Technical Proposal for the CMS Phase-II Upgrade

LHCC meeting June 2, 2015

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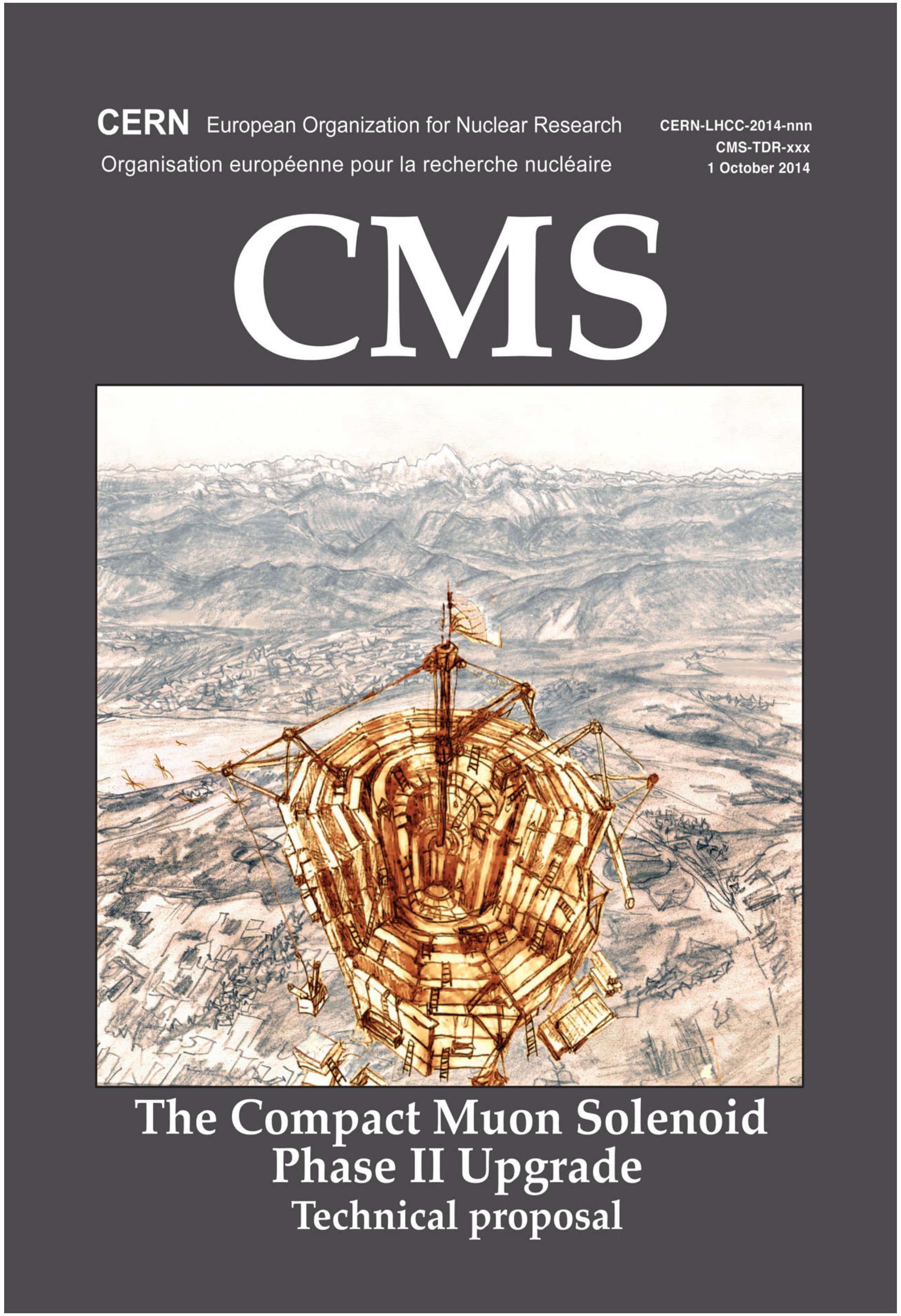
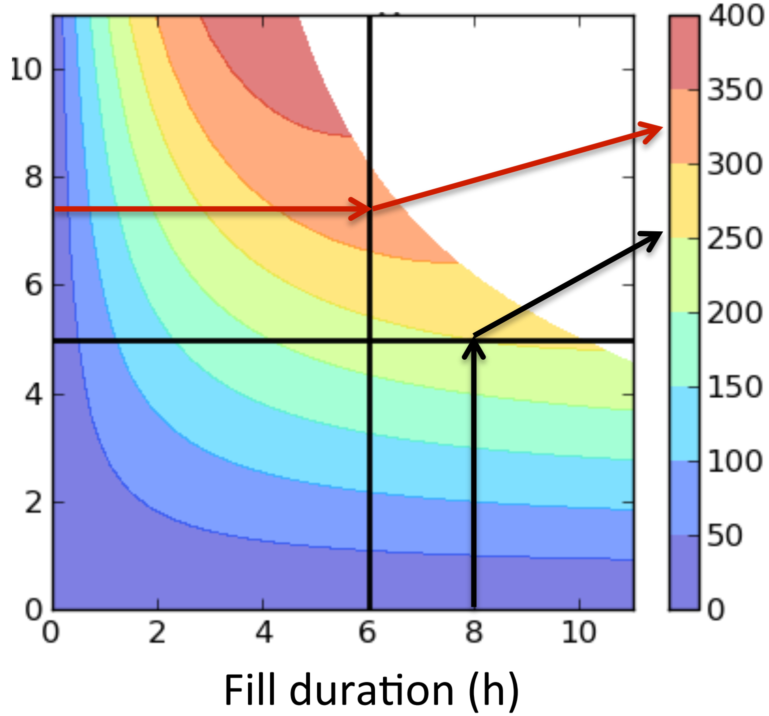


Driving considerations for the CMS Phase-II upgrades
Conceptual Designs, Technical Solutions and Performance
Project planning and cost

HL-LHC luminosity goals

"Ultimate" leveling
7.5 x 10^{34} (Hz/cm^2)
200PU

"Nominal" Leveling
5 x 10^{34} (Hz/cm^2)
140 PU

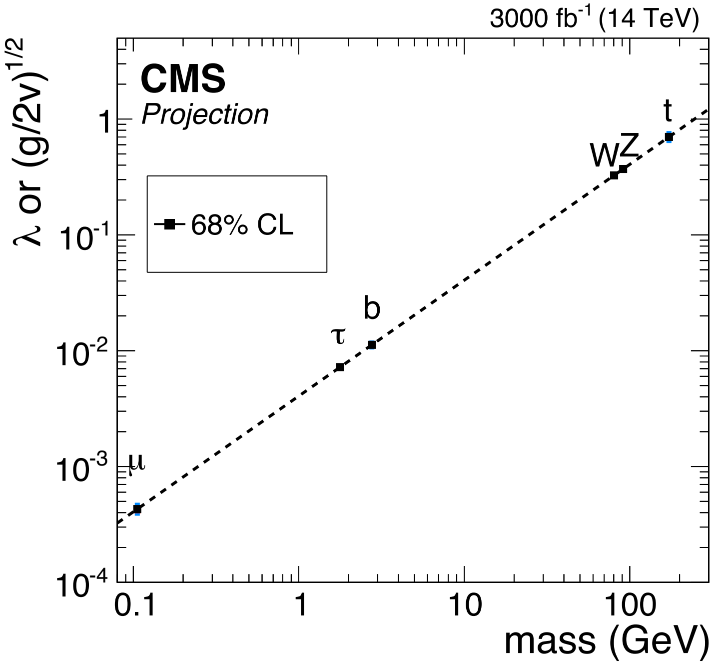


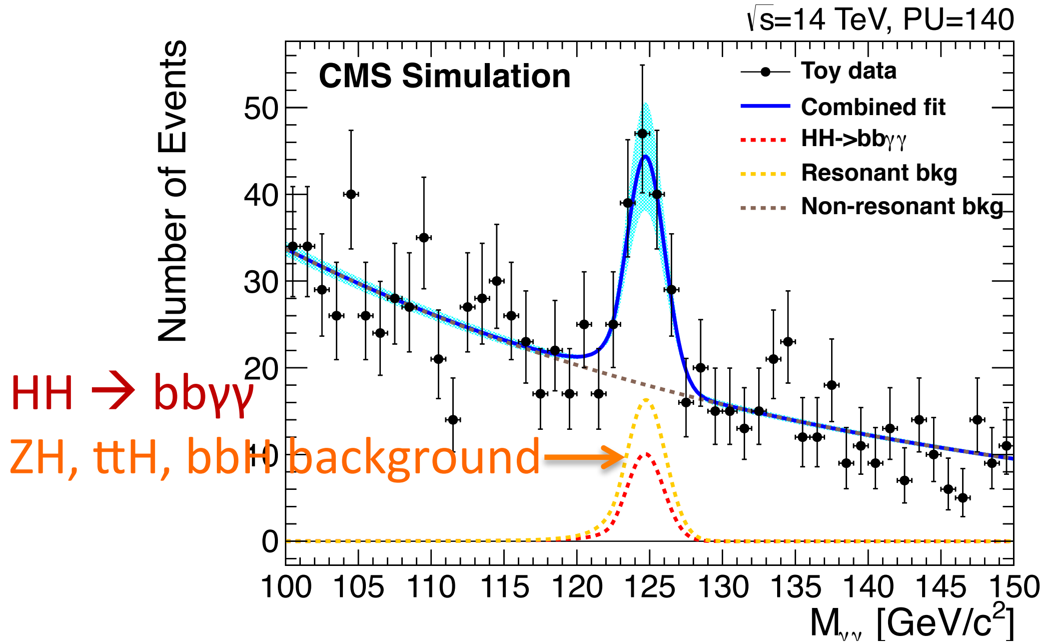
Integr. Lumi./year (fb^{-1})
160 days operation

Ultimate luminosity represents ≃ 30% gain in operation time to reach expected additional integrated luminosity of ≃ 2500 fb^{-1}

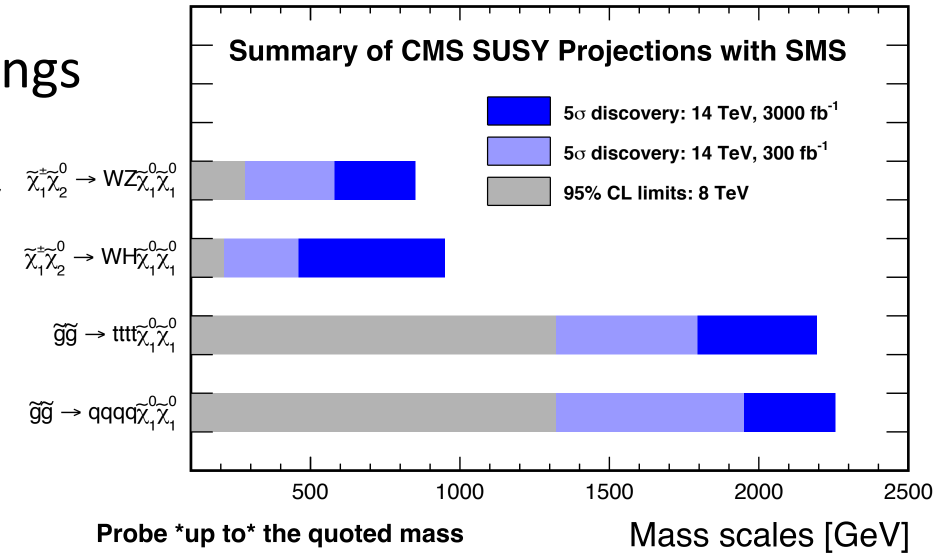
CMS upgrades enable operation at 200 PU, target Phase-I performance at 140 PU, allowing moderate degradation up to 200 PU, and radiation tolerance ≥ 3000 fb^{-1}

Physics reach at 3000 fb^{-1}





- 2 to 10% 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
- And increased mass range

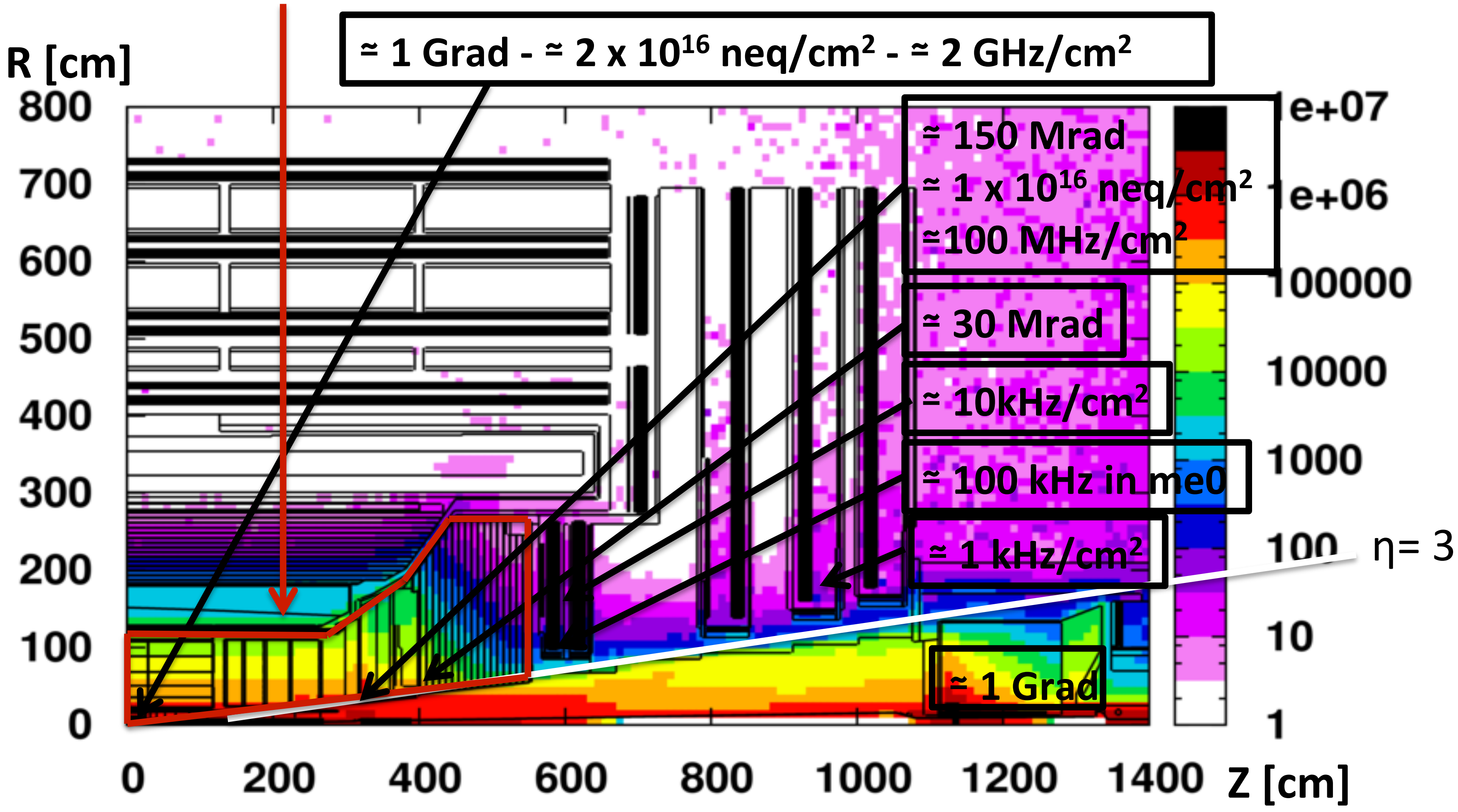


Requirements for the upgrades and TP studies

- All physics objects - detectors - remain equally important
- Enhanced role of forward region, particularly to study VBF/VBS processes
- Need to maintain low momentum/energy thresholds in event selection
- In TP simulation studies performed for few key physics channels in all areas (Higgs, SUSY, Exotica, SM) where enabled by upgrades
- CMSSW simulations with Geant used for all physics objects and physics signals (reconstruction still need substantial improvements and tuning to new designs and high PU conditions)
- DELPHES used for physics simulations including background with parameterizations provided by CMSSW studies
- Comparison of Phase-I 50 PU - reference for performance - with Phase-I aged 140 PU and Phase-II 140 PU

Radiation dose - neutron fluence - particle rates

- 3000 fb^{-1} Dose map in [Gy] simulated with MARS and FLUKA
- Numbers in boxes indicate maximum doses - neutron equivalent fluence - particle rates (for 5 x 10^{34} Hz/cm^2) seen by the various detectors
- Aging studies show that Tracker & End cap Calorimeters need replacement



Summary of the CMS upgrades for Phase-II

Trigger/HLT/DAQ

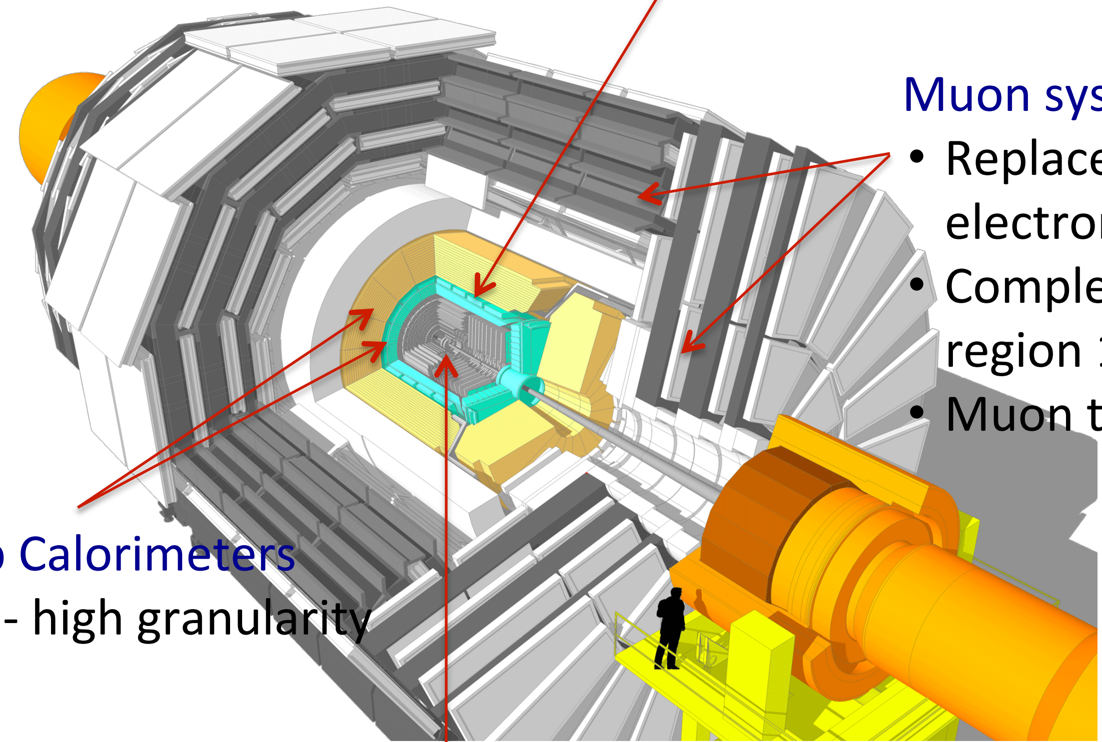
- Track information at L1-Trigger
- L1-Trigger: 12.5 μs latency - output 750 kHz
- HLT output ≃7.5 kHz

Barrel EM calorimeter

- Replace FE/BE electronics
- Lower operating temperature (8∘)

