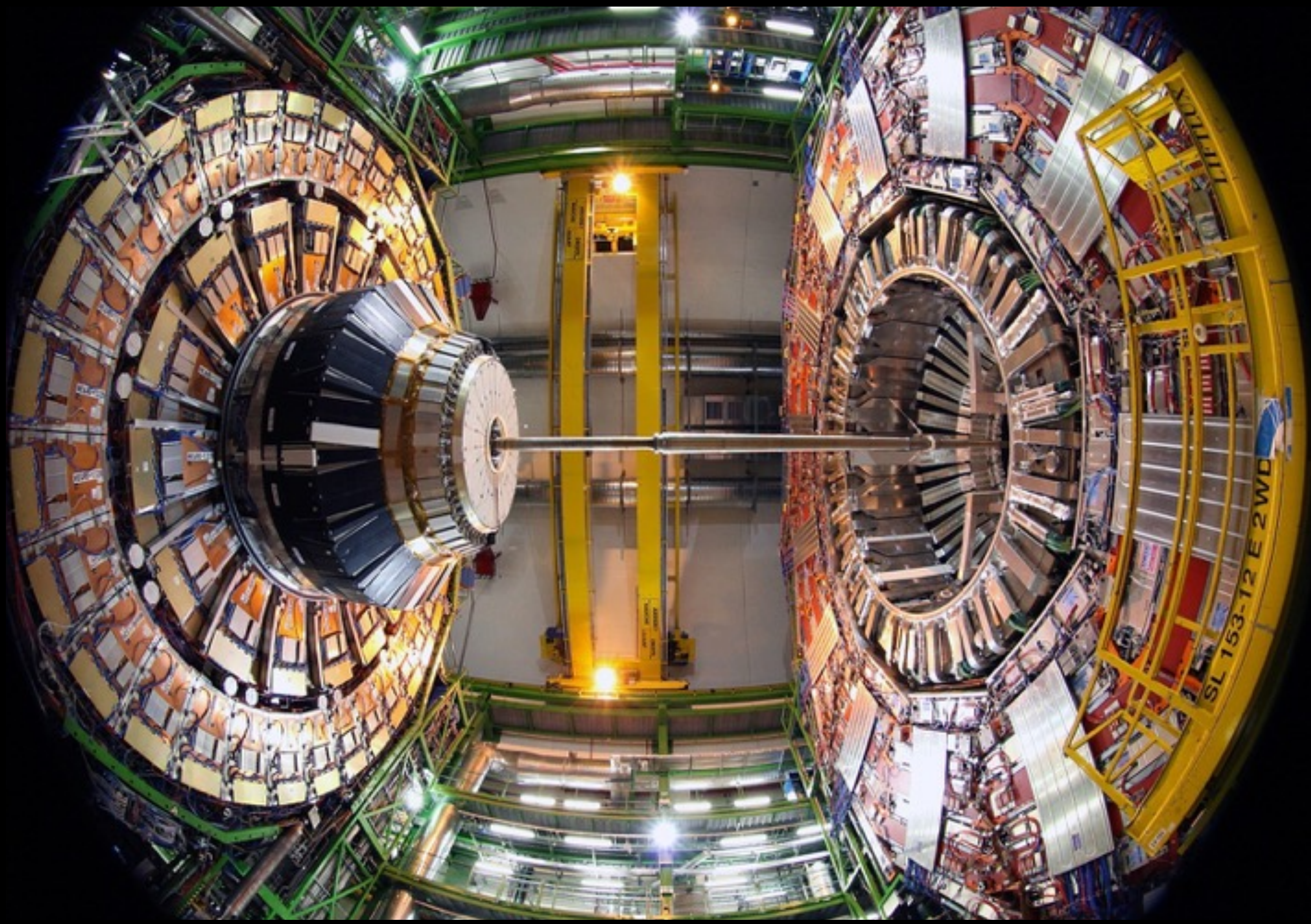
Why do we upgrade ATLAS and CMS?



9th Terascale Detector
Workshop, April 4th, 2016

Markus Klute
Massachusetts Institute of Technology

Answers by ATLAS & CMS

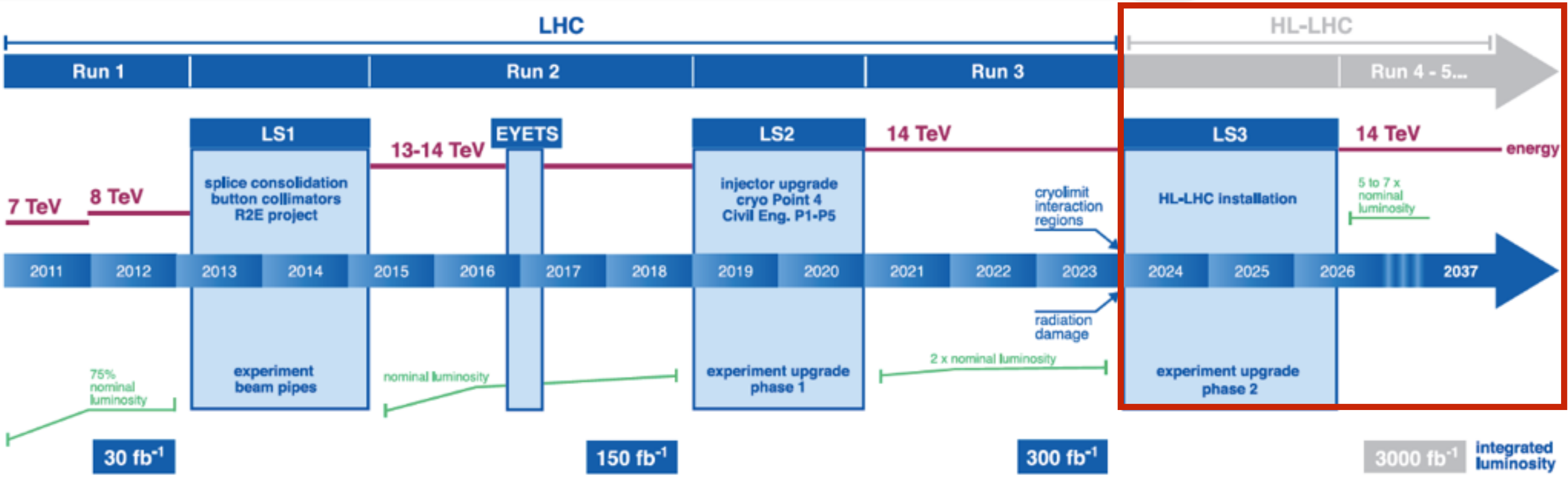
➡ **Baseline upgrade detectors and physics program documented in**

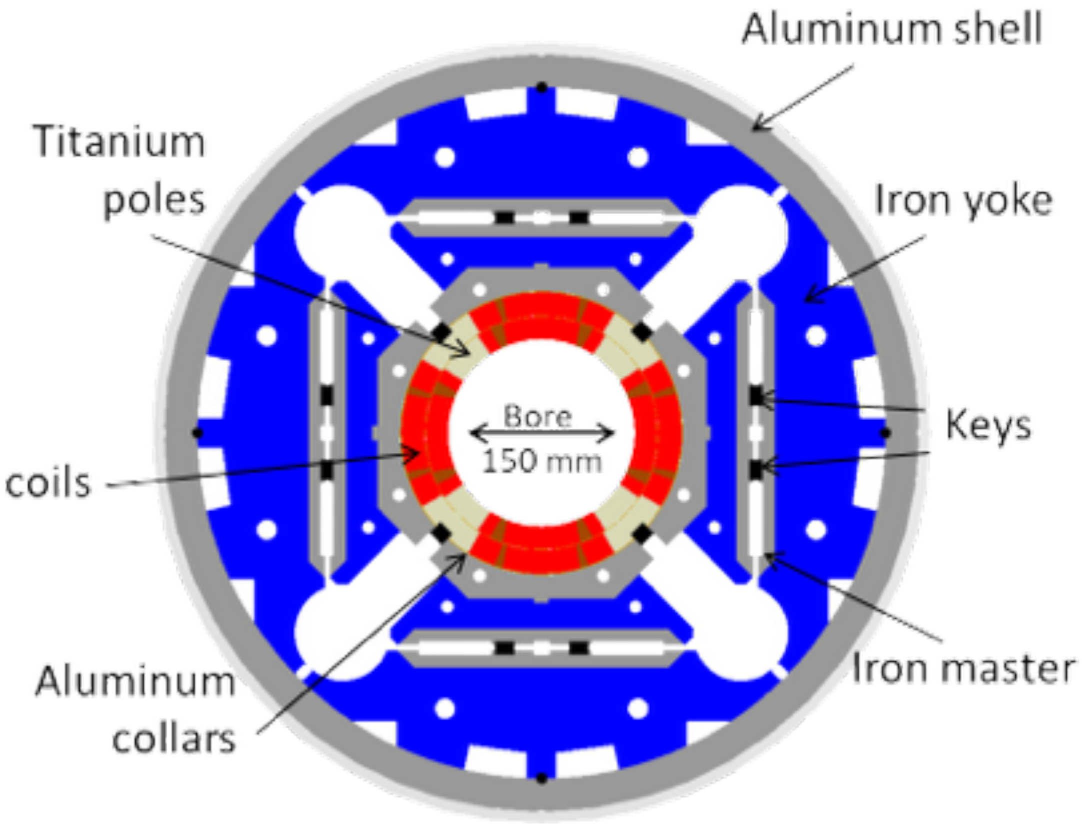
- ATLAS Letter of Intend [CERN-LHCC-2012-022]
- CMS Phase-II Technical Proposal [CERN-LHCC-2015-010]
- Additional public results
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

➡ **Scope documents discuss**

- Includes performance comparisons of <PU>=140 and 200
- Identify explicitly the benefits from extension of the tracker and muon coverage
- Document impact of reduced scope
- ATLAS [CERN-LHCC-2015-020], CMS [CERN-LHCC-2015-019]

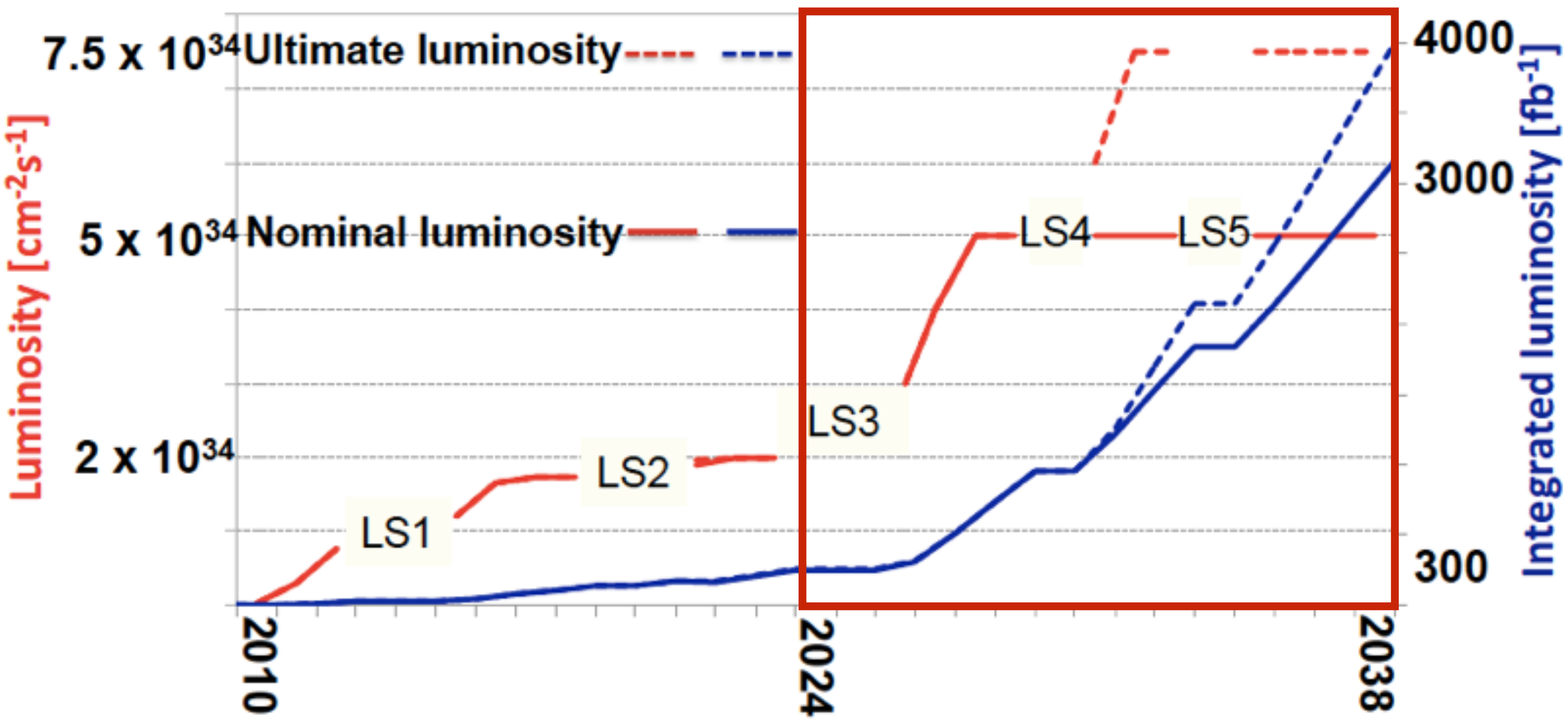
HL-LHC Schedule





- **LHC dipoles stretched NbTi technology to its limit**
  - 8.3T in central region via operation at 1.8k
- **HL-LHC needs new technology in iteration region: Nb_3SN**
  - 12T quadrupoles with 150mm aperture to shrink β^*
- **Operating and upgrading the LHC is a very significant investment**

