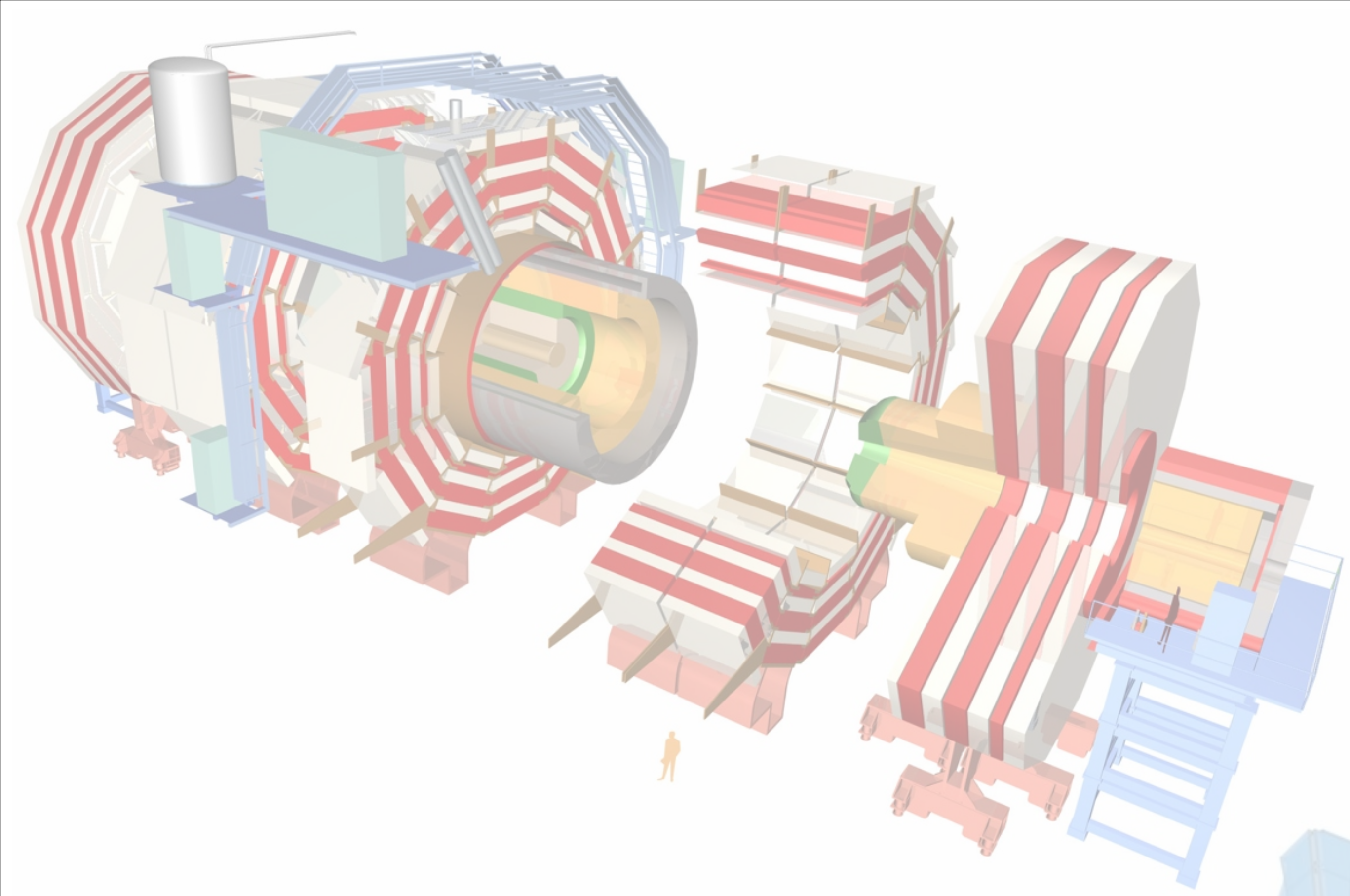
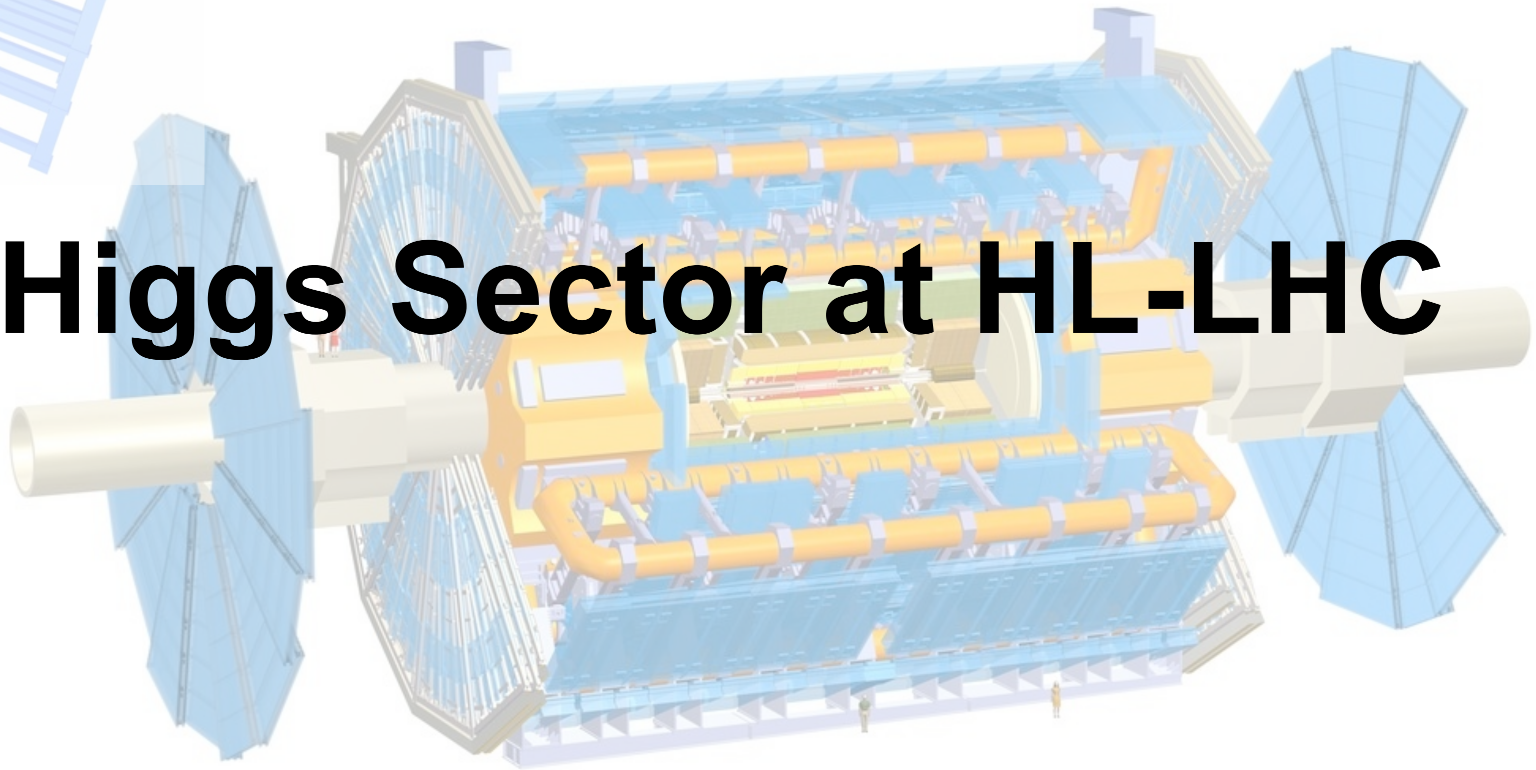


Prospects of the Higgs Sector at HL-LHC



High Luminosity LHC

Paolo Giacomelli (INFN Bologna)

What Next at LHC?, TIFR, Mumbai

Wednesday, January 8th, 2014

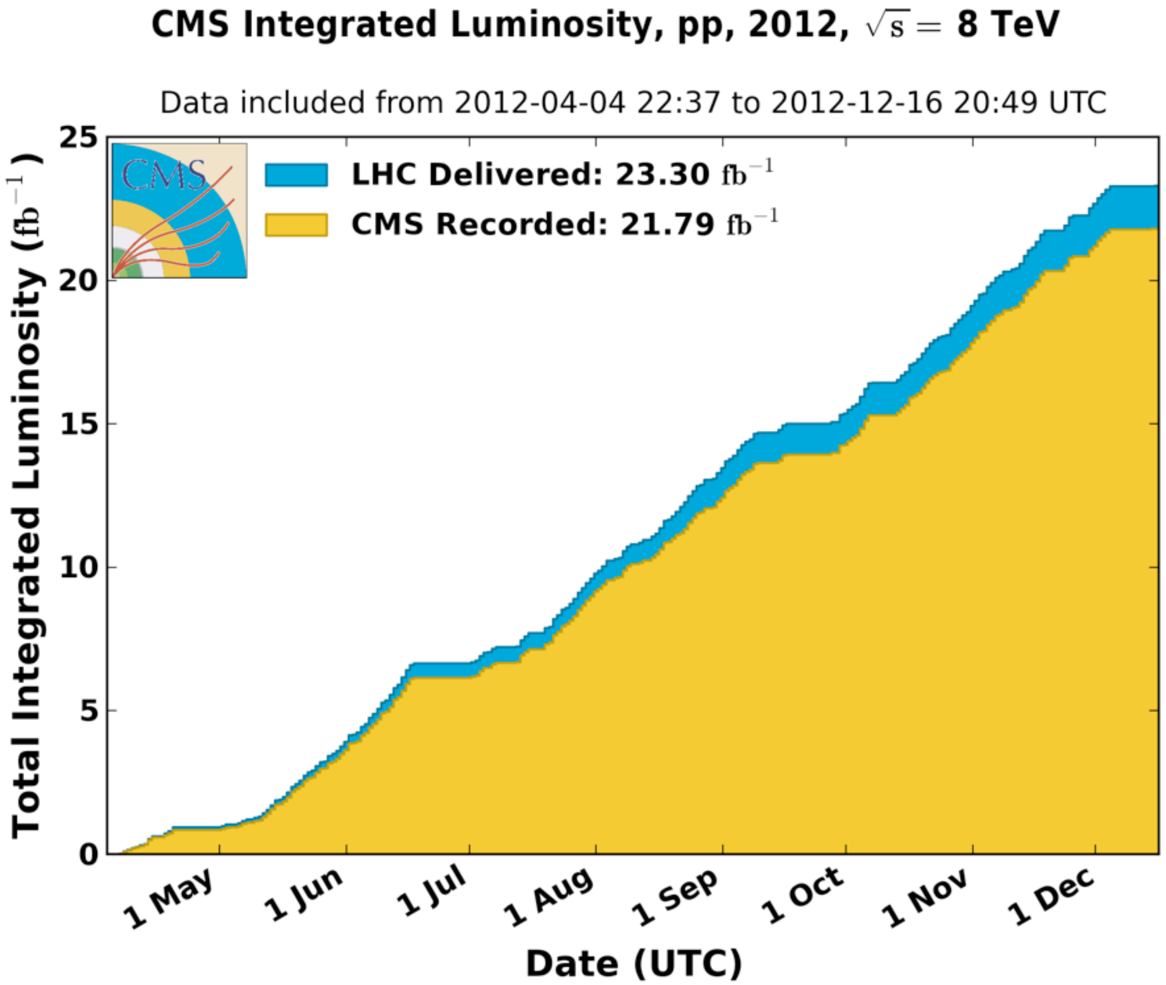
Outline

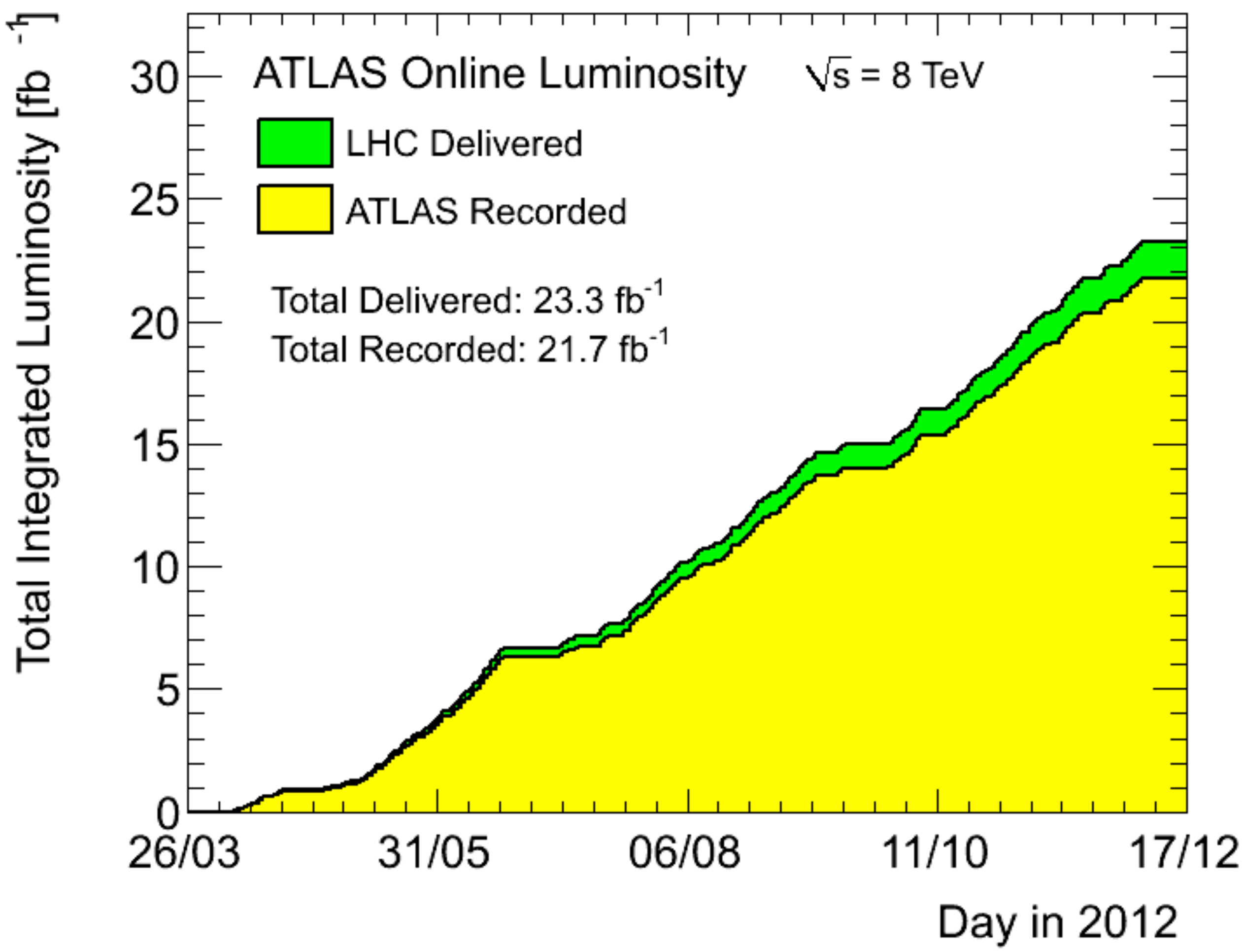
- Where we stand today
- LHC and HL-LHC luminosity projections
- Physics priorities
- CMS and ATLAS upgrade programs
- Higgs Physics at HL-LHC
- Higgs boson couplings projections
- Higgs boson rare decays
- Higgs boson pair-production
- VV scattering

Integrated luminosity in 2012

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

2011: L=~6 fb^{-1}





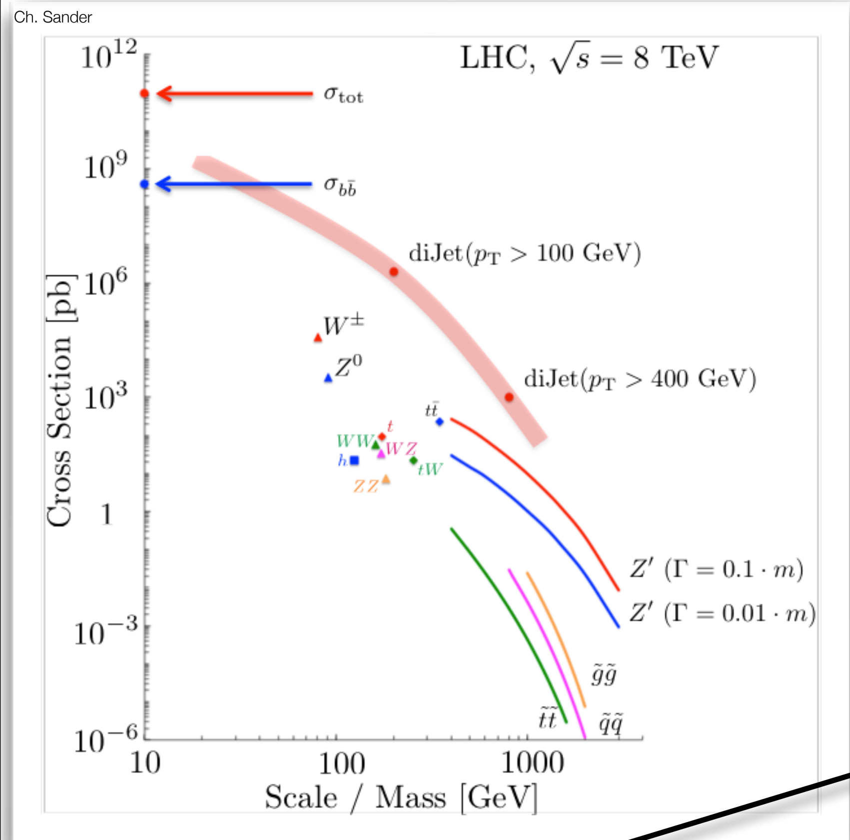
Total delivered luminosity: **~30 fb^{-1}**

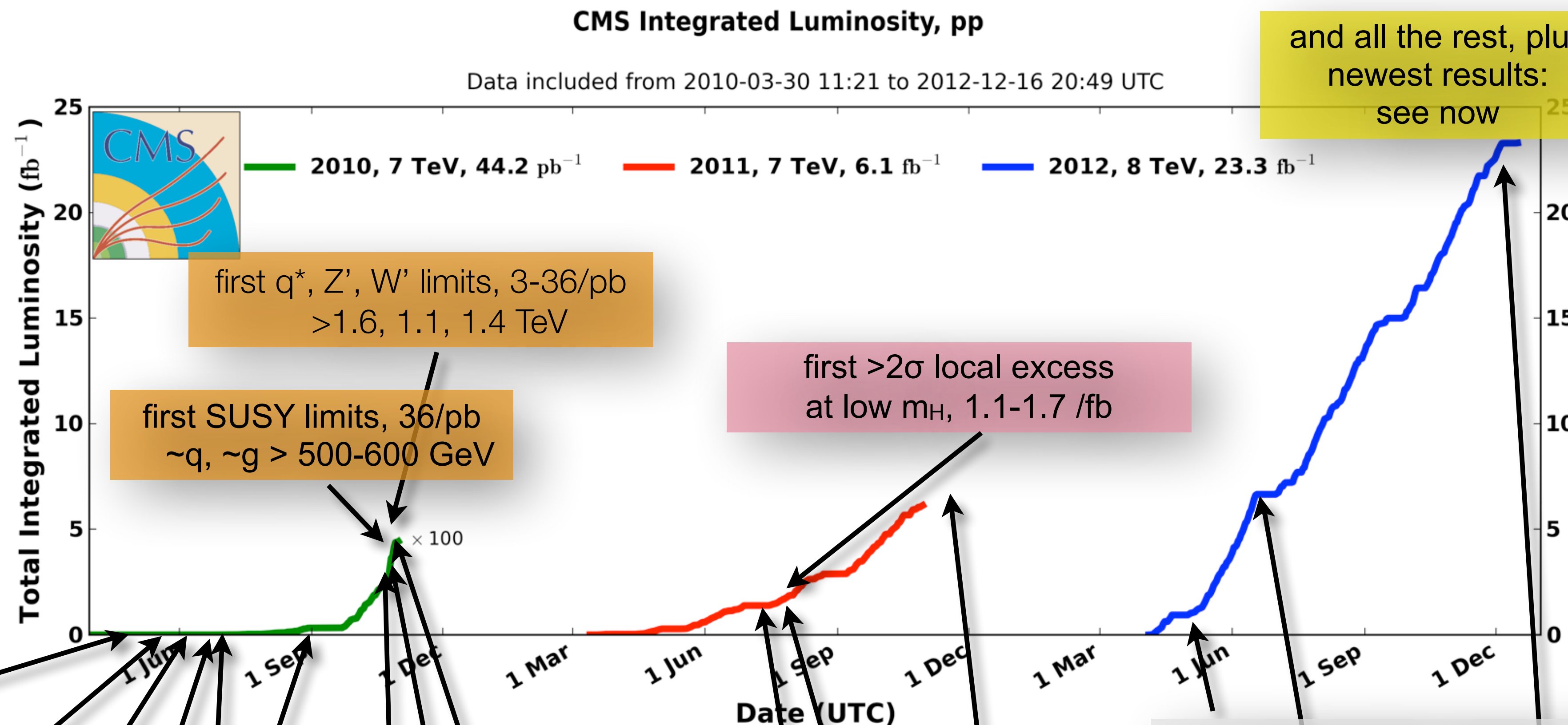
Total recorded luminosity: **~27 fb^{-1}**

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

A 3-year long sprint….

CMS as example …





and all the rest, plus newest results: see now

first q*, Z’, W’ limits, 3-36/pb
>1.6, 1.1, 1.4 TeV

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<1.9x10^{-8}

first particle discovered
by CMS: Ξ_b

BSM searches continue,
limits pushed

a new boson is
announced, 5 /fb

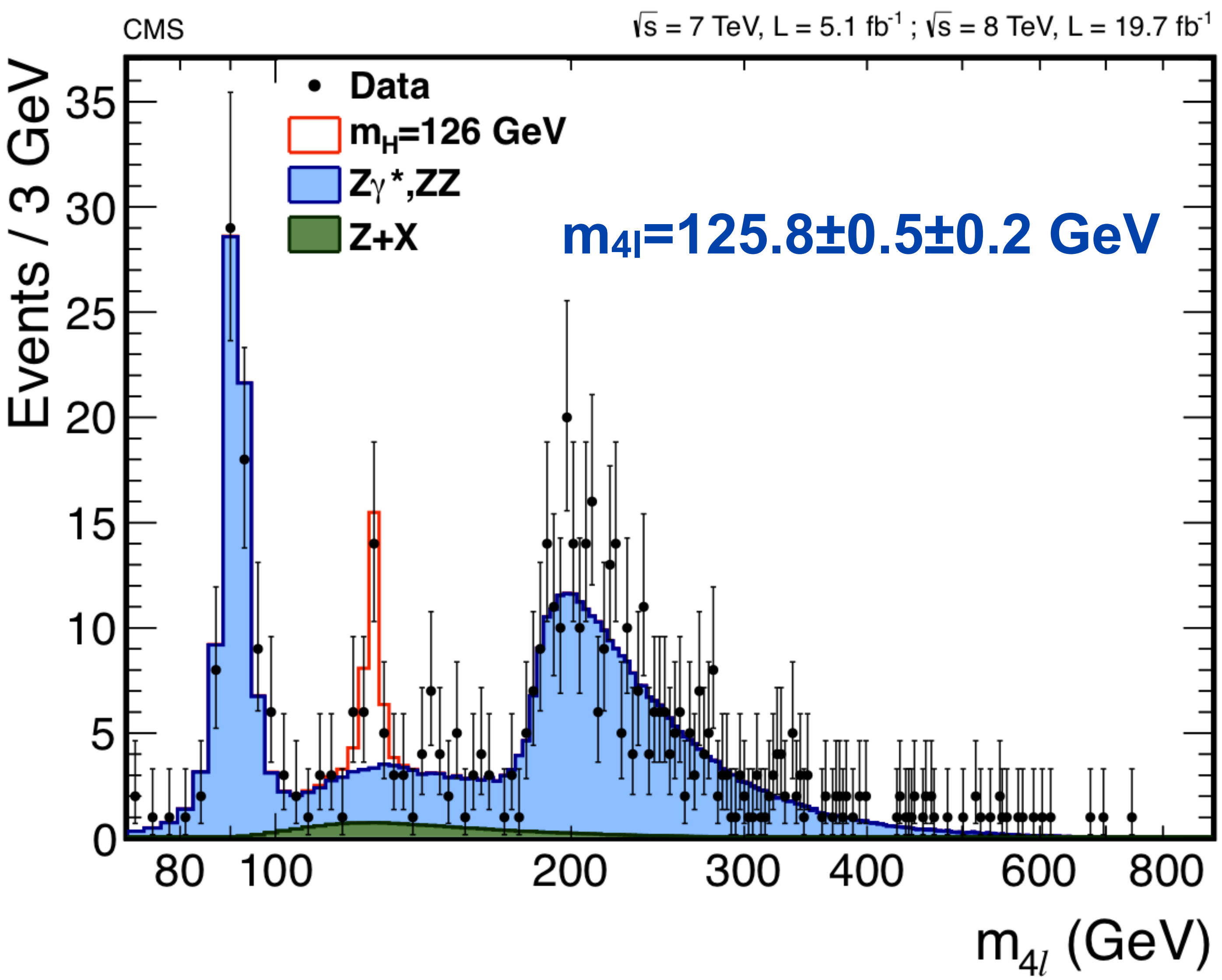
first spin parity analysis
of the boson, 17 /fb

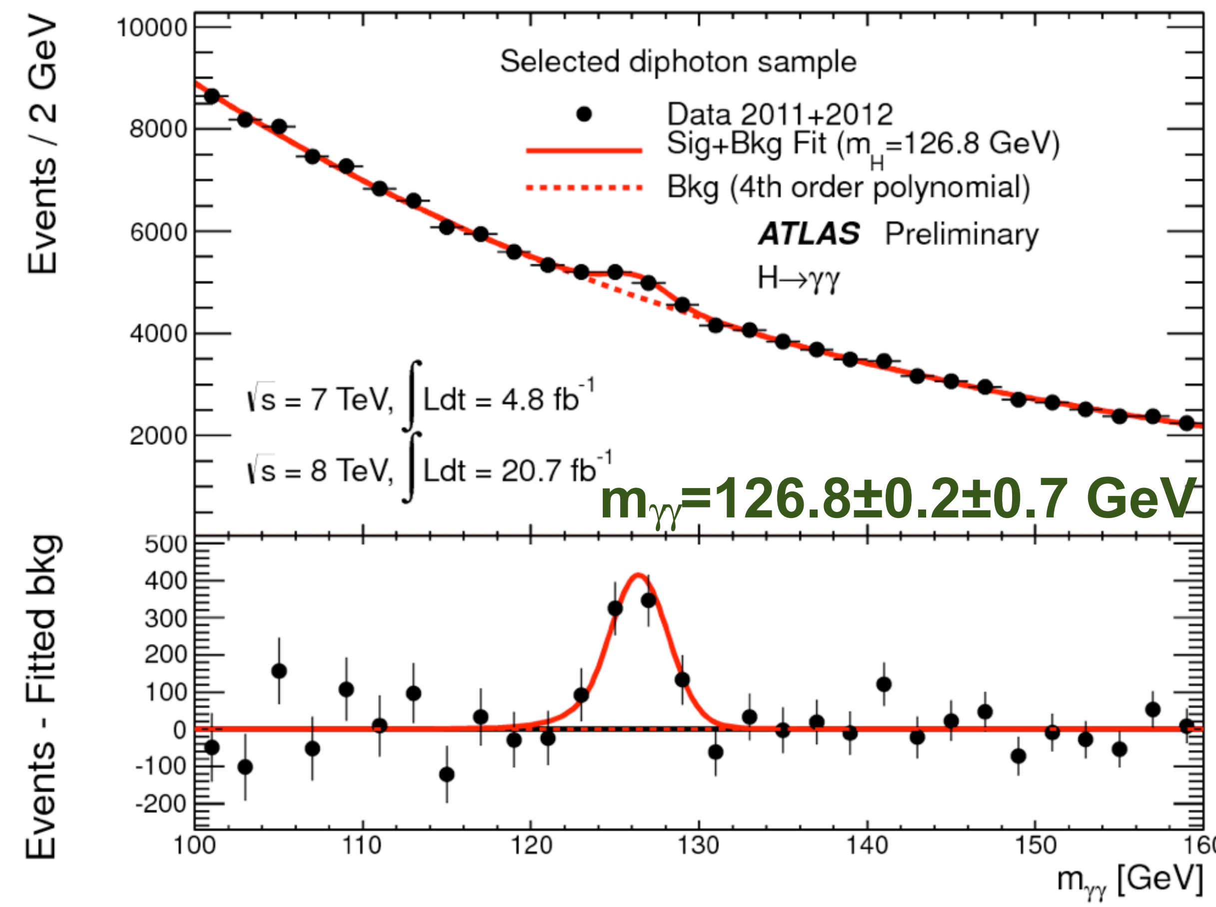
From G. Dissertori (ETH)

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

New boson with a mass of ~125 GeV

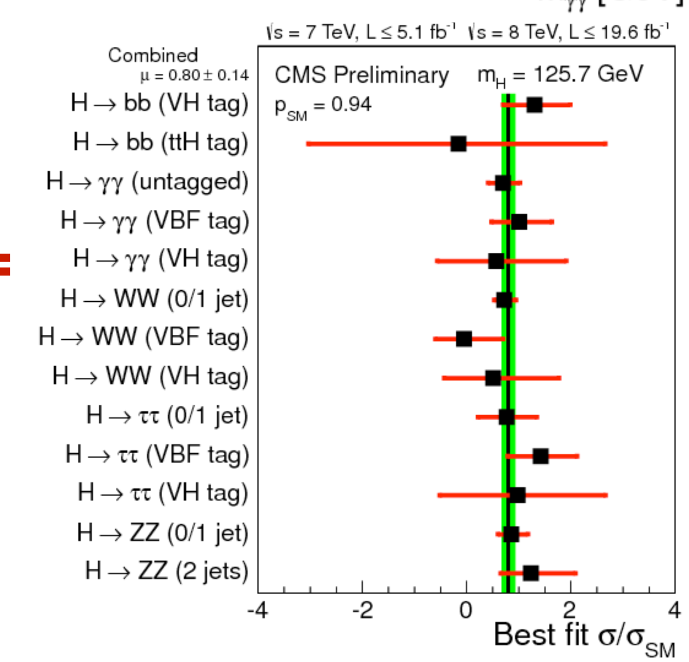
- We have discovered a SM-like scalar boson with a mass of ~125 GeV.
- J^{PC}, consistent with SM scalar boson, couplings will need more data.





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

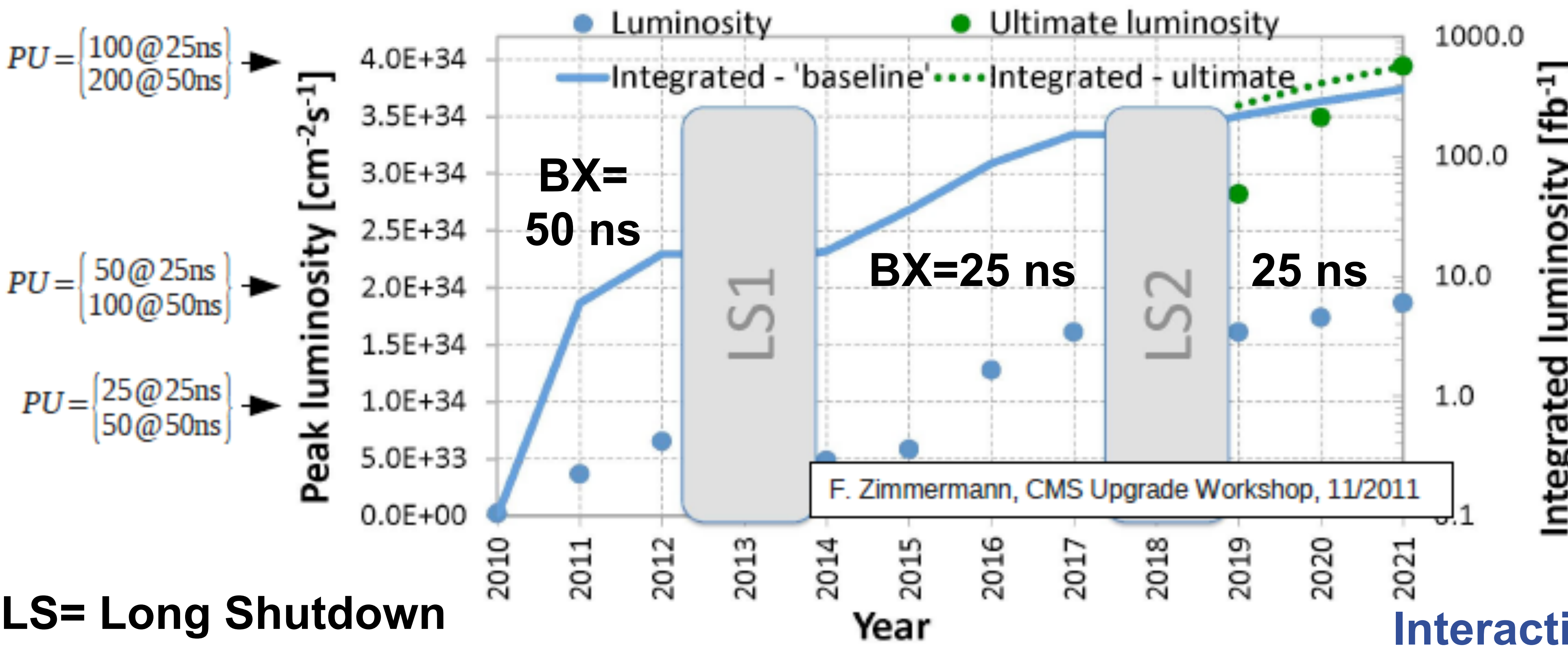
0.80±0.14



The new boson is consistent with being the SM Higgs boson

LHC and HL-LHC

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



LS= Long Shutdown

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

		LS1		Interaction region upgrade / 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

ATLAS, CMS Upgrade plan

Phase 1 Upgrade

Phase 2 Upgrade

New LHC schedule

CMS Pixel installation

CMS target for LS3

LHC schedule beyond LS1

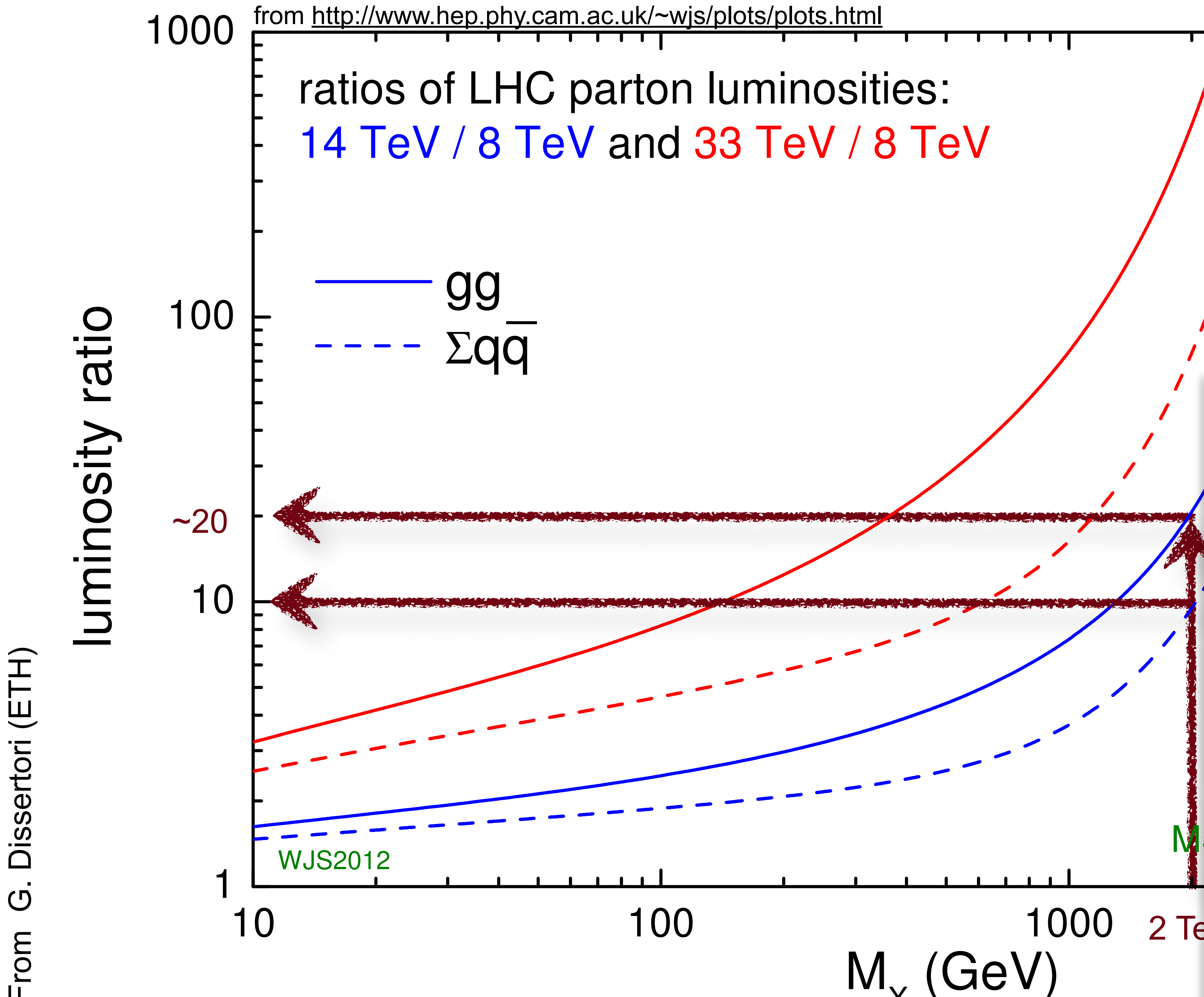
Only EYETS (19 weeks) (no Linac4 connection during Run2)

