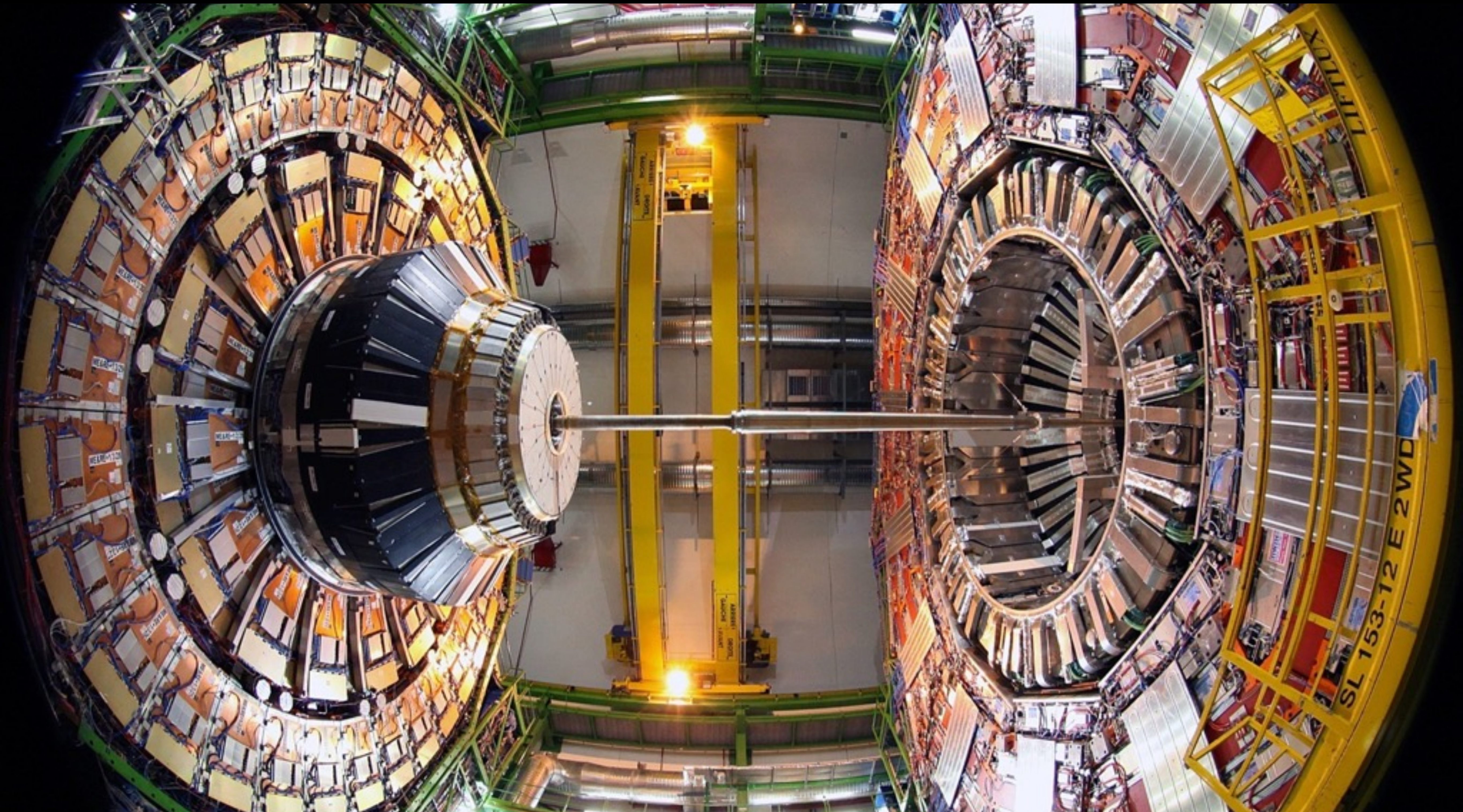
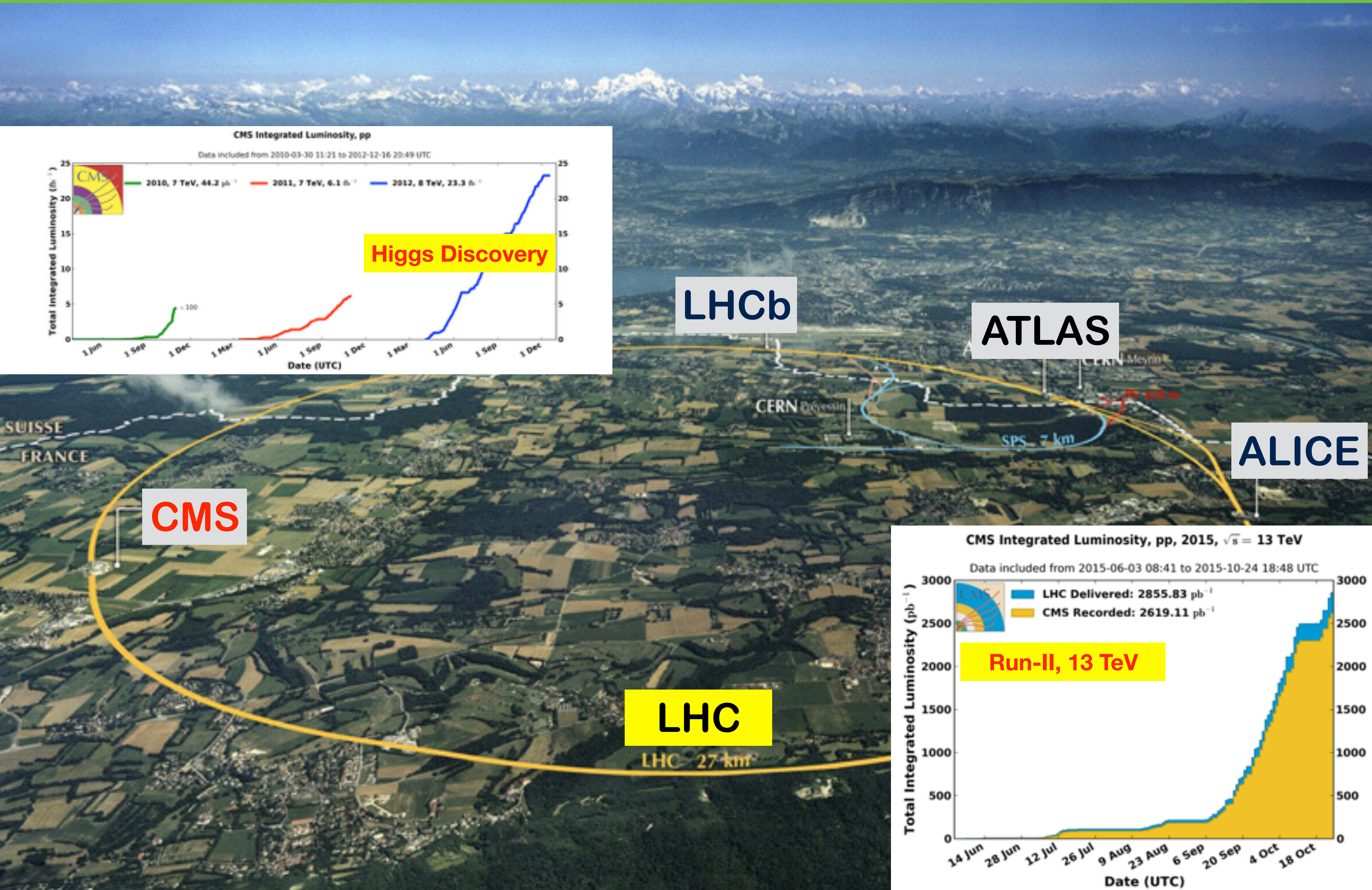
Exploiting the LHC Physics Potential



Cornell LEPP Journal Club,
Oct 30th, 2015, Markus Klute (MIT)

Large Hadron Collider

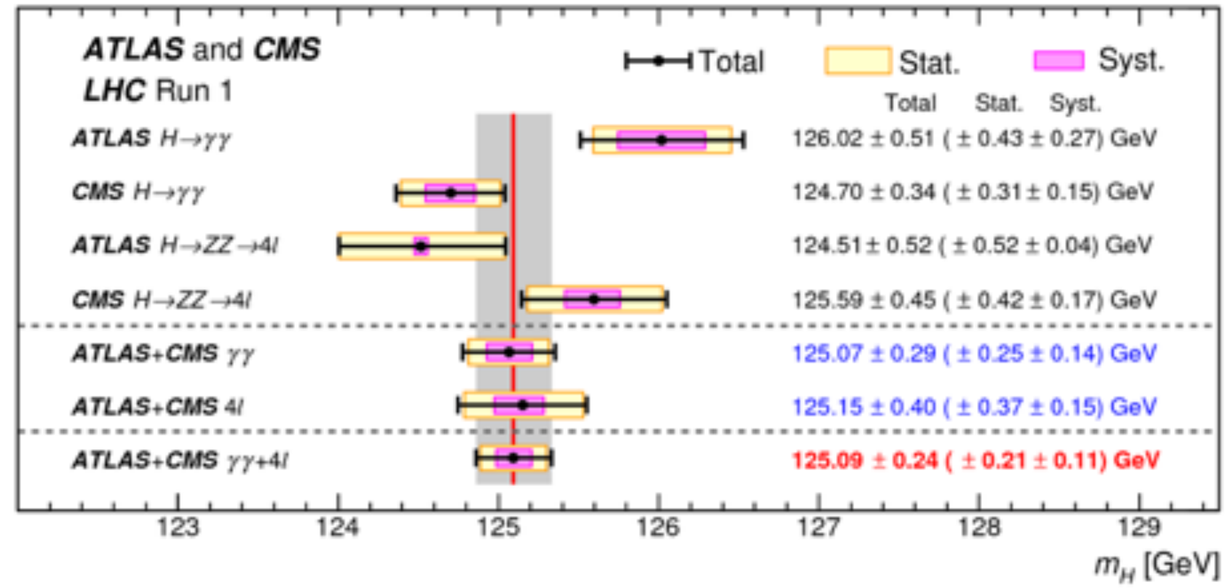


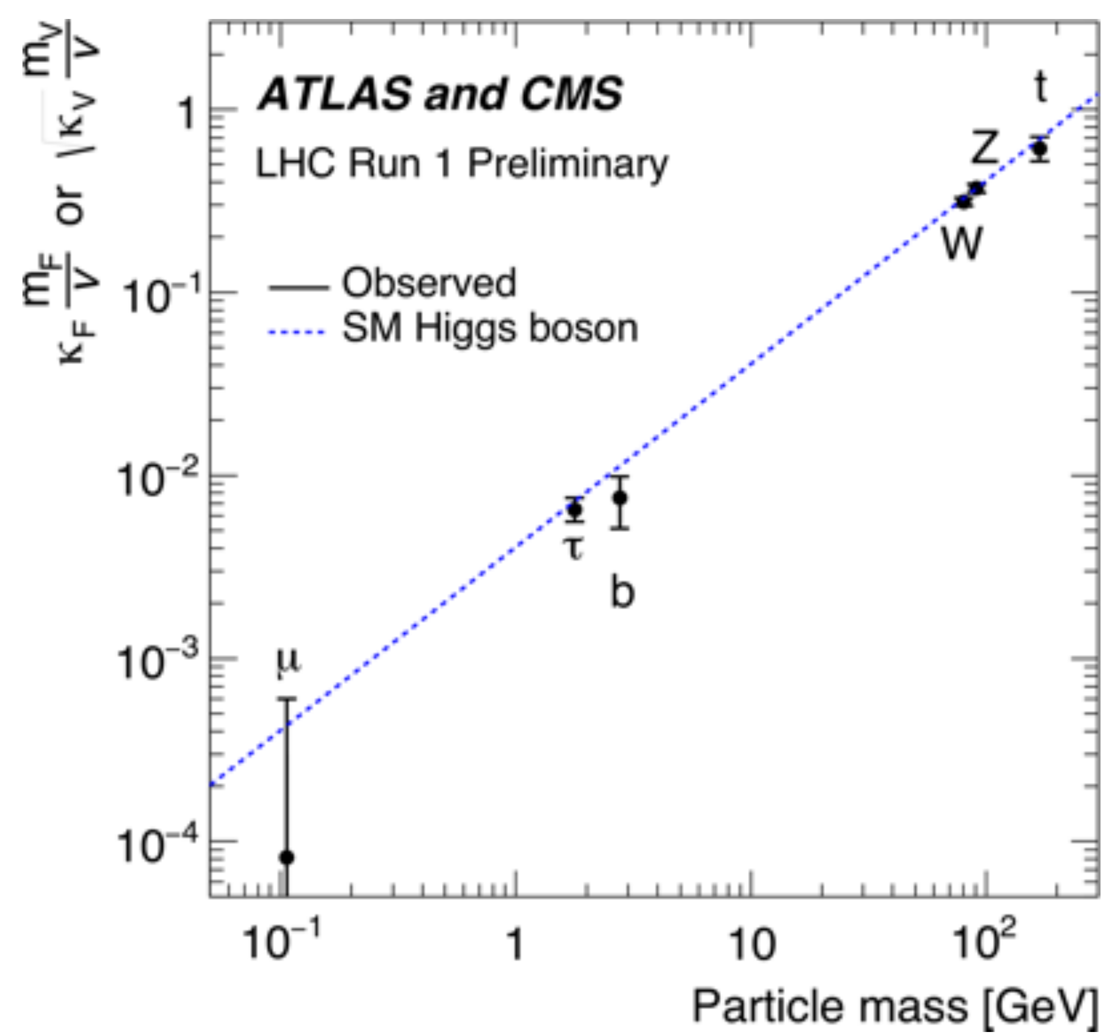
Higgs Physics Program

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

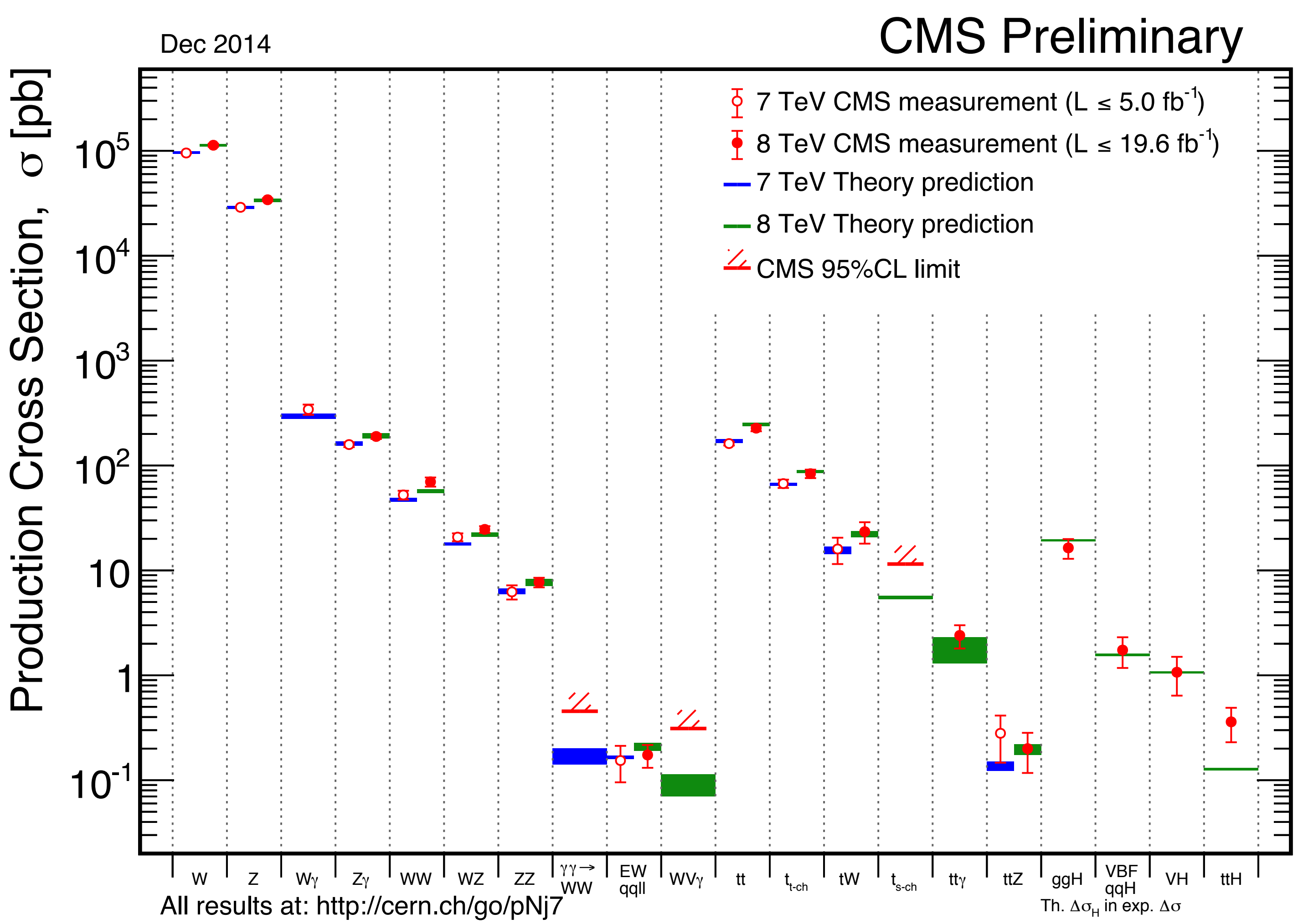
  m_H = 125.09 ± 0.21 (stat.) ± 0.11 (syst) GeV

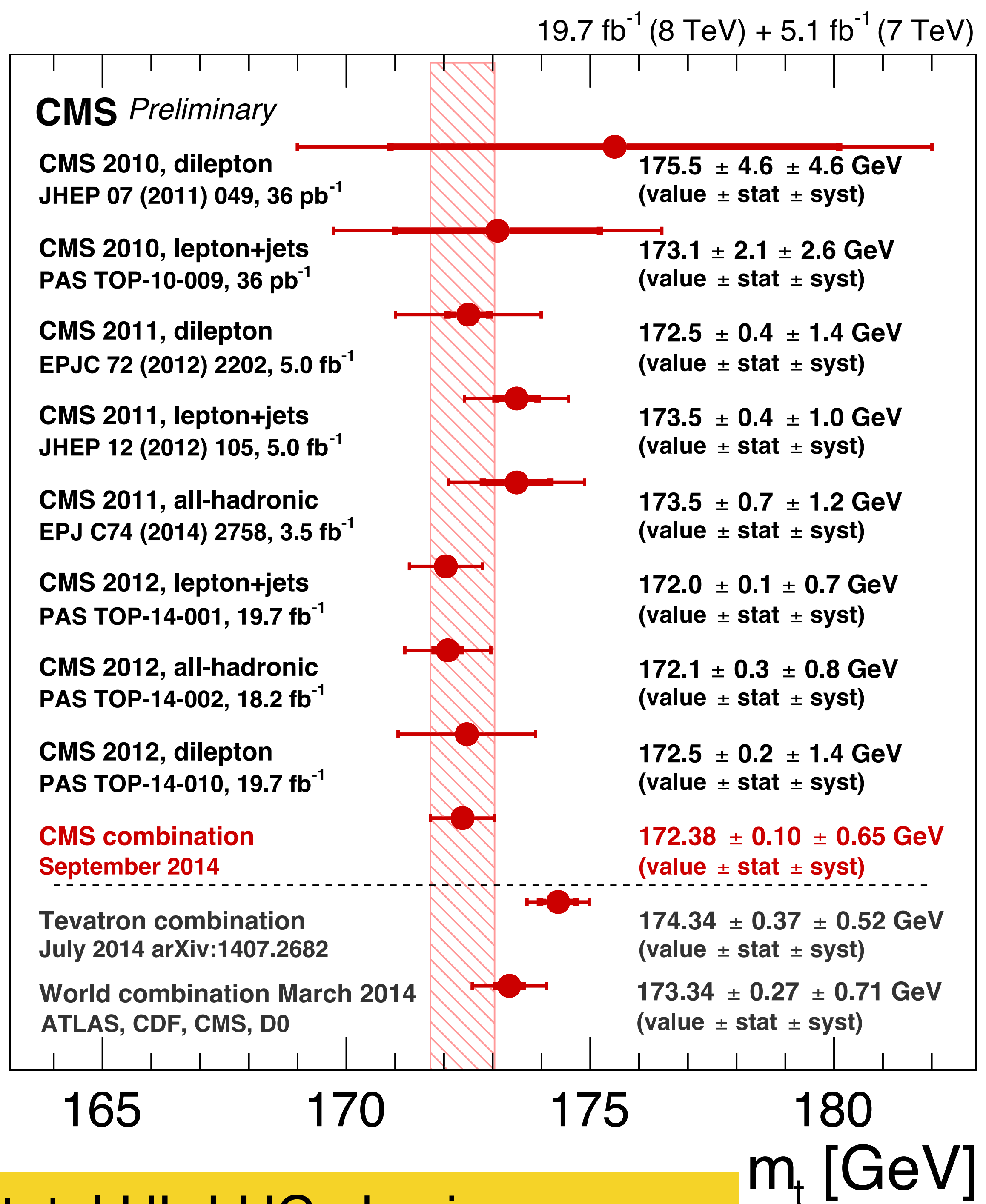
- ➡ **Precision (0.2%) limited by statistical uncertainty**
- ➡ **Established that particle masses and couplings to the Higgs boson relate**
- ➡ **No additional Higgs bosons or BSM decays observed**





LHC Physics Program

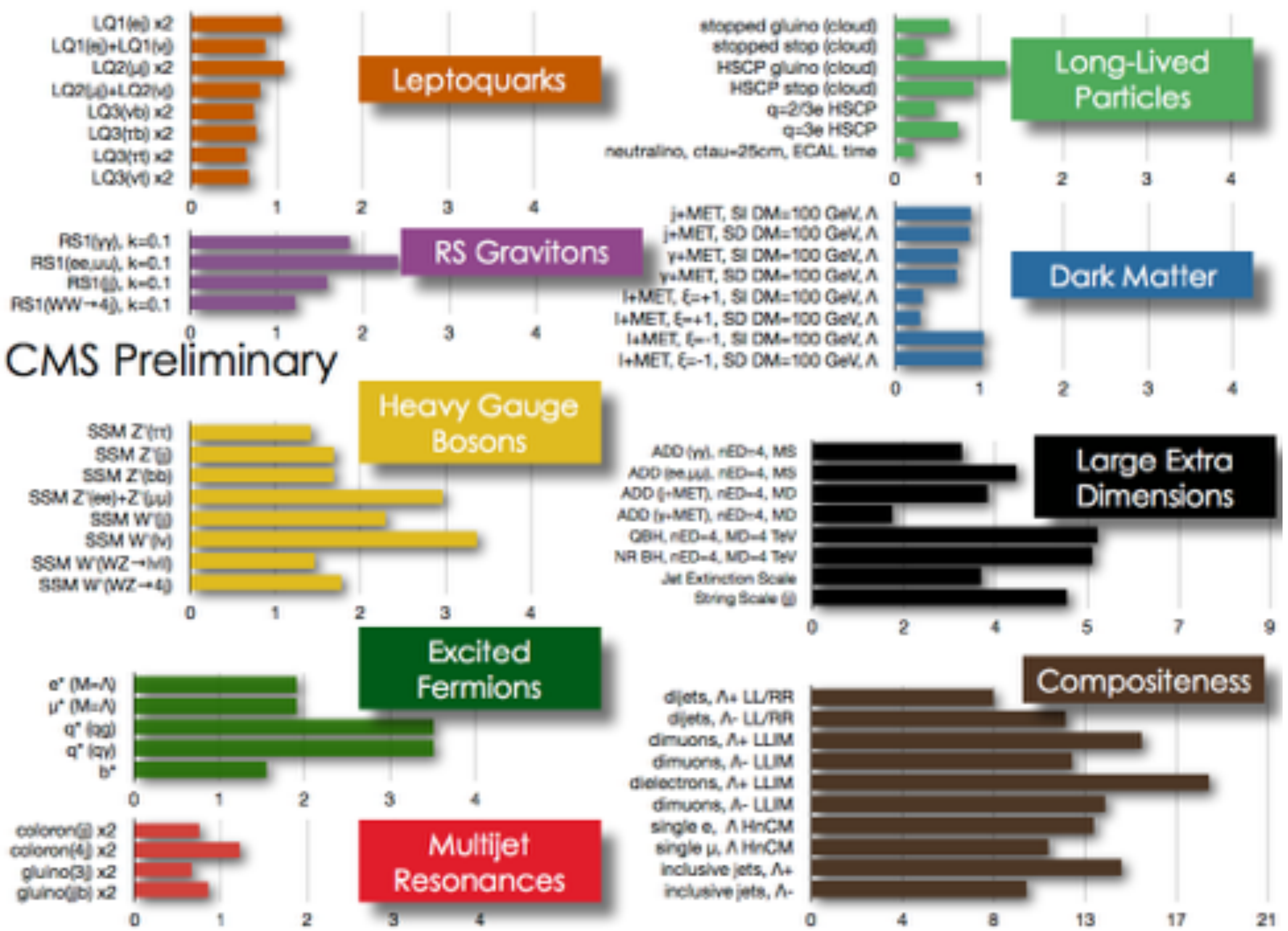


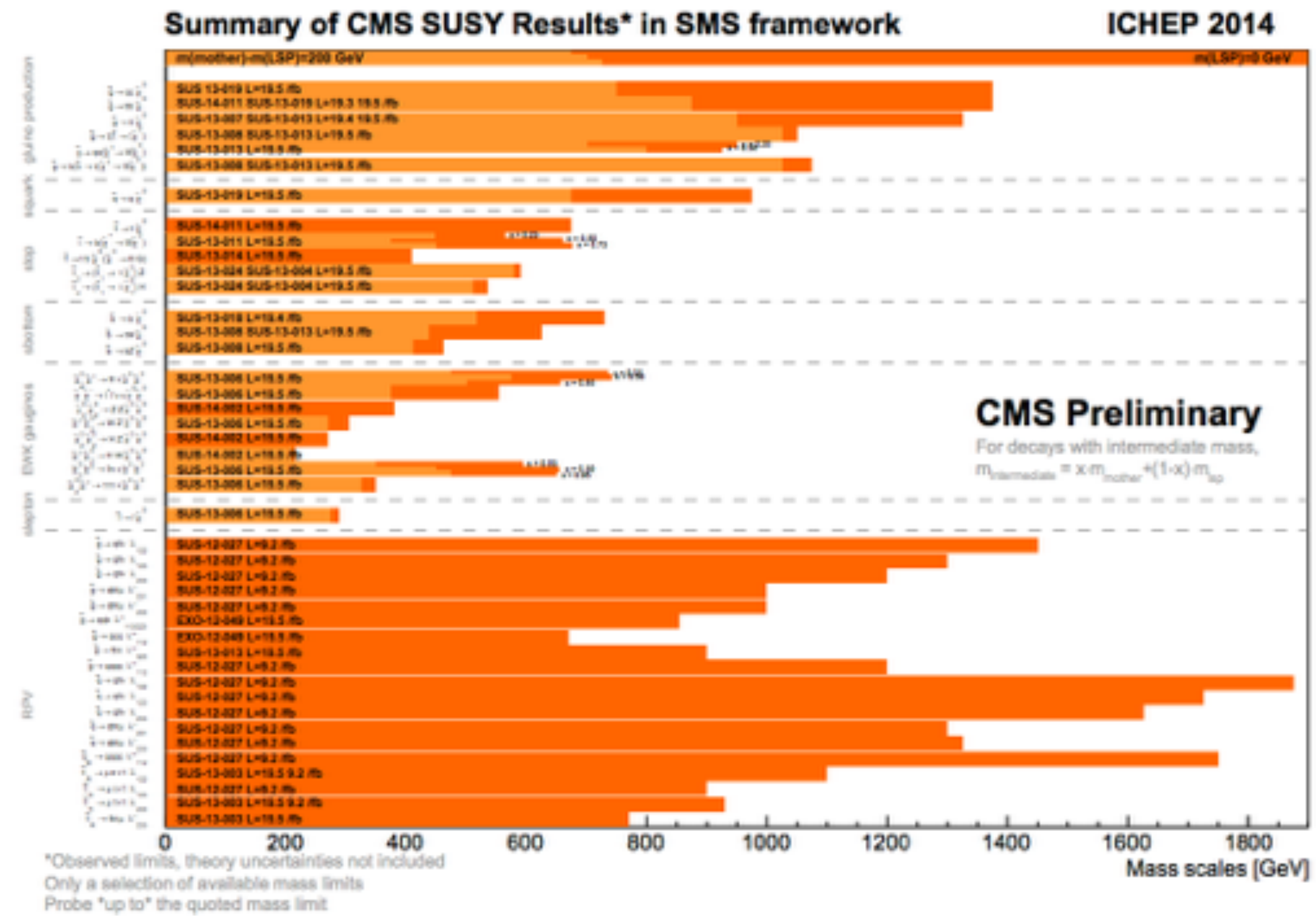


More than 800 paper between ATLAS and CMS, not even counting LHCb and ALICE results

Selected topics are minor fraction of the total HL-LHC physics program

LHC New Physics Searches





➡ **No (other) new physics found at the LHC Run I probing the TeV scale**

➡ The standard model explains / **describes all observations** and measurements from high-energy collider

➡ For the first time in history, we have a **self-consistent theory that can be extrapolated to exponentially higher energies**

Is this the end?

