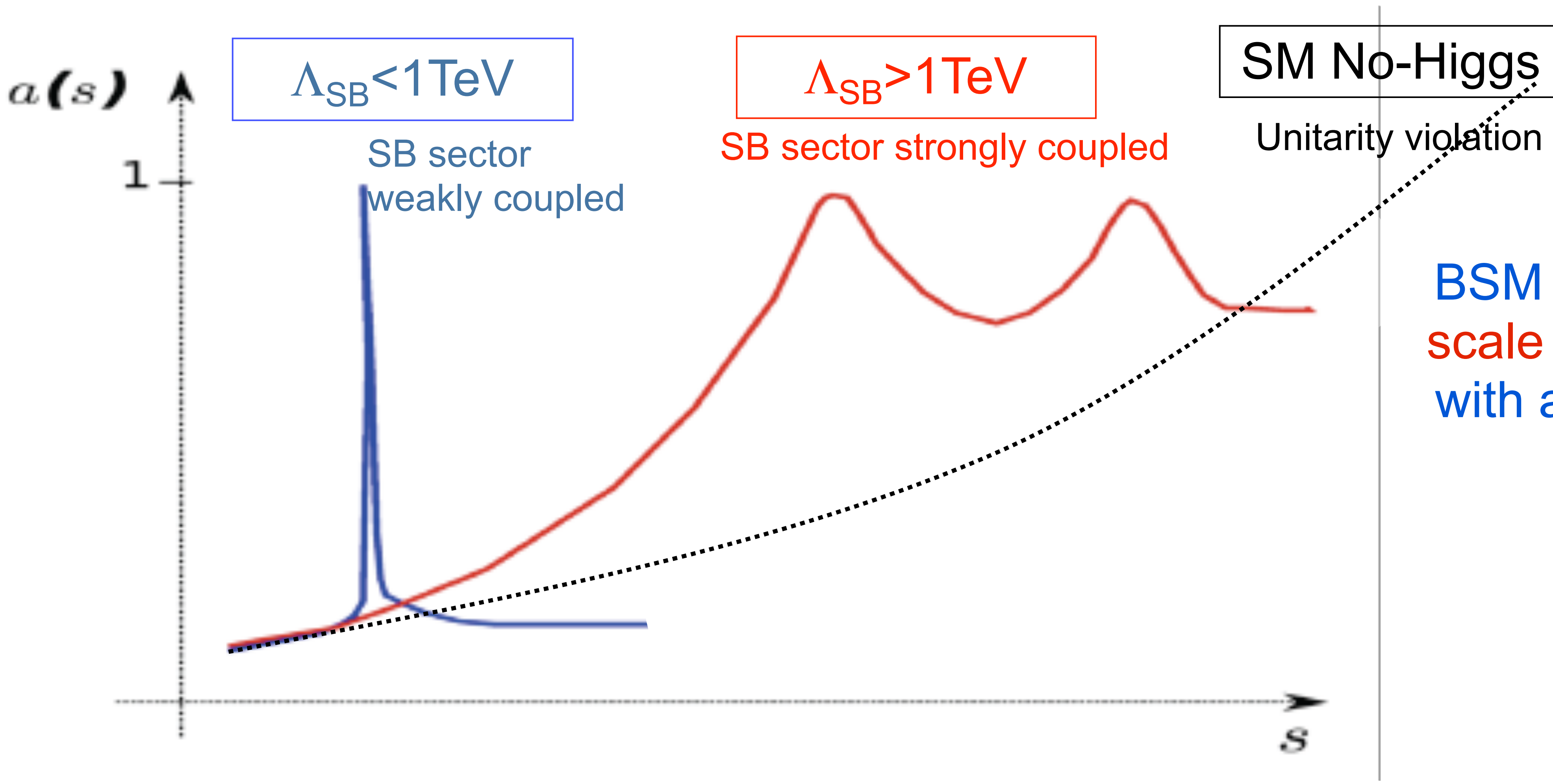

BSM models predict TeV-scale resonances "paired" with a light scalar particle

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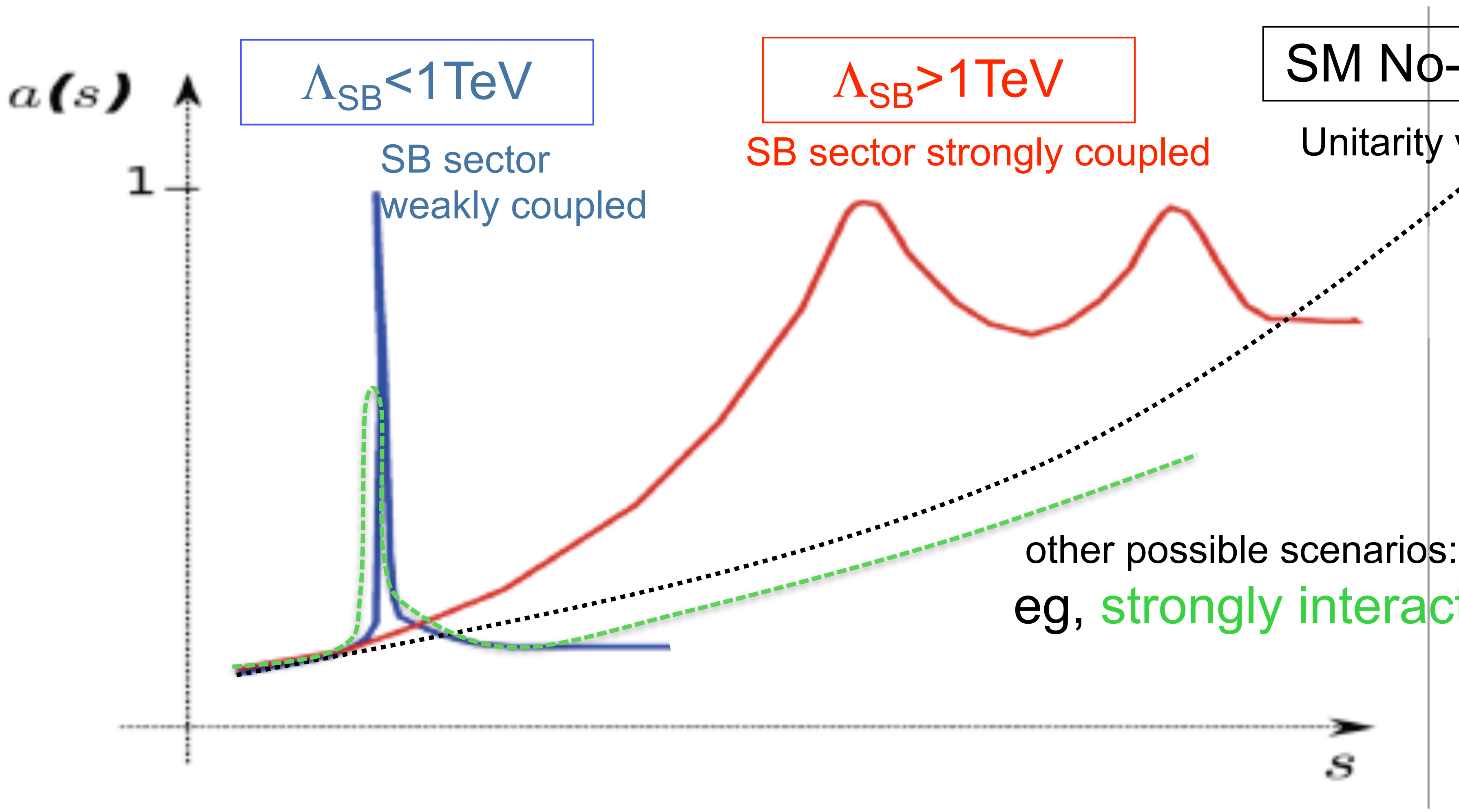

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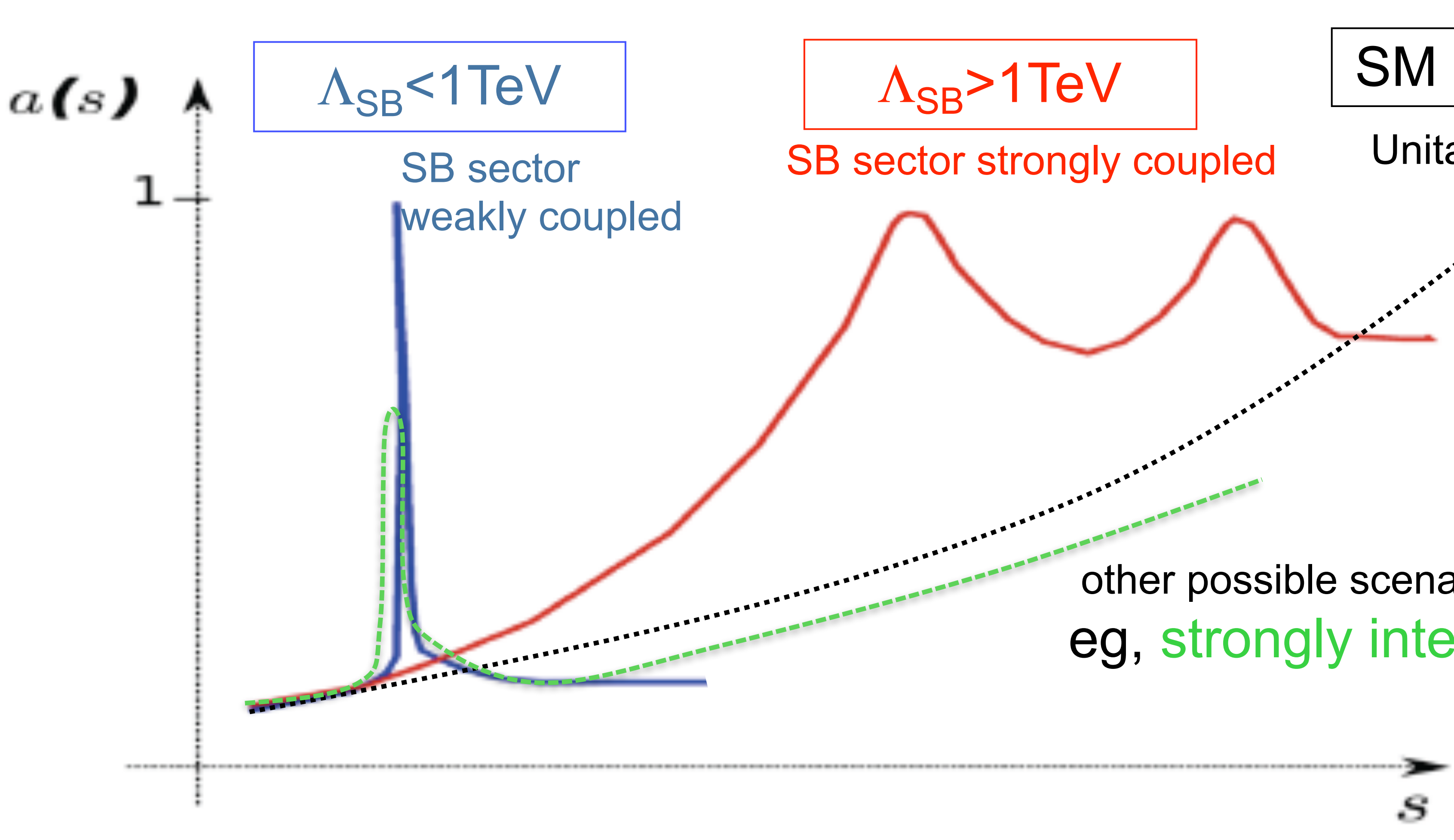

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Search for possible resonances in VV scattering (VBS) spectrum

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VBS experimental signature

From **“Study of Vector Boson Scattering including Pile-up with the ATLAS Detector”**
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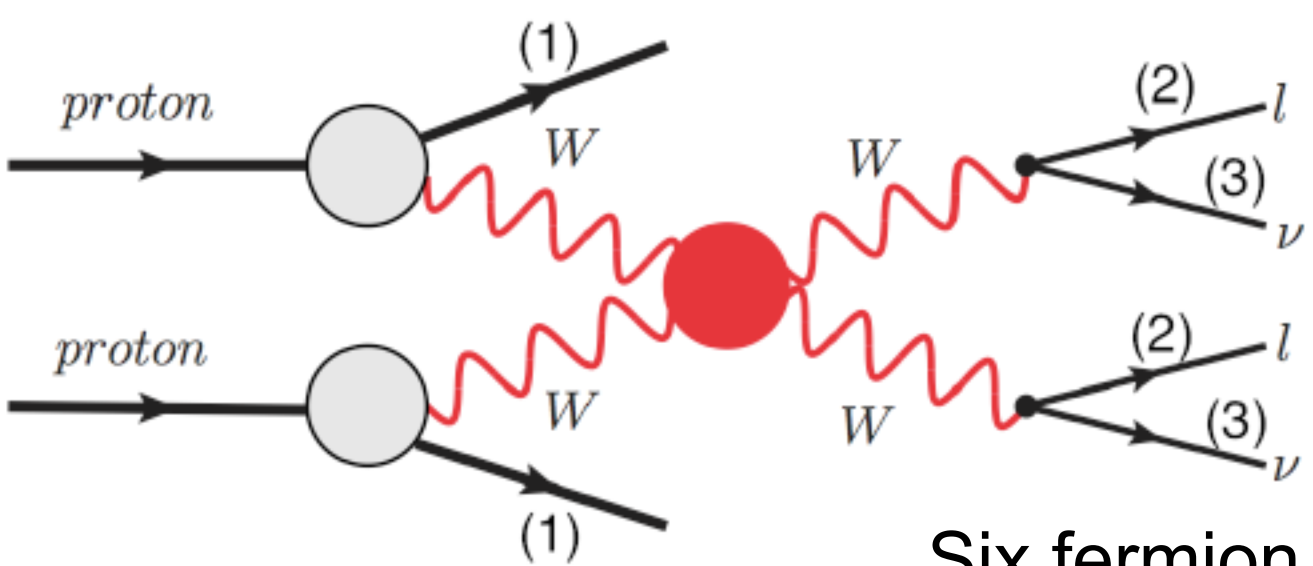

Six fermion final state

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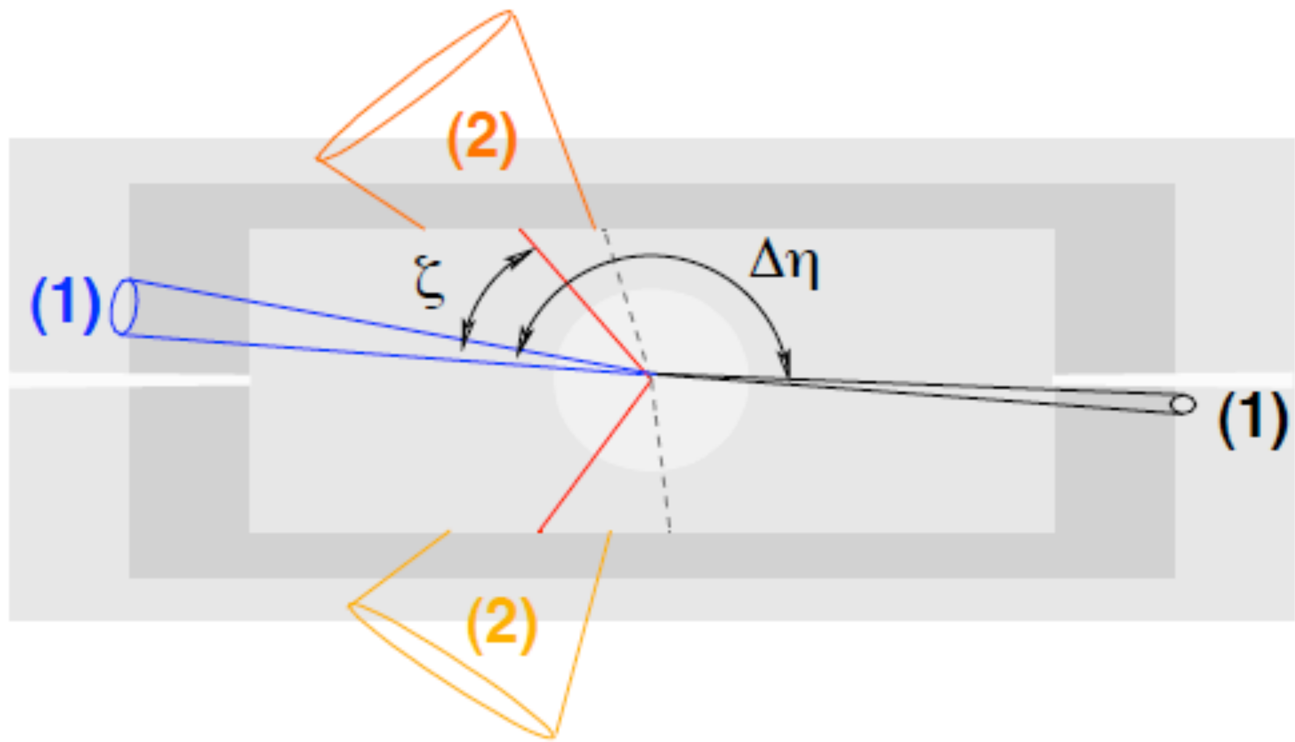

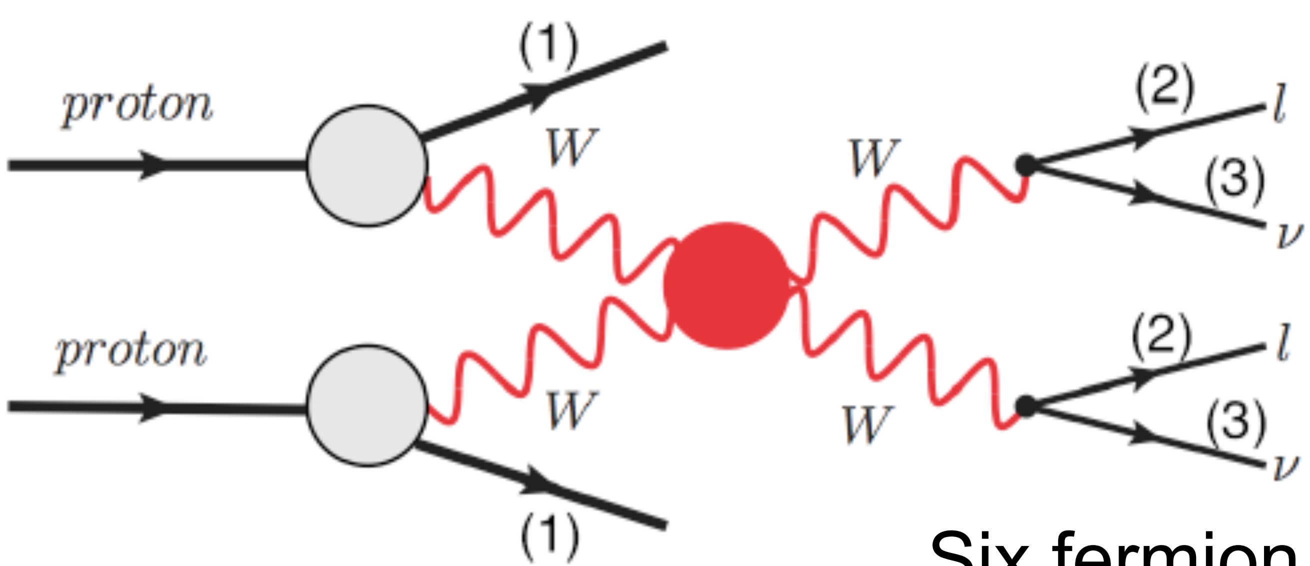

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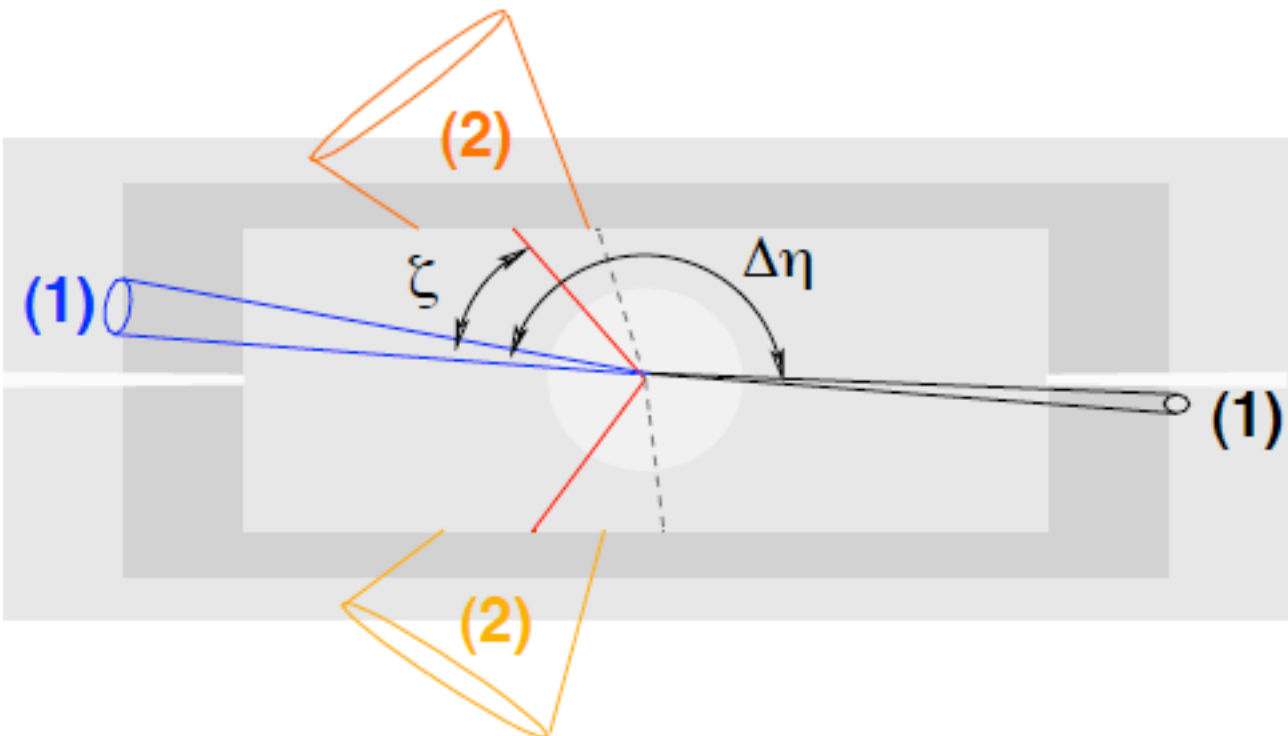

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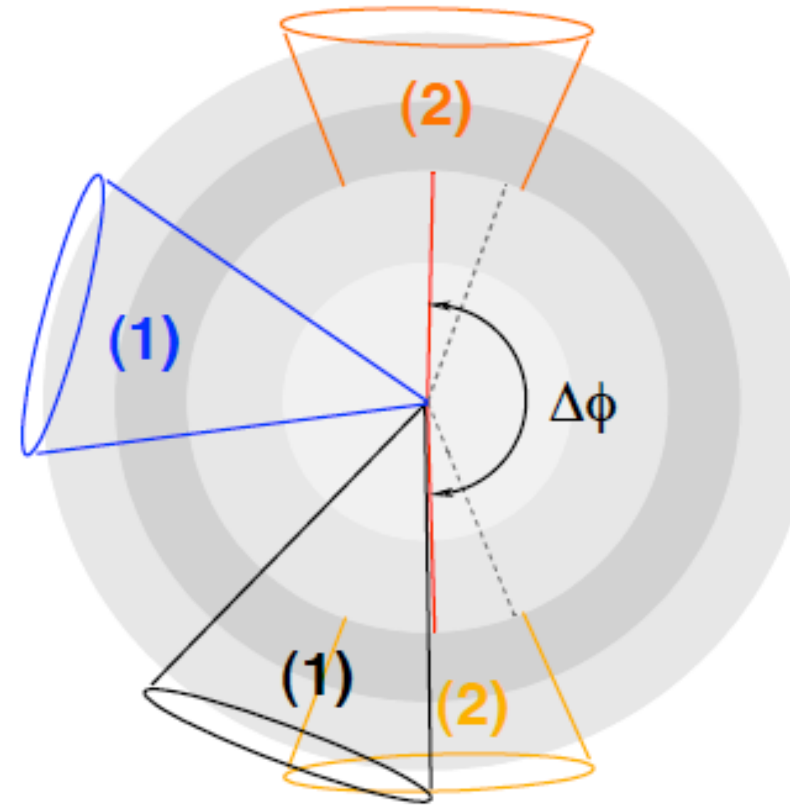

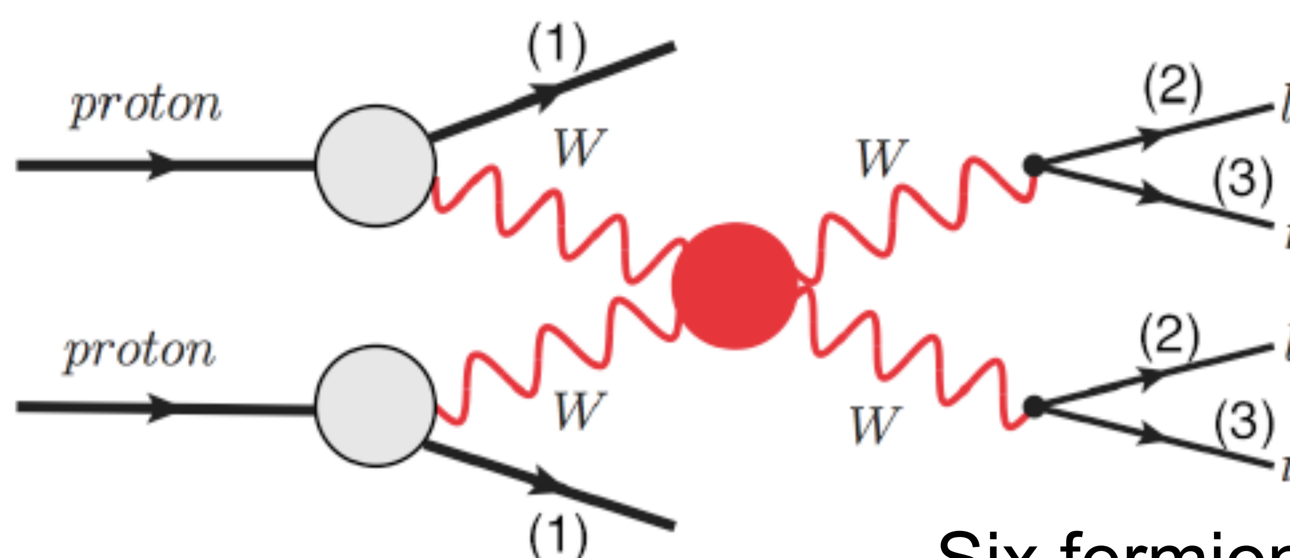

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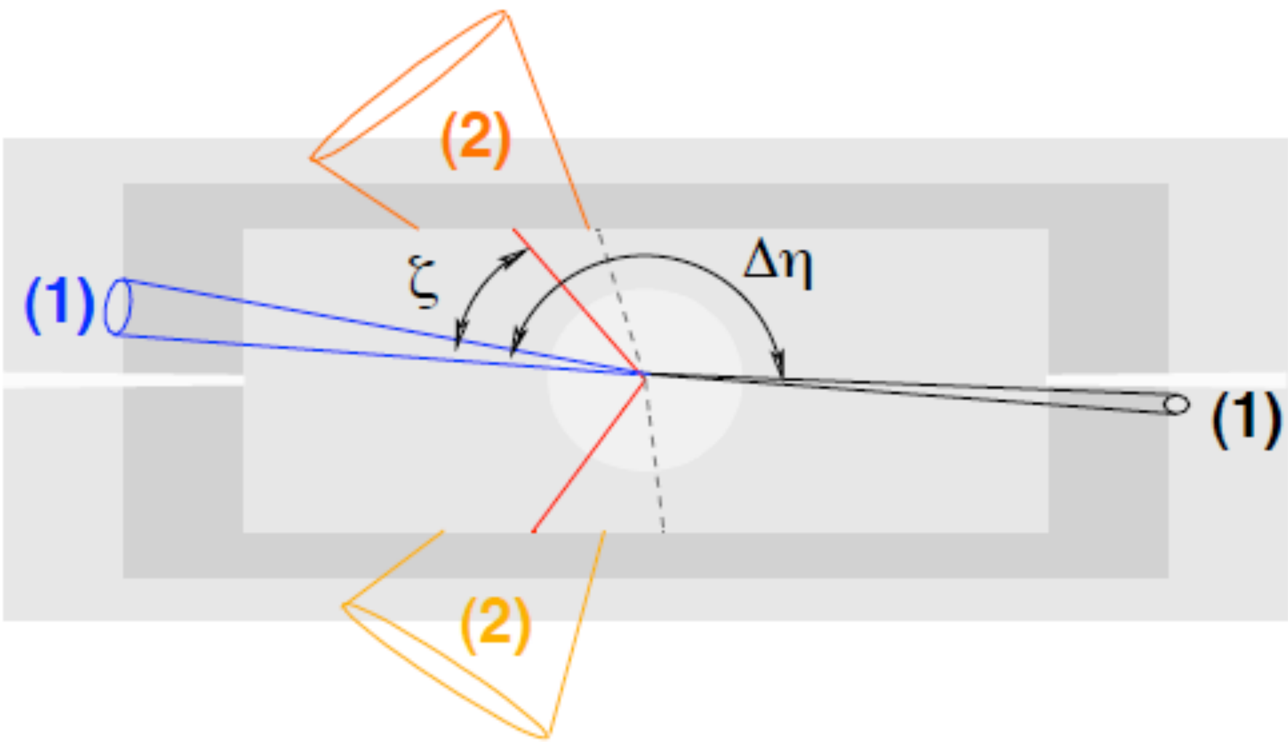

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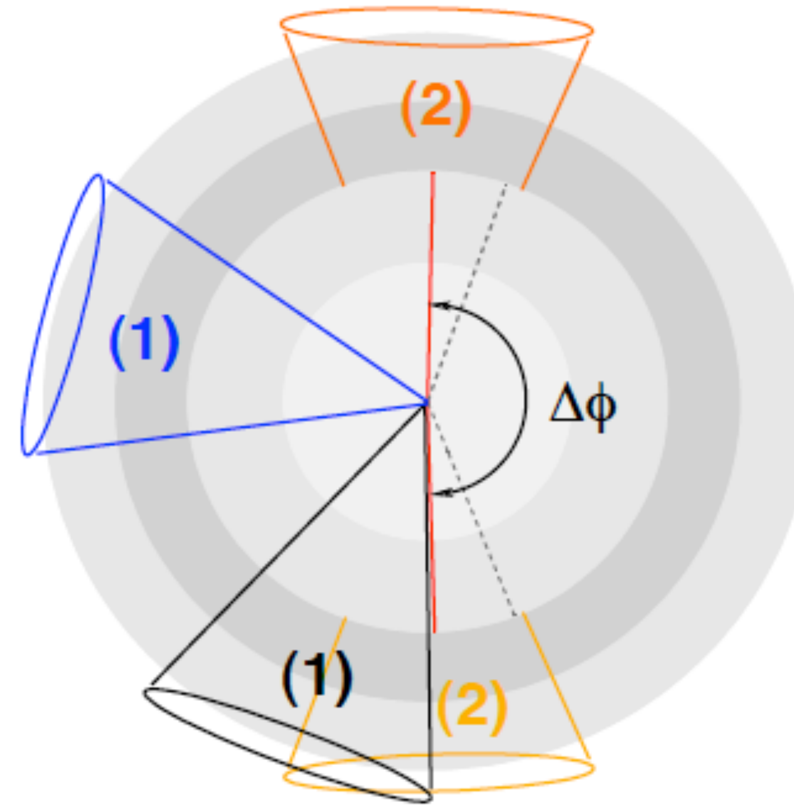
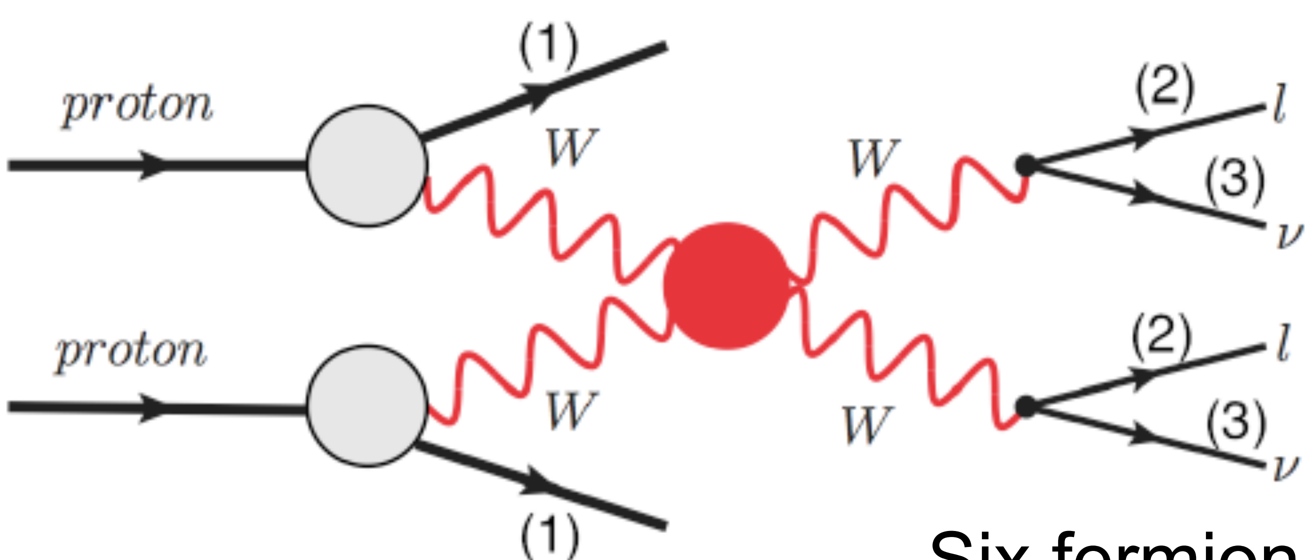


