E/Gamma Performance & Jet/MET Performance

Focused on Extension

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Wednesday 5th October, 2016

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4. Missing E_T
   - Phase-I Performace
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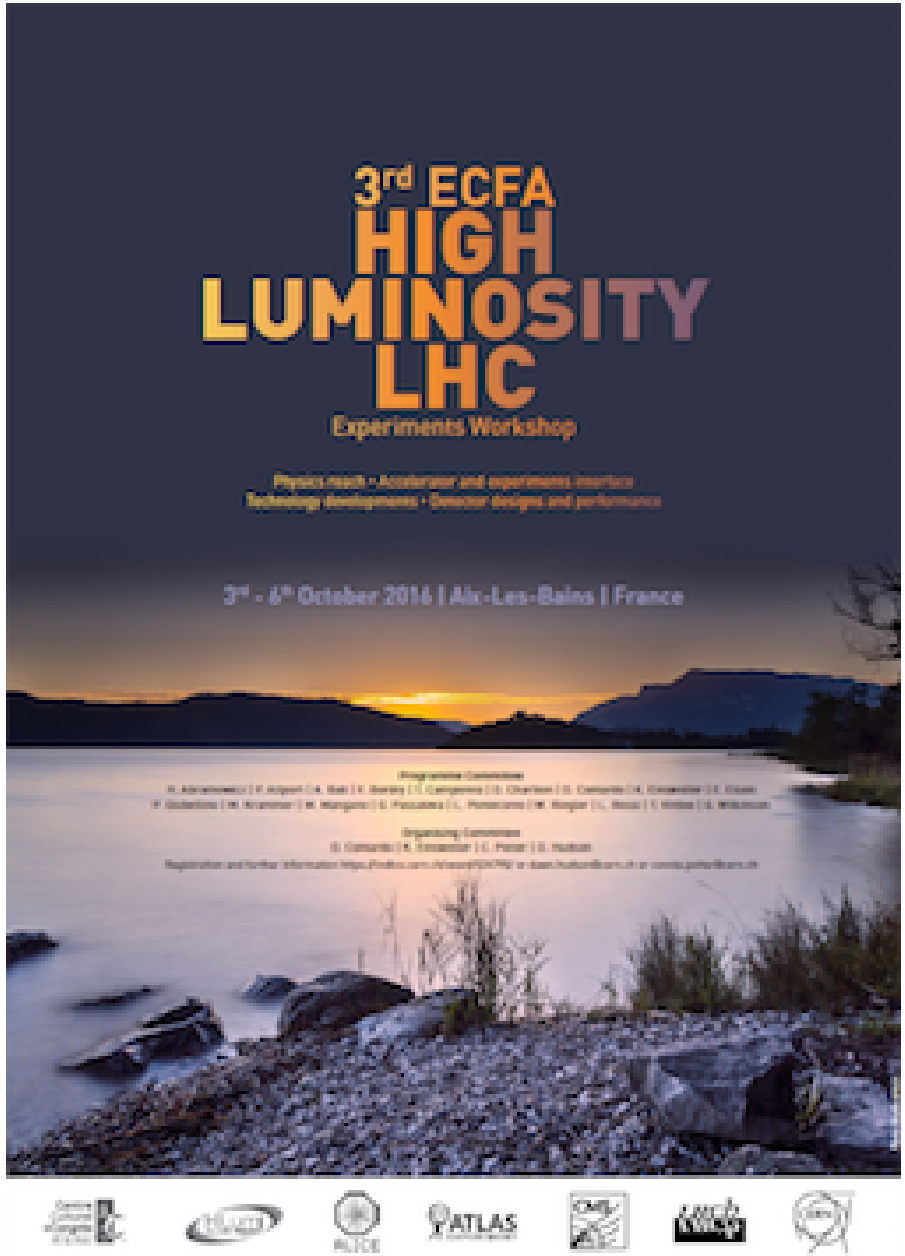
   - Extension Performance
5. Conclusion



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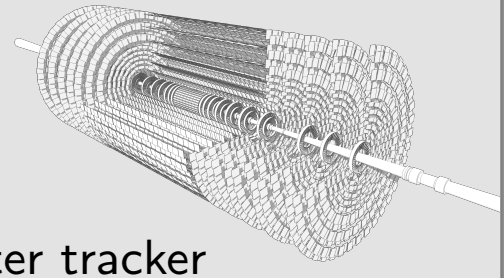

- New Tracker:
  - Radiation tolerant
  - High granularity
  - Tilted modules in outer tracker
  - Less material
  - Tracks in hardware trigger (track trigger)
  - Extended coverage up to $|\eta| \approx 4$
- New Endcap Calorimeters:
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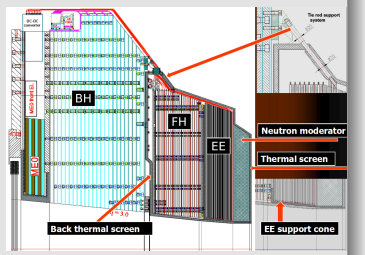
  - High granularity
  - Coverage of $1.5 < |\eta| < 3.0$



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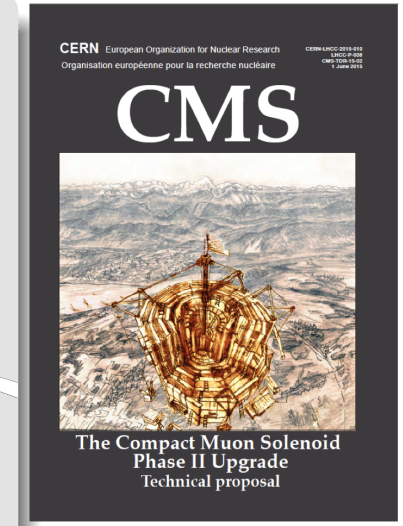

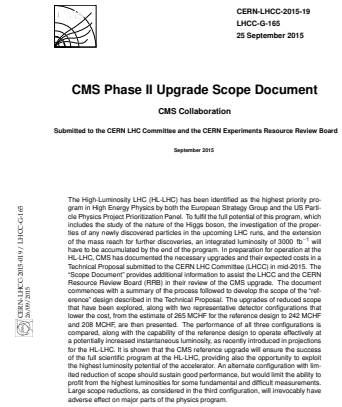

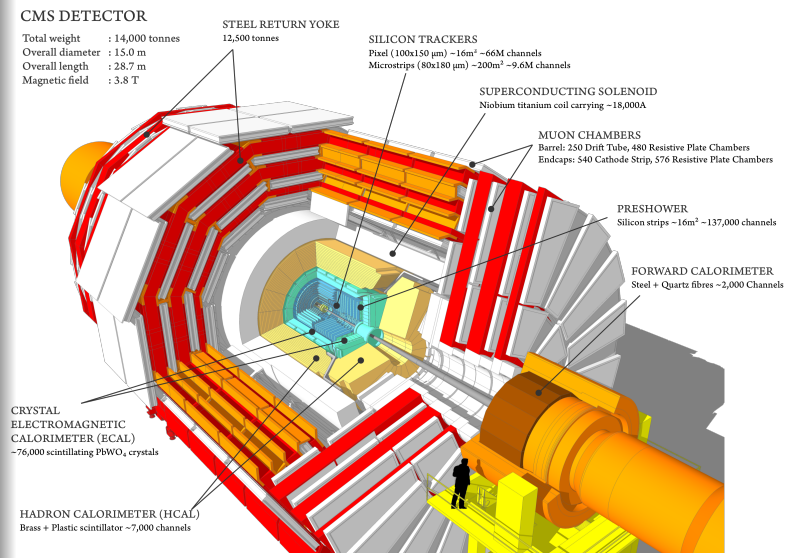

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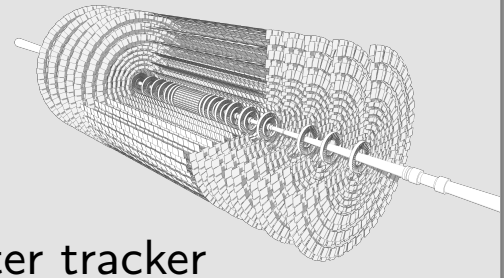

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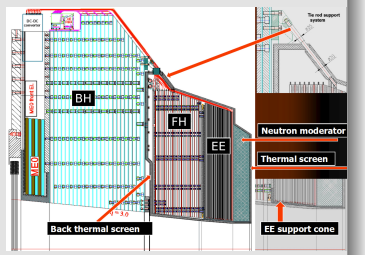

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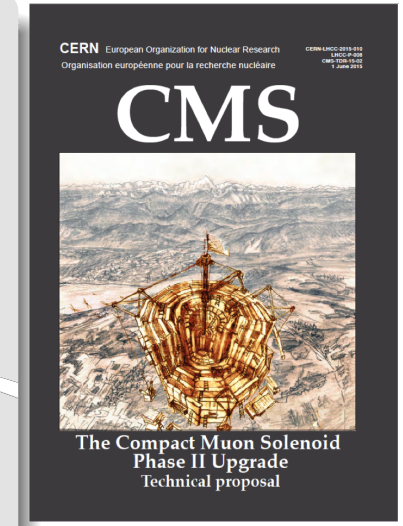
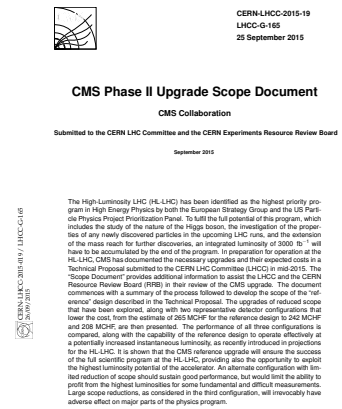
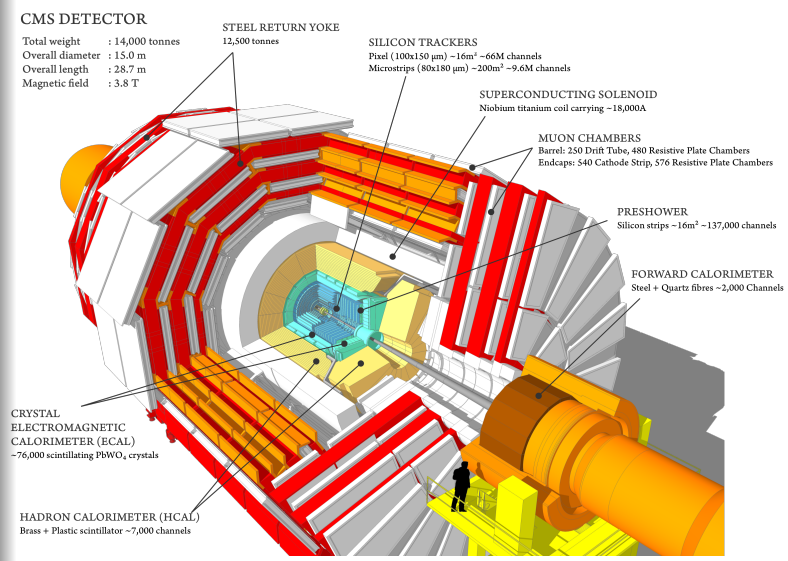




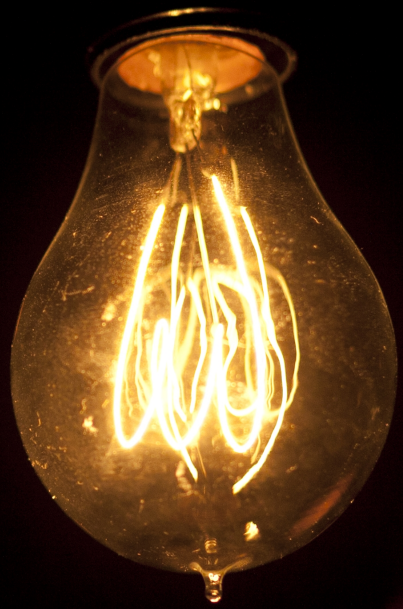


Detector Simulations

Configurations

- Baseline Simulations - What we are comparing to:
  - Un-aged Phase-I detector at $\langle\mu\rangle = 50$
    - Desired performance to maintain
  - Aged Phase-I detector at $\langle\mu\rangle = 140$
    - Radiation damage to outer tracker and calorimeters after exposure to 1000 fb^{-1}
    - Demonstrates why upgrades are needed
- TP/SD Reference Detector:
  - Upgraded tracker, muon system, and calorimetry
  - Extended Phase-I pixel detector
  - Instantaneous luminosities:
    - $5.0\times10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ ($\langle\mu\rangle = 140$)
    - $7.5\times10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ ($\langle\mu\rangle = 200$)
- Eventually we will have the all components of the upgrade implemented in the simulation framework (i.e. Phase-II pixel detector, finalized reconstruction algorithms for HGCAL, etc.)

e/γ Performance



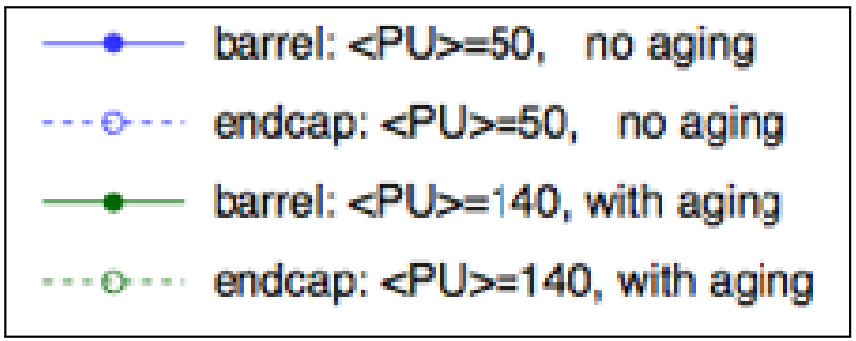
Phase I e/γ Performance

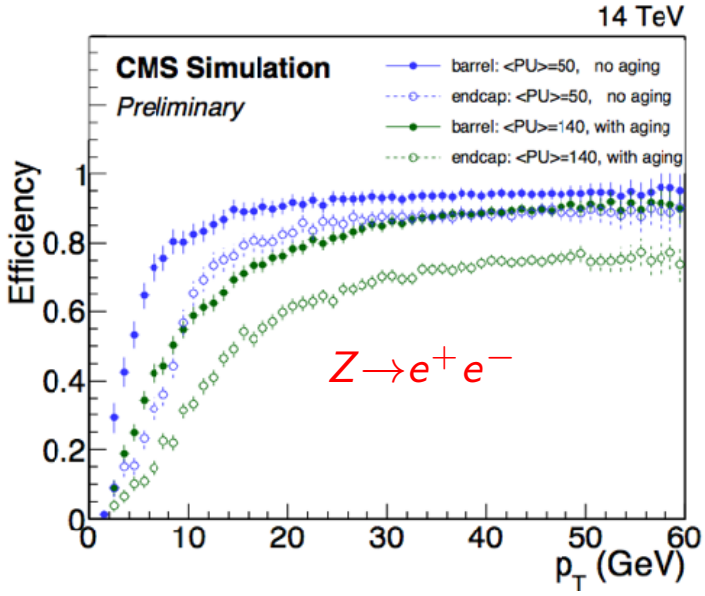
Efficiency

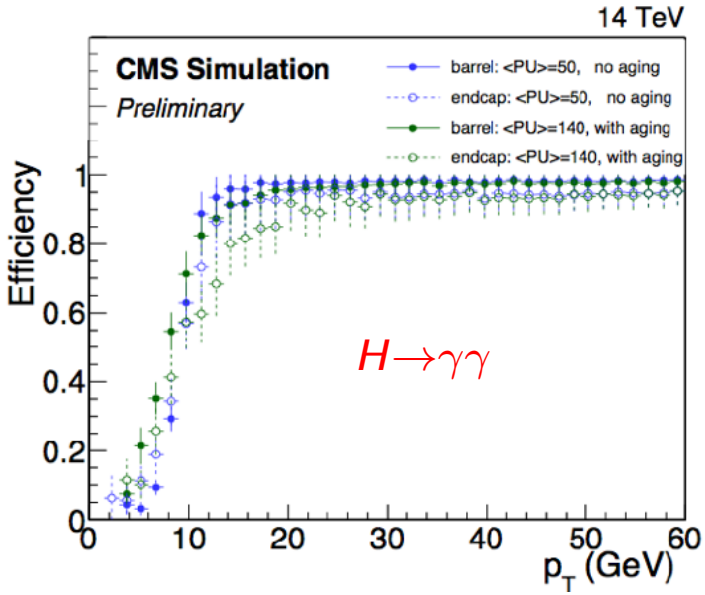
Reconstruction Efficiency

$$\epsilon = \frac{N_{e/\gamma}^{reco,matched}}{N_{e/\gamma}^{truth}} \quad (1)$$

- Degradation in efficiency due to pileup and aging
- Aging due to irradiation corresponding to 1000 fb^{-1} of integrated luminosity
- The turn-on for electron efficiency is slow when using the aged detector
- Smaller, but noticeable drop in efficiency for photons