In 1900, the widely respected and honored British physicist Lord Kelvin is said to have pronounced:

“There is **nothing new to be discovered** in physics now. All that remains is more and more precise measurement.”

Of course not!

➡ **The SM fails to explain important observations**

➡ **Experimental proof for physics beyond the SM**

- Cosmological dark matter (DM)
- Baryon asymmetry
- Non-zero, but very small neutrino mass
- Gravity
- A hint: the small Higgs boson mass is rather unnatural

Where is the corner?

- ➡ **Often heard: New physics MUST be "around the corner"**
  - At higher mass scales or at smaller couplings? Or both?
  - Many good ideas, but limited theoretical guidance
  - Only way to find out: **keep exploring**

- ➡ **Direct searches for new heavy particles**
  - Need colliders with larger energies

- ➡ Searches for the imprint of new physics on flavor physics, W, Z, top quark, Higgs boson
  - Need measurements with unprecedented accuracy

- ➡ **The LHC and HL-LHC programs will deliver both**

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**

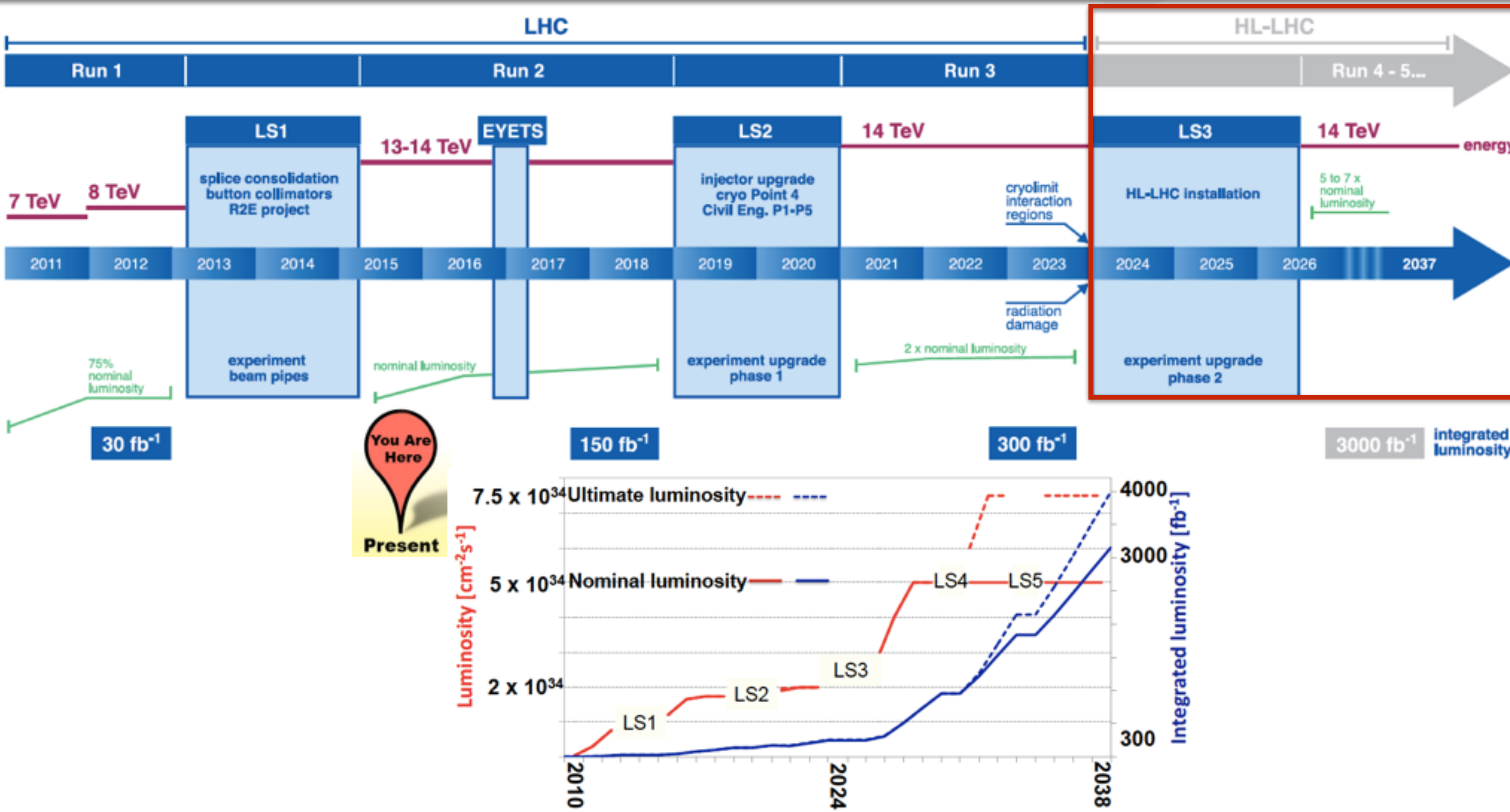
➡ **Precision measurements of SM parameters (including the Higgs boson)**

➡ **Sensitivity to rare SM & rare BSM processes**

➡ **Extension of discovery reach in high-mass region**

➡ **Determination of BSM parameter**

HL-LHC Schedule

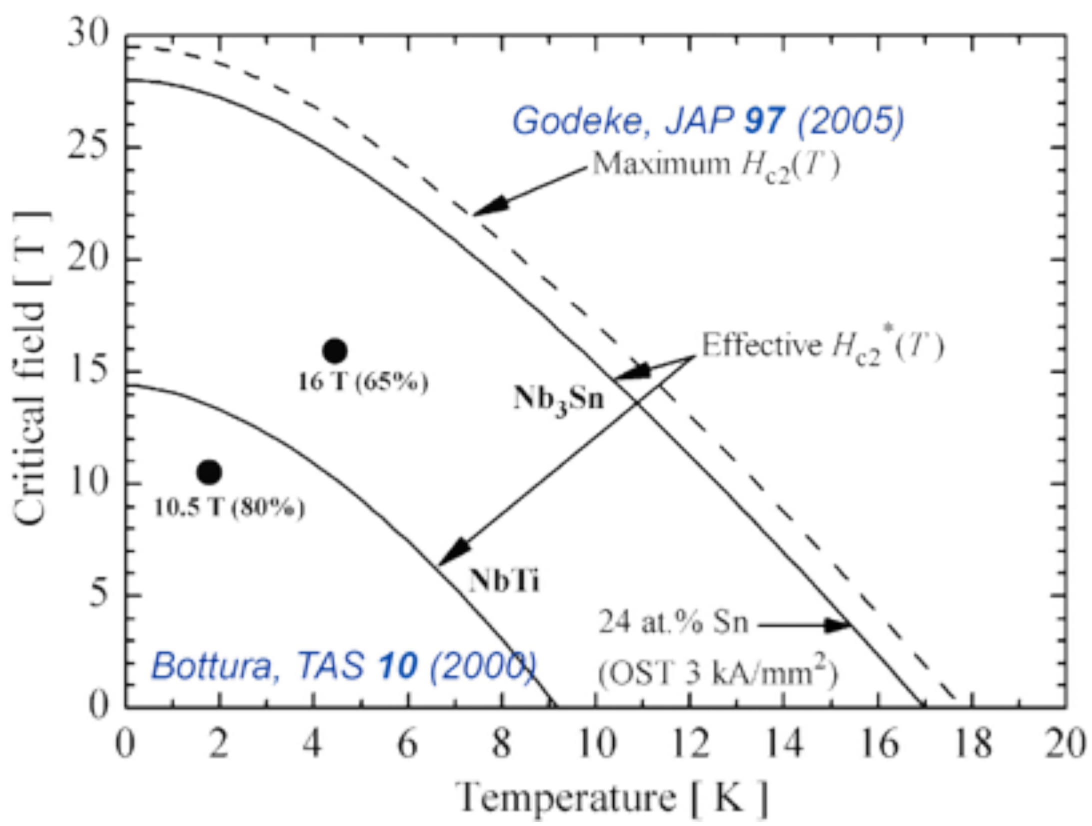


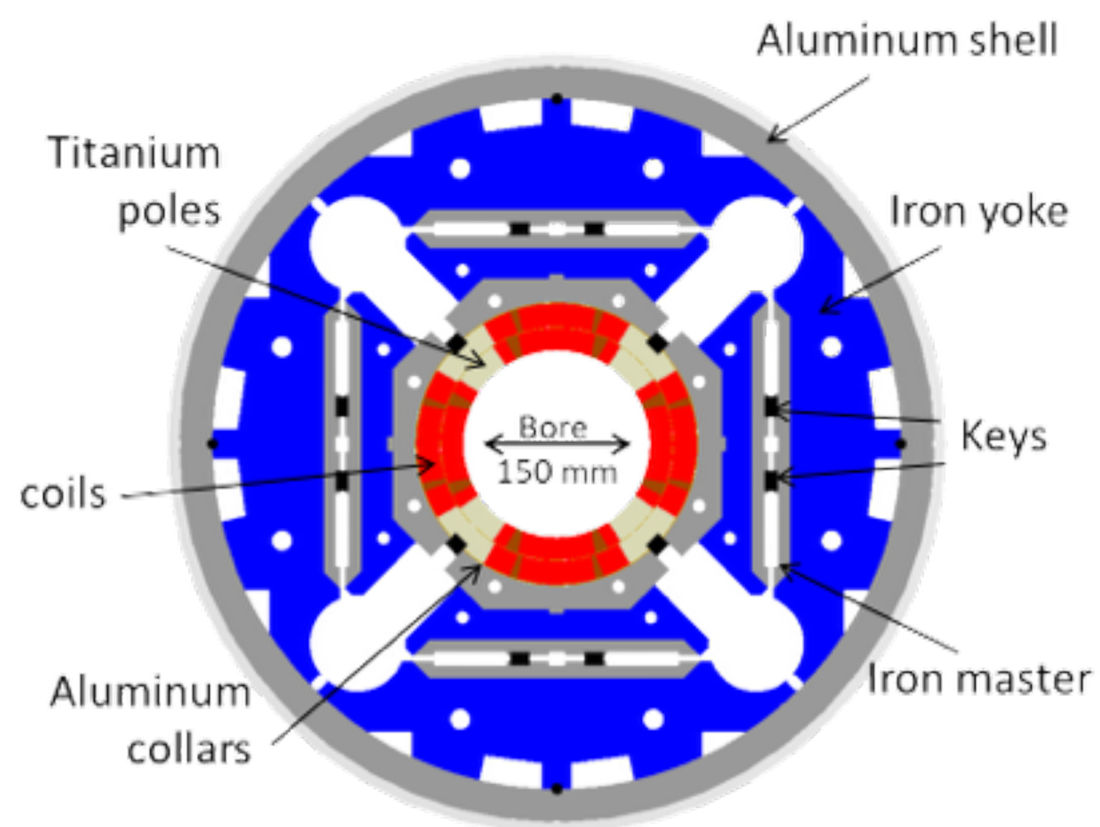
LHC / HL-LHC projects provide increase in **energy** and **luminosity** (accuracy)

HL-LHC Challenges

- ➡ **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*

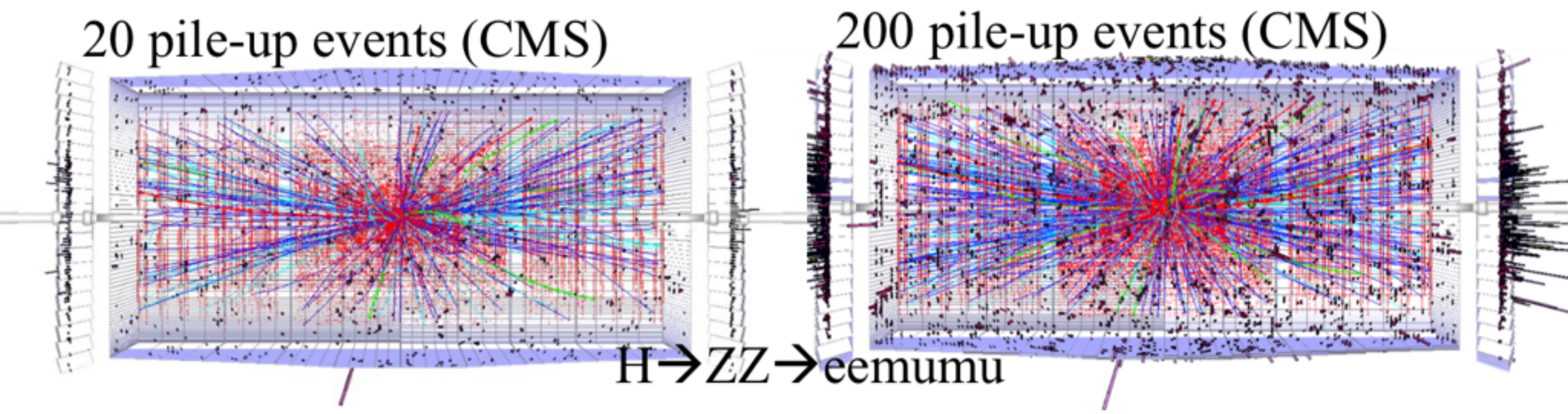
$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$





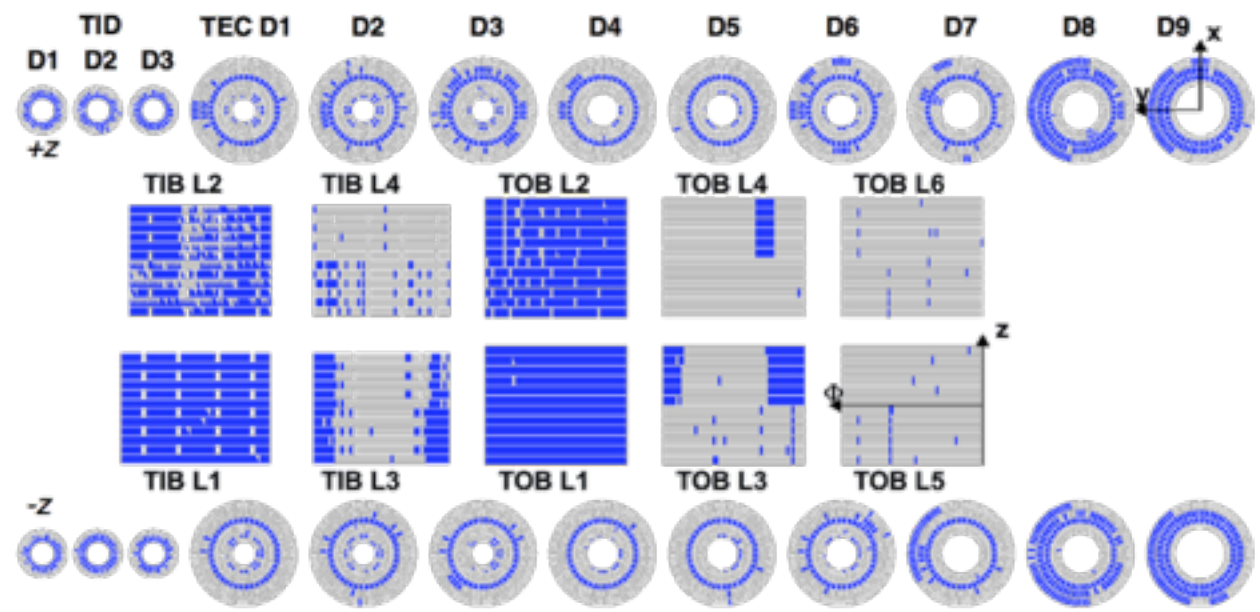
Experimental Challenges

- ➡ 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 $5 \times 10^{34} cm^{-2} s^{-1}$
  - $\langle\mu\rangle \cong 200$ at $7 \times 10^{34} cm^{-2} s^{-1}$
- ➡ 2.5 - 3.5 increase wrt LHC design

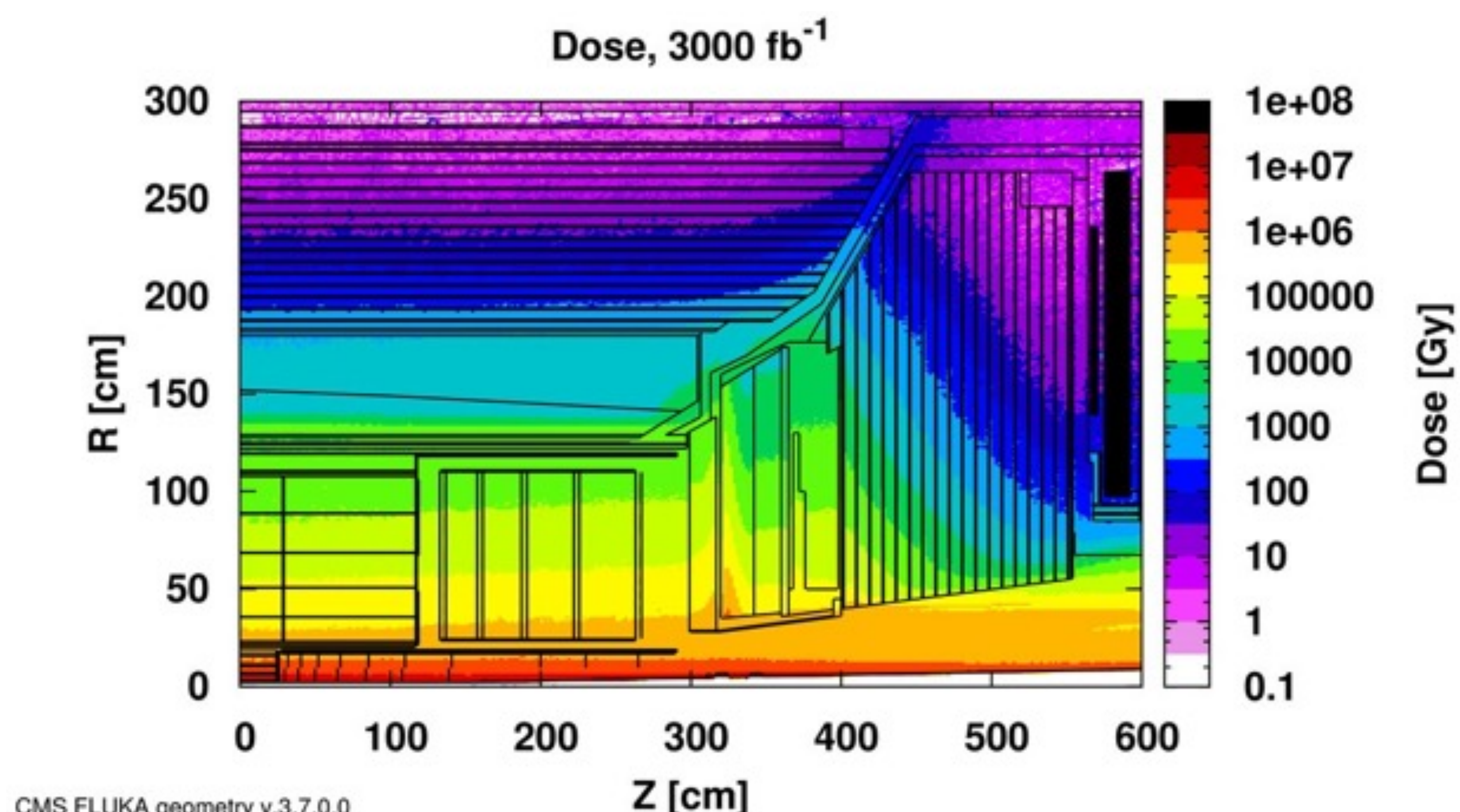


Experimental Challenges

- ➡ Detectors have to operate in **extreme environment**
- ➡ In 2025 the detectors will be running (radiated) for 15 years. Severe **aging** effects.
- ➡ Coherent **upgrade plan in place** to meet these challenges for ATLAS and CMS



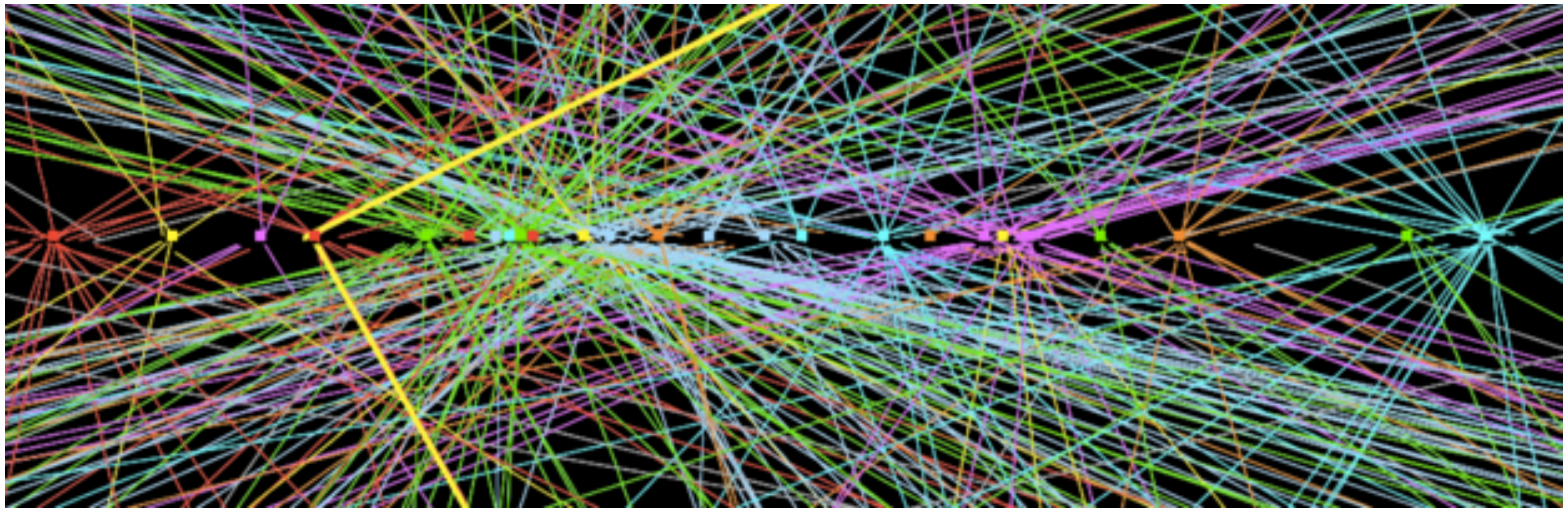
Blue tracker modules are inactive after 1000 fb^{-1} due to very high leakage currents induced by neutron fluence.



