MULTI-PARTICLE PRODUCTION OF HADRONS AT THE LARGE HADRON COLLIDER

(With emphasis on Multiple Parton Interactions Studies in CMS)

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MIÉRCOLES 12 DE FEBRERO DE 2014.

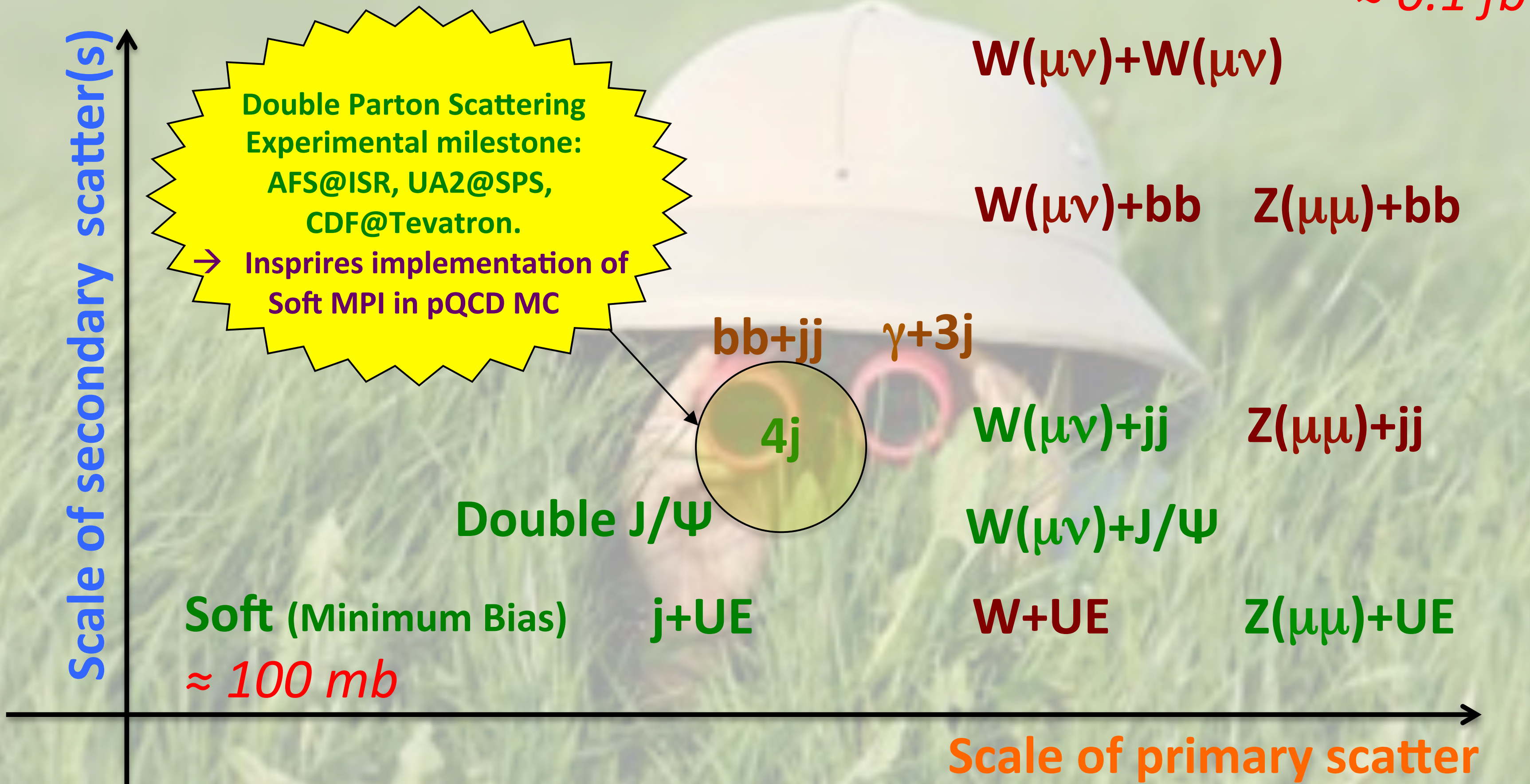
Disclaimer: I should necessarily select a restricted sample of highlights.
Let's focus on data, relevant MC info in back-up slides.

Update of my review paper published in **Mod.Phys.Lett. A28 (2013) 1330010.**

Where can we look for Multiple Parton Interactions?

Credits:
- Ellie Dobson

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



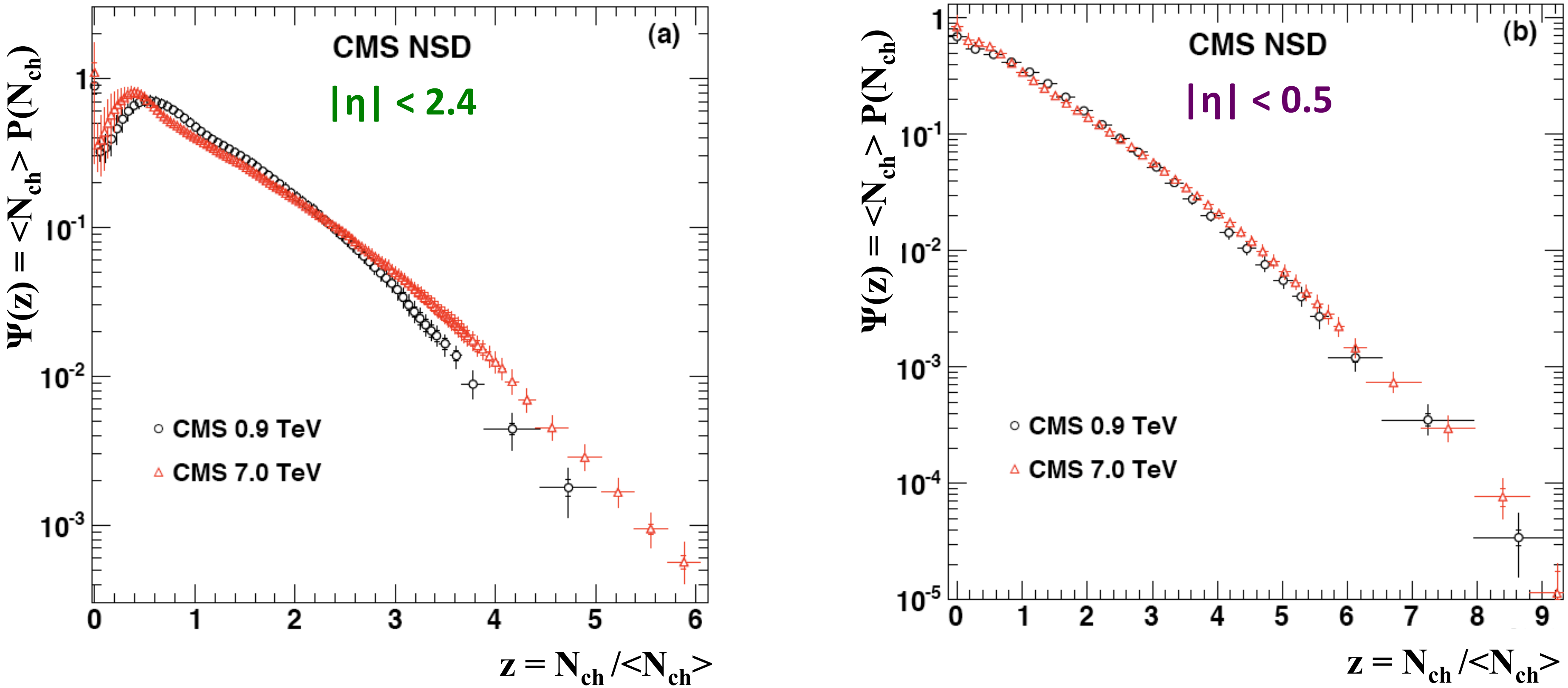
LHC measurements available
LHC measurements not yet available

Complement with
p-A and A-A

1st Part
Multiplicities, Kinematics

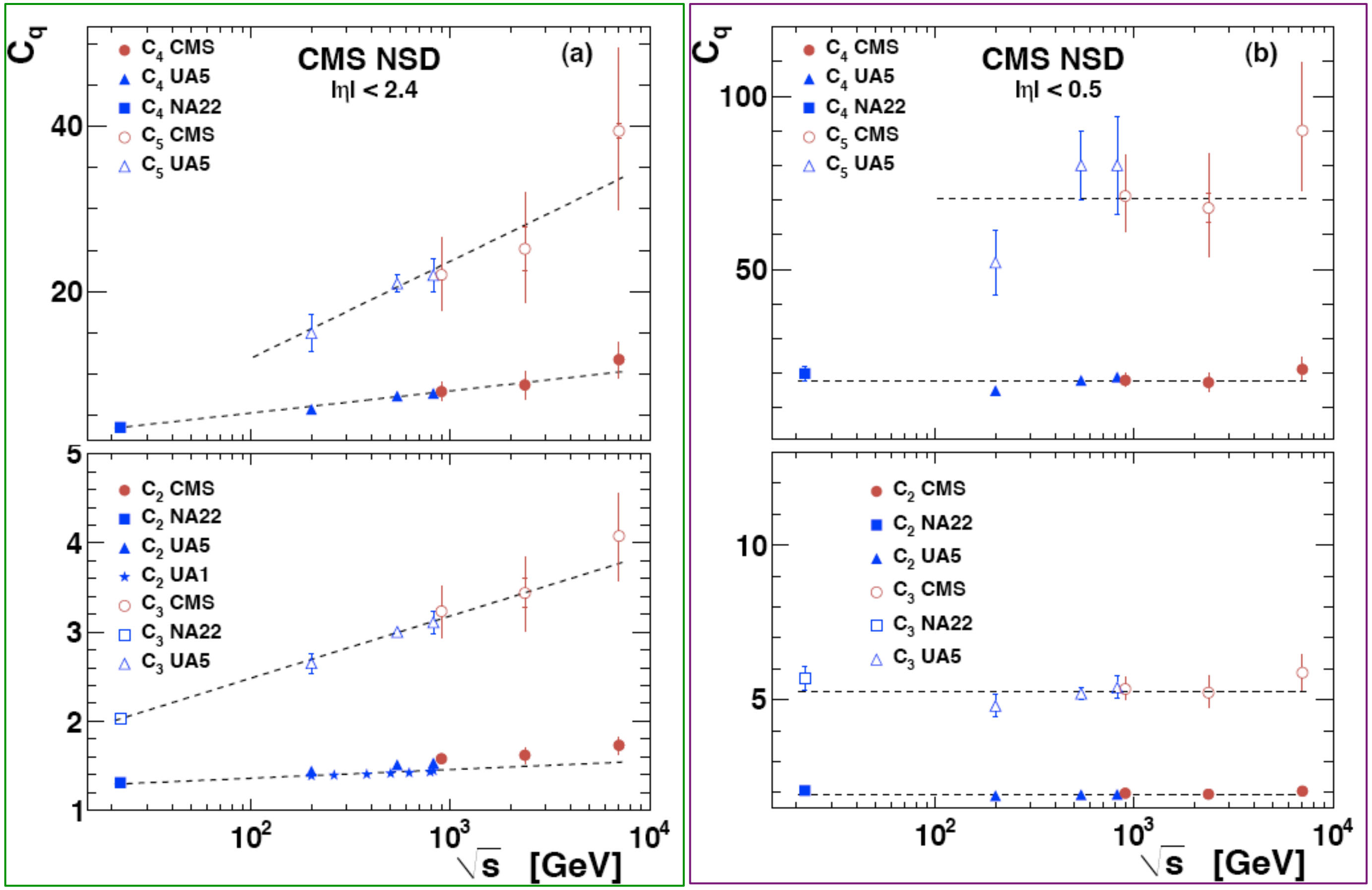
The early papers at the LHC

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 $C_q = \langle N_{ch}\rangle^q / \langle N_{ch}{}^q\rangle$



√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

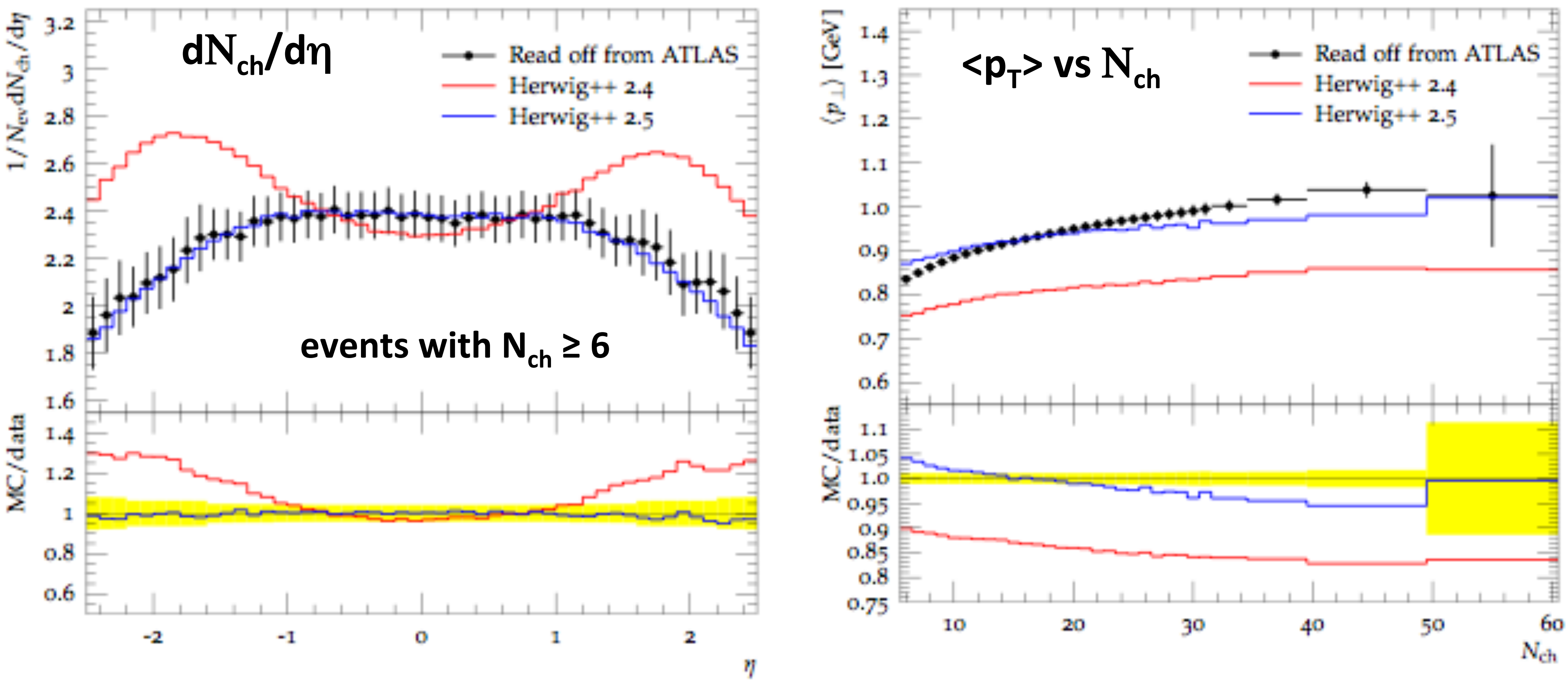
If KNO scaling holds, also C_q are independent from √s.

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.

Impact of color reconnection

ATLAS, pp √s = 0.9 TeV, charged particles with p_T > 0.5 GeV & |η| < 2.5



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

1^{st} Part: bottom line

- Basic soft QCD measurements with charged tracks in pp inelastic and not single diffractive events at at different √s (0.9 TeV, 2.36 TeV, 7 TeV)
  - multiplicity, multiplicity per unit of pseudo-rapidity vs pseudo-rapidity, p_T spectrum, <pT> vs N_{ch}.
    - LHC Tracker detectors are essential tools for these measurements: charged track reconstruction from p_T as low as 100 MeV.
    - Fast increase of average multiplicity vs √s (> ln (s)) confirmed by the data, described by few TH predictions and by tuned QCD MPI models.
    - MPI MC models also essential to describe the N_{ch} tails.
    - √s Scaling of $<p_T>$ vs N_{ch}
    - Violation of KNO scaling confirmed in many different ways (also looking at normalized order q-moments) in particular when extending to large pseudo-rapidity ($|\eta|<2.4$).
    - KNO scaling seems to apply when restricting to central region / small pseudo-rapidity range ($|\eta|<0.5$).
    - Color reconnection unavoidable to describes the shapes of pseudo-rapidity and <pT> vs Nch.

2nd part
Correlations

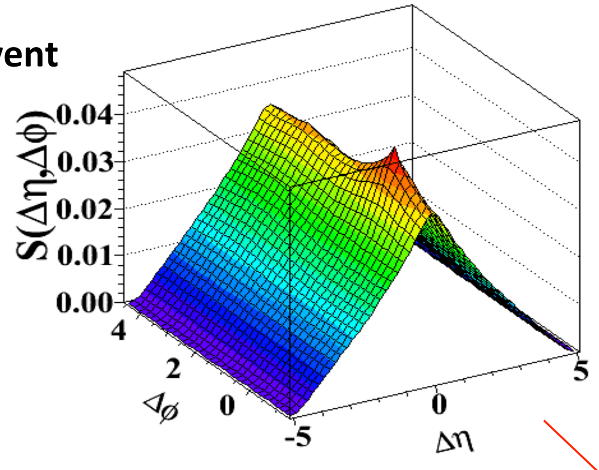
Emphasis on long range correlations,
i.e. the first evidences of new physics at the LHC

Definition of di-hadron correlation function

Signal distribution:

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

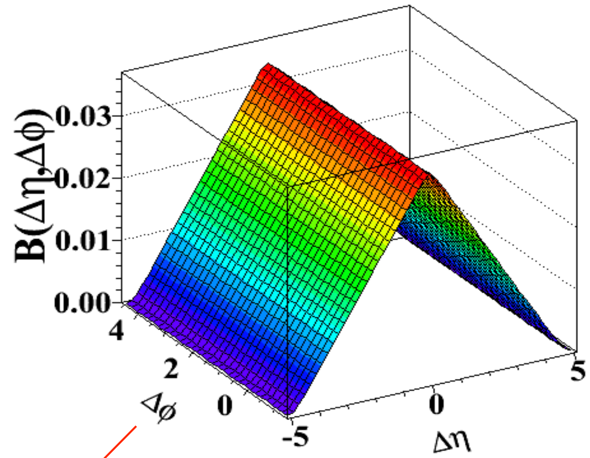
Particle pairs from same event



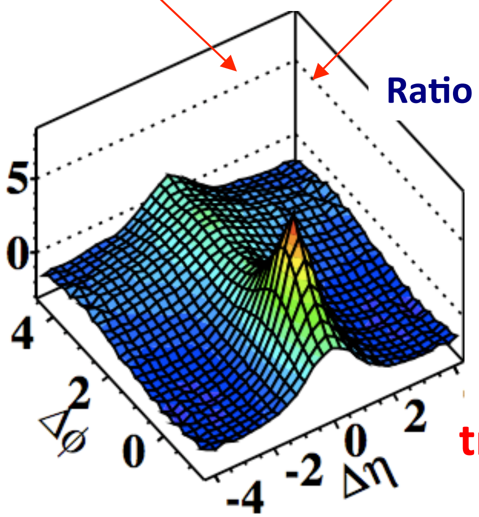
Background distribution:

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

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:

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

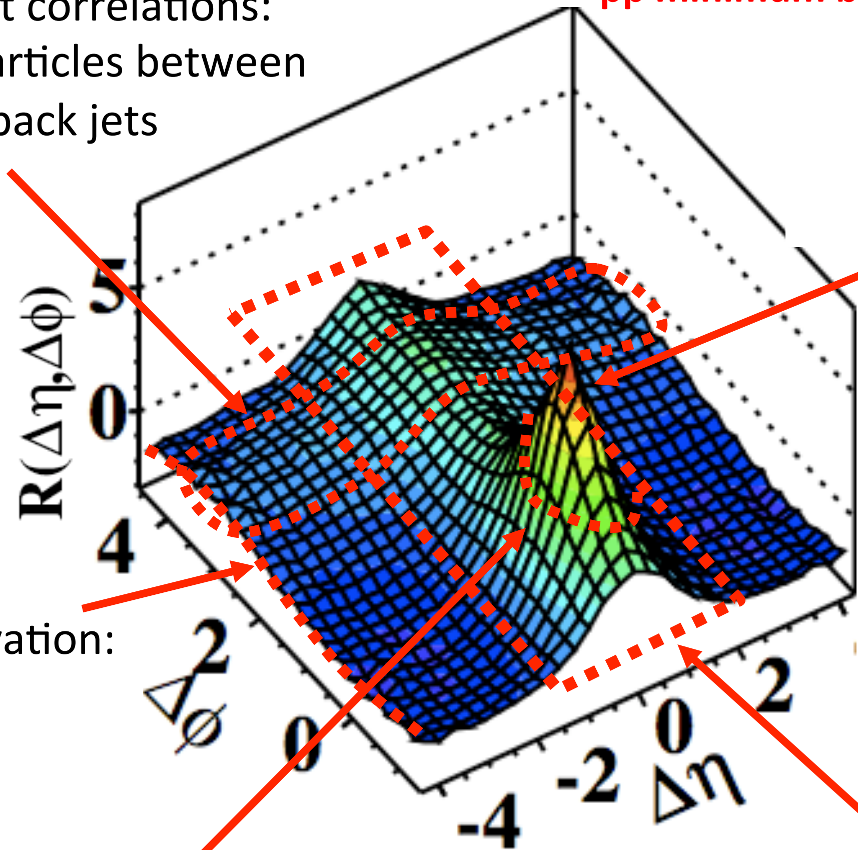
Can specify selected pair of trigger (p_T^{trig}) and associated (p_T^{assoc}) particle p_T ranges.