Signature: forward-backward "spectator" jets with very high energy



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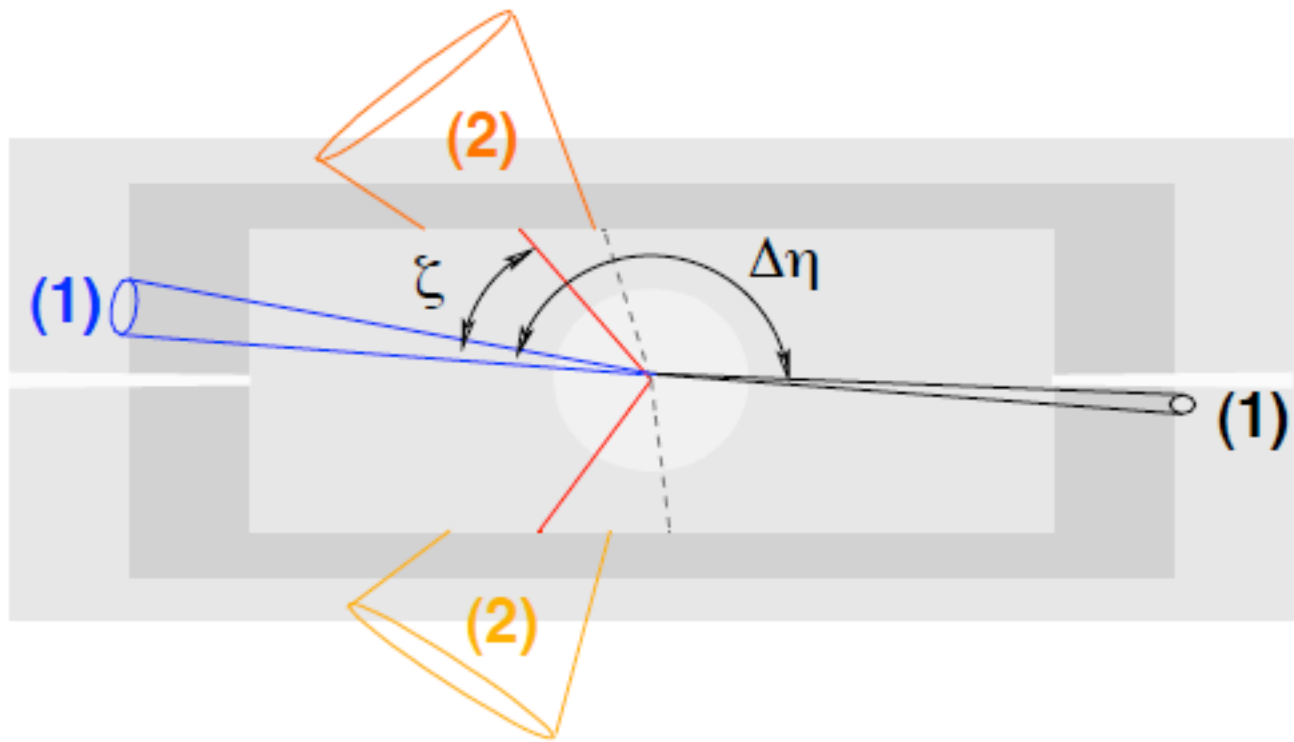

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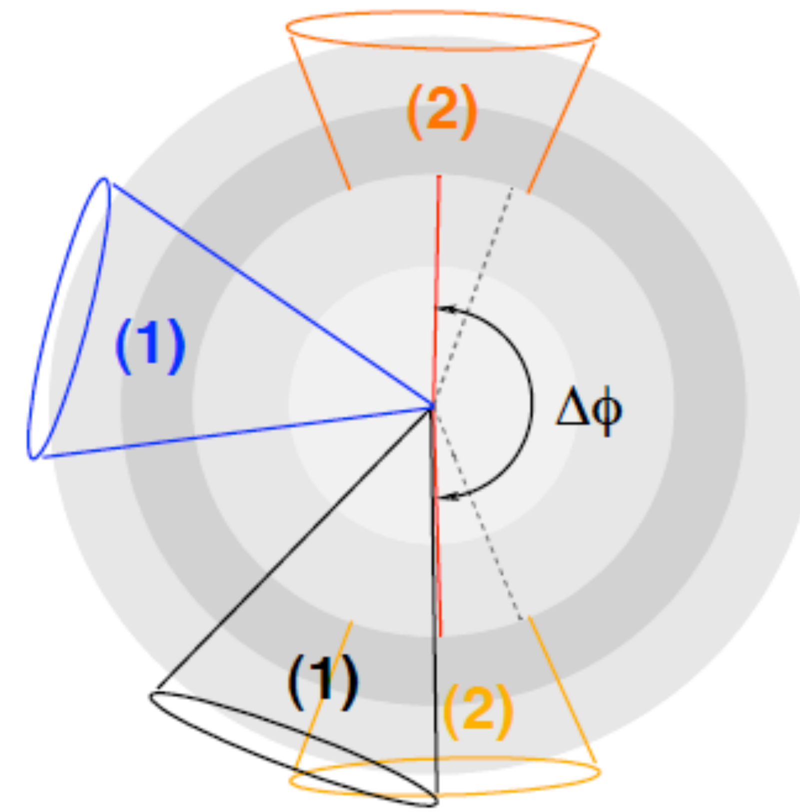
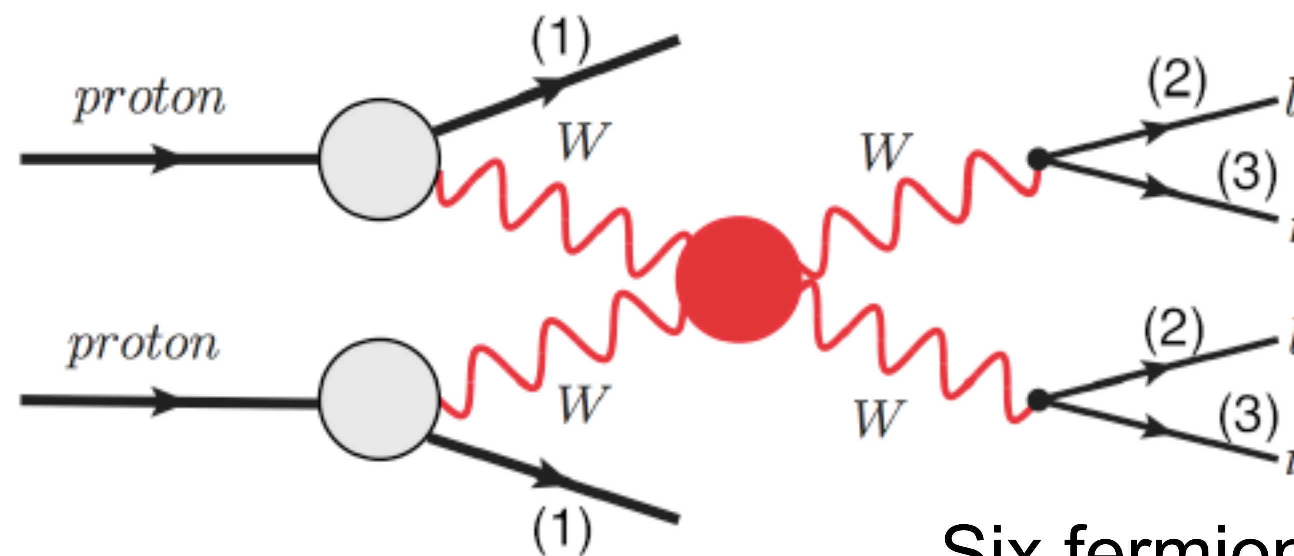


Signature: forward-backward “spectator” jets with very high energy

- *tagging jets* (1): large p_{T}, large $\Delta\eta$
- few jets between tagging jets
- final state $\ell\nu\ell\nu$:
  - *leptons* (2) between tagging jets
  - missing E_{T}(3)



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VBS final states

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- According to the vector bosons' decays we have a multitude of possible final states. We can group them in:

  - Fully leptonic
    - pp→qq ℓℓℓℓ (ℓ=μ,e)
    - pp→qq ℓℓℓν
    - pp→qq ℓℓνν

  - Semi-leptonic
    - pp→qq jetjet ℓℓ
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Detector needs

Excellent lepton ID, energy resolution, hermeticity, jet tagging at high η

VBS 2e2μ candidate event

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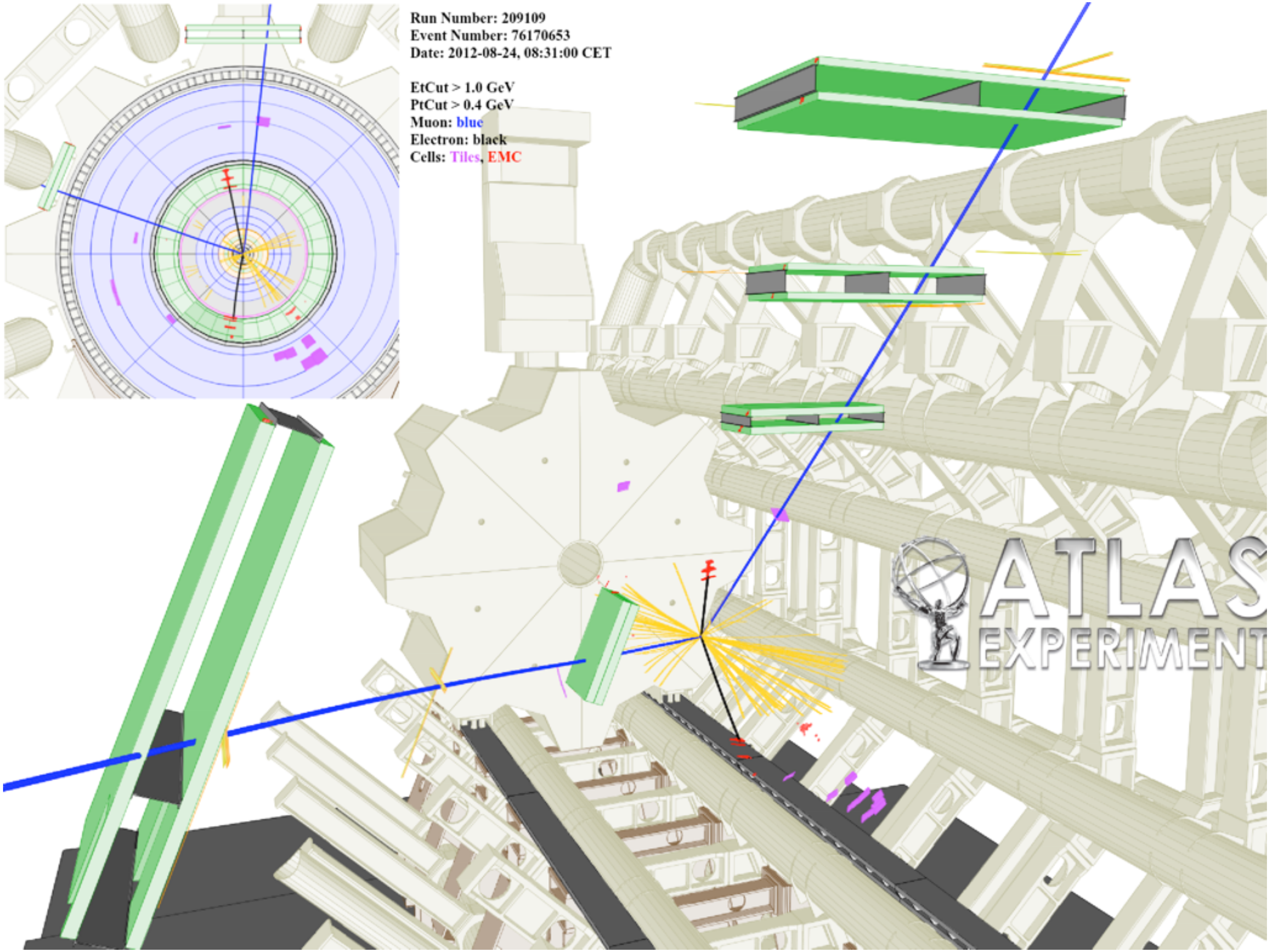

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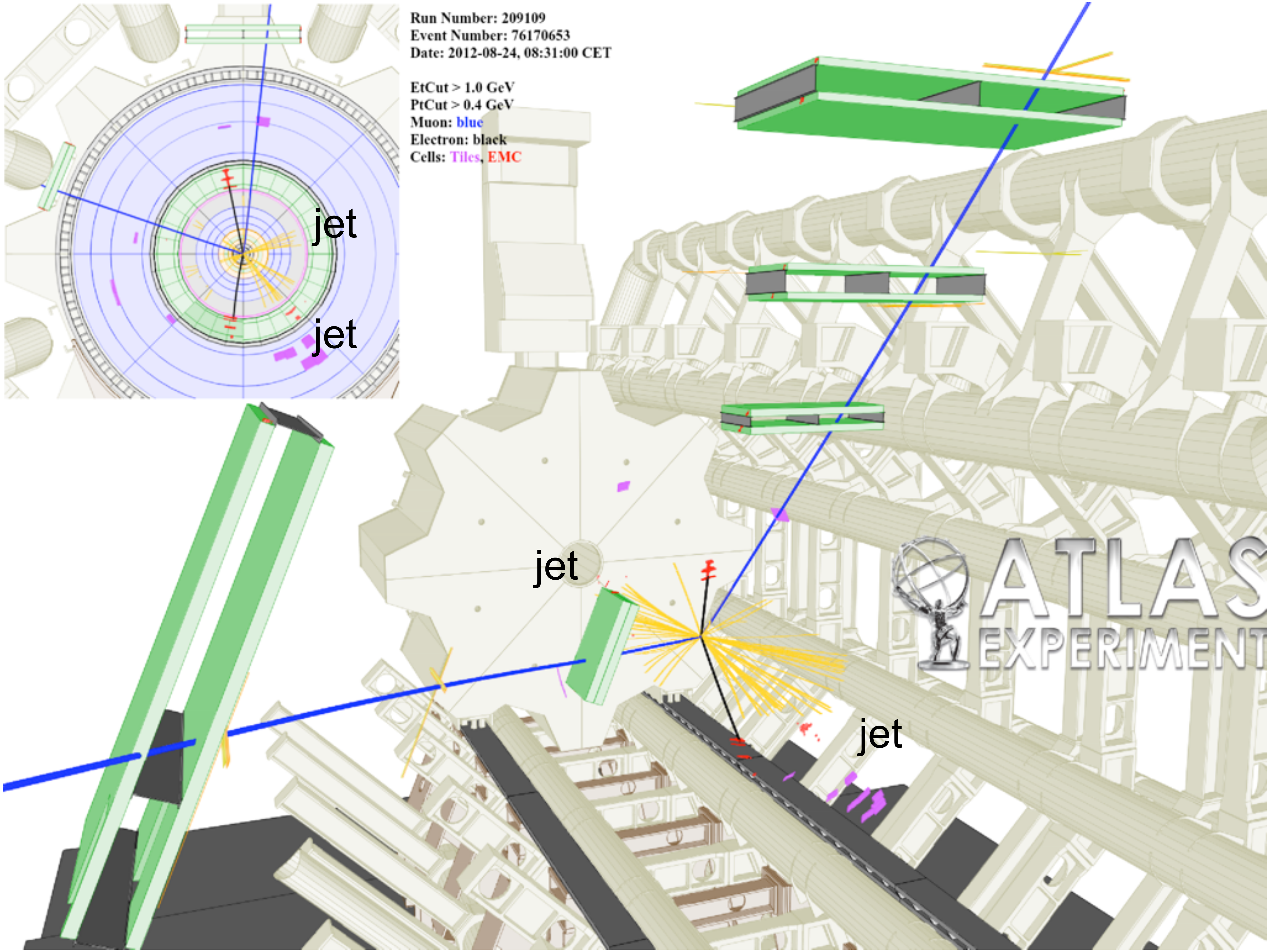

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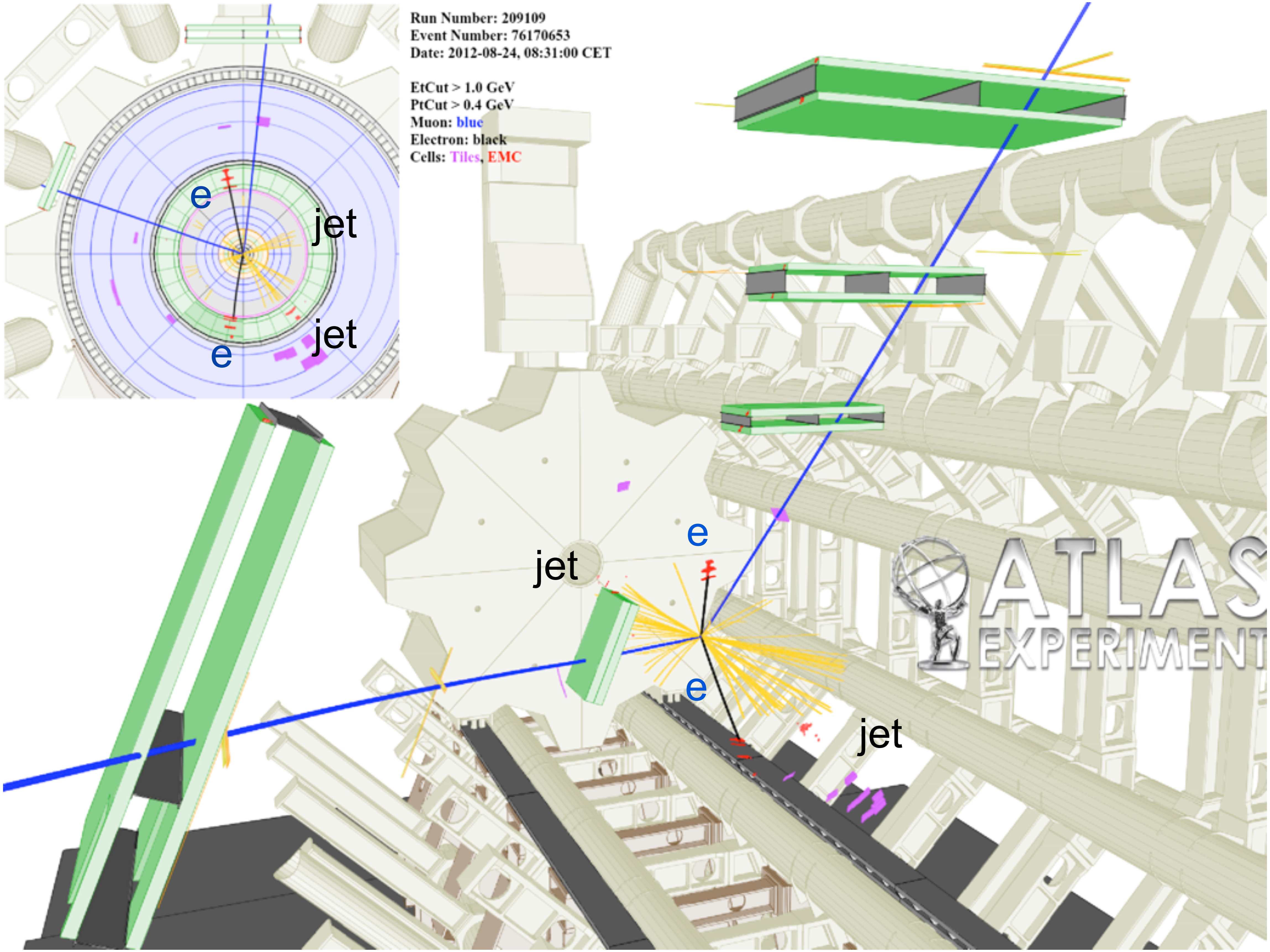

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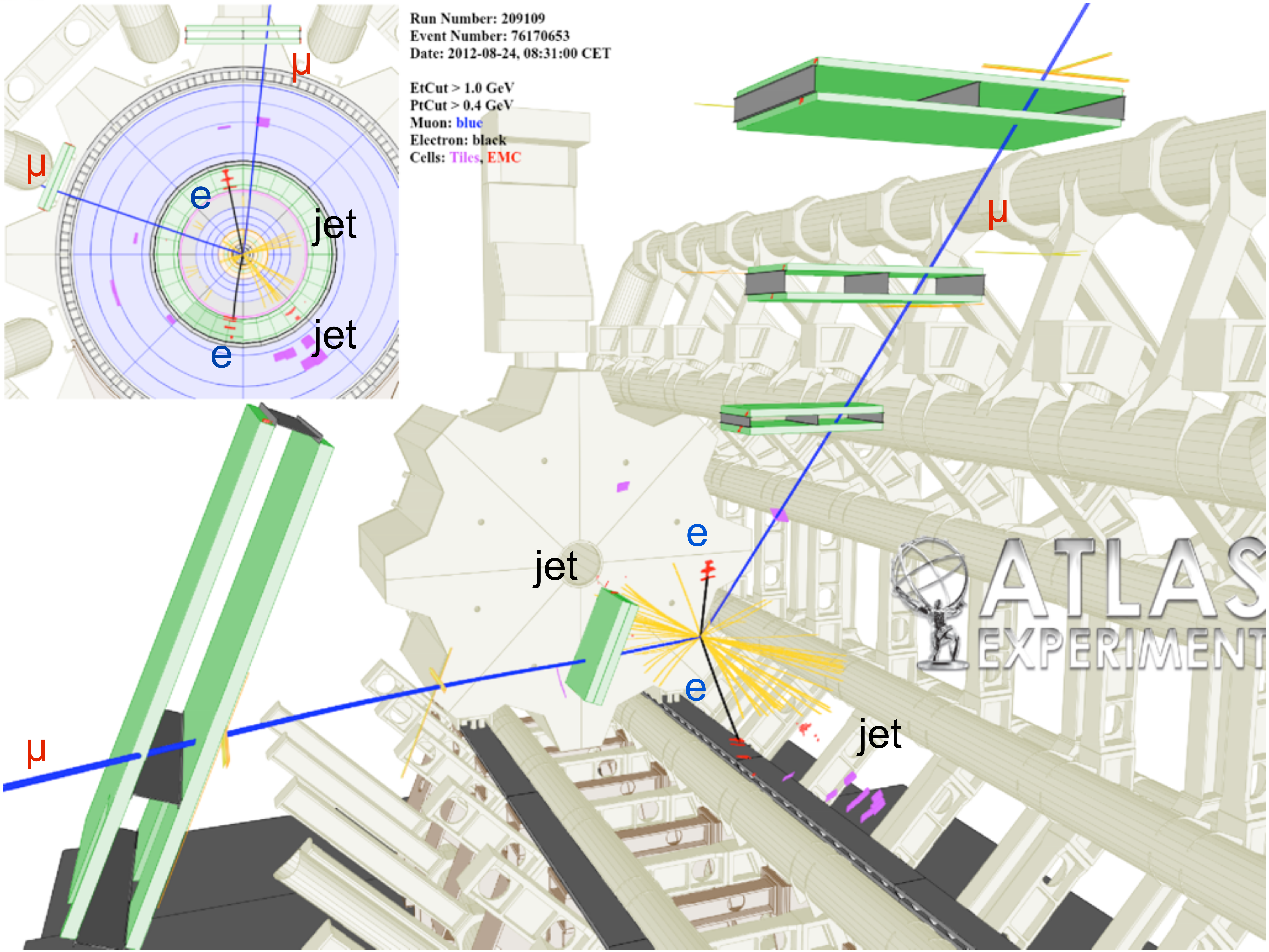

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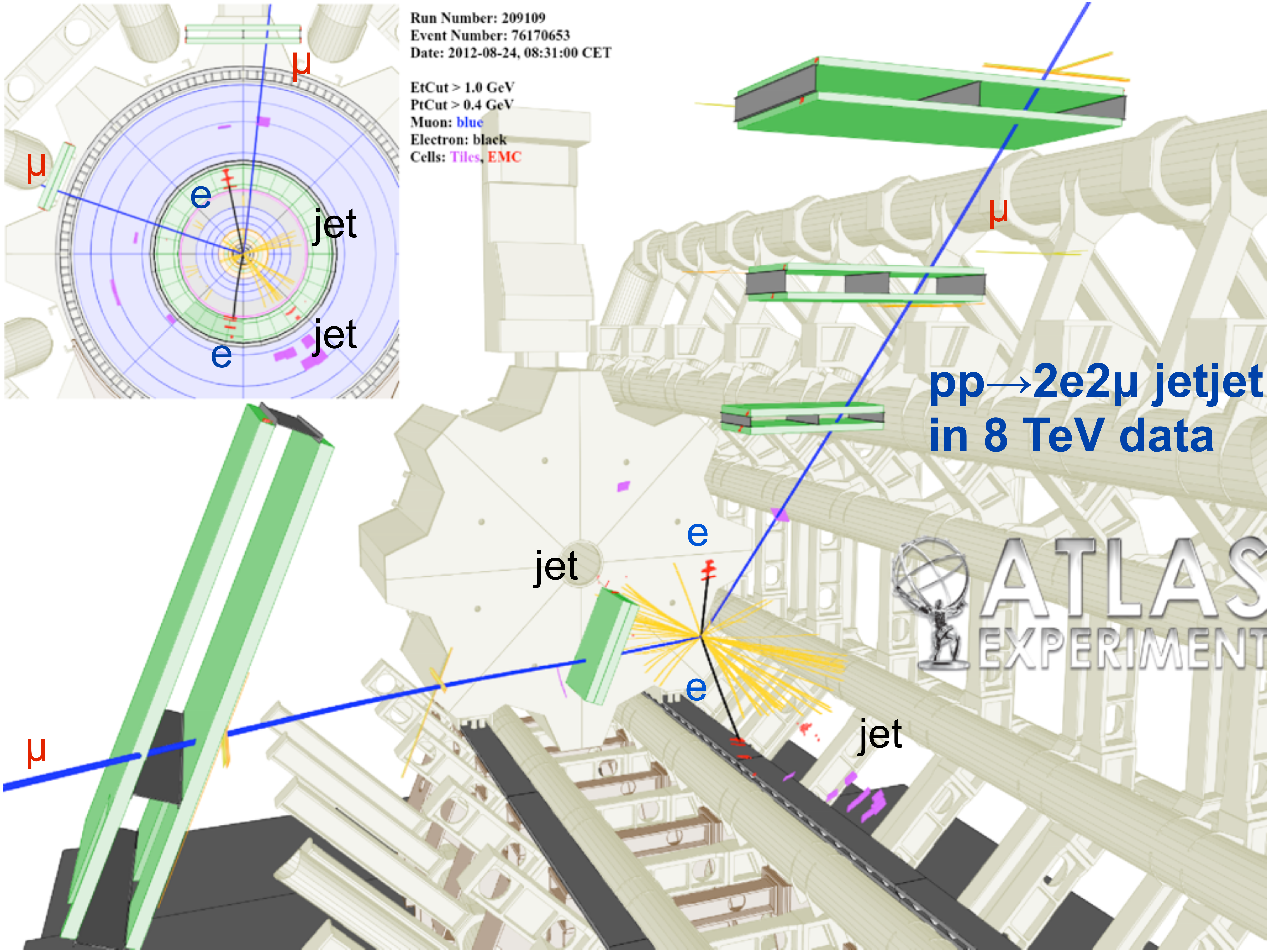

pp→2e2μ jetjet in 8 TeV data

WZ resonance

WZ resonance

pp→WZ+2j→ℓ+ν+2ℓ+2j channel

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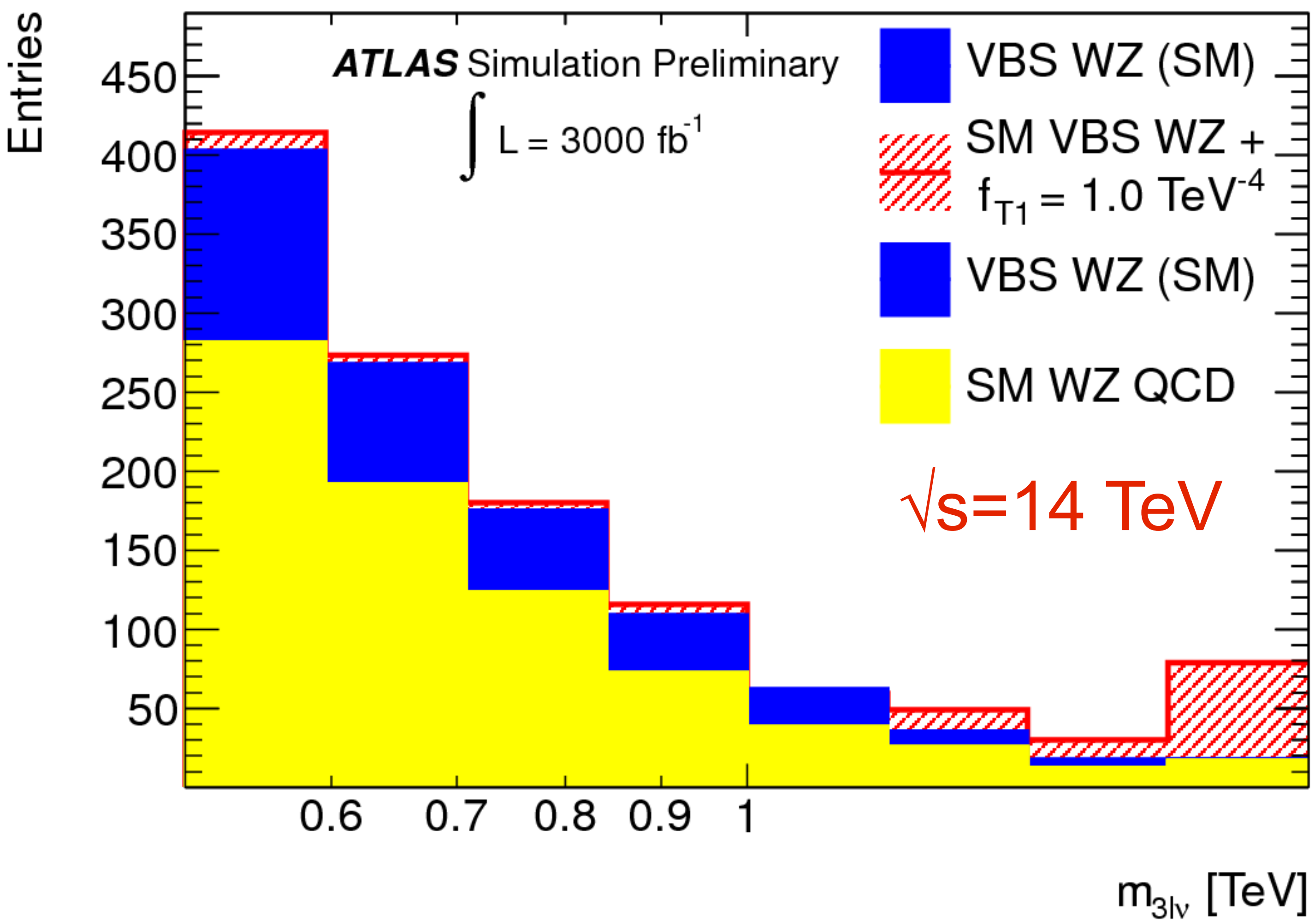

$$\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} \mathrm{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$$

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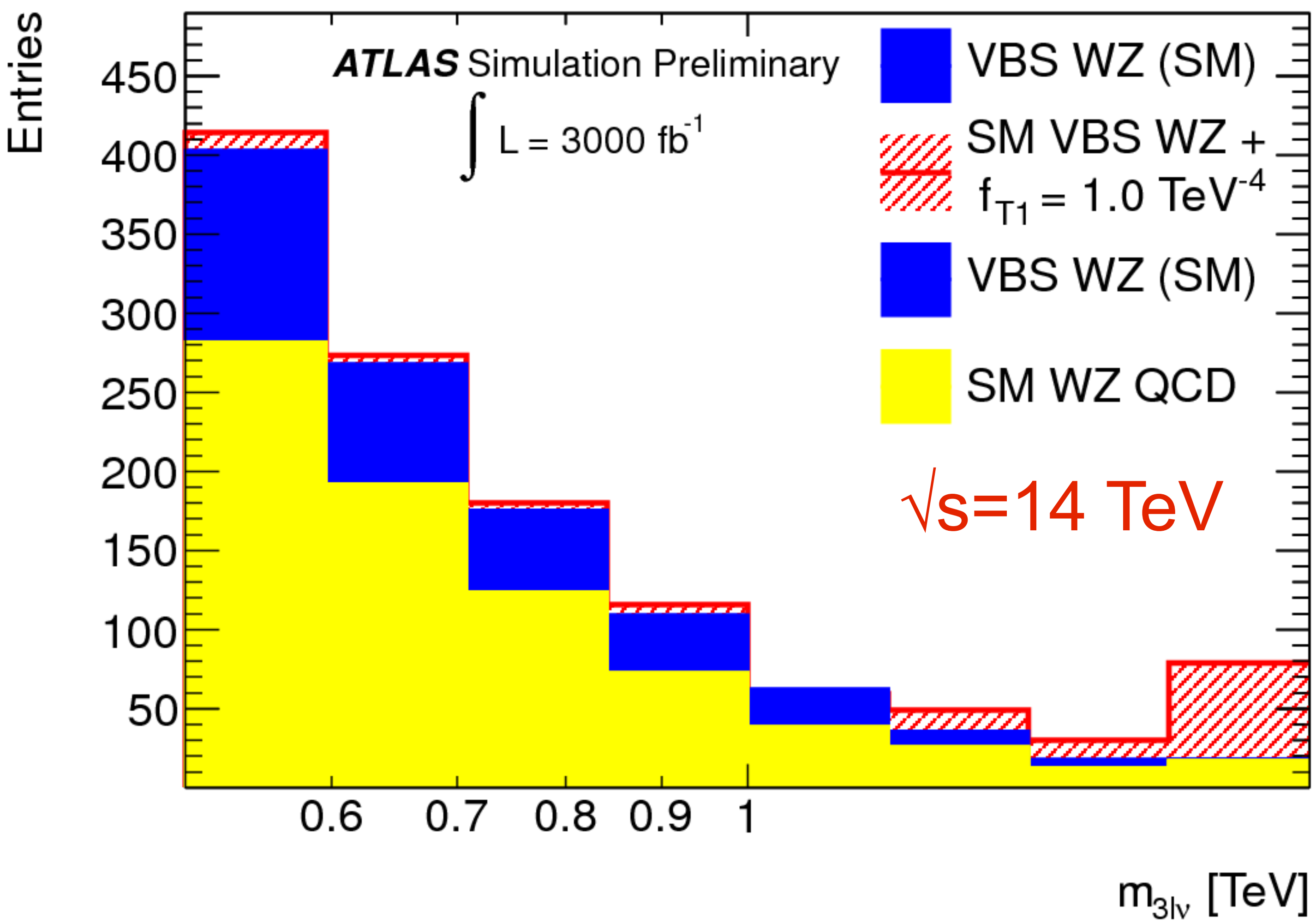

