CMS Future Prospects and Physics Potential

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On behalf of the CMS collaboration

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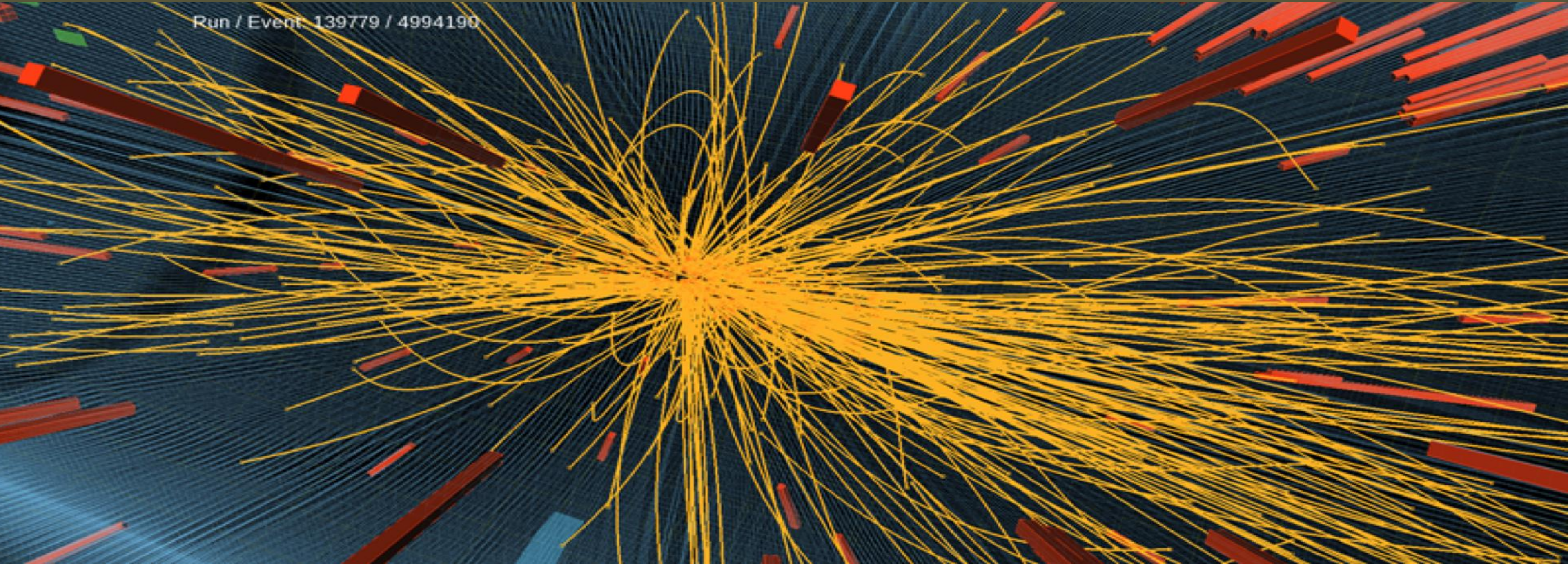
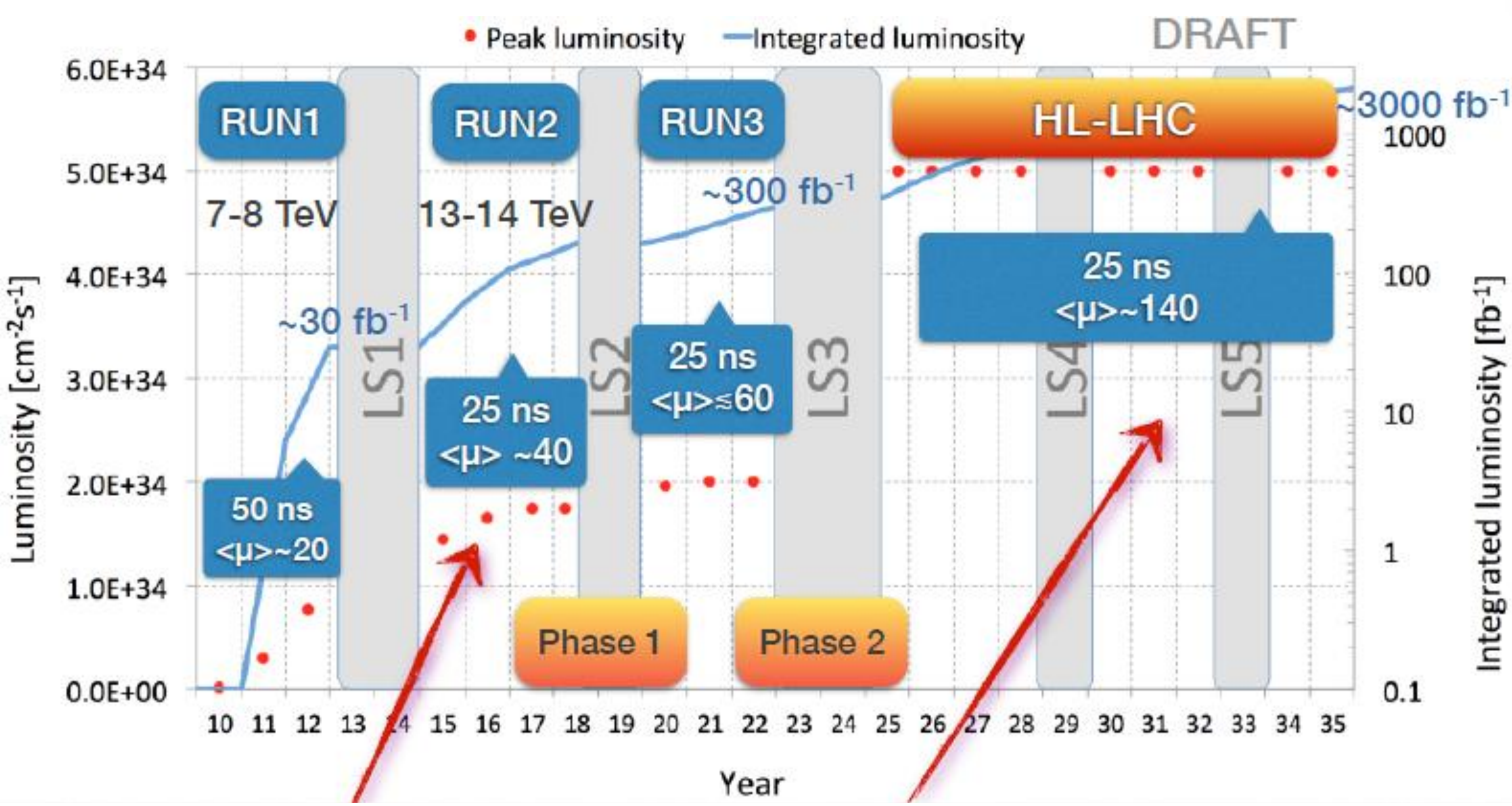


Schedule of LHC up to HL

Rich harvest of LHC run-1 at √s = 8 TeV.

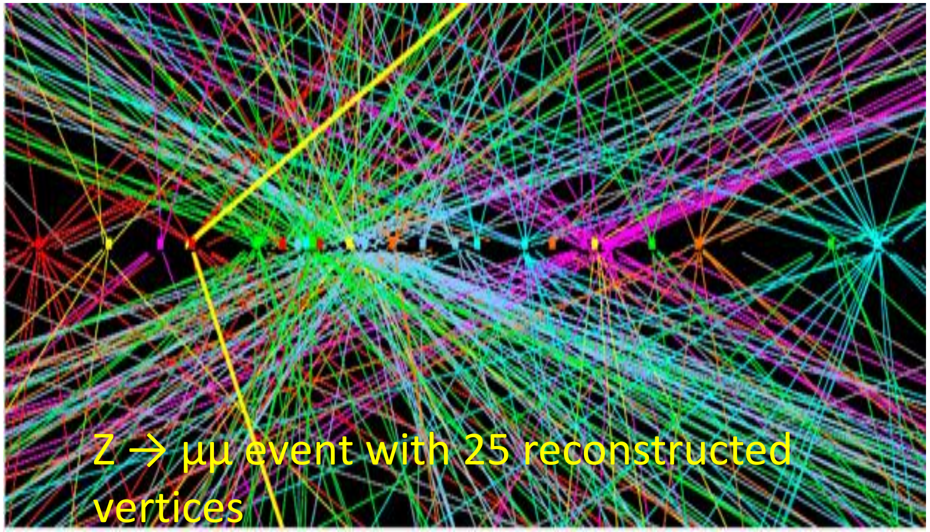
Expect more to come in run-2 with increased √s = 13-14 TeV.

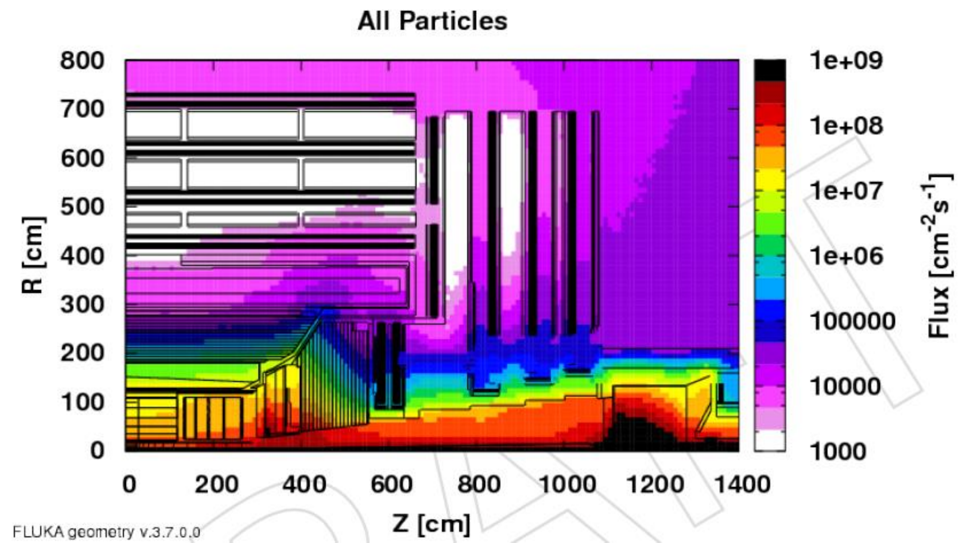
Start planning the future of LHC…. **High luminosity (HL)**



We are here We want to go there….

