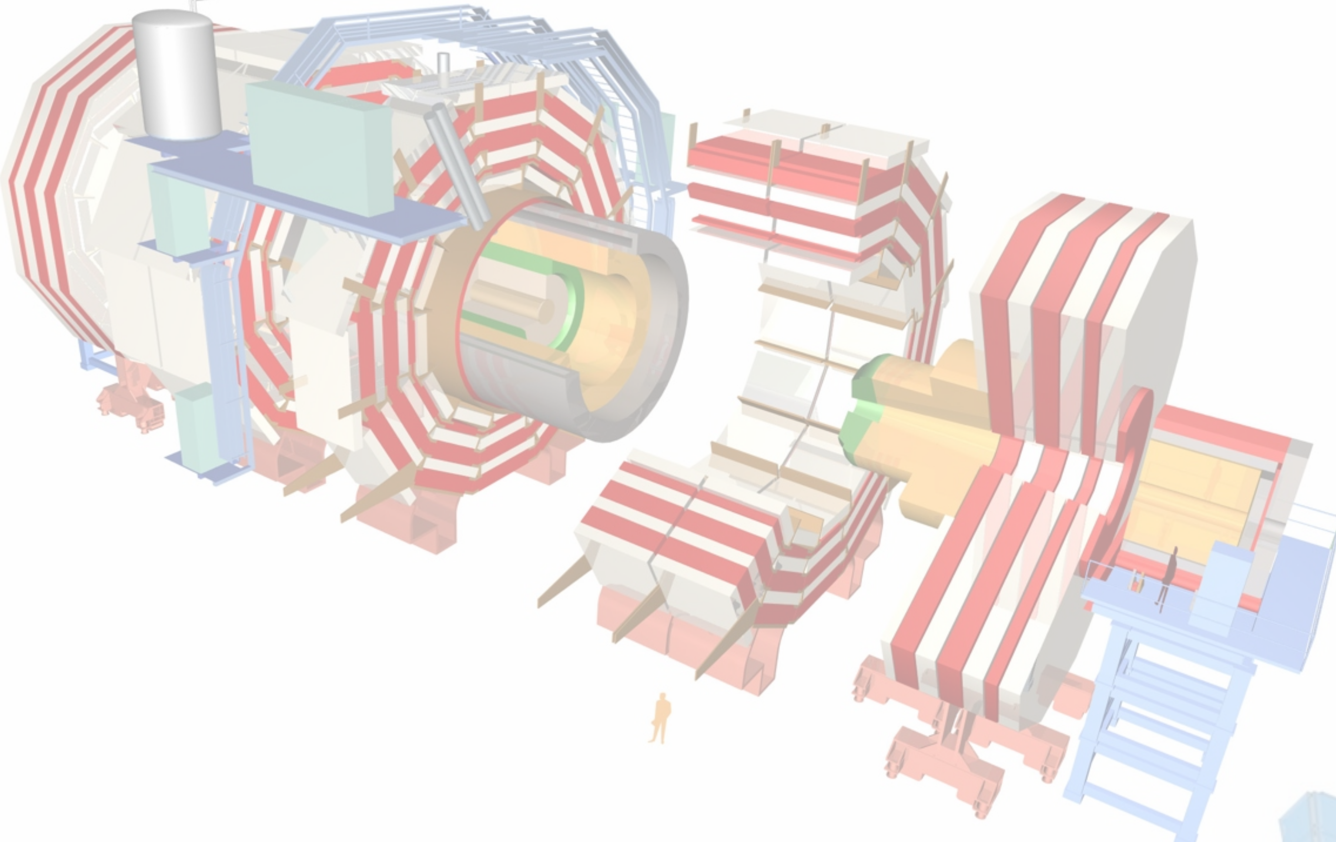
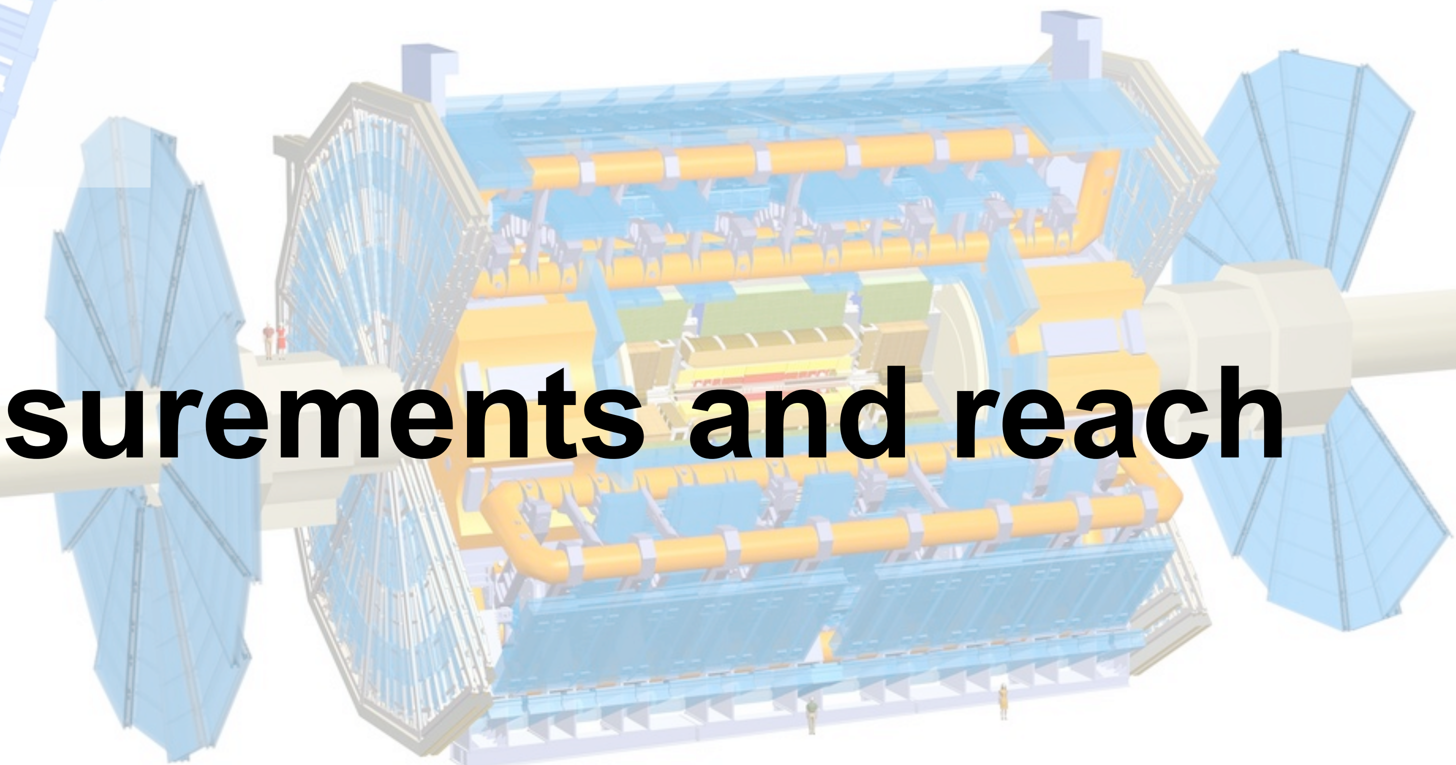




LHC: future measurements and reach

Paolo Giacomelli (INFN Bologna)
Facing the Scalar Sector, Solvay Workshop
Friday, May 31st, 2013

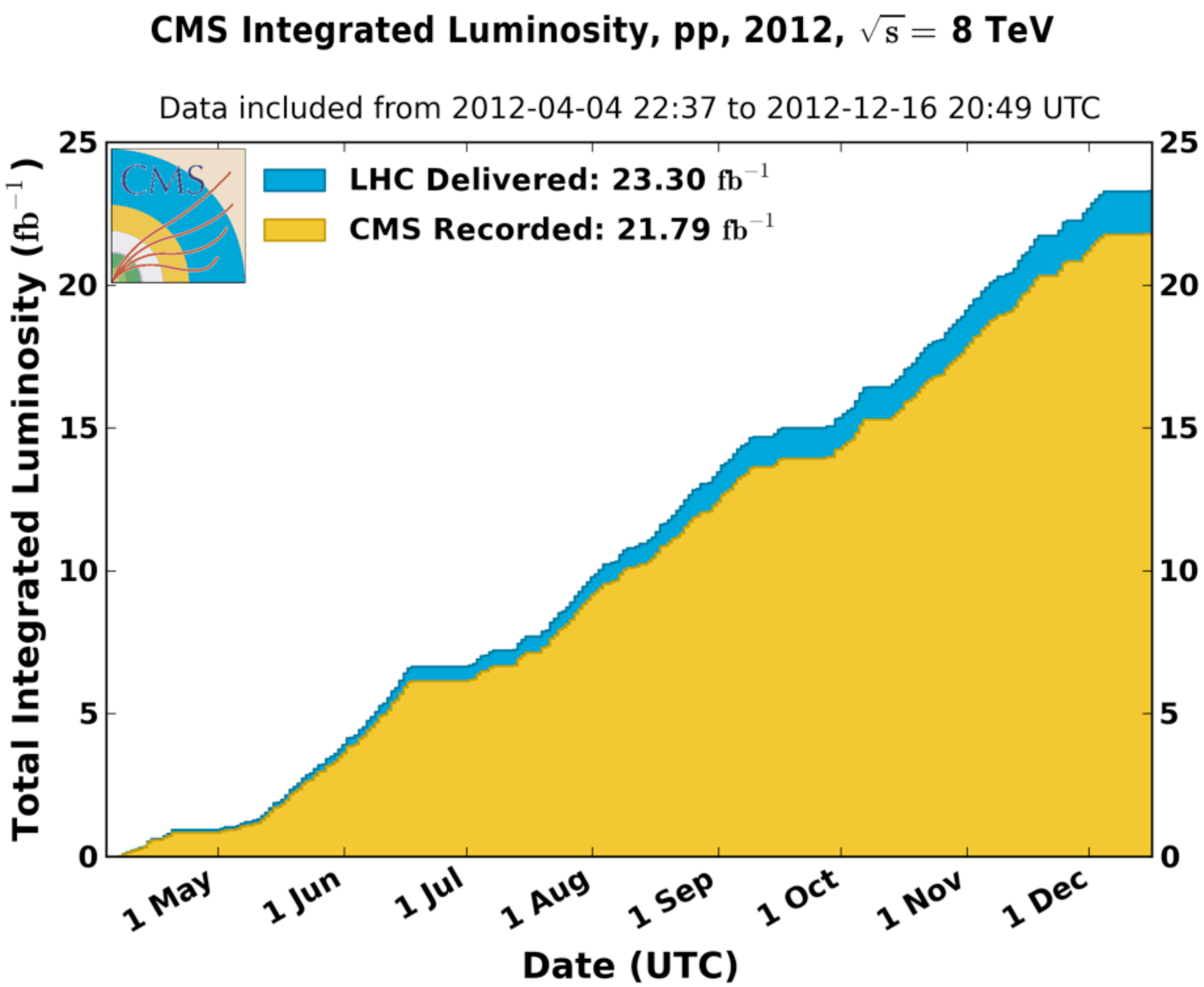
Outline

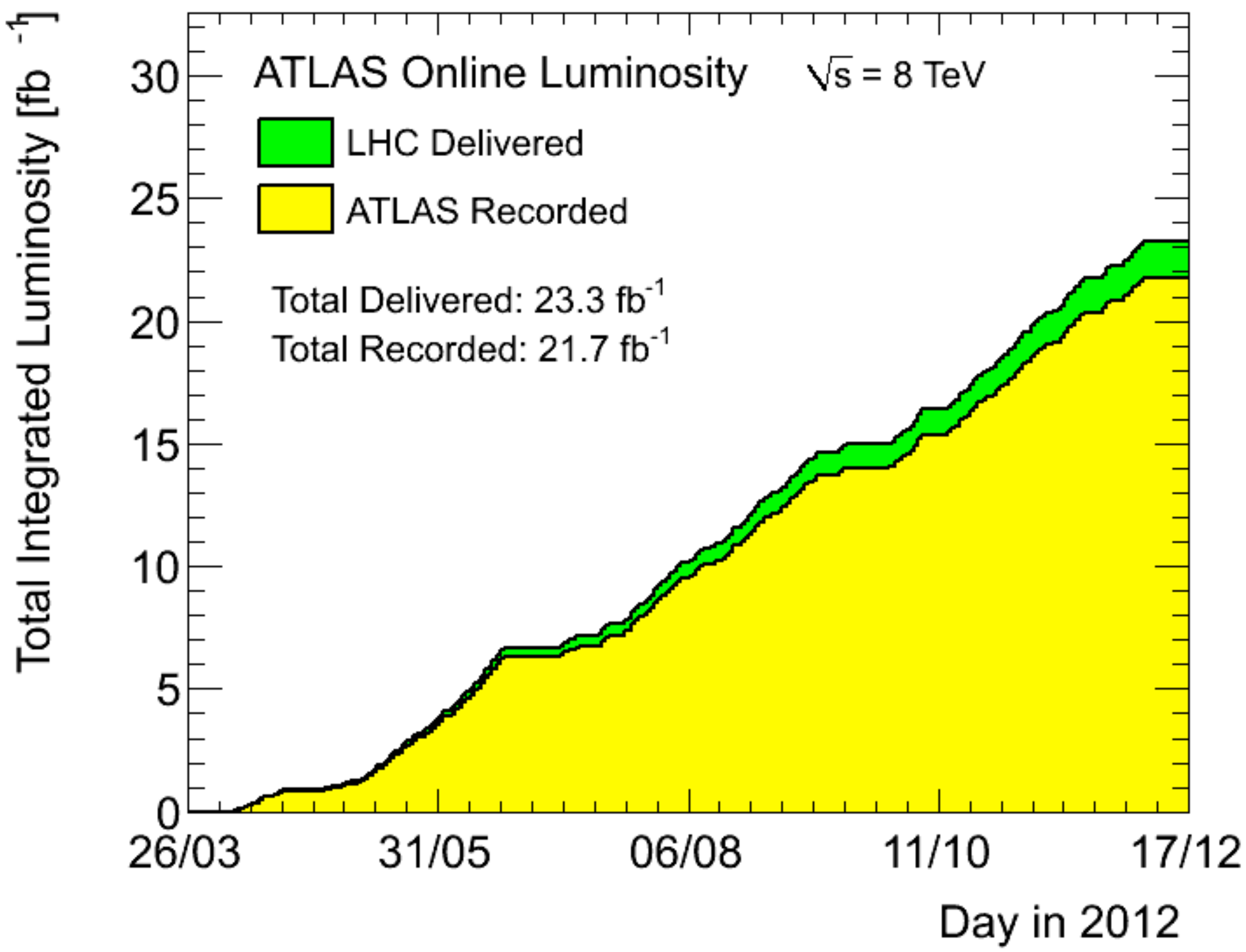
- Where we stand today
- LHC and HL-LHC luminosity projections
- Physics priorities
- CMS and ATLAS upgrade programs
- Scalar boson physics projections
- Scalar boson rare decays
- Scalar boson self-coupling
- VV scattering
- SUSY prospects
- Exotics projections

Integrated luminosity in 2012

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

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





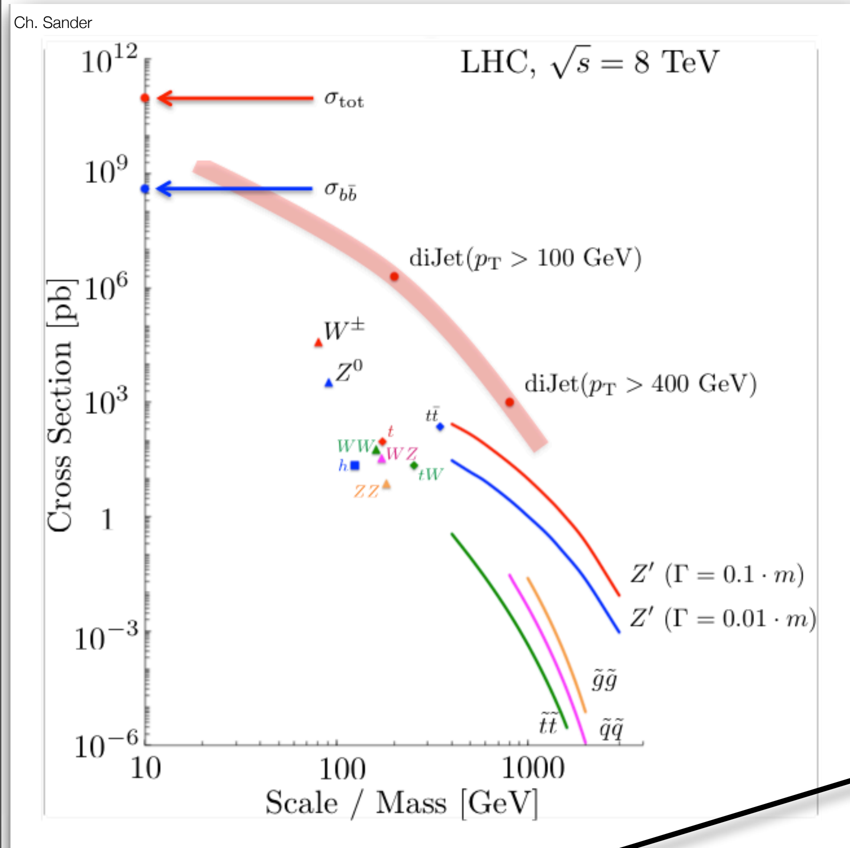
Total delivered luminosity: **~30 fb^{-1}**

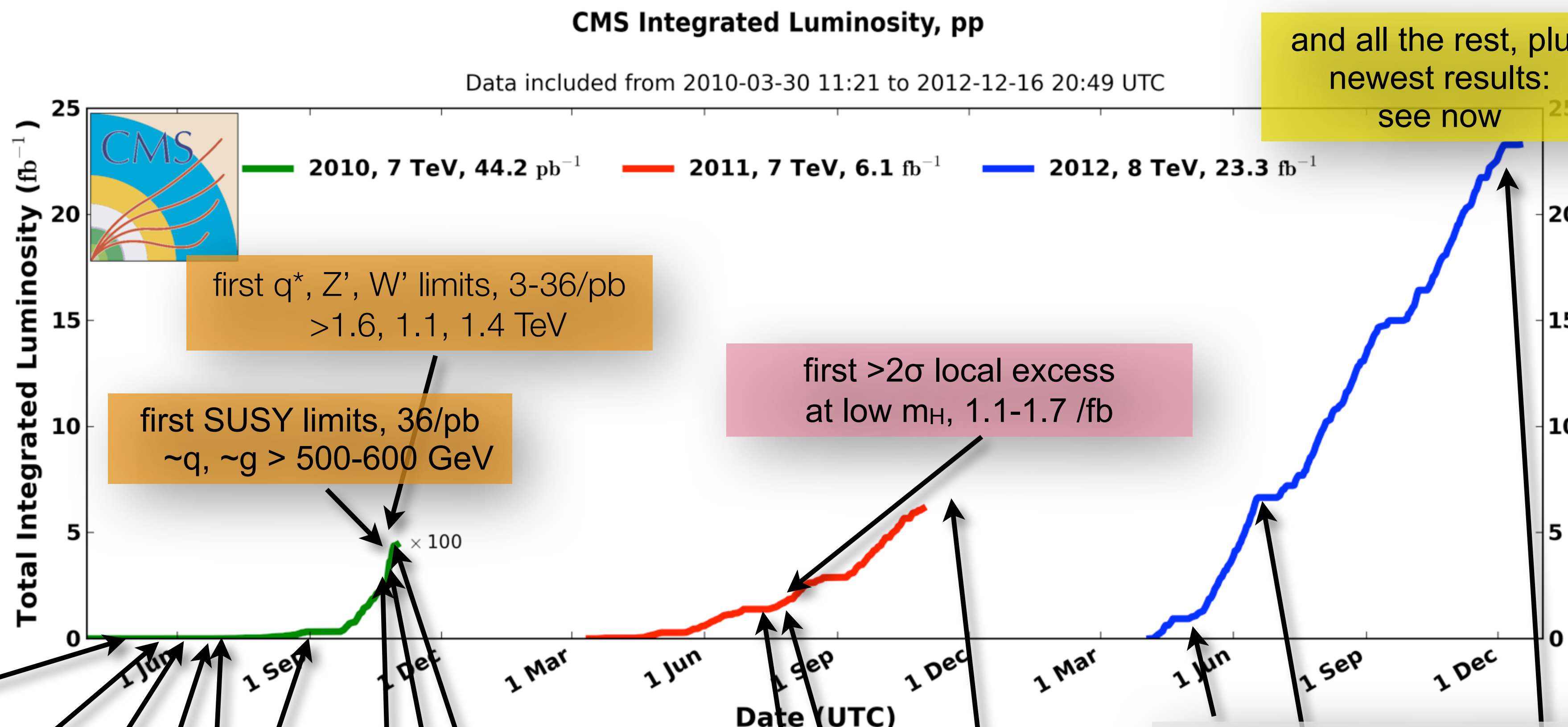
Total recorded luminosity: **~27 fb^{-1}**

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

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

repeating the program at 8 TeV

a new boson is announced, 5 /fb

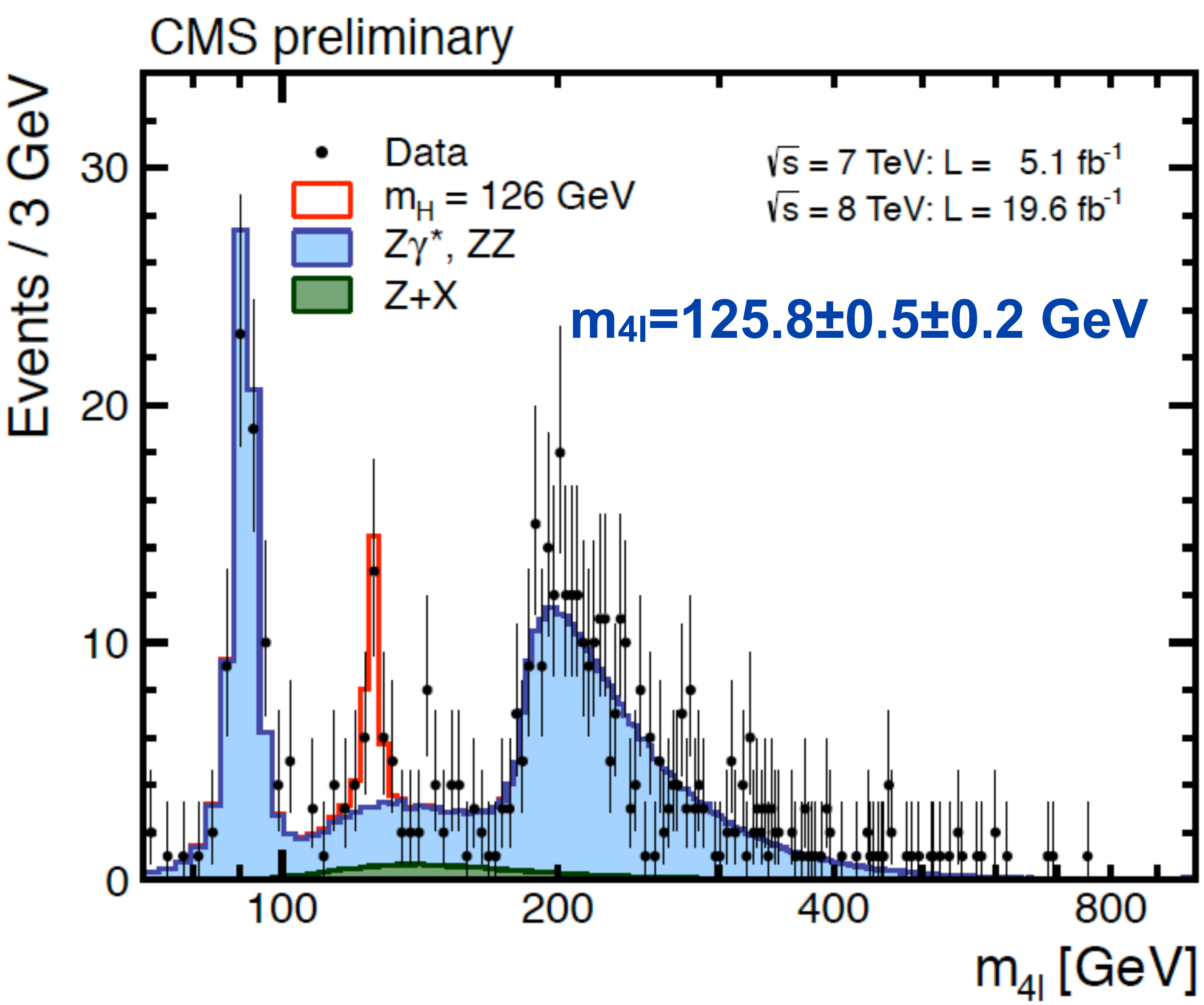
first spin parity analysis of the boson, 17 /fb

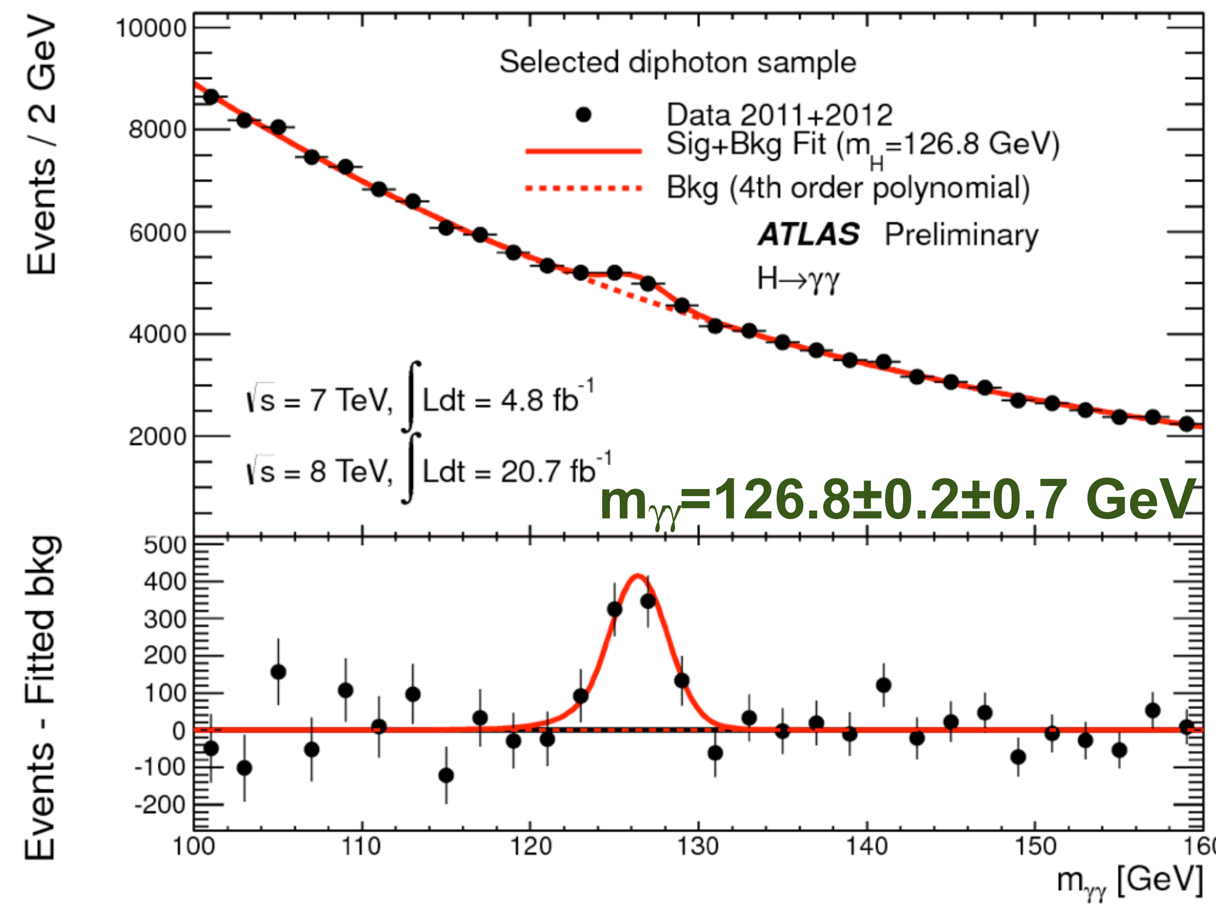
From G. Dissertori (ETH)

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

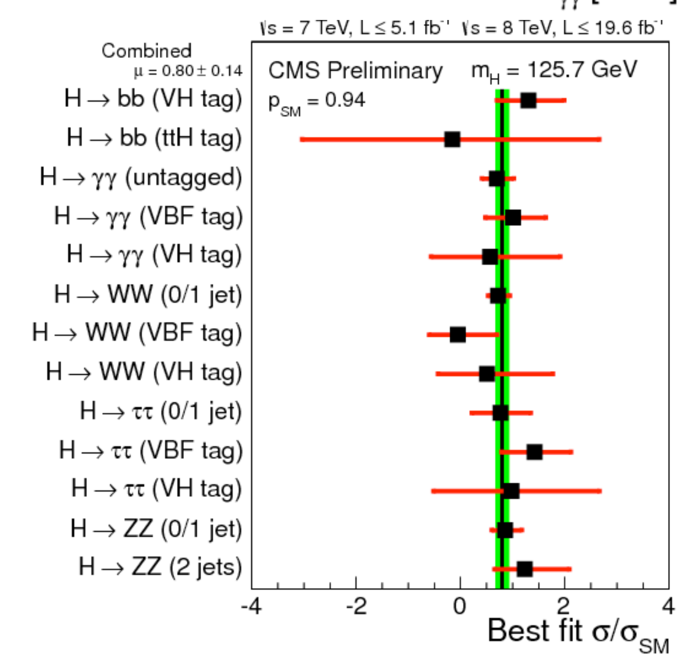
New boson with a mass of ~125 GeV

- 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.





