Battaglia del Trasimeno - Bernabei (1527)

Multiple Parton Interactions

- first LHC run -

Livio Fano'
Università degli Studi di Perugia e INFN

First Italian Workshop on Hadron Physics and Non-Perturbative QCD - Cortona

Motivations for MPI

1. Multiplicities

Phenomenology/Characterization:

2. "Soft" - MPI
3. "Hard" - MPI (Double Parton Scattering)
4. Correlations

Conclusions/Highlights

Motivations for MPI

1. Multiplicities

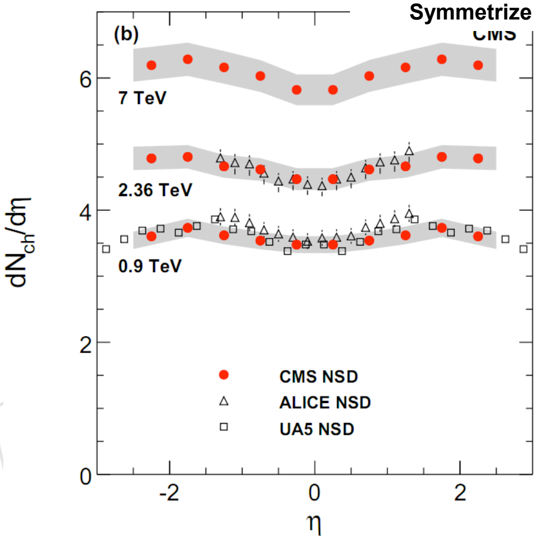
Phenomenology/Characterization:

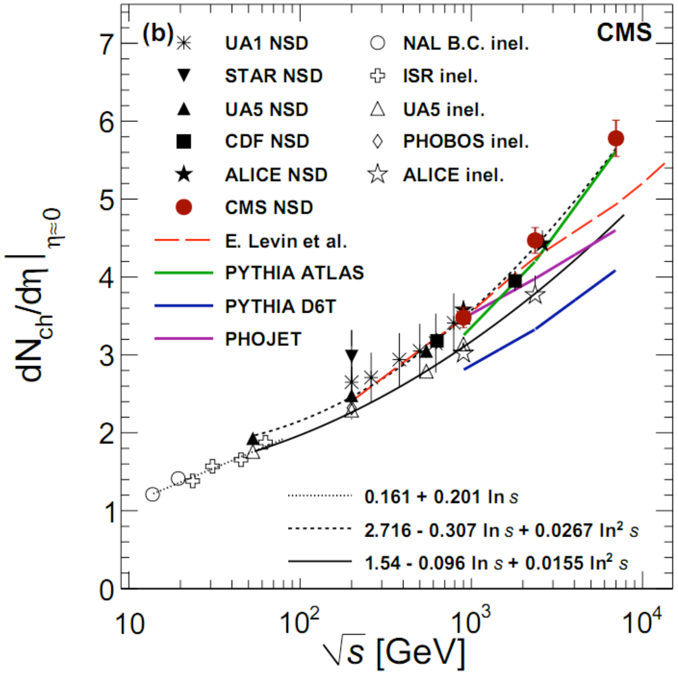
2. "Soft" - Stefano Camarda
3. "Hard" - Paolo Gunnellini
4.

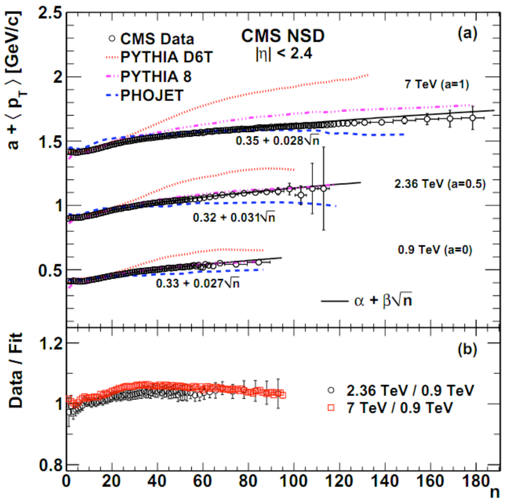
Fiorella Fionda

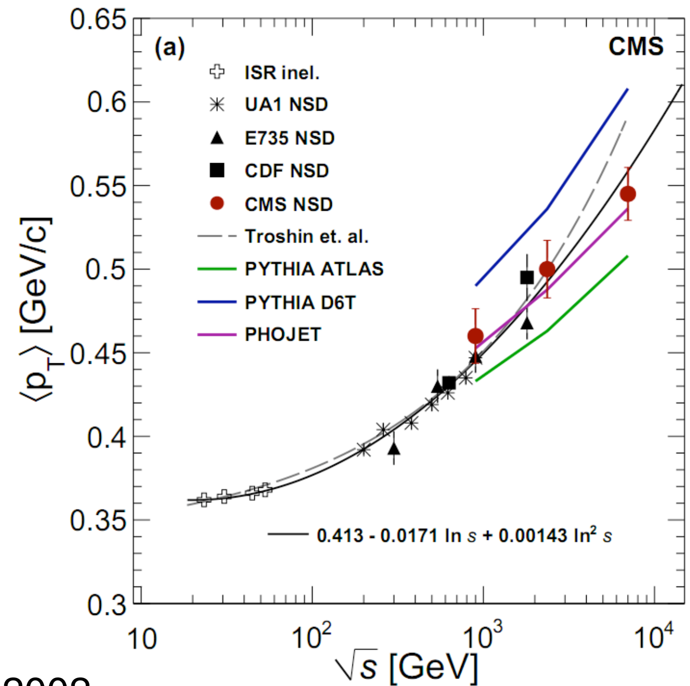
Conclusions/Highlights

Pseudorapidity and pT distribution









Most models are not able to describe simultaneously both energy evolution in $\rho(0)$ and $\langle p_T \rangle$

Why do these quantities rise faster than ln(s) ?

Solution: Multiple Parton Interactions

[T. Sjöstrand et al. PRD 36 (1987) 2019]

Introduce IP correlations in MPI

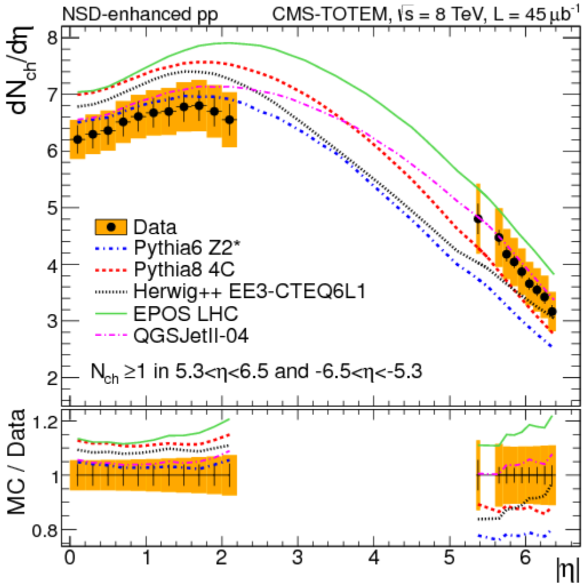
Turn off of the cross section at P_T cut-off

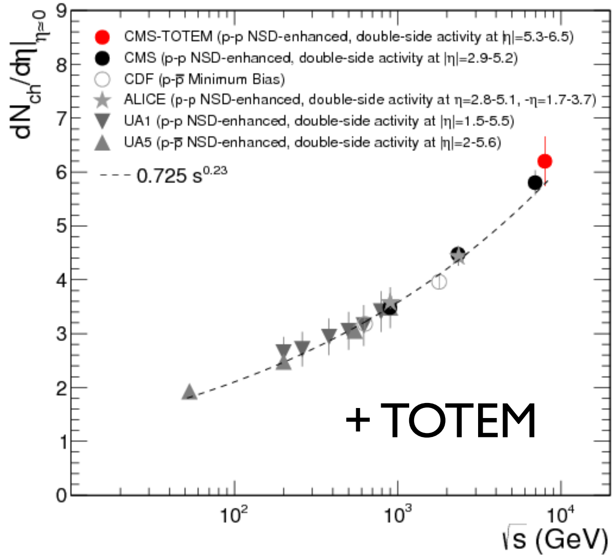
$$\langle N_{MPI} \rangle = \sigma_{parton\text{-}parton} / \sigma_{proton\text{-}proton}$$

JHEP 02 (2010) 041

Phys. Rev. Lett. 105 (2010) 022002

Pseudorapidity and pT distribution

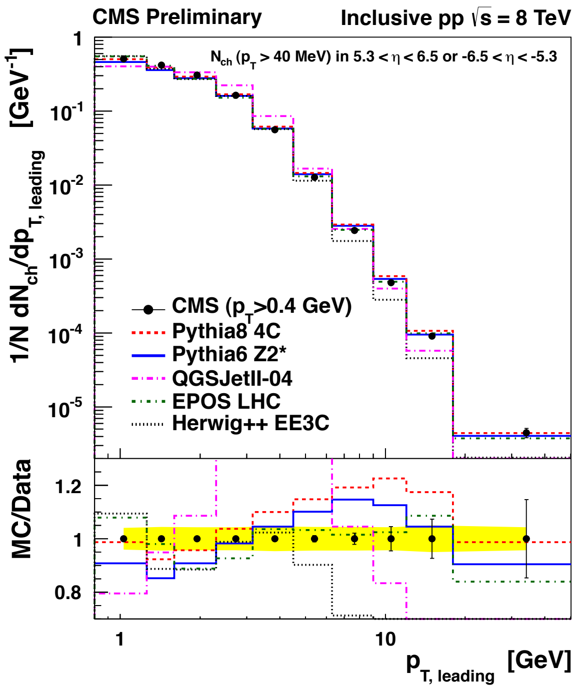




QCD radiation violates Feynman scaling at high energies

even when assuming Feynman scaling, the possibility of creating more strings in **MPI** gives rise of ρ(0) stronger than ln(s)

8 TeV - NSD Enhanced



Z-generation pythia, tuned on MPI observables, does the best job in central region but fails forward

$< p_T >$ is energy independent for soft processes, raise in hard processes:

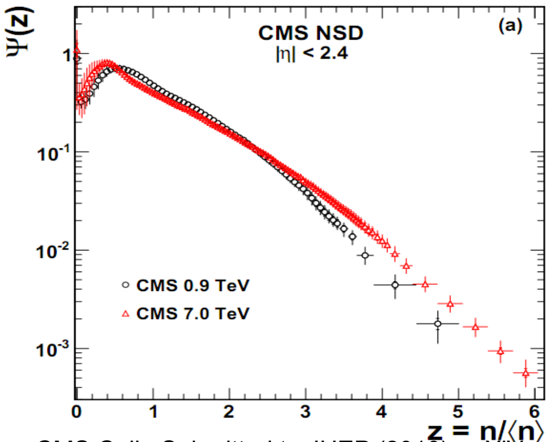
- production of jets in hard scatters
- and **MPI**

Eur.Phys.J. C74 (2014) 10, 3053

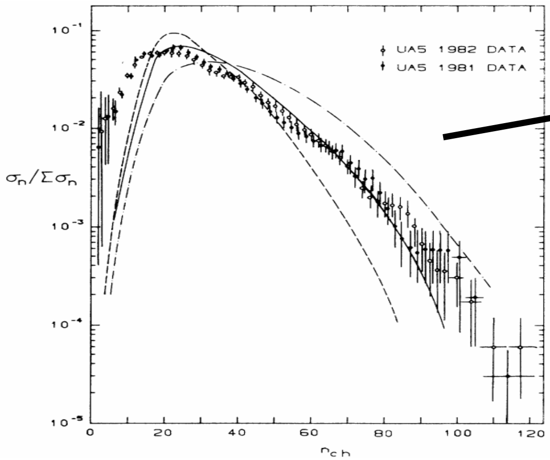
Multiplicities and KNO scaling

KNO (Koba-Nielsen-Olesen) Scaling is not a consequence of Feynman scaling, but of hadrons produced by the self-similar branching of a single string

