Multiple Parton Interactions an experimental vision

focusing on High Multiplicities

Paolo Bartalini
(Central China Normal University)

Outline

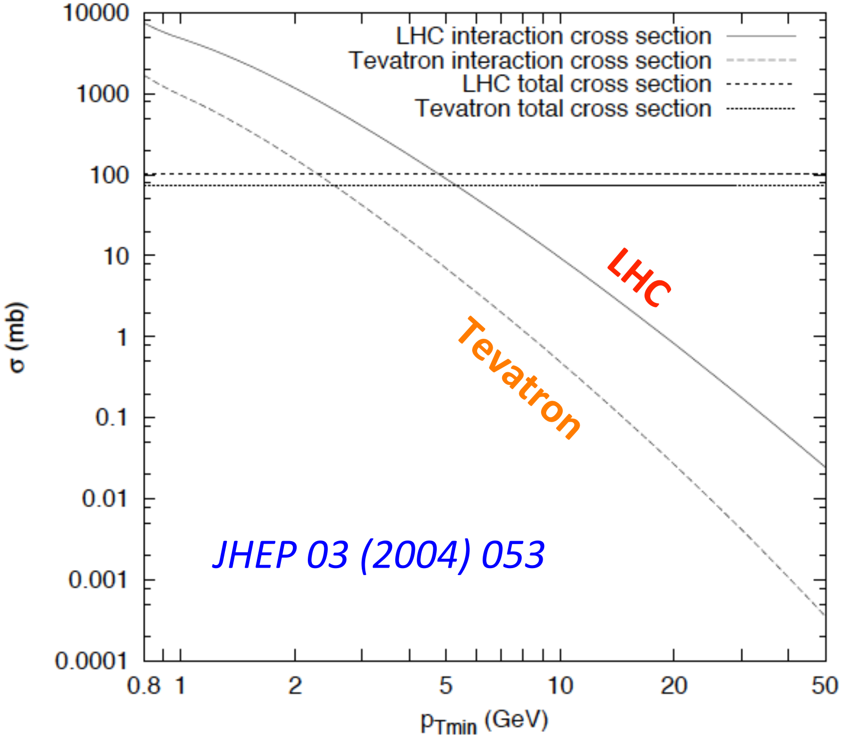
- Double Parton Scattering (DPS) phenomenology
  - Critical review of the relevant phenomenology

  (New results on multiple HF production and same sign WW production reported by other speakers: Liupan An, Alessandro Rossi, …)
- Underlying Event
- Multiplicity dependent results
  - Particle yields, Correlations, jet and event shapes, …

Focusing on small systems

2nd NPQCD – Pollenzo (Bra) – May 22-24 2017

Why Multiple Parton Interactions?



Dislaimer: Theory will be covered by other speakers: Matteo Rinaldi, Mirko Serino. Here just a brief introduction

Integrated inclusive cross section of jet production σ_{int} above P_{Tmin} at **Tevatron (1.8 TeV)** and **LHC (14 TeV)**

The flat lines represent the respective total cross section

- At high energy of the interacting hadrons, the integrated inclusive jet cross section exceeds the value of the total cross section
- Unitarity is restored by introducing Multiple Parton Interactions (MPI)
- NOTA BENE: Multiple Parton Interactions in the same hadron-hadron collision!

i.e. MPI is not referring to the trivial pile-up effects

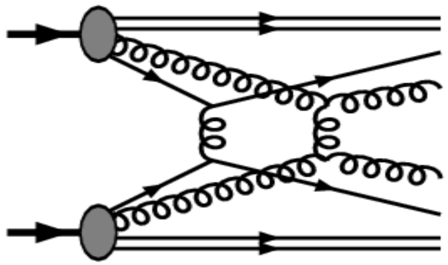
MPI in the pQCD Models

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

→

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

Inspired by early observations of double high P_T scatterings



(dampening)

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

- ✓ Cross section regularization for $p_T \rightarrow 0$.
- ✓ p_{T0} can be interpreted as inverse of effective colour screening length.
- ✓ Controls the number of interactions: $\langle N_{MPI} \rangle = \sigma_{parton-parton} / \sigma_{hadron-hadron}$

$p_{T0} \approx$ few GeV → perturbative description

Lipatov-like behavior of the post-HERA PDFs: $x\, g(x,Q^2) \rightarrow x^{-\varepsilon/2}$ (for $x \rightarrow 0$)

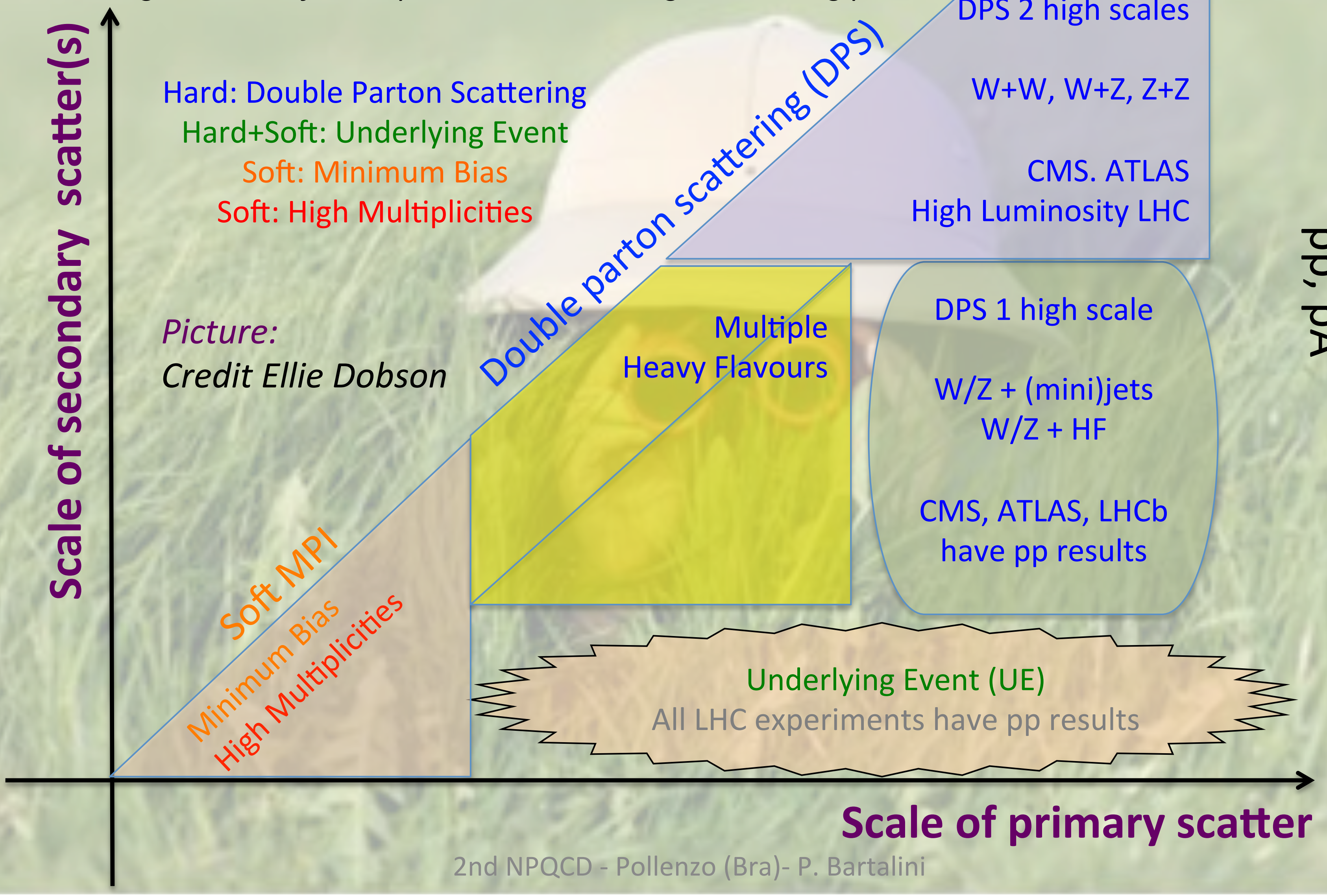
Color Screening Effects Increase at Higher Energy: $p_{T0}(s') = p_{T0}(s)\,(\sqrt{s'} / \sqrt{s})^{\varepsilon}$

Typical event: one leading interaction accompanied by several soft MPI at $p_T \approx p_{T0}$.
→ Apart from the bias of the leading interactions Multiplicities proportional to N_{MPI}

Correlations:
Scale of leading interaction influence N_{MPI} (Pedestal effect, relevant for Underlying Event)
Optional Colour Reconnection (CR) of partons → minimise String length in Fragmentation

Multiple Parton Interactions (MPI) at the LHC

MPI measurements give us a picture of the gluons within the hadrons
Very much along the lines of a Deep Inelastic Scattering with strong probes