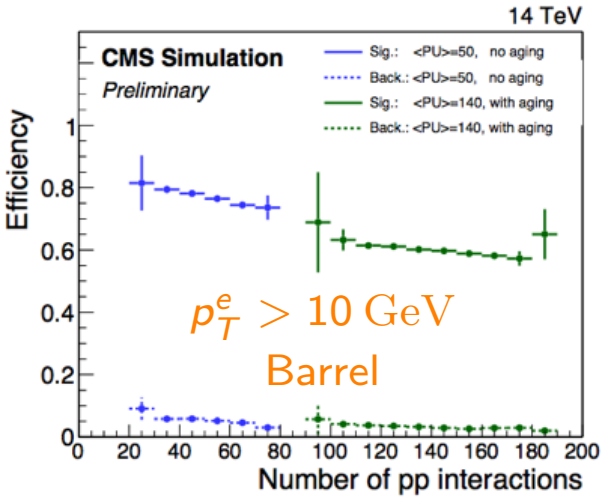


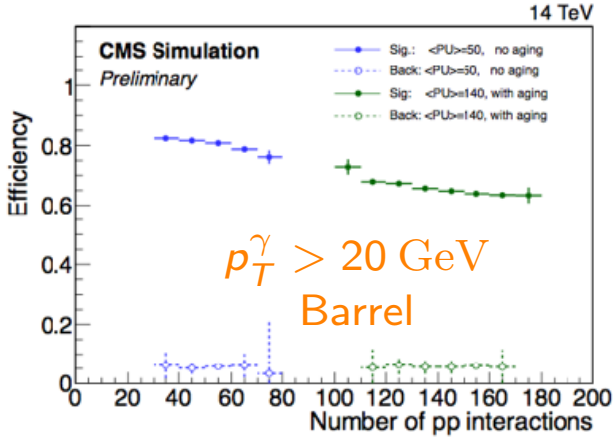
Phase I e/γ Performance

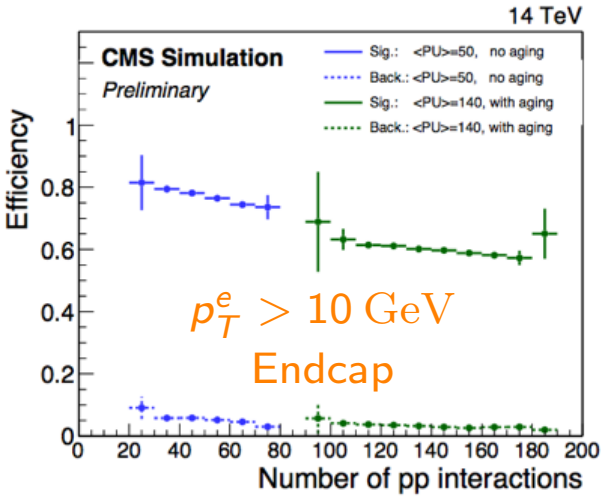
Efficiency

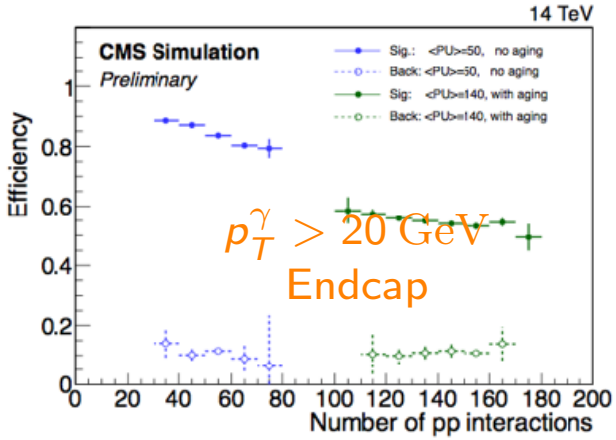
Identification Efficiency

- Efficiency of the e/γ cut-based ID selection as a function of the PU
  - With respect to the reconstruction efficiency
- Selection cuts are tuned to have the same background efficiency for the different PU regimes
  - Less signal efficiency for aged Phase I detector
- The efficiency continues to degrade as pileup increases









Signal: $Z \to e^+e^-$
Background: QCD

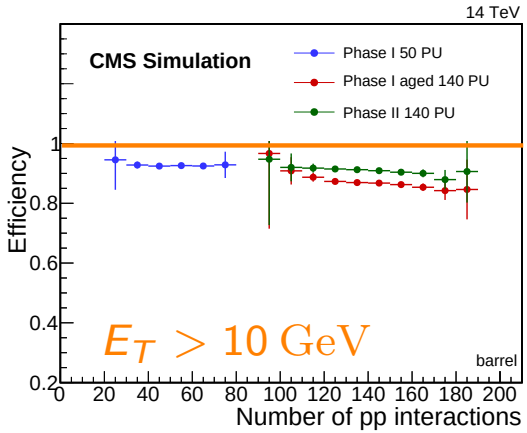
Signal: $H \to \gamma\gamma$
Background: $\gamma + jet$

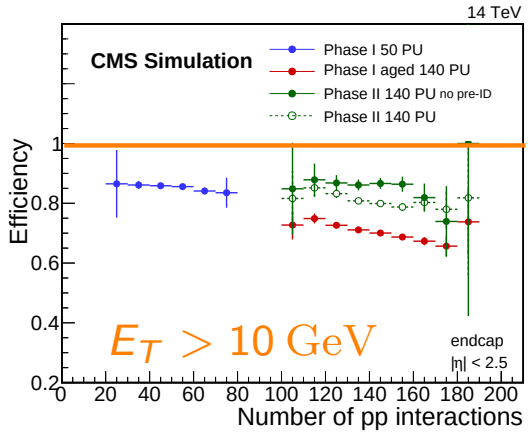
Upgrade Performance

Electrons

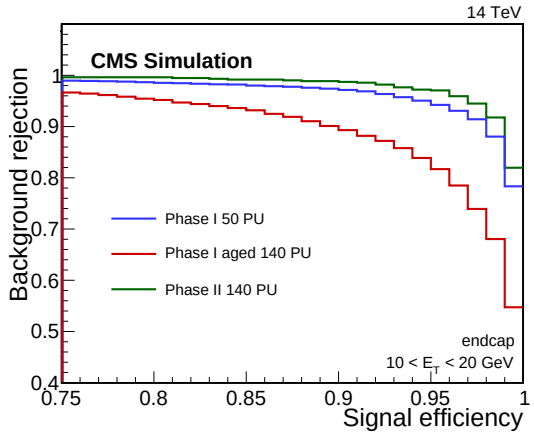
- Degradation in Phase-I aged electron **reconstruction** efficiency
  - Endcap degradation up to $\sim 20\%$
  - Phase-II upgrade fully recovers the reconstruction efficiency
  - Fake rate kept under control
- Electron **identification** similar or better after the upgrade
  - Background rejection within 1% for $E_T > 20\,\mathrm{GeV}$
  - Fake rate at the Phase-I un-aged level

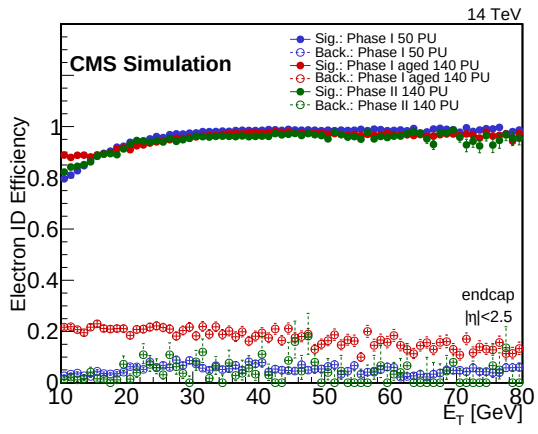
Reconstruction Efficiency ($\epsilon = N_e^{matched}/N_e^{truth}$)





Identification Performance ($\epsilon = N_e^{passing}/N_e^{reco}$)





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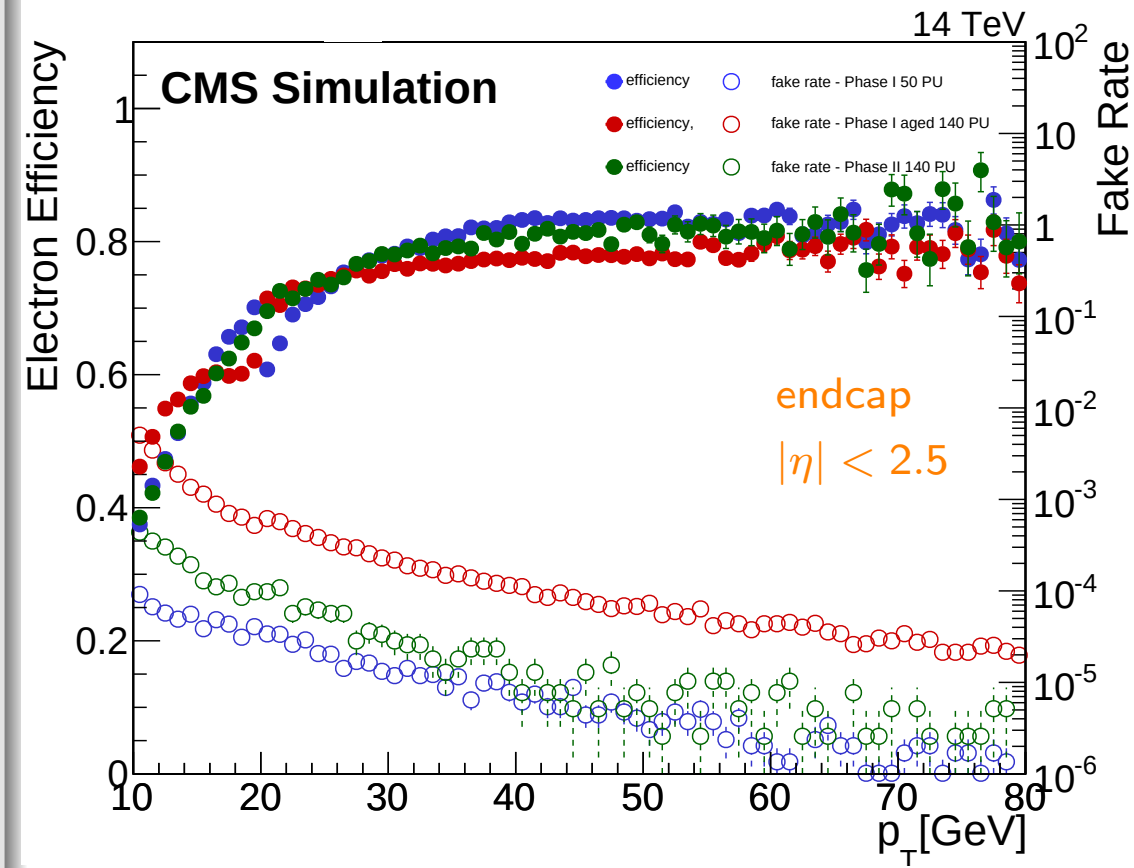
- Electron selection efficiency at the desired performance with the Phase-II upgrade
  - Fake rate almost at Phase-I PU50 level

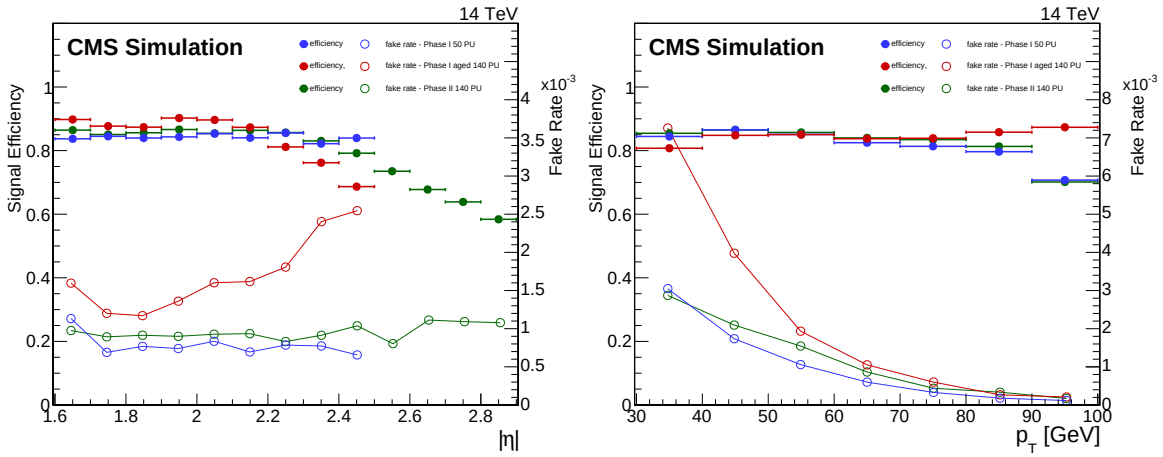


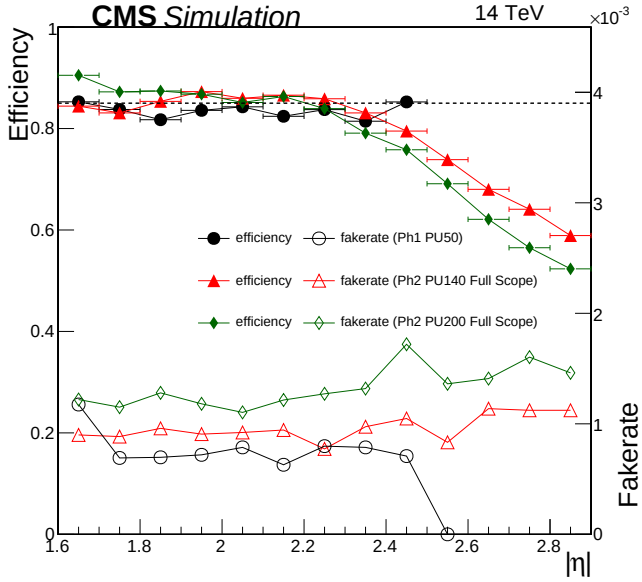
Upgrade Performance

Photons

- Photon selection efficiency at the desired performance with the Phase-II upgrade
  - Fake rate almost at Phase-I PU50 level
- Fake rate explodes for the Phase-I aged sample
- Clear extension to photon reconstruction ability in $|\eta|$
- Selection performance at $\langle\mu\rangle = 200$ is similar, but degraded to the performance for $\langle\mu\rangle = 140$

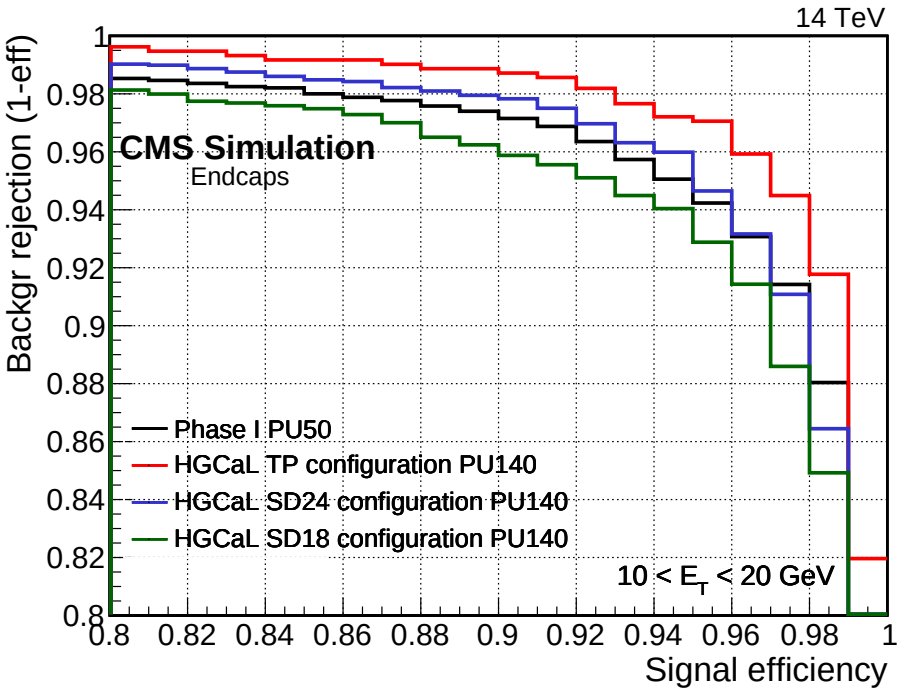
Selection Efficiency ($\epsilon = N_\gamma^{passing} / N_\gamma^{truth}$)

