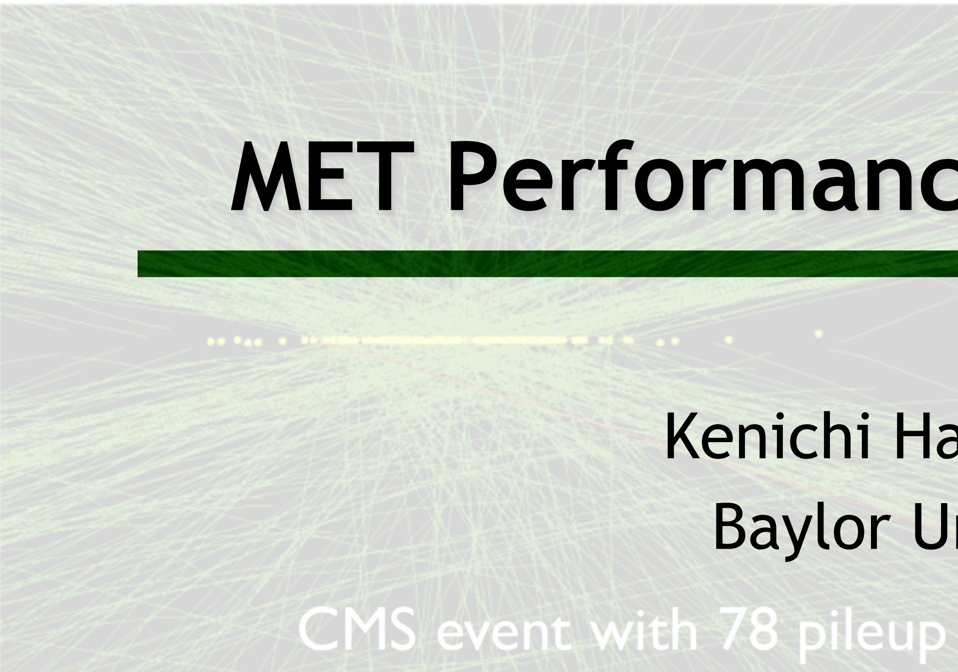
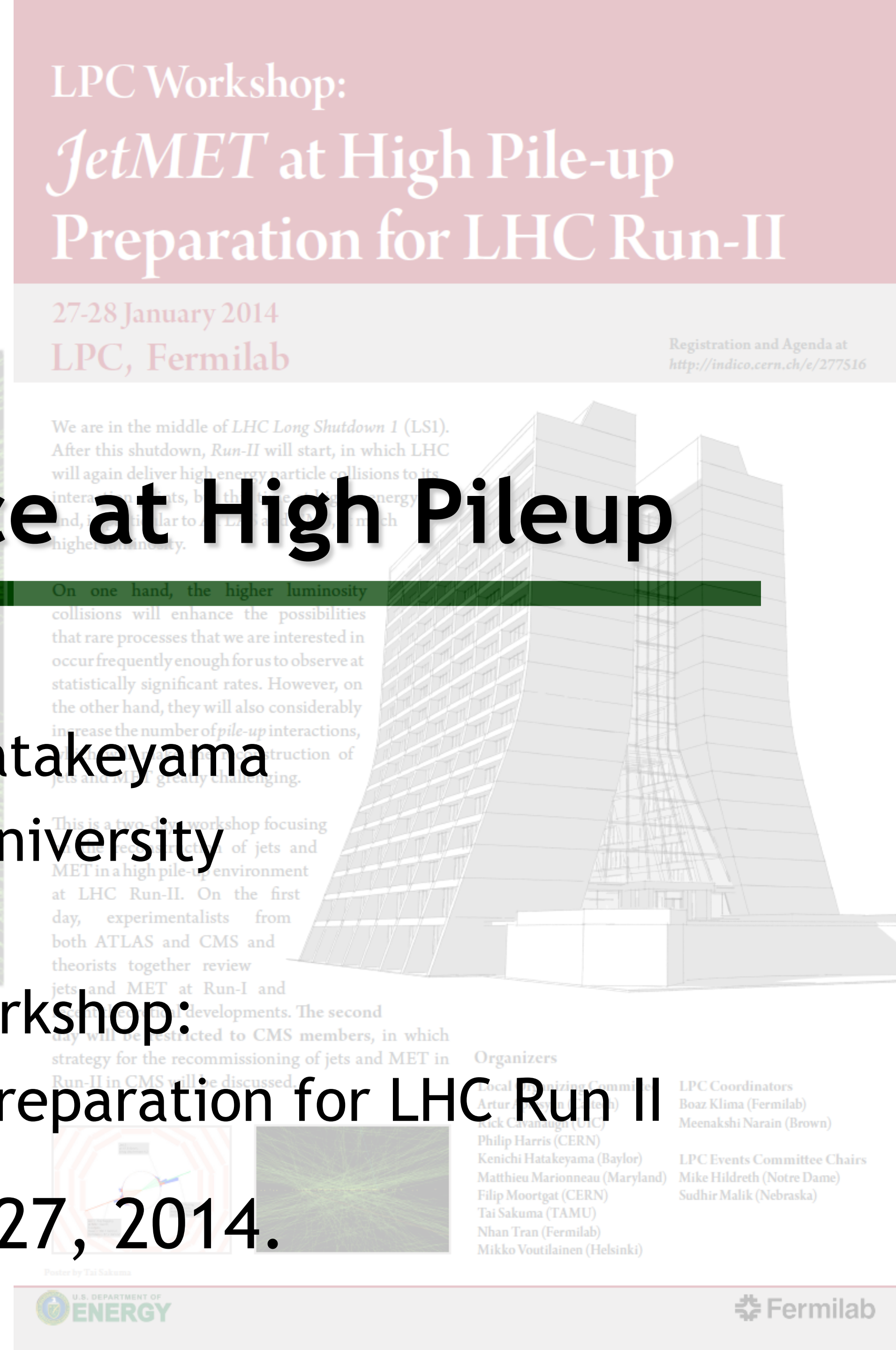




MET Performance at High Pileup

Kenichi Hatakeyama
Baylor University

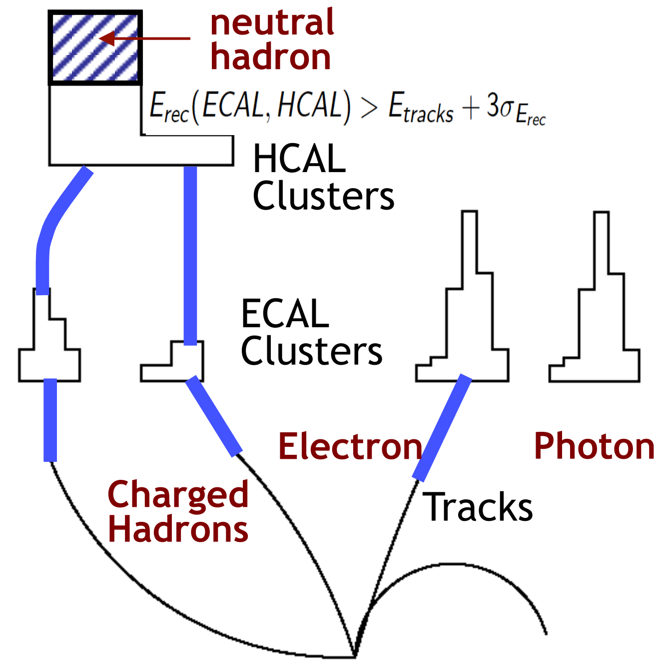
LPC Workshop:
JetMET at High Pileup, Preparation for LHC Run II

January 27, 2014.

MET Reconstruction

- CMS uses the missing ET reconstructed by the particle-flow (PF) algorithm for a majority of physics analyses
  - PF algorithm uses all CMS detector subsystems (i.e. calorimeter, tracker, muon detector) to reconstruct a full list of stable particles (PF objects)
  - → charged hadrons, photons, neutral hadrons,electrons, muons
  - PFMET is reconstructed from all PF objects

$$\vec{\not{E}}_T = -\sum_{i}^{\text{PF objects}} \vec{p}_{\mathrm{T},i}$$

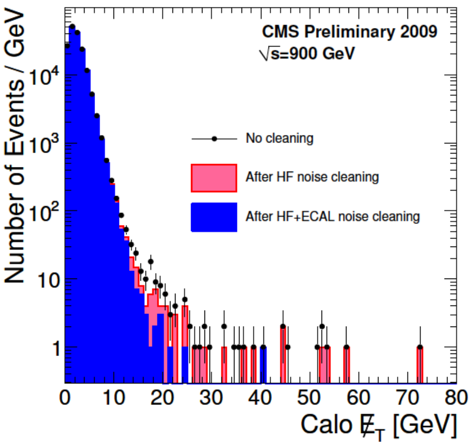


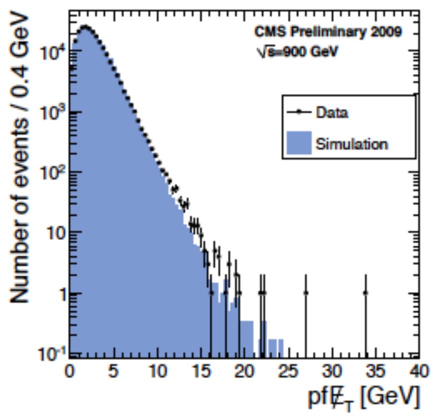
- The type-I correction for propagating jet energy corrections

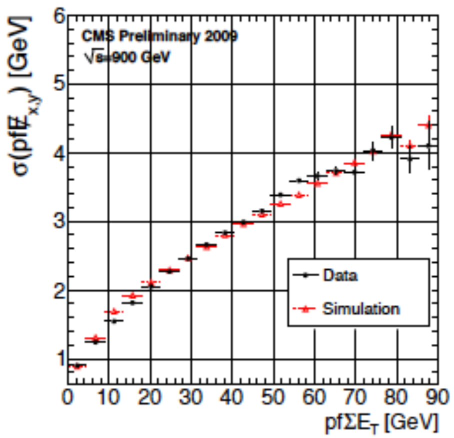
$$\vec{\not{E}}_T = -\sum_{i\in\text{jets}} \vec{p}_{\mathrm{T},i} - \sum_{i\notin\text{jets}} \vec{p}_{\mathrm{T},i} \Longrightarrow \vec{\not{E}}_T = -\sum_{i\in\text{jets}} \vec{p}_{\mathrm{T},i}^{\,\mathrm{JEC}} - \sum_{i\notin\text{jets}} \vec{p}_{\mathrm{T},i}$$

MET Commissioning in 2009-10

- 900 GeV, ~10 μb^{-1}, ~10^{26} cm^{-2} s^{-1}

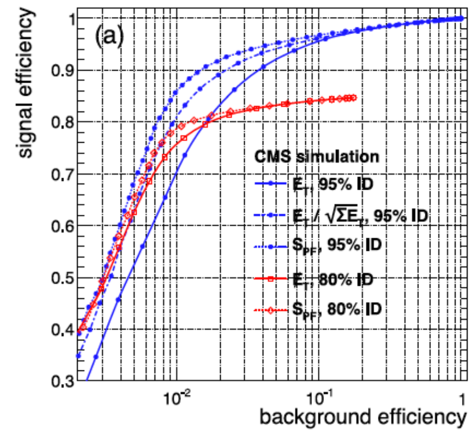




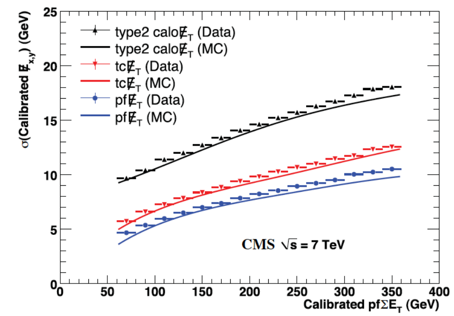


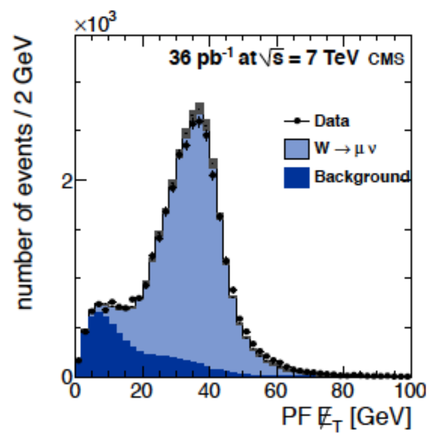
[CMS-PAS-JME-10-002]