Impact of HL on detectors



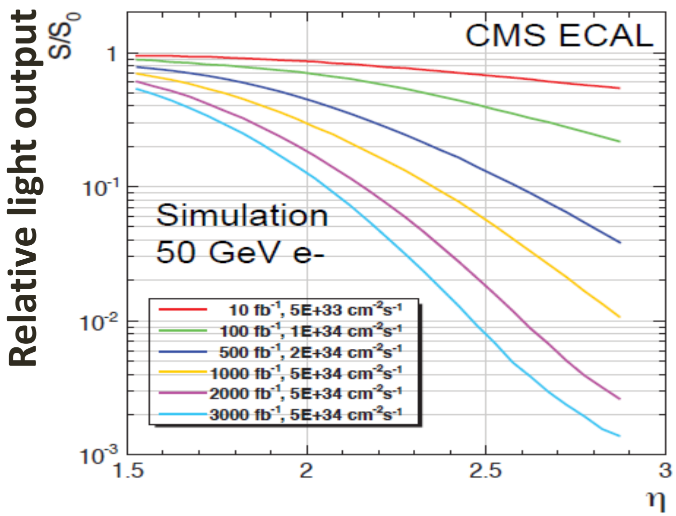


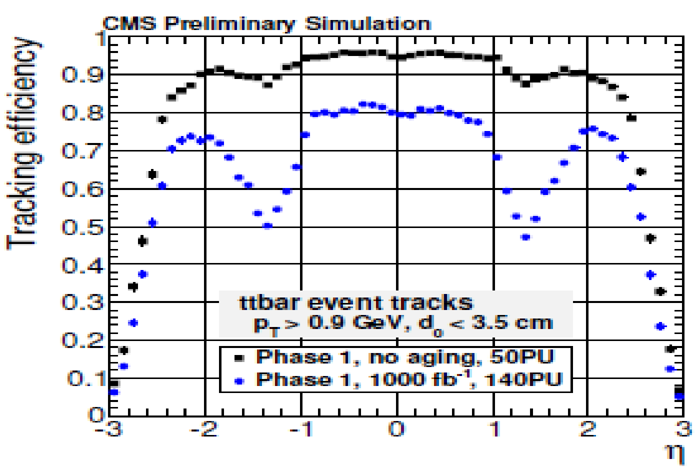
Radiation six times higher than nominal LHC design
More pile-up (PU) but maintain detector performance
→ Upgrade several detector components

Failure rate of 20-yr old detectors increases
→ Redesign electronics, trigger and DAQ

Consequences

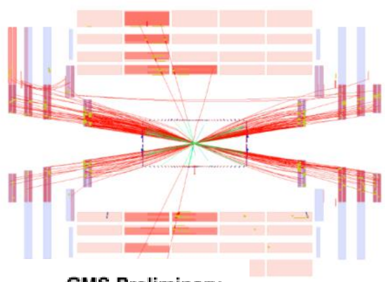
Detector ages and performance deteriorates

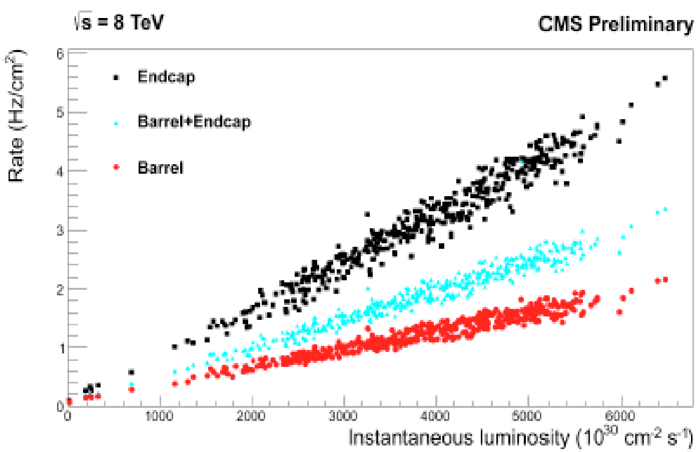




→ Need to replace tracker and forward detectors with radhard material

Higher rates, in particular in the forward region





RPC backgroound rates vs luminosity

Triggers need to stay efficient (MHz→kHz). Keep trigger thresholds low for Higgs, B-physics and particles from cascade decays

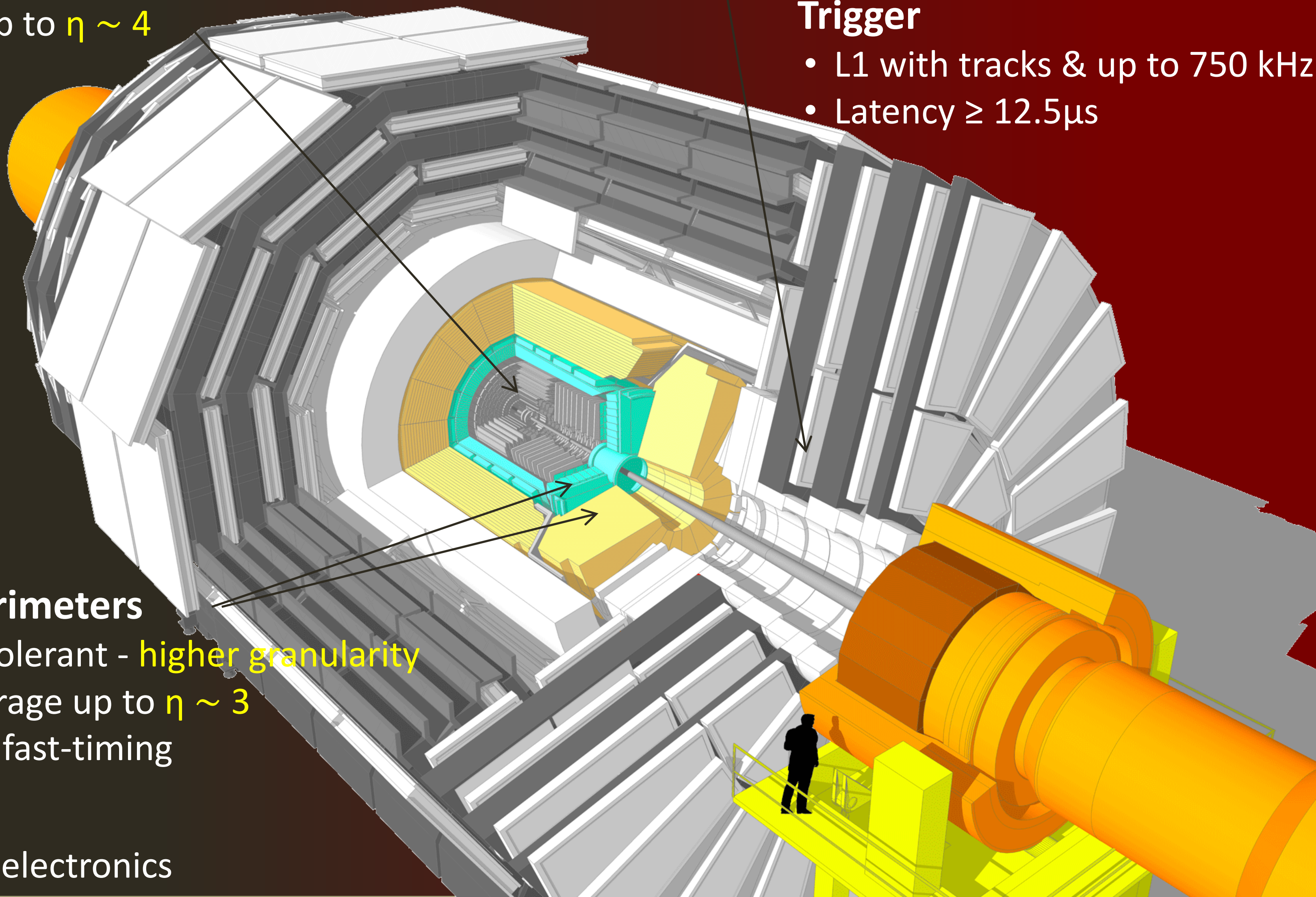
→ Finer granularity detectors and larger trigger bandwidth

CMS Phase II Detector Upgrades

Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Complete coverage in forward region (new GEM/RPC technology) |η|>1.6
- Investigate muon-tagging up to η ~ 3

Trigger
- L1 with tracks & up to 750 kHz
- Latency ≥ 12.5μs



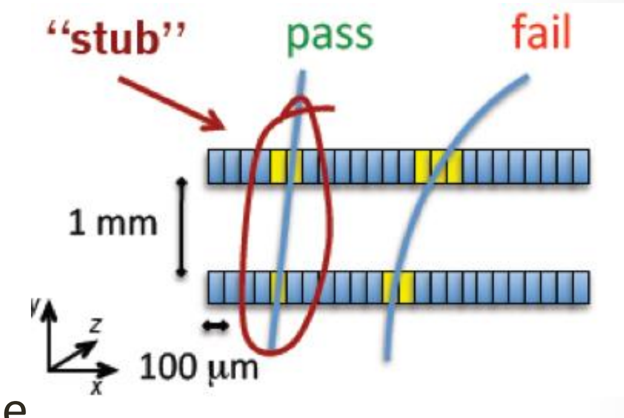
Endcap Calorimeters
- Radiation tolerant - higher granularity
- Study coverage up to η ~ 3
- Investigate fast-timing

Barrel ECAL
- Replace FE electronics

Trigger Challenge: Track Trigger

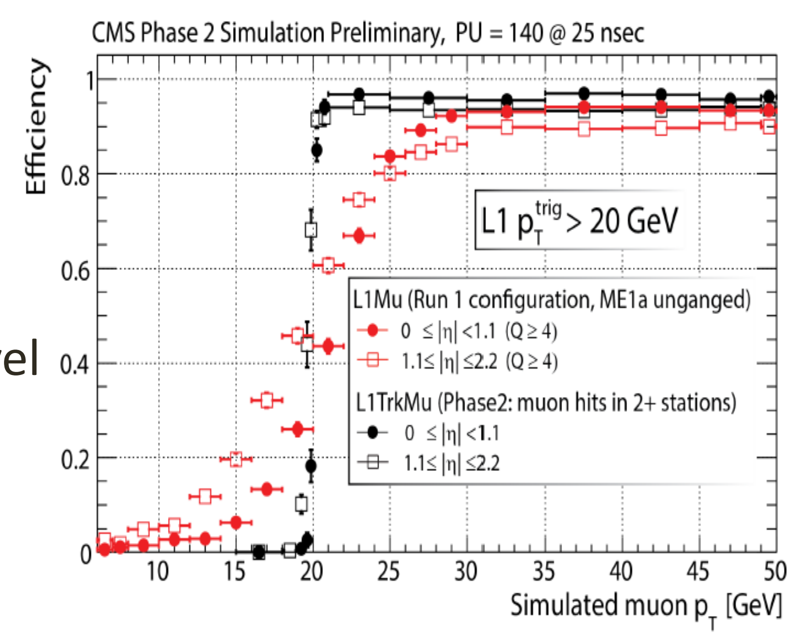
B=3.8T

Objective: reconstruct all tracks with p_T>2 GeV **at trigger level**. Identify primary vertex along beam line with ~1mm precision.