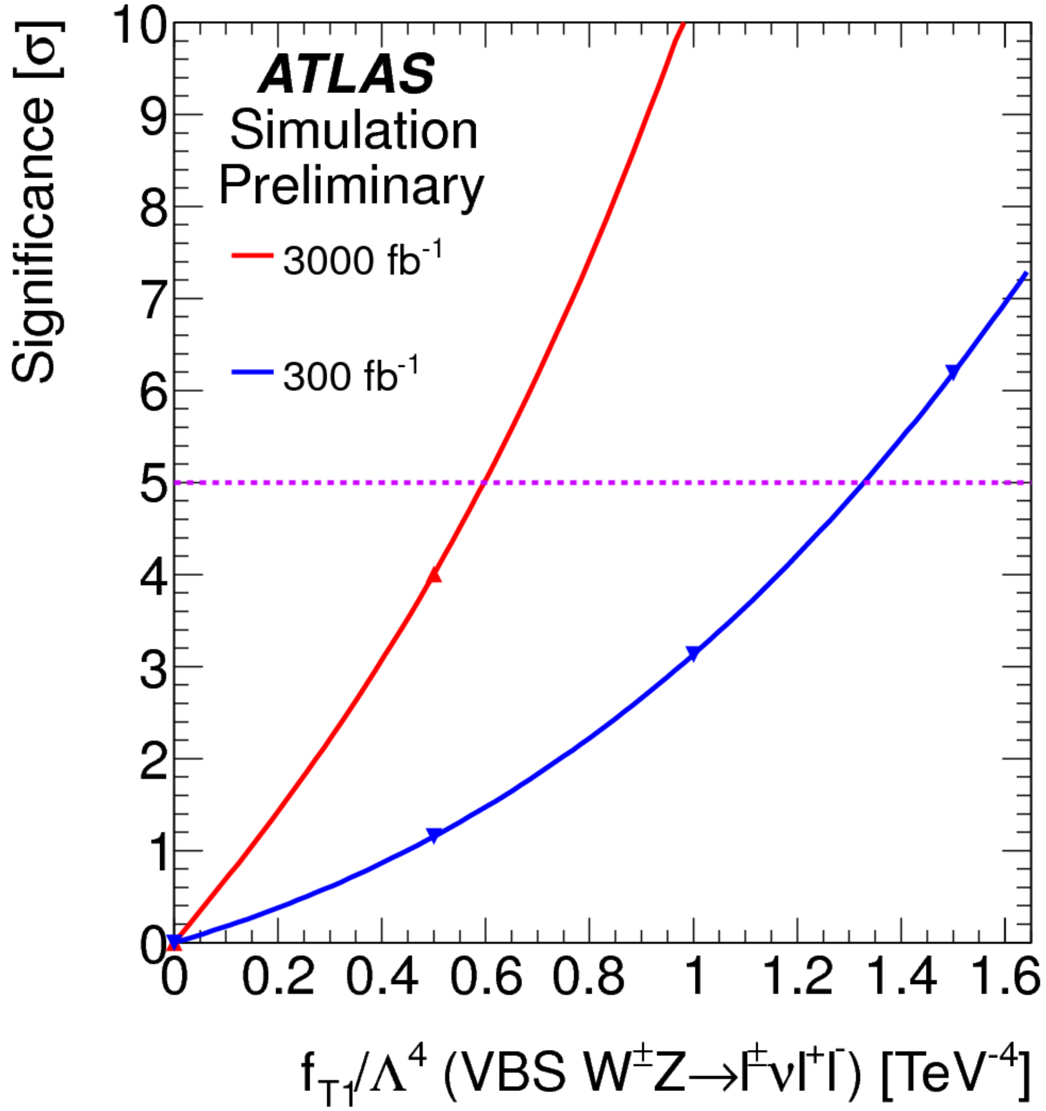

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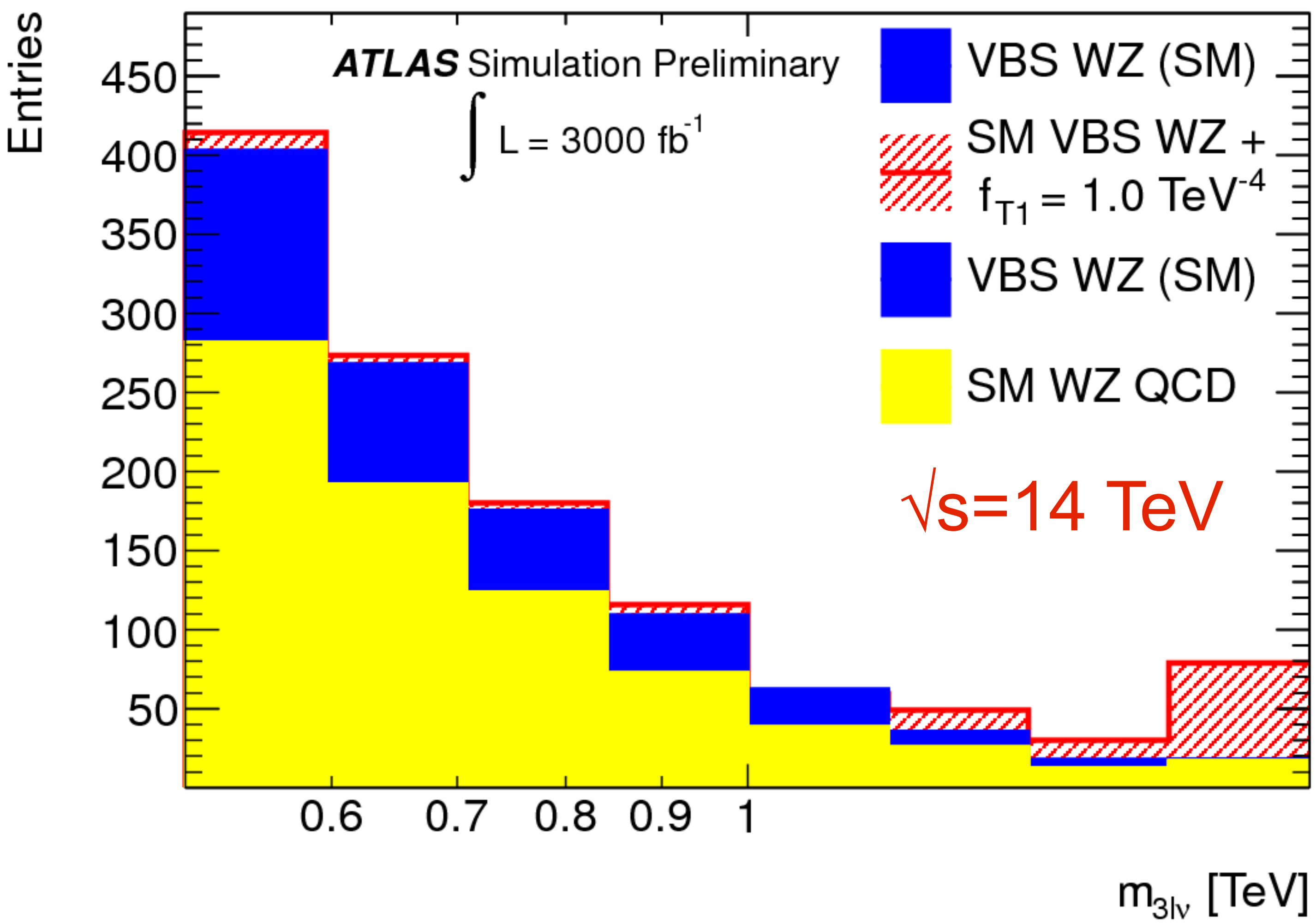

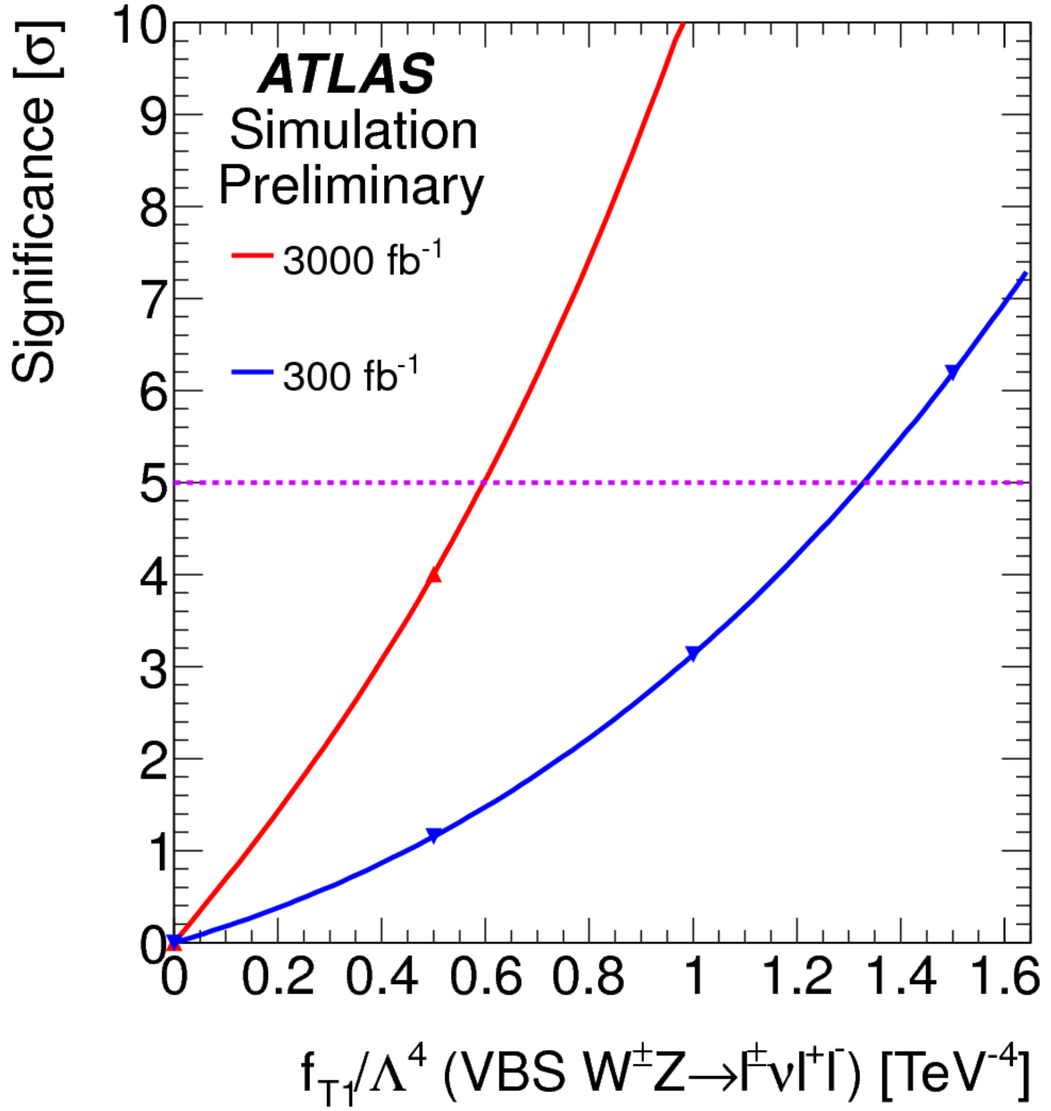

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	$300\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
f_{T1}/Λ^4	$1.3\ \mathrm{TeV}^{-4}$	$0.6\ \mathrm{TeV}^{-4}$

Sensitivity to anomalous WZ resonances in Vector boson scattering

WW resonance

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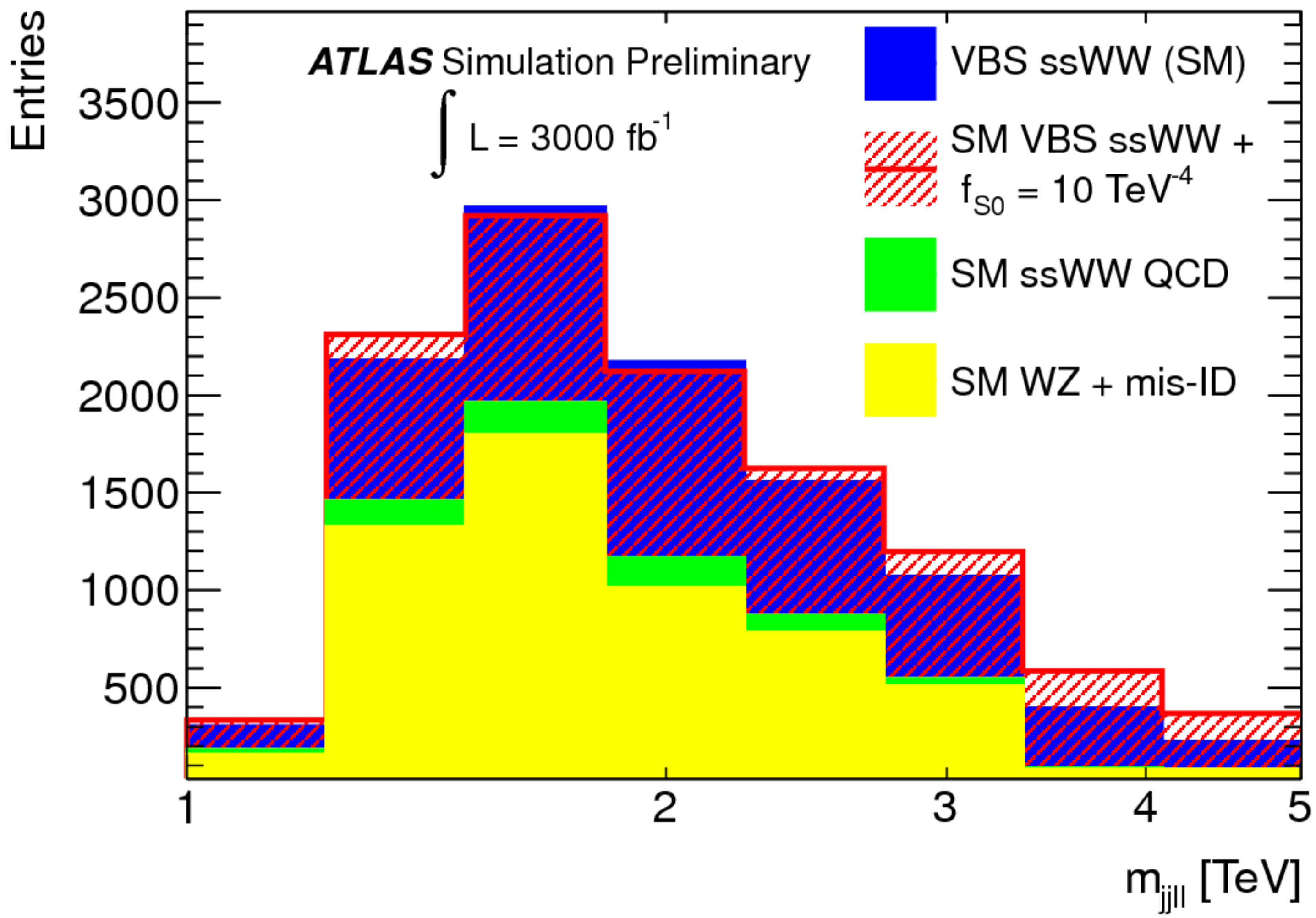

$$\mathcal{L}_{S,0} = \frac{f_{S0}}{\Lambda^4}[(D_\mu\phi)^\dagger D_\nu\phi)] \times [(D^\mu\phi)^\dagger D^\nu\phi)]$$

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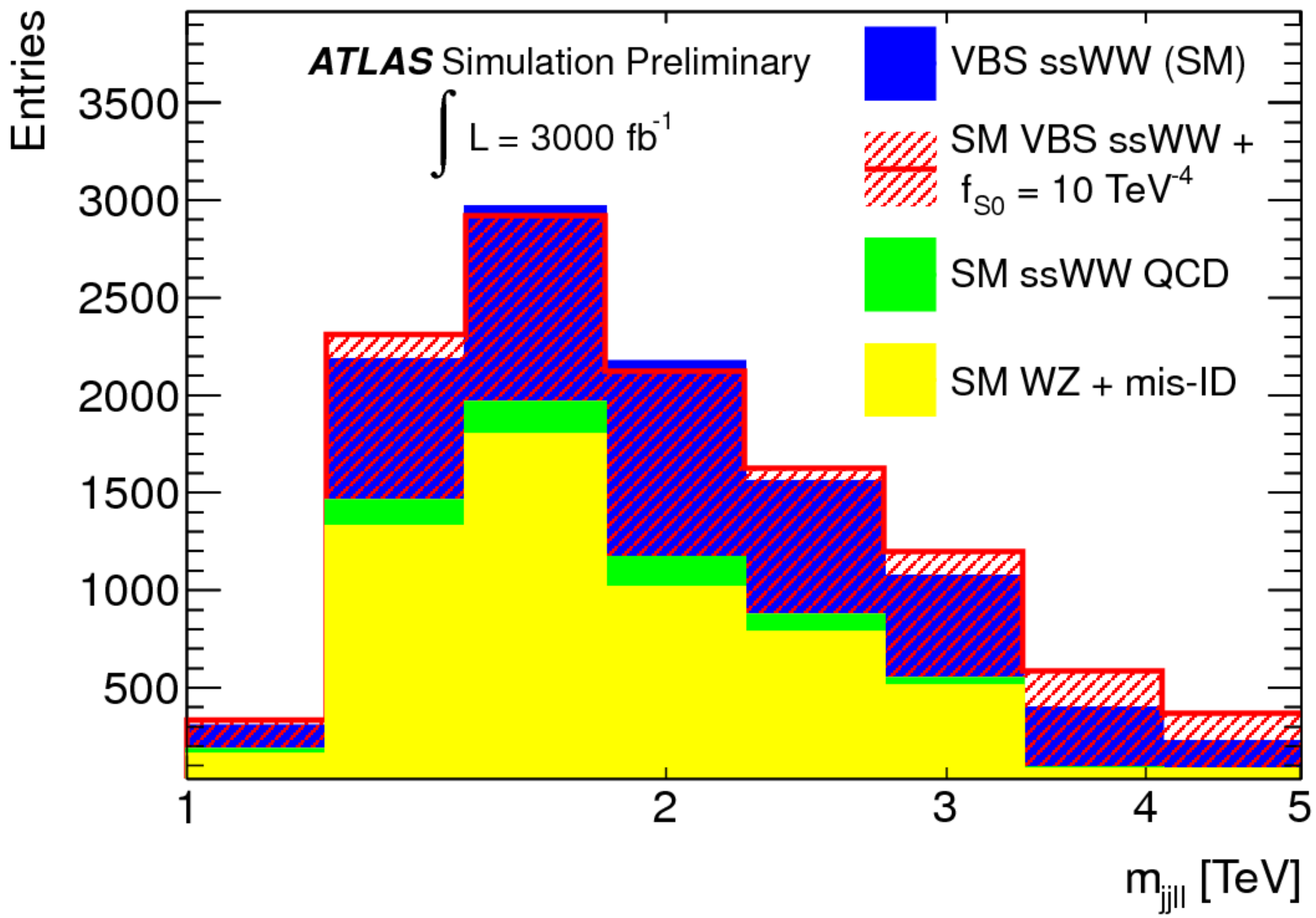

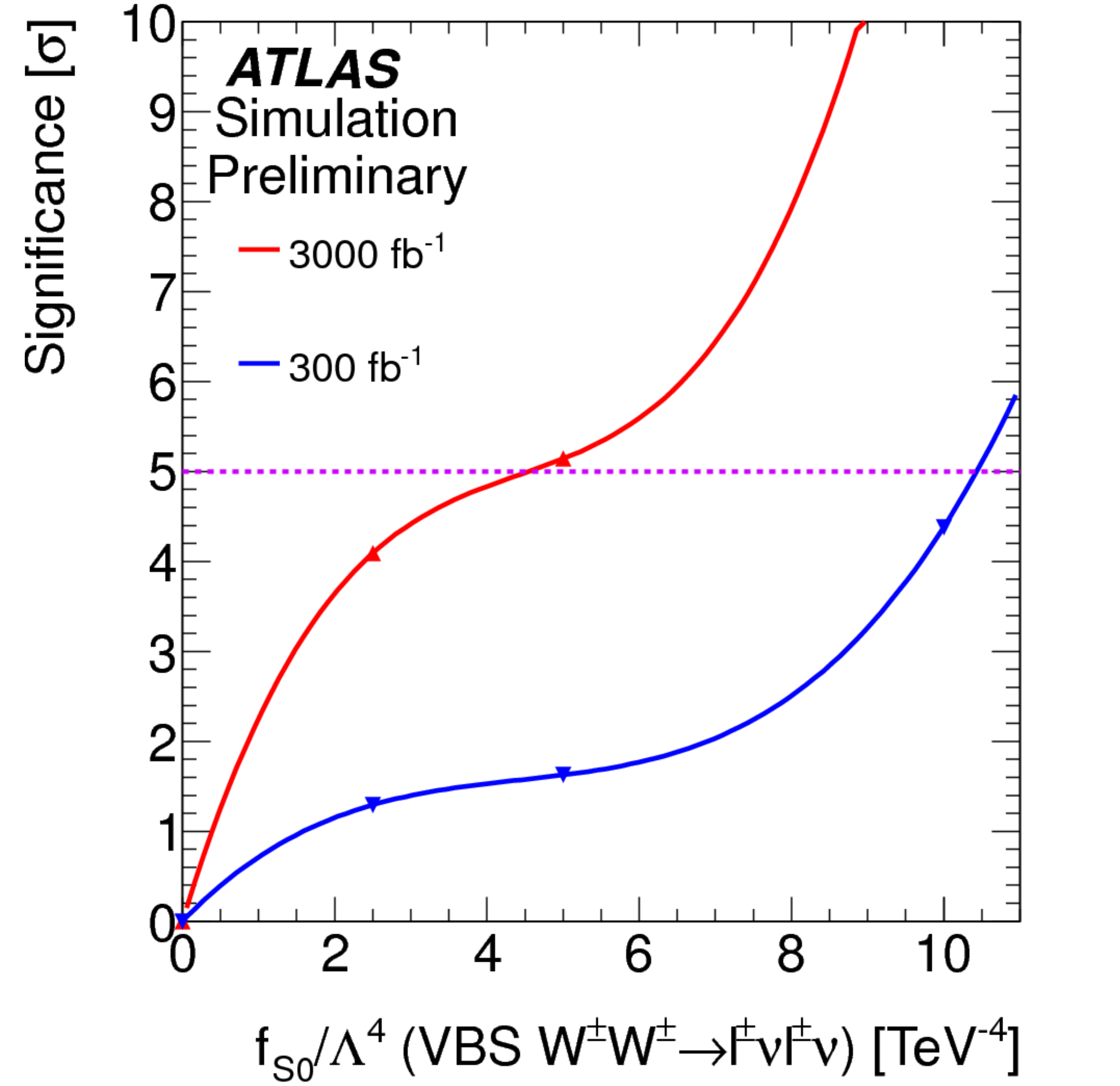

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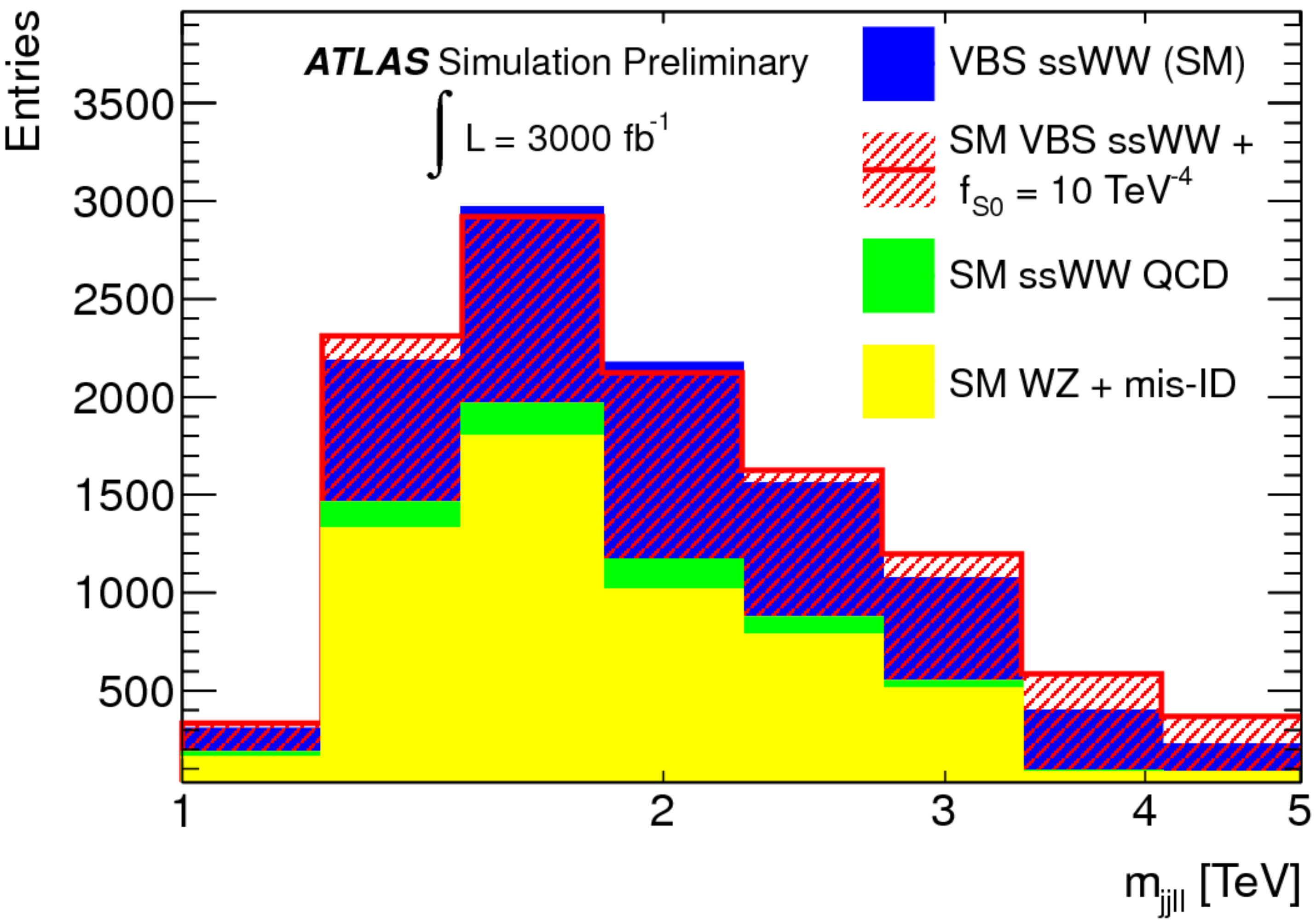

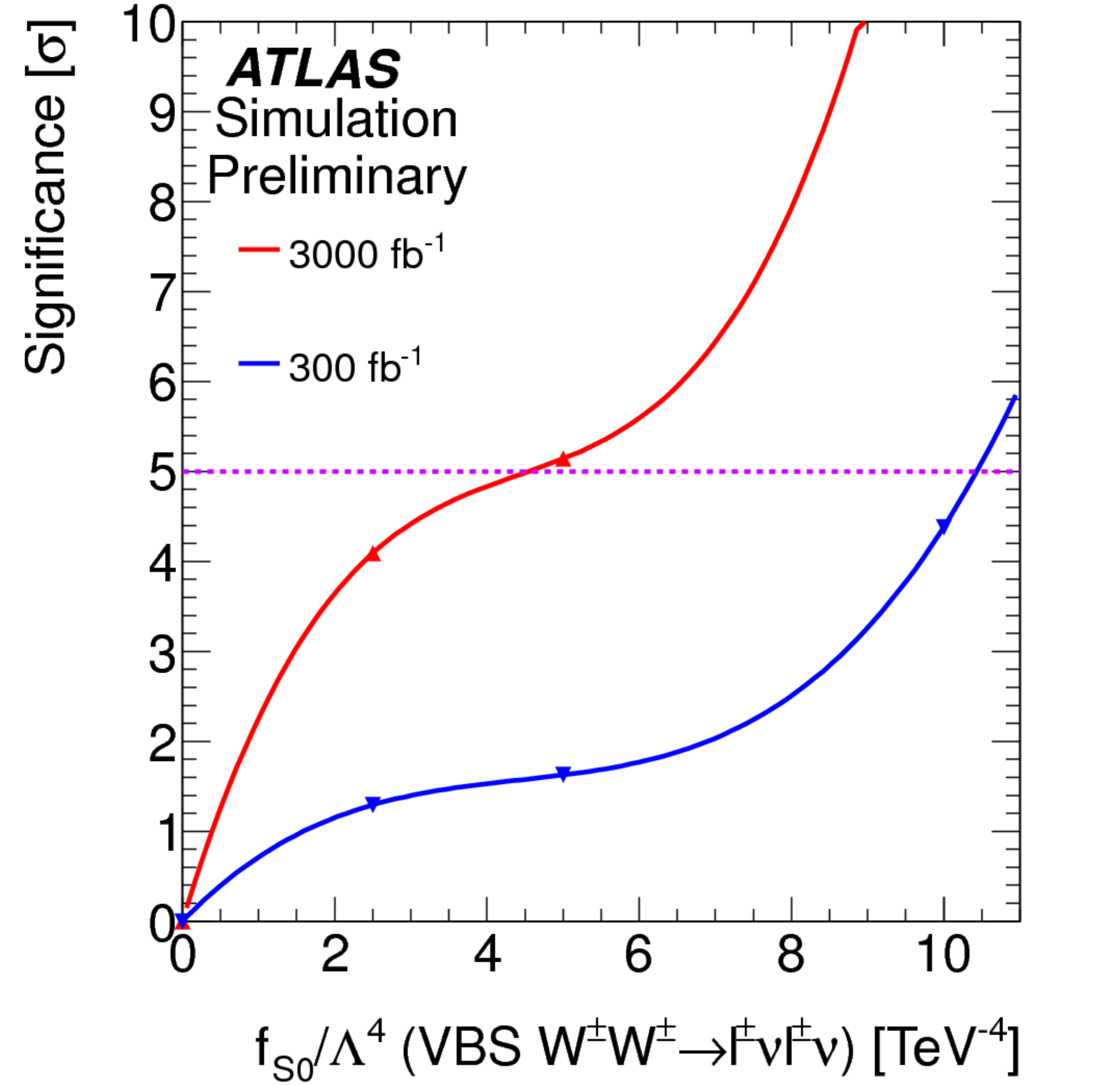

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model	300 fb^{-1}	3 ab^{-1}
f_{S0}/Λ^4	10 TeV^{-4}	4.5 TeV^{-4}

Sensitivity to anomalous WW resonances in Vector boson scattering

Conclusions

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  - Higgs self-coupling studies possible
  - VV scattering will be probed
- LHC has an exciting physics program for the next twenty years!

I would like to dedicate this talk to my father,

Prof. Giorgio Giacomelli

a worldwide known physicist,

who passed away on January 30th 2014

Giorgio Maria Giacomelli
30/05/1931 - 30/01/2014

Backup

New LHC schedule

LHC schedule beyond LS1

CMS Pixel installation

CMS target for LS3

Only EYETS (19 weeks) (no Linac4 connection during Run2)

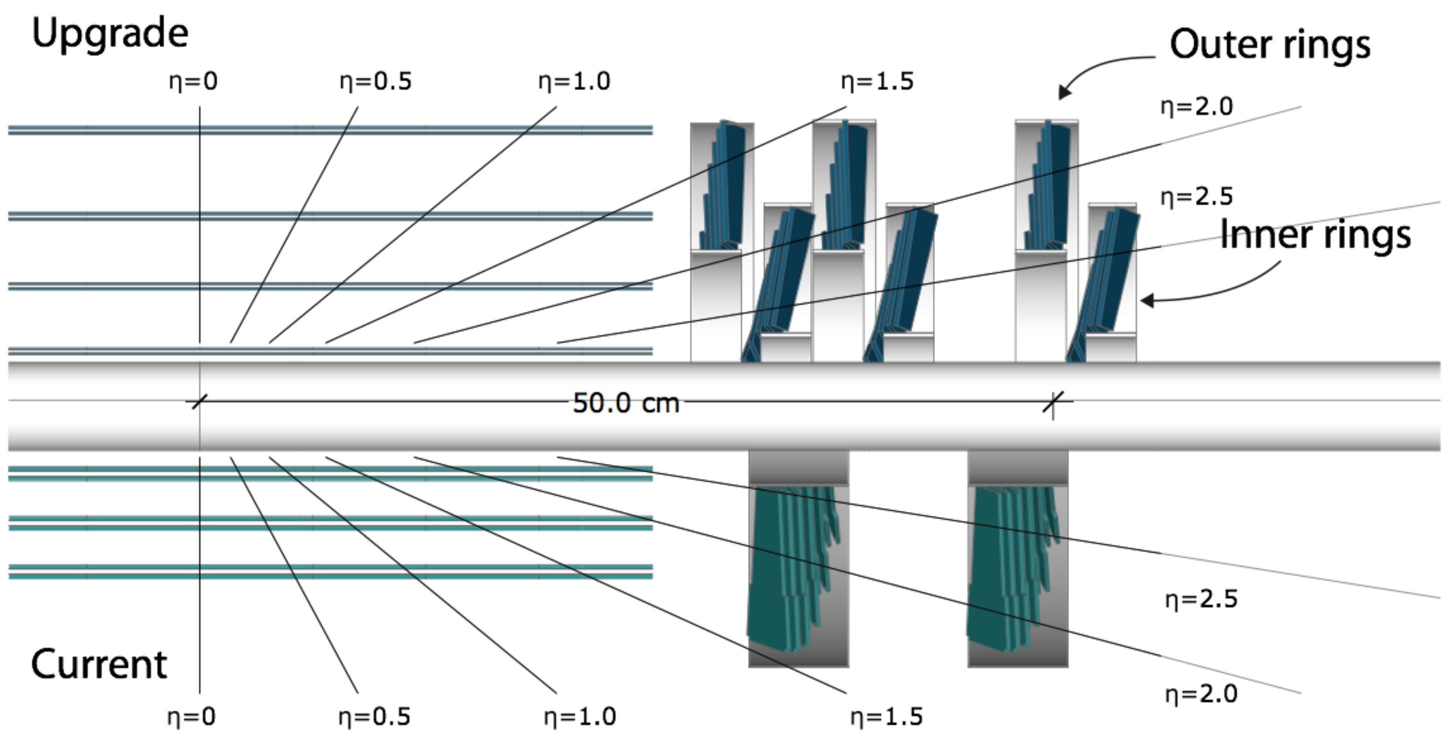
LS2 starting in 2018 (July) 18 months + 3months BC (Beam Commissioning)

