Measurements of the underlying event activity and double parton scattering processes using the CMS detector

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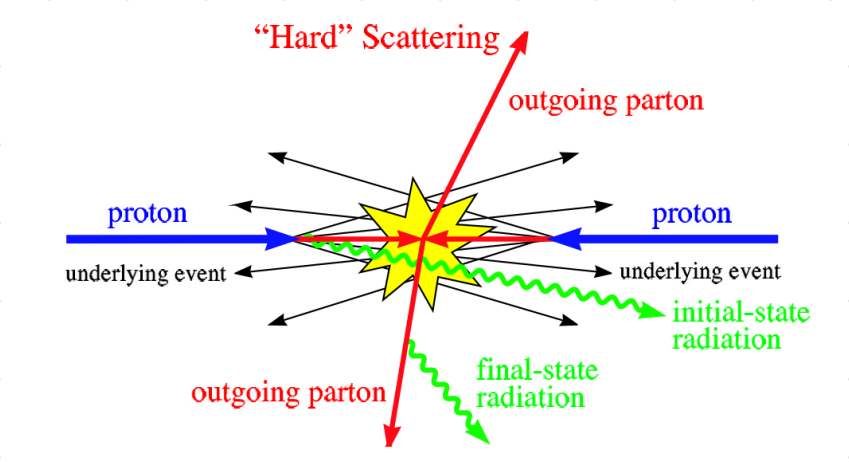
Outline

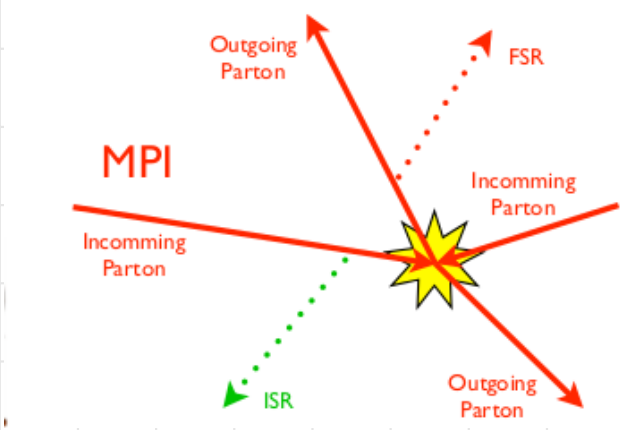
Underlying Event Activity and Multi Parton Interactions

Hadron Hadron Collision → Hard scattering between partons ⊕ underlying event (UE) activity



UE activity gets contributions from:

- Beam-Beam Remnants (BBR)
- Multiple Parton Interactions (MPI)
- Soft Initial state & final state radiations (ISR & FSR)



Generally UE is a softer contribution, but some MPI can be relatively hard → Double Parton Scattering (DPS)

Importance of UE Activity Measurements

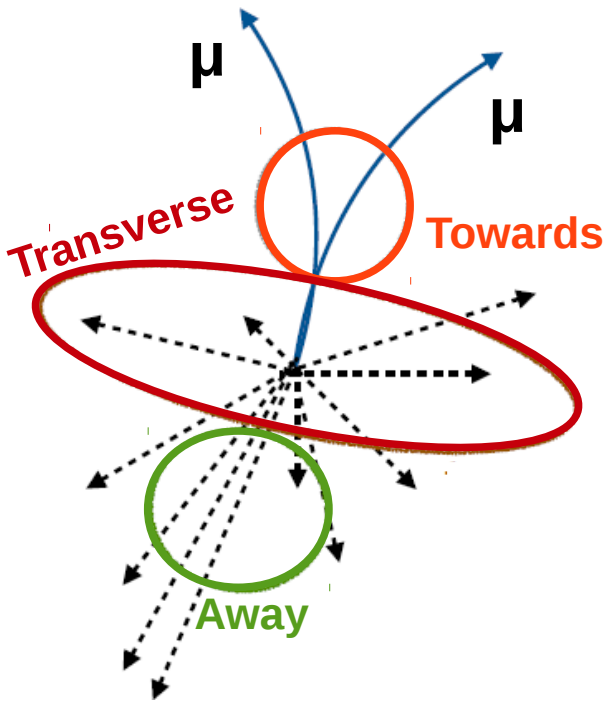
- Important in the study of soft interactions during high luminosity collisions @ LHC
- UE consists of semi-hard and low momentum processes, cannot be completely described with pQCD methods
- UE activity affects the efficiency of isolation criteria for photons and leptons → Needs to be undersstood for Higgs and SUSY searches
- **Experimental study of UE :** Probe to understand interplay of pQCD methods describing the hard processes and phenomenological models of the soft interactions
- PYTHIA8 tune CUETP8M1 & HERWIG++ tune EE5C constructed by fitting the UE data at various center-of-mass energies
- UE activity measured using different processes → Test to check the universality of the UE tunes
- **Understanding UE → Better tuning of MC → Precise measurements of SM and BSM processes**

- **Topological structure of hard hadron-hadron collisions is used to study the UE experimentally**
- **UE has been measured using minimum bias, Drell-Yan events, and $t\bar{t}$ events**

Measurement of the underlying event using the Drell-Yan process in proton-proton collisions at $\sqrt{s} = 13$ TeV

(CMS-PAS-FSQ-16-008)

- First results on measurement of UE activity @ 13 TeV with Z boson events, 2.1 fb^{-1} of pp collisions data
- Experimentally clean signature: $Z \to \mu\mu$, Absence of QCD FSR
- **Observables: Charged particle density & $\sum p_T$ density**



Regions

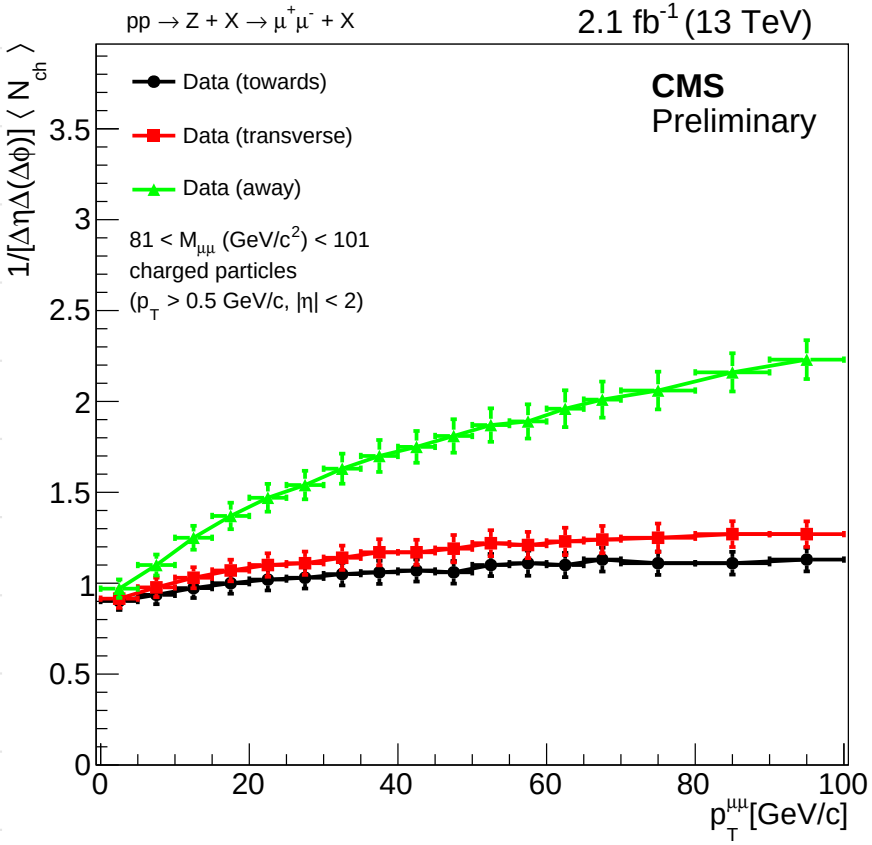
- $|\Delta\phi| < 60°$: *Towards*
- $|\Delta\phi| > 120°$: *Away*
- $60° < |\Delta\phi| < 120°$: *Transverse*; **Most sensitive to UE activity**

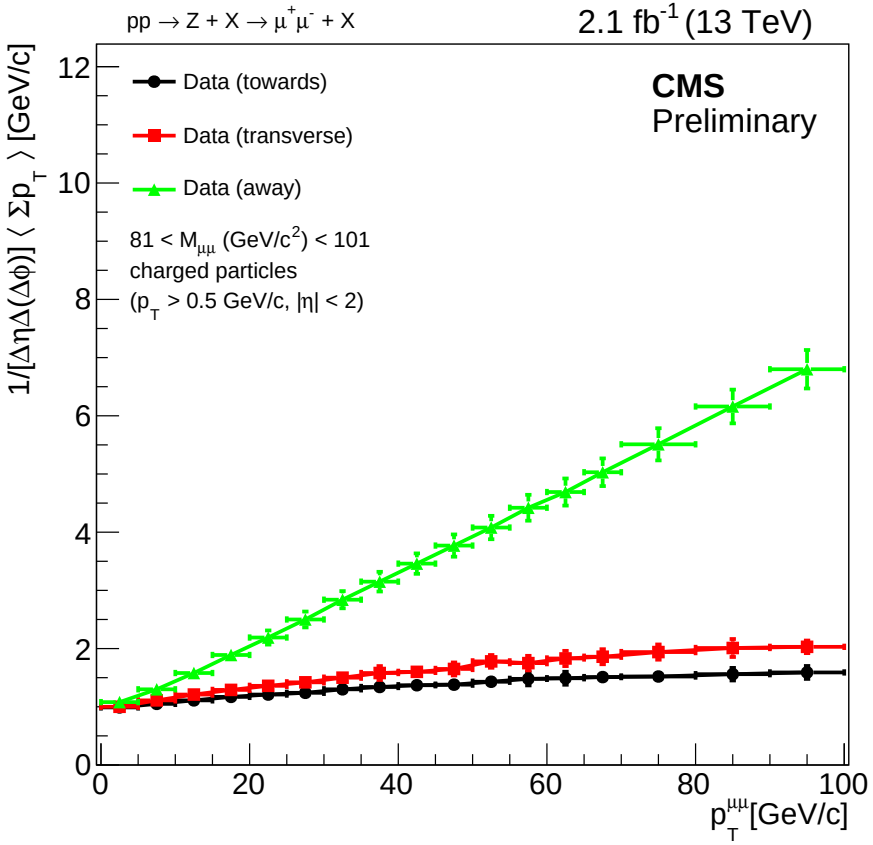
Systematic Uncertainties

- **Model dependency: 2–5%**
- **Tracking efficiency: 4–6%**
- Pileup (0.5%) & Trigger (0.1%)