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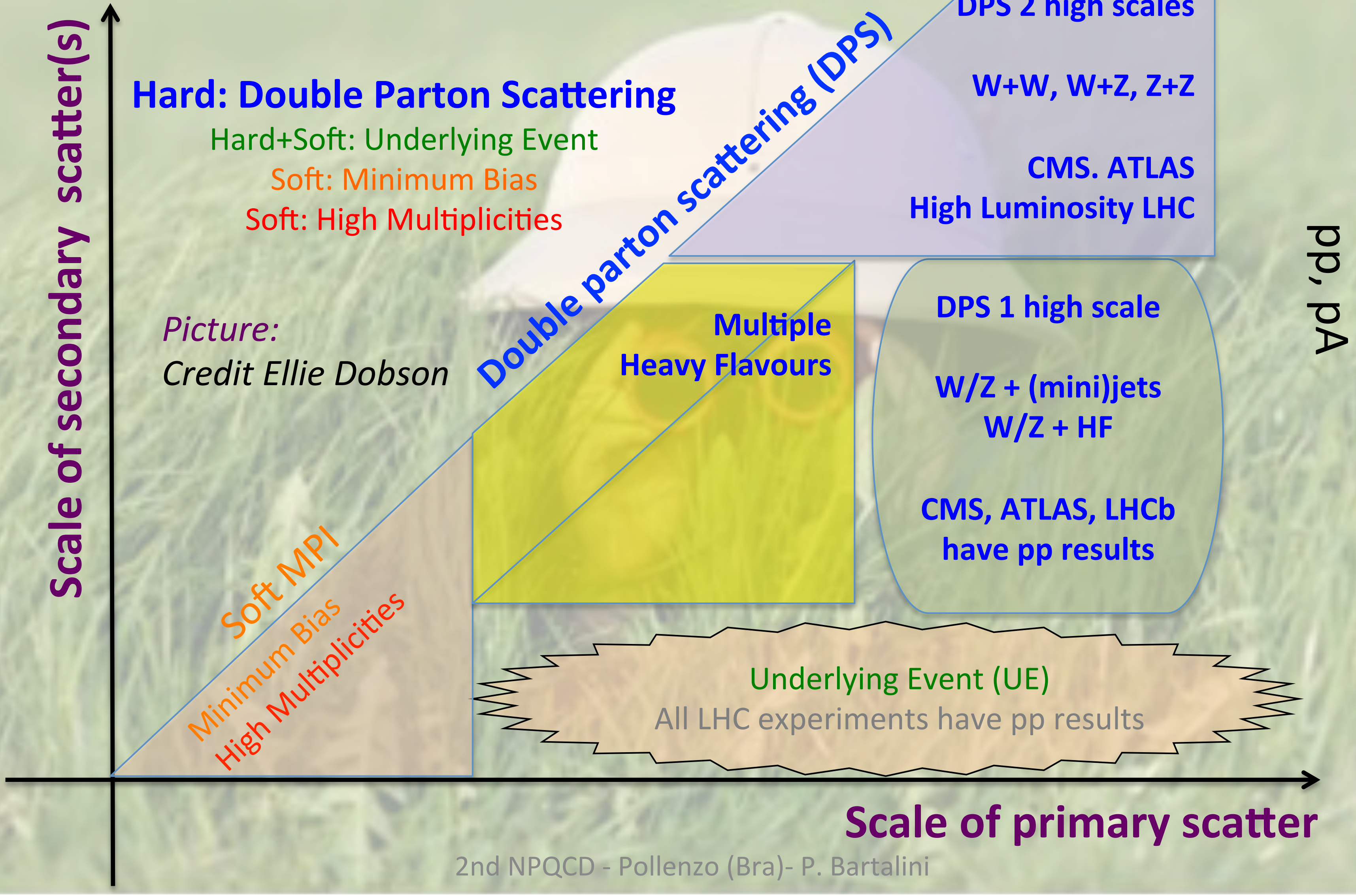
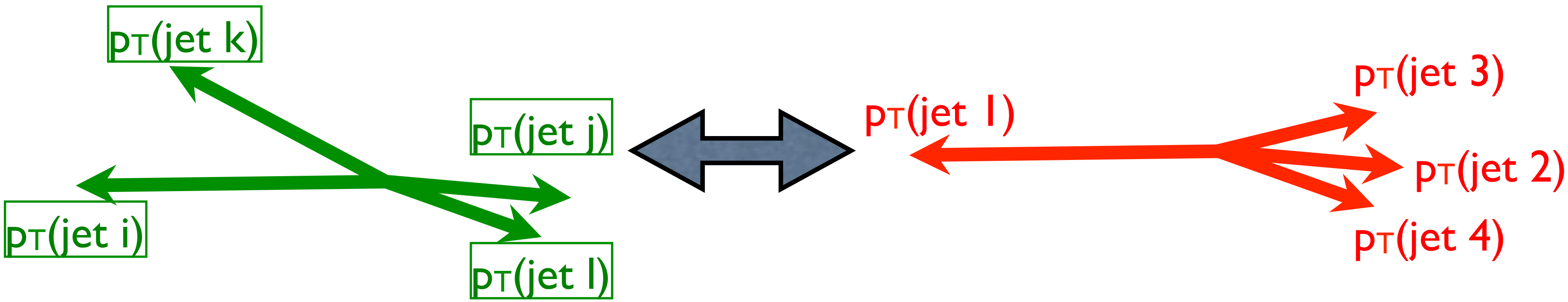


The Double Parton Scattering (DPS) and the effective cross section σ_{eff}

- $\sigma_{DPS}(A+B+X) = m * \sigma(A+X) * \sigma(B+X) / \sigma_{eff}$
  - m = ½ for identical interactions, m = 1 otherwise
  - Probabilistic interpretation: P(B|A) = P(B) * **($\sigma_{inel}/\sigma_{eff}$)**
  - Trivial case of no correlations → $\sigma_{eff} = \sigma_{inel}$ (Probability unchanged)
  - Formalism applies to inclusive processes only
  - σ_{eff} can be regarded as a hadronic form factor
  - Huge ongoing TH effort to understand correlations: IP, Flavour, Spin, Color, …
- Under the assumption of purely geometrical correlations:
  - $\sigma_{eff} \approx$ geometrical quantity, energy scale and √s independent. [D.Treleani]
  - TH predictions have large uncertainties: σ_{eff} = 20÷60 mb
- Measurements use the relationship in the following way:
  - $\sigma_{eff} = m * \sigma(A+X) * \sigma(B+X) / \sigma_{DPS}(A+B+X)$
  - Need an accurate Single Parton Scattering (SPS) background
  - Checking Scale and √s independency is in the EXP TODO list
  - Statistics often limits the possibility to extract σ_{eff} in a differential way

Double Parton Scattering in 4 "objects" topologies

Disentangle double-parton-scattering from bremsstrahlung



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

After PAIRING (based on the p_T balance of each pair) , one can define different correlation angles between the 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!

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

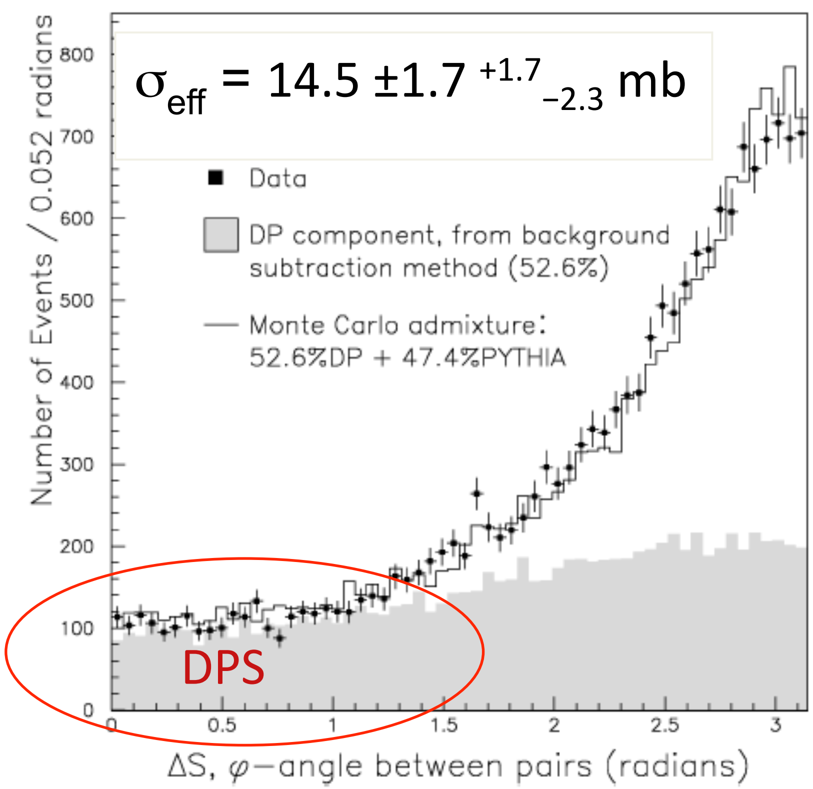
Effect of triple interactions:

→ 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
←	$E_{T4} < 5$ GeV
	$E_{T2}, E_{T3} < 7$ GeV



D0: σ_{eff} ~ 16.4 ±0.3(stat) ±2.3(syst)
Phys.Rev. D81 (2010) 052012 (Still not inclusive)

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

- A lot of emphasis in the definition of a data oriented methodology for the SIGNAL
- However the big issue is the BACKGROUND modeling:

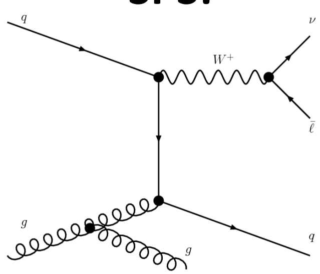
Single Parton Scattering (SPS) with direct photon and three extra jets is not trivial at all (modern ME tools badly needed but these tools were not available in the last century…)
At least one can say that the systematic uncertainties are strongly underestimated

CMS: DPS in W → $\mu\nu$ + 2 jets

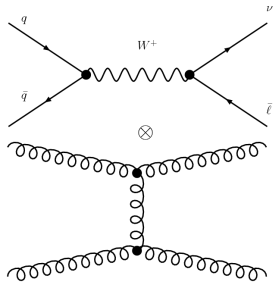
JHEP 03 (2014) 032

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

SPS:



DPS:



→ DPS signal fractions from fit to templates

Data:

Collision data at $\sqrt{s}$ = 7 TeV, Single Muon data streams with integrated luminosity of ~ 5 fb^{-1}

High stat.

