Signals of Multiple Parton Interactions: current status and future experimental challenges

Paolo Bartalini (China Central Normal University)

Correlations between partons in nucleons

Second International Summer School of the GDR PH-QCD

(30 June – 4 July 2014 LPT Orsay)

References (this school) → lectures of Markus Diehl, Leif Lönnblad, Sarah Porteboeuf-Houssais.

See also the review paper published in Mod.Phys.Lett. A28 (2013) 1330010.

Where can we look for Multiple Parton Interactions?

Credits:
- Ellie Dobson

NOTA BENE:
Multiple Parton Interactions in the same collision vertex!
i.e. here we are not discussing the trivial pile-up effects.

Z(μμ)+Z(μμ)
≈ 0.1 fb

LHC measurements available
LHC measurements not yet available

Complement with
p-A and A-A

The Double Parton Scattering (DPS)

detecting patterns of two (or more)
High-p_T Multiple Parton Interactions

See also the lecture of **Markus Diehl** at this school

Effective cross section σ_{eff}

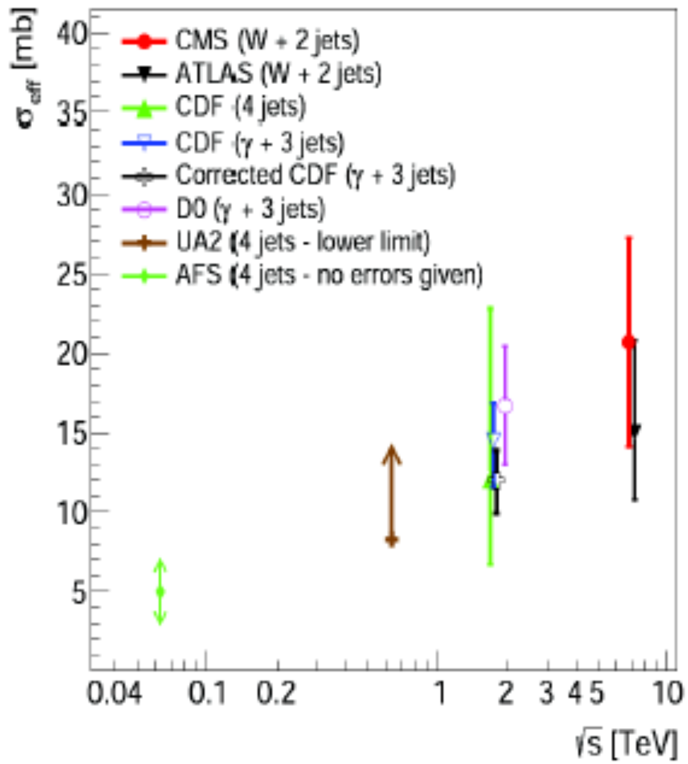
- Ref. "pocket formula" in Markus' lectures [2nd lecture, slides 15-18] derived under the assumption of no correlations in Double Parton Densities: $F(x_A, x_B, b) = f(x_A) * f(x_B) * G(b)$
  - $\sigma_{DPS}(A+B+Y) = m * \sigma(A+Y) * \sigma(B+Y) / \sigma_{eff}$ (m = ½ for identical interactions, m = 1 otherwise)
  - $\sigma_{eff} \approx$ geometrical quantity i.e. in principle scale and √s independent [D. Treleani et al.]
  - Formalism applies to inclusive processes only
- Measurements use the relationship in the following way:
  - $\sigma_{eff} = m * \sigma(A) * \sigma(B) / \sigma_{DPS}(A+B)$ → Probabilistic interpretation: $P(B|A) = P(B) * (\sigma_{Non\text{-}Diffractive}/\sigma_{eff})$
  - Scale and √s independency are not assumed
  - Statistics often limits the possibility to extract σ_{eff} in a differential way
  - First results on 4jets already 30 years ago: AFS , UA2 $\sigma_{eff} < 10$ mb.
  - Tevatron measurements from the years nineties + updates (4jets, 3jet+γ) $\sigma_{eff} \approx 10 \div 15$ mb.
  - LHC (W+2jet, etc.) $\sigma_{eff} \approx 15 \div 20$ mb. Larger systematics from background modeling.

Time

- Predictions
  - Markus quote 36÷41 mb. Correlations matter? Questionable experimental methodologies?
  - significant 3→4 contribution, rising with $x_{Bjorken}$ [B.Blok, MPI@LHC 2013]
  - pQCD Models: σ_{eff} = tune dependent: Pythia 6 & 8 soft MPI tunes $\sigma_{eff} \approx 20 \div 30$ mb
  - Herwig++ proposes a first tune describing both soft and hard MPI [A.Siódmok, MPI@LHC 2013]

Effective cross section σ_{eff}

- Ref. "pocket formula" in Markus' lectures [2nd lecture, assumption of no correlations in Double Parton Densit
  - $\sigma_{DPS}(A+B+Y) = m * \sigma(A+Y) * \sigma(B+Y) / \sigma_{eff}$ (m = ½ for iden
  - σ_{eff} ≈ geometrical quantity i.e. in principle scale and √s in
  - Formalism applies to inclusive processes only
- Measurements use the relationship in the followi
  - $\sigma_{eff} = m * \sigma(A) * \sigma(B) / \sigma_{DPS}(A+B)$ → Probabilistic interpr
  - Scale and √s independency are not assumed
  - Statistics often limits the possibility to extract σ_{eff} in a dif
  - First results on 4jets already 30 years ago: AFS , UA2 σ_{eff}
  - Tevatron measurements from the years nineties + updat
  - LHC (W+2jet, etc.) σ_{eff} ≈ 15÷20 mb. Larger systematics fro



- Predictions
  - Markus quote 36÷41 mb. Correlations matter? Questionable experimental methodologies?
  - significant 3→4 contribution, rising with $x_{Bjorken}$ [B.Blok, MPI@LHC 2013]
  - pQCD Models: σ_{eff} = tune dependent: Pythia 6 & 8 soft MPI tunes σ_{eff} ≈ 20÷30 mb
  - Herwig++ proposes a first tune describing both soft and hard MPI [A.Siódmok, MPI@LHC 2013]

Some DPS figures for pp at $\sqrt{s}$ = 14 TeV

- σ_{DPS} **(4jets@100 GeV)** = ½ * $(\sigma\,(2jets))^2/\sigma_{eff}$ = ½ * $(1\mu b)^2/\sigma_{eff}$ = $5\ 10^{-5}\ \mu b$ = **50 pb**
  - apply extra **1%** factor for each b-jet pair requirement
- σ_{DPS} **(2γ+2jets@20 GeV)** = ½ * $(\sigma\,(\gamma+jet))^2/\sigma_{eff}$ = ½ * $(0.1\mu b)^2/\sigma_{eff}$ = $5\ 10^{-7}\ \mu b$ = **0.5 pb**

Present

- σ_{DPS} **($W^\pm \rightarrow \mu\nu$, $W^\pm \rightarrow \mu\nu$)** = ½ * $(\sigma\,(W^\pm \rightarrow \mu\nu))^2/\sigma_{eff}$ = ½ * $(20nb)^2/\sigma_{eff}$ = $2\ 10^{-5}$ nb = **20 fb**
  - half of which (**10 fb**) corresponds to same sign muons
- σ_{DPS} **($Z \rightarrow \mu\mu$, $Z \rightarrow \mu\mu$)** = ½ * $(\sigma\,(Z \rightarrow \mu\mu))^2/\sigma_{eff}$ = ½ * $(2nb)^2/\sigma_{eff}$ = $2\ 10^{-7}$ nb = **0.2 fb**

Future, including HL-LHC

σ_{eff} = 10 mb is assumed to allow for possible easy rescaling

Inferring the DPS content: basic experimental guidelines

Connection to theory

- For the time being the effective cross section (σ_{eff}) should be regarded as the most natural link to the theory.
- Using particle level observables is desirable: it makes the comparison to TH predictions more straightforward.
- √s and scale (in)dependency should not be assumed, they should be rather tested/measured although the first benchmark measurements should focus on simpler tasks **(DPS observation?)**.
- Process dependency is studied considering the global picture of DPS measurements.
- Inclusive measurements.

→Although exclusive measurements may be interesting, don't forget that they don't allow to apply the σ_{eff} formalism directly.

→Let's use more than one DPS observable, quoting the corresponding systematic uncertainty.

Data oriented approaches?

- **When modeling the DPS signal with two separate interactions (for example in a data oriented way) we are making several approximations, in particular we clearly violate energy conservation, possible flavor effects (which are expected to be huge in the case of two interactions from valence quarks), possible color effects, spin correlations etc.**
- Although data oriented modeling is welcome, one should always x-check the effect of these correlations within the available MPI models.

Inferring the DPS content: basic experimental guidelines (contd.)

MC matters, often it is the only way to define SIGNAL and/or BACKGROUNDS in DPS analyses

- Parton Showers are wonderful tools but a deep understanding of what they can do (soft emissions, small angles) and what they cannot do (hard emissions, large angles) is necessary in order to avoid trivial mistakes.
- In particular, backgrounds often deal with the description of several hard objects produced in a Single Parton Scattering (SPS). In the case of jets in the final state, the appropriate number of extra-emissions in the Matrix Elements along with matching to the Parton Shower have to be used. **I will give a practical example in the case of W+2jets @ LHC.**

→ Let's put enough "brain" in the Matrix Elements used in BACKGROUND description otherwise one may easily end-up overestimating the DPS content.

- ALWAYS MAKE SURE that SIGNAL+BACKGROUND(S) cover the full phase space.

→IF SIGNAL IS "2nd interaction ABOVE a given scale (for example given by the jet p_T)" THEN BACKGROUND IS NOT MPI OFF IT IS RATHER "2nd interaction BELOW a given scale".

(switching off MPI also turns out to screw-up basic observables like UE, isolations etc.)

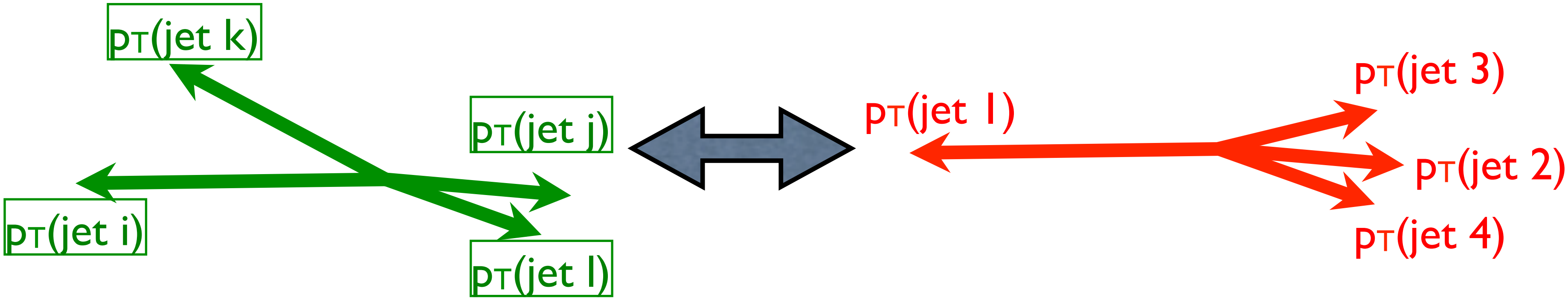
→Let's use more than one MC, quoting the corresponding systematic uncertainty.

The Double Parton Scattering (a)

in final states with jets

Double Parton Scattering in 4 "objects" topologies

Disentangle double-parton-scattering from bremsstrahlung



- No correlation (DPS) vs Strong correlation (SPS)

After **PAIRING**, one can define different correlation angles between jet pairs:

AFS solution:

- Study $\Delta\varphi$ between p_{T1} - p_{T2} and p_{T3} - p_{T4}

CDF solution:

- Study $\Delta\varphi$ between p_{T1} + p_{T2} and p_{T3} + p_{T4} (CDF nomenclature: ΔS)

Measurement of DPS @ Tevatron (3jet + γ)

Double high P_T interactions observed by AFS, UA2 and CDF in 4jets topologies.
CDF and D0 use also 3jet + γ
IMPROVED PAIRING!

Effect of triple interactions:

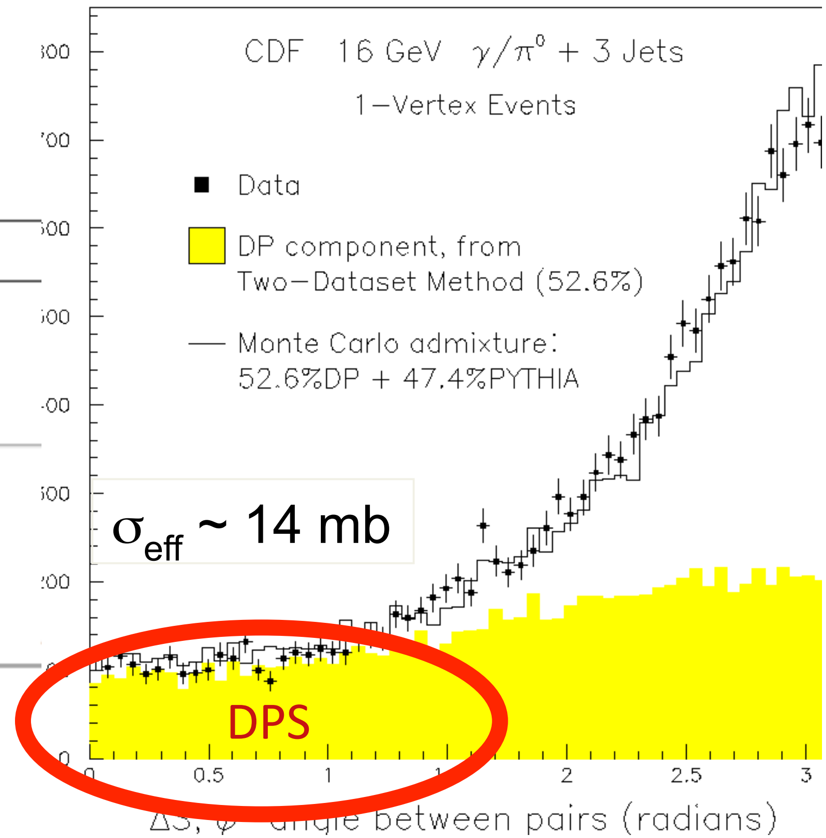
→ σ_{eff} ~ 11 mb

[Treleani et al., PRD76:076006,2007]

(based on the CDF paper)

	CDF
Photon	$\lvert\eta\rvert \leq 1.1$
	$E_T \geq 16$ GeV
	Cone $R = 0.7$
Jets	$\lvert\eta\rvert \leq 4.2$
	$E_T > 5$ GeV
	$\boxed{E_{T4} < 5\ \mathrm{GeV}}$
	$E_{T2}, E_{T3} < 7$ GeV

[CDF Collab, Phys. Rev. Lett. 79, 584 (1997)]



D0: σ_{eff} ~ 16 mb [Phys.Rev. D81 (2010) 052012]
+ recent update with HF jets [arXiv:1402.1550]

Are the SIGNAL and BACKGROUND templates used in these analyses reliable?

- A lot of emphasis in the definition of a data oriented methodology for the SIGNAL

- However the big issue is the BACKGROUND modeling:

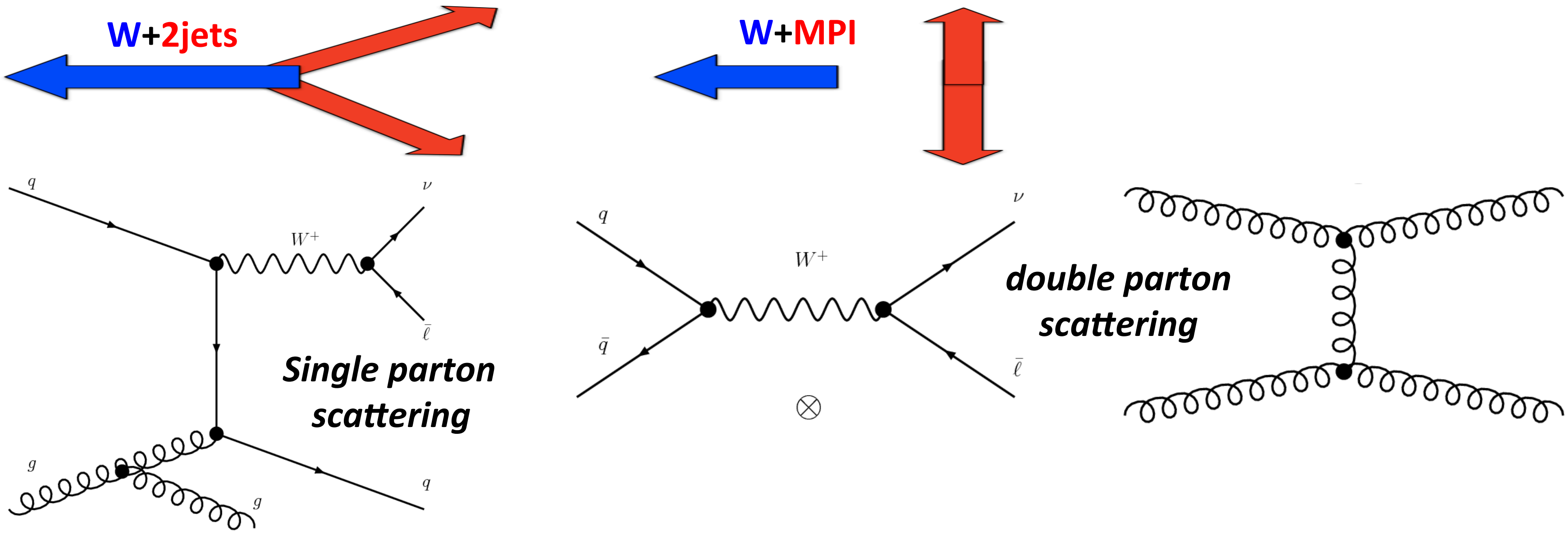
Single Parton Scattering (SPS) with direct photon and three extra jets is not trivial at all (modern ME tools badly needed but these tools were not available in the last century…)

The Double Parton Scattering (b)

looking for extra di-jets in events with heavy bosons

(the W+2jets benchmark)

ATLAS: W → lν + 2 jets



$$d\sigma^{(tot)}_{W+2j}(s) = d\sigma^{(dir)}_{W+2j}(s) + d\sigma^{(DPI)}_{W+2j}(s)$$

- **Measure fraction of $W_0 + 2j_{DPI}$ in the W+2jet sample** $f^{(D)}_{DP} = \frac{N_{W_{0j}+2j_{DPI}}}{N_{W+2j}} = \frac{N_{W_{0j}+2j_{DPI}}}{N_{W_{2j}} + N_{W_{0j}+2j_{DPI}}}$
    - **use difference in kinematics (p_T, …)**
- **Extract σ_{eff}**

$$\sigma_{\rm eff} = \frac{N_{W_{0j}}\, N_{2j}}{f^{(D)}_{DP} \cdot N_{W+2j}} \cdot \frac{1}{\varepsilon_{2j}} \cdot \frac{1}{\mathscr{L}_{2j}}$$

W selection

Single lepton trigger
1 lepton (e, μ) p_T > 20 GeV, η < 2.5
MET > 25 GeV, m_T > 40 GeV

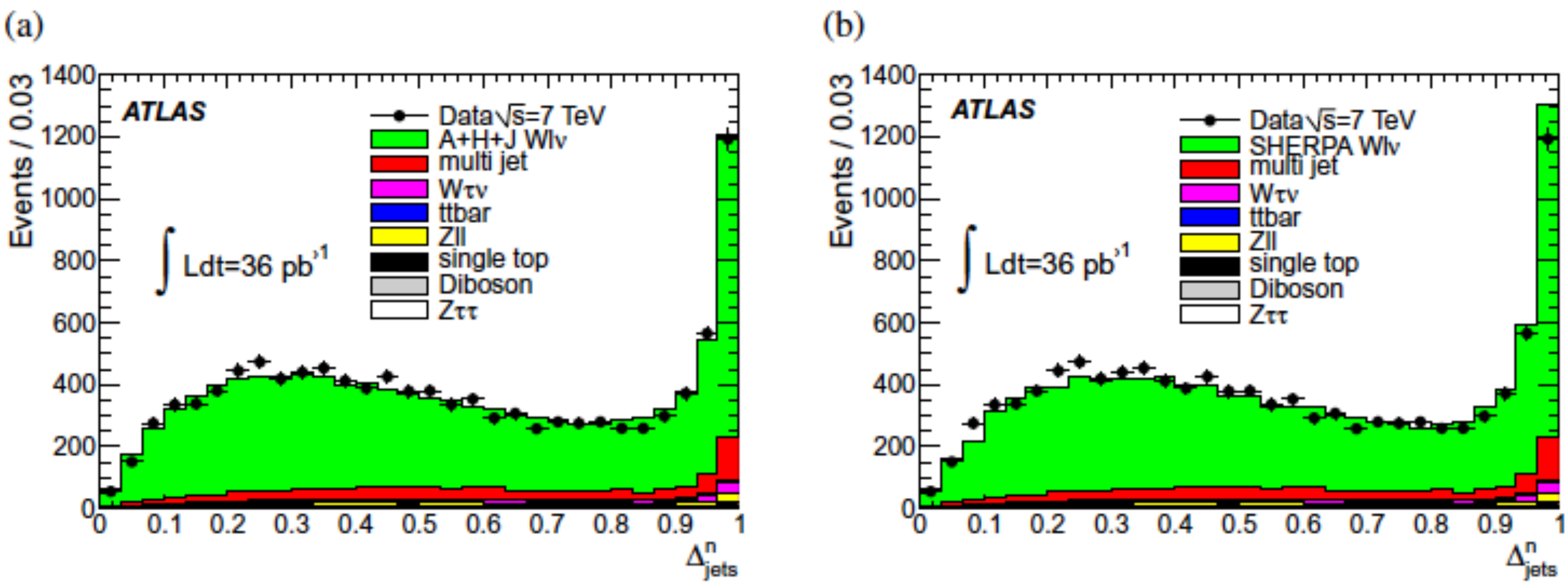
Jet selection

(Minimum bias trigger used to measure di-jet x-section alone)
2 jets, p_T > 20 GeV, |η| < 2.8

New J.Phys. 15 (2013) 033038.

ATLAS: W → lν + 2 jets : DPS Rate

- Focusing on the jet p_T balance in the transverse plane: $\Delta^n_{jets} = |p_{jet1}+p_{jet2}|/(|p_{jet1}|+|p_{jet2}|)$
- Two different MC sets used to describe the inclusive W production:
  Alpgen+Herwig+Jimmy (A+H+J) reported on the left plot and Sherpa reported on the right plot.
- Notice that inclusive W production contains both the SPS and the DPS components
- Of course other (i.e. non W) Standard Model backgrounds need to be taken into account.



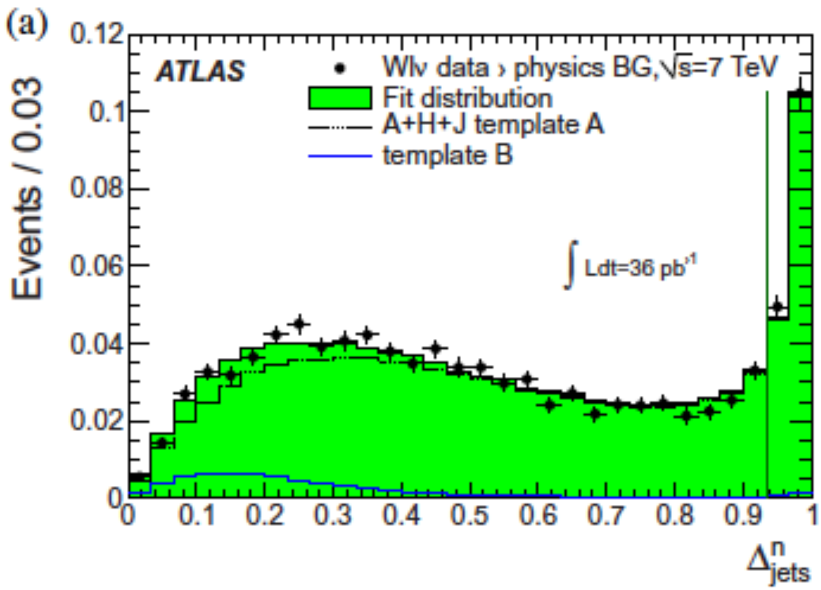
DPS signal expected at small Δ^n_{jets}
(back-to-back di-jet in transverse plane).

New J.Phys. 15 (2013) 033038.

ATLAS: W → lν + 2 jets : DPS Rate

- Subtraction of other (i.e. non W) Standard Model Backgrounds.
- Extraction of f^{R}_{DP} using fit to data with two templates:
- Template A (SPS sample): both jets originate from the primary scatter (MC relying on ME tools)
- Template B (DPS sample): both jets originate from the DPS scatter (from data).

$$(1- f^{(D)}_{DP})*A + f^{(D)}_{DP}*B$$



$$f^{(D)}_{DP} = 0.076 \pm 0.013\ (\text{stat.}) \pm 0.018\ (\text{sys.})$$

Table 1. Summary of the fractional uncertainties on $f^{(D)}_{DP}$

Systematic source	Uncertainty (%)
Theory	10
Pile-up	13
Jet energy scale	12
Jet energy resolution	8
Background modelling and lepton response	11
Total systematic	24
Total statistical	17

Signal at small Δ^{n}_{jets}
(back-to-back di-jet in transverse plane).

$$\sigma_{\text{eff}}(7\ \text{TeV}) = 15 \pm 3\ (\text{stat.})\ ^{+5}_{-3}\ (\text{syst.})\ \text{mb}.$$

New J.Phys. 15 (2013) 033038.

Bottom line on ATLAS W → lν + 2 jets

☺ Low luminosity. Good for pile-up rejection.

☺ Exclusive W+jets: no ambiguity in the choice of the DPS-jets candidates.

☺ Data oriented signal.

☺ Usage of modern ME tools for the background description (SHERPA etc.)

☺ First DPS result at the LHC (consistent with previous measurements at lower energies).

The measurement is not inclusive however the appropriate formalism is used to compute σ_{eff}

Hybrid SPS (from MC) vs DPS (from DATA) makes hard to guarantee the unitarity requirement.

☹ The analysis relies on just one DPS observable.

☹ Statistical uncertainty is significant (comparable to the sum of systematic uncertainties).
→ Integrated luminosity 36 pb^{-1} only.

DPS Observables in $W \rightarrow l\nu$ + 2 jets + X analysis

Using different observables may bring to significant differences in σ_{eff} extraction (see for example the talk of R.Kumar to the 4th MPI@LHC, CERN, December 2012).

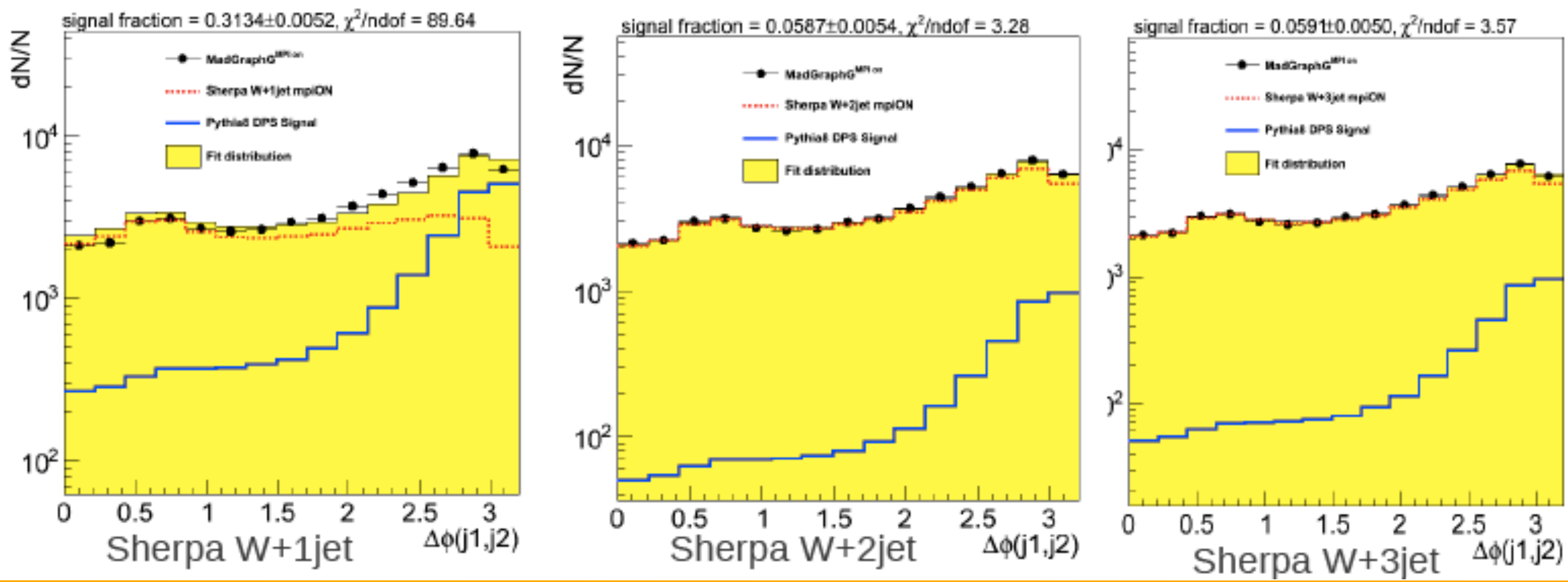
- $\Delta\phi$ (also called S_{ϕ}(2jets))
  - Angle between the momenta of the extra-jets projected in the transverse plane.
- $\Delta^{rel} p_T$ (also called Δ^{n}_{jets} and S_{pT}(2jets))
  - $|p_{jet1}+p_{jet2}|/(|p_{jet1}|+|p_{jet2}|)$ where p_{jet1} and p_{jet2} are the jet momenta projected in the transverse plane.
- Δp_T (also called Δ_{jets})
  - $|p_{jet1}+p_{jet2}|$ where p_{jet1} and p_{jet2} are the jet momenta projected in the transverse plane.
- ΔS
  - Angle between total momenta of paired objects projected in the transverse plane.
  - Widely used in published DPS phenomenology (3jet+γ analyses)

Pseudo-data experiment
(data = Madgraph W+3jets matched to Pythia 6 with MPI on)

MC = Sherpa W+njets with MPI on, Extra-DPS-Signal = Pythia 8 W+2jets DPS

Fitted DPS Signal fraction and reduced χ^2 reported in the table

MC	$\Delta\phi$	$\Delta^{rel} p_T$	ΔS
Sherpa W+0 jet mpi on	17.05+-0.75, 15.18	5.32+-0.48, 25.14	8.32+-0.41, 40.51
Sherpa W+1jet mpi on	31.34+-0.52, 89.64	23.16+-0.031, 286.29	9.84+-0.030, 32.24
Sherpa W+2jet mpi on	**5.87+-0.54, 3.28**	**6.68+-0.29, 5.81**	**5.55+-0.25, 2.64**
Sherpa W+3jet mpi on	**5.91+-0.50, 3.57**	**6.66+-0.29, 5.09**	**3.48+-0.25, 0.90**



Pseudo-data experiment (data = Madgraph with MPI on)

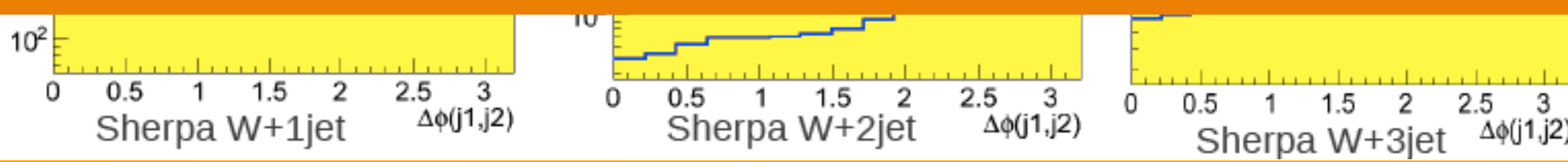
MC = Sherpa W+njets with MPI on, Extra-DPS-Signal = Pythia 8 W+2jets DPS

Fitted DPS Signal fraction and reduced χ^2 reported in the table

MC	$\Delta\phi$	$\Delta^{rel}\, p_T$	ΔS
Sherpa W+0 jet mpi on	17.05+-0.75, 15.18	5.32+-0.48, 25.14	8.32+-0.41, 40.51
Sherpa W+1jet mpi on	31.34+-0.52, 89.64	23.16+-0.031, 286.29	9.84+-0.030, 32.24
Sherpa W+2jet mpi on	**5.87+-0.54, 3.28**	**6.68+-0.29, 5.81**	**5.55+-0.25, 2.64**
Sherpa W+3jet mpi on	**5.91+-0.50, 3.57**	**6.66+-0.29, 5.09**	**3.48+-0.25, 0.90**

Conclusions:

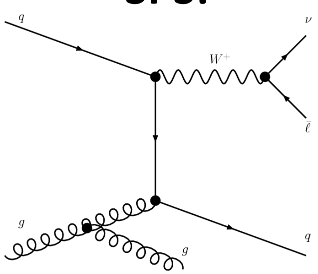
- Uncertainties and bad fit seen for W+0jet, W+1jet indicate that we can trust only ME tools having at least 2 extra emissions → general purpose MCs ruled out.
- Identical results in rows for W+2jet and W+3jet indicate that adding the 3rd emmission does not affect the results in a significant way.
- Fitted signal fraction significantly different from 0% means that Sherpa and Madgraph tunes have different intrinsic DPS content. MadGraph+tune has more DPS than Sherpa+DPS.
- The choice of the observable influence the quoted DPS fraction.



