CMS Upgrades Plans and Potential

LHCP 2015

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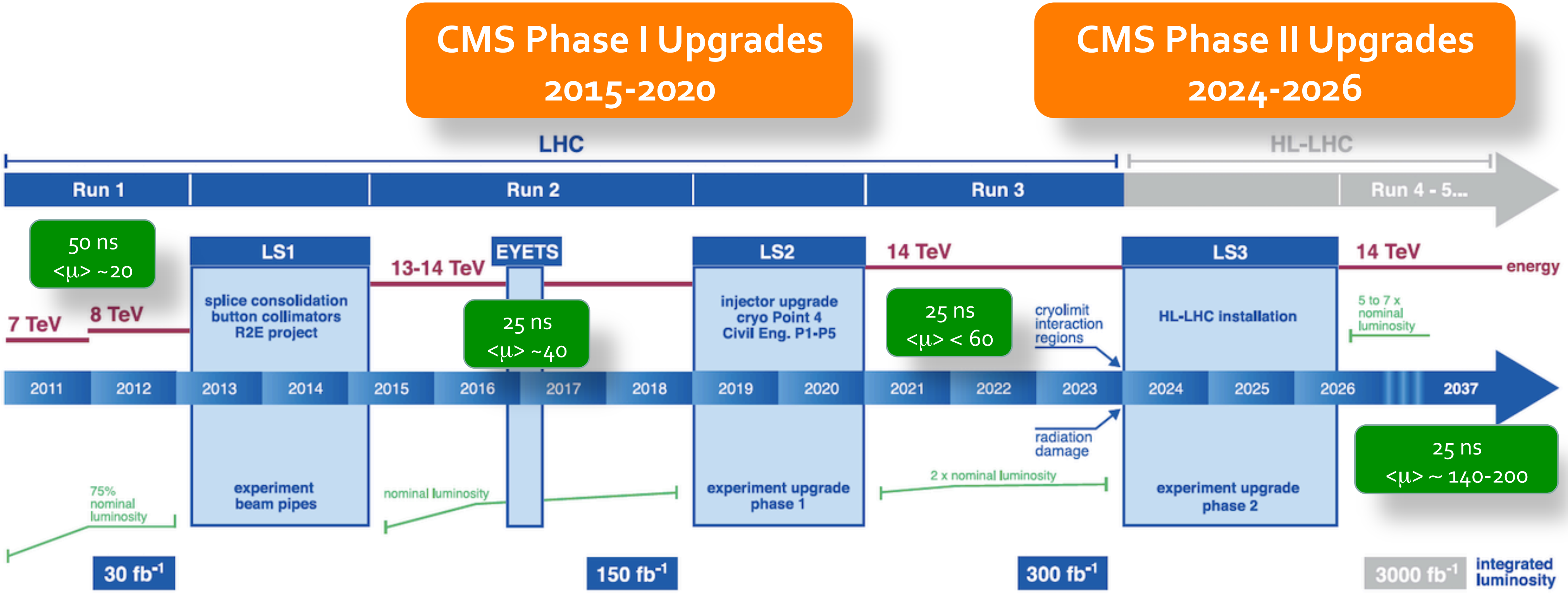
On behalf of the CMS Collaboration

CMS as function of time

CMS has foreseen two upgrade phases to adapt to the challenges of the LHC and to fully exploit physics performance for luminosities up to 7.5 x 10^{34} and manage radiation-damage effects up to 3000/4000 fb^{-1}.



CMS Phase I Upgrades

- Pixel tracker : four-layer barrel and 3 forward-disk pixel tracker with new readout chip capable of higher hit rate (installation during end of 2016 extended technical stop)

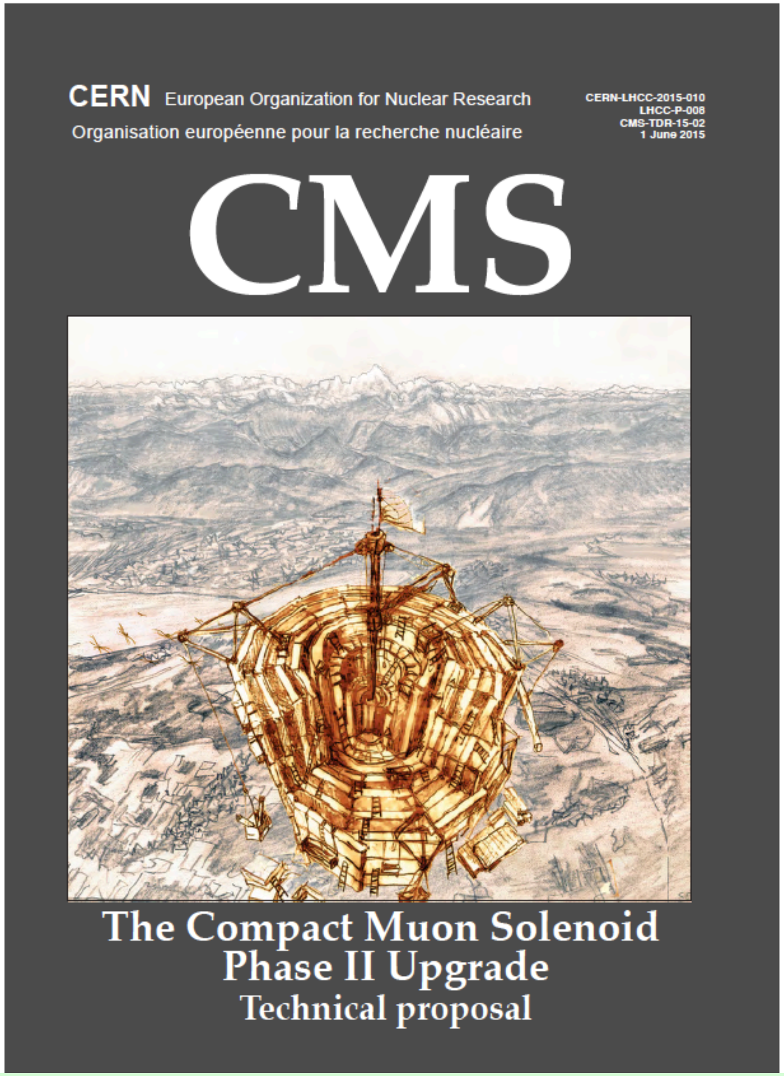
- Hadron calorimeter : Installation of SiPM devices into barrel/endcap calorimeters (installation during LS2) and new electronics in the forward calorimeter (installation during Xmas break 2015) allowing timing-based background rejection

- Trigger : upgrade the muon and calorimeter Level-1 trigger systems and global trigger processor to handle higher luminosities without loss of efficiency for key physics channels (installation and commissioning during 2015-2016)

CMS Phase II Upgrades

- Brief Physics Motivation
- Detector Upgrades
- Physics Object Performance
- Summary & Conclusions

Performance results are assessed using full simulation. The physics object performance is however parameterized in a simplified simulation for the physics benchmark analyses to allow MC generation of large background samples



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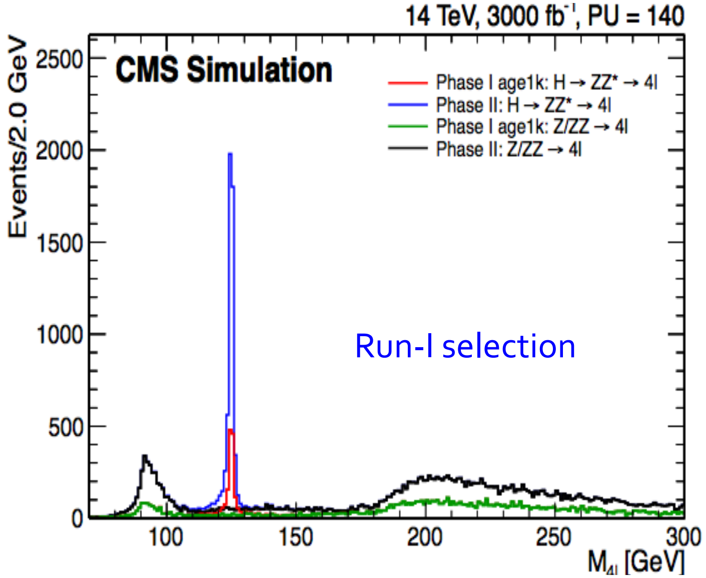
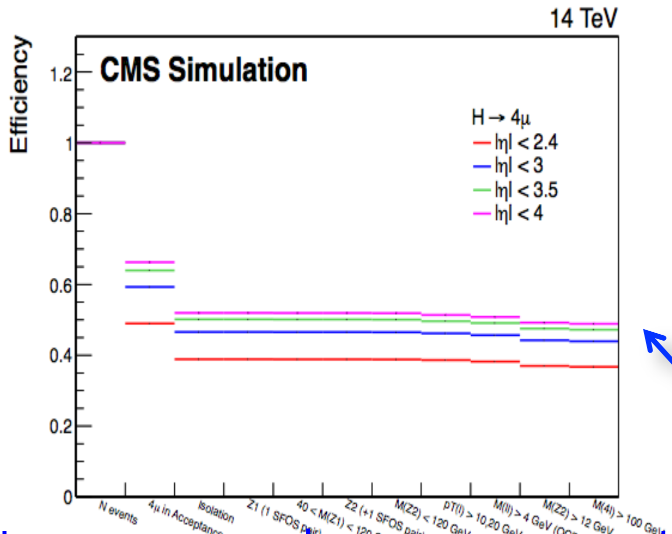
https://cds.cern.ch/record/2020886

Motivators for HL-LHC

$H \rightarrow ZZ^{*} \rightarrow 4l$: precision measurements



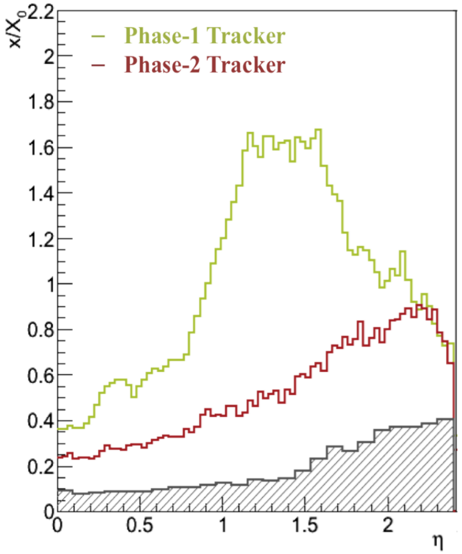


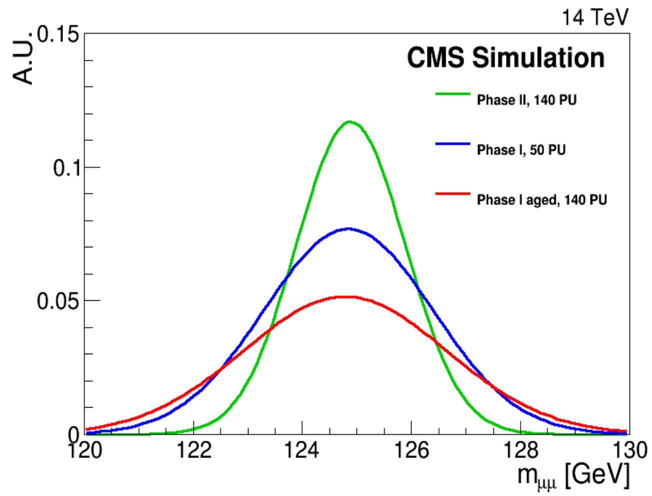
HL-LHC is an Higgs factory !

See talk by A. Nisati on Thursday

$H \rightarrow \mu\mu$ (rare decay): probes the 2nd generation couplings

Search of narrow resonance with huge DY background





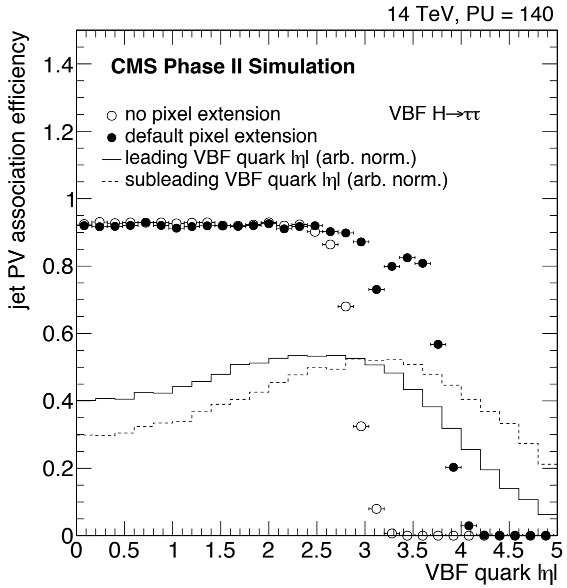
Improvements: 20% efficiency & 45% mass resolution

→ expect ~5% uncertainty on κ_μ

Improvements: lepton reconstruction efficiency at low-pT & ~20% increase in acceptance

VBF H → ττ and di-H: Excellent probes for BSM physics

VBF H → ττ: enabled by VBF jet tagging, τ-ID, MET resolution



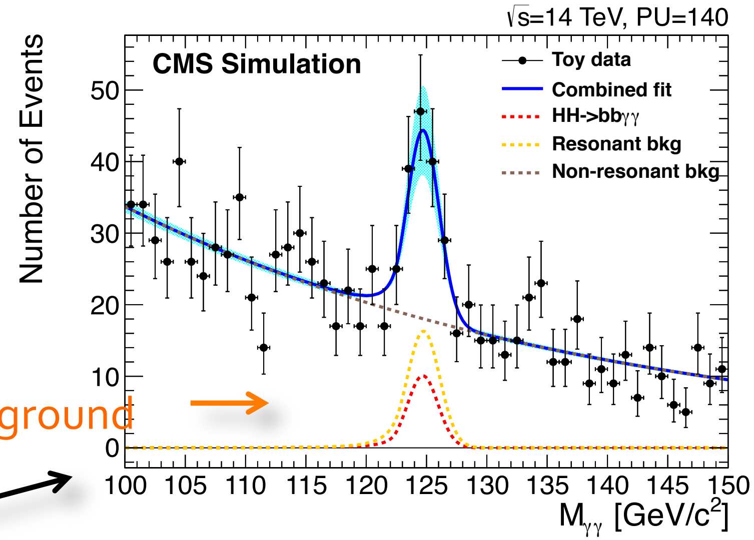
Improvements:

- Track-Trigger (~5.5 x acceptance)
- Less fake jets (Tracker extension)
- 90% efficiency for Jet-ID with tracks
- Improved mass resolution (MET) ~15% gain

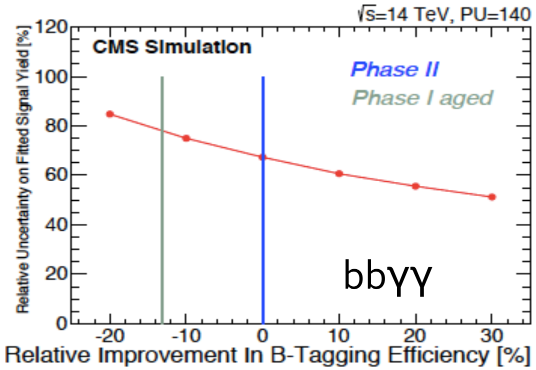
→ expect ~ 5% uncertainty on κ_τ

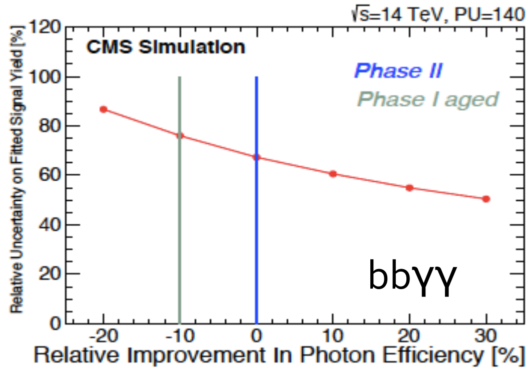
HH → bbγγ

ZH, ttH, bbH background



HH → bbγγ – 60% cross section uncertainty
enabled by Tracker b-tagging, EC γ resolution performance

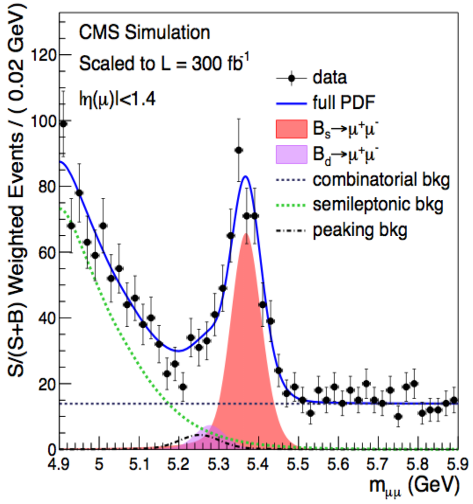


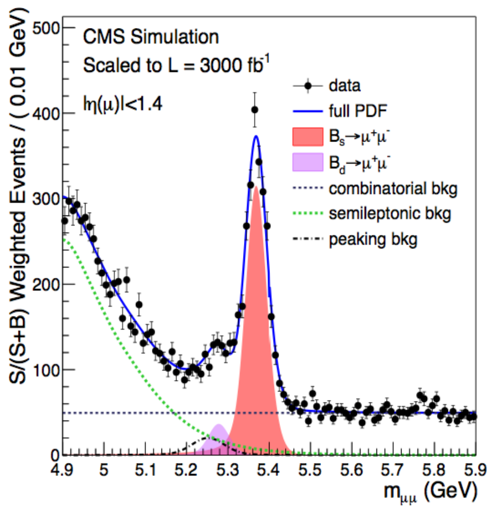


HH → bbττ- 100 % cross section uncertainty
enabled by Tracker-Trigger (x2 acc) and b-tagging, τ-ID performance

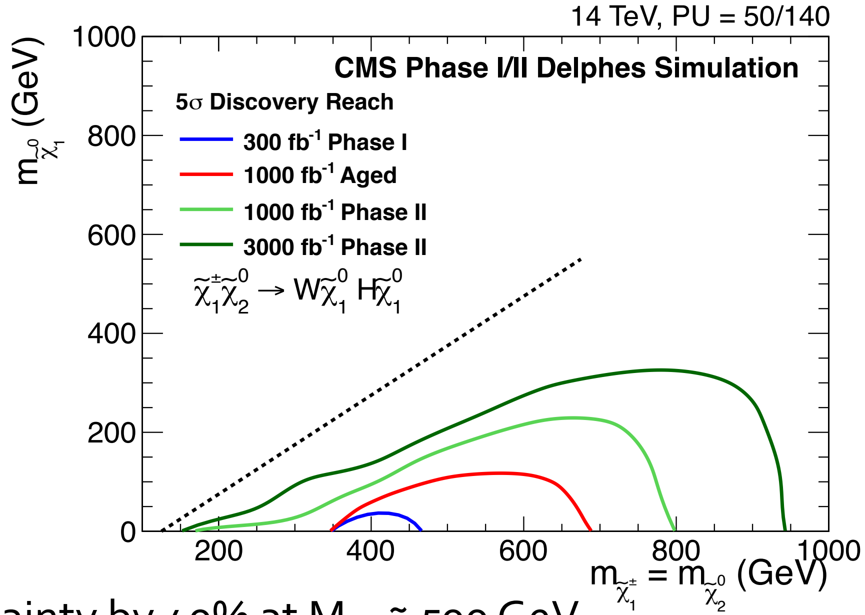
See talk by D. Derkach on Thursday

$B_d/B_s \rightarrow \mu\mu$ resolve the two decay peaks; enabled by Tracker & Track-Trigger



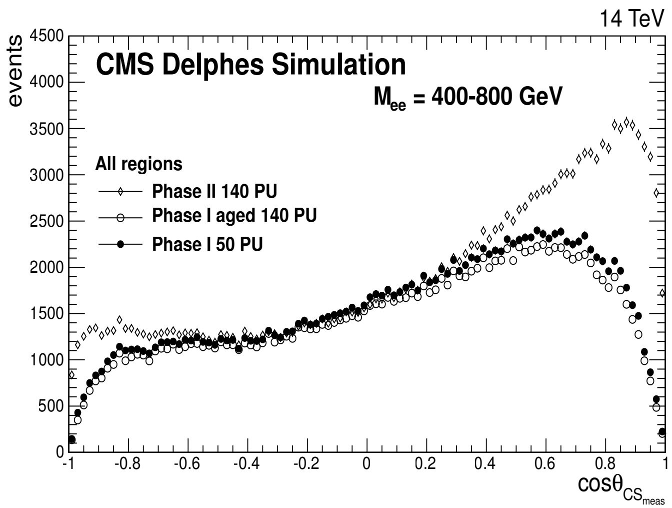


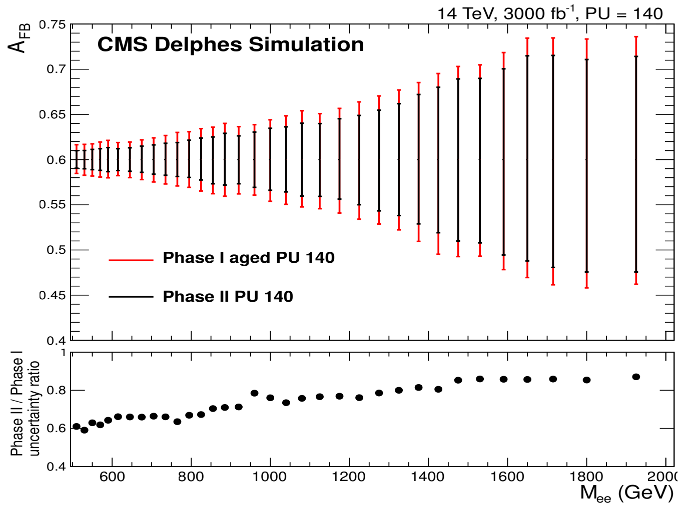
Neutralino mass range increase - enabled by Tracker extension (MET) & b-tagging



New physics search in A_{FB} of DY ee – improved uncertainty by 40% at M_{ee} ≈ 500 GeV

Resolution (charge assignment) new EC and coverage up to |η| = 3 See talk by J. Richman on Thursday





HL-LHC Physics Drivers

HL-LHC, with 3'000fb^{-1} at 13~14Tev will bring high intensity frontier physics to the energy frontier

