CMS Phase-2 Upgrades, Future Plans & Prospects

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On behalf of the CMS collaboration

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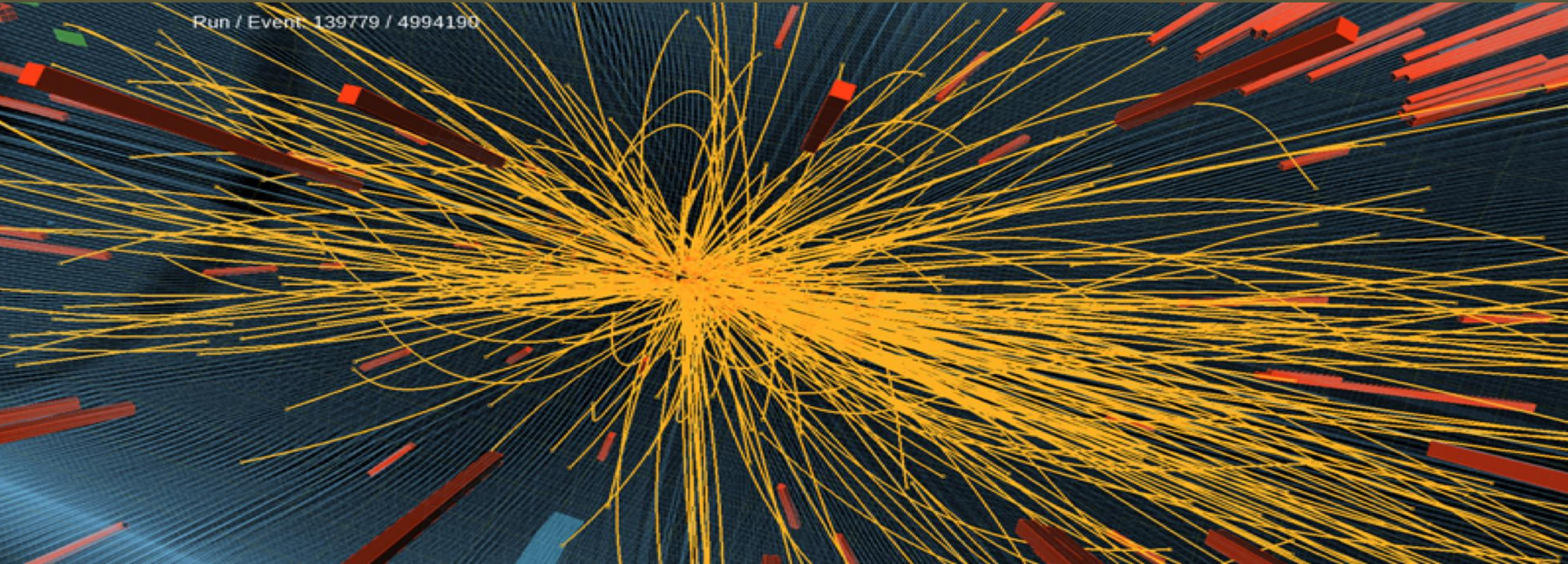
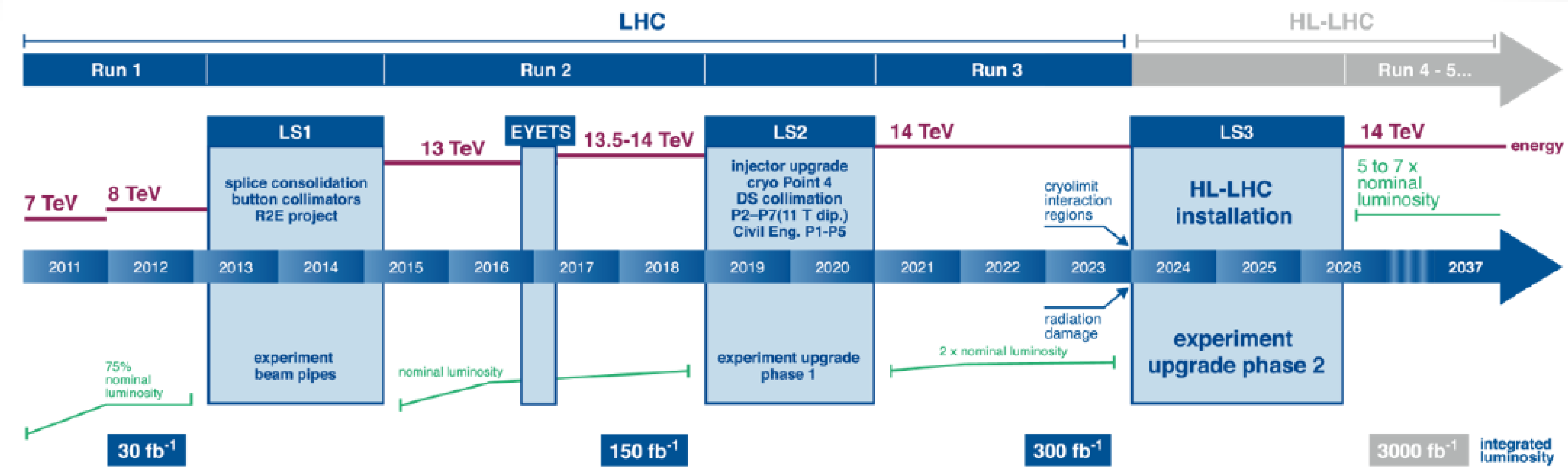


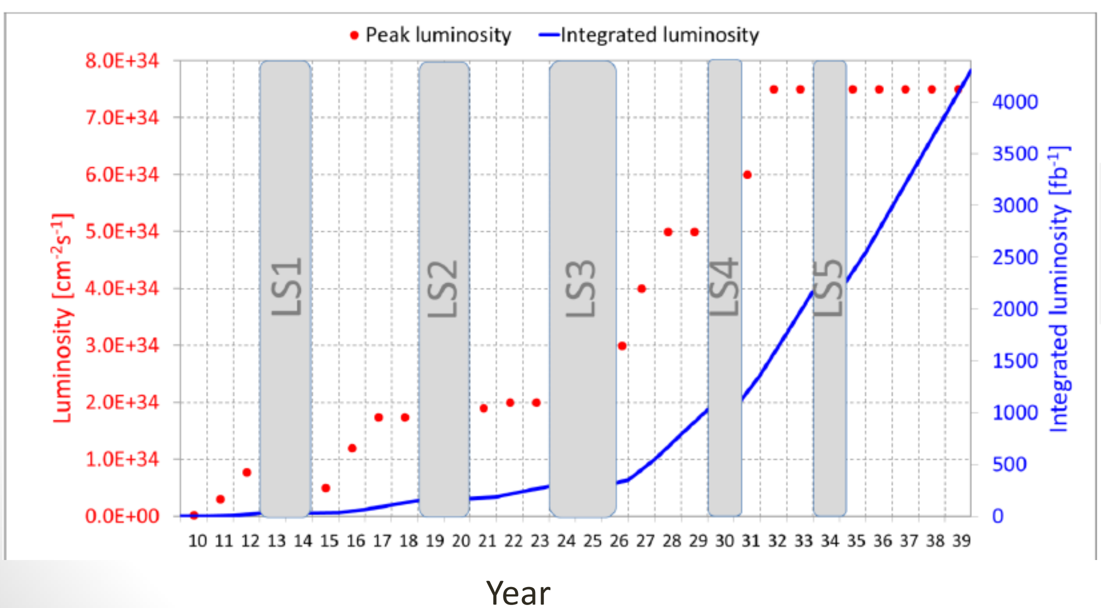
From LHC to HL-LHC

HL-LHC

Upgrade installation 2024/25

Data taking >2026





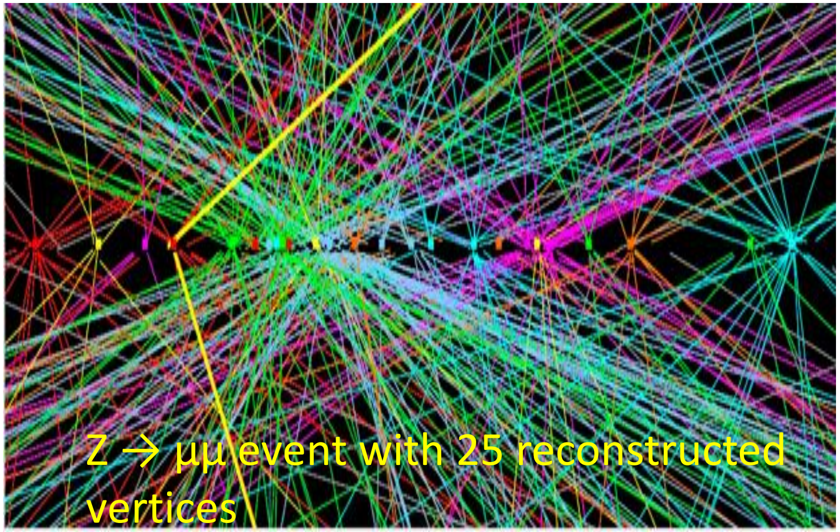
High lumi LHC

- Luminosity : $5 \times 10^{34}\ cm^{-2}s^{-1}$
- Integrated luminosity : $3000\ fb^{-1}$
- Fluences : up to $10^{16} neq/cm^2$ in ECAL endcap
- Average pileup : 140 (maximum of 200)

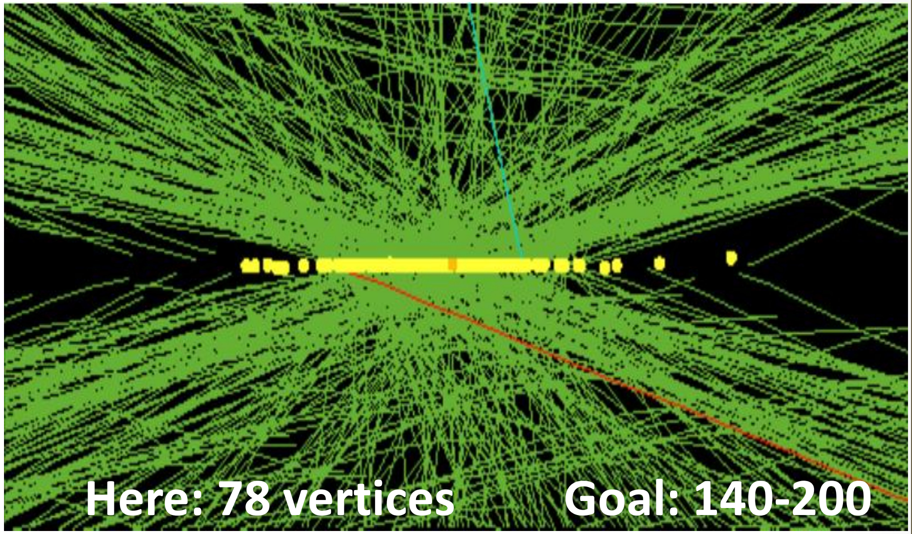
Particle physics program until ~2040

Impact of HL on detectors

Phase-1



Phase-2



Radiation six times higher than nominal LHC design

About 8x more pileup (PU) but maintain detector performance

→ Upgrade several detector components

→ Maintain trigger thresholds in higher PU and control trigger rates.

