Measurement of Underlying Event and Double Parton Scattering with CMS

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Rencontres du Vietnam: Windows on the Universe
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Introduction

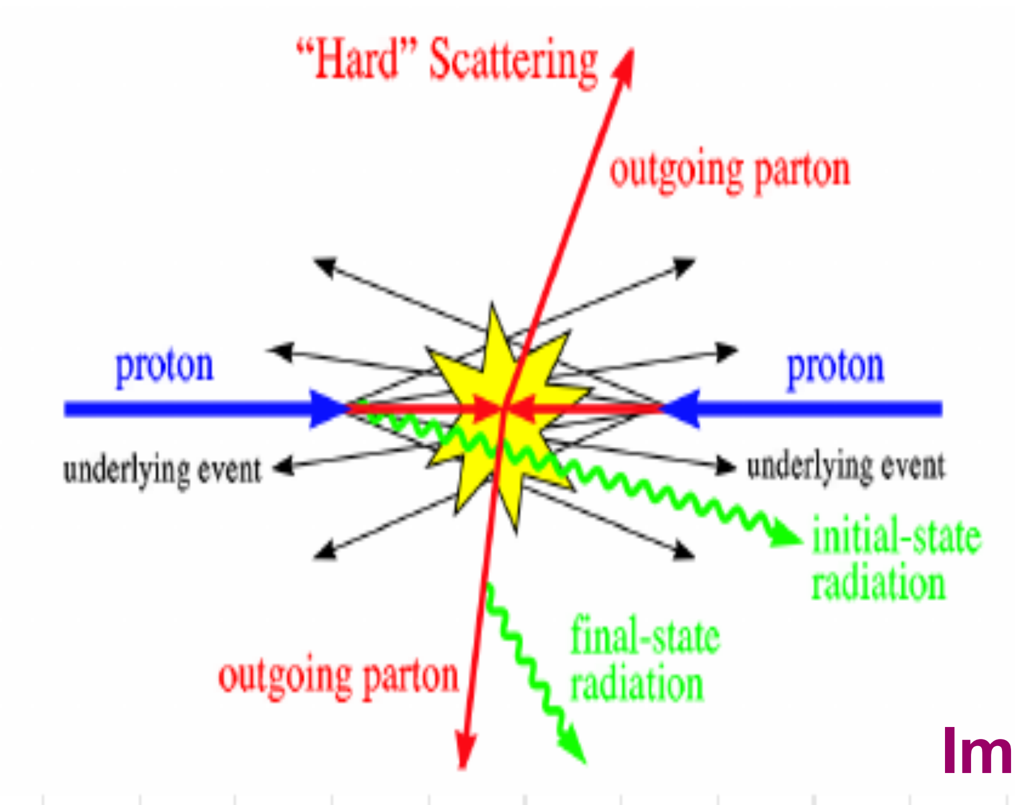
Hadron-Hadron Collision →Hard scattering between partons in addition to UE activity (basic QCD, hard to measure and predict)

@LHC: Important to understand soft & semi-hard interactions so that Hard processes are well understood

MC Tuning: Such soft processes (MPI-DPS an exception!) cannot be described by pQCD, need Pheno models→parameters tuned by fits to data

Underlying Event

Underlying Event (UE) : Anything that does not originate from hard scatter outgoing partons.



Components of UE :

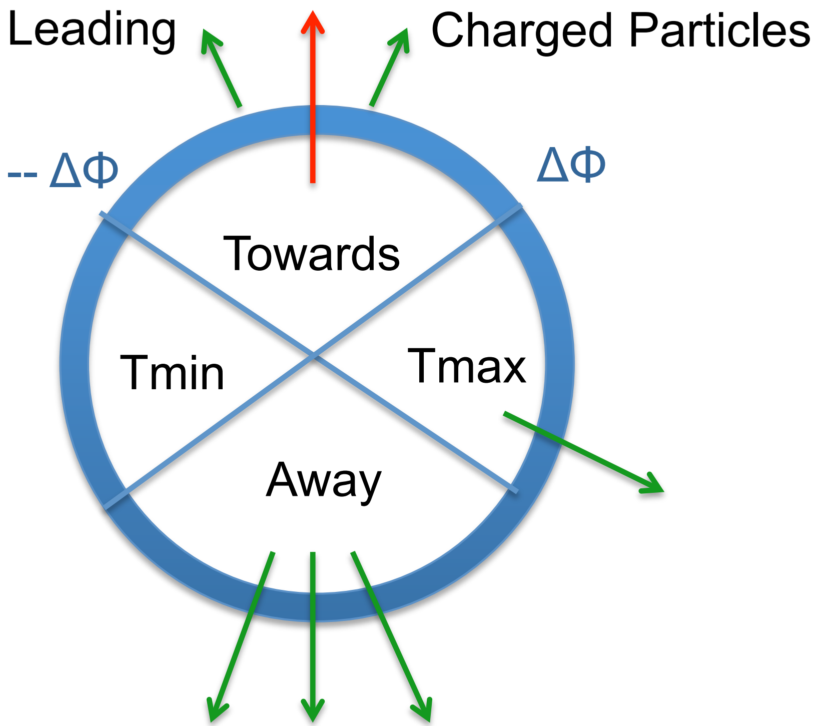
- Initial State Radiation (ISR)
- Final State Radiation (FSR)
- **Multiple Parton Interactions** (MPI)
- Beam Beam Remnants (BBR)