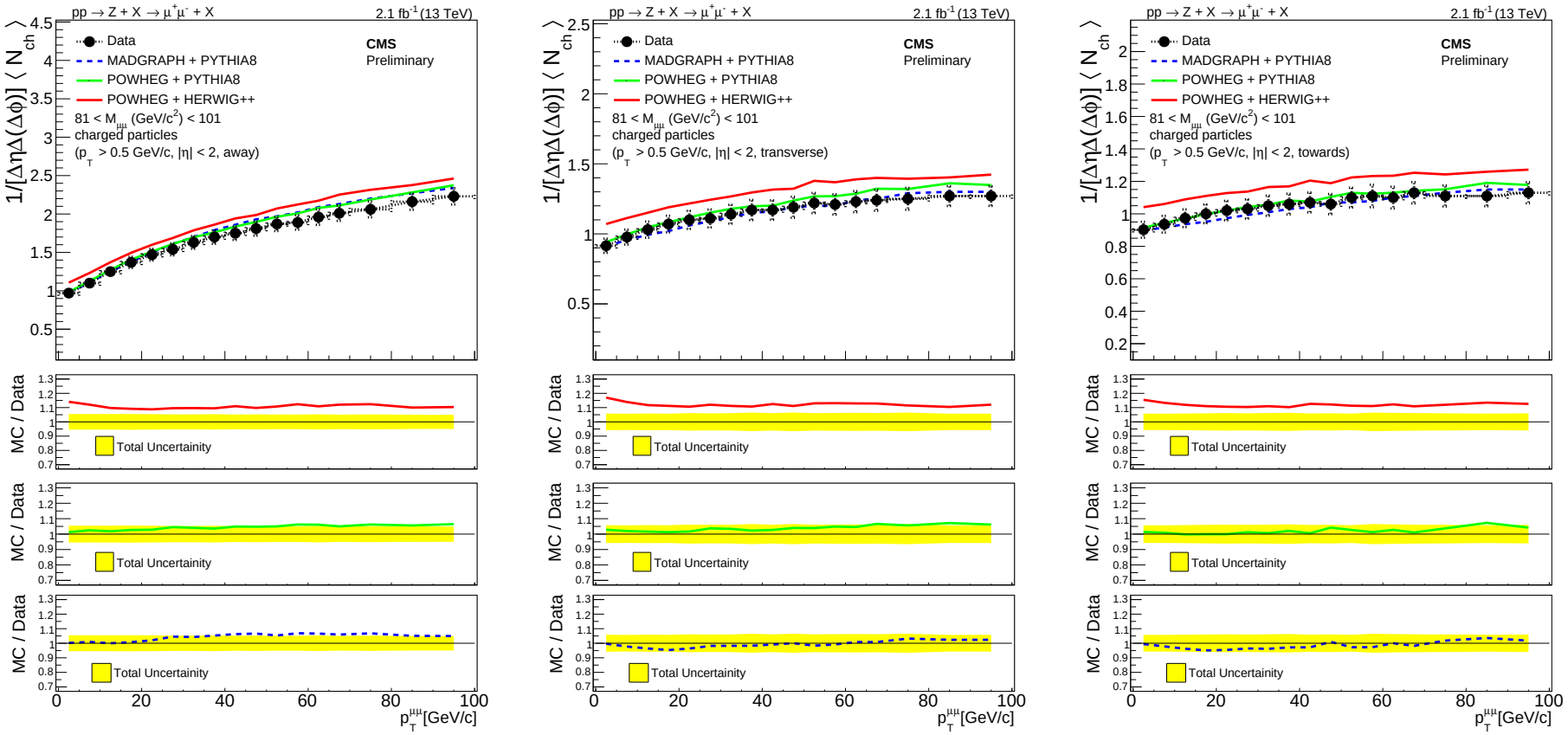
UE Activity in Different Regions

- Different behavior of UE activity for three regions → Varying radiation contributions
- UE activity in the *away region* increases sharply with $p_T^{\mu\mu}$ as compared to other two regions
- Observed rise in UE activity for the three regions with $p_T^{\mu\mu}$ due to increasing ISR contributions





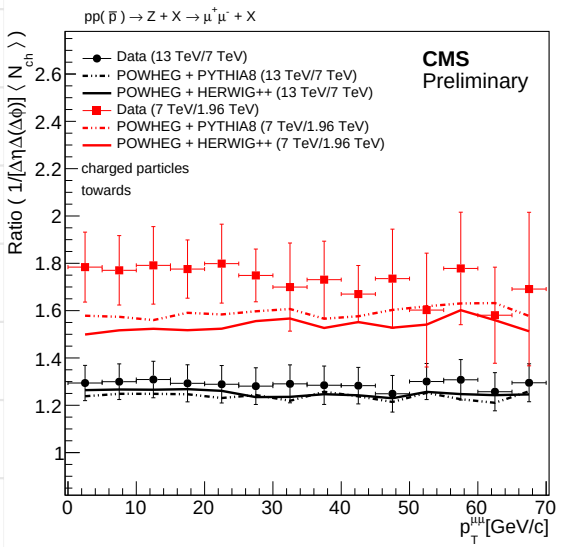
Comparison b/w Unfolded Data Distributions & Simulations



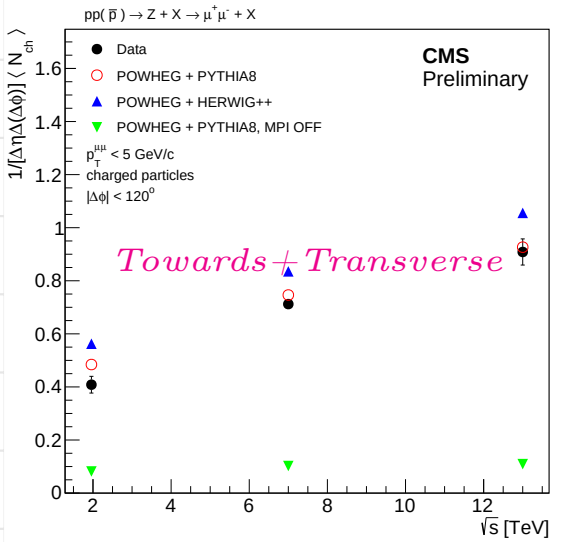
- POWHEG+HERWIG++: Overestimates the UE activity by 10%
- POWHEG+PYTHIA8: Agreement with data ∼5%
- MADGRAPH+PYTHIA8 → Best description

Energy Dependence of UE activity

- Current results are compared with those @ 1.96 TeV (CDF) & 7 TeV (CMS)
- Significant rise in UE activity with $\sqrt{s}$
  - 25–30% from 7 TeV to 13 TeV → best described by POWHEG+PYTHIA8 & POWHEG+HERWIG++
  - 60–80% from 1.96 TeV to 7 TeV → Simulations predict a slower rise with $\sqrt{s}$, better agreement with data at high $p_T^{\mu\mu}$

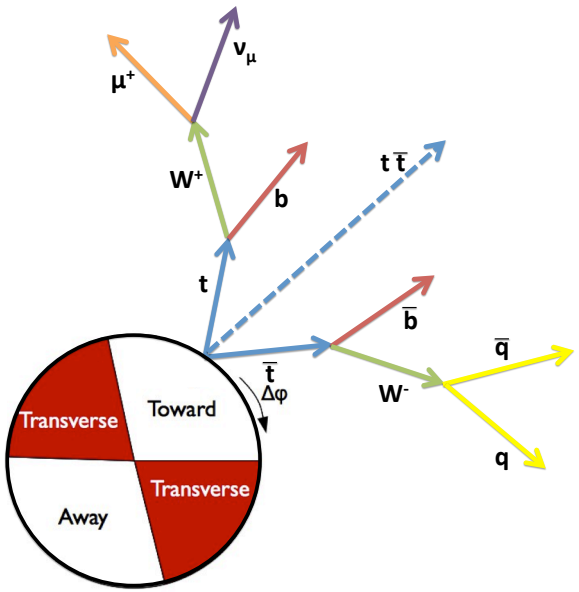


- Upper cut on $p_T^{\mu\mu}$ → Reduced radiation contribution → UE activity mainly from MPI
- Similar activity in *Towards* & *Transverse* regions
- Logarithmic increase with $\sqrt{s}$ well reproduced by POWHEG
- Better description by POWHEG+PYTHIA8
- POWHEG+HERWIG++ overestimates the data



Underlying event measurement with UE activity in $t\bar{t}$ + X events $\sqrt{s} = = 13$ TeV (CMS-PAS-TOP-15-017)

