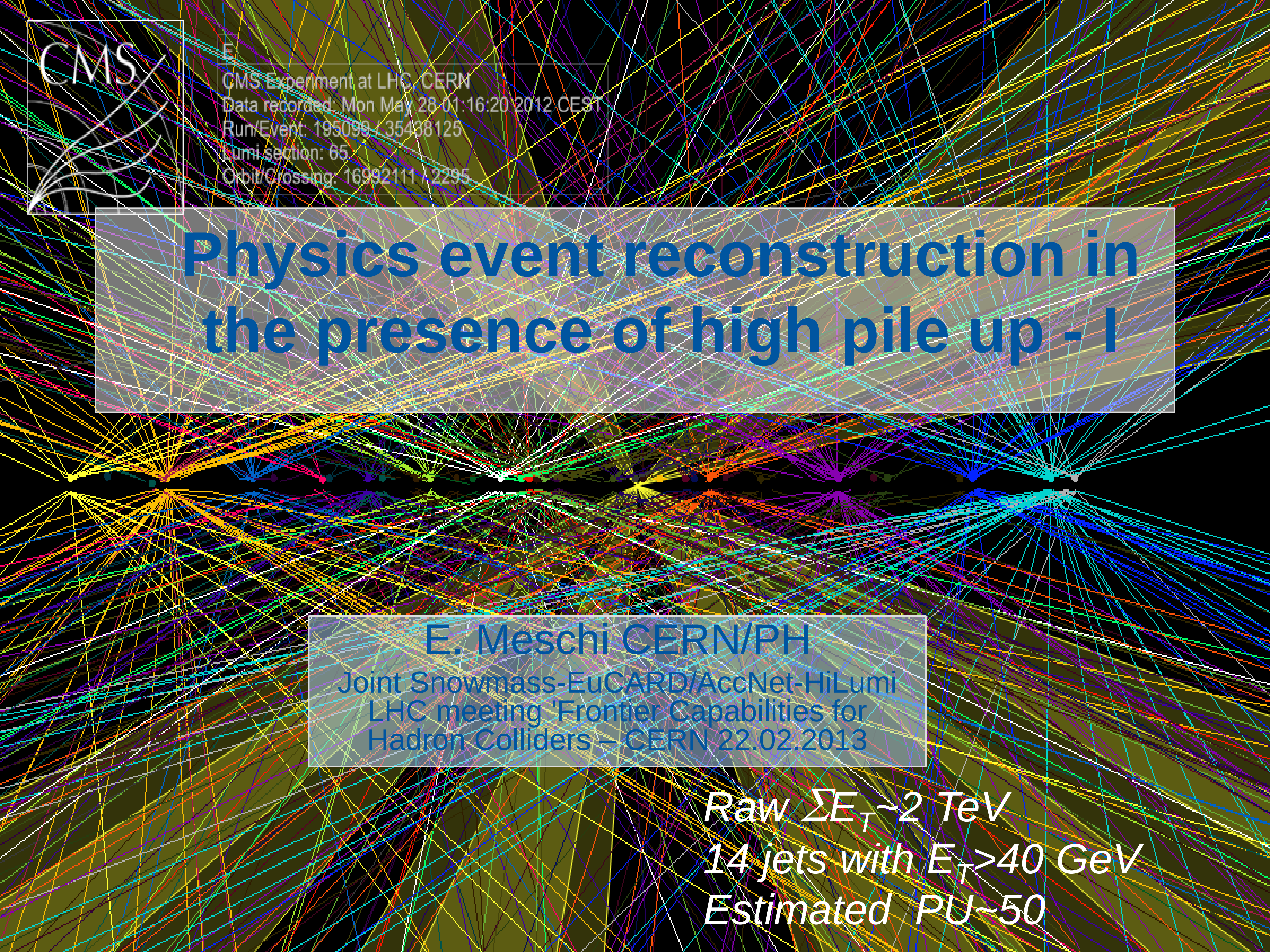


Physics event reconstruction in the presence of high pile up - I

E. Meschi CERN/PH

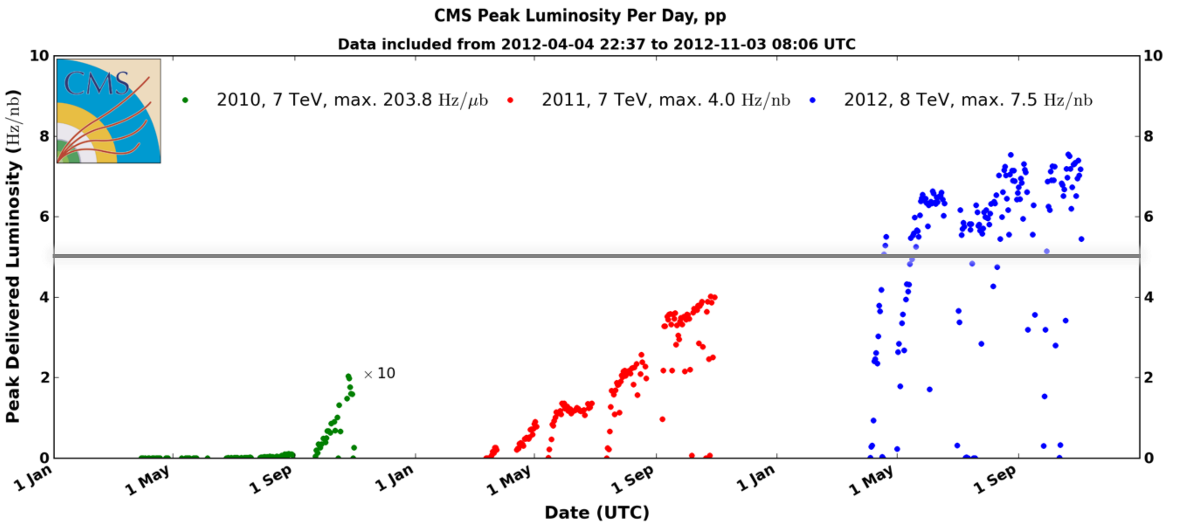
Joint Snowmass-EuCARD/AccNet-HiLumi LHC meeting 'Frontier Capabilities for Hadron Colliders – CERN 22.02.2013

Raw ΣE_T*~2 TeV*
14 jets with E_T*>40 GeV*
Estimated PU~50

Summary

- Briefly touch on various current issues with pileup
  - No attempt to be exhaustive or go into any detail
- Broad directions of R&D for HL
- What we should look into for XLHC

CMS: Pileup in 2012 data

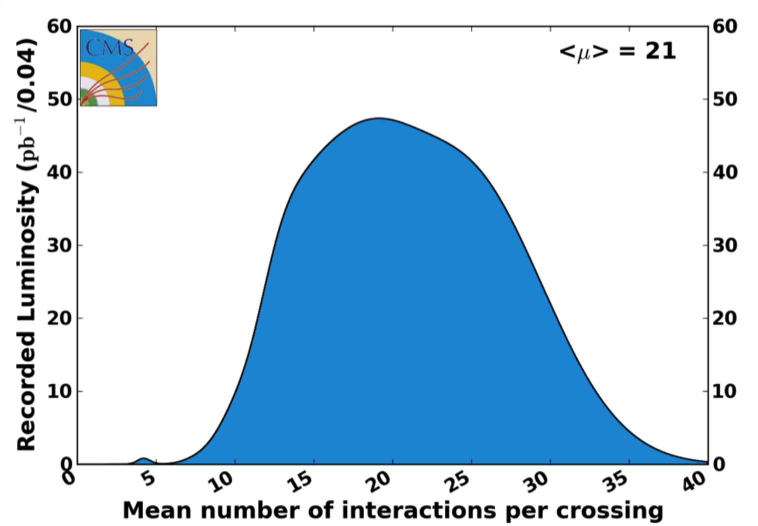


Peak: 35 pileup events

Design value

25 pileup events

(L=10^{34}, 25 ns)



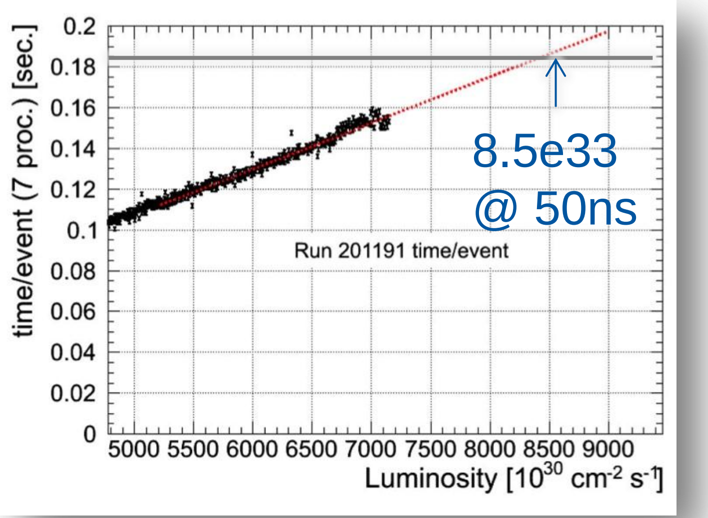
Pileup distribution in 2012 data sample

Average: 21 pileup events

Trigger Challenges

High trigger efficiency for Higgs physics while keeping the trigger rate within budget was one of the biggest challenges in 2012

High Level Trigger CPU time:

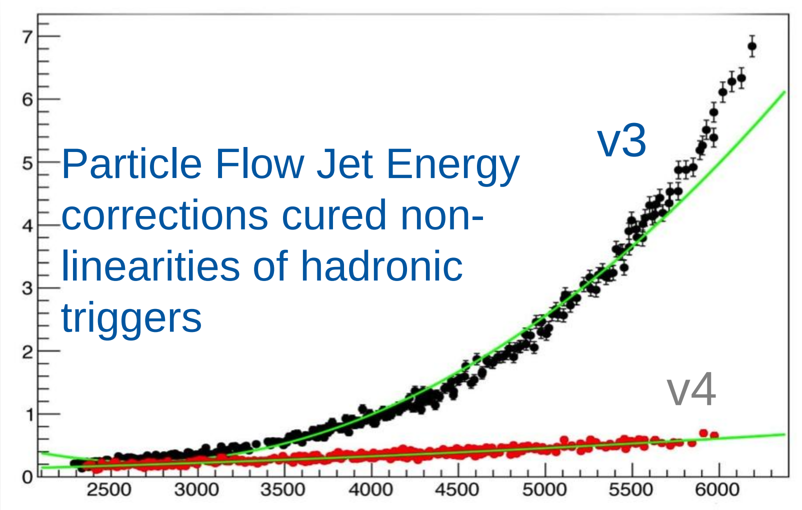


8.5e33 @ 50ns

2012 limit of HLT farm

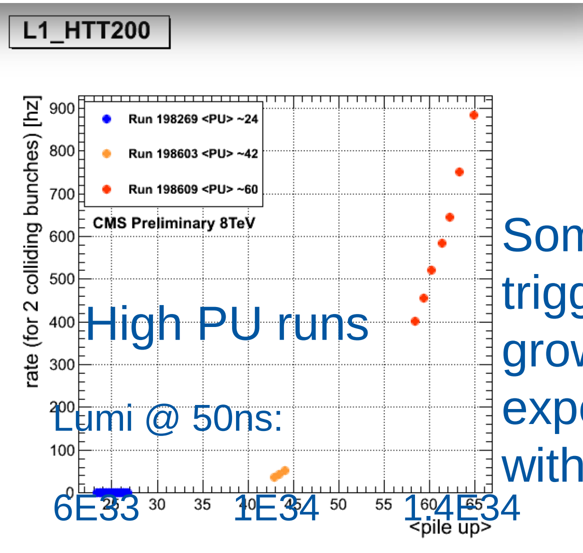
Trigger Cross-sections:

IsoMu24_PFjet30_PFJet25_Deta3_CentralPFJET25



Particle Flow Jet Energy corrections cured non-linearities of hadronic triggers

Luminosity μ$b^{-1}s^{-1}$



High PU runs

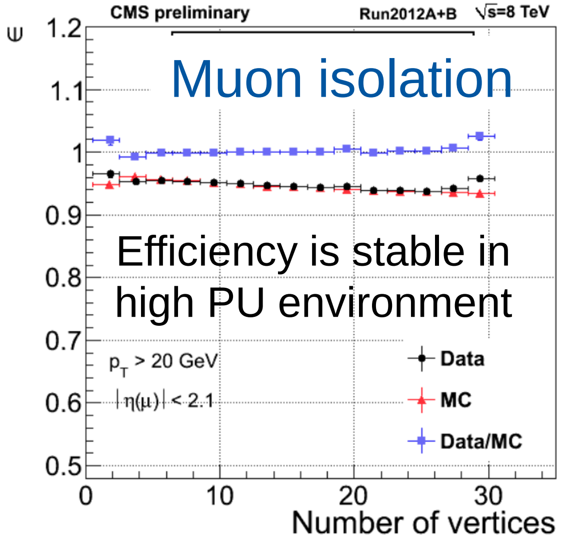
Lumi @ 50ns:

6E33 1E34 1.4E34

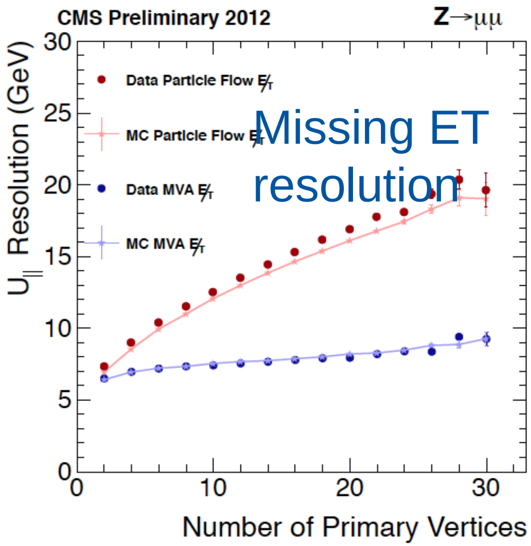
Some hadronic trigger rates grow exponentially with PU

Event reconstruction challenges: some examples

- Reconstruction of hard collisions in high pileup environment in CMS exploits:
  - detectors with very high granularity (tracker)
  - 3.8 T magnetic field
- Event reconstruction remains robust at PU of 20-30 events
  - precise jet energy measurement
  - robust missing energy measurement
  - efficient identification of isolated leptons
- But impact on final physics results (e.g. Higgs) for data samples with average PU larger than 20.
  - H→4l looses 20% efficiency at 50 PU
  - Diphoton mass resolution degrades by 20% at 30 PU


Muon isolation

Efficiency is stable in high PU environment


Missing ET resolution

Jets: Pileup Subtraction

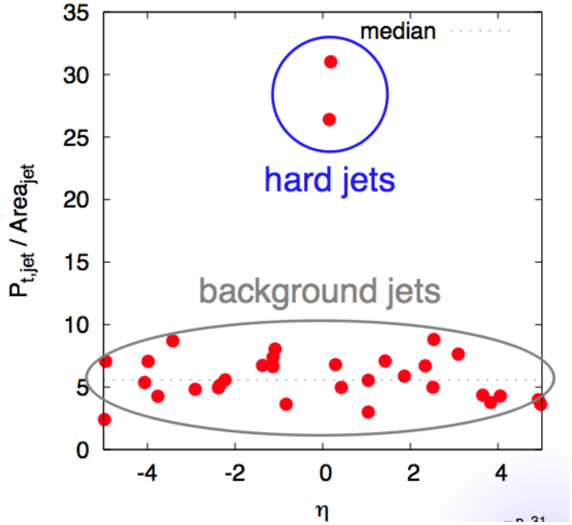
Basic idea: [M.Cacciari, G.Salam, 08]

$$p_{t,\text{subtracted}} = p_{t,\text{jet}} - \rho_{\text{pileup}} \times \text{Area}_{\text{jet}}$$

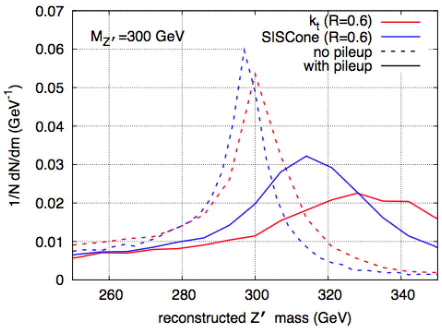
- Pileup density per unit area: ρ_{pileup}

  e.g. estimated from the median

  of $p_{t,\text{jet}}/\text{Area}_{\text{jet}}$



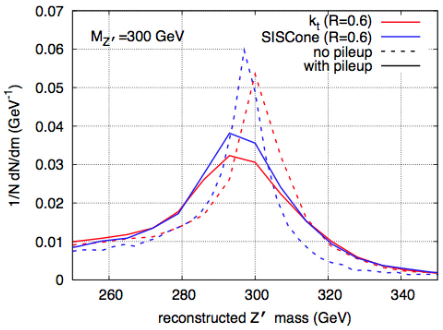
Pileup unsubtracted



width = 29.5 GeV

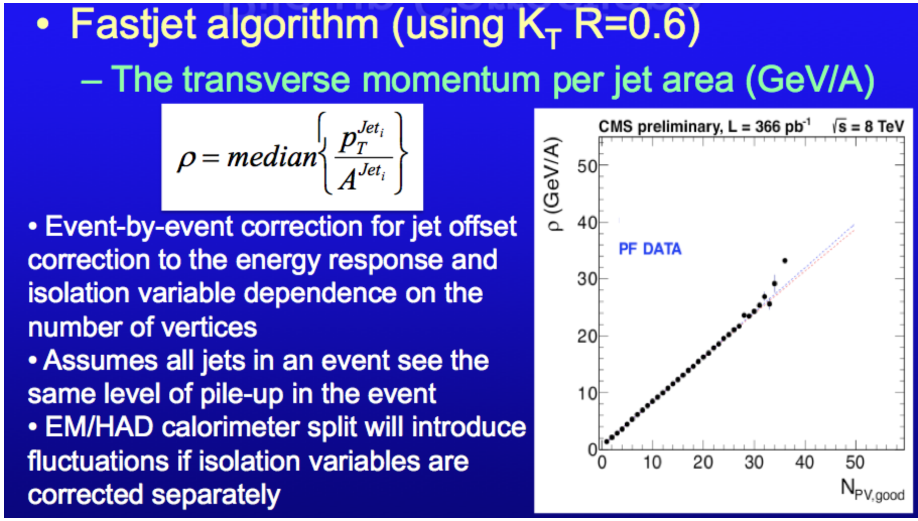
width = 21.0 GeV

pileup subtracted



width = 21.0 GeV

width = 17.7 GeV



- Fastjet algorithm (using K_T R=0.6)
  - The transverse momentum per jet area (GeV/A)

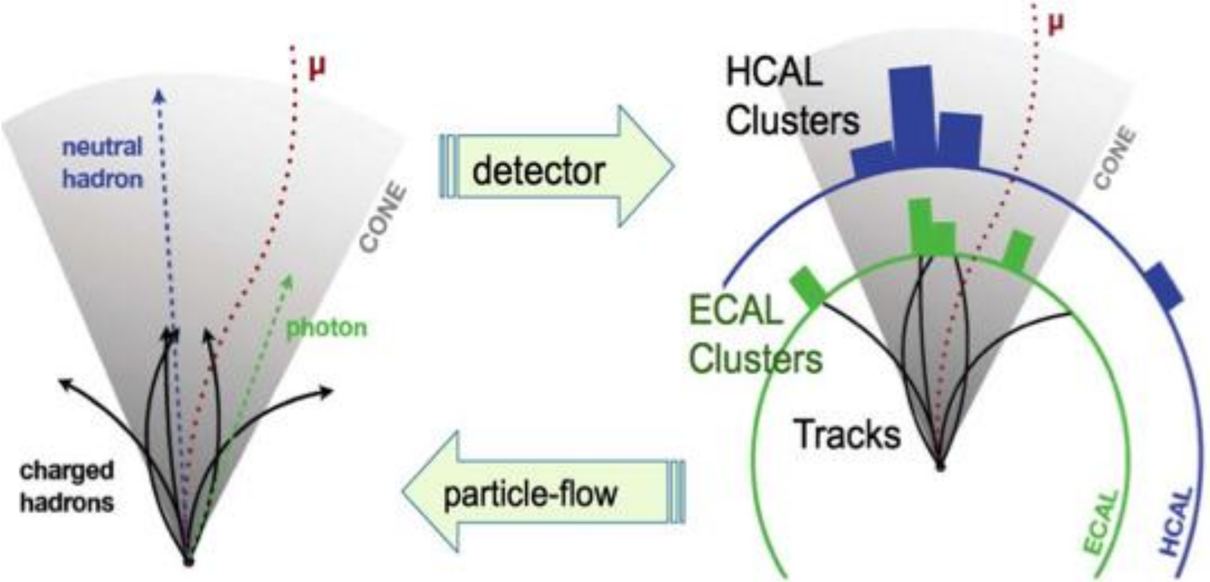
$$\rho = median\left\{\frac{p_T^{Jet_i}}{A^{Jet_i}}\right\}$$

- Event-by-event correction for jet offset correction to the energy response and isolation variable dependence on the number of vertices
- Assumes all jets in an event see the same level of pile-up in the event
- EM/HAD calorimeter split will introduce fluctuations if isolation variables are corrected separately

Jets: Particle Flow

Leverage tracking system and high granularity crystal calorimeter to identify charged hadrons and remove the corresponding HCAL measurements, using the HCAL for neutral hadrons only.
HCAL resolution only affects neutral component

(20%)



Make more use of depth **segmentation** and timing info – B field spreads showers in φ. Improve

separation in η using rear calorimeter depths where hit occupancy and overlaps are lower,
Pile-up contribution: Negligible for charged hadrons **from primary vertex**
Neutral contribution corrected using the average energy density (ρ) from the pile-up and underlying

