Prospects for the BSM physics searches in collider experiments

Markus Klute

BSM Physics around the corner

➡ **Often heard: BSM (new) Physics must be around the corner**

- At **higher mass scales** or with **smaller couplings** (or both)?
- Or did we simply miss the signatures due to trigger or backgrounds?
- Many good ideas, but limited theoretical guidance
- Only way to find out: **keep exploring**

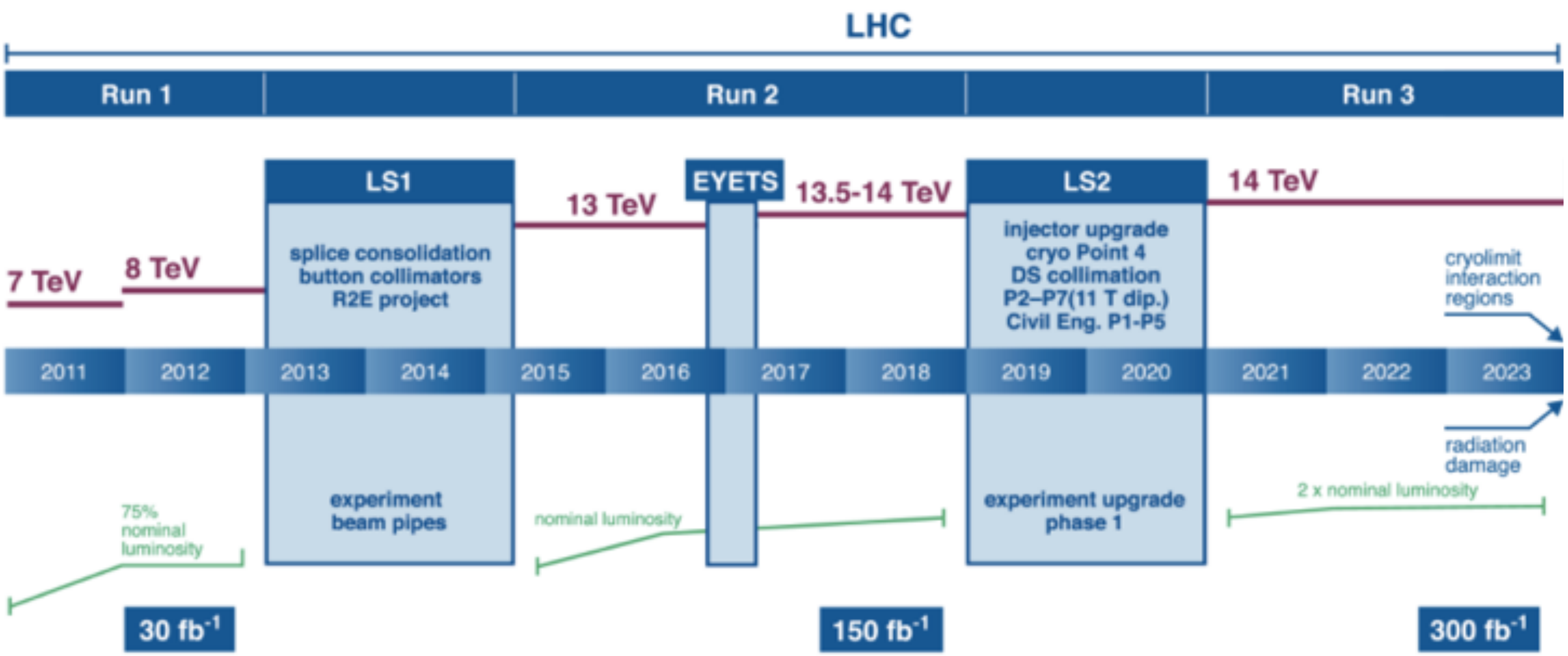
➡ **Driving principle: What is the origins of phenomena not explained by the Standard Model?**

➡ **Strategy at collider experiments**

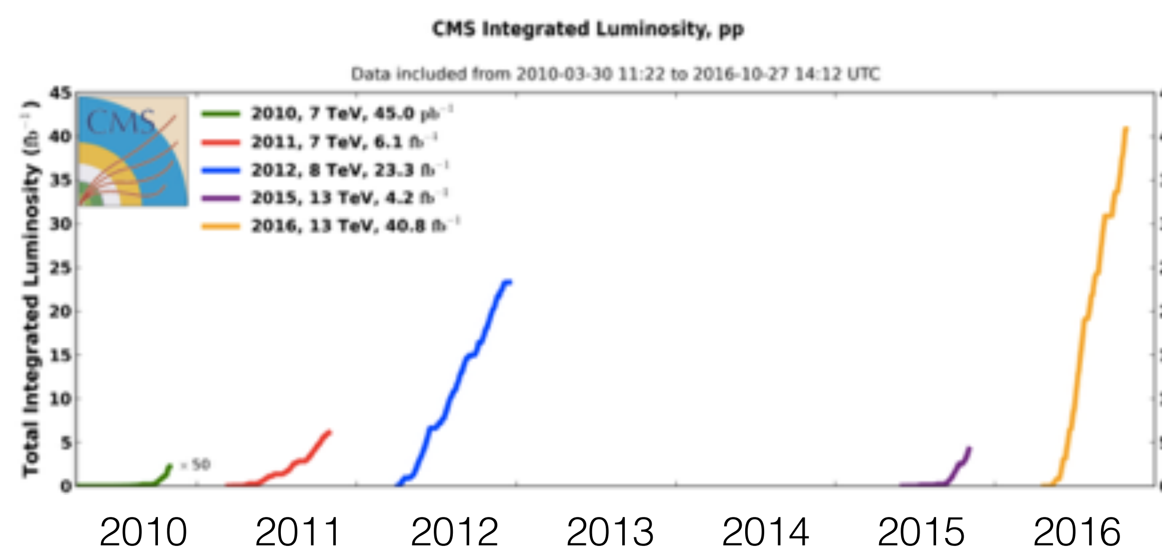
- **Searches for the imprint of new physics** on neutrino and flavor physics, W, Z, top quark, and the **Higgs boson**
- **Direct searches for new states**

➡ BSM physics searches in collider experiments can succeed through **larger energies**, **larger intensity** (more or better data), or **new ideas**

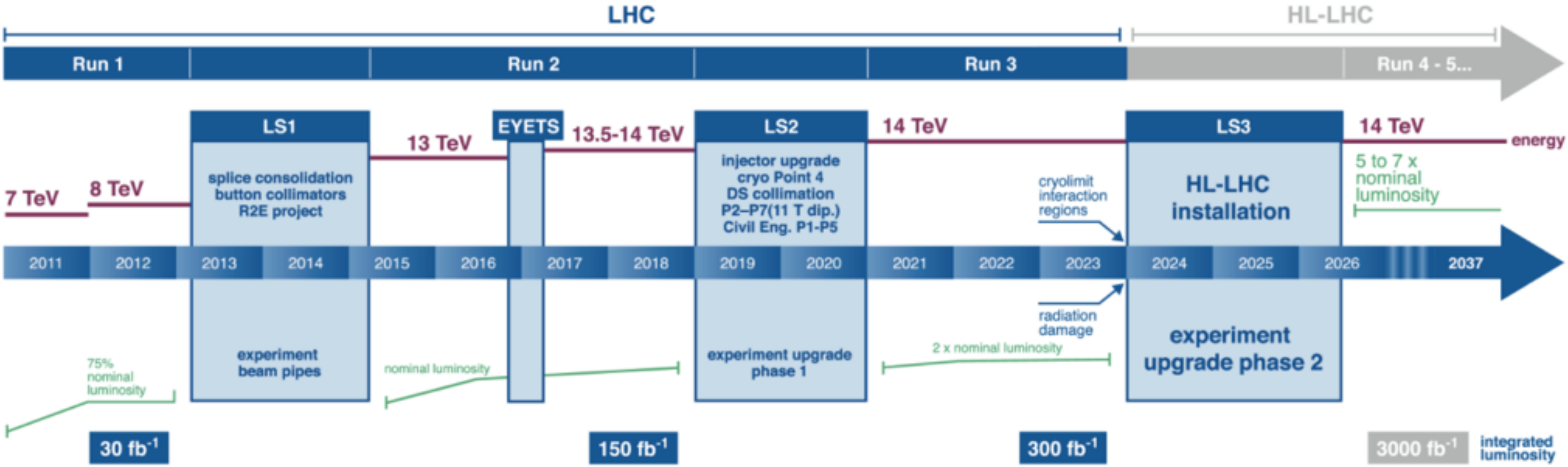
Roadmap for Collider Experiments



- ➡ **Run 2**
  - recording first collisions in 2017
  - 2 years of data taking ahead
- ➡ **Long Shutdown 2**
  - substantial upgrades for ALICE and LHCb
  - Phase-1 upgrades for ATLAS and CMS
- ➡ **2023 marks the end of the original LHC project**



