TECHNISCHE UNIVERSITÄT DRESDEN
Fakultät Mathematik und Naturwissenschaften Institut für Kern- und Teilchenphysik

Overview of Monte Carlo tuning to LHC data

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(on behalf of the ATLAS and CMS collaborations)

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Deutsche Forschungsgemeinschaft
DFG

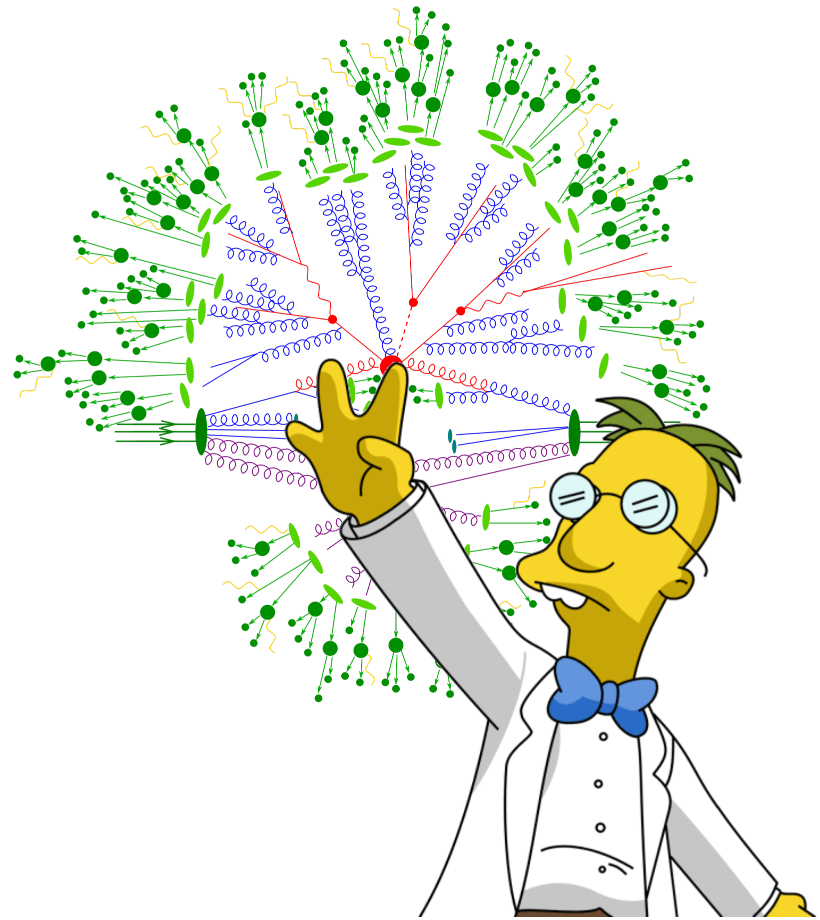
Monte Carlo tuning according to Google Images

Top 1 … 500

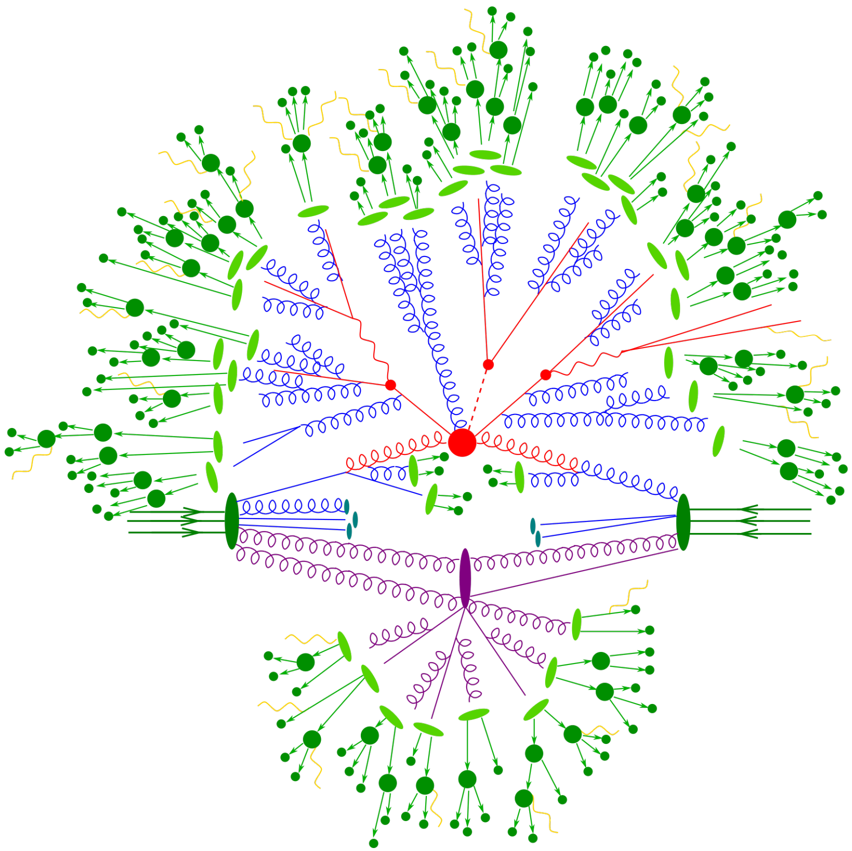
Monte Carlo tuning according to Google Images

Top 1 … 500

… and far at the end:

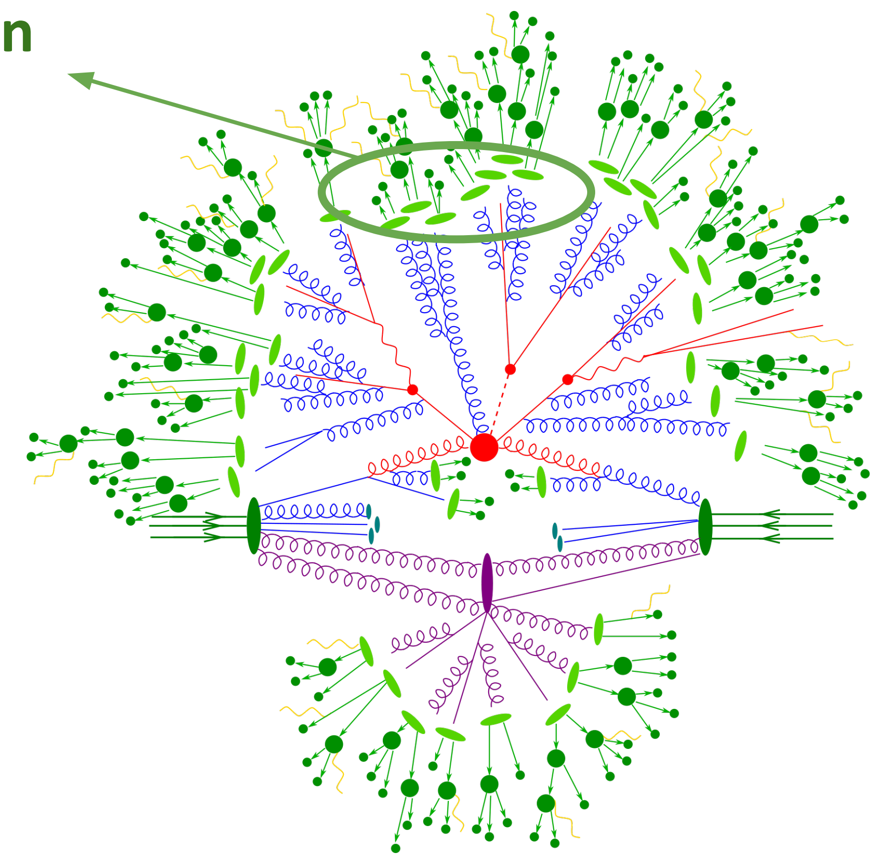


Tuning aspects of event generators



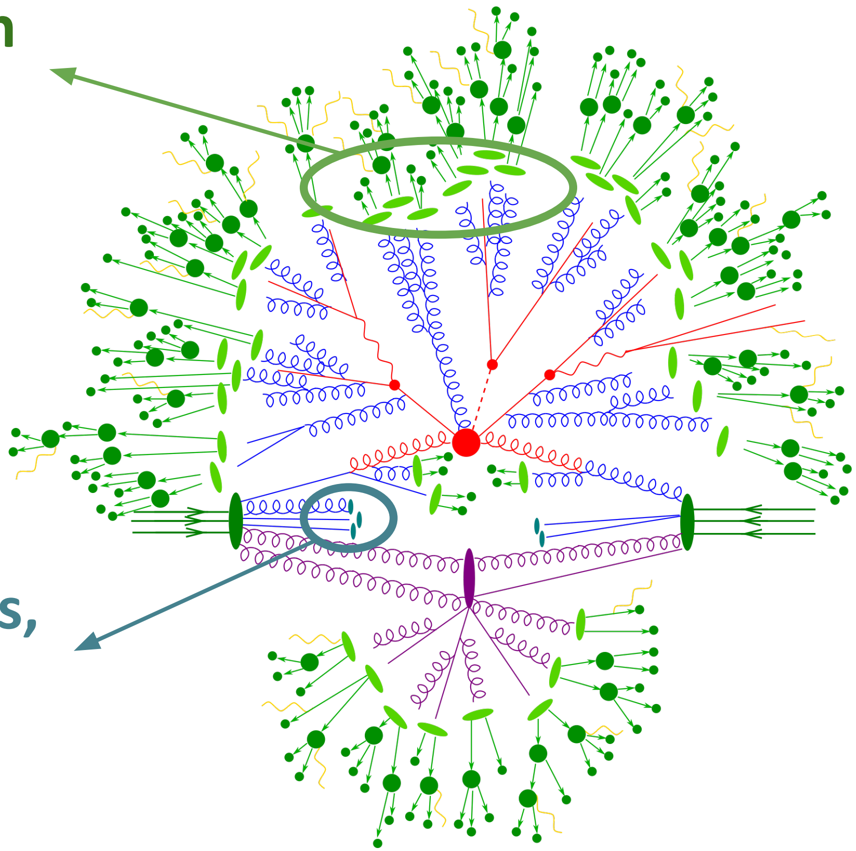
Tuning aspects of event generators

Hadronisation modelling



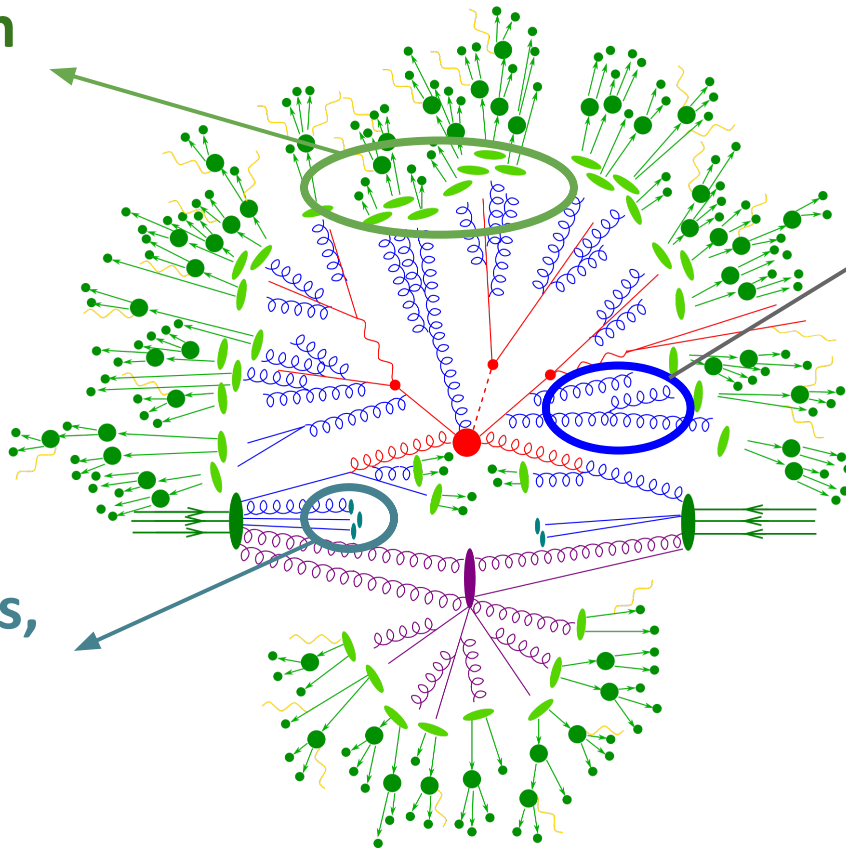
Tuning aspects of event generators

Hadronisation modelling

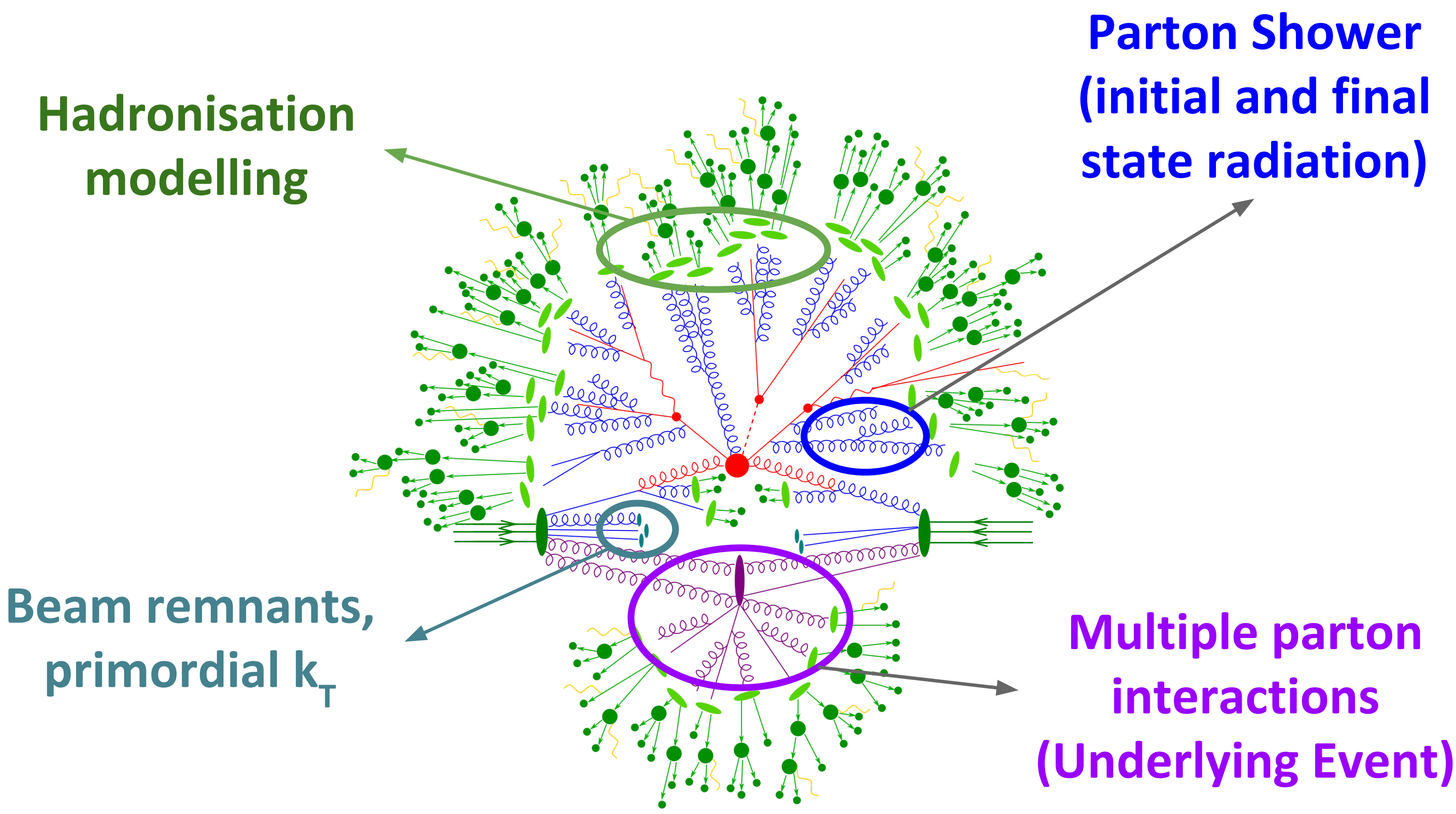


Beam remnants, primordial k_T

Tuning aspects of event generators



Tuning aspects of event generators



The need for tuned generators

- Pile-up simulation
  - **multiple simultaneous proton-proton collisions** modelled with event generators for **very inclusive inelastic collisions**
  - tuning to data obtained with very inclusive triggers (**minimum bias**)
- Calibration
  - e.g. **jet/tau** identification and reconstruction (substructure)
- Unfolding
  - correction for detector effects using generator truth vs. full detector simulation
  - **dependence on truth model** typically small, but still adds to systematic uncertainties $\longrightarrow$ need reliable tunes
- Background estimates in analyses
  - analyses use **background subtraction from MC generators** directly or via extrapolation from control regions
  - reliable tuning of non-perturbative aspects necessary for precision measurements and discoveries!

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Tuning basics and tools

Basic tuning workflow

1. choose **generator parameter** ranges
2. choose relevant **experimental data**
3. sample parameter space
4. **generate and analyse** events
5. **interpolate** generator response
6. data/MC difference **minimisation over full parameter space**

Example toolchain

- **Human thinking**
- **Rivet toolkit**
  - particle-level analysis framework

- **Professor toolkit**
  - random sampling of parameter space
  - interpolation of generator response
  - minimisation procedure

Bread and Butter: Minimum Bias Tuning

Minimum Bias Tuning

- Mainly relevant for **pile-up simulation**
- Very inclusive event generator setup for **inelastic collisions**, dominated by:
  - soft jet production, including multiple parton interactions (MPI)
  - single diffraction
  - double diffraction
- Data from events passing **minimum bias trigger**
- Main generators: **Pythia 8, Herwig++, Epos**
- **Closely related** to tuning of “Underlying Event”
  - MPI parameters tuned in both cases
  - ATLAS: separate dedicated tunes for Min Bias and Underlying Event
  - CMS: common tuning from UE data used also for Min Bias events in pile-up simulation

ATLAS Minimum Bias tune

ATL-PHYS-PUB-2012-003

- **"A2"** = dedicated Pythia 8 tuning used for pile-up
- Update of existing ATLAS MB tunes using new x-dependent proton size in Pythia 8.153

$$\rho(r,x) \sim \frac{1}{a^3(x)} \exp\left(-\frac{r^2}{a^2(x)}\right)$$
$$a(x) = a_0(1 + a_1 \ln(1/x))$$

- ATLAS data at **900 GeV** and **7 TeV** was used
  - modelling previously shown to be incapable of describing three different energy points in a simultaneous tune
    → Tevatron data ignored here
  - main weight on track quantities at 7 TeV for tracks with p_T>500 MeV
- Based on tune 4C (Sjöstrand, Corke) with variation of beam remnant parameters (`reconnectRange`) and MPI cut-off

$$p_{T,0}(\sqrt{s}) = p_{T,0}^{\mathrm{ref}} \times (\sqrt{s}/1800\ \mathrm{GeV})^{\mathrm{ecmPow}}$$

ATLAS Minimum Bias tune

ATL-PHYS-PUB-2012-003

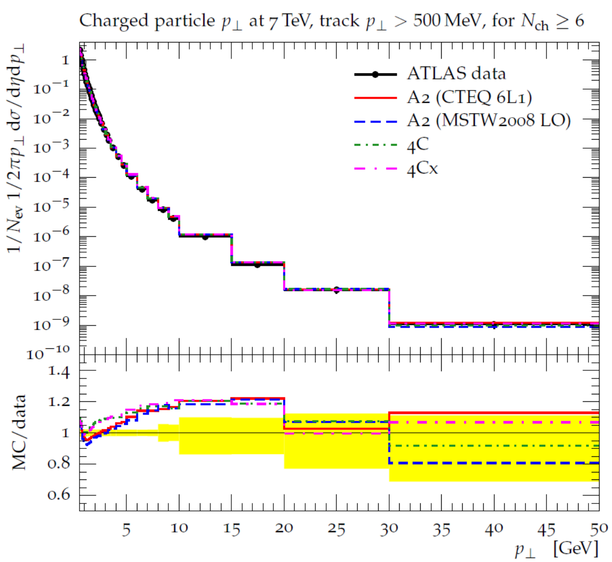
- 200 runs with 1M events each
- 2 different LO PDF sets considered: CTEQ6L1, MSTW2008LO
- Results:

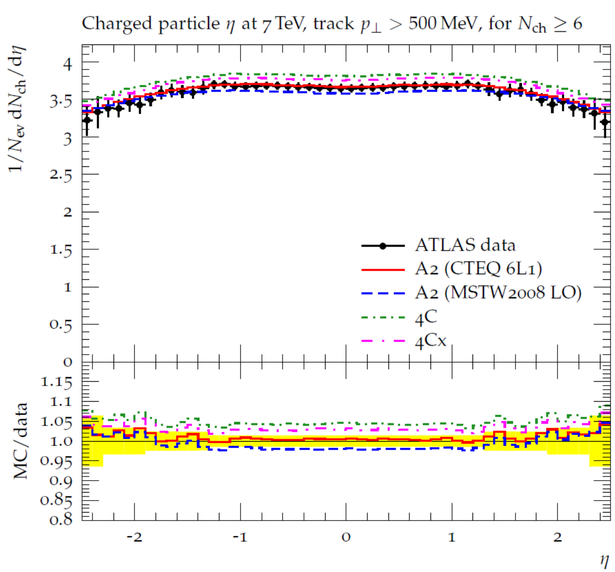
Parameter	Sampling range	Result (CTEQ6L1)	Result (MSTW2008LO)
MultipleInteractions:pT0Ref	1.5 - 2.8	2.18	1.90
MultipleInteractions:ecmPow	0.14 - 0.30	0.22	0.30
MultipleInteractions:a1	0.00 - 1.00	0.06	0.03
BeamRemnants:reconnectRange	0.00 - 9.00	1.55	2.28