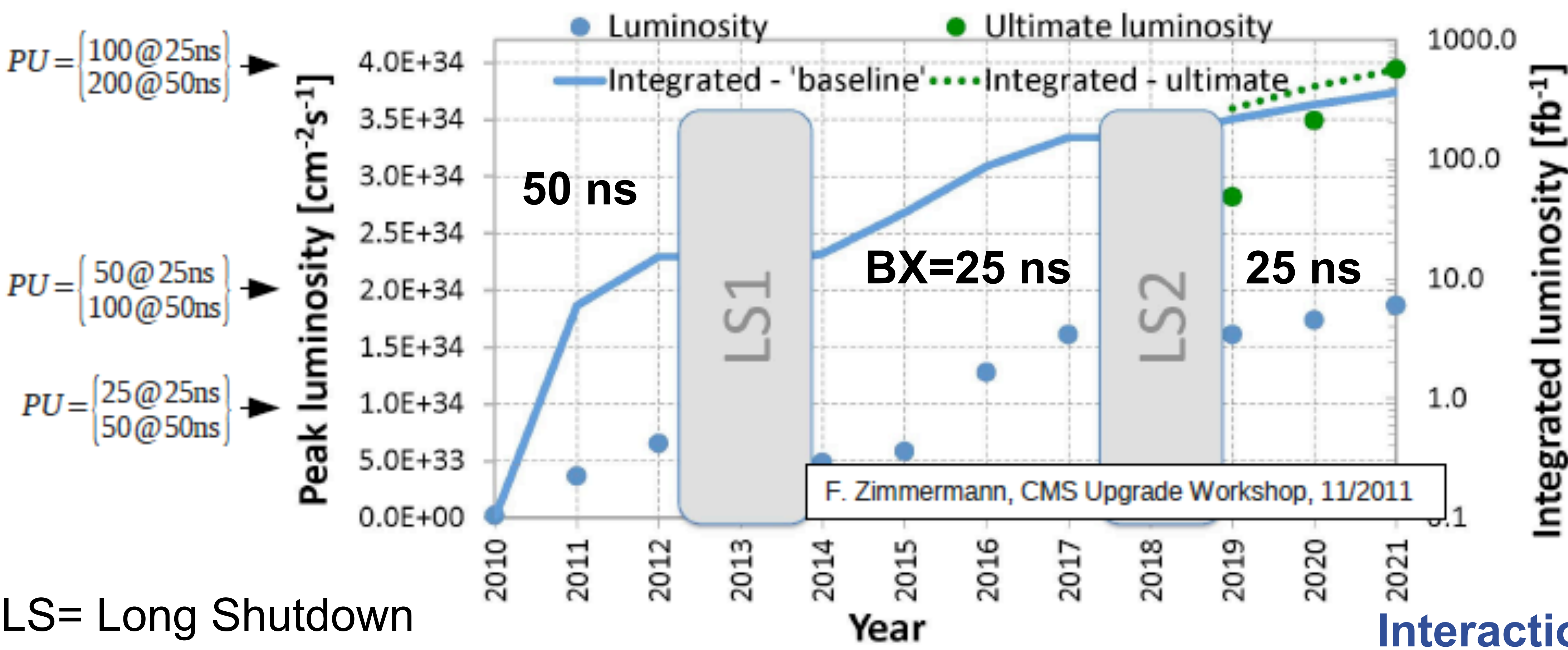
σ/σ_{SM} = 0.80±0.14



The new boson is consistent with being the SM scalar boson

LHC and HL-LHC

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



LS= Long Shutdown

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

Interaction region upgrade

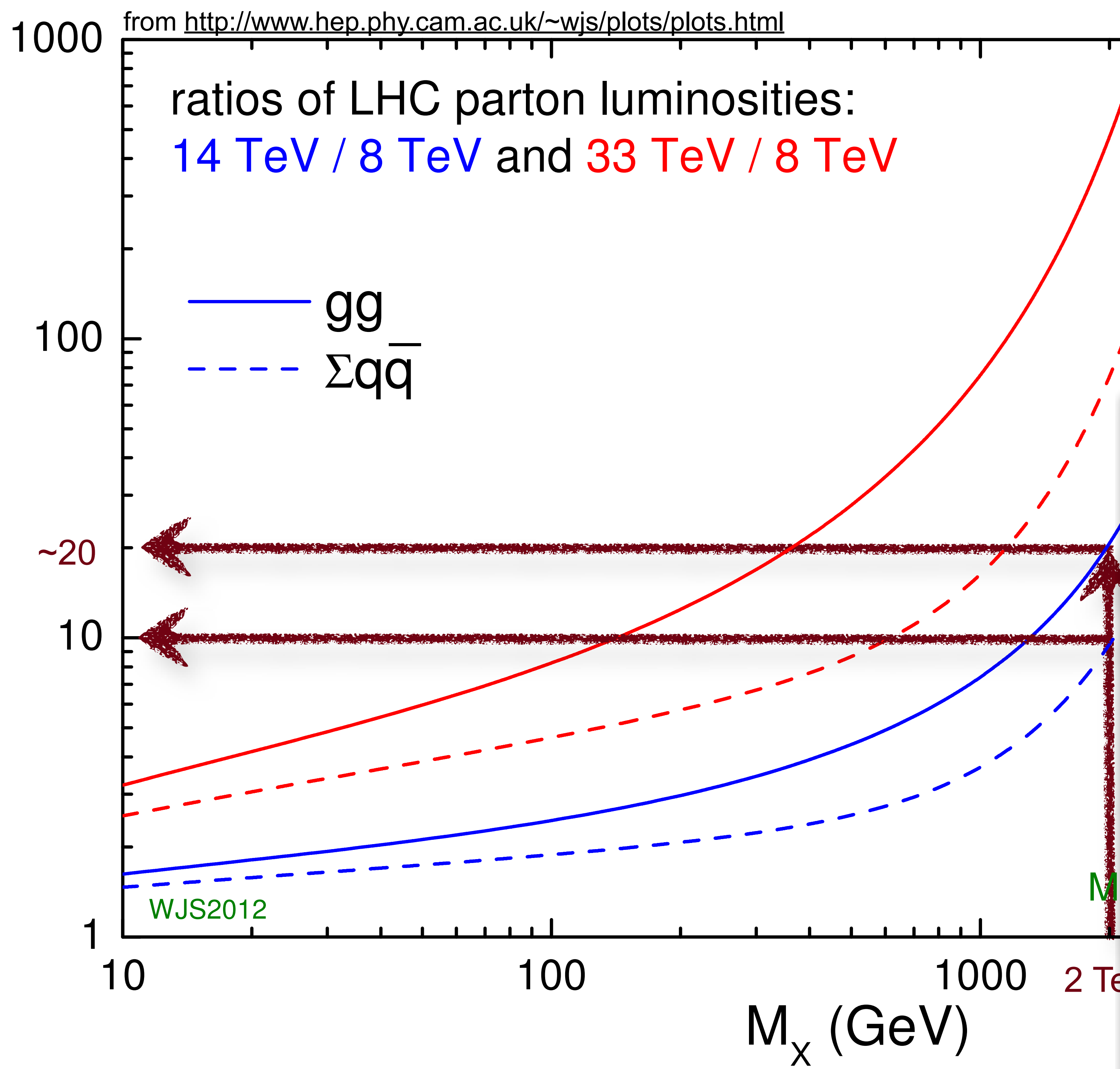
8x10^{33} Hz/cm^2 **30 fb^{-1}** **PU ~40**	LS1	**2x10^{34} Hz/cm^2** **300 fb^{-1}** **PU ~50**	LS3	**5x10^{34} Hz/cm^2** **3000 fb^{-1}** **PU ~140**

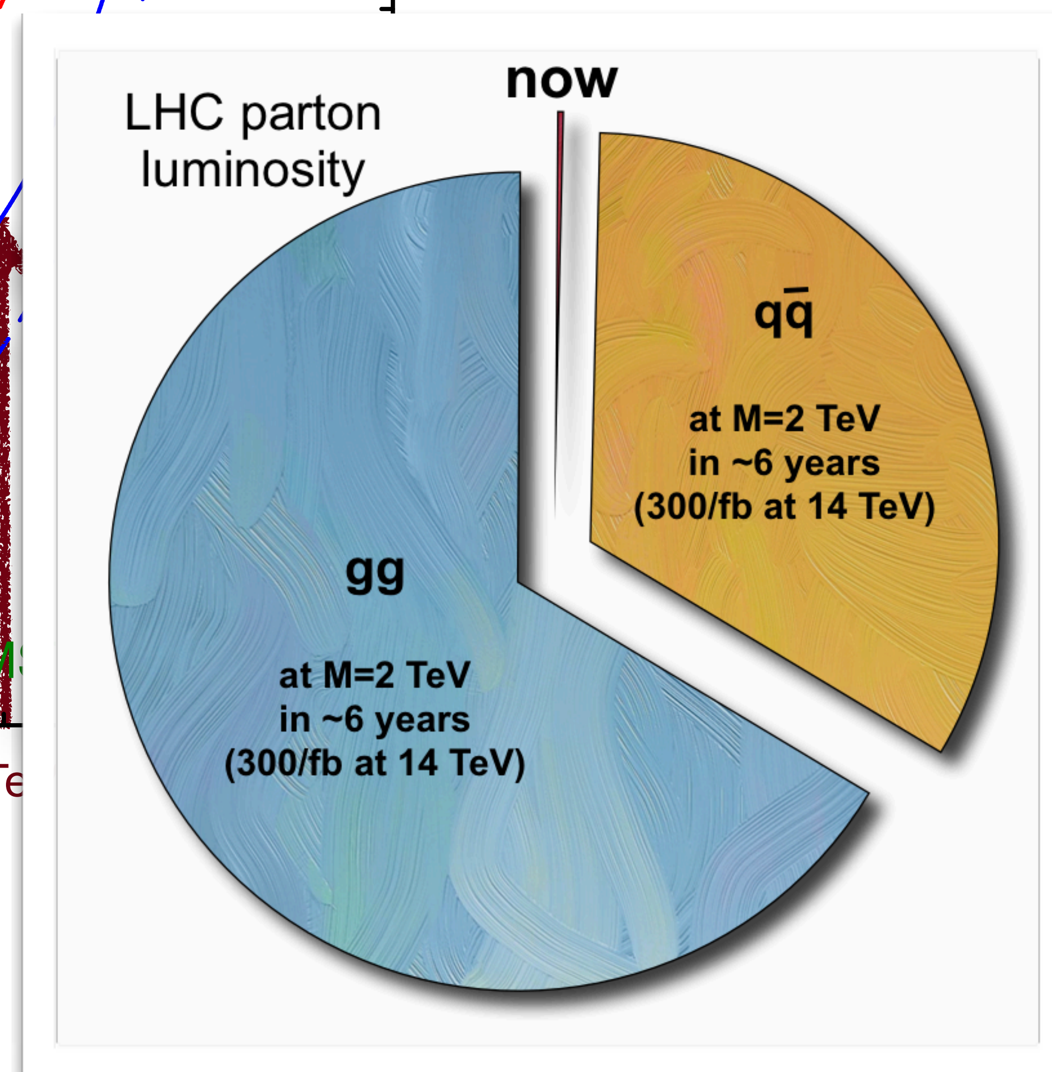
ATLAS, CMS Upgrade plan

Phase 1 Upgrade

Phase 2 Upgrade

LHC after LS1





From G. Dissertori (ETH)

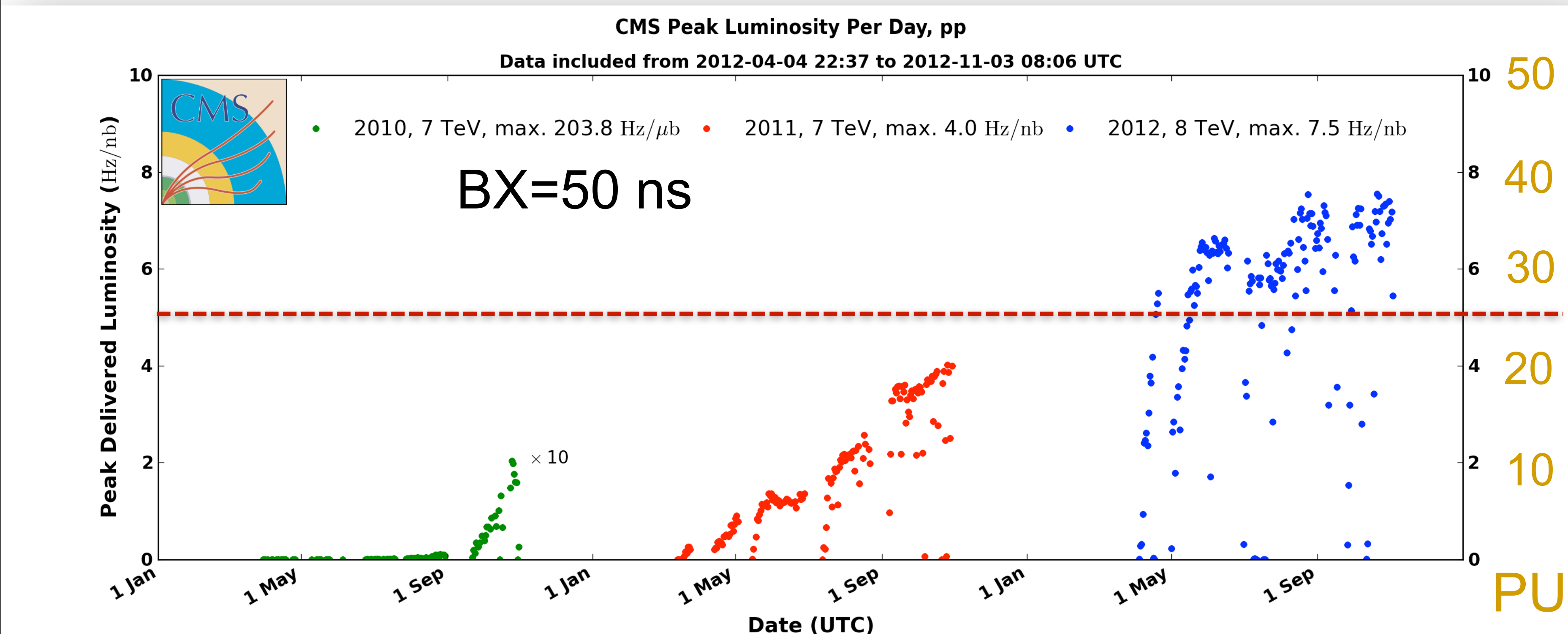
We are about to explore a new territory!

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

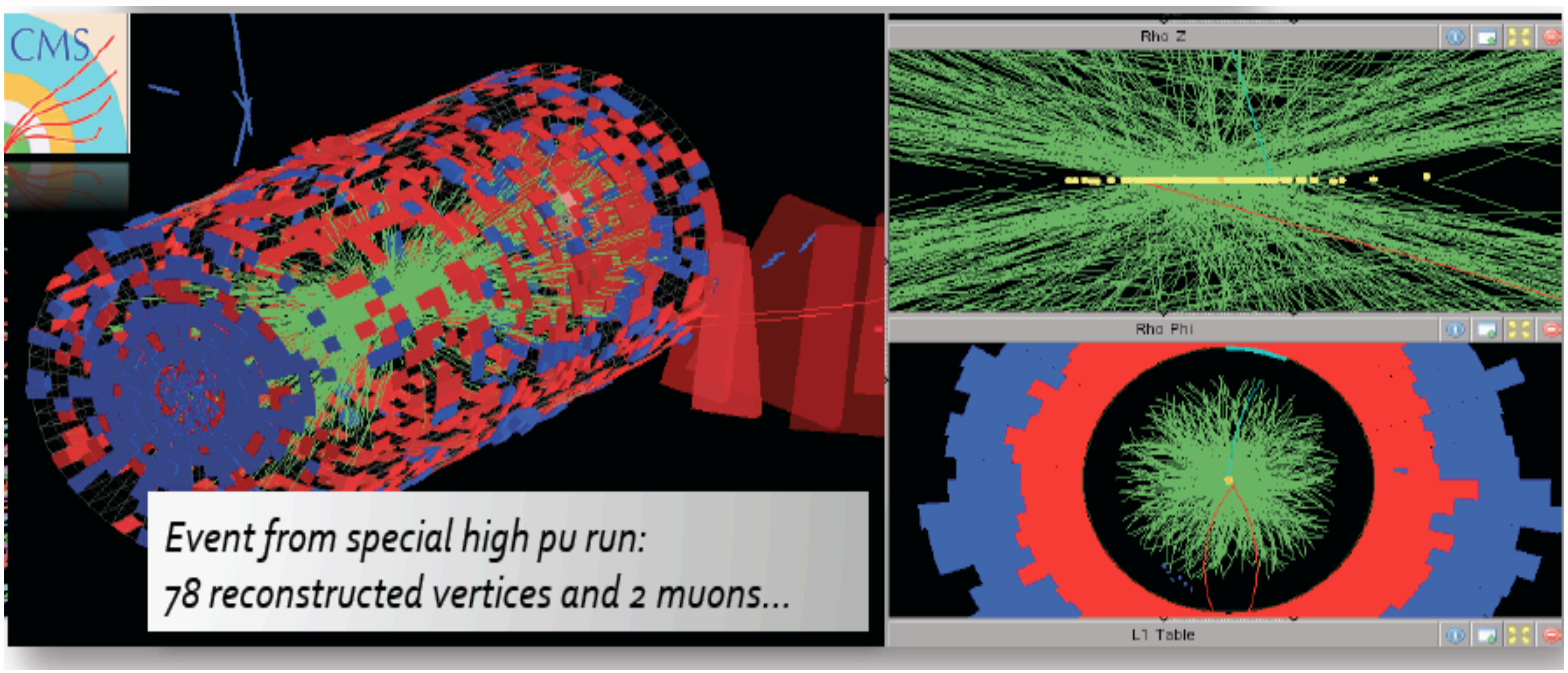
ATLAS and CMS were designed to cope with L= 1-2 $x10^{34}$ $cm^{-2}s^{-1}$