Event selection:

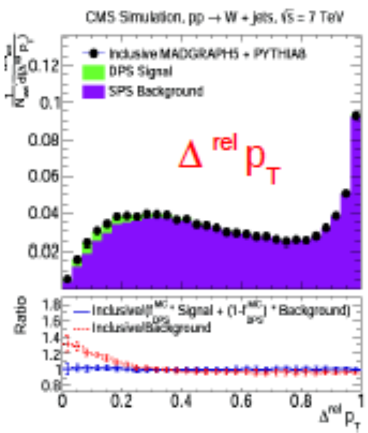
Unfolding

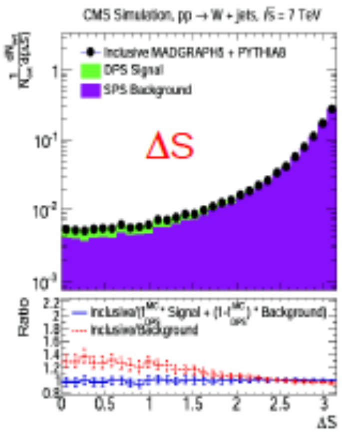
- Exactly one μ
- with p_T > 35 GeV, $|\eta|$ < 2.1
- Required to be isolated and to pass tight ID criteria
- particle flow Missing Transverse Energy, MET > 30 GeV
- transverse mass of (μ and MET) > 50 GeV
- Exactly 2 anti-KT jets with pT > 20 GeV and $|\eta|$ < 2.0

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

$\Delta^{rel} p_T$ = Relative p_T balance of the di-jet system.

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

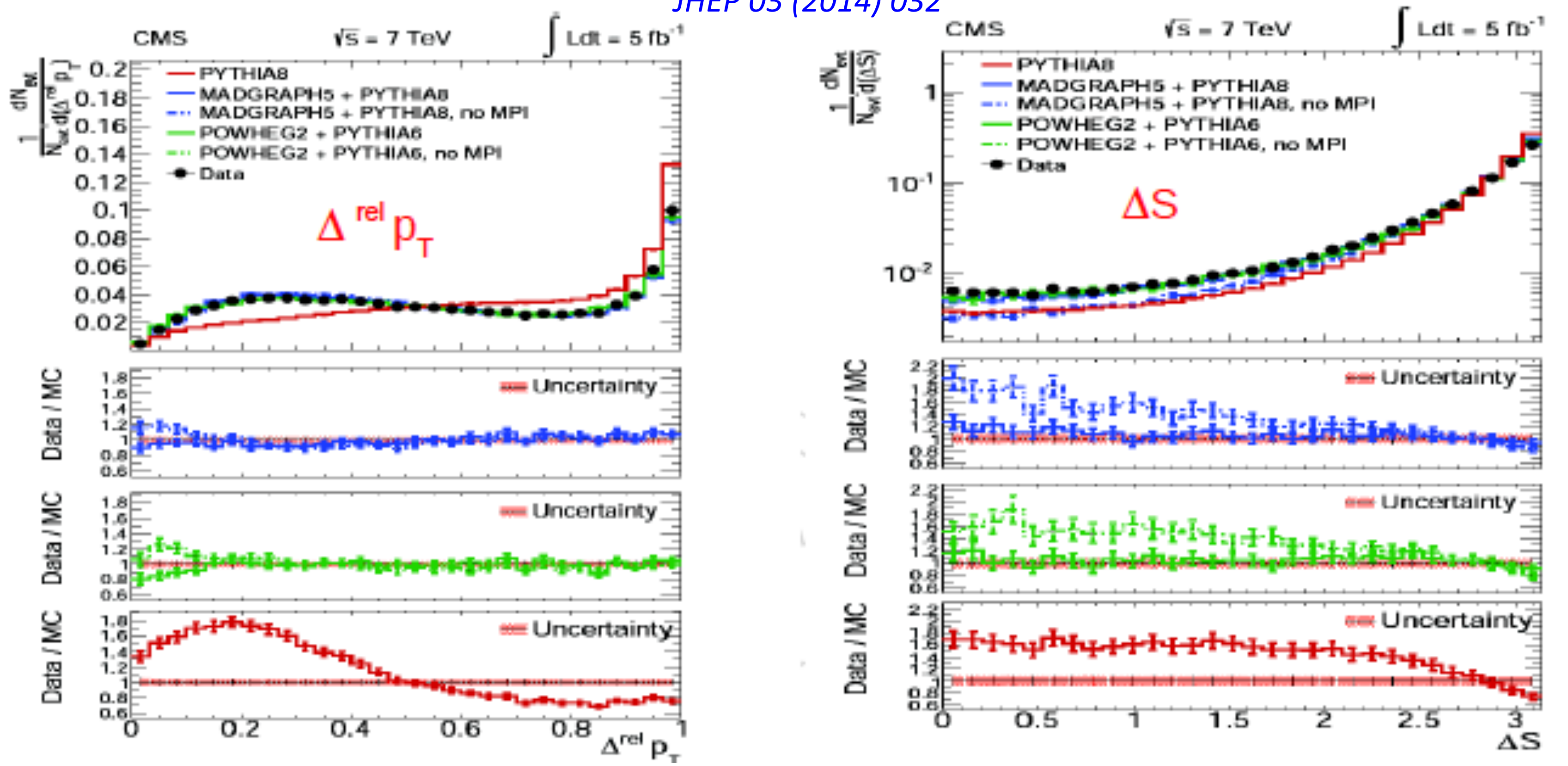




- Signal at small ΔS (DPS is flat while SPS is peaked at π) and small $\Delta^{rel} p_T$ (back-to-back di-jet in transverse plane).
- Signal Template combining W+0jets and di-jet samples.
- Backg. Template Madgraph+Pythia 8 (no jets from MPI)
- No double counting or phase space gaps
- DPS signal fraction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

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

JHEP 03 (2014) 032



- Even including MPIs, the Pythia predictions fail to describe the data due to missing contributions of higher order processes
- Without MPIs, both the LO (MG + Pythia) and NLO (Powheg + Pythia/Herwig) predictions don't describe the data
- Including MPIs, both the LO and NLO predictions provide the same level of agreement to the data

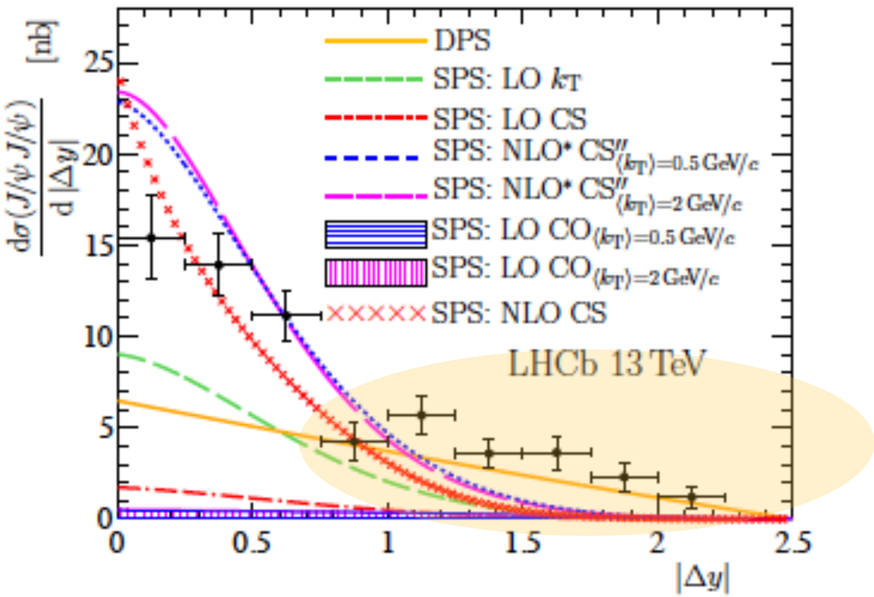
→ σ_{eff} = 20.7 ± 0.8 (stat.) ± 6.6 (syst.) mb