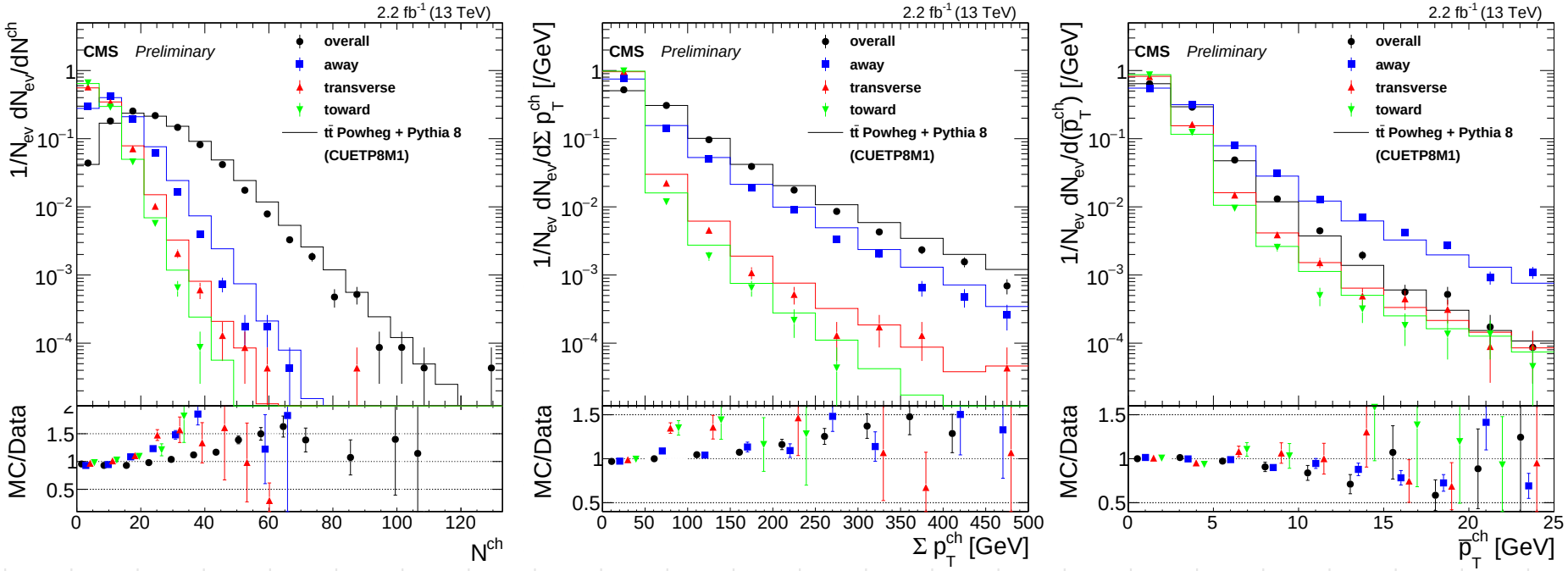
- Limited information about UE activity in heavy quark production
- UE activity is measured w.r.t $t\bar{t}$ system
- **Charged particle activity with N^{ch}, $\sum p_T^{ch}$, $\langle p_T^{ch} \rangle$ vs $p_T(t\bar{t})$ & N_{jets}**
- Detector-level top-quark production data @ 13 TeV compared with PYTHIA8(CUETP8M1) and HERWIG++(EE5C)
- 2.2 fb^{-1} of pp collisions data @ 13 TeV



- *Transverse* & *Towards* regions sensitive to MPI & BBR
- *Away* region sensitive to recoil of the $t\bar{t}$ system

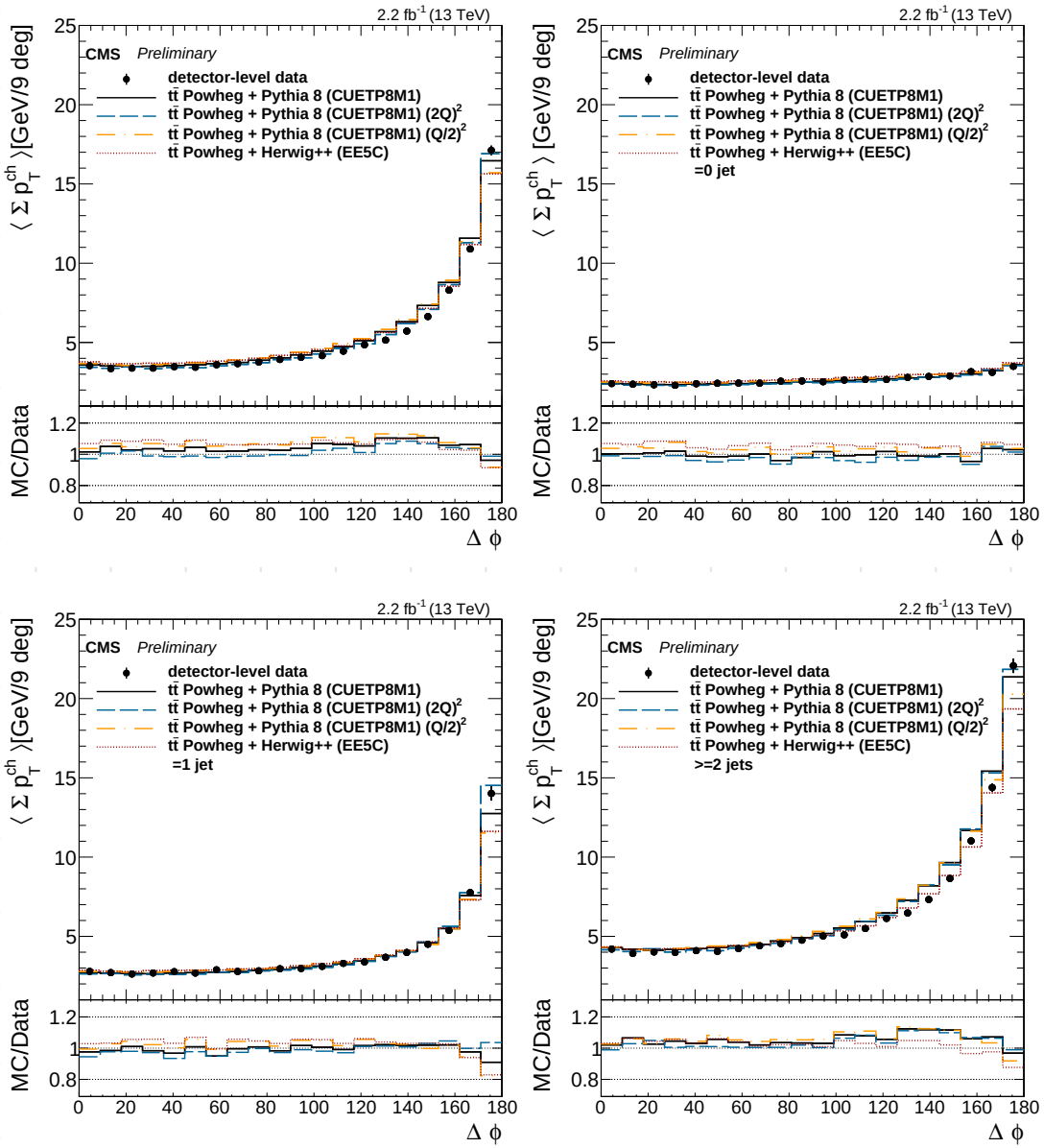
UE Activity in Different Regions

Detector level distributions compared with POWHEG+PYTHIA8 predictions



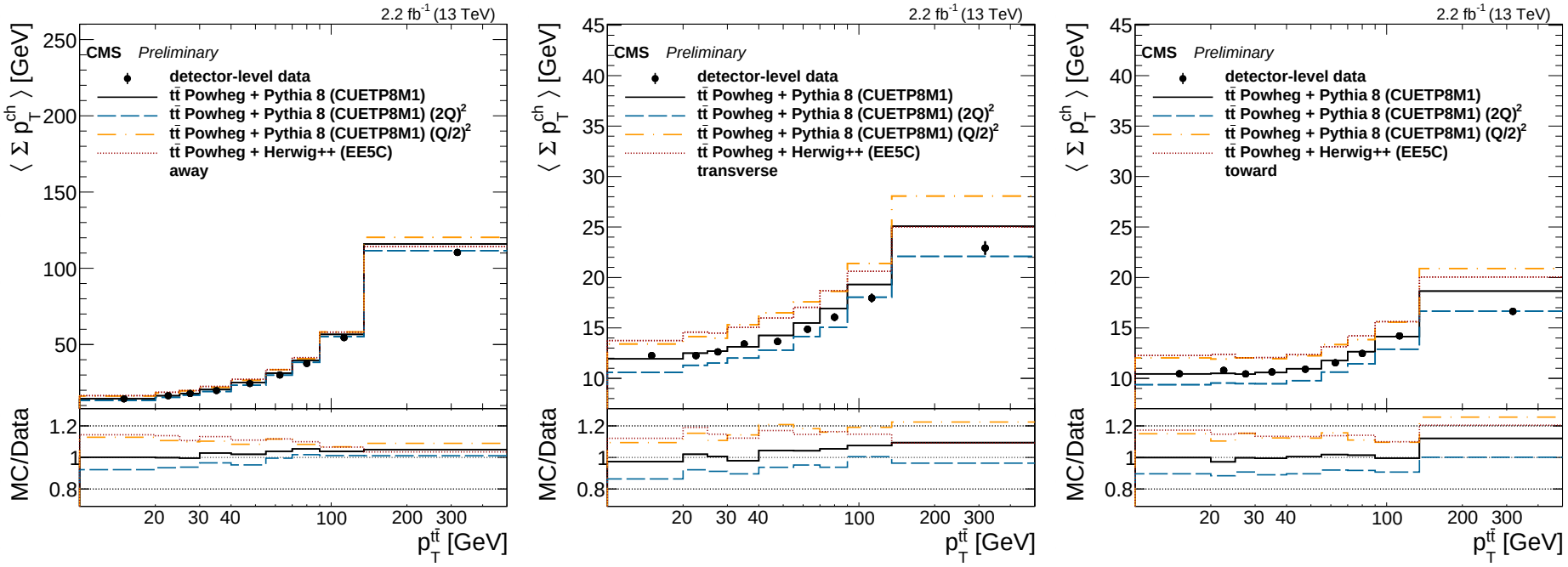
- POWHEG+PYTHIA8(CUETP8M1) tune fairly describes data
- Discrepancies observed for N_{ch} & $\sum p_T^{ch}$
- Slightly better agreement for $N_{ch} < 50$
- For charged particle multiplicities >50, POWHEG+PYTHIA8 predicts a higher multiplicity especially in the away region