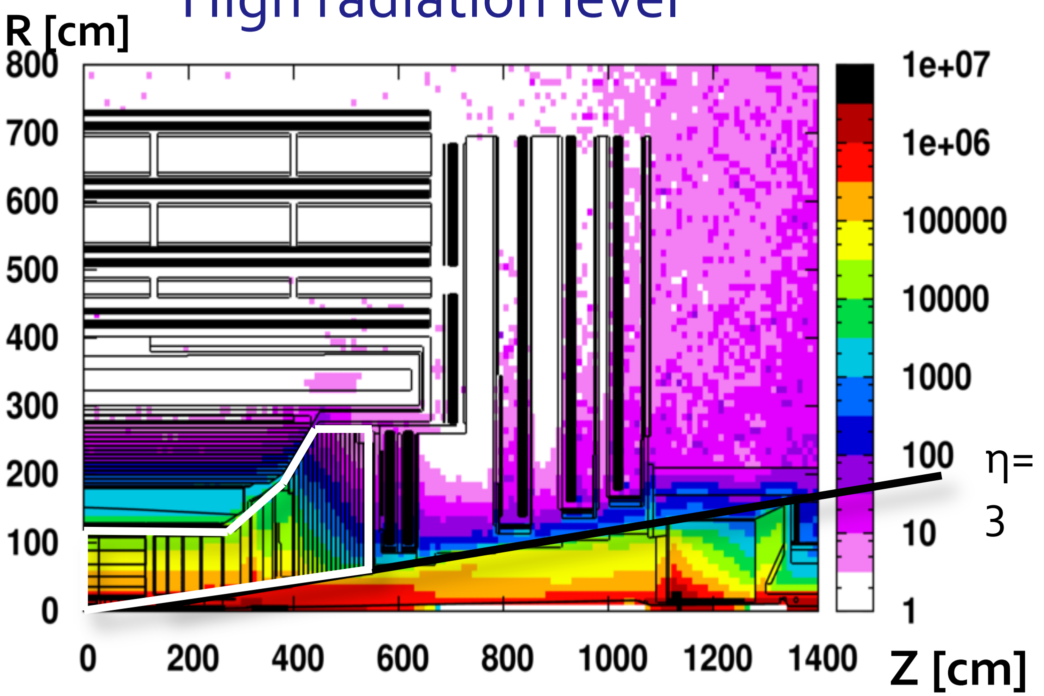
- Precision SM, EWSB and Higgs physics
- Further extend potential for discovery and characterization of new physics
  - Extend mass reach by ~ 1TeV
  - Open broad scope for rare, unusual processes

This is Very Challenging: it requires

- Precision measurements of
  - Leptons (e, μ, τ), γ, Jets, b (c) quarks, MET
- Reconstruction of complex event topologies to identify
  - W/Z, top, VBF, etc.
- Over the full range from low to high p_T
  - In a very high rate and high pile-up environment

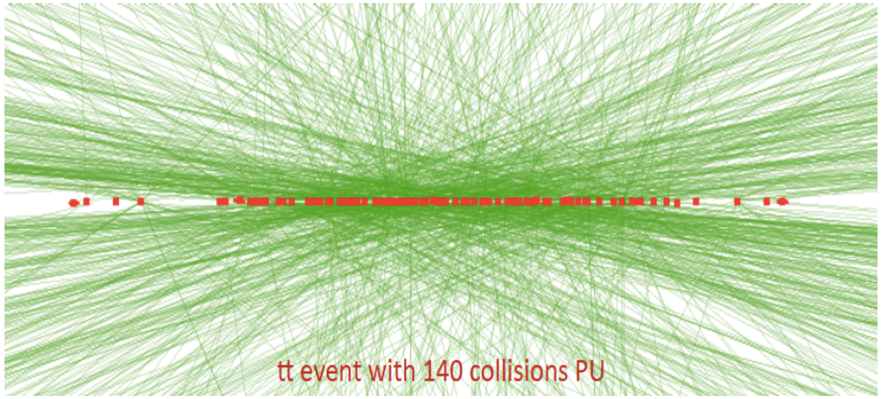
HL-LHC Challenges

High radiation level



High Pile-Up

ttbar event with 140 PU collisions



Annual dose in HL-LHC will be similar to total dose from LHC start to LS3

→Aging studies show that Tracker & Endcap Calorimeters need replacement

Maintain detector performance in the presence of higher pileup (PU)

→ Upgrade several detector components

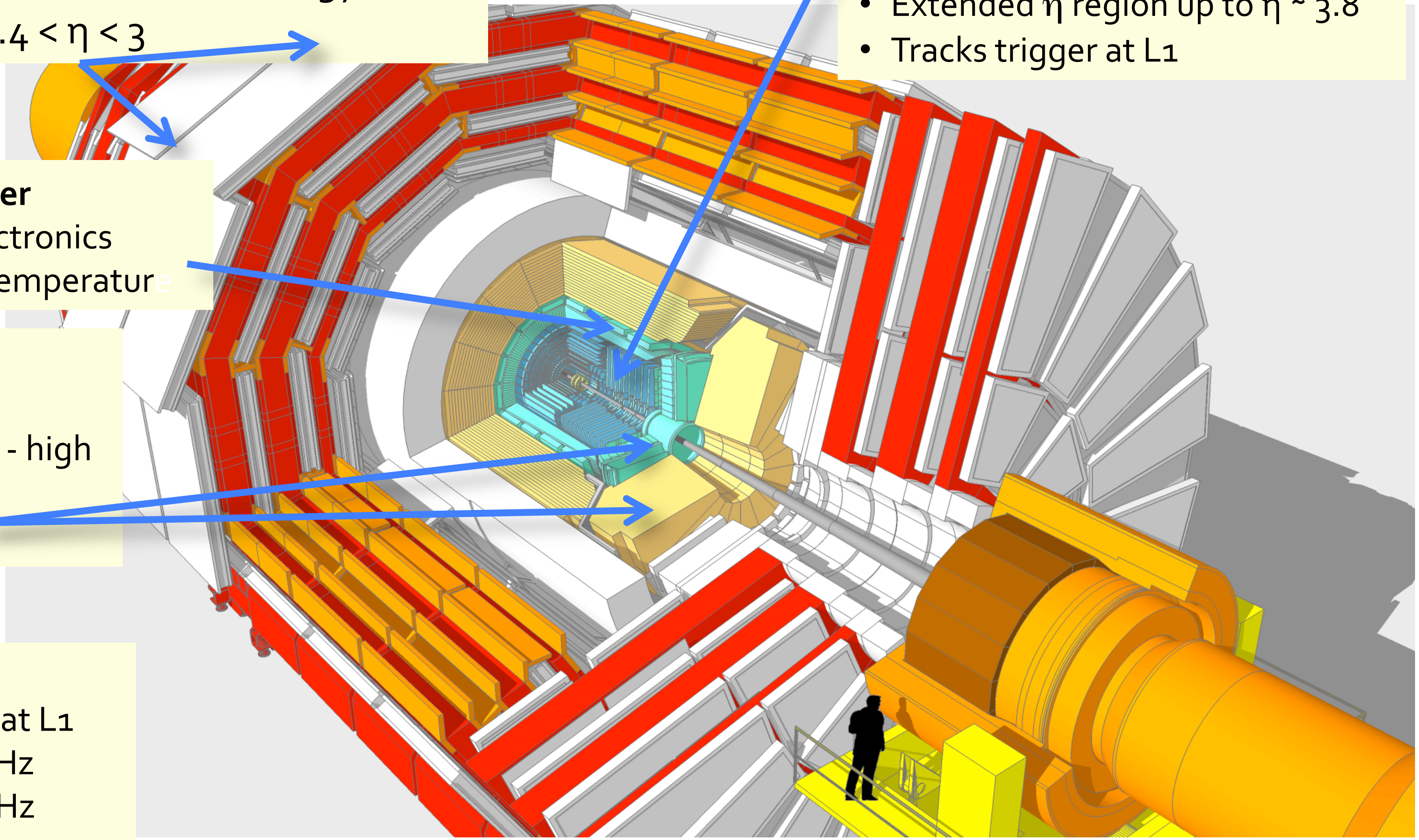
→ Redesign some electronics, trigger and DAQ

Phase II Upgrades

Muon System
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region

$1.5 < \eta < 2.4$ (new GEM/RPC technology)
- Muon-tagging $2.4 < \eta < 3$

Replace Tracker
- Radiation tolerant - higher granularity - less material -better p_T resolution
- Extended η region up to η ~ 3.8
- Tracks trigger at L1



Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature

Replace endcap Calorimeters
- Radiation tolerant - high granularity
- 3D capability

Trigger/HLT/DAQ
- Track information at L1
- L1-Trigger ~ 750 kHz
- HLT output ~7.5 kHz

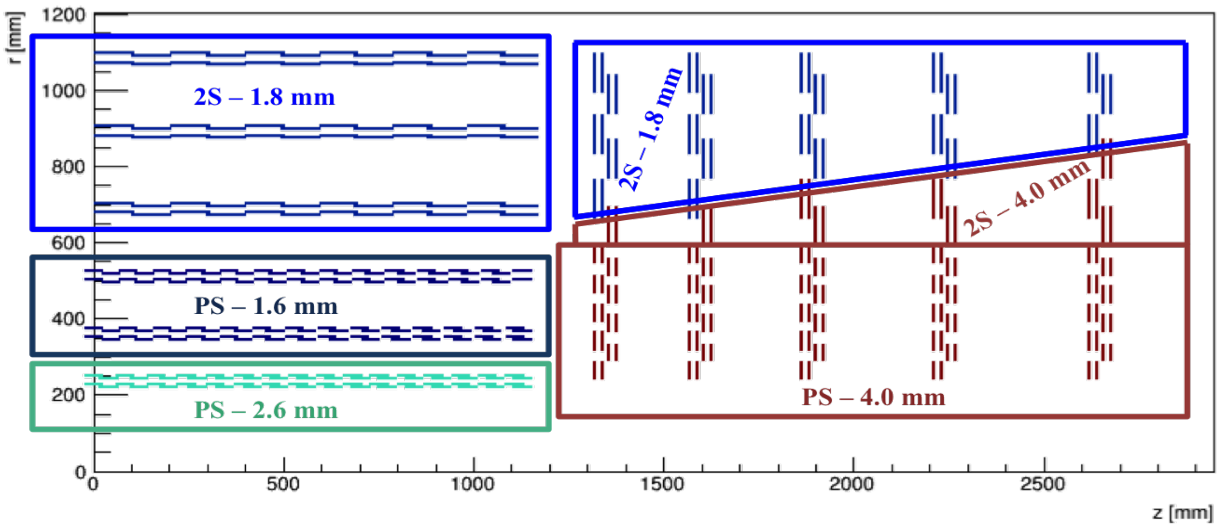
Phase II Tracker Design: Outer Tracker

Several configurations investigated with simplified simulation to define baseline:

- 6/5 barrel/endcap layers/disks - instead of 10/11 in current OT
- Increased granularity through short strips - ≃ x 4 current OT
- 2 sensors modules in all layers for Trigger purpose
- Long Pixel in 3 inner layer modules (PS) for z-coordinate measurement
- Light module design & mechanics - CO_2 cooling (-30◦) - DC/DC powering

Total Outer Tracker

- 220 m^2 area - 15500 modules
- 50M strips - 220M macro-pixels
- 90/100 µm pitch (2S/PS modules)
- 2.5/5 cm strips (2S/PS) - 1.5 mm macro-pixels in PS modules
- 200 µm active or physical thickness



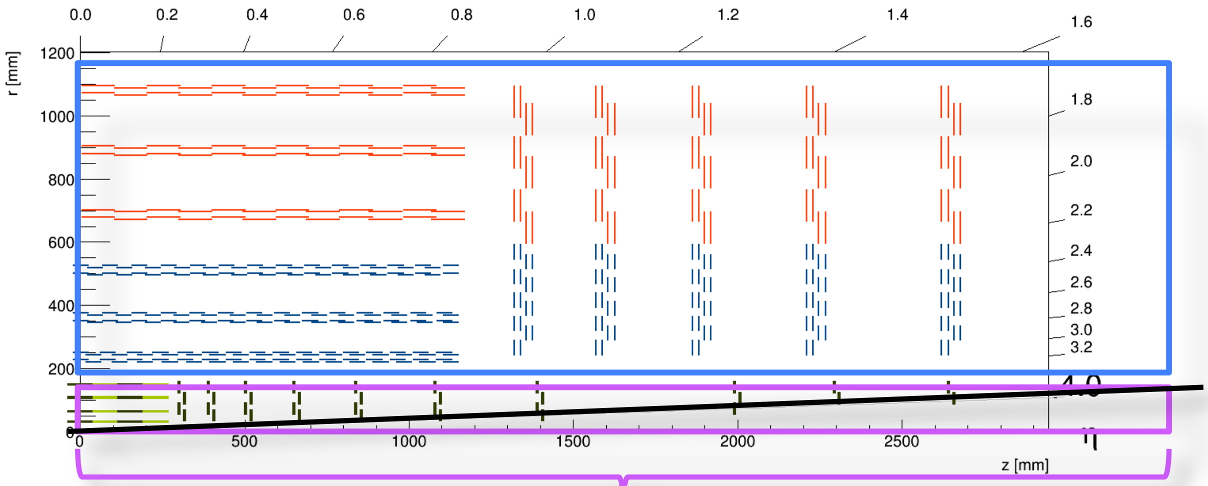
Ongoing study of alternative design with tilted modules in PS layers

- Further reduce material and number of modules

Phase II Tracker Design: Pixel Detectors

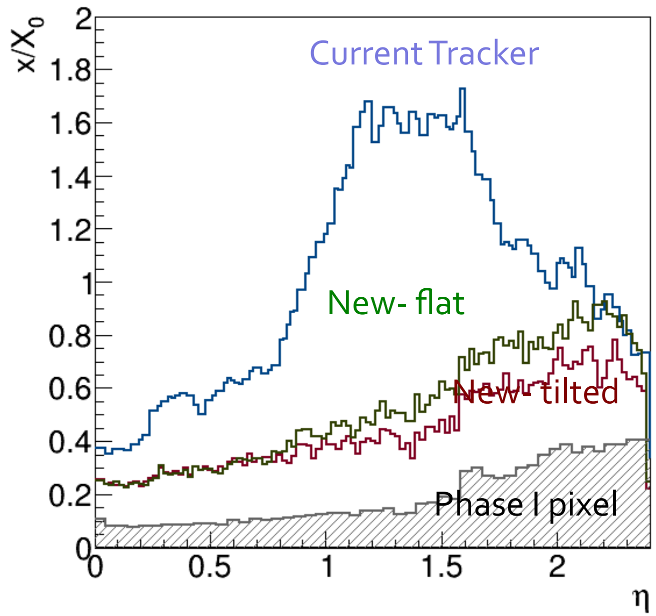
Current configuration based on Phase-I design - ongoing studies to reduce material and to improve/adapt resolution through reduced pixel size

- Barrel pixel with 4 layers at 3, 7, 11 and 16 cm
- Forward pixel with 10 disks extending coverage to $\eta = 3.8$
- Data readout at 750 kHz
- Maintainable during winter shutdown



Pixel modules

Tracker extension up to η=3.8



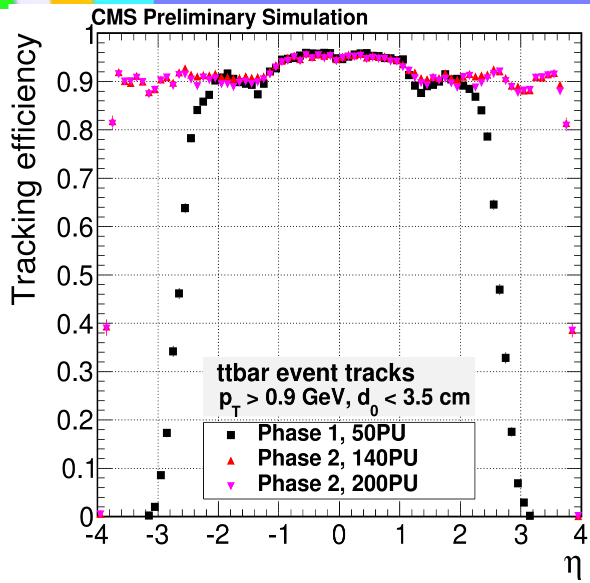
Material (lighten up!)

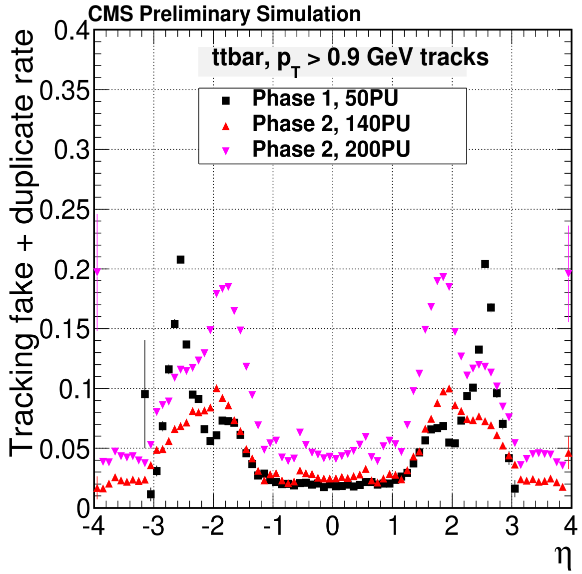
- Tracker weight ½ of current
- Improved track p_T resolution & reduce rate of γ conversion (factor 2 to 3 depending on η)
- ex. HH -> bbγγ; ttH -> γγ ; H -> μμ - $B_{s,d}$ -> μμ ..

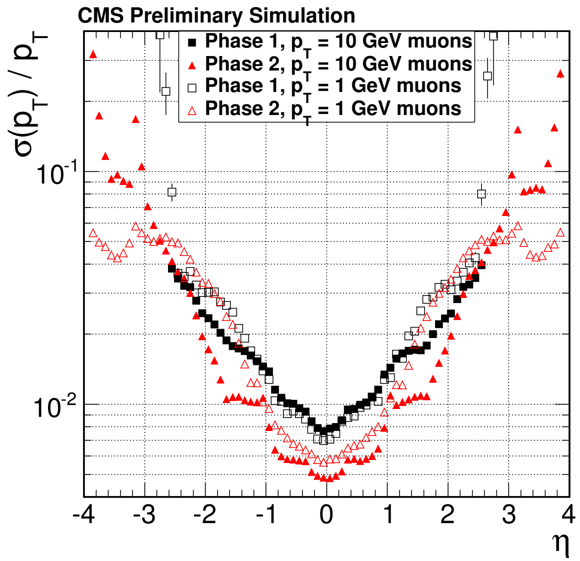
Total pixel area ~ 4.0 m²

- 50x50 - 25x100μm² pixels
- ≤ 150 μm sensor physical thickness

Track and Vertex Reconstruction Performance



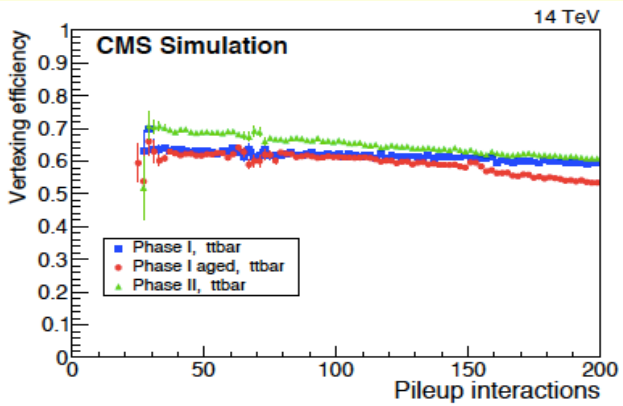


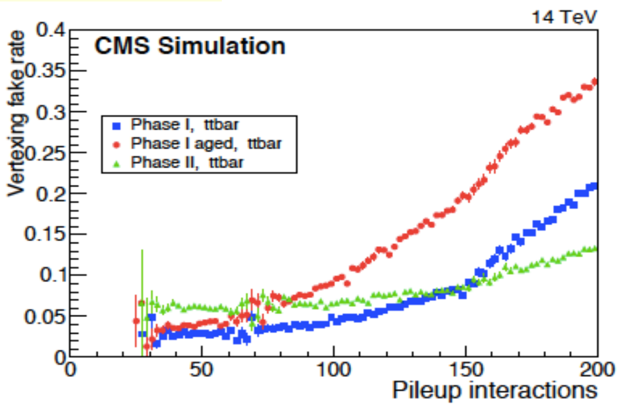


- Track efficiency and fake rate for Phase-II 200 PU similar to Phase-I 50
  - tolerable fake increase at 200 PU
- Momentum resolution substantially improved (lower pitch & less material)

ttbar

Signal primary vertex efficiency ≥ 95% with 20 μm resolution at 200 PU





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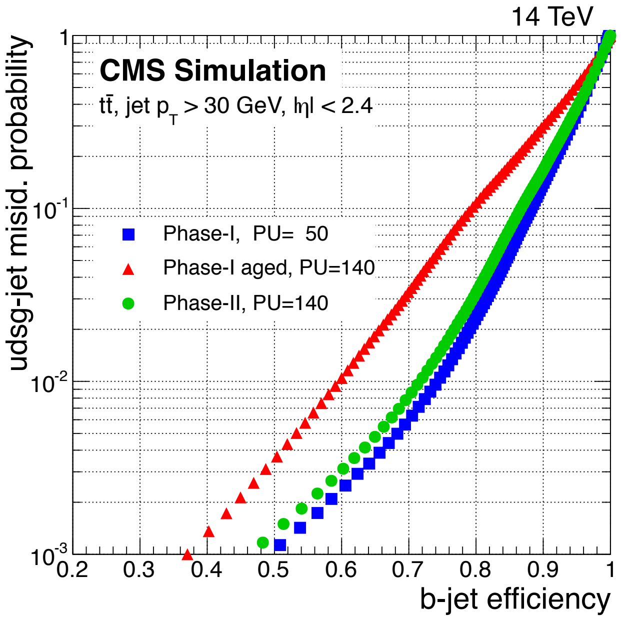
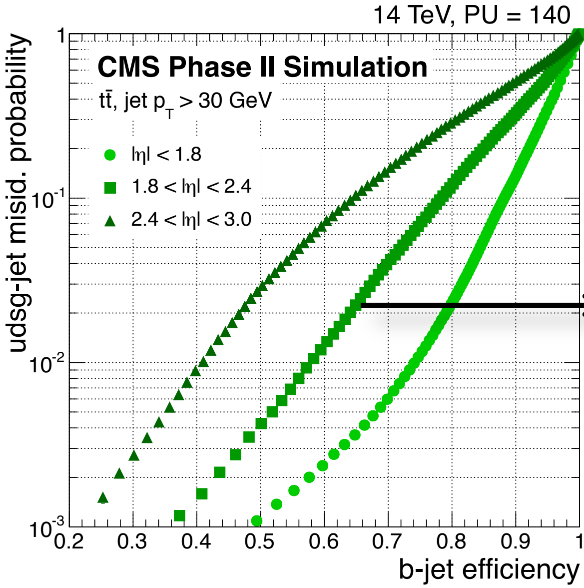
b-tagging Phase-II recovers Phase-I performance