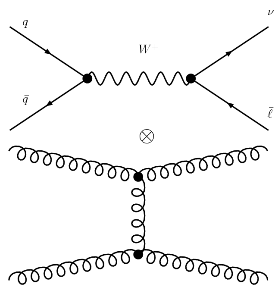
CMS: DPS in W → $\mu\nu$ + 2 jets

Along the lines of the ATLAS experience [New J.Phys. 15 (2013) 033038] with more MCs, Unfolding, higher stat, more observables, etc.

SPS:



DPS:



→ DPS signal fractions from fit to templates

Data:

Full 2011 collision data at √s = 7 TeV, Single Muon data streams with integrated luminosity of ~ 5 fb^{-1}

High stat.

Event selection:

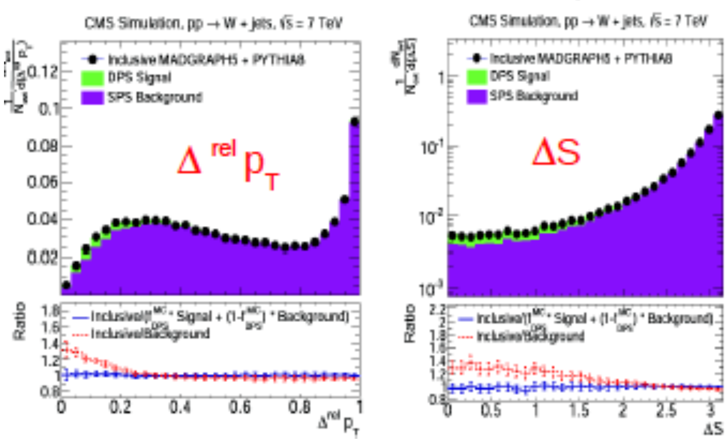
Unfolding

- **Exactly one μ**
- **with p_T > 35 GeV, $|\eta| < 2.1$**
- **Required to be isolated and to pass tight ID criteria**
- **particle flow Missing Transverse Energy, MET > 30 GeV**
- **transverse mass of (μ and MET) > 50 GeV**
- **Exactly 2 anti-KT jets with pT > 20 GeV and $|\eta| < 2.0$**

(not inclusive, need correction to use the σ_{eff} formalism)

$\Delta^{rel} p_T = \Delta^{n}_{jets}$ (ATLAS terminology) = relative p_T balance of the di-jet system.

ΔS = Angle between total momenta of paired objects ($\mu\nu$, di-jet) projected in the transverse plane.

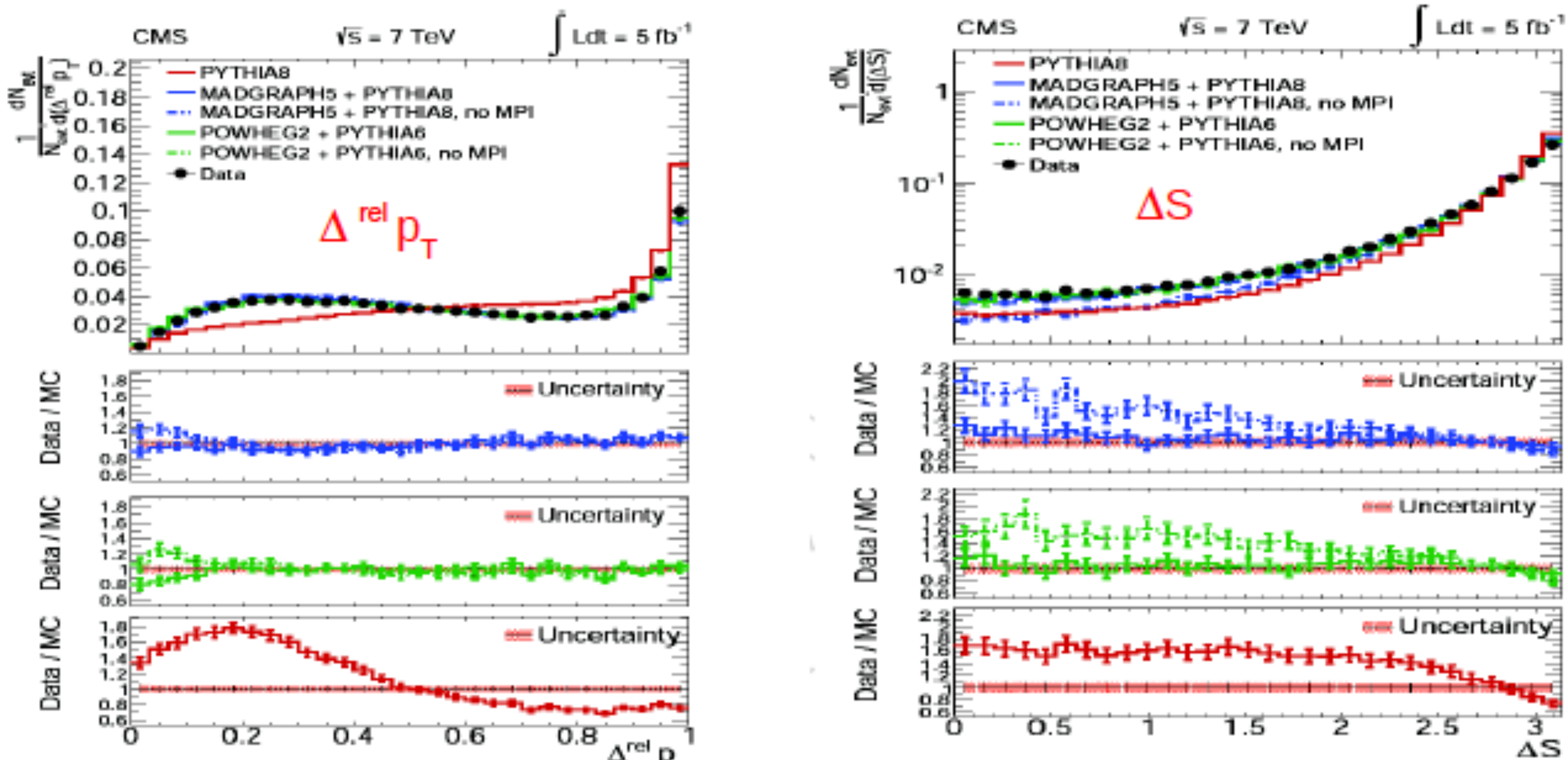


- **Signal at small ΔS (DPS is flat while SPS is peaked at π) and small $\Delta^{rel} p_T$ (back-to-back di-jet in transverse plane).**
- **Signal Template combining W+0jets and di-jet samples.**
- **Backg. Template Madgraph+Pythia 8 (no jets from MPI).**
- **No Signal/Background overlap or phase space gaps.**
- **DPS signal fraction from simultaneous fit to $\Delta^{rel} p_T$ and ΔS.**
- **Extract σ_{eff} from signal fraction.**

[S.Bansal, 5th MPI@LHC, Antwerp December 2013]

CMS: W → lν + 2 jets – Data vs Models (particle level)

- W + 2-jet cross section; 53.4 ± 0.1 (stat.) ± 7.6 (syst.), consistent with MC



- Pythia8 fails; due to missing contribution of higher order processes.
- LO (MG + Pythia) and NLO (Powheg + Pythia/Herwig6) MCs provide same level of agreement with the measurement.
- Both LO and NLO calculations fails in absence of MPI. *Next step is to extract contribution of hard MPI*

[S.Bansal, 5th MPI@LHC, Antwerp December 2013]

CMS: W → lν + 2 jets – Extraction of σ_{eff}

Measured di-jet x-section

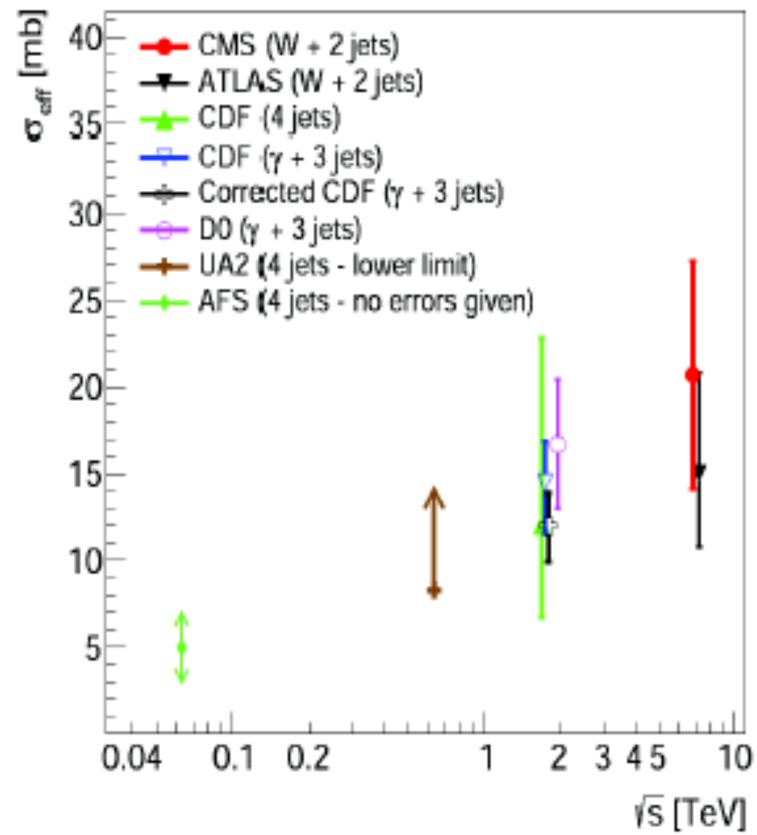
Measured Ratio between W+2jets and W+0jets x-sections

$$\sigma_{\rm eff} = \frac{R}{f_{\rm DPS}} \cdot \sigma'_{2j}$$

- Combining all inputs, σ_{eff} calculated to be:

  20.7 ± 0.8 (stat.) ± 6.5 (syst.) mb

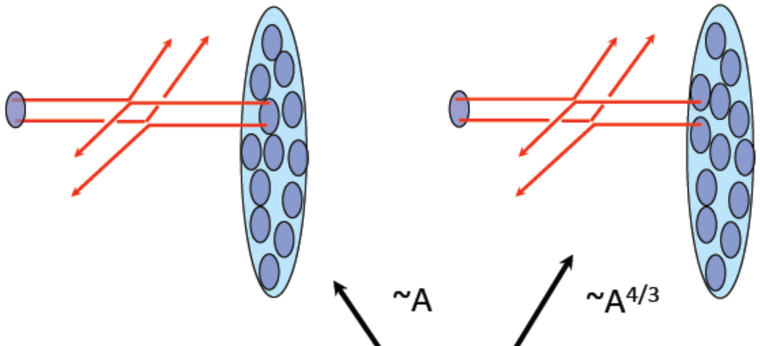
- Measured value is consistent (within uncertainties) with the previous results by ATLAS, CDF, and D0.
- Large uncertainties: can not conclude dependence on collision energy.
- Consistent with value obtained for Herwig++ by fitting UE data from LHC and Tevatron.
- Pythia ~ 20-30 mb (tune dependent).



Main systematics from SPS background modeling

[S.Bansal, 5th MPI@LHC, Antwerp December 2013]

DPS in pA collisions: W(→lν)+2jet



$$\sigma_D^A = \sigma_D^A|_1 + \sigma_D^A|_2$$

$$\sigma_D^{pA}(WJJ)|_1 = \frac{1}{\sigma_{eff}}\left[Z\sigma_S^{p[p]}(W)\sigma_S^{p[p]}(JJ) + (A-Z)\sigma_S^{p[n]}(W)\sigma_S^{p[n]}(JJ)\right]$$

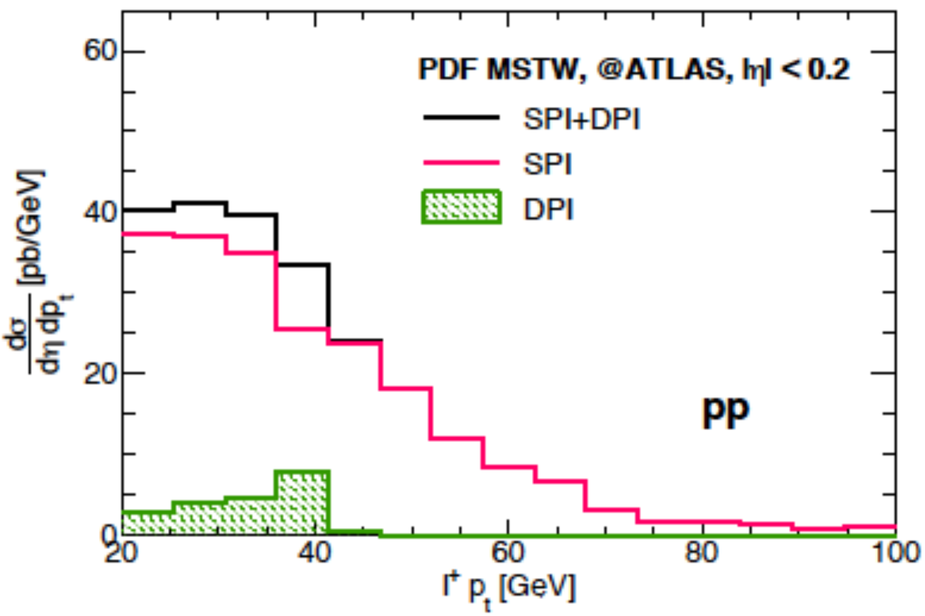
$$\sigma_D^{pA}(WJJ)|_2 = K\left[\frac{Z}{A}\sigma_S^{pp}(W) + \frac{A-Z}{A}\sigma_S^{pn}(W)\right]\sigma_S^{pp}(JJ) \times \left[\int T(B)^2 d^2B - 2\int \rho(B,z)^2 d^2B dz \times r_c \mathcal{C}_K\right]$$

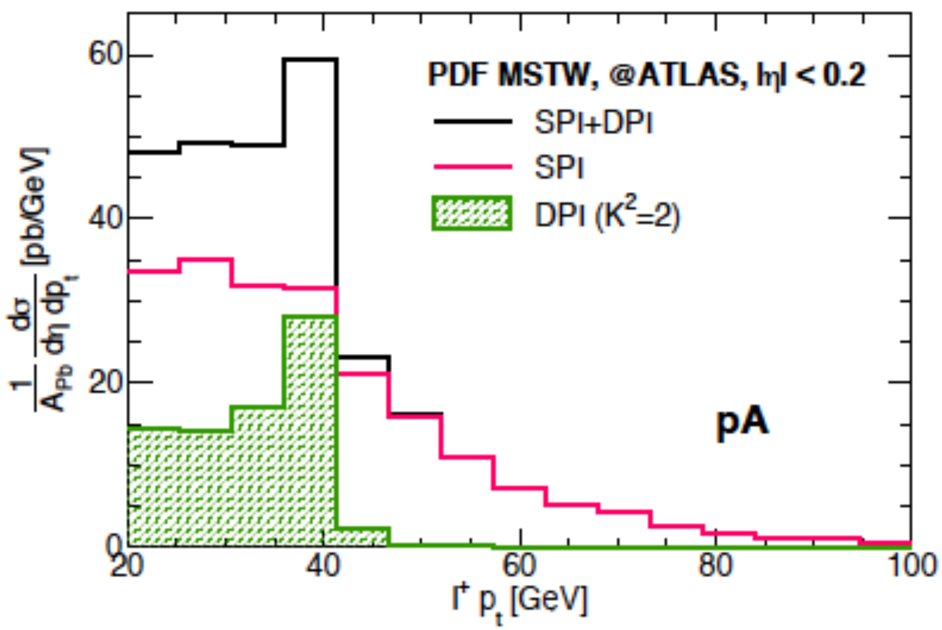
anti-shadowing contribution

short range nuclear correlation

nuclear thickness function => growth as A$^{4/3}$

nuclear density => growth as A





[D.Treleani, MPI@LHC 2013, Antwerpen]

Enhanced shoulder at ≈ 40 GeV in pA interactions!

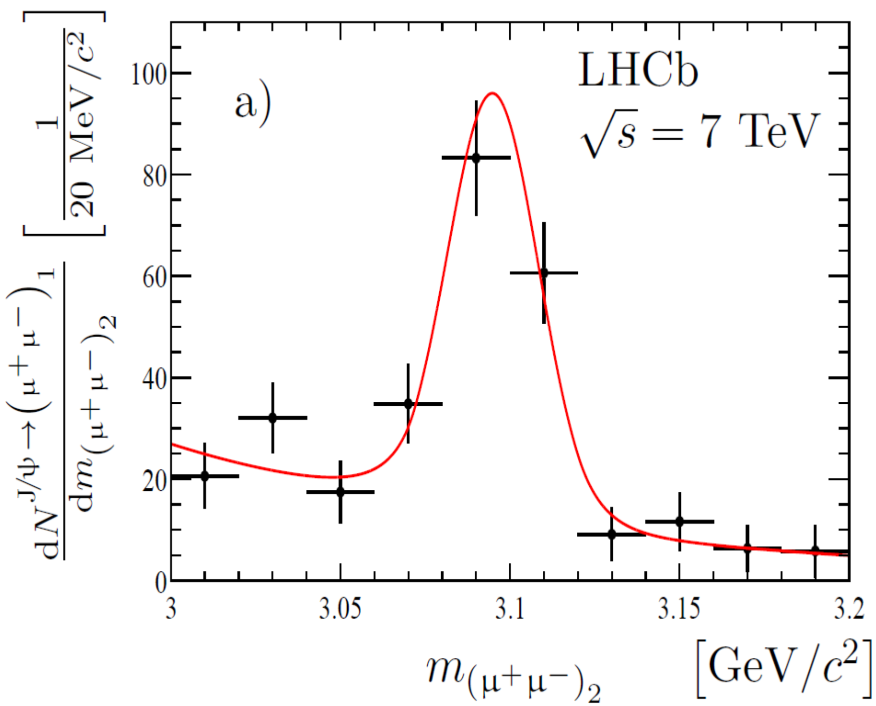
The Double Parton Scattering (c)

the charm laboratory

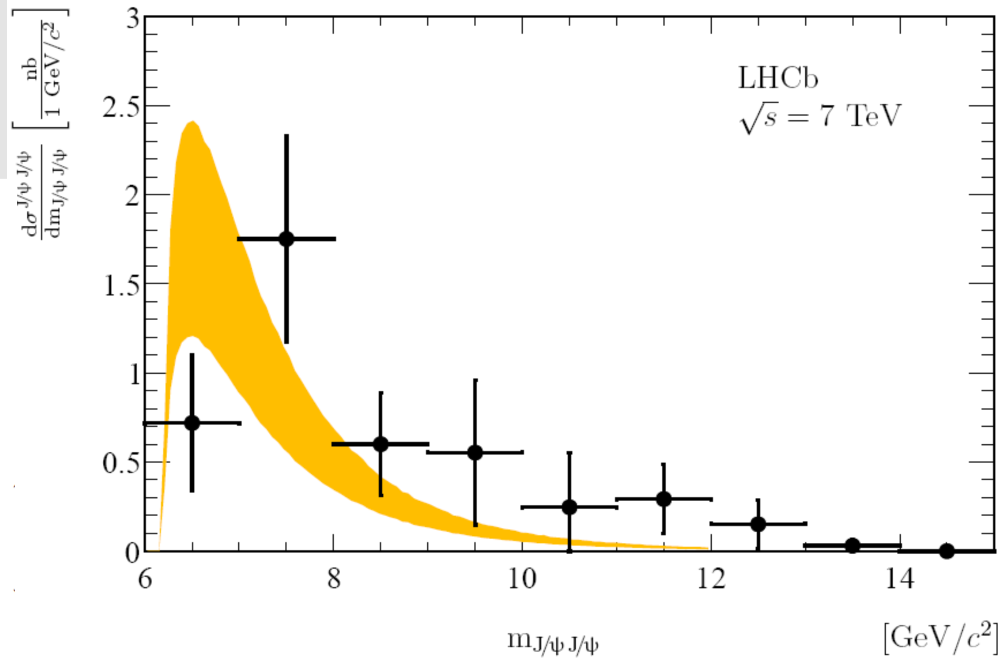
LHCb: Double J/ψ Production

$p_T^{\mu} > 650$ MeV ($\mu^+\mu^-$ channel)
$3.0 < m_{\mu^+\mu^-} < 3.2$ GeV, $2 < y^{J/\psi} < 4.5$,
$p_T^{J/\psi} < 10$ GeV

2×J/ψ : fit one μμ-mass in bins of another μμ-pair mass: 141±19 events



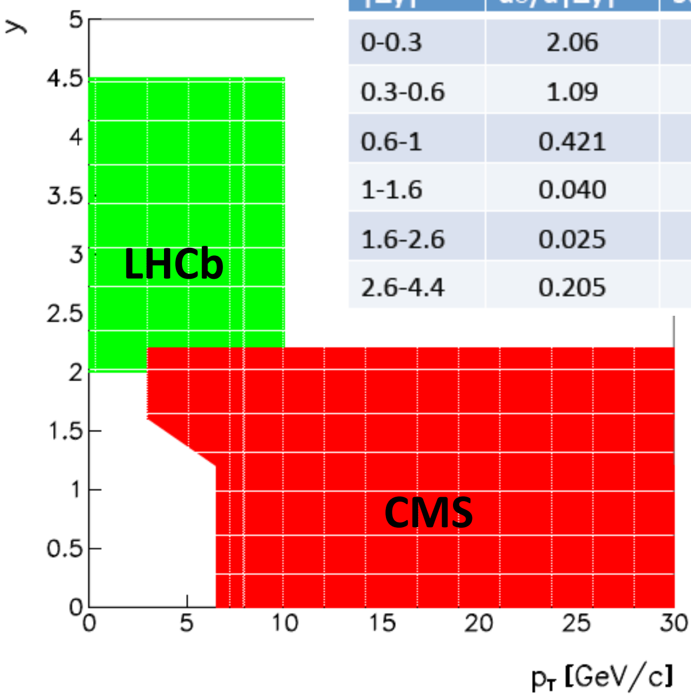
SPS Prediction for $m_{J/\psi J/\psi}$ (in orange) includes direct production and feed down from ψ(2S).



$\sigma^{J/\psi J/\psi}$ = 5.1 +- 1.0 (stat) +- 1.1 (syst) nb i.e. around 20% higher than the SPS predictions → contribution from DPS?

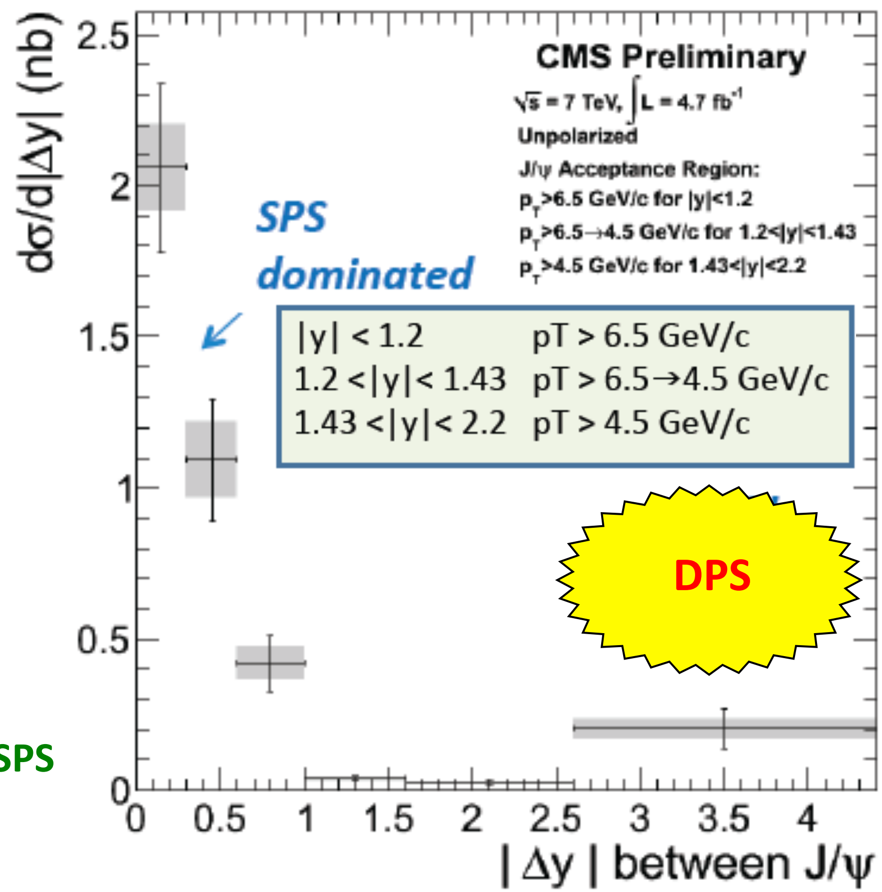
See [S.P. Baranov, A.M. Snigirev, N.P. Zotov, Phys. Lett. B 705 (2011) 116–119]

CMS: Double J/ψ production



nb

$\|\Delta y\|$	$d\sigma/d\|\Delta y\|$	Stat. Err.	Syst. Err.
0-0.3	2.06	0.143	0.251
0.3-0.6	1.09	0.125	0.156
0.6-1	0.421	0.057	0.077
1-1.6	0.040	0.006	0.006
1.6-2.6	0.025	0.005	0.005
2.6-4.4	0.205	0.033	0.058



Evidence for excess at $|\Delta y| > 2.6$

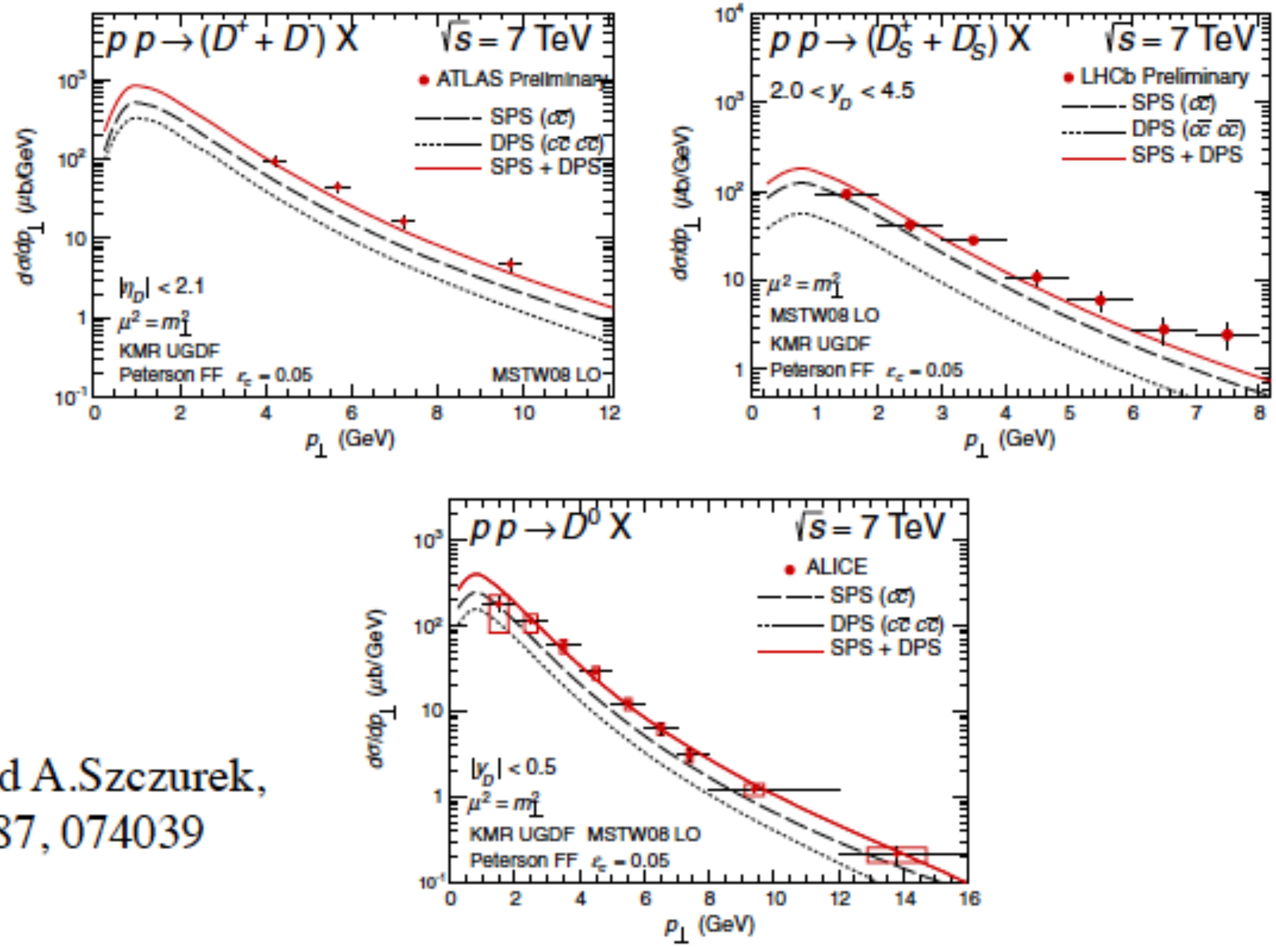
Computations of Double-quarkonium production via SPS at the LHC not developed for CMS acceptance e.g. assume dominance of color-singlet productIon.