LS3 LHC: starting in 2023 => 30 months + 3 BC

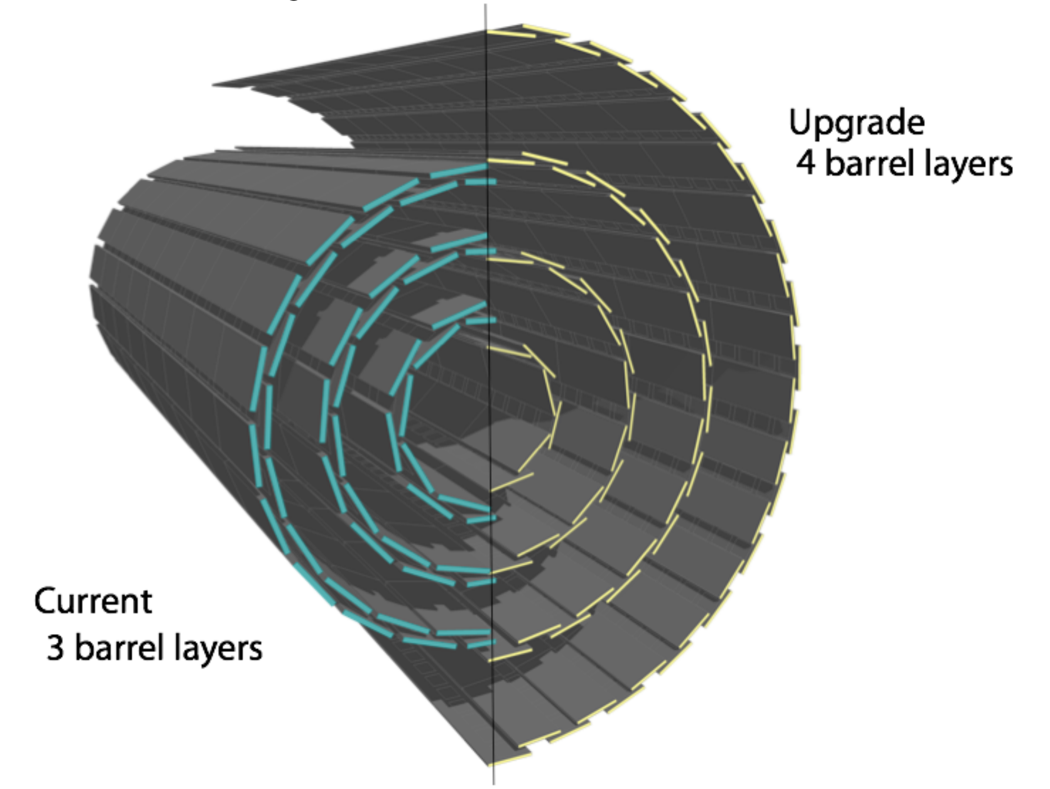
injectors: in 2024 => 13 months + 3 BC

Pixel and HCAL phase 1 upgrades

Pixel and HCAL phase 1 upgrades



New 4-layer pixel detector Pixel



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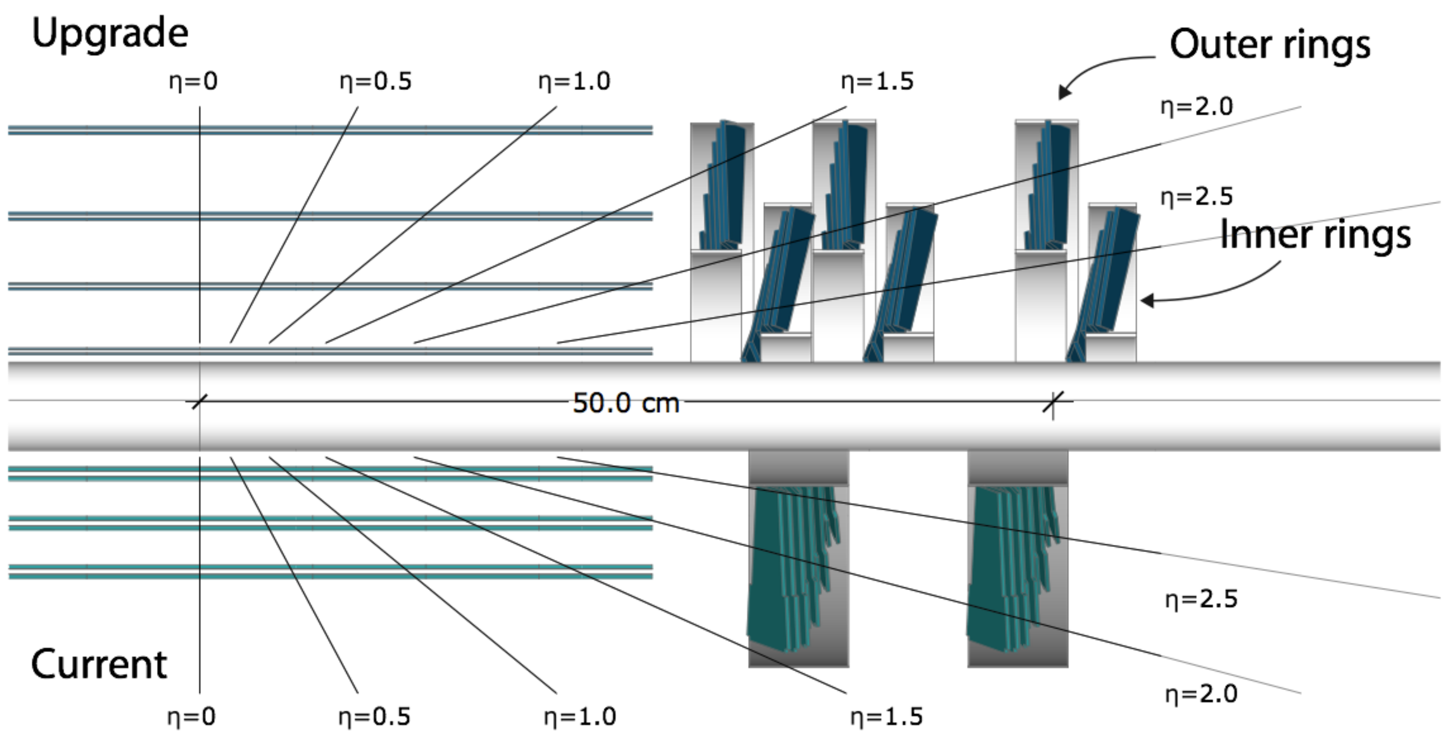

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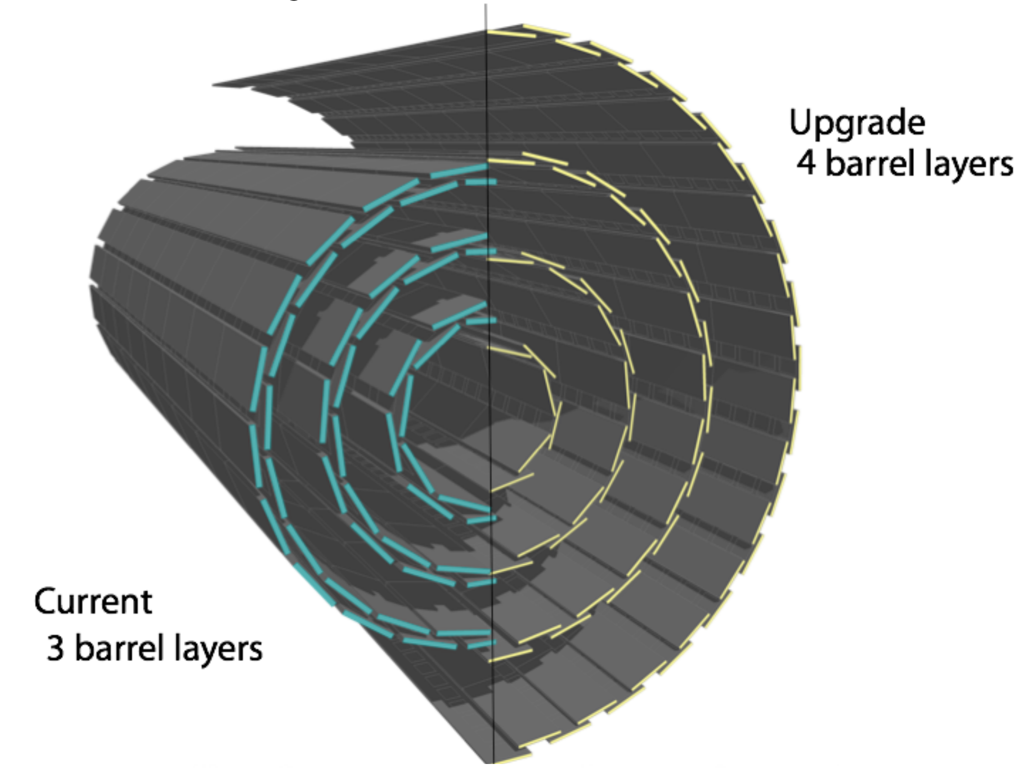
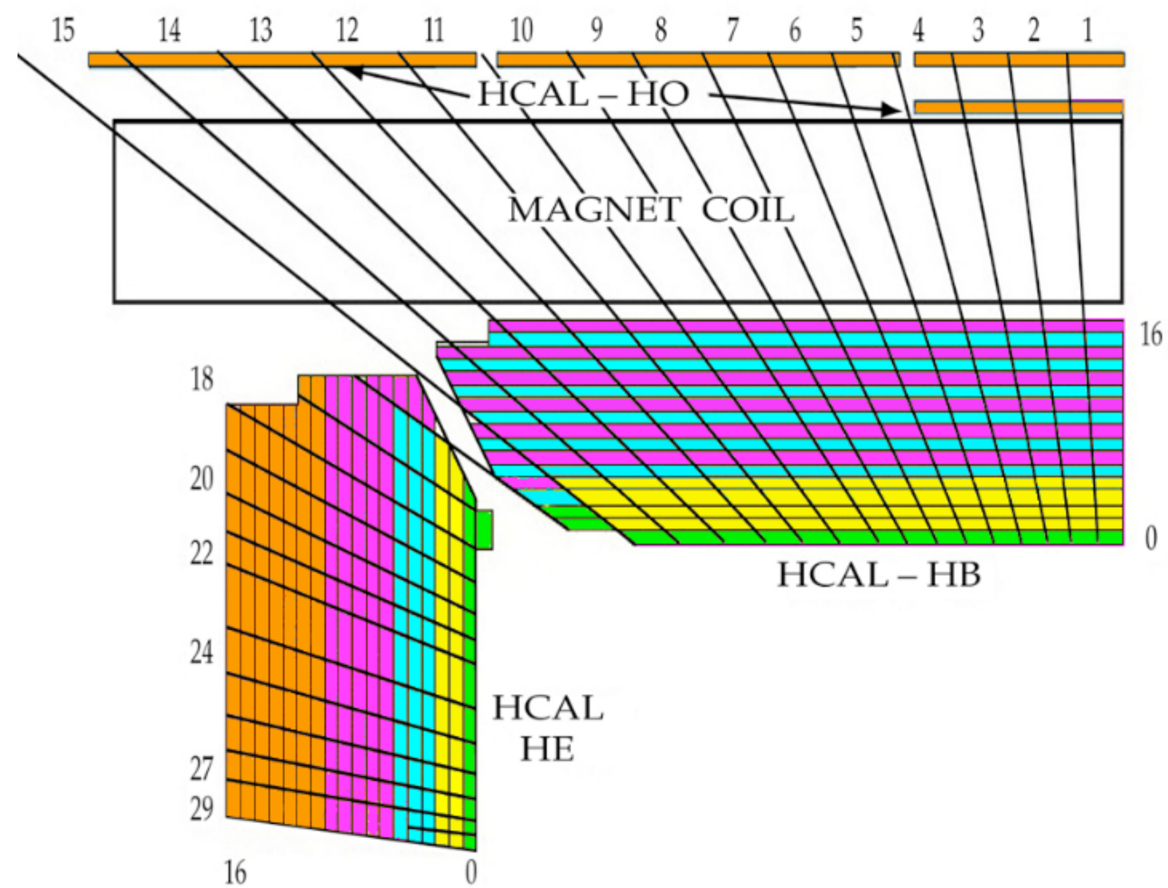


- Upgraded HCAL
  - New photodetectors
  - New electronics (frontend, backend)
  - Improved longitudinal segmentation
  - Improved background rejection, Missing E_T resolution and Particle Flow reconstruction



Signal strength @3000 fb^{-1}

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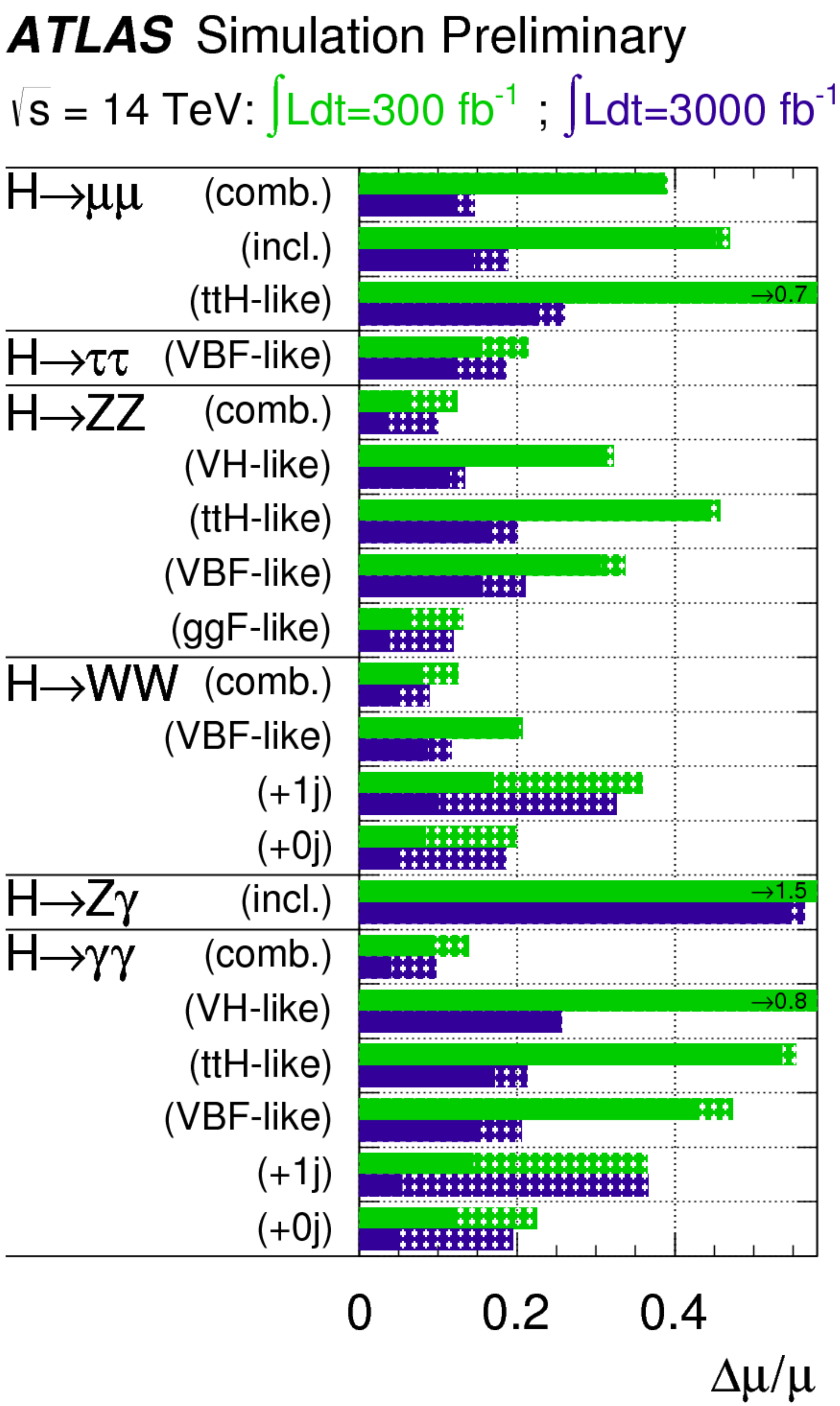

$\mu = \sigma/\sigma_{SM}$

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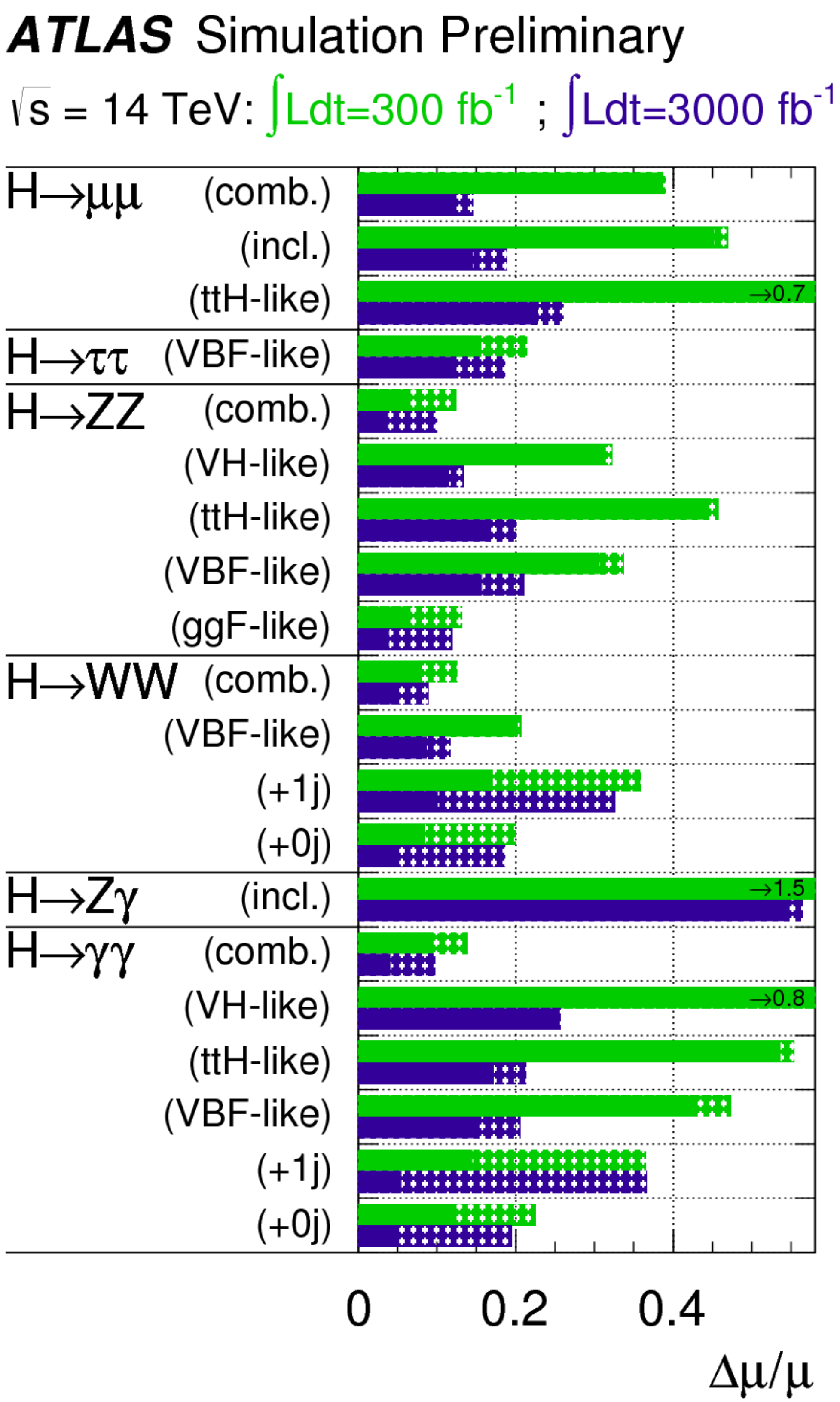

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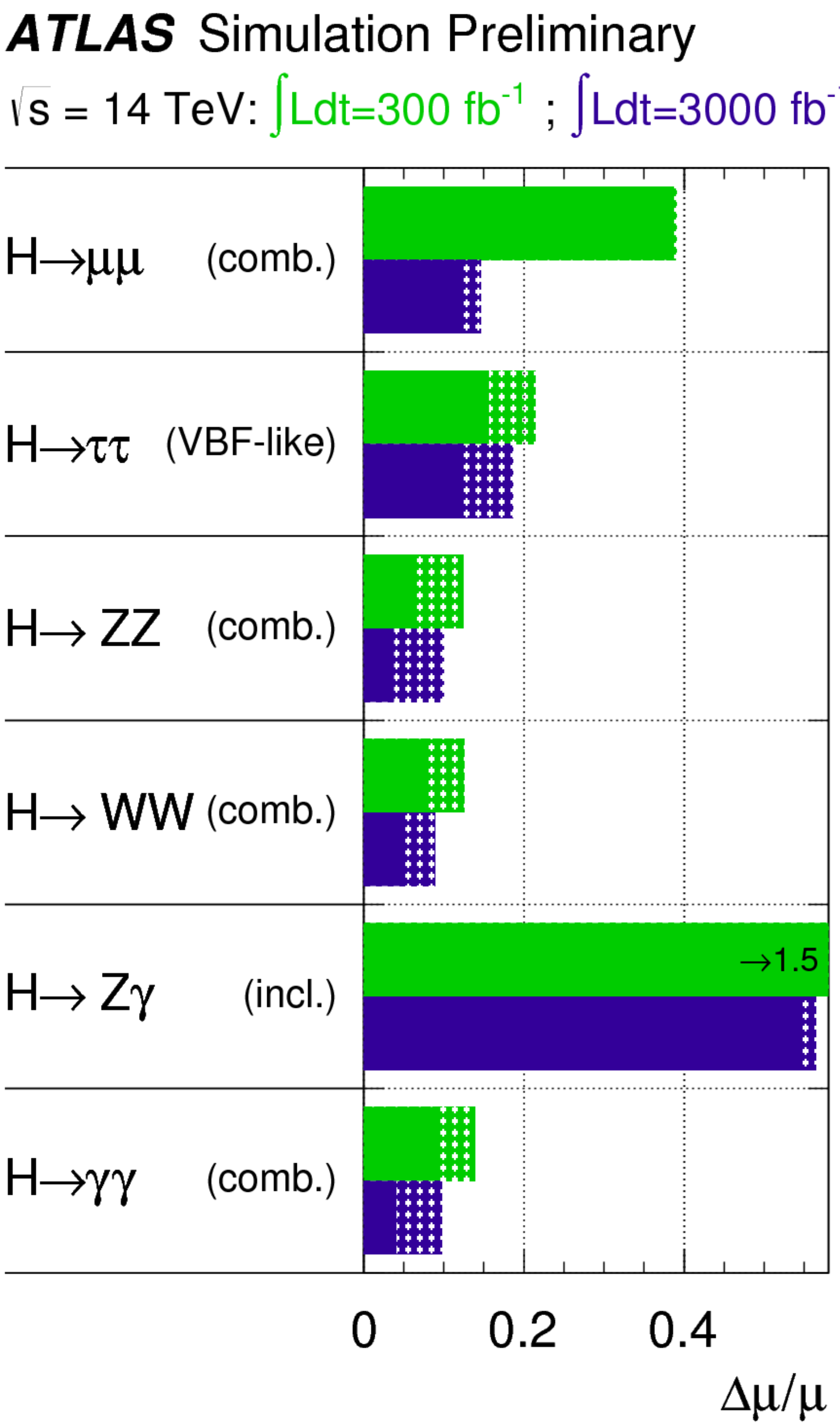

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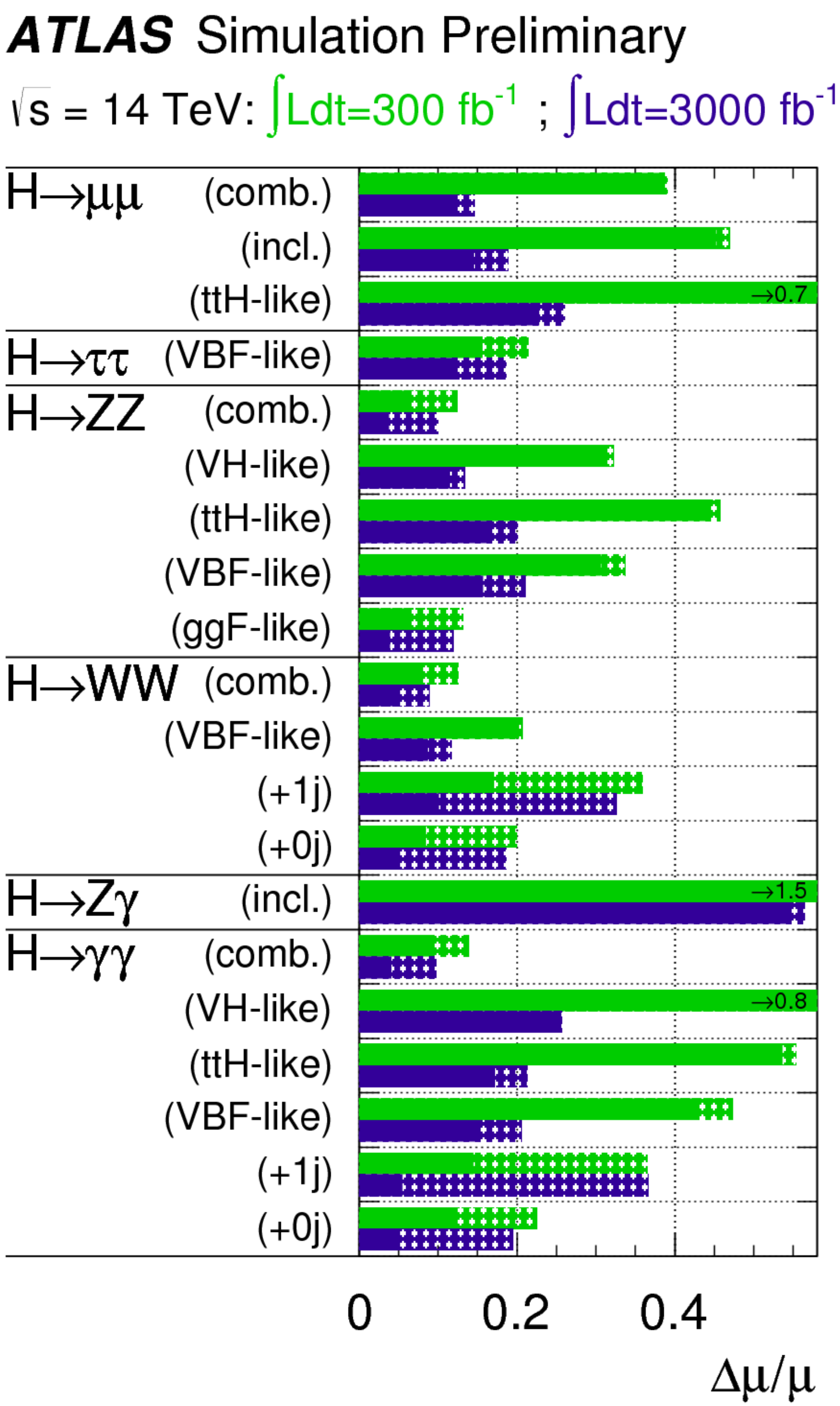

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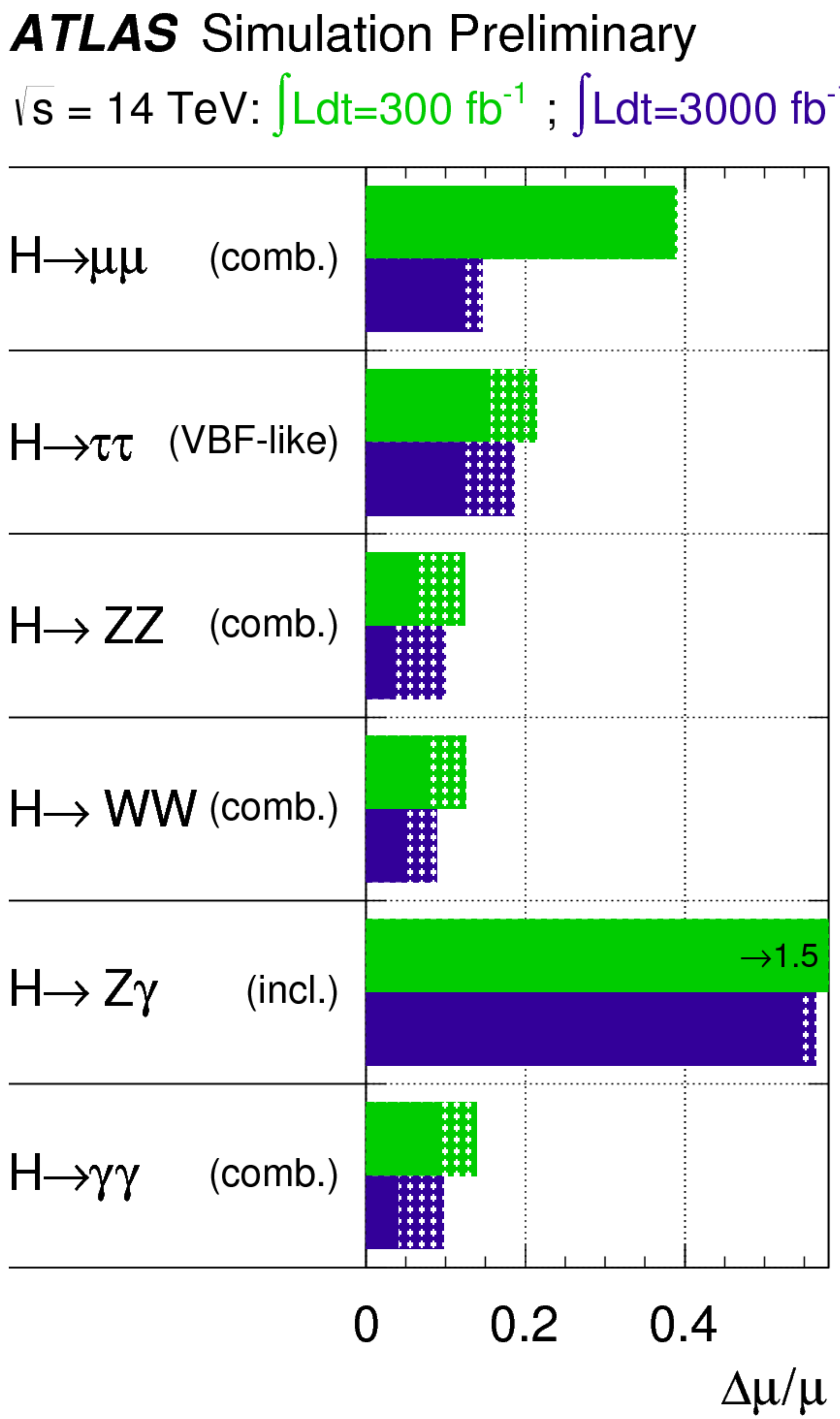
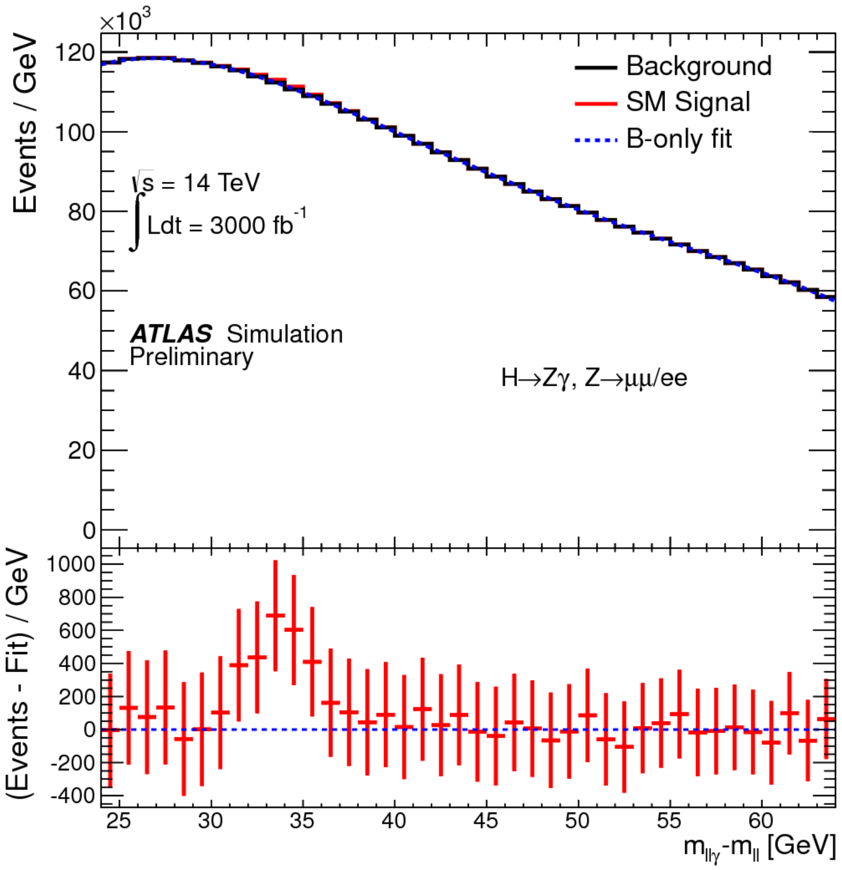


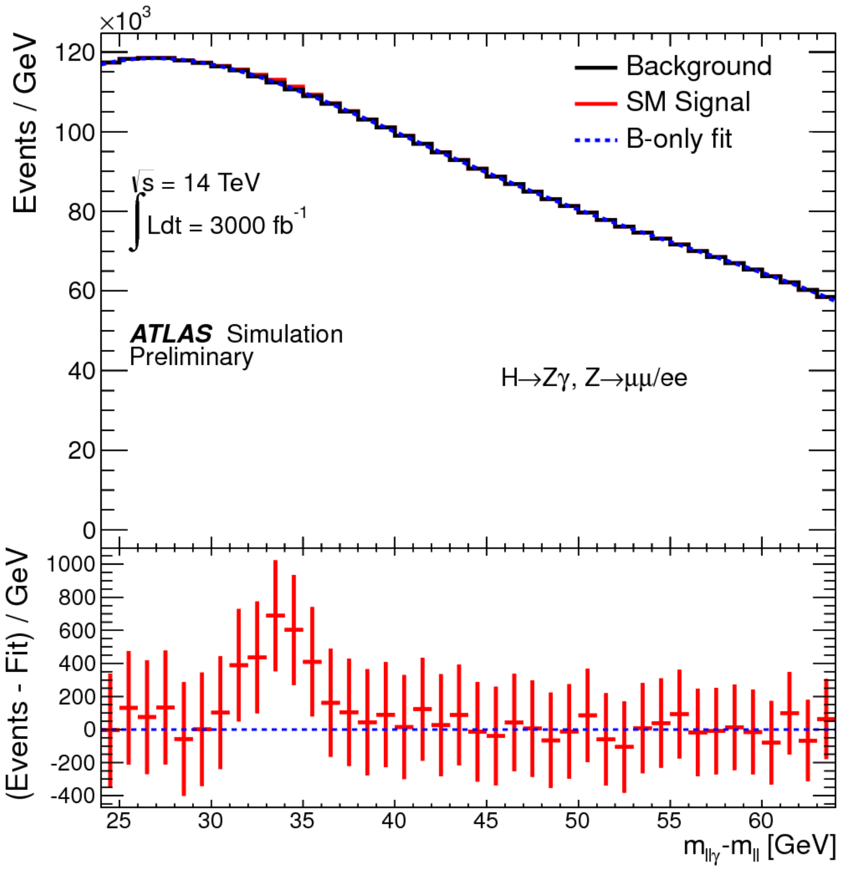
- With 3000 fb^{-1} the couplings can be determined with high precision (a few %)

H→Zγ



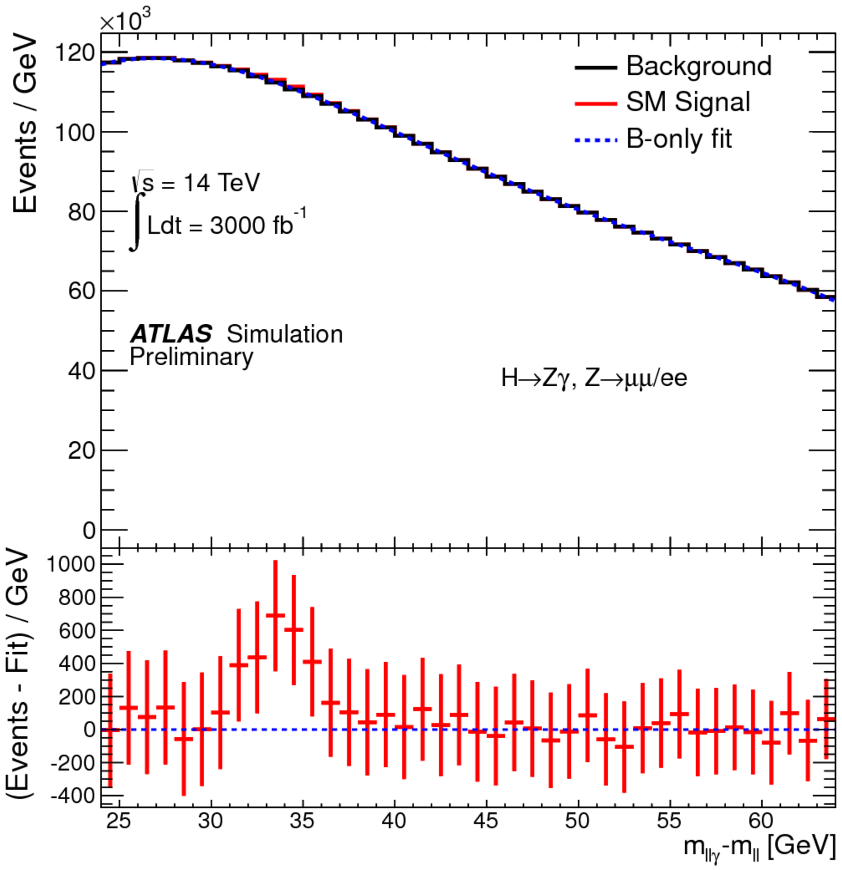
×10^3
Events / GeV
Background
SM Signal
B-only fit
√s = 14 TeV
∫Ldt = 3000 fb^-1
ATLAS Simulation
Preliminary
H→Zγ, Z→μμ/ee
(Events - Fit) / GeV
m_llγ-m_ll [GeV]

