Underlying Event in Top Quark Pair Production

(based on arXiv:1807.02810/CMS-TOP-17-015)

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Top Quark and QCD

- Top quark measurements
  - Test and understand QCD effects → ultimate precision in top quark mass, its interpretation and in other properties.
  - Beyond standard model effects.
- Top quark pair cross section measurements better than NNLO+NNLL precision.
- Top quark measurements precision ~0.3-0.4% with dominant uncertainties
  - Hadronization
  - Modeling of hard scattering (parton shower – matrix element matching, top quark pT, PDF)
  - Jet energy calibration and pile-up
  - Underlying event

Some theory uncertainties (hadronization, top pT, underlying event, …) may be decreased.

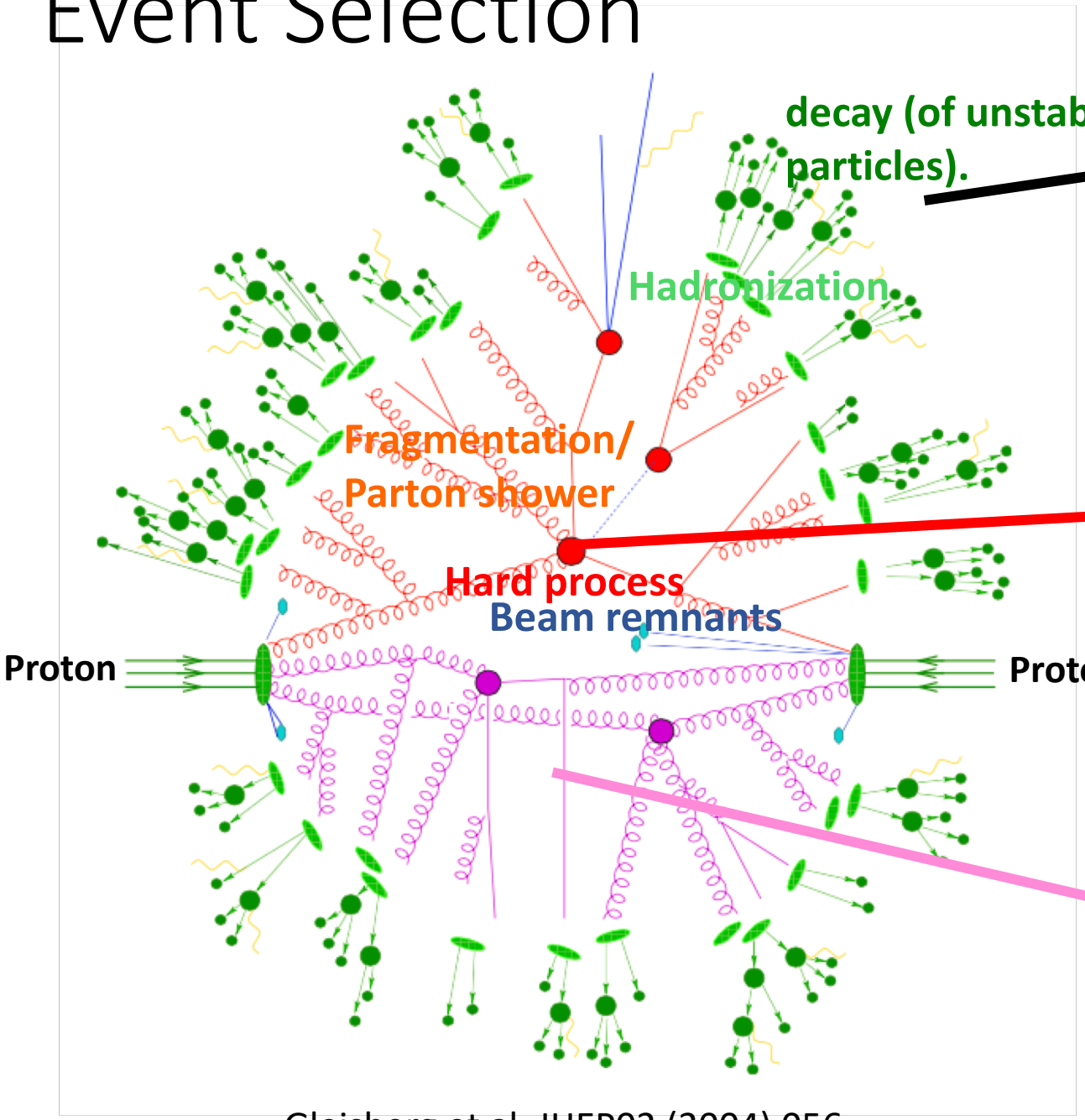
Goal/expectation for HL-LHC Direct top mass measurements < 0.1% precision.

How to Decrease Uncertainties

- Test matrix element + parton shower configurations and tunes using well-defined differential measurements.
- Detailed studies of each source of modelling uncertainty.
- Measurements (e.g. top mass) in different phase-space regions.
- …

In this talk, we present a dedicated underlying event measurement in ttbar events to test the tune used in top quark measurements and to test some commonly used event generator configurations.