- Very low values for a_1 = **small x-dependence** of matter profile

ATLAS Minimum Bias tune

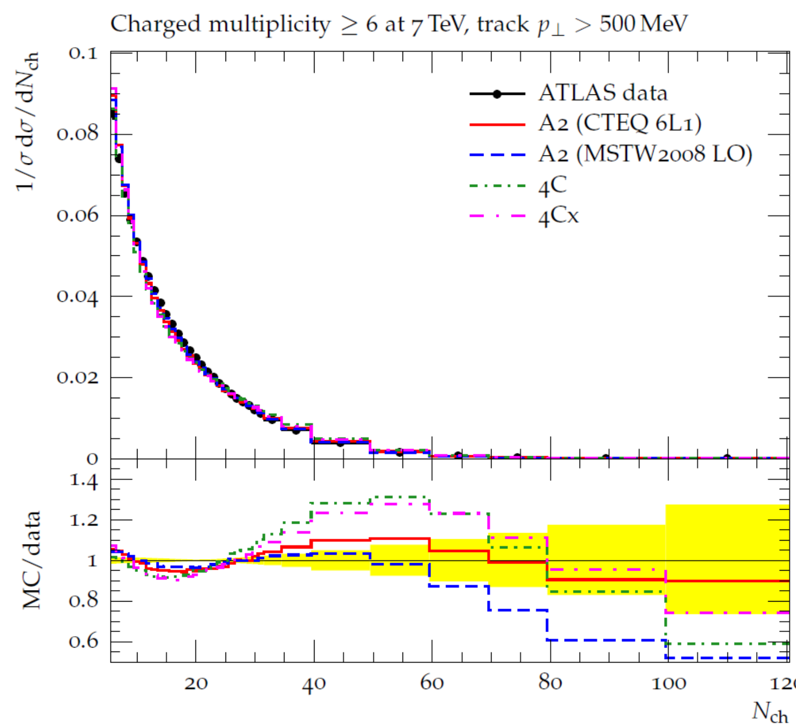
ATL-PHYS-PUB-2012-003





- Comparisons with author tunes 4C(x) shows **improvement** for min-bias measurement

  → improved pile-up simulation



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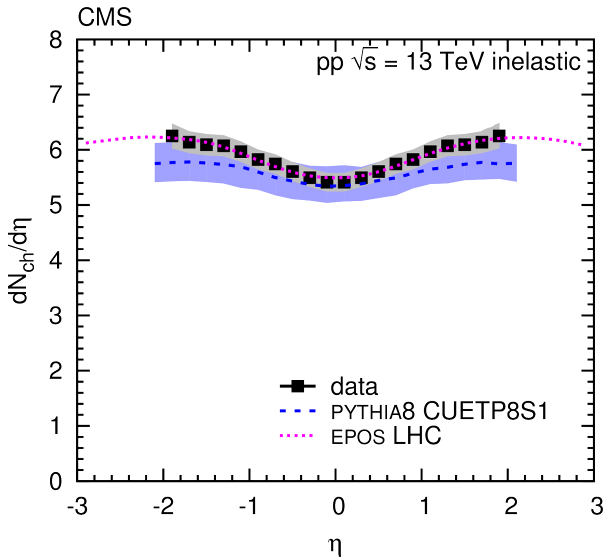
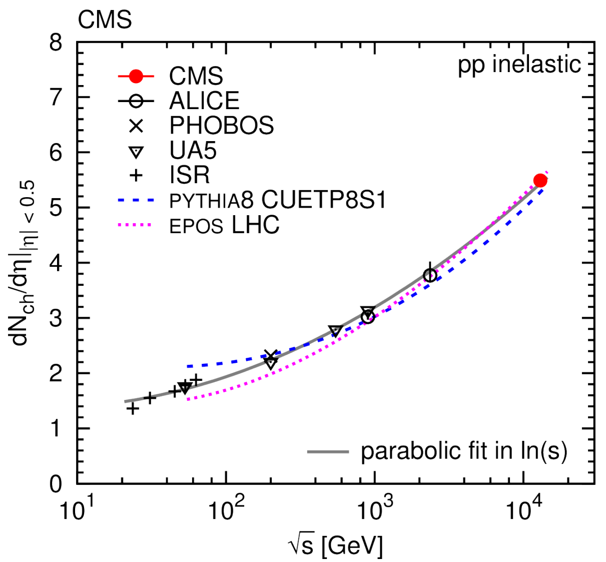
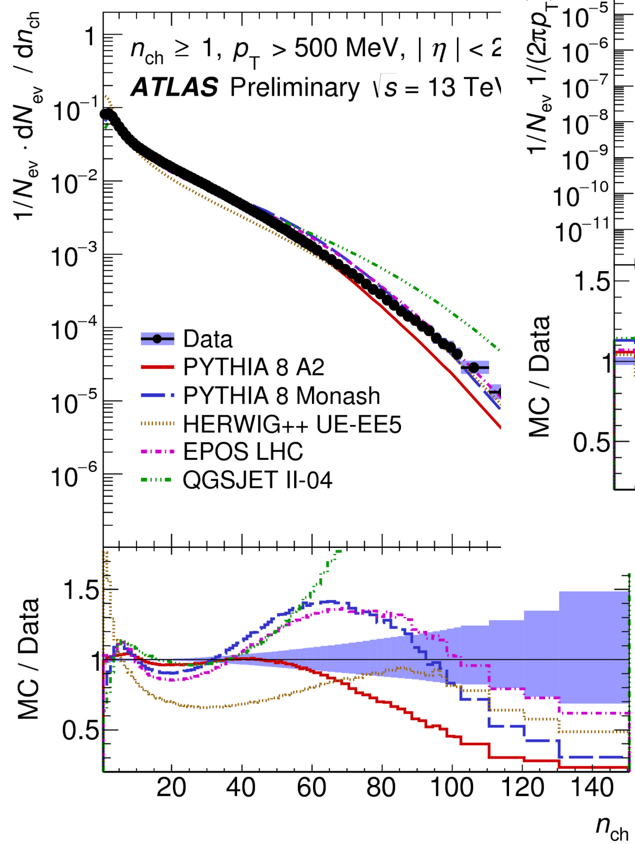
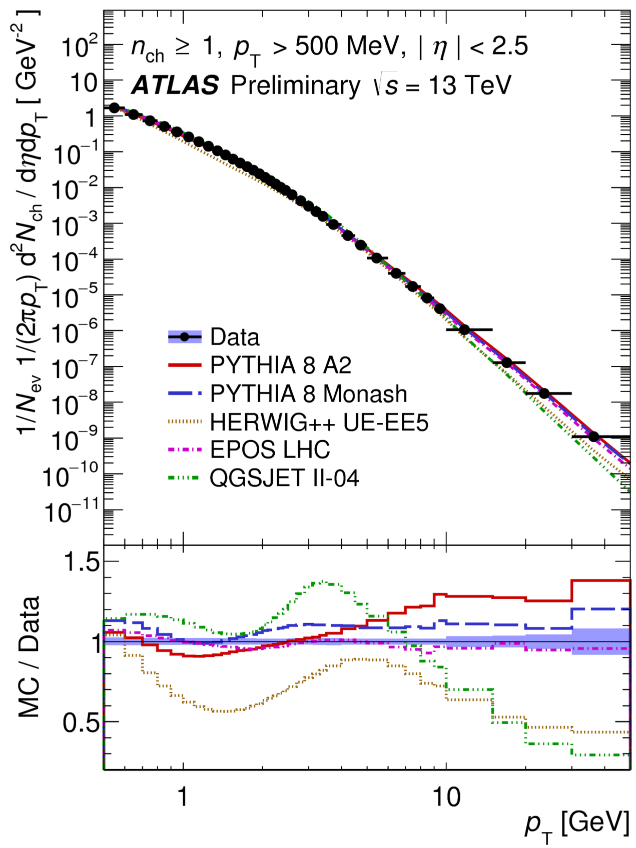
MB tune performance at 13 TeV

arXiv:1507.05915   ATLAS-CONF-2015-028





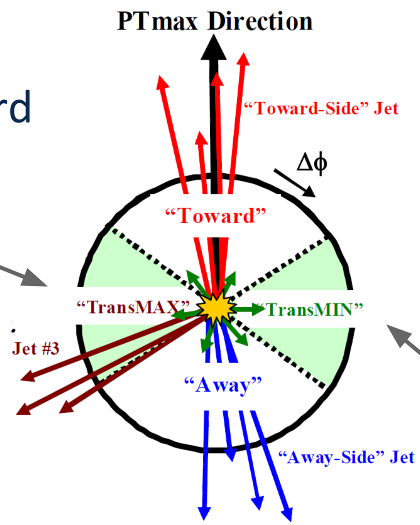




+ Lettuce & Tomato: Underlying Event Tuning

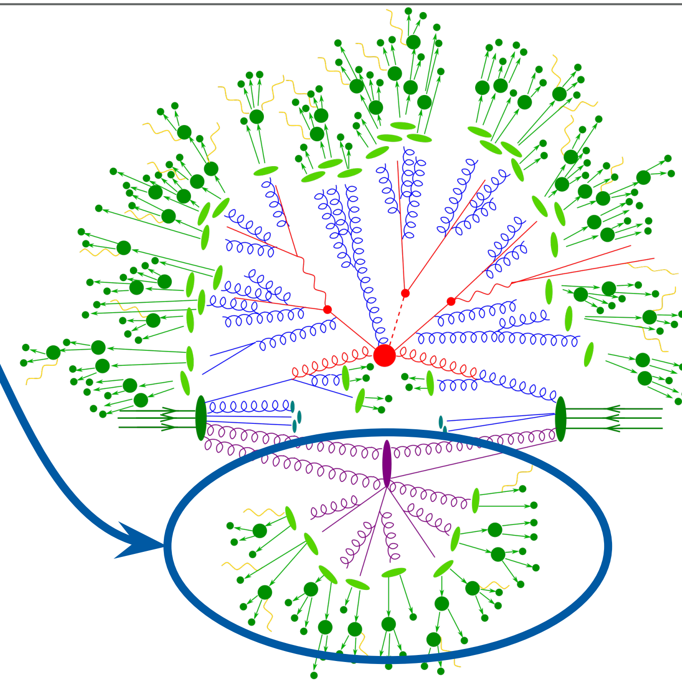
CMS Underlying Event tune

- Underlying Event at generator level: **Multiple Parton Interactions**
- Typical measurements of UE activity:



Sensitive to hard additional QCD radiation and MPI

Sensitive to MPI



- Both ATLAS and CMS measure the energy flow in these **transverse regions**

= Main input for UE tune

CMS Underlying Event tune

CMS PAS GEN-14-001

- Pythia 8 tune based again on tune 4C
- PDF sets considered: CTEQ6L1 and HERAPDF1.5LO
- typical **MPI parameter variation**, similar to ATLAS MB tune but with old matter profile (expPow parameter)

Parameter	Sampling range	Result (CTEQ6L1)	Result (HERAPDF1.5LO)
MultipleInteractions:pT0Ref	1.0 - 3.0	3.1006	2.0001
MultipleInteractions:ecmPow	0.0 - 0.4	0.2106	0.2499
MultipleInteractions:expPow	0.4 - 10.0	1.6089	1.6905
BeamRemnants:reconnectRange	0.00 - 9.00	3.3126	6.0964

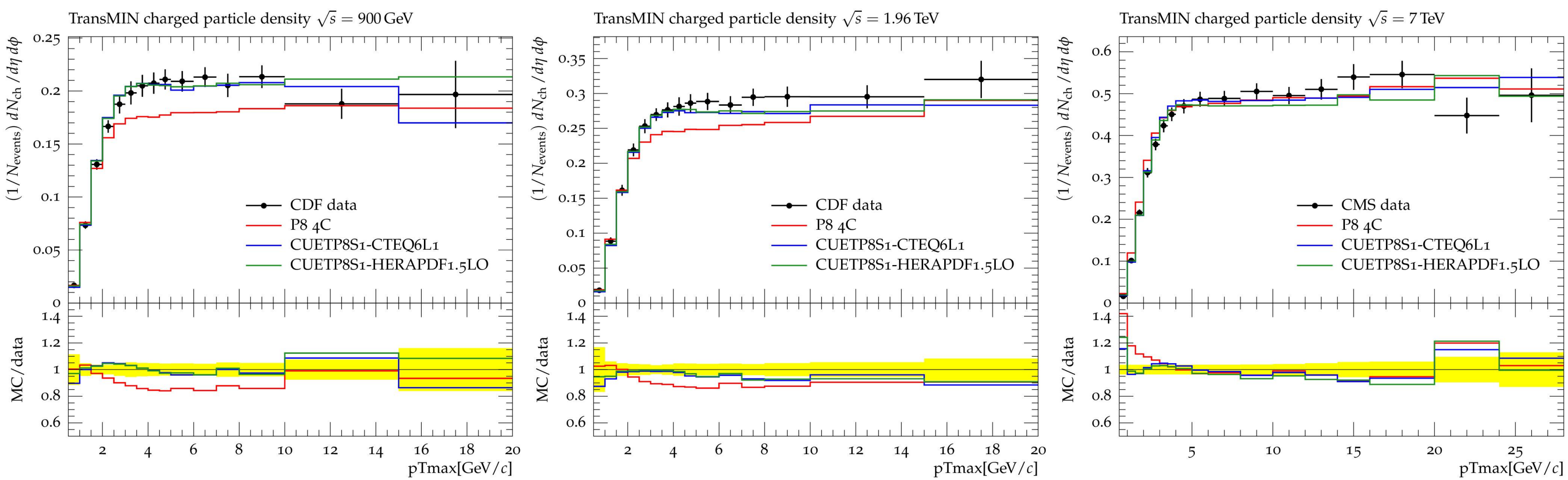
ATLAS: 1.55

- reconnectRange higher than in ATLAS MB tune
- updated tune based on Monash (CUETP8M1) available

CMS Underlying Event tune

CMS PAS GEN-14-001

- **Energy extrapolation** tuned using CDF and CMS data at 900, 1960 and 7000 GeV
  - 300 GeV from Tevatron energy scan left out due to bad fit result
- Color reconnection different for both PDFs, both allowing connection up to harder event scales than in ATLAS tune (sensitive to parton dynamics at small x)



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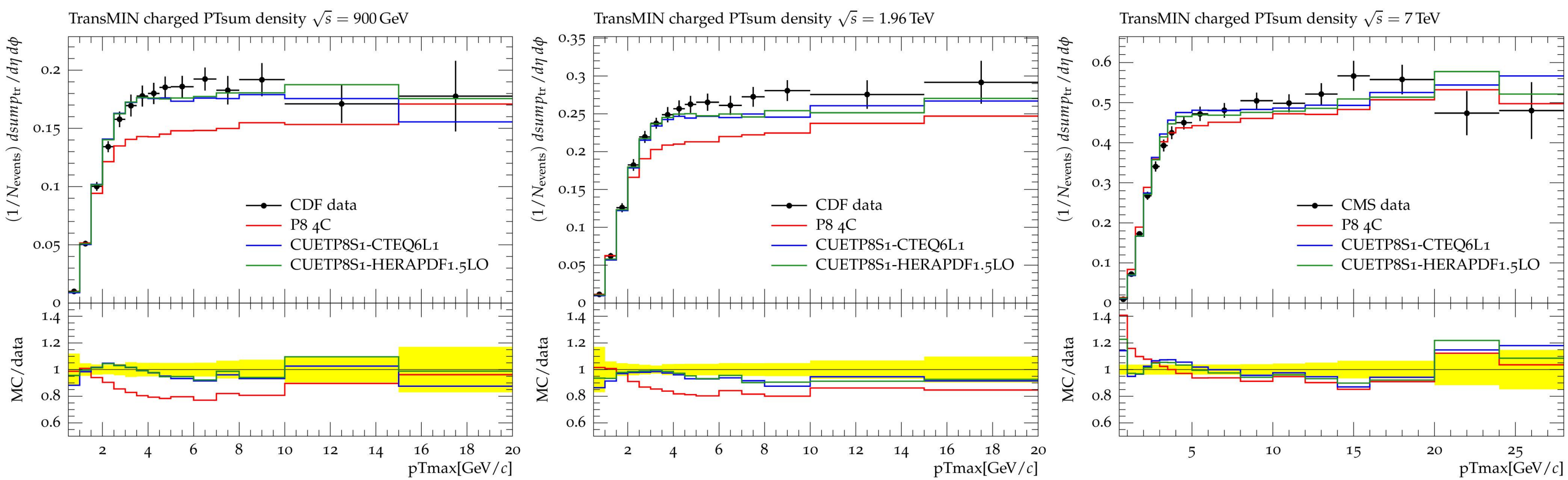

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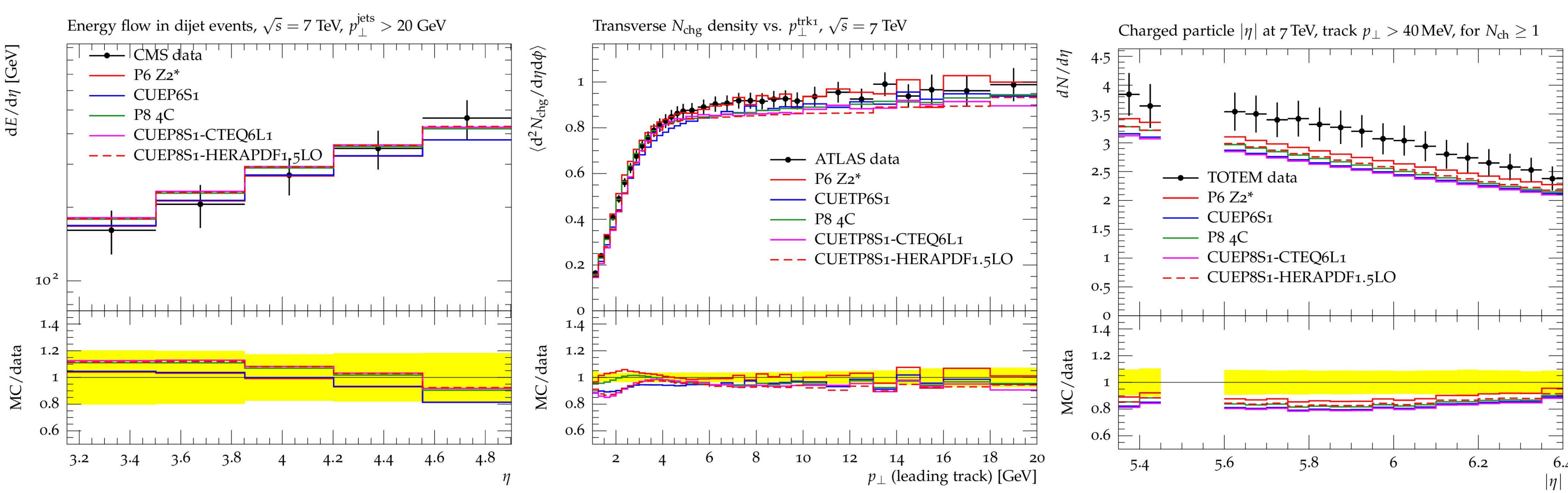
CMS Underlying Event tune

CMS PAS GEN-14-001

- **Validation** with other measurements:
  dijet events, ATLAS UE data, and minimum bias



- **Good agreement** for most compared measurements
- Slightly low min-bias activity in the forward region

Double Parton Scattering

- Interesting offshoot from multiple parton interaction picture: **Double Parton Scattering** with two hard scatterings A, B
- Description with **effective cross section**

$$\sigma_{AB} = \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}}$$

  - expect independence from A and B, and so far also $\sqrt{s}$
  - each tune corresponds to unambigious value of σ_{eff}

- Alternative: Measure σ_{eff} in double-scattering processes **directly**, e.g. in 4-jet or W + dijet production