- Expected further improvements with new pixel design (smaller pitch & less material)

ttbar

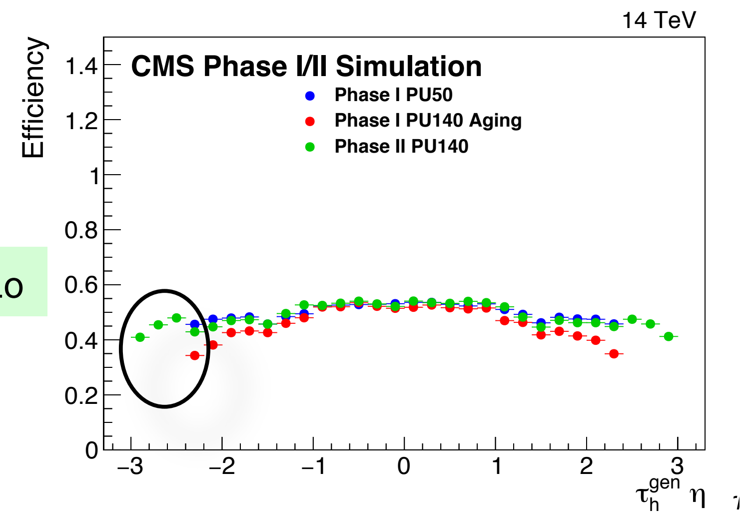


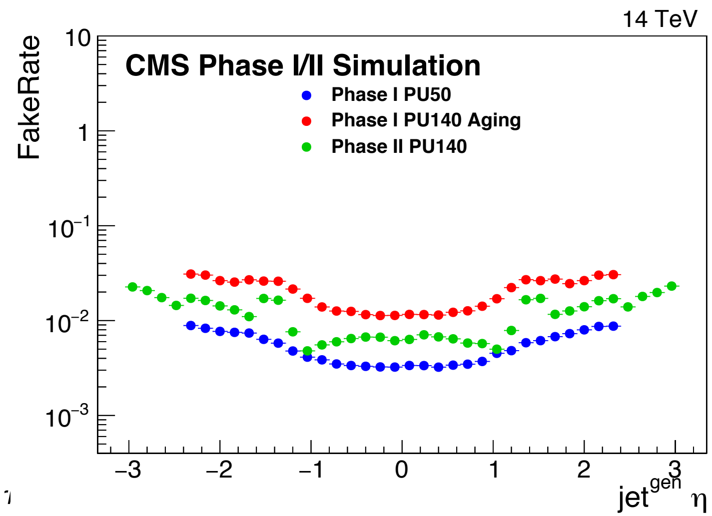


Coverage to η = 3.8

τ-ID based on track isolation (robust to PU) same efficiency working point below

Z → ττ





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Track Trigger Performance

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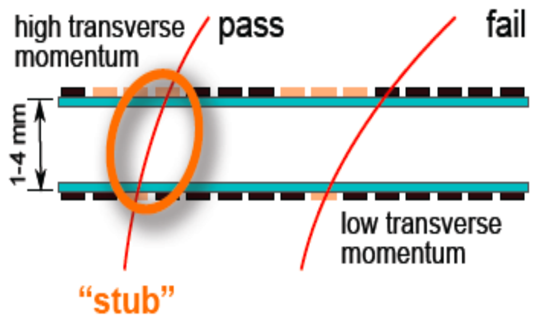
Objective: reconstruct all tracks with of $p_T \geq 2$ GeV **at trigger level**.
Identify primary vertex along beam line with ~1mm precision

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

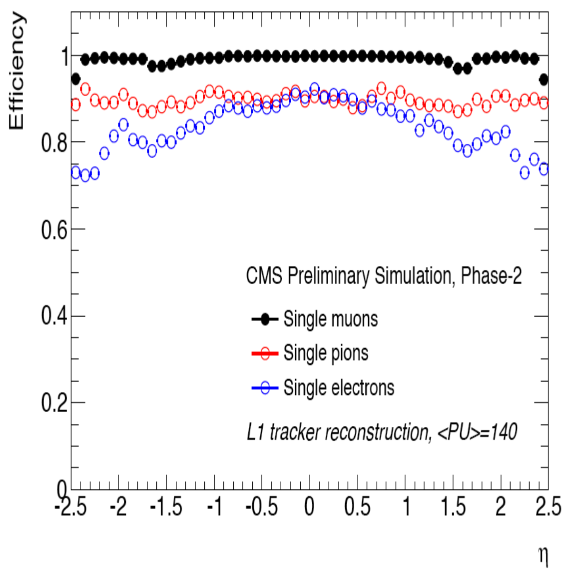
- Correlate hits in two closely-spaced sensors to provide vector ("stubs") in transverse plane: angle is a measure of p_T
- Exploit the strong magnetic field of CMS

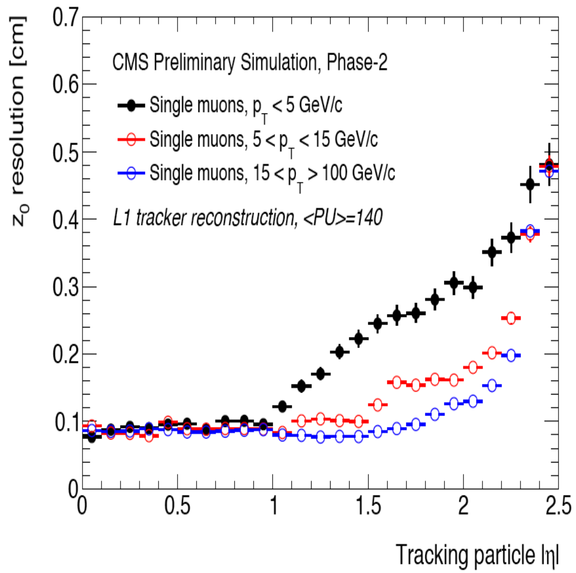


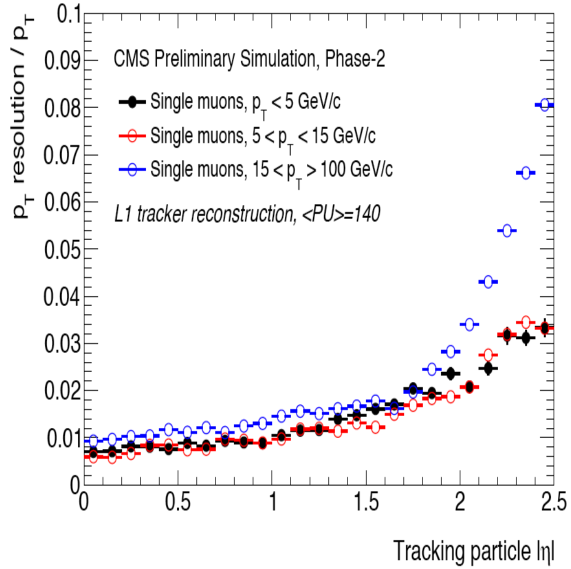
Physics benefit:

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

L1 Track Trigger reconstruction performance



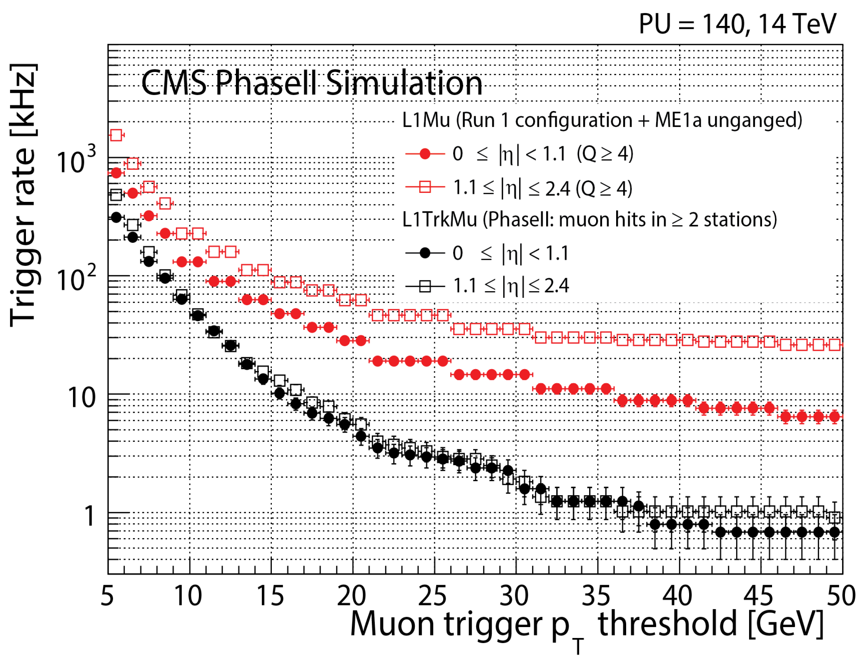


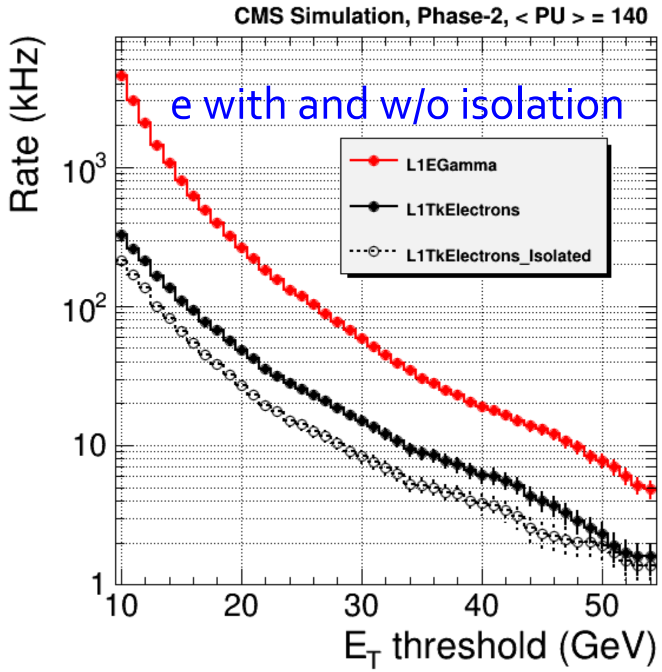


L1 Trigger performance with Track-Trigger

Powerful scheme to control all inclusive trigger rates at first 40 MHz stage

- Single-μ rate divided by 10
- Single-e rate divided by 5(10) w/o (with) isolation
- γγ rate/5 from isolation
- τ efficiency x 2 at same rate
- Vertex ≃ 1 mm resolution → HT & MET rates divided by 10 to 100





L1-Trigger studies with Phase-I menu thresholds including Track-Trigger:

- Requires ≃ 500/750 kHz rate at 140/200 PU (with 1.5 safety margin)

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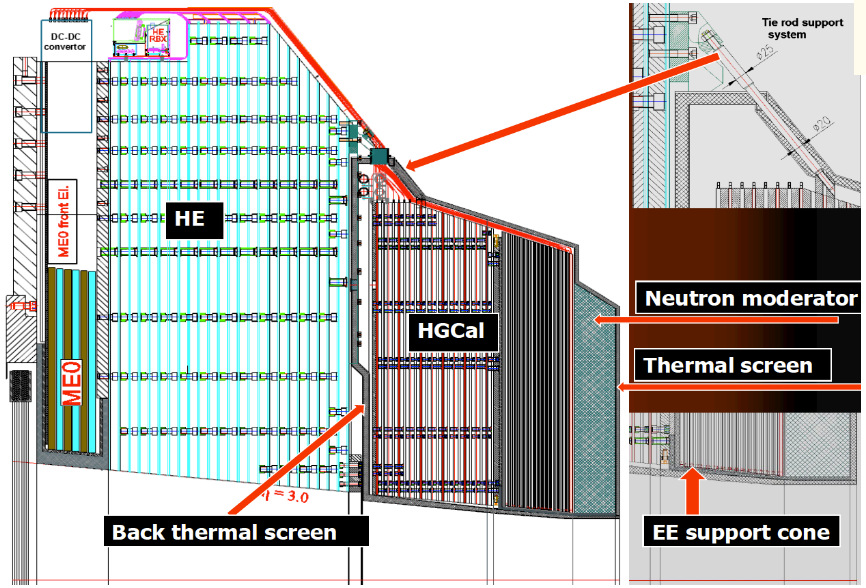
Phase Endcap Calorimeters

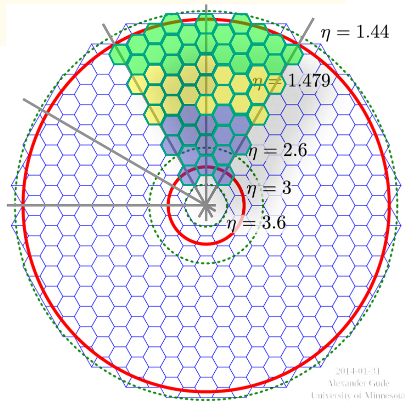
– 3D shower measurement in High Granularity Calorimeter (HGC)
  - Electromagnetic EE (Σ_{depth}~26 X_o, 1.5λ): 28 layers of Silicon-W absorber
  - Front Hadronic FH (Σ_{depth}~3.5 λ): 12 layers of Silicon/Brass

– Back Hadronic Calorimeter (BH) (Σ_{depth}~5 λ): 12 layers of Scintillator/Brass

Total Depth >10λ

EE: 380 m² - 4.3 Mch - 13.9k modules - 16t
FG: 209 m² - 1.8 Mch - 7.6k modules - 36.5t
BH: 428 m² - 5184 SiPMs





sensors: three active thicknesses 100-200-300 μm
0.5(1) cm² pads for 100(200/300) μm

ΔE/E ~ 20%/√E; 3D shower reconstructio
- **Use shower topology to mitigate PU effect**

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Electron efficiency recovered with gradual decrease up to 200 PU

DY→ ee

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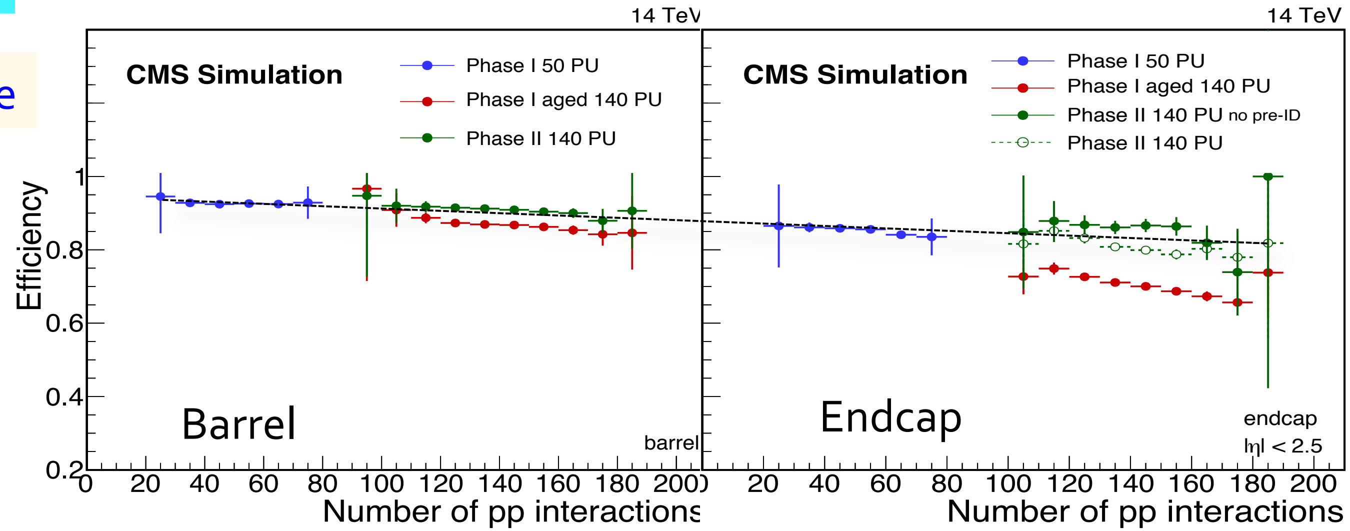
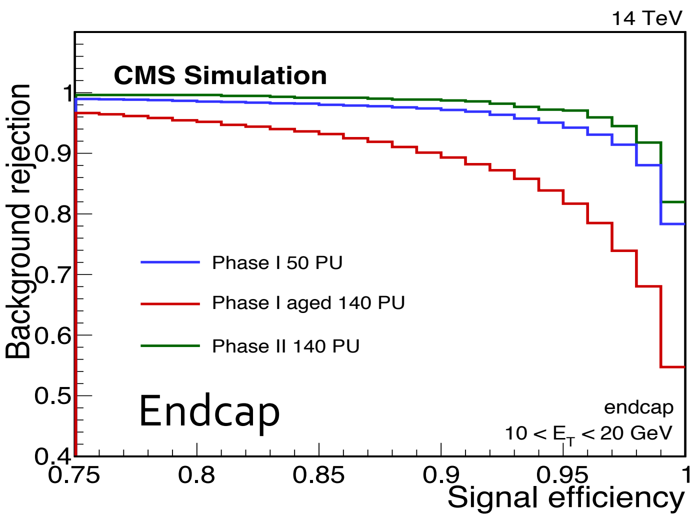
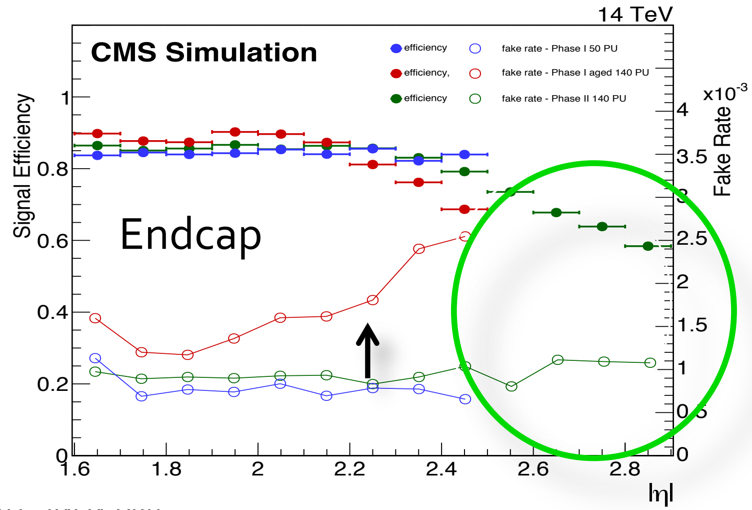


BDT efficiency for DY electrons vs background rejection for Jets (left) and BDT efficiency for γ and Jet fake rate for a WP at ≃ 85% efficiency (right)





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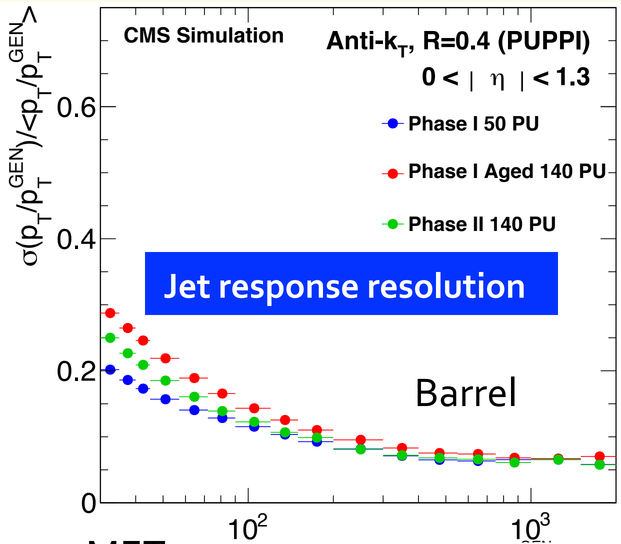
Jet and MET performance

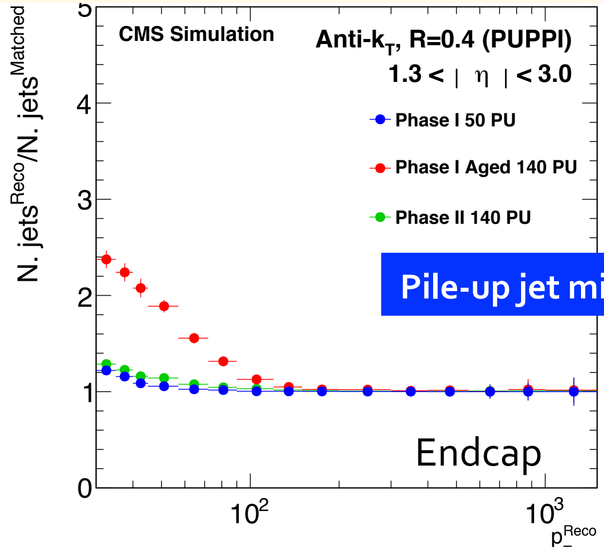
Combined effect of new EC and Tracker extension allows Phase-II to mostly recover energy resolution & fake rate of Phase-I detector at 50 PU

QCD

Jet response resolution

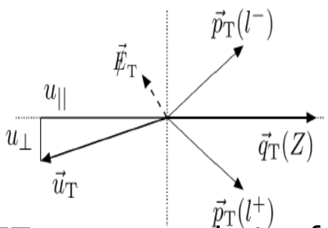


Pile-up jet mis-identification

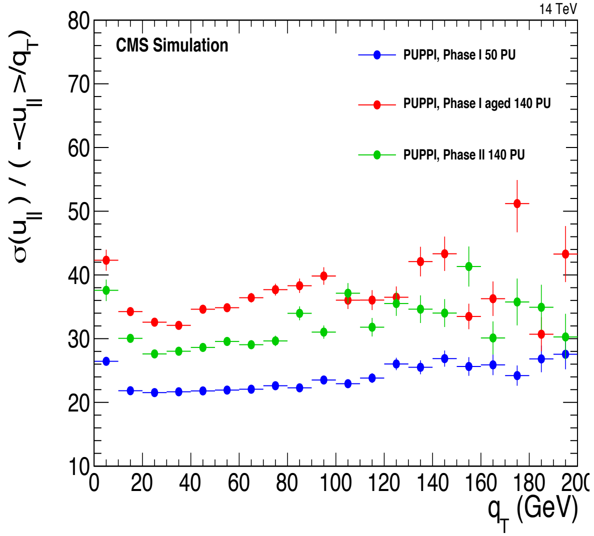


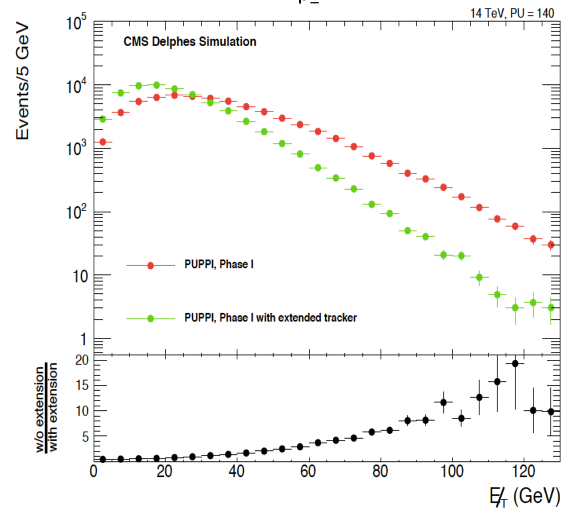
Phase-II detector recovers MET resolution partially