Event Selection



Gleisberg et al. JHEP02 (2004) 056

In this case,
Final state from the hard process:
dilepton, ≥ 2 bjets,

$e^{\pm}\mu^{\mp}$ for the main analysis

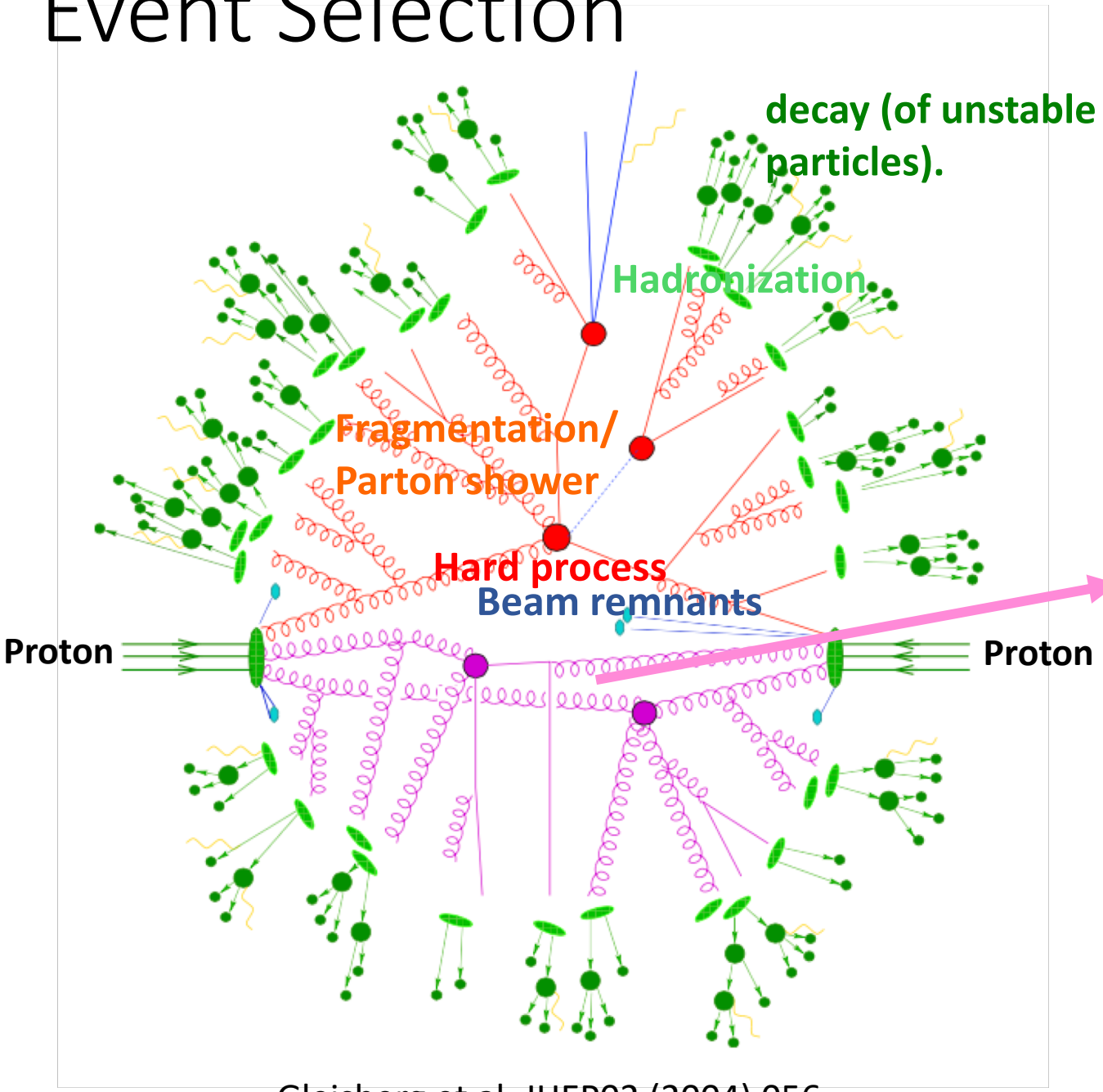
$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$ For the normalization of the Drell-Yan background.

(all other backgrounds from simulation)

In this case, the hard process is ttbar.

Underlying event/Multi-parton interactions:
Here, defined as the charged particle activity that can't be attributed to the hard process:
→ select charged particles that are not associated to the leptons, b jets or pile-up.

Event Selection



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Underlying event/Multi-parton interactions:

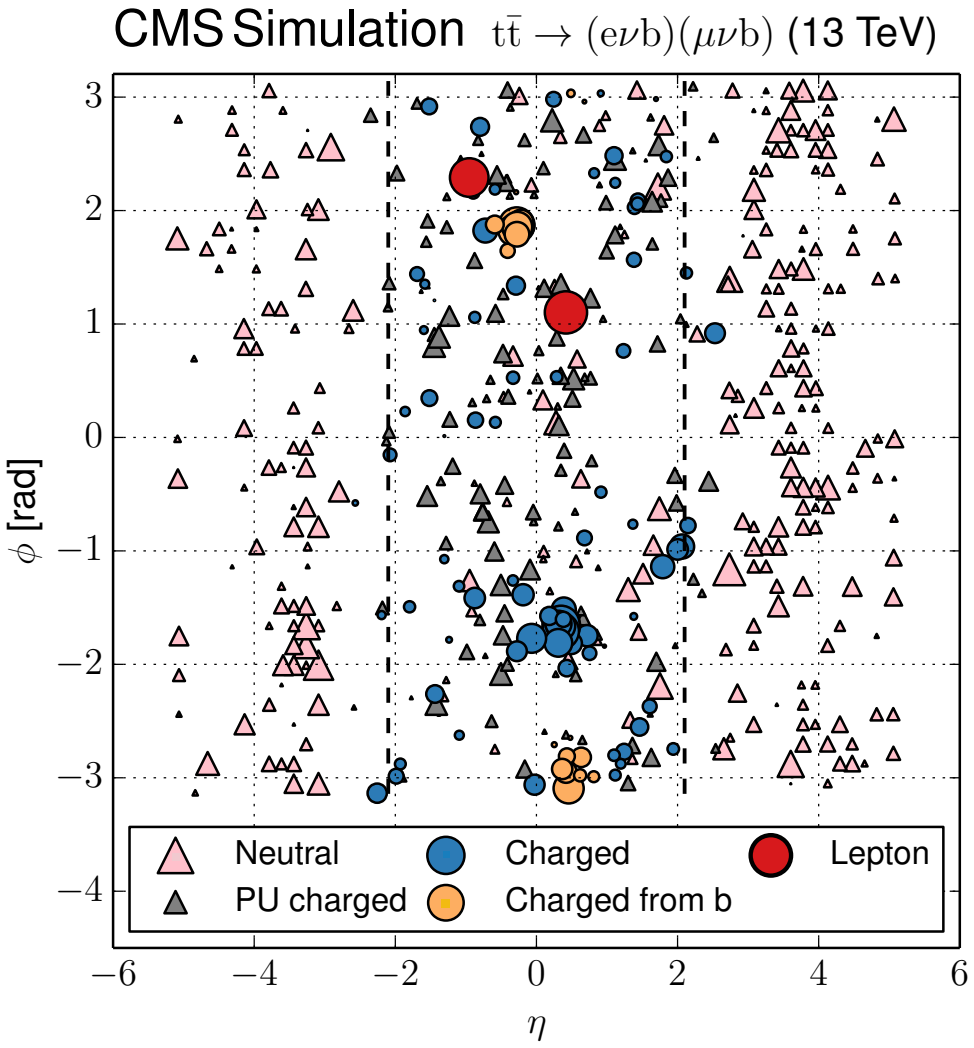
→ Contribution from both pileup and hard process identified and excluded.

→ Track associated to the charged particle flow candidate is required to be compatible with the primary vertex ➔ reduces the pileup contamination in the charged particle collection to negligible amounts +

→ All charged particle candidates with pT>900 MeV and |eta|<2.1 are selected

→ If a charged particle is clustered in a jet or if it matches to a hard lepton from ttbar, it is removed from the collection of underlying event particles.

Underlying Event in ttbar



Distribution of all particle flow candidates reconstructed in a Powheg + Pythia8 simulated ttbar event.

Big filled red circles = leptons from ttbar.
Big filled orange circles = charged particles clustered in b-jet from ttbar.

For all particles pT> 900 MEV

→ Using clean dilepton state makes it easy to isolate the underlying event from the products of the hard scattering .