event

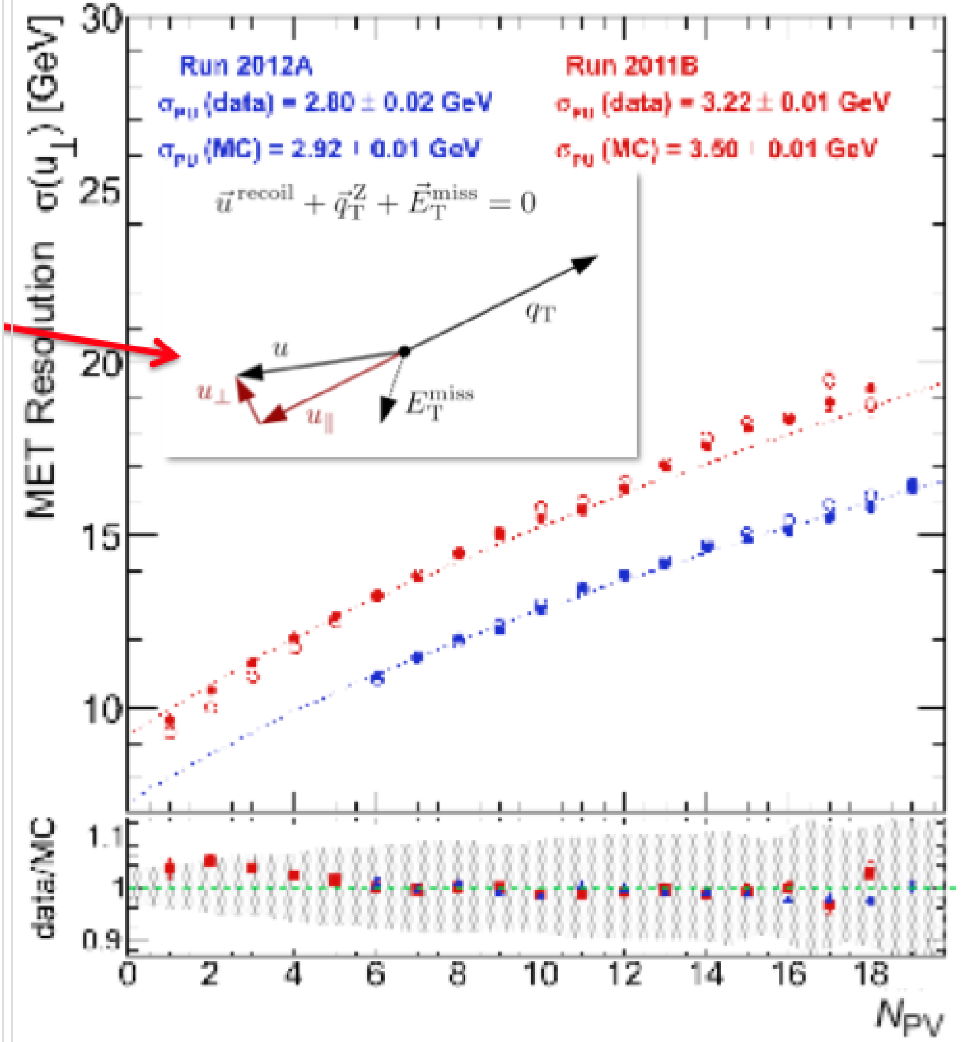
Missing Et

- MET Resolution From Z

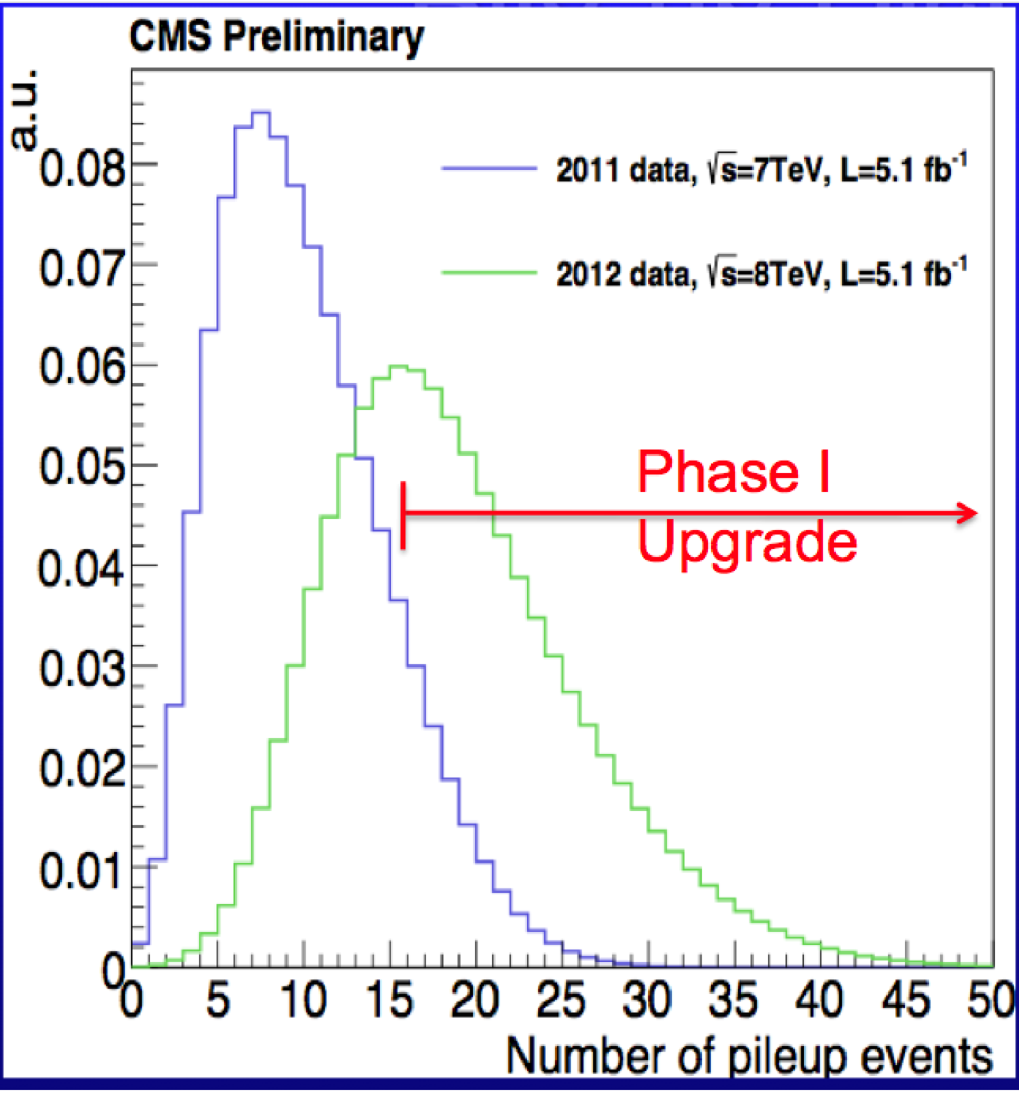
- Use muon transverse momentum

$$\sigma_{MET}(\mu_\perp) = \sqrt{c^2 + \frac{N_{PV}}{0.7} \cdot \sigma_{PU}}$$

- Clear pile-up dependence reduced in 2012 by reducing the number of HCAL time samples

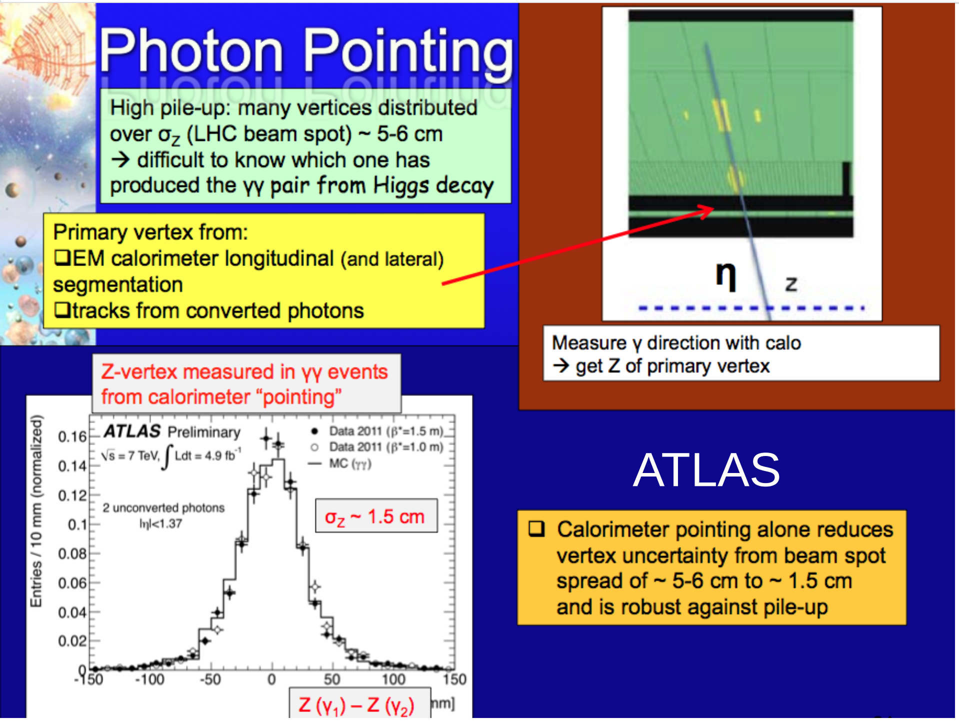


Simulation and Pileup



- Pile-up distributions
  - Distributions are broad and change as the proton intensity drops in the "fill"
- Pile-up reweighting
  - A given set of integrated luminosity also has a corresponding distribution of instantaneous luminosities that needs to be matched by the simulation
  - Abort gap effects also need simulation

Mass resolution H->γγ



Photon Pointing

High pile-up: many vertices distributed over σ_Z (LHC beam spot) ~ 5-6 cm
→ difficult to know which one has produced the γγ pair from Higgs decay

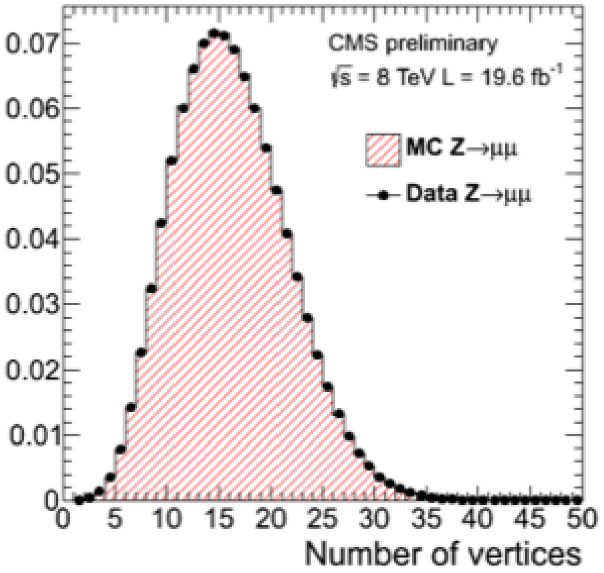
Primary vertex from:
- ☐ EM calorimeter longitudinal (and lateral) segmentation
- ☐ tracks from converted photons

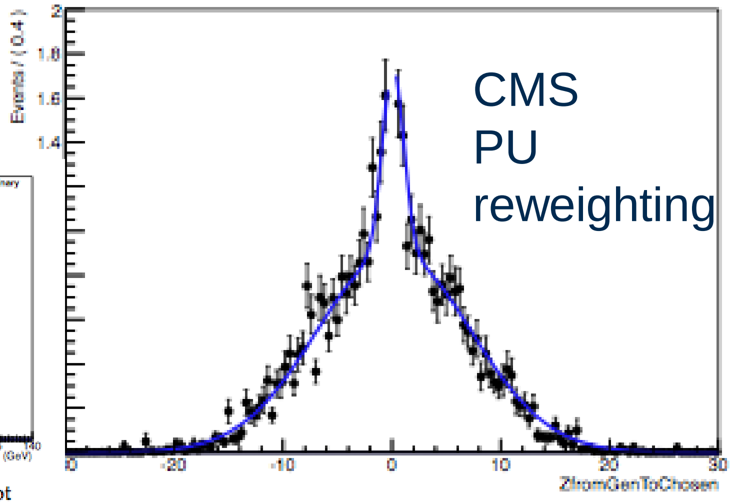
Measure γ direction with calo
→ get Z of primary vertex

Z-vertex measured in γγ events from calorimeter "pointing"

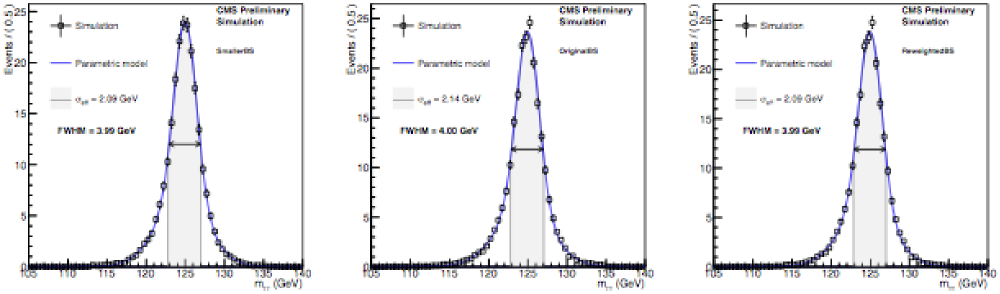
ATLAS

- ☐ Calorimeter pointing alone reduces vertex uncertainty from beam spot spread of ~ 5-6 cm to ~ 1.5 cm and is robust against pile-up



