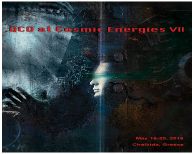


Review of final-state structure of pp interactions at the LHC

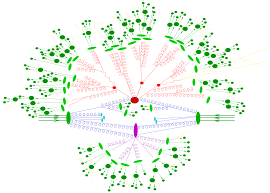
Paolo Gunnellini

DESY (Deutsches Elektronen Synchrotron), Hamburg

QCD at cosmic energies
Kalchida (Greece)
May 2016

Outline

1. **Final states at the LHC**
2. **Generalities on Monte Carlo event generators**
3. **Generator tuning and machinery**
   - **Available tunes**
   - **Our understanding of QCD exp. data**
   - **Current issues and incompatibilities**
4. **Comparison between predictions and measurements**
   - **Diffractive selections**
   - **Hard QCD events and multijet scenarios**
   - **Vector-boson final states**
   - **Top-antitop final states**
5. **Universality of tunes?**
6. **Summary and conclusions**



DISCLAIMER: Mainly results from ATLAS and CMS!

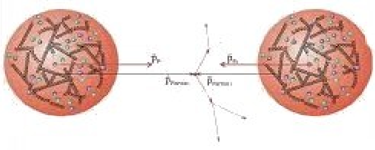
Hard scattering at the LHC

To simulate proton-proton collisions, physicists generally use

Monte Carlo event generators

Ingredients of the hard scattering

→ Factorization theorem
→ Parton distribution functions
→ Matrix element calculation
..starting from lowest order in α_S but might include additional real and virtual corrections



$$\sigma_{ab\to F}(Q^2) = \int dx_1 dx_1' \; f_a^1(x_1, Q^2) \; f_b^2(x_1', Q^2) \; \hat{\sigma}_{ab}(x_1, x_1', Q^2)$$

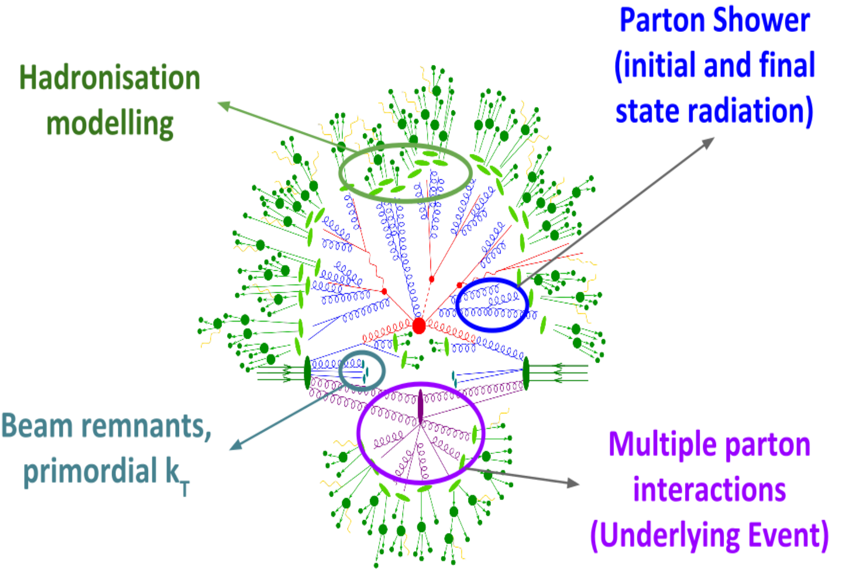
Total Cross Section

Parton Distribution Functions

Partonic Cross Section

with x = longitudinal proton momentum fraction carried by the parton
Q^2 = scale of the scattering

The underlying event at the LHC



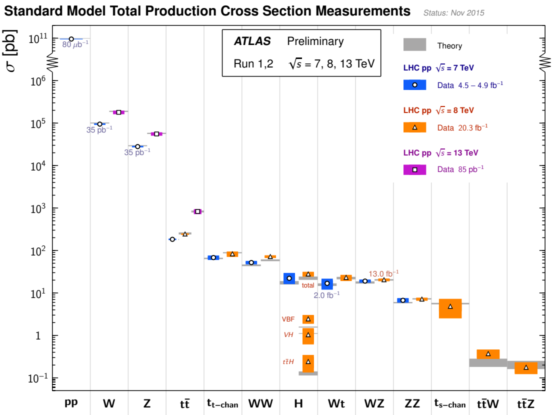
From Frank Siegert

Final states at the LHC

What can be produced in proton-proton collisions?

From soft to hard..

- Soft particles
- Jets
- Heavy flav. jets
- Vector boson
- Top quark
- Vector boson pair
- Higgs
- ....



Huge collection of measurements about these final states..in this talk only some of them with focus on our understanding of the experimental results!

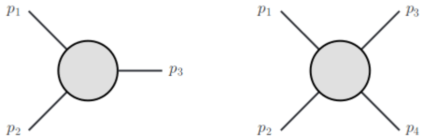
MC generator types

- Pure matrix element (ME) simulation
  - MC integration of cross section + PDF
  - No hadronization nor UE
  - Useful for theoretical studies, no exclusive events generated
- Event generators
  - Combination of ME and parton showers
  - Generator for fixed-order ME combined with leading log (LL) parton shower MC
  - Exclusive events, useful for experimentalists

MC generator types

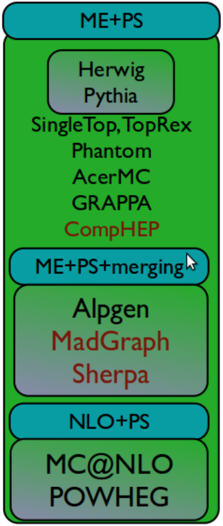
Type I : Leading order matrix element &
leading log parton shower

LO ME for hard processes
[2→1 or 2→2]



Parton Shower:
Re-summation of leading logarithms ...

[Examples: Pythia, Herwig]



[F. Maltoni]

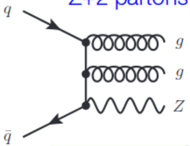
Type II : Leading order matrix element, parton shower & merging

i.e.: MEs for 2 ➛ n processes (e.g. W/Z + jets)
PS with LO generator [Pythia or Herwig]

Examples: ALPGEN, MadGraph, Sherpa

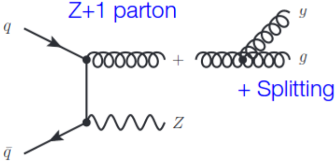
Challenge: Remove overlap between jets from ME and jets from parton shower [MLM matching, CKKW]

Z+2 partons



Overlap?

