Measurements of soft MPI

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Measurements of soft MPI

- Motivation
- Observables
- Recent measurements of underlying event in Drell-Yan, Jets, and $t\bar{t}$ production at the LHC
- MPI tuning and interplay with PDF
- Conclusions

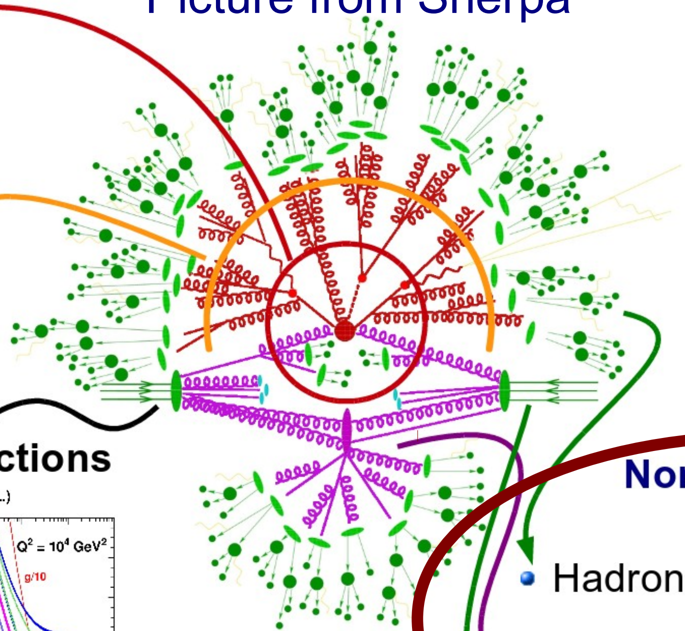
Motivation

- Measurements at hadron colliders always require modelling of QCD effects
- Almost every observable is influenced by non perturbative QCD effects, including PDF, multi parton interactions, and hadronisation
- A good non perturbative QCD modelling is a prerequisite for precision physics and searches
- Measurements of underlying event associated to QCD and EW signatures help to constrain the parameters of soft QCD models, and to understand the structure of the proton at low-x

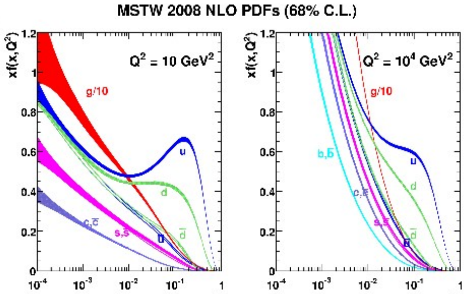
Perturbative QCD

- **Hard scattering**
  - Fixed Order
  - Resummation
- **Fragmentation**
  - Parton Shower
    - Initial state
    - Final state

Picture from Sherpa



Parton Distribution Functions (PDF)

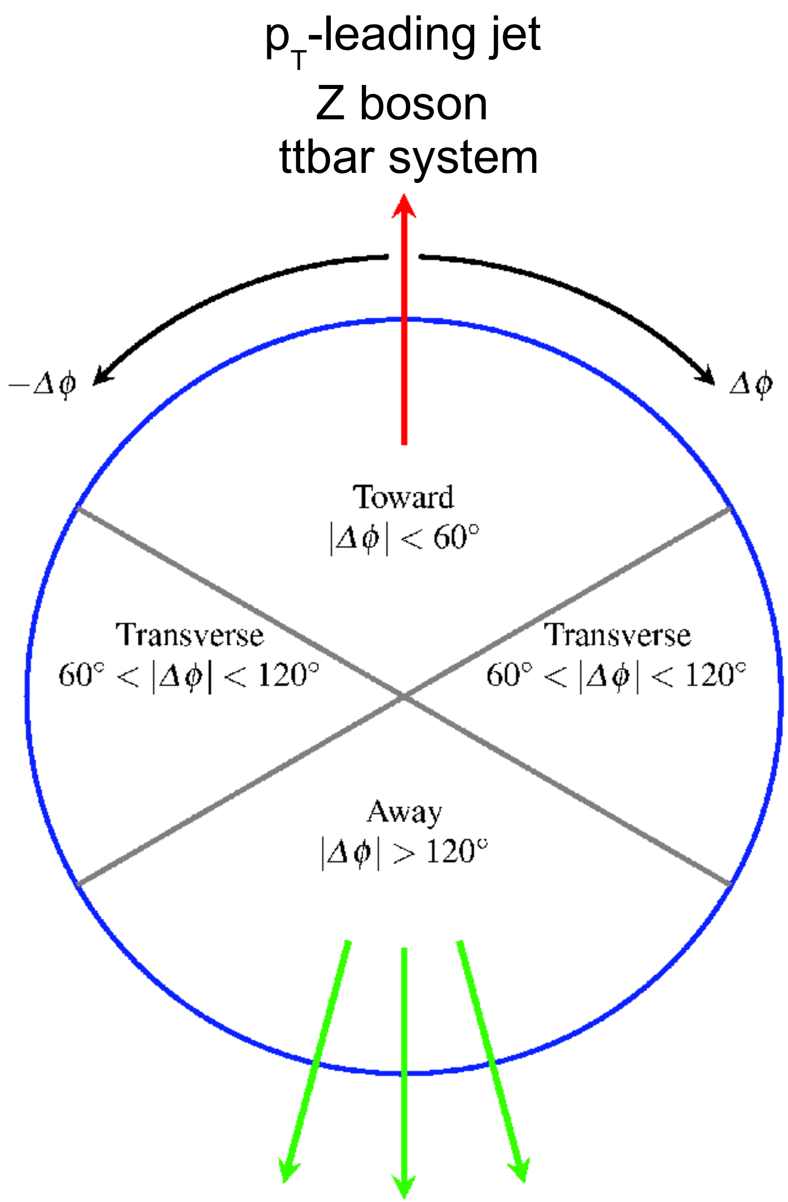


Non perturbative QCD

- Hadronization
- Multi-parton interactions
- Primordial k_T

Underlying event observables

- Underlying event refers to event activity in hadron collisions, not associated to the hard process
- Includes soft ISR and FSR, MPI, and color reconnection with beam remnants
- Observables are charged particles multiplicity N_{ch} and transverse energy or momentum flow Σp_T, ΣE_T
- Transverse, toward and away regions are defined with respect to the p_T-leading jet or Z boson
- Toward and transverse regions are sensitive to the UE, away region has larger contributions from high p_T recoil, which is modelled by perturbative QCD
- Transverse regions are further distinguished in trans-max and trans-min, depending on the amount of N_{ch}, Σp_T, ΣE_T



Underlying event observables

- Densities and averages
  - Charged particles average p_T $< p_T >$
  - Charged particles density $N_{\mathrm{ch}}/\delta\eta\delta\phi$
  - Charged particles p_T density $\sum p_T/\delta\eta\delta\phi$
  - Particles E_T density $\sum E_T/\delta\eta\delta\phi$
- Particles spectra
  - Charged particle p_T spectrum
  - Charged particle multiplicity spectrum

Event selection of UE measurements

- p_T-leading object
  - Z boson: $66 < m_{ll} < 116$, $p_T^l > 20$, $|\eta^l| < 2.4$
  - Jet: anti-kt R=0.4, $p_T > 20$ GeV, $|\eta| < 2.8$

    Inclusive jet selection, and dijet exclusive selections in order to suppress QCD radiation
  - $t\bar{t}$: dileptonic and semileptonic channels

- Charged particles are identified by tracks with
  - $p_T > 0.5$ GeV
  - $|\eta| < 2.0$ or 2.5
- Charged and neutral particles measured with calorimeter clusters (only in the jet measurement)
  - Charged particles $p > 0.5$ GeV
  - Neutral particles $p > 0.2$ GeV
  - $|\eta| < 4.8$

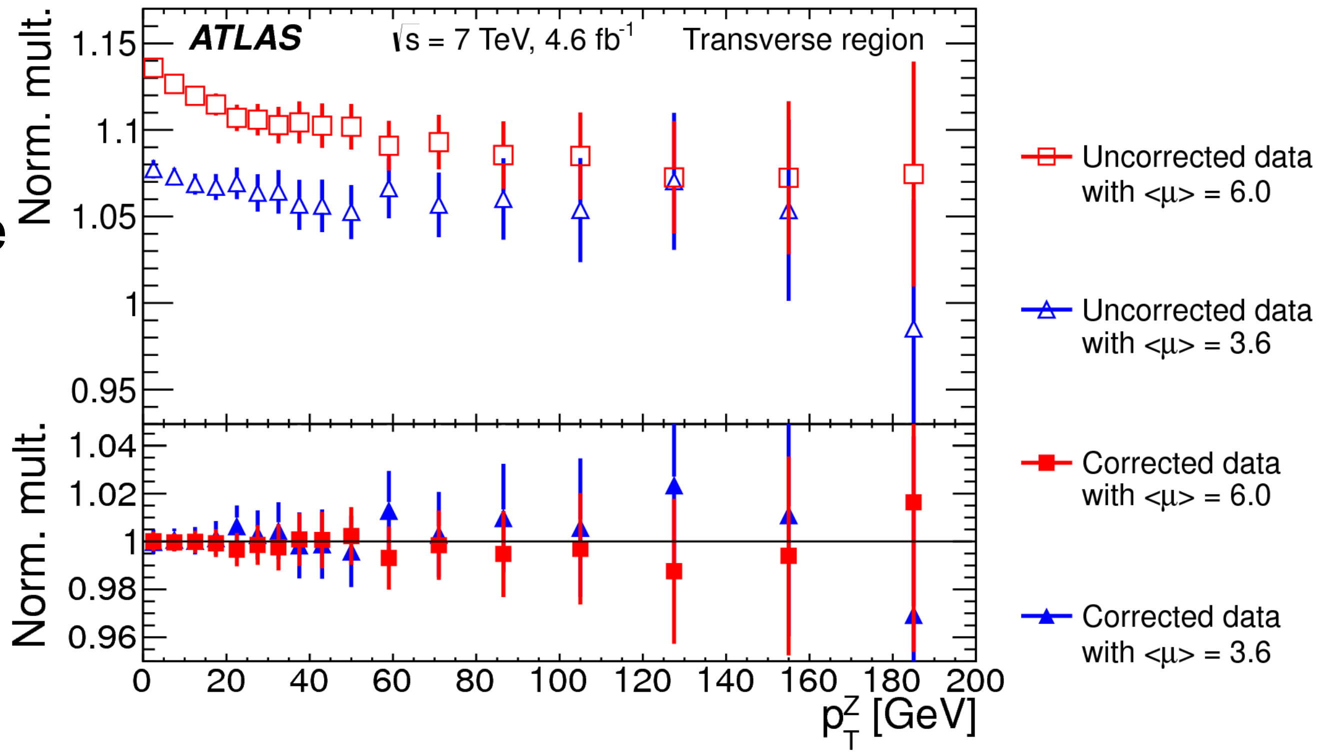
- Measurements are unfolded to the particle level to allow comparison with MC predictions