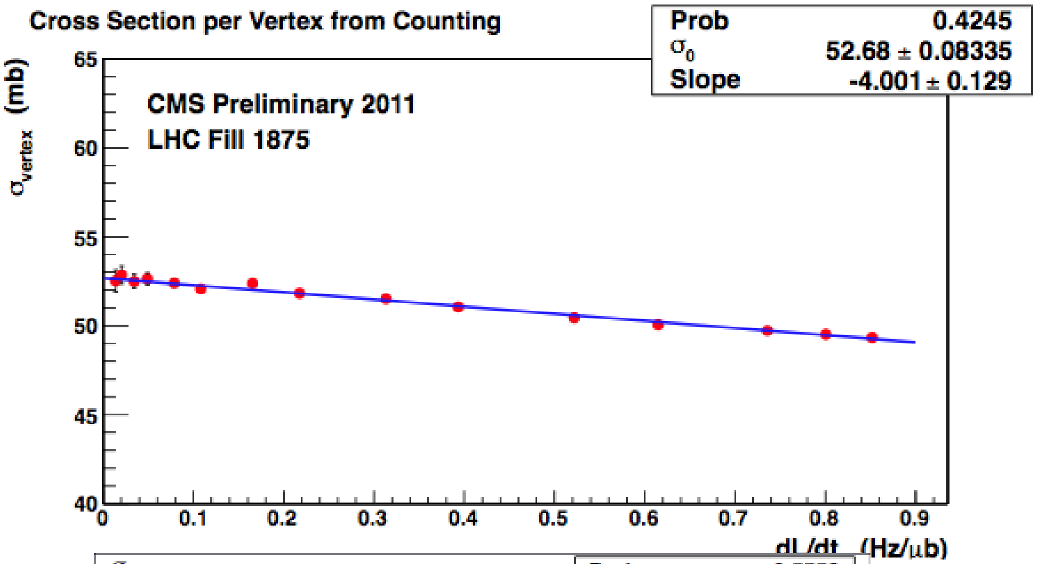


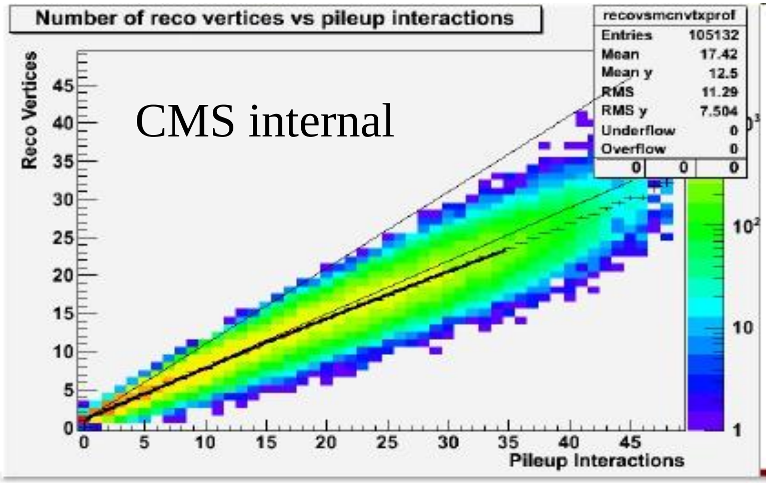
CMS
PU
reweighting

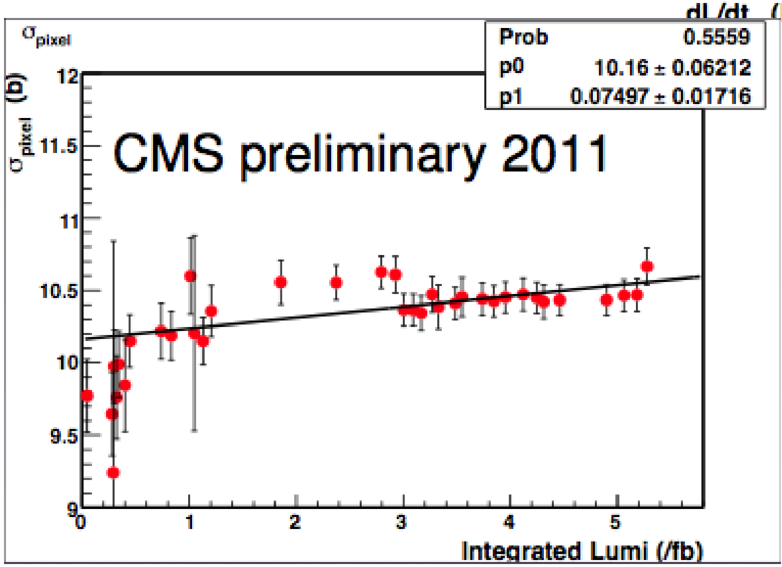


(a) σ_{BS}=4.8cm (b) σ_{BS}=6.2cm (c) Reweighted Beamspot

Luminosity Measurement







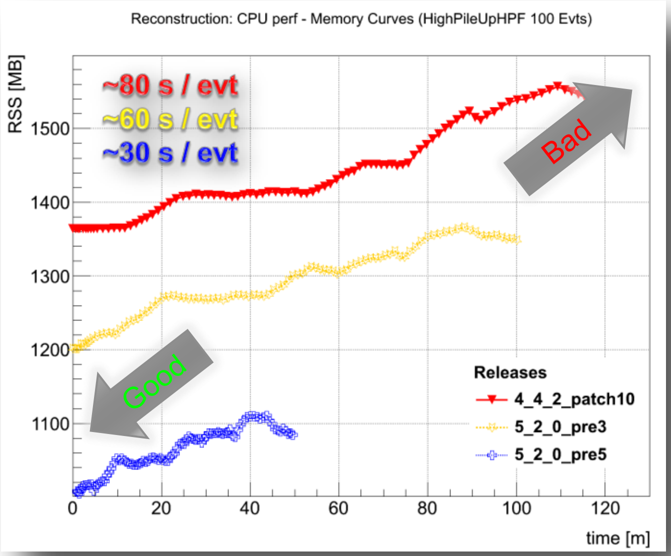
Non-linearities of luminometer **vs pileup**
Systematic drifts due to radiation damage

Computing

From 2011 to 2012, better code allowed to gain:

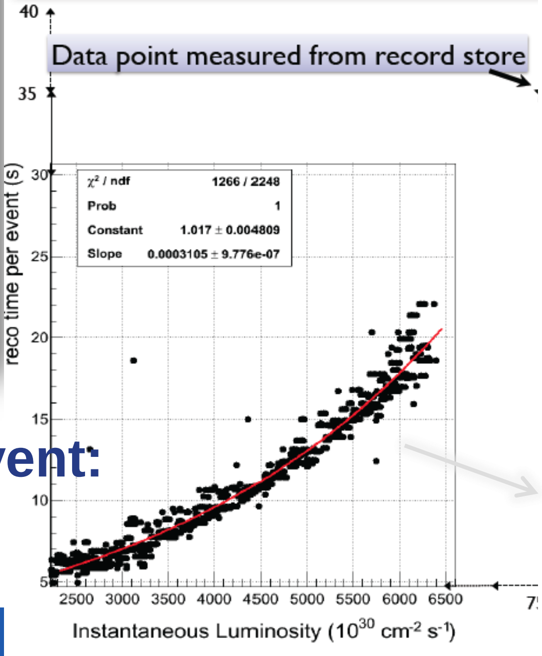
- factor 2.5 reduction in CPU time
- 50% in memory footprint

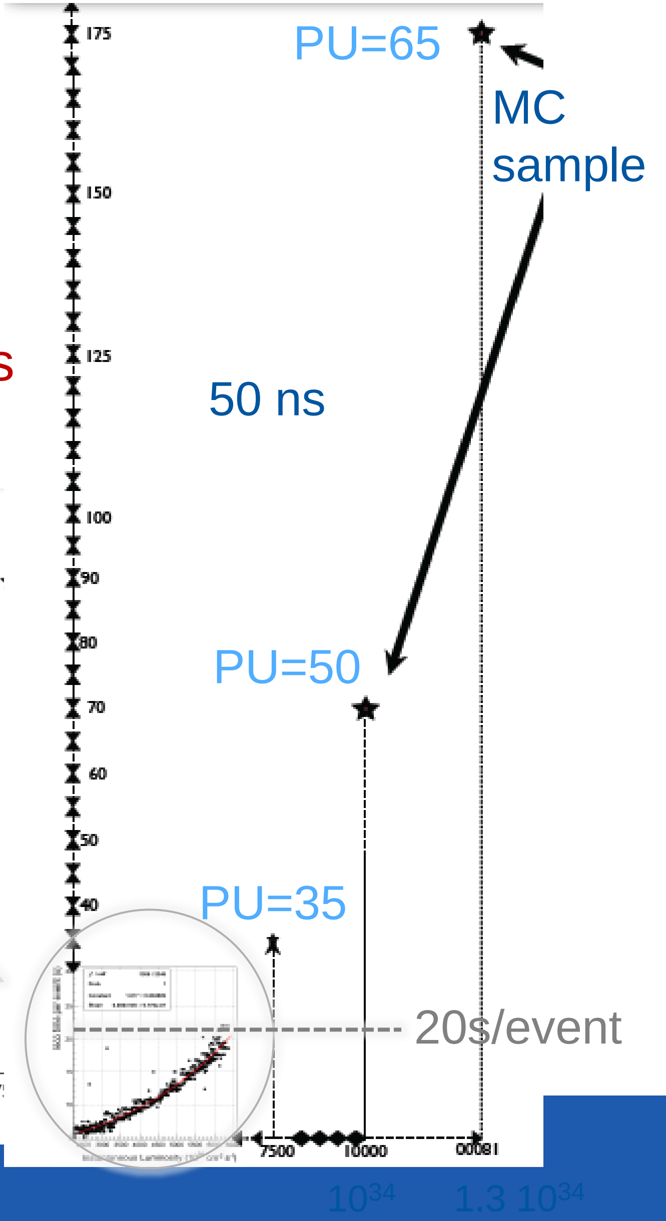
Further gains are not expected without loss for physics



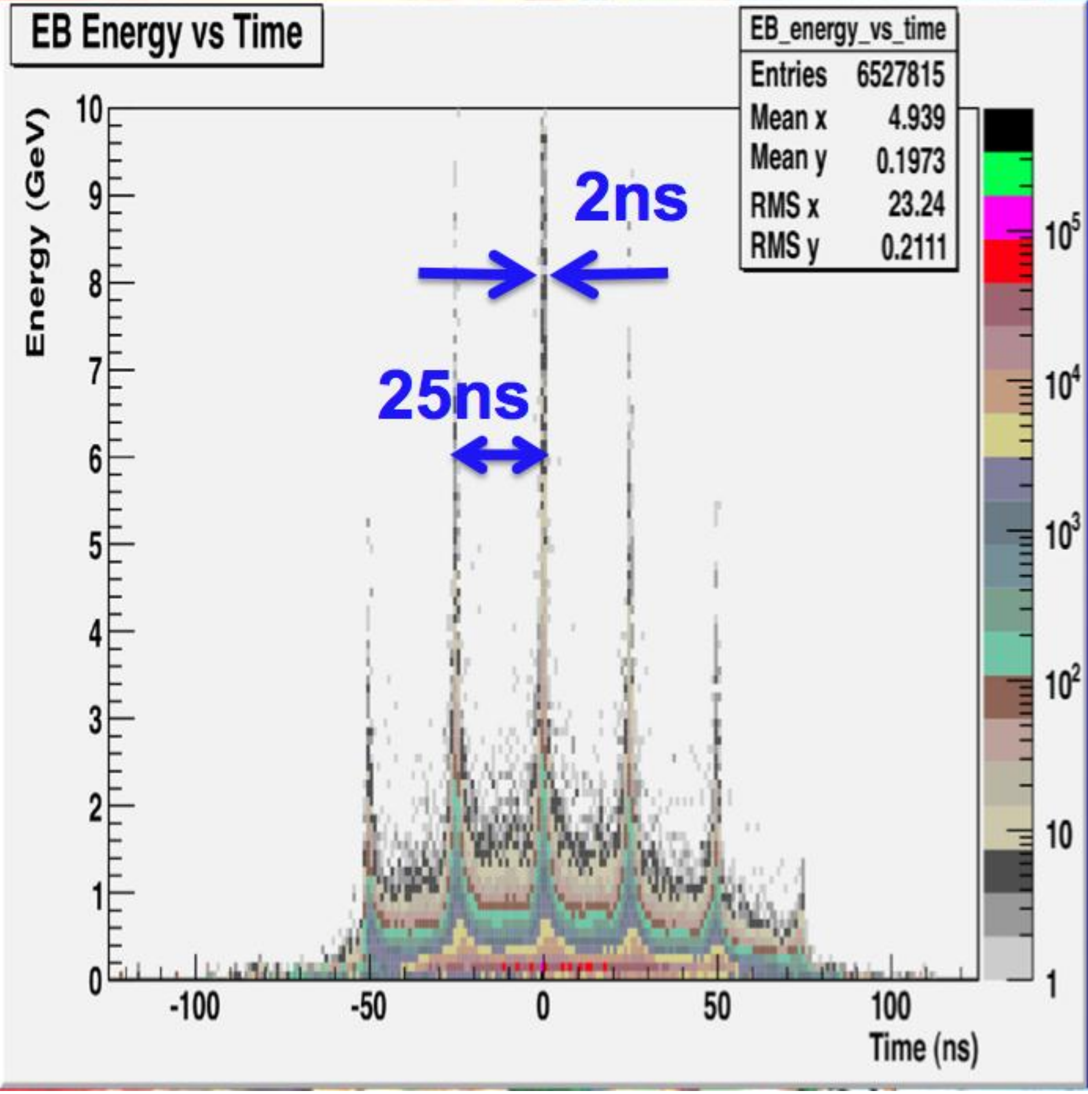
In 2012,
average at Tier0 was
<20 s/event

Reconstruction time/event:





Last but not least: Out of Time Pileup



Some subdetectors, typically those than make precision energy measurements, have signal pulses that last ~100-150ns (or 600ns).

High pile-up will swamp the low energy pulses making it difficult to determine the correct bunch crossing assignment from the pulse shape alone.