Underlying Event in ttbar Events

- Properties of the underlying event is studied for the first time at a scale of > 2mt (i.e. > ~340 GeV)
- > 200 distributions investigated.
- Measurements unfolded to particle level:

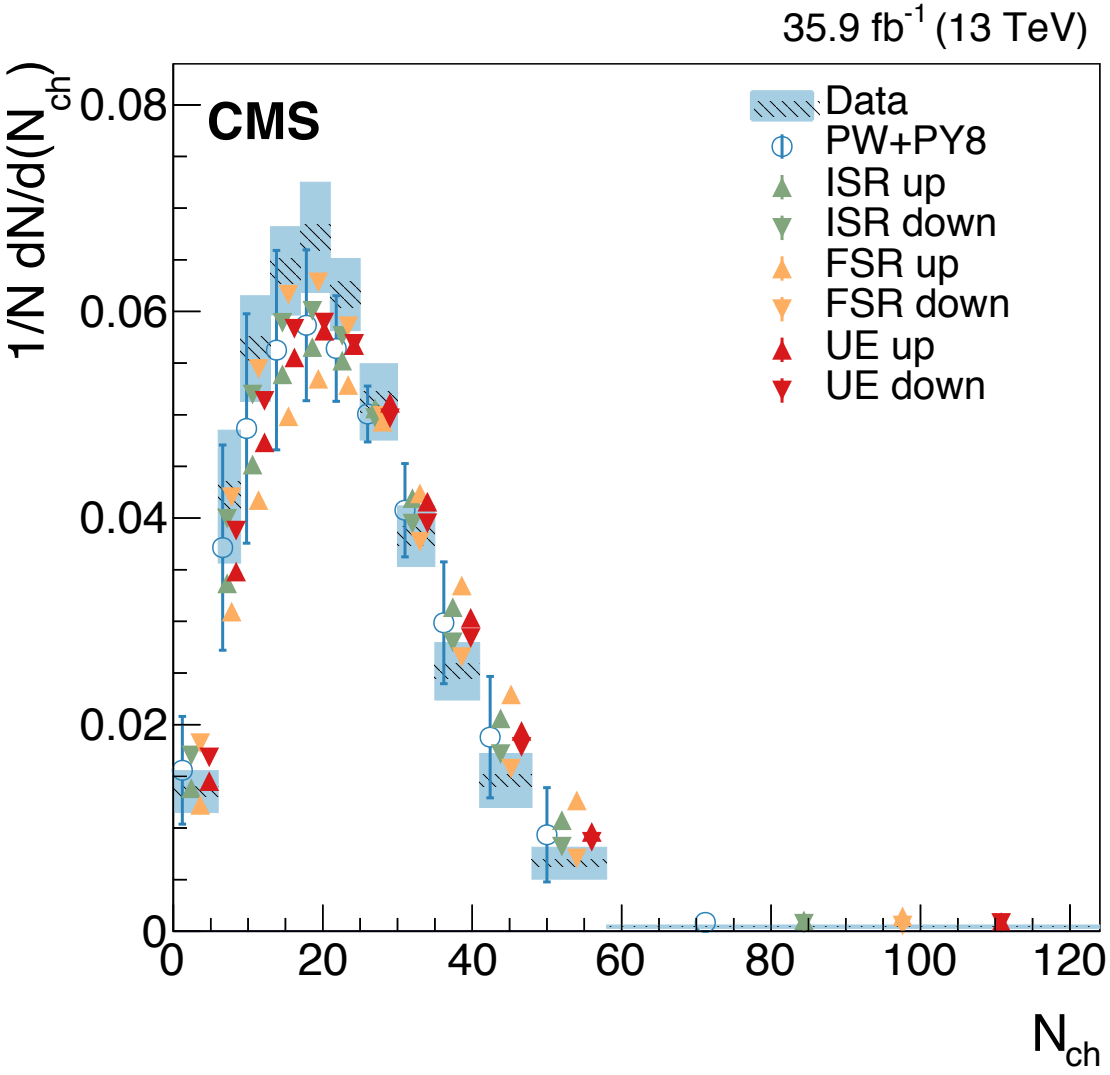
- charged-particle multiplicity: N_{ch};
- magnitude of the p_{T} of the charged particle recoil system: $|\vec{p}_{\mathrm{T}}| = |\sum_{i=1}^{N_{\mathrm{ch}}} \vec{p}_{\mathrm{T},i}|$;
- scalar sum of the p_{T} (or p_z) of charged particles: $\sum p_{\mathrm{k}} = \sum_{i=1}^{N_{\mathrm{ch}}} |\vec{p}_{\mathrm{k},i}|$, where $\mathrm{k} = \mathrm{T}$ or z;
- average p_{T} (or p_z) per charged particle: computed from the ratio between the scalar sum and the charged multiplicity: $\overline{p_{\mathrm{T}}}$ (or $\overline{p_z}$).

- Aplanarity: $A = \frac{3}{2}\lambda_3$ measures the p_{T} component out of the event plane, defined by the two leading eigenvectors. Isotropic (planar) events are expected to have $A = 1/2\,(0)$.
- Sphericity: $S = \frac{3}{2}(\lambda_2 + \lambda_3)$ measures the p_{T}^2 with respect to the axis of the event. An isotropic (dijet) event is expected to have $S = 1\,(0)$.
- $C = 3(\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3)$ identifies 3 jet events (tends to be 0 for dijet events).
- $D = 27\lambda_1\lambda_2\lambda_3$ identifies 4 jet events (tends to be 0 otherwise).

Defined using the sphericity tensor

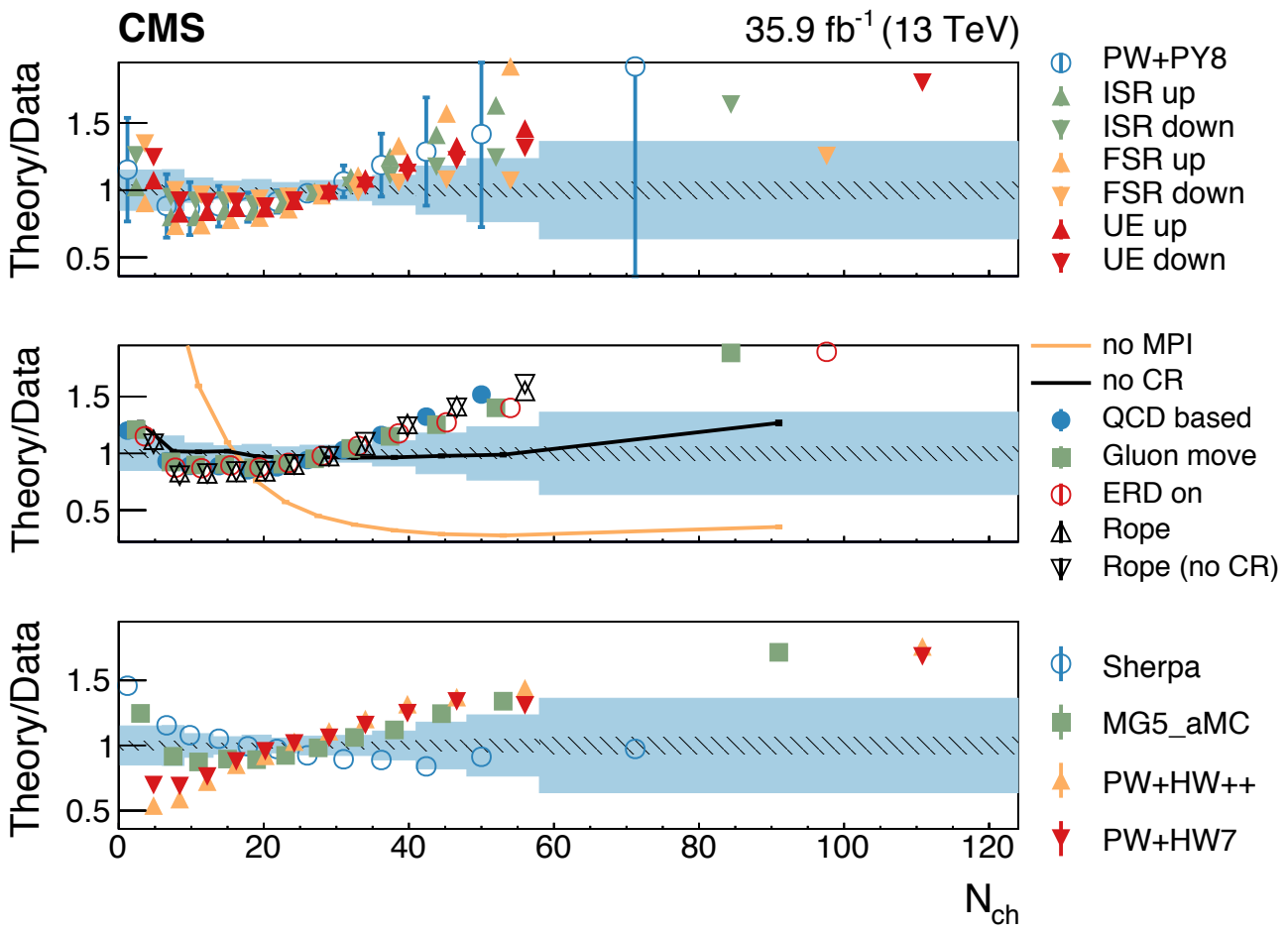
$$S^{\mu\nu} = \sum_{i=1}^{N_{\mathrm{ch}}} p_i^{\mu} p_i^{\nu} / |p_i| \Big/ \sum_{i=1}^{N_{\mathrm{ch}}} |p_i|$$