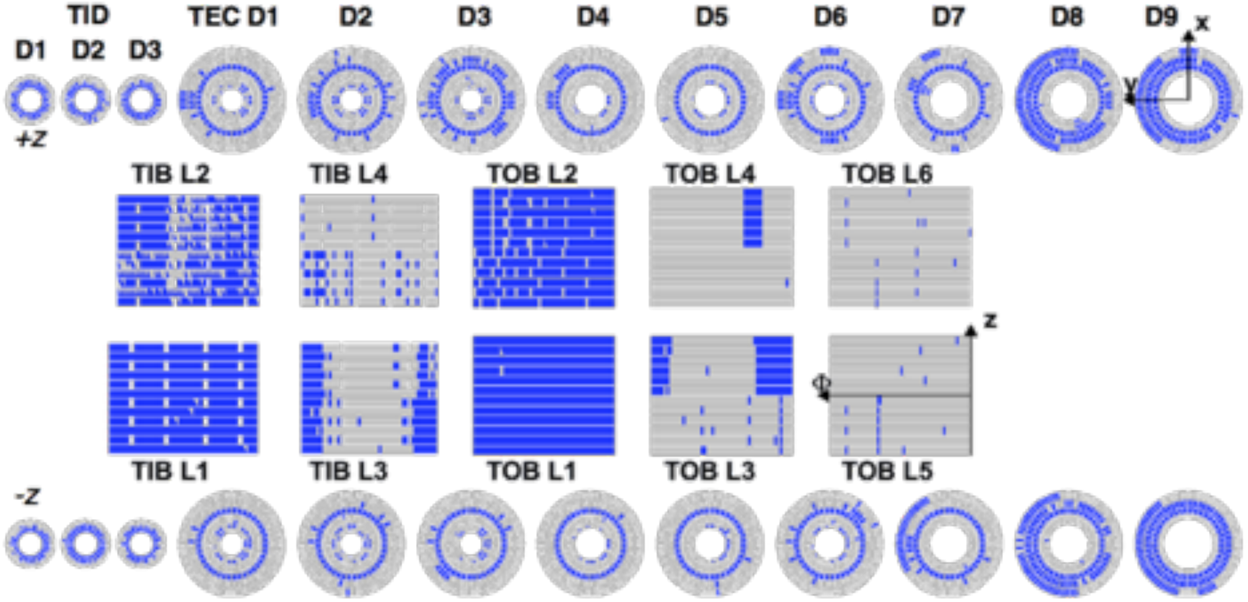
HL-LHC Schedule



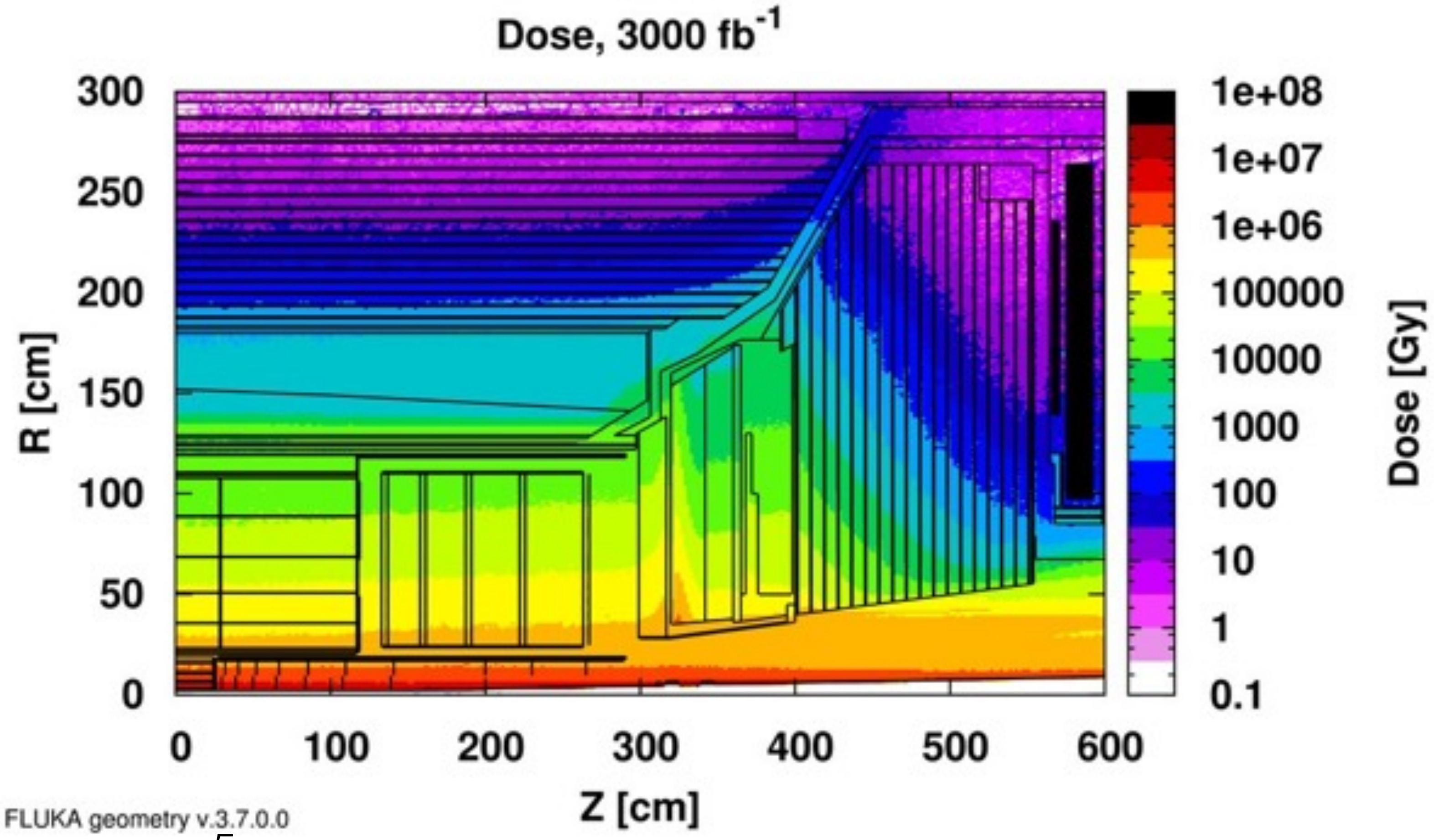
LHC / HL-LHC projects provide increase in **energy** and **luminosity** (accuracy)

Experimental Challenges

- ➡ Detectors have to operate in **extreme environment**
- ➡ In 2025 the detectors will be running (radiated) for 15 years. Severe **aging** effects.



Blue tracker modules are inactive after 1000 fb^{-1} due to very high leakage currents induced by neutron fluence.

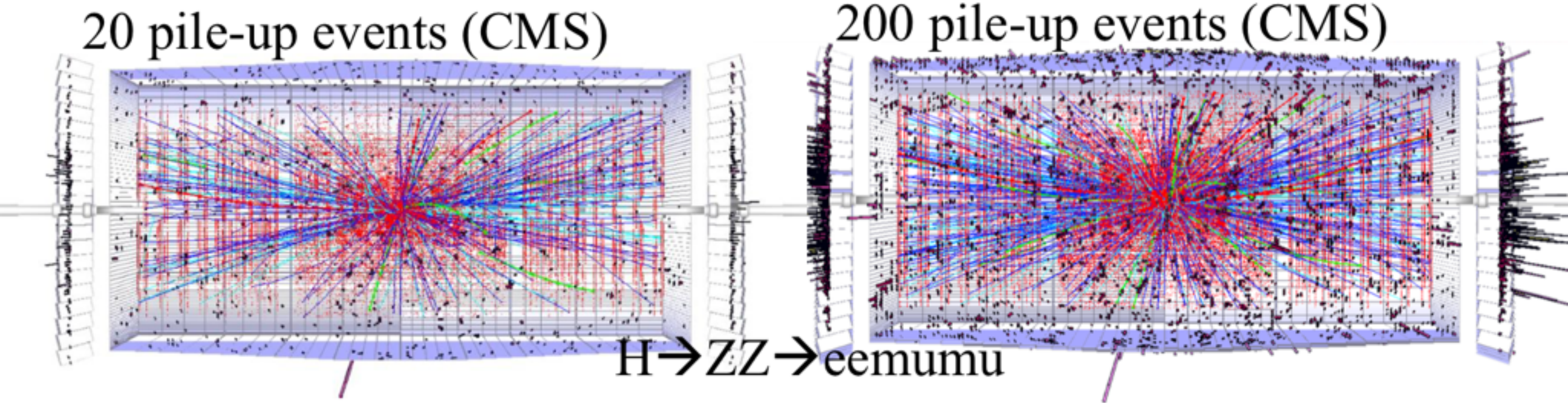


CMS FLUKA geometry v.3.7.0.0

Experimental Challenges

- Luminosity comes at the cost of **pileup**. Mean number of interaction scales with instantaneous luminosity
- Can be mitigated by reducing the bunch spacing, hence 25ns running from 2015
- Expect:
  - $\langle\mu\rangle \cong 140$ at $5\mathrm{x}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - $\langle\mu\rangle \cong 200$ at $7\mathrm{x}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- 2.5 - 3.5 increase wrt LHC design

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$



Pileup Mitigation

➡ **Tracking**

- High granularity and thin active region to reduce hit occupancy
- Increase the number of tracking layers

➡ **Calorimetry**

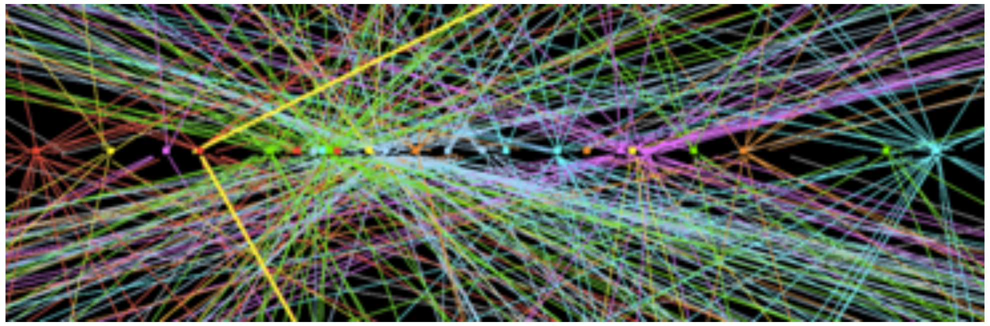
- Fit pulse shapes to extract in-time energy deposition
- Upgrade readout electronics
- Combine in-time energy measurements with tracking information using particle flow techniques

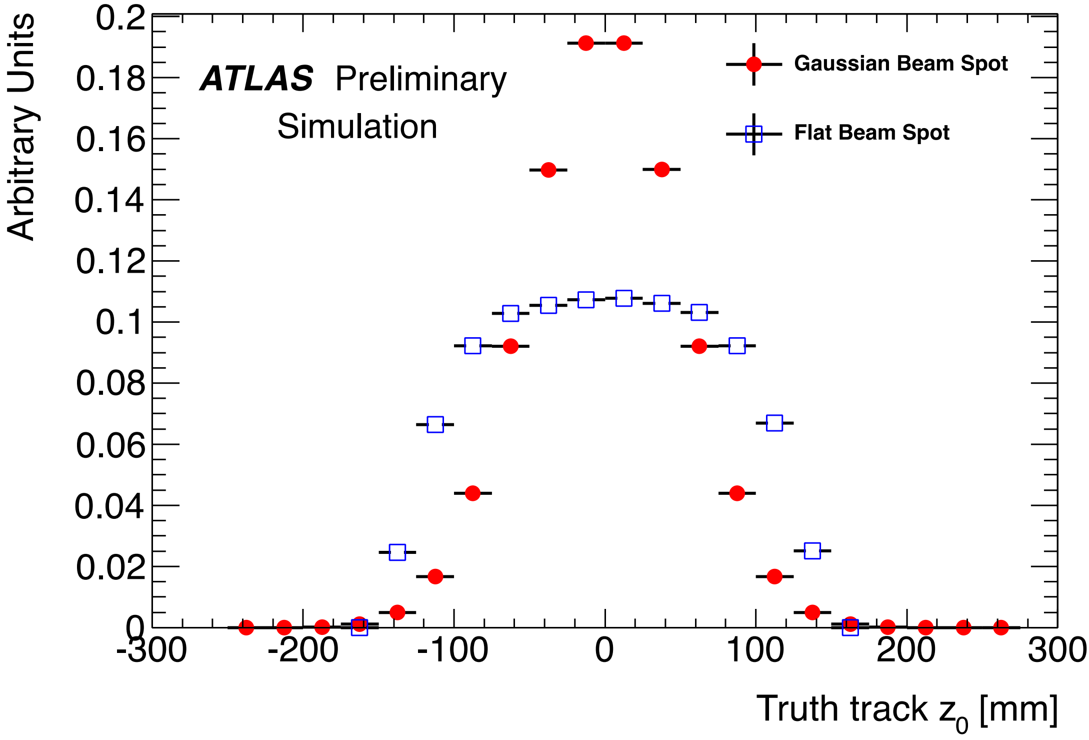
➡ **Precision timing**

- Reduce in-time pileup using the time distribution of collisions within the same bunch crossing
- Interaction time of a bunch crossing has rms of ~160ps
- Current ATLAS and CMS calorimeter timing resolution insufficient for significant rejection of PU

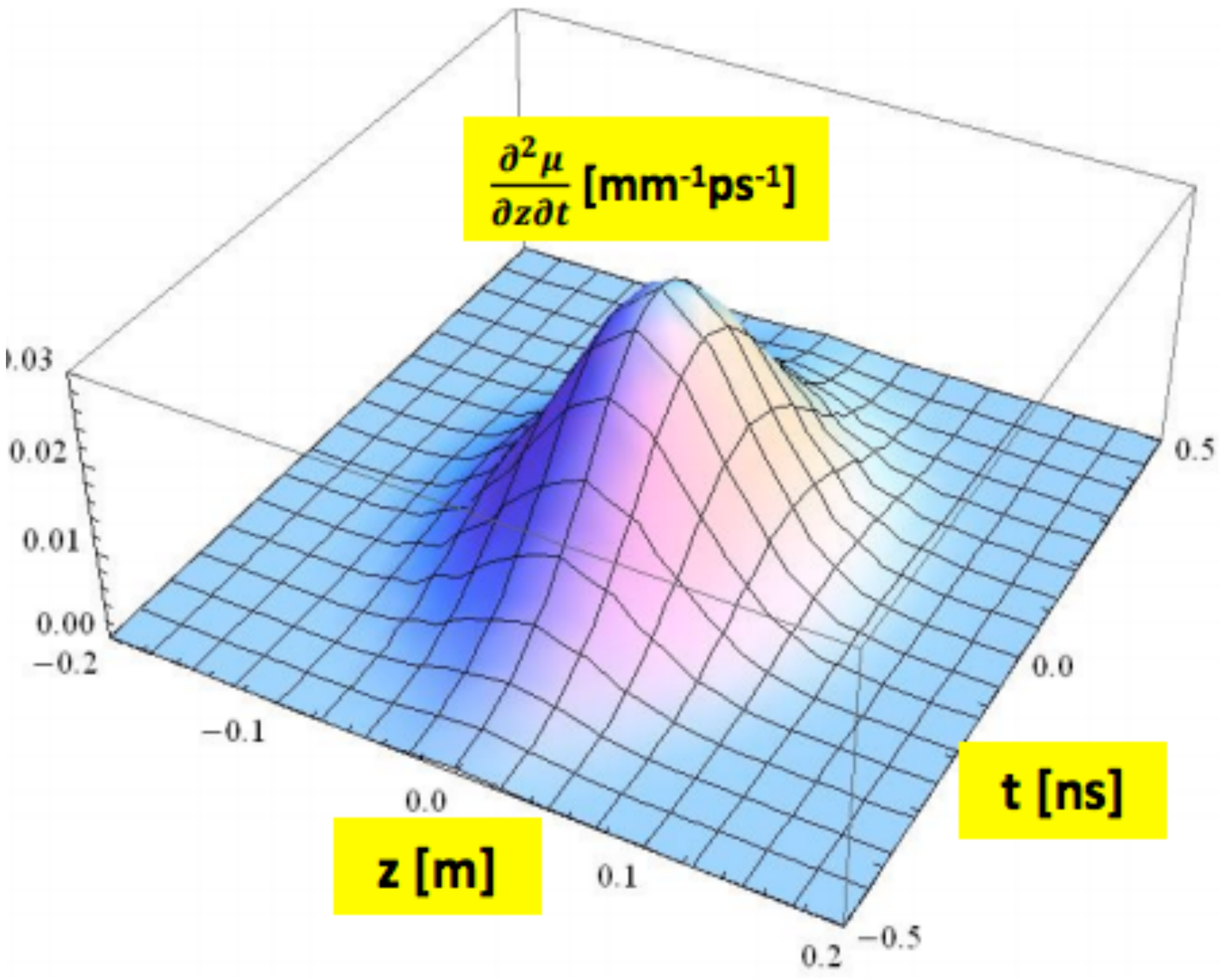
➡ **Pointing**

- Reduce in-time pileup directional information for neutral particles





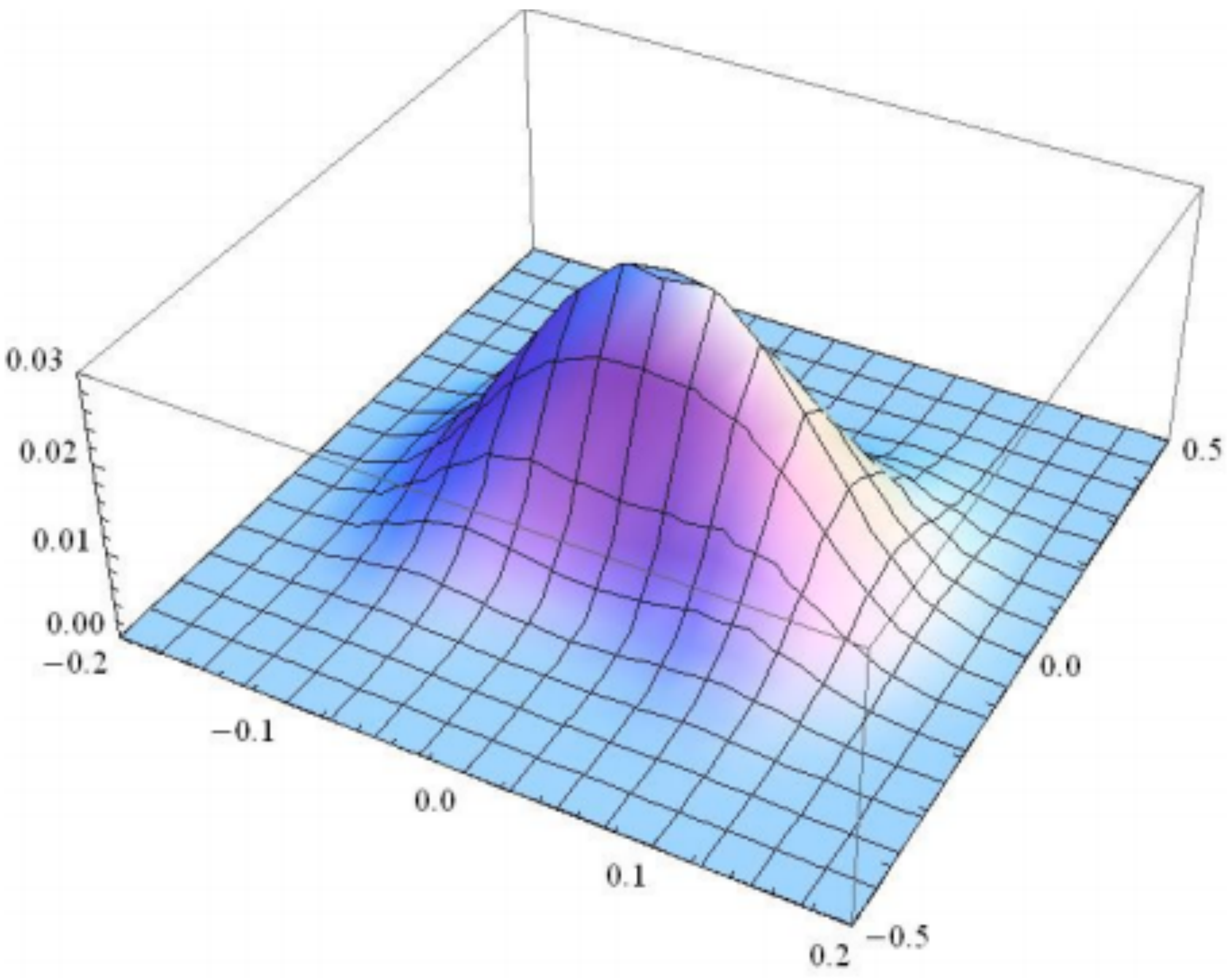
Luminous Region



HL-LHC Baseline

σ_{lum} = 5cm r.m.s.