Long and short range correlations

pp minimum bias events √s = 7 TeV

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

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



Momentum conservation:
~ cos(Δϕ)

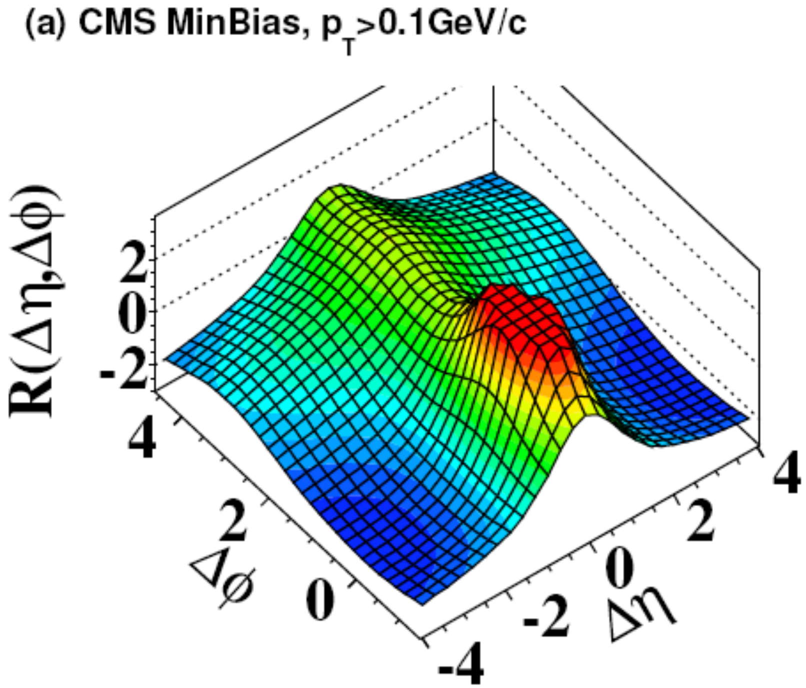
“Near-side”, Δϕ~ 0 jet peak:
Correlation of particles within a single jet

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

Associated 2D Yields for Particles with $P_T > 0.1$ GeV

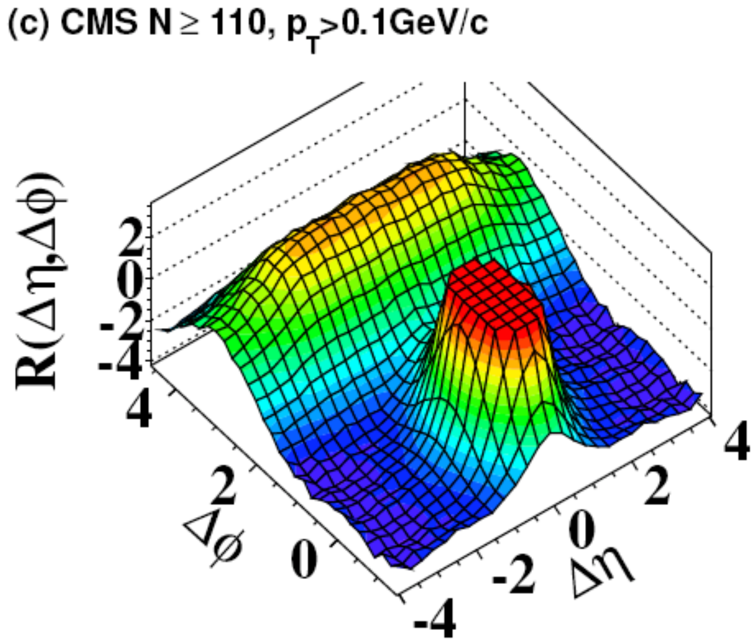
pp interactions at 7 TeV

MinBias



High Multiplicity (N>110)

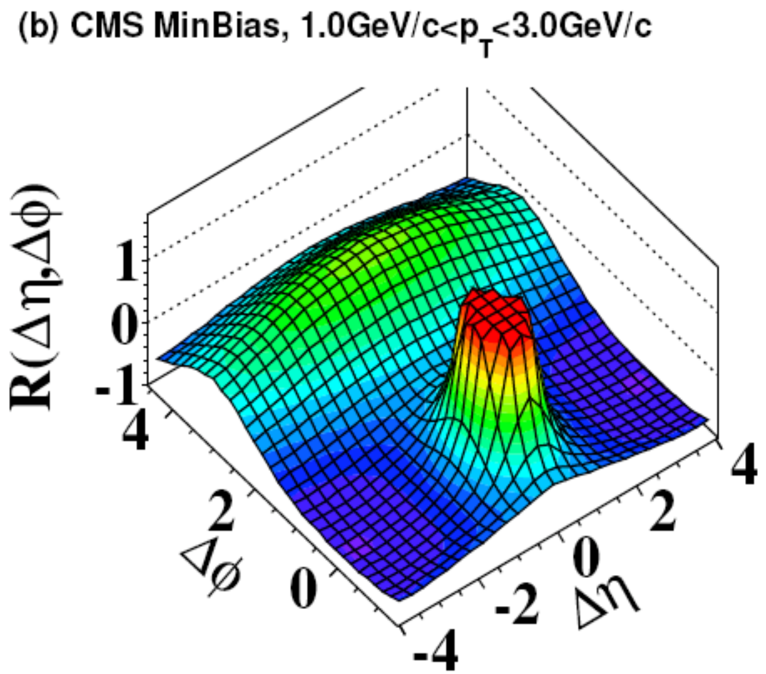
Special trigger developed to collect these rare O(10^{-5}) events.
It doesn't rely on jet triggers!



- 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



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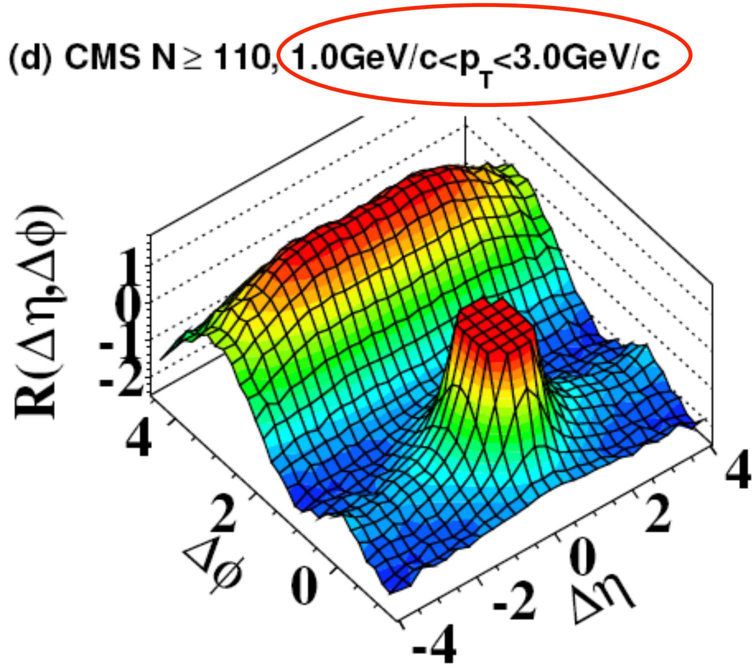
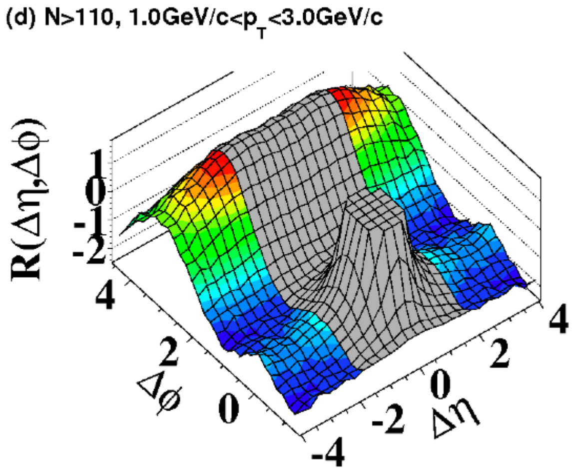


- Limiting p_T of particles to $1<p_T<3$ GeV
  → Gives a pronounced structure at large Δη around ΔΦ=0 in the high multiplicity events.

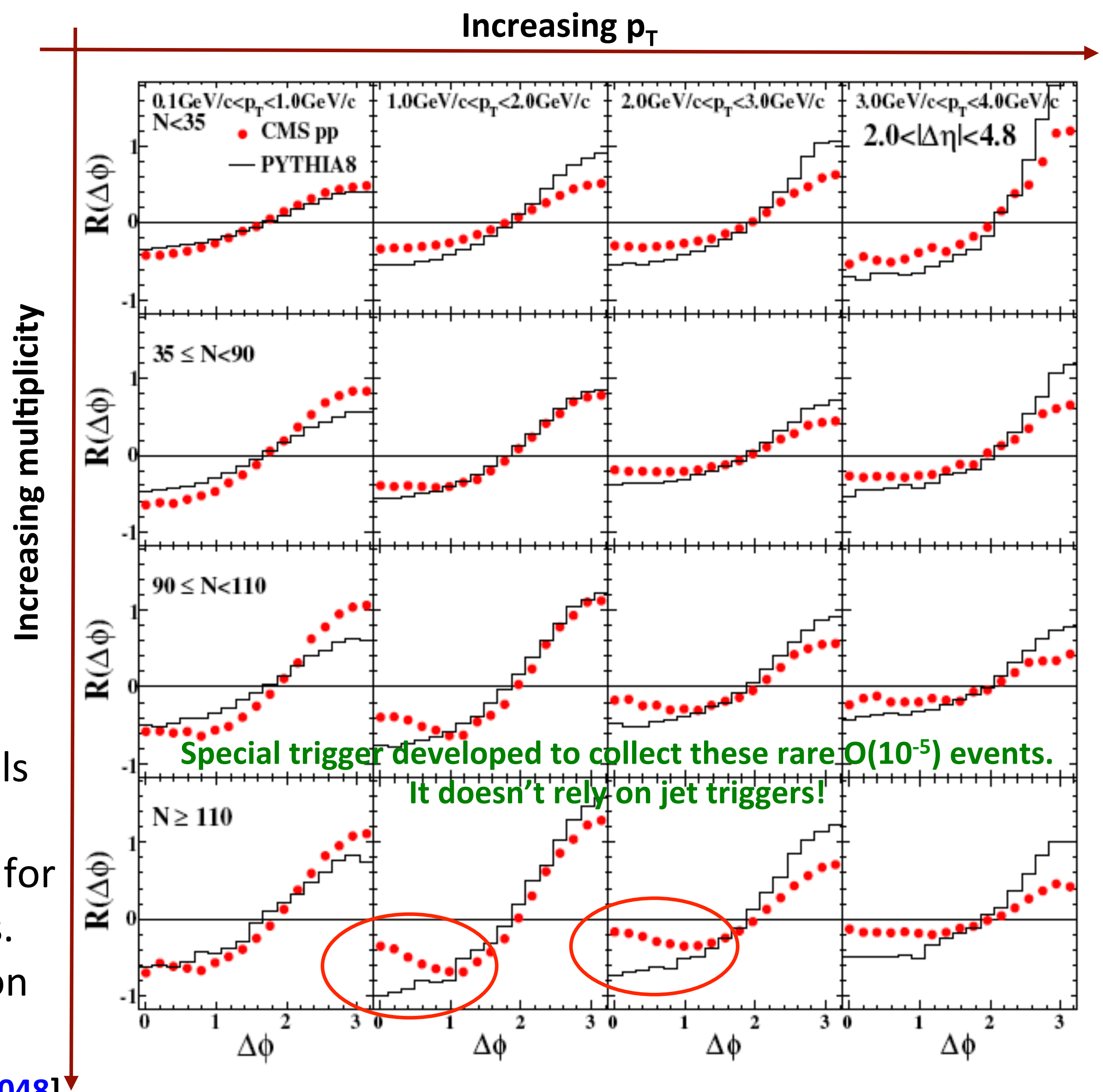
Associated 1D yields in bins of p_T and N_{ch}

Long range:
Project $2 < |\Delta\eta| < 4.8$ onto $\Delta\phi$:

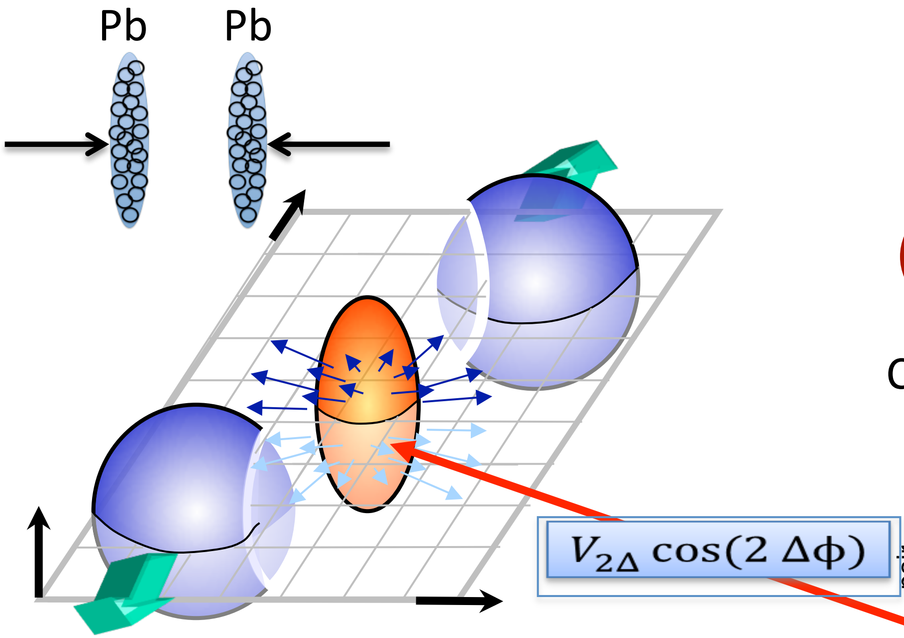


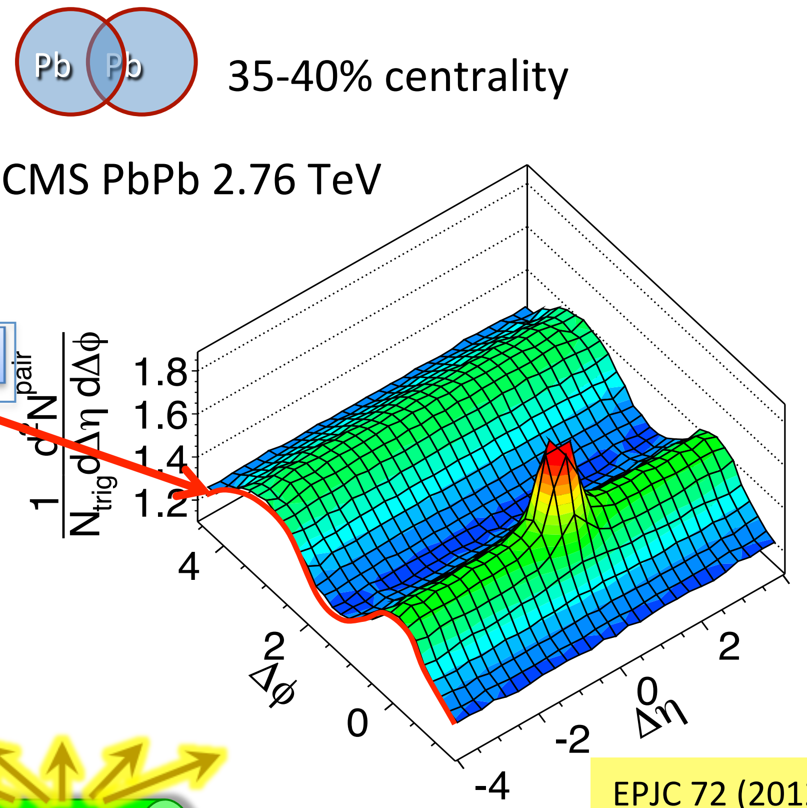
- **Ridge most pronounced for high multiplicity events and at $1 < p_T < 3$ GeV.**
- No ridge seen in tested MC models (Pythia 8, Pythia6, Herwig++, etc.)
- Several interpretations proposed for this HI-like effect in pp interactions.
- Clear major role of Multiple Parton Interactions.

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



Ridge in Pb-Pb interactions





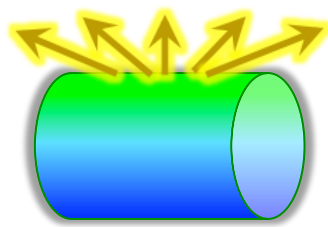
EPJC 72 (2012) 2012

p_T^{trig}: 4–6 GeV/c

p_T^{assoc}: 2–4 GeV/c

Particle azimuthal distributions:

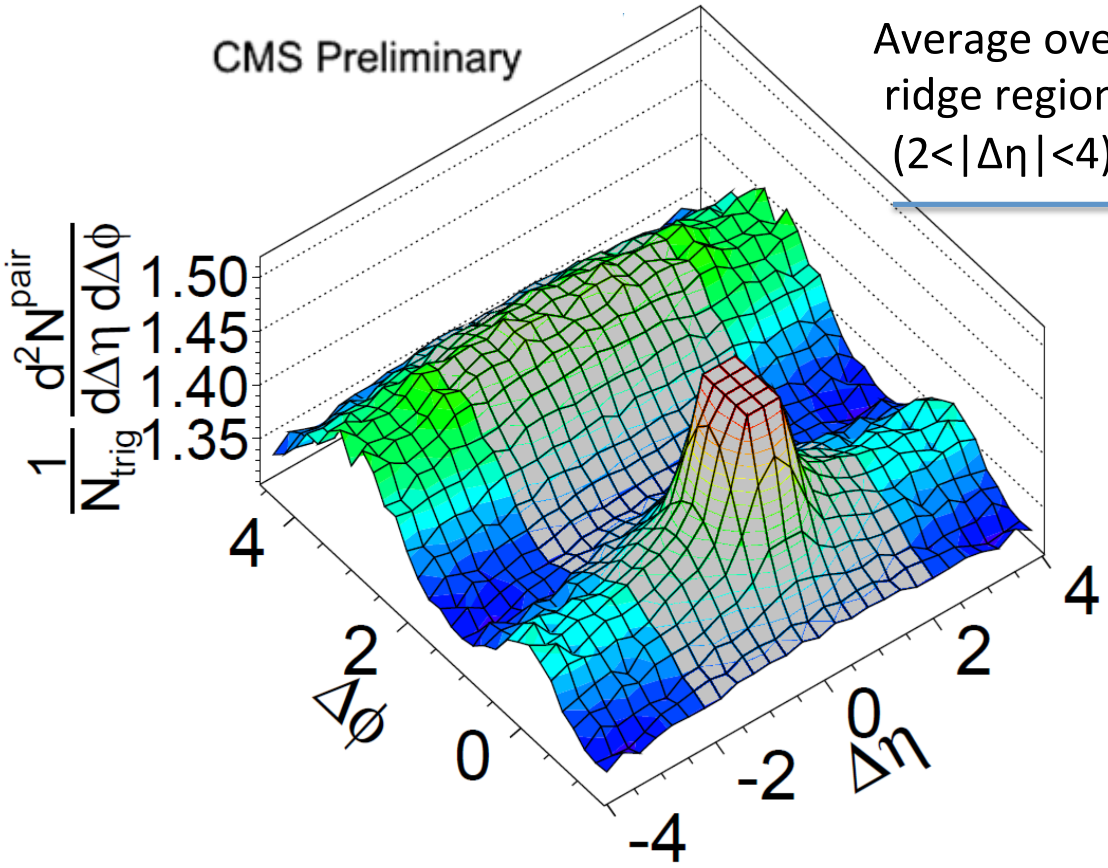
$dN/d\phi \propto 1 + \Sigma\, 2V_n \cos(n(\phi-\phi_0))$



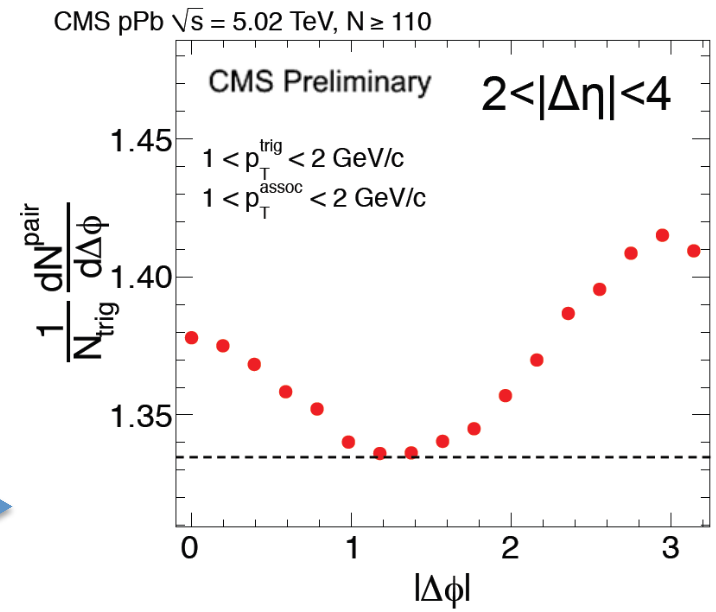
EPJC 1272 (2012) 2012.

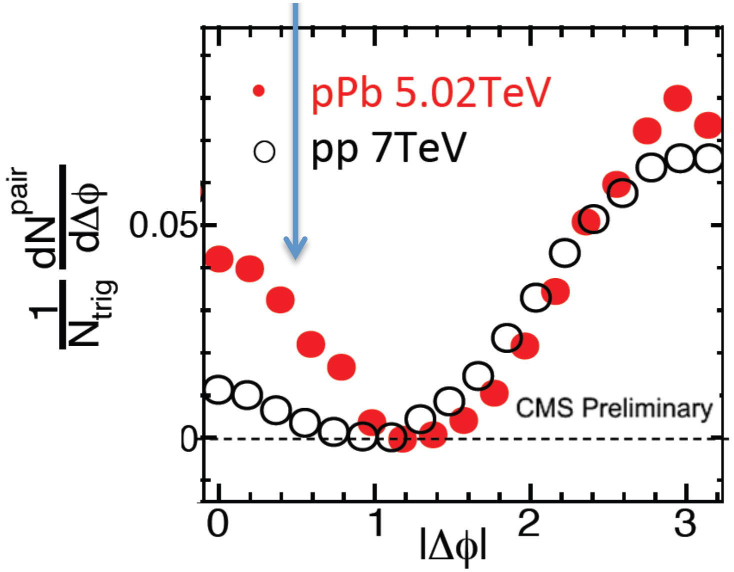
Ridge in p-Pb interactions

We use the same approach as in pp ridge paper for "apples-apples" comparison.
Same qualitative conclusions, from a quantitative point of view the effect is much larger in p-Pb



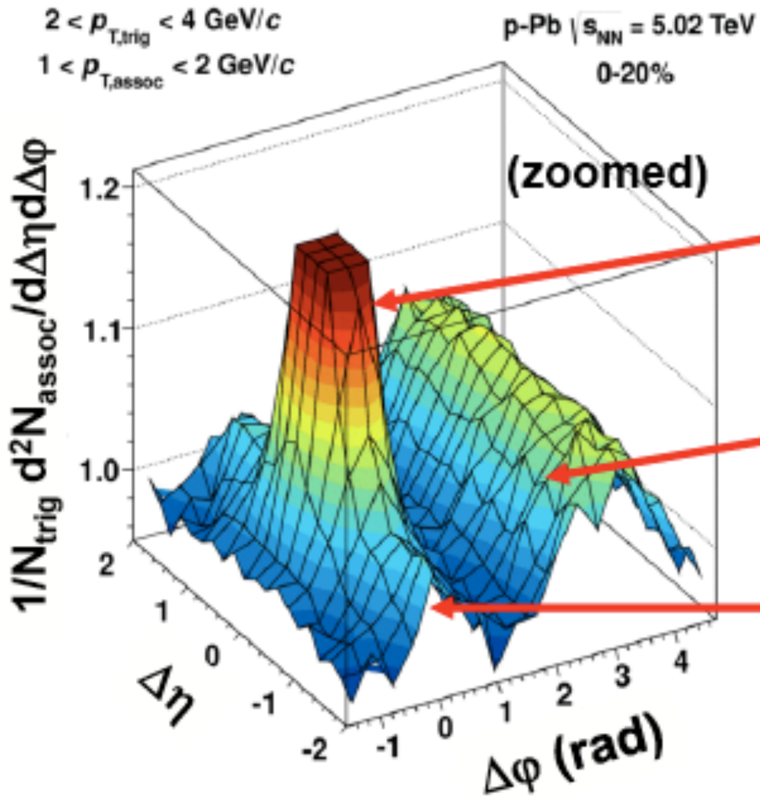
Average over ridge region ($2<|\Delta\eta|<4$)





Phys. Lett. B718 (2013) 795-814.