Importance of UE :

- Better modeling of MC simulation
- To probe hadron production.

UE Observables & Regions of Measurements

Observables: Average Charged particle multiplicity ($<N_{ch}>$) and average scalar sum of p_T of the charged particles ($<\Sigma p_T>$)



Regions of Measurements

- Towards : $|\Delta\Phi| < 60^o$
- $\Delta\Phi$ - (the leading object, charged particle)
- Away Region : $|\Delta\Phi| > 120^o$
- Transverse : $60^o < |\Delta\Phi| < 120^o$

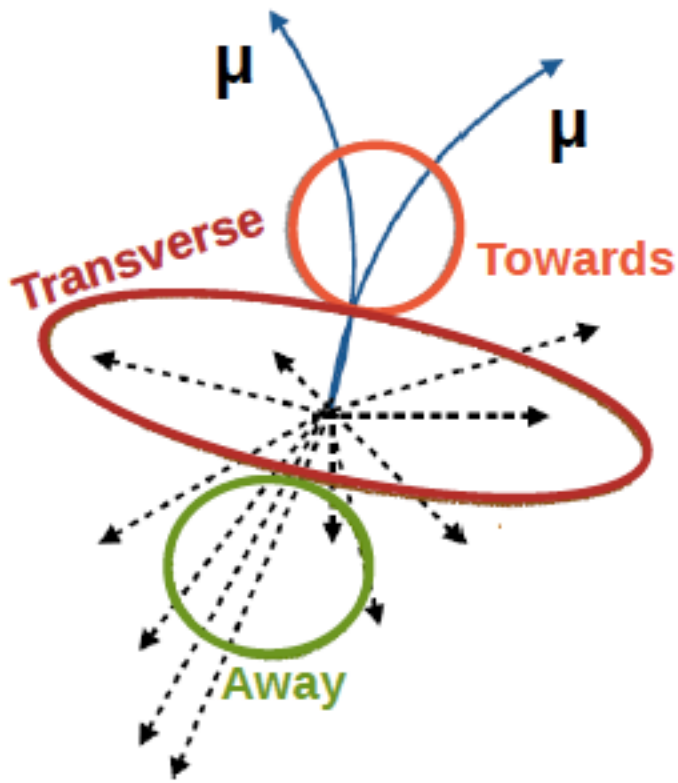
- TransverseMax : Maximum value of UE observable
- TransverseMin : Minimum value of UE observable

UE measurements at CMS experiment

- Leading Charged Particles & Leading Jets @ 13 TeV – **CMS-PAS-FSQ-15-007**
- ttbar Events @ 13 TeV – **submitted to EPJC, arXiv: 1807:02810**
- Drell-Yan Events @ 13 TeV – **JHEP 07 (2018) 032**