σ_{lum} =160ps r.m.s.



Crab-Kissing

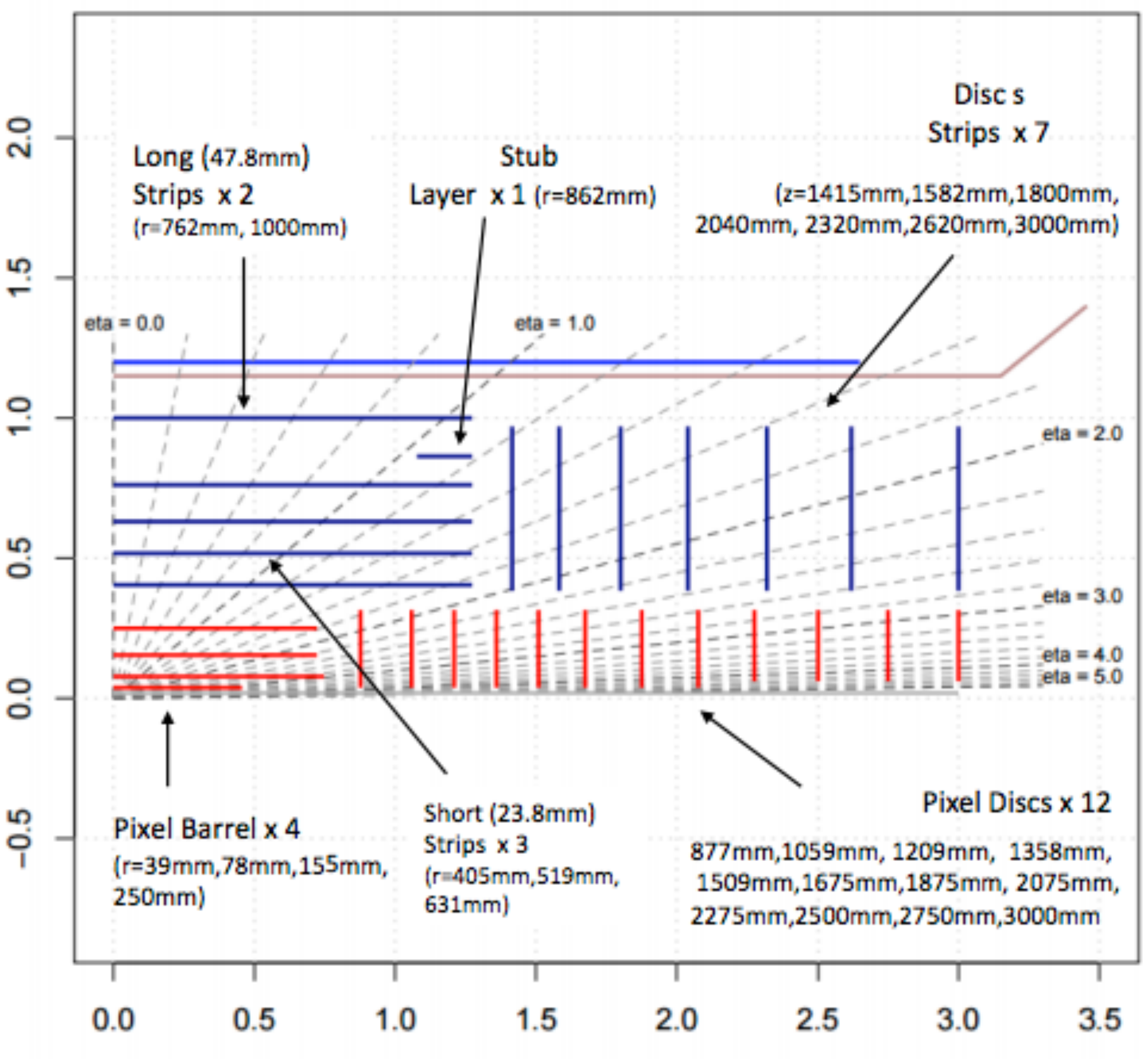
S. Fartoukh

σ_{lum} = 7cm r.m.s.

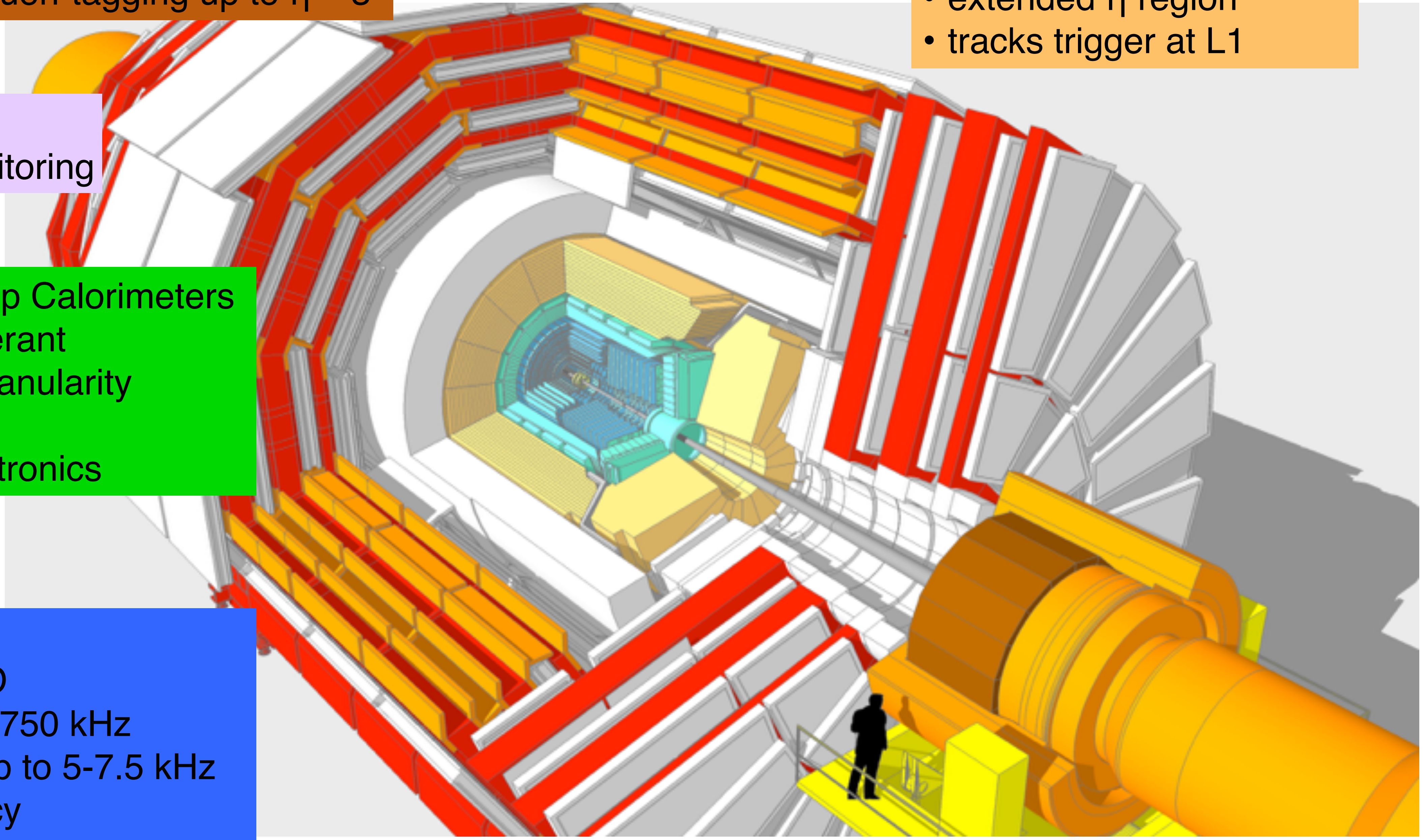
σ_{lum} =100ps r.m.s.

ATLAS Detector Upgrades

- **Trigger and Data-Flow system**
  - Introduction of level 0/1 trigger
  - Level 1 track trigger
  - DAQ upgrade
  - Muon trigger system
- **All new inner tracking detector**
- **Calorimeter Electronics**
- **Enhancements to high-eta regions**



CMS Phase-II Upgrade Detector



Muon System
- new DT FE electronics, CSC FEBs in inner rings
- extended η region (GEM & iRPC)
- investigate Muon-tagging up to η ~ 3

Tracker
- higher granularity
- less material
- better p_T resolution
- extended η region
- tracks trigger at L1

New luminosity and beam monitoring

Replace Endcap Calorimeters
- radiation tolerant
- increased granularity

Barrel ECAL
- new FE electronics

Trigger/DAQ
- new FE & RO
- L1 up to 500-750 kHz
- HLT output up to 5-7.5 kHz
- 12.5μs latency
- tracking @L1

Defining the HL-LHC Physics Program

- **Higgs case at the start of the LHC was exceptional**
  - something to built on, not the reference
- **SM is self-consistent theory that can be extrapolated to exponentially higher energies**
- **Goal for the future LHC and HL-LHC program**
  - **Explore the energy frontier**

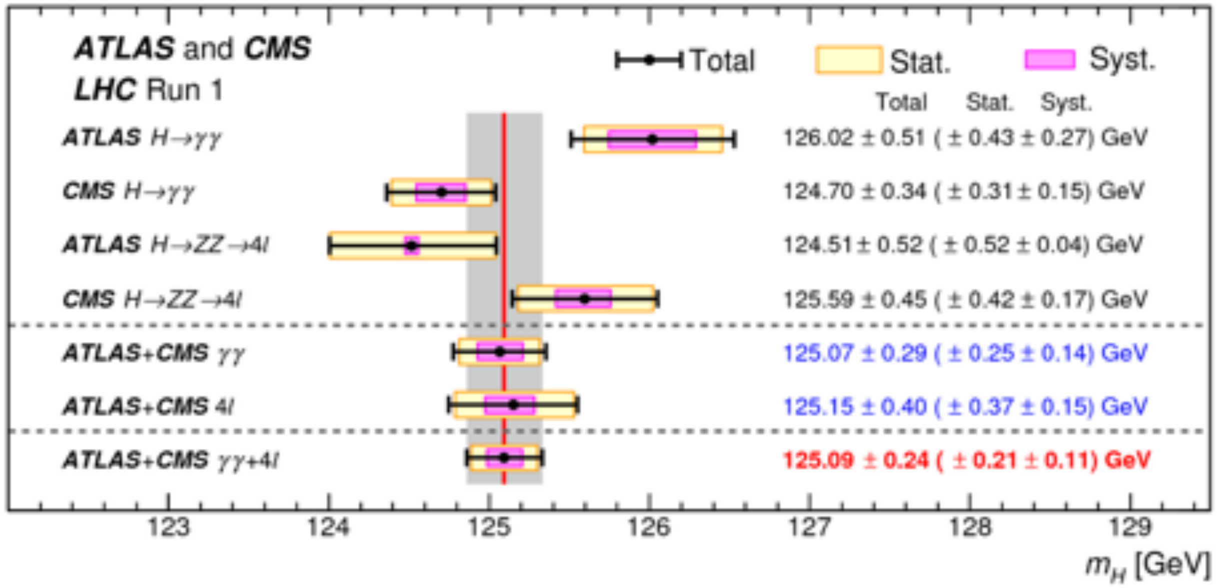
- **Precision measurements of SM parameters (including the Higgs boson)**
- **Sensitivity to rare SM & rare BSM processes**
- **Extension of discovery reach in high-mass region**
- **Determination of BSM parameter**

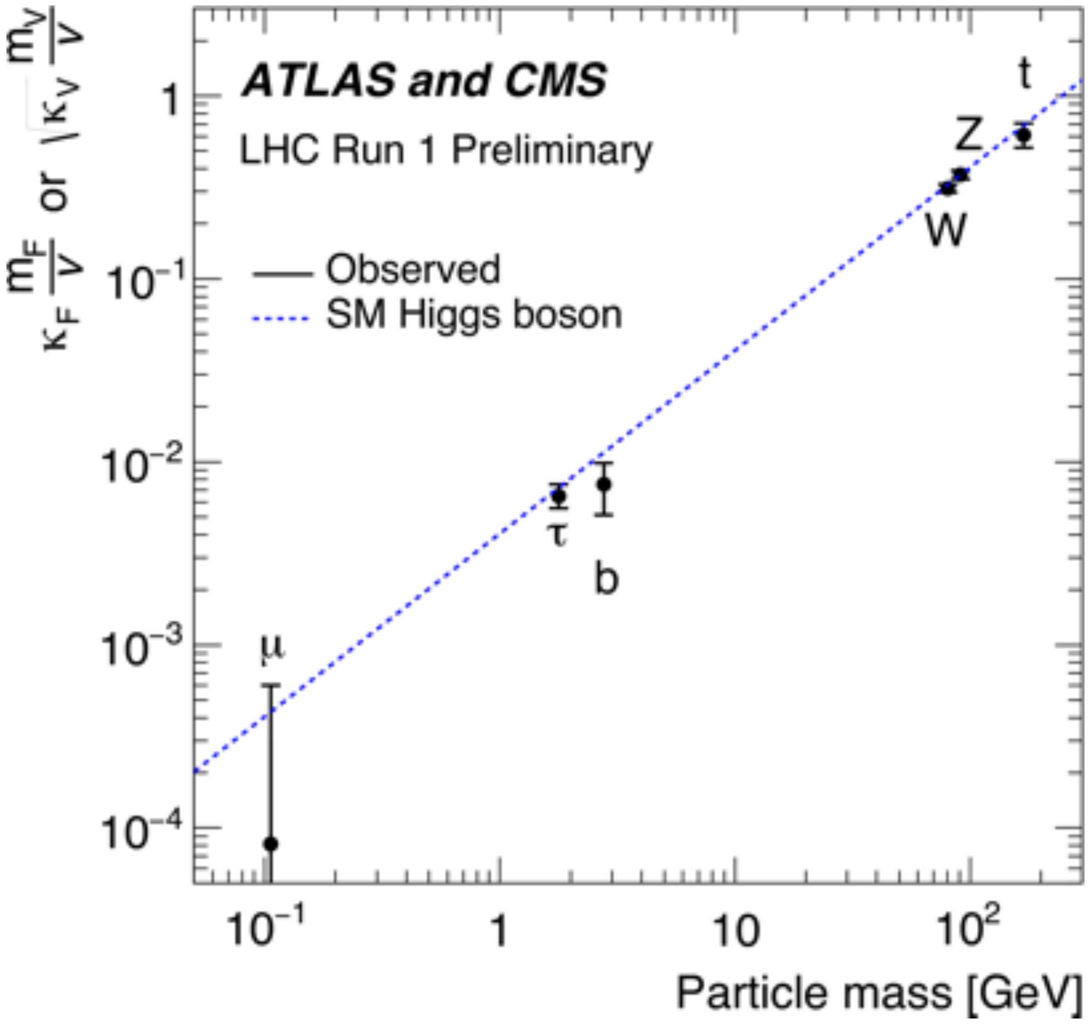
Higgs Physics Program

- ➡ **Combined measurement using LHC Run-1 dataset**

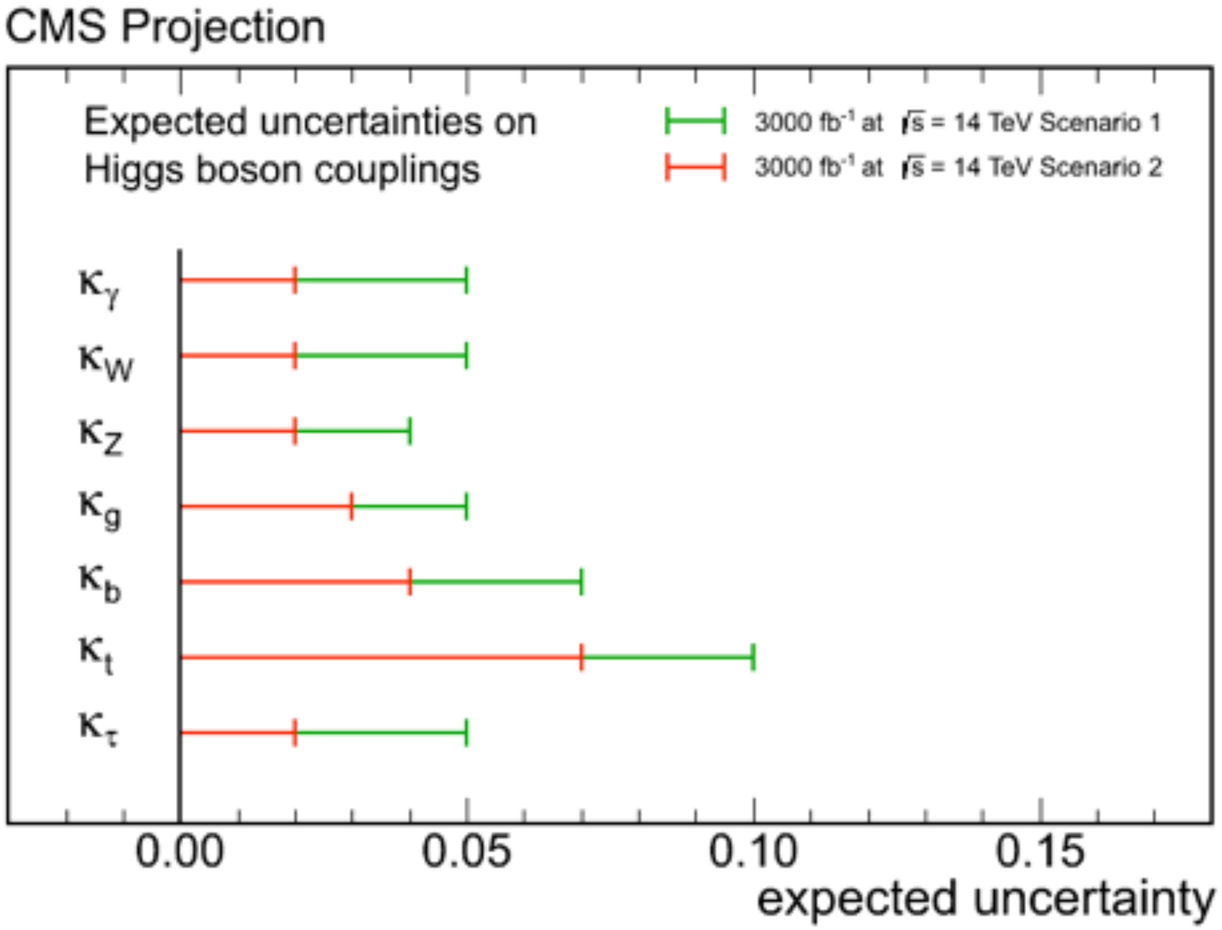
  m_H = 125.09 ± 0.21 (stat.) ± 0.11 (syst) GeV