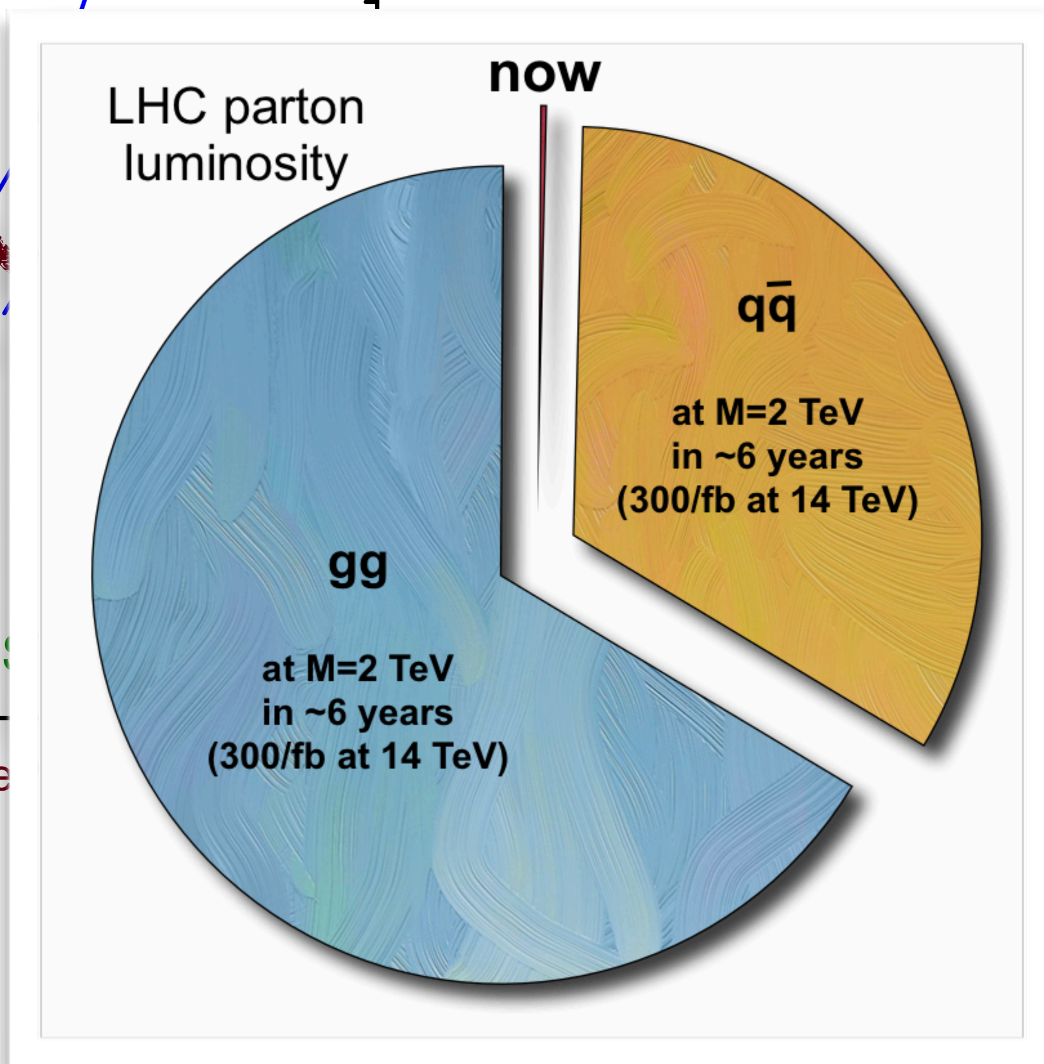
LS2 starting in 2018 (July) 18 months + 3months BC (Beam Commissioning)

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

injectors: in 2024 => 13 months + 3 BC

LHC after LS1





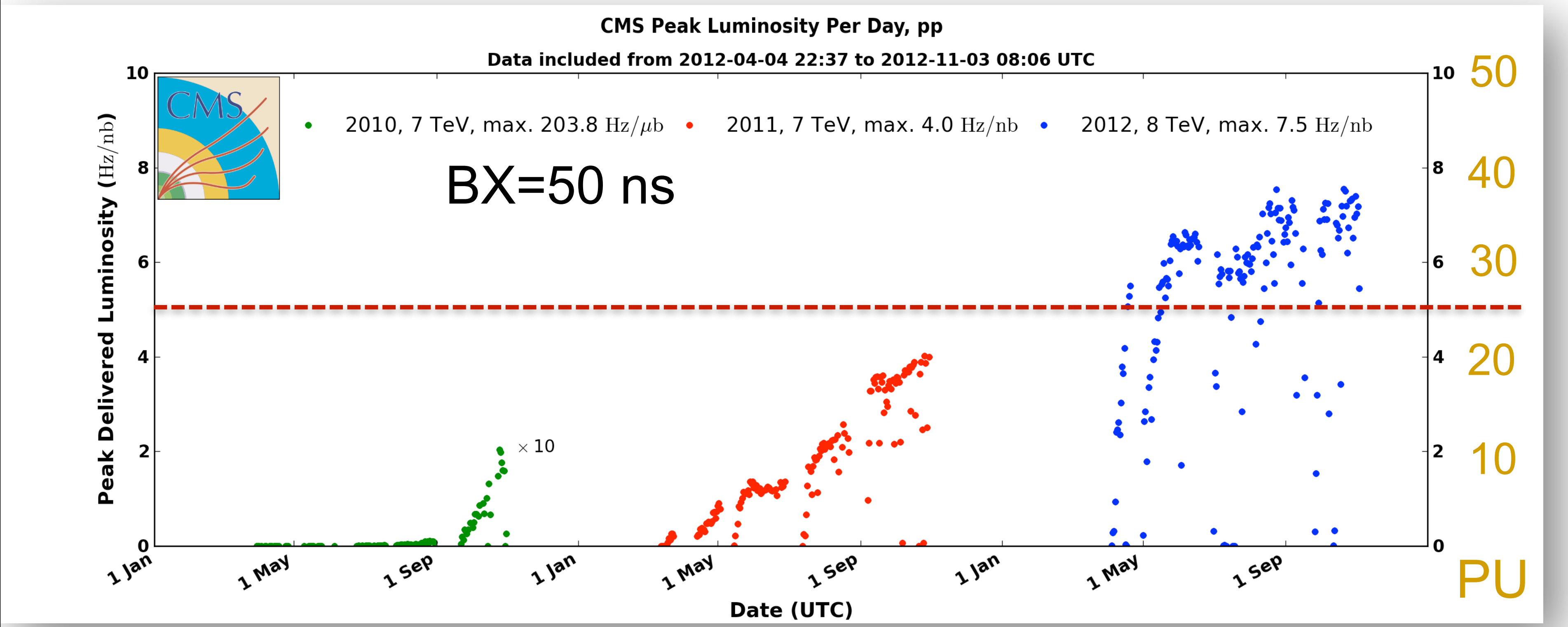
We are about to explore a new territory!

Detector and trigger challenges

- Need detectors and trigger with high performances from low to high energy scales
  - 125 GeV SM-like boson measurements
  - Multi-TeV new physics searches
- Phase 1 Upgrade: twice LHC design luminosity
  - Event pileup reaches ~50 collisions per beam crossing (@ 25 ns)
  - Factor 5 increase in trigger rates relative to 2012 run
- Phase 2 Upgrade: 5x LHC design luminosity
  - Event pileup reaches ~140 collisions per beam crossing (@ 25 ns)
  - Need solutions to cope with very high rates (10-15 x 2012), radiation and pileup

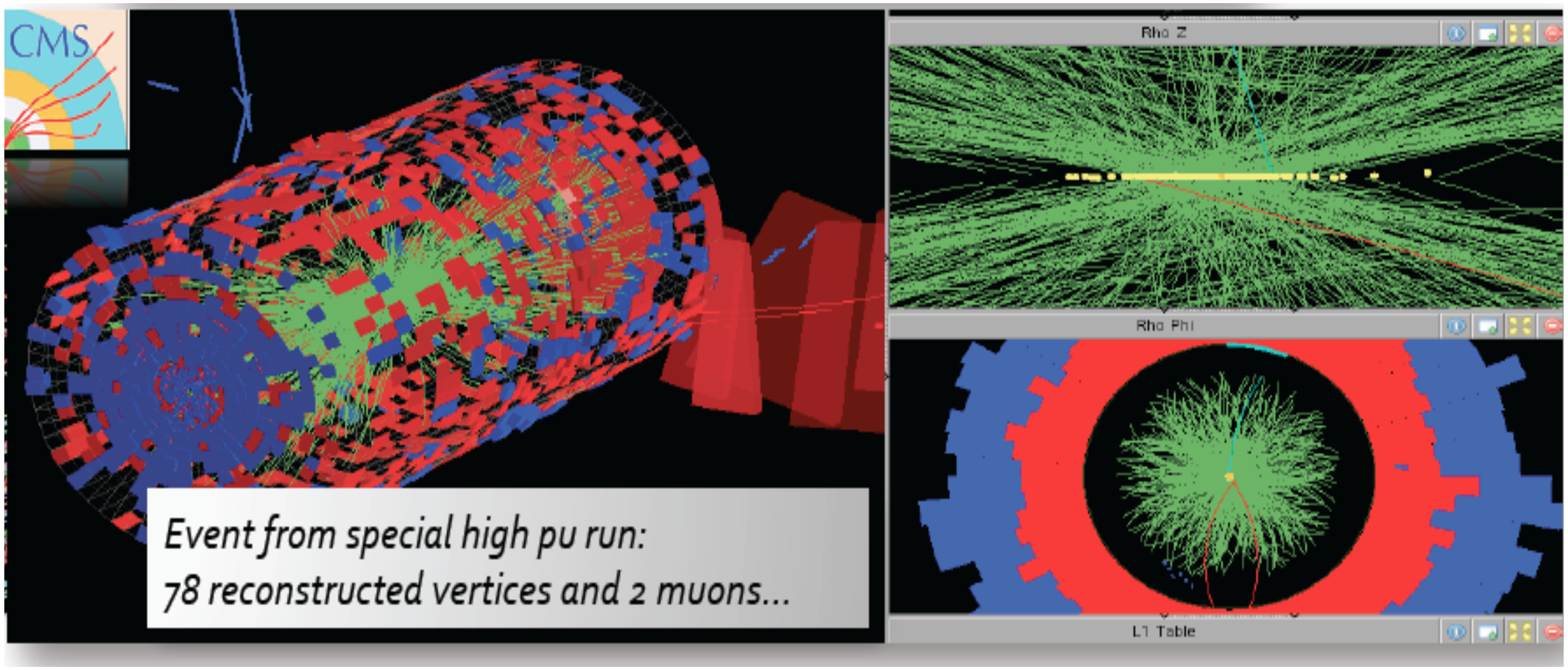
ATLAS and CMS were designed to cope with L= 1-2 $x10^{34}$ $cm^{-2}s^{-1}$

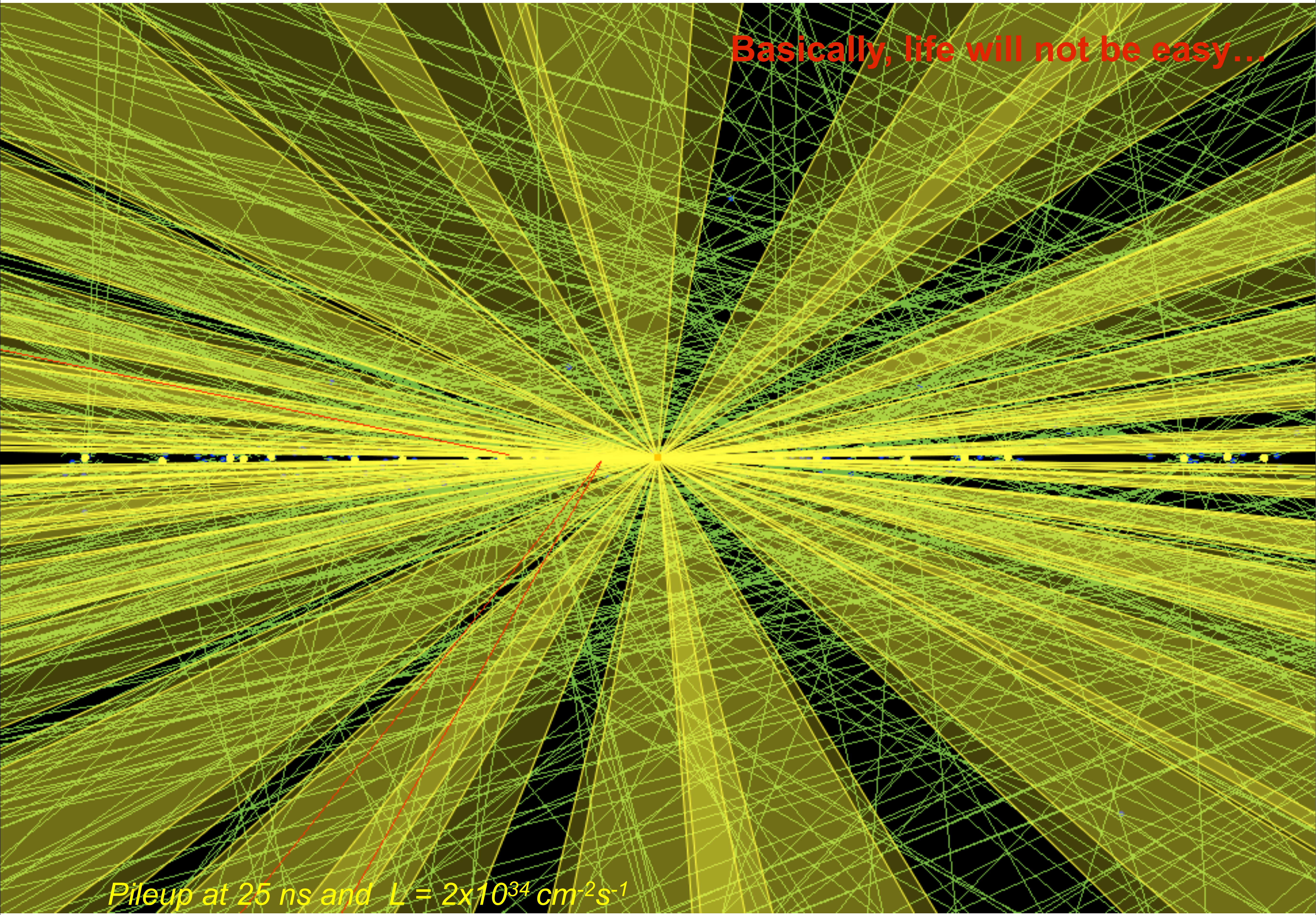
Pileup in 2012



Peak: 37 pileup events

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



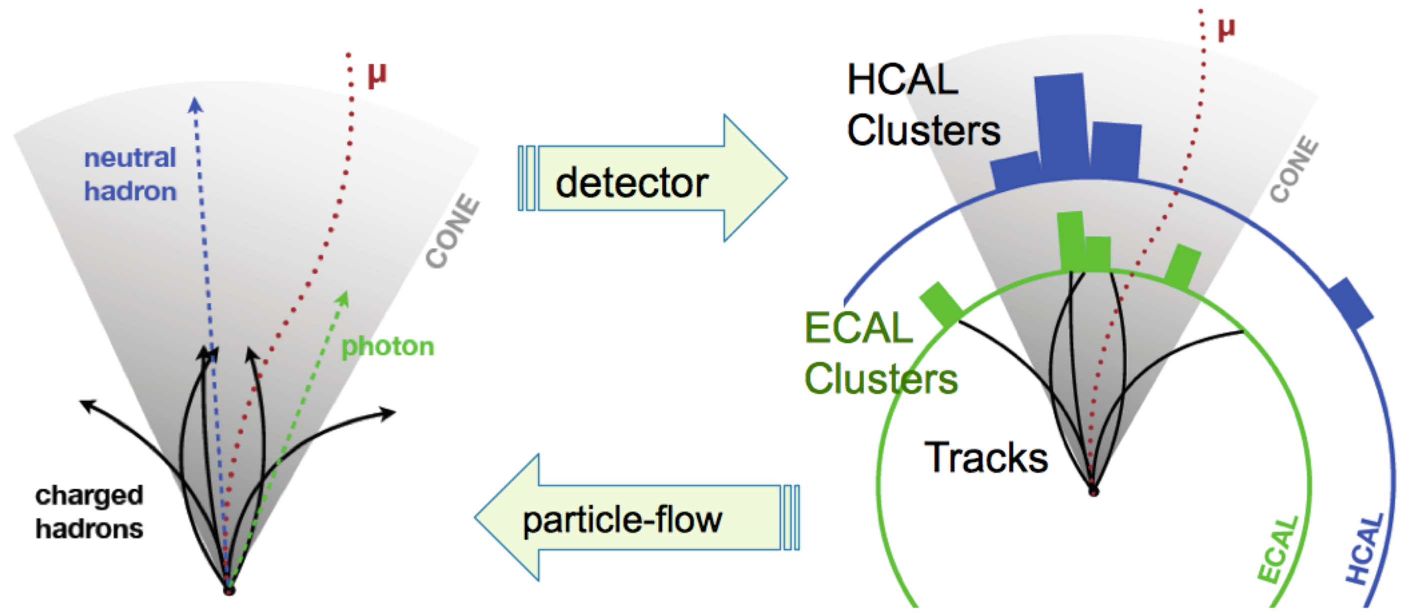

Basically, life will not be easy…
Pileup at 25 ns and L = 2x10^34 cm^-2 s^-1

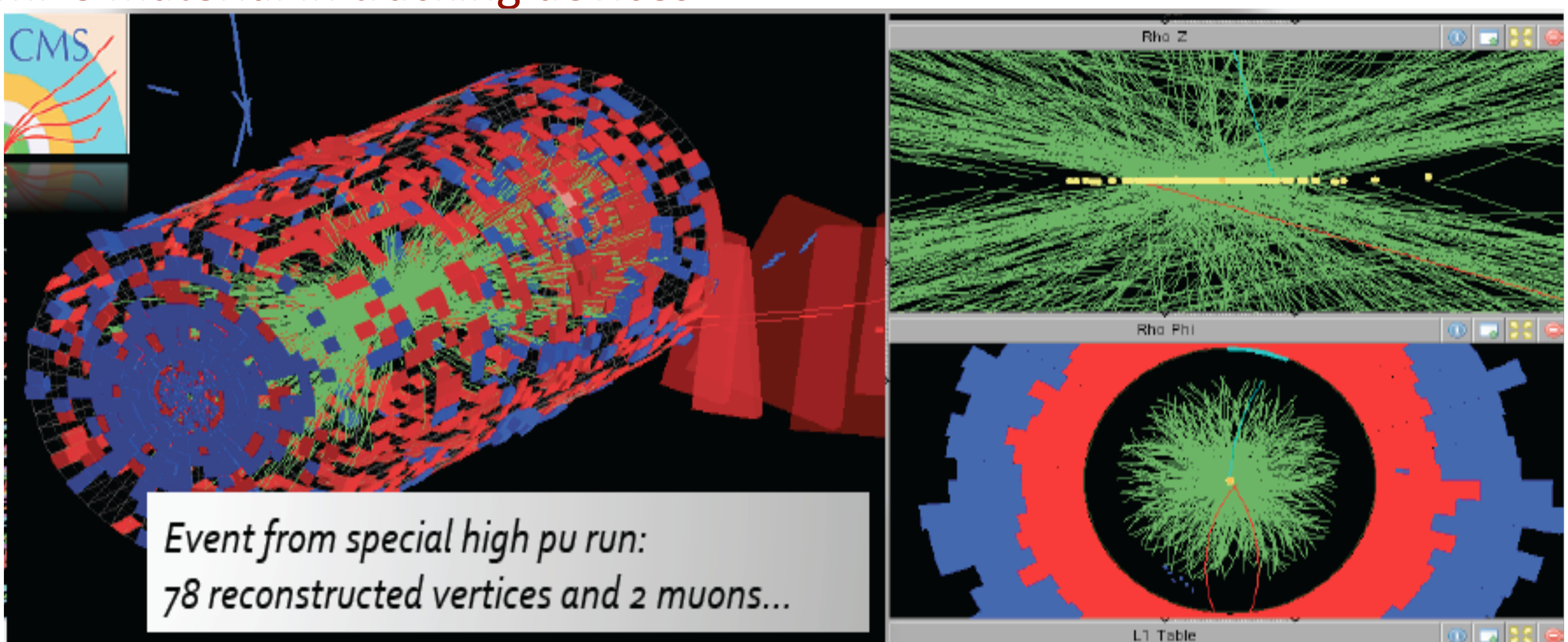
Upgrade challenges and recipe

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

Need new technology R&Ds to:

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





Physics program priorities

The discovery of a SM-like scalar boson at m_H~125 GeV defines the physics priorities

- With LHC 13/14 TeV data until ~2022 (~300 fb^{-1})
  - Measure SM-like scalar boson properties
    - mass, J^{PC}
    - individual couplings with 5-15% precision
  - Search for new physics at a higher mass scale (new energy region)
    - SUSY
    - Exotics
- With HL-LHC 14 TeV data until ~2032 (~3000 fb^{-1})
  - High Precision SM scalar boson measurements
  - Study Higgs boson rare decays and self-coupling
  - Study VV scattering
  - Characterize any New Physics discovered during Phase 1 at 14 TeV
  - Search for new physics in very rare processes

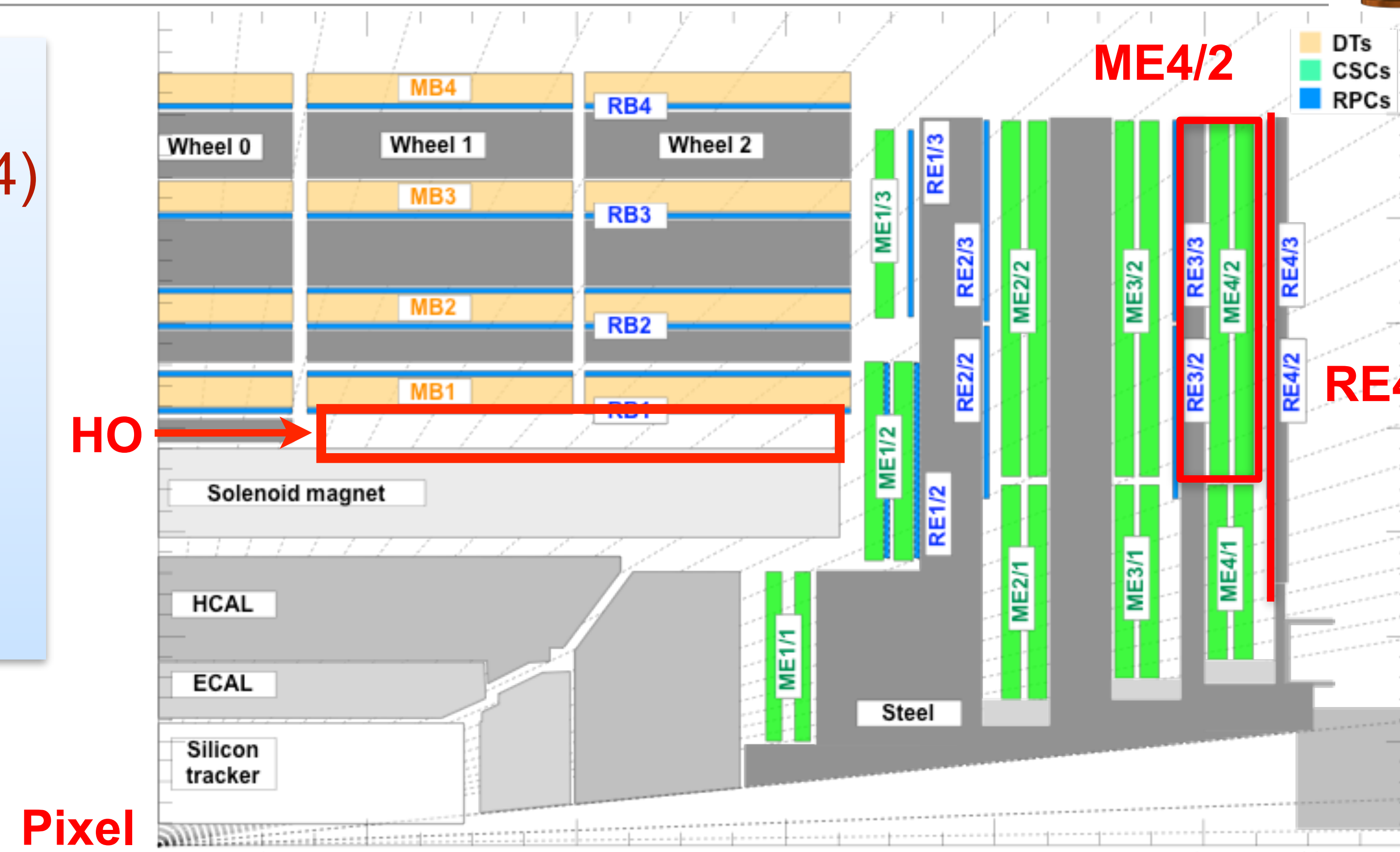
Higgs Physics at HL-LHC

- What can we do at HL-LHC in the Higgs sector?
  - Measure existing decay channels with the highest precision
  - Observe rare Higgs decays
    - $H \rightarrow \mu\mu$
    - $H \rightarrow Z\gamma$
    - $H \rightarrow cc$ (?)
  - Double Higgs production (Higgs self-coupling)
  - Vector boson scattering
  - Look for small deviations from SM predictions

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 LS2 LS3

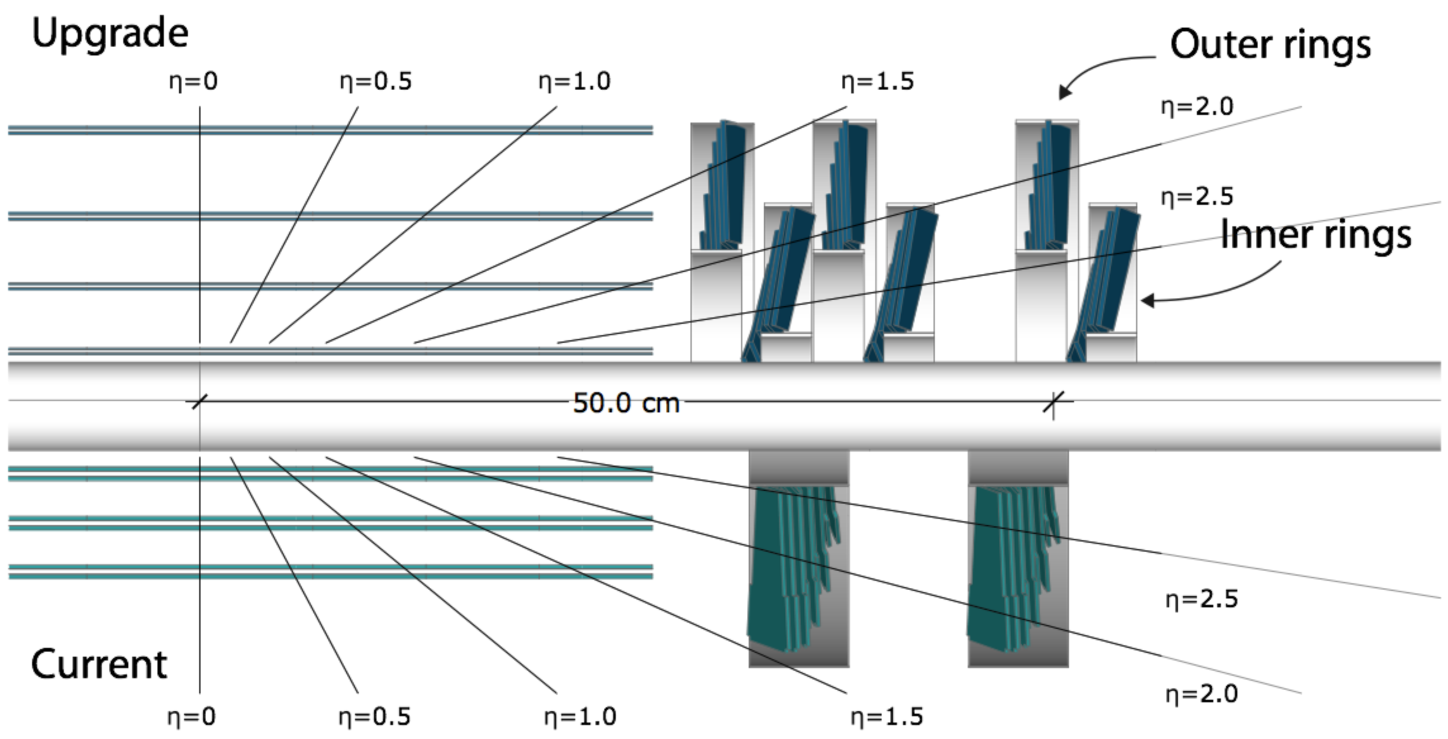
Phase 1 Upgrades

- New Pixel detector, HCAL electronics and L1-Trigger upgrade
- 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

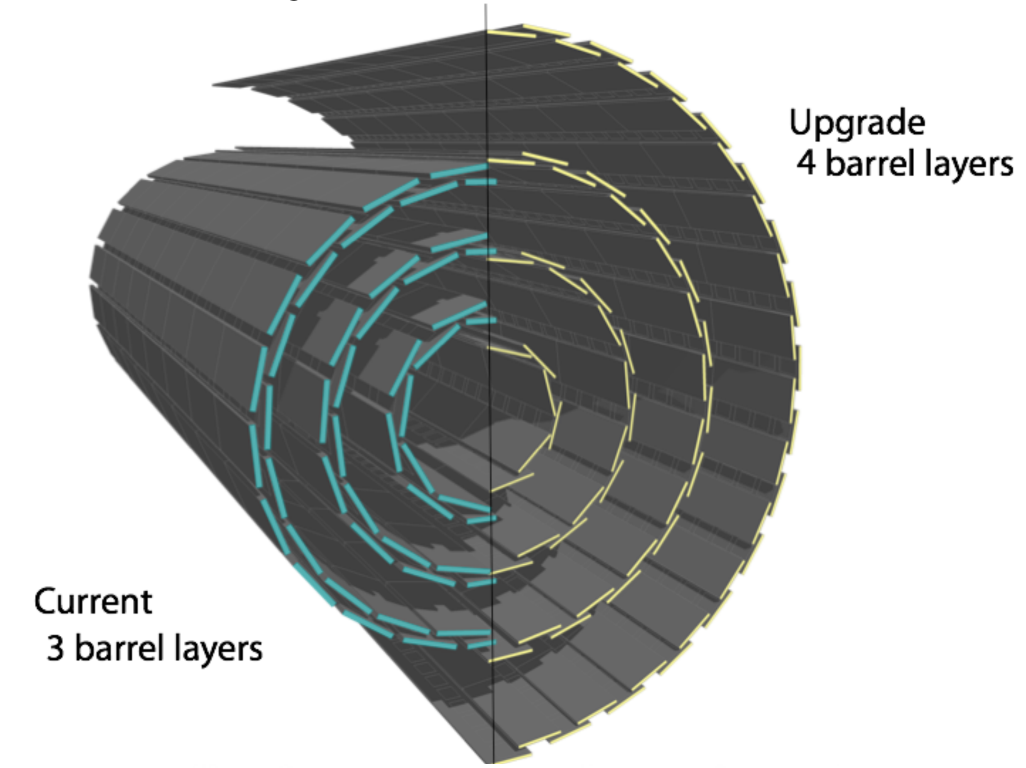
Phase 2: being defined now

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

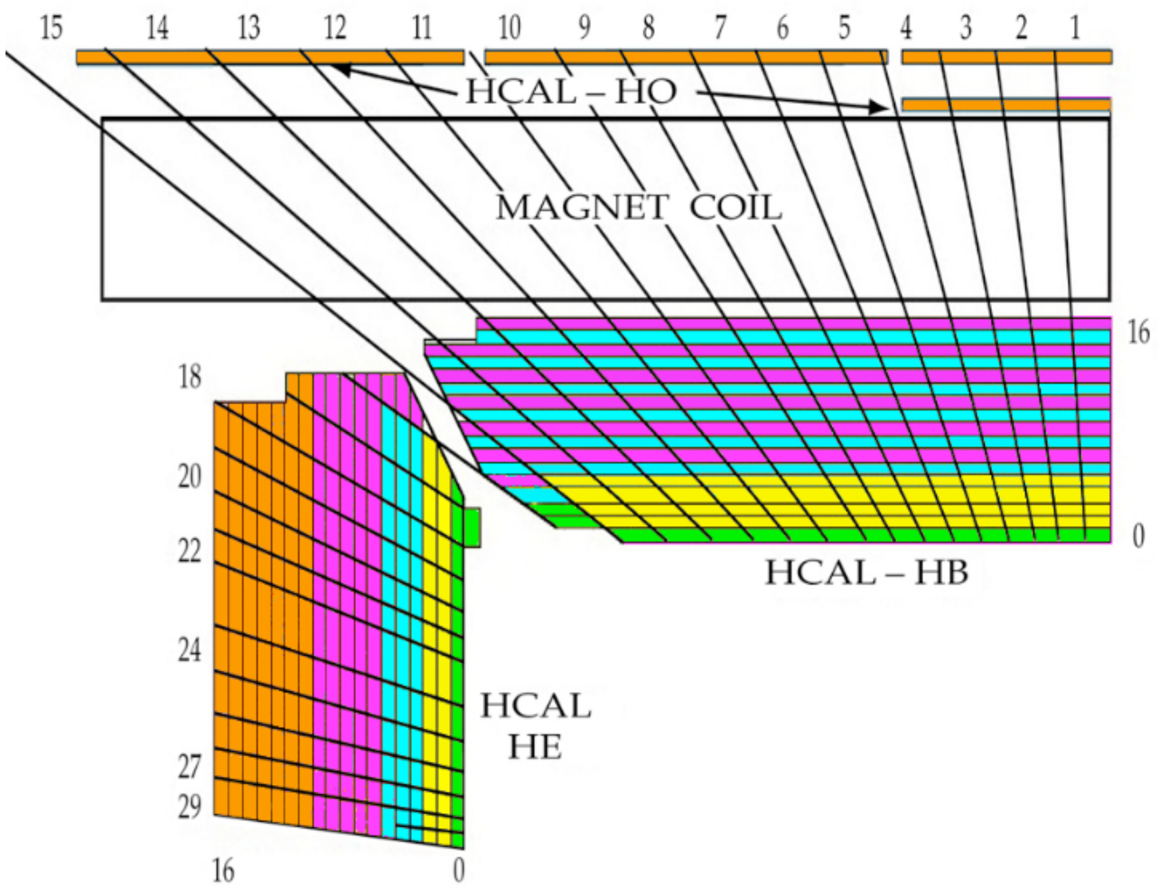
Pixel and HCAL phase 1 upgrades



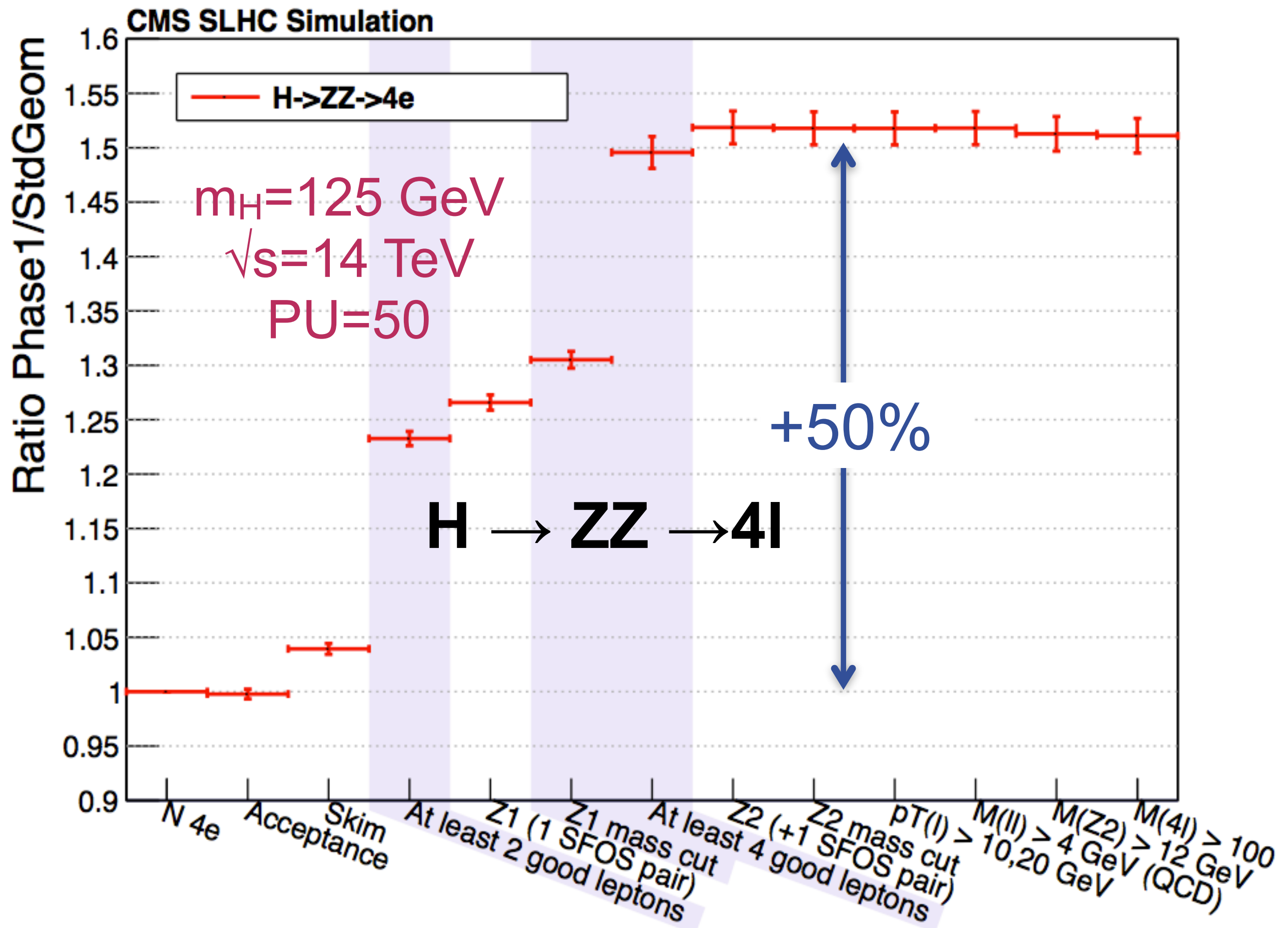
New 4-layer pixel detector Pixel

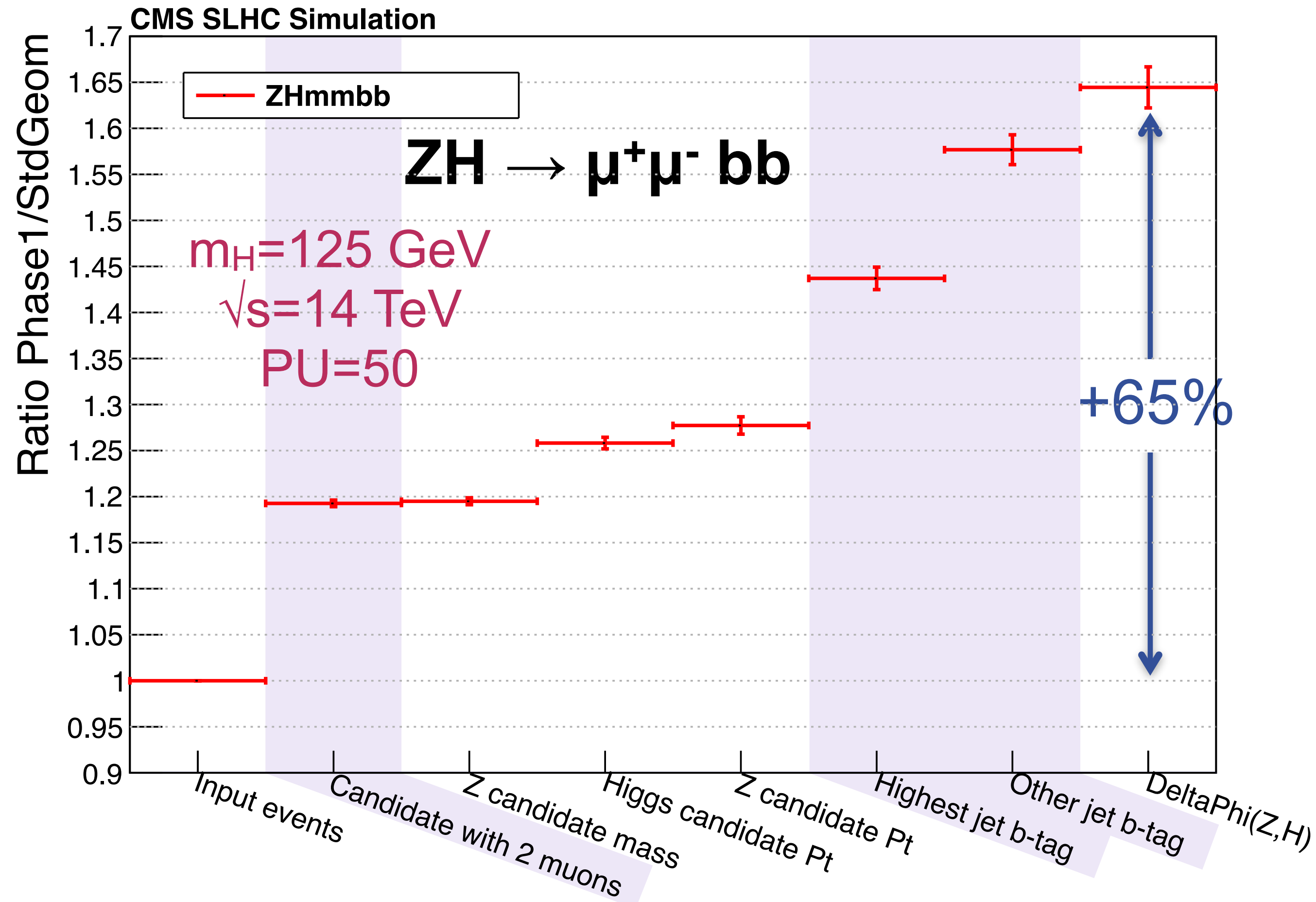


- Upgraded HCAL
  - New photodetectors
  - New electronics (frontend, backend)
  - Improved longitudinal segmentation
  - Improved background rejection, Missing E_T resolution and Particle Flow reconstruction