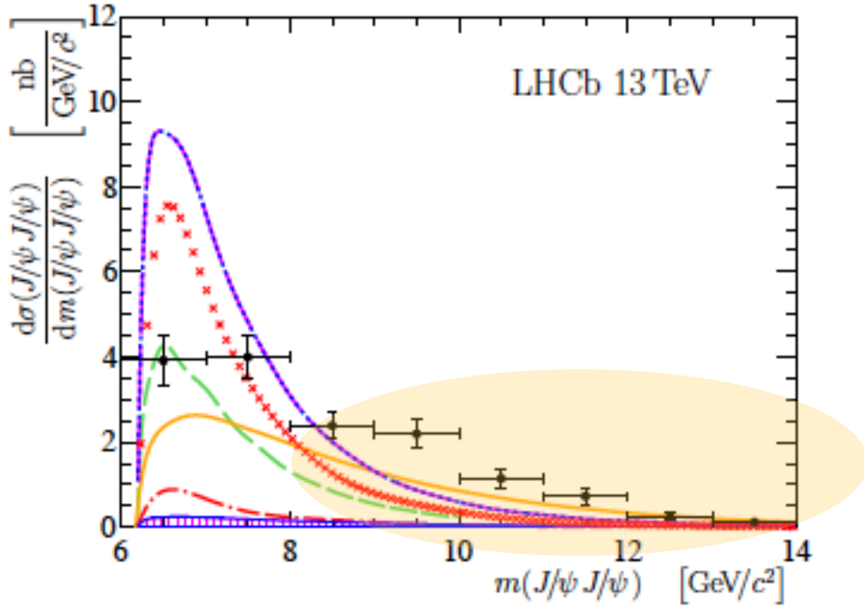
LHCb: Measurement of the *J/ψ* pair production cross section in pp collisions at √s = 13 TeV

arXiv:1612.07451

- Cross section measured for *J/ψ* mesons $p_T < 10$ GeV/c and 2.0 < y < 4.5
- Large uncertainties on inclusive SPS cross sections from NRQCD
- However differential cross sections show evidence for DPS
- Effective cross section determined using SPS+DPS template fit

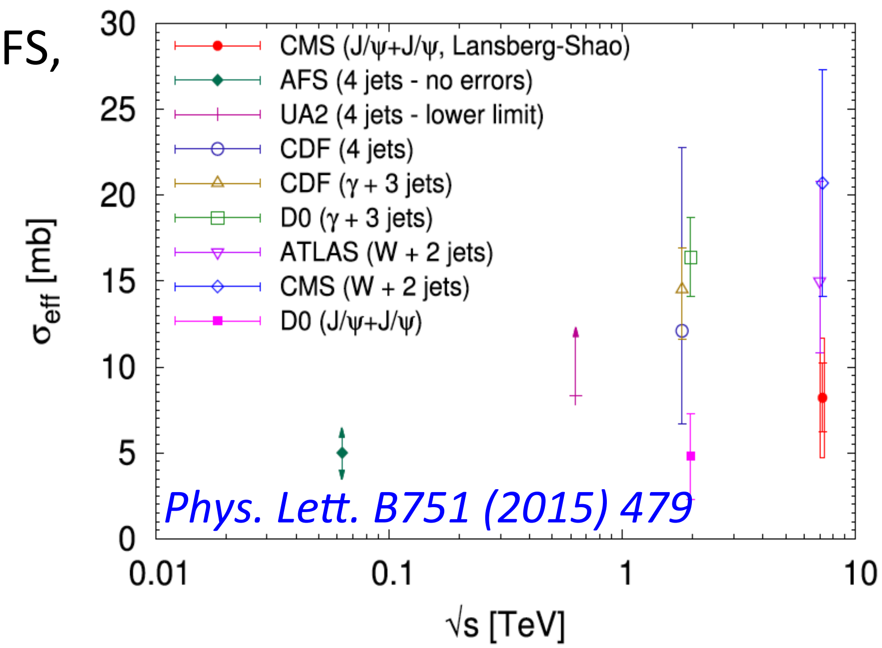
→ σ_{eff} values between 10.0 and 12.5 mb are quoted for the considered SPS models



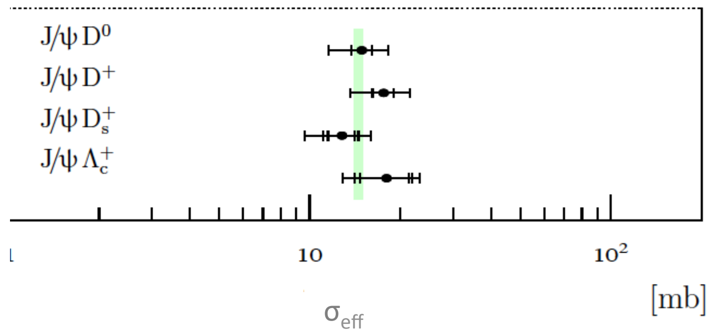


Measurement of the effective cross section σ_{eff}

- First results on 4jets already 30 years ago: AFS, UA2: σ_{eff} < 10 mb
- Tevatron measurements from the years nineties: $\sigma_{eff} \approx$ 10÷15 mb
  - insufficient effort on SPS background modeling
- W+2jet by ATLAS & CMS $\sigma_{eff} \approx$ 15÷20 mb
  - More compatibility with soft MC tunes
  - *arXiv:1512.00815*
- DPS with HF: LHCb
  - Double J/ψ at 13 TeV → Previous slide!
  - Double J/ψ at 7 TeV: *Phys. Lett. B707 (2011) 52*
  - J/ψ + open charm and double open charm at 7 TeV: *JHEP 06 (2012) 141 + JHEP 03 (2014) 108*
  - Z+ open charm at 7 TeV: *JHEP04 (2014) 091*
  - Υ + open charm at 7 and 8 TeV: *JHEP07 (2016) 052*
- Recent D0 (*double quarkonia*): $\sigma_{eff} \approx$ 2 mb !
  - *Phys.Rev.Lett. 116 (2016) no.8, 082002*
  - Hint of not understood SPS backgrounds?



JHEP 06 (2012) 141



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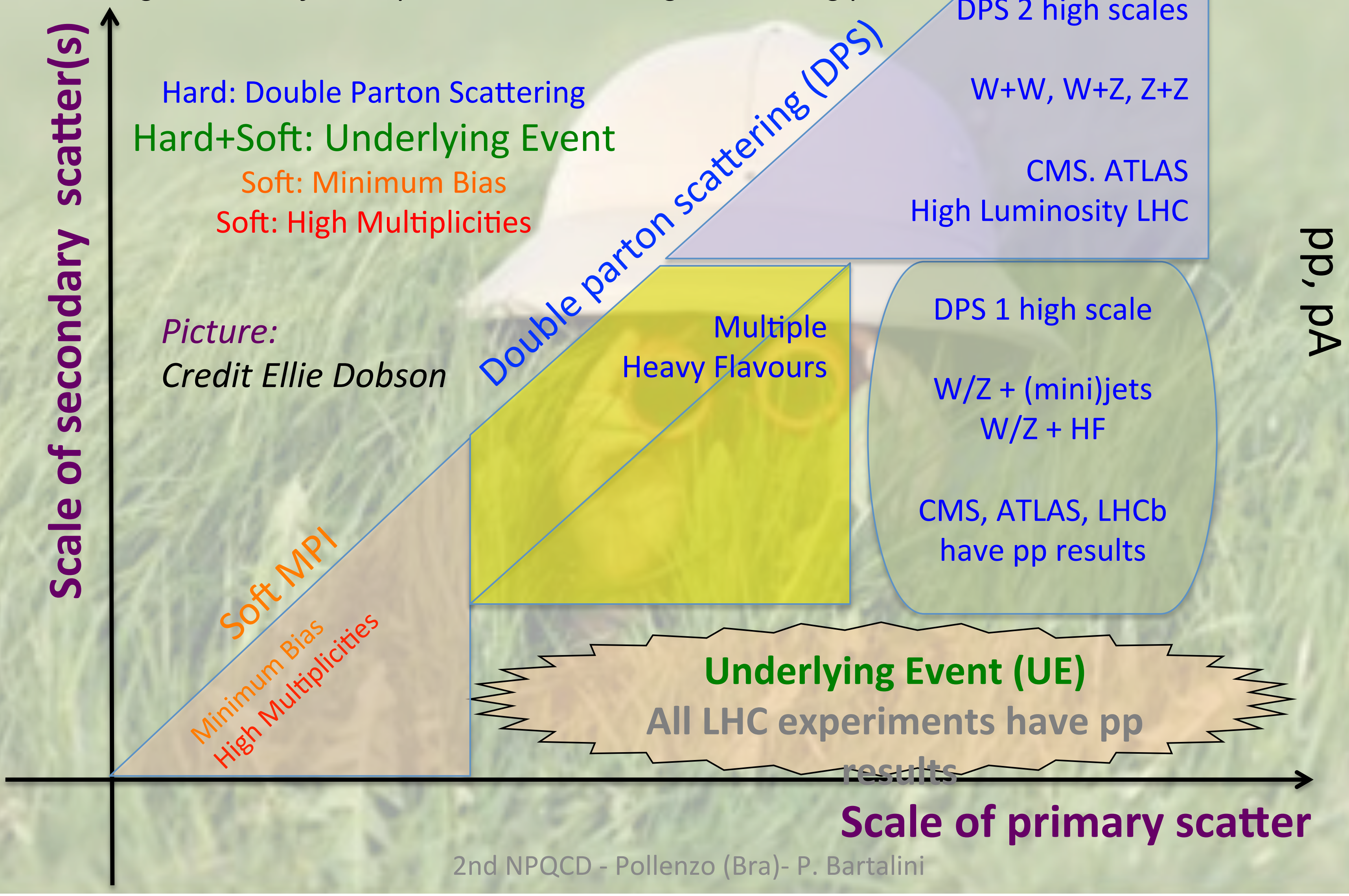


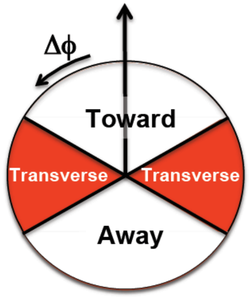
The Underlying Event (UE)

Measuring the complementary activity
in the presence of a leading interaction
(usually a hard scattering)

Relying on charged Tracks is very convenient
Tracker detectors @ LHC allow to
Count tracks from $p_T \approx 50$ MeV/c
Reconstruct them from $p_T \approx 150$ MeV/c

Traditional metodhology (à la Rick Field)

Leading object (i.e. track, charged jet, jet, γ, Z, etc.)



