CMS: an experimental challenge

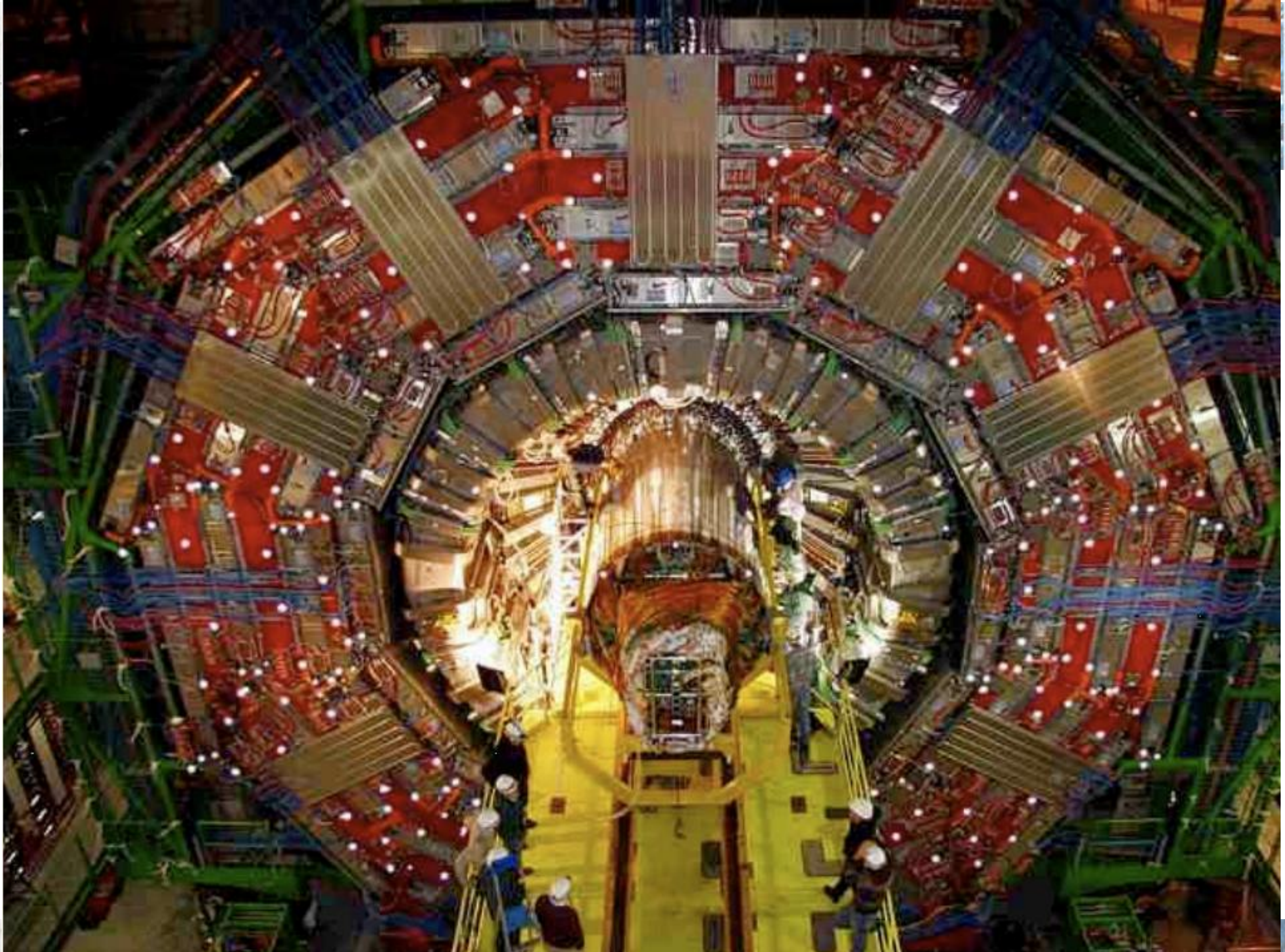
CMS experiment: why?

LHC success: Upgrade phase I

High Luminosity future : Upgrade phase II

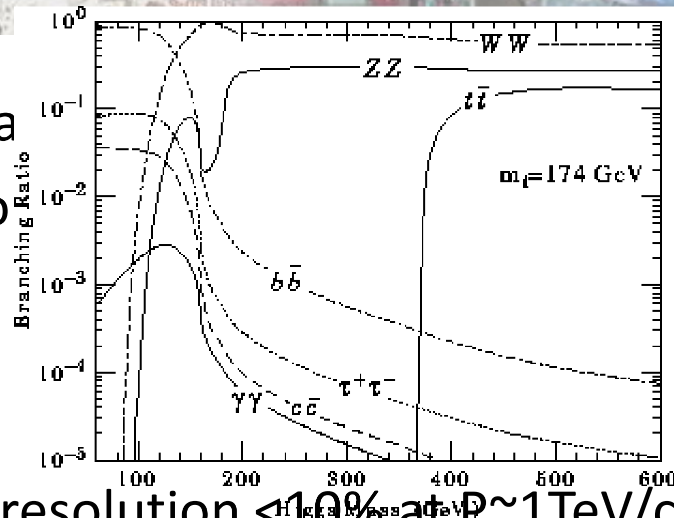
Part 2: why silicon sensors all over the upgrade?

T. Camporesi

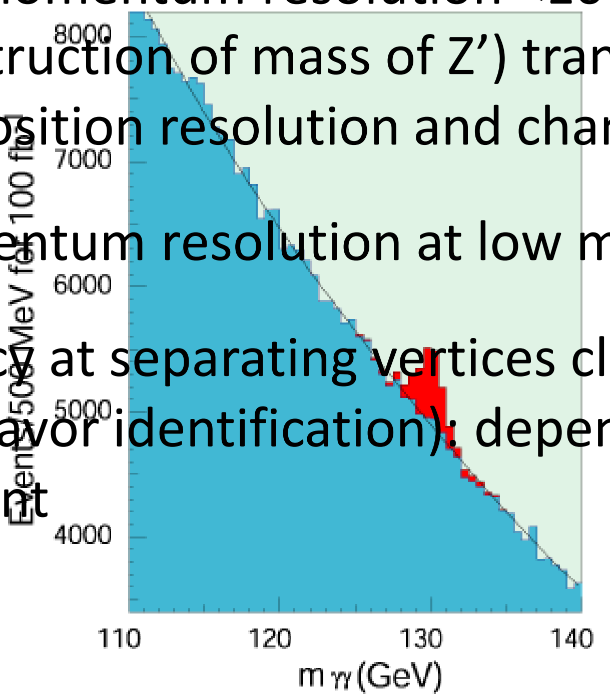


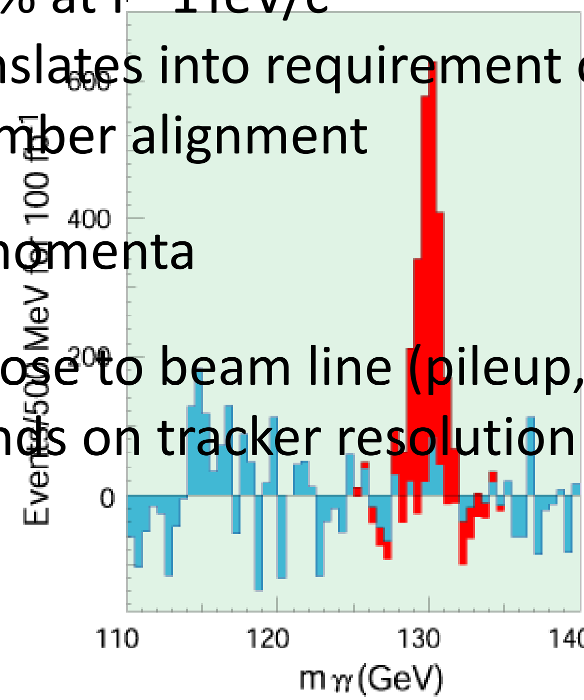
pp physics objectives

- The LHC primary goa … etry breaking:
- Higgs decay in γγ: co … n of EM energy resolution <0.5%

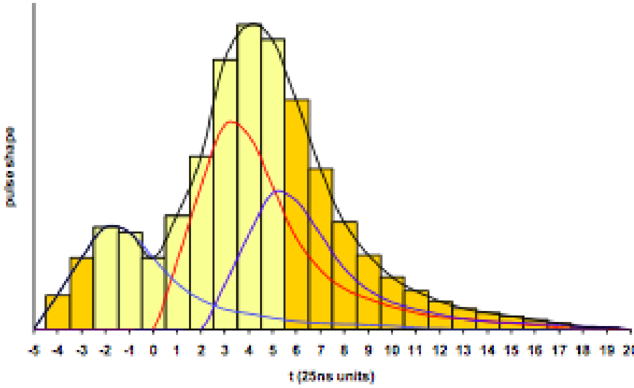


- Muon momentum resolution <10% at P~1TeV/c (reconstruction of mass of Z') translates into requirement on m-hit position resolution and chamber alignment
- % momentum resolution at low momenta
- Efficiency at separating vertices close to beam line (pileup, heavy flavor identification): depends on tracker resolution and alignment

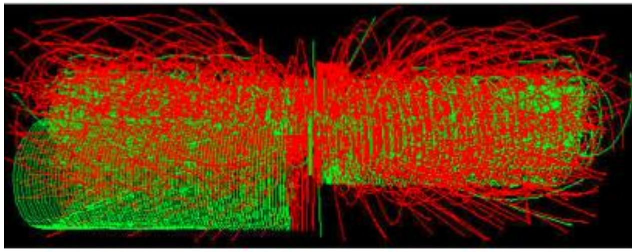




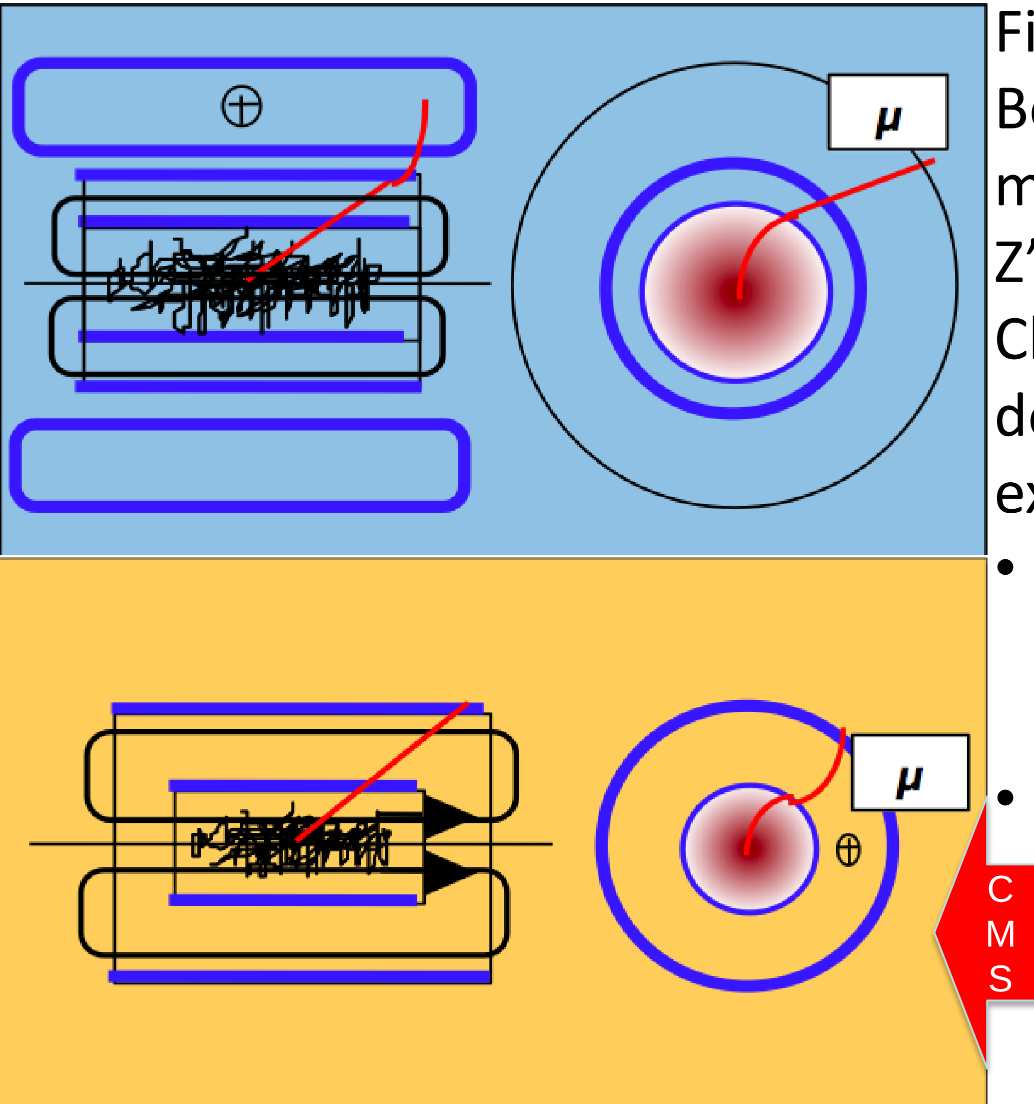
The LHC constraints



- Bunch separation 25 ns: a challenge for the readout electronics
  - Need of fast electronics to avoid piling up signals from one bunch to the next
  - Need of bunch identification (even a trigger level)
- Ultimate luminosity 2 10^{34} cm^2/s : ~ 40 interactions per cross
  - Need highly granular detector to mitigate 'channel' pile-up: many channels
- Radiation damage: the high rate hadron production in LHC requires development of radiation hard detector/electronics
  - Forward calorimeters elements will integrate in excess of 10^{16} neutron over 10 years of LHC operation
  - Forward trackers will integrate in excess of 10^{16} charged particles over the operation of LHC



A pp general purpose detector



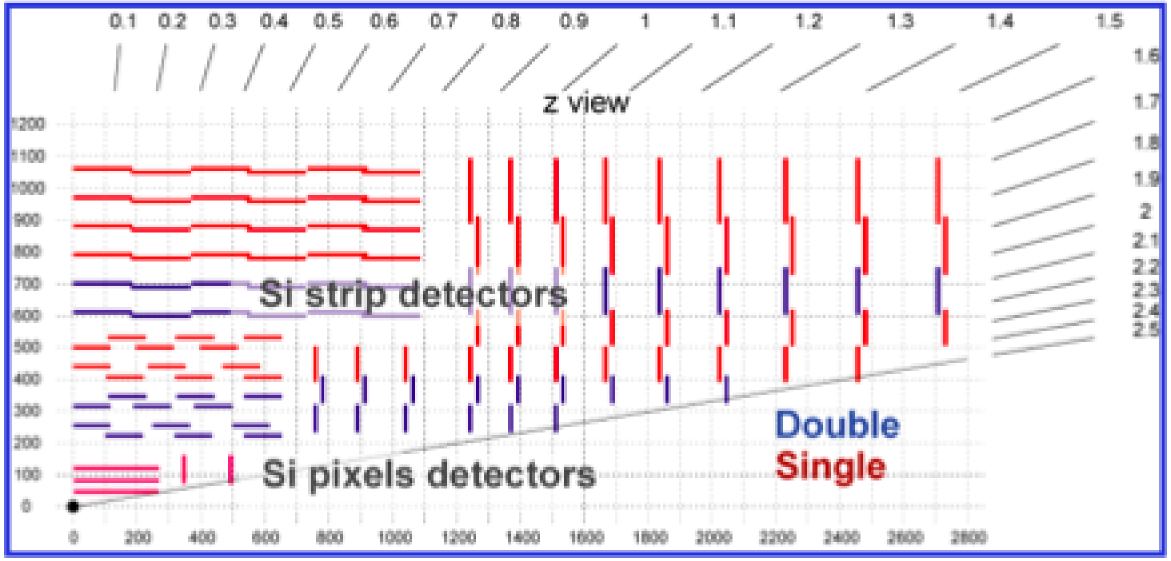
First thing first: tracking:
Benchmark 10% P resolution for muons of 1 TeV (in order to detect Z')
Choice of magnet configuration determines the geometry of the experiment: CMS

- Measurement of p in tracker and B return flux; Iron-core solenoid.
- Properties:
  - Can use vertex to constrain track
  - Large B and large dL

Tracker

- Resolution goals:
  - $\Delta p_T/p_T \sim 0.1 p_T[\text{TeV}]$
  - Good resolution for narrow Signal ($H \rightarrow 4\mu$)
  - Match calo resolution / Calo calibration ($W \rightarrow e\nu$)
  - ..and good isolation capability (2 particle separation etc.)
- CMS solution: 10 Si Strip (4 double) layers + 3 Si pixel layers/fwd disks (added after initial proposal)

Tracker



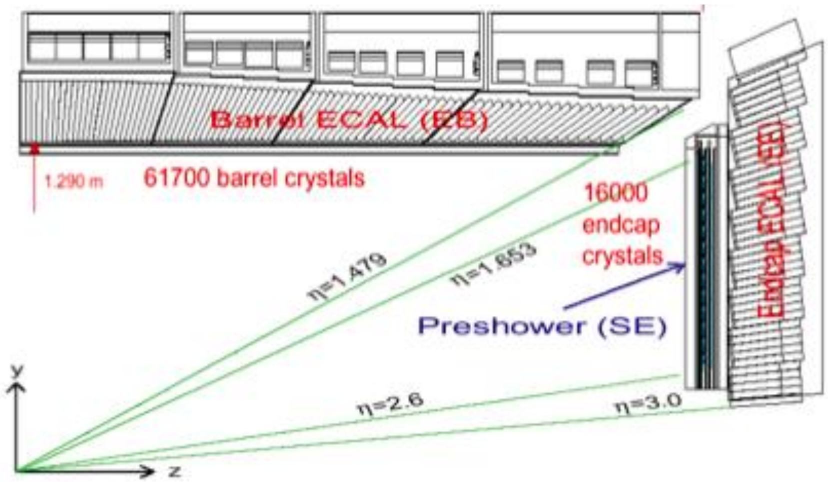
Outer radius: 110 cm
Length = 270 cm
B= 4Tesla
On average 12 hits per track
Hit resol: pitch/√12

$$\frac{\Delta p}{p} \approx 0.12\left(\frac{pitch}{100\mu m}\right)^{1}\left(\frac{1.1m}{L}\right)^{2}\left(\frac{4T}{B}\right)^{1}\left(\frac{p}{1Tev}\right)$$

Pitch ~100 μm
66 Million pixels, 10 million strips: low occupancy at ultimate Lumi
Run at <-10ºC for rad hardness (>100 time better than at 25ºC)

ECAL

- Benchmark: H→γγ. S/N determined by calo resolution (Higgs width very narrow and QCD background 2 order of magnitude larger)
- CMS choice : Crystal calorimeter



Properties of some crystals

Crystal	X_0 (cm)	R_M (cm)	Light Yield Gammas/MeV	Peak (nm)	Decay (ns)
BaF_2	2.06	3.4	2000	210	0.6
			6500	310	620
CeF_3	1.68	2.6	2000	300	5
				340	20
$PbWO_4$	0.89	2.2	250 !	440	5-15

76000 Crystals
Need of new Photodetector (B-Field)

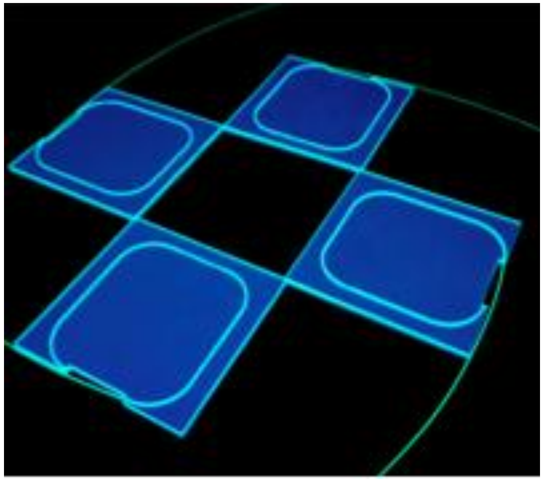
Avalanche Photo Detector (APDs)

HCAL

- HCAL requirement:
  - Jet energy resolution:
    limited by jet algorithm, fragmentation, magnetic field and pileup at high luminosity . At high momentum need fine lateral segmentation as jets are collimated.
  - Missing transverse energy resolution (SUSY searches)
    Forward coverage to $|\eta|<5$
    Hermeticity – minimize cracks and dead areas
    Absence of tails in energy distribution: more important that a low value in the stochastic term
- Good forward coverage required to tag processes from vector-boson fusion

HCAL

$$\frac{\sigma_E}{E}(\%) \sim \frac{100-150\%}{\sqrt{E}}$$

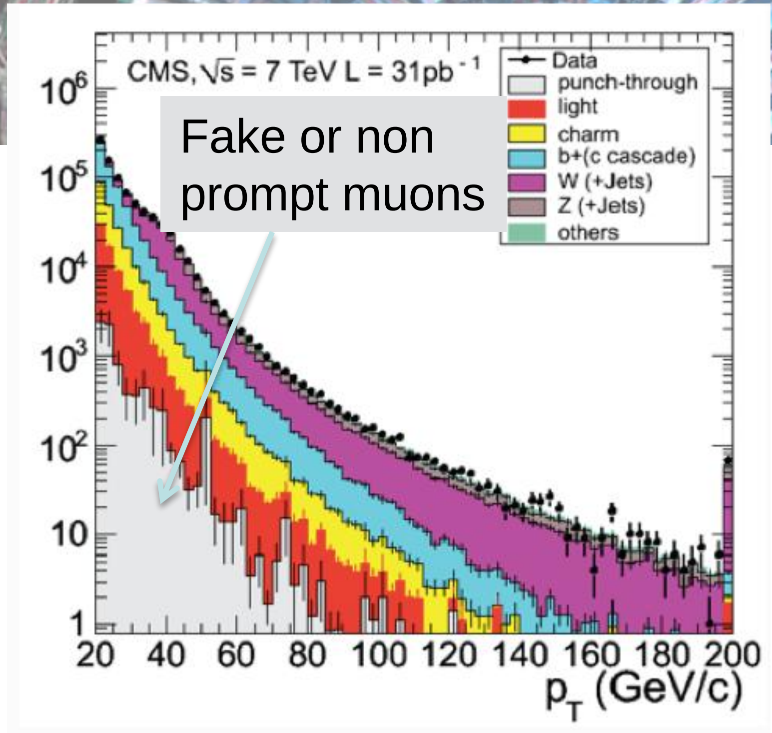


Tower size: $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$

This is the basic trigger unit

Muons

- Performance requirements
  - L1 trigger: very high rate from Real muons (semileptonic decays of b,c). Need to keep p_T cut as low as possible (~5 GeV)
  - P_T Resolution: need very high $Bd\ell$ for high momentum muons and good chamber hit resolution (~100 μm).
    At low momentum Si tracking is better
  - Charge mis-id ~1% at 1 TeV



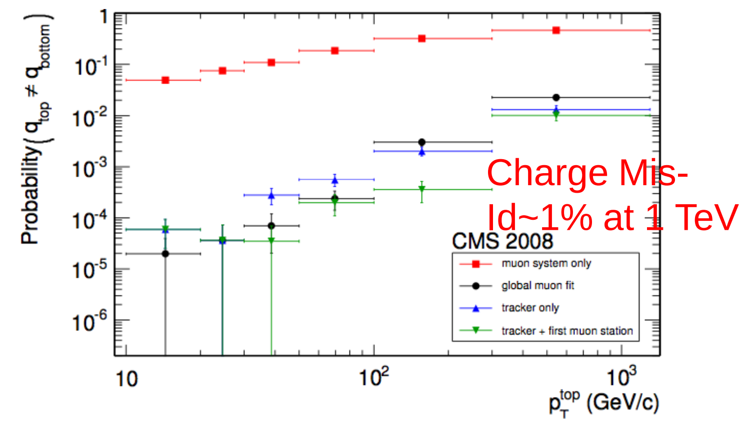
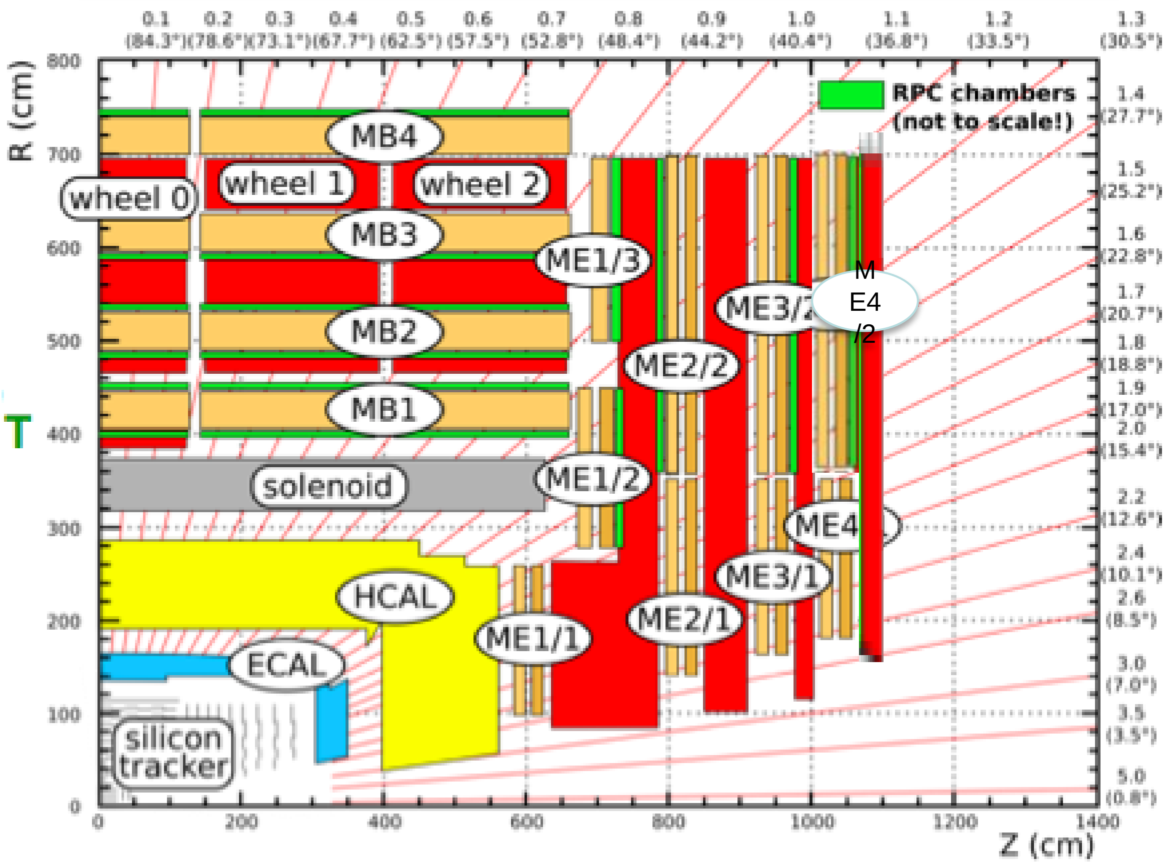


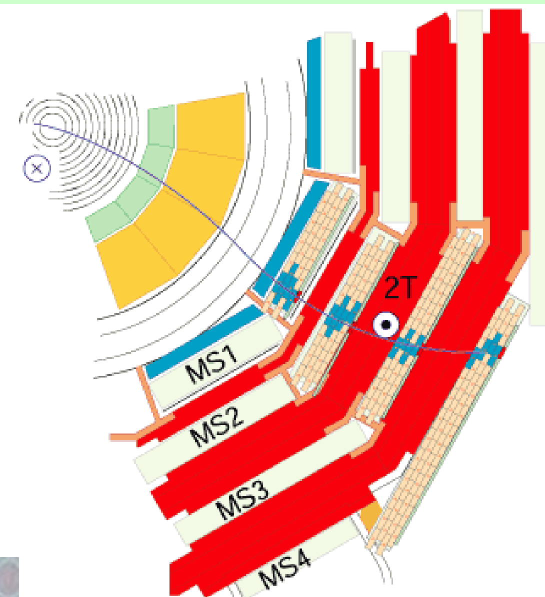
Figure 21. Rate of charge misassignment as a function of p_T of the tracker track reconstructed in the top hemisphere, for standalone muons (squares), tracker tracks (triangles), global muons (circles), and the TPFMS refit (upside-down triangles).