Muon systems

- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$



Replace Endcap Calorimeters

- Rad. tolerant - high granularity
- 3D capability

Replace Tracker

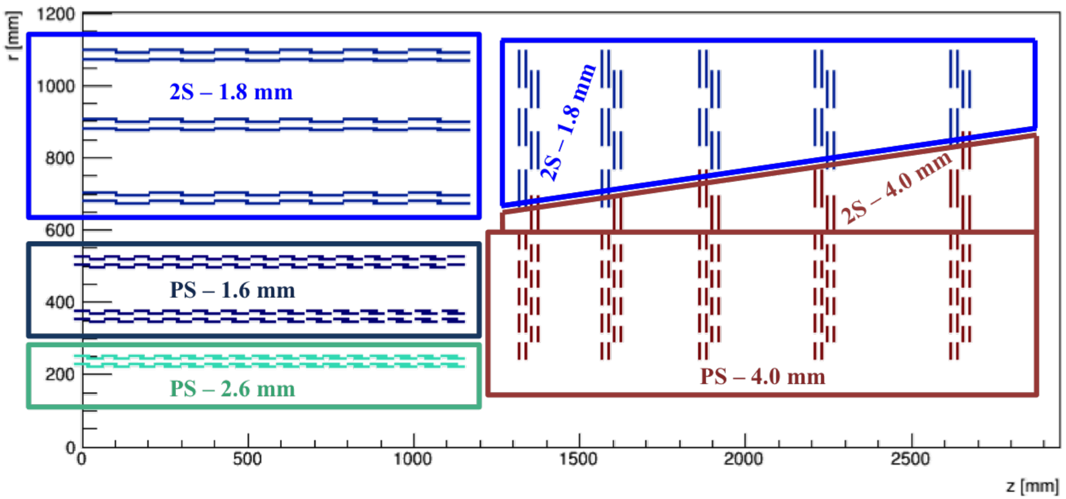
- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to $\eta = 3.8$

Tracker

Outer Tracker configuration

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 - CO2 cooling (-30◦) - DC/DC powering



- 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

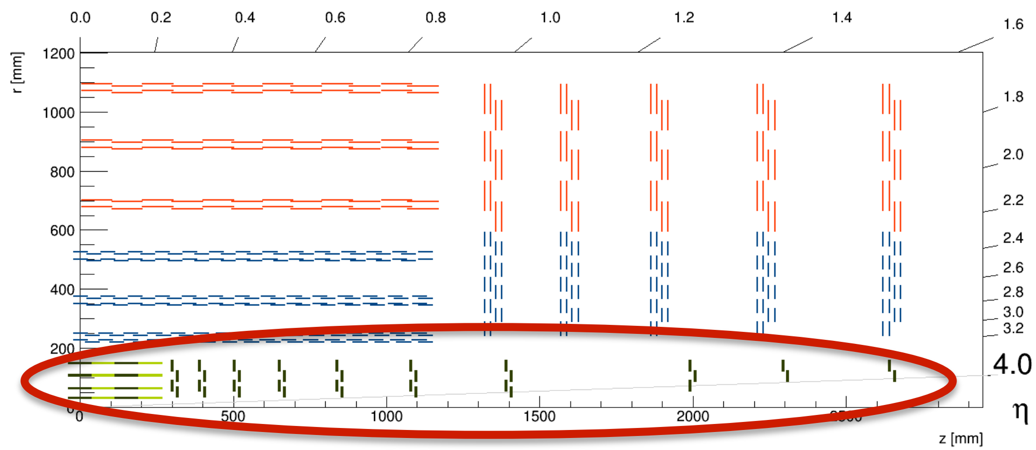
Ongoing study of alternative design with tilted modules in PS layers

- Further reduce material and number of modules

Pixel detector configuration

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

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



- Total pixel area ~ 4 m^2
- 50x50 to 25x100 μm^2 pixels
- ≤ 150 µm sensor physical thickness

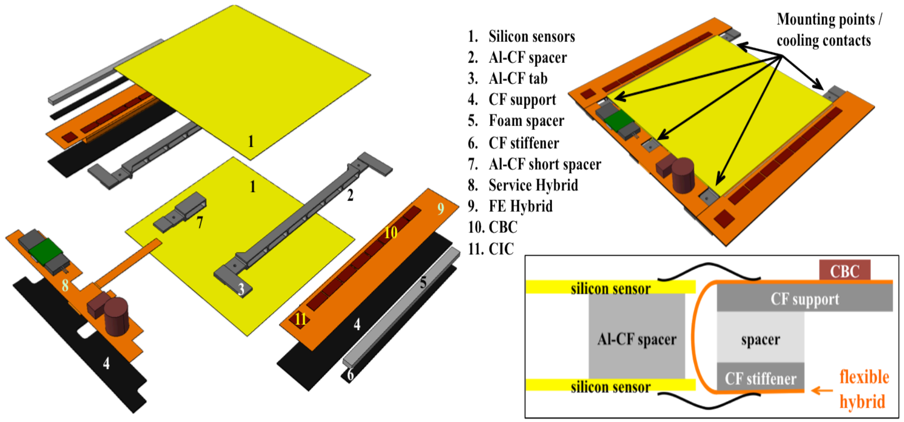
Tracker components

- 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

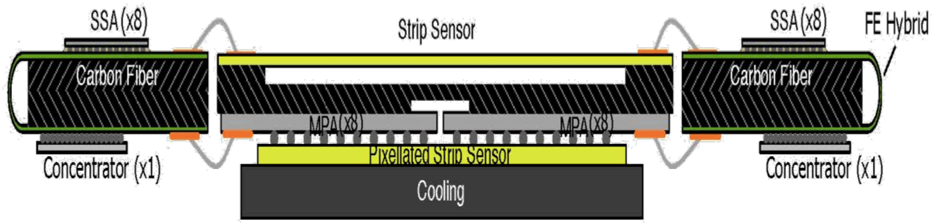
- Only two types of modules: light designs with single frame for two sensors - FEA performed and first experience of prototype assemblies (w/o hybrids)

2S modules - 35-40 g

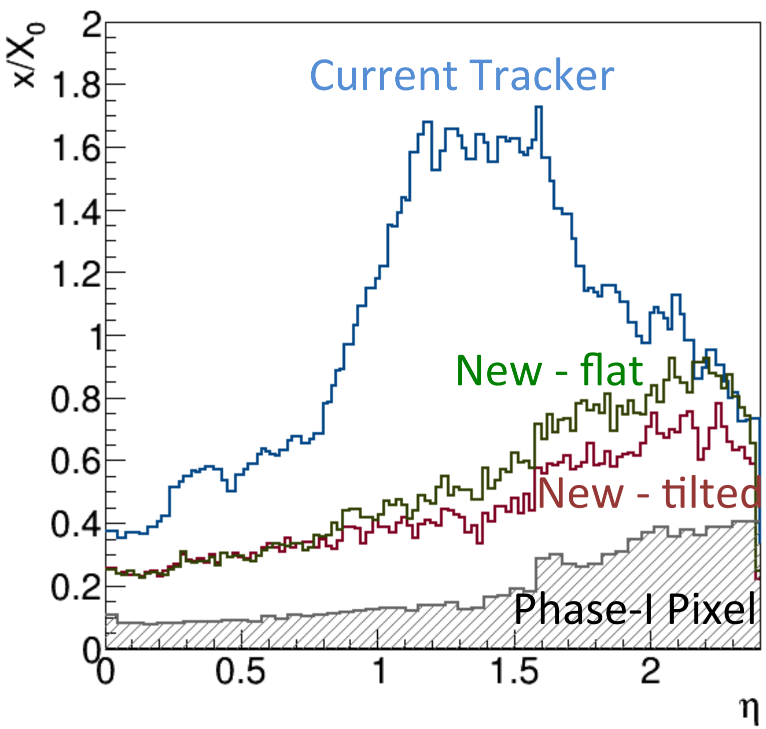


Sensor T ≃ -20◦ for -30◦ cooling

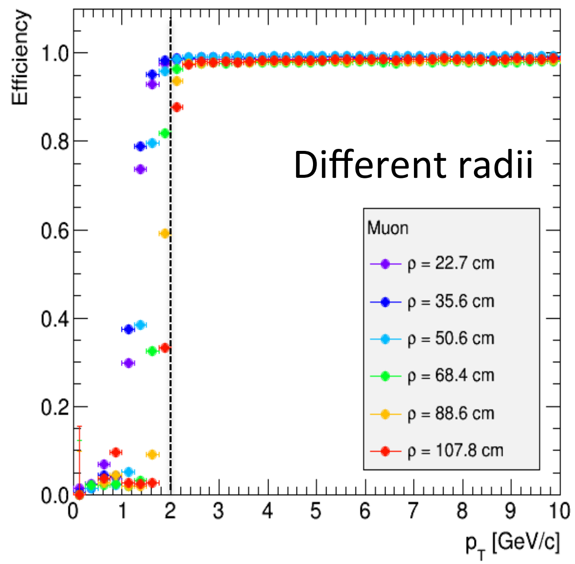
PS modules



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



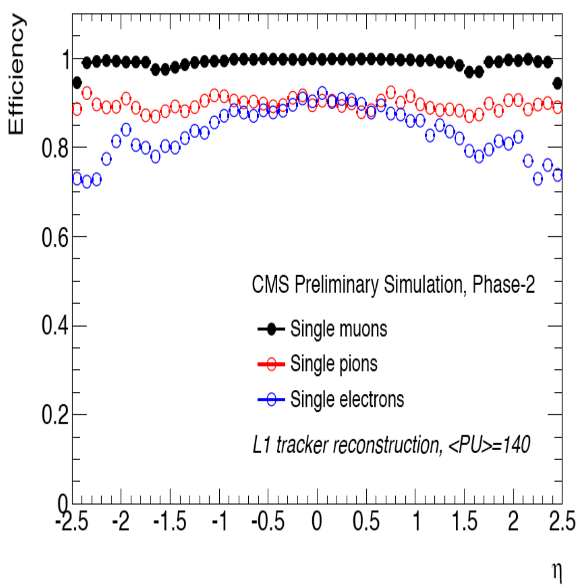
Tracking Trigger

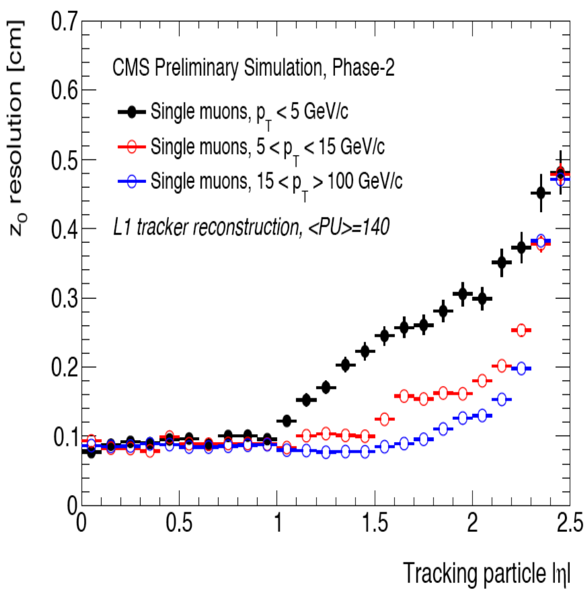


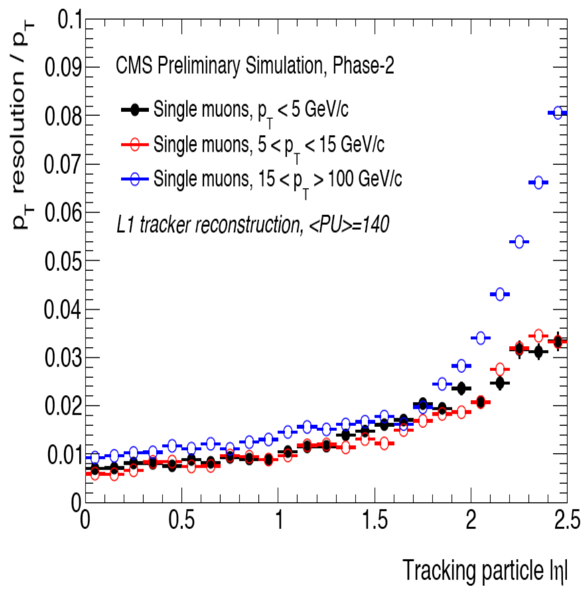
High B-field allows to measure bending of tracks in few mm spacing between two sensors of a module

- Selective readout of track hits down to $P_T \simeq 2$ GeV reduce Band Width for readout at 40 MHZ
- 3 techniques investigated for track reconstruction

L1 Track Trigger reconstruction performance



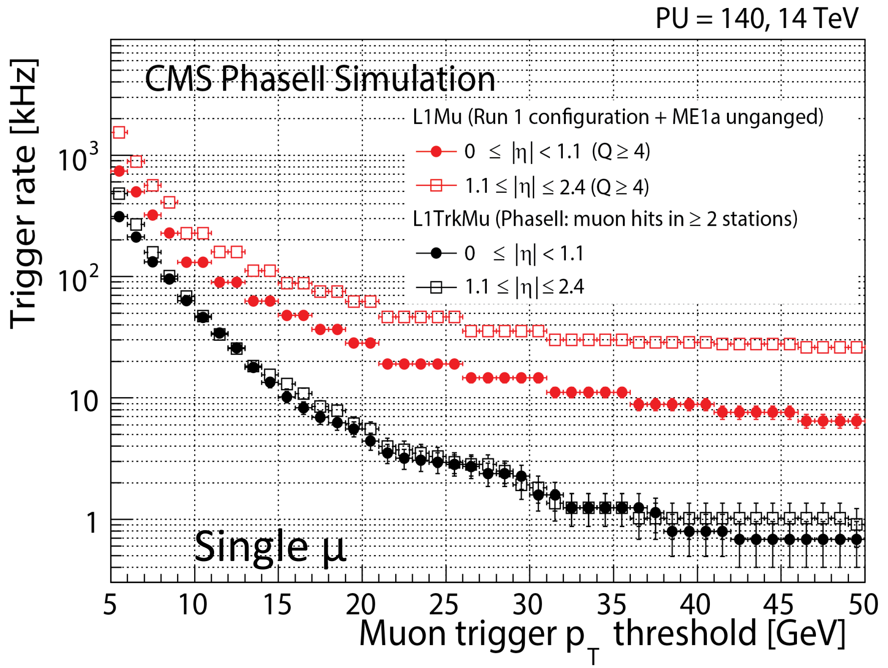


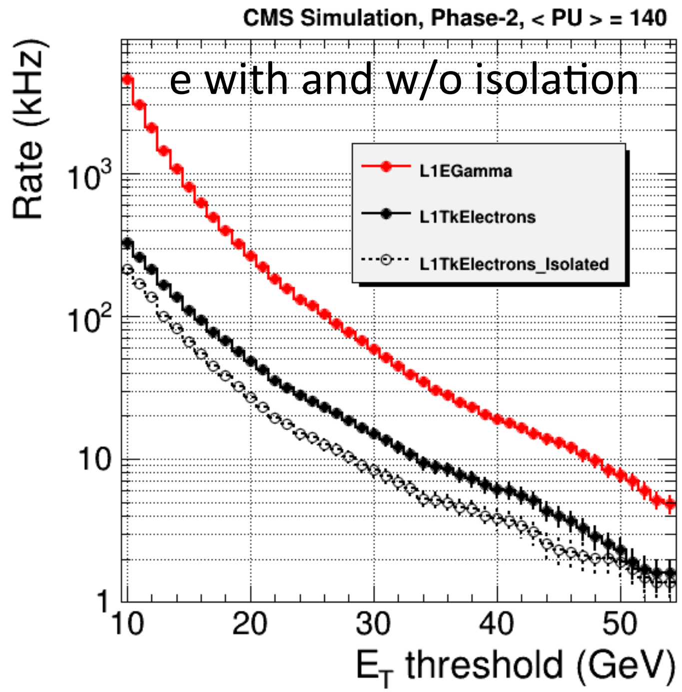


L1 Trigger performance with Track-Trigger

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



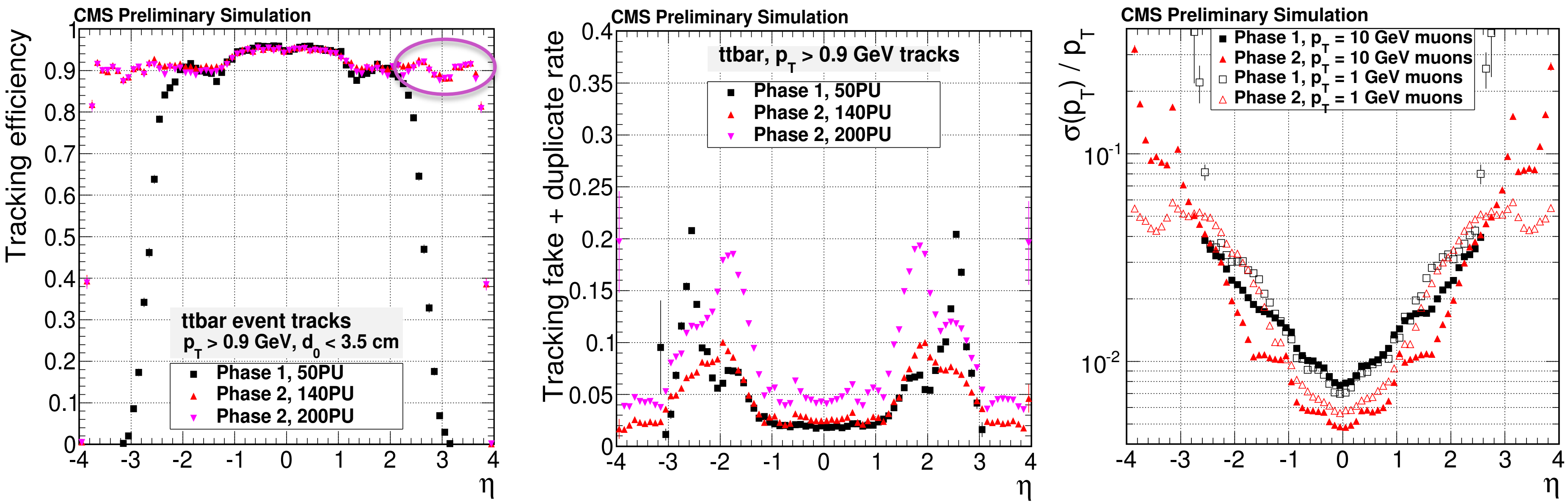


L1-Trigger studies with Phase-I menu thresholds including Track-Trigger:

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

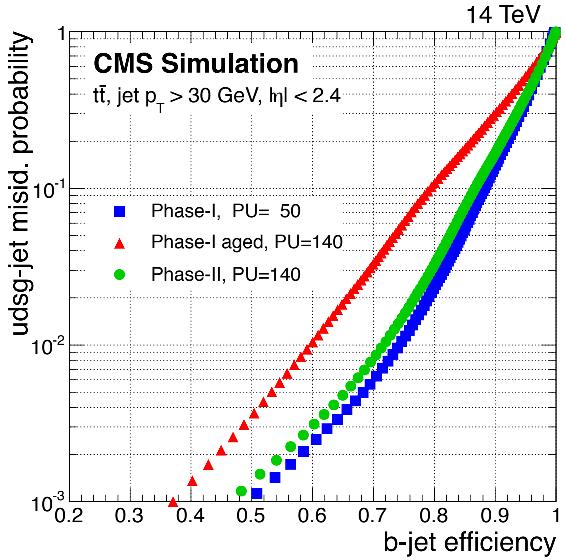
Track and Primary Vertex reconstruction performance