Roadmap for Collider Experiments



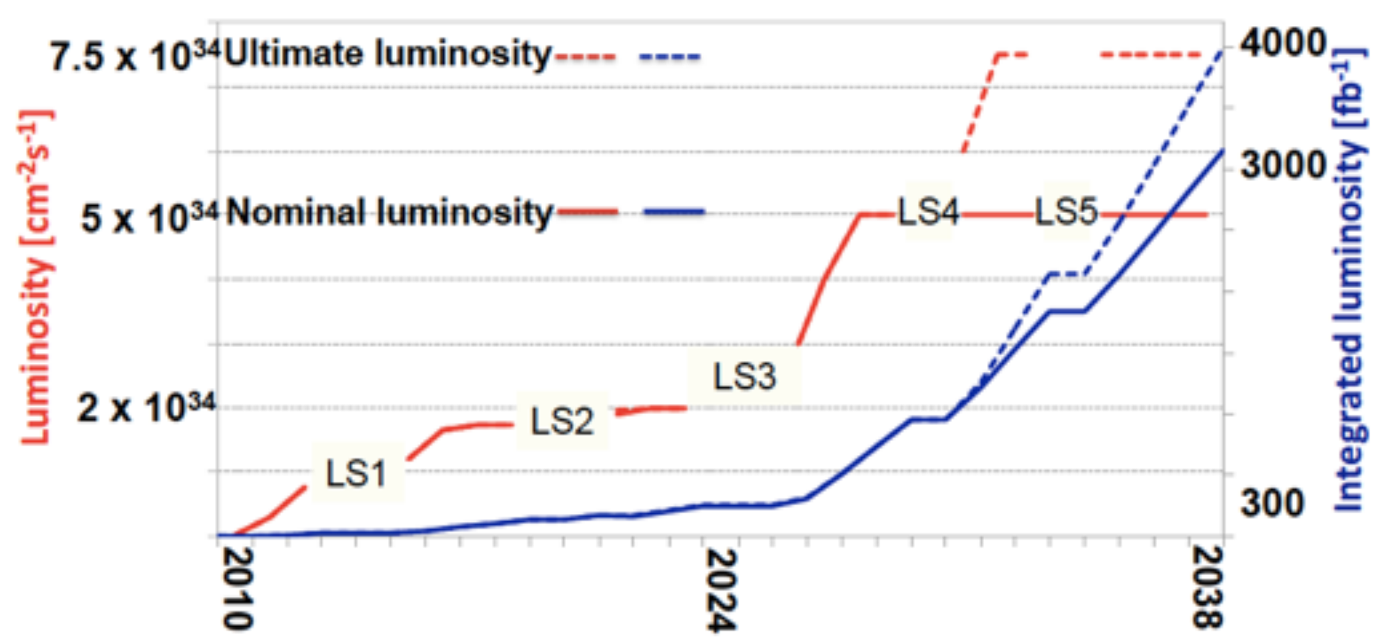
➡ **Long Shutdown 3: 2024-26**

- HL-LHC installation
- Phase-2 upgrades for ATLAS and CMS

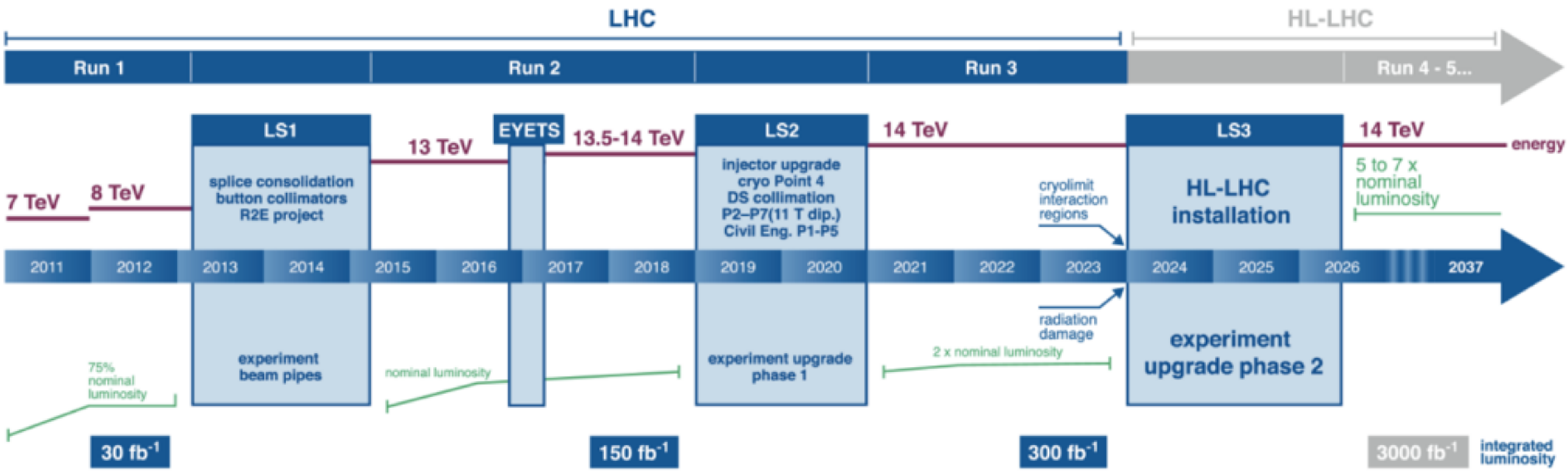
➡ **Run 4 - ...**

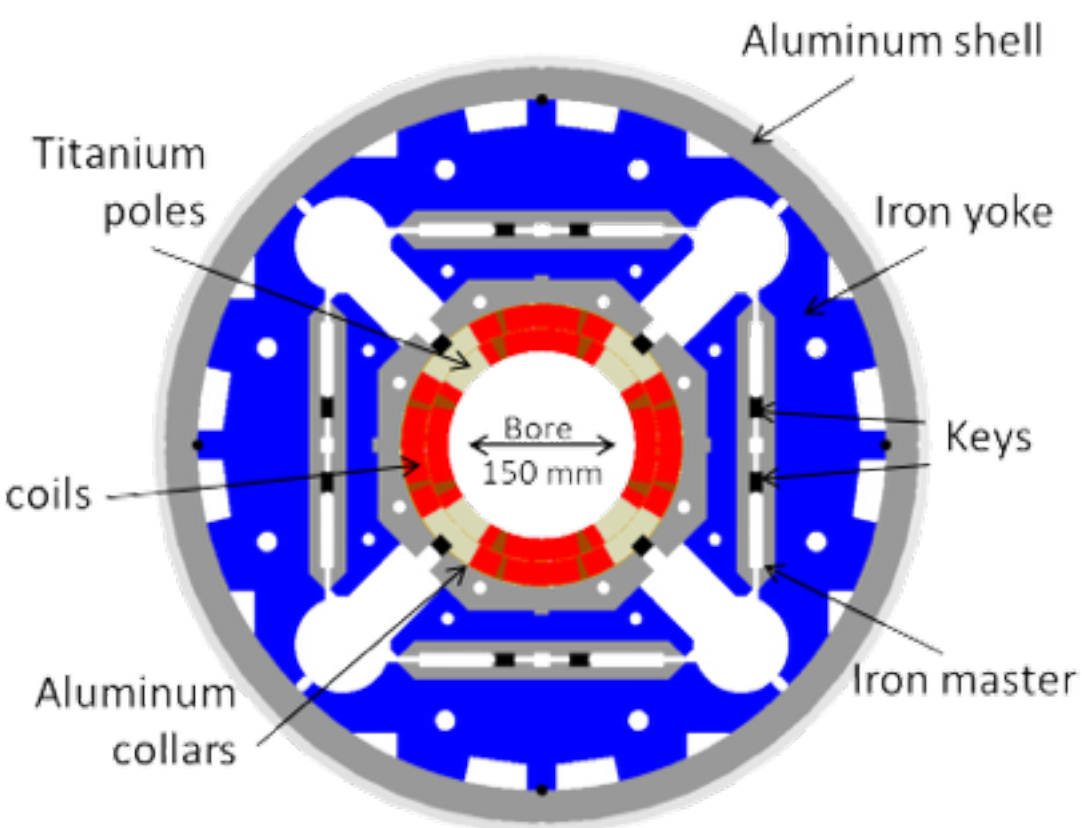
- 5×10^{34} cm^{-2} s^{-1} leveled
- 3000 fb^{-1} by 2035

➡ **More than 20 years and a factor of ~100 times more data ahead of us**



Roadmap for Collider Experiments

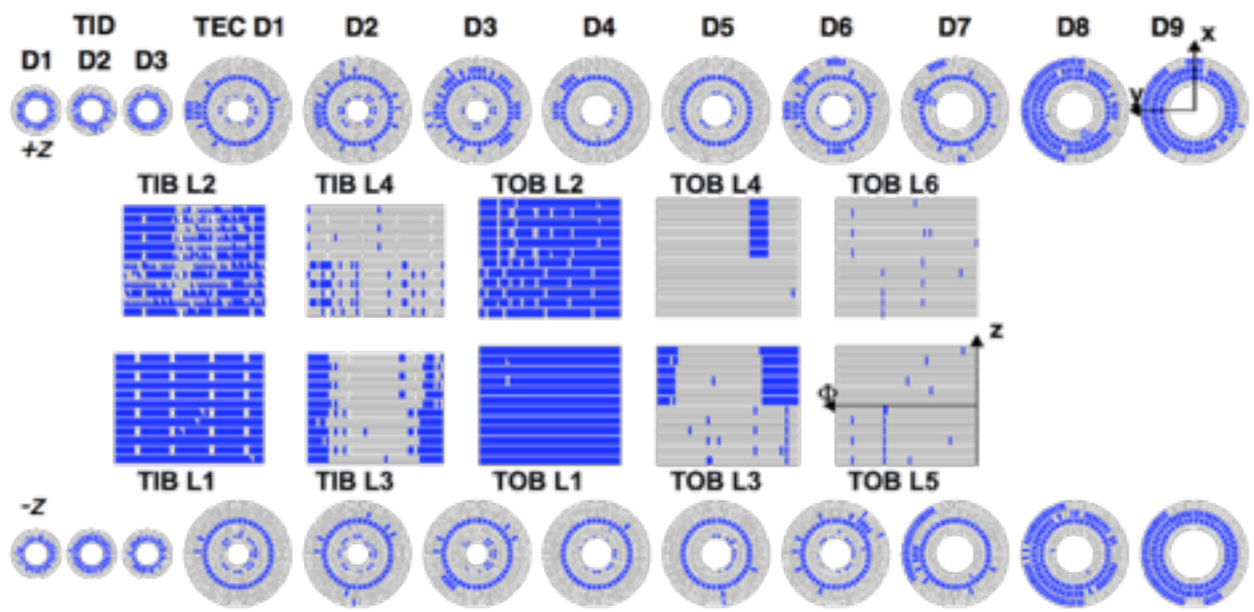




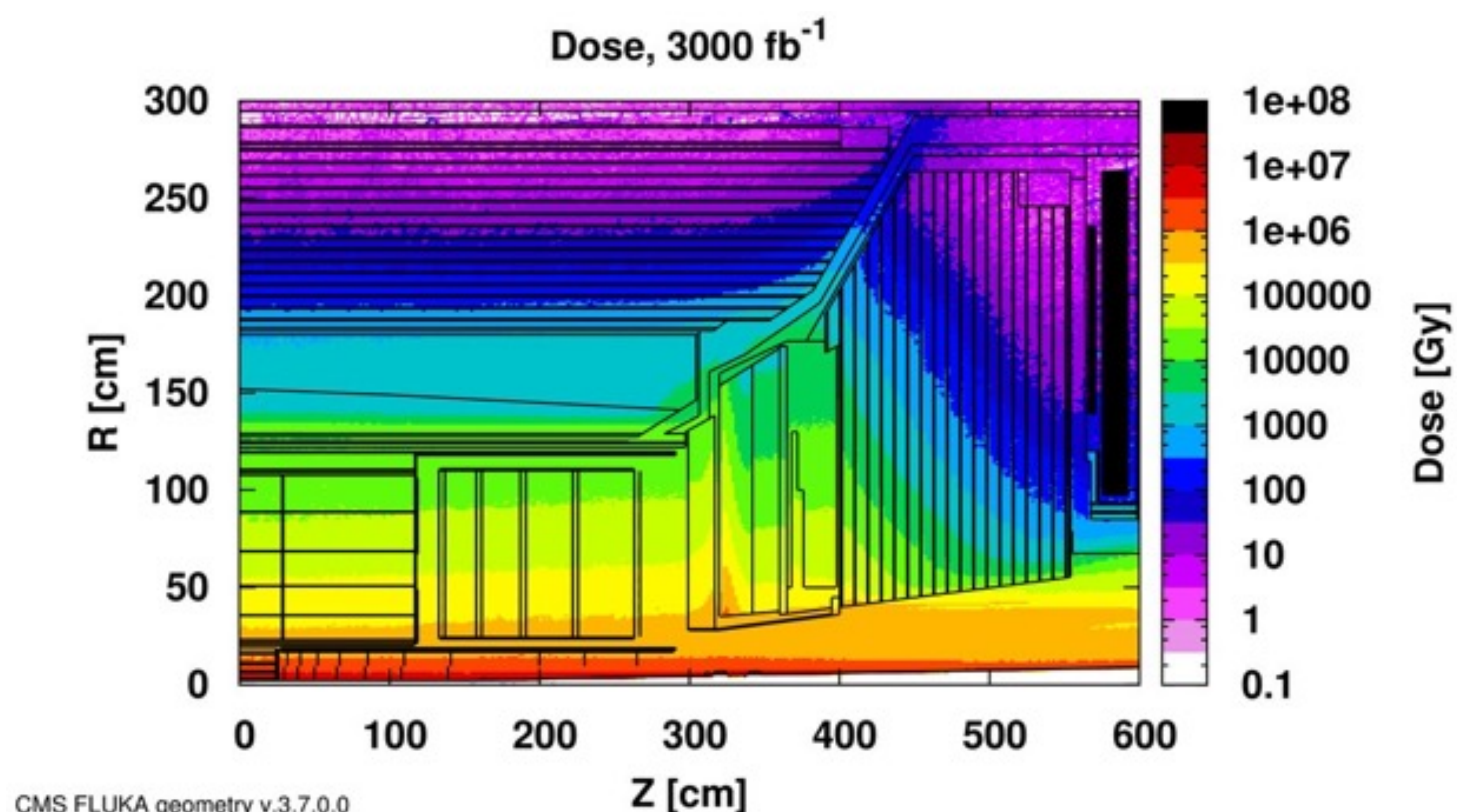
- ➡ **LHC dipoles stretched NbTi technology to its limit**
  - 8.3T in central region via operation at 1.8k
- ➡ **HL-LHC needs new technology in iteration region: Nb_3SN**
  - 12T quadrupoles with 150mm aperture to shrink β*
- ➡ **Operating and upgrading the LHC is a very significant investment**

HL-LHC Challenges

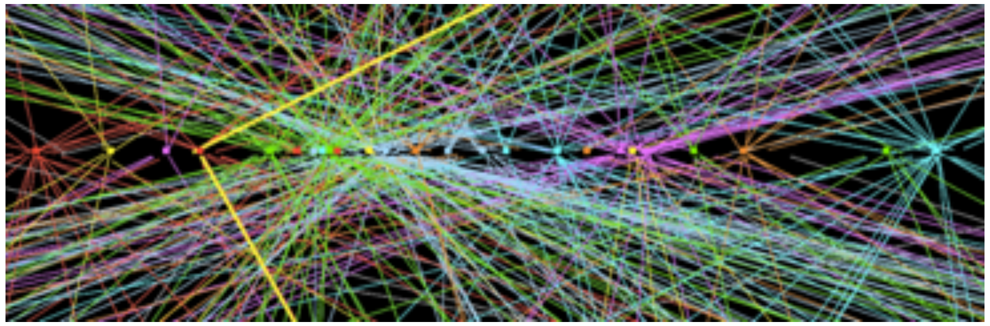
- ➡ Detectors have to operate in **extreme environment**
- ➡ In 2025 the detectors will be running (radiated) for 15 years. Severe **aging** effects.
- ➡ **ATLAS and CMS will undergo significant upgrades**



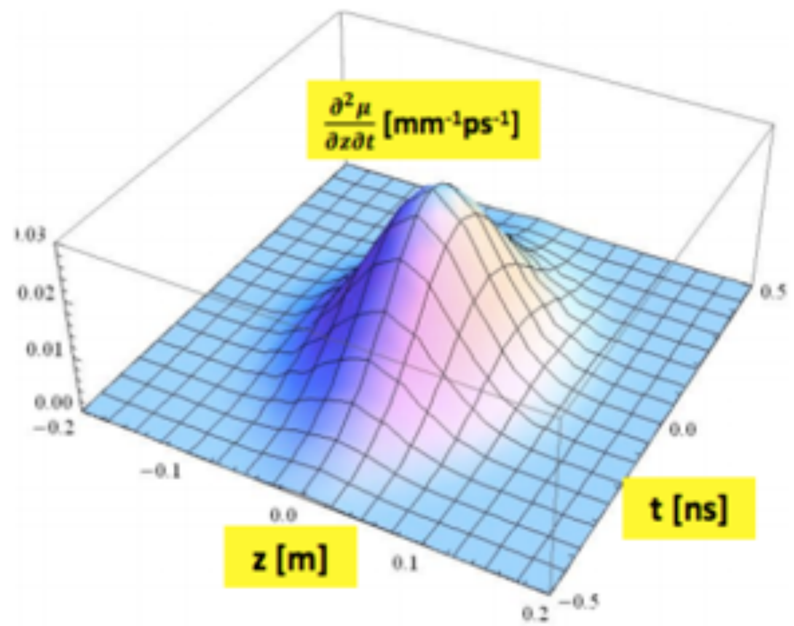
Blue tracker modules are expected to be inactive after 1000 fb^{-1} due to very high leakage currents induced by neutron fluence.



HL-LHC Challenges



- ➡ **Expect**
  - $<\mu> \cong 140$ at $5\mathrm{x}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - $<\mu> \cong 200$ at $7\mathrm{x}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



HL-LHC Baseline

σ_{lum} = 5cm r.m.s.

σ_{lum} =160ps r.m.s.