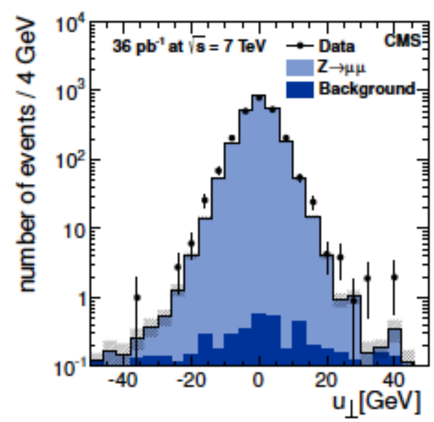
- 7 TeV, 36 pb-1, ~2x10^{29} cm^{-2} s^{-1}



[JINST 6, P09001] (2001)







MET Reconstruction in 8 TeV

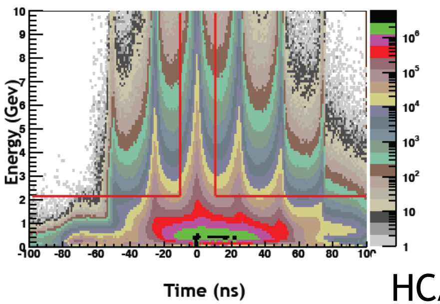
- PFMET algorithms were further extended:
  - The corrections for phi modulations (phi correction) and PU charged hadron subtraction (CHS) and balance for PU neutral hadrons (type-0 correction)

$$\not{E}^{\mathrm{corr}}_{\mathrm{x(y)}} = \not{E}_{x(y)} - \langle \not{E}_{x(y)} \rangle = \not{E}_{x(y)} - (c_{x(y)0} + c_{x(y)s} \cdot N_{\mathrm{vtx}})$$ Phi correction

$$\vec{\not{E}}^{\mathrm{corr}}_{\mathrm{T}} = \vec{\not{E}}_{\mathrm{T}} - \vec{\Delta}_{\mathrm{PU}} = \vec{\not{E}}_{\mathrm{T}} - \sum_{\text{PU-vertices}} f(v)\frac{\vec{v}}{v}, \quad \text{with} \quad \vec{v} = \sum_{\text{charged}} \vec{p}_{\mathrm{T}} \quad \text{for a given vertex}$$ Type-0 correction

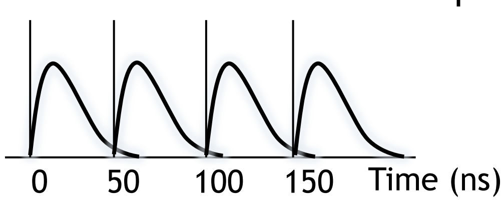
  - Also, improved ECAL and HCAL reconstruction from 7 TeV to 8 TeV
    - ECAL: Reject out-of-time energy deposits not only in the barrel but also in the endcap
    - HCAL: 100ns time window in 2011, 50ns time window in 2012

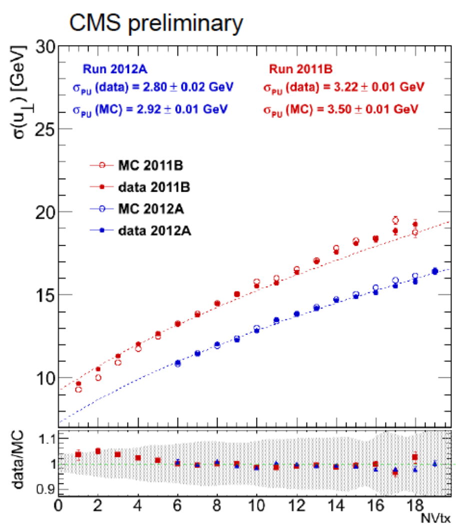
ECAL Endcap

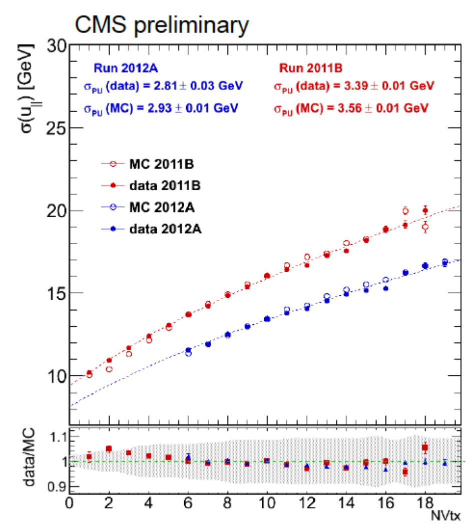


Special 25ns BX run

HCAL Barrel/Endcap







MET Reconstruction in 8 TeV

- More advanced MET reconstruction algorithms were put into place:
  - No-PU PFMET: divide PF objects into two classes
    - From hard scattering (HS) interactions → leptons/photons, particles in p_T>30 GeV jets passing PU jet ID, charged hadron associated to the HS vertex
    - Particles from pileup → charged hadron not associated to HS vertex, neutral particles not clustered, particles in jets failing the PU jet ID

C. Veelken's talk

$$\vec{E\!\!\!/}_{\mathrm{T}} = -\left[\sum_{\text{leptons}} \vec{p}_{\mathrm{T}} + \sum_{\text{HS-jets}} \vec{p}_{\mathrm{T}} + \sum_{\text{HS-charged}} \vec{p}_{\mathrm{T}} \right.$$

$$\alpha = 1.0,\ \beta = 0.6,\ \gamma = 1.0,\ \delta = 1.0$$

$$\left. + S_{\mathrm{F}} \cdot \left(\alpha \cdot \sum_{\text{PU-charged}} \vec{p}_{\mathrm{T}} + \beta \cdot \sum_{\text{neutrals}} \vec{p}_{\mathrm{T}} + \gamma \cdot \sum_{\text{PU-jets}} \vec{p}_{\mathrm{T}} + \delta \cdot \vec{\Delta}_{\mathrm{PU}} \right) \right] \text{with} \quad S_{\mathrm{F}} = \frac{\sum_{\text{HS-charged}} p_{\mathrm{T}}}{\sum_{\text{HS-charged}} p_{\mathrm{T}} + \sum_{\text{PU-charged}} p_{\mathrm{T}}}$$

  - MVA PFMET: based on 2-step regression (for recoil direction and magnitude)

    Inputs to regression:

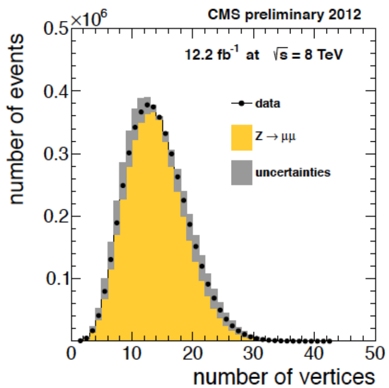
P. Harris's talk

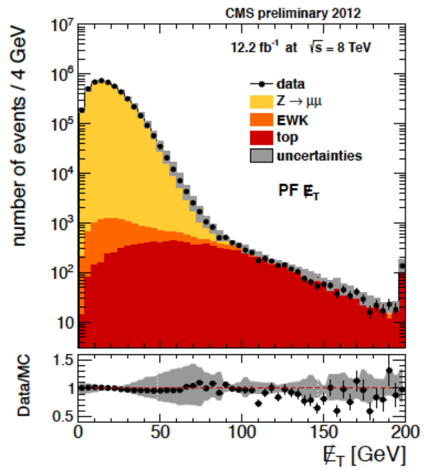
    - Recoil magnitude and phi angle associated to the following METs :
      1) PF MET
      2) MET based on charged PF objects linked to the HS vertex
      3) same as 2) + neutrals within jets associated to the hard scatter vertex (using the jetPU ID)
      4) MET based on charged particles not associated to the HS vertex + neutrals within PU jets
      5) same as 2) + neutrals (except those in PU jets)
    - Two leading jets vectorial p_T
    - Vertex multiplicity

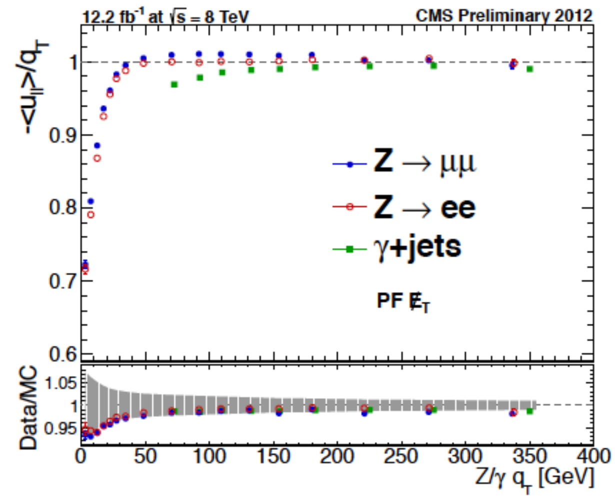
MET in 8 TeV Data

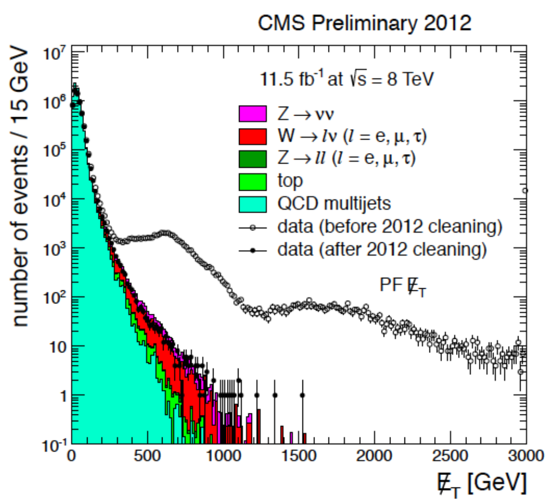
CMS-PAS-JME-12-002

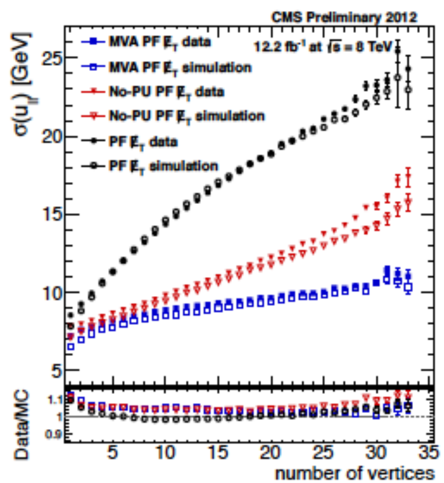
- 8 TeV, 12 (20) fb^{-1}, $3.5 \times 10^{33}\ cm^{-2}s^{-1}$