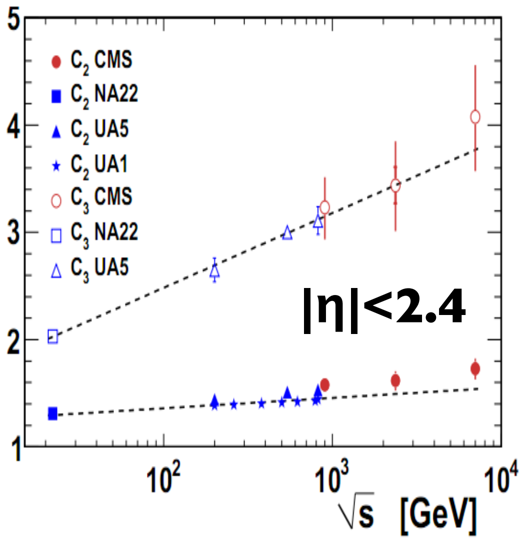
Strong KNO scaling violation in intermediate-range of pseudorapidity intervals is an **indication of MPI**

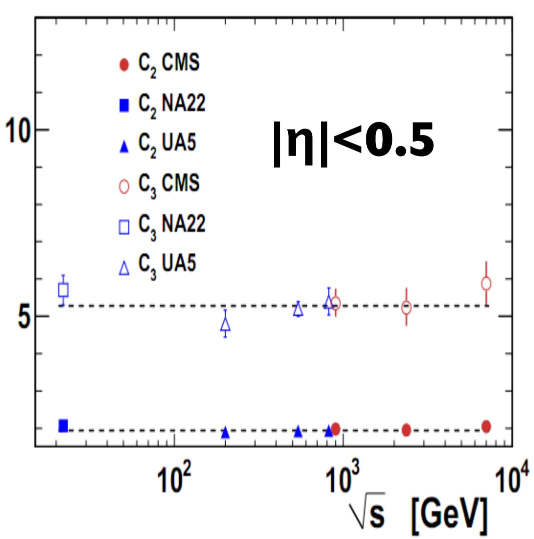


CMS Coll., Submitted to JHEP (2010), arXiV



Interpretation of UA5 540 GeV data:
T. Sjostrand and M. van Zijl,
Phys. Rev. D36(1987) 2019



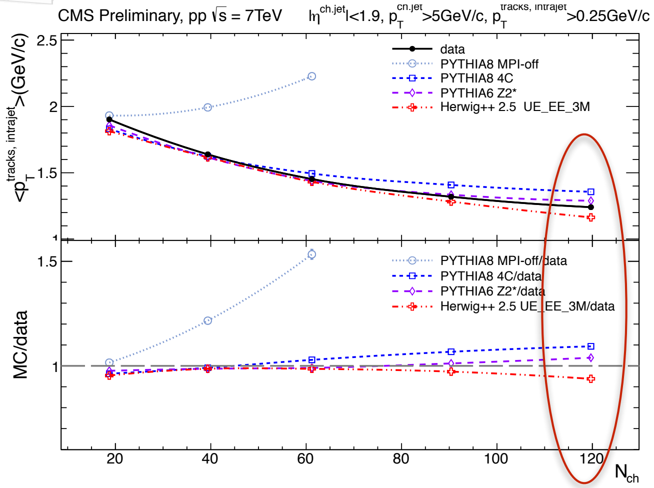


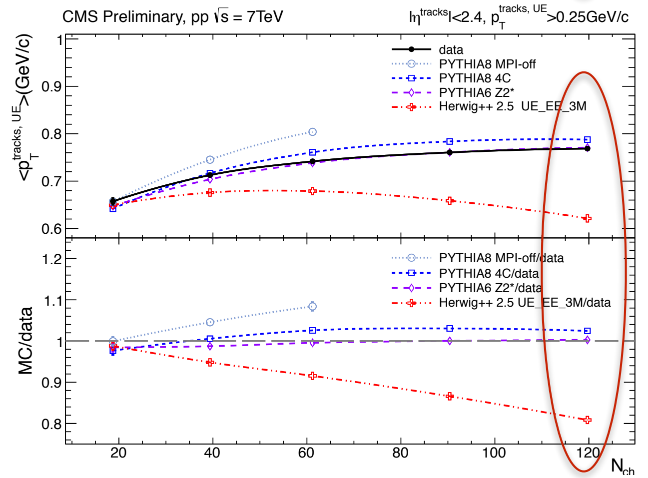
$$C_q = \frac{\langle n^q \rangle}{\langle n \rangle^q}$$

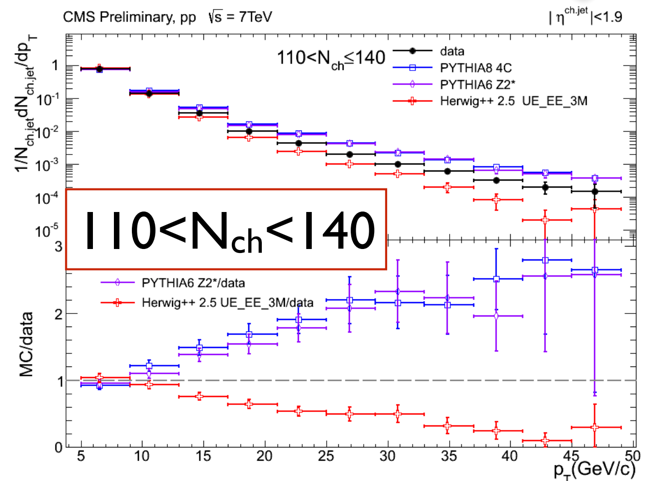
Increase with s indicates KNO scaling violation

KNO scaling holds for small rapidity intervals

charged energy in/out track-jet definition







good agreement with MPI (pQCD model) prediction (especially Z-generation tunes) for charged inside and outside jet

Intra-jet flow turns out to be well described by pQCD MPI models (start diverging at large N_{ch})

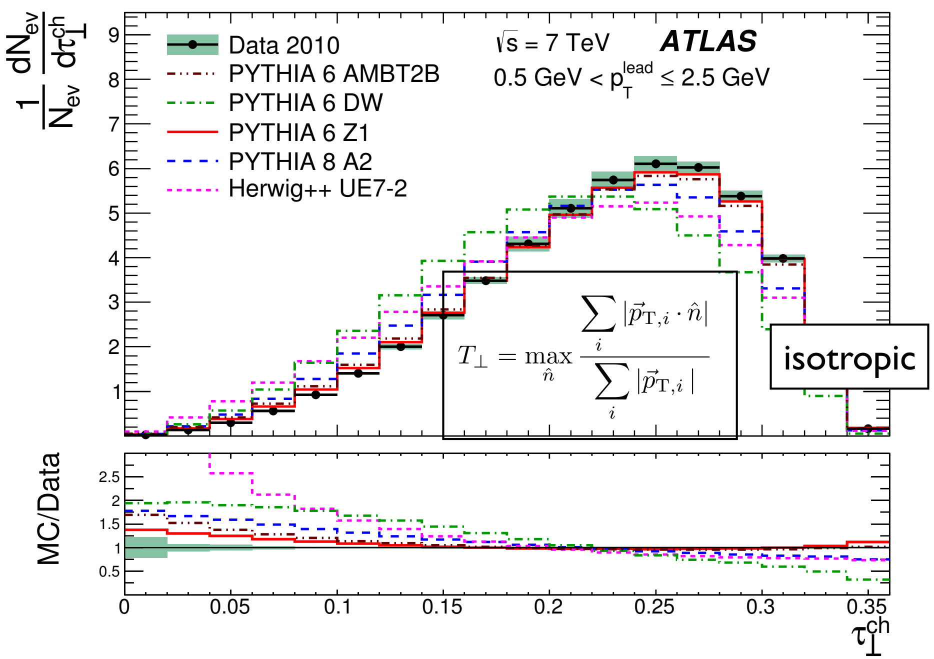
After removing all intra-jet particles from the event, the remaining particles are considered as belonging to the underlying event.

for **high-multiplicity events**, PYTHIA predicts **higher jet rates** and harder pT spectra whereas HERWIG shows the opposite trend

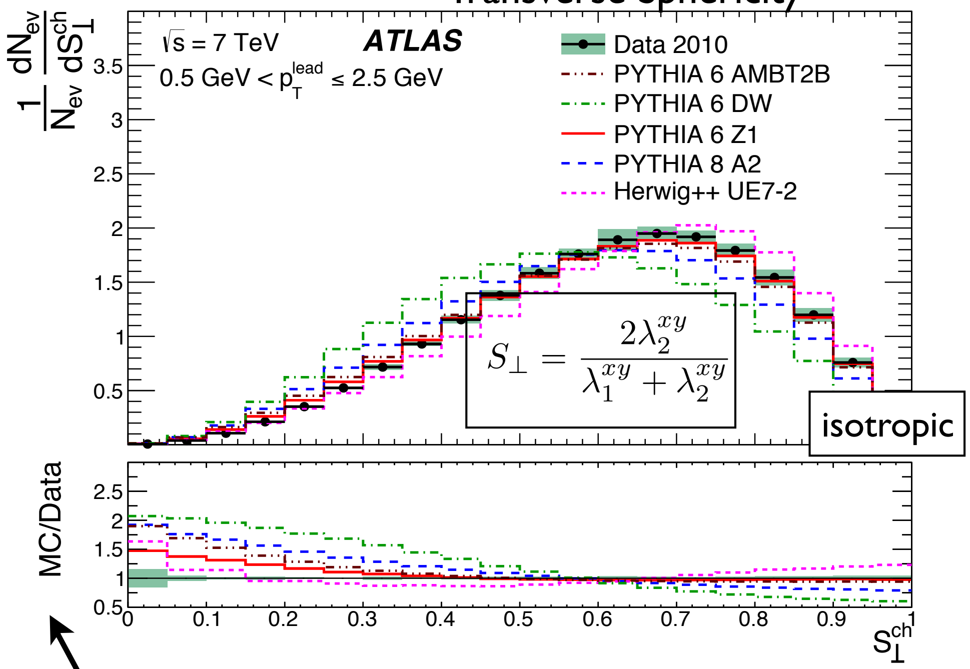
Eur.Phys.J. C73 (2013) 2674

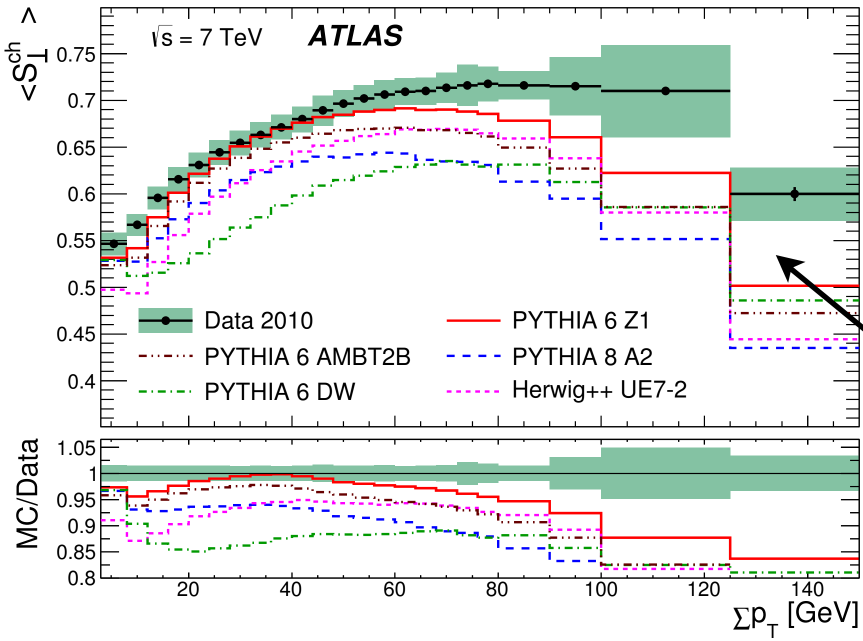
Event Shapes

1-Transverse Thrust



Transverse Sphericity





prevalence of spherical events

Z-generation Pythia Tune provide the best description

all models fail in reproducing shapes at high pTsum (and high multiplicity events - next slide)