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.**

Phys. Lett. B 719 (2013) 29.

2^{nd} Part: bottom line

- Significant ridge structures are observed in high multiplicity p-p ($\sqrt{s}$ = 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 = 1-3 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.
  - No MC capable to reproduce the observed effect in p-Pb and p-p.
  - Large multiplicities without jetty structures point to an important role played by Multiple Parton Interactions.
  - Indications that angular momentum conservation in MPI may intervene in the interpretation.
  - Color reconnections may also play a role.
  - Are we missing anything?
    - Studies focusing on event shapes to tag events with several MPI should be encouraged → Sphericity/Spherocity analysis by G.Paić et al.

3rd part
The Underlying Event (UE)

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…" **[JHEP 1109, 109 (2011)*]*.**

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

Soft MPI in high p_T events

Credits:
- Ellie Dobson

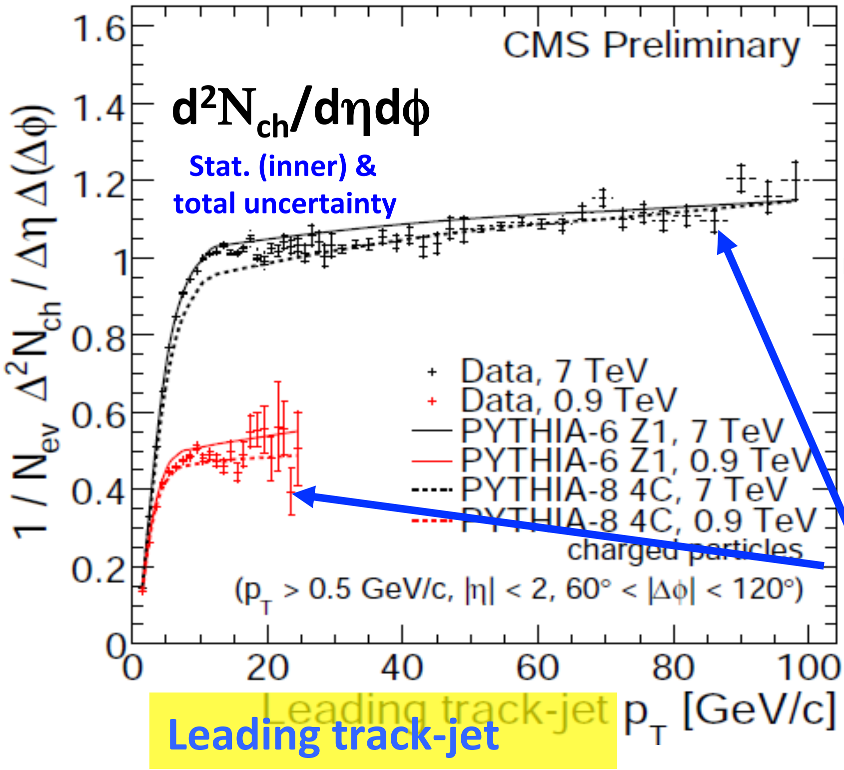
Z(μμ)+Z(μμ)
≈ 0.1 fb

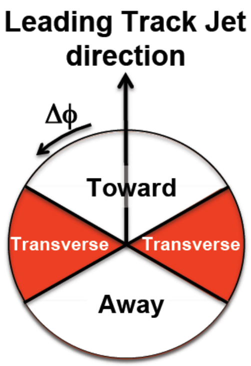
LHC measurements available
LHC measurements not yet available

Complement with p-A and A-A

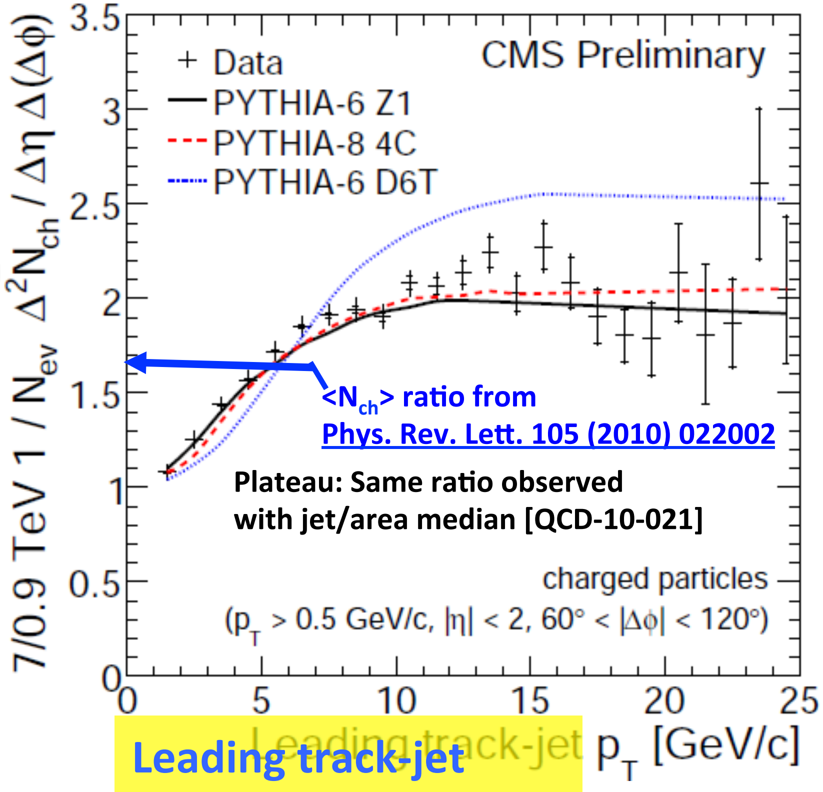
UE in Jets: densities in the Transverse Region

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.

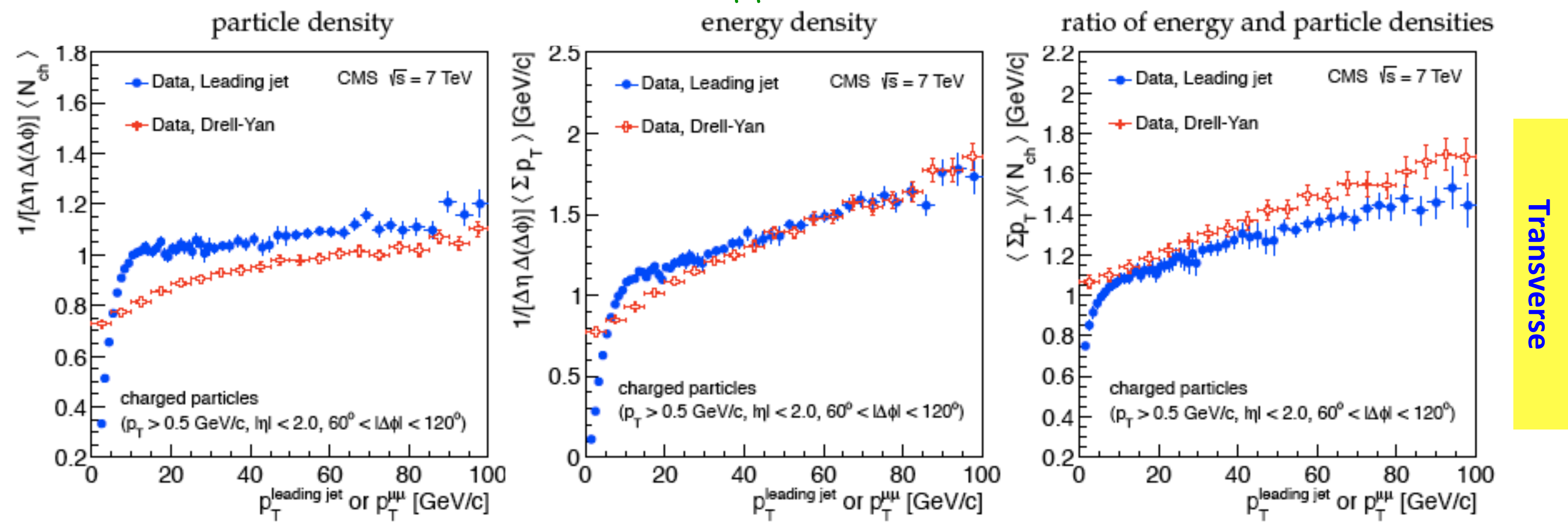
UE Measurements in Drell-Yan:

MPI saturated. Radiative increase of UE activity with p_T di-lepton.

Constant vs $M_{\text{di-lepton}}$.

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

81 GeV < Mμμ < 101 GeV



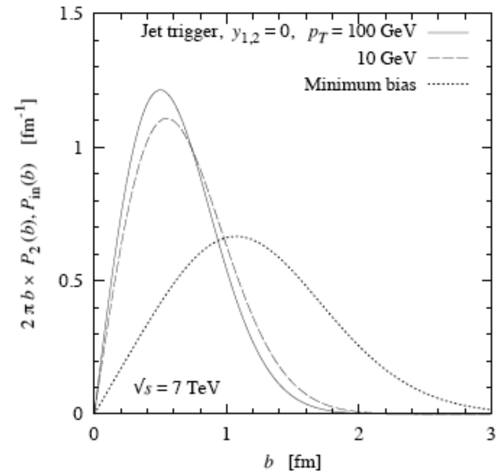
Eur.Phys.J. C72 (2012) 2080.

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

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

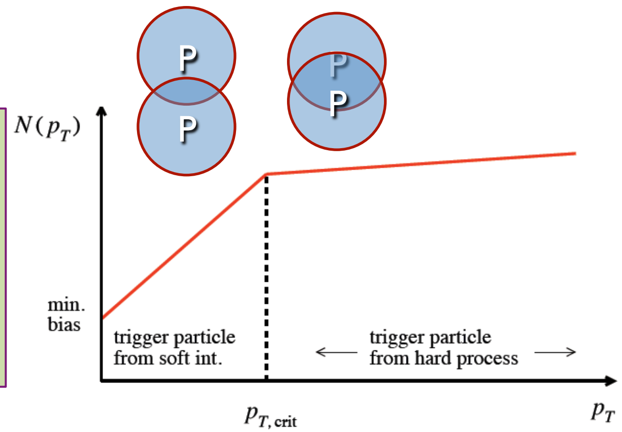
$$\langle \rho^2 (x > 10^{-2}) \rangle \ll R^2_{soft}$$

$$\Downarrow$$

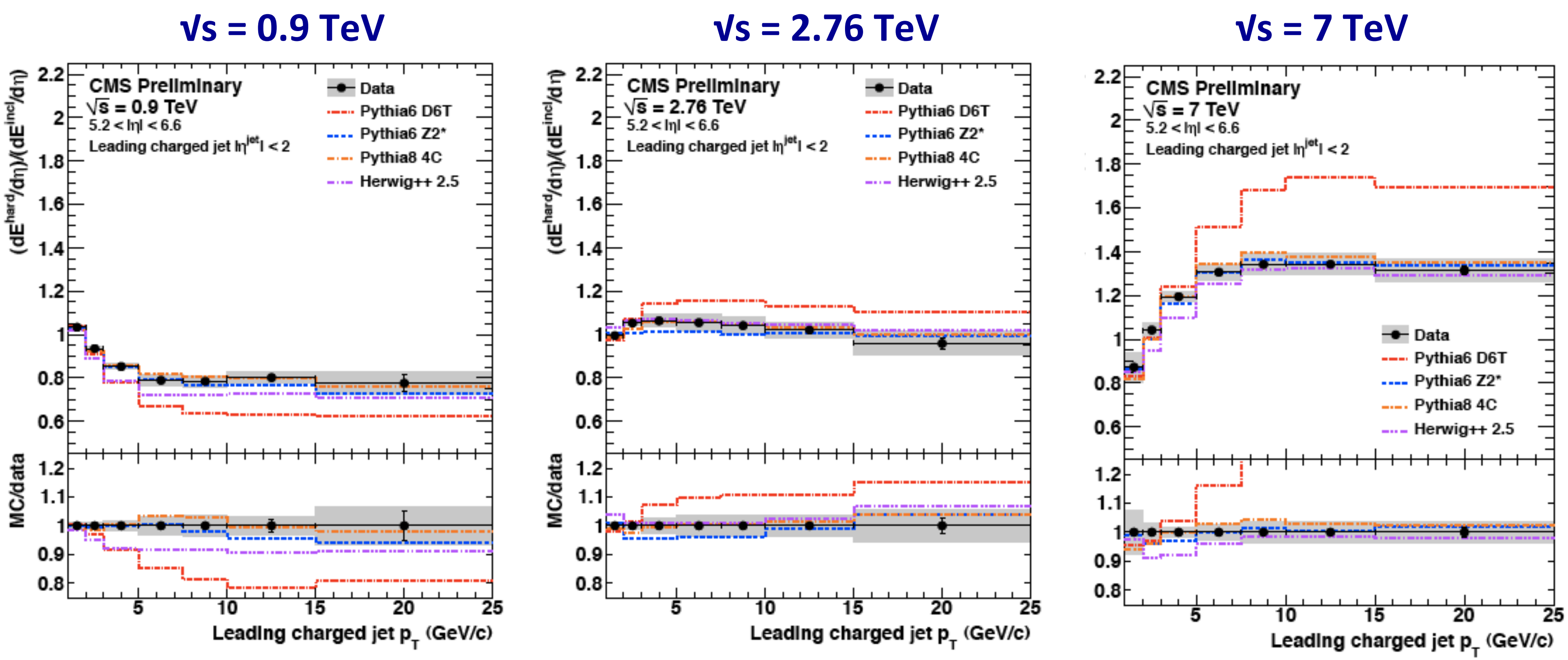
Two scale picture

Also explains general features of UE @ hadron colliders

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



Energy flow in the VERY forward region



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 **√**s (decreasing at low **√**s, increasing at high **√**s)

→ Post LHC models adopting pT-ordered showers are favored by data (agreement within 5-10%)

→ Good agreement also for ***EPOS 1.99, QGSJET01, QGSJETII-03, SIBYLL 2.1*** (within 20%)

Soft Multiple Parton Intractions: highlights

- Charged multiplicity measurements:
  – LHC confirms large multiplicity tails and KNO violation more pronounced at high energies.
  → On the other hand MPI models have been invented to describe large multiplicity tails and KNO violation at the SPS.

- Long-range correlations in high multiplicity events
  – No jetty events, i.e. multiplicities cannot be contributed by a single interaction.
  → Clear role of MPI

- UE Measurements
  – Two scale picture in the case of jets (rise at low p_T + plateau at high p_T). Single scale picture (plateau) in the case of DY.
  → Straightforward MPI interpretation; MPI tunes work in a wide η range.
    - **GPDF: Relative size of UE(DY)/UE(jets) connected to $<\rho^2>_g$ / $<\rho^2>_q$**

4^{th} part

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

Introduction to Double Parton Scattering (A+B+X)

- **$\sigma(A+B) = m * \sigma(A) * \sigma(B) / \sigma_{eff}$** (m = ½ for identical interactions, m = 1 otherwise)
  - **$P(B|A) = P(B) * (\sigma_{Non\text{-}Diffractive}/\sigma_{eff})$**
  - σ_{eff} mostly depends on geometry
  - $\sigma_{eff} \approx$ (process,) scale and √s independent according [D. Treleani et al., rich bibliography]
  - 3→4 processes may give significant contributions, rising with $x_{Bjorken}$ [Y. Dokshitzer et al.]

INCLUSIVE MEASUREMENTS!!!

- **Of course from an experimental point of view these possible properties should be tested!**

- $\sigma_{eff} \approx 10 \div 20$ mb. Lowest figures at Tevatron (3jet+γ), intermediate figures by ATLAS W+jets, highest figures from CMS W+jets. LHCb reports discrepancies when comparing numbers from different channels (double J/ψ, J/ψ + open charm and double open charm prodution). ALICE doesn't quote σ_{eff} yet.
  - Pythia: $\sigma_{eff} = \sigma_{Non\text{-}Diffractive} / \langle f_{impact} \rangle$
  - where $\langle f_{impact} \rangle$ is tune dependent → σ_{eff} (Tevatron) $\approx 20 \div 30$ mb **(i.e. 2 times higher than data)**

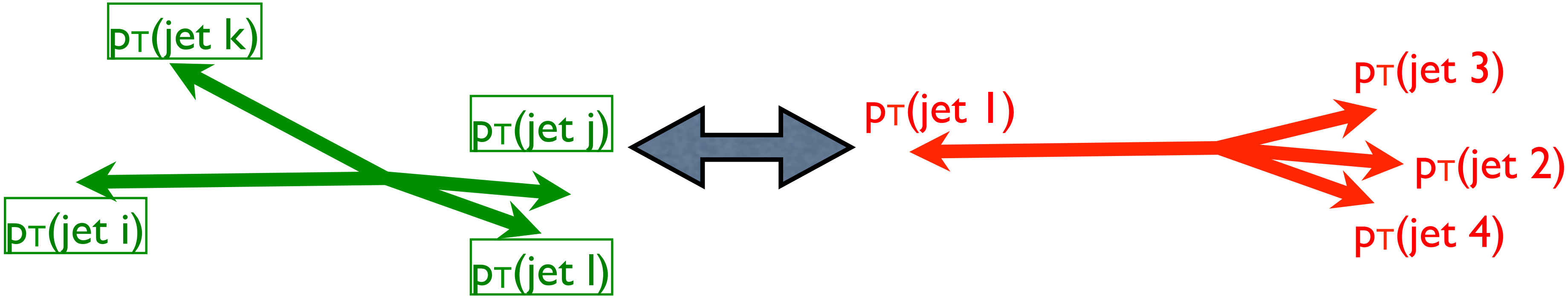
- **DPS underestimated in the models tuned on Soft QCD phenomenology?**
- **What are the relationships between "soft" and "hard" MPI measurements?**
- **Which is the impact on new physics at the LHC/LIC?**

The Double Parton Scattering (a)

in final states with four objects

Double Parton Scattering in 4 "objects" topologies

Disentangle double-parton-scattering from bremsstrahlung



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

After pairing, 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:

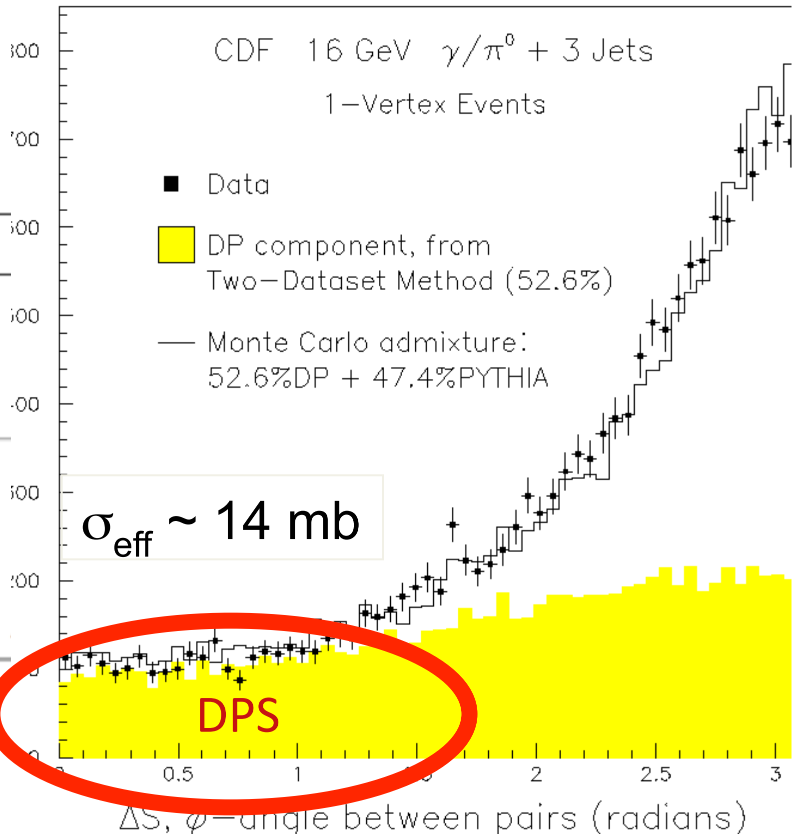
→ σ_{eff} ~ 11 mb

[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
←	$\boxed{E_{T4} < 5 \text{ GeV}}$
	$E_{T2}, E_{T3} < 7$ GeV

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



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

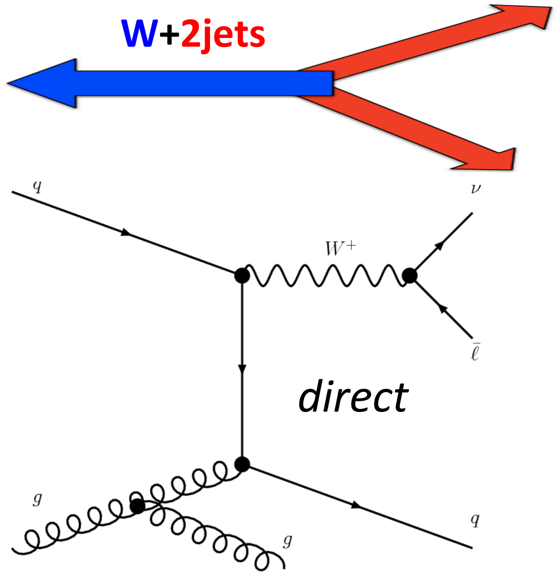
Are the SIGNAL and BACKGROUND simulations used in these analysis reliable?
- A lot of emphasis in the definition of a data oriented methodology for the SIGNAL
- However the big issue is the BACKGROUND modeling: Single Parton Scattering (SPS) with direct photon and three extra jets was not considered.