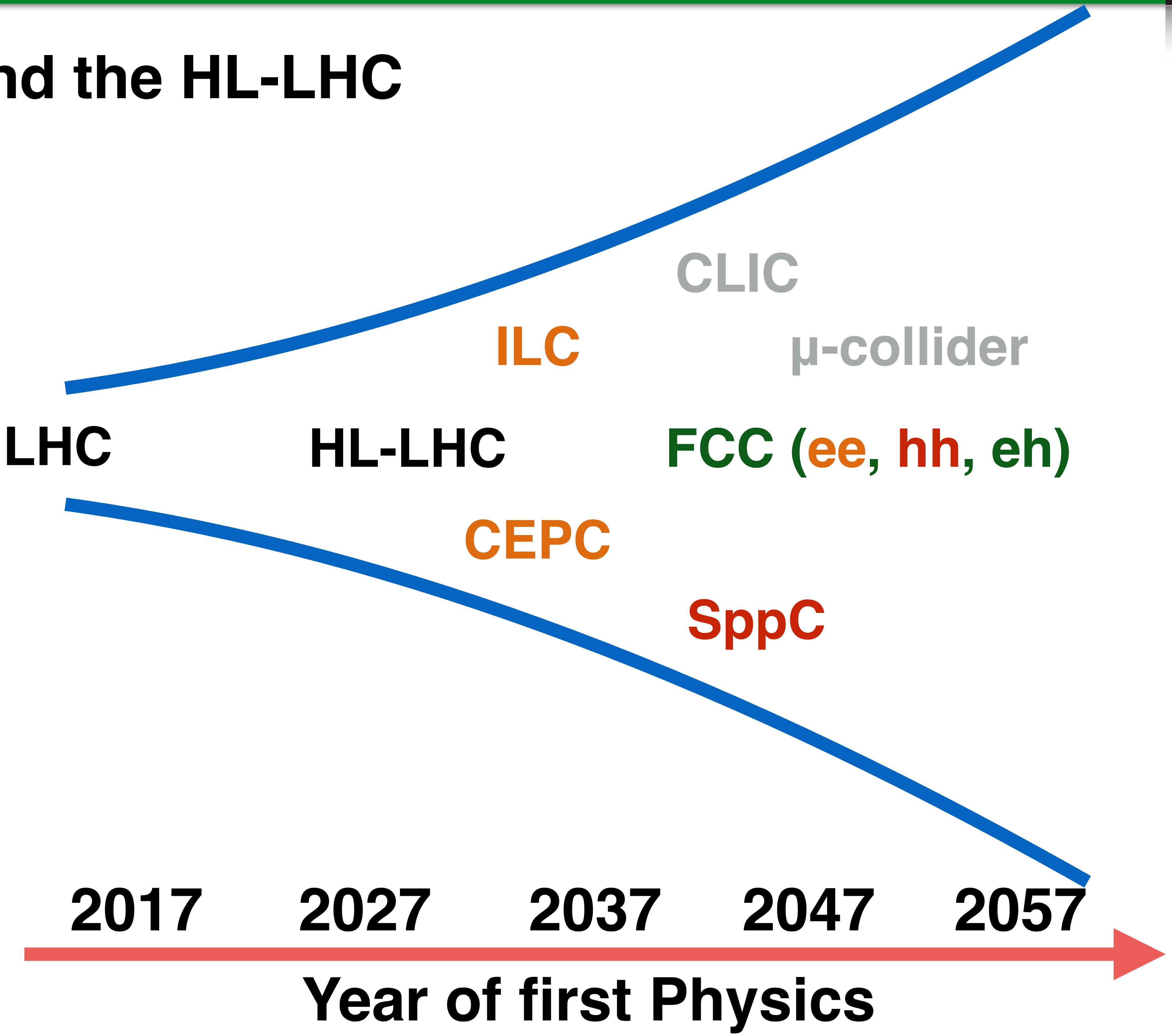
- ➡ **Tracking**
  - High granularity and thin active region to reduce hit occupancy
  - Increase the number of tracking layers
- ➡ **Calorimetry**
  - Fit pulse shapes to extract in-time energy deposition
  - Upgrade readout electronics
  - Combine in-time energy measurements with tracking information 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
  - ATLAS and CMS calorimeter timing resolution insufficient for significant rejection of PU
  - **CMS just extended its Phase-II upgrade scope to include an precision timing layer**
- ➡ **Pointing**
  - Reduce in-time pileup directional information for neutral particles

HL-LHC Physics Program

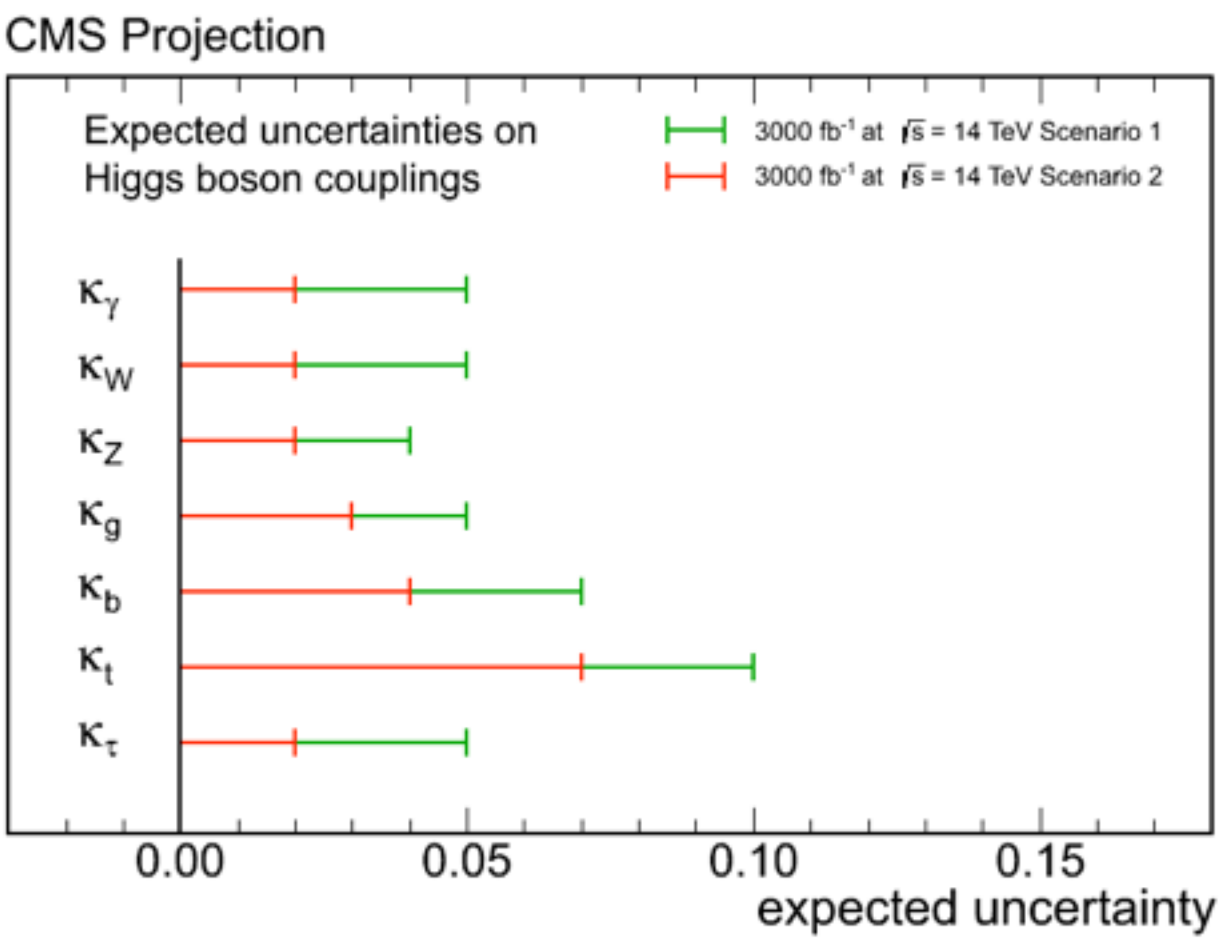
- ➡ **Higgs case at the start of the LHC was exceptional**
  - something to built on, not the reference
- ➡ **SM is self-consistent theory that can be extrapolated to exponentially higher energies**
- ➡ **Goal for the future LHC and HL-LHC program**
  - **Explore the energy frontier**
    - ➡ **Precision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

Roadmap for Particle Physics

➡ **Beyond the HL-LHC**



Higgs Prospects



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

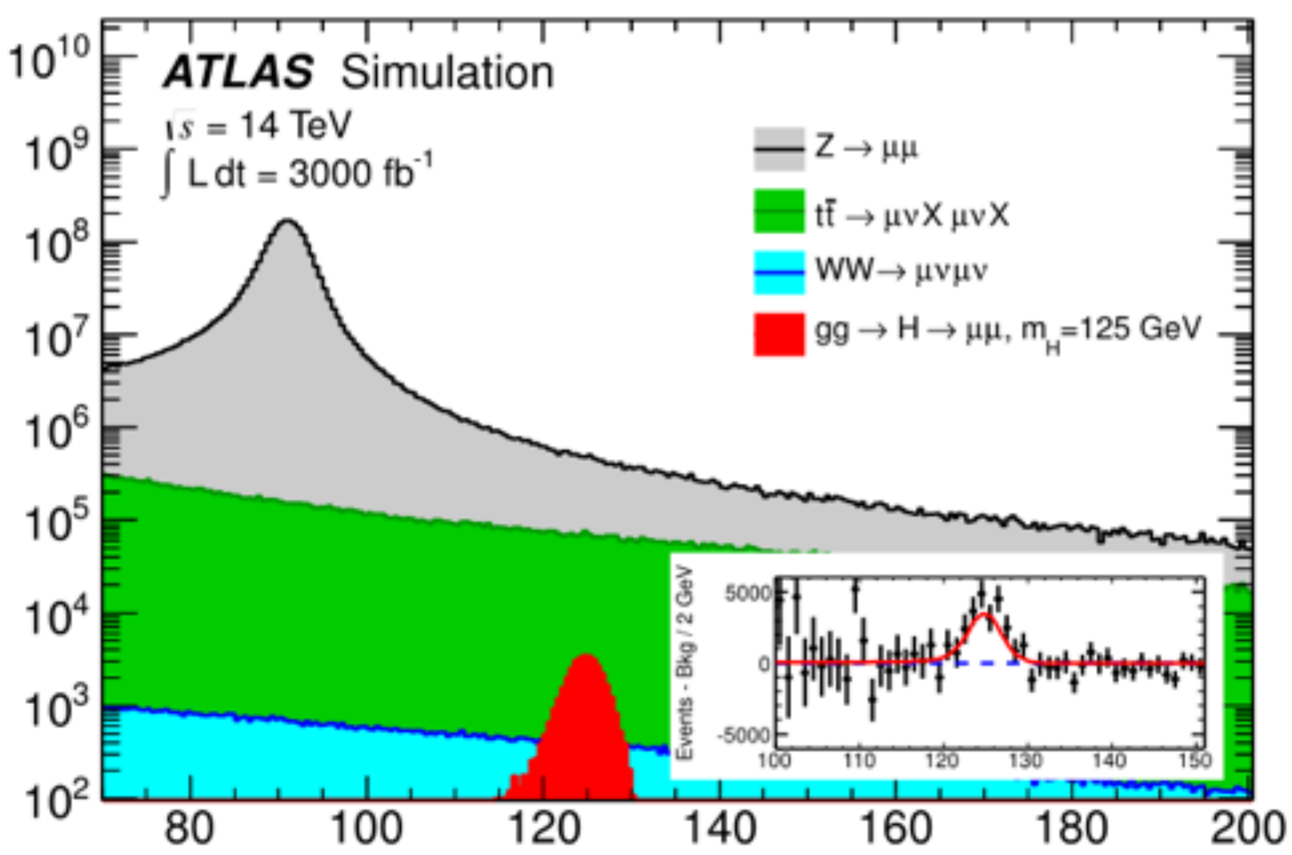
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

arXiv:1307.7135

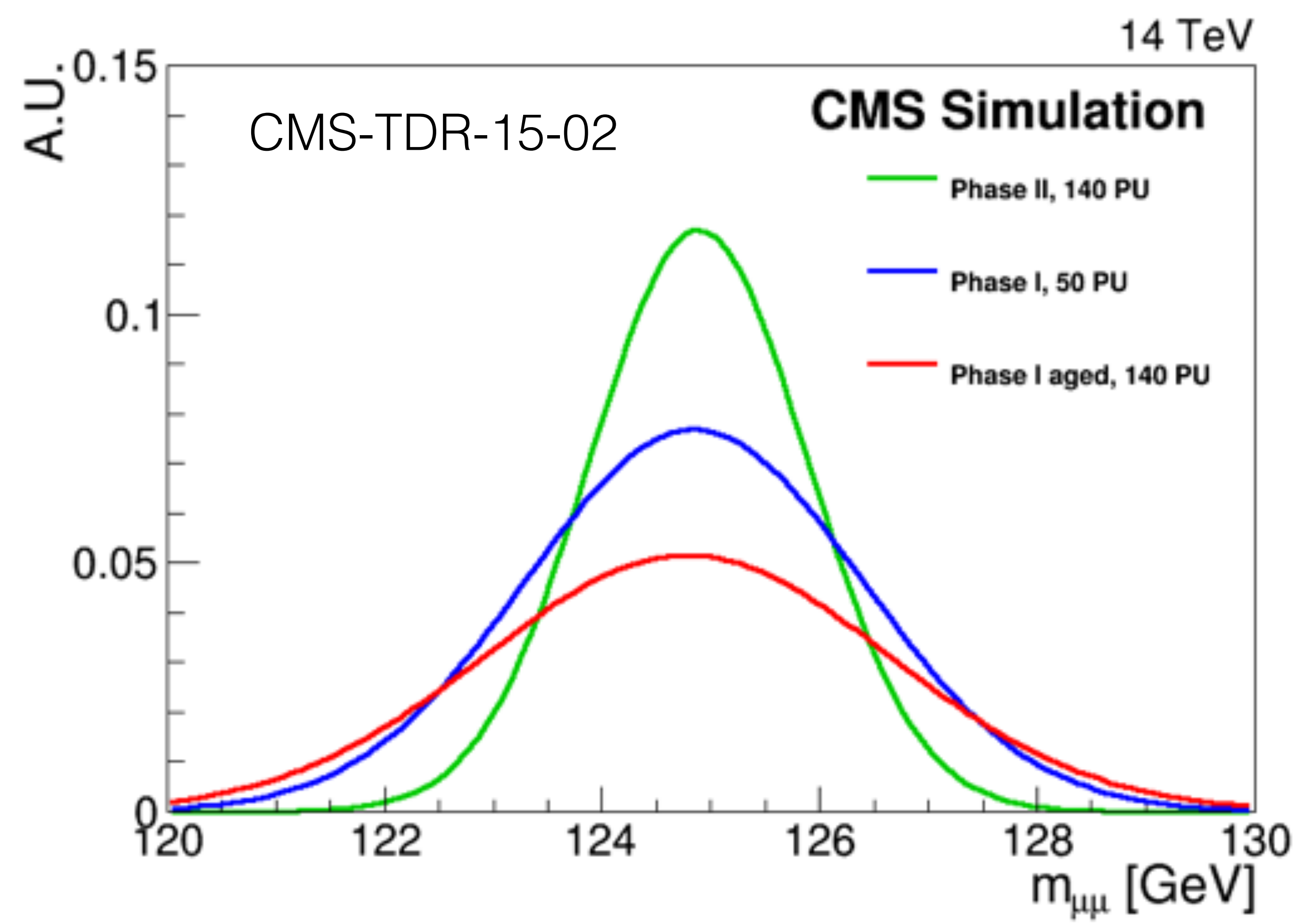
Higgs Prospects

➡ **H → μμ**

- 2nd generation fermion coupling
- search for narrow resonance with huge DY background
- **expect ~5% uncertainty second generation Higgs coupling**



ATL-PHYS-PUB-2013-007



Higgs Prospects

➡ **Lepton Collider allow model independent coupling measurements at sub-percent level precision**