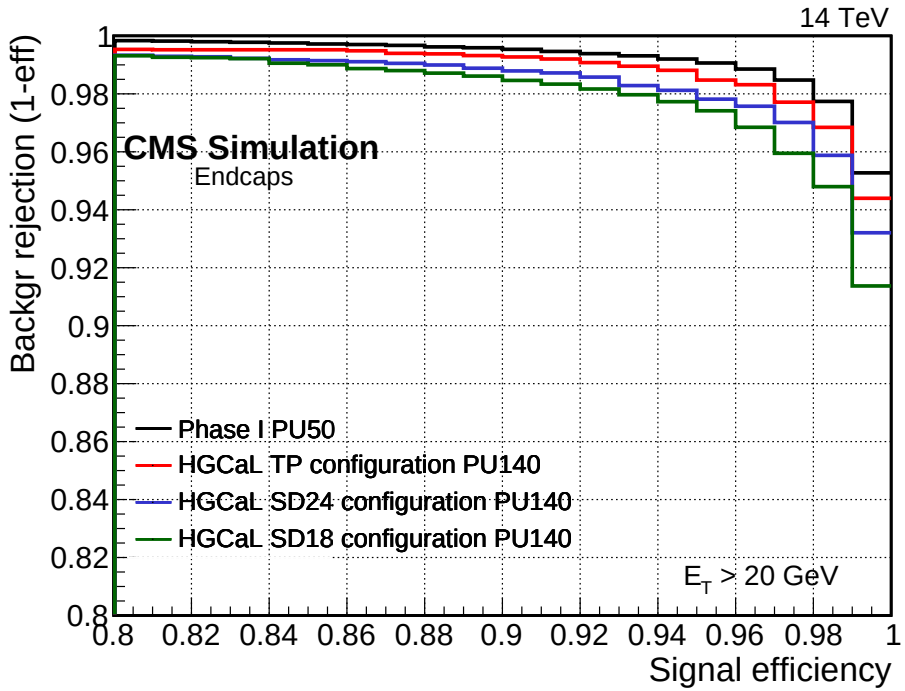




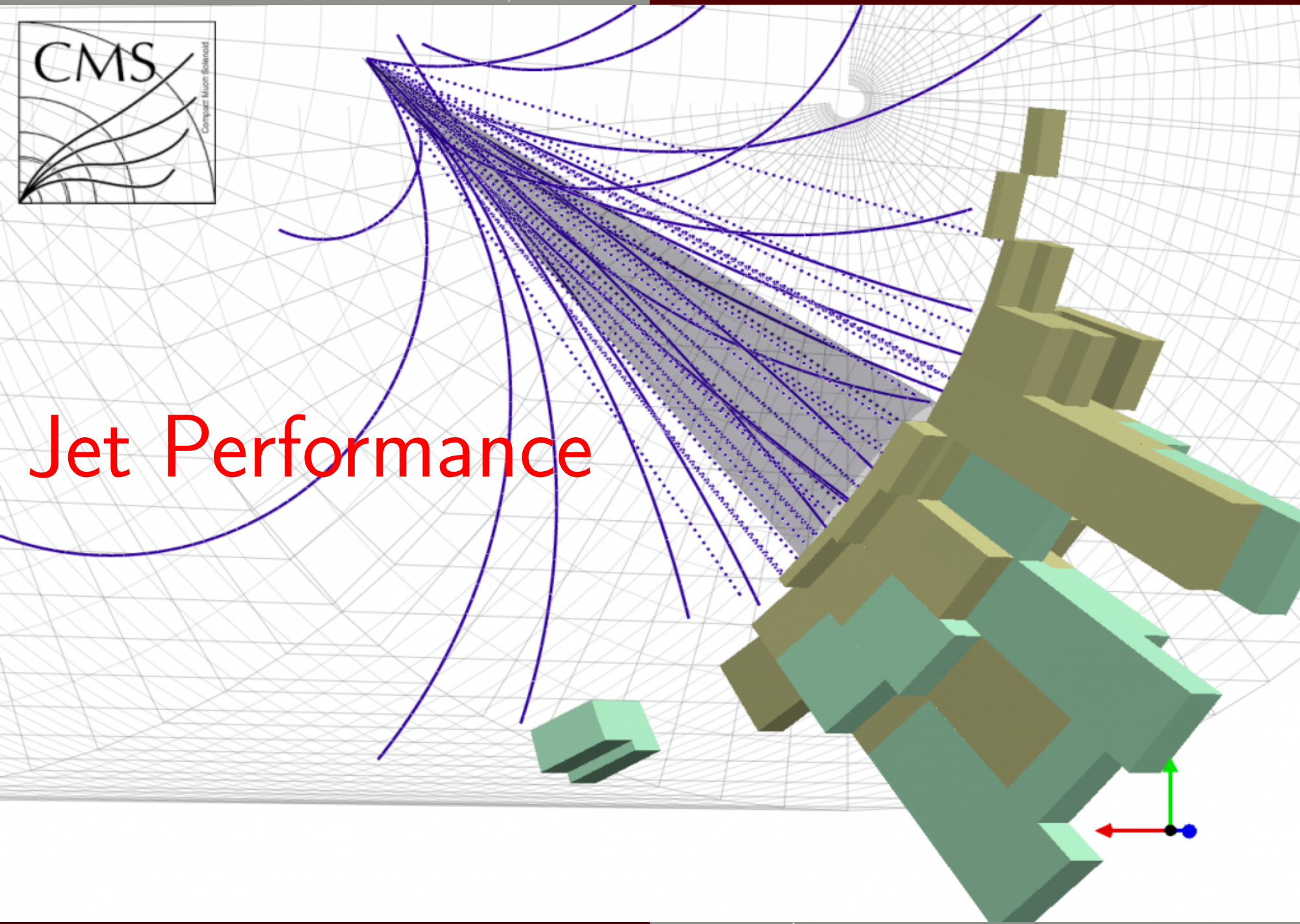
Performance With Reduced Extension

- Any reduction in the tracker coverage will reduce extended e/γ reconstruction (see previous slide for example)
- Similarly there will be performance losses when reducing the scope of the HGCAL
  - Any loss in layers means a degradation in electron identification efficiency
    - For a given signal efficiency we lose in background rejection
    - This has a significant impact on analyses like $H \rightarrow 4e$





Jet Performance



Pileup Mitigation Algorithms

- CMS makes use of three types of jets called PF, PFchs, and PUPPI jets
  - All jets start with the output of the particle-flow (PF) algorithm
  - Candidates come from the primary interaction, pileup interactions, or from an overlap of many interactions
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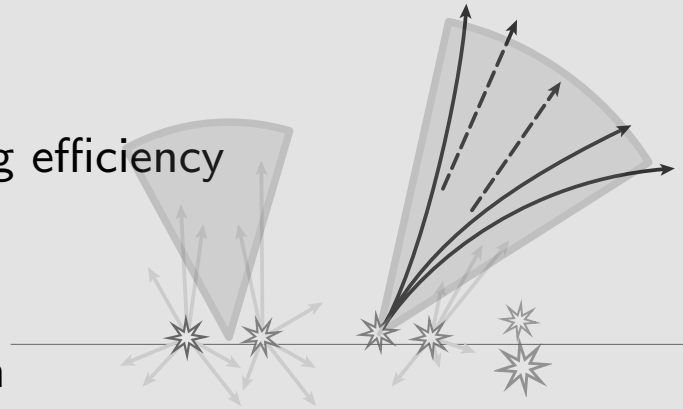
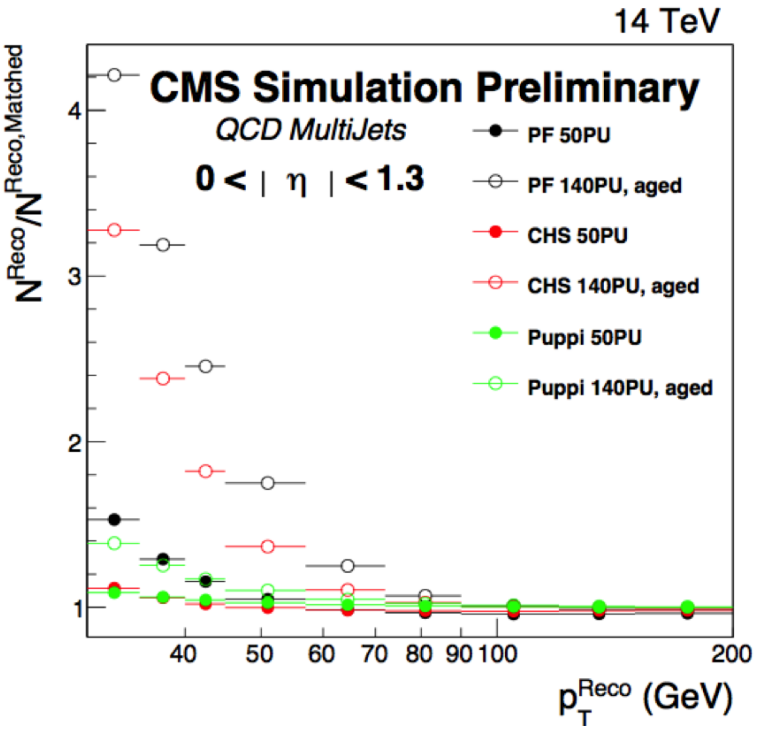
  - PF candidates whose tracks can be traced to a pileup vertex are removed before clustering
  - Only removes charged hadrons, but cannot remove photons and neutral hadrons
- Pile-Up Per Particle Identification (PUPPI) performs better at pileup mitigation than both PF and PFchs jets
  - Computes a likelihood that a particle come from the primary vertex and then weights that particle according to the likelihood
  - The weighted particles are passed to the clustering algorithm
  - Because it removes soft and non-collinear pileup particles very well, PUPPI improves the jet resolution over PF and PFchs jets

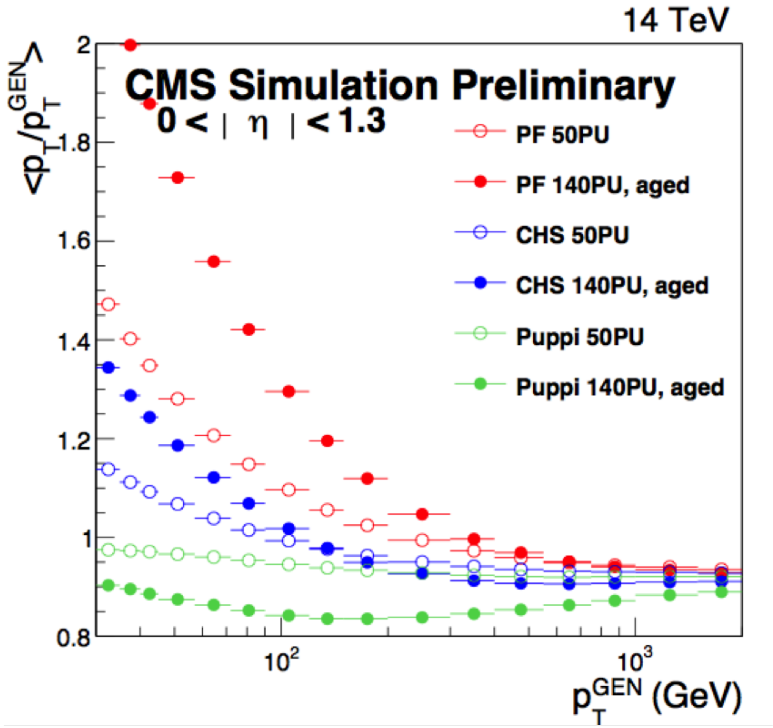
Phase I Jet Performance

Response & Multiplicity

- Significant increase in jet multiplicity cause by:
  1. Increased pileup
  2. Increased number of fake tracks, lower tracking efficiency
  3. Age/radiation damage and lower acceptance
- PUPPI keeps this increase at a reasonable level
- The jet response is also worse for each jet collection



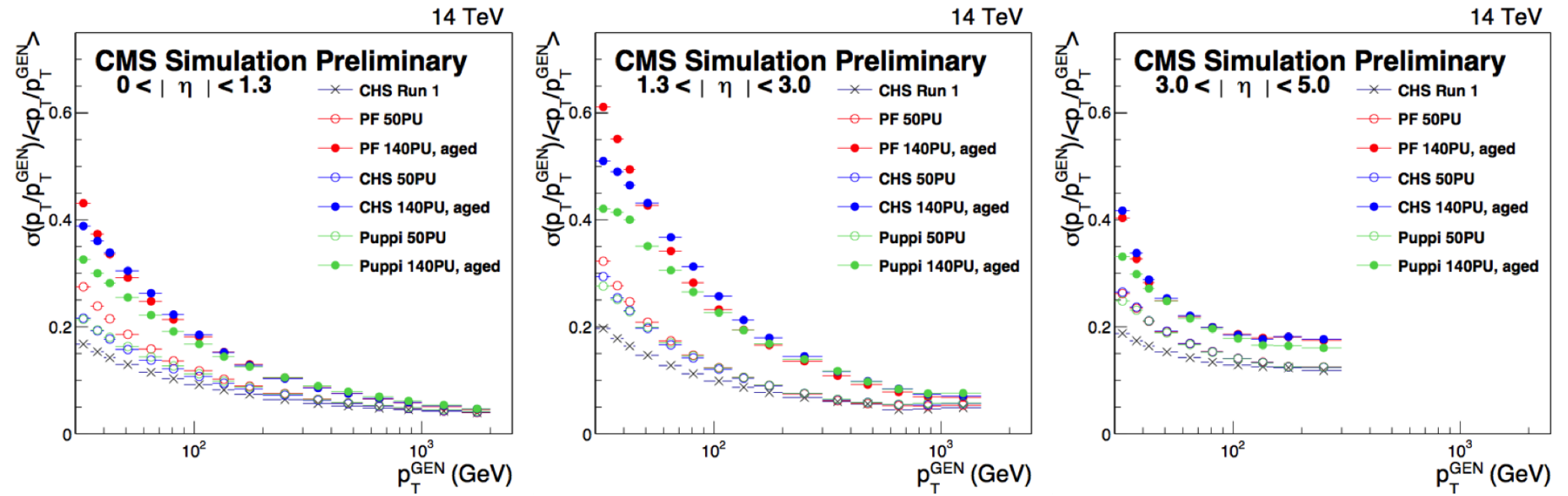




Phase I Jet Performance

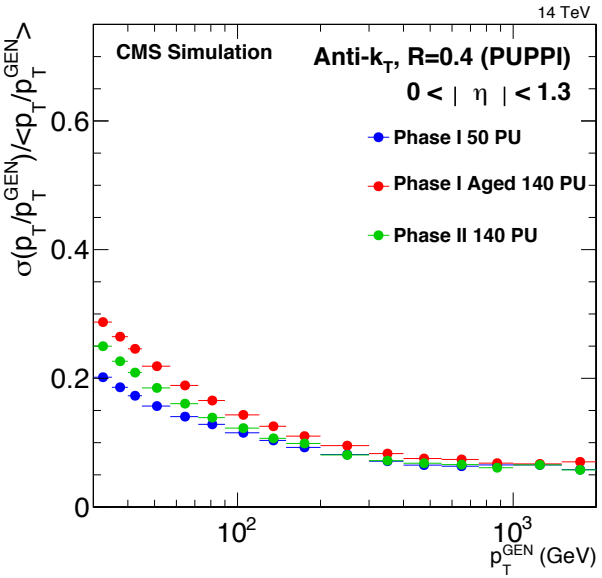
Resolution

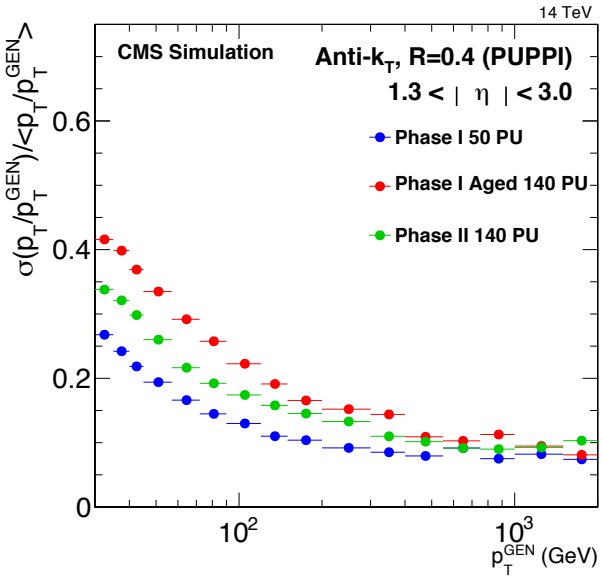
- Jet resolution is degraded by both the increased pileup and the aged Phase I detector
- Charged Hadron Subtraction no longer enough:
  - Increased amount of fake tracks, lower tracking efficiency
  - Age and acceptance are also factors
- PUPPI provides an improvement at low p_T
  - Even at at $|\eta| > 2.5$ where there is no tracker
- The Phase-II tracker and calorimeter upgrades should recover the lost jet resolution