Phase I upgrades

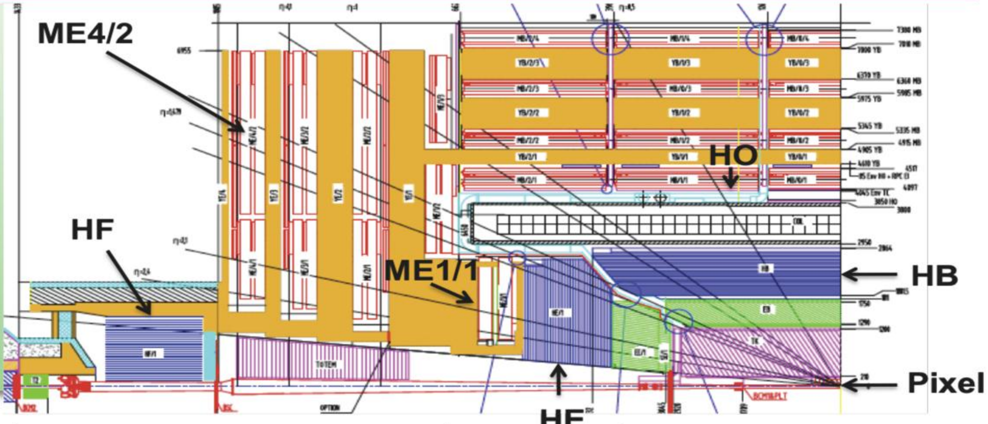
Technical
Coordination

LHCC refs Dec 2012 AB

CMS Consolidation & upgrade

Phase 1: LS1 tasks underpin 2015 -->LS3

- Complete muon coverage (4'th endcap layer)
- Improve muon operation (1'st endcap layer), and barrel drift tube electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD→SiPM)
- DAQ1 → DAQ 2
- Overhaul common systems for long-term



LS1(22mo) LS2 (14mo) LS3 (24-36mo)

Phase 1: up to end LS2 (LOI app. Sep 12)

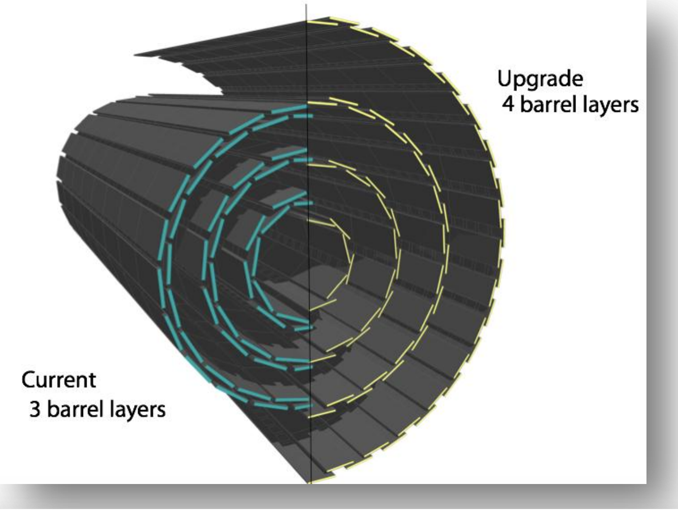
- TDR's approved:4 layer Pixel tracker
  (install in YEETS 2016-17),
  HCAL electronics/granularity
- TDR in 2013: L1-Trigger
- Preparatory work during LS1
  - New beam pipe (for 4 layer pixel tracker)
  - Test slices: *Pixel(CO2 cooling), HCAL, L1-trig*
  - Install ECAL optical splitters
    - *L1-trigger upgrade in parallel with run.*

Phase 2 Upgrades (Tech.Proposal in 2014)

- Tracker Replacement, Track Trigger
- Endcap/Forward region improvements :
  Calorimetry, Muon system and tracking
- Further Trigger upgrade
- Further DAQ upgrade
- Many obsolescence/lifetime replacements
- Shielding/beampipe for higher aperture

CMS Pixel and HCAL Upgrades

- Upgraded Pixel Detector
  - Less material, better radial distribution
    - two-phase CO_2 cooling
    - Powering using DC-DC converters • New cabling
  - *New readout chip*
  - *extra barrel/disk layer recovers tracking efficiency*
    - *reduce fakes*



- Upgraded HCAL
  - Improve background rejection
  - Improve MET resolution
  - Improve Particle Flow
    - *via improved S/N photodetectors*
  - Identify depth of shower max
    - *via longitudinal segmentation, timing*

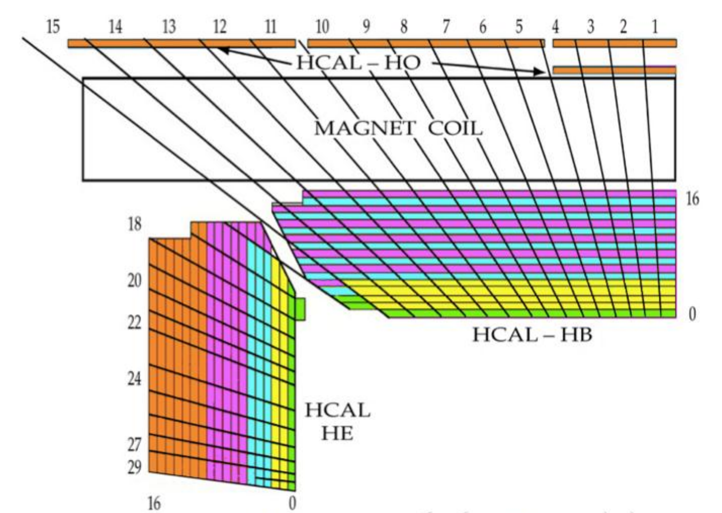
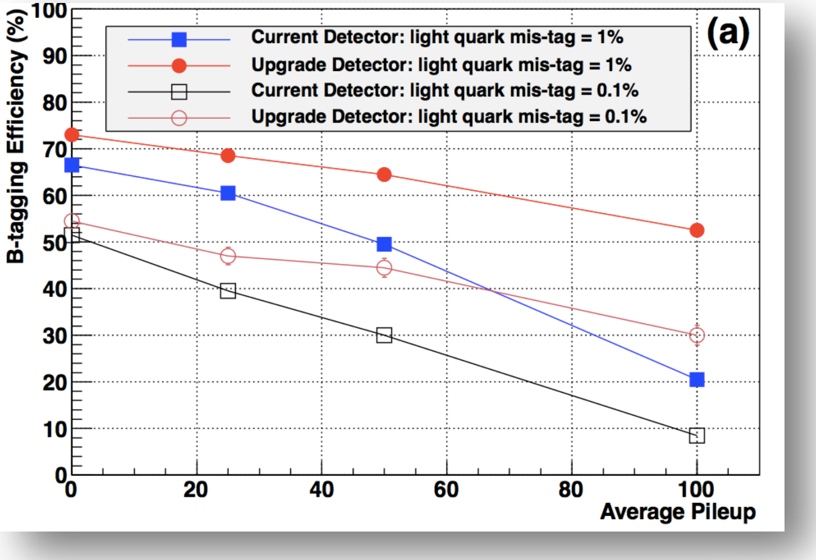
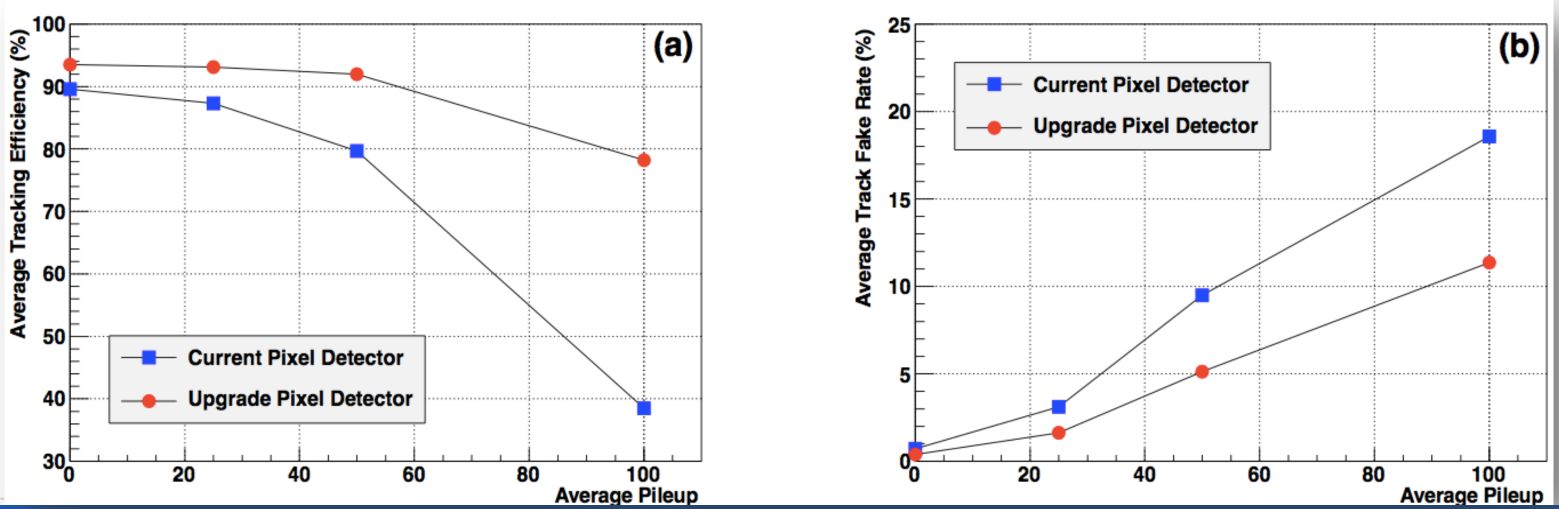


Figure 3.1: Current proposed depth segmentation structure for the HB and HE calorimeters, made possible by the use of SiPM photodetectors.

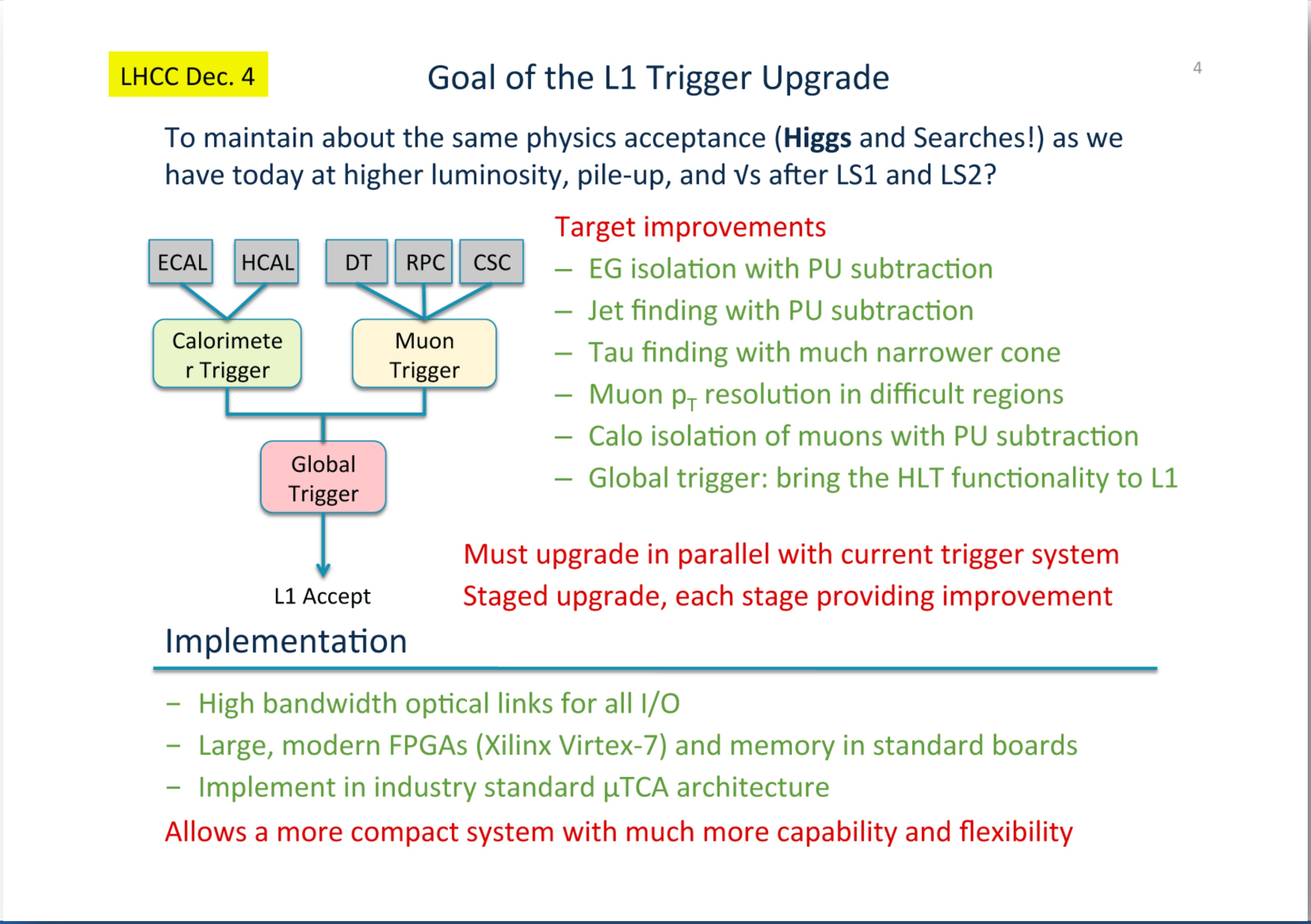
Improved Tracking & Btagging

- CMS Full simulation comparisons vs PU
  - B-tag performance (Top-Right)
  - Tracking performance (Bottom)
    - Efficiency (Left) and Fake rate (Right)
- Very powerful even without optimization!
  - B tagging, tracking efficiency at 65-70 PU equal to current detector at 25 PU
  - Fakes not quite as big improvement





L1 Trigger Upgrade



LHCC Dec. 4

Goal of the L1 Trigger Upgrade

To maintain about the same physics acceptance (**Higgs** and Searches!) as we have today at higher luminosity, pile-up, and √s after LS1 and LS2?