Muons

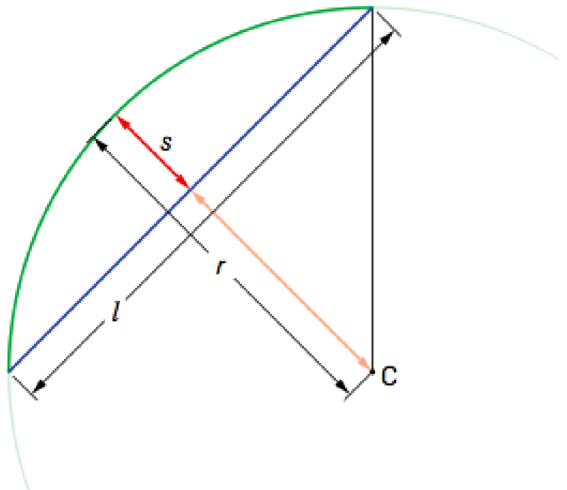


12 ktons of iron absorber and B-field flux return

Bending in iron + muon tracking: trigger info; and link with main tracker
Sophisticated alignment system



Particle radius in B field



$$r = \frac{\ell^2}{8s} + \frac{s}{2}$$

$$r \text{ » } \frac{\ell^2}{8s}$$

When s small (ie. Relatively high Pt)

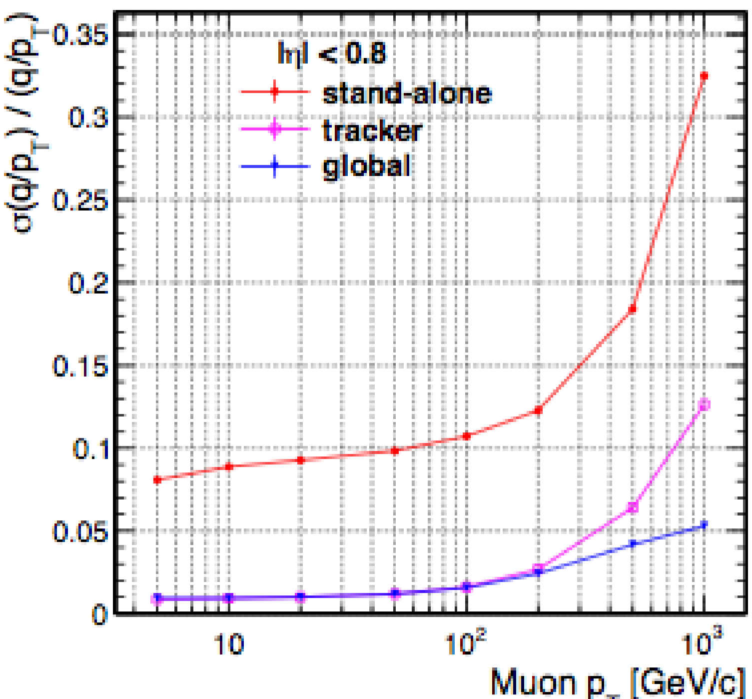
Note about CMS μ measurement

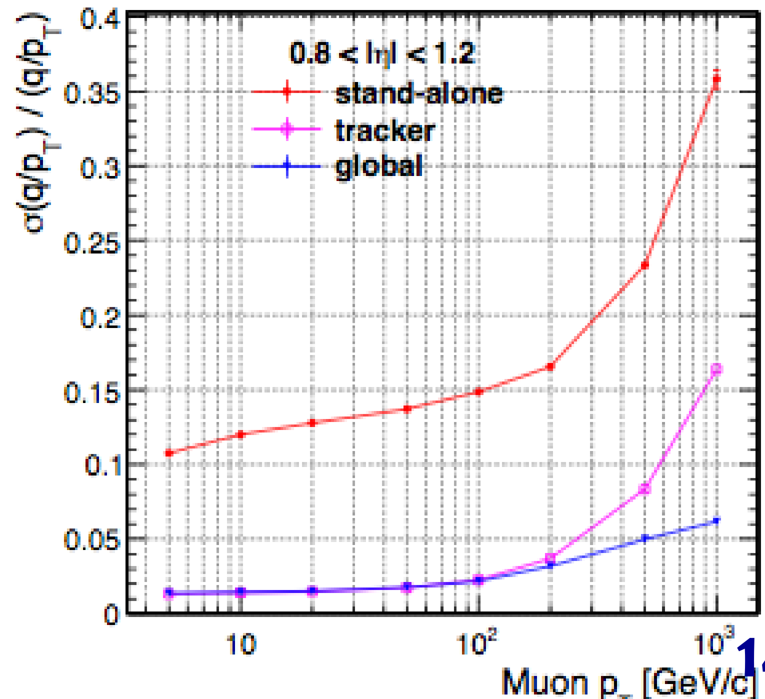
$$P_t \mu 0.3 \times B \times r$$

$$r \gg \frac{\ell^2}{8s} \qquad \frac{\Delta P_t}{P_t} \propto \frac{\Delta s}{\ell^2} + \ldots$$

Where ℓ is the 'cord' length of the track in the B field and S the sagitta

In CMS the tracker ends at 1.1 m radius while the first layer of the DT is just outside the coil (i.e. a track integrates constant B up to the inner edge of the solenoid i.e. ~3 m)





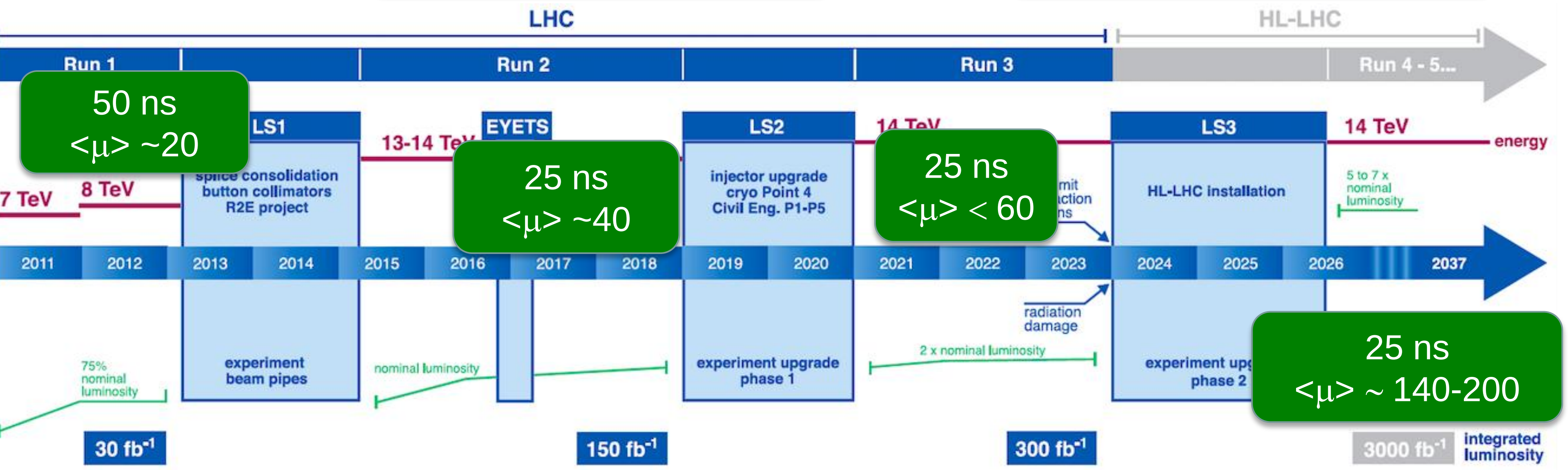
LHC success

- LHC has exceeded their expectation in the first run:
  - Bunch intensities: reached 1.7 10^{11} p/bunch (ultimate reach at design time was 1.2!) … remember lumi goes with the square of the BI
  - New developments at injector level have demontrated that with the BCMS scheme normalized emittances can be reduced to less than 1.5 μm (was ~4 μm at design time) ...and lumi is linear in emittances
  - β*: the final focusing strength which is foreseen for next year is 40 cm .. Was assumed it could reach 50 cm by the end of the LHC programin the roginal proposal
  - The ‘imperfections’ of the magnetic lattice are more than a factor 10 better than originally estimated (leading to b beating of order %)
- This leads to conditions which exceed the original design parameters of CMS: the instantaneous luminoisty and pileup being one of the constraints for the design...and LHC is likely to exceed the design 10^{34} $cm^{-2}s^{-1}$ design already next year
- This has led CMS to start an upgrade program immediately after the the start of operation: so called phase I upgrade

CMS as a function of time

CMS Phase I Upgrades 2015-2020

CMS Phase II Upgrades 2024-2026



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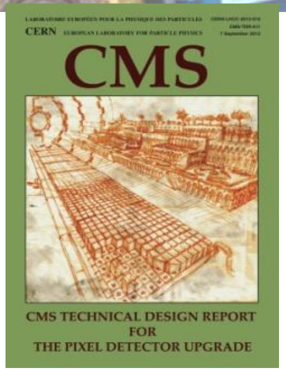
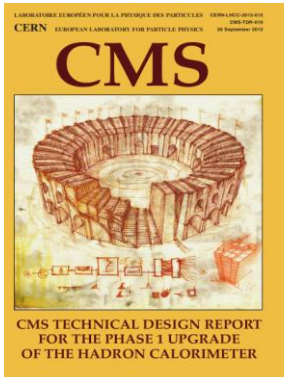
CMS phase I upgrade

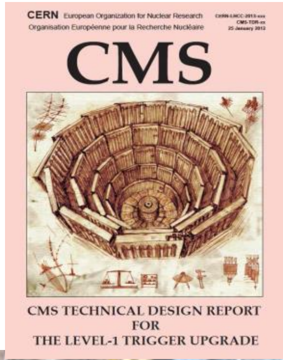
- Pixel tracker : four-layer barrel and 3 forward-disk pixel tracker with new readout chip capable of higher hit rate (installation during end of 2016 extended technical stop)

- 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 upgrade strategy

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

LS3

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)

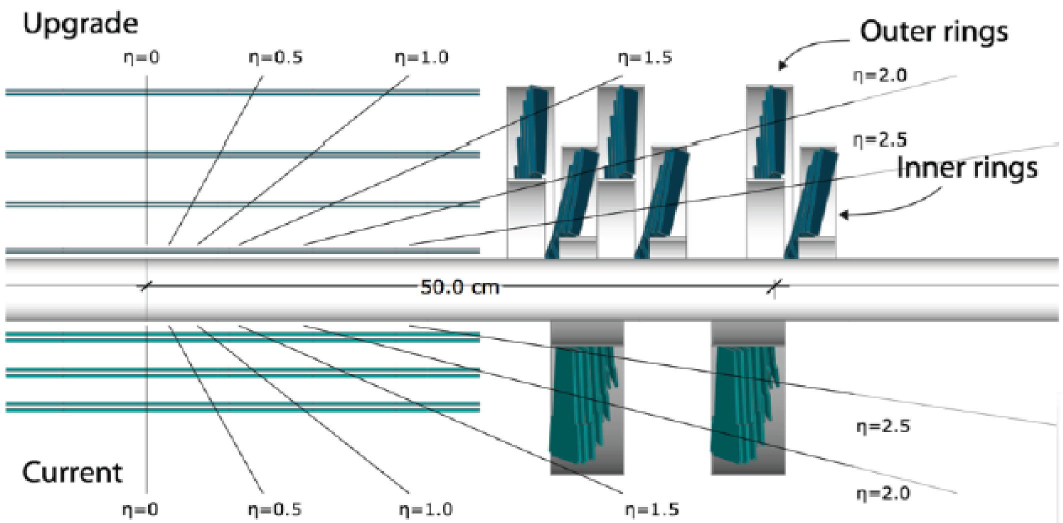
- Further Trigger/DAQ upgrade
- Barrel ECAL Electronics upgrade
- Tracker replacement/ Track Trigger
- End-Cap Calorimeter replacement
- Tracker extension to $|\eta| \sim 4$
- Muon extension from $|\eta| = 2.4$ to $|\eta| \sim 3$

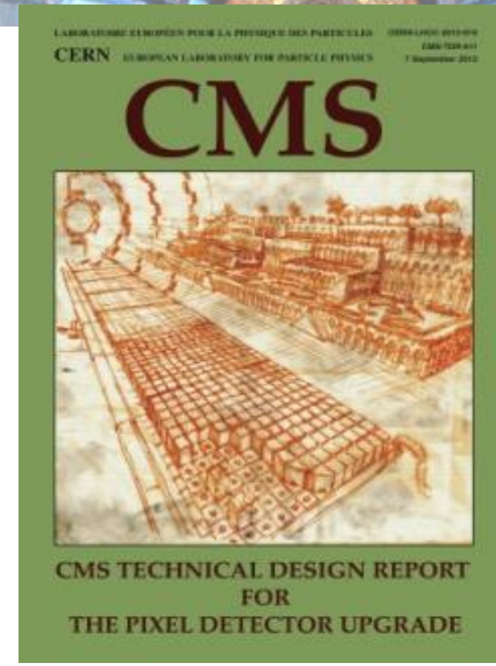
Maintain/Improve performance at high PU

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

Phase I pixel upgrade

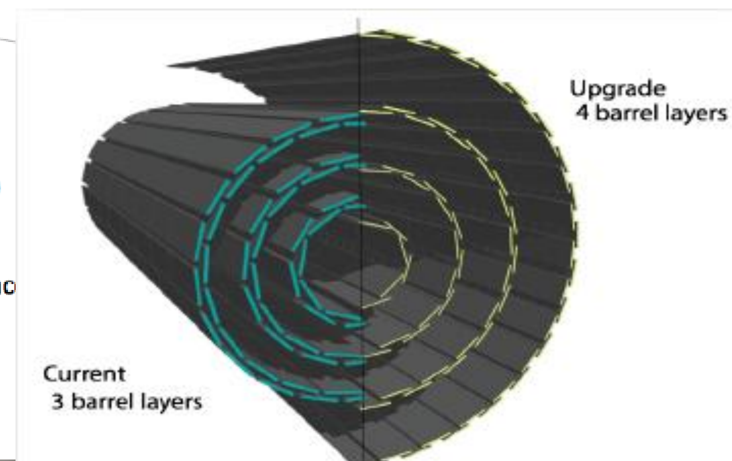
- 4^{th} barrel layer at r =16 cm, 3^{rd} disk at z = ±51.4 cm
- 4-hit coverage up to $|\eta| \sim 2.5$
- Smaller radius of innermost barrel layer from 4.4 cm to 3 cm : New beam pipe with smaller diameter





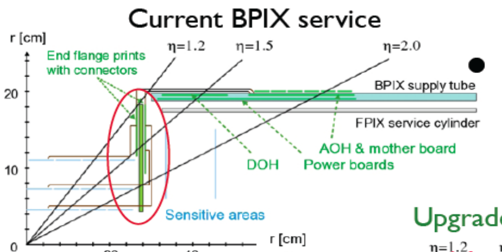
Targets of Pixel Upgrade: (To be installed in end of 2016 extended technical stop)

- Baseline $L = 2\times10^{34}\ cm^{-2}sec^{-1}$ & 25ns → 50 pileup (50PU)
- Tolerate $L = 2\times10^{34}\ cm^{-2}sec^{-1}$ & **50ns** → 100 pileup (100PU) , with reduced performanc
- Survive Integrated Luminosity of $500fb^{-1}$

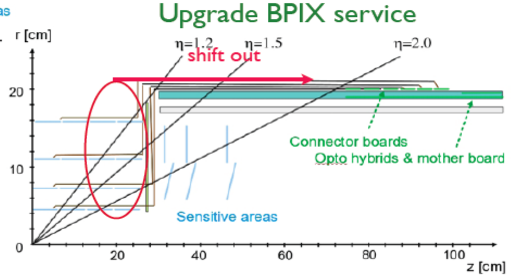


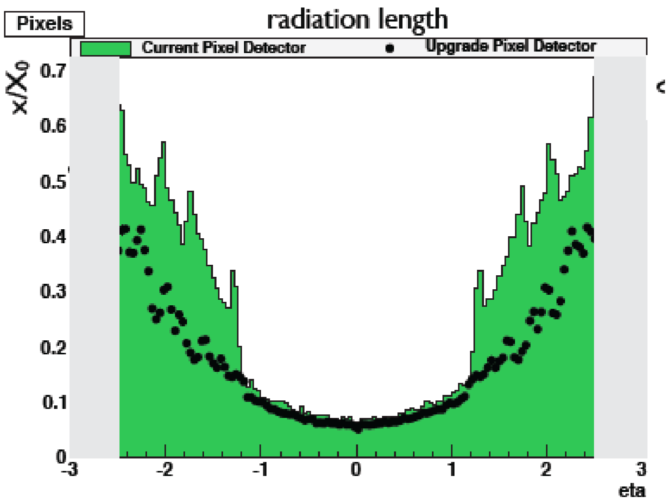
Phase I Pixel Upgrade

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

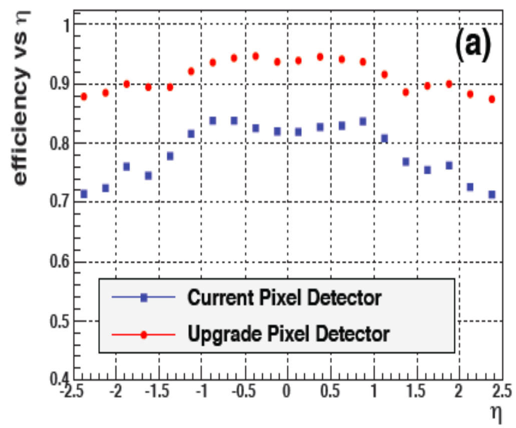


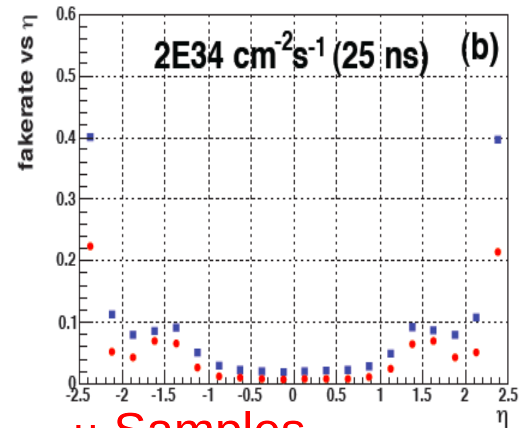
- Move the service outside of |η|=2





ttbar samples

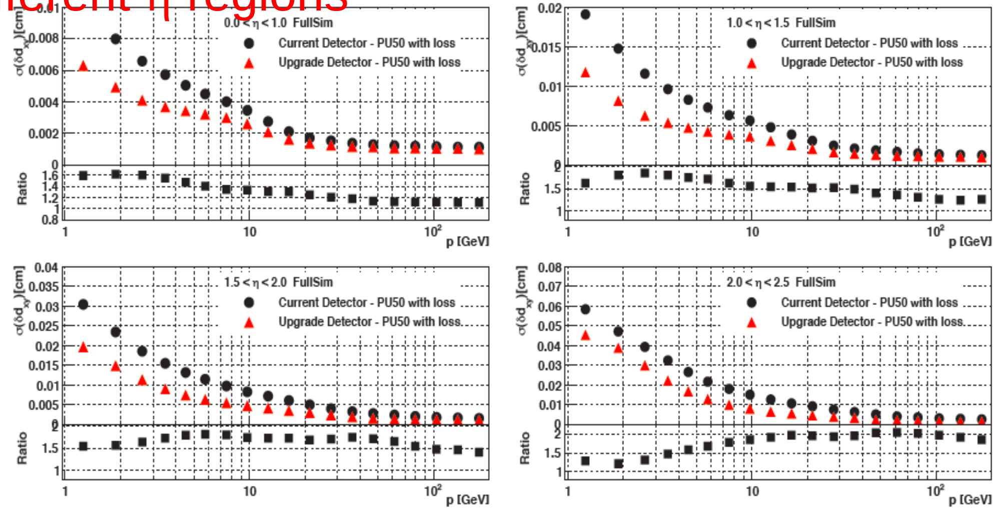




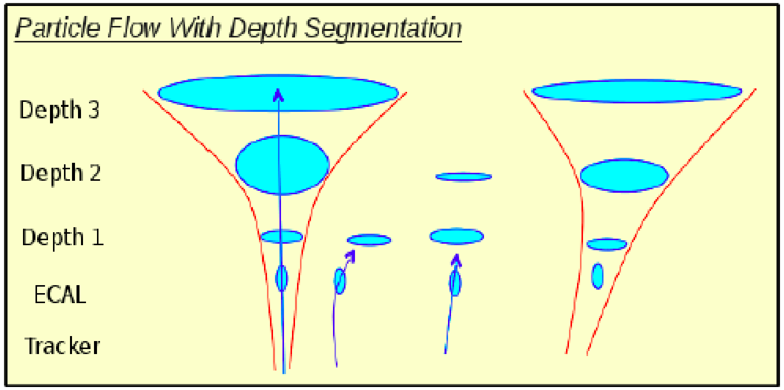
μ Samples

Different η regions

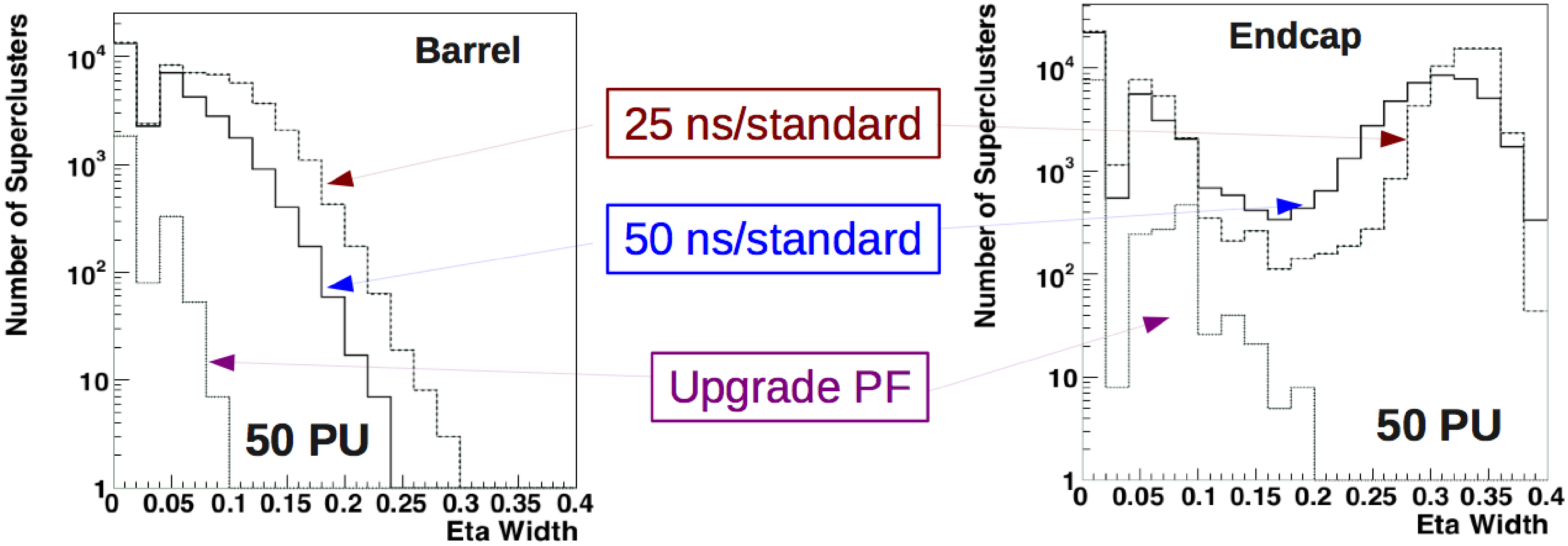
transverse IP



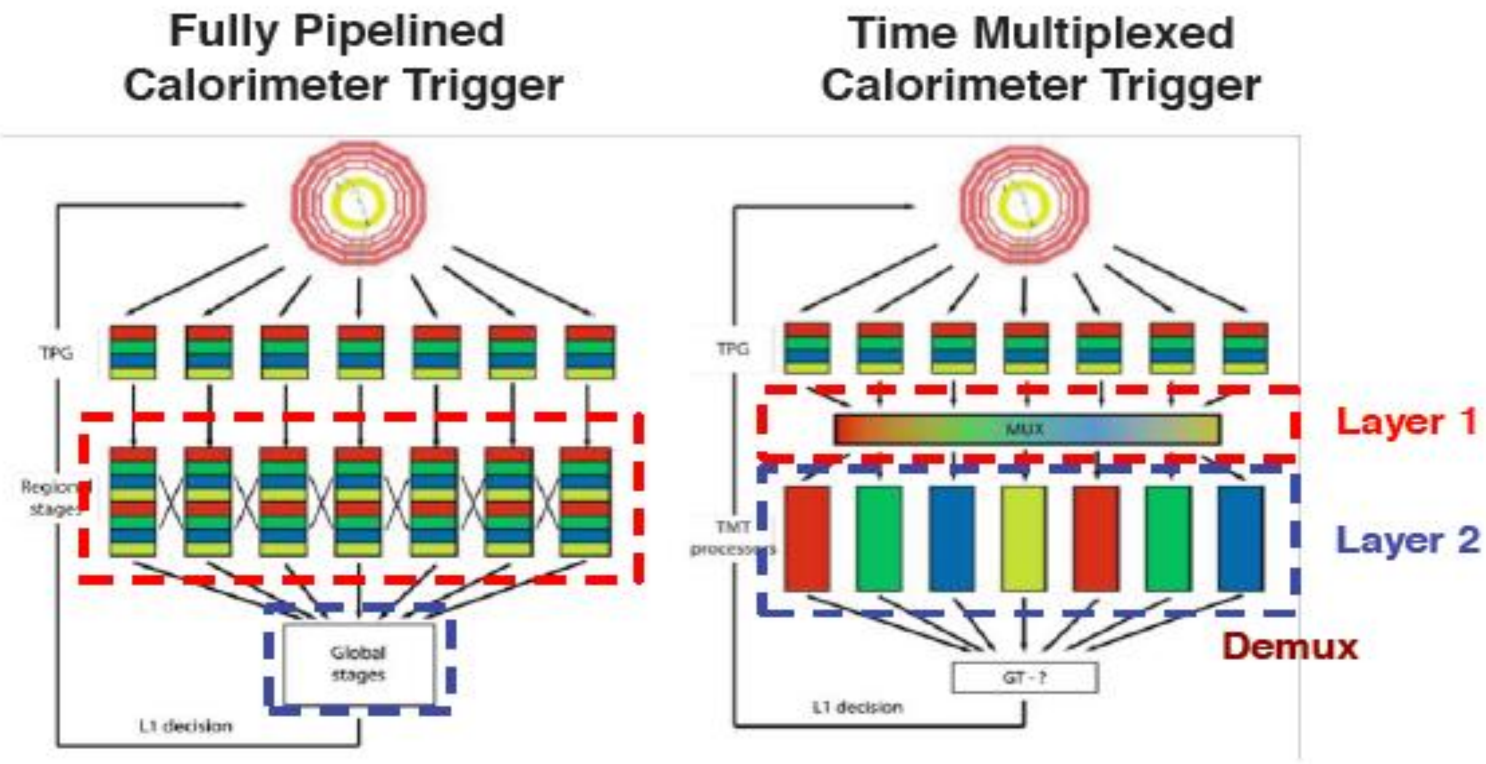
Phase I HCAL readout Upgrade



- 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



Phase I Calorimeter trigger Upgrade



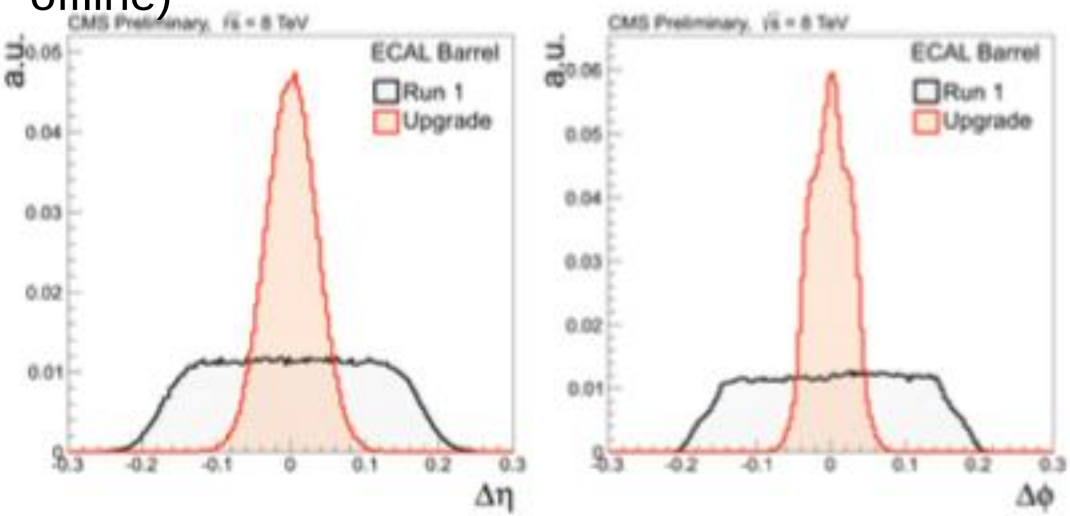
Layer 1 is optimized for backplane connectivity; Layer 2 for front-panel optical bandwidth
Access full granularity ECAL/HCAL Trigger Tower granularity for clustering, isolation etc.