Z+1 parton



ME+PS
- Herwig
- Pythia
- SingleTop, TopRex
- Phantom
- AcerMC
- GRAPPA
- CompHEP

ME+PS+merging
- Alpgen
- MadGraph
- Sherpa

NLO+PS
- MC@NLO
- POWHEG

[F. Maltoni]

MC generator types

Type III: Next-to-leading order ME & leading-log parton shower

hard processes simulated to NLO accuracy including real & virtual corrections ...

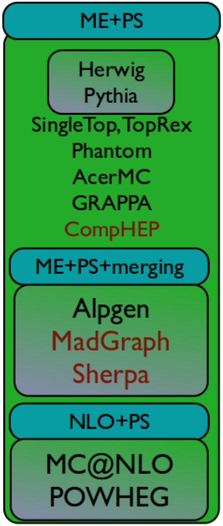
➛ improved description of cross sections & kinematic distributions

Remove phase-space overlap between jets from NLO ME and leading log PS ...

Mechanism: subtraction of PS emissions already generated in hard process at NLO ...

Fairly recent development,
but heavily used in ATLAS and CMS ....

Examples:
MC@NLO (since 2002), POWHEG (since 2007)



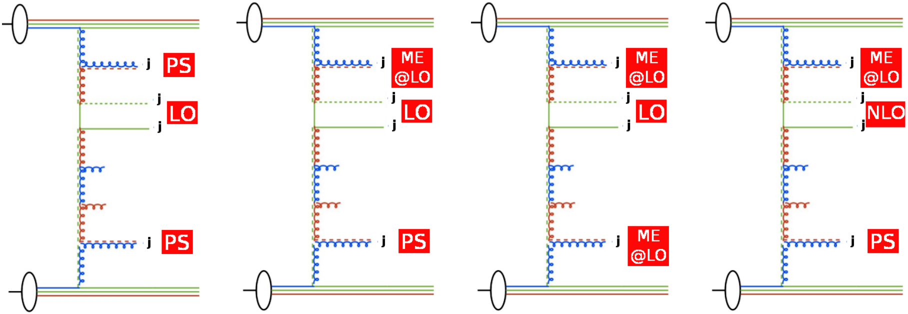
[F. Maltoni]

Details of the Monte Carlo generators

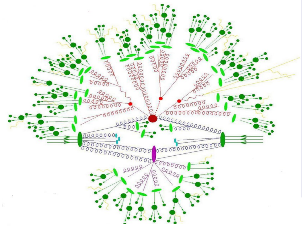
Example: multijet final state

- PYTHIA8 and HERWIG++: LO MC generators with extra jets from PS & MPI
- SHERPA, MADGRAPH: matrix element with N-jets (extra real emission)
- POWHEG: matrix element with a hard emission @ NLO (real & virtual)

PYTHIA, HERWIG | SHERPA | MADGRAPH@LO | POWHEG



The Underlying Event at the LHC



Hard scattering

Initial and Final State Radiation

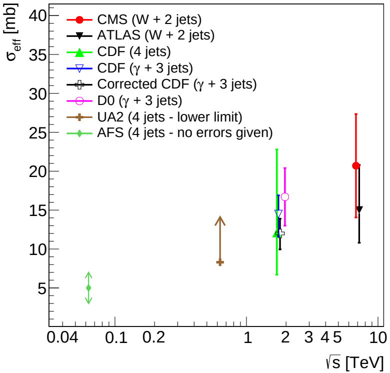
Multiple Parton Interactions (MPI)

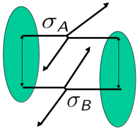
Beam-beam remnants

Hadronization

In general, the UE is a softer contribution but..
some MPI can be hard!

Double Parton Scattering





$$P_A = \frac{\sigma_A}{\sigma^{pp}_{tot}}$$

$$P_B = \frac{\sigma_B}{\sigma^{pp}_{tot}}$$

$$\sigma^{DPS}_{AB} \propto \frac{m}{2} P_A P_B \sigma^{pp}_{tot}$$

$$\sigma^{DPS}_{AB} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

$$\sigma_{eff} \ll \sigma^{pp}_{tot}$$

Need for correlations!

How do we deal with that?

Montecarlo event generators (PYTHIA, HERWIG, SHERPA..)

Parameters need to be adjusted (tuned) to describe data

- MPI — e.g. $p_T^0 = p_T^{ref} \cdot (E/E_{ref})^\epsilon$
  Proton matter distribution profile
  Colour reconnection
- Primordial k_T — e.g. Width of the gaussian used for modelling the parton primordial k_T inside the proton
- Parton shower — e.g. Strong coupling value
  Regularization cut-off
  Upper scale
- Hadronization — e.g. Length of fragmentation strings
  Strange baryon suppression

How does one tune all these?

- Choice of parameter ranges and sensitive observables
- Predictions for different parameter choices and interpolation of the MC response
- Data-MC difference and minimisation over parameter space

Some "official" tunes from the authors..

- PYTHIA 8 — **Monash Tune - PDF: NNPDF2.3LO** (EPJ C74 (2014) 8)
- HERWIG++ — **UE-EE-5C - PDF: CTEQ6L1** (JHEP 1310 (2013) 113)

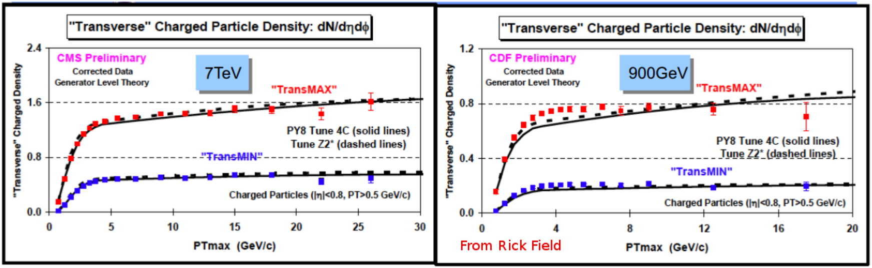
	PYTHIA 8 Monash	HERWIG++ UE-EE-5C
(soft) MPI	UE pp($\bar{\mathrm{p}}$) data at various $\sqrt{s}$	UE pp($\bar{\mathrm{p}}$) data at various $\sqrt{s}$ Value of measured σ_{eff}
Primordial k_T	p_T spectrum of lepton pair from Z decays in hadronic collisions	p_T spectrum of Z boson in hadronic collisions
Parton shower	Event shapes in p$\bar{\mathrm{p}}$ interactions (taken from previous tune)	Jet multiplicity, jet rates and shapes at various colliders
Hadronization	Particle multiplicities in hadronic Z decays in e^+e^- collisions	Particle production at various colliders

General approach is a "factorized" tuning procedure with only some of the components investigated

N.B. For the DPS simulation, generators normally use parameters of soft MPI and extrapolate to harder scales

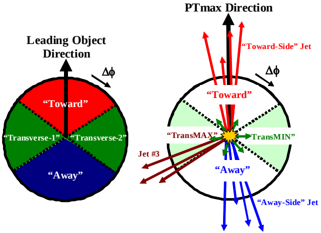
Can they be refined?