Toward: $|\Delta\varphi|<\pi/3$

Transverse: $\pi/3<|\Delta\varphi|<2\pi/3$

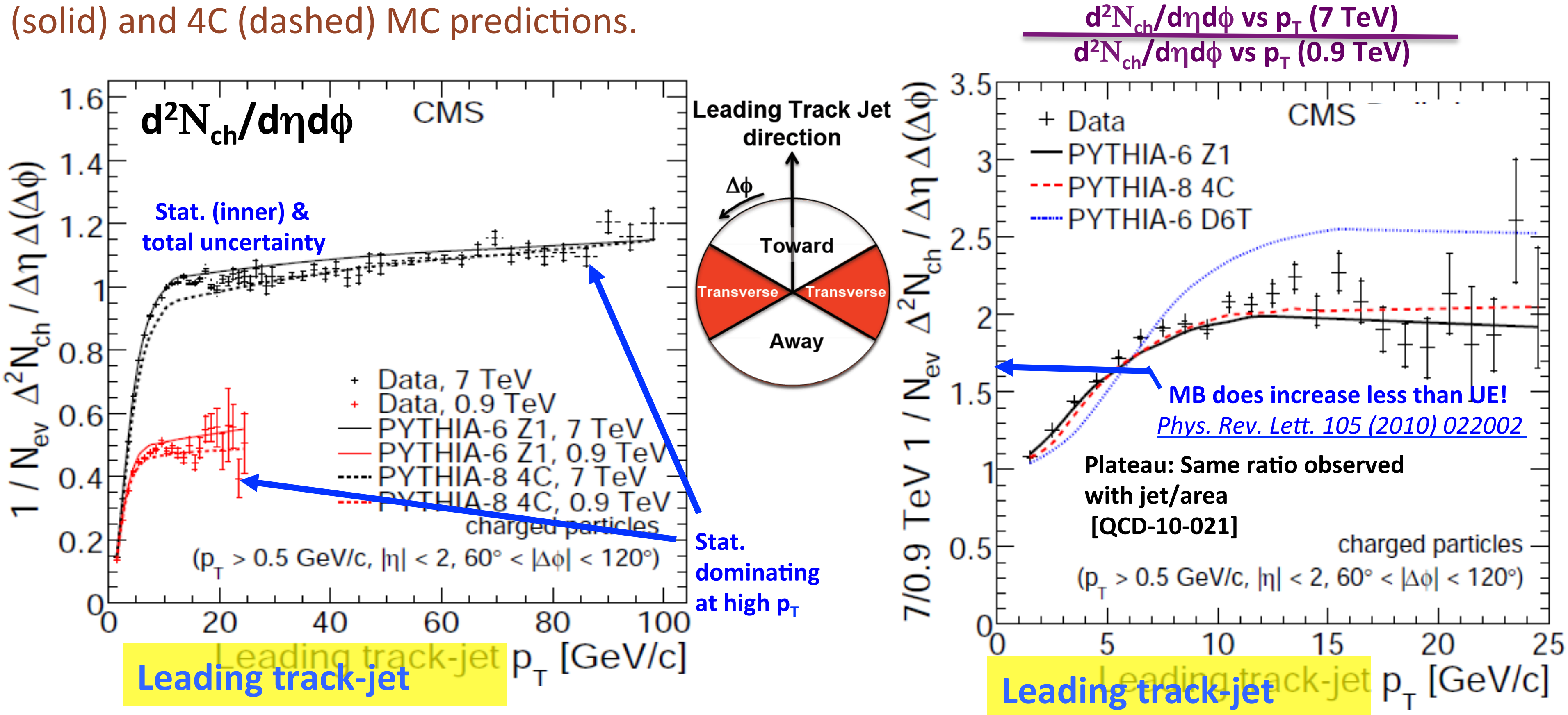
Away: $|\Delta\varphi|>2\pi/3$

Impact on isolations, jet pedestals, vertex reconstruction etc.
Actually UE is interesting per se: handle on soft MPI and beam remnants.

CMS: UE densities in the Transverse Region

JHEP 1109, 109 (2011).

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



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**.

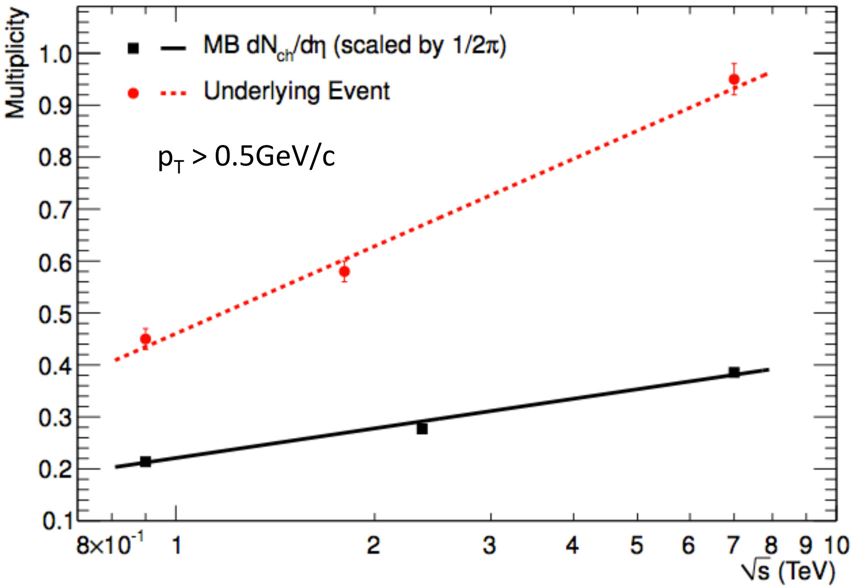
A factor 2 UE increase going from 0.9 TeV to 7 TeV to be compared with 1.66 for MB.

Nota bene: corrected distributions!

ALICE: UE & MB activities at different √s

JHEP 1207 (2012) 116

Comparison of the charged particle density in the plateau of the Transverse Region and the average charged particle density per unit of pseudorapidity ($<dN_{ch}/d\eta>$) in minimum bias events (scaled by $1/2\pi$).



Under the assumption that most of the activity is due to MPI, the ratio between he UE and the MB curves is:

$\approx <N_{MPI}\,(UE)> / <N_{MPI}\,(MB)>$

Confirms the DPS results:
at the LHC MPI are enhanced of a factor 2 - 3 from a rather modest energy scale

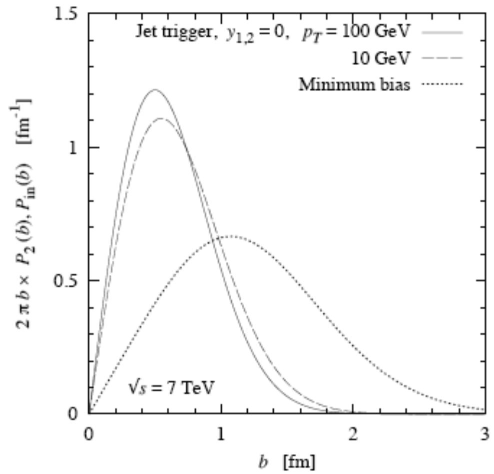
→ UE Pedestal Effect
Increasing with √s as $\sigma_{inel}/\sigma_{eff}$

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

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

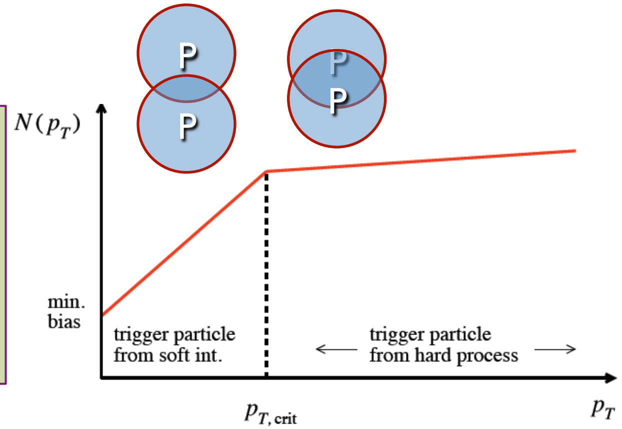
$$\langle\rho^2(x>10^{-2})\rangle \ll R^2_{soft}$$