Parameter	Current* 7+8+13 TeV $\mathcal{O}$ (70 fb^{-1})	HL-LHC* 14 TeV (3 ab^{-1})	FCC-ee Baseline (10 yrs)
σ(HZ)	–	–	0.4%
g_{ZZ}	10%	2–4%	0.15%
g_{WW}	11%	2–5%	0.2%
g_{bb}	24%	5–7%	0.4%
g_{cc}	–	–	0.7%
$g_{\tau\tau}$	15%	5–8%	0.5%
$g_{t\bar{t}}$	16%	6–9%	13%
$g_{\mu\mu}$	–	8%	6.2%
$g_{e^+e^-}$	–	–	<100%
g_{gg}	–	3–5%	0.8%
$g_{\gamma\gamma}$	10%	2–5%	1.5%
$g_{Z\gamma}$	–	10–12%	(
Δm_H	200 MeV	50 MeV	11 MeV
Γ_H	<26 MeV	5–8%	1.0%
Γ_{inv}	<24%	<6–8%	<0.45%

arXiv:1701.02663

➡ **Comparison with (HL-LHC)**

- Model dependent fit

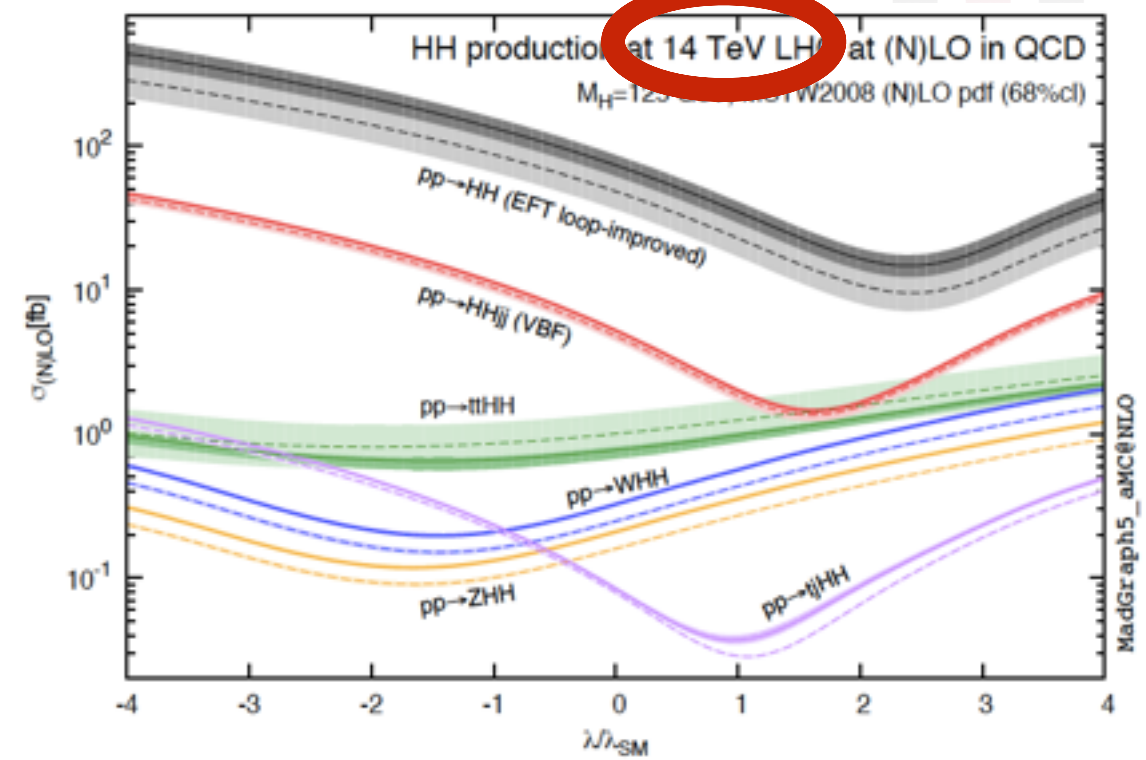
➡ **Factor >10 improvement for most couplings**

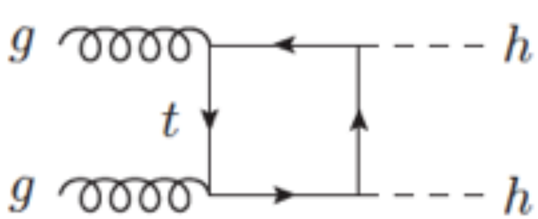
➡ **Sensitivity to new physics at multi-TeV scale**

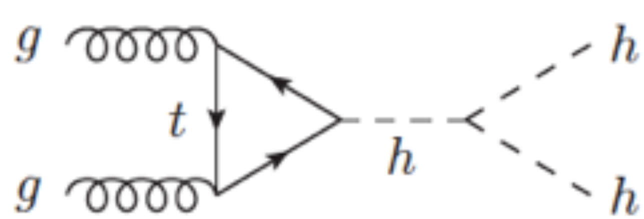
Triple-Higgs Coupling

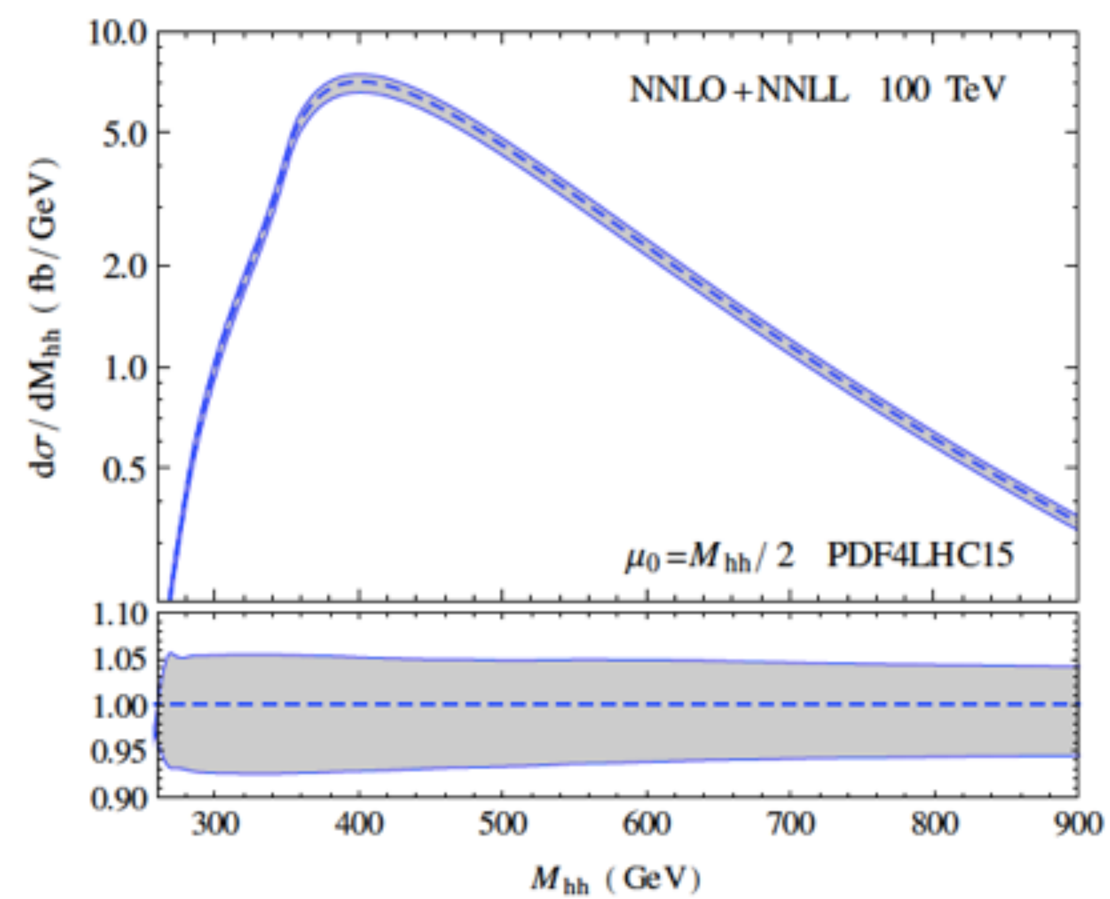
➡ **Probing triple-Higgs coupling with double Higgs production**

- Consistency of check of EWSB
- Reconstructing the Higgs potential
- Sensitivity through yields and kinematics
- Large enhancement through BSM possible
- Exhaustive program at the (HL-)LHC





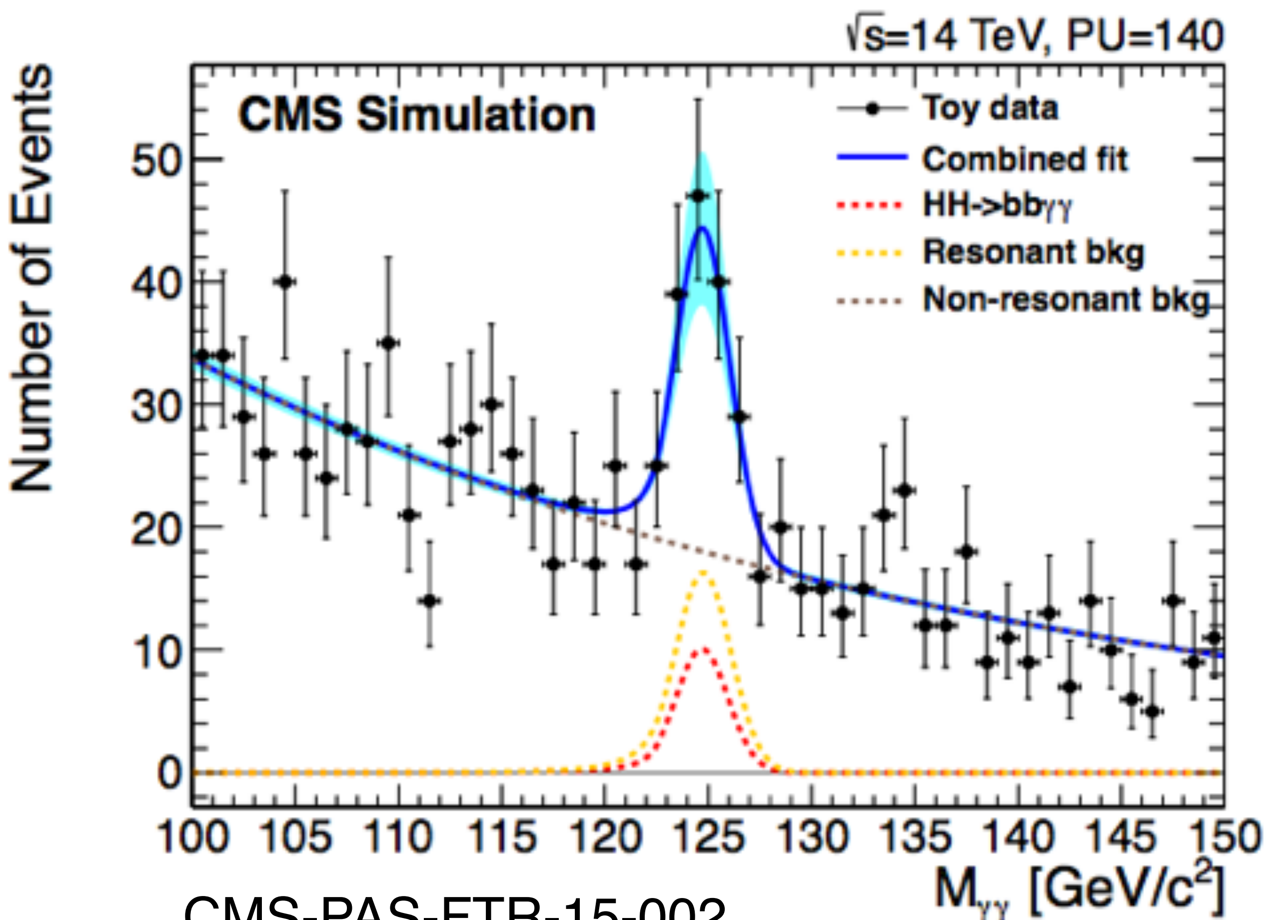




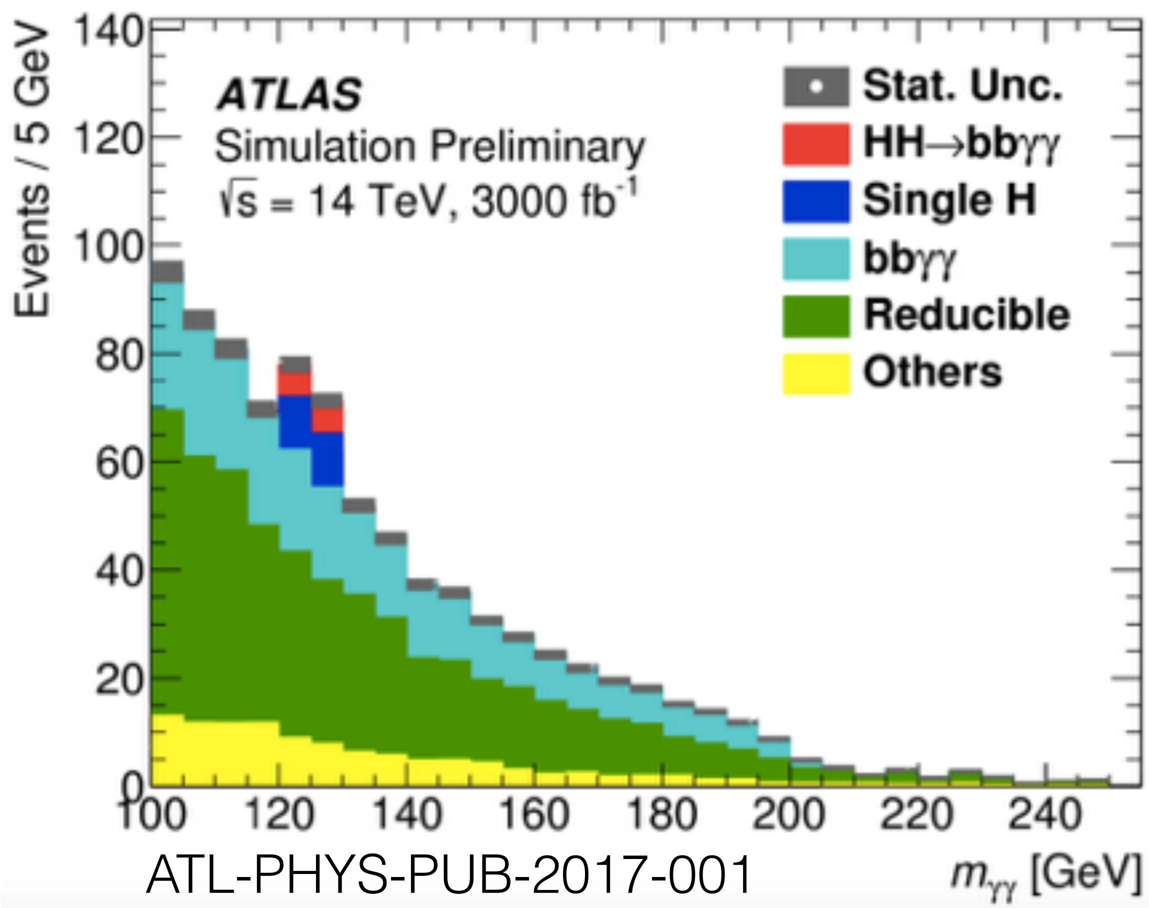
$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