How well do they describe observables at different energy?



→ N_{ch} and p_T^{sum} as a function of the leading charged particle

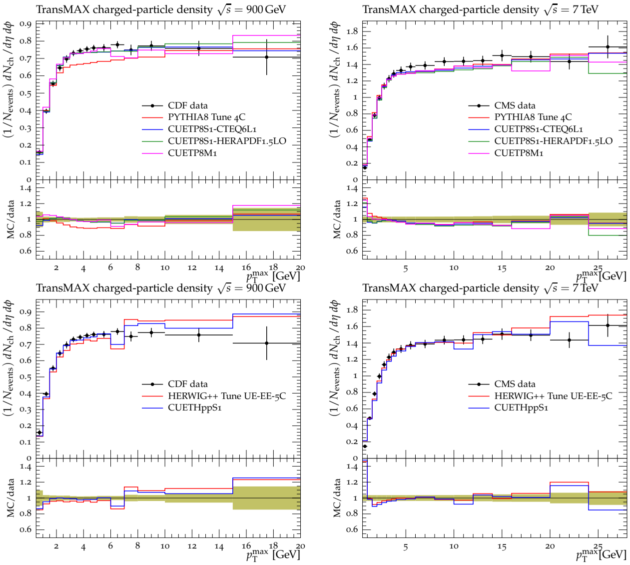
- TRANS MIN: sensitive to MPI
- TRANS MAX: sensitive to MPI and PS
- TRANS DIF: sensitive to PS
- TRANS AVE: sensitive to MPI and PS



PURPOSE: Tuning MPI and colour reconnection parameters

Results of the energy-dependence tuning

Charged particle mult. in the MAX reg. @ 0.9 (left) and 7 (right) TeV



New tunes!

- PYTHIA 8 (CUETP8)
- HERWIG++ (CUETHpp)

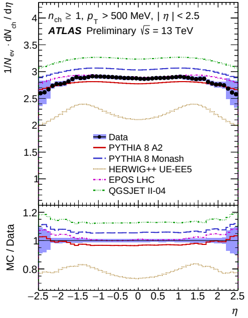
with various PDFs

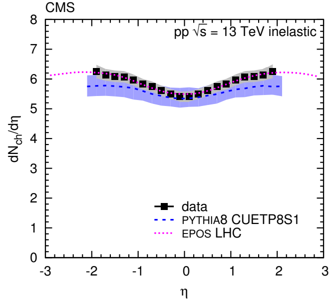
Better constrain of the energy extrapolation
CR changes with the choice of the PDF

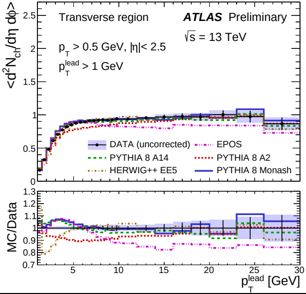
Rising part and plateaux region are well predicted by the new tunes

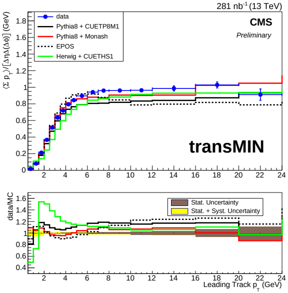
(arXiv 1512.00815)

Tune performance at the new energy









$\sqrt{s}$ = **13 TeV**

TOP:
dN/dη

ATLAS-CONF-2015-028,
PLB751 (2015)

BOTTOM:
N_{ch} vs p_T^{lead}

ATLAS-PHYS-2015-019,
CMS-FSQ-15-007

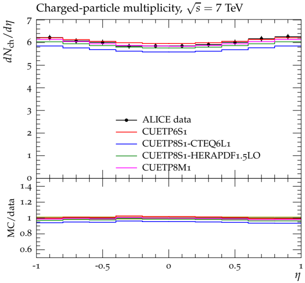
Current tunes reproduce the data at 13 TeV!

May the energy dependence of the MPI be improved in the generators?

$$p_T^0 = p_T^{ref} \cdot (E/E_{ref})^{\epsilon}$$

What about other observables? (arXiv 1512.00815)

Min. Bias observables ✓



Forward region

UE vs p_T^{jet}

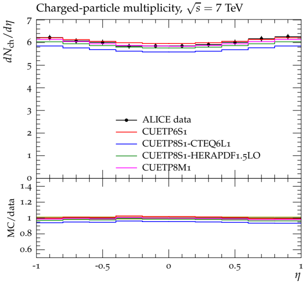
Incl. jet cross sections

Z-boson observables

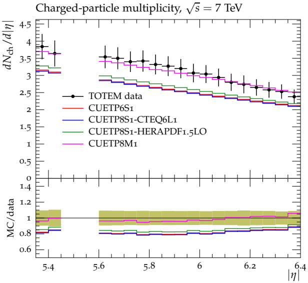
DPS observables

What about other observables? (arXiv 1512.00815)

Min. Bias observables ✓



Forward region ✓



UE vs p_T^{jet}

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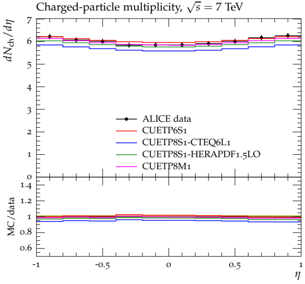
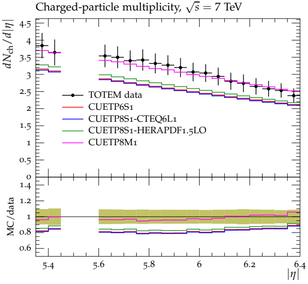
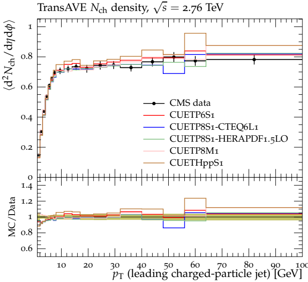