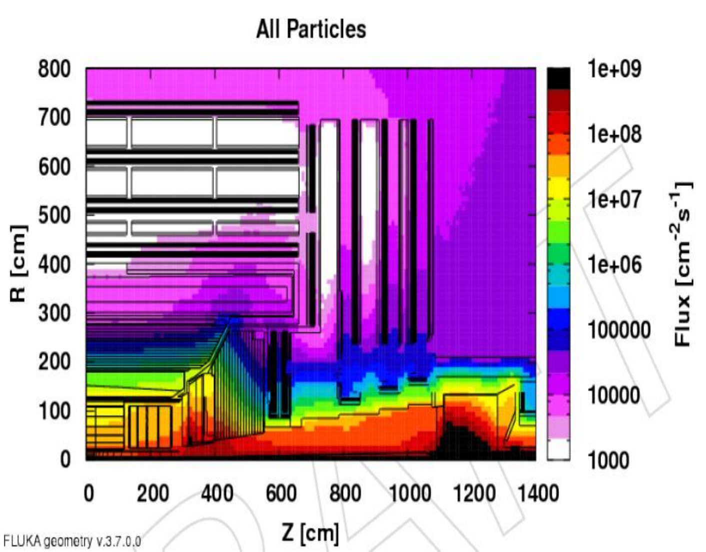
What we need to do

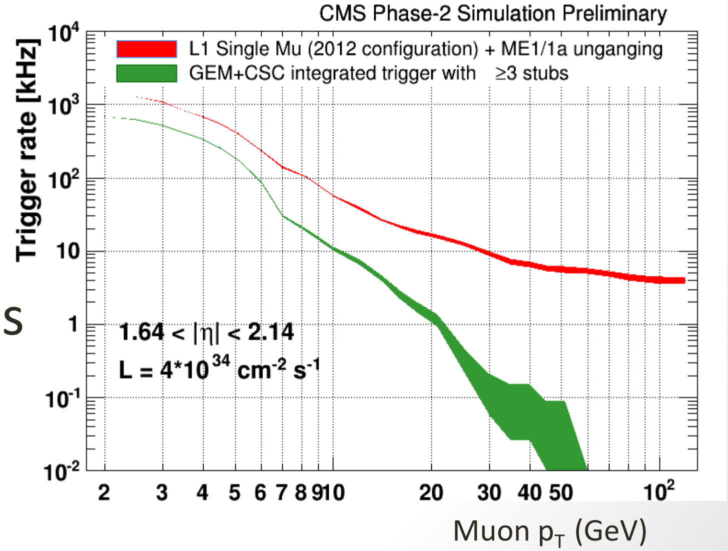
Replace some detector components which suffer from **radiation damage**: tracker and forward with highest radiation. Optimize new components to HL environment.

Adapt trigger rate capabilities and **band-width** to higher needs. Increase readout granularity and depth of storage buffers. More time (latency) for trigger decision.

Increase L1 Trigger **latency 3.4 µs → 12.5 µs**
L1 Trigger **rate 100 kHz → 750 kHz**

Exploit detector/electronics developments of the last two decades (present technologies are from ~1990-2000).



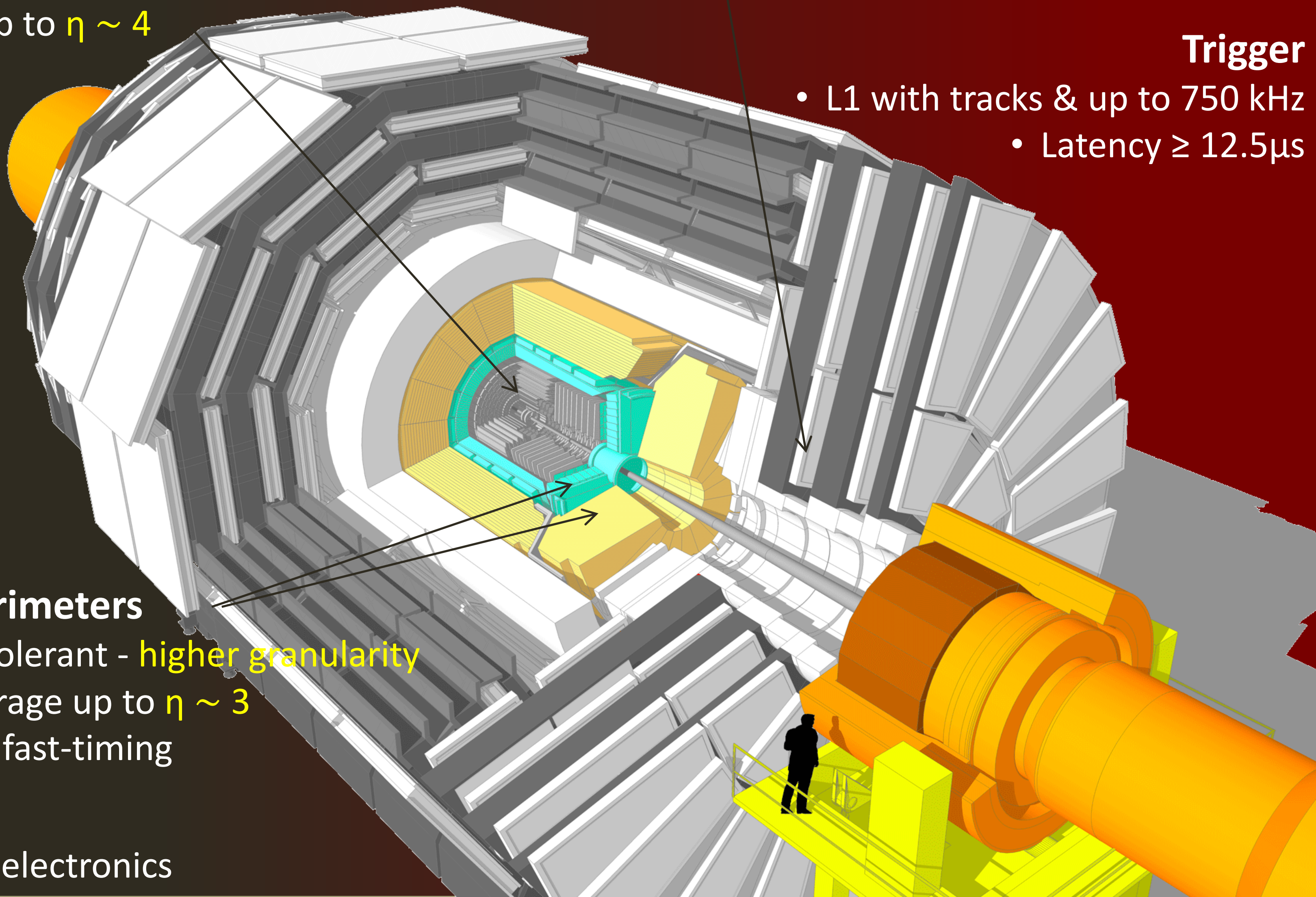


CMS Phase-2 Detector Upgrades

Muons
- Complete coverage in forward region (new GEM/RPC technology) $|\eta|>1.6$
- Investigate muon-tagging up to η ~2.8
- New RPC link-boards with ~1 ns timing

Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to $\eta \sim 4$

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



Endcap Calorimeters
- Radiation tolerant - higher granularity
- Study coverage up to $\eta \sim 3$
- Investigate fast-timing

Barrel ECAL
- Replace FE electronics

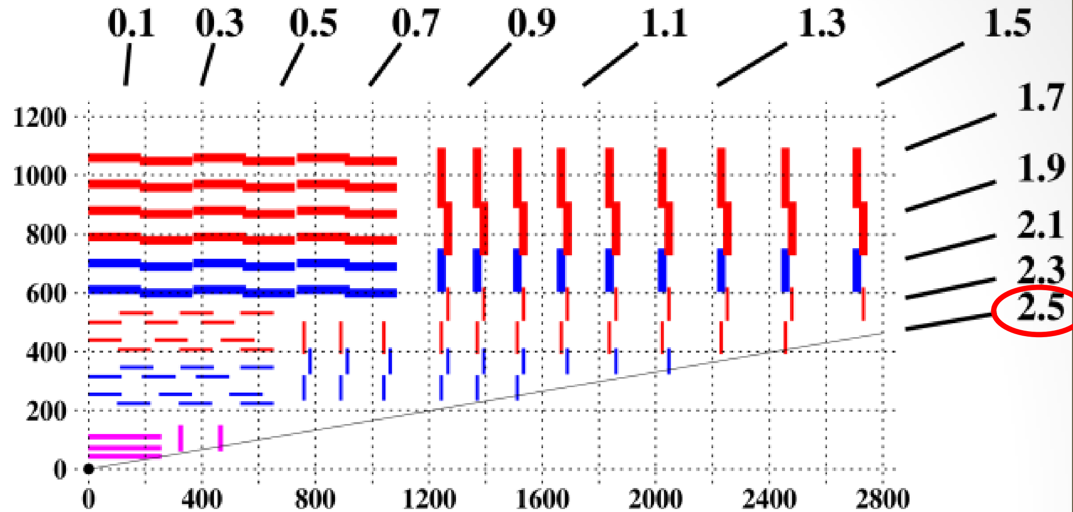
Present to Upgraded Tracker

CMS Si Tracker in Run-1

B=3.8T

Current & Phase1: Planar pixels

Becomes inefficient due to radiation damage → replace all



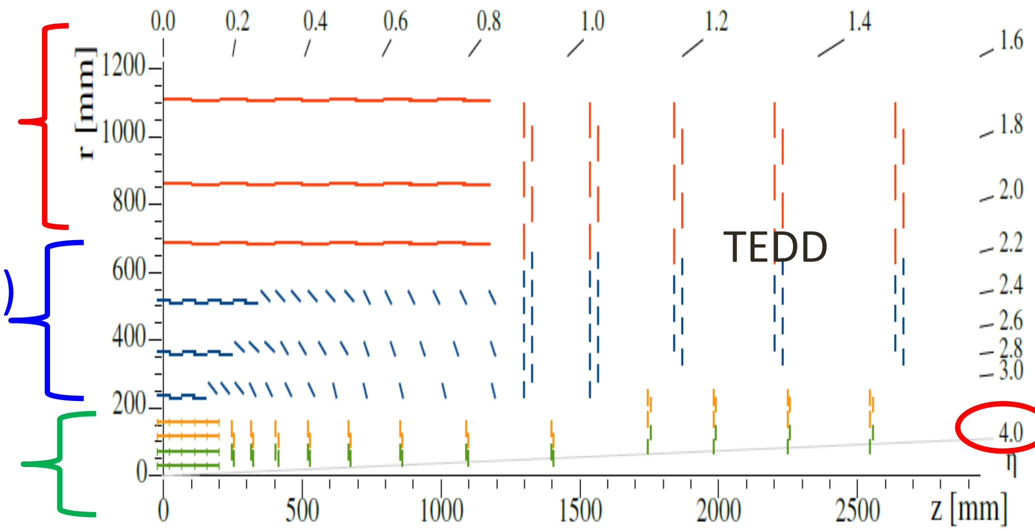
CMS Si Tracker in 2025

Less layers but more pixel stations, new Pt modules
3 more pixelated layers
5 more pixelated disks