MET tails significantly reduced by tracking extension

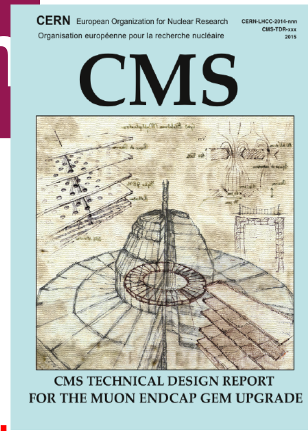


MET energy resolution from hadronic recoil in Z → μμ





Forward Muon system



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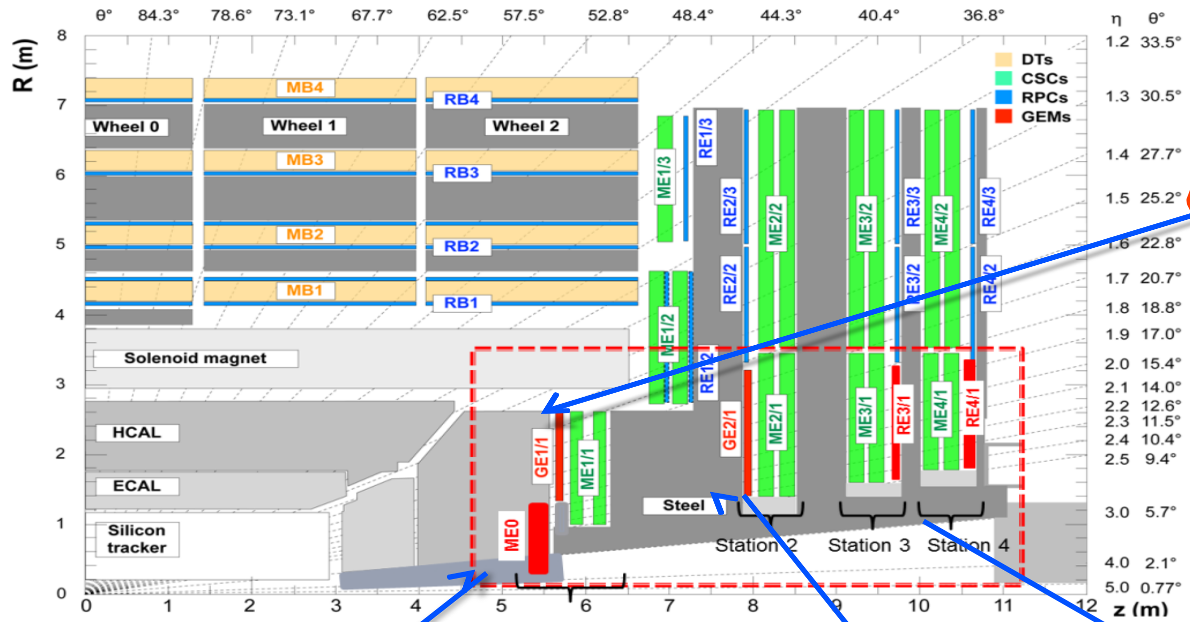

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GE1/1

Trigger and reconstruction

- **1.55 < |η| < 2.18**
- baseline detector for GEM project
- 36 staggered super-chambers (SC) per endcap, each super-chamber spans 10°
- One super-chamber is made of 2 back-to-back triple-GEM detectors
- **Installation: LS2**

MEo

Muon tagger

- **2.4 < |η| < 3.0**
- 6 layers of Triple-GEM
- each chamber spans 20°
- Installation: LS3

GE2/1

Trigger and reconstruction

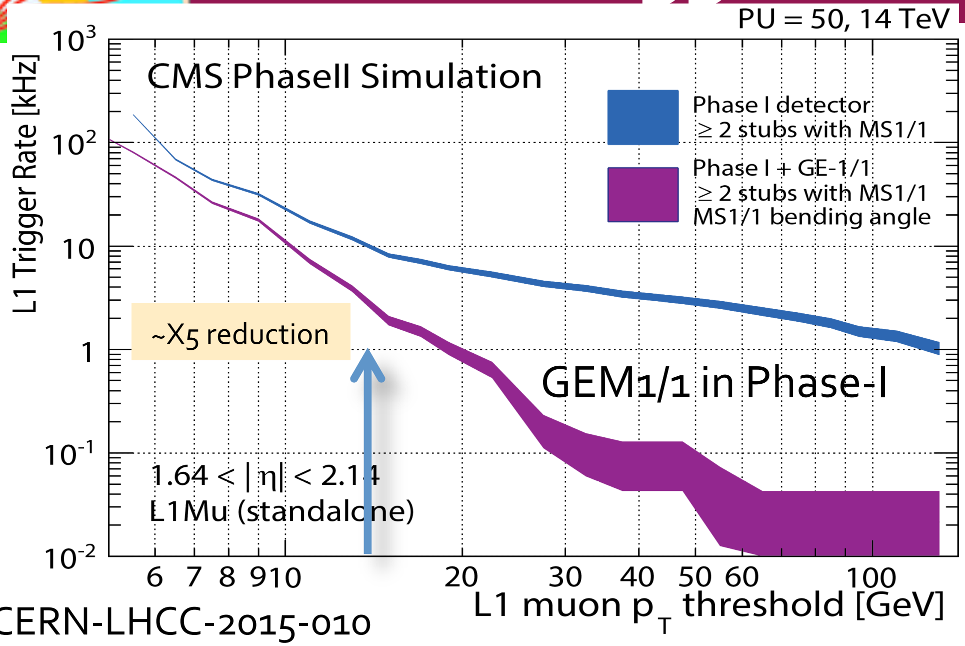
- **1.55 < |η| < 2.45**
- 18 staggered SC per endcap, each chamber covers 20°, 3.5 x GE1/1 area
- Installation: LS3

RE 3/1 –RE4/1

Trigger and reconstruction

- **1.8 < |η| < 2.4**
- Improved RPC (iRPC), finer pitch
- 18 chambers per endcap, each chamber spans 20°
- Installation: LS3

Muon trigger and reconstruction performance



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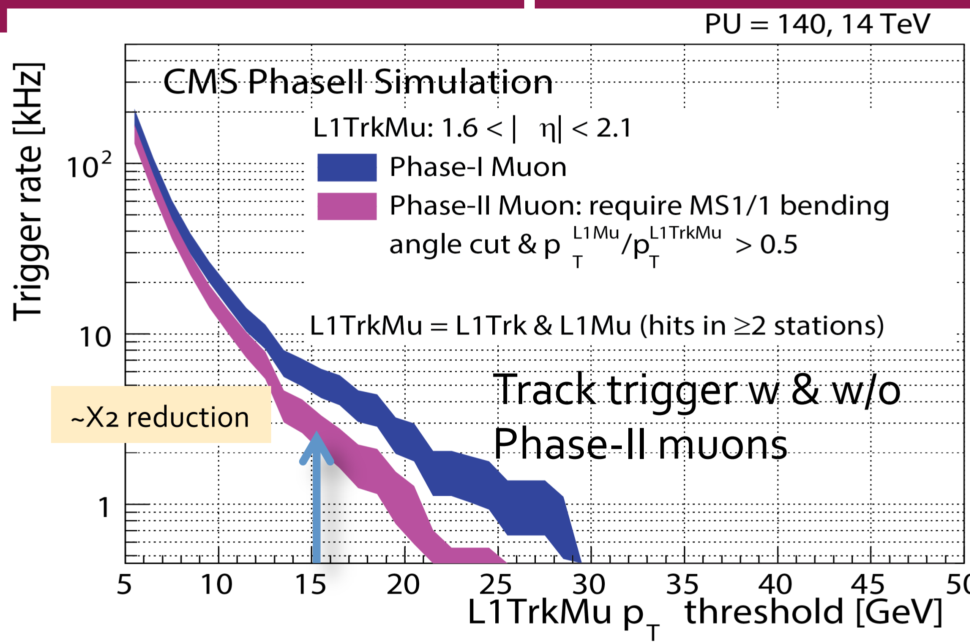
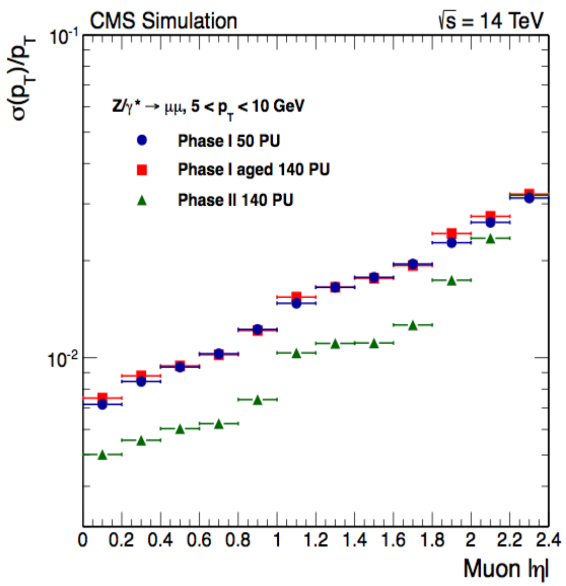
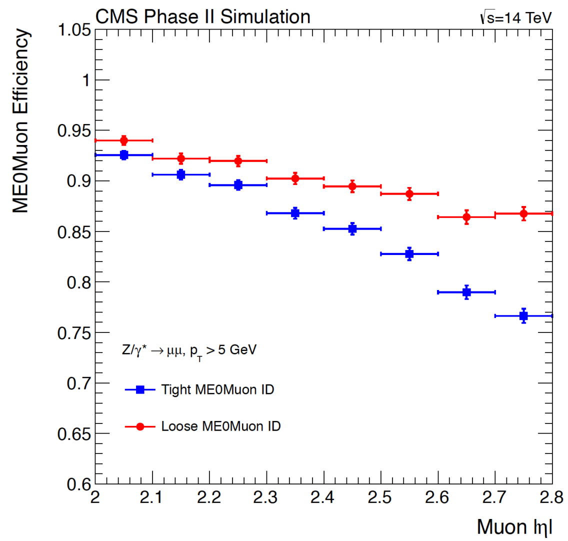


- Good standalone L1-Trigger capability - GEM1 important already after LS2
- Improved rate reduction combined with Track-Trigger
- Trigger on displace vertices
- Better offline reconstruction resolution - sign assignment
- ME0 provides efficient muon identification with reasonable background rates





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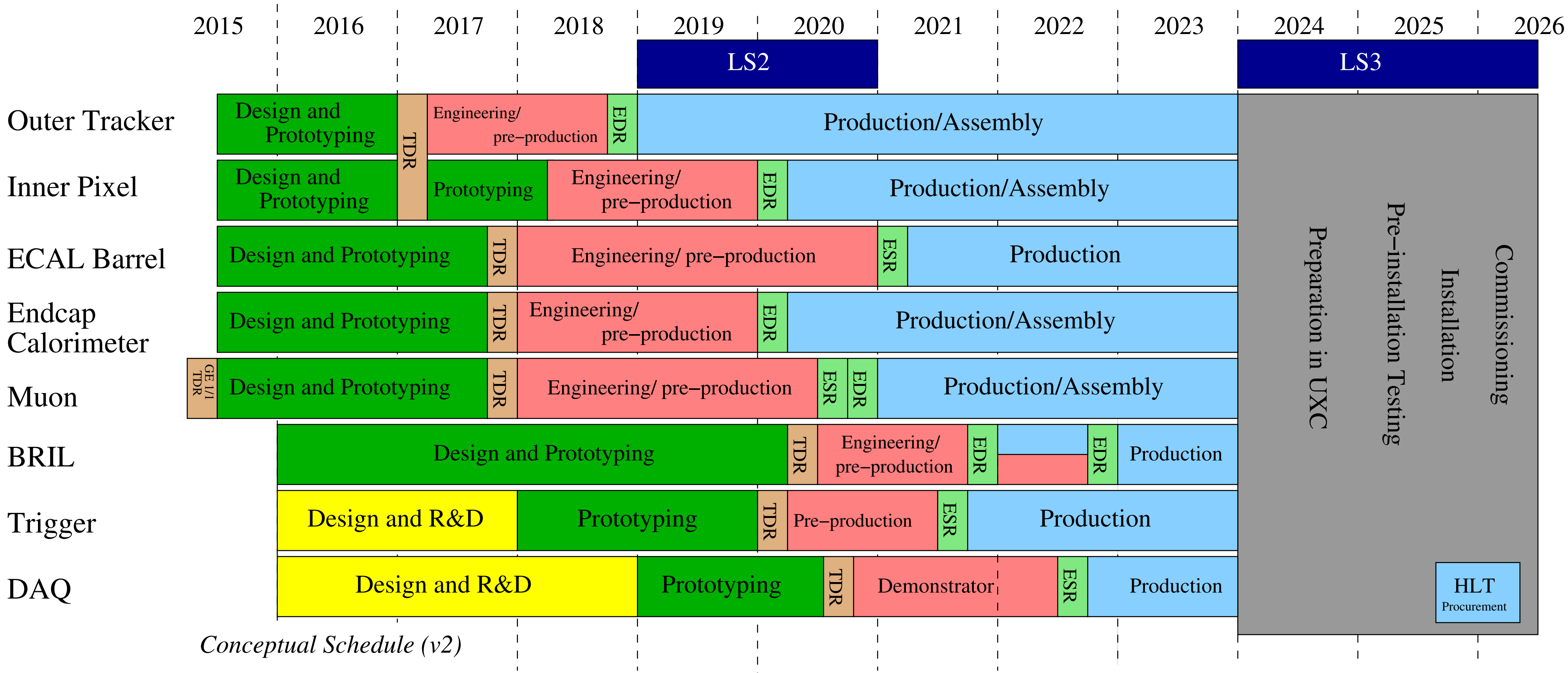
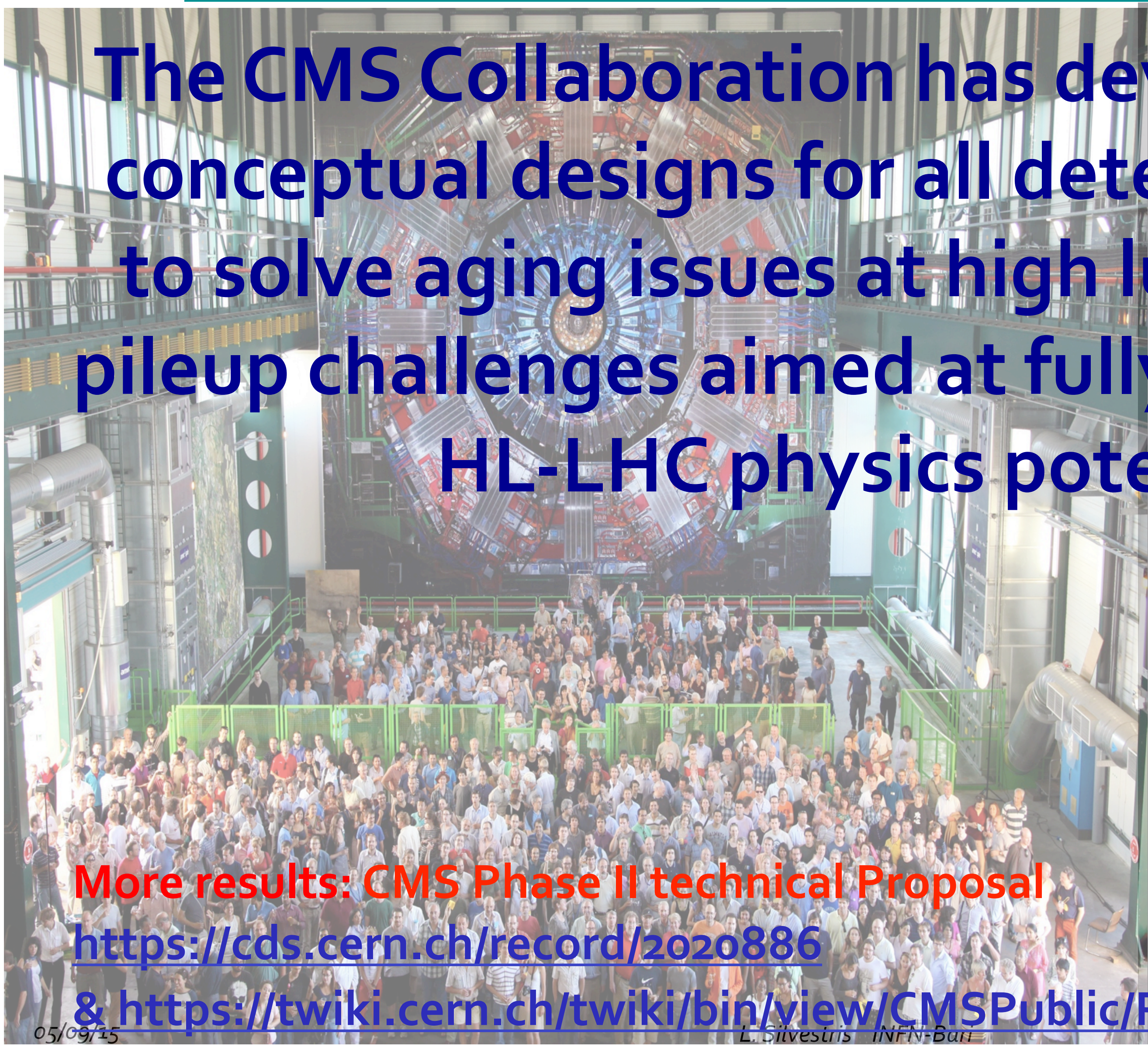
CMS Phase II Planning

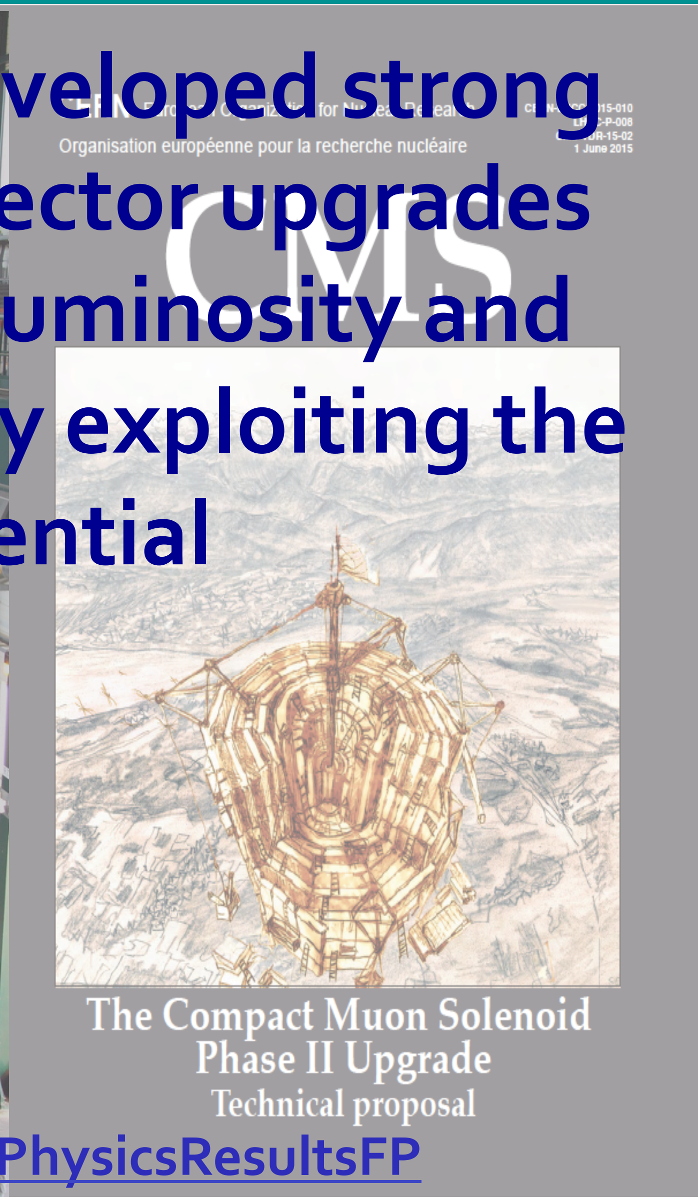
R&D program well established for all upgrades;
TDRs foreseen in 2017 will include design optimization and main technical choices



Conclusions



The CMS Collaboration has developed strong conceptual designs for all detector upgrades to solve aging issues at high luminosity and pileup challenges aimed at fully exploiting the HL-LHC physics potential

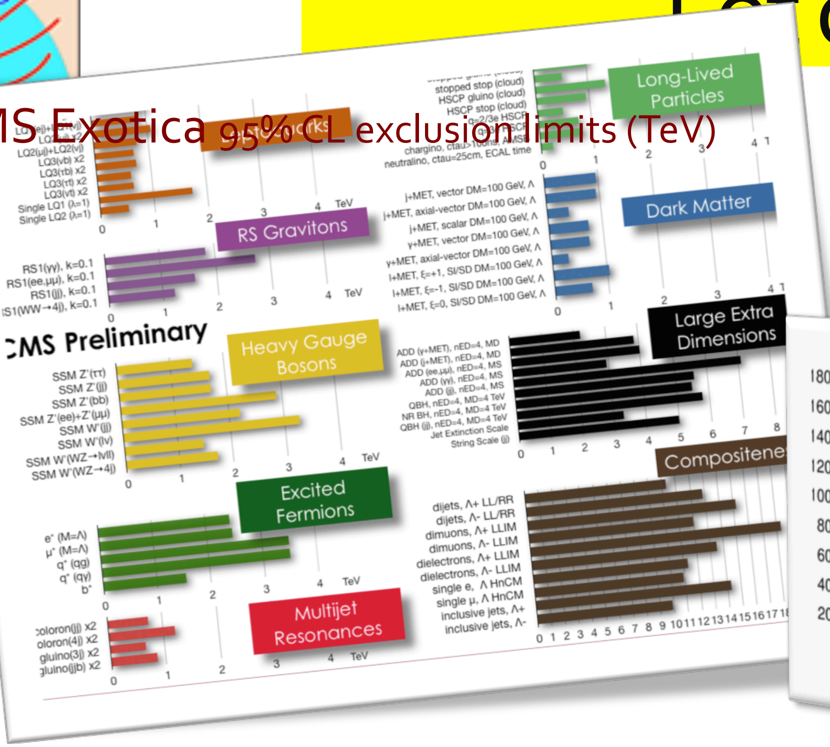


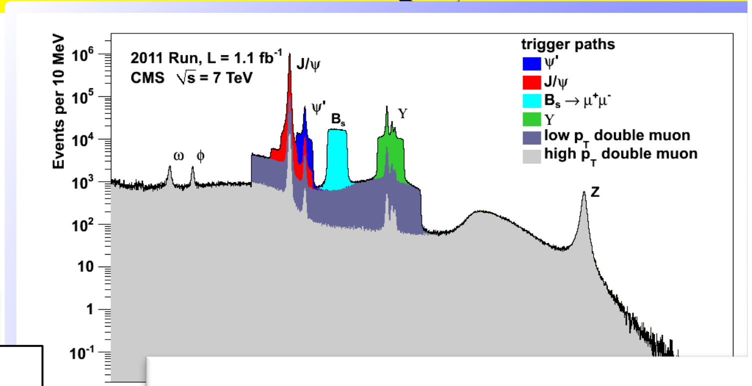
More results: CMS Phase II technical Proposal
https://cds.cern.ch/record/2020886
& https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