Pileup

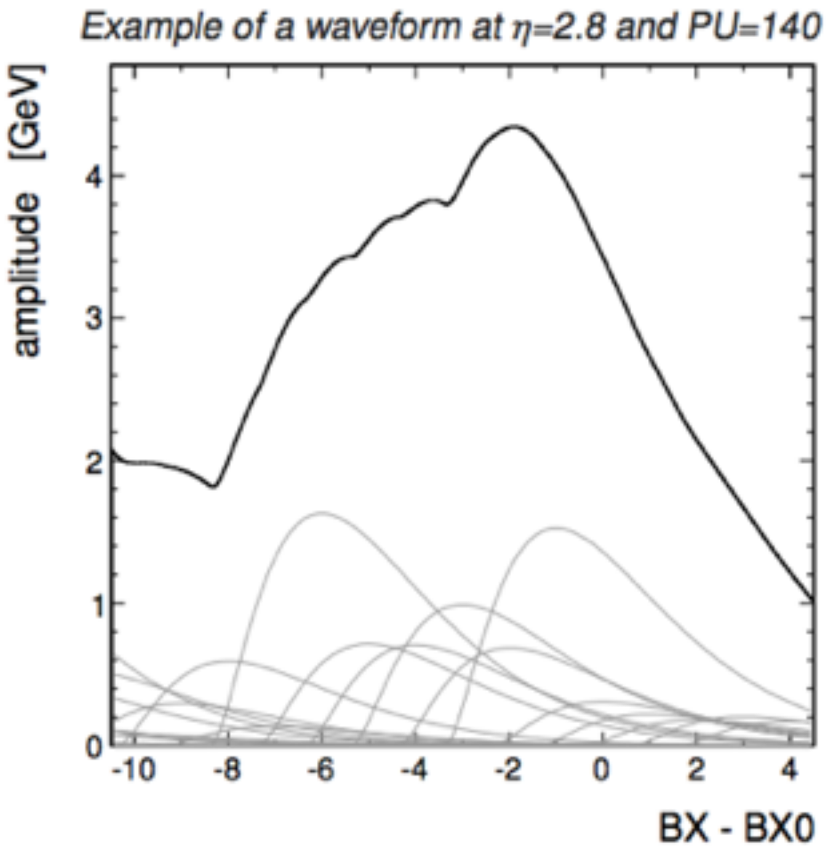
➡ **In-time pileup**

- Multiple interactions per bunch crossing
- Mis-association of **particles** to primary interaction



➡ **Out-of-time pileup**

- **Particles** from previous or following interaction mis-association to primary bunch crossing
- Caused by slow detector response



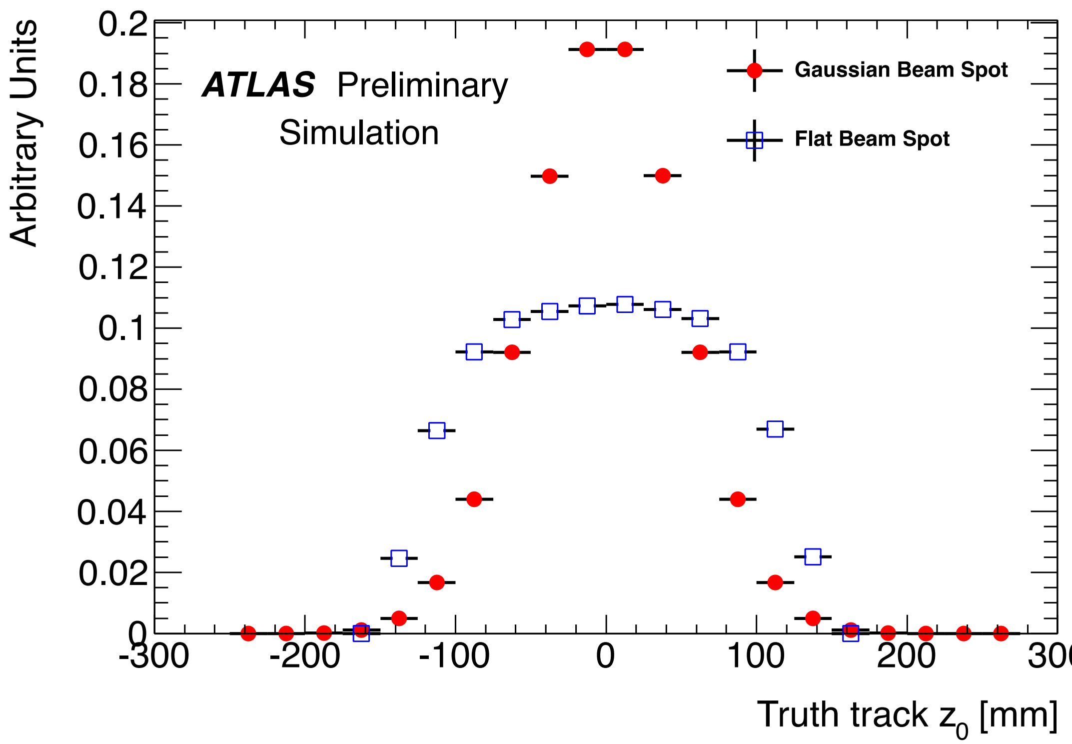
Pileup Mitigation

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

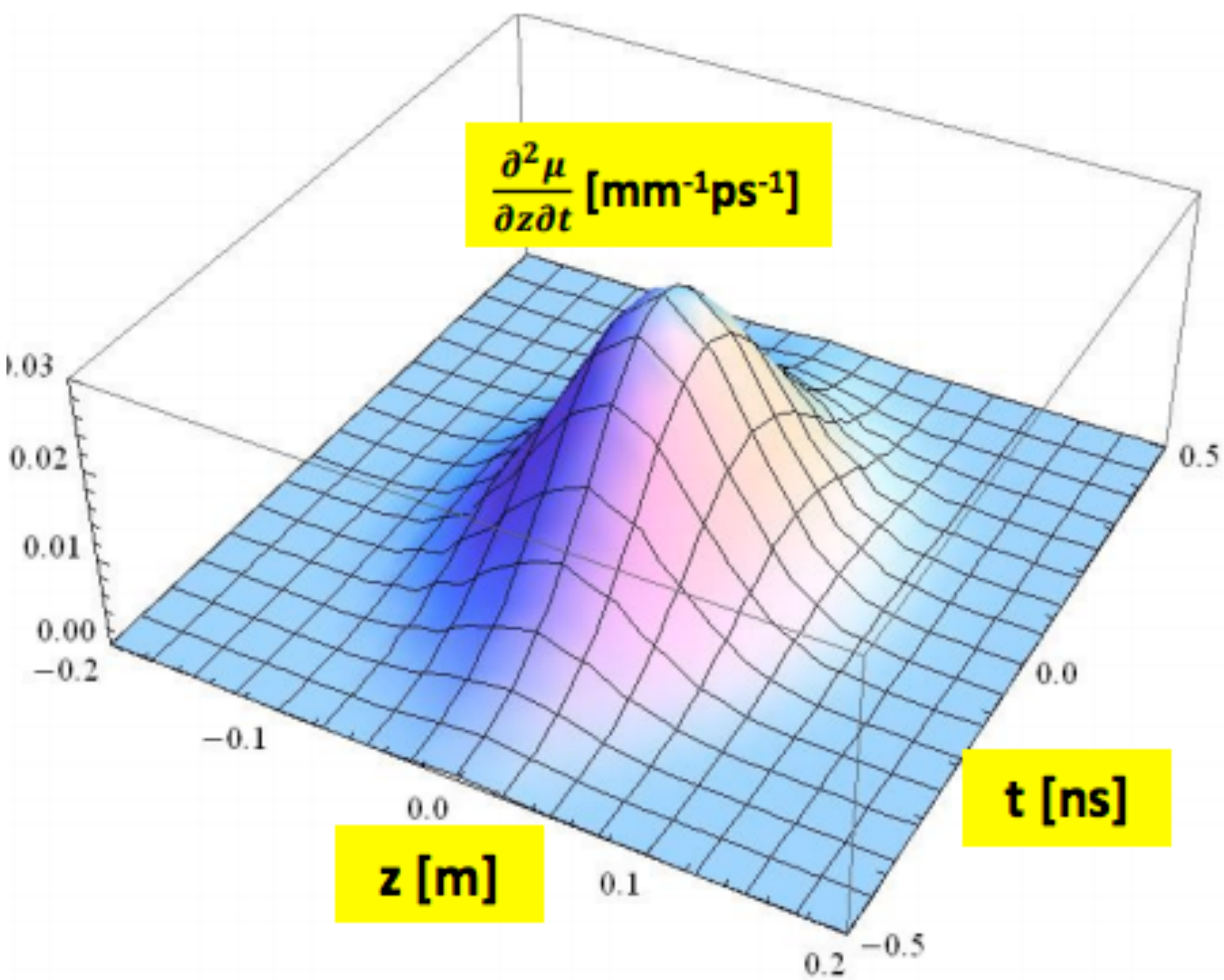
➡ **Calorimetry**
- Fit pulse shapes to extract in-time energy deposition
- Upgrade readout electronics
- Combine in-time energy measurements with tracking information using particle flow techniques

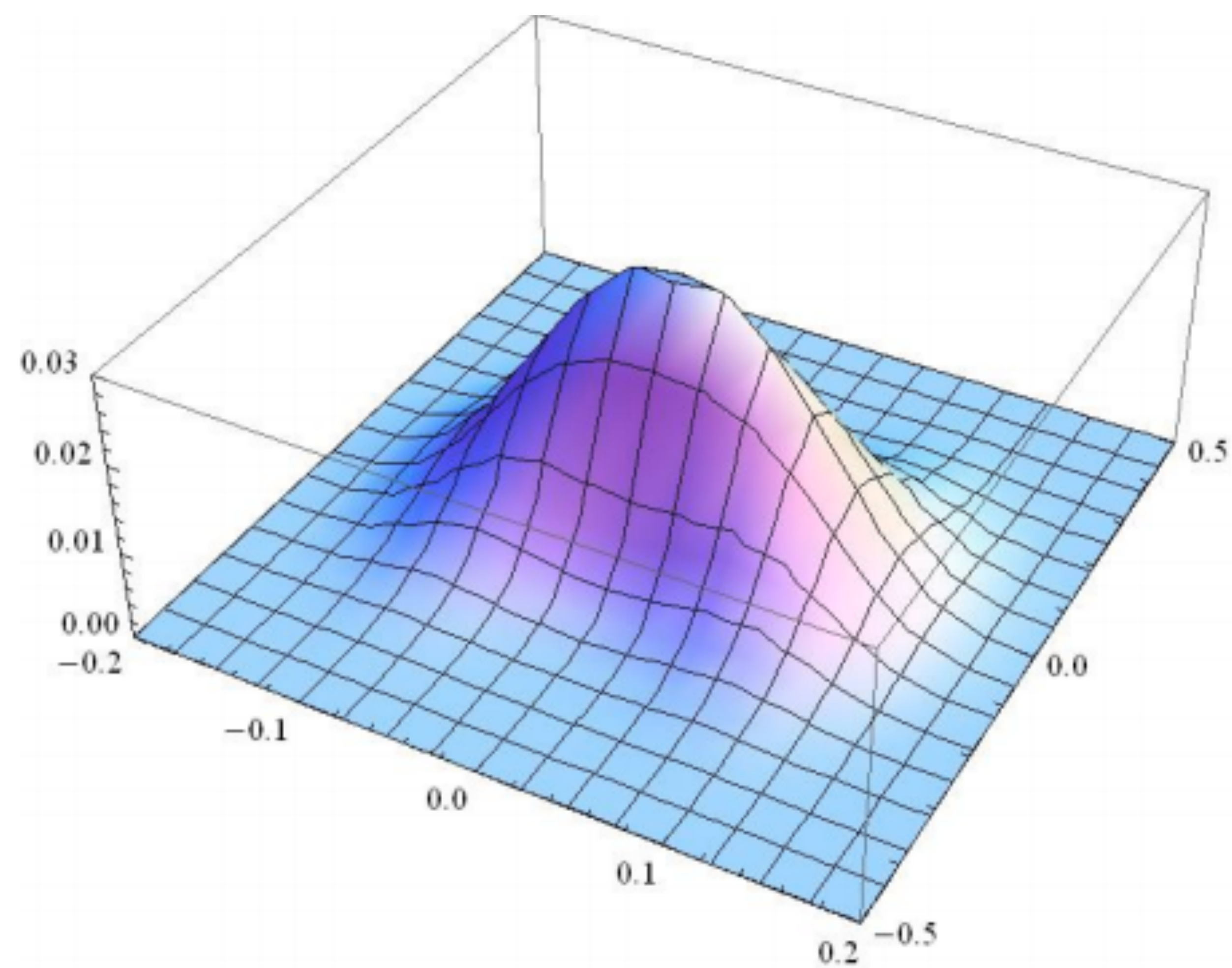
➡ **Precision timing**
- Reduce in-time pileup using the time distribution of collisions within the same bunch crossing
- Interaction time of a bunch crossing has rms of ~160ps
- Current ATLAS and CMS calorimeter timing resolution insufficient for significant rejection of PU

➡ **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

σ_{lum} = 7cm r.m.s.

σ_{lum} =100ps r.m.s.

S. Fartoukh

ATLAS & CMS Upgrades

➡ **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]

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

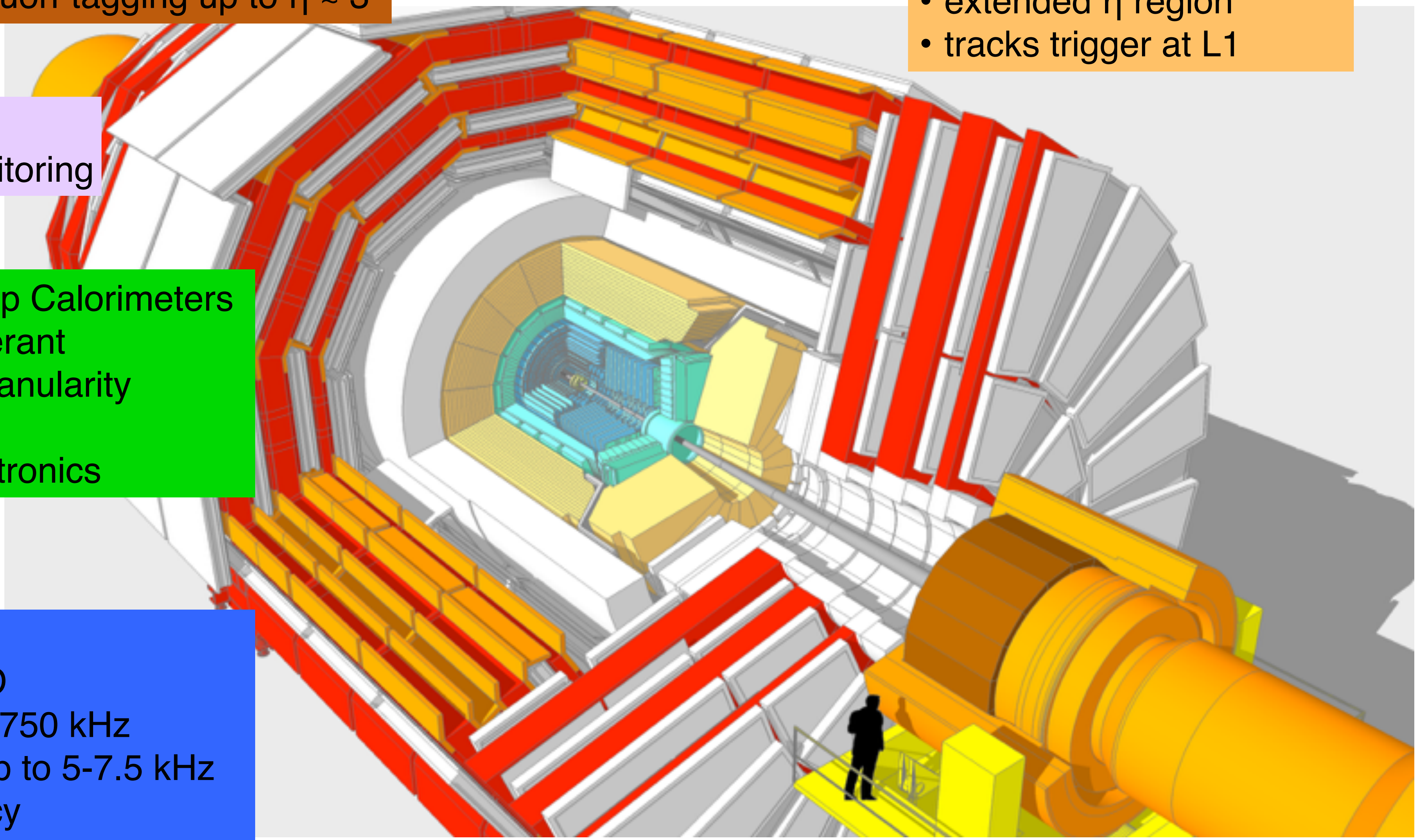
New luminosity and beam monitoring

Replace Endcap Calorimeters
- radiation tolerant
- increased granularity

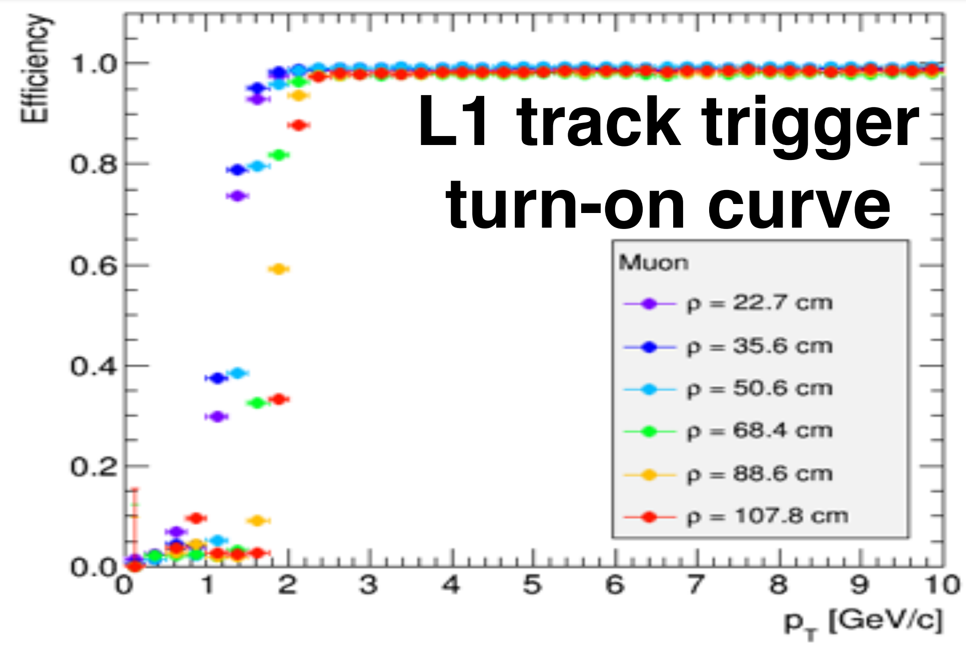
Barrel ECAL
- new FE electronics

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

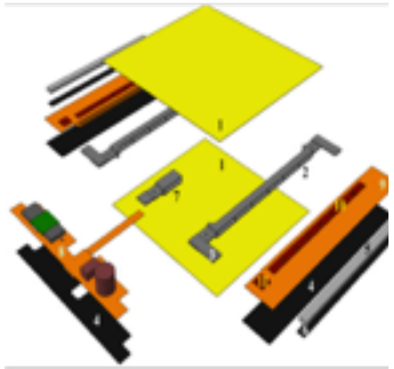
Tracker
- higher granularity
- less material
- better p_T resolution
- extended η region
- tracks trigger at L1

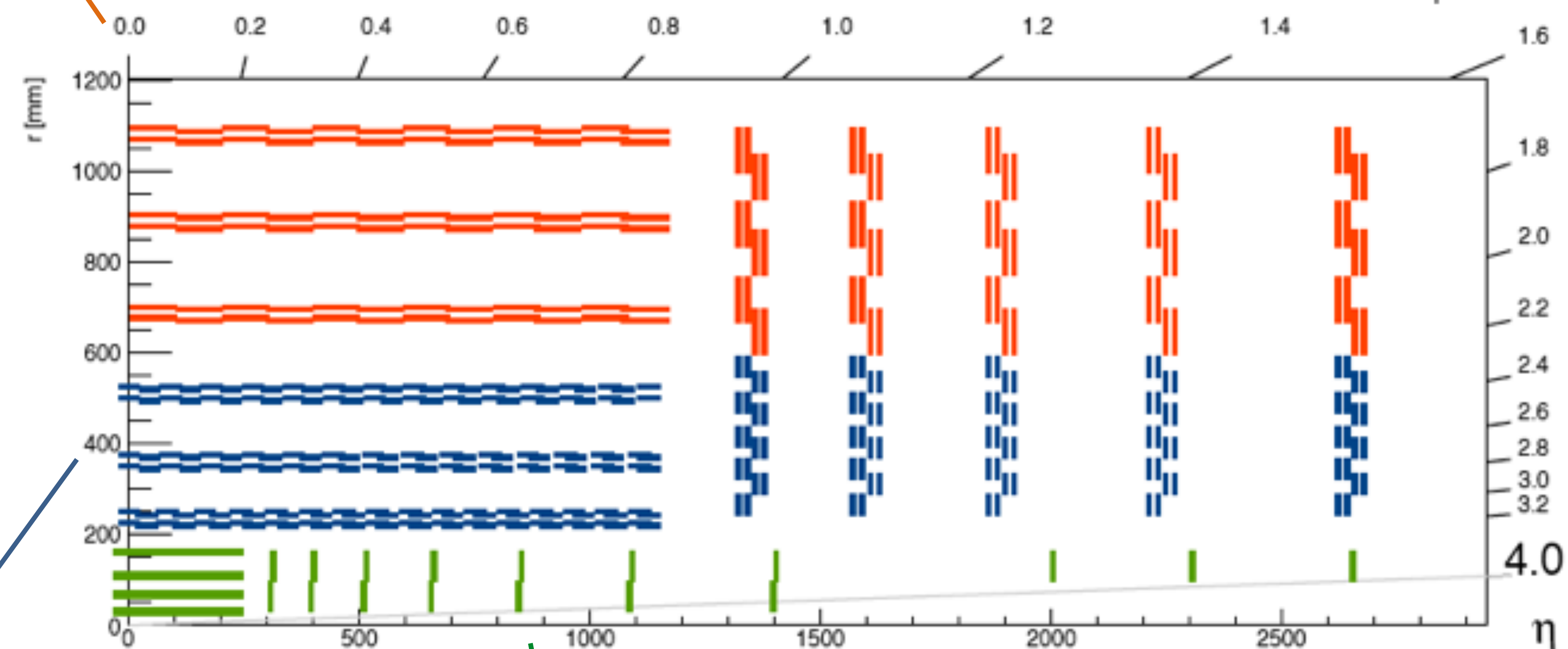


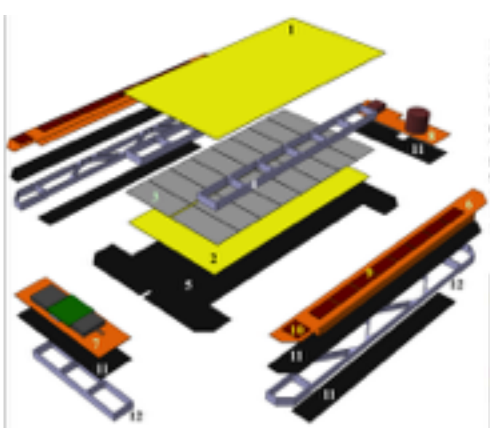
CMS Phase-II Silicon Detector



Strip/Strip Modules
90µm pitch / 5cm length

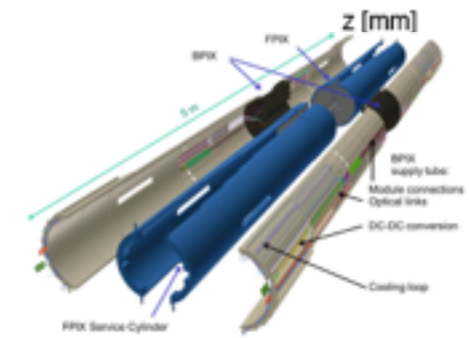






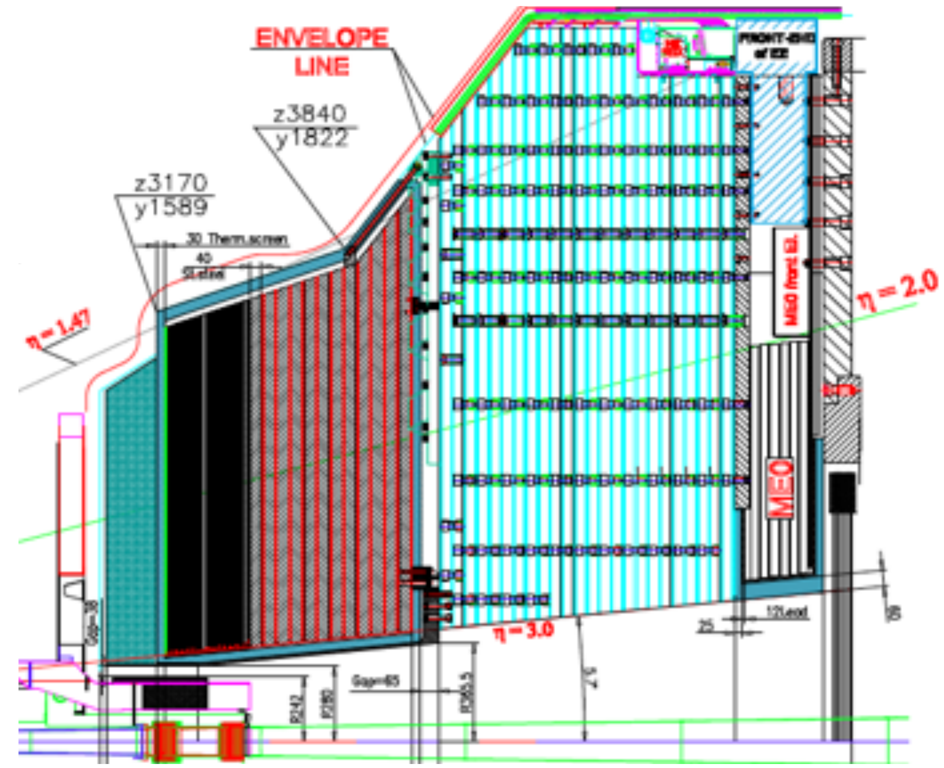
Strip/Pixel Modules
100µm pitch / 2.5cm length
100µm x 1.5 mm “macropixels”