Strip/Strip modules in outer layers (TB2S)

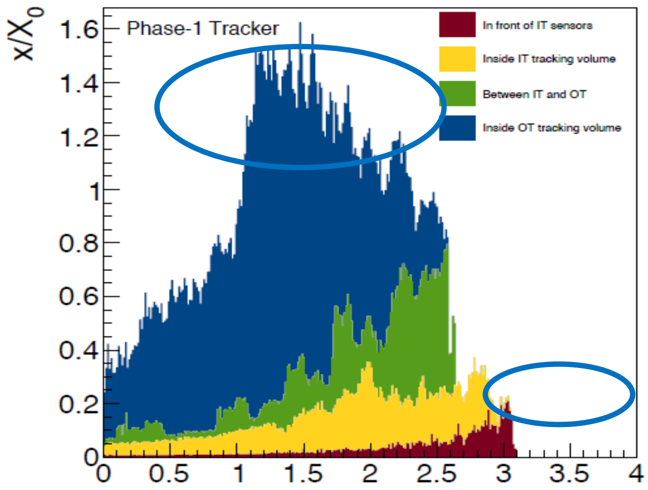
Macro Pixel/Strip modules (TBPS) in inner layers (z-measurement)

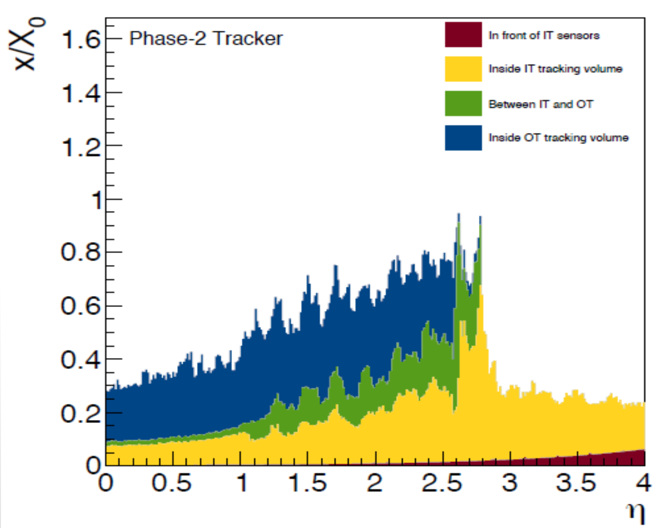
Pixel modules, new Disks to $\eta=4$
Possible pixel size ~$25\times100\mu m^2$

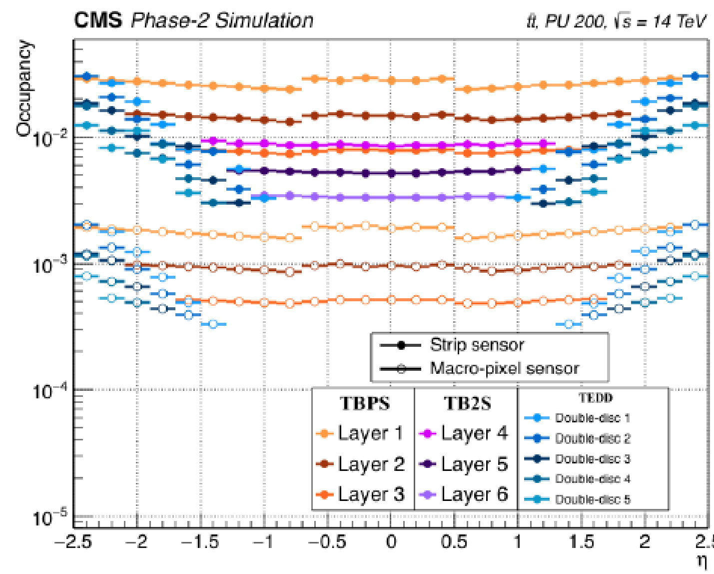


Performance

Significant reduction of material budget in front of ECAL

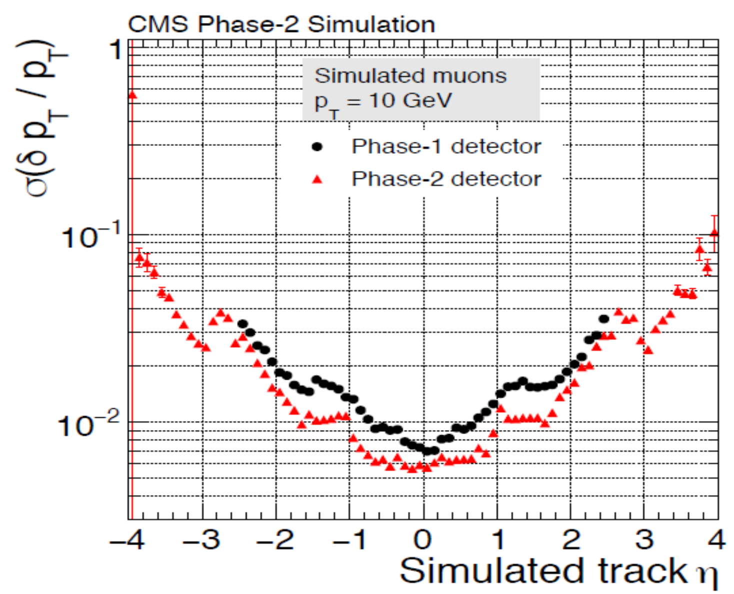






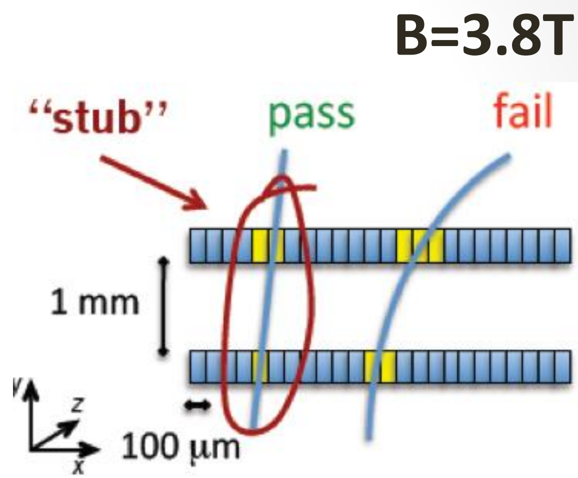
Highest occupancy ~ 3% in Layer 1 Strips
Drop at eta ~ 1.5 (tilted geometry)

p_T resolution in high PU kept O(%). Extend in η



Trigger Challenge: Track Trigger

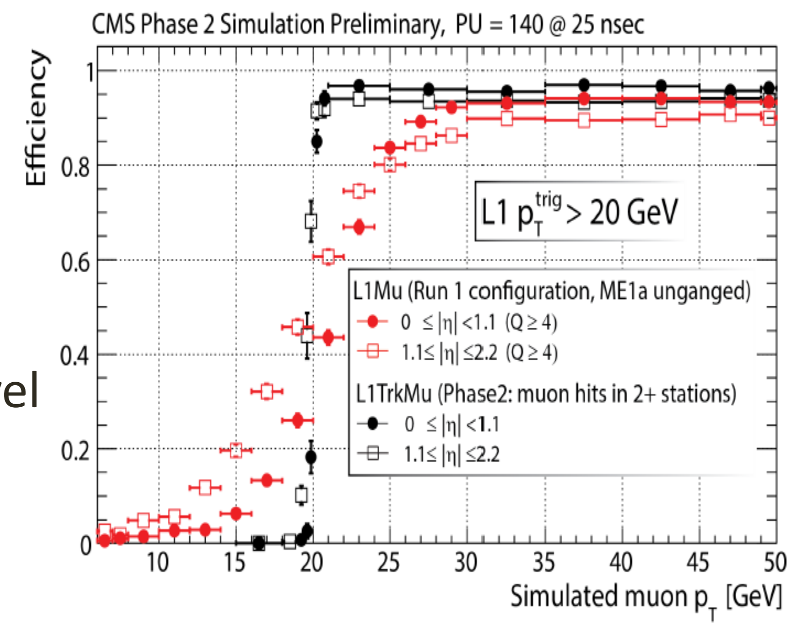
Objective: reconstruct all tracks with p_T>2 GeV **at trigger level**. Identify primary vertex along beam line with ~1mm precision.



Transmitted at 40 MHz to L1

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
- Drives tracker design (inner barrel partially tilted to mitigate stub ineff.)
- Exploit the strong magnetic field of CMS



Physics benefit:

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

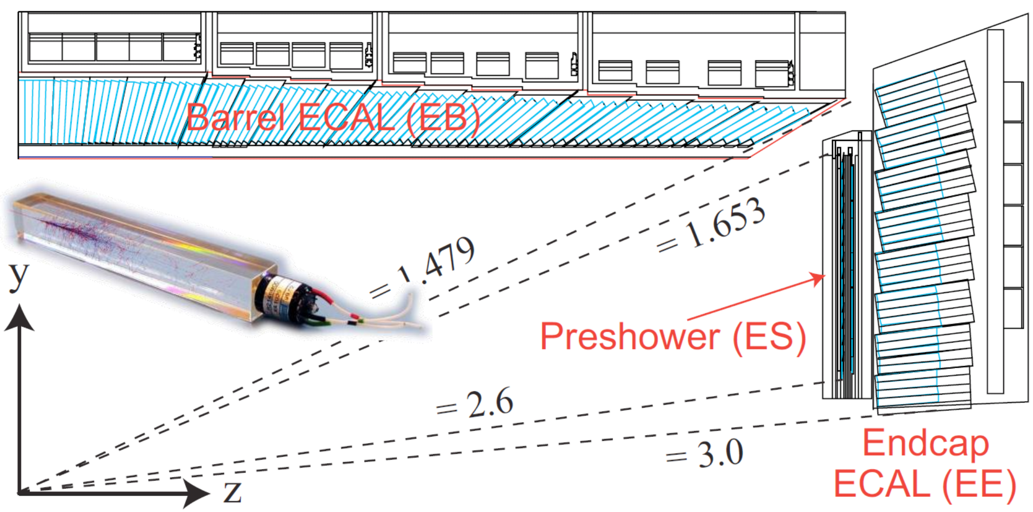
ECAL Barrel Upgrade

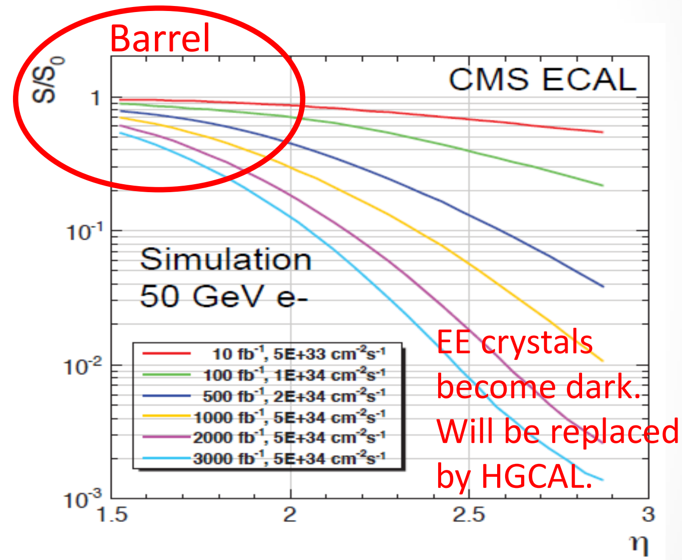
Present ECAL: $PbWO_4$ crystals with APD readout (this will stay)