Effective Lagrangian

Triple-Higgs Coupling



CMS-PAS-FTR-15-002



ATL-PHYS-PUB-2017-001

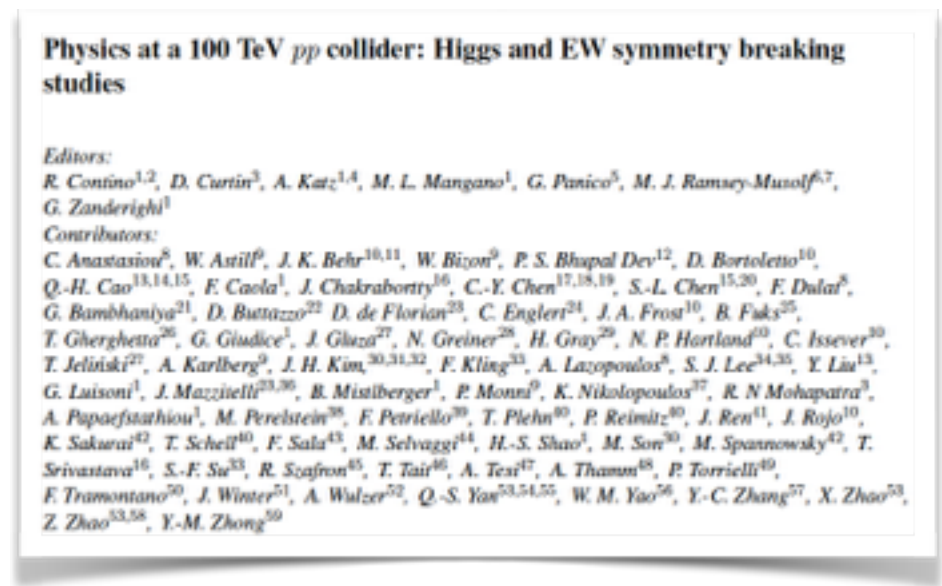
- ➡ **Demonstrate Phase-II detector capabilities**
  - b-tagging, photon, and tau-Id
  - case for the track trigger
- ➡ **Sensitivity per experiment**
  - ~10 signal events in bb$\gamma\gamma$
  - ~2σ per experiment

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

Triple-Higgs Coupling

➡ **Prospect dramatically improved with FCC-hh**

- 100 TeV pp collider
- Total program 20ab^{-1} per detector



Physics at a 100 TeV *pp* collider: Higgs and EW symmetry breaking studies

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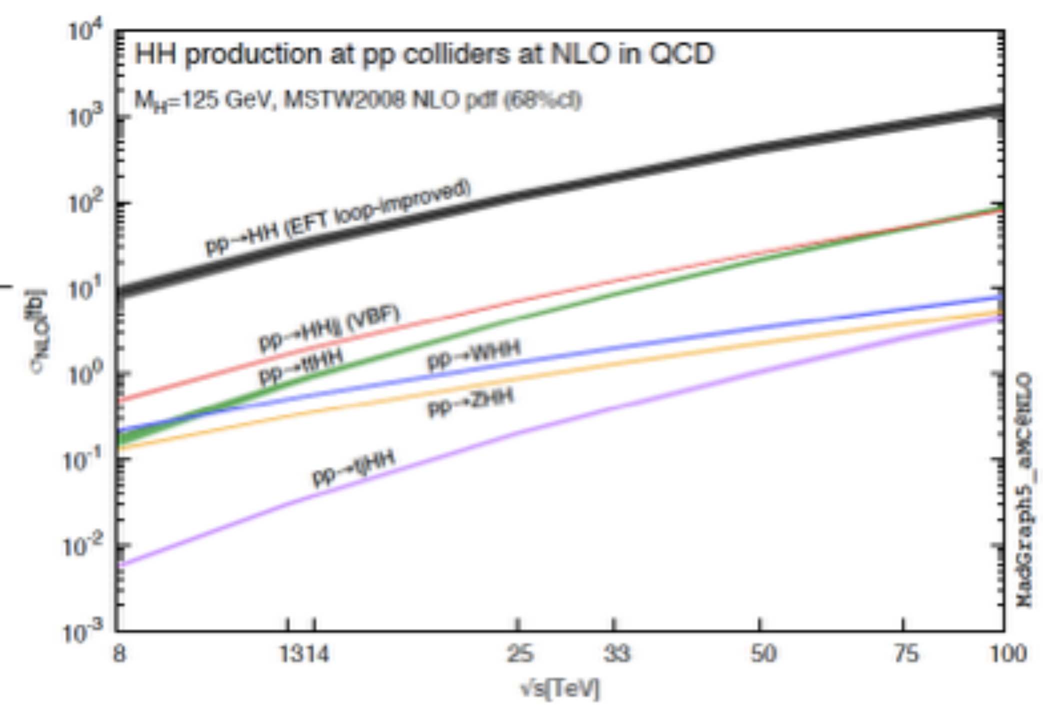
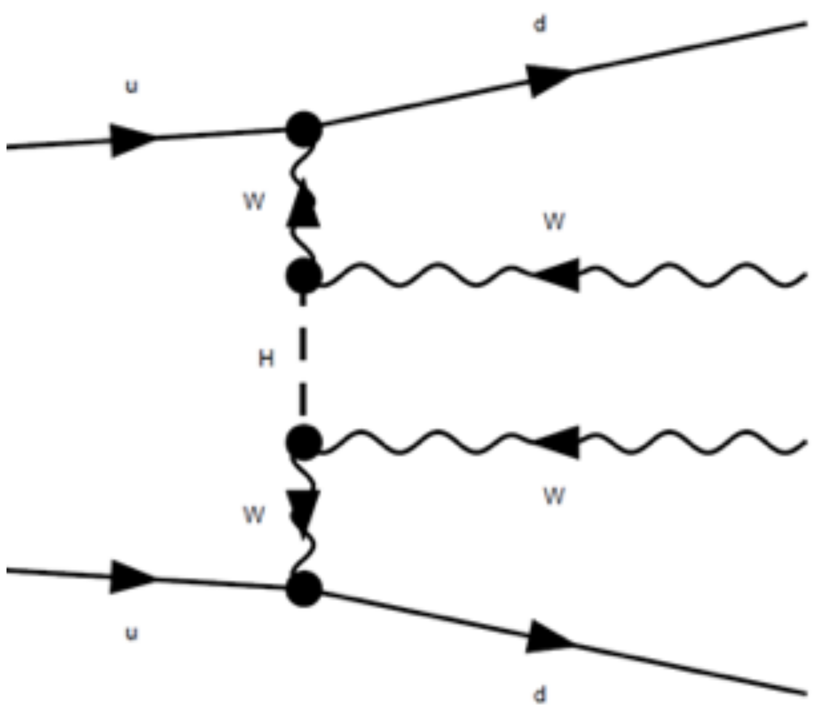
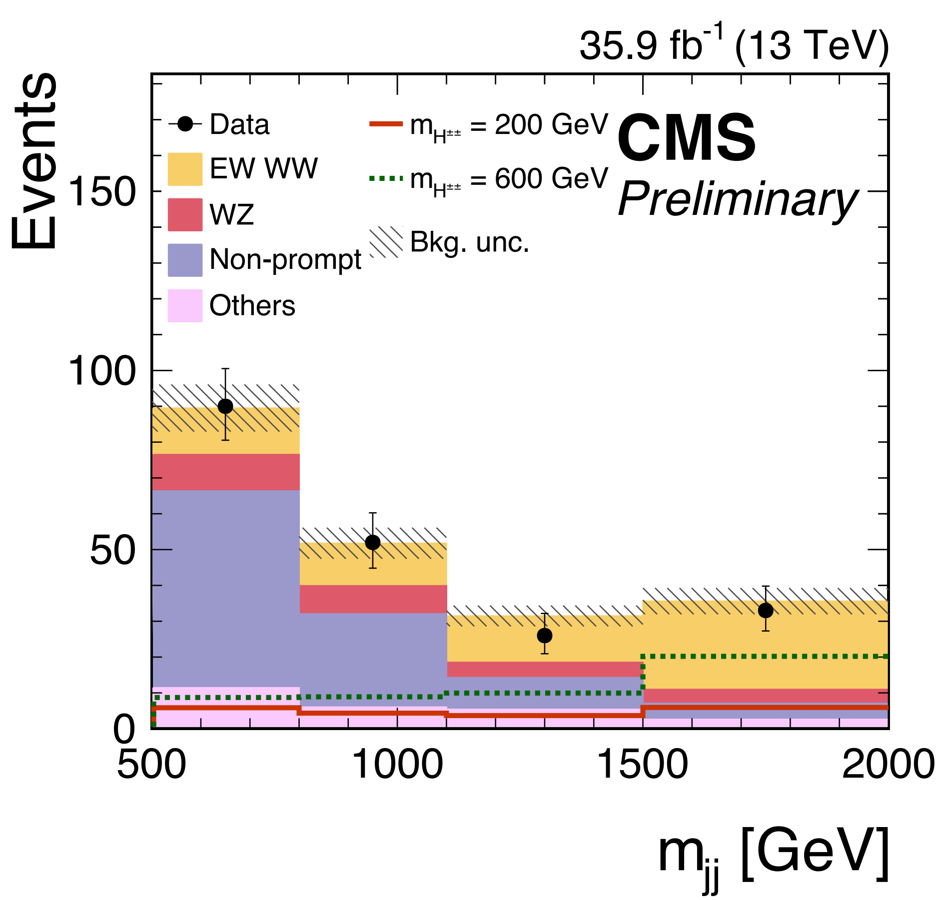
process	precision on σ_{SM}	precision on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	2%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$\sim 25\%$	$\lambda_3 \in [\sim 0.6, \sim 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$\sim 15\%$	$\lambda_3 \in [\sim 0.8, \sim 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$\sim 100\%$	$\lambda_4 \in [\sim -4, \sim +16]$

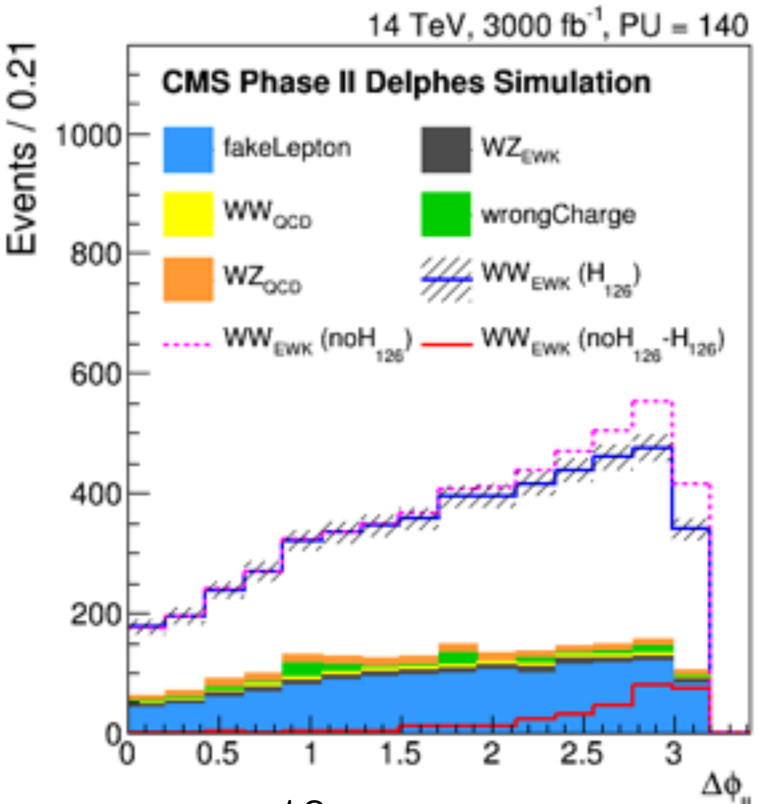


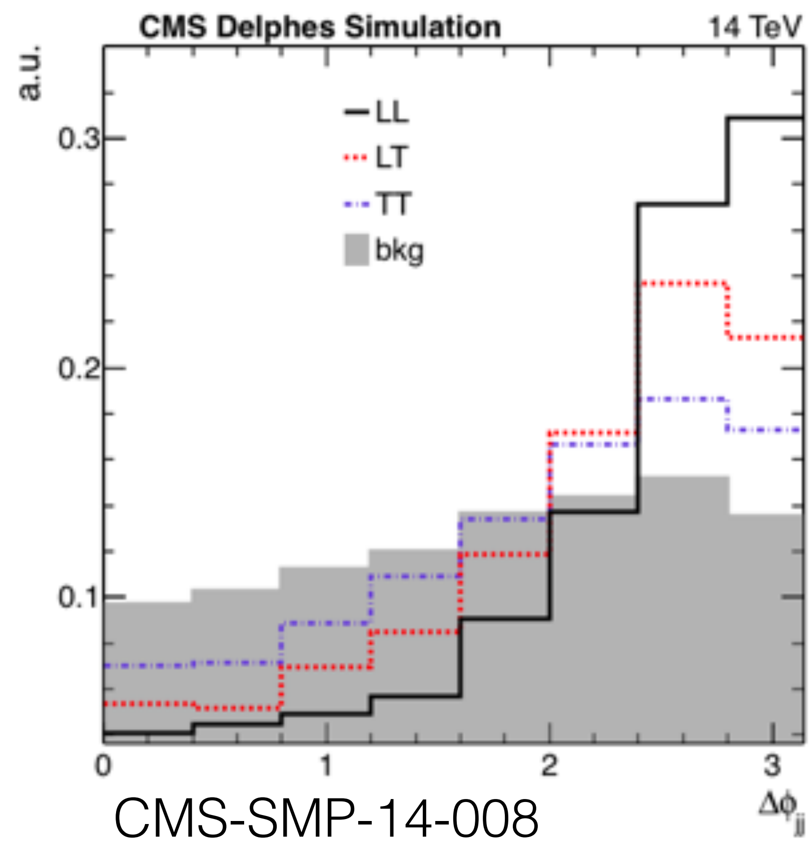
Vector Boson Scattering

- ➡ **Assess VBS sensitivity using same-sign WW and WZ**
  - CMS made first observation of same-sign W pair production public last week (CMS-SMP-17-004)
  - utilizing unique event topology
  - longitudinal scattering cross section
  - anomalous couplings
  - input to Higgs couplings
  - HL-LHC has ~3σ sensitivity for $V_L V_L$ scattering