Subtraction of pile-up of multiple pp interactions

- In the ATLAS Z-boson underlying event measurement with 4.6 fb^{-1}, Pile-up contribution to the underlying event observables needs to be accounted
- To reduce pile-up, tracks are required to be associated to the primary vertex (PV) in $|d_0| < 1.5$ mm and $|z_0| \sin\theta < 1.5$ mm

arXiv:1409.3433

- Residual contribution is estimated and subtracted with a data driven technique
- Tracks associated to points at distance larger than 2 cm from the PV are selected, and used to estimate the pile-up contribution



- Pile-up correction is checked in subsamples with different average number of pile-up interactions

Underlying event in jets production – ATLAS

- Jets inclusive and dijet exclusive selections

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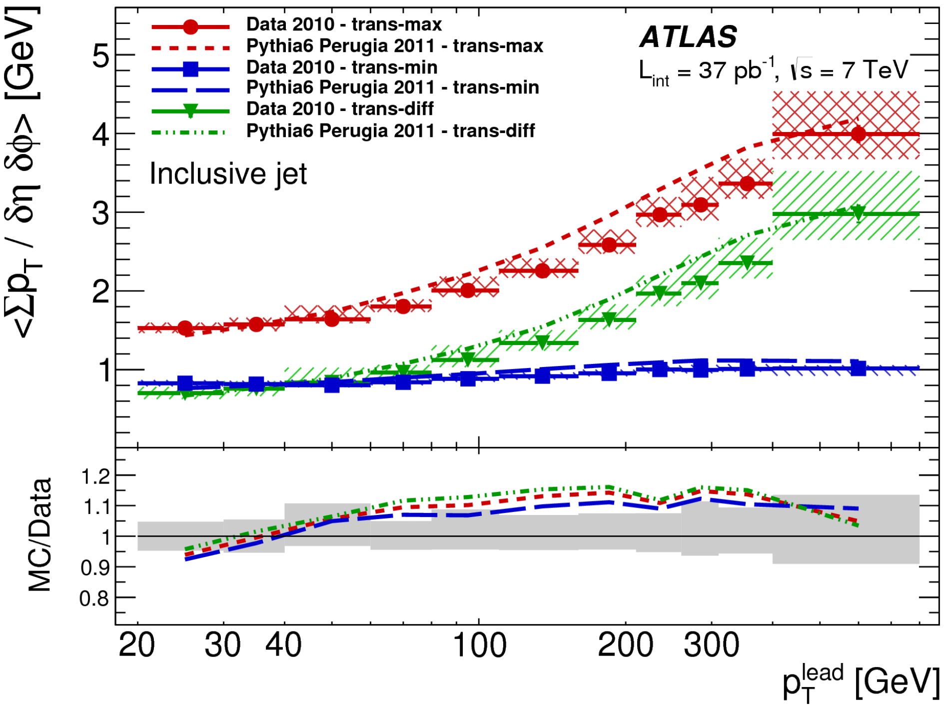

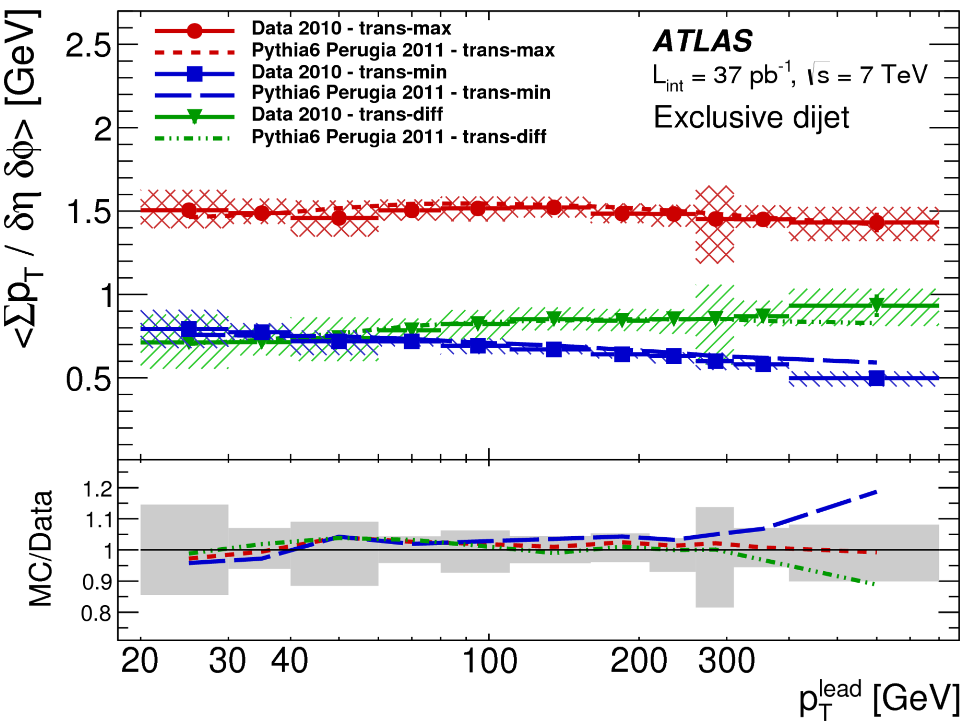

- In the inclusive jet sample, Trans-max region shows increase as a function of jet p_T, trans-min region is flat
- Trans-max has a large contribution from pQCD
- In the exclusive dijet sample also the trans-max region is flat