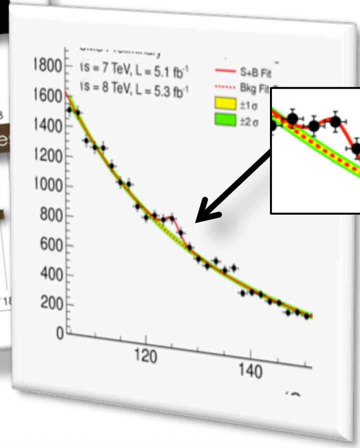
Back-up material

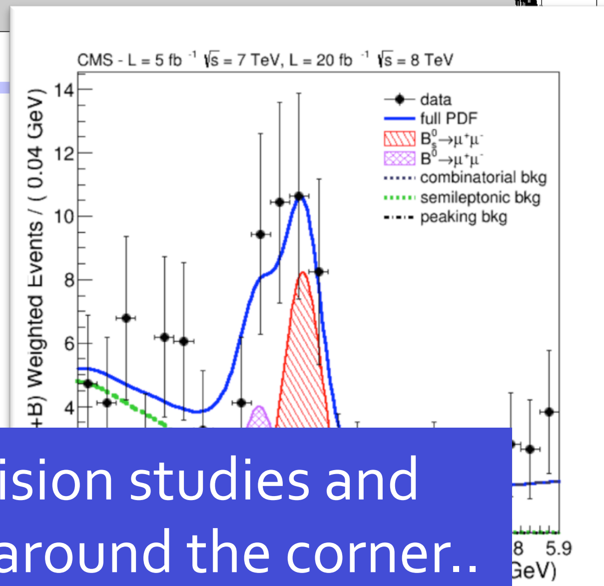
Lot of Physics Results @ RUN1

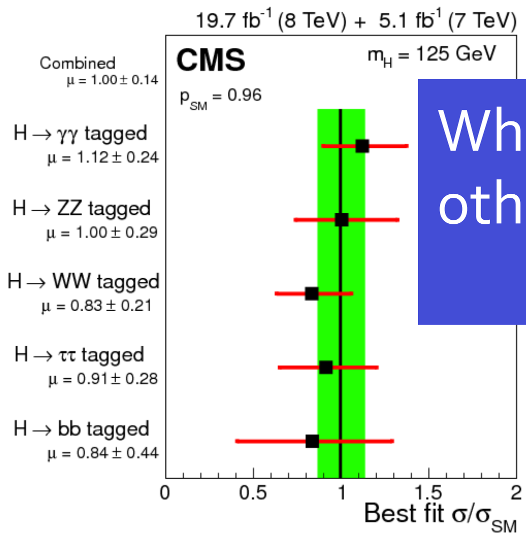
CMS Exotica 95% CL exclusion limits (TeV)

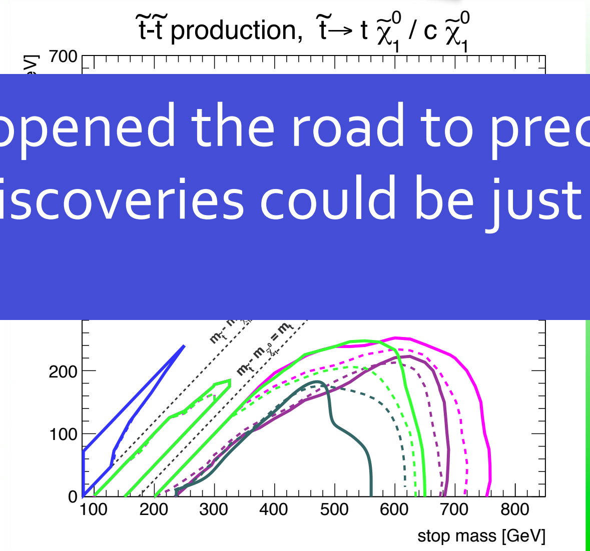


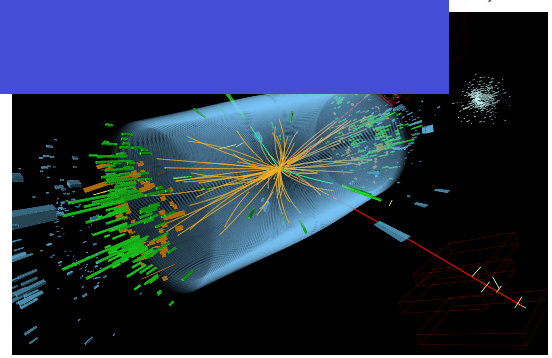












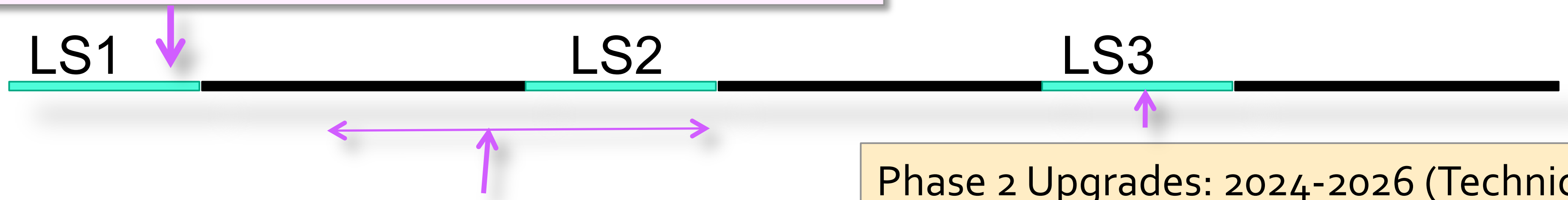
Which opened the road to precision studies and other discoveries could be just around the corner..

CMS Upgrade Strategy - Overview

Upgrades 2013/14 :

- Completes muon coverage (ME4)
- Improve muon trigger (ME1), DT electronics
- Replace HCAL photo-detectors in forward (new PMTs) and outer (HPD → SiPM)
- A lot of consolidation work

Complete original detector
Address operational issues
Start upgrade for high PU



Phase 1 Upgrades 2017/19 (TDRs):

- New Pixels, HCAL SiPMs and electronics, and L1-Trigger
- Preparatory work during LS1:
  - new beam pipe
  - test slices of new systems Pixel cooling, HCAL, L1-trigger)

Phase 2 Upgrades: 2024-2026 (Technical Proposal)

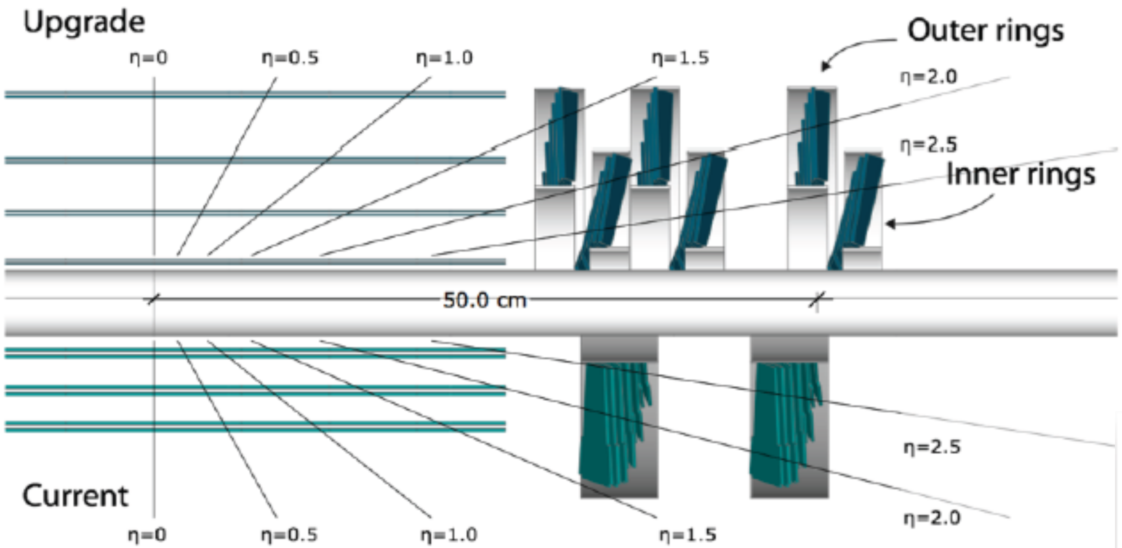
- Further Trigger/DAQ upgrade
- Barrel ECAL Electronics upgrade
- Tracker replacement/ Track Trigger
- End-Cap Calorimeter replacement
- Tracker extension to $|\eta| \sim 4$
- Muon extension from $|\eta| = 2.4$ to $|\eta| \sim 3$

Maintain/Improve performance at high PU

Maintain/Improve performance at extreme PU
Sustain rates and radiation doses

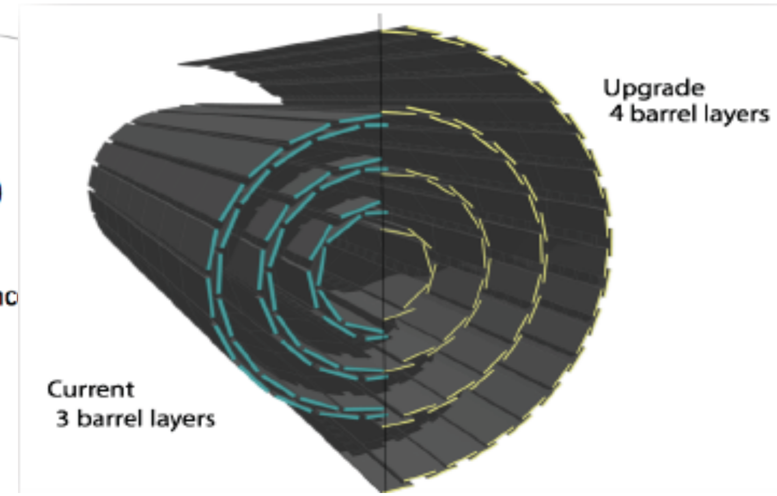
Phase I Pixel Tracker Upgrade

- 4^{th} barrel layer at r =16 cm, 3^{rd} disk at z = ±51.4 cm
- 4-hit coverage up to $|\eta| \sim 2.5$
- Smaller radius of innermost barrel layer from 4.4 cm to 3 cm : New beam pipe with smaller diameter



<u>Targets of Pixel Upgrade:</u> (To be installed in end of 2016 extended technical stop)

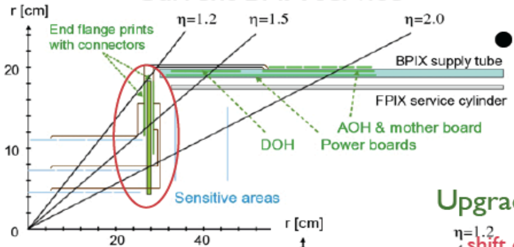
- Baseline L = $2x10^{34}$ $cm^{-2}sec^{-1}$ & 25ns → 50 pileup (50PU)
- Tolerate L = $2x10^{34}$ $cm^{-2}sec^{-1}$ & **50ns** → 100 pileup (100PU) , with reduced performanc
- Survive Integrated Luminosity of $500fb^{-1}$



Phase I Pixel Tracker Upgrade

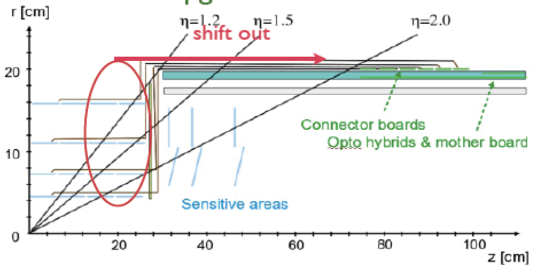
Minimize Material within Tracking Volume:
Optimize Performance of 4 Pixel Layer System

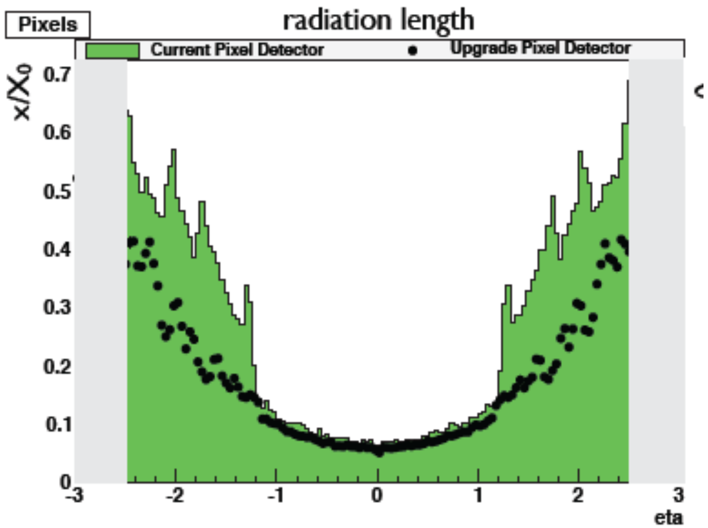
Current BPIX service



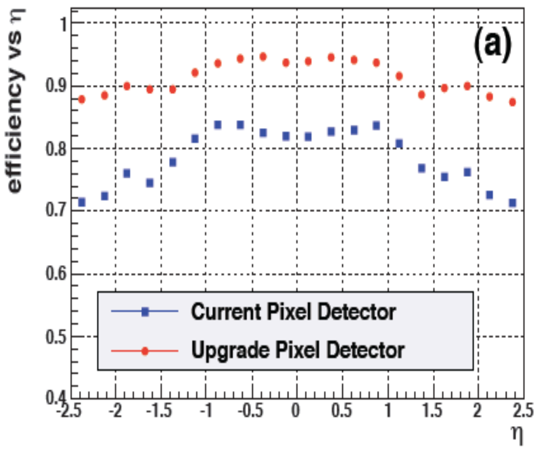
- Move the service outside of |η|=2

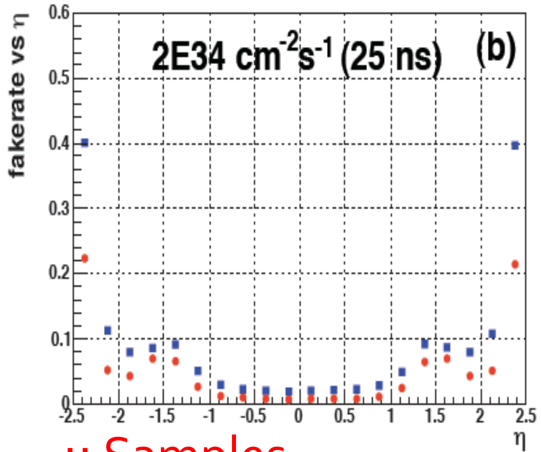
Upgrade BPIX service





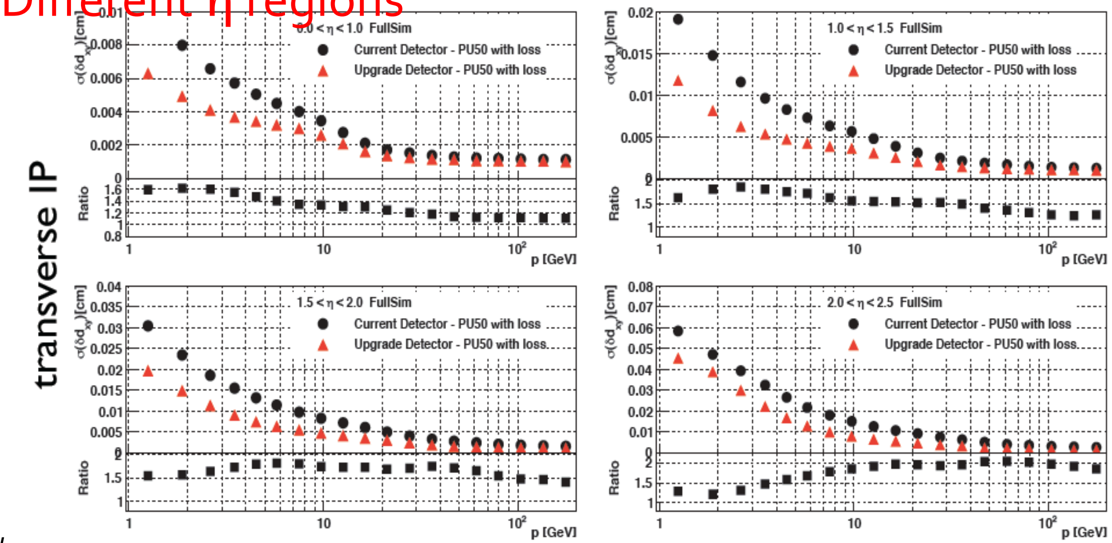
ttbar samples



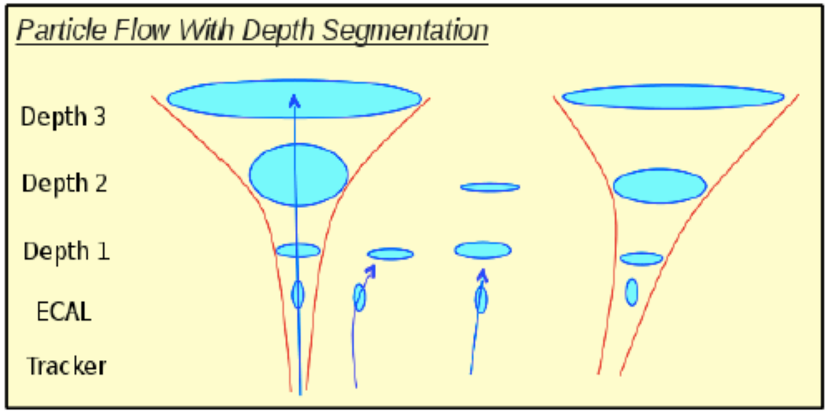


Different η regions

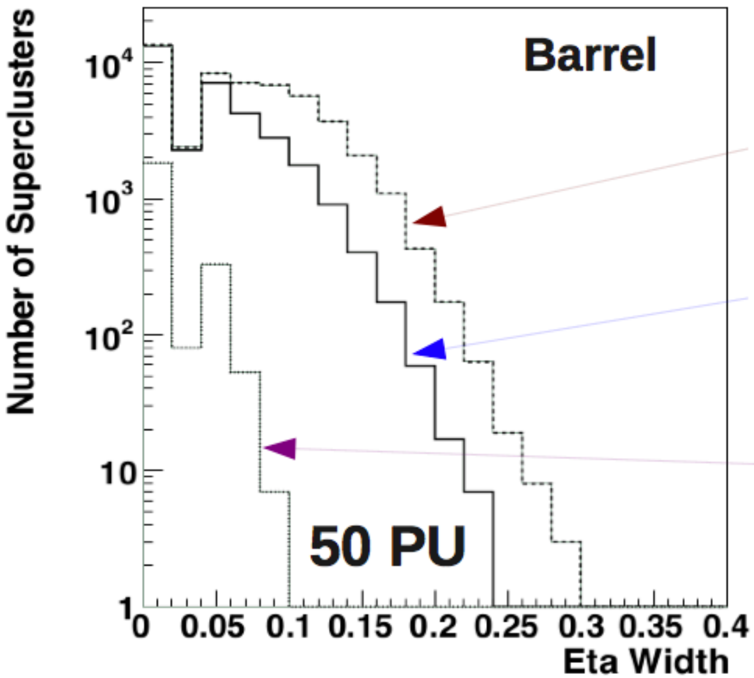
μ Samples



Phase I HCAL Read-Out Upgrades



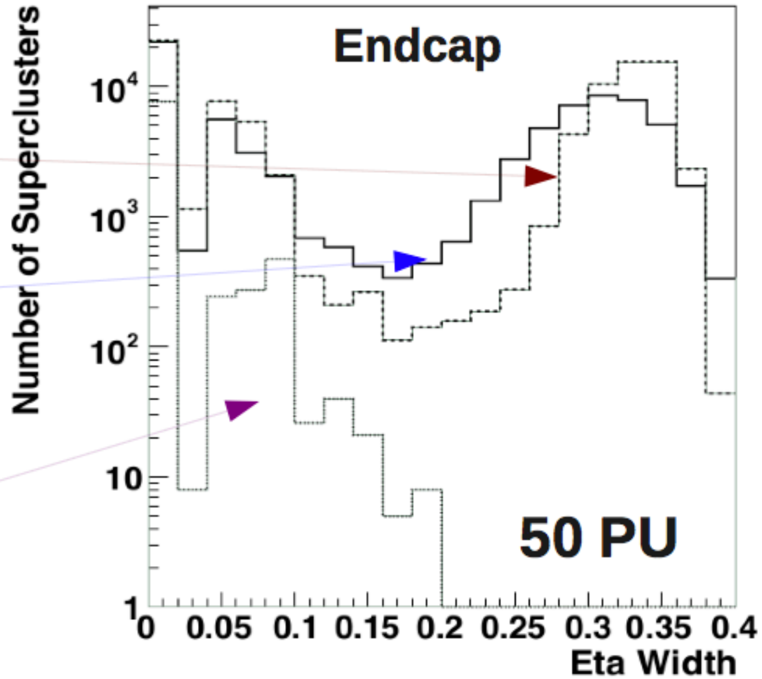
- Hadronic showers spread out with increasing depth
  - With a single–depth readout, pile-up energy will be pulled into a charged hadron cluster or true energy will be left out and labeled as a neutral hadron
  - With multi-depth readout, clusters can remain bounded