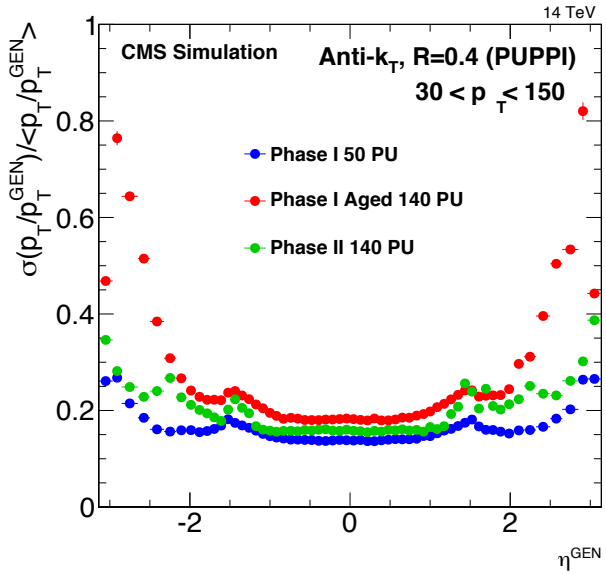


Upgraded Performance

- Jet resolution is a good metric of the Phase-II upgrade performance
- Resolution degrades significantly going from the Phase-I 50 PU sample to the Phase-I aged 140 PU sample, for all jet types
  - This is due to the age of the detector and the larger amount of pileup
- All jet types show some improvement with the Phase-II detector
  - PUPPI takes the most advantage and shows the greatest improvement (i.e. $\sim 20\%$ in the barrel for $p_T^{gen} = 30\,\mathrm{GeV}$)
- Radiation damage clearly seen in the endcap region of the Phase-I aged detector
  - This effect is mitigated by the tracker extension, upgraded electromagnetic calorimeter, and rebuilt hadronic calorimeter in the Phase-II detector



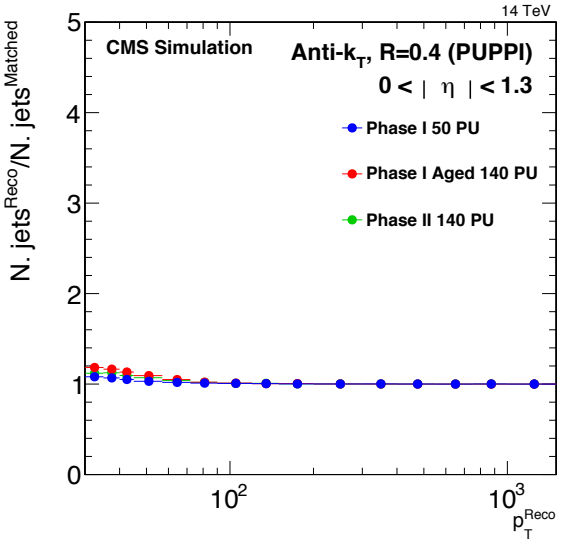


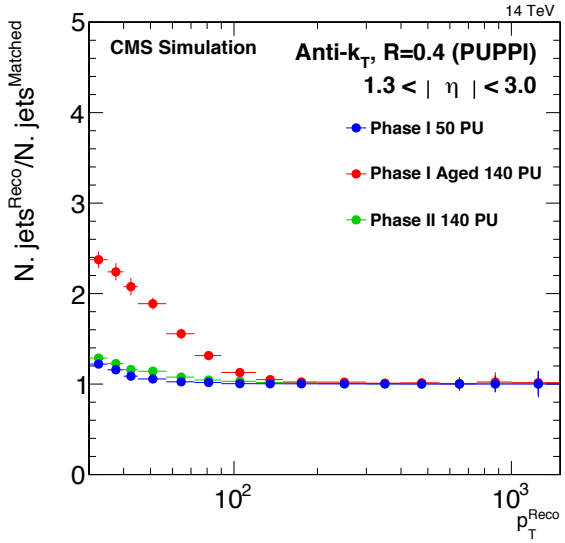


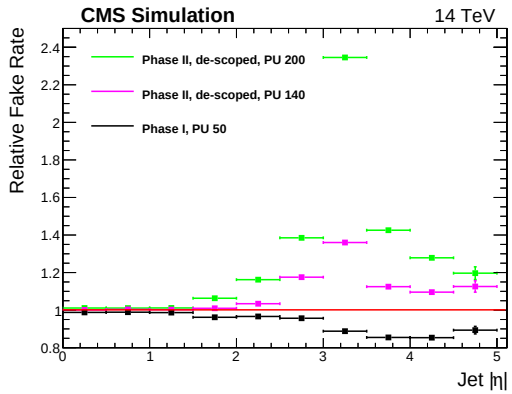
Performance Due to Extension

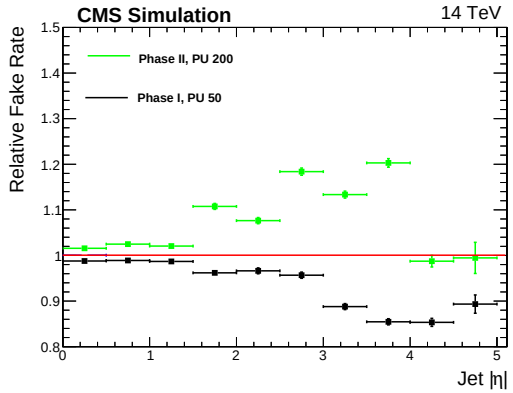
Pileup-Jet Misidentification

- There is an increase in the number of "fake" hard-scatter jets as pileup increases
  - The number of these "pileup jets" depends on the p_T, η and jet algorithm
- The fake-rate can be quantified as $N_{jets}^{reco}/N_{jets}^{matched}$
- For the aged Phase-I sample this number more than doubles at low p_T, even with the PUPPI algorithm
  - This effect is mitigated almost completely by the Phase-II upgrade
  - No tracking extension or a reduced HGCAL leads to an increase in the fake rate at higher η





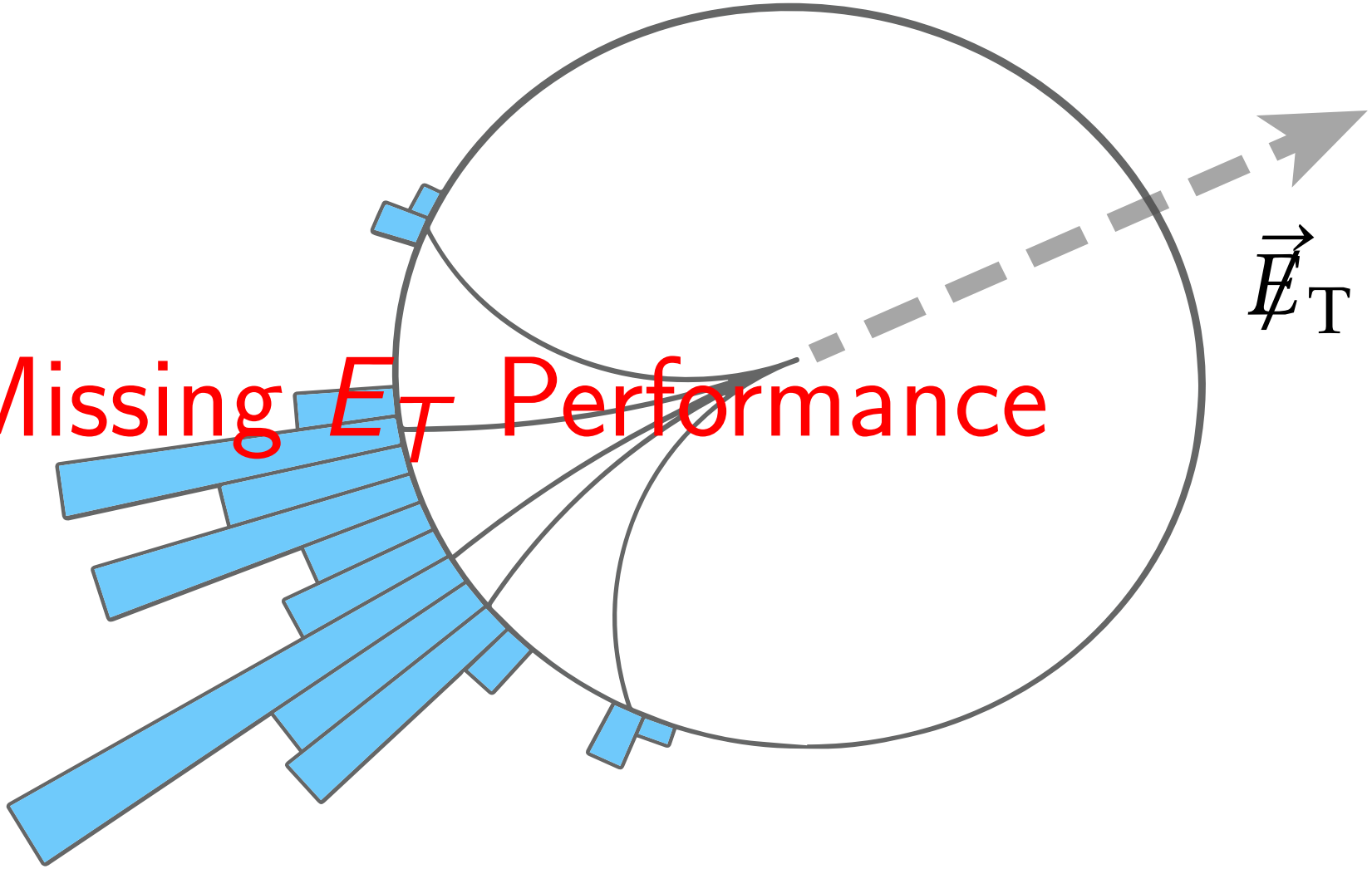




Note

Charged particles outside the tracking acceptance not associated with a vertex
⇒Reduces the efficacy of pileup mitigation algorithms

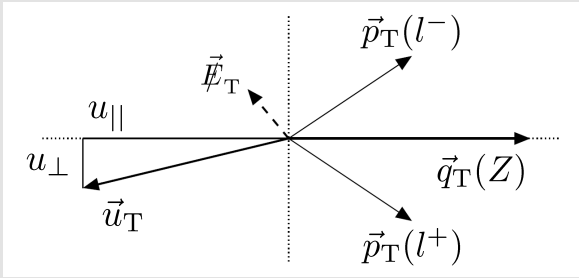
Missing E_T Performance

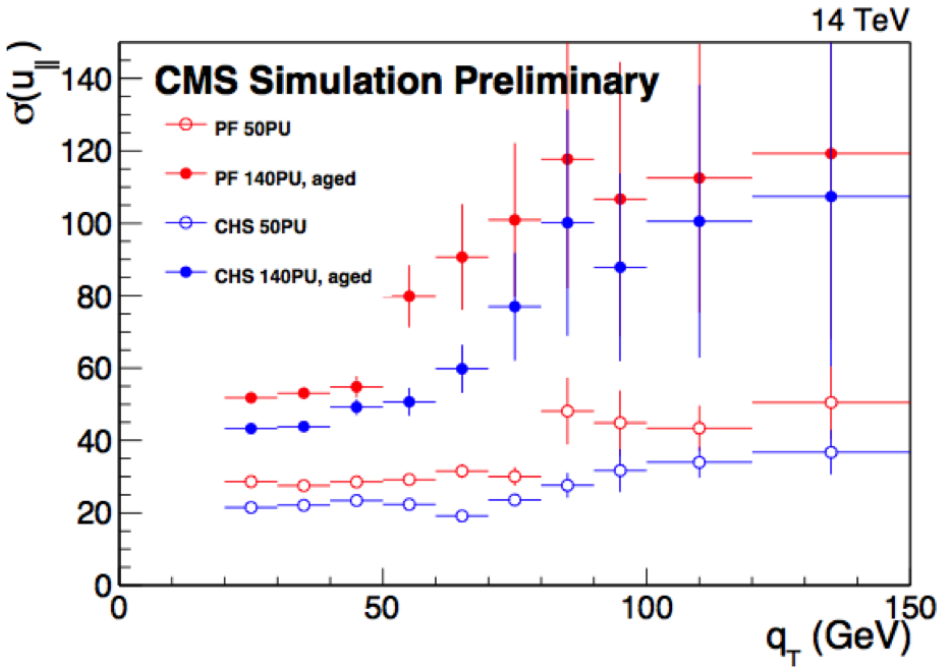


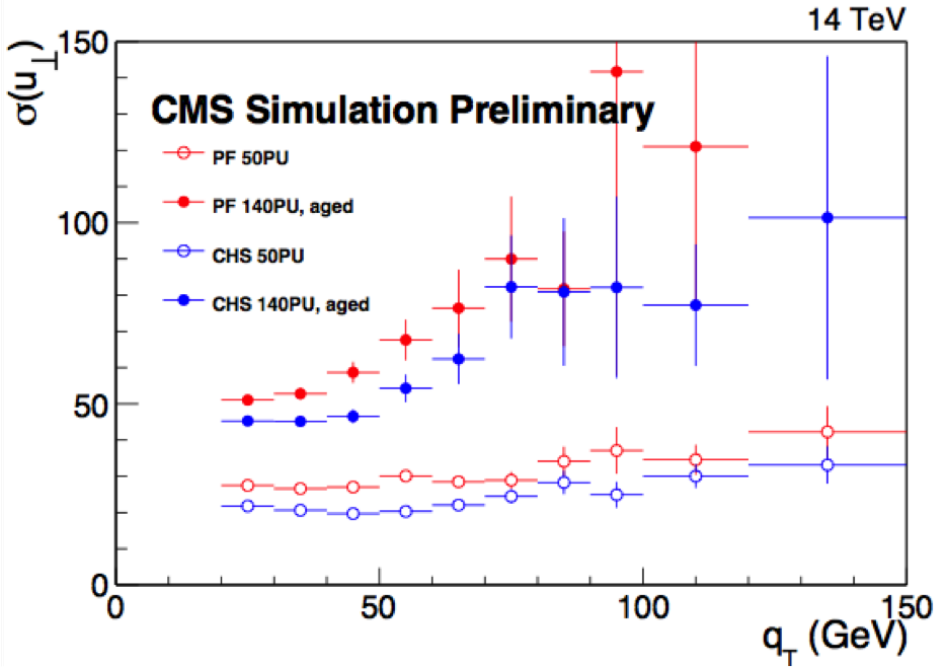
Phase I Missing E_T Performance

Resolution

- The Missing E_T (MET) performance was studied using $Z \to \mu^+\mu^-$ decays
- Clearly there is a degradation in the MET resolution when we move to higher PU and an aged detector





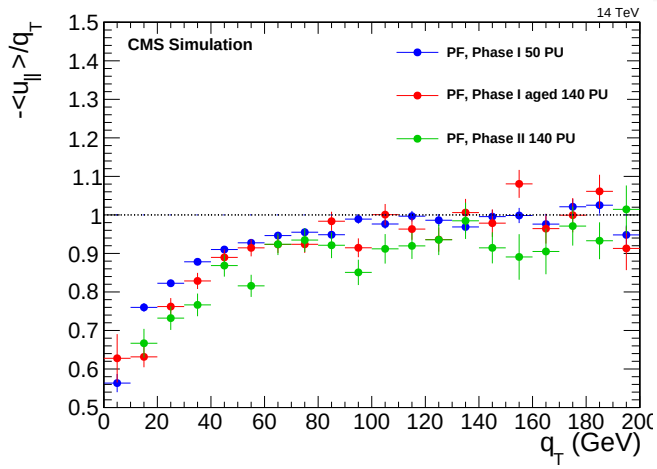


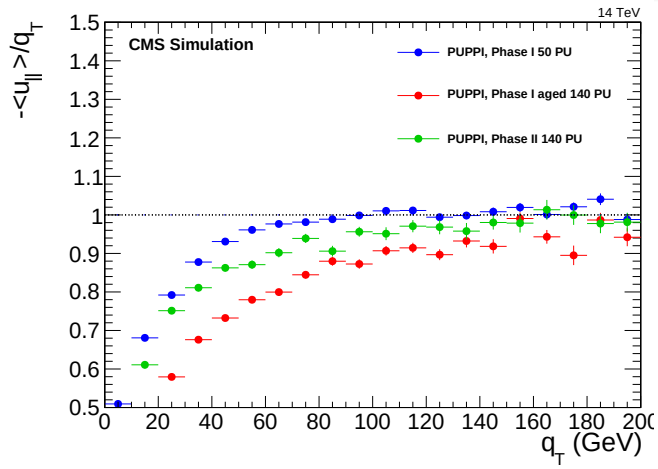
Upgrade Performance

Response & Resolution

Response

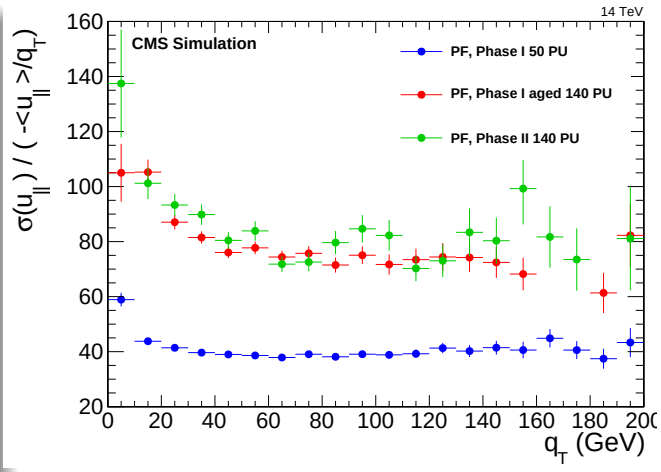
- Response is improved with the Phase-II detector over the aged Phase-I detector
- Better JEC and PUPPI tuning will help the response