UE Activity for Different Extra Jet Multiplicities



- **Small sensitivity to scale variations**
- **Small differences b/w POWHEG+HERWIG++(EE5C) & POWHEG+PYTHIA8(CUETP8M for low $\Delta\phi$ for inclusive, 0j and 1j cases**

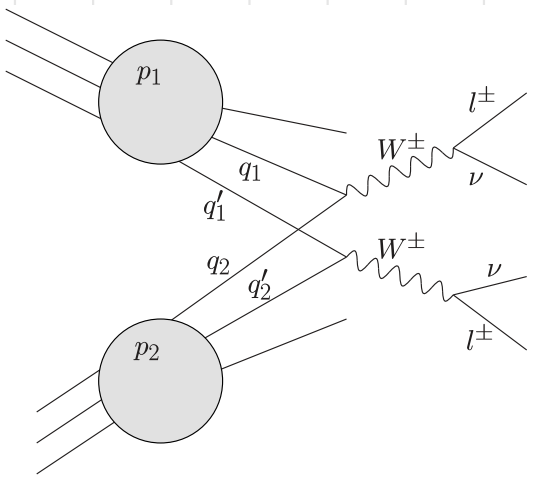
UE Activity as a function of $p_T^{t\bar{t}}$



- More sensitive to scale variations
- Small difference b/w POWHEG+HERWIG++(EE5C) & POWHEG+PYTHIA8(CUETP8M1) in *Transverse* & *Towards* regions

Measurement of double parton scattering in same-sign WW production in p-p collisions at $\sqrt{s} = 13$ TeV with the CMS experiment (CMS-PAS-FSQ-16-009)

- DPS events allow for the study of transverse and longitudinal parton correlations within the proton
- DPS $\rightarrow$ background for new physics searches @ LHC
- $\sigma_{\mathrm{WW}}^{\mathrm{DPS}}$ can be factorized as: $\sigma_{\mathrm{WW}}^{\mathrm{DPS}} = \frac{\sigma^2_{\mathrm{W}\rightarrow l\nu}}{2\sigma_{\mathrm{eff}}}$
- σ_{eff} $\rightarrow$ Effective area parameter, can provide information about hadron structure in transverse plane
- σ_{eff} $\rightarrow$ Measured using 4jets, 2b+2jets, W/Z+2jets, γ+3jet productions etc.
- Large systematics related to model dependence $\rightarrow$ **No firm conclusions about its dynamics**



- First results on DPS measurements @13 TeV with 35.9 fb^{-1} of pp collisions data

- Almost same cross section for same-sign WW production via DPS & SPS
- Clean final state with leptonically decaying W bosons

Analysis Strategy

Event Selection

- 2 same sign leptons ($\mu\mu$ or eμ) with $E_{\mathrm{T}}^{\mathrm{miss}}$; $\mathrm{p_T(l_{1/2})} > 25/20$ GeV;$E_{\mathrm{T}}^{\mathrm{miss}} > 15$ GeV
- $\mathrm{N_{jets}} < 2$ ($\mathrm{p_T} > 30$ GeV); $\mathrm{N_{bjets}} = 0$ ($\mathrm{p_T} > 25$ GeV)
- Veto on additional leptons & hadronically decaying τs

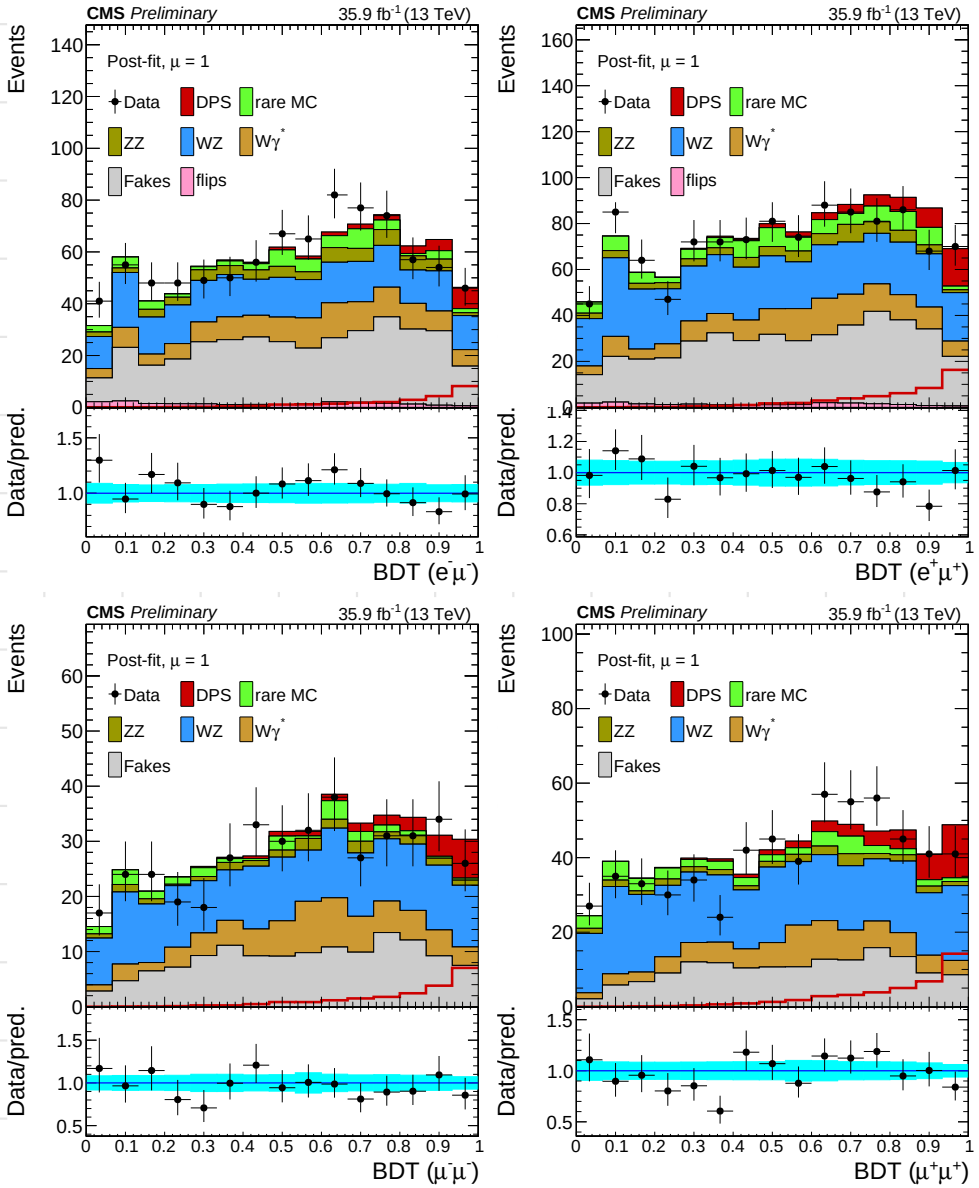
Background Processes

- WZ: Estimated from MC; Shape & normalization uncertainty from 3l control region
- Jet induced backgrounds: Estimated from data; Shape & scale uncertainties from variations in fake rate and MC closure tests
- Wγ^*, ZZ, & WWW $\rightarrow$ estimated from MC
- Z $\rightarrow \tau\tau$ estimated by measuring charge flip probability of electrons

Signal Extraction

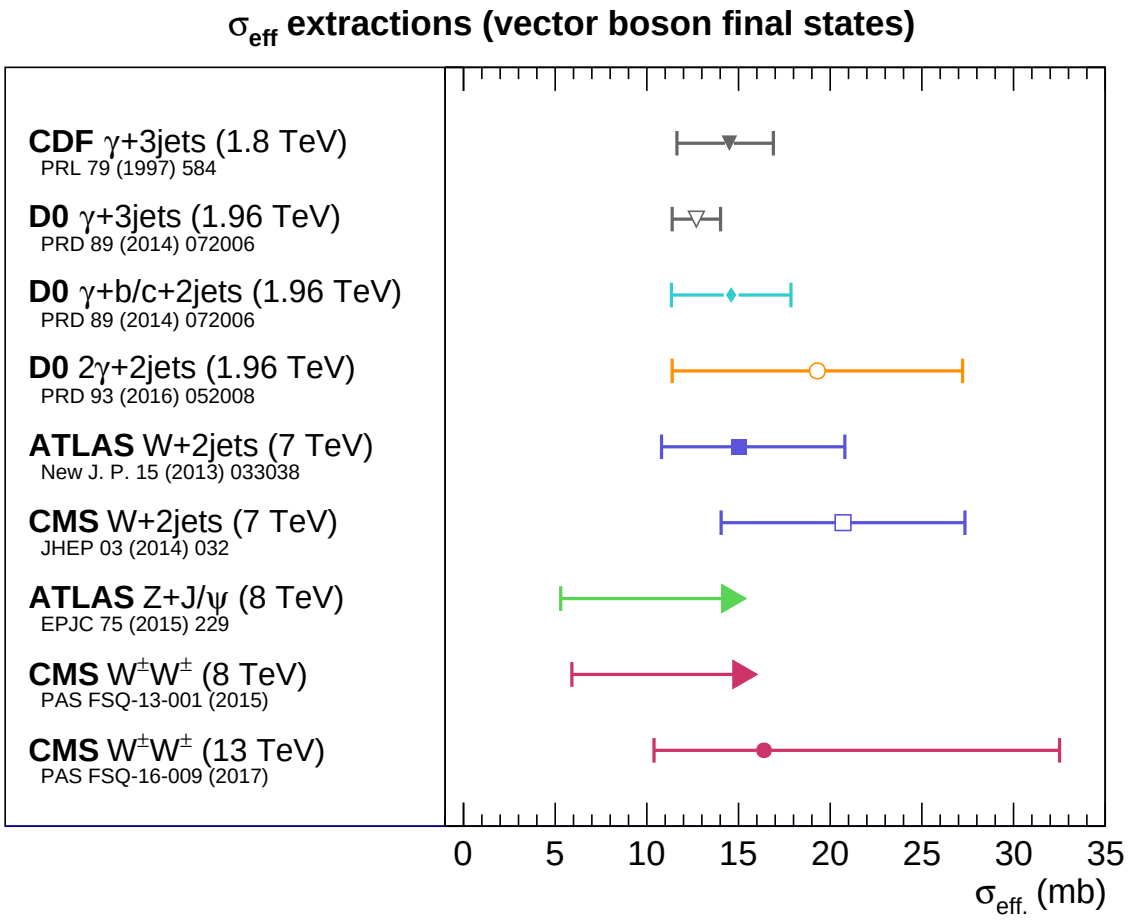
- **MVA based on BDTs trained against WZ production**
- Input variables based on lepton kinematics & $E_{\mathrm{T}}^{\mathrm{miss}}$

