Run-II results on minimum bias collisions and underlying event activity from CMS

Ankita Mehta

(on behalf of the CMS Collaboration)

Eötvös Loránd University, Budapest

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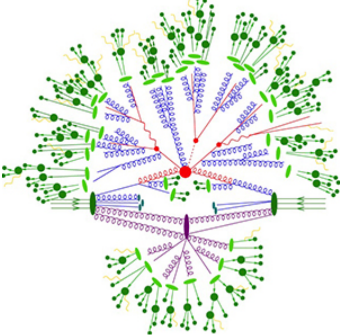
QCD description → hard interaction & Underlying event activity (UE)



- Particle production in the central regions → pQCD calculations in the framework of collinear factorization
- Soft diffractive processes dominate in forward regions → probed using **minimum-bias collisions (MB)** → benifits from CMS forward detector system

UE → semi-hard/soft interactions (**BBR, ISR, FSR, MPI**) → large fraction of σ_{total} @LHC

MB → **Events with no/zero bias from trigger**

Why study MB & UE??

- Hadron collisions dominated by soft partonic interactions
- Important to study MB & transition between the pQCD & soft QCD models
- UE → very important ingredient of MC event generation
- Non-perturbative phenomenological models → free parameters tuned to data
- Forward energy drives development of cosmic ray induced air showers
- Calibration of physics tools (**pileup, isolation, background estimation...**)

Included in this talk...

- CMS recorded $\sim$135 fb^{-1} of "good" pp collisions during Run-II
- Special runs:
    - Low pileup runs $\sim$273 pb^{-1} CMS data during 2015–2018 (includes 85.6 nb^{-1} of data @ 0T collected using CASTOR)
    - 6 pb^{-1} CMS+TOTEM data collected during 2015–2018

A variety of results from CMS using Run-II pp collisions data

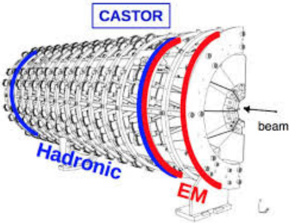
- Minimum-bias collisions @ 13 TeV
    - → Average very forward energy
- Inelastic pp cross section measurement
- Charged particle spectra
- Underlying event activity @ 13 TeV
    - → UE activity using $t\bar{t}$ events
- UE activity using Drell–Yan events

Complete list of results from CMS

Average very forward energy using CASTOR (EPJC(2019)79:893)

- First correlation study of hadron activity at very forward & central rapidities performed at 13 TeV using CASTOR
- 0.22 nb^{-1} of low-pileup pp data selected using Zerobias triggers @*Zero Tesla*

- Atleast one reconstructed track within $|\eta| < 2$
- Tracking efficiency ~76% & misreconstruction probability ~5% for charged particles with $p_{\mathrm{T}} >$ 200 MeV
- Activity in atleast one HF tower
- CASTOR energy scale → Dominating source of systematic uncertainty
- Data compared to a variety of models



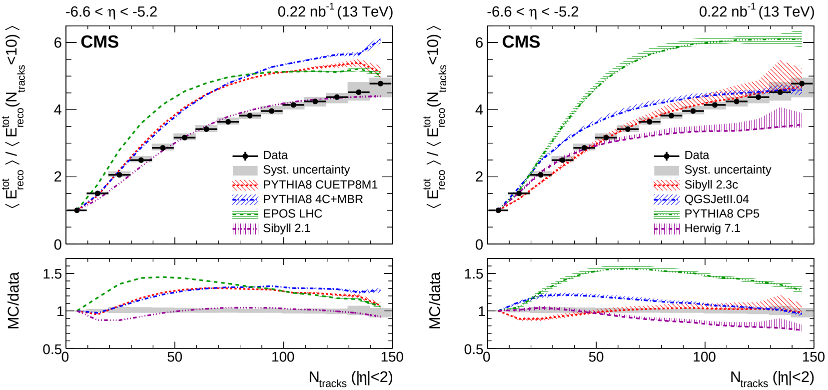
Average energy (had. + em) reconstructed with CASTOR in $6.6 < \eta < -5.2$ *vs* $N_{\mathrm{tracks}}(|\eta| < 2)$

Novel forward folding technique

- Model/theory → Detector level
- Particle multiplicity and CASTOR energy are smeared