Conceptual design: to implement tracks in hardware trigger (40 MHz)

- Correlate hits in two closely-spaced sensors to provide vector ("stub") in transverse plane: angle is a measure of p_T
- Exploit the strong magnetic field of CMS

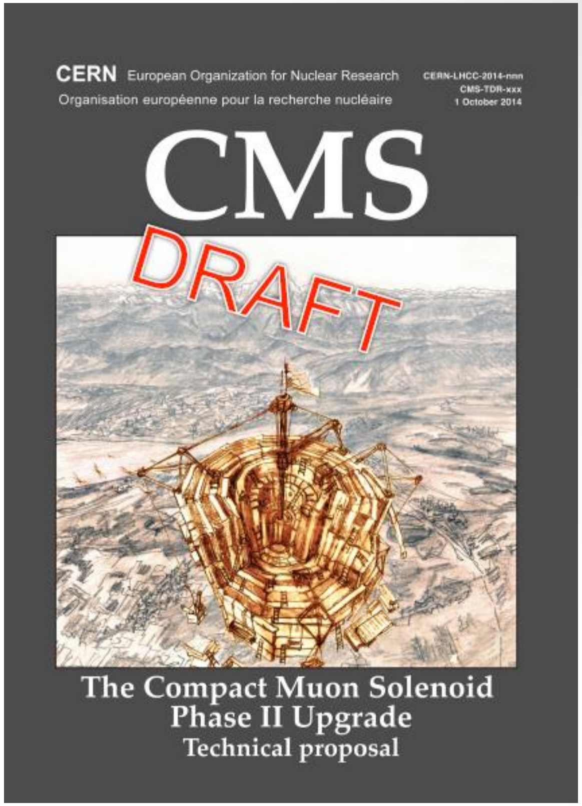


Physics benefit:

- Threshold can stay roughly at present level
- Sharp trigger turn on

Physics Program

- **Precision studies** of 125 GeV Higgs (couplings, rare decays, etc.)
- Search for **extended** Higgs sector
- **Vector boson scattering** (VBS)
- **B-physics**
- Searches for **physics beyond SM** (BSM), e.g. dark matter (DM), heavy vector bosons (Z‘, W‘), long-lived exotic particles. Searches for SUSY



Detector scenarios:

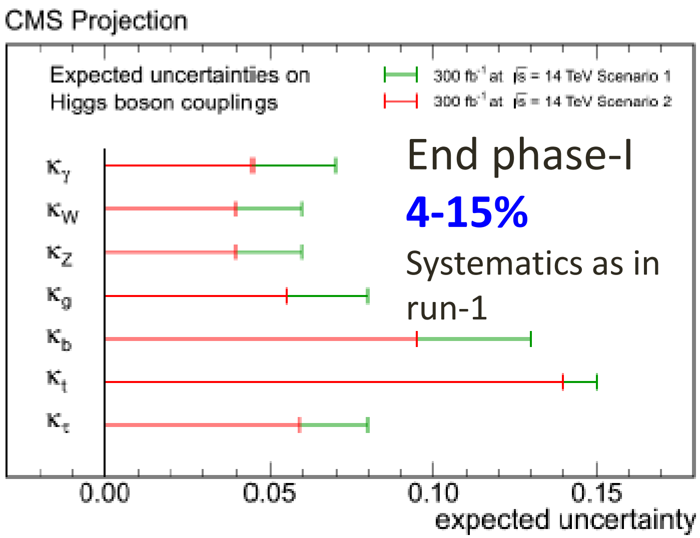
- Phase-1 detector, PU=50, 300/fb
- Phase-1 aged (except pixels) PU=140, 1000/fb
- Phase-2 detector PU=140, 3000/fb

Higgs Boson Properties

HL-LHC → Higgs precision measurements

HL-LHC → Search for extended Higgs sector

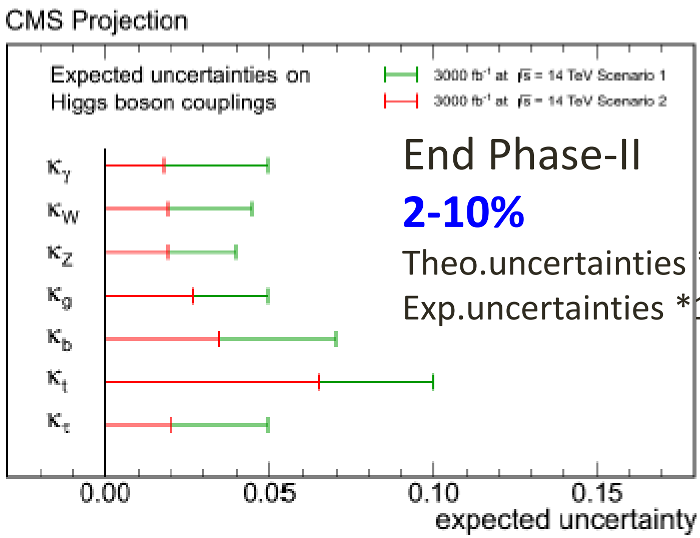
Precise determination of Higgs couplings



End phase-I

4-15%

Systematics as in run-1



End Phase-II

2-10%

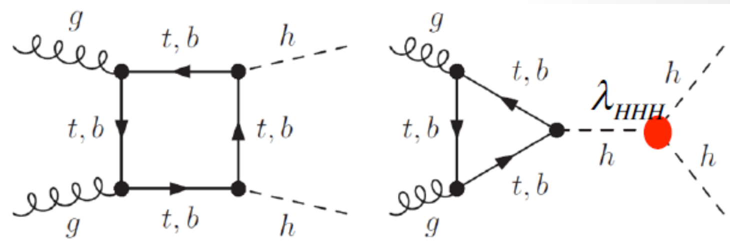
Theo.uncertainties *1/2

Exp.uncertainties *1/√int L

Measure rare decays (H→μμ, H→Zγ), all couplings to other particles.

Higgs possibly a portal to dark matter.

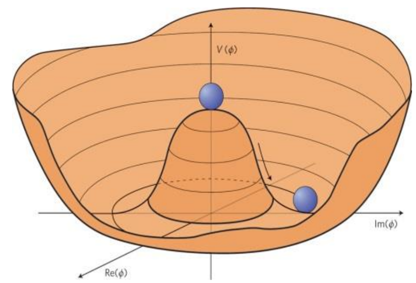
Rare: Higgs Pair Production



Can only be studied at HL-LHC

$\sigma_{HH} \sim 10^{-3}\, \sigma_{single\text{-}H}$

„Today'd discovery is tomorrow's bkgr"



HH production probes **Higgs self-coupling**

and is **sensitive to BSM**

Leads to **multi-particle** final states: **bbγγ, bbττ**, bbWW, etc.

Select Higgs decays with large BR → final state objects sensitive to detector performance and require upgrade.

If several channels combined, it can be observed with 3000/fb

Significance for combination bbγγ + bbττ ATLAS + CMS = 1.9 sigma

Trigger thresholds are crucial, **needs track-trigger**!! With(out) TT di-tau thresholds 56 GeV (95 GeV), single muon 18 GeV (50 GeV)

Performance needed for HH

bbγγ

320 evts with 3000/fb

Bkgr: resonant HZ(bb/tt) and non-resonant QCD incl. mis-ID jets/γ

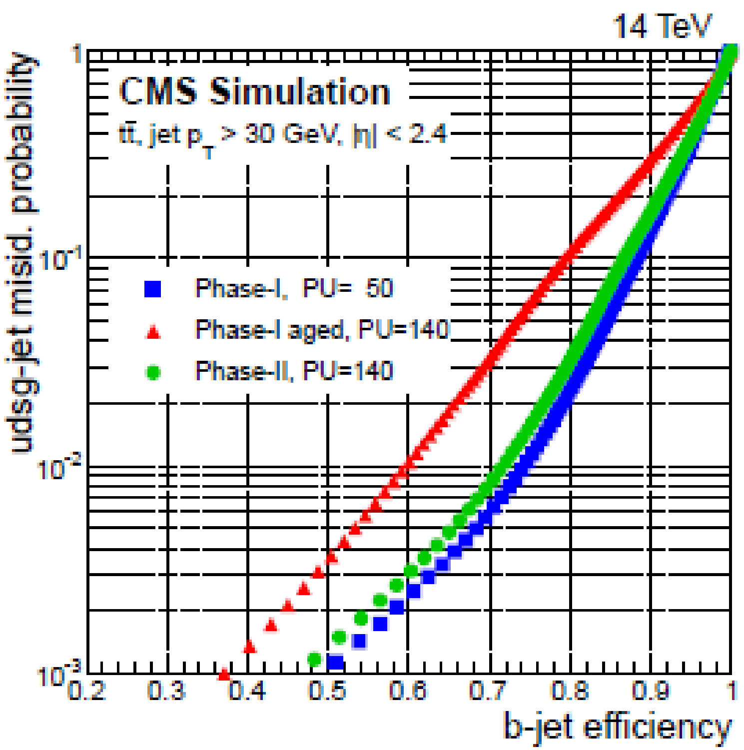
Needs: γ-resolution, b-tagging

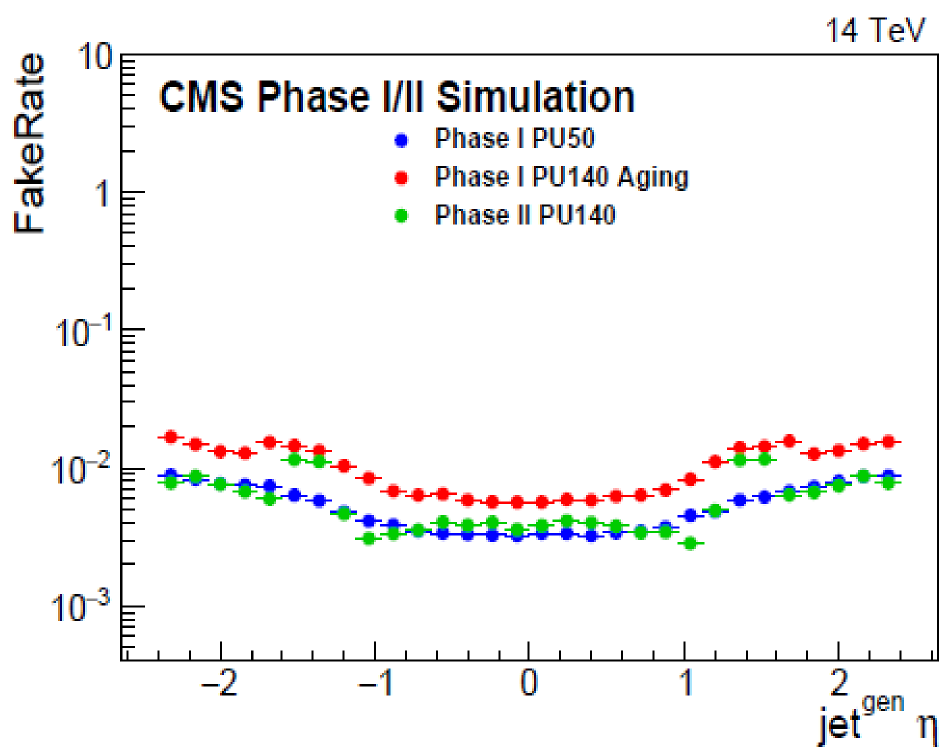
bbττ

9000 evts with 3000/fb

Bkgr: tt, DY(tautau)+j, ZH, ttH

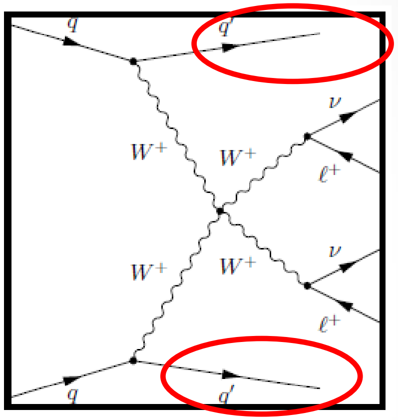
Needs: b-tagging, tau reconstruction, low fake rate





Essential: Vector Boson Scattering (VBS)

Can only be measured at HL-LHC. Small signal xsec's O(fb)@14 TeV and large irreducible background from strong production of WW+jj and from PU.