- ➡ **Precision (0.2%) limited by statistical uncertainty**
- ➡ **Established that particle masses and couplings to the Higgs boson relate**
- ➡ **No additional Higgs bosons or BSM decays observed**





Higgs Precision Physics



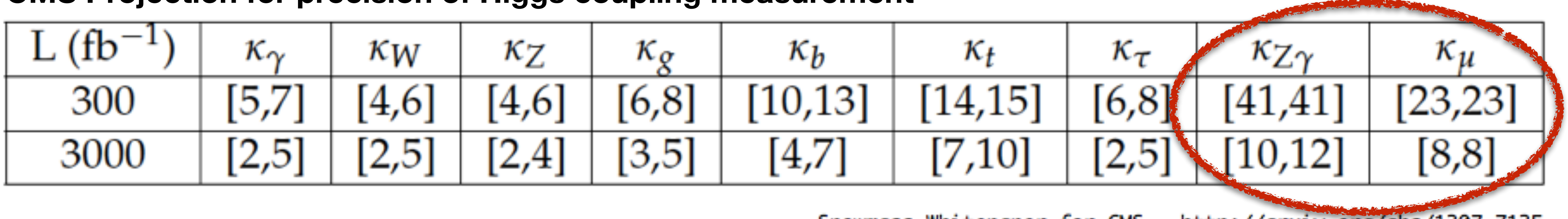
Coupling precision 2-10 %
factor ~2 improvement from HL-LHC

Key question is the
evolution systematic uncertainty

Assumptions made on cross section uncertainties already superseded

CMS Projection for precision of Higgs coupling measurement

Rare-decays

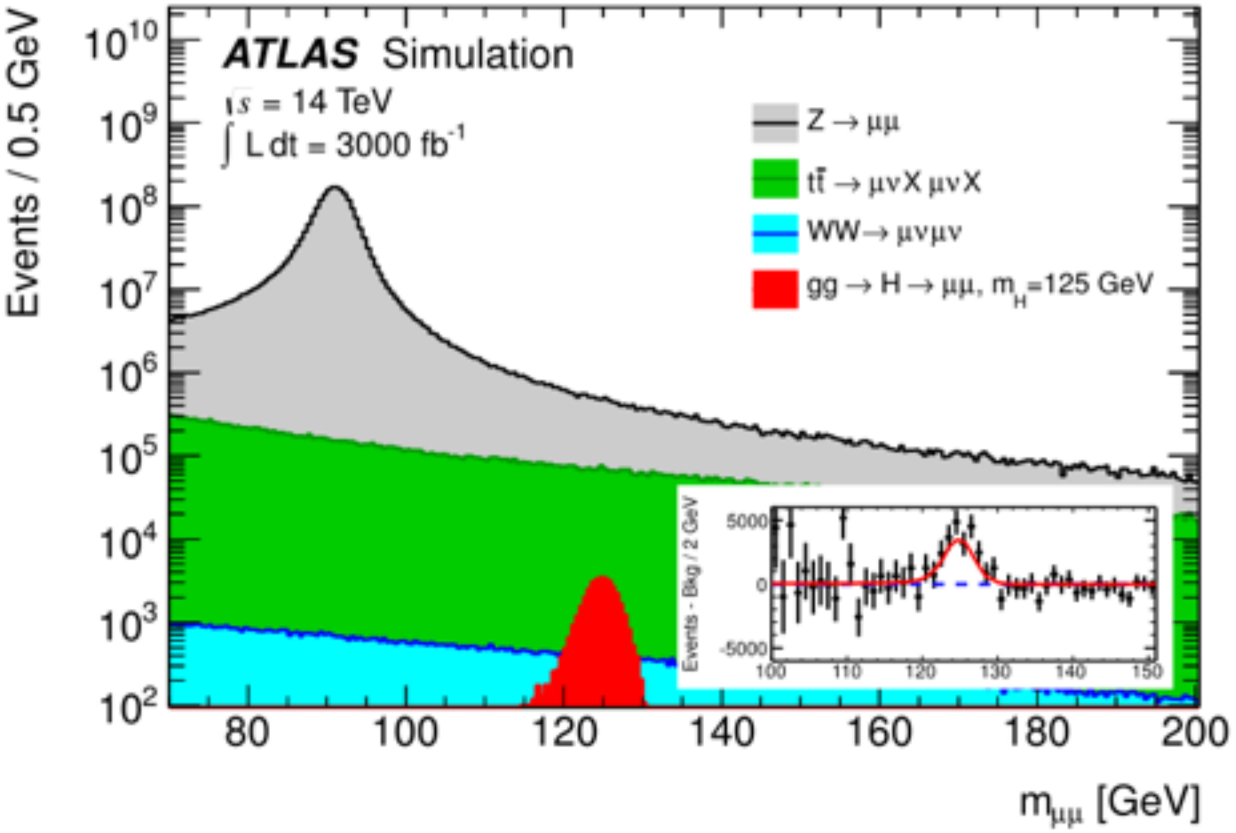


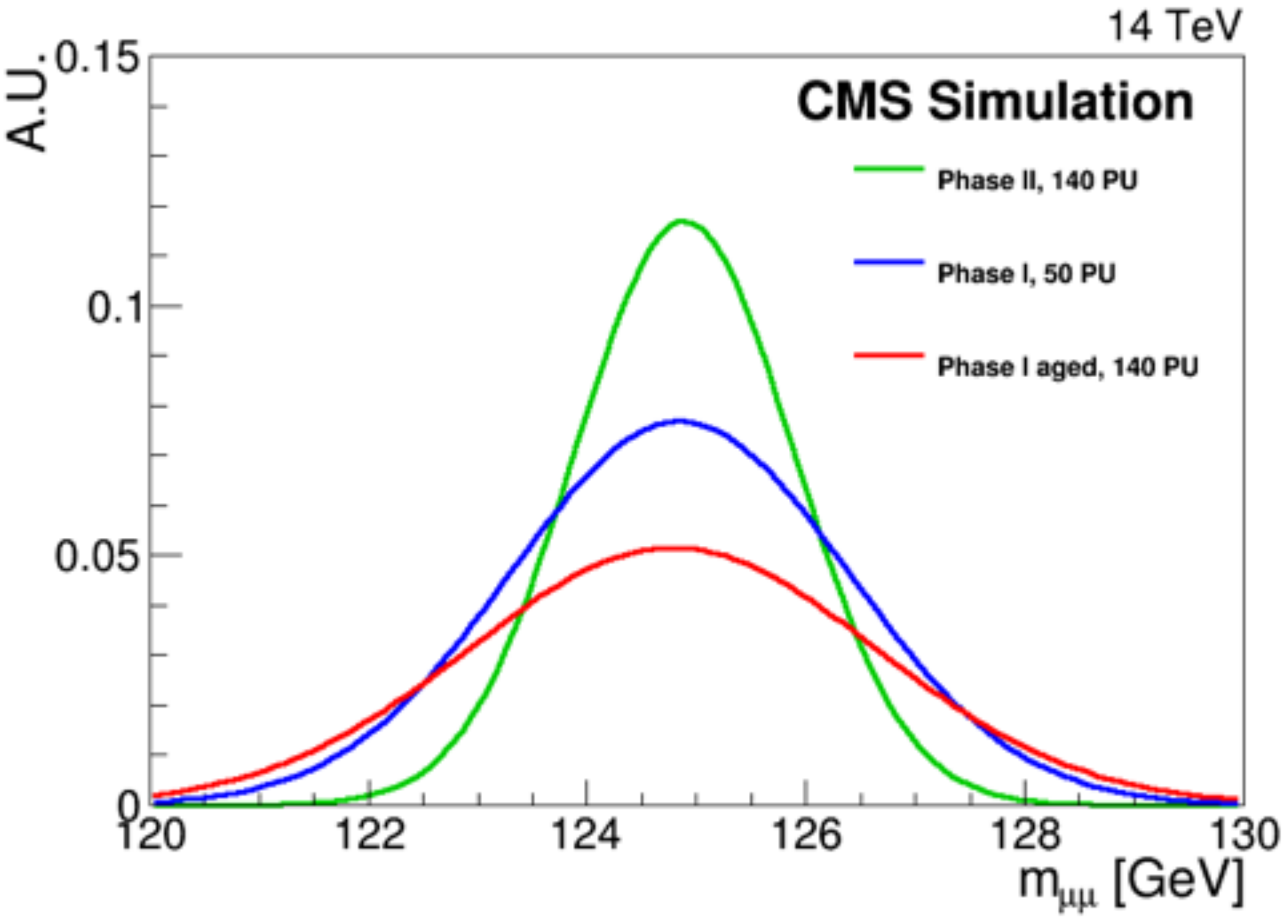
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

Snowmass Whitepaper for CMS - http://arxiv.org/abs/1307.7135

Rare Higgs Decays

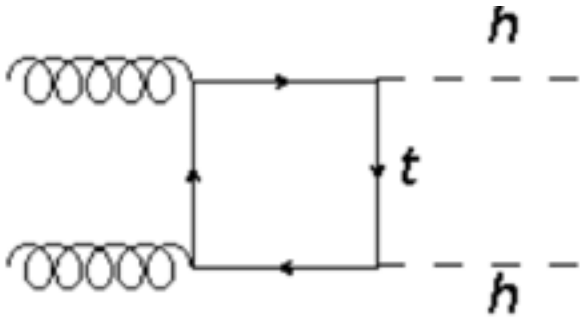
- **H → μμ**
  - 2nd generation fermion coupling
  - search for narrow resonance with huge DY background
  - CMS: ~45% improvement in resolution wrt Phase-I aged PU =140
  - CMS: ~20% improvement in efficiency wrt Phase-I aged PU =140
  - results scale with square-root of improvements
  - **expect ~5% uncertainty second generation Higgs coupling**

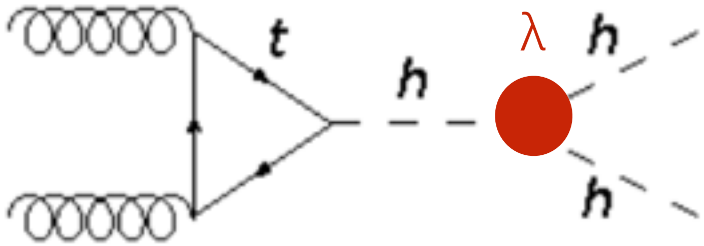


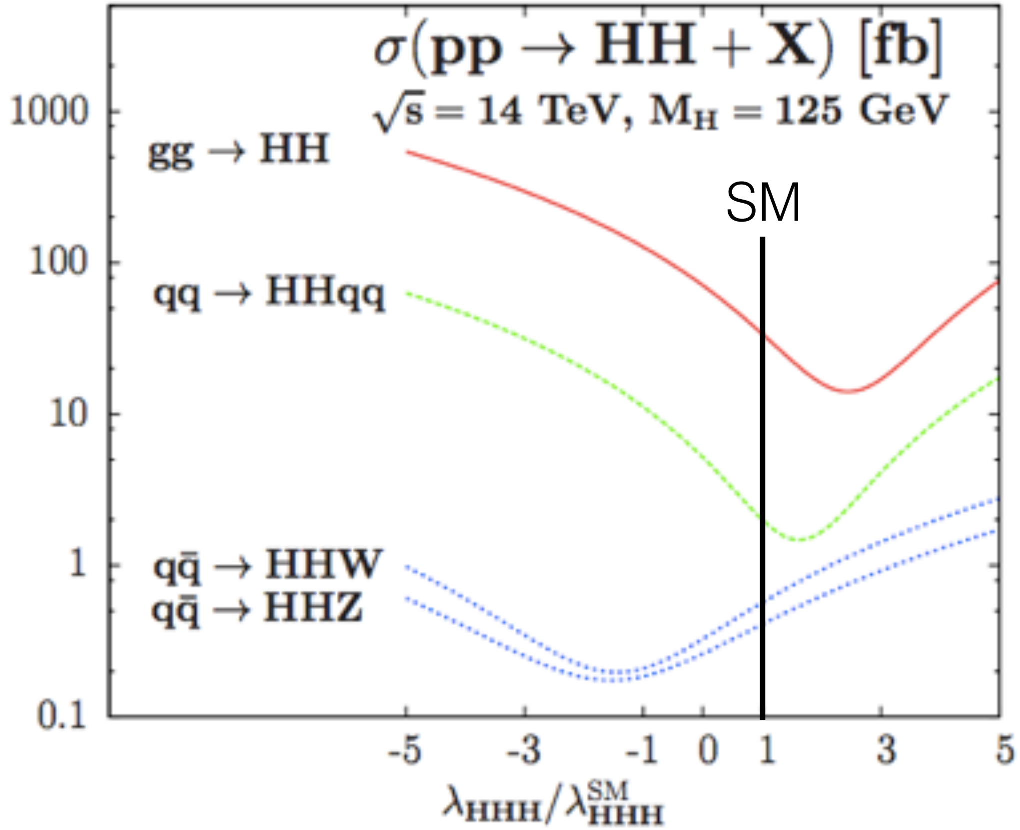


Very Rare Higgs Decays

- **Exciting prospects of the HL-LHC**
  - A process like di-Higgs production has not been observed in nature
  - Gluon fusion cross section is only **40.2fb** [NNLO] at 14 TeV
  - Vector boson fusion cross section is 2fb
  - Challenging measurement
- **Destructive interference in gluon fusion**