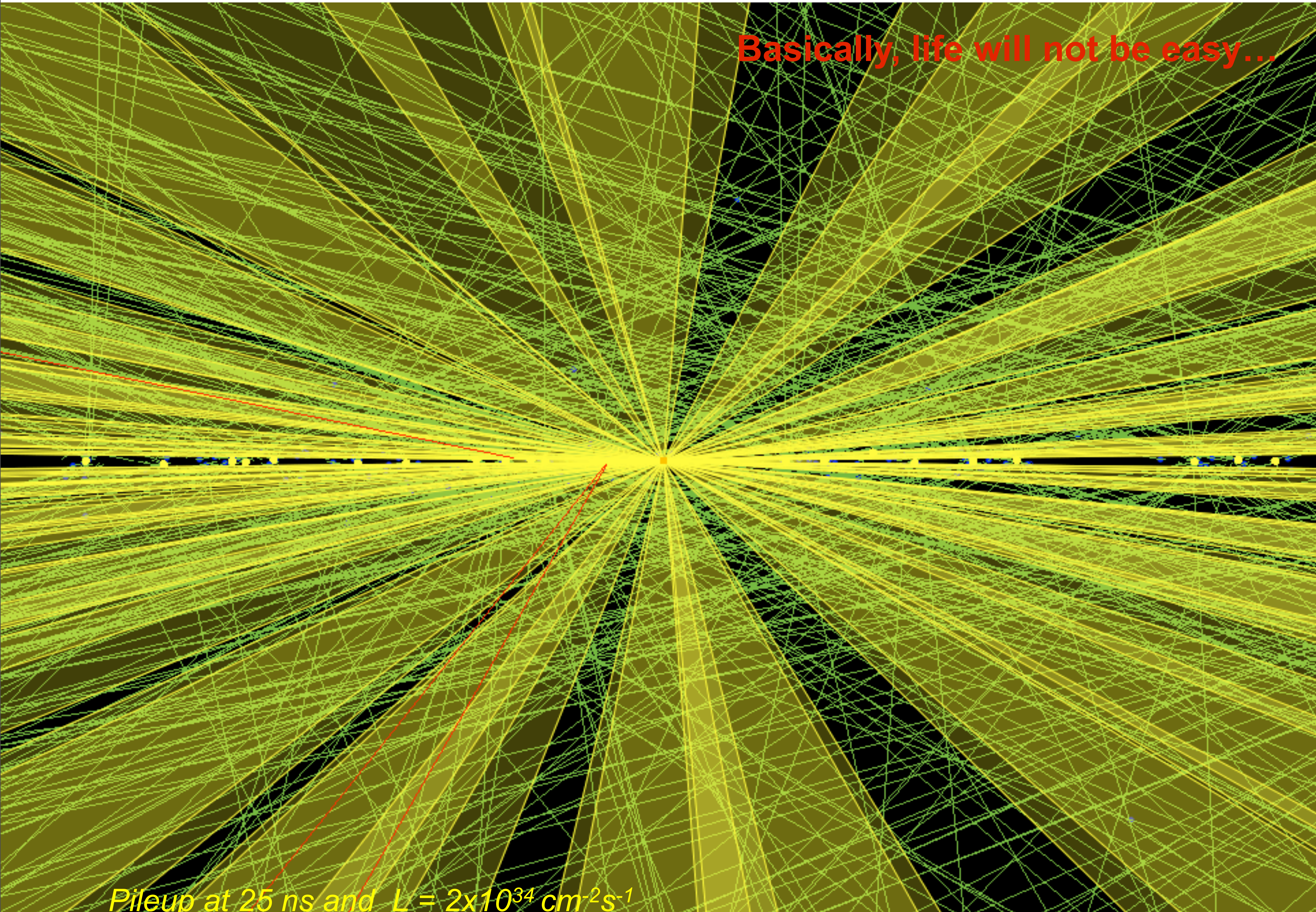
Pileup in 2012



Peak: 37 pileup events

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



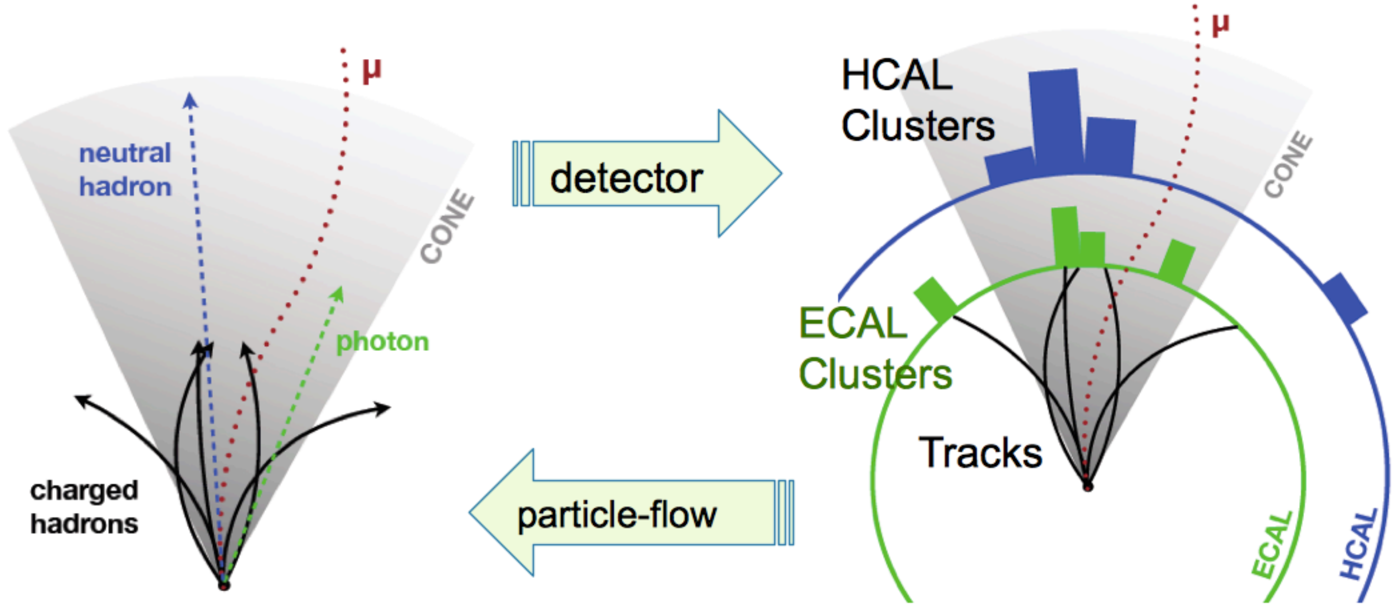

Basically, life will not be easy…
Pileup at 25 ns and L = 2x10^34 cm^-2s^-1

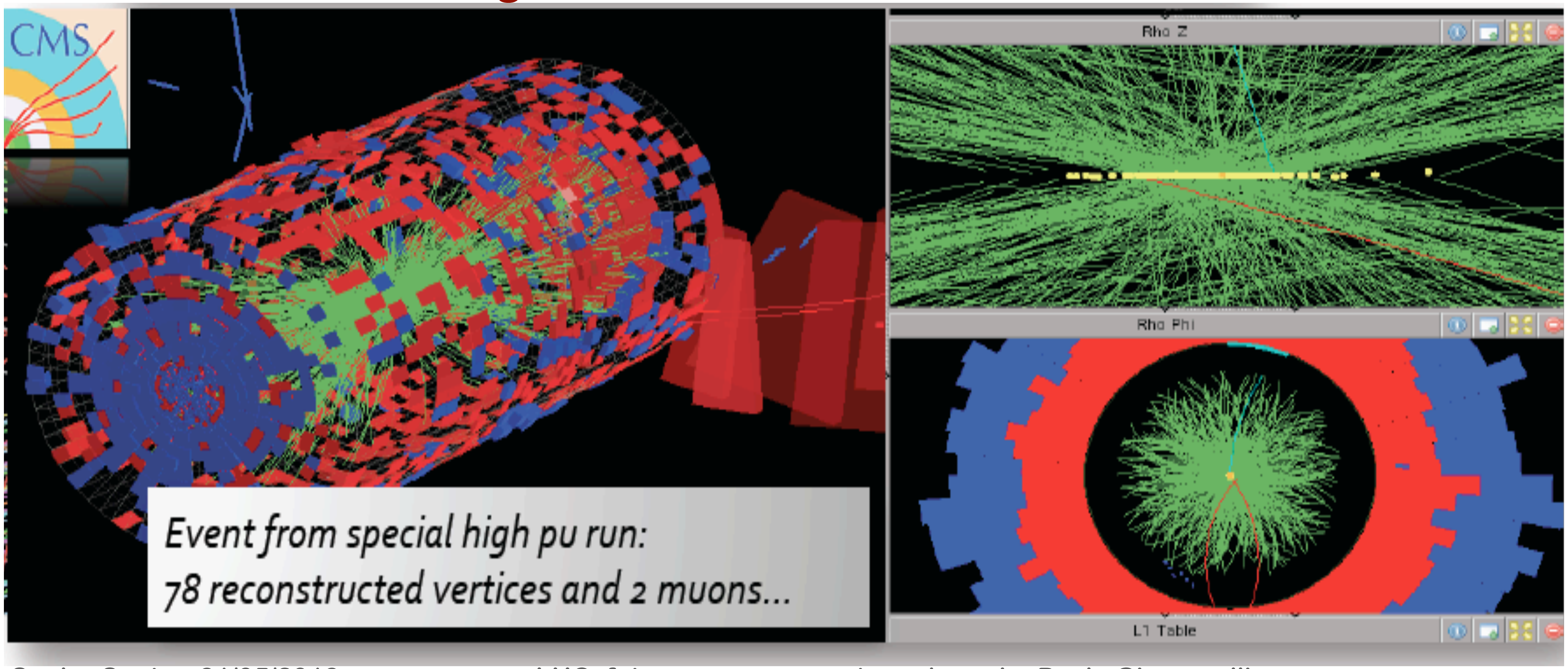
Upgrade challenges and recipe

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

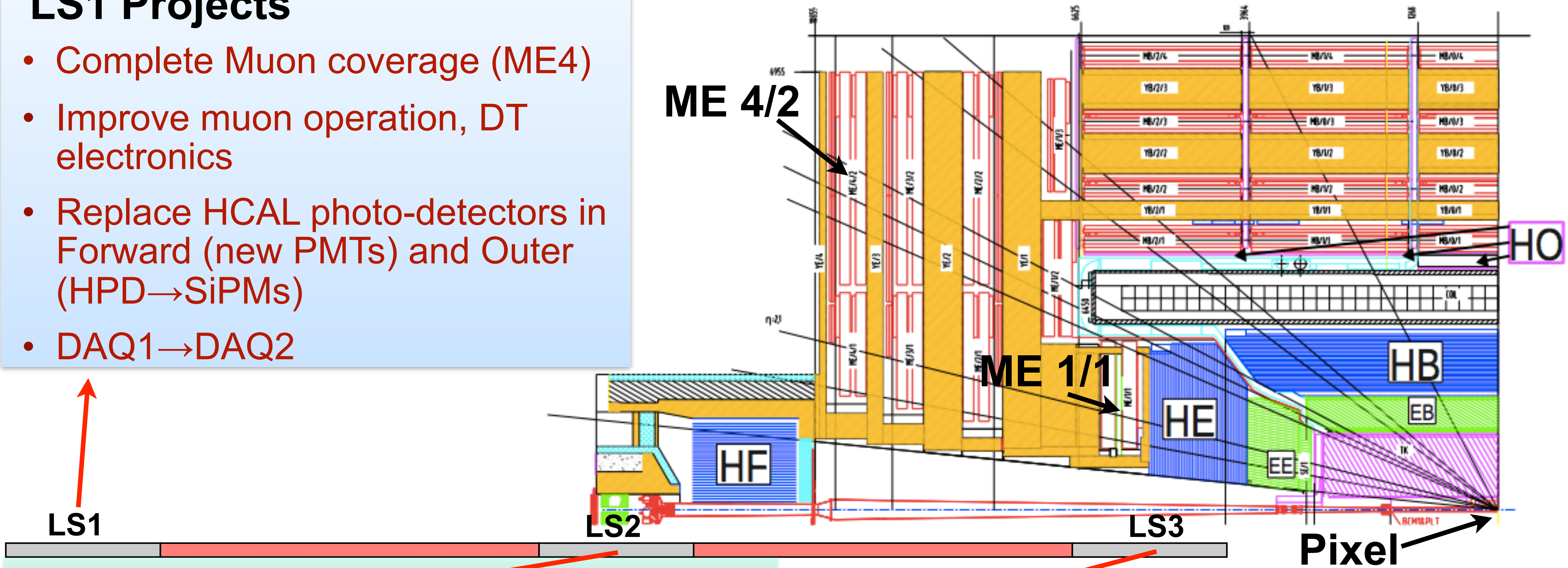
The discovery of a SM-like scalar boson at m_H~125 GeV defines the physics priorities

- 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 scalar 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

CMS upgrade program

LS1 Projects

- Complete Muon coverage (ME4)
- Improve muon operation, DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD→SiPMs)
- DAQ1→DAQ2



Phase 1 Upgrades

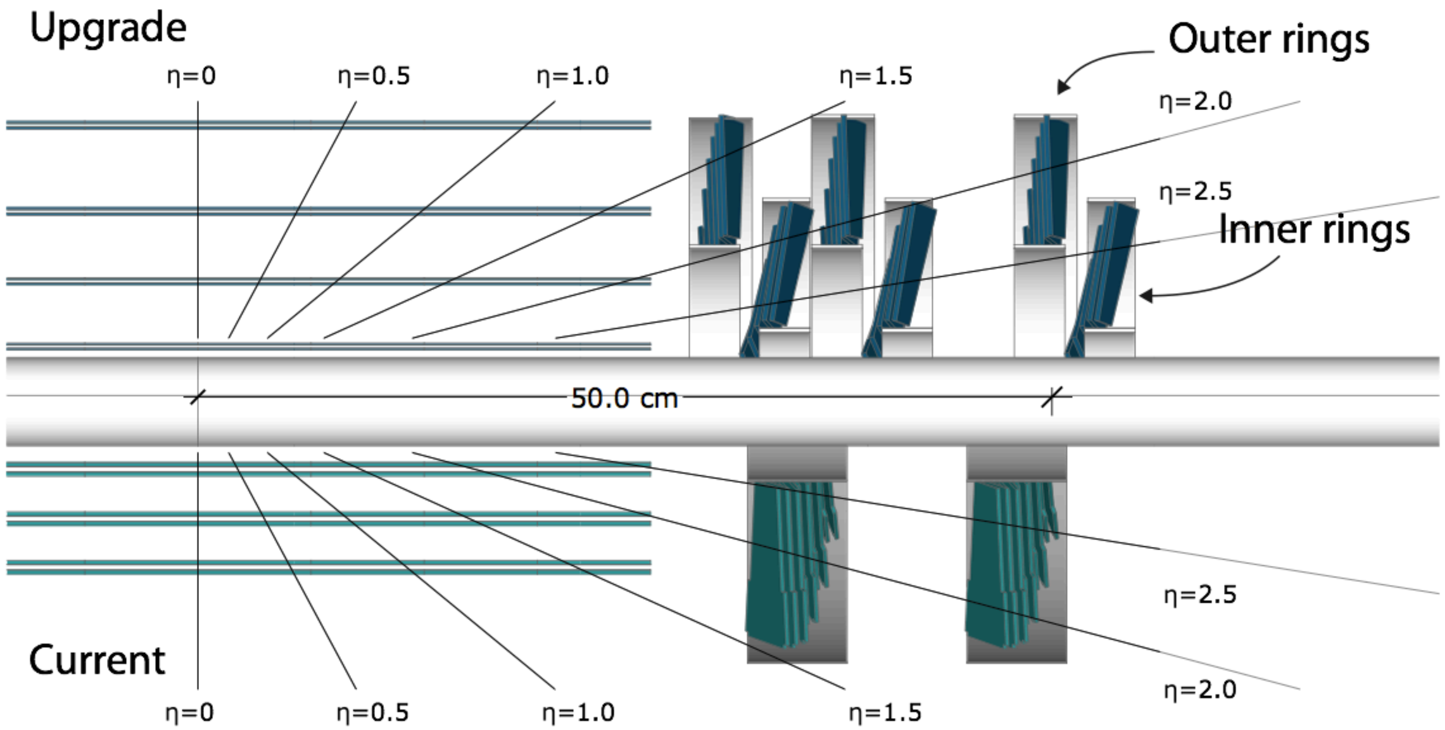
- New Pixel detector, HCAL electronics and L1-Trigger upgrade
- GEMs for forward muon det. under review
- Preparatory work during LS1
  - New beam pipe for pixel upgrade
  - Install test slices of pixel, HCAL, L1-trigger
  - Install ECAL optical splitters for L1-trigger

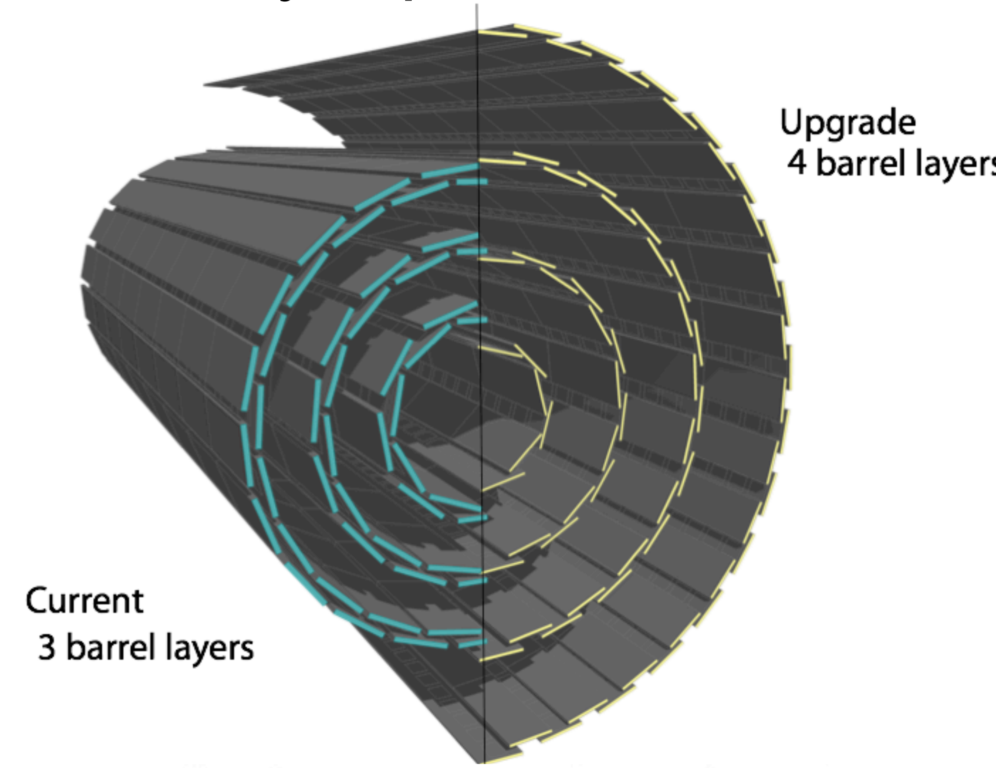
Phase 2: being defined now

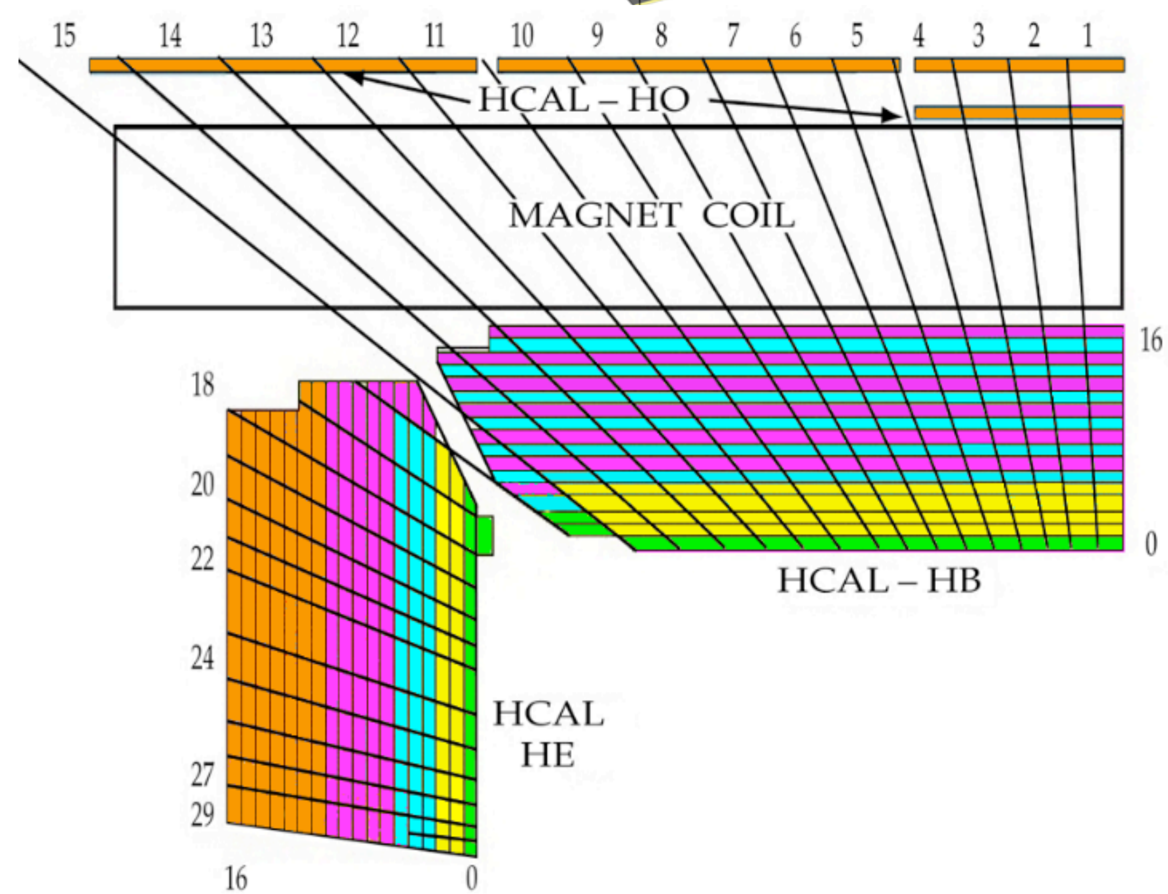
- Tracker replacement, L1 Track-Trigger
- Forward: calorimetry, muons and tracking
- High precision timing for PU mitigation
- Further Trigger upgrade
- Further DAQ upgrade

Pixel and HCAL phase 1 upgrades

New 4-layer pixel detector Pixel

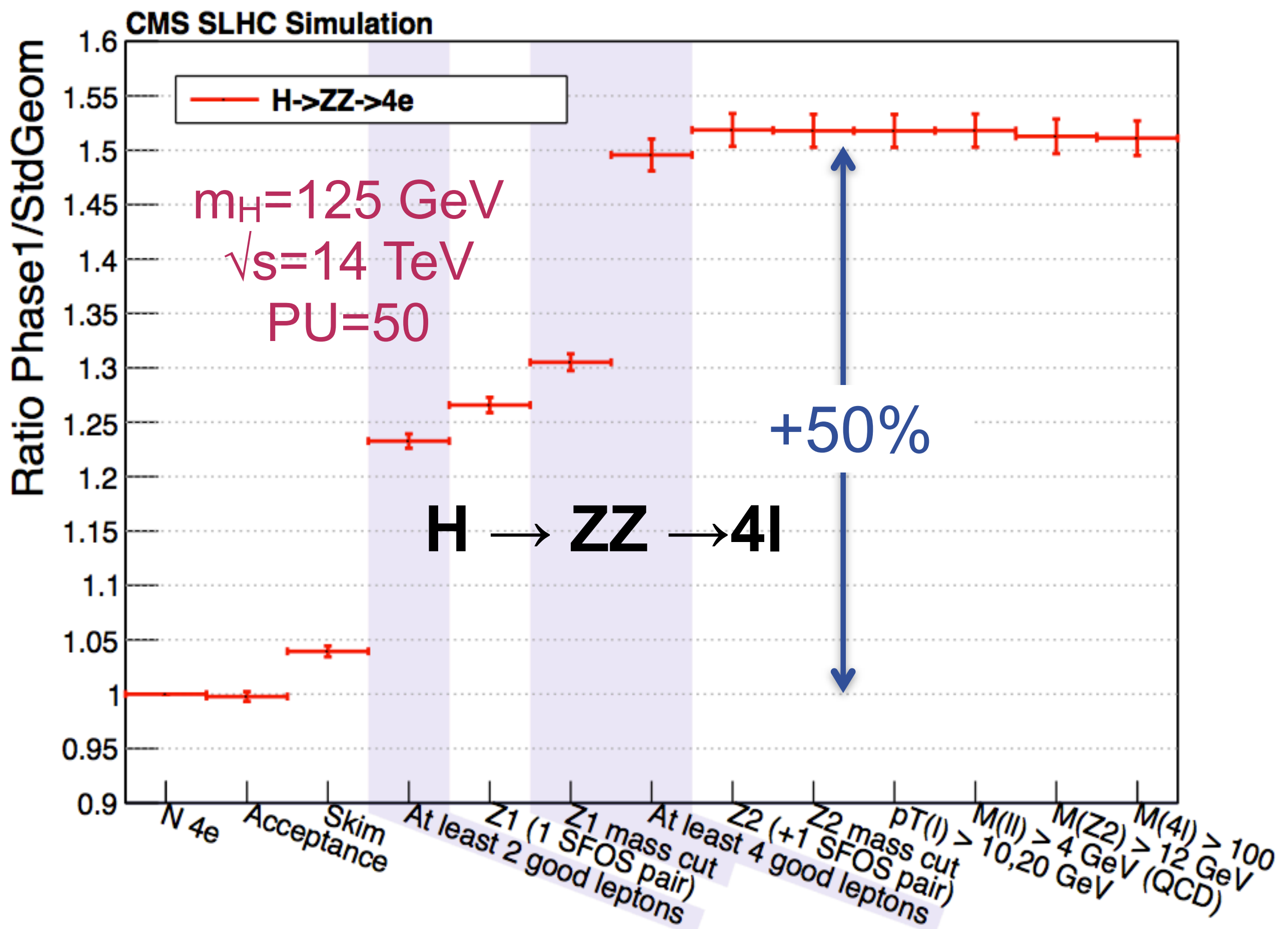


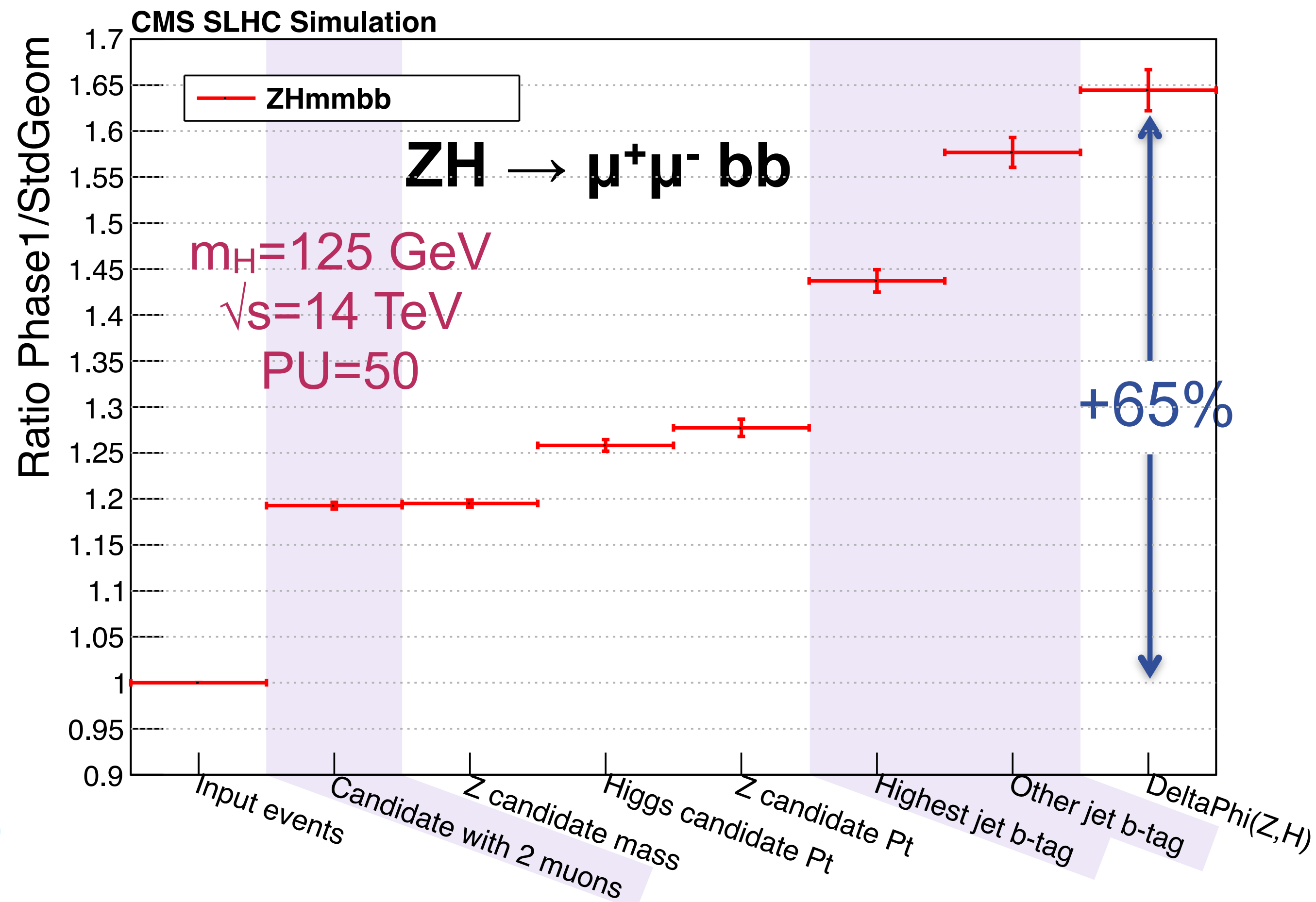




- Upgraded HCAL
  - New photodetectors
  - New electronics (frontend, backend)
  - Improved longitudinal segmentation
  - Improved background rejection, Missing E_T resolution and Particle Flow reconstruction

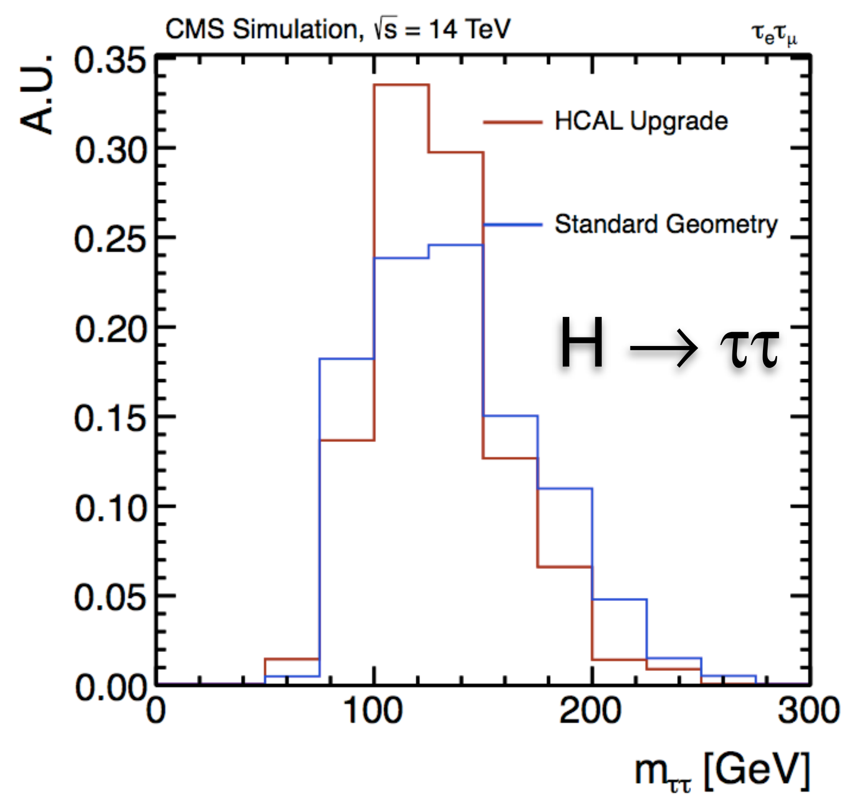
Expected Phase 1 improvements





Significant gain in signal reconstruction efficiency:

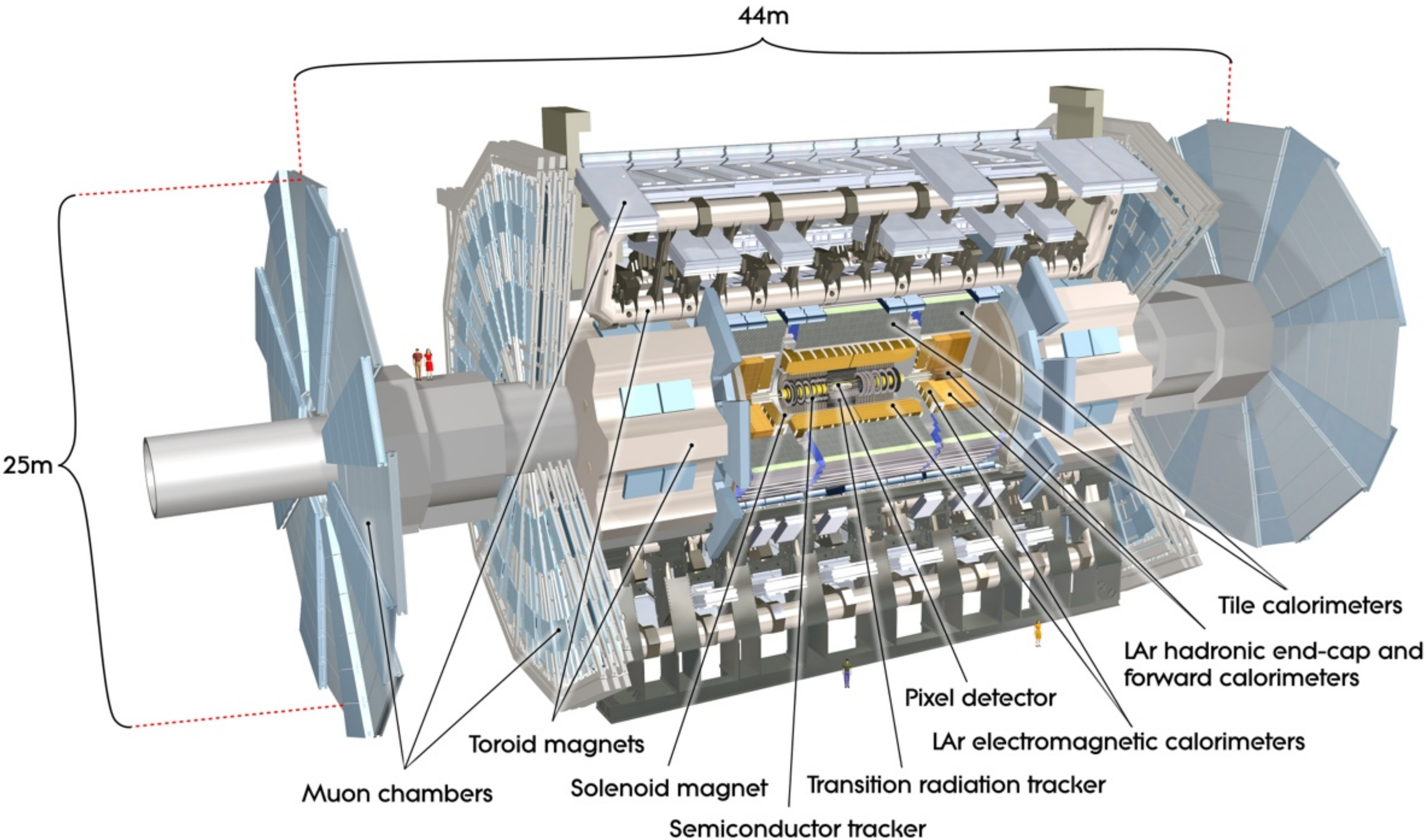
H→ 4μ	+41%
H→ 2μ2e	+48%
H→ 4e	+51%



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

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

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

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

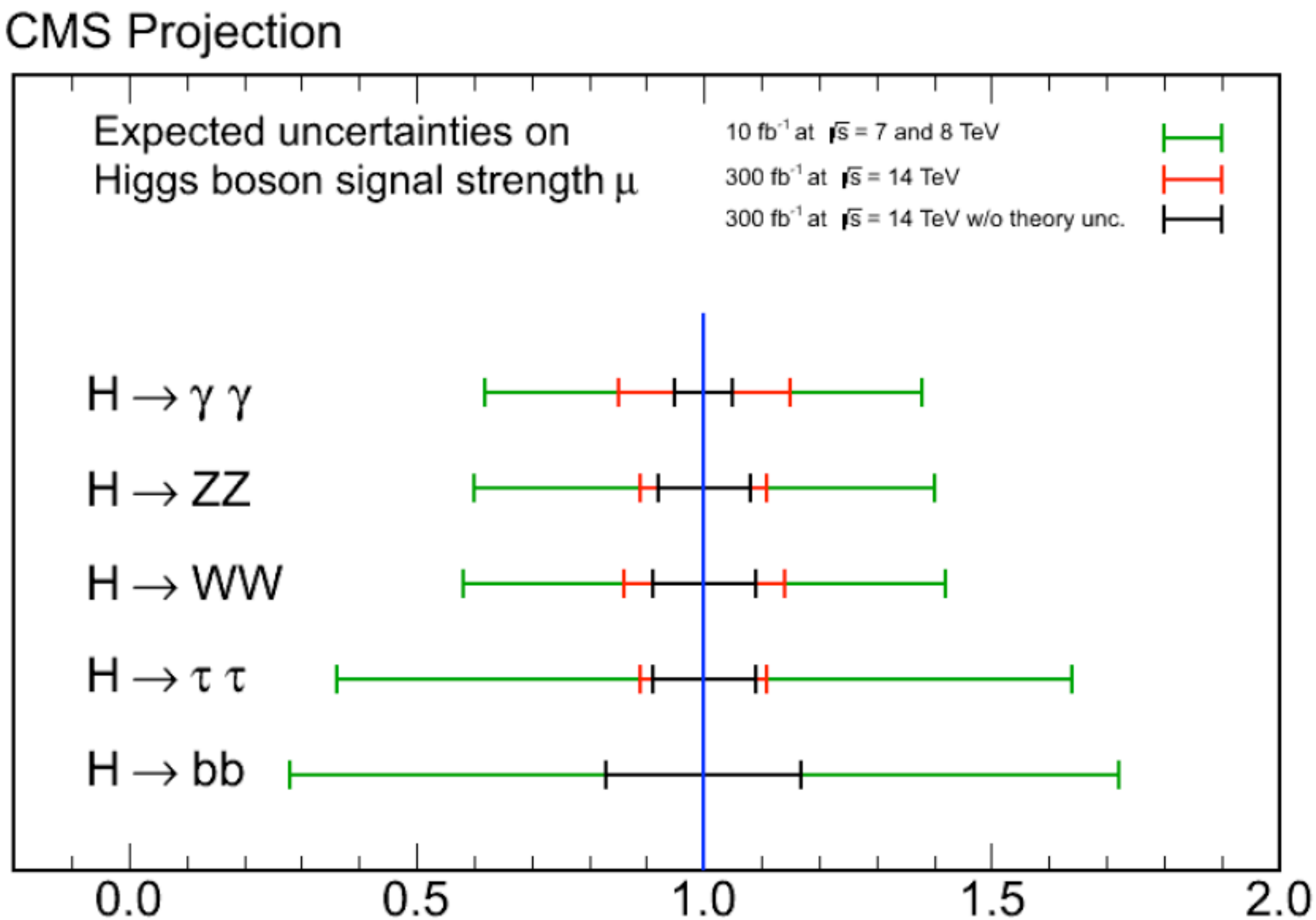
Scalar boson projections after LS1

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

Scalar boson signal with 300 fb^{-1}

- Upgraded detector performances assumed the same as 2012 detector
- Three scenarios:
  - Scenario 1: same systematics as in 2012
  - Scenario 2: theory systematics scaled by a factor ½, other systematics scaled by $1/\sqrt{L}$
  - Scenario 3: same exp. syst. as in 2012, w/o theory uncertainty

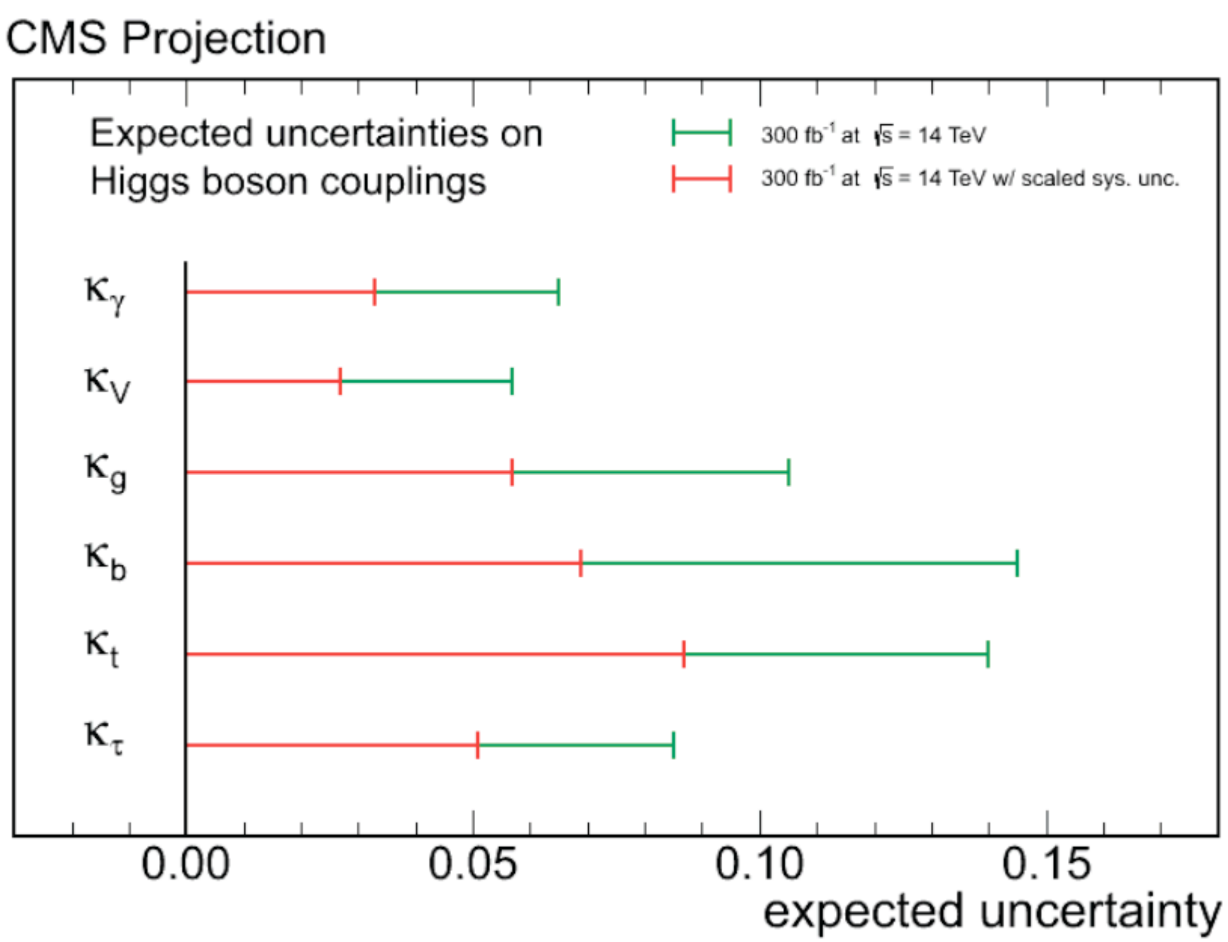


10 fb^{-1}, 7 and 8 TeV (Scenario 1)
300 fb^{-1} , 14TeV (Scenario 1)
300 fb^{-1} , 14TeV (Scenario 3)

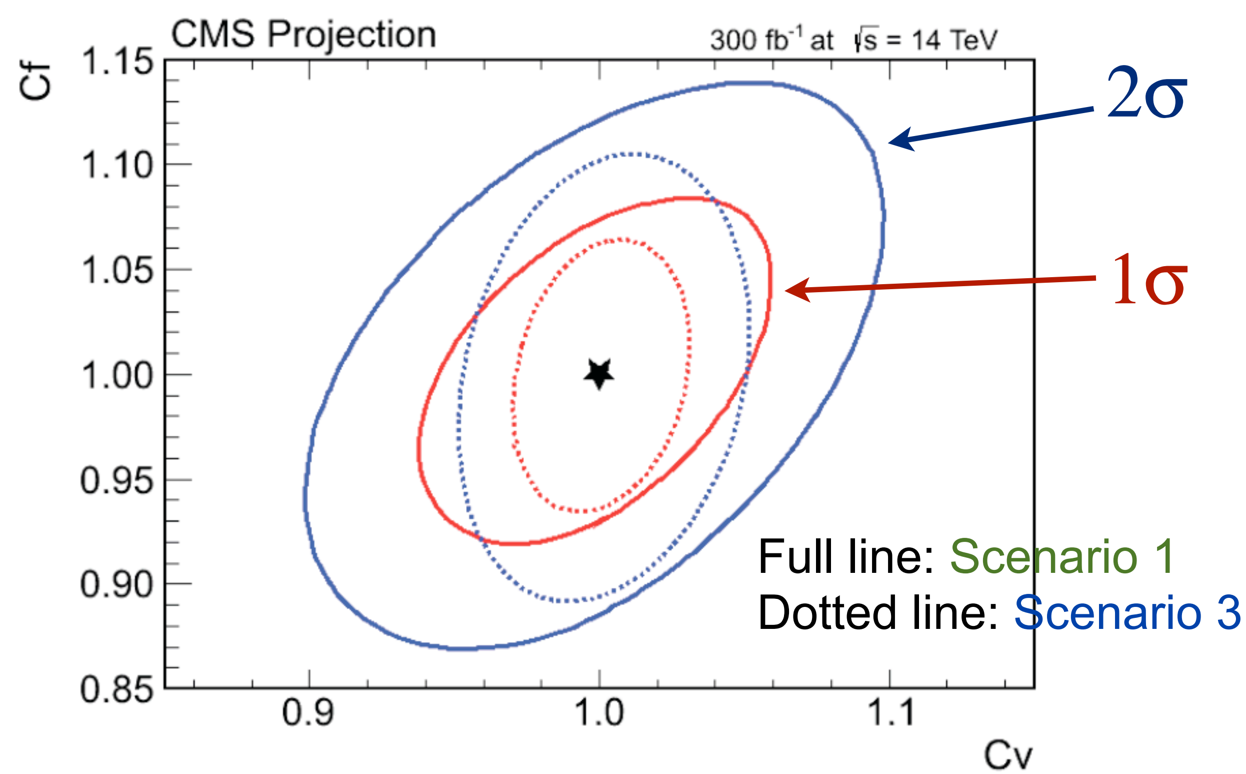
With 300 fb^{-1} the precision on the signal strength is expected to be 10-15% per channel

Scalar boson couplings @300 fb^{-1}

- Three scenarios:
  - Scenario 1: same systematics as in 2012
  - Scenario 2: theory systematics scaled by a factor ½, other systematics scaled by $1/\sqrt{L}$
  - Scenario 3: same exp. syst. as in 2012, w/o theory uncertainty

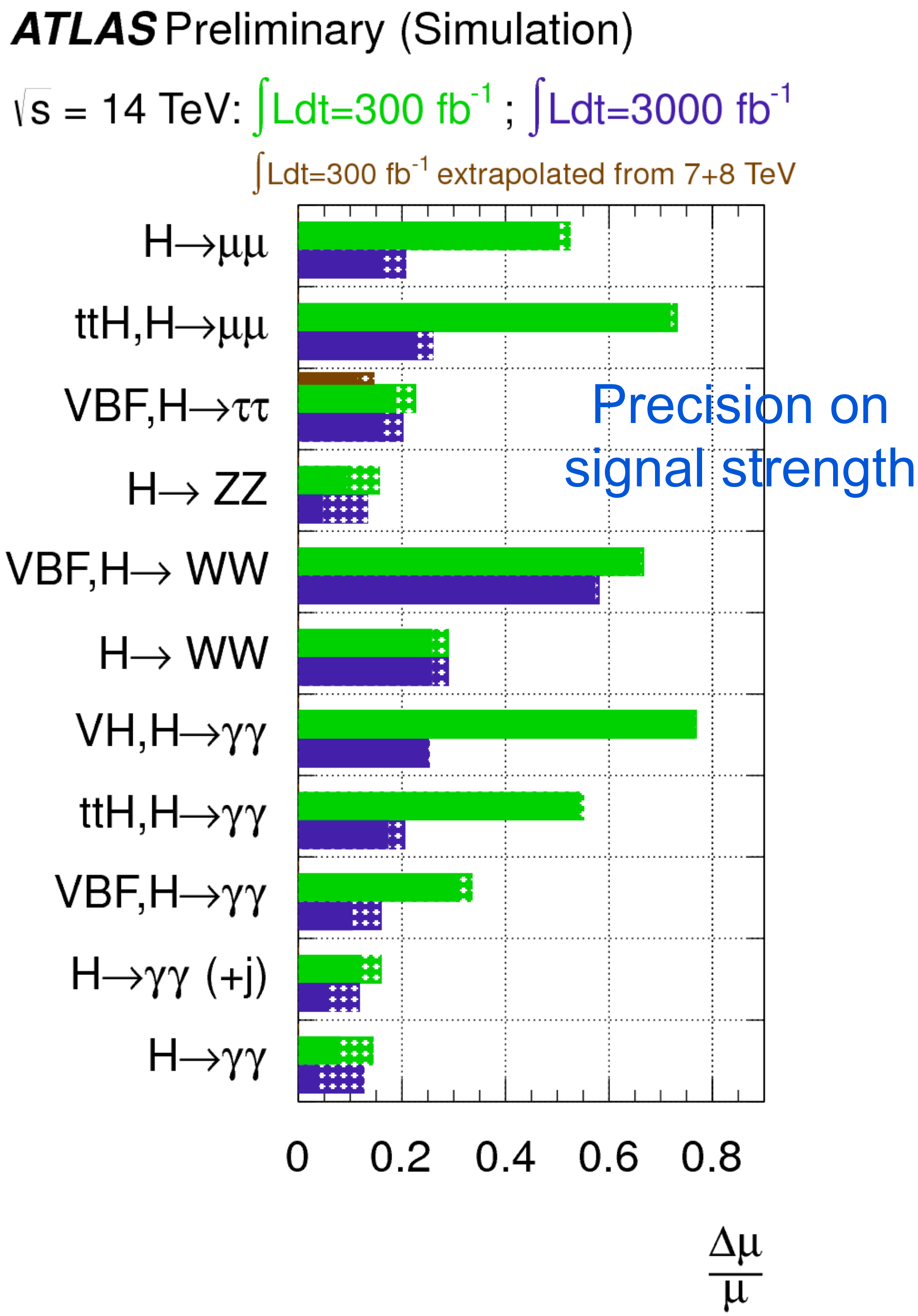


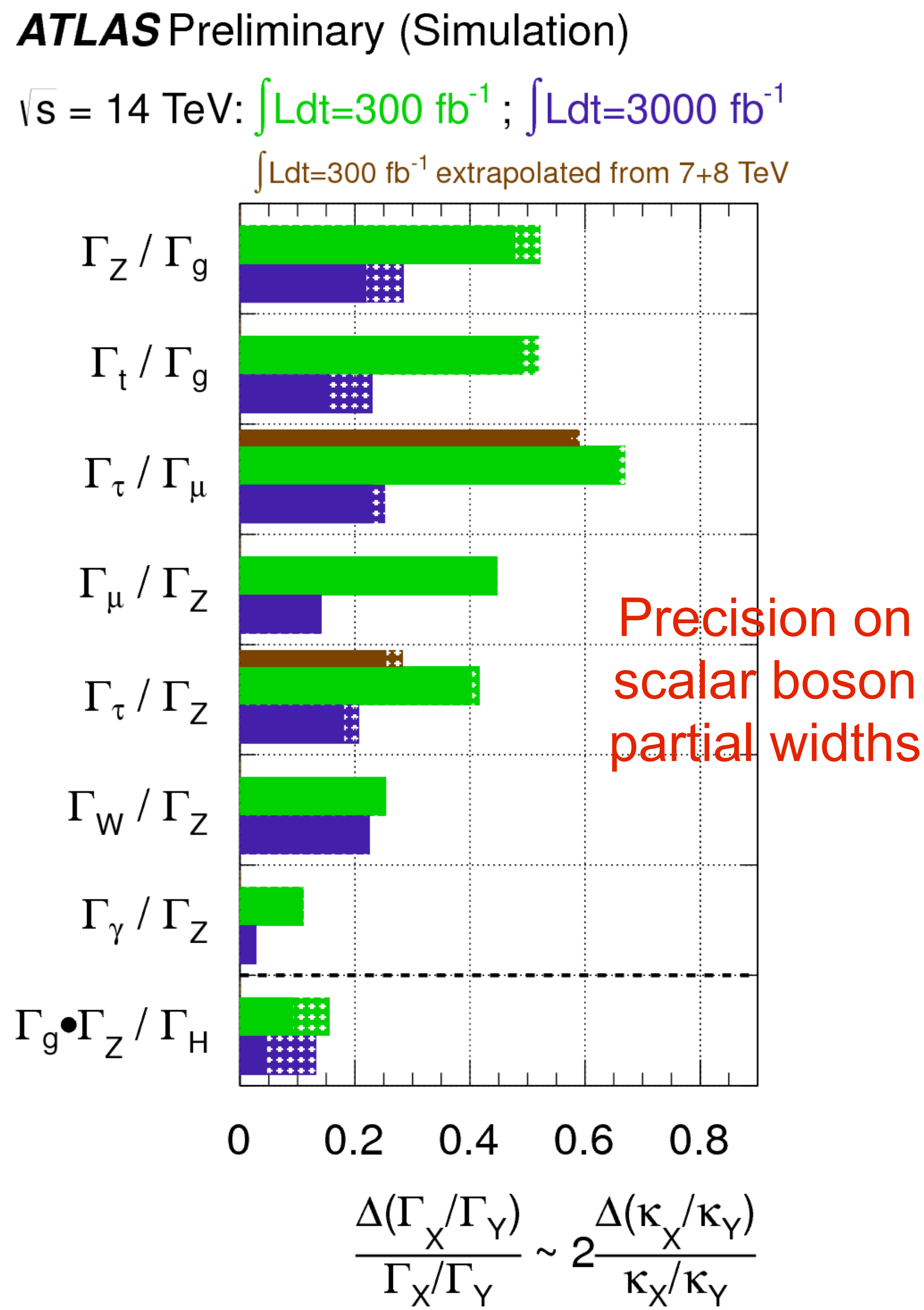
300 fb^{-1} 14 TeV, Scenario 1
300 fb^{-1} 14 TeV, Scenario 2



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%

Scalar boson couplings @3000 fb^{-1}





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

HL-LHC boson couplings @3000 fb^{-1}

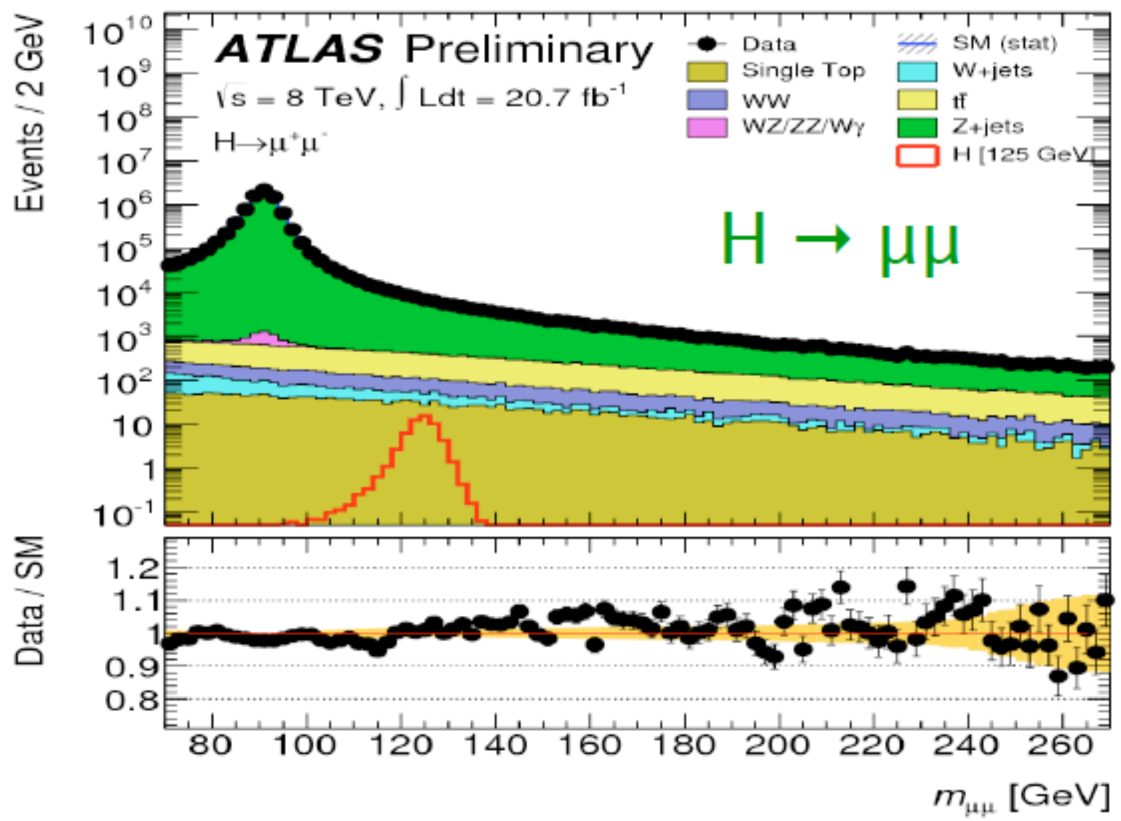
- Extrapolation by two orders of magnitude to higher luminosity
  - is subject to large uncertainties
  - scenarios 1 and 2 provide likely upper and lower bounds
- Experience at LEP and Tevatron indicates that scaling with $1/\sqrt{L}$ is not unrealistic

- With 3000 fb^{-1} the Higgs couplings can be determined with high precision (1-4%)

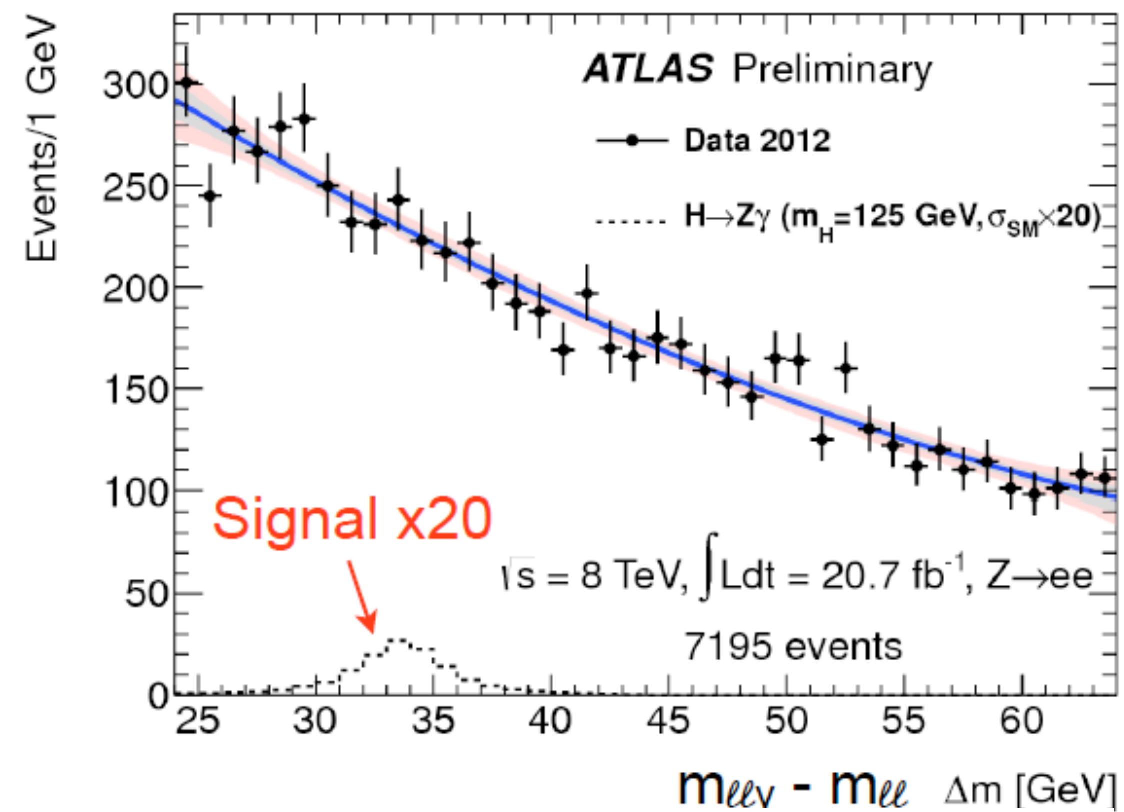
CMS Coupling	Uncertainty (%) 3000 fb^{-1} Scenario 1	Uncertainty (%) 3000 fb^{-1} Scenario 2
κ_γ	5.4	1.5
κ_V	4.5	1.0
κ_g	7.5	2.7
κ_b	11	2.7
κ_t	8.0	3.9
κ_τ	5.4	2.0

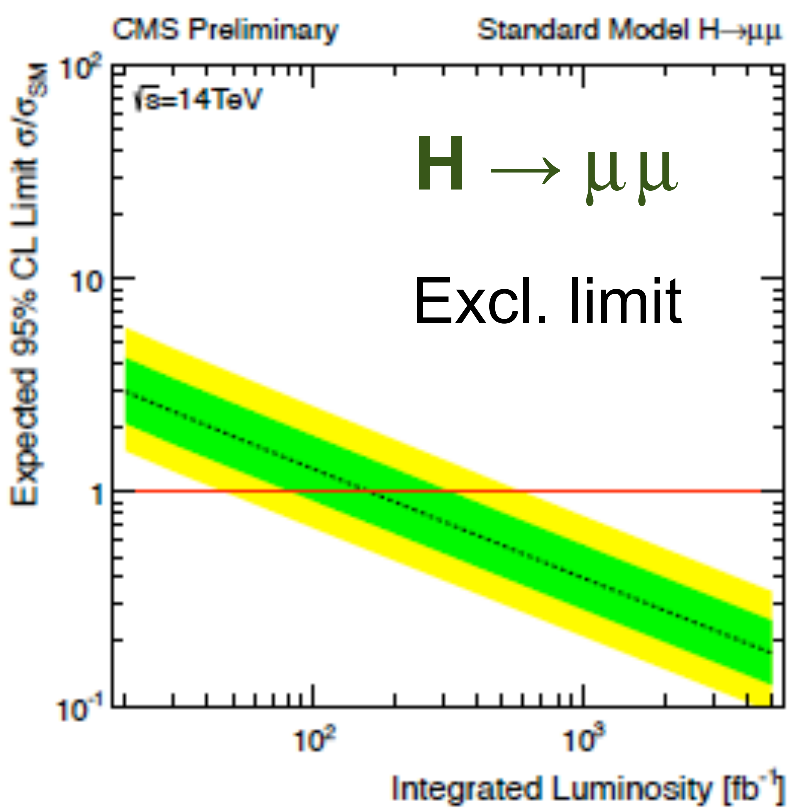
Scenario 1: systematics as in 2012
Scenario 2: theory syst. scaled by a factor ½, other systematics scaled by $1/\sqrt{L}$

