CMS Underlying Event and Double Parton Scattering Tunes

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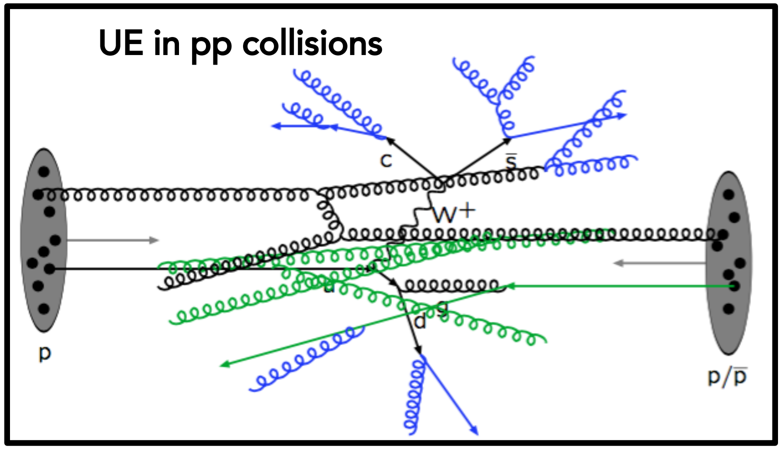
Outline

- Underlying Event and Observables
- Motivation
- CMS UE tunes
- CMS DPS tunes
- Comparisons with other UE measurements
- Inclusive jets, Z boson production, Z boson in Drell-Yan
- Predictions and Extrapolation to 13 TeV
- dN/dη of charged hadrons at 13 TeV (1st LHC Run II paper)
- Summary and Conclusions

Underlying Event @ LHC

- The hard pp-collision at the LHC can be interpreted as a "hard scattering" between partons accompanied by the underlying event (UE).



- UE consists of particles from
  - Beam-Beam Remnants (BBR)
  - Multiple Parton Interactions (MPI)
  - Soft Initial and final state radiation (ISR&FSR)

- But two hard 2-to-2 parton scatters can take place within the same hadron-hadron collision called Double-Parton-Scattering (DPS)

  - DPS is described by an effective cross section parameter σ_{eff}

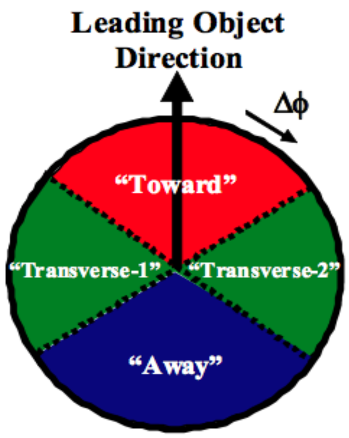
$$\sigma_{AB} = \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

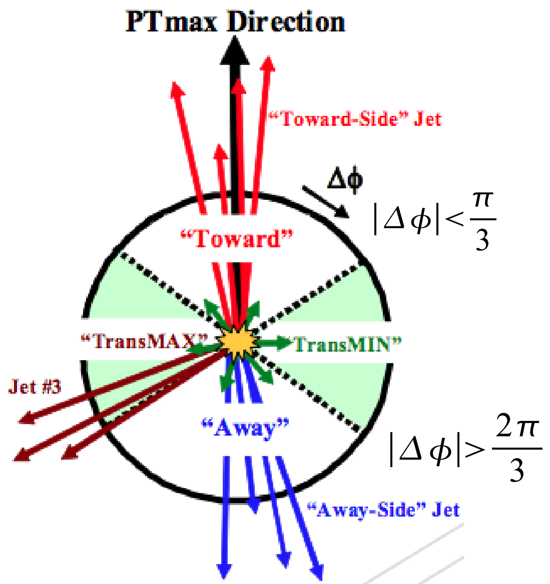
  - σ_{eff} is not a directly observed but a parton-level quantity
  - calculalable from the overlap function of the two transverse profile distributions of the colliding hadrons, implemented in a given MPI model.

Underlying Event Observables

- **TransMAX and TransMIN Charged Particle Density:**
  - Number of charged particles (p_T > 0.5 GeV/c, $|\eta|$ < 0.8) in the the maximum (minimum) of the two "transverse" regions as defined by the leading charged particle, PTmax, divided by the area in η - ϕ space, 1.6×2π/6, averaged over all events with at least one particle with p_T > 0.5 GeV/c, $|\eta|$ < 0.8.
- TransMAX and TransMIN Charged Ptsum Density:
  - Scalar p_T sum of charged particles (p_T > 0.5 GeV/c, $|\eta|$ < 0.8) in the the maximum (minimum) of the two "transverse" regions as defined by the leading charged particle, PTmax, divided by the area in η - ϕ space, 1.6×2π/6, averaged over all events with at least one particle with p_T > 0.5 GeV/c, $|\eta|$ < 0.8.
- Transverse density TransAVE = (TransMIN+TransMAX) / 2
  TransDIFF = TransMAX - TransMIN
- TransMIN very sensitive to MPI and BBR
- TransMAX often contains a 3rd jet in events with hard ISR or FSR.
- TransDIFF very sensitive to ISR and FSR

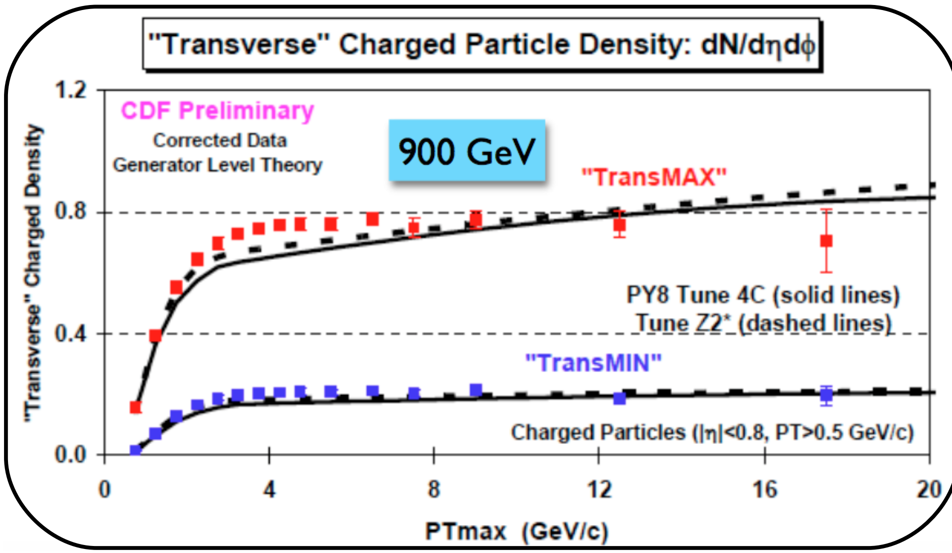
$|\Delta\phi| < \pi/3 \rightarrow$ TOWARD region
$\pi/3 < |\Delta\phi| < 2\pi/3 \rightarrow$ TRANSVERSE region
$|\Delta\phi| > 2\pi/3 \rightarrow$ AWAY region

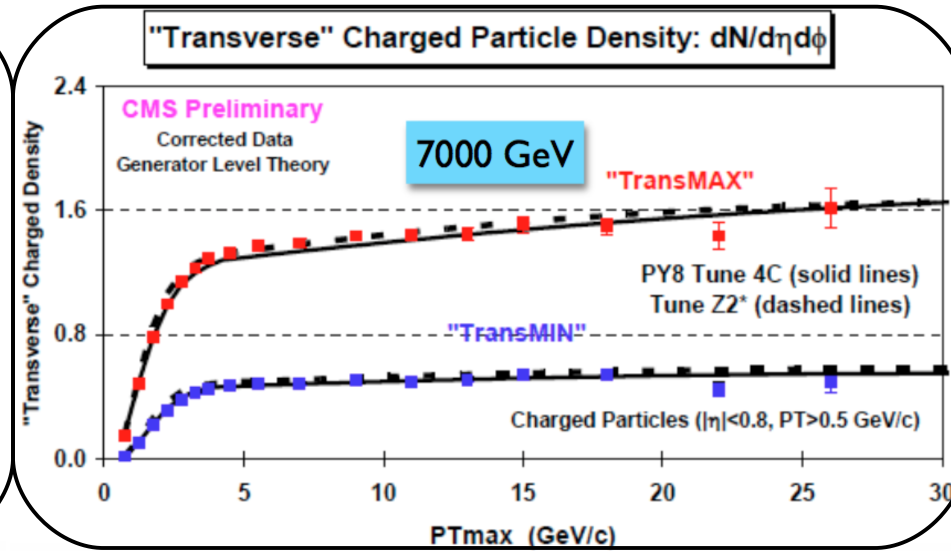




Motivation

- Understanding of the UE data is important for the analyses which use MC predictions
- Previous MC tunes did not well describe the energy dependence of UE data
  - Predictions @ 7 TeV reproduce well the data spectrum
  - But do not have optimal description for 900 GeV
- Charged particle density and charged particle PTsum density





- More precise prediction needed for the new LHC data at 13 TeV
  - So need a better tune to provide energy dependence
  - Vary parameters, which are sensitive to the underlying event
  - Start with Pythia6 Z2*lep and Pythia8 4C
  - Tune to CDF (0.3, 0.9 and 1.96 TeV) and CMS (7 TeV) data at different center-of-mass energies
  - Use two different PDF sets CTEQ6L1 and HERAPDF1.5LO

CMS UE Tunes: PYTHIA 8

- Use CDF and CMS data for the tunes
  - Select the leading charged particle (pTmax)
  - Use charged particles with | η | < 0.8 & p_T> 0.5 GeV.
- The software used for the tunes RIVET (A. Buckley et al, doi:10.1016/j.cpc.2013.05.021)
  PROFFESSOR (A. Buckley et al. , Eur.Phys.J.C65(2010) 331357)
- Take PYTHIA8 Tune 4C as reference tune then construct **two new UE tunes**
  - using CTEQ6L1 (**CUETPS1-CTEQ6L1**)
  - using HREAPDF1.5LO (**CUETP8S1-HERAPDF1.5LO**)
  - varying the four parameters within the Tuning Range

$$p_{T0}(\sqrt{s}) = p_{T0}^{ref} \times \left(\frac{\sqrt{s}}{\sqrt{s_0}}\right)^{\epsilon}$$

PYTHIA8 Parameter	Tuning Range	Tune 4C (CTEQ6L1)	CUETP8S1 (CTEQ6L1)	CUETP8S1 (HERAPDF1.5LO)
MultipartonInteractions:pT0Ref [GeV]	1.0 - 3.0	2.085	2.101	2.000
MultipartonInteractions:ecmPow	0.0 - 0.4	0.19	0.211	0.250
MultipartonInteractions:expPow	0.4 -10.0	2.0	1.609	1.691
ColourReconnection:range	0.0 - 0.9	1.5	3.313	6.096

- By using the output from PYTHIA 8:
  - it is possible to predict the σ eff value in the tune, defined by the UE parameters
  - PROFFESSOR gives the eigentunes in order to get the uncertainties of the parameters

CMS UE Tunes: PYTHIA 8, PYTHIA 6 and HERWIG++

- Combines updated fragmentation parameter for NNPDF2.3LO
  - NNPDF2.3LO has a gluon distribution @ small-x different than CTEQ6L1 & HERAPDF1.5LO
  - Affecting predictions especially in the forward region
- New tune PYTHIA8 CUETP8M1
  - using parameters of Monash Tune
  - Fitting two MPI energy dependence parameters to UE data @ $\sqrt{s}$ = 0.9, 1.96 & 7 TeV