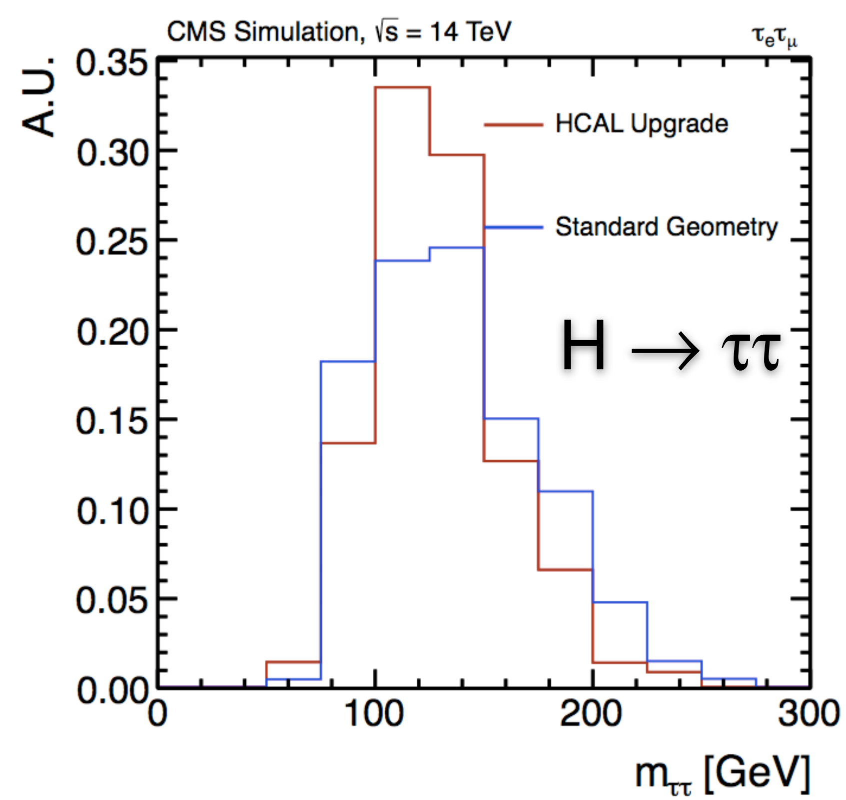
Expected Phase 1 improvements





Significant gain in signal reconstruction efficiency:

$H \to 4\mu$	+41%
$H \to 2\mu 2e$	+48%
$H \to 4e$	+51%

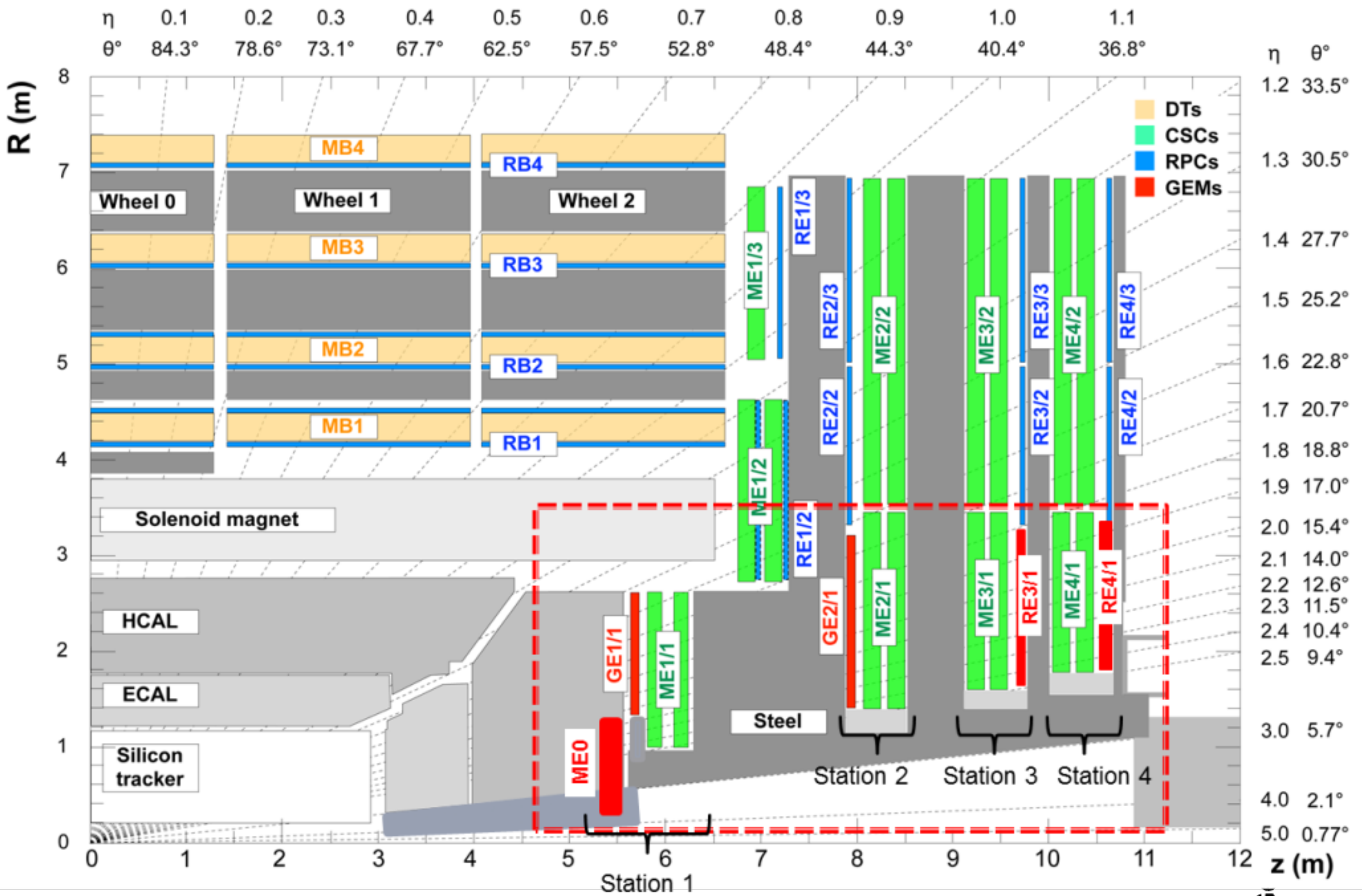


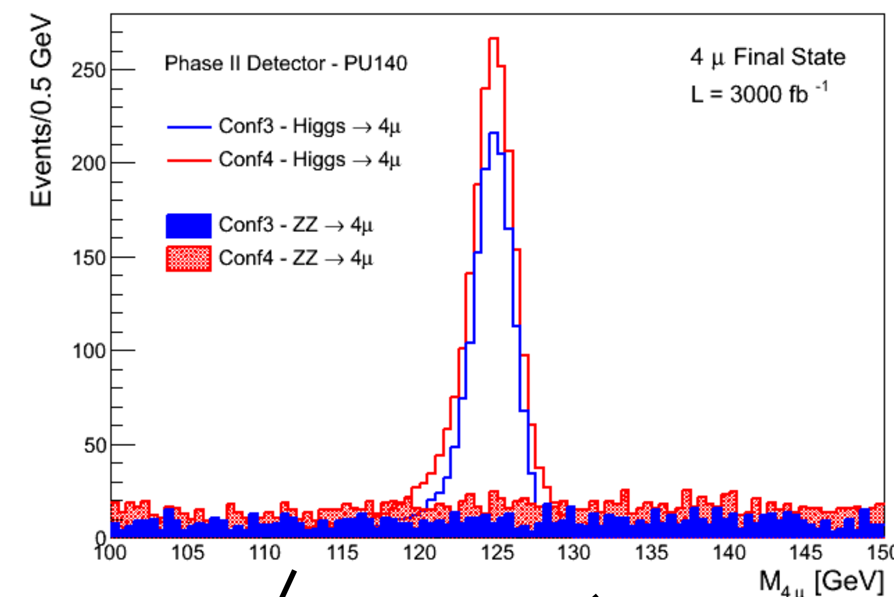
Total efficiency improvement: factor of 2.5 (4.5% → 11%)

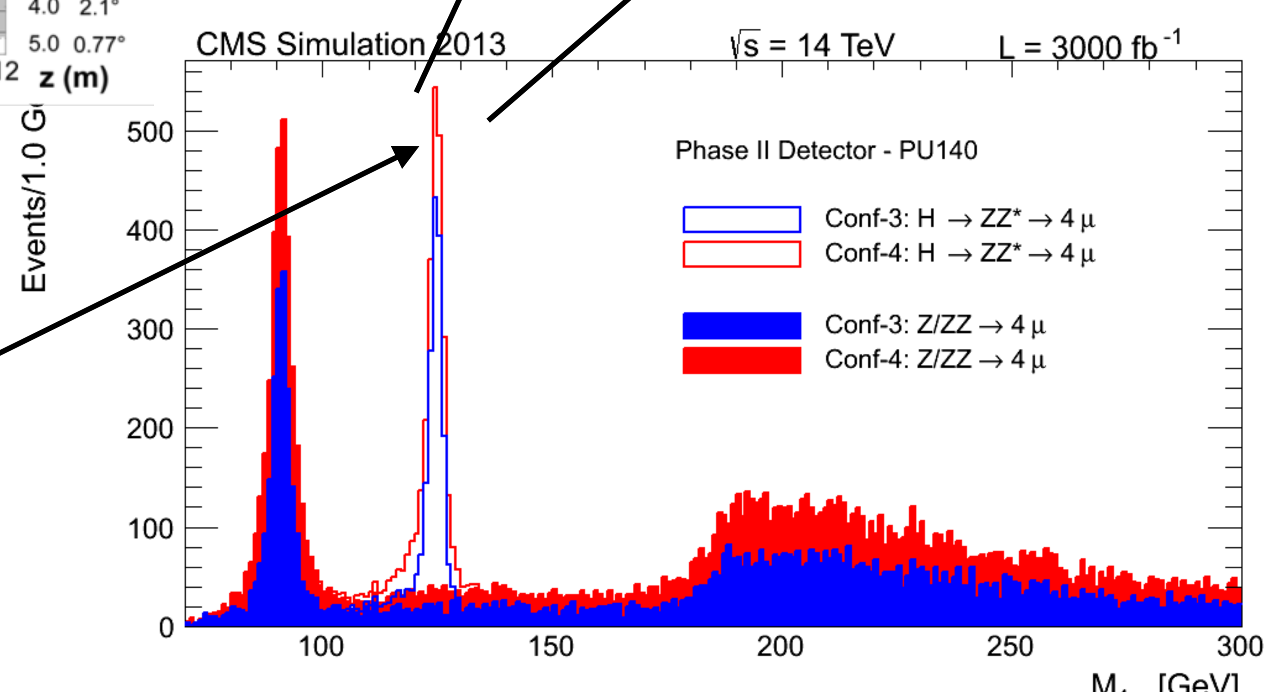
Improved jet and MET → 25% improvement in $m_{\tau\tau}$ resolution

CMS Phase II Muon detector

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

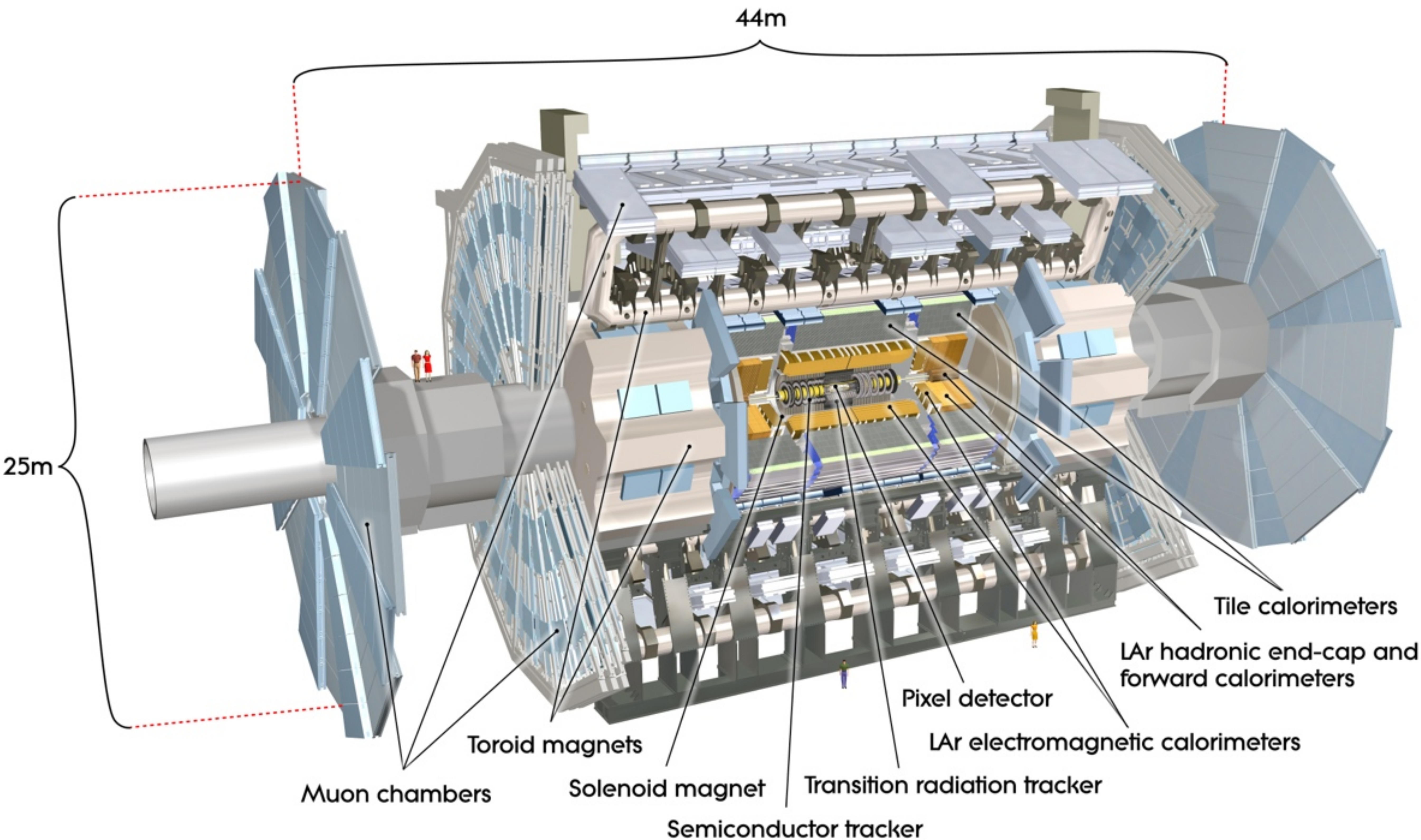






$>40\%$ more $H\to 4\mu$ events

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

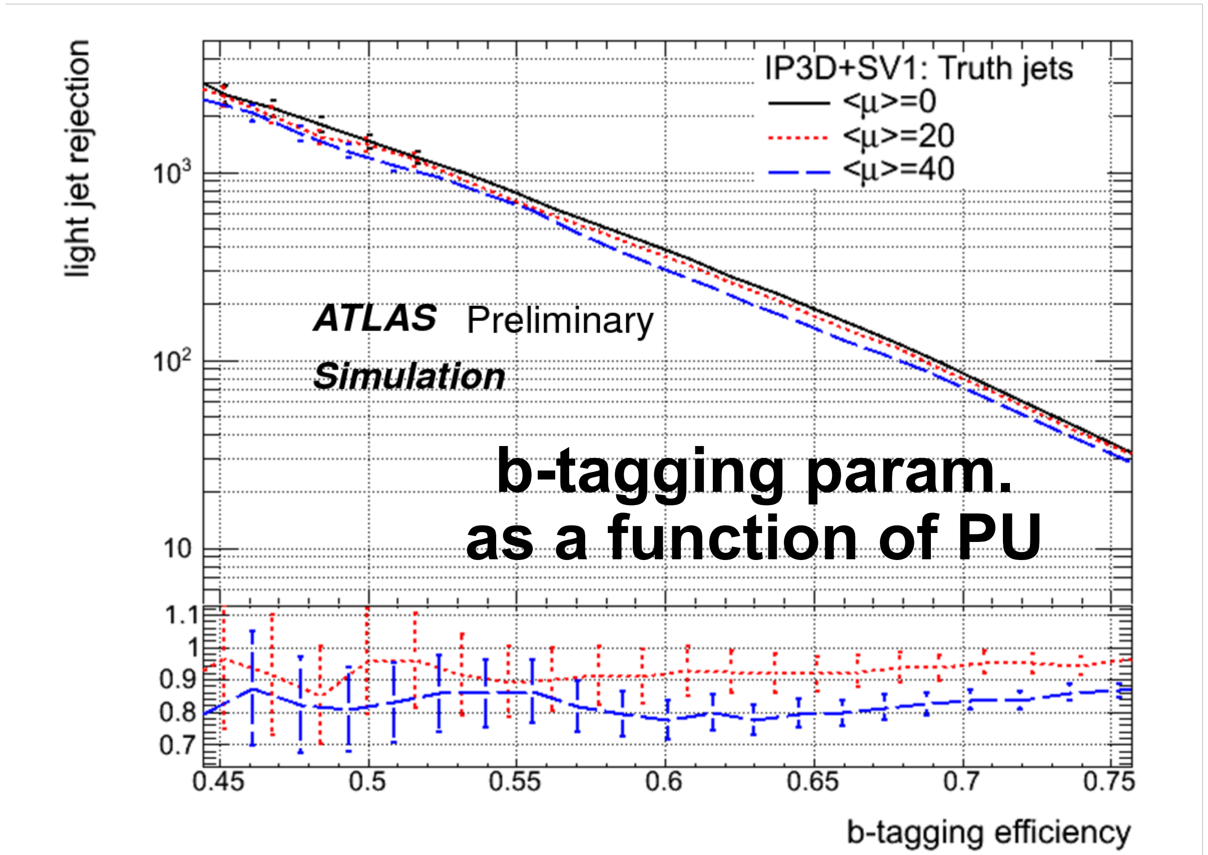
- New insertable pixel b-layer (IBL)
- New Al beam pipe
- New pixel services
- Complete installation of EE muon chambers
- New evaporative cooling plant
- Consolidation of detector services
- Specific neutron shielding
- Upgrade magnet cryogenics

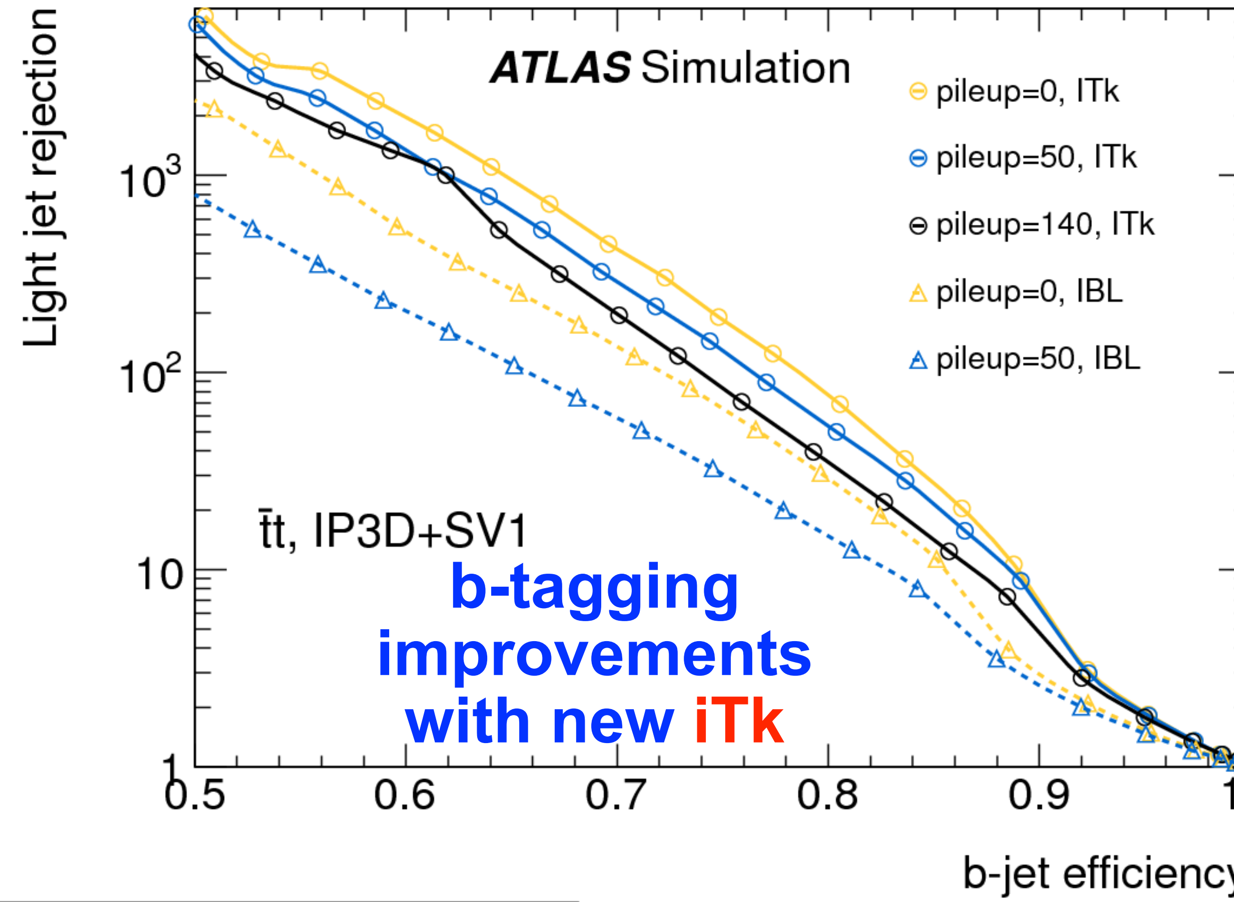
- New Small Wheel (nSW) for the forward muon Spectrometer
- High Precision Calorimeter L1-Trigger
- Fast TracKing (FTK) for L2-trigger
- Topological L1-trigger processors
- New forward diffractive physics detectors (AFP)

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

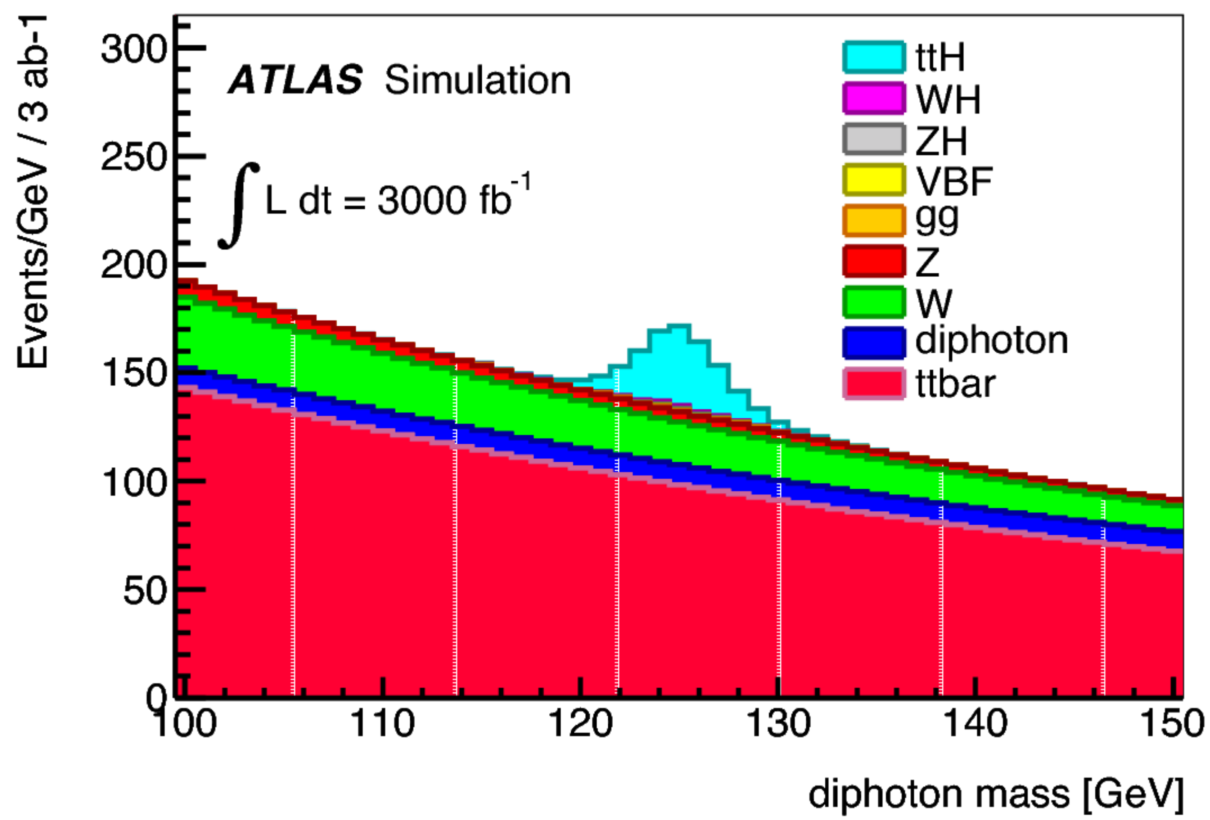
From M. Diemoz

ATLAS upgrade performances





di-photon mass resolution in ttH channel



From 2013 to HL-LHC

- From 30 to 3000 fb^{-1}: two orders of magnitude extrapolation in luminosity

To calculate physics projections at HL-LHC

Similar trigger and reconstruction peformances as in 2012

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

ATLAS and CMS have launched a comprehensive upgrade program

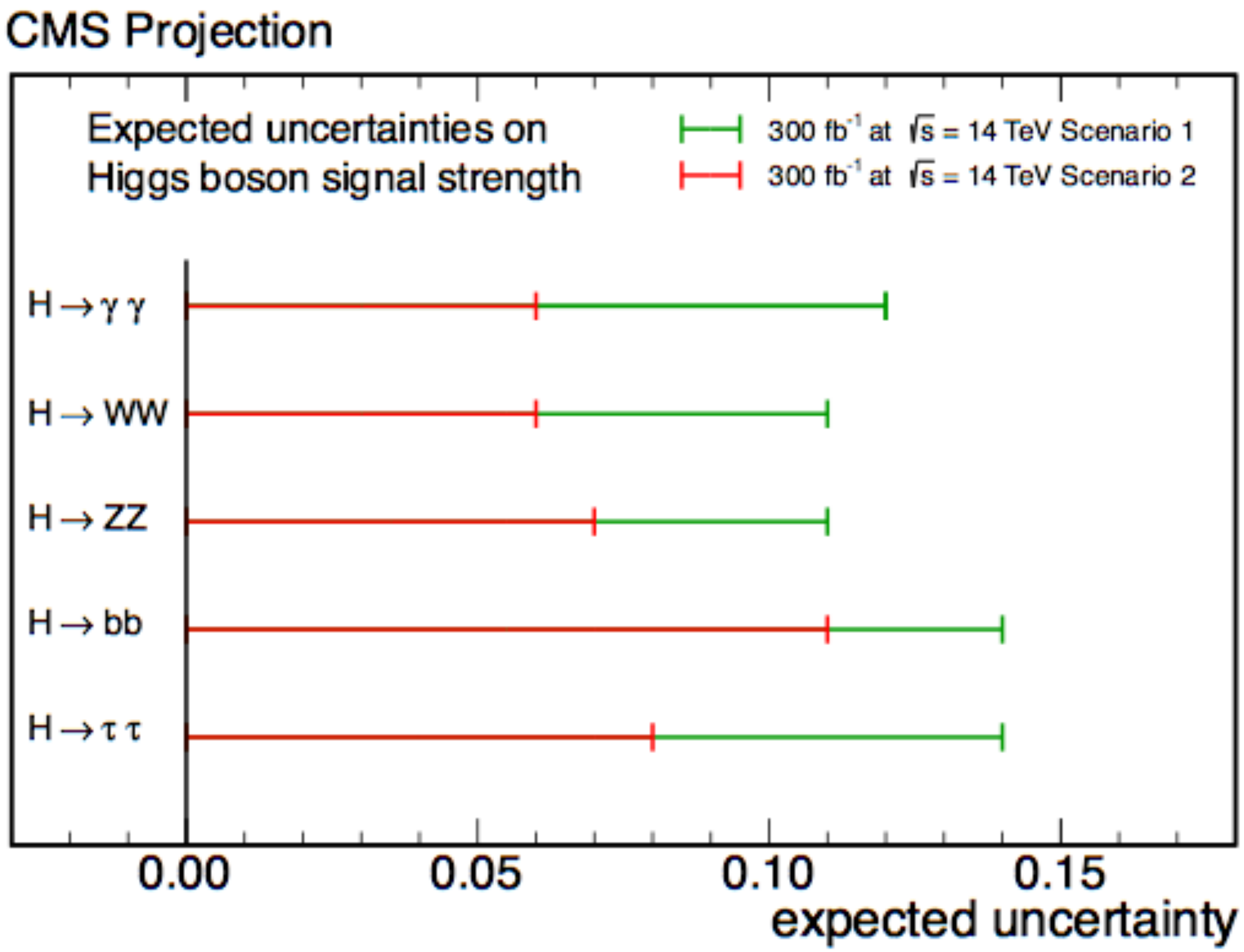
Higgs boson projections after LS1

Approaches adopted for physics projections

- **ATLAS**: perform physics studies using fast simulation to mimic the beam effects on momentum and energy resolution, acceptance, identification and reconstruction efficiencies, fake rates, etc.
- **CMS**: assume that an upgraded detector will compensate the effects of the higher pile-up, using three different scenarios:
  - Scenario 1: all systematic uncertainties are kept unchanged with respect to those in current data analyses
  - Scenario 2: the theoretical uncertainties are scaled by a factor of 1/2, while other systematical uncertainties are scaled by $1/\sqrt{L}$
  - Scenario 3: set theoretical uncertainties to zero, leave other syst. uncertainties the same as in 2012

Higgs signal strength with 300 fb^{-1}

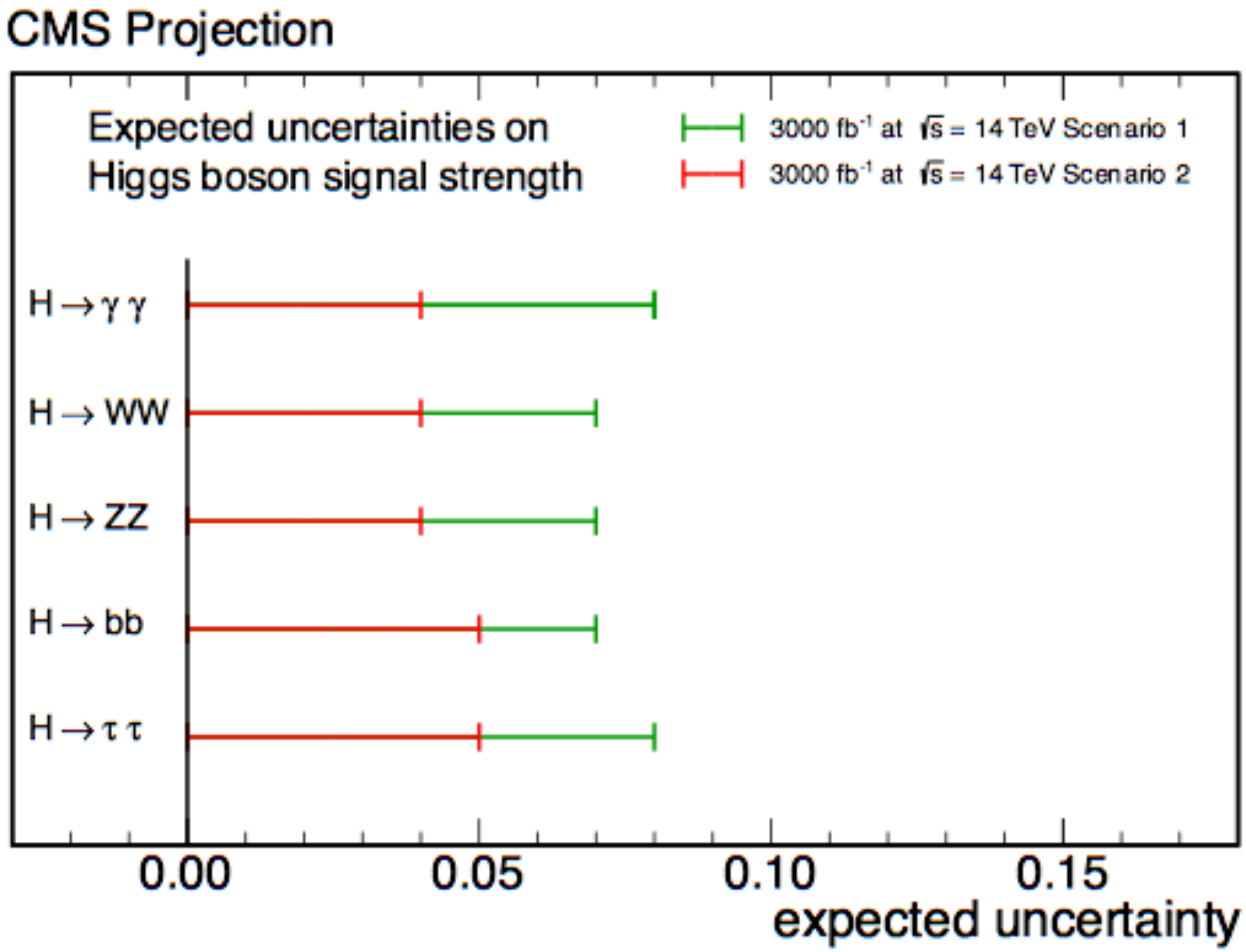
- Extrapolation by two orders of magnitude to higher luminosity
  - is subject to large uncertainties
  - scenarios 1 and 2 provide likely upper and lower bounds
- Experience at LEP and Tevatron indicates that scaling with $1/\sqrt{L}$ is not unrealistic



10 fb^{-1}, 7 and 8 TeV (Scenario 1)
300 fb^{-1} , 14TeV (Scenario 1)