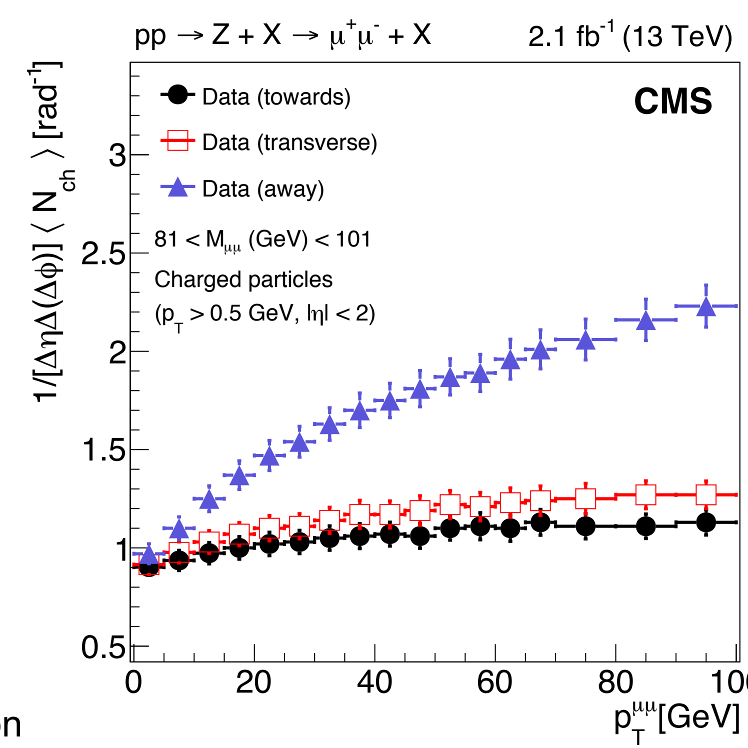
UE Activity using Z→ μμ events - JHEP 07(2018)

- **Experimentally Clean signature and absence of QCD FSR**
- **Observables: Charged-particle density & Σp_T**