Forward region ✓



UE vs p_T^{jet} ✓



Incl. jet cross sections

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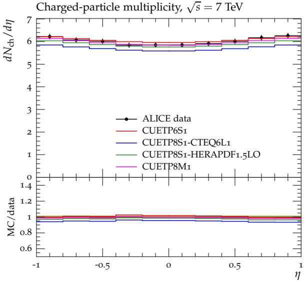
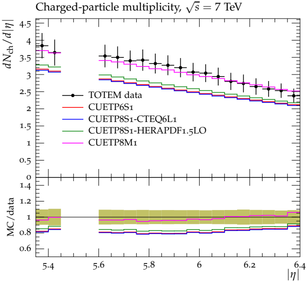
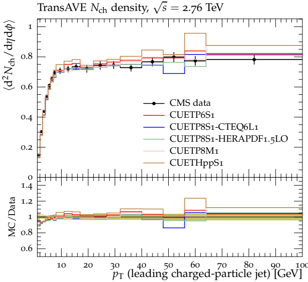


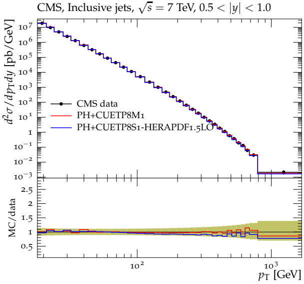
Forward region ✓



UE vs p_T^{jet} ✓



Incl. jet cross sections ✓

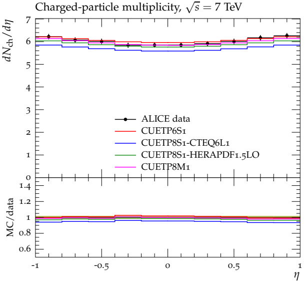


Z-boson observables

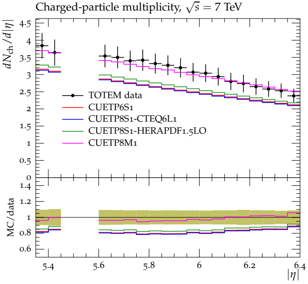
DPS observables

What about other observables? (arXiv 1512.00815)

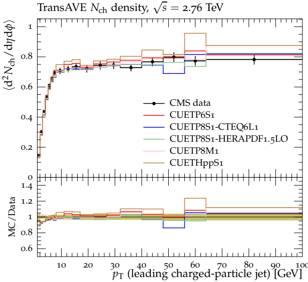
Min. Bias observables ✓



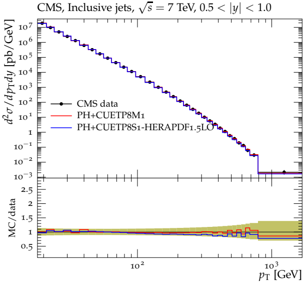
Forward region ✓



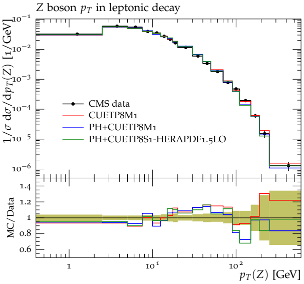
UE vs p_T^{jet} ✓



Incl. jet cross sections ✓



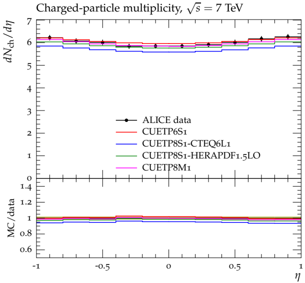
Z-boson observables ✓



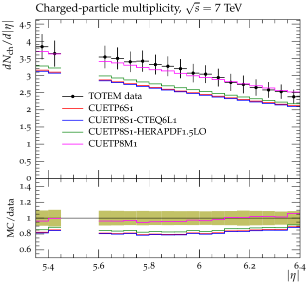
DPS observables

What about other observables? (arXiv 1512.00815)

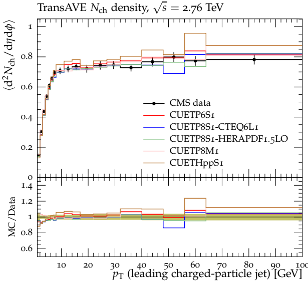
Min. Bias observables ✓



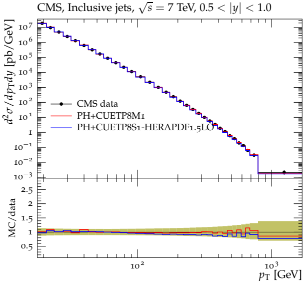
Forward region ✓



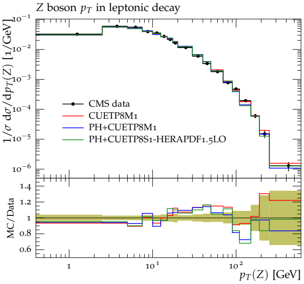
UE vs p_T^{jet} ✓



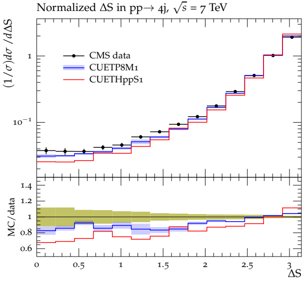
Incl. jet cross sections ✓



Z-boson observables ✓



DPS observables X

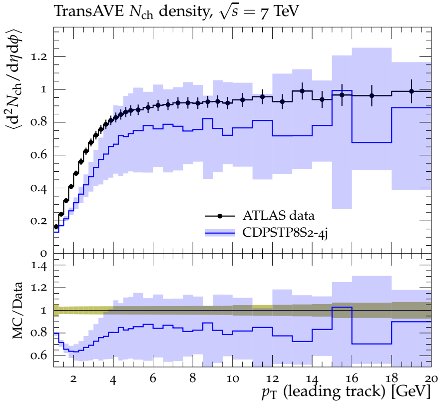


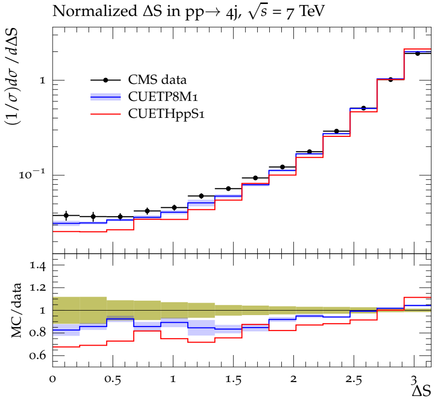
Further look at UE/DPS comparisons (arXiv 1512.00815)