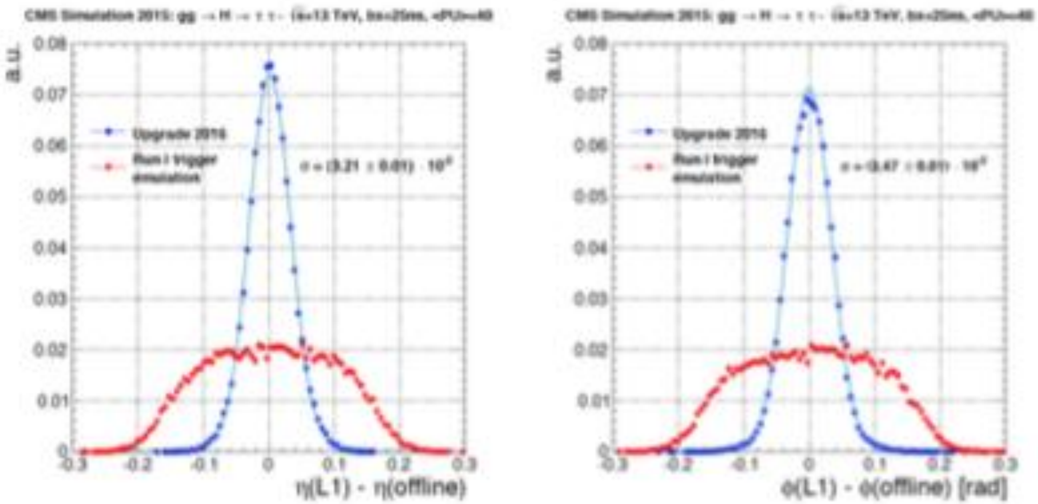
Calorimeter trigger upgrade

18x14:legacy

72x56: upgraded

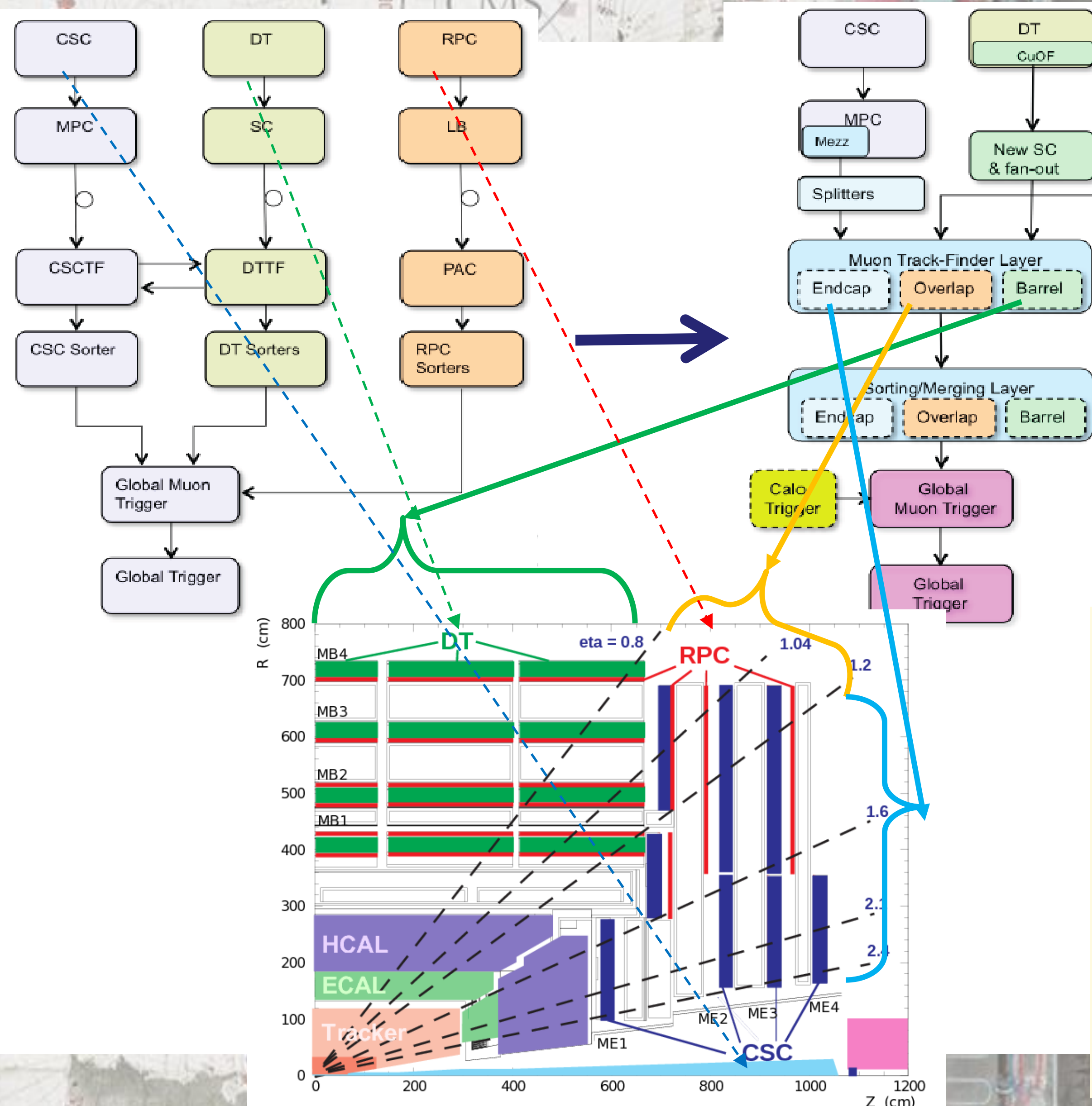
e-γ: trigger angular resolution (trigger vs offline)





τ: trigger angular resolution

Phase I Muon trigger upgrade



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

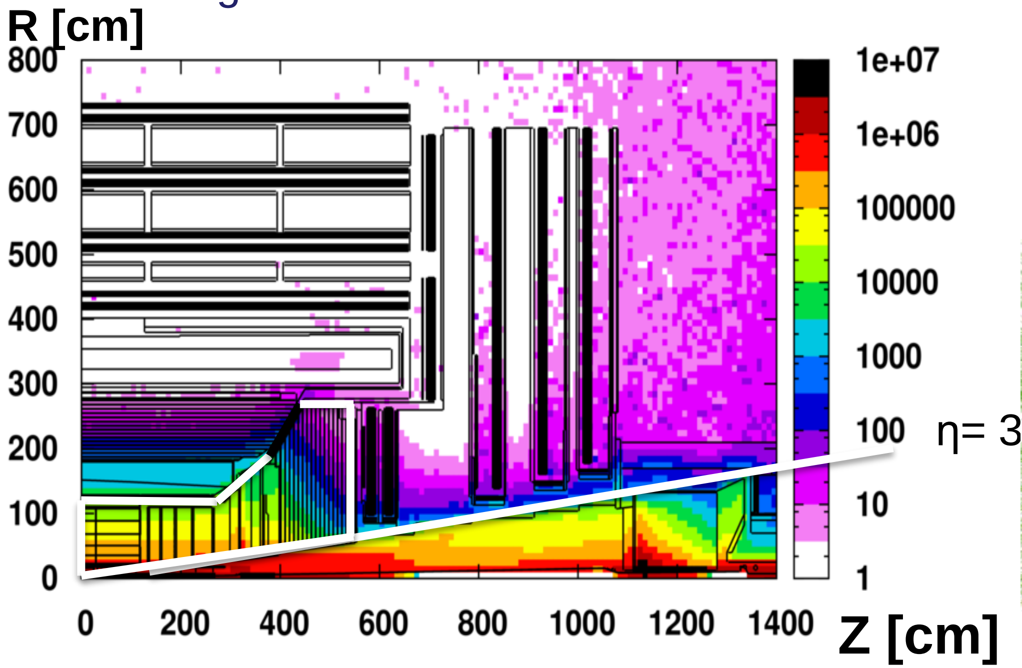
Upgrade allows merging of CSC, DT & RPC segments for combined muon track finding => Improved robustness and efficiency

High Luminosity LHC

- In 2012 the European Council defined the priorities for the medium term future of European HEP to be the full exploitation of the LHC complex, through upgrading the Accelerator complex to be able to reach instantaneous luminosities in excess of 10^{35}
- Such luminosities would imply prohibitive experimental conditions and very fast beam burnout, so in practice the future upgraded machine will be one with lumi levelled at 5-7 10^{34} allowing lumi accumulation of several hundreds of fb^{-1} per year
- The P5 committee in the US last year defined the HI Lumi LHC as the priority of the US HEP frontier program

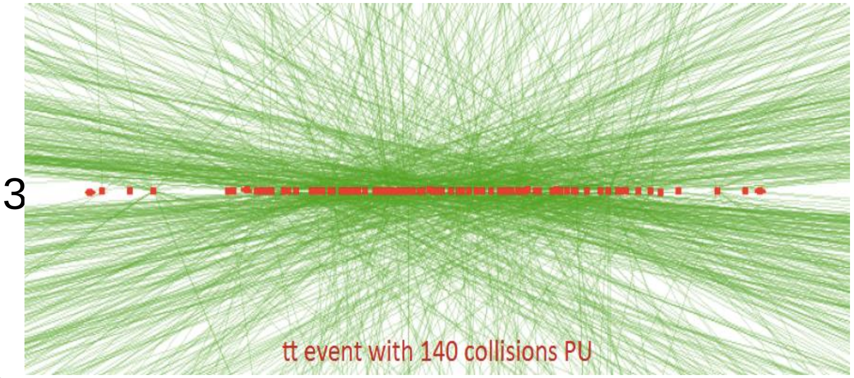
High Lumi LHC challenges

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

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

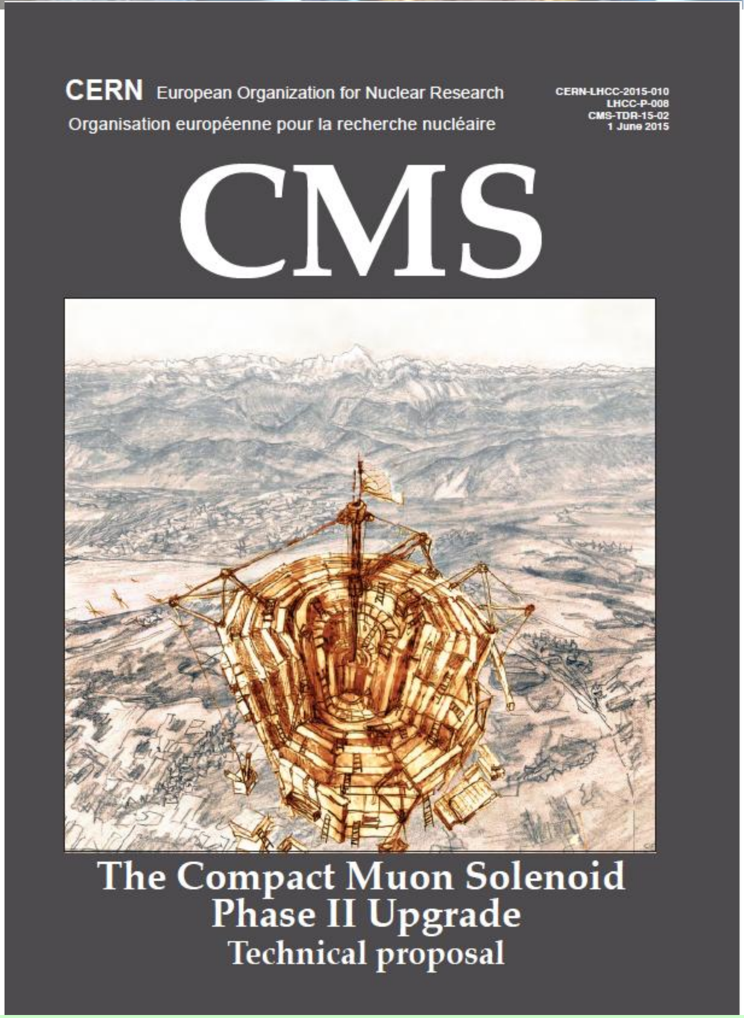
This is Very Challenging: it requires

- 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

CMS Phase II upgrade

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

Performance results are assessed using full simulation. The overall goal is to maintain similar physics performance at luminosity of $5\ 10^{34}$ Hz/cm^2 as we have at 10^{34} Hz/cm^2 and be able to exploit without too much degradation up to $7.5\ 10^{34}$ Hz/cm^2

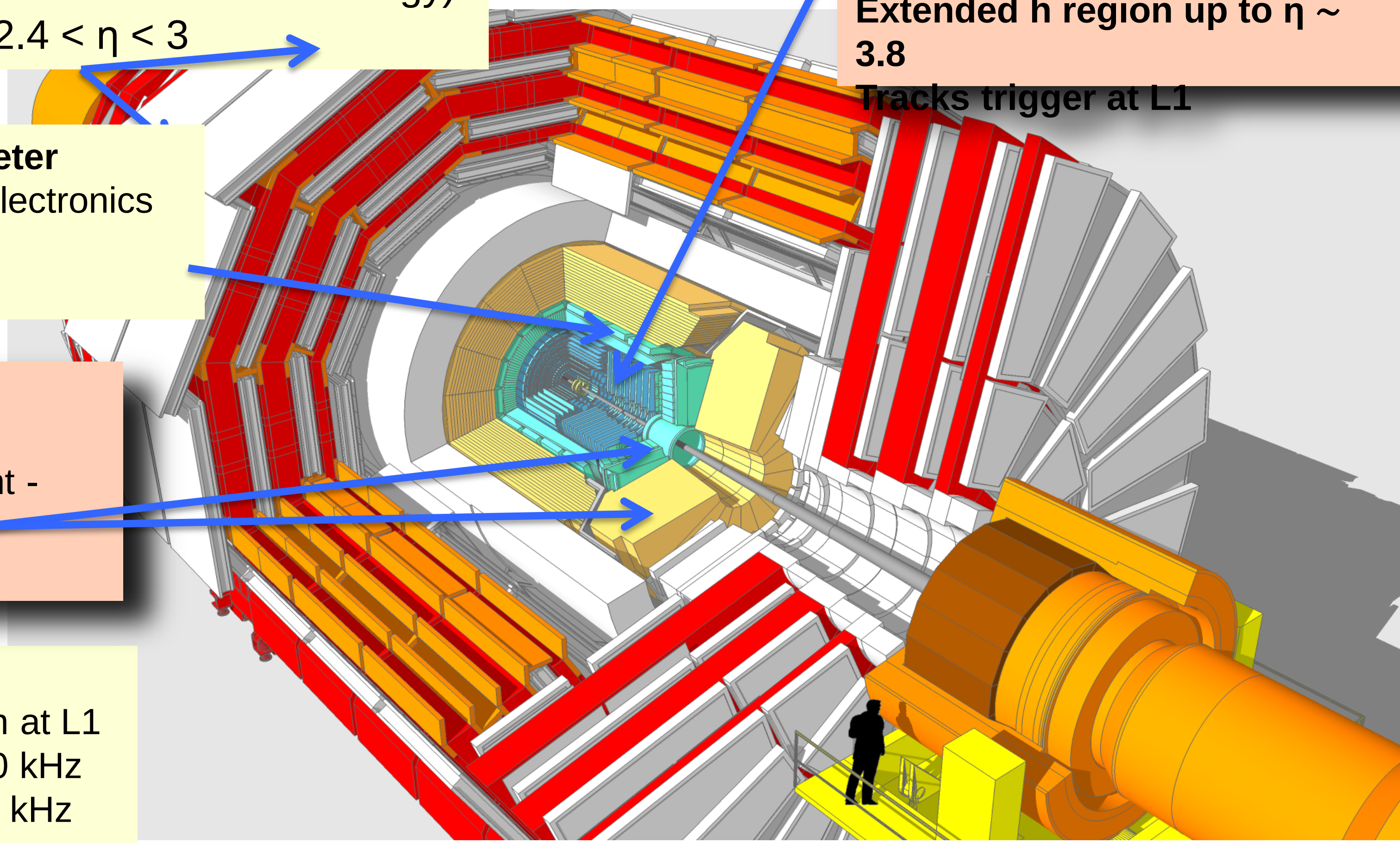


CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886

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 pT resolution
Extended h region up to $\eta \sim 3.8$
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

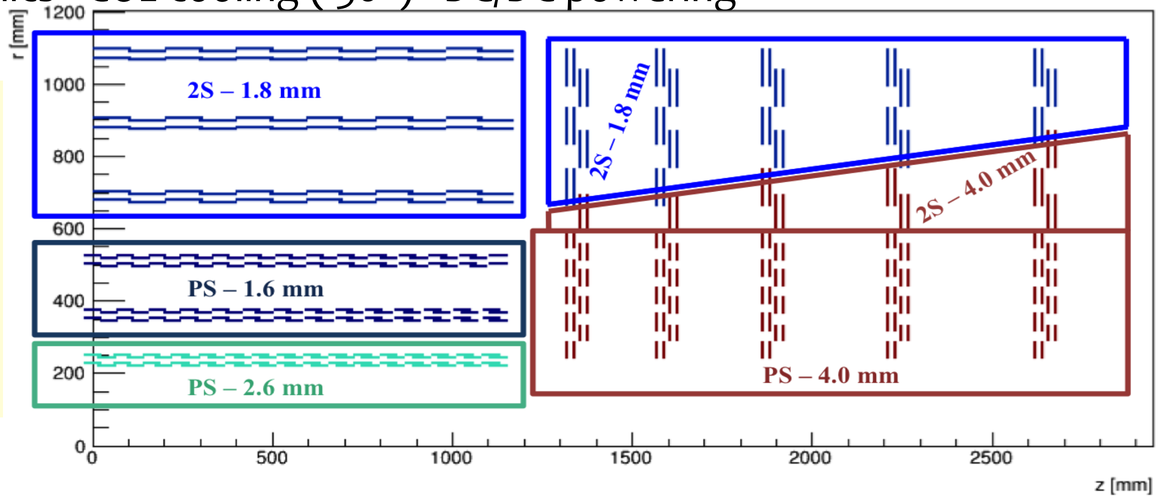
Outer tracker upgrade

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



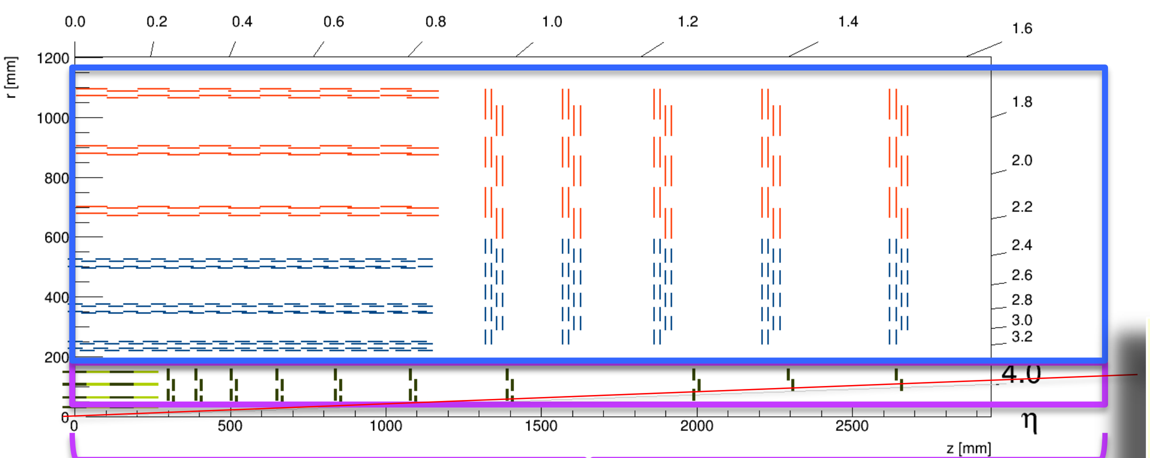
Ongoing study of alternative design with tilted modules in PS layers

- Further reduce material and number of modules

Pixel upgrade

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

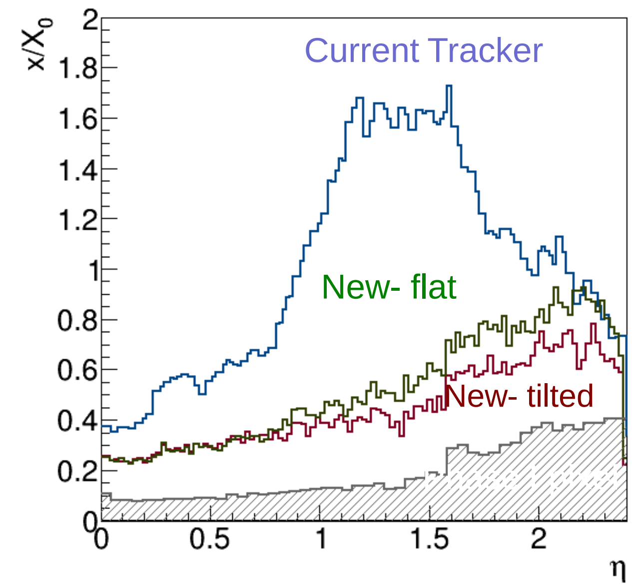


Pixel modules

Tracker extension up to η=3.8

Total pixel area ~ 4.0 m²

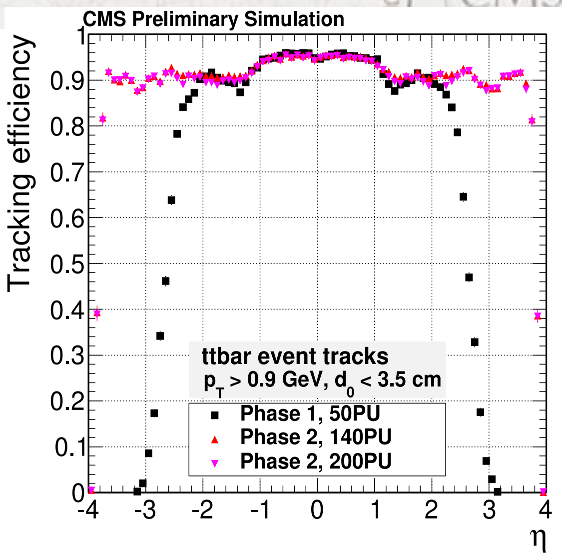
- 50x50 - 25x100μm² pixels
- ≤ 150 μm sensor physical thickness

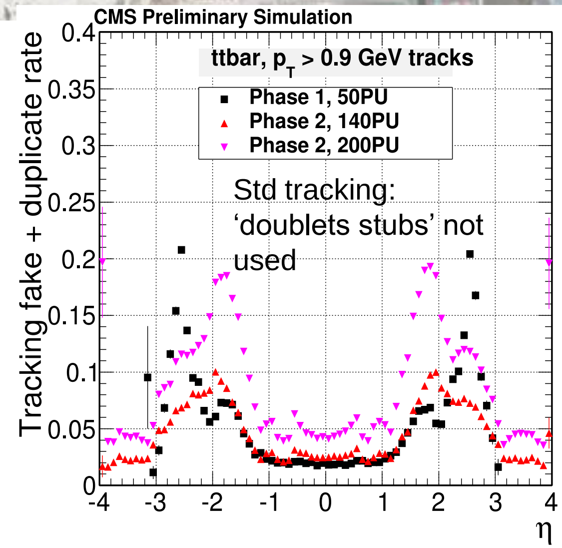


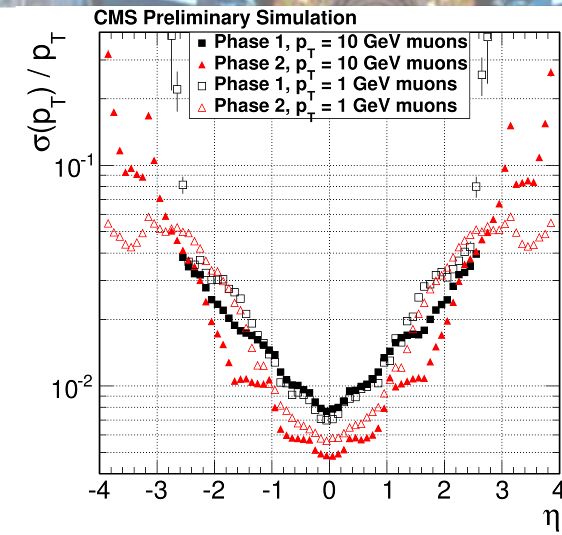
Material (lighten up!)