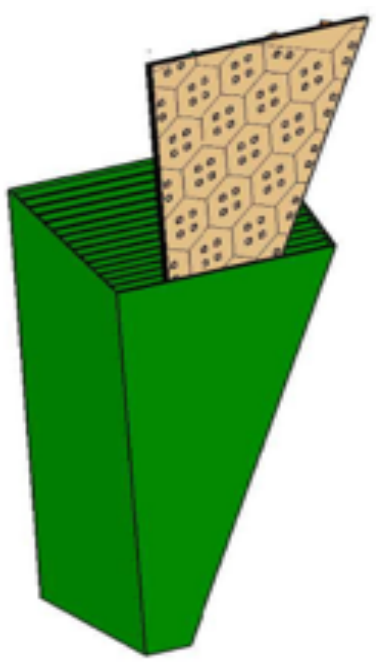
Inner Pixel
Covers up to η=4.0

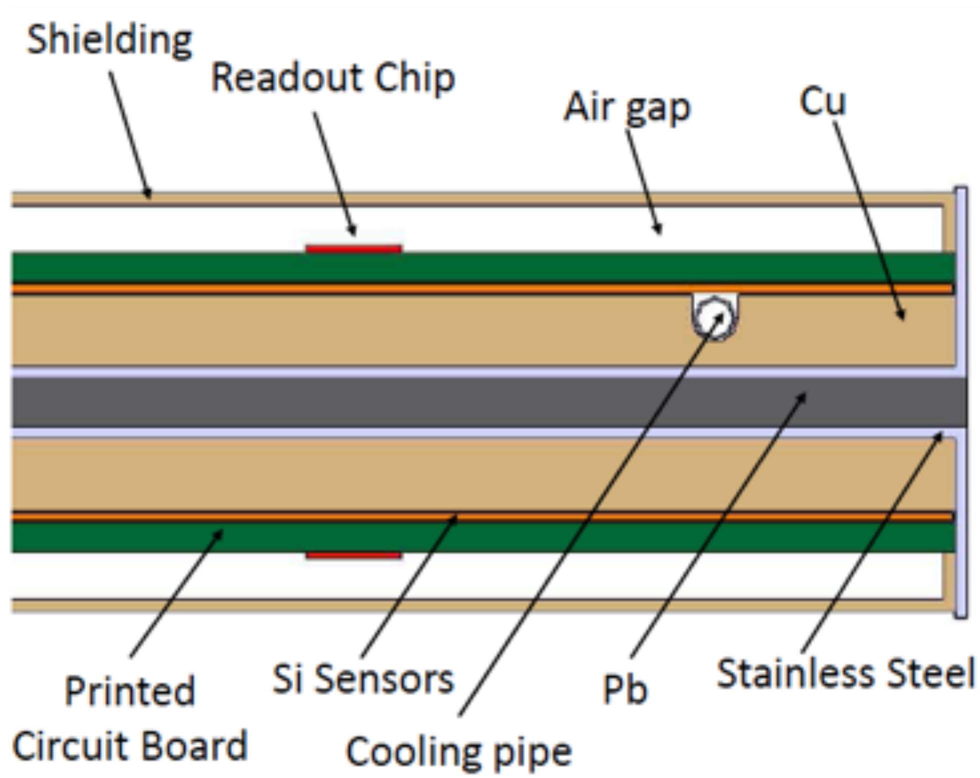


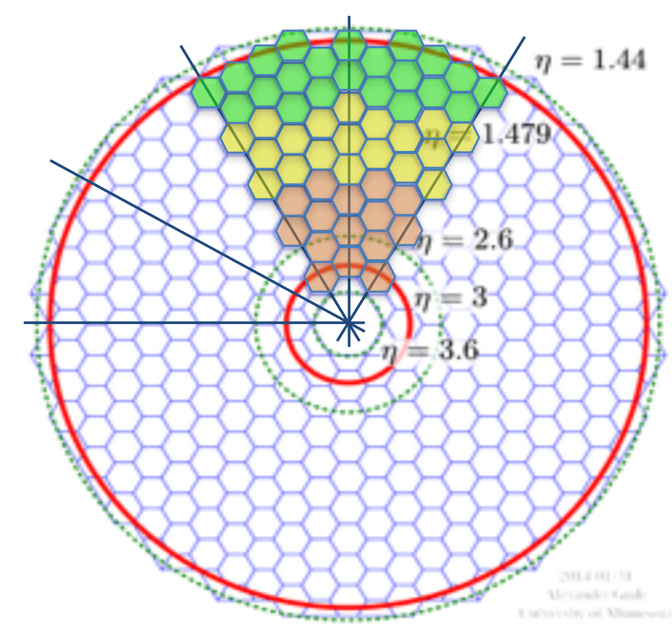
CMS Phase-II Endcap Calorimeter: HGCAL

- ➡**Silicon-tungsten/lead/copper EM (25 X_0, 1λ) and silicon/brass front hadron (3.5λ) calorimeter**
  - 8.7M channels, pad sizes 0.9cm² or 0.45cm² depending on η
- ➡**Scintillator-brass backing calorimeter (5.5λ, low radiation environment)**









CMS Phase-II Muon Detectors

➡**Improvements of existing detectors**

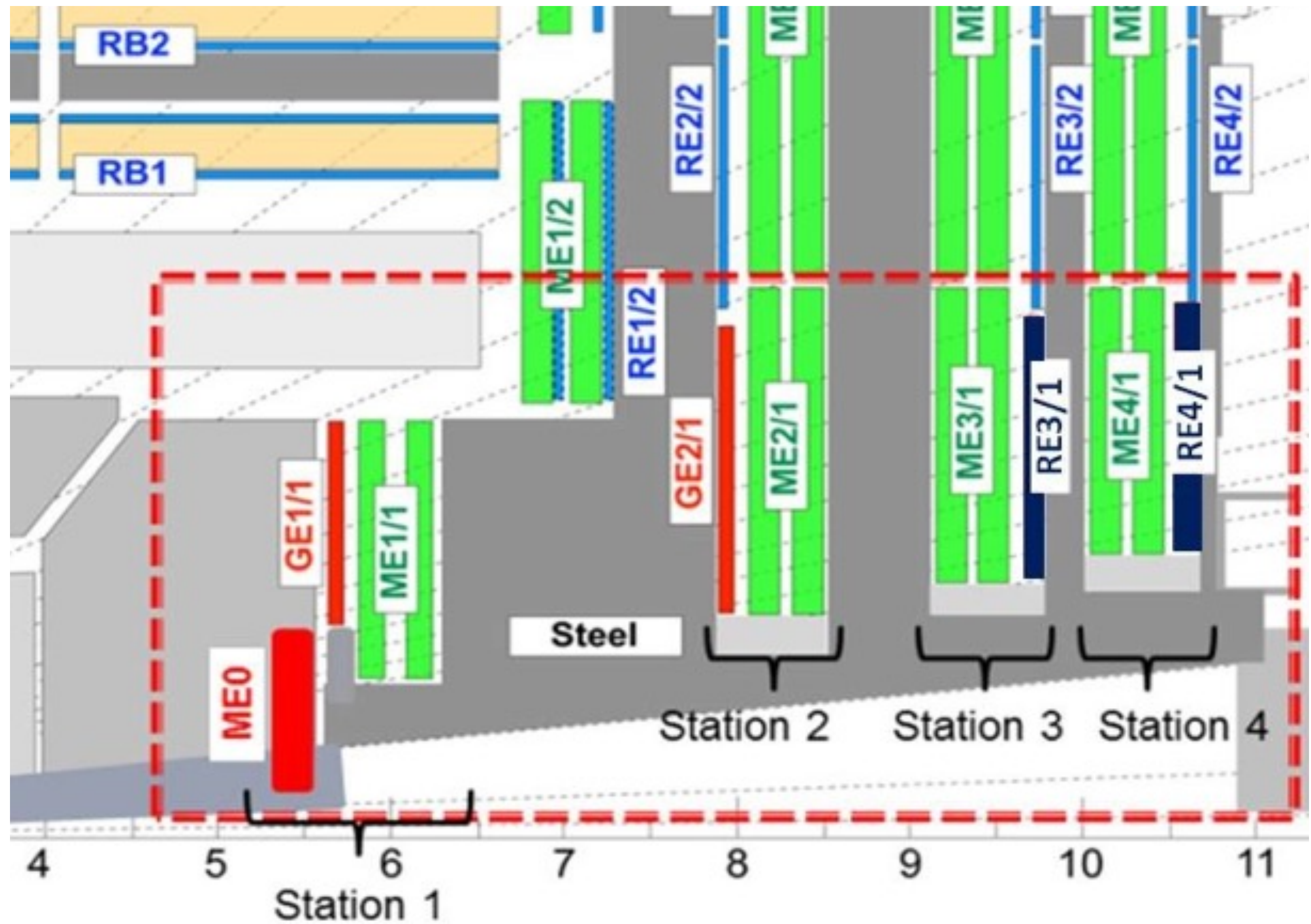
- Electronics: DT minicrates, CSC inner MEx/1 readout
  - needed for trigger upgrade

➡**Forward 1.6 < Iηl < 2.4 upgrades**

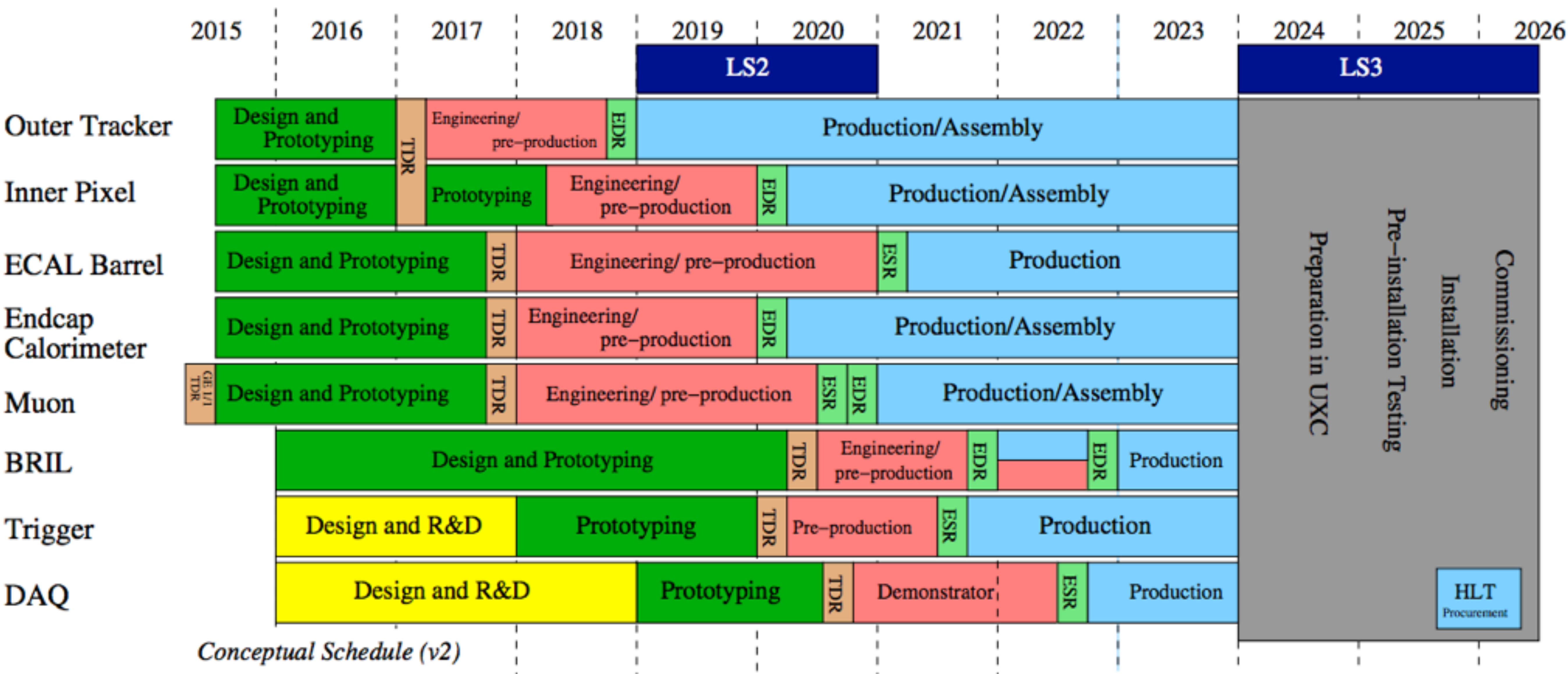
- L1 trigger rate reduction, enhanced redundancy
- GEMs: GE1/1 and GE2/1
- iRPCs: RE3/1 and RE4/1
  - operation in higher rate

➡**Very forward extension**

- muon tagging
- ME0 with GEMs
- 6 layer stub
- baseline 2.0 < Iηl < 3.0

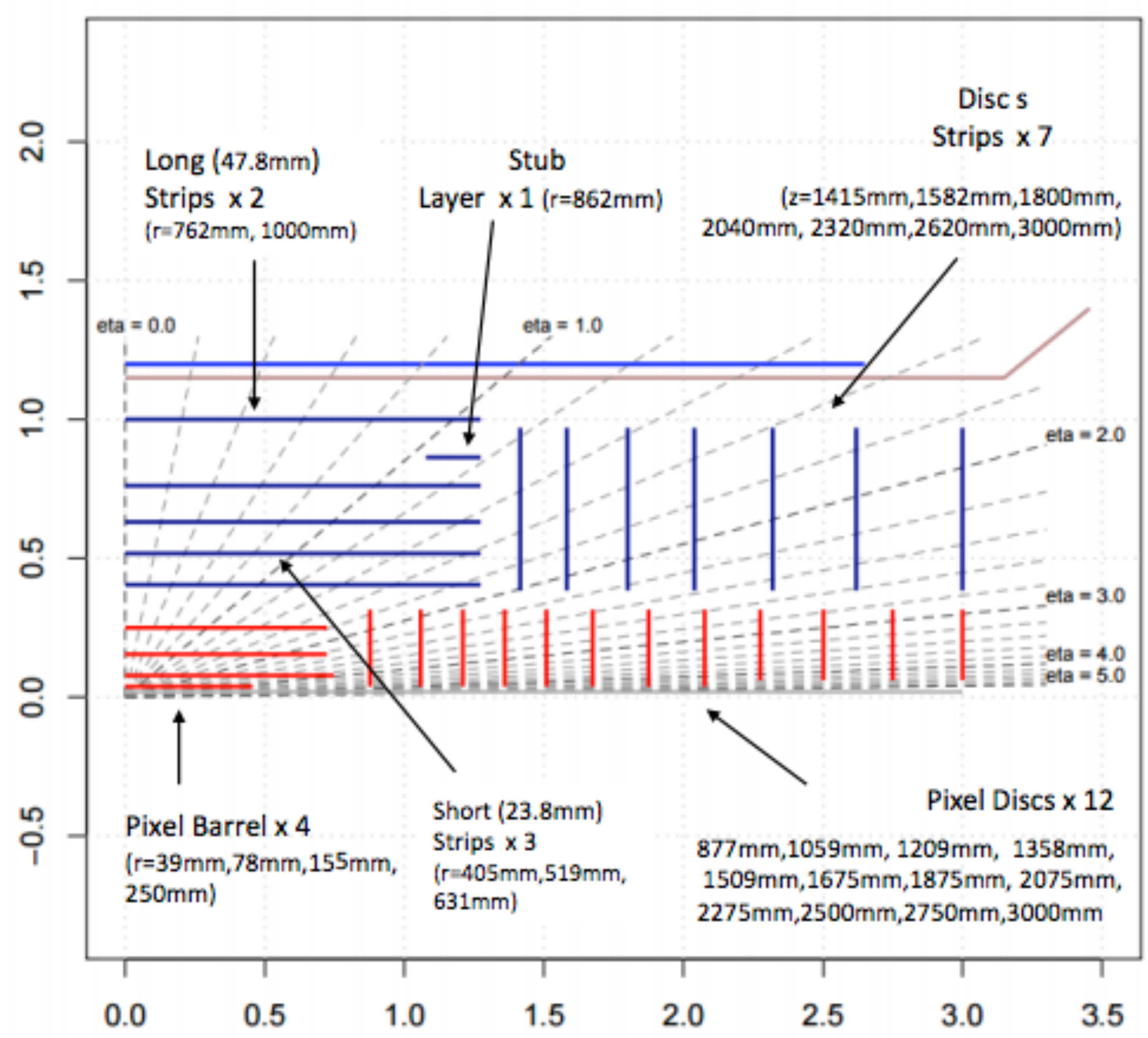


CMS Phase-II Upgrade Schedule



ATLAS Detector Upgrades

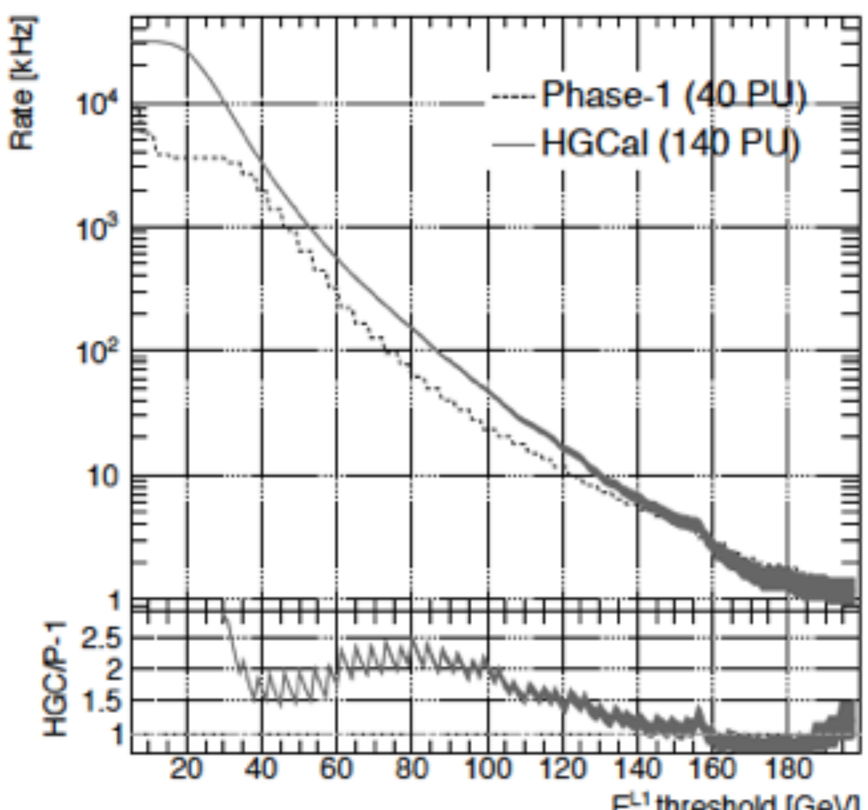
- ➡ **Trigger and Data-Flow system**
  - Introduction of level 0/1 trigger
  - Level 1 track trigger
  - DAQ upgrade
  - Muon trigger system
- ➡ **All new inner tracking detector**
- ➡ **Calorimeter Electronics**
- ➡ **Enhancements to high-eta regions**



Trigger

➡ Level 1 trigger menu

- 500 (750) kHz for 140 (200) PU with safety margin
- Offline thresholds comparable to Run-I
- Crucial to exploit physics program, esp. Higgs physics
- Track trigger provides highly efficient trigger with sharp turn-ons
- HGCAL provide additional handle in region outside the track-trigger acceptance

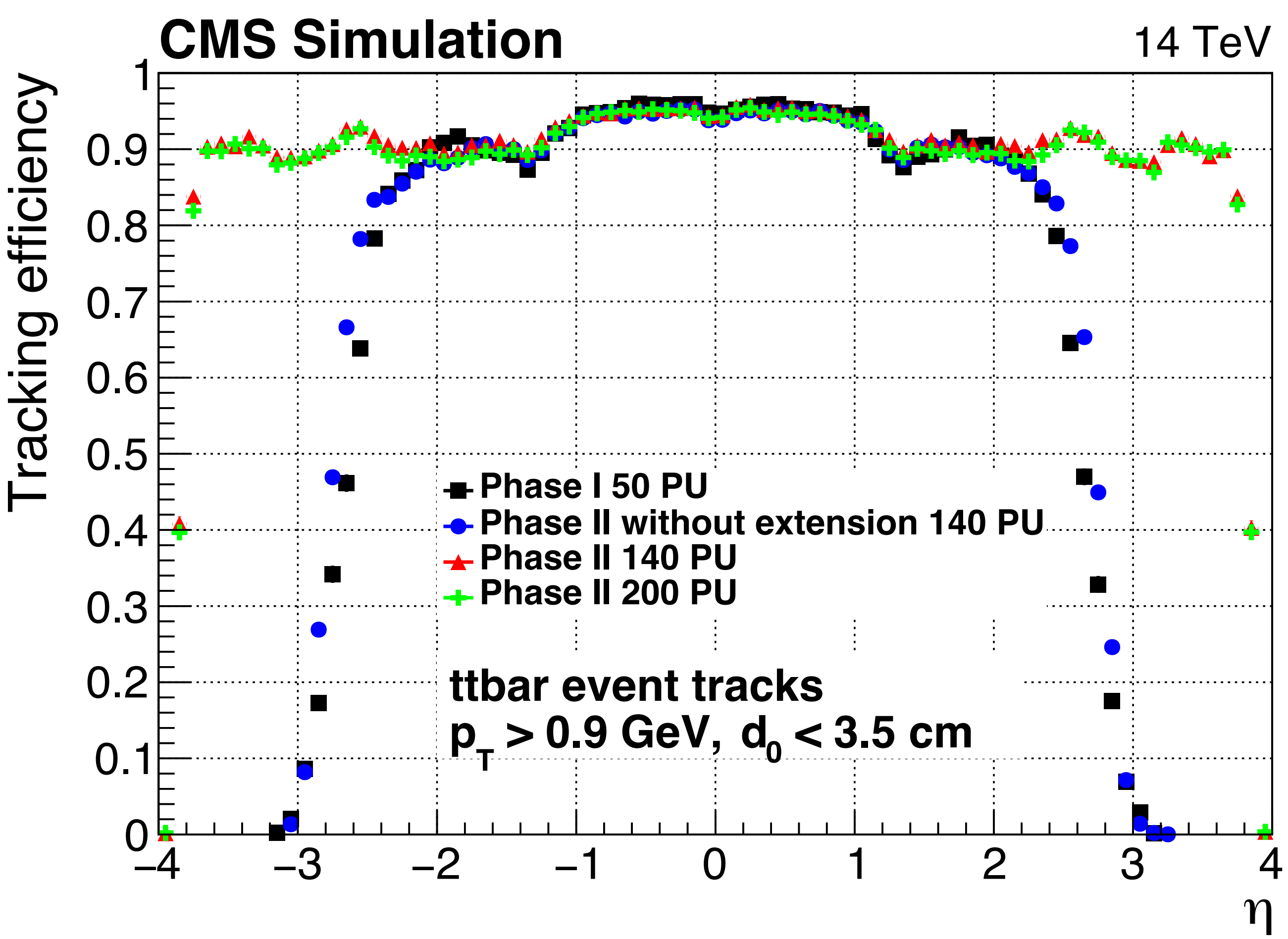


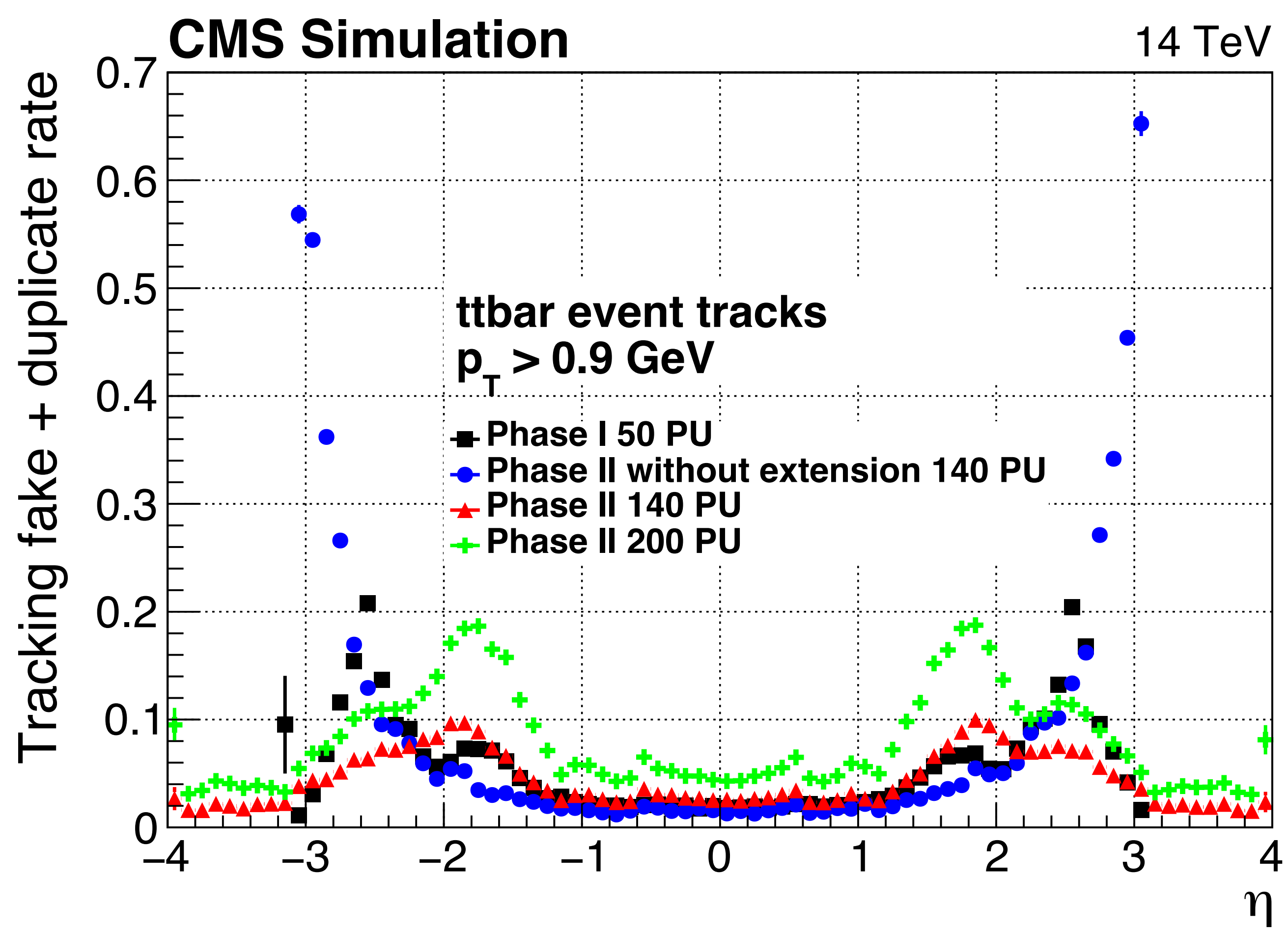
$L = 5.6 \times 10^{34}$ cm^{-2}s^{-1} $\langle PU \rangle = 140$	Level-1 Trigger with L1 Tracks	
Trigger Algorithm	Rate [kHz]	Offline Threshold(s) [GeV]
Single Mu (tk)	14	18
Double Mu (tk)	1.1	14 10
ele (iso tk) + Mu (tk)	0.7	19 10.5
Single Ele (tk)	16	31
Single iso Ele (tk)	13	27
Single γ (tk-veto)	31	31
ele (iso tk) + e/γ	11	22 16
Double γ (tk isol)	17	22 16
Single Tau (tk)	13	88
Tau (tk) + Tau	32	56 56
ele (iso tk) + Tau	7.4	19 50
Tau (tk) + Mu (tk)	5.4	45 14
Single Jet	42	173
Double Jet (tk)	26	2@136
Quad Jet (tk)	12	4@72
Single ele (tk) + Jet (tk)	15	23 66
Single Mu (tk) + Jet (tk)	8.8	16 66
Single ele (tk) + H_T^{miss} (tk)	10	23 95
Single Mu (tk) + H_T^{miss} (tk)	2.7	16 95
H_T (tk)	13	350
Rate for above Triggers	180	
Est. Total Level-1 Menu Rate	**260**	