ECAL
HCAL
DT
RPC
CSC
Calorimeter Trigger
Muon Trigger
Global Trigger
L1 Accept

Target improvements

- EG isolation with PU subtraction
- Jet finding with PU subtraction
- Tau finding with much narrower cone
- Muon p_T resolution in difficult regions
- Calo isolation of muons with PU subtraction
- Global trigger: bring the HLT functionality to L1

Must upgrade in parallel with current trigger system

Staged upgrade, each stage providing improvement

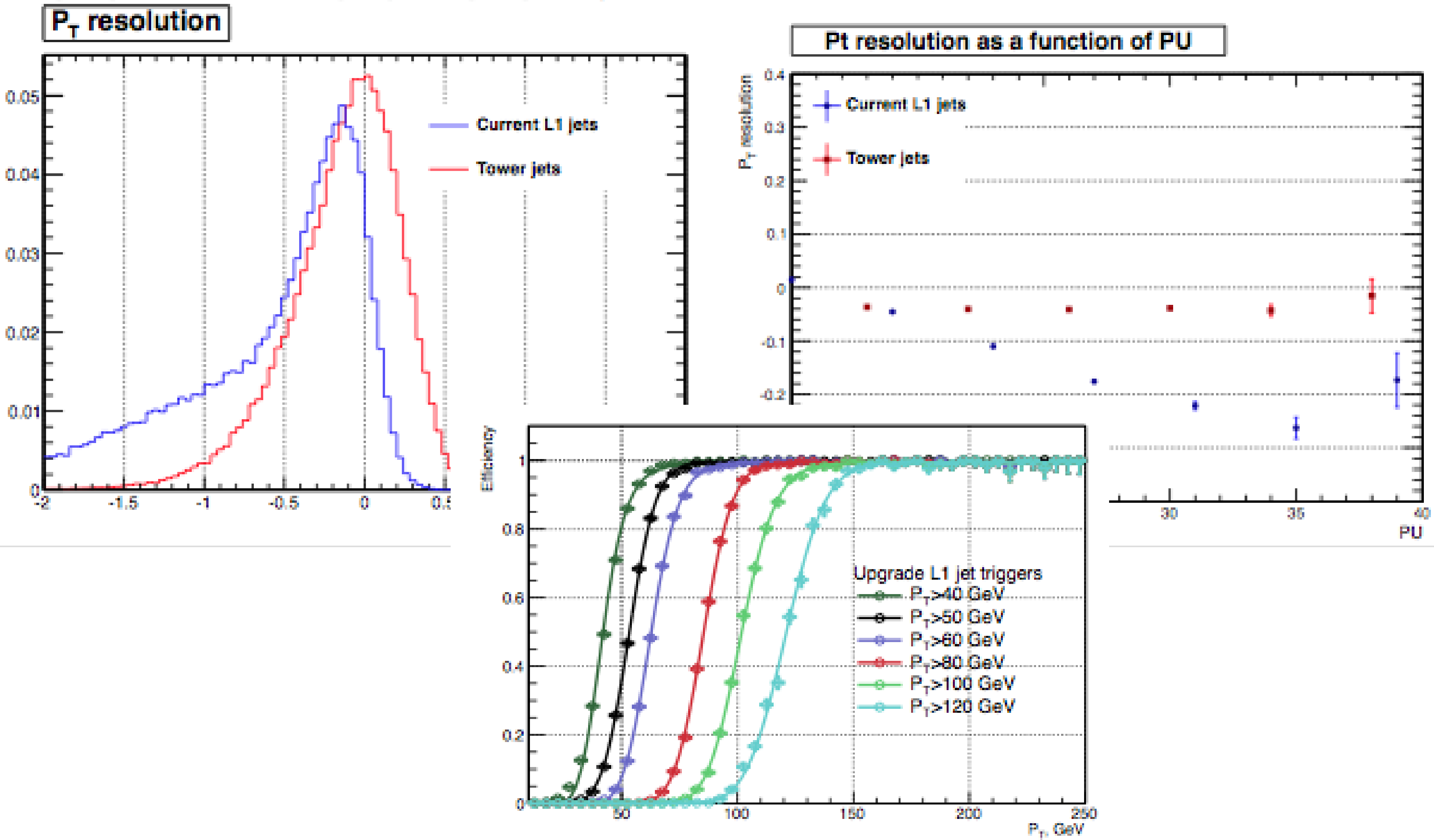
Implementation

- High bandwidth optical links for all I/O
- Large, modern FPGAs (Xilinx Virtex-7) and memory in standard boards
- Implement in industry standard μTCA architecture

Allows a more compact system with much more capability and flexibility

https://indico.cern.ch/getFile.py/access?contribId=9&resId=2&materialId=slides&confId=218619

L1 Trigger Upgrade



HL-LHC

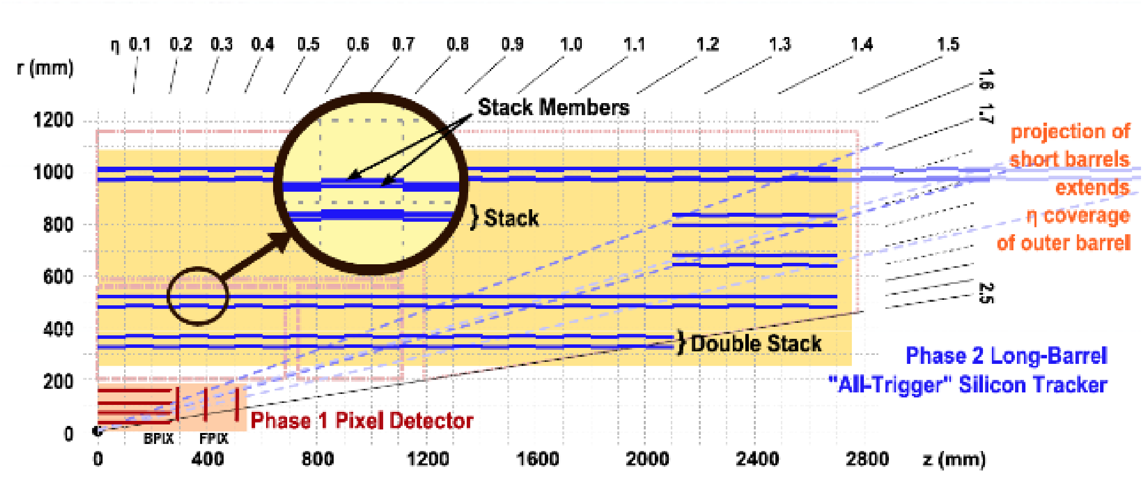
CMS Phase II guidelines (e.g. tracker)

- Radiation hardness
  - Ultimate integrated luminosity considered~3000fb-1
  - To be compared with original ~ 500 fb-1
- Resolve **up to ~200 collisions per bunch crossing, with few % occupancy**
  - Higher granularity
- Improved tracking performance
  - Improve performance @ low pT,, reduce rates of particle interactions
    - Reduce material in the tracking volume
  - Improve performance @ high pT • Reduce average pitch
- Tracker input to Level-1 trigger
  - μ,e and jet rates would exceed 100kHz at high luminosity even considering “phase-1” trigger upgrades
  - Readout @ 1MHz also under consideration for phase II
  - Add tracking information at Level-1
  - Move part of HLT reconstruction into Level-1!
- Objective:
  - Reconstruct “all” tracks above 2 ÷ 2.5 GeV
  - Identify the origin along the beam axis with ~ 1 mm precision

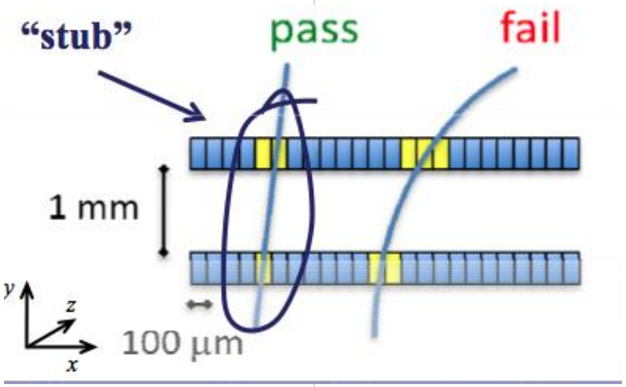
Main R&D paths

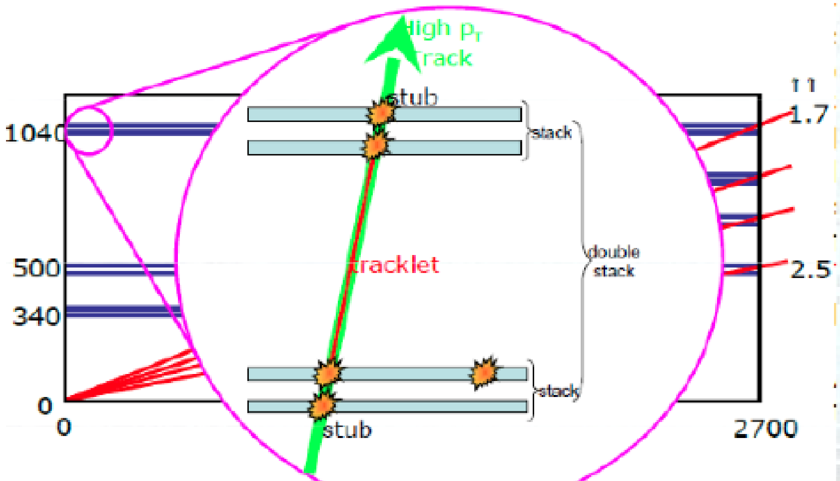
- Pixels: Aiming at a significantly smaller pixel size.
  - Possibly as small as 30×100 µm2, 65 nm technology for the ASIC
  - Thin planar sensors with small pixels could be a robust baseline
  - 3D silicon very appealing option with potentially excellent performance
- Tracker: Aiming at reducing material budget while increasing efficiency for high pileup
  - 2S modules: sensors wirebond to the hybrid on the two sides – 2048 channels on each hybrid
  - Chips bump-bonded onto the hybrid
  - PS (Pixel-Strip) modules

Phase II tracker

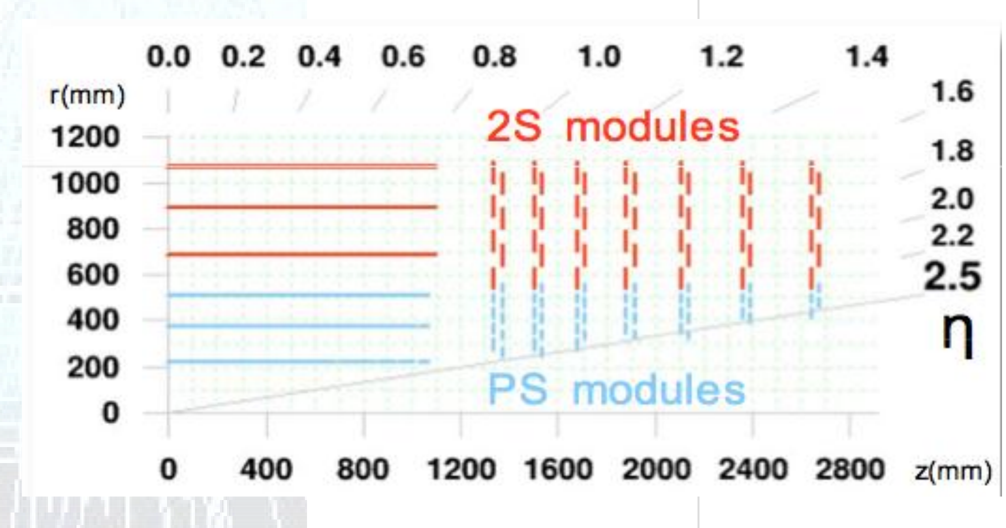


6 long layers = 3 Super layers





Pairs of stubs are combined to form "tracklets"