- 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 ..

Track and vertex resolution







- 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)

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

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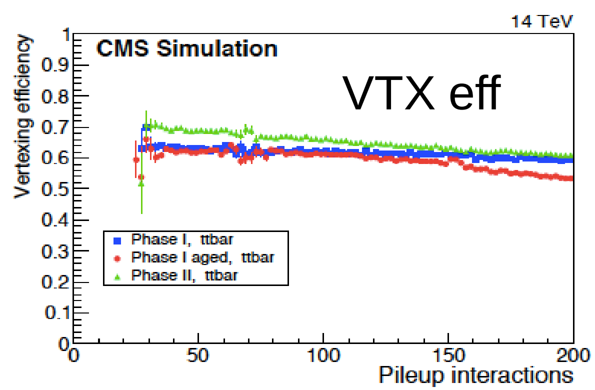
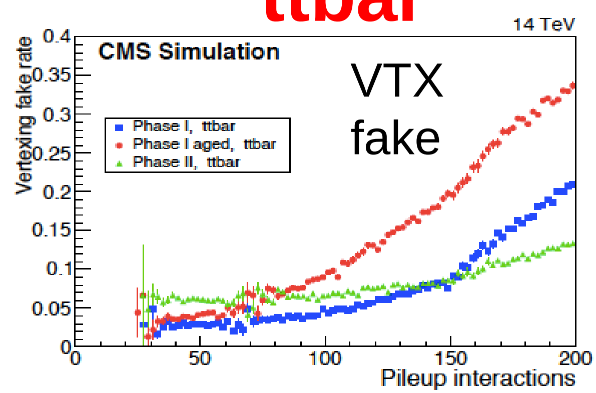


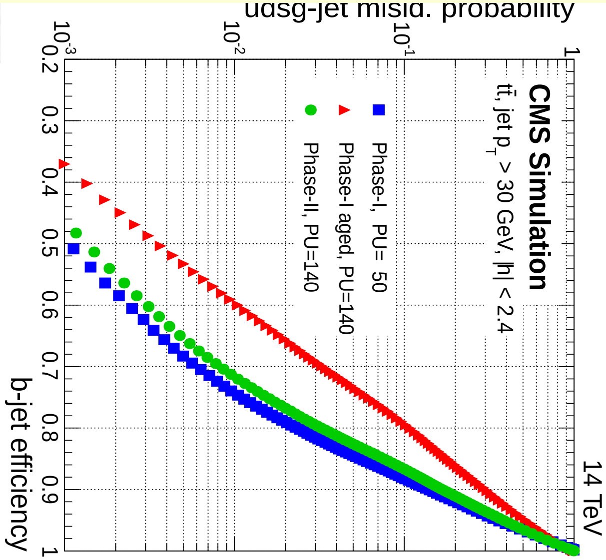
ttbar

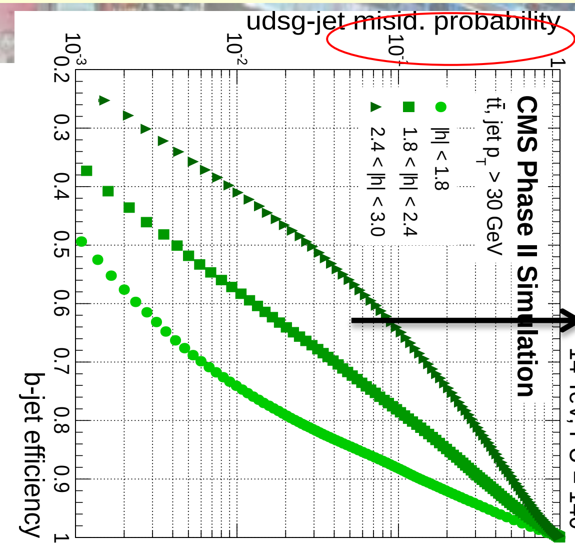


b-tagging Phase-II recovers Phase-I performance

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

ttbar

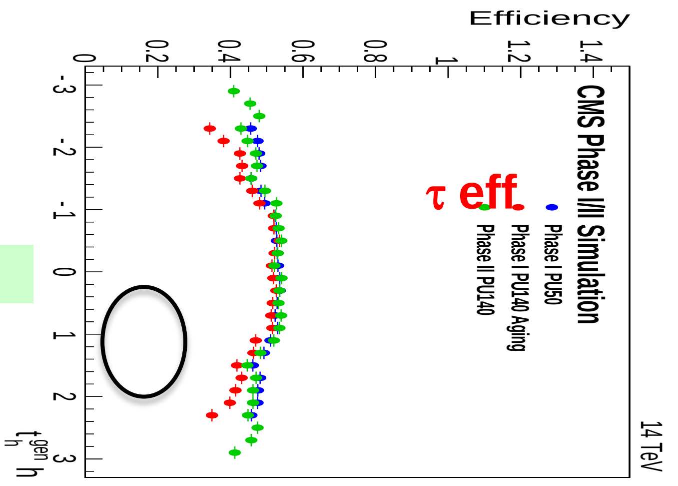


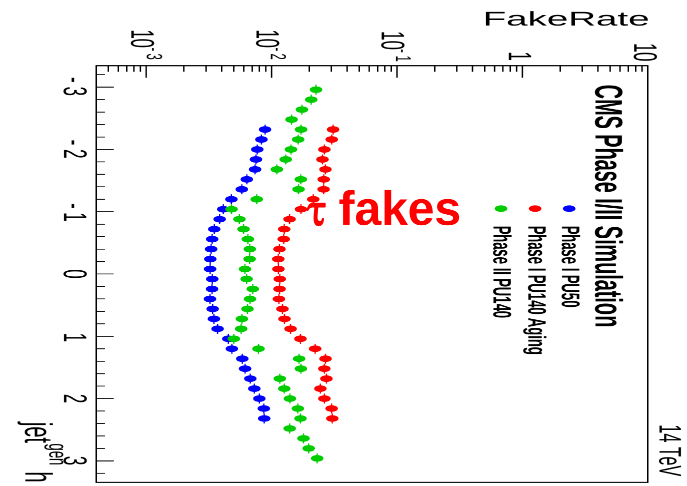


Coverage to η = 3.8

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

Z → ττ





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Track Trigger performance

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.

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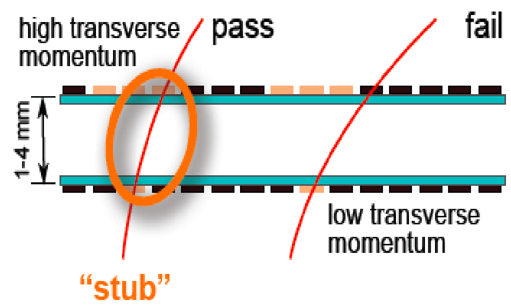
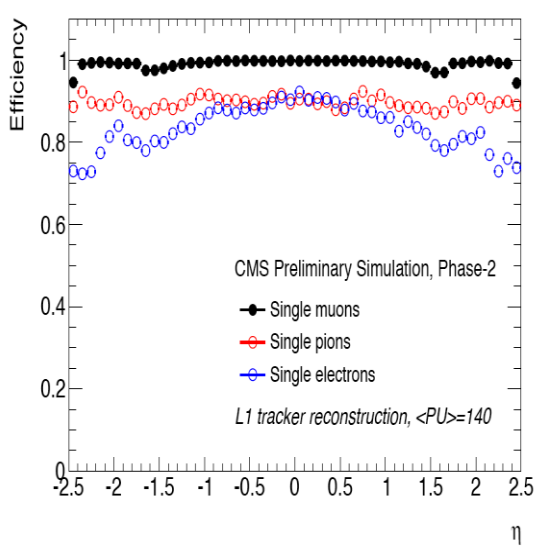
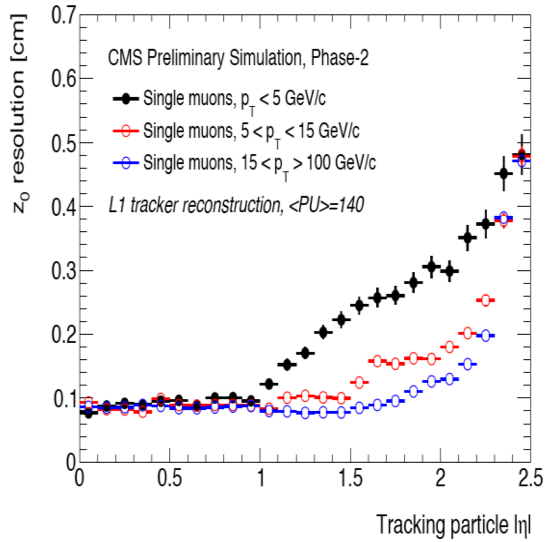
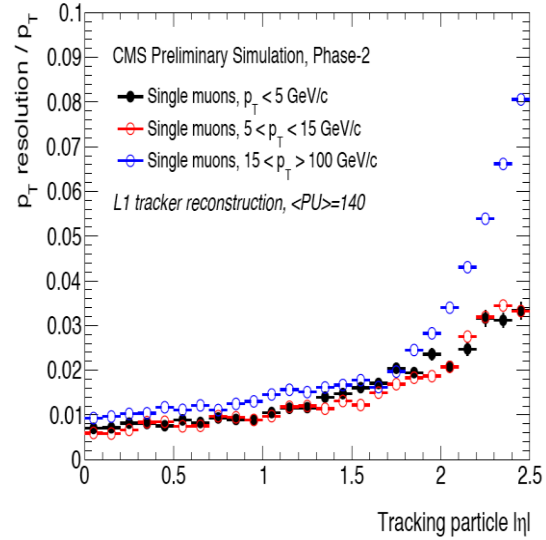


L1 Track Trigger reconstruction performance



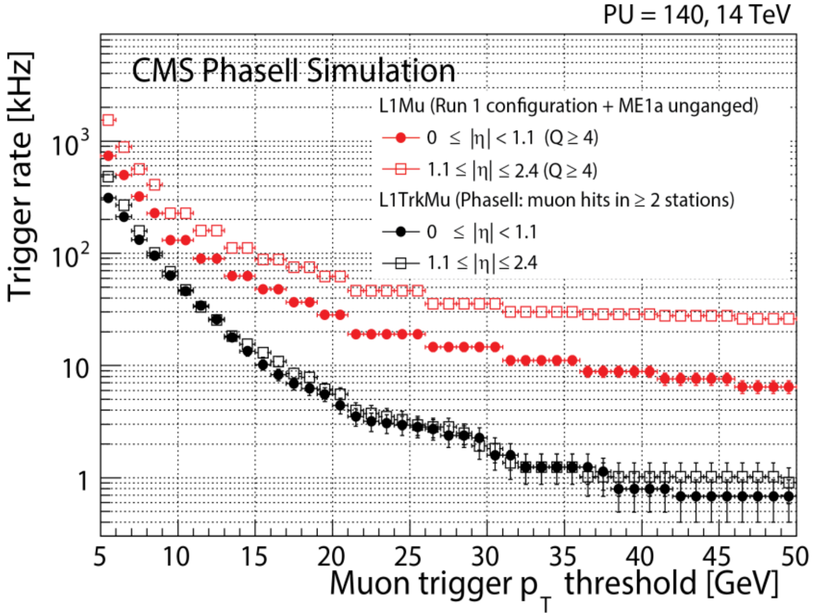


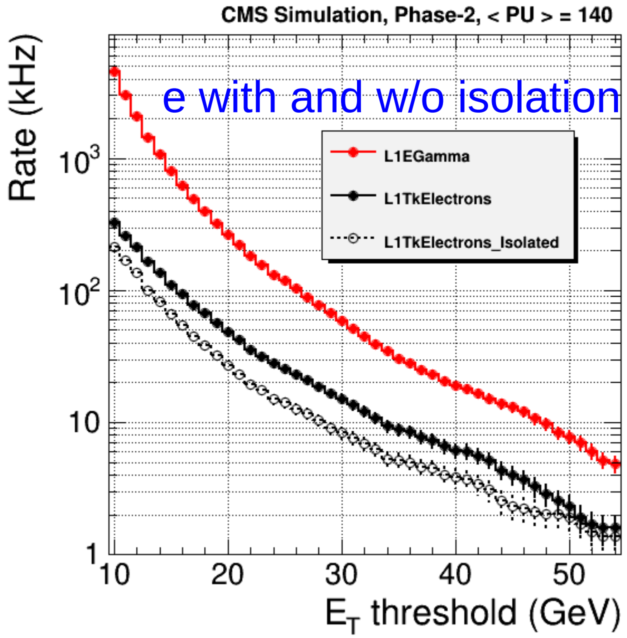


L1 trigger performance with L1 Trk

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
- | 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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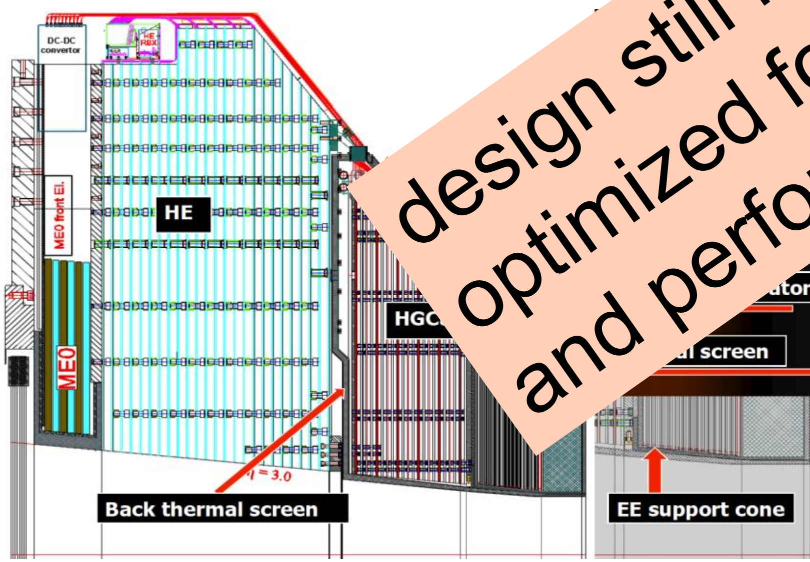
Endcap calorimeter upgrade

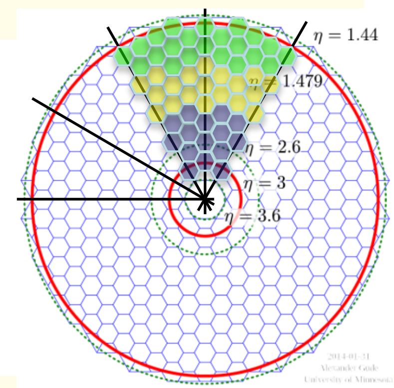
- 3D shower measurement in High Granularity Calorimeter (HGC)
  - Electromagnetic EE (Σ_{depth}~26 X_0, 1.5λ): 28 layers of Silicon-W absorber
  - Front Hadronic FH (Σ_{depth}~3.5 λ): 12 la... Silicon/Brass
- Back Hadronic Calorimeter (BH) (Σ_{d}... ...rs of Scintillator/Brass

Total Depth >10λ

...ch - 13.9k modules - 16t
...ch - 7.6k modules - 36.5t
...184 SiPMs

design still being optimized for cost and performance





sensors: three active thicknesses 100-200-300 μm
0.5(1) cm^2 pads for 100(200/300) μm

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

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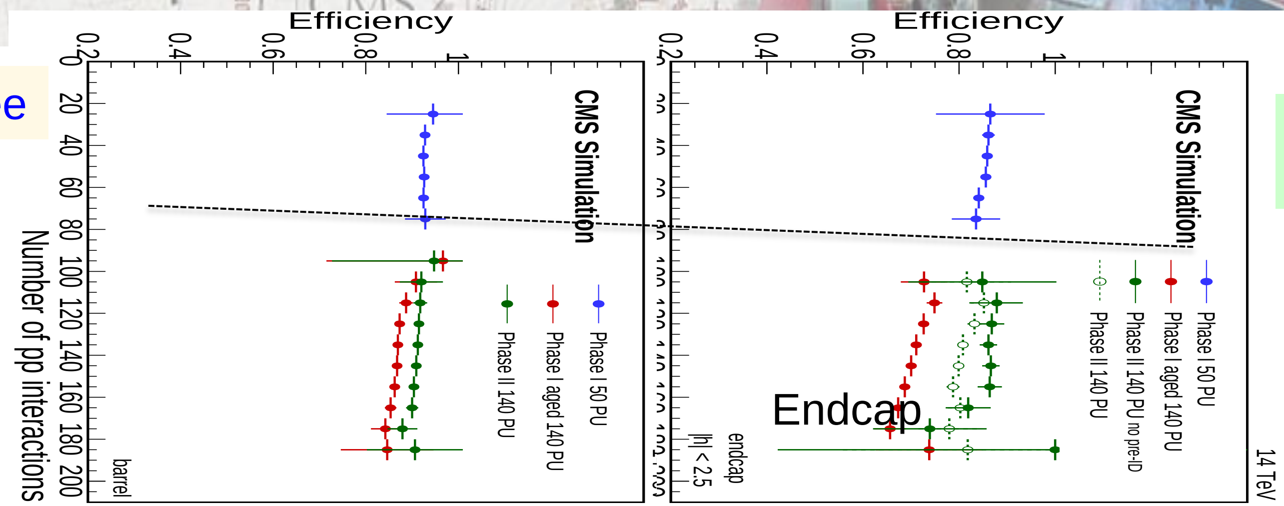
Electron efficiency recovered with gradual decrease up to 200 PU

DY→ ee



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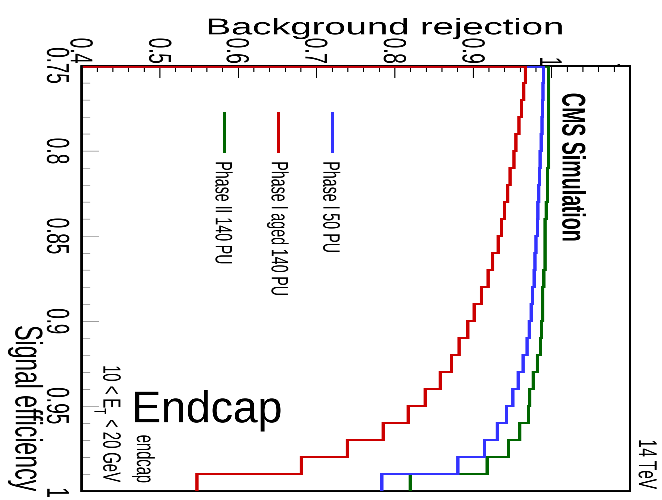
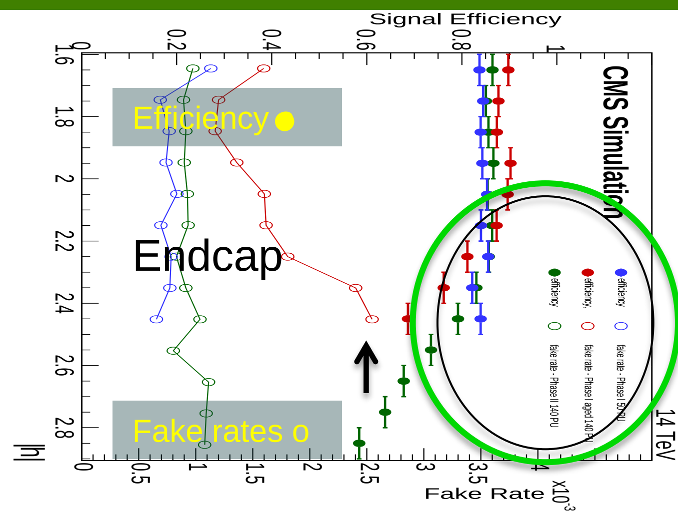
BDT efficiency for DY electrons vs background rejection for Jets (left) and BDT efficiency for γ and Jet fake rate for a WP at ≃ 85% efficiency (right)

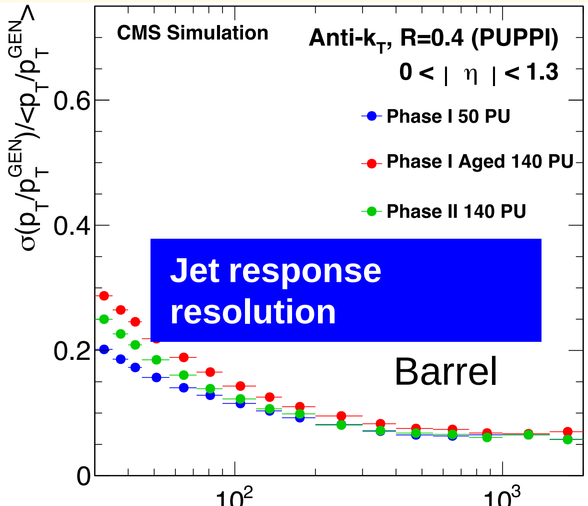


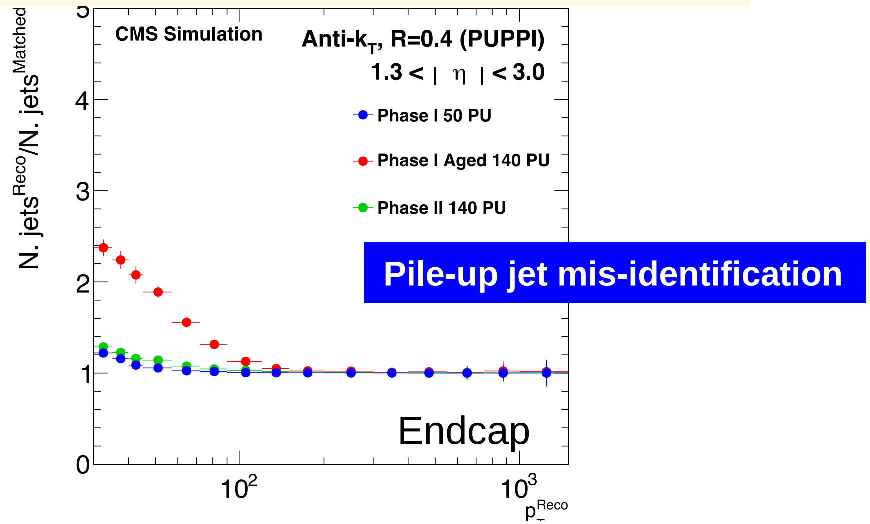


Jet and MET performance

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

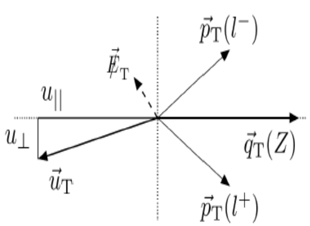
QCD



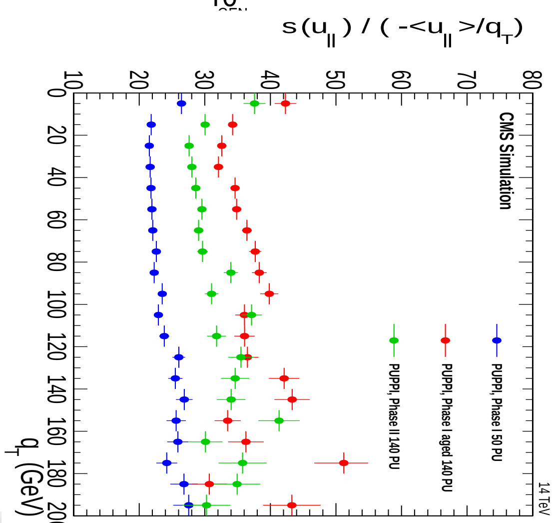


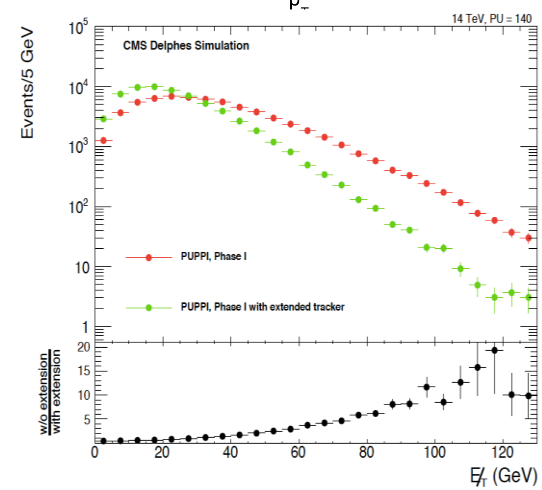
Phase-II detector recovers MET resolution partially

MET tails significantly reduced by tracking extension

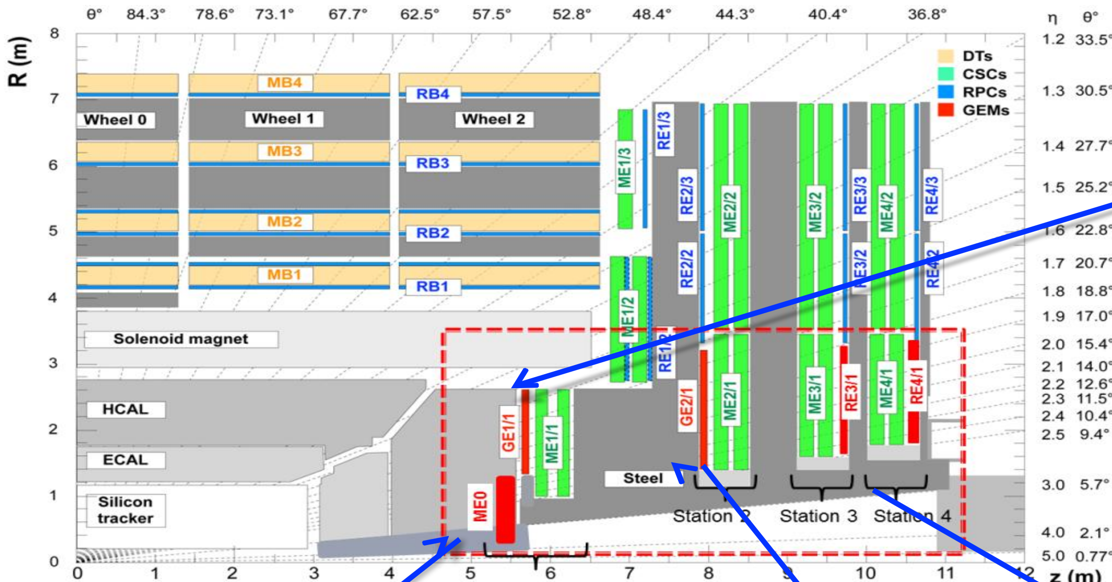


MET energy resolution from hadronic recoil in Z → μμ





Forward Muon System



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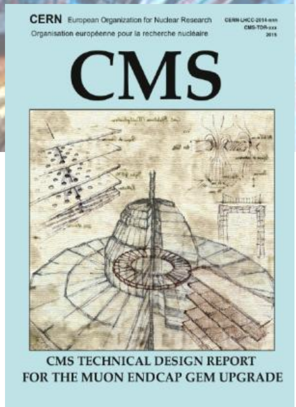