Tagging jets

Cornerstone of SM = EWSB

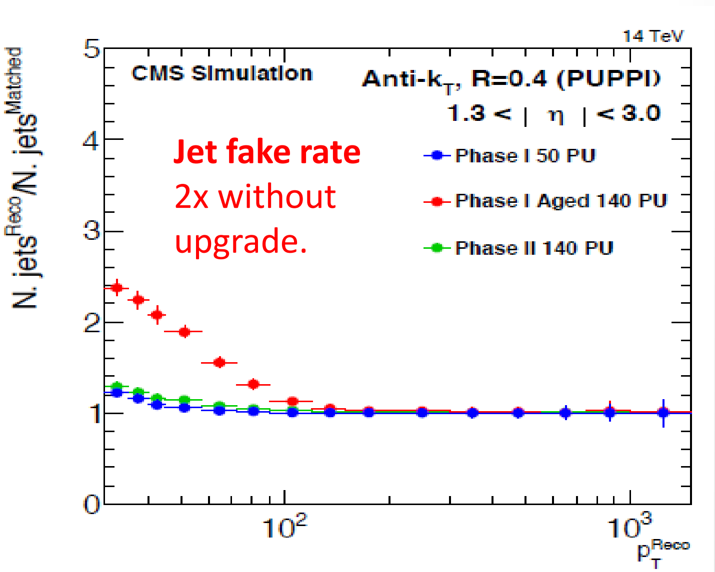
VBS amplitude $V_L V_L \rightarrow V_L V_L$ regularized in SM by Higgs

→Test role of Higgs in EWSB sector

→Model-independent search for BSM

Upgraded detector needed to reduce fake jets due to PU and separate from VBS signal jets (primary vertex).

Due to **larger coverage** from extending pixel to |η|~4.0 and improved jet reconstruction algorithm.

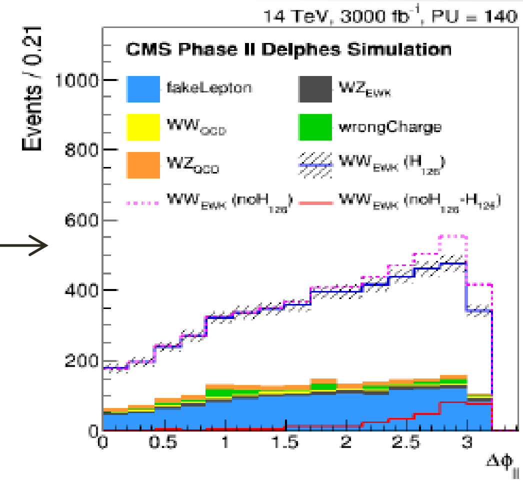


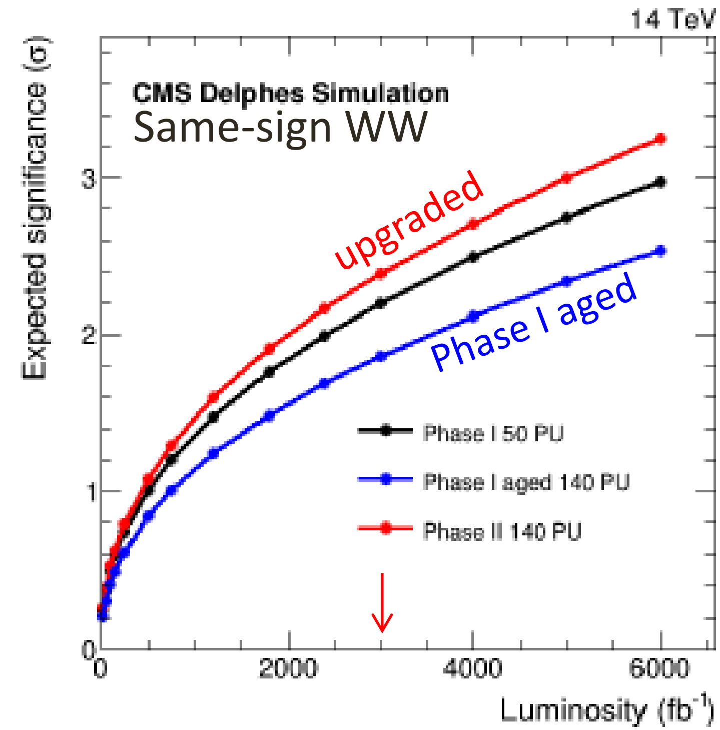
VBS Performance

Most sensitive channels: WW (same sign) and WZ

Kinematic properties to select signal evts: $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$ →

Then 2D binned template fits





Similar for WZ (not shown). Significance for 3000/fb for Phase II about 1.3

Combination of WW and WZ:

$3000\ fb^{-1}$, 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

Upgraded detector needed for maximum performance.

B-Physics

CMS B-physics complementary to LHCb (see e.g. combined publication)

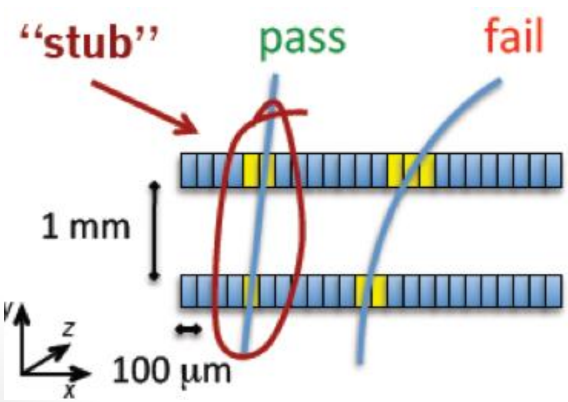
B→μμ and B_s→μμ

Needs very low thresholds!

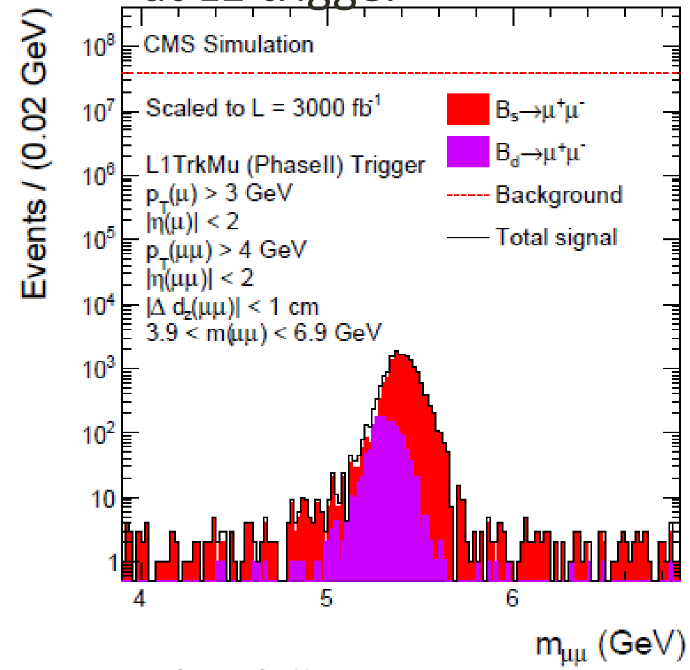
High mass resolution to separate peaks

Only way to trigger is track-trigger

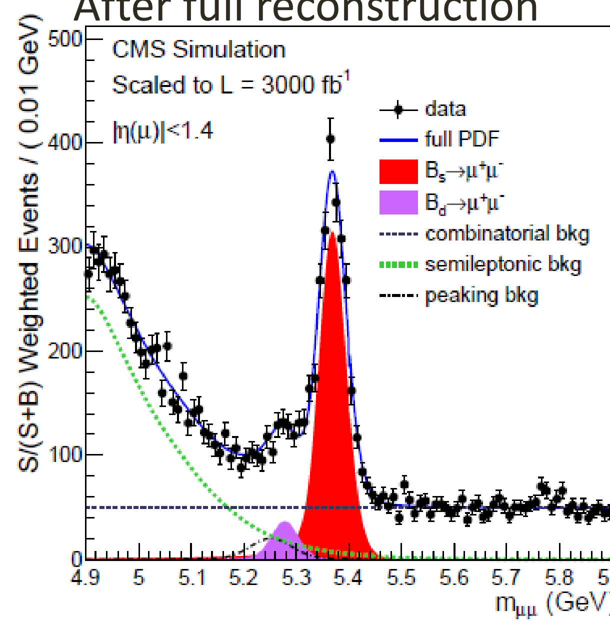
Combined with muon-ID



Selection and resolution at L1 trigger



After full reconstruction

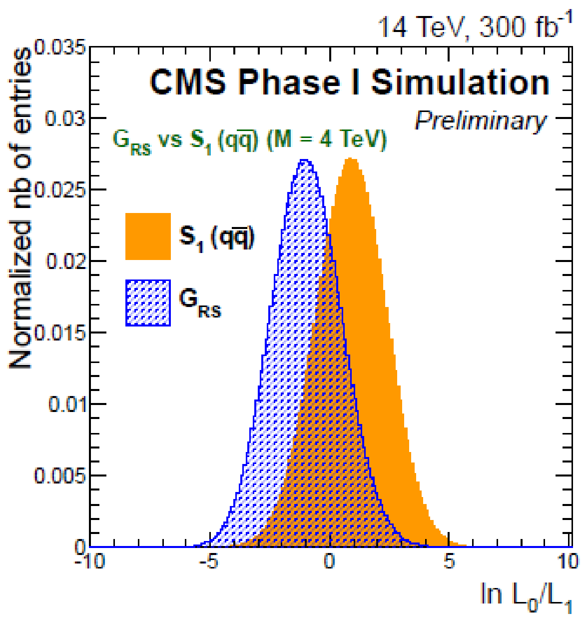


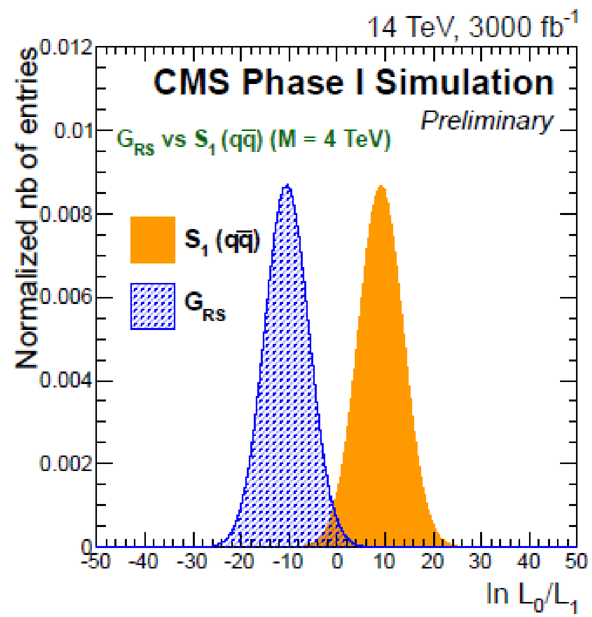
Search for New Physics

Assume a hint of a signal was seen at the end of phase-1

→ Study its properties (spin, production mode, rapidity) in phase-2

- Chosen models RS-graviton (G_{RS}), spin-1 ee-resonances.
- Hypothesis test using a likelihood ratio.