Temp stabilization to 0.1K since light yield proportional to Temp

Rad length X_0 = 0.89 cm
Moliere radius 2.2 cm

Radiation damage

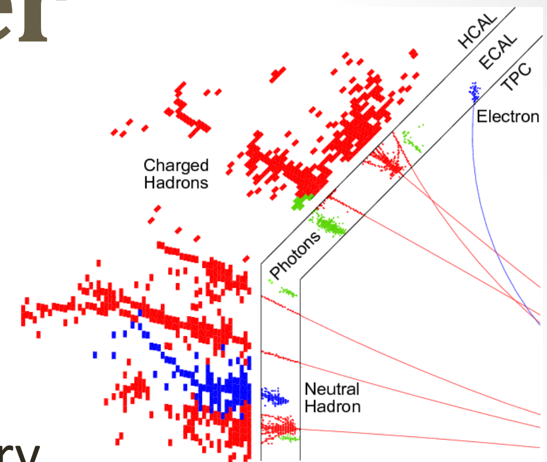




Primary driver for upgrade: trigger latency to 12.5 us, 750 kHz L1 rate

At the same time, optimize electronics and temperature system to adjust to radiation-induced noise in APDs

New High-Granularity Forward Calorimeter



High granularity calorimeter (HGCal) based on ILC/CALICE development.

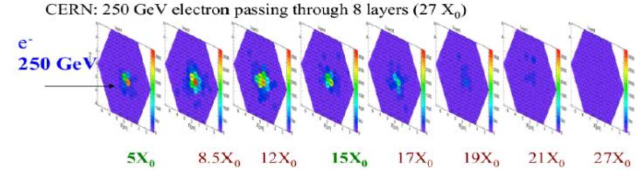
Key point: "visualize" energy flow through fine granularity and longitudinal segmentation.

- Good **resolving power for single particles** in very dense jets. $\Delta E/E = 10\%/\sqrt{E}$
- Planes of Si (sci) separated by absorber layers
- Exploits developments on Si rad.hardness and price

Structure:

- CE-E: 25 X_0, 1.3λ, 28 layers. Si, Cu & CuW & Pb
- CE-H: 8.5λ, 24 layers, Si & Sci, steel absorber

CERN: 250 GeV electron passing through 8 layers (27 X_0)



On the right: from CERN testbeam

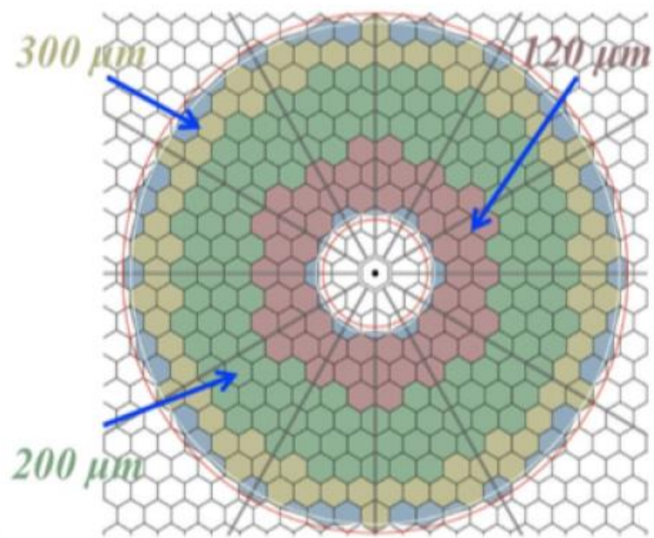
HGCal Layout

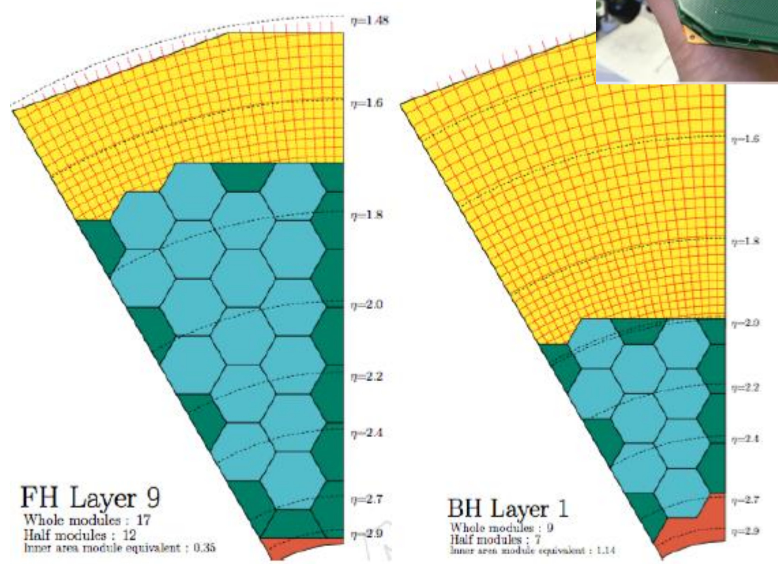
Silicon sensors: 3 different active thicknesses to match expected radiation dose. Sizes 1 cm^2 and 0.5 cm^2.

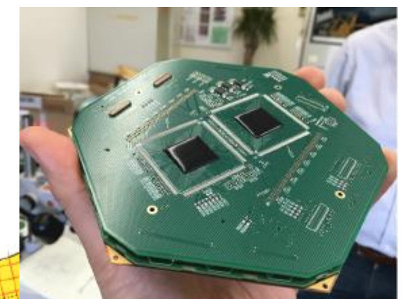
Thinnest and smallest sensors in innermost region to reduce noise.

Hexagonal Si-sensor with PCB with holes for wire-bonding on back.

For CE-H low eta (less radiation), plastic scintillator with on-tile SiPM







2 x 64 channels per sensor

Challenges Muon Upgrade

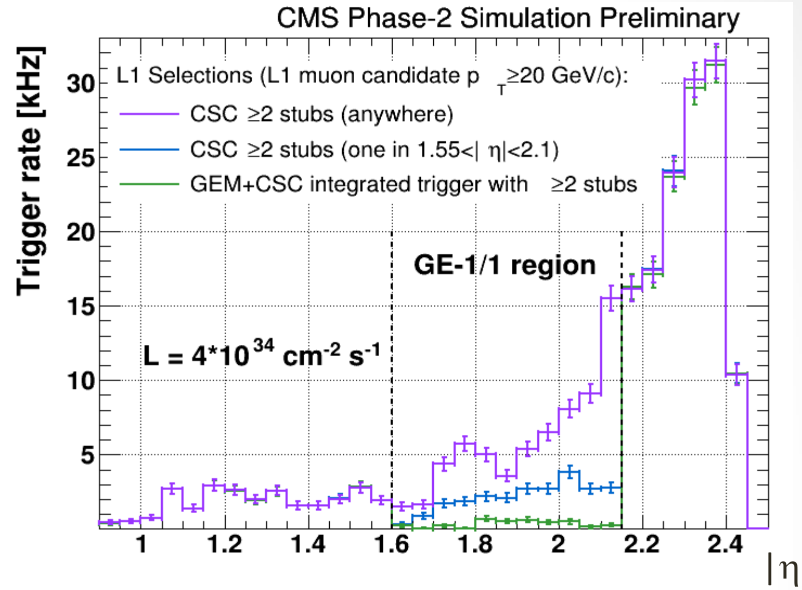
Golden channels often with muons because of clean signature! It is CMS.

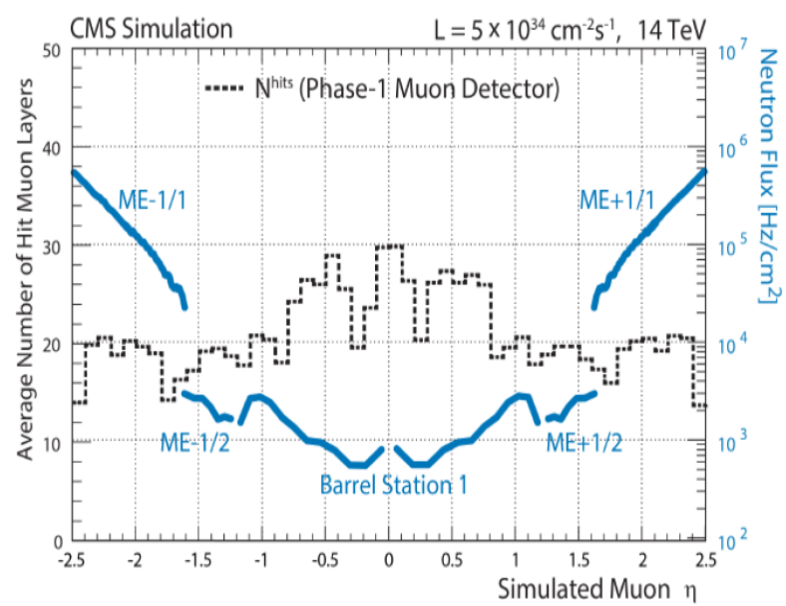
Challenging conditions:

- Forward region |η|≥2.0 with rates in 10's of kHz/cm^2 and higher towards higher η
- Reduced resolution and longevity
- New requirements often exceed capabilities of existing detectors

Challenging instrumentation:

- Concentrate on areas without redundancy in forward region.
- Solenoidal B-field weakens with η
- MPGD with high resolution but many readout channels ($$$)





Forward Muon Upgrade

Phase-2

Enhance region without redundancy 1.6 < |η| < 2.4 with maximum rate.