GE1/1:

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)**

ME0:

Muon tagger

- **2.4 < |η| < 3.0**

GE2/1:

Trigger and reconstruction

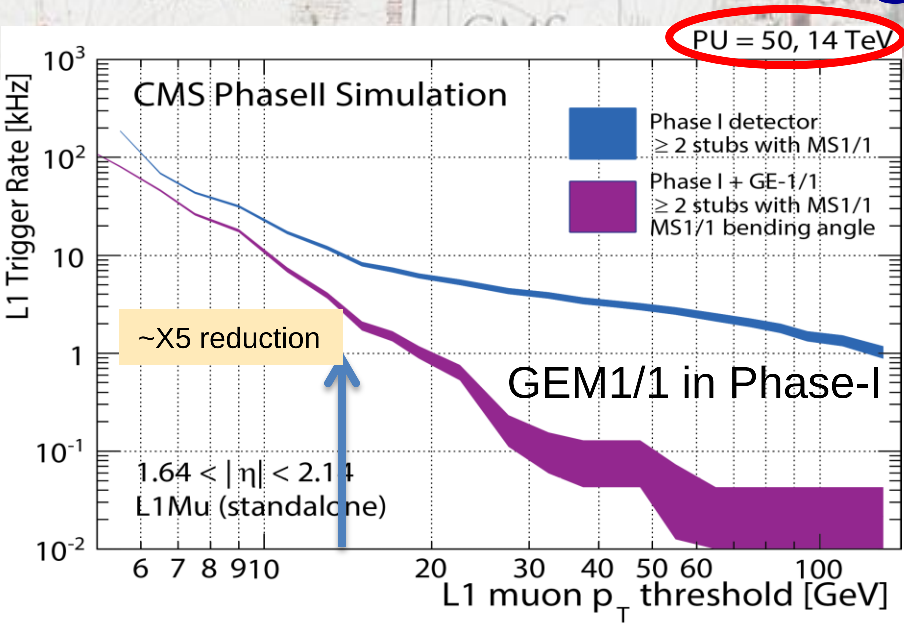
- **1.55 < |η| < 2.45**
- 18 staggered SC per endcap, each chamber covers 20°, 3.5 x GE1/1 area
- Installation: LS3

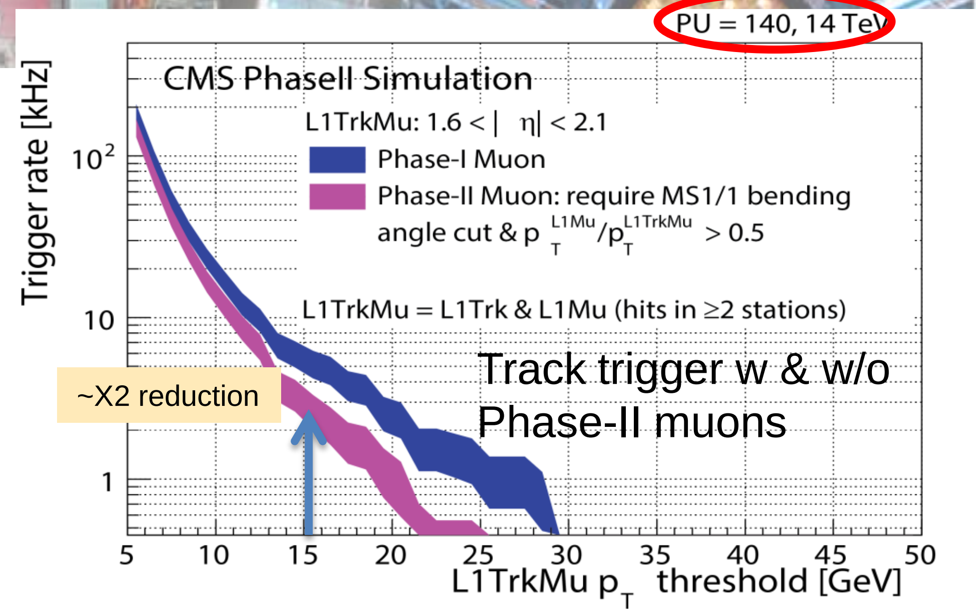
RE 3/1 –RE4/1 :

Trigger and reconstruction

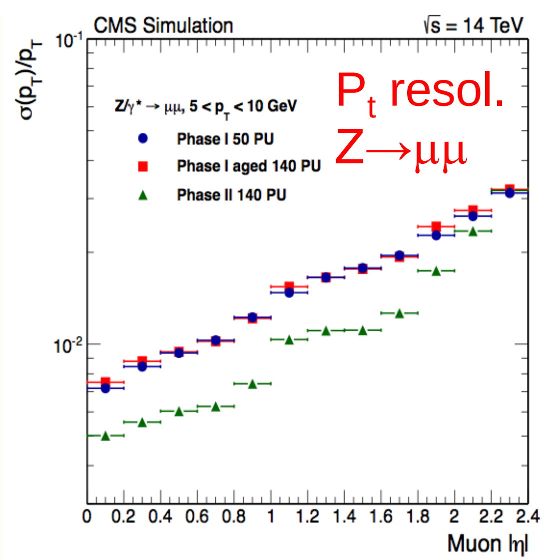
- **1.8 < |η| < 2.4**
- Improved RPC (iRPC), finer pitch
- 18 chambers per endcap, each chamber spans 20°
- Installation: LS3

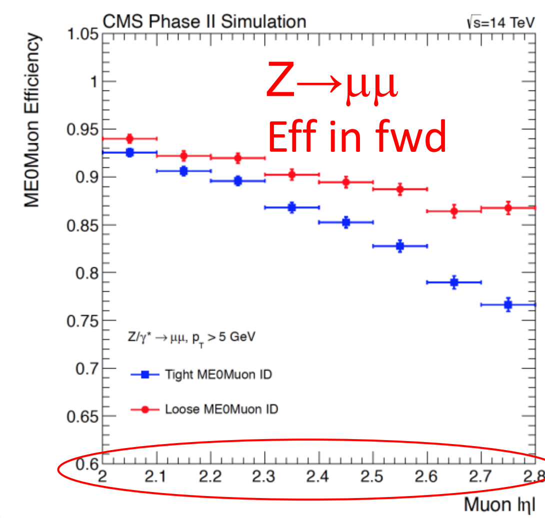
Muon reco and trigger performance





- 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
- ME0 provides efficient muon identification with reasonable background rates





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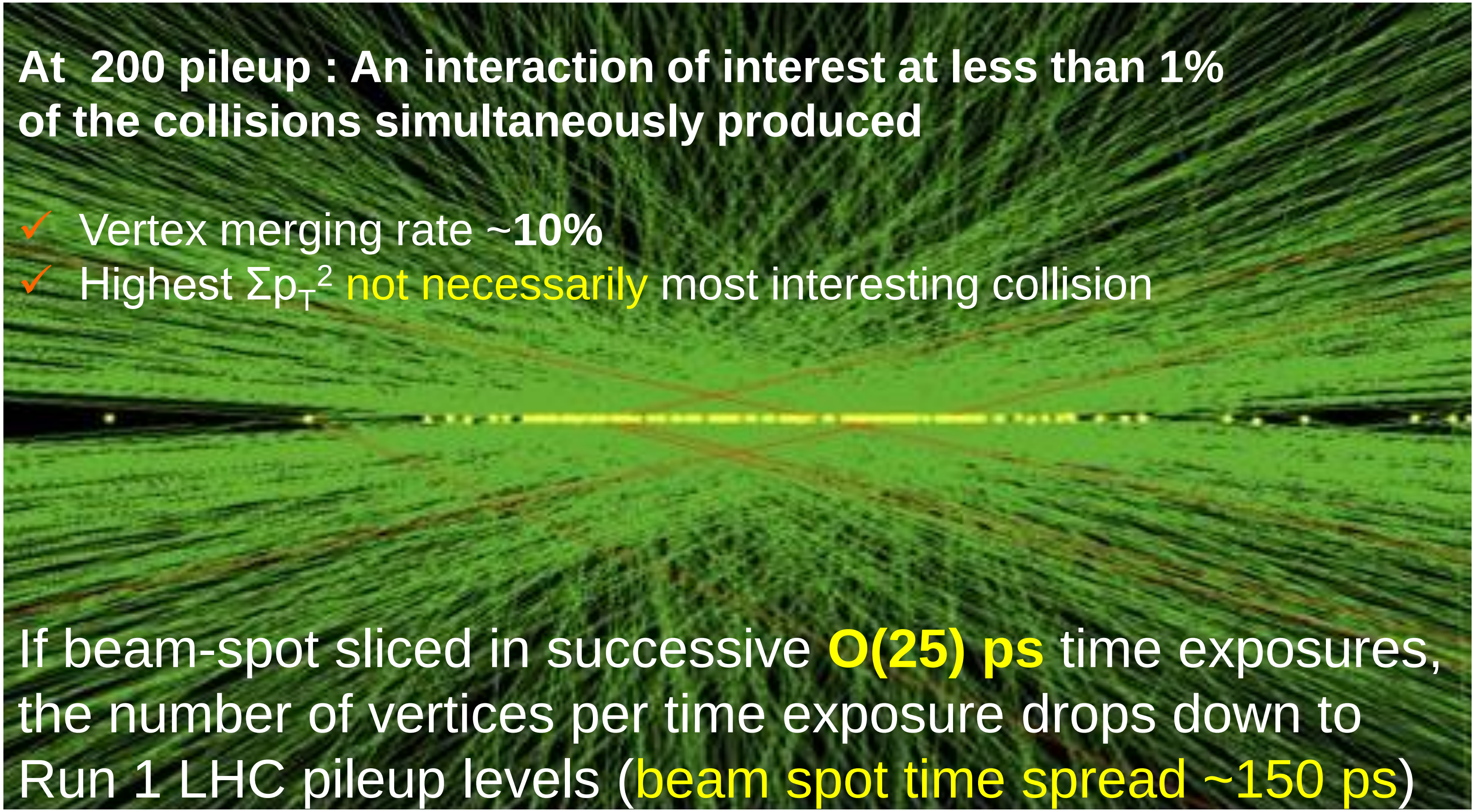
Being explored: 4D reco … exploting timing



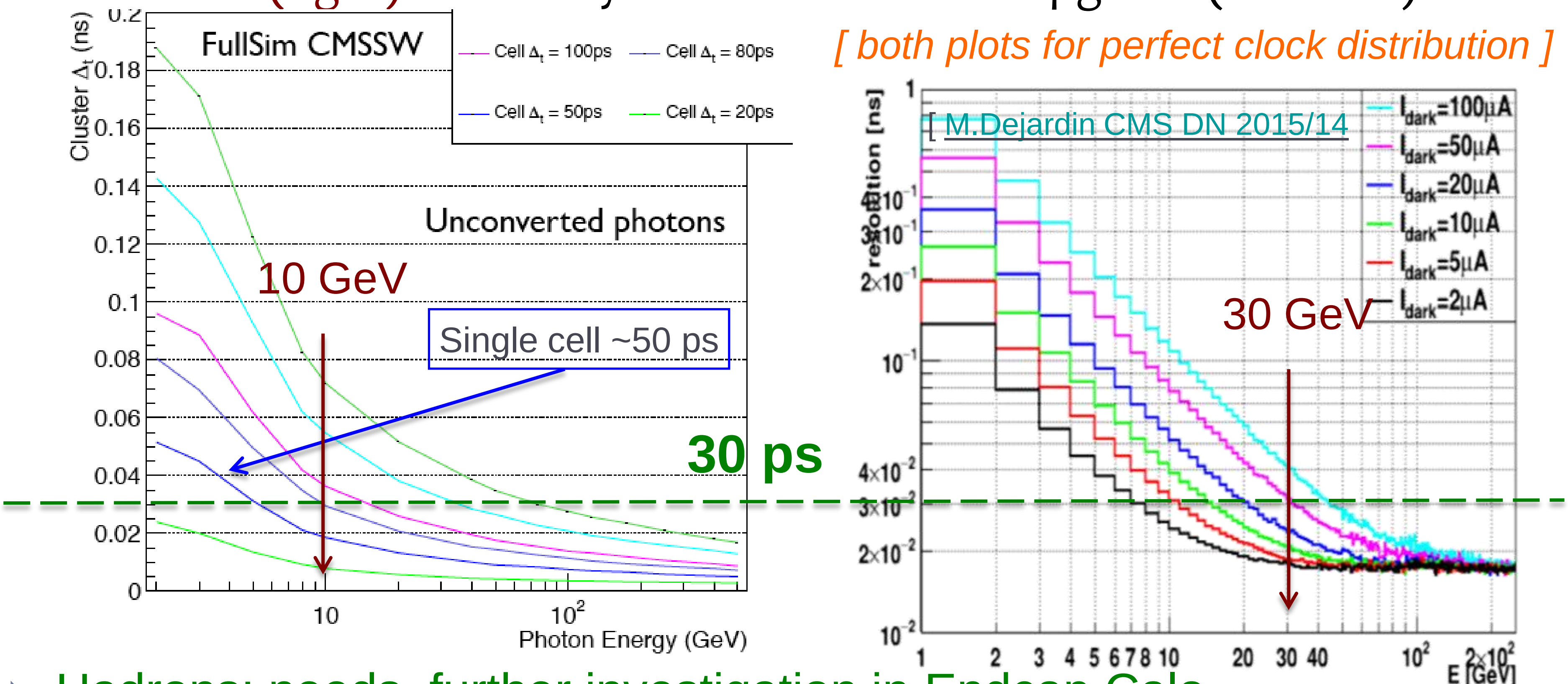
At 200 pileup : An interaction of interest at less than 1% of the collisions simultaneously produced

- ✓ Vertex merging rate ~**10%**
- ✓ Highest Σp_T^2 not necessarily most interesting collision

If beam-spot sliced in successive **O(25) ps** time exposures, the number of vertices per time exposure drops down to Run 1 LHC pileup levels (beam spot time spread ~150 ps)

Timing in CMS Upgraded systems

- Calorimeters (photons):
  - Endcap calo (left): Single cell timing for more than 30 MIP signals
  - ECAL (right): Seriously considered for the upgrade (new VFE)

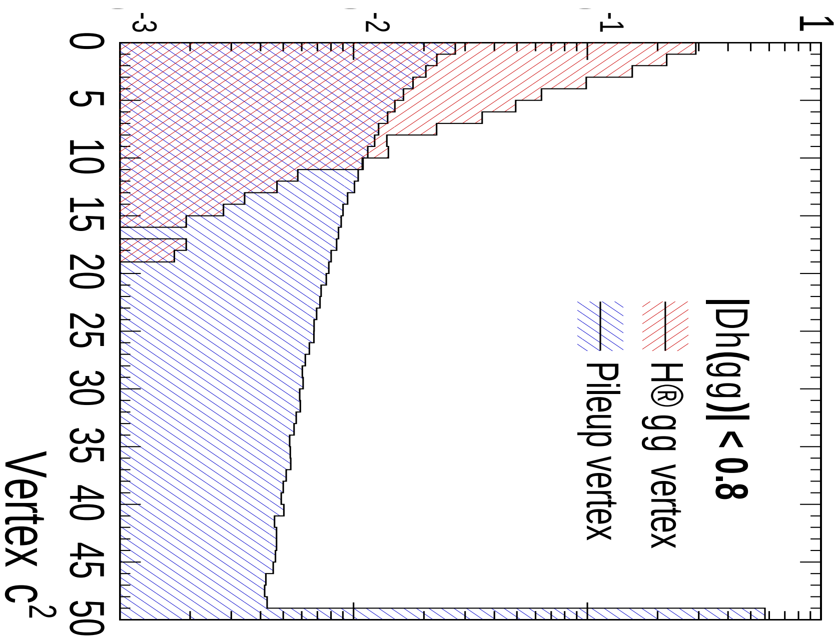


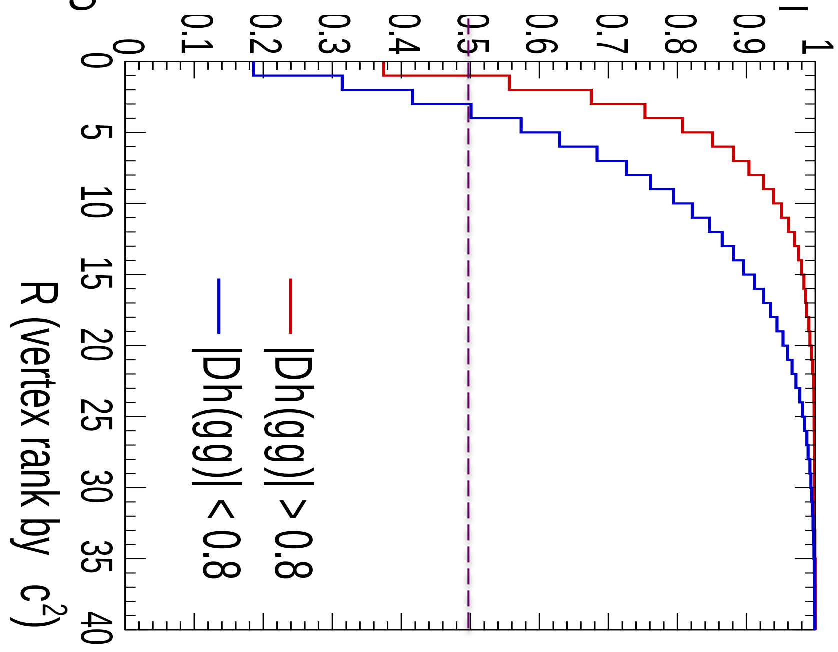
- Hadrons: needs further investigation in Endcap Calo
- **Limited / no timing performance for charged tracks (MIPs)**

Effective pileup reduced to LHC conditions

- At 140-200 PU more than one match, but
  - Rank vertices by: $\chi^2 = \Sigma_{i=1,2} [t_i^{meas} - t_i(z_0, t_0)]^2 / \sigma_i^2$
  - No more than about 20 acceptable matches at 140 PU (ie. Conditions similar to the ones of Run1)

- Assuming 30 ps calo resolution and 25 ps resolution on MIPs (timing layer for MIPs not in baseline CMS upgrade program... So far a matter of R&D_





Intensive R&D on fast timing

- There is intensive R&D ongoing to identify fast sensors which could have ~ 10 ps timing resolution also for MIPs…
- If affordable having a timing layer in front of the calorimeters which could provide MIP timing would allow full 4D reconstruction of the charged physics objects (muons. Electrons, Jets) and effectively allow an order of magnitude reduction of the ‘confusion’ due to pileup (this is not in our baseline upgrade program !)

Part 2: Silicon sensors

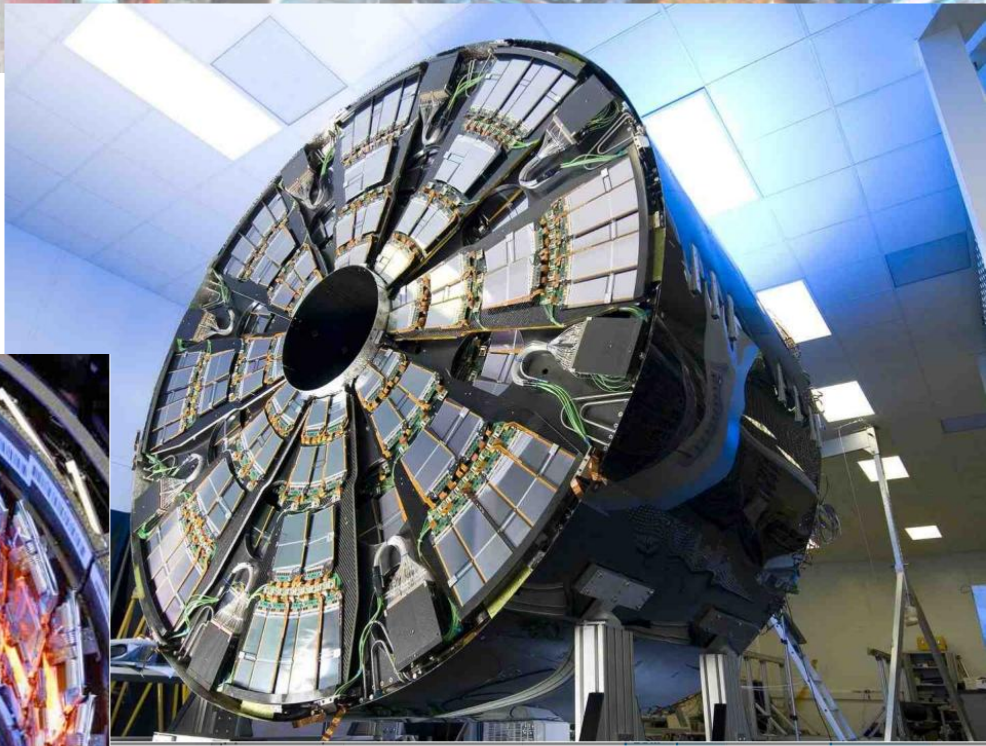
Silicon sensors will be at the basis of a large fraction of the Phase II upgrade

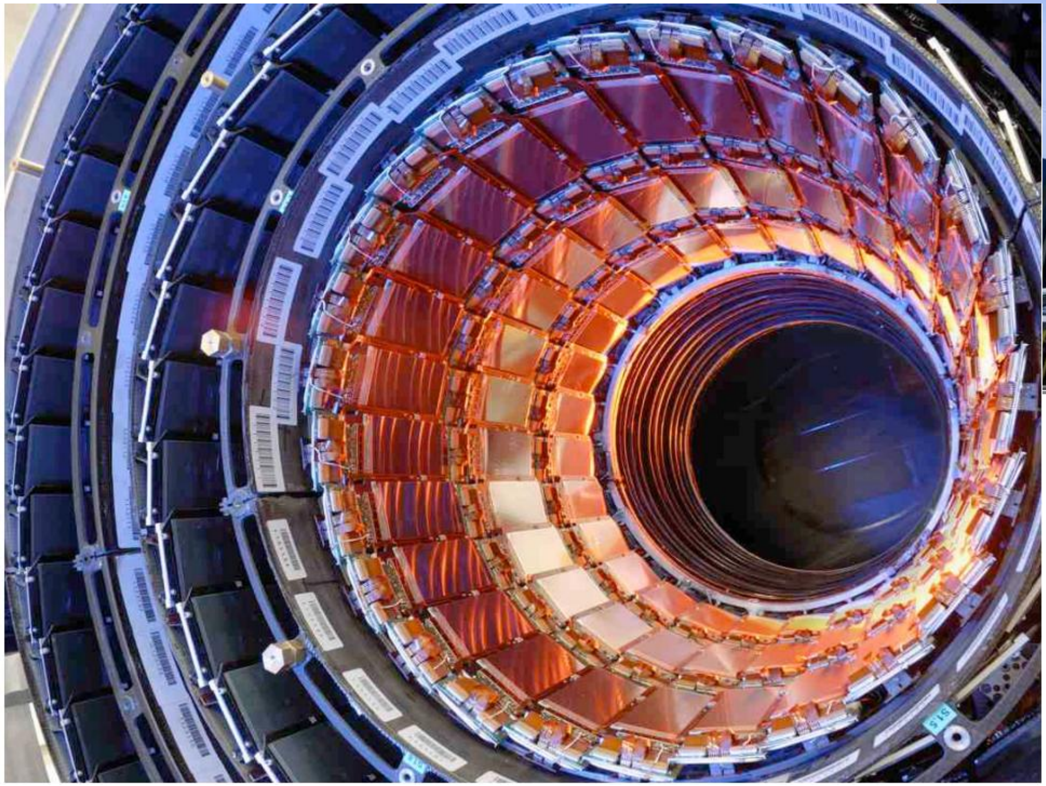
The main reason being the fact that we have understood how to make these sensors withstand the radiation fields of the High Lumi LHC

- Basics
- Radiation behaviour

Most of the material taken from a very complete CERN Academic training session 2004-2005 by Michael Moll

The CMS Si tracker



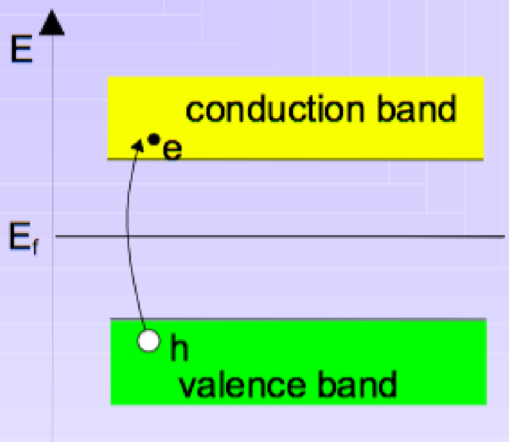


Why silicon?

- **Some characteristics of Silicon crystals**

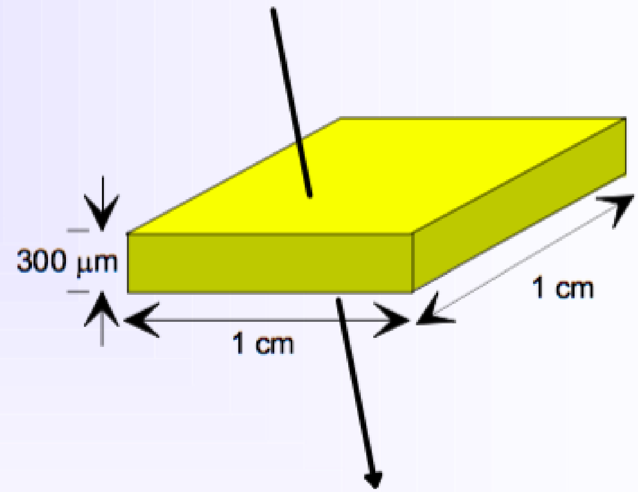
  - Small band gap: E_g = 1.12 eV ⇒ E(e-h pair) = 3.6 eV (≈ 30 eV for gas detectors)
  - High specific density: 2.33 g/cm^3 ; dE/dx (M.I.P.) ≈ 3.8 MeV/cm ≈ 106 e-h/μm (average)
  - High carrier mobility: μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs ⇒ fast charge collection (<10 ns)
  - Very pure: < 1ppm impurities and < 0.1ppb electrical active impurities
  - Rigidity of silicon allows thin self supporting structures
  - Detector production by microelectronic techniques
    ⇒ well known industrial technology, relatively low price, small structures easily possible

How to get a signal ?



In a pure intrinsic (undoped) semiconductor the electron density *n* and hole density *p* are equal.

$n = p = n_i$ For Silicon: $n_i \approx 1.45 \cdot 10^{10}\ \text{cm}^{-3}$



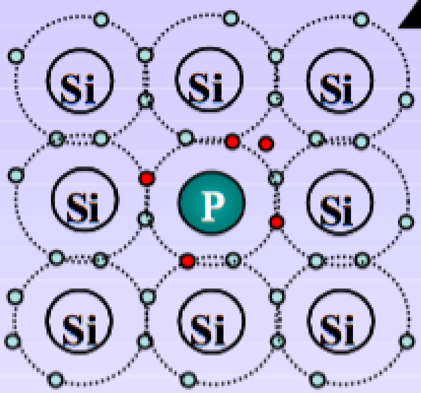
$4.5 \cdot 10^{8}$ free charge carriers in this volume,
but only $3.2 \cdot 10^{4}$ e-h pairs produced by a M.I.P.