→ Less sensitive to perturbative QCD effects

Underlying event in jets production – ATLAS

- Jets inclusive and dijet exclusive selections

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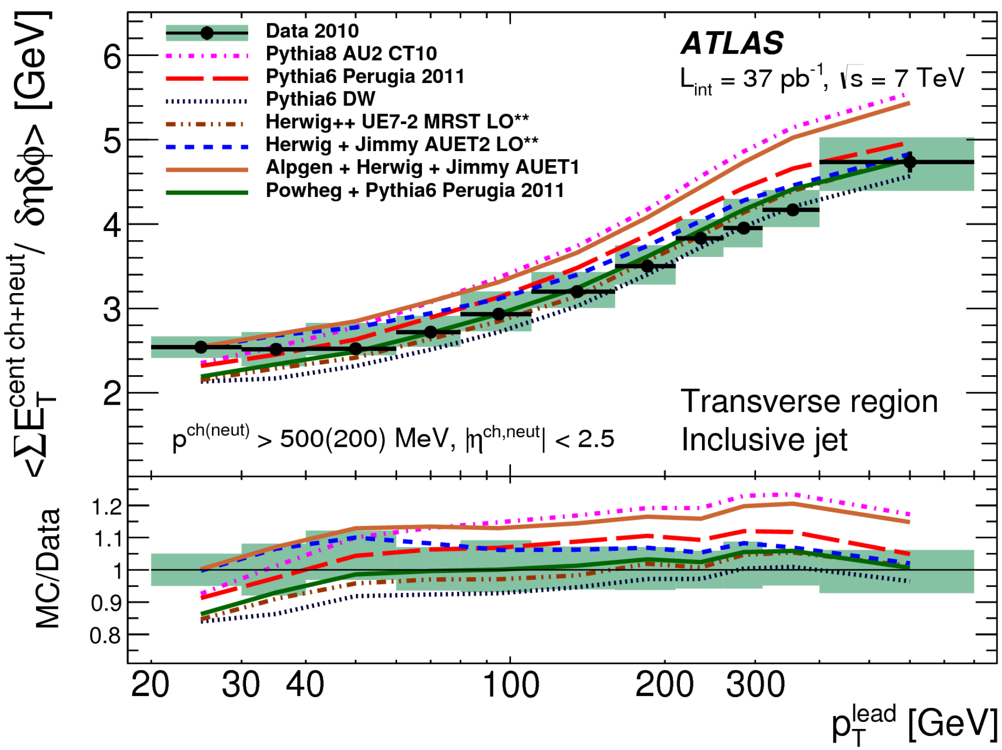
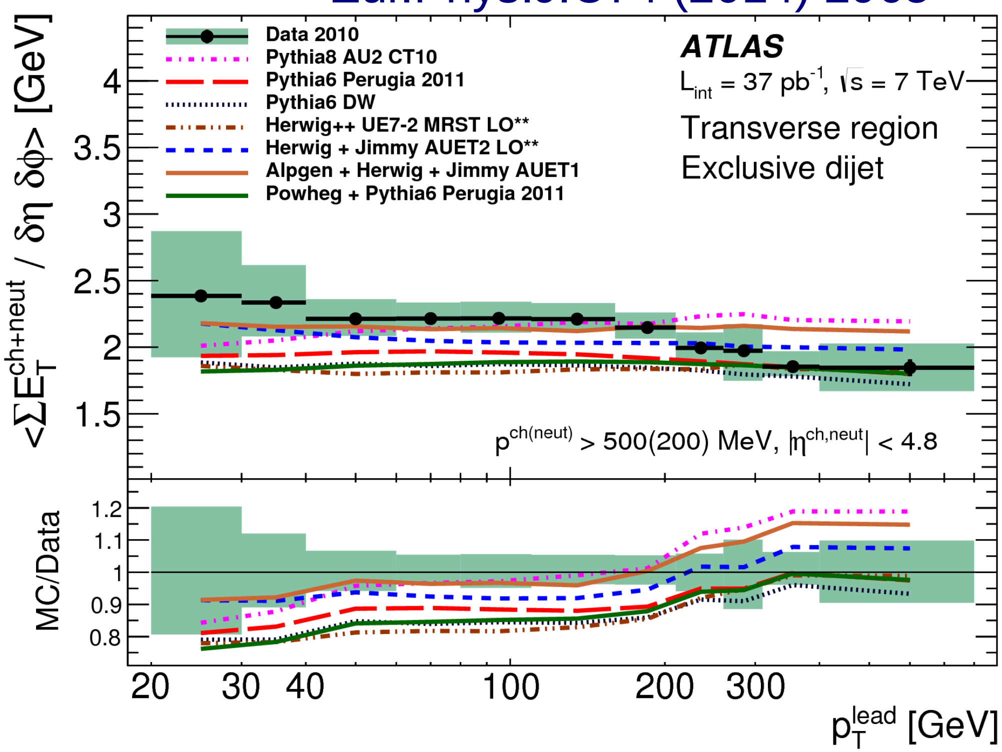
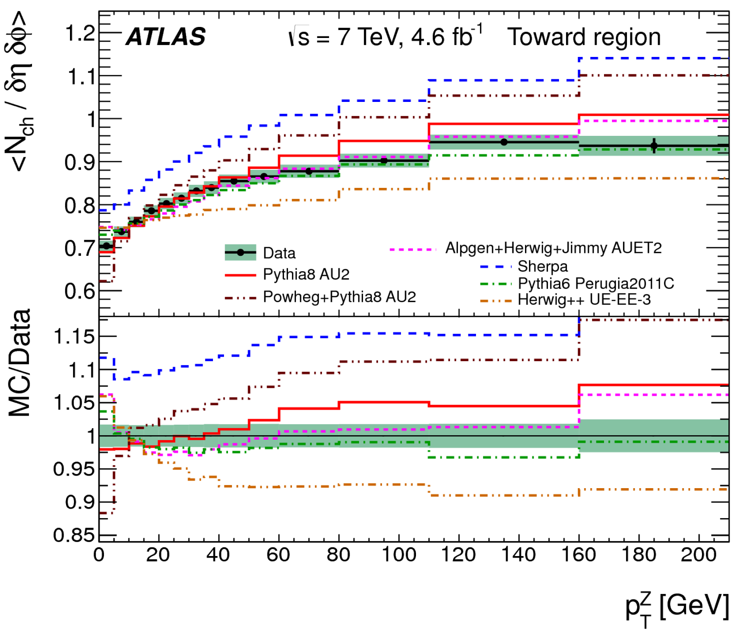
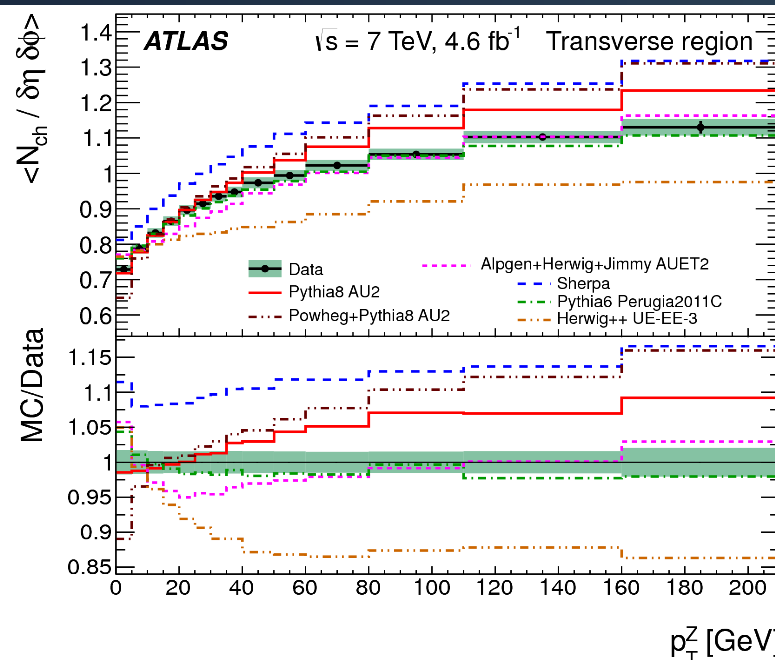


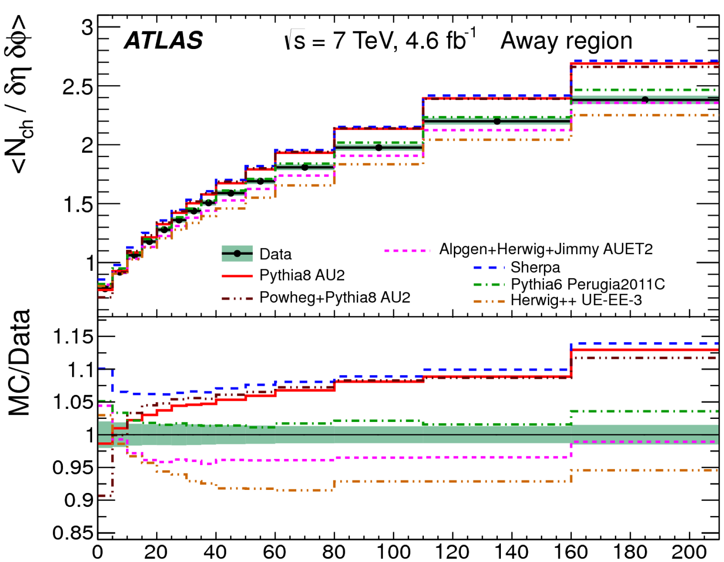


- Similar distributions also for ΣE_T measured with calorimeter clusters

Underlying event associated to Z boson – ATLAS







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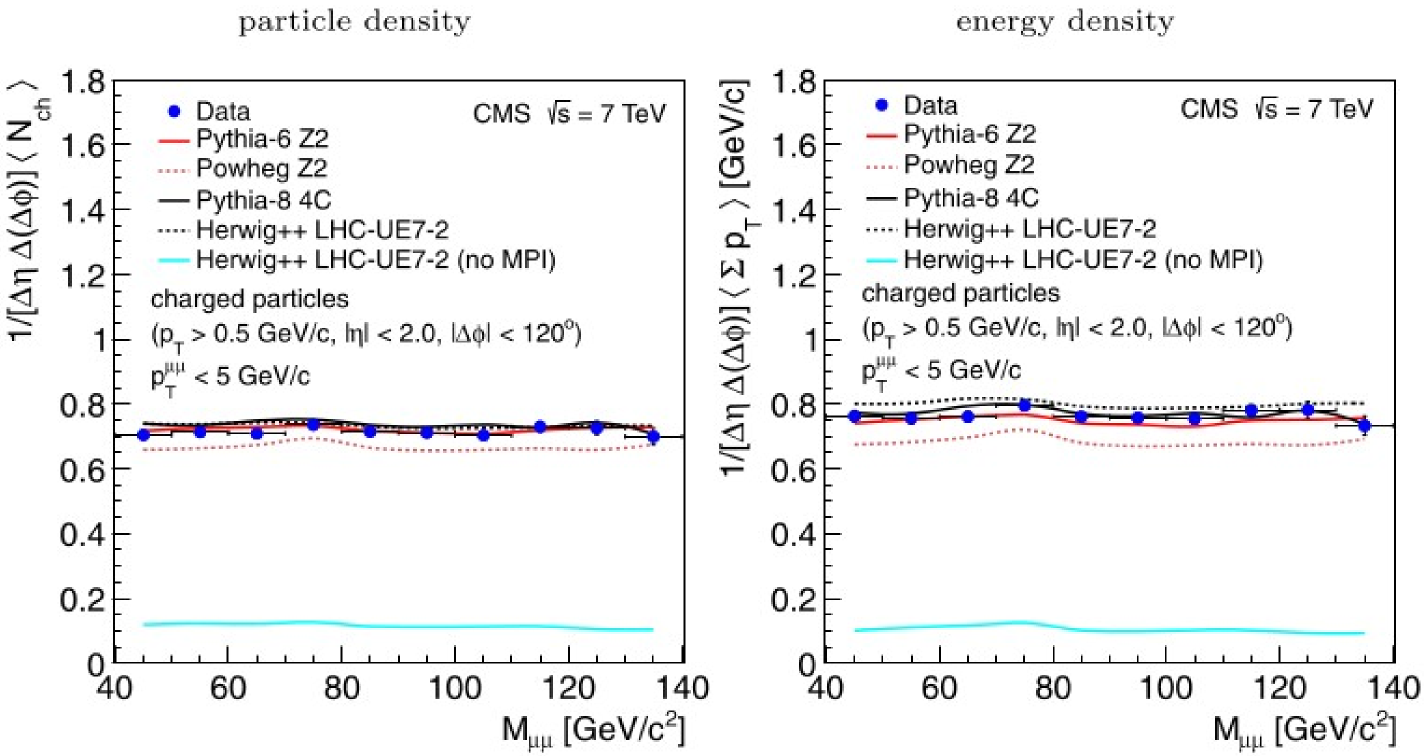
p_T^Z [GeV]