Underlying Event in ttbar Events



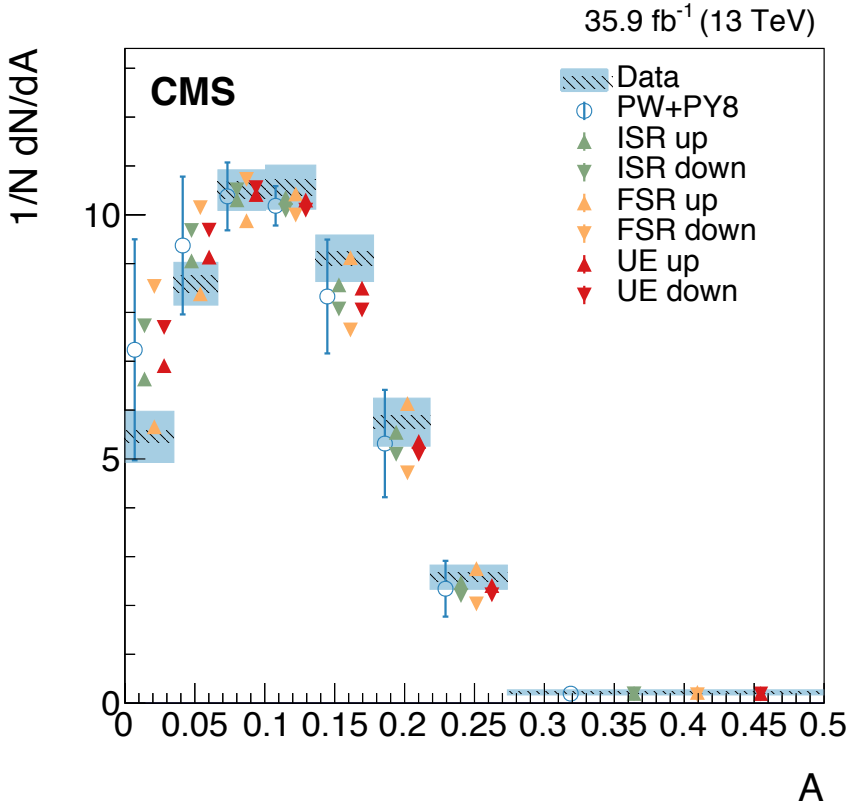
- Unfolded UE data in ttbar compared to Powheg+Pythia8
  - ~20 charged particles with $\overline{p_T} \sim \overline{p_Z} \approx 2GeV$
    - → vectorially summing to ~10 GeV recoil.
  - Sensitive to
    - Parton shower Initial State Radiation (ISR) and Final State Radiation (FSR)
    - Underlying event tune fit (UE up and down)

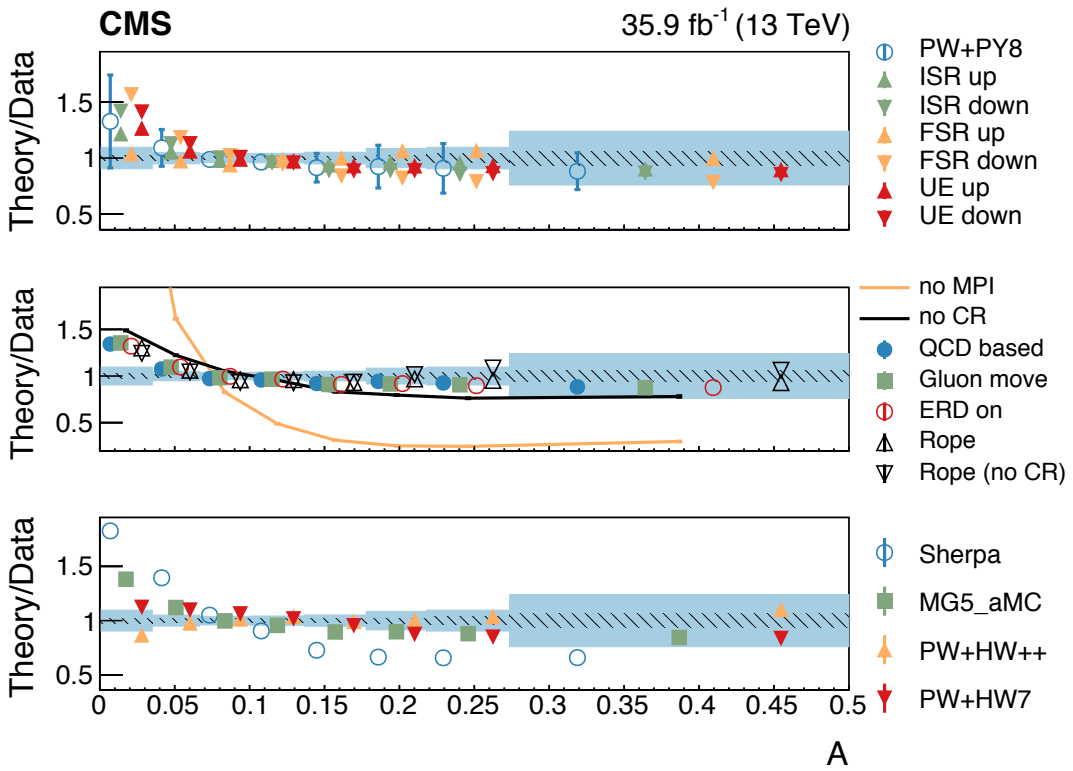
Underlying Event in ttbar Events



- Parton shower Initial State Radiation (ISR) and Final State Radiation (FSR)
- Underlying event tune fit (UE up and down)
- Color reconnection models
- Different matrix element generators and parton shower codes.

