Misure di doppie interazioni partoniche a LHC

Paolo Gunnellini

DESY (Deutsches Elektronen Synchrotron), Hamburg

Universitá degli Studi
di Perugia
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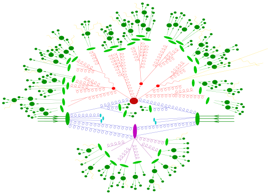
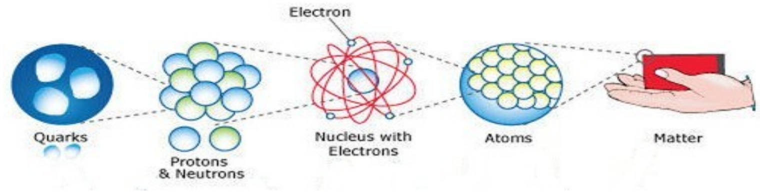


C è molto di piú non trattato in questa presentazione!

- Dettagli della teoria di DPS
- Altre misure pubblicate da LHCb
- Altri studi di correlazioni partoniche in simulazioni (ATL-PHYS-PUB-2012-003)

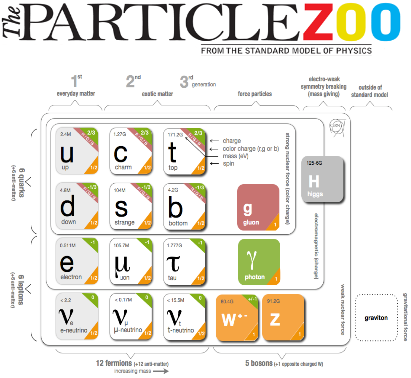
The Standard Model of particle physics



Elementary particles grouped in fermions and bosons

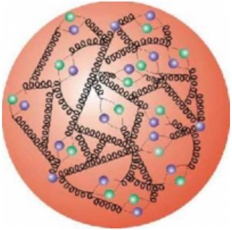
Fermions interact through the exchange of a gauge boson

Mass of particles acquired via interaction with Higgs field



BUT..not the final word..

The strong interaction in the Standard Model

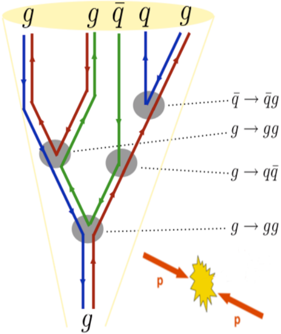


Protons are made of quarks and gluons continuously emitted and absorbed through strong interaction

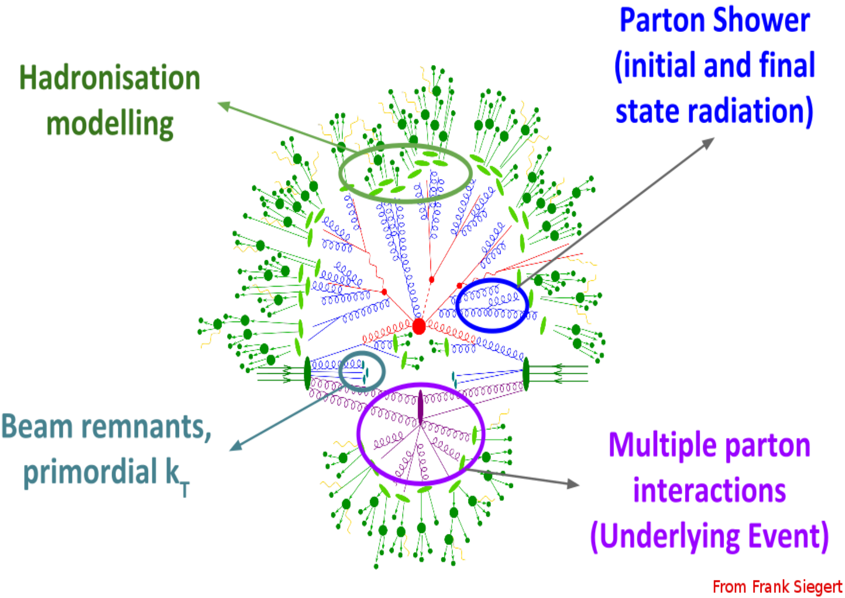
Quarks and gluons carry colour

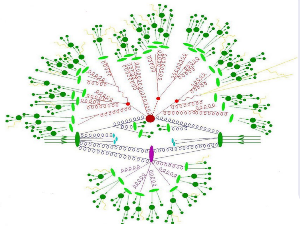
Parton shower: emission of coloured gluons and quarks

Hadronization: rearrangement in colourless hadrons



The underlying event at the LHC





Hard scattering

Initial and Final State Radiation

Multiple Parton Interactions (MPI)

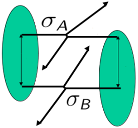
Beam-beam remnants

Hadronization

In general, the UE is a softer contribution but..

some MPI can be hard!

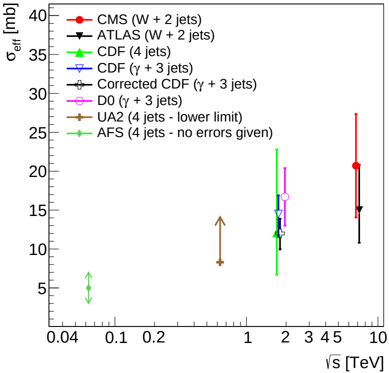
Double Parton Scattering



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

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

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



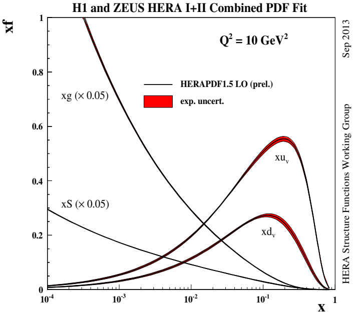
$$\sigma^{DPS}_{AB} = \frac{m}{2} \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

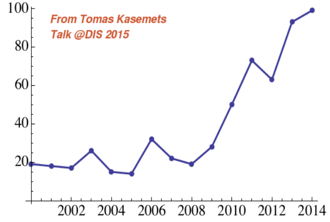
$$\sigma_{eff} \ll \sigma^{pp}_{tot}$$

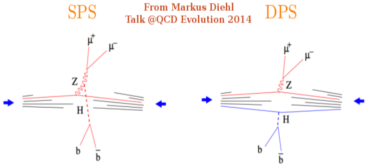
Need for correlations!

Why do we care about DPS?

- **Increasing contribution at the LHC when going to higher energy**
- **Sizeable background for LHC processes (SM and searches), e.g. Higgsstrahlung**
- **Information about the structure of the proton, i.e. parton correlations**







And...increasing interest and number of entries in Spires!

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

Internal structure of the proton
DPS background for any physics channel

Double parton scattering and experimental overview

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

Internal structure of the proton
DPS background for any physics channel

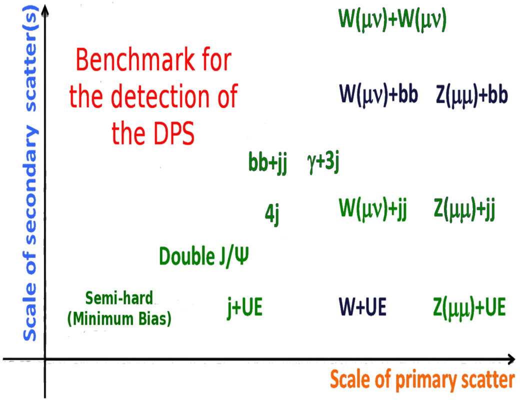
→ Which channels can be used to look for DPS signals?

Double parton scattering and experimental overview

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

Internal structure of the proton
DPS background for any physics channel

$\rightarrow$ Which channels can be used to look for DPS signals?