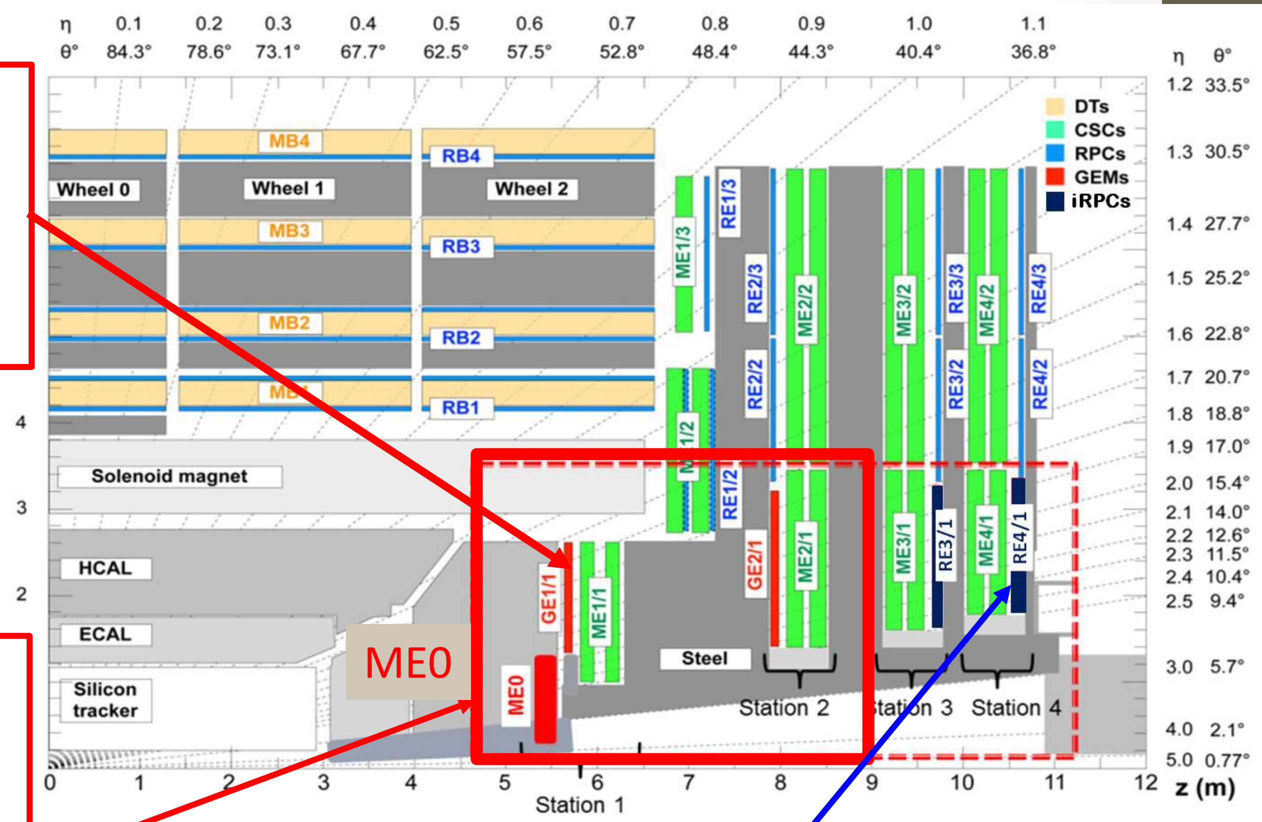
Future technologies: MPGD and RPC's

Triple GEM for stations 1 & 2 (GE1/1, GE2/1): precision chambers to **improve trigger momentum selectivity and reconstruction**

First demonstrator of GE1/1 chambers installed 2016/17, see talk on CMS performance

Extended coverage provides muon **tag** in forward region |η|<2.8

Several tens of kHz expected → GEM technology



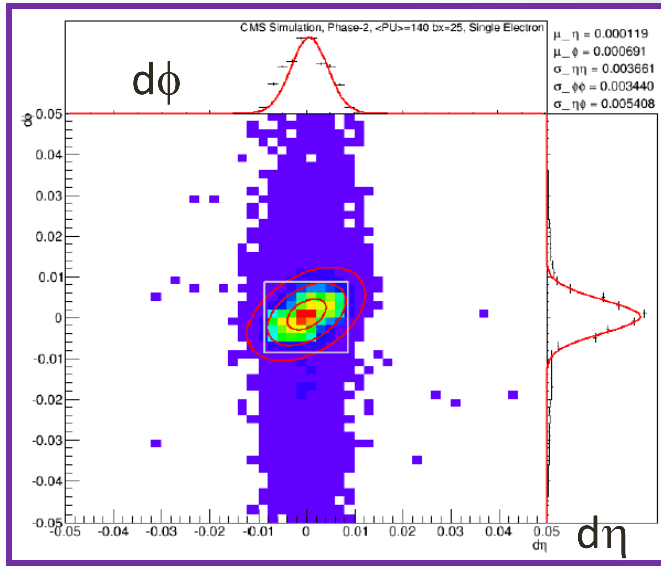
For stations 3 and 4 use improved high-rate RPC (RE3/1 and RE4/1)

Trigger

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

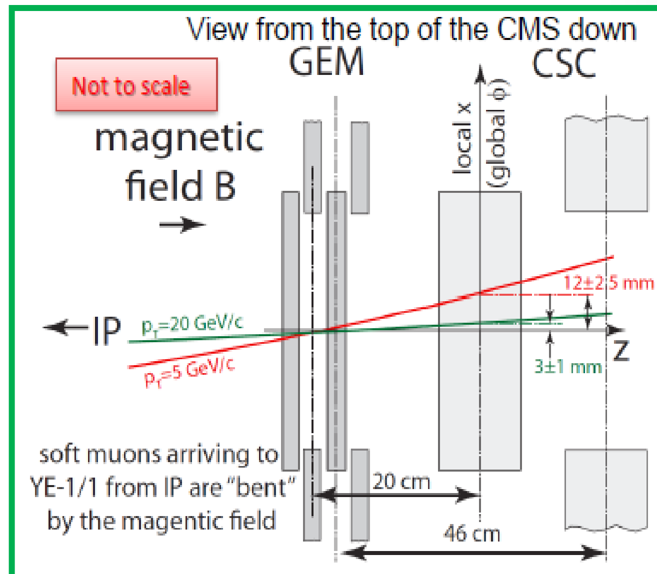
& L1 Trigger **rate 100 kHz → 750 kHz**

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



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)



Physics Program

PAS-FTR-16-005, PAS-FTR-16-006, PAS-EXO-14-007, PAS-SUS-14-012 , Technical proposal LHCC-2015-010

Selected analyses profiting from HL and from upgrades

Precision studies of Higgs boson

See talk by R. Mankel

Precision measurements of SM processes

Vector boson scattering (VBS), Top mass measurement, B-physics

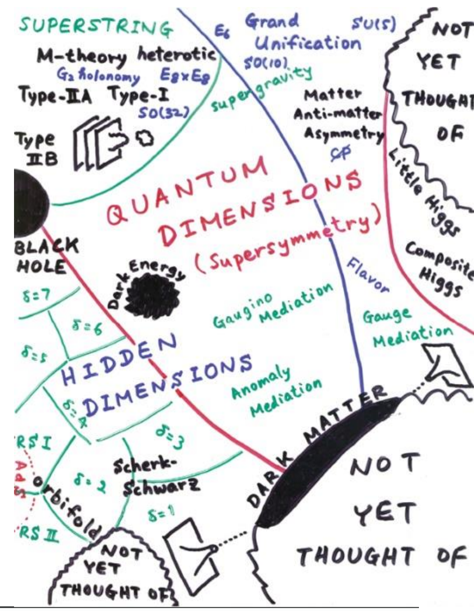
Searches for new physics beyond SM

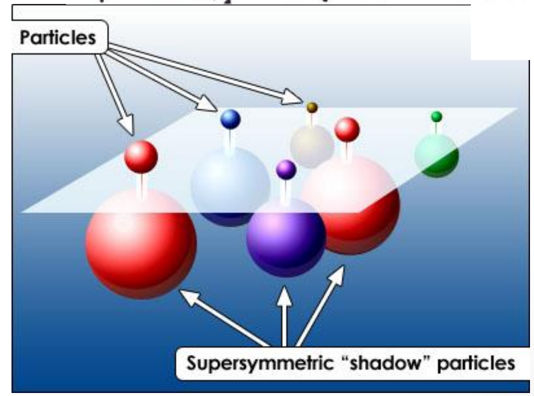
Many models and their number grows. Examples are dark matter (DM), heavy vector bosons (Z‘, W‘), long-lived exotic particles

Searches for SUSY

Recent shift to natural SUSY models which stabilize (low) Higgs mass through loops.

SUSY provides DM candidate (LSP)

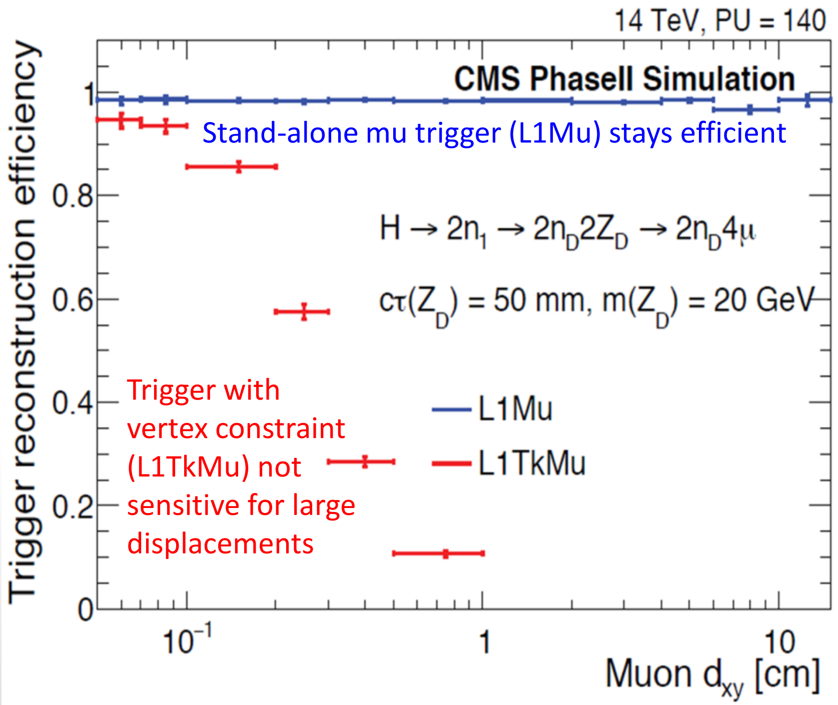




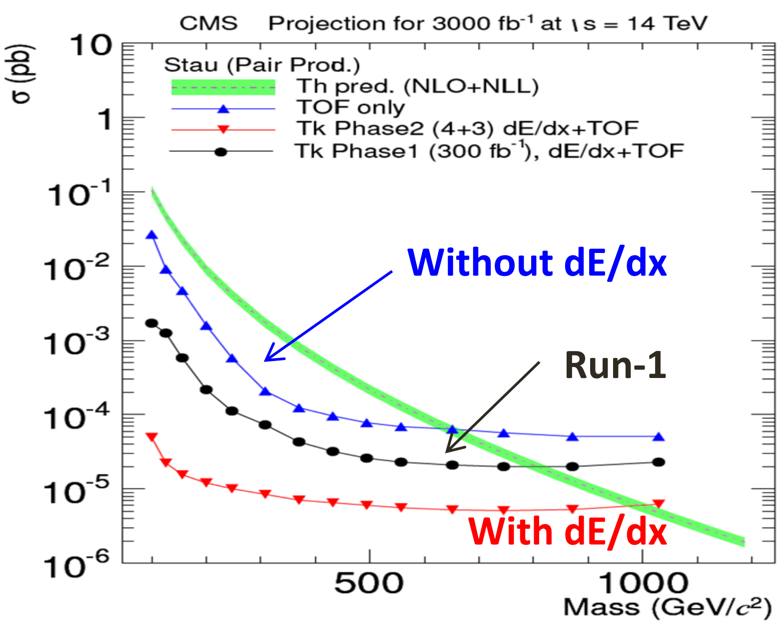
Ensure Detection of Unusual Signatures

Not known how new physics will look like. Could be a non-standard signature – need to maintain trigger & sensitivity in upgraded detector.