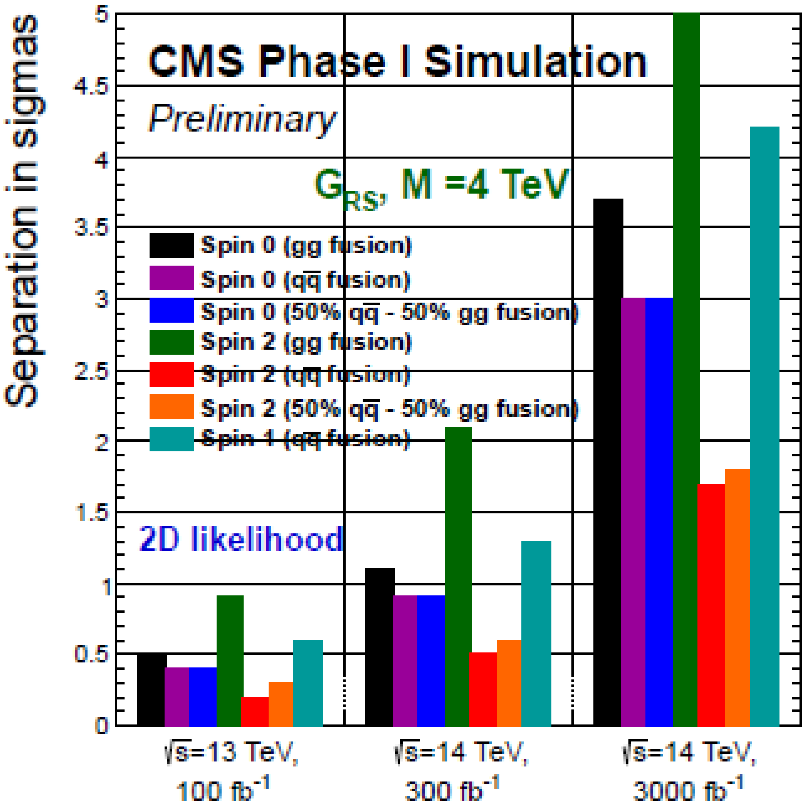


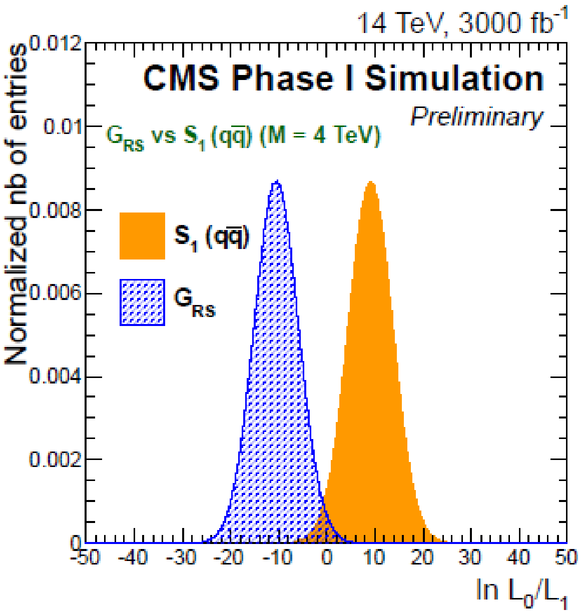
End of phase-1
300/fb

End of phase-2
3000/fb

Search for New Physics

Separation in sigma for various spin states. Spin 0,1 can be identified with ≥3 sigma.



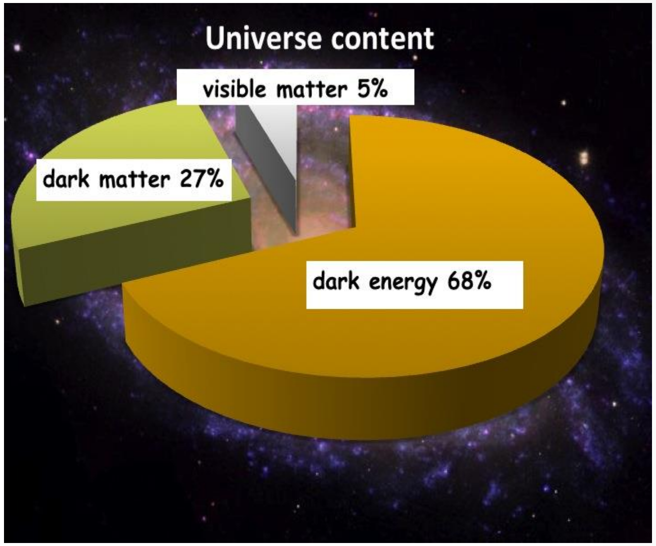


End of phase-2 3000/fb

Dark Matter – Next Discovery?

BSM physics with an existing experimental hint

Many experiments, **not unlikely to see somewhere a signal-like excess.**



Direct detection (DD) experiments superior for vector coupling. Long term **limited by irreducible neutrino** background.

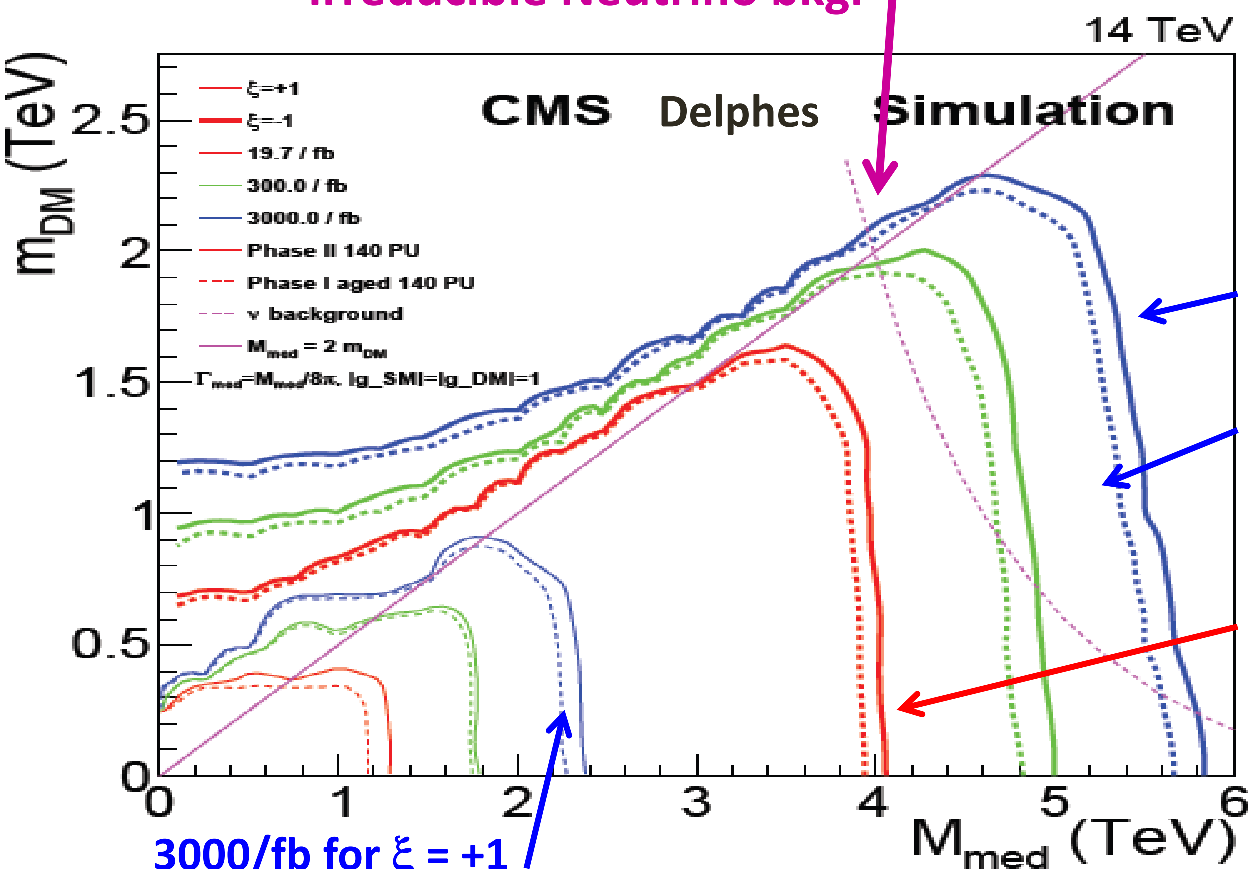
LHC superior for **light** dark matter (DM) and **other** (scalar, axial-vector, pseudoscalar) couplings.

Different channels and high √s allow property studies, e.g. potentially different u/d couplings.