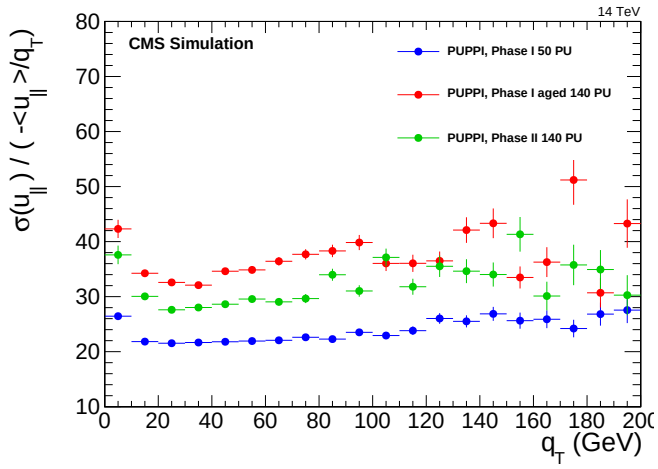




Resolution

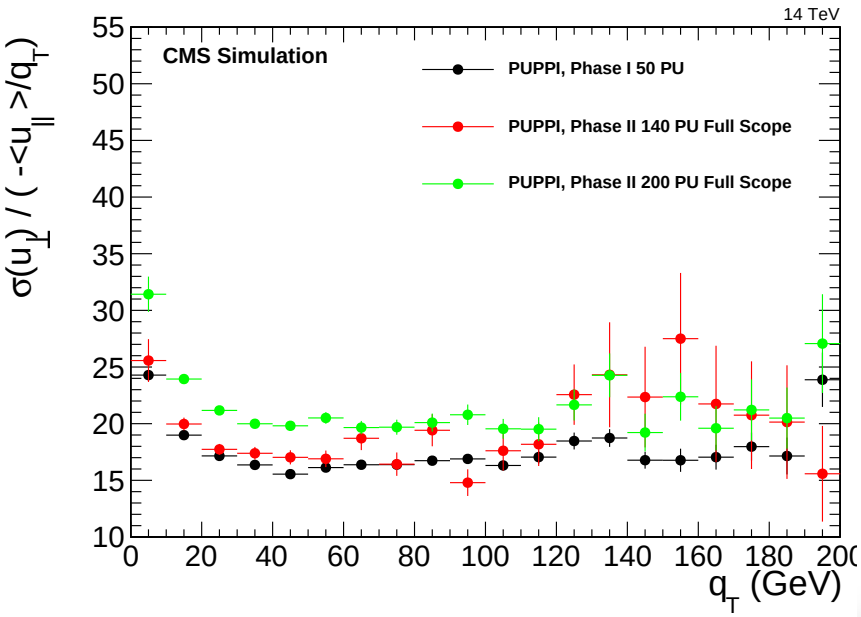
- PUPPI MET resolution recovered with Phase-II detector (left and right plots)
- PUPPI MET resolution is **twice** as good as PF and improves with the Phase-II detector

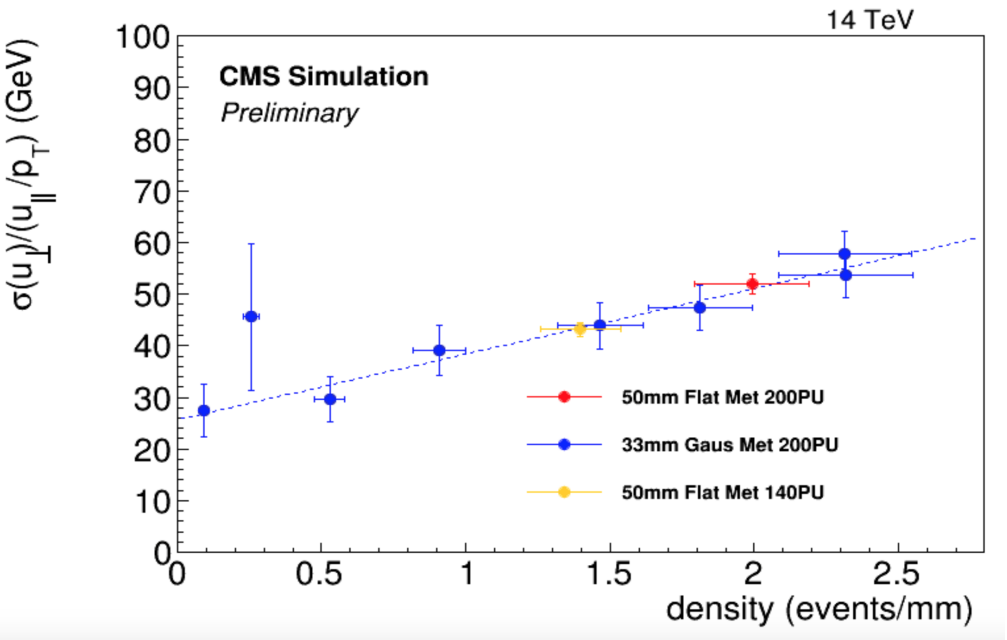




Upgrade Performance

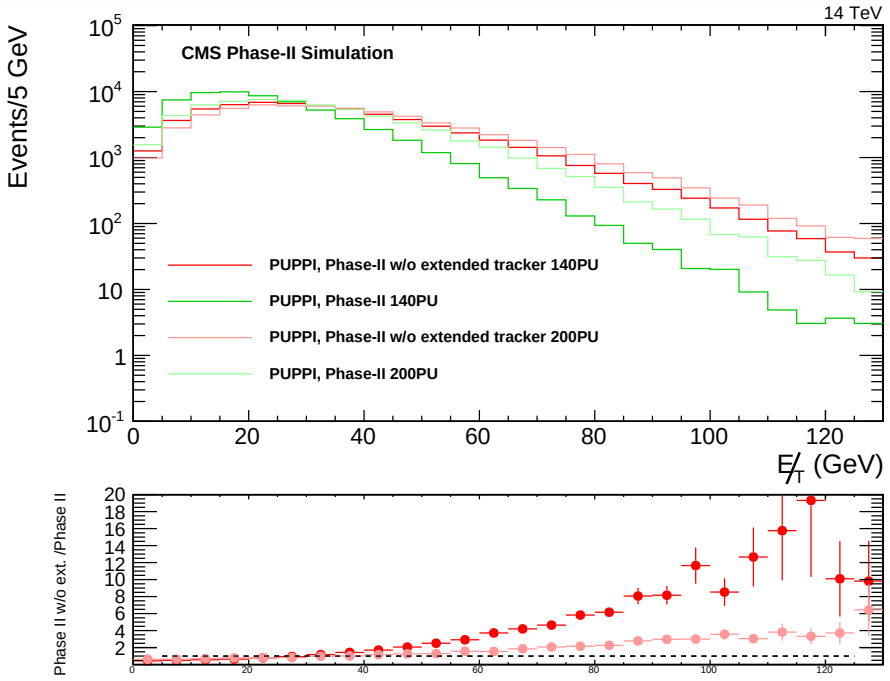
Resolution Vs. Pileup

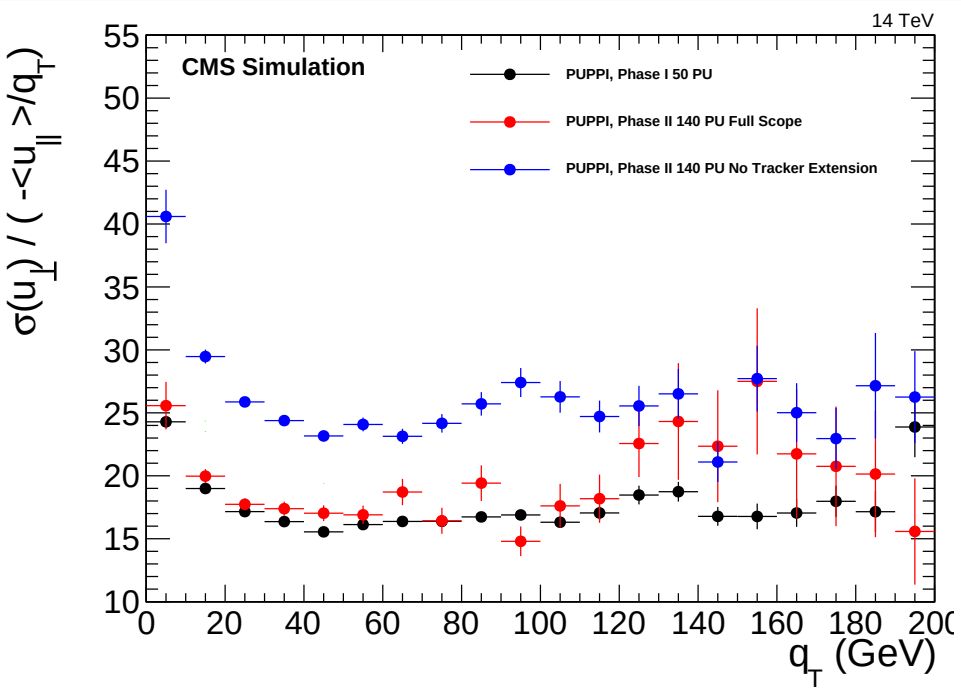




- PUPPI MET resolution at $\langle\mu\rangle = 200$ is slightly worse than at $\langle\mu\rangle = 140$, but not by much
  - PUPPI makes good use of vertexing
  - The resolution is far more dependent on the **pileup density** than on the absolute value of $\langle\mu\rangle$
- In contrast, PF MET is more dependent upon $\langle\mu\rangle$ because it does not use vertexing for pileup mitigation

Performance Due to Extension





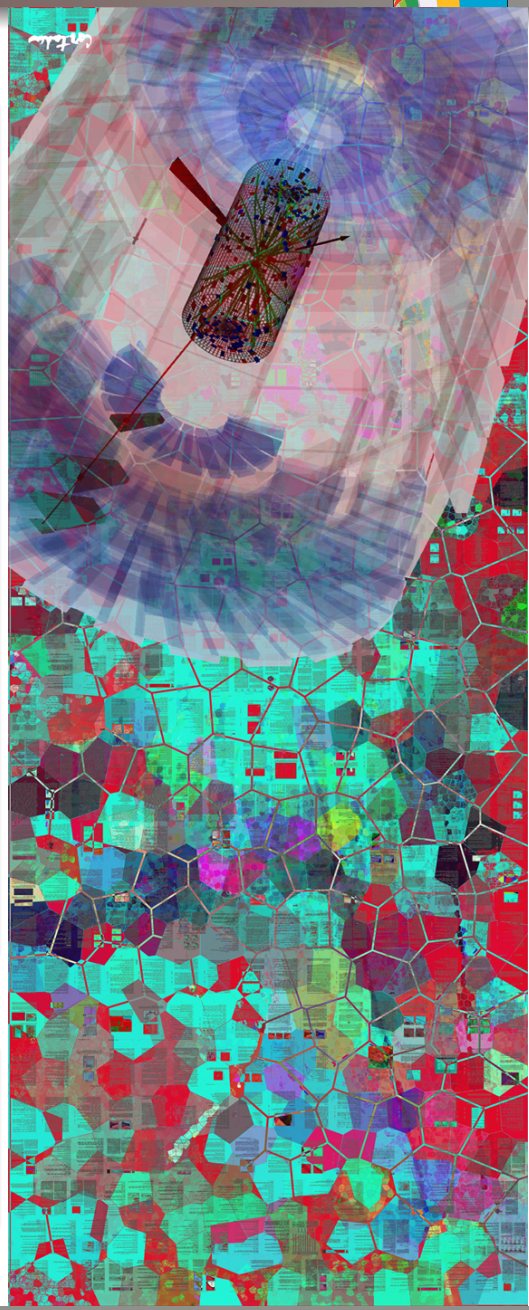
- PF and pileup mitigation strongly influenced by tracking performance
  - In Phase-I and a reduced version of Phase-II there is no tracking help at $|\eta| > 2.5$
- Without the tracker extension the rate of mis-reconstructed MET increases
  - Since these are Drell-Yan events, less (false) MET means better reconstruction
- The MET resolution is also degraded by $\sim 25\%$ at 140 pileup without the tracker extension

Conclusion

Summary

- The electron, photon, jet, and MET object performances have been show using several reference detectors
  - Demonstrates a clear need for an upgrade at the end of the Phase-I lifespan
- Upgraded tracker η coverage and calorimeters help maintain or improve the e/γ selection performance
- Forward tracking useful for jets and MET in mitigating the effects of high pileup likely to be seen at HL-LHC
  - Will gain even more in performance when PUPPI is tuned for the actual detector configuration and finalized reconstruction algorithms

- Object performance studies are still ongoing and the detector simulations are still evolving
  - New results right around the corner!



References

[1] J Butler et al. *CMS Phase II Upgrade Scope Document*. Tech. rep. CERN-LHCC-2015-019. LHCC-G-165. Geneva: CERN, Sept. 2015. URL: https://cds.cern.ch/record/2055167.

[2] The CMS Collaboration. *Updates on Projections of Physics studies with the upgraded CMS detector for HL-LHC, prepared for ECFA 2016*. Tech. rep. CMS DP-2016/065. Geneva: CERN, Oct. 2016. URL: https://twiki.cern.ch/twiki/pub/CMS/AnalysisNotesECFA2016/ECFA2016_PhysicsProjections_final_Oct032016.pdf.

[3] D Contardo et al. *Technical Proposal for the Phase-II Upgrade of the CMS Detector*. Tech. rep. CERN-LHCC-2015-010. LHCC-P-008. CMS-TDR-15-02. Upgrade Project Leader Deputies: Lucia Silvestris (INFN-Bari), Jeremy Mans (University of Minnesota) Additional contacts: Lucia.Silvestris@cern.ch, Jeremy.Mans@cern.ch. Geneva, June 2015. URL: https://cds.cern.ch/record/2020886.

Backup Slides

Upgraded Detector

Scoped

- In addition to the technical proposal, CMS produced a scope document (SD) with two upgrade configurations of lesser cost
  - This talk will include some performance plots from this document as well

De-scoped Configuration 1		
De-scoped item	**Operation and performance impact**	**Recoverability**
Tilted modules in the outer tracker (fewer modules)	Track-trigger resolution	No
No muon endcap station 3 and 4	Redundancy, efficiency, resolution	Yes
No replacement of CSC station 3 and 4 readout	Efficiency at trigger rate $\geq$ 500 kHz	Yes
Reduced HLT/DAQ power	Trigger rate $\leq$ 300 kHz	Yes
HGCAL with 24/11 layers	Energy resolution, pileup mitigation, shower pointing, timing	No

De-scoped Configuration 2		
De-scoped item	**Operation and performance impact**	**Recoverability**
Tilted modules in the outer tracker (fewer modules)	Track-trigger resolution	No
No muon endcap station 3 and 4	Redundancy, efficiency, resolution	Yes
No replacement of CSC station 3 and 4 readout	Efficiency at trigger rate $\geq$ 500 kHz	Yes
Reduced HLT/DAQ power	Trigger rate $\leq$ 300 kHz	Yes
No muon endcap station 2	Redundancy, efficiency, resolution	Yes
No muon extension to $\eta \simeq 3$	Muon acceptance	No
HGCAL with 18/9 layers	Energy resolution, pileup mitigation, shower pointing, timing	No
No Pixel extension to $\eta \simeq 3.8$	Pileup, jet tagging, Missing ET	Yes
No replacement of Muon DT readout	Efficiency and trigger rate $\leq$ 300 kHz	Yes
One less layer in outer tracker barrel	Track-trigger efficiency	No

*e/γ
*Jet/MET
*Both

Upgraded Detector

Scoped

- In addition to the technical proposal, CMS produced a scope document (SD)

Reduced HGCal - Impact

- Energy resolution
- Reconstruction and identification (e/γ/jet)
- Reduction in pattern recognition and shower separation (hard to quantify at this time)

Reduced Tracking - Impact

- Charged particles outside the tracking acceptance not associated with a vertex
  - Reduces the efficacy of pileup mitigation algorithms
- Reduction in e/γ acceptance

No replacement of Muon DT readout	Efficiency and trigger rate $\leq$ 300 kHz	Yes
One less layer in outer tracker barrel	Track-trigger efficiency	No