PYTHIA8 Parameter	Tuning Range	Monash	CUETP8M1
PDF	-	NNPDF2.3LO	NNPDF2.3LO
MultipartonInteractions:pT0Ref [GeV]	1.0 - 3.0	2.280	2.402
MultipartonInteractions:ecmPow	0.0 - 0.4	0.215	0.252
MultipartonInteractions:expPow	-	1.85	1.6*
ColourReconnection:range	-	1.80	1.80**
MultipartonInteractions:ecmRef [GeV]	-	7000	7000**

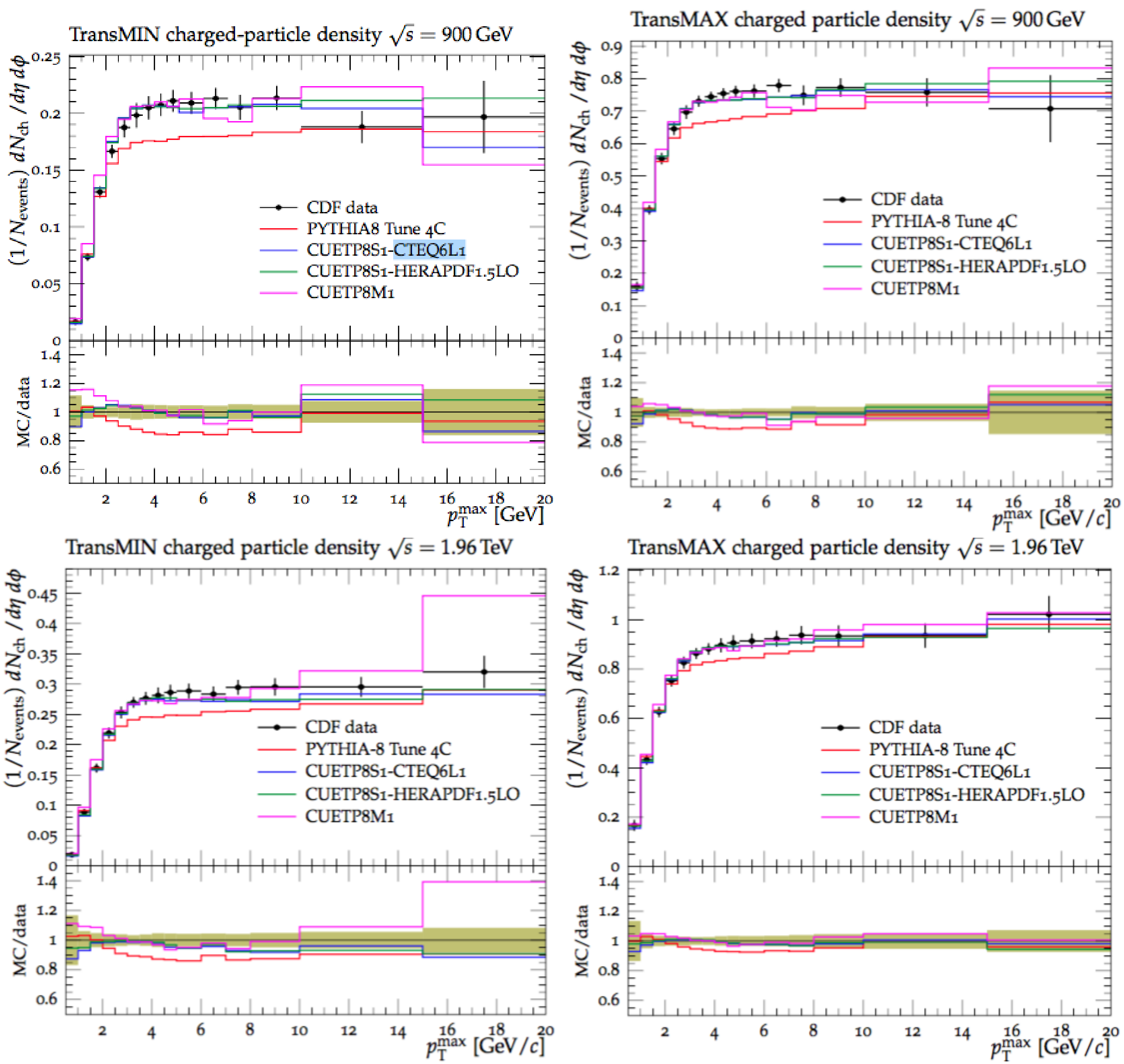
- Two new PYTHIA6 UE tunes are constructed
  - Starting with Tune Z2*lep parameters,
  - Using CTEQ6L1 (**CUETP6S1-CTEQ6L1**)
  - Using HERAPDF1.5LO (**CUETP6S1-HERAPDF1.5LO**).
  - Not only MPI energy-dependence parameters but
    - the core-matter fraction PARP(83),
    - color reconnection (CR) strength PARP(78),
    - CR suppression PARP(77) are also varied.
- New HERWIG++ UE tune, CUETHppS1
  - obtained varying four parameters in table.
  - set MPI cut-off p_T^0 and ref. energy to Tune UE-EE-5C
  - vary MPI extrap. parameter

HERWIG++ Parameter	Tuning Range	UE-EE-5C	CUETHppS1
PDF	-	CTEQ6L1	CTEQ6L1
MPIHandler:Power	0.1 - 0.5	0.33	0.371
RemnantDecayer:colourDisrupt	0.1 - 0.9	0.8	0.628
MPIHandler:InvRadius [GeV^2]	0.5 - 2.7	2.30	2.255
ColourReconnector:ReconnectionProbability	0.1 - 0.9	0.49	0.528

Results @ $\sqrt{s}$ = 0.9 and 1.96 TeV

CMS GEN-14-001

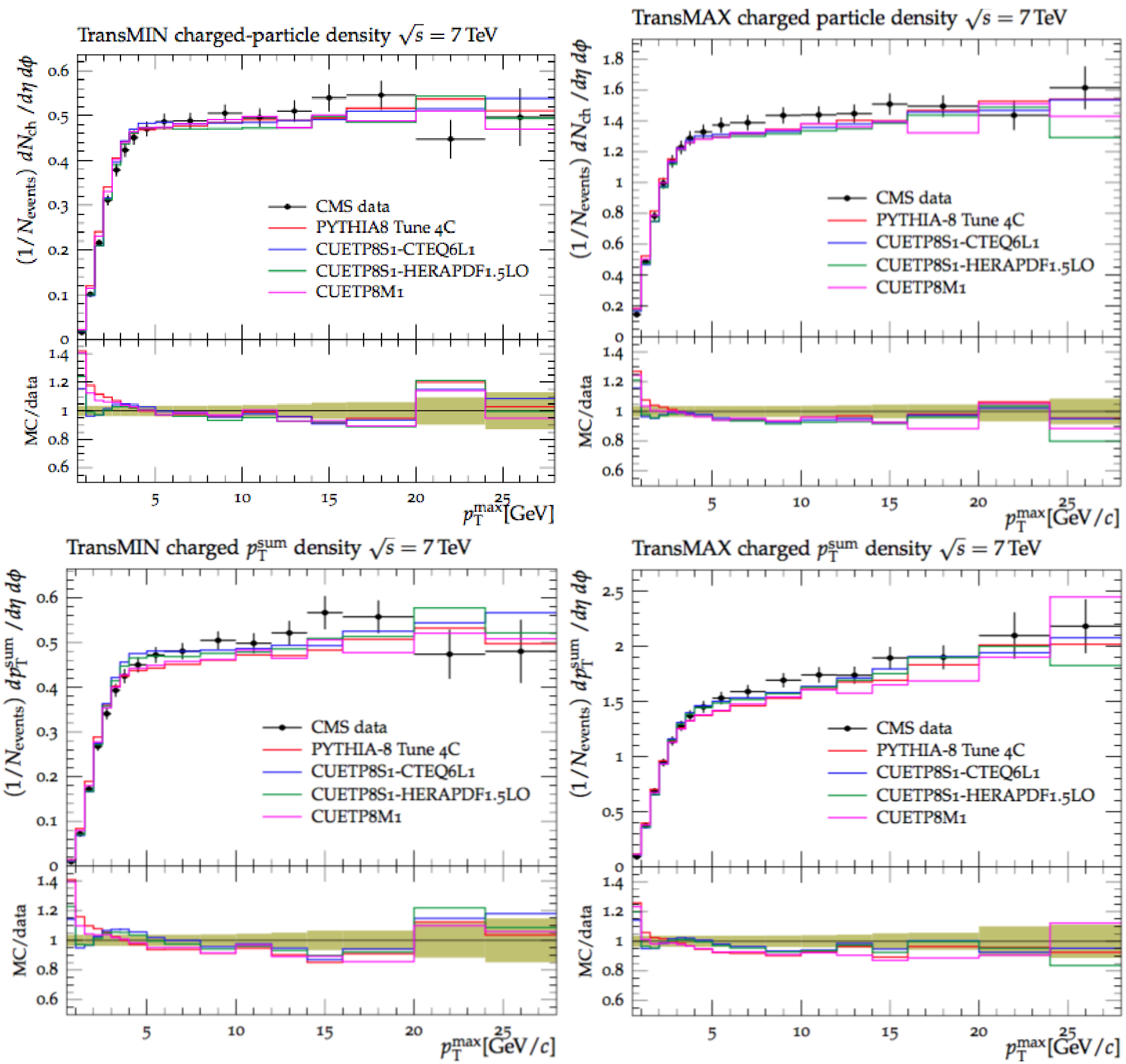
- Charged particle multiplicity, Σp_T in TransMIN and TransMAX regions fro CDF data @ 0.9 and 1.96 TeV



- Data compared to new CMS Tunes:
  - CUETP8S1-CTEQ6L1
  - CUETP8S1-HERAPDF1.5LO
  - CUETP8M1.
- Significant improvement in the description of TransMIN and TransMAX regions
  - due to the better choice of parameters used in the MPI energy dependence
  - and the extraction of the CR in the retuning.
- Green bands in the ratios represent the total experimental uncertainties.

Results @ $\sqrt{s}$ = 7 TeV

- Charged particle multiplicity, Σp_T in TransMIN and TransMAX regions fro CMS data @ 7 TeV



- CMS data at $\sqrt{s}$ = 7 TeV for charged particles with p_T > 0.5 GeV and $|\eta|$ < 0.8 in the TransMIN and TransMAX regions for
  - particle density (top)
  - p_T^{sum} density (bottom)
- Significant improvement in the description of TransMIN and TransMAX regions
- Both rising and plateau regions are well described by new CMS Tunes
- Green bands in the ratios represent the total experimental uncertainties.