(P.Ko et al., Novoselov et al., Berezhnoy, et al., etc.)

→ Differences expected in Δy and $p_{T\ J/\psi J/\psi}$ distributions.

However SPS at large Δy is expected to be very suppressed. Although σ_{eff} is not quoted, to date, this is one of the most clear evidences of DPS production at colliders. *[D.Ciangottini, 5th MPI@LHC]*

More on DPS in open charm production at the LHC

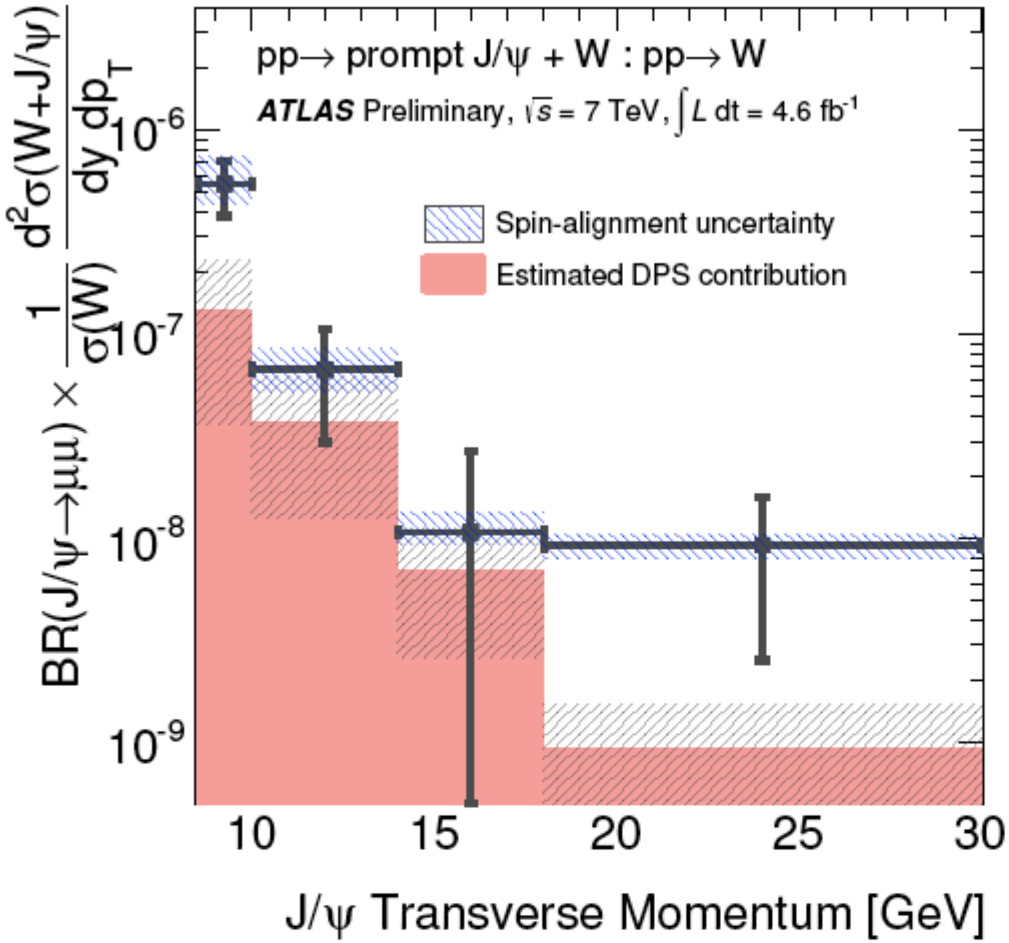


σ_{eff}= 15 mb

R.Maciula and A.Szczurek, Phys. Rev. D87, 074039

FIG. 12 (color online). Inclusive transverse momentum distributions of different charmed mesons measured by different groups at the LHC. The long-dashed line corresponds to the standard SPS $c\bar{c}$ production, and the dotted line represents the DPS $c\bar{c}c\bar{c}$ contribution.

ATLAS: W + prompt J/ψ



In this study from ATLAS the opposite approach is adopted

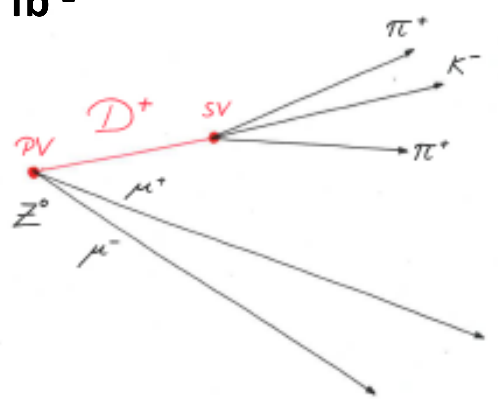
– σ_{eff} from W+2jets is assumed in order to estimate the DPS contribution to W+J/ψ

[C.Melachrinos, 5th MPI@LHC]

SPS predictions still below the DPS subtracted data. DPS higher than expected?

LHCb: Z + D

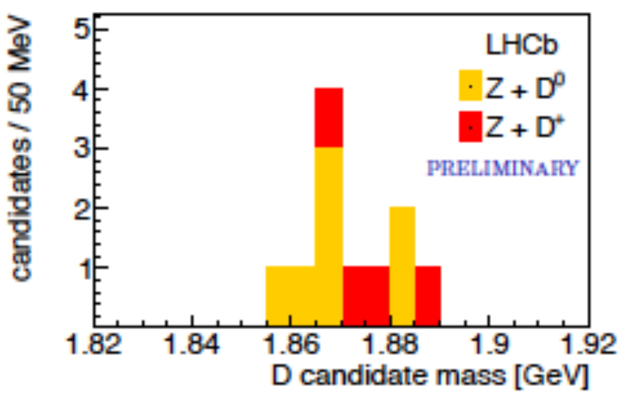
pp collisions at √s = 7 TeV
1 fb^{-1}

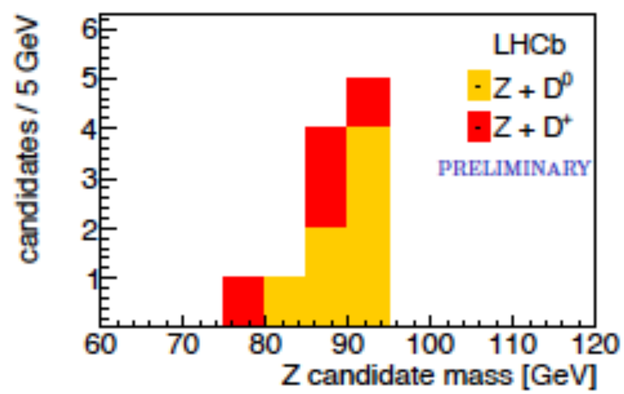


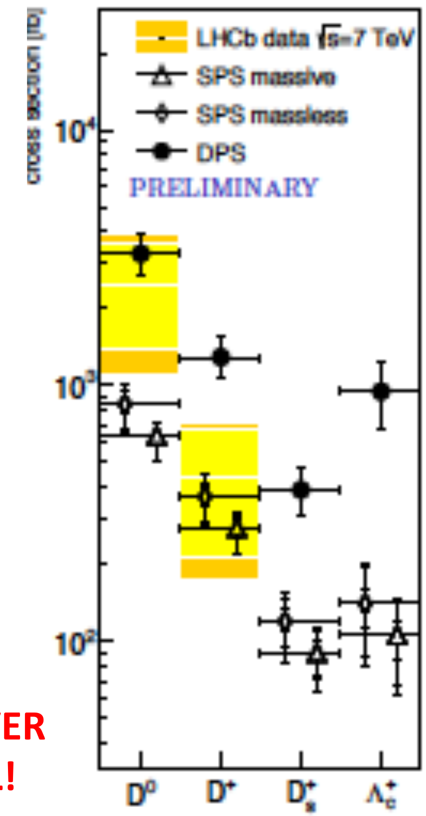
- $q\bar{q}$ initial state
- $2 < \eta_\mu < 4.5$
- $p_{T,\mu} > 20\,\mathrm{GeV}$
- $60 < m_{\mu^+\mu^-} < 120\,\mathrm{GeV}$
- Large statistics available

- D from secondary vertex but associated to the same PV as the Z.
- $2 < p_{T,\mathrm{D}} < 12\,\mathrm{GeV}$

[A.Bursche, 5th MPI@LHC]







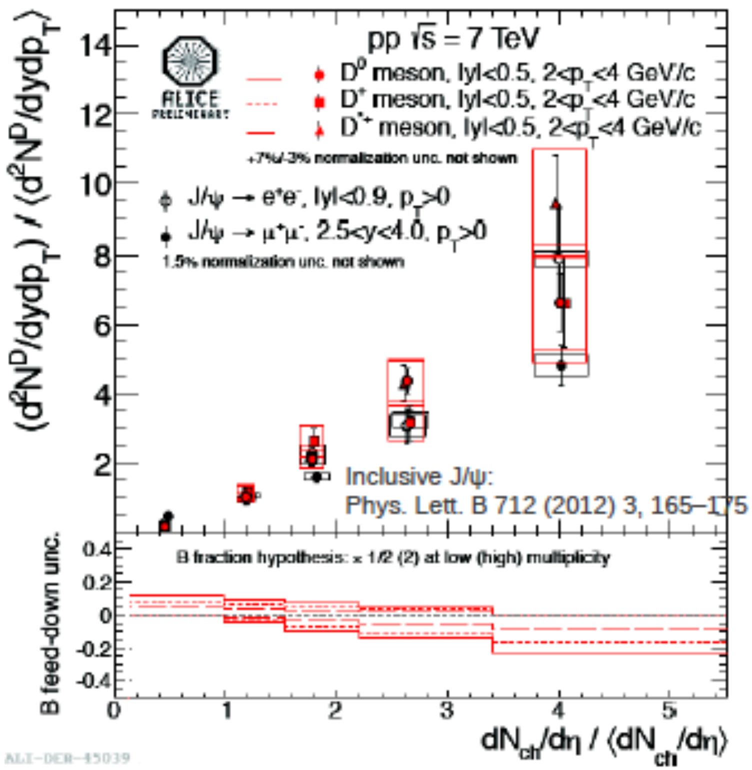
$\sqrt{s} = 7\ \mathrm{TeV}$

- Preliminary Measurements!
- $\sigma_{Z\to\mu^+\mu^-,D^0}\mathcal{B}_{Z\to\mu^+\mu^-} = 2.50 \pm 1.12 \pm 0.22\,\mathrm{pb}$
- $\sigma_{Z\to\mu^+\mu^-,D^+}\mathcal{B}_{Z\to\mu^+\mu^-} = 0.44 \pm 0.23 \pm 0.03\,\mathrm{pb}$

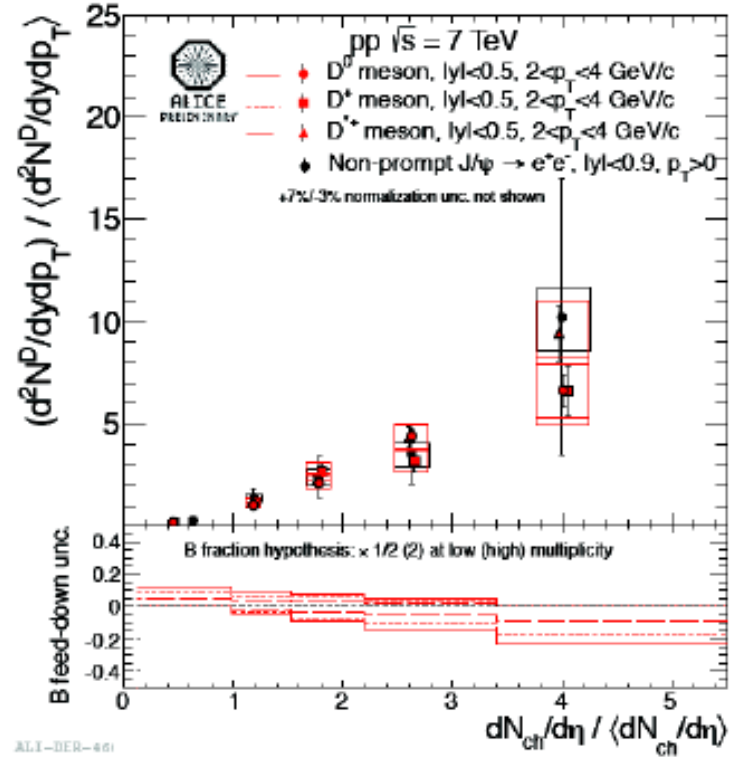
VERY FEW EVENTS, HOWEVER SPS BACKGROUND SMALL!

ALICE: event yields as a function of charged particle multiplicity

D-mesons – inclusive J/ψ



D-mesons – non-prompt J/ψ



→ **Prompt D meson ($2<p_T<4$ GeV/c) and J/ψ ($p_T>0$) yields (both inclusive and non prompt) show a similar increase with charged particle multiplicity within the current statistical and systematic uncertainties.**

→ **Reproduced by Pythia 8, which implements Heavy Flavors production in MPI (in contrast to Pythia 6).**

→ **Interpretation: at least in the pQCD models N_{ch} is basically proportional to N_{MPI}, as a trivial consequence all the yields are expected to be correlated with N_{ch}.**

→ **VERY INTERESTING HIGHLIGHT, PREPARING THE GROUND TO THE CONNECTION BETWEEN HARD AND SOFT MPI!**

The Double Parton Scattering (d)

a glance to the future

(pairs of heavy bosons etc.)

μ pairs from same sign WW

Double Parton Scattering same sign WW and Single Parton Scattering same sign WW are expected to have comparable cross sections ≈ O(10 fb).

However they cover the phase space in a different way: low pT(W) vs large pT(W).

The kinematic information can be used to normalize σ(DPS) to σ(SPS).

Generator level distributions, √s = 8 TeV

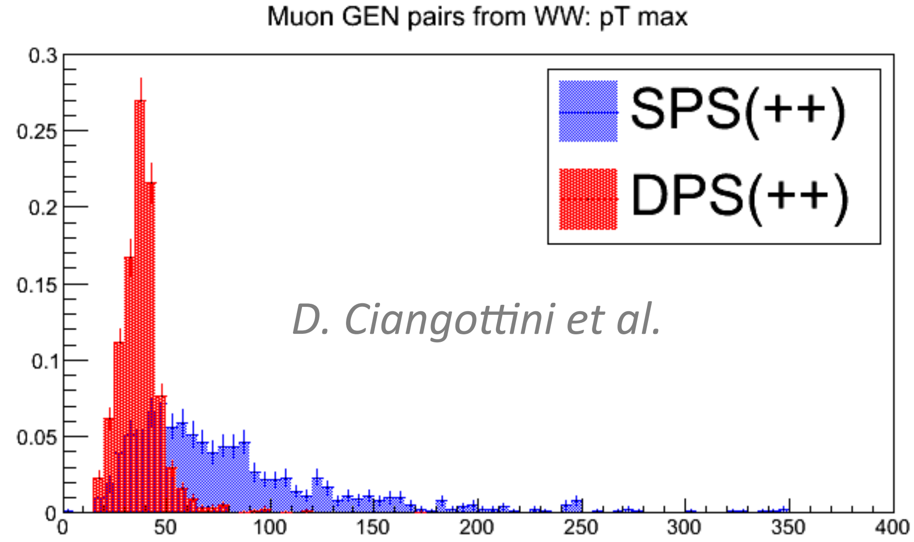
DPS = Pythia 8

SPS = Madgraph

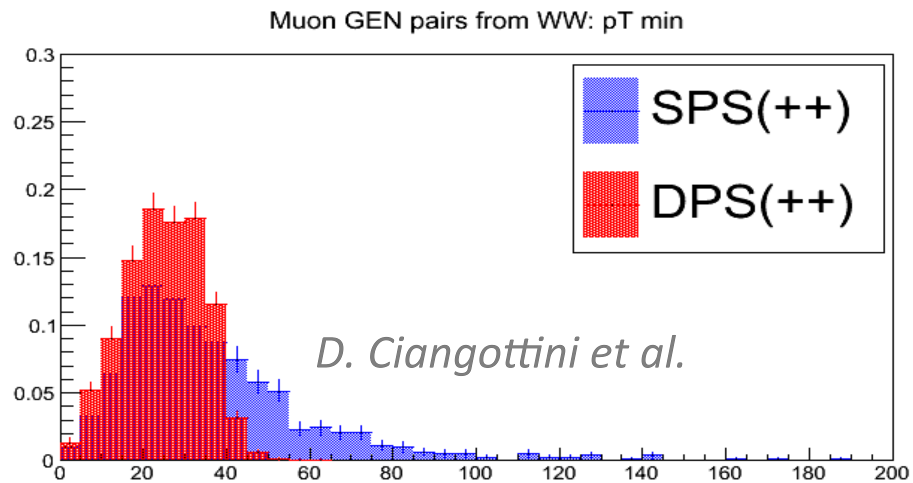
σ(DPS) ≈ σ(SPS)

Refs. [Stirling et al. arXiv: 1003.3953v1]

[Treleani et al., Int. J. Mod. Phys. A20: 4462-4468 (2005) and Phys. Rev. D 72, 034022 (2005).]



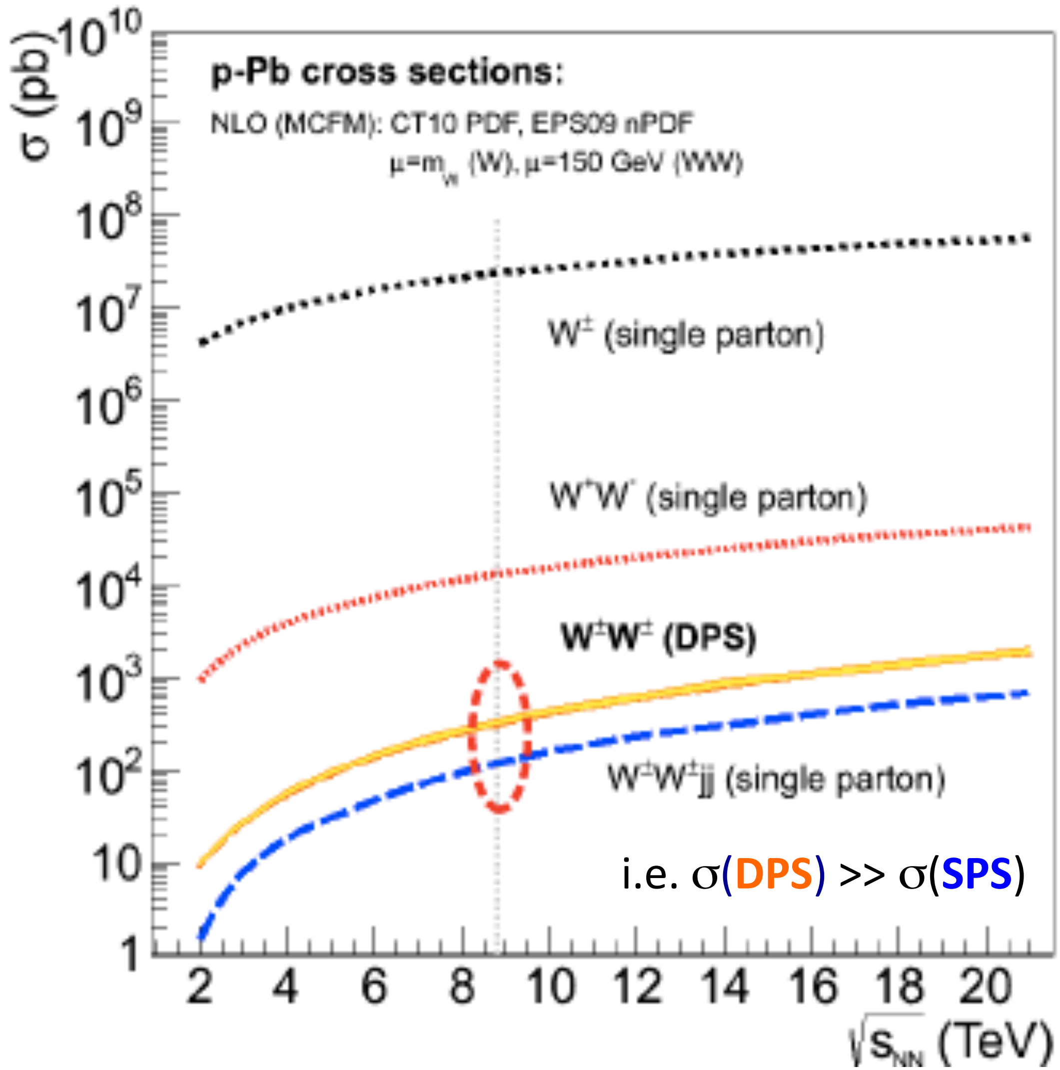
μ-related discriminating observable: p_T^{max}



μ-related discriminating observable: p_T^{min}

$W^{\pm}W^{\pm}$ production in p-Pb interactions

- Cross sections for all relevant SPS and DPS processes vs sqrt(s):



p-Pb, 8.8 TeV:

σ(WW,DPS)~300 pb

σ(WWjj)~100 pb

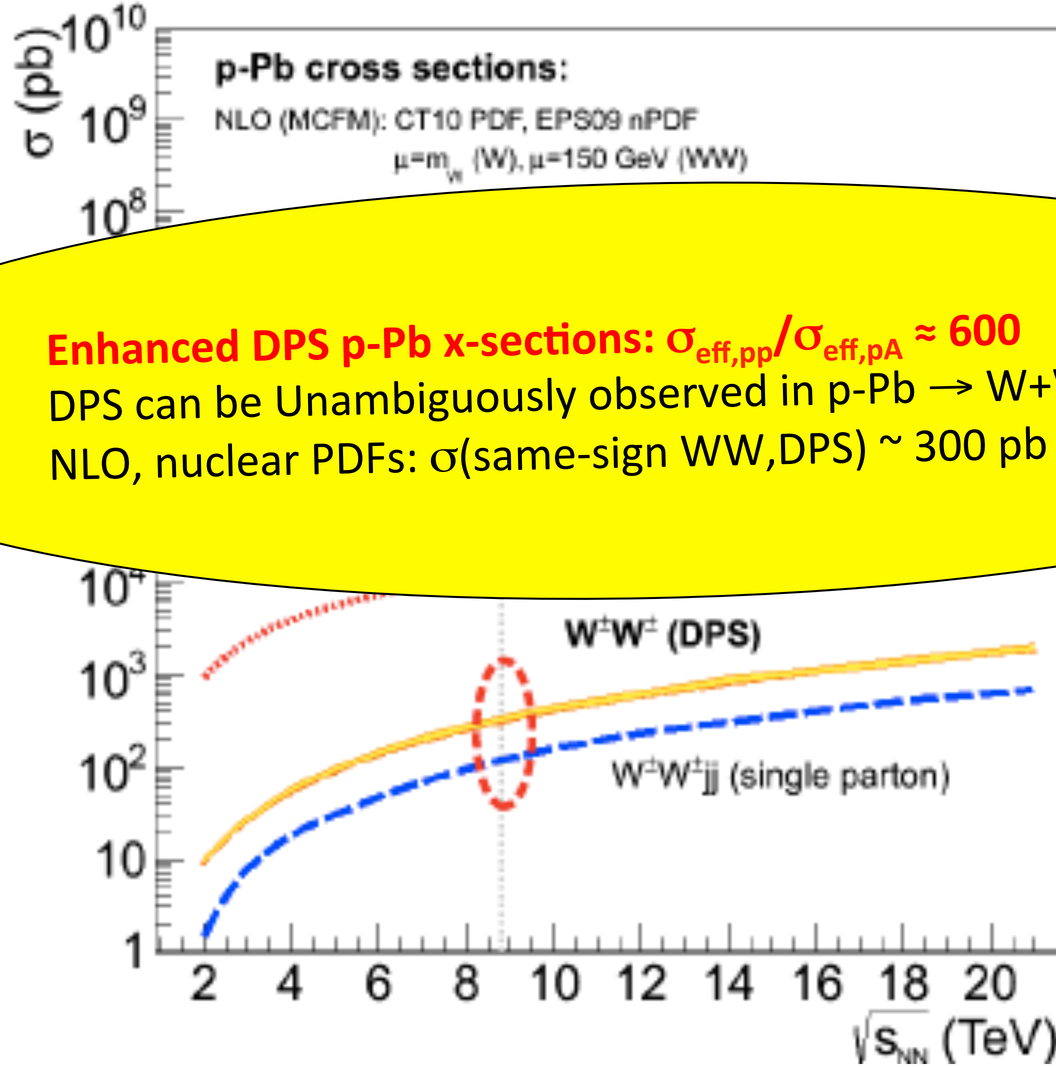
±18% uncertainties:

±15% for σ_{eff}

±10% for scales&PDFs

W±W± production in p-Pb interactions

- Cross sections for all relevant SPS and DPS processes vs sqrt(s):



Enhanced DPS p-Pb x-sections: $\sigma_{eff,pp}/\sigma_{eff,pA} \approx 600$

DPS can be Unambiguously observed in p-Pb → W+W+, W-W- ,

NLO, nuclear PDFs: σ(same-sign WW,DPS) ~ 300 pb (2 – 20 counts/year)

σ(WW,DPS)~300 pb

σ(WWjj)~100 pb

±18% uncertainties:

±15% for σ_{eff}

±10% for scales&PDFs

D'Enterria & Snigirev, arXiv:1211.0197.

Double Parton Scattering Status & Milestones @ LHC

1. corrected distributions for several DPS-sensitive observables.

Achieved for 4jets, W+2jets, W+J/Ψ, Z+D, double J/Ψ, double open charm, other channels in progress.

2. Interpretation, consistency checks

In progress, still no striking DPS evidence at hadron colliders. Large systematics on σ_{eff} can gain a lot on model dependency.

3. Including more processes: study process dependency.

In progress, precision of the measurements still doesn't allow to compare σ_{eff} in q-initiated and g-initiated processes, confronting with corresponding UE ratios.

4. Differential distributions

Requires more integrated luminosity: HL-LHC, i.e. FUTURE…

Extension of the DPS measurements to pA should proceed in parallel, for now we have some nice/promising TH predictions and feasibility studies.

Overall, big progress with respect to the early Tevatron DPS studies, in particular for what concerns the definition of Signals and Backgrounds. However it is necessary to refrain from making steps backwards. See the recommendations in the back-up slides.

Soft Multiple Parton Interactions

keeping an eye on the pQCD MPI models

$$N_{ch} \approx c * N_{MPI}$$

See also the lecture of **Sarah Porteboeuf-Houssais** at this school

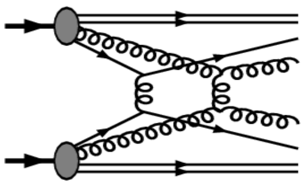
pQCD Models

RADIATION, SPECTATORS…
not enough to account for
the observed multiplicities
& p_T spectra

→

The Pythia solution:
[T. Sjöstrand et al. PRD 36 (1987) 2019]
Multiple Parton Interactions (MPI)
(now available in other general purpose MCs:
Herwig/Jimmy, Sherpa, etc.)

Inspired by early observations of
double high P_T scatterings



(dampening)

$$\sigma(\widehat{P}_T) \rightarrow \sigma(\widehat{P}_T) \cdot \frac{(\widehat{P}_T)^4}{((\widehat{P}_{T0})^2 + (\widehat{P}_T)^2)^2}$$

Main Parameter: P_T cut-off P_{T0}

- ✓ Cross Section Regularization for $P_T \rightarrow 0$.
- ✓ P_{T0} can be interpreted as inverse of effective colour screening length.
- ✓ Controls the number of interactions: $\langle N_{MPI} \rangle = \sigma_{parton-parton} / \sigma_{proton-proton}$

Perturbative description! $P_{T0} \approx$ few GeV

"post HERA" PDFs have increased color screening at low x
$x\,g(x,Q^2) \rightarrow x^{-\varepsilon/2}$ for $x \rightarrow 0$

$$P_{T0}^{s'} = P_{T0}^{s} (\sqrt{s'} / \sqrt{s})^{\varepsilon}$$

Typical event: one leading interaction accompanied by several soft MPI at $P_T \approx P_{T0}$.
Scale of leading interaction may influence N_{MPI} (Pedetal effect, relevant for Underlying Event).
Apart from the bias of the leading interaction → (charged) multiplicities proportional to N_{MPI}.