Energy deposited in CASTOR

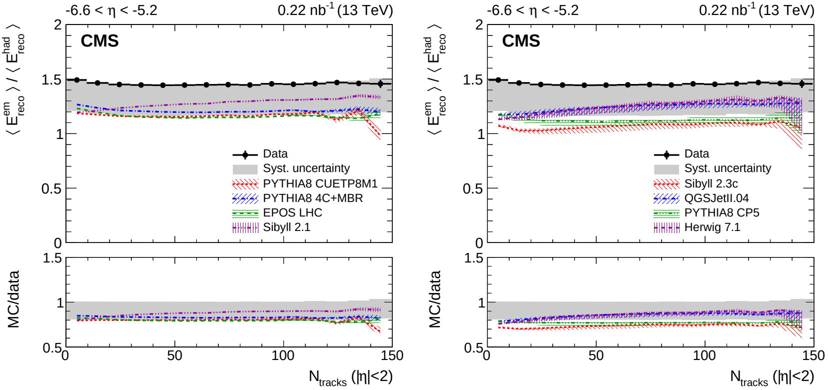
$$E^{tot}_{reco} = \sum_{i=towers} E_i; E_i > \text{Noise threshold}$$



- $\langle E^{tot}_{reco} \rangle$ increases with N_{tracks}
- Increase of energy with multiplicity is driven by MPI
- Only Sibyll 2.X & Herwig 7.1 describe the relative increase well
- Mismatch strongest for EPOS LHC & PYTHIA8 CP5

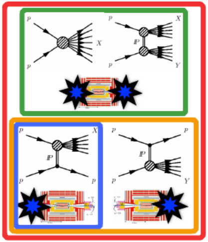
Energy ratios

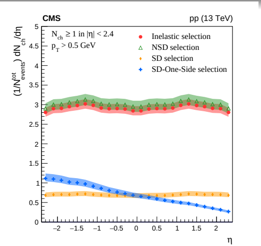
- Sensitive to differences in underlying final state hadron production mechanisms

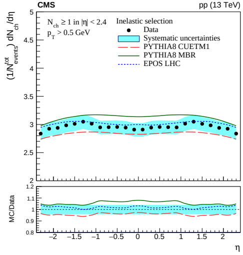


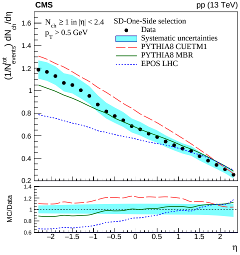
- Ratio is almost constant over the whole track multiplicity range → No dramatic change of the particle production mechanism in forward regions
- All model predictions are lower than the data
- Energy ratio best described by QGSJETII.04, SIBYLL2.1, & HERWIG7.1

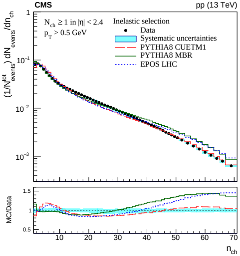
- Low pileup data from 2015
- Charged particles with $p_T > 0.5\,\text{GeV}$ & $|\eta| < 2.4$
- Activity requirement in HF
- Event categories: Inelastic, NSD-enhanced, SD-enhanced







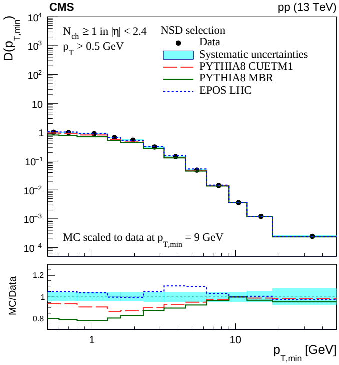


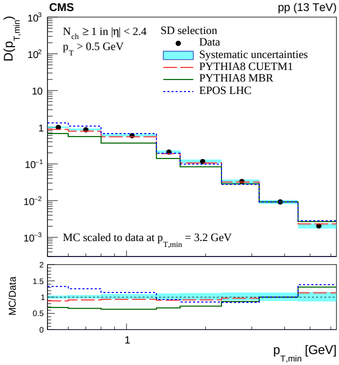


- SD-One-Side enhanced: PYTHIA8 MBR4C description within uncertainties
- Room for improvement in high multiplicity regions (dominated by MPI)

Results

- Integrated p_T spectrum of charged particles → Sensitive to the transition b/w the non-perturbative & perturbative QCD regions