Rare decays

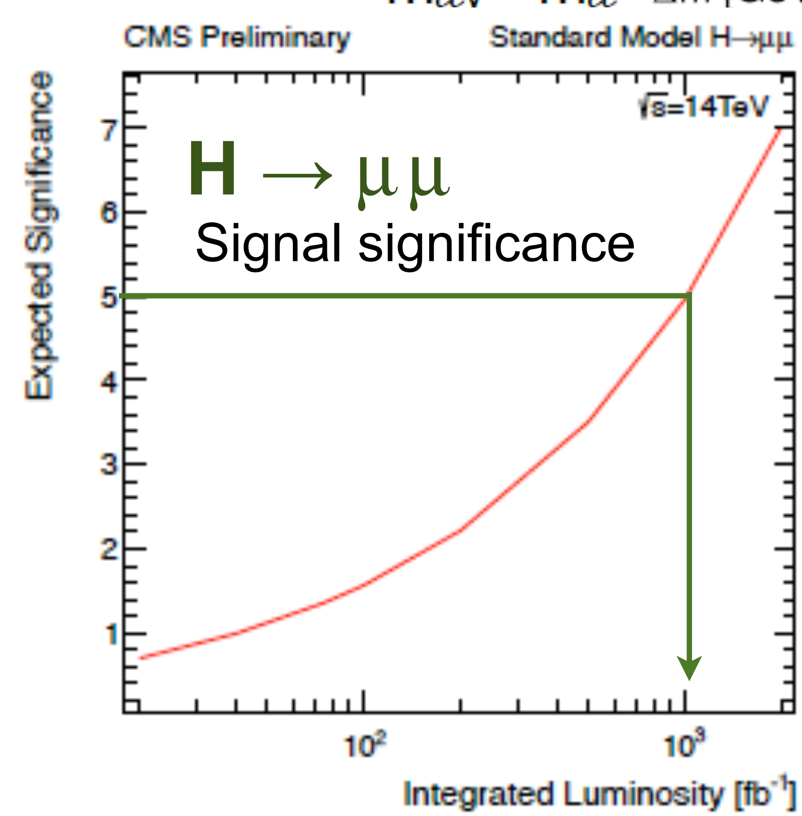


H → Z(ee)γ



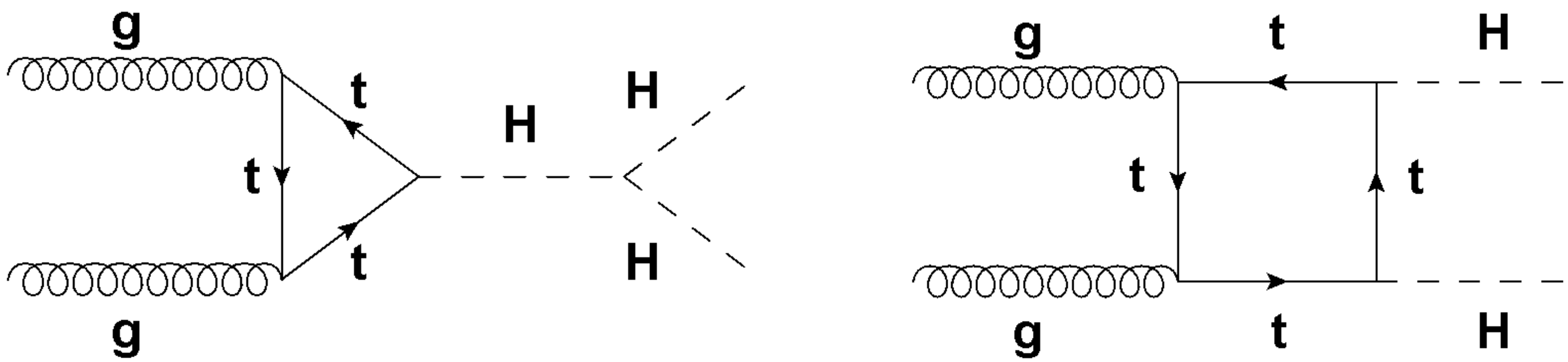


- The decay H→μμ can be observed with a significance of 5 sigma
  - measurement of the Hμμ coupling with a precision of ~10%



Scalar boson self-coupling

Destructive interference between the two diagrams



Many channels to investigate. Most promising ones:

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

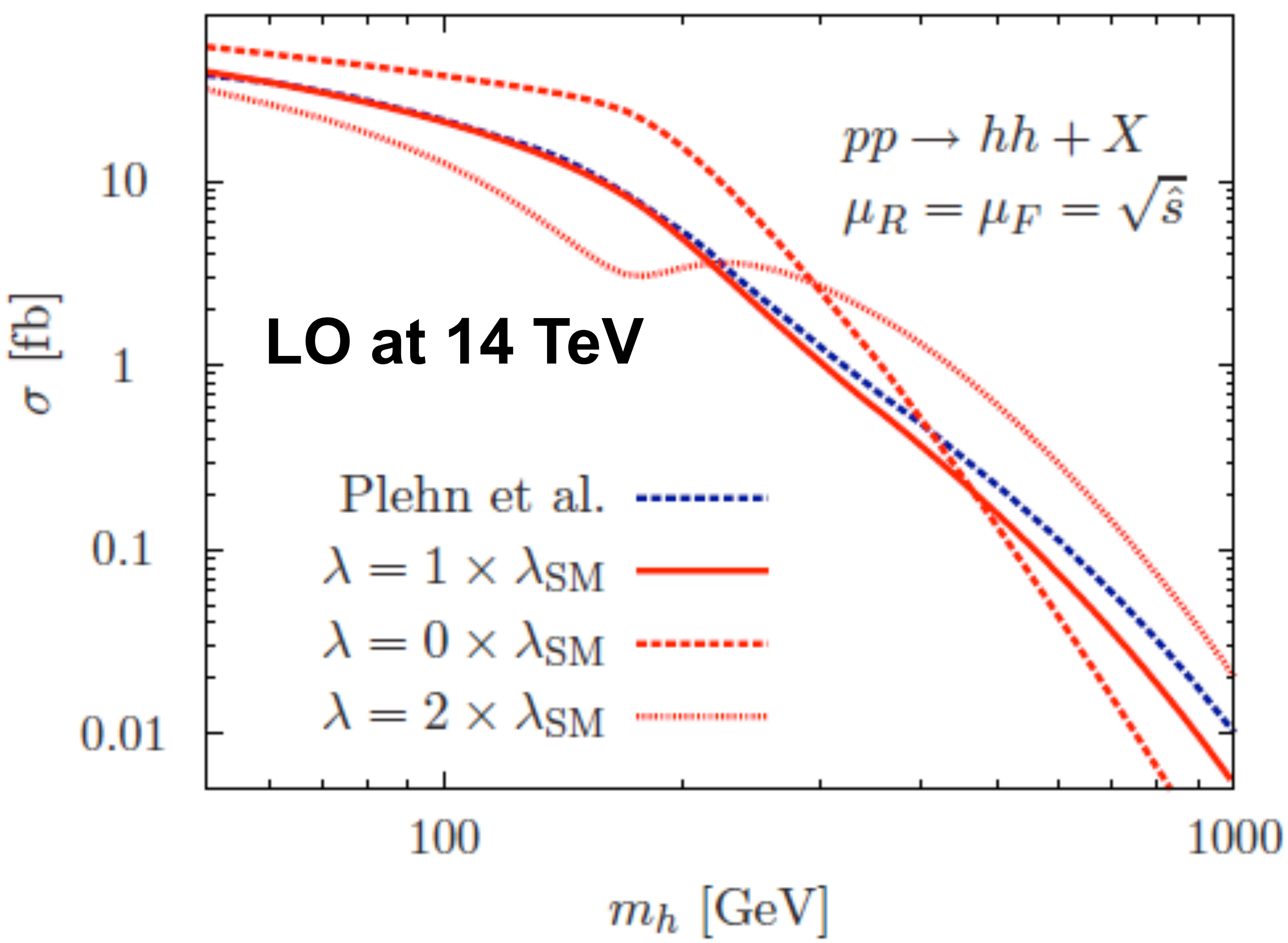
$b\bar{b}\gamma\gamma$ (clean but small BR)

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

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

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

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

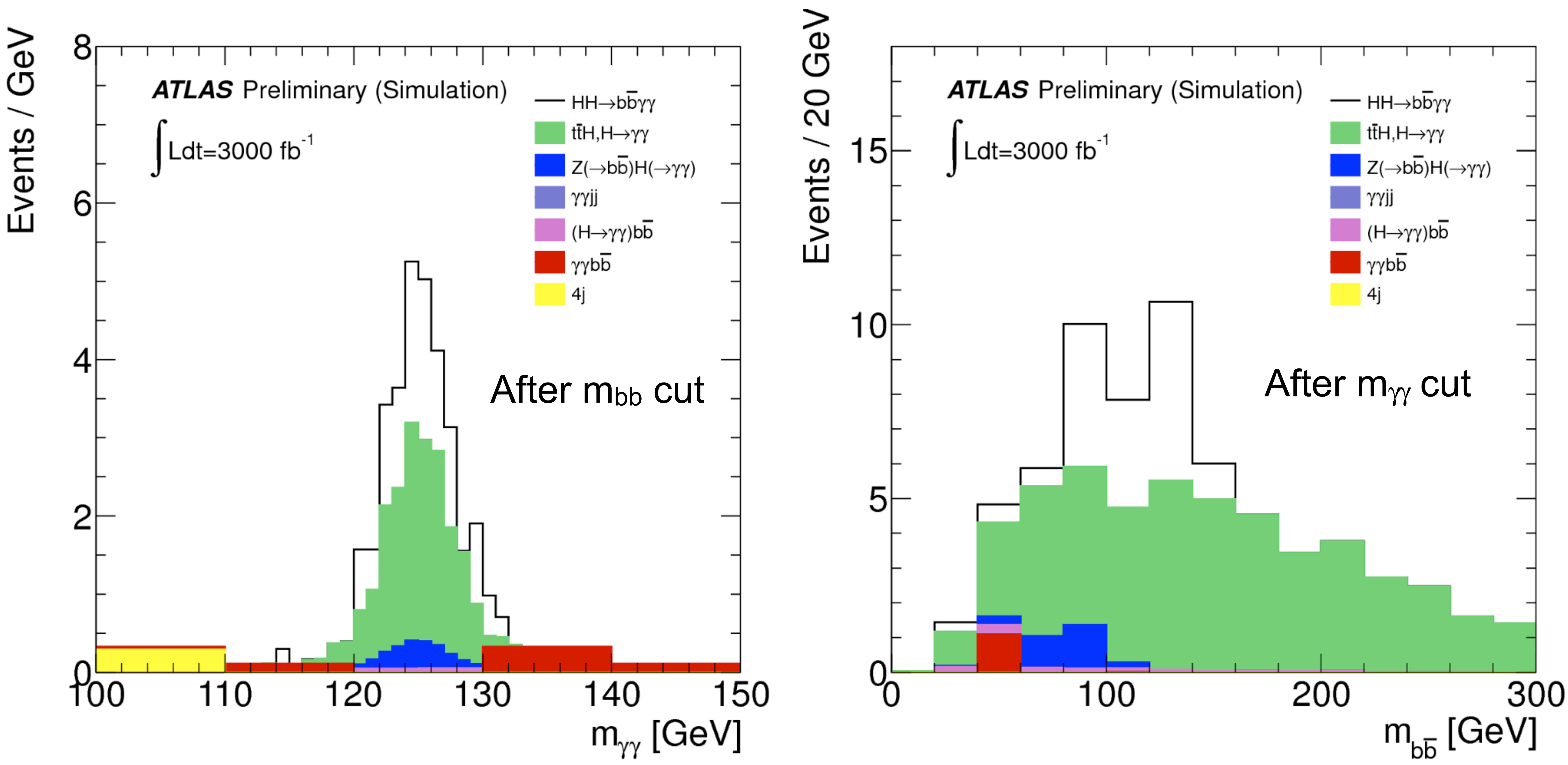


NLO cross-section at m_H=125 GeV:

σ = 34 fb$^{+18\%}_{-15\%}$ (QCD scale) ± 7% (PDF+α_s) ± 10% (EFT)

Self-coupling

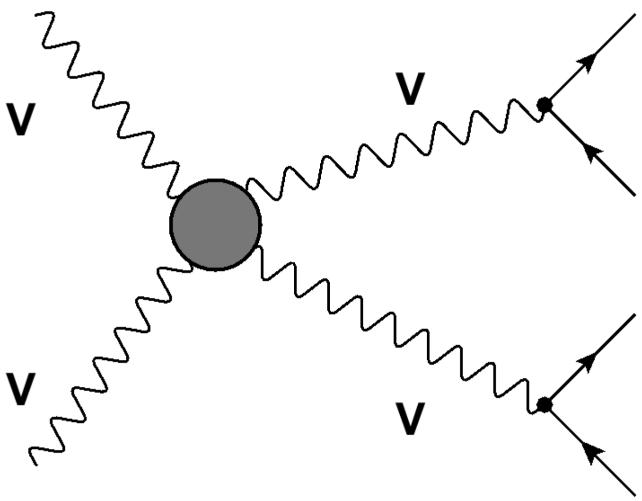
$HH \to b\bar{b}\gamma\gamma$

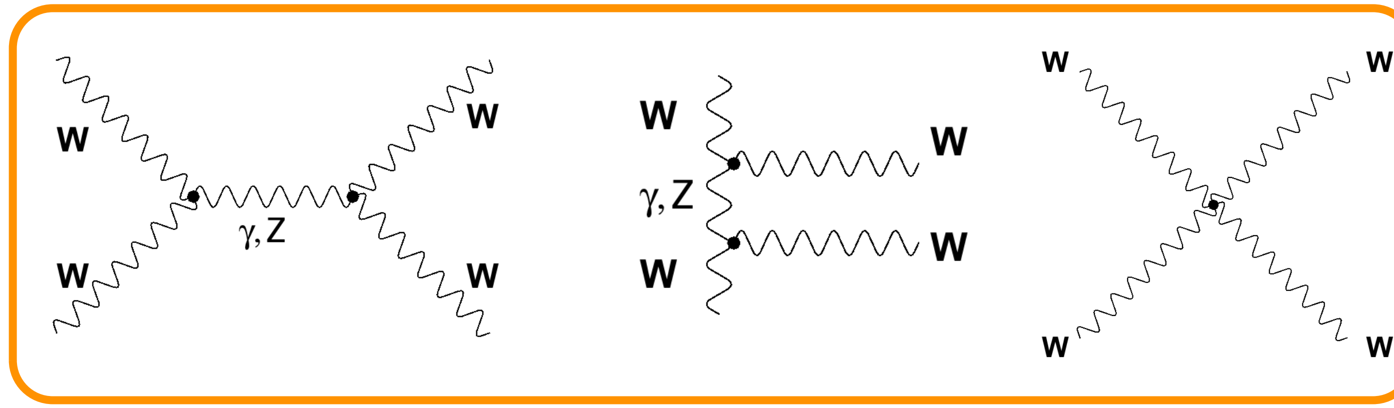


A sensitivity of 3σ per experiment is within reach with L=3000 fb^{-1}

VV scattering: unitarity violation

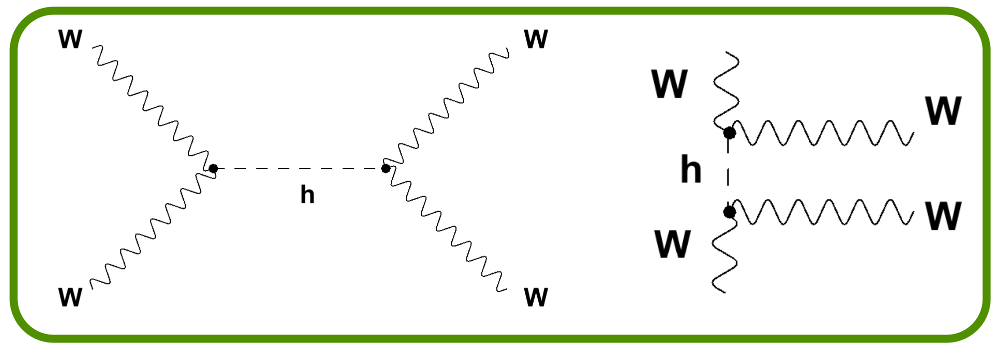
VV→VV





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:

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

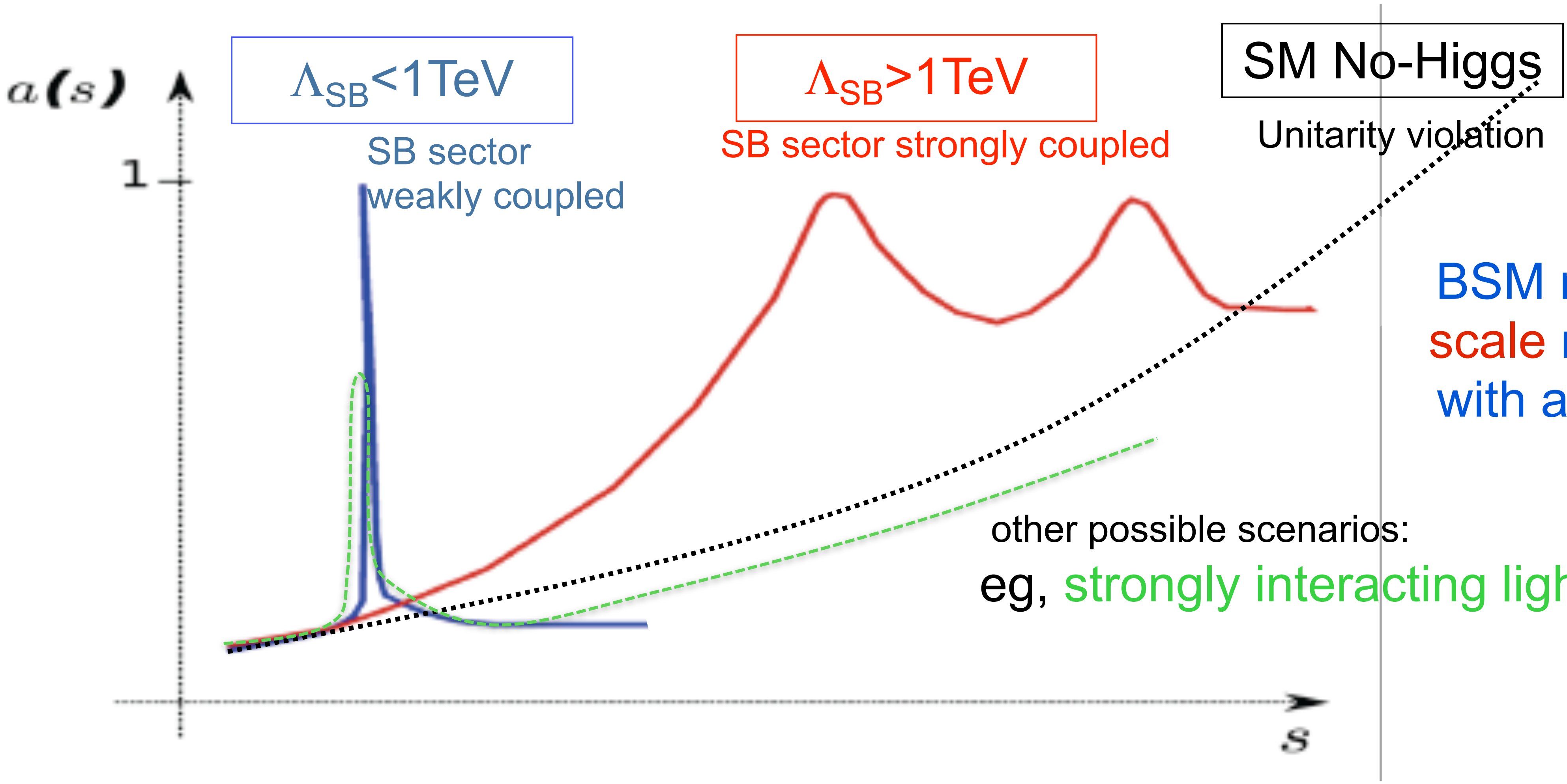
VV scattering is the smoking gun for EWSB!

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

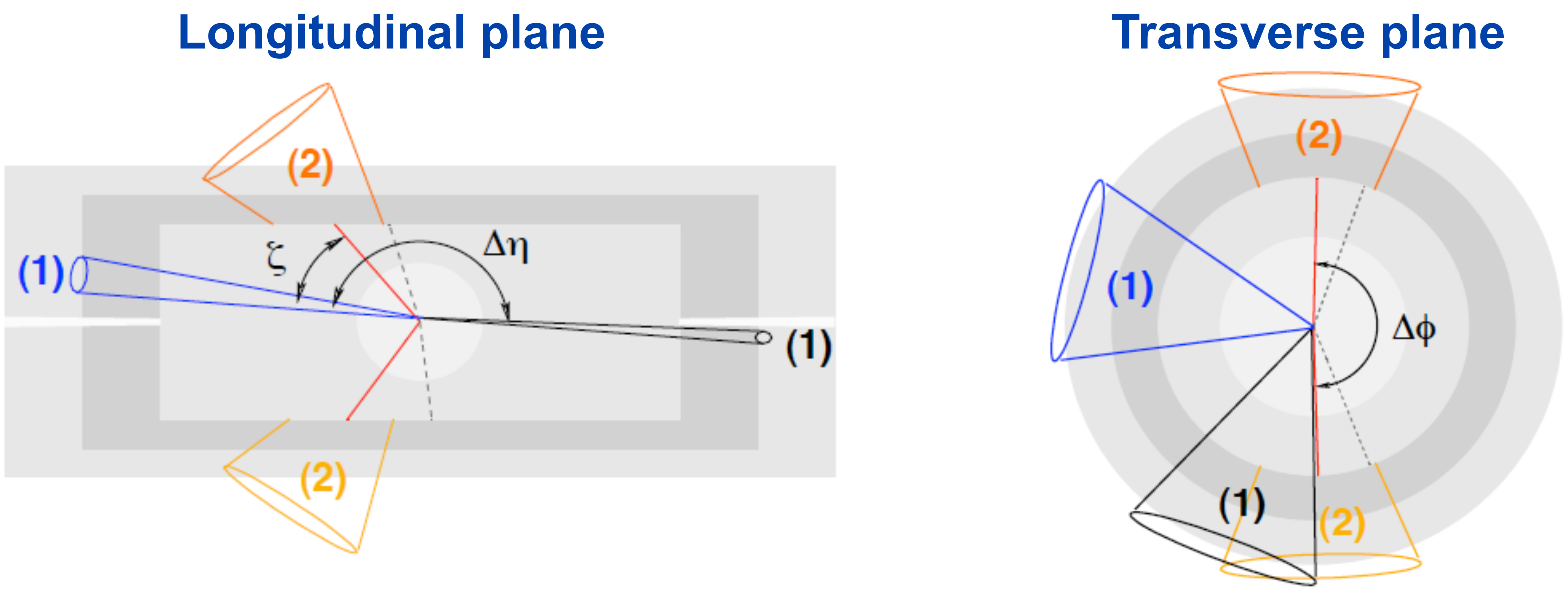


BSM models predict TeV-scale resonances "paired" with a light scalar particle

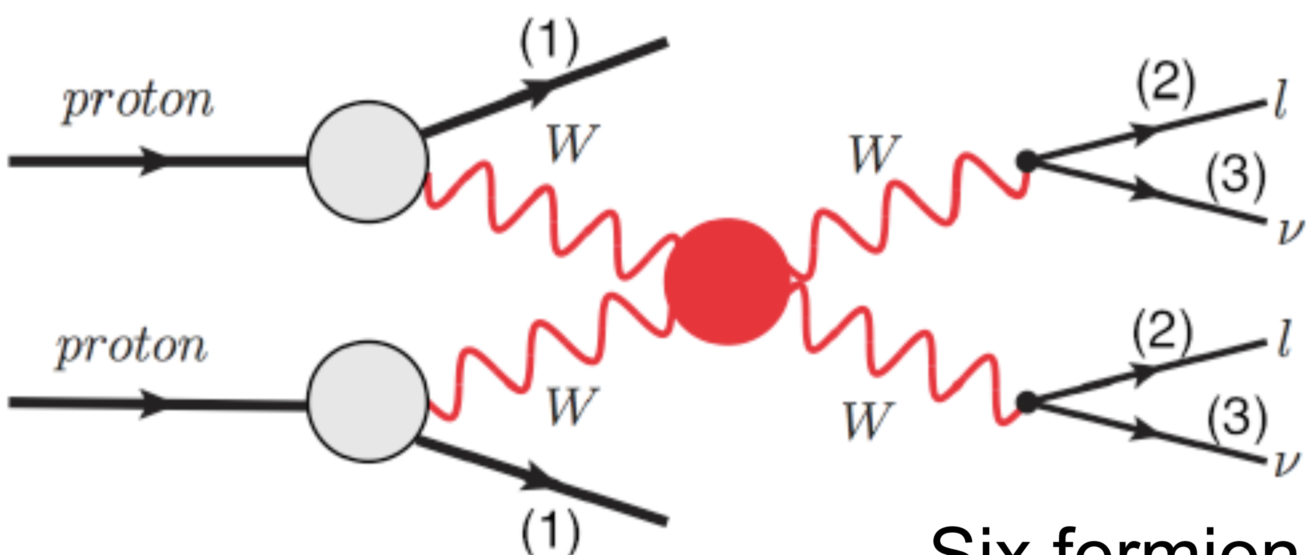
Search for possible resonances in VBF spectrum

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

VBF experimental signature



- *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

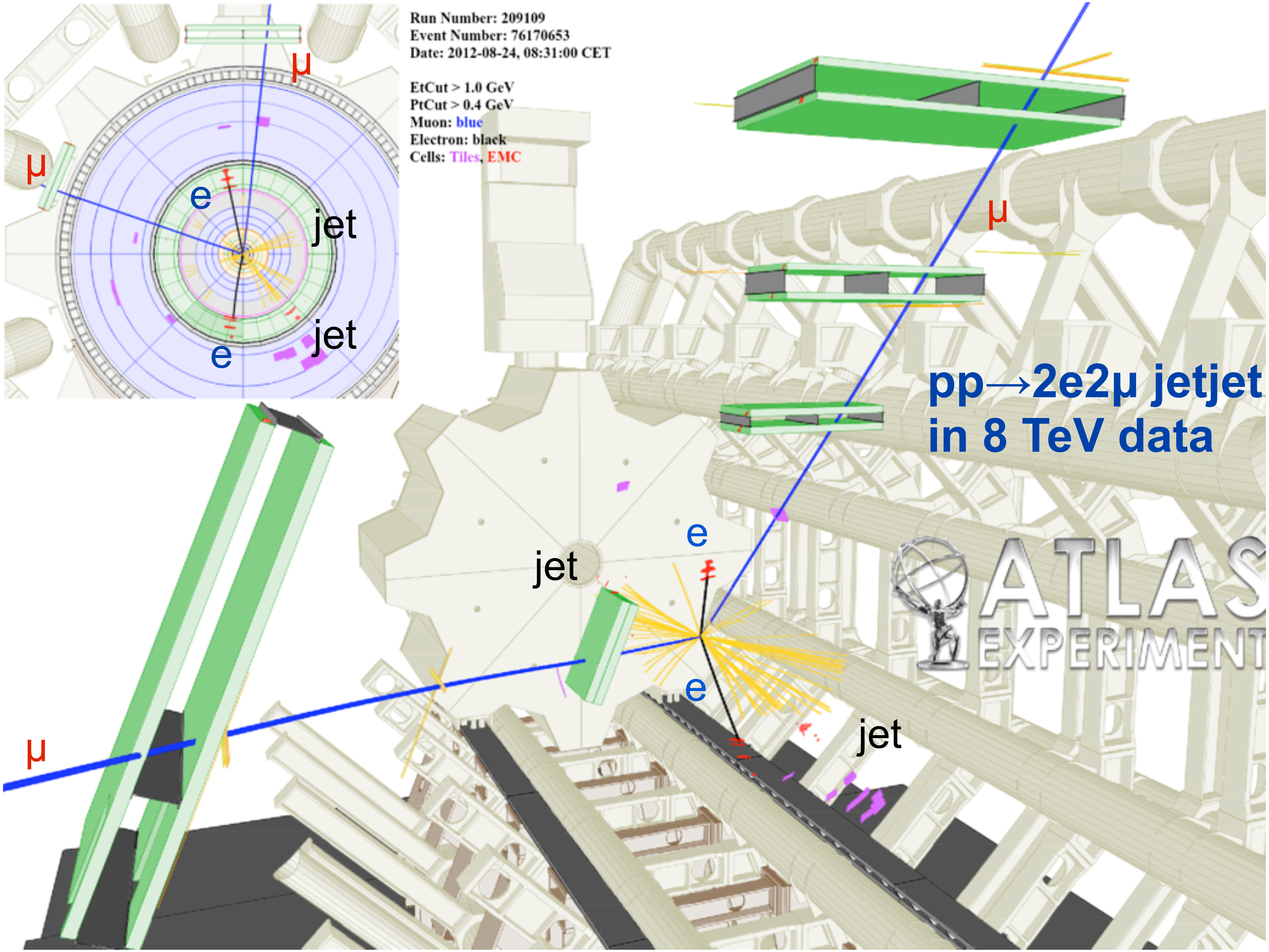
  Better yields...