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}



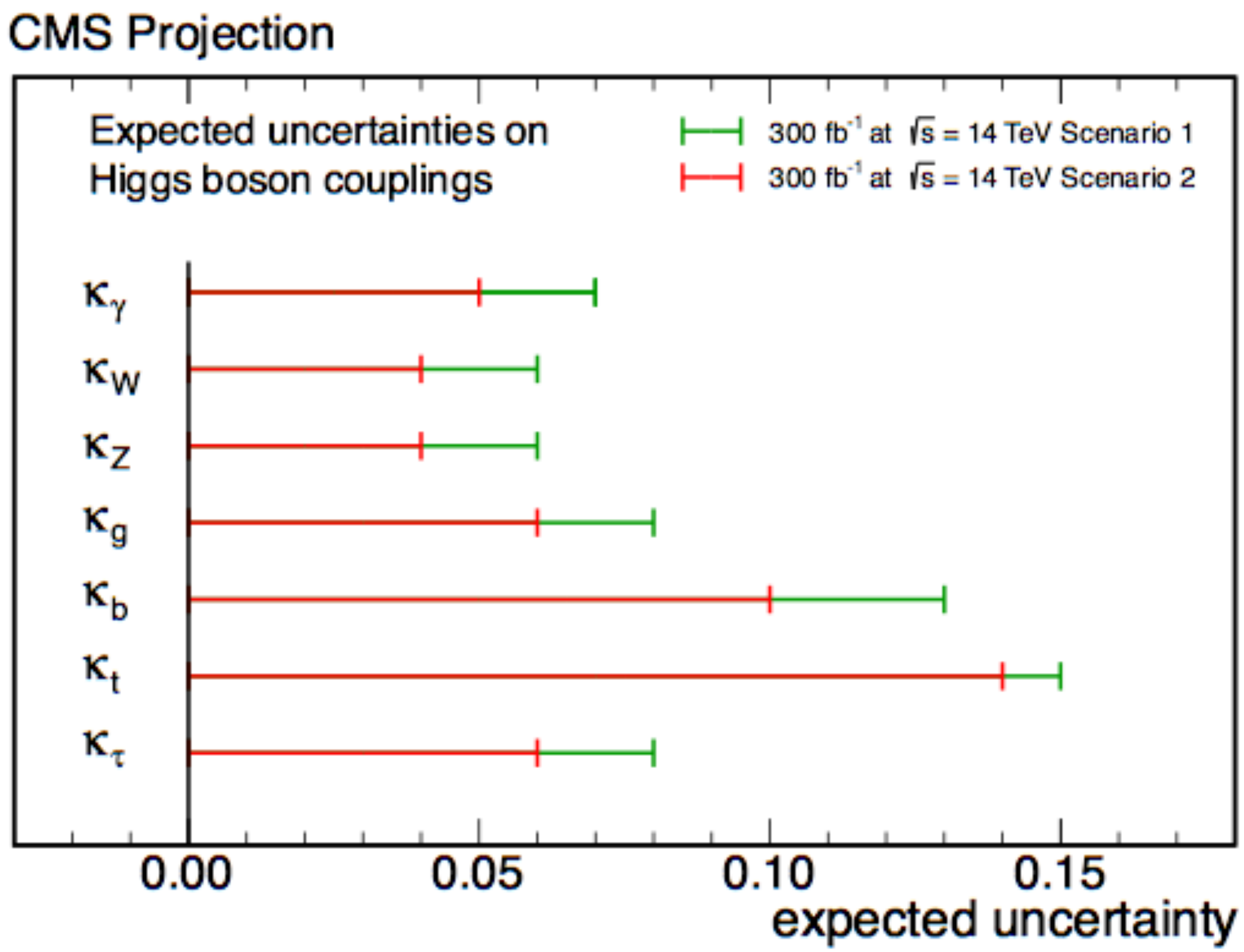
$\mu = \sigma/\sigma_{SM}$

L (fb^{-1})	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]

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

Higgs boson couplings @300 fb^{-1}

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

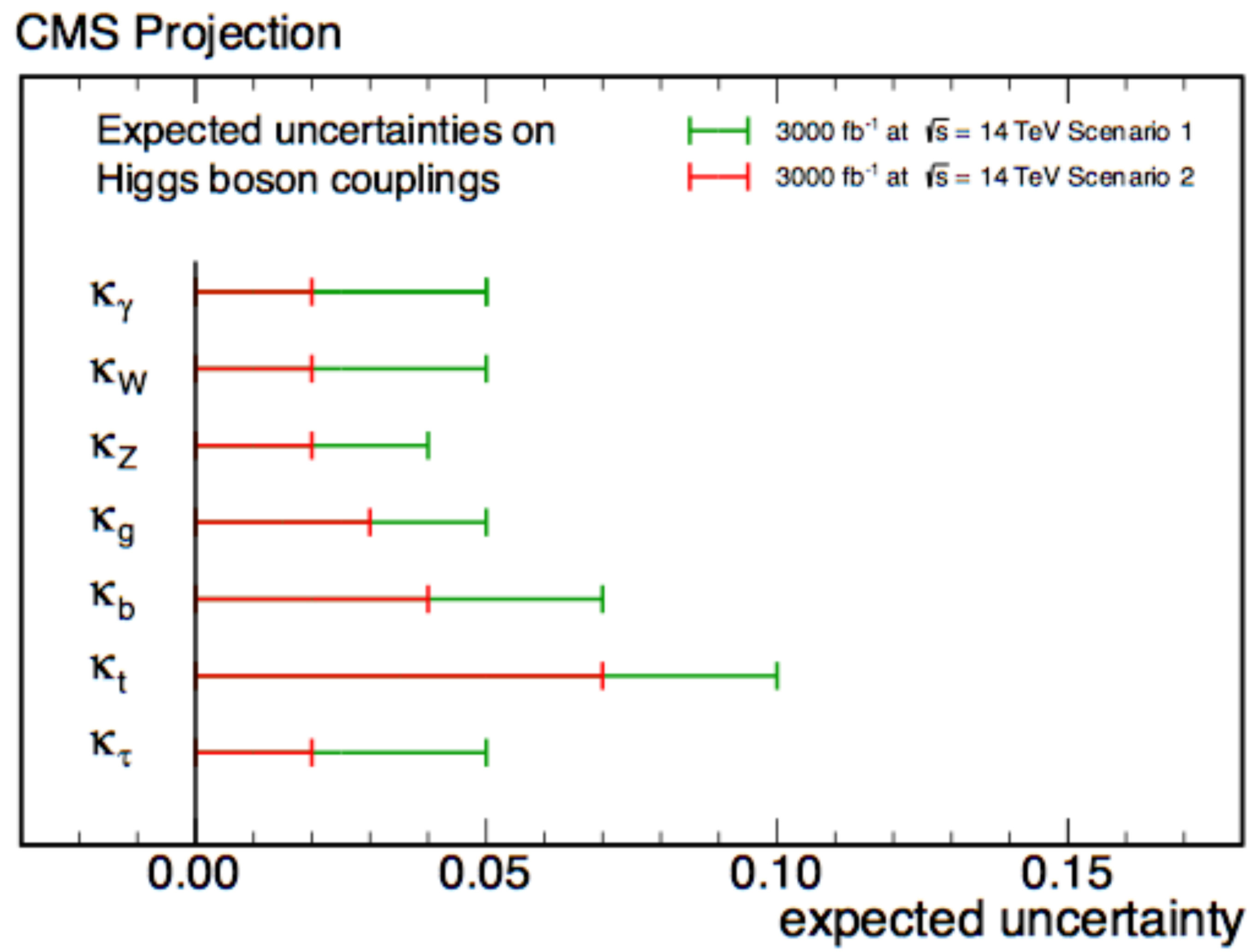


300 fb^{-1} 14 TeV, Scenario 1
300 fb^{-1} 14 TeV, Scenario 2

With 300 fb^{-1} the uncertainties on the Higgs couplings are expected in the range $\sigma(\kappa_V) \sim$ 3-6%

$\sigma(\kappa_f) \sim$ 5-15%

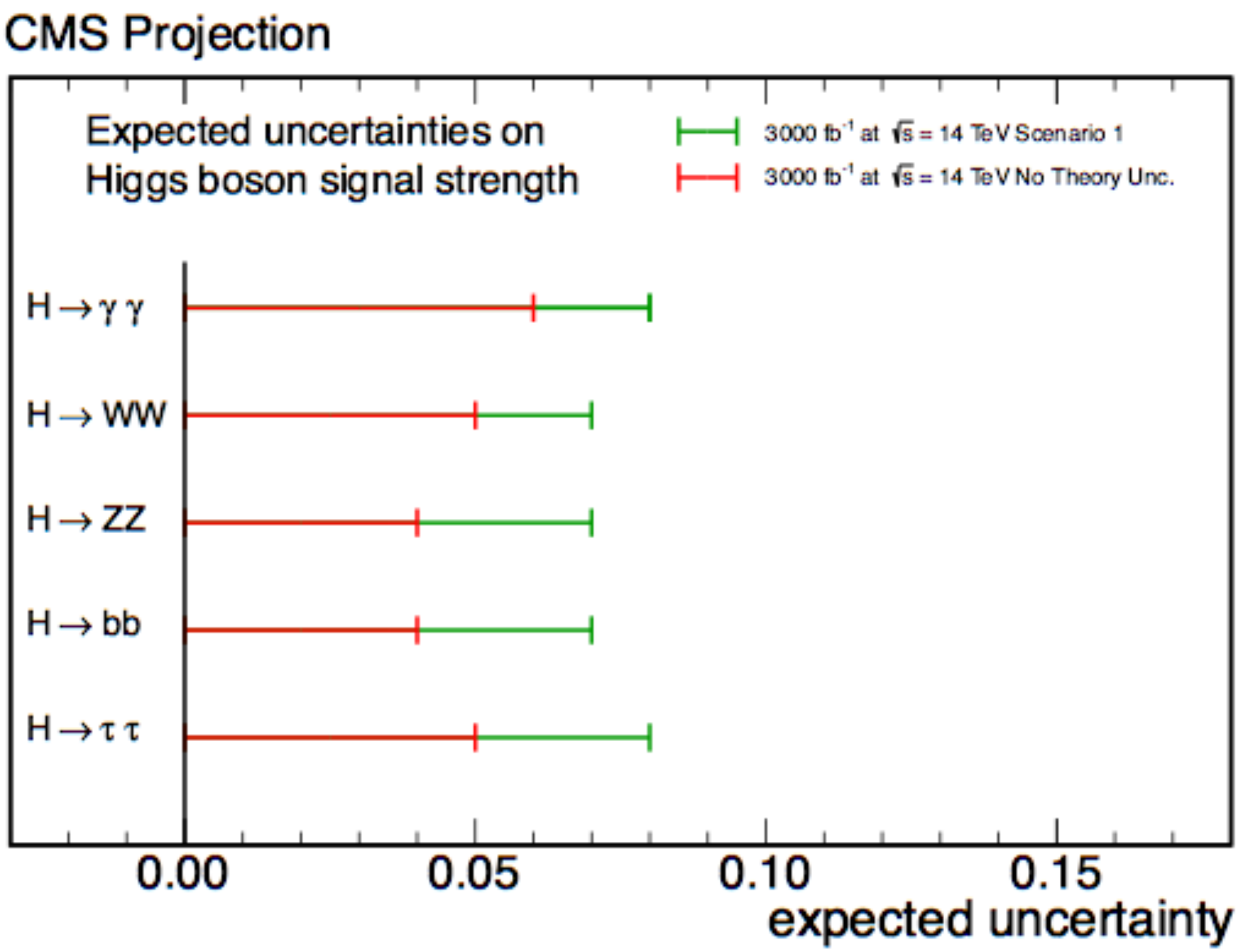
Higgs boson couplings @3000 fb^{-1}

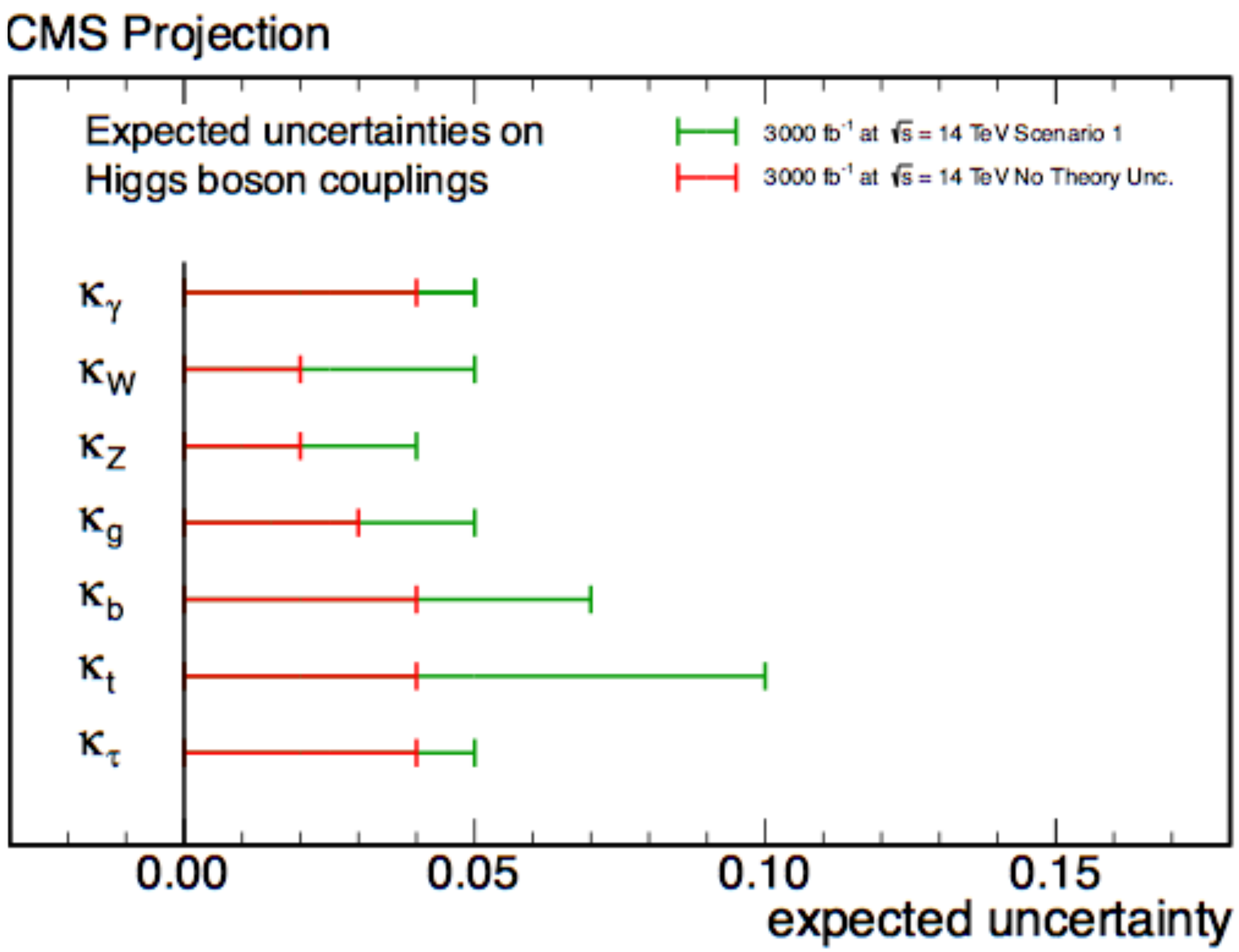


L (fb^{-1})	K_γ	K_W	K_Z	K_g	K_b	K_t	K_τ	$K_{Z\gamma}$	$K_{\mu\mu}$	BR_{SM}
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]	[14,18]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]	[7,11]

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

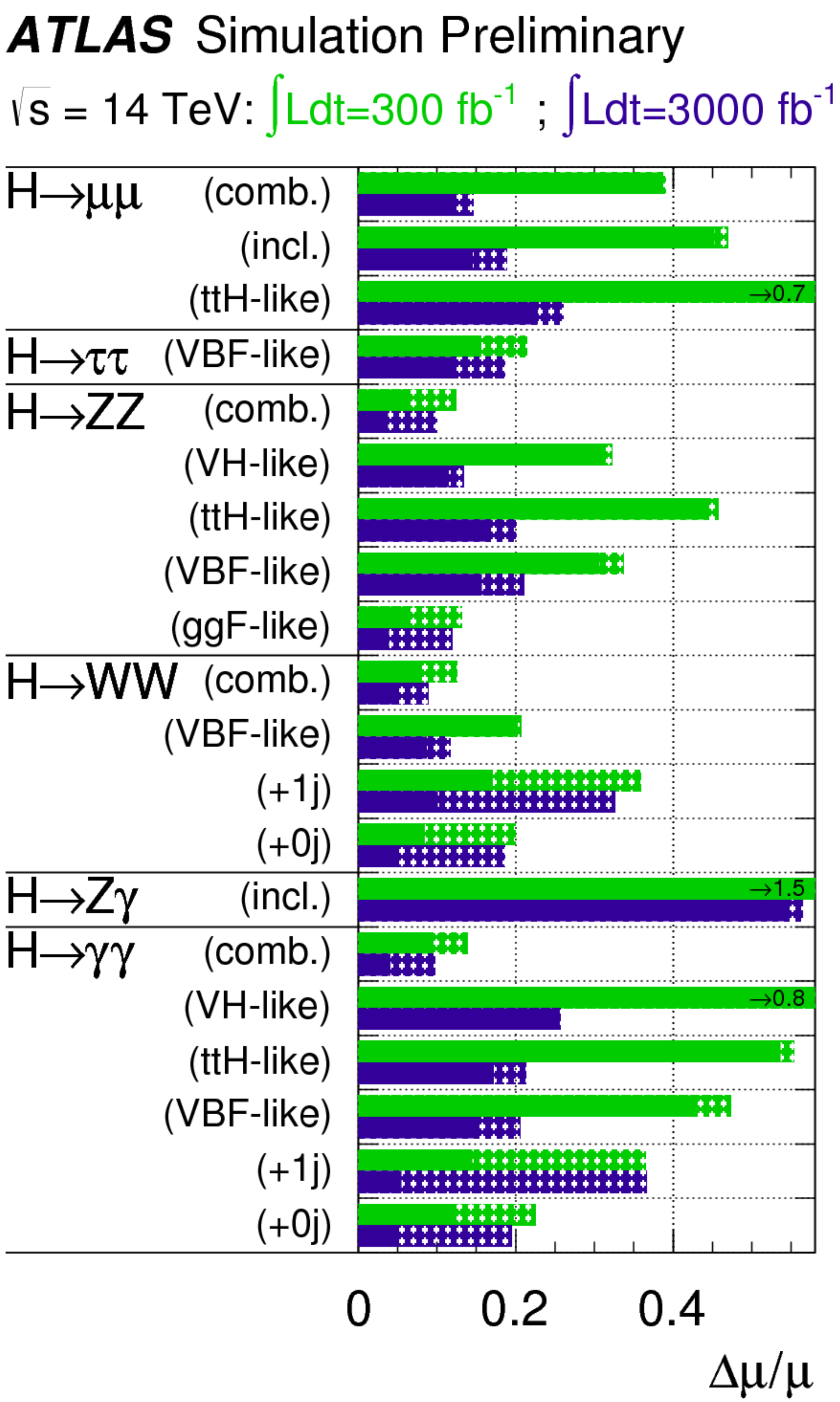
Higgs projections @3000 fb^{-1}



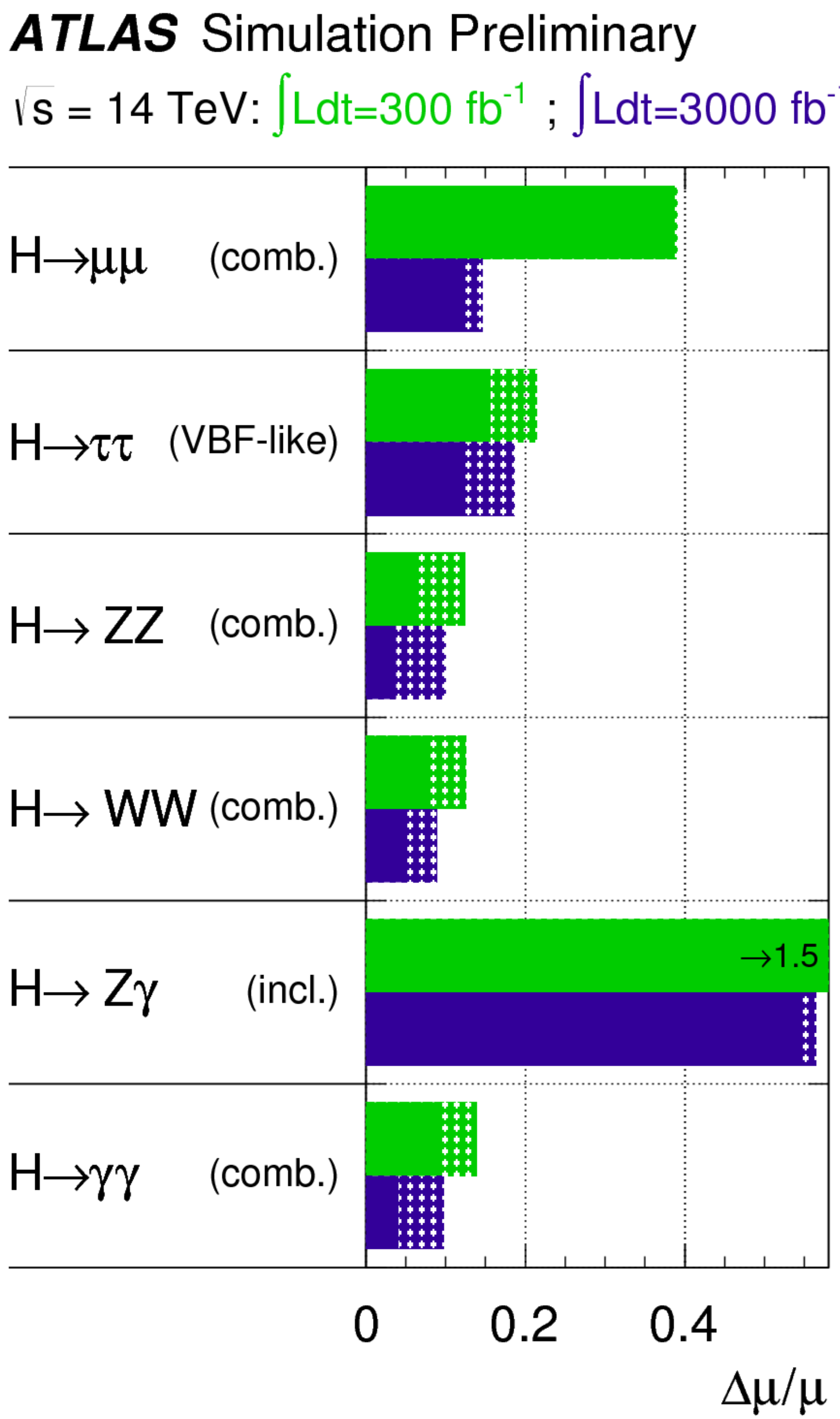


- Extrapolation by two orders of magnitude to higher luminosity
  - is subject to large uncertainties
- Results will become syst. limited due to theory uncertainties. We must encourage our theoretical friends to improve their calculations!

Signal strength @3000 fb^{-1}

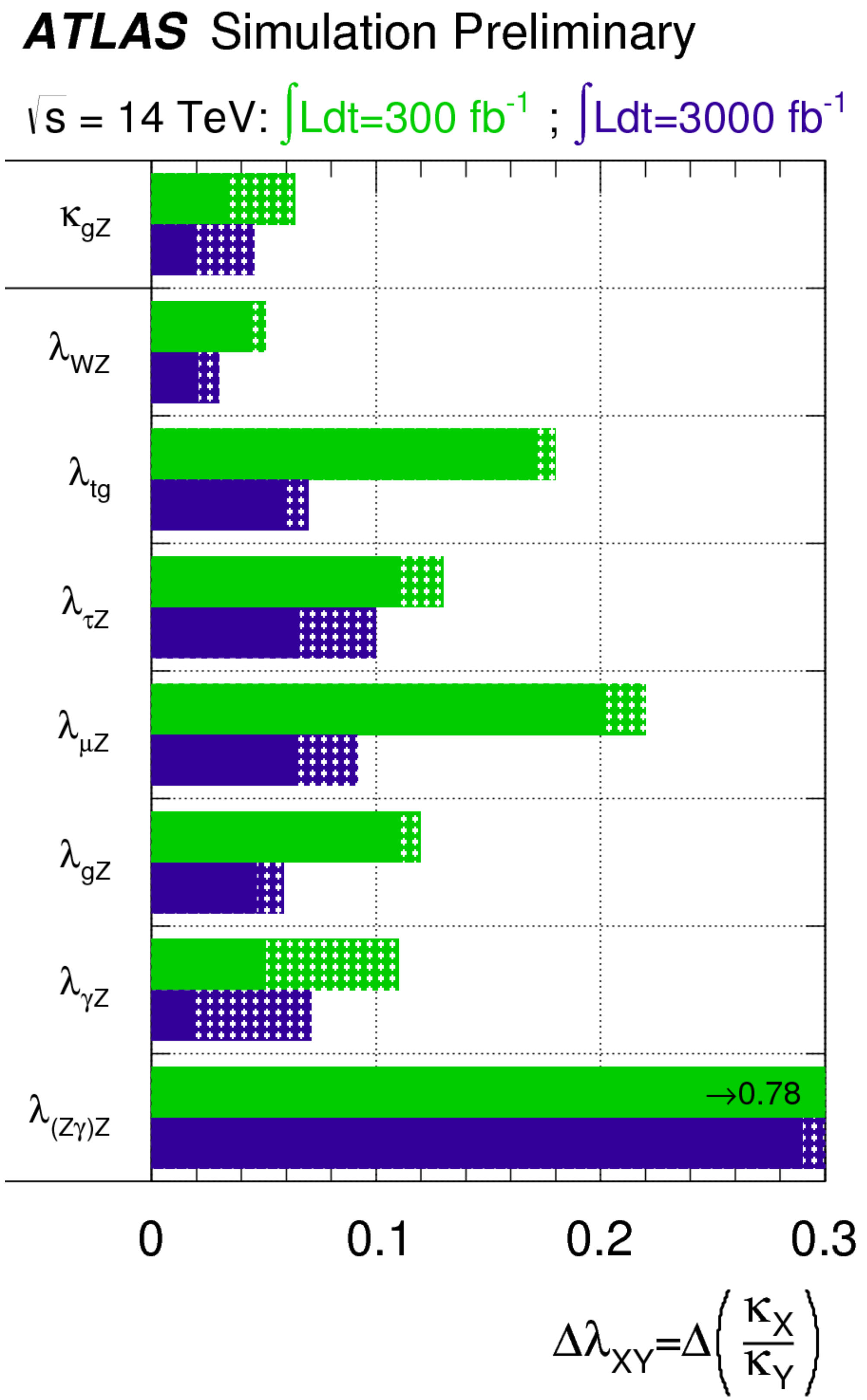


$\mu = \sigma/\sigma_{SM}$



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

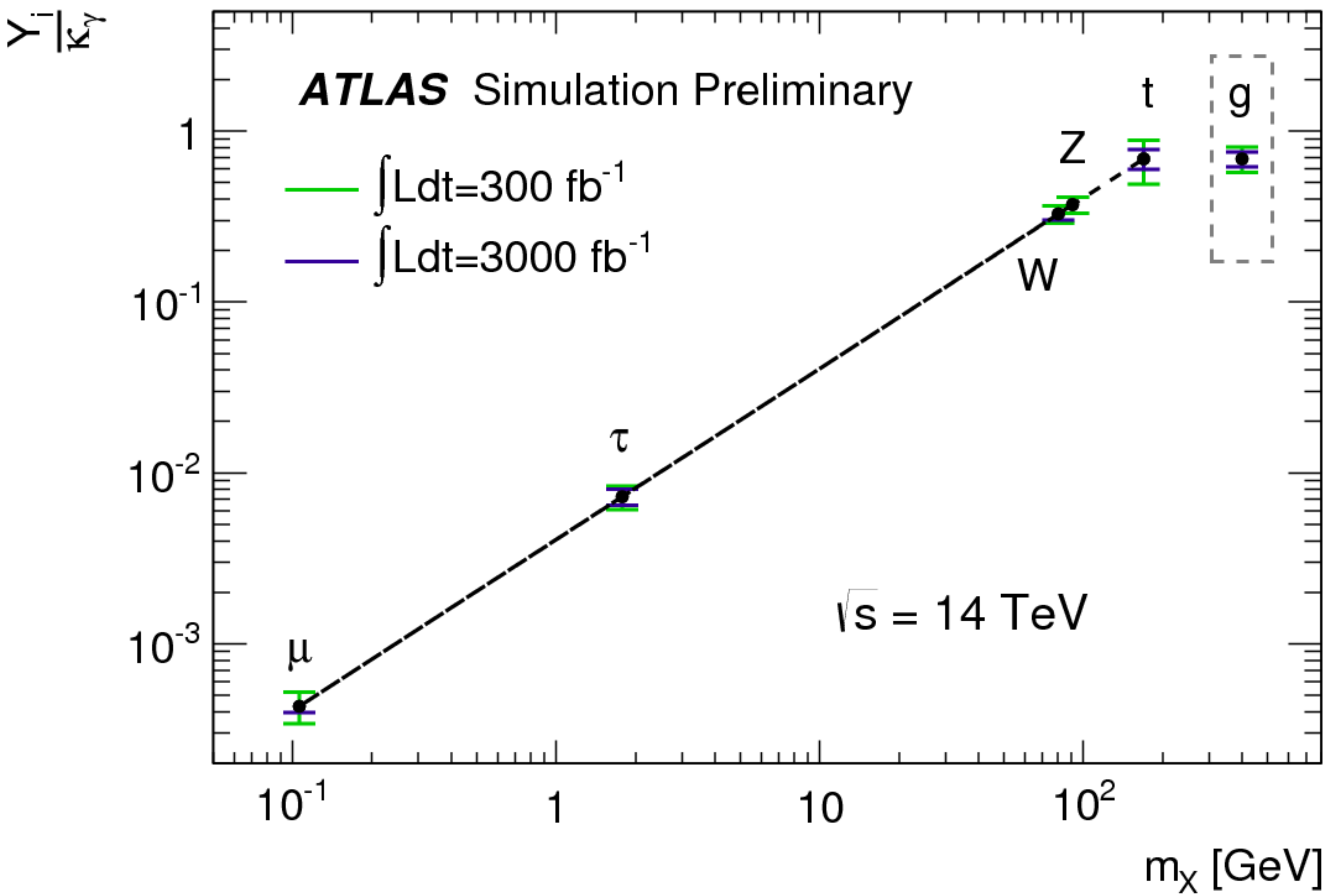
Higgs couplings @3000 fb^{-1}



- 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



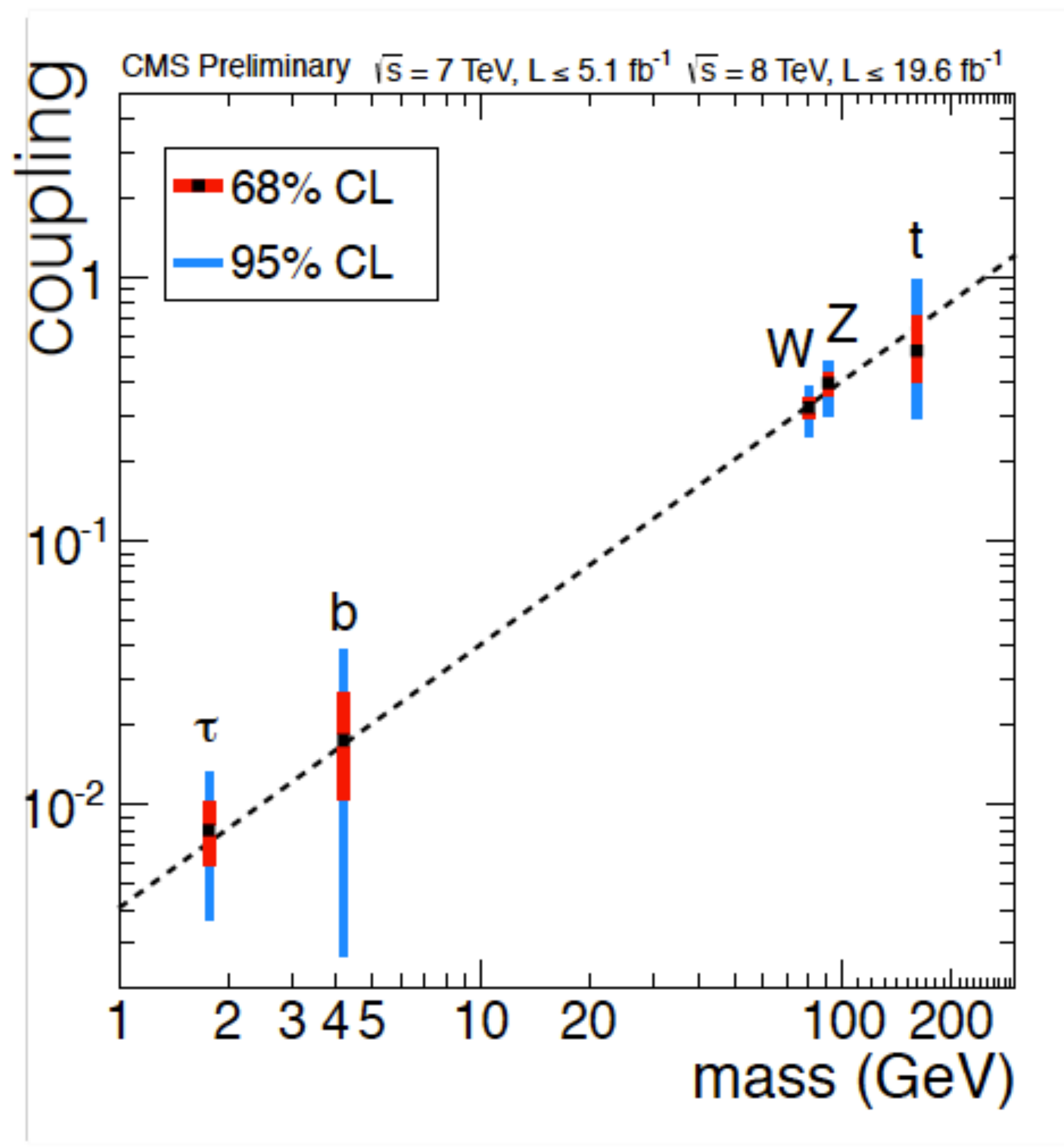
H→μμ

G. Salam, A. Weiler

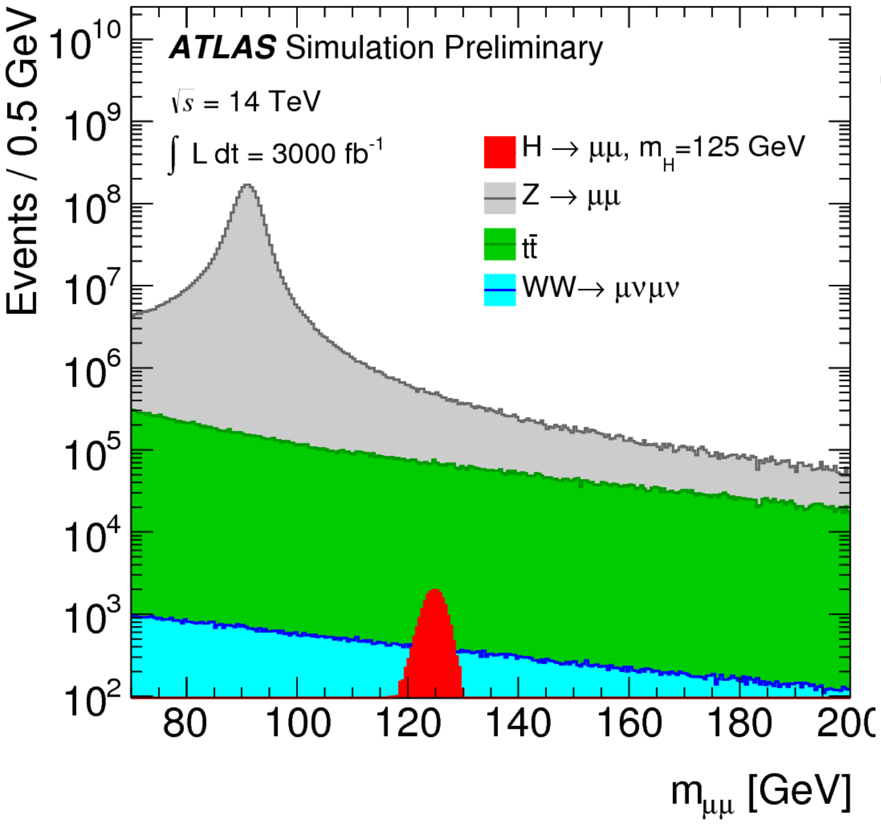
- By LHC14@300, we'll have probed all 3rd generation fermion couplings to O(10–20%)
- $H \to \mu^+\mu^-$ gives us access to 2nd lepton generation, i.e. is the mass-generation mechanism same for all generations, for quarks and leptons?

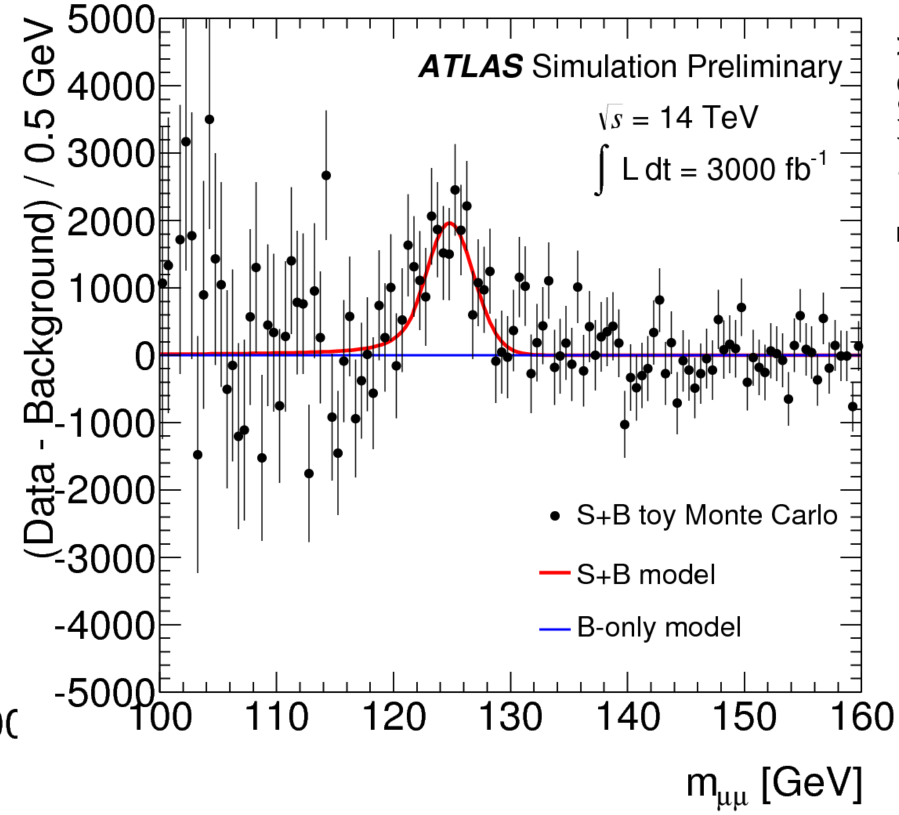
mass ∝ coupling to Higgs ?