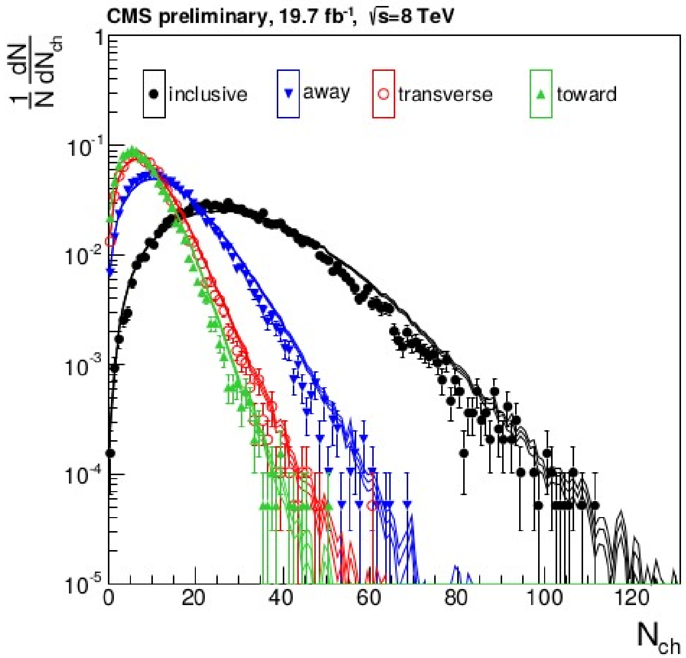
- In $Z \rightarrow ll$ events, it is possible to measure the UE in the toward, transverse and away regions
- In the high p_T region, the contribution from pQCD ME starts at different jets multiplicity for the away (Z+≥1jet), toward (Z+≥2jets), trans (Z+≥3 jets)
- Low p_T region is less sensitive to perturbative QCD, and can be used for tuning the non-pQCD parameters

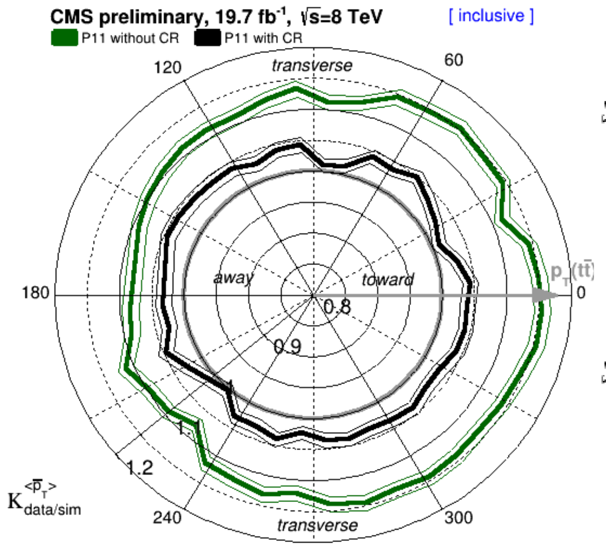
Underlying event associated to Z boson – CMS

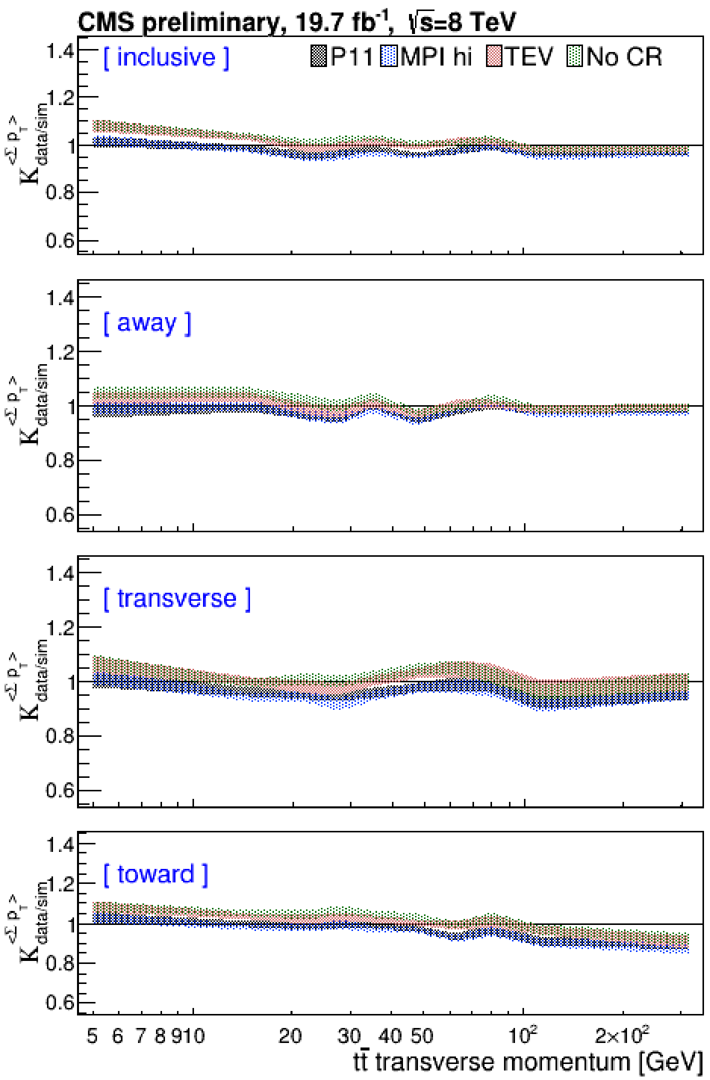


- Measured the charged density and energy flow as a function of the dimuon invariant mass → uniform distributions
- Notice that the same Z2 tune with Powheg+Pythia6 is 10% lower than with Pythia6
- Known issue due to MPI interleaving: the first QCD radiation of Powheg is not interleaved → wrong MPI Sudakov
- Can be fixed by starting the PS at the kinematic limit and vetoing emissions above the Powheg emission

Underlying event associated to $t\bar{t}$ – CMS







- At the LHC, for the first time the UE can be measured also in $t\bar{t}$ production
- Crucial for precision measurement in the $t\bar{t}$ final state, including the mass of the top quark
- Allows to test models of colour reconnection

Comparison between UE and Minimum bias

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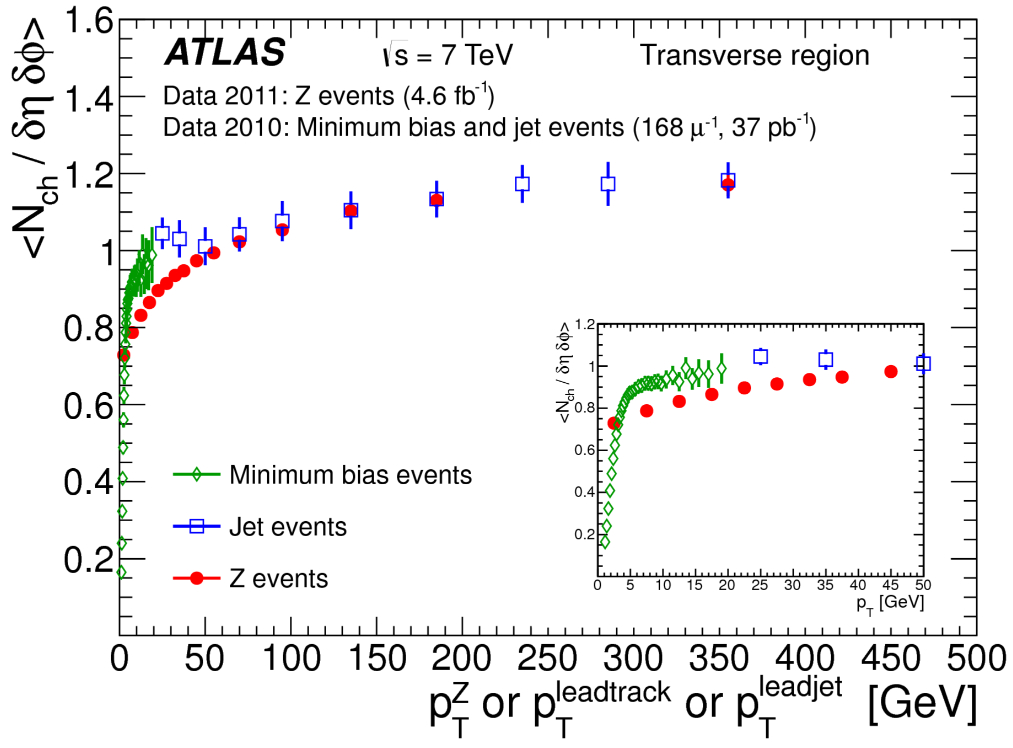
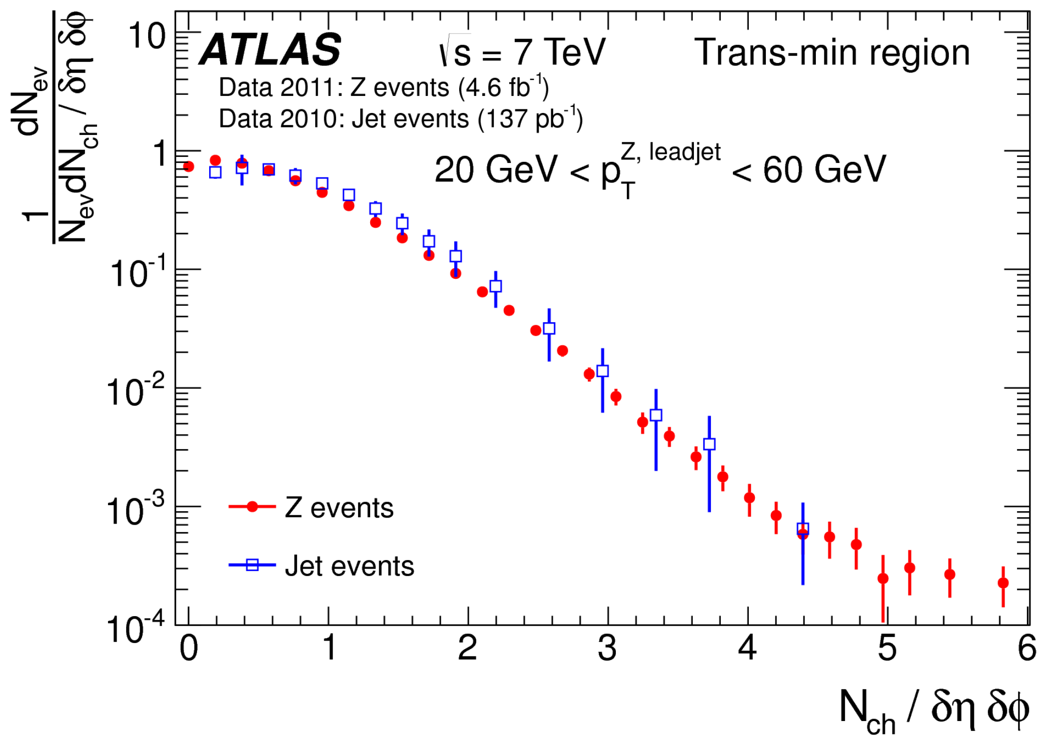
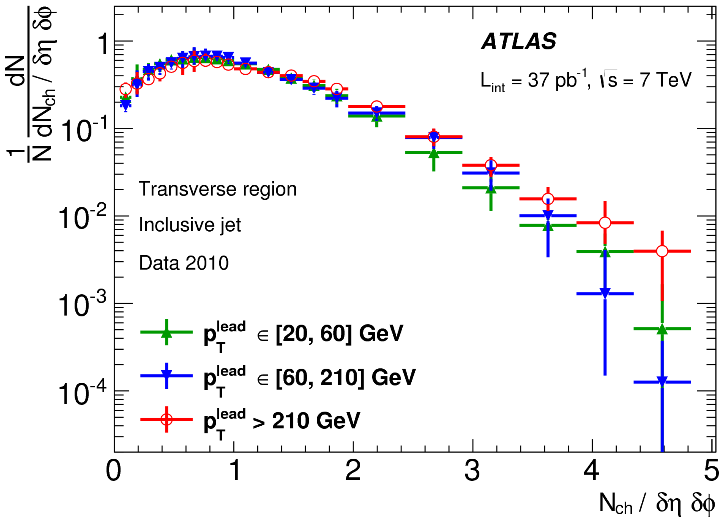
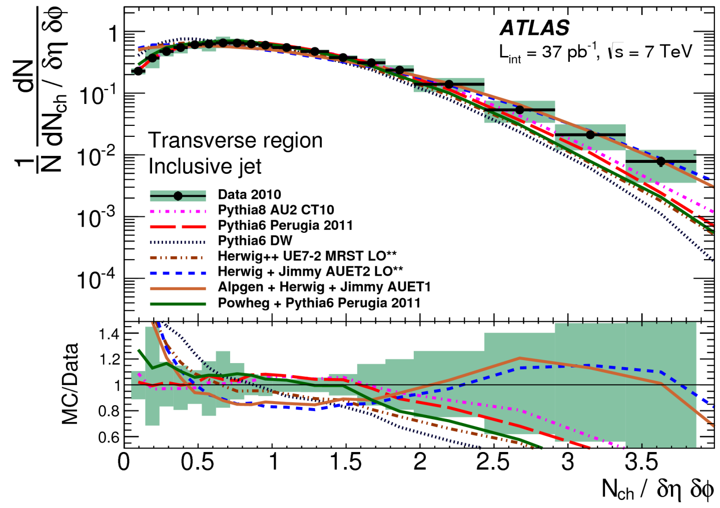