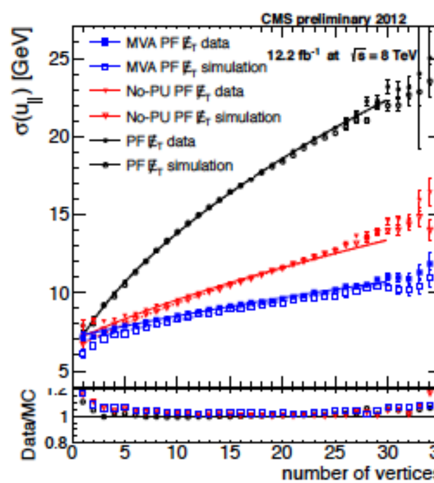








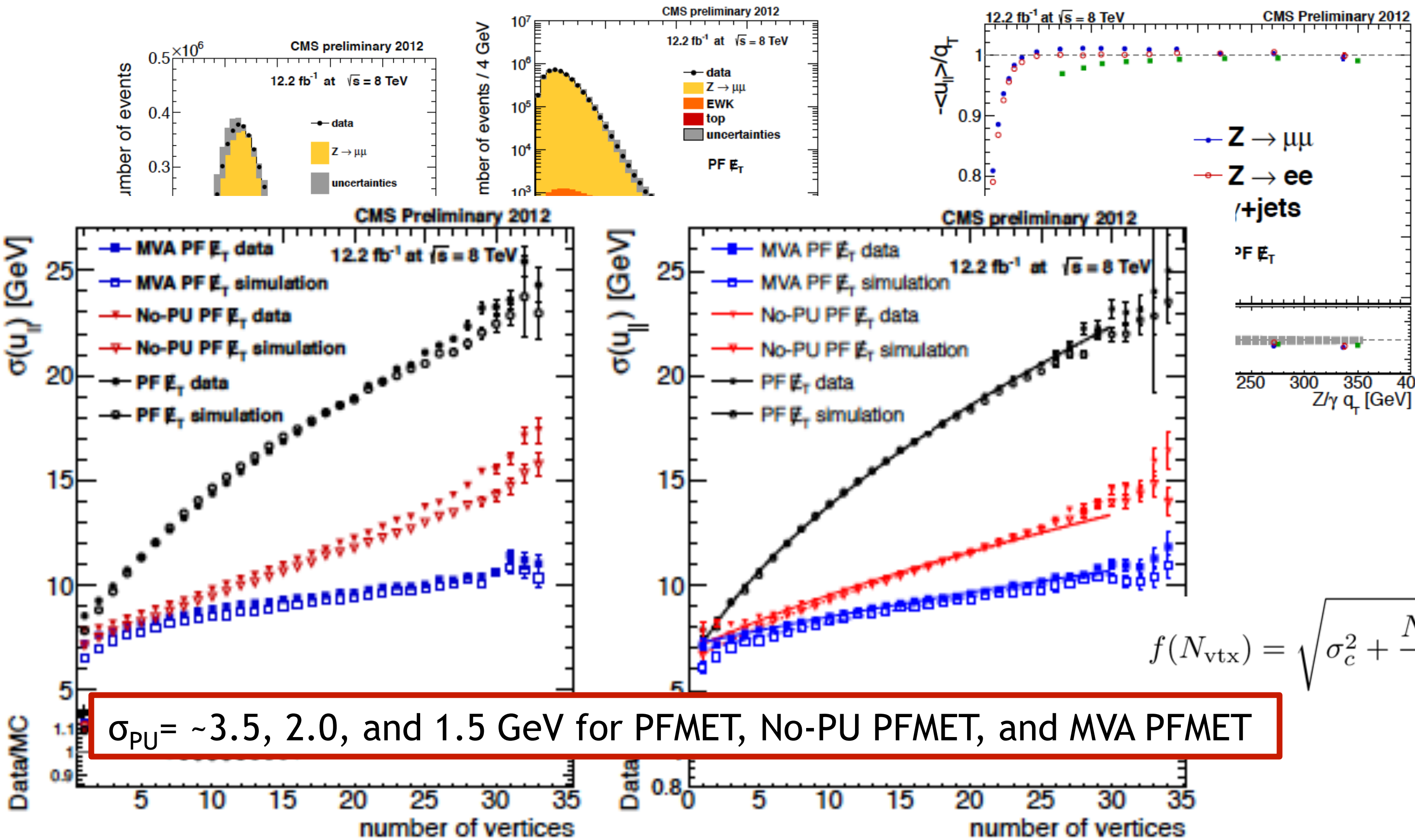




MET in 8 TeV Data

- 8 TeV, 12 (20) fb^{-1}, 3.5×10^{33} $cm^{-2}s^{-1}$

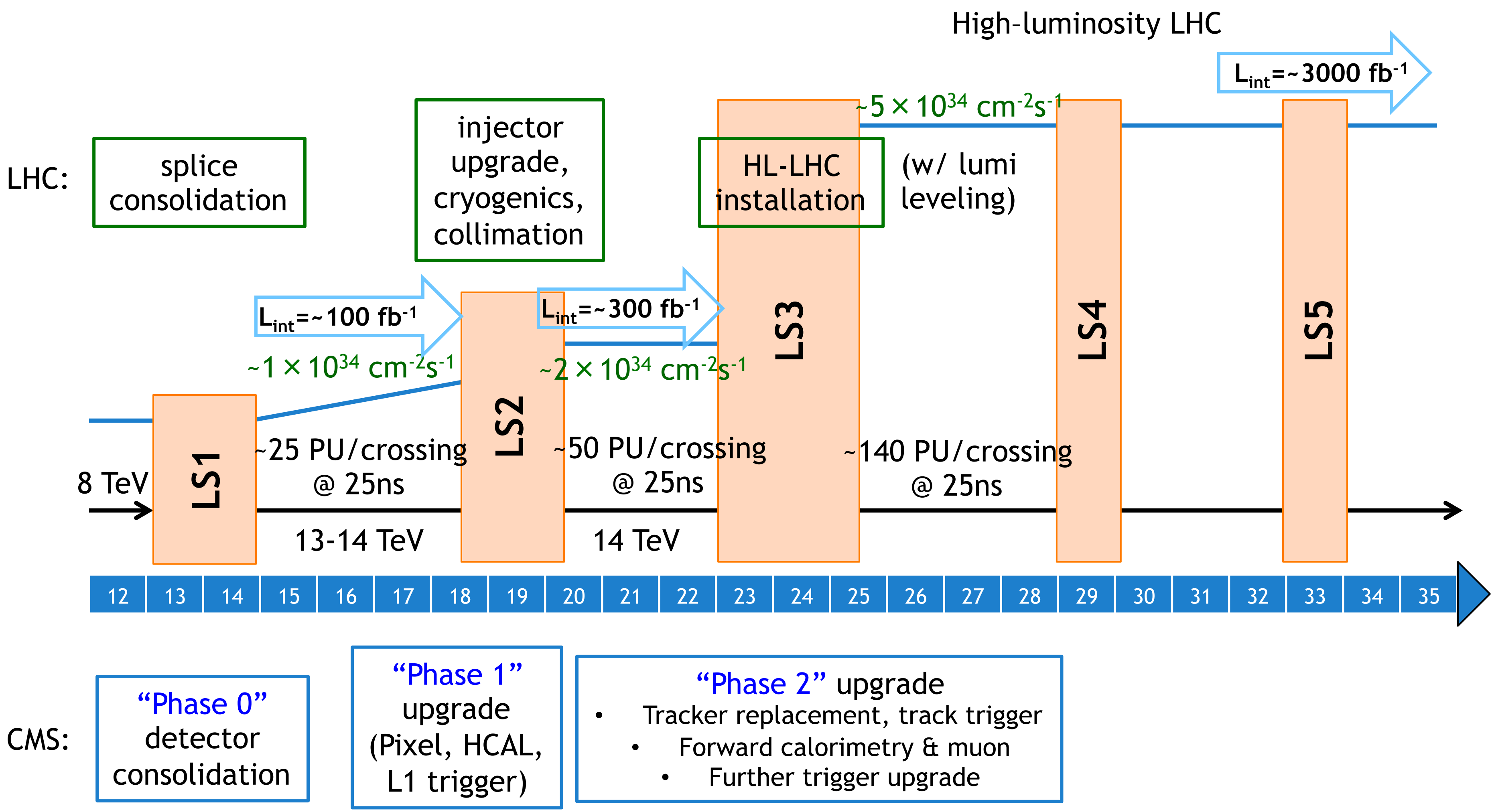
CMS-PAS-JME-12-002



$$f(N_{\rm vtx}) = \sqrt{\sigma_c^2 + \frac{N_{\rm vtx}\times\sigma_{\rm PU}^2}{\epsilon_{\rm vtx}}}$$

σ_{PU}= ~3.5, 2.0, and 1.5 GeV for PFMET, No-PU PFMET, and MVA PFMET

LHC/CMS Evolution



Based on [LHC schedule approved by CERN management, LHC experiment spokespersons and technical coordinators on Dec 2, 2013](#) Also, Bordry at ECFA HL-LHC workshop & Gregor.

Studies with Delphes Simulation

- Delphes 3: https://cp3.irmp.ucl.ac.be/projects/delphes, arXiv:1307.6346
  - Fast multipurpose detector response simulation based on object resolution and efficiency
  - Can include pileup

From J. Stupak

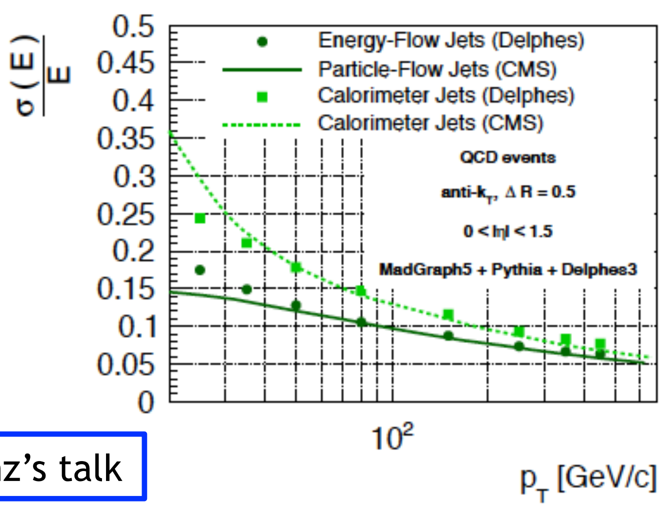
Detector configuration card:
- Tracking efficiency
- Tracking resolution
- Calorimeter resolution
- Reconstruction/tagging efficiencies (e, μ, τ, γ, b)

Generator events

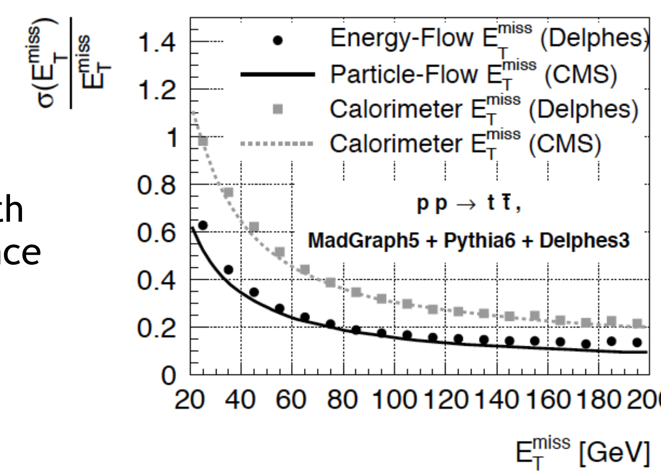
+PU

CHS in tracker vol.
Fastjet ρ subtraction in calorimeter vol.

e
μ
τ
ϒ
jet
MET



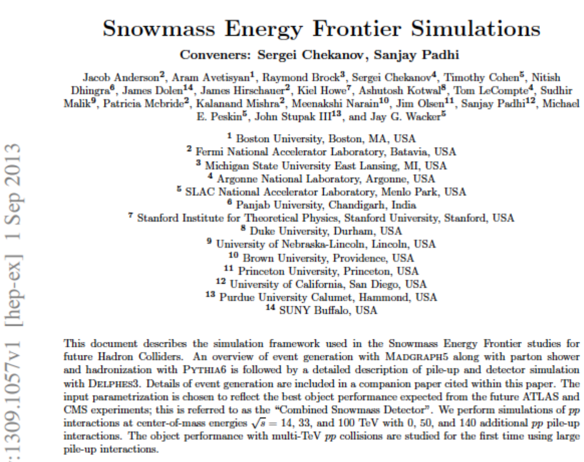
Consistent with CMS performance



S. Zenz's talk

Snowmass Simulation

- In the context of the Snowmass 2013 process, a generic "LHC" detector was formulated for Delphes's config card: arXiv:1309.1057
  - Take best of CMS/ATLAS detector performance or assume the current CMS/ATLAS performance



v:1309.1057v1 [hep-ex] 1 Sep 2013

Snowmass Energy Frontier Simulations

Conveners: Sergei Chekanov, Sanjay Padhi

Jacob Anderson[2], Aram Avetisyan[1], Raymond Brock[3], Sergei Chekanov[4], Timothy Cohen[5], Nitish Dhingra[6], James Dolen[14], James Hirschauer[2], Kiel Howe[7], Ashutosh Kotwal[8], Tom LeCompte[4], Sudhir Malik[9], Patricia Mcbride[2], Kalanand Mishra[2], Meenakshi Narain[10], Jim Olsen[11], Sanjay Padhi[12], Michael E. Peskin[5], John Stupak III[13], and Jay G. Wacker[5]