Results-I



- Shapes of BDT → fitted using a likelihood fit for e^+e^+,e^-e^-,$\mu^+\mu^+$,$\mu^-\mu^-$
- Dividing into charge configurations maximizes the sensitivity
- **2σ sensitivity → Ist time in WW DPS**

Summary of DPS Measurements



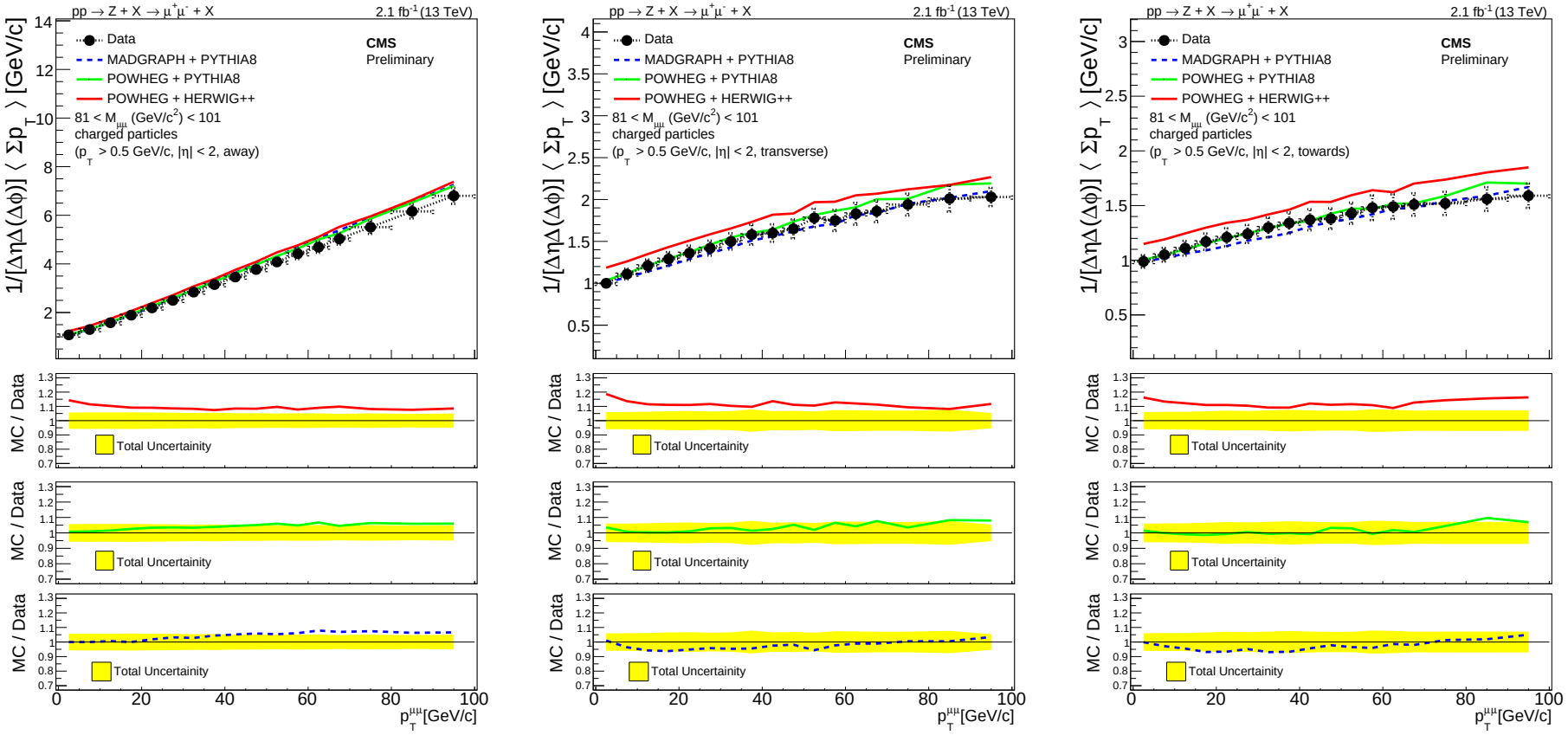
- **Results are consistent within systematic uncertainties for different experiments at different center-of-mass energies**
- **Huge systematics involved on most of the measurements**
- **Unable to draw firm conclusion on the model & energy dependence of σ_{eff}**

Conclusions

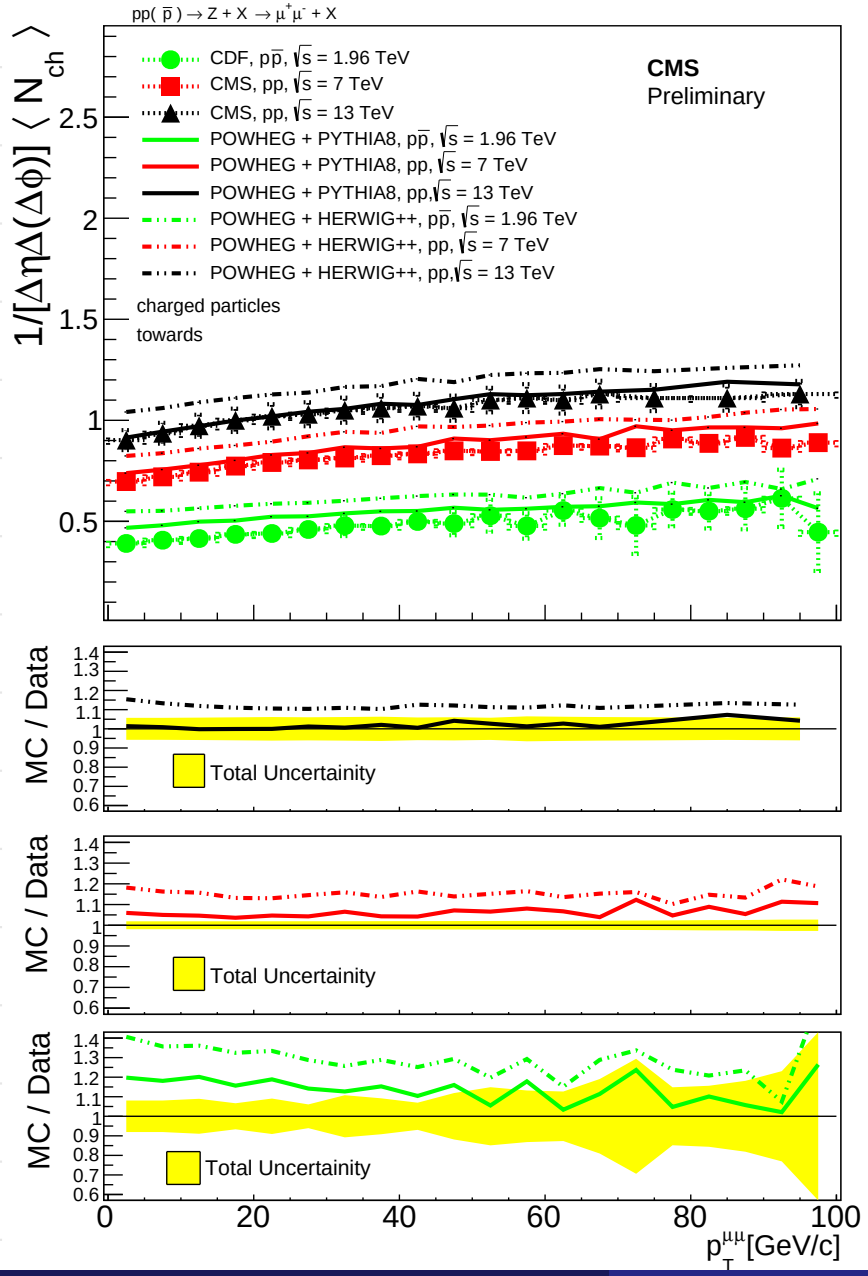
- Important to study UE activity and DPS processes for complete understanding of hadron-hadron collisions
- Measurement of UE activity with Z boson events:
  - Observed change in UE activity from 7 TeV to 13 TeV $\rightarrow$ best described by POWHEG + PYTHIA8 & powheg + herwig ++
  - Further improvement in simulations is needed for UE modeling, especially to describe its energy dependence observed in data
- Measurement of UE activity with top quark events:
  - Some variables sensitive to renormalization scale variations
  - Difference b/w POWHEG+HERWIG++(EE5C) & POWHEG+PYTHIA8(CUETP8M1) in *Transverse* & *Towards* regions for low $\Delta\phi$
- Measurement of DPS using same-sign WW events:
  - Current results are consistent with previous measurements
  - No firm conclusion could not be drawn on the model & energy dependence of σ_{eff}