Underlying Event in ttbar Events

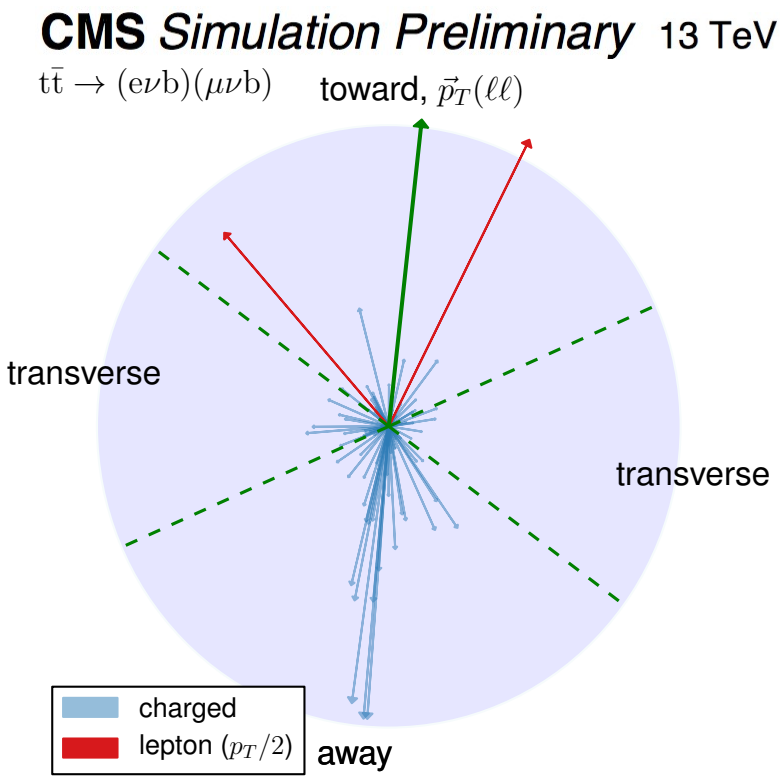


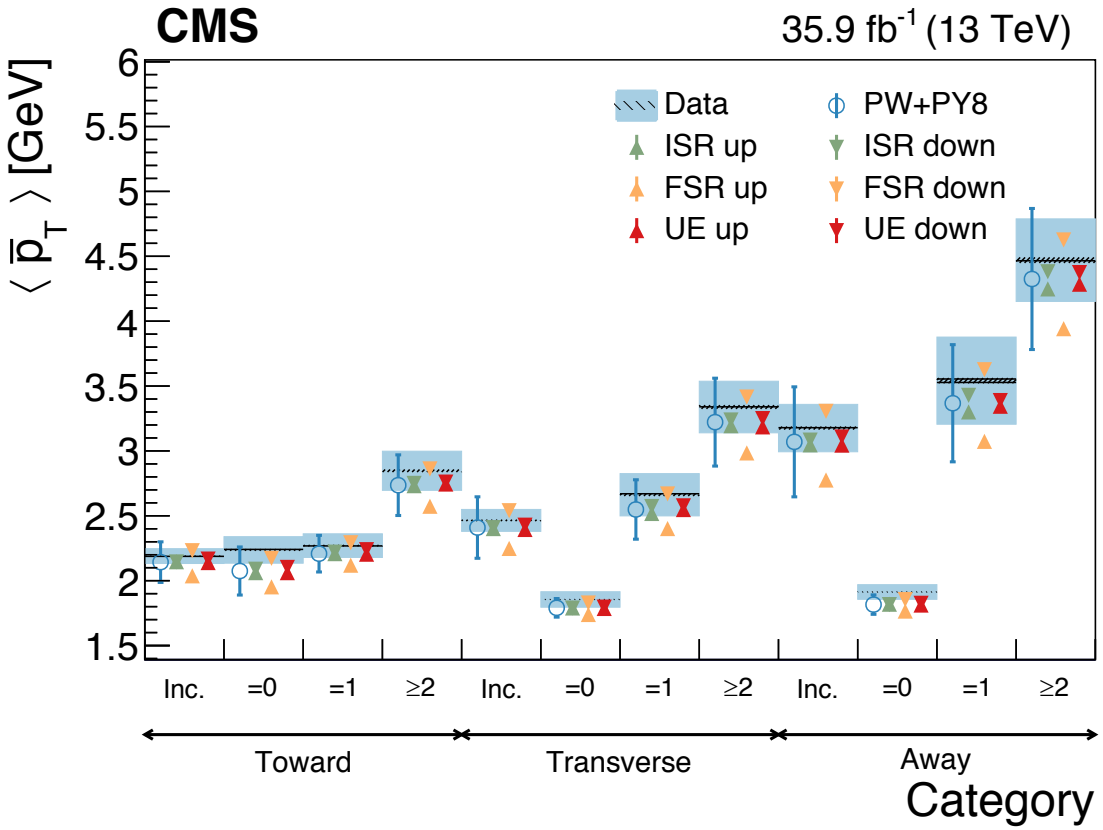


- Aplanarity peaks at ~0.1 → UE events are close to planar.
- MPI is essential.
- Color reconnection effect is subtle.
- Using MG5_aMC+Pythia8 or Powheg+Pythia8 doesn't make significant difference.
  - These are the two main codes used in top quark simulation in CMS.
- Sherpa, and Herwig++/7 need dedicated tuning.

Underlying Event in ttbar Events

- Further categorize events using the dilepton transverse momentum, mass and number of jets.
  - High correlated to reconstructed top kinematics: pT(ttbar), m(ttbar) and ISR but easier to measure than reconstrued top kinematics.
  - Dilepton direction is also used to define standard underlying event regions (towards, away, transverse).