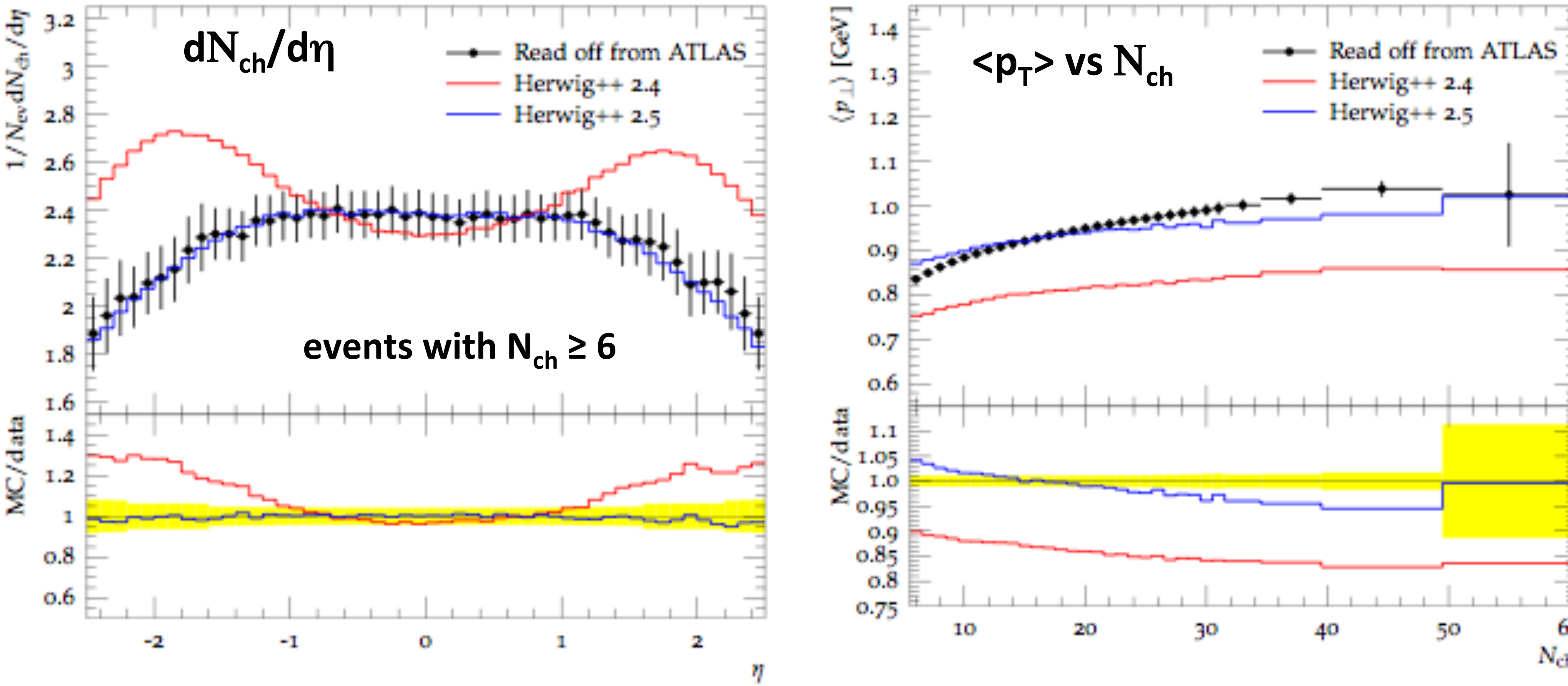
*[For more info see **Leif Lönnblad's** lectures at this school]*

Early LHC measurements with charged tracks

- A reminder of the LHC Legacy (see also the back-up slides)
  - soft QCD measurements with charged tracks in pp inelastic and not single diffractive events at different √s (0.9 TeV, 2.36 TeV, 7 TeV, 8 TeV).
    - $\langle N_{ch} \rangle$, N_{ch} $dN_{ch}/d\eta$ vs η, $\langle pT \rangle$ vs N_{ch}.
    - LHC Tracker detectors turn out to be essential tools for these measurements: full charged track reconstruction from p_T as low as 100 MeV.
  - Fast increase of average multiplicities vs √s (> ln (s)) confirmed by LHC data, described by few TH predictions and by tuned pQCD MPI models.
  - pQCD MPI models also essential to describe the N_{ch} tails & KNO violation.
    - KNO scaling applies when restricting to small pseudorapidity range ($|\eta|<0.5$).
  - $\langle p_T \rangle$ vs N_{ch} studied at different √s
    - It smoothly rises with N_{ch} and scales with √s!
    - Interpretation in the context of the pQCD MPI models:
      - » the deviation from flatness indicate correlations in MPI.
      - » the √s scaling means that all the properties are driven by N_{ch} (N_{MPI}).

Herwig++: Impact of color reconnection on $dN_{ch}/d\eta$

ATLAS, pp $\sqrt{s}$ = 0.9 TeV, charged particles with p_T > 0.5 GeV & $|\eta|$ < 2.5



Color reconnection model by Röhr, Siodmok and Gieseke based on momentum structure, implemented from Herwig++ 2.5.

→ Color reconnection unavoidable to describes the shapes of pseudo-rapidity and $\langle p_T \rangle$ vs N_{ch}.

[M. Seymour, MPI@LHC 2013, Antwerpen]

Further measurements with (several) charged tracks

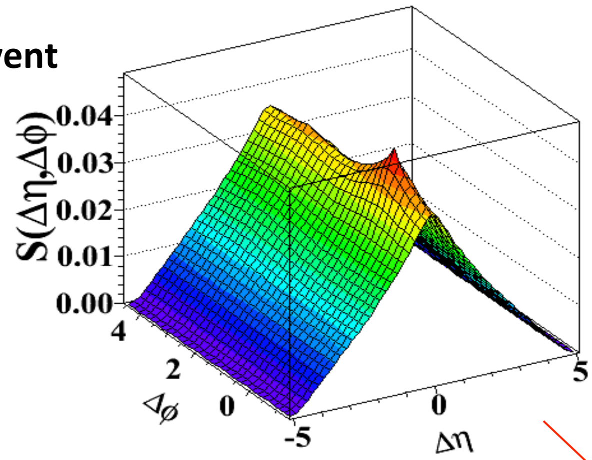
The Long Range Correlations

Definition of di-hadron correlation function

Signal distribution:

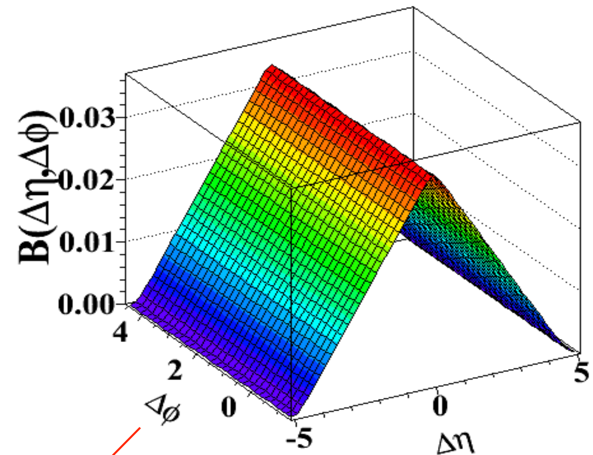
$$S_N(\Delta\eta,\Delta\varphi) = \frac{1}{N(N-1)} \frac{d^2N^{signal}}{d\Delta\eta\, d\Delta\varphi}$$

Particle pairs from same event



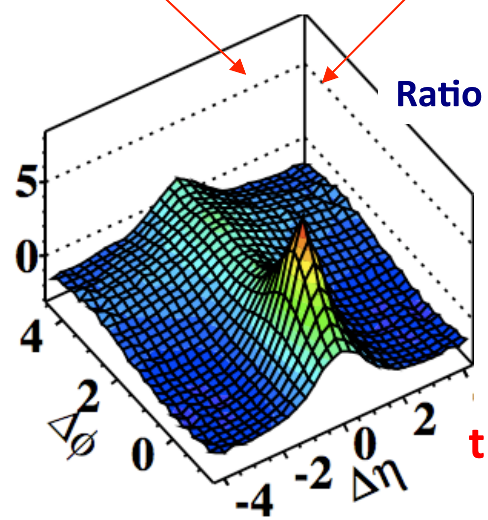
Background distribution:

$$B_N(\Delta\eta,\Delta\varphi) = \frac{1}{N^2} \frac{d^2N^{bkg}}{d\Delta\eta\, d\Delta\varphi}$$



Pairs from mixed events

$$\boxed{\begin{aligned}\Delta\eta &= \eta_1 - \eta_2\\ \Delta\varphi &= \varphi_1 - \varphi_2\end{aligned}}$$

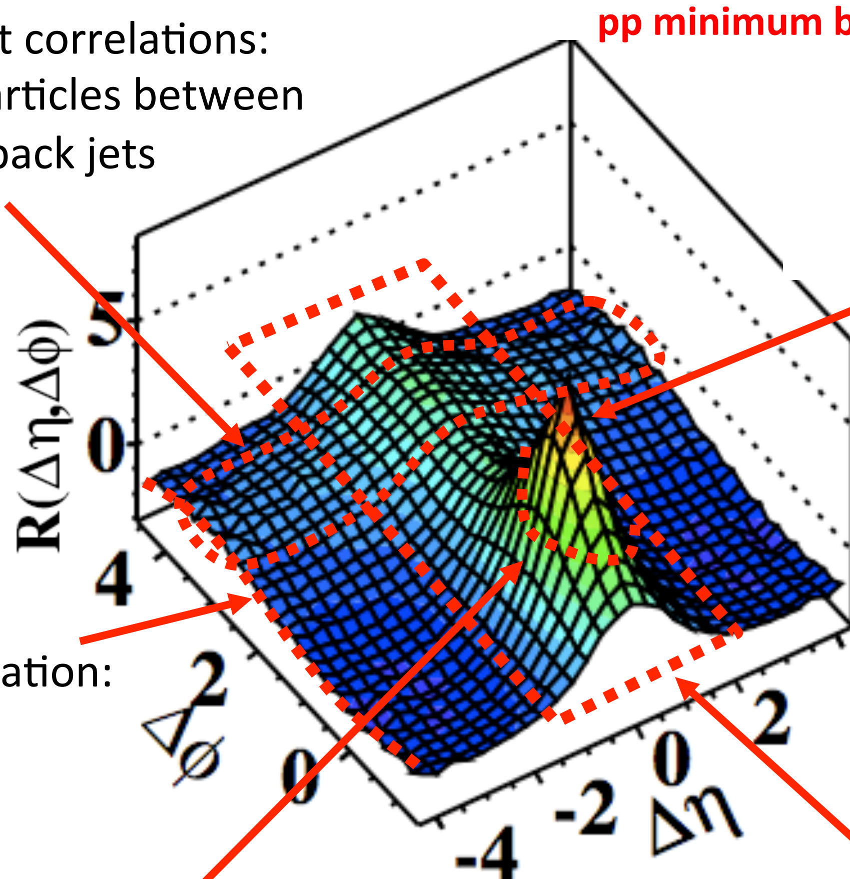


Ratio Signal/Background = Associated 2D Yields:

$$R(\Delta\eta,\Delta\varphi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)} - 1\right)\right\rangle_{bins}$$

Can specify selected pair of trigger (p_T^{trig}) and associated (p_T^{assoc}) particle p_T ranges.

Long and short range correlations



"Away-side" jet correlations:
Correlation of particles between back-to-back jets

Bose-Einstein correlations:
(Δϕ,Δη) ~ (0,0)

Momentum conservation:
~ cos(Δϕ)

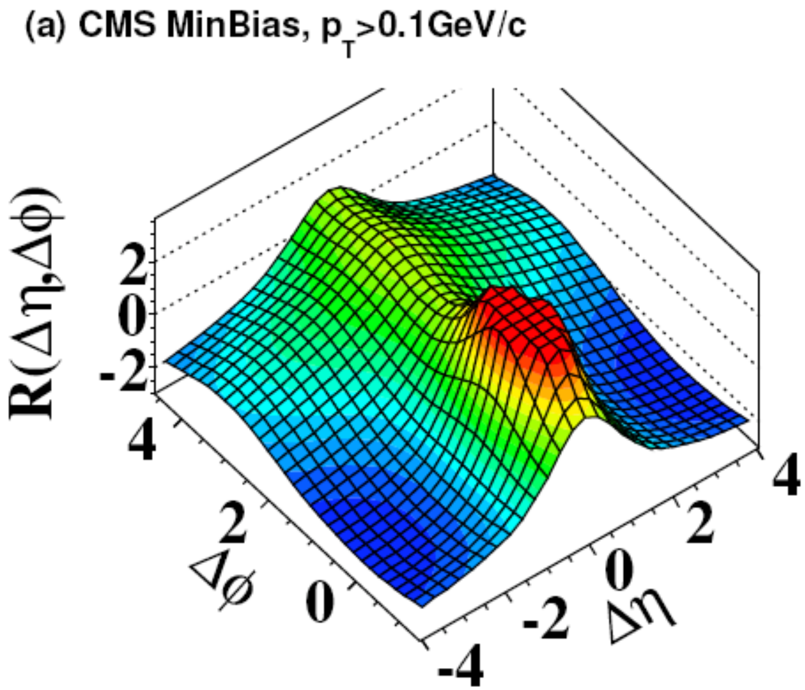
"Near-side", Δϕ~ 0 jet peak:
Correlation of particles within a single jet

Short-range correlations (|Δη| < 2):
Resonances, string or cluster fragmentation

Associated 2D Yields for Particles with P_T > 0.1 GeV

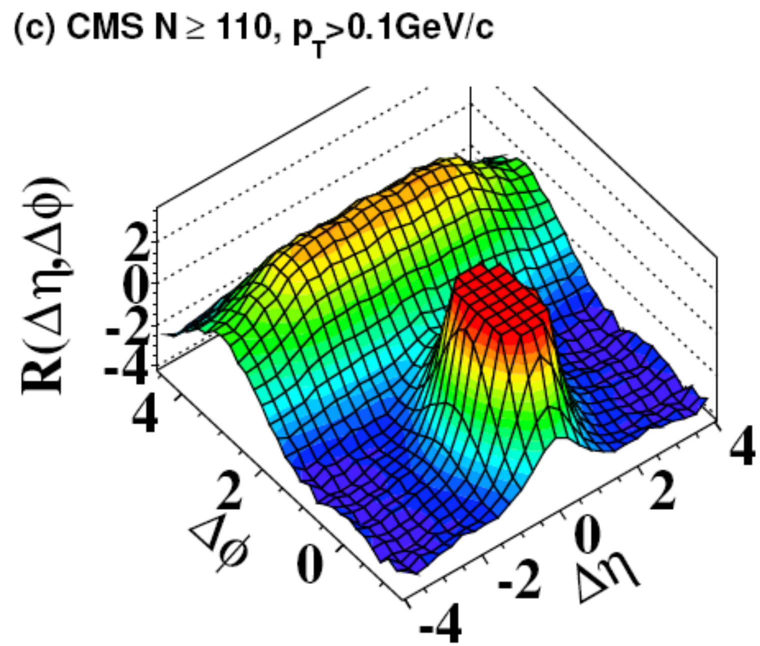
pp interactions at 7 TeV

MinBias



High Multiplicity (N>110)

Special trigger developed to collect these rare O(10^{-5}) events.
It doesn't rely on jet triggers!



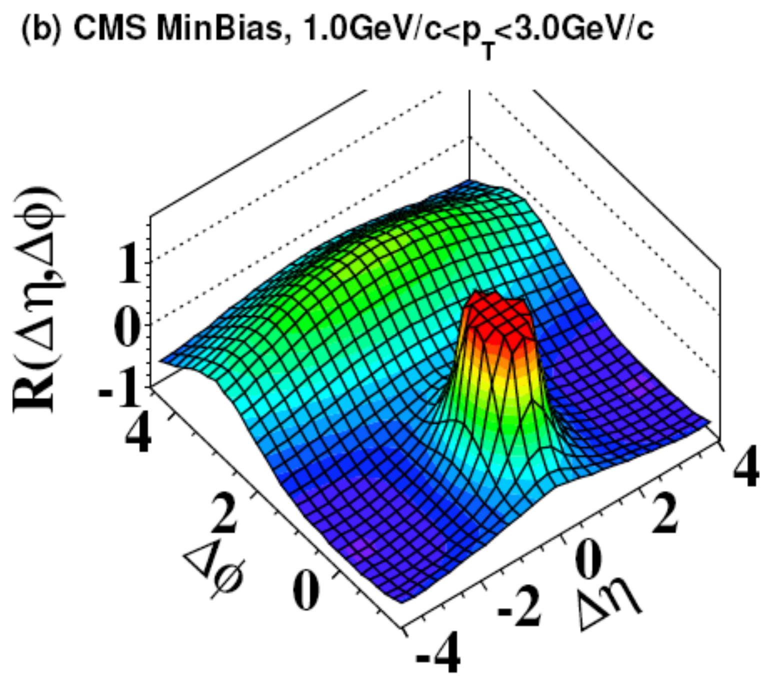
- The jet peak is cut for better visibility of the correlations.
- Jet peak correlations with away-side – stronger in the high multiplicity events
- No significant "new" structure seen in the high multiplicity events.

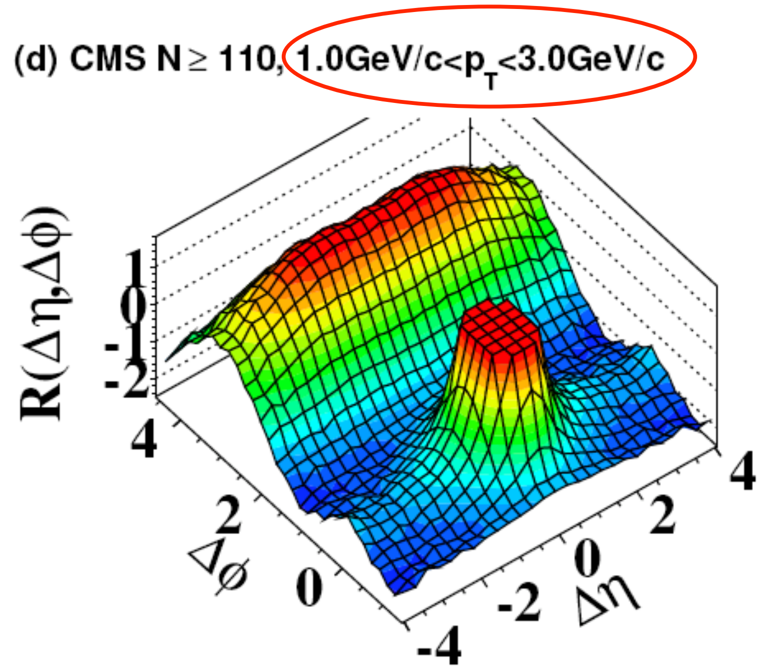
Associated 2D Yields for Particles with 1.0 < P_T < 3 GeV

MinBias

High Multiplicity (N>110)

Special trigger developed to collect these rare O(10^{-5}) events.
It doesn't rely on jet triggers!

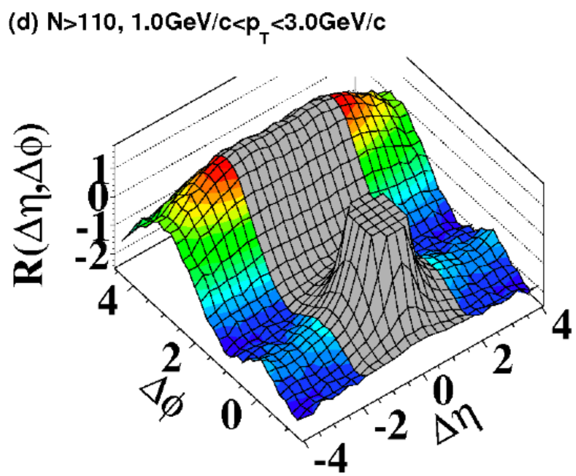




- **Limiting p_T of particles to 1<p_T<3 GeV**
  → Gives a pronounced structure at large Δη around ΔΦ=0 in the high multiplicity events.

Associated 1D yields in bins of p_T and N_{ch}

Long range:
Project 2 < |Δη| < 4.8 onto Δϕ:

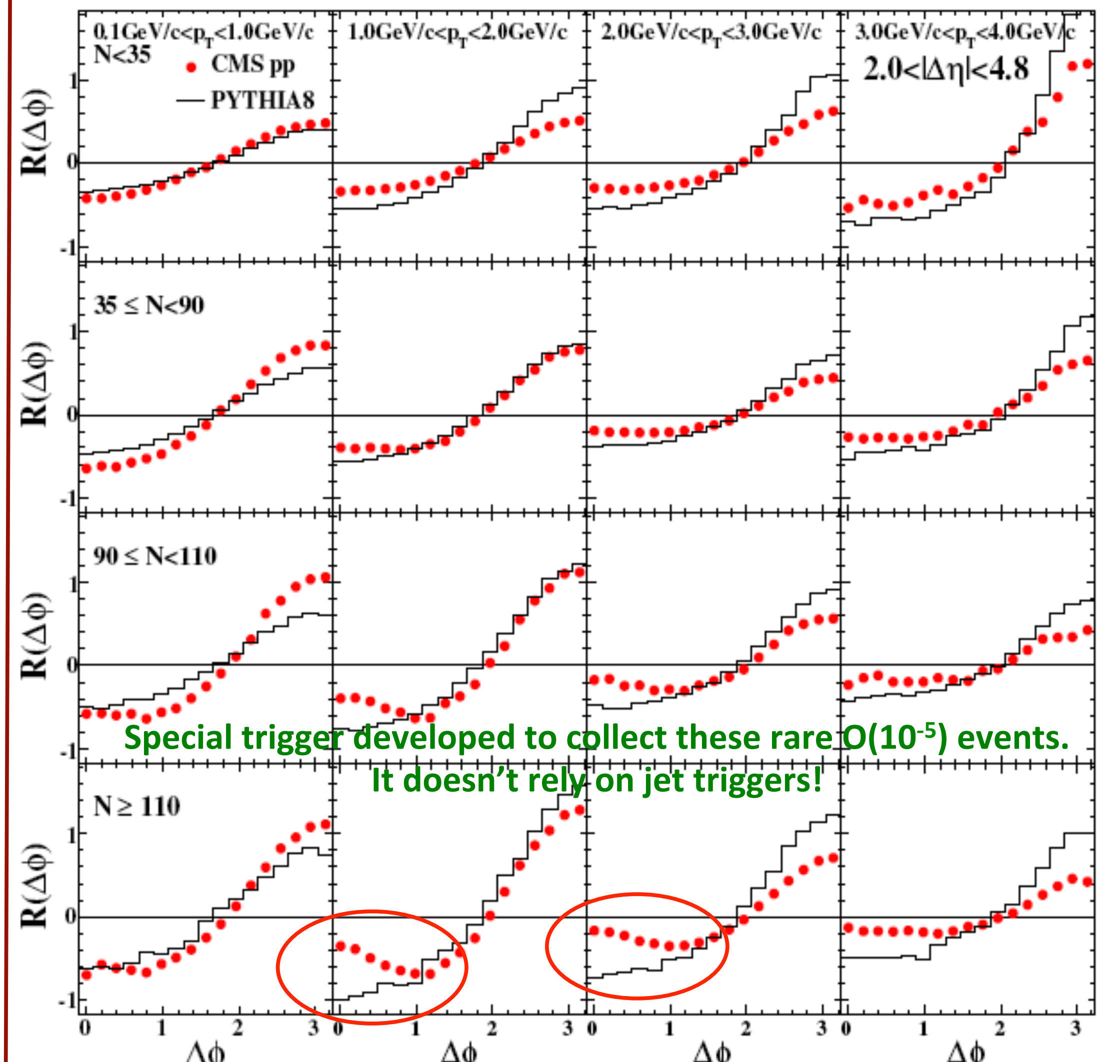


- **Ridge most pronounced for high multiplicity events and at $1 < p_T < 3$ GeV.**
- No ridge seen in tested MC models (Pythia 8, Pythia6, Herwig++, etc.)
- Several interpretations proposed for this HI-like effect in pp interactions.
- Clear major role of Multiple Parton Interactions.

[S. Alderweireldt, P.Mechelen arXiv:1203.2048]

Increasing p_T

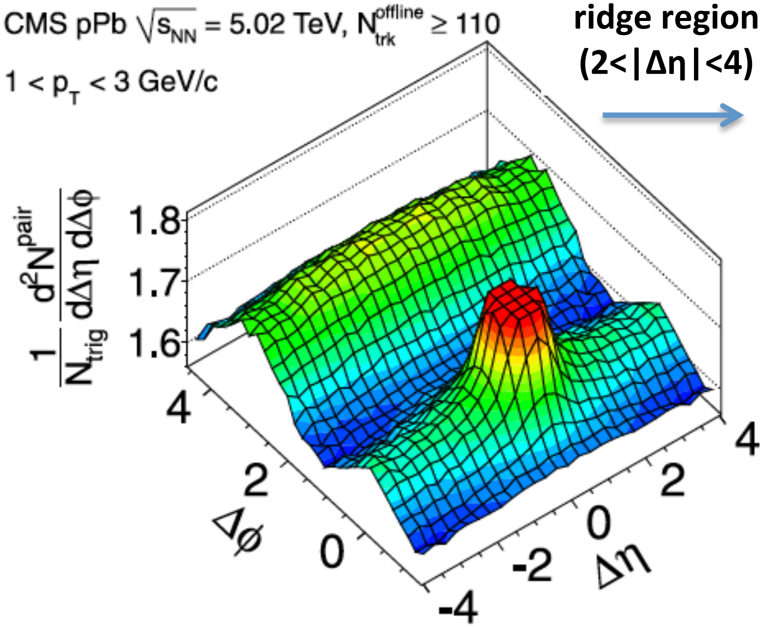
Increasing multiplicity



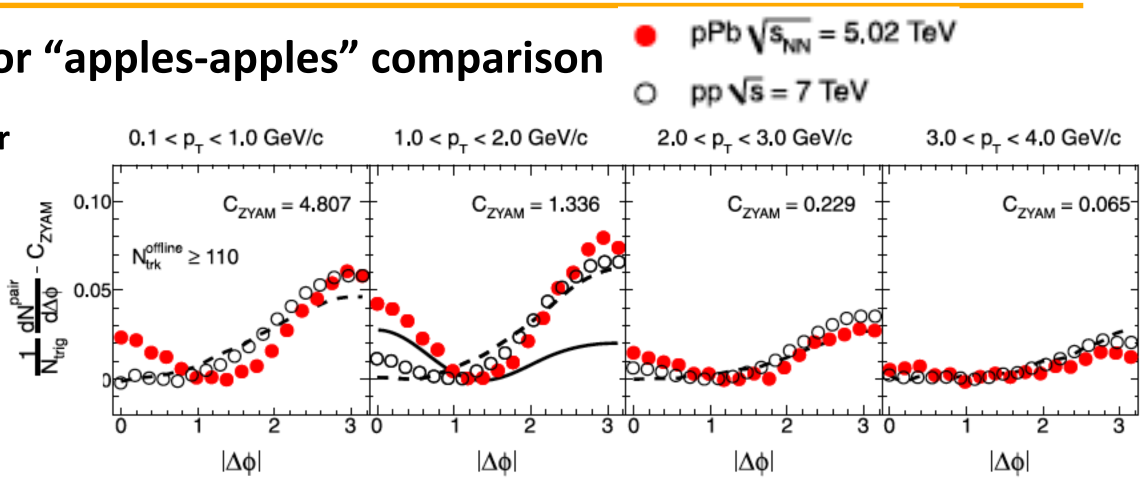
Special trigger developed to collect these rare $O(10^{-5})$ events.
It doesn't rely on jet triggers!

CMS: Ridge in p-Pb interactions

Same approach as in pp ridge paper for “apples-apples” comparison



Average over ridge region (2<|Δη|<4)

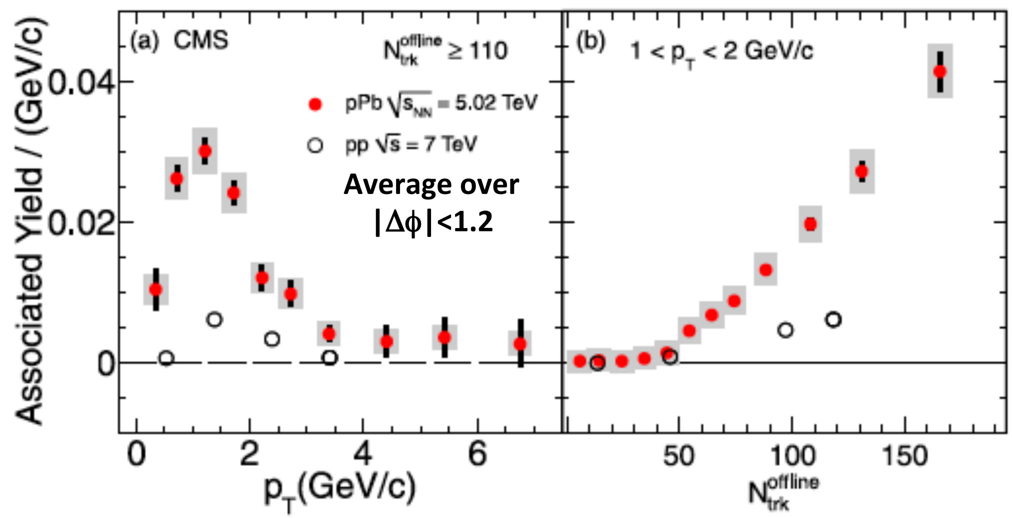


Neither HIJING nor the tested hydro model do describe the ridge

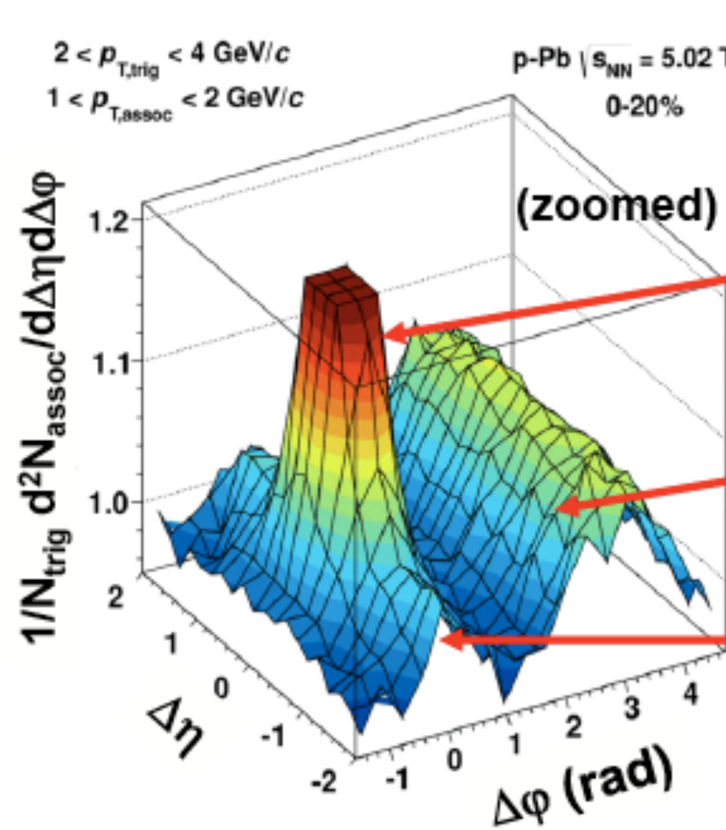
More successful models: APMT, EPOS etc.