ATLAS, Phys. Rev. D 88, 032004 (2013)

Transverse Sphericity

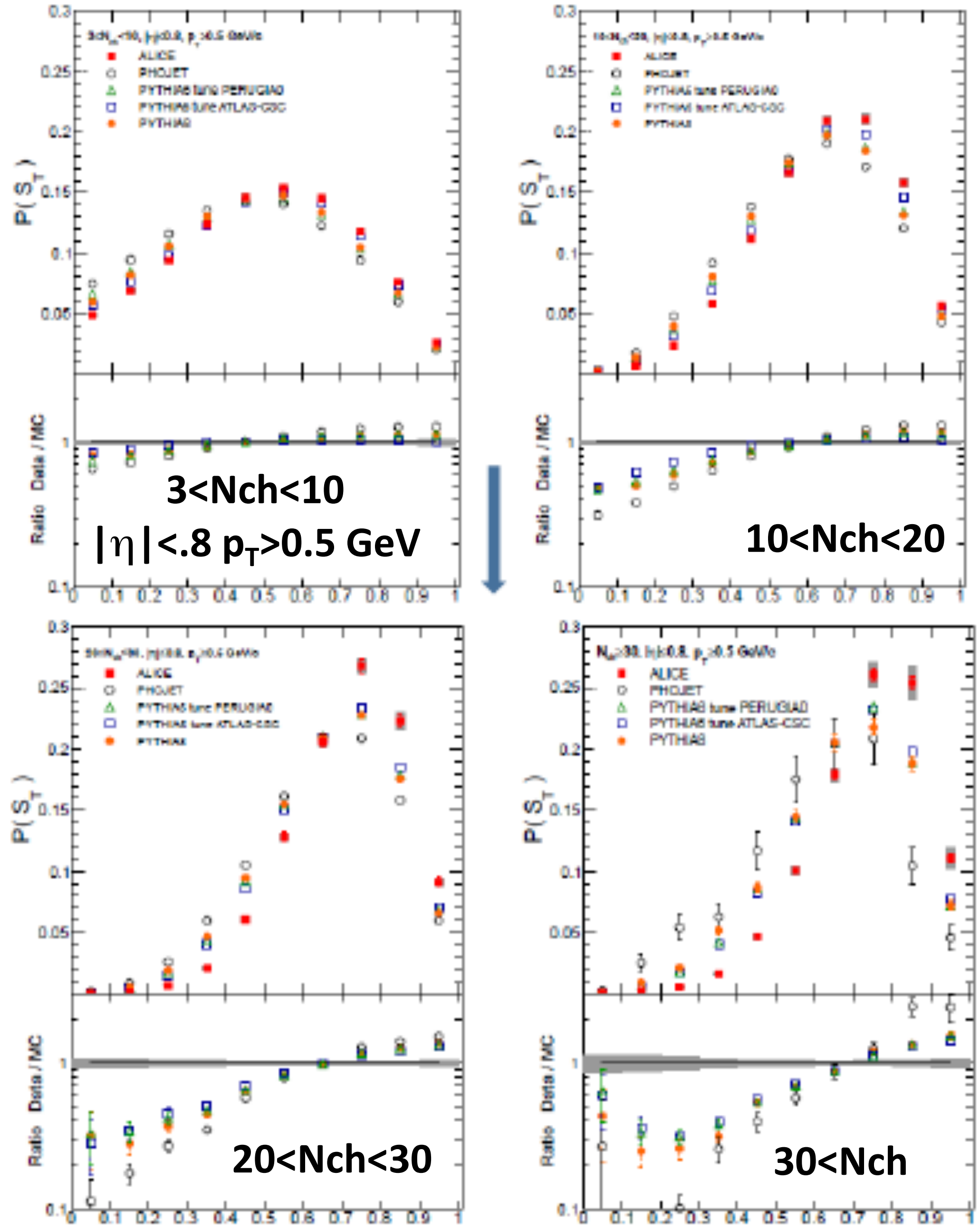
$S_T \approx 0$ jetty events

$S_T \approx 1$ 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 very correlated to N_{MPI} may provide additional handles to study large multiplicity features.



ALICE, Eur.Phys.J. C72 (2012) 2124

Section 1 - multiplicities

Energy evolution in $\rho(0)$ and $<p_T>$ as well as KNO violation, modeled by MPI

< pT > vs Nch is also very well described in both the intra-jet and the UE: <pT> of jet constituents decrease with N_{ch} while it smoothly rises in UE constituents.

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.

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

Herwig++ provides additional proofs that $dN_{ch}/d\eta$ shapes and <pT> vs Nch normalization favor implementation of color reconnections in MPI models

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

Strong indication of the role played by MPI
a focussed investigations is needed

The MPI@LHC forum is a consequence of a series of WS
[Perugia 2008, Glasgow 2010, DESY 2011, CERN 2012, Antwerpen 2013, Krakow 2014]
aiming to:

Bring Exp and Theo communities on the same topic
Setup a characterization program for LHC

Soft MPI phenomenology → Underlying Event
Hard MPI phenomenology → Double Parton Scattering

Section 1 - multiplicities

Energy evolution in $\rho(0)$ and $\langle p_T \rangle$ as well as KNO violation, modeled by MPI

Strong indication of the role played by MPI

a focussed investigations is needed

$\langle pT \rangle$ vs Nch is also very well described in both the intra-jet and the UE: $\langle pT \rangle$ of jet ... ses in UE constituents.

High multiplicity events turn out to be much less jetty than predicted by Pythia.

The MPI@LHC forum is a consequence of a series of WS

[Perugia 2008, Glasg ... 4]

aiming to:

Bring Exp and ...

Setup a chara...

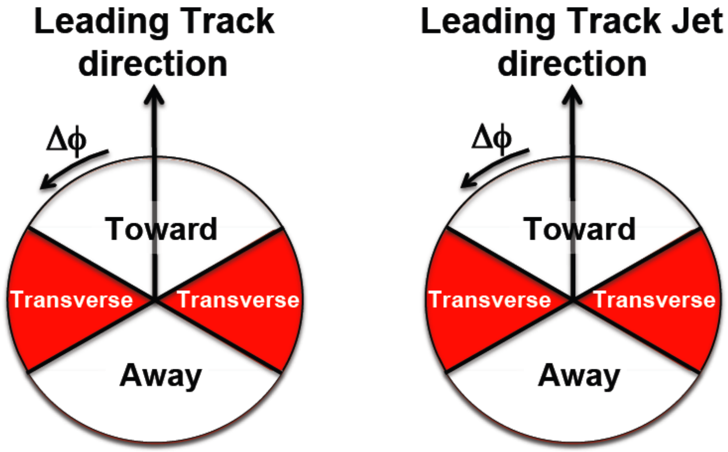
Multi-Parton Interactions at the LHC - 2015 (MPI@LHC)
will take place at the ICTP, Trieste, Italy
November 23 to 27, 2015.

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

Soft MPI phenomenology → Underlying Event

Hard MPI phenomenology → Double Parton Scattering

Section 2 - Underlying Event



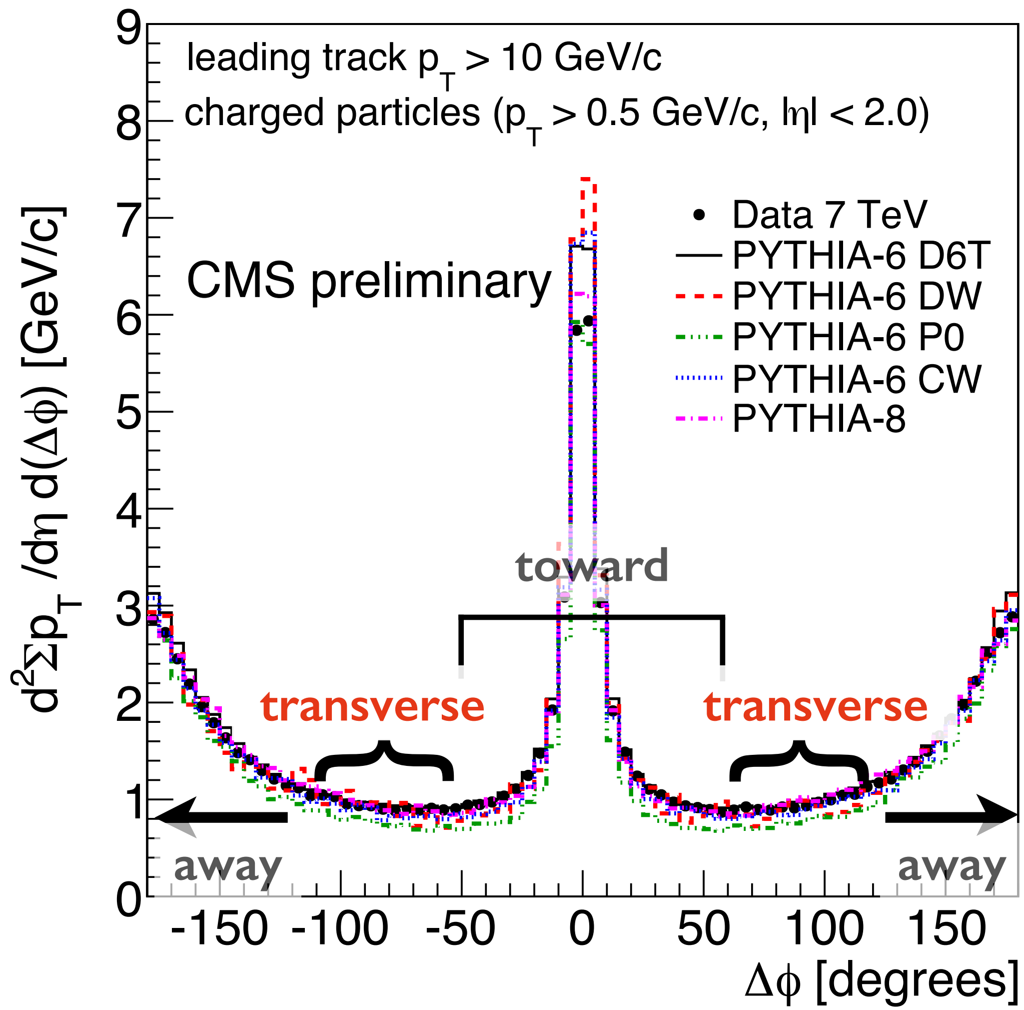
Traditional approach (R. Field)

Leading Track or Leading Track-Jet define a direction in the phi plane for the Hard Scatter

Track or Track-jet pT provide an energy scale

Observables are built from tracks:

- $d^2N_{ch}/d\eta d\phi$ - multiplicity density
- $d^2\Sigma p_T/d\eta d\phi$ - energy density