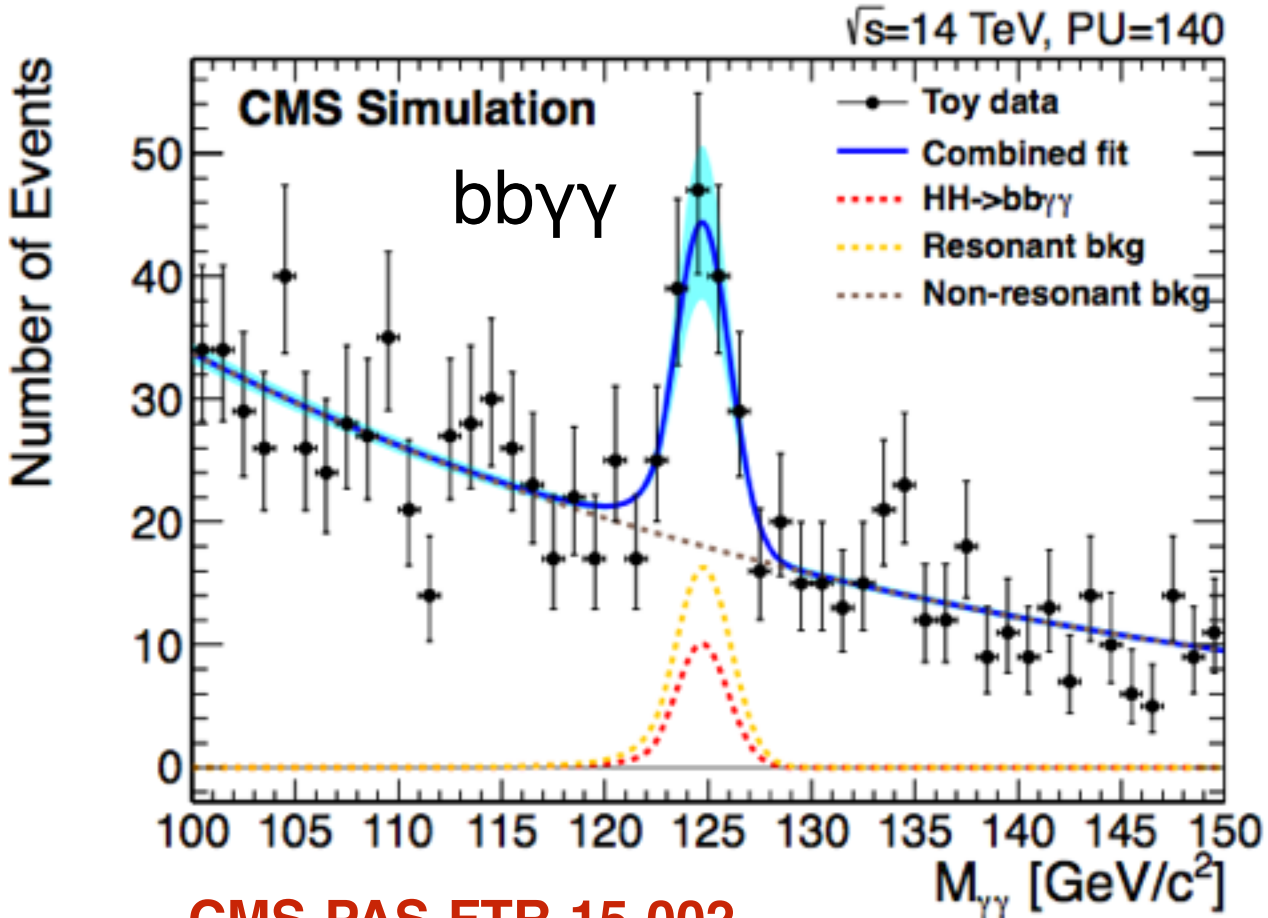
Baglio et al, arXiv:1212.5581

- **Most interesting final states**
  - bbγγ [320 expected events in 3ab-1]
  - bb$\tau\tau$ [9000 expected]
  - bbbb [40k expected (2k in VBF)]
  - bbWW [30000 exp. events]
- **Goal is to reach minimum sensitivity of 3σ for SM production and with that to BSM scenarios**

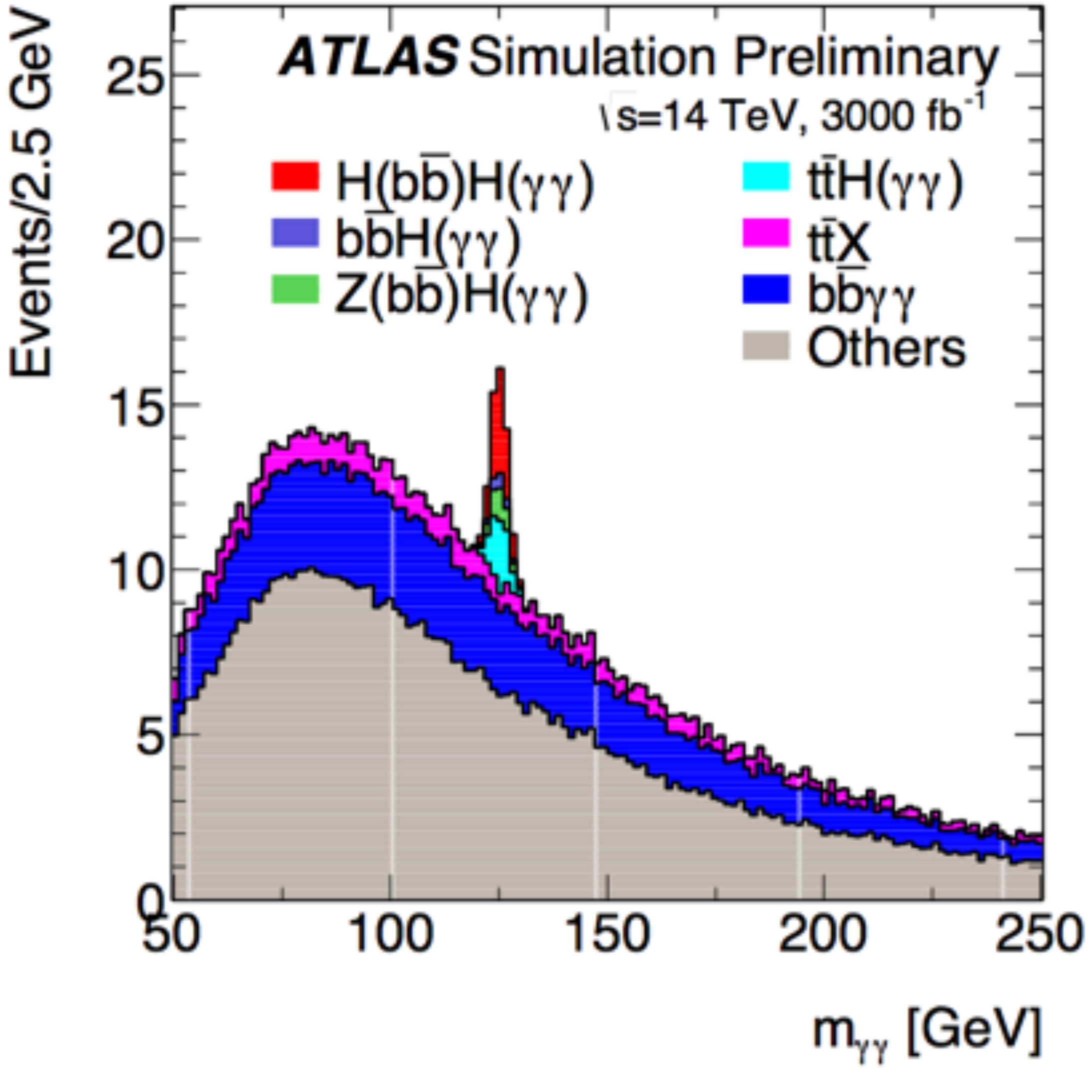
Di-Higgs Searches

- **Demonstrate Phase-II detector capabilities**
  - b-tagging, photon, and tau-Id
  - case for the track trigger
- **Sensitivity**
  - ~2σ per experiment

- **Further improvements**
  - additional channels (bbbb)
  - improved pixel detector (b-tagging)
  - improved resolutions (regression)
  - analysis strategies

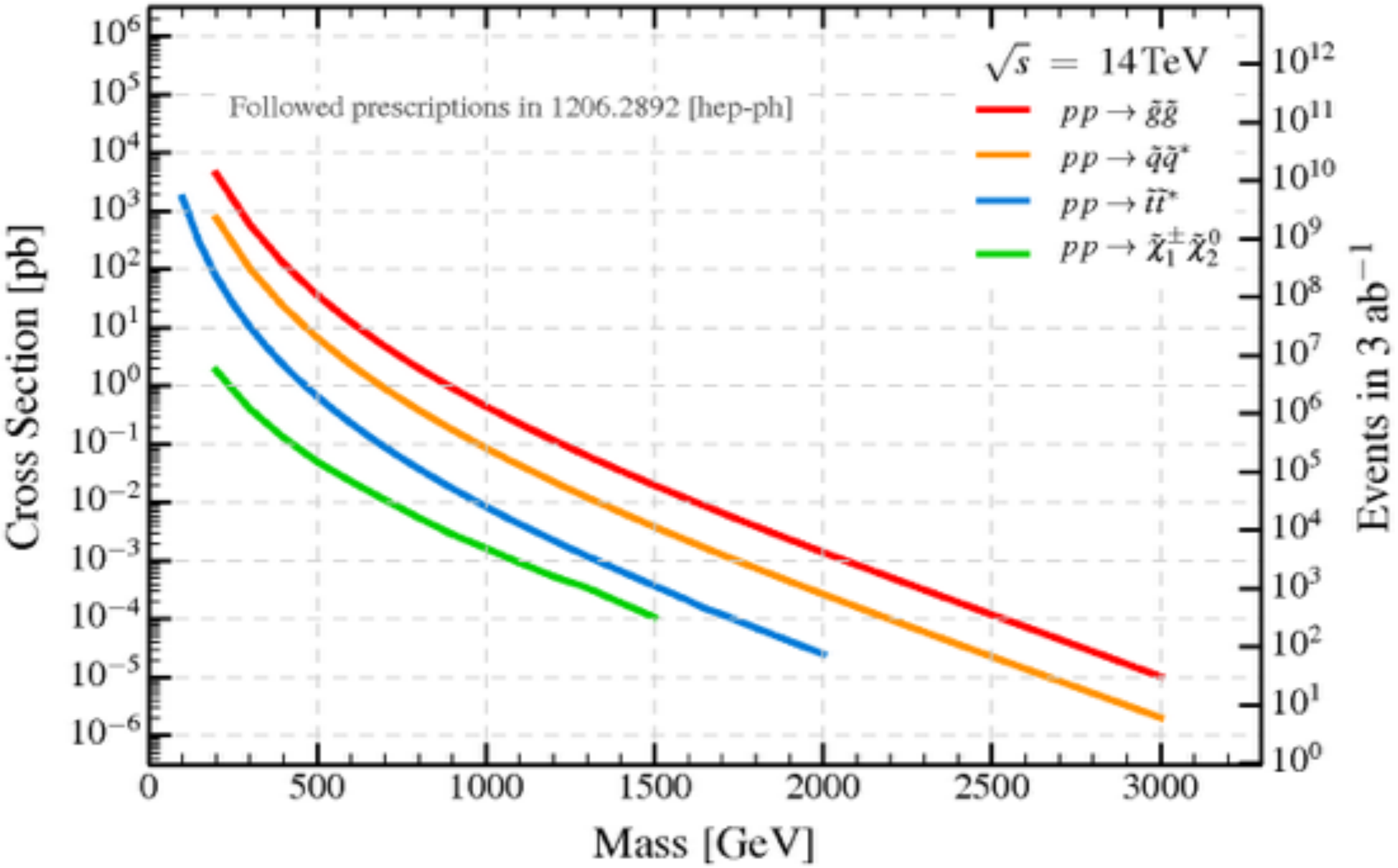


CMS-PAS-FTR-15-002

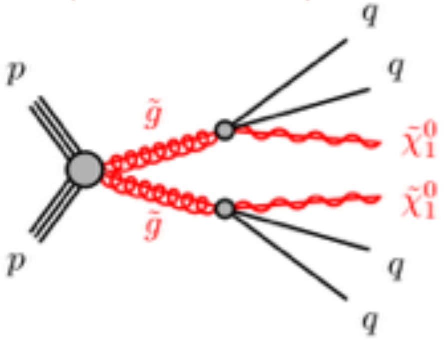


Supersymmetry

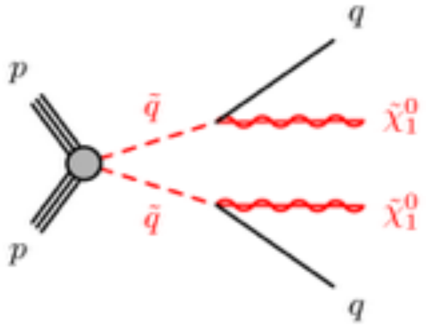
- **Motivation for SUSY has never been stronger**
  - discovery of the Higgs gives new urgency to find “natural” explanation for gauge hierarchy
  - HL-LHC expands discovery reach or allows to investigate SUSY spectrum
  - requires all capabilities of ATLAS & CMS



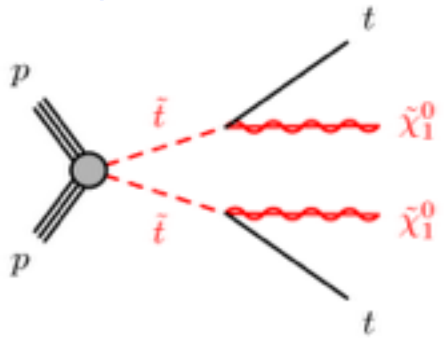
Strong prod. of gluinos



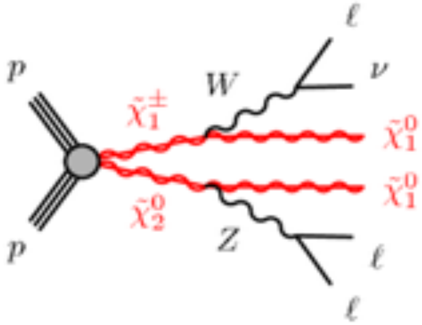
Strong prod. of squarks



Strong prod. of stops

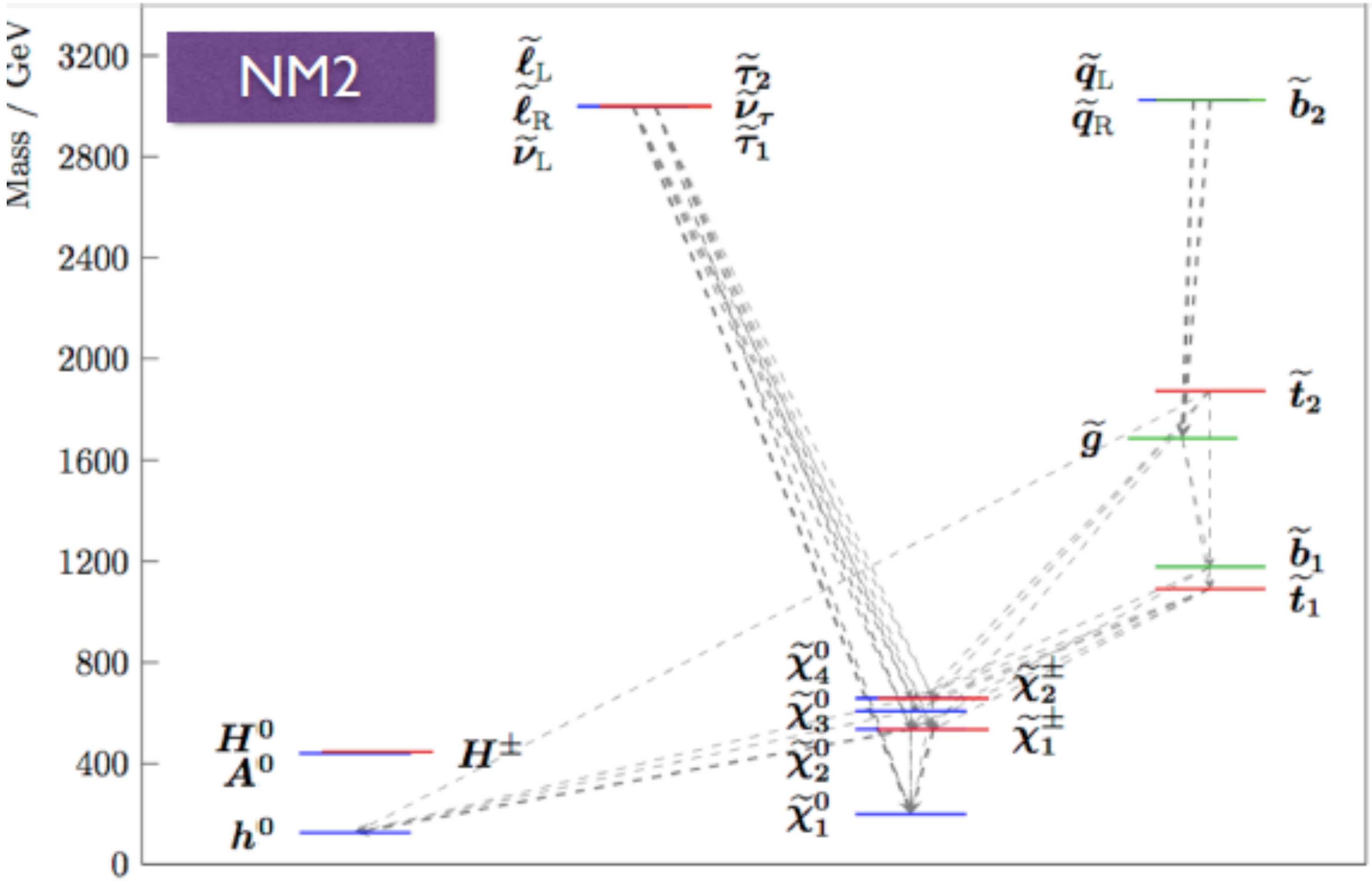


EW prod. of $\chi_1^+\chi_2^0$



Supersymmetry

- **CMS explored five phenomenological models motivated by naturalness**
  - models vary nature of the LSP (bino-, higgsino-like), EWK-inos, and sleptons hierarchies
  - STC (stau) and STOC) co-annihilation models satisfy dark matter constraints