→ See the talk of Klaus Werner at QM2014

Same qualitative conclusions.
From a quantitative point of view the effect is much larger in p-Pb than in pp



ALICE: Double Ridge in p-Pb interactions



$2 < p_{T,trig} < 4$ GeV/c
$1 < p_{T,assoc} < 2$ GeV/c
20% highest multiplicity

Near-side jet
($\Delta\varphi \sim 0$, $\Delta\eta \sim 0$)

Away-side jet
($\Delta\varphi \sim \pi$, elongated in $\Delta\eta$)

Near-side ridge
($\Delta\varphi \sim 0$, elongated in $\Delta\eta$)

Recent ALICE paper reporting double "ridge" structure in p-Pb interactions at $\sqrt{s_{NN}}$ = 5.02 TeV.

Correlation profile for lower multiplicity data (60%-100% lowest) is subtracted from the one for higher multiplicity (20% highest), revealing a second ridge at $\Delta\phi \approx \pi$ identical to the first one at $\Delta\phi \approx 0$.
→ **corroborating and extending the results reported by CMS.**

[*Sarah Porteboeuf-Houssais, this school*]

Correlations: bottom line

- **Long-range correlations:**
  - Significant ridge structures are observed in high multiplicity pp ($\sqrt{s}$ = 2.76 and 7 TeV), p-Pb ($\sqrt{s_{NN}}$ = 5.02 TeV) and Pb-Pb ($\sqrt{s_{NN}}$ = 2.76 TeV) collisions.
  - effect showing up in the intermediate momentum range: p_T = 1-2 GeV
  - strong mechanism to produce particles in a plane.
  - Pb-Pb expected from the elliptic flow.
  - p-Pb and pp observations still miss an agreed interpretation.
  - The size of the effect is huge in p-Pb.
  - Second ridge structure also detected in p-Pb.

  → Interpretation: Large multiplicities without pronounced jetty structures point to an important role played by Multiple Parton Interactions.
    - Angular momentum conservation?
    - Color reconnections?
    - APMT is successful however it also relies on pQCD MPI for the description of the initial state.
- **Short-range (BE) correlations:**
  - The radius of effective emission region (r) grows with N_{ch}
    - r vs N_{ch} scales with $\sqrt{s}$

These unexpected features of large multiplicity events triggered detailed studies on

Event properties vs Multiplicities

CMS: jet p_T vs N_{ch}

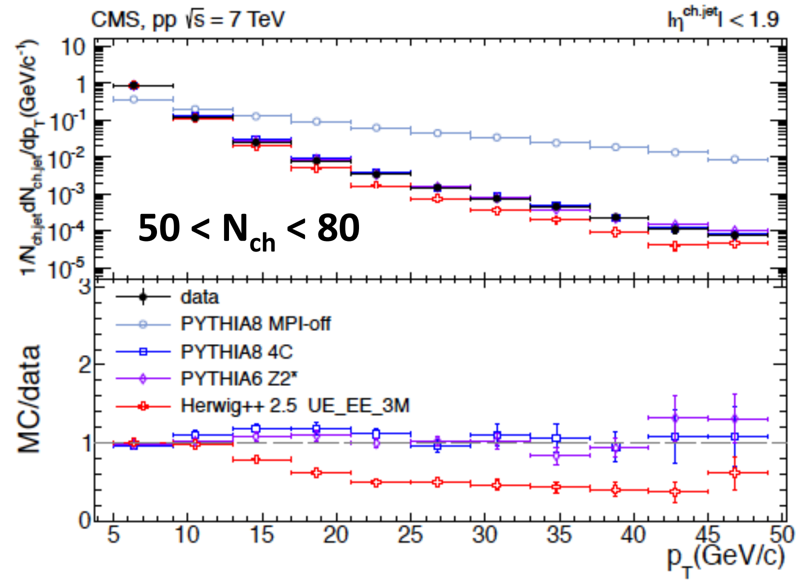
- **Similarly to the centrality classification of events in nuclear collisions, events are sorted according to their charged particle multiplicity:**

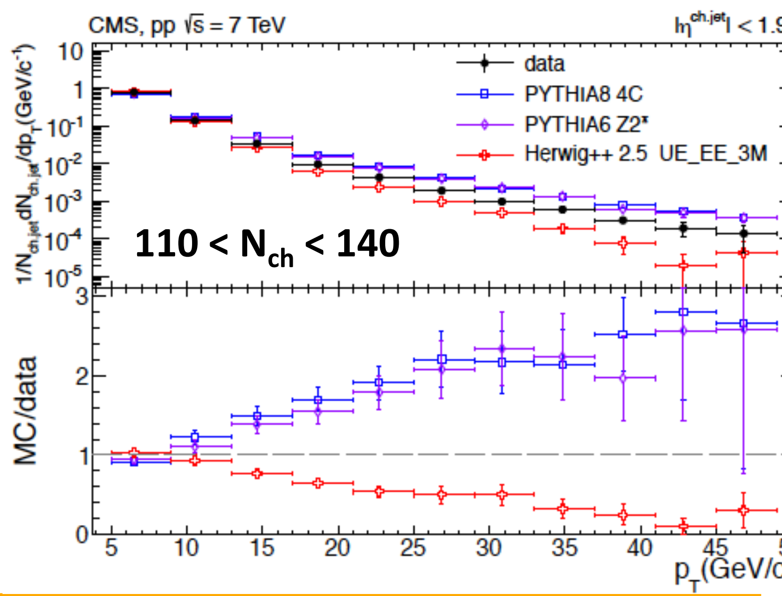
7TeV collected with MinBias trigger during very low PU runs 2010.

Multiplicity Domain	Number of Events
10<N≤30	2 798 793
30<N≤50	1 272 755
50<N≤80	627 829
80<N≤110	105 683
110<N≤140	11 612

Really not much

Charged particles used for the analysis:
p_T>0.25GeV/c, |η|<2.4





- **Let's first of all have a look to jets:**

1. **In each event, jets are found with anti-kT algorithm using charged particles only. The charged particles falling within a jet are further called "intra-jet" particles.**

→MPI clearly needed to describe jet p_T jet vs N_{ch}
→Pythia 6&8 with status of the art tunes OK up to N_{ch}≈ 80
However too many hard jets in the highest multiplicity range
→Herwig++ has always less hard jets than data.

[M. Azarkin, MPI@ LHC 2013, Antwerpen]

CMS: intra-jet energy flow vs N_{ch}

- **Similarly to the centrality classification of events in nuclear collisions, events are sorted according to their charged particle multiplicity:**

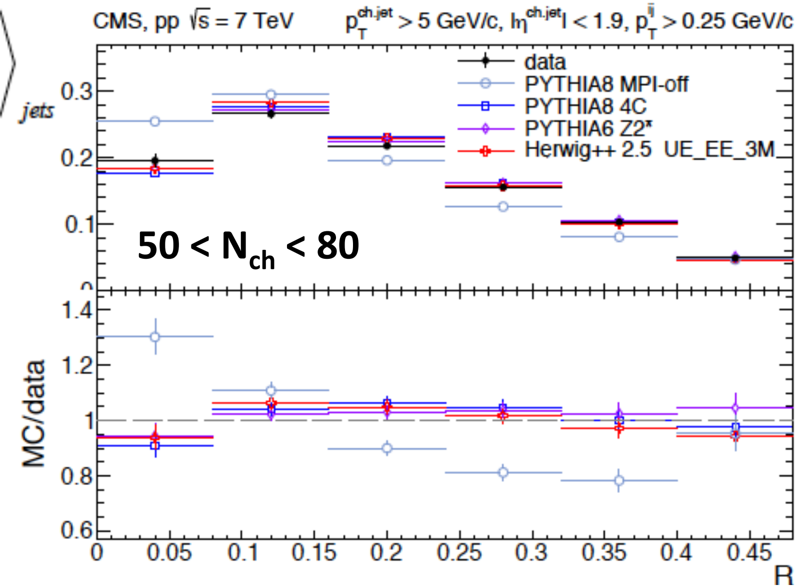
$$\rho = \left\langle \frac{1}{p_T^{jet}} \frac{dp_T^{tracks}}{dR} \right\rangle_{jets}$$

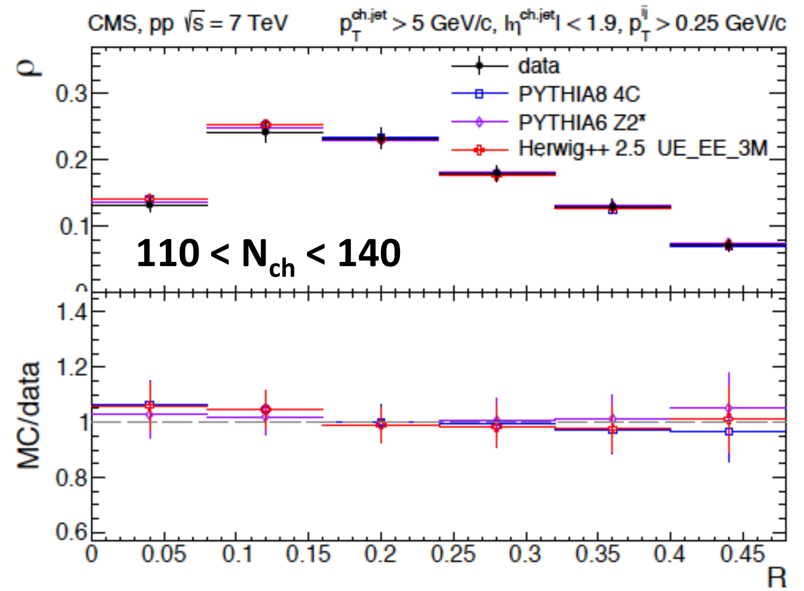
7TeV collected with MinBias trigger during very low PU runs 2010.

Multiplicity Domain	Number of Events
10<N≤30	2 798 793
30<N≤50	1 272 755
50<N≤80	627 829
80<N≤110	105 683
110<N≤140	11 612

Really not much

Charged particles used for the analysis:
p_T>0.25GeV/c, |η|<2.4





- **Let's first of all have a look to jets:**

1. **In each event, jets are found with anti-kT algorithm using charged particles only. The charged particles falling within a jet are further called "intra-jet" particles.**

→Intra-jet flow turns out to be very well described by pQCD MPI models, with MC slightly broader at low N_{ch} and slightly narrower at large N_{ch}.

[M. Azarkin, MPI@ LHC 2013, Antwerpen]

CMS: $<p_T>$ vs N_{ch} for intra-jet and UE charged particles

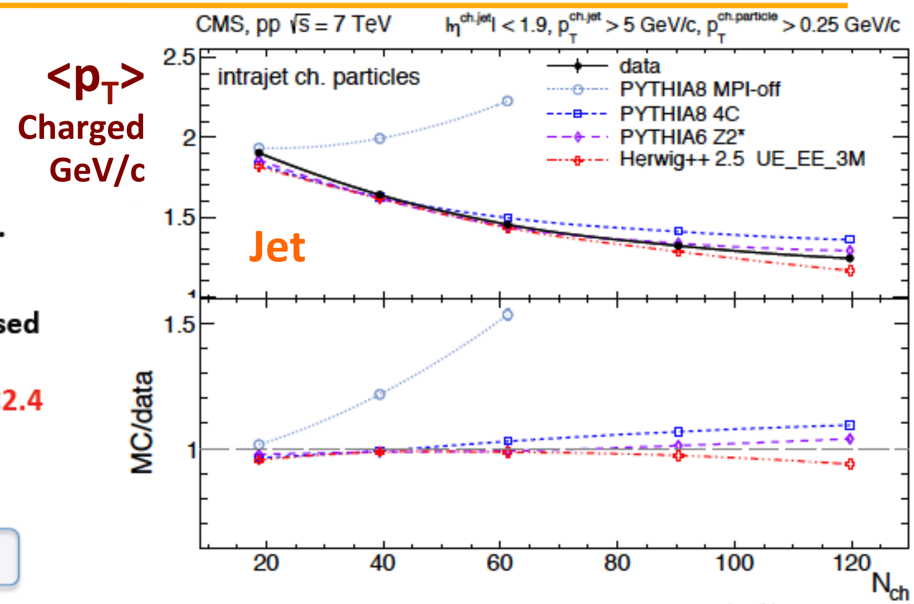
- **Similarly to the centrality classification of events in nuclear collisions, events are sorted according to their charged particle multiplicity:**

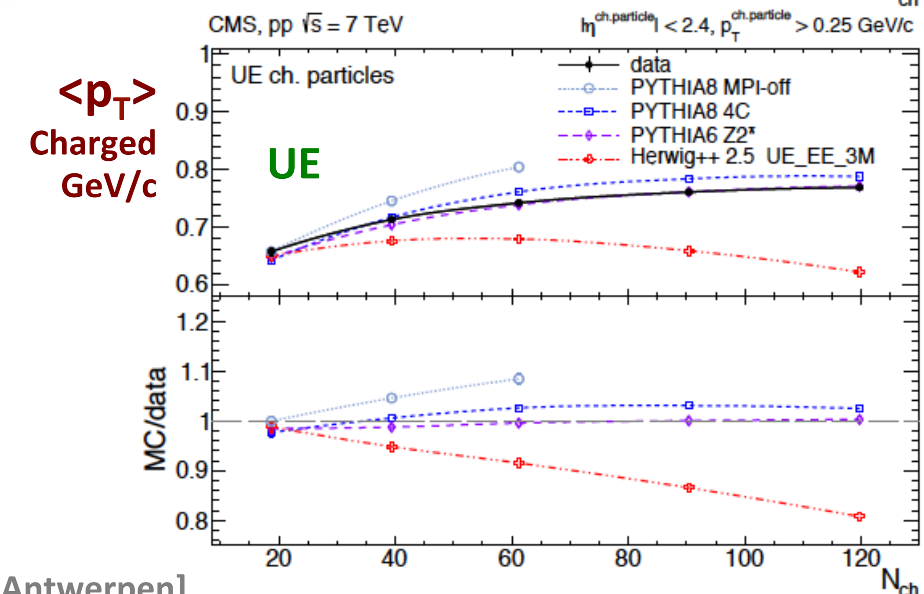
7TeV collected with MinBias trigger during very low PU runs 2010.

Multiplicity Domain	Number of Events
10<N≤30	2 798 793
30<N≤50	1 272 755
50<N≤80	627 829
80<N≤110	105 683
110<N≤140	11 612

Really not much

Charged particles used for the analysis:
p_T>0.25GeV/c, |η|<2.4





- **Decomposition of event into jets and UE:**

1. **In each event, jets are found with anti-kT algorithm using charged particles only. The charged particles falling within a jet are further called "intra-jet" particles.**
2. **After removing all intrajet particles from the event, the remaining particles are considered as belonging to the underlying event.**

→PQCD MPI models describe well jet $<p_T>$ vs N_{ch}.
→UE $<p_T>$ vs N_{ch} OK just for Pythia 6&8.

[M. Azarkin, MPI@ LHC 2013, Antwerpen]

ALICE: Transverse Spericity (S_T) analysis

$$S_T = \frac{2\lambda_2}{\lambda_2 + \lambda_1}$$

where l_1 and l_2 are the eigenvalues of S_{xy}:

$$\mathbf{S_{xy}} = \frac{1}{\sum_j p_{T_j}} \sum_i \frac{1}{p_{T_i}} \begin{pmatrix} p_{x_i}^2 & p_{x_i} p_{y_i} \\ p_{y_i} p_{x_i} & p_{y_i}^2 \end{pmatrix}$$

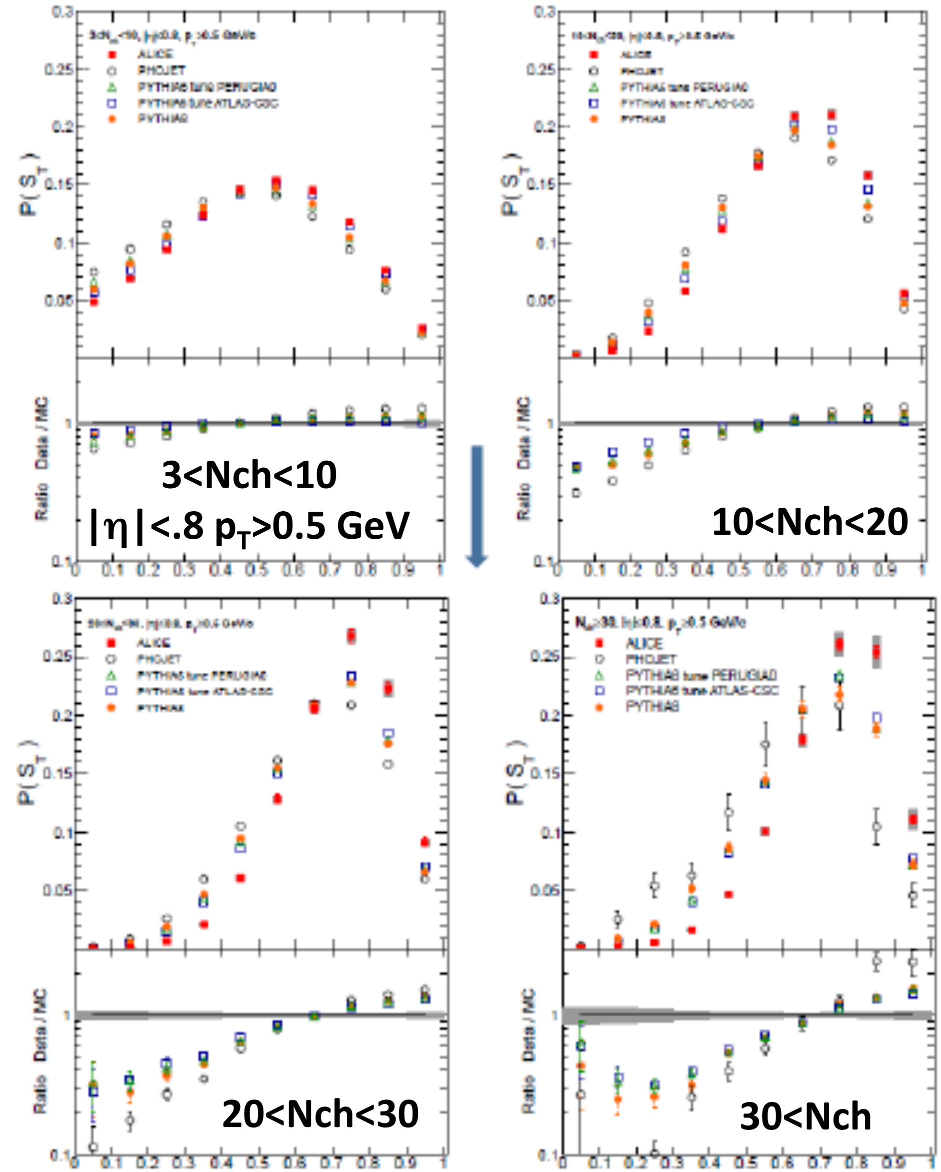
$S_T \approx 0$ → jetty events
$S_T \approx 1$ → isotropic events

→Average Transverse Sphericity grows with N_{ch}, as expected.

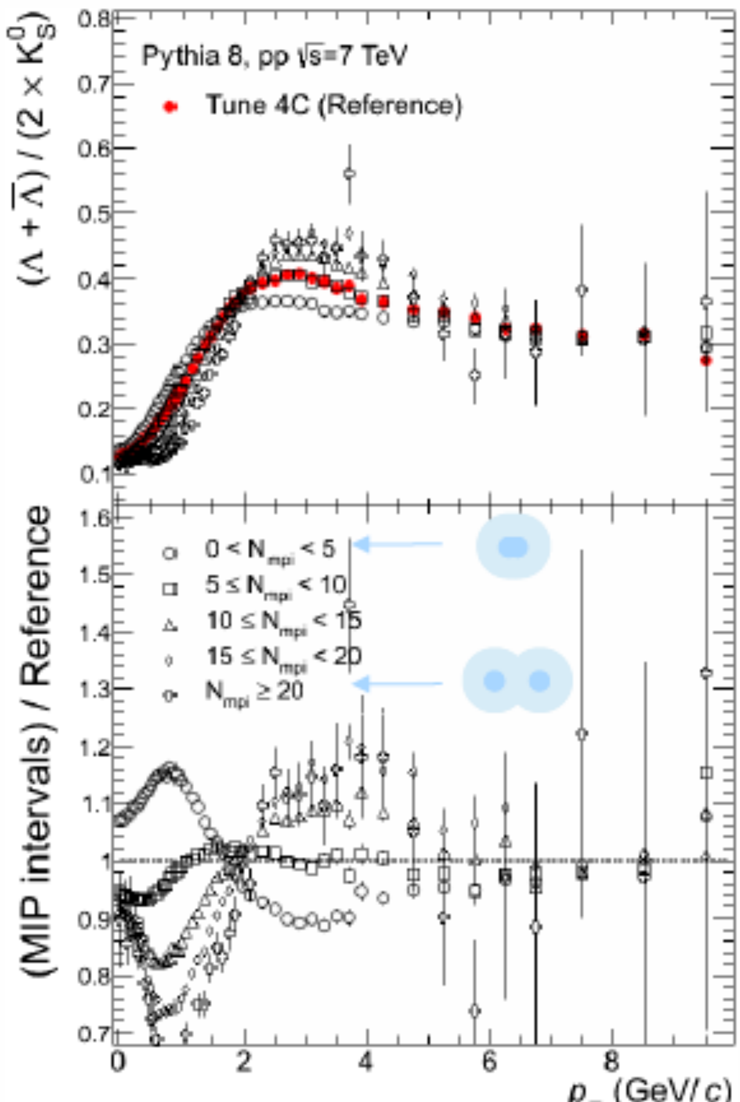
→Additional evidence that large multiplicity events are less jetty than expected: no model reproduces the ALICE observations for $N_{ch} > 30$

Sphericity observables may provide additional handles to study large multiplicity features.

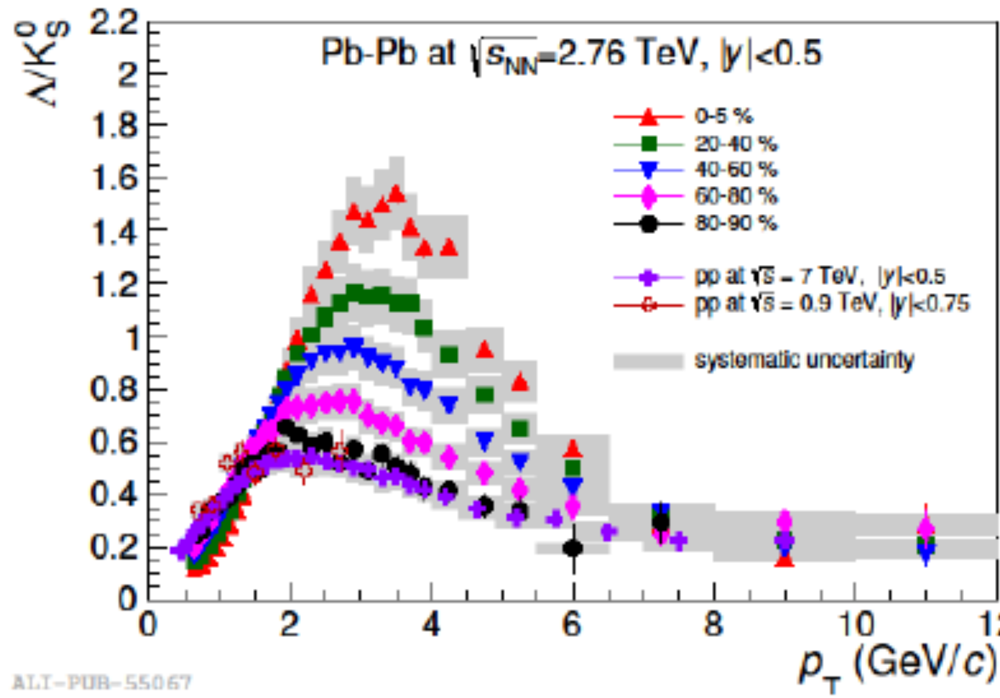
[G.Paic, MPI@LHC 2013, Antwerpen]
See also arXiv:1404.2372



Color reconnection and flow-like patterns in pp



pp interaction simulated with Pythia 8 Tune 4C don't know about flow, however, qualitatively, the Λ/K_S^0 ratio in different N_{ch} ranges evolve as the Λ/K_S^0 ratio in different centrality ranges in Pb-Pb interactions (measured by ALICE).



[G.Paic, MPI@LHC 2013, Antwerpen]
See also [arXiv:1404.2372]

Color reconnection matters! Flat shapes otherwise.

Bottom line: Event properties vs Multiplicity

- Additional proofs that $dN_{ch}/d\eta$ shapes and <pT> vs Nch normalization favor implementation of color reconnections in MPI models.
- High multiplicity events turn out to be much less jetty than predicted by Pythia. In the context of the pQCD MPI models they can be regarded as the result of several MPI.
- This is confirmed by the Transverse Sphericity analysis.
- Still jet shapes are very well described by pQCD MPI models.
- < pT > vs Nch is also very well described by Pythia in both the intra-jet and the Underlying Event: <pT> of jet constituents decrease with N_{ch} while it smoothly rises in UE constituents.

→The high multiplicity events are not driven by the leading interaction, they are rather due to large MPI multiplicities.

- Barion/meson ratios vs p_T in pp interactions are know to scale with √s. A first look to their N_{ch} dependence in the context of pQCD MPI reveal sensitivity to color reconnections with qualitative flow-like patterns.

If time allows…

The Underlying Event

Measuring the complementary activity in the presence of a hard scattering

Impact on isolations, jet pedestals, vertex reco etc.
“There would not be a vertex in H → $\gamma\gamma$ events without the Underlying Event…”

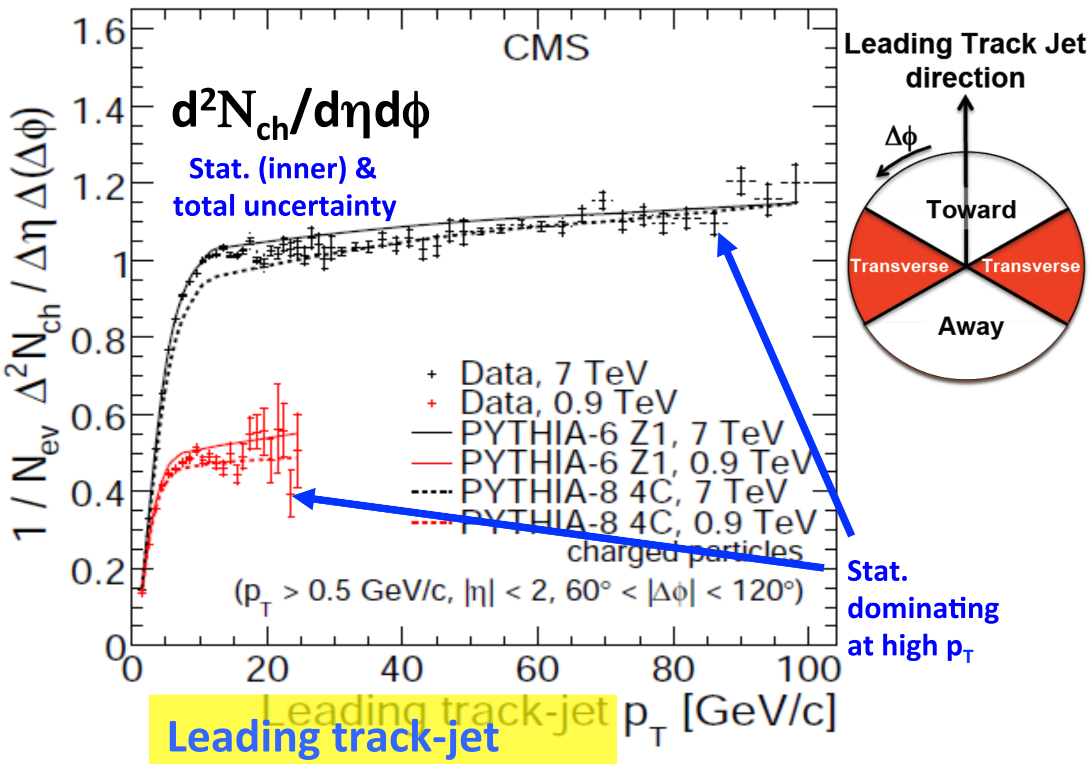
Actually UE is interesting per se: handle on soft MPI and beam remnants.

Soft MPI in high p_T events

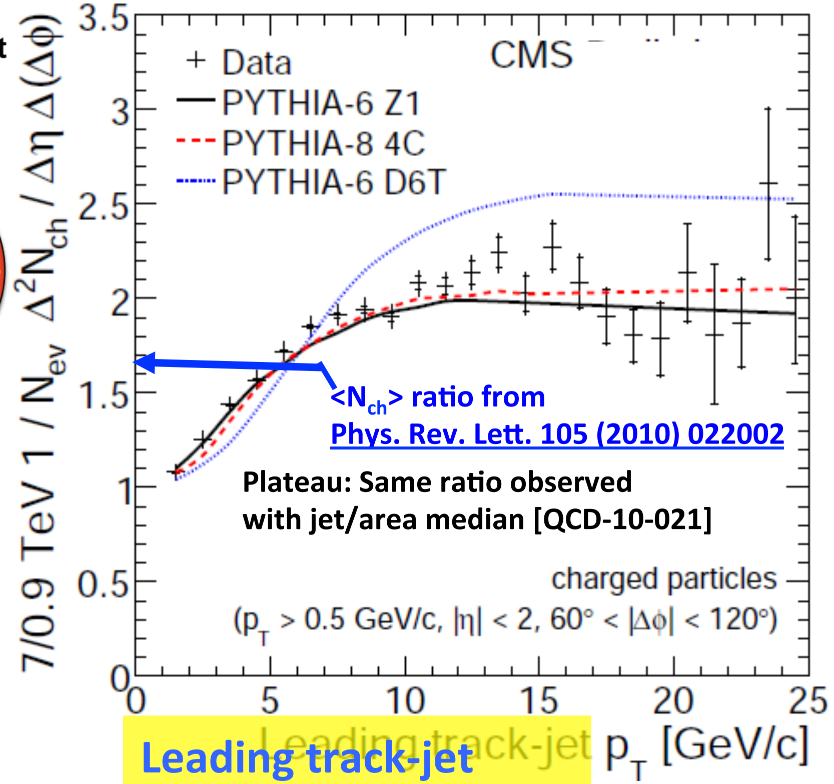
Credits:
- Ellie Dobson

UE in Jets: densities in the Transverse Region

7 TeV and 0.9 TeV results for the reference charged multiplicity density profiles including Z1 (solid) and 4C (dashed) MC predictions.



$$\frac{d^2N_{ch}/d\eta d\phi \text{ vs } p_T \text{ (7 TeV)}}{d^2N_{ch}/d\eta d\phi \text{ vs } p_T \text{ (0.9 TeV)}}$$



Fast rise for p_T < 8 GeV/c (4 GeV/c), attributed mainly to the **increase of MPI activity**, followed by a **Plateau-like region** with ≈ constant average number of selected particles in a **saturation regime**.