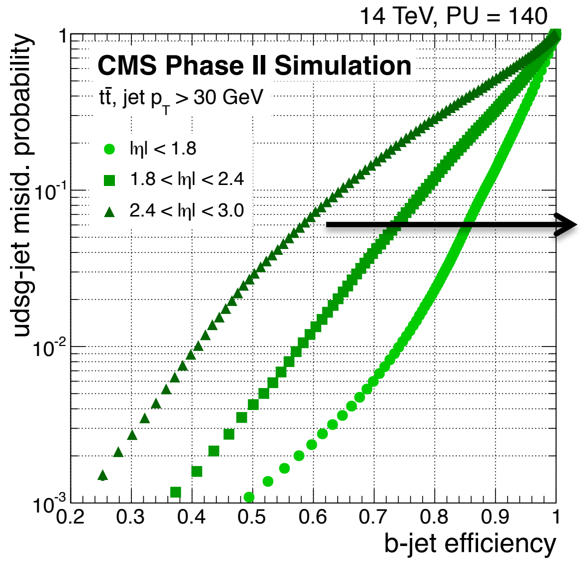
- Track efficiency and fake rates for Phase-II 200 PU similar to Phase-I 50 - tolerable fake increase at 200 PU
- Momentum resolution substantially improved (lower pitch & material)



- Signal Primary Vertex efficiency ≥ 95% with 20 μm resolution at 200 PU

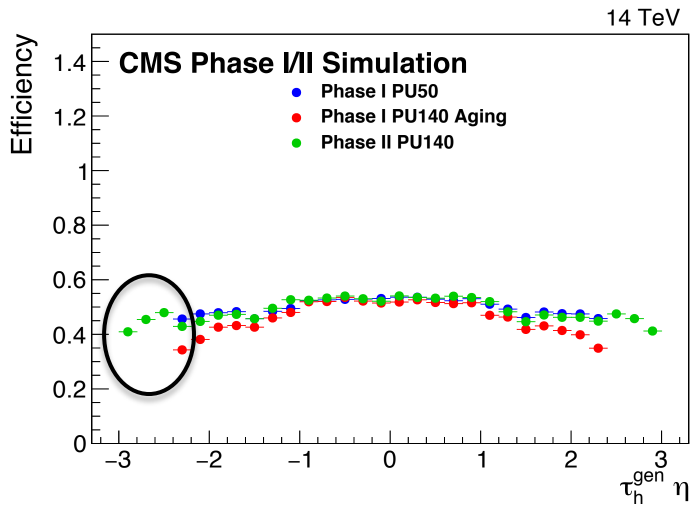
- **b-tagging** Phase-II recovers Phase-I performance - expected to improve with new pixel smaller pitch & material

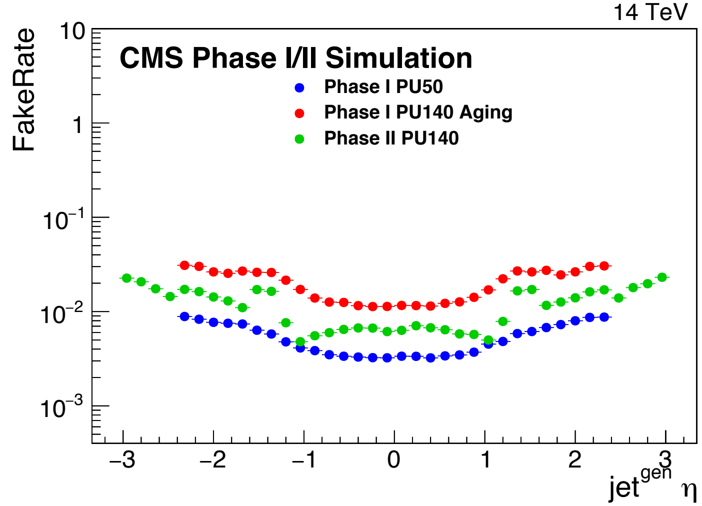




Coverage to
η = 3.8

- **τ-ID** - based on track isolation (robust to PU) same efficiency working point below - need more tuning for new detector geometry

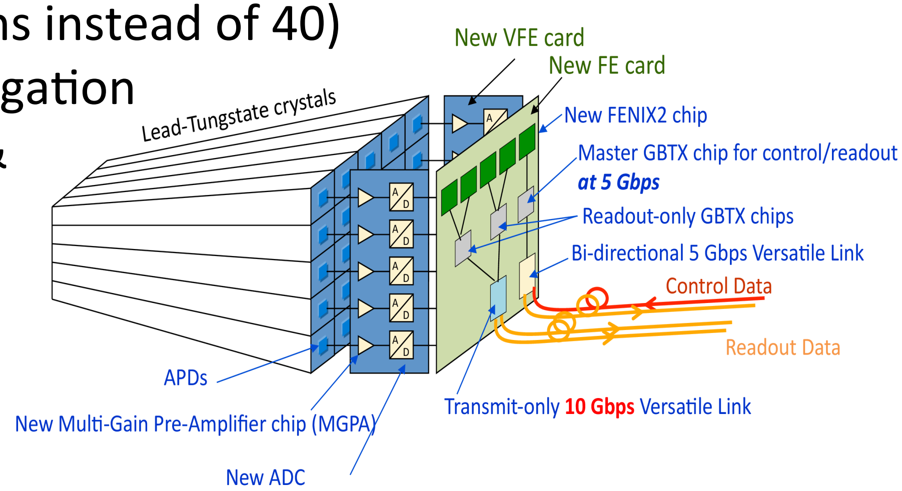


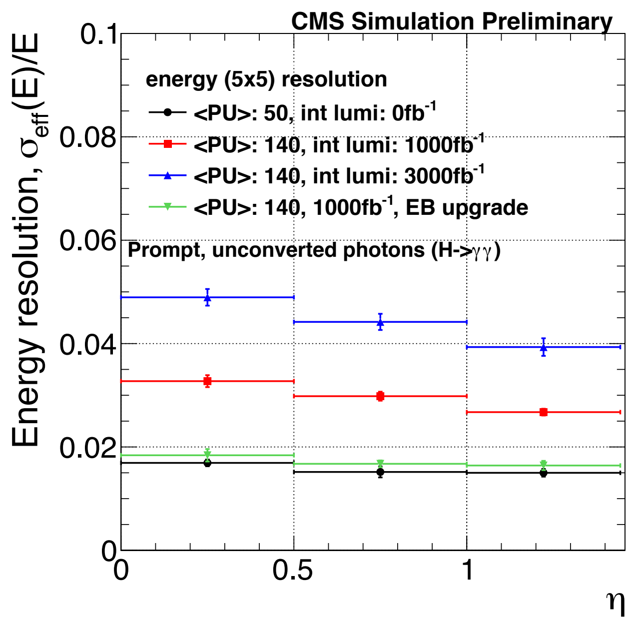


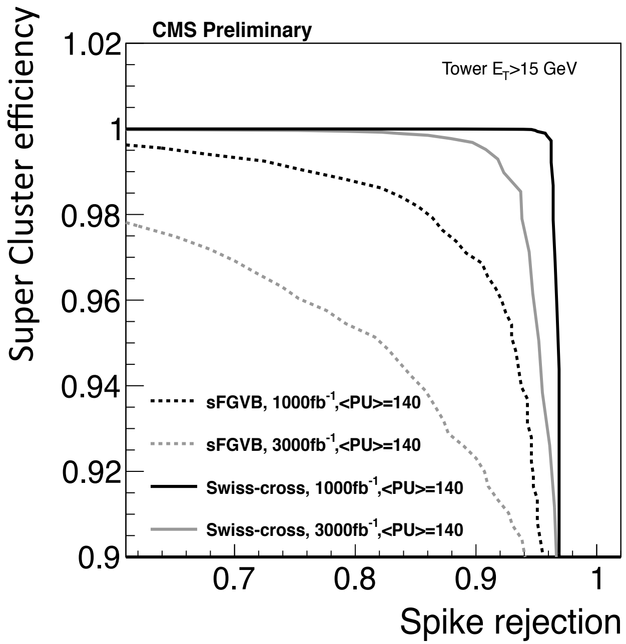
Calorimeters

EB readout and cooling upgrade

- 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

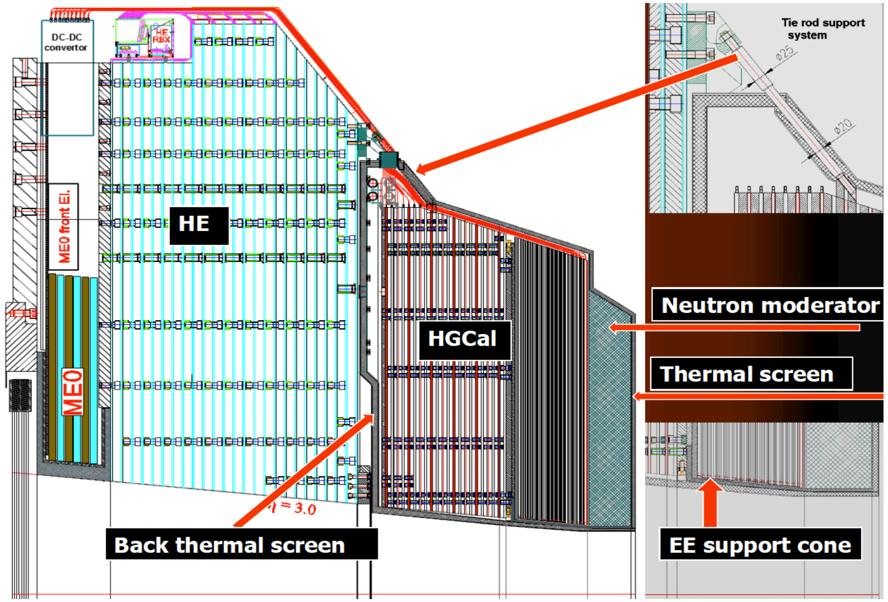




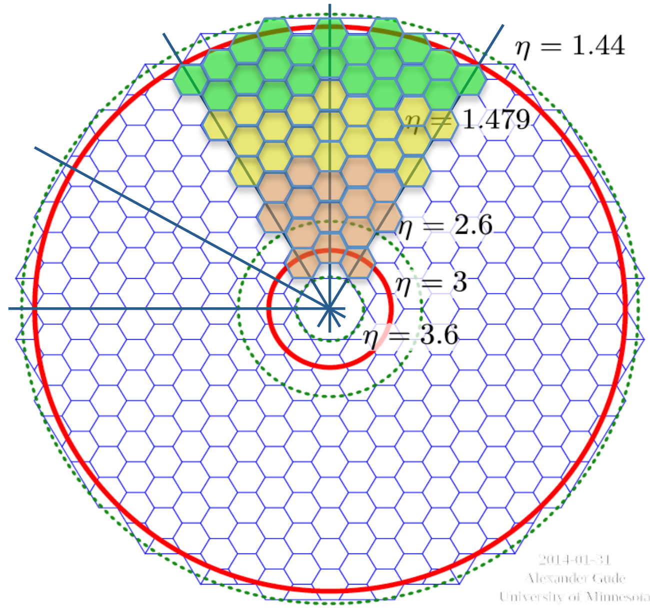


High Granularity (HGC) & Back Hadron (BH) calorimeters

- 3D shower measurement in HGC (layout studies with standalone simulation)
  - Electromagnetic EE (26 X_0, 1.5λ): 28 layers of Silicon-W/Cu absorber
  - Front Hadronic FH (3.5 λ): 12 layers of Silicon/Brass
- Back Hadronic BH (5 λ): 12 layers of Scintillator/Brass (2 depths readout)

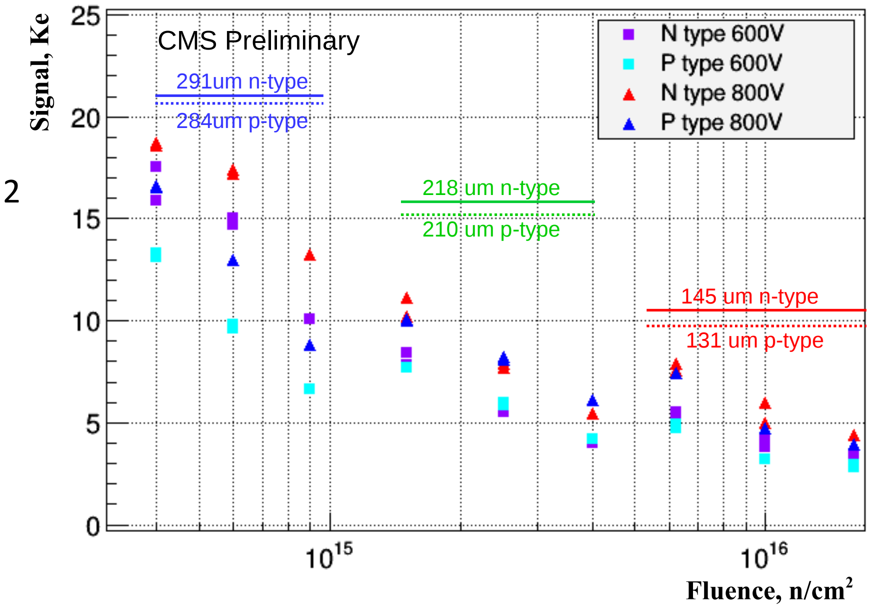


EE: 380 m^2 - 4.3 Mch - 13.9k modules - 16t
FG: 209 m^2 - 1.8 Mch - 7.6k modules - 36.5t
BH: 428 m^2 - 5184 SiPMs



3 sensor active thicknesses 100-200-300 µm
0.5(1) cm^2 pads for 100(200/300) µm

HGC Silicon sensors and Front End ASIC

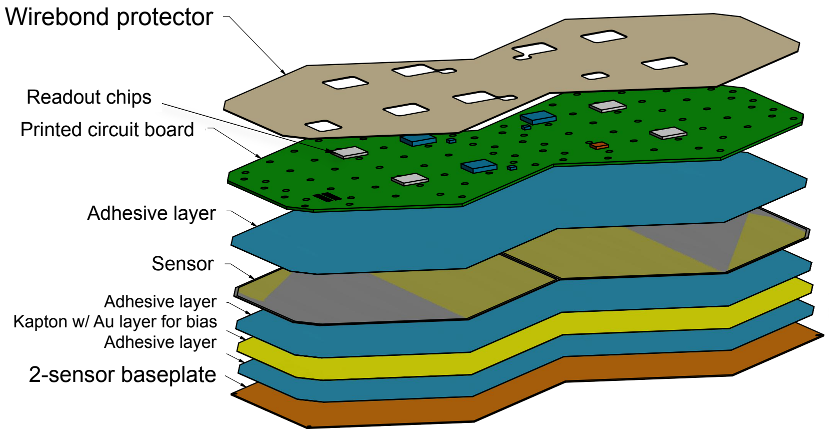


- Sensors: n-in-p pads
  - Rad. test with neutrons 1.5 x 10^{16} neq/cm^2 ≃ 40 % signal loss - I_{leak}≃ 10 μA (at T = -30◦)

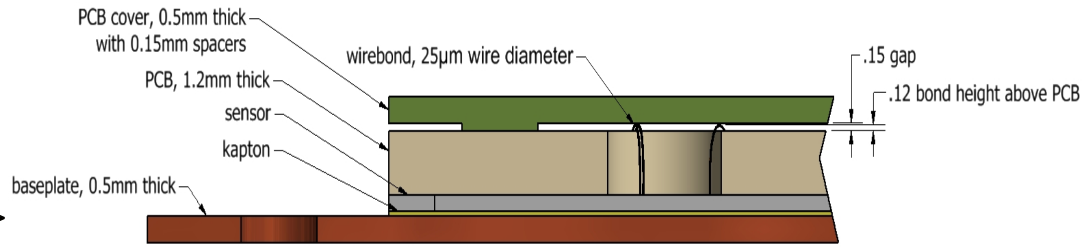
- FE ASIC: 130 nm TSMC - spice simulation:

– Shaping ≃ 15 ns - noise ≤ 2500e^- (after 3000fb^{-1}) with power ≤ 10 mW per channel
– Dynamic range 10 pC - 10 bit ADC ≤ 100 fC and Time over Threshold (ToT) ≥ 80 fC
– Channel calibration better than 1%
– Time resolution ≃ 50 ps - opportunity for precise timing of showers
– MIP inter-calibration ≤ 3% → ≃ 0.5% possible down to 1.7 Signal/Noise after irradiation and redundant measurement with dedicated small pads (S/N>5)

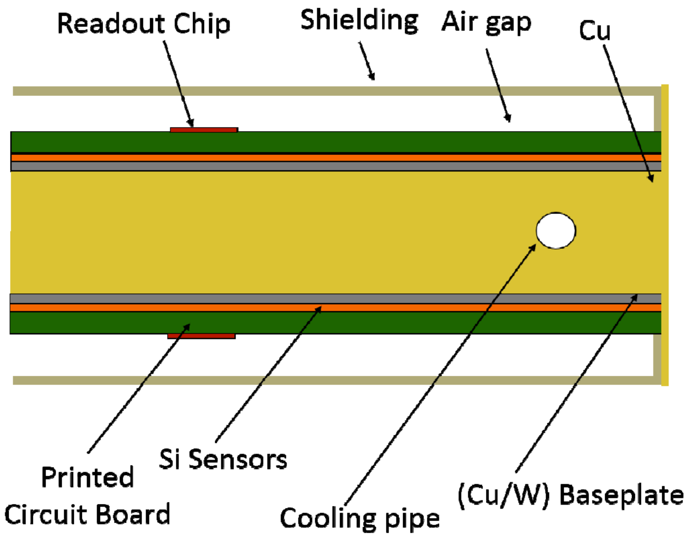
HGC Silicon sensor modules

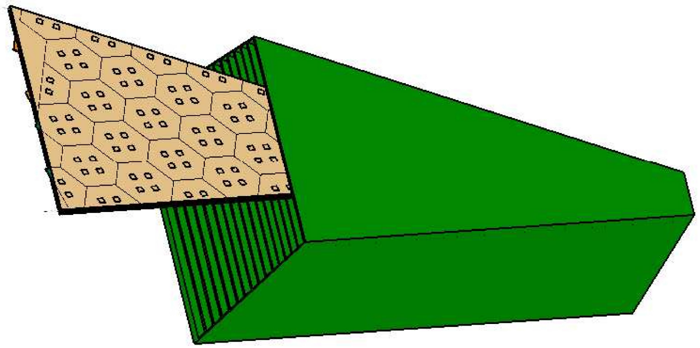


2 x 6" sensor modules 256/512 channels
4/8 chips (depending on pad size)

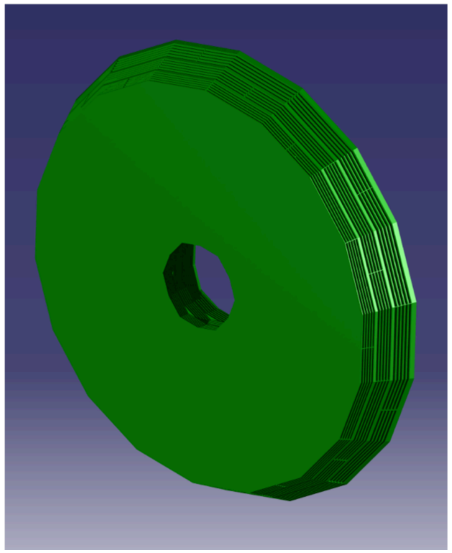


- Silicon operation at -30◦ with CO2 cooling - from FEA studies Si at -28.5◦ with 1.4◦ gradient
- Thermal matching deformation test with prototype indicate ≃ 6 Mpa constraint well below tensile strength
- Total cooling power ≃ 125 kW (after 3000fb^{-1})