H→Zγ



VBF signal (2 jets)

H→Zγ



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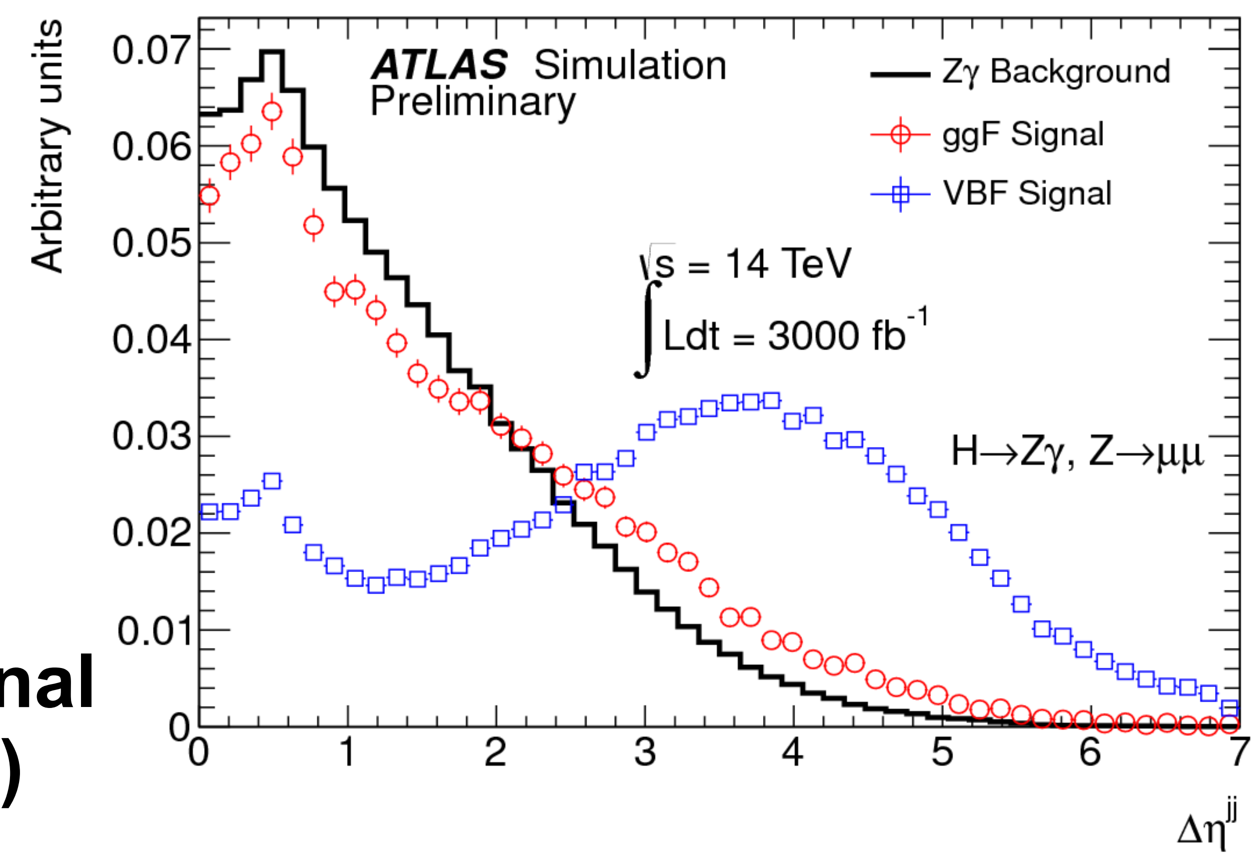

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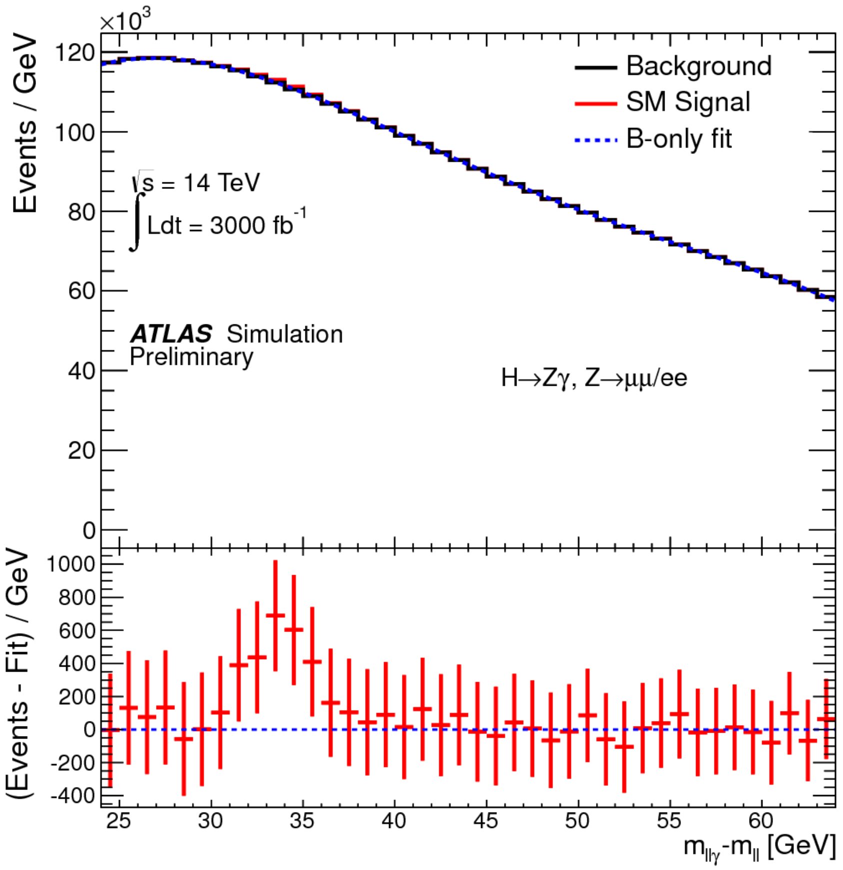

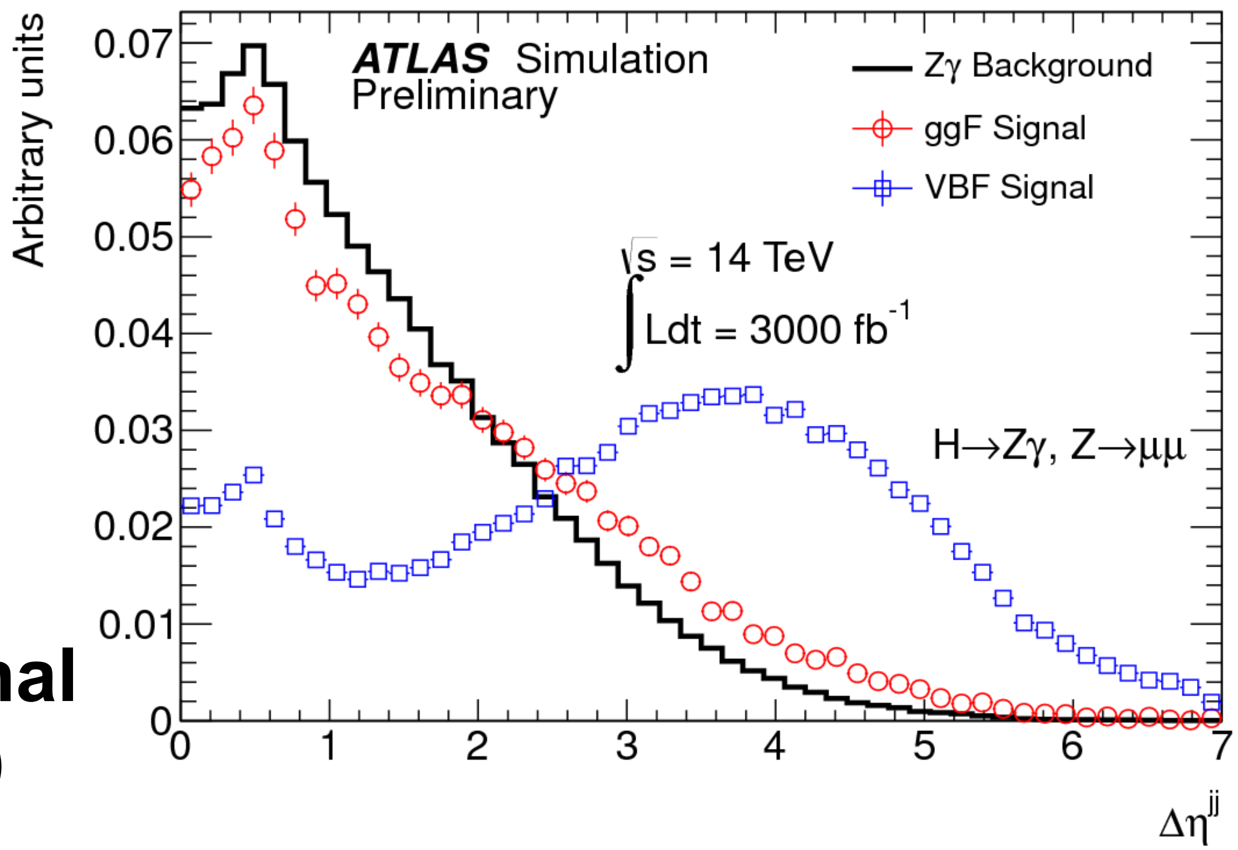

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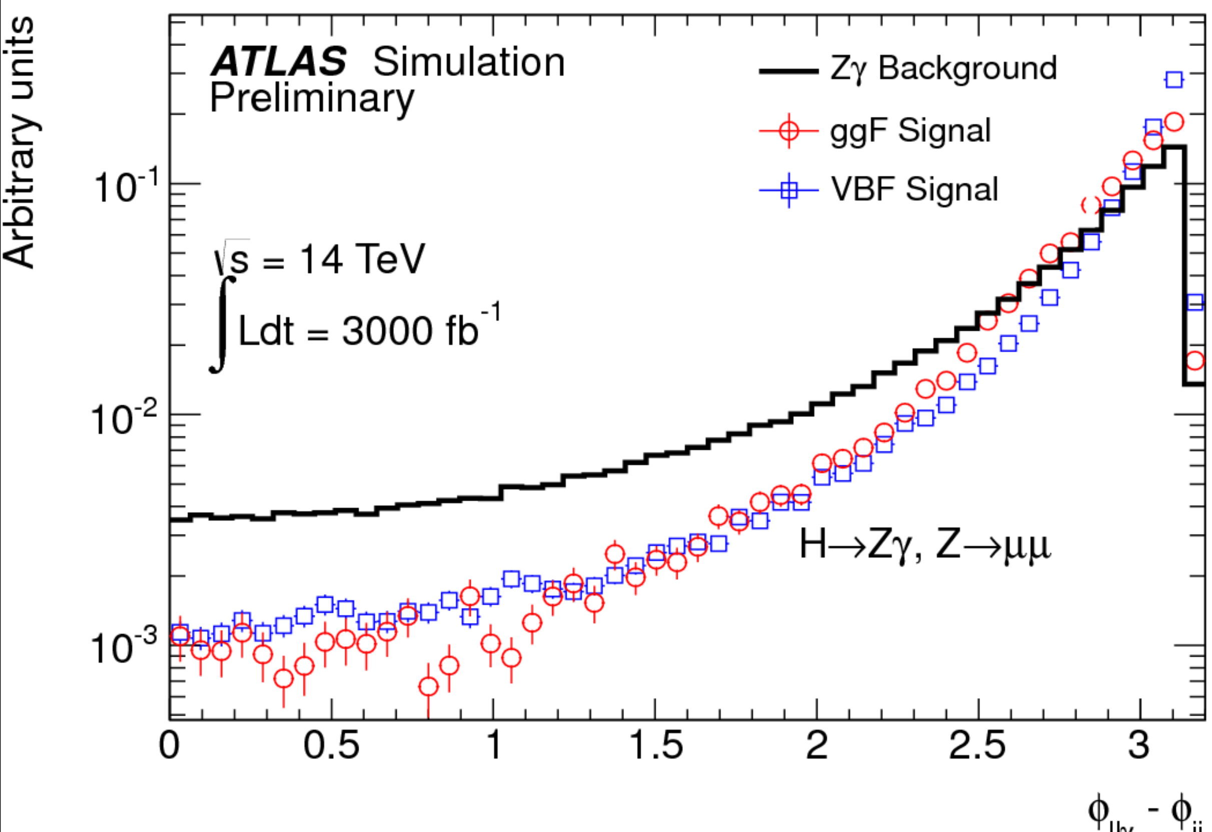

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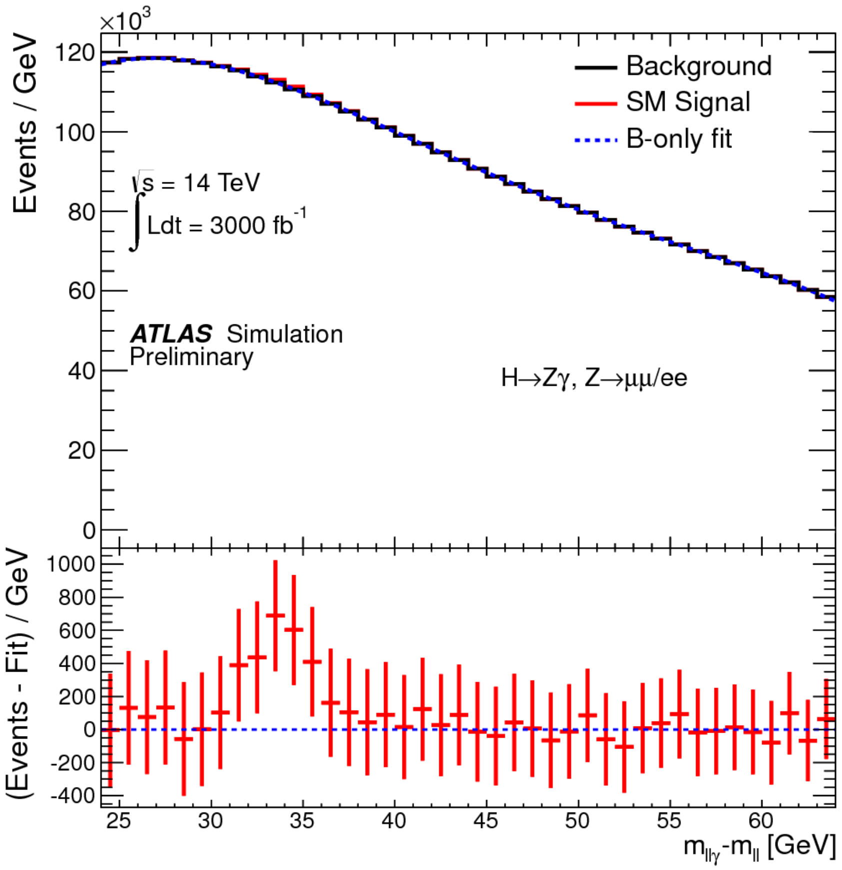

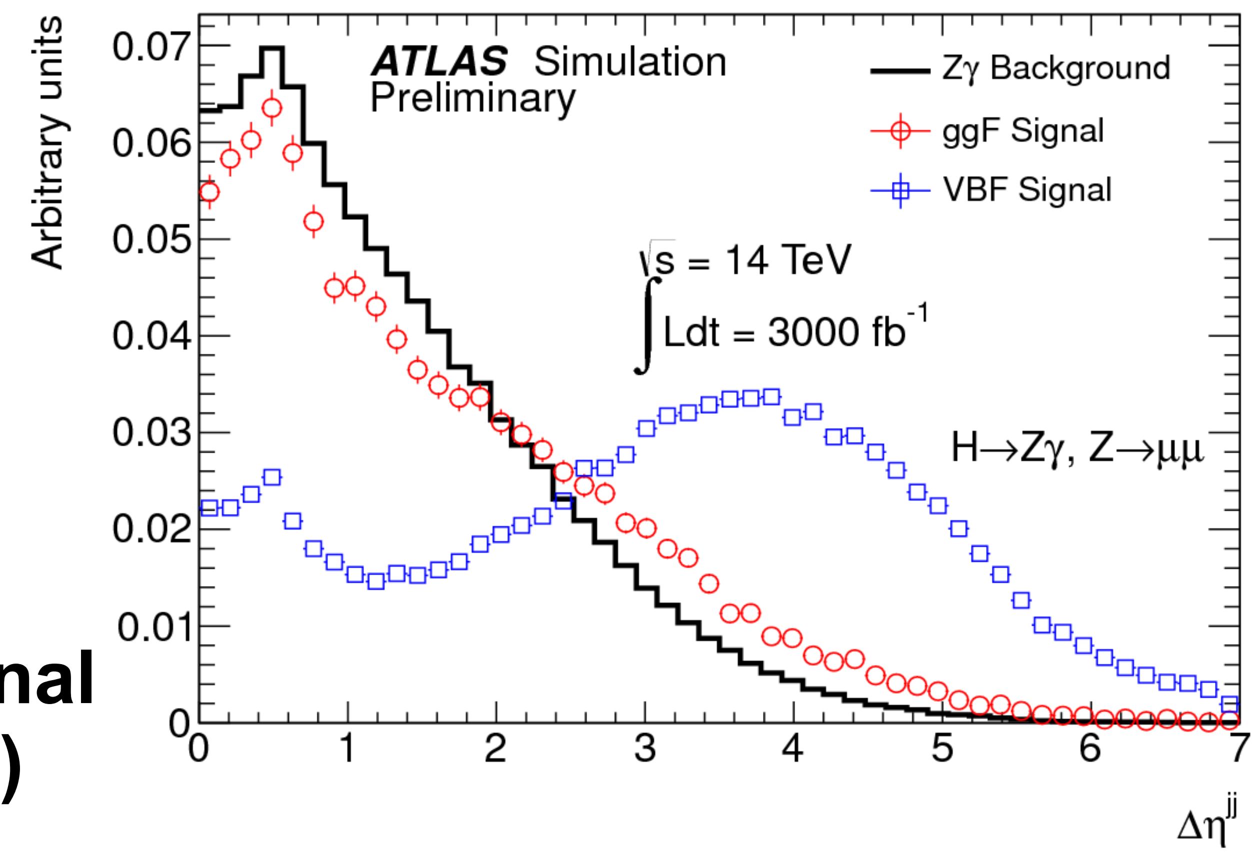

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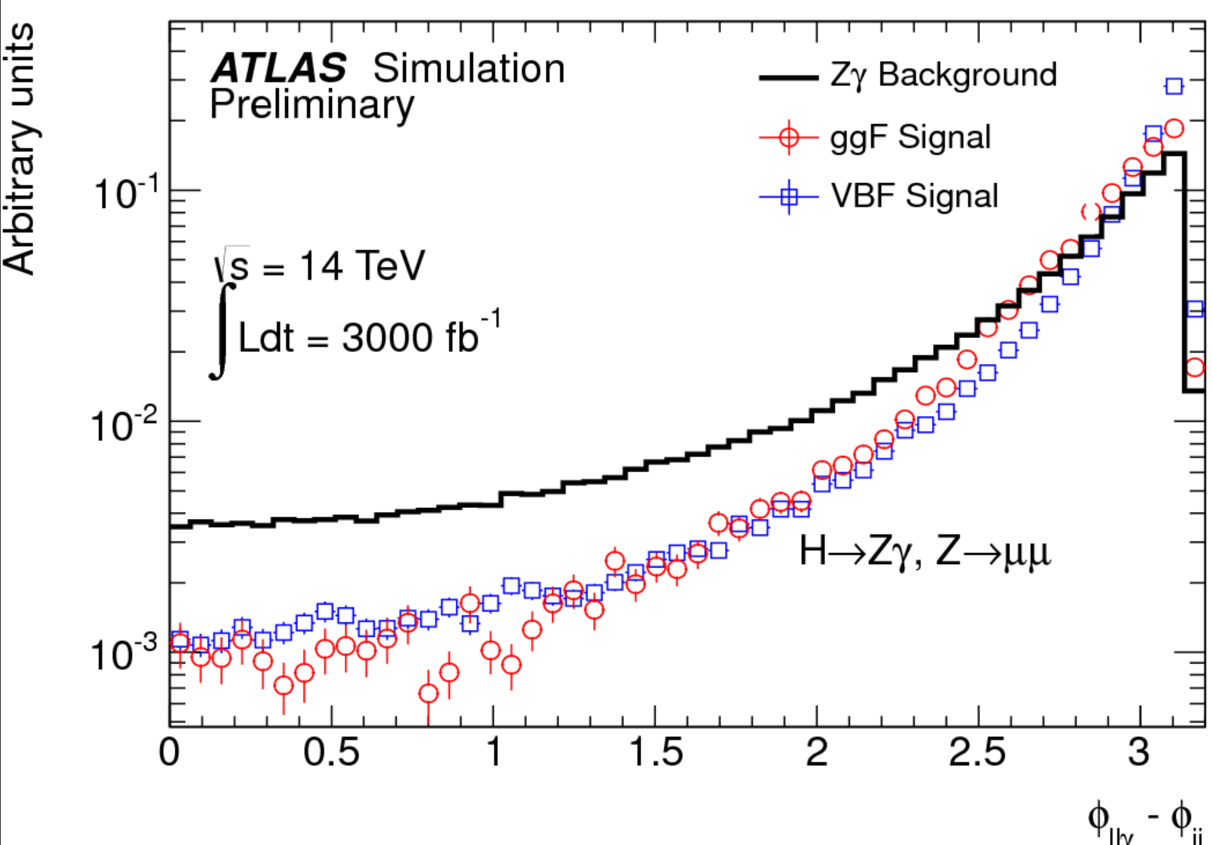
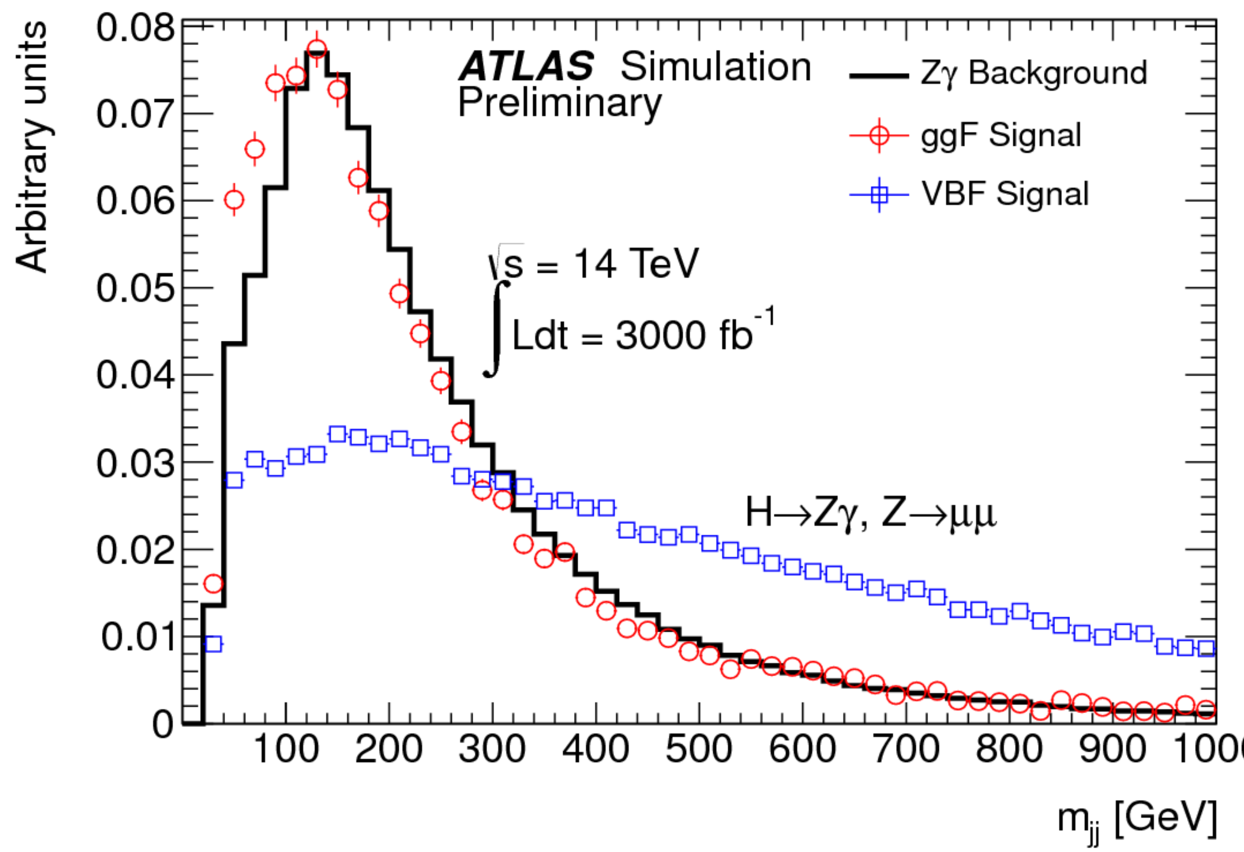




VV scattering: fully leptonic

CMS AN 2007-005

CERN-OPEN-2008-020

Only background VV+jets, very low xsec

Number of events for 20 fb^{-1} (fully MC based, no systematics, 14 TeV)

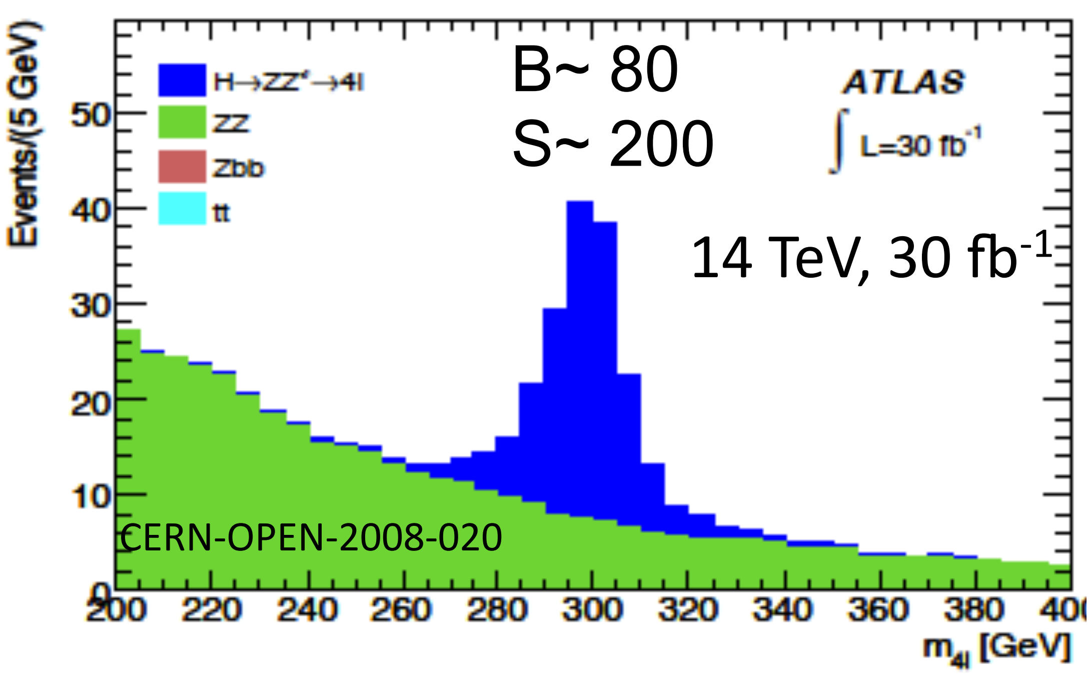
CMS ZZ->4e, 4μ	N signal	N back.
500 GeV	2.2	1.9
>1 TeV	0.1	0.2

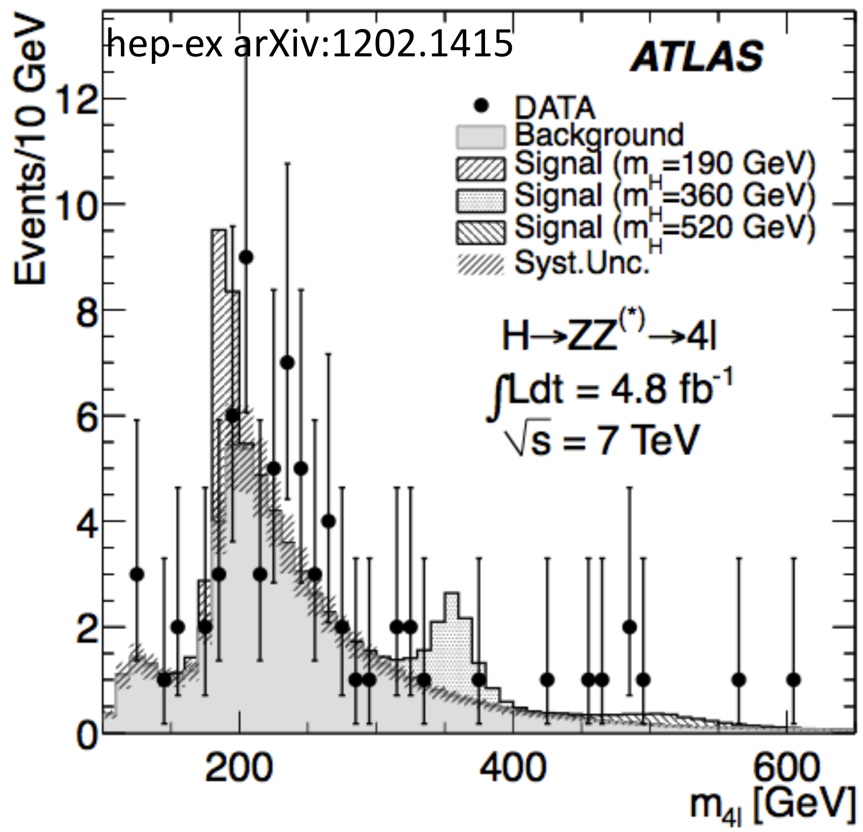
CMS ZW->μμμν	N signal	N back.
>1 TeV	0.9	0.8

ATLAS ZZ->2l2ν	N signal	N back.
500 GeV	6.4	3.0

ATLAS ZW->lllν	N signal	N back.
500 GeV	8	5
1.1 TeV	1.4	0.4

Example: ggF Higgs 300 GeV





Latest results:
B~ 6
S~ 10

- reso m_{4l} as expected
- improved reco-id efficiencies

(eg ele ID: TDR time 85-90% -> today 95%)

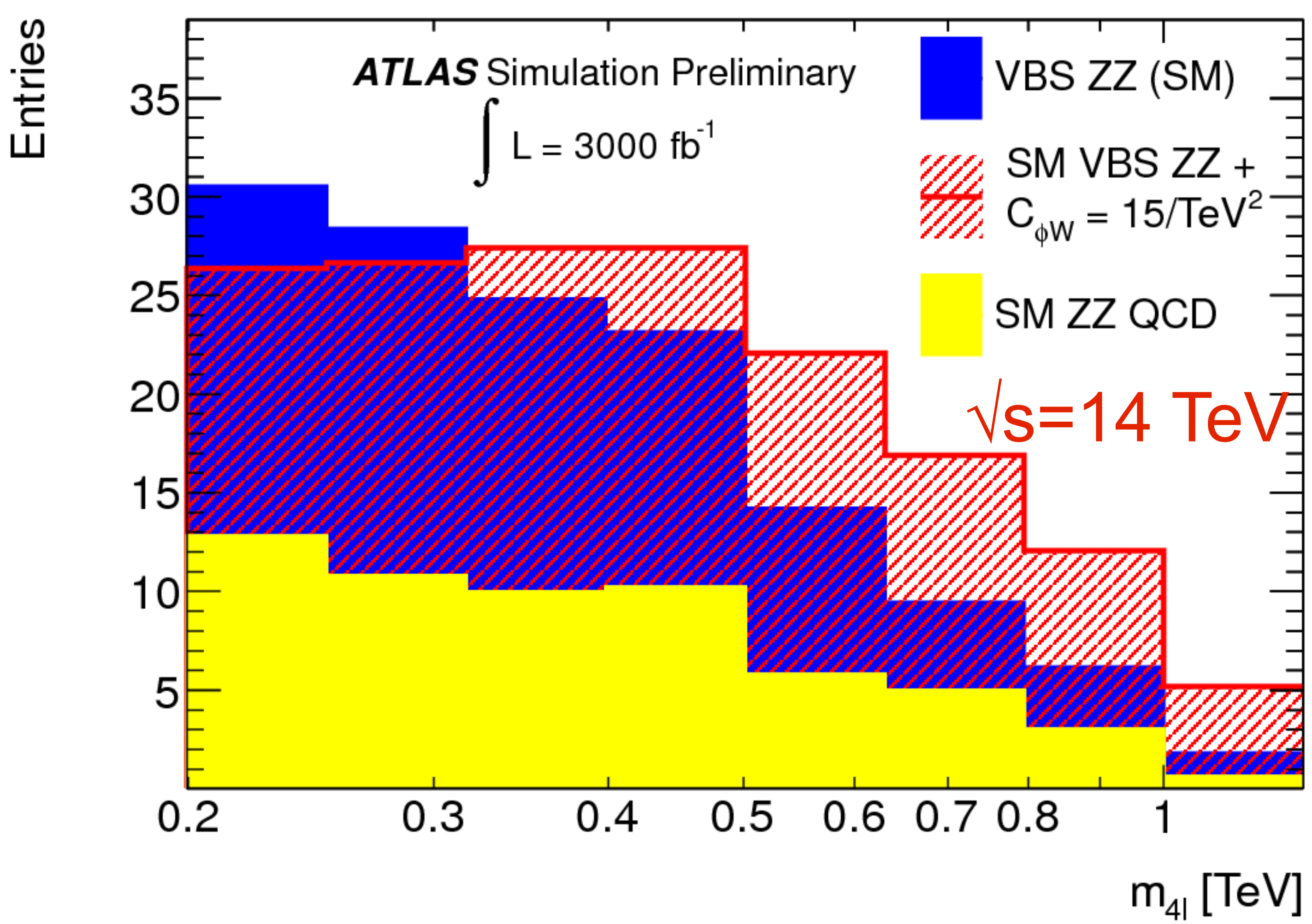
ZZ resonance

ZZ resonance

pp→ZZ+2j→4ℓ+2j channel

ZZ resonance

pp→ZZ+2j→4ℓ+2j channel



$$\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2}\mathrm{Tr}(W^{\mu\nu}W_{\mu\nu})\phi^\dagger\phi$$