25 ns/standard

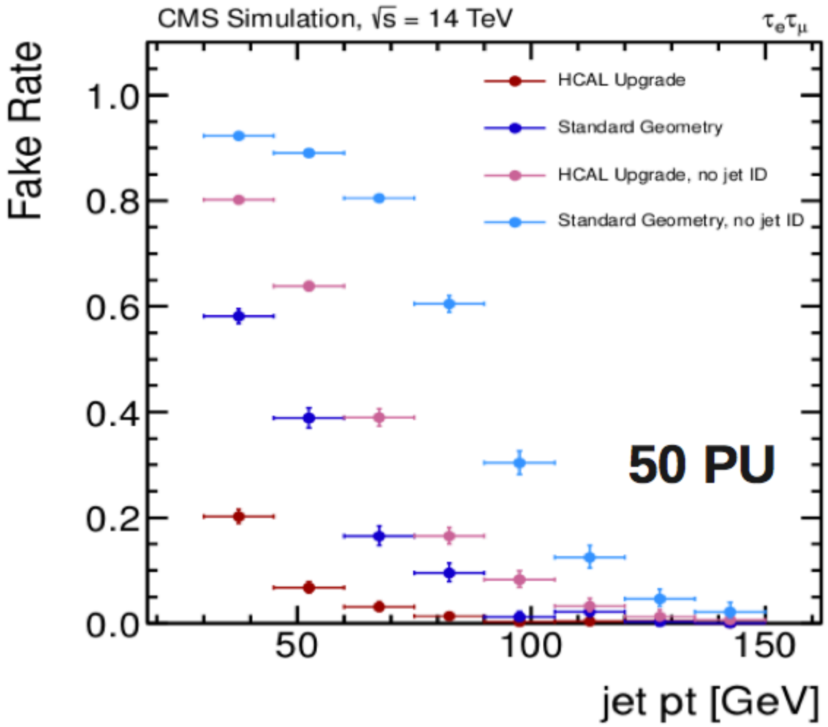
50 ns/standard

Upgrade PF

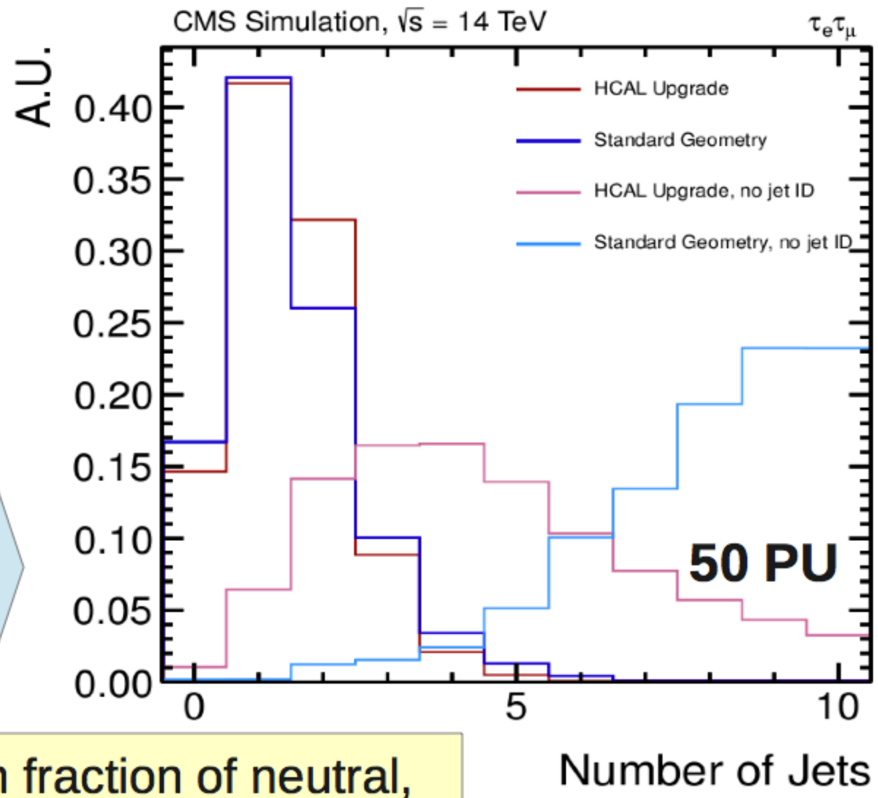


Phase I CMS HCAL Read-Out Upgrades

VBF→ ττ



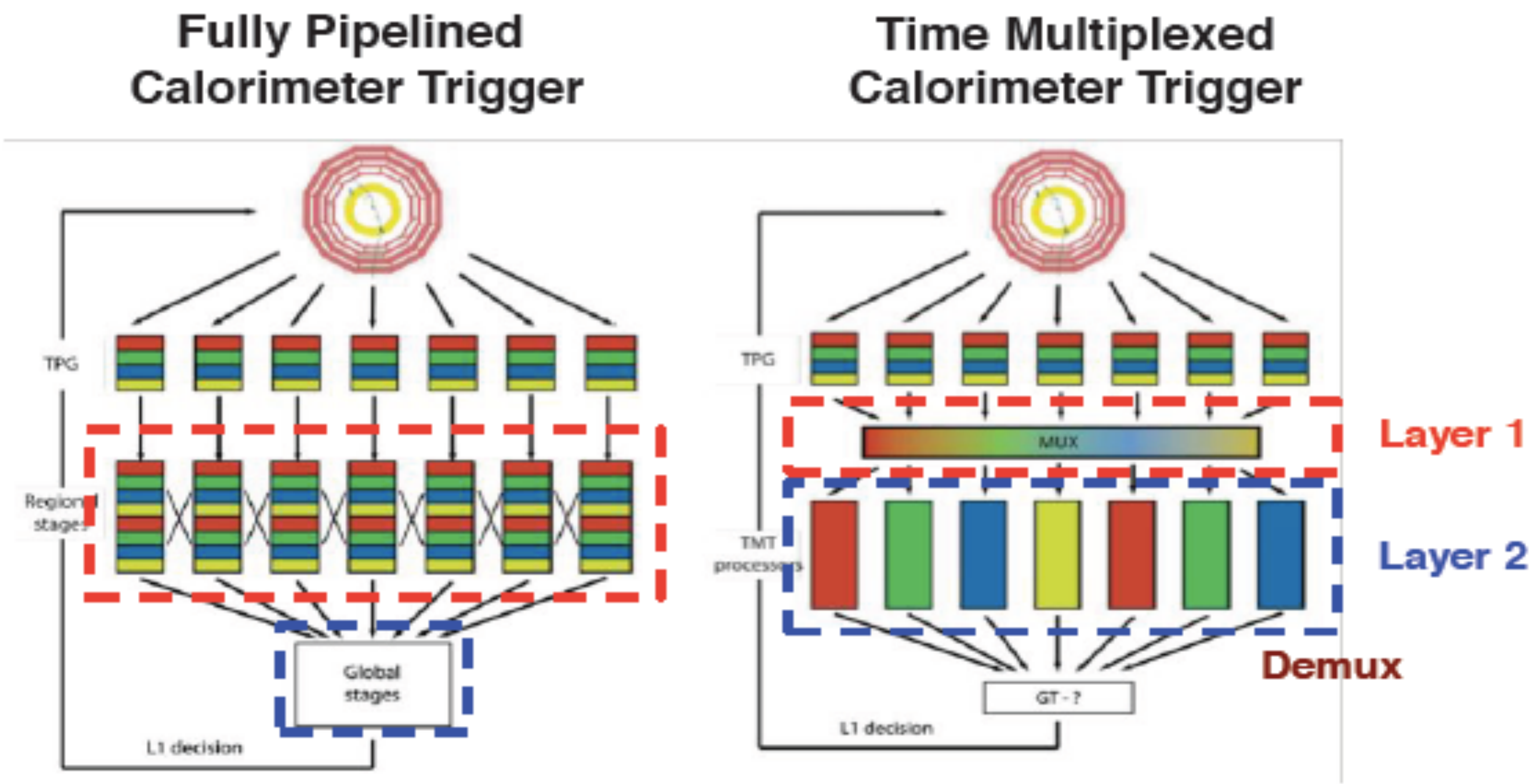
Significant reduction in jet fake rate, as defined as fraction of reconstructed jets not matched to generator jets



Efficiency of identifying true tag jets is improved, without increase in fake jets

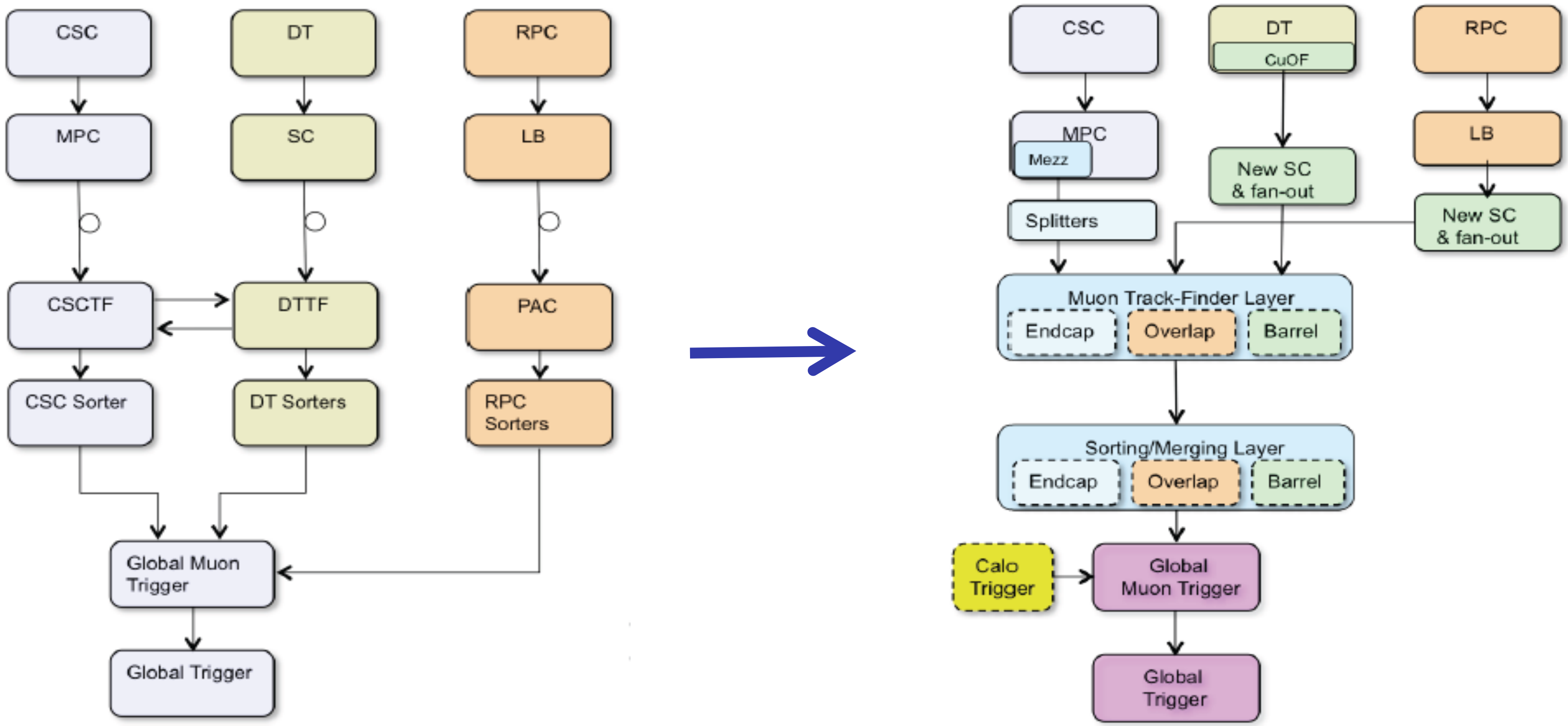
Jet ID from multivariate selection based on fraction of neutral, charged components, comparison of track, jet momentum

Phase I Calorimeter Trigger Upgrade



Layer 1 is optimized for backplane connectivity; Layer 2 for front-panel optical bandwidth
Access full granularity ECAL/HCAL Trigger Tower granularity for clustering, isolation etc.

Phase I Muon Trigger Upgrade



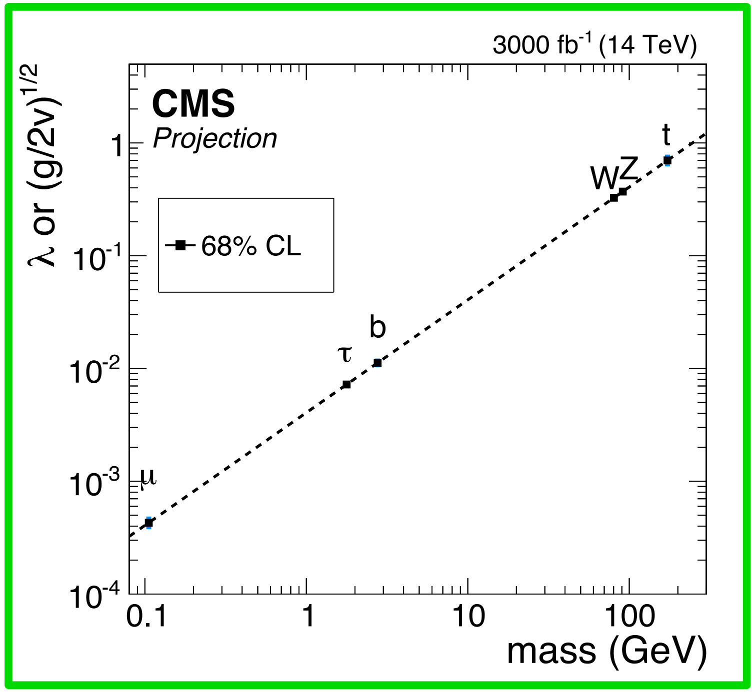
The present muon trigger system has separate CSC, DT & RPC muon track finders

Upgrade allows merging of CSC, DT & RPC segments for combined muon track finding
=> Improved robustness and efficiency

Enhancement of the Physics Reach with CMS Upgrades

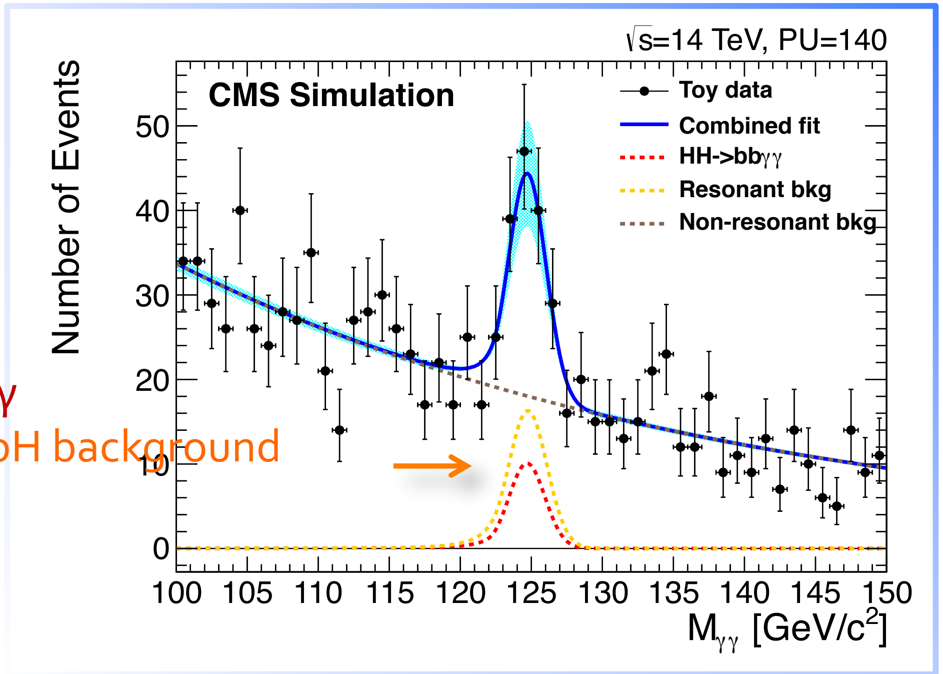
Performance/ Physics	Higgs VBF $H\to\tau\tau$	Higgs $H\to\mu\mu$	Higgs $H\to ZZ\to 4l$	Higgs $HH\to bb\gamma\gamma$	Higgs $HH\to bb\tau\tau$	SMP VBS	SUSY VH(bb) +MET	EXO A_{fb} (Z′)	EXO Dark Matter	EXO HCP	BPH $B_{s,d}\to\mu\mu$
Tracker											
Performance		*mass resolution*	mass resolution	*b-tagging*	*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*		

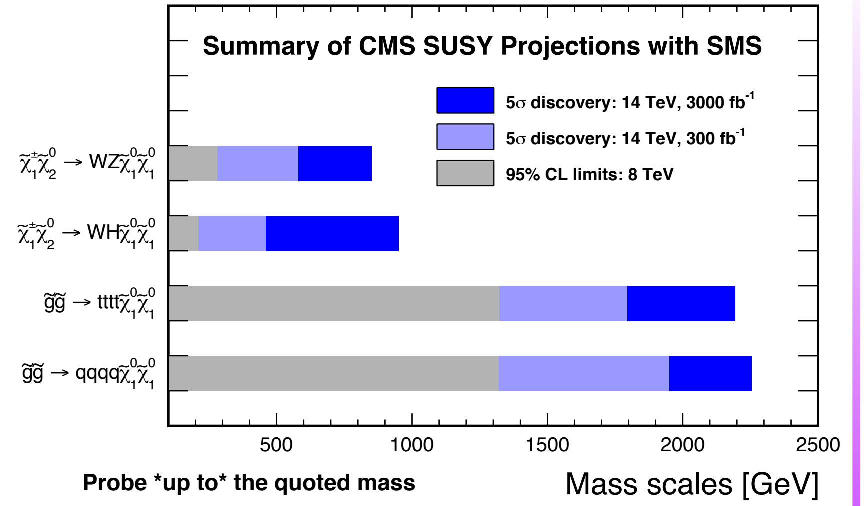
Motivators for HL-LHC



HH → bbγγ

ZH, ttH, bbH background





- Few % precision on Higgs couplings
- Evidence of di-Higgs production
- Access to small cross section SUSY processes
- Several other SM rare processes

and BSM physics predictions

Projection methodology

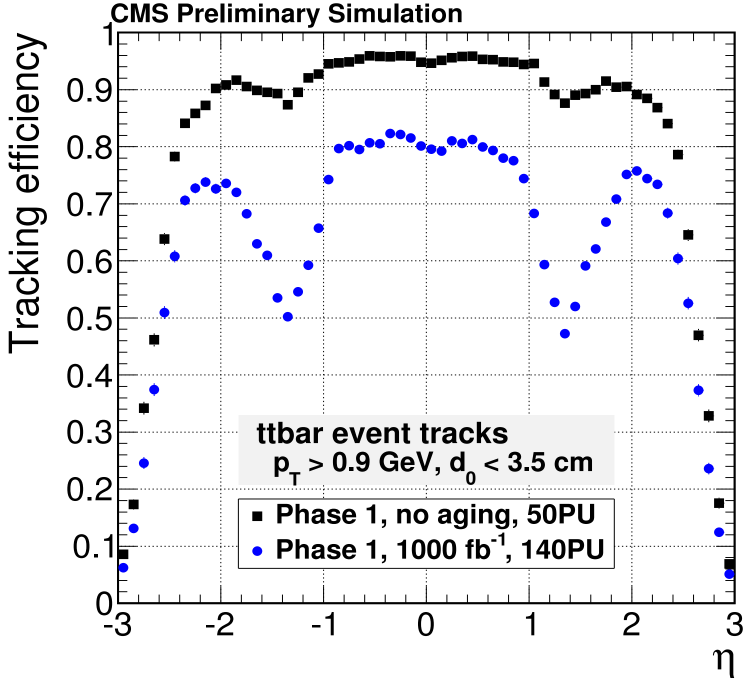
- Scale signal and background yields of the Run I analyses
- Two scenarios for systematic uncertainties
  - Scenario 1: Systematic uncertainties remain the same;
  - Scenario 2: Theoretical uncertainties scaled by ½, other systematic uncertainties scaled by $1/\sqrt{L}$

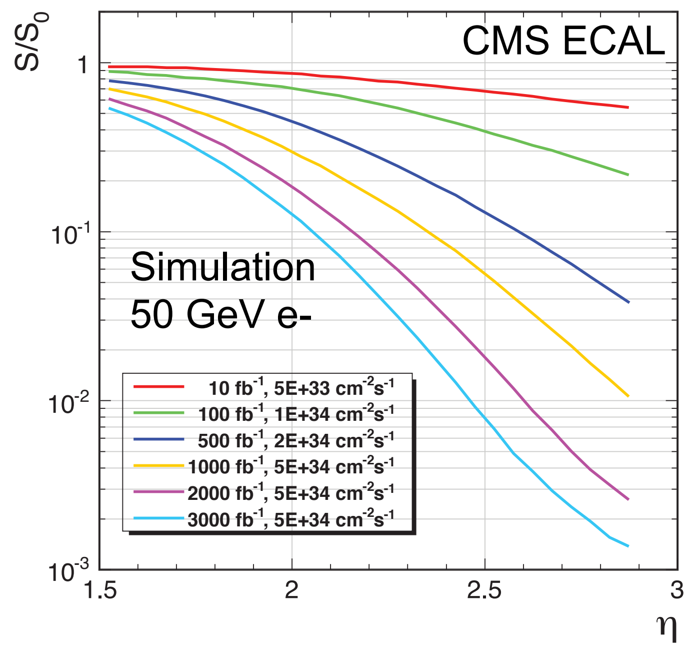
http://arxiv.org/abs/1307.7135

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]

Consequences of HL-LHC on detectors

Detector ages and performance deteriorates





→ **Need to replace tracker and forward detectors with rad-hard material**
Trigger needs to stay efficient (MHz → KHz). Keep trigger thresholds low for Higgs and particles from cascade decays
→ **Finer detector granularity and larger trigger bandwidth**

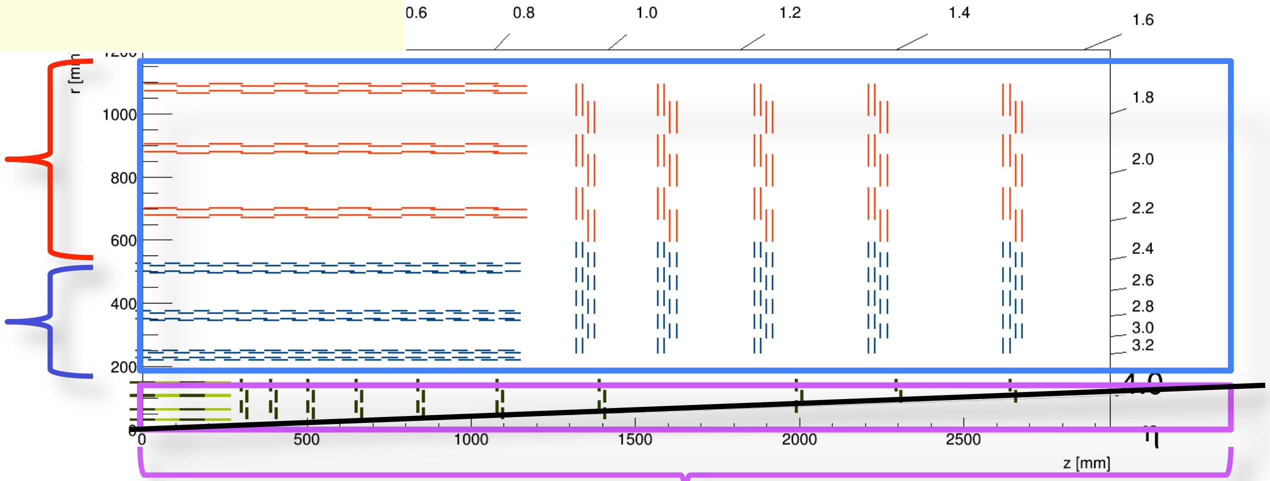
Phase II Tracker Design

Total Outer Tracker 220 m² area - 15500 modules
- 50M strips - 220M macro-pixels
- 90/100 μm pitch (2S/PS modules)
- 2.5/5 cm strips (2S/PS) - 1.5 mm macro-pixels in PS modules
- 200 μm active or physical thickness

Total pixel area ~ 4.0 m²
- 50x50 - 25x100μm² pixels
- ≤ 150 μm sensor physical thickness

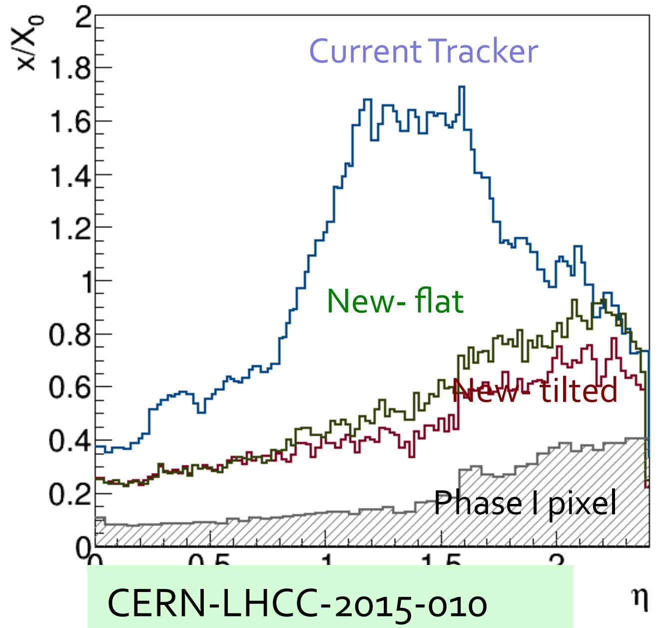
Strip/Strip modules 2S

Macro Pixel/Strip modules PS
Z measurement



Pixel modules

Tracker extension up to η=3.8



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Material (lighten up!)
- Tracker weight ½ of current
- Improved track p_T resolution & reduce rate of γ conversion (factor 2 to 3 depending on η)
- ex. HH -> bbγγ; ttH -> γγ ; H -> μμ - $B_{s,d}$ -> μμ ..