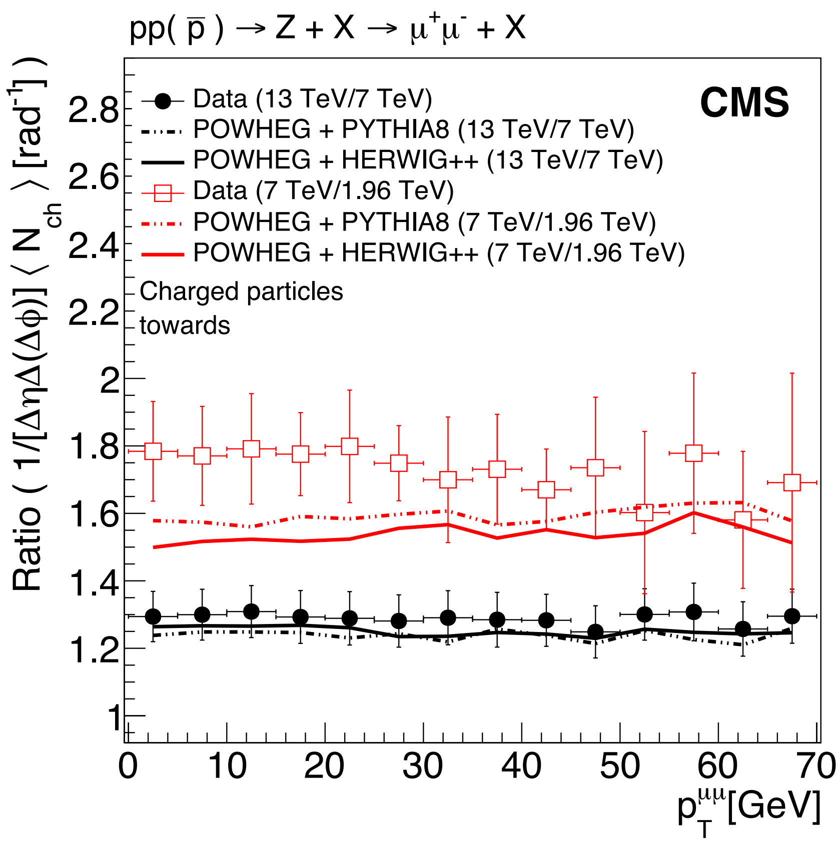


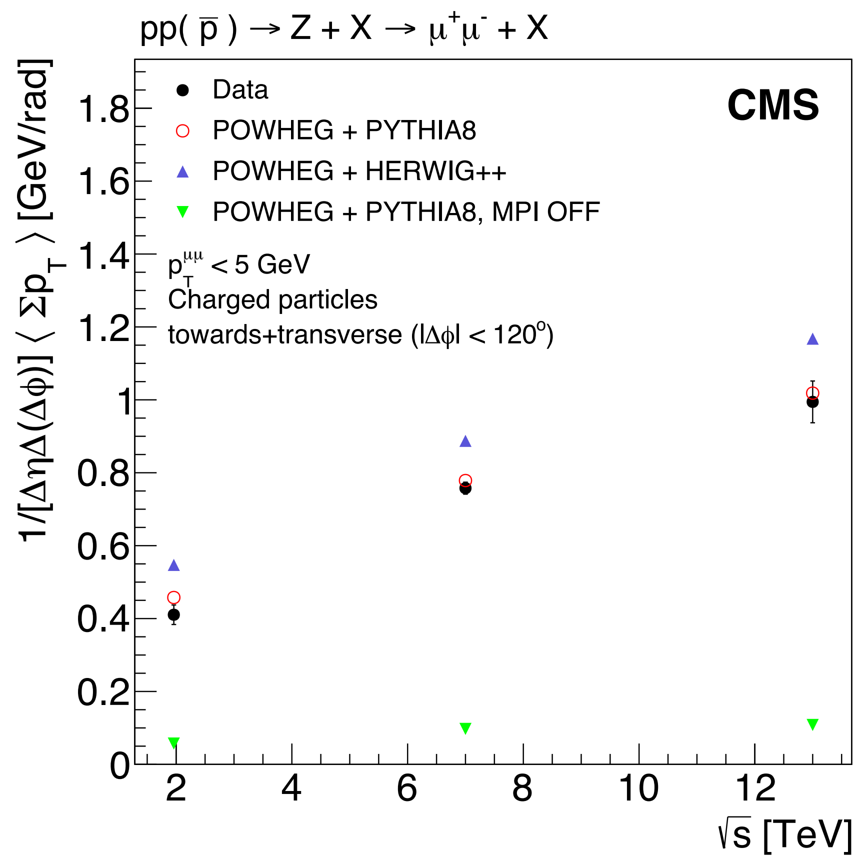
Phase-space Regions

- $|\Delta\phi(\mathrm{Z}, \mathrm{ch.particle})| < 60°$: *Towards* → **Sensitive to MPI/UE**
- $|\Delta\phi(\mathrm{Z}, \mathrm{ch.particle})| > 120°$: *Away*
- $60° < |\Delta\phi(\mathrm{Z}, \mathrm{ch.particle})| < 120°$: *Transverse* → **Sensitive to MPI/UE**



UE Activity at Different Energies





To quantify increase in UE : (UE13 TeV)/(UE7 TeV) & (UE7TeV)/(UE1.96 TeV) for both simulation and data.

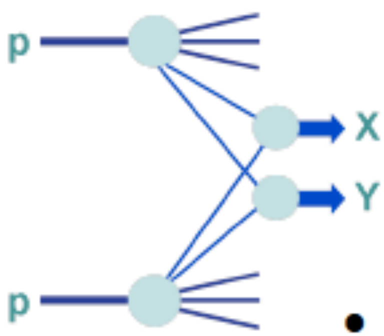
25-30% rise from 7 to 13 TeV.
60-80% rise from 1.96 TeV to 7 TeV.

For POWHEG + PYTHIA8 Without MPI, contribution from radiation very small.
Increase of MPI activity well reproduced by POWHEG + PYTHIA8.
Overestimated by POWHEG + HERWIG++.

UE activity shows strong growth with increase in center-of-mass energy

Double Parton Scattering – DPS

◆ Two hard parton-parton interactions in a single pp collision → DPS



- $\sigma_{XY}^{DPS} = \frac{m\sigma_X\sigma_Y}{2\sigma_{eff}} \Rightarrow$ Assumed factorization of DPDFs
- $\sigma_{eff} \Rightarrow$ Predicted to be independent of process type & collision energy

- Theoretical idea dates back to the parton model
- Double parton scattering signatures: 4 jets, 2 jets and W, 3 jets and photon, etc...
- The ***effective cross section***: overlap of the spatial distributions of the partons in the transverse direction

Importance of DPS Processes

- Provide information about hadron structure in transverse plane
- Estimation of background contributions for interesting SM & BSM processes

Double Parton Scattering (contd.)

- W+2jets (JHEP03(2014)032)
- γ+3jets(CDS Record 2007815)
- Double J/ψ (JHEP09(2014)094)
- 4jets (Phys.Rev.D89(2014)092010)
- 2bjet+2jet (Phys.Rev.D94(2016)112005)
- Same-sign WW (JHEP02(2018)032), (CDS Record 2257583)

More channels still to be explored

Same-sign WW for DPS?