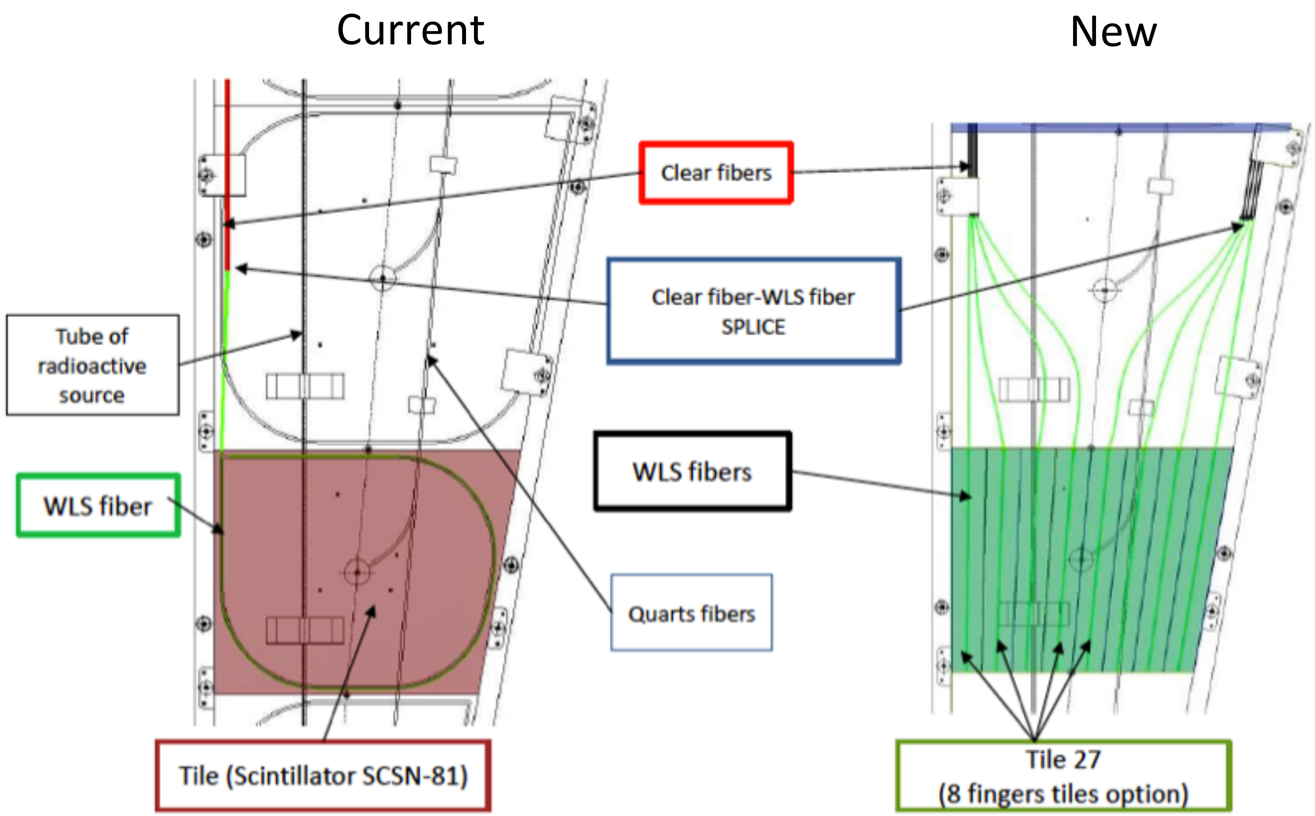


30◦ sectors



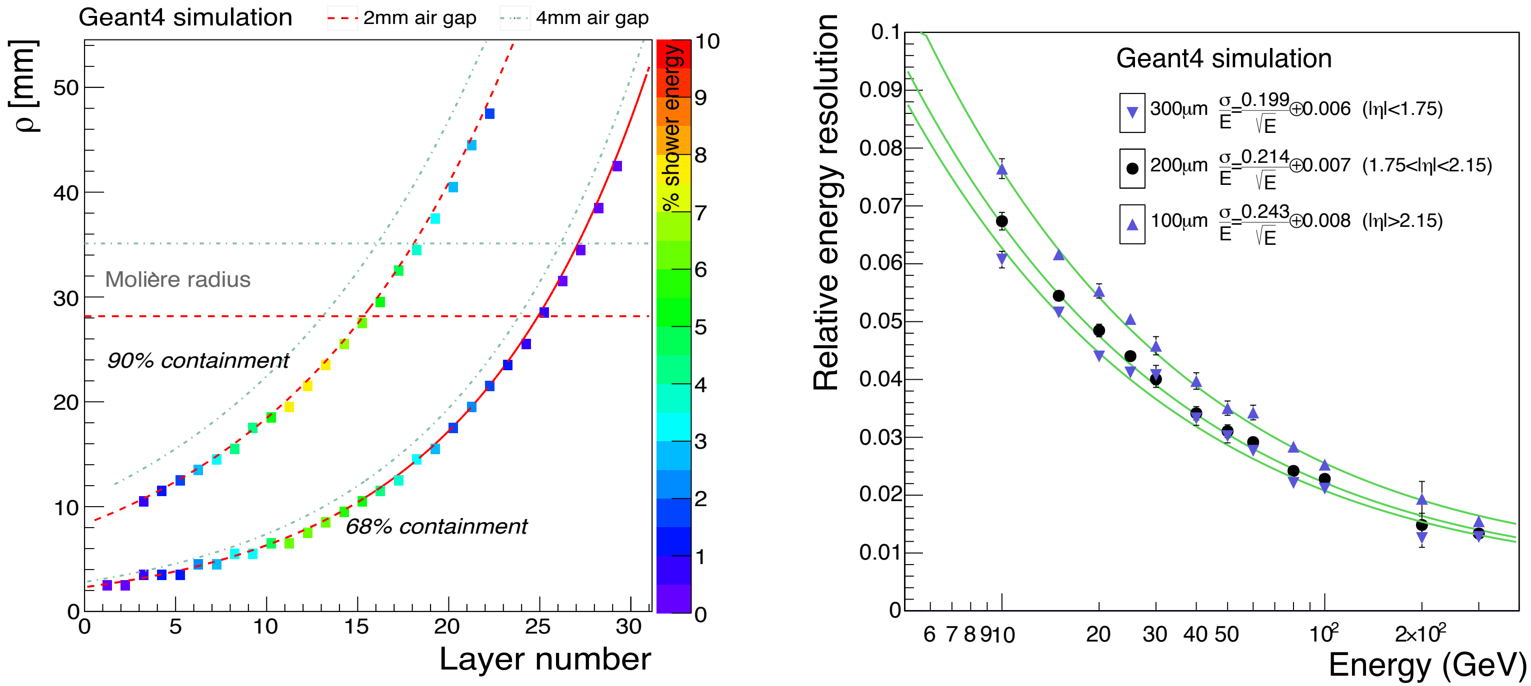
Back Hadron scintillating tiles

- 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

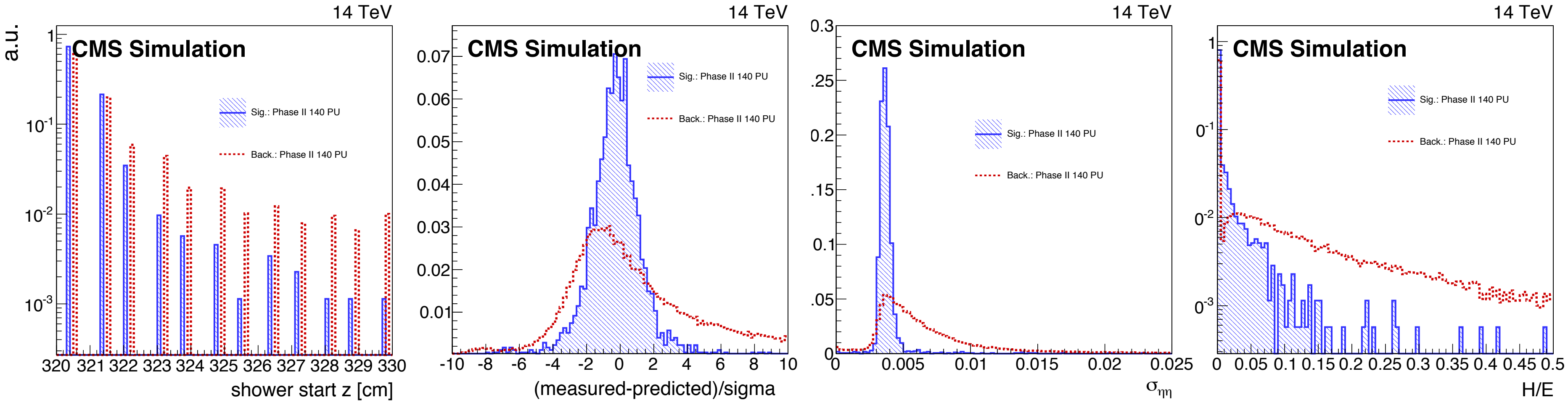
HGC shower profile and EM resolution



- Shower profile simulation containment & fraction of energy vs layer number - Moliere radius is ≃ 28 mm (2mm air gap) but showers are very narrow in the first 10-15 layers for PU effect mitigation
- Intrinsic energy resolution simulation stochastic term is 20% to 24% (300 to 100 µm sensor thickness)

HGC e/γ new ID variables

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



Signal (blue) - background (red)

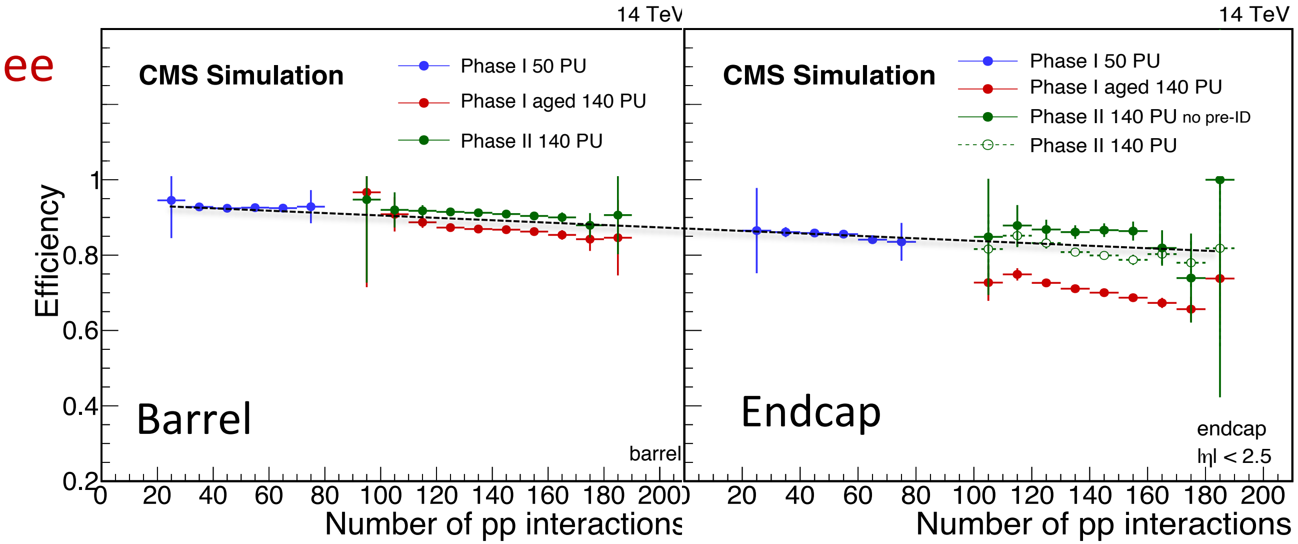
- And to mitigate PU use trans. granularity - cells in ≤ $1.5R_M$ - H/E in tight cone 0.05

However CMSSW software developments are at a very early stage, clustering, link to charged tracks and PU mitigation potential at layer level is far from being fully exploited in current studies

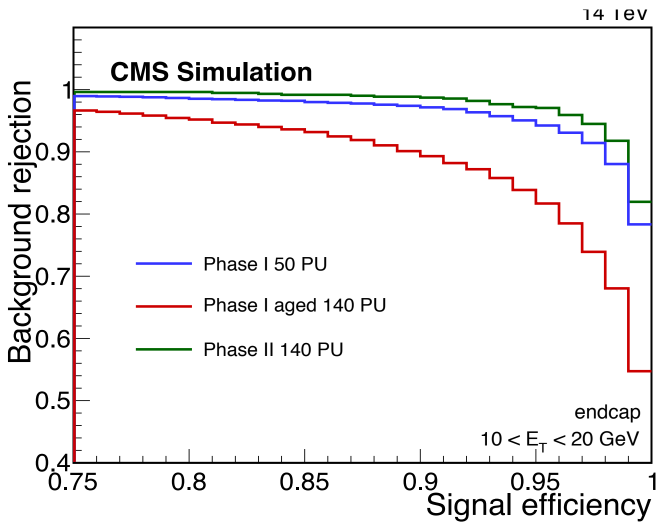
Electron and Photon performance

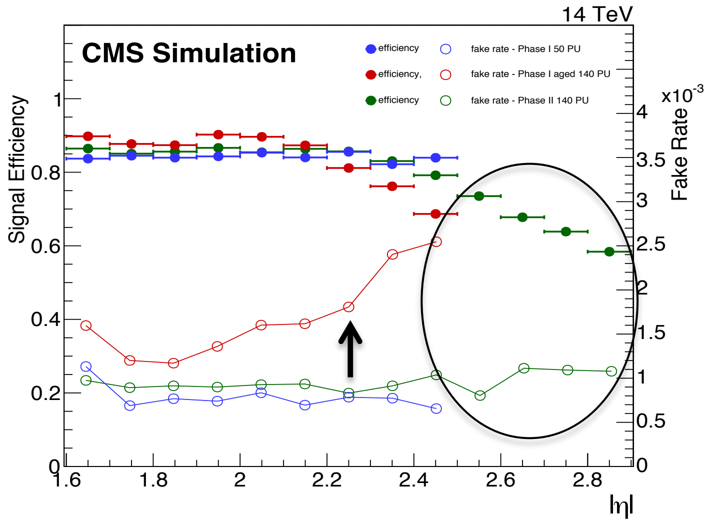
- Electron efficiency recovered with smooth decrease up to 200 PU

Z→ ee



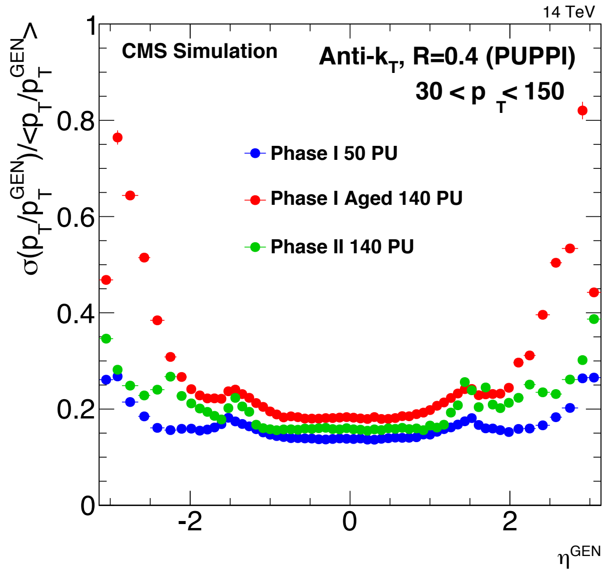
- BDT efficiency for DY electrons and for Jets (left) and BDT efficiency for γ and Jet fake rate for a WP at ≃ 85% efficiency (right)



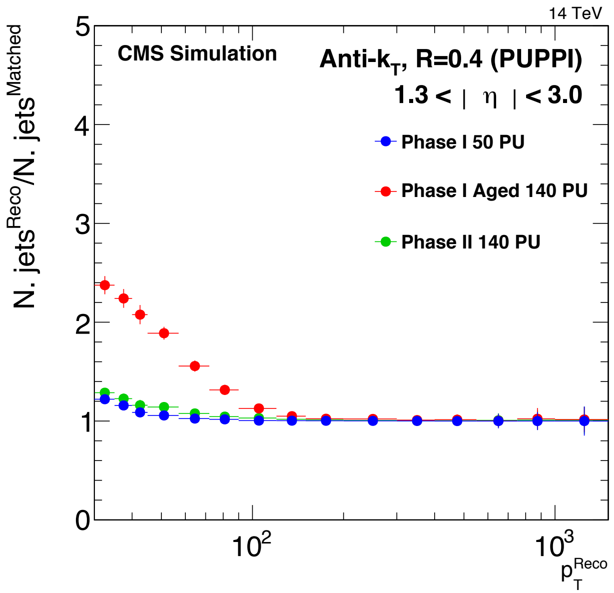


Jet and MET performance

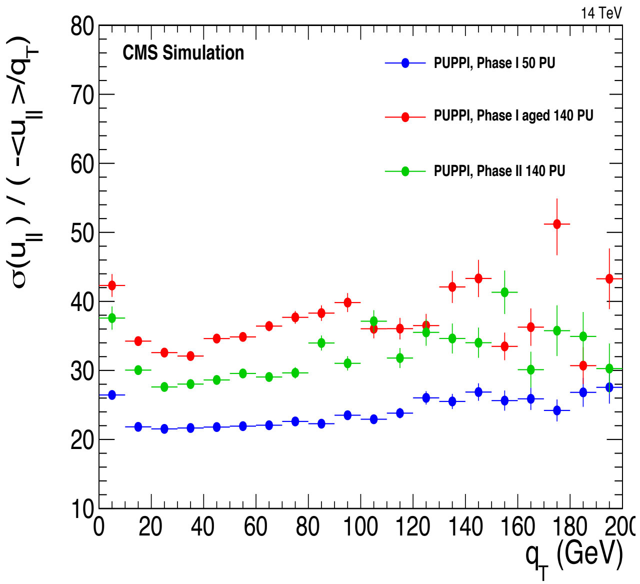
Combined effect of new EC and Tracker extension allows Phase-II to mostly recover energy resolution & fake rate of Phase-I detector at 50 PU



Jet energy resolution



Jet fake rate



MET energy resolution from hadronic recoil in $Z \rightarrow \mu\mu$

Muon Systems

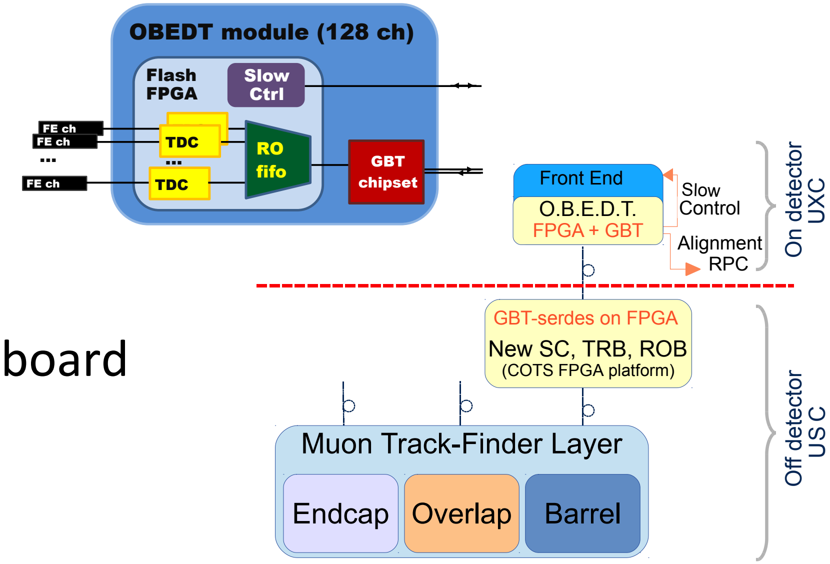
Existing Muon systems longevity

- Rates scale linearly with luminosity and, with integrated charge, are consistent with expectations
- From past test and operation experience Muon detectors are expected to survive 3000 fb^{-1} - most forward region to be re-validated
- All systems will be tested in full scale at GIF++ - fast and large area irradiation with high rate γ and MIP capability
  - Validation of previous aging results and assess margins
  - Validation of high rate operation
  - Study of new gas mixtures compliant with greenhouse rules