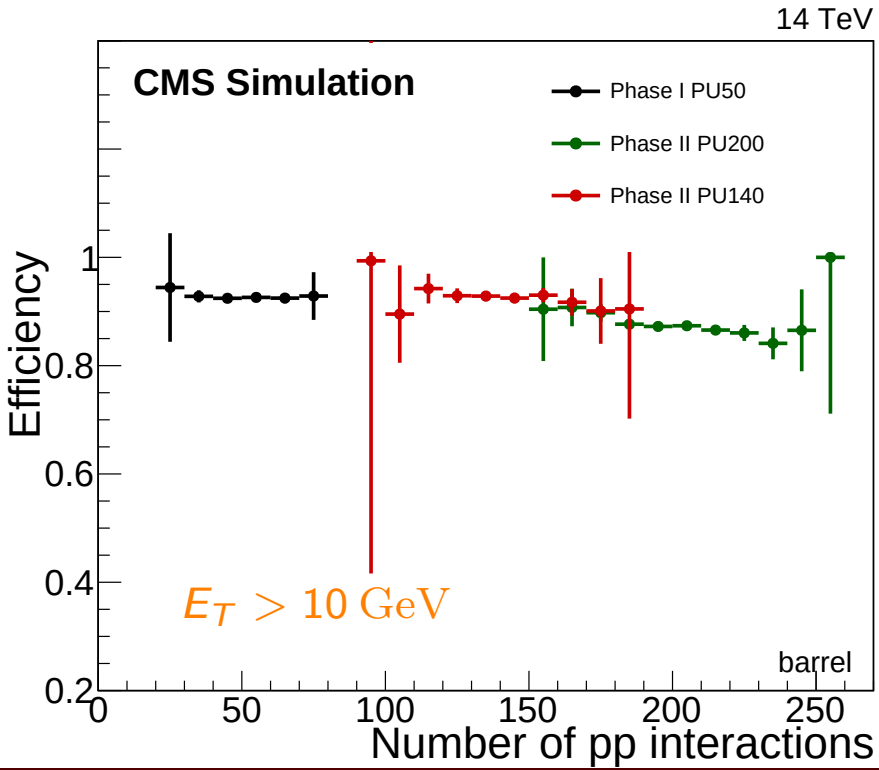
*e/γ
*Jet/MET
*Both

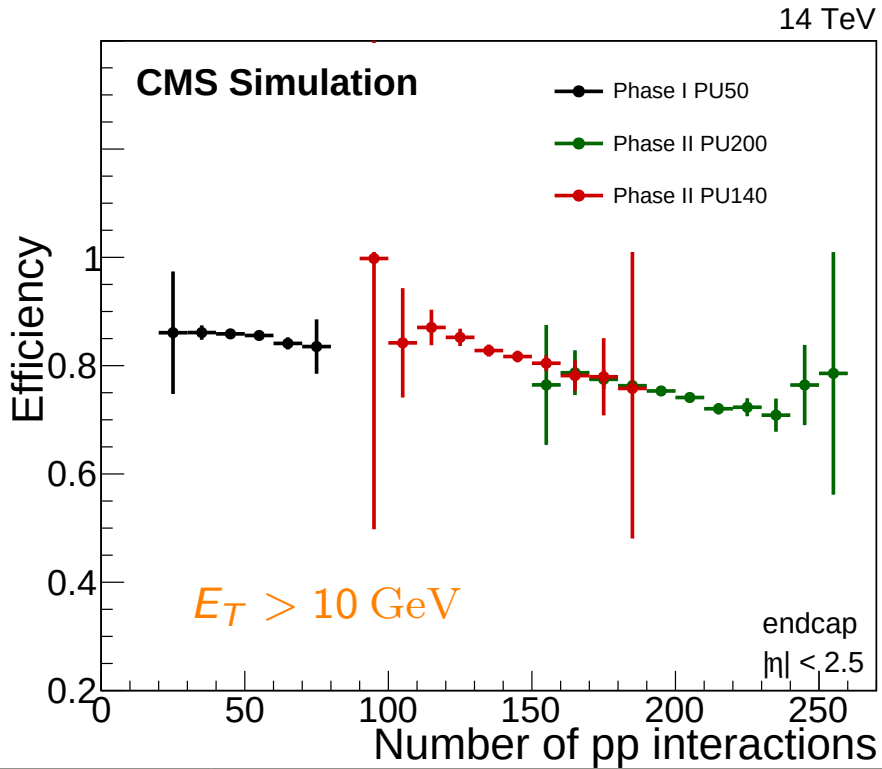
Upgrade Performance

Electrons

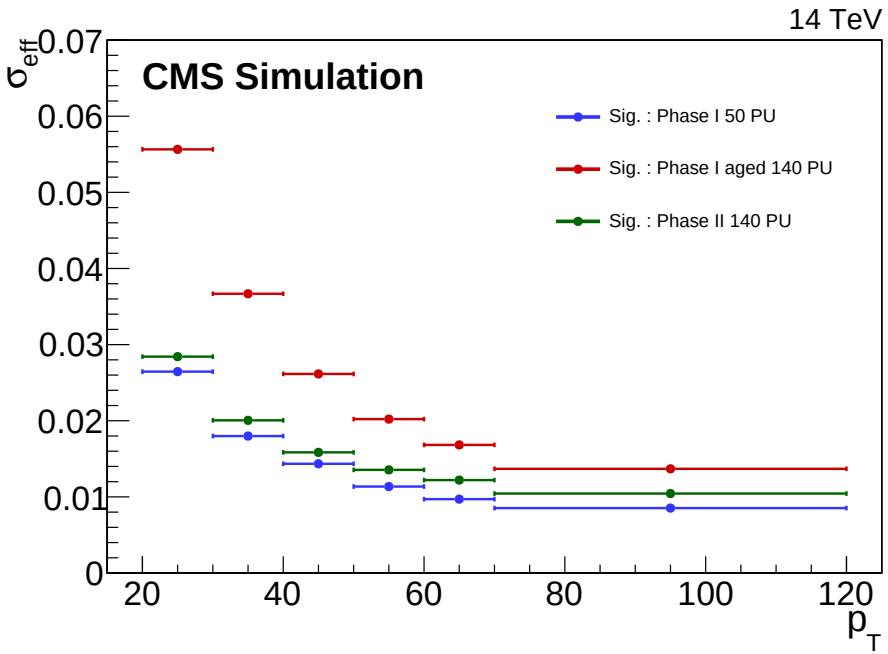
- Phase-II electron reconstruction efficiency mostly stable at higher pileup
  - Average efficiency for $\langle\mu\rangle = 140$ sample same as for the un-aged Phase-I sample
  - Slight degradation in the $\langle\mu\rangle = 200$ sample for the barrel and a clear slope in the endcap

Reconstruction Efficiency ($\epsilon = N_e^{matched}/N_e^{truth}$)

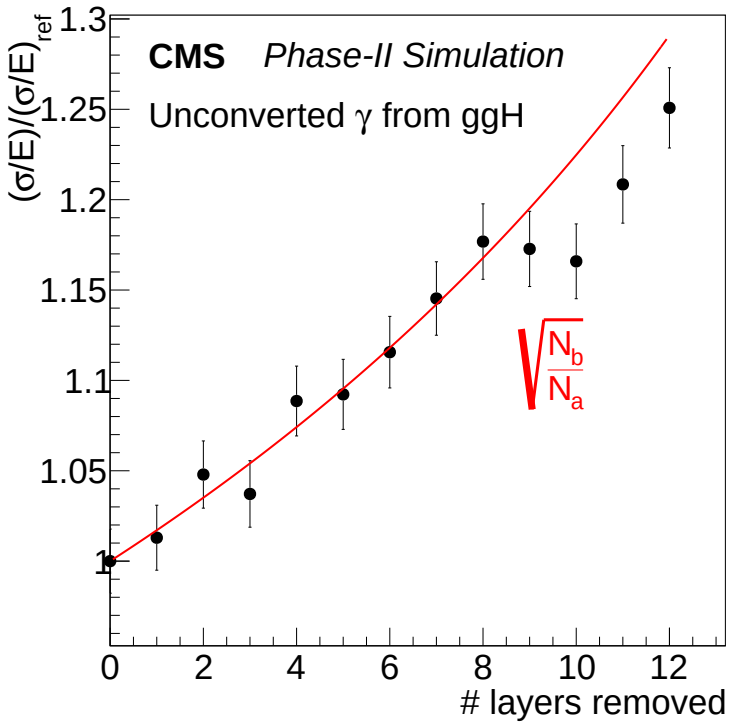




Photon Energy Resolution

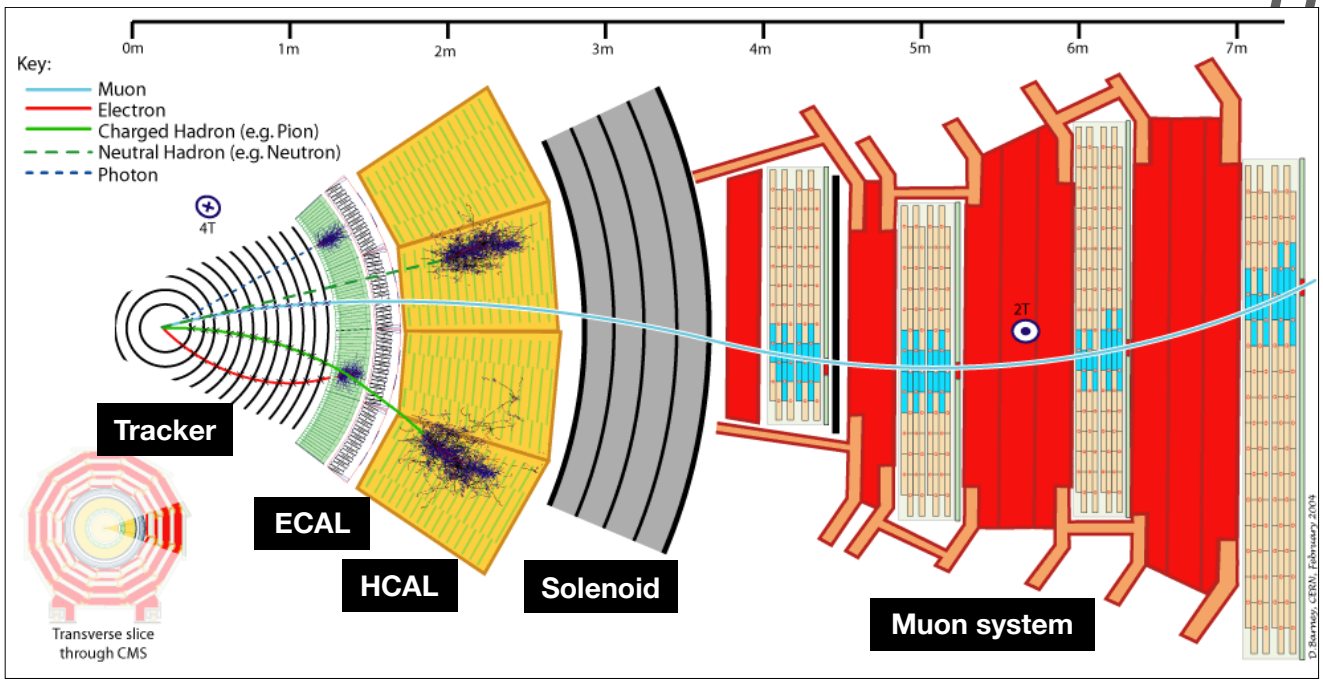


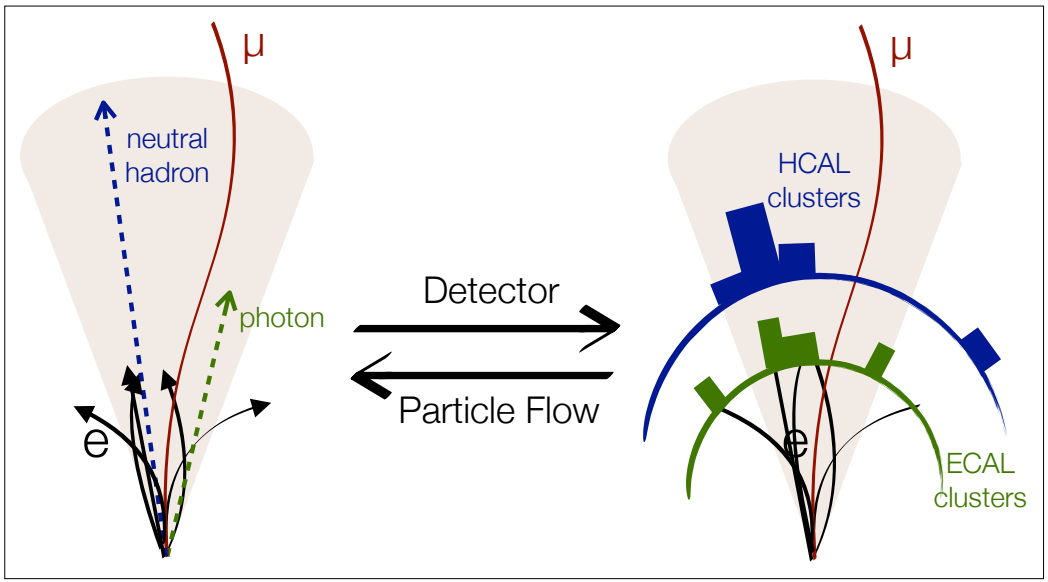
(a) The Phase-II upgraded detector has much less material in the tracker (before the calorimeter) than in the Phase-I detector. In the Phase-I aged scenario there can be up to a factor of ~ 2 degradation at $p_T \sim 20\,\mathrm{GeV}$. The energy resolution in the Phase-II detector is almost the same as in the Phase-I un-aged detector.



(b) Relative degradation in EM energy resolution as a function of the number of layers removed from the HGCAL. N_b and N_a are the number of layers before and after scoping, respectively. The degradation is about 10% and 25% for Scenario 1 and Scenario 2, respectively. In Scenario 2 the stochastic term reaches values above $30\%/\sqrt{E}$.

CMS event reconstruction in one slide





Particle Flow reconstruction

calorimeter clusters and tracks

⇓

muons, electrons, photons, neutral hadrons, charged hadrons

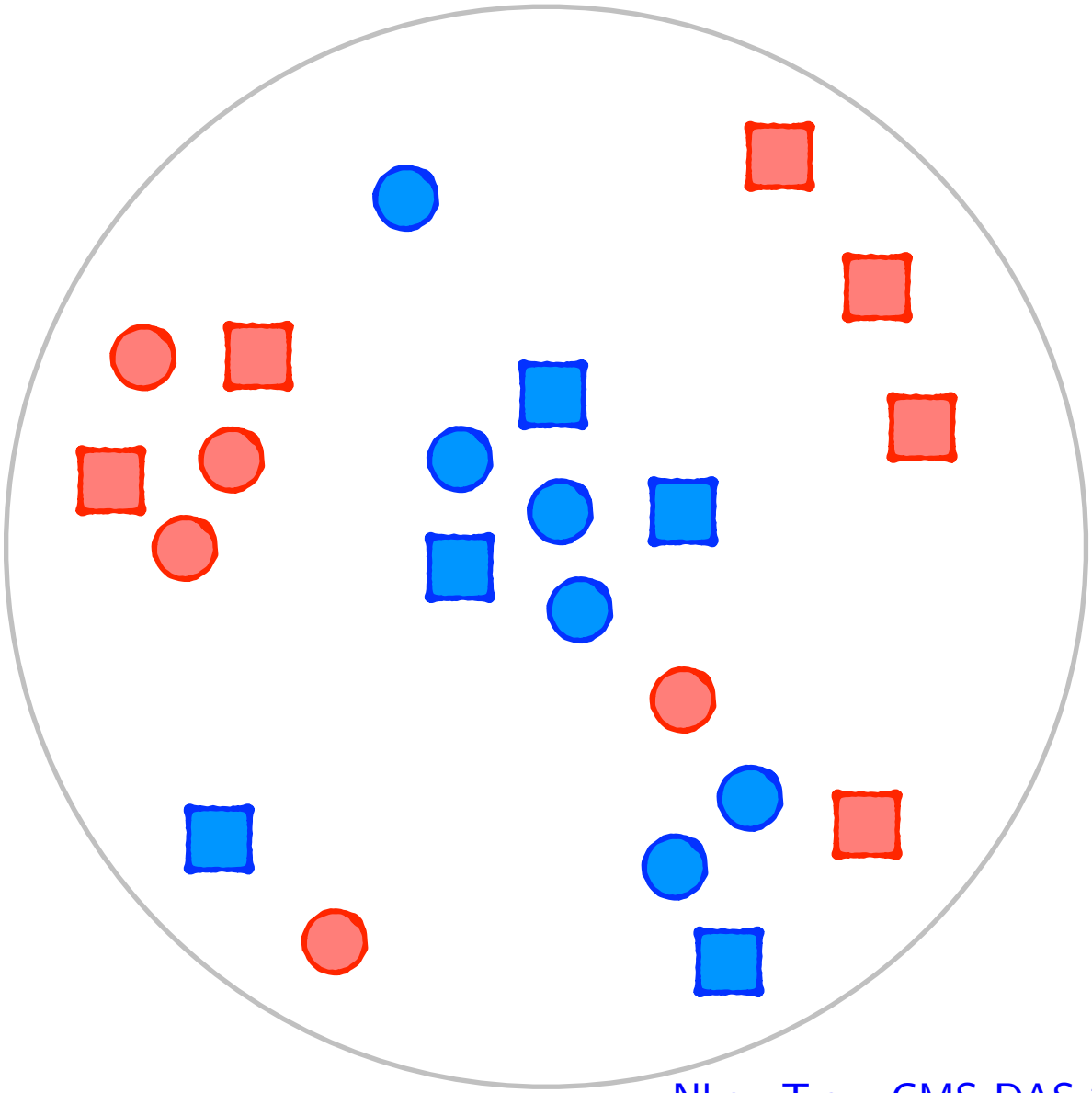
Nhan Tran, CMS DAS 2016

Pile-Up Per Particle Identification (PUPPI)