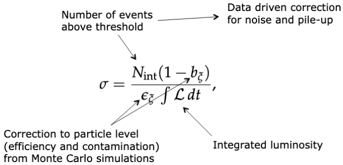


- NSD-enhanced events: Best described by EPOS LHC with small fluctuations
- SD-enhanced events: Low p_T region difficult to describe
- Transition b/w the region dominated by particle production from MPI & hard scattering evident from fast change of slope

- Measured inelastic pp cross section in a fiducial region is extrapolated to the full inelastic phase space
- Challenging to measure precisely; extrapolation is purely model-driven
- Important QCD measurement: crucial to model pileup
- Input to improve phenomenological hadronic interaction models

$$\sigma_{tot}(s) = \sigma_{el}(s) + \sigma_{inel}(s).$$

$$\boxed{\sigma_{inel}(s) = \sigma_{sd}(s) + \sigma_{dd}(s) + \sigma_{cd}(s) + \sigma_{nd}(s).}$$



- 2015 data with and without magnetic field collected using zerobias triggers
- Two different event selections in terms of activity requirement in HF & CASTOR → Different contribution from low-mass diffractive processes
- Data-driven noise cancellation & bunch-by-bunch pileup correction

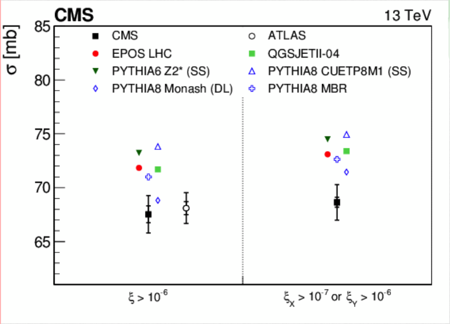
Fully corrected cross section

HF OR

$$\sigma(\xi > 10^{-6}) = 67.5 \pm 0.8(\text{syst}) \pm 1.6(\text{lumi})\,\text{mb}$$

HF OR CASTOR

$$\sigma(\xi_X > 10^{-7}\,\text{or}\,\xi_Y > 10^{-6}) = 68.6 \pm 0.6(\text{syst}) \pm 1.3(\text{lumi})\,\text{mb}$$



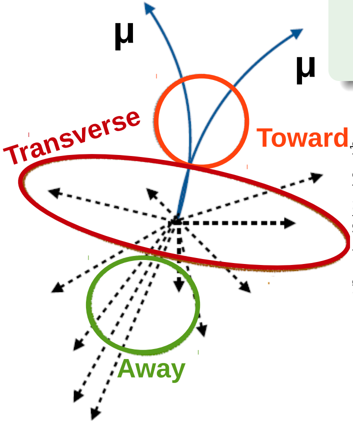
from TOTEM:

$$\sigma_{\text{inel}} = (79.5 \pm 1.8)\,\text{mb}$$

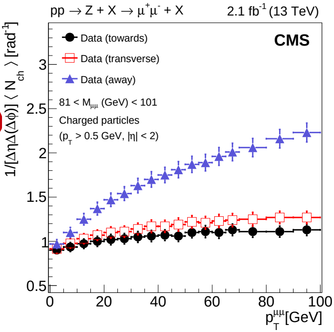
- Consistent with previous measurement in the same phase space
- Smaller than those predicted by the majority of models for hadron-hadron scattering → Underestimation of predicted cross section for low-mass diffractive processes

UE activity using Z boson events (JHEP07(2018)032)

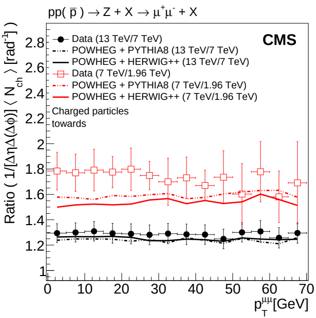
- UE recoiling against the Z boson events with "standard" phase space cuts
- Experimentally clean signature with Z $\rightarrow \mu\mu \rightarrow$ Clear identificiation of UE activity
- Test for the universality of UE process & jet/tracke-driven UE tunes
- **Observables: Charged-particle density & $\sum p_T$ density**



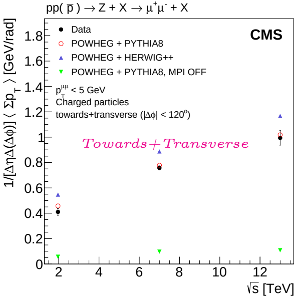
- *Towards & Transverse* → **Sensitive to MPI/UE**
- *Away* → **Dominated by ISR**