CMS DPS Tunes

- MPI parameters are determined by fitting to observables
- The observables:

$$\Delta S = \arccos\left(\frac{\vec{p}_T(\text{object}_1)\cdot\vec{p}_T(\text{object}_2)}{|\vec{p}_T(\text{object}_1)|\times|\vec{p}_T(\text{object}_2)|}\right)$$

$$\Delta^{\text{rel}} p_T = \frac{|\vec{p}_T^{\,\text{jet}_1}+\vec{p}_T^{\,\text{jet}_2}|}{|\vec{p}_T^{\,\text{jet}_1}|+|\vec{p}_T^{\,\text{jet}_2}|},$$

object_1: W-boson object_2 : dijet pair for W+dijet
object_1: hard-jet pair object_2 :soft jet pair for 4j

- Study of W+dijet & 4-jet production scenario performed with PYTHIA8 tune 4C:

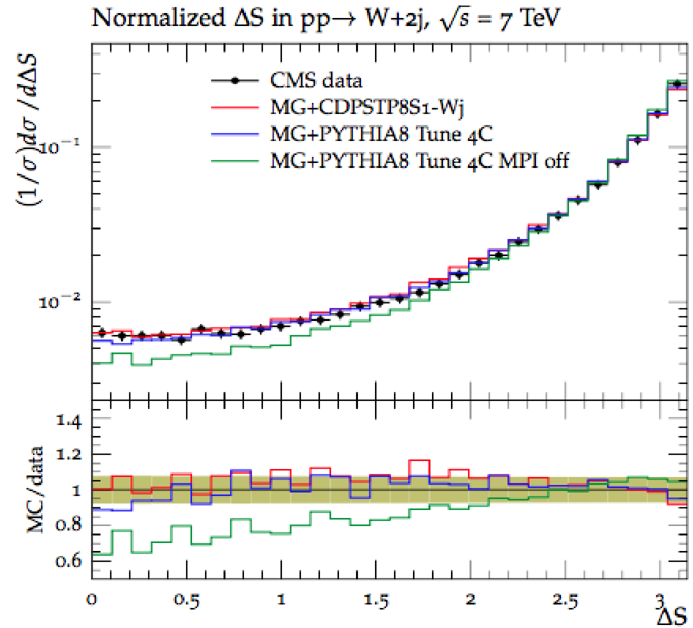
• Only the exponential distribution expPow varied (**CDPSTP8S1-Wj**)

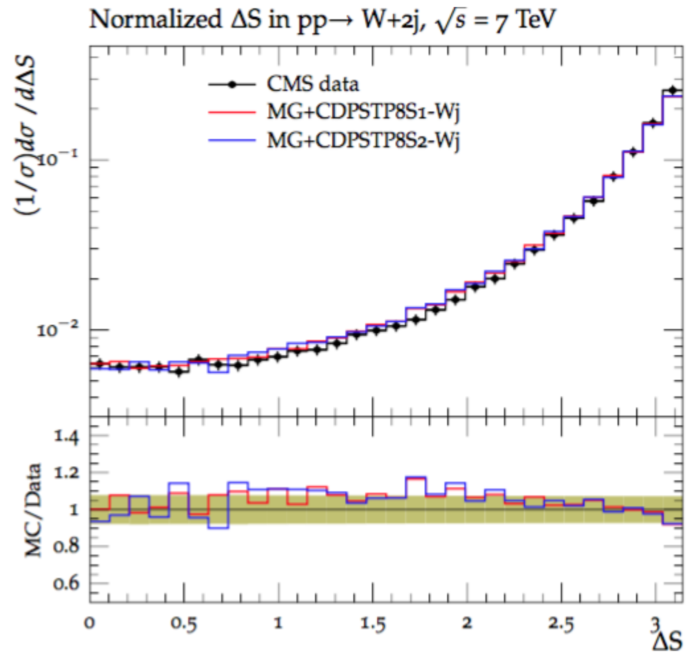
• full tune with all parameters are varied (**CDPSTP8S2-Wj**)

- Uncertainties quoted for σ_{eff} computed from the uncertainties of the fitted parameters given by the eigentunes.

- Compatible with the value measured by CMS using the template method σ_{eff} = 20.6 ± 0.8 (stat) ± 6.6 (sys) mb

PYTHIA Parameter	TUNE 4C	CDPSTP8S1-Wj	CDPSTP8S2-Wj
PDF	CTEQ6L1	CTEQ6L1	CTEQ6L1
Predicted σ_{eff} (in mb)	30.3	$25.9^{+2.4}_{-2.9}$	$25.8^{+8.2}_{-4.2}$





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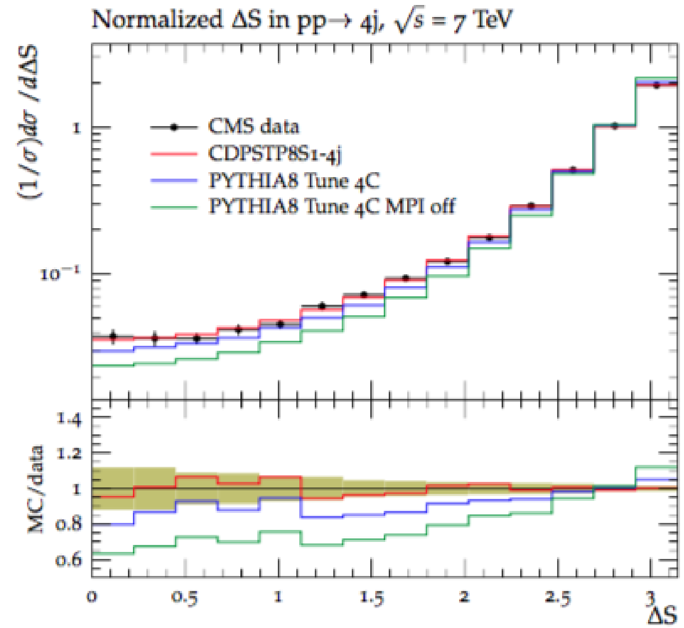
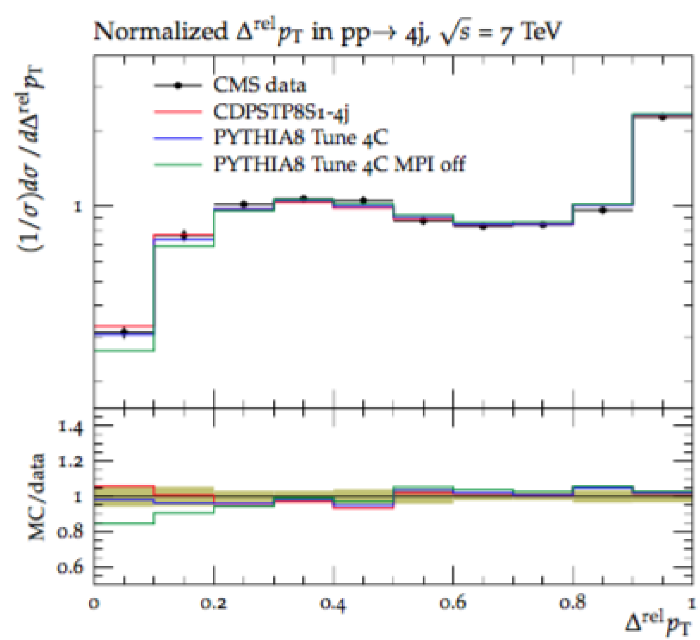
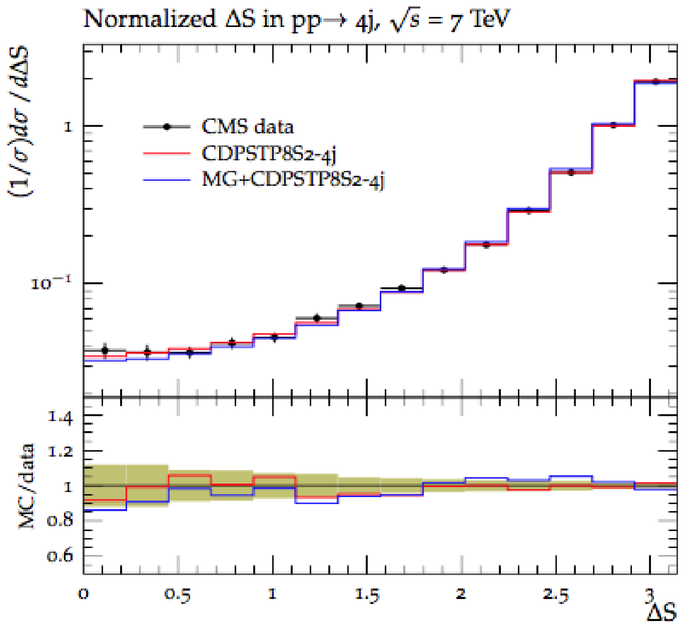
Predicted σ_{eff} (in mb)	30.3	$21.3^{+1.2}_{-1.6}$	$19.0^{+4.7}_{-3.0}$