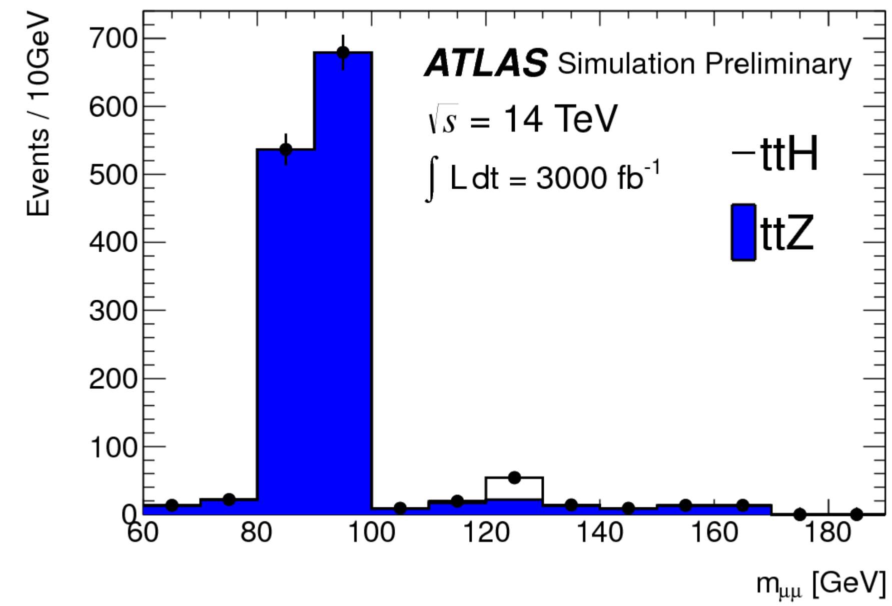
$$Br(H \to \mu^+\mu^-)_{\rm SM} = 2.2 \cdot 10^{-4}$$

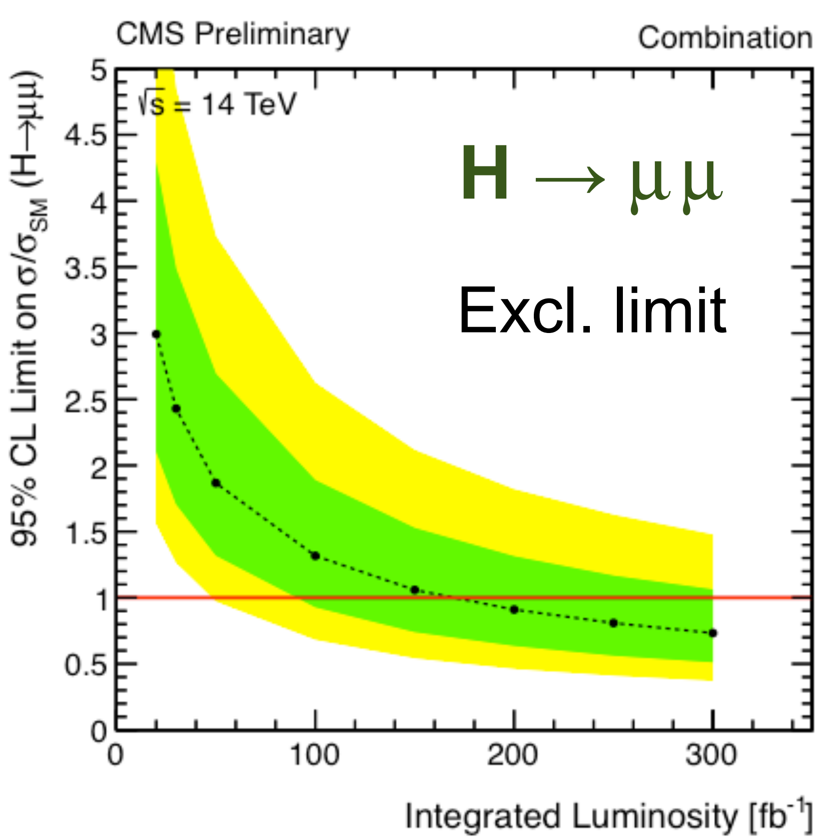


H→μμ

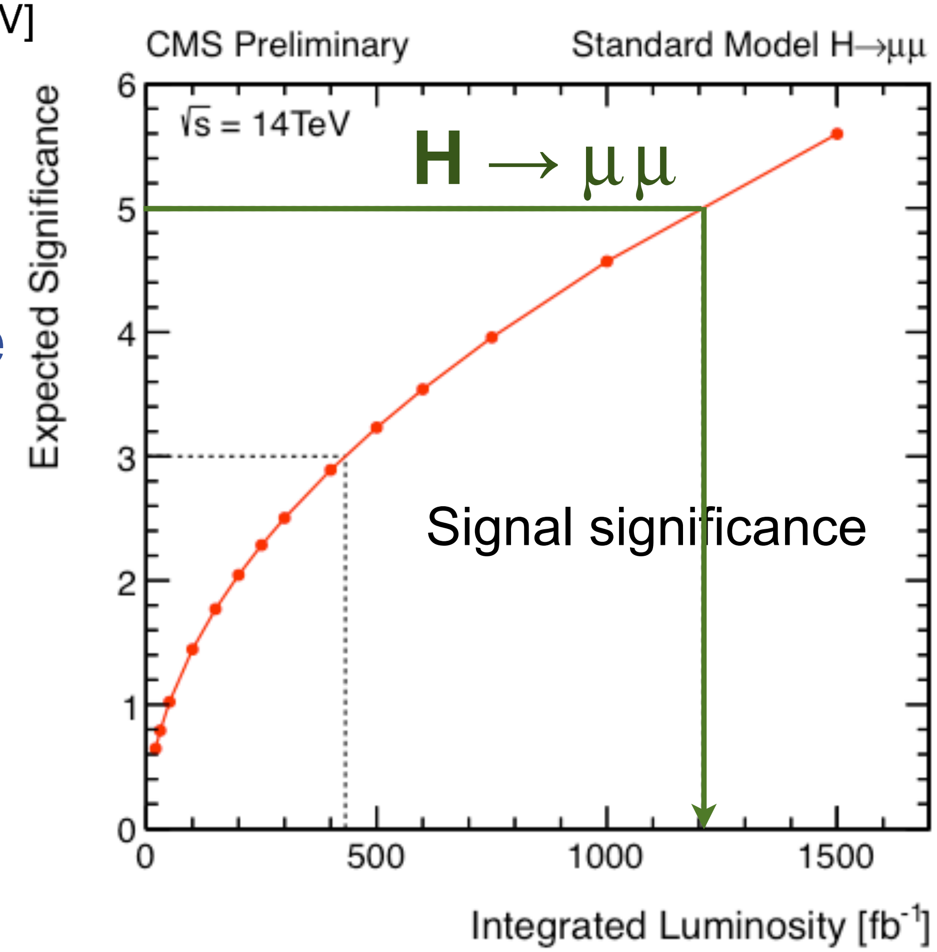








- The decay H→μμ can be observed with a significance of 5 sigma
  - measurement of the Hμμ coupling with a precision of ~10%



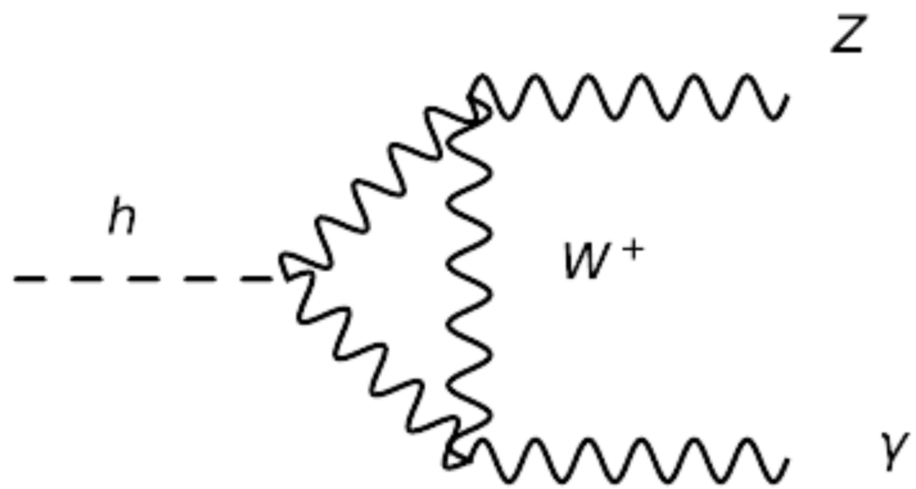
H→Zγ

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

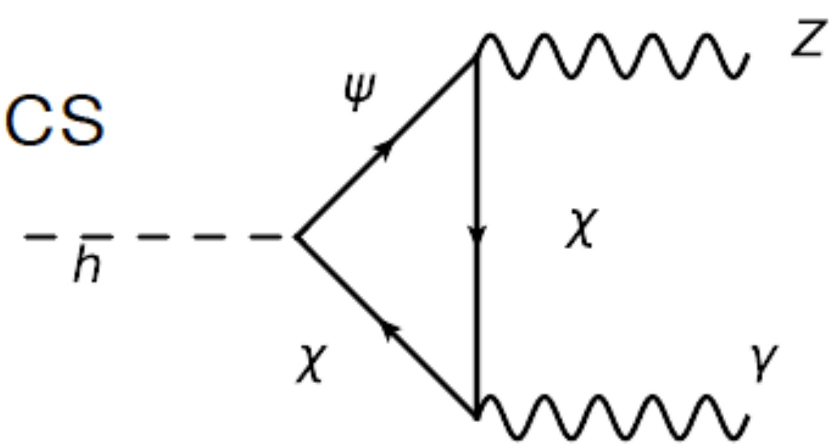
G. Salam, A. Weiler

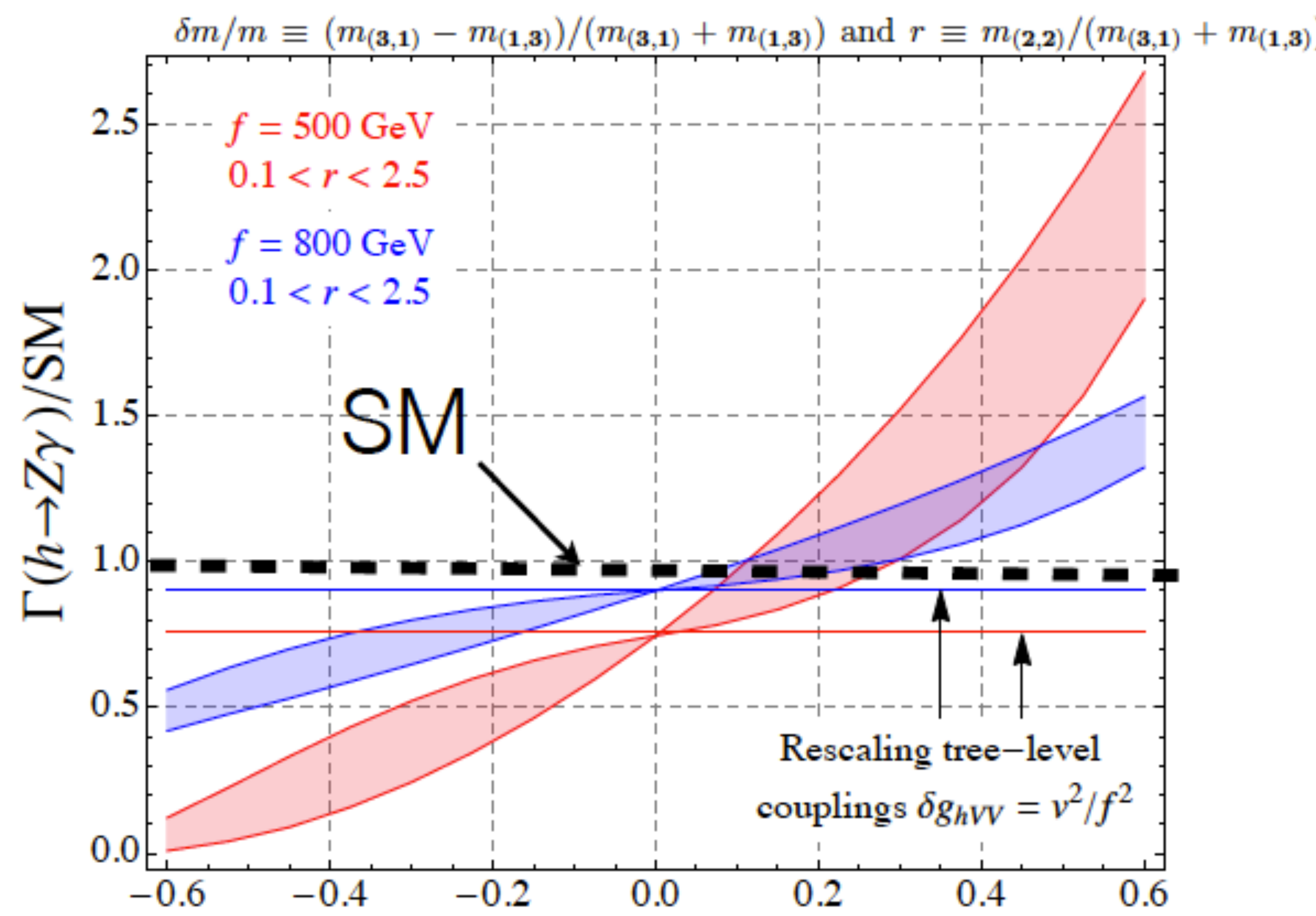
- In composite Higgs: Not protected by Goldstone symmetry, large γZ while γγ and gg small

SM



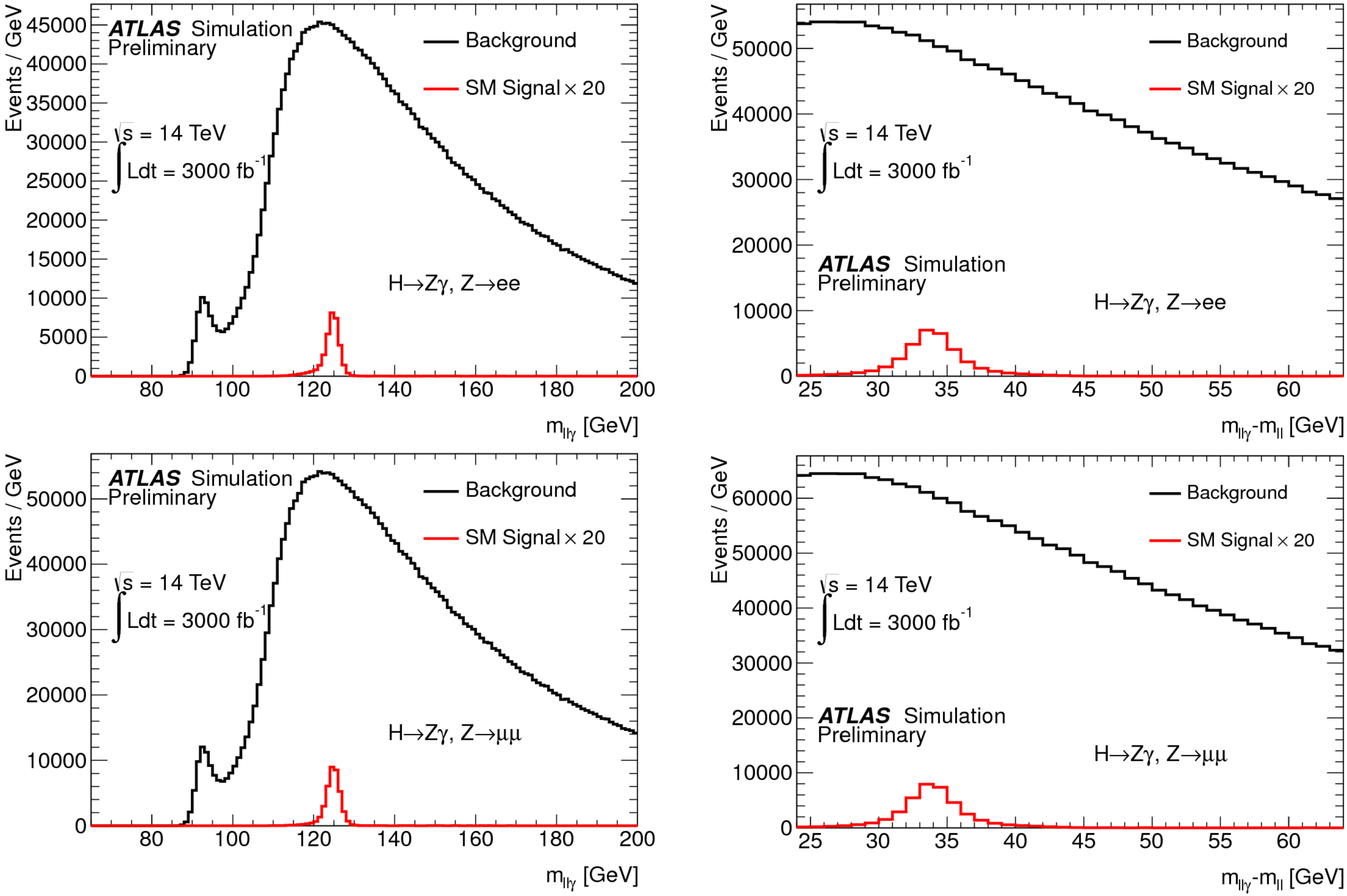
New physics



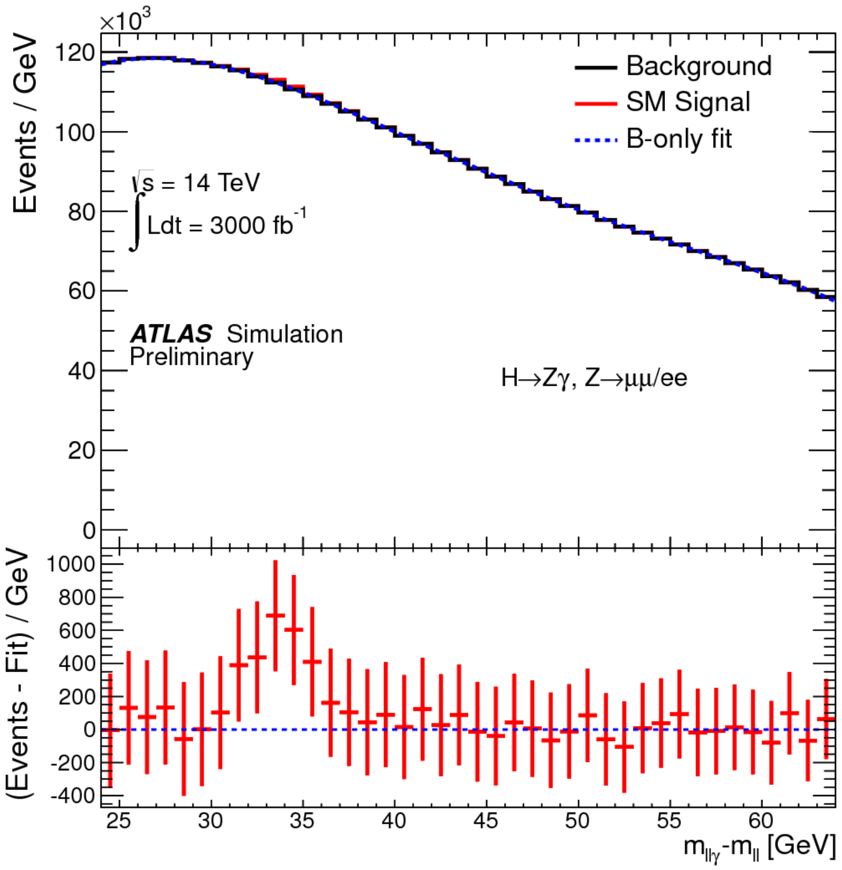


1308.2676

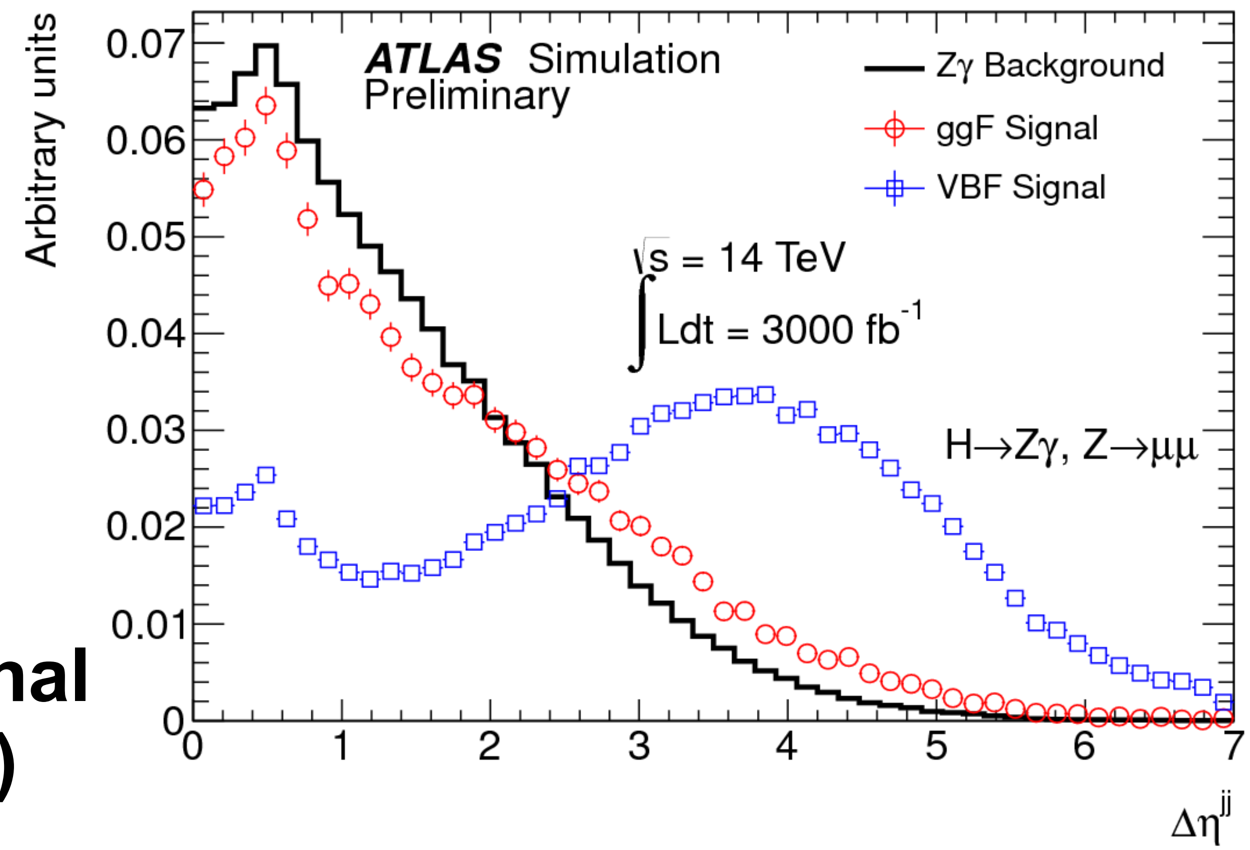
H→Zγ

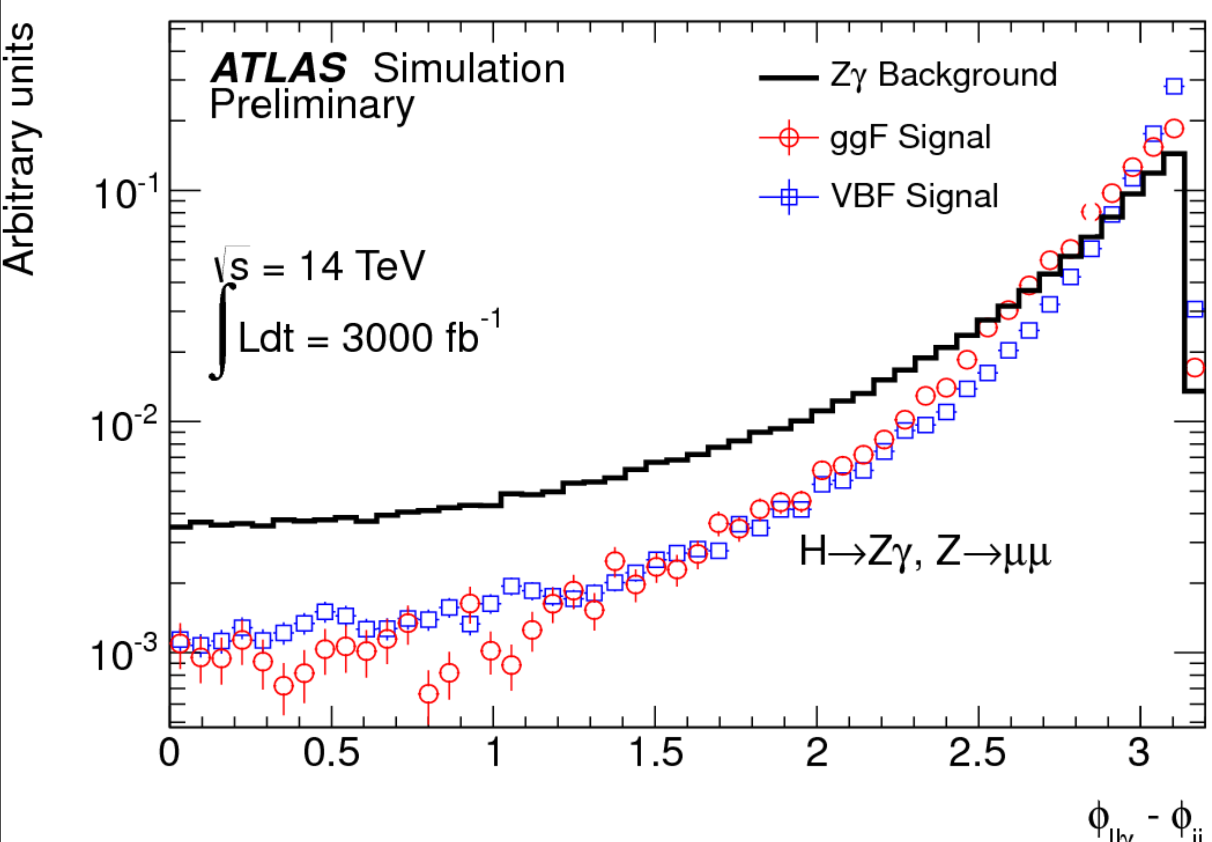

ATLAS Simulation Preliminary
Background
SM Signal × 20
√s = 14 TeV
∫Ldt = 3000 fb^-1
H→Zγ, Z→ee
Events / GeV
m_llγ [GeV]
m_llγ-m_ll [GeV]
H→Zγ, Z→μμ

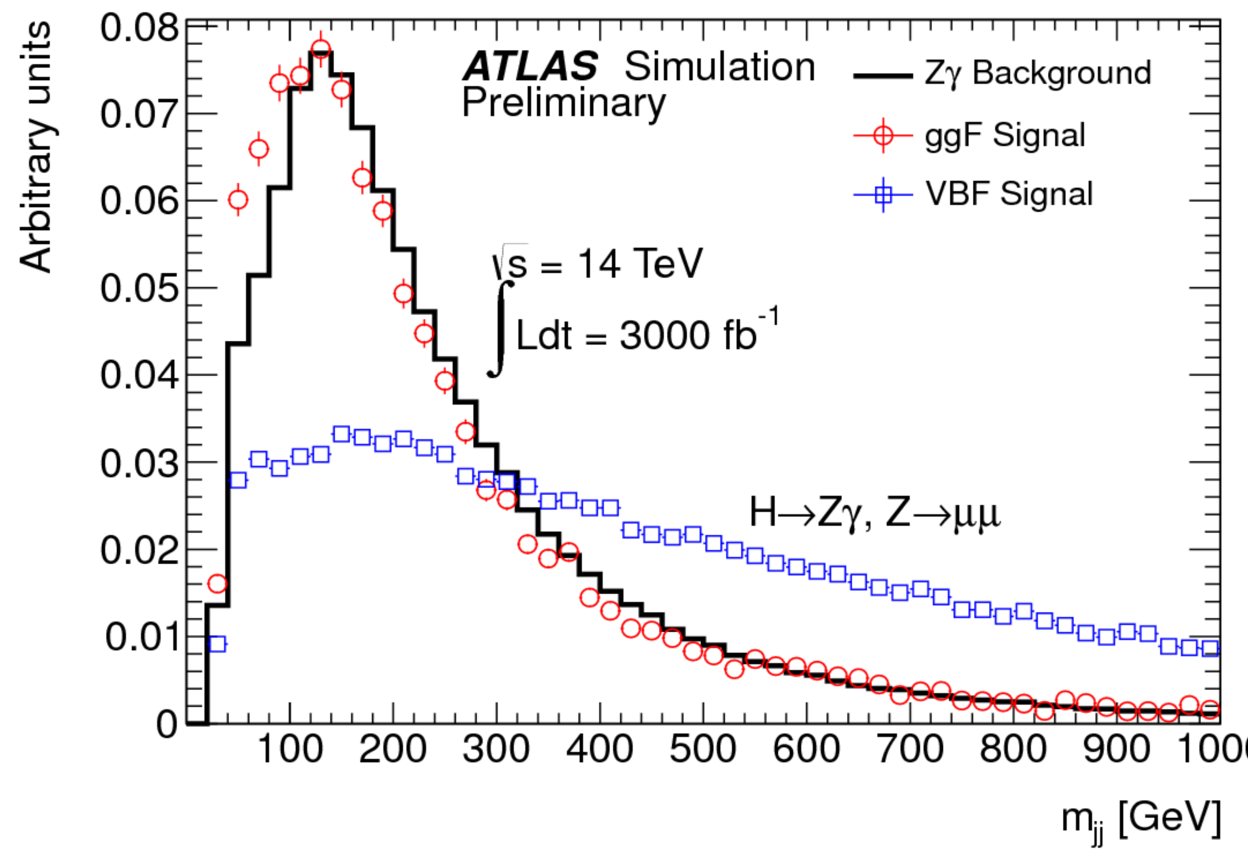
H→Zγ



VBF signal (2 jets)







H→cc

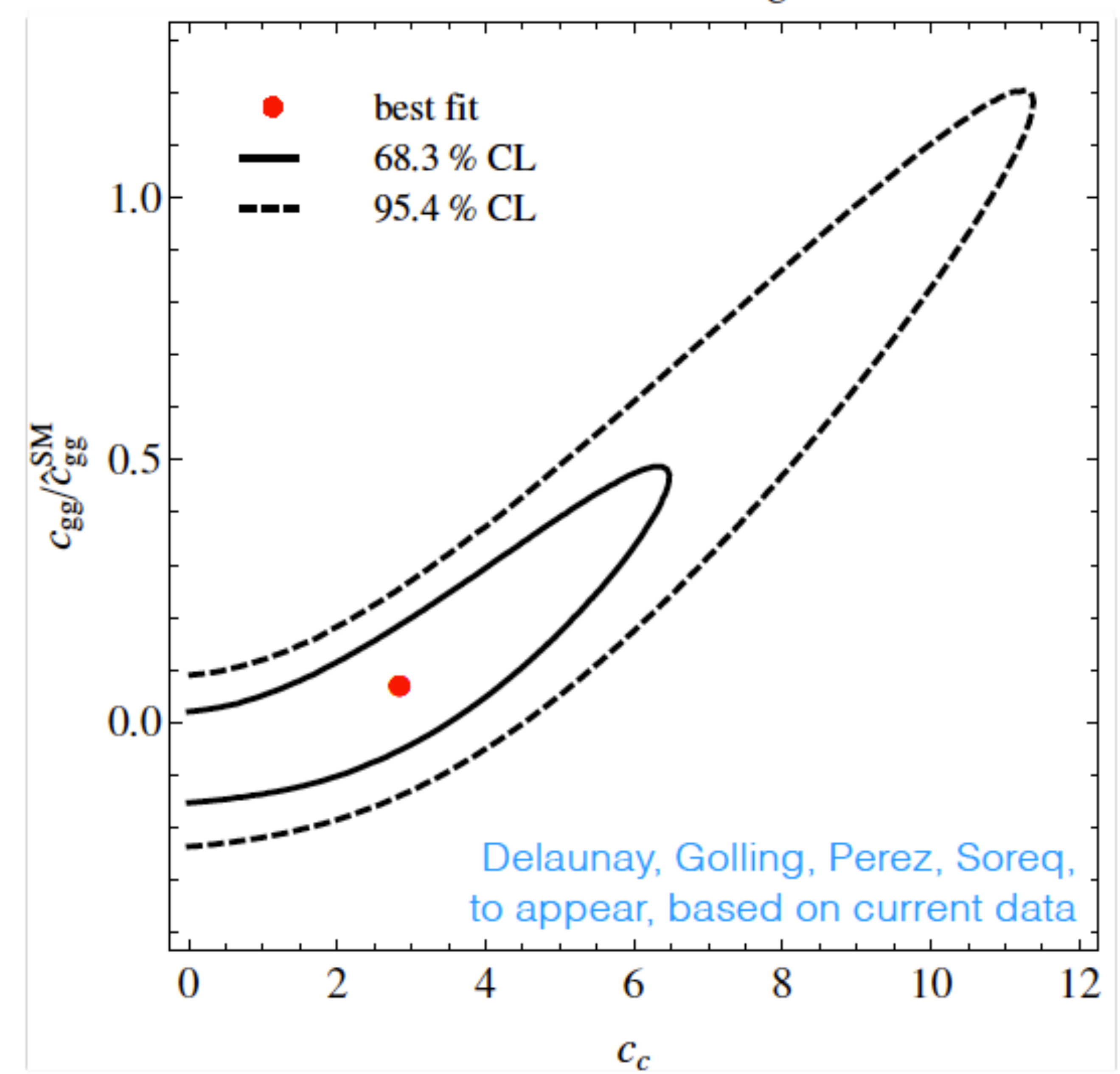
- Hcc coupling can still be 4-8 x SM

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

- 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



Measuring it?

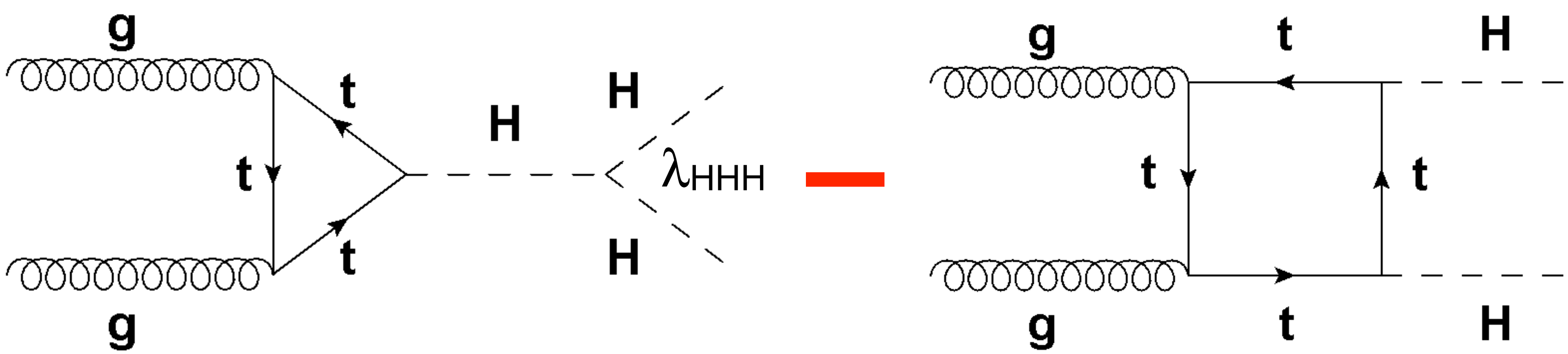
Like H→bb, but with charm tagging?

Or via H→ J/ψ γ ? 1306.5770

G. Salam, A. Weiler

Higgs boson pair-production

Destructive interference between the two diagrams



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)

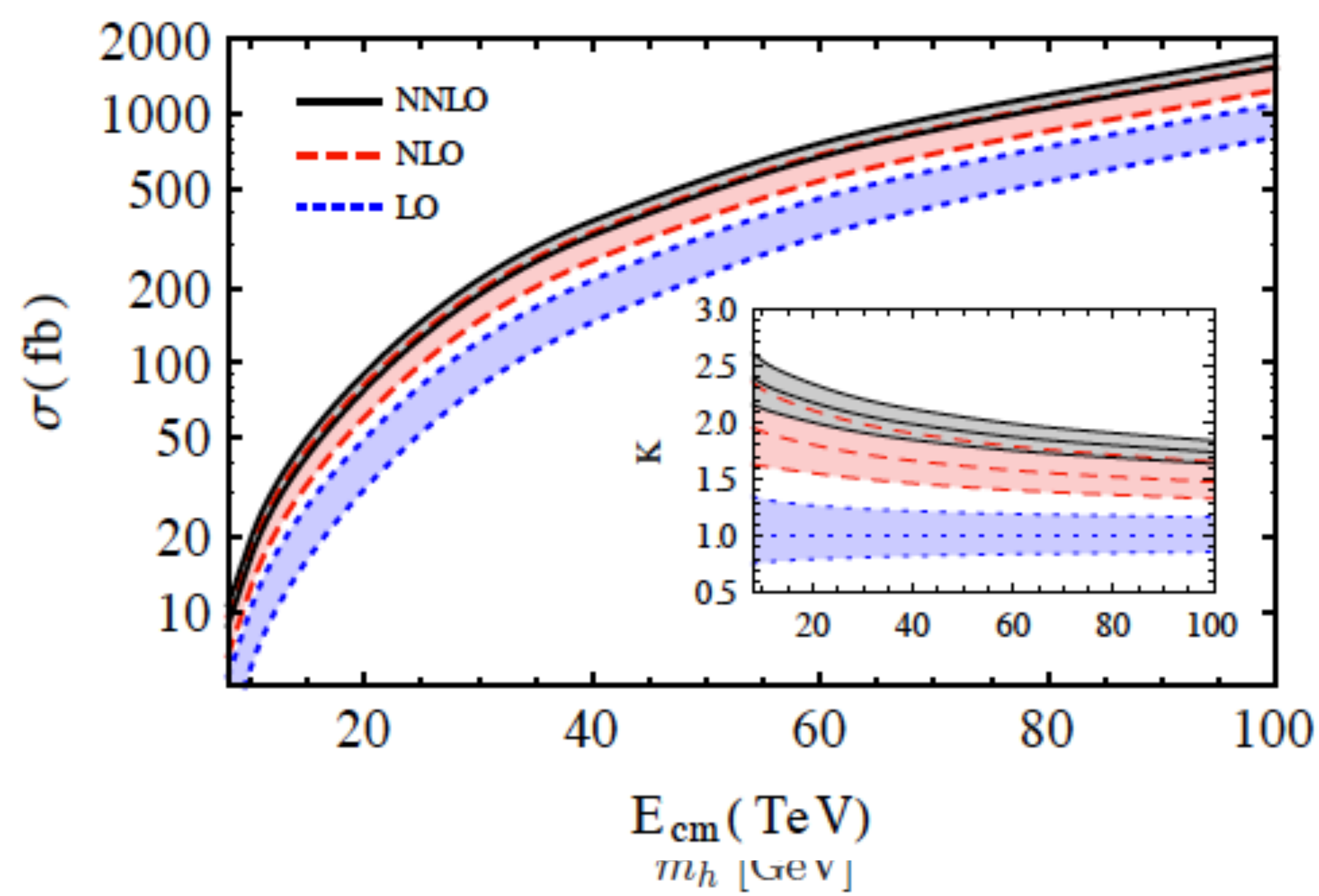
$b\bar{b}\tau^+\tau^-$

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

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

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

Taken from **"Higgs self-coupling measurements at the LHC"** by M. J.