⇒ Reduce number of free charge carriers, i.e. deplete the detector

⇒ **Most detectors make use of reverse biased p-n junctions**

Practical sensors: doping, junctions

e.g. Phosphorus

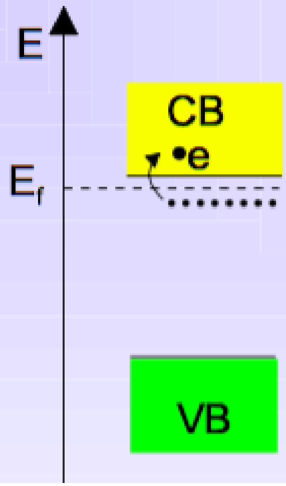


- **Doping: n-type Silicon**

- add elements from V^{th} group

  ⇒ **donors** (P, As,..)

- electrons are majority carriers

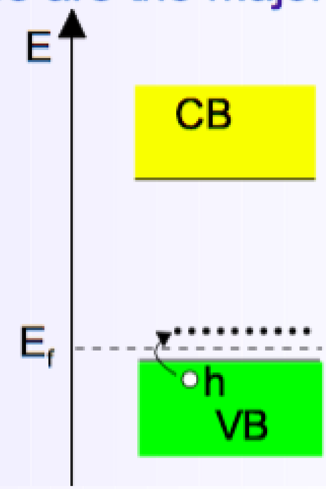


- **Doping: p-type Silicon**

- add elements from III^{rd} group

  ⇒ **acceptors** (B,..)

- holes are the majority carriers



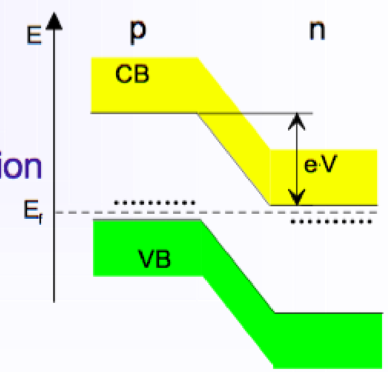
- **p-n junction**

There must be a single Fermi level !

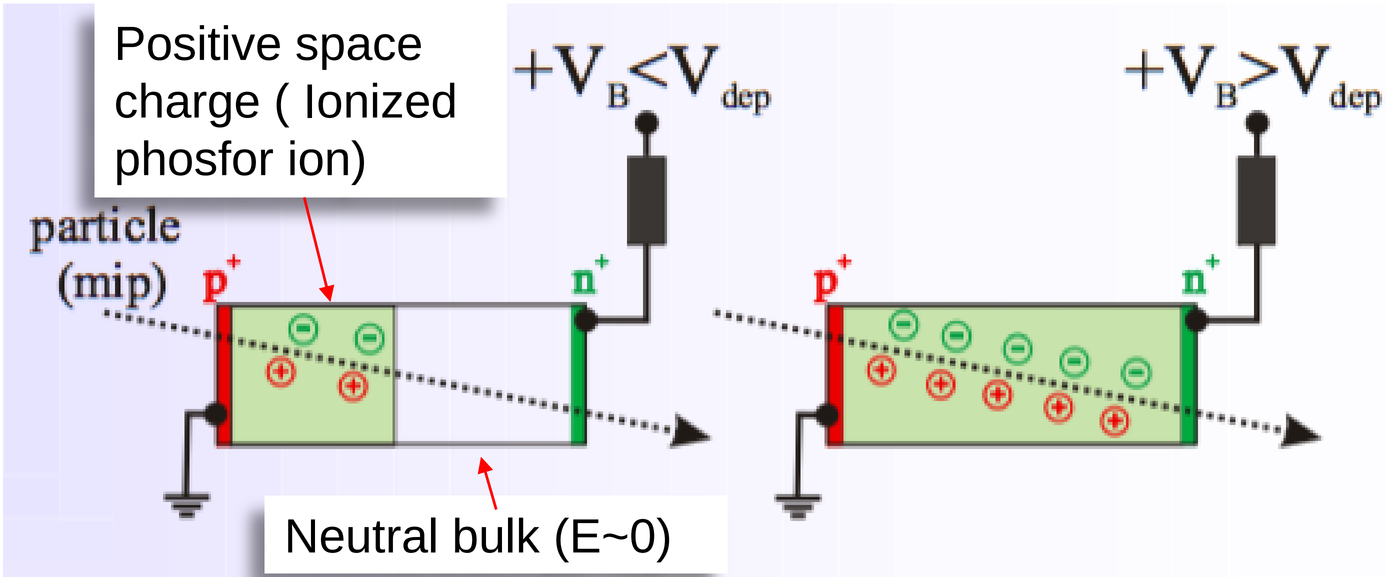
⇒ band structure deformation

⇒ potential difference

⇒ depleted zone



Making it work



Full charge collection only for $V_B>V_{dep}$!

- **Resistivity**
  - carrier concentrations *n*, *p*
  - carrier mobility μ_n, μ_p

$$\rho = \frac{1}{q_0(\mu_n n + \mu_p p)}$$

	detector grade	electronics grade
doping	$\approx 10^{12}$ cm^{-3}	$\approx 10^{17}$ cm^{-3}
resistivity ρ	≈ 5 kΩ·cm	≈1 Ω·cm

depletion voltage

$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0} \cdot \left|N_{eff}\right| \cdot d^2$$

effective space charge density

The charge signal

- **Collected Charge for a Minimum Ionizing Particle (MIP)**

- **Mean energy loss**
  dE/dx (Si) = 3.88 MeV/cm
  ⇒ 116 keV for 300μm thickness

- **Most probable energy loss**
  ≈ 0.7 ×mean
  ⇒ 81 keV

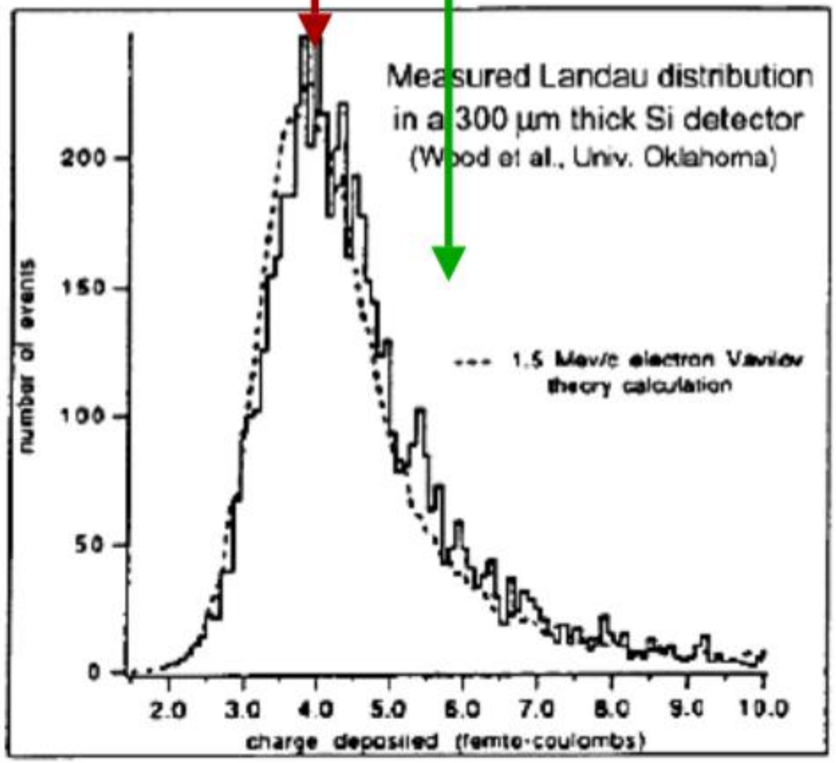
- **3.6 eV to create an e-h pair**
  ⇒ 72 e-h / μm (mean)
  ⇒ 108 e-h / μm (most probable)

- **Most probable charge** (300 μm)

  ≈ 22500 e ≈ 3.6 fC

Most probable charge ≈ 0.7× mean

Mean charge

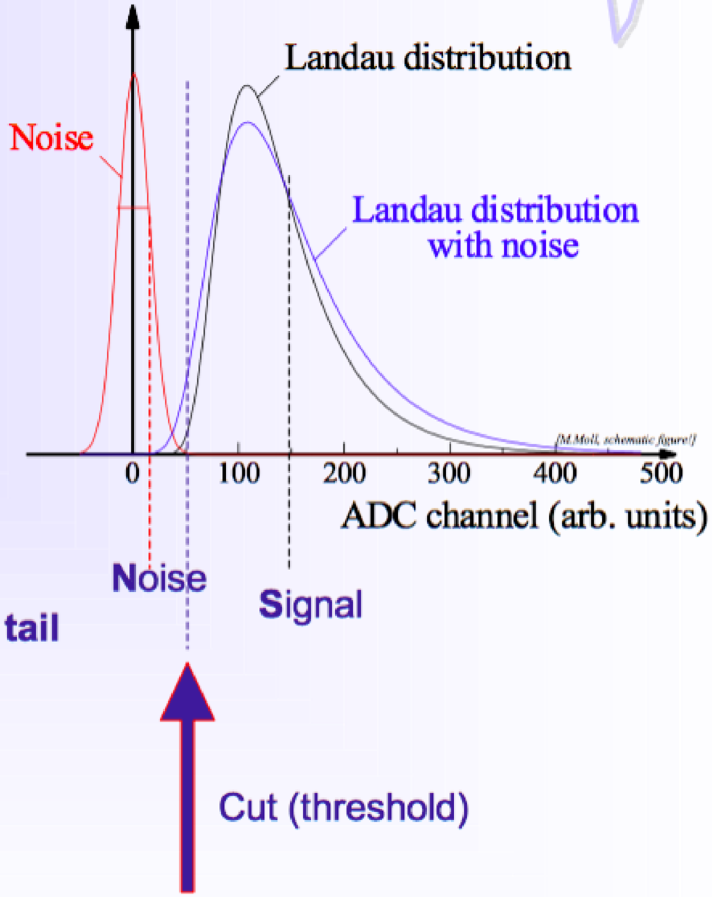


Signal/Noise

- **Landau distribution** has a low energy tail
  - becomes even lower by noise broadening

Noise sources: (ENC = Equivalent Noise Charge)

- Capacitance $ENC \propto C_d$
- Leakage Current $ENC \propto \sqrt{I}$
- Thermal Noise (bias resistor) $ENC \propto \sqrt{k_B T / R}$

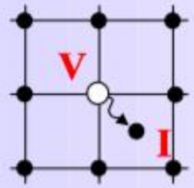


- **Good hits selected by requiring N_{ADC} > noise tail**
  - **If cut too high ⇒ efficiency loss**
  - **If cut too low ⇒ noise occupancy**
- **Figure of Merit: Signal-to-Noise Ratio S/N**
- **Typical values >10-15, people get nervous below 10.**
  Radiation damage severely degrades the S/N.

Radiation damage

- **Damage to the silicon crystal:** Displacement of lattice atoms

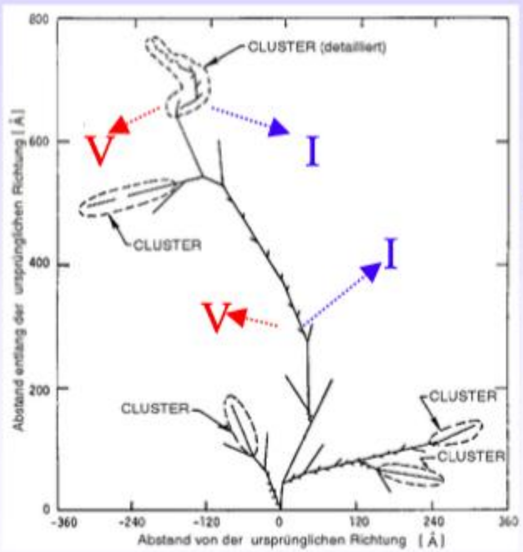
particle → Si_S — $E_K > 25$ eV →



Vacancy + Interstitial ⇔ **"point defects", mobile in silicon can react with impurities (O,C,..)**

Si_S — $E_K > 5$ keV → **point defects and clusters of defects**

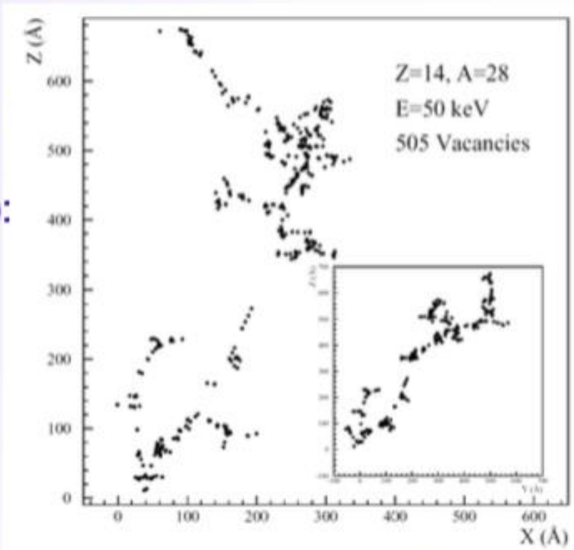
80 nm



Distribution of vacancies created by a 50 keV Si-ion in silicon (typical recoil energy for 1 MeV neutrons):

← **Schematic** [Van Lint 1980]

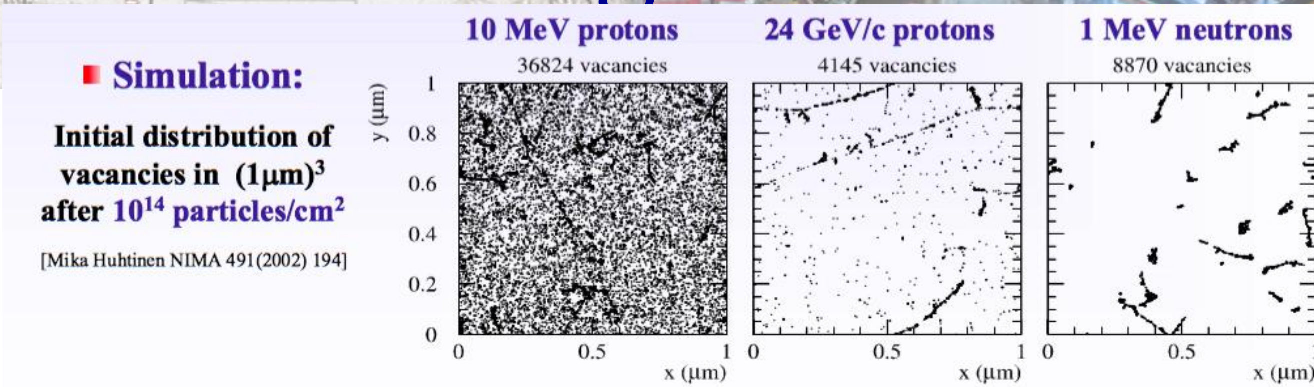
Simulation [M.Huhtinen 2001] →

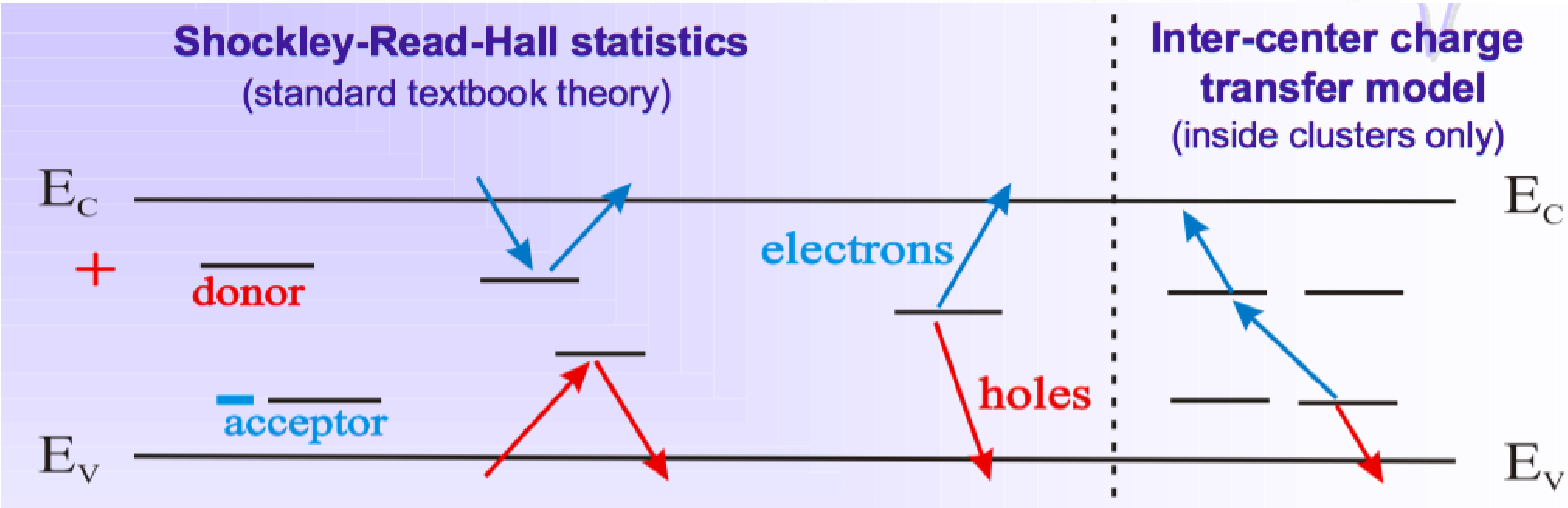


- **Defects can be electrically active (levels in the band gap)**
  - capture and release electrons and holes from conduction and valence band

  ⇒ can be charged - can be generation/recombination centers - can be trapping centers

Radiation damage effects





charged defects
⇒ N_{eff} , V_{dep}
e.g. donors in upper and acceptors in lower half of band gap

trapping (e and h)
⇒ **CCE**
shallow defects do not contribute at room temperature due to fast detrapping

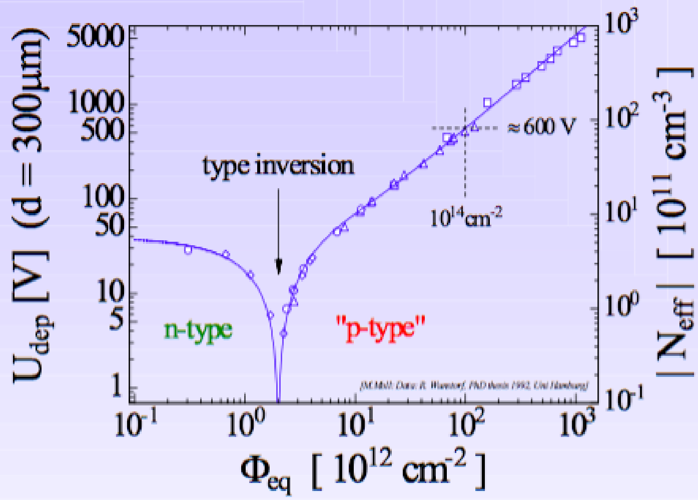
generation
⇒ **leakage current**
Levels close to midgap are most effective

enhanced generation
⇒ **leakage current**
⇒ **space charge**

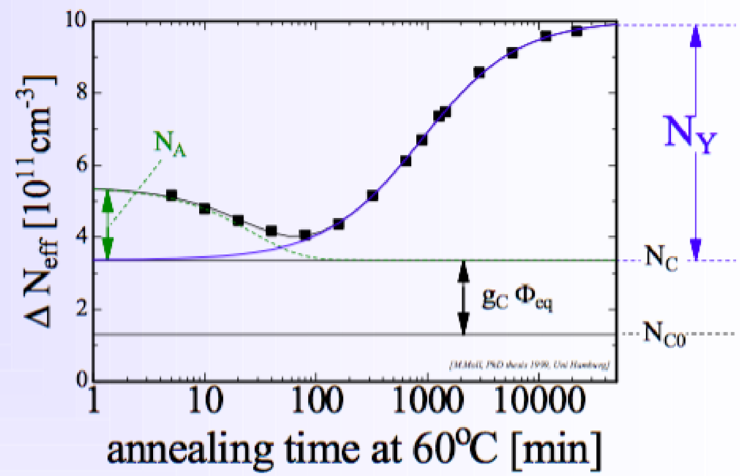
Rad dam: depletion voltage

Change of Depletion Voltage V_{dep} (N_{eff})

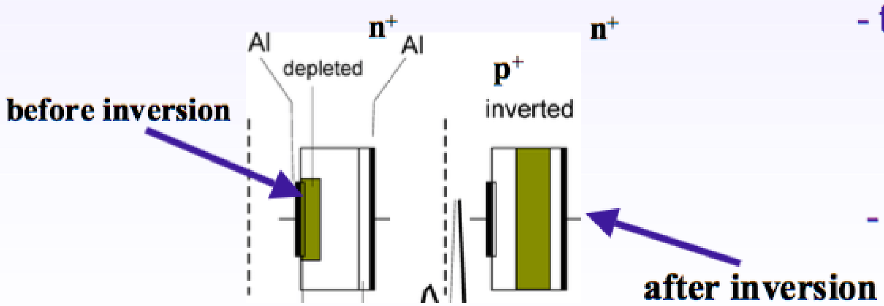
…. with particle fluence:



…. with time (annealing):



- "Type inversion": N_{eff} changes from positive to negative (Space Charge Sign Inversion)

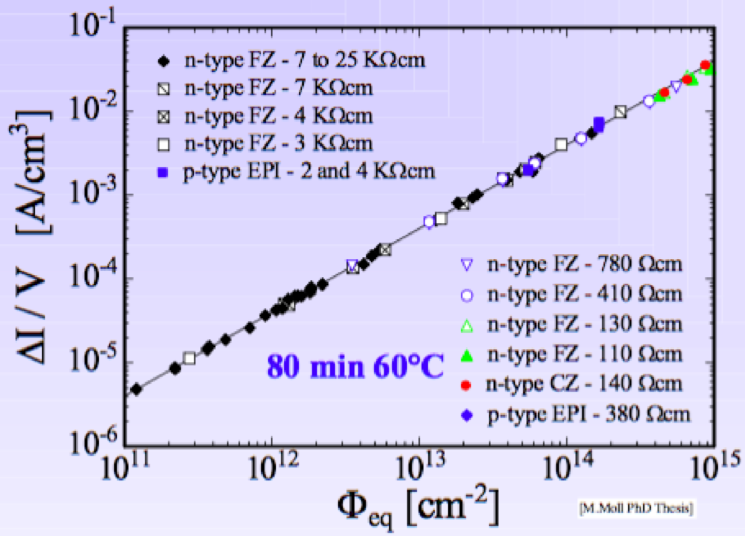


- **Short term:** "Beneficial annealing"
- **Long term:** "Reverse annealing"
  - time constant depends on temperature:
    - ~ 500 years (-10°C)
    - ~ 500 days (20°C)
    - ~ 21 hours (60°C)
  - **Consequence:** Detectors must be cooled even when the experiment is not running!

Rad Dam: Leakage Current

Change of Leakage Current (after hadron irradiation)

…. with particle fluence:



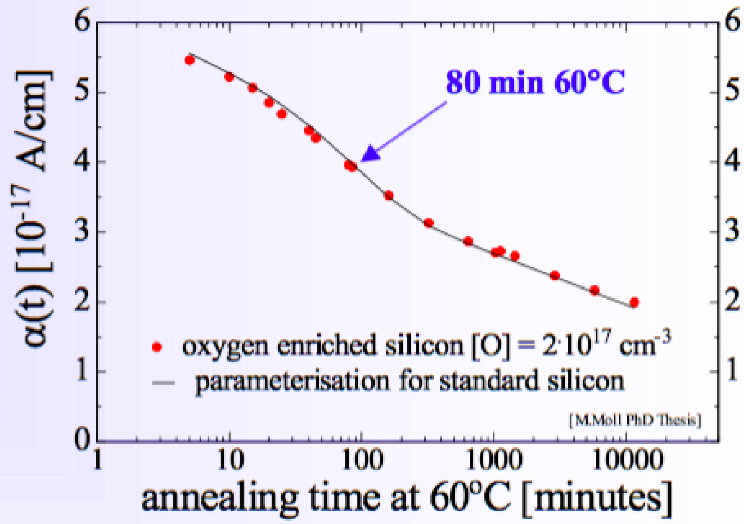
- Damage parameter α (slope in figure)

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

Leakage current per unit volume and particle fluence

- α is constant over several orders of fluence and independent of impurity concentration in Si
  ⇨ can be used for fluence measurement

…. with time (annealing):



- Leakage current decreasing in time (depending on temperature)
- Strong temperature dependence

$$I \propto \exp\left(-\frac{E_g}{2k_B T}\right)$$

Consequence:
Cool detectors during operation!
Example: $I(-10°C) \sim 1/16\ I(20°C)$

Rad Dam: Charge Collection Eff.