- Current results are compared with those @ 1.96 TeV (CDF) & 7 TeV (CMS)
- 60–80% rise from 1.96 TeV to 7 TeV → Simulations predict a slower rise with $\sqrt{s}$
- 25–30% rise from 7 TeV to 13 TeV

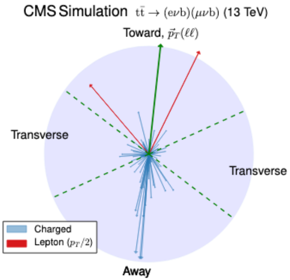


- Upper cut on $p_T^{\mu\mu}$ → UE activity mainly from MPI
- Better description: POWHEG+PYTHIA8
- POWHEG+HERWIG++ overestimates the data



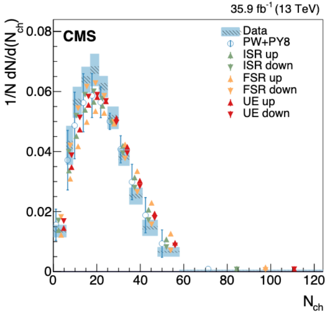
UE activity in $t\bar{t}$ events (EPJC(2019)79:123)

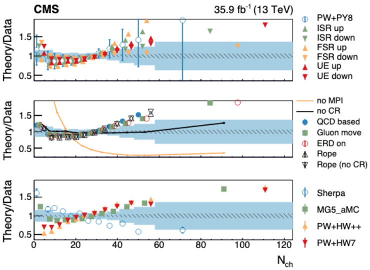
- I[st] measurement with UE recoiling against $t\bar{t} \rightarrow WbWb \rightarrow e\mu p_{\mathrm{T}}^{\mathrm{miss}} + 2bjets$ system
- Test "universality" assumptions at further "higher" scales & input to improve modeling of top quarks
- Direct probe of color reconnection
- Main challange → characterize the soft component of $t\bar{t}$ events

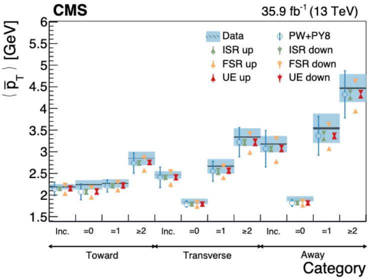


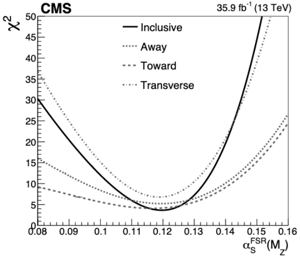
Variables to characterize UE

- Multiplicity & momentum flux: N_{ch}, $\sum p_{\mathrm{T}}$ or $\sum p_{z}$, $\bar{p}_{\mathrm{T}}$ (or $\bar{p}_{z}$)
- Event shape observables from linearized sphericity tensor: $S^{\mu\nu} = \frac{\sum_{i=1}^{N_{ch}} p_i^{\mu} p_i^{\nu}/|p_i|}{\sum_{i=1}^{N_{ch}} |p_i|}$
- Evolution of observables in different categories of $t\bar{t}$ system kinematics → sensitive to the recoil activity









- POWHEG+PYTHIA8 ~ MC@NLO+PYTHIA8: Minimal dependence on ME generator
- Significant contributions from MPI
- CR effects subtle in data
- Variation in $\alpha_S^{FSR}(M_Z)$ → largest impact on UE → dominates the theory uncertainty

Value of $\alpha_S^{FSR}(M_Z) = 0.120 \pm 0.006 < \alpha_S^{FSR}(M_Z)$(LO)

New approach: PDF and $\alpha_S^{FSR}(M_Z)$ consistency in ME, PS, & MPI

- A set of results based on CMS Run-II data are presented
- Essentially all physics at LHC connected to quark & gluon interactions
- Hard processes $\rightarrow$ Well described by pQCD while soft interactions require non-perturbative phenomenological models
- MB collisions $\rightarrow$ dominated by soft interactions $\rightarrow$ explore fundamental aspects of hadron-hadron collisions
- Energy evolution studies of UE $\rightarrow$ Important for model tuning & constraining
- Model parameters tuned to UE data at central rapidities are consistent with the very forward data within experimental uncertainties
- Significant improvement in MC models, though there is still room for improvement

thanks !!!