Measurements at 7 and 8 TeV

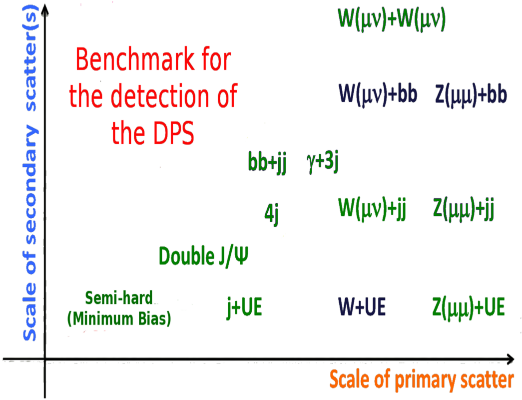
Eur.Phys.J. C72
CMS-PAS-BPH-11-021
CMS-PAS-FSQ-12-020
JHEP 1403 (2014) 032
CMS-PAS-FSQ-13-001
CMS-PAS-FSQ-13-010
CMS-PAS-FSQ-12-017
PRD89.092010
Eur.Phys.J. C74 (2014) 2965
Arxiv 1409.3433
New J. Phys. 15 (2013) 033038
ATLAS-CONF-2015-058
JHEP 1404 (2014) 172

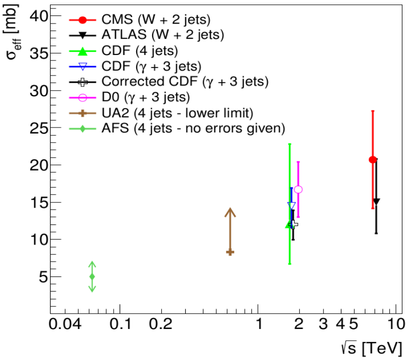
Double parton scattering and experimental overview

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

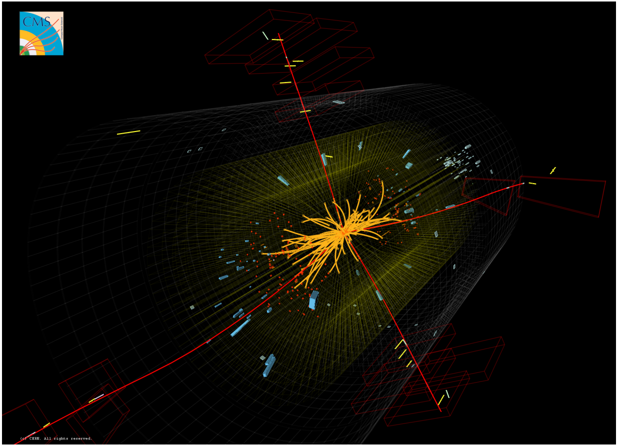
Internal structure of the proton
DPS background for any physics channel

→ Which channels can be used to look for DPS signals?





What do we use to perform the measurements?



The Large Hadron Collider at CERN, Geneva

- 27-km underground ring collider
- Bending magnetic field of 8.4 T
- Proton beams accelerated up to 6.5 TeV

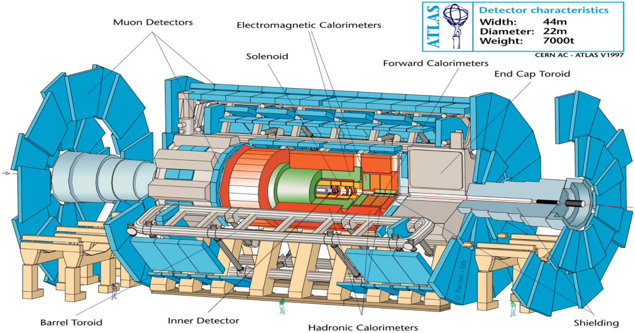
Three years of data taking in Run I:

$\sqrt{s} = 7\text{-}8$ TeV

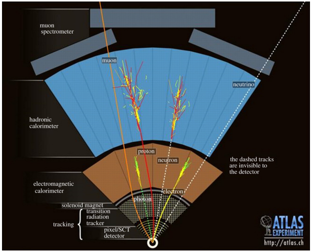
Run II started in 2015

$\sqrt{s} = 13$ TeV

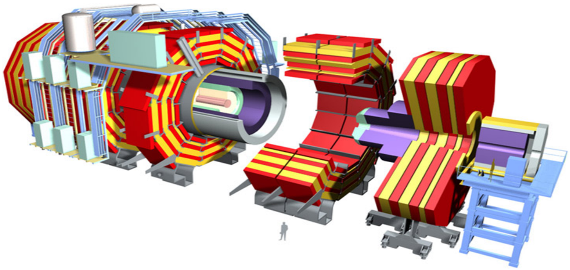
The ATLAS experiment



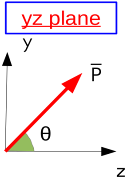
- Toroidal magnetic field of 2 T
- Tracking system for measurement of the momentum of charged particles
- Calorimeter system for measurement of the particle energy
- External muon system for the muon identification



The Compact Muon Solenoid experiment

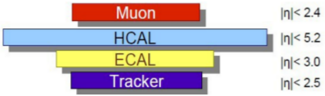


- Length: 21 m
- Diameter: 15 m
- Weight: 12500 ton



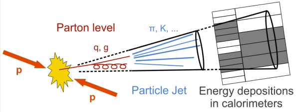
$$\eta = \text{-ln}\left(\tan\frac{\theta}{2}\right)$$

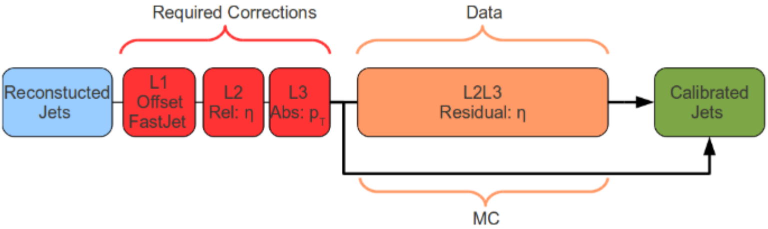
- Solenoidal magnetic field of 4 T
- Tracking system consisting of many detector layers
- Calorimeter system organized in two subdetectors
- Muon system outside the return coke



Jet reconstruction in CMS

- A jet in CMS is seen as a bunch of particles in the detector
- Information from the subdetectors is combined through the Particle Flow algorithm
- The reconstructed particles are clustered with the anti-k_T algorithm





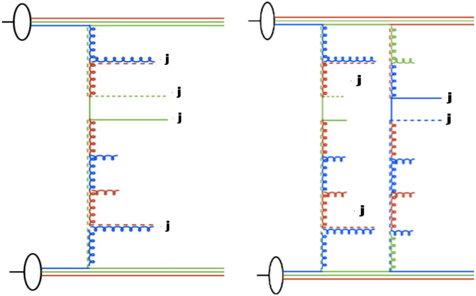
→ Corrections applied to p_T raw information for jet calibration

- Factorized approach in three different levels

Choice of sensitive observables (I): a four-jet scenario

A four-jet final state may arise from one or two chains:

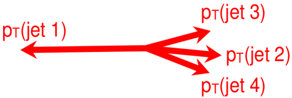
- the two additional jets may be produced via PS or a 2nd hard scattering

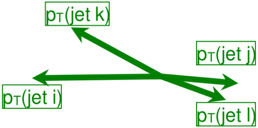


Various kinematical observables can discriminate the two processes:

$$\Delta^{rel}_{soft} p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$$

$$\Delta S = \arccos\left(\frac{\vec{p}_T(j^i, j^k) \cdot \vec{p}_T(j^l, j^m)}{|\vec{p}_T(j^i, j^k)| \cdot |\vec{p}_T(j^l, j^m)|}\right)$$





! Selection of jet pairs at different scales helps the jet association !

Choice of sensitive observables (II): a four-jet scenario

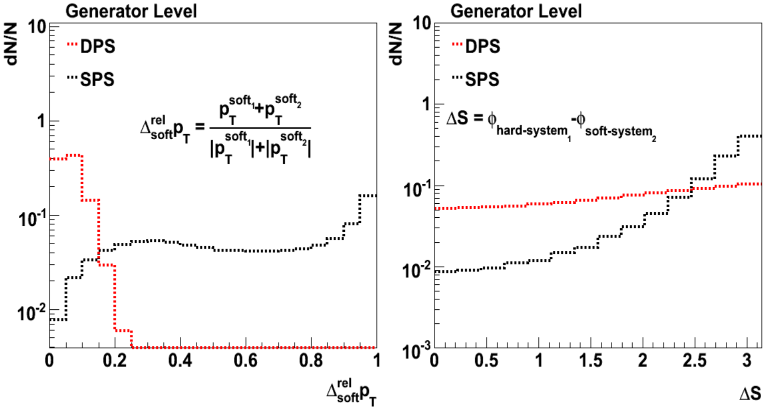
Which regions of the phase space are interesting for DPS detection?