Supersymmetry

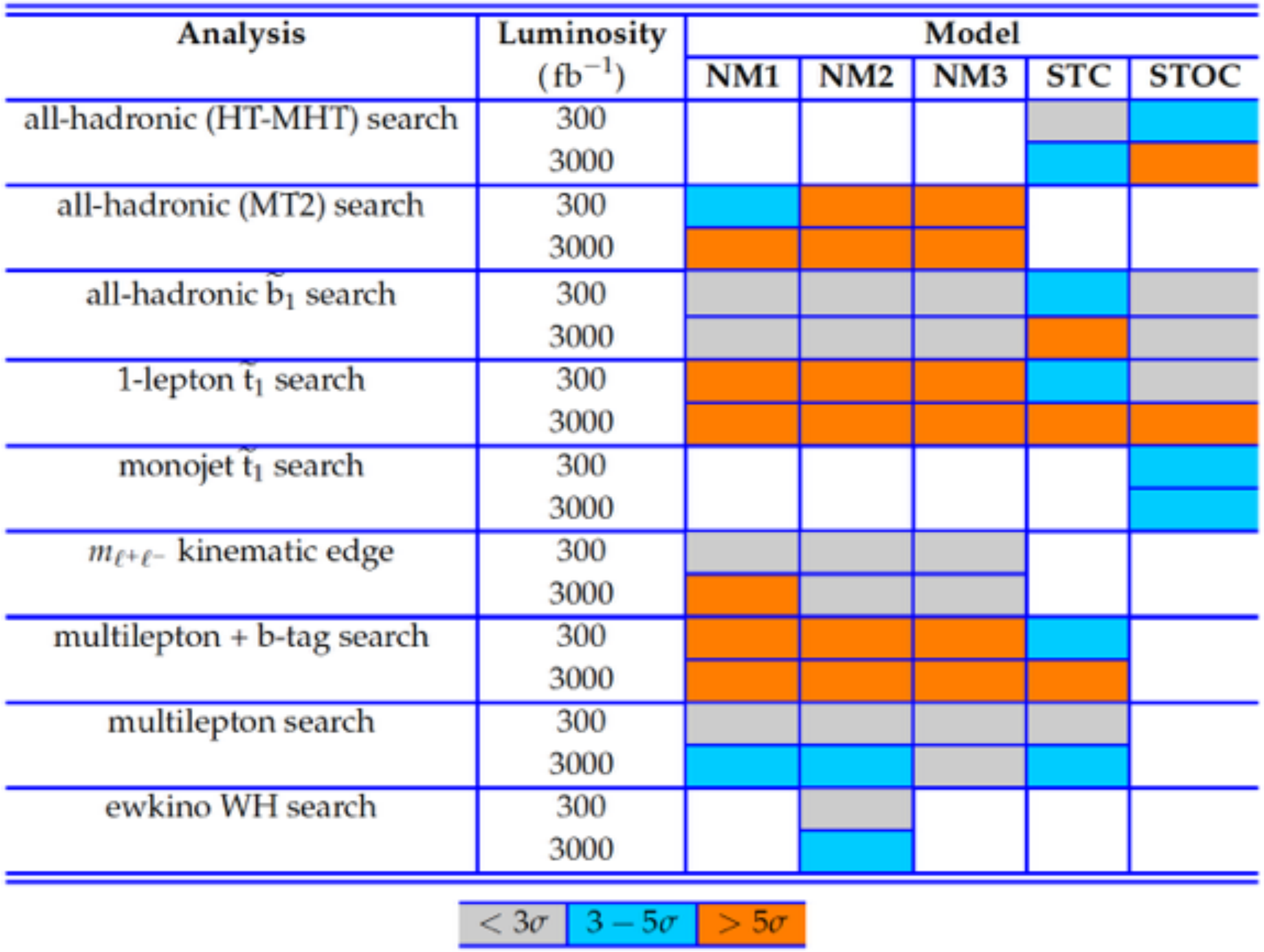
Explored:

- 9 different experimental signatures.
- 5 different types of SUSY models.

Different types of SUSY models lead to different patterns of discoveries in different final states after different amounts of data

Exploring experimental signature space

Exploring SUSY model space

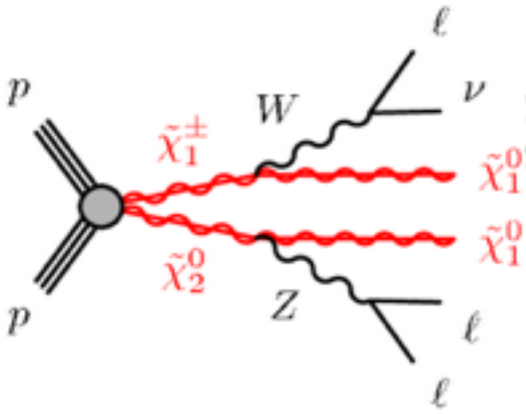


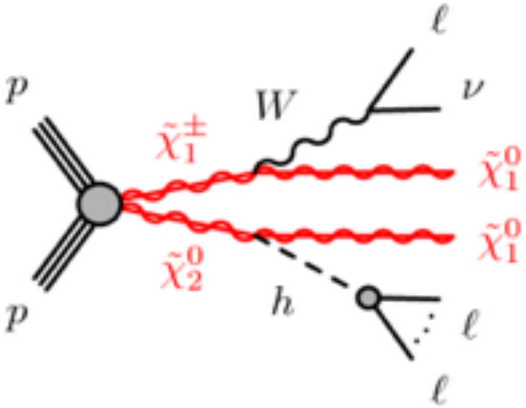
Analysis	Luminosity (fb^{-1})	Model				
		NM1	NM2	NM3	STC	STOC
all-hadronic (HT-MHT) search	300				▨	🟦
	3000				🟦	🟧
all-hadronic (MT2) search	300	🟦	🟧	🟧		
	3000	🟧	🟧	🟧		
all-hadronic $\tilde{b}_1$ search	300	▨	▨	▨	🟦	▨
	3000	▨	▨	▨	🟧	▨
1-lepton $\tilde{t}_1$ search	300	🟧	🟧	🟧	🟦	▨
	3000	🟧	🟧	🟧	🟧	🟧
monojet $\tilde{t}_1$ search	300					🟦
	3000					🟦
$m_{\ell^+\ell^-}$ kinematic edge	300	▨	▨	▨		
	3000	🟧	▨	▨		
multilepton + b-tag search	300	🟧	🟧	🟧	🟦	
	3000	🟧	🟧	🟧	🟧	
multilepton search	300	▨	▨	▨	▨	
	3000	🟦	🟦	▨	🟦	
ewkino WH search	300		▨			
	3000		🟦			

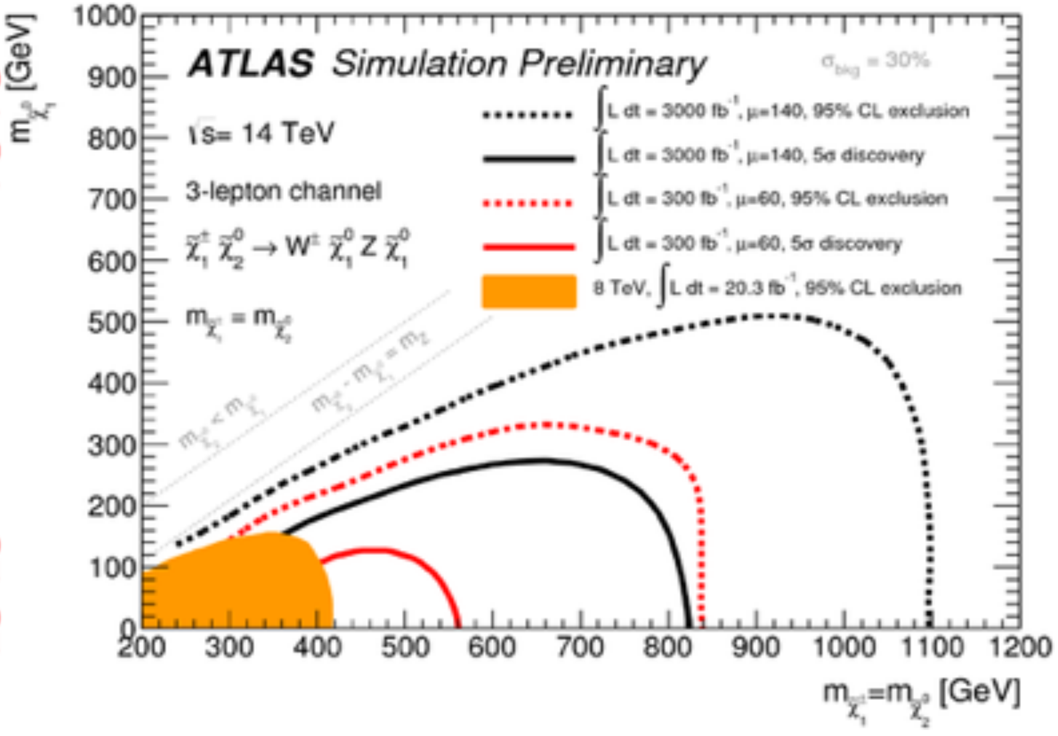
▨ $< 3\sigma$ 🟦 $3 - 5\sigma$ 🟧 $> 5\sigma$

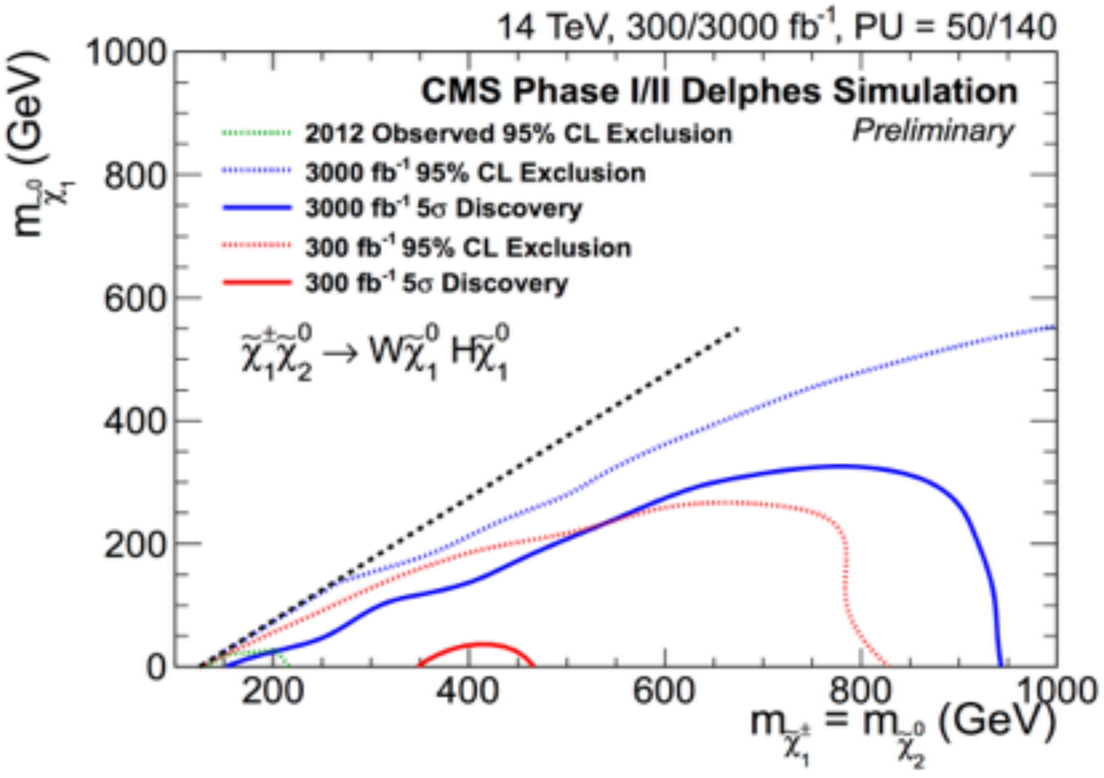
HL-LHC measurements can be crucial to illuminate a Run 3 discovery, and thus answer fundamental questions about gauge hierarchy or dark matter

Electroweak SUSY Production





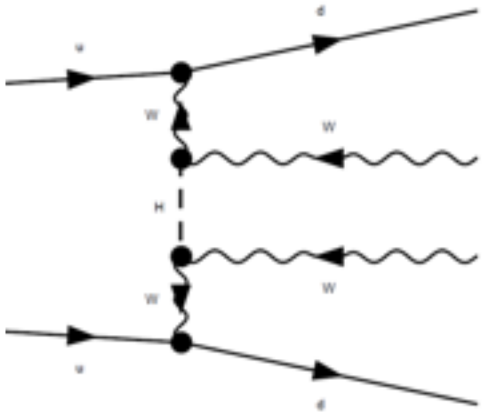


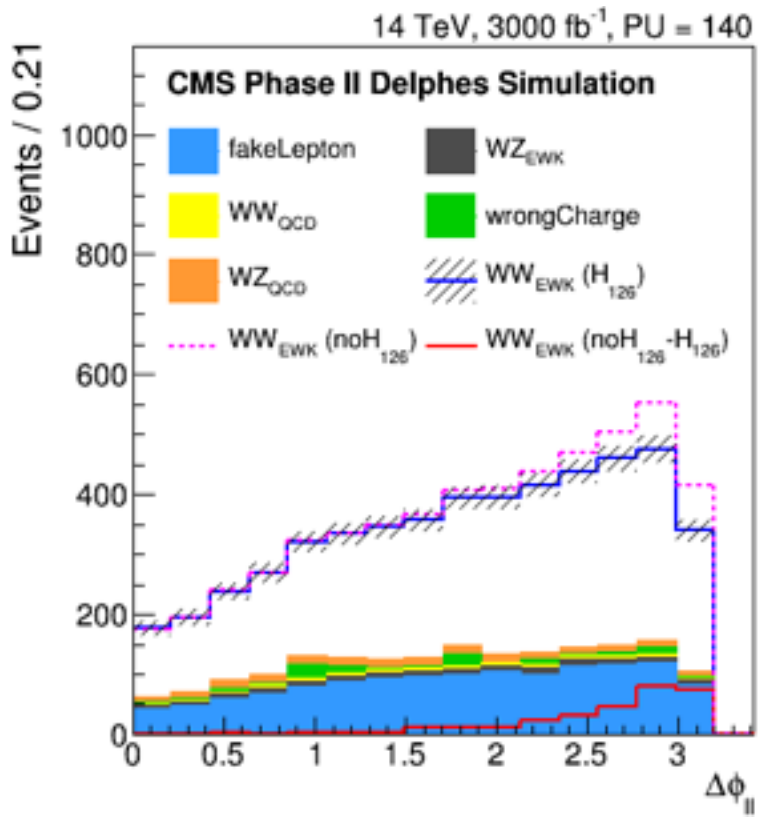


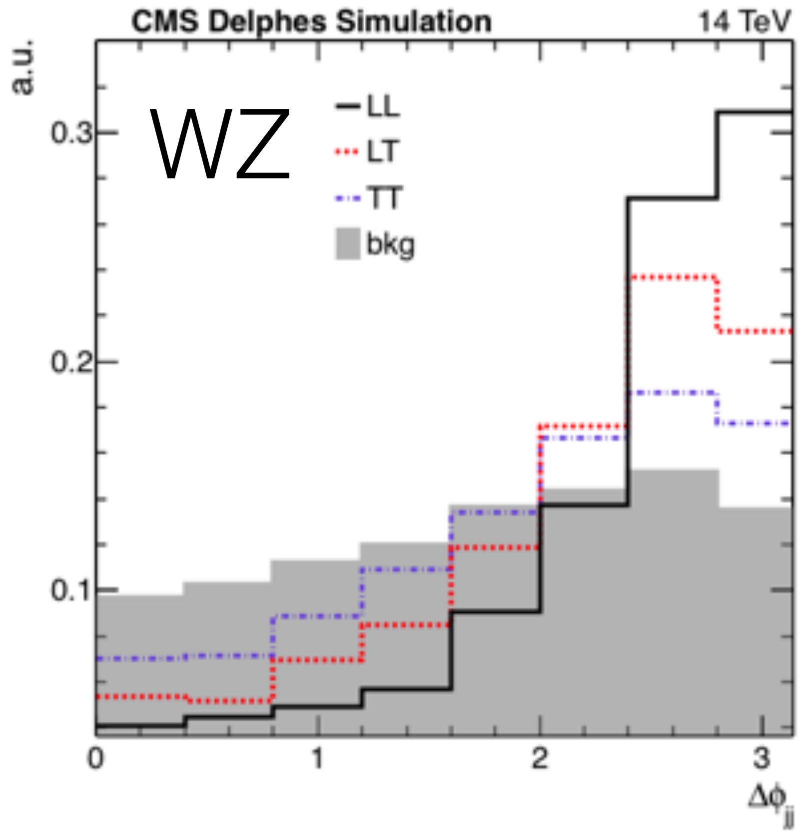
Chargino mass 5σ discovery, simplified model	300 fb^{-1}	3000 fb^{-1}
WZ (3l analysis) [ATLAS]	Up to 560 GeV	Up to 820 GeV
WZ (3l analysis) [CMS]	Up to 600 GeV	Up to 900 GeV
WH (3l analysis) [ATLAS]	(<5σ reach)	Up to 650 GeV
WH (bb analysis) [ATLAS]	(<5σ reach)	Up to 800 GeV
WH (bb analysis) [CMS]	350-460 GeV	Up to 950 GeV