Tracker components

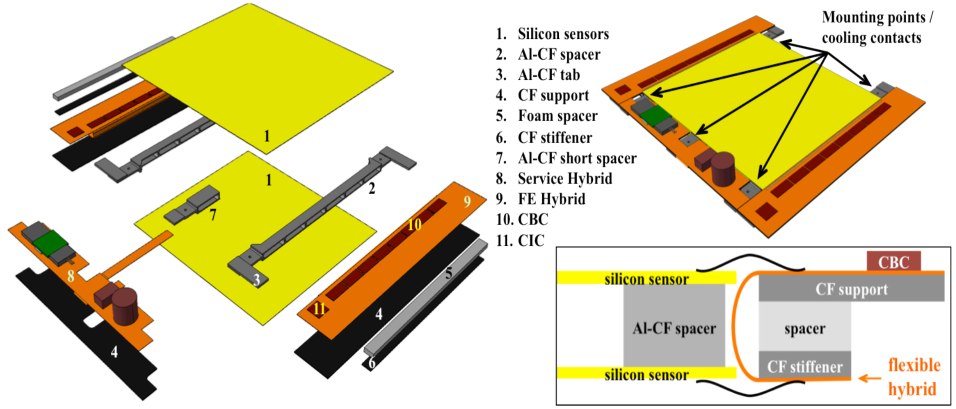
- Silicon sensors
  - Outer Tracker (max. fluence 1.5 x 10^{15} neq/cm^2 at 3000 fb^{-1}):
    - n-in-p technology selected
    - Now qualifying potential vendors for final specifications (physical thickness, bulk material, wafer size 6" or 8")
  - Pixels (max. fluence 2 x 10^{16} neq/cm^2 at 3000 fb^{-1}):
    - n-in-p preferred for cost, investigating 3D technology for innermost layer (finalizing layout - pixel size ability - comparing rad. tolerance)

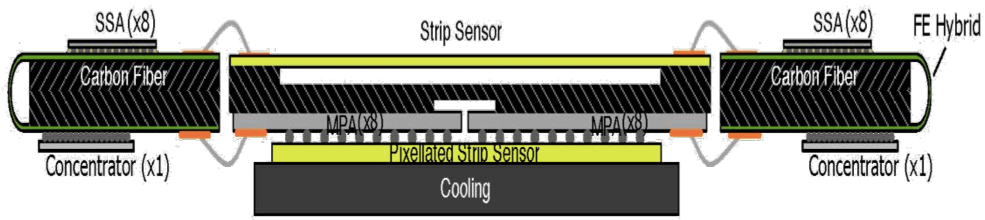
- Detector Readout
  - Outer Tracker: Binary chip CBC 130 nm IBM (2S modules) tested on flex hybrid - First version of MPA 65 nm TSMC ASIC (PS modules) available
  - Pixels: Common R&D53 with ATLAS - defined rules for radiation tolerance - design on-going
  - Data transfer: Work to increase Band Width of GBTs and lower power consumption
  - Powering scheme: DC/DC for OT and serial powering considered for pixels

Outer Tracker modules

- Only two types of modules: light designs with single frame for two sensors - FEA performed and first experience of prototype assemblies (w/o hybrids)

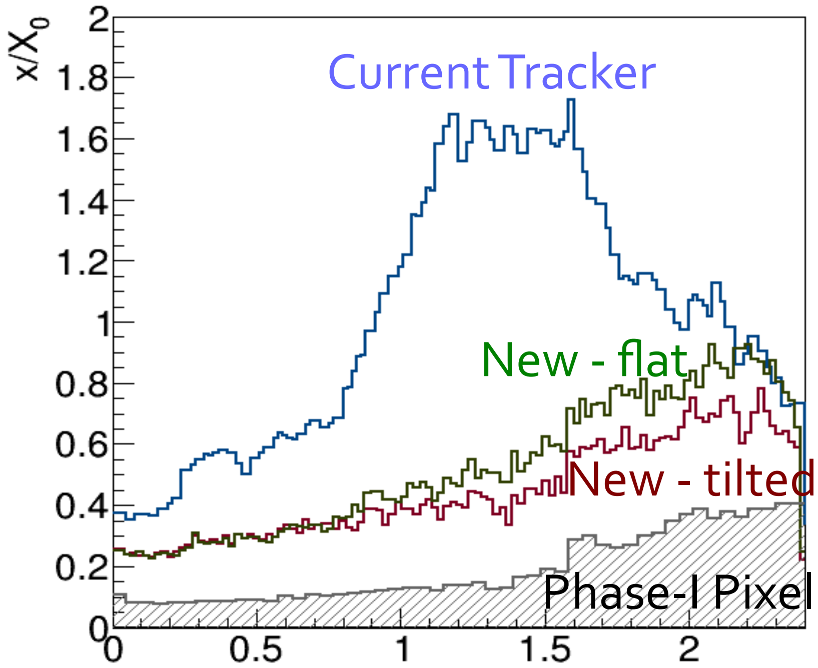
2S modules - 35-40 g





Sensor T ≃ -20° for -30° cooling

- Material
  - Tracker weight ½ of current
  - Gain of a factor 2 to 3 on photon conversion rates depending on η



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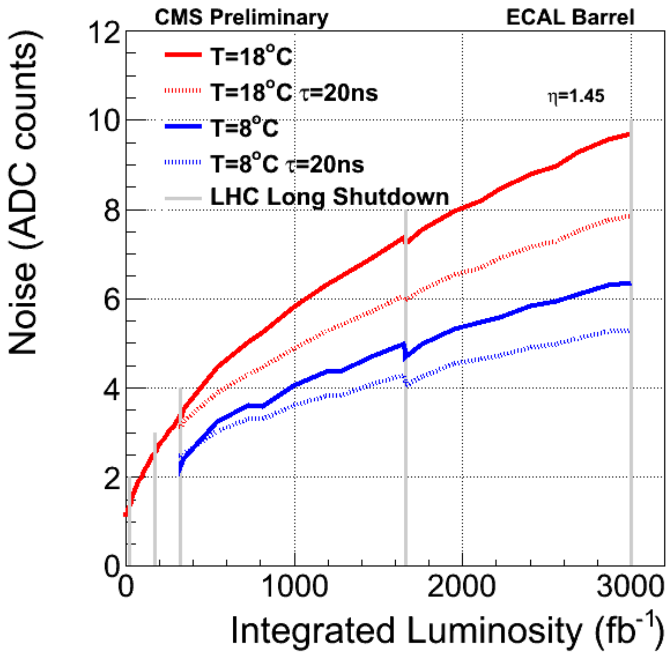
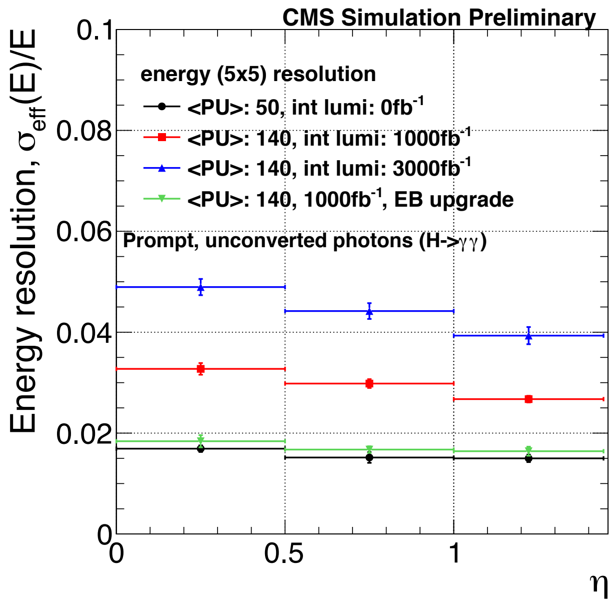
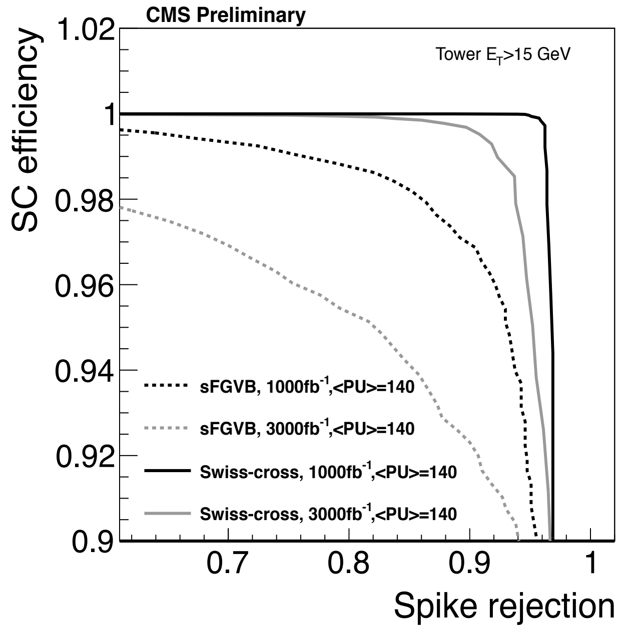
Phase II ECAL Barrel

- Replace VFE: Shorter shaping time (20 ns instead of 40) for PU/spike rejection & APD noise mitigation
- Replace FE: Overcome L1-Trigger rate & latency limitations and provide crystal granularity at 40 MHz
- Lower temperature: 8◦ instead of 18◦ reduce APD noise

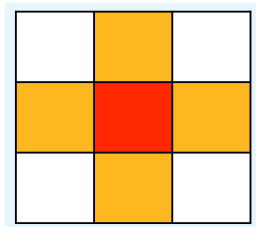






Predicted improvements in efficiency/rejection performance when single-crystal information is used to reject spikes.

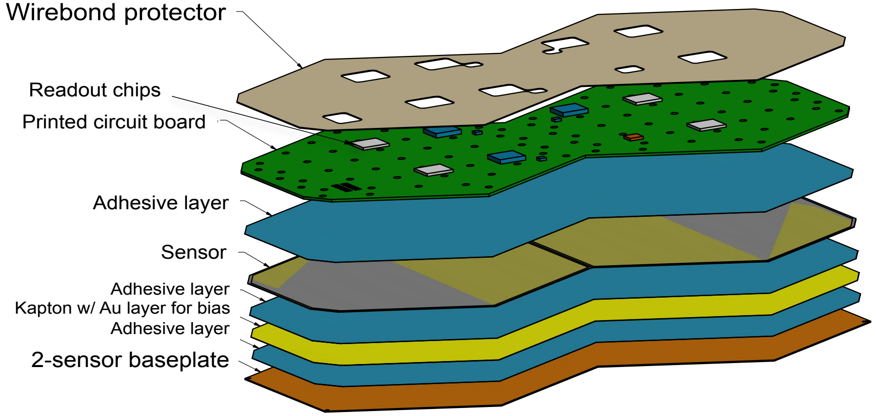
Energy resolution for unconverted photons calculated from a 5x5 crystal matrix vs η for various aging scenarios.



Swiss Cross Algorithm

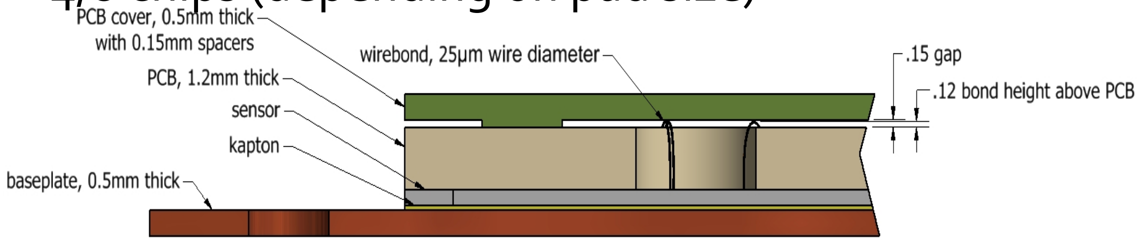
Cooling from 18°C to 8°C will reduce noise by 40%
Upgrading VFE reduces by further 30%

HGC Silicon sensor modules

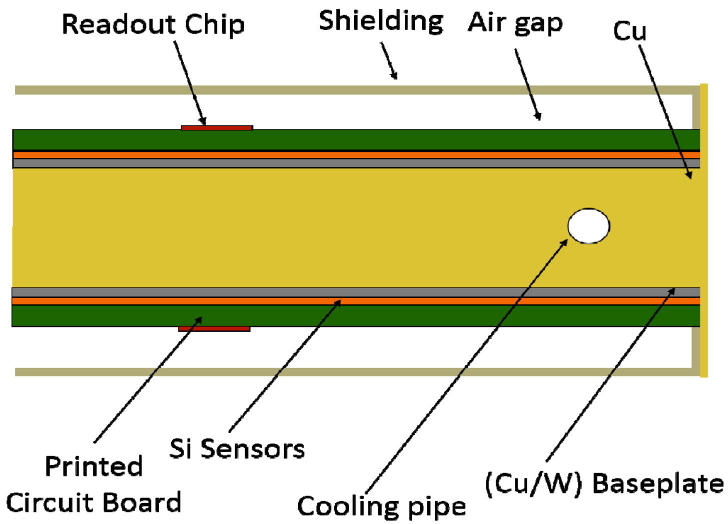


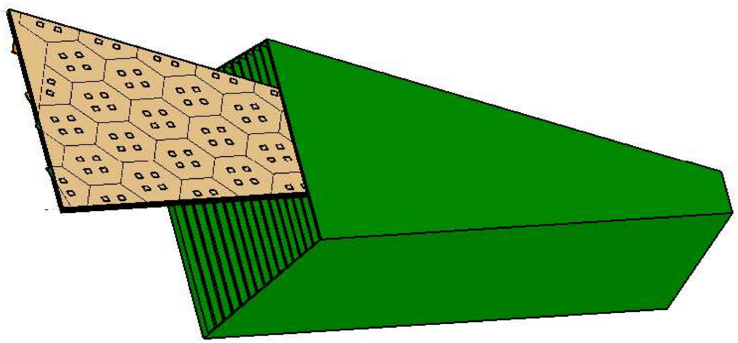
2 x 6" sensor modules 256/512 channels

4/8 chips (depending on pad size)

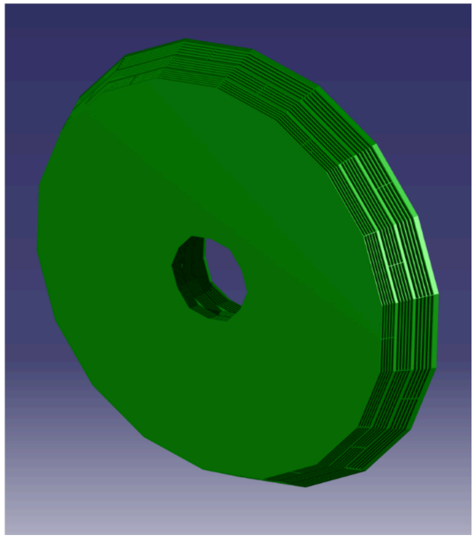


- Silicon operation at -30° with CO_2 cooling - from FEA studies Si at -28.5° with 1.4° gradient
- Thermal matching deformation test with prototype indicate ≃ 6 Mpa constraint well below tensile strength
- Total cooling power ≃ 125 kW (after 3000fb^{-1})





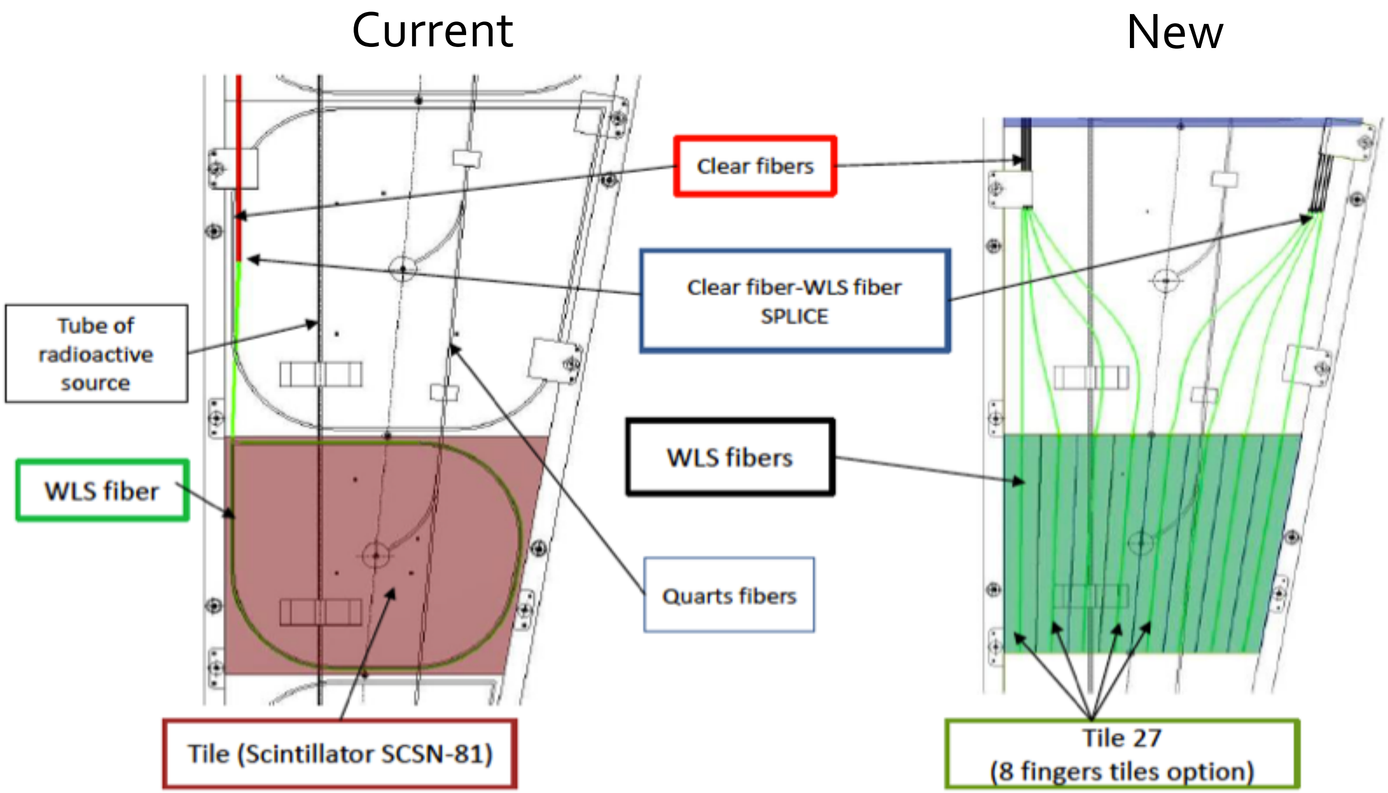
30° sectors



L. Silvestris INFN-Bari

Back Hadron scintillating tiles

- Improvement of current HE tiles for ≃ 5 Mrad tolerance
  - Doubly-doped plastic scintillator x 2 light after irradiation
  - Finger tile design - shorter light path

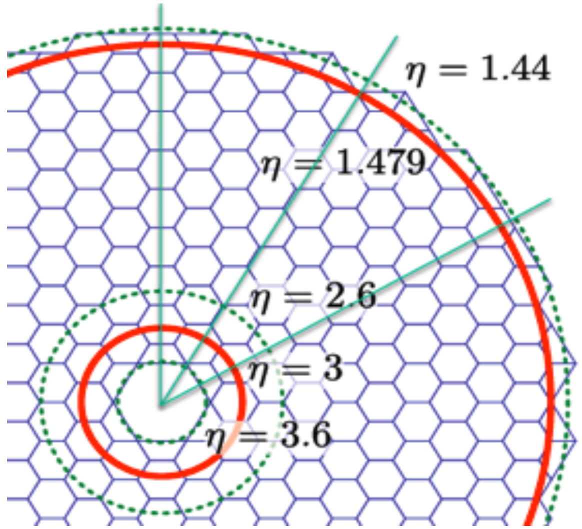


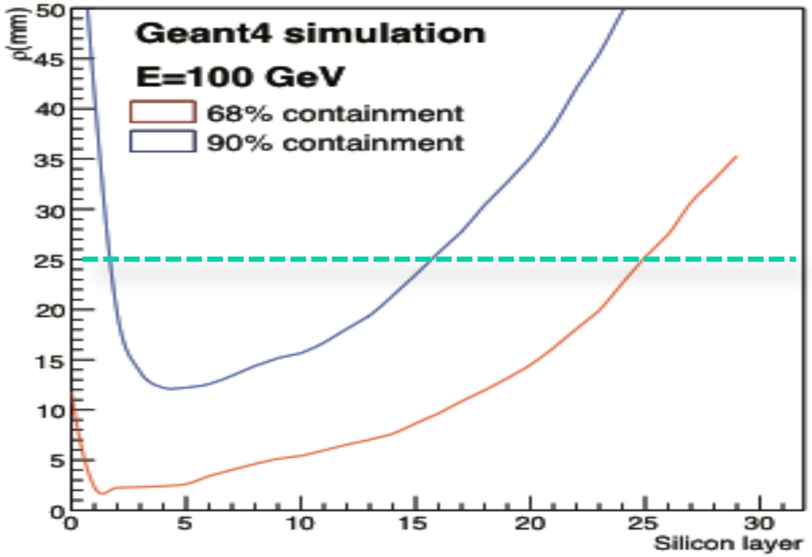
  - And also increased granularity ≃ x 2 in Φ & x 1.3 in η

High Granularity Calorimeter (HGCAL)

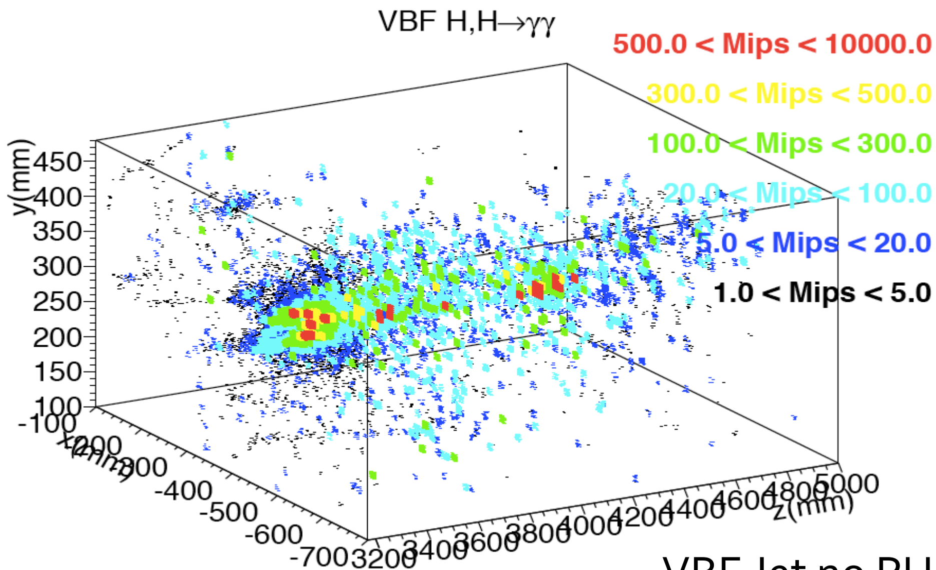
- 3D measurement of the shower topology
  - 25 mm Moliere radius (shower narrower before max)
  - Expected e/γ resolution ~ 20%/sqrt(E) + ≤ 1%
- Studies and R&D
  - Many common R&D areas with Tracker
    - Si sensors (similar fluence as in innermost pixel layer)
    - Readout and cooling concepts
  - Engineering studies
    - Module design and thermal properties
    - Mechanical design, thermal shield and services