Detector	Bck. rate LHC	Bck. rate HL-LHC	Max. rate tested	Max int. charge 3000 fb^{-1}	Max int. charge tested
DT	5	25	100	0.15 C/cm	0.48 C/cm
CSC	900	4500	20000	0.3 C/cm	0.35 C/cm
RPC	50	250	300	0.27 C/cm^2	0.05 C/cm^2

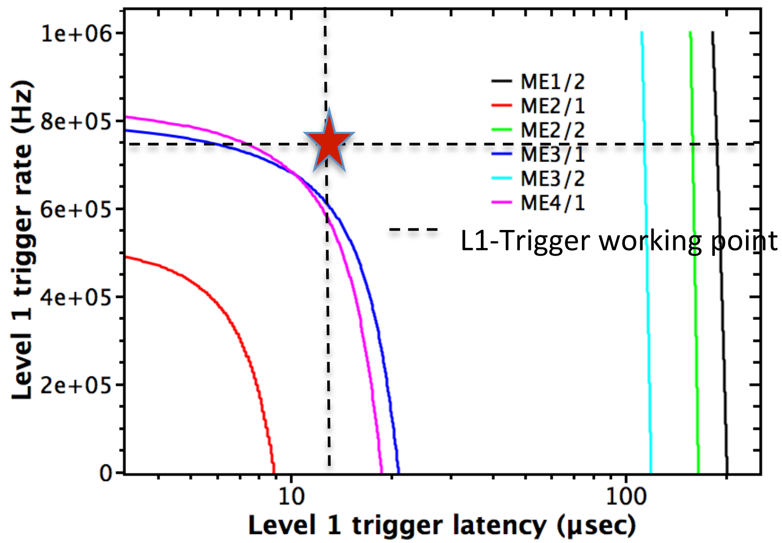
Rates seen in Hz/cm^2 at 5 x 10^{34} Hz/cm^2

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

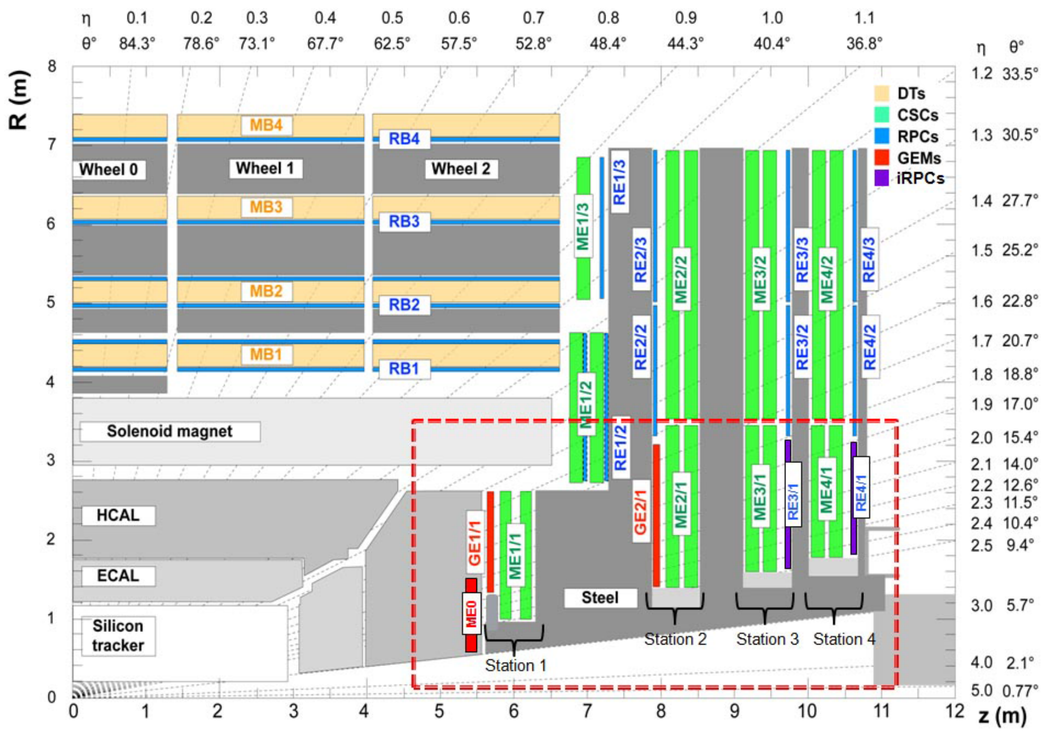
- CSC FEB replacement
  - Remove latency and rate limitation at L1-Trigger in inner rings of station 2, 3 & 4
  - Based on the DCFEB developed for the upgrade of the ME1/1 station in LS1



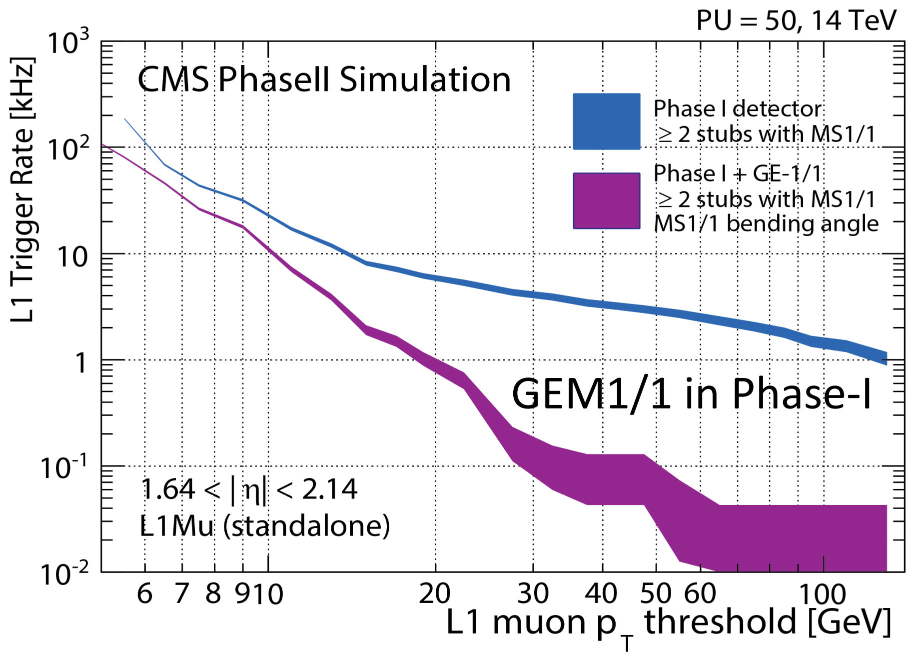
2% loss contour extrapolation from data

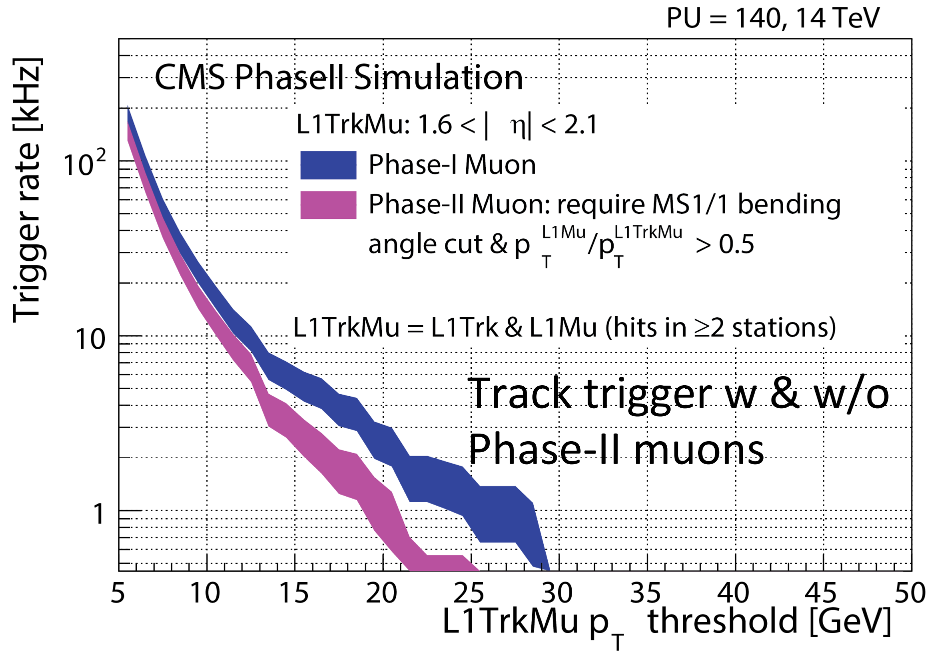
New Muon detectors in the forward region

- Complete RPC coverage in 1.5 < η < 2.4 (foreseen in CMS initial design)
  - Pairs of triple GEM chambers in 2 first stations - high rate and high resolution capability - improve trigger
  - iRPC in stations 3 and 4 - higher rate capability - consolidate reconstruction & reject background
- Extend coverage up to η = 3
  - 6 triple GEM (ME0) in space freed behind more compact EC, for muon-tagging with matching in Tracker extension

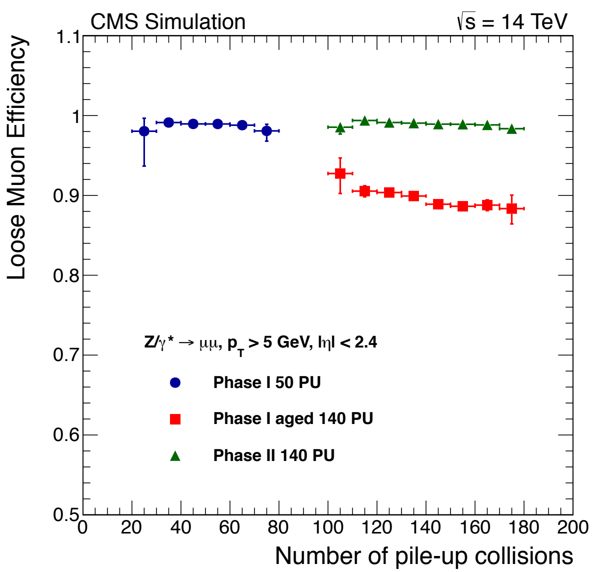


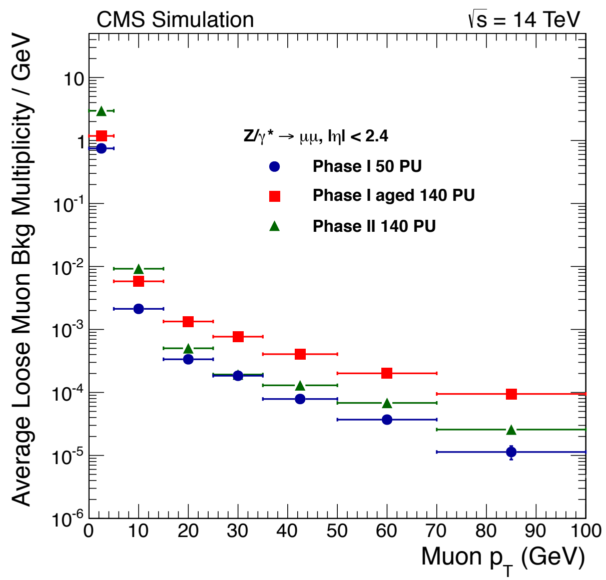
Muon Trigger and reconstruction performance





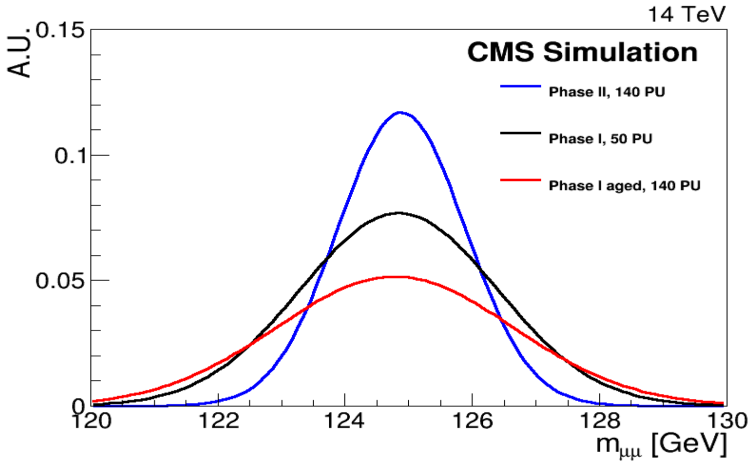
- Good standalone L1-Trigger capability - GEM1 important already after LS2
- Improved rate reduction combined with Track-Trigger
- Trigger on displace vertices
- Better offline reconstruction resolution - sign assignment



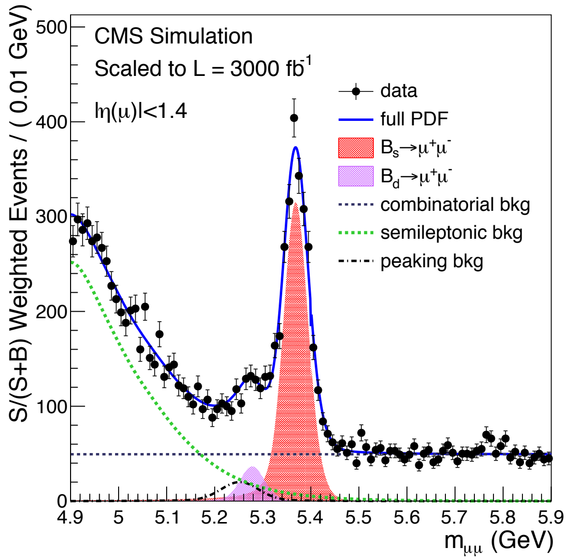


Enhancement of the Physics reach (examples)

- Tracker momentum resolution



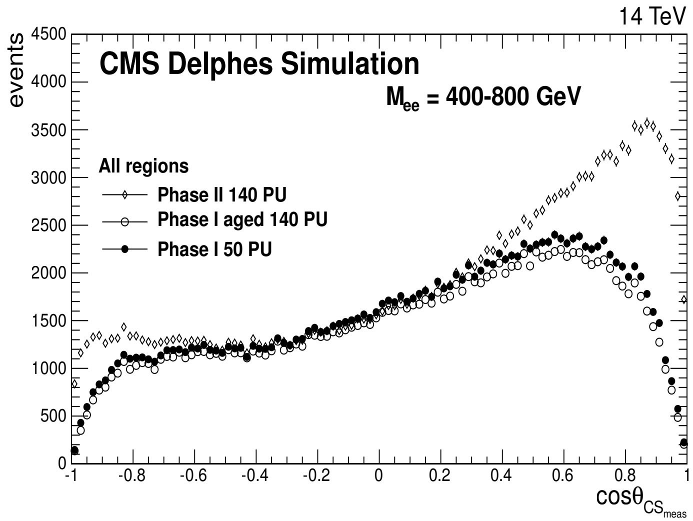
H→μμ - 20% efficiency & 40% mass resolution improvement

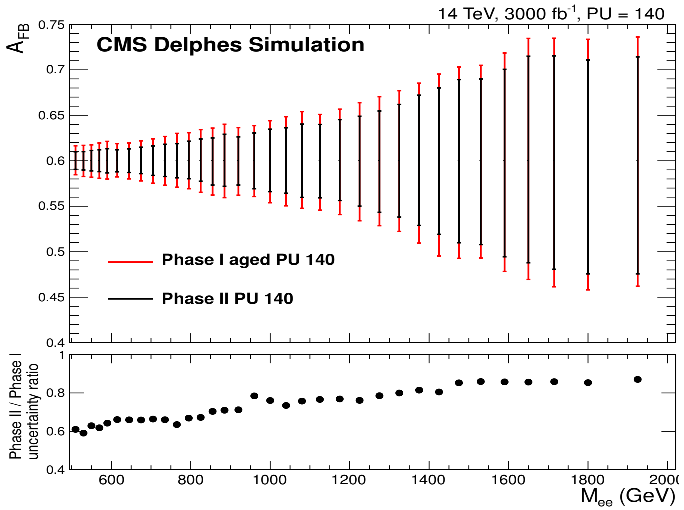


B_d/B_s → μμ resolved two decay peaks measure also enabled by Track-Trigger

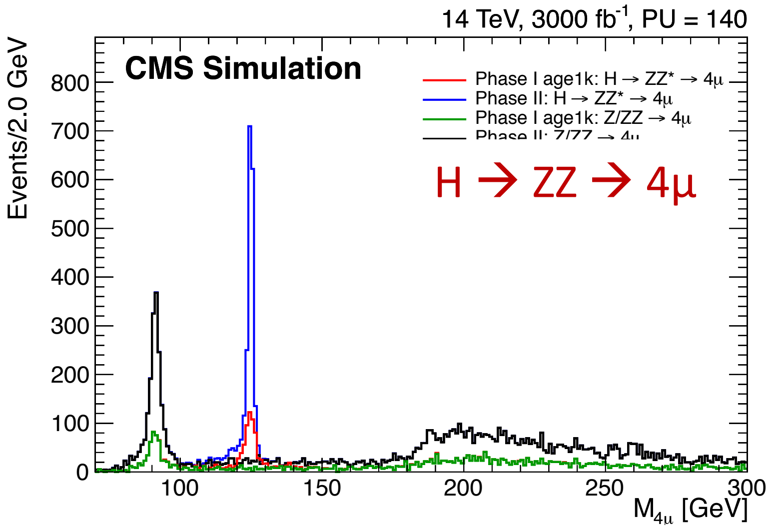
- Resolution (charge assignment) new EC and coverage up to η = 3

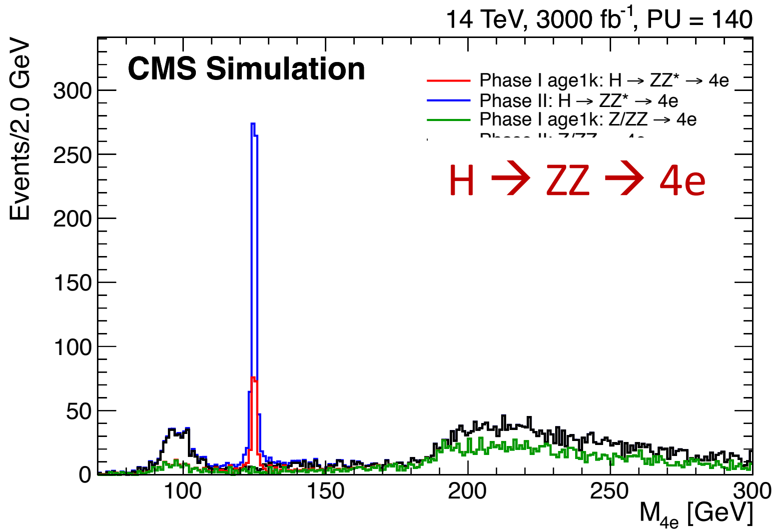
New physics search in A_{FB} of DY ee - improved uncertainty by 40% at Mee ≃ 500 GeV