ZZ resonance

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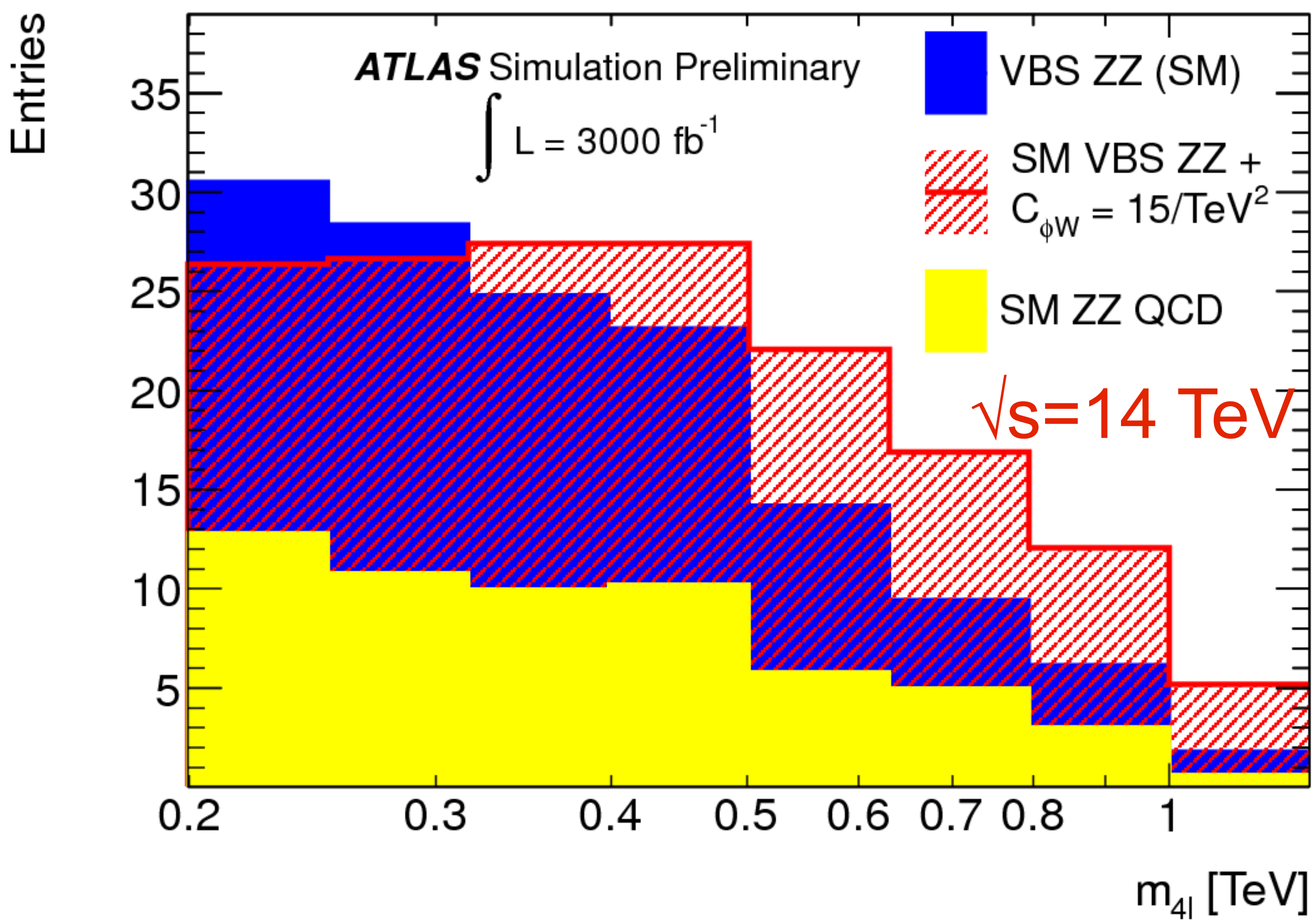

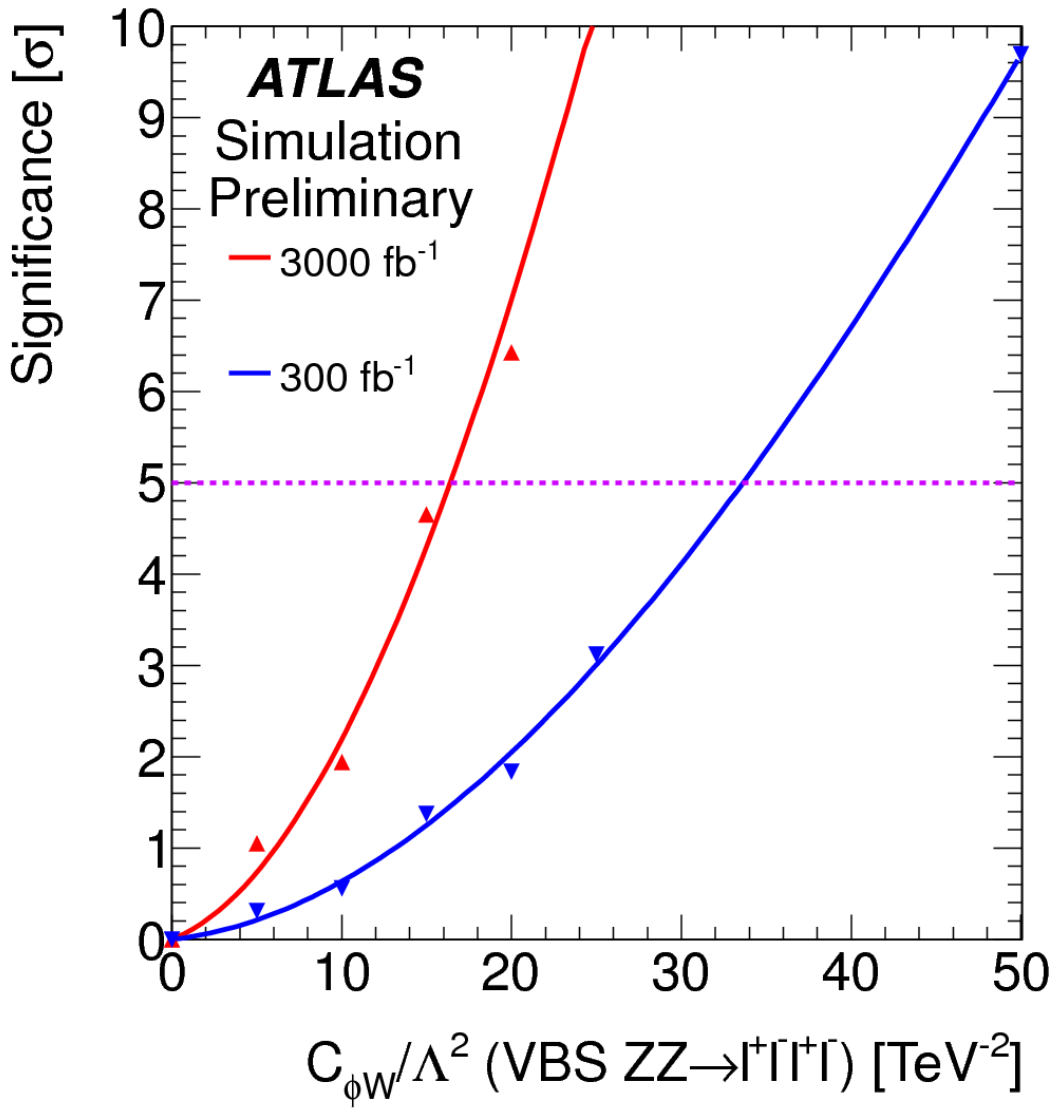

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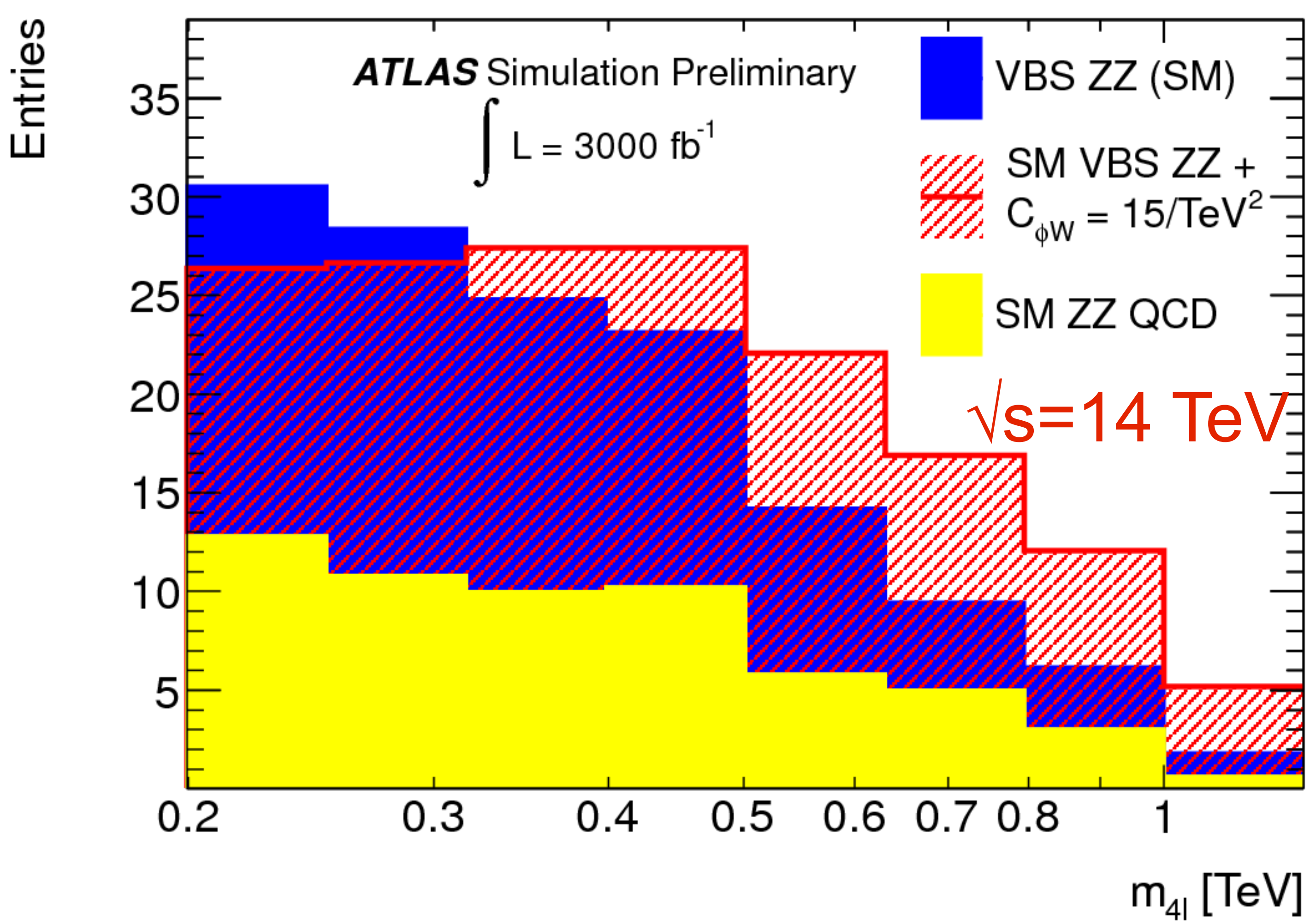

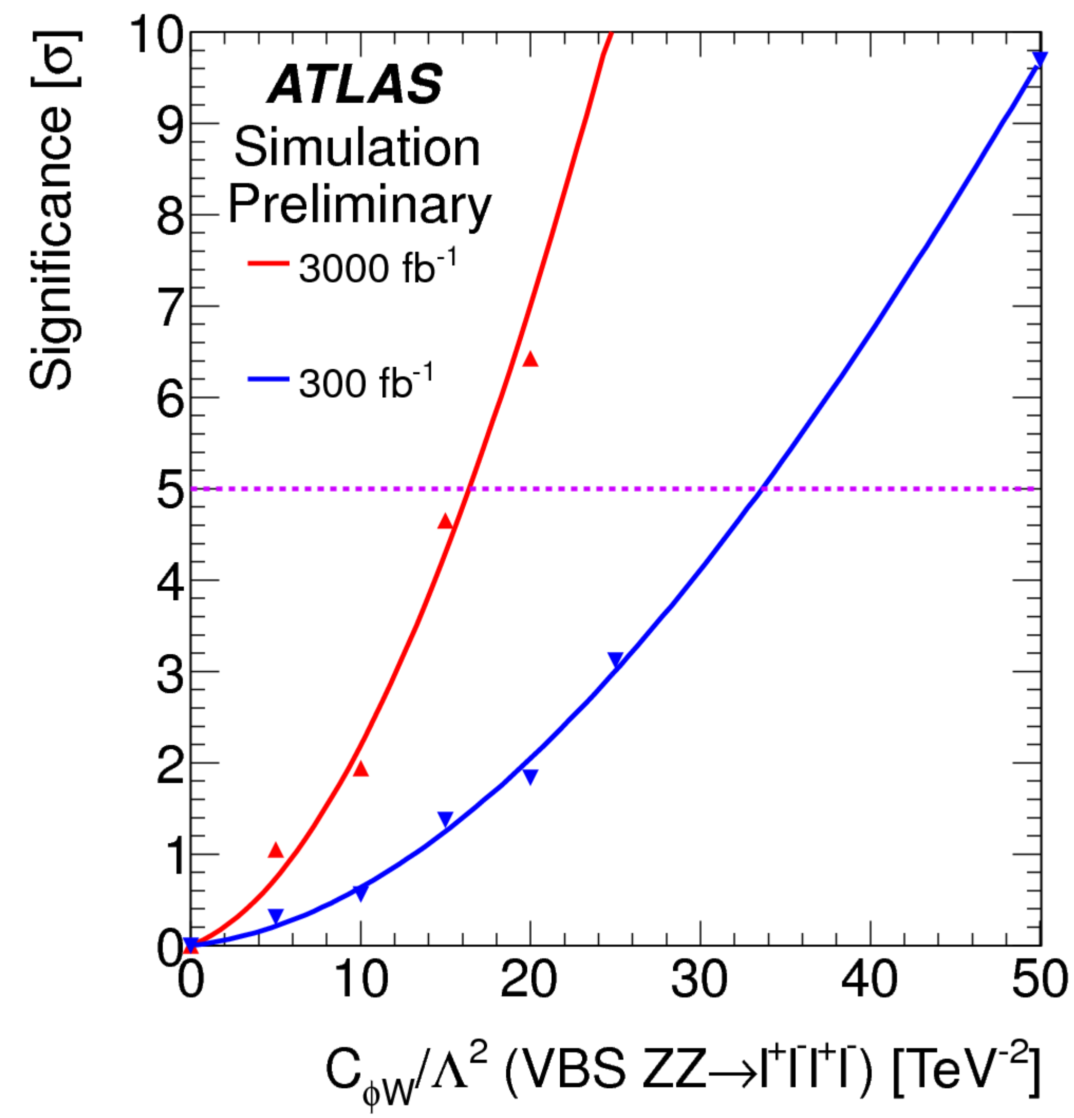

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	300 fb^{-1}	3000 fb^{-1}
$c_{\phi W}/\Lambda^2$	34 TeV^{-2}	16 TeV^{-2}

Sensitivity to anomalous ZZ resonances in Vector boson scattering

WZ scattering

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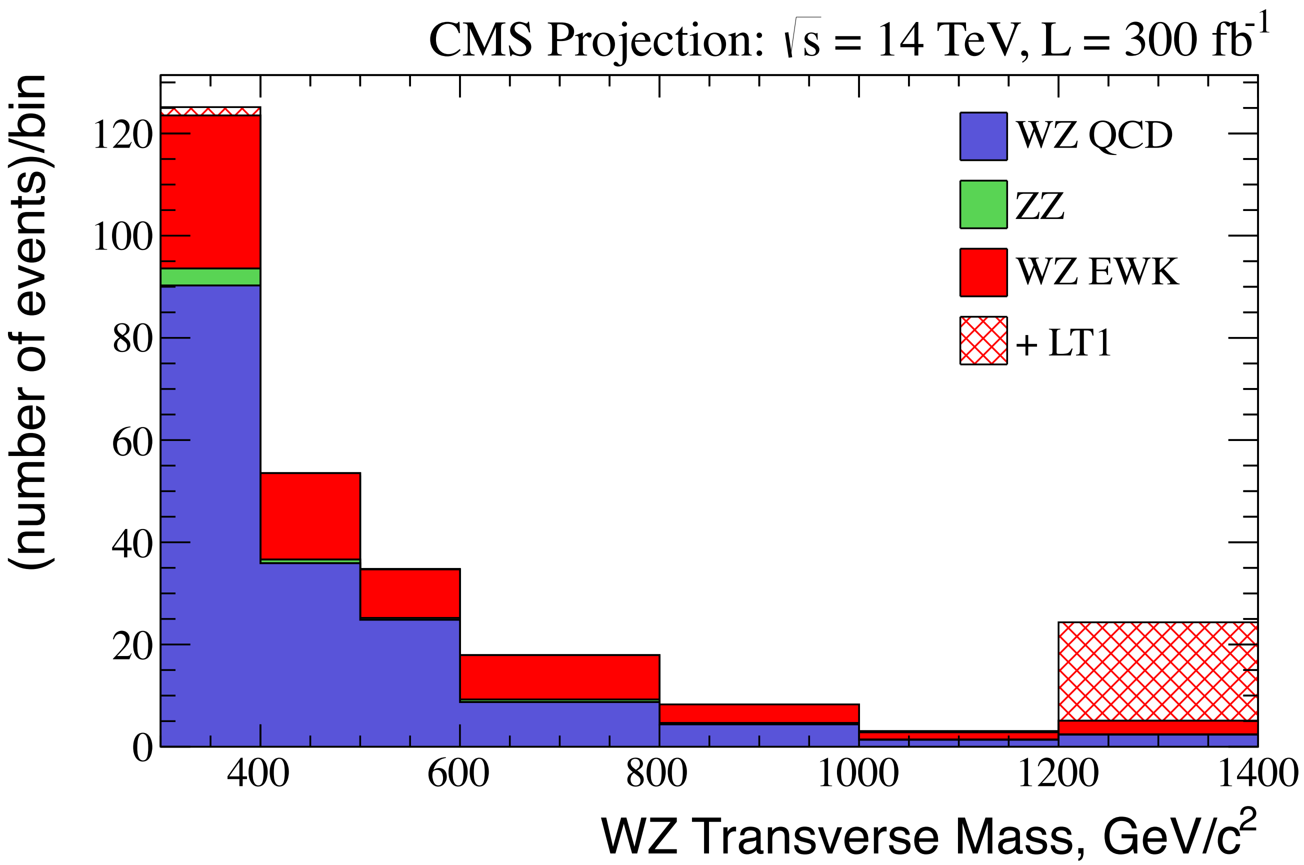

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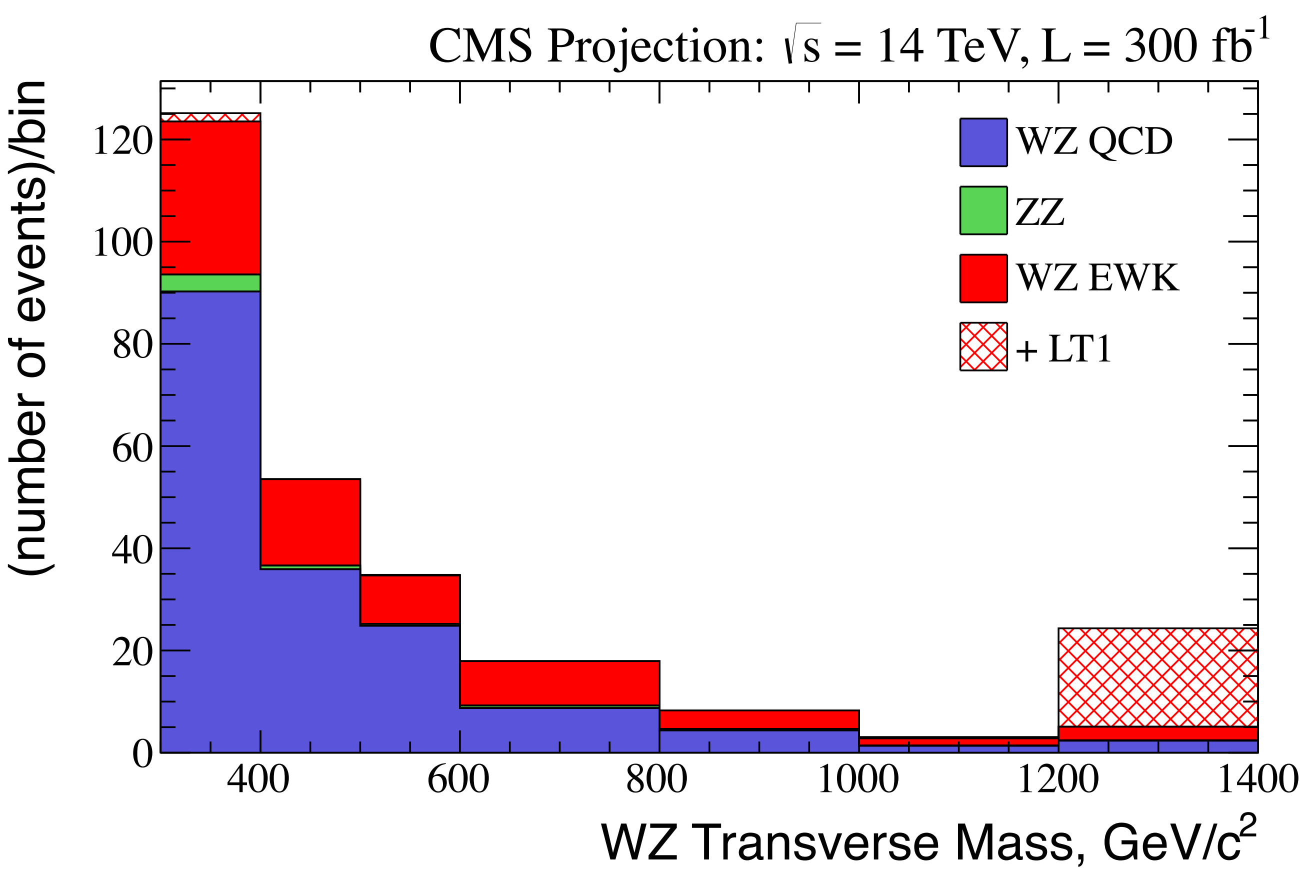

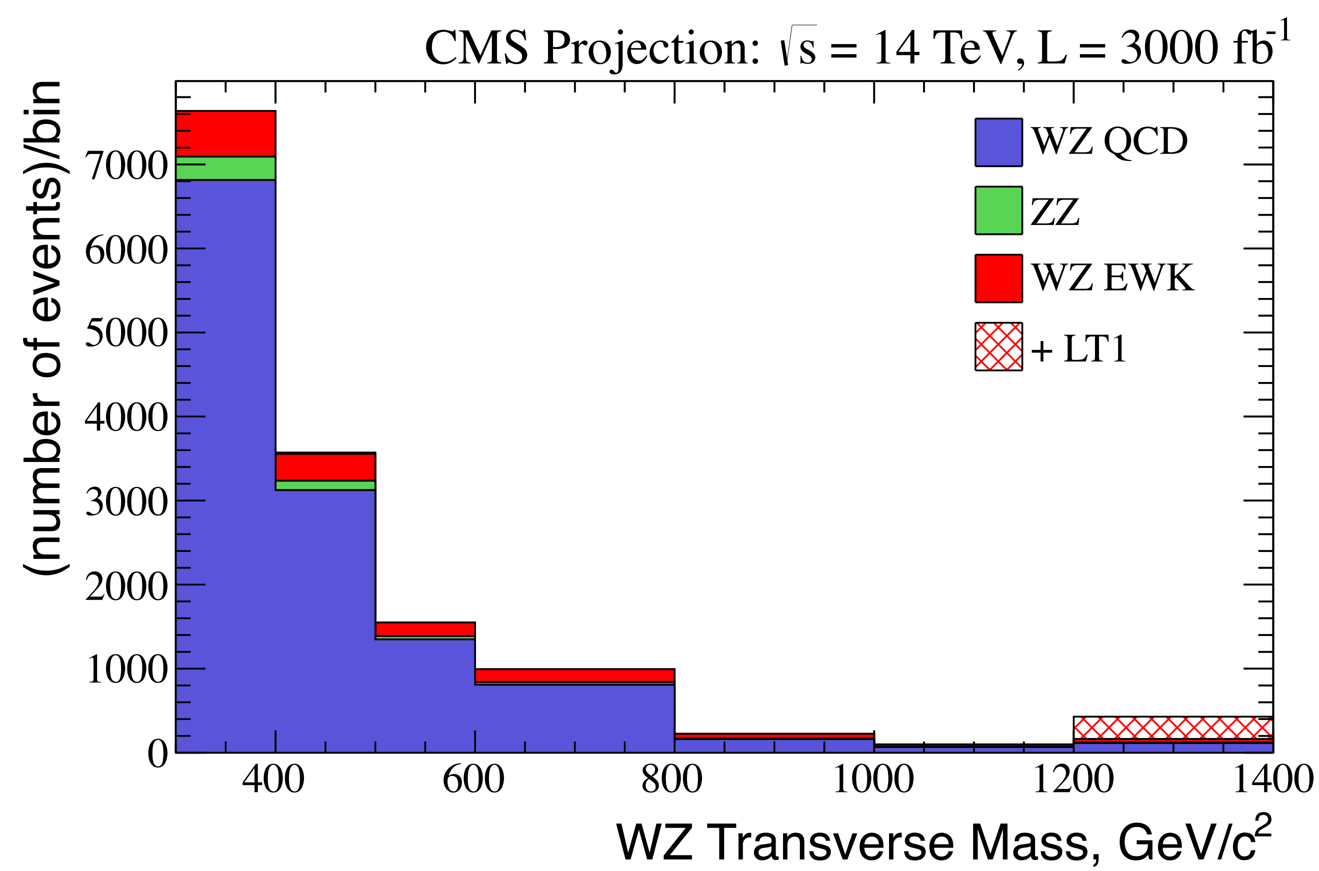

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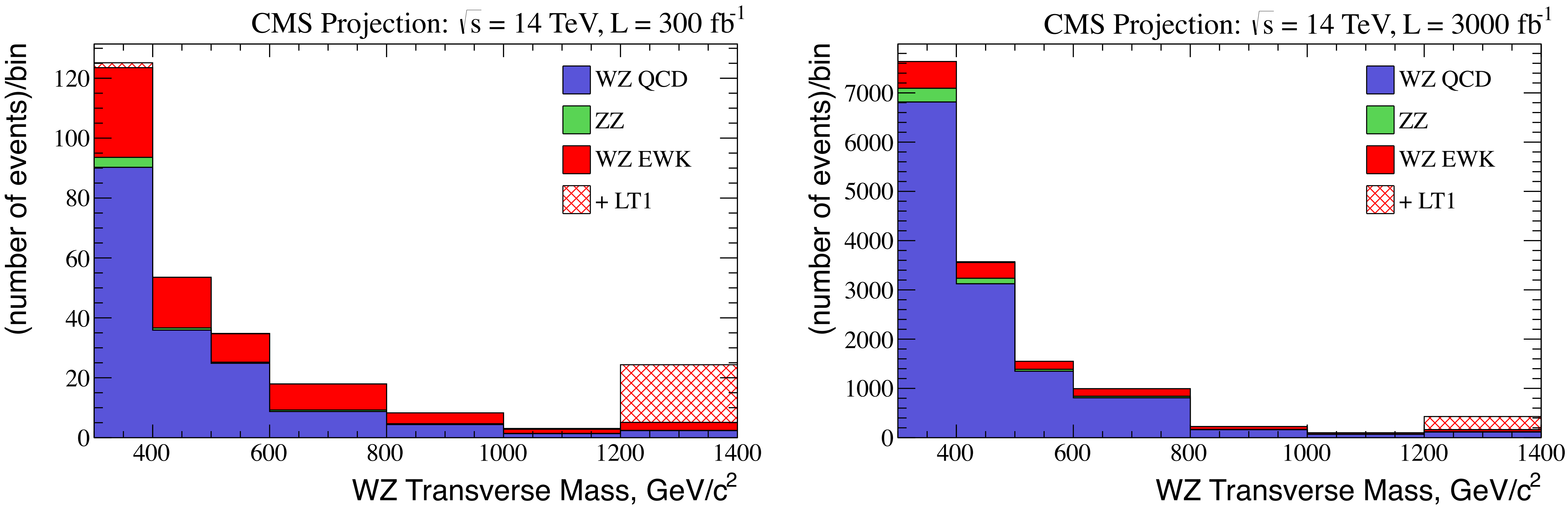


Significance	3σ	5σ
SM EWK Scattering Discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}
f_{T1}/Λ^4 at 3000 fb^{-1}	0.45 TeV^{-4}	0.55 TeV^{-4}

Sensitivity to anomalous WZ resonances in Vector boson scattering

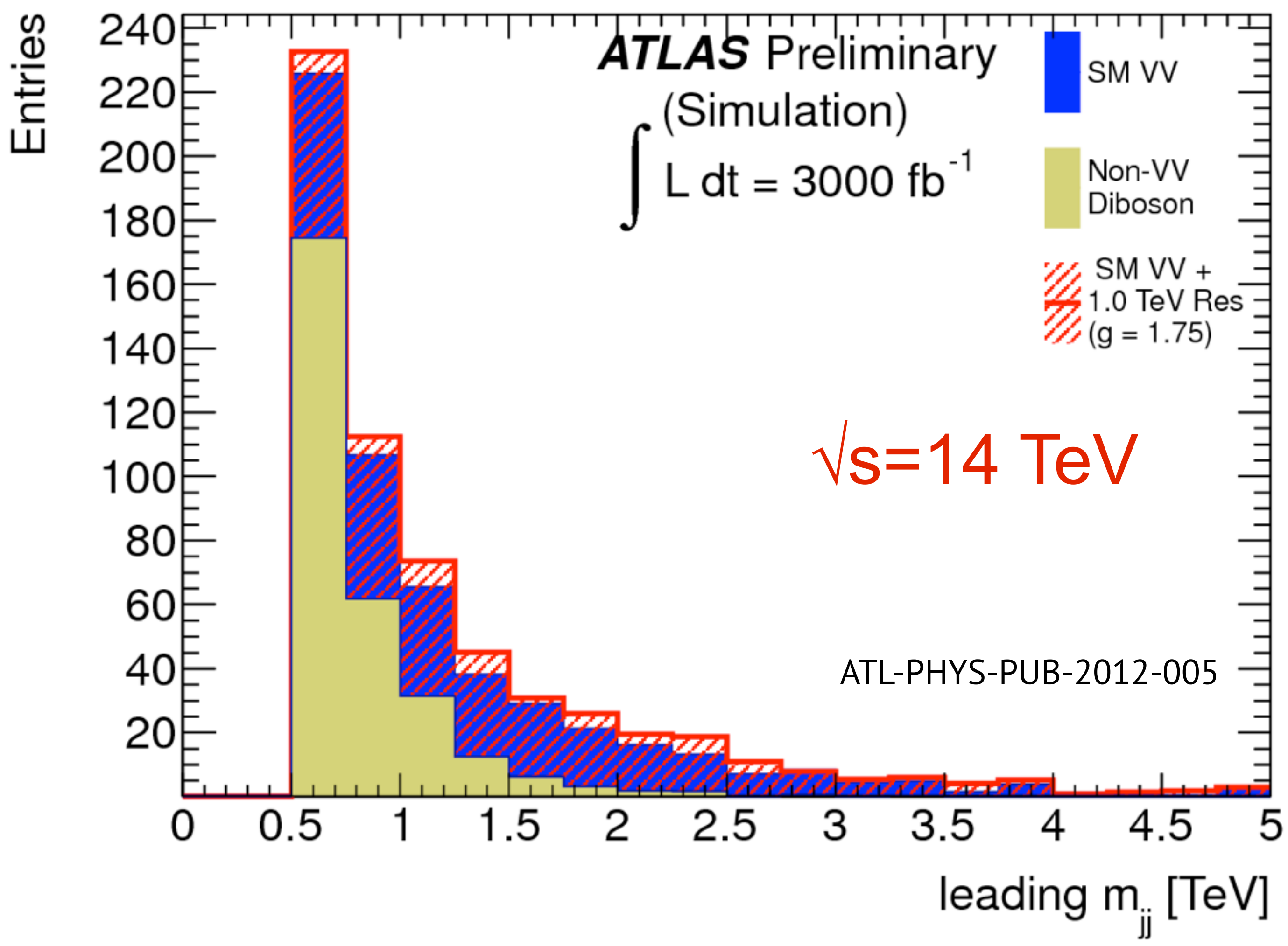
ZZ resonance

ZZ resonance

pp→ZZ+2j→4ℓ+2j channel

ZZ resonance

pp→ZZ+2j→4ℓ+2j channel



ZZ resonance

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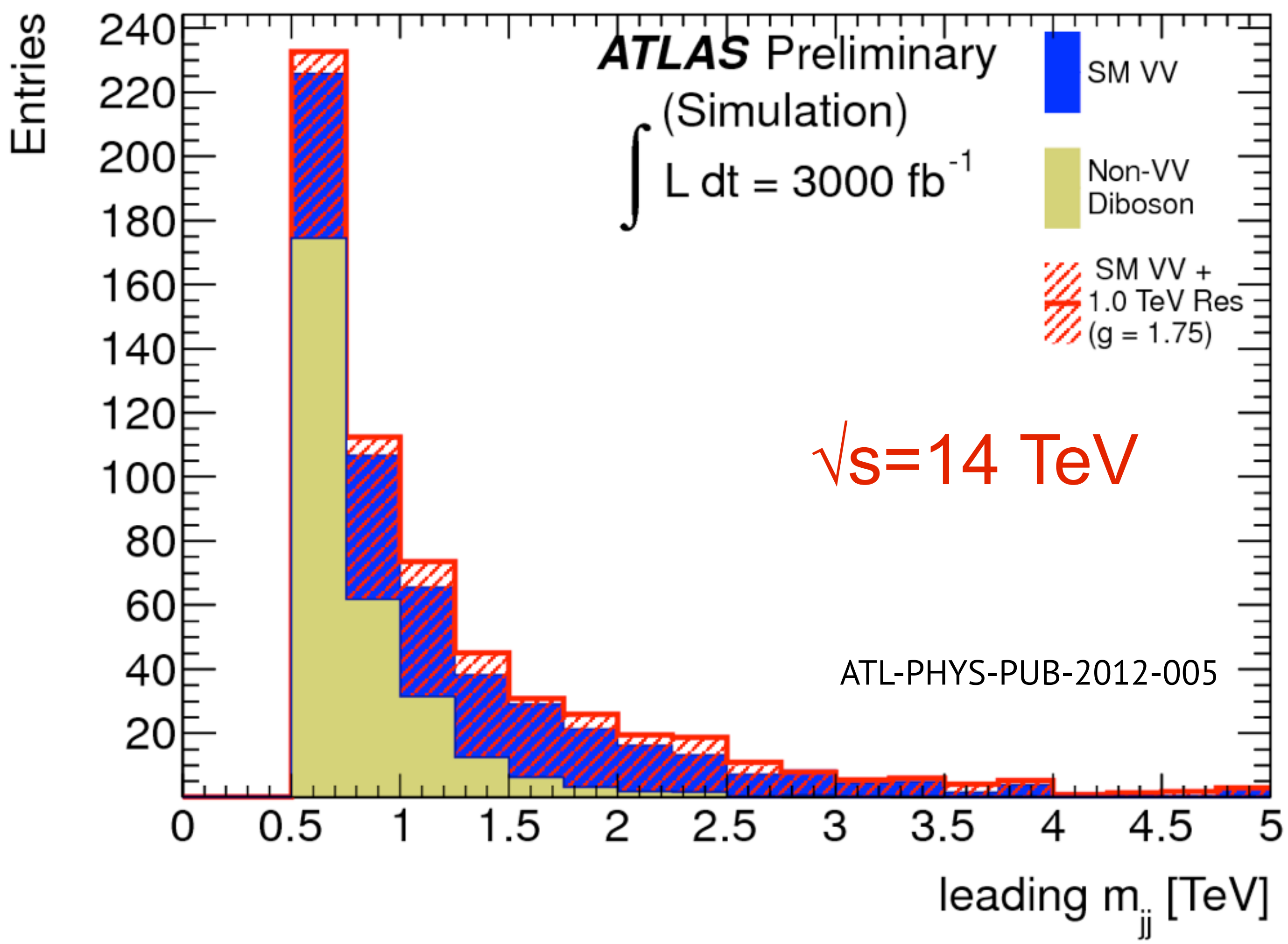