Dark Matter Projected Sensitivity

Channel: Mono-W with W→eν

Irreducible Neutrino bkgr



Phase-II 3000/fb
For ξ = -1
with max xsec

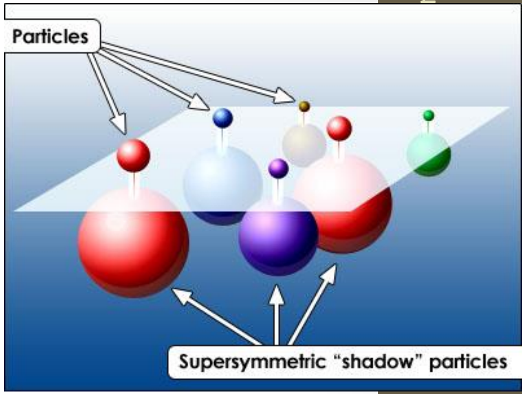
Phase-I Aged
For ξ = -1

30/fb
For ξ = -1

3000/fb for ξ = +1
with min xsec

DMV interpretation Fox & Kopp et al. arXiv:1109.4398
Neutrino bkgr from arXiv:1407.8257

Supersymmetry (SUSY)



Search for SUSY is a major goal for run-2 and HL-LHC

- Higgs discovery poses new urgency to hierarchy problem
- Natural SUSY models stabilize Higgs mass through loops
- Candidate for DM (lightest supersymmetric particle, LSP)
- Gauge unification

Complex theory with many flavours → program for many years

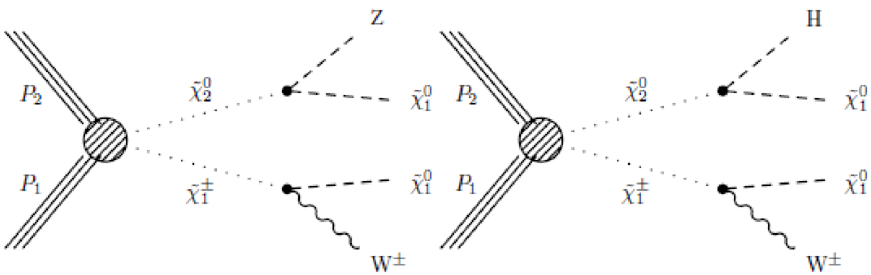
Simplified models

Done so far. Allows projections to HL.

Full spectrum models

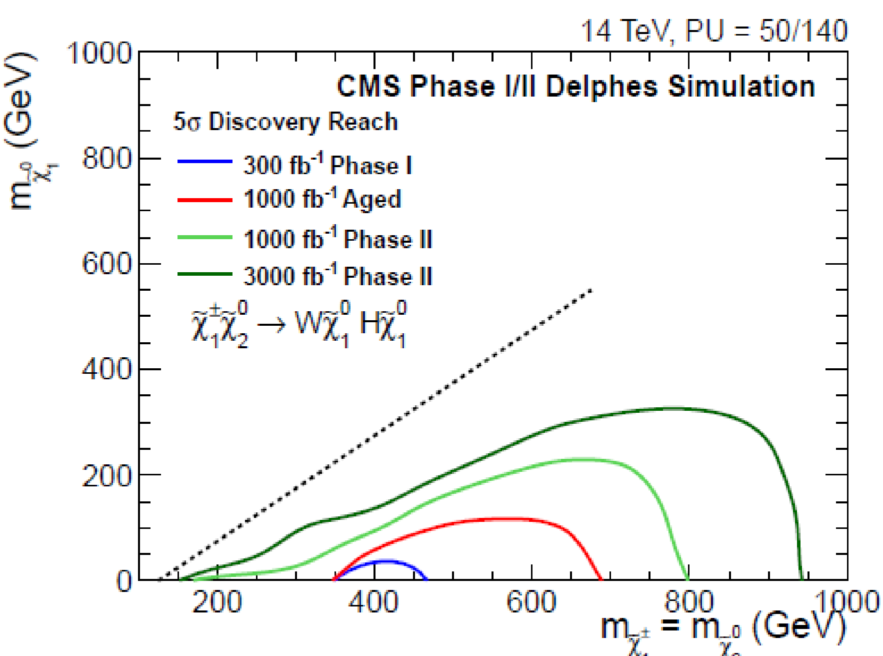
More model-independent, driven by final states, study upgraded detector

Simplified Model $\chi^{\pm}\chi^{0}$ Searches

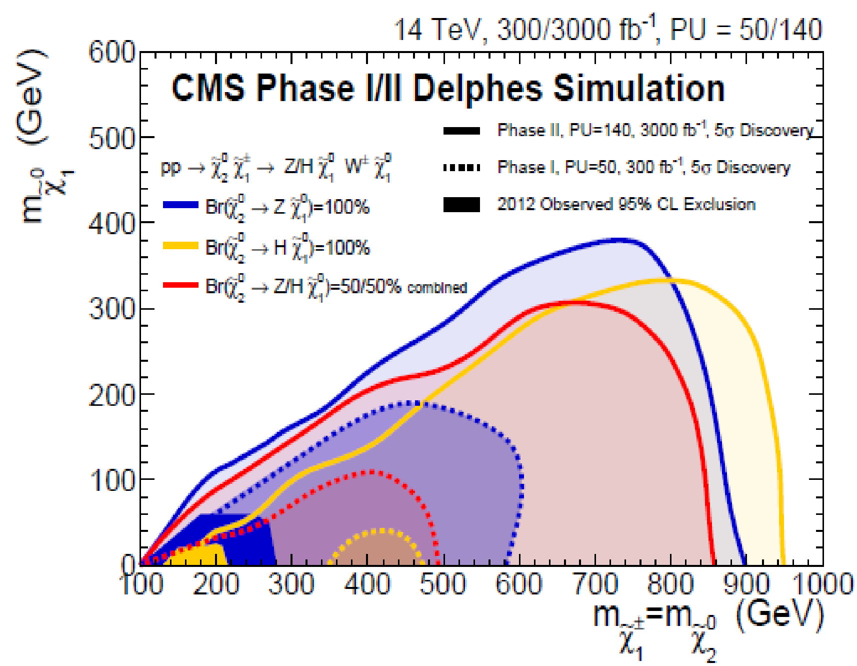


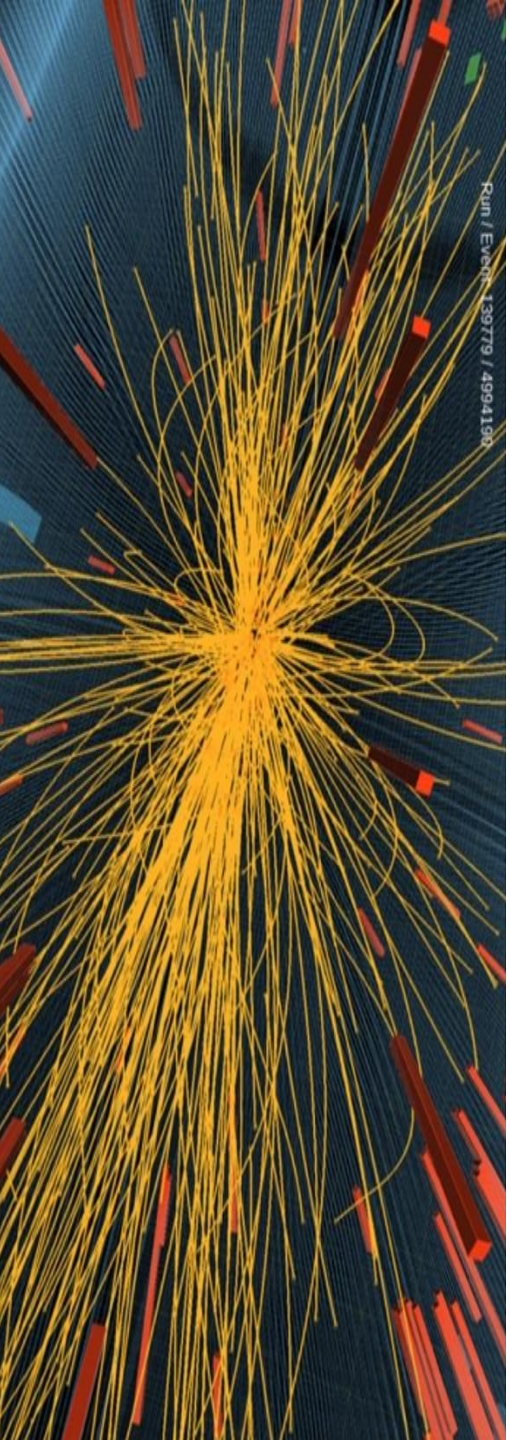
10x more luminosity allows to probe production of EWK-inos expected to be light from naturalness arguments.

Effect of detector aging on WH-MET final state



Projected excluded regions





Summary

Preparing for LHC high-luminosity operation in ≥2025. Expect 10x more luminosity.

New detectors designed to cope with high rates, high pile-up and radiation. Ageing and radiation damage requires to rebuild the inner tracker and forward detectors. New trigger concepts implemented.

Large gain in Higgs precision physics, only possibility to study VV scattering as an important closure test. Low cross-section measurements such as B→$\mu\mu$. Signficantly enhanced discovery potential for BSM and SUSY physics.

For more results see CMS technical proposal and twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

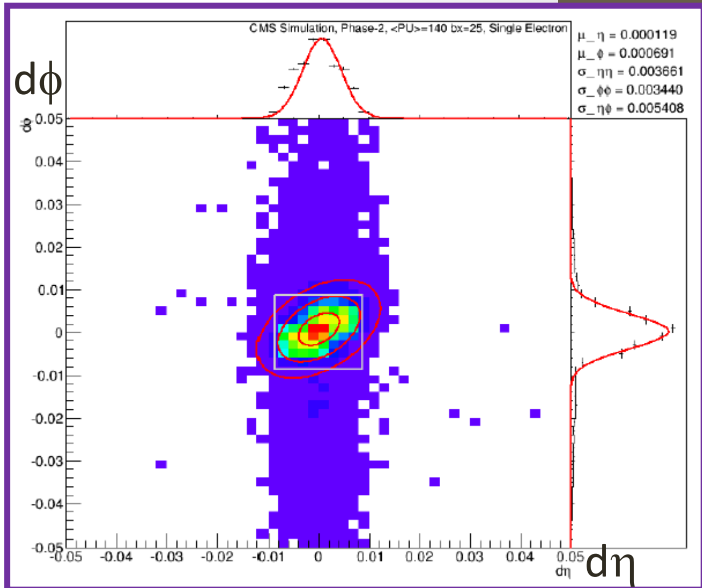
Spares

Trigger Challenge

Increase L1 Trigger **latency 3.4 µs → 12.5 µs**

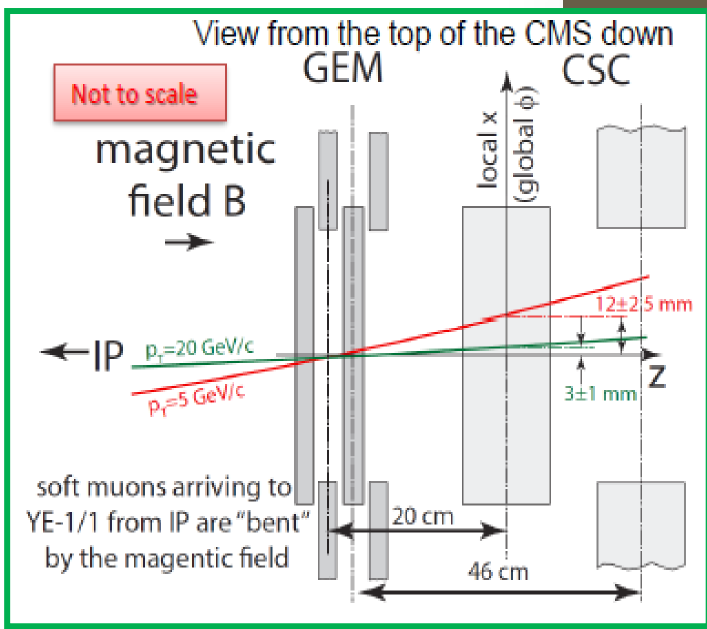
& L1 Trigger **rate 100 kHz → 750 kHz**

- New readout electronics, including sub-detectors that will not be replaced (ECAL barrel, muon)