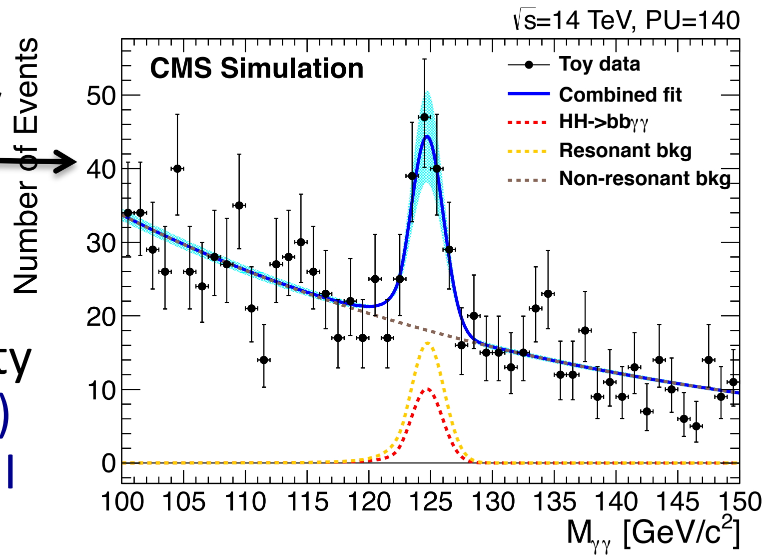
- With aged Phase-I Tracker huge loss of efficiency for H→ ZZ → 4l Phase-II restore efficiency and extensions increase the acceptance by 20%



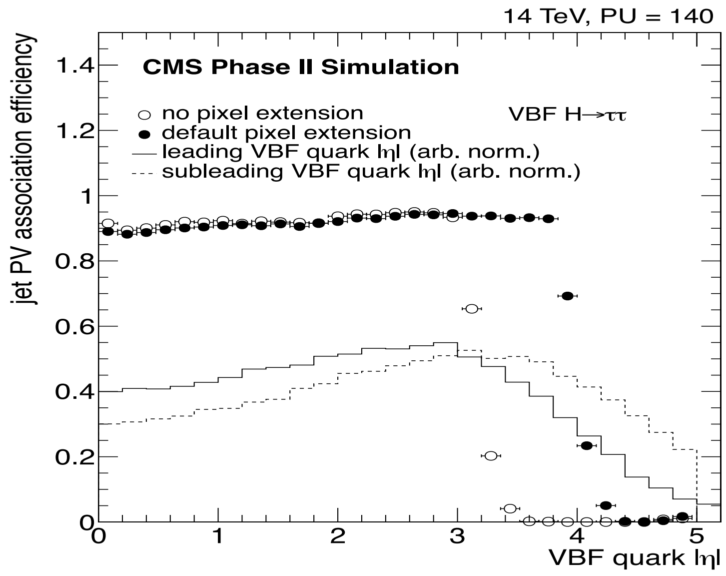


- HH→ bbγγ - 60% cross section uncertainty enabled by Tracker b-tagging, EC γ-ID performance of Phase-II

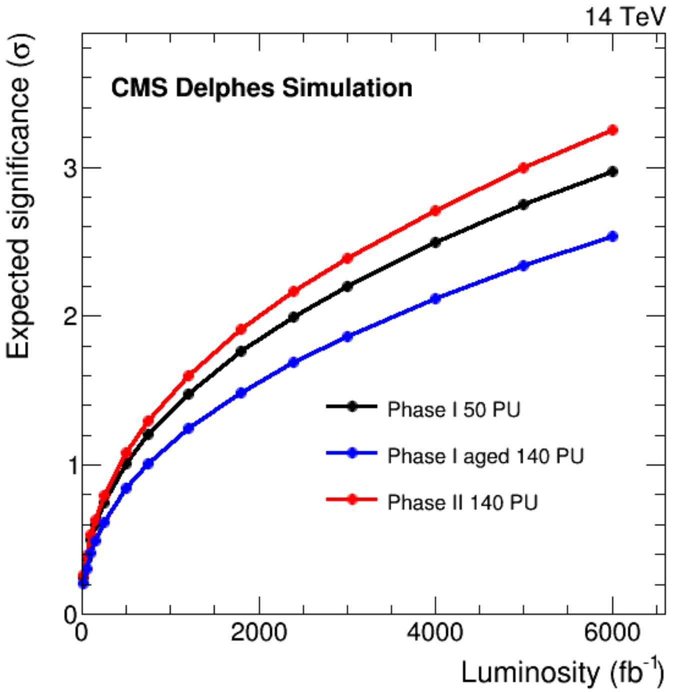
- HH → bbττ - 100% cross section uncertainty enabled by Tracker-Trigger (x2 acceptance) and b-tagging, τ-ID performance of Phase-II



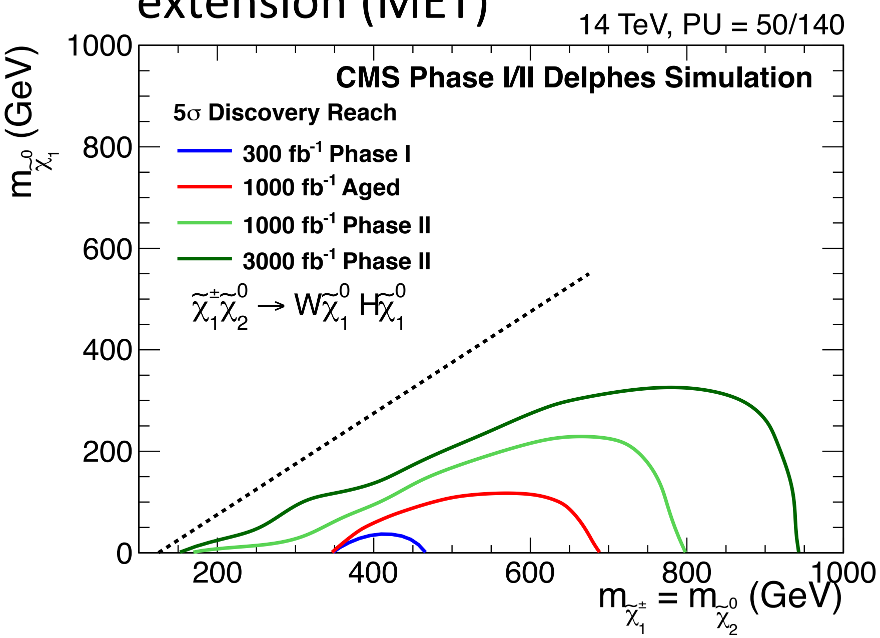
- **VBF H → ττ** - x 5.5 acceptance with Track-Trigger - 90% efficiency for Jet-ID with tracks and 15 % gain expected from improved mass resolution (MET)



- **$W_L W_L$ scattering better significance with 140 PU Phase-II than 50 PU Phase-I** - enabled by Tracker extension - EC Lepton-ID, b-tagging



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



Beam Radiation Instrumentation and Luminosity

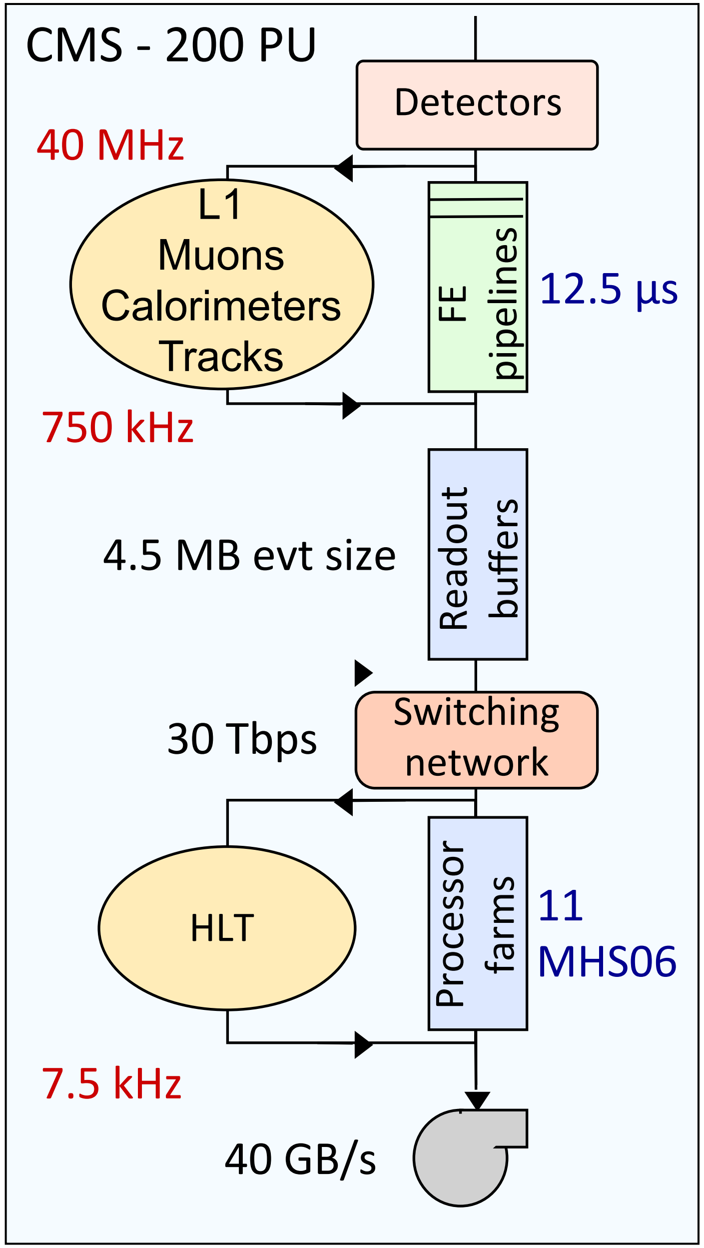
Beam Radiation Instrumentation and Luminosity upgrades

- Active protection and Background monitoring
  - Replace Diamond detectors due to radiation tolerance
  - New mechanics (new pixel and beam apertures)
  - Replace Beam Halo detector Photosensors
- Radiation monitoring:
  - Medipix-timepix: discriminate particles and energies - prototypes in 2016
  - New neutron (RADMON) detectors
- Luminosity measurement - bunch by bunch with 1% precision:
  - Replace PLT due to radiation - use new dedicated forward pixel plans in extension of Tracker with specific trigger and BE

L1-Trigger/HLT/DAQ

L1-Trigger/HLT/DAQ upgrade features

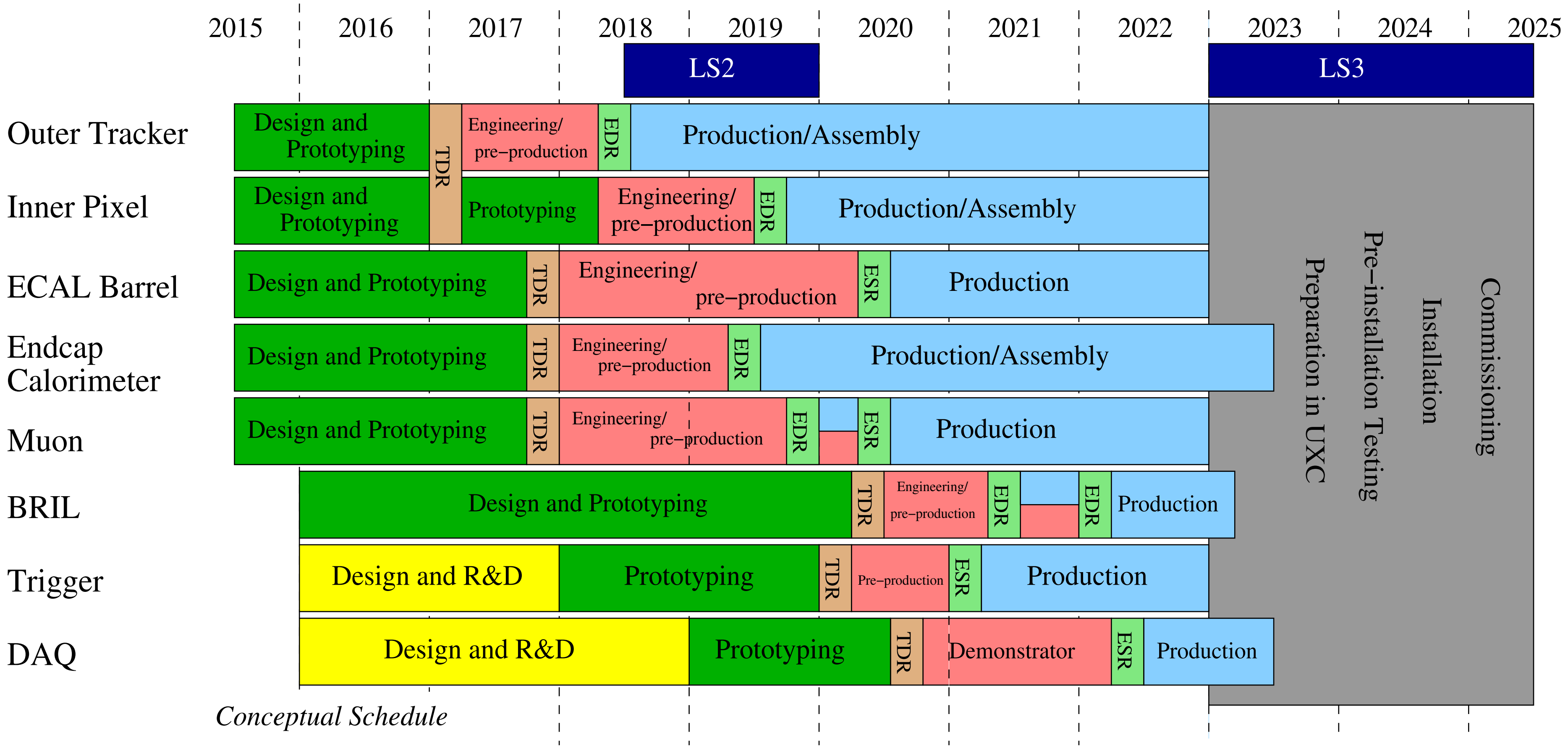
- L1-Trigger
  - High BW and processing power boards
  - First layer to match detector information
  - Second layer to produce Trigger objects
- Trigger timing, throttling and control
  - High Band Width bi-directional link allowing trigger information to steer readout
- DAQ
  - Similar evt builder, 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



Upgrade Planning & Cost estimates

Upgrade planning

- R&D program well established for all upgrades with set of major milestones
- TDRs mostly in 2017 - including design optimization, main technical choices, improved cost estimates, and construction funding and sharing model
- Production & assembly staged according to project needs (with contingencies)



CORE Cost estimates

- Funding of Material & Services starting at pre-production - no manpower apart from contracts & P5 installation - no contingencies - 2014 mean exchange rates
- Component level breakdown - estimates based on: vendor quote/catalog prices recent similar purchases, engineering designs where sub-components are know, conceptual designs or scaling of similar systems

CORE cost estimate	MCHF (2014)
Pixel Detector	23
Outer Tracker	89
Tracking System	**112**
EB electronics	10
HB scintillators	1
Endcap HGC+BHE	64
Calorimeters	**75**
DT and CSC electronics	10
Muon stations:GE11,GE21, RP31 and RP41	10
Muon extension ME0	5
Muon Systems	**25**
Beam Monitors and Luminosity	**4**
L1 Trigger	7
HLT	11
DAQ	6
Trigger and DAQ	**24**
Infrastructure, Systems and Support, Installation	**25**
Total	**265**

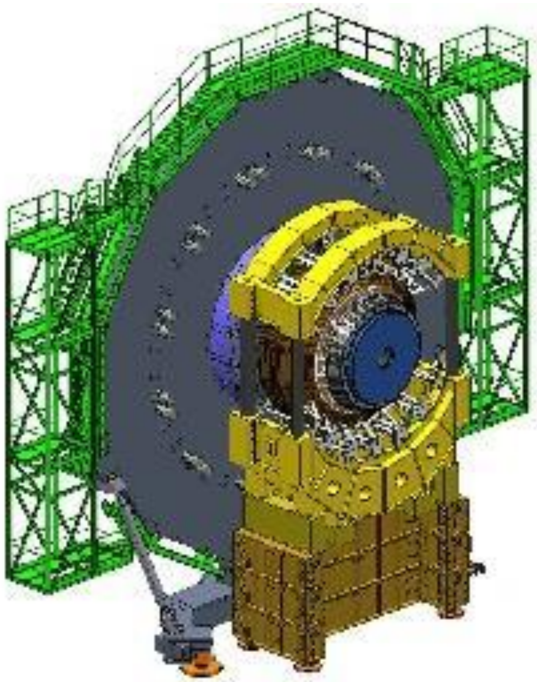
Concluding remarks

- CMS has developed strong conceptual designs for all detector upgrades to solve aging issues and high luminosity and PU challenges, covering the entire physics reach at the HL-LHC
- The Technical Proposal describes in details :
  - Configurations and technical solutions for all projects together with the established plans to develop components
  - The preliminary cost estimates have been built from component level costs in most cases, scaled from existing systems in others
- In a Scope Document the impact of de-scoping on performance and cost will be presented (targeting agreed funding scenarios)
- Design and technical optimizations for performance/cost-effective upgrades will continue during the preparation of individual project TDRs
- These TDRs are foreseen in 2017 to allow preparing funding and sharing of the construction work within the current HL-LHC schedule