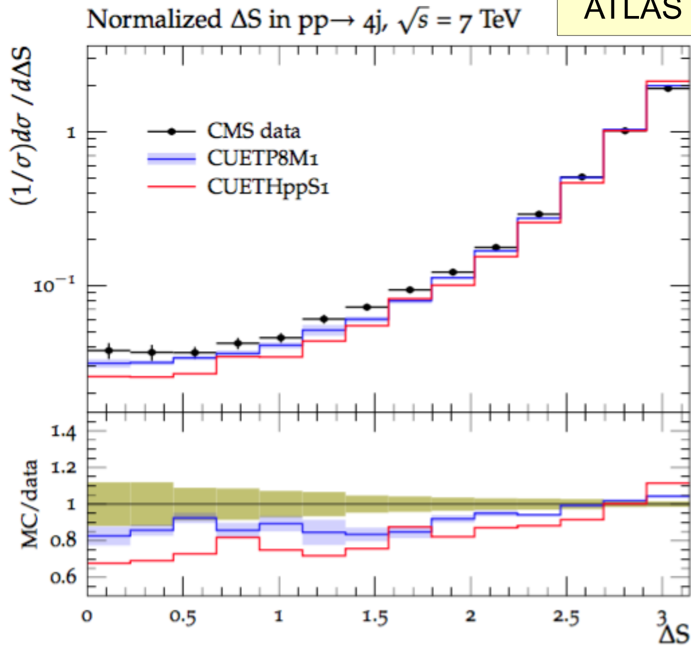


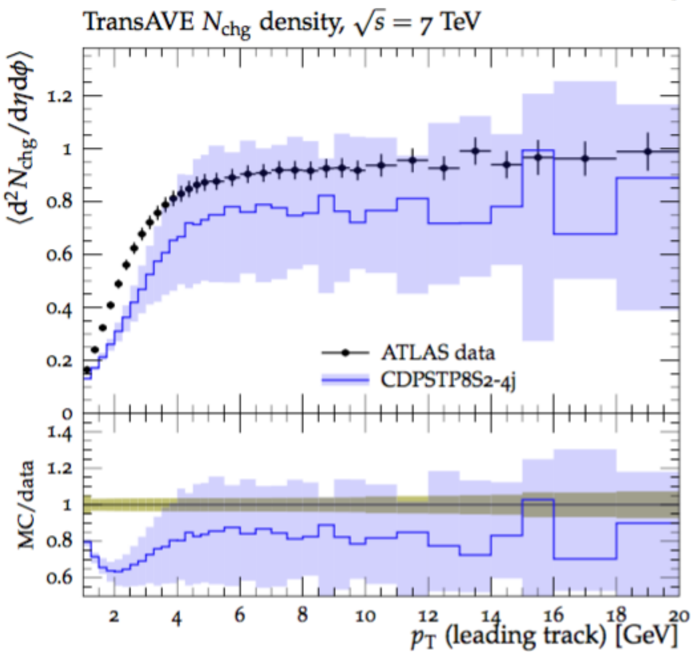


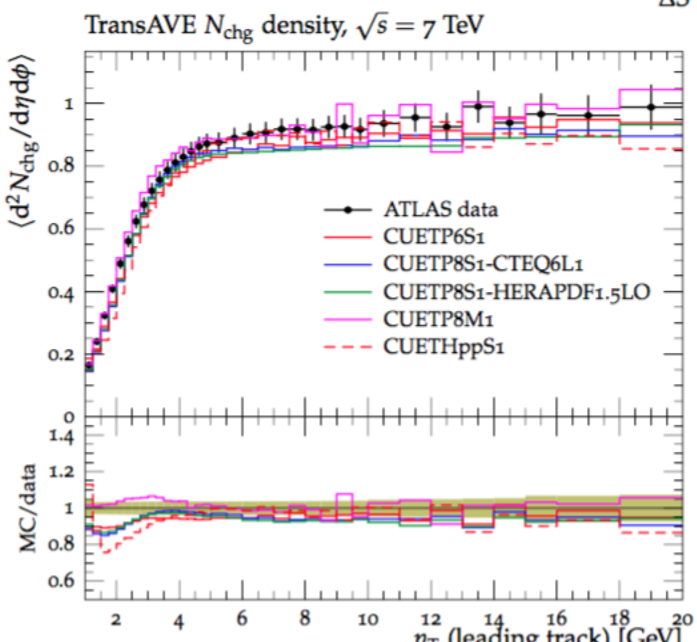
Compatibility of CMS Tunes

ATLAS Coll. Phys.Rev. D83 (2011) 112001



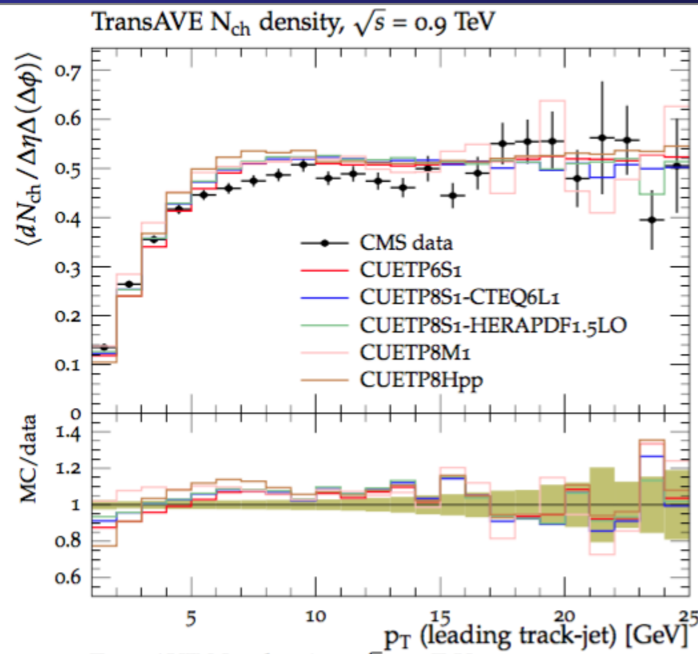


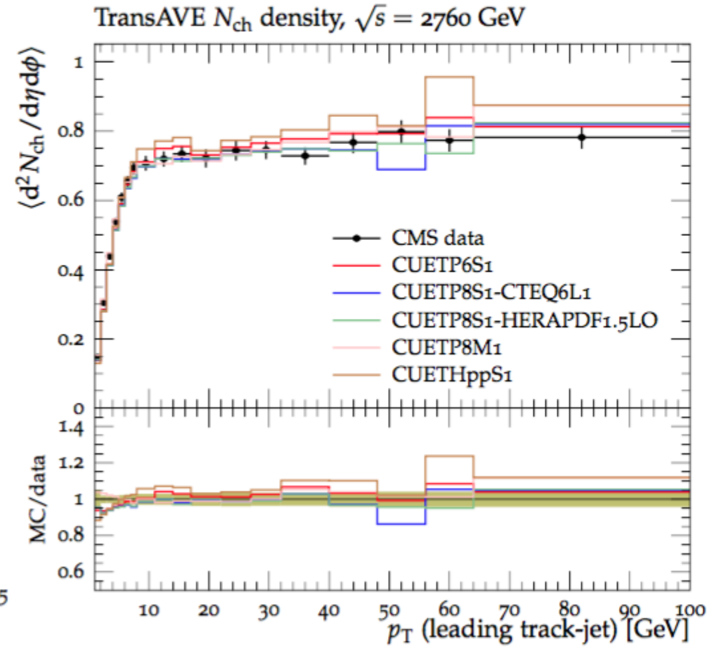


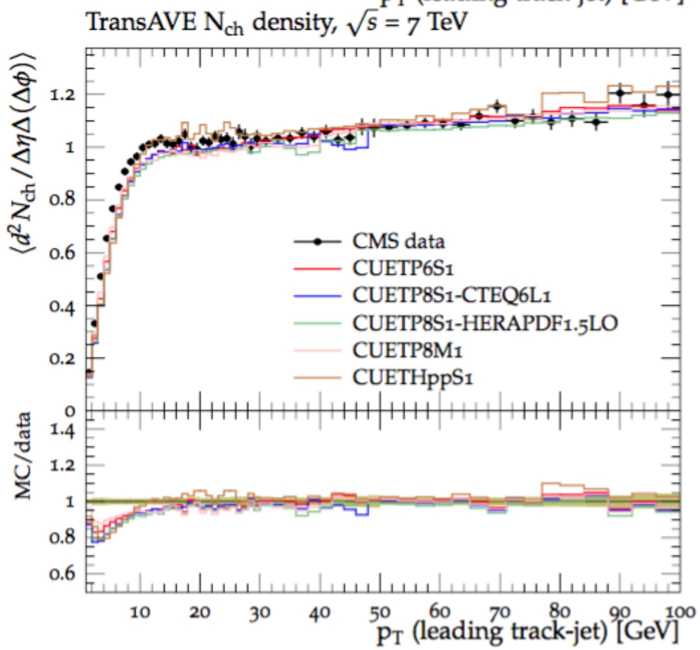


- Comparison of CMS DPS-sensitive data for 4-jet production @ 7 TeV (top)
- ATLAS UE data @ $\sqrt{s}$ = 7 TeV compared to predictions obtained with various tunes (bottom)
- σ eff ≈ 20 mb (CMS DPS tunes)
- σ eff ≈ 26–29 mb (CMS P Y T H I A 8 UE tunes)
- Reasonably well description for DPS observables by predictions from P Y T H I A 8 using CUETP8M1
- Predictions using CDPSTP8S2-4j do not fit the UE data as the UE tunes do.
- Predictions using CUETP8M1describe the DPS-sensitive observables better than CUETHppS1, but not quite as well as the DPS tunes.

Comparison with other UE measurements

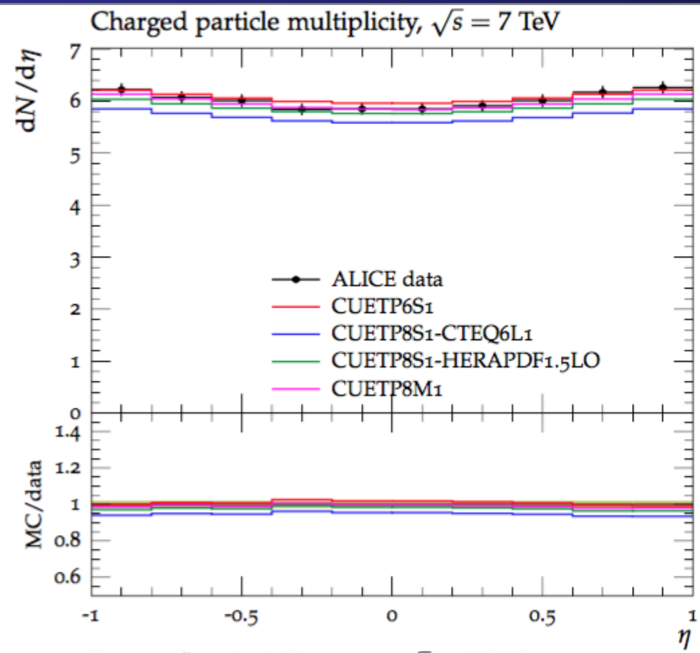


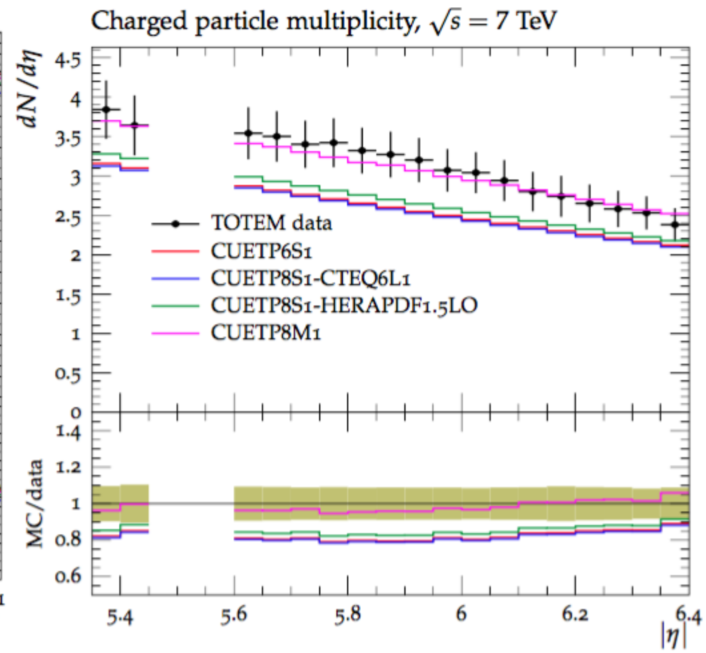


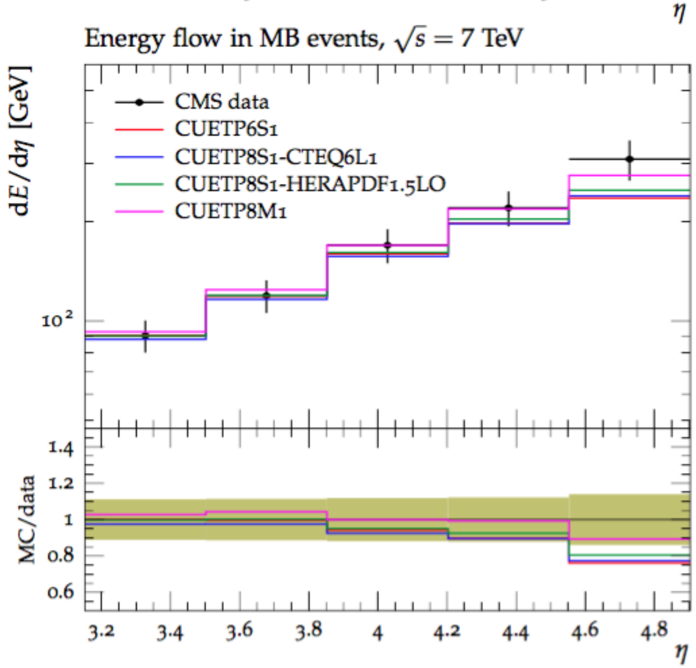


- Charged particle densities @ $\sqrt{s}$ = 0.9, 2.76 and 7TeV p_T > 0.5 GeV and $|\eta|$ < 2.0 in the TransAVE region as defined by the leading jet reconstructed by using just the charged particles (also called "leading track-jet")
- CMS UE tunes describe quite well the UE measurement using the leading charged particle as well as the leading charged-particle jet.