Studies of SPS and DPS contributions performed with PYTHIA8:

Selection of a four-jet final state in $|\eta| < 4.7$ at two different p_T thresholds (20 and 50 GeV)

A SIMPLE scenario:

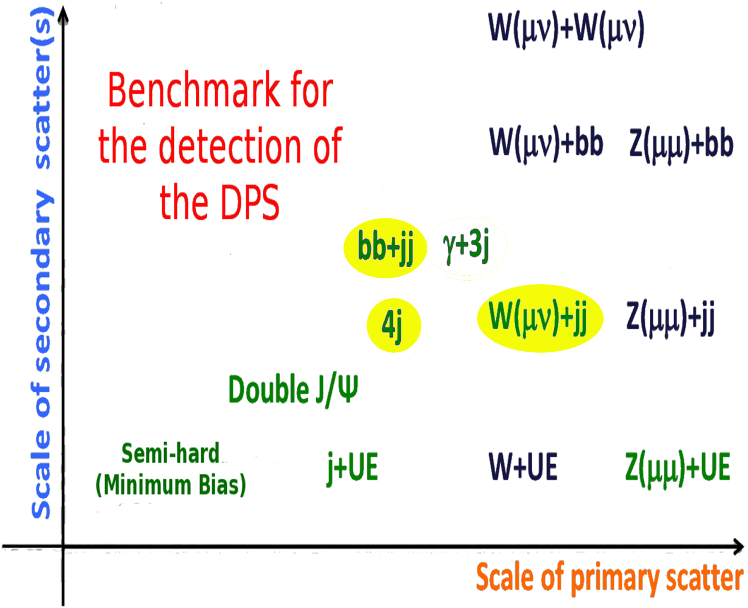
- SPS: MPI contribution switched off
- DPS: Two hard scatterings at the parton level forced to happen w/o parton shower



Different regions of the phase space are filled by the two processes

Discriminating power

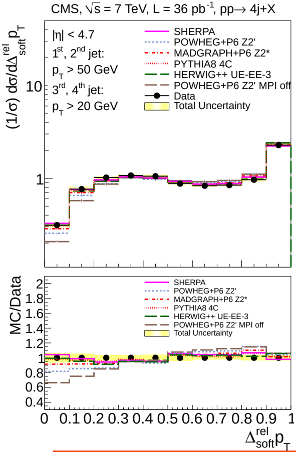
Choice of physics channels

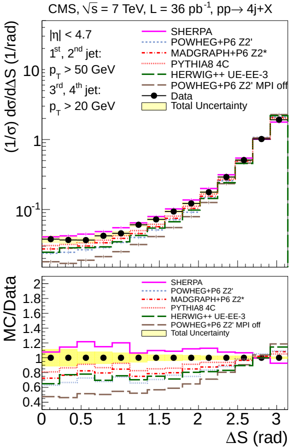


Measurement of a four-jet final state

Event selection

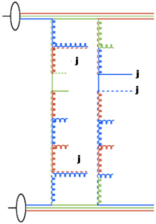
Exactly four jets in the final state in $|\eta| < 4.7$:
2 jets: $p_T > 50$ GeV (hard), 2 jets: $p_T > 20$ GeV (soft)





$$\Delta^{rel}_{soft} p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$$

$$\Delta S = \arccos\left(\frac{\vec{p}_T(j^i, j^k) \cdot \vec{p}_T(j^l, j^m)}{|\vec{p}_T(j^i, j^k)| \cdot |\vec{p}_T(j^l, j^m)|}\right)$$



Soft jets are expected to be produced also by a 2nd scattering

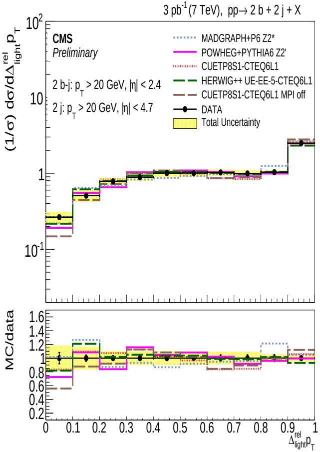
PRD 89 (2014) 092010

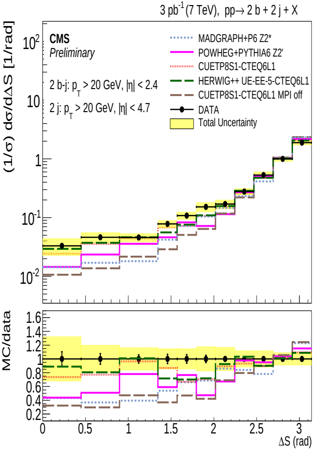
ΔS and $\Delta^{rel}_{soft} p_T$ sensitive to MPI contribution: → ROOM for DPS!

Measurement of a four-jet final state with b-jets

Event selection

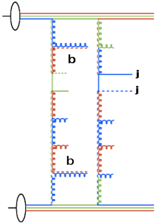
Selection of at least four jets with $p_T > 20$ GeV:
2 b-jets: $|\eta| < 2.4$, 2 other jets: $|\eta| < 4.7$





$$\Delta^{rel}_{soft} p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$$

$$\Delta S = \arccos\left(\frac{\vec{p}_T(j^i, j^k) \cdot \vec{p}_T(j^l, j^m)}{|\vec{p}_T(j^i, j^k)| \cdot |\vec{p}_T(j^l, j^m)|}\right)$$



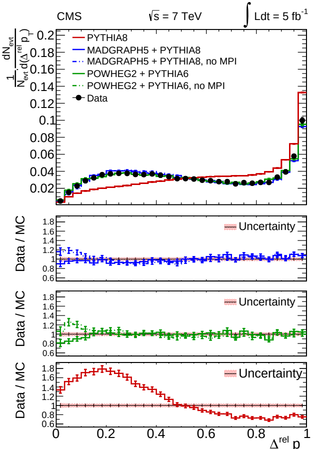
A pair of jets is expected to be produced also by a 2^{nd} scattering

CMS-FSQ-13-010

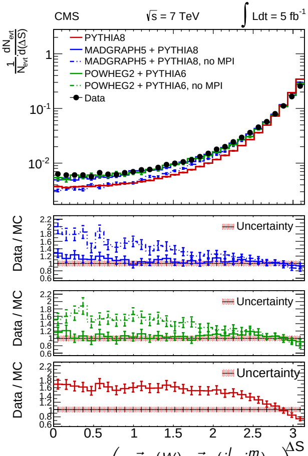
Measurement of a W+dijet final state

Event selection

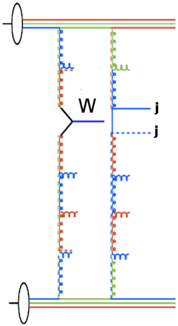
Presence of a muon with $p_T > 35$ GeV in $|\eta| < 2.1$ and $E_T^{miss} > 50$ GeV
+ at least 2 jets: $p_T > 20$ GeV in $|\eta| < 2.0$



$$\Delta^{rel}_{soft} p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$$



$$\Delta S = \arccos\left(\frac{\vec{p}_T(W) \cdot \vec{p}_T(j^l, j^m)}{|\vec{p}_T(W)| \cdot |\vec{p}_T(j^l, j^m)|}\right)$$

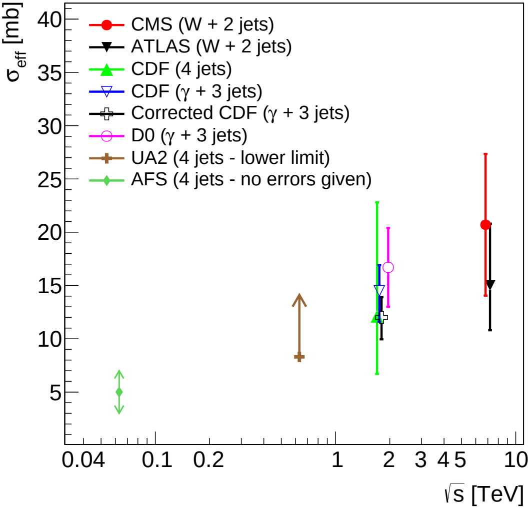


The jets are expected to be produced also by a 2^{nd} scattering

JHEP 03 (2014) 032

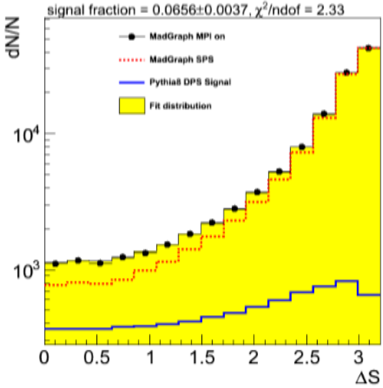
Sensitivity to DPS!

How can one extract the DPS contribution from the measured observables?