NNLO cross-section at m_H=125 GeV:

σ = 40 ± 3 fb

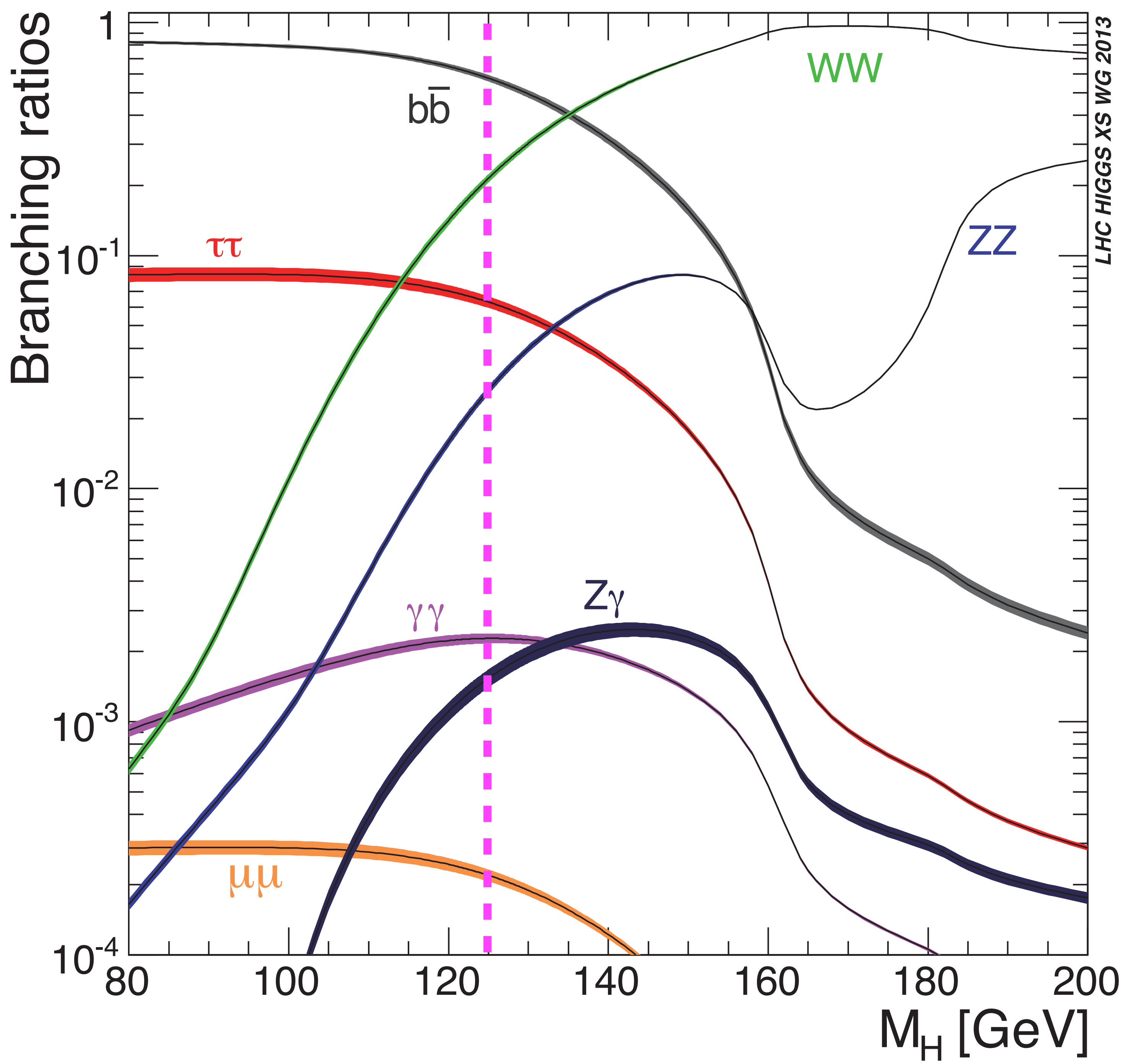
G. de Florian, J. Mazzitelli, 1309.6594

di-Higgs production

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

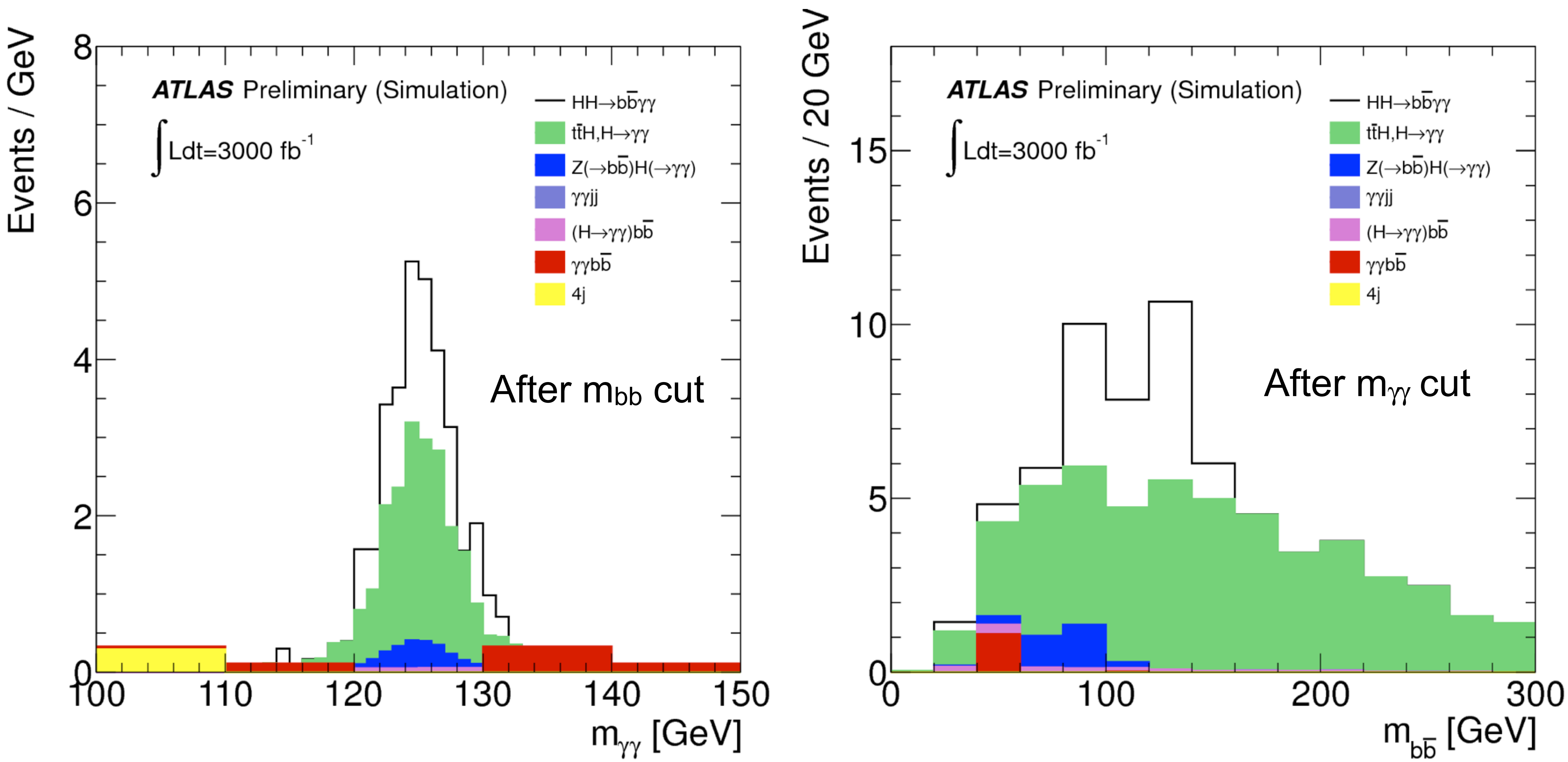
However we pay a big price in BR's …

$b\bar{b}W^+W^-$	~14000 events
$b\bar{b}\gamma\gamma$	~ 150 events
$b\bar{b}\tau^+\tau^-$	~ 4300 events
$b\bar{b}2l2\nu$	~ 730 events



di-Higgs production

HH→b$\bar{b}$γγ



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

di-Higgs production

$b\bar{b}W^+W^-$ is being studied. Looks very difficult

$b\bar{b}\tau^+\tau^-$ seems more promising, studies just began

$b\bar{b}2l2\nu$ could be an interesting possibility, studies not yet started

Higgs boson pair-production is a flagship channel of HL-LHC.

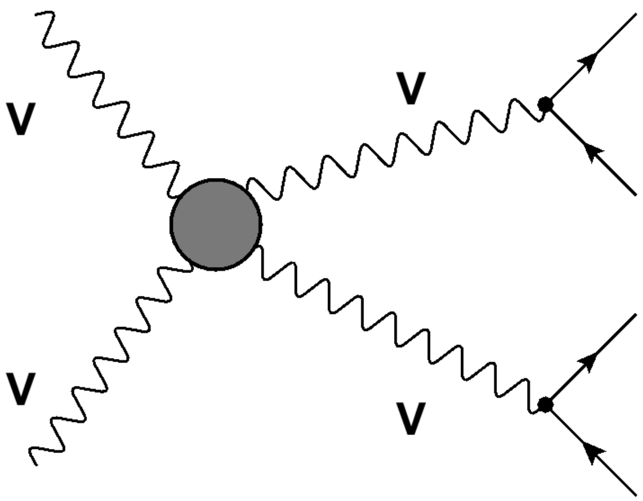
There is ongoing work in both experiments in order to be able to assess the full potential at HL-LHC.

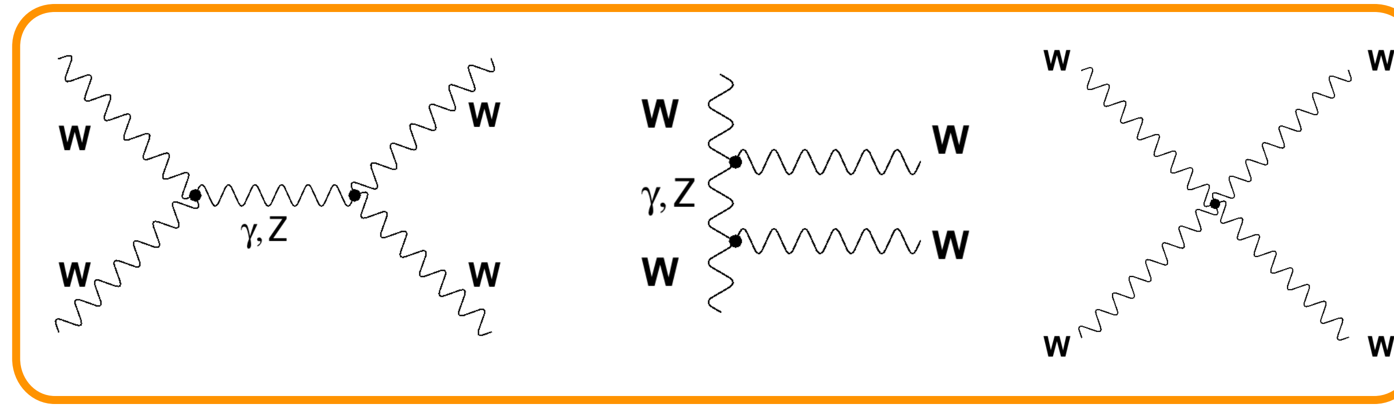
Personal opinion

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

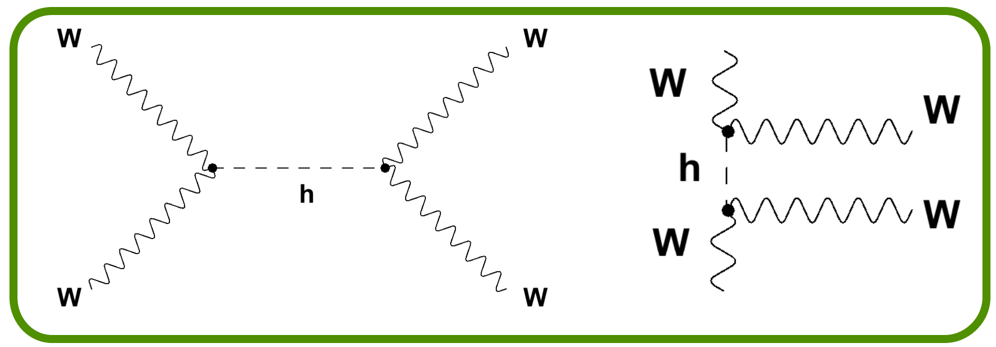
VV scattering: unitarity violation

VV→VV





S channel T channel QGC



Without the SM boson, $W^+_L W^-_L \rightarrow W^+_L W^-_L$ violates unitarity at $\sqrt{s} \geq 1.2$ TeV

W, Z masses (→ longitudinal degrees of freedom) arise from the BEH mechanism:

$$A\left(W_L^+ W_L^- \rightarrow W_L^+ W_L^-\right) \approx \frac{1}{v^2}\left(-s-t+\frac{s^2}{s-m_H^2}+\frac{t^2}{t-m_H^2}\right)$$

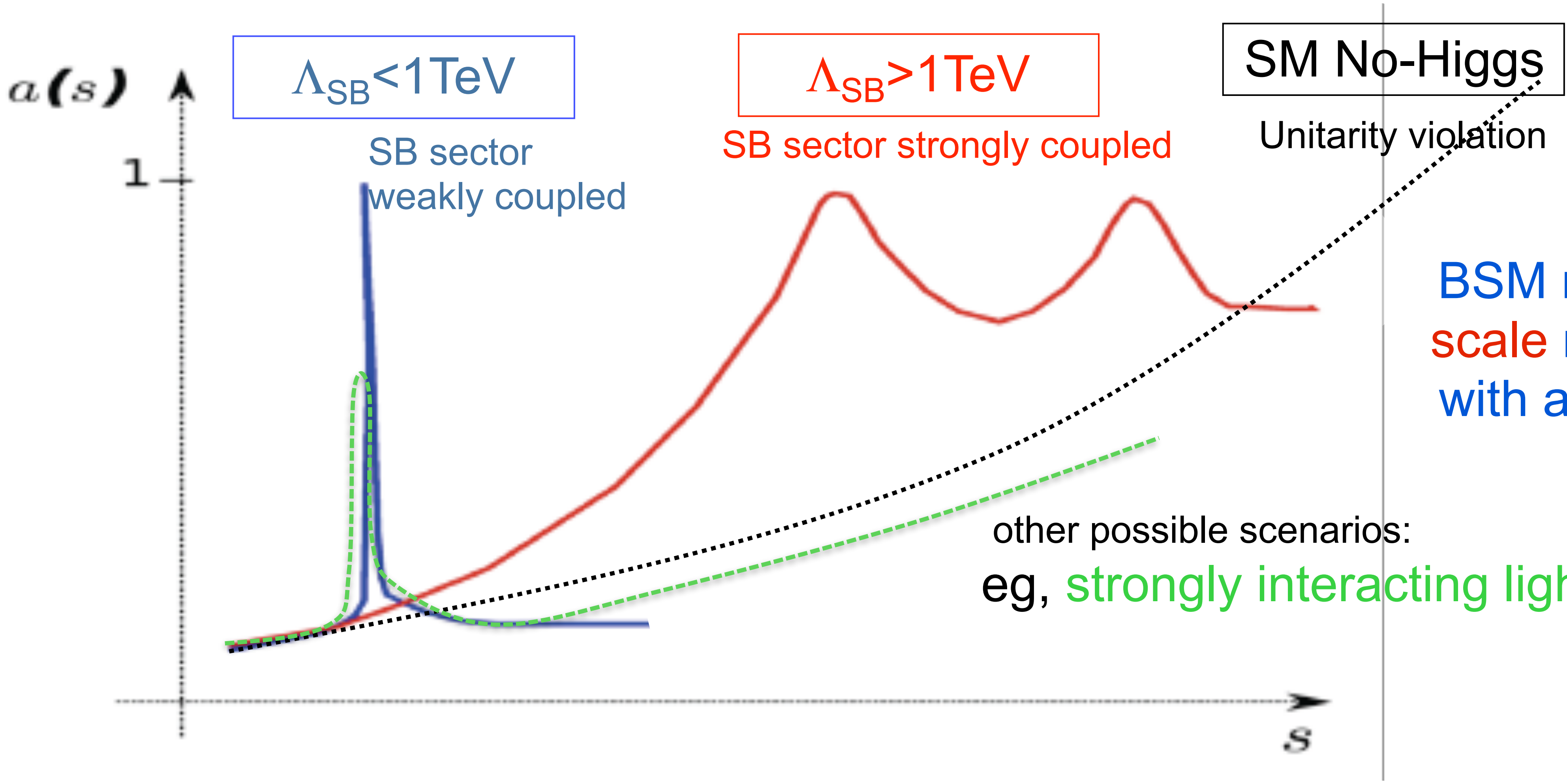
VV scattering is the smoking gun for EWSB!

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 as a probe for EWSB

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



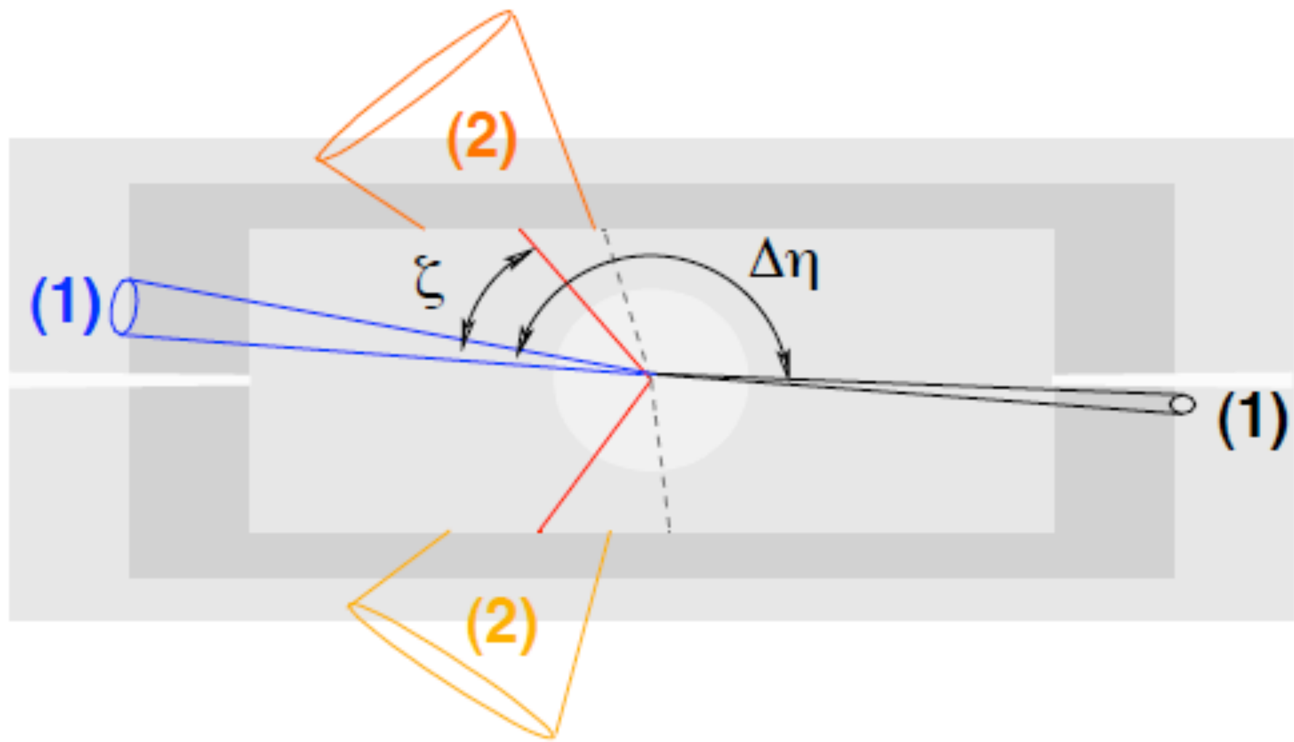
BSM models predict TeV-scale resonances "paired" with a light scalar particle

Search for possible resonances in VBF spectrum

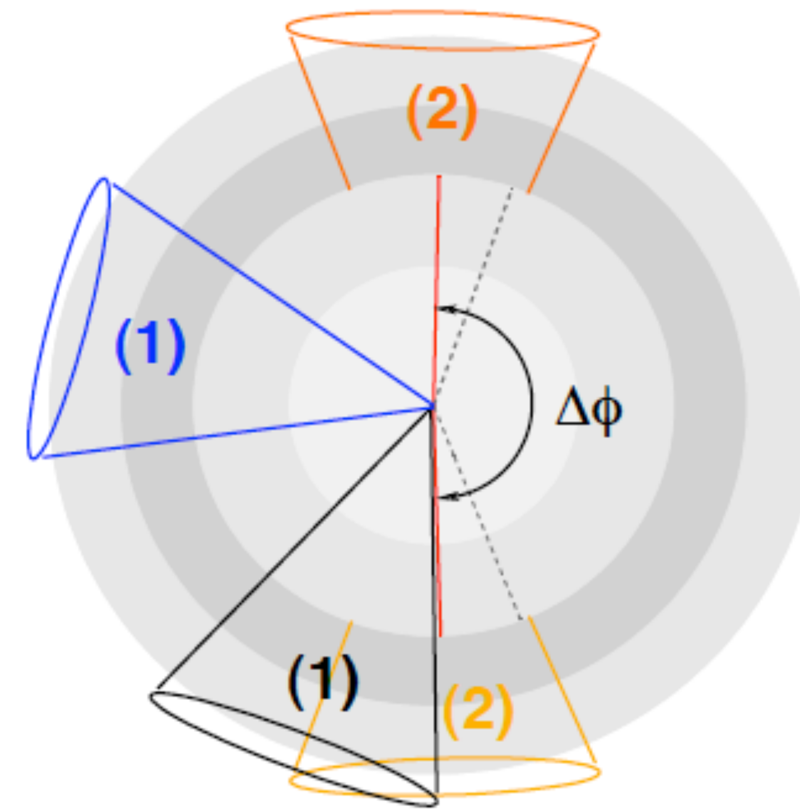
Adaptation from **"Boson Boson scattering analysis"** by A.Ballestrero (INFN Torino) talk at First LHC to Terascale Workshop (Sept 2011):

VBF experimental signature

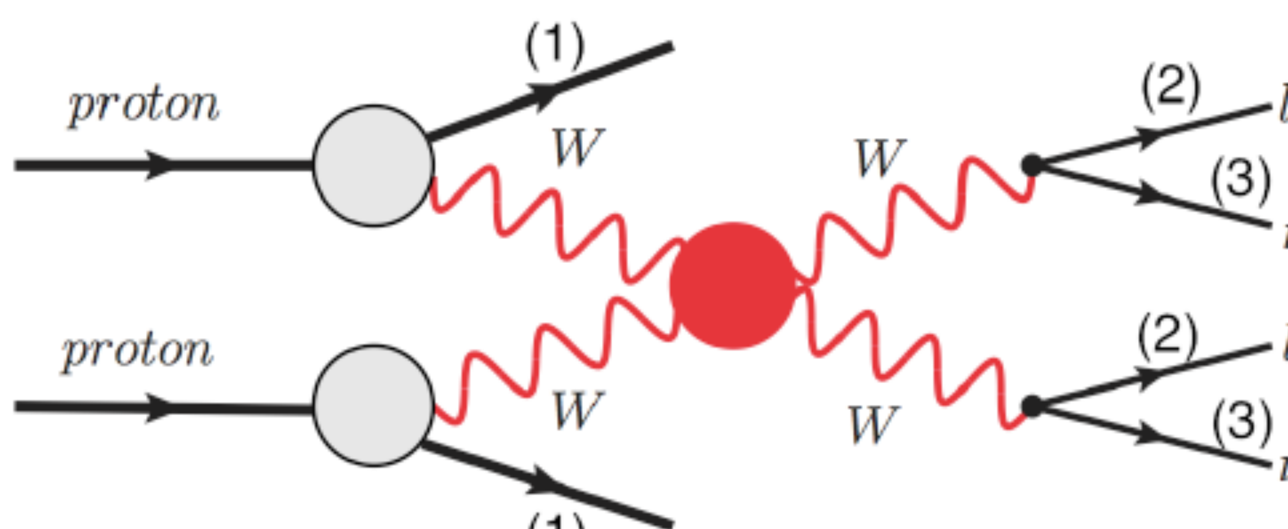
Longitudinal plane



Transverse plane



- *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)



Six fermion final state

From **"Study of Vector Boson Scattering including Pile-up with the ATLAS Detector"** by P. Anger (TU Dresden), DPG Frühjahrstagung Karlsruhe 2011

VBF final states

- 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

    Clean
    Can reconstruct m_{VV} (not with 2ν)
    Very low yields...

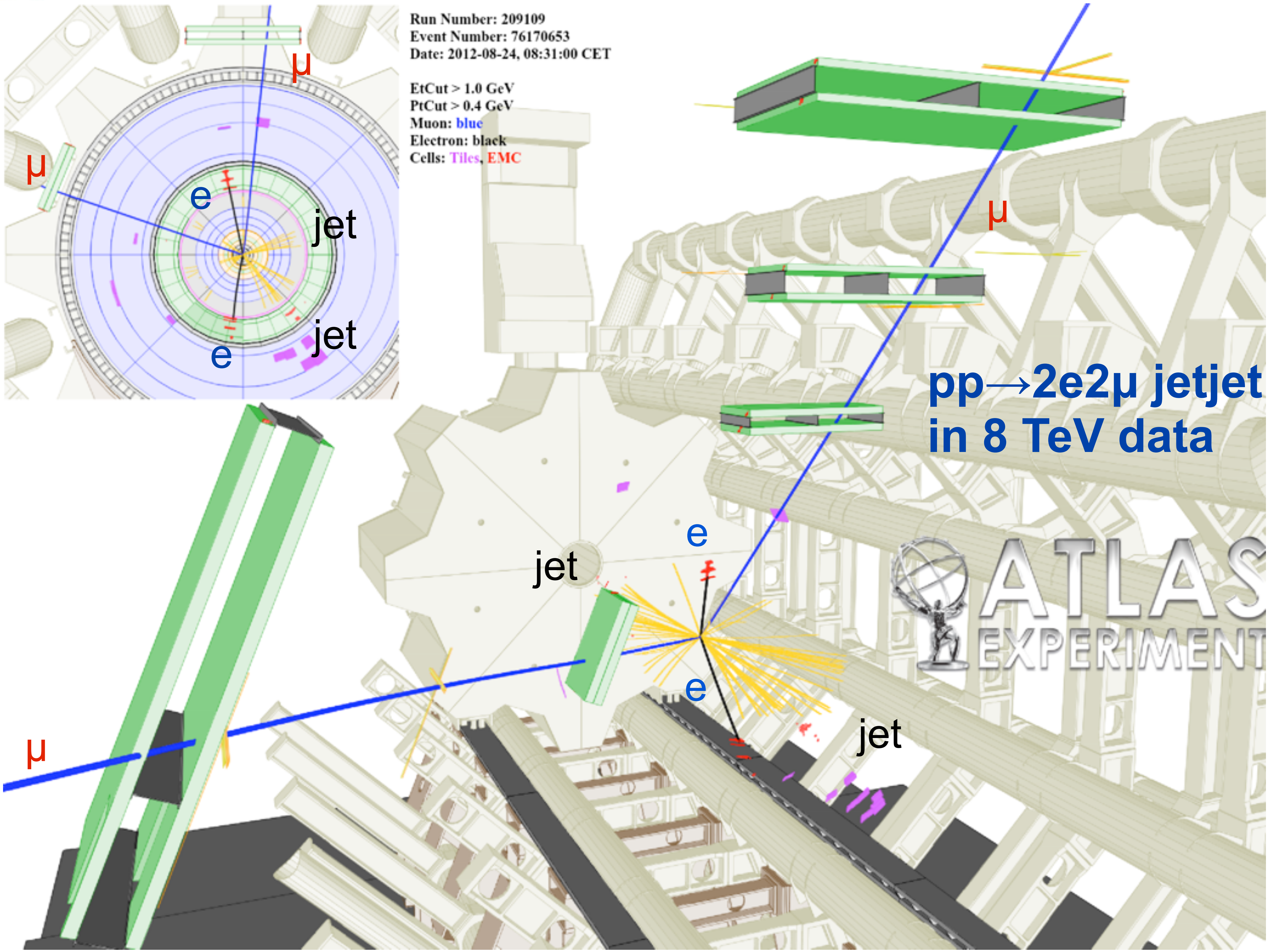
  - Semi-leptonic
    - pp→qq jetjet ℓℓ
    - pp→qq jetjet ℓν

    Better yields...
    Large backgrounds

Detector needs

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

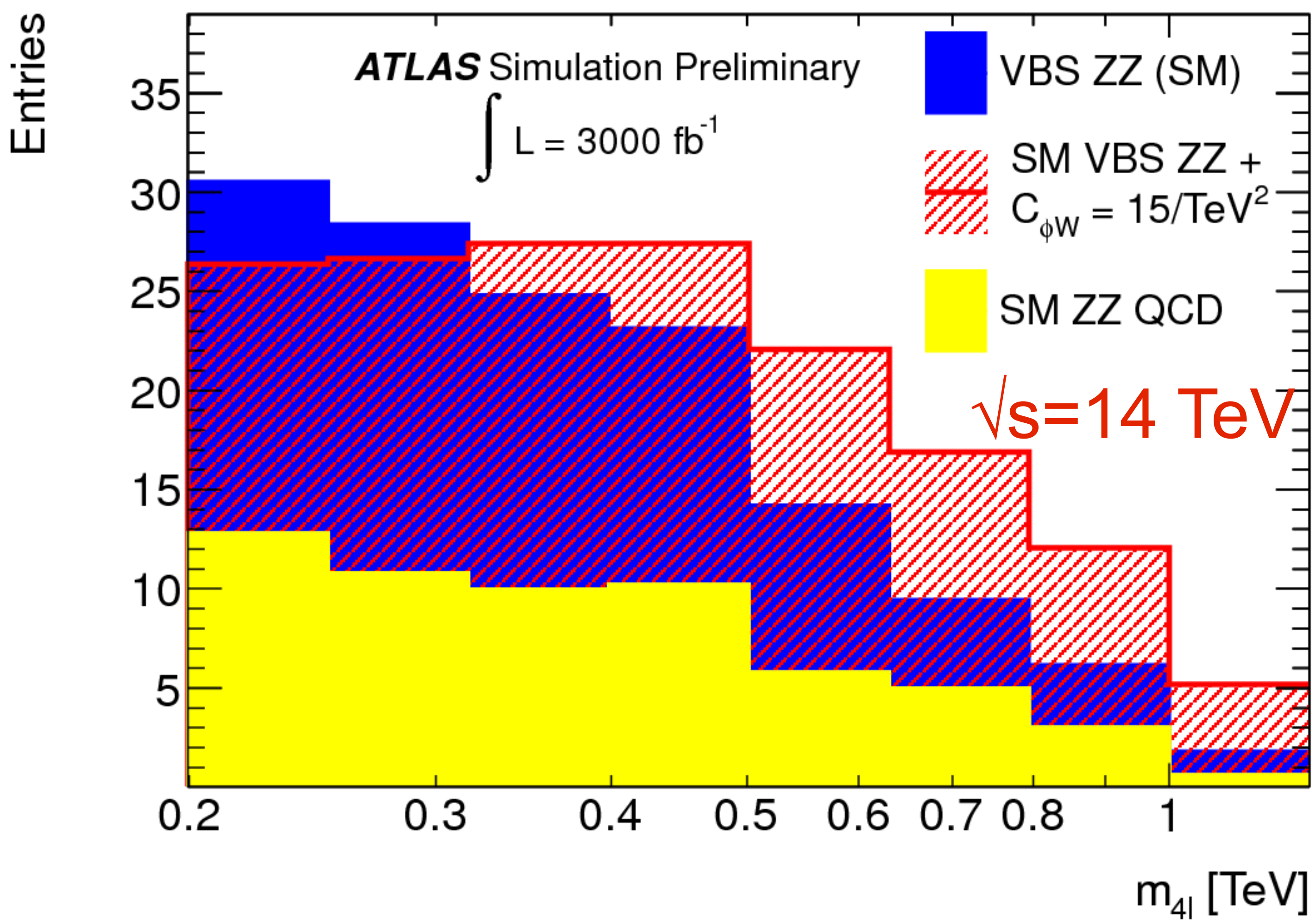
VBF 2e2μ candidate event

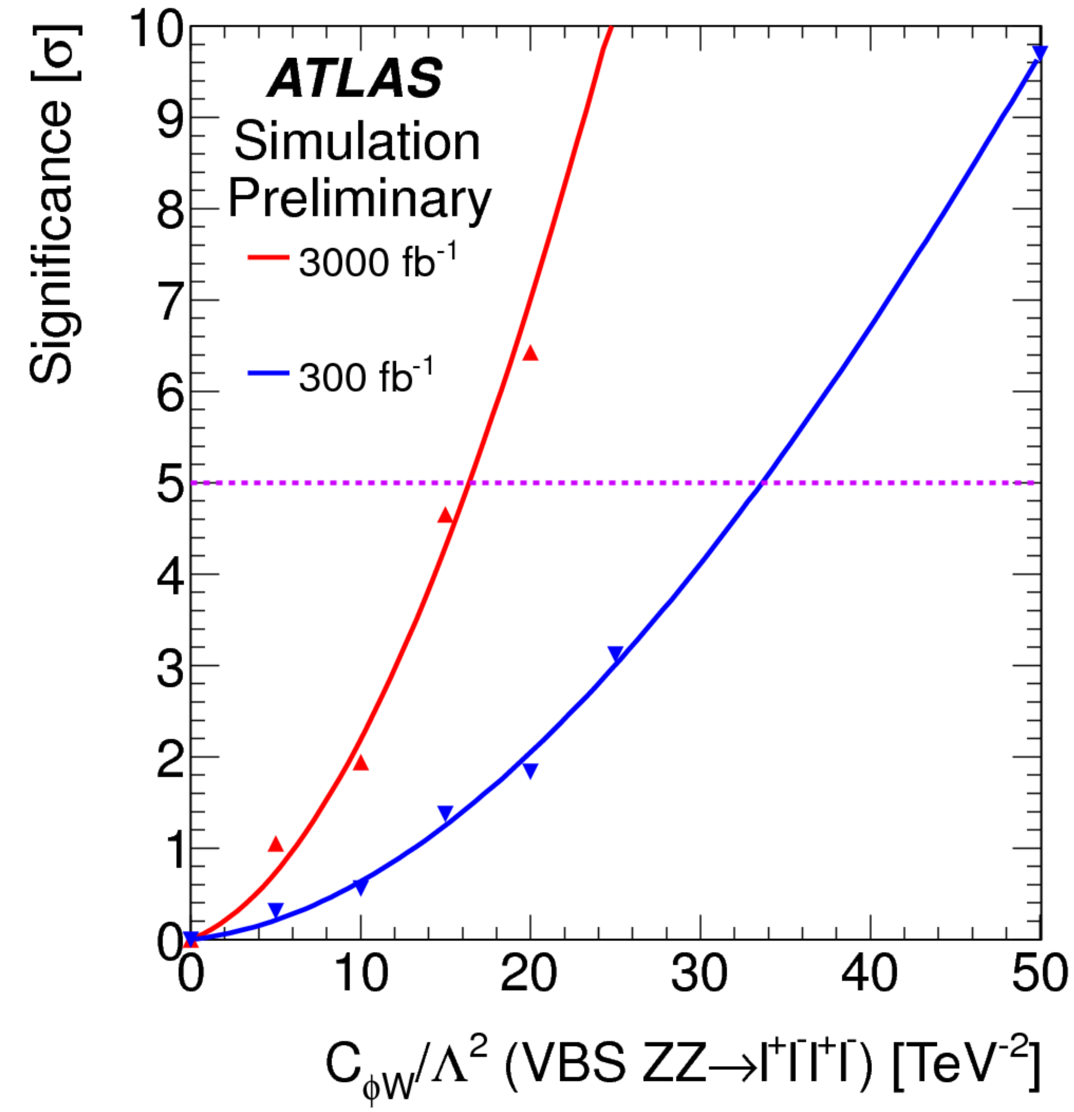


pp→2e2μ jetjet in 8 TeV data

ZZ resonance

pp→ZZ+2j→4ℓ+2j channel





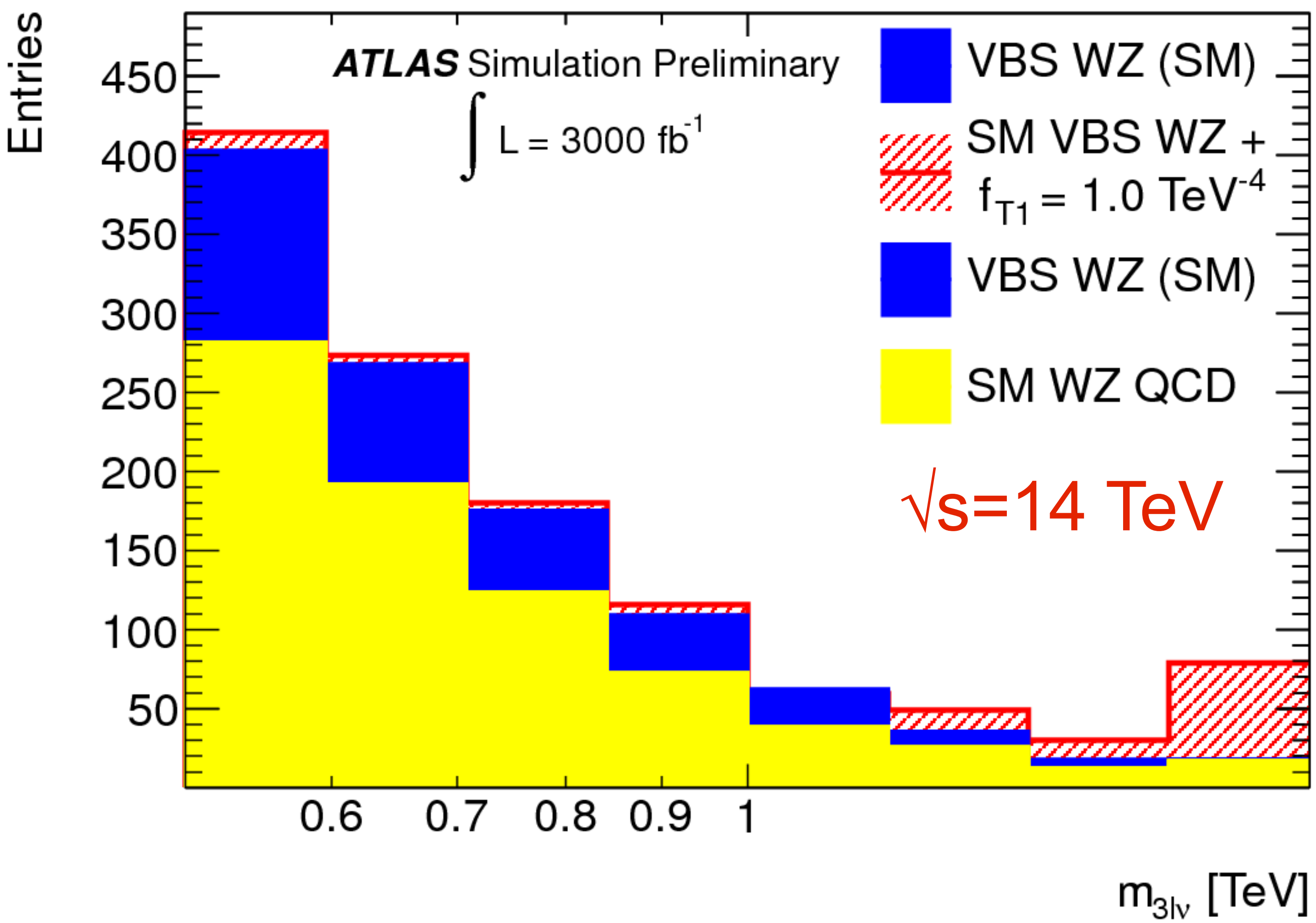
$$\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2} \mathrm{Tr}(W^{\mu\nu}W_{\mu\nu})\phi^\dagger\phi$$