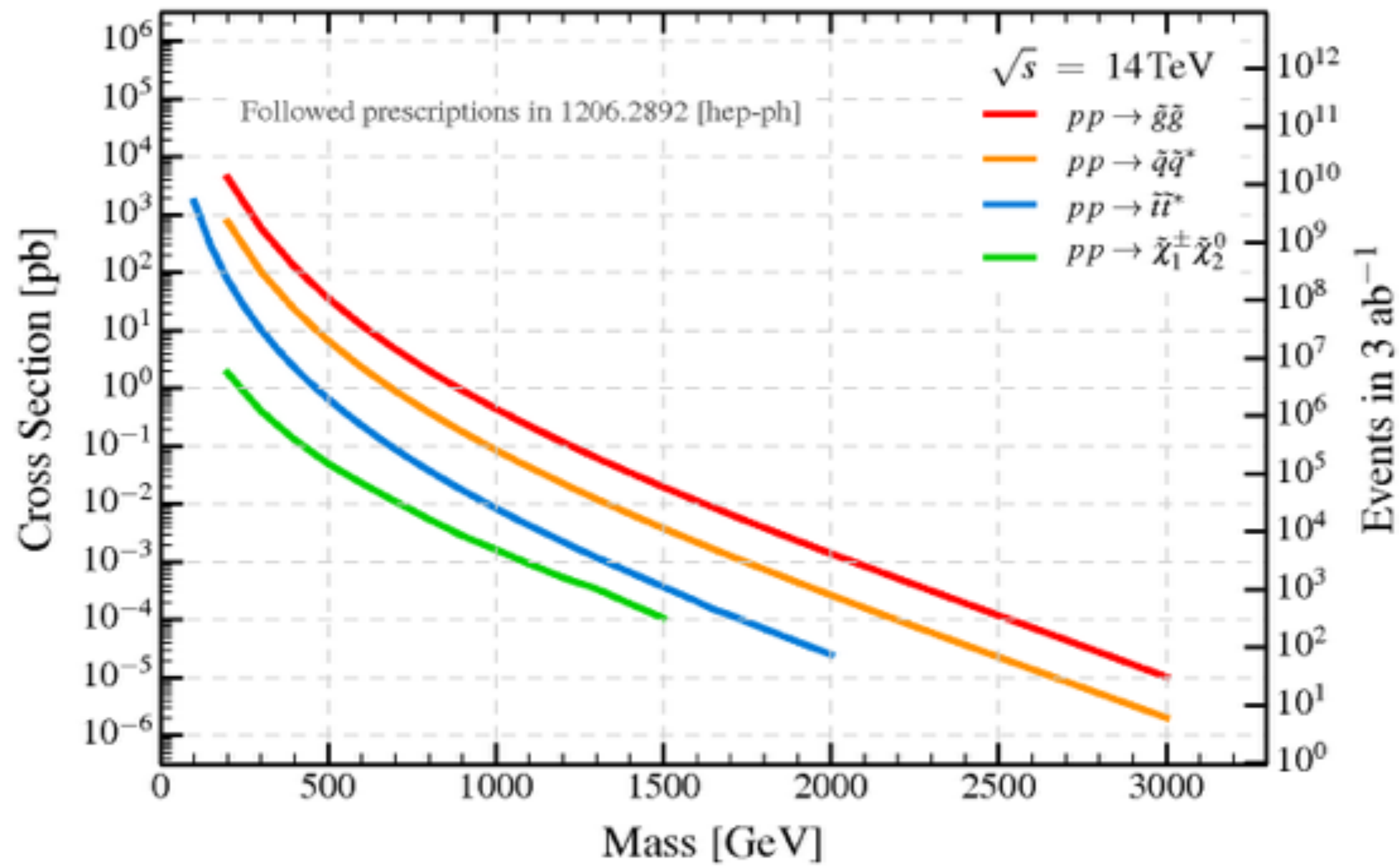


CMS-SMP-14-008

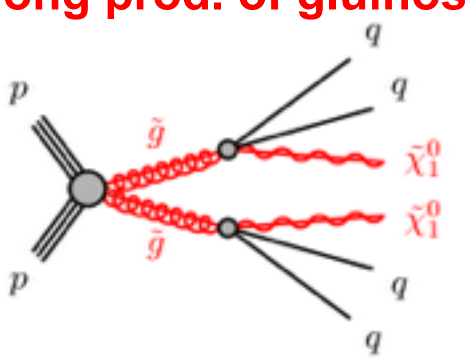
Supersymmetry

➡ **Strong motivation for SUSY**

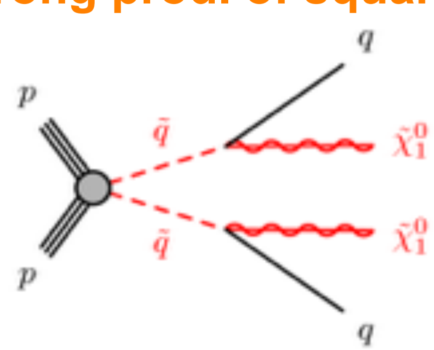
- discovery of the Higgs gives new urgency to find "natural" explanation for gauge hierarchy
- HL-LHC expands discovery reach or allows to investigate SUSY spectrum
- requires all capabilities of ATLAS & CMS