Tune name	σ_{eff} value (mb)
CUETP8M1	$26.0^{+0.6}_{-0.2}$
CUETHppS1	$15.2^{+0.5}_{-0.6}$

Dedicated tune to DPS-sensitive observables in four-jet final state

CDPSTP8S2 $\rightarrow$ $\sigma_{eff} = 19.0^{+4.7}_{-3.0}$ mb



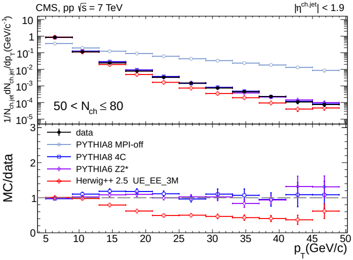


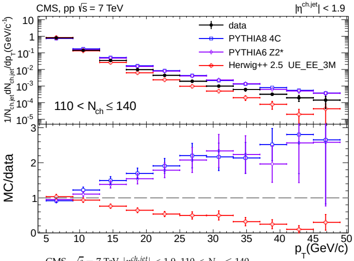
Not able to describe both UE and DPS observables at with the same set of tunes

Indication for need of a refinement of the current MPI model?

High multiplicity scenarios

Low multiplicities → mainly softer MPI components
High multiplicities → contribution of harder MPI



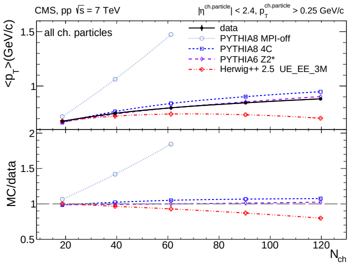


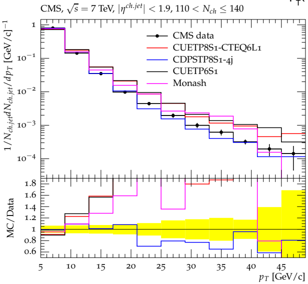
1- **Charged-particle measurement**

2- **Jet measurement**

Good agreement for UE tunes at low multiplicities but worse for increasing multiplicities

→ Better description at high multiplicities for the DPS tunes!



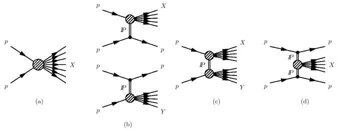


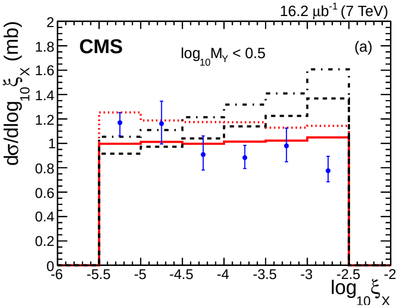
Normalized jet p_T spectrum at different multiplicities (top and bottom right)
Charged particle spectra p_T as a function of multiplicity (bottom left)

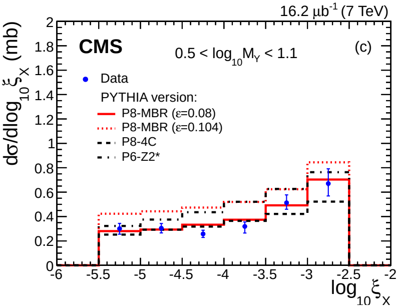
Eur.Phys.J. C73 (2013) 2674

Diffractive-enhanced final states (I)

Diffractive dissociation cross sections as a function of the fraction of the dissociated mass in different ranges dominated by different components
→ **Test of models for diffractive scenarios**







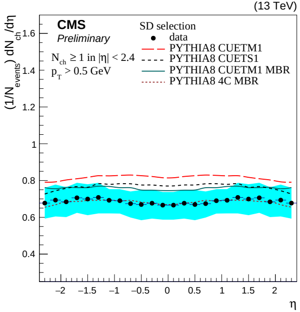
Best description is provided by MBR generator (arXiv.0203141) which fully simulates the diffractive components and is tuned to Tevatron data

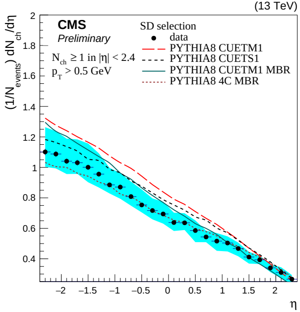
It uses different hadronization parameters to describe charged particle p_T spectra

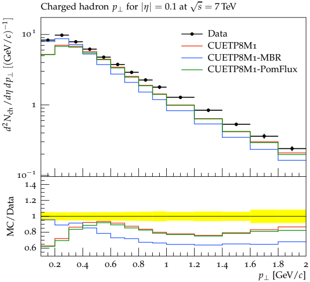
LEFT: SD-enhanced, RIGHT: DD-enhanced

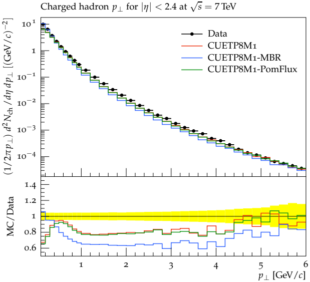
Phys. Rev. D 92 (2015) 012003

Diffractive-enhanced final states (II)

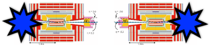








SD-enhanced selection: activity in one region, veto in the other



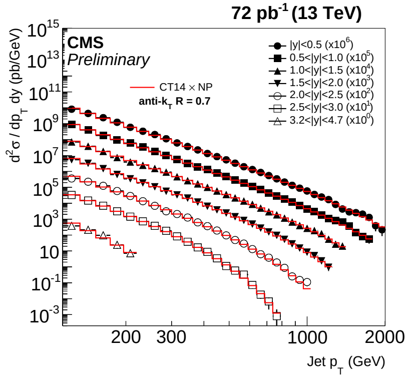
MBR diffraction model and parameters help to improve the SD observables, due to a better description of low trans.mom. region

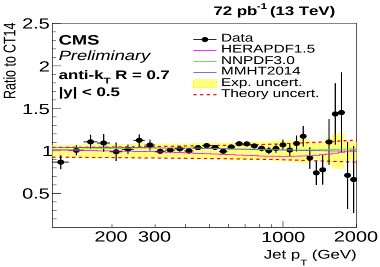
CMS-FSQ-15-008

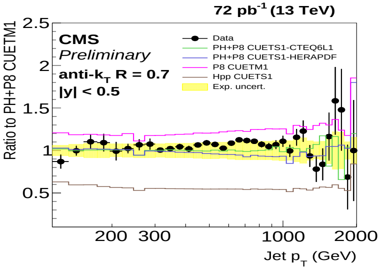
Need for different hadronization parameters for diffractive observables than for nondiffractive?