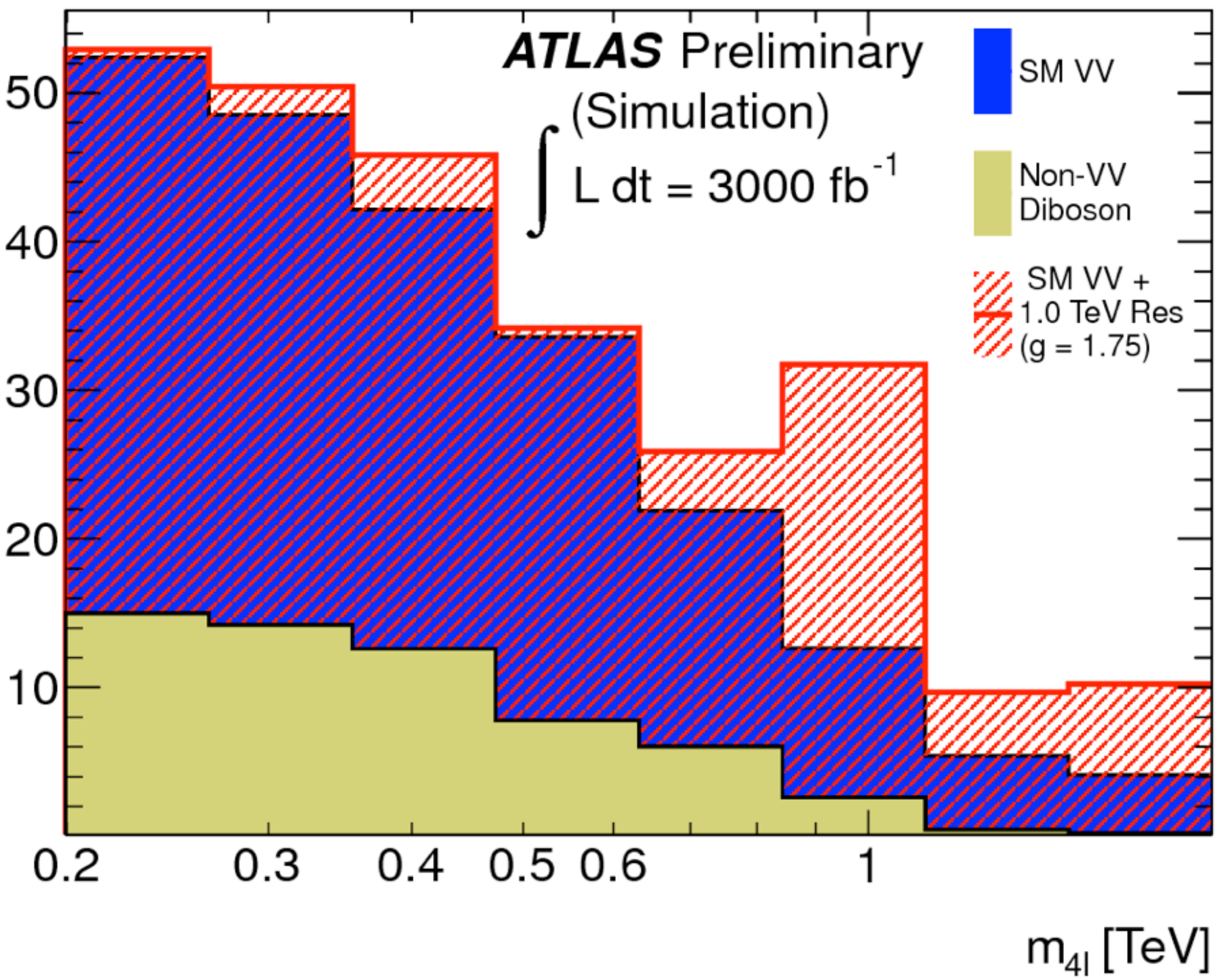

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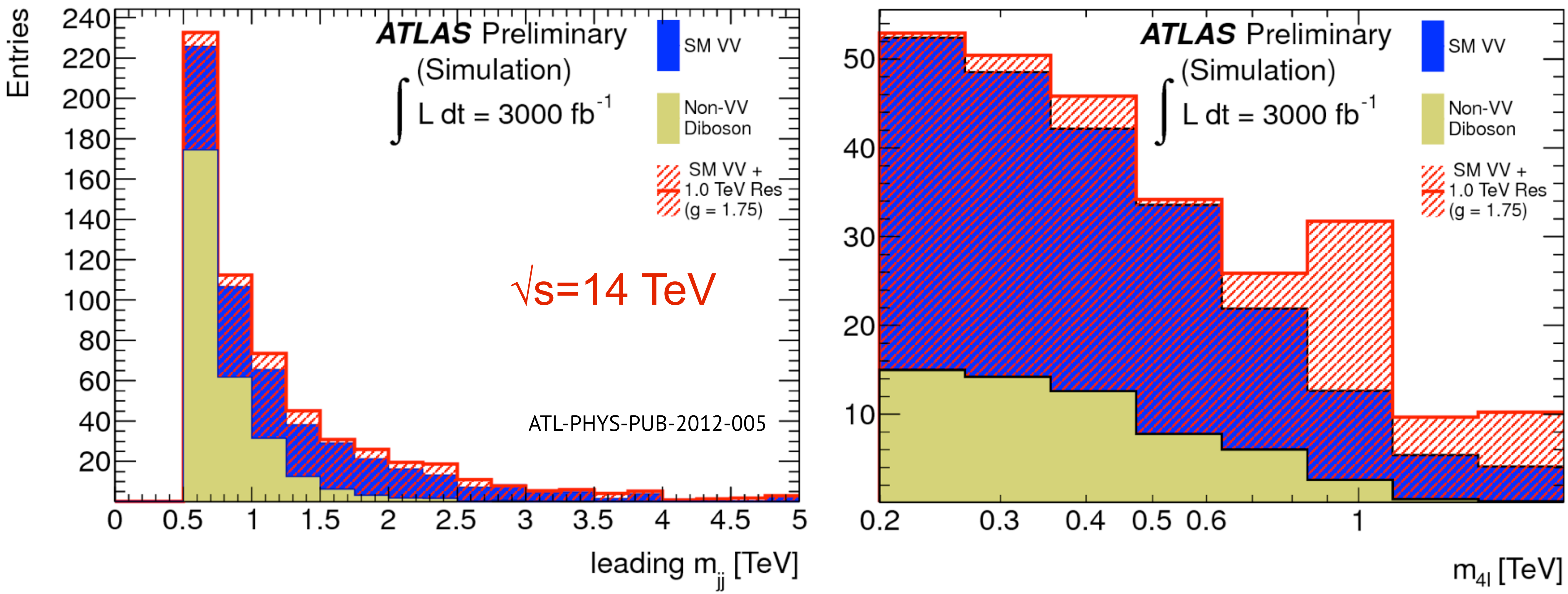


model	$300\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
$m_{\mathrm{resonance}} = 500$ GeV, $g = 1.0$	2.4σ	7.5σ
$m_{\mathrm{resonance}} = 1$ TeV, $g = 1.75$	1.7σ	5.5σ
$m_{\mathrm{resonance}} = 1$ TeV, $g = 2.5$	3.0σ	9.4σ

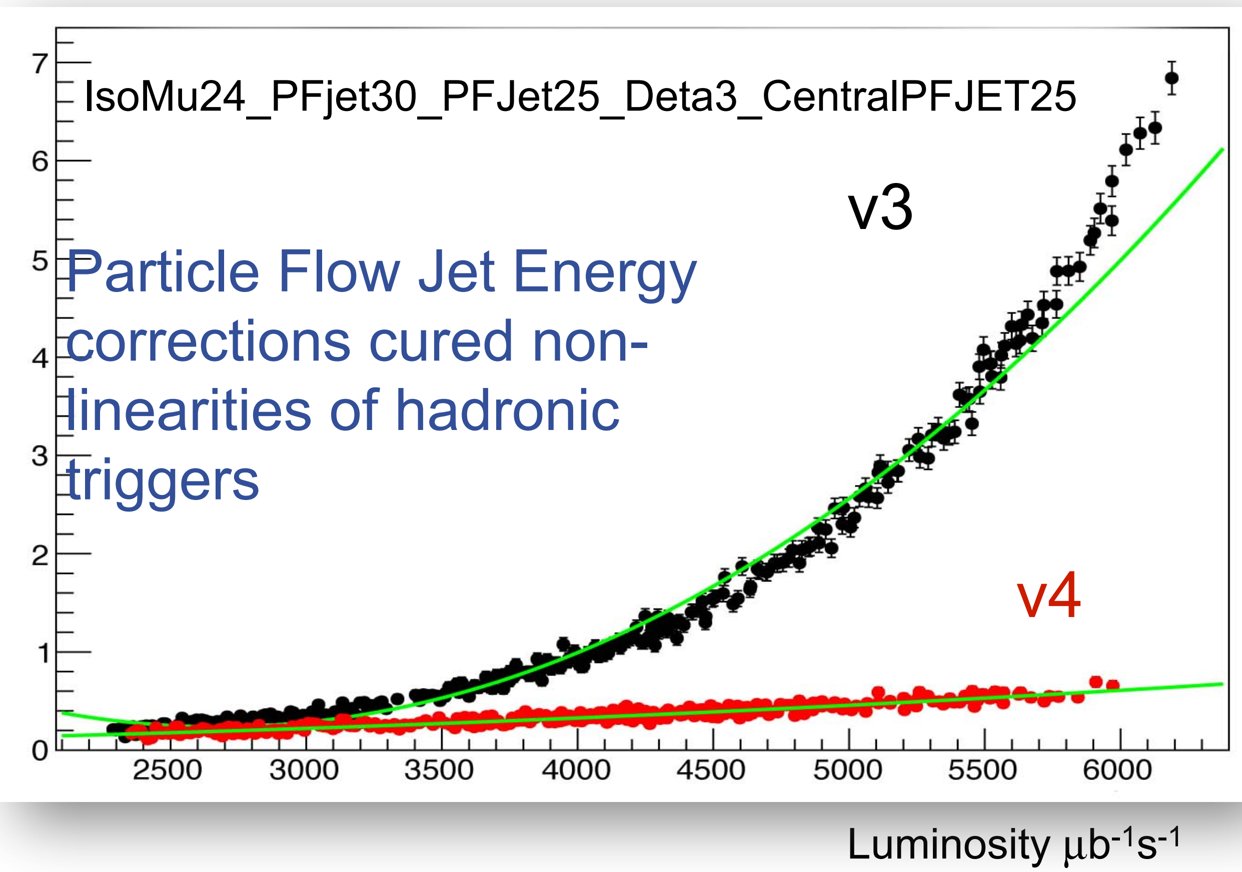
Sensitivity to anomalous ZZ resonances in Vector boson scattering

Trigger challenge in 2012

Maintaining high trigger efficiency while keeping the trigger rate within budget was one of the biggest challenges of the CMS experiment in 2012

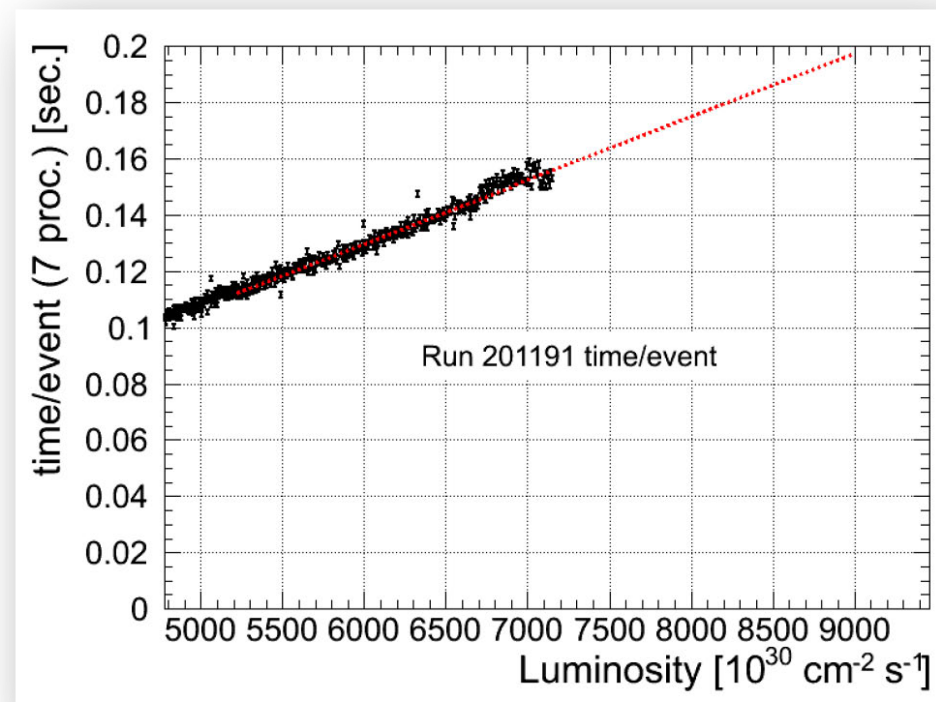
The experience obtained in 2012 with peak pileup of ~35 events gives us confidence for high-luminosity running post Long Shutdown 1

Trigger Cross-sections:



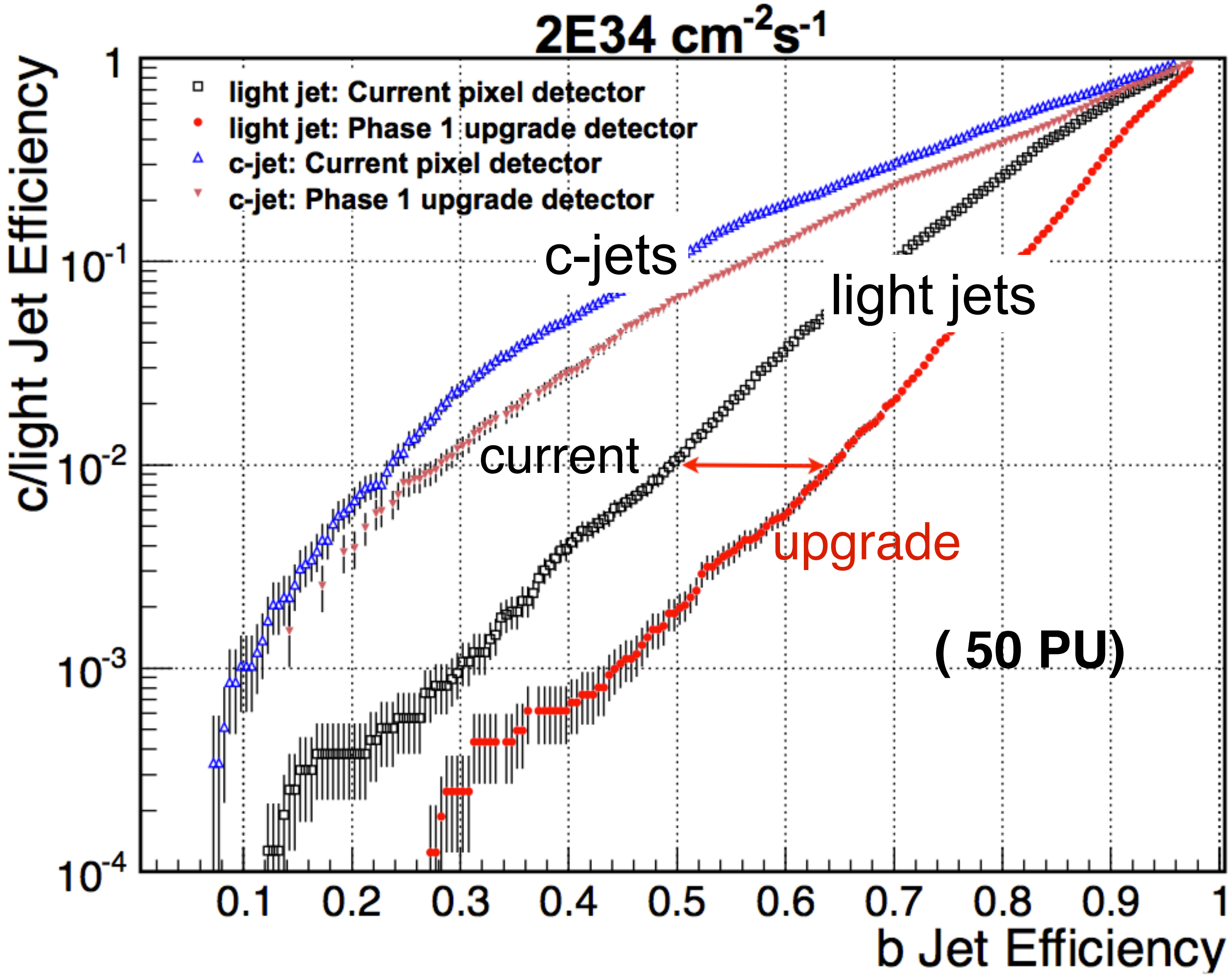
HLT CPU time:

- linear with PU, no signs of runaway

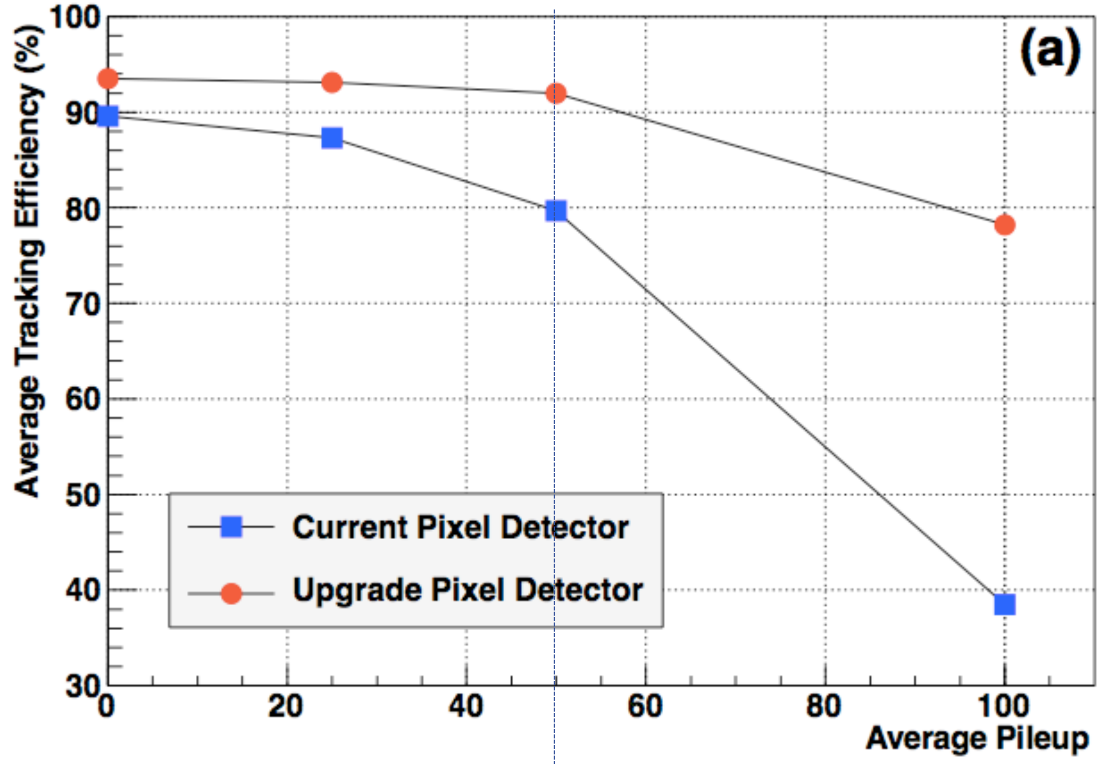


Tracking and b-tagging performance

Improvement of b-tagging efficiency with new pixel detector



Improvement in tracking efficiency w/ new pixel detector, in ttbar events, as a function of pileup



50 pileup

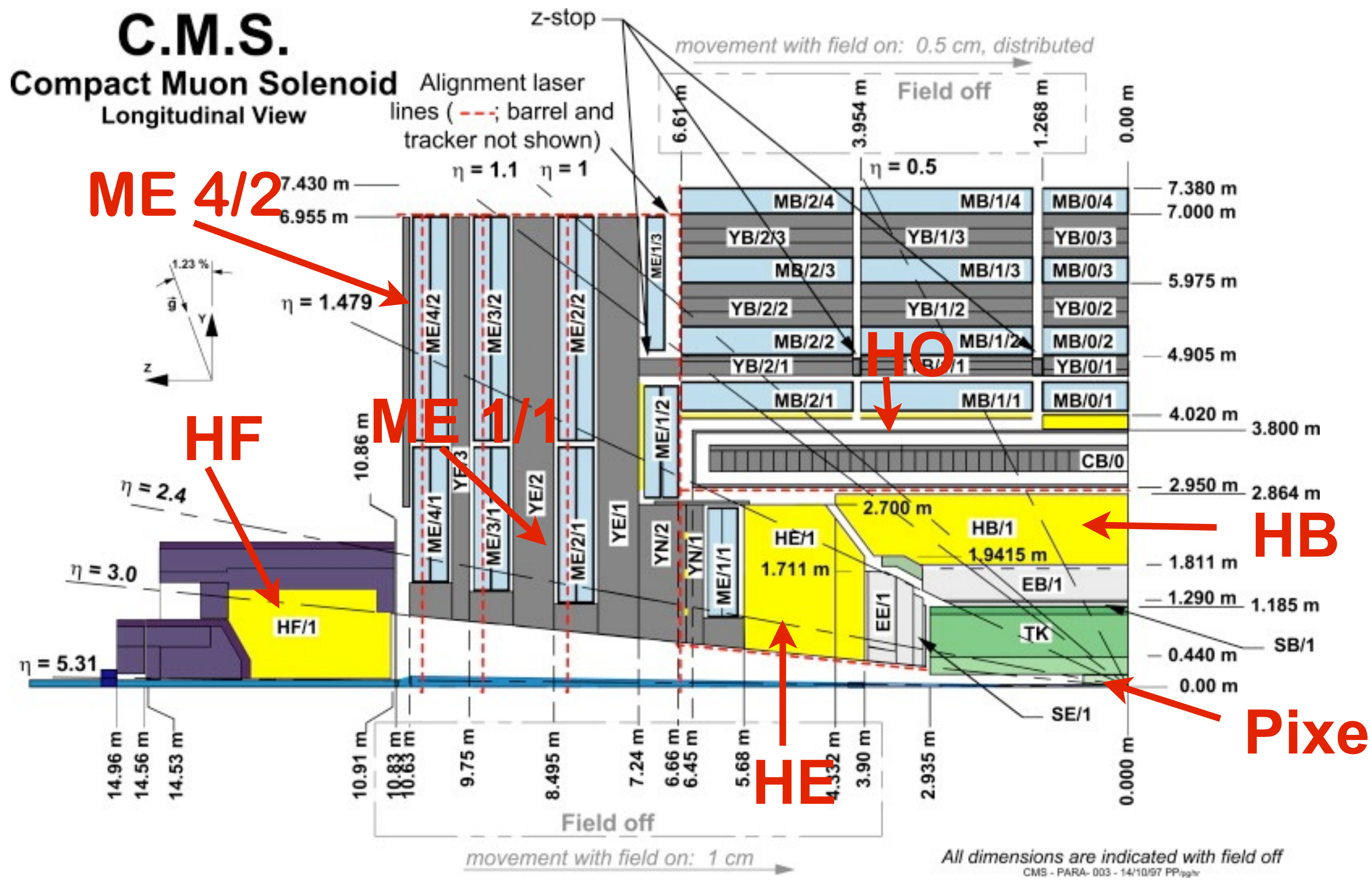
b-tagging efficiency ~ 1.3x better

2 b-jets → $(1.3)^2 \sim 1.69$

Primary vertex resolution improved by factor ~1.5 - 2

CMS Upgrade program

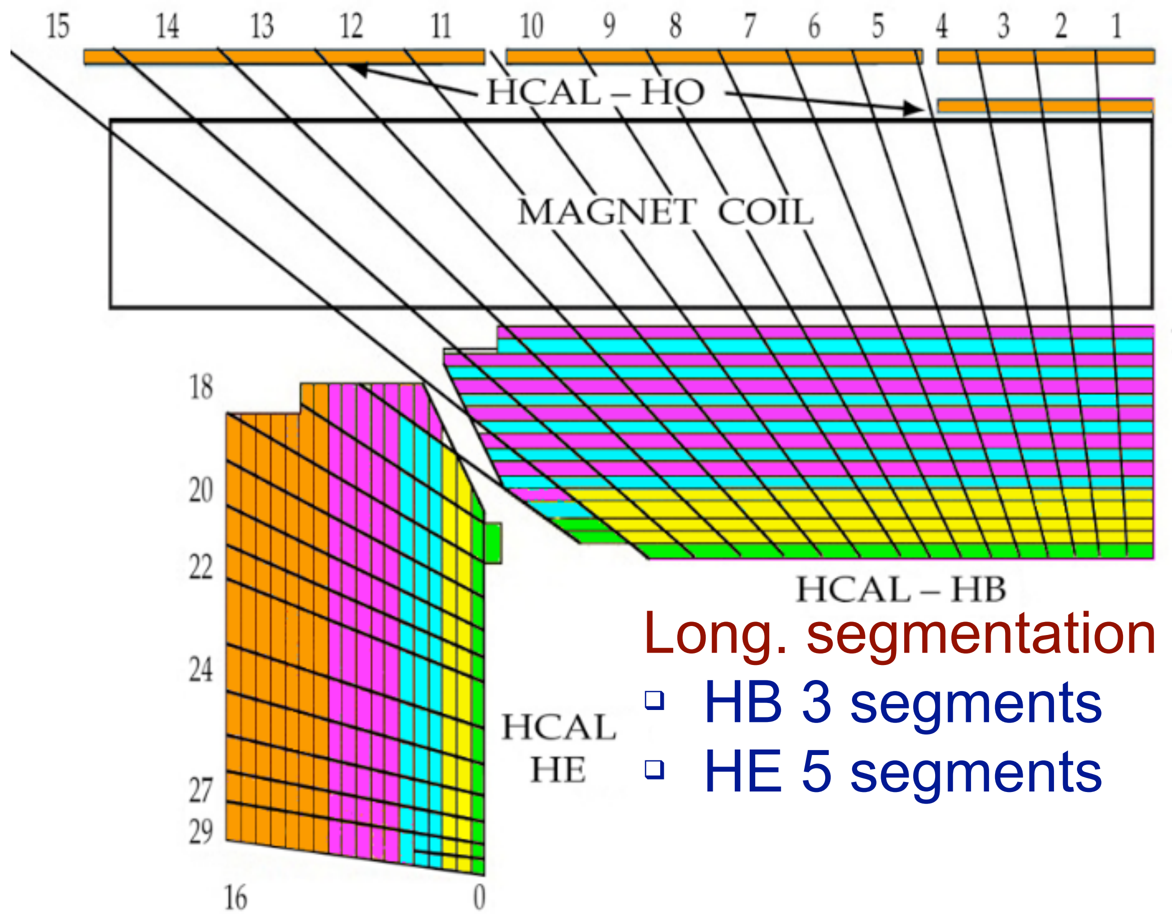
LS1 and Phase 1



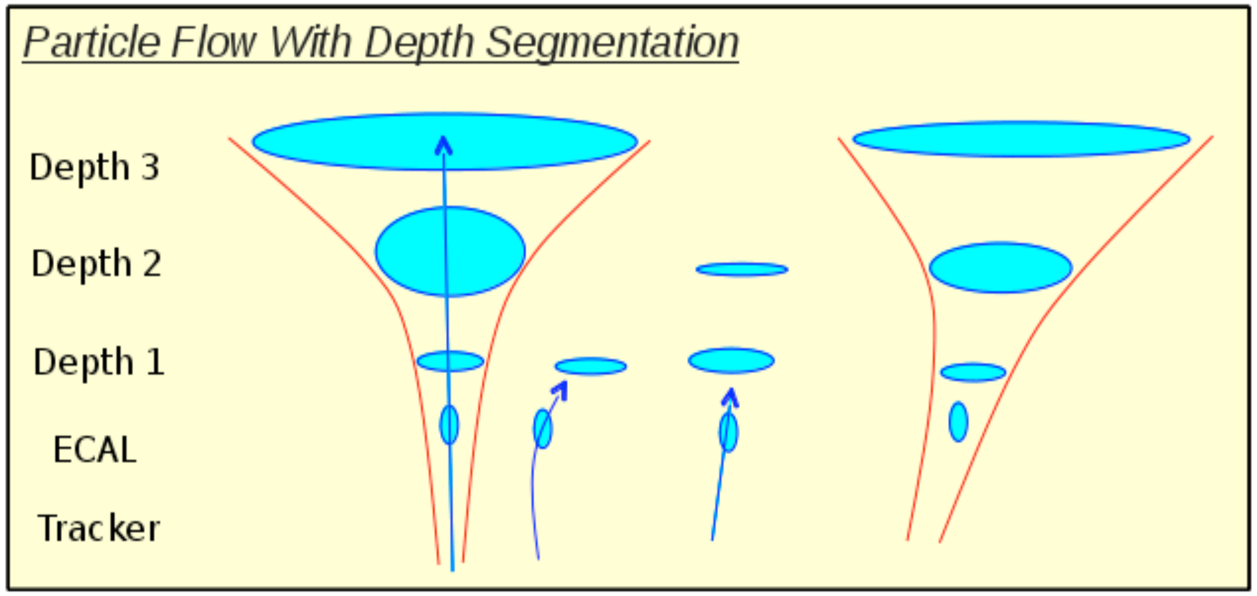
HCAL Upgrade

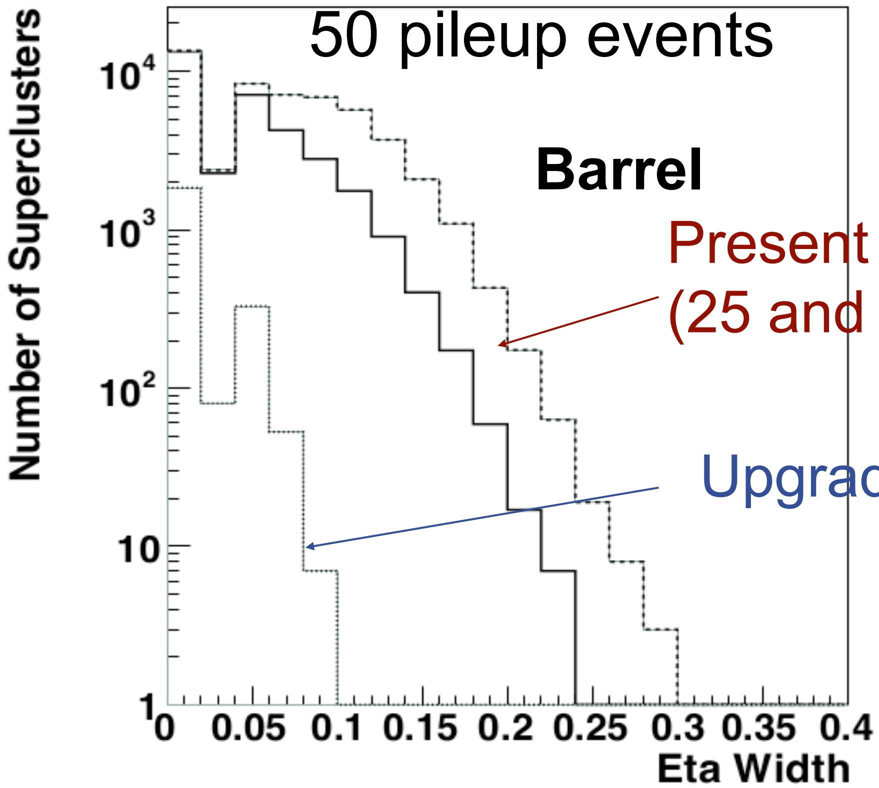
- Upgraded HCAL
  - New photodetectors
  - New electronics (frontend, backend)
  - Improved longitudinal segmentation
  - Improved background rejection, Missing E_T resolution and Particle Flow reconstruction

- Hadronic showers spread out with increasing depth



Long. segmentation
- HB 3 segments
- HE 5 segments



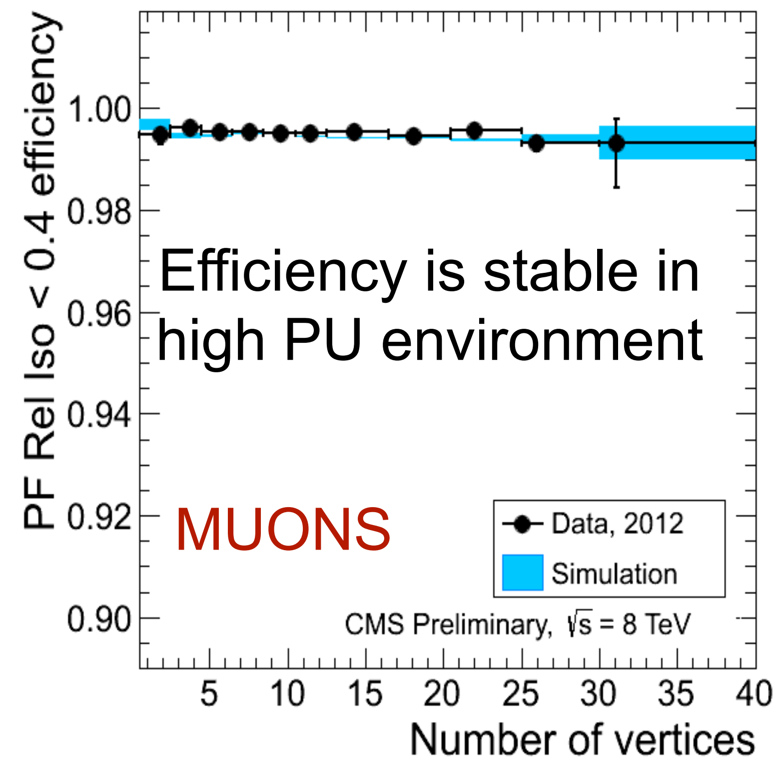


Pileup challenges

Reconstruction of hard collisions in high pileup environment requires detectors with very high granularity:

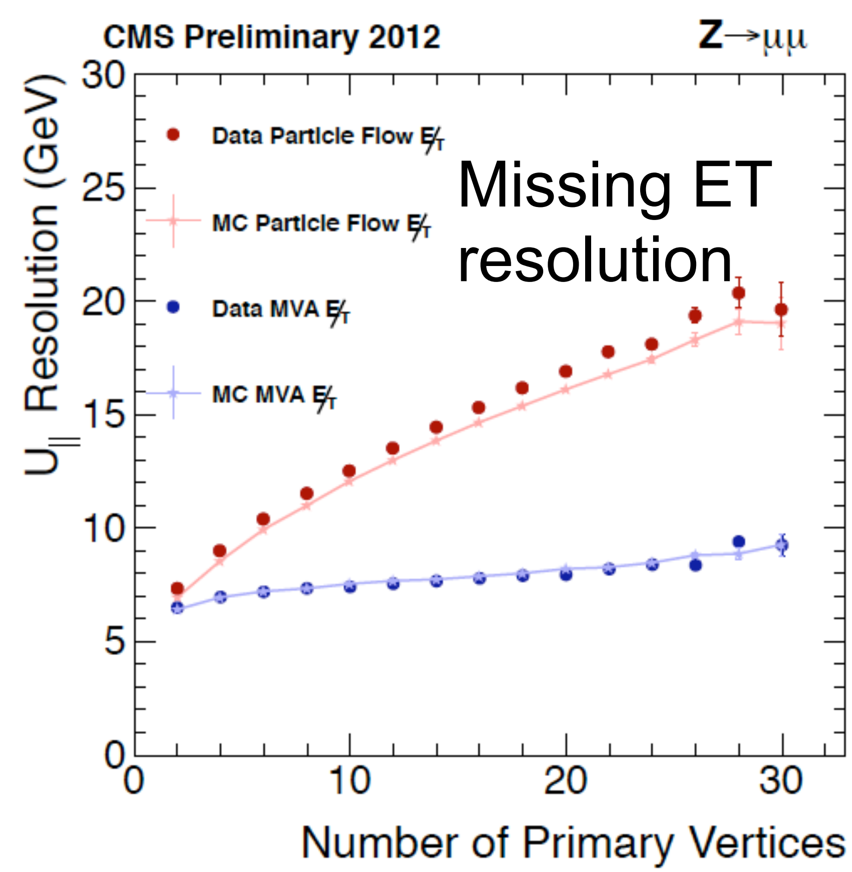
- efficient association of charged tracks to collision vertices
- reconstruction of charged and neutral particles in jets
- pileup neutrals corrected w/global energy density (ρ)

Muon isolation



Physics with high pileup requires full particle flow reconstruction assuring:

- precise jet energy correction
- robust missing energy measurement
- efficient lepton isolation

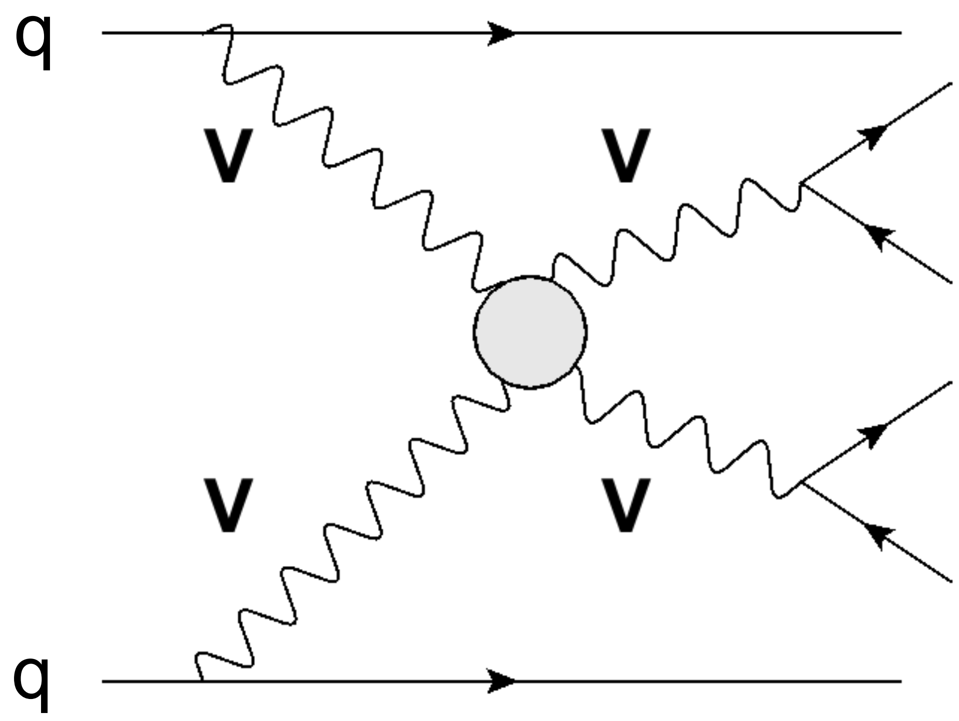


Very efficient reconstruction code is needed to stay within computing budget

Vector Boson Fusion (VBF)

Vector Boson Fusion (VBF)

Generic diagram for vector boson fusion (VBF) process



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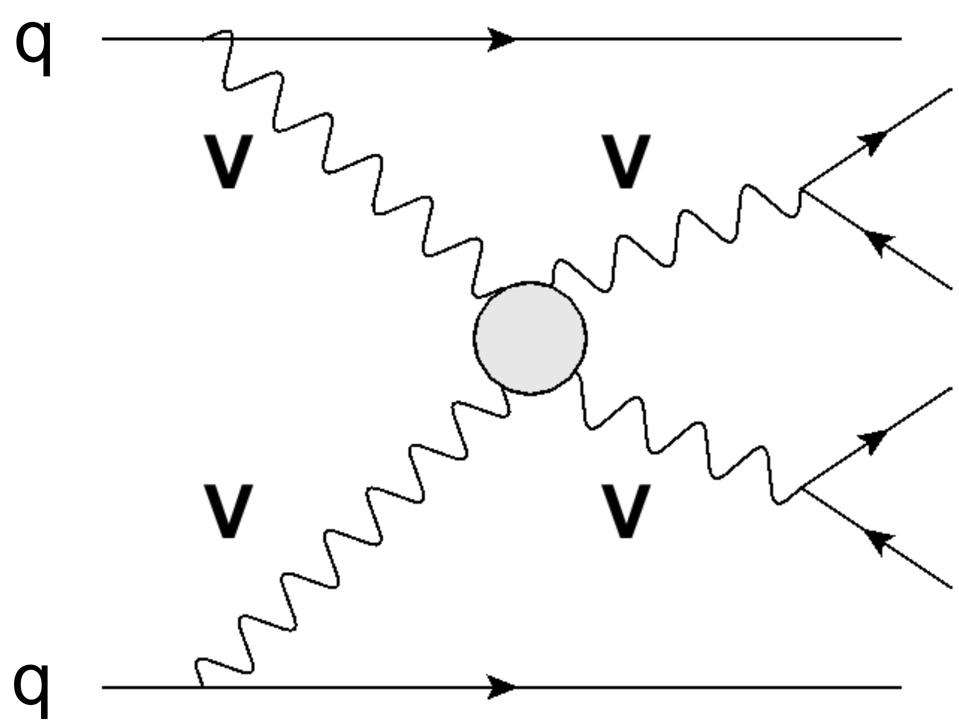

Signature: forward-backward "spectator" jets with very high energy

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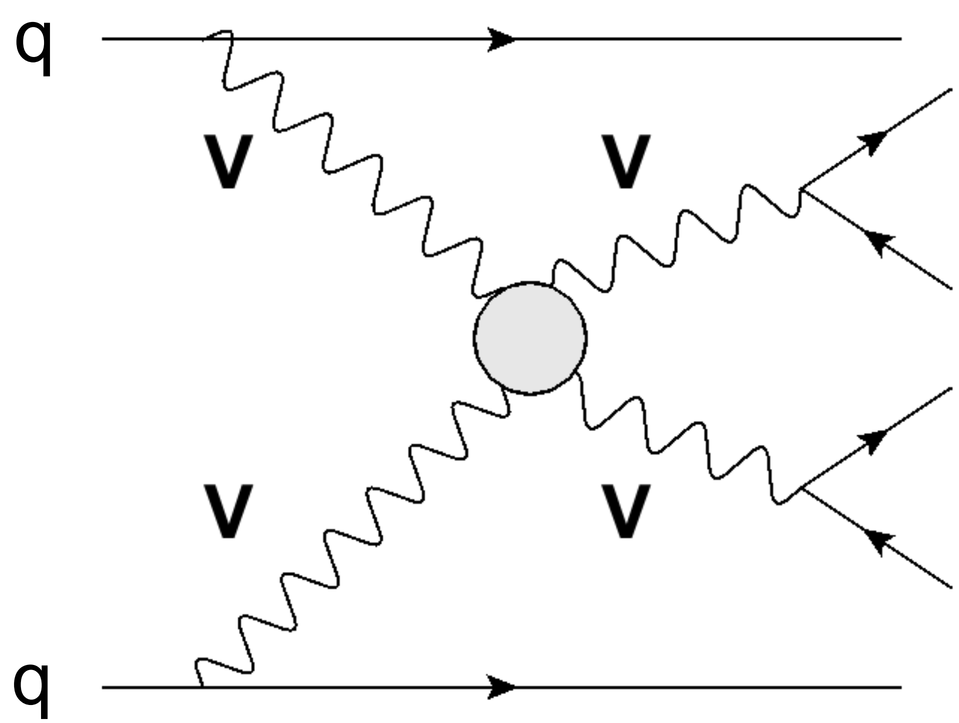

Signature: forward-backward "spectator" jets with very high energy

- Once the vector bosons decay, we have a six-fermion final state
- The full set of qq→6 fermions diagrams has to be considered
- In order to investigate EWSB, one has to isolate VV processes from all other six-fermion final states

➡ Apply tight kinematic cuts

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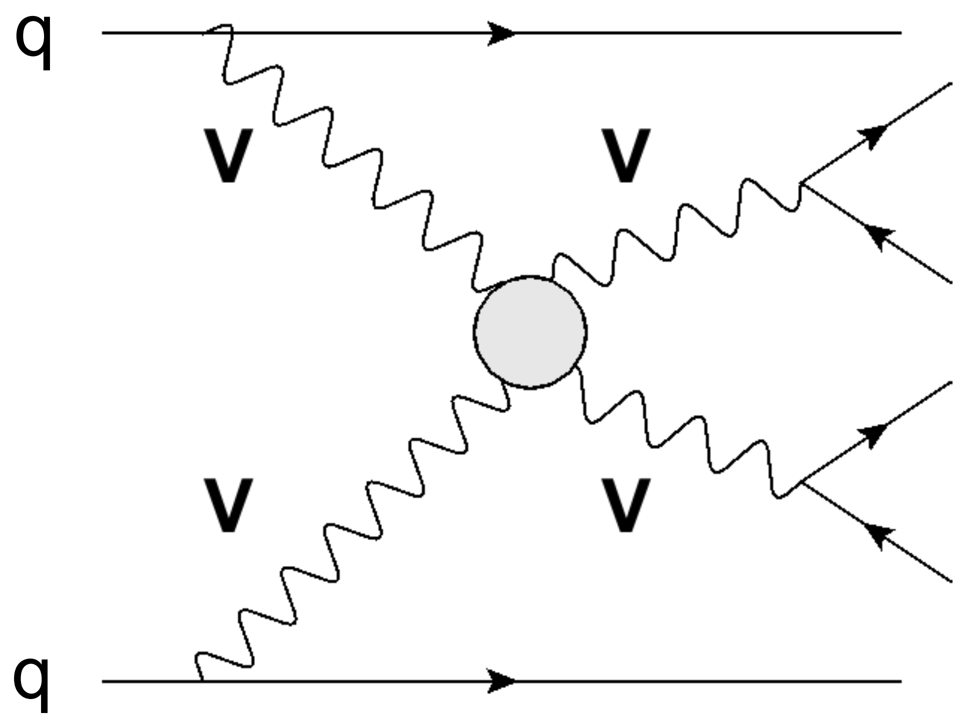

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➡ Apply tight kinematic cuts

Typical kin. cuts

$p_{T,j} > 20$ GeV $|\eta_j|<5$ $p_T^{tag} > 30$ GeV $|\eta_{j1}-\eta_{j2}|>4.0$

$\eta_{j1} \cdot \eta_{j2} < 0$ $m_{jj} > 600$ GeV

VV scattering: semileptonic

Semileptonic is most promising: reasonable signal yield

Number of events for 20 fb^{-1} (fully MC based, no systematics, 14 TeV)

WV -> lnjj

ATLAS	N sign.	N back.
500 GeV	6.2	16
800 GeV	13	17
1.1 TeV	4.8	9.2

CMS	N sign.	N back.
500 GeV	337	20759
>1 TeV	45	3281

ZV -> lljj

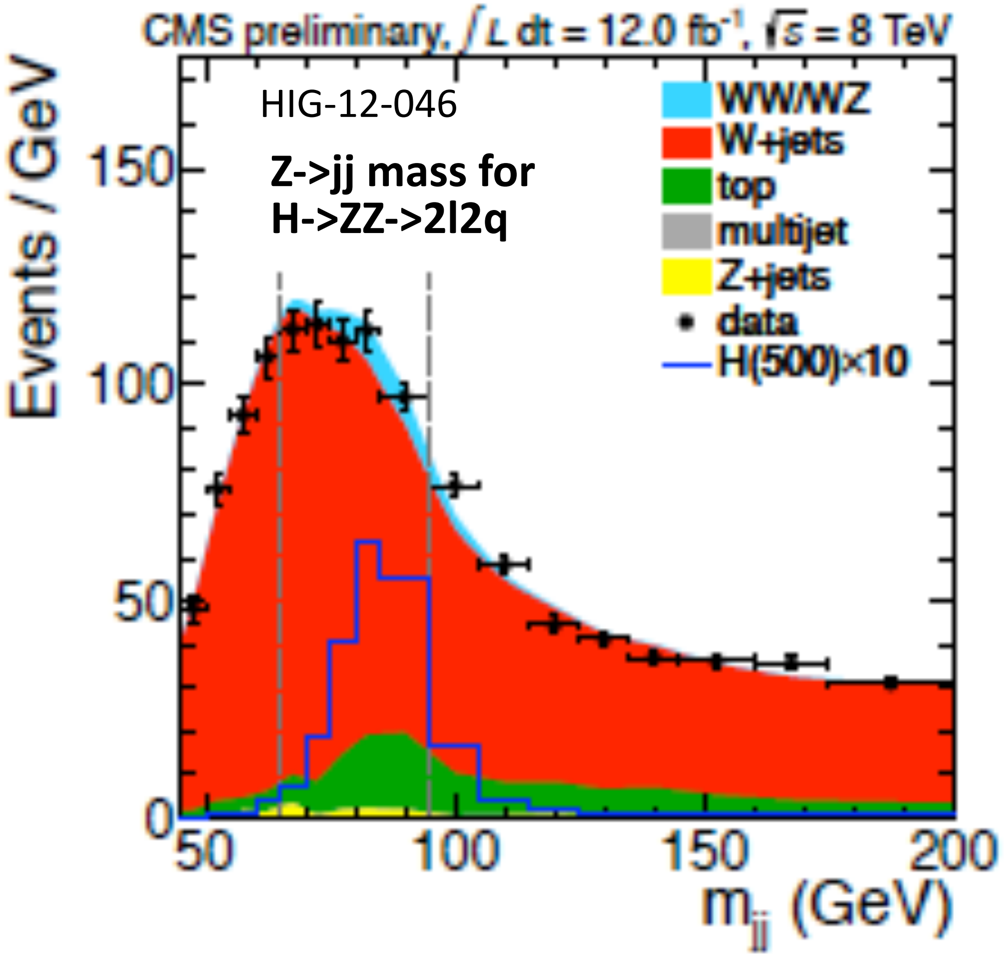
CMS	N sign.	N back.
500 GeV	62	3415
>1 TeV	5	348

For recent inclusive Higgs search:

- more sophisticated analysis developed
(btag categories, angular analyses,
$m_{jj} = m_Z$ kinematic fit)

- data driven background

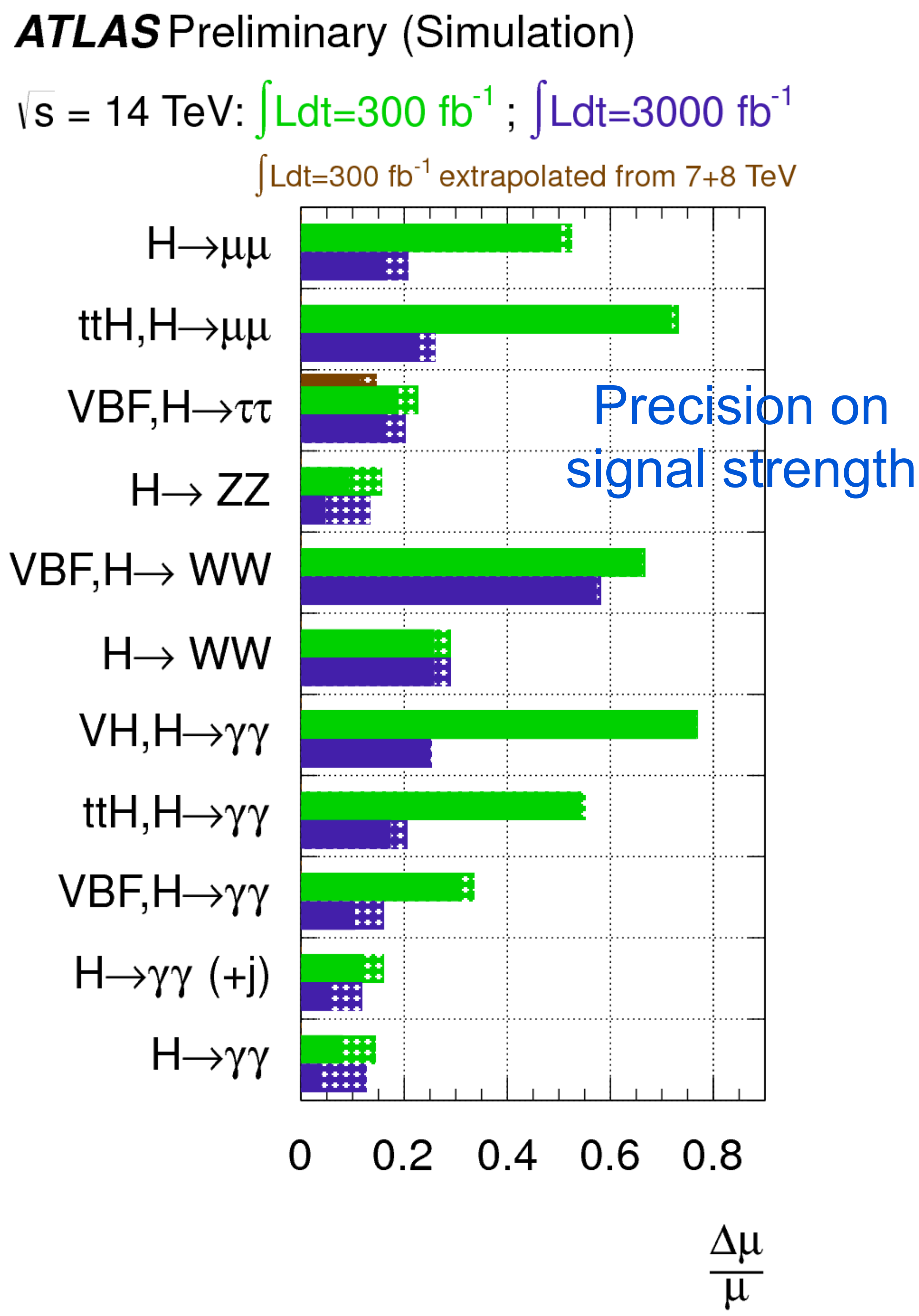
Improved JES: m_{jj} reso from 20-25% to 10-15%



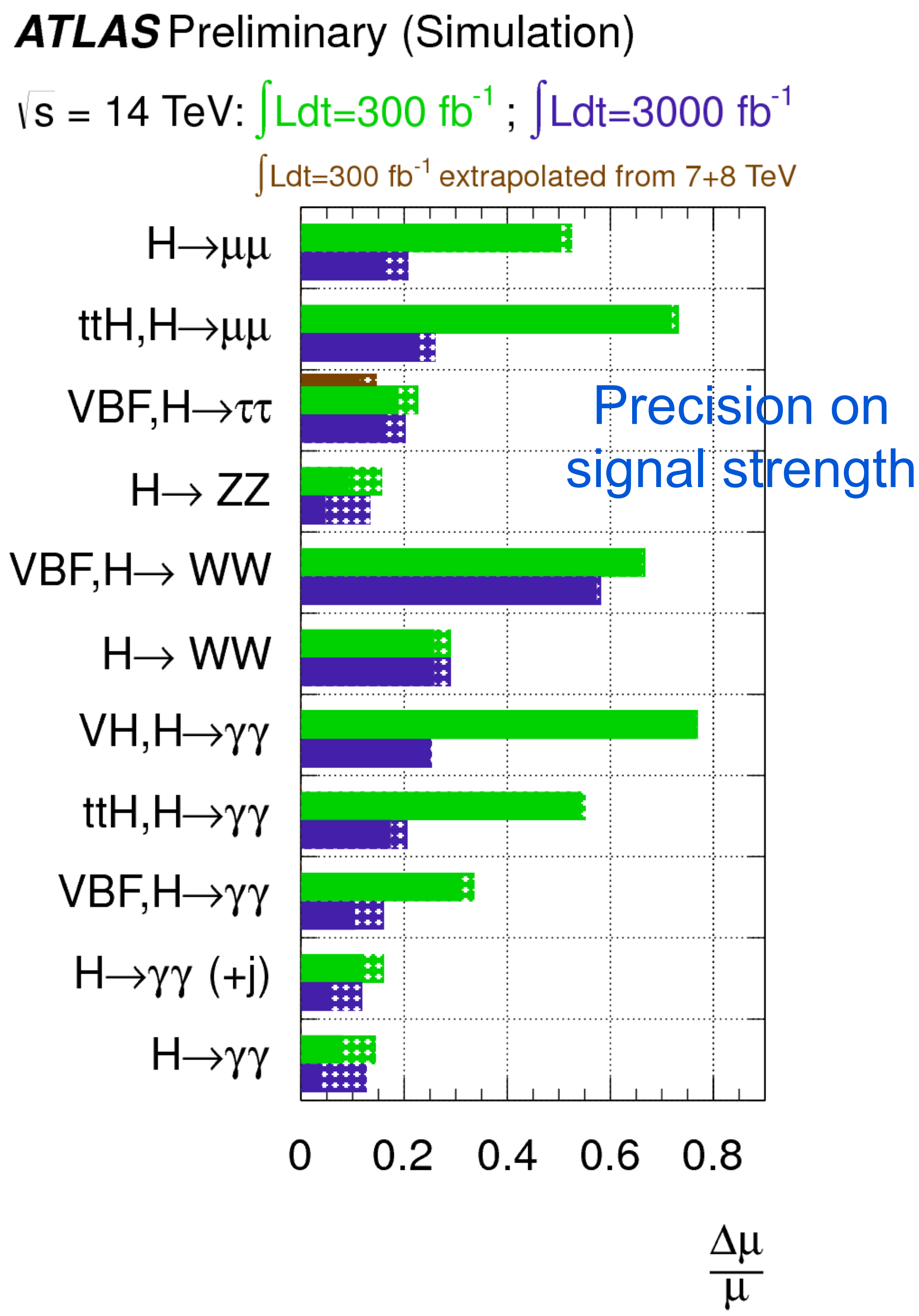
CERN-OPEN-2008-020

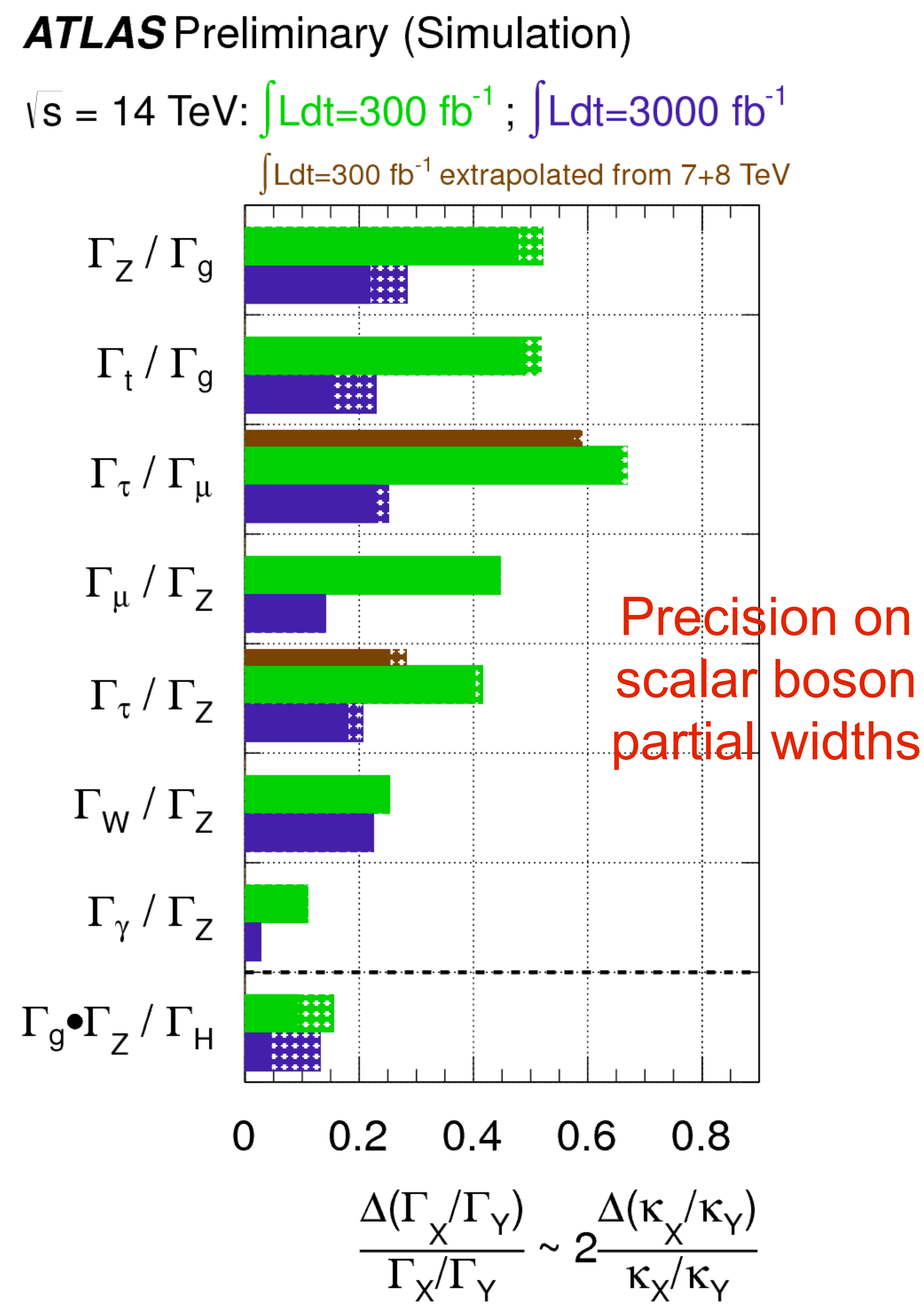
Ratios of partial widths @3000 fb^{-1}

Ratios of partial widths @3000 fb^{-1}



Ratios of partial widths @3000 fb^{-1}





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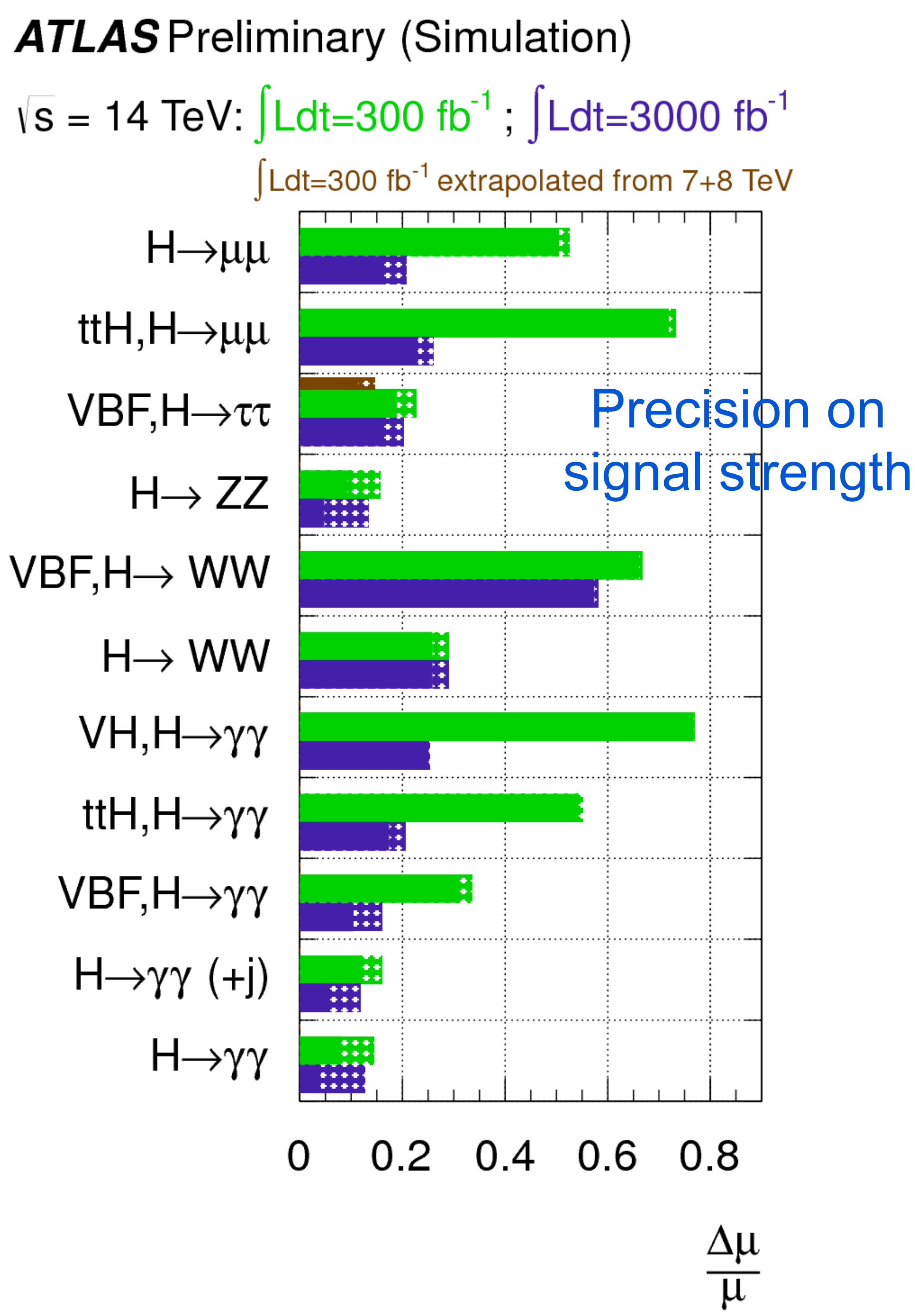

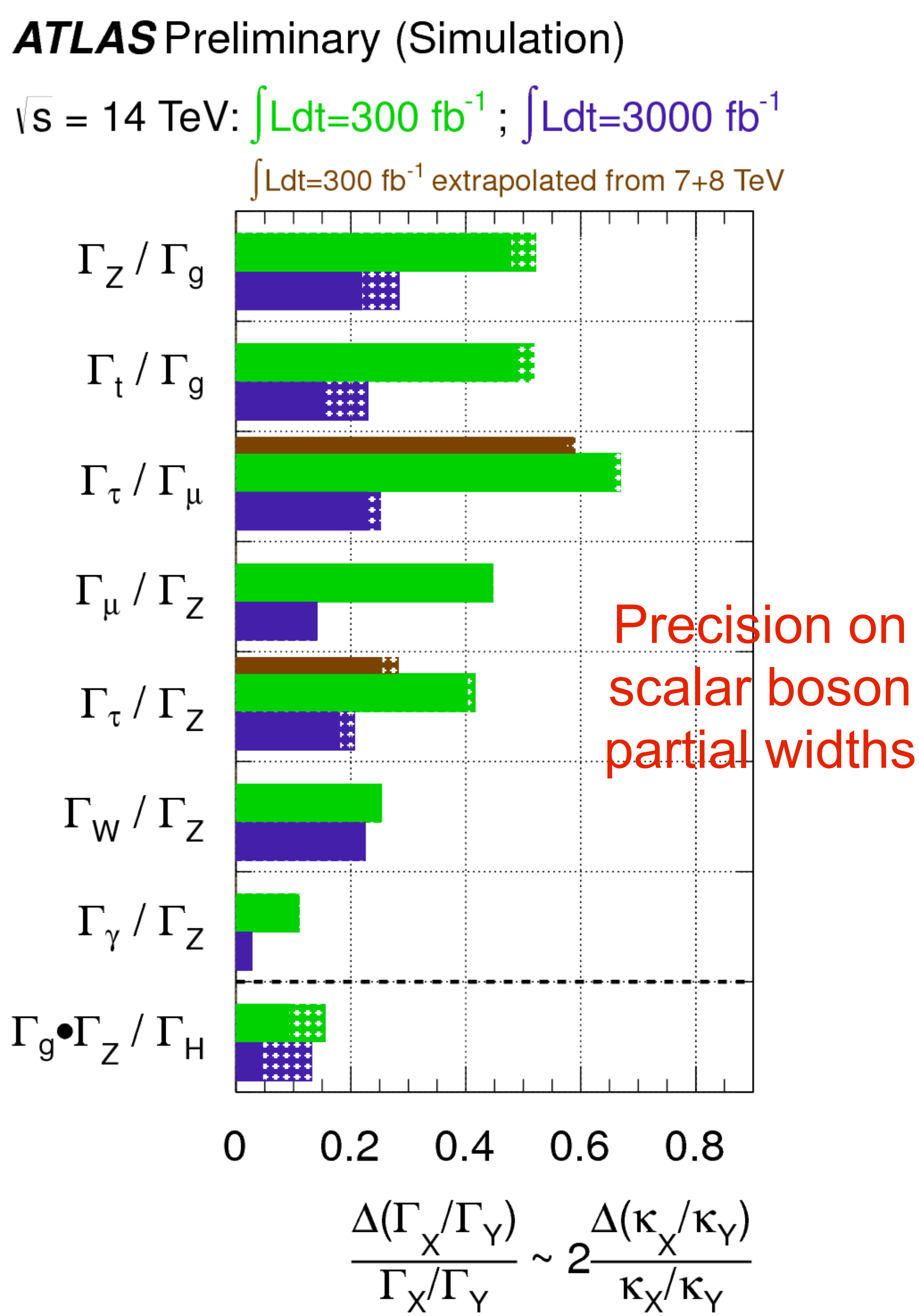

- With 3000 fb^{-1} the couplings can be determined with high precision (a few %)

Ratios of partial widths

CMS

Scenario 1

partialWidths	300/fb (% err.)	3000/fb (% err)
r_bZ	24 / -18	12 / -9
r_gZ	16 / -13	8
r_tZ	18 / -15	9 / -7
r_WZ	15 / -12	7 / -6
r_topglu	32 / -24	17 / -13
r_Zglu	17 / -16	10 / -9
c_gluZ	12 / -11	8

Scenario 2

partialWidths	300/fb (% err.)	3000/fb (% err)
r_bZ	17 / -14	4.5
r_gZ	9	4.5
r_tZ	11	3.5
r_WZ	10 / -7	2.5
r_topglu	28 / -22	11
r_Zglu	11 / -10	5
c_gluZ	7.5 / -5.5	4

Scenario 1: systematics as in 2012
Scenario 2: theory syst. scaled by a factor ½,other systematics scaled by $1/\sqrt{L}$