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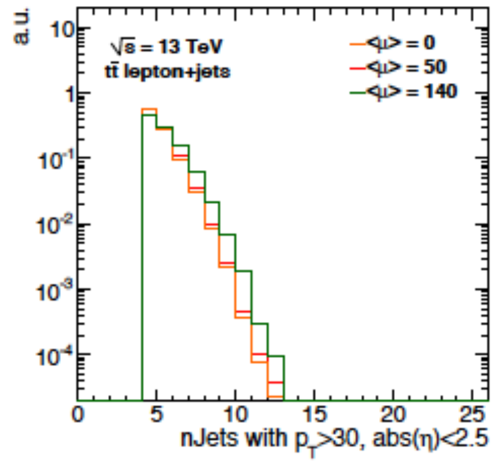
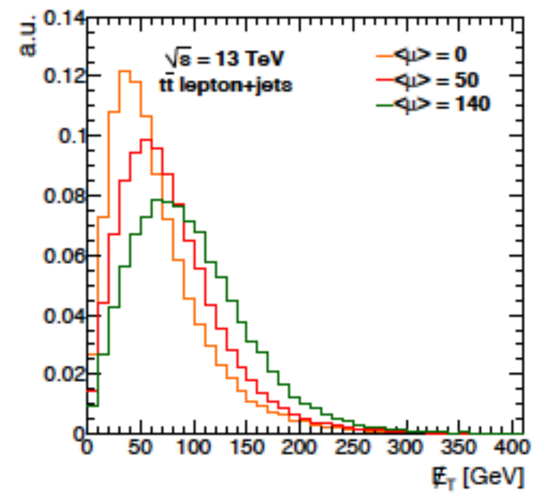
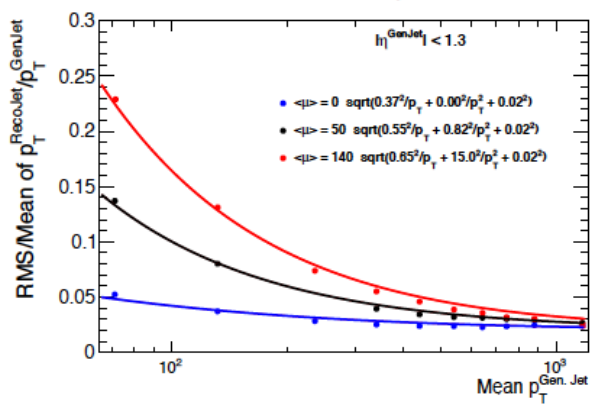
[2] Fermi National Accelerator Laboratory, Batavia, USA
[3] Michigan State University East Lansing, MI, USA
[4] Argonne National Laboratory, Argonne, USA
[5] SLAC National Accelerator Laboratory, Menlo Park, USA
[6] Panjab University, Chandigarh, India
[7] Stanford Institute for Theoretical Physics, Stanford University, Stanford, USA
[8] Duke University, Durham, USA
[9] University of Nebraska-Lincoln, Lincoln, USA
[10] Brown University, Providence, USA
[11] Princeton University, Princeton, USA
[12] University of California, San Diego, USA
[13] Purdue University Calumet, Hammond, USA
[14] SUNY Buffalo, USA

This document describes the simulation framework used in the Snowmass Energy Frontier studies for future Hadron Colliders. An overview of event generation with MADGRAPH5 along with parton shower and hadronization with PYTHIA6 is followed by a detailed description of pile-up and detector simulation with DELPHES3. Details of event generation are included in a companion paper cited within this paper. The input parametrization is chosen to reflect the best object performance expected from the future ATLAS and CMS experiments; this is referred to as the "Combined Snowmass Detector". We perform simulations of pp interactions at center-of-mass energies $\sqrt{s} = 14$, 33, and 100 TeV with 0, 50, and 140 additional pp pile-up interactions. The object performance with multi-TeV pp collisions are studied for the first time using large pile-up interactions.

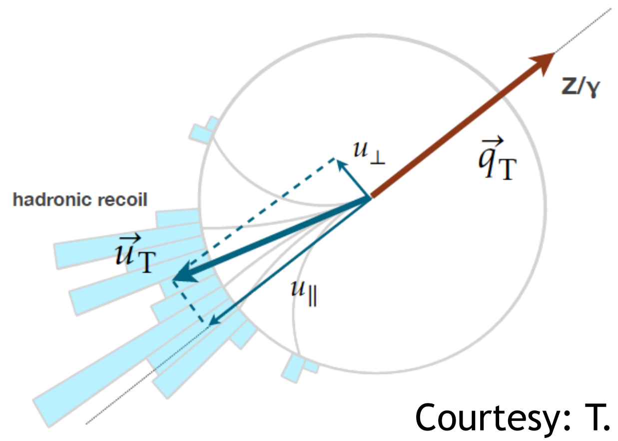






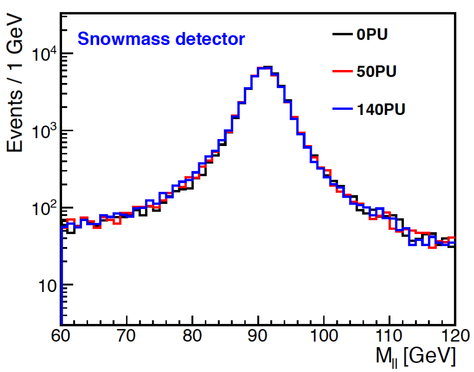
Studies w/ Snowmass Simulation

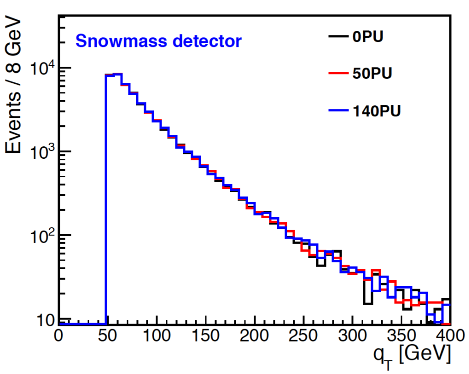
- Performed a MET performance study with Drell-Yan Z->μμ events using Z as a reference
- Event selection:
  - Two opposite-sign muons
  - 60 < M(μμ) < 120 GeV
  - $P_T(\mu\mu)$ > 50 GeV
- MET definition:
  - (Raw) MET from all Eflow (PF) objects
  - MHT
    - Jets with P_T>30 GeV & |η|<5
    - And all other objects with |η|<5



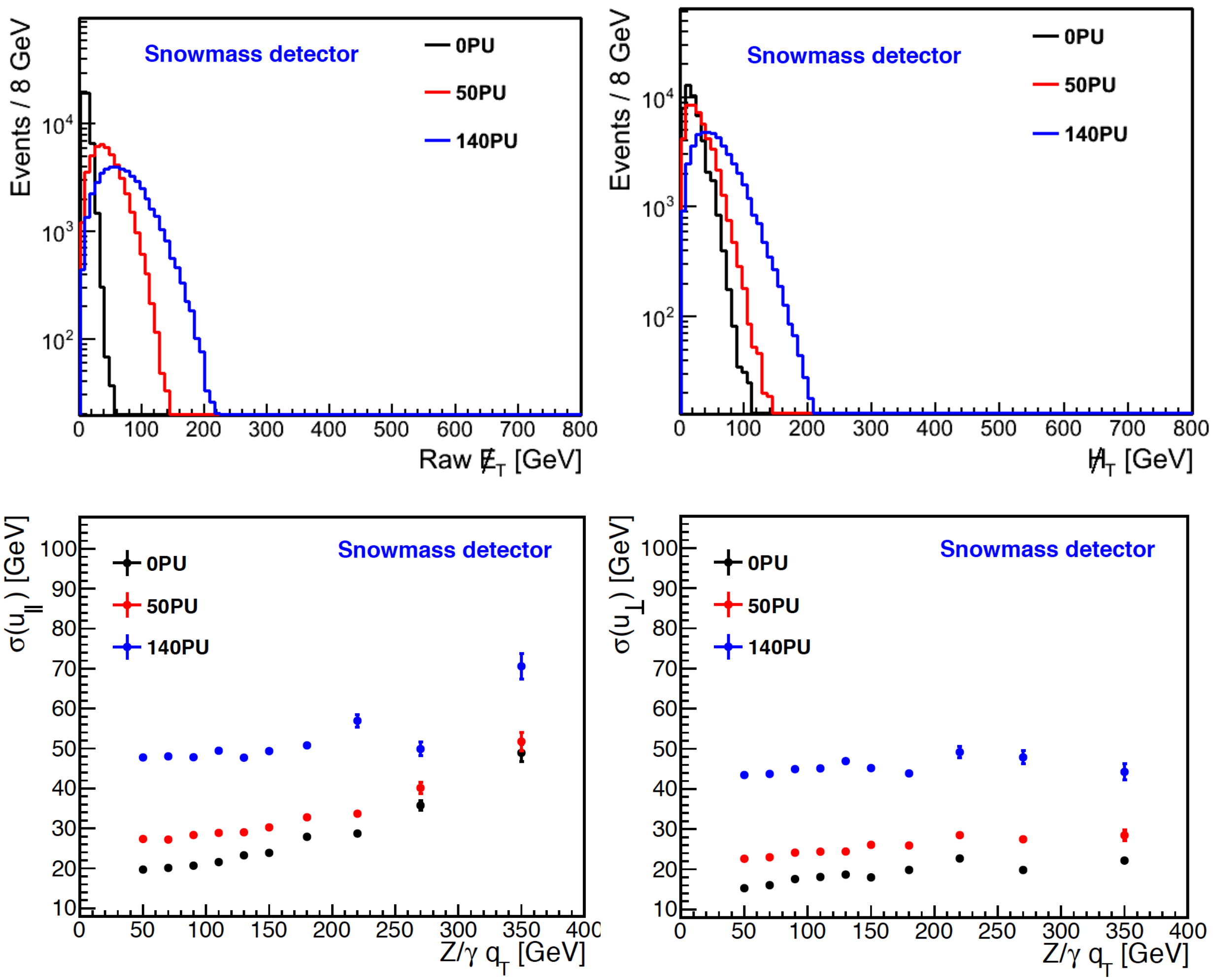
Courtesy: T. Sakuma

Z. Wu's talk



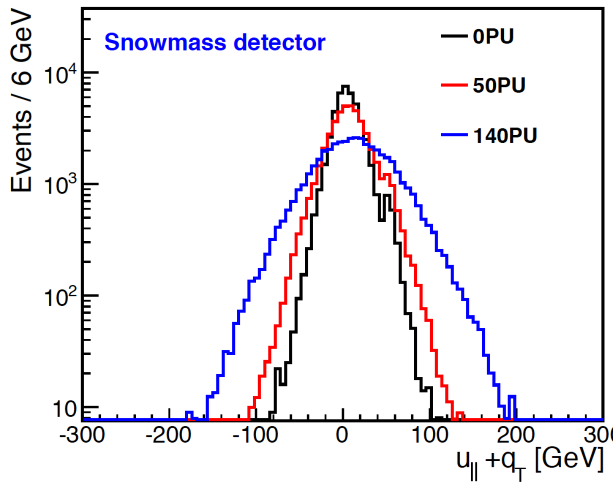


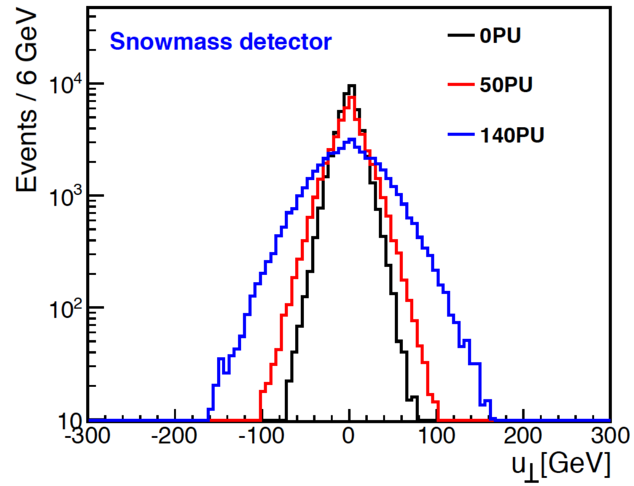
Studies w/ Snowmass Simulation



- Sizable pileup dependence in particular for MET
- See how much Drell-Yan background is going to increase in searches with MET
  - Larger effect than in ttbar lepton+jets events
  - Events without intrinsic MET show larger PU effects
- Recoil ($u_{||}$ and u_{perp}) variables are computed using MHT
- Similar pileup dependence for both $u_{||}$ and u_{perp}