⇓

Two scale picture

Does explain general features of UE @ hadron colliders

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



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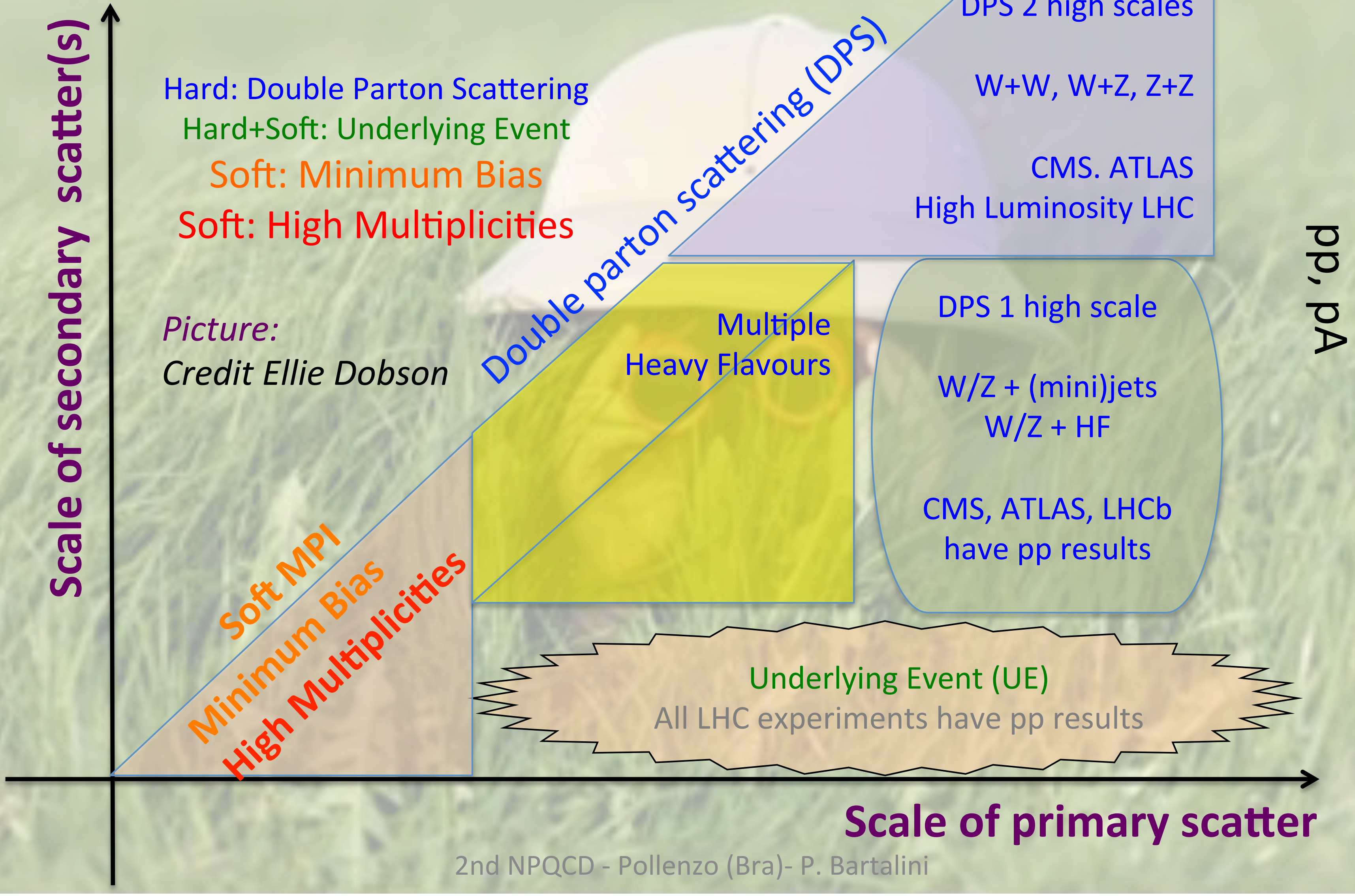
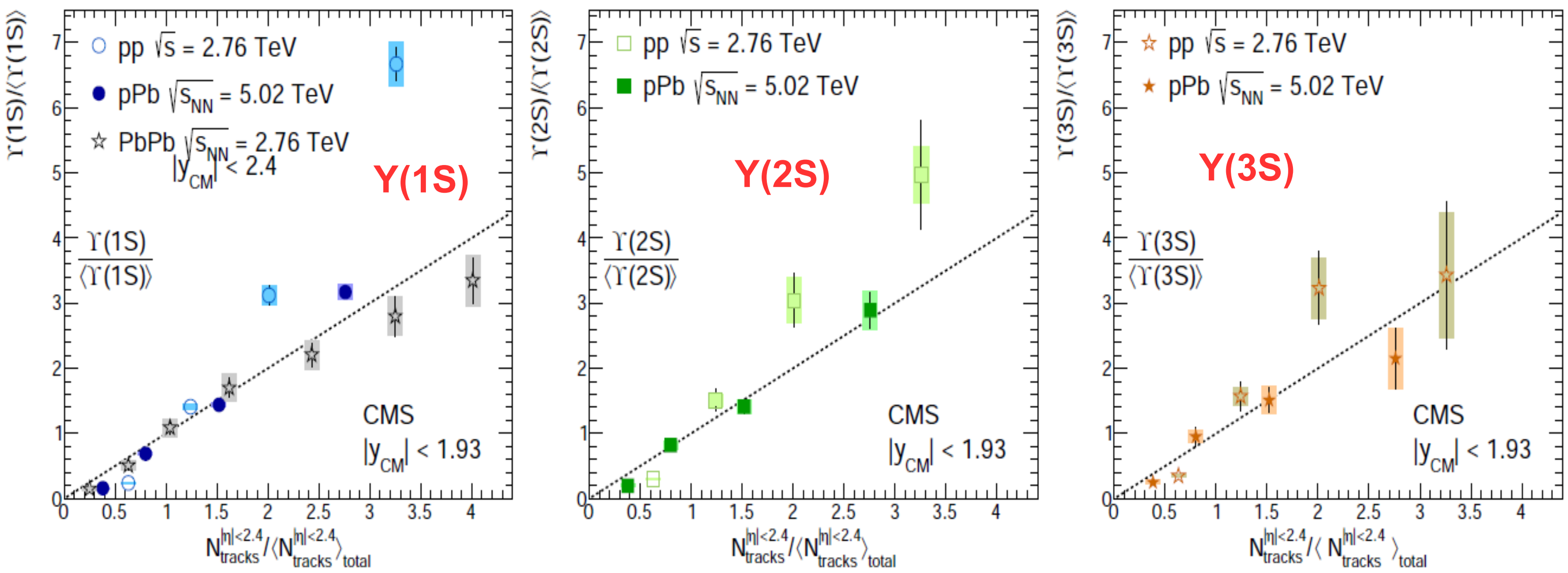


- Yields vs Multiplicity

CMS: Υ(nS) yields vs multiplicity (pp / p-Pb / Pb-Pb)

JHEP 04 (2014) 103

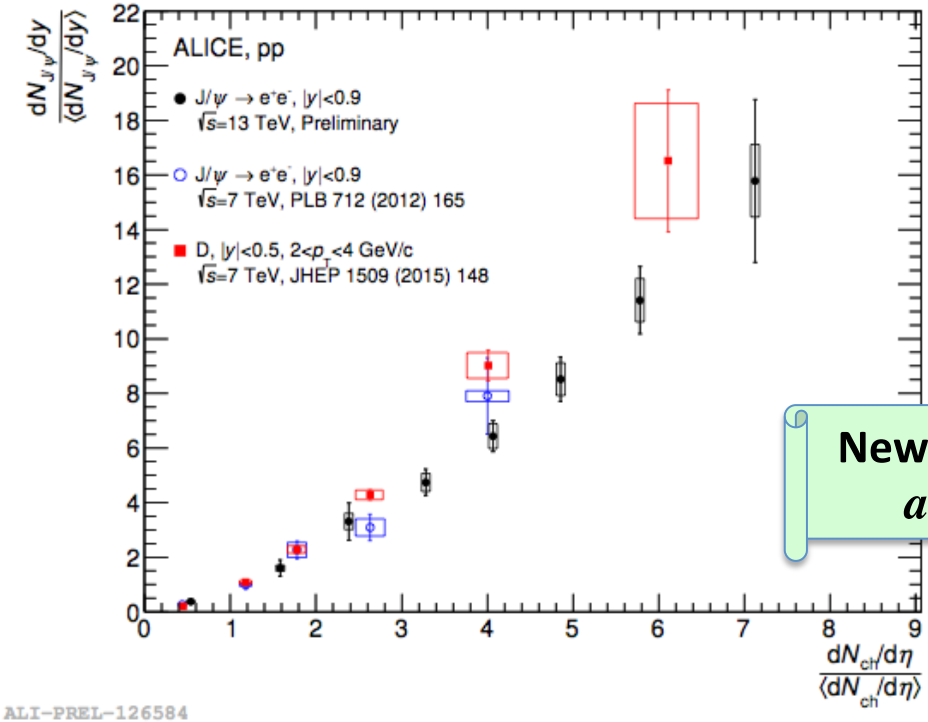
- CMS: Υ(nS) yields self-normalized to their integrated values as a function of particle multiplicity at mid rapidity normalized to the average number