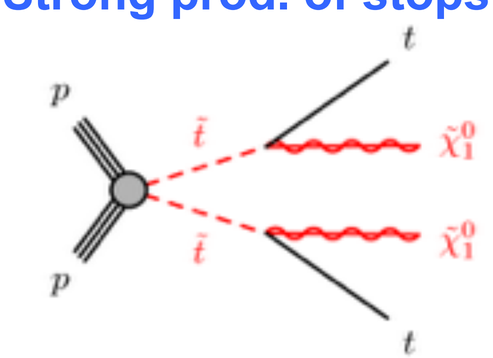
Strong prod. of gluinos



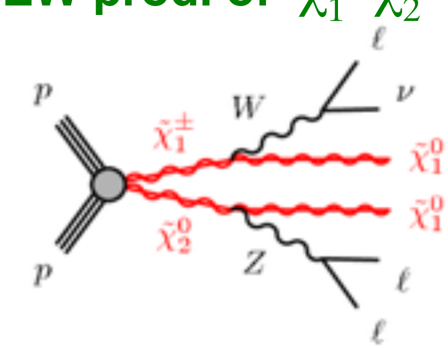
Strong prod. of squarks



Strong prod. of stops



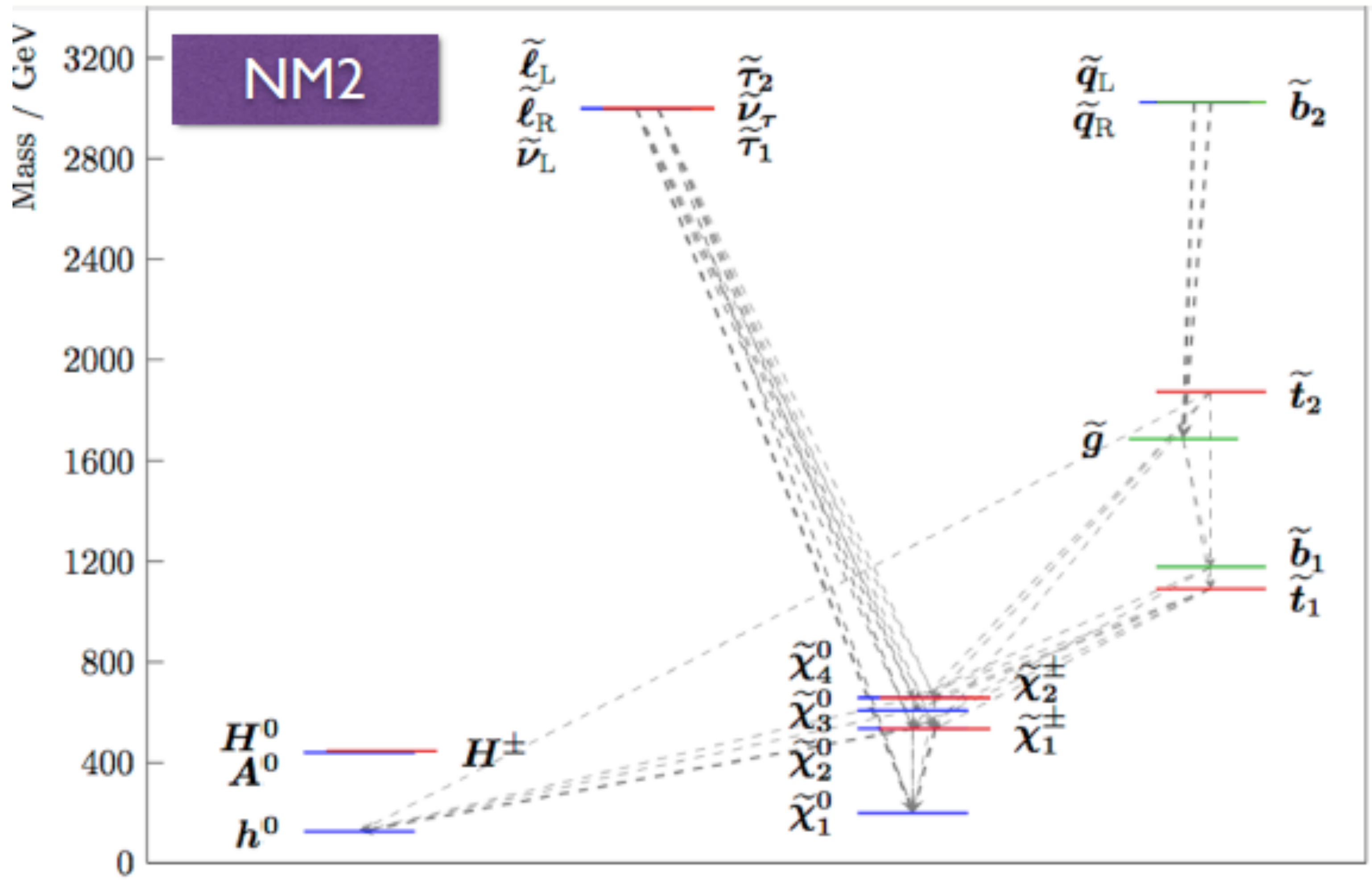
EW prod. of $\chi_1^+ \chi_2^0$



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

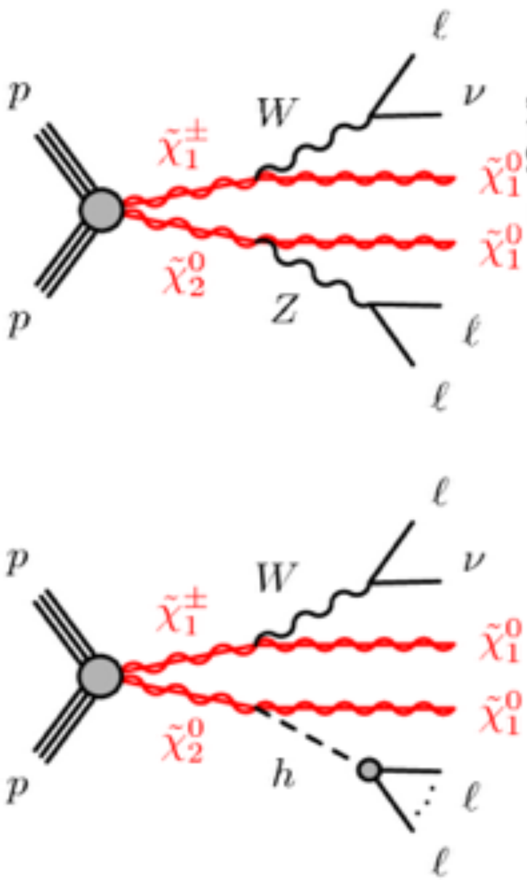
CMS-SUS-14-012 CMS-TDR-15-02

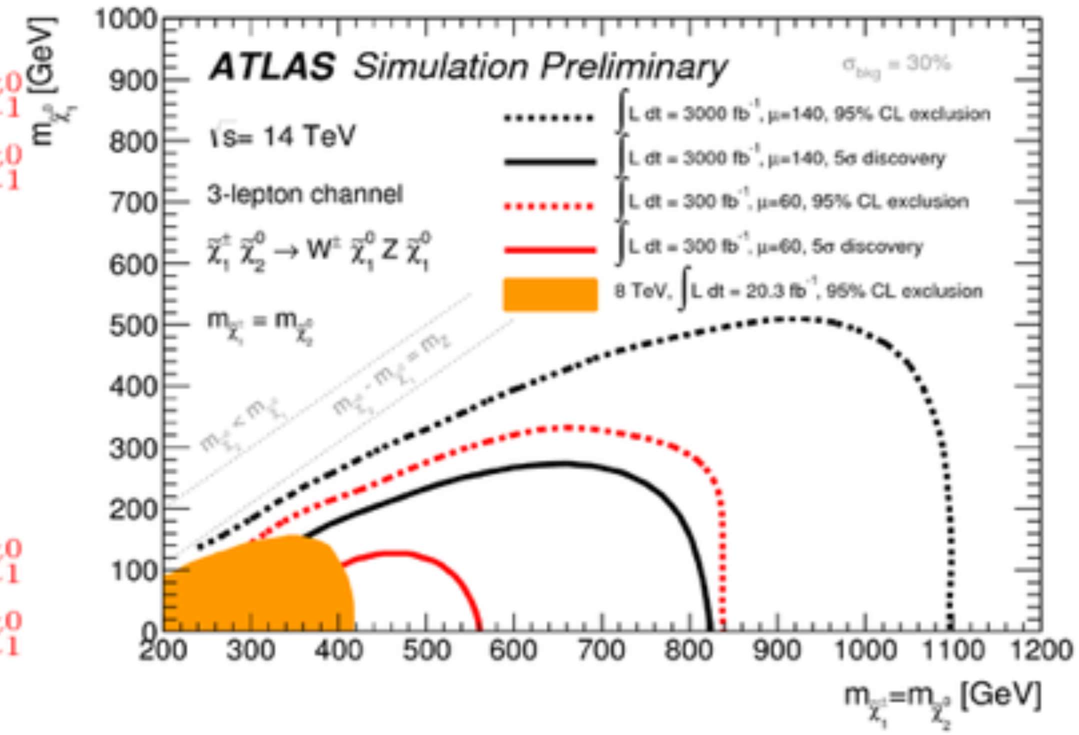
Analysis	Luminosity (fb^{-1})	Model: NM1	NM2	NM3	STC	STOC
all-hadronic (HT-MHT) search	300				$< 3\sigma$	$3-5\sigma$
	3000				$3-5\sigma$	$> 5\sigma$
all-hadronic (MT2) search	300	$3-5\sigma$	$> 5\sigma$	$> 5\sigma$		
	3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$		
all-hadronic $\tilde{b}_1$ search	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$3-5\sigma$	$< 3\sigma$
	3000	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$> 5\sigma$	$< 3\sigma$
1-lepton $\tilde{t}_1$ search	300	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$3-5\sigma$	$< 3\sigma$
	3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$
monojet $\tilde{t}_1$ search	300					$3-5\sigma$
	3000					$3-5\sigma$
$m_{\ell^+\ell^-}$ kinematic edge	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$		
	3000	$> 5\sigma$	$< 3\sigma$	$< 3\sigma$		
multilepton + b-tag search	300	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$3-5\sigma$	
	3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	
multilepton search	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	
	3000	$3-5\sigma$	$3-5\sigma$	$< 3\sigma$	$3-5\sigma$	
ewkino WH search	300		$< 3\sigma$			
	3000		$3-5\sigma$			

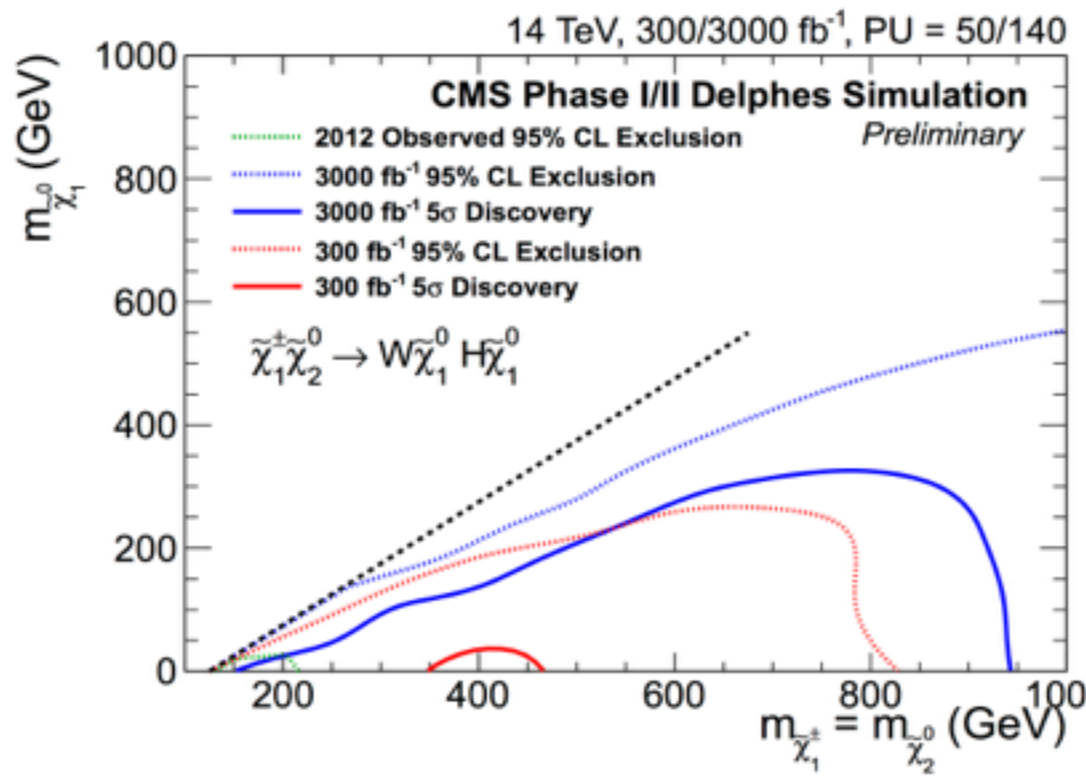
$< 3\sigma$ $3-5\sigma$ $> 5\sigma$

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

arXiv:1603.09549

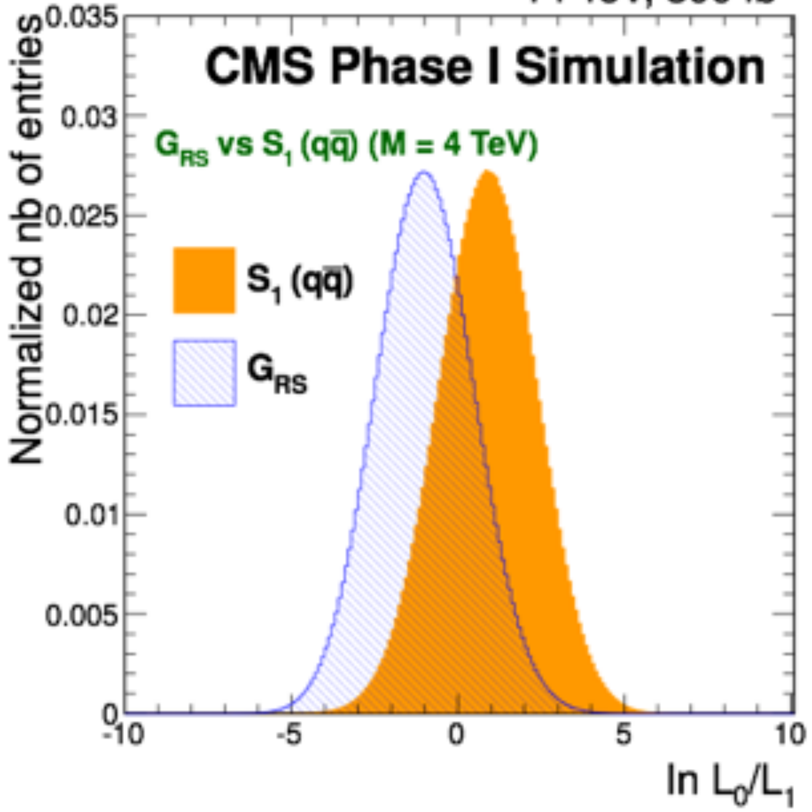
Heavy New States

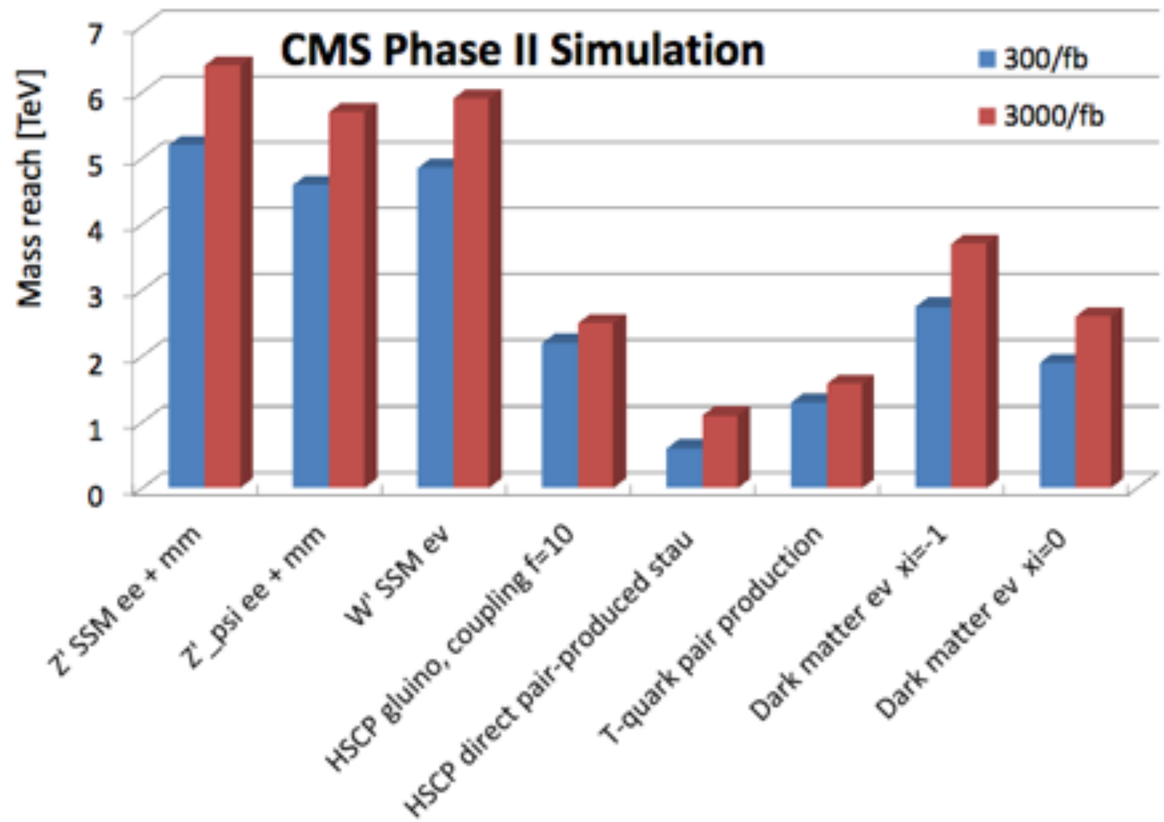
➡ **Window to new physics beyond SUSY**

- heavy gauge boson search and properties
- dark matter
- highly ionizing particle
- displaced vertices
- ~20% increase in mass reach with factor 10 in data

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

CMS-TDR-15-02





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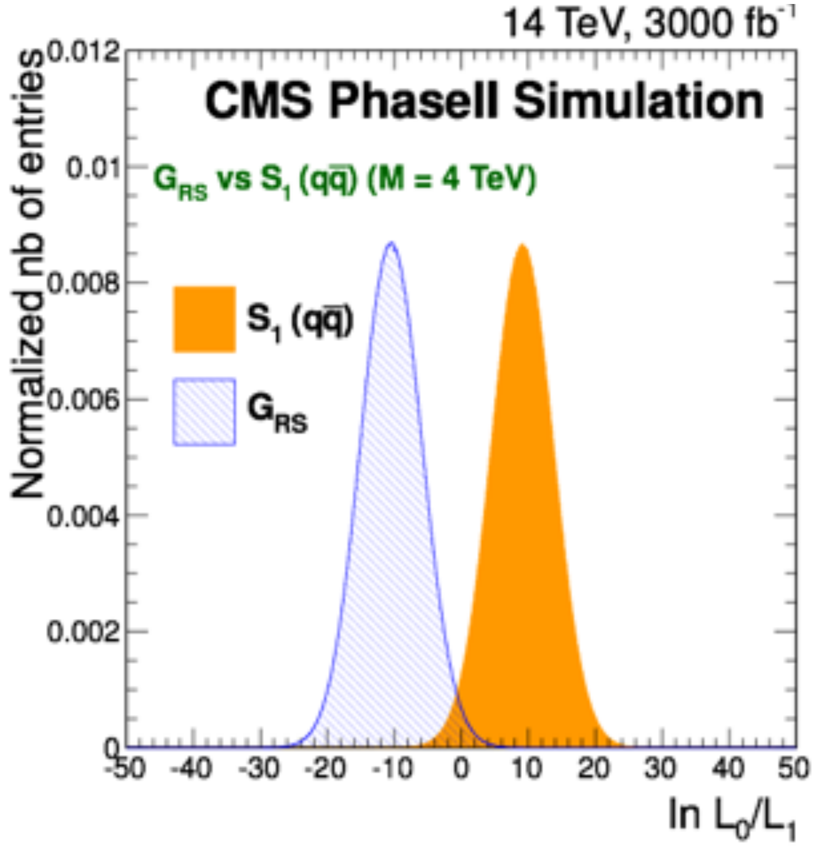
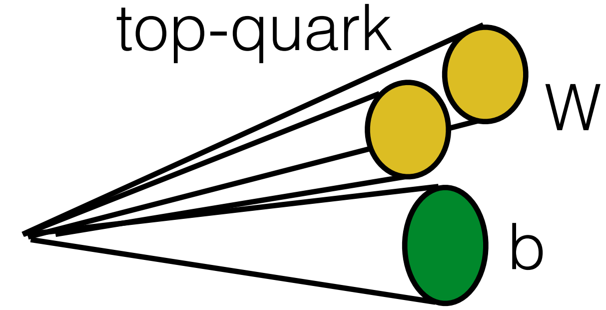