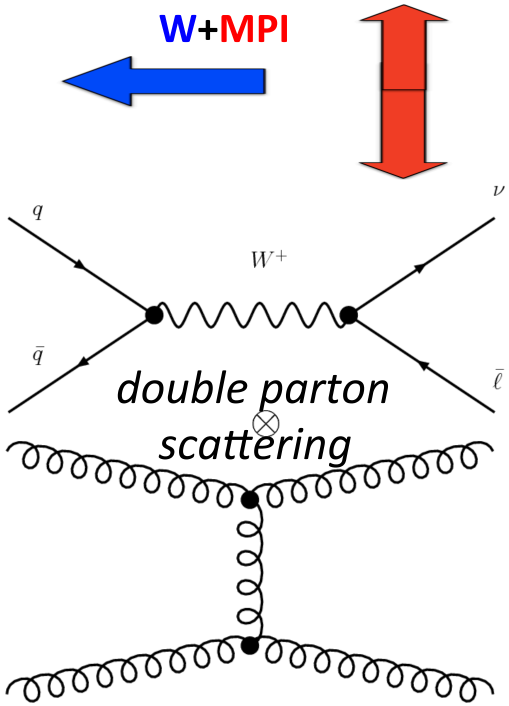
The Double Parton Scattering (b)

looking for extra di-jets in events with heavy bosons

(the W+2jets benchmark)

ATLAS: W → lν + 2 jets





$$f^{R}_{DP} = \frac{N_{W_0+2j_{DPI}}}{N_{W+2j}}$$

$$\sigma_{eff} = \frac{1}{f^{R}_{DP}} \cdot \frac{N_{W_0} N_{2j}}{N_{W+2j}} \cdot \frac{1}{\varepsilon_{2j} L_{2j}}$$

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

- measure fraction of $W_0 + 2j_{DPI}$ in the *W+2jet* sample (f^{R}_{DP})
  - use difference in kinematics (p_T, …)
- σ_{eff}

W selection
Single lepton trigger
1 lepton (e, μ) $p_T > 20$ GeV, $\eta < 2.5$
MET > 25 GeV, $m_T > 40$ GeV
2 jets, $p_T > 20$ GeV, $|y| < 2.8$

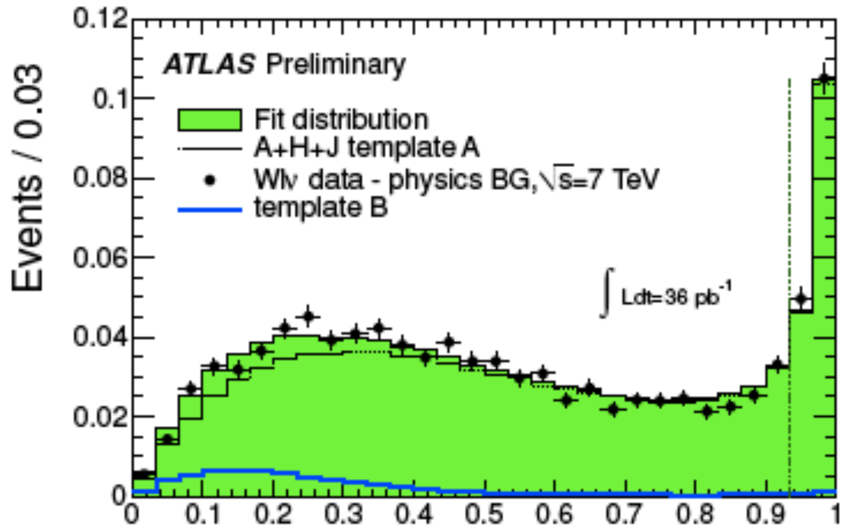
Jet selection
(Minimum bias trigger used to measure di-jet x-section alone)
2 jets, $p_T > 20$ GeV, $|y| < 2.8$

New J.Phys. 15 (2013) 033038.

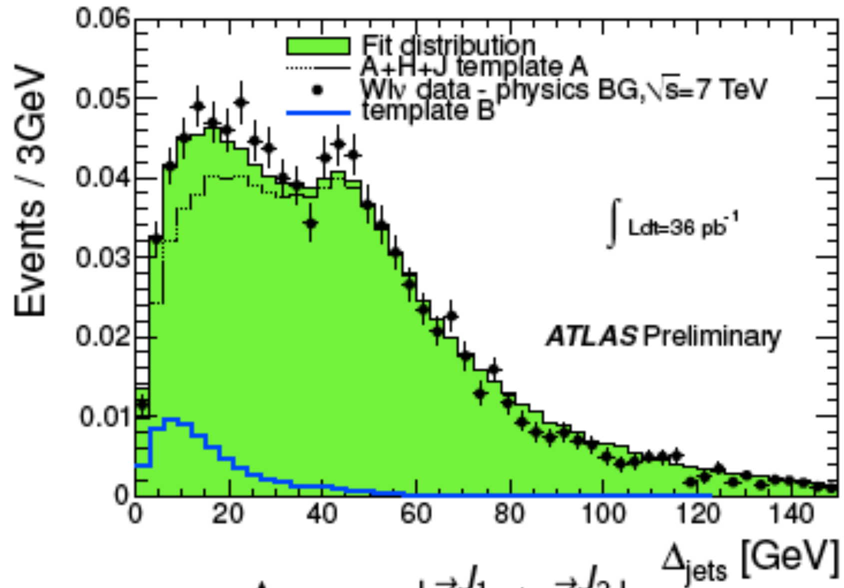
ATLAS: W → lν + 2 jets : DPS Rate

- Extraction of f^{R}_{DP} using fit to data with two templates
- Template A (non DPS sample): both jets originate from the primary scatter
- Template B (a DPS sample) : both jets originate from the DPS scatter (data oriented).

$$(1-f^{R}_{DP})\cdot A + f^{R}_{DP}\cdot B$$



$$\Delta^{n}_{jets} = \frac{|\vec{p}_T^{J1}+\vec{p}_T^{J2}|}{|\vec{p}_T^{J1}|+|\vec{p}_T^{J2}|}$$



$$\Delta_{jets} = |\vec{p}_T^{J_1}+\vec{p}_T^{J_2}|$$

$$f^{(D)}_{DP} = 0.08 \pm 0.01\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{sys.})$$

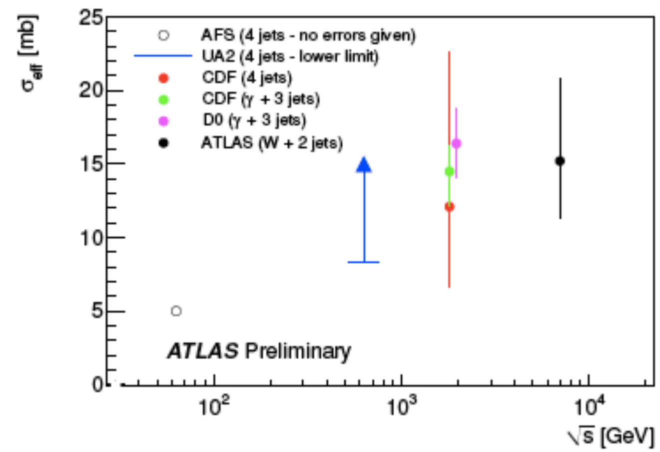
$$\sigma_{\mathrm{eff}} = 15 \pm 3\,(\mathrm{stat.})\,^{+5}_{-3}\,(\mathrm{sys.})\ \mathrm{mb}$$

New J.Phys. 15 (2013) 033038.

Bottom line on ATLAS W → lν + 2 jets

☺ DPS fraction is extracted from a fitted combination of two templates: SPS (based on SHERPA, x-check with different MCs) and DPS (W and dijet events from data) on the normalized transverse momentum balance of the di-jet: $\mathbf{|p_{jet1}+p_{jet2}|/(|p_{jet1}|+|p_{jet2}|)}$.

☺ Result for σ_{eff} is consistent with previous measurements at lower energies, center of mass dependence cannot be confirmed or excluded.



☹ The measurement is not inclusive.

☺ No ambiguity in the choice of the DPS jets.

☹ Distributions are not deconvoluted at particle level

☹ The analysis relies on just one DPS observable.

☹ SPS+DPS is not demonstrated to fully cover the phase space.

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

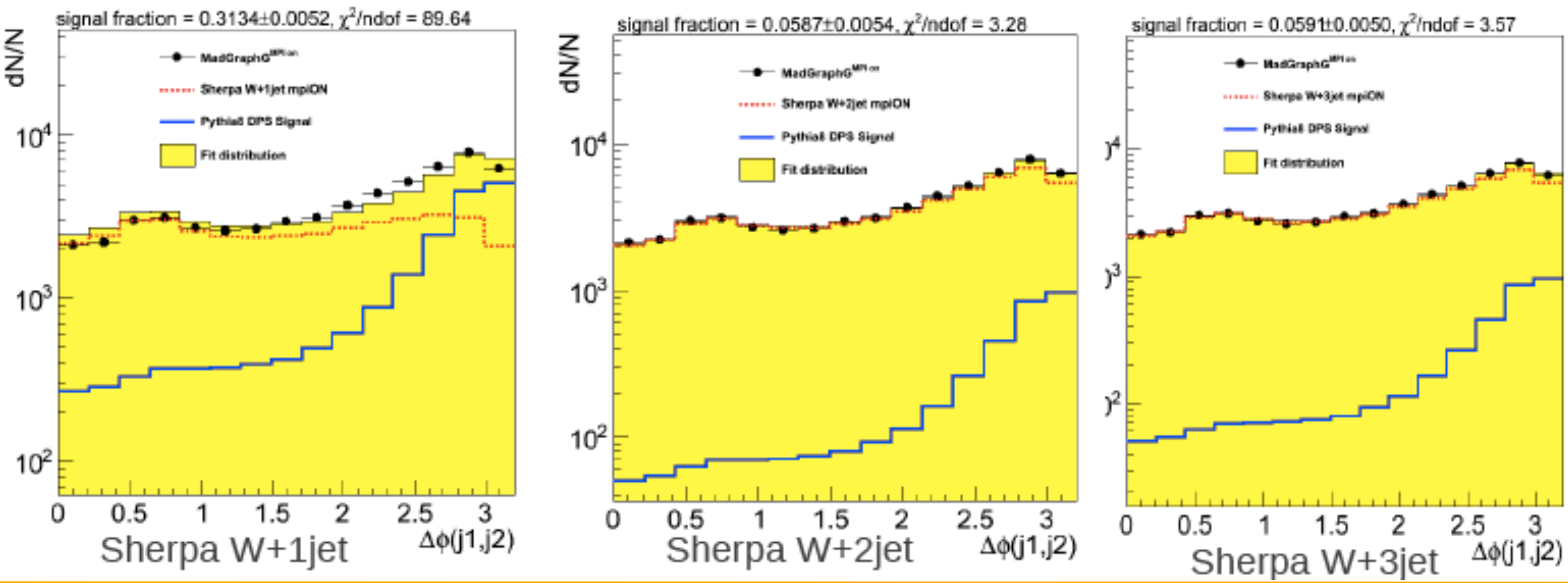
Using different observables may bring to significant differences in σ_{eff} extraction (see for example the talk of R.Kumar to the 4th MPI@LHC, CERN, December 2012).

- **$\Delta\phi$ (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.**
- **$\Delta\, p_T$ (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 (Madgraph with MPI on)

Inclusive = Sherpa W+njets with MPI on, Extra-Signal = Pythia 8 W+2jets DPS
Fitted DPS Signal fraction and reduced χ^2 reported in the table

Inclusive	$\Delta\phi$	$\Delta^{rel}\,p_T$	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**



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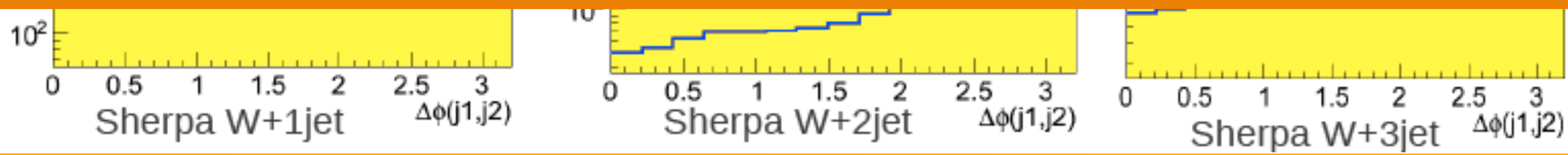
Sherpa W+3jet mpi on	**5.91+-0.50, 3.57**	**6.66+-0.29, 5.09**	**3.48+-0.25, 0.90**

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: W → lν + 2 jets - Unfolding

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

W selection:

- Exactly one μ
- with p_T > 35 GeV, |η| < 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 |η| < 2.0

<u>**Detector level**</u>

$p_T(\mu)$ > 35 GeV, |η| < 2.1
MET > 30 GeV
Transverse Mass (W) > 50
Jets with p_T > 20 GeV and |η| < 2.0

unfolding

<u>**Particle level**</u>

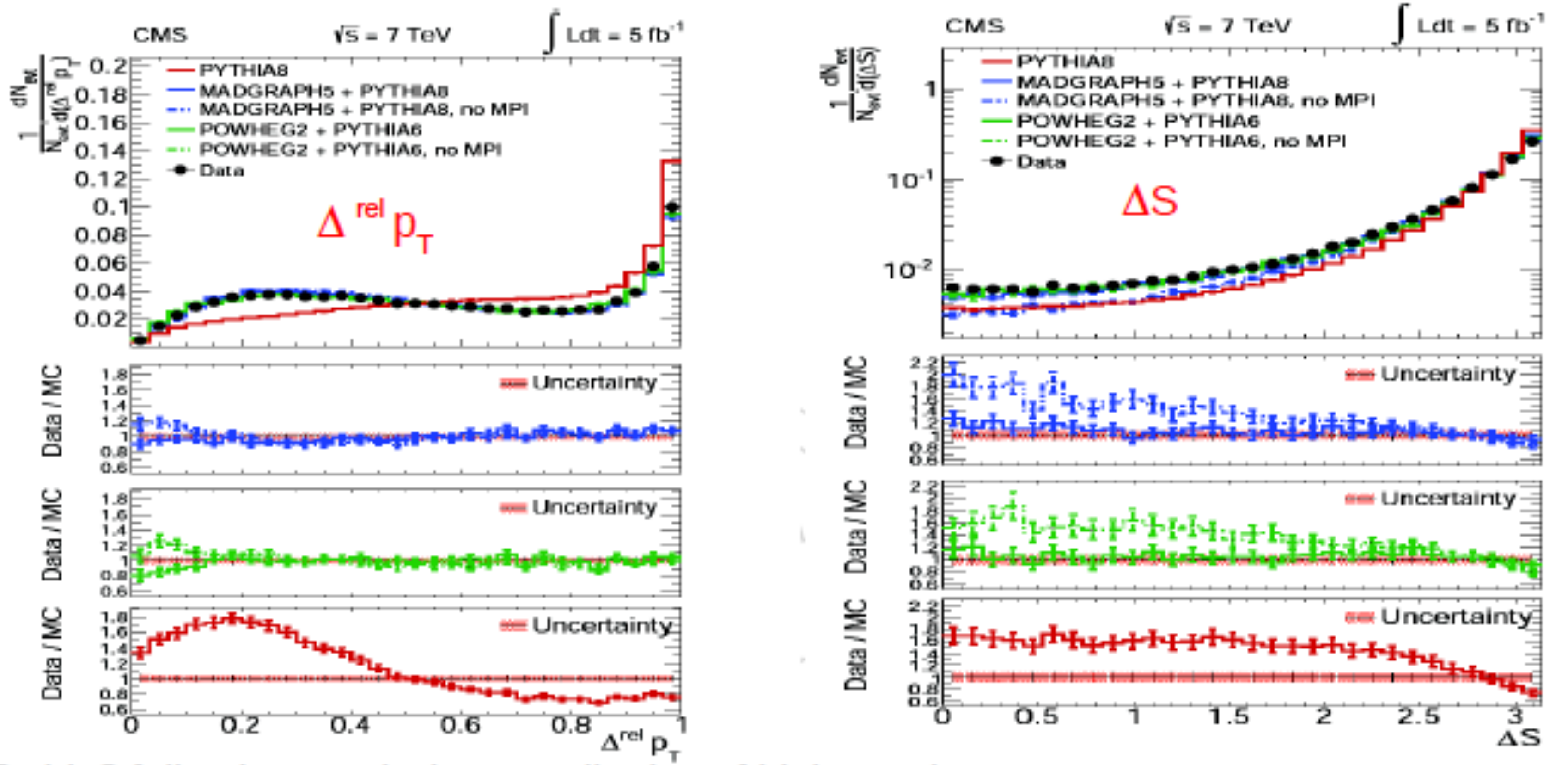
$p_T(\mu)$ > 35 GeV, |η| < 2.1
MET > 30 GeV
Transverse Mass(W) > 50
Jets with p_T > 20 GeV and |η| < 2.0

- **Unfolding is performed using Bayesian method.**
- **A technique in the rooUnfold Package.**
- **Considers bin-to-bin migration in a proper way.**
- **Response Matrix and closure tests rely on several different Monte Carlo generators.**

arXiv:1312.5729.

CMS: W → lν + 2 jets – Particle Level Distributions

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



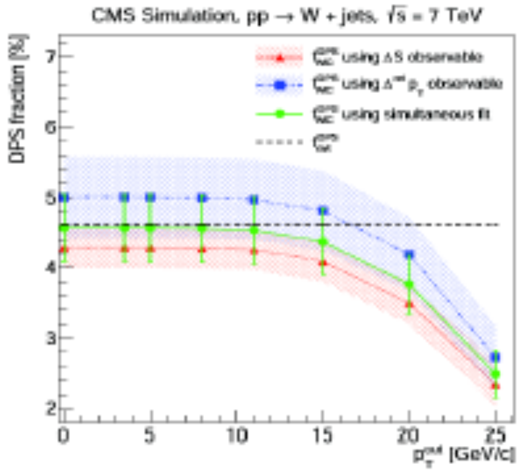
- Pythia8 fails; due to missing contribution of higher order processes.
- LO (MG + Pythia) and NLO (Powheg + Pythia/Herwig6) MCs provide same level of agreement with the measurement.
- Both LO and NLO calculations fails in absence of MPI. *Next step is to extract contribution of hard MPI*

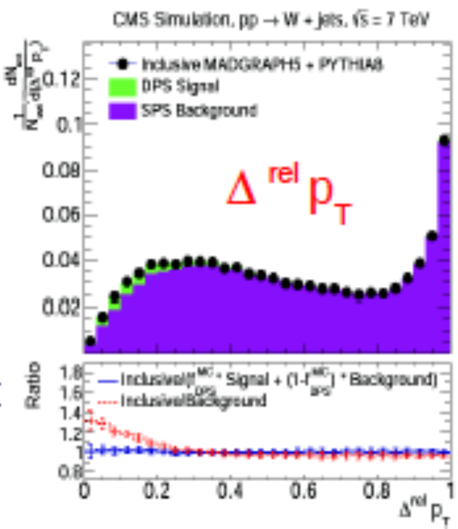
CMS: W → lν + 2 jets – Extraction of DPS Fraction f_{DPS}

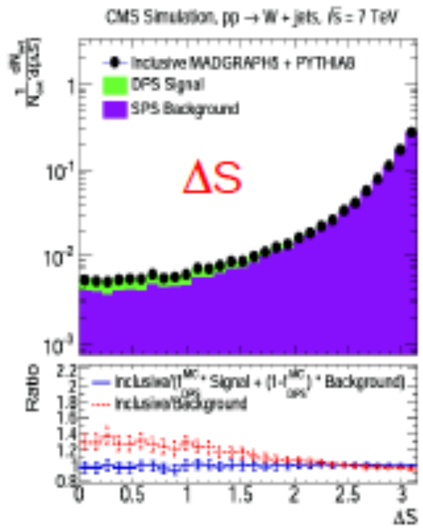
- Binned likelihood fit
- Signal templates: Random of W + 0-jet and dijet events from MCs, ***templates are validated with data.***
-
- Background templates:
  - MadGraph + Pythia8; MPI parton tagged with status code
  - NO jet-parton matching,

  - 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)

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

Measured di-jet x-section

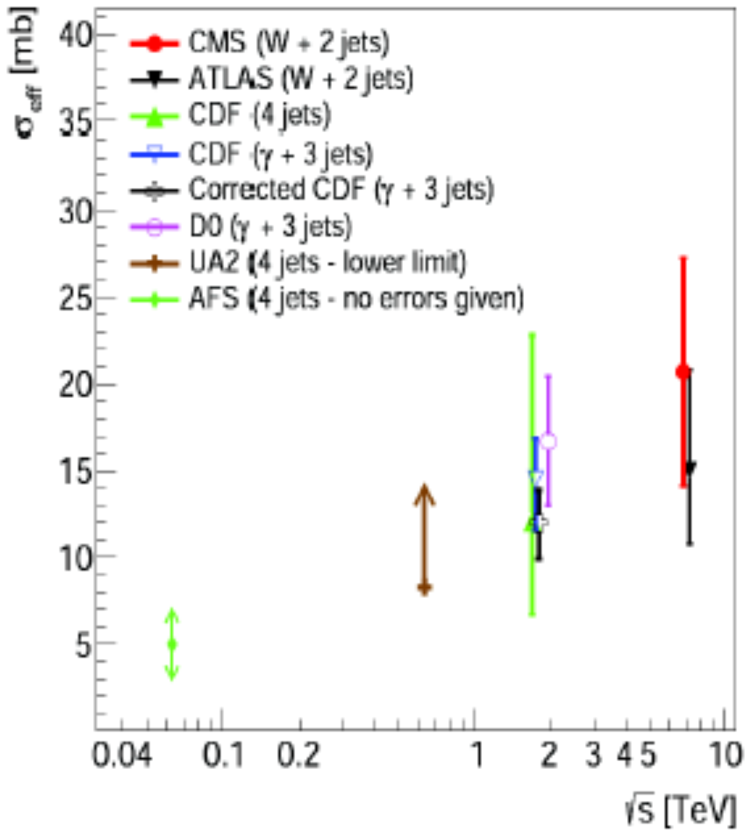
Measured Ratio between W+2jets and W+0jets x-sections

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

- 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).

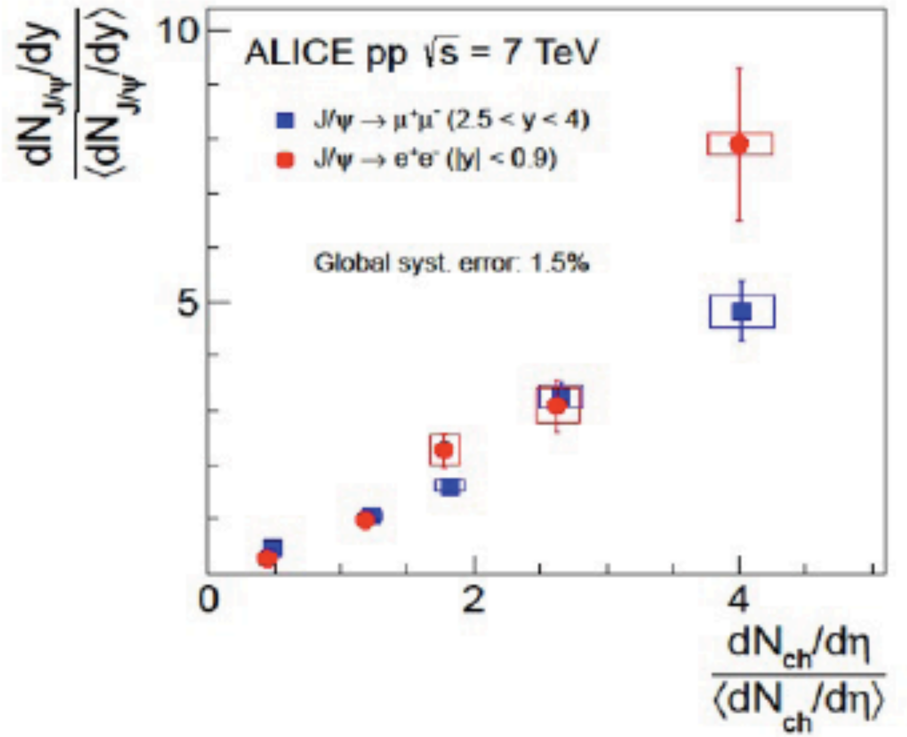


Main systematics from SPS background modeling

The Double Parton Scattering (c)

looking for extra J/ψ (and other charmed hadrons)

ALICE: J/ψ multiplicity vs charged multiplicity



- NA27 observed that events with charm have on average a larger charged particle multiplicity in 400 GeV/*c* pp collisions. NA27 Coll. Z.Phys.C41:191,1988.
- ALICE observed a linear increase of the relative inclusive J/ψ yields vs charged particle density in pp collisions at $\sqrt{s}$ = 7 TeV.