- LV charged
- LV neutral
- PU charged
- PU neutral

chosen

removed

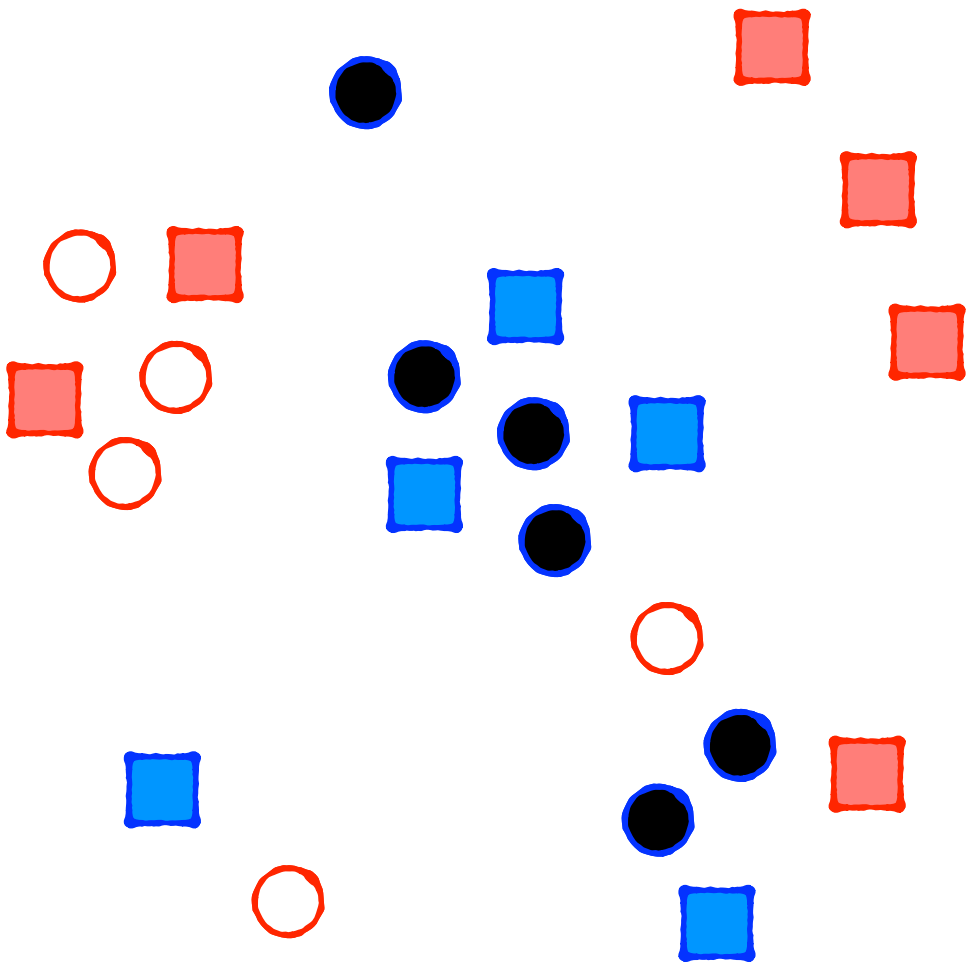


Nhan Tran, CMS DAS 2016

Pile-Up Per Particle Identification (PUPPI)

- LV charged
- LV neutral
- PU charged
- PU neutral
- chosen
- removed

1. use tracking info

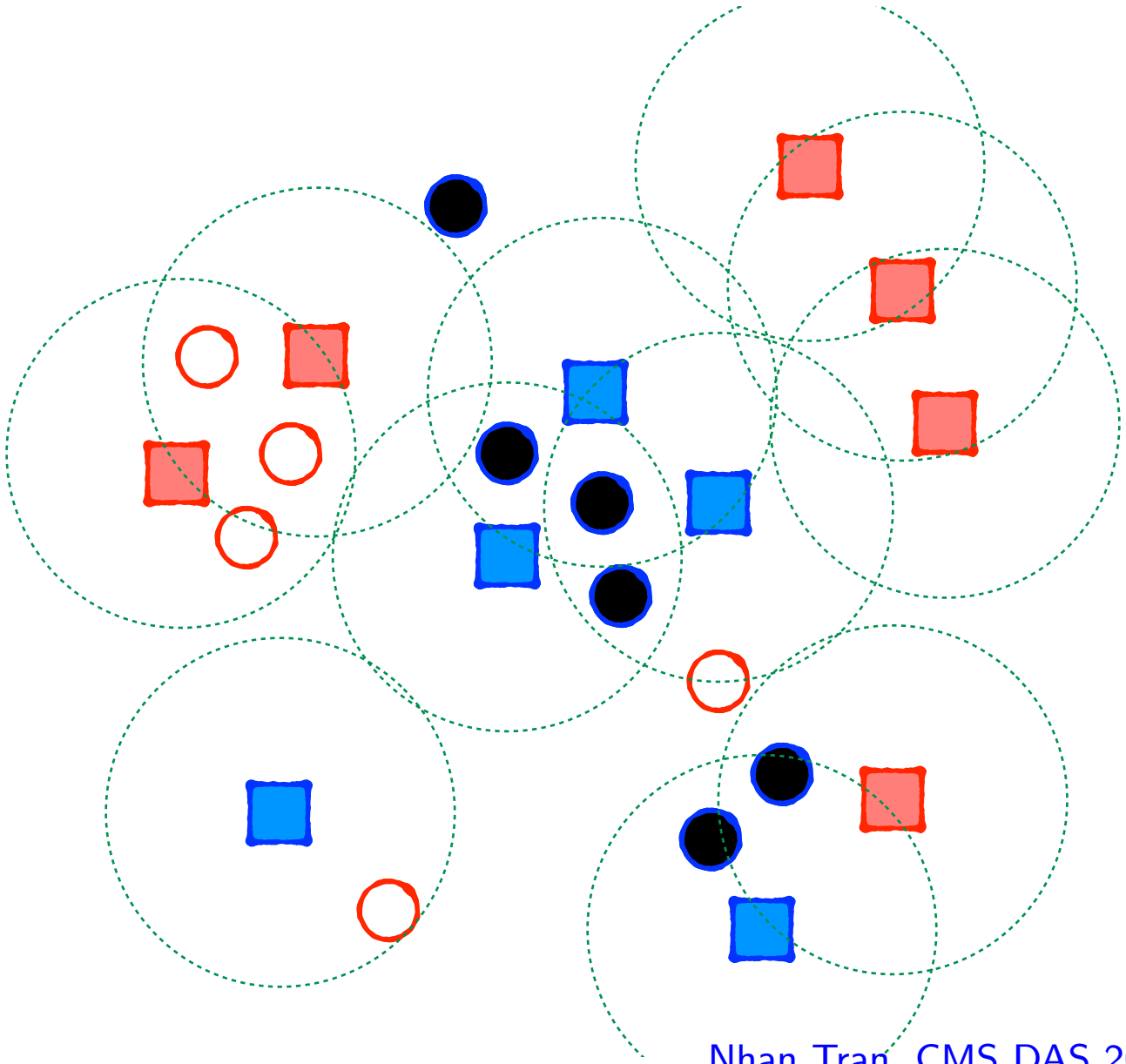


Nhan Tran, CMS DAS 2016

Pile-Up Per Particle Identification (PUPPI)

- LV charged
- LV neutral
- PU charged
- PU neutral
- chosen
- removed

1. use tracking info
2. look around neutrals

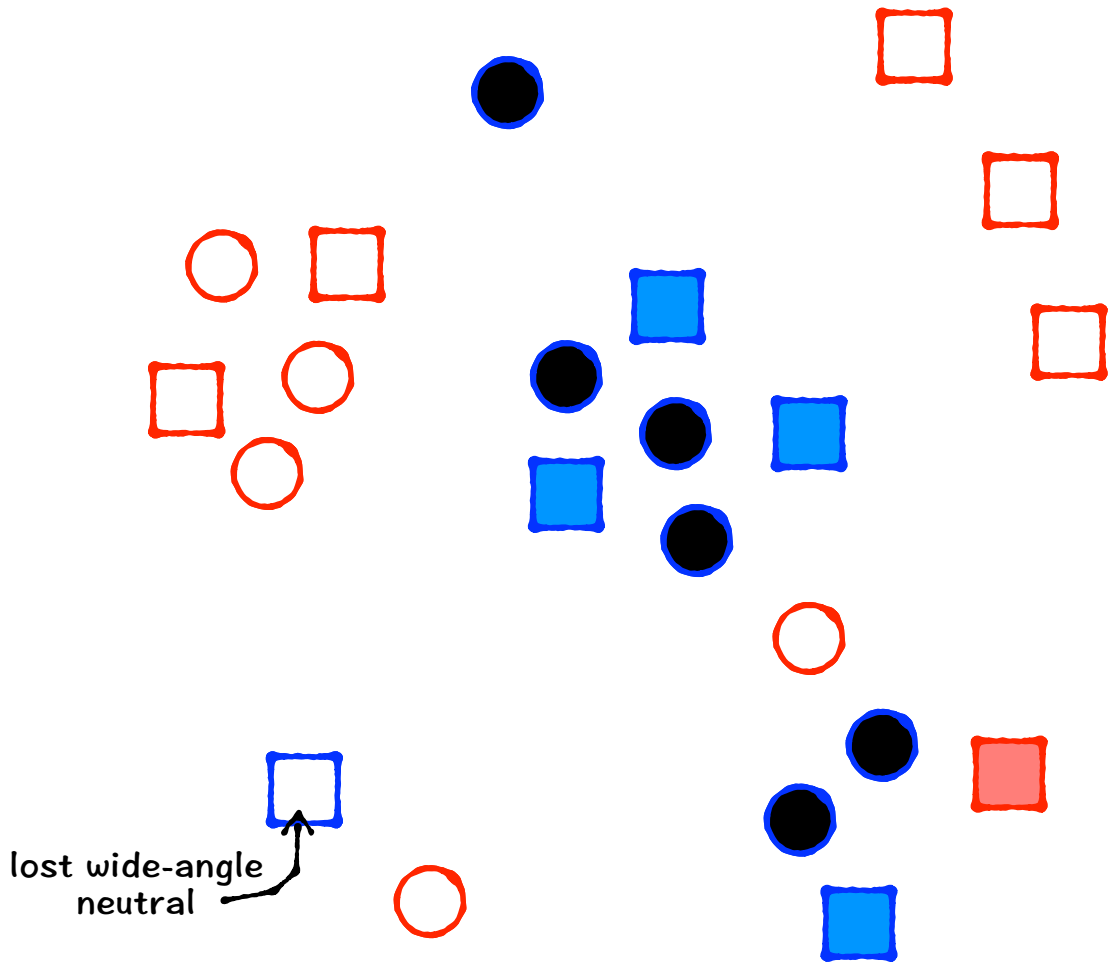


Nhan Tran, CMS DAS 2016

Pile-Up Per Particle Identification (PUPPI)

- LV charged
- LV neutral
- PU charged
- PU neutral
- chosen
- removed

1. use tracking info
2. look around neutrals
3. remove "0" neutrals

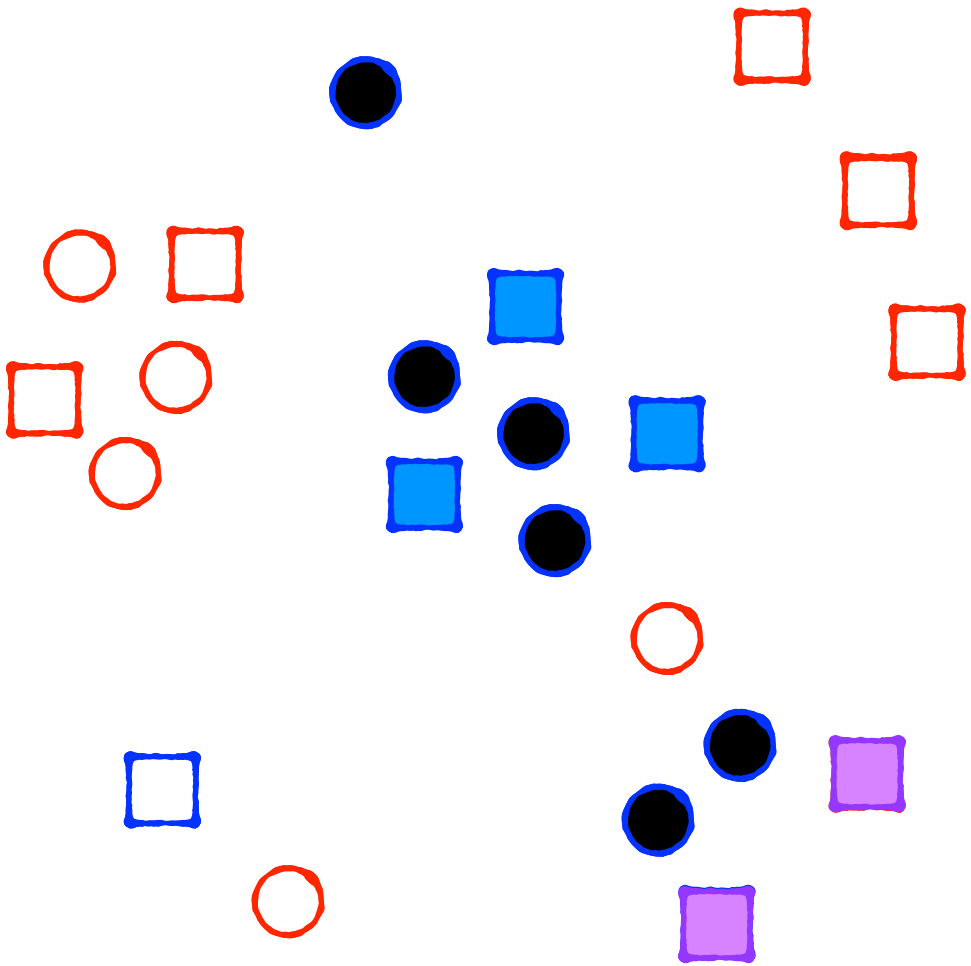


Nhan Tran, CMS DAS 2016

Pile-Up Per Particle Identification (PUPPI)

- LV charged
- LV neutral
- PU charged
- PU neutral
- chosen
- removed

1. use tracking info
2. look around neutrals
3. remove “0” neutrals
4. assign fractional weight to ambiguous cases



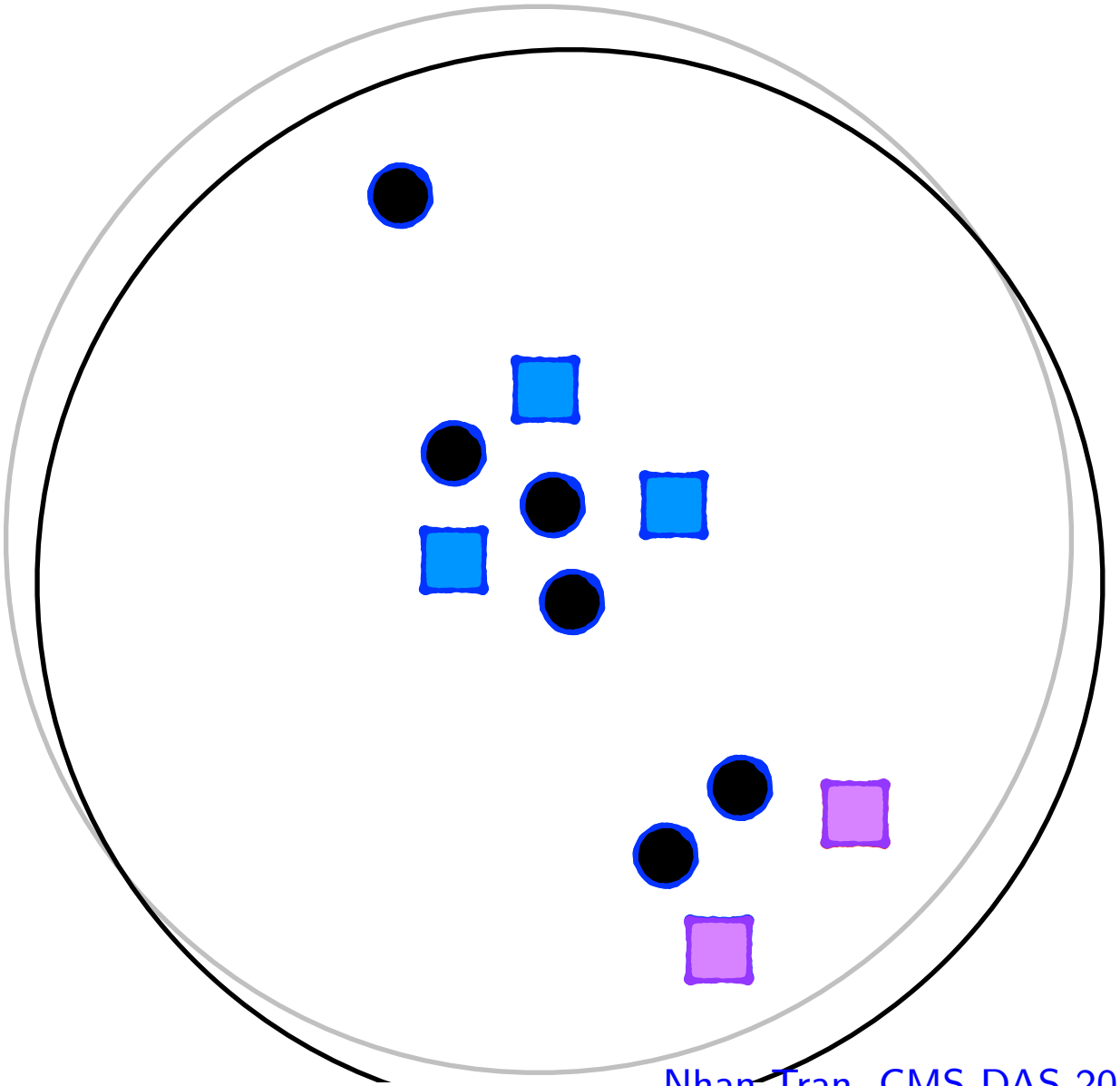
Nhan Tran, CMS DAS 2016

Pile-Up Per Particle Identification (PUPPI)