- $\sigma^{\rm DPS}_{\rm W^\pm W^\pm} \approx \sigma^{\rm SPS}_{\rm W^\pm W^\pm}$ & a clean final state with leptonically decaying W bosons

- **Experimental Challenges:**
  - **DPS final state can also be produced by SPS**
  - **Complicated Multivariate Analyses**

DPS in same-sign WW Production at 13 TeV

- $W^{\pm} W^{\pm}$ studied in the $\mu^{\pm}\mu^{\pm}$ and $e^{\pm}\mu^{\pm}$ final states
- Single parton scattering (SPS): 2 jets in the final state
  - So, the event selection makes use of a jet veto!

two leptons: $e^{\pm}\mu^{\pm}$ or $\mu^{\pm}\mu^{\pm}$

$$p_T^{\ell 1} > 25\text{ GeV}\ ,\ p_T^{\ell 2} > 20\text{ GeV}$$

$$|\eta_e| < 2.5,\ |\eta_\mu| < 2.4$$

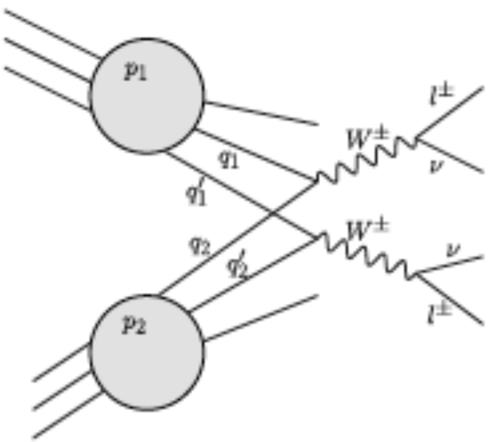
$$E_{\mathrm{T}}^{\mathrm{miss}} > 15\text{ GeV}$$

$$N_{\text{jets}} < 2\ (p_{\mathrm{T}} > 30\text{ GeV})$$

$$N_{\text{b-jets}} = 0\ (p_{\mathrm{T}} > 25\text{ GeV})$$

veto on additional leptons

veto on hadronic τ lepton decays



DPS in same-sign WW Production at 13 TeV

- PYTHIA8 (CUETP8M1 TUNE) Signal Sample
- Backgrounds: WZ, Jet induced backgrounds, Dibosons, Tribosons & Z → τ τ

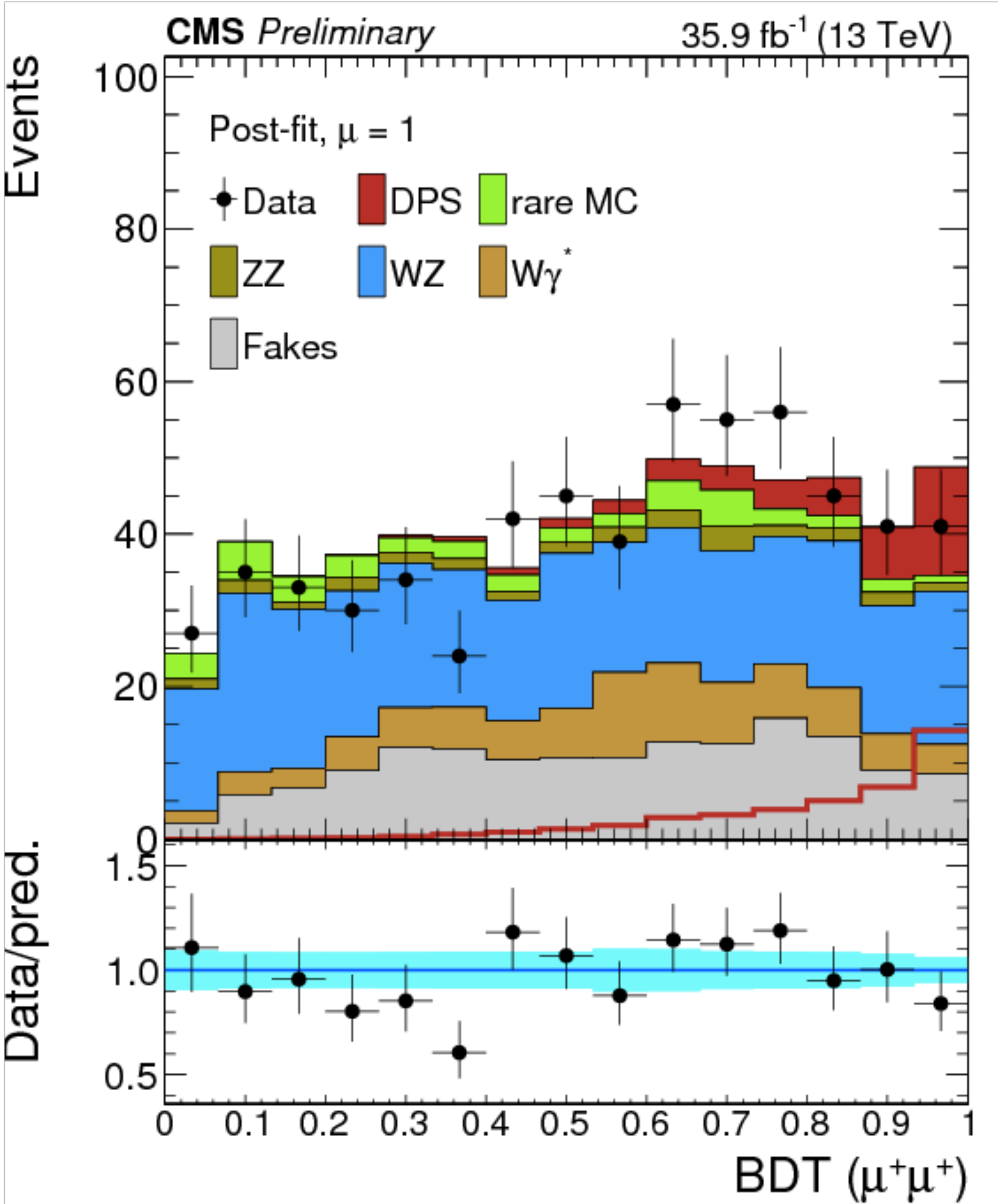
BDTs trained against the WZ background process using 11 input parameters