Predicting MB observables

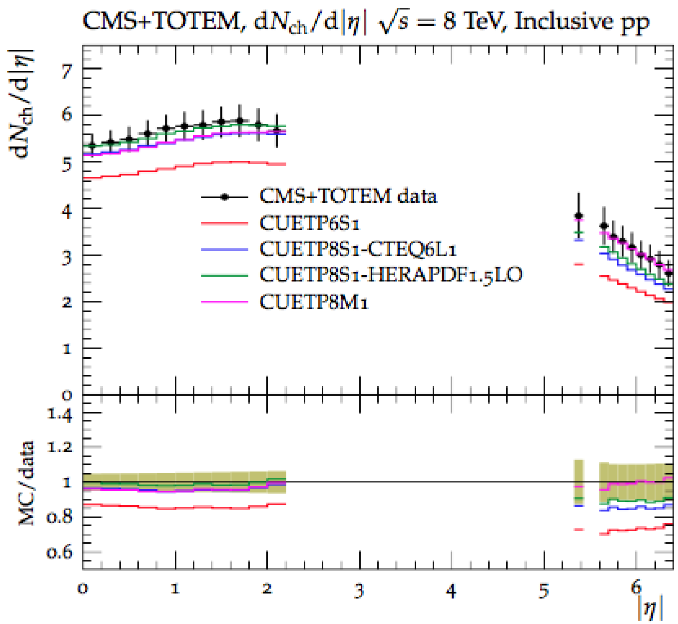


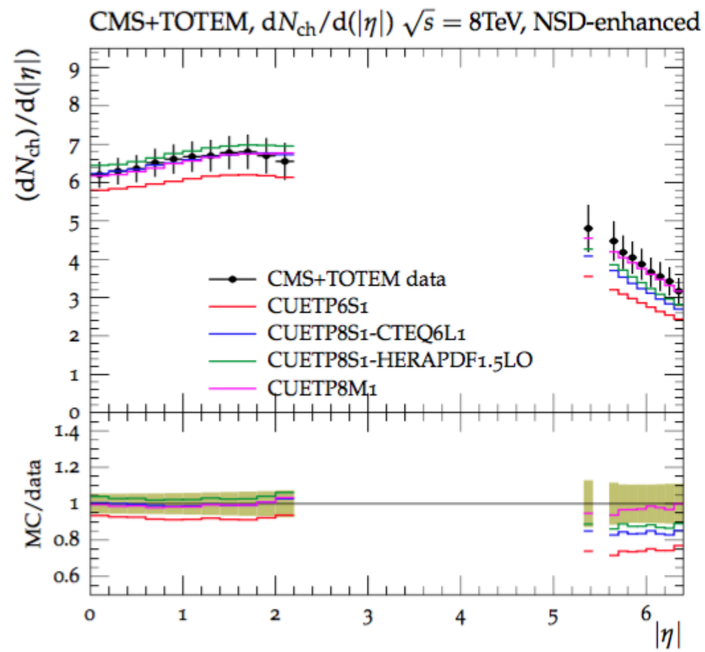


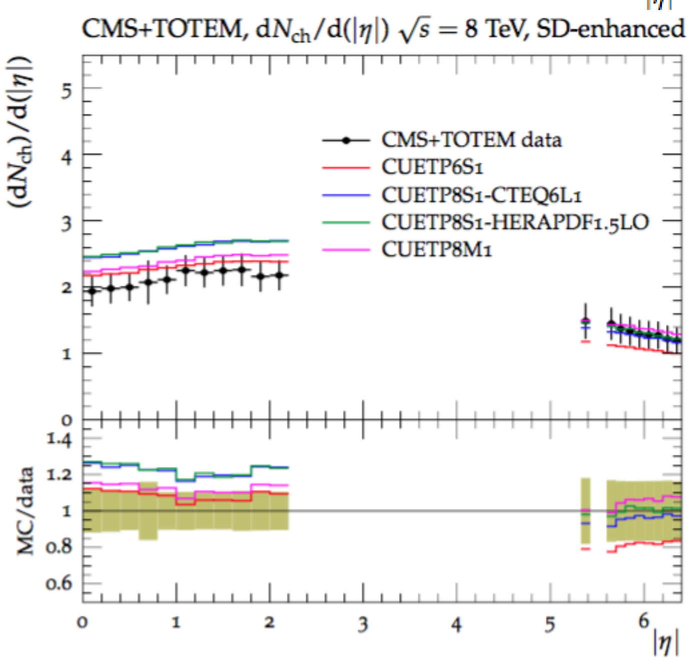


- Interesting to see how well CMS UE tunes can describe the properties of MB distributions.
- Charged-particle pseudorapidity distributions in inelastic pp collisons @ $\sqrt{s} = 7$ TeV for ALICE, TOTEM and CMS
- $dN_{ch}/d\eta$ is a sensitive observable to SD, CD, and DD, which modeled in PYTHIA.
- HERWIG++ not shown since does not include a model for SD, CD and DD.

Predicting MB observables (II)

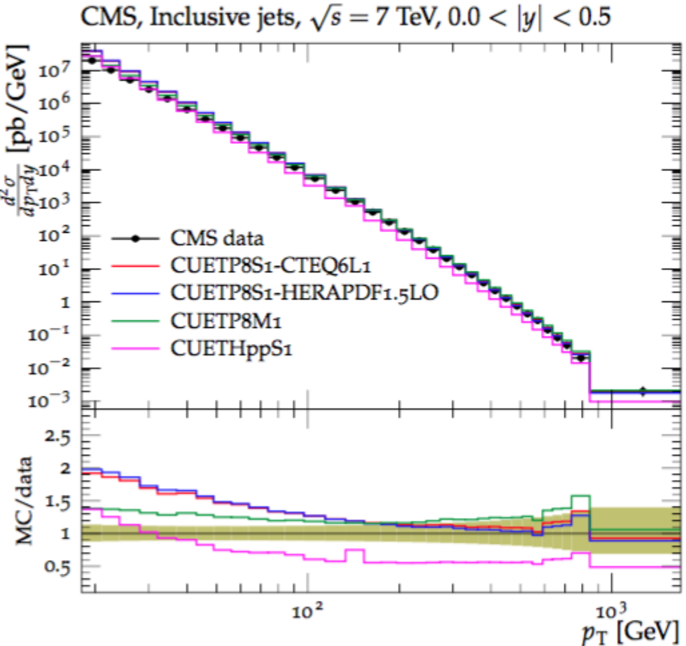


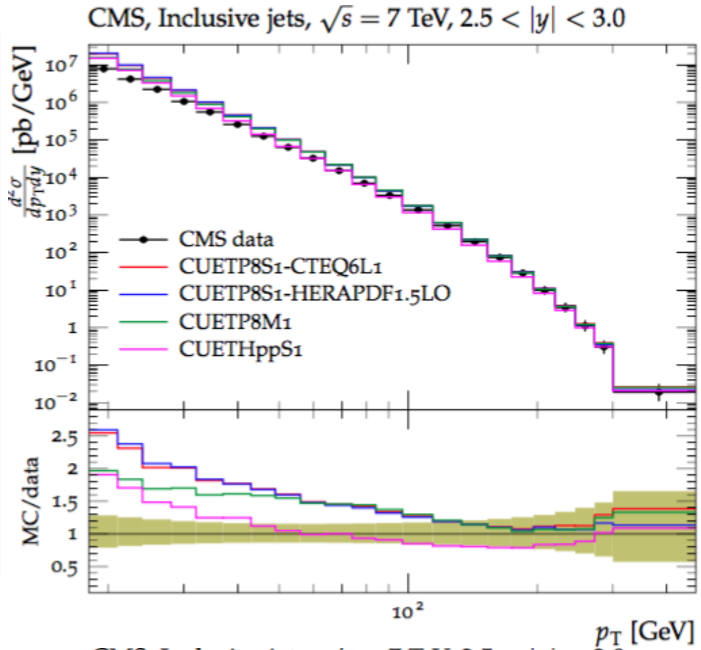


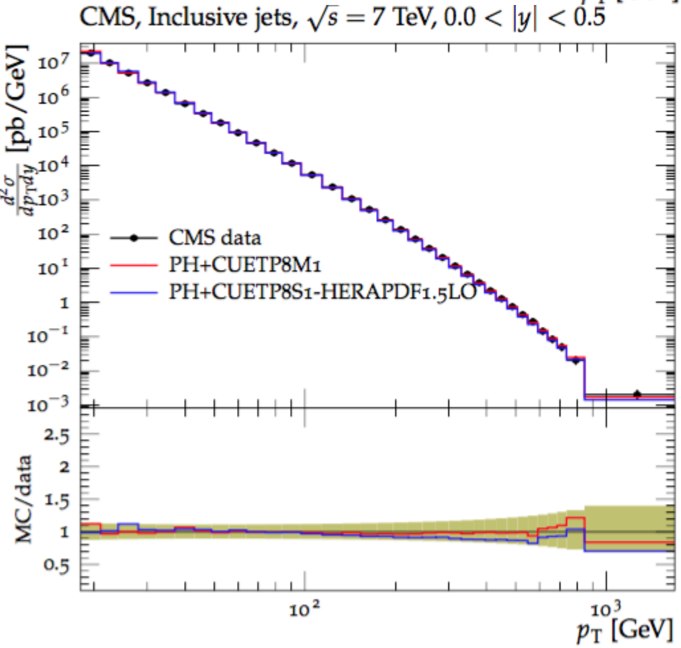


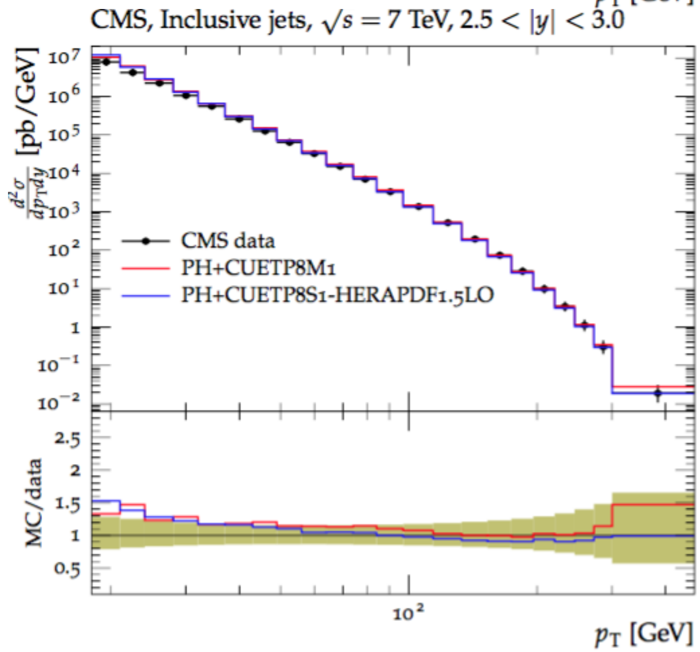
- Combined CMS and TOTEM data for $dN_{ch}/d\eta$ @ $\sqrt{s}$ = 8 TeV in inclusive inelastic, NSD-enhanced, SD-enhanced pp collisions.
- Due to the improved modeling of SD, CD, and DD in PYTHIA8, PYTHIA8 using UE tunes describes the MB data, better than PYTHIA6 with UE tune
- Predictions with all UE tunes describe fairly well MB observables in $|\eta| < 2$.
- Only predictions obtained with CUETP8M1 describes the data in $|\eta| > 4$
  - due to the PDF used in CUETP8M1.