Studies w/ Snowmass Simulation





- The pileup dependence of recoil resolution can be parametrized by

$$f(N_{\rm vtx}) = \sigma({\rm RMS}) = \sqrt{\sigma_c^2 + N_{\rm PU} \times \sigma_{\rm PU}^2}$$

$$\sigma_{\rm PU} \sim 3.5 \text{ GeV for PFMET}$$

From CMS 8 TeV data (JME-12-002)

	σ(RMS) (GeV)	Estimation w/ $\sigma_{\rm PU} = 3.5$ GeV	Estimation w/ $\sigma_{\rm PU} = 1.5$ GeV
$N_{\rm PU} = 0$	16.5	–	
$N_{\rm PU} = 50$	23.5	29.8	19.6
$N_{\rm PU} = 140$	44.3	44.6	24.2

- Can we maintain σ_{PU}~3.5 GeV in a more realistic full simulation?
- How can we get closer to σ_{PU}=1.5 GeV using e.g. MVA-PFMET-like approach?

High Luminosity Studies: ATLAS

- ATLAS performed a "full" simulation study on jet and MET performance at high luminosity (see e.g. Snowmass QCD WG report. arXiv:1310.5189)
- Production of dedicated datasets at several $\mu(=<N_{PU}>)$ and pileup noise values (σ)
  - Optimized calorimeter signal reconstruction
    - From single pion Monte Carlo at each μ value
  - Jet energy scale for all configurations
- Calorimeter-only simulation:
  - No tracks available in the analysis
  - Focus on optimization of calorimeter-level reconstruction
  - Room for improvements utilizing tracks

A. Schwartzman @Snowmass Minnesota

50ns

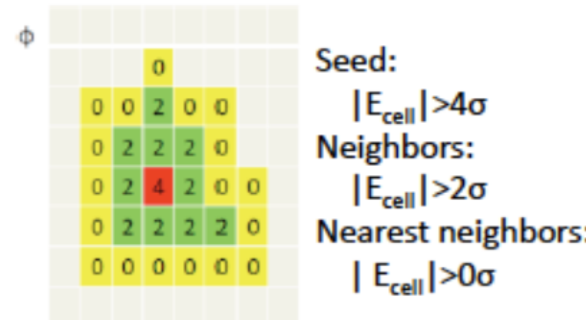
MU\σ	30	40	60	80	100	140	200
0	X	x	x	x	x	x	x
40		X					
60			X				
80	x	x	x	X	x	x	
140						X	
200							X

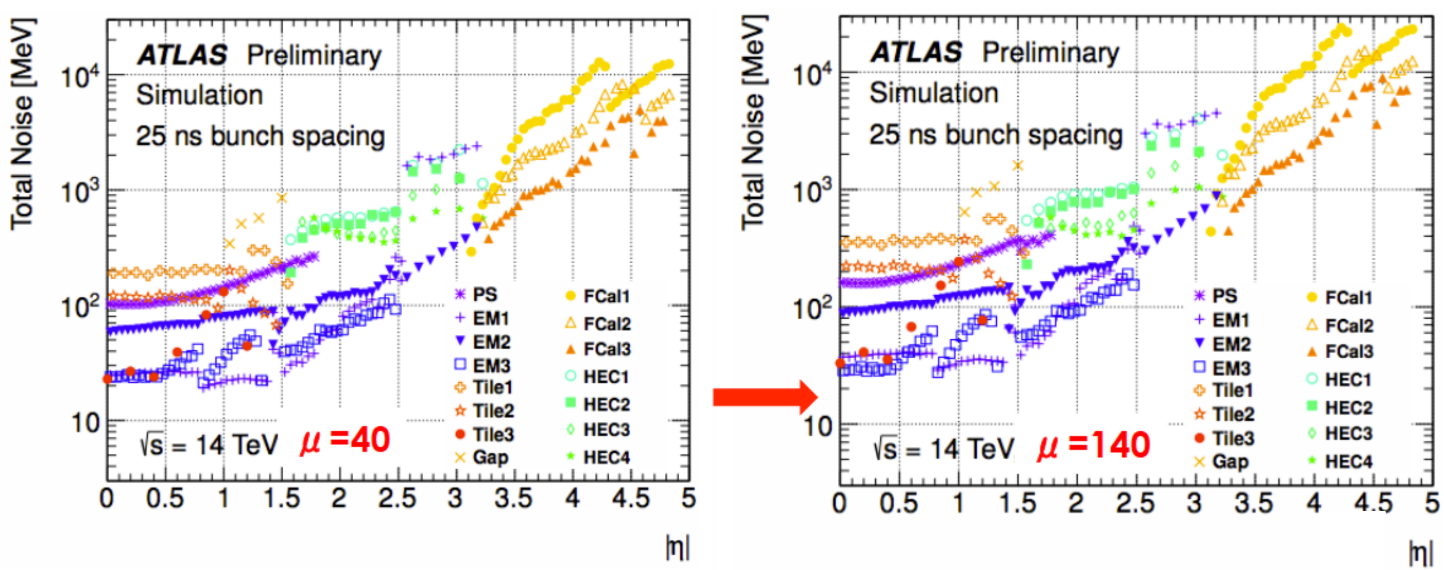
25ns

MU\σ	30	40	60	80	100	140	200
0	X	x	x	x	x	x	x
40	x	X	x	x			
60	x	x	X	x	x		
80			x	X	x		
140					x	X	x
200						x	X

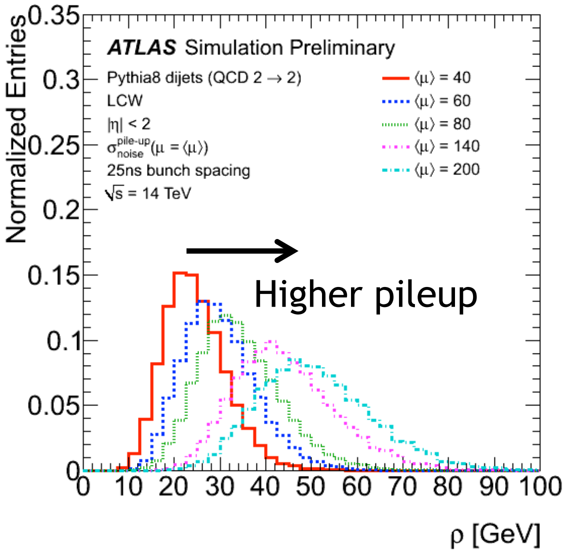
Topological Clusters: ATLAS

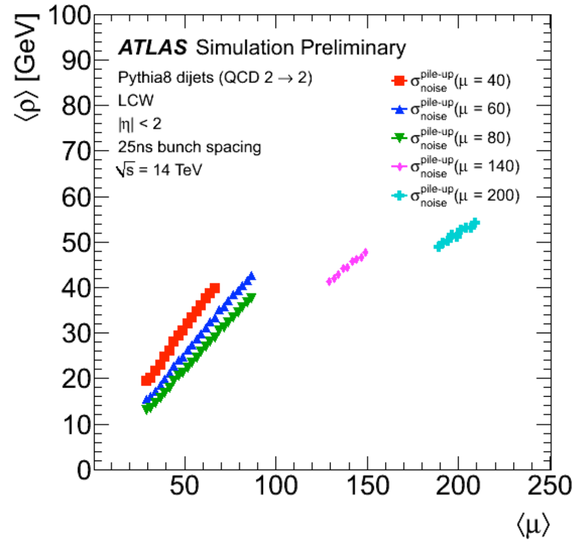
- Topological clusters are designed to follow shower development in the calorimeter
- Involves electronics + pileup noise suppression
- EM/HAD local calibration performed to correct for calorimeter non-linearity, energy losses in dead material, and out-of-cluster energy
  - Derived from single pion simulation

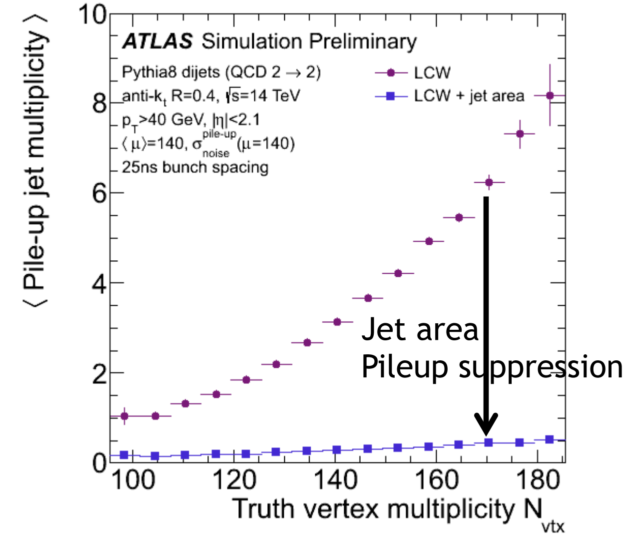




PU Subtraction/Suppression: ATLAS

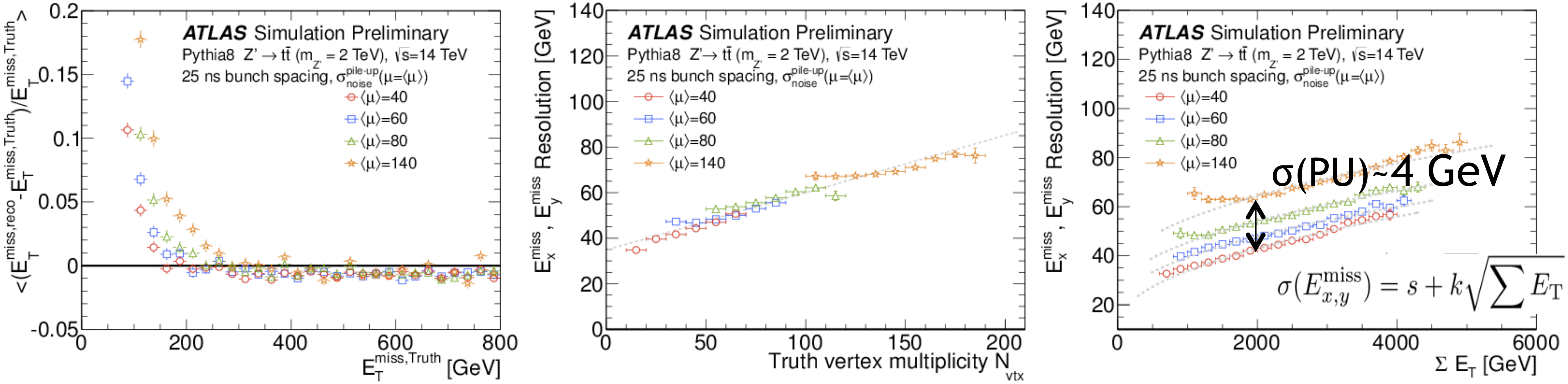






- **Pileup subtraction:**
  - Significant increase on the width of the ρ distribution with pileup
  - Linear behavior of ρ up to high μ for fixed pileup noise values
  - Higher pileup noise values lead to suppression of pile-up
- **Pileup suppression:**
  - Pileup subtraction significantly reduces the mean number of pileup jets
  - Further improvements expected using tracking and vertexing information