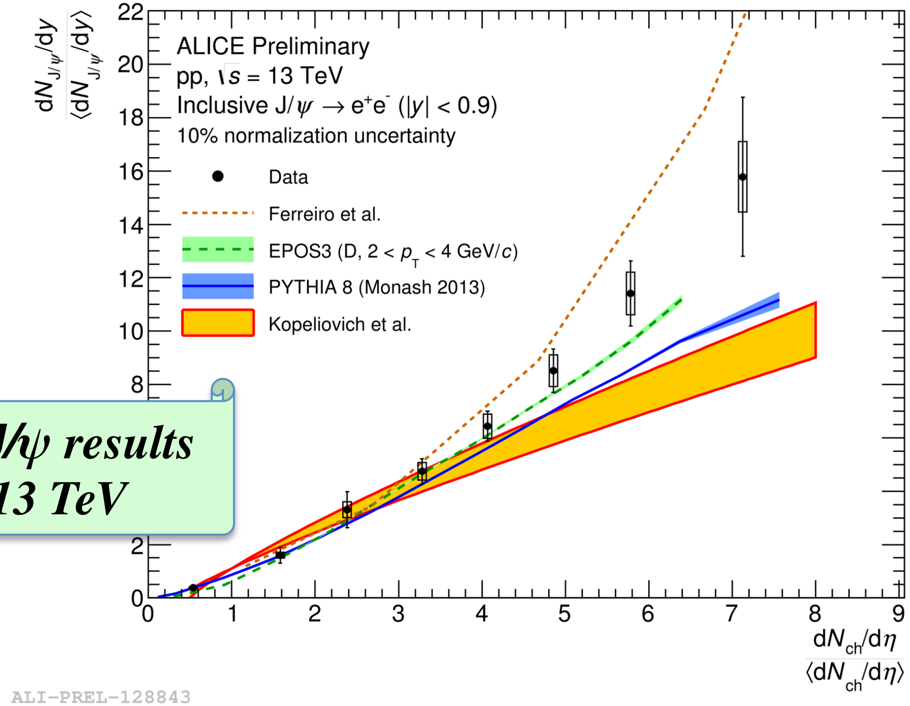


- Υ(nS) yields increase with multiplicity: similar linear (diagonal) patterns observed in the heavier systems
- More pronounced yields in pp at high multiplicity

ALICE: J/ψ and Open Charm production vs charged multiplicity in pp

***D* at 7 TeV, *J/ψ* at 7 and 13 TeV**



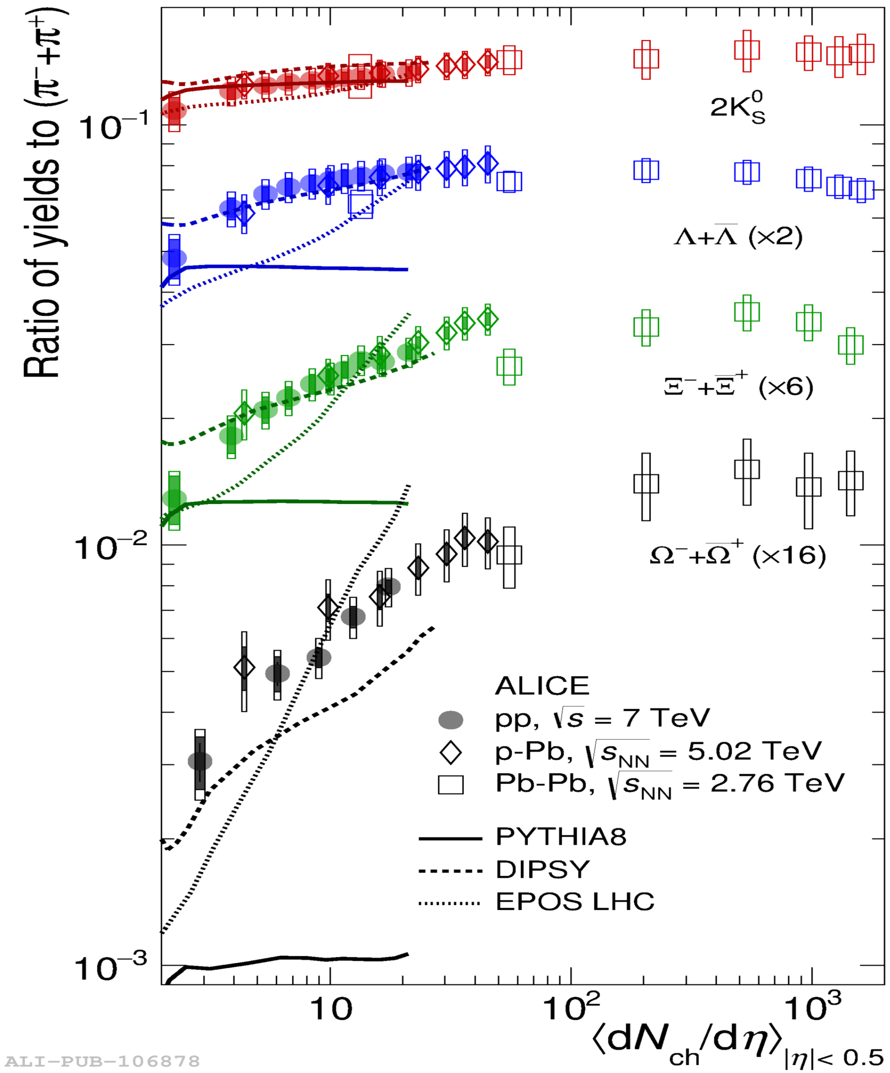


New J/ψ results at 13 TeV

Increase of J/ψ and *D*-mesons yields with multiplicity (stronger than linear)

Models including Multi-Parton Interactions are favored by data

ALICE: Study of strangeness production vs charged multiplicity in pp collisions at √s = 7 TeV



- Significant enhancement of strange and multi-strange particle production at High Multiplicity

- Yields in pp and p-Pb interactions are the same (within uncertainties) despite of the differences in the initial state and even match the Pb-Pb ones at higher <**d**N_{ch}/**d**η>

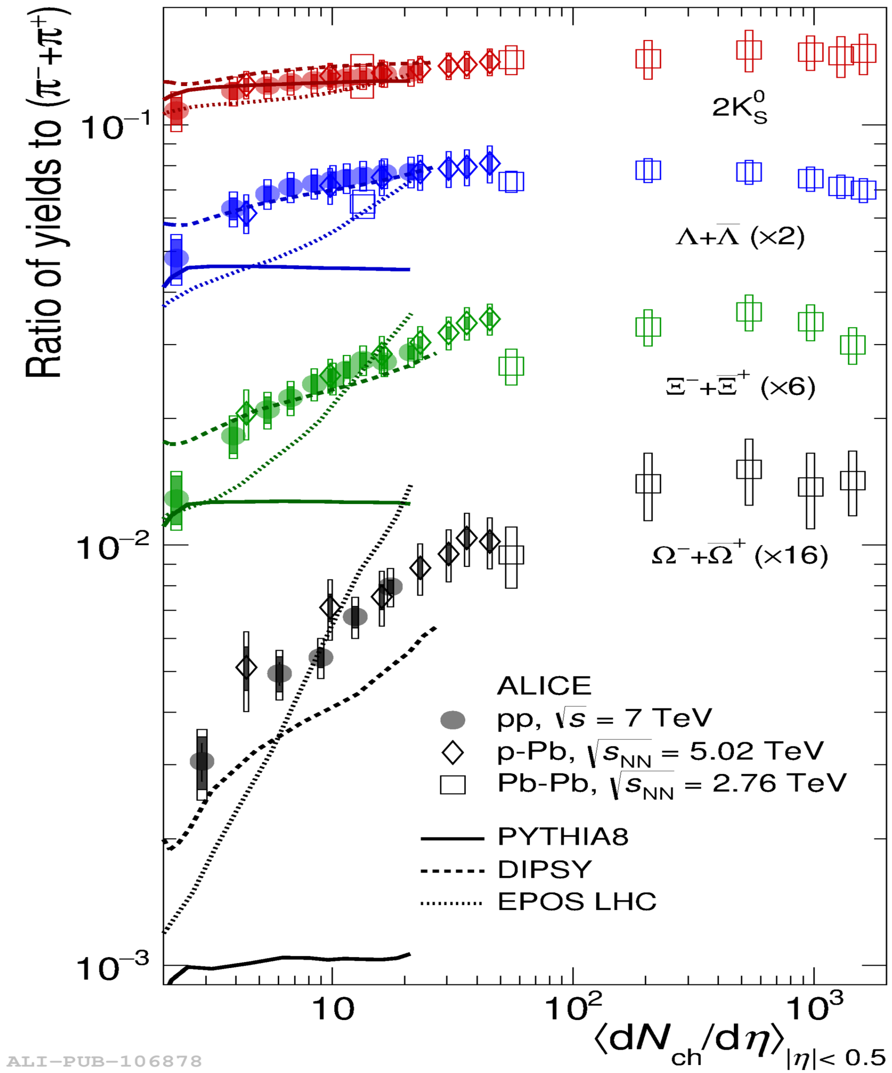
- They basically depend just on the charged multiplicity at mid-rapidity, <**d**N_{ch}/**d**η>