  ALICE Coll., Phys. Lett. B 712 (2012) 3, 165–175

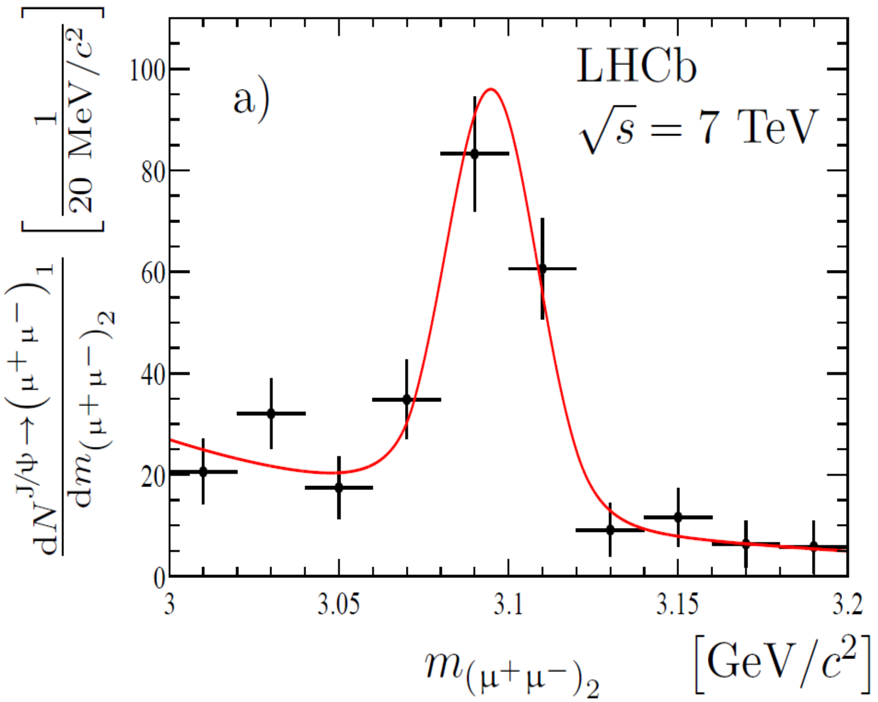
  S. Porteboeuf talk at MPI 2011

→ Very much compatible with the soft QCD picture $N_{ch} \approx$ proportional to N_{MPI}

LHCb: Double J/ψ Production

p_T^{μ} > 650 MeV (μ+μ− 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



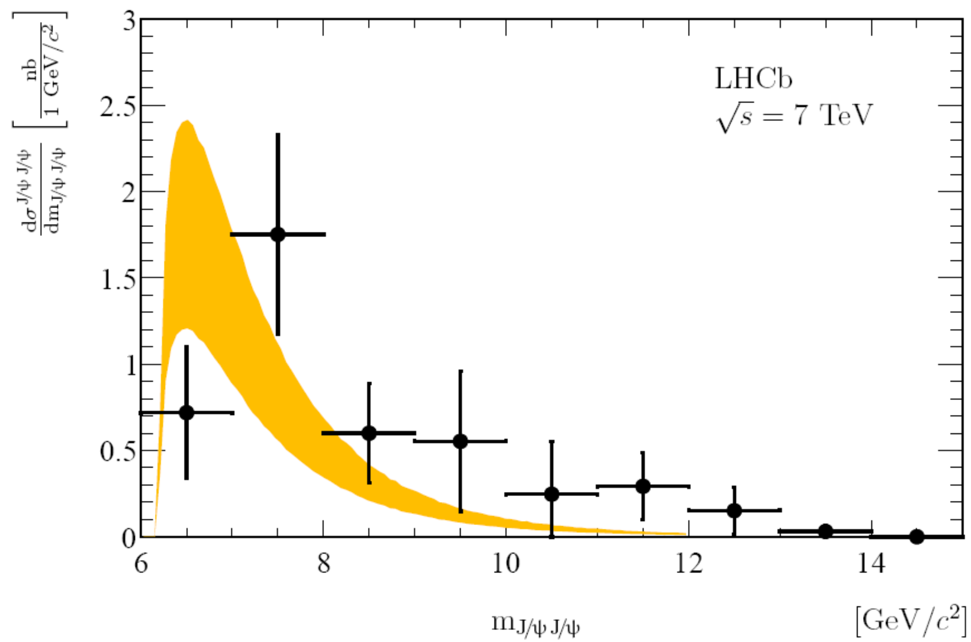
Prediction of $\sigma^{J/\psi J/\psi}$ includes direct production and freed down from ψ(2S), but no DPS

Measured cross-section:

$\sigma^{J/\psi J/\psi}$ = 5.1 +- 1.0 (stat) +- 1.1 (syst) nb

reasonable agreement between data and theory

→ *contribution from DPS?*



LHCb: Double J/ψ and DPS

Using σ^{eff} formulation, we can obtain estimation of the contribution from the double parton scattering (single J/ψ production cross-section was measured by LHCb):

$$\sigma_{\text{DPS}}^{J/\psi\, J/\psi} = \frac{1}{2}\frac{\sigma_{\text{SPS}}^{J/\psi}\,\sigma_{\text{SPS}}^{J/\psi}}{\sigma_{\text{eff}}} \simeq 2.0\ \text{nb}$$

Cross-section through the standard gg→2J/ψ mechanism gives:

$$\sigma_{\text{SPS}}^{J/\psi\, J/\psi} = 4.15\ \text{nb}$$

A.V. Berezhnoy, A.K. Likhoded,
A.V. Luchnsky, A.A. Novoselov, [arXiv:1101.5881]

Theoretical prediction from both modes : $\boxed{\sigma_{\text{SPS}}^{J/\psi\, J/\psi} + \sigma_{\text{DPS}}^{J/\psi\, J/\psi} = 6.15\ \text{nb}}$

- close to the $\sigma^{J/\psi J/\psi}$ cross-section measured by LHCb ($\sigma^{J/\psi J/\psi}$ = 5.1 +- 1.0 +- 1.1 nb)

A hint of Double Parton Scattering
in the double J/ψ production

- Large TH uncertainties (α_s scale, J/ψ wave function, gluon distr.,…) give factor 2-3

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

LHCb: J/ψ + open charm and DPS

- Use per-event efficiency, mainly from DATA: trigger, particle ID, background etc.

$$\sigma^{J/\psi\, J/\psi} = 5.1 \pm 1.0 \pm 1.1\ \text{nb},$$

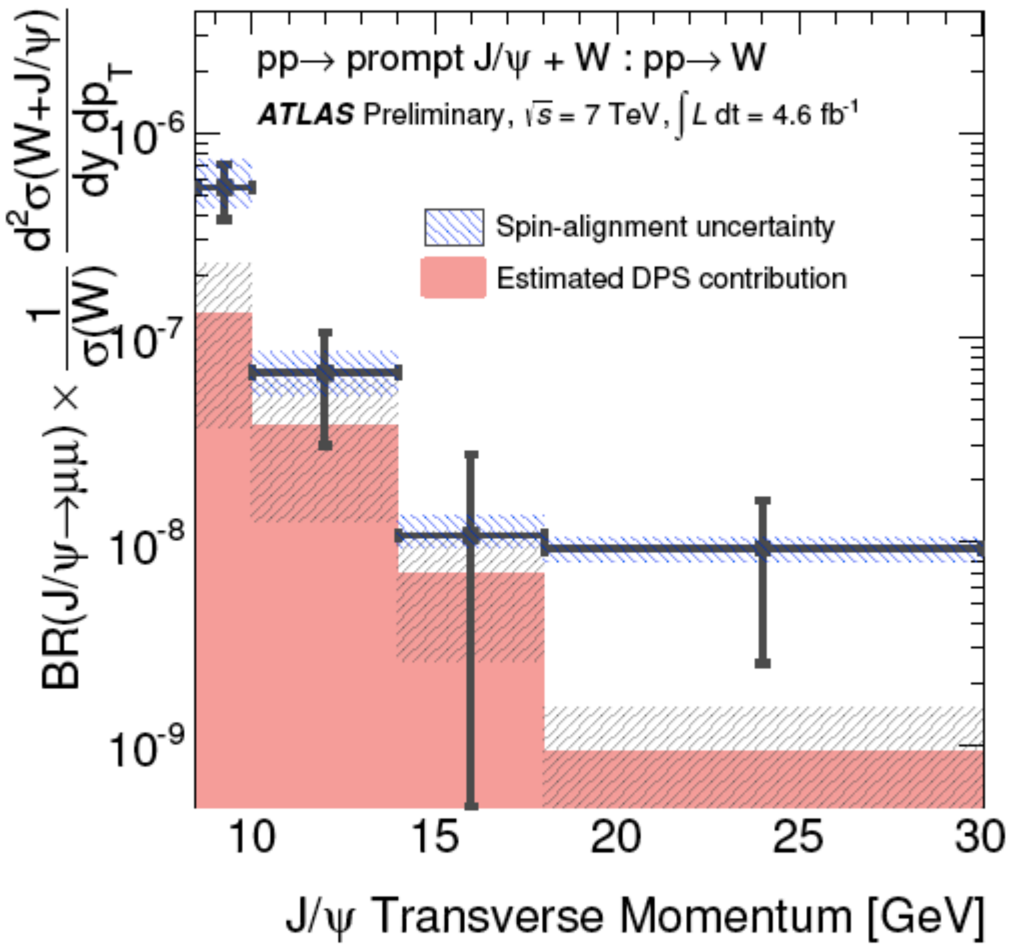
- Major systematic:
  tracking (reducible)
  $Br(\Lambda_c)$, $Br(D_s)$, ….

Mode	σ [nb]
$J/\psi\, D^0$	$161.0 \pm 3.7 \pm 12.2$
$J/\psi\, D^+$	$56.6 \pm 1.7 \pm 5.9$
$J/\psi\, D_s^+$	$30.5 \pm 2.6 \pm 3.4$
$J/\psi\, \Lambda_c^+$	$43.2 \pm 7.0 \pm 12.0$

Mode	$\sigma_{J/\psi C}/\sigma_{J/\psi}$ $[10^{-3}]$	$\sigma_{J/\psi C}/\sigma_{C}$ $[10^{-4}]$	$\sigma_{J/\psi}\sigma_{C}/\sigma_{J/\psi C}$ [mb]
$J/\psi\, D^0$	$16.2 \pm 0.4 \pm 1.3^{+3.4}_{-2.5}$	$6.7 \pm 0.2 \pm 0.5$	$14.9 \pm 0.4 \pm 1.1^{+2.3}_{-3.1}$
$J/\psi\, D^+$	$5.7 \pm 0.2 \pm 0.6^{+1.2}_{-0.9}$	$5.7 \pm 0.2 \pm 0.4$	$17.6 \pm 0.6 \pm 1.3^{+2.8}_{-3.7}$
$J/\psi\, D_s^+$	$3.1 \pm 0.3 \pm 0.4^{+0.6}_{-0.5}$	$7.8 \pm 0.8 \pm 0.6$	$12.8 \pm 1.3 \pm 1.1^{+2.0}_{-2.7}$
$J/\psi\, \Lambda_c^+$	$4.3 \pm 0.7 \pm 1.2^{+0.9}_{-0.7}$	$5.5 \pm 1.0 \pm 0.6$	$18.0 \pm 3.3 \pm 2.1^{+2.8}_{-3.8}$

However kinematics indicate more correlations between the charmed hadrons with respect to the ones predicted by DPS.

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
- The DPS contribution is subtracted in order to test the SPS predictions.

SPS predictions still below the DPS subtracted data

The Double Parton Scattering (d)

a glance to the future

(pairs of heavy bosons etc.)

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} μb = **50 pb**

  – apply extra **1%** factor for each b-jet pair requirement

- σ_{DPS} **(4γ@20 GeV)** = ½ * $(\sigma\,(2\gamma))^2/\sigma_{eff}$

= ½ * $(0.1\mu b)^2/\sigma_{eff}$ = 5 10^{-5} μb = **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

μ pairs from same sign WW

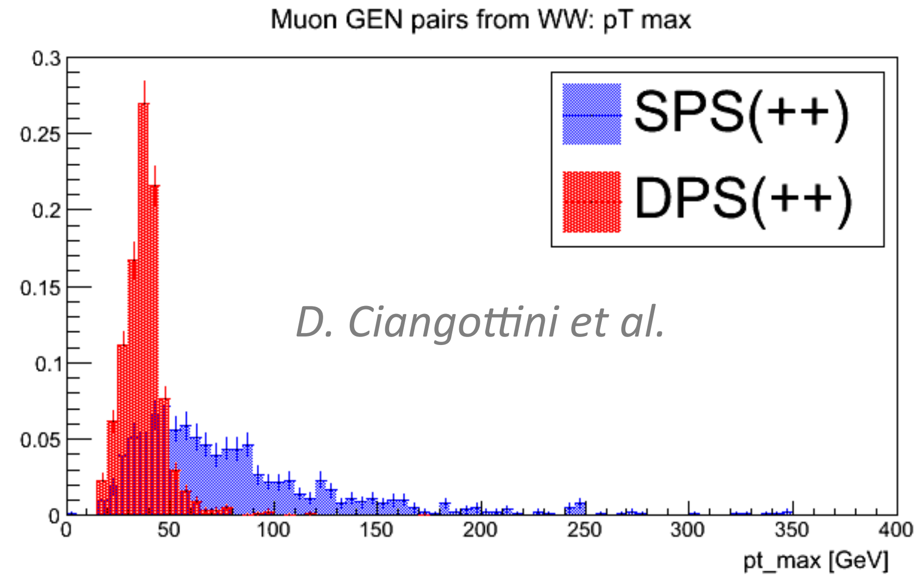
μ-related discriminating observables

Double Parton Scattering and **Single Parton Scattering** cover the phase space in a very different way, the kinematic information can be used to normalize σ(**DPS**) to σ(**SPS**).

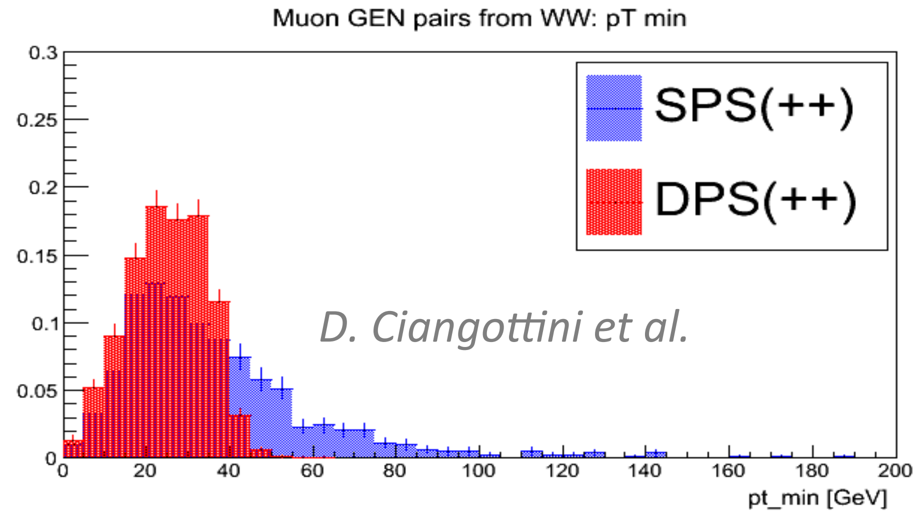
Generator level distributions, √s = 8 TeV
DPS = Pythia 8
SPS = Madgraph

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).]

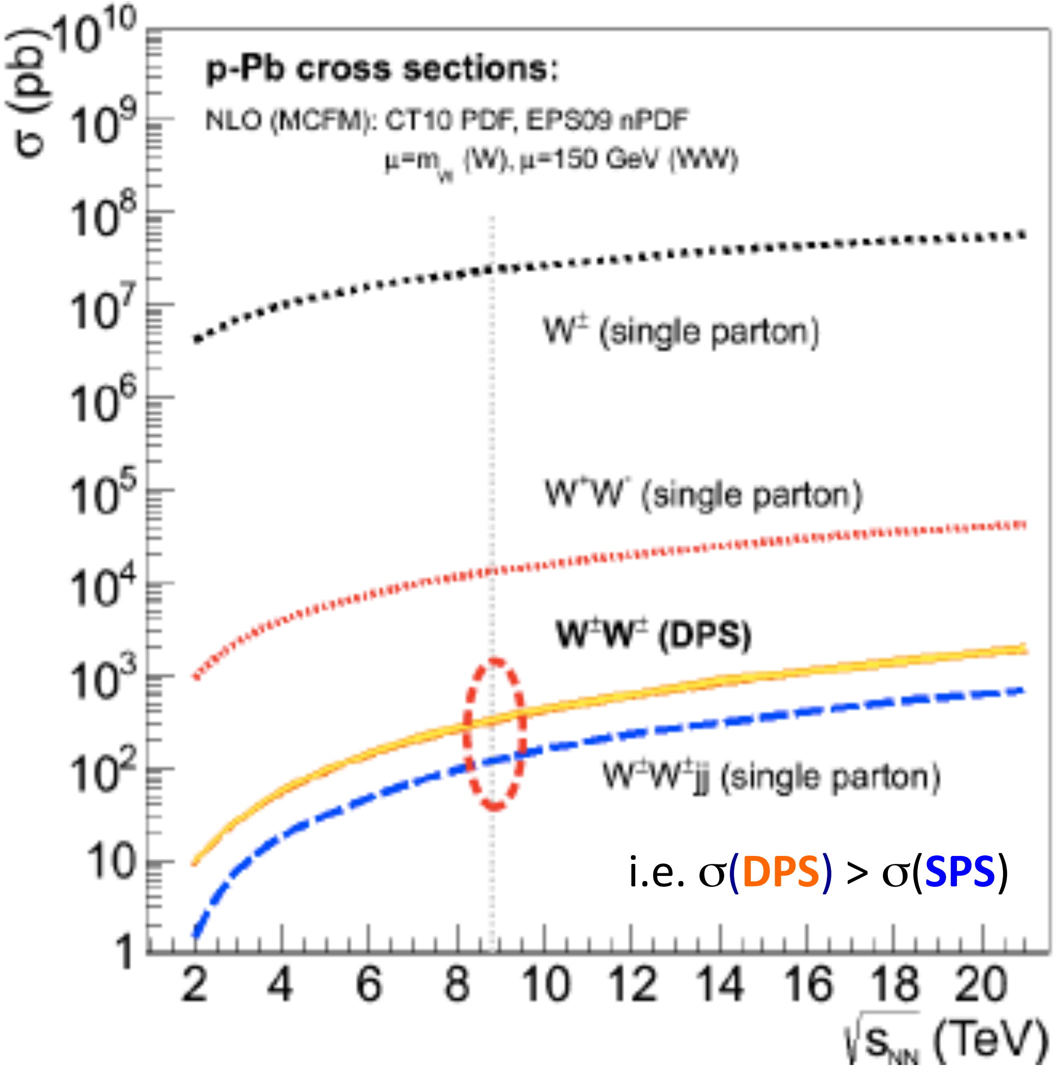


σ(**DPS**) ≈ σ(**SPS**)



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

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



i.e. σ(DPS) > σ(SPS)

p-Pb, 8.8 TeV:

σ(WW,DPS)~300 pb

σ(WWjj)~100 pb

±18% uncertainties:

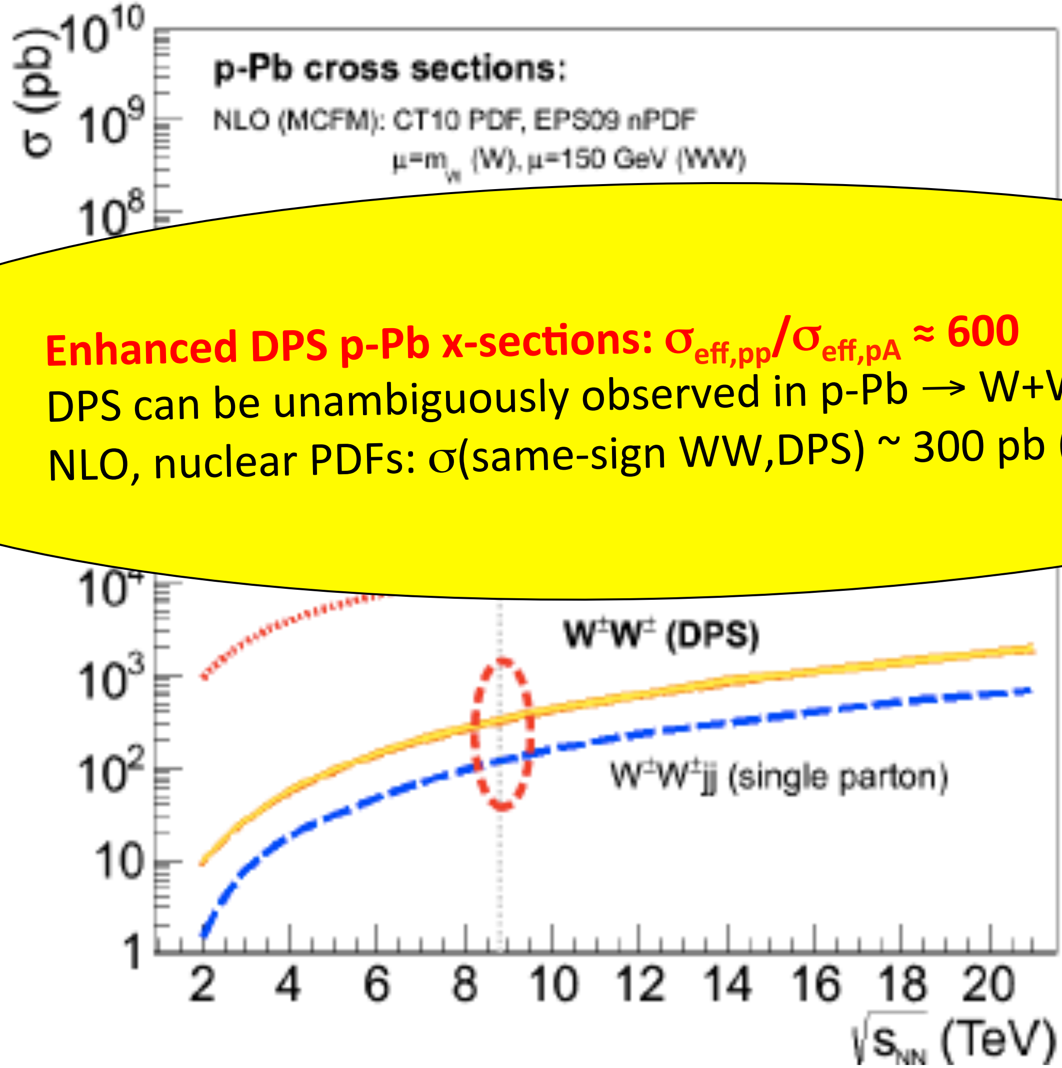
±15% for σ_{eff}

±10% for scales&PDFs

D'Enterria & Snigirev, arXiv:1211.0197.