- Underlying event observables can be compared between jets and Z boson production, and also to minimum bias measurements
- Similar behaviour between jets and Z boson, especially in the trans-min region, which is most sensitive to the MPI
- Qualitative check of the universality of the MPI model in different hard processes

Charged particle p_T and multiplicity spectra





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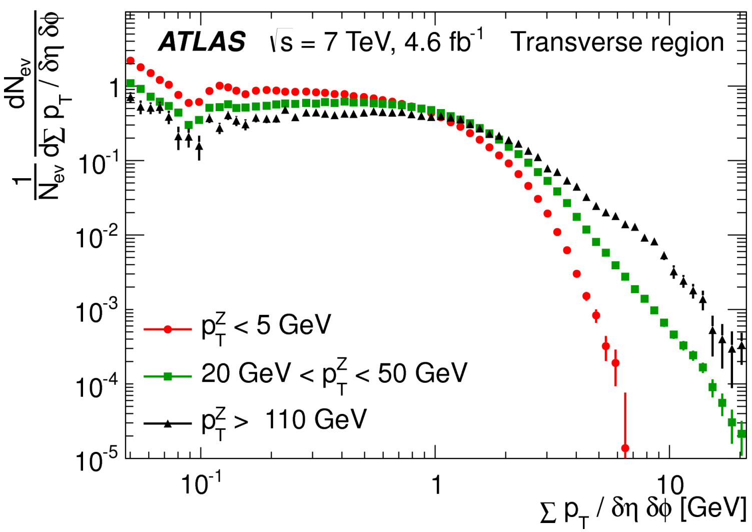

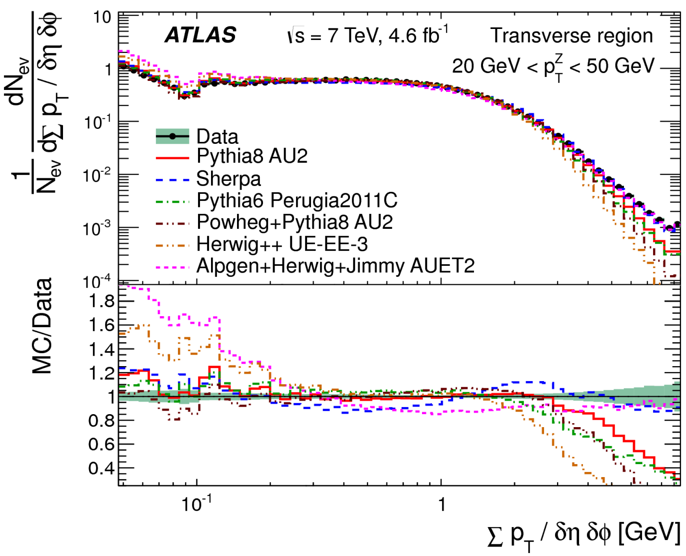

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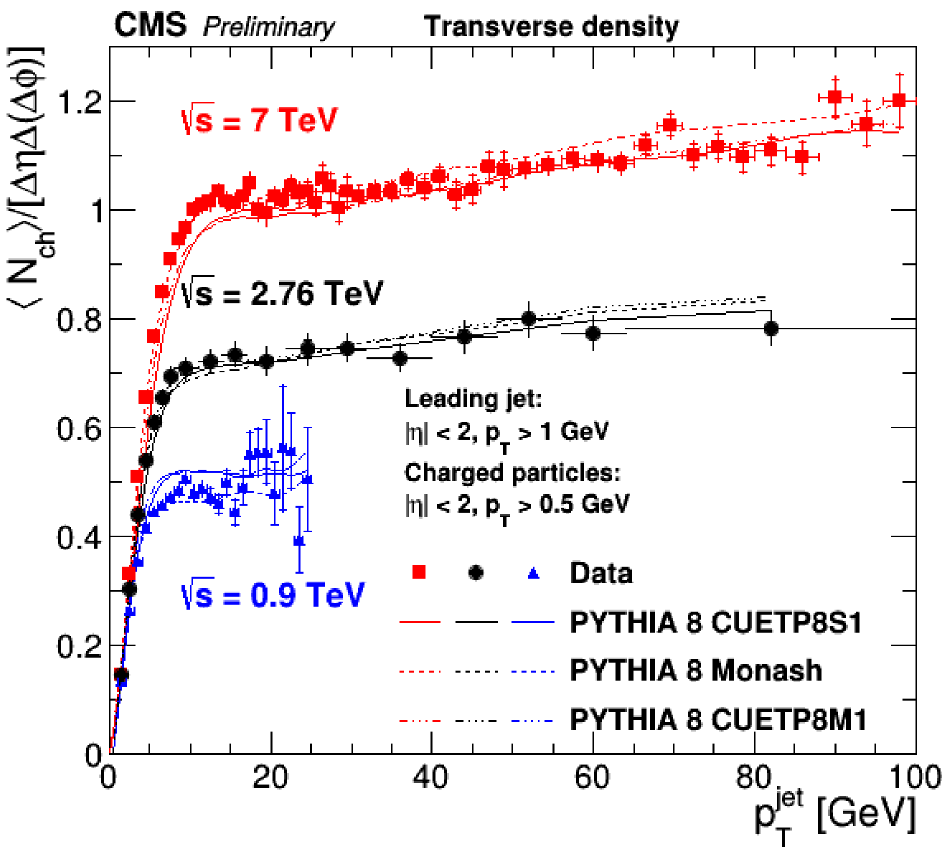
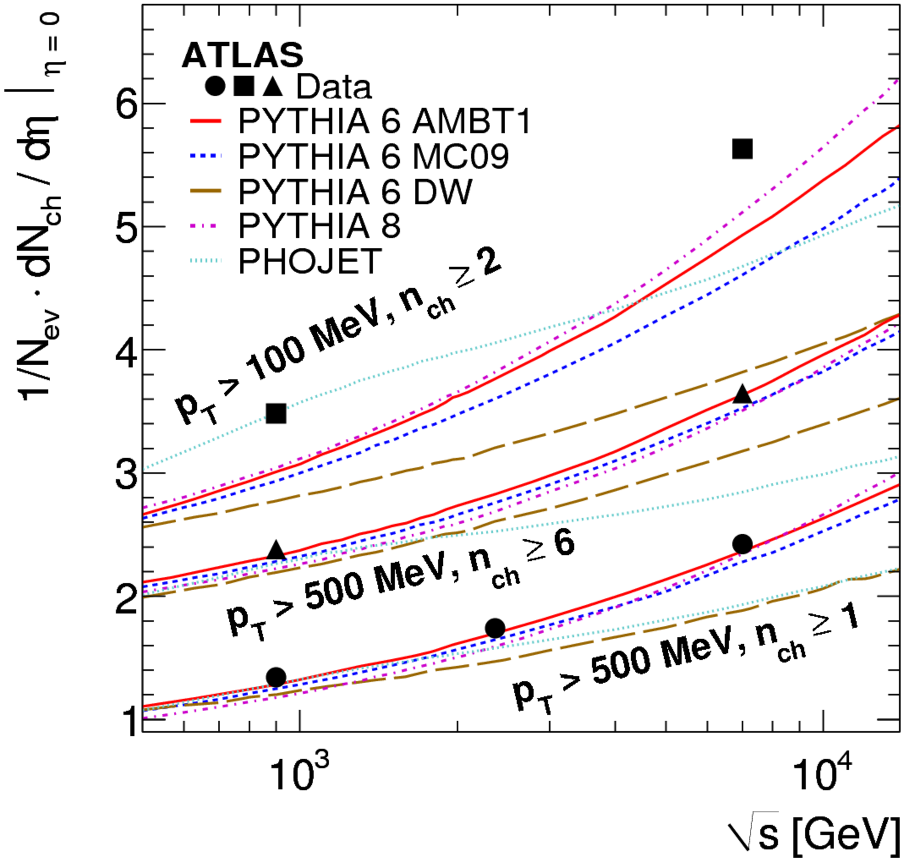
- Differential and double differential particles multiplicity and Σp_T spectra provide further discrimination between MC models
- Very challenging for the soft QCD models implemented in the MC to describe these observables