How to extract σ_{eff}: the template method

- Measurement of DPS-sensitive observables
- Definition of signal and background
- Fit the relative fraction of signal and background
- The signal fraction translates into a value for σ_{eff}



From Ramandeep Kumar,
Talk at MPI@LHC 2012

W + jets channel

$$\sigma_{eff} = \frac{\sigma_A \cdot \sigma_B}{\sigma_{DPS}}$$

$$\sigma_{eff} = \frac{N_A^{ev}}{N_{A+B(DPS)}^{ev}} \cdot \sigma_B$$

$$\sigma_{eff} = \frac{N_A^{ev}}{f_{DPS} \cdot N_{A+B}^{ev}} \cdot \sigma_B$$

First measurement of DPS signal at 7 TeV

New J. Phys. 15 (2013) 033038

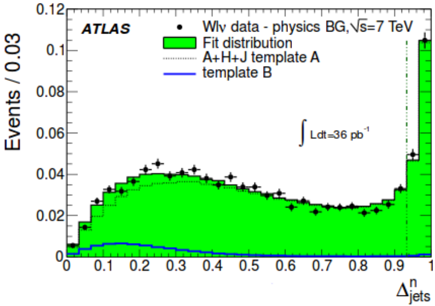
SELECTION: 2j with $p_T > 20$ GeV in $|y| < 2.8$, standard W selection

CONSIDERED OBSERVABLES: normalized $\Delta^n_{jets} = \frac{|\vec{p}_T^{1j} + \vec{p}_T^{2j}|}{|\vec{p}_T^{1j}| + |\vec{p}_T^{2j}|}$

BACKGROUND: ALPGEN+HERWIG+JIMMY with hard MPI excluded

SIGNAL: selection of two independent collisions from data

DRIVING UNCERTAINTY: model dependence



$$\sigma_{eff} = \frac{N_{W+0j}}{f_{DPS} \cdot N_{W+2j}} \cdot \sigma_{2j}$$

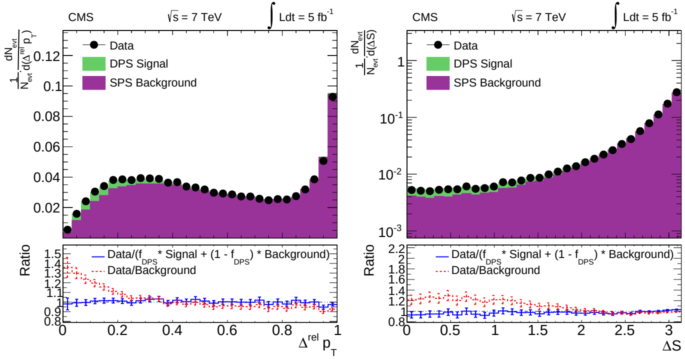
with $f_{DPS} = 8.0\%$ and

$$\frac{N_{W+0j}}{N_{W+2j}} = 23$$

$$\sigma_{eff} = 15.0 \pm 3 \text{ (st.) } ^{+5}_{-3} \text{ (sys.) mb}$$

Extraction of σ_{eff} from W+dijet final state (CMS)

CONSIDERED OBSERVABLES: normalized ΔS and $\Delta^{rel} p_T$
BACKGROUND: MADGRAPH+P8 with hard MPI above 15 GeV excluded
SIGNAL: Two mixed independent scatterings generated with P8 and MG+P8
DRIVING UNCERTAINTY: model dependence



$$\sigma_{eff} = \frac{N_{W+0j}}{f_{DPS} \cdot N_{W+2j}} \cdot \sigma_{2j}$$

$$f_{DPS} = 5.5\%,$$

$$\frac{N_{W+0j}}{N_{W+2j}} = 27.8$$

JHEP 03 (2014) 032

$$\sigma_{eff} = 20.7 \pm 0.8 \text{ (stat.)} \pm 6.6 \text{ (syst.) mb}$$

Experimental difficulties of the template method

→ **How to define the background?**

- Good to exclude hard MPI..but no such possibility in some generators

→ **How to define exclusive and inclusive events?**

- N_{W+0j} and N_{W+2j} are sensitive to the jet scales

→ These issues have an impact on the systematic uncertainty!

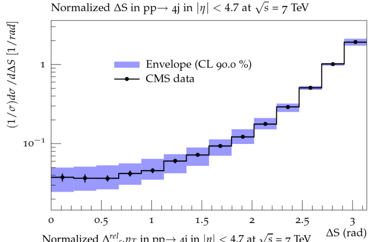
Is there a way out?

The inclusive fit method

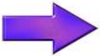
- Run predictions for different choices of UE parameters
- Fit the MC predictions to the considered observables
- Improve the data description with the examined model
- (..look at the corresponding σ_{eff}..)

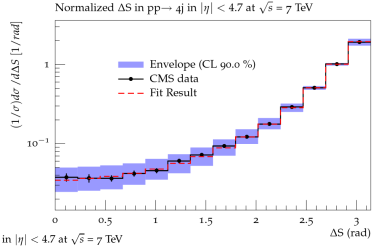
Extraction of σ_{eff} in four-jet final states

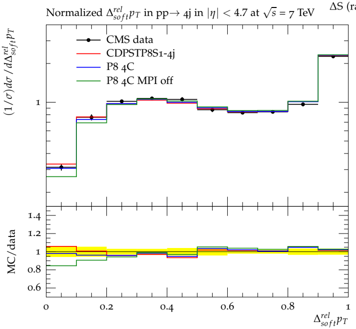
Minimization of the binned $\chi^2 = \sum_O \sum_{b \in O} \frac{(MC^b - DATA^b)^2}{\Delta_b^2}$

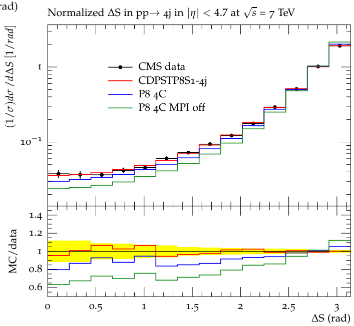


MINIMIZ.









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

LEFT: ΔS
RIGHT: $\Delta^{rel}_{soft} p_T$

arXiv 1512.00815

Combined fits to DPS measurements

Fitting measurements separately..

Fitted measurements	σ_{eff} value (mb)	Reference
4j	$\mathbf{19.0}^{+4.7}_{-3.0}$	arXiv 1512.00815
W2j	$\mathbf{25.8}^{+8.2}_{-4.2}$	arXiv 1512.00815
2b2j	$\mathbf{23.2}^{+3.3}_{-2.5}$	DESY-THESIS-15-010

What happens if we try to fit more measurements at the same time?

Fitted measurements	σ_{eff} value	χ^2/Ndf
4j+2b2j	**24.37 mb**	0.631
W2j+2b2j	**25.32 mb**	0.807
W2j+4j	**23.20 mb**	0.948
2b2j+W2j+4j	**22.57 mb**	0.876

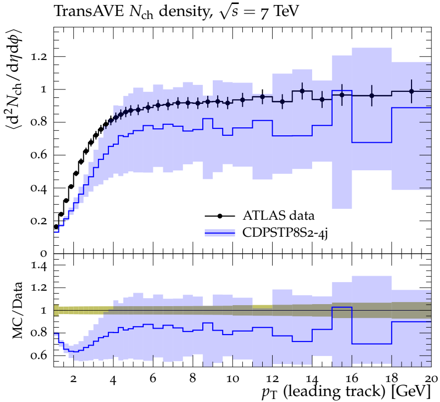
It works! But..we might wash out DPS dependences..

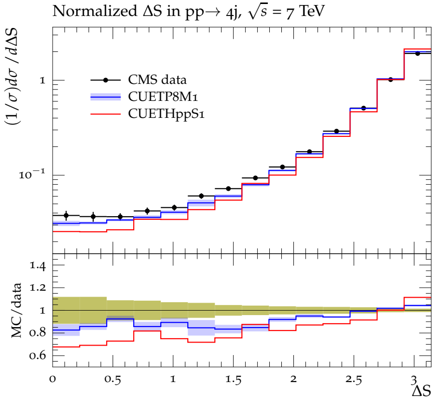
Further look at UE/DPS comparisons (arXiv 1512.00815)

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



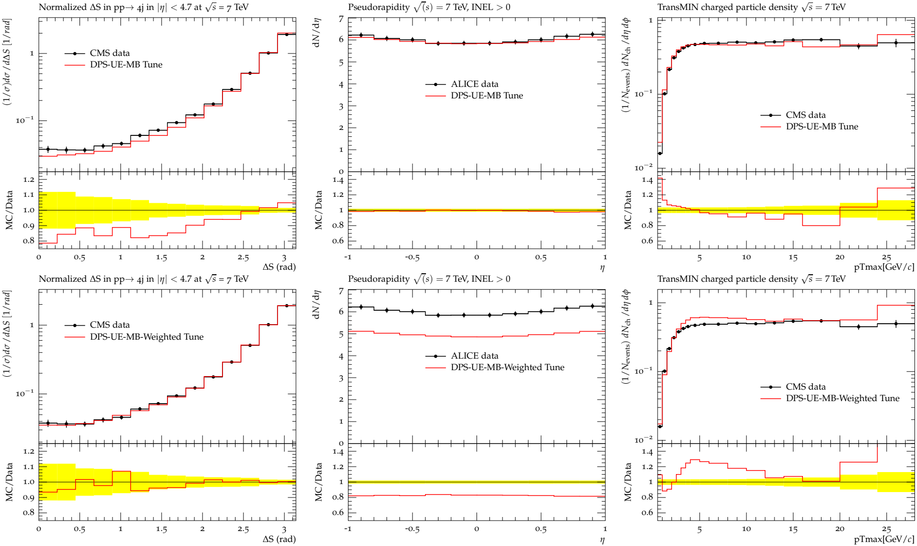


Not able to describe both UE and DPS observables at with the same set of tunes

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

Combined fits to whole MPI spectrum

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



No hope to get the measurements well described altogether

What about possible correlations included? (I)