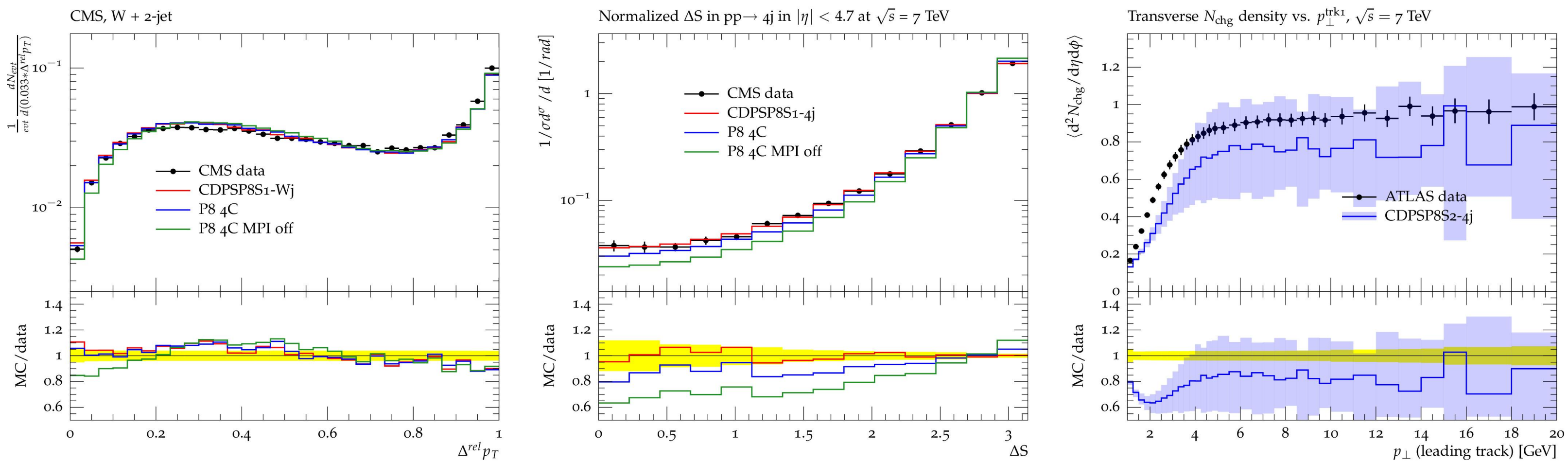
Source	Pythia8 Tune 4C	CUETP8S1-CTEQ6L1	CUETP8S1-MSTW2008LO	ATLAS W+dijet arXiv:1301.6872	CMS W+dijet arXiv:1312.5729
σ_{eff} [mb]	30.3	$27.8^{+1.2}_{-1.3}$	$29.1^{+2.3}_{-2.0}$	15 ± 3 (stat) $^{+5}_{-3}$ (syst)	20.7 ± 0.8 (stat) ± 6.6 (syst)

- Direct measurements typically **lower than tunes**!

Double Parton Scattering

CMS PAS GEN-14-001

- Idea: What about σ_{eff} in **MPI tunes to** the observables used in **DPS** measurements?
  - CMS prepared 2 tunes for W+dijet and 2 tunes for 4-jet DPS



Source	CDPSTP8S1-Wj	CDPSTP8S2-Wj	CDPSTP8S1-4j	CDPSTP8S2-4j
σ_{eff} [mb]	$25.9^{+2.4}_{-2.9}$	$25.8^{+8.2}_{-4.2}$	$21.3^{+1.2}_{-1.6}$	$19.0^{+4.7}_{-3.0}$

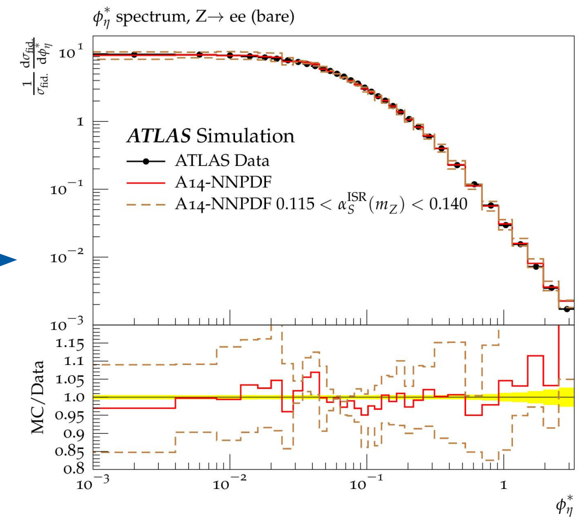
- Better agreement with measurements but worse for UE data $\longrightarrow$ modelling not sufficient for **simultaneous description**

+ Cheese:
Parton Shower Tuning

ATLAS Pythia 8 shower tuning

ATL-PHYS-PUB-2014-021

- **Parton shower modelling**
  - contains parameters and ambiguities
  - Example: α_s values for initial/final state radiation vs. Φ^*



- So far only considered tuning of **multiple parton interactions**
  - many observables sensitive to both
  - even more so for Pythia 8 with interleaved shower+MPI
  - **simultaneous** tuning necessary
- Tuning with **comprehensive ATLAS dataset**:
  - UE with jets and track-jets
  - jet structure (track jet properties; jet shapes, masses, substructure)
  - jet production (jet multiplicities, $\Delta\Phi$, Z pT, gap fractions in ttbar)

→ Sensitivity to MPI, final and initial state radiation

ATLAS Pythia 8 shower tuning

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- Tuning based on Pythia 8.186 Monash tune + simultaneous variation of **10(!) parameters**:

Parameter	Definition	Sampling range
`SigmaProcess:alphaSvalue`	The α_S value at scale $Q^2 = M_Z^2$	0.12 – 0.15
`SpaceShower:pT0Ref`	ISR p_T cutoff	0.75 – 2.5
`SpaceShower:pTmaxFudge`	Mult. factor on max ISR evolution scale	0.5 – 1.5
`SpaceShower:pTdampFudge`	Factorisation/renorm scale damping	1.0 – 1.5
`SpaceShower:alphaSvalue`	ISR α_S	0.10 – 0.15
`TimeShower:alphaSvalue`	FSR α_S	0.10 – 0.15
`BeamRemnants:primordialKThard`	Hard interaction primordial $k_\perp$	1.5 – 2.0
`MultipartonInteractions:pT0Ref`	MPI p_T cutoff	1.5 – 3.0
`MultipartonInteractions:alphaSvalue`	MPI α_S	0.10 – 0.15
`BeamRemnants:reconnectRange`	CR strength	1.0 – 10.0

damped shower for ttbar

- Parameter space sampled with 500 runs of 1M events
- 4 different leading-order PDF sets considered:
  - CTEQ6L1, MSTW2008LO, NNPDF23LO, HERAPDF15LO

ATLAS Pythia 8 shower tuning

ATL-PHYS-PUB-2014-021

- Tuning based on Pythia 8.186 Monash tune + simultaneous variation of **10(!) parameters**:

Parameter	Definition	Sampling range	CTEQ	MSTW	NNPDF	HERA
SigmaProcess:alphaSvalue	The α_S value at scale $Q^2 = M_Z^2$	0.12 – 0.15	0.144	0.140	0.140	0.141
SpaceShower:pT0Ref	ISR p_T cutoff	0.75 – 2.5	1.30	1.62	1.56	1.61
SpaceShower:pTmaxFudge	Mult. factor on max ISR evolution scale	0.5 – 1.5	0.95	0.92	0.91	0.95
SpaceShower:pTdampFudge	Factorisation/renorm scale damping	1.0 – 1.5	1.21	1.14	1.05	1.10
SpaceShower:alphaSvalue	ISR α_S	0.10 – 0.15	0.125	0.129	0.127	0.128
TimeShower:alphaSvalue	FSR α_S	0.10 – 0.15	0.126	0.129	0.127	0.130
BeamRemnants:primordialKThard	Hard interaction primordial $k_\perp$	1.5 – 2.0	1.72	1.82	1.88	1.83
MultipartonInteractions:pT0Ref	MPI p_T cutoff	1.5 – 3.0	1.98	2.22	2.09	2.14
MultipartonInteractions:alphaSvalue	MPI α_S	0.10 – 0.15	0.118	0.127	0.126	0.123
BeamRemnants:reconnectRange	CR strength	1.0 – 10.0	2.08	1.87	1.71	1.78

damped shower for ttbar

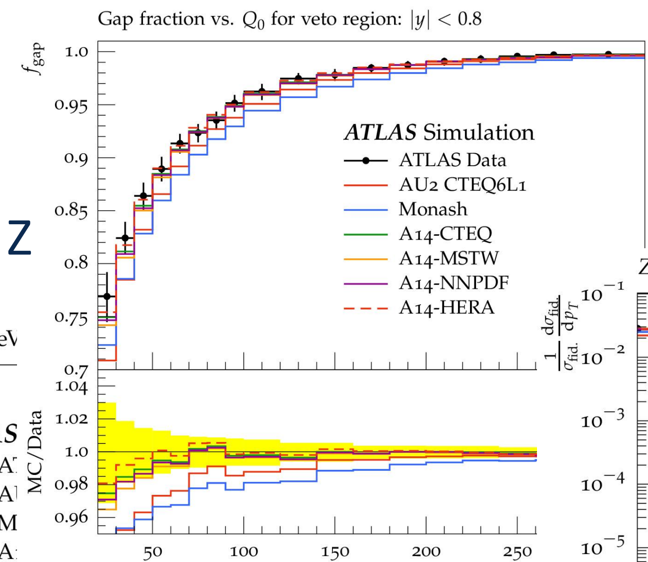
- Parameter space sampled with 500 runs of 1M events
- 4 different leading-order PDF sets considered:
  - CTEQ6L1, MSTW2008LO, NNPDF23LO, HERAPDF15LO
- α_S tuning results **similar** for all PDFs
  - quite high in hard process (0.140-0.144)
  - lower in shower (0.125-0.130)

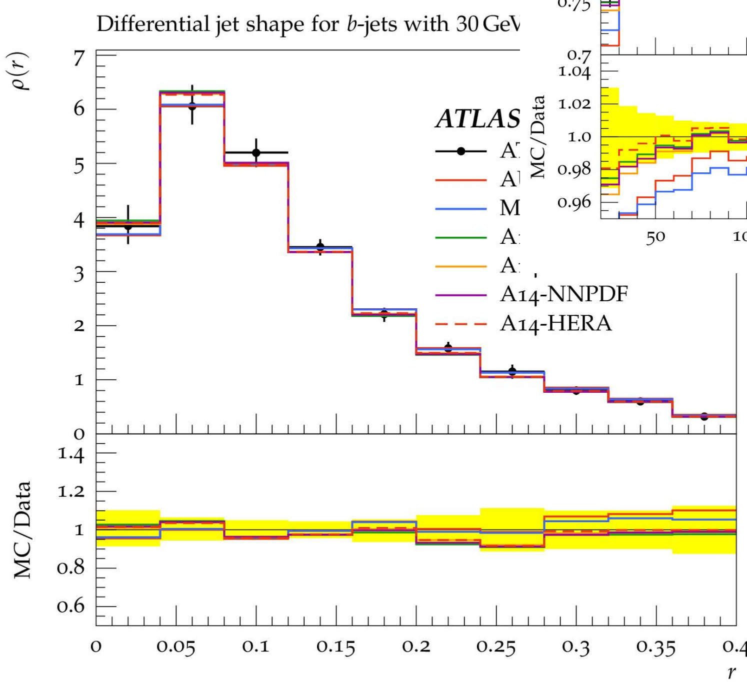
ATLAS Pythia 8 shower tuning

ATL-PHYS-PUB-2014-021

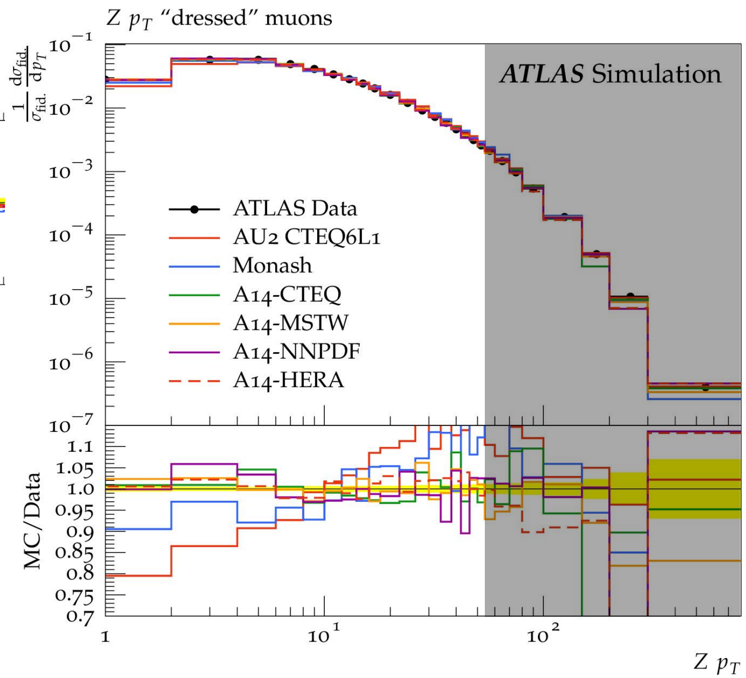
- Significant improvement over AU2 & Monash in **ttbar and Z**