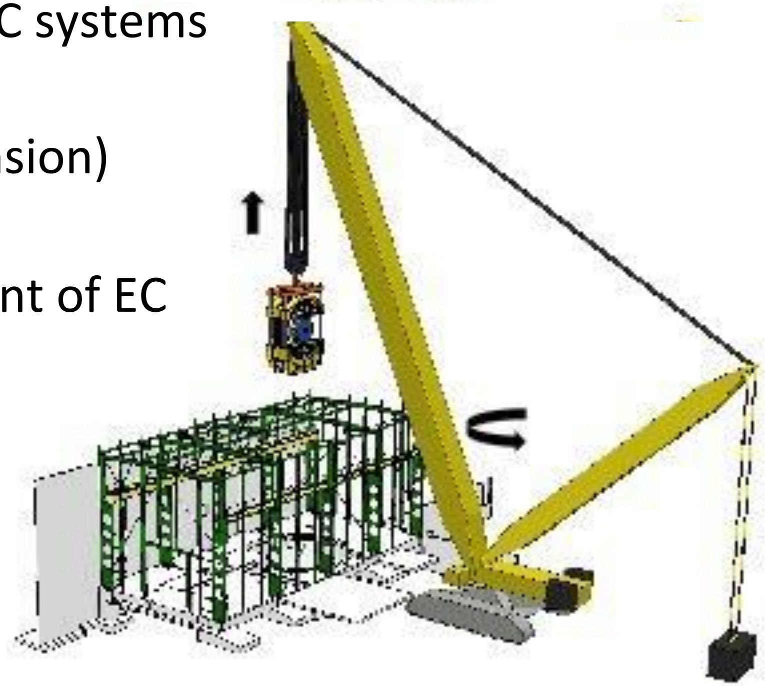
Back-up slides

Infrastructure and Logistic of work in LS3

Infrastructure upgrades

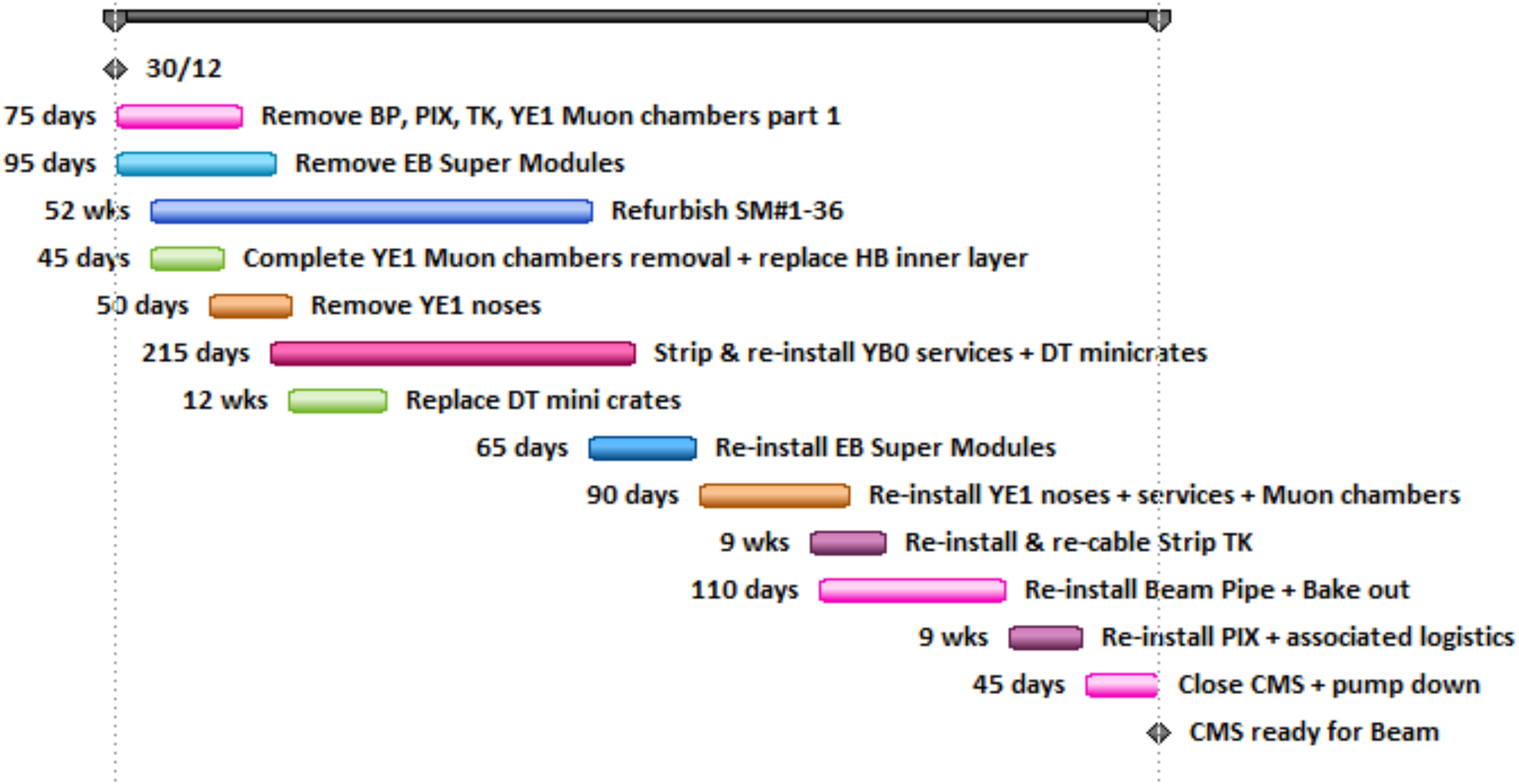


- Solenoid Magnet
  - Cryogenics, powering & control to prolong lifetime (cooled freewheel thyristor)
- Beam pipe
  - Replace all steel portions with Aluminium alloy
- Crane systems
  - Second carriage
- Service supplies
  - Gas, water, electrical power, dry gas, HVAC systems
- Common facilities and equipment
  - Assembly labs, workshops , storage (extension)
- Moving systems and access equipment
  - Winching system- removal and replacement of EC
- Safety systems and radio protection
- Integration & installation of all detectors



Logistic of work and schedule of LS3

- Anticipate work during LS2 or soon after
  - GEM1, CSC readout, outer beam pipe, thryristor, new crane, lifts, new facilities…
- Preliminary but detailed work sequence (76 tasks) (1 shift/day/task)
  - Duration is driven by EB electronics refurbishment and YB0 services
  - → 137 weeks - aim to reduce exploiting 2'nd UXC crane & duplicate tooling (EB)



Offline & Computing

Offline and Computing upgrade

- CPU increase: ratios to run 2 in table below - assuming x 8 gain in power at constant resources and x 2 improvement from software
  → x 4/12 to be further gained at 140/200 PU
- Raw data: At 5-7.5 kHz CMS would collect 25TB-37TB per year

Detector	HLT output rate (kHz)	Data Reco.	Simulation Detector sim.	Digi.	Reco.	Total
Phase 1	1	4	1	3.5	4	3
Phase-II (140)	5	100	5	47	100	65
Phase-II (200)	7.5	340	7.5	100	340	200

- Ongoing developments following new computing trends:
  - Low power ARM processors, and high performance GPU systems
  - More broadly distributed resources (opportunistic computing) and improved techniques in data provisioning (cloud tools)
  - More efficient use of storage and data distribution - SSD, dynamic data placement, remote services through Content Delivery Networks

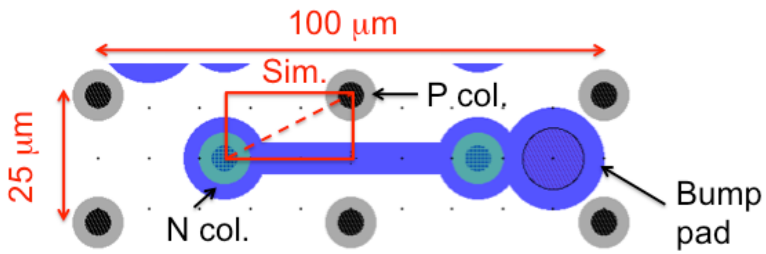
TP studies

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*		

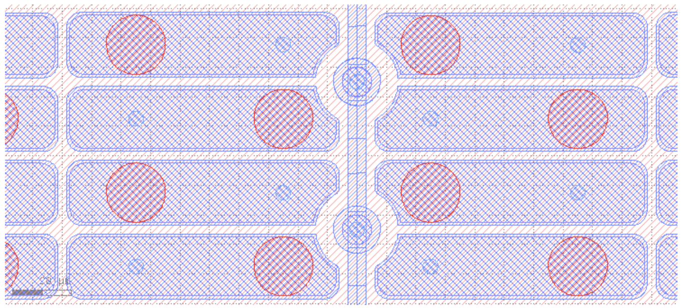
Silicon sensors

- Outer Tracker (max. fluence 1.5 x 10^{15} neq/cm^2 at 3000 fb^{-1}):
  - n-in-p, 200 μm active thickness from 300 μm deep diffusion FloatZone material available
  - 200 μm physical thickness & Magnetic Czochralsky preferred
  - 6” or 8” depending on availability and cost
  - → Now qualifying potential vendors

- Pixels (max. fluence 2 x 10^{16} neq/cm^2 at 3000 fb^{-1}):
  - n-in-p preferred for cost
  - Also investigating 3D technology for innermost layer
  - → Finalize layout - ability for small pixels - compare radiation tolerance



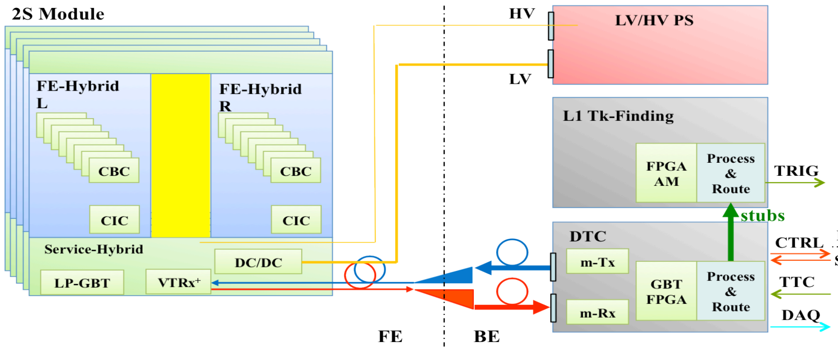
3D

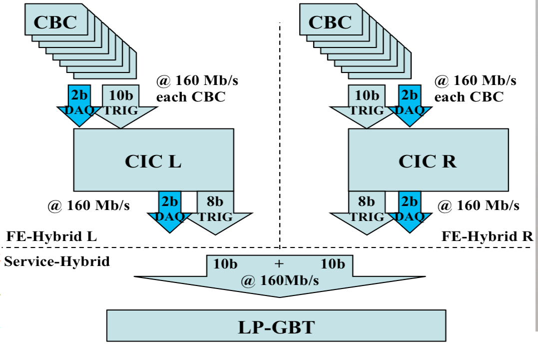


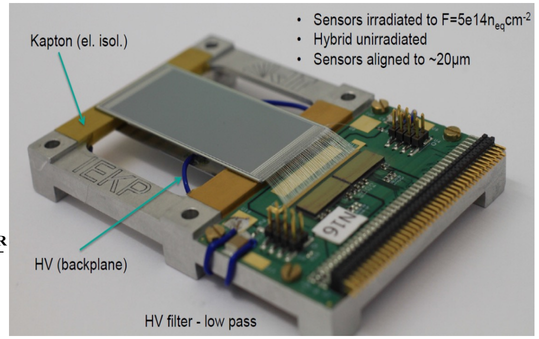
n-in-p

Front end electronics

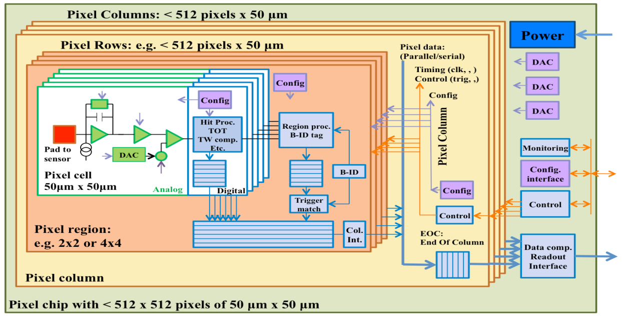
- Outer Tracker: Binary chip CBC 130 nm IBM (2S modules) and flex hybrid tested - First version of MPA 65 nm TSMC ASIC (PS modules) available - Concentrator (CIC) 65 nm TSMC verylog implementation

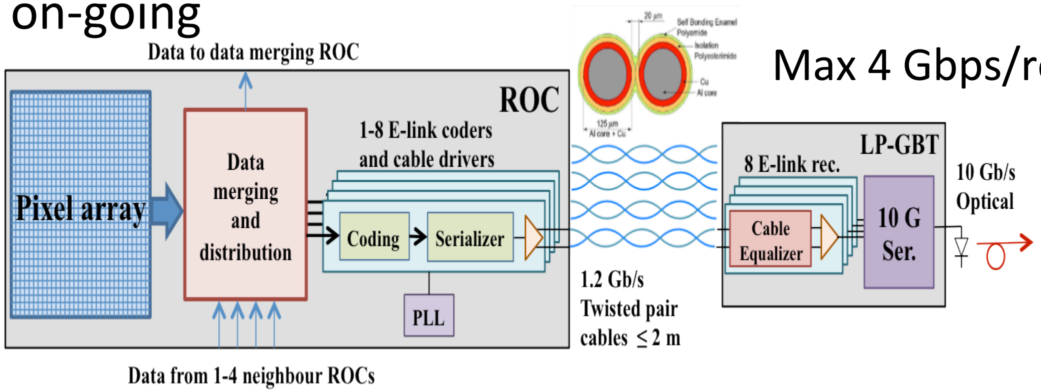






- Pixels: RD53 FE chip common R&D with ATLAS - defining rules for radiation tolerance ≥ 200 Mrad - design on-going



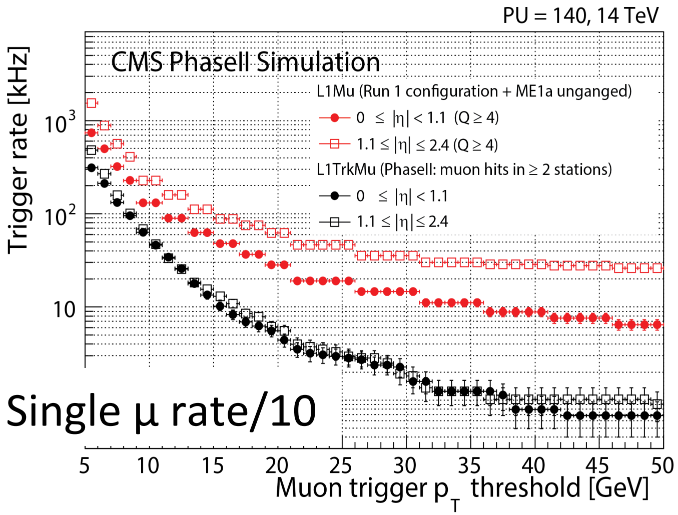


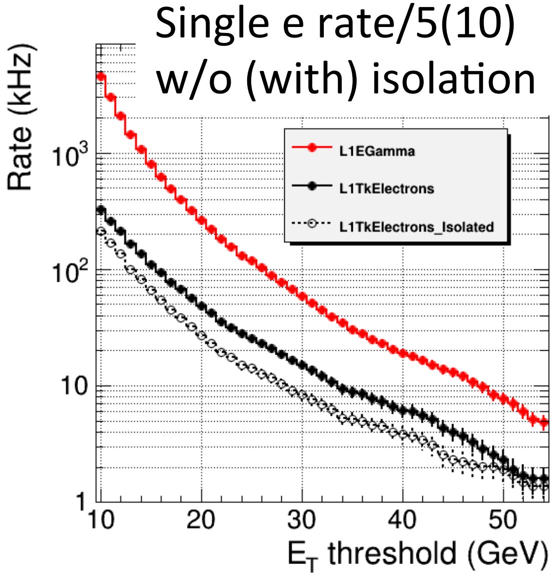
Max 4 Gbps/roc

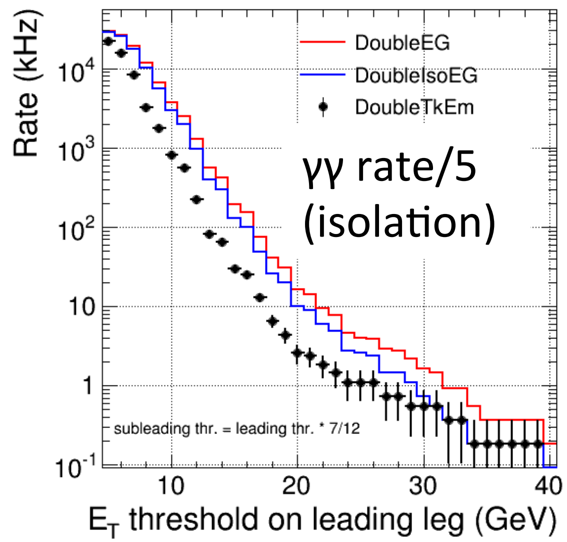
- Data transfer: on-going work to increase BW of GBTs with low power consumption (up to 2 x 3.2 Gb/s) also light 2 m electrical links for pixels
- Powering scheme: both DC/DC and serial powering considered

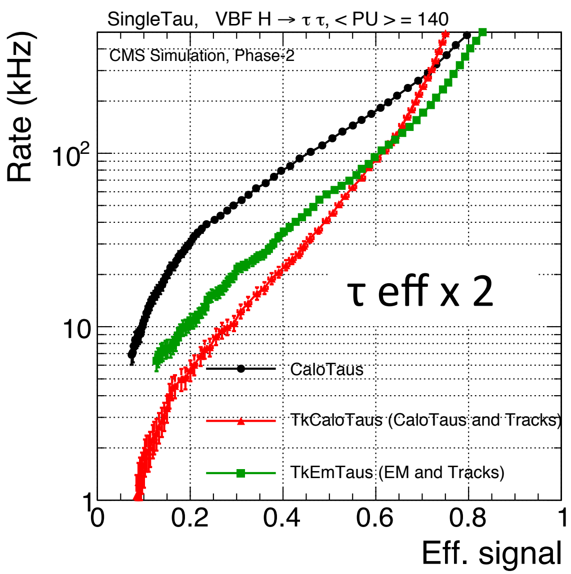
L1 Trigger performance with Track-Trigger

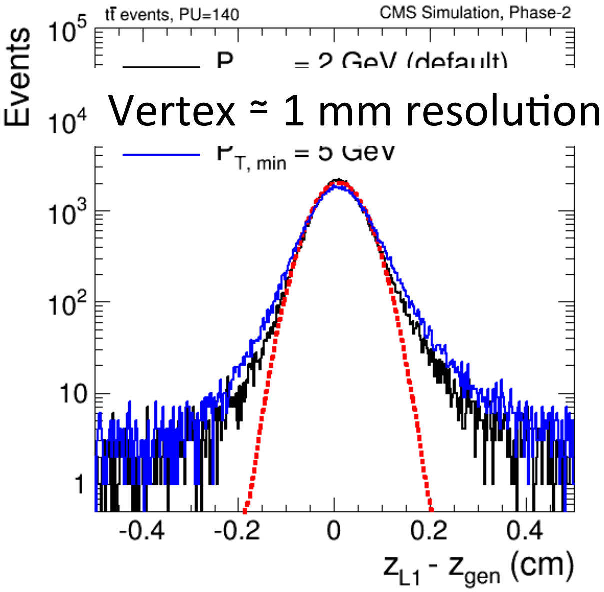
Powerful scheme to control all inclusive trigger rates at first 40 MHz stage