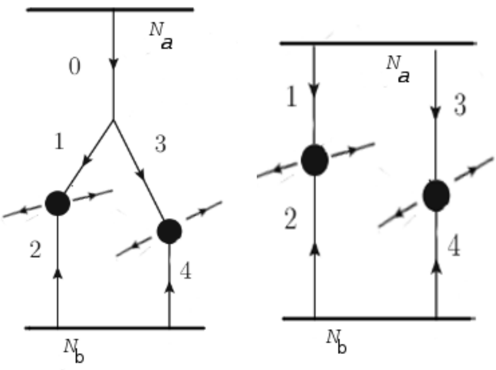
Current status of MPI simulation

MPI are simulated in an interleaved way, treated in the same way as ISR and FSR

Whole machinery is based on single PDFs

The so-called 1×2 and 2×2 mechanisms also contribute to MPI processes

The 1×2 mechanisms lead to a signicant transverse-scale dependence of MPI cross sections



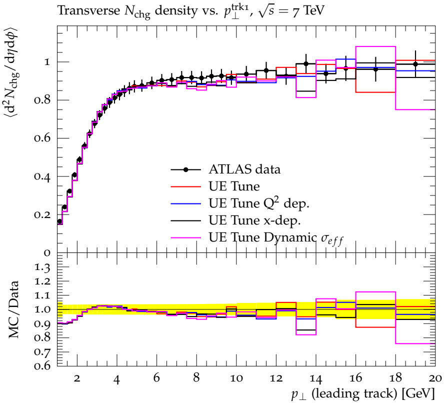
EPJC75 (2015) 6 282, arXiv 1510.07436

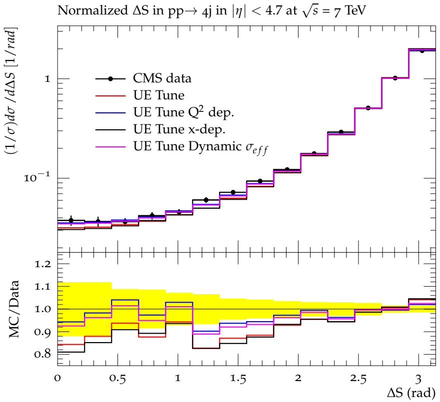
BUT ... No Monte Carlo simulation available with such model
Reweighting of standard MC events to account for these processes

What about possible correlations included? (II)

UE parameters obtained by fitting the low p_T region of observables in hadronic events

LEFT: part. mult., RIGHT: ΔS
EPJC75 (2015) 6 282





Introducing a dynamic σ_{eff} dependence brings the predictions closer to the data

Improvement of 10% for ΔS with respect to standard predictions

Riassunto e conclusioni

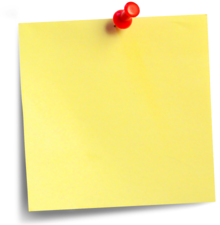
Lo studio di interazioni partoniche multiple è molto importante per descrivere collisioni di protoni a LHC

- Dati indicano che allo stato attuale non è possibile una descrizione delle misure con simulazioni senza il contributo di DPS
- E' possibile ottenere un fit consistente con molte misure di DPS a 7 TeV..**MA..non vengono considerate le correlazioni partoniche**
- Fino ad ora, non siamo in grado di ottenere un fit che descriva ad un buon livello interazioni partoniche in tutto lo spazio delle fasi
- Introducendo correlazioni, la situazione sembra migliorare

Molti progressi fatti nella teoria delle DPS

Confronto con dati sperimentali necessario

Stay tuned!



Riassunto e conclusioni

Lo studio di interazioni partoniche multiple è molto importante per descrivere collisioni di protoni a LHC

- Dati indicano che allo stato attuale non è possibile una descrizione delle misure con simulazioni senza il contributo di DPS
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Molti progressi fatti nella teoria delle DPS

Confronto con dati sperimentali necessario

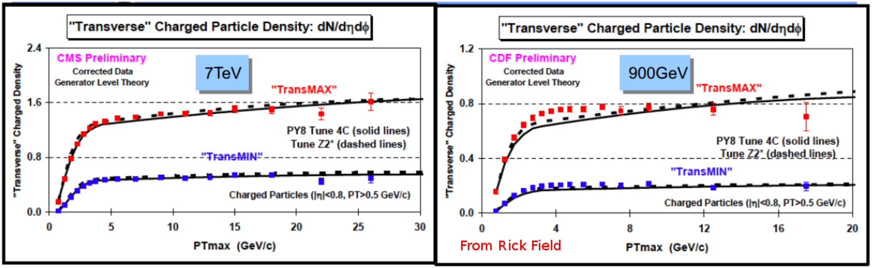
Stay tuned!

GRAZIE PER L'ATTENZIONE

BACKUP SLIDES

Can they be refined?

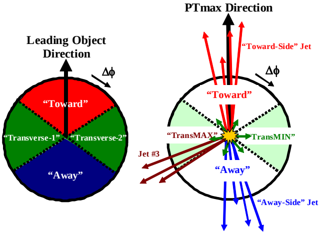
How well do they describe observables at different energy?



From Rick Field

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

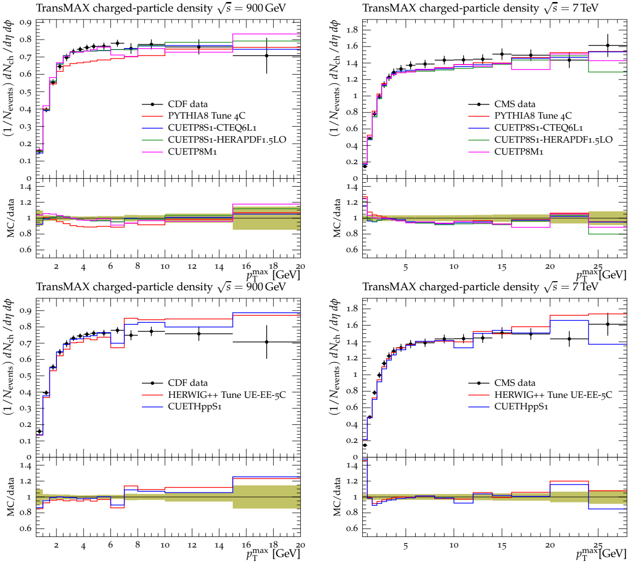
- TRANS MIN: sensitive to MPI
- TRANS MAX: sensitive to MPI and PS
- TRANS DIF: sensitive to PS
- TRANS AVE: sensitive to MPI and PS



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

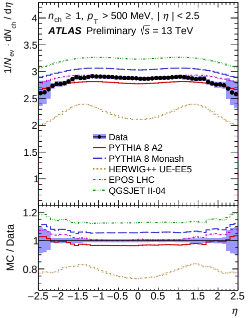
Better constrain of the energy extrapolation

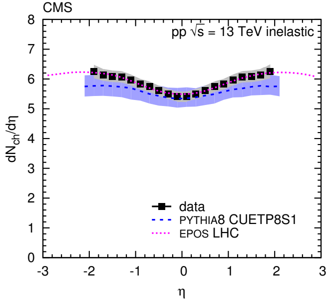
CR changes with the choice of the PDF

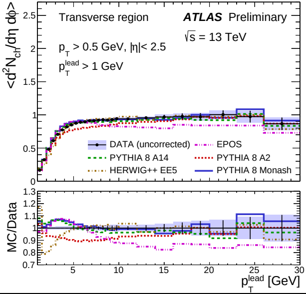
Rising part and plateaux region are well predicted by the new tunes

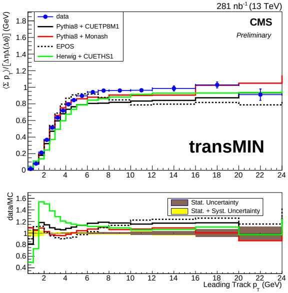
(arXiv 1512.00815)

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

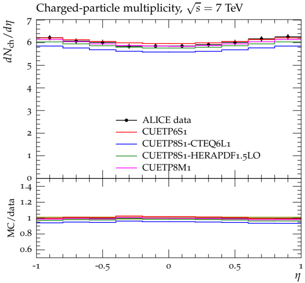
None of the tunes reproduce the data perfectly!