Inclusive jet production





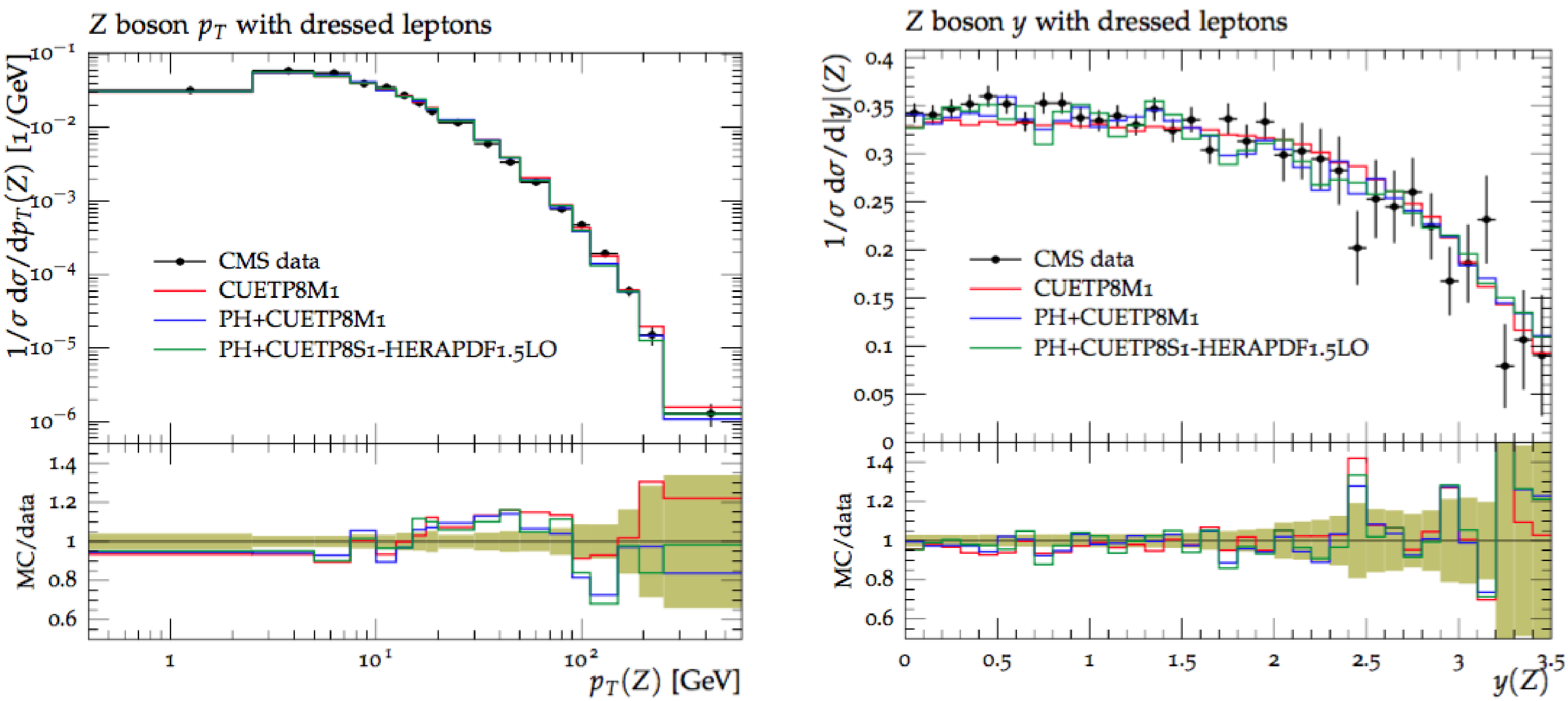




- Inclusive jet cross section as a function of p_T in different rapidity ranges @ $\sqrt{s} = 7$ TeV
- Data compared to different predictions
- Predictions using CUETP8M1 describe the data best
- All the tunes overshoot the jet spectra at small p_T.
- CUETHppS1 underestimate the high p_T region

- Predictions from P O W H E G interfaced to P Y T H I A 8 using CUETP8S1-HERAPDF1.5LO and CUETP8M1 provide very good description.

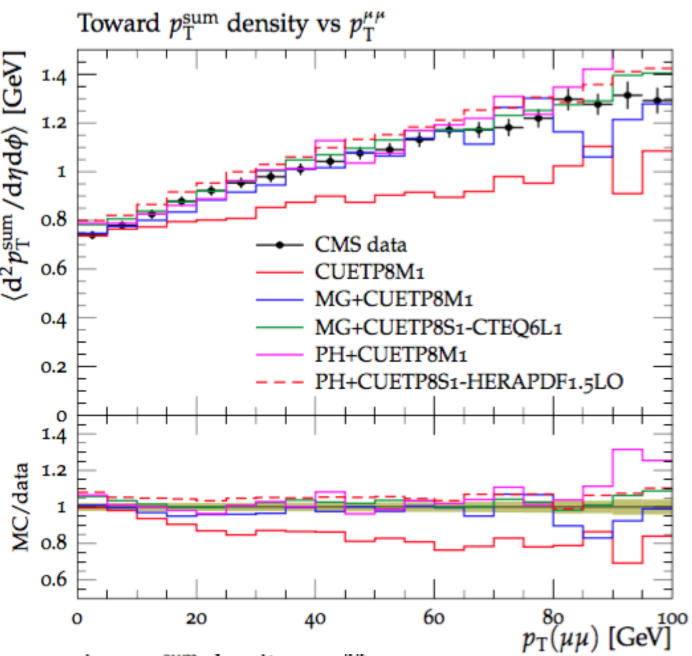
- p_T and y distributions of the Z boson in pp collisions at $\sqrt{s}$ = 7 TeV

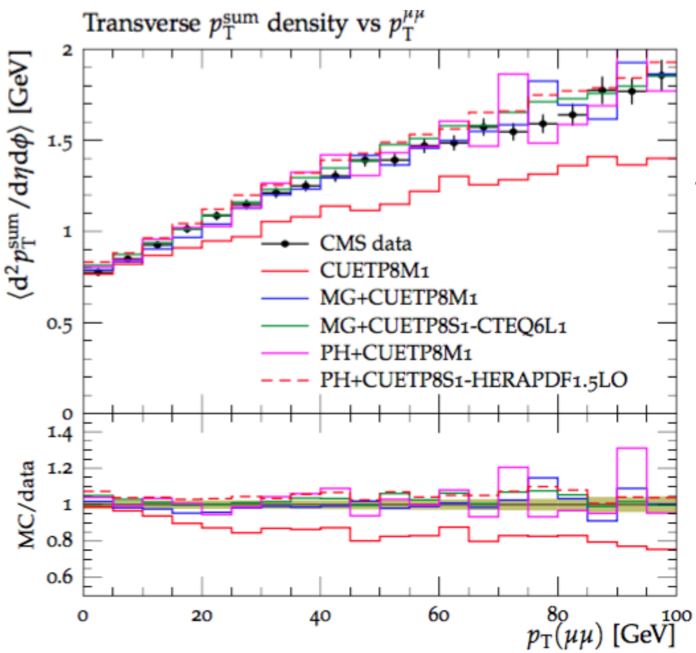


- Prediction using P Y T H I A 8 with CUETP8M1 (without POWHEG) agrees reasonably well @ small p_T

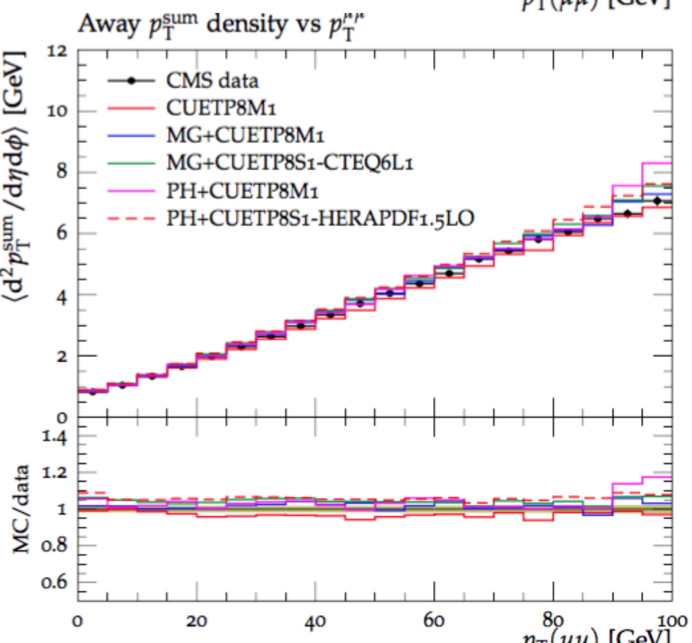
- POWHEG interfaced to PYTHIA8 using CUETP8S1-CTEQ6L1 and CUETP8M1 provides good agreement overall.

Z boson in Drell-Yan production





- Charged particle p_T^{sum} densities in the toward, transverse and away regions

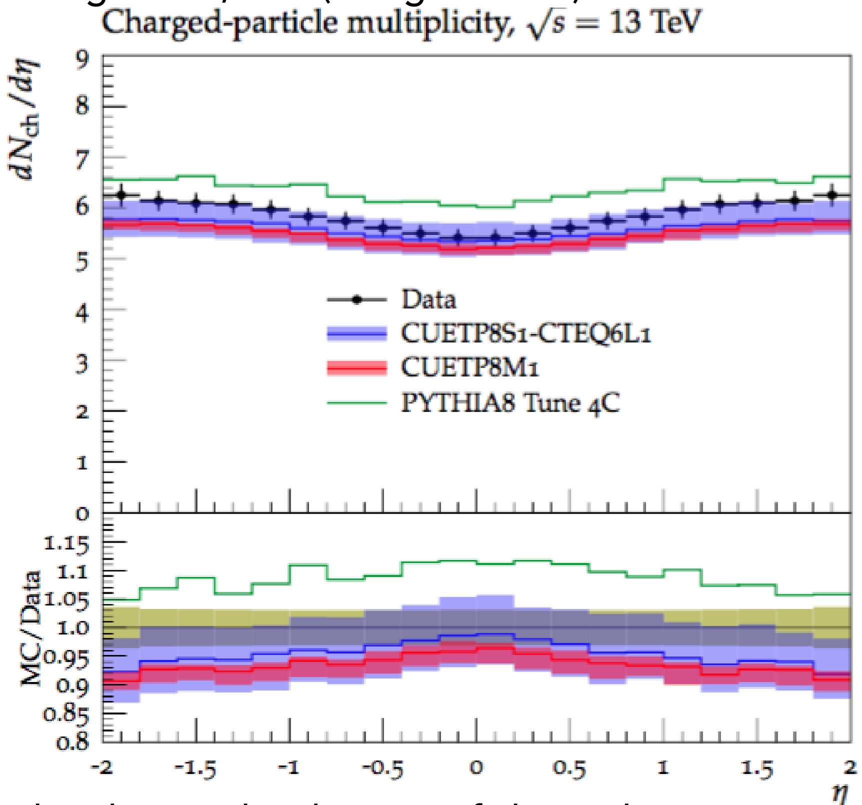


- Predictions based on CUETP8M1 do not fit the Z boson data unless interfaced to a higher-order ME generator.
- ME configuration agrees well with the observables in the away region in data
- Larger discrepancies between data and P Y T H I A 8 predictions @ high p_T in transverse and toward regions
- Higher-order contributions (starting with Z+dijet), (interfacing PYTHIA to POWHEG or MADGRAPH), must be included for describing Z-boson production in all regions.

dN/dη of charged hadrons @ 13 TeV

arXiv:1507.05915

- **First LHC Run II paper at 13 TeV**
- Datasets:
  - data taken June 7, 2015
  - number of collisions per bunch crossing: ~0.05
  - CMS tracker and pixel detectors ON
  - CMS magnet off, B=0 (straight tracks)



- Pseudorapidity density distributions of charged hadrons in the region $|\eta| < 2$ for inelastic pp collisions
- **Charged hadron multiplicity at midrapidity:**
  5.49 ± 0.01 (stat.) ± 0.17 (syst.)