  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

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)

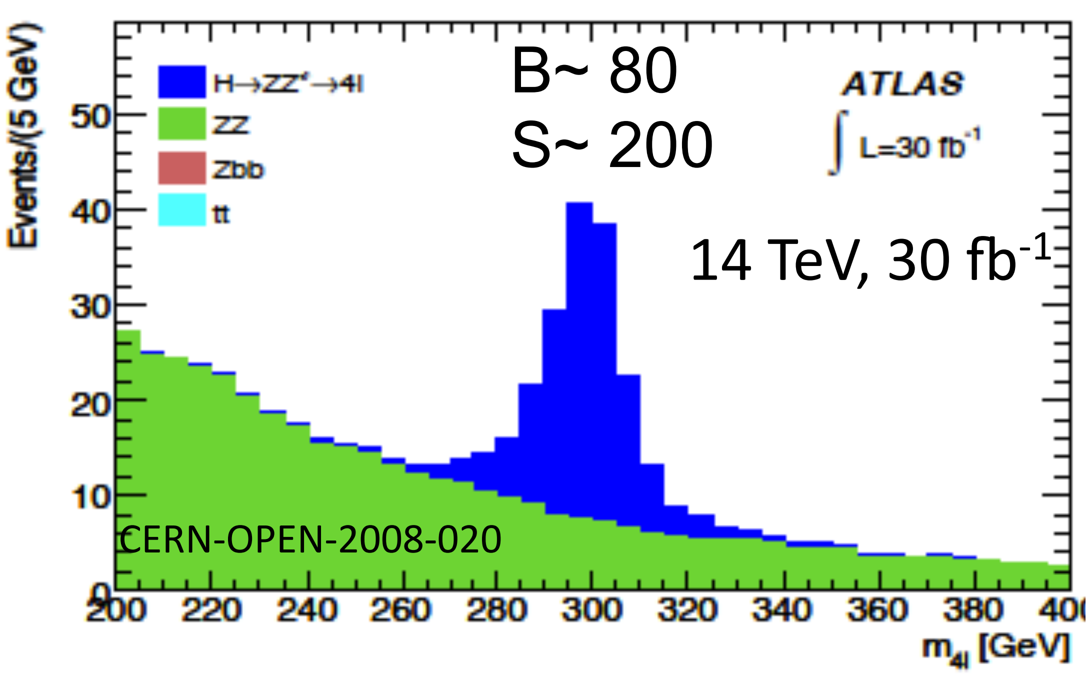
CMS ZZ->4e, 4μ	N signal	N back.
500 GeV	2.2	1.9
>1 TeV	0.1	0.2

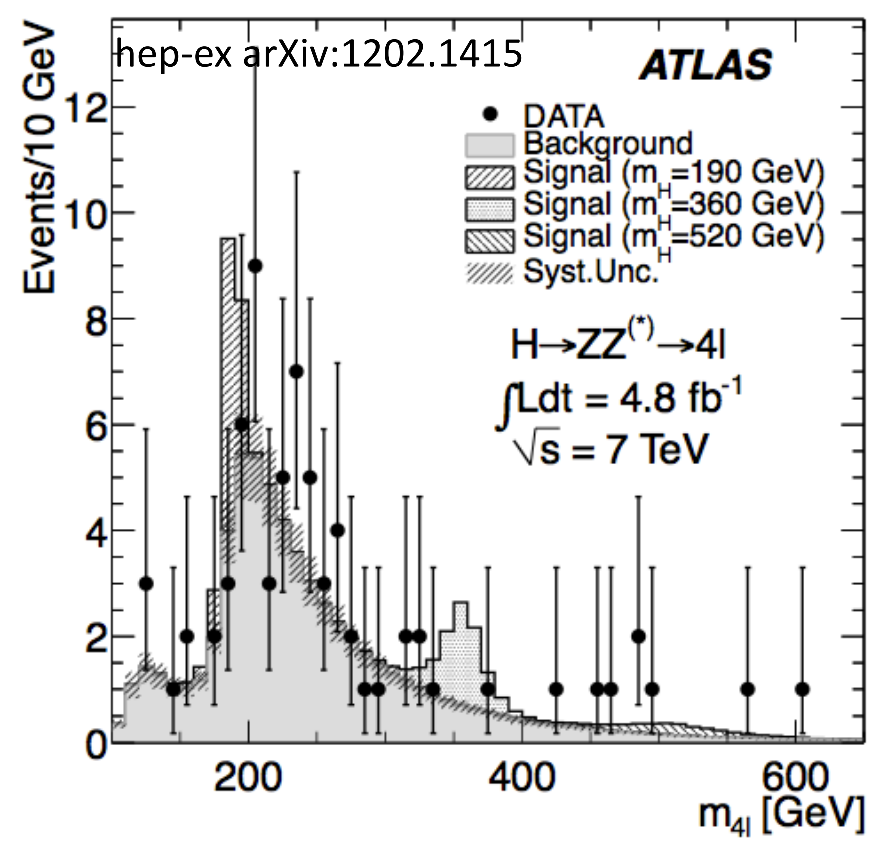
CMS ZW->μμμν	N signal	N back.
>1 TeV	0.9	0.8

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





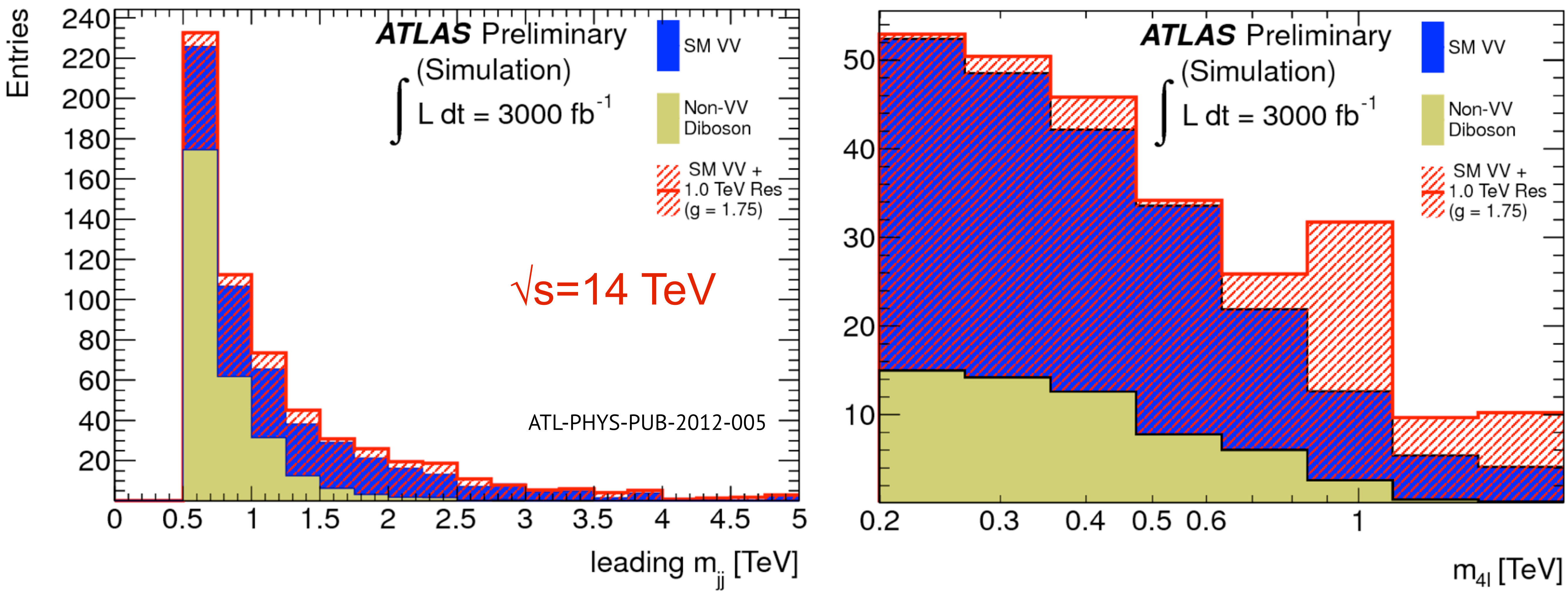
Latest results:
B~ 6
S~ 10

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

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

ZZ resonance

pp→ZZ+2j→4ℓ+2j channel

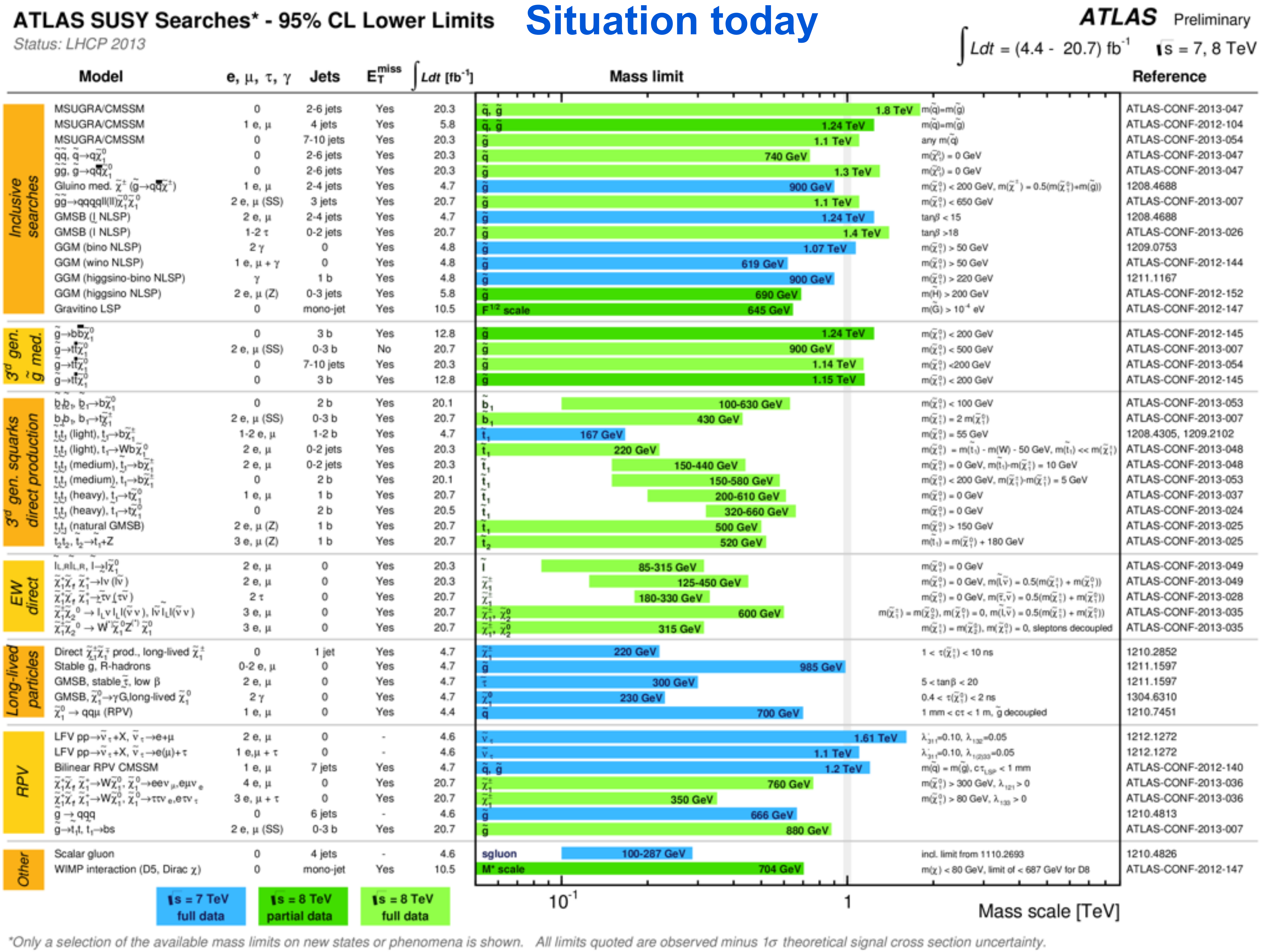


model	300 fb^{-1}	3000 fb^{-1}
$m_{resonance}$ = 500 GeV, $g = 1.0$	2.4σ	7.5σ
$m_{resonance}$ = 1 TeV, $g = 1.75$	1.7σ	5.5σ
$m_{resonance}$ = 1 TeV, $g = 2.5$	3.0σ	9.4σ

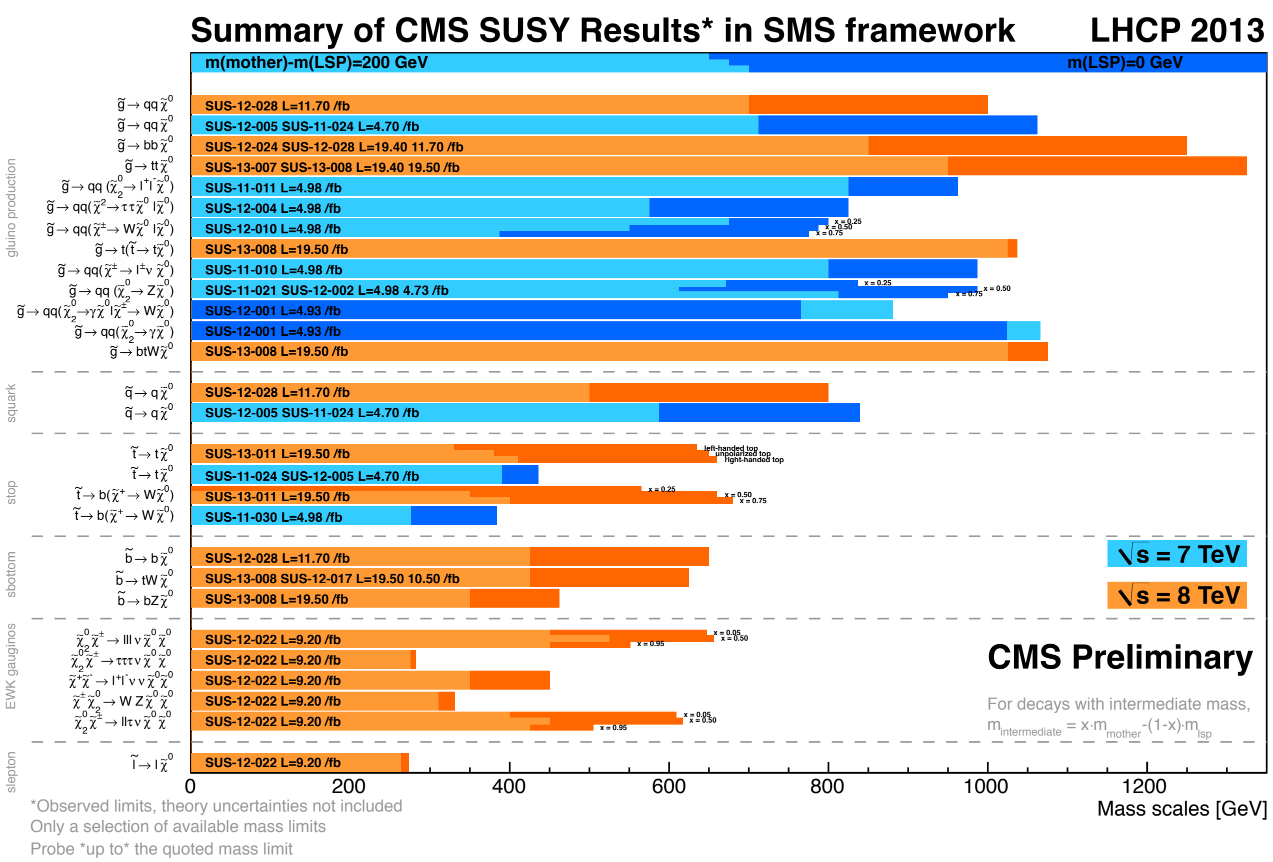
Sensitivity to anomalous ZZ resonances in Vector boson scattering