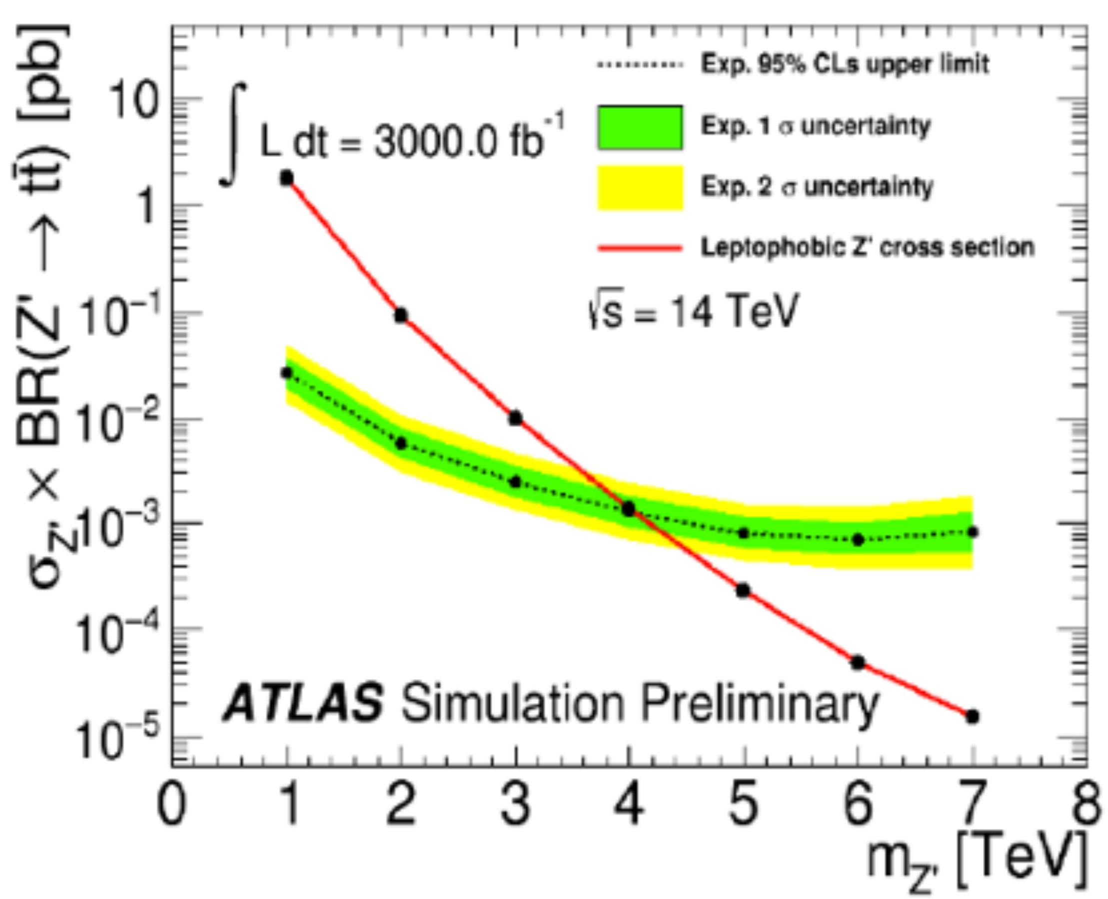
Heavy New States

➡ **top anti-top resonance searches**

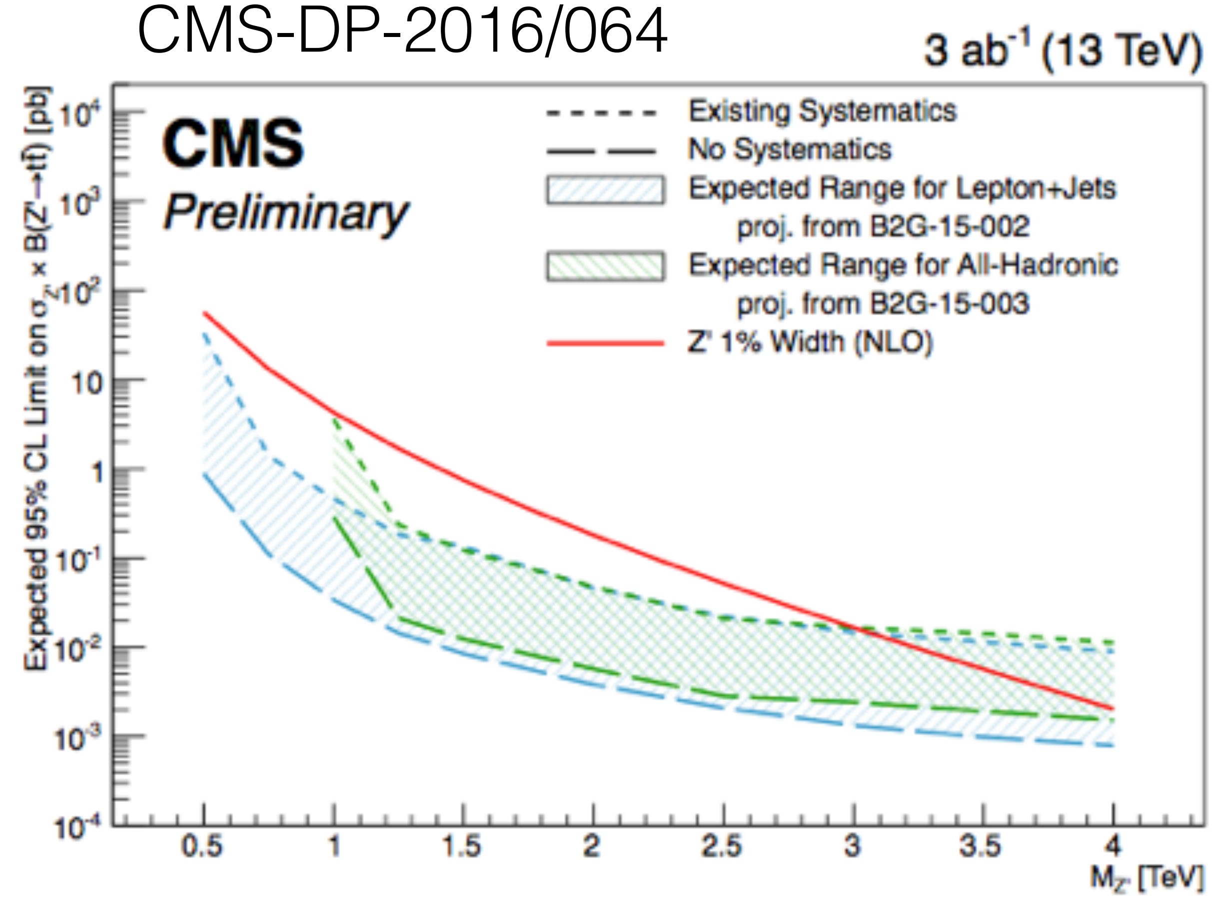
- using top-color Z’ model as benchmark
- top quark reconstructed in one fat-jet
- HL-LHC extents mass reach from 3 to 4 TeV
- Current limit 2.1 TeV (JHEP 08(2015) 053)



ATL-PHYS-PUB-2017-002

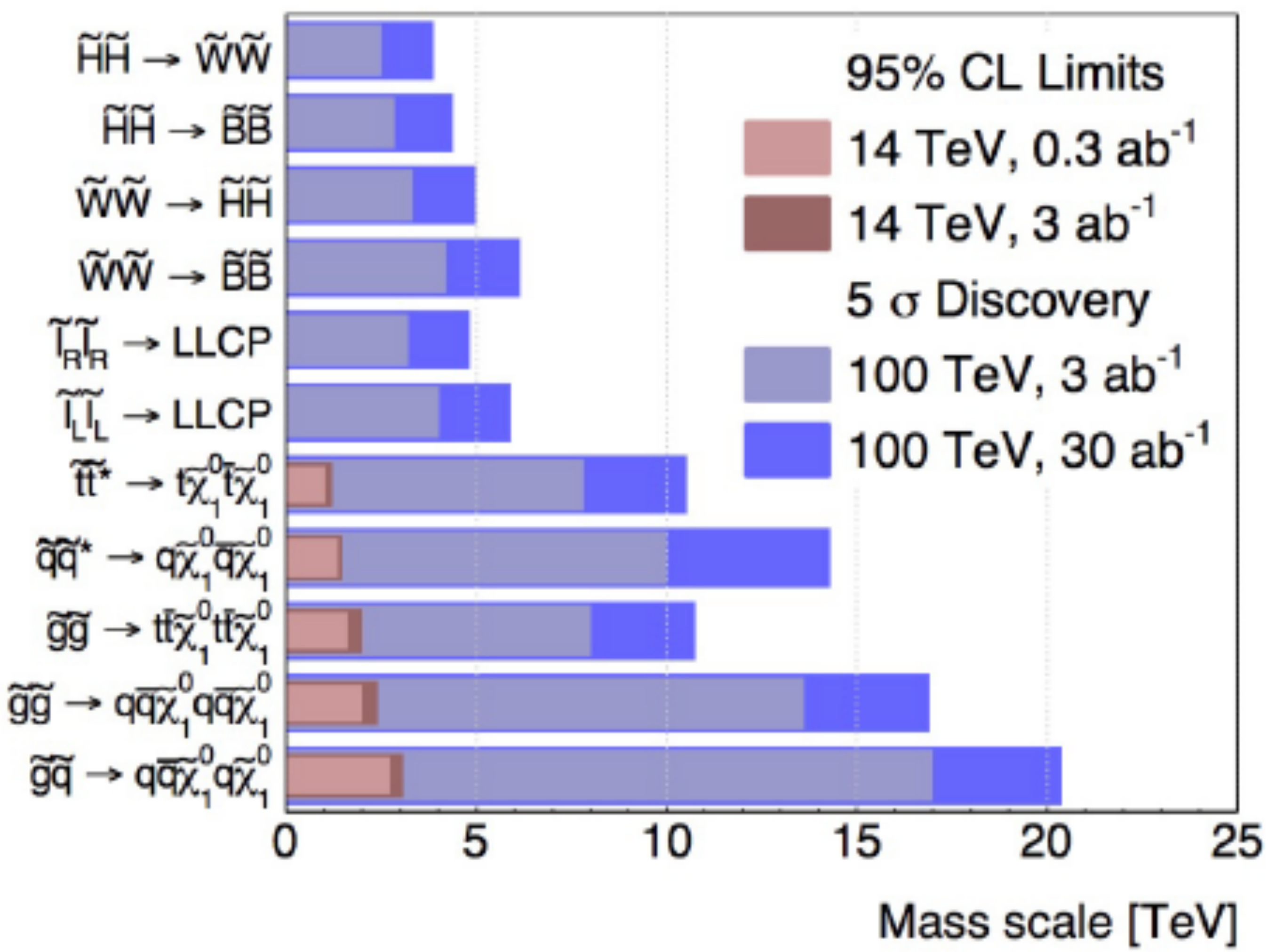


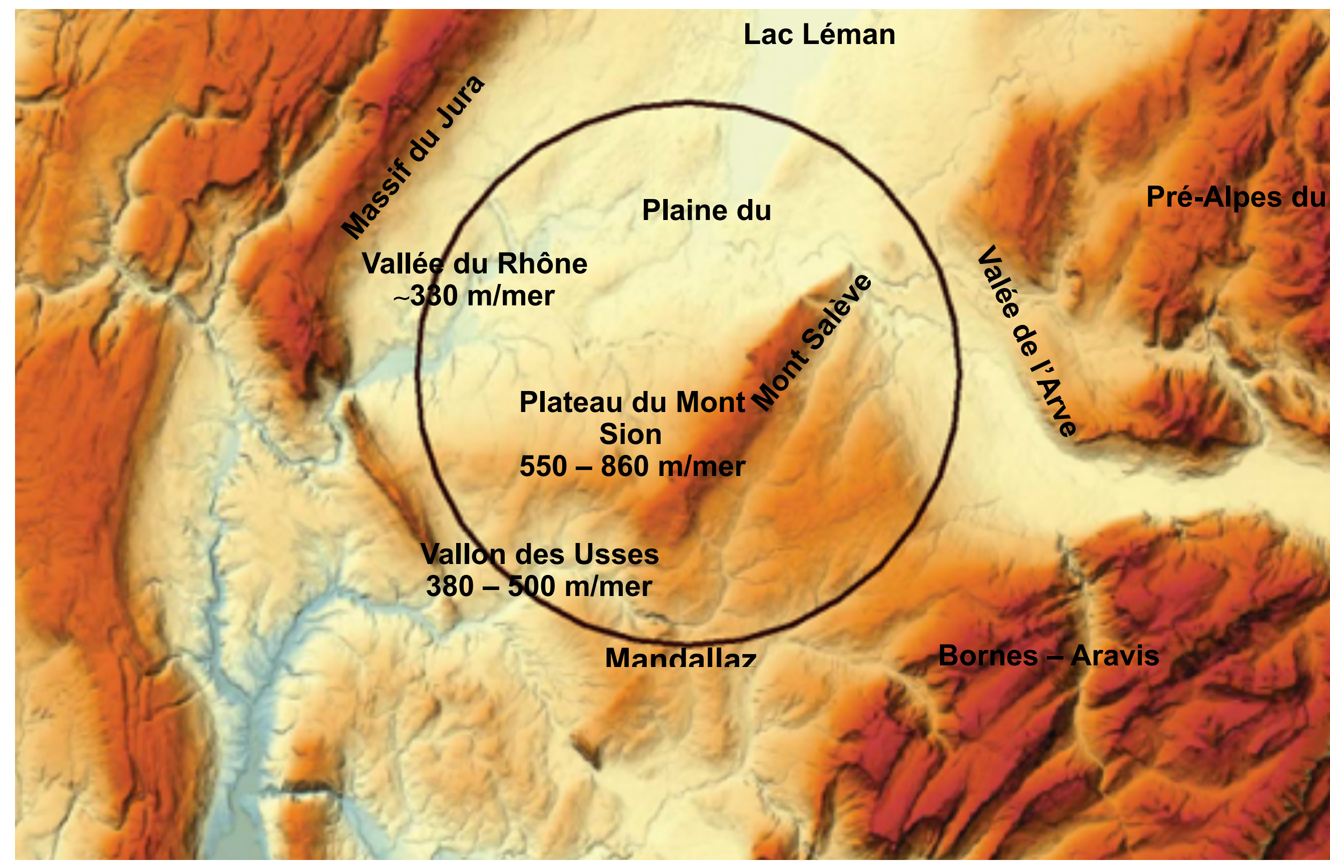
CMS-DP-2016/064



Heavy New States

➡ **FCC-hh extents mass reach for direct discovery by factor ~5**





Conclusion

- ➡ **HL-LHC enables a 20+ years research program with large discovery potential**
  - **ATLAS & CMS upgrades required to fully exploit the (HL-)LHC**
- ➡ **Physics case is based on the large dataset (selected examples shown)**
  - **Precision measurements of SM parameters (including the Higgs boson)**
  - **Sensitivity to rare SM & (weakly produced) BSM processes**
  - **Extension of discovery reach in high-mass region**
  - **Determination of BSM parameter**
- ➡ **Studied physics channels only scratch the surface of possibility**
- ➡ **Future Lepton and Hadron Collider projects enhance discovery potential significantly and are complementary**
- ➡ **Goal: Exploring the energy frontier**