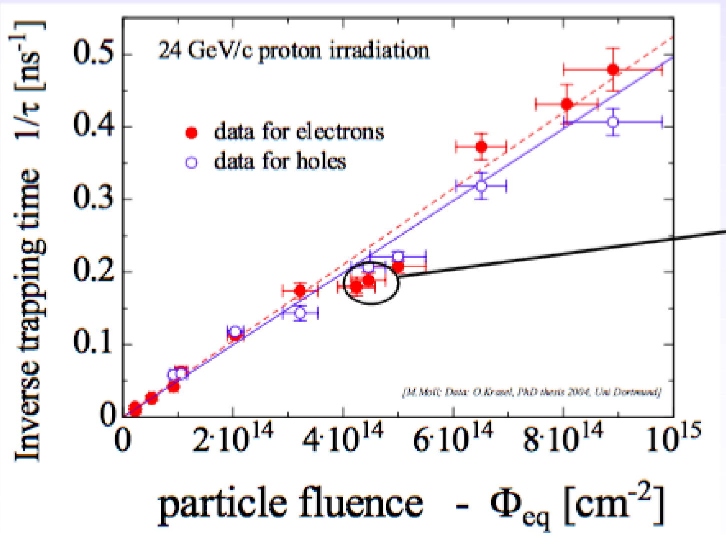
- **Deterioration of Charge Collection Efficiency (CCE)**

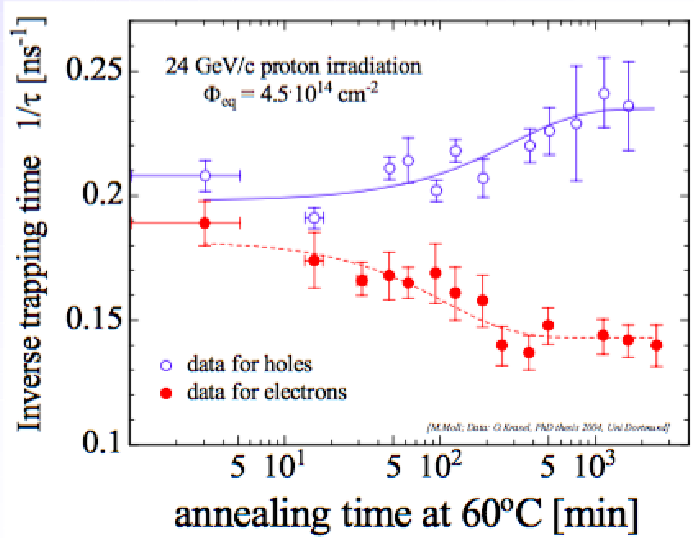
  2 mechanisms: - Trapping of electrons and holes
  - Underdepletion (loss of active detector volume due to increase of V_{dep})

Trapping is characterized by an effective trapping time τ_{eff} for electrons and holes:

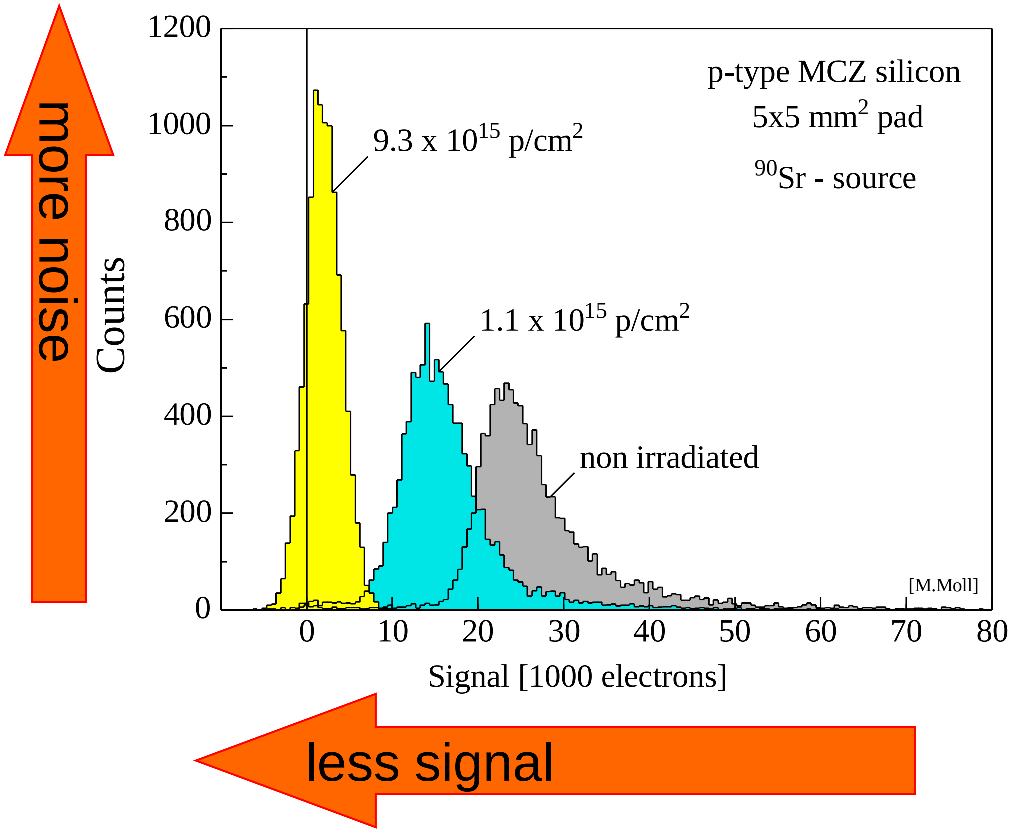
$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right) \qquad \text{where} \qquad \frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$

Increase of inverse trapping time ($1/\tau$) with fluence ….. and change with time (annealing):





Rad dam: Signal/noise if the figure of merit



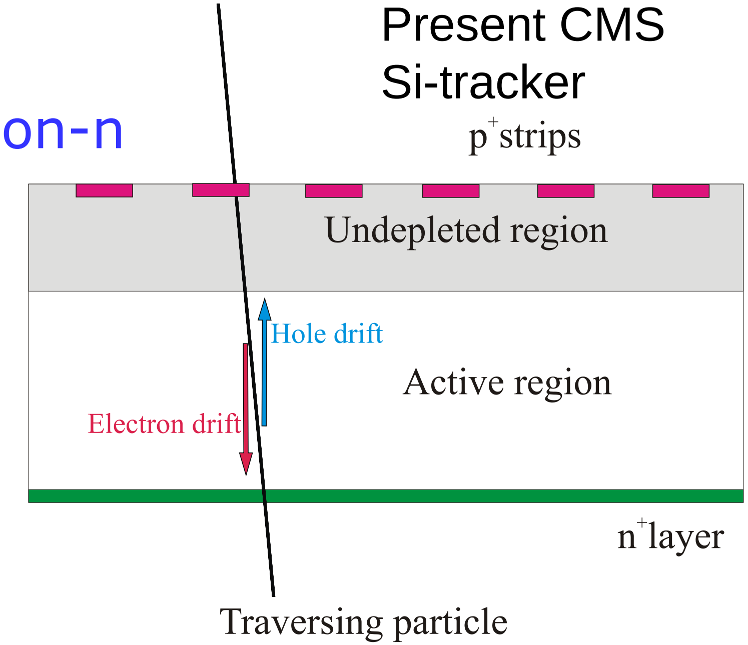
p-on-n sensors do not survive

Device engineering: making it more rad-hard

n-type silicon after high fluences:

Present CMS Si-tracker

p^+on-n



p-on-n silicon, under-depleted:

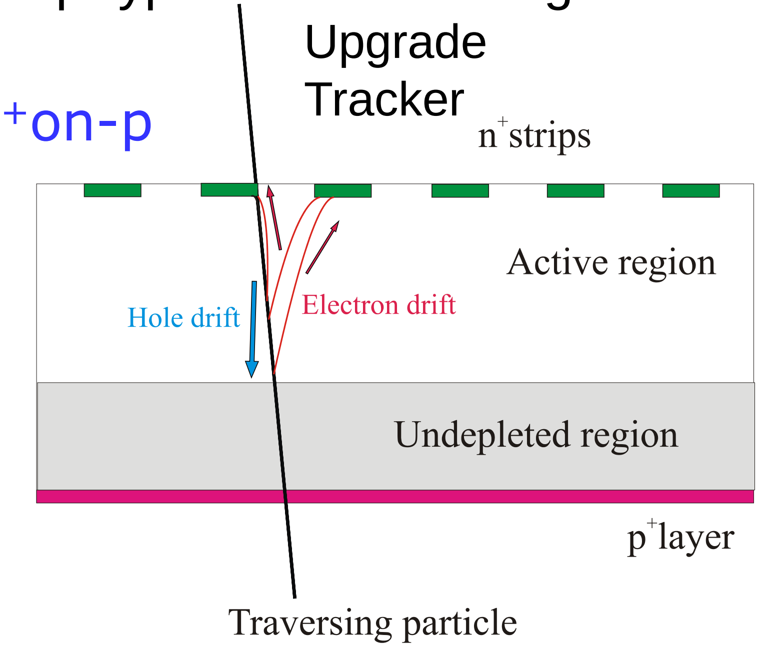
- Charge spread – degraded resolution
- Charge loss – reduced CCE

Be careful, this is a very schematic explanation, reality is more complex !

p-type silicon after high fluences:

Upgrade Tracker

n^+on-p



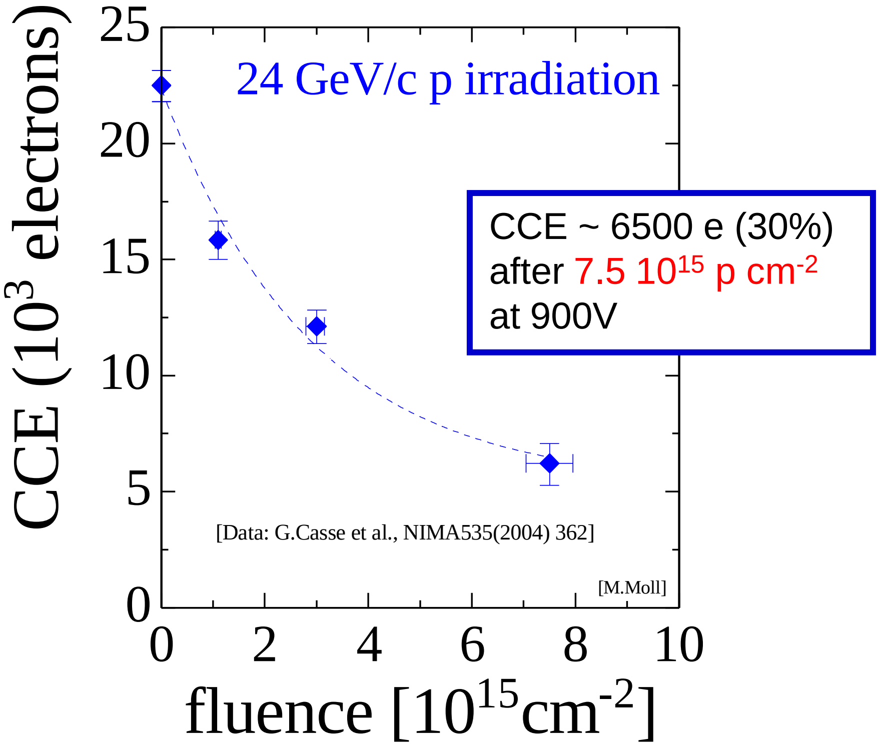
n-on-p silicon, under-depleted:

- Limited loss in CCE
- Less degradation with under-depletion
- Collect electrons (fast)

Note: N-in-p costs more as it more complex to manufacture

n-in-p sensors still viable at the end of HI-Lumi-LHC

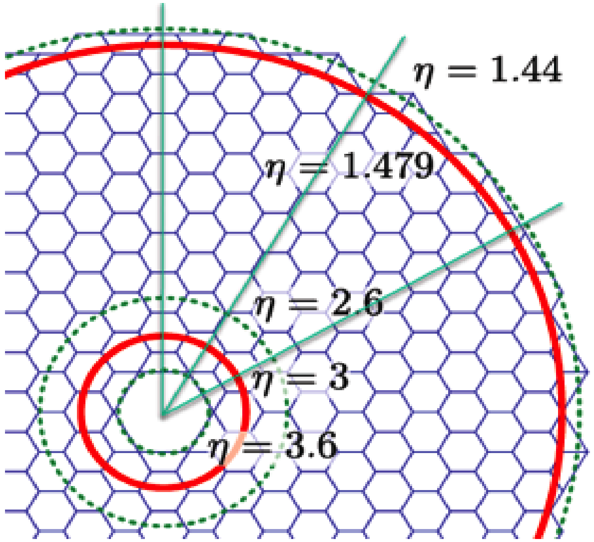
- n-in-p microstrip detectors (280μm) on p-type FZ silicon
- Detectors read-out with 40MHz



Things are more complex for pad sensors

- The plan at the moment is to use **n-in-p** in the inner rings and possibly **p-in-n** in the outer ones
- The signal for Pad detectors due to largely different weighting fields is due to both electrons and holes
- In reality the charges induce a signal when they move - before the really reach the electrodes.
- With pixel and strip geometries the main (fast movement) happens close to the electrodes with a much higher field (concentration of field); with pads the field simply goes linearly across the bulk with no change at the pads therefore nothing special at the electrodes. The more pointlike the electrode the less relevant the concept of signal via induction; for n-in-p strips/pixel the induction of electrons is more relevant and they also collect the electrons.
- For n-in-p pads they collect the electrons but also hole movement participate via induction (RAMO-Shockley) to the signal even when they are not collected at the electrode.

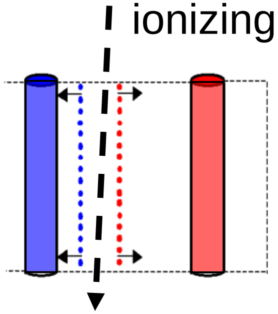
Tiling of 8" hexagonal Si-sensors Endcap calorimeter modules: pads are ~1 cm^2

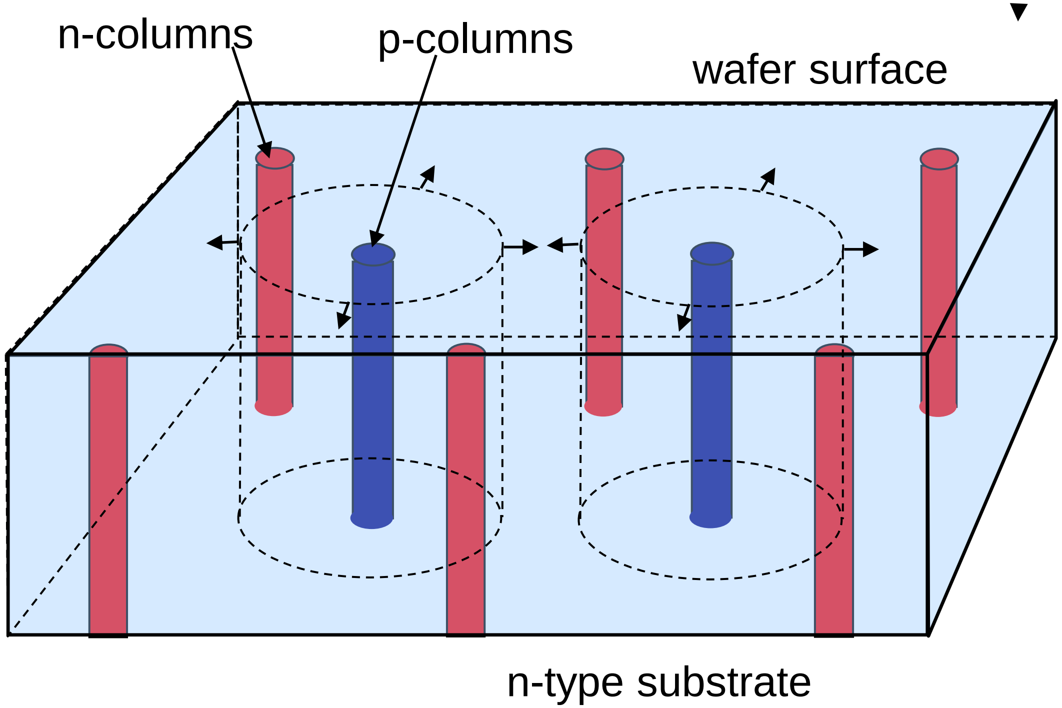


The Jury is still out: extensive tests are ongoing to fully define the detailed engineering of the pad

Lots of R&D to find viable Pixel detector :e.g. 3D sensors

- **"3D" electrodes:** - narrow columns along detector thickness,
  - diameter: 10μm, distance: 50 - 100μm
- **Lateral depletion:** - lower depletion voltage needed
  - thicker detectors possible
  - fast signal
  - radiation hard





Introduced by: S.I. Parker et al., NIMA 395 (1997) 328

And more (which I cannot cover here)

- New Materials like SiC and GaN have been characterized
  - ⇨ CCE tests show that these materials are not radiation harder than silicon
  - ⇨ Silicon (operated at e.g. -30°C) seems presently to be the best choice

- At fluences up to 10^{15}cm^{-2} (Outer layers of SLHC detector) the depletion voltage change and the large area to be covered is major problem:

  – p-type (FZ and MCZ) silicon microstrip detectors show good results:
  CCE ≈ 6500 e; $\Phi_{eq} = 4\times10^{15}$ cm^{-2}, 300μm, collection of electrons,
  no reverse annealing observed in CCE measurement!

- At the fluence of 10^{16}cm^{-2} (Innermost layer of a SLHC detector) the active thickness of any silicon material is significantly reduced due to trapping. New options:

  – Thin/EPI detectors : drawback: radiation hard electronics for low signals needed
  – 3D detectors : drawback: very difficult technology

Further information: http://cern.ch/rd50/

Rad hard sensors recipe

Radiation hardness "recipe"

P-on-N sensors work after bulk type inversion, Provided they are biased well above depletion

At room temperature and above, radiation induced defects diffuse and some eventually form clusters which further increase the sensor depletion voltage "reverse annealing"

Defect mobility below ~ 0C is sufficient low that reverse annealing is effectively frozen out

- Maintain radiation damaged silicon below ~0C (constantly)

Sensor leakage current depends ~ exponentially on temperature: it doubles for every ~7C temperature increase

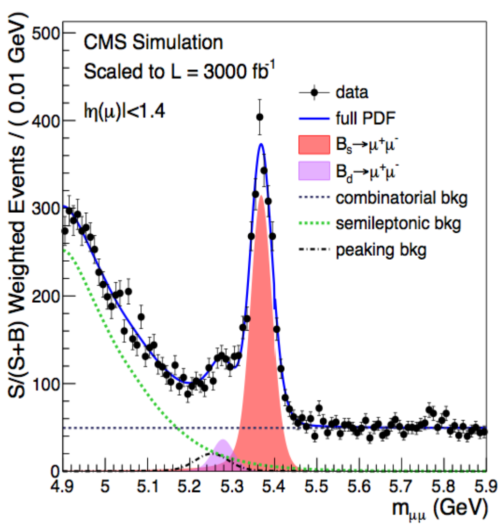
Insufficient cooling efficiency will result in an exponential "thermal run-away" of the irradiated sensor

- Operate sensors below ~ -10C, to reduce required cooling efficiency & material

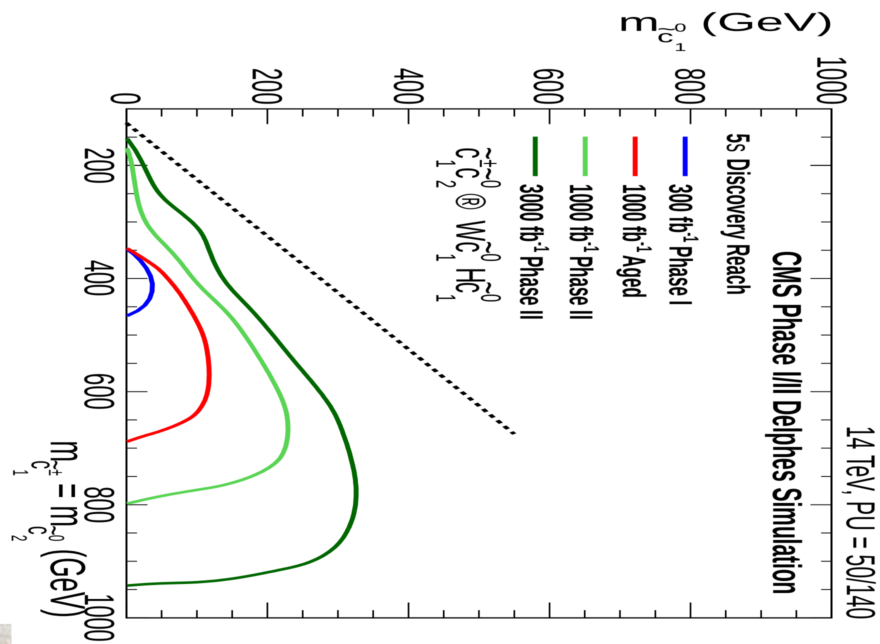
Back to physics

- Example of reach for the upgraded detector

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

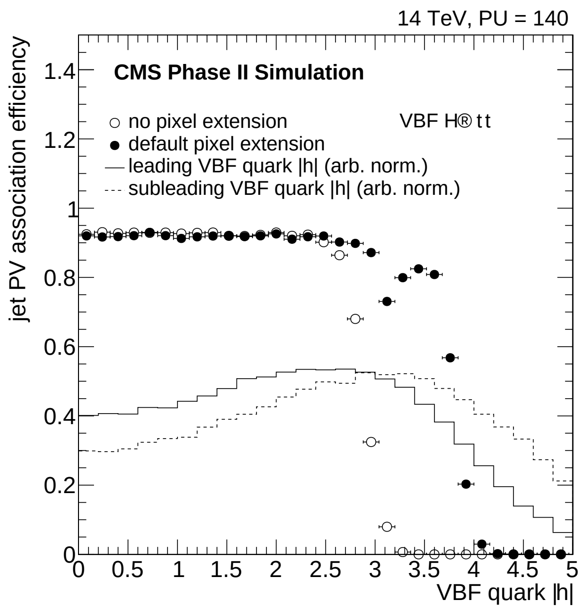


Neutralino mass range increase - enabled by Tracker extension (MET) & b-tagging

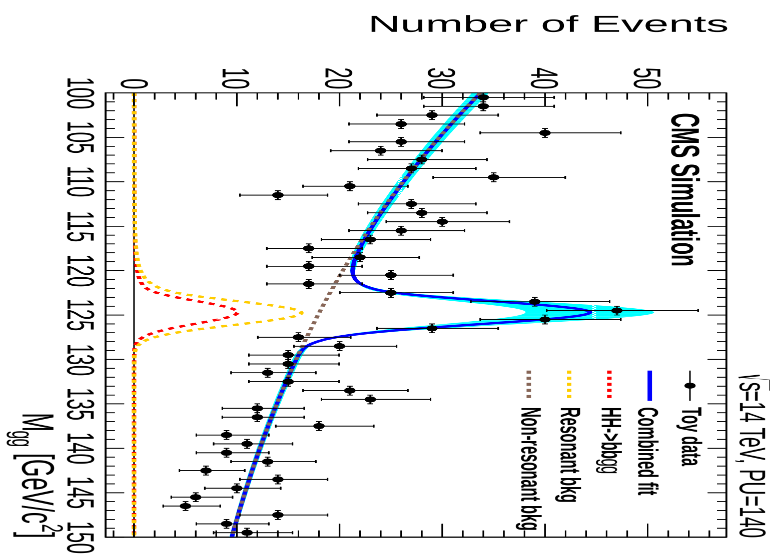


Higgs physics (portal to new physics)

VBF H $\rightarrow \tau\tau$:
enabled by VBF jet tagging, τ-ID, MET resolution



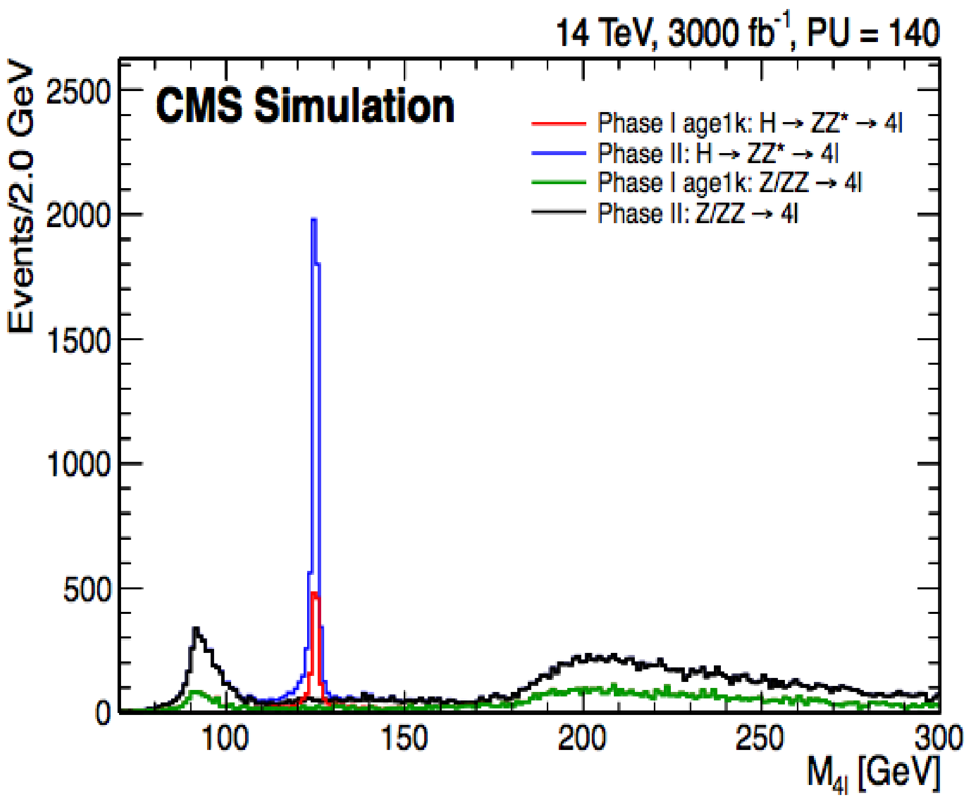
HH $\rightarrow$ bbγγ
ZH, ttH, bbH background



HH $\rightarrow$ bbγγ
enabled by Tracker b-tagging, EC γ resolution performance

High precision Higgs measurements

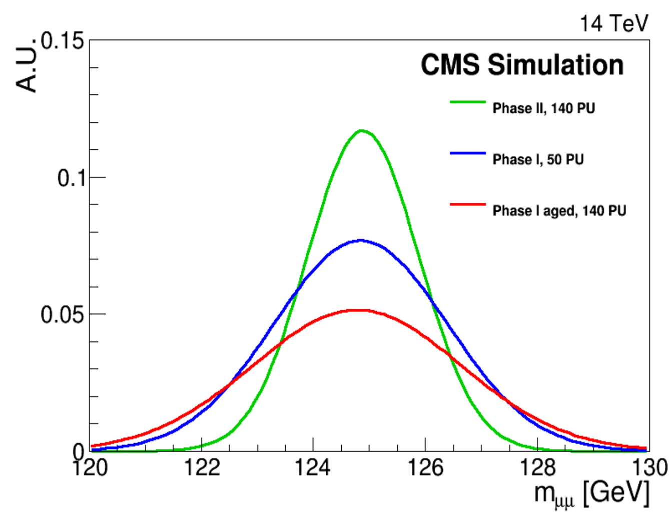
H → ZZ* → 4l: precision measurements



H → ⌠μ (rare decay):

probes the 2nd generation couplings

Search of narrow resonance with huge DY background



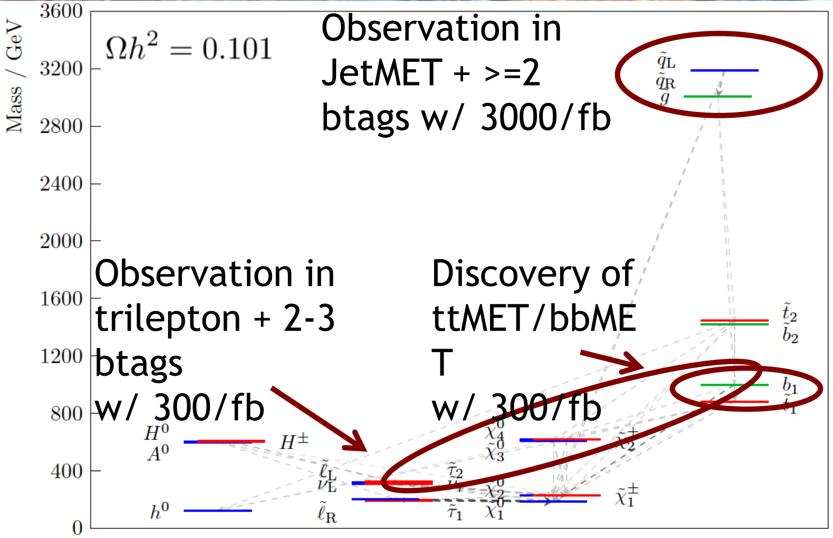
Improvements: 20% efficiency & 45% mass resolution