Ongoing work!

Jet observables at 13 TeV





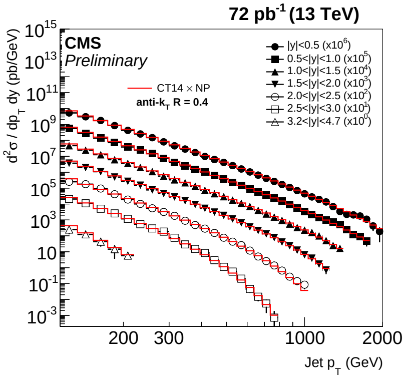


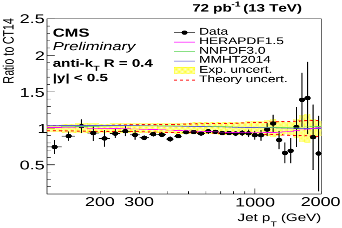
Inclusive jet cross section in different rapidity bins

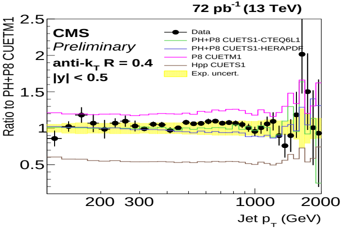
- Various cone sizes probe different aspects of parton evolution
- Jets clustered with R = 0.7 are described by NLO fixed-order calculations and predictions from NLO MC generators
- LO MC event generators are not able to reproduce the measurement

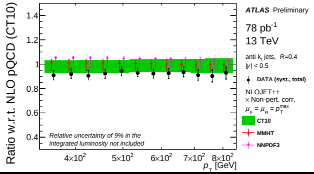
→ Fixed-order NLO ME corr. for NP effects with diff. PDF sets
→ MC generators with LO or NLO dijet ME + PS and UE sim.

CMS-PAS-SMP-15-007 ATLAS-CONF-2015-034



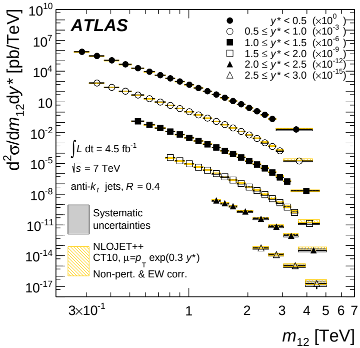






Inclusive jet cross section in different rapidity bins

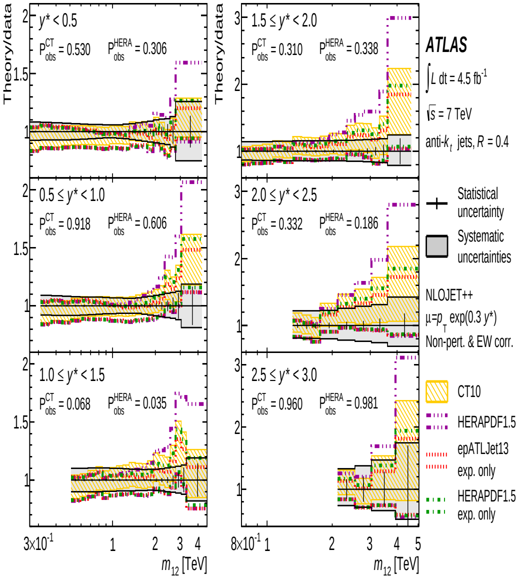
- Various cone sizes probe different aspects of parton evolution
- Jets clustered with R = 0.4 are not described by NLO fixed-order calculations but only by predictions from NLO MC generators
- Effect of missing PS contributions relevant for smaller cones

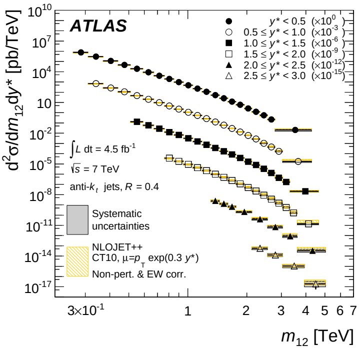


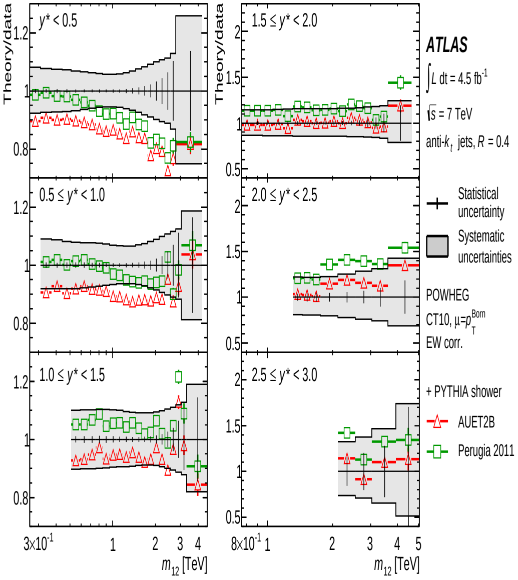
Inclusive dijet cross section in different rapidity bins as a function of dijet mass

- Jets clustered with R = 0.4 are reproduced by NLO fixed-order calculations

JHEP05(2014)059





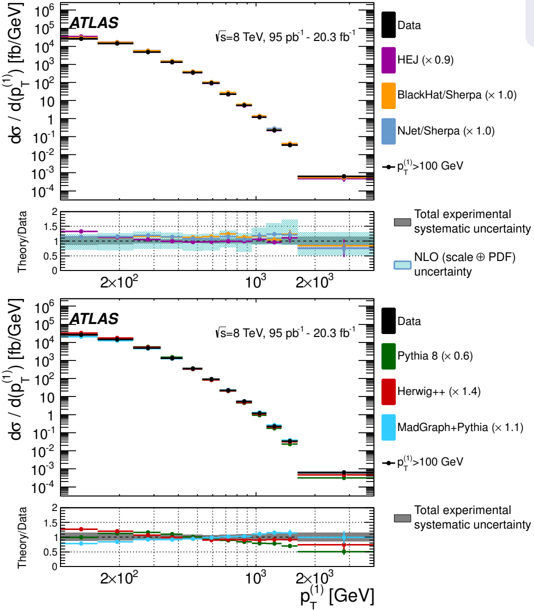


Inclusive dijet cross section in different rapidity bins as a function of dijet mass