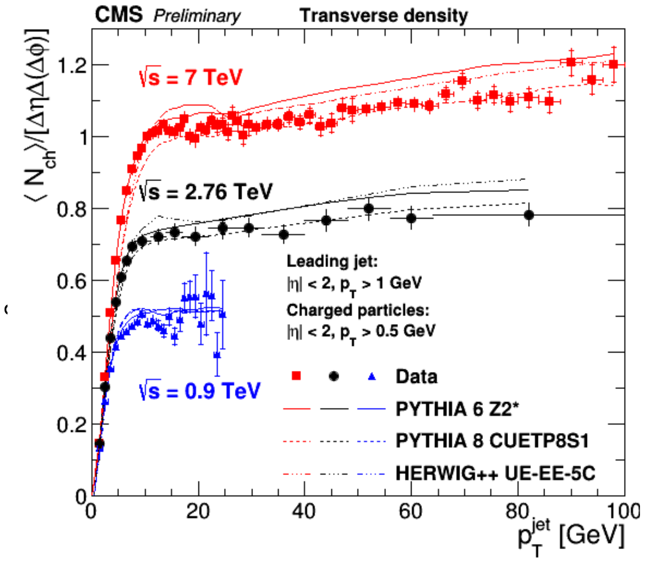


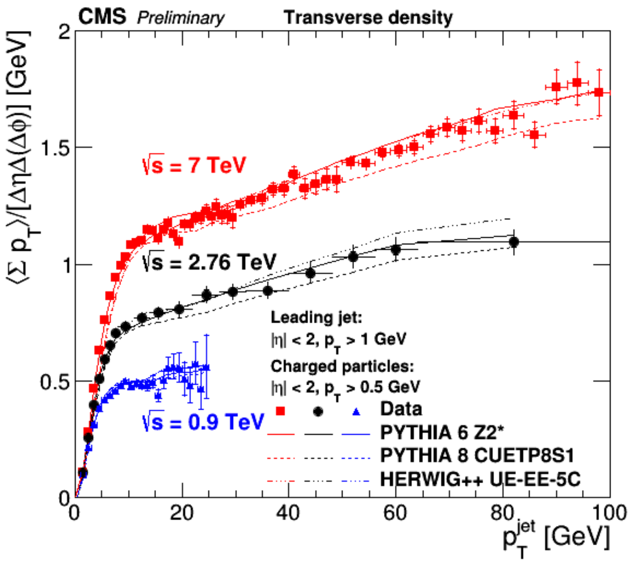
900 GeV - Eur.Phys.J.C70:555-572,2010
7 TeV - JHEP09 (2011) 109

Observables can be defined using Δφ correlations relative to main activity

Transverse region is expected to be sensitive to the UE

The transverse region - jet events



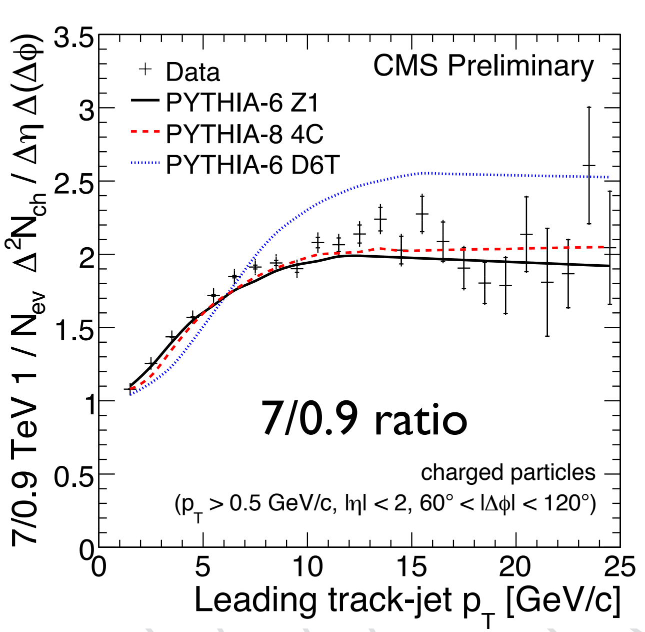


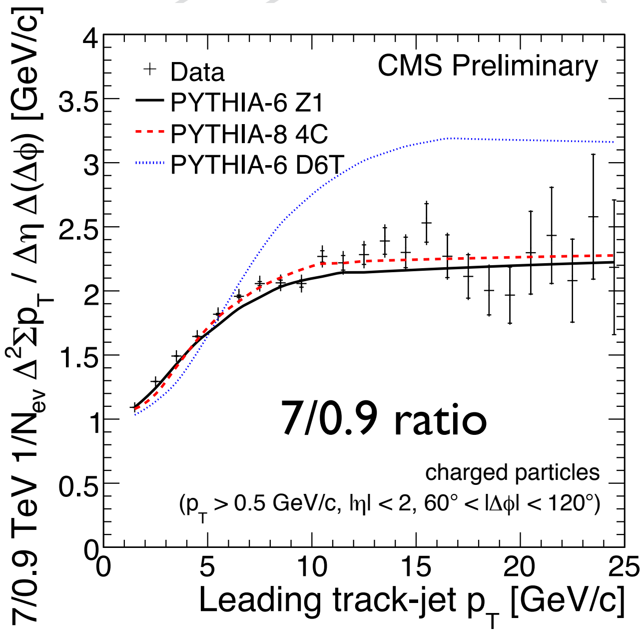
Leading track-jet p_T [GeV/c] Leading track-jet p_T [GeV/c]

Fast rise for pT< 4-8 GeV/c due to the increase of the MPI activity

Plateau region with ~constant charged density and slow increase of pT_sum in a saturation regime

Increase of the activity with √S → more MPI



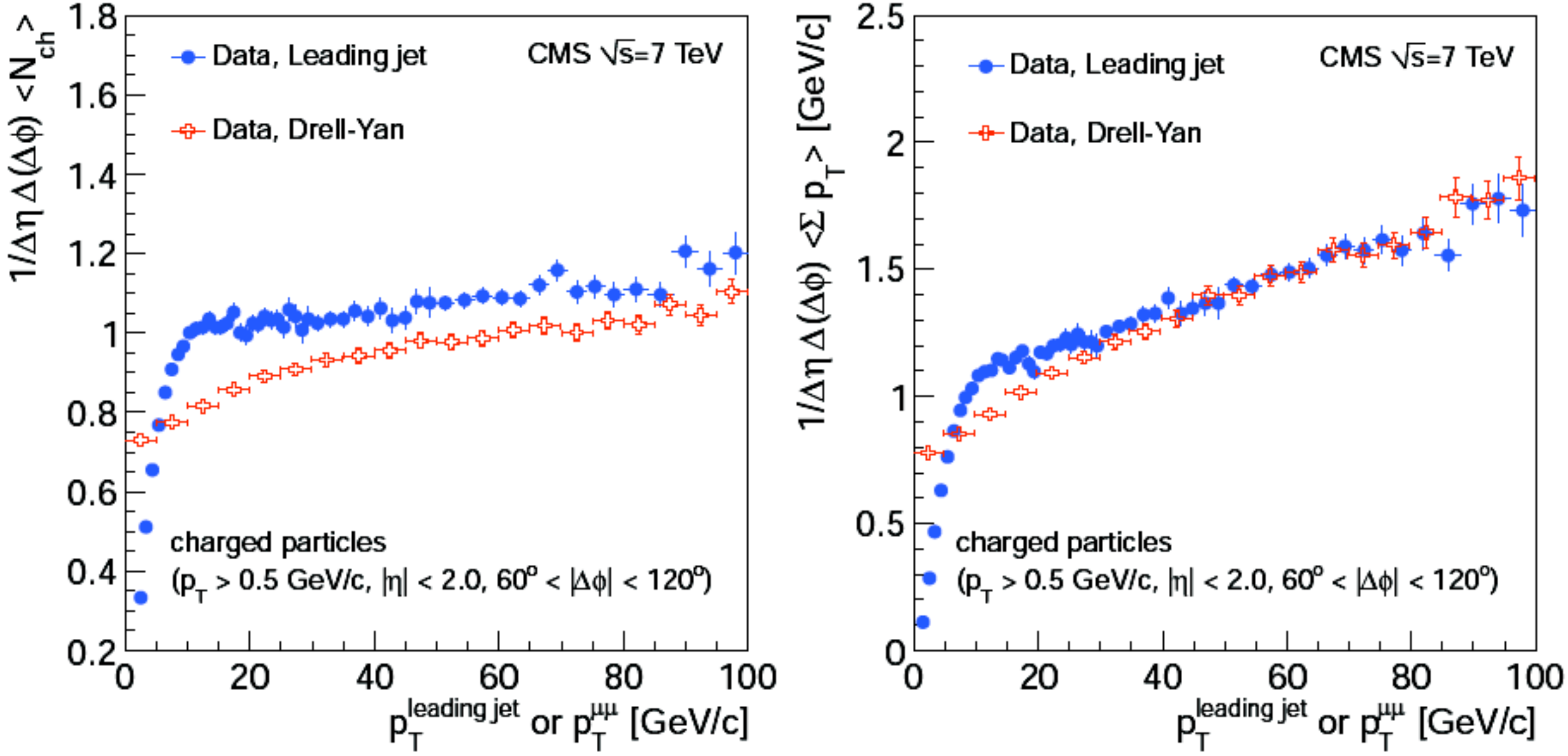


Fast rise:
peripheral collision
weakly dependent on $\sqrt{s}$

Plateau:
mainly central collisions
The ratio reflects the ratio of the sizes of the central, high parton density regions for the two $\sqrt{s}$ domains

JHEP09 (2011) 109 - PAS FSQ-12-025 (JHEP)

The transverse region - Drell-Yan events



+ **Hard energy scale (81 < $M_{\mu\mu}$ < 101 GeV/c²)**:

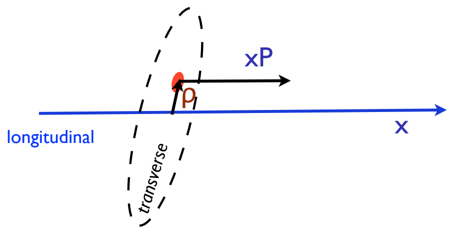
no sharply rising part only the slow growth due to the ISR

+ For $p_T^{\mu\mu}$ and leading $p_T^{\text{leading jet}}$ > 10 GeV/c DY events have a smaller particle density with a harder p_T due to the presence of **only ISR initiated by quarks**
[Hadronic events have both initial and final state radiation predominantly initiated by gluons]

Eur. Phys. J. C 72 (2012) 2080

Transverse activity interpretation

M. Strikman et al. - "Transverse nucleon structure and diagnostics of hard parton-parton processes at LHC"
[Phys. Rev. D83 (2011) 054012]



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

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

gluon transverse size decreases with increasing x

pT_crit, indicates the critical value of pT above which particle production is dominated by hard parton–parton processes

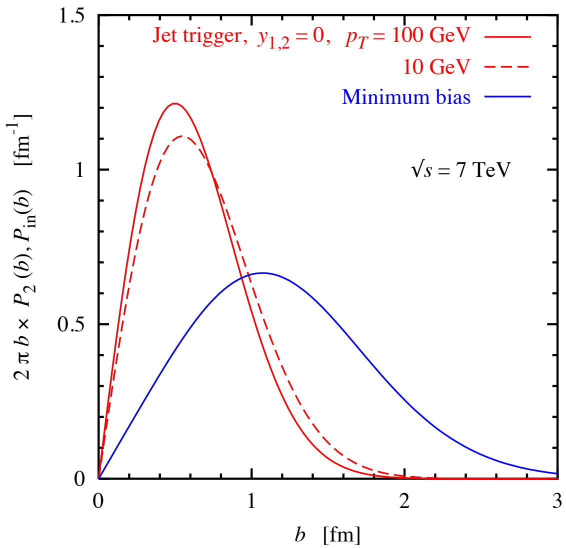
helpful to explain:

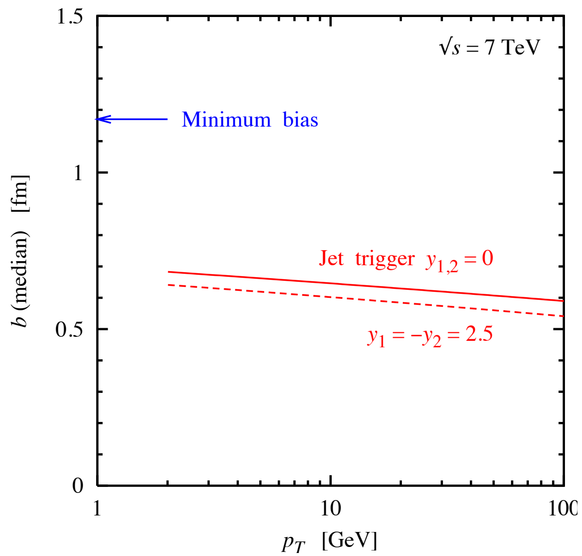
+ general UE feature

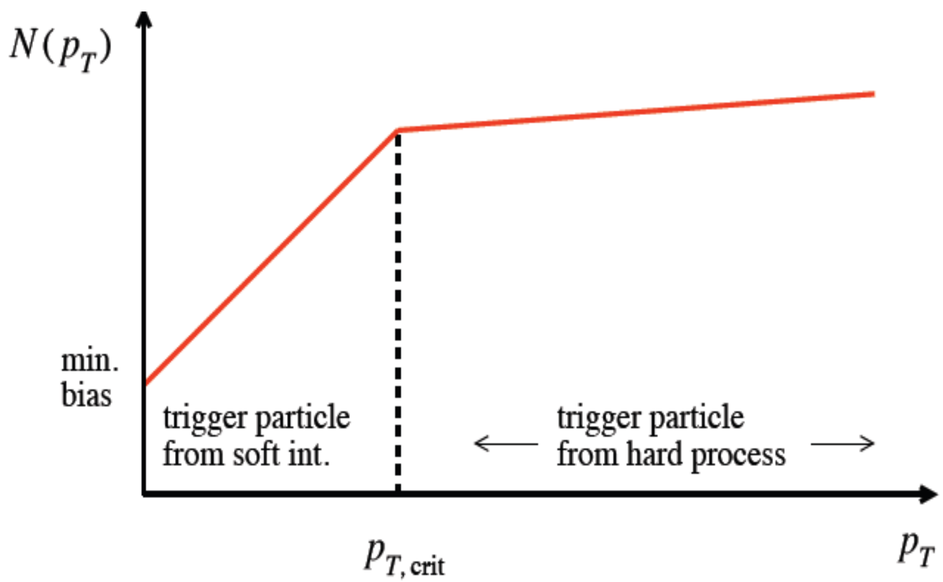
+ $<\rho^2>_g$ < $<\rho^2>_q$
UE in DY < UE in Jets

2 scale picture

$$N(p_T) = \lambda_{\text{hard}}(p_T) N_{\text{hard}} + [1 - \lambda_{\text{hard}}(p_T)] N_{\text{soft}}$$







Section 2 - soft MPI

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 larger MPI multiplicity.

Single scale picture (plateau) in the case of DY

Interpretation: DY events always select central collisions hence large MPI multiplicity.

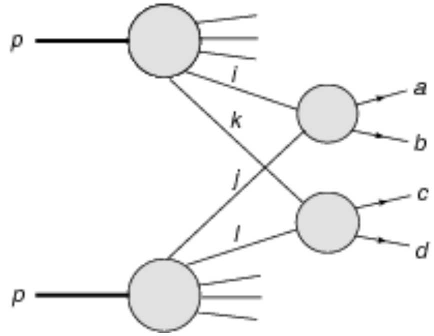
Connection to $\langle\rho^2\rangle_g / \langle\rho^2\rangle_q$

no FSR $\rightarrow$ lower multiplicity, harder fragmentation

Section 3 - Double Parton Scattering

Double high P_T interactions observed 30 years ago by AFS, UA2 in 4jets topologies

20-10 years ago CDF and D0 used also 3jet + γ



$$\sigma(A+B) = m * \sigma(A) * \sigma(B) / \sigma_{eff}$$

(m = ½ for identical interactions, m = 1 otherwise) - P(B|A) = P(B) * ($\sigma_{Non\text{-}Diffractive}/\sigma_{eff}$)

naïve prediction: $\sigma_{eff} \approx 1/\pi R_{EM}^2 \approx 60$ mb

$\sigma_{eff} \approx$ (process,) scale and $\sqrt{s}$ independent [D. Treleani et al., very rich bibliography]

σ_{eff} mostly depends on geometry

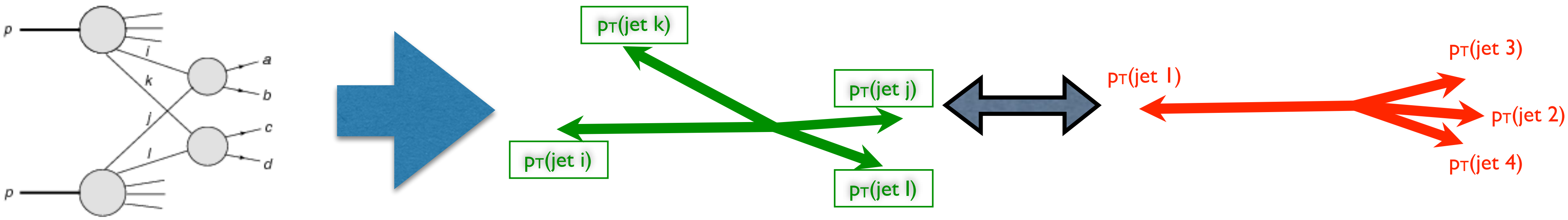
$\sigma_{eff} \approx 34$ mb considering 4 → 4 processes [M. Strikman et al.]

3 in 4 processes give significant contributions, rising with $x_{Bjorken}$ [B.Blok, MPI@LHC 2013]

Pythia 6 and Pythia 8: $\sigma_{eff} = \sigma_{Non\text{-}Diffractive} / \langle f_{impact} \rangle \sim 20\text{-}30$ mb

where $\langle f_{impact} \rangle$ is tune dependent → soft MPI tunes: $\sigma_{eff} \approx 20\div30$ mb

Experiments - Double Parton Scattering

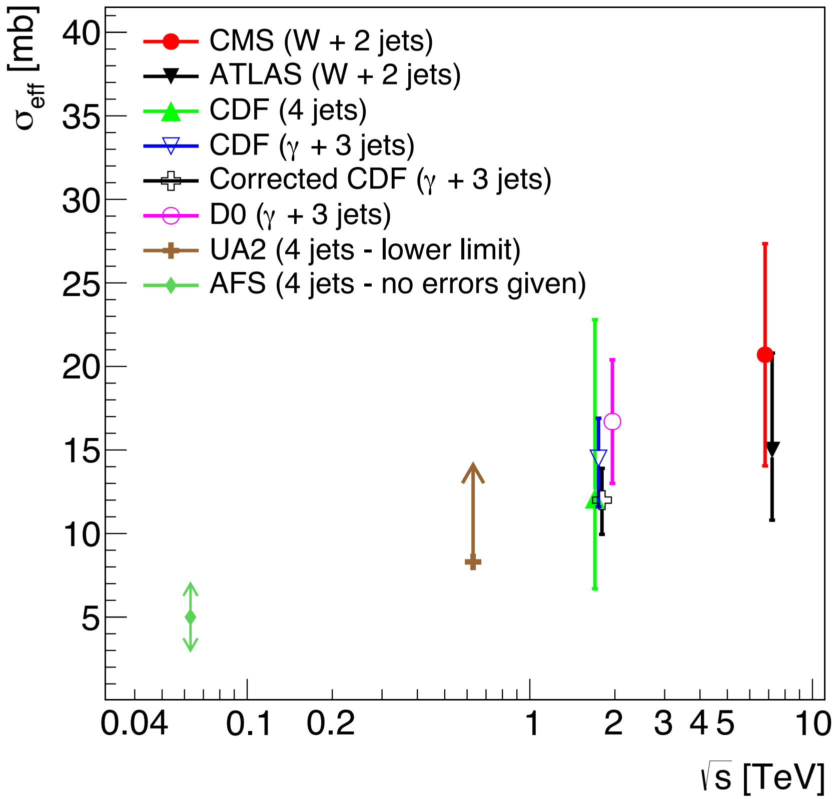


$\sigma_{eff} \approx$ 10÷20 mb (Tevatron+LHC)
lowest figures at Tevatron (3jet+γ)
higher figures from LHC (W+2jet)

from previous slide, prediction on $\sigma_{eff} \approx$ 20÷60 mb

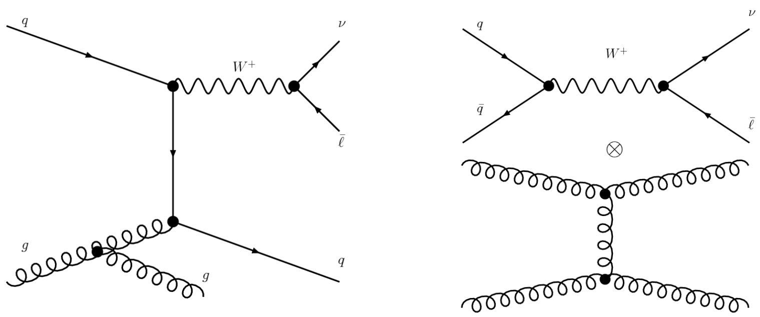
DPS underestimated in the models tuned on Soft QCD phenomenology?

What are the relationships between "soft" and "hard" MPI measurements?



CMS Coll. - *JHEP 03 (2014) 032*

W+2j - Double Parton Scattering (ATLAS and CMS)



Measured di-jet x-section

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

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

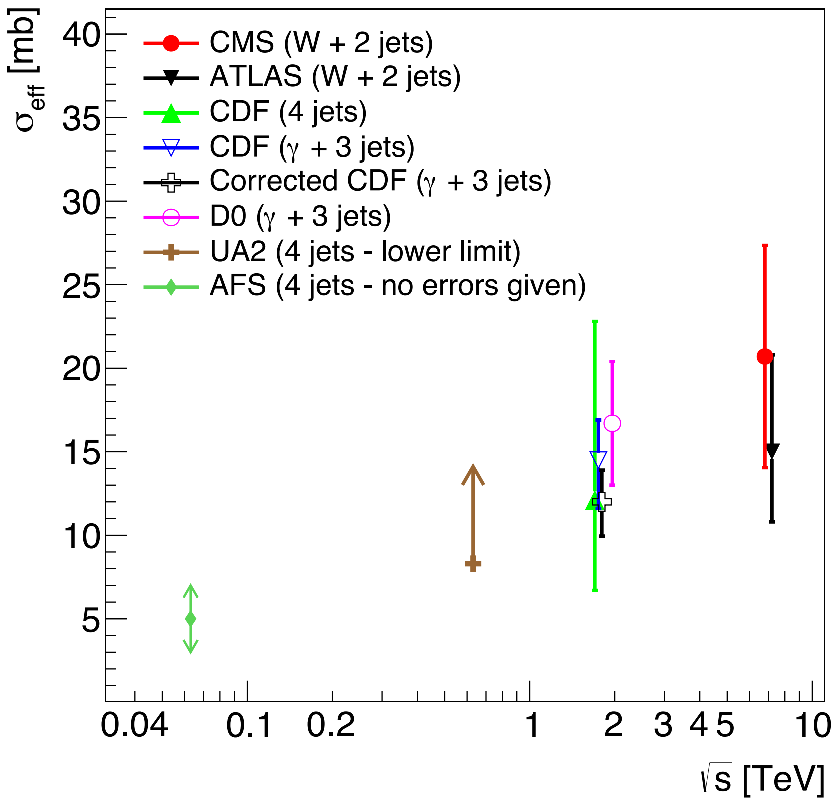
σ_{eff} = 20.7 ± 0.8 (stat) ± 6.5 (syst) mb (CMS)

Measured value is consistent (within uncertainties) with the previous resuls by ATLAS, CDF and D0

Large uncertainties: can not conclude dependance on collision energy

Consistent with value obtained for Herwig++ by fitting UE data from LHC and Tevatron

Main systematics from SPS background modeling



ATLAS Coll. - New J.Phys. 15 (2013) 033038

CMS Coll. - *JHEP 03 (2014) 032*

Double Parton Scattering - what else ?

hadronic:

σ_{DPS} (4jets@100 GeV) = ½ * (σ (2jets))$^2/\sigma_{eff}$= ½ * (1μb)$^2/\sigma_{eff}$ = 5 10^{-5} μb = **50 pb**

σ_{DPS} (2γ+2jets@20 GeV) = ½ * (σ (γ+jet))$^2/\sigma_{eff}$ = ½ * (0.1μb)$^2/\sigma_{eff}$ = 5 10^{-7} μb = **0.5 pb**

hadronic - incoming/future:

σ_{DPS} ($W^\pm \to \mu\nu, W^\pm \to \mu\nu$) = ½ * ($\sigma$ ($W^\pm \to \mu\nu$))$^2/\sigma_{eff}$ = ½ * (20nb)$^2/\sigma_{eff}$ = 2 10^{-5} nb = **20 fb**

σ_{DPS} ($Z \to \mu\mu, Z \to \mu\mu$) = ½ * ($\sigma$ ($Z \to \mu\mu$))$^2/\sigma_{eff}$ = ½ * (2nb)$^2/\sigma_{eff}$ = 2 10^{-7} nb = **0.2 fb**

heavy flavor final-state:

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

(20% higher than the SPS predictions. contribution from DPS? SPS contribution suppressed at large Δy)

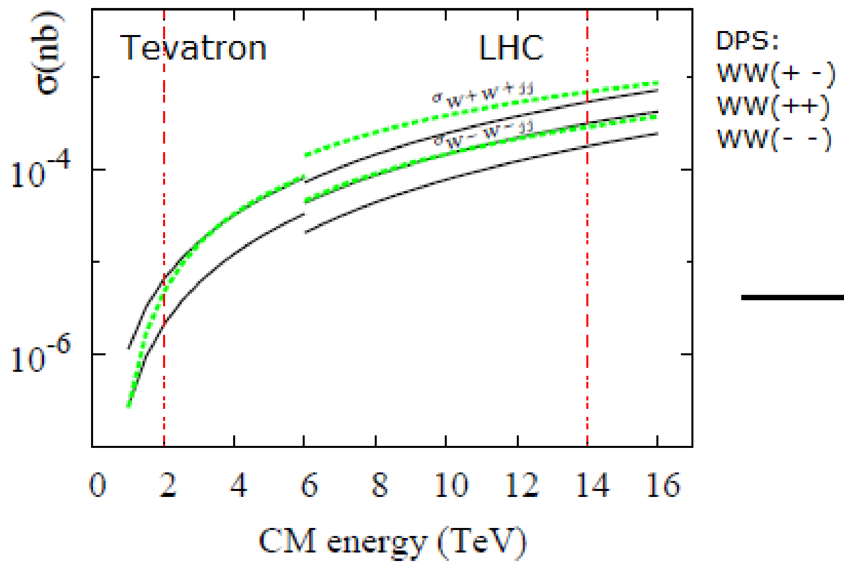
heavy flavor final-state - incoming/future:

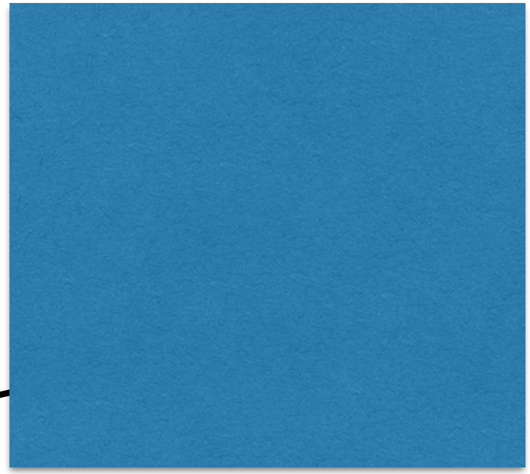
[W+prompt J/ψ - hint for DPS contribution higher than assumption]

[Z+D - DPS higher than SPS]

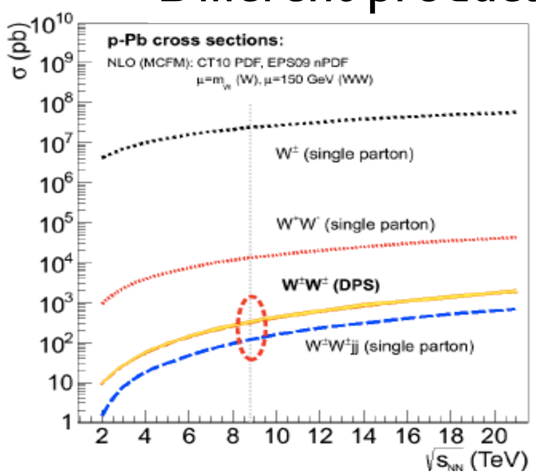
same sign WW - Double Parton Scattering

very low stat available from run-I, only lower limit on σ_{eff}





Different production



p-Pb 8.8 TeV configuration

1) **DPS/SPS separation increased**
(D'Enterria & Snigirev,
Phys.Lett. B718 (2013) 1395-1400)

DPS~300 pb
SPS~100 pb

2) **Additional information on MPI correlations**
(talk from Daniele Treleani)
Salvini, Treleani, Calucci - Phys.Rev. D89 (2014) 1, 016020

Section 3 - Double Hard Scattering

Measurements 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.

Interpretation, consistency checks
In progress, still no striking DPS evidence at hadron colliders
Model dependency - Large systematics on σ_{eff}

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, comparing with corresponding UE ratios.

Differential distributions
More integrated luminosity required: probably Run-2 (, HL-LHC…)

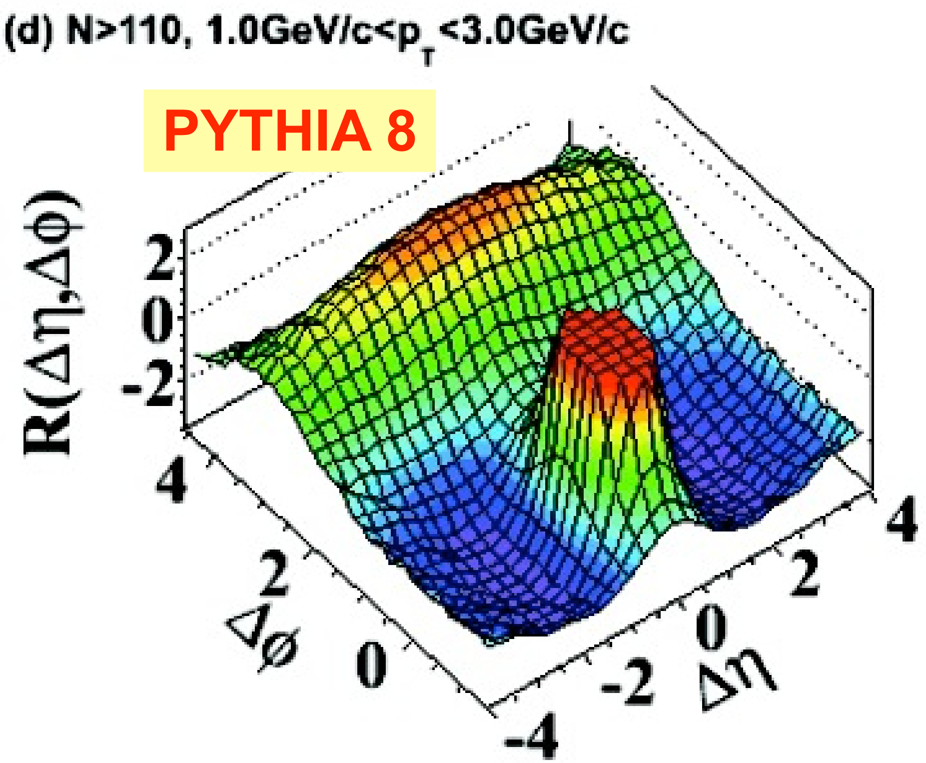
Extension of the DPS measurements to p-Pb
Nice/promising TH predictions and feasibility studies - **Run-2**

Section 4 - High multiplicity correlations

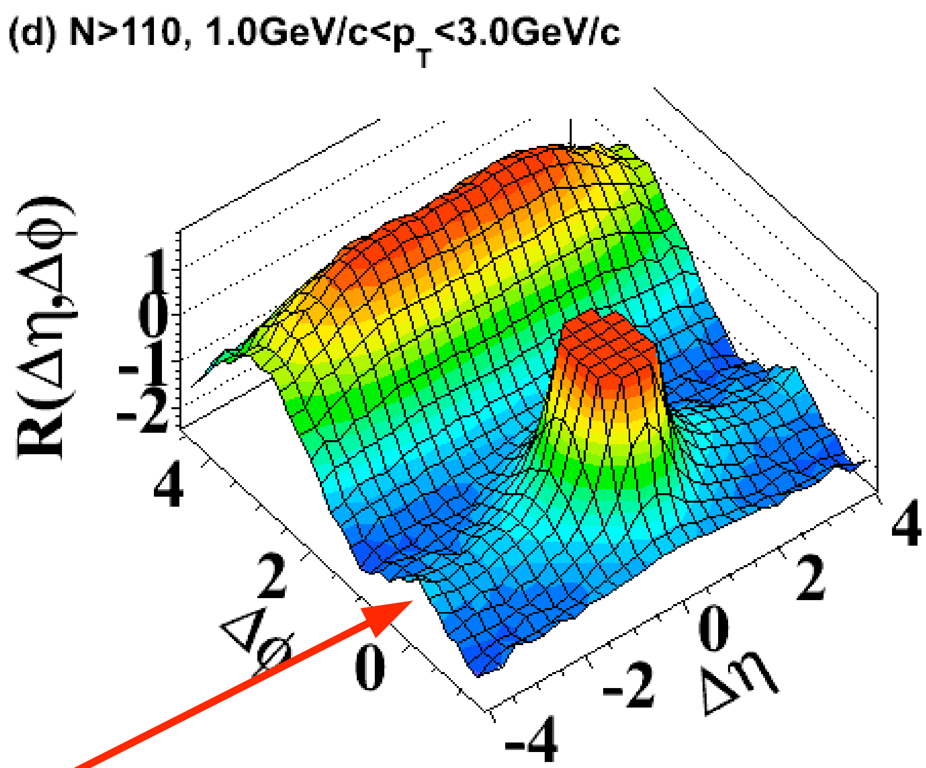
CMS Coll., JHEP 1009 (2010) 091

Intermediate pT : 1 < p_T < 3 GeV/c

High Multiplicity: N>110



High Multiplicity: N>110

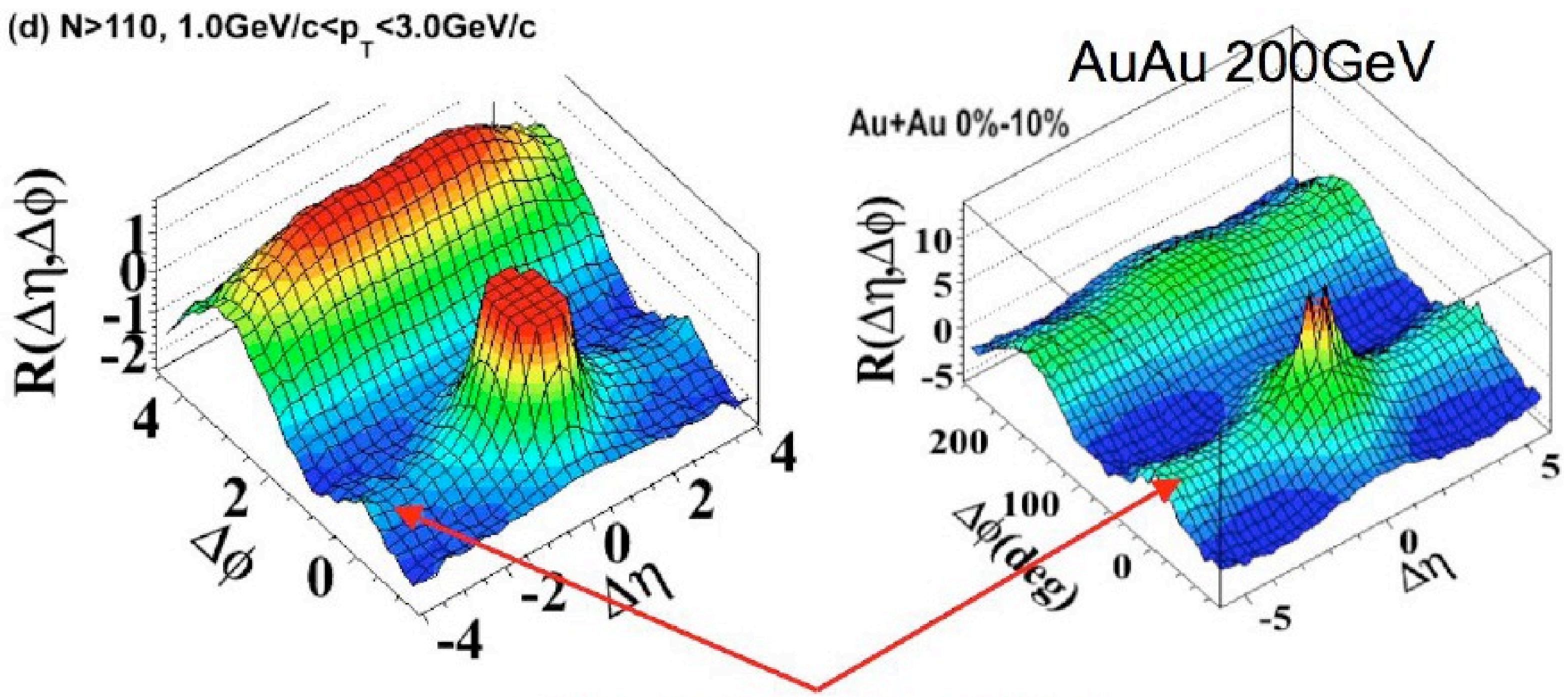


Observation of a Long-Range, Near-Side angular correlations at high multiplicity in pp events at intermediate pT (Ridge at $\Delta\phi \sim 0$)

not reproduced by actual models

High multiplicity correlations

A similar feature observed at RHIC that was interpreted as being due to the **hot and dense matter** formed in relativistic heavy ion collisions