Is the energy dependence of the MPI to be improved in the generators?

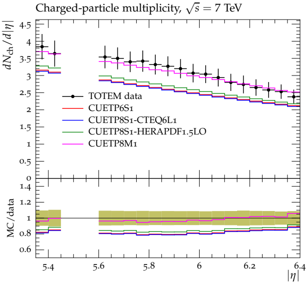
$$p_T^0 = p_T^{ref} \cdot (E/E_{ref})^{\epsilon}$$

What about other observables? (arXiv 1512.00815)

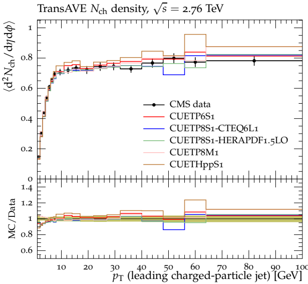
Min. Bias observables ✓



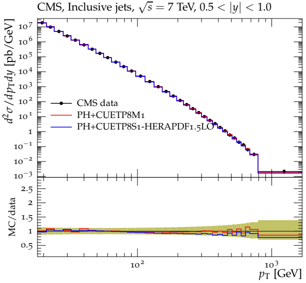
Forward region ✓



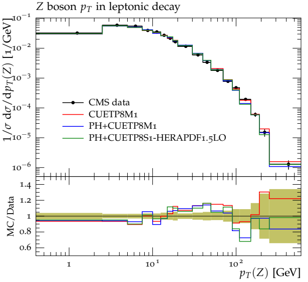
UE vs p_T^{jet} ✓



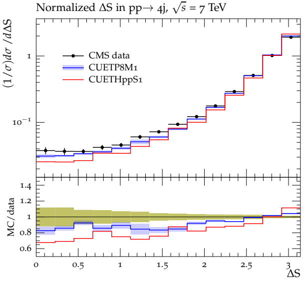
Incl. jet cross sections ✓



Z-boson observables ✓



DPS observables X



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

Tune uncertainties

Nominal tune uncertainty: Set of (MANY) eigentunes obtained from Professor

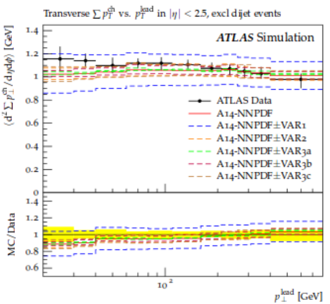
$\rightarrow$ How to reduce the numbers of eigentunes?

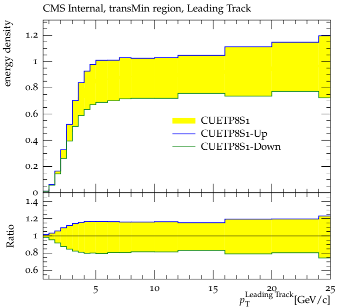
ATLAS strategy ATL-PHYS-PUB-2014-021

Only the pair of eigentunes showing the maximal variation for the considered observables is considered for the uncertainty $\rightarrow$ procedure repeated for different observables

CMS strategy arXiv 1512.00815

Fit of the upper and the lower part of the UE predictions at 13 TeV obtained with full set of eigentunes $\rightarrow$ The new pair of tunes is assigned as uncertainty





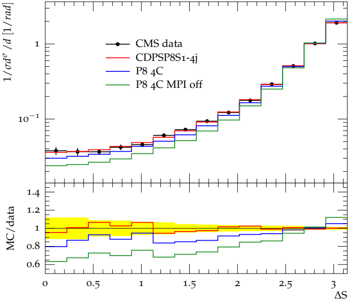
Fundamental question: how can one cover all (most of) physics effects?

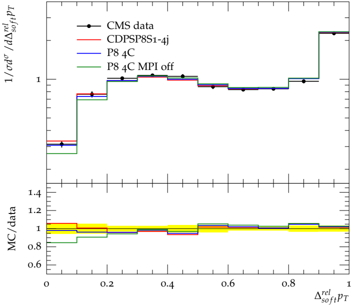
Tuning the four-jet distributions in the tuning range [0.8,2.5]

Parameter	New Tune	4C
MultipleInteractions:expPow	1.160	2.0
+Unc	1.2096	-
-Unc	1.1109	-
Goodness of fit	0.751	-

$$\sigma_{eff} = 21.3^{+1.2}_{-1.6} \text{ mb}$$

$\rightarrow \sigma_{eff}$ (Tune 4C) $\sim$ 30.2 mb





Improved agreement with the new tune

New set of parameters: CDPSP8S1-4j

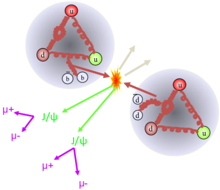
LEFT: ΔS
RIGHT: $\Delta^{rel}_{soft} p_T$

CMS-GEN-14-001

Cross section measurements sensitive to DPS

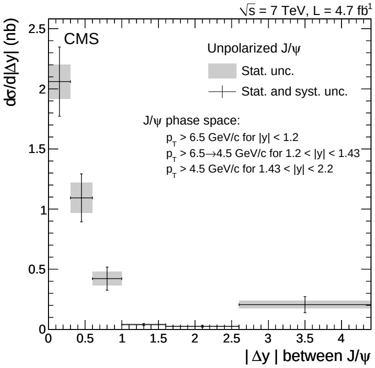
Event selection

Presence of two pairs of same-sign muons in $|\eta| < 2.2$; the two pairs must have invariant mass close to J/ψ



$\sigma(J/\psi J\psi + X)$

1.49±0.07±0.13 nb



Correction and phase-space extrapolation assuming unpolarized production

SPS background should dominate the fall at low Δy

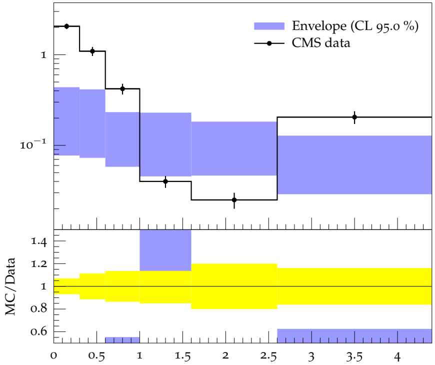
DPS expected to fill the high Δy region

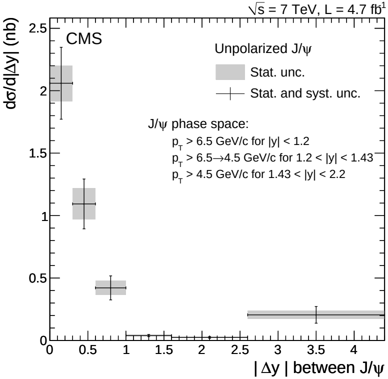
Useful baseline for building reliable models of J/ψ production before extracting DPS signal

Tuning other measurements?

Parameter name	Variation range
MPI p_T regulator	1.5 – 3.5
Overlap matter distr.	0.5 – 3.0

DPS signal expected at high rapidity separation





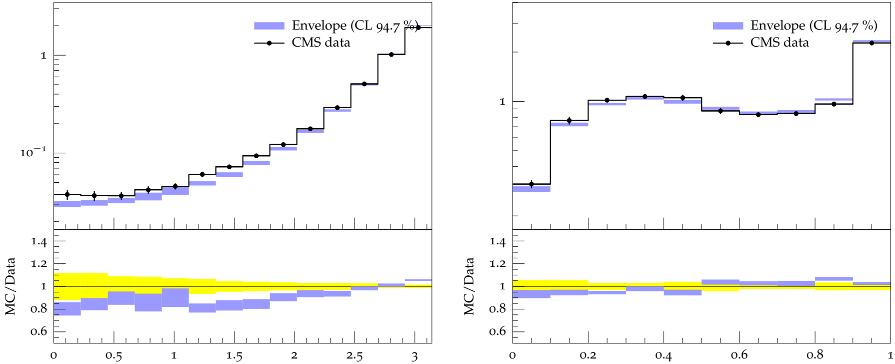
Clearly we need a better model to describe double J/ψ observables

This measurement will not be accounted for in the global DPS fit

Tuning other parameters? (II)

Tuned parameter	Variation range
α_S (hard scattering)	0.1 – 0.15

LEFT: ΔS, RIGHT: $\Delta^{rel} p_T$



By changing the strong coupling of the hard-scattering matrix element, we do not get a good description of these data