Performance with increased pileup

➡ General statement

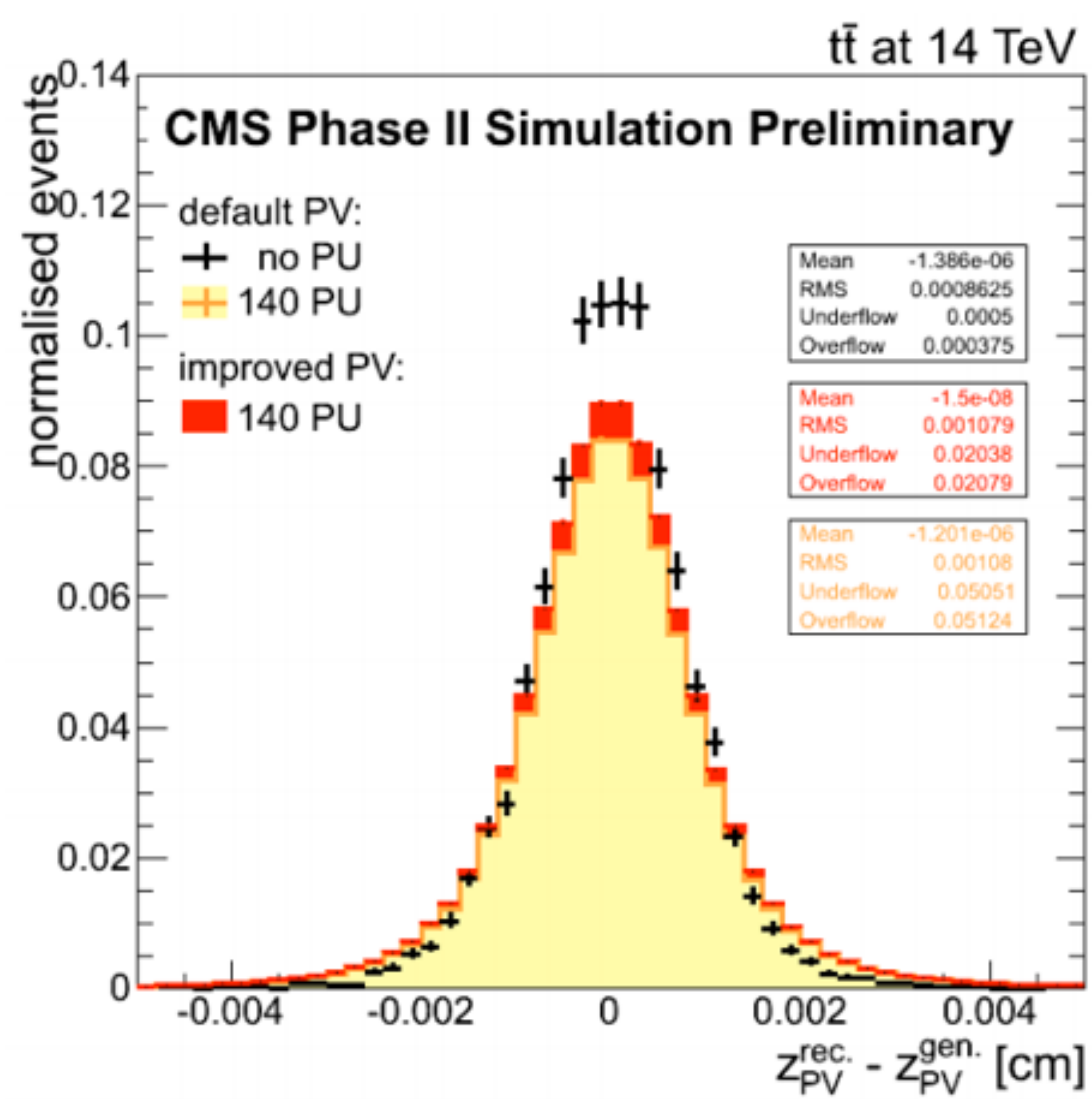
- excellent tracking used for pileup mitigation
- most affected are calorimetric measurements at low pT

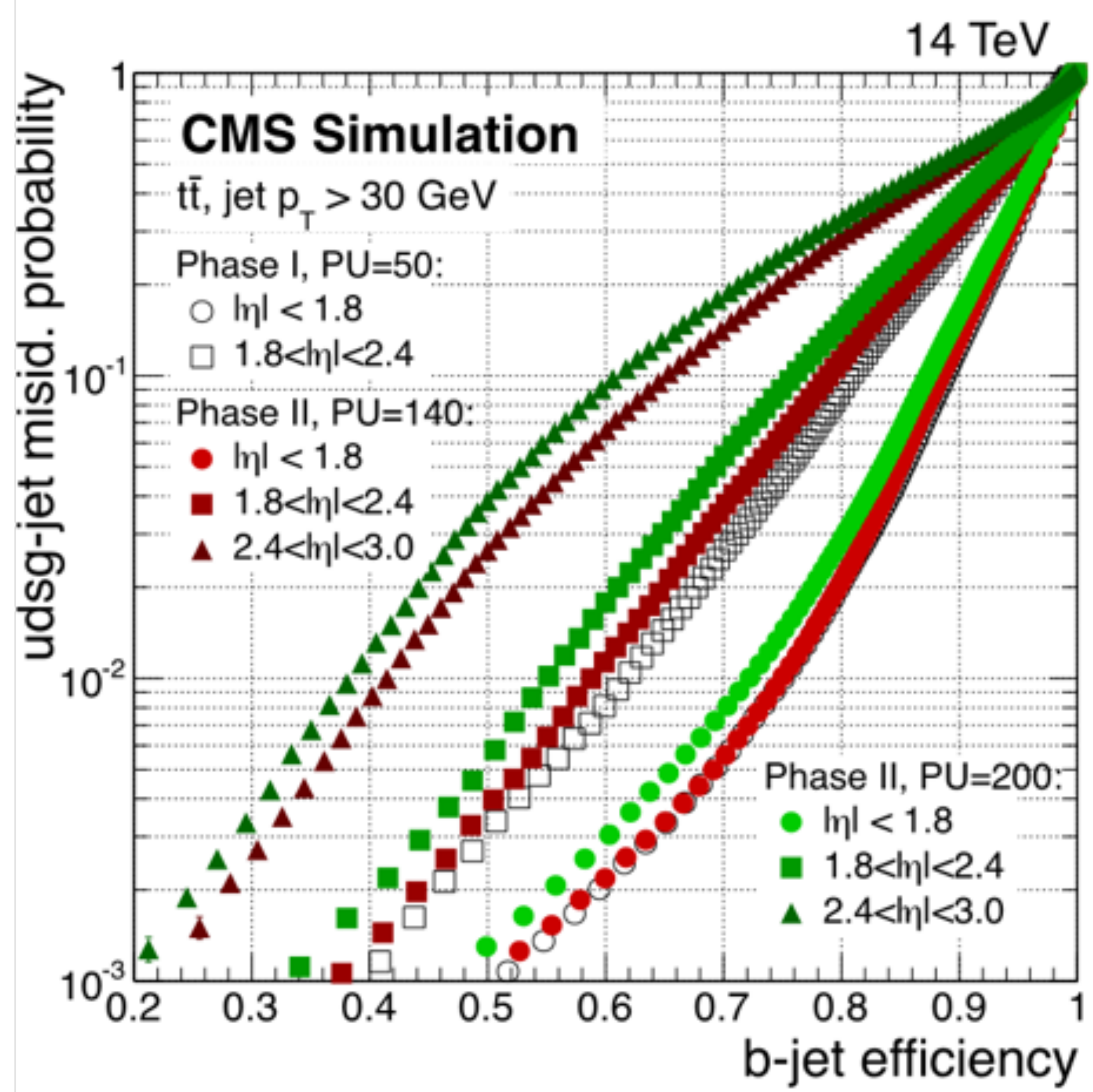




Detector Performance

➡ **Vertexing and B-tagging**





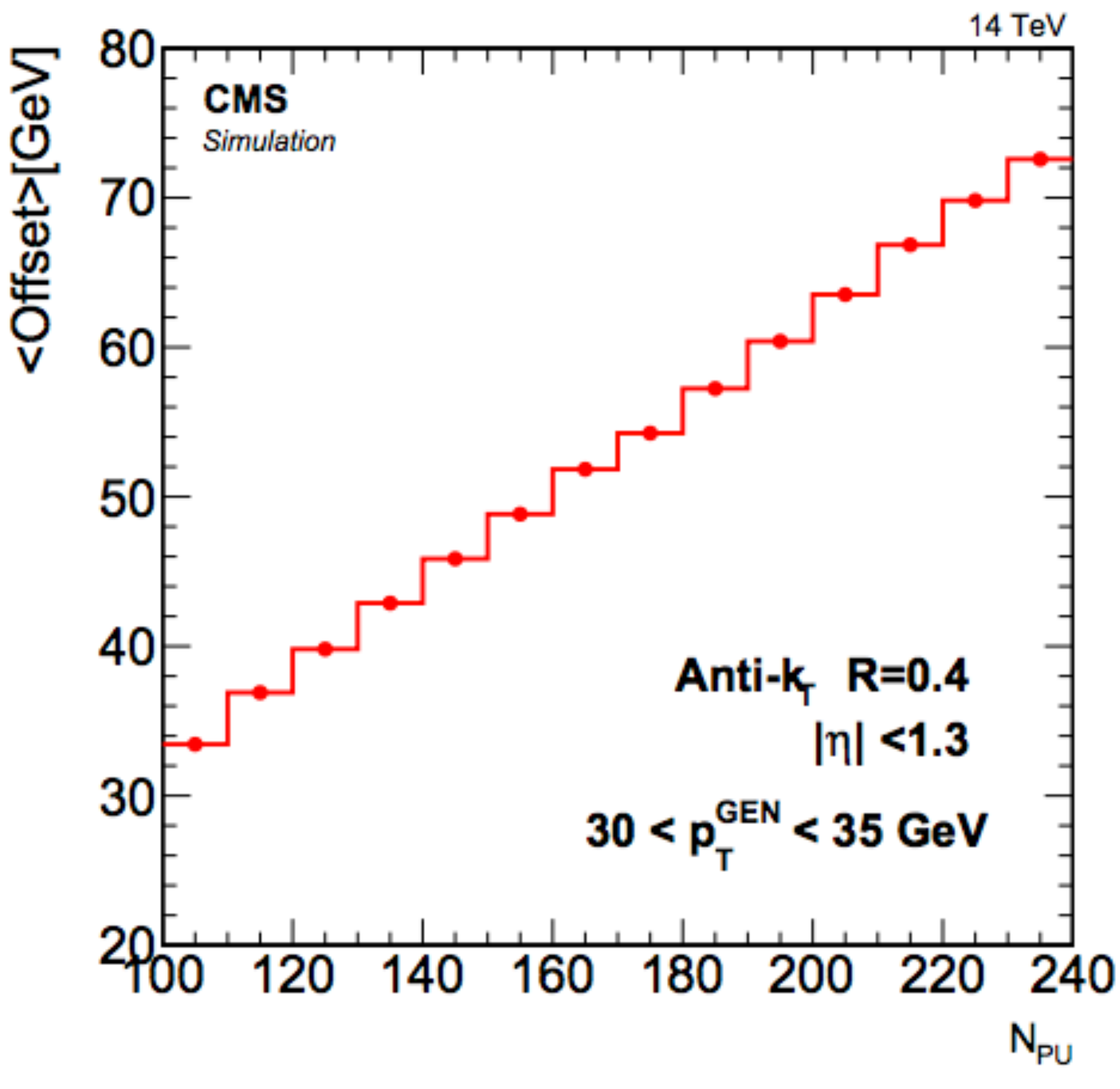
➡ 98% vertex finding efficiency with 140 PU

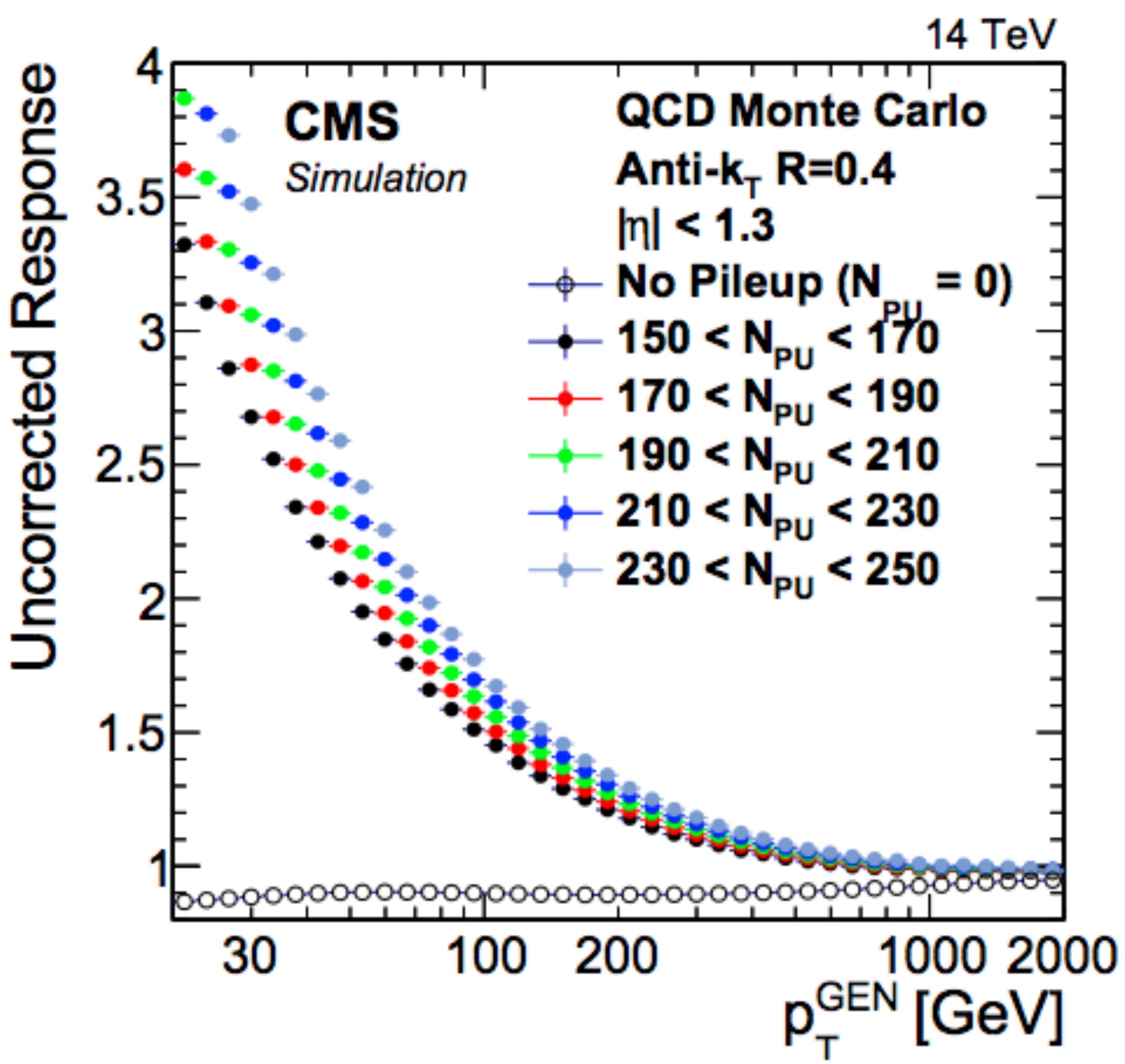
➡ Recover low pileup performance

➡ Further optimization possible

Jet Performance

➡ **Jet corrections mainly correct for PU, lots of it!**

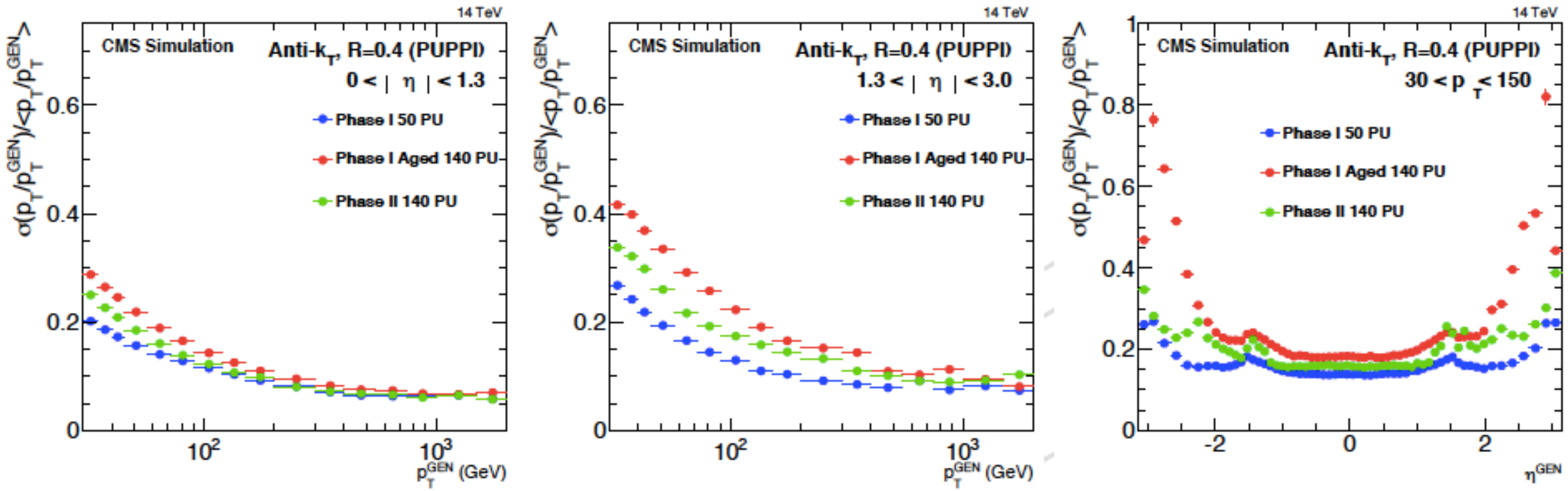




Jet Performance

➡ **Jet performance derived for fully corrected jets**

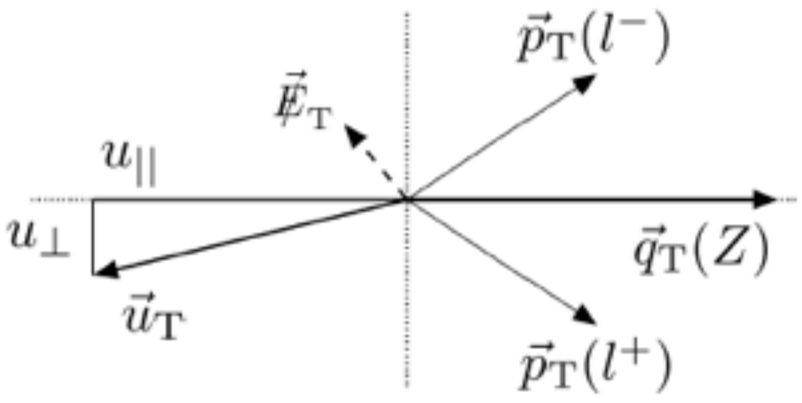
- PUPPI algorithm applies weights to PF candidates based on how likely they stem from pileup
- Phase-II detector improved resolution significantly w.r.t. Phase-I (both PU=140)
- large improvements for |η| > 2.5 due to extended tracker and upgraded endcap calorimeter

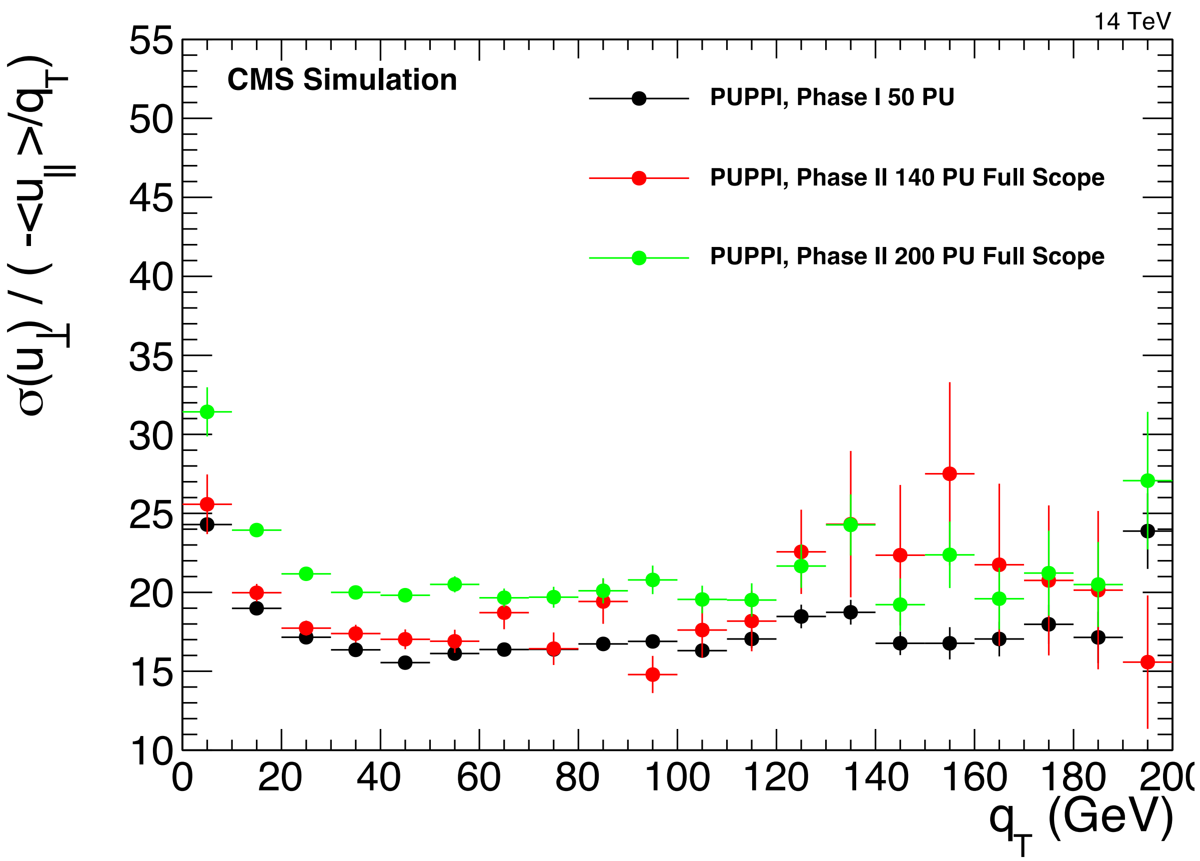


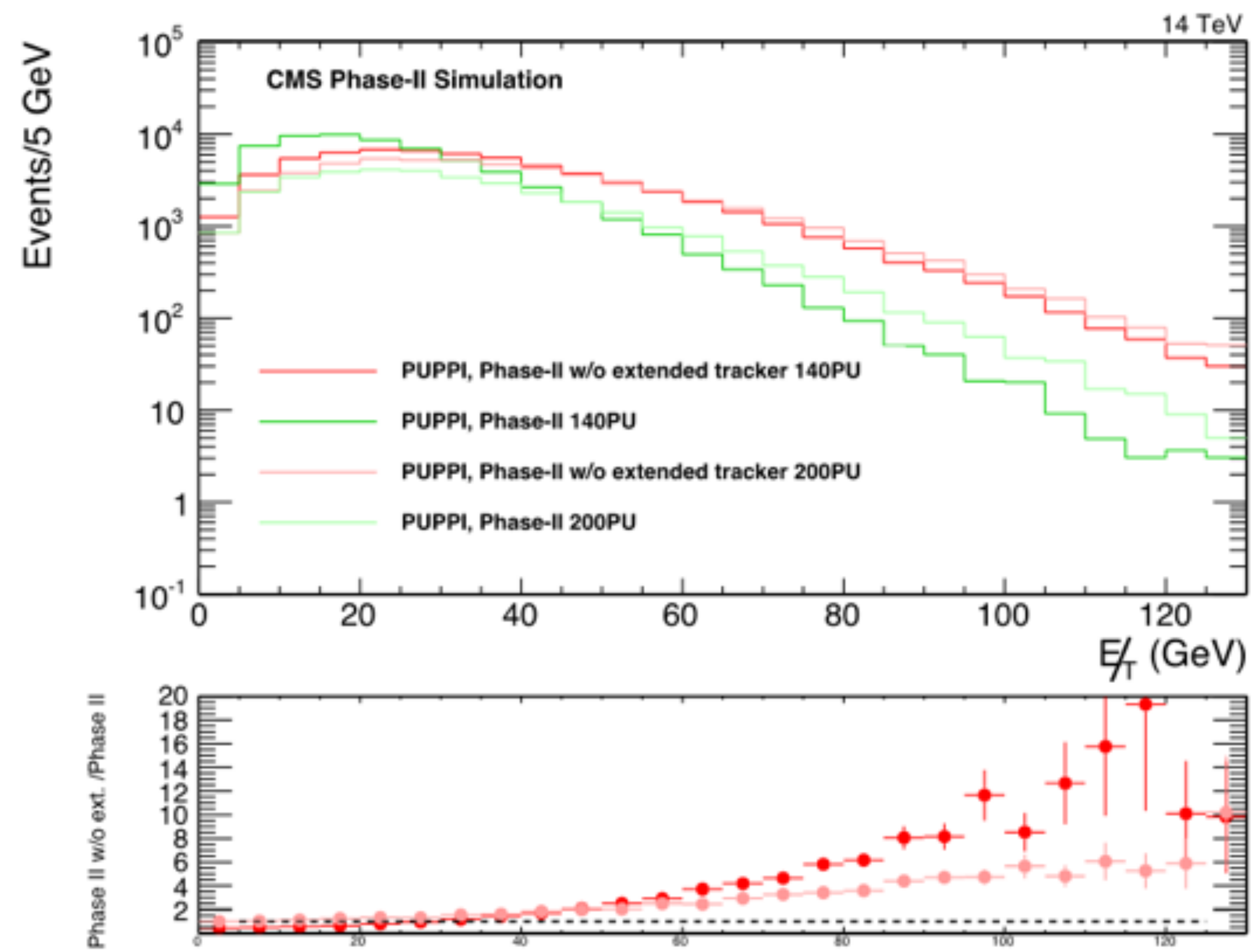
Missing Transverse Energy

➡ **Missing ET performance**

- performance evaluated with DY events
- resolution measured using recoil method
- Phase-II detector recovers MET resolution partially
- MET tails significantly reduced by tracking extension