The trigger challenge: keep the **thresholds** at 5x higher PU. Sharpen **turn-on** curves and reduce **fake** triggers. Tools:

- **Single ECAL crystal readout** improves track matching, spike rejection (noise) and timing
- Additional muon detectors (GE1/1) enable **measurement of bending angle** in forward region → reduce mis-measurement
- Tracking information at L1 (tracking trigger)

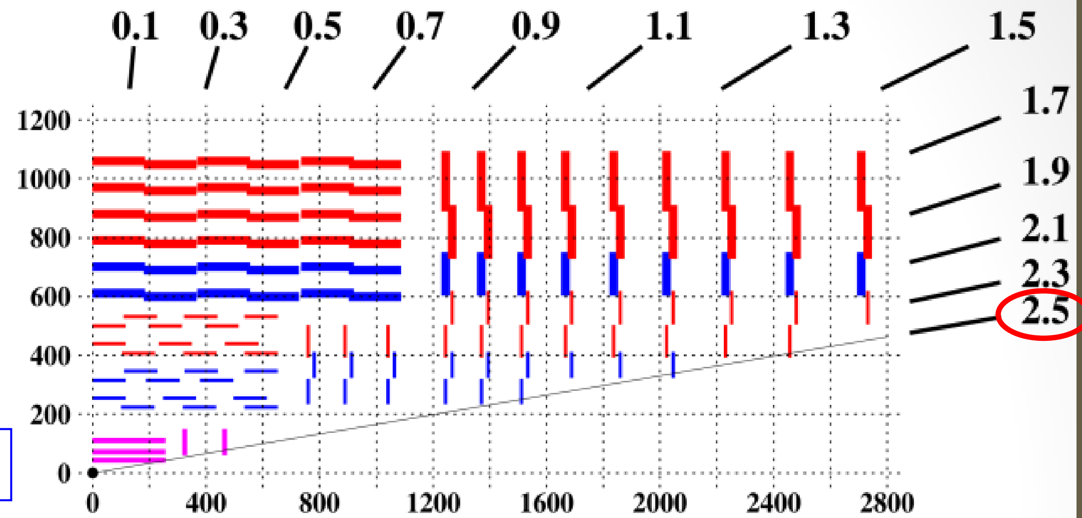


Present to Upgraded Tracker

CMS Si Tracker today

B=3.8T

Current & Phase1: Planar pixels



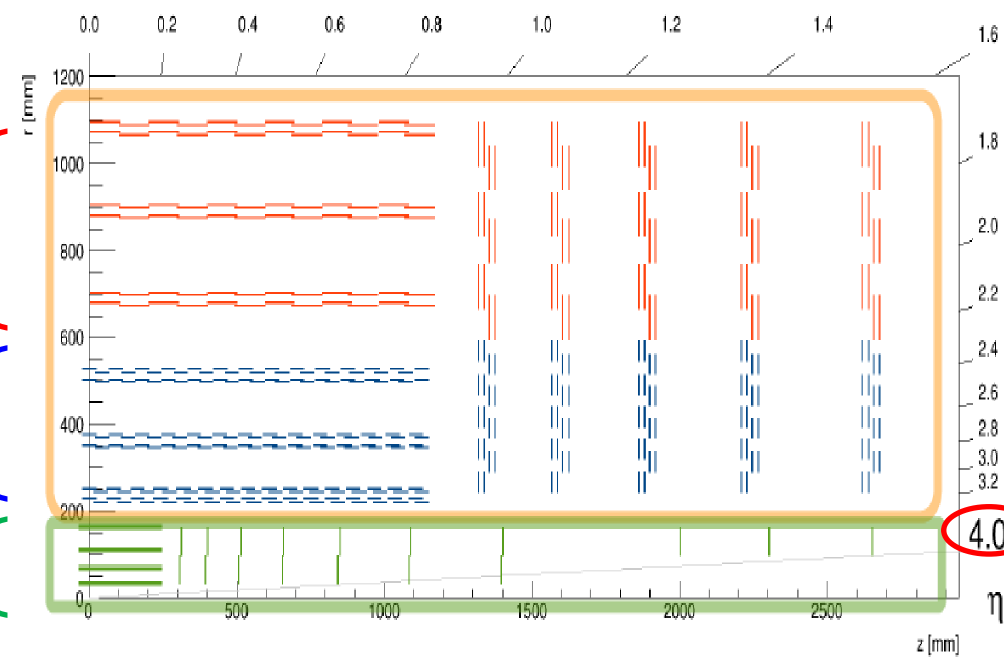
CMS Si Tracker as it could be in 2025

Outer Tracker, new Pt modules
3 more Pixelated layers
5 more Pixelated disks

Strip/Strip modules SS in outer layers

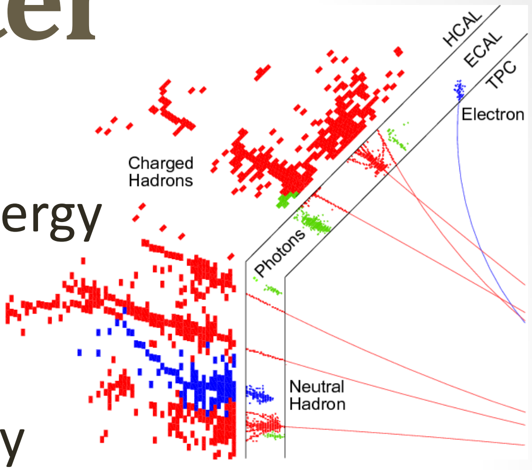
Macro Pixel/Strip modules PS in inner layers (z-measurement)

Pixel modules, new Disks to η=4
Possible pixel size ~25x100μm^2
Planar or 3D?

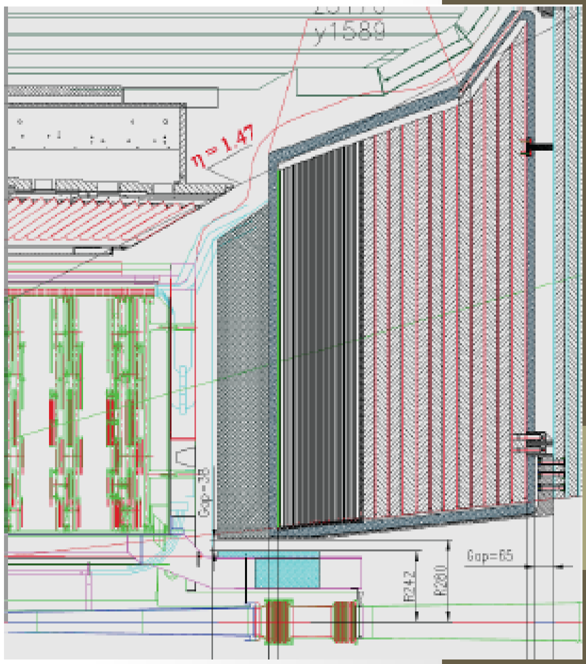


New high-granularity combined calorimeter

High granularity calorimeter (HGCAL) based on ILC/CALICE development. Key point: “visualize” energy flow through fine granularity and longitudinal segmentation.



- Good **resolving power for single particles** in very dense jets. $\Delta E/E = 10\%/\sqrt{E}$



- Planes of Si separated by layers of Pb/Cu or brass
- Exploits developments on Si rad.hardness and price

Structure:

- E-HG: 33 cm, 25 X_0, 1λ, 31 layers. Absorber W/Pb
- H-HG: 66 cm, 3.5λ, 12 layers, Absorber brass
- B(back)-HG as HE re-build 5 λ

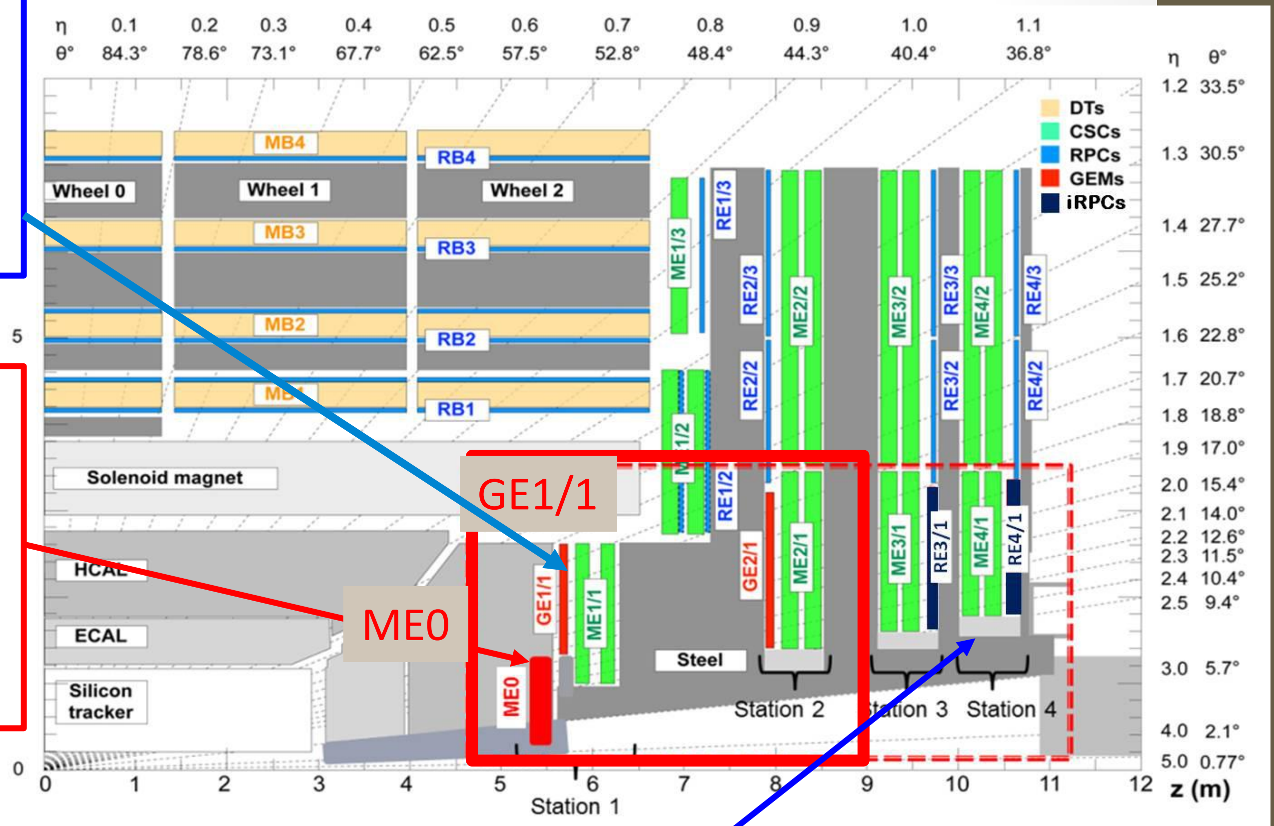
Opens up possibility to extend to $|\eta|$~4

Forward Muon Upgrade

Triple GEM detector (GE1/1): precision chambers to **improve trigger momentum selectivity and reconstruction** already in late LHC phase-1. Installation in LS2 (2018).