Vector boson scattering

- ➡ **Assess VBS sensitivity using same-sign WW and WZ**
  - ◉ utilizing unique event topology
  - ◉ longitudinal scattering cross section
  - ◉ anomalous couplings
  - ◉ SM-noH measurement (input to Higgs couplings)





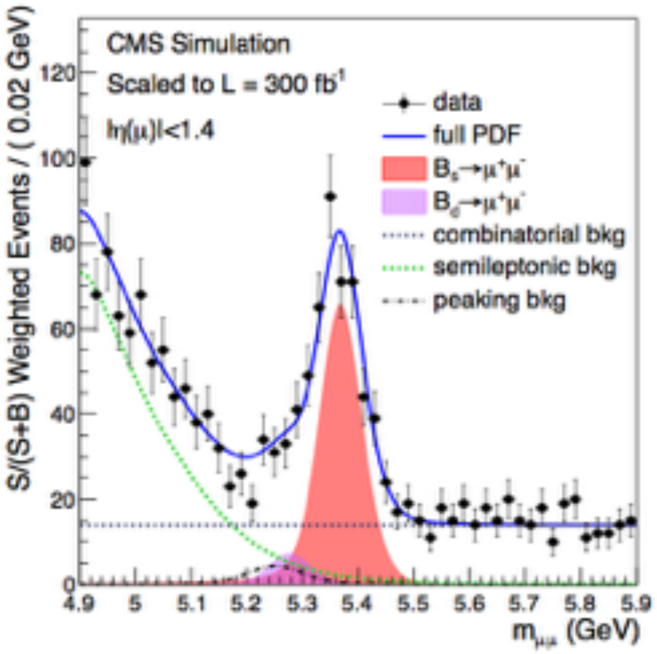


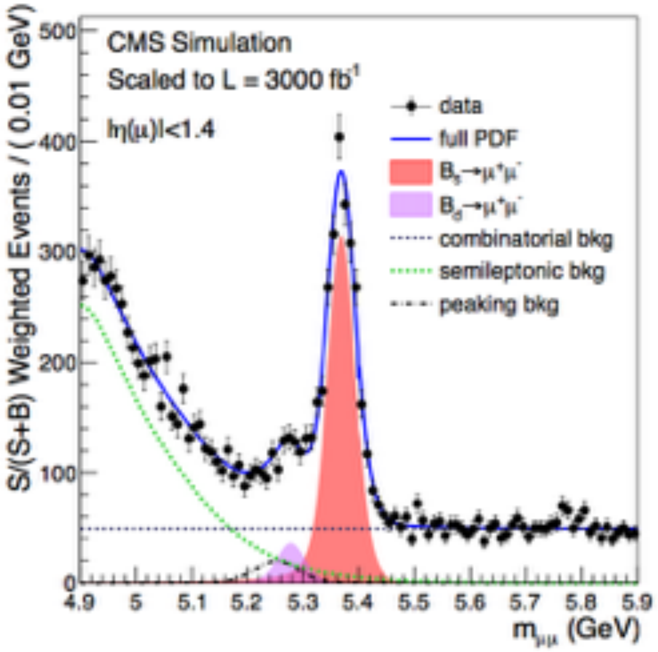
Combined performance

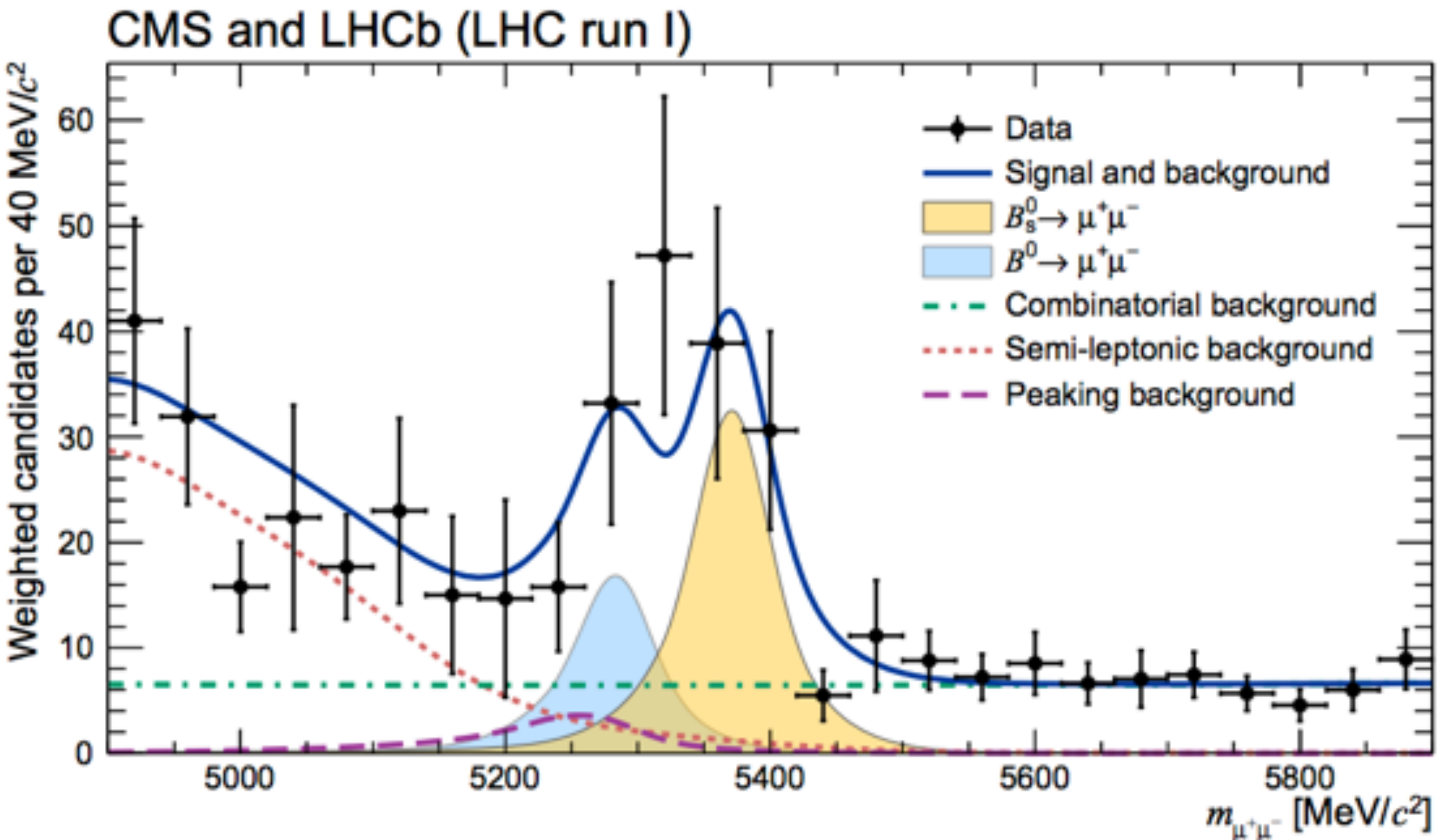
3000 fb^{-1}, 14 TeV	Phase-I	Phase-II	Phase-I aged
Higgsless 95% CL μ exclusion	0.14	0.14	0.20
V_L V_L scattering significance	2.50	2.75	2.14

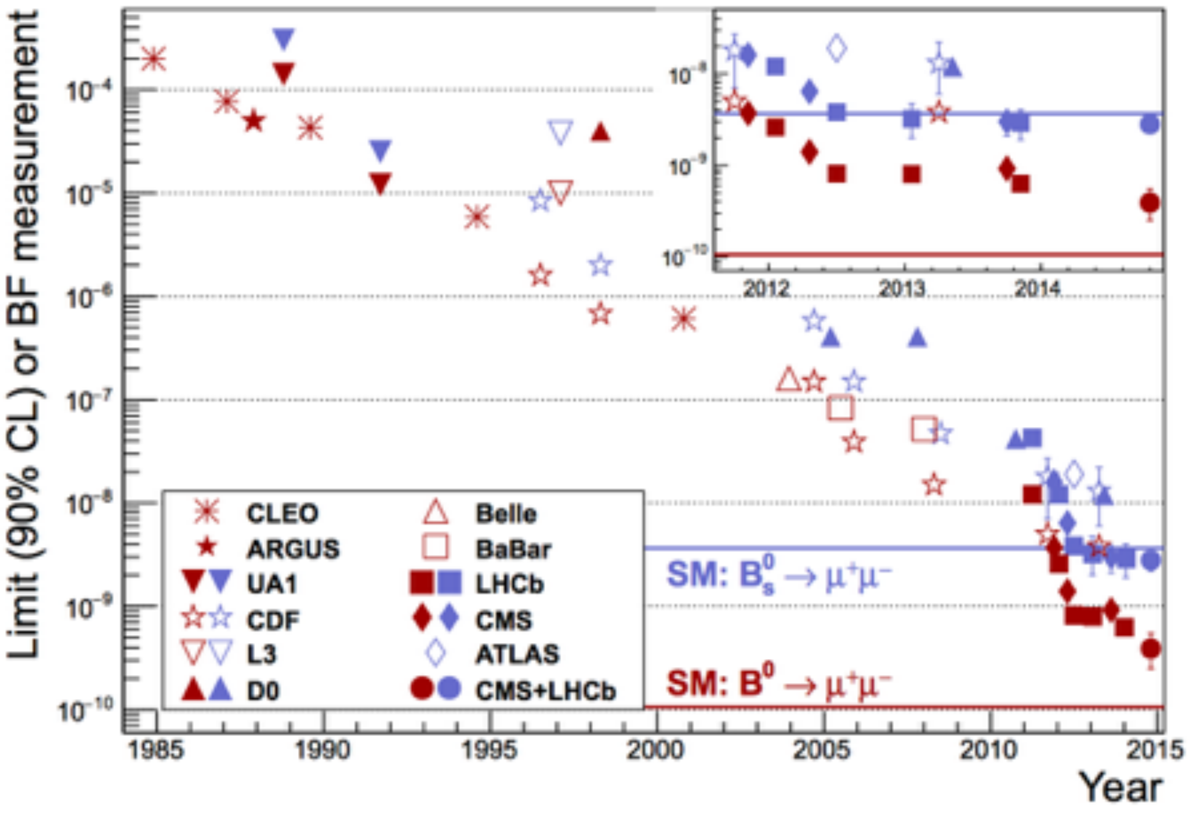
B Physics

- **First $B_s \to \mu\mu$ observation**
- **Combined CMS and LHCb analysis**
- **Concluded a three decade long search**
- **$B_{d,s} \to \mu\mu$ - tracking resolution**
- **Measurement enabled by tracker upgrade with tracker trigger.**





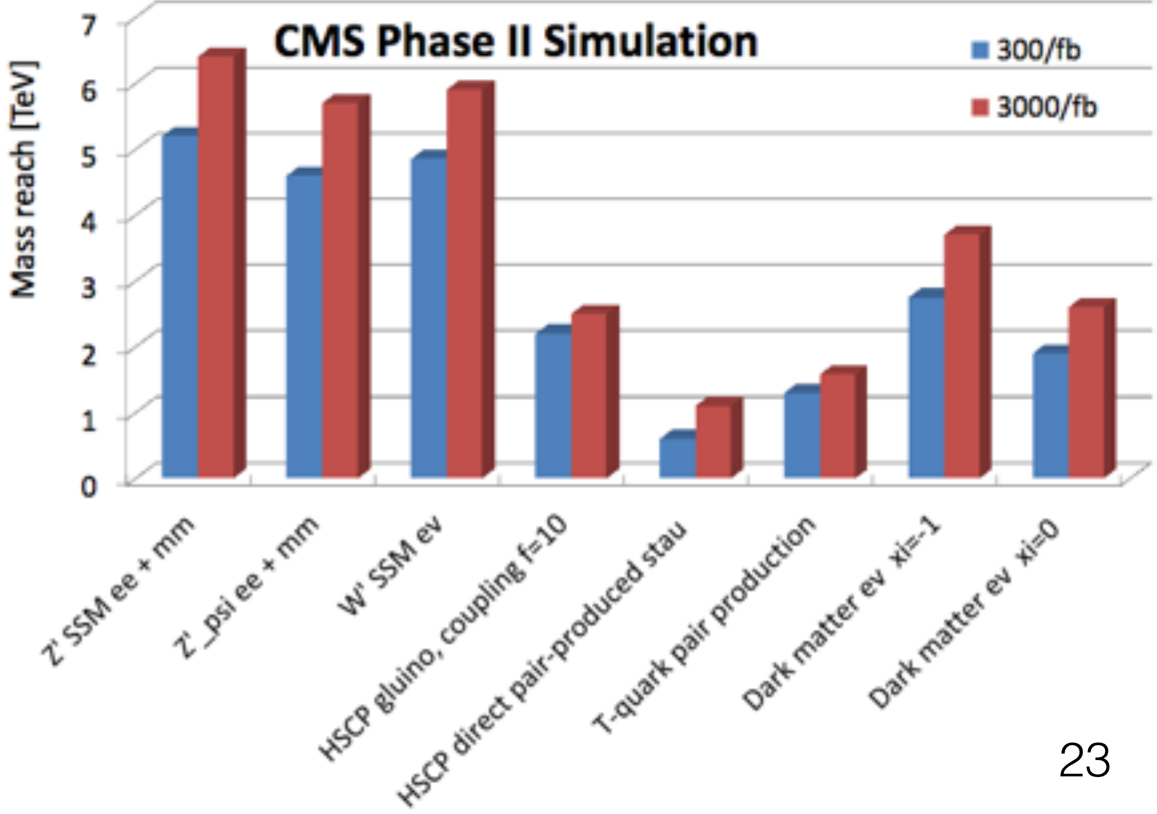


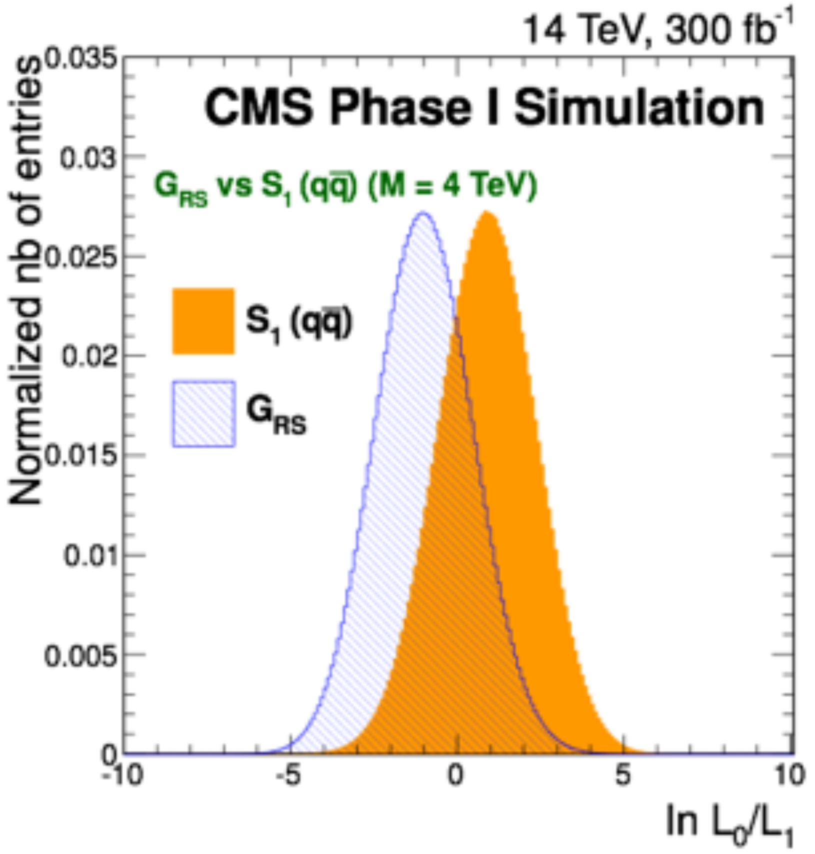


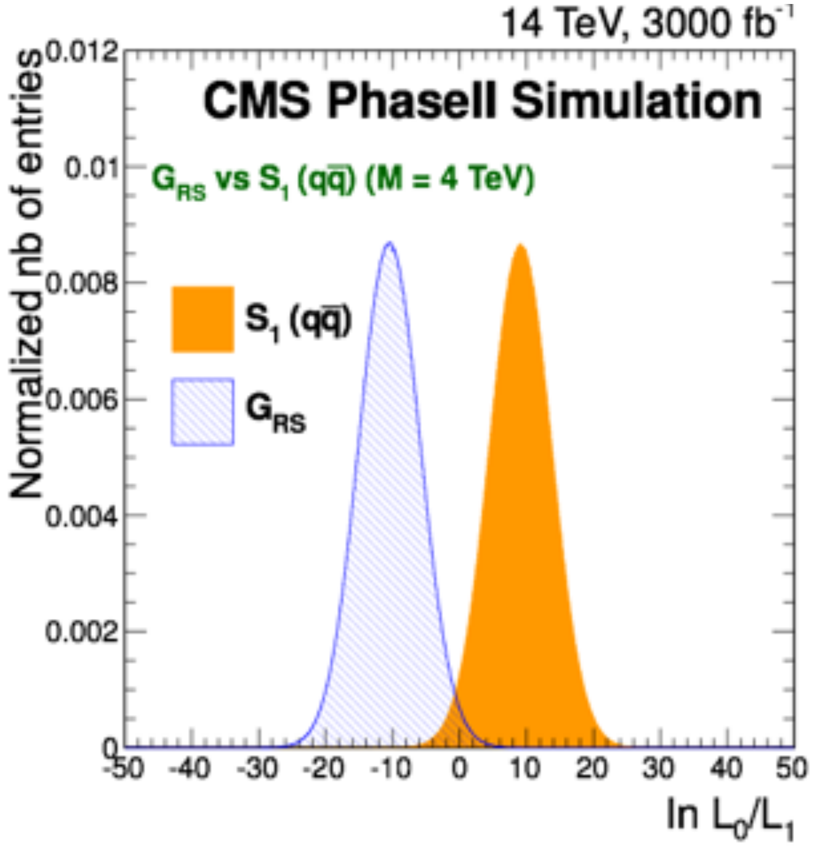
Exotica

➡ **Window to new physics beyond SUSY**
- heavy gauge boson search and properties
- dark matter
- highly ionizing particle
- displaced vertices