Measurements of UE in minimum bias





- The MPI activity is expected to increase with the center-of-mass energy
- Measurements of charged particles density and energy flow at various collider energies provide a stringent test of the MPI models

MPI (and PS) Tunes

- The Underlying and Minimum bias measurements are used to constrain the parameters of the MPI models in the MC generators
- In the Pythia MC model, the MPI is simulated as additional $2 \rightarrow 2$ scattering
- The parameters of the MPI model tuned to the data are
  - MPI cut-off: Regulate the overall charged density and energy flow, behaves as a pedestal
  - Effective value of α_s for the MPI: Usually in the range 0.130-0.140
- Other parameters of the MC generators
  - Primordial kT: width of a gaussian smearing of the partons initiating the hard scattering
  - Parton shower ISR and FSR effective values of α_s, shower cut-offs
  - Range (strength) of colour reconnection

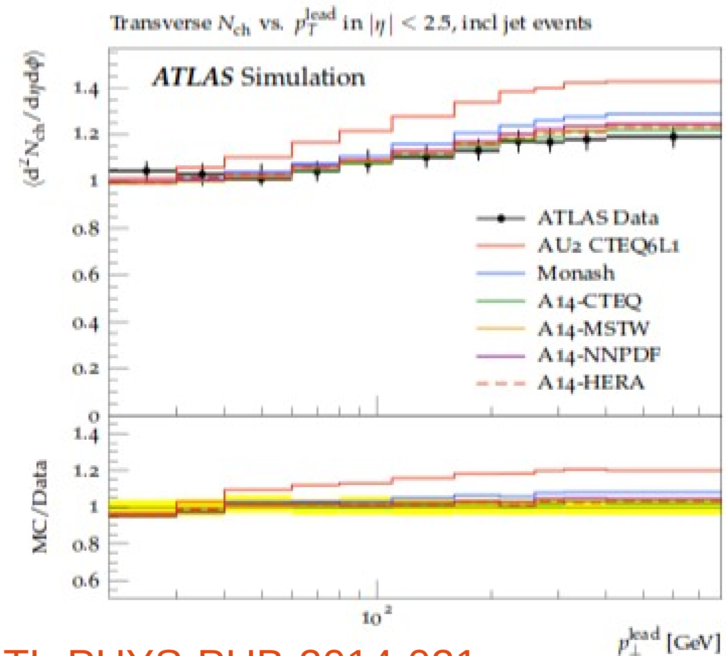
ATLAS A14 tune – a global tune of PS and MPI

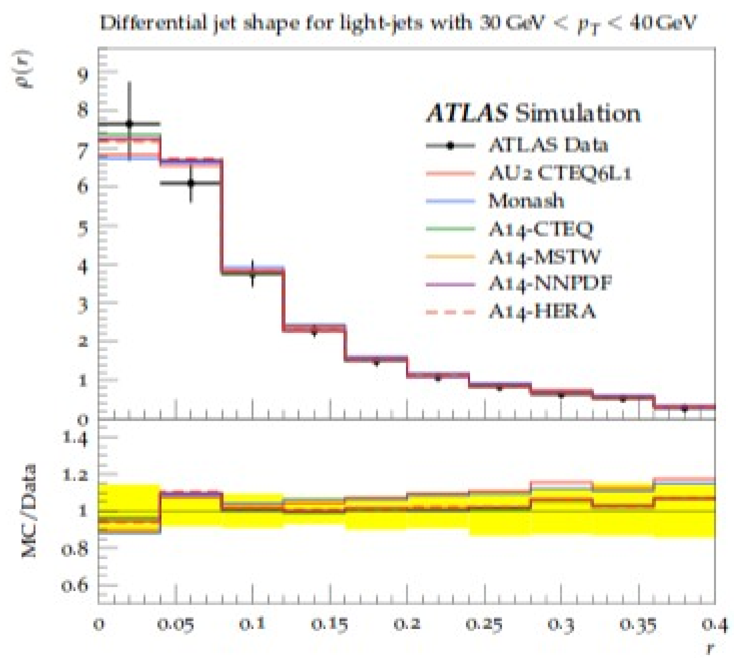
- New set of tunes exploiting all the available 7 TeV ATLAS data
- The simultaneous Tune of MPI and shower parameters allows to account for correlation between the various parameters
- No need to iterate between shower and MPI tune, no risk of spoiling the shower performance with a MPI retuning
- Studied the dependence of the parameters with respect to the PDF (used only LO PDF, following authors' recommendation)

ATL-PHYS-PUB-2014-021

Param	CTEQ	MSTW	NNPDF	HERA
SigmaProcess:alphaSvalue	0.144	0.140	0.140	0.141
SpaceShower:pT0Ref	1.30	1.62	1.56	1.61
SpaceShower:pTmaxFudge	0.95	0.92	0.91	0.95
SpaceShower:pTdampFudge	1.21	1.14	1.05	1.10
SpaceShower:alphaSvalue	0.125	0.129	0.127	0.128
TimeShower:alphaSvalue	0.126	0.129	0.127	0.130
BeamRemnants:primordialKThard	1.72	1.82	1.88	1.83
MultipartonInteractions:pT0Ref	1.98	2.22	2.09	2.14
MultipartonInteractions:alphaSvalue	0.118	0.127	0.126	0.123
BeamRemnants:reconnectRange	2.08	1.87	1.71	1.78

A14 tune





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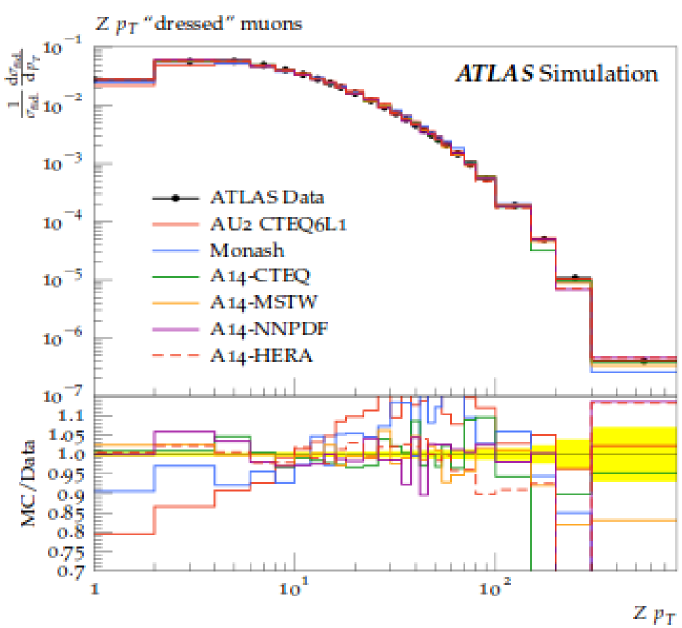


- Overall good performance on jets, W/Z, and $t\bar{t}$ processes, success of the global tune strategy
- However, small tensions between the various processes are observed and complementary work on specific tunes is needed to identify these tensions, possible model pitfalls, need for higher order corrections

MPI energy extrapolation – CMS CUET tunes

- The study of the UE as a function of the hard scale at several centre-of-mass energies provides an insight into the UE dynamics, its evolution with the collision energy, and further constrains of MPI parameters
- Tunes of Pythia6 and Pythia8
- The MPI cut-off is parametrised as a function of the center-of-mass energy E_{CM}:

$$p_{T_0}(E_{cm}) = p_{T_0^{REF}} \times (E_{cm}/E_0)^{\epsilon}$$

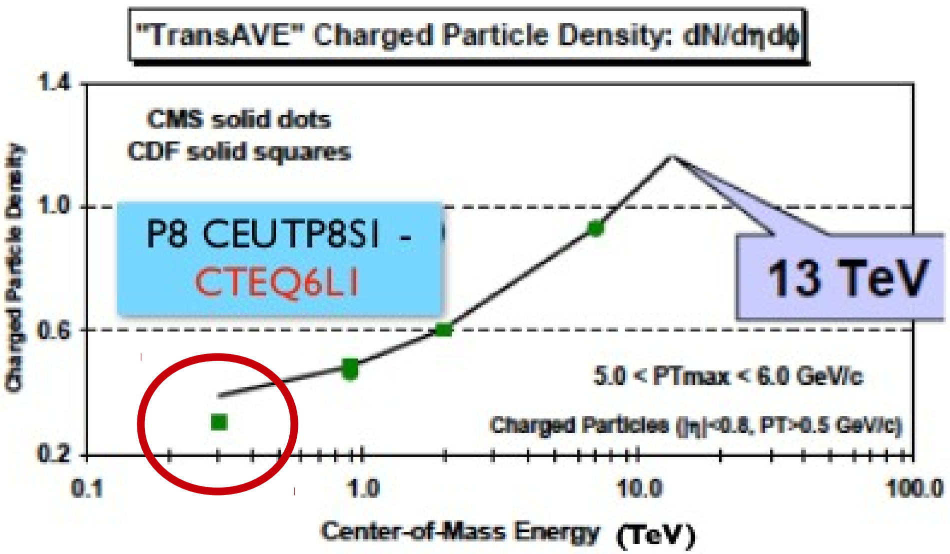
- E_0 is an arbitrary reference energy (1.8 TeV)
- $p_{T,0}^{REF}$ is the cut-off at E_0
- ε controls the energy dependence