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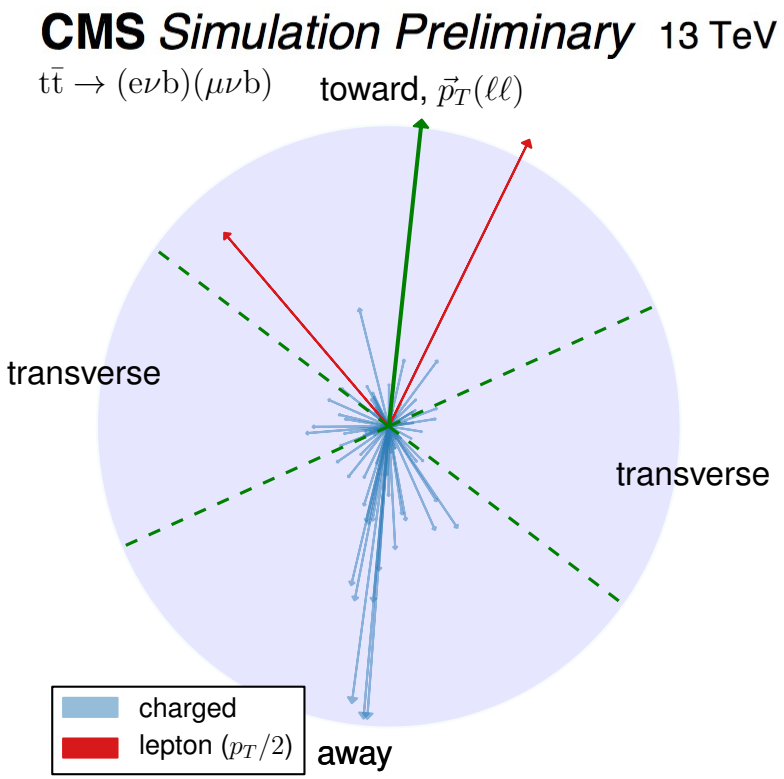
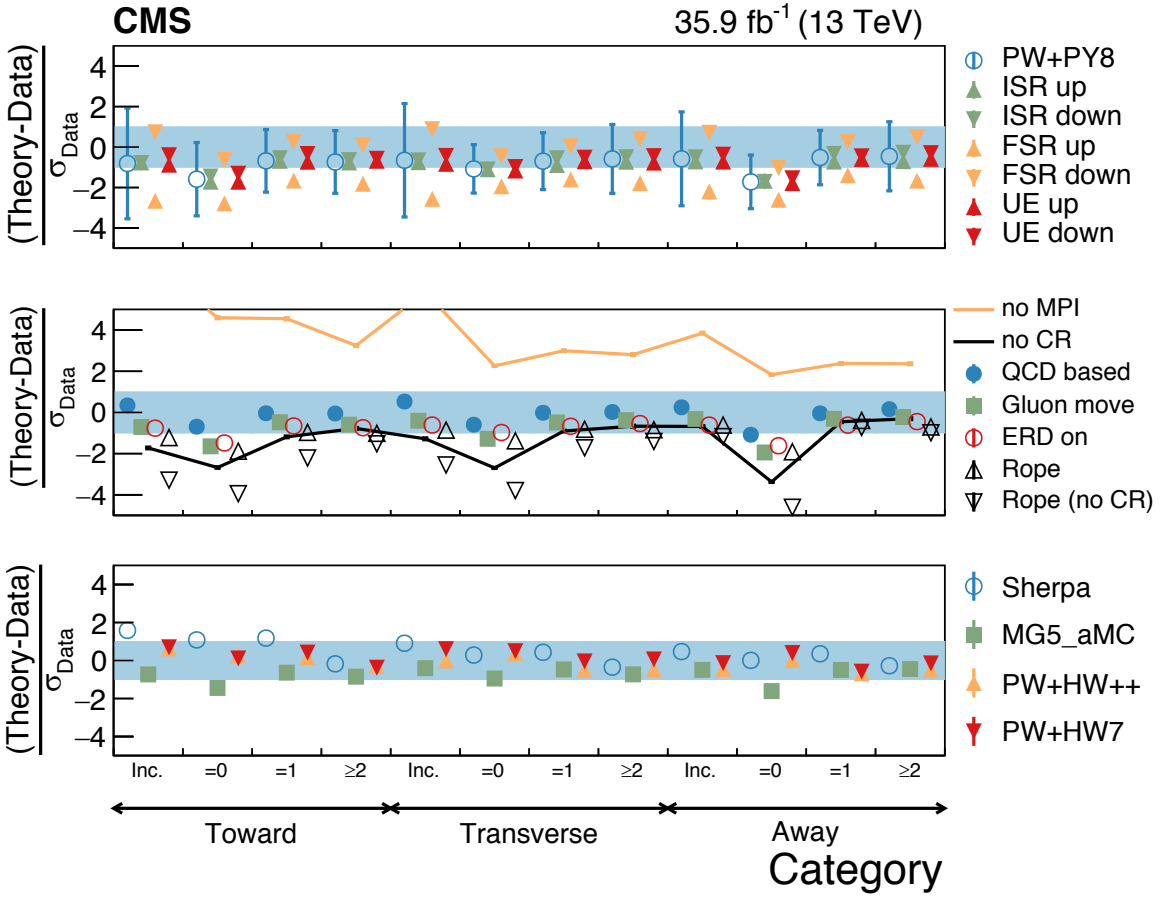
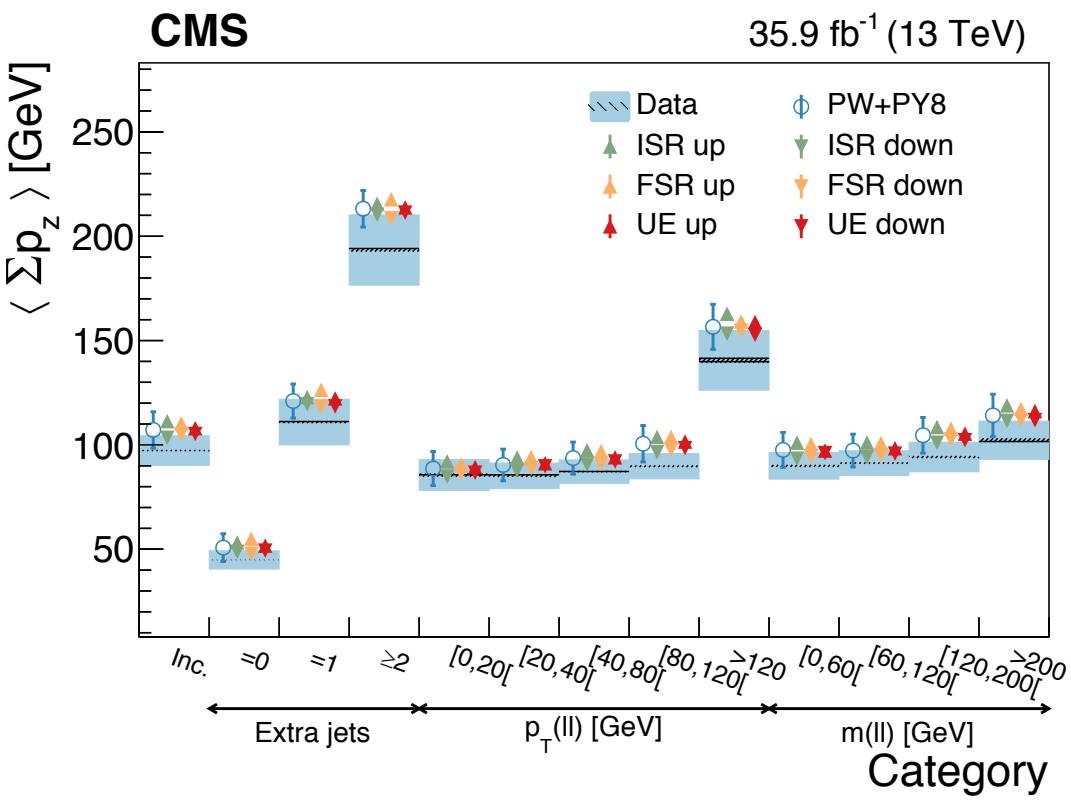
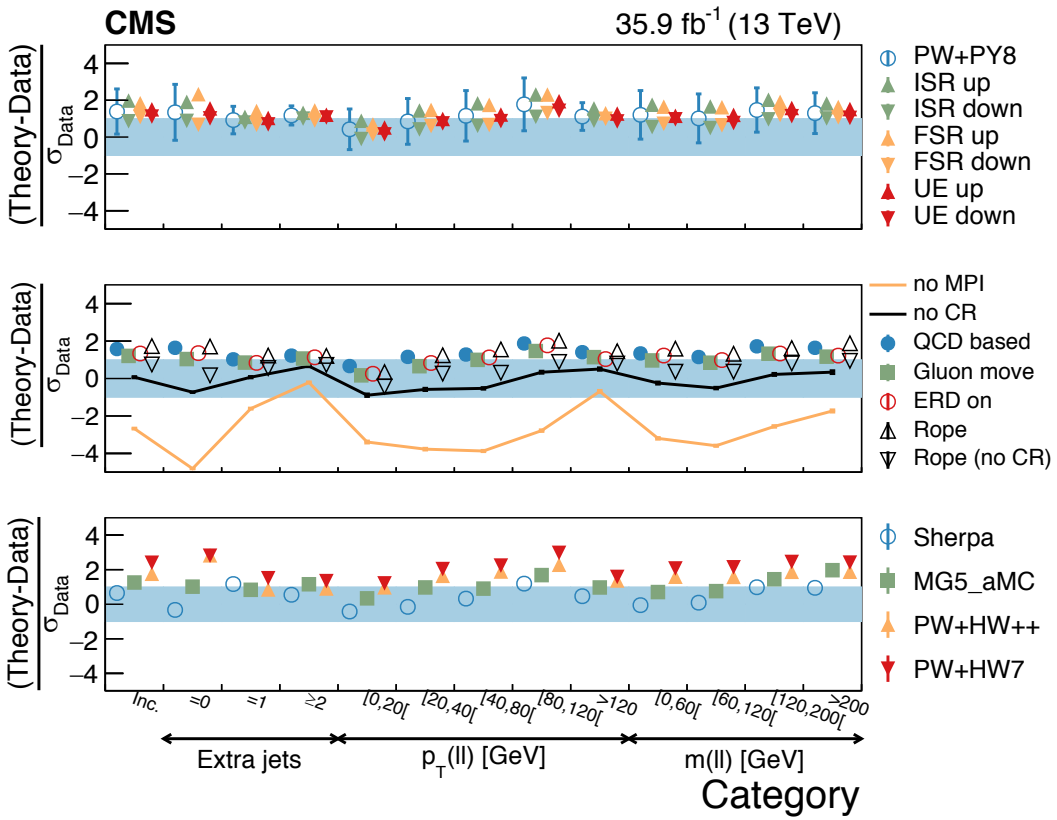