Extended coverage provides muon **tag** in forward region |η|<3

Several tens of kHz expected → GEM technology

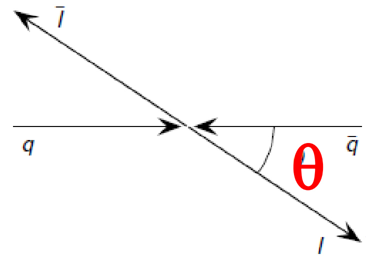


Enhance region without redundancy 1.6 < |η| < 2.4 with **maximum rate.**
Technology = GEM (GE2/1) and improved high-rate RPC (RE3/1 and RE4/1)

Search for new physics model independent

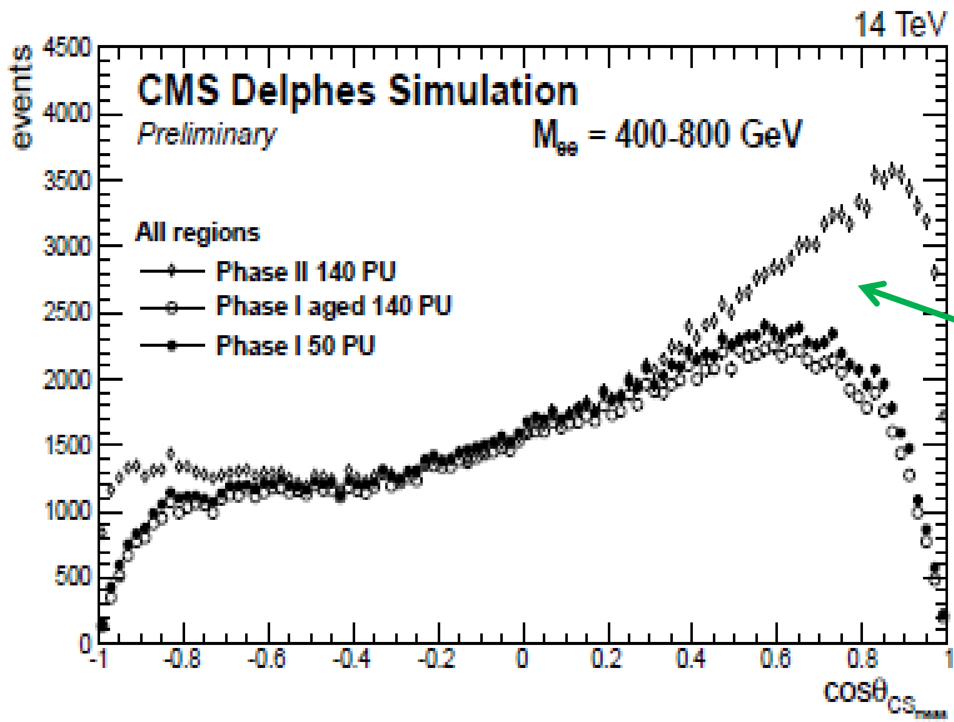
Concept: use quantity AFB and measure SM DY with high precision

Expect AFB to be affected by performance of forward regions, since max sensitivity for events where $\cos\theta \approx \pm 1$
AFB measurement requires charge & direction



direction

Determine lepton charge and direction



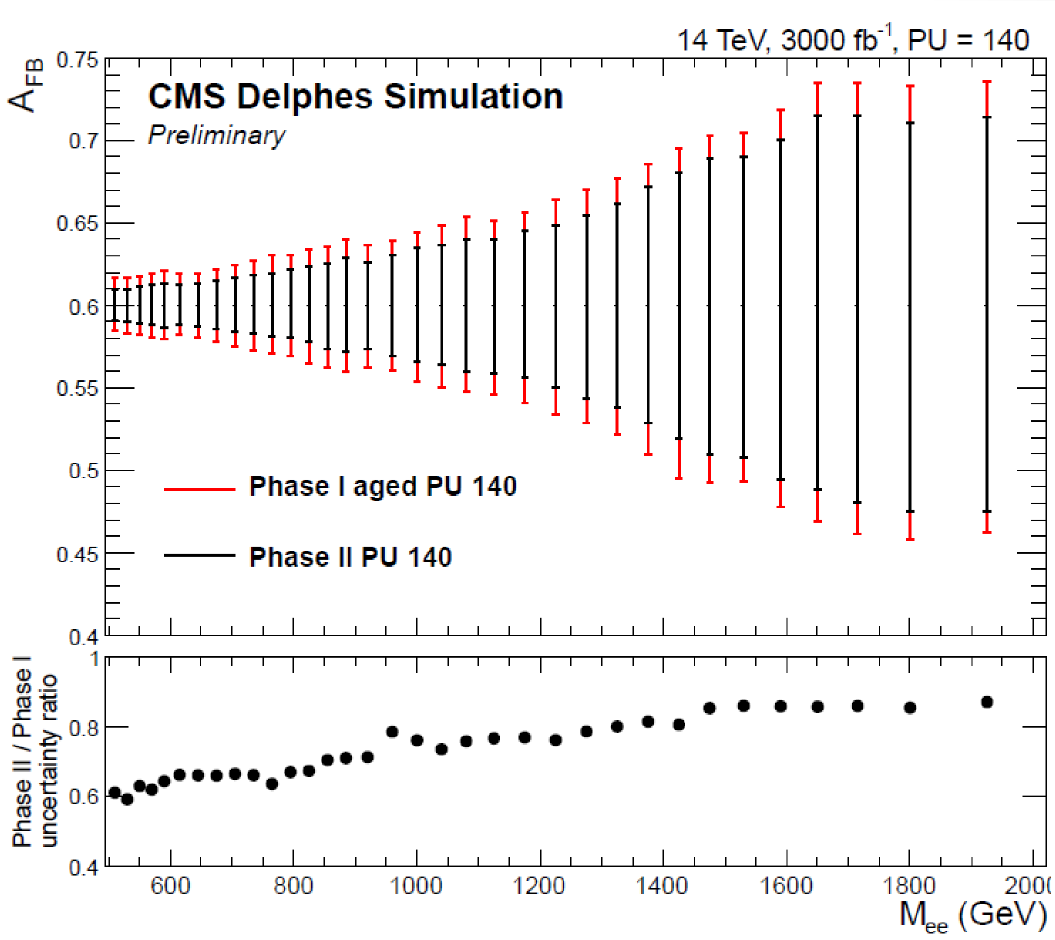
Gain in phase-II

For low masses, M(ee) < 500 GeV, about 5% of events recovered with upgraded tracker. **Events in very important forward region! Large impact, see next slide.**

Search for new physics in high-mass DY tail

At low masses high SM background. High masses nearly background free.

Some nubers:
DY AFB = + 0.6
BSM AFB might be anything between -0.75… +0.75,
e.g. Z´_SSM AFB ≈ 0.08,
Z´_I ≈ - 0.75



Large impact: AFB uncertainty reduced with phase-II geometry by ≈ 40% at 500 GeV and by ≈ 15% at 2 TeV. Based on recovered events.

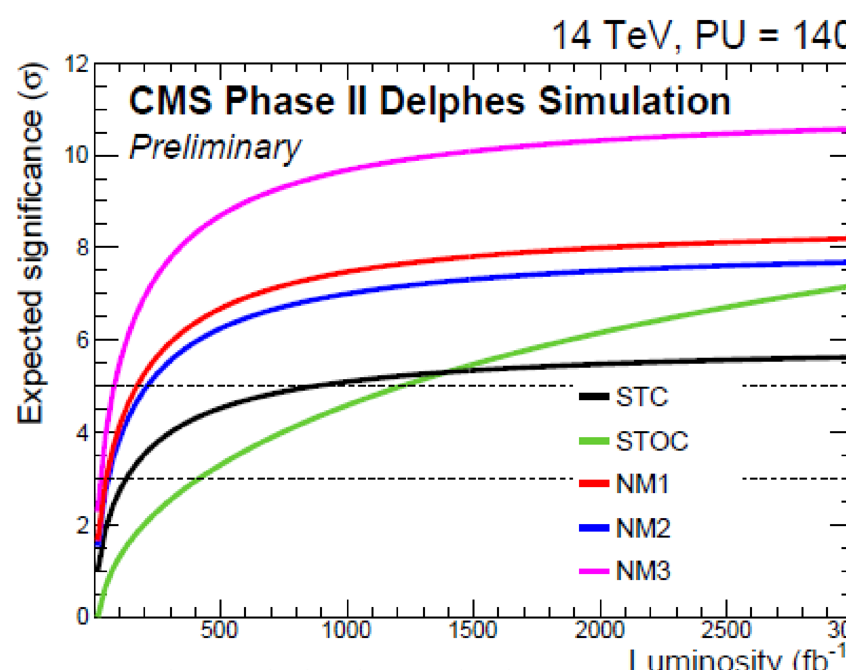
Full Spectrum Models

Five phenomenological models motivated by naturalness explored through a number of signature-based searches.

Models differ by nature of LSP, EWK-ino and slepton hierarchies.

STC (Stau) and STOC (stop) co-annihilation models satisfy DM needs.

Analysis	Luminosity (fb^{-1})	Model				
		NM1	NM2	NM3	STC	STOC
all-hadronic (H_T-H_T^{miss}) search	300				grey	blue
	3000				blue	orange
all-hadronic (M_{T2}) search	300	blue	orange	orange		
	3000	orange	orange	orange		
all-hadronic $\tilde{b}_1$ search	300	grey	grey	grey	blue	grey
	3000	grey	grey	grey	orange	grey
1-lepton $\tilde{t}_1$ search	300	orange	orange	orange	blue	grey
	3000	orange	orange	orange	orange	orange
monojet $\tilde{t}_1$ search	300					blue
	3000					blue
$m_{\ell^+\ell^-}$ kinematic edge	300	grey	grey	grey		
	3000	orange	grey	grey		
multilepton + b-tag search	300	orange	orange	orange	blue	
	3000	orange	orange	orange	orange	
multilepton search	300	grey	grey	grey	grey	
	3000	blue	blue	grey	blue	
ewkino WH search	300		grey			
	3000		blue			



PAS CMS-SUS-14-012

Something about LL Signatures

HH to ZZ