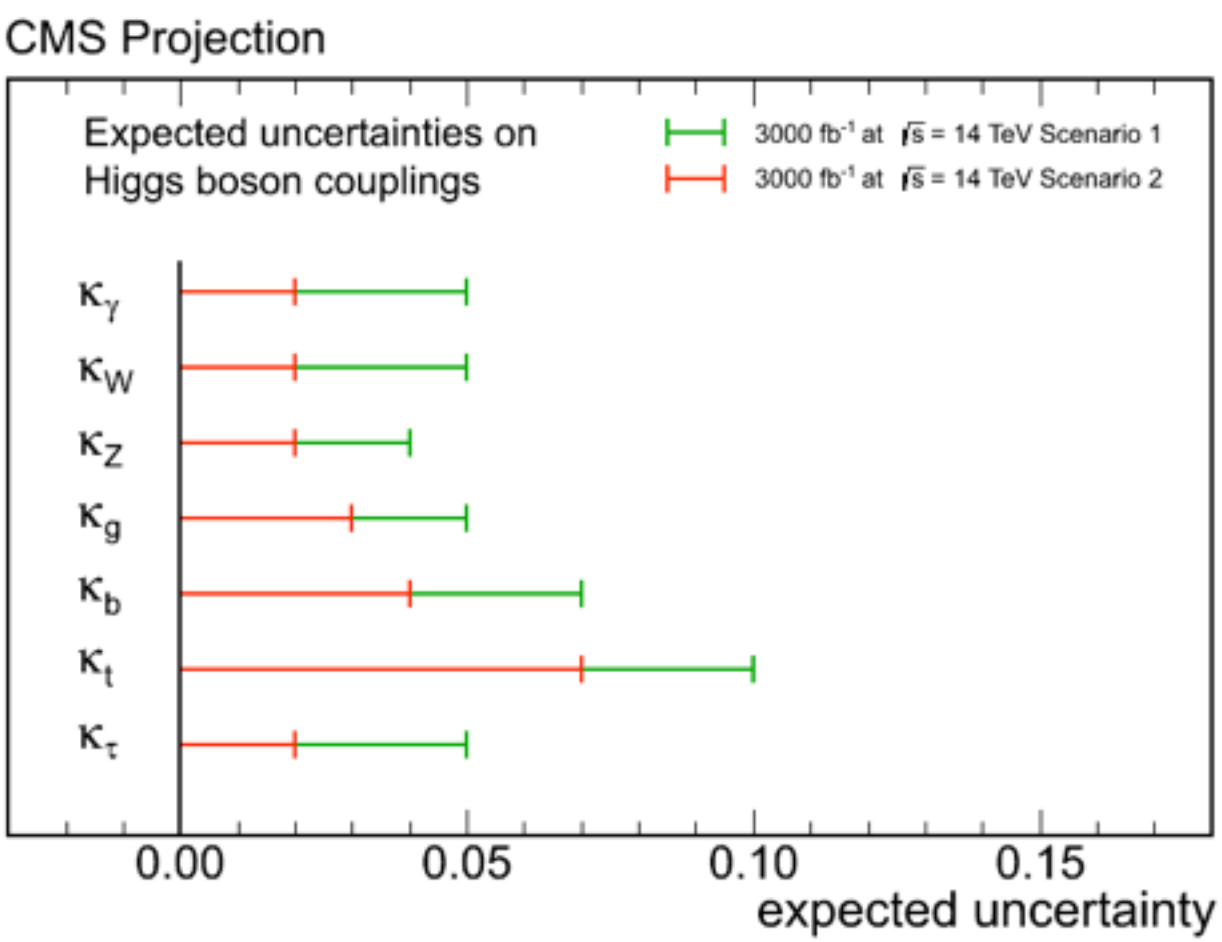




Physics Performance

Performance/ Physics	Higgs VBF $H \to \tau\tau$	Higgs $H \to \mu\mu$	Higgs $H \to ZZ \to 4l$	Higgs $HH \to bb\gamma\gamma$	Higgs $HH \to bb\tau\tau$	SMP VBS	SUSY VH(bb) +MET	EXO A_{fb} (Z')	EXO Dark Matter	EXO HCP	BPH $B_{s,d} \to \mu\mu$
Tracker											
Performance		***mass resolution***	***mass resolution***	***b-tagging***	***b-tagging***						***mass resolution***
Extensions	***forward jets / MET***		***acceptance***		***MET resolution***	***forward jets***	***MET resolution***	***acceptance***	***acceptance***		
Trigger											
Bandwidth	***acceptance***				***acceptance***						
Track Trigger	***background rejection***				***background rejection***						***background rejection***
Calorimeter											
ECAL	***forward jets / MET***		***acceptance***	***acceptance***	***MET resolution***	***forward jets***	***MET resolution***	***acceptance***	***acceptance***		
HCAL	***forward jets / MET***				***MET resolution***	***forward jets***	***MET resolution***				
Muons											
Extension			***acceptance***					***acceptance***	***acceptance***		

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

Rare-decays

CMS Projection for precision of Higgs coupling measurement

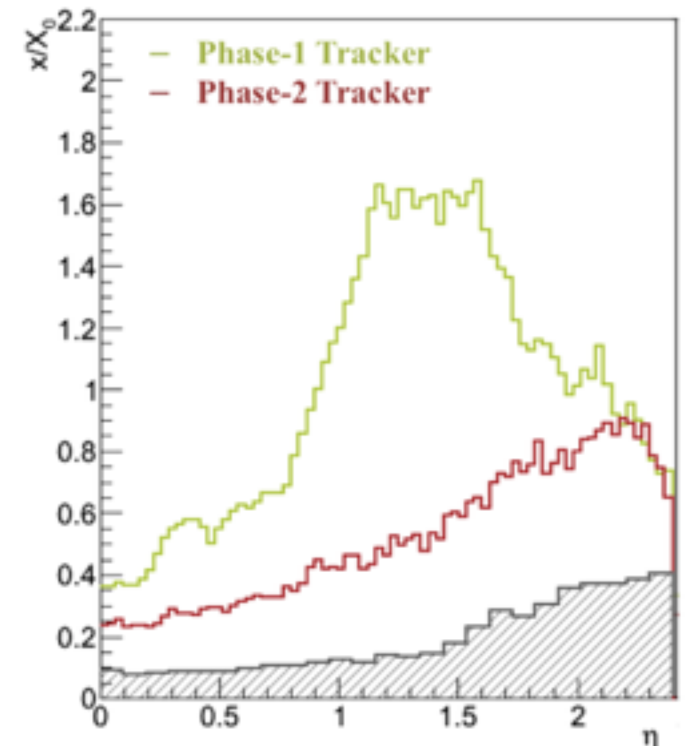
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

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

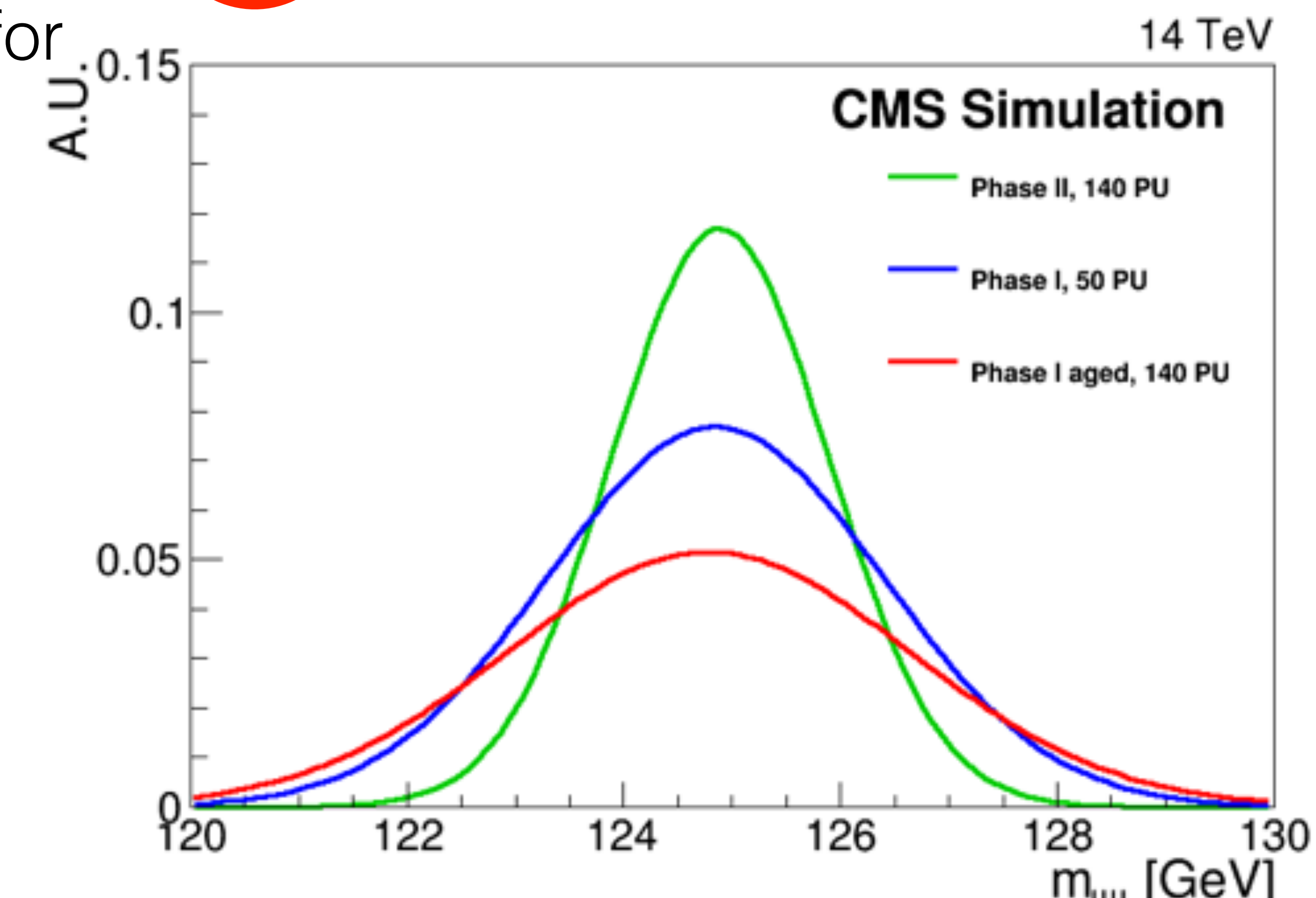
Rare Higgs Decays

- **H → μμ**
  - 2nd generation fermion coupling
  - search for narrow resonance with huge DY background
  - projection using Run-I performance

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	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]

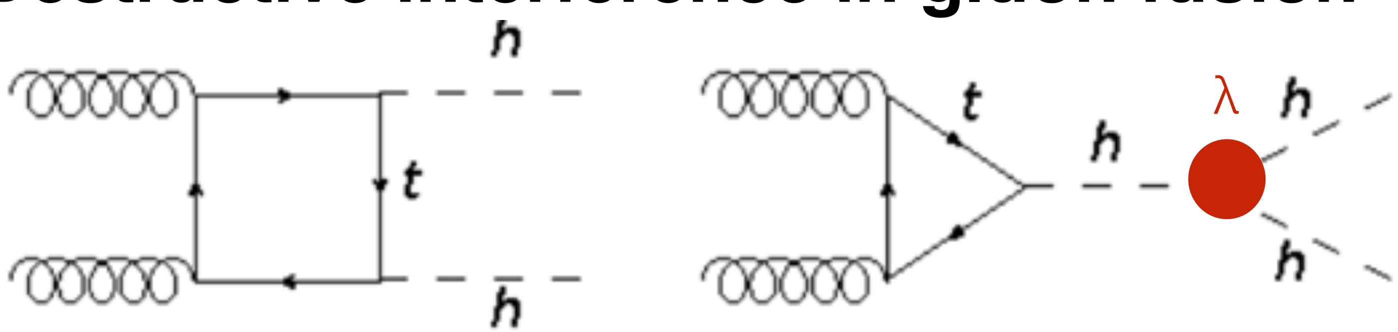


  - investigated resolution and efficiency for Run-I, Phase-I, and Phase-II
  - ~45% improvement in resolution wrt Phase-I aged PU =140
  - ~20% improvement in efficiency wrt Phase-I aged PU =140
  - results scale with square-root of improvements
  - **expect ~5% uncertainty on κ_μ**

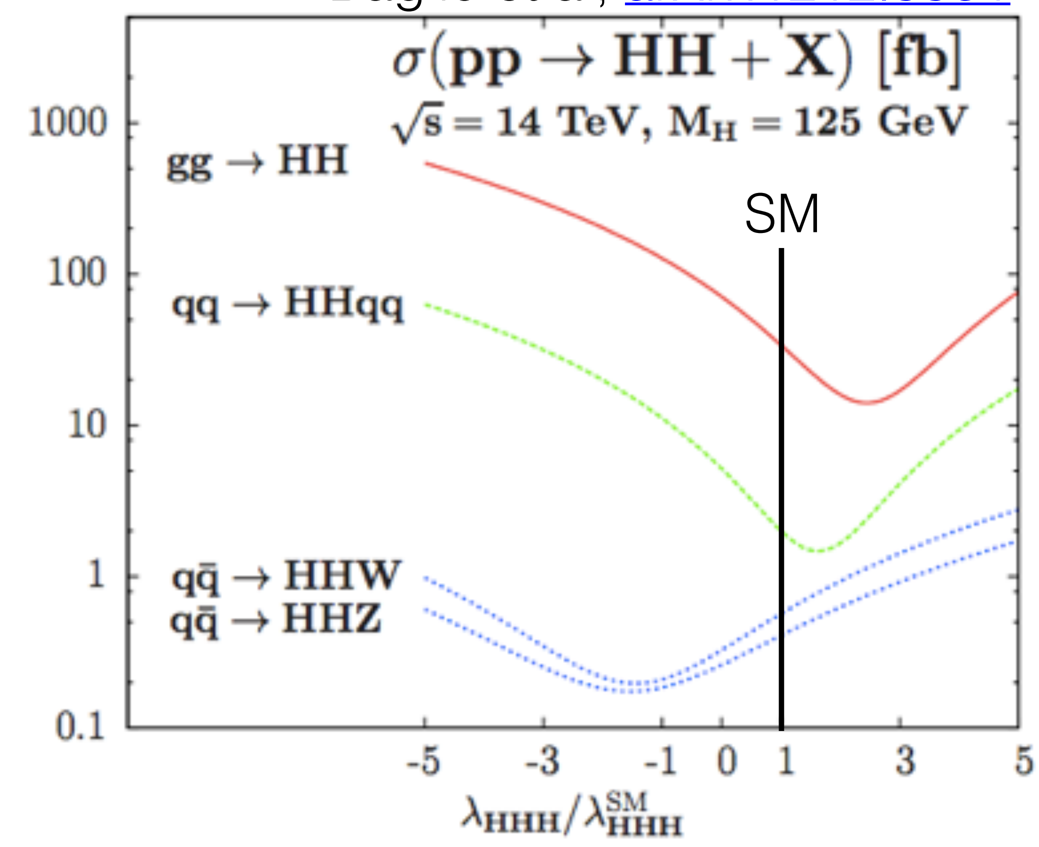


Very Rare Higgs Decays

- ➡ **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

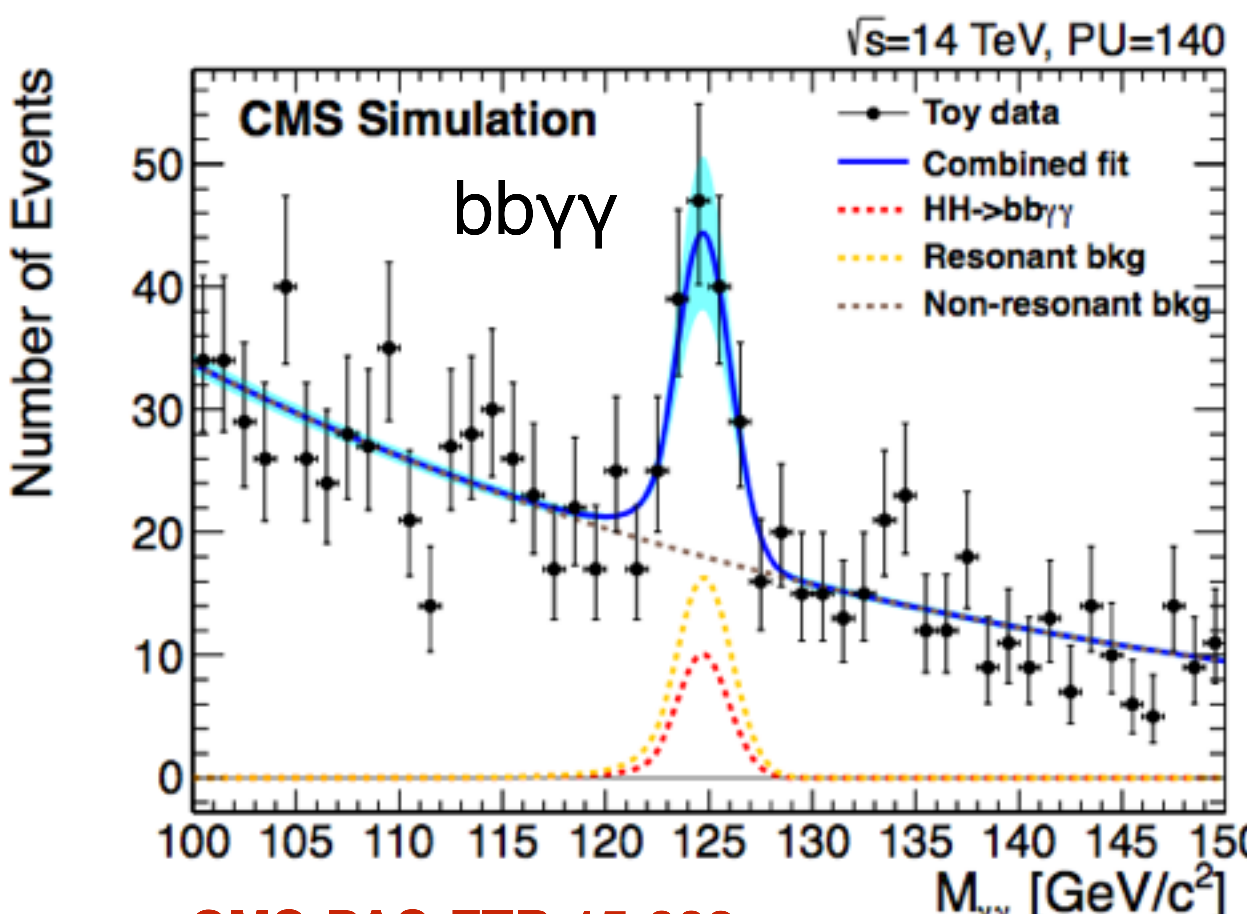


- ➡ **Most interesting final states**
  - ◉ bbγγ [320 expected events in 3ab-1]
  - ◉ bb$\tau\tau$ [9000 expected]
  - ◉ bbbb [40k expected (2k in VBF)]
  - ◉ bbWW [30000 exp. events]
- ➡ **Goal is to reach minimum sensitivity of 3σ for SM production and with that to BSM scenarios**

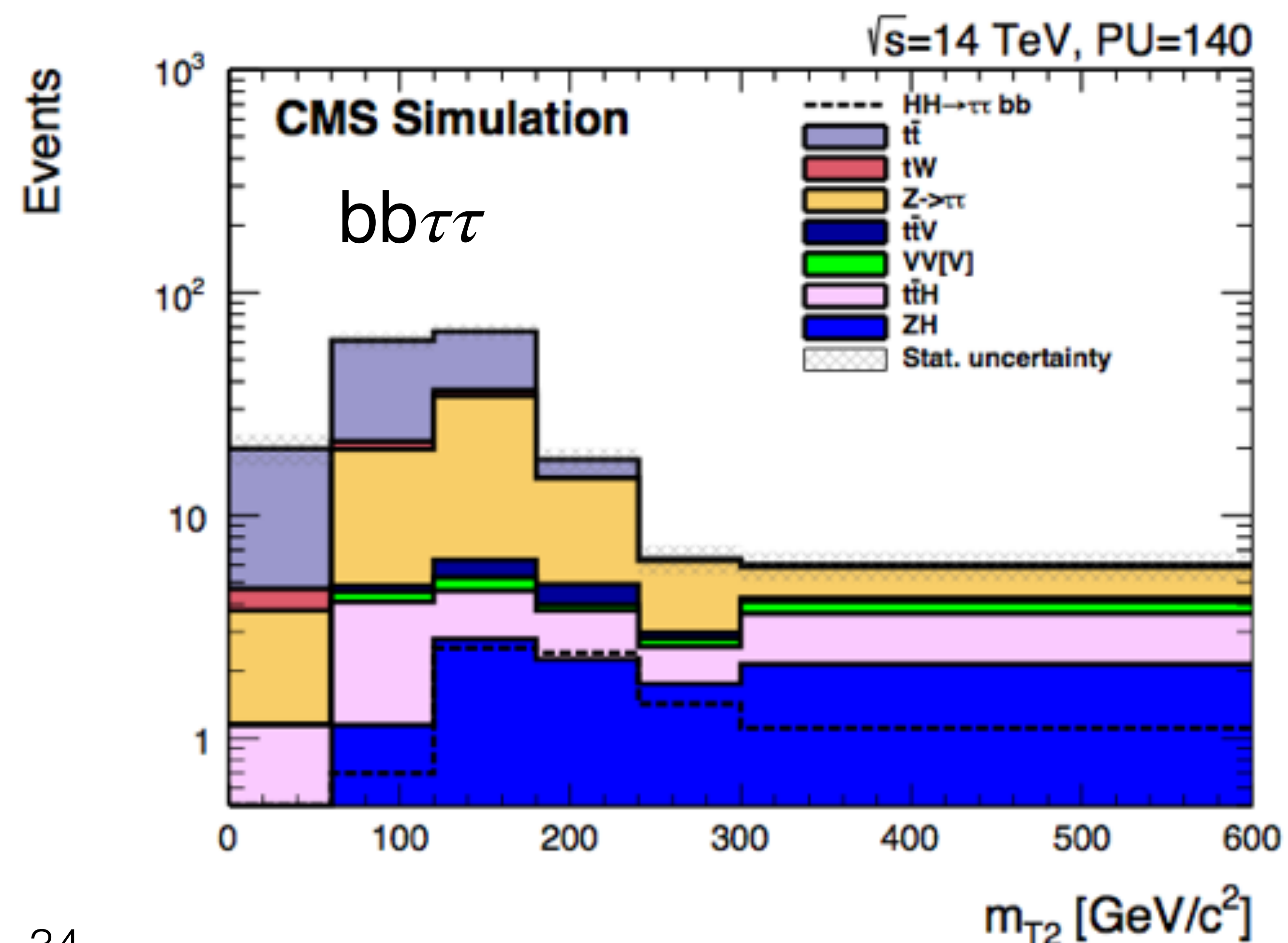
Di-Higgs Searches

- ➡ **Demonstrate Phase-II detector capabilities**
  - b-tagging, photon, and tau-Id
  - case for the track trigger
- ➡ **Sensitivity**
  - ~2σ or 54% measurement