MET at HL-LHC: ATLAS



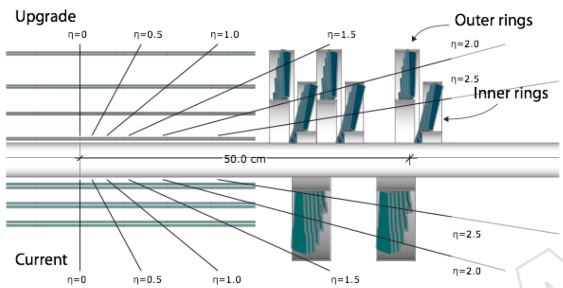
- MET computed using only topological clusters and calibrated jets
- Linearity of the response is within 1% up to μ=140
  - Positive bias at low MET is due to the finite resolution
- MET resolution scaling with the number of vertices is independent of <μ>, when the optimal pileup noise values are used
- MET resolution deteriorates with pileup, but slope with μ is unchanged
  - Pileup affects the s-term, but k-term stays approximately constant
  - Large room for improvements using tracks to suppress pileup

Phase 1 Upgrade: CMS

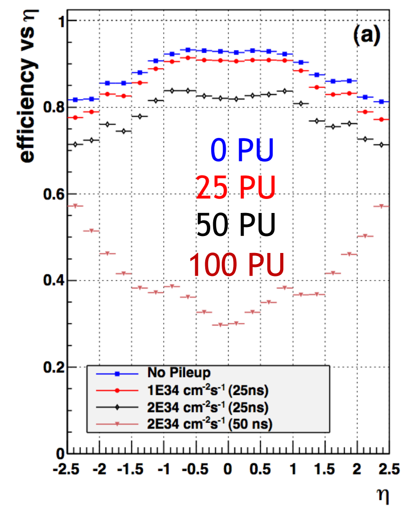
CMS-TDR-011

Main components for phase 1 upgrade

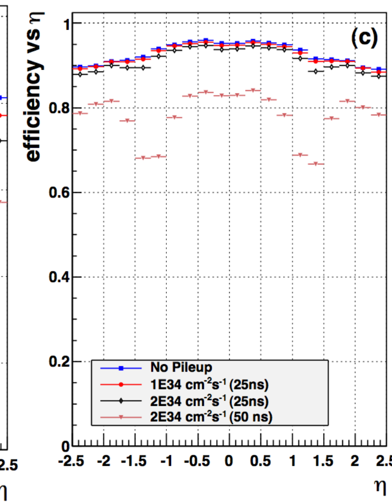
- ☐ New Pixel detector:
  - ■ The upgraded detector will have high rate capability and significantly improved tracking performance at high pile-up



Current detector

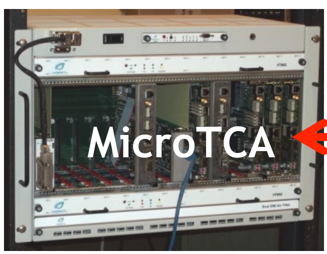


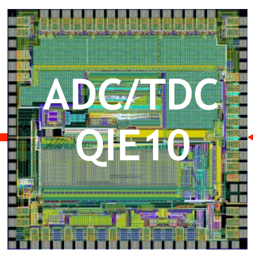
Upgrade detector

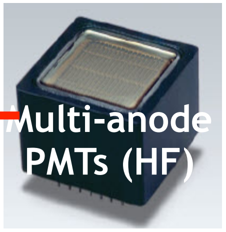


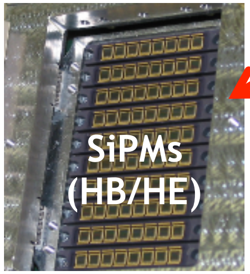
Fake Rate= 6% (η=0) Fake Rate= 2% (η=0)

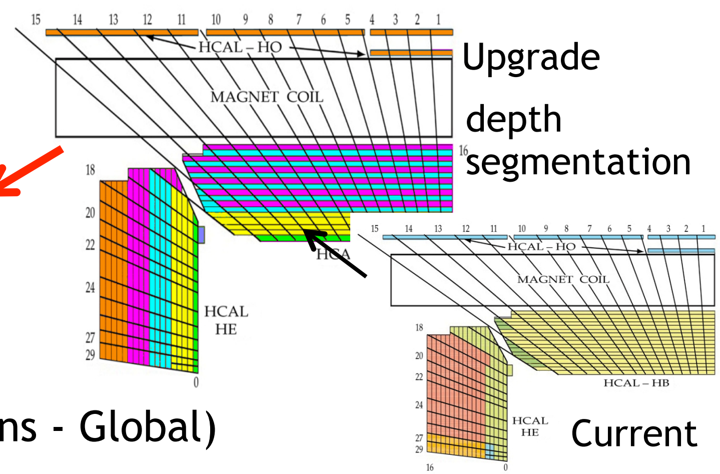
- ☐ HCAL upgrade: photodetectors and electronics
  - ■ Depth segmentation, TDC timing, etc











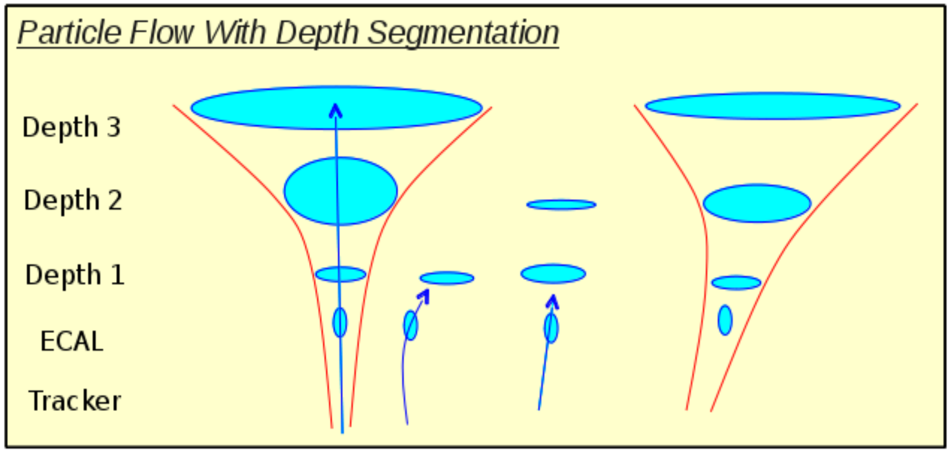
Upgrade depth segmentation

Current

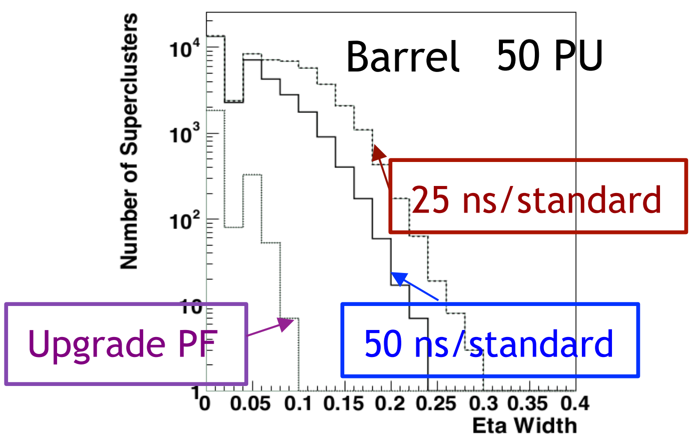
- ☐ Also, new L1-trigger systems (Calorimeter - Muons - Global)

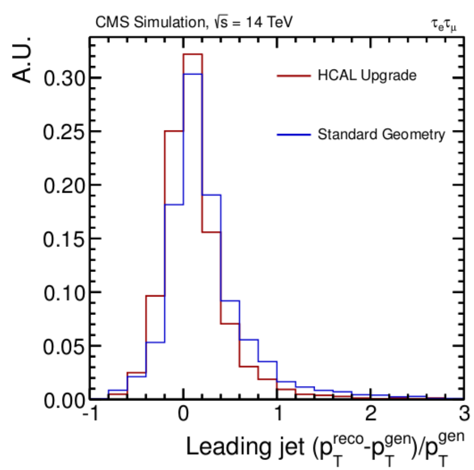
Tully et al for HCAL TDR

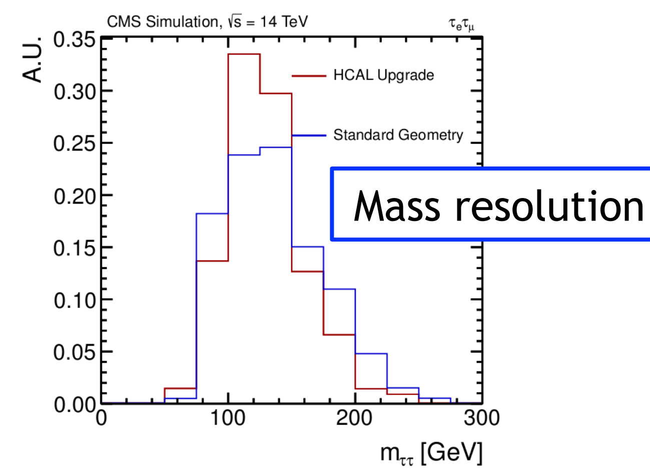
Particle Flow w/ High Pileup



- Hadronic showers spread out with increasing depth
  - With a single-depth readout, pileup energy will be pulled into a charged hadron cluster or true energy will be left out and labeled as a neutral hadron
  - Depth segmentation provides better pileup separation



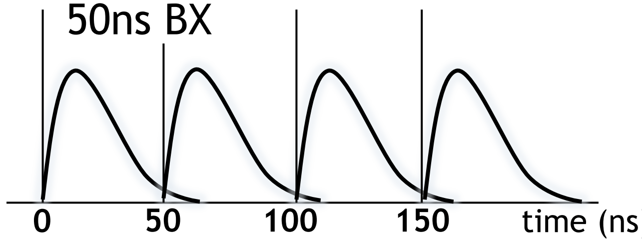


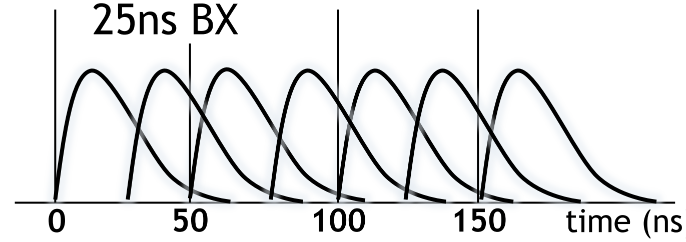


- Improved jet and MET resolution allows 25% improvement in $m_{\tau\tau}$ resolution
- Total efficiency improvement for VBF H→ττ: factor of 2.5 (4.5% → 11%)