- Jets clustered with R = 0.4 are reproduced by MC event generators using NLO dijet ME but sensitivity to UE tunes

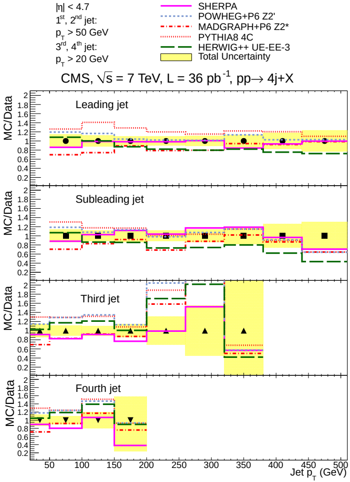
JHEP05(2014)059

Multijet observables (III)



Four-jet scenarios also well described in a wide region of the phase space

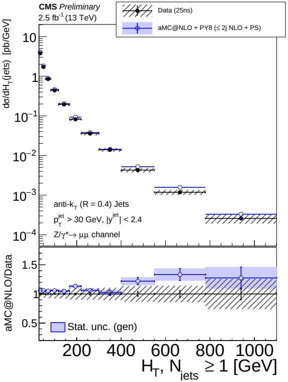
JHEP 12 (2015) 105
Phys.Rev.D89(2014)092010

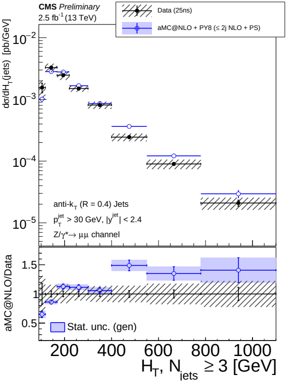


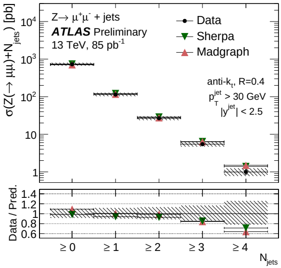
Z boson observables

Jets associated to a Z boson

Measurement of differential cross sections for different jet multiplicities
→ Crucial test of our QCD predictions!







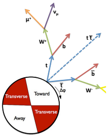
CMS-SMP-15-010
ATLAS-CONF-2015-041

Predictions describe measurements as long as the multiplicity matches the number of partons in the matrix element

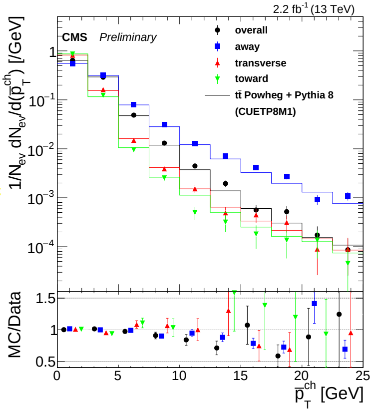
Top observables (I)

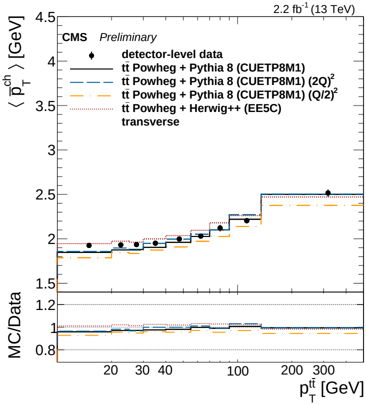
Underlying event in top pair events

Measurement of event content in terms of charged particle multiplicity and p_T
$\rightarrow$ Test of final-state universality of UE contribution



CMS-TOP-15-017

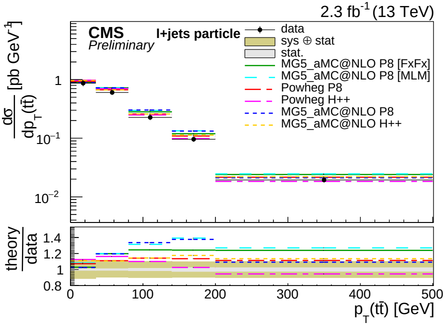


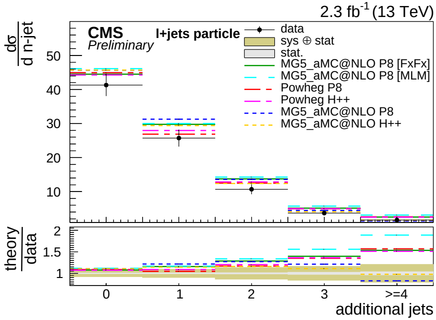


Predictions of POWHEG NLO matrix-element interfaced to P8 tunes from hadronic events are able to reproduce all measured observables in each considered region

Top pair in lepton + jets final states

Measurement of differential cross sections as a function of top pair p_T and jet multiplicity → Test of reliability of predictions in top sector





NLO predictions describe well the measurements but sensitivity to matching scheme and PS generator

CMS-TOP-16-008

Parton shower and MPI tuning

TUNING OF PYTHIA 8 TO OBSERVABLES MEASURED IN DIFFERENT PROCESSES

Study of the interplay between MPI and parton shower
Various PDF sets investigated

Observables
Track jet properties
Jet shapes
Dijet decorrelations
Multijets
Z boson p_T
$t\bar{t}$ gap and jet shapes
Track-jet and jet UE

`SigmaProcess:alphaSvalue`	The α_S value at scale $Q^2 = M_Z^2$
`SpaceShower:pT0Ref`	ISR p_{T} cutoff
`SpaceShower:pTmaxFudge`	Mult. factor on max ISR evolution scale
`SpaceShower:pTdampFudge`	Factorisation/renorm scale damping
`SpaceShower:alphaSvalue`	ISR α_S
`TimeShower:alphaSvalue`	FSR α_S
`BeamRemnants:primordialKThard`	Hard interaction primordial $k_\perp$
`MultipartonInteractions:pT0Ref`	MPI p_{T} cutoff
`MultipartonInteractions:alphaSvalue`	MPI α_S
`BeamRemnants:reconnectRange`	CR strength