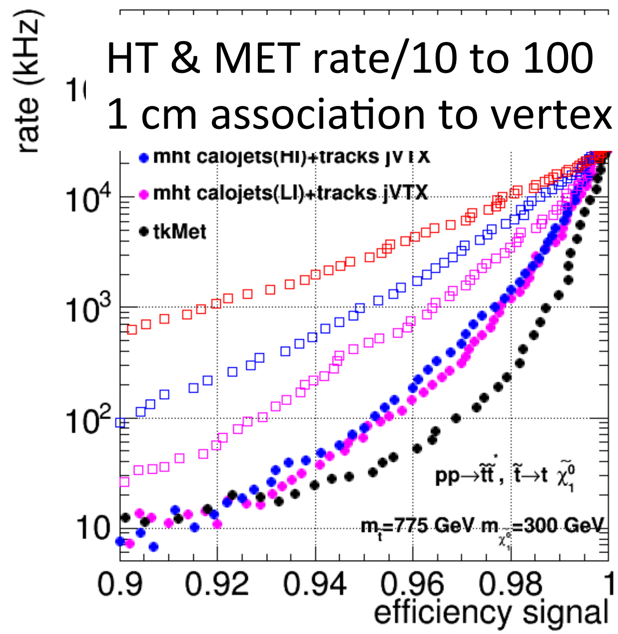








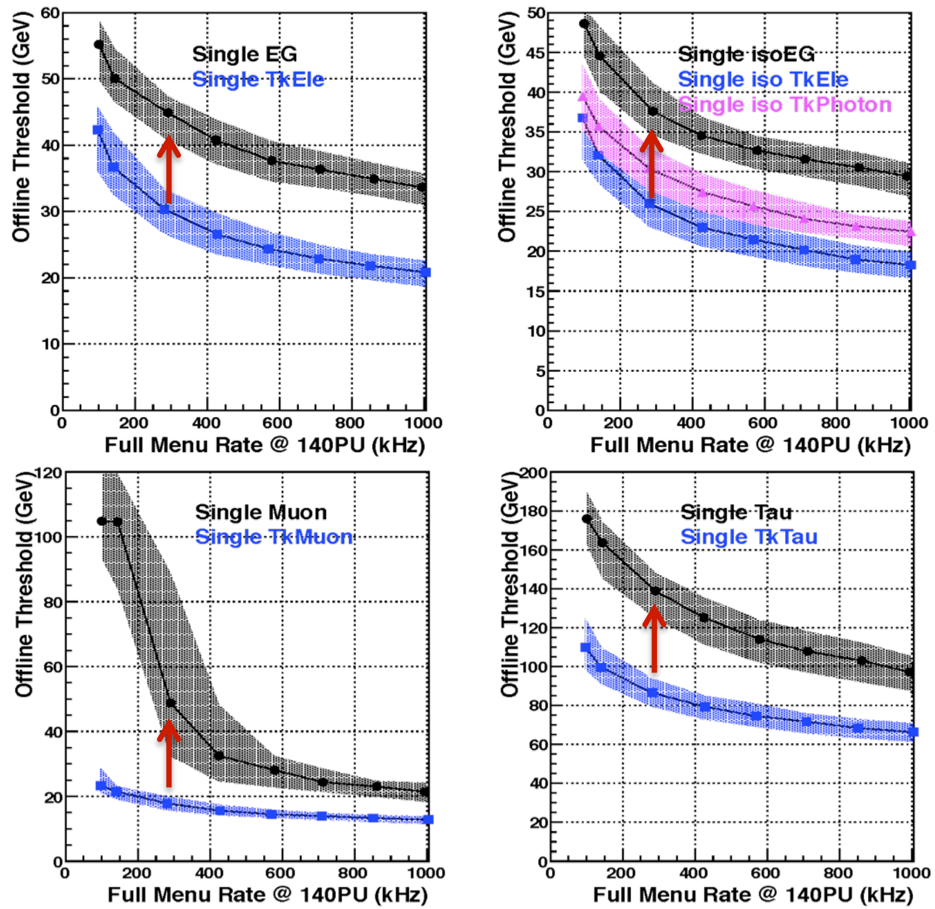




L1 Trigger rate - example of menu

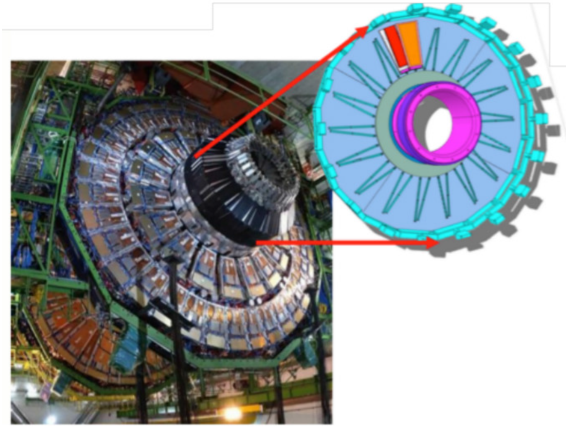
A Phase-I Trigger menu with Track-Trigger needs ≃ 500/750 kHz rate at 140/200 PU (including a 1.5 margin) - Track-Trigger will also allow dedicated multi-objects & topological trigger with very low thresholds

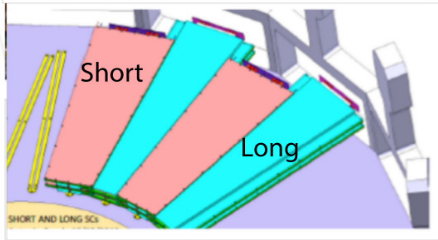
$L = 5.6 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ $\langle PU \rangle = 140$	Level-1 Trigger with Level-1 Tracks	
Trigger Algorithm	Rate [kHz]	Offline Threshold(s) [GeV]
Single Mu (tk)	14	18
Double Mu (tk)	1.1	14 10
ele (iso tk) + Mu (tk)	0.7	19 10.5
Single Ele (tk)	16	31
Single iso Ele (tk)	13	27
Single γ (tk-iso)	31	31
ele (iso tk) + e/γ	11	22 16
Double γ (tk-iso)	17	22 16
Single Tau (tk)	13	88
Tau (tk) + Tau	32	56 56
ele (iso tk) + Tau	7.4	19 50
Tau (tk) + Mu (tk)	5.4	45 14
Single Jet	42	173
Double Jet (tk)	26	2@136
Quad Jet (tk)	12	4@72
Single ele (tk) + Jet	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**	

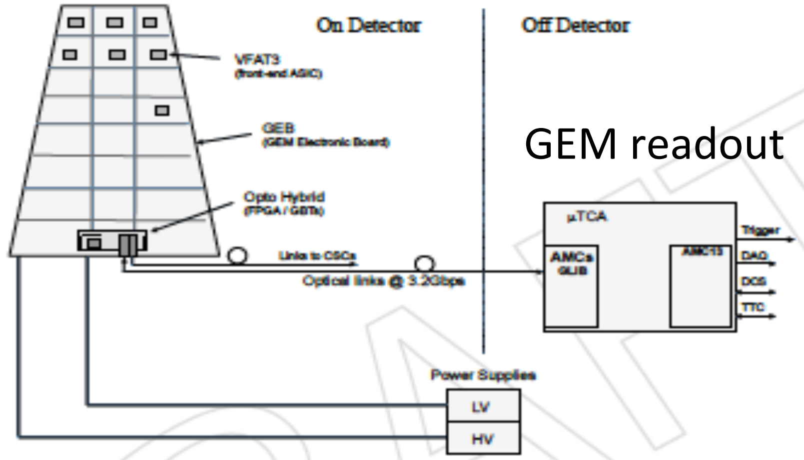


70 % Phase-I menu at 140 PU with Track-Trigger (left) & threshold with & w/o as a function of L1 rate (right)

New Muon detectors in the forward region

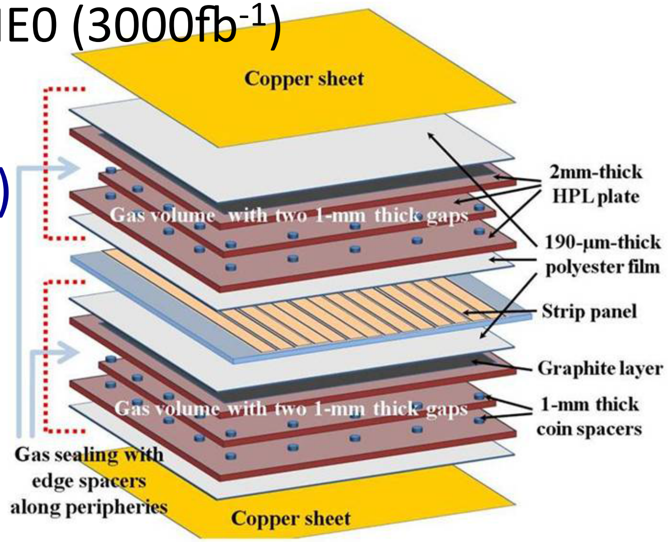






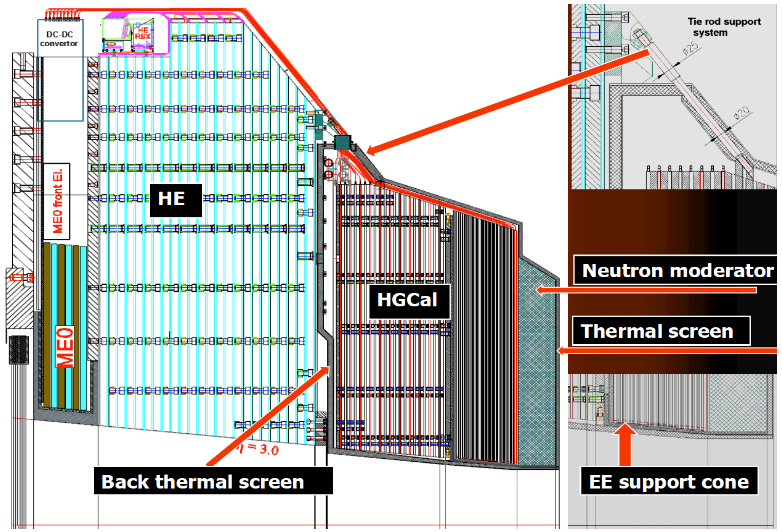
- GEM chambers in station 1 & 2 (high rate capability)
  Thin ≤ 9 cm and ≃ 140-350 µm resolution in the high B-field region
  - 10/20◦ wedge 8/6 rings - 20 mm between readout plans
  - Pitch 0.5-1.2 mm in GEM1/1 strip length about 12.5 cm
  - Current 100 mC/cm^2 in GEM1/1 few mC/cm^2 in ME0 (3000fb^{-1})
  - Installation of GEM1/1 planned during LS2

- iRPCs in station 3 & 4 (enhanced rate capability)
  - Low resistivity bakelite or glass - higher gain FE - multi-gap/thinner electrodes
  - Good time resolution ≥ 100 ps for background rejection - HSCP measurement



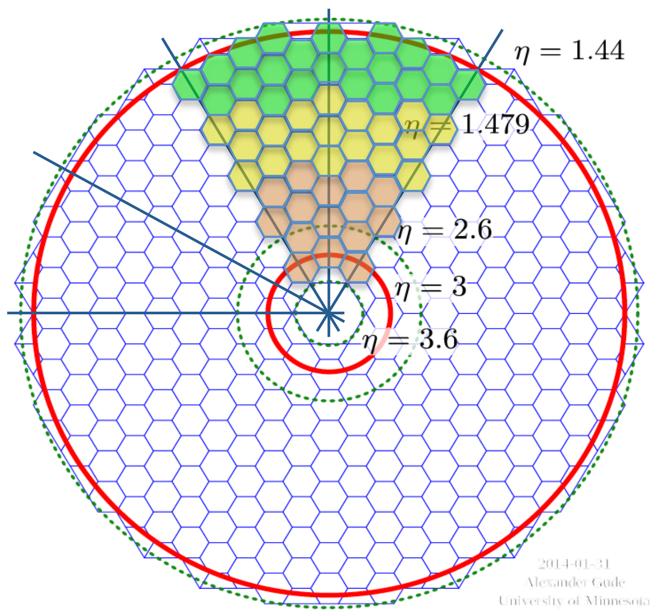
High Granularity (HGC) & Back Hadron (BH) calorimeters

- 3D shower measurement in HGC (layout studies with standalone simulation)
  - Electromagnetic EE (26 X_0, 1.5λ): 28 layers of Silicon-W/Cu absorber
  - Front Hadronic FH (3.5 λ): 12 layers of Silicon/Brass
- Back Hadronic BH (5 λ): 12 layers of Scintillator/Brass (2 depths readout)



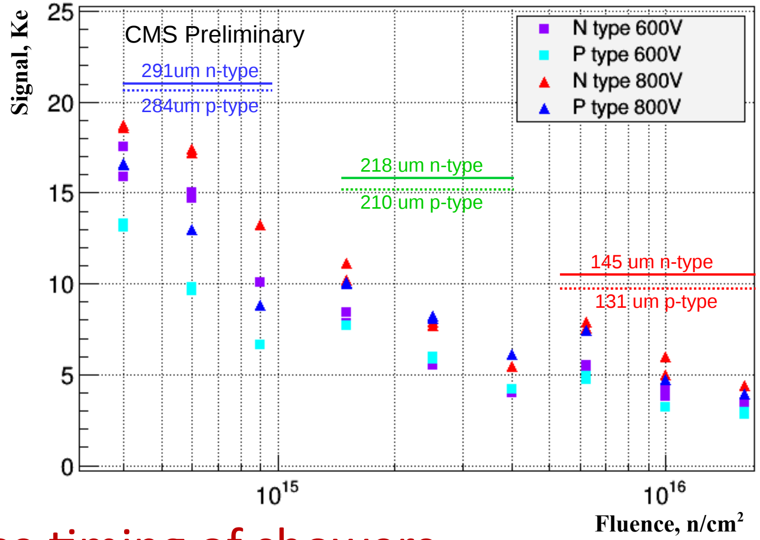
EE: 380 m² - 4.3 Mch - 13.9k modules - 16t
FG: 209 m² - 1.8 Mch - 7.6k modules - 36.5t
BH: 428 m² - 5184 SiPMs

Thickness	300 μm	200 μm	100 μm
Maximum dose (Mrad)	3	20	100
Maximum n fluence (cm^{-2})	6×10^{14}	2.5×10^{15}	1×10^{16}
EE region	$R > 120$ cm	$120 > R > 75$ cm	$R < 75$ cm
FH region	$R > 100$ cm	$100 > R > 60$ cm	$R < 60$ cm
Si wafer area (m^2)	290	203	96
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance (pF)	40	60	60
Initial S/N for MIP	13.7	7.0	3.5
S/N after 3000 fb^{-1}	6.5	2.7	1.7

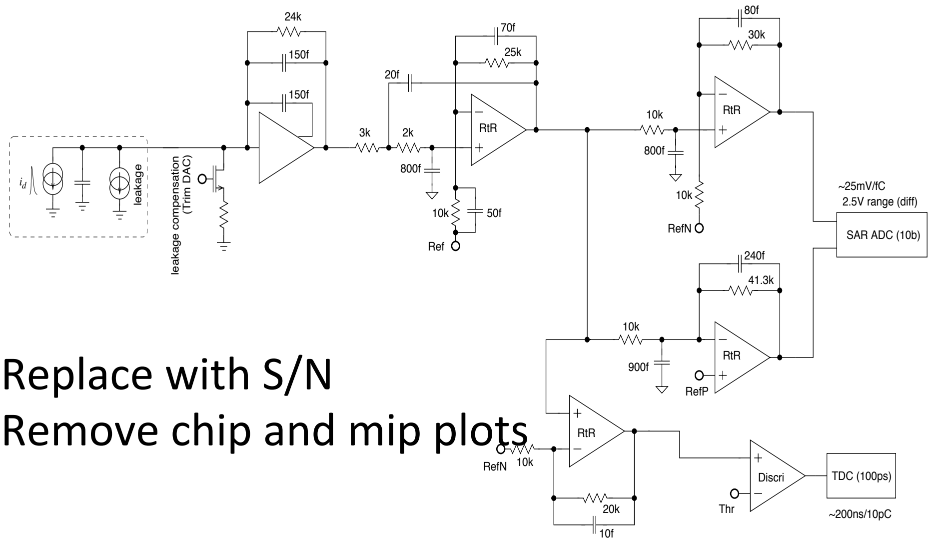


HGC Silicon sensors and Front End ASIC

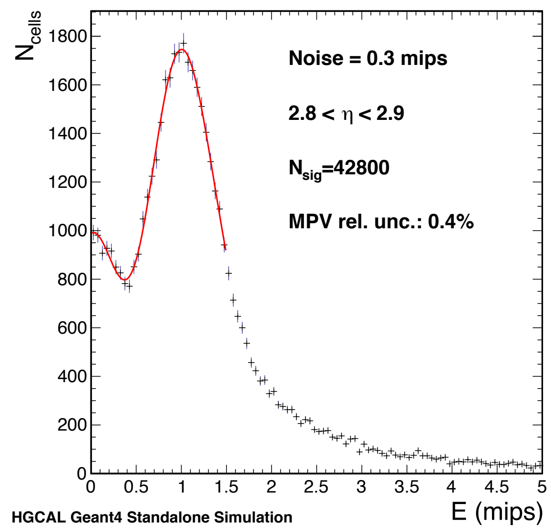
- Sensors: n-in-p pads - rad. test with neutrons 1.5 x 10^{16} neq/cm^2 (≃ 4500 fb^{-1}) ≃ 40 % signal loss - I_{leak} ≃ 10 µA (at T = -30◦)
- FE ASIC - 130 nm TSMC - spice simulation:



– Shaping ≃ 15 ns
– Noise ≤ 2500 e$^-$ (after 3000 fb^{-1})
– Dynamic 10 pC - 10 bit ADC ≤ 100 fC and Time over Threshold (ToT) ≥ 80 fC
– Channel calibration better than 1%
– Power ≤ 10 mW per channel
– Time resolution ≃ 50 ps - opportunity for precise timing of showers
– MIP inter-calibration ≤ 3% → ≃ 0.5% in constant term and dedicated small pads



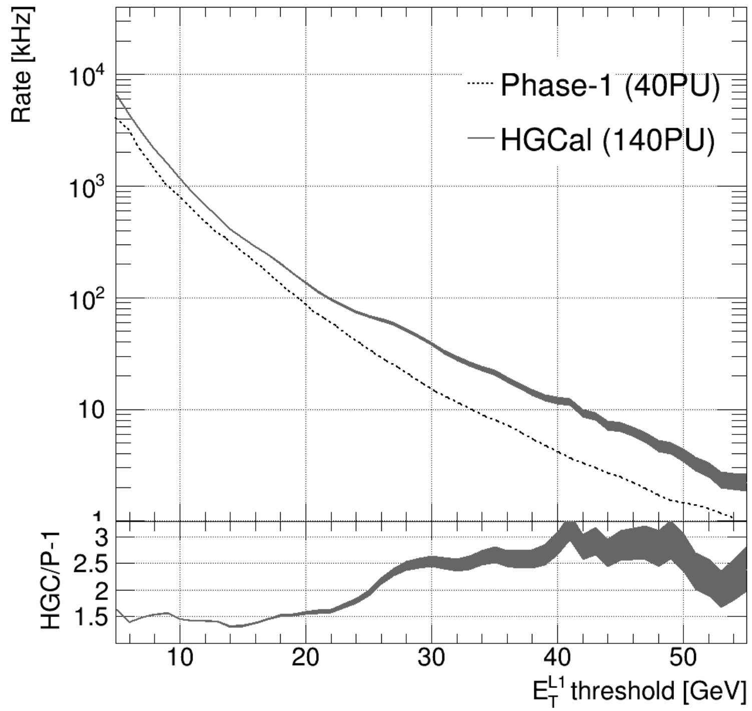
Replace with S/N
Remove chip and mip plots



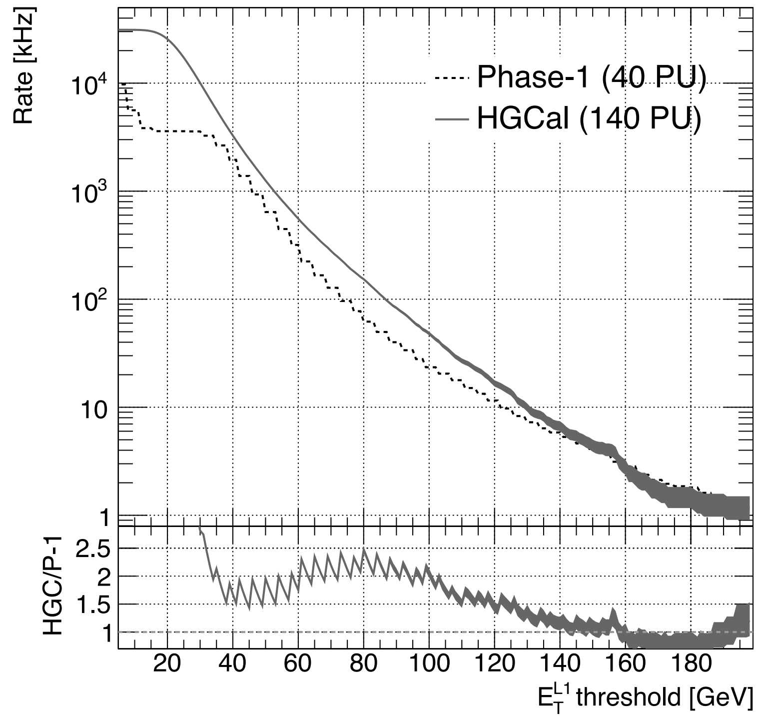
HGC Trigger performance

Expect improvements compared to present detector, particularly benefit where no (or less efficient) Track-Trigger (e.g γ, & VBF/S jets beyond η = 2.4)

- Trigger data: 2(2x2) pad sums (inner/outer) from alternate layers in EE/FH, full BH



e/γ rate x 2.5 Phase-I (similar efficiency)



Jet trigger x 2 Phase-I