Tiling of 8″ hexagonal Si-sensors modules





Simulation of energy deposit containment 150 GeV e



VBF Jet no PU

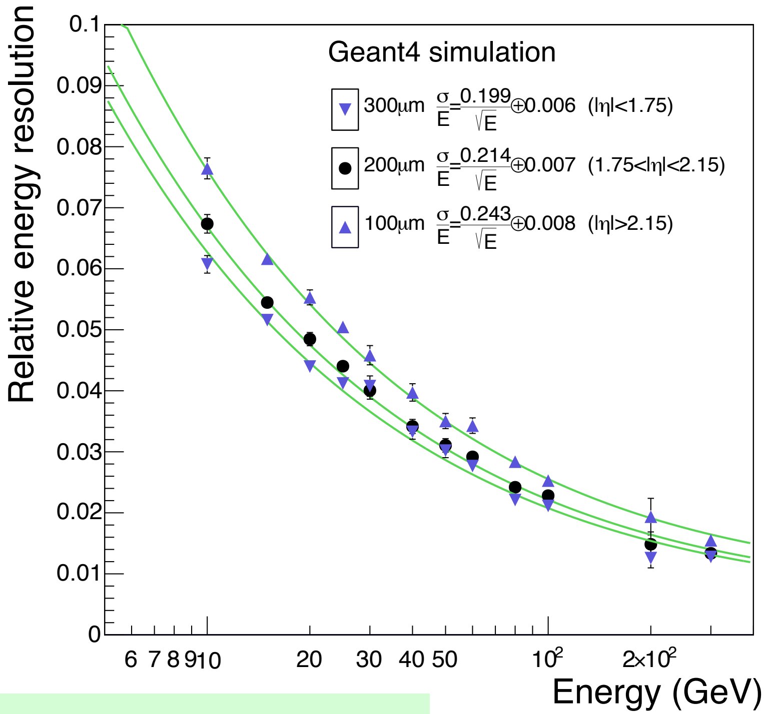
HGCAL Performance Studies in standalone set-up

Simulation benchmarked against published CALICE test-beam results

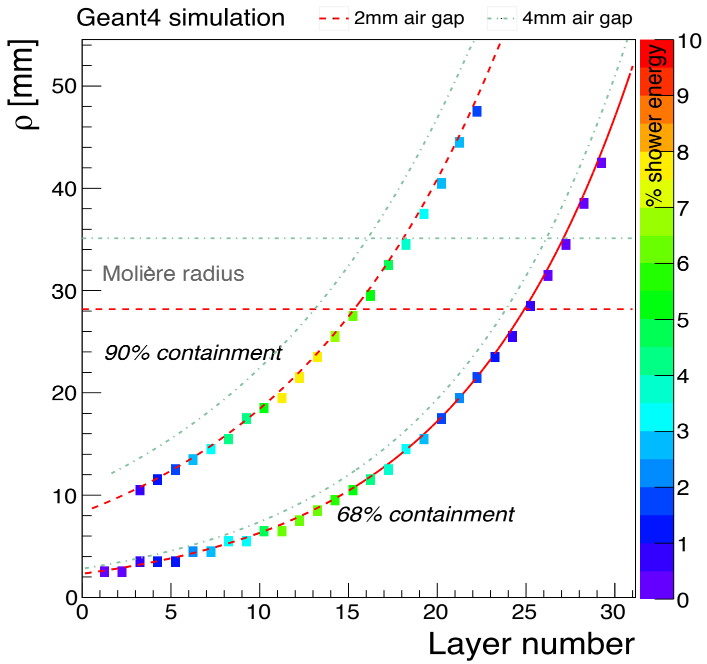
Electrons

Target 1% constant term (em)

Energy Resolution v/s Si thickness



em shower energy containment



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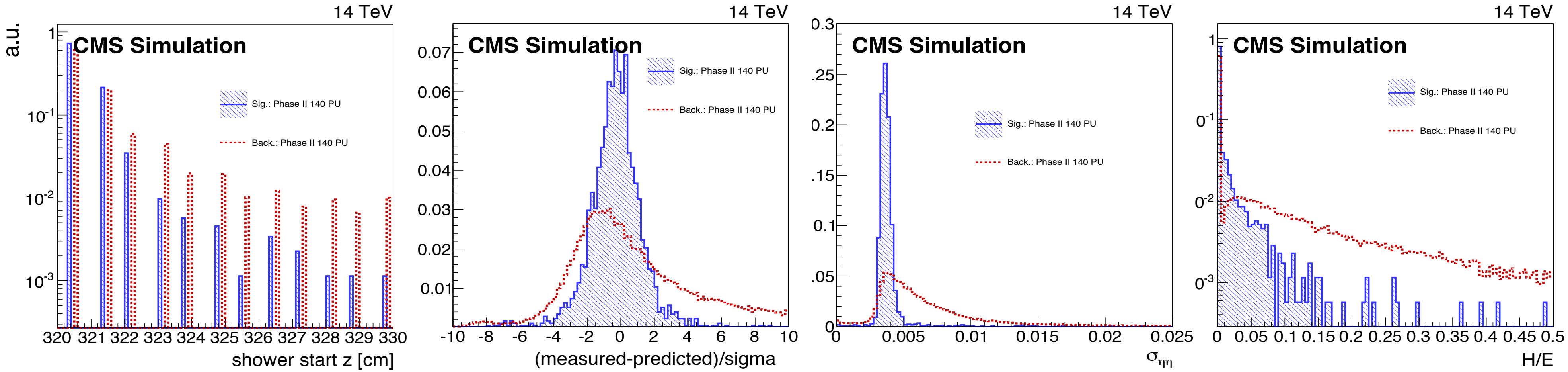
HCG e/γ new ID variables

Shower start | Length compatibility | η width | H/E



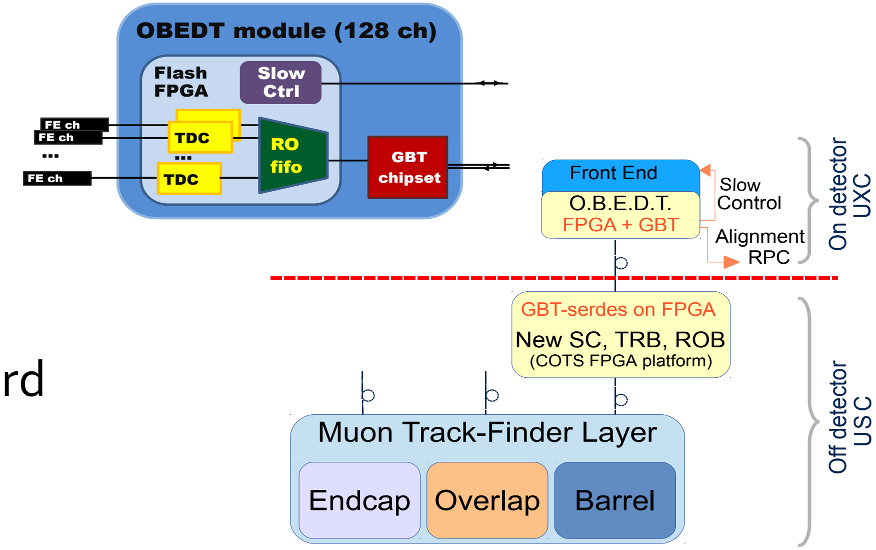
Signal (blue) - background (red)

- And to mitigate PU use trans. granularity - cells in ≤ 1.5R_M - H/E in tight cone 0.05

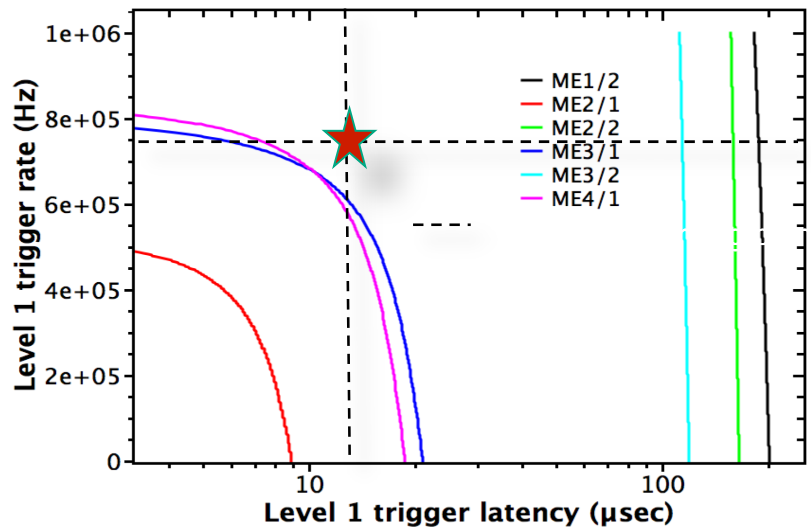
Variables used to perform the electron identification using BDT trained algorithm.

Upgrades to Muon system readout electronics

- DT Minicrates replacement
  - Radiation tolerance of some FPGA
  - Overcome 300 kHz L1-Trigger rate limit
  - Provide full DT resolution at L1
  - Maintain only TDC function in 1 single FE board

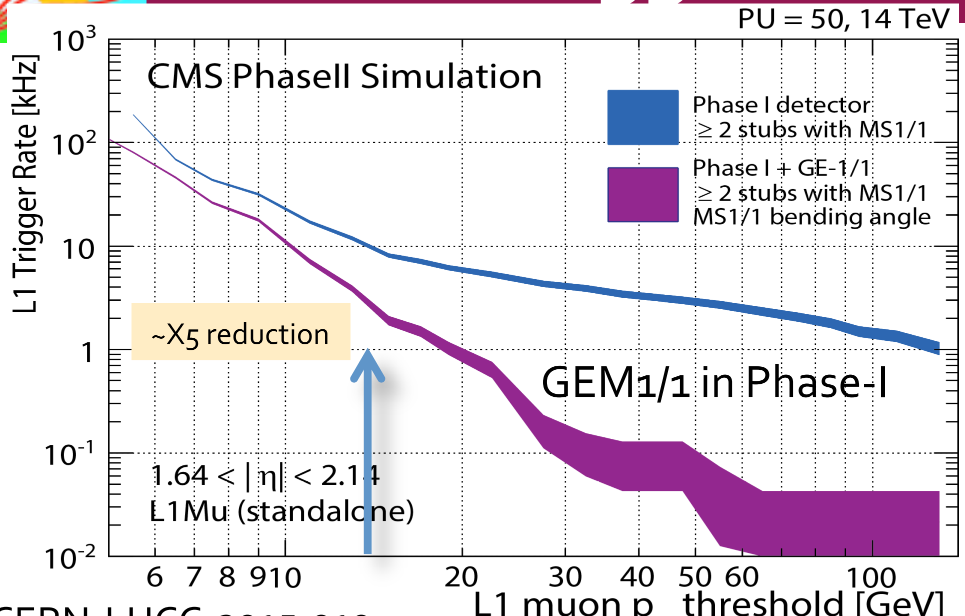


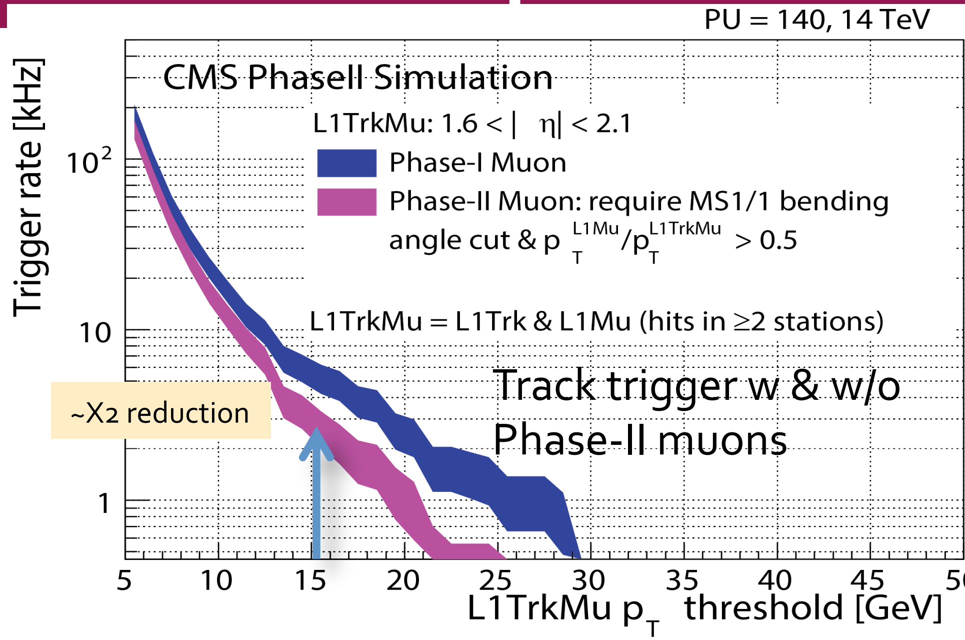
- CSC FEB replacement
  - Remove latency and rate limitation at L1-Trigger in inner rings of station 2, 3 & 4
  - Based on the DCFEB developed for the upgrade of the ME1/1 station



2% loss contour extrapolation from data

Muon trigger and reconstruction performance





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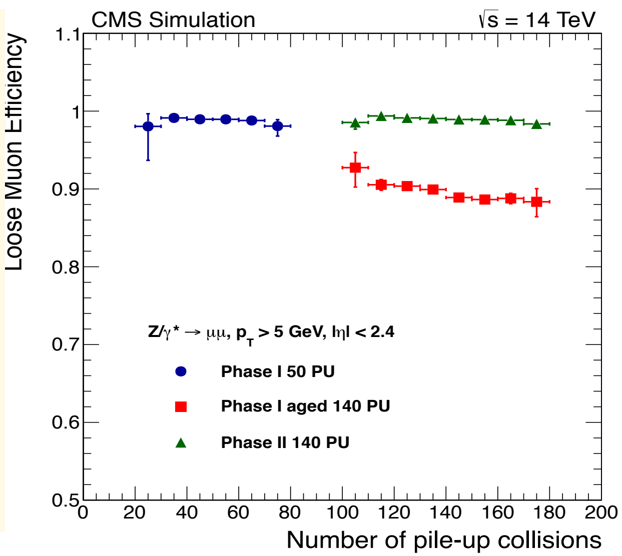
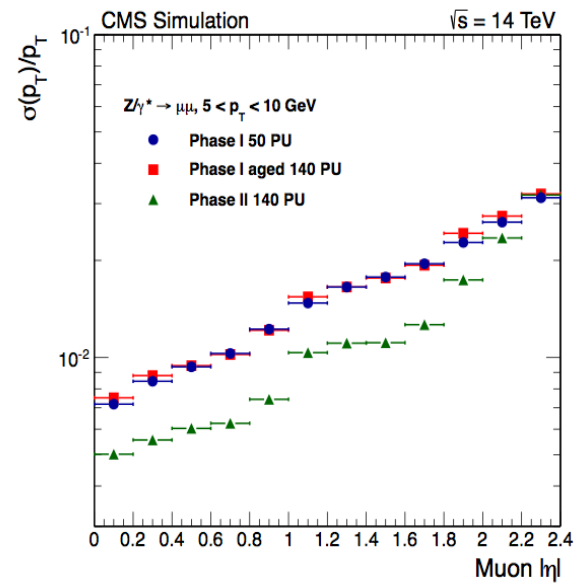
- Good standalone L1-Trigger capability - GEM1 important already after LS2
- Improved rate reduction combined with Track-Trigger
- Trigger on displace vertices
- Better offline reconstruction resolution - sign assignment





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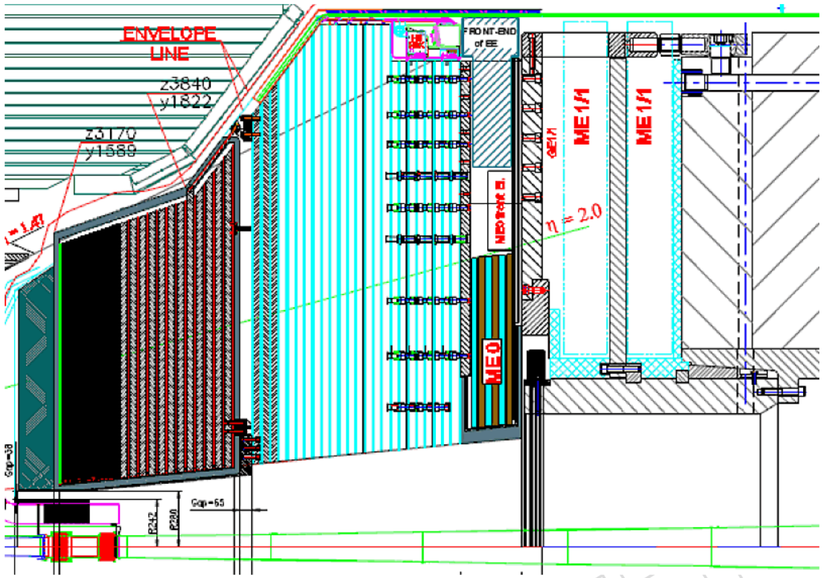
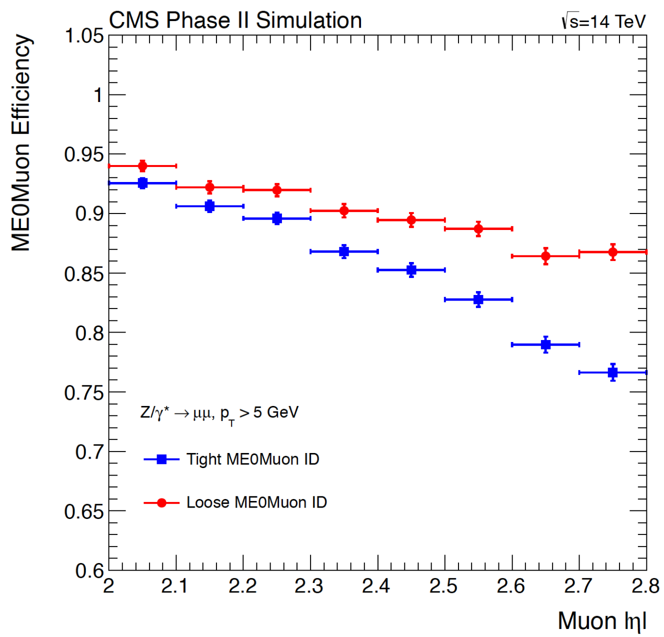
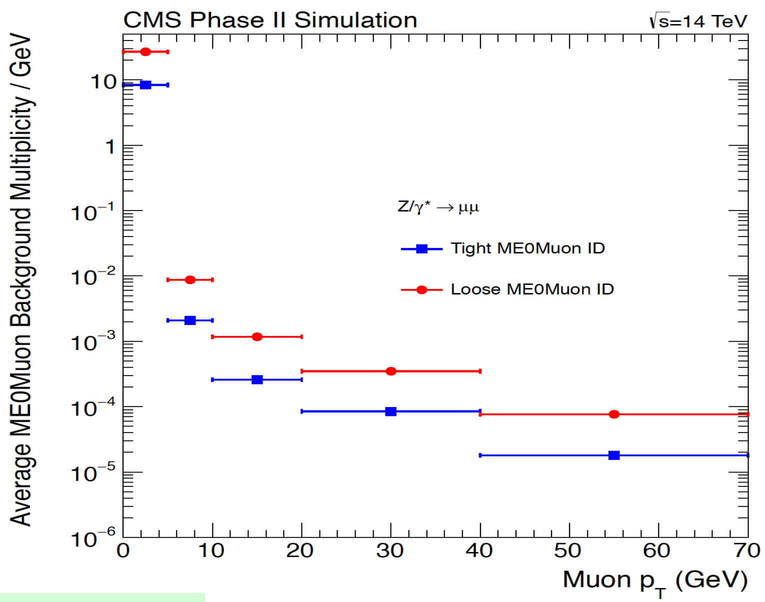
Muon tagger



- New muon detectors MEo (6-layer GEM detector) cover 2.0 < |η| < 2.8
- segments matched with tracker tracks
- MEo provides efficient muon identification with reasonable background rates





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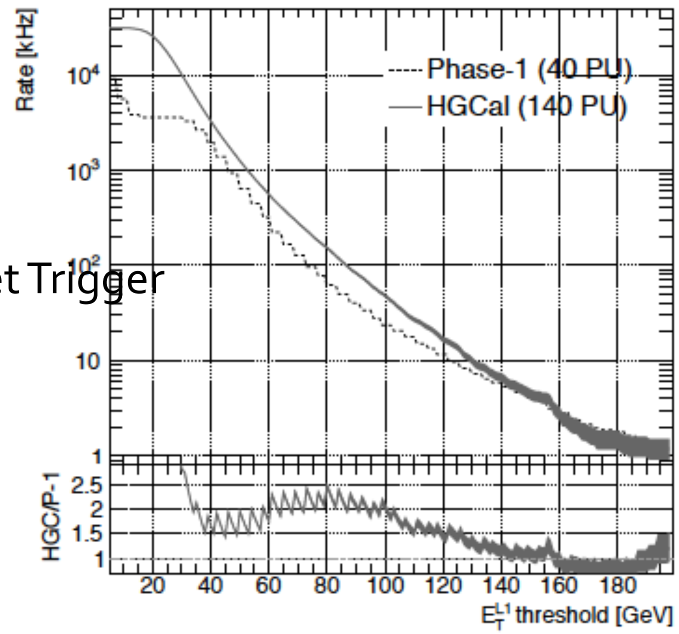
Object Performance Summary

- Demonstrated that reconstruction of Physics Object is possible in HL-LHC environment
  - High efficiency
  - Low background
  - Good resolution
- Matching Phase 1 performance with PU=50 in most cases
- Phase 2 detector will allow CMS to fully benefit from the data delivered by the HL-LHC

Level 1-Trigger

- 500 (750) kHz for 140 (200) Pile-up with safety margin (1.5)
- Offline threshold comparable to Run 1
- Crucial to exploit the 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

L1 single Jet Trigger



Warning: this menu is just a sample table only for evaluating bandwidth

$L = 5.6 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ $\langle PU \rangle = 140$	Level-1 Trigger with L1 Tracks	
Trigger Algorithm — Menu with L1 Track Trigger	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-veto)	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@125
Quad Jet (tk)	12	4@72
Single ele (tk) + Jet	15	23 66
Single Mu (tk) + Jet	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**	

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L1-Trigger/HLT/DAQ upgrade features

- L1-Trigger
  - High BW and processing power boards
  - First layer to match detector information
  - Second layer to produce Trigger objects
- Trigger timing, throttling and control
  - High Band Width bi-directional link allowing trigger information to steer readout
- DAQ
  - Similar evt builder, HLT and storage as present Increase Band Width - 800 links x 100 Gbps with 30% occ. will provide 30 Tbps evt building throughput
- HLT
  - Processing power scales as PU x L1 rate - need increase by a factor ≃ 52 wrt Run 2 at 200 PU