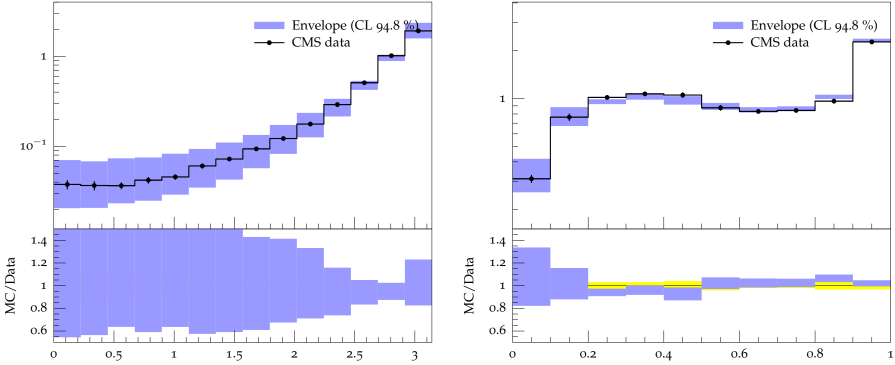
The shape of the ΔS observable does not depend strongly on α_S^{hard}

Tuning other parameters? (III)

Parameter name	Variation range
α_S (final-state radiation)	0.1 – 0.15
α_S (initial-state radiation)	0.1 – 0.15
Primordial k_T	1.5 – 2.0
MPI p_T regulator	1.5 – 3.5
Overlap matter distr.	0.5 – 3.0
ISR p_T regulator	0.75 – 2.5
α_S (MPI)	0.1 – 0.15

LEFT: ΔS,
RIGHT: $\Delta^{rel} p_T$

Full tune in "ATLAS style":
ATL-PHYS-PUB-2014-021



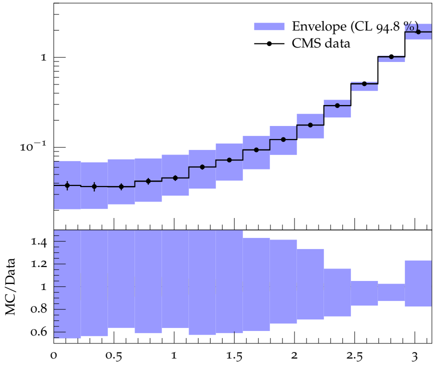
Tuning other parameters? (IV)

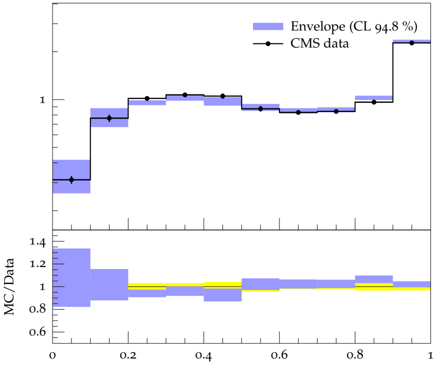
Parameter name	Fit value
α_S (final-state radiation)	0.146
α_S (initial-state radiation)	0.121
Primordial k_T	1.6529
MPI p_T regulator	2.55
Overlap matter distr.	1.79
ISR p_T regulator	0.936
α_S (MPI)	**0.1454**

χ^2**/Ndf = 3.10e-01**

σ_{eff} **= 24.78 mb**

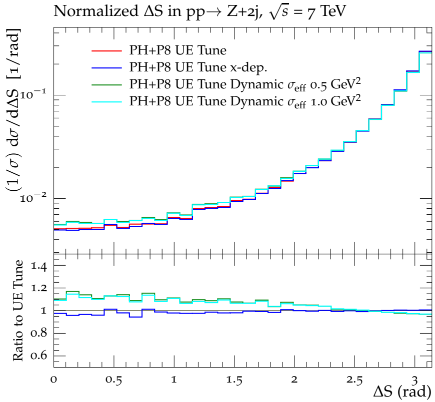
LEFT: ΔS,
RIGHT: $\Delta^{rel} p_T$

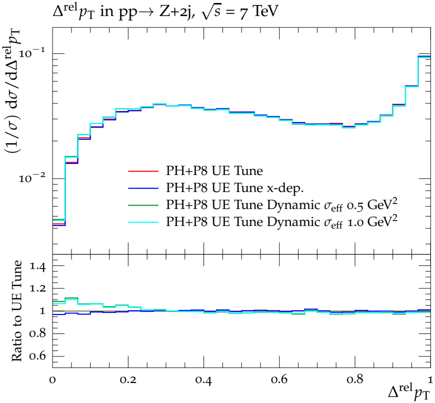




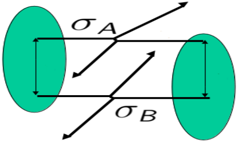
Comparison with DPS measurements in Z+jets

LEFT: ΔS, RIGHT: $\Delta^{rel} p_T$





A double parton scattering (DPS)



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

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

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:

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

It is thus defined:

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

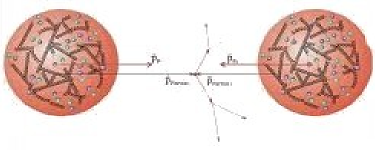
The hard scattering at the LHC

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

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

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!

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($\bar{p}$) data at various $\sqrt{s}$	UE pp($\bar{p}$) 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$\bar{p}$ 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

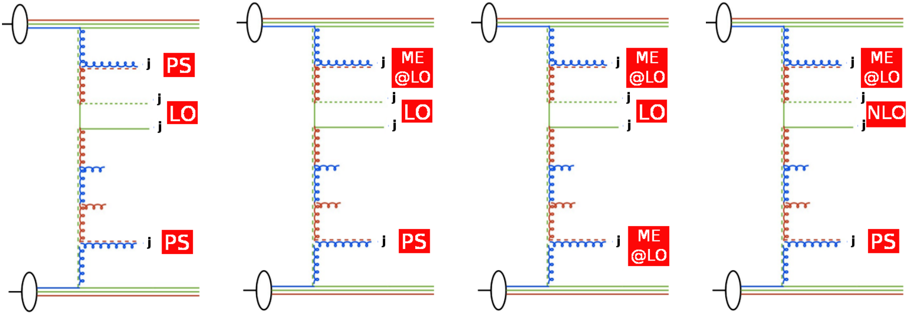
N.B. For the DPS simulation, generators normally use parameters of soft MPI and extrapolate to harder scales

Details of the Monte Carlo generators

AIM: Comparison between data and various MC generators

- 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 | POWHEG



A bit more details..

$$\frac{1}{\sigma_{eff}} \equiv \int \frac{d^2\vec{\Delta}}{(2\pi)^2}[\ _{[2]}G_2(x_1, x_3, Q_1^2, Q_2^2; \vec{\Delta})_{[2]}G_2(x_2, x_4, Q_1^2, Q_2^2; -\vec{\Delta})$$

$$+\ _{[1]}G_2(x_1, x_3, Q_1^2, Q_2^2; \vec{\Delta})_{[2]}G(x_2, x_4, Q_1^2, Q_2^2; -\vec{\Delta})$$

$$+\ _{[1]}G_2(x_2, x_4, Q_1^2, Q_2^2; \vec{\Delta})_{[2]}G_2(x_1, x_3, Q_1^2, Q_2^2; -\vec{\Delta})].$$

x-dependence:

$$\frac{1}{\sigma^0_{eff}} = \frac{1}{2\pi}\frac{1}{\Sigma_i\ f(log[x_0/x_i^{-1}])}$$

Q^2 dependence:

$$R(Q_1^2, Q_2^2, Q_0^2)$$

REMARKS:

→ Inputs of the models are the standard single PDF, and the gluon form factors which are obtained from J/ψ photoproduction measurements in ep collisions

→ R functions are calculated by solving iteratively the nonlinear evolution equations, and the only one free parameter Q_0 is the separation between soft and hard scales

What about possible correlations included? (III)

How is it practically done? - PYTHIA 8

- The "underlying" UE tune is provided by fitting charged particle observables at low scales
- A value of σ_{eff} is calculated through functions obtained from electron-proton collision data
- Reweight the PYTHIA events on an event-by-event basis

Key formula for amount of DPS:

$$\sigma_{eff} = \frac{\sigma^0_{eff}(x_i)}{1+R(Q_j^2)}$$

1. UE Tune: no σ_{eff} reweight
2. UE Tune - Q^2-dep: reweighting vs parton scales
3. UE Tune - x-dep: reweighting vs parton x
4. UE Tune - dynamic σ_{eff}: reweighting vs parton scales and x