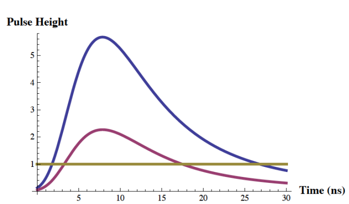
25ns BX Consideration

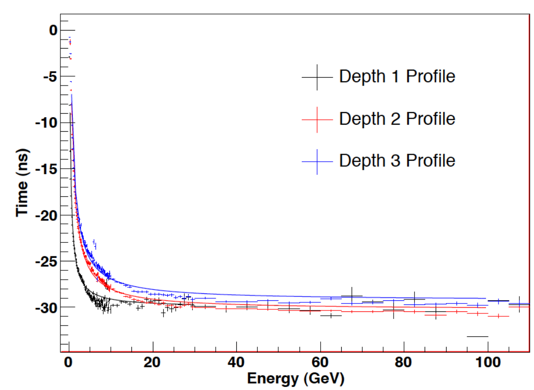
- With 50ns, out-of-time (OOT) pileup was not a major concern, but 25ns BX would increase the out-of-time PU for HCAL

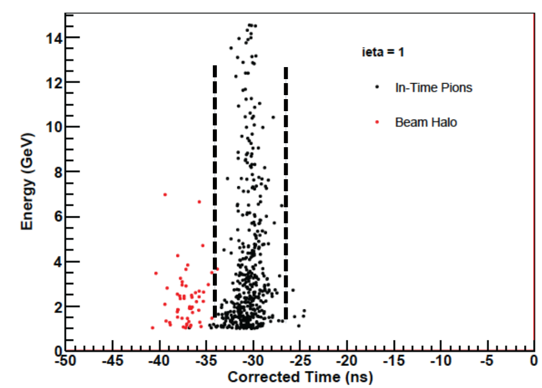




- HCAL phase 1 upgrade upgrade will introduce TDC timing
  - “Raw” TDC time needs to be calibrated to give a pulse-height-independent time
  - The calibrated time resolution of a few ns will help the OOT pileup mitigation
  - Even without the TDC (i.e. before LS2), we have a good potential of reducing OOT pileup by pulse-shape analysis

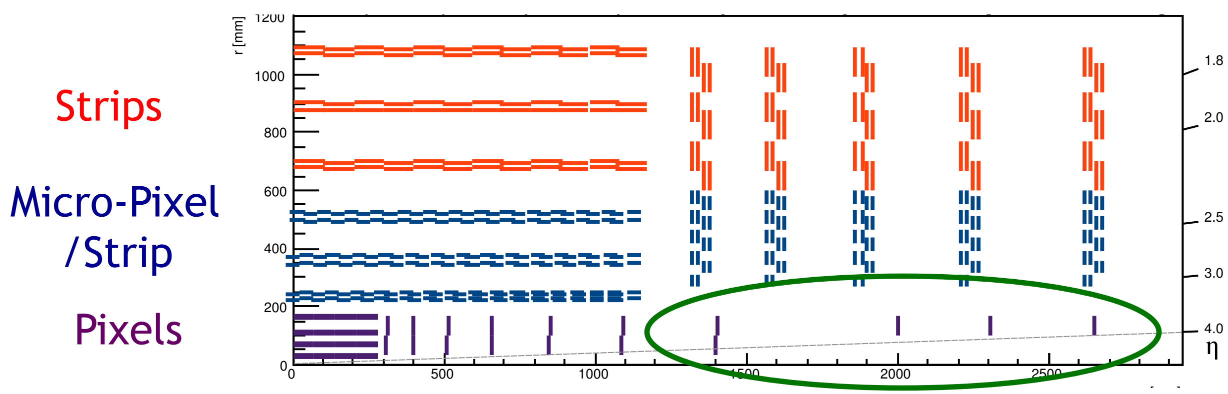






Phase 2 Upgrade: CMS

- Main components considered for upgrade
  - New tracker with possible increased coverage to |η|~4, with an L1 track trigger (p_T>2 GeV)
  - DAQ and HLT upgrade: L1 1 MHz out, HLT 10 kHz out & event storage
  - Replace endcap and forward calorimeters
    - Shashlik EM + retrofit HAD, Dual-readout (scintilator&cerenkov), Particle-flow CAL
  - Complete the muon stations at 1.6<|η|<2.4 & possible |η| extension
  - Possible electromagnetic (preshower) system to provide photon pointing and pileup discrimination from time-of-flight
- Scope of the upgrade to be defined in Technical Proposal (2014)



Potential tracker layout with forward pixel disks

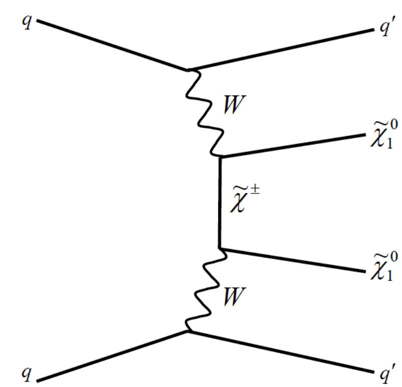
Phase 2 Upgrade Simulation: CMS

- A combination of full & fast (Delphes) simulation is employed
  - Phase 1 detector with PU=0, 140
    - Phase 1 PU=140 scenario used for comparison of full simulation and Delphes
  - Two Phase 2 detector (PU = 140) scenarios considered using Delphes

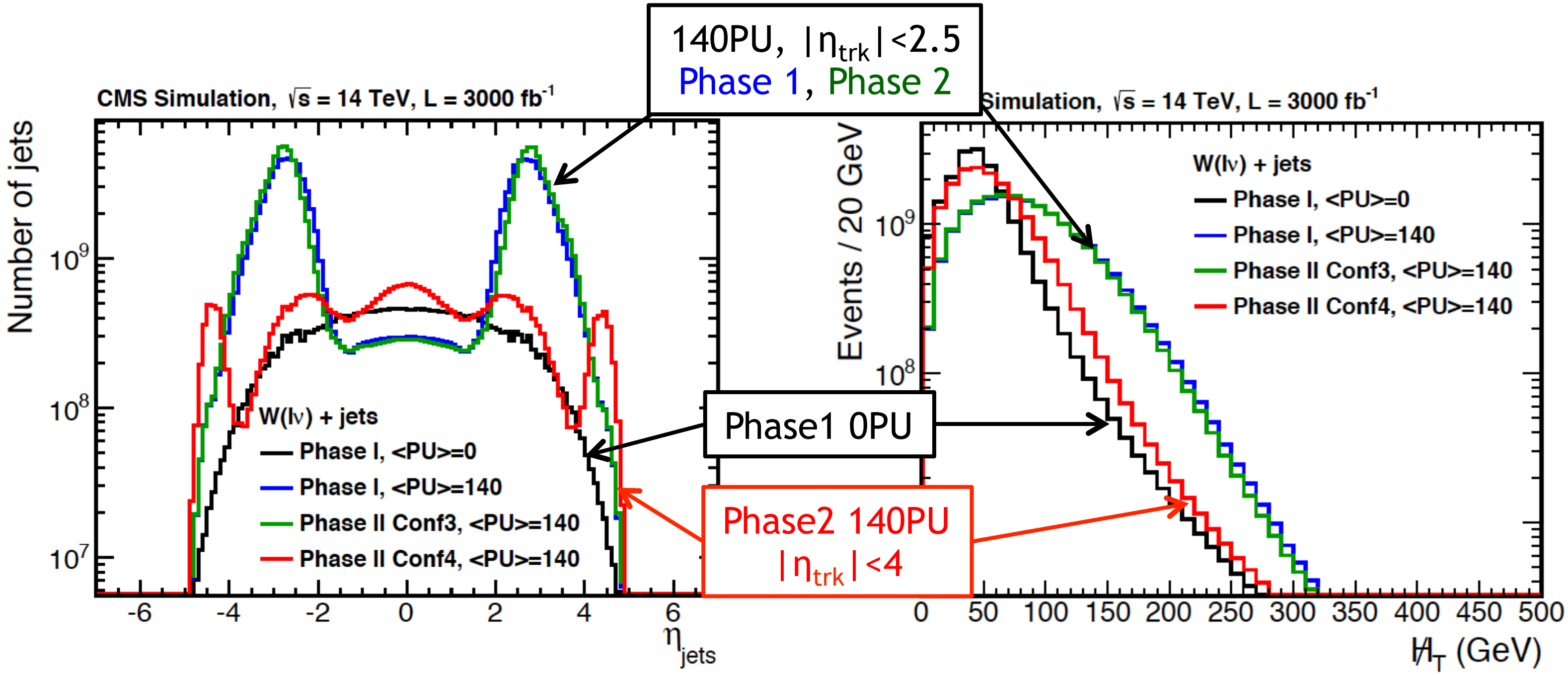
"Configuration 3"
- Replace ECAL endcap, retrofit HCAL endcap
- Phase 2 tracker in barrel & endcap
- Full muon system coverage to $|\eta|<2.4$

"Configuration 4"
- Full endcap calorimeter replacement
- Full tracker & muon coverage to $|\eta| < 4.0$

- SUSY/new physics search studies with VBF jets + MET (CMS-PAS-FTR-13-014)
  - Vector boson fusion (VBF) provides a unique opportunity to search for new physics with electroweak couplings
  - Consider lightest neutralino is the LSP (viable dark matter candidate) and other colored particles are beyond the LHC reach
  - The potential discovery channel for such a model is VBF jets + MET



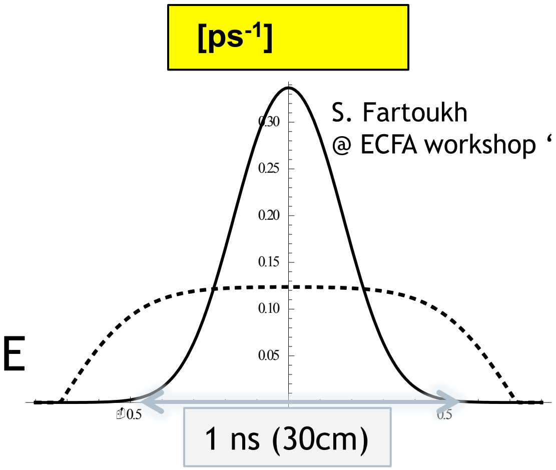
VBF Jets & MET w/ Phase2 Upgrade

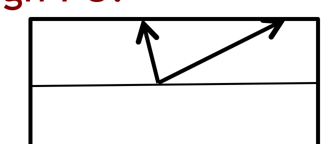


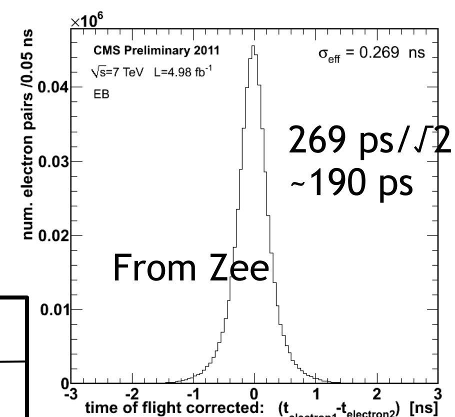
- Simulation uses the charged hadron subtraction in the tracker volume and fastjet ρ subtraction in calorimeter volume for PU subtraction
- The forward tracking extension can introduce a strong PU jet suppression power and improve the MET(MHT) resolution
- Together with the improved lepton veto capabilities by forward tracking/ muon, the S/B ratio improves by a factor of 5.
- Full simulation based studies pending for Technical Proposal

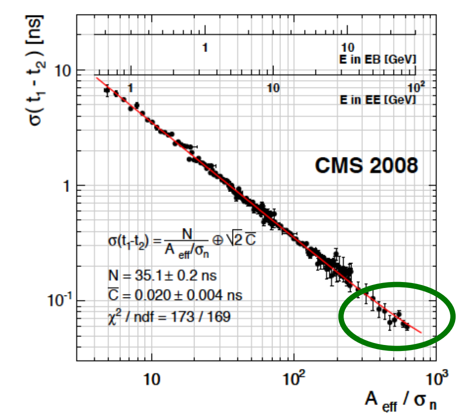
Precision Timing for PU Mitigation?