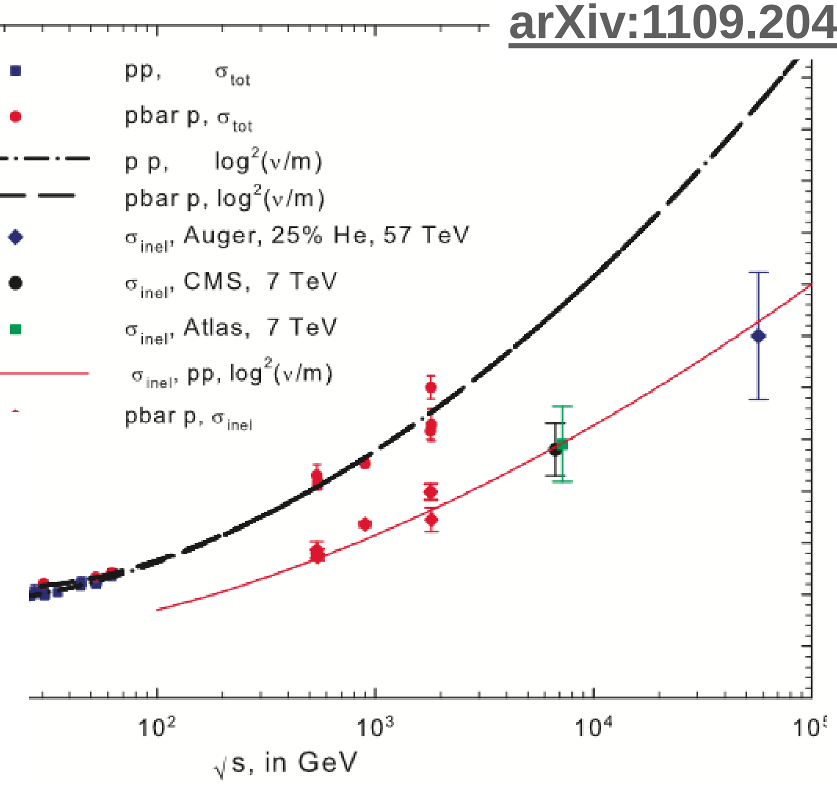
XLHC and other stories

What to expect at 100 TeV

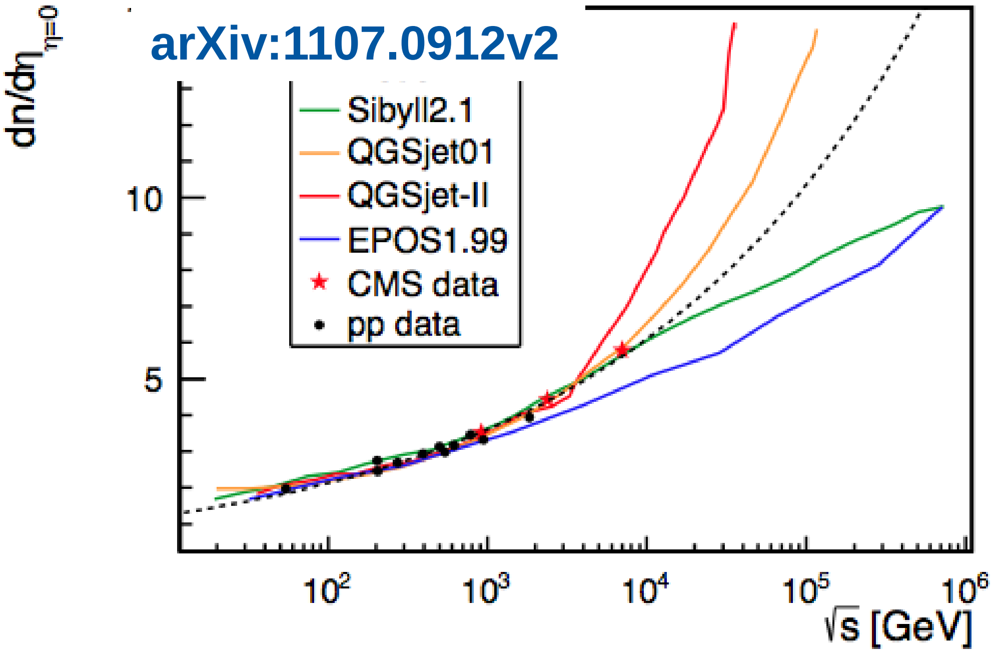
$\mu = \sigma_{inel} L_{bb} / f_{rev}$

@33 TeV, 5E34 (27Km)
μ=270(135)@50(25)ns
@100 TeV,5E34 (80 Km)
μ=250(125)@50(25)ns

arXiv:1109.2041



arXiv:1107.0912v2



Detector occupancy up by factor 2-10
Wrt eq. PU at 8 TeV
Occupancy in a 0.1x0.1 det cell (Δη×Δφ)

LHC	HL-LHC	HE-LHC	X-LHC
0.1	1.	2.5	2.

Synergies with a possible TLEP project

- Experimental Infrastructure (civil engineering, Interaction point design, size of the caverns) are tailored for the ultimate pp collider (100 TeV, 5E35)
- Modular detector design allows to evolve them from TLEP-H to XLHC
  - By adding or replacing, or simply turning on features
  - Paying attention to not introduce brick walls
- "Options" (TeraZ, GigaWW) are a clear way to foster the above (e.g. TeraZ 2600 bunches, lumi ~1E36!!!)
- Some design choices will lend themselves better than others to this modular, evolutionary scheme
  - Identify them and promote R&D in that direction

Some example

- Solenoid: at XLHC strong fields and large lever arm will be needed to preserve *some* momentum resolution for multi-TeV tracks
- Large bore diameter solenoids would allow bigger lever arm
  - Relatively compact silicon tracker (or TPC) sufficient for TLEP (and all its variations) – material budget fundamental
    - Cooling, infrastructure
    - Power distribution and readout -> low-power rad-hard VFE, on-chip photonics (lots of fun R&D)
    - Will pay off already at the TeraZ stage
  - Additional layers can be added (resolution ~ $1/L^2\sqrt{N}$) -> large silicon surfaces… R&D needed, cost, channel count ☹
  - Initial cost of calorimeters higher ☹ due to larger volume to cover
  - Can be partially compensated (in the active material) by reducing granularity as showers will be “opened up” further ☺
  - Absorber cost will definitely increase ☹

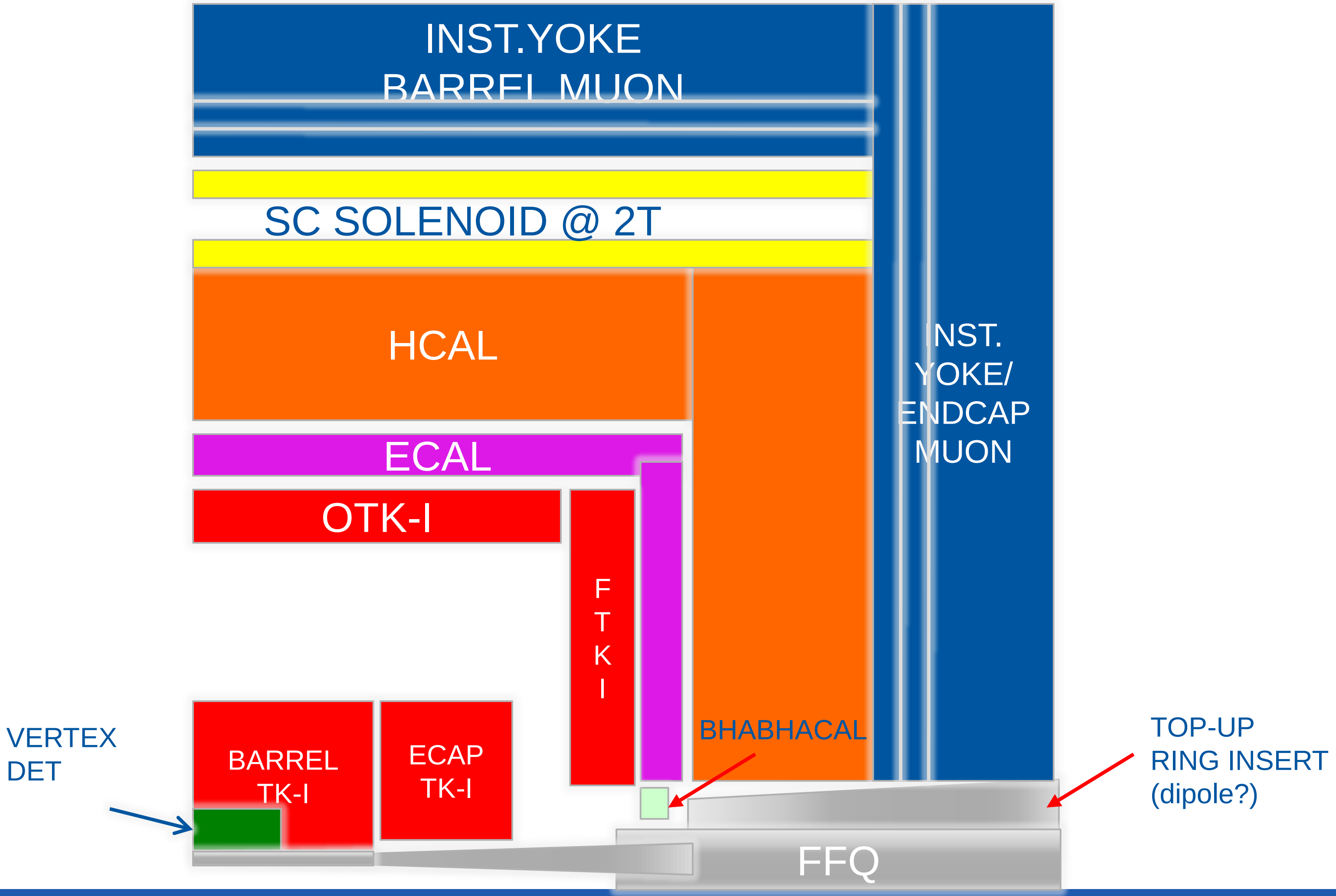
Some example

- TLEP-H poses most stringent requirements on i.p. resolution (e.g. c-tagging)
- Unlike LC or LHC, beam structure makes readout relatively “easy”
  - Already no longer the case for TeraZ (2600 bunches, 100ns)
  - modular architecture: design with pp detector in mind
- Calorimetry
  - ECAL: Moderate increase in transverse segmentation (wrt LHC detectors) sufficient to reach necessary resolutions for LEP-H
    - Can be profited of in pp
    - Longitudinal segmentation, what are the real needs ?
  - HCAL: Increasing the solenoid field and/or radius will help the Particle Flow algorithms by separating the charged/neutral components further
  - Longitudinal segmentation a must