- $p_{T} l_{1,2}$, p_{T}^{miss}, $\eta_1 \times \eta_2$, $|\eta_1 + \eta_2|$
- M_{T2}^{ll}, $m_T(l_1, p_T^{miss})$, $m_T(l_1, l_2)$
- $\Delta\phi(l_1, l_2)$, $\Delta\phi(l_2, p_T^{miss})$, $\Delta\phi(l_1 l_2, l_2)$

➢ A Multivariate classifier is used to distinguish signal and background

➢ Shapes of BDT → Fitted using a likelihood fit for $e^+ e^+$, $e^- e^-$, $\mu^+ \mu^+$, $\mu^- \mu^-$

Results: DPS in same-sign WW events at 13 TeV



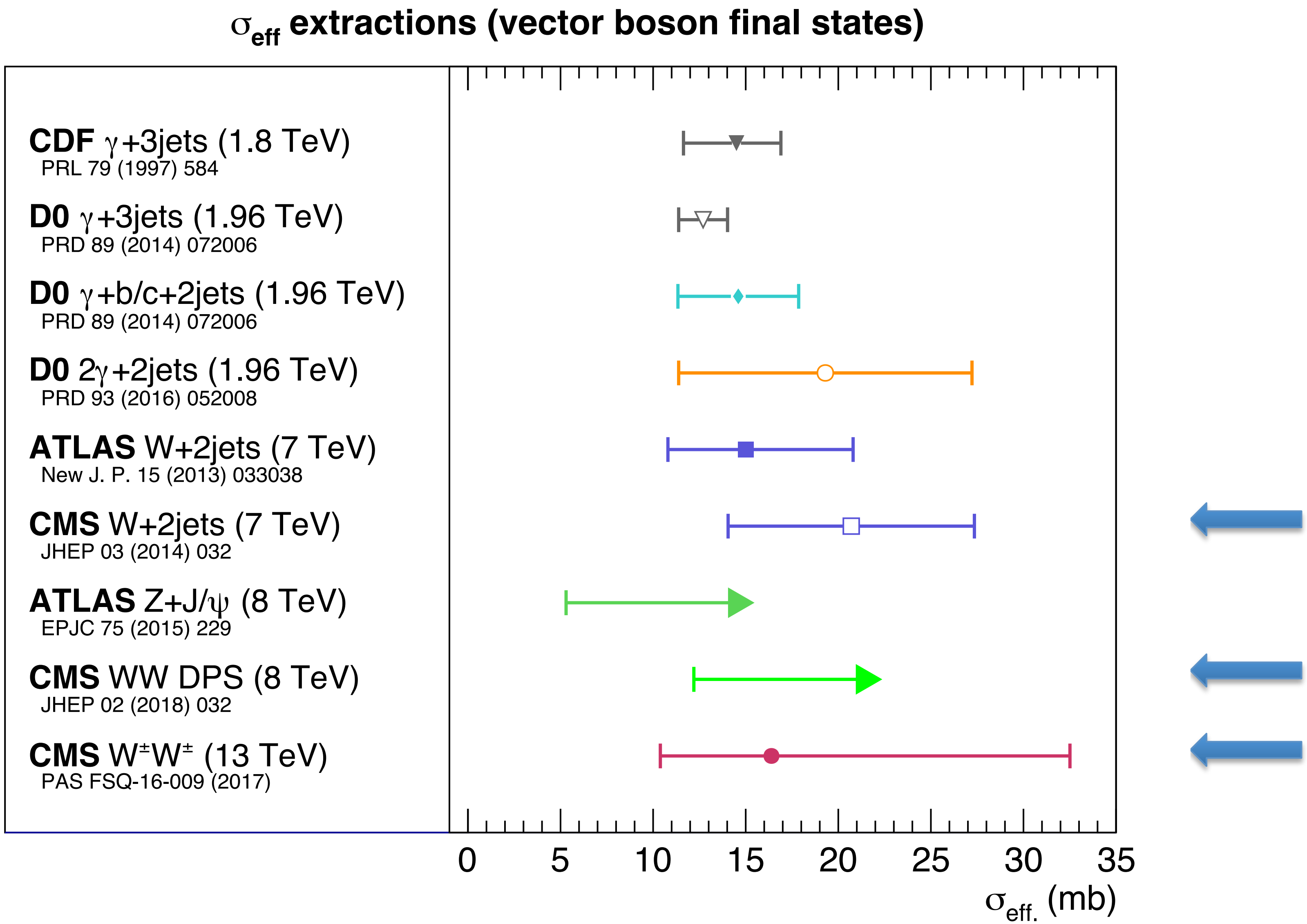
Result: $1.09^{+0.50}_{-0.49}$ pb (2.23σ), PYTHIA 8 prediction: 1.64 pb

	expected	observed
$\sigma^{\text{pythia}}_{\text{DPSWW}}$	1.64 pb	$1.09^{+0.50}_{-0.49}$ pb
$\sigma^{\text{factorized}}_{\text{DPSWW}}$	0.87 pb	
significance for $\sigma^{\text{pythia}}_{\text{DPSWW}}$	3.27 σ	2.23 σ
significance for $\sigma^{\text{factorized}}_{\text{DPSWW}}$	1.81 σ	
UL in the absence of signal	< 0.97 pb	< 1.94 pb

2σ sensitivity $\rightarrow$ I$^{\text{st}}$ time in WW DPS

Results: Effective cross section

◆ **Summary of the effective DPS cross section measurement**



Summary

- Observed change in UE activity in Z boson events from 7 TeV → 13 TeV, best described by POWHEG + PYTHIA8 and POWHEG + HERWIG++
- Overall good description of UE activity by simulations → Universality of UE Tunes

- Multi Parton Interactions can be studied in many ways
  - Multiple jets
  - Vector bosons and multijets
  - Vector boson pairs,…
- Complicated multivariate analyses methods along with finding proper and sensitive observables is challenging
- Still very active field: observation of very small cross sections put SM to test
- High Luminosity is a boon!
- 2σ sensitivity observed in DPS with same-sign WW analysis