- **Damped** shower reduces tension between ttbar and Z





- Restricted to $p_T(Z)<50$ GeV in tuning



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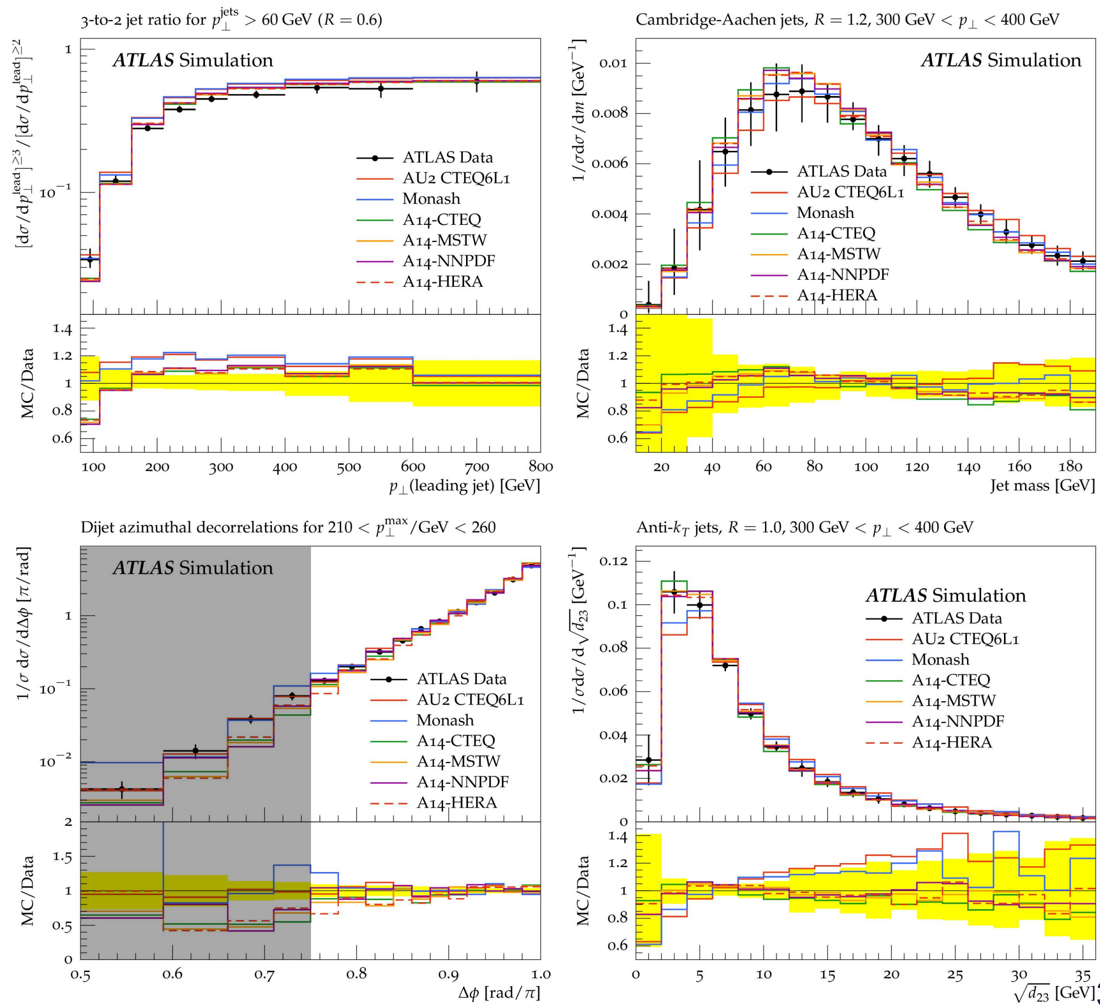
ATLAS Pythia 8 shower tuning

ATL-PHYS-PUB-2014-021

- **jet production/substructure** equally good or slightly improved

- 3/2-jet ratio: tension between description of soft/hard region, → focusing on hard region due to targeted use-case of **BSM simulations**

- Tuning restricted to back-to-back region *ΔΦ*>0.75 to avoid need for multi-jet MEs



ATLAS Pythia 8 shower tuning

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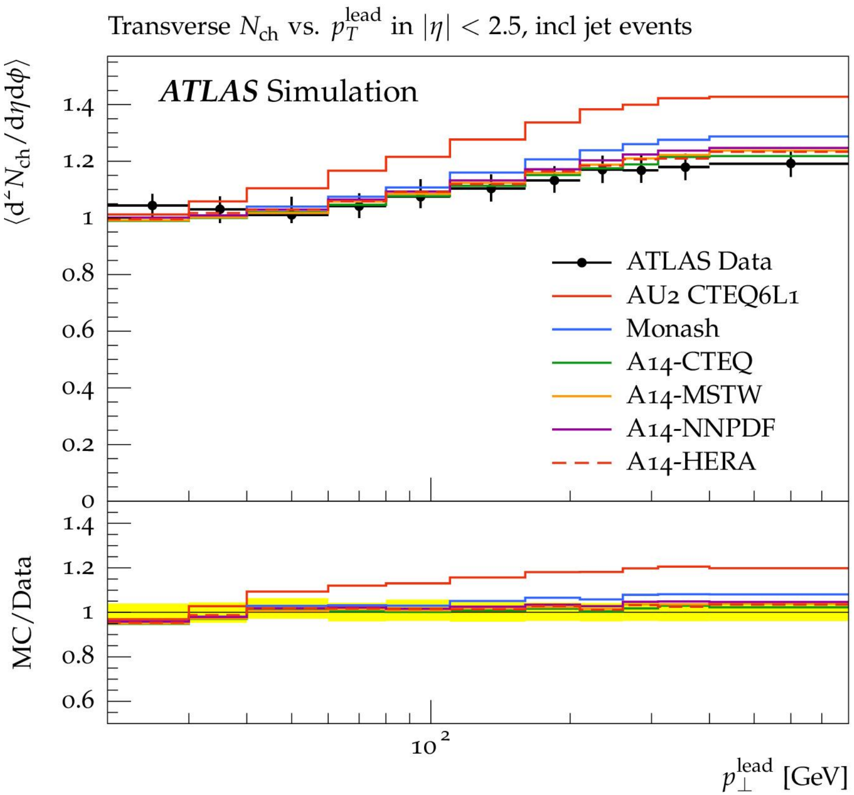
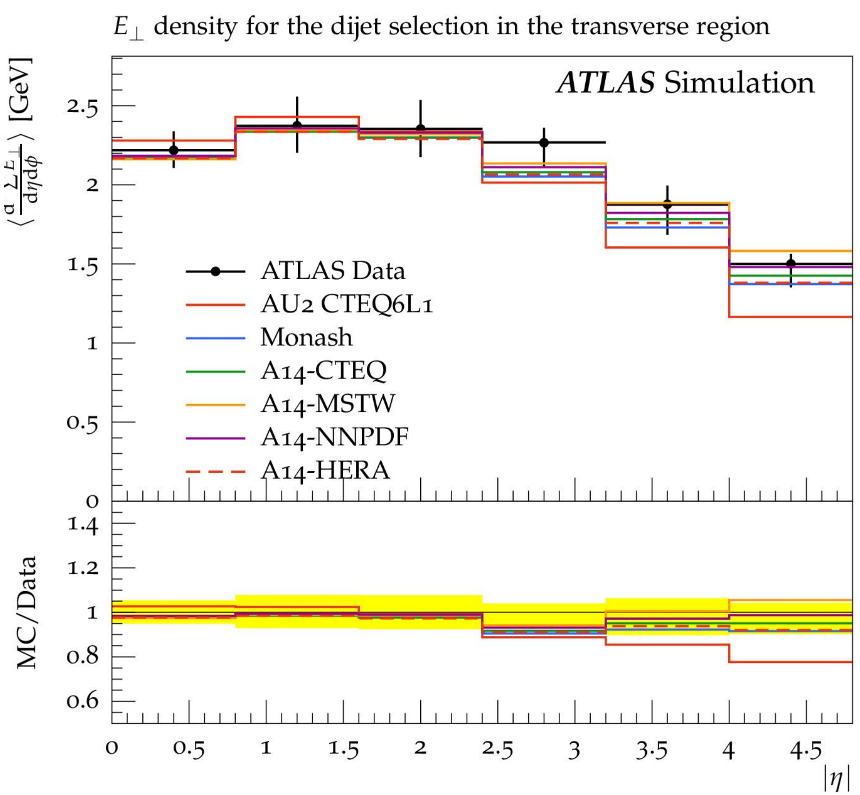
- **Underlying Event/transverse energy flow** improved over previous ATLAS UE tune (AU2), now similar to Monash