- Center-of-mass energy dependence
- Green band stands for total experimental uncertainty on the data

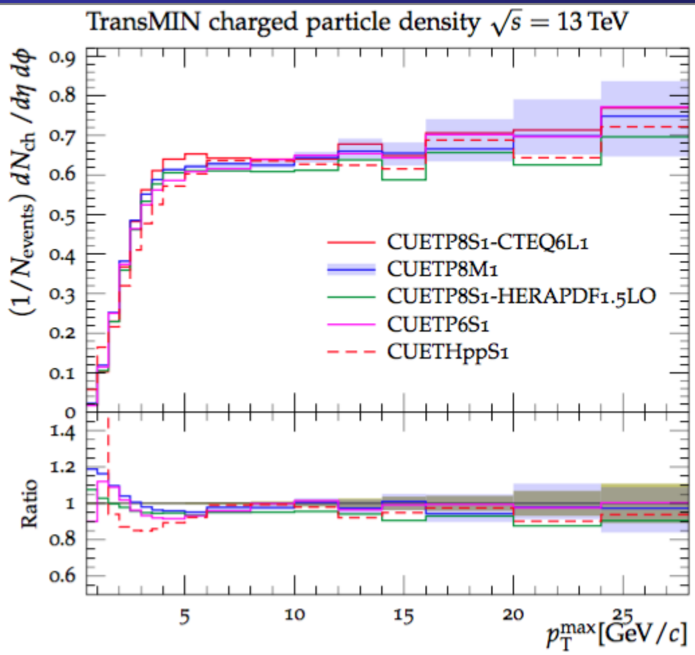
Summary

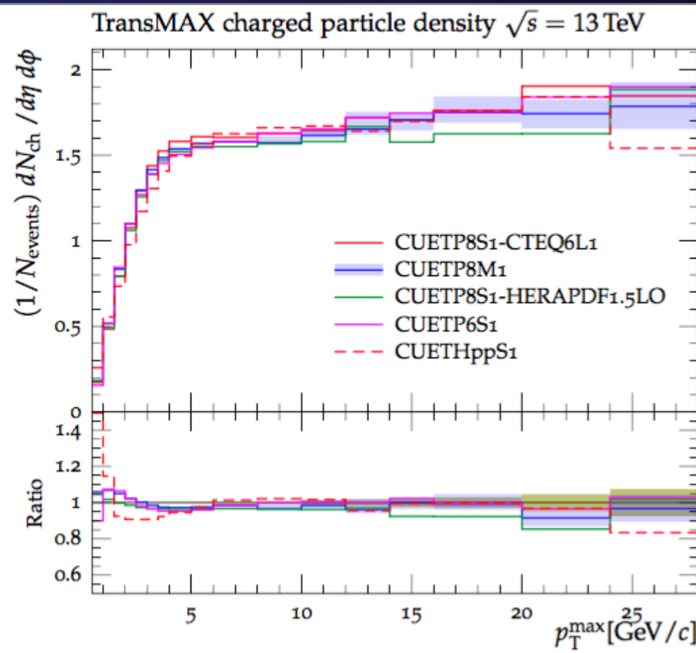
- CMS has constructed new P Y T H I A UE tunes using different PDFs
- All the new CMS UE tunes predict remarkably similar results for the UE observables @ 13 TeV.
- DPS sensitive observables were fitted directly by tuning the MPI parameters
  - Two PYTHIA8 W+dijet DPS tunes and two PYTHIA8 4-jet DPS tunes were constructed
- CMS UE tunes perform fairly well in the description of DPS observables,
  - do not fit the DPS data as well as the DPS tunes do.
- At present, not able to describe both soft and hard MPI within the current PYTHIA and HERWIG++ frameworks.
- σ eff is also calculated by fitting the DPS-observables.
- Predictions of P Y T H I A 8 using the CMS UE tunes agree fairly well with the MB observables in the central region
  - interfacing to higher-order, i.e. POWHEG, and multileg, i.e. MADGRAPH, ME generators is possible without destroying their good description of the UE.
  - No need to produce separate tunes for these generators.
- All of the new CMS tunes come with the eigentunes
  - can be used to estimate the uncertainties of the theoretical predictions.
- The new CMS tunes will play an important role in predicting and analyzing LHC data @ 13 & 14 TeV!

Thank you for your attention!

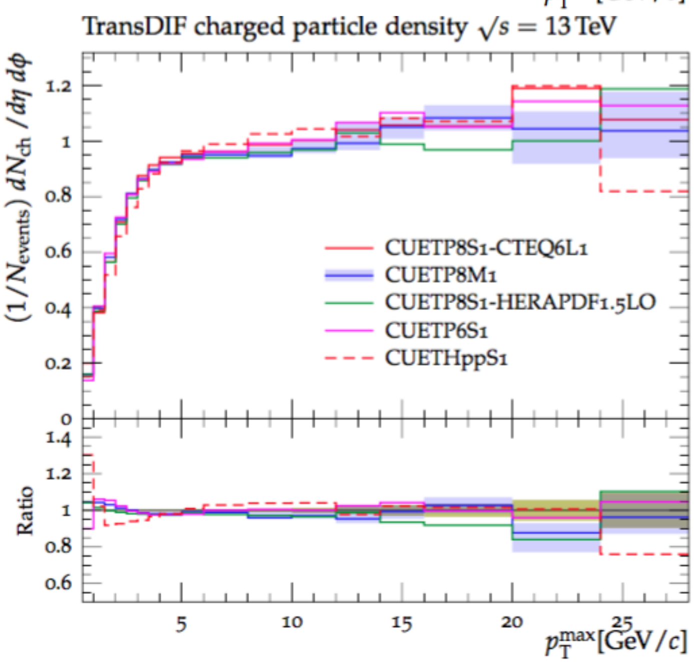
BACKUP

Extrapolation to 13 TeV



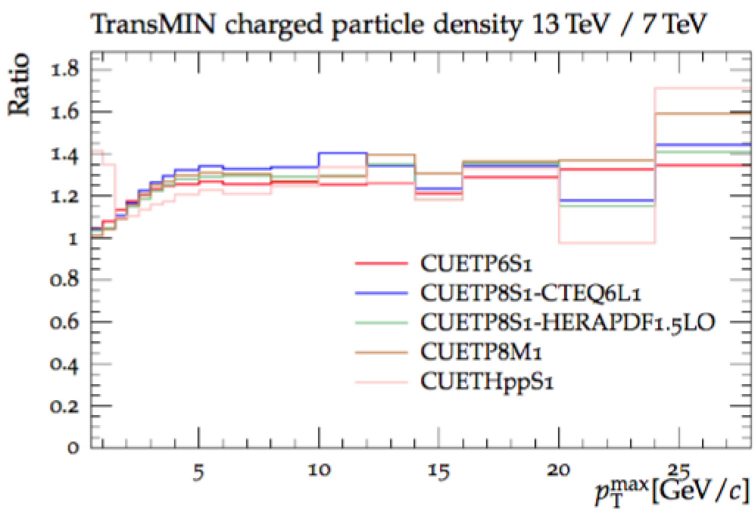


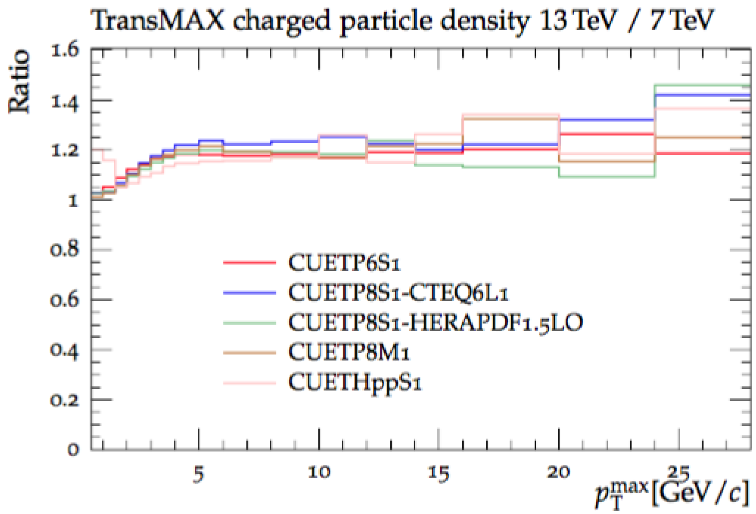
- Predictions @ 13 TeV for the charged-particle densities in TransMIN, TransMAX and TransDIF
- five new CMS UE tunes:
  - CUETP6S1- CTEQ6L1,
  - CUETP8S1-CTEQ6L1,
  - CUETP8S1-HERAPDF1.5LO,
  - CUETP8M1,
  - CUETHppS1.
- Ratio of the tunes to predictions of CUETP8S1-CTEQ6L1.

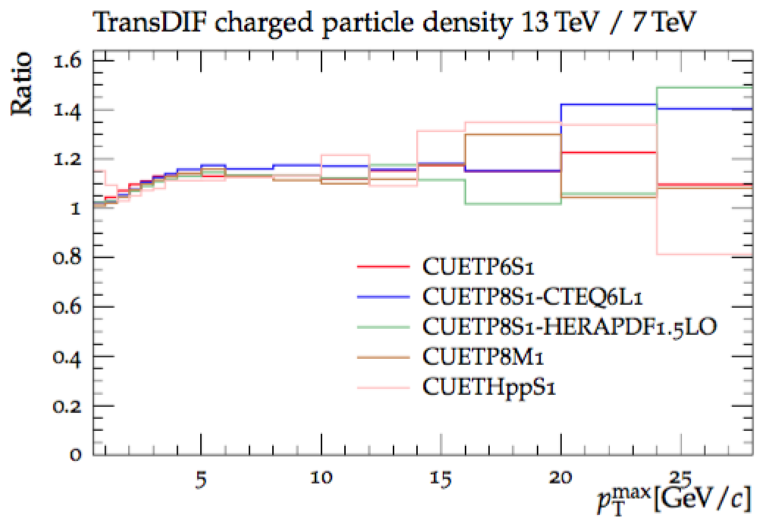


- The new PYTHIA8 tunes give results @ 13 TeV similar to the new CMS PYTHIA6 tune and the new CMS HERWIG++ tune.
- Predictions for CUETP8M1 are shown along with the envelope of the corresponding eigentunes.
  - uncertainties on the predictions based on the eigentunes do not exceed 10% relative to the central value.

Extrapolation to 13 TeV (II)