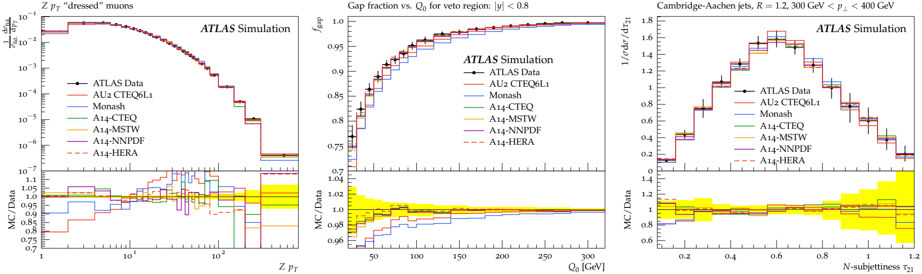
Extremely important for:

- testing the universality of the parton shower in leptonic and hadronic collisions
- testing the performance of UE simulation for different hard scattering processes

ATL-PHYS-PUB-2014-021

Parton shower and MPI tuning

Significant improvement of description of observables in:
Drell-Yan (left), top-antitop (center) and jet substructure (right) sectors



- α_S values are similar for all PDF used
  - quite high for the hard processes
  - lower for initial- and final-state radiation
  - significantly lower than previous tunes for ISR and FSR
- Damped shower needed to describe gap fraction in $t\bar{t}$ events and p_T^Z simultaneously

Tuning higher-order ME matched to parton showers

OBSERVABLES: gap fraction, jet shapes and jet multiplicity in $t\bar{t}$ events

GENERATORS: PYTHIA 8 standalone, MADGRAPH_aMC@NLO and POWHEG + PYTHIA 8

Different steps of tuning:

- tuning of ISR and FSR separately, then simultaneous tune to account for their interplay
- application of tune to matched generators
- tune of the matched MADGRAPH_aMC@NLO + PYTHIA 8

(Some of the) Outcomes

- Significant improvement in the description of $t\bar{t}$ observables
- Parameters of simultaneous ISR-FSR tune do not differ much from the separate tunes
- Tune of matched MADGRAPH+PYTHIA 8 has similar parameters to standalone PYTHIA 8

ATL-PHYS-PUB-2015-007, ATL-PHYS-PUB-2015-048

Summary and conclusions

High energy physics strongly relies on predictions from Monte Carlo event simulation

- Very sophisticated tunes are available and are able to describe a wide range of observables at different collision energies
- Actual measurements are sensitive to ME, UE and PS contributions and are able to disentangle them
- Tunes obtained at 7 TeV (or below) are able to reproduce data at 13 TeV in a good level of agreement
- It is difficult to reproduce data relative to some corners of the phase space within a unique set of parameters (e.g. DPS-sensitive observables, diffraction)
- Need for more sophisticated models/parametrizations?

New measurements, more advanced simulation..
Stay tuned!

Summary and conclusions

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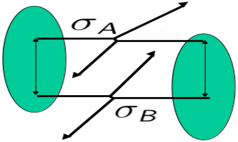
THANK YOU FOR YOUR ATTENTION

BACKUP SLIDES



- Two different x values for the two partons in each proton
- Impact parameter b

$$\sigma_{A,B}^{DPS} = \frac{m}{2} \int dx_1 dx_1' \hat{\sigma}_A(x_1, x_1') \int dx_2 dx_2' \hat{\sigma}_B(x_2, x_2') \int d^2b\ f(x_1, x_2, b)\ f(x_1', x_2', b)$$

DPS Cross Section

Partonic cross sections

Double parton distribution functions

If the partons are assumed to be uncorrelated:

$$f(x_1, x_2, b) = f(x_1) f(x_2) F(b)$$

The two scatterings factorize in the cross section formula:

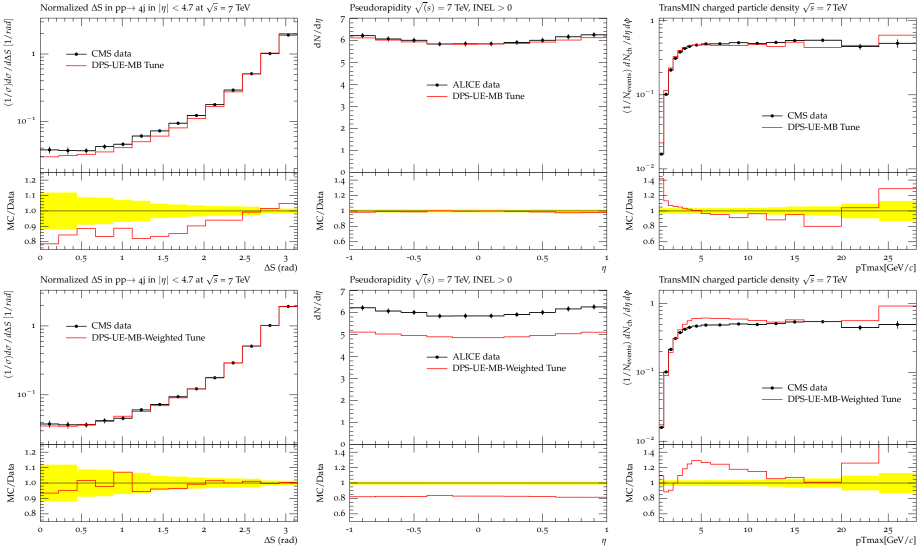
$$\sigma_{AB}^{DPS} = \frac{m}{2} \int dx_1 dx_1' \hat{\sigma}_A f(x_1) f(x_1') \int dx_2 dx_2' \hat{\sigma}_B f(x_2) f(x_2') \int d^2b\ [F(b)]^2$$

It is thus defined:

$$\sigma_{eff} = \frac{1}{\int d^2b\ [F(b)]^2}$$

Combined fits to whole MPI spectrum

Combined fits of observables sensitive to soft, semi-hard and hard MPI



No hope to get the measurements well described altogether

Why do we actually tune?

Not only for fun!

1. Correct description of the data
   - Pile-up simulation
   - Evaluation of detector effects and unfolding
   - Estimation of background (in MC-driven approach)
   - Models are not "allowed" to fail
2. Good physics predictions
   - Correct evaluation of physics effects
   - Models are "allowed" to fail

The danger is overtuning!