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.

The Double Parton Scattering (e)

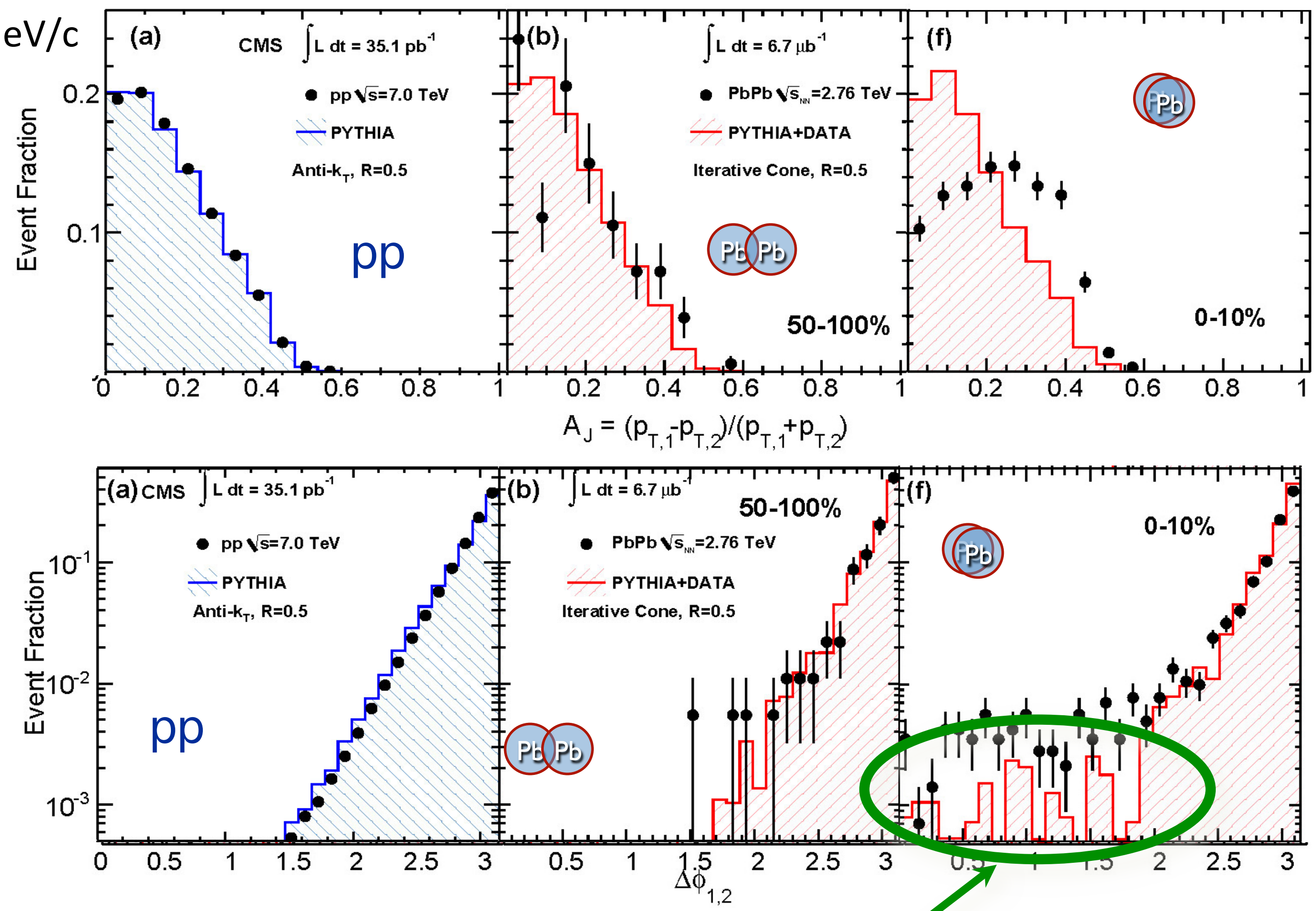
in Heavy Ions

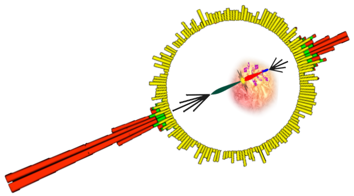
HI: Jet quenching via large dijet energy imbalance & DPS!

- 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?

Double Parton Scattering Status & Milestones @ LHC

1. corrected distributions for several DPS-sensitive observables.

Achieved for 4jets, W+2jets, double J/Ψ, 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 p-Pb and Pb-Pb should proceed in parallel, for now we have some nice/promising feasibility studies)

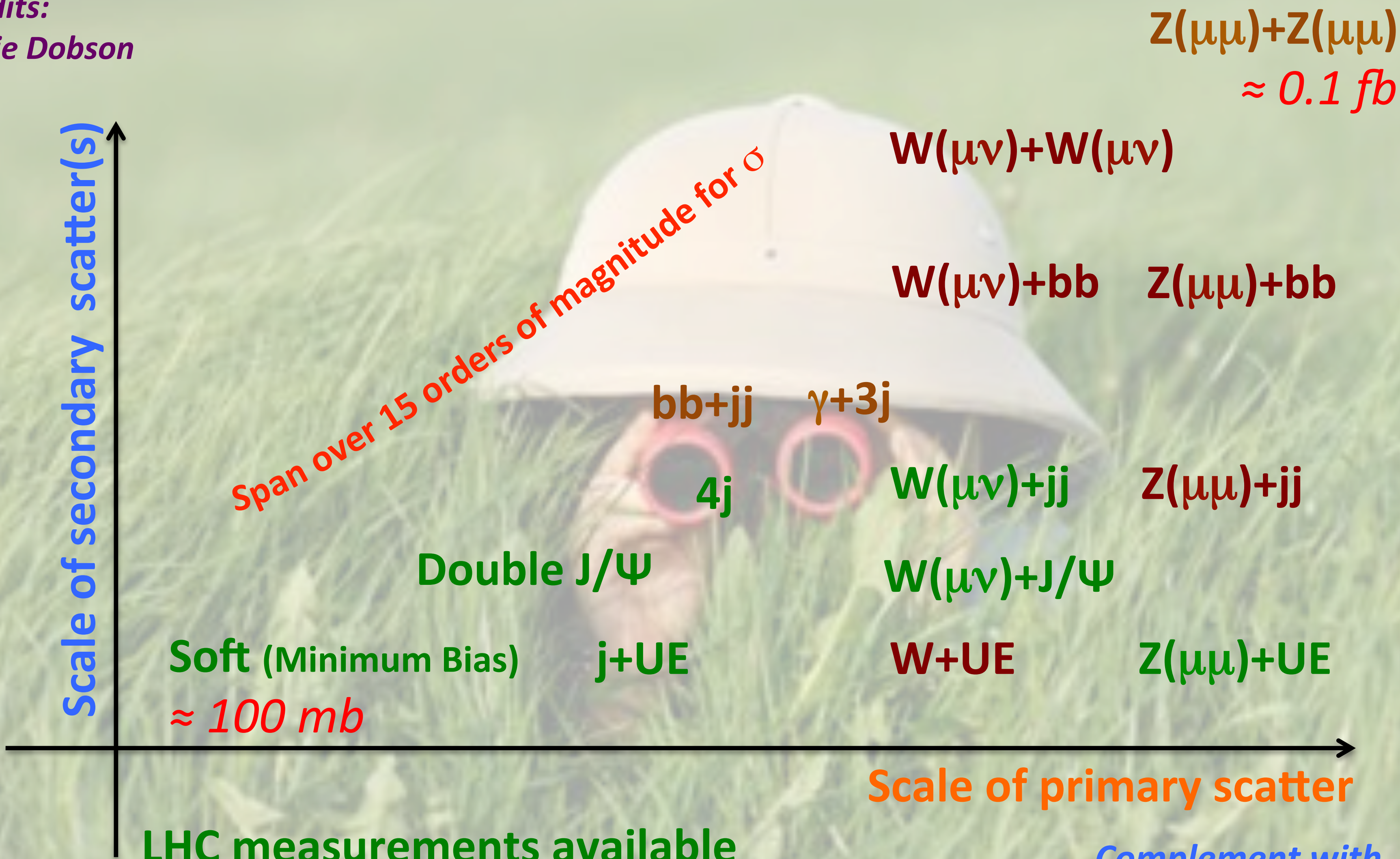
Overall, big progress with respect to the early Tevatron DPS studies, in particular for what concerns the definition of Signals and Backgrounds.
However it is necessary to refrain from making steps backwards. See the recommendations in the back-up slides.

Multiple Parton Interactions at the LHC/LIC

- Theoretical basis: unitarity of pQCD x-sections.
- Unavoidable tool in Monte Carlo models to describe hadron production at hadron colliders.
- Experimental evidences of MPI on Soft QCD measurements at the LHC
  - KNO violation, Underlying Event, Forward-Central correlations, “ridge”?
- Double Parton Scattering (i.e. two hard scatterings) in hadron-hadron interactions has still no striking evidences.
  - Even the Tevatron measurements lack of an adequate description of the Single Parton Scattering background and should be re-interpreted in the light of modern Matrix Element tools.
- Rich DPS LHC measurement plan also to understand possile additional backgrounds to new physics.
  - Preliminary results on 4jets, W+2jets, double J/Ψ , Multiple open charm, etc.
  - Other pairs of hard processes also investigated.
- Double-Parton-Scattering in proton-nucleus collisions.
  - DPS x-section enhancement factor ~600 for p-Pb.

Continue… news expected from both soft and hard MPI

Credits:
- Ellie Dobson



LHC measurements available
LHC measurements not yet available

Complement with p-A and A-A

- BACK-UP

- MC Tools

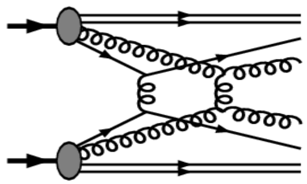
pQCD Models

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 observations of double high P_T scatterings



Main Parameter: P_T cut-off P_{T0}

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

(dampening)

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

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

Tuning for the LHC: Emphasis on the Energy-dependence of the parameters.

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

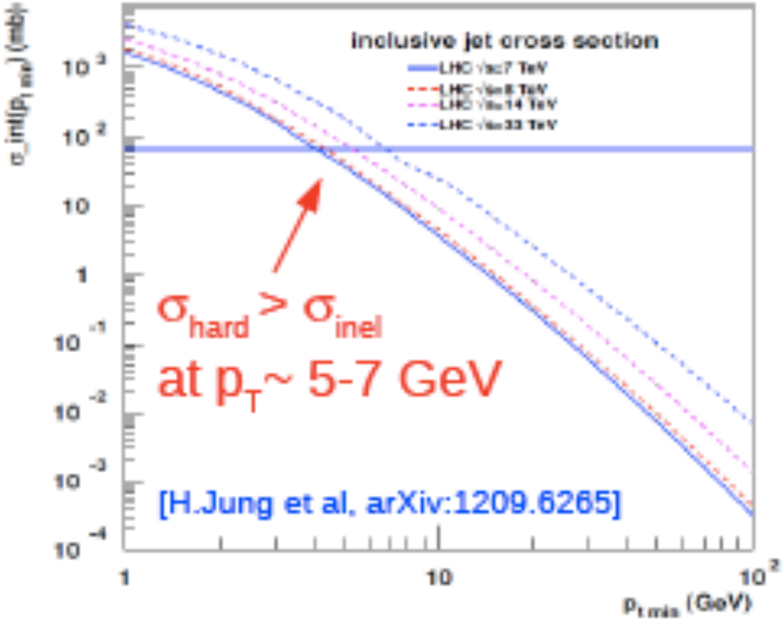
$$P_{T0}^{s'} = P_{T0}^{s} (\sqrt{s'} / \sqrt{s})^{\varepsilon}$$

More on Pythia p_T cut-off

- pQCD (mini)jet production x-section is bigger than total inel p-p x-section for p_{Tmin}~ 5-7 GeV at the LHC !

$$\sigma_{\mathrm{hard}}(p_{\perp\mathrm{min}}) = \int_{p^2_{\perp\mathrm{min}}}^{s/4} \frac{\mathrm{d}\sigma}{\mathrm{d}p^2_\perp}\,\mathrm{d}p^2_\perp$$

... Why this happens ?

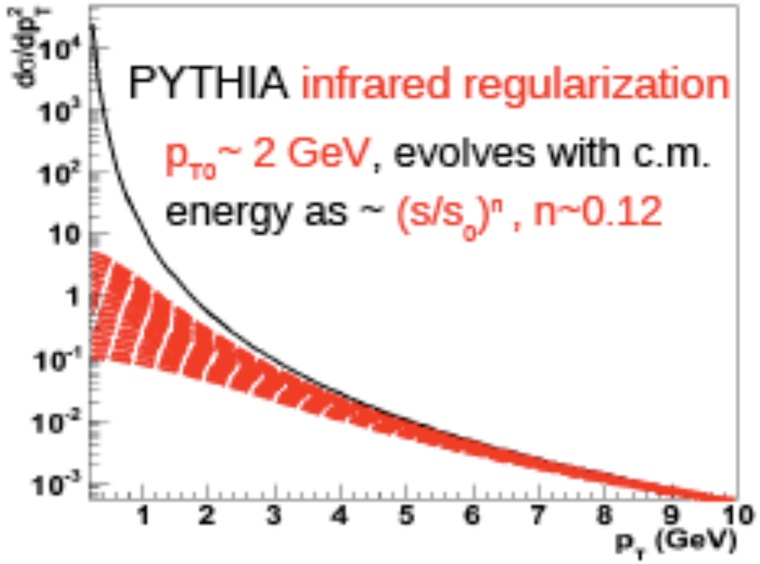


- Very high gluon densities at small-x.
- Solution (1): Gluon saturation around perturbative "saturation scale" Q_s:

$$Q^2_{\mathrm{sat}} \propto (1/x)^n \propto (\sqrt{s})^n$$

- Equivalent to (adhoc) PYTHIA p_T-cutoff:

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p^2_\perp} \propto \frac{\alpha^2_s(p^2_\perp)}{p^4_\perp} \to \frac{\alpha^2_s(p^2_{\perp 0} + p^2_\perp)}{(p^2_{\perp 0} + p^2_\perp)^2}$$



Pythia Tunes in CMS

PRE-LHC

– 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

– 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 ε ≈ 0.16 - 0.21 (CTEQ6LL)**

DW, Z1, Z2 → **large ε ≈ 0.24 - 0.30 (CTEQ5L, CTEQ6LL** for Z2)

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

MPI in MC – Some Heuristic considerations

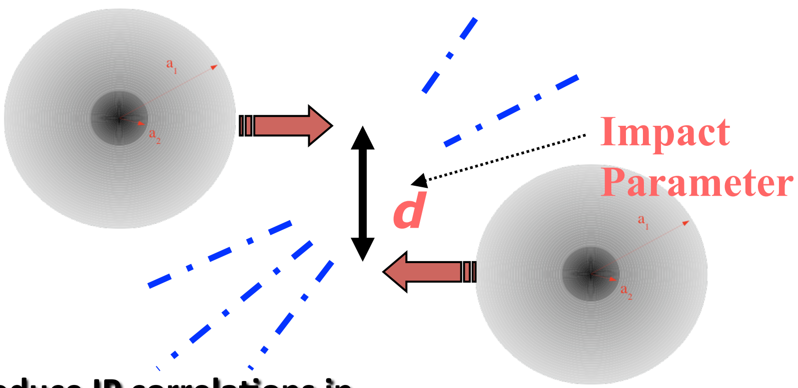
- **Multiple Parton Interactions**
  - **Huge progress, several recent papers, however still missing a factorization theorem.**
  - **QCD/MPI MC models very successful: unavoidable tools to describe a wide set of observables at hadron colliders.**
    - **Correlations between interactions needed!**
      - **Absence of correlations would predict flat $<p_T>$ vs N_{ch}…**
    - **Eikonal description (IP correlations) needed to describe large multiplicity tails in N_{ch}, KNO scaling violations, shape of the UE profiles etc.**
    - **Further correlations (color flow between interactions, etc.) not widely accepted**
      - **D.Treleani: "Interactions happen in different points of the phase space".**

UA5 Charged Multiplicity Distribution

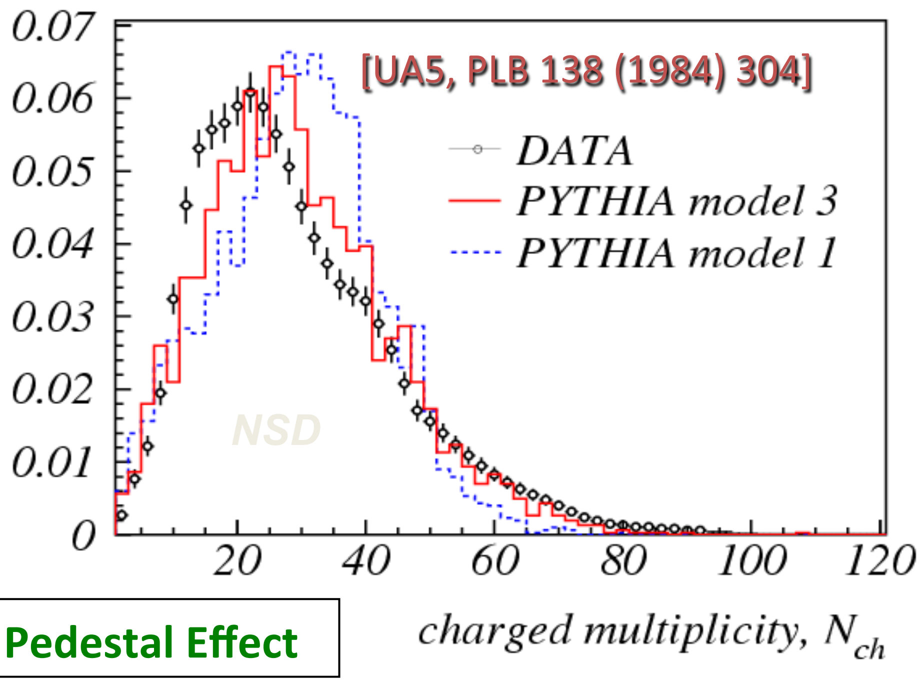
Choice of the (old) multiple parton interaction model in Pythia:

- **All hadron collisions equivalent (MSTP(82)=1)**
  - → **Abrupt turn off of the cross section at P_T cut-off**
  - → **All the partonic interactions equivalent**
- **Varying impact parameter between the colliding hadrons.**
  - → **Continuous turn off of the cross section at P_T cut-off**
  - → **Correlated partonic interactions.**
  - → **Hadronic matter described by one (MSTP(82)=3) or two (MSTP(82)=4) Gaussians.**

Model with Varying impact parameter between the colliding hadrons; hadronic matter is described by Gaussians



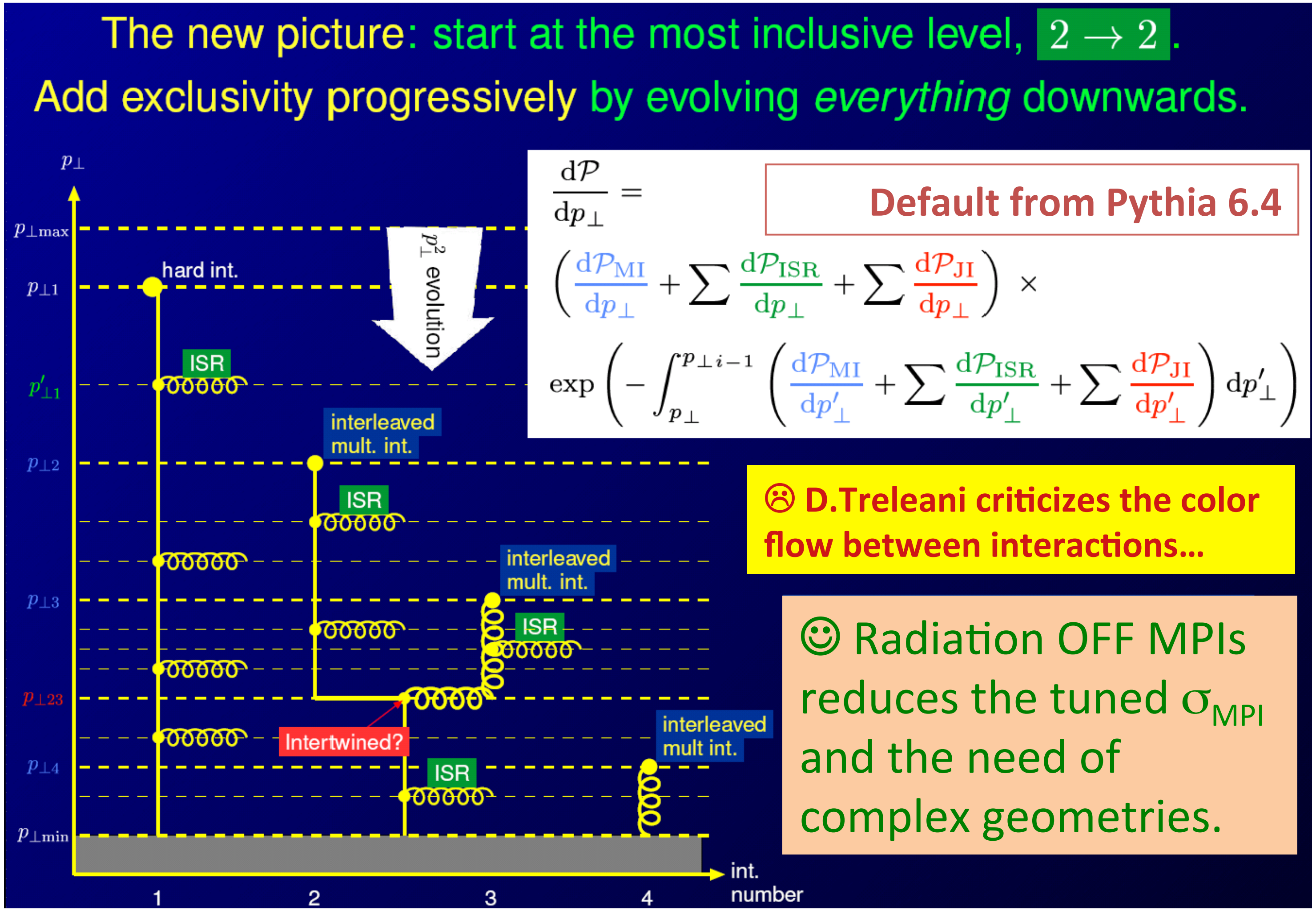
Introduce IP correlations in Multiple Parton Interactions →



Also essential to describe UE Pedestal Effect

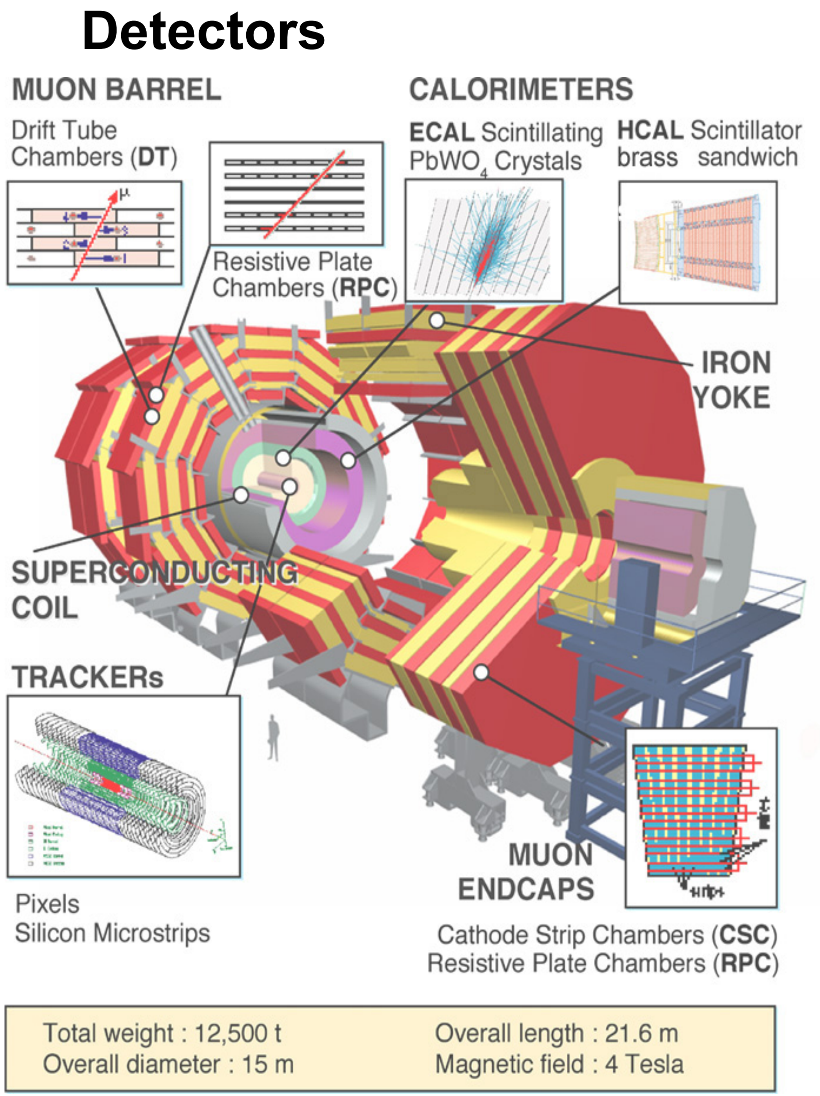
“Interleaved evolution” with multiple interactions

T. Sjöstrand & P. Skands - Eur.Phys.J.C39(2005)129 + JHEP03(2004)053



- Detectors

CMS Design features



CMS design choice: optimize performance for muon / track momentum and electromagnetic energy resolution.