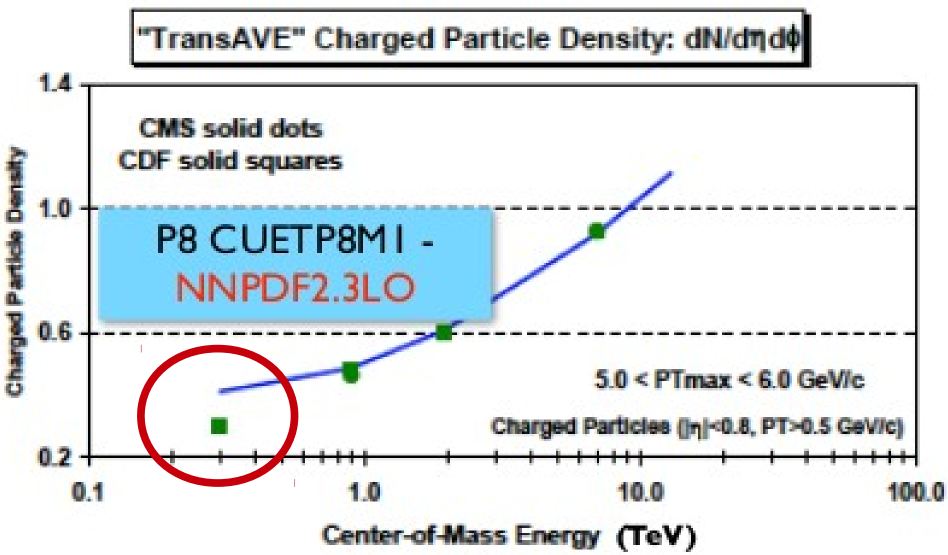
} tunable parameters

- Other colour reconnection and impact parameter profile model switches are tuned

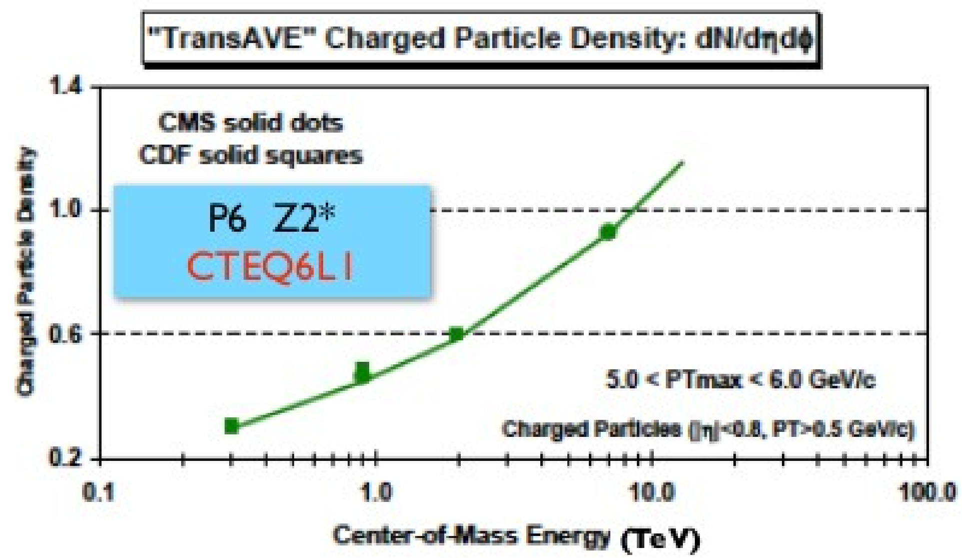
MPI energy extrapolation – CMS CUET tunes

Figures from R. Field



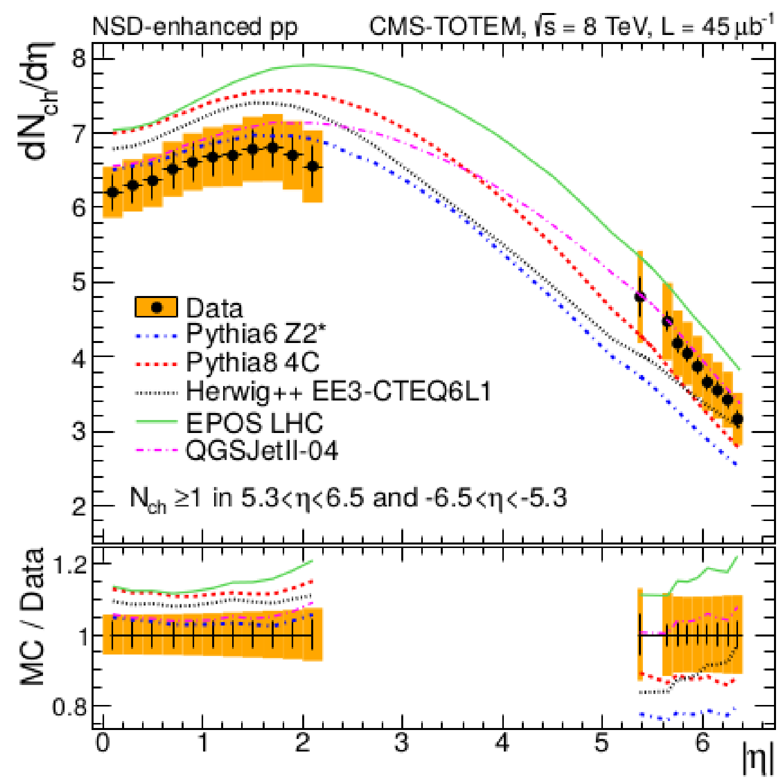


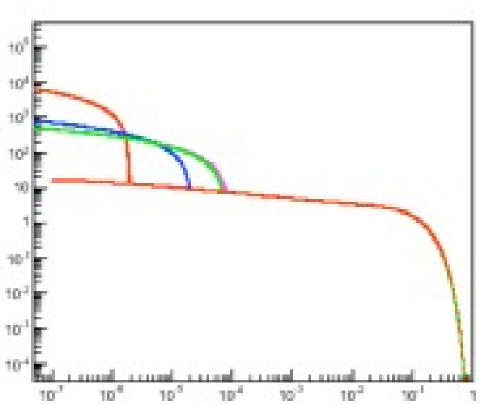
- Pythia8 tune fails to describe simultaneously 300 GeV and 7 TeV data, 300 GeV removed from the tune
- Pythia6 tune works better
- Effect under investigation, excluded the different matter profile between P6 and P8,

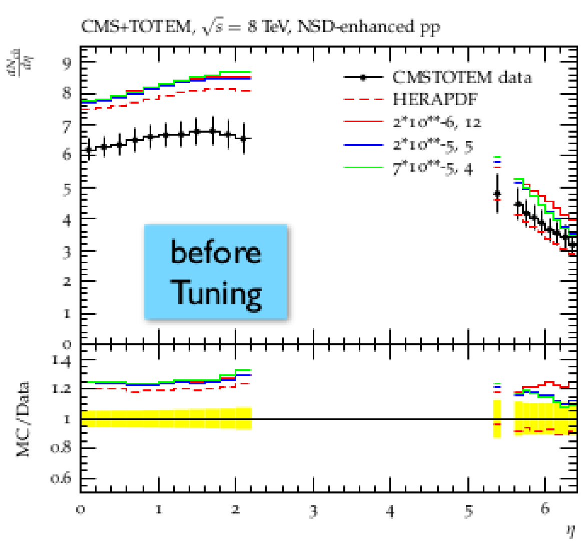


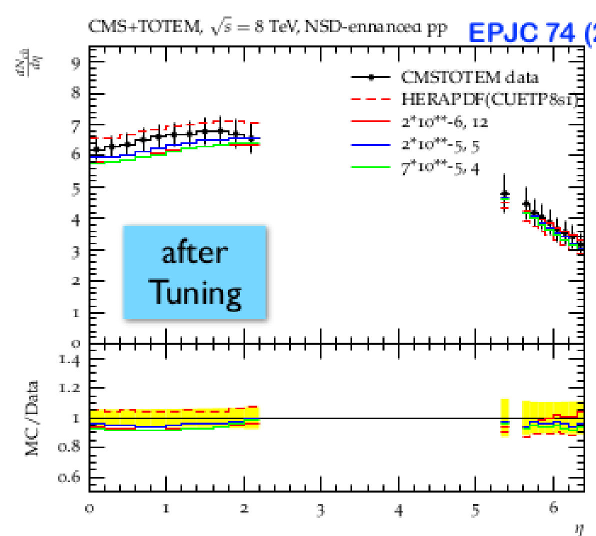
Central and forward charged particles density

- Combined measurement of charge particles density in the central and forward regions with CMS and TOTEM
- None of the models and tunes is able to describe both regions simultaneously
- A reasonable agreement can be achieved db adding a linear term at low-x to the gluon PDF, and retuning
- The procedure (slightly) violates momentum sum rule, is there a better way to account for the interplay of MPI and PDF?