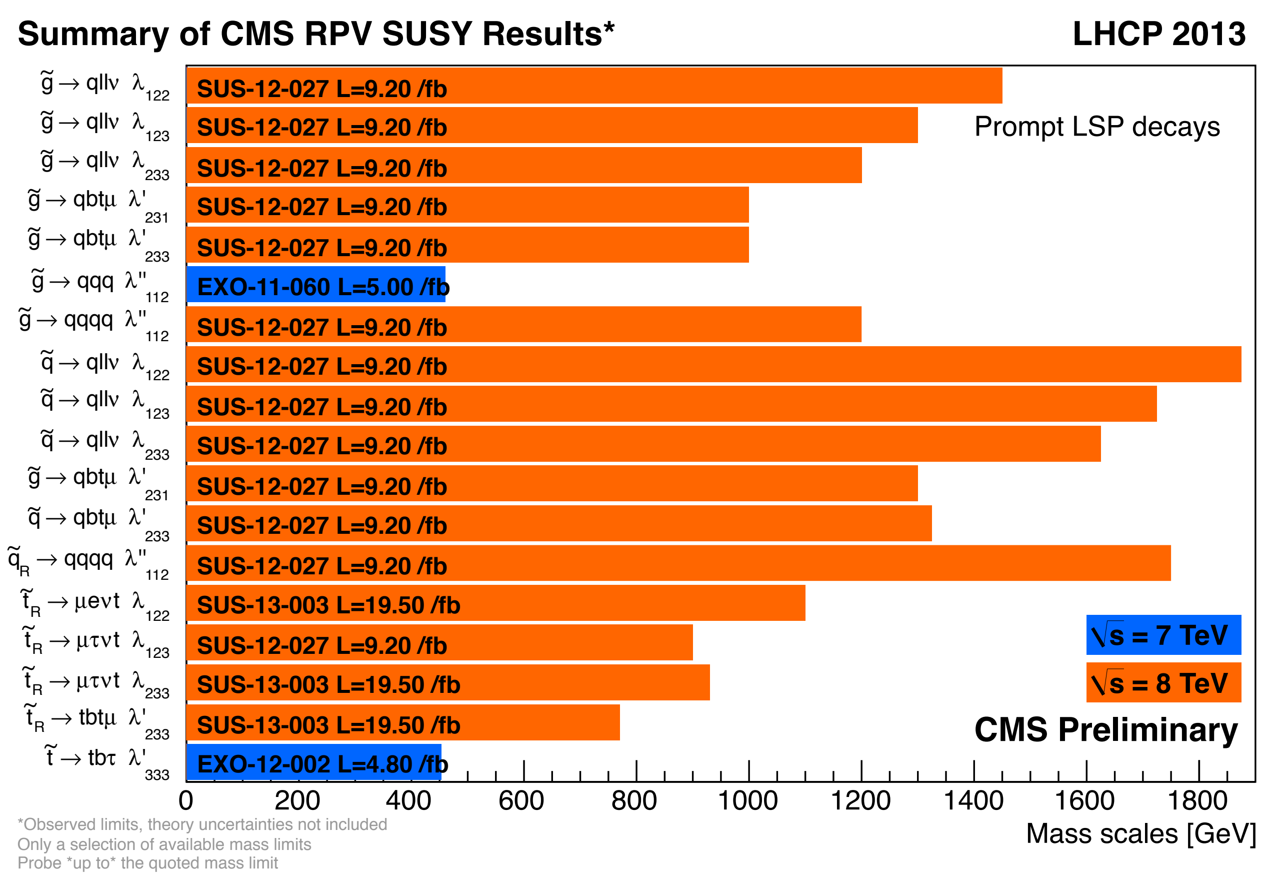
SUSY

Situation today



SUSY

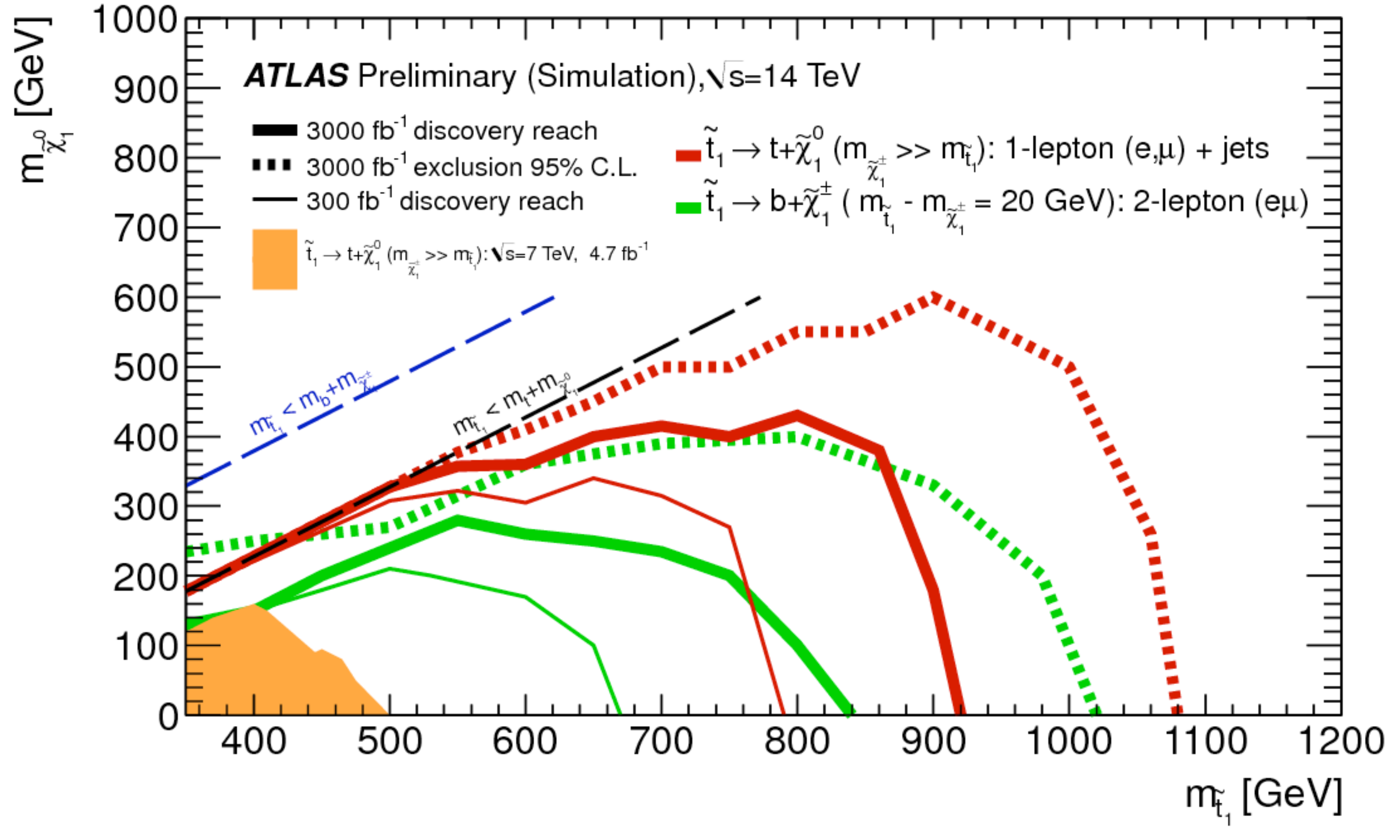


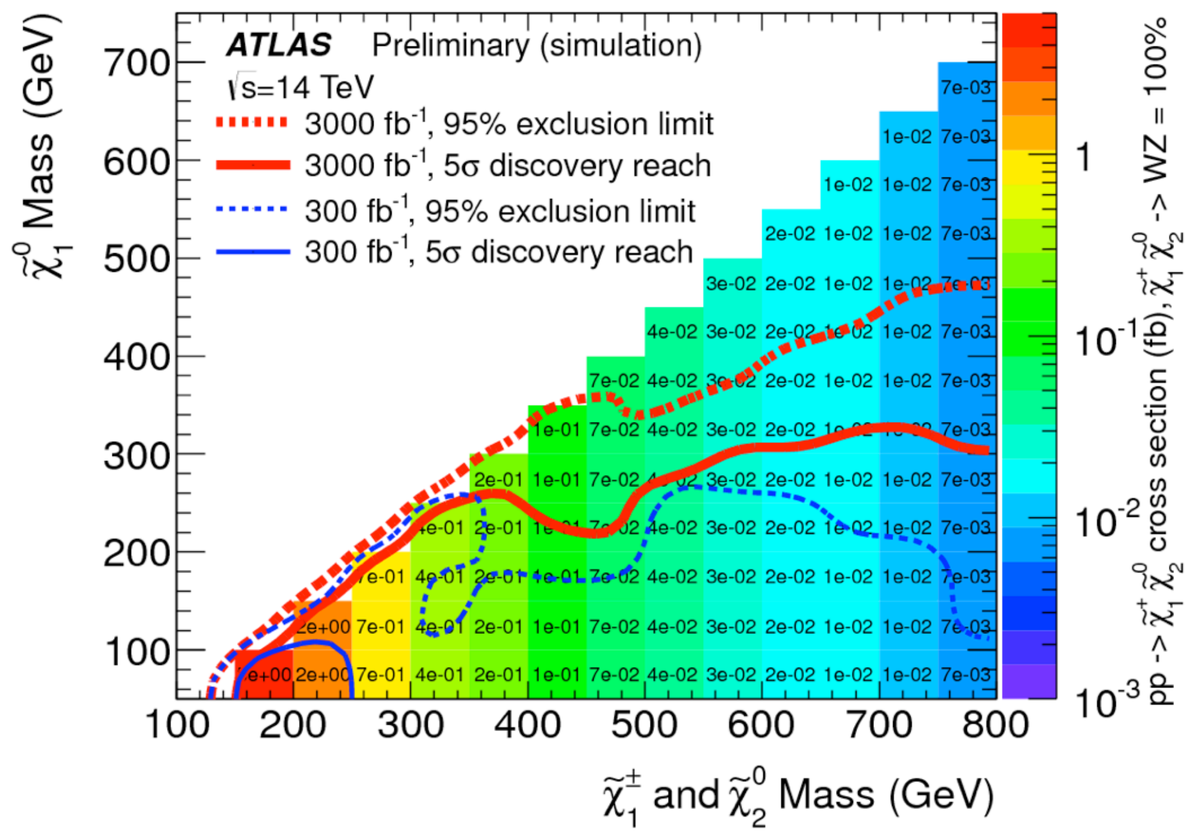


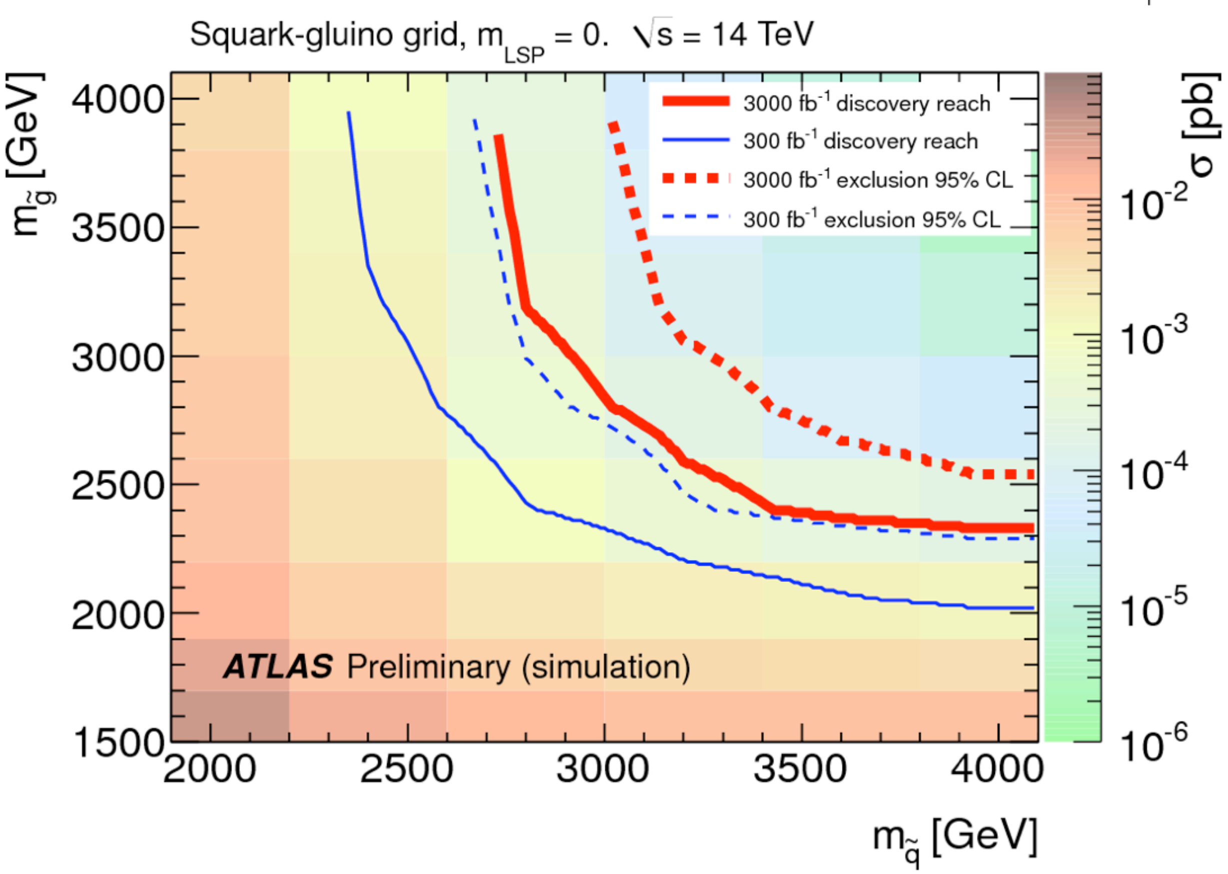
SUSY limits at a glance

EWKinos	~200-400 GeV
Stop, sbottoms	~200-600 GeV
Squarks, gluinos	~600-1300 GeV

SUSY reach at higher luminosity





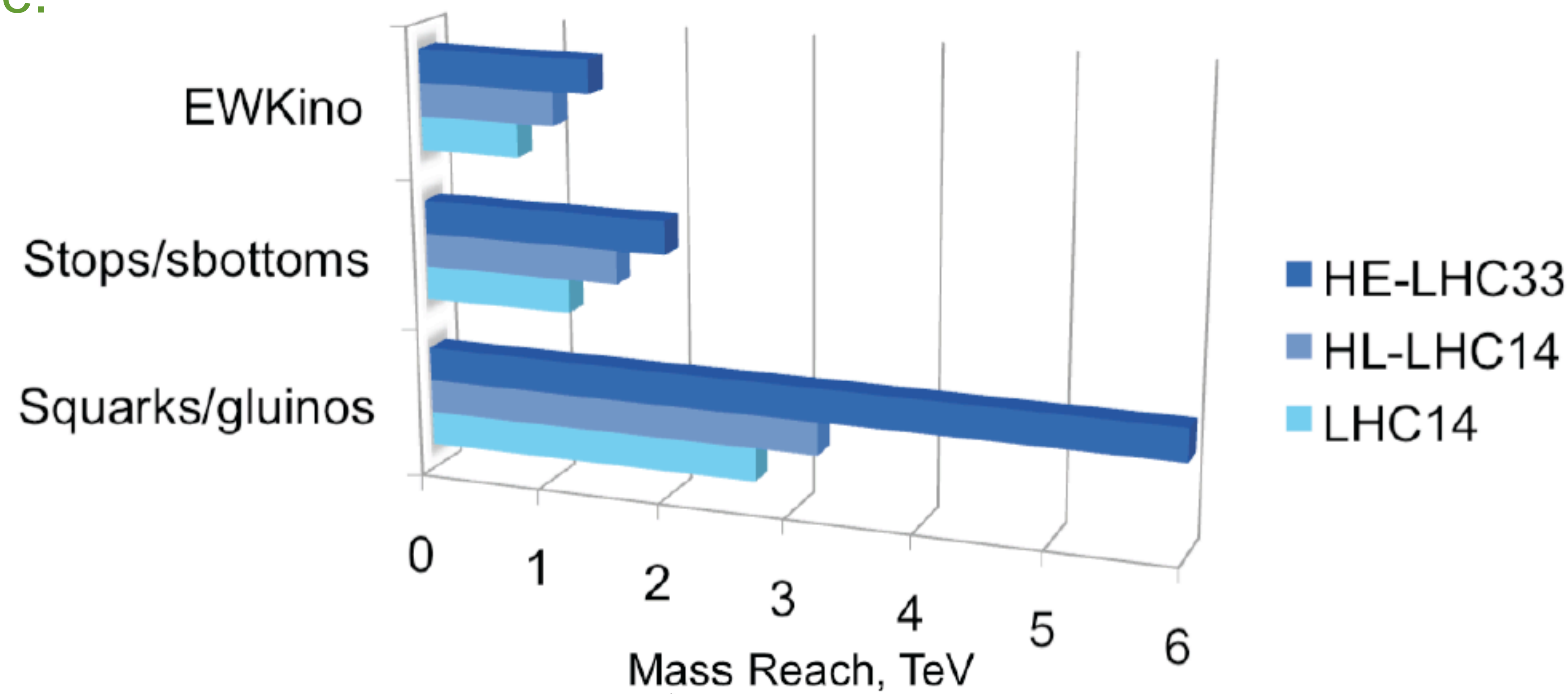


Going from L=300 fb^{-1} to L=3000 fb^{-1} the sensitivity to 1st and 2nd gen squarks and gluinos improves by ~400-500 GeV, while to stops by about 200 GeV

SUSY reach at higher luminosity

LHC at 14 TeV expands the reach for SUSY particles to much higher masses. (HE-LHC at 33 TeV does it even more)

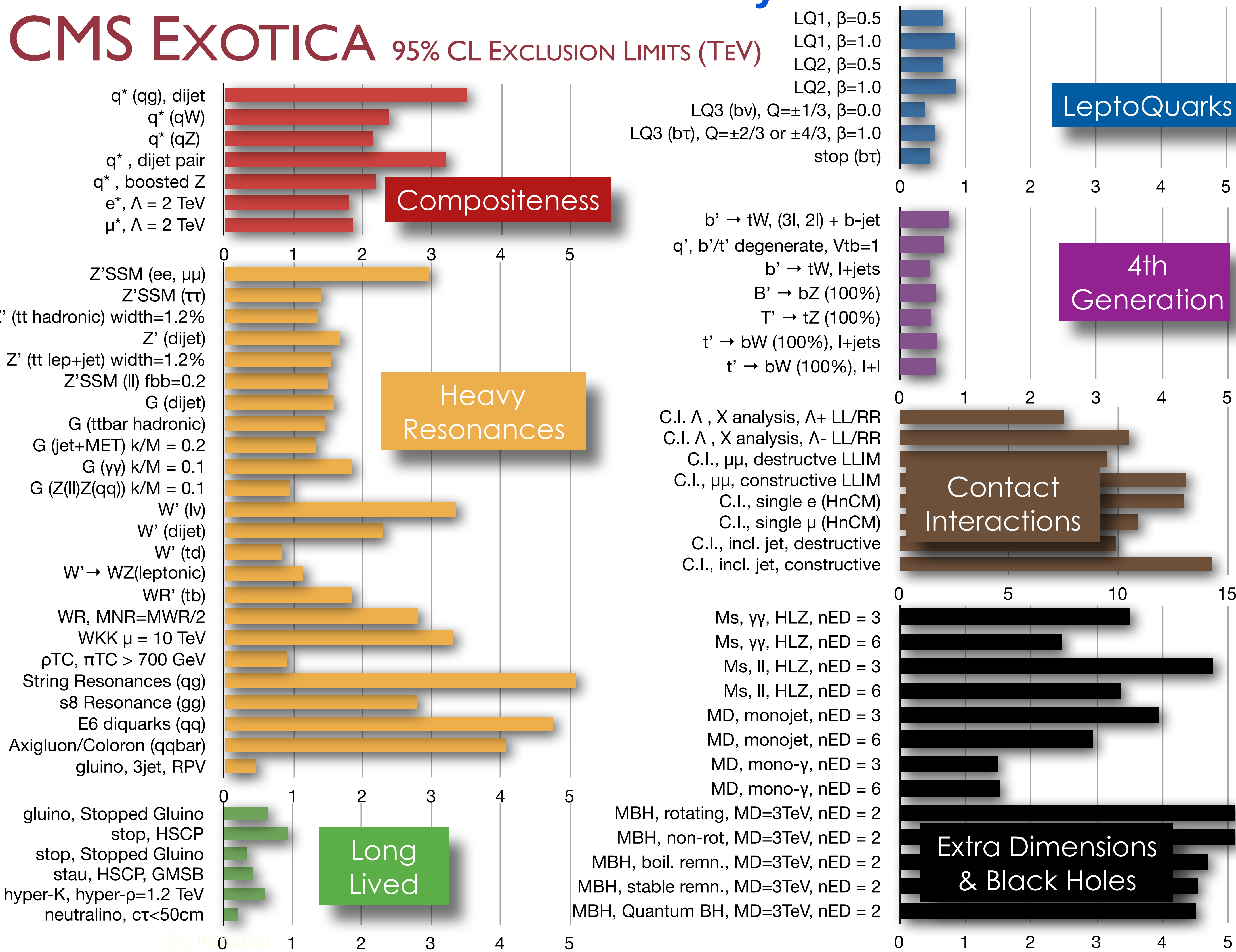
As expected, the gain with HL-LHC is more modest (~25%) in this case.



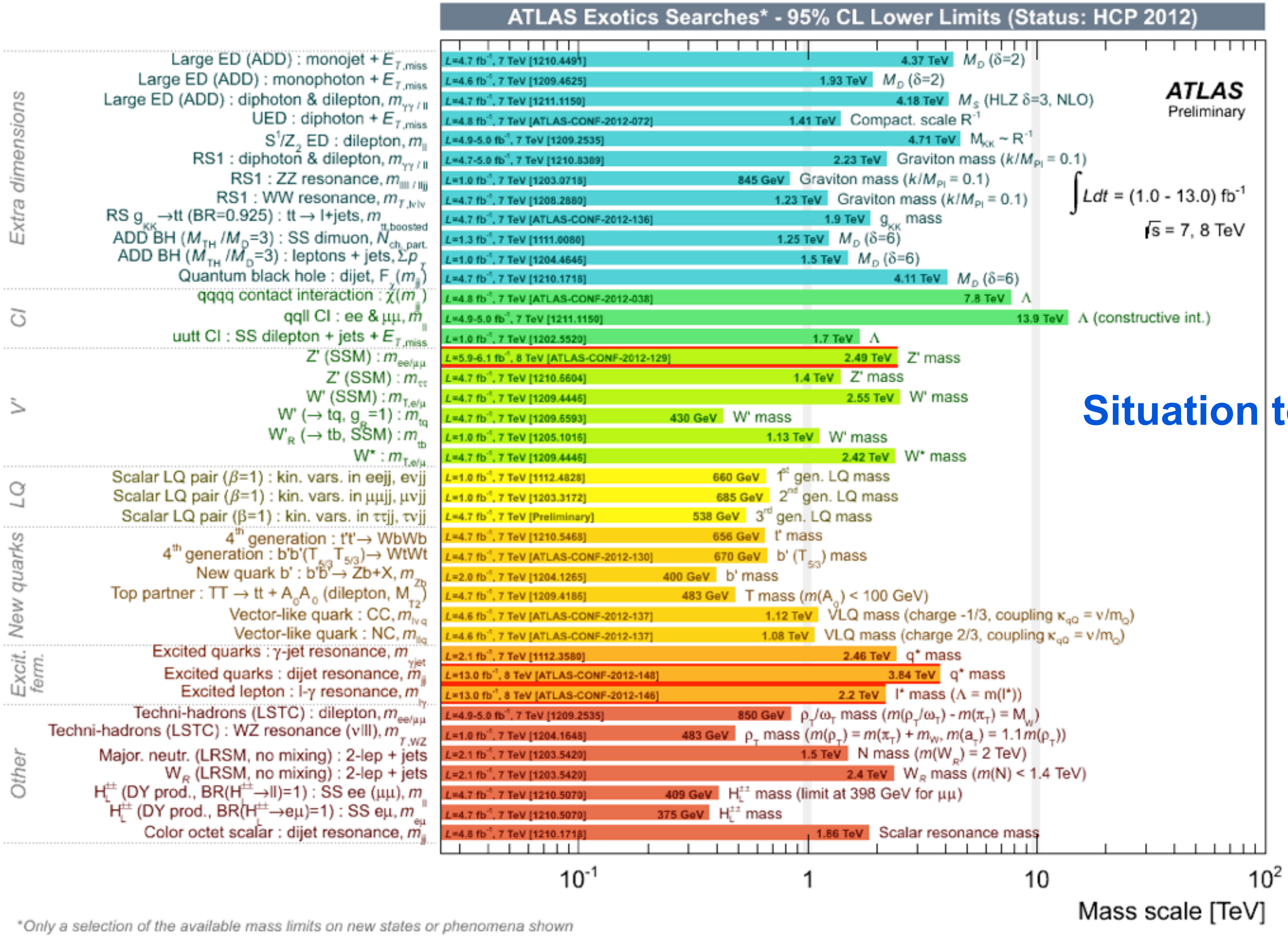
SUSY reach with 300 fb^{-1}
EWKinos up to ~ 800 GeV
Stops,sbottoms up to ~ 1TeV
squarks,gluinos up to ~2.5 TeV

Exotics searches results

Situation today

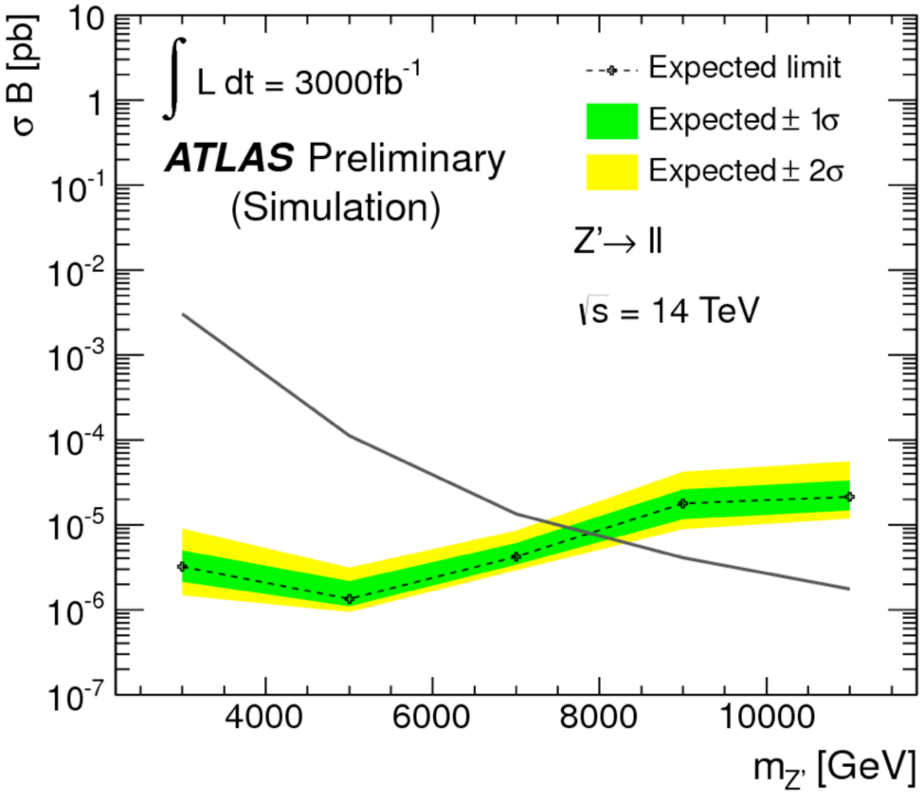


Exotics searches results

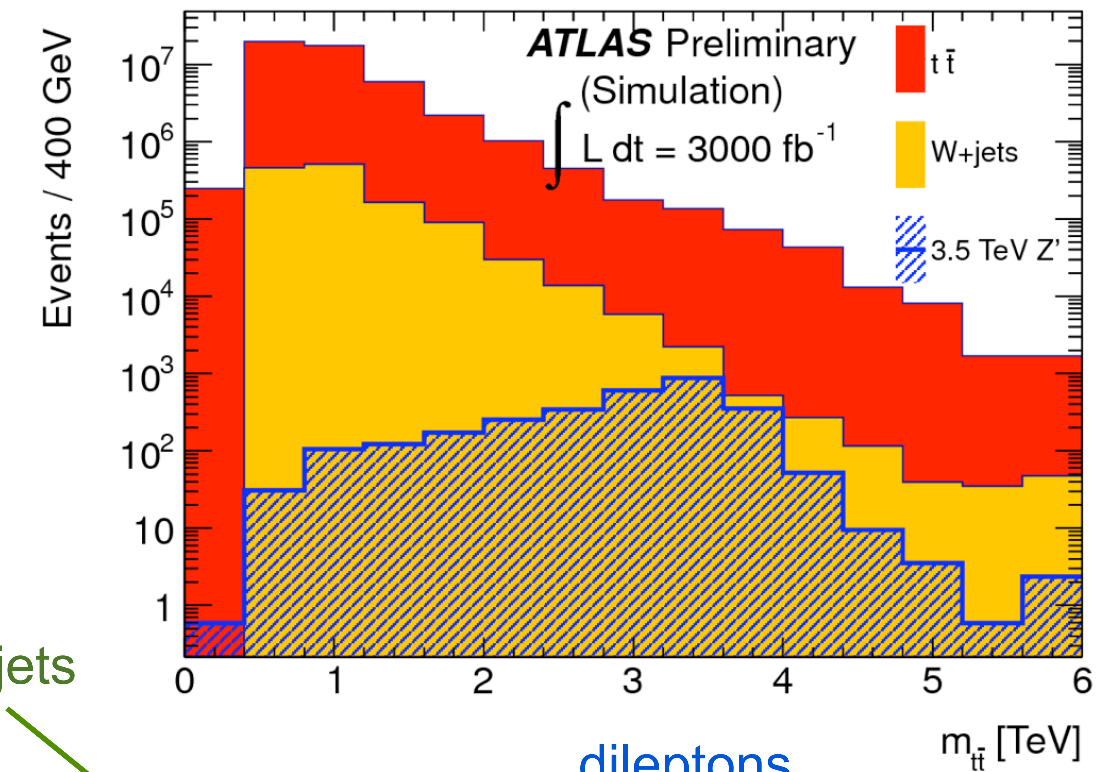


Situation today

Exotics searches at HL-LHC



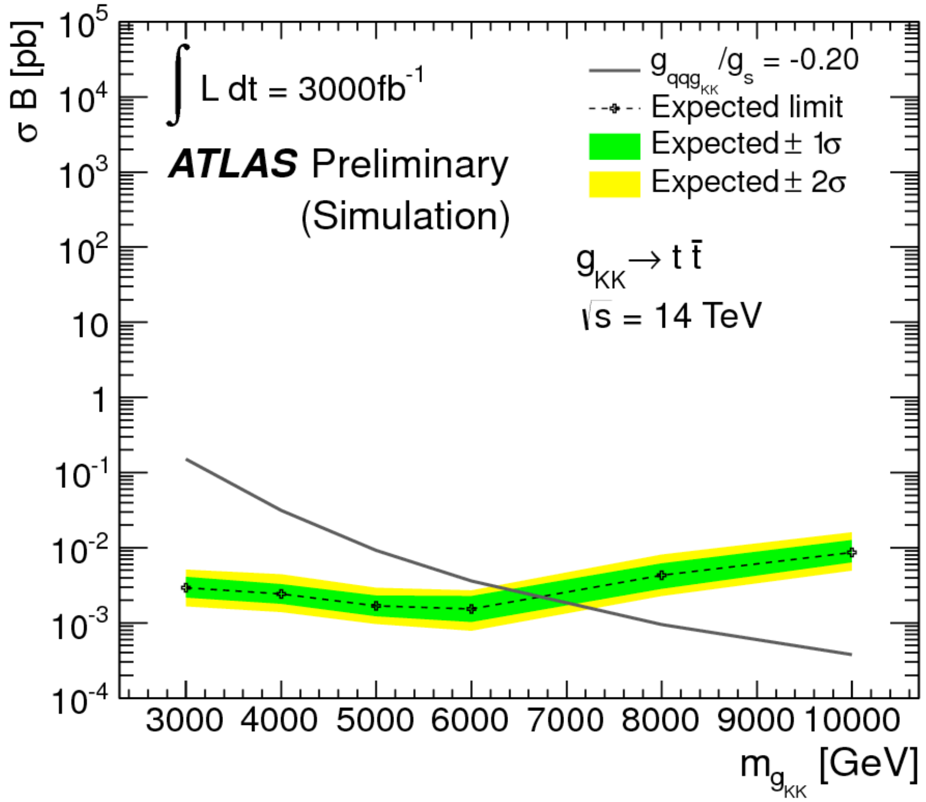
Z'Topcolour



lepton+jets

dileptons

Kaluza-Klein gluons in extra-dimensional models



model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{\mathrm{Topcolour}}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)
$Z'_{SSM} \rightarrow ee$	6.5	7.2	7.8
$Z'_{SSM} \rightarrow \mu\mu$	6.4	7.1	7.6

Summary of expected limits for various signatures in the Sequential Standard Model. All mass limits are in TeV.

LQ at HL-LHC

Mass reach (in TeV) for the leptoquark search in the ee jetjet channel

CMS

Scenario	LHC	HL-LHC	HE-LHC
Low S/B	1.6	1.8	2.5
High S/B	1.7	2.3	3.5

Caveat

Many of the projections and studies that I presented are being improved and updated for the ECFA workshop of october 2013, so stay tuned...

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 with 300 fb^{-1}, collected at $\sqrt{s}$=14 TeV and instantaneous luminosities up to $2x10^{34}cm^{-2}s^{-1}$.
  - A new energy domain with a vast potential for new physics discoveries
  - All existing searches will be very quickly updated
- With HL-LHC a further increase of the discovery phase-space is possible.
- Precision SM scalar 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.
  - scalar boson couplings can be measured with few percent precision
  - rare scalar boson decays, self-coupling studies possible
  - VV scattering will be probed
- LHC has an exciting physics program for the next twenty years!

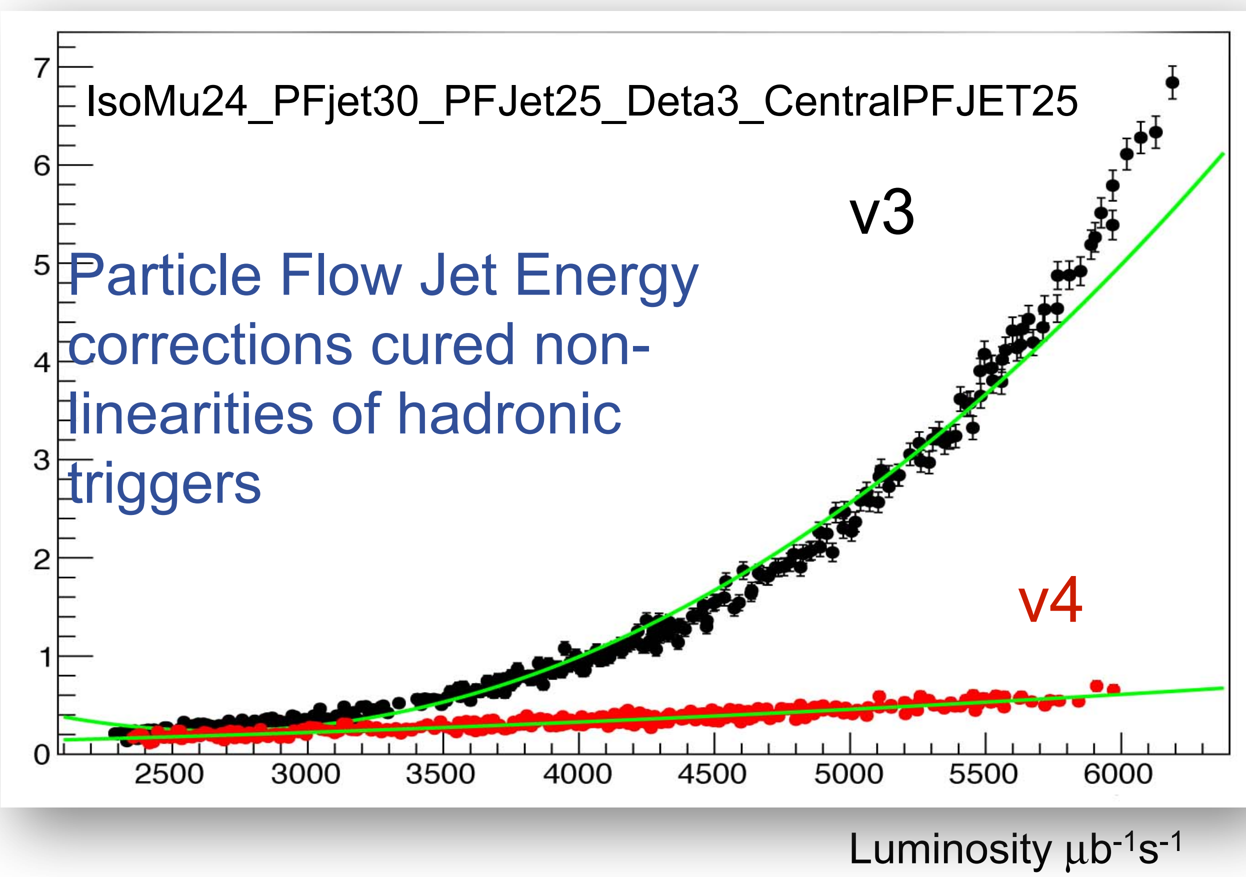
Backup

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

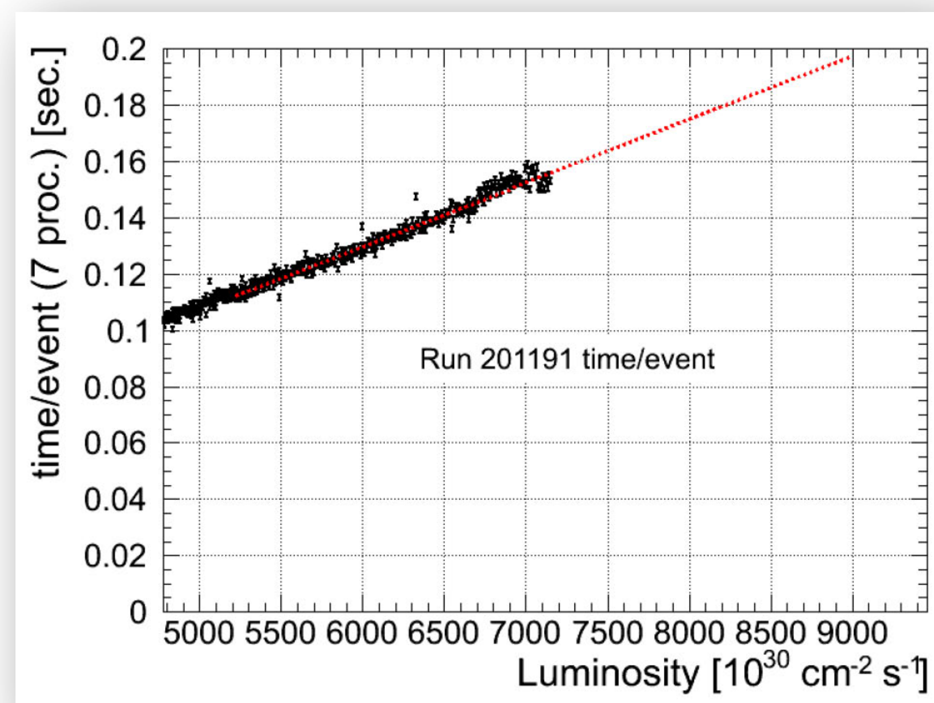
The experience obtained in 2012 with peak pileup of ~35 events gives us confidence for high-luminosity running post Long Shutdown 1