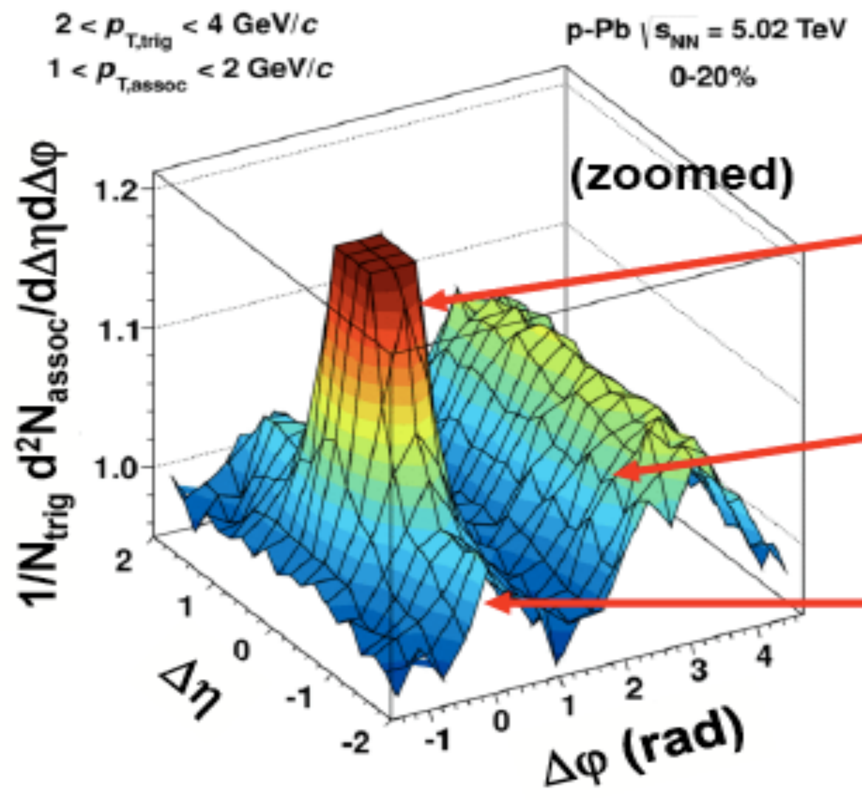


This is a subtle effect in a complex environment careful work is needed to establish physical origin

High multiplicity correlations

ALICE and CMS: reported same structure in p-Pb collisions (5.02 TeV)

Phys.Lett. B719 (2013) 29-41
Phys.Lett. B718 (2013) 795-814



$2 < p_{T,trig} < 4$ 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 $\Delta\eta$)

Correlation profile for lower multiplicity (60-100%) is subtracted from the one for higher (20% highest)

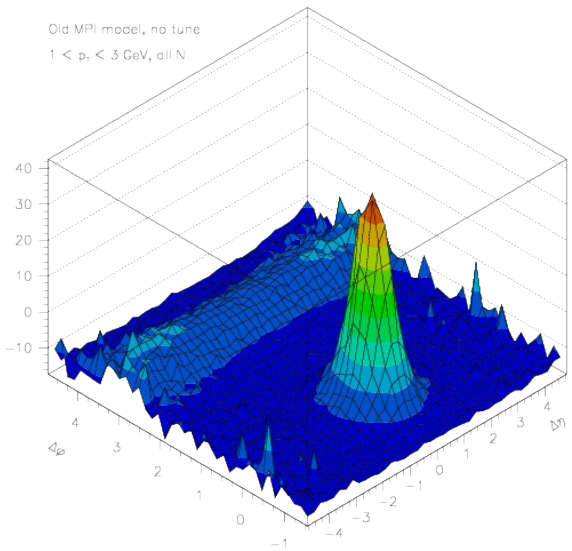
Possible interpretations (beyond elliptic flow)

MPI model does not take into account angular momentum conservation

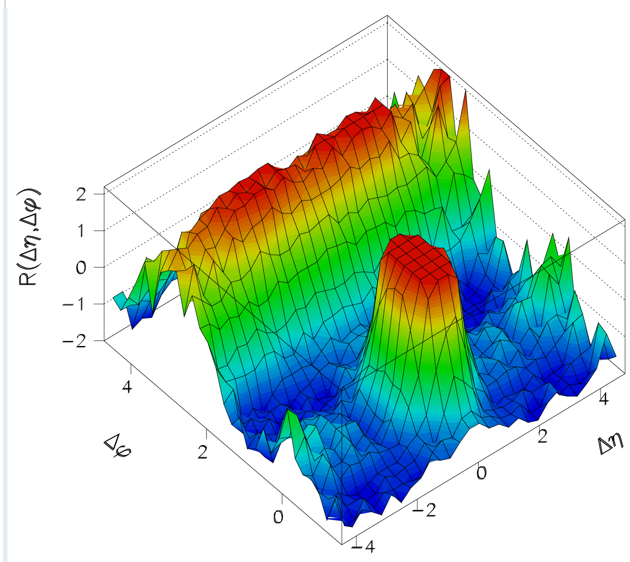
The number of MPI is regularized by the IP, but the azimuth of the scattering plane is chosen randomly for each MPI → no long-range near-side angular correlations in PYTHIA

With a impact-parameter dependent smearing: $\phi_i = \phi_{hardest} + \mathrm{Gauss}(\mu = 0, \sigma = 1)\arctan(b_{avg}/b)$

1 < pT < 3 GeV, all N



1 < pT < 3 GeV, N > 90



Such a correlation can be naturally explained in a physical picture based on the impact parameter between the protons

Warnings:
Azimuthal correlation of MPIs was studied experimentally at Tevatron but no evidence was observed

Section 4 - 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

Expected a strong mechanism to produce particles in a plane

Pb-Pb - expected from the elliptic flow

pp (and p-Pb) - still miss an agreed interpretation

MPI Interpretation: large multiplicities without pronounced jetty structures point to an important role played by Multiple Parton Interactions
Angular momentum conservation?

Next:

Explore the full potential ("3D correlations" from p-N collisions)

(see contribution from D. Treleani)

Can one analyze double-PDFs @ LHC kinematics (very low x, high momentum scale) within relativistic quark models ?

(see contribution from S. Scopetta)

Conclusions/Highlights

Multiple Parton Interactions solve the unitarity problem generated by the fast raise of the inclusive hard cross sections at small x

MPI are an instruments to probe proton matter distribution, understand the collision dynamics and define at the best unexpected background to new physics search

Past experiments indicating Double Parton Scattering suggested the extension of the same perturbative picture to the soft regime, giving rise to the first implementation of the MPI processes in a pQCD Monte Carlo model (T.Sjöstrand and M.van Zijl). Such model turned out to be successful in reproducing the charged multiplicity distributions and KNO scaling violation

Several observations don't have a straightforward interpretation with independent interactions, i.e. increasing <pT> vs Nch. A large amount of colour reconnections recover, but is this the correct interpretation? To what extent can colour reconnection affect observables like the meson/barion ratios that can be attributed to effects dealing with transport in dense matter?

Conclusions/Highlights

The status of the art of Multiple Parton Interactions needs to be reviewed in the light of the recent LHC measurements on both hard and soft MPI

The MPI@LHC workshop is providing a common theo/exp platform for MPI understanding

Hard-MPI measurement still don't provide a crystal clear DPS evidence (strong model-dependence)

From the observation of high-multiplicity final state (jets structure, sphericity, ridge-like structure,…): these events are less jetty than predicted by the models

What should be considered to be the most striking evidence of MPI via DPS?

And what are the features of large multiplicity production?

To what extent we can trust the general-purpose pQCD MPI models?

Explore scaling properties: observables in pp, pPb and PbPb driven by charged multiplicity?

What role is played by correlations ?

Higher Energies...higher luminosities...

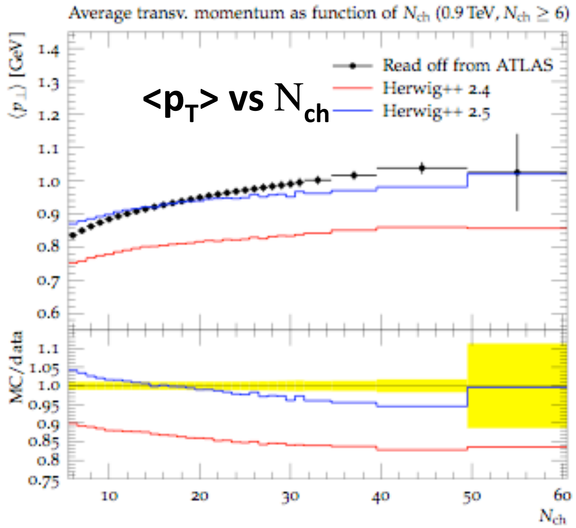
1) DPS/SPS Heavy Flavors production is expected to increase with $\sqrt{S}$ (experimental challenging ?)