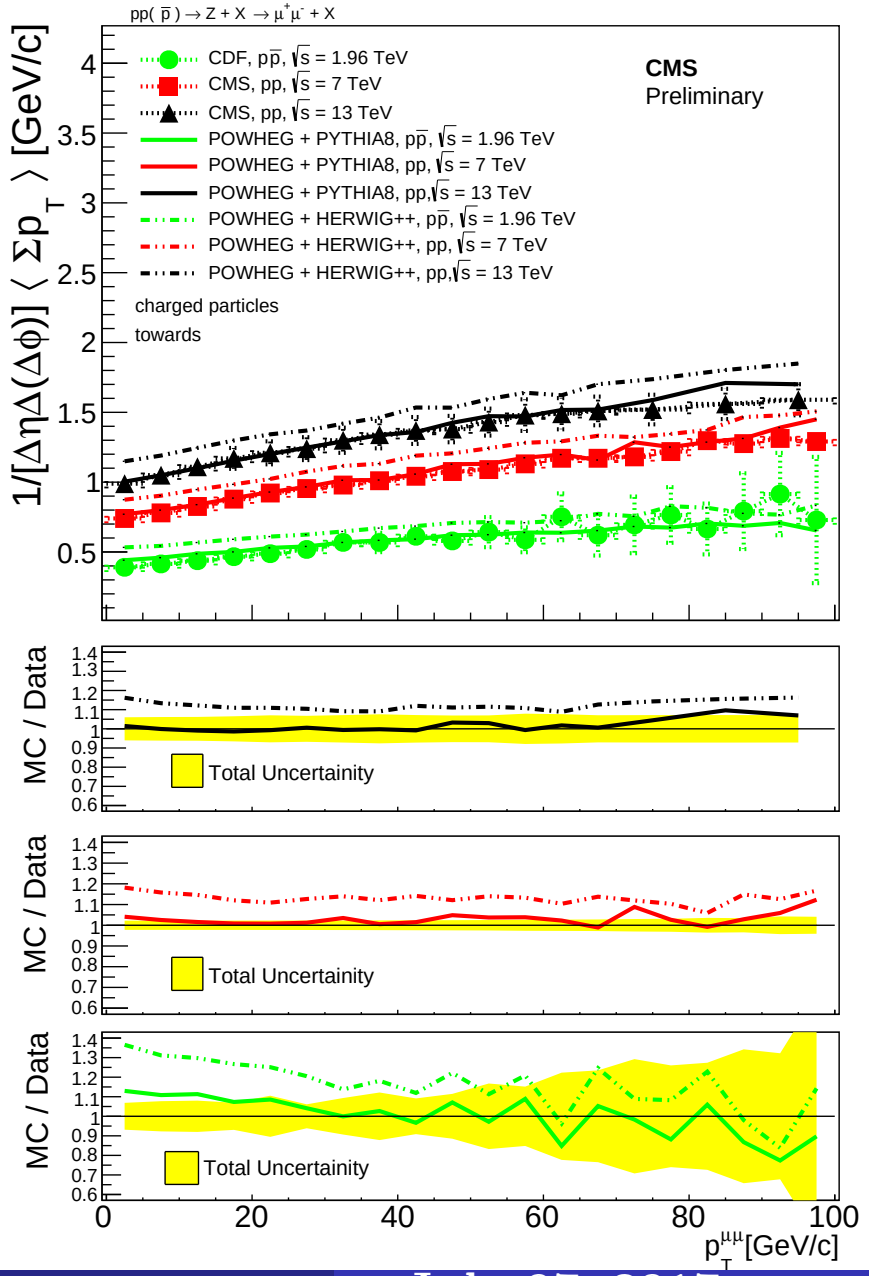

Backup

Comparison b/w Unfolded Data Distributions & Simulations

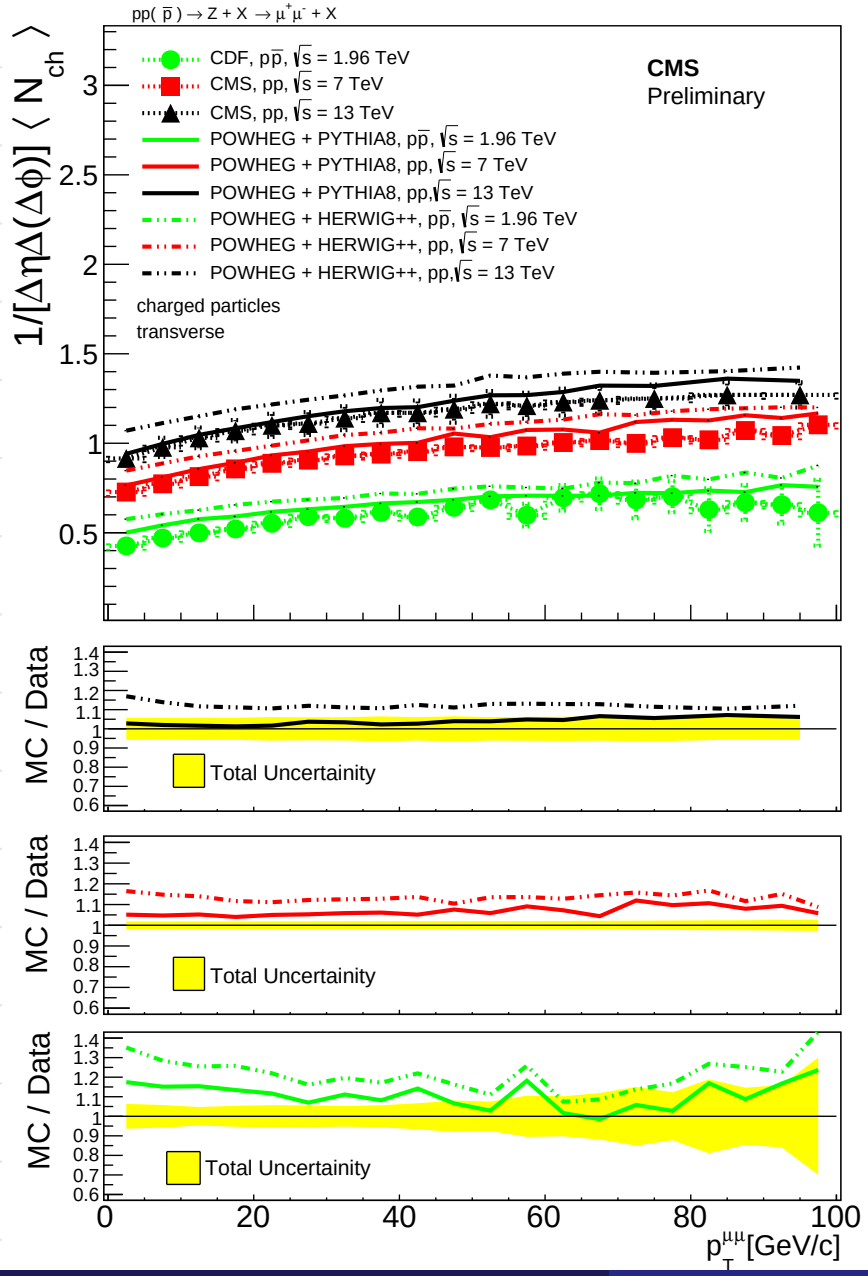


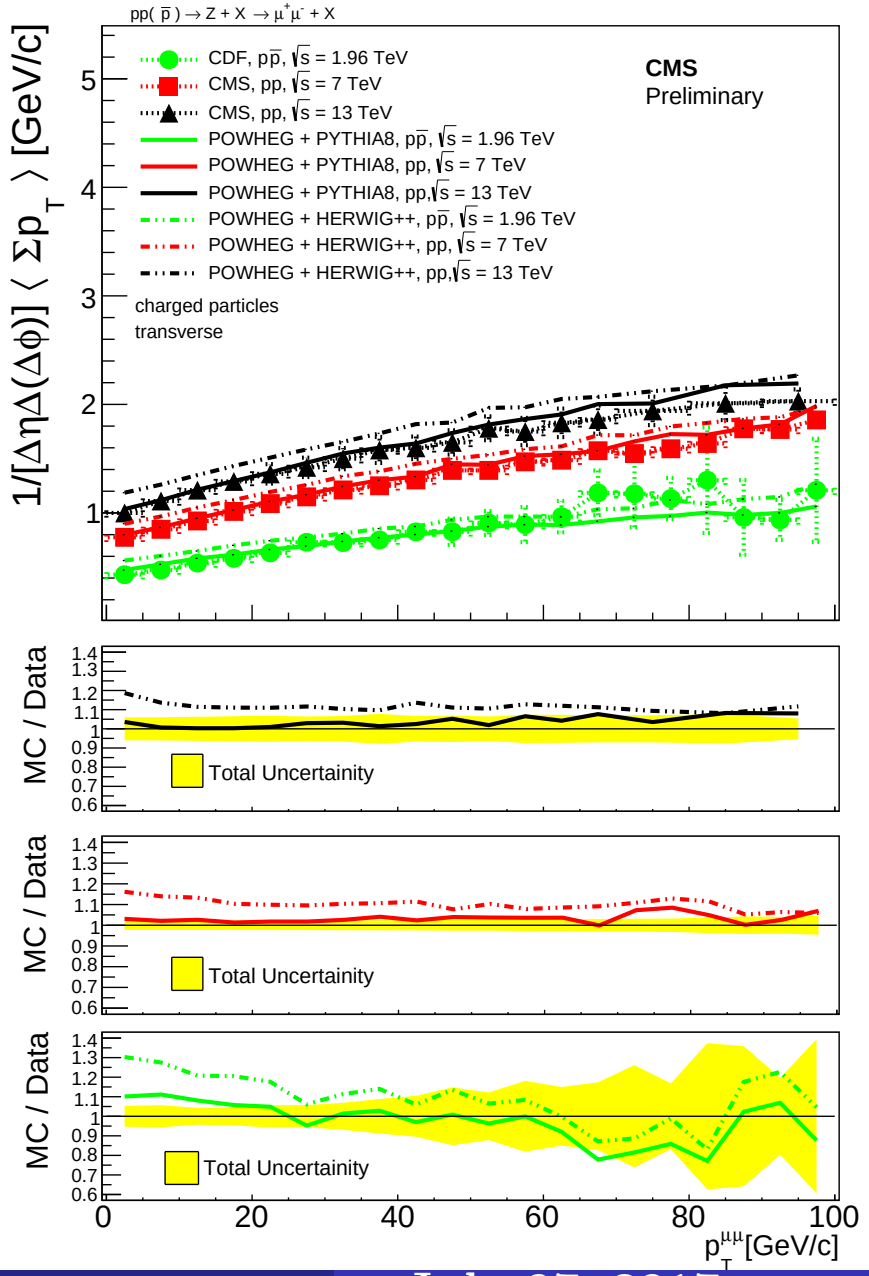
UE for different expts-I



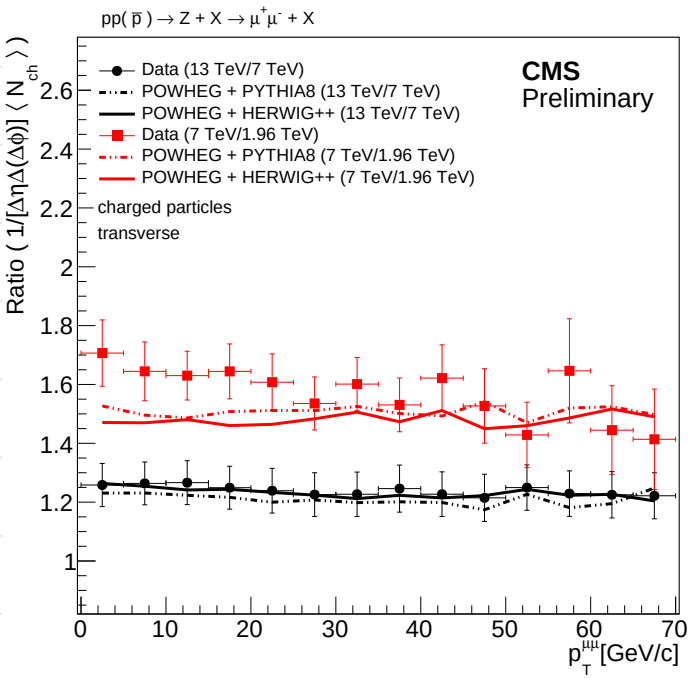


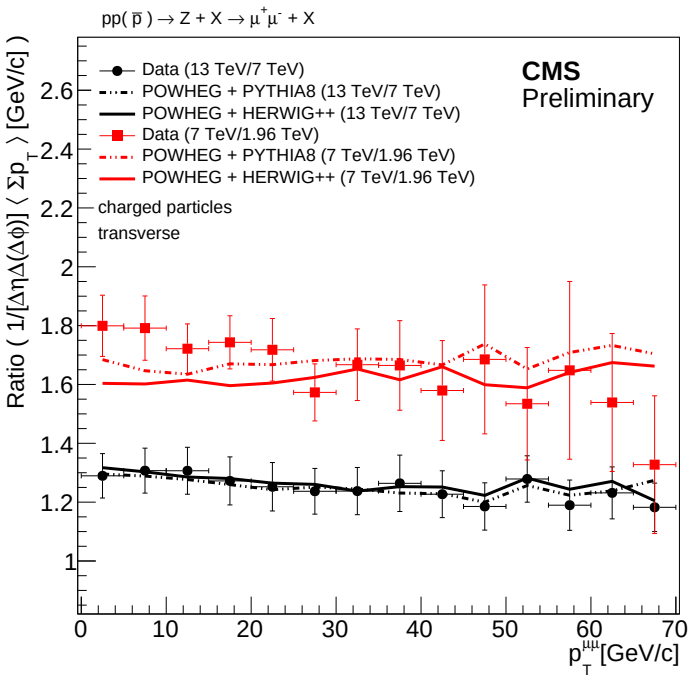
UE for different expts-II





Energy Dependence of UE activity





Energy Dependence of UE activity-II