- LV charged
- LV neutral
- PU charged
- PU neutral
- chosen
- removed

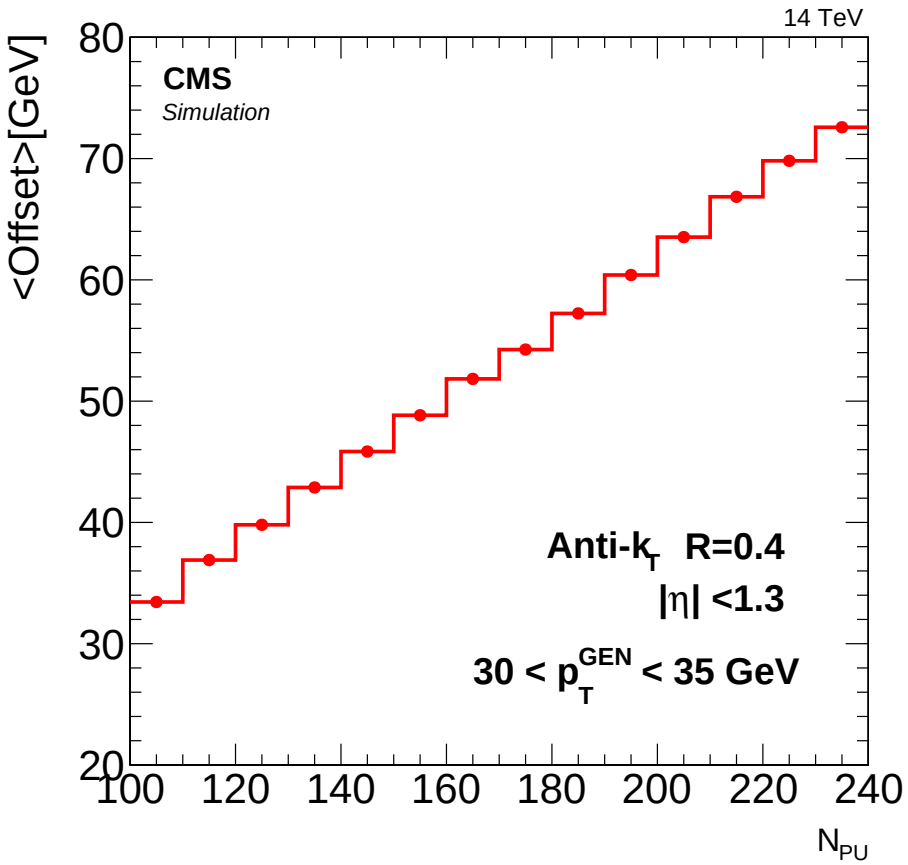
1. use tracking info
2. look around neutrals
3. remove “0” neutrals
4. assign fractional weight to ambiguous cases

recluster event, new jet!

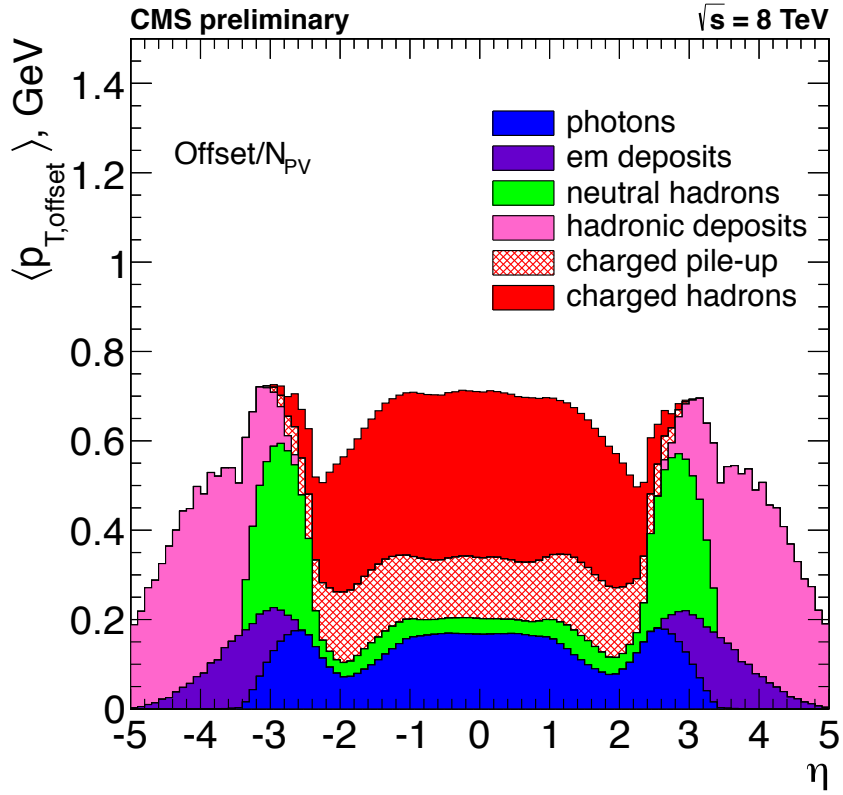


Nhan Tran, CMS DAS 2016

Pileup

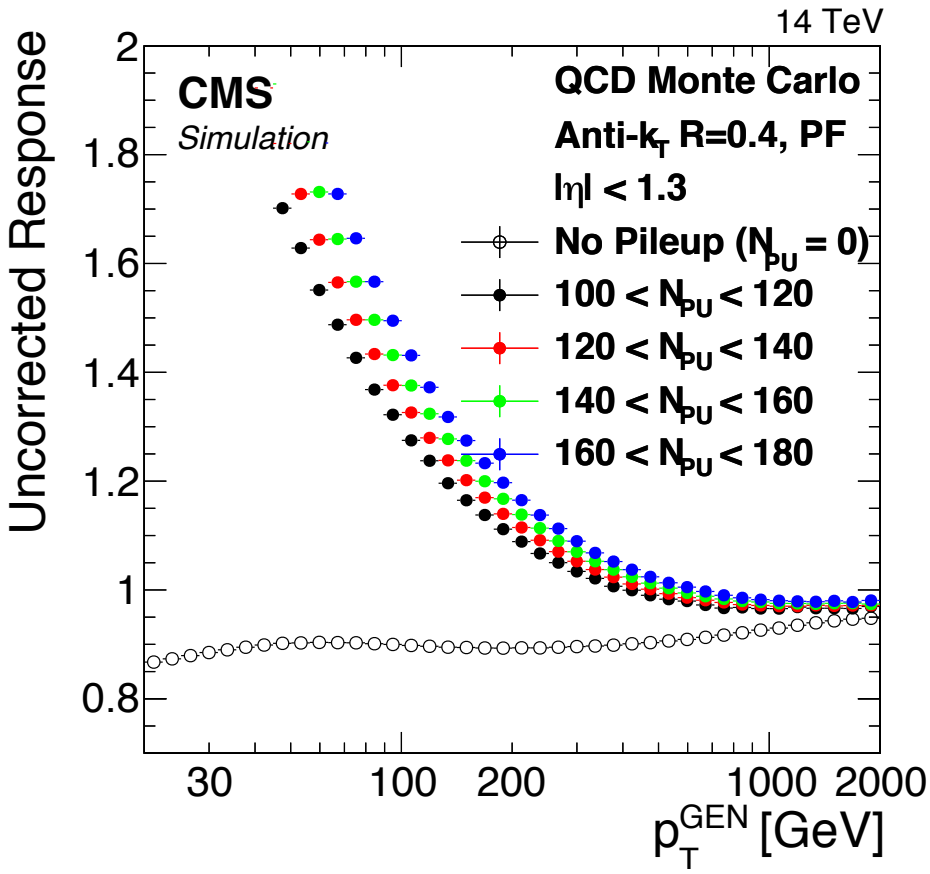


(a) Pileup energy added to a jet as a function of N_{PU}. About 45 GeV is added to a typical jet in the barrel. This varies by $\sim$ 10% as the jet energy varies from 20 GeV to 1 TeV and can be as high as 70 GeV in the forward region.

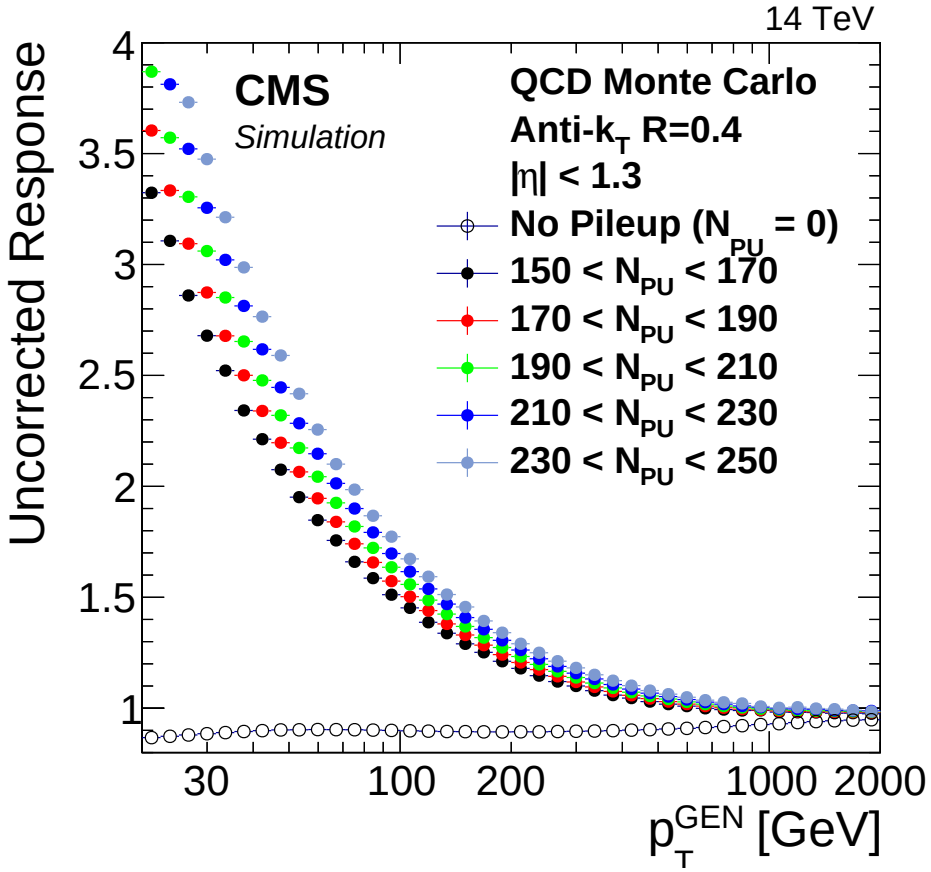


(b) Pileup energy per N_{PV} broken down by particle classification. This roughly breaks down as 65% from charged hadrons, 25% from photons, and 10% from neutral hadrons.

Jet Response

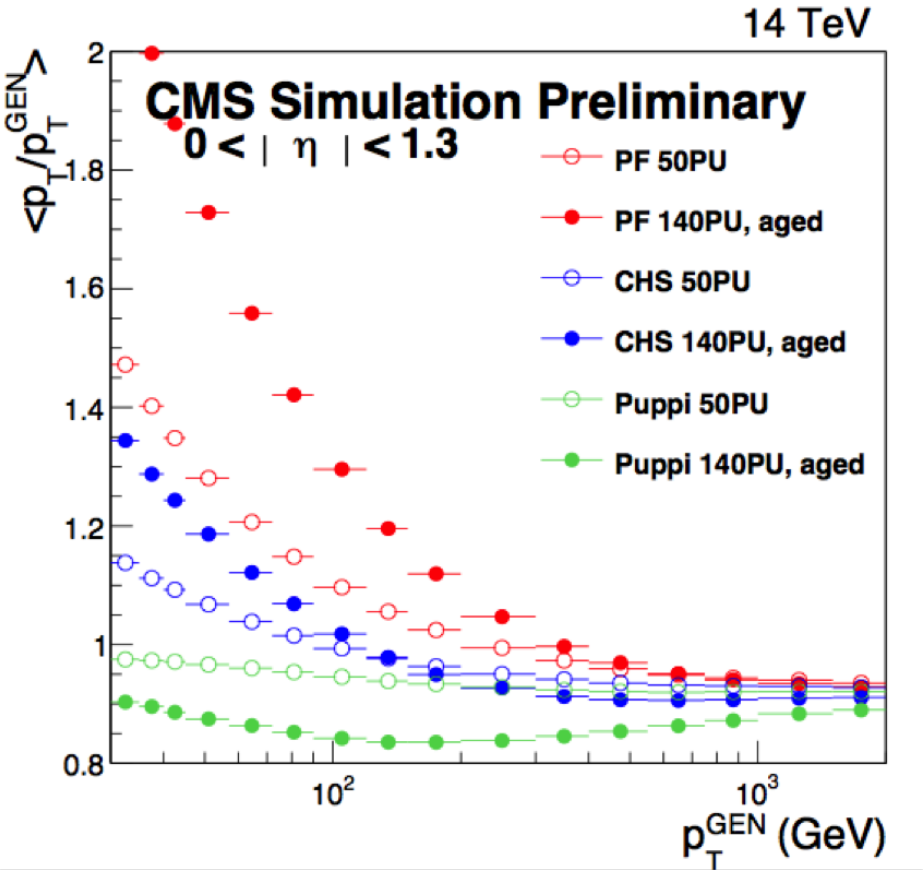


(a) Uncorrected jet response for PF jets in a sample with $\langle\mu\rangle = 140$

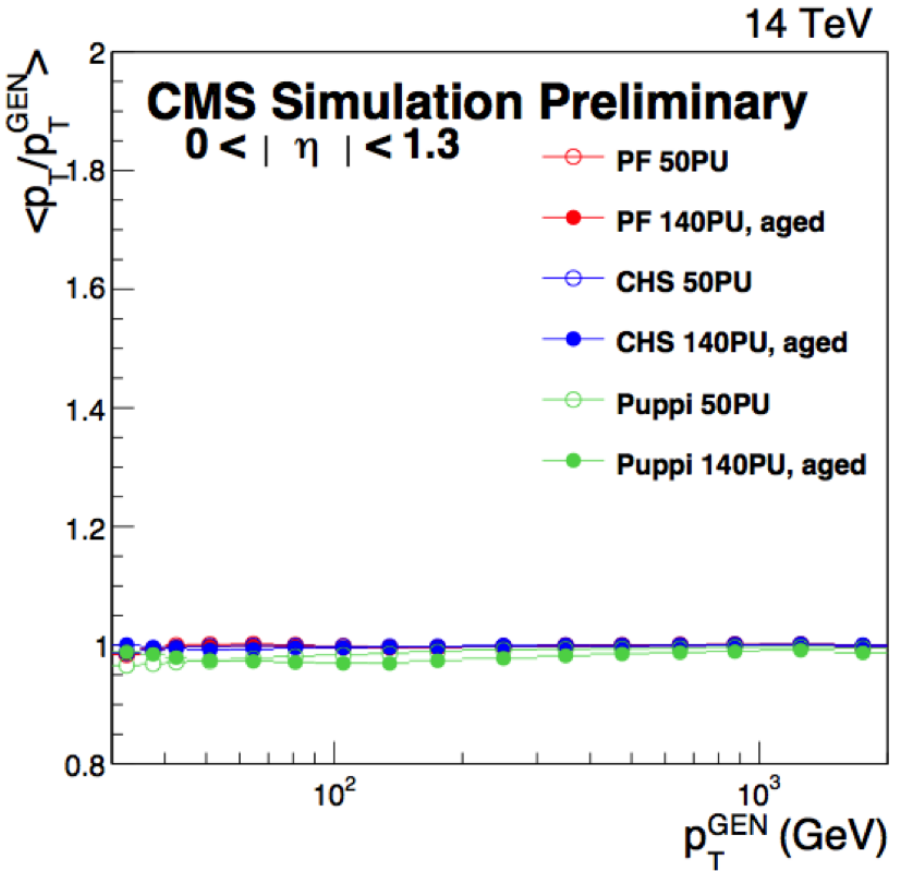


(b) Uncorrected jet response for PF jets in a sample with $\langle\mu\rangle = 200$

Jet Energy Corrections



(a) Uncorrected jet response in the barrel



(b) Corrected jet response in the barrel