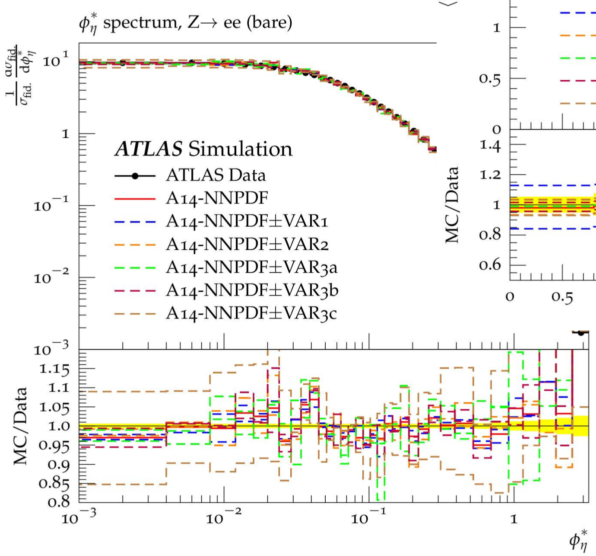


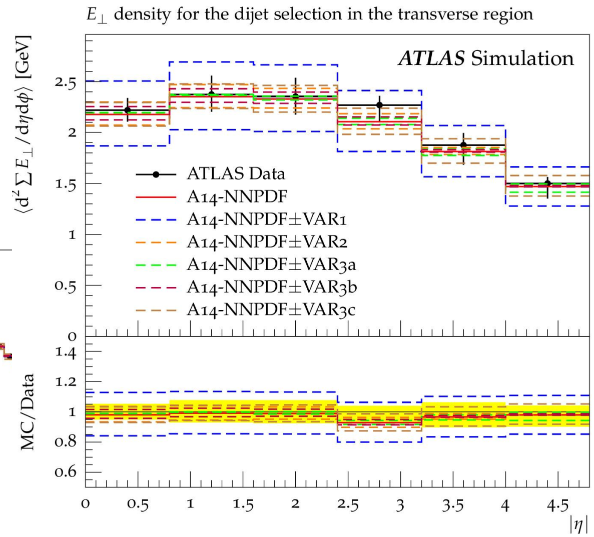


ATLAS Pythia 8 shower tuning

ATL-PHYS-PUB-2014-021

- Systematic variation tunes for A14-NNPDF done using Professor **eigentunes** approach
  - normally: 2 variations for each parameter (up/down), with fixed $\Delta\chi^2$
- 20 variations too unwieldy $\longrightarrow$ reduced to variation sets for **UE activity, jet structure, jet production** (3 options)



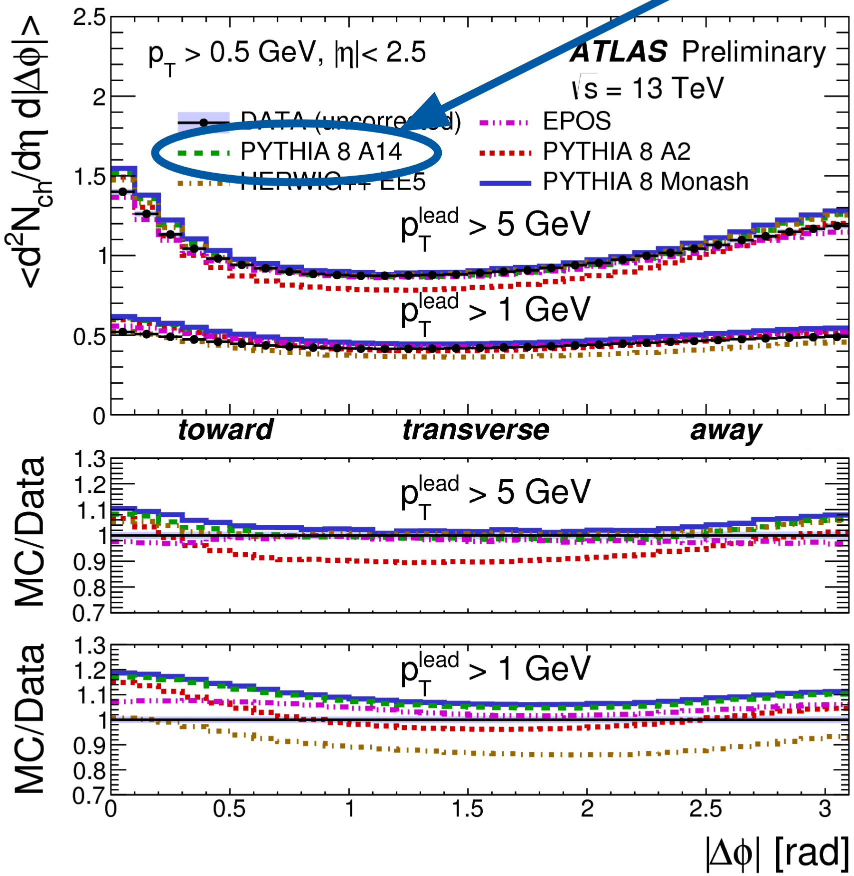


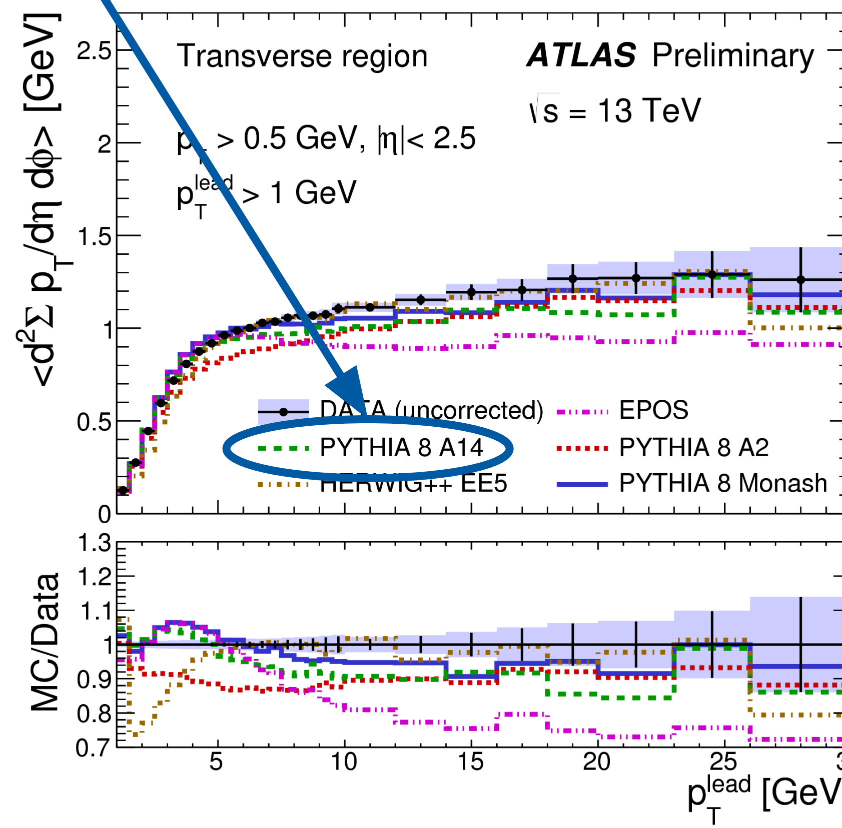
Param	+ variation	− variation
VAR1: MPI+CR (UE activity and incl jet shapes)		
`BeamRemnants:reconnectRange`	1.73	1.69
`MultipartonInteractions:alphaSvalue`	0.131	0.121
VAR2: ISR/FSR (jet shapes and substructure)		
`SpaceShower:pT0Ref`	1.60	1.50
`SpaceShower:pTdampFudge`	1.04	1.08
`TimeShower:alphaSvalue`	0.139	0.111
VAR3a: ISR/FSR ($t\bar{t}$ gap)		
`MultipartonInteractions:alphaSvalue`	0.125	0.127
`SpaceShower:pT0Ref`	1.67	1.51
`SpaceShower:pTdampFudge`	1.36	0.93
`SpaceShower:pTmaxFudge`	0.98	0.88
`TimeShower:alphaSvalue`	0.136	0.124
VAR3b: ISR/FSR (jet 3/2 ratio)		
`SpaceShower:alphaSvalue`	0.129	0.126
`SpaceShower:pTdampFudge`	1.04	1.07
`SpaceShower:pTmaxFudge`	1.00	0.83
`TimeShower:alphaSvalue`	0.114	0.138
VAR3c: ISR ($t\bar{t}$ gap, dijet decorrelation and Z-boson p_T)		
`SpaceShower:alphaSvalue`	0.140	0.115

ATLAS Pythia 8 shower tuning

ATLAS-PHYS-PUB-2015-019

- Example for application of A14 tune in ATLAS UE **at 13 TeV**





+ (Tofu) Bacon: Tuning in ME-improved shower simulations

Example: ttbar tuning

ATL-PHYS-PUB-2015-007

- LO + parton shower often not good enough, e.g. ttbar
- **LHC measurements** of ttbar production for the first time accurate enough for tuning
  - can compare to **global** tuning, or **dedicated Z**, or even **LEP** tuning $\longrightarrow$ testimony to model universality (or not)
- Here: ATLAS measurements of **jet multiplicities/pT**, central jet **gap-fractions** and **jet shapes** in ttbar events
- Tuning in two steps
  - tuning of **standalone** Pythia 8.201 (normalised to data)
    - » first ISR/FSR separately, but observables sensitive to interplay $\longrightarrow$ combined tuning
  - application of tune to matched Powheg/aMC@NLO+Pythia8 simulation and adjustment of **matching parameters**
    - » Powheg damping factor for real-radiation exponentiation
    - » aMC@NLO upper scale for real-radiation subtraction

Example: ttbar tuning

ATL-PHYS-PUB-2015-007

- Pythia **standalone** tune
  - "ATTBAR" tune, based on Monash tune, using NNPDF23LO
  - alternative based on 4C tune, using CTEQ6L1
- **Correlation** of experimental uncertainties
  - taken into account for the first time in MC tuning
  - meaningful definition of χ^2
  - reduced uncertainties for tuning parameters

Parameter	ATTBAR	Tune without uncertainties correlations
$\alpha_s^{ISR}(m_Z)$	0.121 ± 0.004	$0.118^{+0.007}_{-0.006}$
$p_{T,damp}^{ISR}$	$1.18^{+0.08}_{-0.07}$	$1.17^{+0.10}_{-0.09}$
$\alpha_s^{FSR}(m_Z)$	0.137 ± 0.003	$0.138^{+0.006}_{-0.005}$
$p_{T,min}^{FSR}$ [GeV]	1.26 ± 0.17	1.35 ± 0.35
χ^2_{min}/dof	92/85	13/85

- MadGraph5_aMC@NLO tuning ("ATTBAR-MG5aMCNLO")
  - additional one-parameter tune of **f ≡ frac_upp = frac_down**
  - compatible for both global (recommended) and local **recoil** options: $f_{global} = 0.57(3)$ vs. $f_{local} = 0.54(3)$
- Powheg ("ATTBAR-POWHEG")
  - additional one-parameter tune of **hdamp = h × m$_{top}$** factor
  - result: $h = 1.8^{+0.4}_{-0.3}$