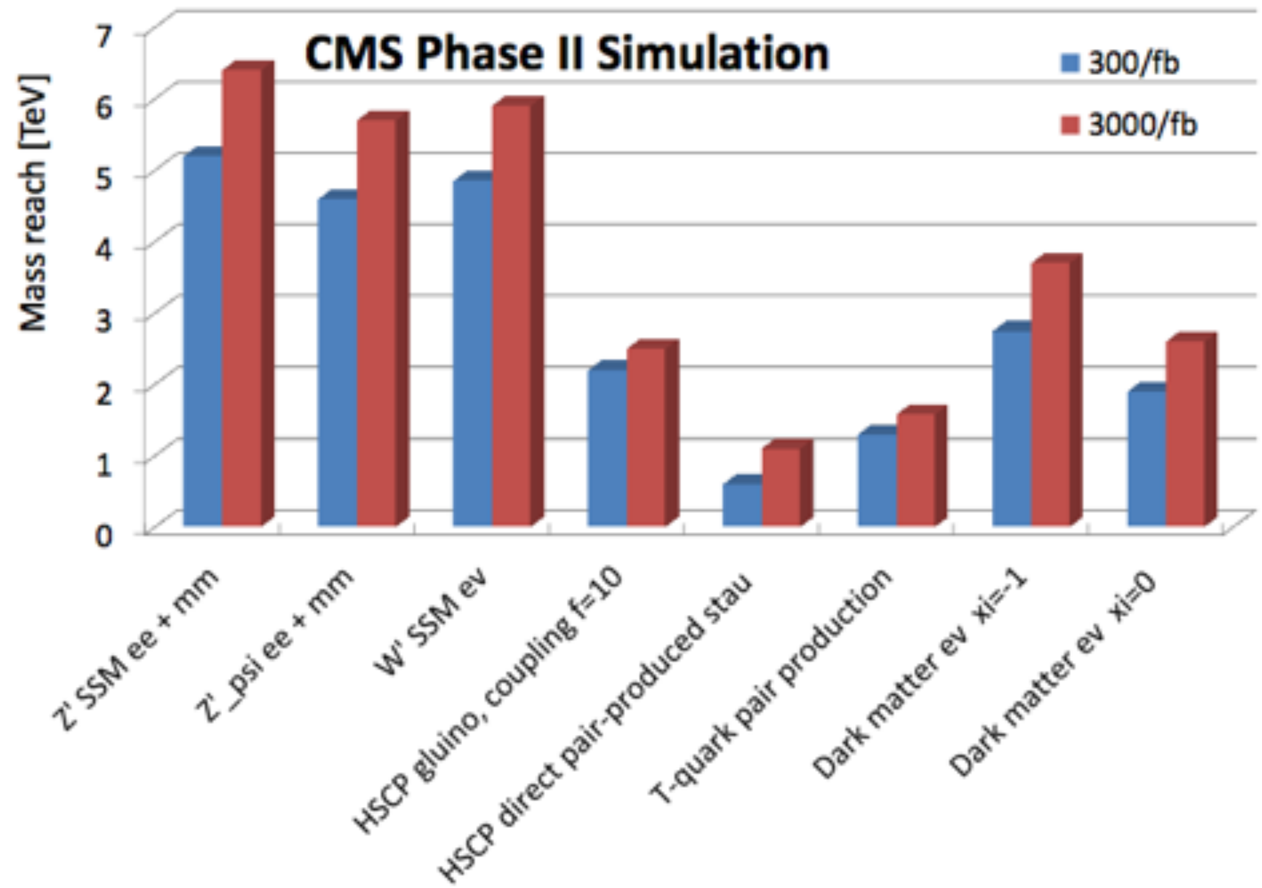
- ➡ **Further improvements**
  - additional channels (bbbb)
  - improved pixel detector (b-tagging)
  - improved resolutions (regression)
  - analysis strategies
  - combination with ATLAS

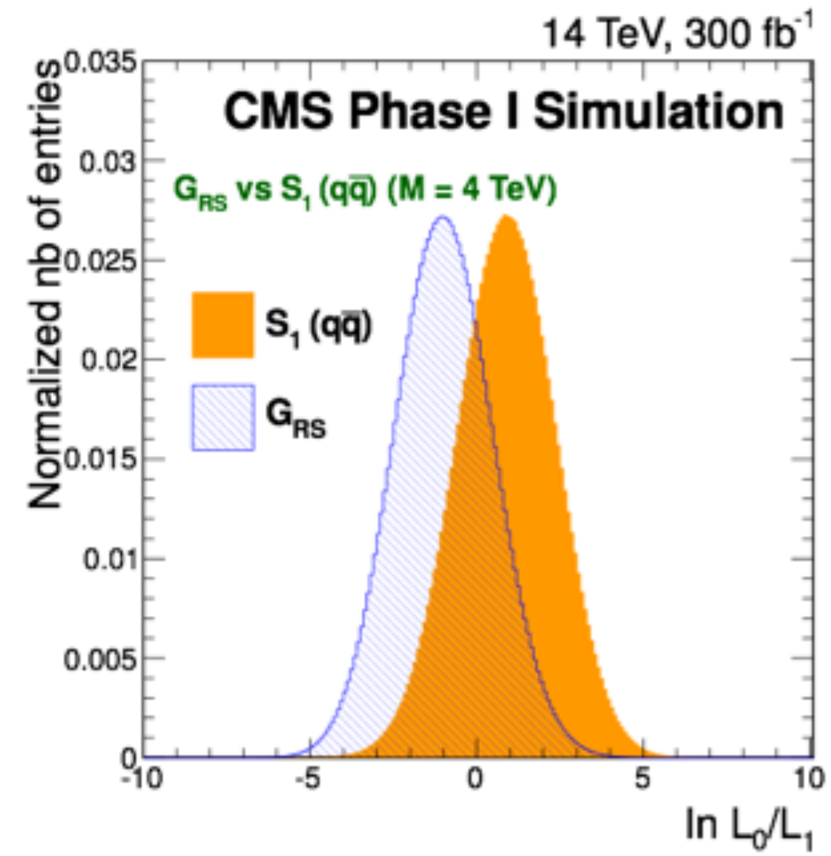


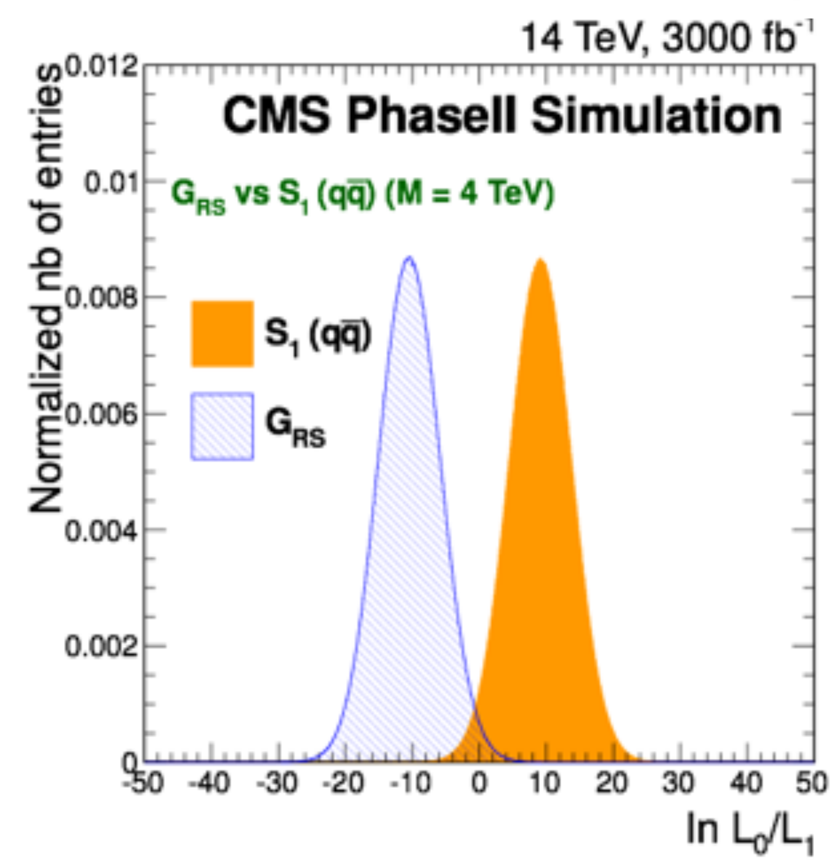
CMS-PAS-FTR-15-002



Exotica





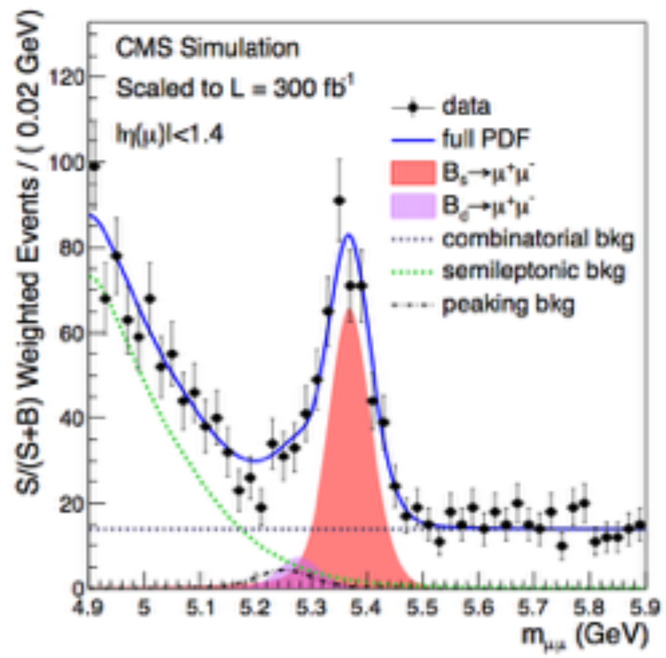


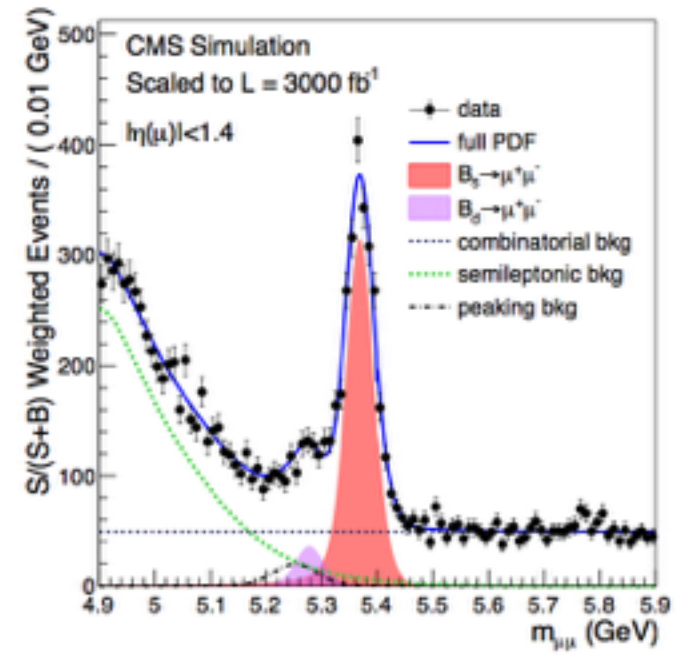
➡ **Window to new physics beyond SUSY**

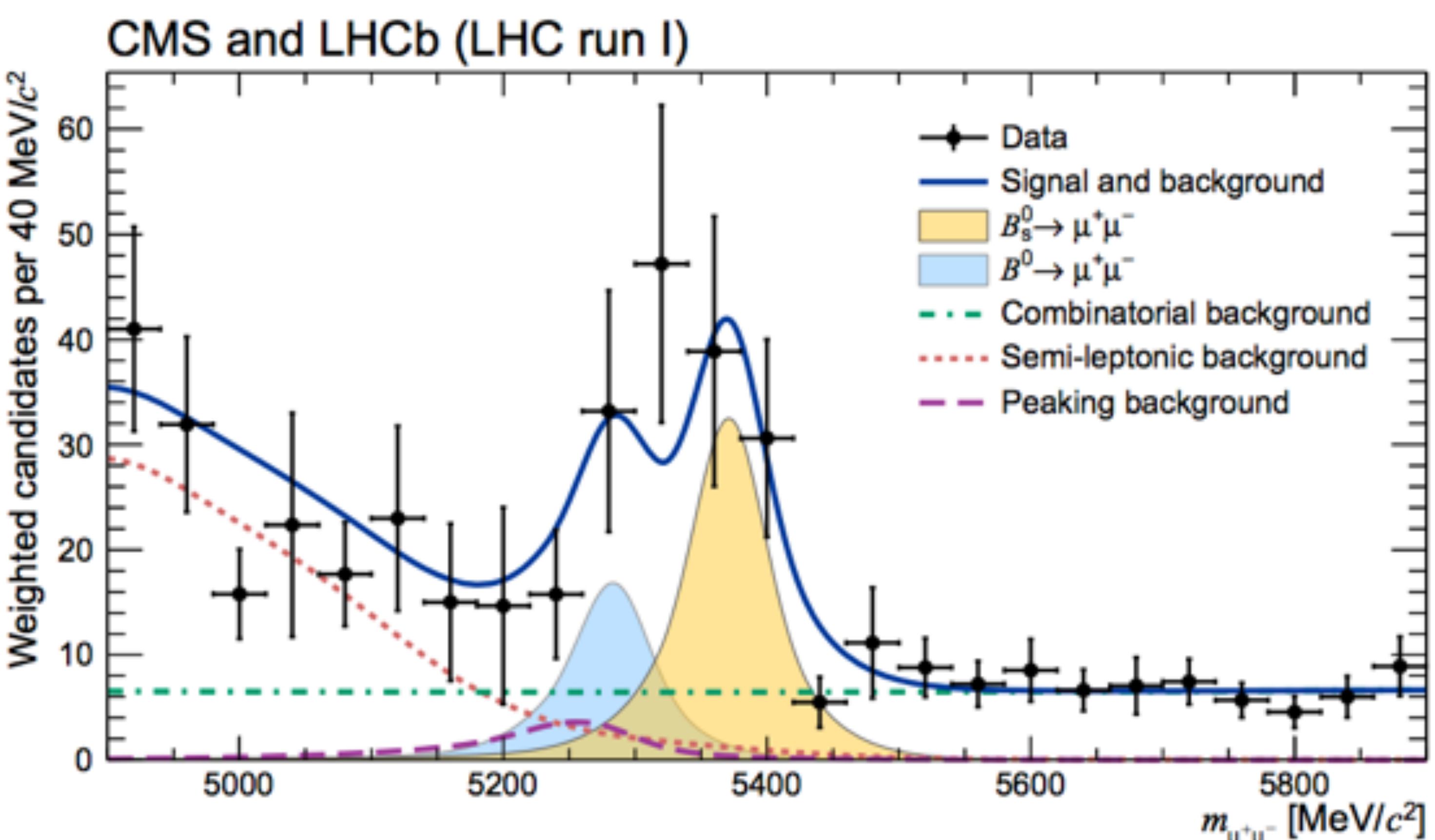
- heavy gauge boson search and properties
- dark matter
- highly ionizing particle
- displaced vertices

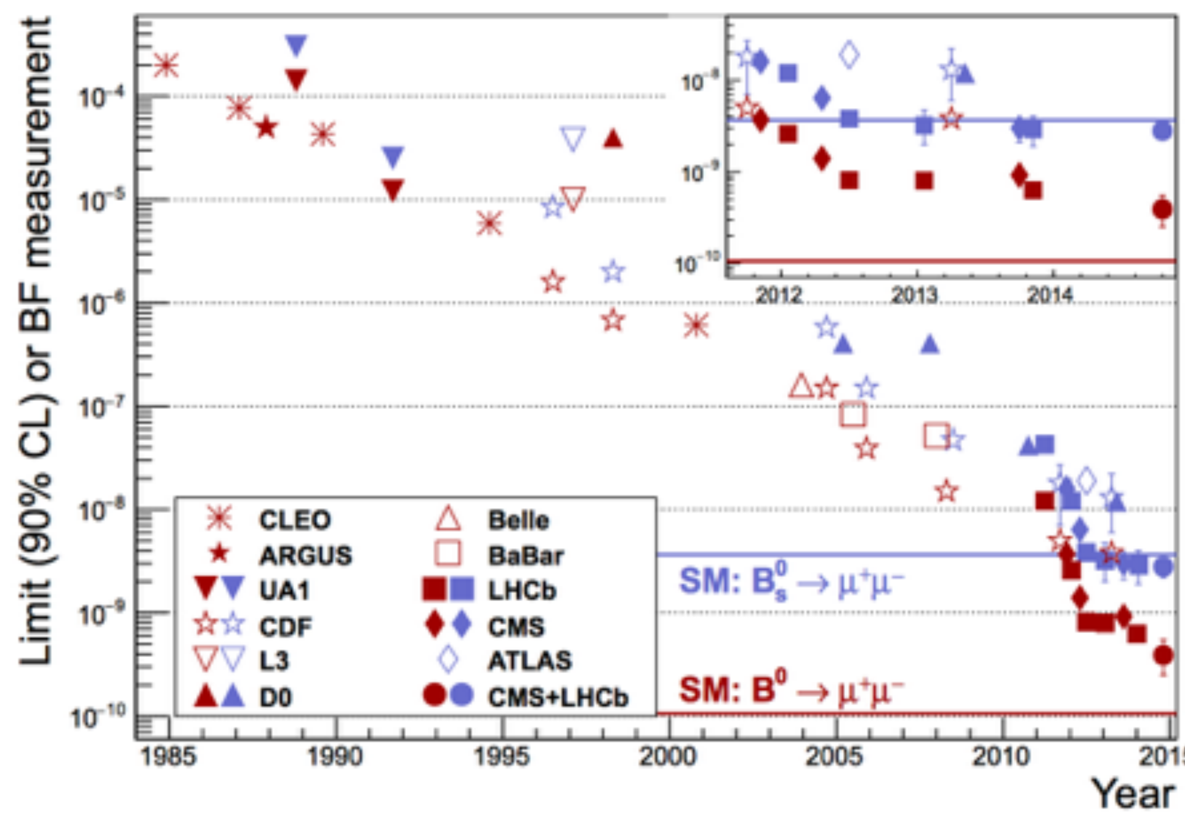
B Physics

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





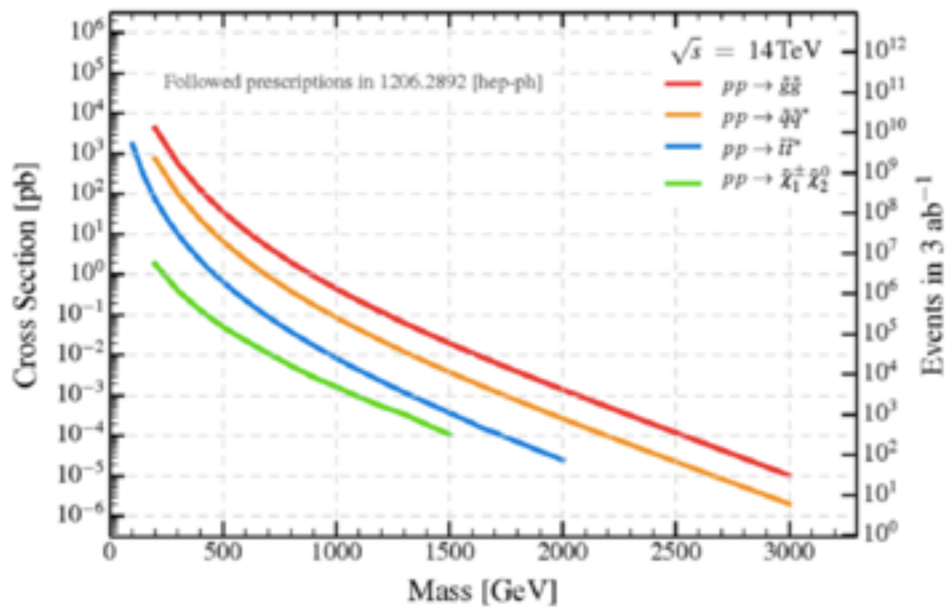


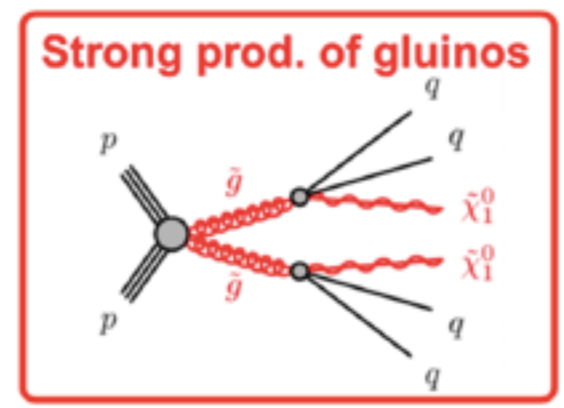


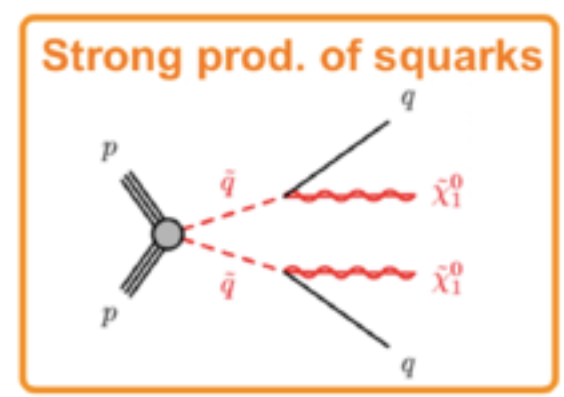
Supersymmetry

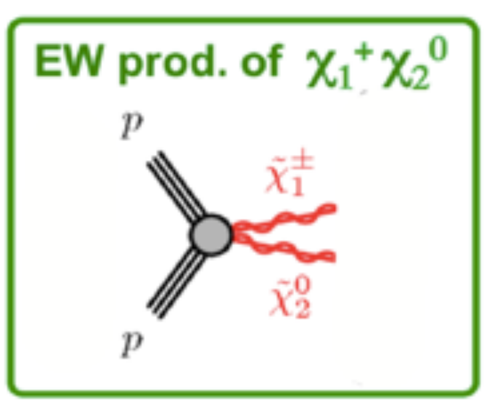
➡ **Motivation for SUSY has never been stronger**

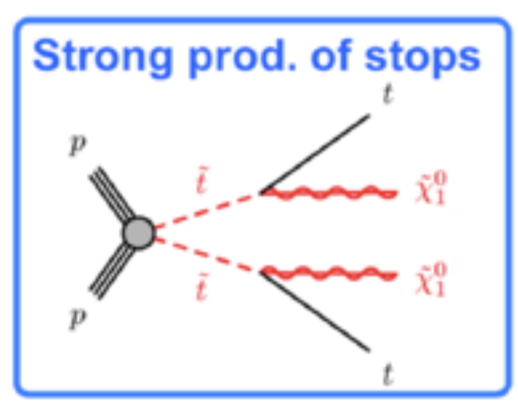
- discovery of the Higgs gives new urgency to find “natural” explanation for gauge hierarchy
- HL-LHC expands discovery reach or allows to investigate SUSY spectrum
- requires all capabilities of CMS