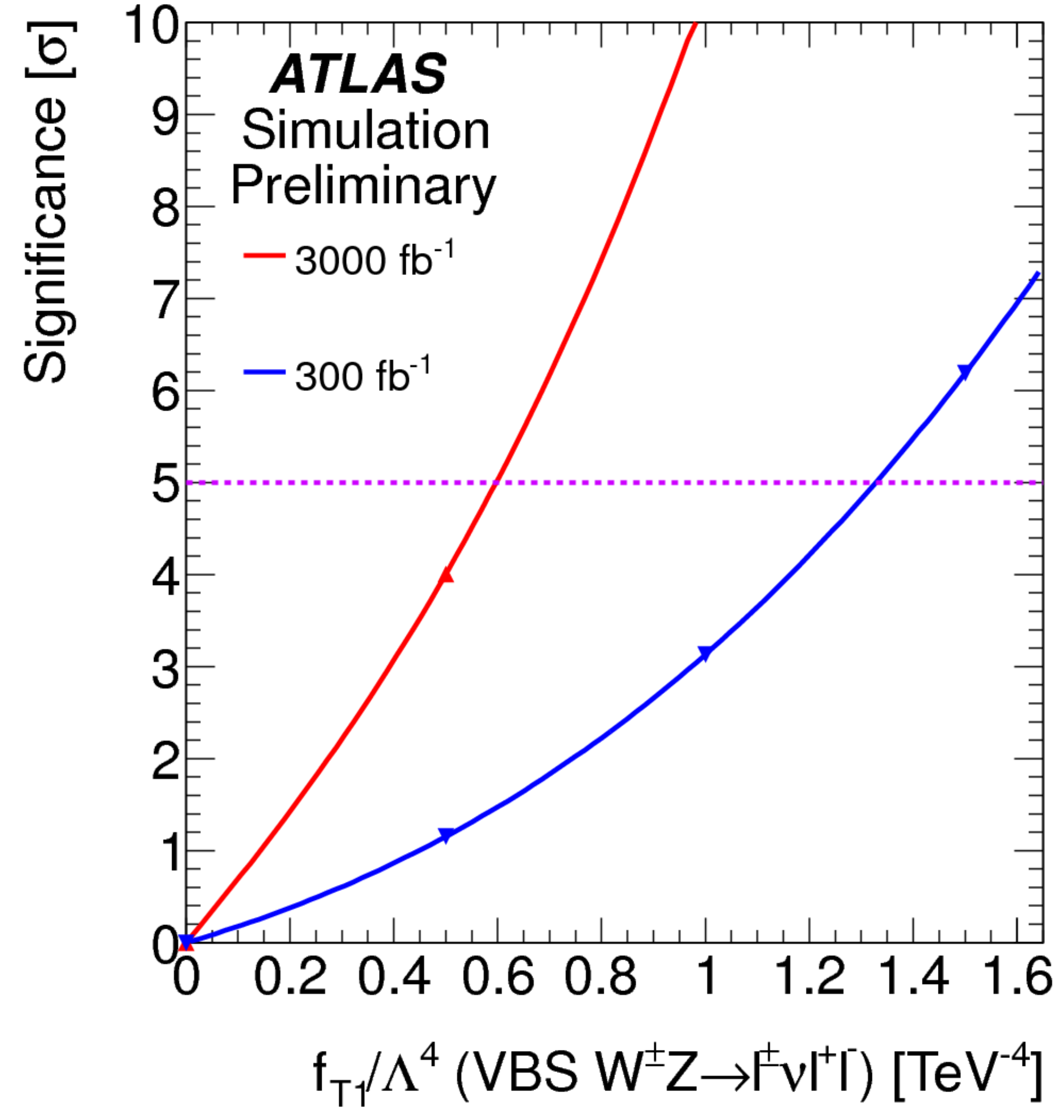
	$300\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
$c_{\phi W}/\Lambda^2$	$34\ \mathrm{TeV}^{-2}$	$16\ \mathrm{TeV}^{-2}$

Sensitivity to anomalous ZZ resonances in Vector boson scattering

WZ resonance

pp→WZ+2j→ℓ+ν+2ℓ+2j channel





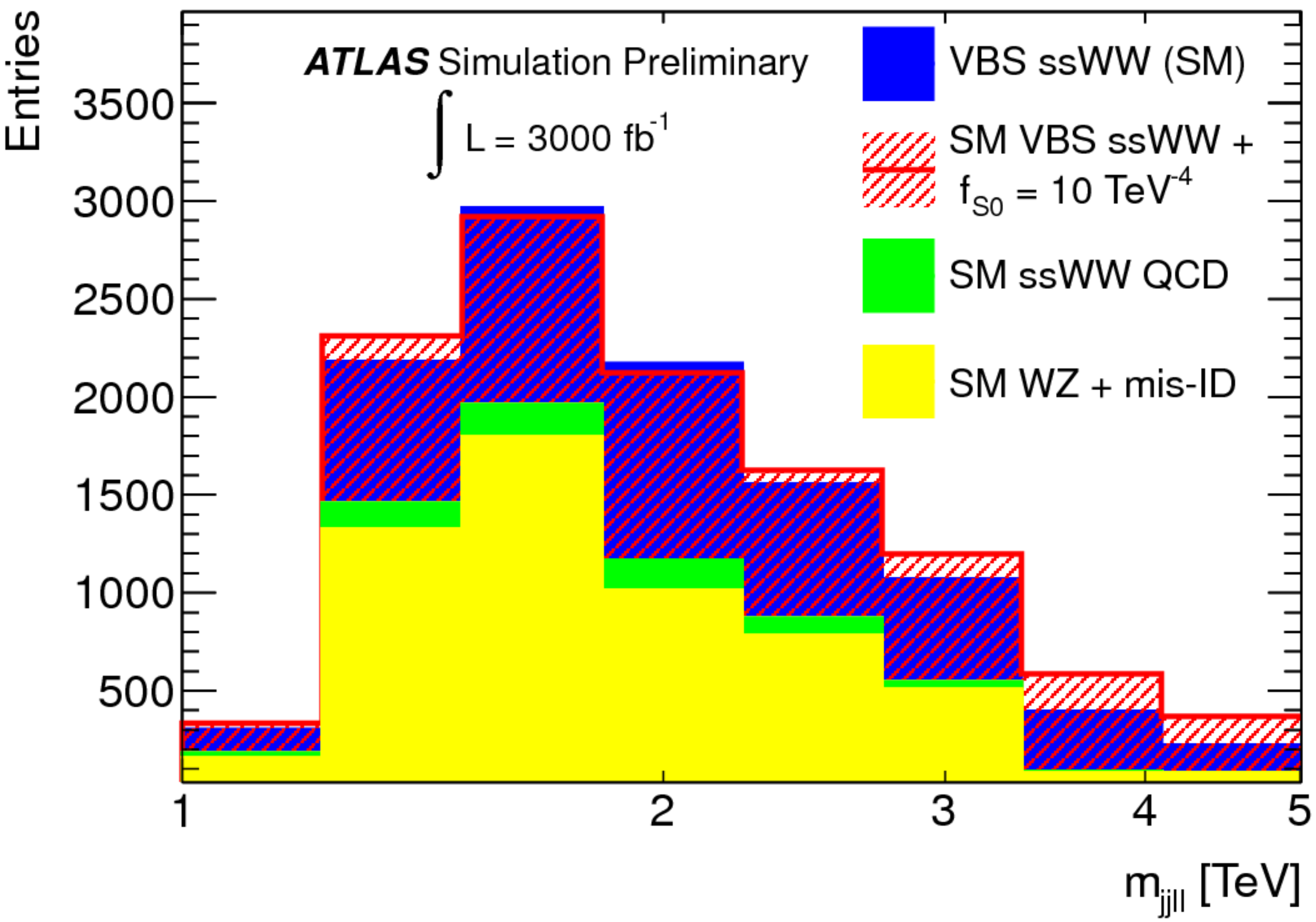
$$\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} \mathrm{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$$

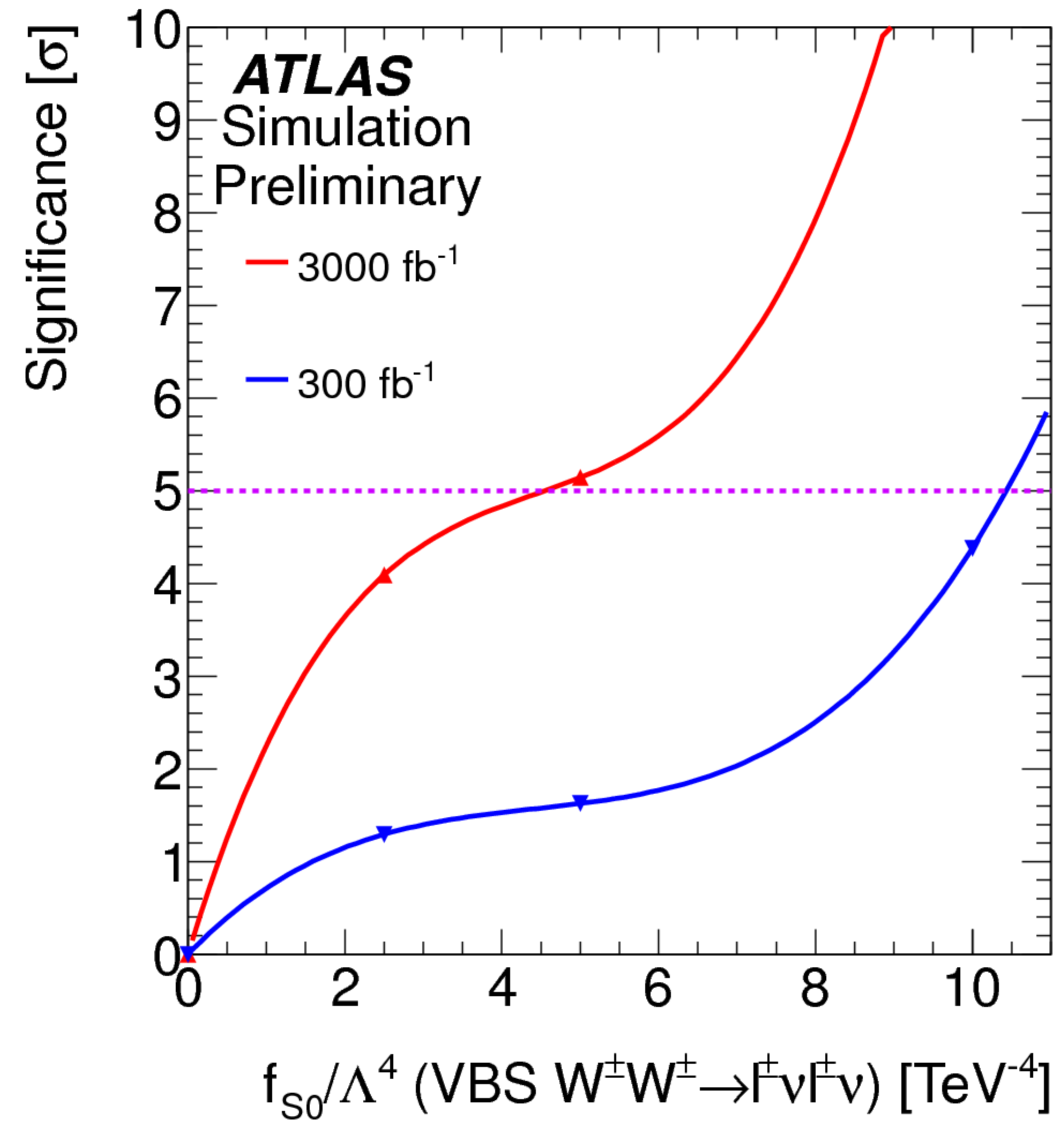
	$300\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
f_{T1}/Λ^4	$1.3\ \mathrm{TeV}^{-4}$	$0.6\ \mathrm{TeV}^{-4}$

Sensitivity to anomalous WZ resonances in Vector boson scattering

WW resonance

pp→WW+2j→2ℓ+2ν+2j channel





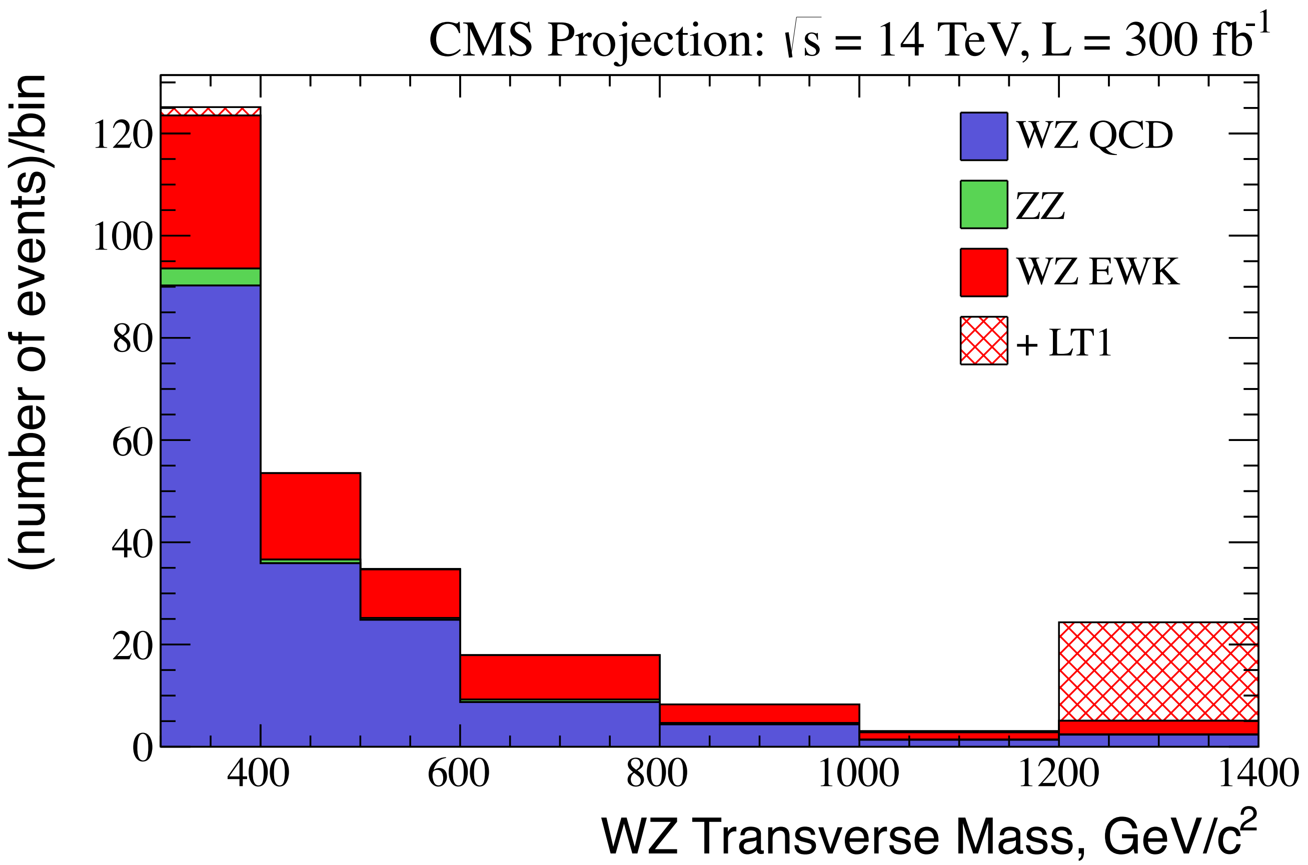
$$\mathcal{L}_{S,0} = \frac{f_{S0}}{\Lambda^4}[(D_\mu\phi)^\dagger D_\nu\phi)] \times [(D^\mu\phi)^\dagger D^\nu\phi)]$$

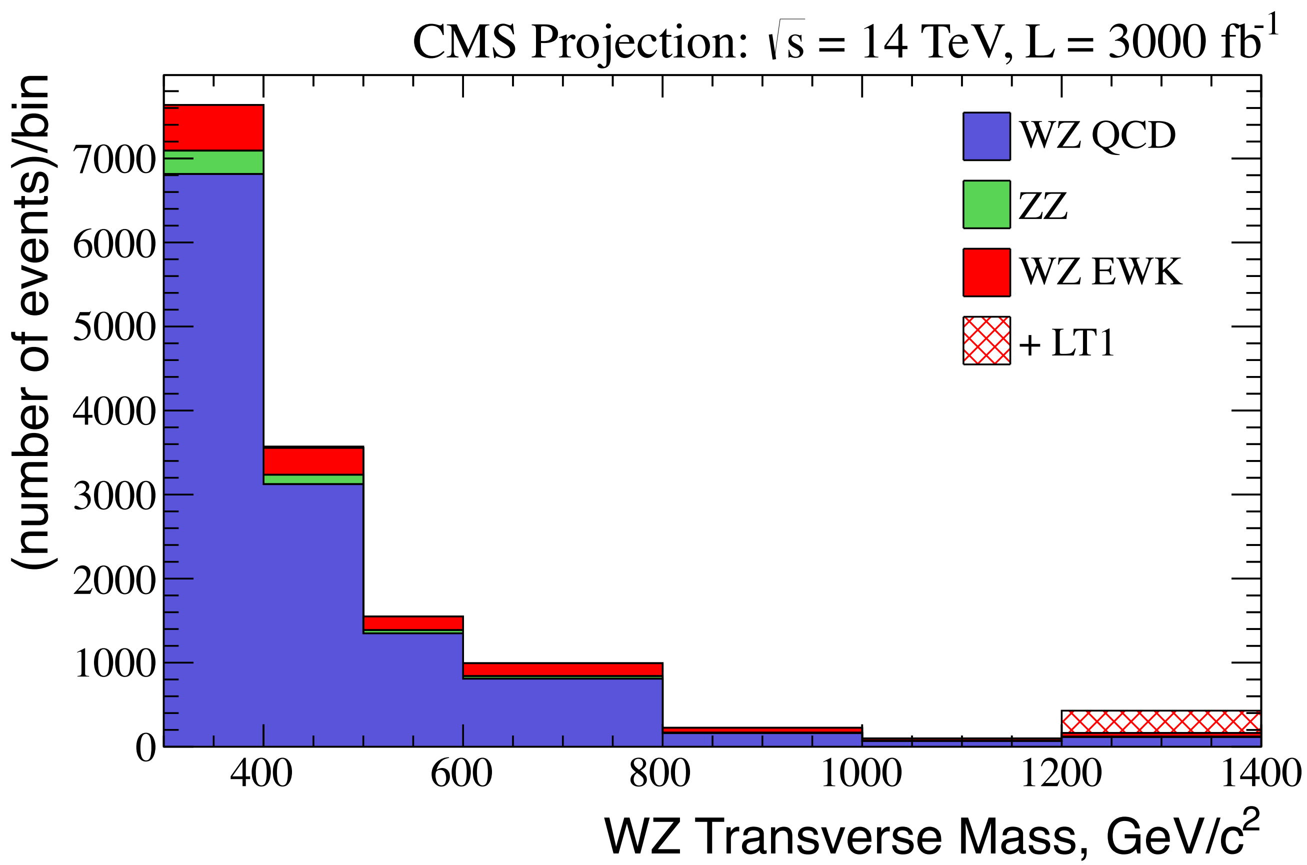
model	$300\ fb^{-1}$	$3\ ab^{-1}$
f_{S0}/Λ^4	$10\ TeV^{-4}$	$4.5\ TeV^{-4}$

Sensitivity to anomalous WW resonances in Vector boson scattering

WZ scattering

pp→WZ+2j→ℓ's+ν+2j channel





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

Conclusions

- ATLAS and CMS have exceeded their design performances during the first LHC run, showing that precision physics can be made under these conditions.
- The experience gained and a sound program of upgrades gives us confidence that the experiments will meet the physics expected at HL-LHC with 3000 fb^{-1}, collected at $\sqrt{s}=14$ TeV and instantaneous luminosities of 5×10^{34} cm^{-2} s^{-1}.
- Precision Higgs boson physics at HL-LHC is an attractive future scenario deserving substantial studies and R&D
  - it is a challenging project involving major upgrades of full detectors
  - Higgs boson couplings can be measured with few percent precision
  - rare Higgs boson decays can be probed
  - Higgs self-coupling studies possible
  - VV scattering will be probed
- LHC has an exciting physics program for the next twenty years!

Backup

VV scattering: fully leptonic

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

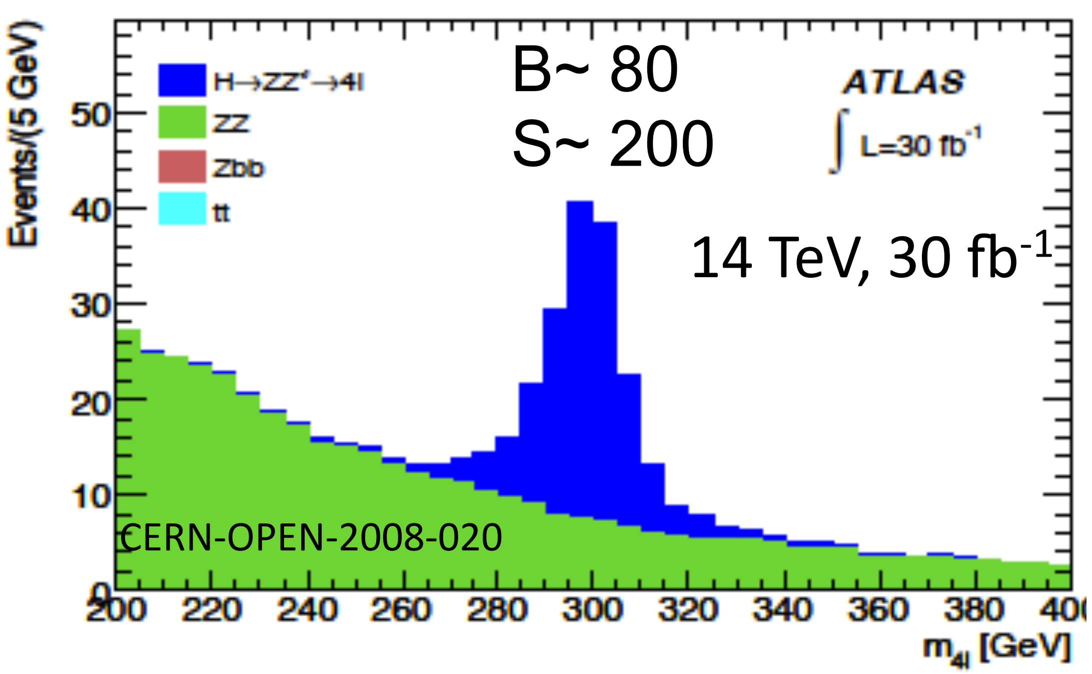
ATLAS ZZ->2l2ν	N signal	N back.
500 GeV	6.4	3.0

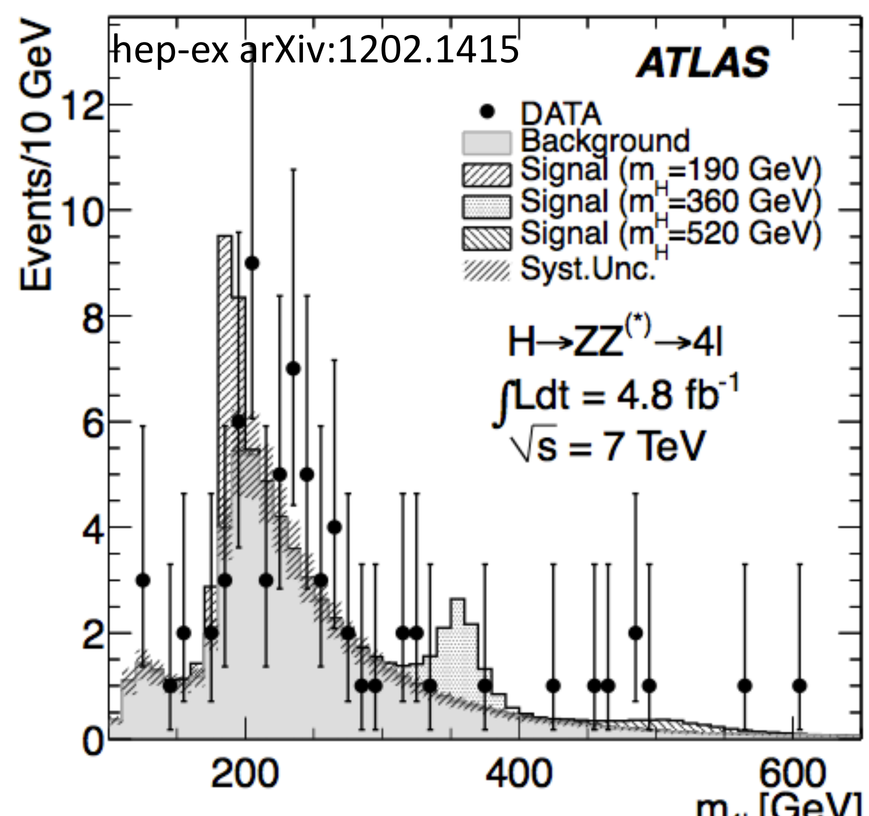
ATLAS ZW->lllν	N signal	N back.
500 GeV	8	5
1.1 TeV	1.4	0.4

CMS AN 2007-005

CERN-OPEN-2008-020

Example: ggF Higgs 300 GeV





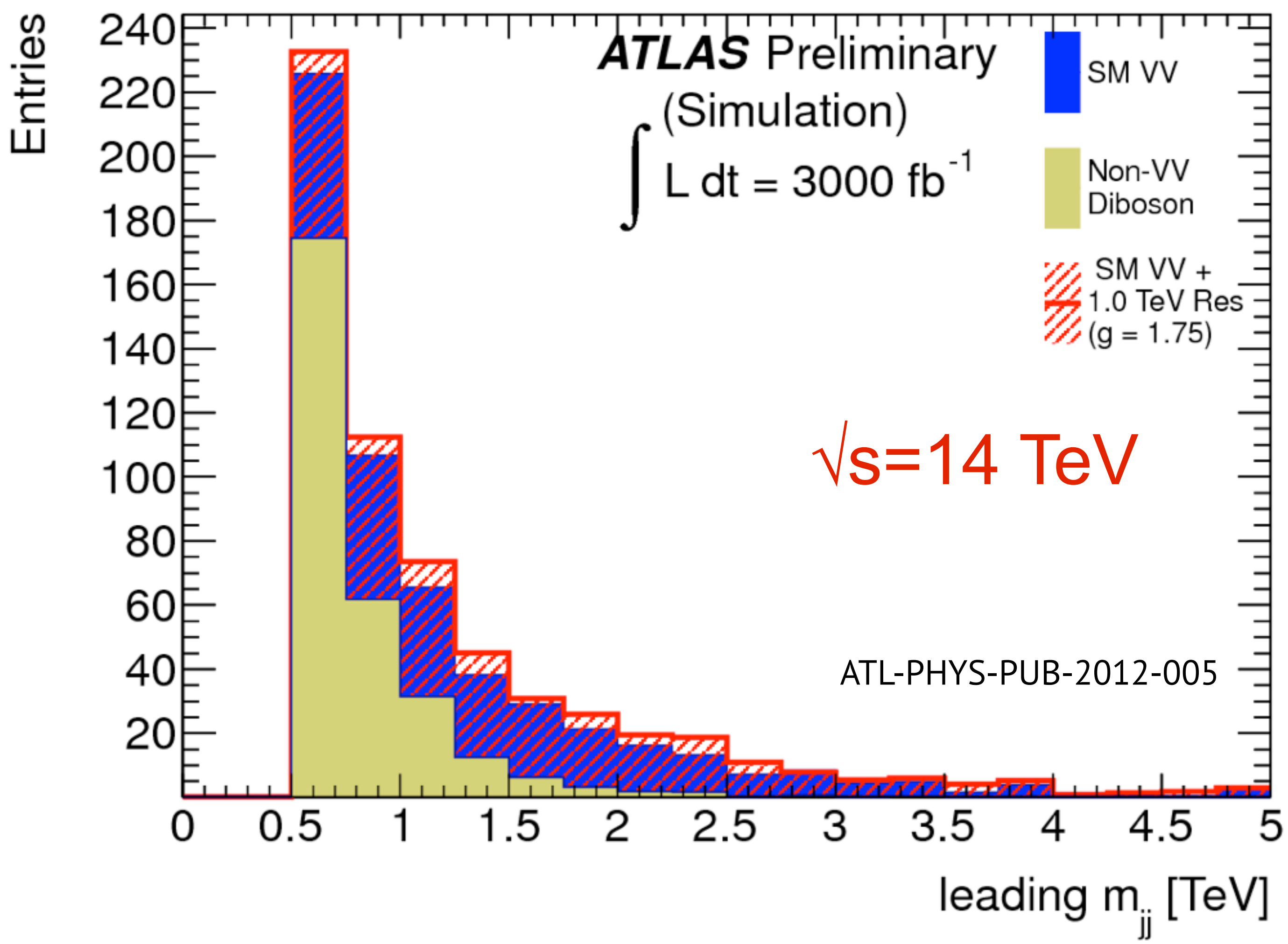
Latest results:
B~ 6
S~ 10

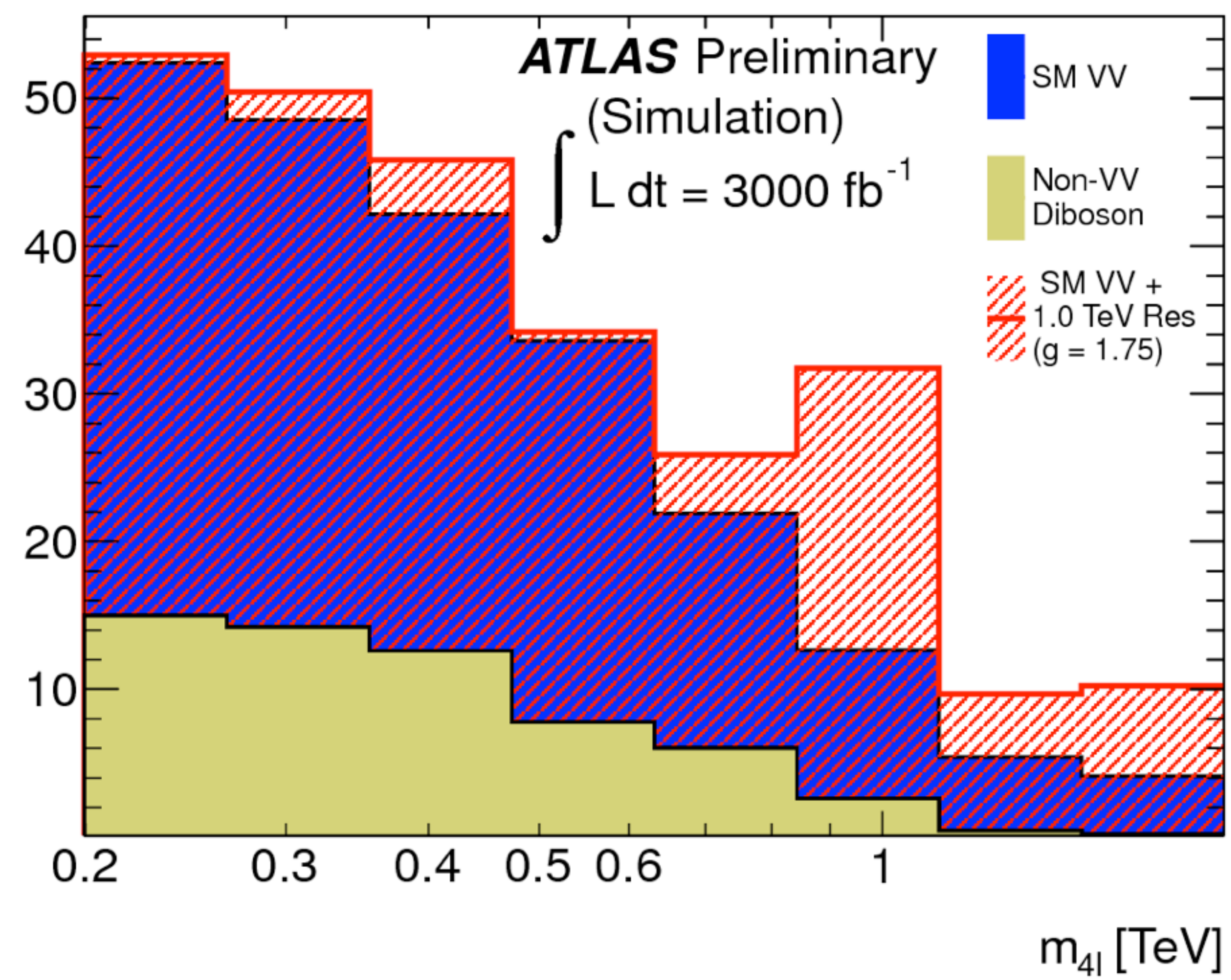
- reso m_{4l} as expected
- improved reco-id efficiencies

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

ZZ resonance

pp→ZZ+2j→4ℓ+2j channel





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

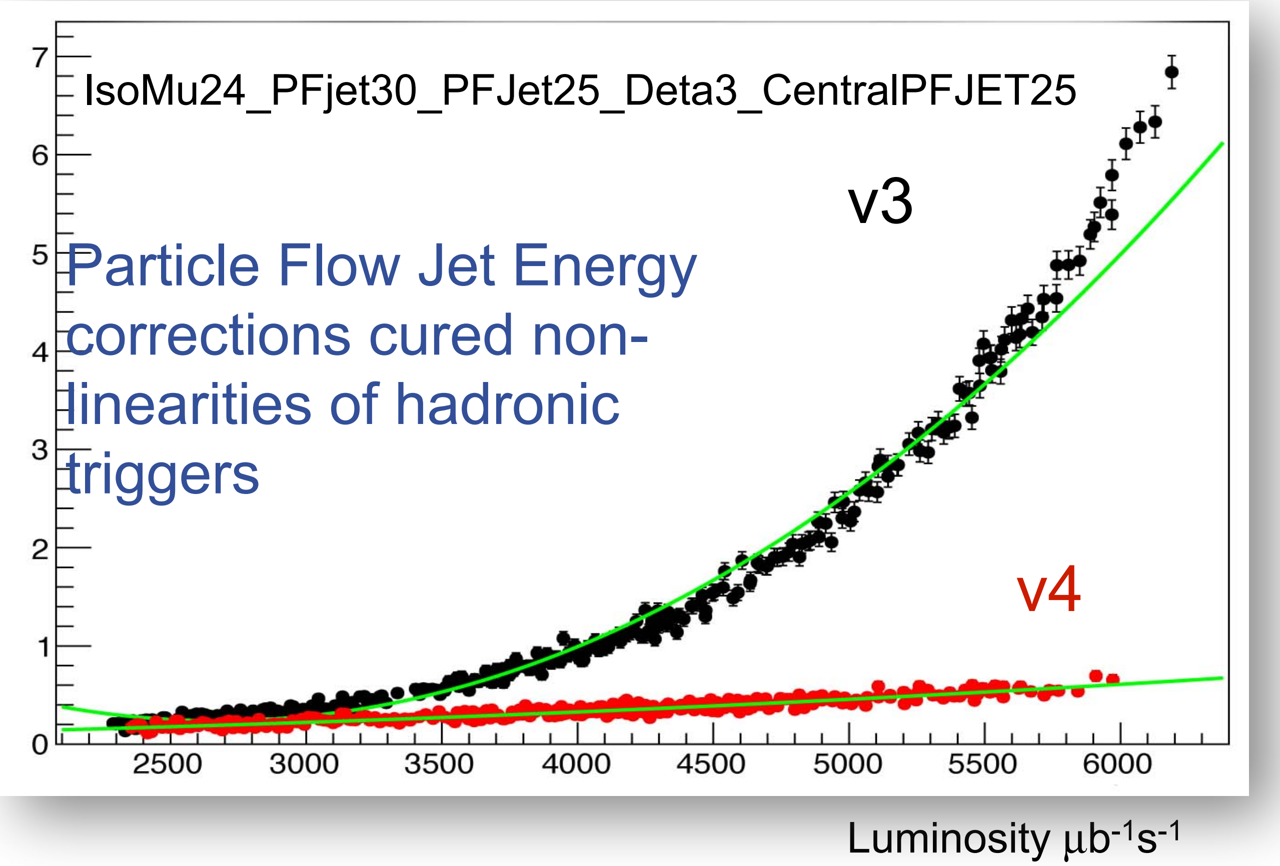
Sensitivity to anomalous ZZ resonances in Vector boson scattering