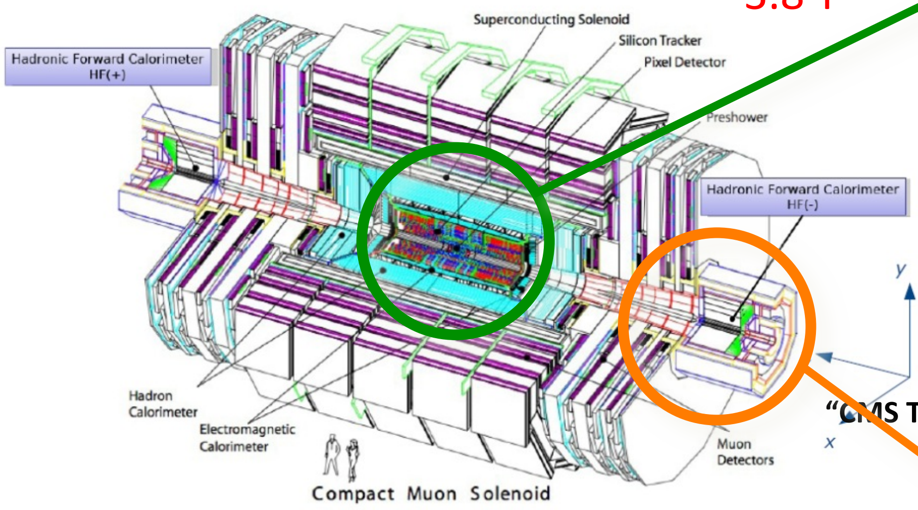
Long 3.8 Tesla Solenoid containing Tracker, ECAL and HCAL
Tracking up to η ~ 2.5
μ system in return iron
First μ chamber just after Solenoid (max. sagitta)
Big lever arm for P_T measurement

Event Rates:	~10^9 Hz
Event size:	~1 MByte
Level-1 Output	~100kHz
Mass storage	~10^2Hz
Event Selection:	~$1/10^{13}$

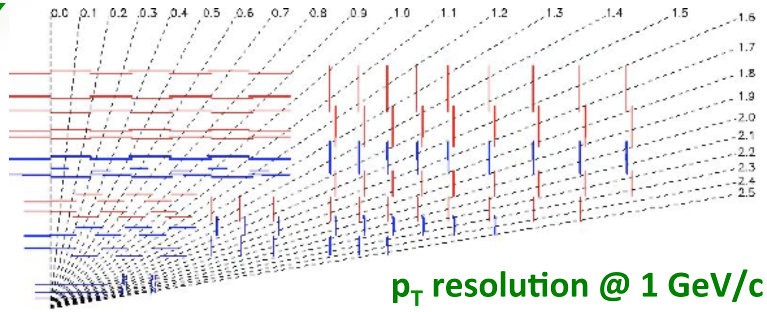
Measuring tracks in Minimum Bias

CMS Detector

3.8 T



CMS Tracker



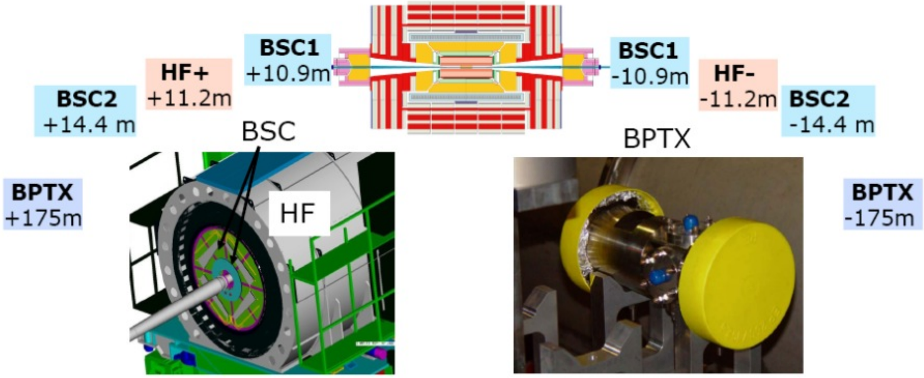
p_T resolution @ 1 GeV/c is:
0.7% at η = *0 and*
2% at $|\eta|$ = 2.5

"CMS Tracking Performance Results from early LHC Operation", [Eur. Phys. J. C70 (2010) 1165–1192]

Beam Scintillator Counters (BSC) → 96.3% efficiency for MIPs and time resolution of 3 ns.

Beam Pick-up Timing for eXperiments (BPTX) time resolution better than 0.2 ns.

Trigger System



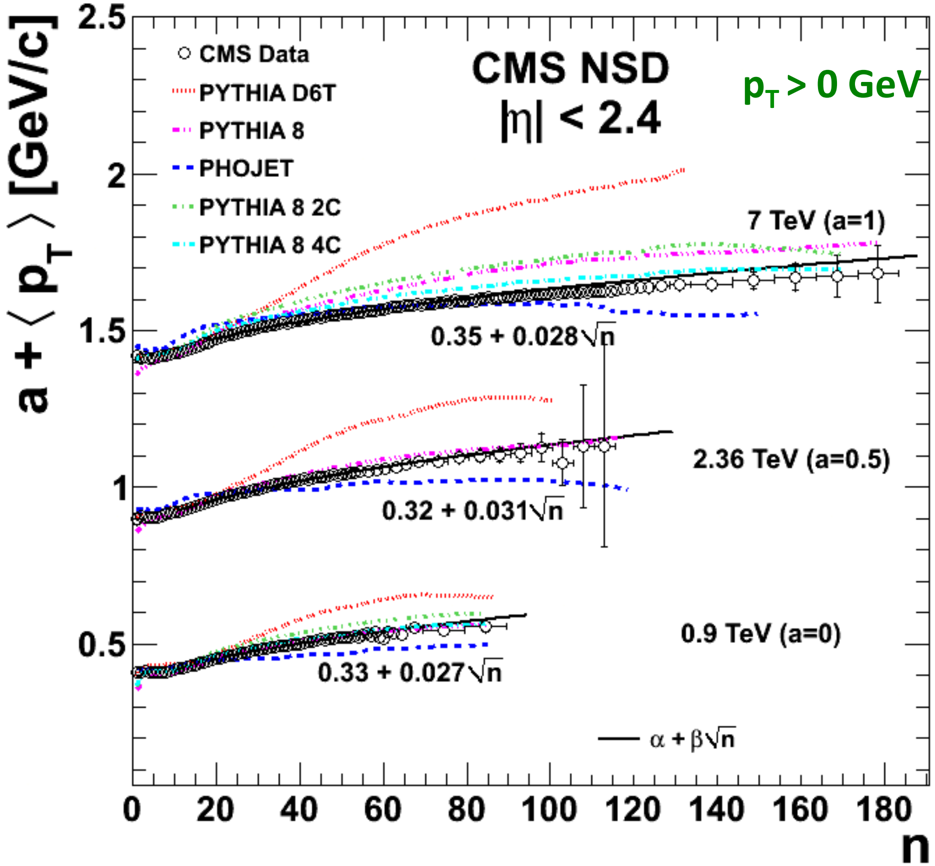
Hadron Forward:

- @11.2m from interaction point
- rapidity coverage: $3 < |\eta| < 5$
- Steel absorbers/ quartz fibers (Long +short fibers)
- 0.175x0.175 η/φ segmentation

- Kinematics

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.

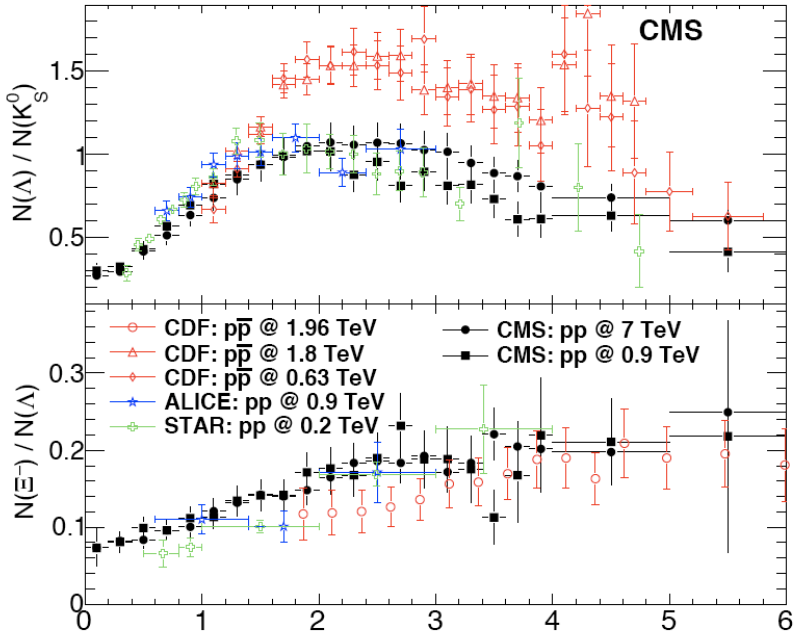
- Correlations diluted including particles pT → 0. Lack of universal descriptions.

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.**

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

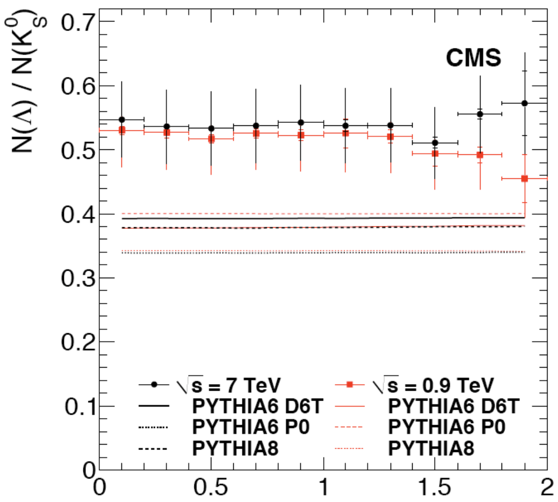
Ratio of s-rates in NSD events

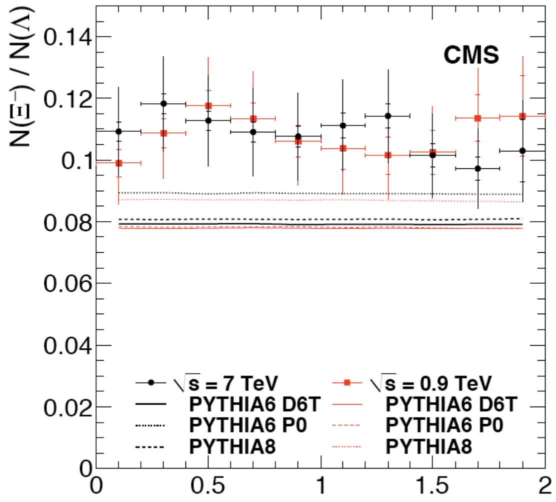


CDF: arXiv:1101.2996 (CDF MB trigger)

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]

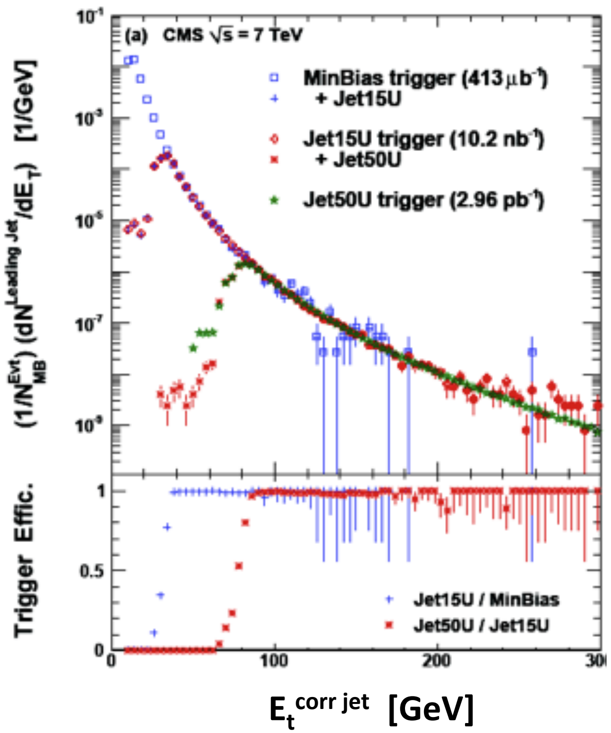
Single Charged Particle Spectra: dN_{ch}/dp_T

≈ large p_T tracks (for pp interactions at $\sqrt{s}$ = 0.9 and 7 TeV)

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

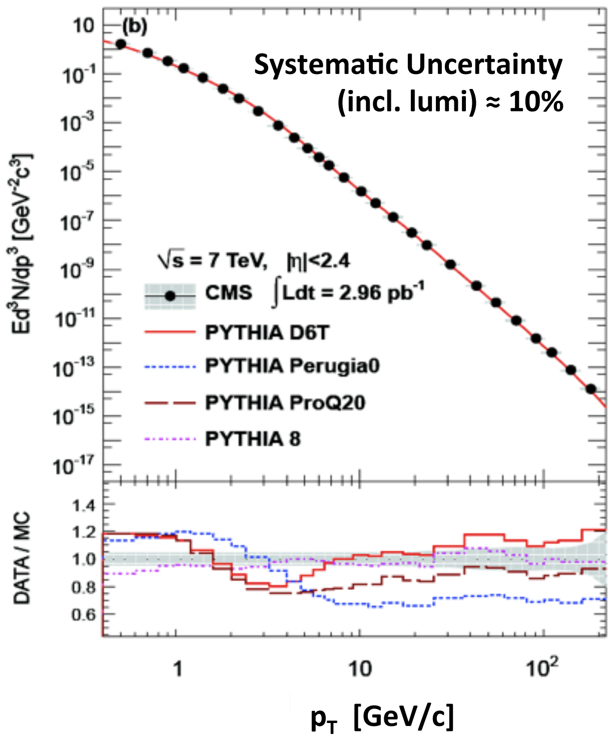
$$E\frac{d^3\sigma}{dp^3} = F(x_T)/p_T^{n(x_T,\sqrt{s})} = F'(x_T)/\sqrt{s}^{n(x_T,\sqrt{s})}$$

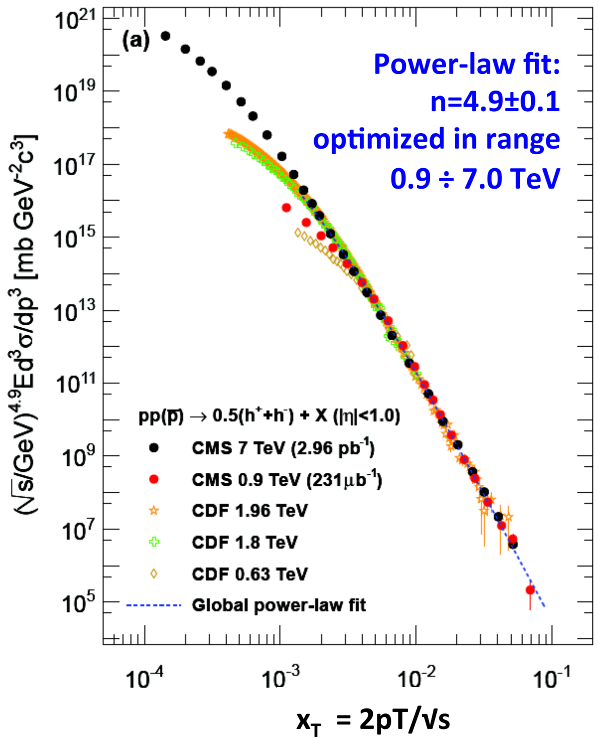
[F. Arleo et al. JHEP 583 06 (2010) 035]



Measuring charged tracks up to p_T ~ 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]

- Correlations

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

$P(p_1,p_2)$: 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 $\quad\quad$ δ : Long distance correlations

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

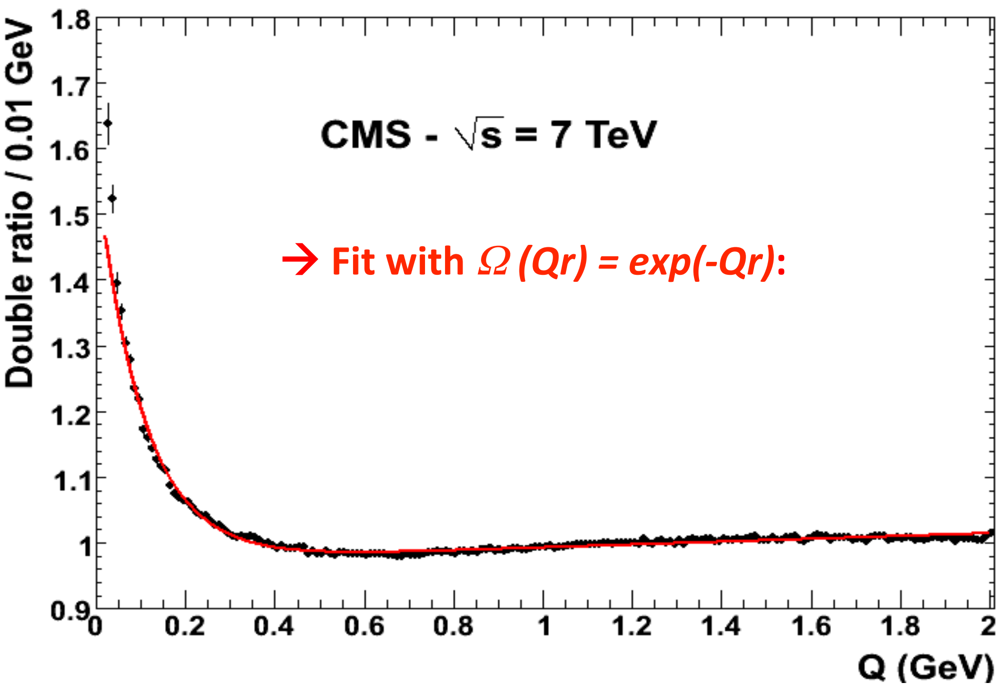
Bose-Einstein Correlations

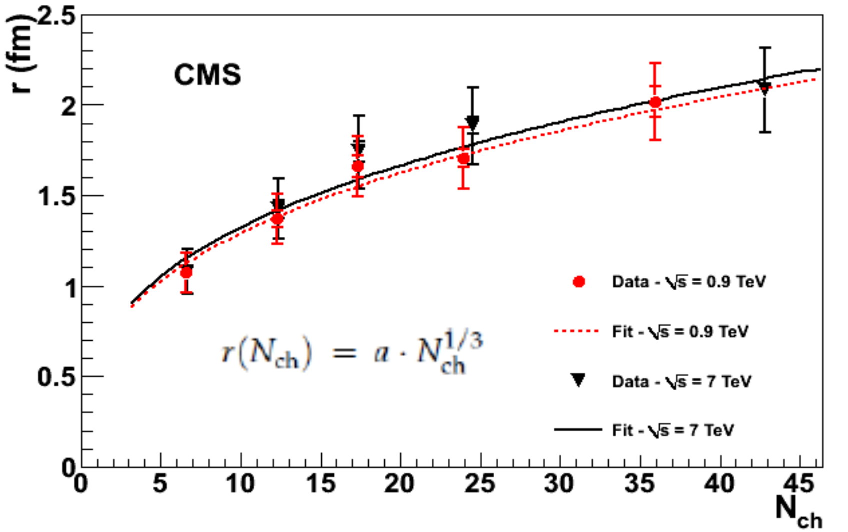
Reference samples:

- **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.





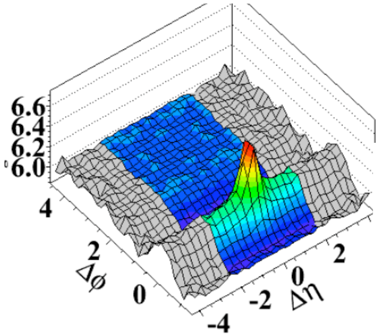
→ BEC effective emission region grows with N_{ch}, as observed by previous experiments.
→ r vs N_{ch} ≈ scales with √s.