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  - 25–30% from 7 TeV to 13 TeV → best described by POWHEG + PYTHIA8 & POWHEG + HERWIG++
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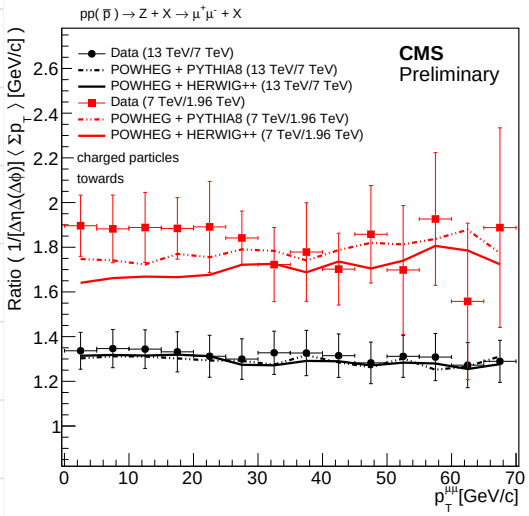

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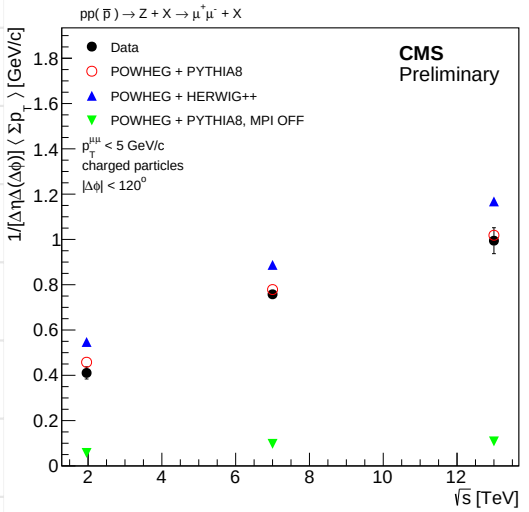
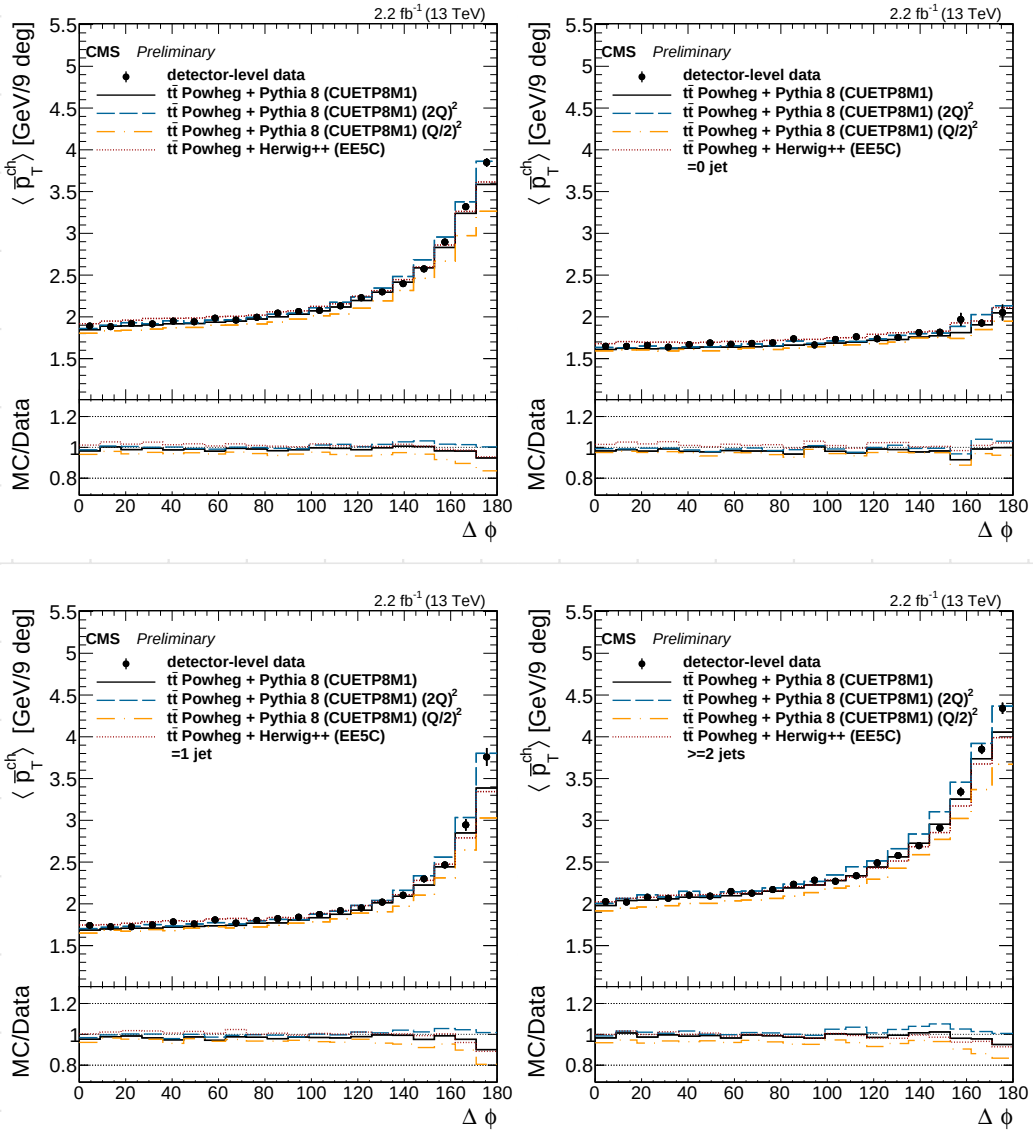
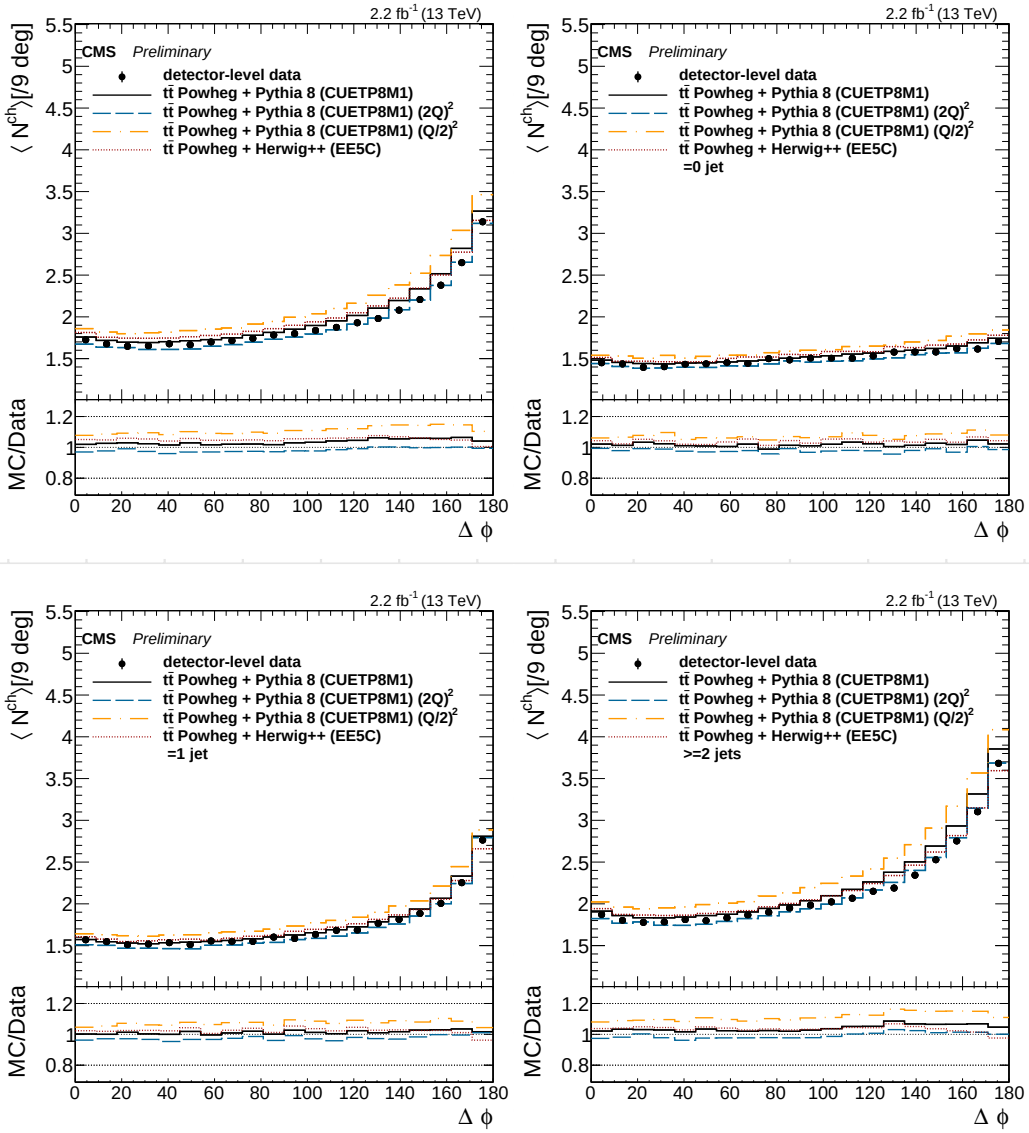