2) Rare productions with top and heavy bosons, unavoidable BGs to new physics searches

3) proton-Nuclei interactions, DPS enhanced, longitudinal correlations, help the 3D definition of σ_{eff}

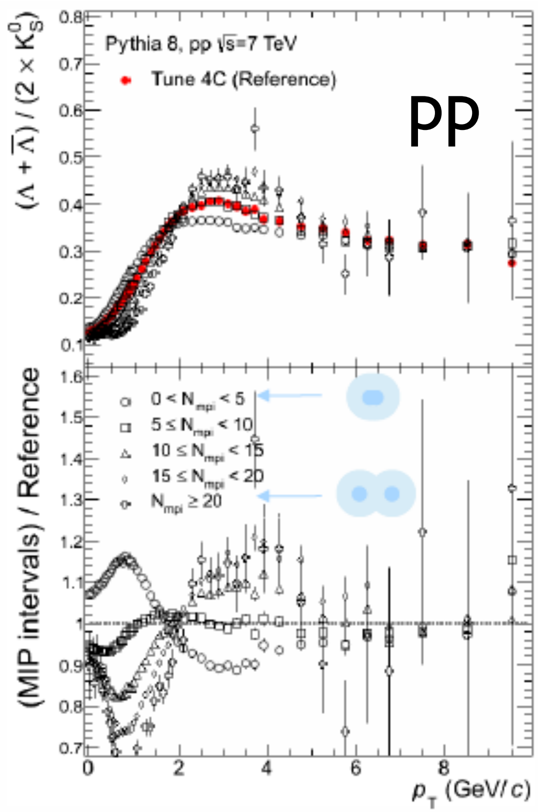
BU

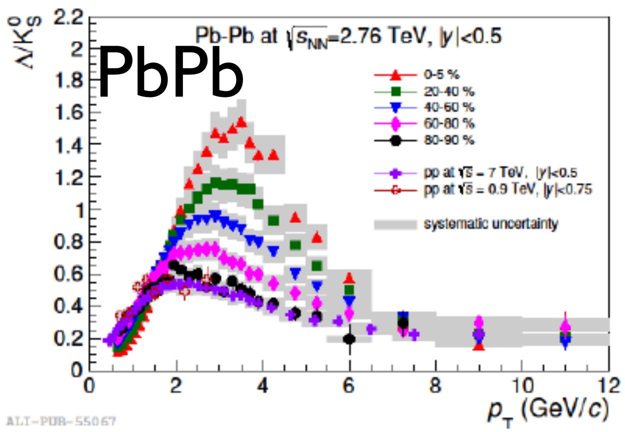
Color Reconnection



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

Color reconnection unavoidable to describes the shapes of pseudo-rapidity and <p_T> vs N_{ch}.





flow-like patterns in pp

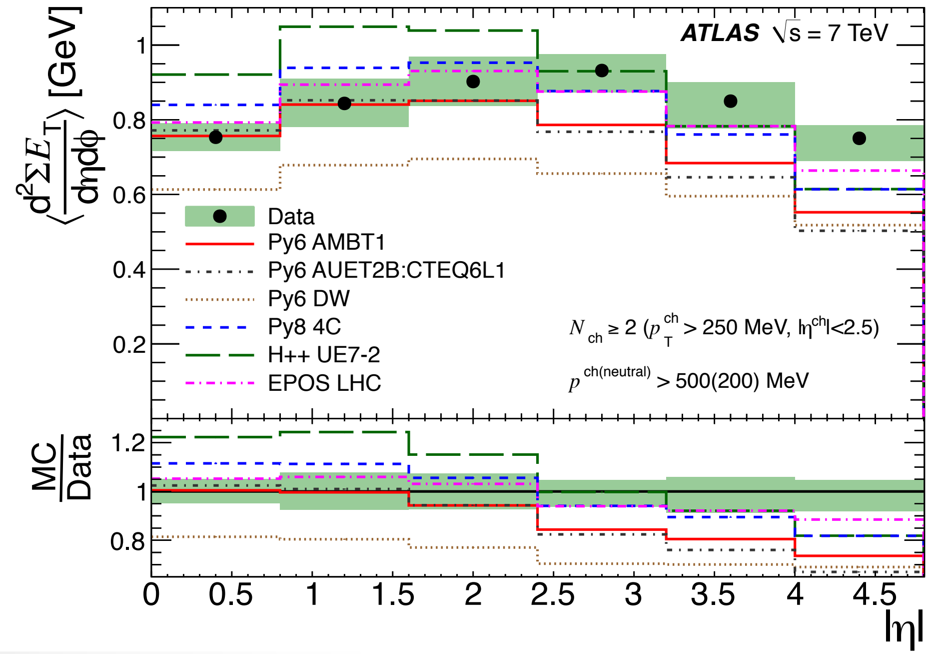
[G.Paic, MPI@LHC 2013, Antwerpen]
See also arXiv:1404.2372

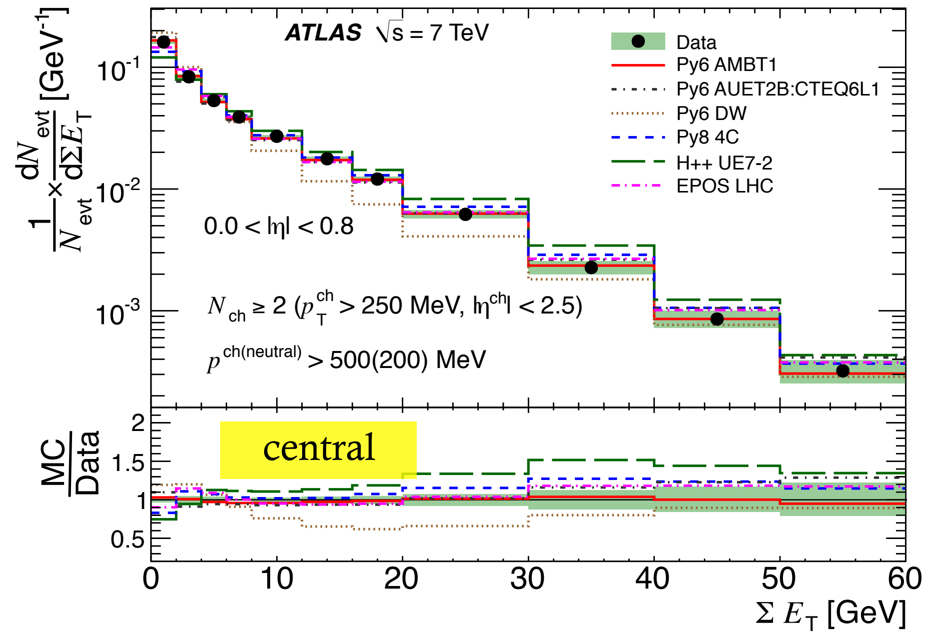
pp interaction simulated with Pythia 8 Tune 4C don't know about flow

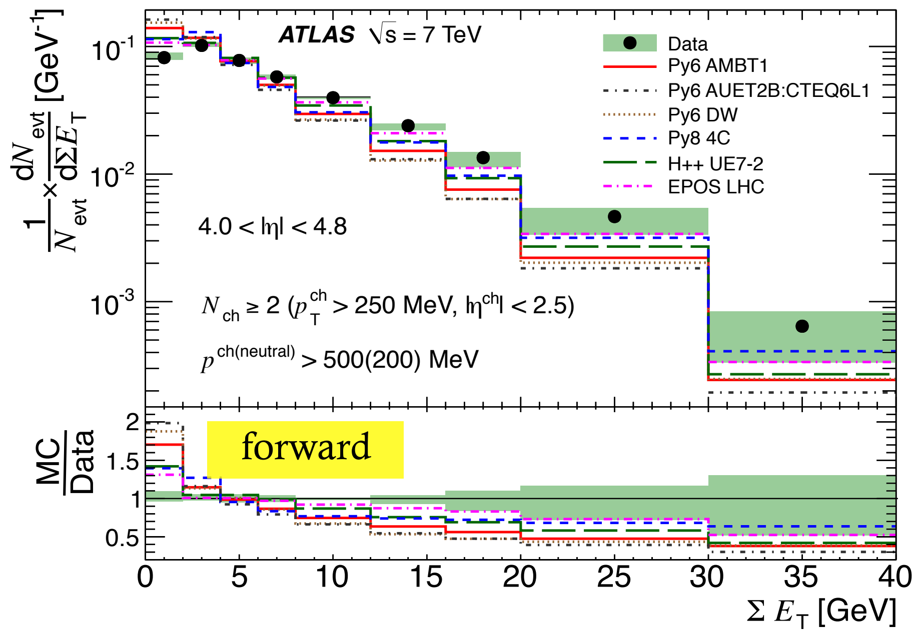
Λ/K_S^0 ratio in different N_{ch} ranges evolve as the Λ/K_S^0 ratio in different centrality ranges in Pb-Pb interactions (measured by ALICE)

Color reconnection matter. Flat shapes otherwise.

Transverse Energy Flow







charged and neutral components included (using the full acceptance of ATLAS calorimeter)
important complementary measurement to charged particle distributions

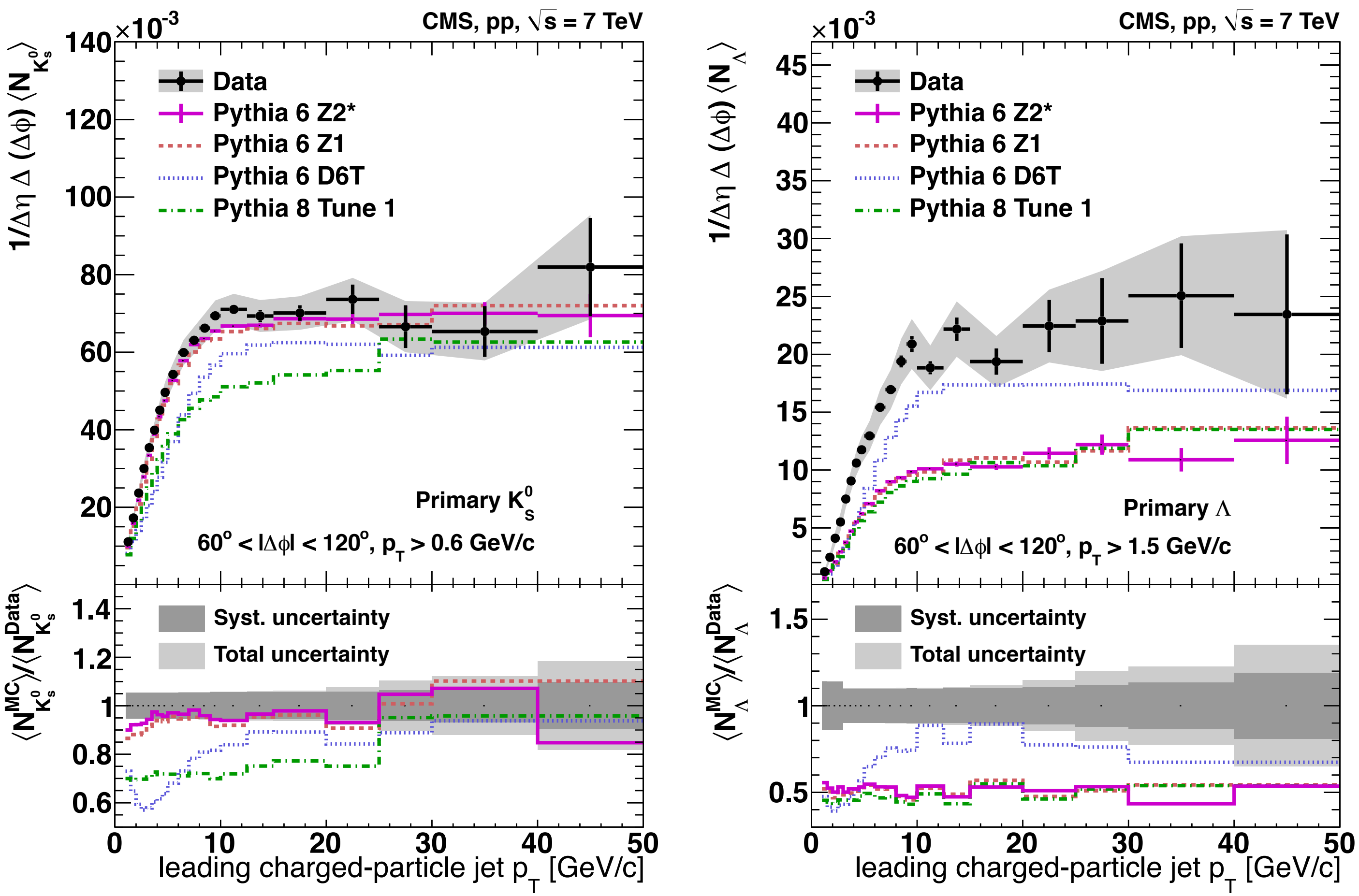
MCs underestimate the forward activity

sensitivity to diffractive component is small

sensitivity to choice of proton PDFs and Underlying Event tune is observed

ATLAS, JHEP 11 (2012) 033

The transverse region - identified particles



Same pattern observed for standard UE measurement, compatible with the IP interpretation

PYTHIA underestimate the data by 15–30% for K_S mesons and by about 50% for Λ baryons

Deficit similar to that observed for the inclusive strange particle production in pp collisions

CERN-PH-EP-2013-086