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

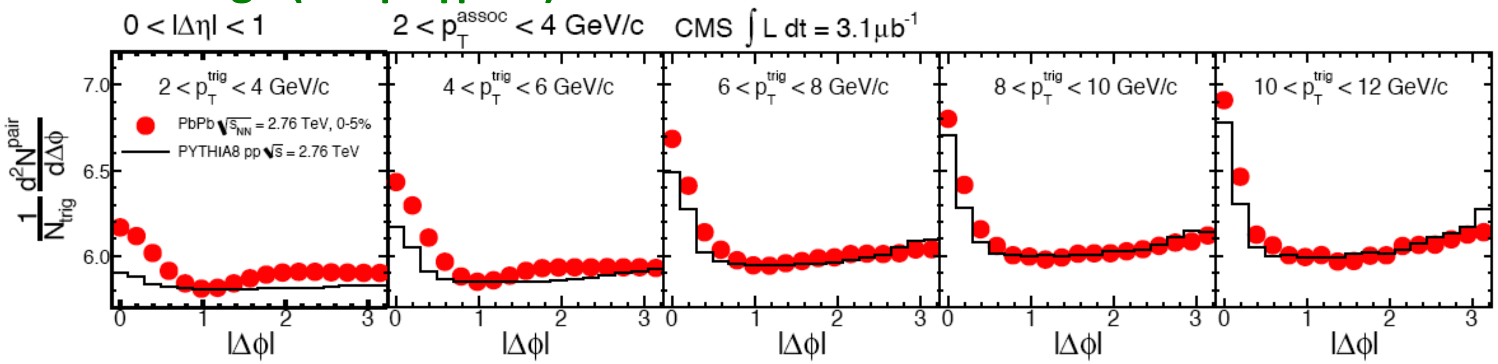
Short and Long Range Correlations in PbPb ($\sqrt{s_{NN}}$ = 2.76 TeV)

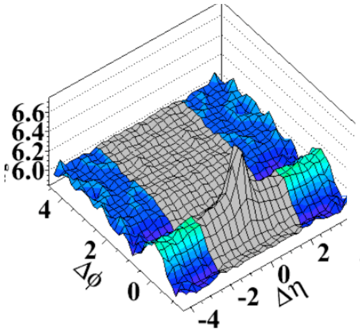
Ridge seen in Heavy Ion collsions.

Centrality 0-5%

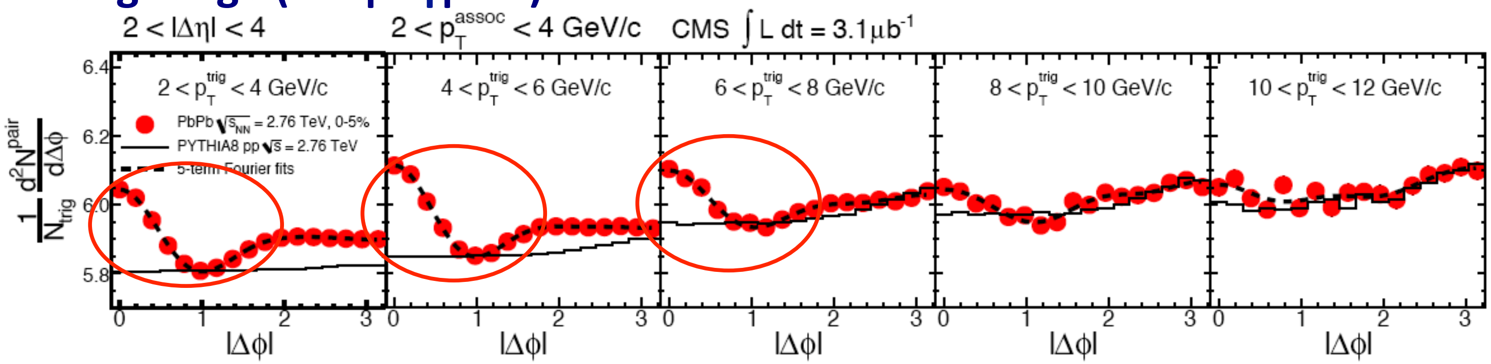


Short range ($0 < |\Delta\eta| < 1$)





Long range ($2 < |\Delta\eta| < 4$)

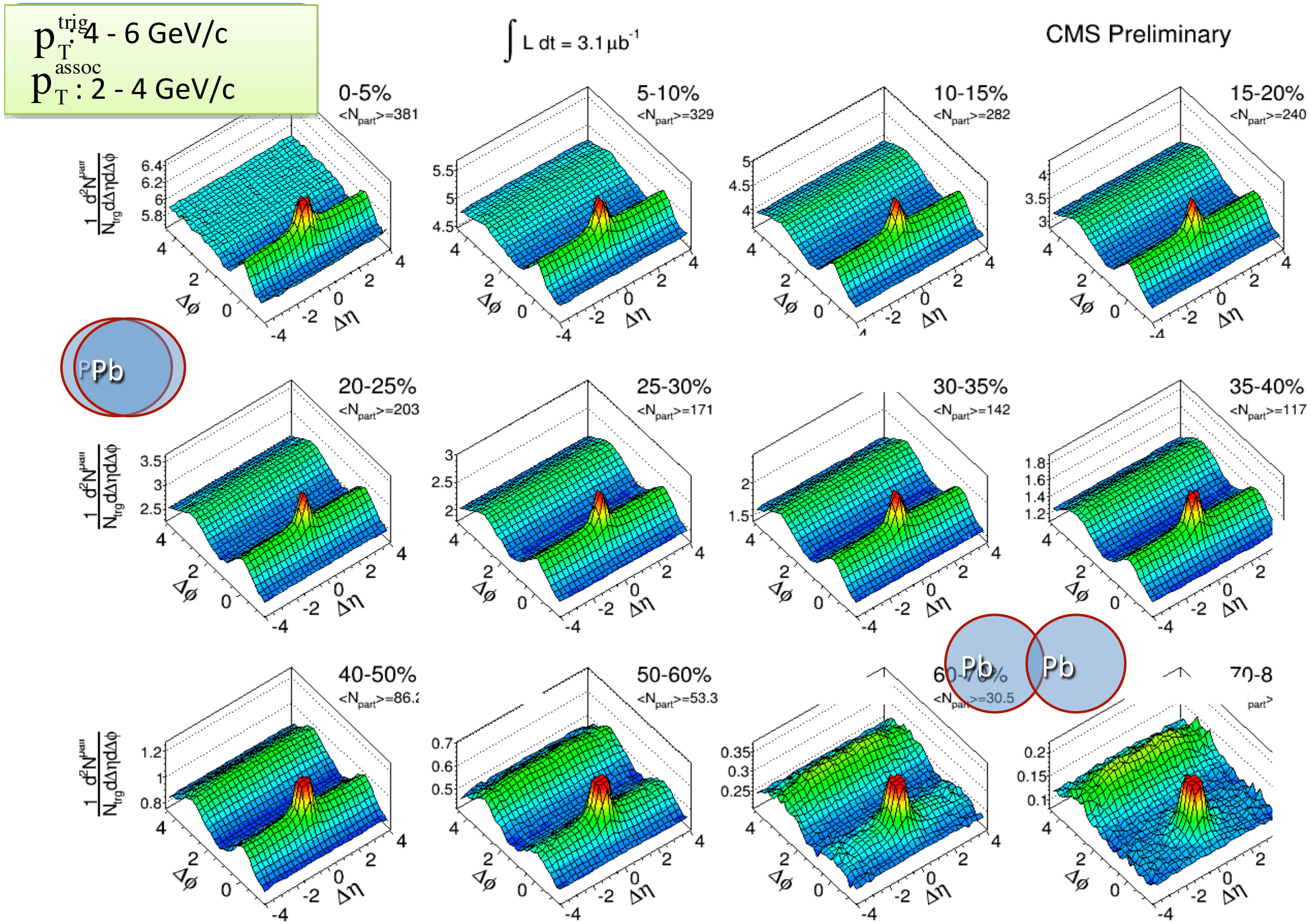


- **Short** & **long range** correlations studied for different p_T^{trig}.
- **Long range** correlations: large deviation from predictions (No ridge in MC).
- **Ridge effect maximal for $p_T^{trig} \approx$ 2-6 GeV then it does disappear beyond 10 GeV. (also in pp)**

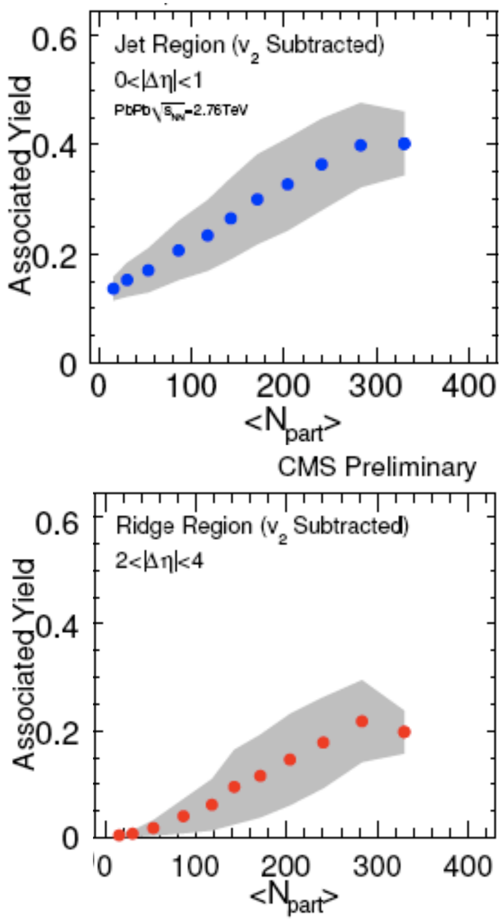
[HIN-11-001]

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.

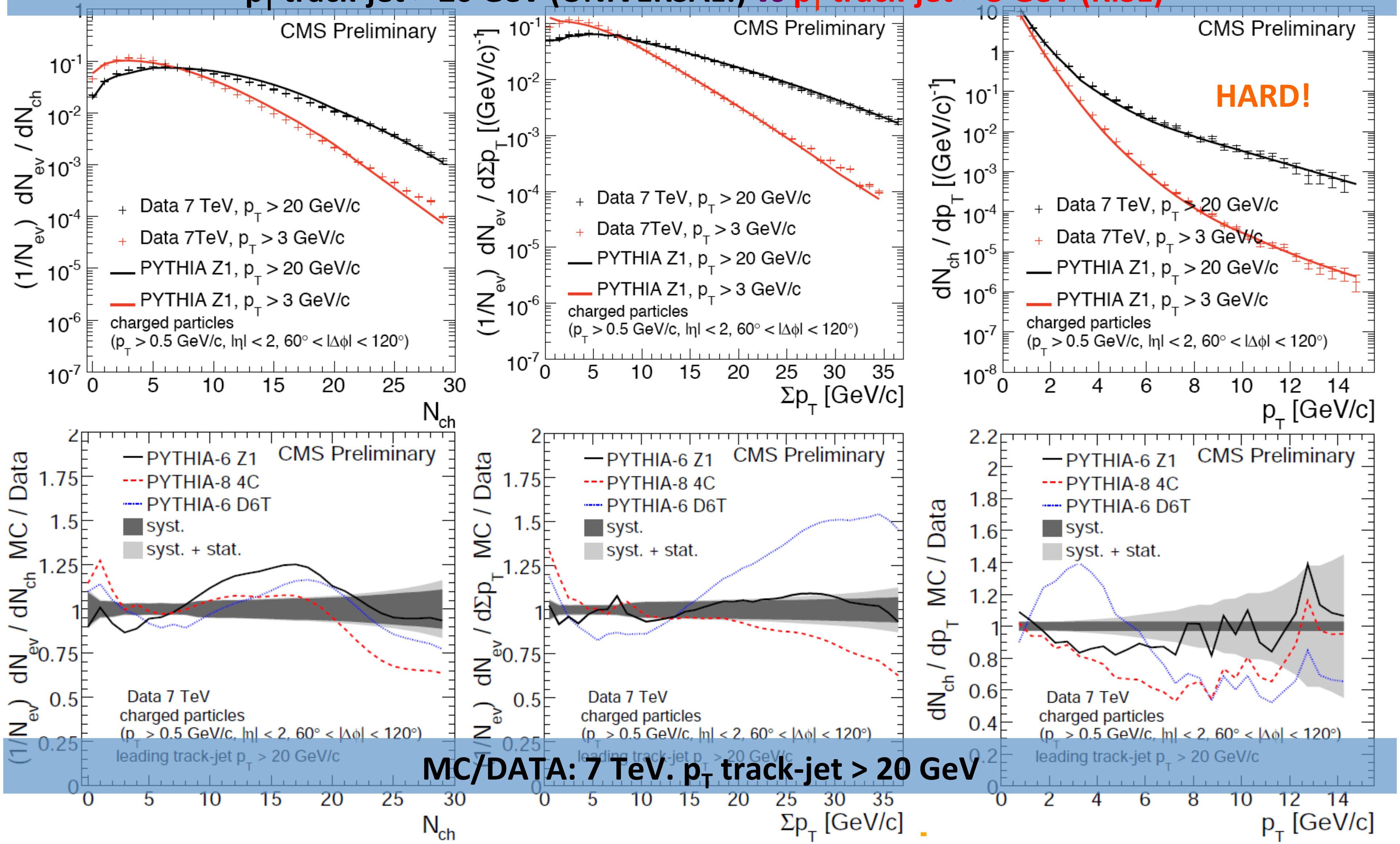


[HIN-11-006]

- UE

UE in Jets: $\sqrt{s}$ = 7 TeV. N_{ch}, $\Sigma(p_T)$ and p_T in Transverse Region

p_T track-jet > 20 GeV (UNIVERSAL!) vs p_T track-jet > 3 GeV (RISE)



MC/DATA: 7 TeV. p_T track-jet > 20 GeV

- DPS

CMS: DPS - four jets

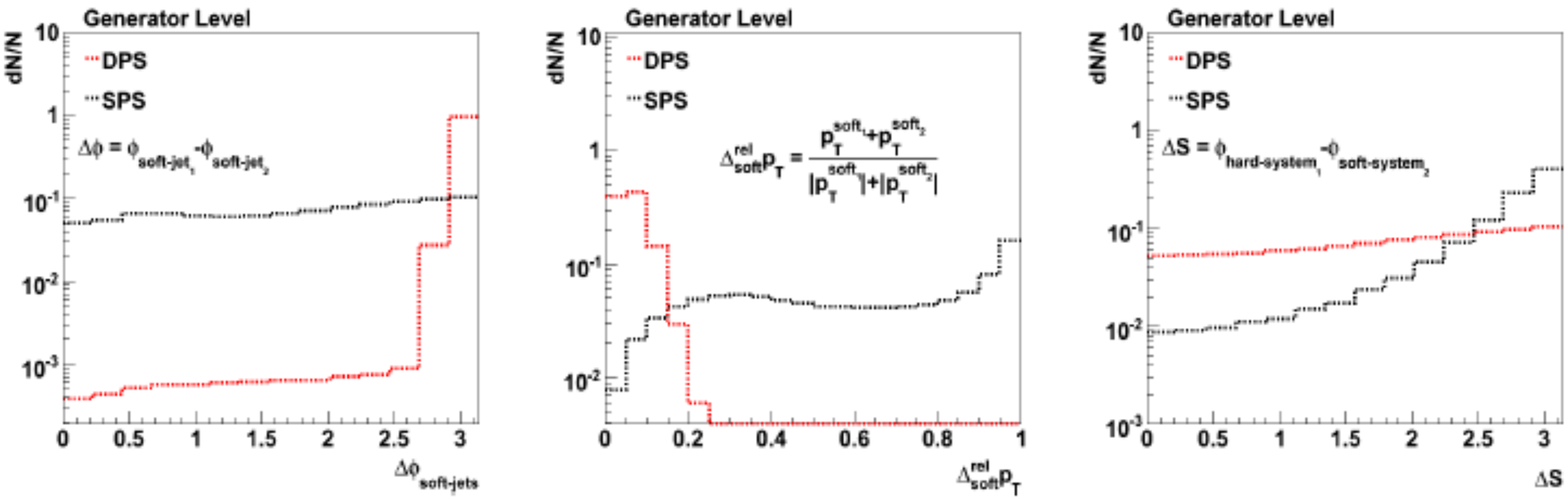
Which regions of the phase space are interesting for DPS detection?

Studies of SPS and DPS contributions performed with PYTHIA8 generator tune 4C:

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

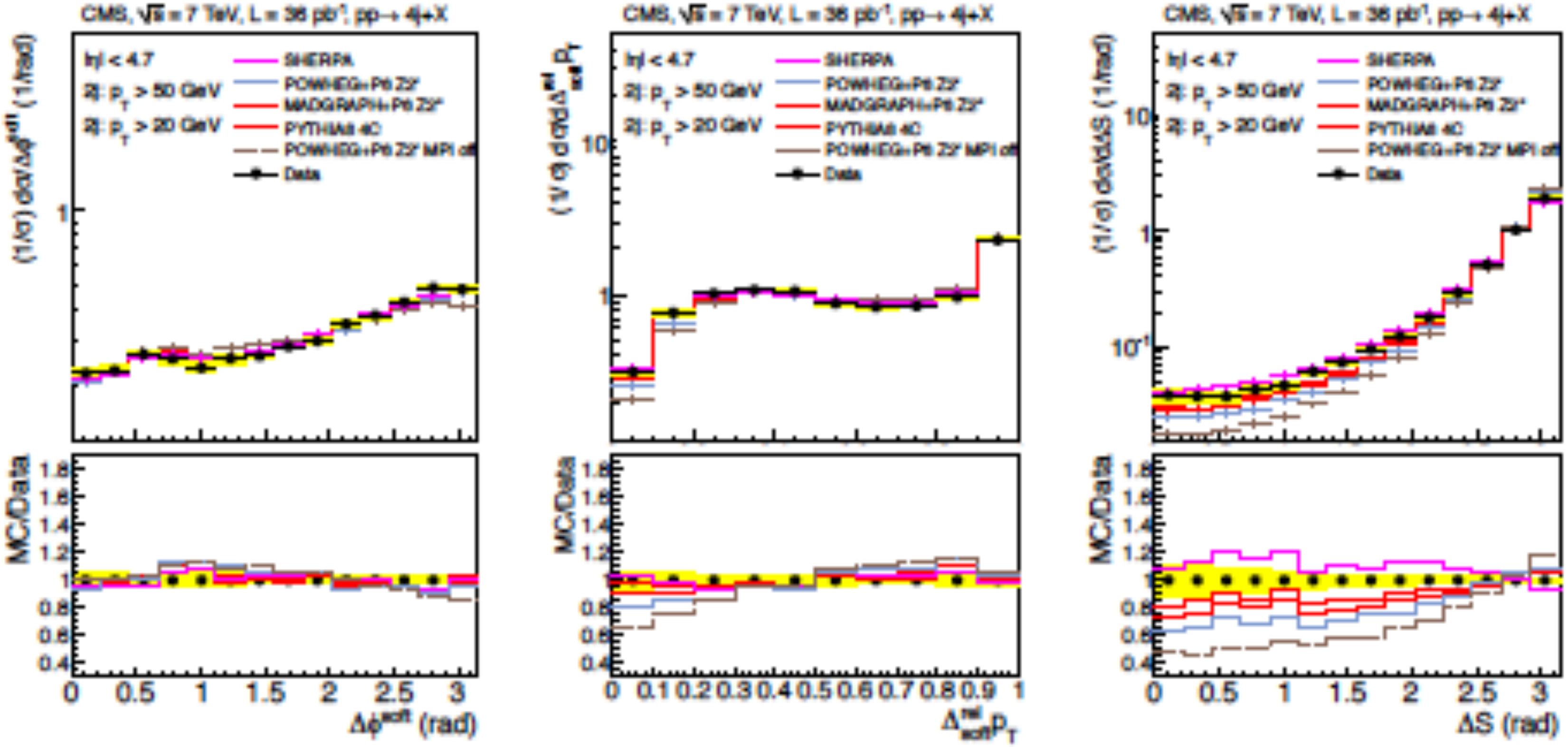


- Discriminating power: The two processes exhibit different shapes and specific regions of the phase space can be exploited to extract the DPS contribution

CMS: DPS - four jets

Normalized distributions are useful to constrain systematics

$\Delta\phi(j_i,j_k) = \phi_i - \phi_k$ $\quad \Delta^{rel}_{soft}p_T = \dfrac{|p_T(j_i,j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$ $\quad \Delta S = \arccos\left(\dfrac{\vec{p}_T(j^i,j^k)\cdot\vec{p}_T(j^l,j^m)}{|\vec{p}_T(j^i,j^k)|\cdot|\vec{p}_T(j^l,j^m)|}\right)$



- No significant differences in $\Delta\phi$ and $\Delta^{rel}_{soft}p_T$ among generators
- POWHEG w/o MPI is far below for $\Delta^{rel}_{soft}p_T$ and ΔS
- SHERPA and PYTHIA8 perform best for ΔS
- ΔS and $\Delta^{rel}_{soft}p_T$ sensitive to MPI contribution: ROOM for DPS!

CMS: W $\rightarrow$ lν + 2 jets – DPS fraction in data

→ Background templates; remove events which have leading MPI partons $|\eta| < 2$.

→ Simultaneous fit of $\Delta^{rel} p_T$ and ΔS, effect of correlation is small (less than 5%).

→ DPS fraction in data is measured to be:

$$f_{DPS} = 0.055 \pm 0.002\ (\text{stat.}) \pm 0.014\ (\text{syst.})$$

→ Dominated by systematic uncertainties (next slide).

CMS: W → $l\nu$ + 2 jets – Uncertainty on f_{DPS}

- Signal templates:
  - different MCs for dijet events.
  - template with Pythia8, to see effect of momentum conservation and color reconnection.
- Background templates:
  - different MCs i.e. MadGraph + Pythia6 Z2*, Powheg + Pythia6 Z2*, and Powheg + Herwig6
  - renormalization and factorization scale (by a factor 2)
  - matching scale (15-25 GeV)
- Limited MC stat.
- Systematic on the corrected distributions
- PDFs

Systematic uncertainties

Source	Uncertainty (%)
Signal template	9
Background template	20
PDFs	5
Limited MC statistics	5
Uncertainty in corrected data	10
Total	25

CMS: W → lν + 2 jets – Measurement of R

- pp @ 7 TeV, integrated luminosity 5 fb^{-1}
- R, ratio of W + 0-jet and W + 2-jet events
- Corrected to particle level using MadGraph + Pythia6
- Measured value of R (at particle level) is:

  27.8 ± 0.2 (stat.) ± 3.3 (syst.)

- Consistent with MC predictions.

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

Systematic uncertainties (%)

Source	Uncertainty (%)
Model dependence	9
JES	7
JER	2
Background	2
Pileup	1
Total	12

arXiv:1312.5729.

Inferring the DPS content: EXP and TH guidelines

Connection to the DPS theory

- The effective x-section (σ_{eff}) should be regarded as the most natural link to the theories.
- √s and scale (in)dependency should not be assumed, it should rather be tested/measured although the first benchmark measurements should focus on simple working points.
- Process dependency is studied regarding 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!

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

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

- It is desirable to have more generator level studies to quote the effect of extra-emissions (Matrix Element tools) and softer showers: how DPS signals are diluted?
- At the same time it is ESSENTIAL to use appropriate DPS SIGNAL (Pythia8, Herwig++, etc.).
- BACKGROUND **IS NOT** **MPI OFF** **IT IS RATHER** **"2nd interaction below a given p_T".**
- **ALWAYS MAKE SURE** that SIGNAL+BACKGROUND(S) cover the full phase space.

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

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 billions 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, as stressed in slide 3, 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, this is a serious issue as most of the events we currently use in CMS are ME + Pythia 6.
- 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 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.