- Use precision timing (30ps?), associate charged and neutral clusters to reconstructed vertices, and filter out pileup clusters
  - We often use timing to mitigate out-of-time pileup interactions; however, precision timing may offer in-time pileup mitigation
- HL-LHC will provide 0.12-0.34 PU/ps depending on bunch structure:
  - 30ps timing can reduce intime PU from 140 to ~7-20 interactions
- Current ECAL time resolution is 190/280ps for EB/EE
  - Test beam indicates we can go down to 80ps
  - How much further can we improve with e.g. MCP-PMT?
  - What much can we improve MET resolution at high PU?









CMS-DP-2012/007 JINST 5:T03011 (2010)

Summary

- MET reconstruction has been performing quite at the LHC experiments
  - It was ready for use from day 1.
  - Data and simulation has been showing reasonable agreement and MET tail is well under control
  - Advanced algorithms for pileup suppression are developed

- High pileup condition will impose a challenge on MET reconstruction
  - The HL-LHC condition can deteriorate the MET resolution by up to ~40 GeV, whose impact will depend on physics analyses (e.g. background compositions, low-mass vs high-mass analysis, etc)
  - The phase 1 detector upgrade will give us extra handles for pileup mitigation
    - Better tracking efficiency, HCAL depth segmentation, and TDC timing
    - Even before the completion of phase 1 upgrade, there are rooms for improvements
  - The phase 2 upgrade design is likely to have a large impact on MET performance at high luminosity LHC
    - Forward tracking extension, precision timing
    - Should define the upgrade design for the best of our future physics

Backup

LHC Schedule

LHC schedule beyond LS1

Only EYETS (19 weeks) (no Linac4 connection during Run2)

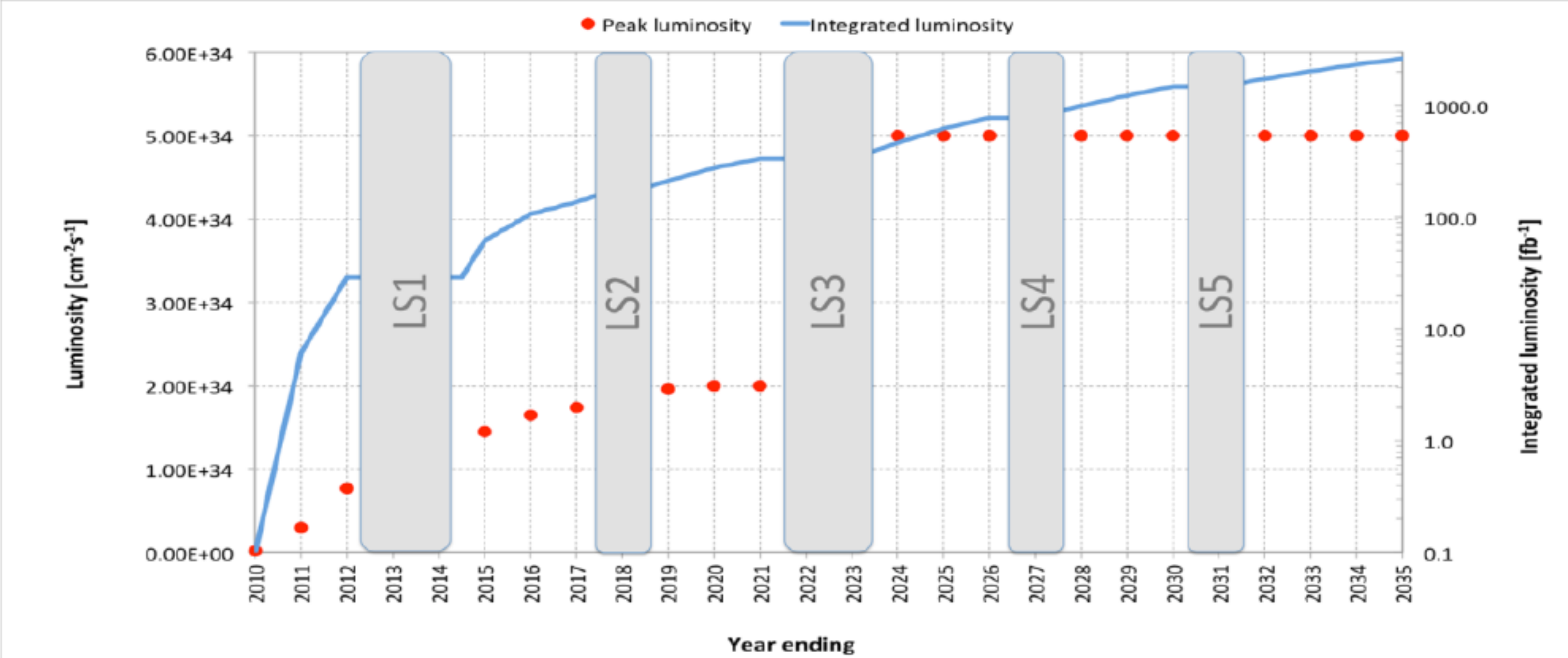
LS2 starting in 2018 (July) 18 months + 3months BC (Beam Commissioning)

LS3 LHC: starting in 2023 => 30 months + 3 BC

injectors: in 2024 => 13 months + 3 BC

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators
Monday 2nd December 2013

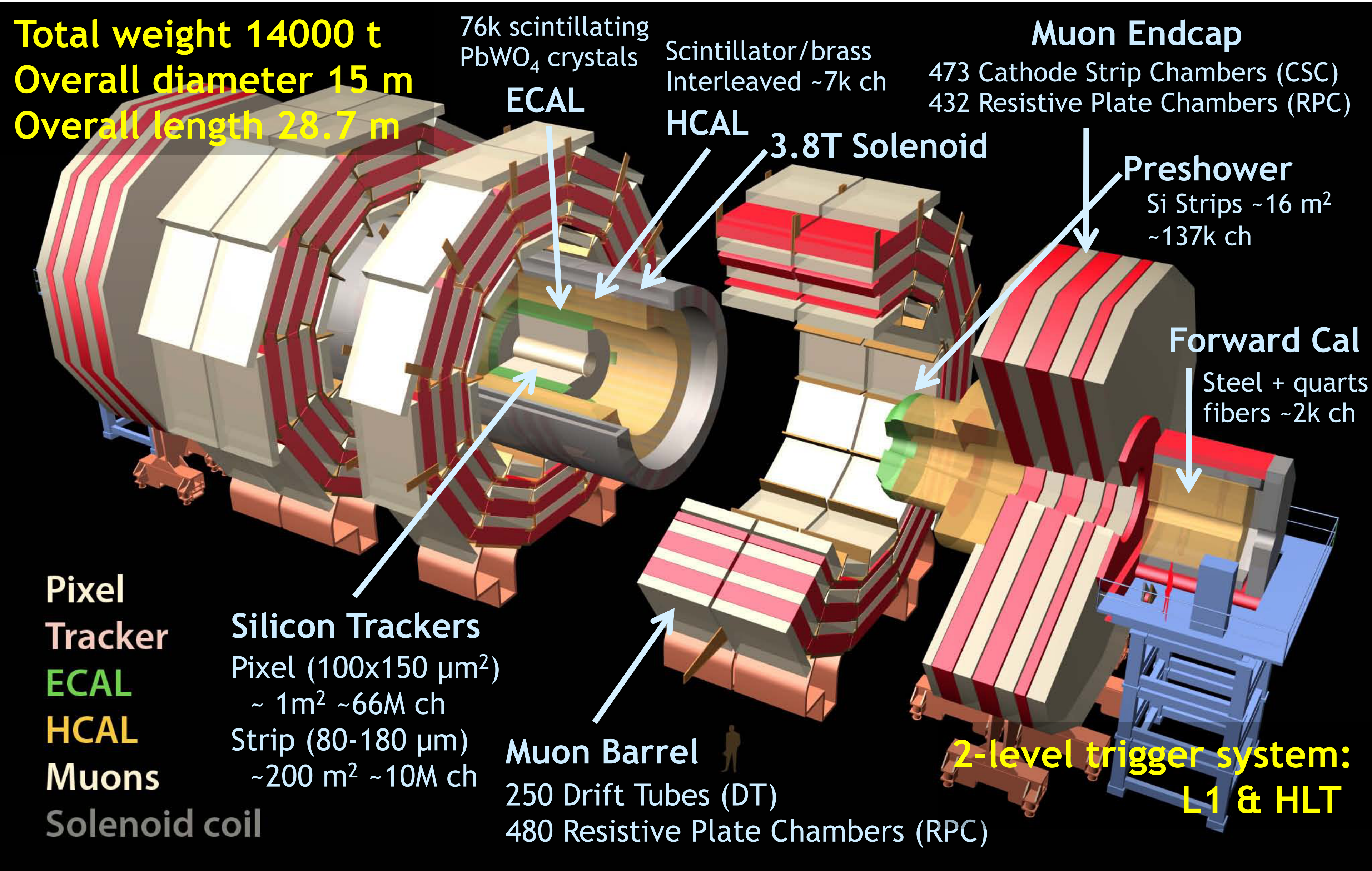
LHC Schedule



Levelling at 5 10^{34} cm^{-2} s^{-1}: 140 events/crossing in average, at 25 ns; several scenarios under study to limit to 1.0 → 1.3 event/mm
("Pile-up at HL-LHC and possible mitigation" Stephane Fartoukh on Wed. 2^{nd} Oct.)

Total integrated luminosity of 3000 fb^{-1} for p-p by 2035, with LSs taken into account and 1 month for ion physics per year.

CMS Detector Overview



CMS Upgrade Overview

LS1 Projects: in production
- Completion of muon coverage (ME4)
- Improve muon operation (ME1), DT electronics
- HCAL: HF (new PMTs) and HO (SiPM)

Phase 1 “Preperation Work”
- Beampipe for pixel upgrade
- Splitters for parallel trigger development
- HF backend electronics (Phase 1)
- Interim L1-Trigger upgrade (Phase 1)

Phase 2 Projects: scope to be defined in 2013-2014
- Tracker replacement, track trigger
- Forward calorimetry and muons?
- Further trigger upgrade?

LS1 (2013-14) **LS2 (2018)** **LS3 (2022-23)**

Phase 1 Upgrades: TDRs
- Pixel detector replacement
- HCAL electronics upgrade
- L1-Trigger upgrade

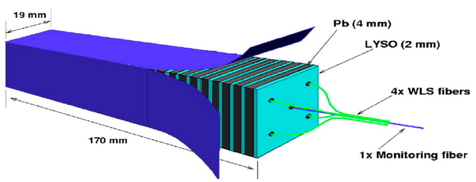
- Pixel and HCAL TDRs approved by LHCC September 2012
  Pixel: http://cdsweb.cern.ch/record/1481838/files/CMS-TDR-011.pdf
  HCAL: http://cdsweb.cern.ch/record/1481837/files/CMS-TDR-010.pdf
- L1-Trigger will be early 2013

Phase 2 Endcap Calorimetry: CMS

Two approaches:

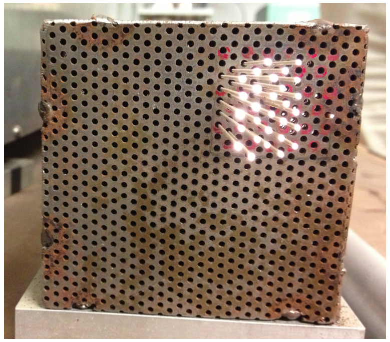
- Maintain standard tower geometry - develop radiation tolerant solutions for EE and HE to deliver the necessary performance to 3000 fb^{-1}
  - Build EE towers in e.g. Shashlik design (crystal scintillator: LYSO, CeF)
  - Rebuild HE with more fibers, rad-hard scintillators

Shashlik concept



- Study alternative geometry/concepts with potential for improved performance and/or lower cost.
  - Dual-readout Combined Forward Calorimeter (CFC) – follow work of DREAM/RD52
    - using doped/crystal fibers - allows e/h correction for improved resolution
  - Particle Flow Calorimeter (PFCAL) –follow work of CALICE
    - using GEM/Micromegas – fine transverse & longitudinal segmentation to measure shower topology

DREAM concept



CALICE concept