UE Activity for Different Extra Jet Multiplicities-II



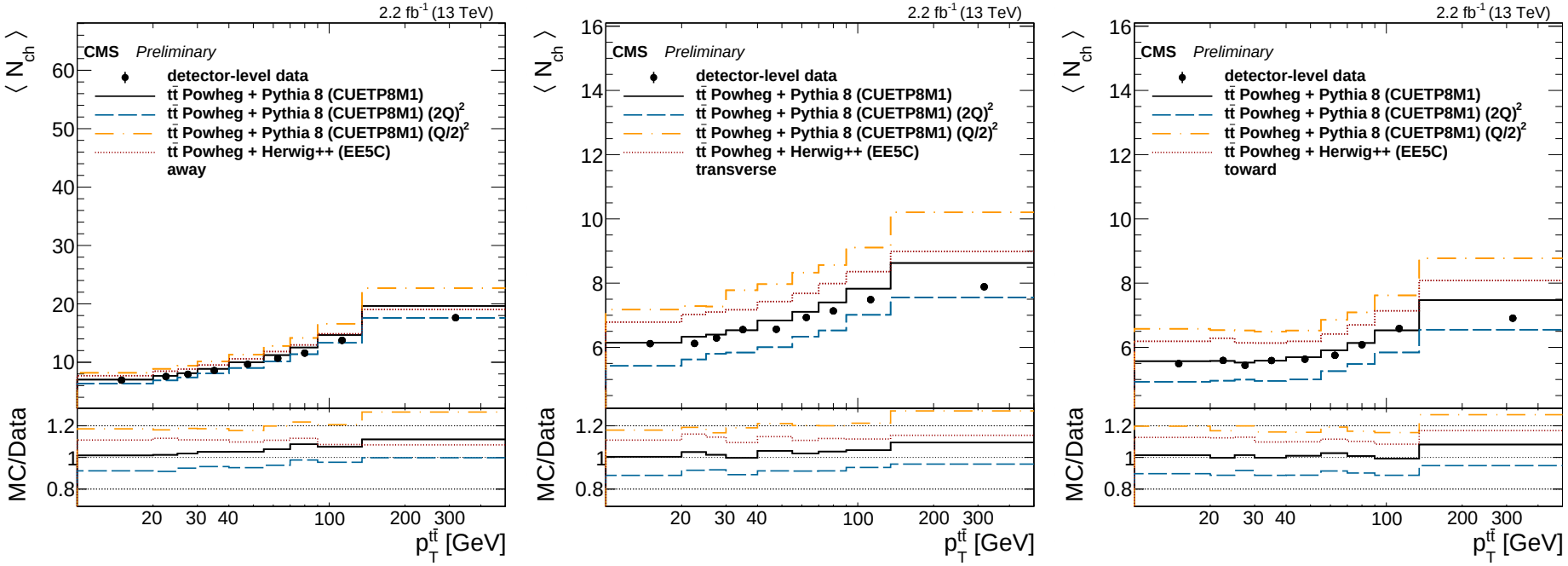
- Some sensitivity to scale variations
- Good agreement b/w POWHEG+HERWIG++(EE5C) & POWHEG+PYTHIA8(CUETP8M1)

UE Activity for Different Extra Jet Multiplicities-III



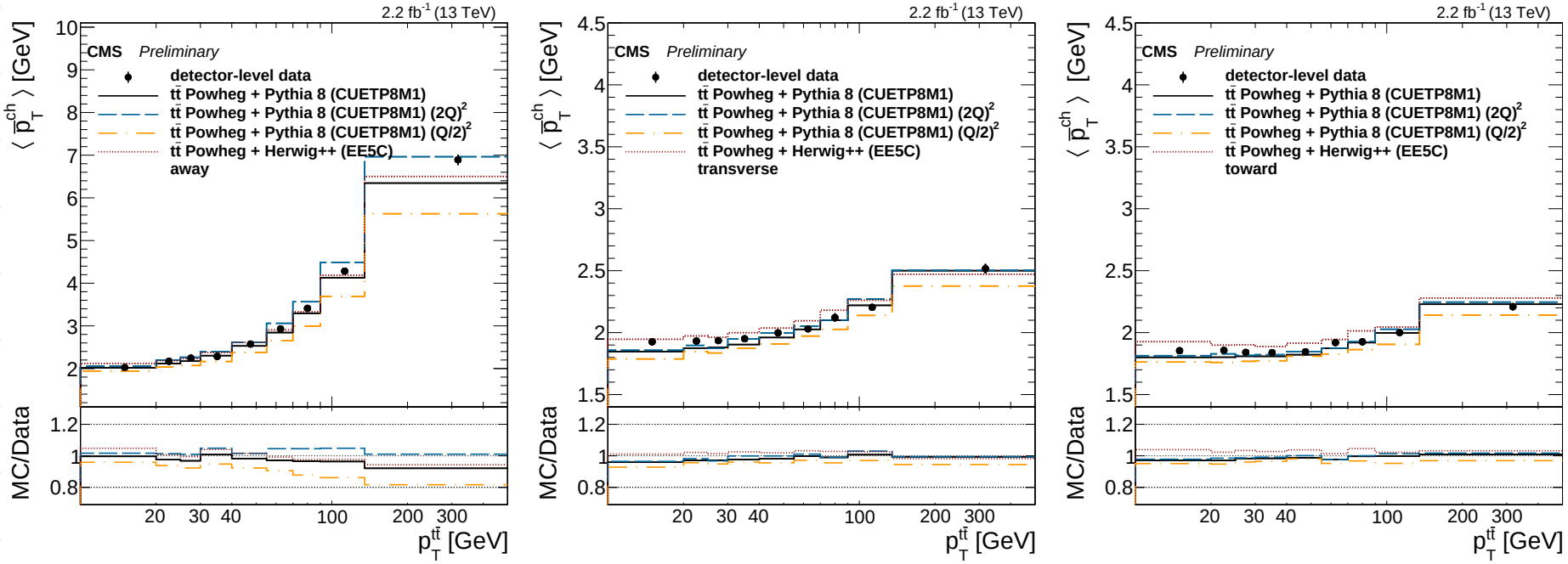
- Large $\Delta\phi$ dominated by soft jets
- Data tends to prefer scale up distributions
- Flatter N_{ch} with $\Delta\phi(\text{charged particle}, t\bar{t})$ for 0j events
- Good agreement b/w POWHEG+HERWIG++(EE5C) & POWHEG+PYTHIA8(CUETP8M1) for all cases

UE Activity as a function of $p_T^{t\bar{t}}$-I



- Extra jet contribution mainly in *Away* region @ high $p_T^{t\bar{t}}$
- Difference b/w POWHEG+HERWIG++(EE5C) & POWHEG+PYTHIA8(CUETP8M1) in *Transverse* & *Towards* regions @ low $p_T^{t\bar{t}}$

UE Activity as a function of $p_T^{t\bar{t}}$-III



- More sensitive to scale variations
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