A factor 2 UE increase going from 0.9 TeV to 7 TeV to be compared with 1.66 for MB.

Nota bene: corrected distributions!

UE activity in Jets and Drell-Yan Z(μμ) events

UE Measurements in (track) Jets:

Fast rise followed by plateau. Indication of two different regimes (two scale picture). MPI rise dominates at low p_T, radiation rise dominates at higher p_T.

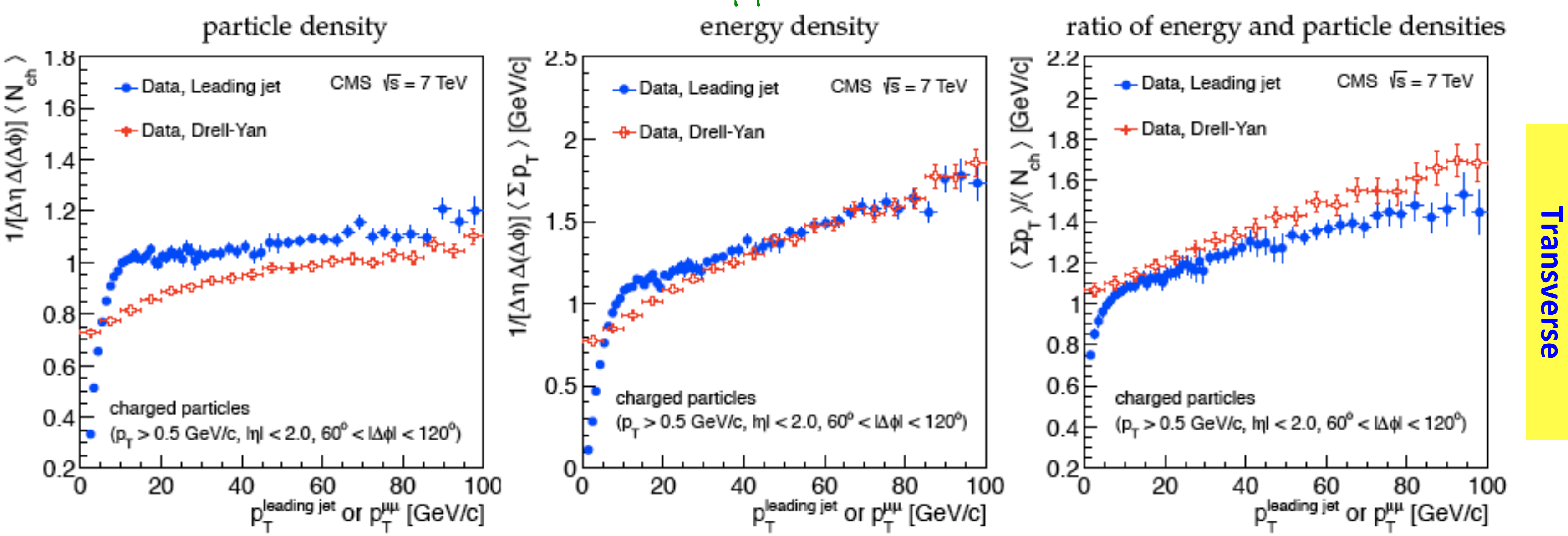
→ UE in high p_T di-jet events is ≈ universal.

UE Measurements in Drell-Yan:

MPI saturated. Radiative increase of UE activity with p_T di-lepton. Constant vs $M_{di\text{-}lepton}$.

→ Min activity around 80% with respect to the plateau in jet events.

81 GeV < Mμμ < 101 GeV



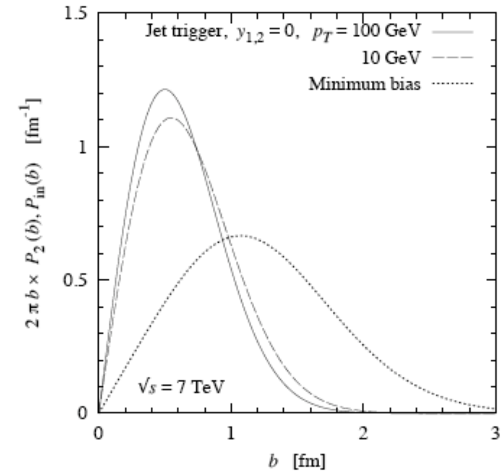
Eur.Phys.J. C72 (2012) 2080.

MPI vs Generalized Parton Distributions

"Inter-parton correlations and MPIs".
[M.Strikman, **Phys. Rev. D83 (2011) 054012**]

Gluon transverse size decreases with increase of x

$<\rho^2>_g$ from analysis of GPDs from J/ψ photo production



Impact parameter distributions of inelastic pp collisions at $\sqrt{s}$ = 7TeV. Solid (dashed) line: Distribution of events with a dijet trigger at zero rapidity, $y_{1,2}$ = 0, c, for p_T = 100 (10) GeV . Dotted line: Distribution of minimum–bias inelastic events (which includes diffraction).

Transverse size of large x partons is much smaller than the transverse range of soft strong interactions

$$\langle \rho^2 \rangle_g = \frac{\partial}{\partial t} \frac{G(x.t)}{G(x,0)}$$

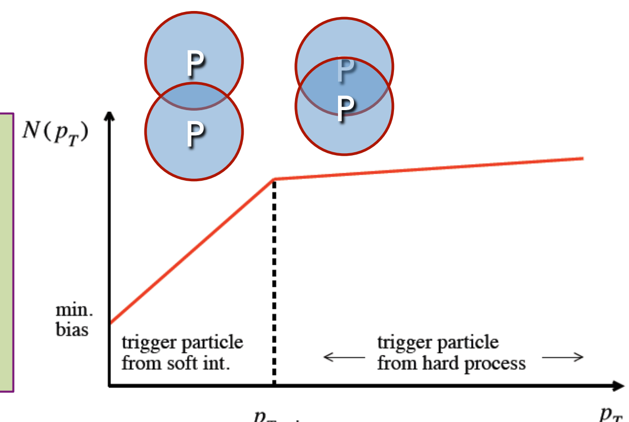
$$\langle \rho^2 (x > 10^{-2} \rangle \ll R^2_{soft}$$

$\Downarrow$

Two scale picture

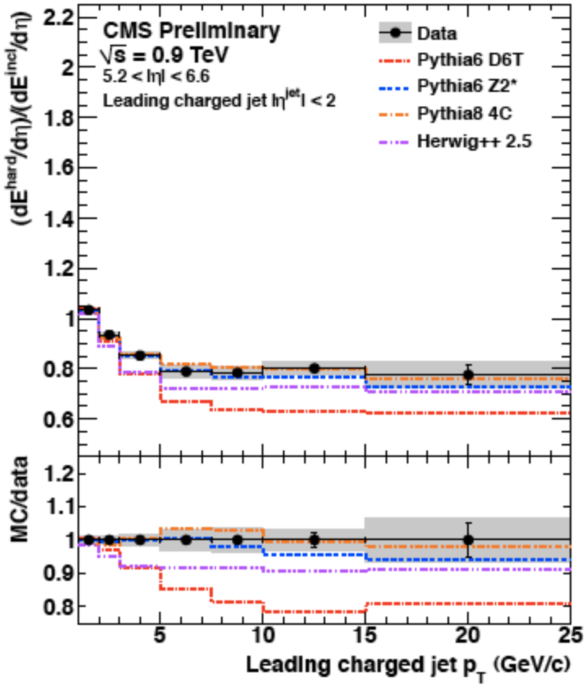
Also explains general features of UE @ hadron colliders

$<\rho^2>_g$ < $<\rho^2>_q$ explains UE in DY < UE in Jets

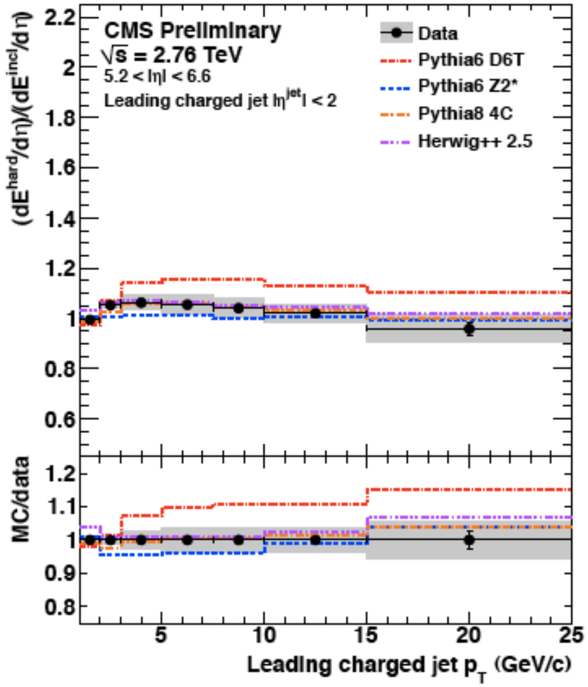


CMS: Energy flow in the VERY forward region

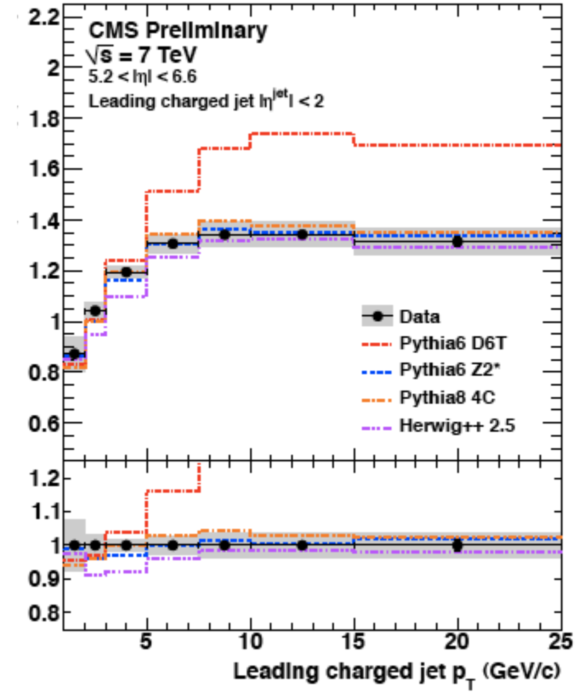
$\sqrt{s}$ = 0.9 TeV



$\sqrt{s}$ = 2.76 TeV



$\sqrt{s}$ = 7 TeV



Energy deposited in CASTOR (5.2 < $|\eta|$ *< 6.6) for events* with a charged particle jet in the central pseudorapidity region $|\eta_{jet}|$ *< 2, as a* function of charged particle jet transverse momentum p_T
(normalized to the average energy in inclusive events)

→ p_T evolution of observable changes trend with $\sqrt{s}$ (decreasing at low $\sqrt{s}$, increasing at high $\sqrt{s}$)
Interpretation: at low $\sqrt{s}$ drag fragmentation effects, at high $\sqrt{s}$ the major role of the MPI is restored.
→ pQCD models adopting pT-ordered showers and tuned@LHC in the central region are favored by forward data (agreement within 5-10%)
→ Good agreement also for *EPOS 1.99, QGSJET01, QGSJETII-03, SIBYLL 2.1* (within 20%)

JHEP 1304, 072 (2013).

Bottom Line: Underlying Event

- Two scale picture in the case of jet events: rise at low p_T + plateau at a rather modest energy dependent p_T (O(few GeV)).
  - Interpretation: high p_T jets select central collisions hence large MPI multiplicity.
- Single scale picture (plateau) in the case of DY.
  - Interpretation: DY events always select central collisions hence large MPI multiplicity.

→MPI+GPDF analysis also explains UE(DY)/UE(jets). What about DPS?

→ connection to $\langle\rho^2\rangle_g$ / $\langle\rho^2\rangle_q$. [M.Strikman,Phys.Rev. D83 (2011) 054012]

- Energy flow in the forward region (for central jets)
  - » Energy flow decreases with p_T at low √s and increases with p_T at high √s, where the well known Underlying Event pattern is reproduced

→ Interpretation: at low √s drag fragmentation effects, at high √s the major role of the MPI is restored:

  - » MC tunes optimized for the Underlying Event measurements in the central region reproduce well the forward Energy Flow.

MPI bottom line

- **Hard MPI: the Double Parton Scattering.**
  - **In the years '80 claimed observation of uncorrelated di-jet production inspired the first (soft) MPI implementation in the pQCD models.**
  - **Pletora of pp channels @LHC, however still no striking DPS evidence.**
    - **Large errors on σ_{eff}.**
    - **Promising results from multiple heavy flavors @LHC & same sign WW and ZZ production @HL-LHC.**
  - **Stringent to have soon pA extension of these pp measurements.**
- **Basic soft QCD Measurements at different √s**
  - **$<N_{ch}>$, N_{ch} (& KNO violations), $dN_{ch}/d\eta$ vs η, p_T, $<p_T>$ vs N_{ch}, UE, …**
    - **Very good performances of the pQCD MPI models, color correlations essential.**
    - **N_{ch} proportional to N_{MPI} → straightforward interpretation of measurements quoting yields vs N_{ch}.**
- **Long-range correlations (ridge) in both pp and pA.**
  - **Intermediate p_T range (1-2 GeV), large multiplicities.**
  - **Major role played by MPI? See next point.**
- **Studies on Large Multiplicity Events**
  - **ALICE: large multiplicity events look more spherical than expected (Pythia)**
  - **CMS: large multiplicity events look less jetty than expected (Pythia)**
  - **→ Nature disfavor jets: large multiplicity events rather obtained through several soft MPI.**

MPI: future progress and discussion items

- MPI are so popular that might be easily neglected
  - Unavoidable ingredient of our pQCD models, they drive the description of the initial state in pp, pA, AA.
  - In the meantime TH progress prepares the ground for the future MPI studies focusing on hard MPI, whose comprehension is stringent to realize the full physics potential of the HL-LHC.
- MPI measurement program @ LHC incomplete and new data is coming…
  - σ_{eff} should be systematically measured in several pp and pA channels
    - differential measurements, universality tests, pA/pp, compatibility of soft MPI vs hard MPI (comparing with the corresponding UE measurements).
  - And we should not forget to extend the standard soft QCD measurements at higher $\sqrt{s}$.
  - More detailed investigations of large multiplicity events focusing on barion/meson ratios and $\langle p_T \rangle$ vs N_{ch} invoking also the additional handles provided by the event shapes (Sphericity, Spherocity etc.)
- Is it possible to describe at least part of the flow-like patterns through MPI +color reconnections?
  - The flow-like patterns in pA and pp might be connected to the description of the initial state in small corners of the phase space dominated by a large number of color-connected soft MPI.

Continue… news expected from both soft and hard MPI

Credits:
- Ellie Dobson

BACKUP

- MC Tools

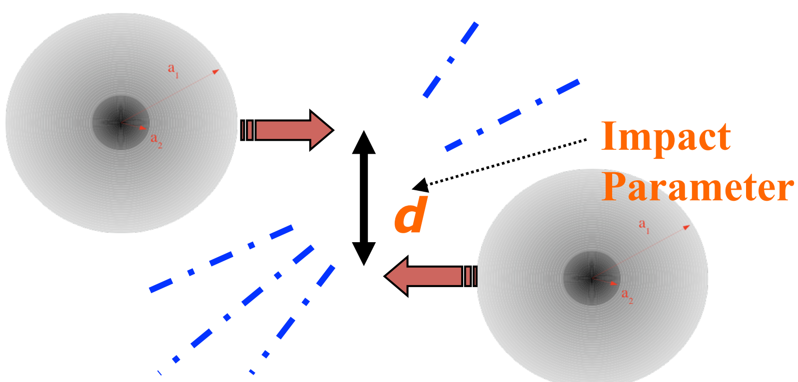
UA5 Charged Multiplicity Distribution

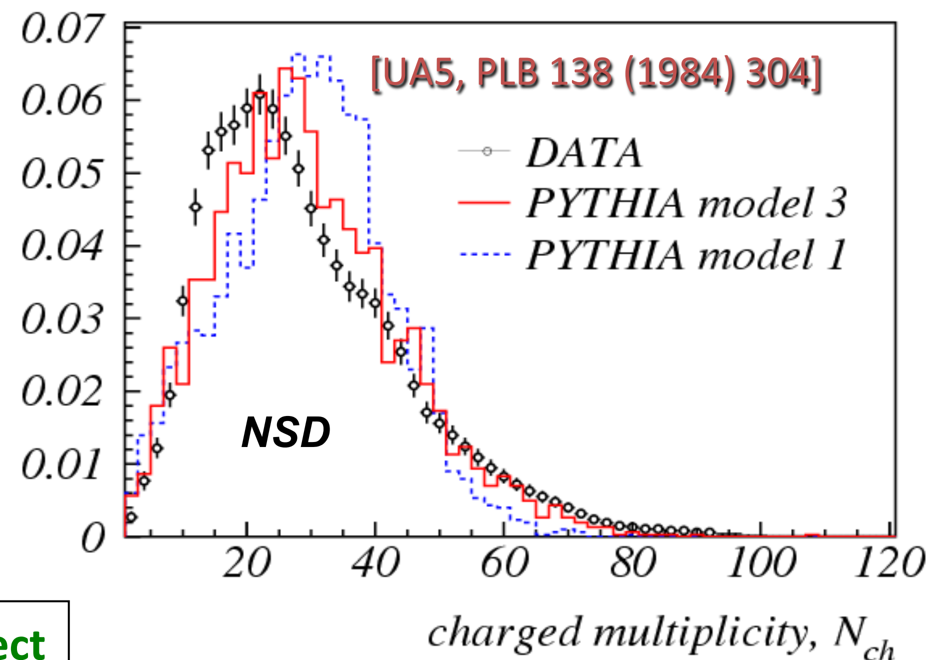
First inspiring/challenging test for the MPI implementation in Pythia

“Vintage” MPI

- **All hadron collisions equivalent (model 1)**
  - → All the partonic interactions equivalent
  - → Abrupt turn off of the cross section at P_T cut-off
- **Varying impact parameter between the colliding hadrons (model 3 and higher)**
  - → Introduce Impact Parameter correlations in Multiple Parton Interactions
  - → Continuous turn off of the cross section at P_T cut-off

Models with varying Impact Parameter between the colliding hadrons: hadronic matter can be described by Gaussians or even more complex geometries





→ Also essential to describe UE Pedestal Effect

Color reconnection in Pythia

In Pythia, the final step at parton level before the hadronization is the color **reconnection** CR, its aim is to describe the hadronization of a many parton system in a single event with multiple hard sub collisions.

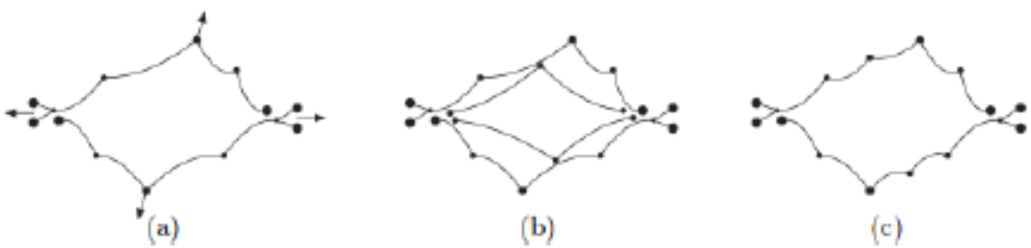


Fig. 2. (a) In a hard gluon-gluon subcollision the outgoing gluons will be colour-connected to the projectile and target remnants. Initial state radiation may give extra gluon kinks, which are ordered in rapidity. (b) A second hard scattering would naively be expected to give two new strings connected to the remnants. (c) In the fits to data the gluons are colour reconnected, so that the total string length becomes as short as possible.

Toy model of (non-perturbative) color reconnections, applicable to any final state

at hadronisation time, each string piece has a probability to interact with the vacuum / other strings:

$$P_{reconnect} = 1 - (1-\chi)^n$$

χ = strength parameter: fundamental reconnection probability (free parameter)

n = number of multiple interactions in current event (~ counts # of possible interactions)

G. Gustafson, Acta Phys.Polon.B40:1981-1996,2009

Pythia Tunes in CMS

- Pythia 6 Virtuality ordered showers, old MPIs
  - CTEQ5L pre-LHC Tune DW(T)
  - CTEQ6LL pre-LHC Tune D6(T)

  [arXiv:1003.4220]
  - Describe UE and other very important observables at Tevatron like p_T(heavy bosons) and Jet azimuthal decorrelation

PRE-LHC

- Pythia 6 new MPIs with interleaved p_T-ordered showers **(MORE RADIATION, LESS MPIs)**
  - **CTEQ5L** LHC Tune **Z1** uses Professor AMBT1 LEP fragm. & ATLAS Min Bias: **Updated Color Rec.**
  - **CTEQ6LL** LHC Tune **Z2** by hand from Z1: decreased p_T cut off

  [arXiv:1012.5104, arXiv:1010.3558v1]

POST-LHC

- Pythia 8, brand new MPI model, inteleaved p_T-ordered showers
  - **CTEQ6LL** Tevatron **Tune 2C** describes the relevant Tevatron phenomenology
  - **CTEQ6LL** LHC **Tune 4C** describes ATLAS MB & UE (leading track)

  [arXiv:1011.1759]

$p_{T0}^{LHC} = p_{T0}^{Tevatron} (\sqrt{s}^{LHC} / \sqrt{s}^{Tevatron})^{\varepsilon}$ **Where ε = PARP(90) or MultipleInteractions:EcmPow**

T versions (for example D6T) 2C, 4C → small $\varepsilon \approx 0.16 - 0.21$ (CTEQ6LL)

DW, Z1, Z2 → large $\varepsilon \approx 0.24 - 0.30$ (CTEQ5L, CTEQ6LL for Z2)

Still no coherent description of Tevatron and LHC (more info in backup slides)

Multiplicities, Kinematics

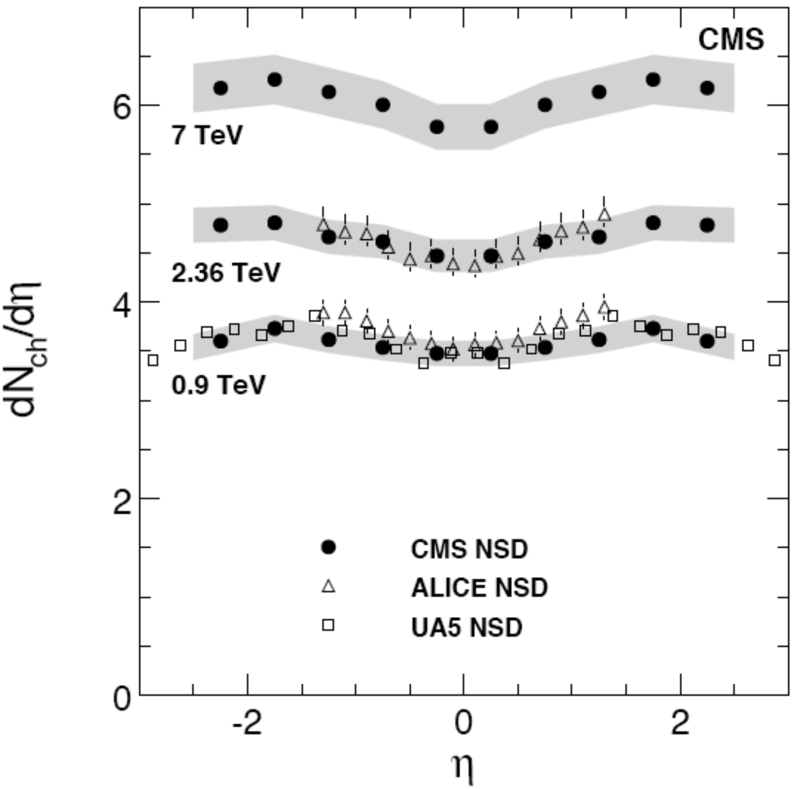
Single charged particle spectra: $dN_{ch}/d\eta$

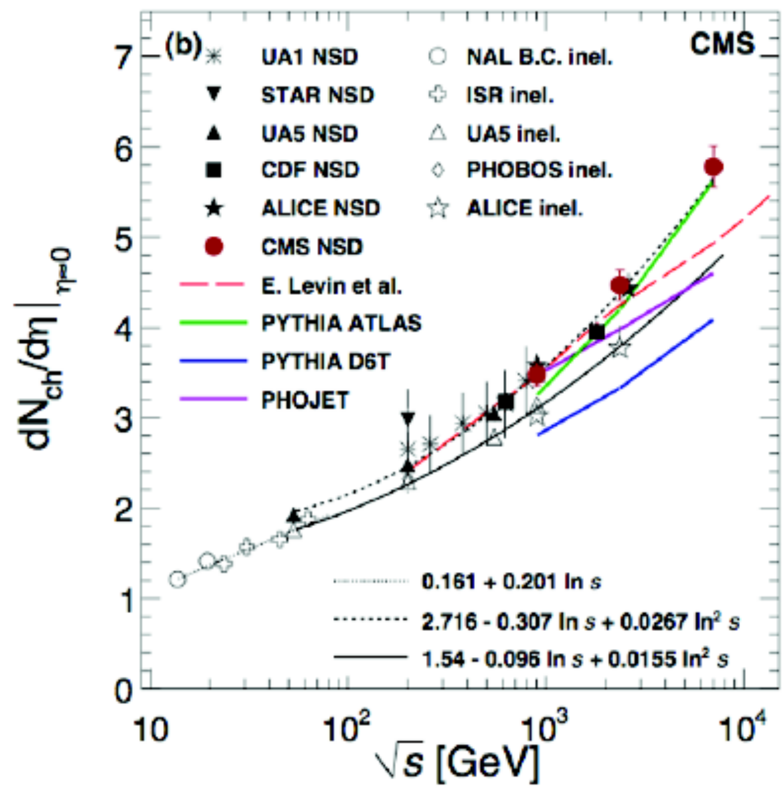
The $dN_{ch}/d\eta$ distributions are obtained with three redundant methods, based on counting:

(i) Reconstructed clusters in the barrel part of the pixel detector (p_T^{MIN} = 30 MeV).

(ii) Pixel tracklets composed of pairs of clusters in different pixel barrel layers (p_T^{MIN} = 50 MeV).

(iii) Tracks reconstructed in the full tracker volume (p_T^{MIN} = 100 MeV) → also allows for p_T measurement.



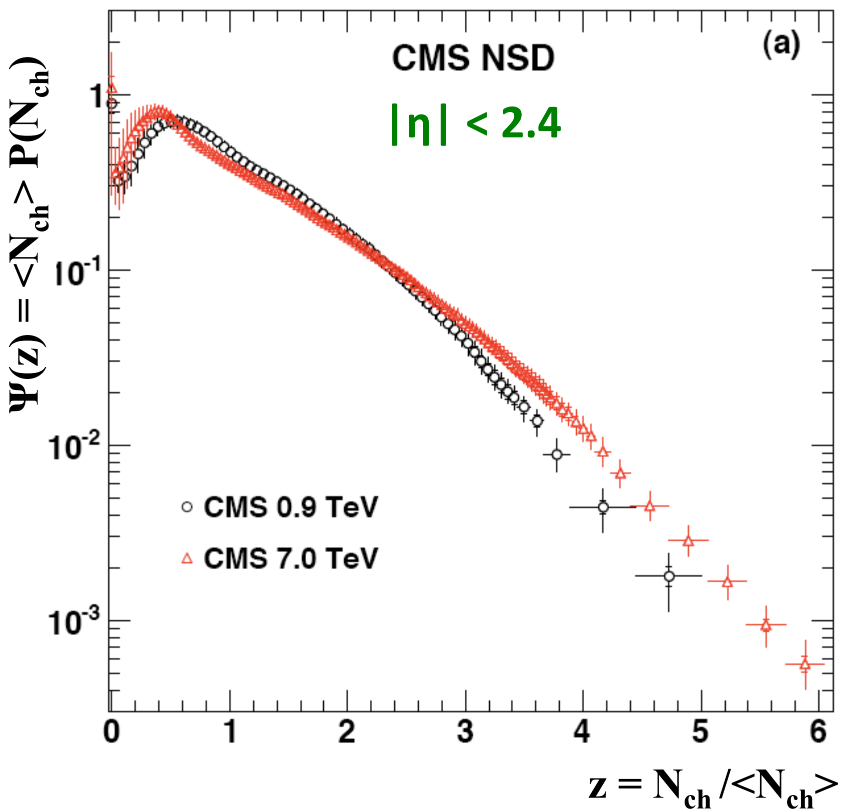


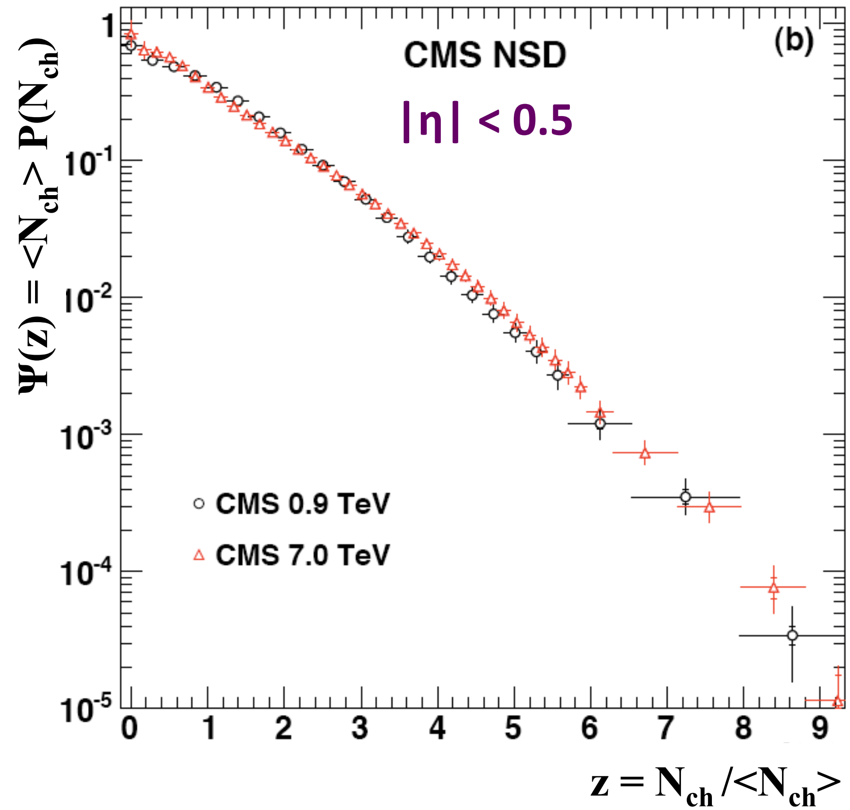
At 7 TeV: $dN_{ch}/d\eta|(|\eta|<0.5)$ = 5.78 ± 0.01 (stat.) ± 0.23 (syst.) for non-single-diffractive events.