ATLAS @14 TeV	Z’ → ee SSM 95% CL limit	g_{KK} → t t RS 95% CL limit	Dark matter M* 5σ discovery
300 fb^{-1}	6.5 TeV	4.3 TeV	2.2 TeV
3000 fb^{-1}	7.8 TeV	6.7 TeV	2.6 TeV





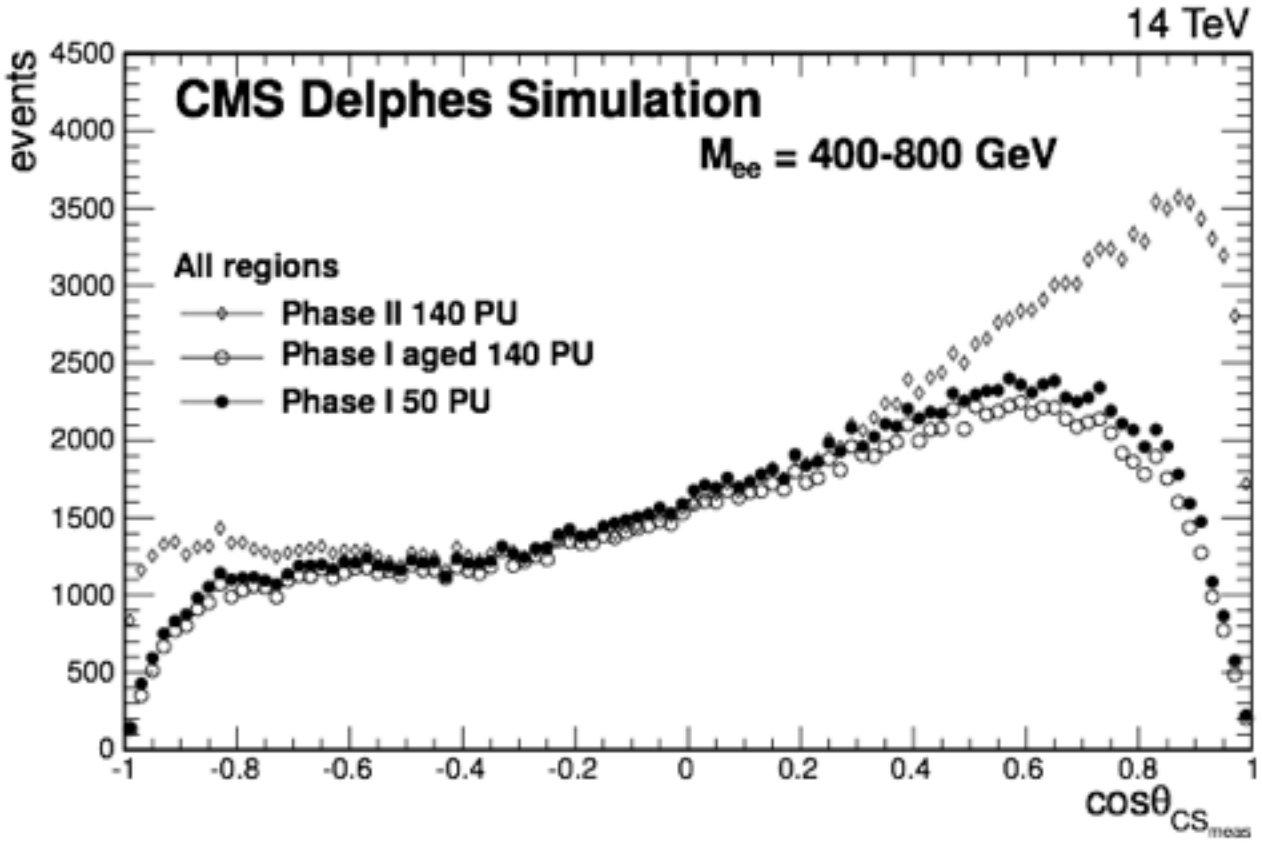


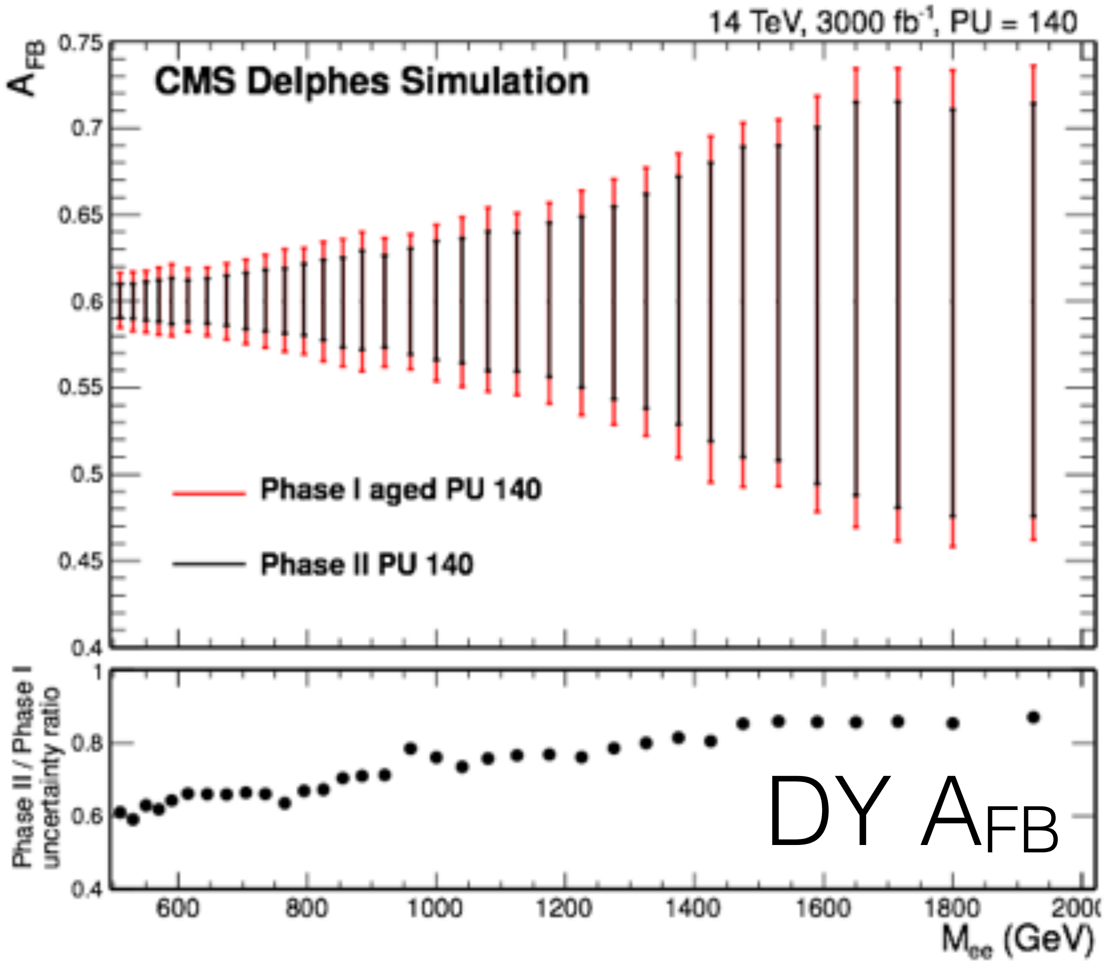
Exotica

➡ Di-lepton resonances - Z' properties

resonance spin and production mode	$d\sigma/d\Omega$
Spin 0 (gg or $q\bar{q}$ fusion)	$\propto 1$
Spin 1 ($q\bar{q}$ fusion)	$\propto 1+\cos^2\theta$ [1]
Spin 2 (gg fusion)	$\propto 1-\cos^4\theta$
Spin 2 ($q\bar{q}$ fusion)	$\propto 1-3\cos^2\theta+4\cos^4\theta$ [1]

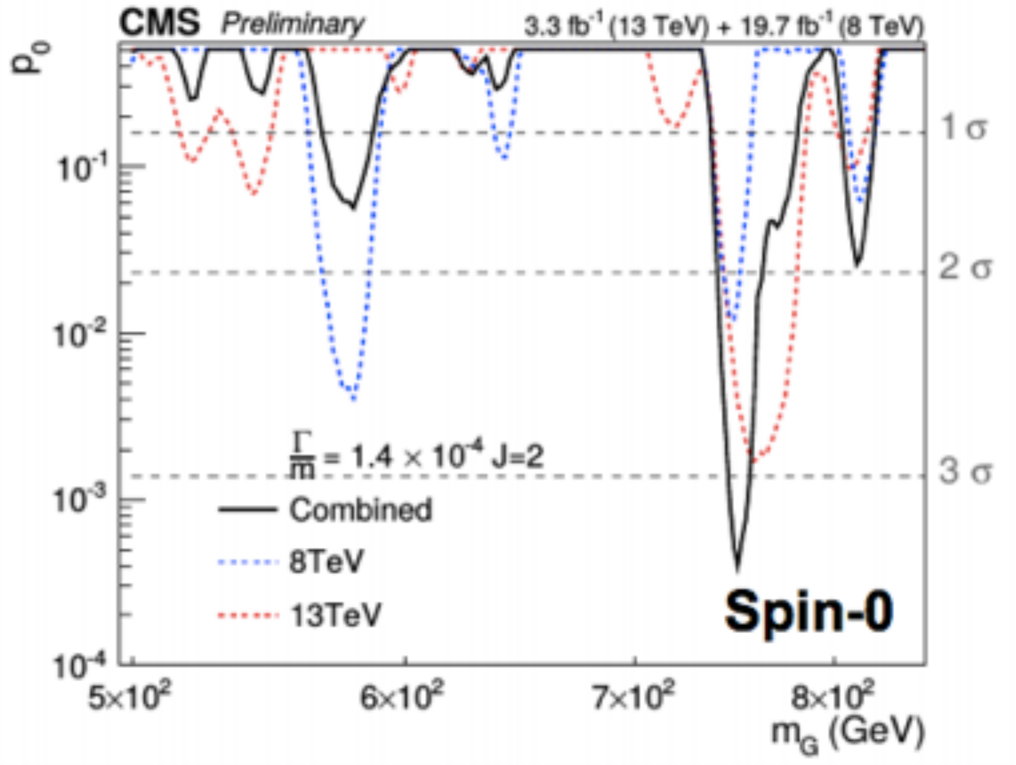
$$A_{FB} = \frac{\sigma_{\theta<\pi/2} - \sigma_{\theta>\pi/2}}{\sigma_{\theta<\pi/2} + \sigma_{\theta>\pi/2}}$$

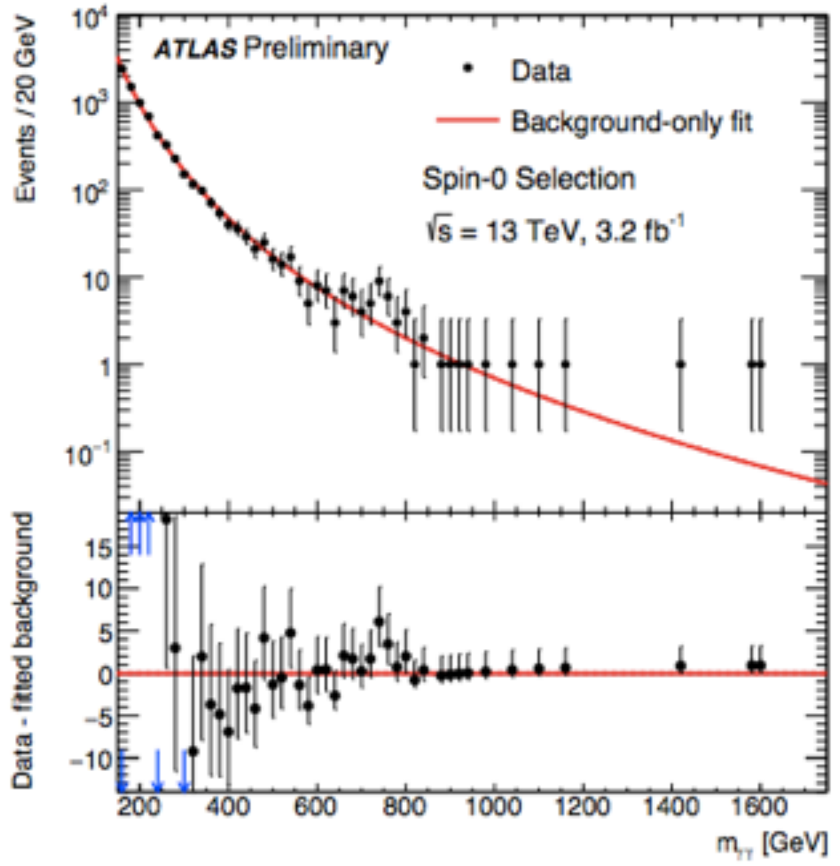




Di-photon excess at 750 GeV

- ➡ **Highlights of Run-II presented at Jamboree Dec 15th**
  - ◉ ATLAS and CMS updated studies for Moriond
  - ◉ Local p-value: 3.4σ for CMS and for 3.9σ ATLAS
  - ◉ Global p-value: 1.6σ for CMS and for 2.0σ ATLAS
  - ◉ Cross section O(10fb)
  - ◉ Huge excitement and avalanche of papers (~300 and counting)
- ➡ **2016 data will show whether or nor this is a sign of new physics**
- ➡ **HL-LHC dataset capable of shining a bright lamp on new physics processes**





Conclusion

- ➡ HL-LHC enables a 20+ years research program with large discovery potential
  - ◉ ATLAS & CMS upgrades required to fully exploit the LHC

- ➡ Physics case is based on the large dataset
  - ◉ Precision measurements of SM parameters
  - ◉ Determination of BSM parameter
  - ◉ Sensitivity to rare SM & (weakly produced) BSM processes
  - ◉ Extension of discovery reach in high-mass region

- ➡ Studied physics channels only scratch the surface of what's possible

- ➡ Goal: Exploring the energy frontier

Exploration and Discovery

Christopher Columbus Discovers America, 1492. Columbus led his three ships - the Nina, the Pinta and the Santa Maria - out of the Spanish port of Palos on August 3, 1492. His objective was to sail west until he reached Asia (the Indies) where the riches of gold, pearls and spice awaited.

1st ECFA HL-LHC workshop

ECFA High Luminosity LHC Experiments Workshop

Physics and technology challenges

1st – 3rd October

Aix-les-Bains

France

https://indico.cern.ch/conferenceDisplay.py?confId=252045

Programme Committee

Allport
Ball
Bertolucci
Campana
Charlton
Contardo
Di Girolamo
Giubellino
Incandela
Jenni
M. Krammer
M. Mangano
Myers
Schmidt
Virdee
Wessels

ocal Organising Committee

Allport, D. Contardo, D. Hudson, C. Potter

Picture Credit: OT Aix-les-Bains / Gilles Lansard

➡ **Summary**

- Followed European Strategy and Snowmass
- Goal to define HL-LHC detectors and physics program
- Provide common approach and consistent presentation of physics goals, detector requirements, technology, accelerator interfaces, long shutdown constraints, and costing methods

➡ **Links**

- agenda, report

2nd ECFA HL-LHC workshop

➡ **Summary**

- ◉ Followed CERN plan up to 2025 and P5 recommendations
- ◉ Improved understanding on all aspects of the HL-LHC project

➡ **Links**

- ◉ agenda
- ◉ report

HL-LHC Physics Workshop

May 11-13th 2015 at CERN

(reference for additional information)

Goals:

- ➡ detailed talk that provide basis for serious discussion
- ➡ stimulate theory community to think about what’s possible
- ➡ stimulate experimental community to test ideas

Day 1: Higgs

Day 2: BSM physics

Day 3: Flavor and SM physics

http://indico.cern.ch/event/360104/