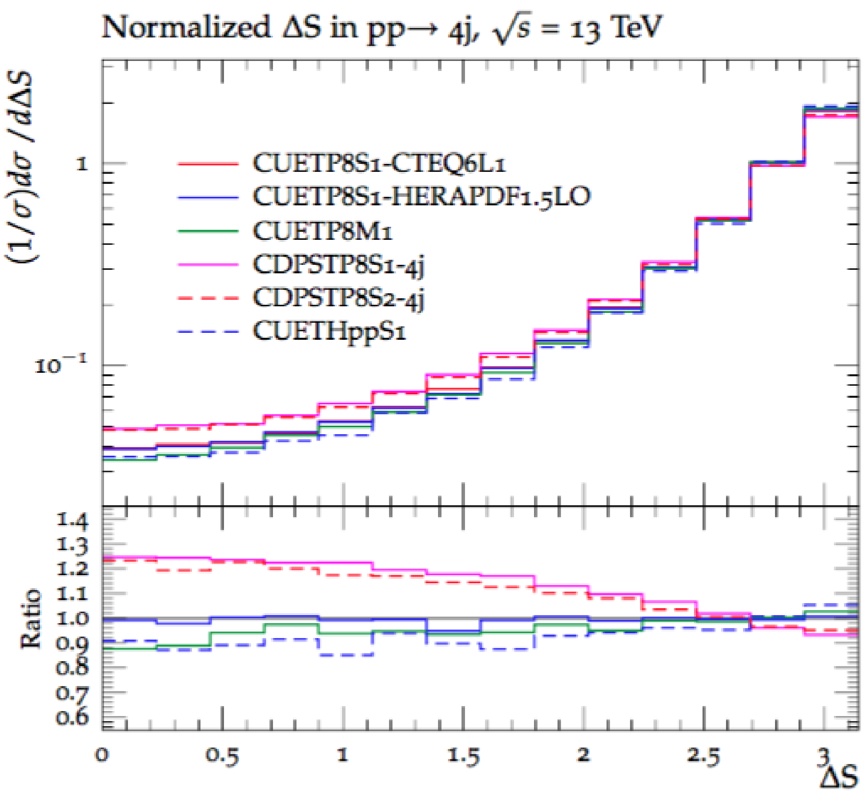


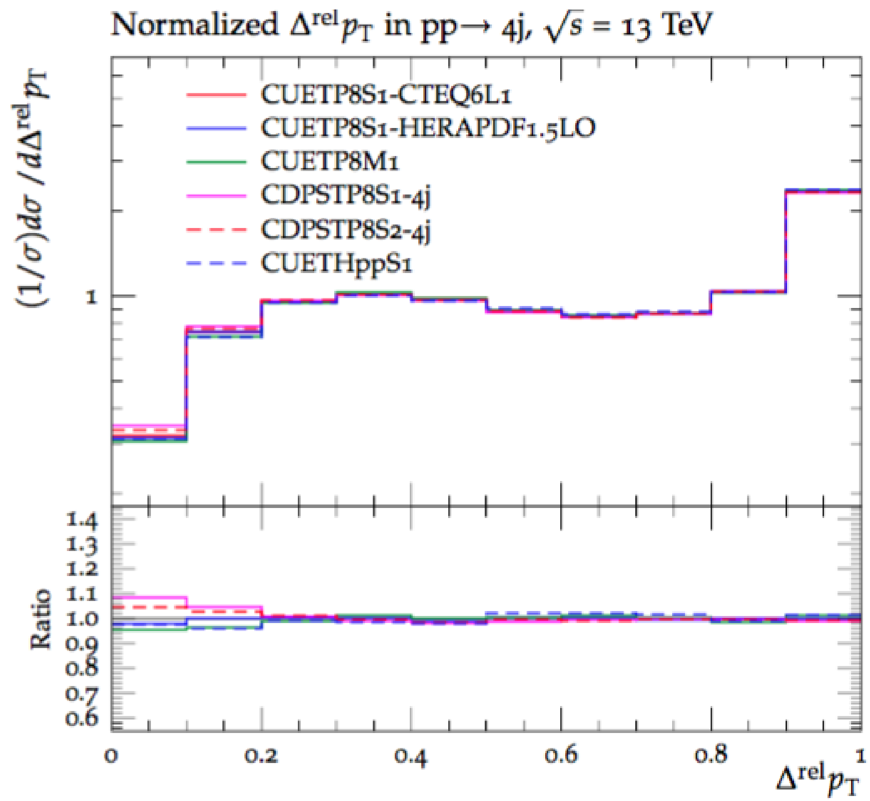


- The ratio of 13 TeV to 7 TeV results for the five tunes.
- TransMIN region increases much more rapidly with energy than TransDIF
  - When using CUETP8M1 the charged particle density for $5 < p_T^{max} < 6$ GeV is predicted to increase by 28%
  - TransDIF region is predicted to increase by 13%

Extrapolating DPS to 13 TeV

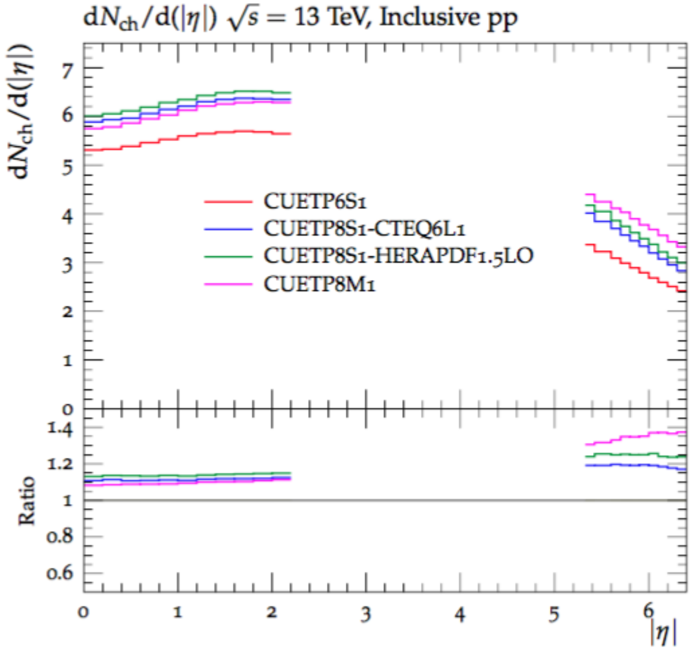
- Predictions for the DPS-sensitive observables @ 13 TeV are shown for
  - CMS PYTHIA8 UE tunes: CUETP8S1-CTEQ6L1, CUETP8S1-HERAPDF1.5LO and CUETP8M1,
  - CMS P Y T H I A 8 DPS tunes: CDPSTP8S1-4j and CDPSTP8S2-4j.

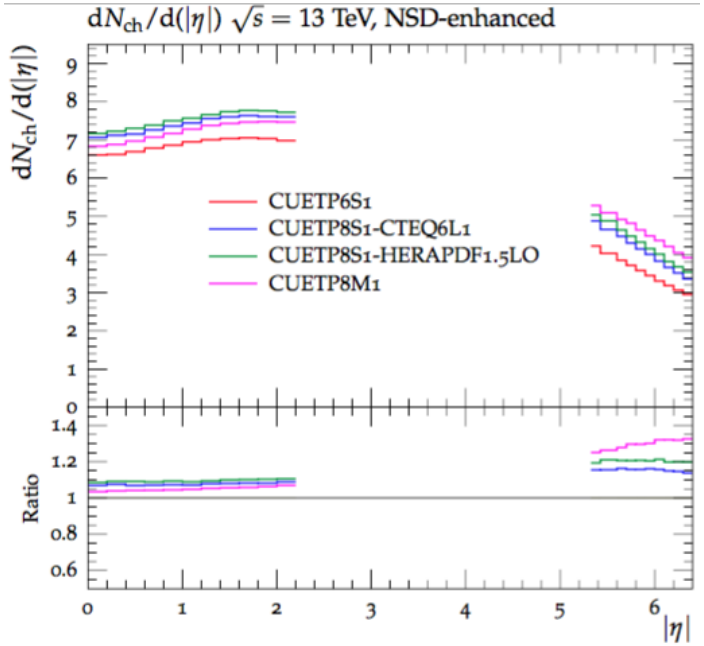


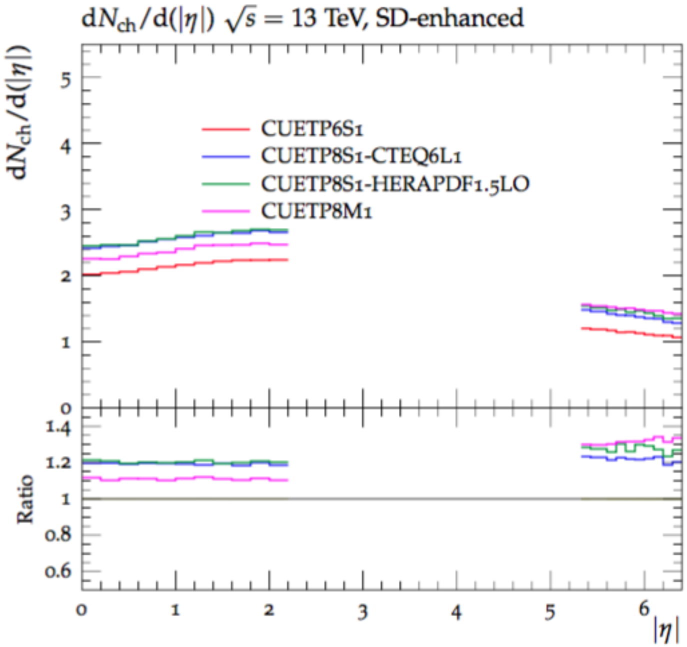


- In HERWIG++, eff is independent of the center-of-mass energy
- PYTHIA8 gives a eff that increases with energy.
- P Y T H I A 8 UE tunes predict ~7% increase in eff between 7 TeV & 13 TeV
- CDPSTP8S2-4j predicts an increase of ~20%.

Extrapolating MB to 13 TeV

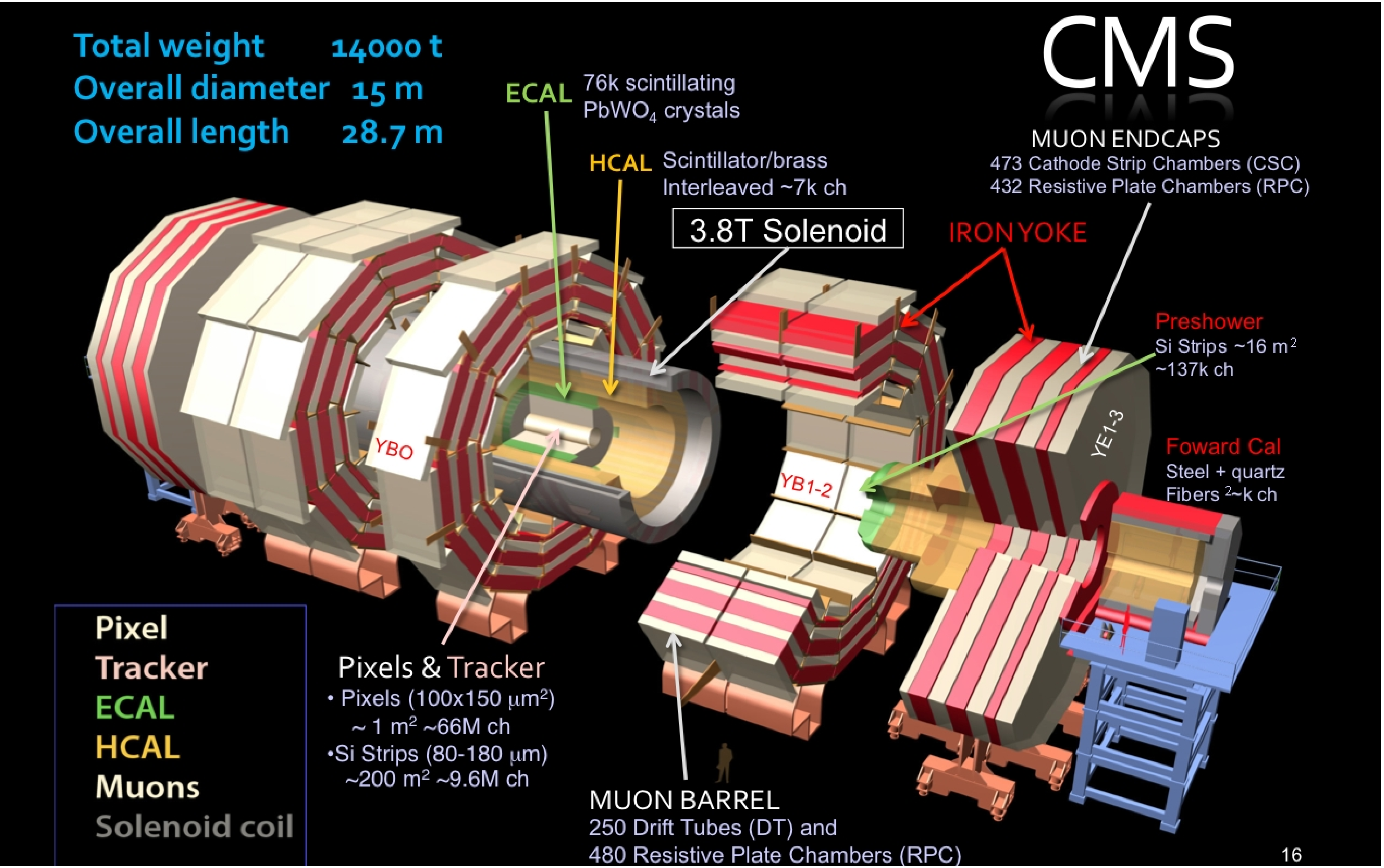






- The charged-particle pseudorapidity distribution for inelastic, NSD-enhanced, and SD-enhanced pp collisions
- The densities in the forward region are predicted to increase more rapidly than the cental region
- However, MB observables slower increase with center-of-mass energy than UE observables.

CMS Detector



CMS Detector