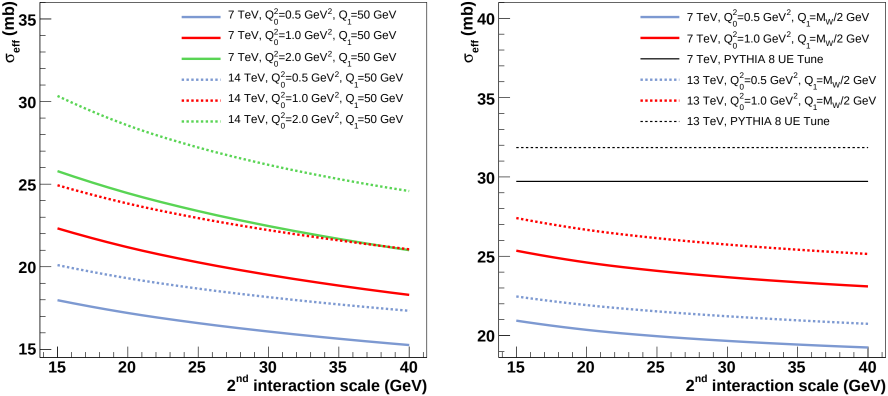
N.B. There is no modification on kinematics of the outgoing partons, but only on the DPS cross section

Dynamic values of σ_{eff} implemented

Different partonic initial states:
gluon-gluon interaction in 4j
quark-quark interaction in Wj

LEFT: four-jet, RIGHT: W+jets

EPJC75 (2015) 6 282, arXiv 1510.07436



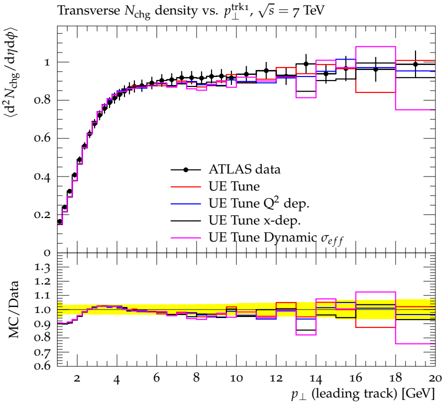
Lower values obtained for gluon-initiated final states

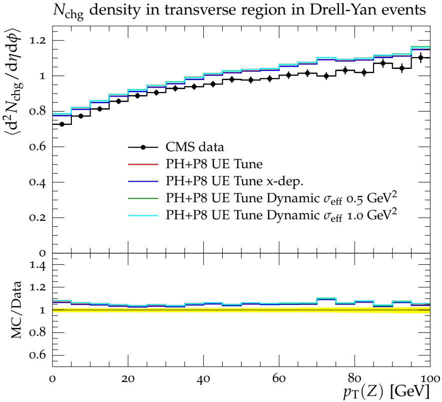
σ_{eff} ranging between 15-25 mb at 7 TeV

Comparison with UE measurements

UE parameters obtained by fitting the low p_T region of observables in hadronic events

Charged particle multiplicity in hadronic (LEFT) and Drell-Yan (RIGHT) events
EPJC75 (2015) 6 282, arXiv 1510.07436





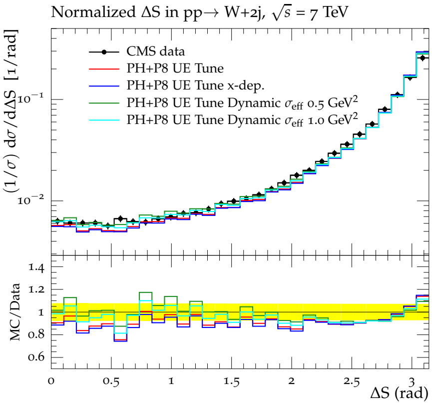
Very good description of both sets of data with all settings

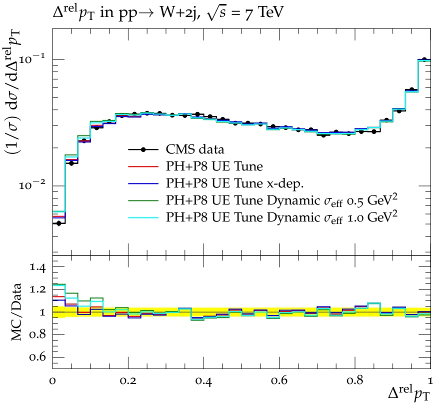
Soft MPI are not sensitive to σ_{eff} variations

Comparison with DPS measurements in W+jets

UE parameters obtained by fitting the low p_T region of observables in hadronic events

LEFT: ΔS, RIGHT: $\Delta^{rel} p_T$
arXiv 1510.07436



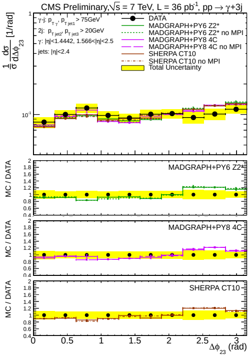


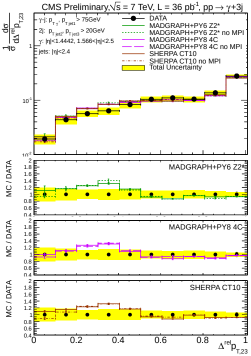
Introducing a dynamic σ_{eff} dependence has a relatively small effect but describes well the measurements

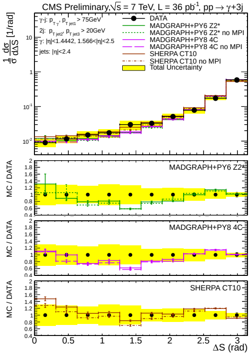
Measurement of a final state with $\gamma +$ 3 jets

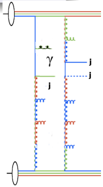
Event selection

Selection of a photon and at least three jets in $|\eta| < 2.5$:
γ+1 jet: $p_T > 75$ GeV, 2 jets: $p_T > 20$ GeV









Soft jets are expected to be produced also by a 2^{nd} scattering

CMS-FSQ-12-017

$$\Delta\phi(j_i, j_k) = \phi_i - \phi_k$$

$$\Delta^{rel}_{soft} p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$$

$$\Delta S = \arccos\left(\frac{\vec{p}_T(\gamma, j^k) \cdot \vec{p}_T(j^l, j^m)}{|\vec{p}_T(\gamma, j^k)| \cdot |\vec{p}_T(j^l, j^m)|}\right)$$

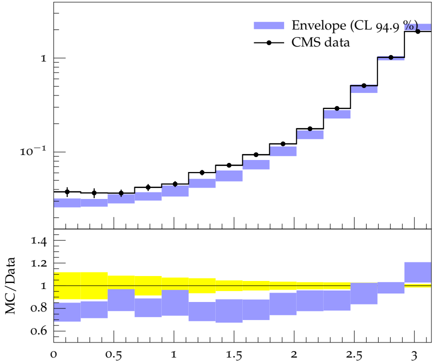
No difference between predictions with and w/o MPI

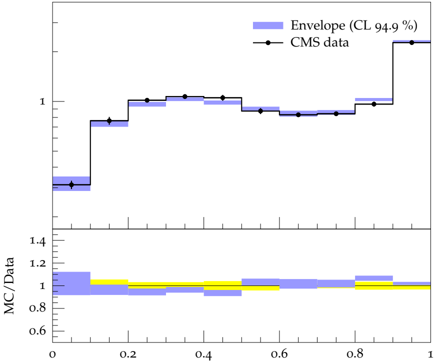
Little DPS sensitivity!

What about tuning other parameters?

Parameter name	Variation range
α_S (initial-state radiation)	0.1 – 0.15
α_S (final-state radiation)	0.1 – 0.15

LEFT: ΔS, RIGHT: $\Delta^{rel} p_T$



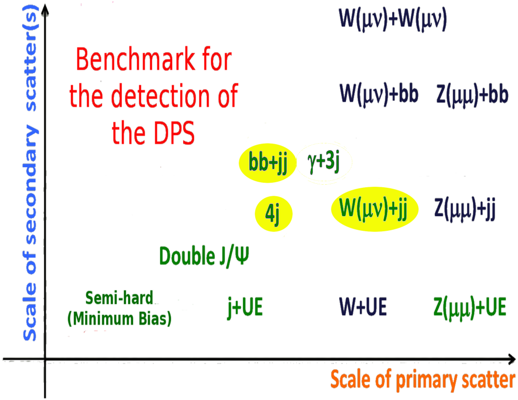


By changing the strong coupling of the parton shower, we do not get a good description of these data

The shape of the ΔS observable does not depend strongly on α_S^{PS}

Where do we stand now?

- Many measurements sensitive to soft and hard MPI in various final states
- Two main research branches:
  - Fit the measurements altogether with the available models
  - New features in the models for an overall coherent picture
- Need for new observables, phase space, and final states



Energy dependence
Channel dependence
Scale dependence
Flavour dependence

Investigation of various models

Large experimental uncertainties

STILL MUCH TO DO!