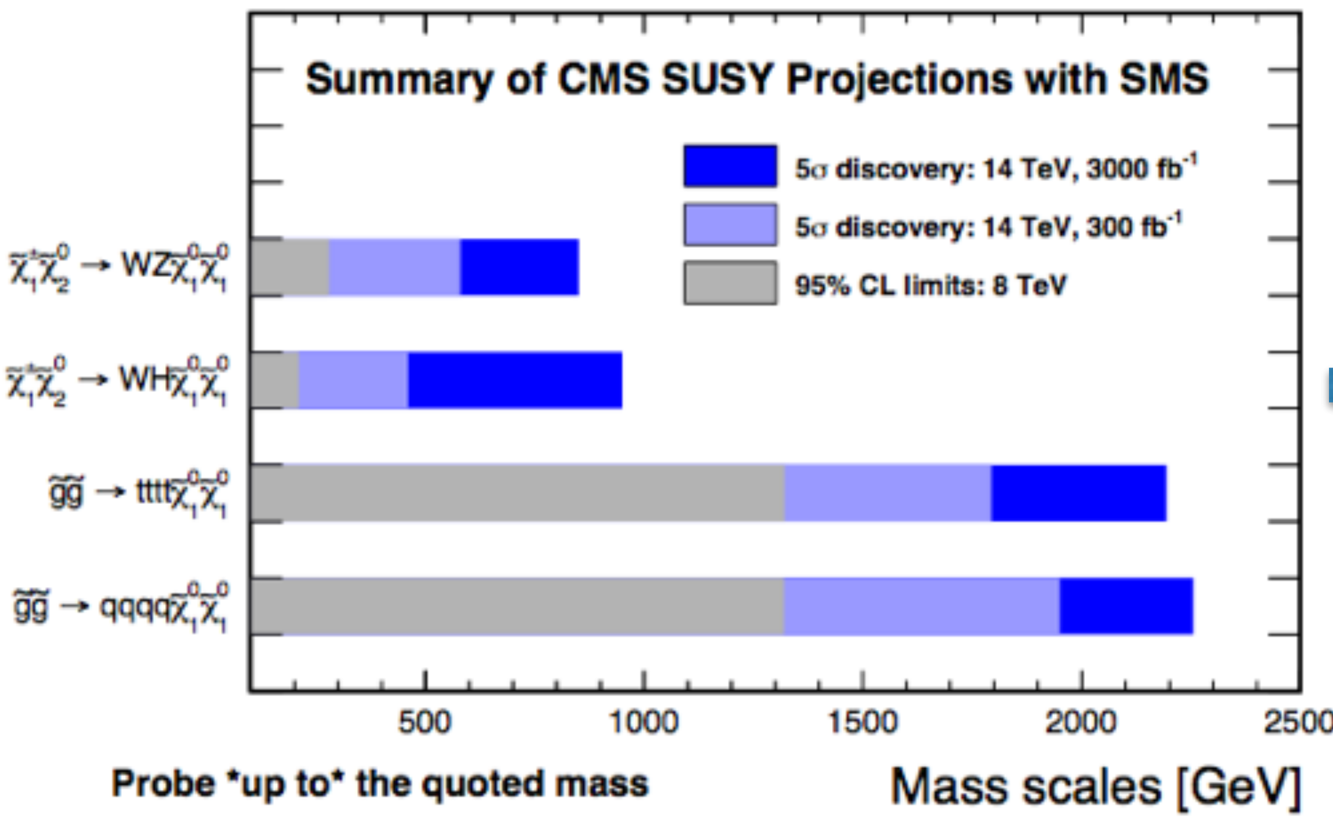


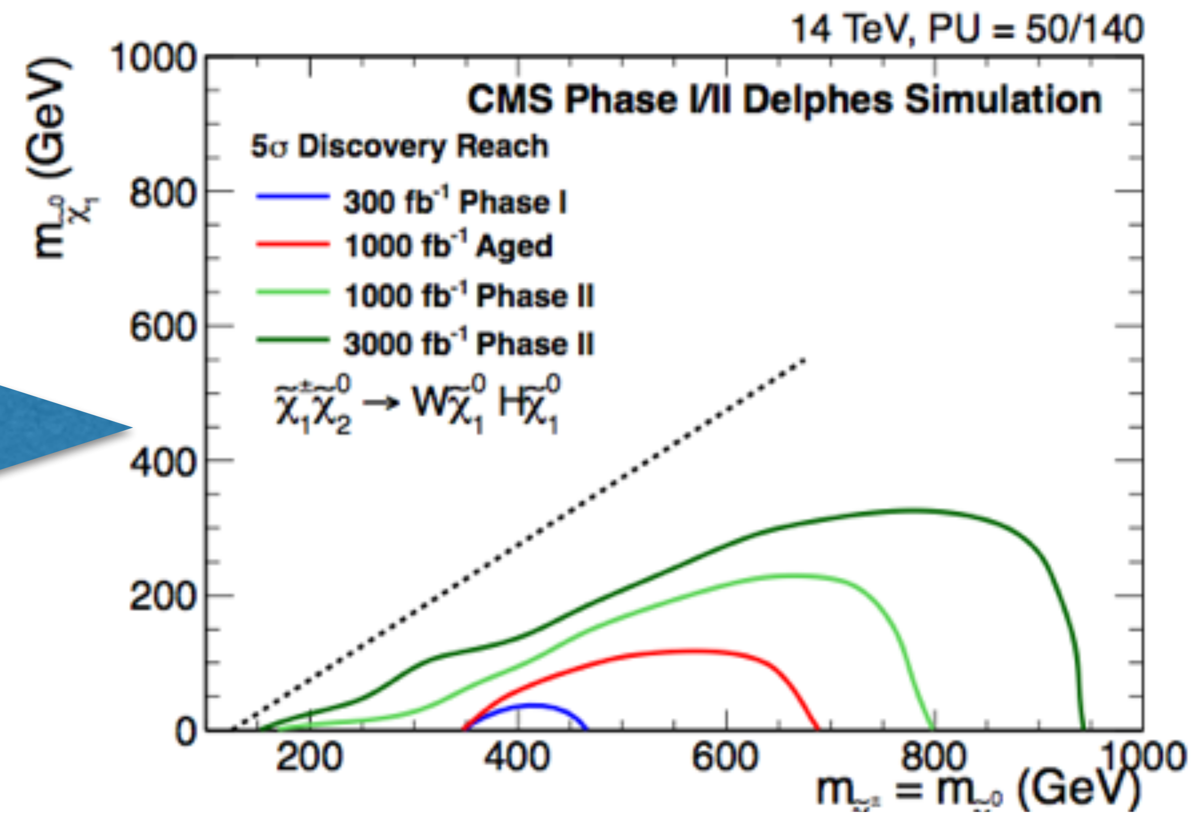


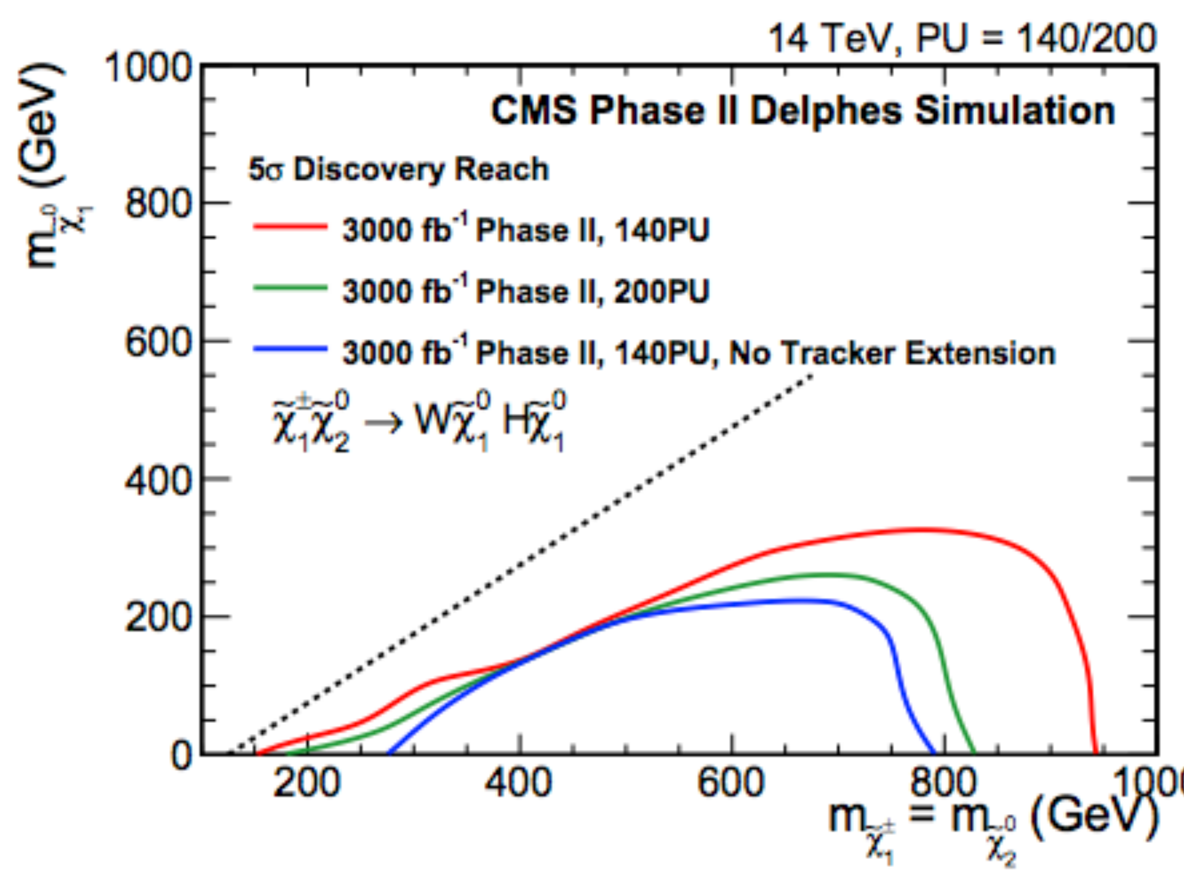




Supersymmetry





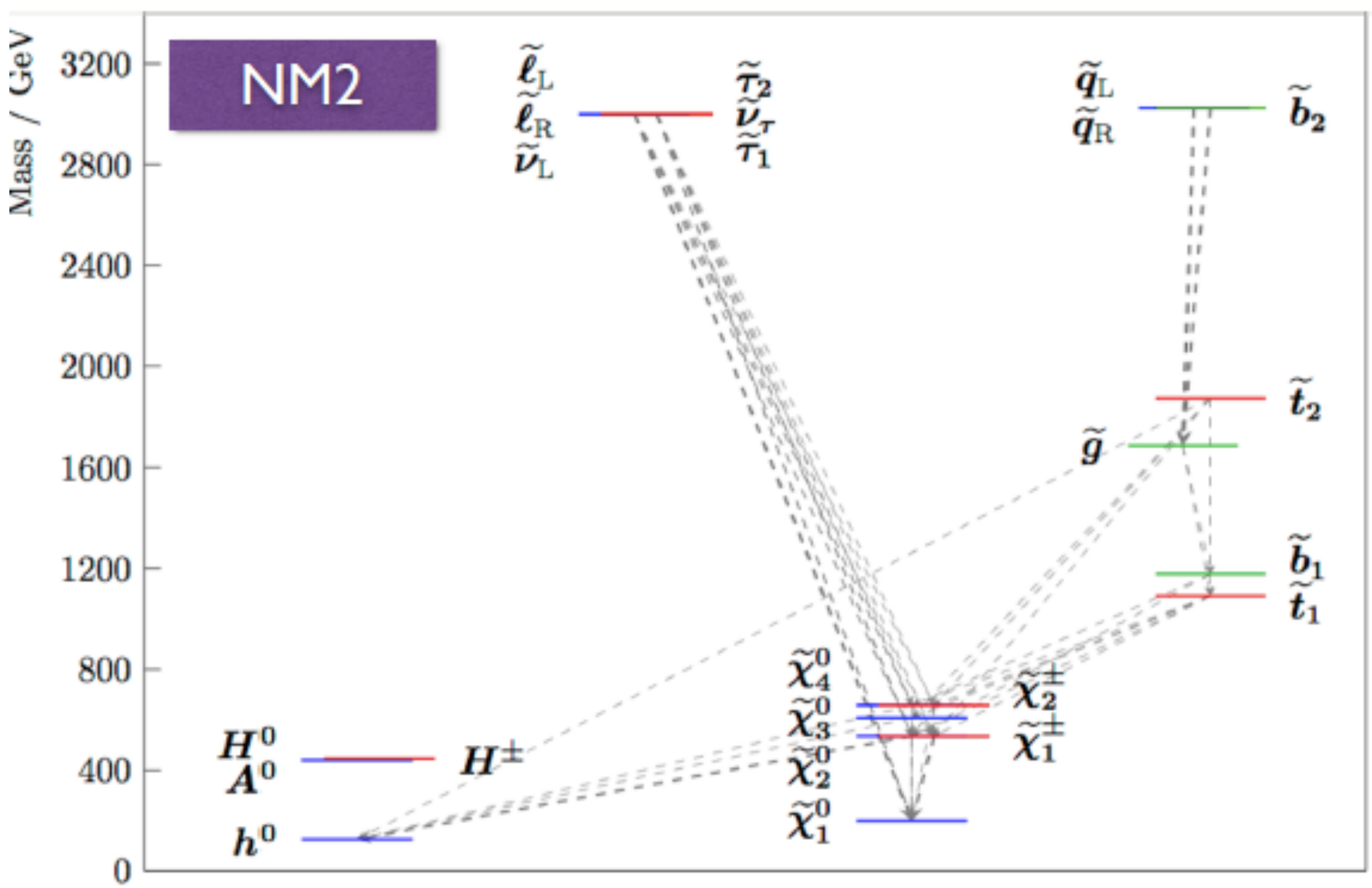


- ➡ **Significant decrease in discovery reach with degraded detector**
  - limited by MET resolution and b-tagging
- ➡ 950 GeV Discovery reach with 3000/fb, 140PU, and upgraded detector
- ➡ 450 GeV Discovery reach with 300/fb, 50PU, existing detector

Supersymmetry

➡ **Five phenomenological models motivated by naturalness explored**

- 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

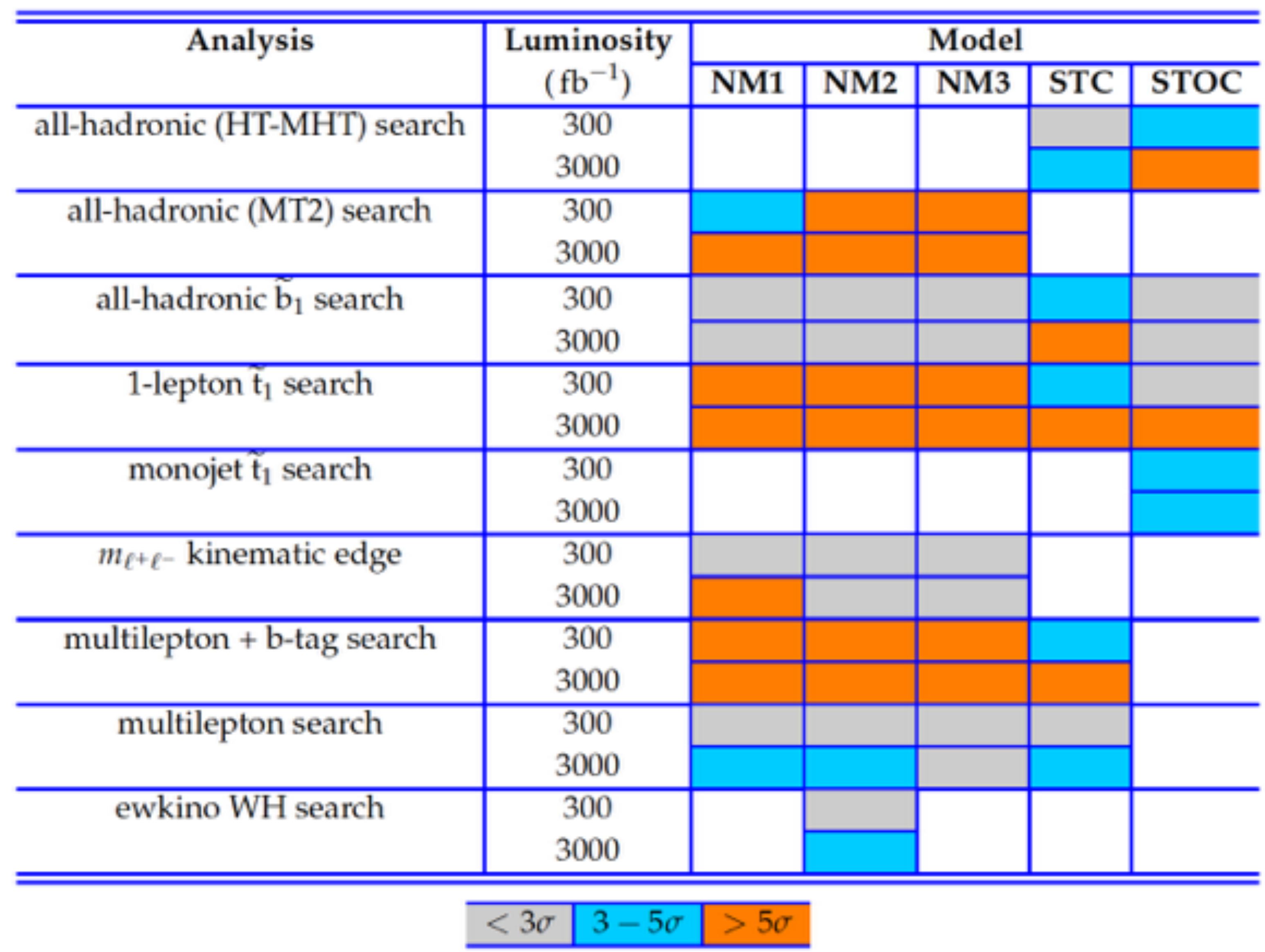
Exploring SUSY model space

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



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

Finding optimal HL-LHC run scheme

➡ **performance of all objects degraded by pileup**

➡ calorimetric objects show larger effects than tracker dominated objects

➡ minor effect on searches for heavy resonances, Higgs to 2 muon or 4 muon measurements

➡ large effects on physics analysis sensitive to MET (resolution) or jet counting

➡ further improvements in reconstruction techniques might be used to partially offset some of these pileup effects

➡ extending the scope by using precision timing can be a game changer

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.

Conclusion

➡ **HL-LHC enables a 20+ years research program with large discovery potential**

- **ATLAS and CMS set a program in motion 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 & BSM processes**
- **Extension of discovery reach in high-mass region**

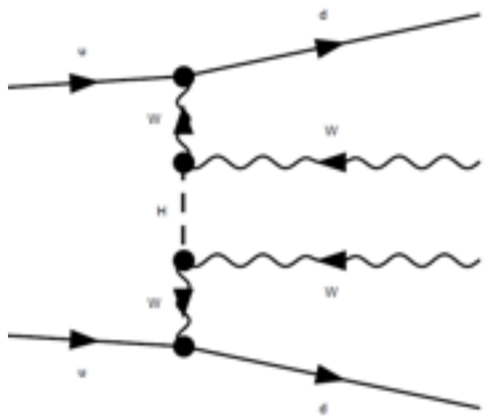
➡ **Studied physics channel only scratch the surface of what's possible**

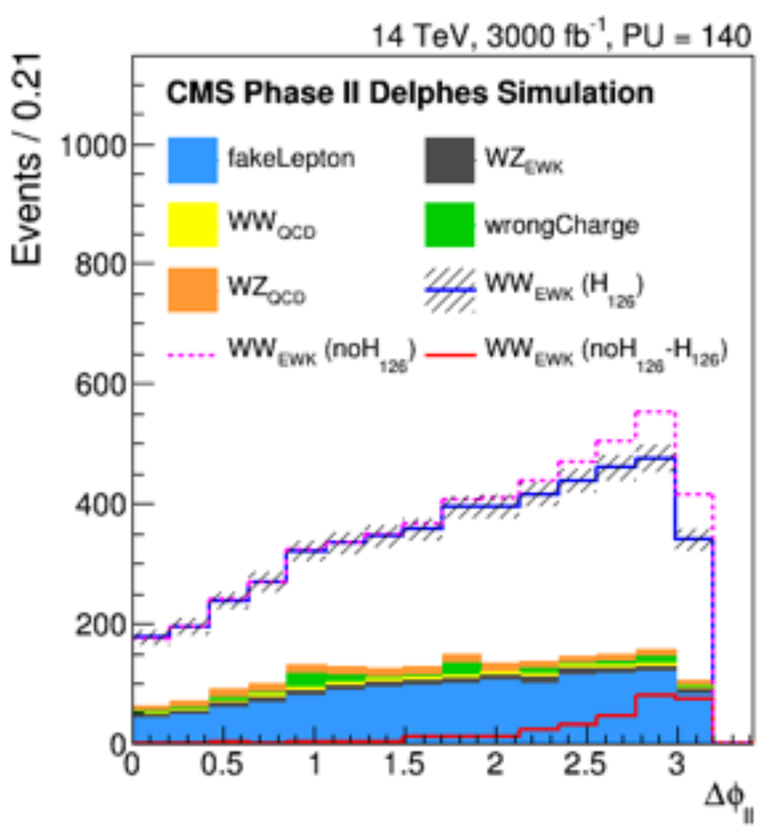
➡ **Goal: Exploring the energy frontier**

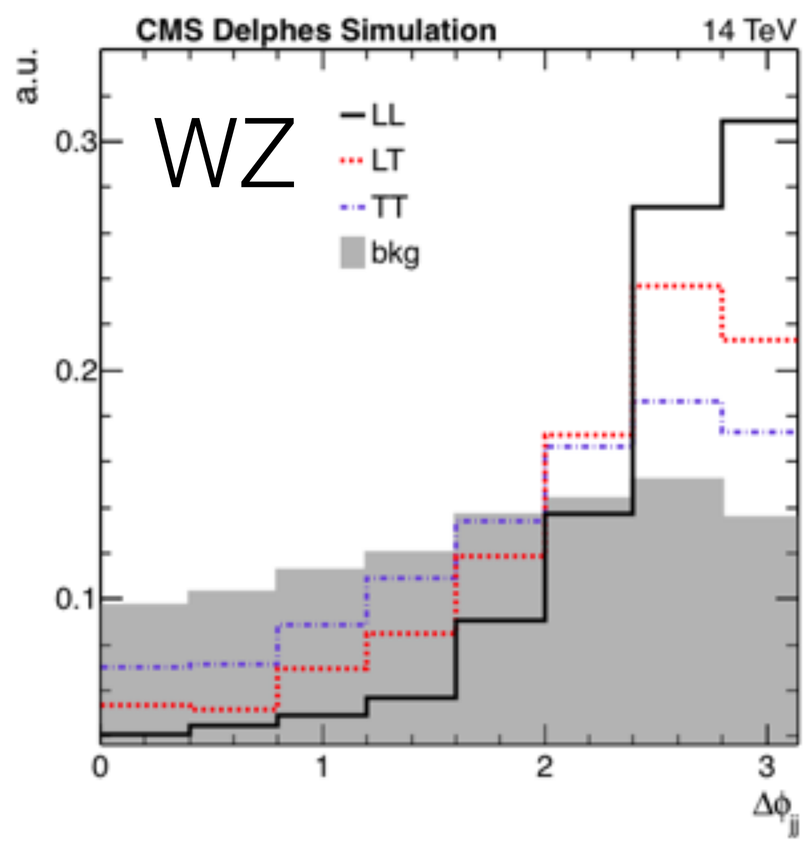
Vector boson scattering

➡ **Assess VBS sensitivity using same-sign WW and WZ**

- cross section measurement
- longitudinal scattering cross section
- anomalous couplings
- SM-noH measurement (input to Higgs couplings)







Combined performance

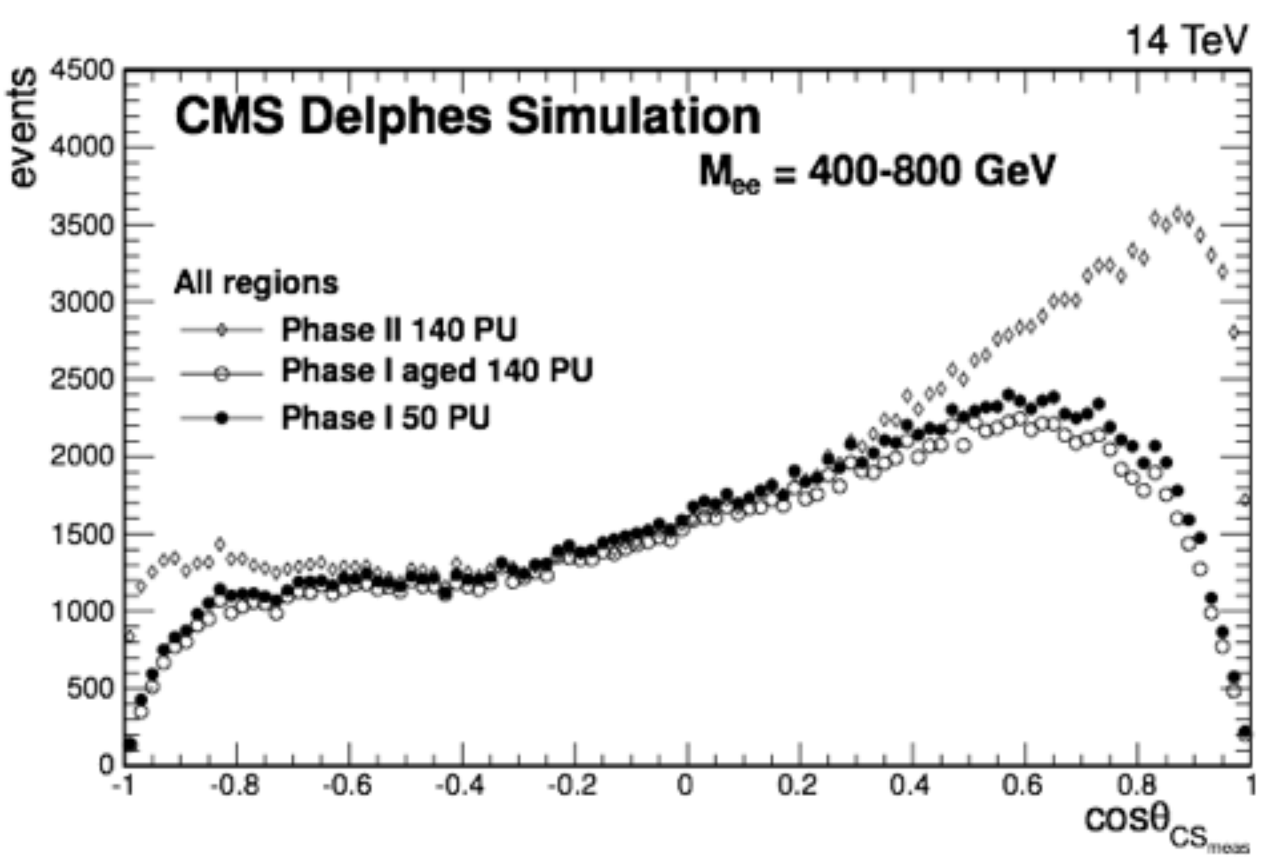
3000 fb^{-1}, 14 TeV	Phase-I	Phase-II	Phase-I aged
Higgsless 95% CL μ exclusion	0.14	0.14	0.20
V_L V_L scattering significance	2.50	2.75	2.14

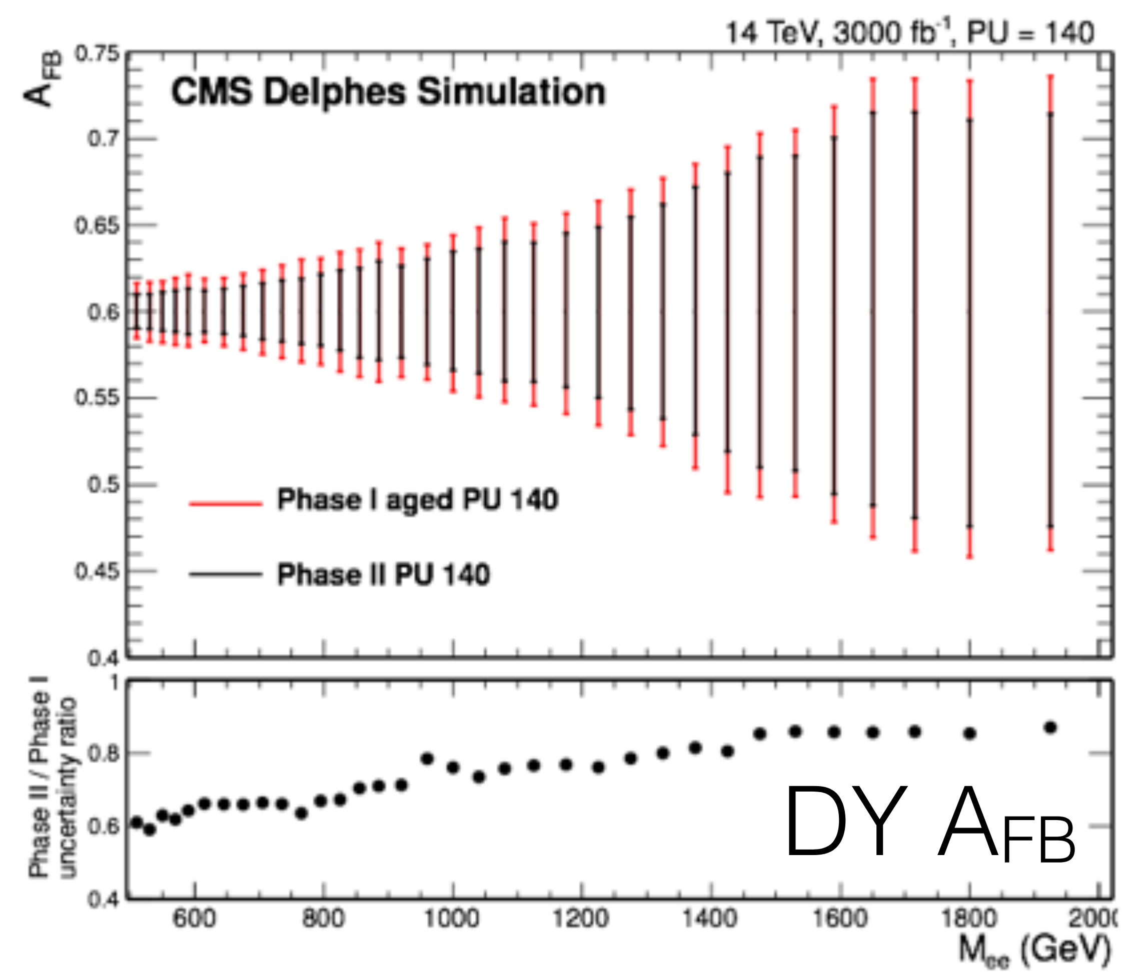
Exotica

➡ 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]

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





HL-LHC Physics Workshop

May 11-13th 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/