Example: displaced muons from long-lived decays (e.g. with large impact parameter d_{xy}) need dedicated muon trigger and reconstruction without vertex constraint. Additional forward detector help.

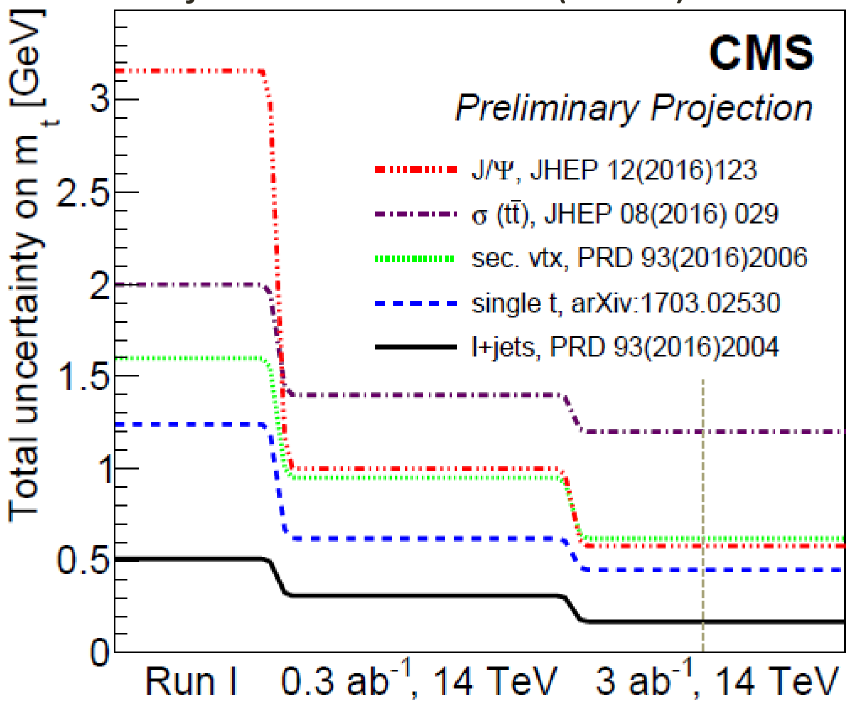


Slow moving particles (HSCP) will deposite anomalous dE/dx in silicon tracker. Feature to be kept for Phase-2. Signature allows efficient separation from background (MIP).



Precision of Top Mass

Projection from run-1 (8 TeV)



Many channels contribute:

1) ttbar -> lepton + jets reference analysis
2) Single t
3) J/psi
4) Secondary vtx

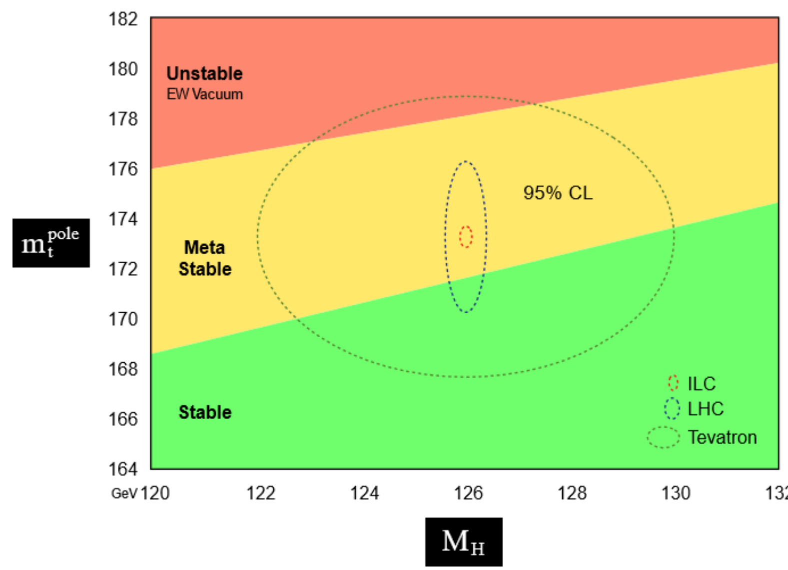
(2 and 3:) Profits from TK extension

Avoid jet reco (and hence JES) or rely solely on leptons

HL beneficial for low stats channels (single top, J/psi). Can do without systematics from JES which limits present resolution.

Why should we care about top mass?

You care if the universe is stable? Wikipedia will tell you that m_{top} is a decisive factor. HL-LHC will provide needed precision (or built a new accelerator).



Essential: Vector Boson Scattering (VBS)

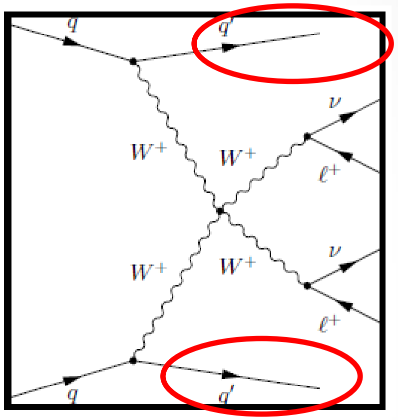
Can only be measured at HL-LHC. Small signal xsec's O(fb)@14 TeV and large irreducible background from strong production of WW+jj and from PU.

Cornerstone of SM = EWSB

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

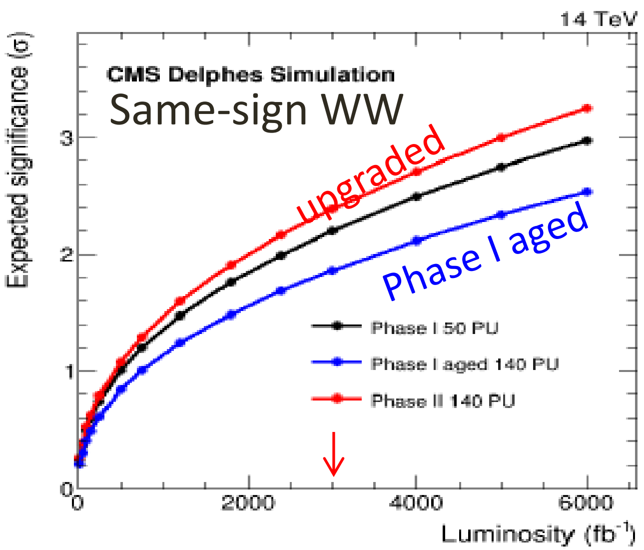
→Test role of Higgs in EWSB sector

→Model-independent search for BSM



Tagging jets

Upgraded detector needed to reduce fake jets due to PU.
Due to **larger coverage** from extending pixel to |η|~4.0 and improved jet reconstruction algorithm.



All VBF processes with forward (tagging) jets profit from tracker extension. Besides SM processes (e.g. WW scattering) can be new physics (e.g. VBF DM).

B-Physics needs low trigger thresholds

CMS B-physics complementary to LHCb

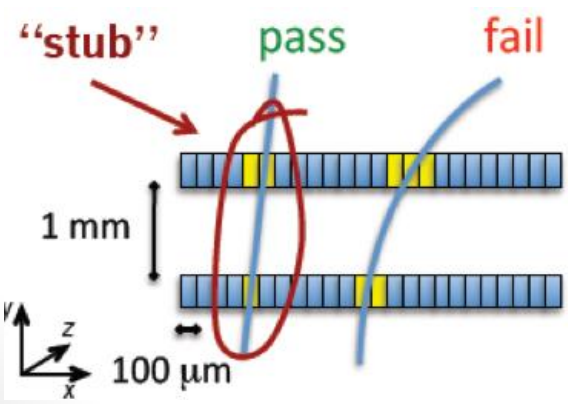
$B \rightarrow \mu\mu$ and $B_s \rightarrow \mu\mu$

Needs very low thresholds!