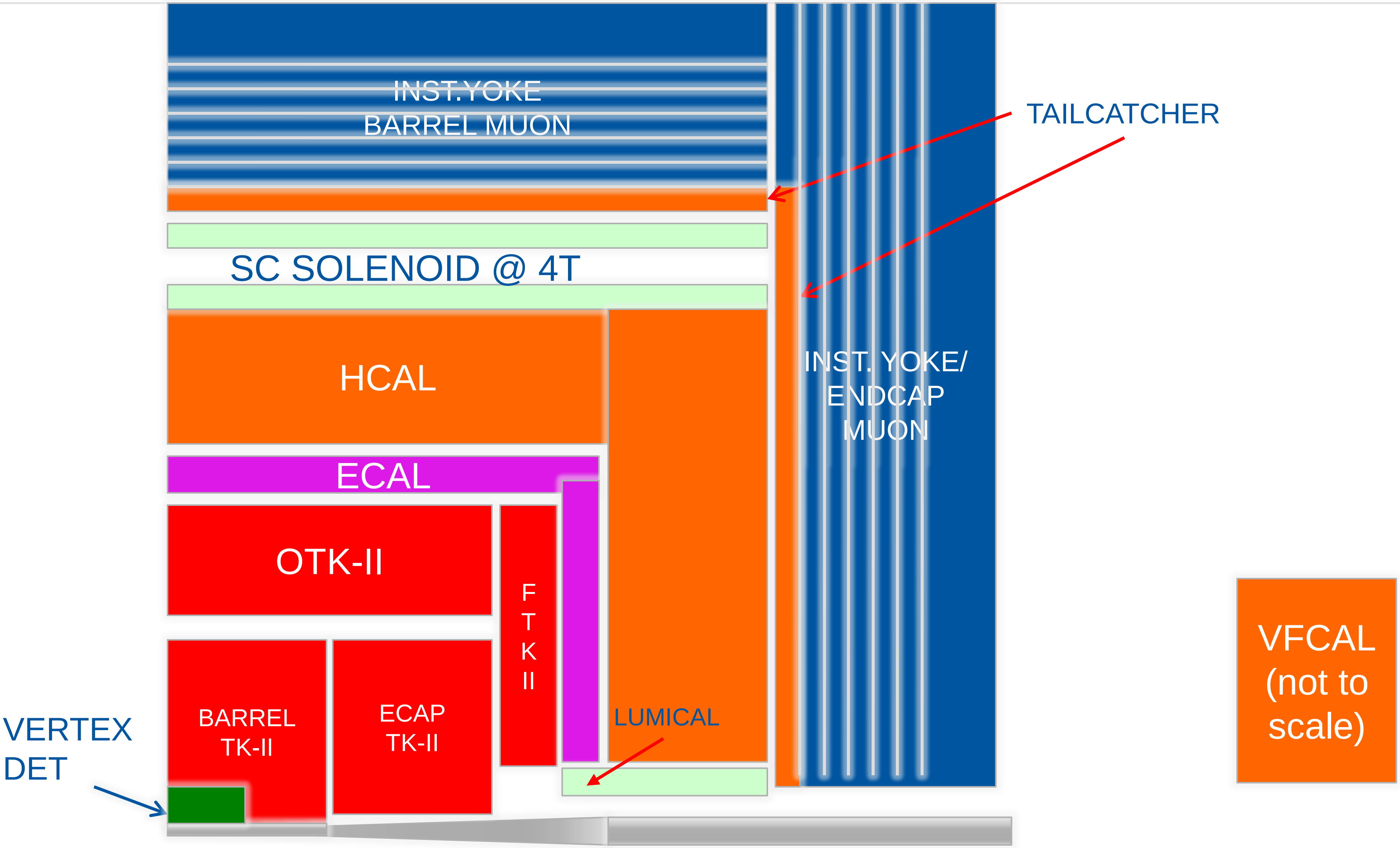
Conclusions

- R&D for LHC phase II probably mostly relevant for XLHC
- Remain open to other possibilities (e.g. “trigger-less” architecture)
- Possible synergies with TLEP to be studied in more detail
- Certain aspects of XLHC detectors require specific simulation
  - Identify a “blueprint detector” (bore diameter, tracking strategy, calorimetry)
  - Choose few physics benchmarks and simulate blueprint

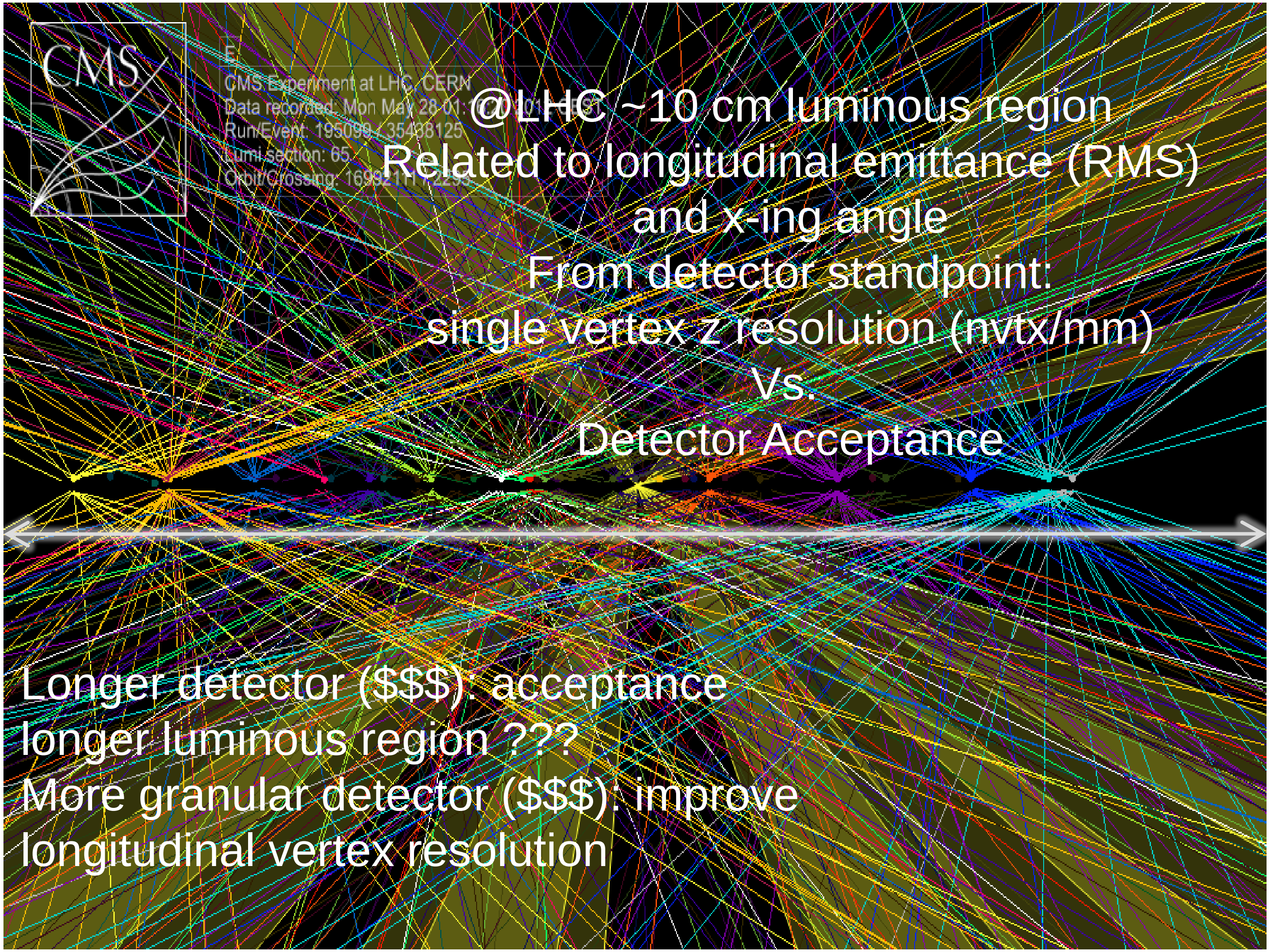
GMS-2T @TLEP


INST.YOKE
BARREL MUON
SC SOLENOID @ 2T
HCAL
INST.
YOKE/
ENDCAP
MUON
ECAL
OTK-I
F
T
K
I
BHABHACAL
TOP-UP
RING INSERT
(dipole?)
VERTEX
DET
BARREL
TK-I
ECAP
TK-I
FFQ

GMS-4T @XLHC


INST.YOKE
BARREL MUON
TAILCATCHER
SC SOLENOID @ 4T
HCAL
INST. YOKE/
ENDCAP
MUON
ECAL
OTK-II
F
T
K
II
VFCAL
(not to
scale)
VERTEX
DET
BARREL
TK-II
ECAP
TK-II
LUMICAL

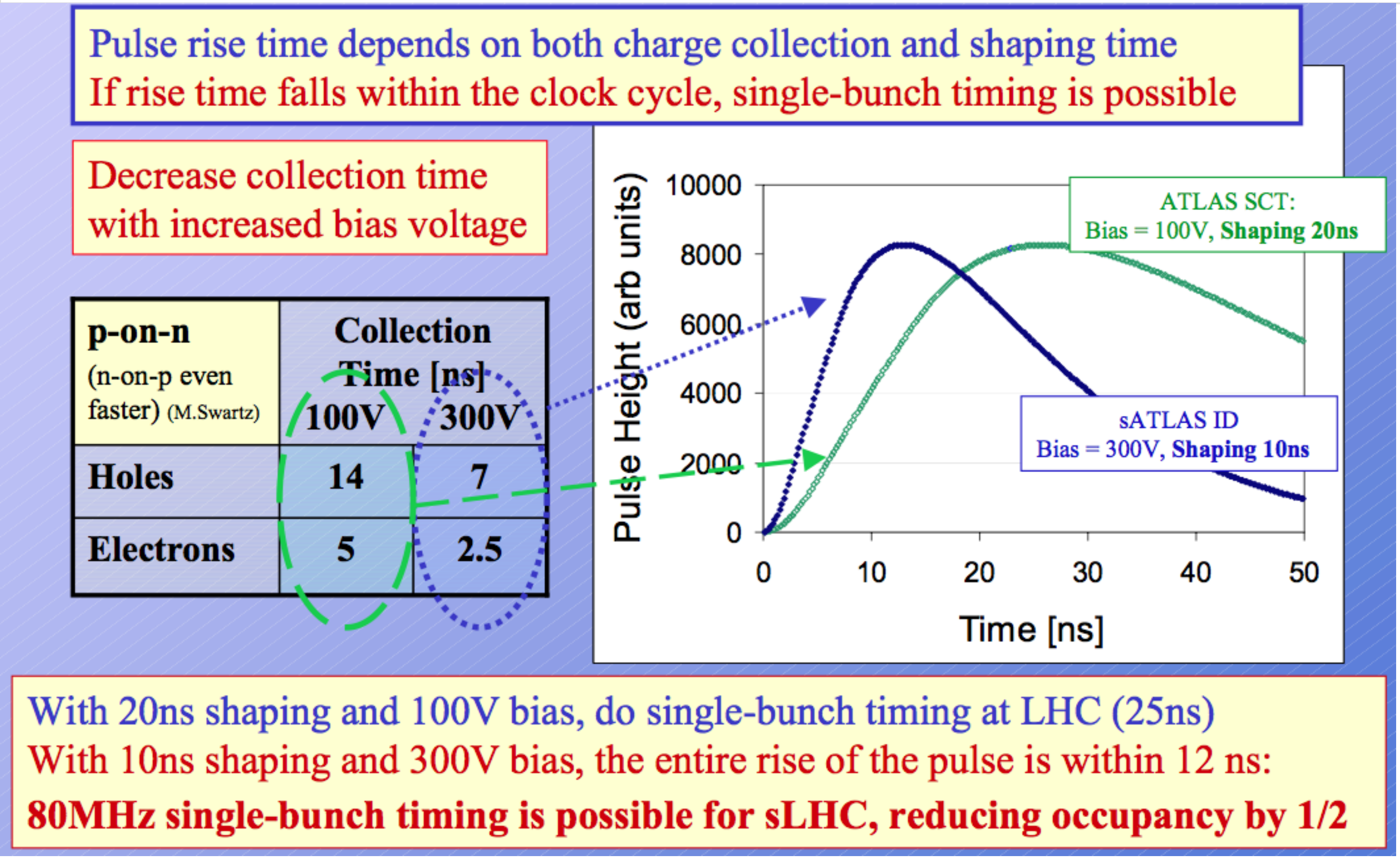
Backup



@LHC ~10 cm luminous region
Related to longitudinal emittance (RMS)
and x-ing angle
From detector standpoint:
single vertex z resolution (nvtx/mm)
Vs.
Detector Acceptance

Longer detector ($$$): acceptance
longer luminous region ???
More granular detector ($$$): improve
longitudinal vertex resolution

Timing



Pulse rise time depends on both charge collection and shaping time
If rise time falls within the clock cycle, single-bunch timing is possible

Decrease collection time
with increased bias voltage

p-on-n (n-on-p even faster) (M.Swartz)	**Collection Time [ns]**	
	100V	**300V**
Holes	**14**	**7**
Electrons	**5**	**2.5**

With 20ns shaping and 100V bias, do single-bunch timing at LHC (25ns)
With 10ns shaping and 300V bias, the entire rise of the pulse is within 12 ns:
80MHz single-bunch timing is possible for sLHC, reducing occupancy by 1/2

Reducing signal collections time
Time stamping

Pixel efficiency and readout