Example: ttbar tuning

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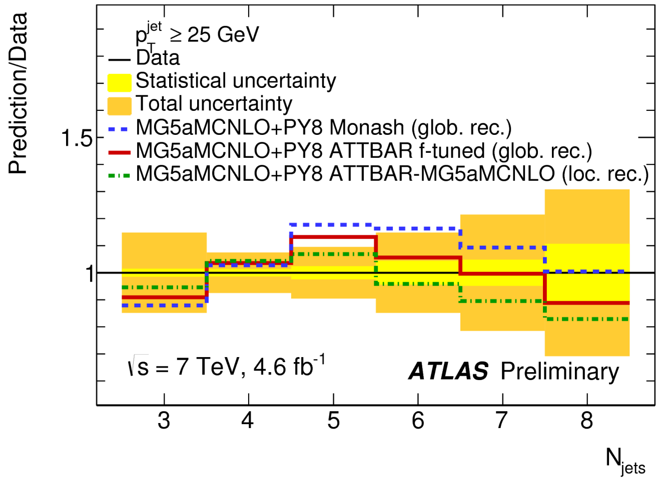
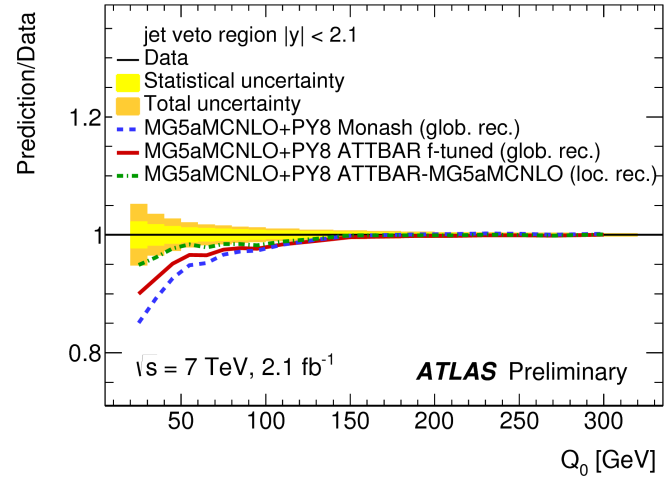
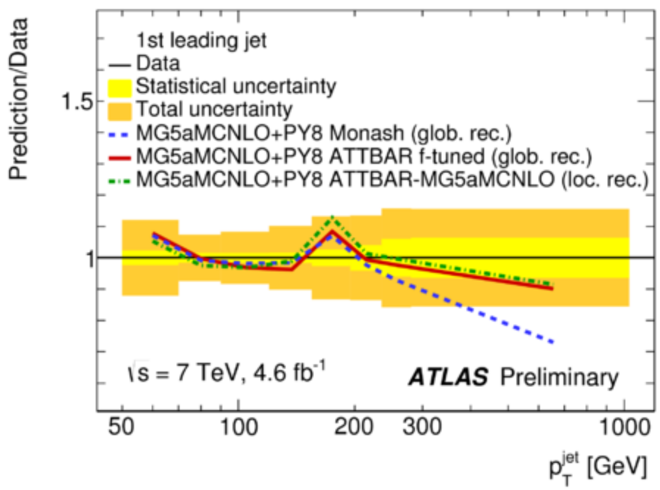
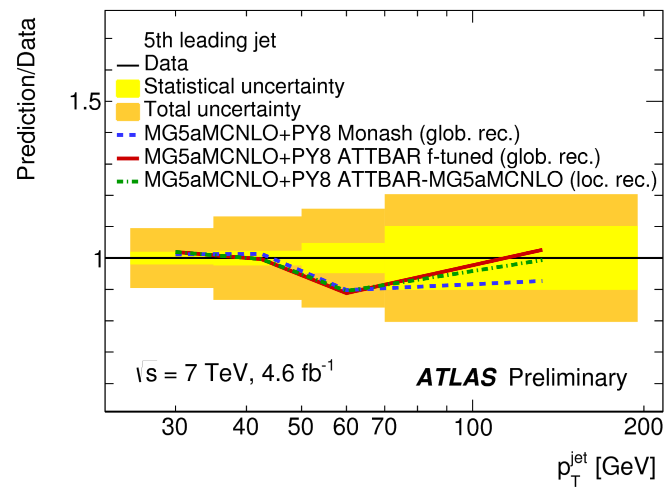
- ATTBAR-MG5aMCNLO with **different recoil** options









Example: ttbar tuning

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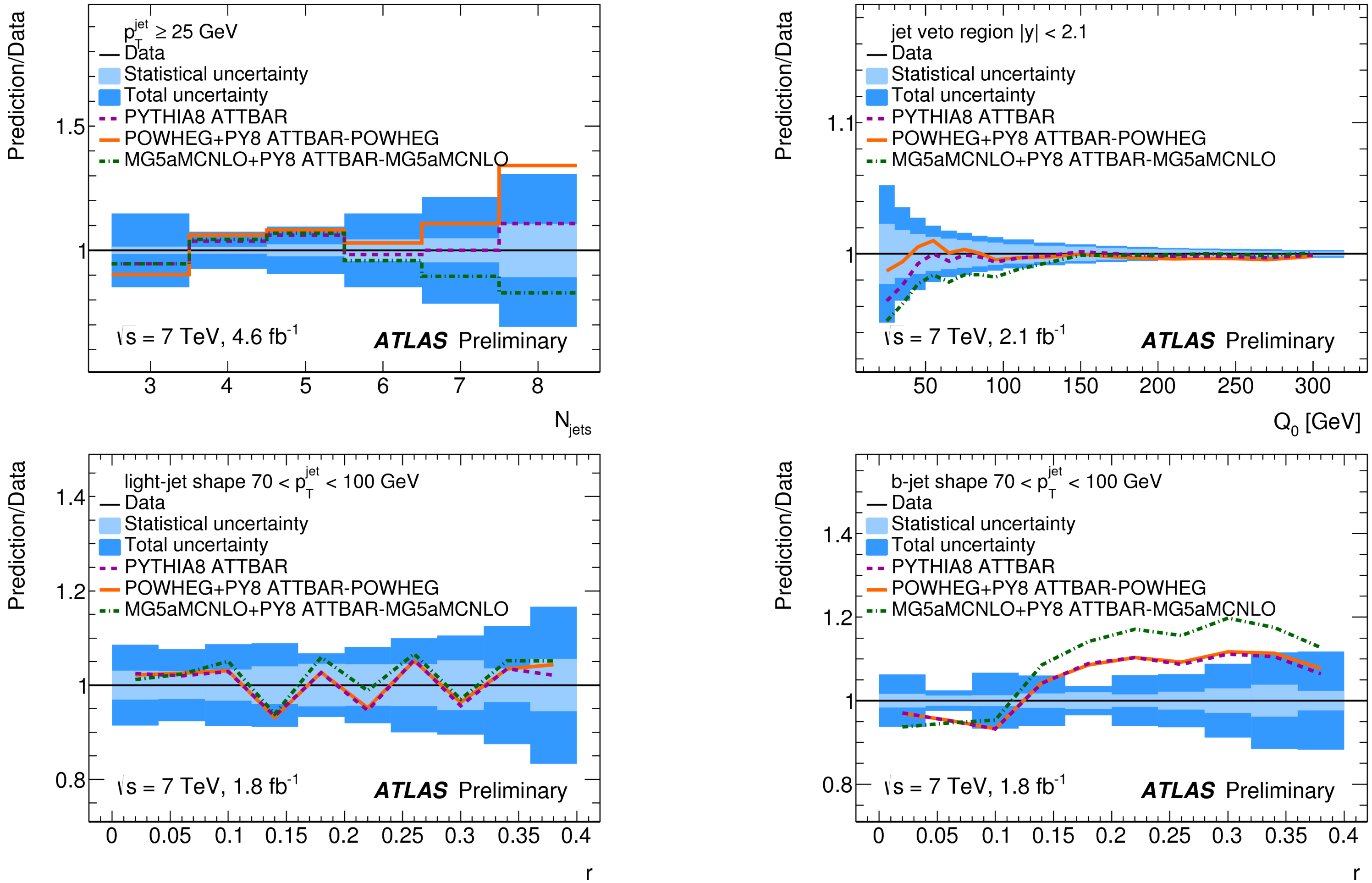
- Comparison of ATTBAR, ATTBAR-{POWHEG,MG5aMCNLO}



Conclusions

Conclusions

- MC tuning is not rigorous, but **necessary**
- Basic toolkit provided by **Professor** and **Rivet** programs
- Used within both **ATLAS** and **CMS** to provide tunes for minimum bias, underlying event, and parton showers
  - CMS UE tune compared to double parton scattering measurements
  - global tuning of ATLAS data for UE, dijet, Z and ttbar production
  - dedicated tunes for Z and ttbar production, also in NLO+PS config's
- Ongoing efforts for tune validation and improvements in particular in **complex untunable processes** (diboson, Higgs, …)
- Perfect tuning does not exist, but we are **prepared well for 13 TeV** simulations!

The End

Thanks for your attention!

Thanks to the ATLAS and CMS MC tuning groups for their work and input!

Backup

ATLAS ttbar tuning results

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- Pythia standalone tune

		Parameter	PYTHIA8 setting	Variation range	4C	Monash
0.127	0.121	$\alpha_s^{\mathrm{ISR}}(m_Z)$	SpaceShower:alphaSvalue	0.110 – 0.140	0.137	0.1365
		ISR damping	SpaceShower:pTdampMatch	1 (fixed)	0	0
1.36	1.18	$p_{\mathrm{T,damp}}^{\mathrm{ISR}}$	SpaceShower:pTdampFudge	0.8 – 1.8	-	-
0.139	0.137	$\alpha_s^{\mathrm{FSR}}(m_Z)$	TimeShower:alphaSvalue	0.110 – 0.150	0.1383	0.1365
0.85	1.26	$p_{\mathrm{T,min}}^{\mathrm{FSR}}$ [GeV]	TimeShower:pTmin	0.1 – 2.0	0.4	0.5

» based on Monash tune, using NNPDF23LO (≡ “ATTBAR”)

» based on 4C tune, using CTEQ6L1

- Correlation of experimental uncertainties taken into account
  - » meaningful definition of χ^2
  - » reduced uncertainties on tuning parameters

Parameter	ATTBAR	Tune without uncertainties correlations
$\alpha_s^{\mathrm{ISR}}(m_Z)$	0.121 ± 0.004	$0.118^{+0.007}_{-0.006}$
$p_{\mathrm{T,damp}}^{\mathrm{ISR}}$	$1.18^{+0.08}_{-0.07}$	$1.17^{+0.10}_{-0.09}$
$\alpha_s^{\mathrm{FSR}}(m_Z)$	0.137 ± 0.003	$0.138^{+0.006}_{-0.005}$
$p_{\mathrm{T,min}}^{\mathrm{FSR}}$ [GeV]	1.26 ± 0.17	1.35 ± 0.35
$\chi^2_{\mathrm{min}}/\mathrm{dof}$	92/85	13/85