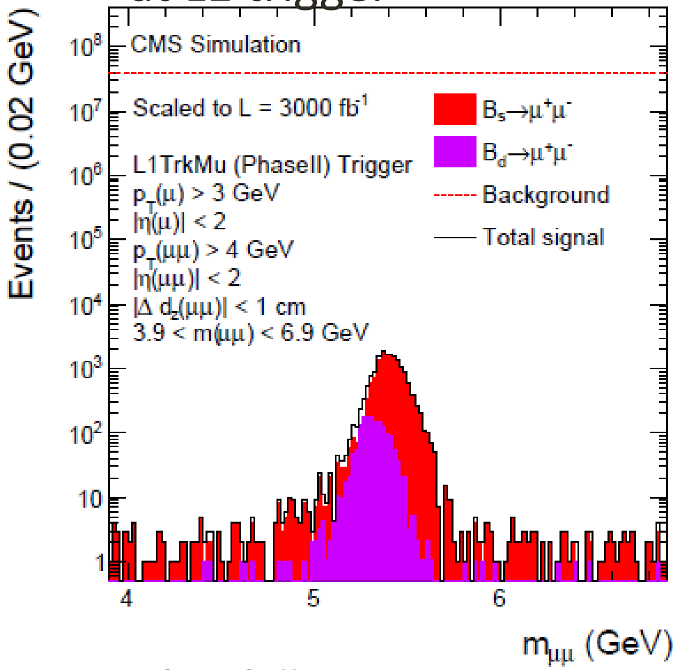
High mass resolution to separate peaks

Only way to trigger is track-trigger

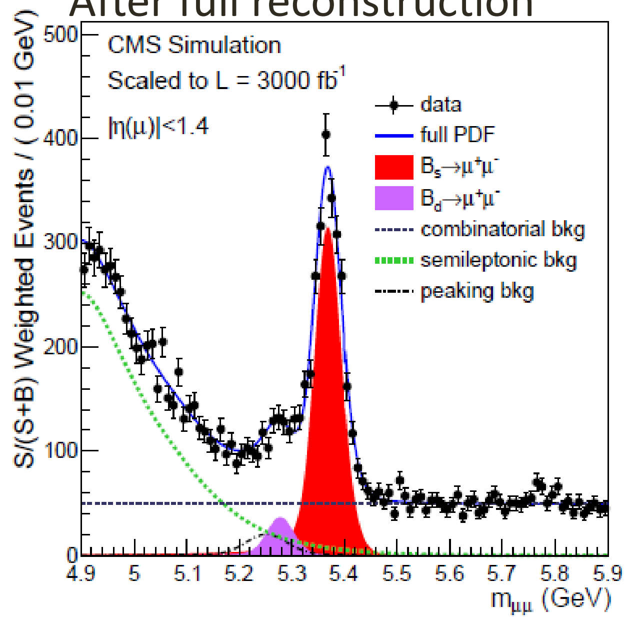
Combined with muon-ID



Selection and resolution at L1 trigger

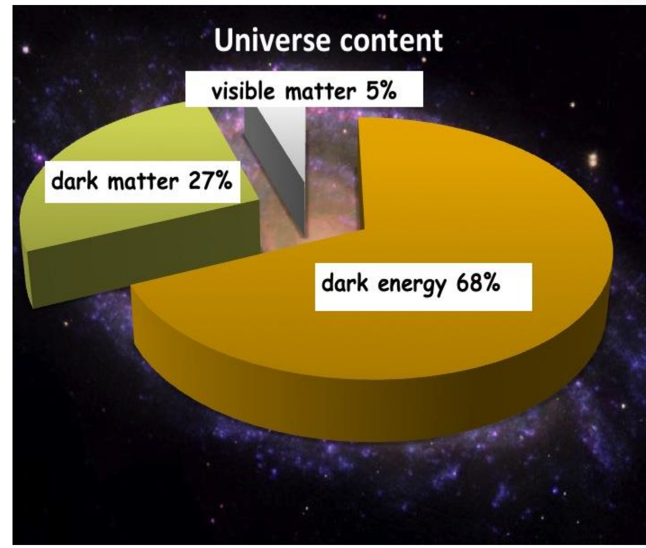


After full reconstruction



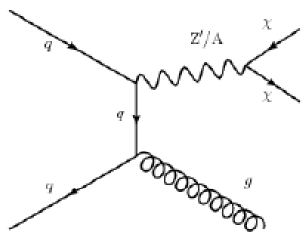
Dark Matter – Next Discovery?

Only BSM physics with an existing experimental hint. Many experiments, **not unlikely to see somewhere a signal-like excess.**



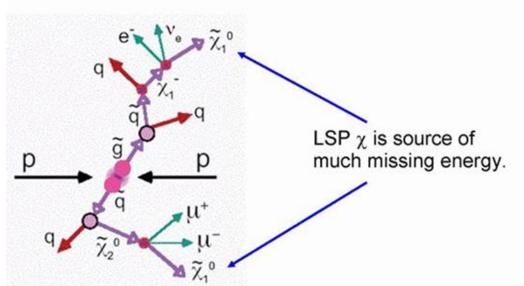
LHC dominant for light dark matter (DM) and scalar/axial-vector/pseudoscalar couplings.

Direct searches via a „tagging particle“, e.g. Jet + MET



Dark matter = MET in detector

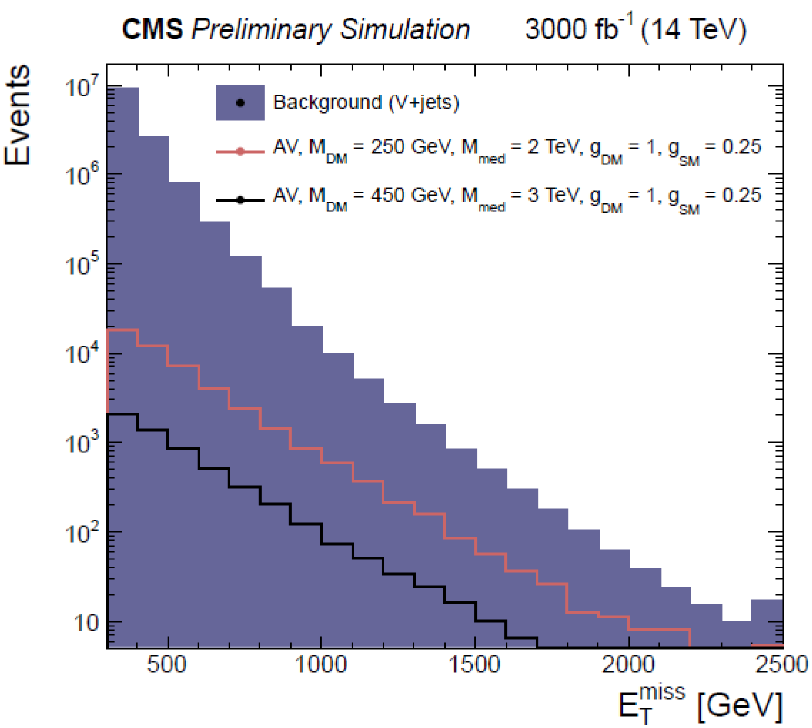
Searches in SUSY decay chains

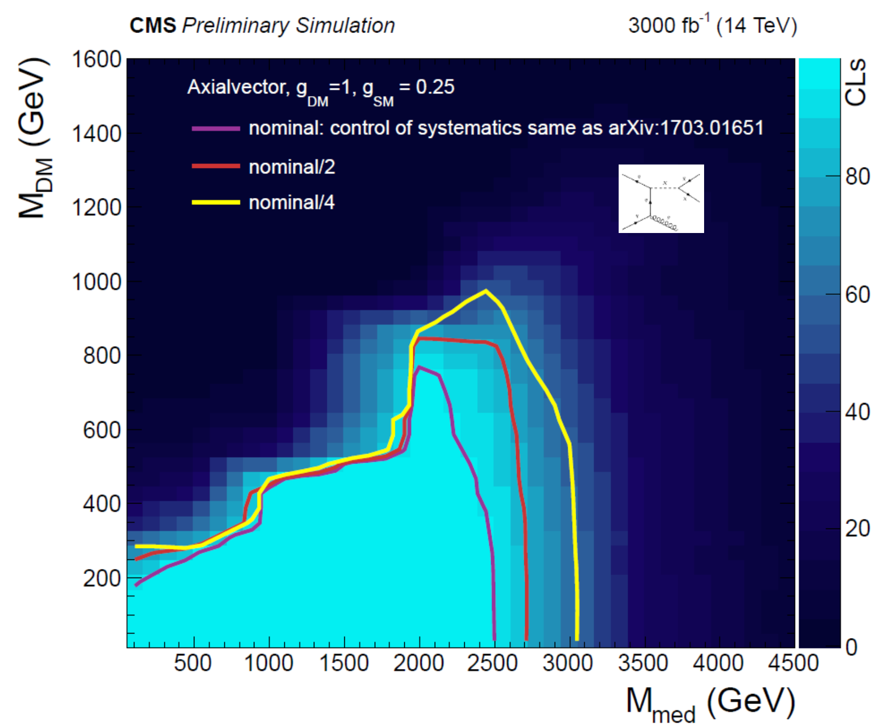


Missing transverse energy (MET) reconstructed from full kinematics → acceptance matters, particle flow beneficial. HGCAL upgrade!

Dark Matter in j+MET

One of top priorities: Jet+Met, a benchmark among many DM collider searches. Interpretation in simplified model following recommendations of LHC DM forum (arXiv: 1507.00996): 4 parameters (**M_{med}**, **M_{DM}**, g_{SM}, g_{DM})



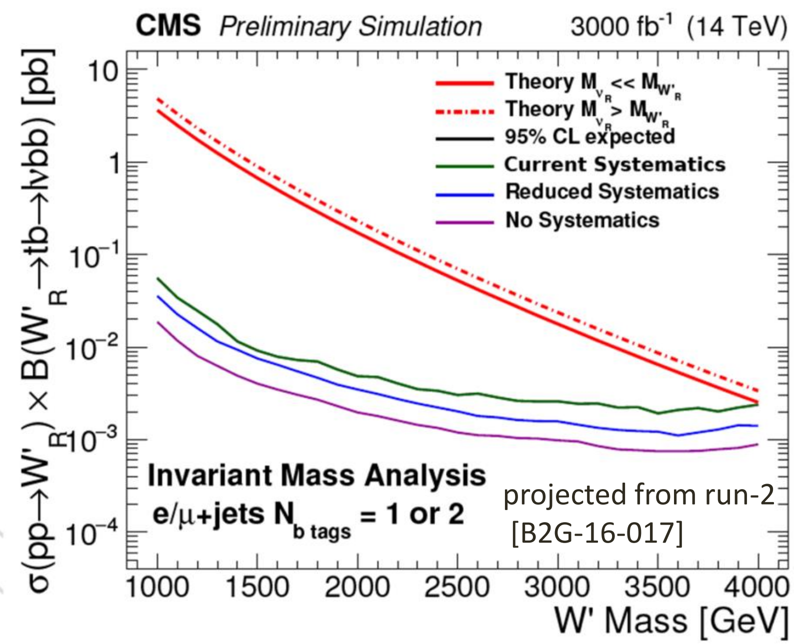


Parametrized DELPHES simulation with run-2 [arXiv:1703.01651] as baseline. Scenarios of systematics: present knowledge and two reductions. Key = understanding MET: very high MET (AV) dominated by size of control sample and background extrapolation.

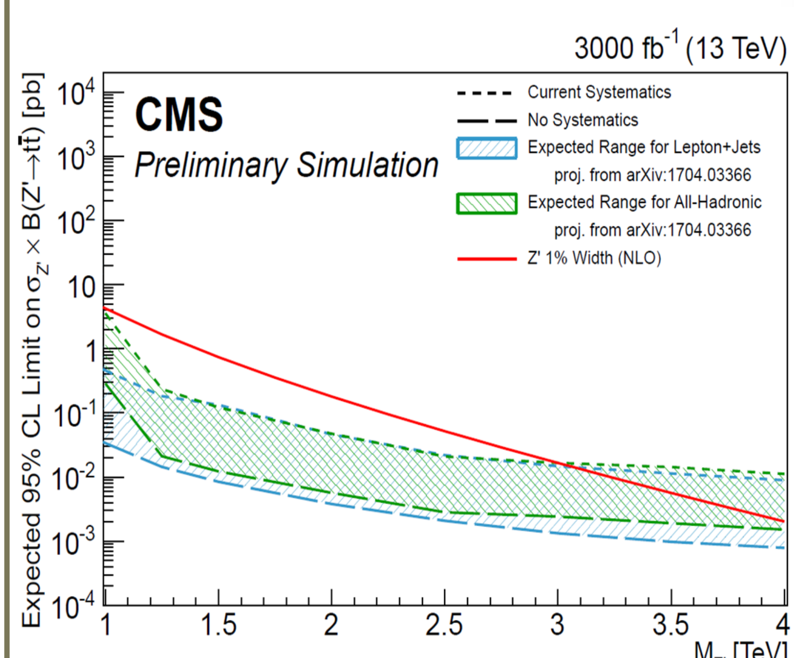
Impact of Systematics

Continue benchmark searches for additional, heavy resonances as pedicted by many models. Couplings to third family may be enhanced.