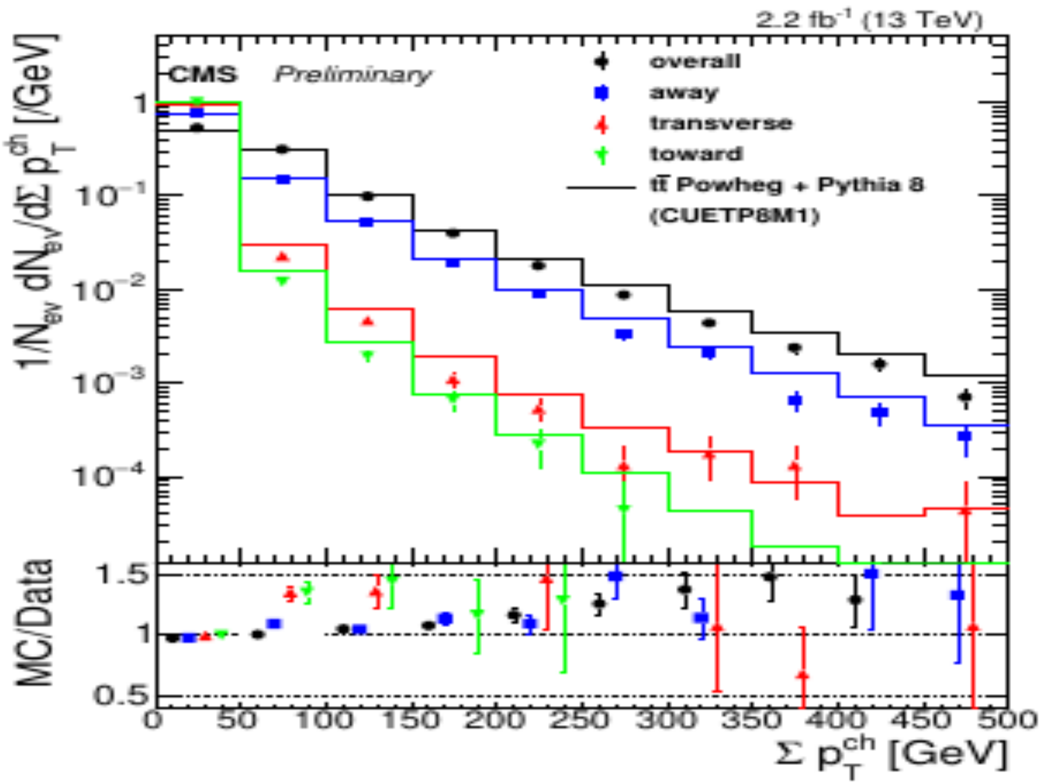
Thank you

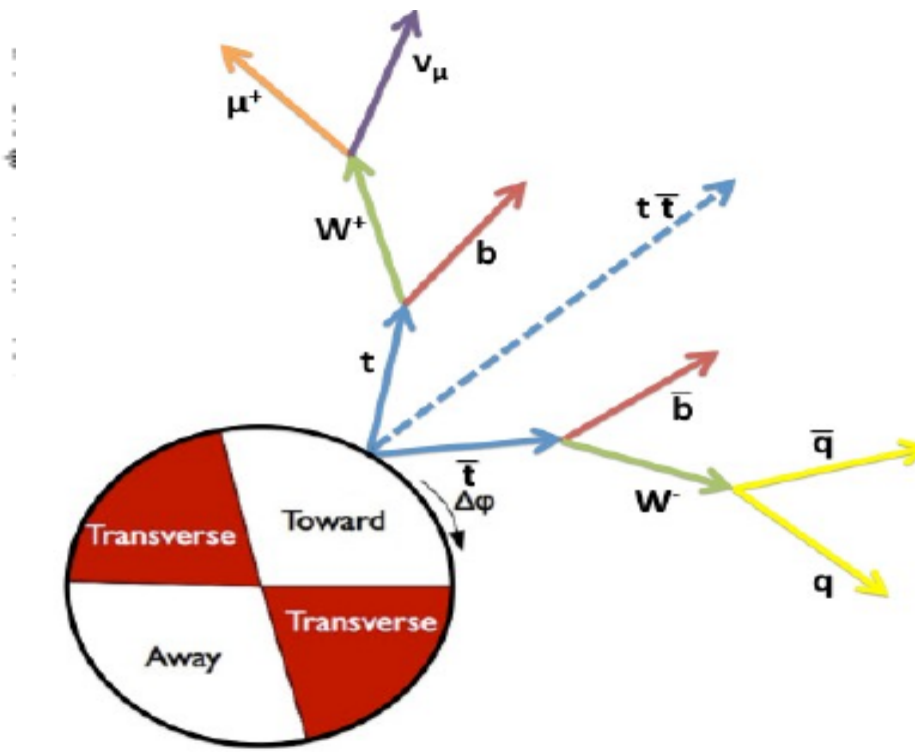
Backup

UE Measurements using ttbar Events @ 13 TeV

arXiv: 1807.02810

- UE measurements are done using 2.2 fb^{-1} of p-p collisions data @ 13 TeV
- UE activity is measured w.r.t. ttbar system





UE activity shows fast rise in away region (due to recoiling hadronic activity) as compared to towards and transverse regions.
Top quark specific Pythia8 tune, CUETP8M2T4 along with Powheg describes the UE data very well.