Trigger Cross-sections:



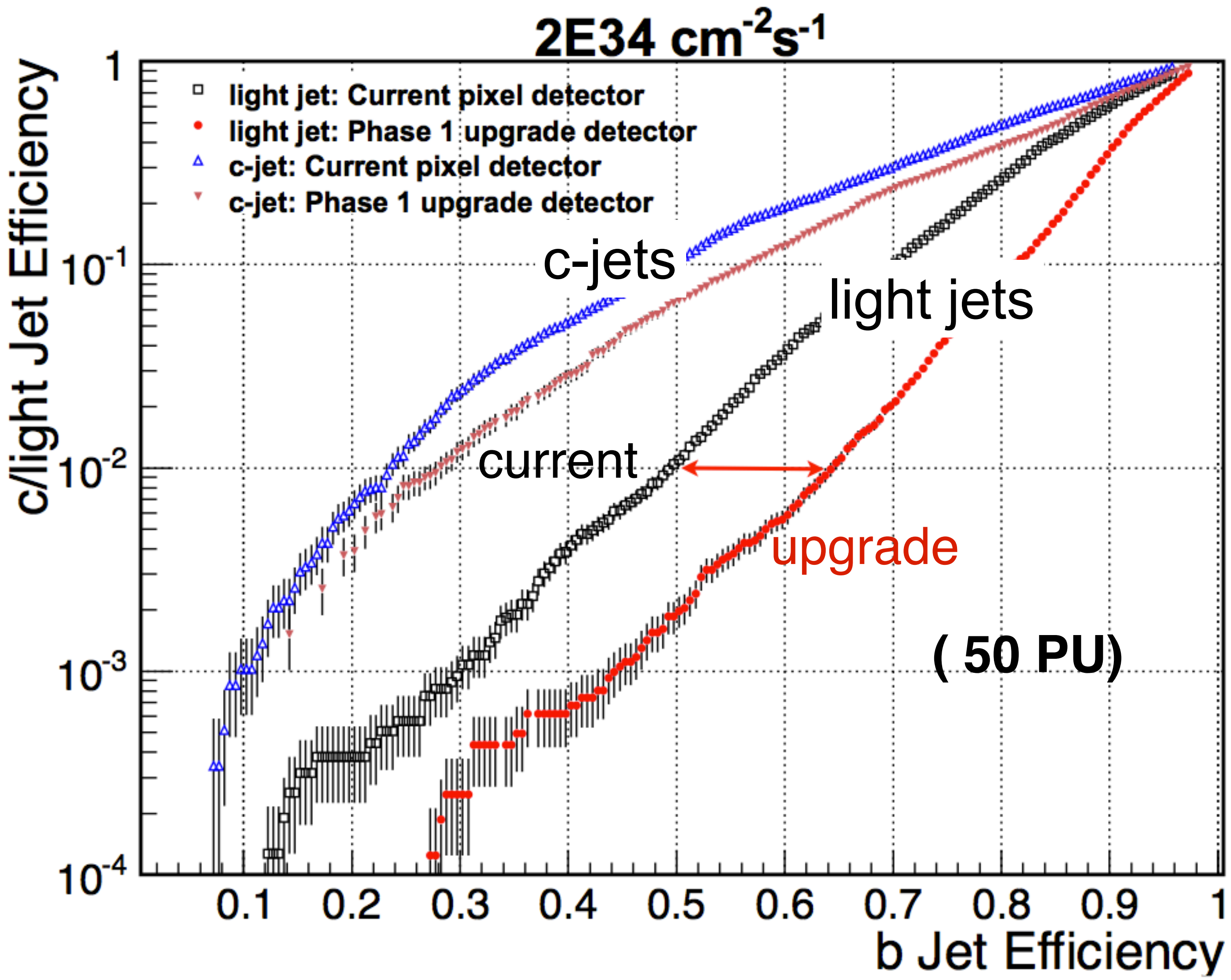
HLT CPU time:

- linear with PU, no signs of runaway

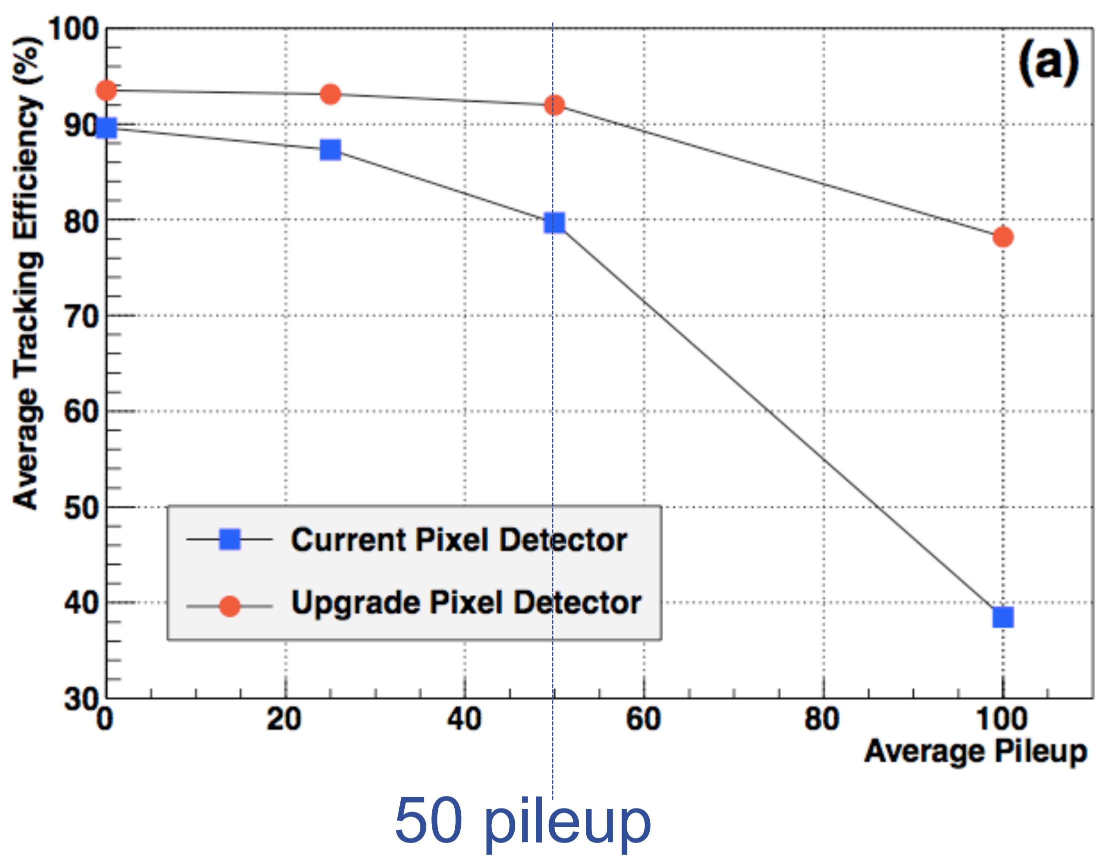


Tracking and b-tagging performance

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



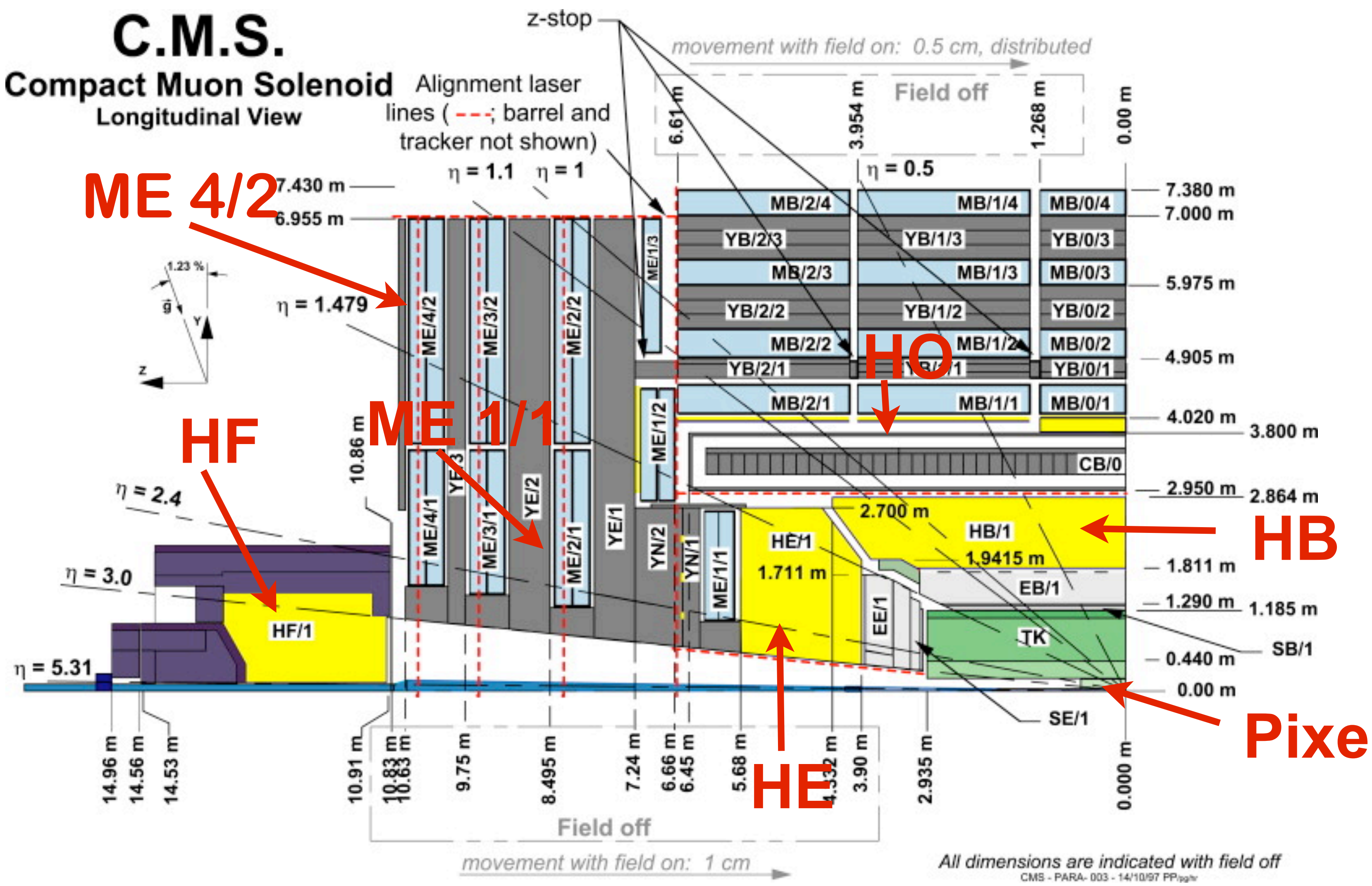
b-tagging efficiency ~ 1.3x better

2 b-jets → $(1.3)^2$ ~1.69

Primary vertex resolution improved by factor ~1.5 - 2

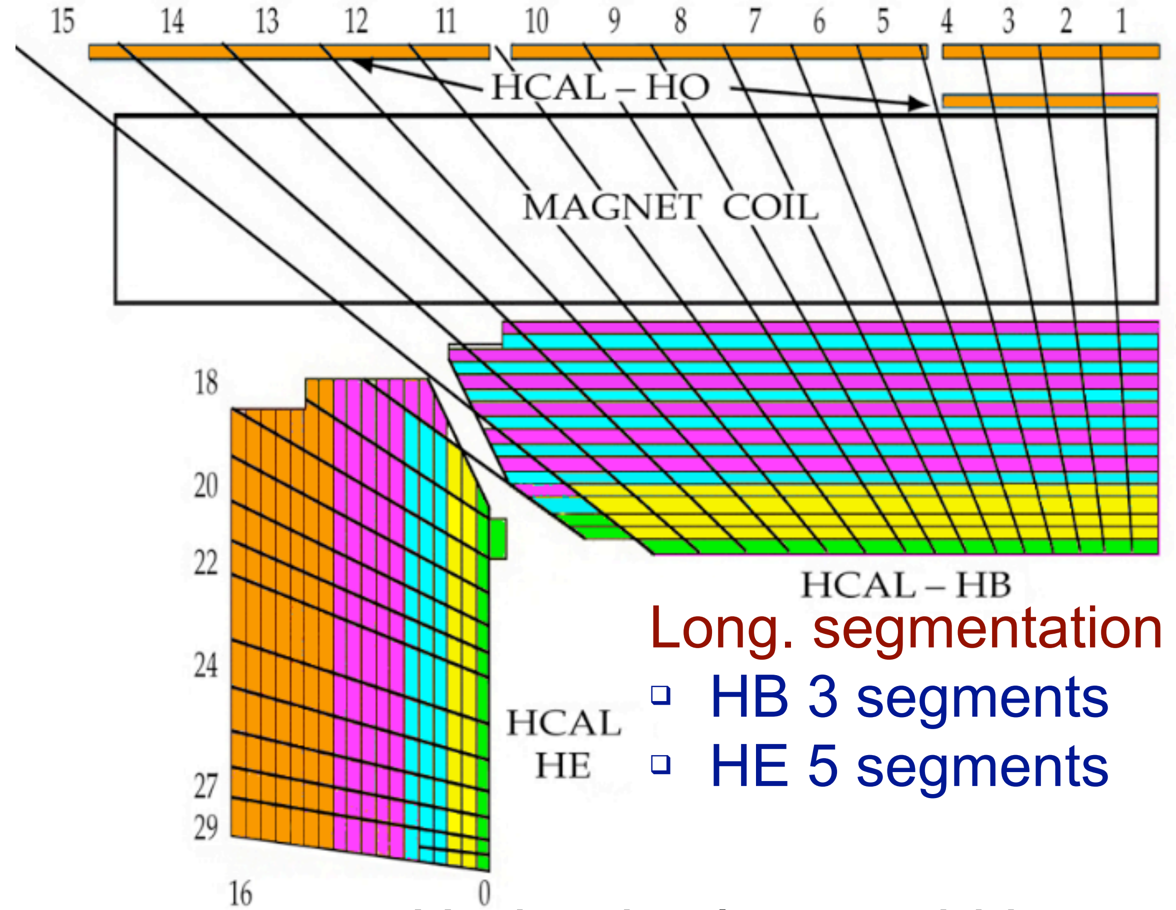
CMS Upgrade program

LS1 and Phase 1

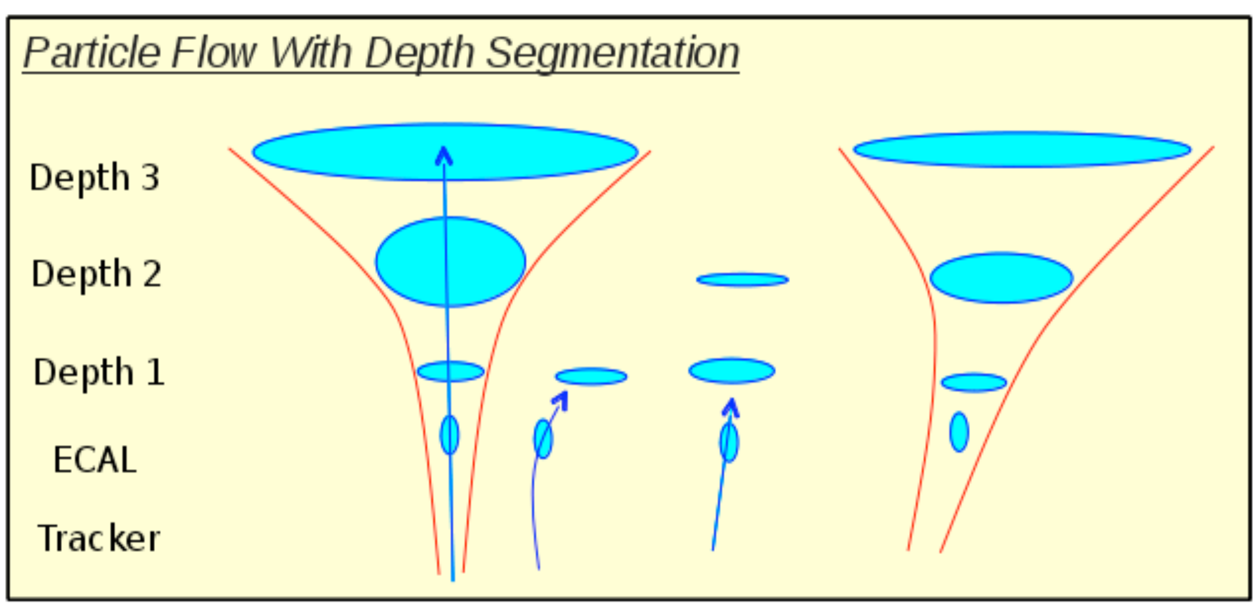


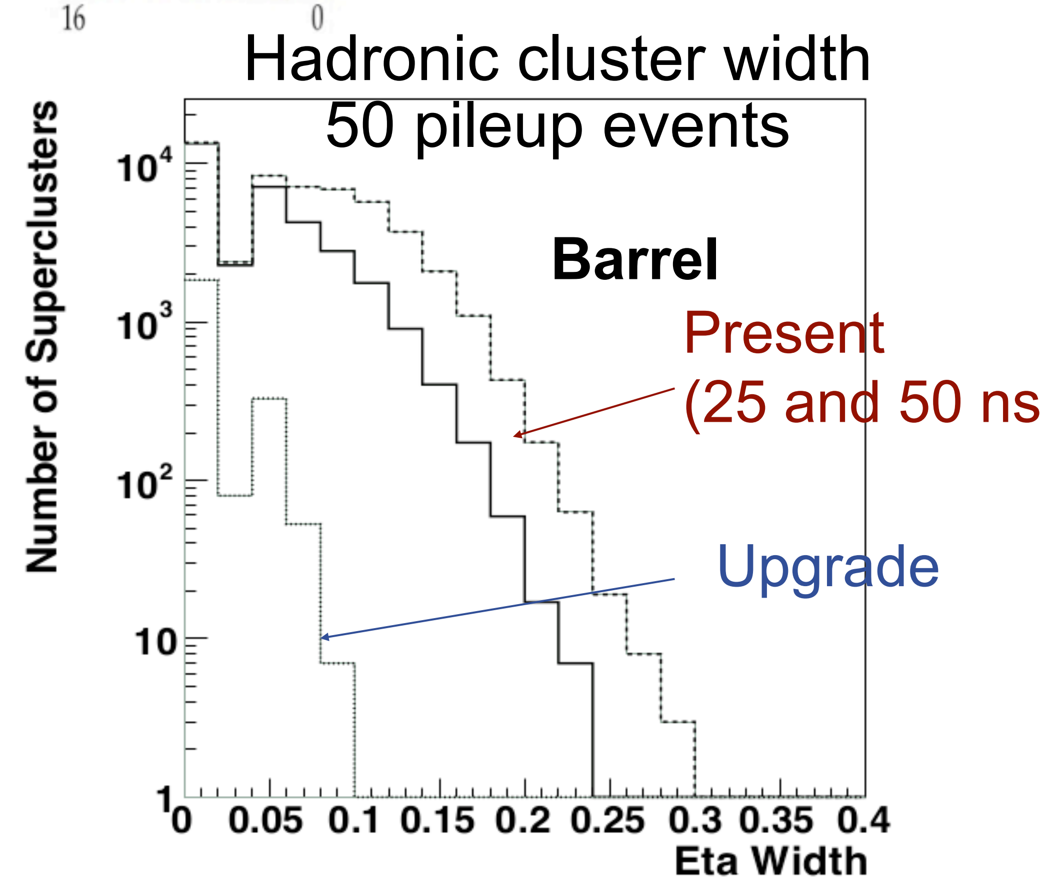
HCAL Upgrade

- 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

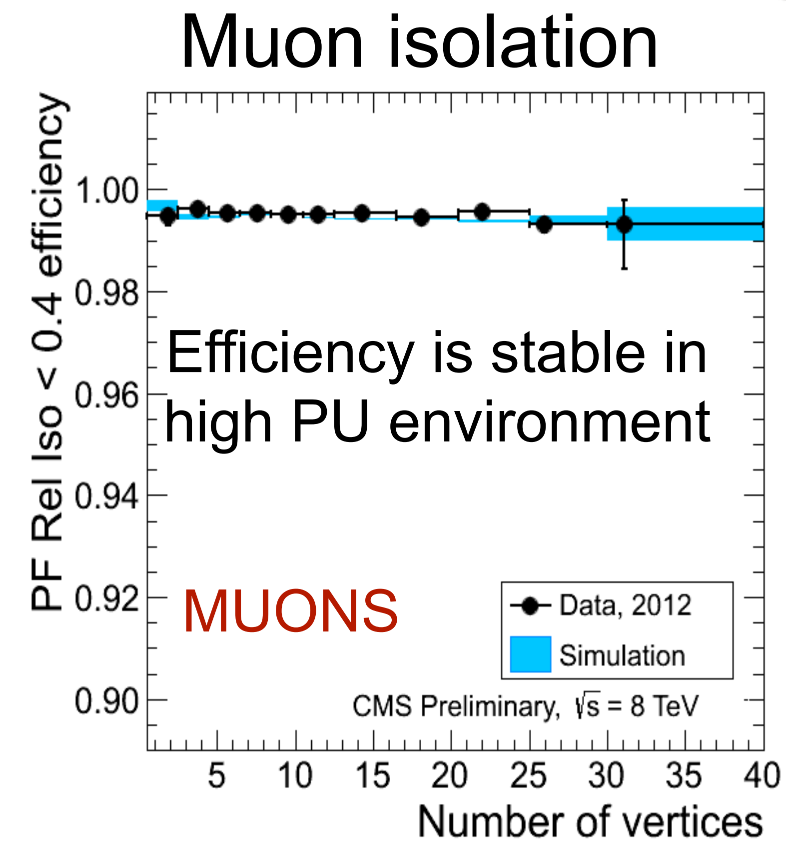




Pileup challenges

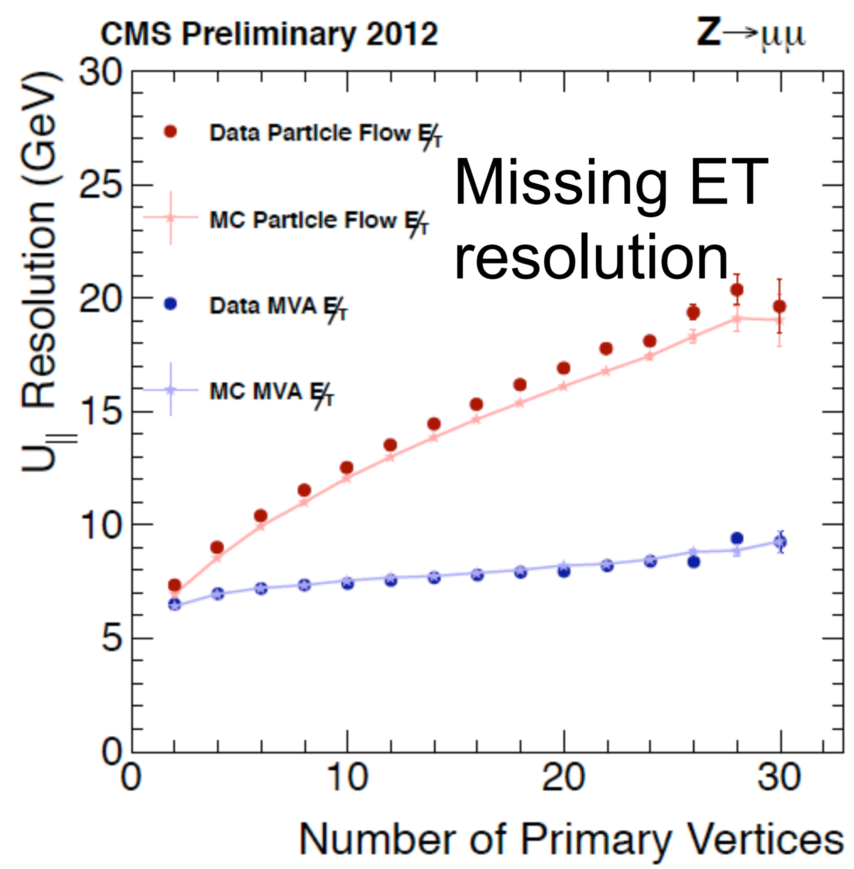
Reconstruction of hard collisions in high pileup environment requires detectors with very high granularity:

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



Physics with high pileup requires full particle flow reconstruction assuring:

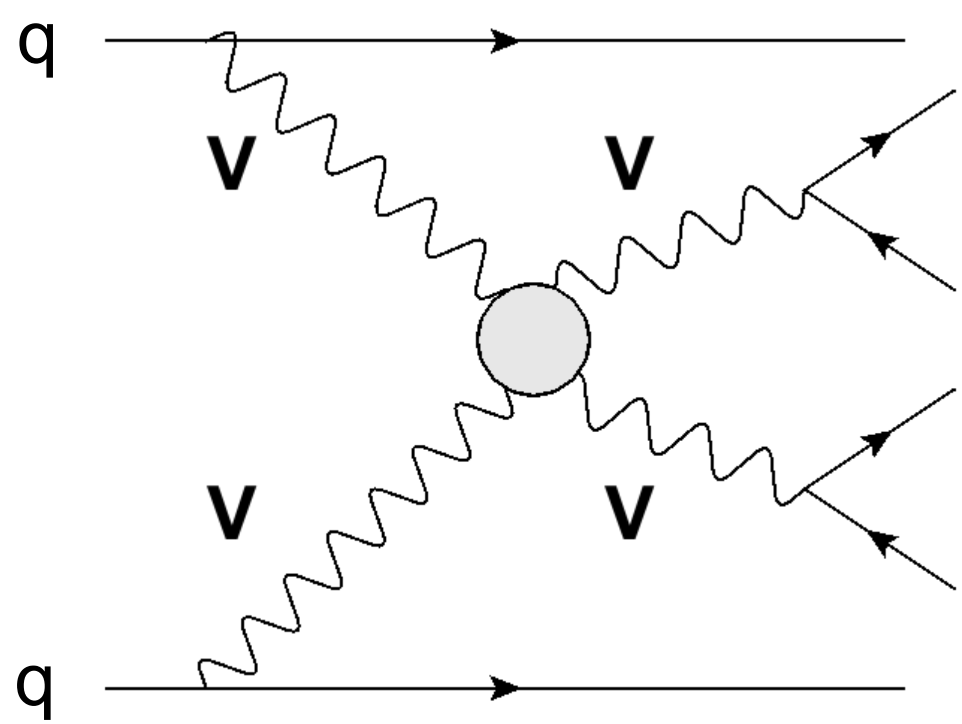
- precise jet energy correction
- robust missing energy measurement
- efficient lepton isolation



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 $qq \rightarrow 6$ 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)

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

CERN-OPEN-2008-020

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%