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

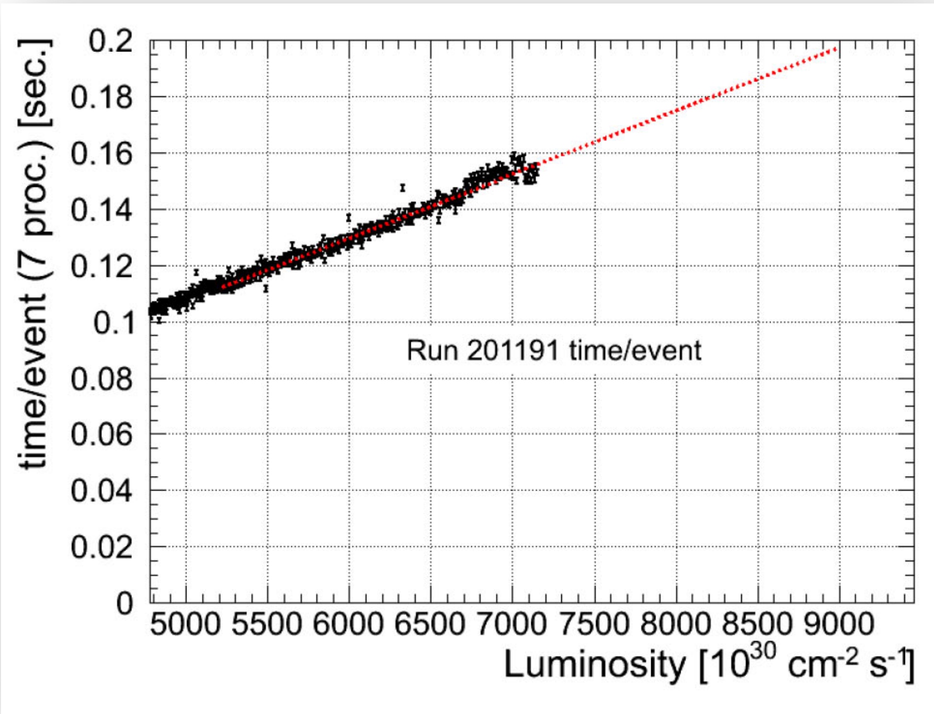
The experience obtained in 2012 with peak pileup of ~35 events gives us confidence for high-luminosity running post Long Shutdown 1

Trigger Cross-sections:



HLT CPU time:

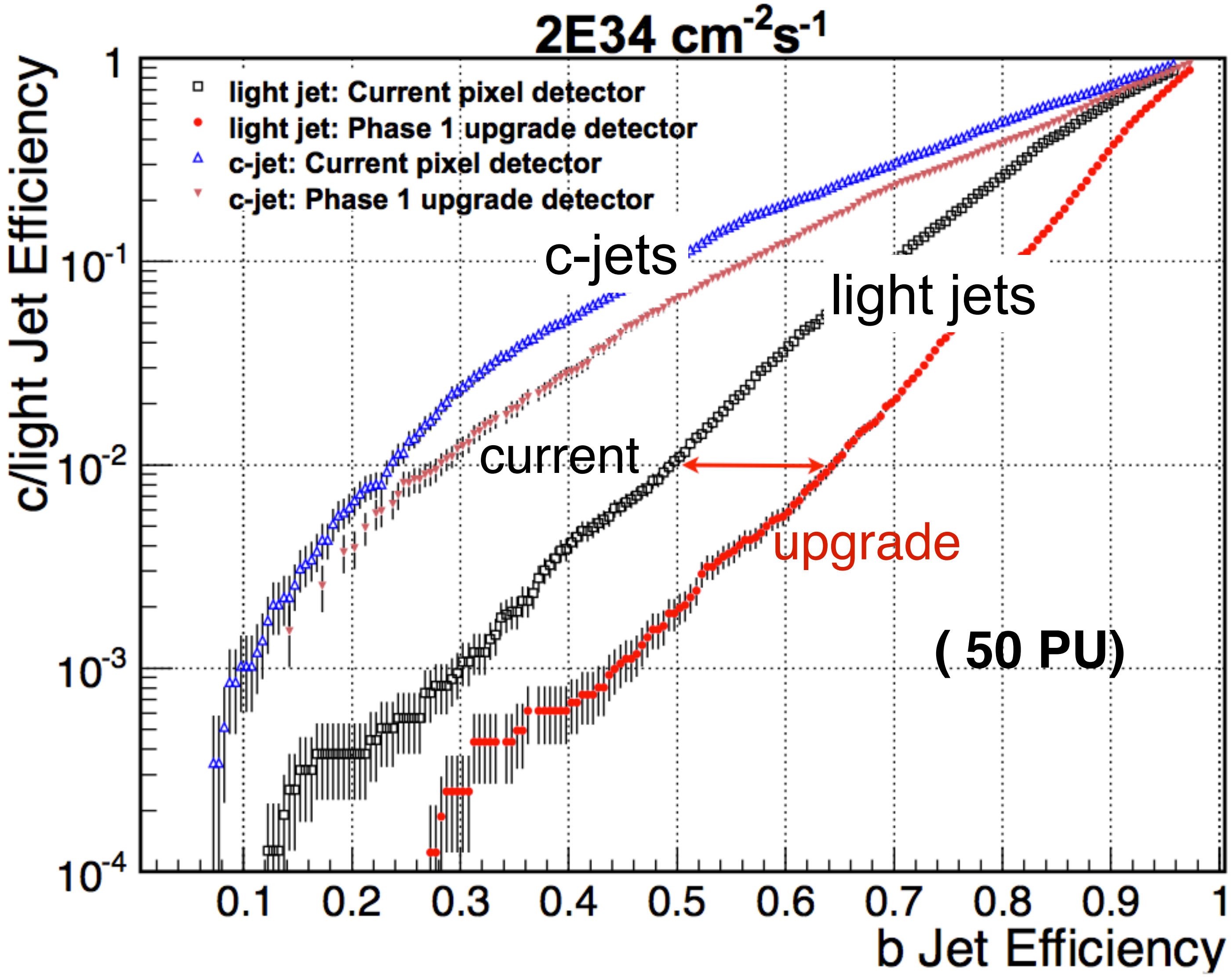
- linear with PU, no signs of runaway

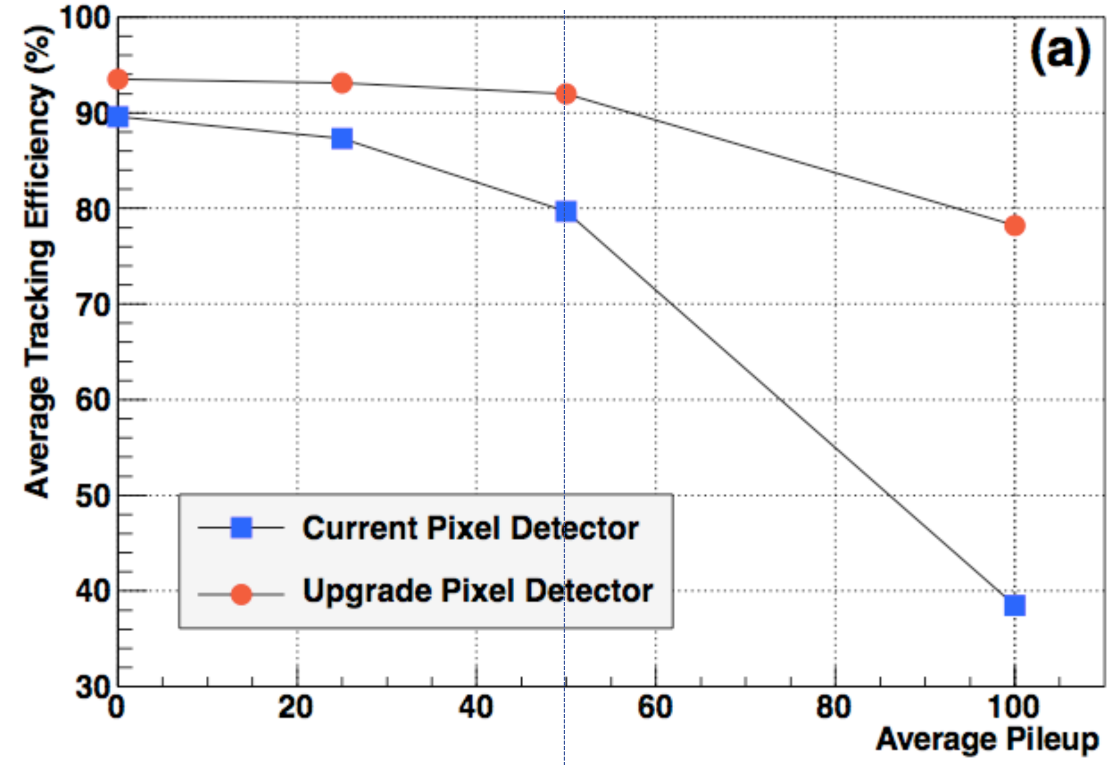


Tracking and b-tagging performance

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

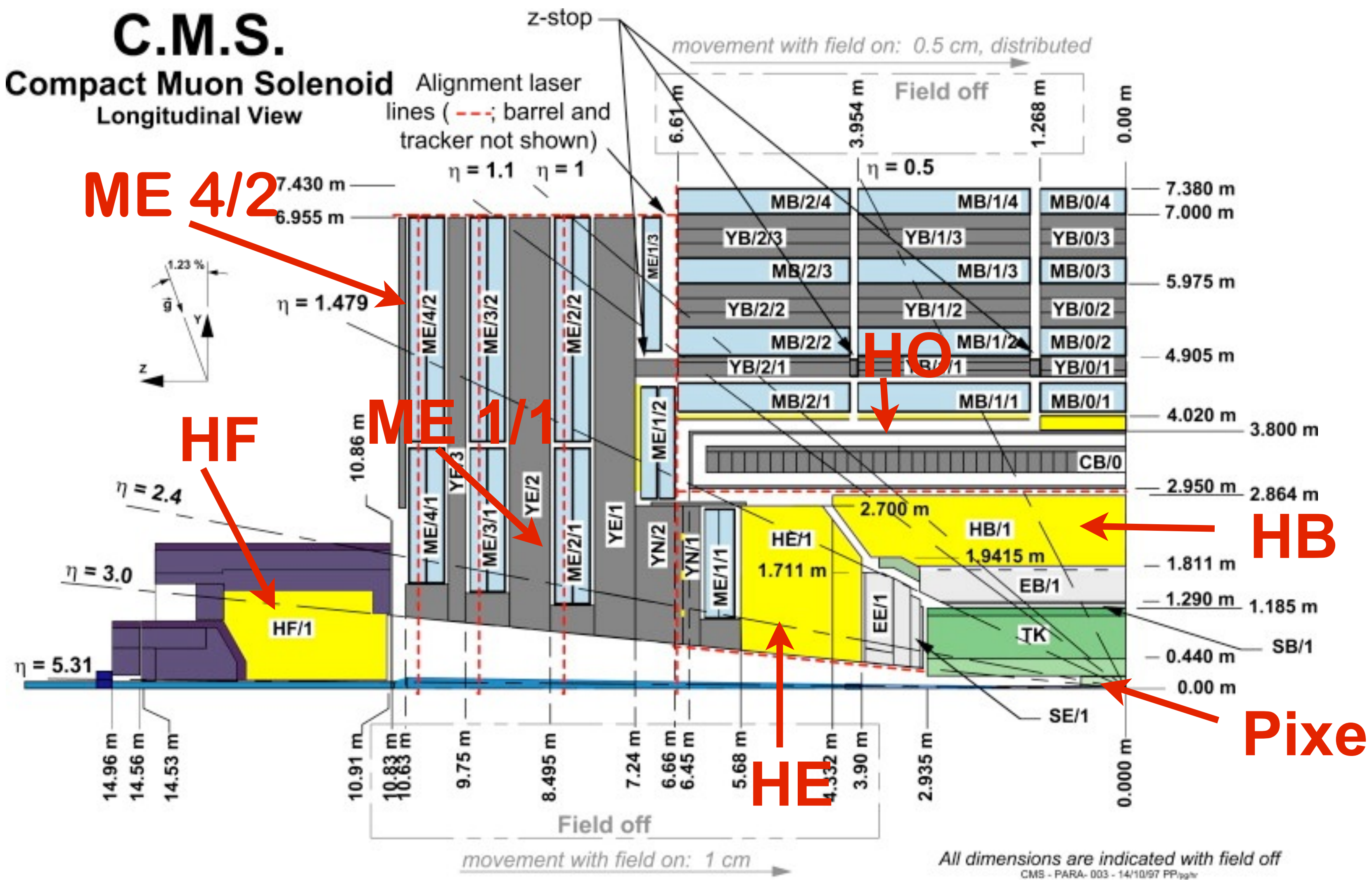
b-tagging efficiency ~ 1.3x better

2 b-jets → $(1.3)^2 \sim 1.69$

Primary vertex resolution improved by factor ~1.5 - 2

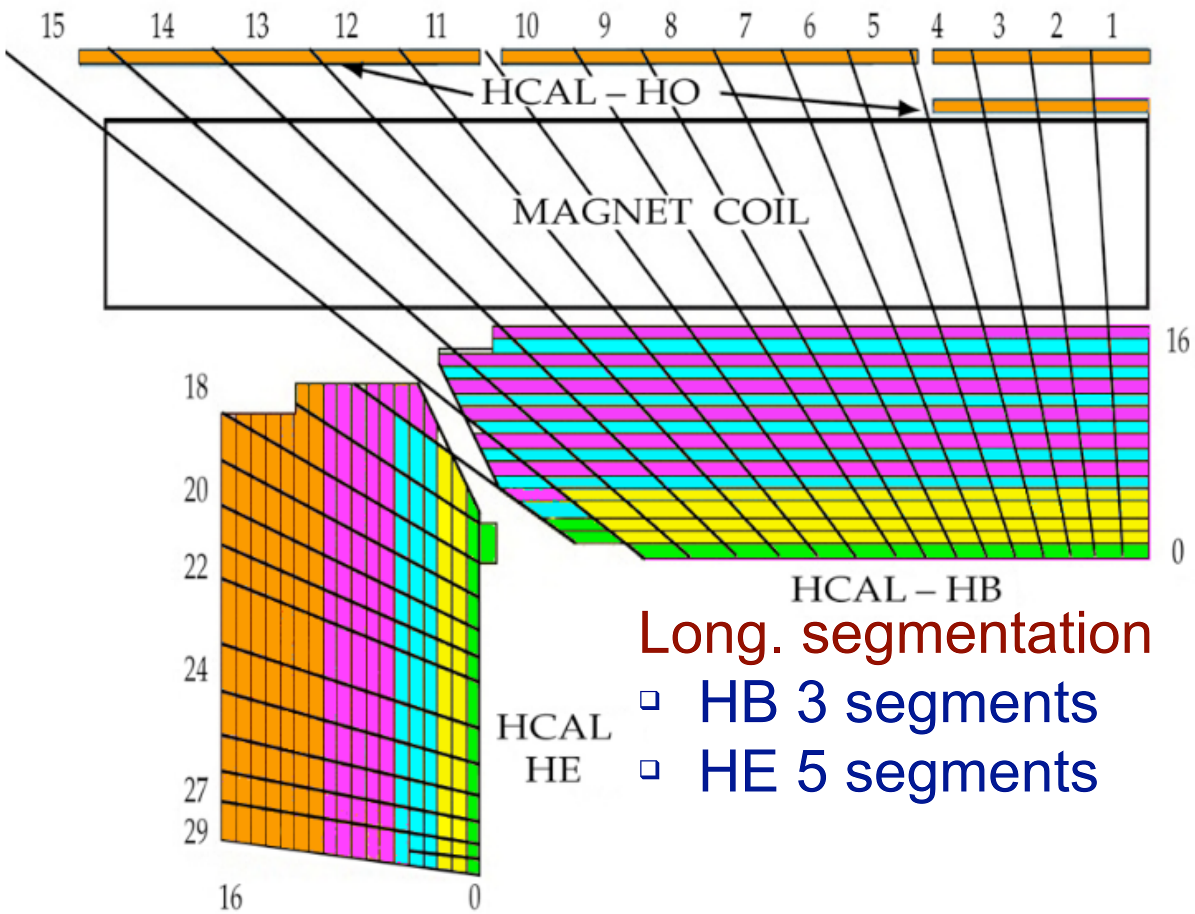
CMS Upgrade program

LS1 and Phase 1



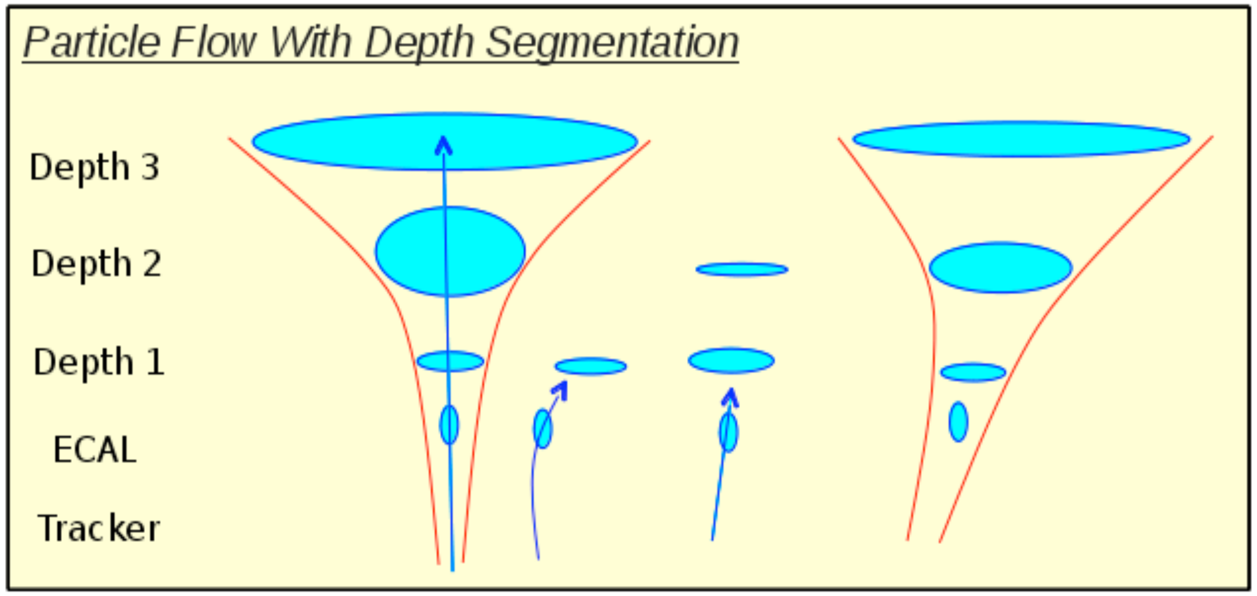
HCAL Upgrade

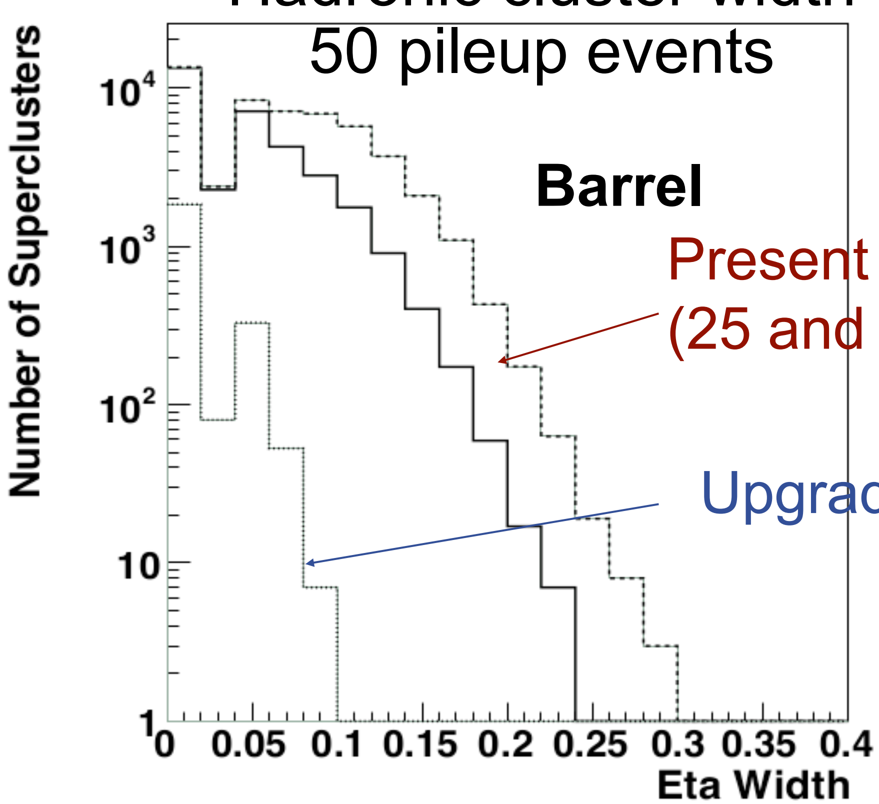
- Upgraded HCAL
  - New photodetectors
  - New electronics (frontend, backend)
  - Improved longitudinal segmentation
  - Improved background rejection, Missing E_T resolution and Particle Flow reconstruction



Long. segmentation
- HB 3 segments
- HE 5 segments

- Hadronic showers spread out with increasing depth



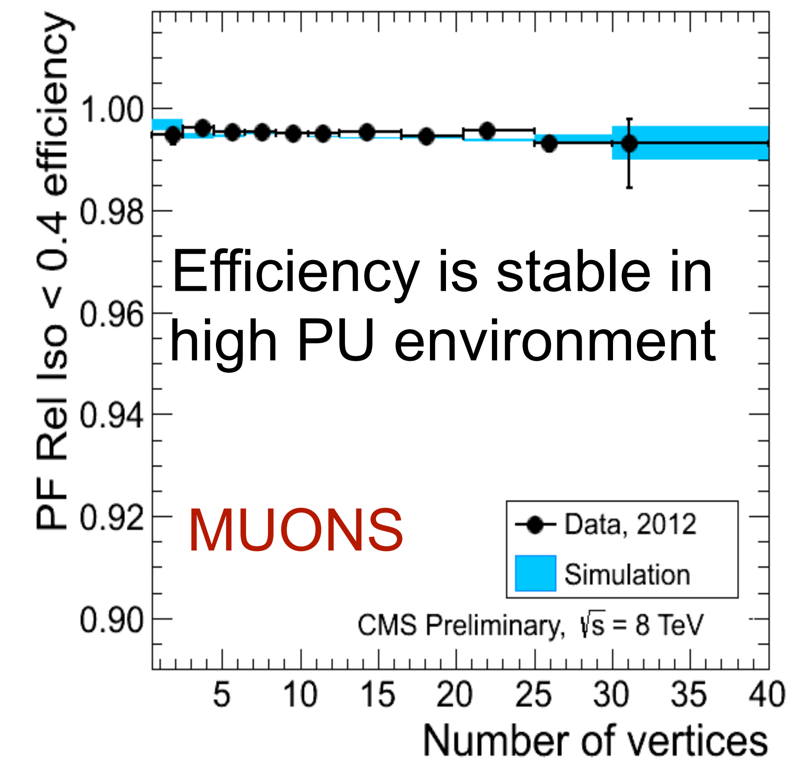


Pileup challenges

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

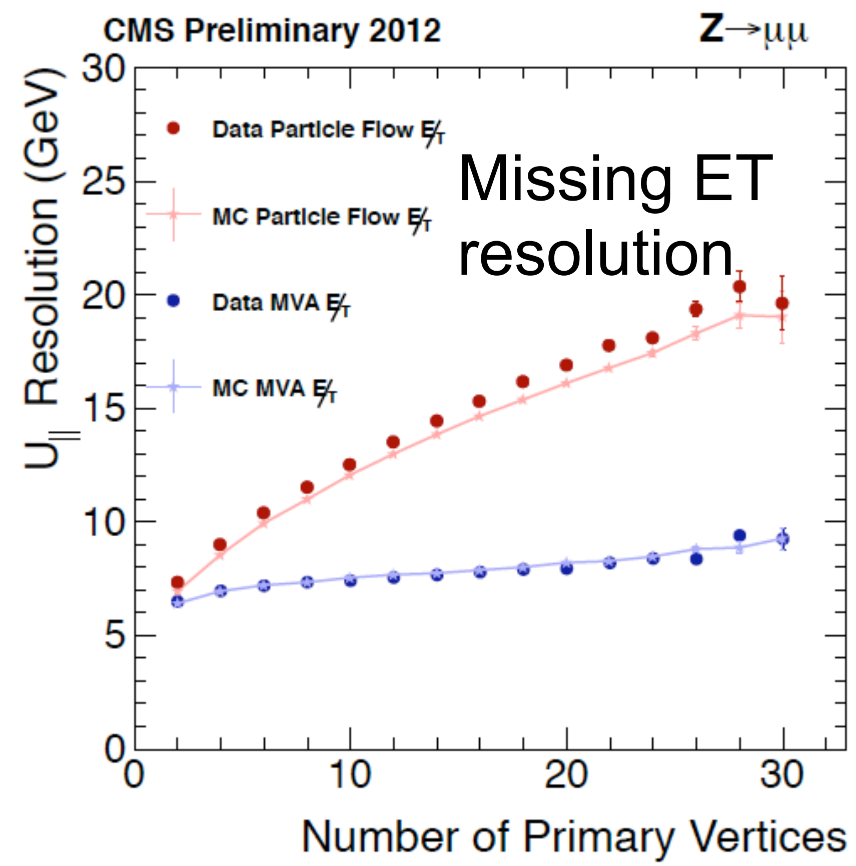
- efficient association of charged tracks to collision vertices
- reconstruction of charged and neutral particles in jets
- pileup neutrals corrected w/global energy density (ρ)

Muon isolation



Physics with high pileup requires full particle flow reconstruction assuring:

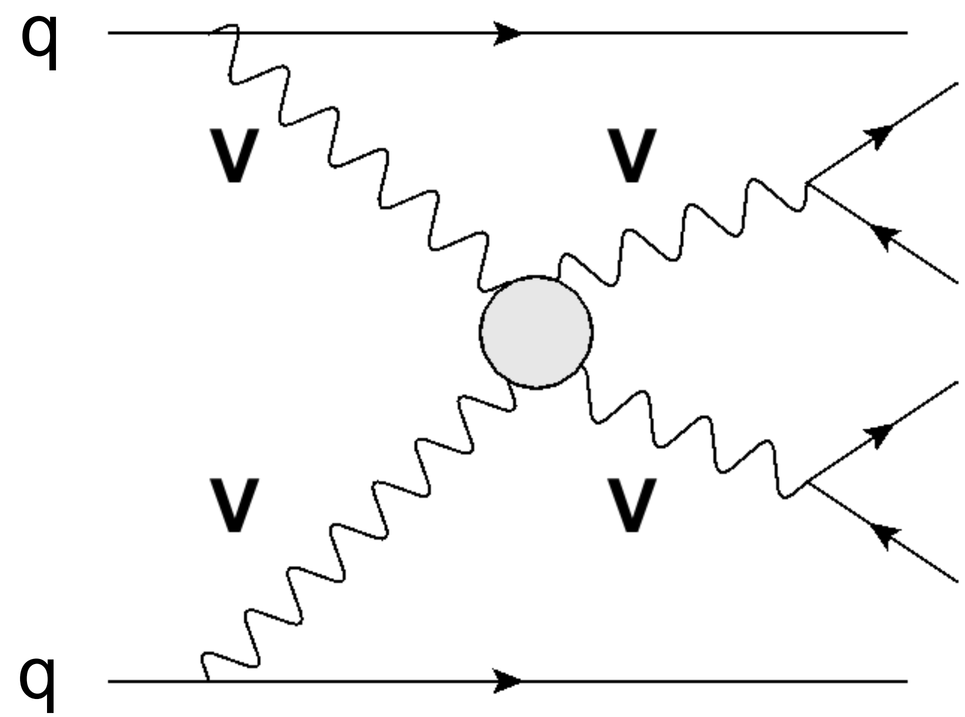
- precise jet energy correction
- robust missing energy measurement
- efficient lepton isolation



Very efficient reconstruction code is needed to stay within computing budget

Vector Boson Fusion (VBF)

Generic diagram for vector boson fusion (VBF) process



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

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)

CERN-OPEN-2008-020

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

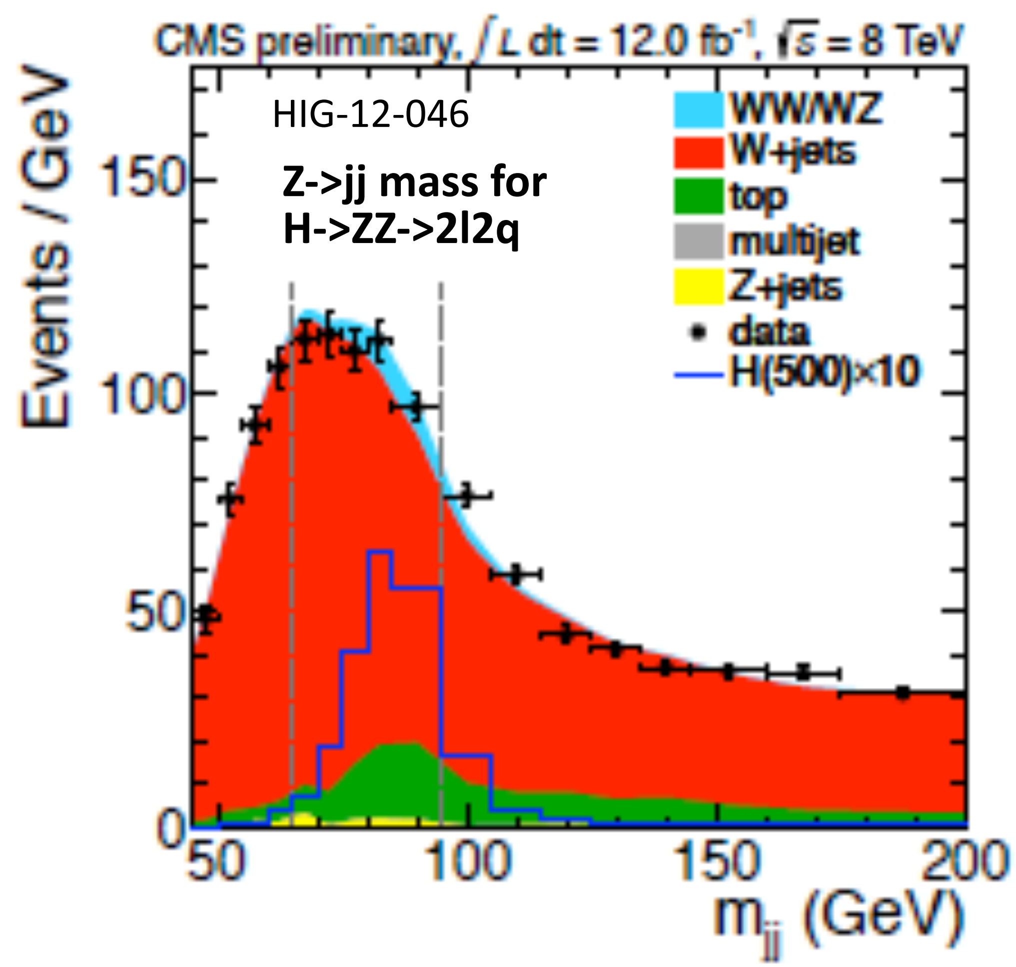
CMS	N sign.	N back.
500 GeV	62	3415
>1 TeV	5	348

For recent inclusive Higgs search:

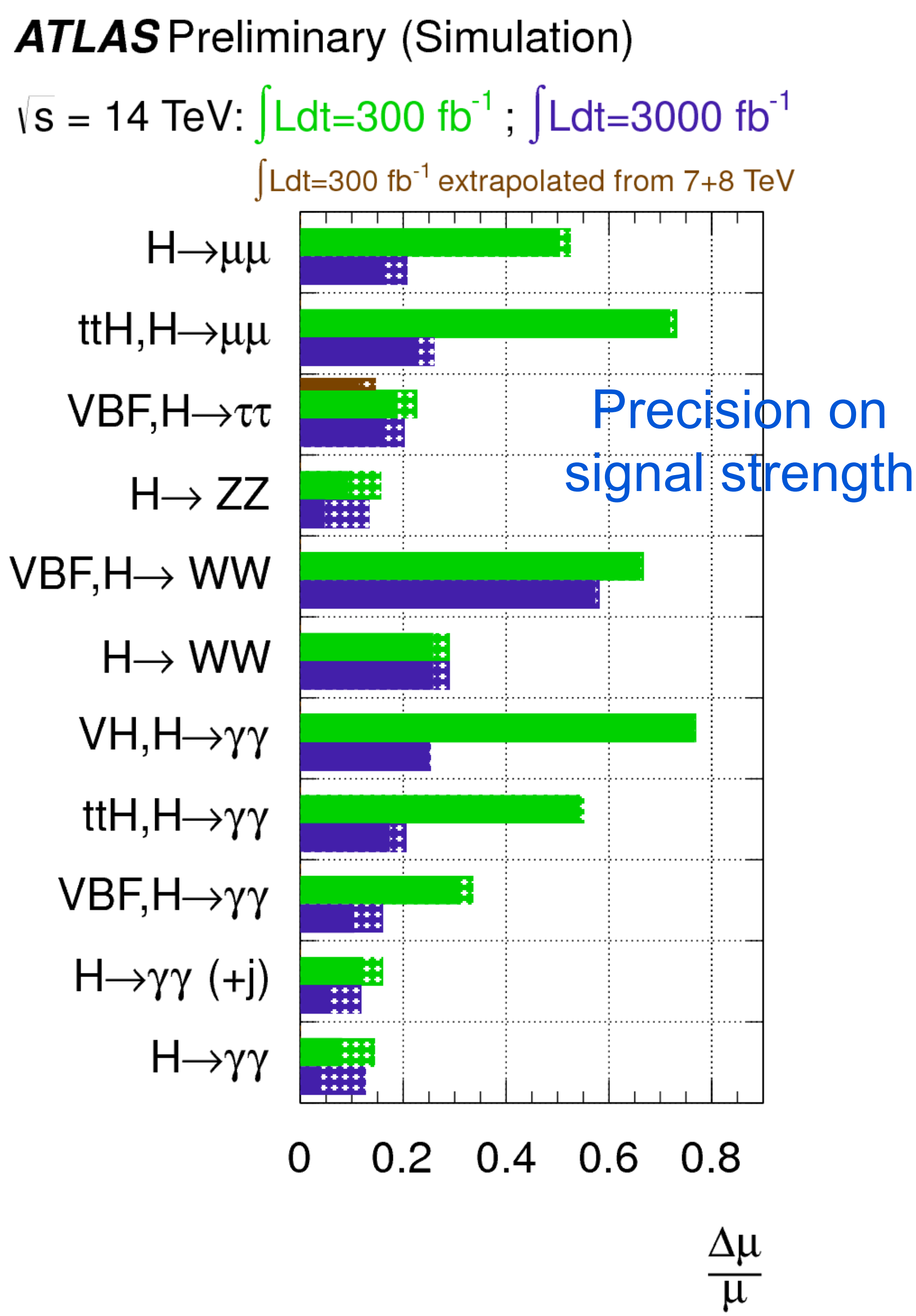
- more sophisticated analysis developed
(btag categories, angular analyses,
$m_{jj} = m_Z$ kinematic fit)

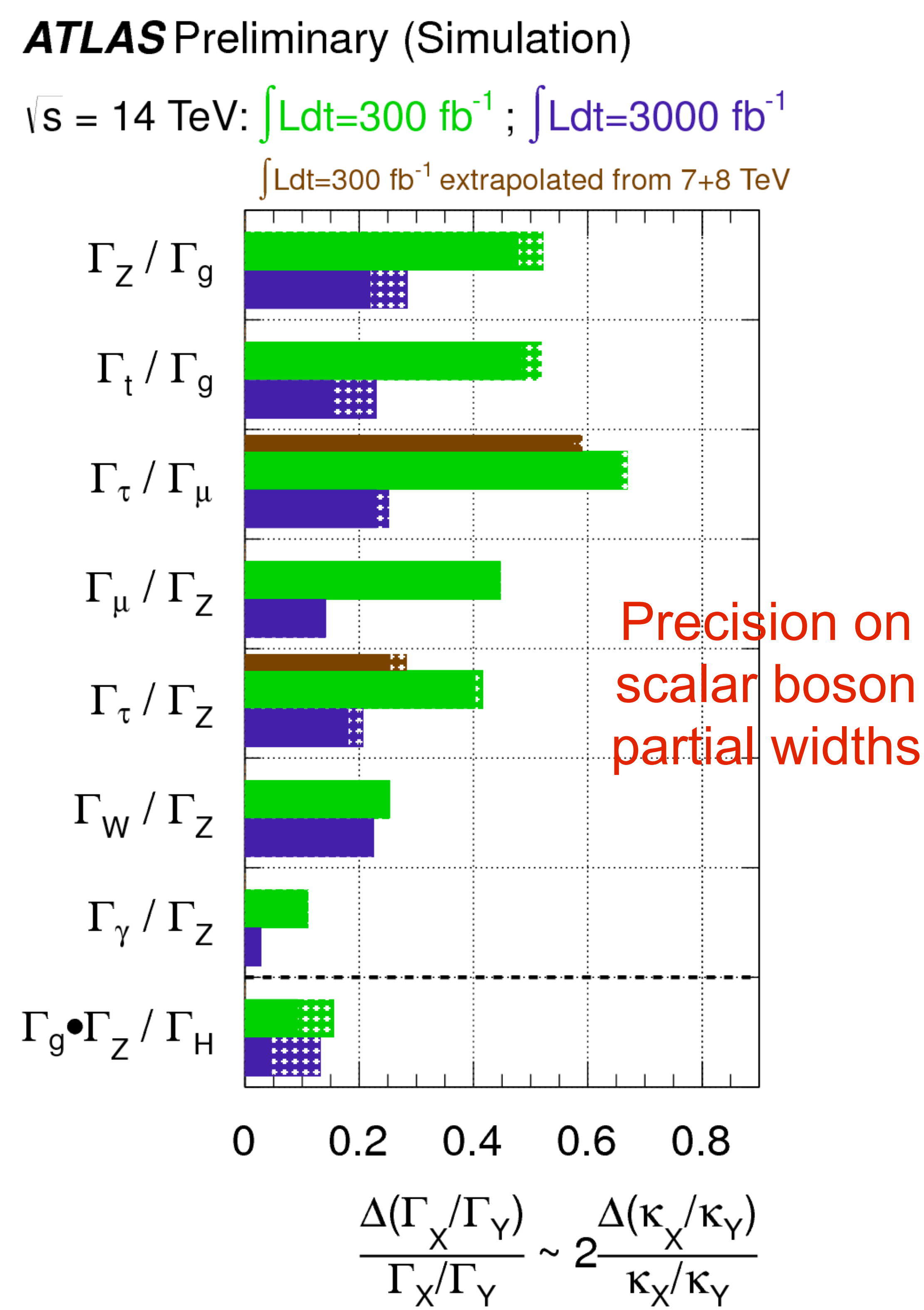
- data driven background

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



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





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

Ratios of partial widths

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

CMS

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 $1/\sqrt{L}$