→ expect ~5% uncertainty on κ_μ

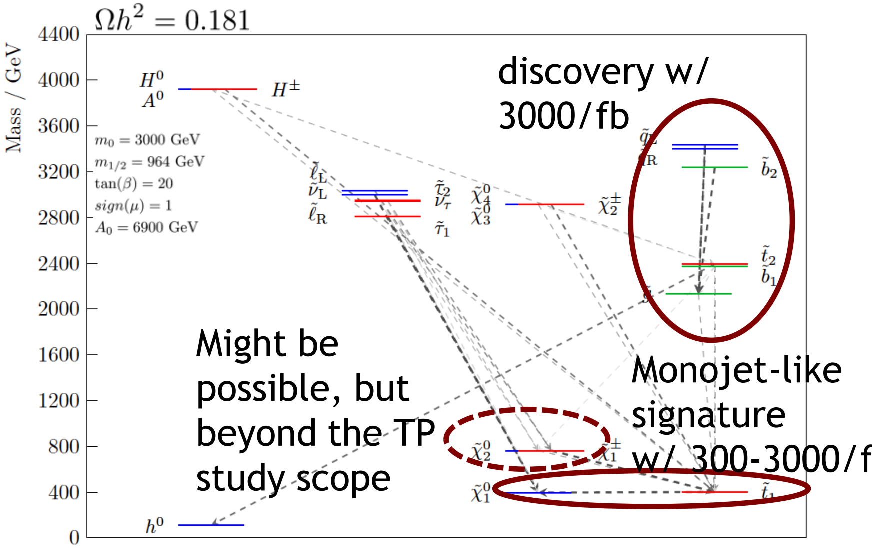
Possible discovery stories: Coannihilation Models

Coannihilation= almost degenracy between LSP and NSLP

- Stau coannihilation model
  - Excess in tt+MET and bb+MET final states to be discovered with 300/fb
  - Observation of trileptons with 2-3 b-tags indicates the complex weakly interacting sector (produced in strong interaction)
  - >3 TeV gluino/squarks still discoverable with HL-LHC



- Stop coannihilation model
  - Compressed stop [$\Delta m(t_1, N1)$ =6 GeV], evidence in monojet search with 300/fb, growing to 5σ with 3000/fb
  - Jets+MET + btags: clear signal with 3000/fb
    - B-tag multiplicities → branching fraction of gluinos
    - Jet multiplicities suggest the existence of 1st and 2nd generation squarks



Discovery could come late

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

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

In summary

- The Physics exploitation of the High Lumi LHC is probably the most challenging undertaking that Experimental Physics has faced in history
- The challenge is made harder by the physics goals which are to make high precision measurement
- Still we are convinced that we will meet the challenge and have detectors which will be able to fully exploit the physics potential of the LHC

Backup

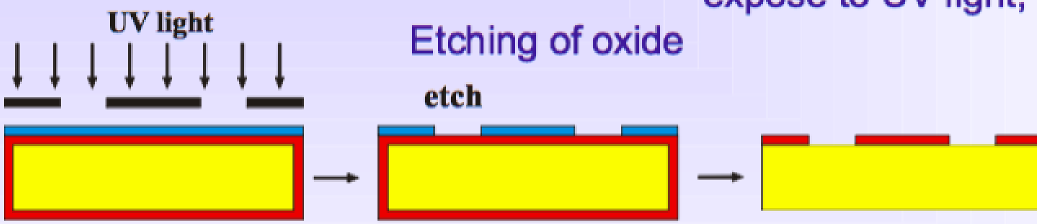
Silicon sensor production

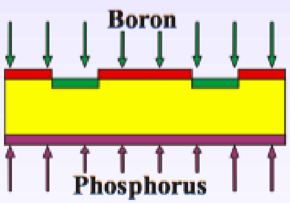
A "simple" production sequence (schematic)

- Polished n-type silicon wafer (typical $\rho \sim$ 1-10 KΩcm)

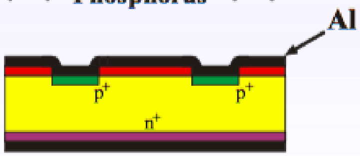
- Oxidation (800-1200°C)

- Photolithograpy (coat with photo resist; align mask, expose to UV light, develop photoresist);
  Etching of oxide

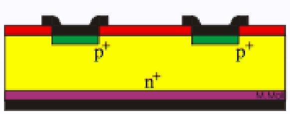




- Doping with boron and phosphorus by implantation (or by diffusion)
  Annealing to cure radiation damage and activate dopants
  - p^+ n junction on front side
  - n n^+ ohmic contact on back side



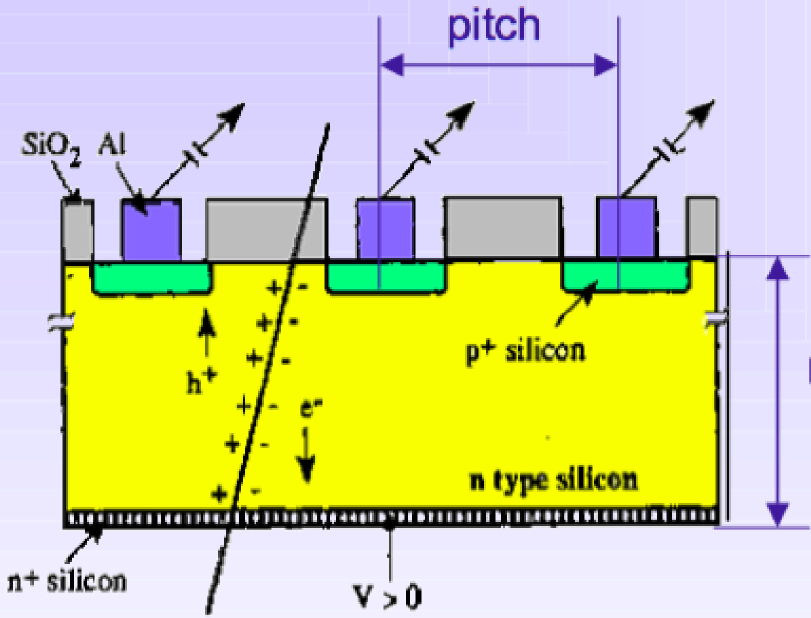
- Aluminize surface (e.g. by evaporation)



- Pattern metal for diode contacts

Strip detector (single sided)

- Segmentation of the p⁺ layer into strips (Diode Strip Detector) and connection of strips to individual read-out channels gives spatial information



typical thickness: 300μm (150μm - 500μm used)

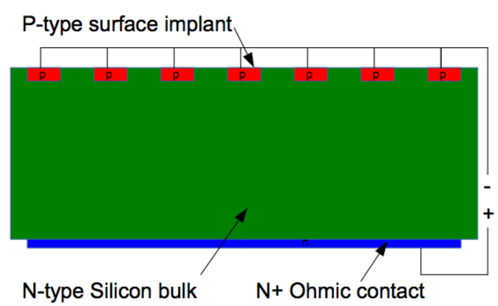
- using n-type silicon with a resistivity of
  ρ = 2 KΩcm (N_D ~$2.2 \cdot 10^{12} cm^{-3}$)
  results in a depletion voltage ~ 150 V

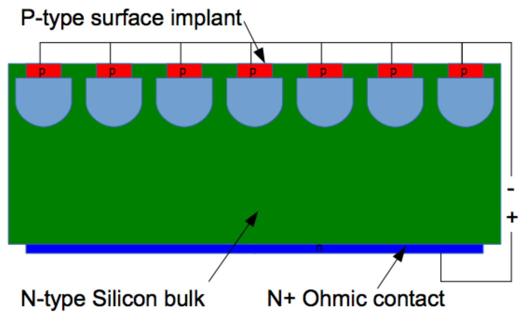
- Resolution σ depends on the pitch p (distance from strip to strip)

  - e.g. detection of charge in binary way (threshold discrimination) and using center of strip as measured coordinate results in

$$\sigma = \frac{p}{\sqrt{12}}$$

typical pitch values are 20 μm– 150 μm ⇒ 50 μm pitch results in 14.4 μm resolution


P-type surface implant
N-type Silicon bulk
N+ Ohmic contact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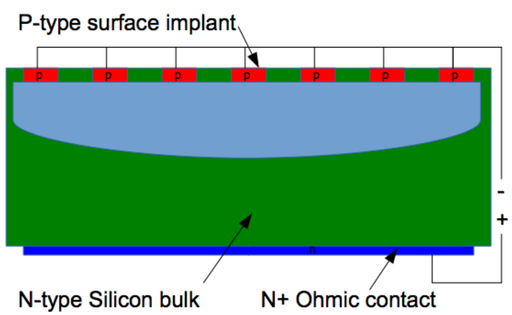
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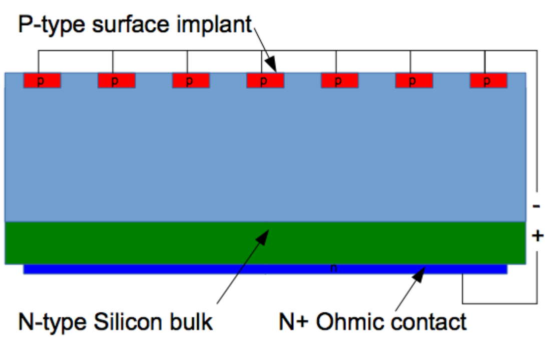
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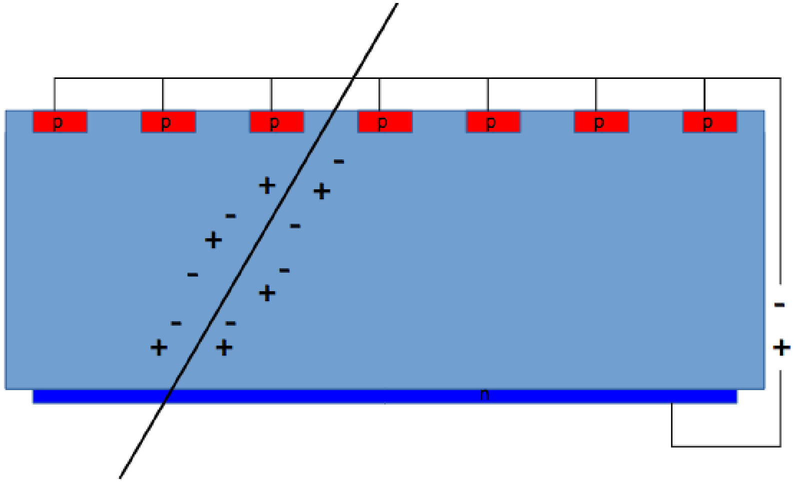
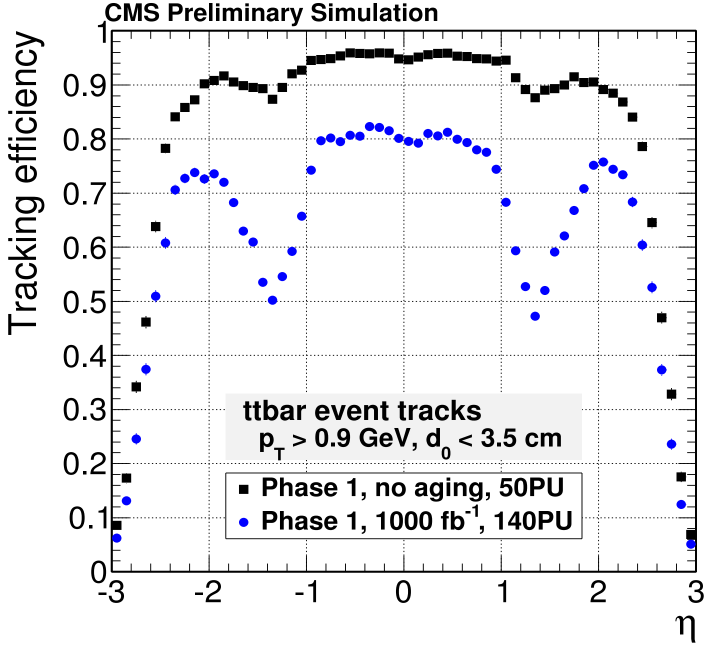
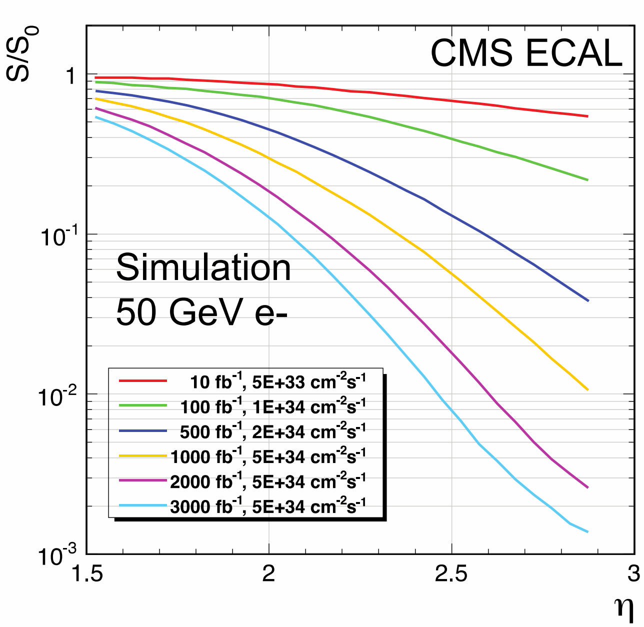


Consequences of HL-LHC on detectors

Detector ages and performance deteriorates





→ **Need to replace tracker and forward detectors with rad-hard material**

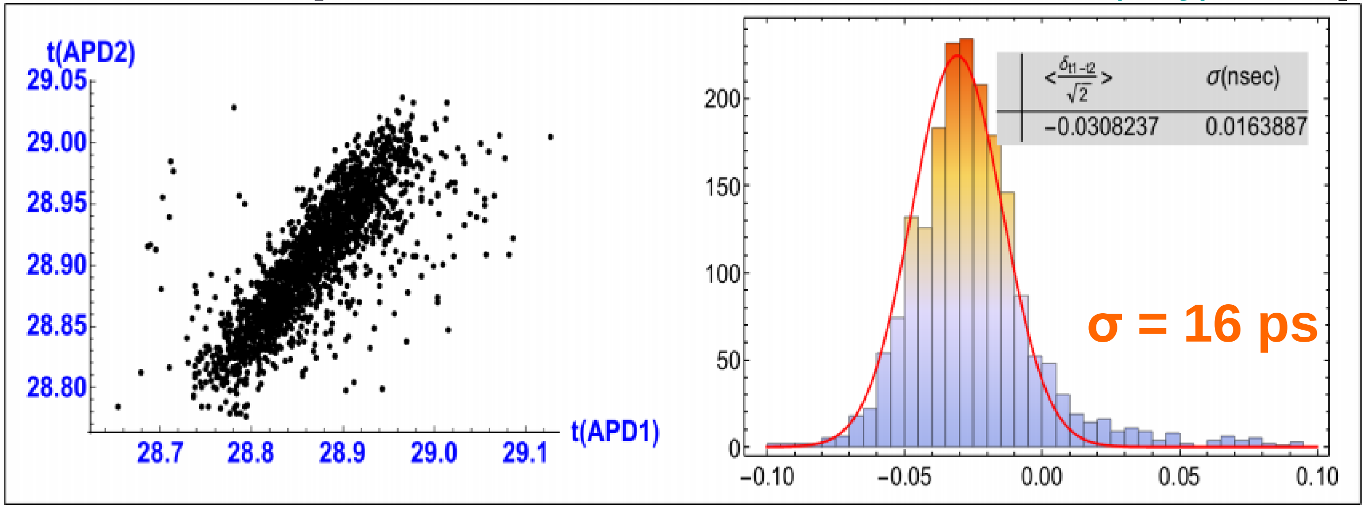
Trigger needs to stay efficient (MHz → KHz). Keep trigger thresholds low for Higgs and particles from cascade decays

→ **Finer detector granularity and larger trigger bandwidth**

Detector technologies tested at H2

- **Si sensors with amplification**
  - Sensitivity to MIPs in Si devices with internal amplification
- **R&D on high gain APDs with field shaping to achieve fast timing over wide (1 cm^2) pixels – *"Hyperfast Silicon"***

[S.White, at Frontier Detectors etc., Elba, (Italy) 2015]

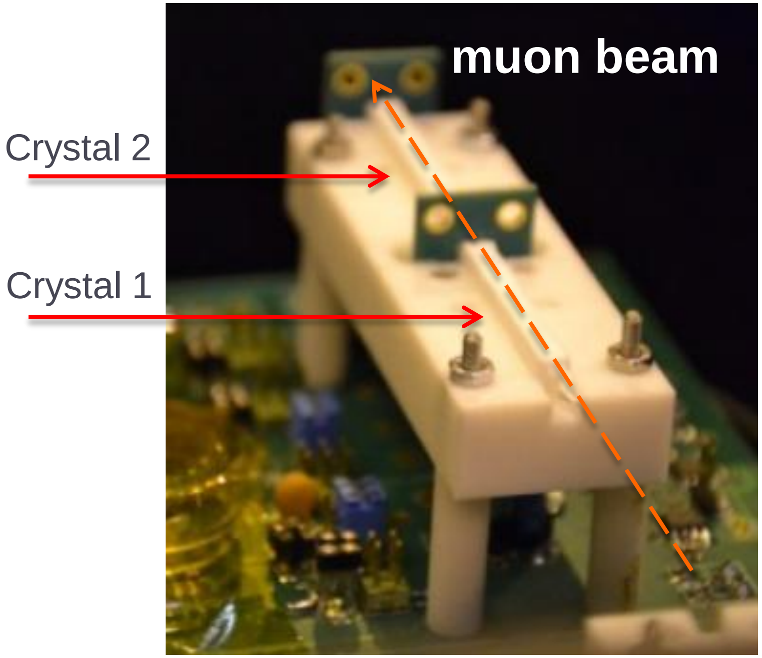


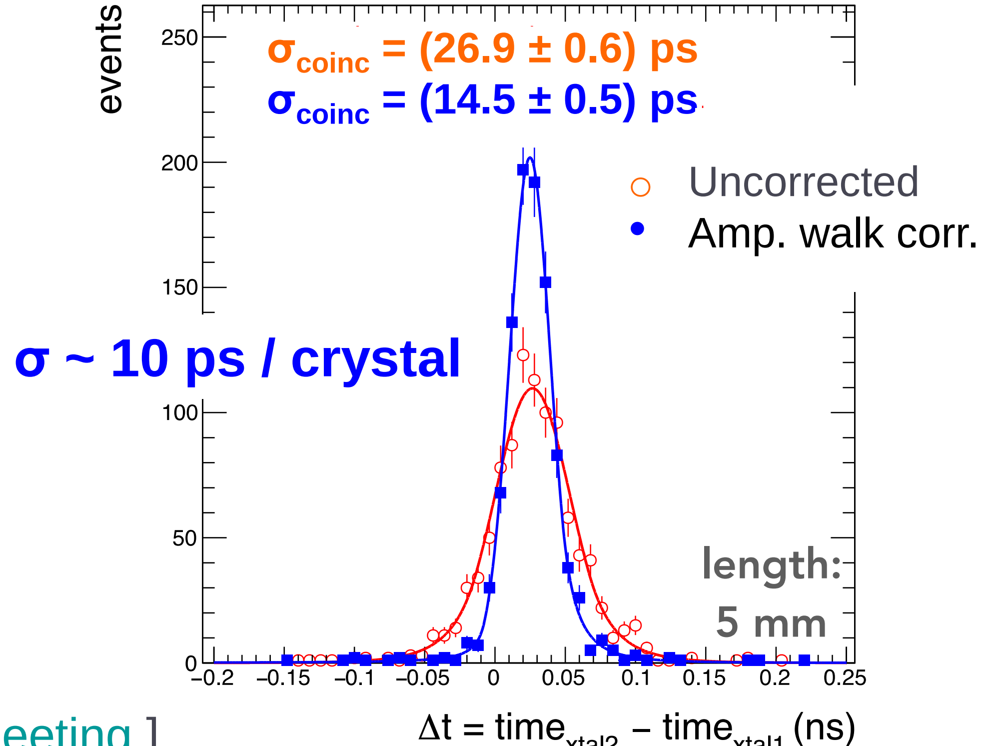
- **Further R&Ds include Ultrafast (thin) Silicon Detector (UFSD)**
  - Aim at <50 ps timing in small pixels (for CT-PPS upgrade)
  - [current generation (thick sensors) 120 ps]

[N.Cartiglia, CERN Seminar, 2014]

Detector technologies tested at H2

- Thin crystals with fast photosensor
  - LYSO:Ce with SiPM+NINO readout tested with **muons**
  - Small size crystals (small light path dispersion):
    3 x 3 x L mm³ (L=5÷30 mm)

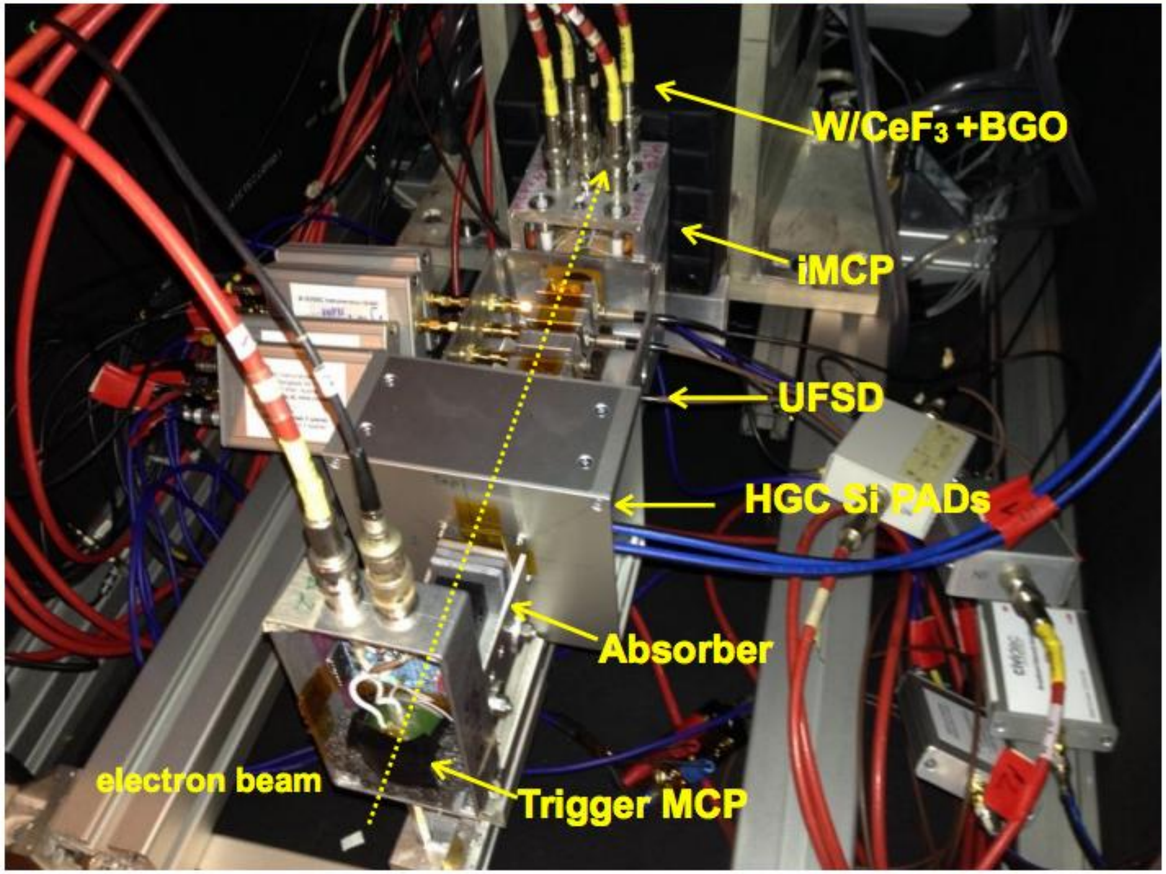




[A.Benaglia et al., ECAL Upgrade Meeting]

Potential of silicon sensors calo timing (I)

I-MCP + Si BOX



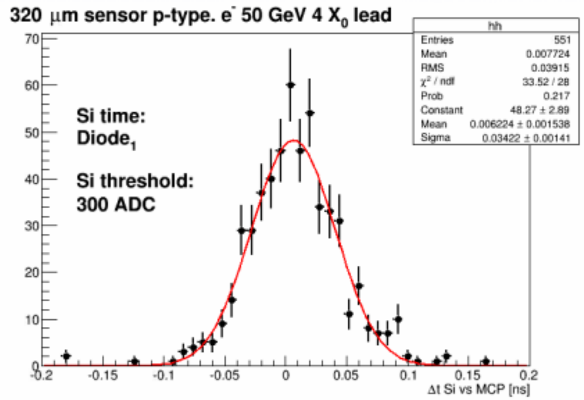
Potential of silicon sensors calo timing (II)

Very Preliminary Time Performance

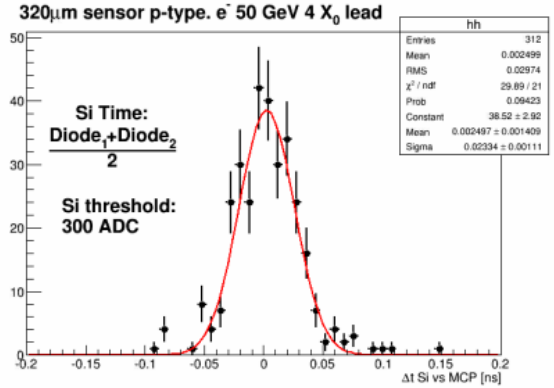
INFN Istituto Nazionale di Fisica Nucleare

Time resolution measured with respect to reference MCP time:

~35ps on a single sensor (320μm) when applying a cut at about 12 MIP



Resolution scales with sqrt(N) when using combination of 2 sensors: ~23ps resolution



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Possible defects in Si crystal lattice

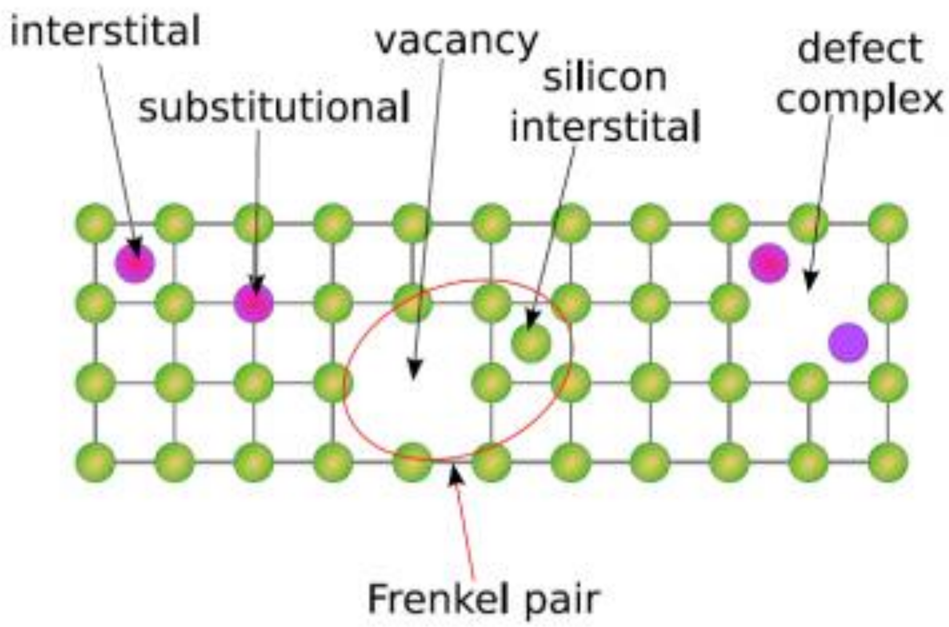

Figure 4.3.: Possible defects that can occur in a crystal lattice [26].