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Summary and conclusions

- Recent LHC measurements of underlying event observables in Jets, Z-boson, and $t\bar{t}$ production, and in minimum bias, provide stringent tests of the MPI model
- Measurements are sensitive to MPI models and to other non-perturbative QCD parameters, and can be used to tune the MC generators
- Started to study the interplay between MPI parameters and PDF, but still much work to do to develop frameworks for fitting together soft QCD parameters and PDF
- Underlying event measurements in Run 2 will provide further insight into the center-of-mass energy dependence of the MPI parameters

BACKUP

Systematic uncertainties

- Jet reconstruction / lepton identication and scale
- Track reconsttruction efficiency
- Calorimeter reconstruction
- Pile-up
- Background
- Unfolding

Quantity	Inclusive jets			Exclusive dijets		
All observables	Pile-up and merged vertices 1–3%			Pile-up and merged vertices 1–5%		
Charged tracks	Unfolding	Efficiency		Unfolding	Efficiency	
$\sum p_T$	3%	1–7%		3–13%	2–7%	
N_{ch}	1–2%	3–4%		3–22%	3–7%	
mean p_T	1%	0–4%		1–9%	1%	
Calo clusters	Unfolding	Efficiency		Unfolding	Efficiency	
$\sum E_T, \lvert\eta\rvert < 4.8$	2–3%	4–6%		5–21%	4–9%	
$\sum E_T, \lvert\eta\rvert < 2.5$	3–5%	4–6%		1–21%	4–7%	
Jets	Energy resolution	JES	Efficiency	Energy resolution	JES	Efficiency
p_T^{lead}	0.3–1%	0.3–4%	0.1–2%	0.4–3%	1–3%	0.3–3%

Observable	Correlation	N_{ch} vs p_T^Z	$\sum p_T$ vs p_T^Z	Mean p_T vs p_T^Z	Mean p_T vs N_{ch}
Lepton selection	No	0.5 – 1.0	0.1 – 1.0	< 0.5	0.1 – 2.5
Track reconstruction	Yes	1.0 – 2.0	0.5 – 2.0	< 0.5	< 0.5
Impact parameter requirement	Yes	0.5 – 1.0	1.0 – 2.0	0.1 – 2.0	< 0.5
Pile-up removal	Yes	0.5 – 2.0	0.5 – 2.0	< 0.2	0.2 – 0.5
Background correction	No	0.5 – 2.0	0.5 – 2.0	< 0.5	< 0.5
Unfolding	No	0.5 – 3.0	0.5 – 3.0	< 0.5	0.2 – 2.0
Electron isolation	No	0.1 – 1.0	0.5 – 2.0	0.1 – 1.5	< 1.0
Combined systematic uncertainty		1.0 – 3.0	1.0 – 4.0	< 1.0	1.0 – 3.5

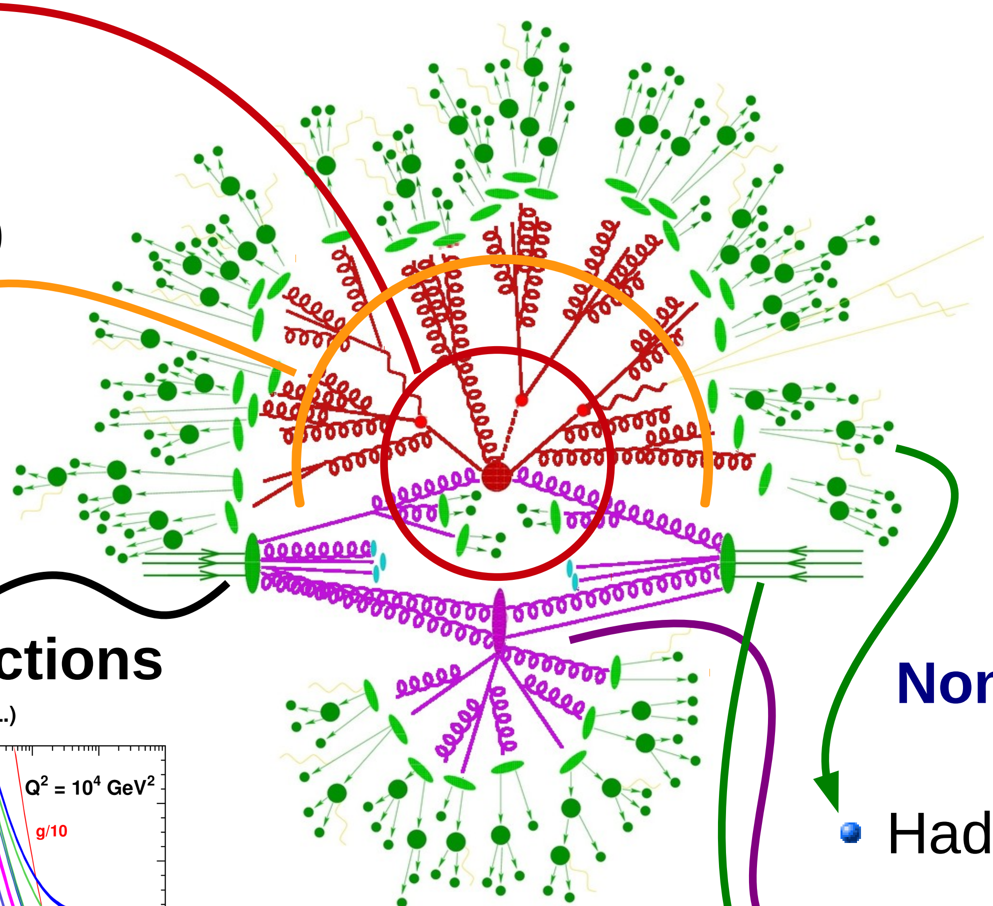
The Monte Carlo event generator model

Perturbative QCD

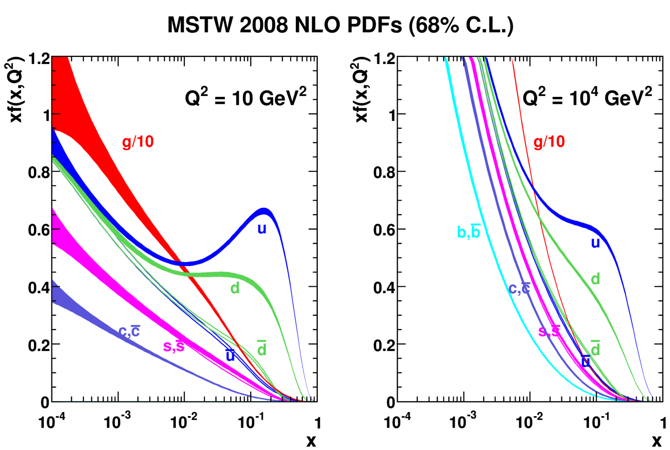
- **Hard scattering**
  - Fixed Order (Powheg, aMC@NLO, etc...)
- Fragmentation
  - Parton Shower
    - Initial state
    - Final state

Factorization

$$\sigma_{p\bar{p}\to X} = \Sigma_{i,j} \int dx_1 dx_2 f_i^p(x_1,\mu) f_j^{\bar{p}}(x_2,\mu) \times \sigma_{i,j}$$



Parton Distribution Functions (PDF)

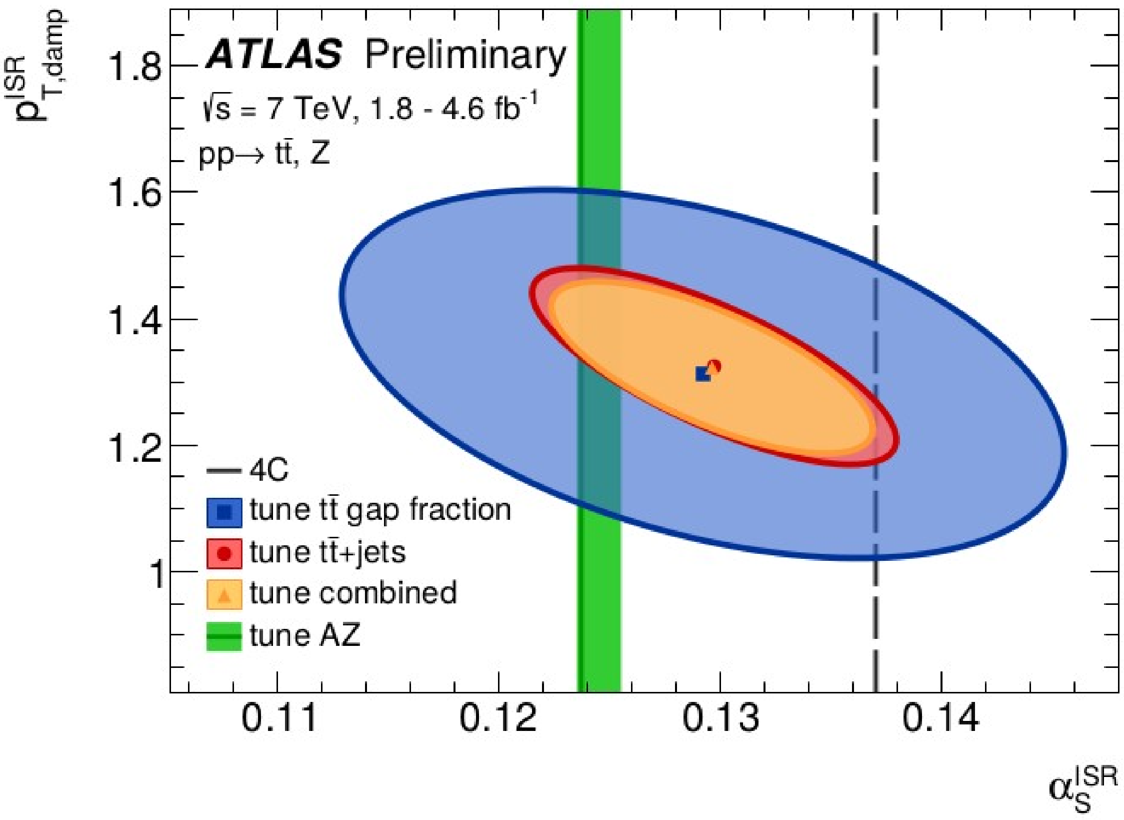


Non perturbative QCD

- Hadronization
- Underlying Event
- Primordial k_T

ATTBAR tunes

- The modelling of ISR and FSR radiation in ttbar production is one of the dominant uncertainties for many top measurements
- Important to verify the universality of the ISR and FSR parton shower between Z and ttbar production, to benefit from global tunes for reducing PS uncertainties



- For the first time in parton shower MC tuning, the uncertainty correlations are accounted in the χ^2 definition

  → Improved sensitivity to the PS parameters