Underlying Event in ttbar Events

- Observables/categories enhance sensitivity to the modeling of MPI, color reconnection, and $\alpha_s^{FSR}(M_Z)$ in Pythia8.
  - Among the parameters with the largest impact on the ttbar modeling.
  - Data disfavor default settings in HERWIG++, HERWIG7, and SHERPA → Need tuning.
  - Choice of NLO ME generator (Powheg or MG5_aMC@NLO[FxFx] + Pythia8) does not impact the UE in ttbar.





Underlying Event in ttbar Events

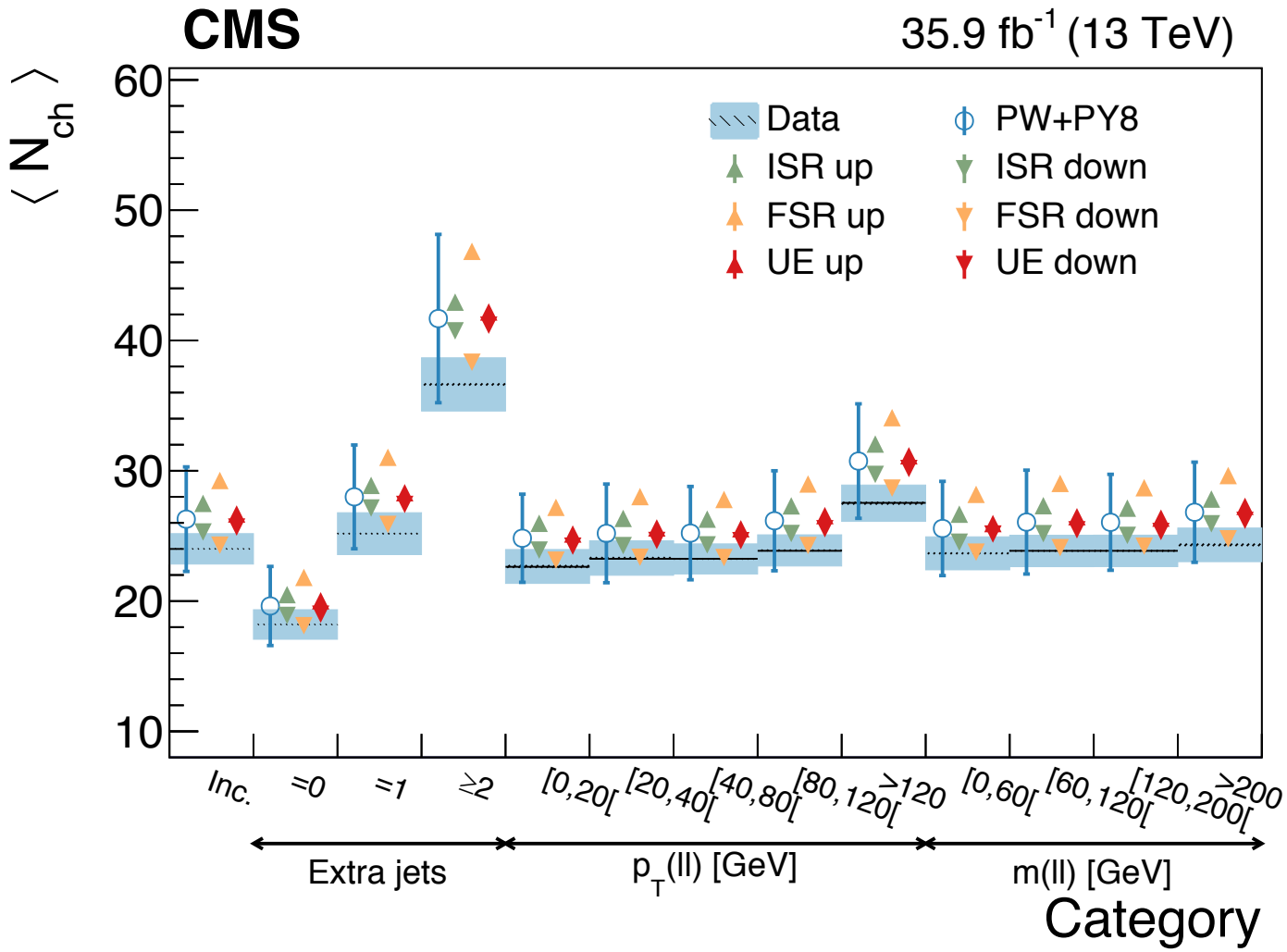
Source	% Uncertainty									
	N_{ch}	$\sum p_T$	$\sum p_z$	$\overline{p_T}$	$\overline{p_z}$	$\lvert\vec{p}_T\rvert$	S	A	C	D
Statistical	0.1	0.2	0.3	0.2	0.2	0.3	0.1	0.1	0.1	0.1
Experimental										
Background	1.2	1.6	1.8	0.4	0.7	1.6	0.4	0.7	0.3	0.7
Tracking eff.	4.4	4.2	4.9	0.8	0.4	4.0	0.4	0.6	0.2	0.6
Theory										
μ_R/μ_F	0.5	0.8	1.0	0.3	0.3	1.0	0.1	0.1	0.1	0.2
Resummation scale	0.2	0.8	0.5	1.1	0.2	1.6	0.8	0.4	0.2	0.7
$\alpha_S^{FSR}(M_Z)$	0.5	0.7	0.7	0.8	1.7	0.7	0.2	1.0	0.2	1.2
$\alpha_S^{ISR}(M_Z)$	0.1	0.3	1.1	1.2	0.7	0.4	0.2	0.5	0.1	1.3
UE model	0.1	0.1	0.2	1.0	0.4	0.5	0.2	0.2	0.1	0.9
m_t	0.4	0.7	1.5	0.6	0.9	0.5	0.1	0.1	0.1	0.7
$p_T(t)$	1.4	4.4	4.5	2.8	2.1	6.7	0.2	0.5	0.2	0.3
Total	4.9	6.5	7.3	3.7	3.1	8.2	1.1	1.6	0.6	2.4