W′ →tb →e/μ + b-jets
Probe scenarios such as $M(v_R) > M(W'_R)$, which cannot be studied with leptonic W′



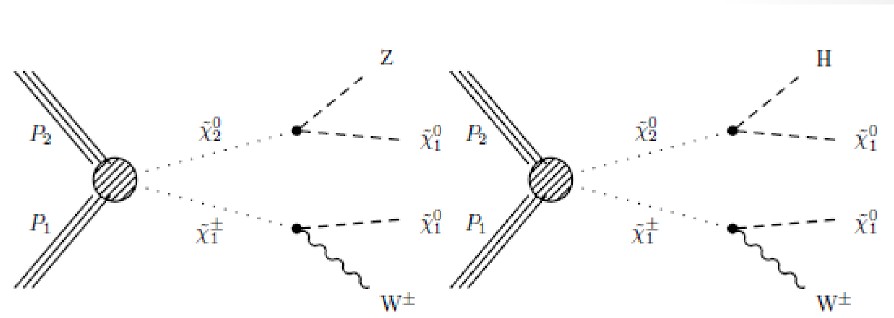
Z′→tt → e/μ + jets (b- or t-tagged jet)
Z′→ tt → all hadronic

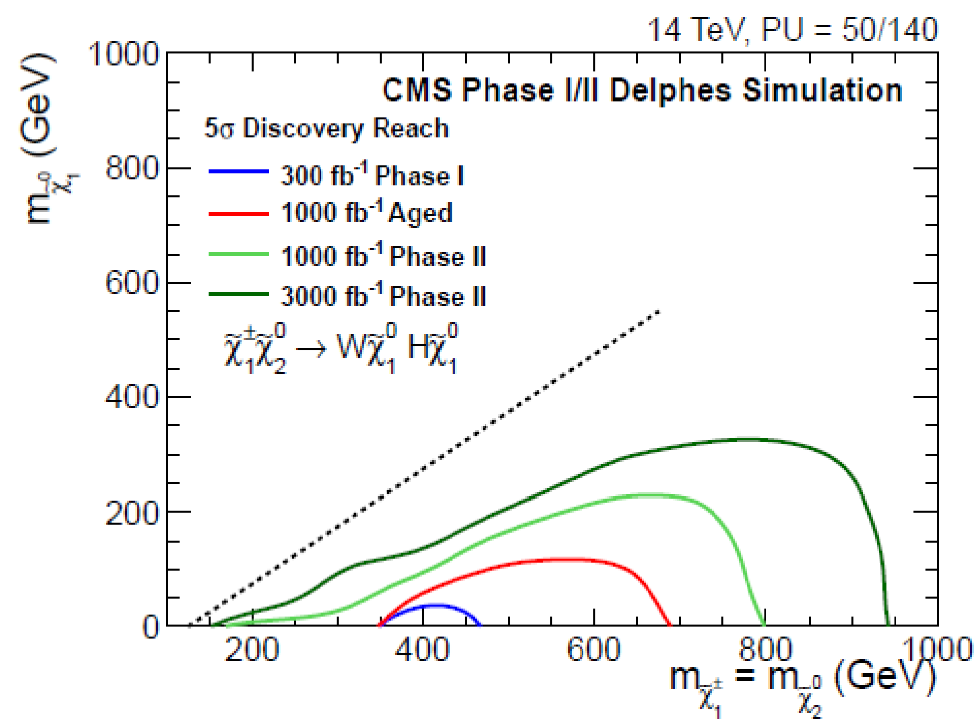


Visible impact of systematic uncertainties on physics reach. Expect improvements on theoretical knowledge of higher order corrections; detector understanding and data-driven methods will profit from larger statistics

Aging affects Sensitivity

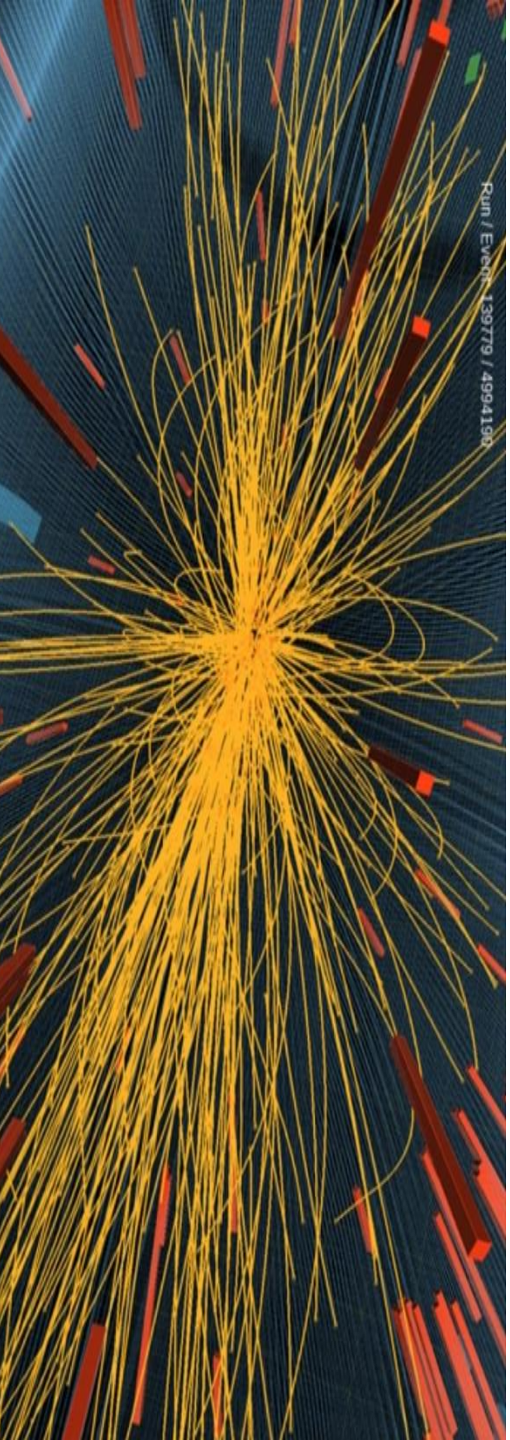
Search for SUSY will continue, at HL concentrate at processes with low cross sections.
Recent shift to natural SUSY models, with light EWK-inos expected from naturalness arguments.





Effect of **detector aging** on WH-MET final state.

With mass degeneracy, triggering leptons may be very soft (~5 GeV) -> needs track trigger.



Summary

Preparing for LHC high-luminosity operation in ≥2026. Expect 10x more luminosity.

Challenges:

to cope with high rates, high pile-up and radiation. Ageing and radiation damage require to rebuild the inner tracker and forward calorimeters. Complete muon coverage. New trigger concepts implemented.

Large physics potential:

SM precision and low cross-section measurements. Important to stay sensitive to unusual signatures, not known where nee physics is. Enhanced discovery potential for BSM and SUSY physics.

References

- Technical proposal CERN-LHCC-2015-010 twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTP
- CMS TDR-17-001 Tracker TDR
- CMS-PAS-FTR-16-005 Enhanced scope of new physics at HL-LHC (ECFA 2016)
- CMS-PAS-FTR-16-006 SM measurements with Phase-2 (ECFA 2016)
- CMS-PAS-EXO-14-007 BSM measurements, supporting TP
- CMS-PAS-SUS-14-012 SUSY measurements, supporting TP

BACKUP

It is taking shape...

First document for all CMS upgrade = technical proposal CERN-LHCC-2015-10 approved by CERN and FA.

Done

Scope document discussing different (de)scoping scenarios.

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

Now going into technical details of detector design & construction, gain in performance & physics.

- Tracker TDR-17-001 (finished)
- Muon TDR-17-003
- ECAL Barrel TDR-17-002
- Timing layer, interim document (TDR Oct 2018)

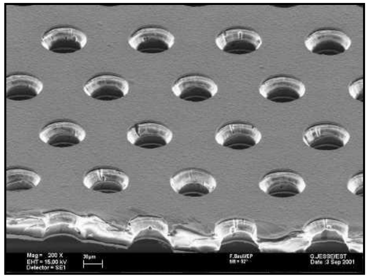
For Nov 2017 LHCC meeting.

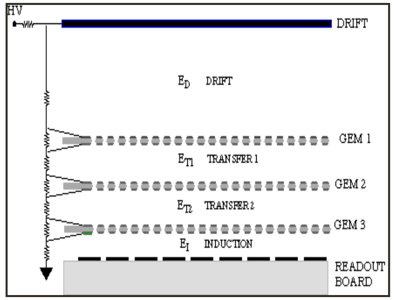
- Endcap calorimeter TDR-17-007 (later LHCC meeting)

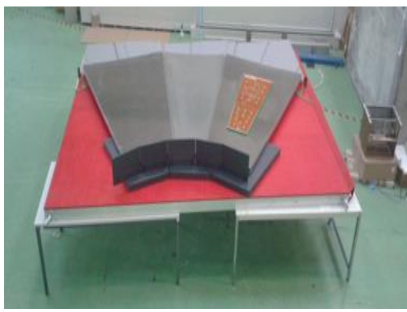
Approve all Phase-2 documents and validate the overall Phase-2 funding plan for endorsement at Apr. 2018 RRB.

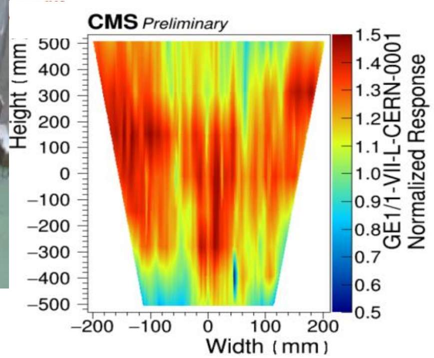
Muon Forward Upgrade

Triple GEM detectors





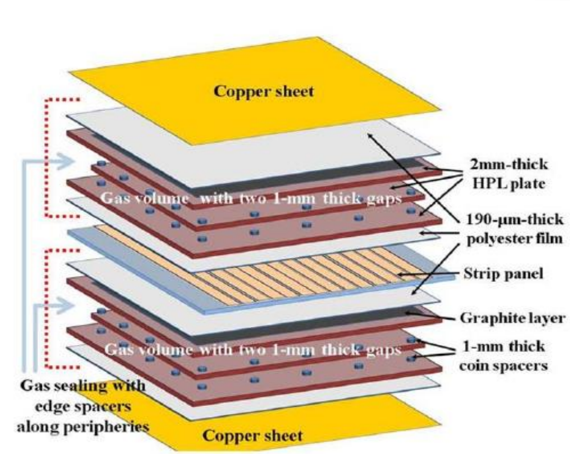




Challenges:

- Large sizes, m^2 detectors!
- Foil production (now max 50 cm width). Single mask, symmetric hole shape for amplification.
- Foil stretching. No spacers in active volume while keeping uniformity.

Improved high-rate RPCs



Rate capability $\Delta V = I R = q \rho d \Phi$

Modifications w.r.t. standard double-gap RPCs already existing:

- Lower electrode resistivity ρ
- Reduced electrode thickness d
- Thinner gaps (2 -> 1mm) reduces charge q, faster extraction
- Increase # gaps