Relative increase from √s = 0.9 to 7 TeV = (66.1 ± 1.0 (stat.) ± 4.2 (syst.))%.

→LHC measurements clearly confirm trend to have a rise stronger than ln (s).

Violation of the KNO scaling at the LHC





KNO Scaling [Koba, Nielsen, Olesen, Nucl. Rev. B40 (1972) 371].

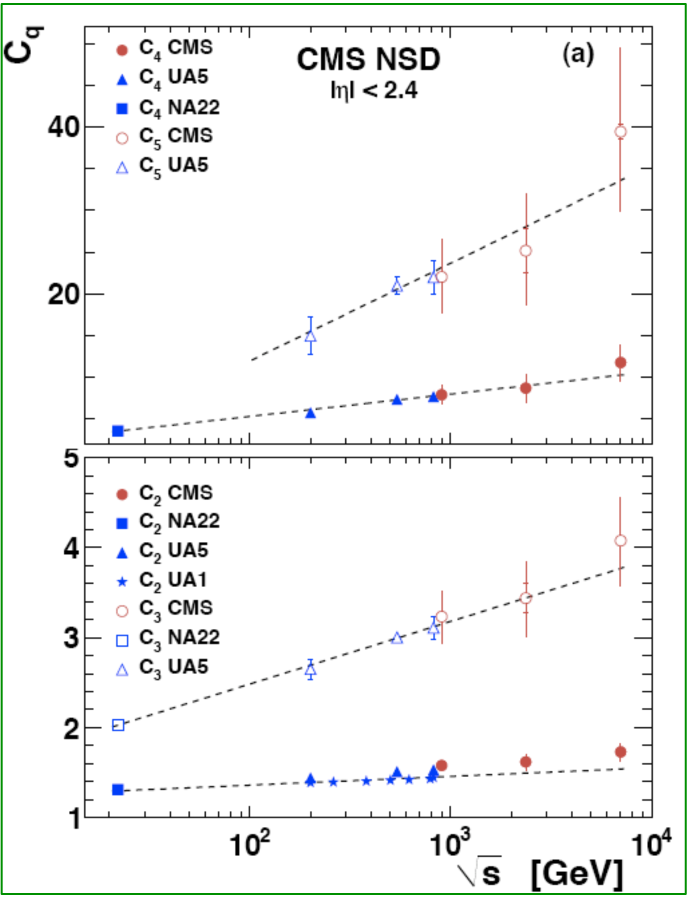
Violation already reported by UA5 (and comparing ISR, SPS, Tevatron).

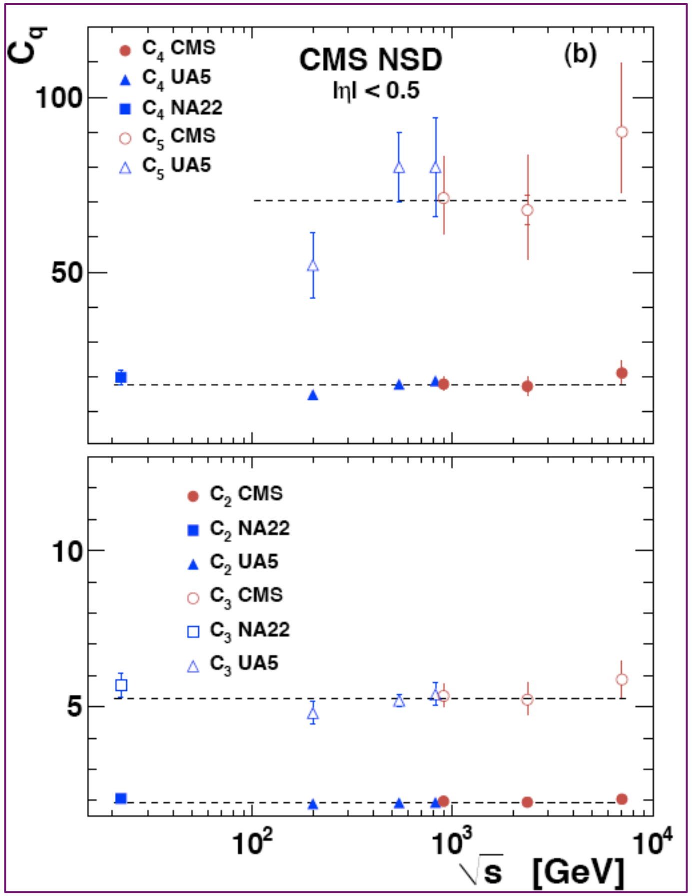
CMS confirms violation for $|\eta|<2.4$. Sensitive effect in the tails (large $z = N_{ch} / \langle N_{ch} \rangle$).

→ Interpretation: connected to the presence of Multiple Parton Interactions.

Normalized order-q moments $C_q = \langle N_{ch}\rangle^q / \langle N_{ch}^q\rangle$

An alternative (compact) representation of the charged multiplicity





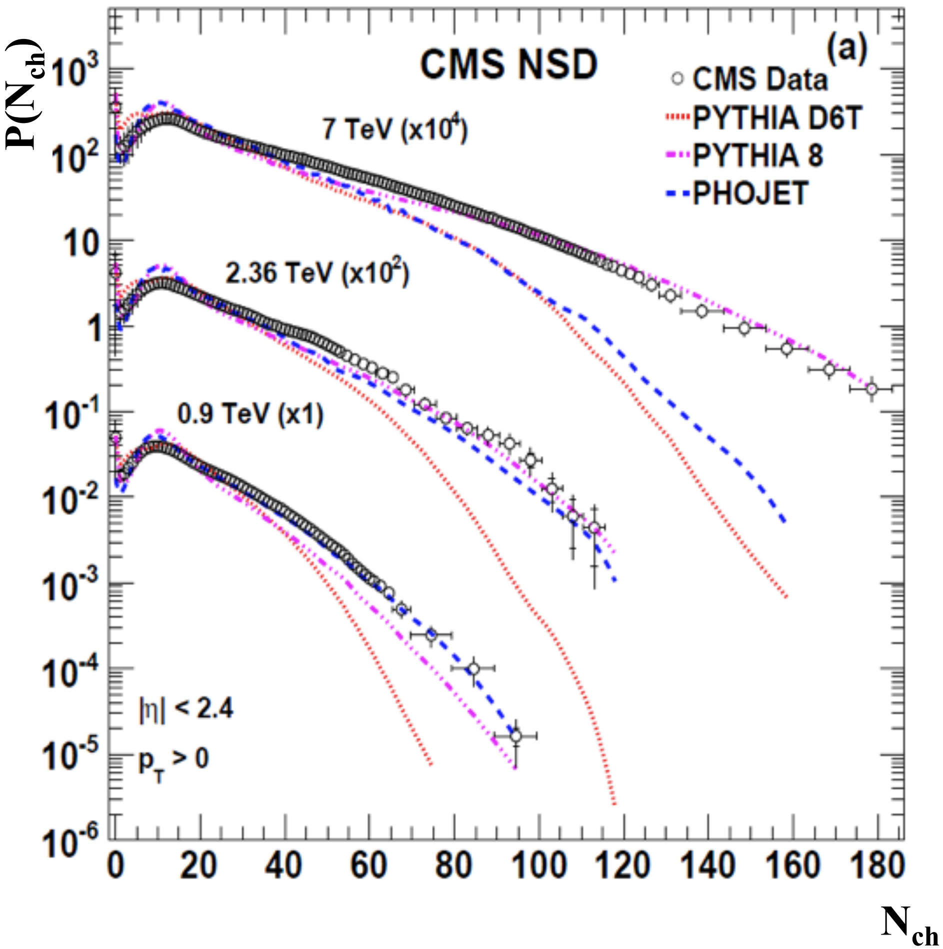
√s dependence of the normalized moments C_q of the multiplicity distribution for:
(a) |η| < 2.4 and
(b) |η| < 0.5

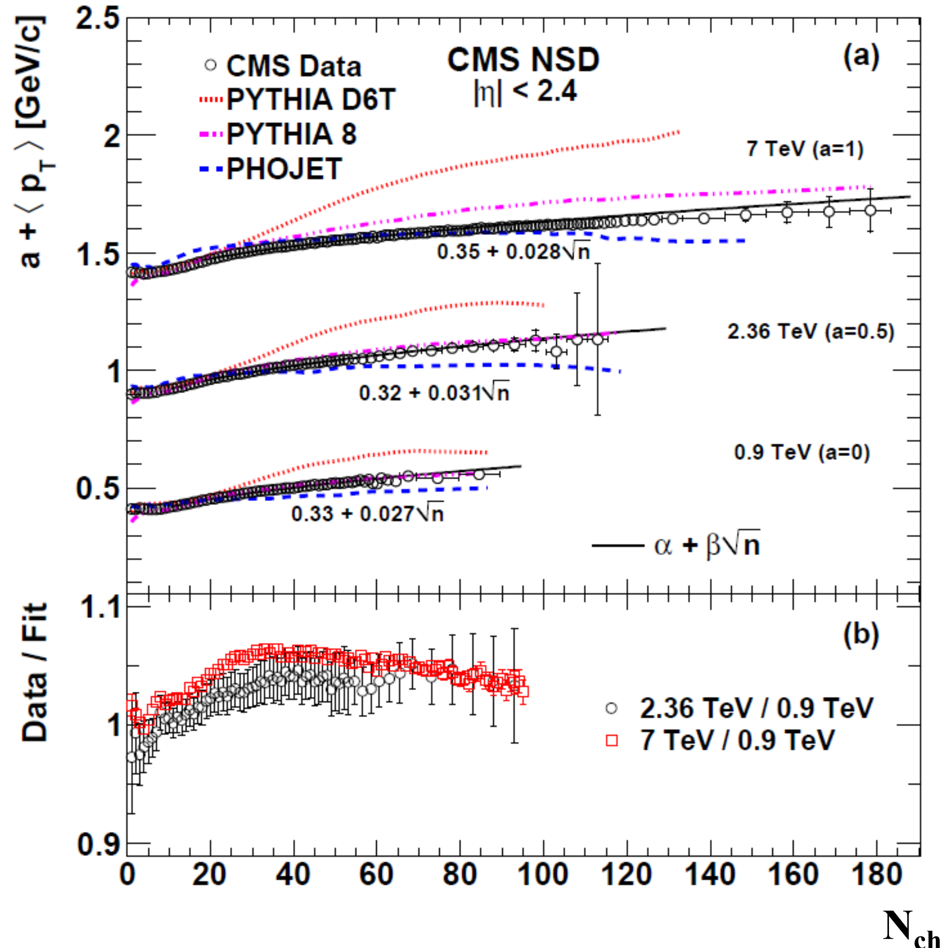
(a) → ln(s) linear fits
(b) → constant fits

If KNO scaling holds, also C_q are independent from √s.
Violation sensitive for |η|< 2.4, i.e. large pseudo-rapidity.
No clear violation for |η|< 0.5 at least up to the order 4.

Selected old (legacy) results are reported in the back-up slides.
→Tagged with blue color in the titles

CMS: Charged multiplicity and <p_T> vs N_{ch}

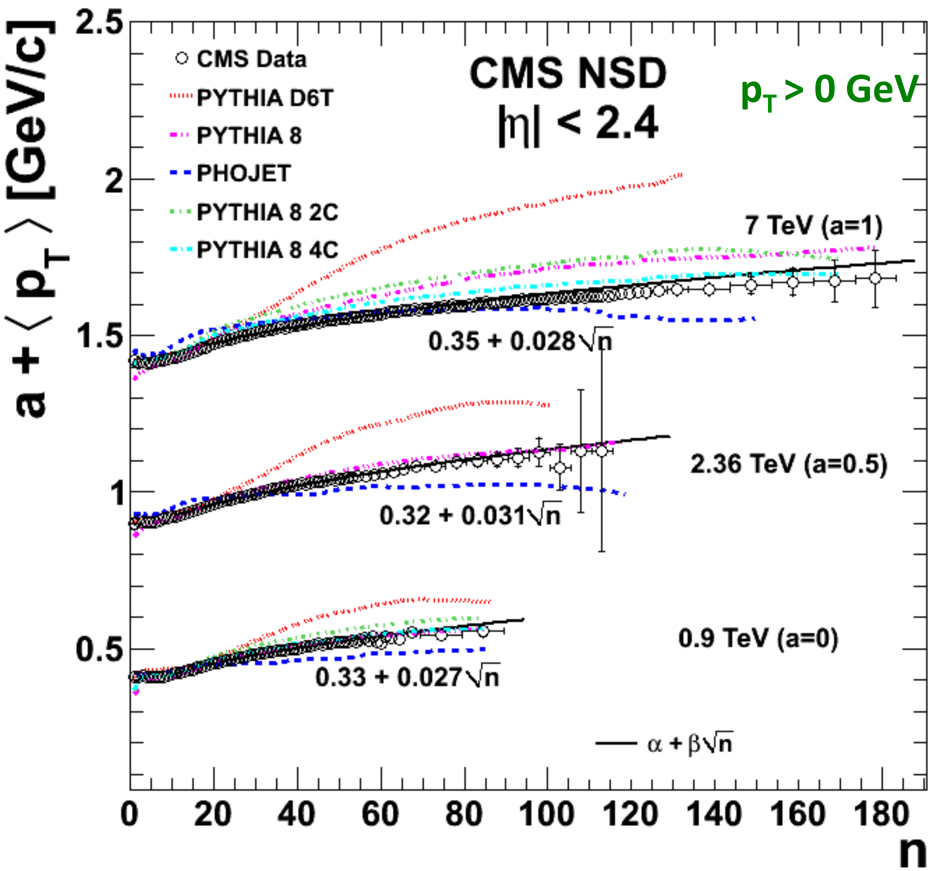




Charged particle multiplicities in Non Single Diffractive (NSD) events.
$P(N_{ch})$ = probability to produce N_{ch} charged particles.
Large multiplicity tail observed at 7 TeV. **<p_T> vs N_{ch} scales with energy.**

Reducing color reconnections…

[CMS, J. High Energy Phys. 01 (2011) 079]



$<p_T>$ vs N_{ch} distribution deeply affected by color reconnection parameters.

- Correlation underestimated by PHOJET.

- Overestimated by pre-LHC Pythia 6 Tunes (maximal color reconnection).

- Pythia 8 4C Tune, with reduced color reconnection with respect to the Tevatron Tune 2C, provides a great description at both 0.9 and 7 TeV.

- Correlations diluted including particles pT → 0. Lack of universal descriptions.

New MC/MPI developments – work in progress:

- Dynamical description of the hadrons in Pythia 8, connecting the size of the hadrons to the p_T of the leading interaction → **Further reduces the need of color reconnections.**

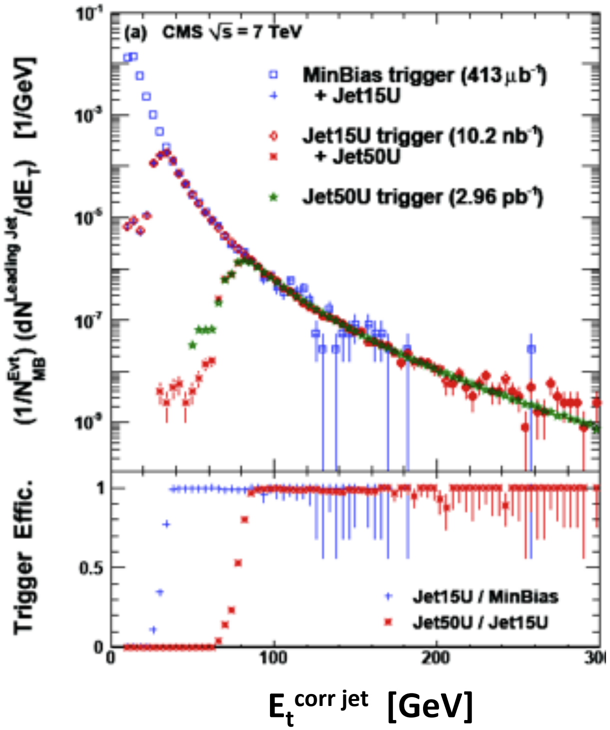
Single Charged Particle Spectra: dN_{ch}/dp_T

≈ large p_T tracks (for pp interactions at √s = 0.9 and 7 TeV)

driven by pQCD + fragmentation → power-law $x_T = 2p_T/\sqrt{s}$ scaling:

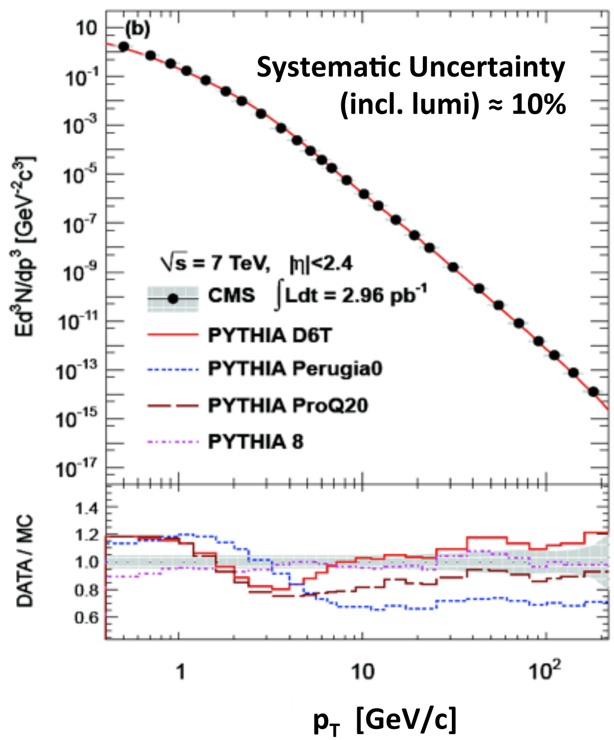
$$E\frac{d^3\sigma}{dp^3} = F(x_T)/p_T^{n(x_T,\sqrt{s})} = F'(x_T)/\sqrt{s}^{n(x_T,\sqrt{s})}$$

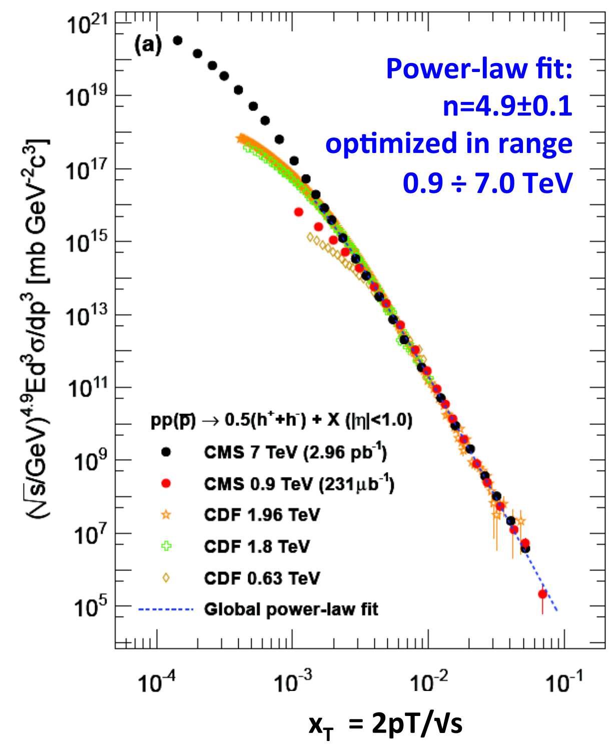
[F. Arleo et al. JHEP 583 06 (2010) 035]



Measuring charged tracks up to $p_T \sim 200$ GeV/c.

→ Using jet triggers to enhance statistics at high p_T





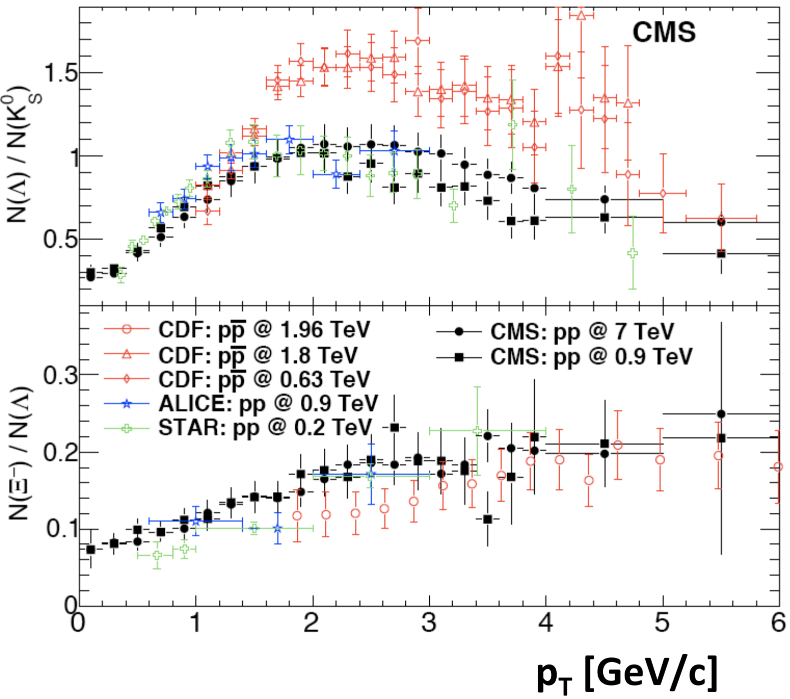
Interpolation → **2.76 TeV pp result used also to normalize nuclear modification factors in the corresponding PbPb measurement**

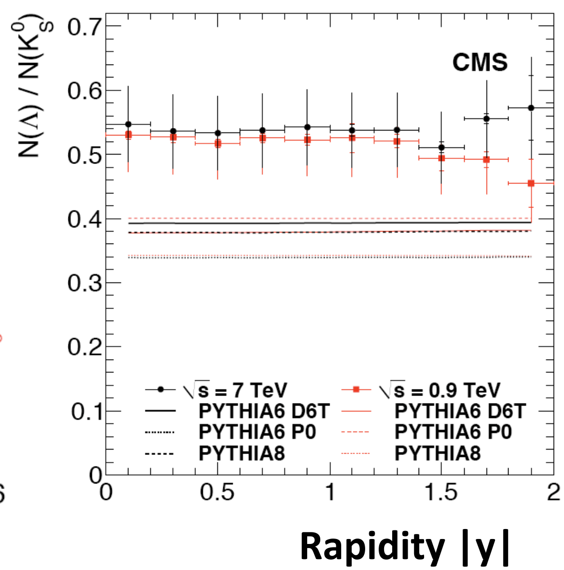
[QCD-10-006, QCD-10-008]

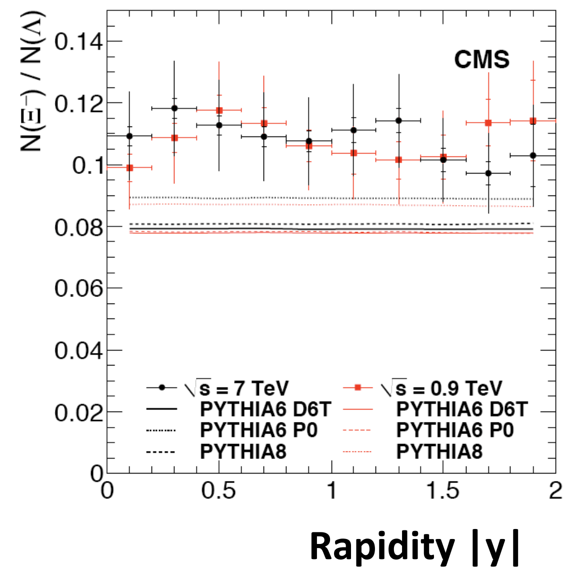
Strange Particle Production: K^0_s, Λ, Ξ^-

Ratio of s-rates in NSD events

CDF: arXiv:1101.2996 (CDF MB trigger)
ALICE: arXiv:1012.3257 (NSD)
STAR: Phys. Rev. C75 (2007) 064901 (NSD)







If a quark-gluon plasma or other collective effects were present, we might expect enhancement of double-strange baryons to single-strange baryons and/or enhancement of strange baryons to strange mesons. However…

→ The production ratios $N(\Lambda)/N(K^0_s)$ and $N(\Xi^-)/N(\Lambda)$ versus rapidity and transverse momentum show no change with centre-of-mass energy.

[QCD-10-007]

Correlations

Emphasis on long range correlations,
i.e. the first evidences of new physics at the LHC

Bose-Einstein Correlations

When wave-functions of identical bosons overlap, Bose-Einstein statistics changes their dynamics

→ Production probability enhanced for identical light boson with similar momenta.

→ BEC measurements give information about size, shape and space-time development of emitting source.

→ First observation in pion-production from p-pbar annihilations – [Phys. Rev. 120 (1960) 300].

→ Many experimental results: e^+e^- @ PETRA, SLAC, LEP / pp @ SPS / ep @ HERA / fix target: NaXX, NOMAD, ...

Observable: $$R = \frac{P(p_1, p_2)}{P(p_1)P(p_2)}$$

$P(p_1,p_2)$: **Joint probability of emission of a pair of bosons**

$P(p_1)$, $P(p_2)$: **Individual probability of emission**

→ Need to define a reference sample of non interfering boson pairs !

$$\rightarrow R(Q) = \frac{dN/dQ}{dN/dQ_{ref}}$$

Assuming particle are mostly pions, Q is:

$$Q = \sqrt{-(p_1 - p_2)^2} = \sqrt{M_{inv}^2 - 4m_\pi^2}$$

Parametrization: $$R(Q) = C[1 + \lambda\Omega(Qr)](1 + \delta Q)$$

$\Omega(Qr)$: Fourier transform of emission region of effective size r

λ : BEC strength δ : Long distance correlations

[QCD-10-003, QCD-10-023]

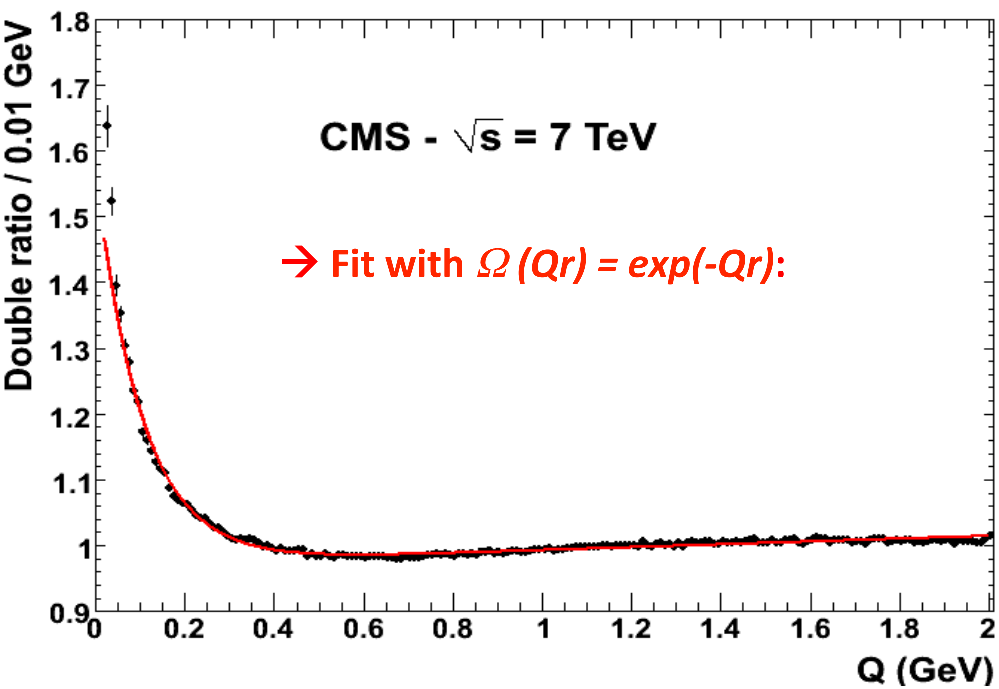
Bose-Einstein Correlations

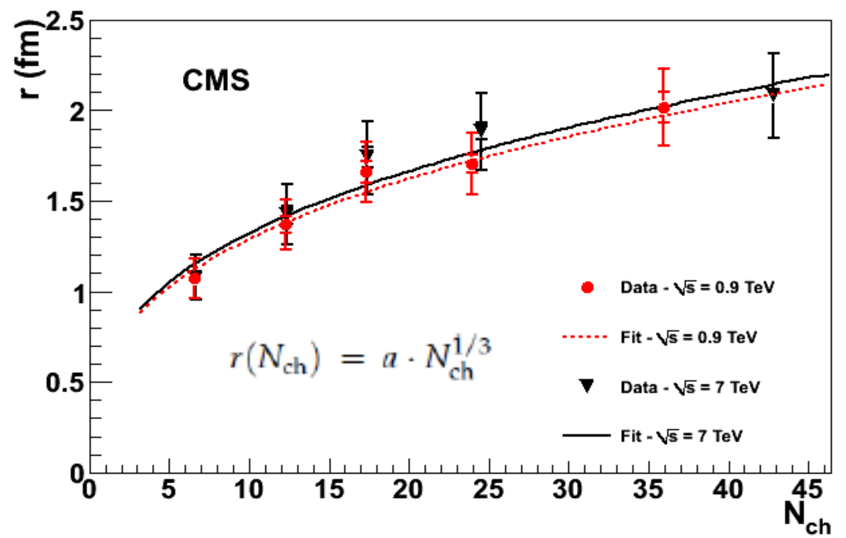
Reference samples:

- **Opposite-charge pairs:** natural reference sample, but containing resonances.
- **Opposite-hemisphere pairs:** Pairing after the inverting of the 3-momenta of one of the two particles (for like- and unlike-sign).
- **Rotate particles:** pairing happen changing sign of x and y component of one particle.
- **Pairs from mixed events:** (i) random events, (ii) events w/ similar charge multiplicity in the same η region, (iii) events in the same invariant mass region of the signal.
- **Double ratio (normalization to R_{MC}) to avoid biases.**

√s	0.9 TeV	7 TeV
r (fm)	1.56 ± 0.02 ± 0.15	1.89 ± 0.02 ± 0.21
λ	0.616 ± 0.011 ± 0.029	0.618 ± 0.009 ± 0.042

→ BEC effective emission region grows with √s while strength is similar.