Uncertainties affecting the measurement of the average of the UE observables. The values are expressed in % and the last row reports the quadratic sum of the individual contributions.

- The measurements of the normalized differential cross sections are dominated by systematic uncertainties although the statistical uncertainty is also a large component in some cases.
- Experimental uncertainties → most relevant is the tracking efficiency.
- Theory uncertainties have in general more effect → better tuning of the model parameters needed.

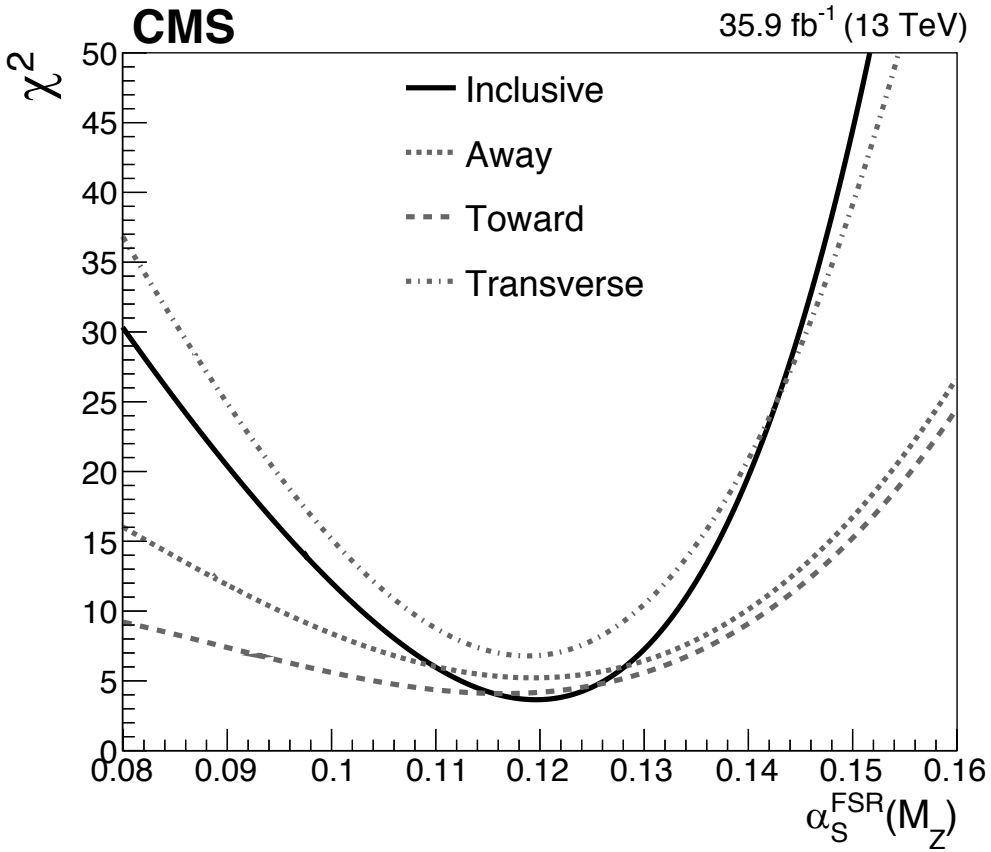
Underlying Event in ttbar Events

- Test the universality of the UE hypothesis to scales up to $2m_t$ than the ones UE models are usually tuned.
  - Measurements in categories of m(ll) indicate that it should be valid at even higher scales.



- The measurements will be used to improve the assessment of systematic uncertainties in future measurements. A first example is given next.

Underlying Event in ttbar Events



- Data prefer lower $\alpha_s^{FSR}(M_Z)$ than *assumed* in Monash.
  - Similar result from jet substructure in ttbar events [CMS-PAS-TOP-17-013: https://arxiv.org/abs/1808.07340]

$p_T(\ell\ell)$ region	Inclusive	Away	Toward	Transverse
Best fit $\alpha_S^{FSR}(M_Z)$	0.120	0.119	0.116	0.119
68% CI	[-0.006,+0.006]	[-0.011,+0.010]	[-0.013,+0.011]	[-0.006,+0.006]
95% CI	[-0.013,+0.011]	[-0.022,+0.019]	[-0.030,+0.021]	[-0.013,+0.012]
μ_R/M_Z	2.3	2.4	2.9	2.4
68% CI	[1.7,3.3]	[1.4,4.9]	[1.6,7.4]	[1.7,3.5]

Uncertainties correspond to a ~√2 variation of μR (instead of a ~2 variation).

We have the data to make similar dedicated studies to control modeling in many different processes and in different phase-space regions.

Summary

- First ever measurement of the underlyinf activity in ttbar events.
- Measurements are expected to be valid for other ttbar final states and can be used as reference for complementary studies
  - Color reconnection models, e.g. in the description of W→qq decays.
- The choice of observables and categories are made to enhance the sensitivity to modelling of multi-parton interactions (MPI), color reconnection and the strong coupling parameter in the PYTHIA8 parton shower.
- Most of the distributions studied indicate a fair agreement between the data and the POWHEG+PYTHIA8 with the CUETP8M2T4 tune, but disfavour the setups in which MPI or CR are switched off of that use a higher value for the strong coupling for FSR.
- Data also disfavour the default configurations in HERWIG++, HERWIG7 or SHERPA.
- It has been also verified that the choice of the next-to-leading order matrix-element generator does not impact the expected characteristics of the UE.

Summary

- The results test the hypothesis of universality of underlying event at an energy scale typically higher than the ones at which these models have been studied.
- The UE model is tested up to a scale of 2 x m(top) and the measurements in ctaegories of diplepton invariant mass indicate that it should be valid even at higher scales.
- The measurements can be used to improve the assessment of systematics uncertainties in future top quark measurements.
- The results show that a value of α_s(FSR)= 0.120 +/- 0.006 is consistent with the data (and the world average value).
- The corresponding uncertainties translate to a variation of the renormalization scale by a factor of √2.