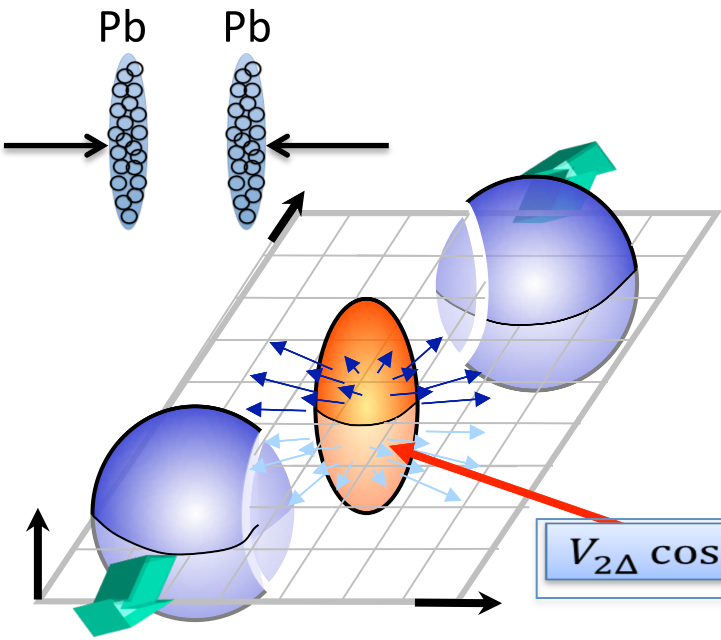


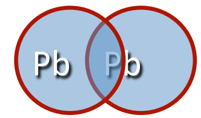
→ BEC effective emission region grows with N_{ch}, as observed by previous experiments.

→ r vs N_{ch} ≈ scales with √s.

[QCD-10-003, QCD-10-023]

Ridge in Pb-Pb interactions

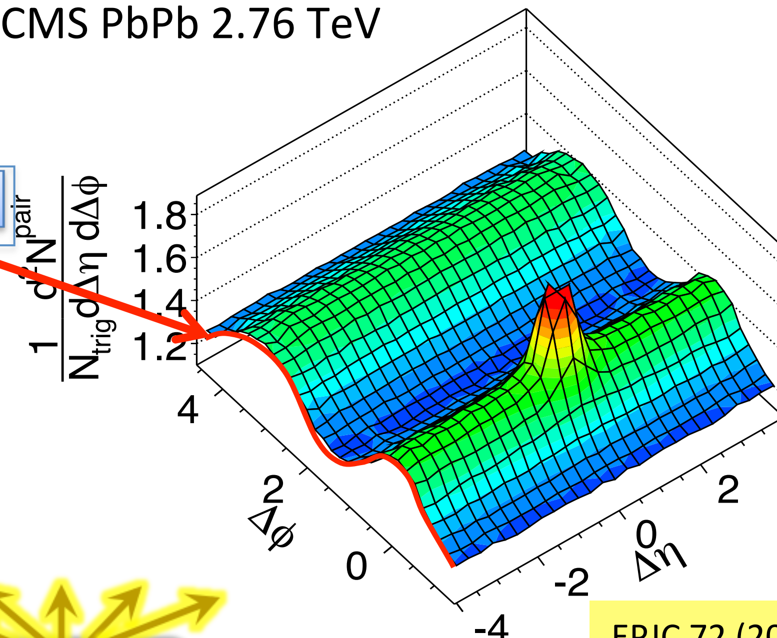




35-40% centrality

CMS PbPb 2.76 TeV

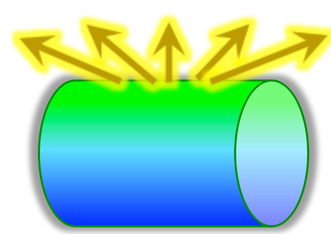
$V_{2\Delta}\cos(2\,\Delta\phi)$



EPJC 72 (2012) 2012

Particle azimuthal distributions:

$dN/d\phi \propto 1 + \Sigma\, 2V_n \cos(n(\phi-\phi_0))$



p_T^{trig}: 4–6 GeV/c

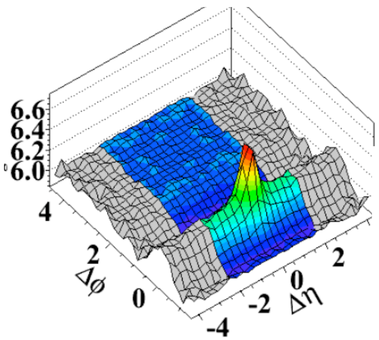
p_T^{assoc}: 2–4 GeV/c

EPJC 1272 (2012) 2012.

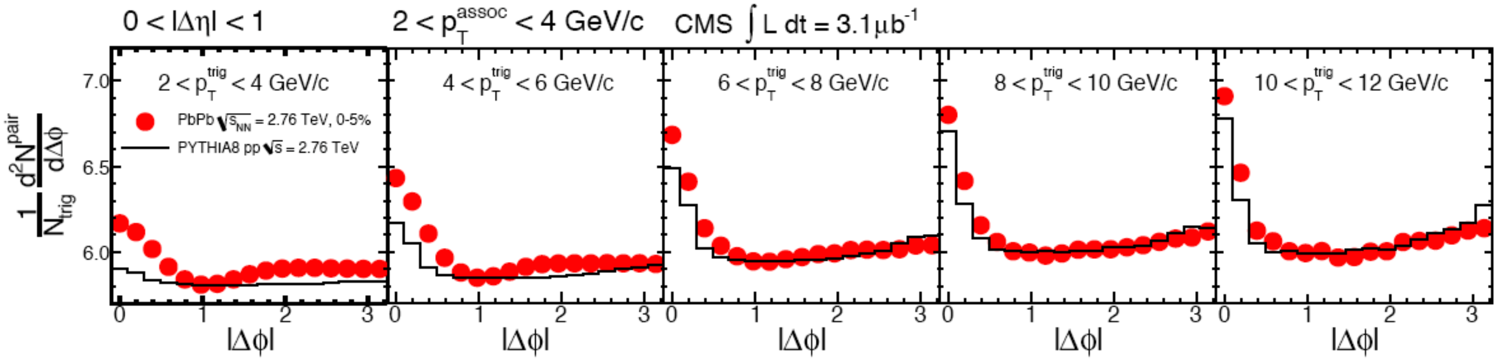
Short and Long Range Correlations in PbPb ($\sqrt{s_{NN}}$ = 2.76 TeV)

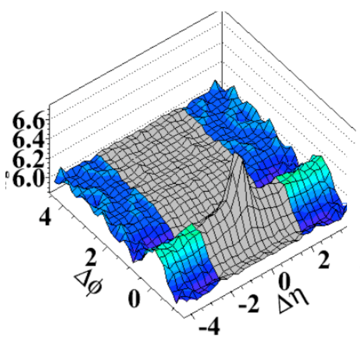
Ridge seen in Heavy Ion collsions.

Centrality 0-5%

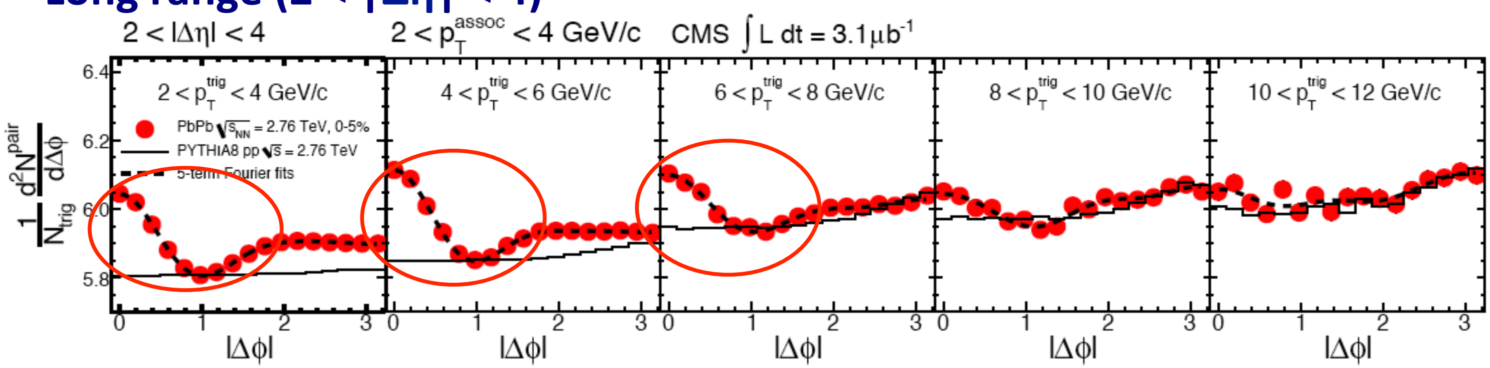


Short range (0 < |Δη| < 1)





Long range (2 < |Δη| < 4)

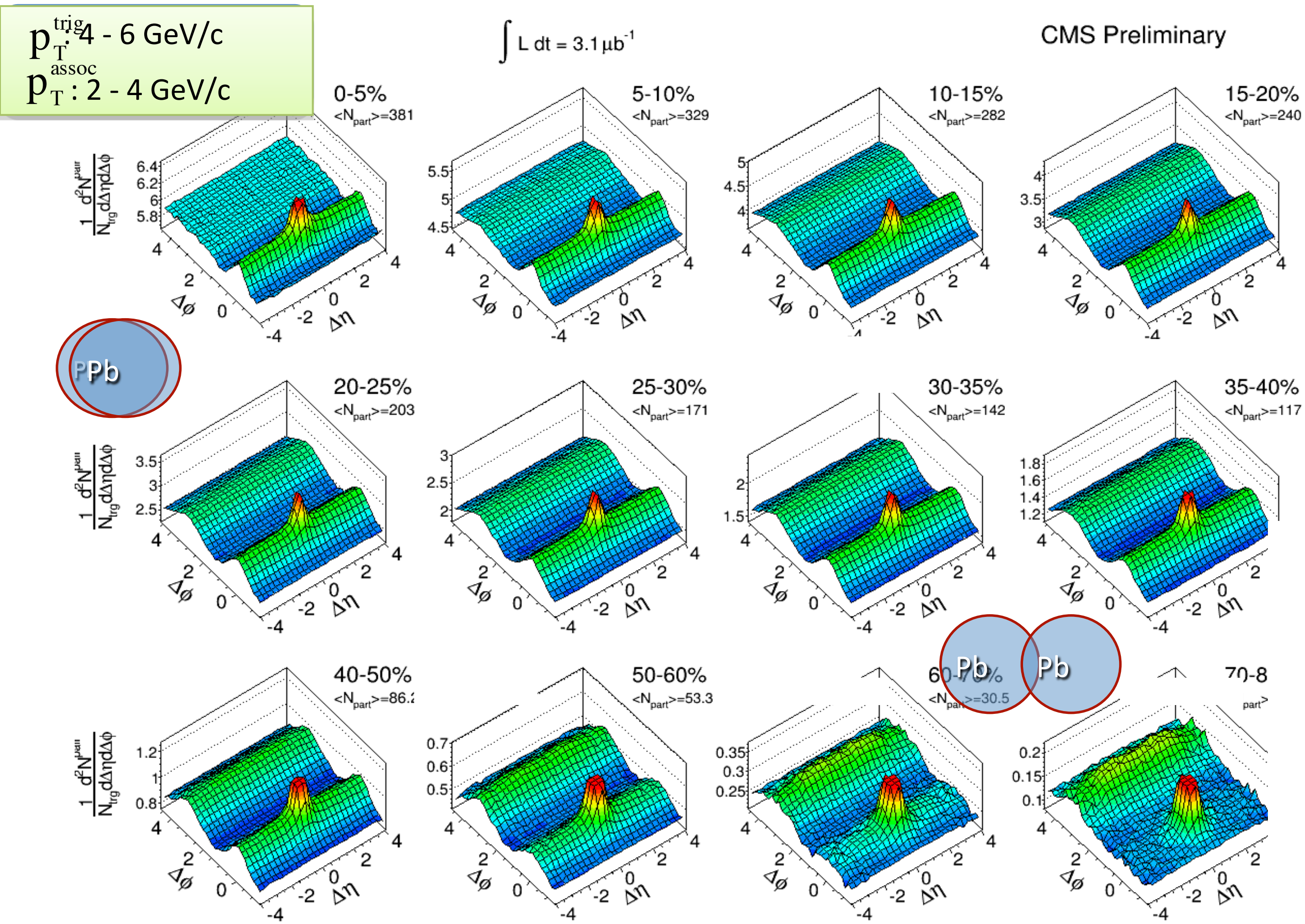


- **Short** & **long range** correlations studied for different p_T^{trig}.
- **Long range** correlations: large deviation from predictions (No ridge in MC).
- **Ridge effect maximal for p_T^{trig} ≈ 2-6 GeV then it does disappear beyond 10 GeV. (also in pp)**

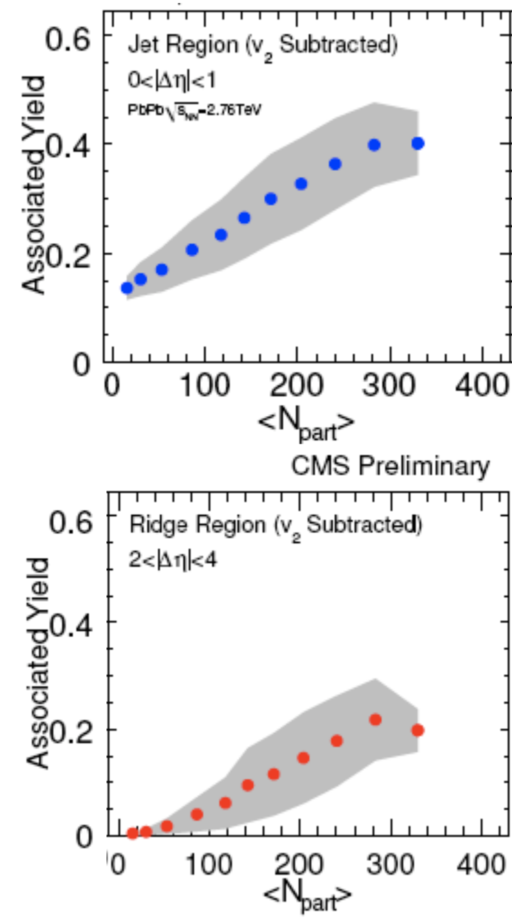
[HIN-11-001]

Centrality effect and elliptic flow subtraction

Centrality dependence of correlations in PbPb ($\sqrt{s_{NN}}$ = 2.76 TeV)



Associated hadron yields of the ridge structure are studied before and after explicit subtraction of the elliptic flow (v_2) component.



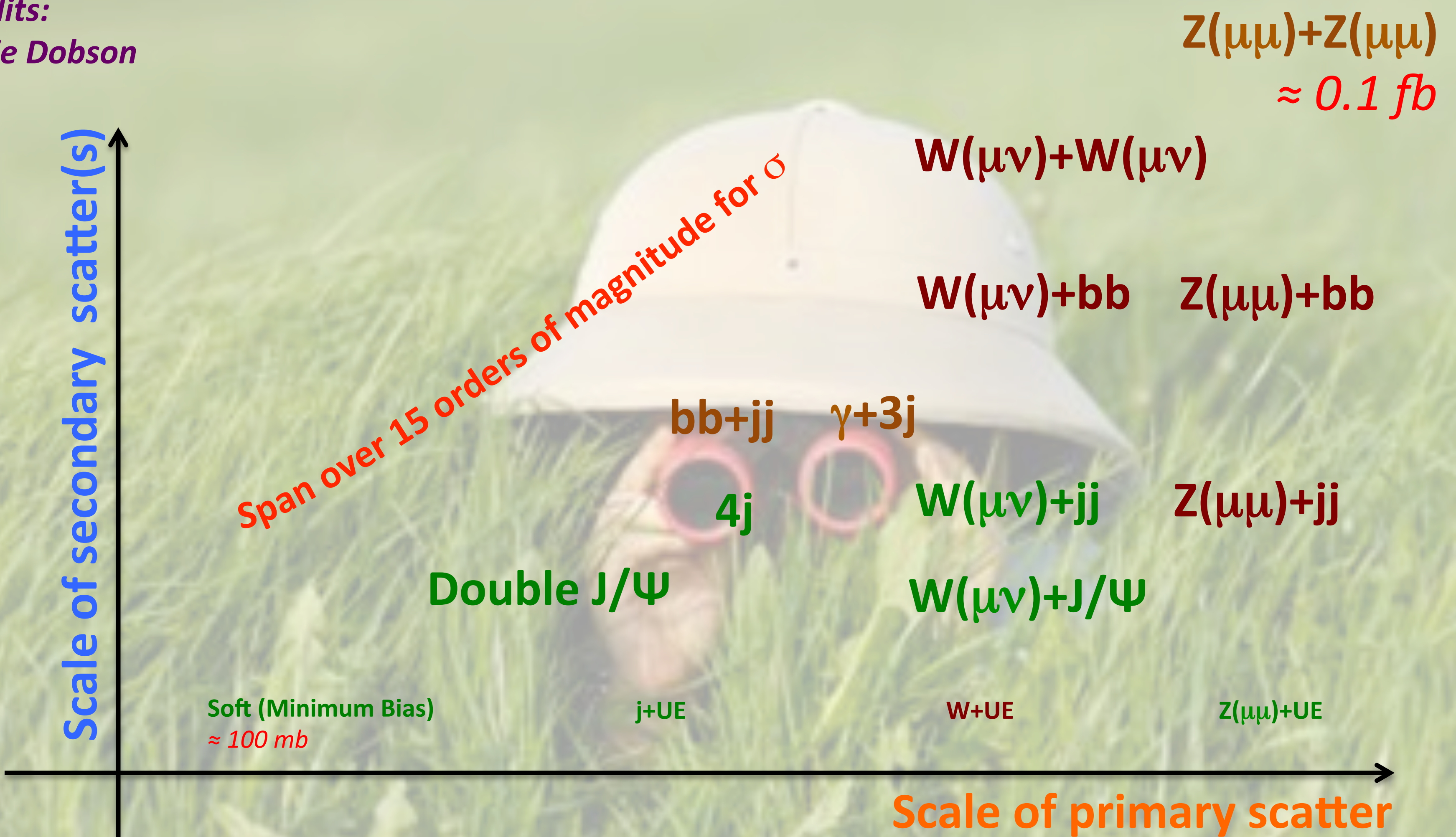
Hard Multiple Parton Interactions

The Double Parton Scattering (DPS)

i.e. detecting patterns of two separate hard scatterings taking place in the same vertex

Looking for at least two hard interactions

Credits:
- Ellie Dobson



LHC measurements available
LHC measurements not yet available

Complement with p-A and A-A

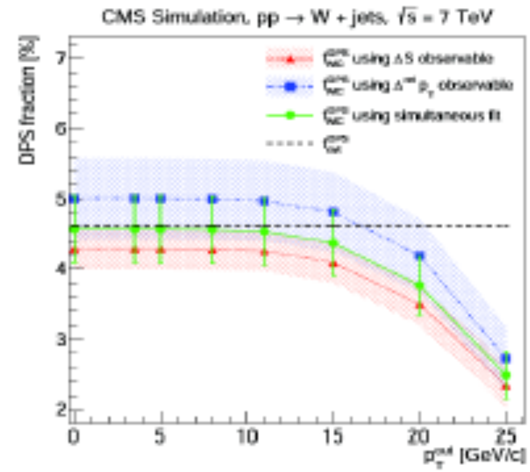
CMS: W $\rightarrow l\nu$ + 2 jets – Extraction of DPS Fraction f_{DPS}

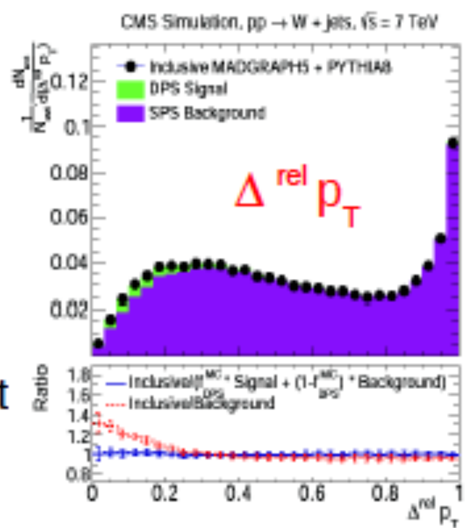
- Binned likelihood fit
- Signal templates: Random of W + 0-jet and dijet events from MCs, ***templates are validated with data.***
-
- Background templates:
  – MadGraph + Pythia8; MPI parton tagged with status code
  – NO jet-parton matching,

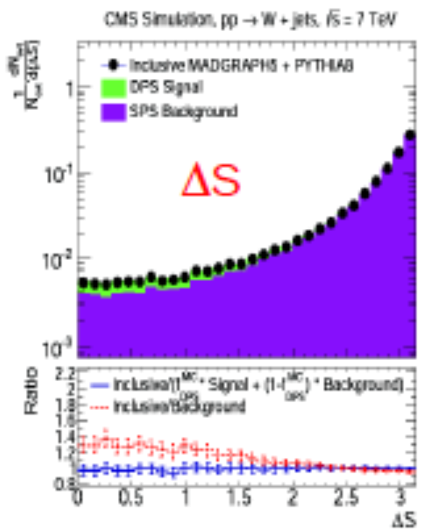
  – NO overlap and/or missing phase space.
  – Remove events which can be identified as signal events at particle level i.e. two MPI partons should not be in η acceptance ($|\eta| < 2$)

  – NO p_T dependence for < 12-15 GeV

- Fractions with two observables are consistent within uncertainties.
- Simultaneous fit of observables; close with f^{DPS}_{evt} (DPS fraction by default MPI model)







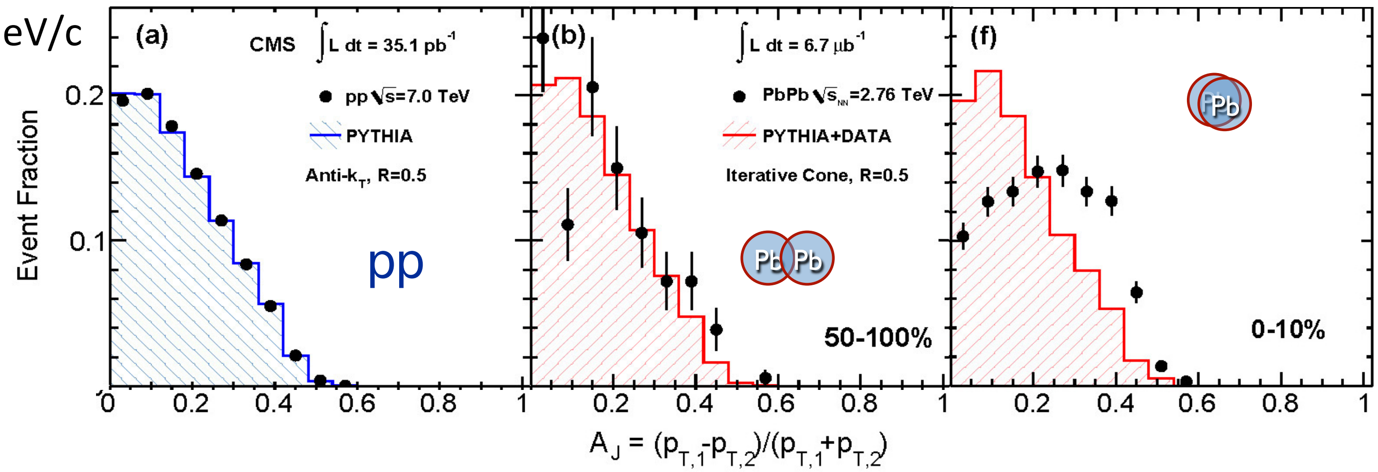
Double Parton Scattering

in Heavy Ions?

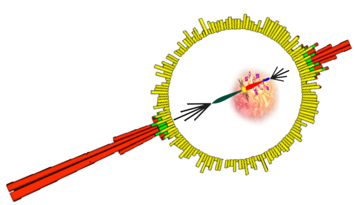
HI: Jet quenching via large dijet energy imbalance & DPS!

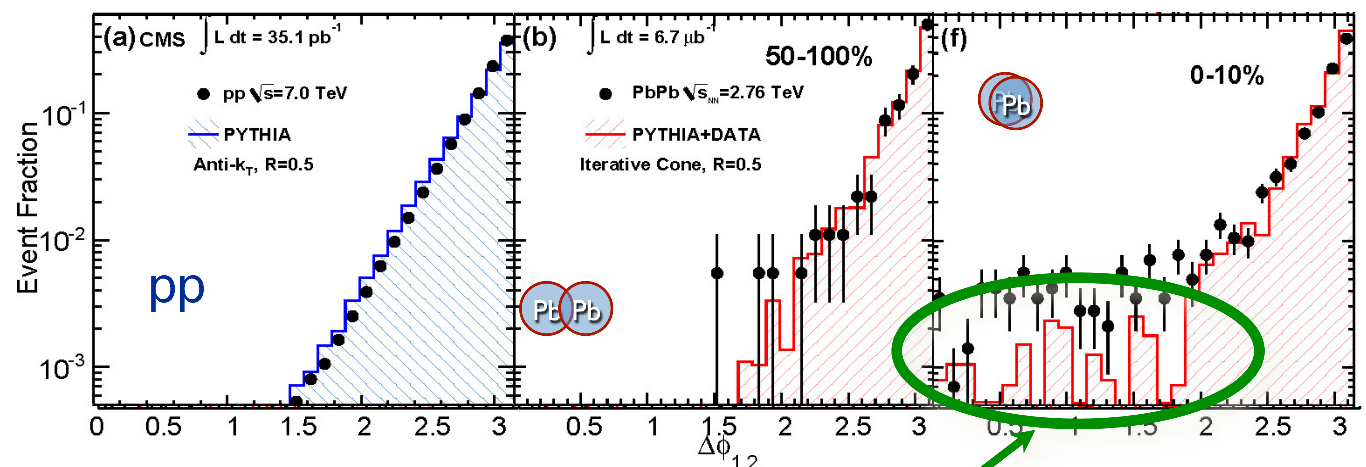
- Dijets, calorimeters only
  - Leading p_T>120 GeV/c
  - Sub-leading p_T>50 GeV/c

pp PbPb, 50 - 100% PbPb 0 - 10%



p_T imbalance, increasing with centrality





Back-to-back $\Delta\phi \sim \pi$ for all centralities

Contribution from Double Parton Scattering?

- Further DPS analysis issues & FAQ

DPS: MC Tools & Frequently Asked Questions

Is Double Parton Scattering already present in the MC samples?

- Let's first of all focus on high rate processes from DPS.
- If you are looking for extra light jets from DPS the answer is YES whenever general purpose MCs with MPI like Pythia6, Pythia8, Herwig++, etc. are used alone or in conjunction with ME tools (Notice that Sherpa has its own MPI framework).
- Indeed a DPS is just a "hard" MPI and what is hard is often arbitrary or analysis dependent; actually even the MPI contributing to the Underlying Event are usually treated in a perturbative way by the QCD models.
- If you are looking for something a bit more rare (b/c-jets, J/psi, photons) the answer is MC-dependent. For example it is YES in Pythia 8 and it is NO in Pythia 6.
- If you are looking for other processes (W, Z, top etc.) the answer is NO. On the other hand you may not want end-up generating zillions of events in order to get just few DPS events.
- However there are MC generators which allow to force DPS for any process: Pythia 8 is probably the best tool to fulfill such requirement.
- Forcing DPS may be useful also for high rate processes in order to get an estimation of σ_{eff} adopted in a specific sample. Indeed, σ_{eff} resulting from the soft QCD tunes are a factor 1.5-2 higher than the corresponding figure measured at hadron colliders. Preliminary CMS DPS measurements seem to be more in agreement with the MC models. Anyway assuming ± 50% uncertainties on σ_{eff}(MC) is prudent.

DPS: MC Tools & Frequently Asked Questions

Is the MPI information available in the MC models?

- Accessing the full information of the secondary interactions is often essential. For example you may want to "tag"/select heavy flavor jets produced by DPS
- In the Pythia 8 event record one can easily track all the MPI (see the Pythia 8 manual) along with the relevant process information of each interaction. This is the trend in all the OO MCs.

-However the MPI information is often lost when using the OO MC in conjunction with a ME tool (ALPGEN, MADGRAPH etc.). This should be regarded as a possible technical limitation of the event generation framework(s) although some physics wise issues need to be carefully x-checked as well:

→For example MPI jets should not be subject to matching! (Mistakes in this respect were done in the past, recent MC tools should be safe from this point of view).

- In the Pythia 6 event record one cannot easily track all the MPIs
- MPI partons in Pythia 6 may be recognized from the fact that they have mother = 0. From such information one can "measure" at least σ_{eff} internally used in a given Pythia 6 sample. In general σ_{eff} depends on the tune and on the process.

DPS: MC Tools & Frequently Asked Questions

Do the correlations between 1st and 2nd interaction matter?

- When modeling the DPS signal with two separate interactions (for example in a data oriented way) we are making several approximations, in particular we clearly violate energy conservation, possible flavor effects (which are expected to be huge in the case of two interactions from valence quarks), possible color effects, spin correlations etc.
- Although data oriented modeling is welcome, one should always x-check the effect of these correlations within the available MPI models.

- Phase space coverage of DPS SIGNAL + DPS BACKGROUND and possible double counting, which are the most important aspects in the DPS and spin-off analyses, should also be monitored using Monte Carlo tools.

- The different "languages" of ME and PS/MPI tools may also result in suppressing correlations (color flow etc.) hence such effects should be studied using the full MPI description of the PS/MPI alone.