- V. Topor Pop, M. Gyulassy, J. Barrette, C. Gale, and A. Warburton, *"Can hyperon/meson ratios in rare high multiplicity pp collisions at Large Hadron Collider energies provide signatures of mini-quark-gluon plasma formation?" Phys.Rev. C86 (2012) 044902*

pp results: *Nature 2017*

p-Pb results: *Phys. Lett. B 758 (2016) 389-401*

ALICE: Study of strangeness production vs charged multiplicity in pp collisions at √s = 7 TeV



pp results: *Nature 2017*

p-Pb results: *Phys. Lett. B 758 (2016) 389-401*

- The description provided by the Monte Carlo Generators is insufficient, however one can rank the models based on their qualitative behavior:

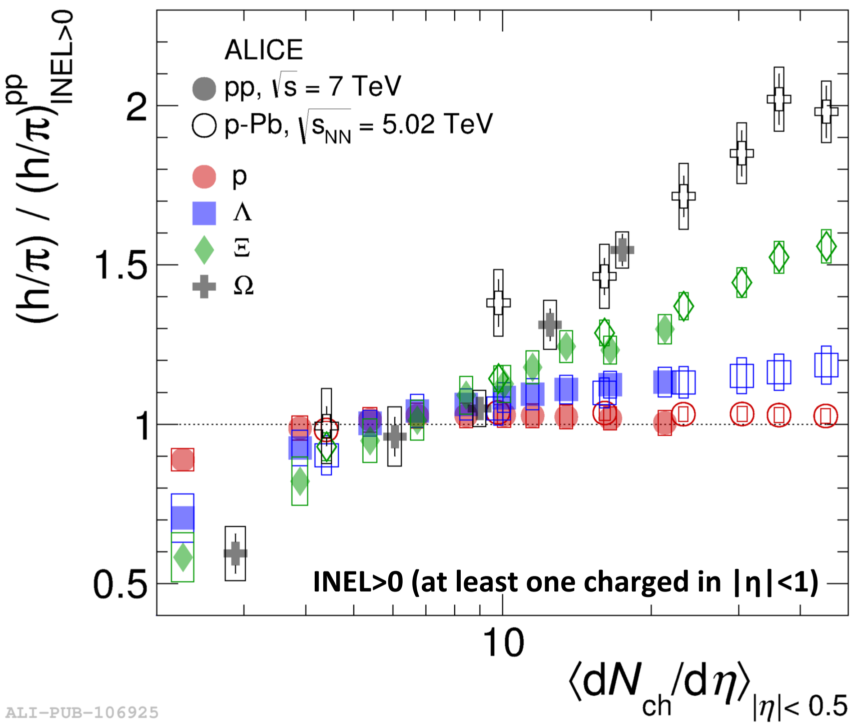
Pythia8 (String fragmentation)
→ **too flat**

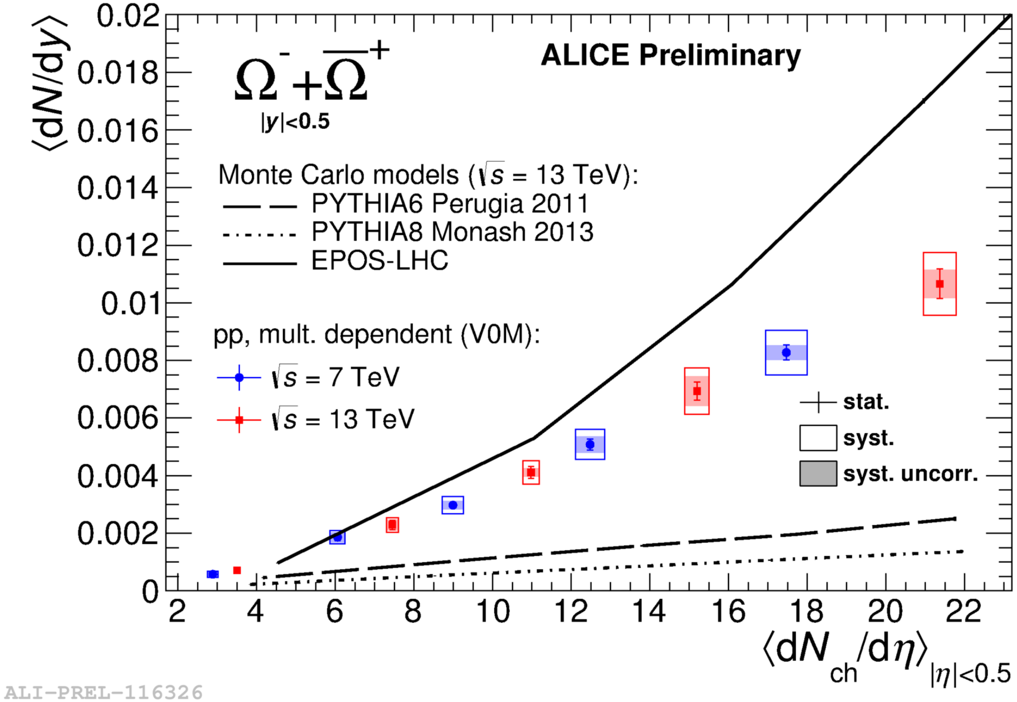
DIPSY (Rope fragmentation)
→ **closer**

EPOS LHC (Collective hadronization)
→ **too steep**

ALICE: Study of strangeness production vs charged multiplicity in pp collisions

strangeness content and center of mass energy





- The observed increase is **even more pronounced** for **baryons with higher strangeness content**.

- Measurements at different center of mass energies as a function of multiplicity indicates that the **hadrochemistry is driven by event activity regardless of √s**

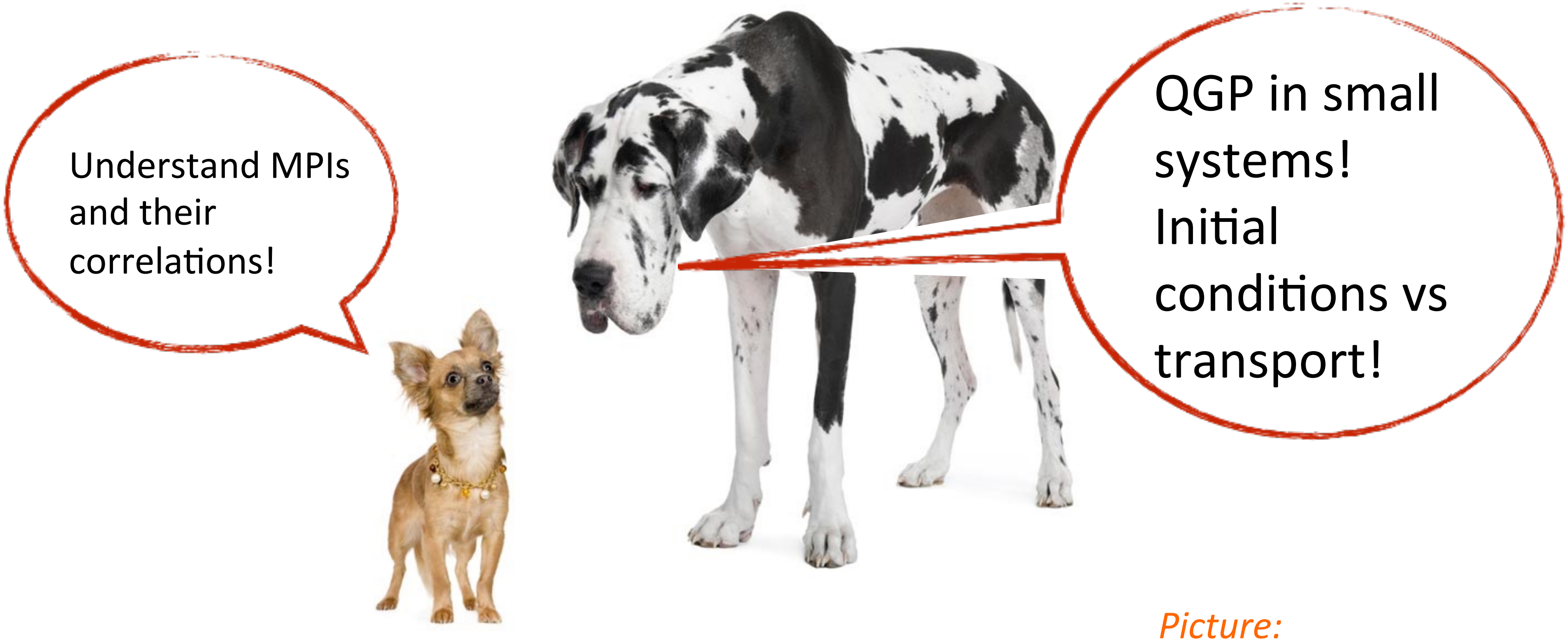
→ Scaling not reproduced by the tested models

pp results: *Nature 2017*

p-Pb results: *Phys. Lett. B 758 (2016) 389-401*

Yet another observation that we **didn't expect**
and we **don't** (fully) **understand** in

High Multiplicity pp & pA collisions



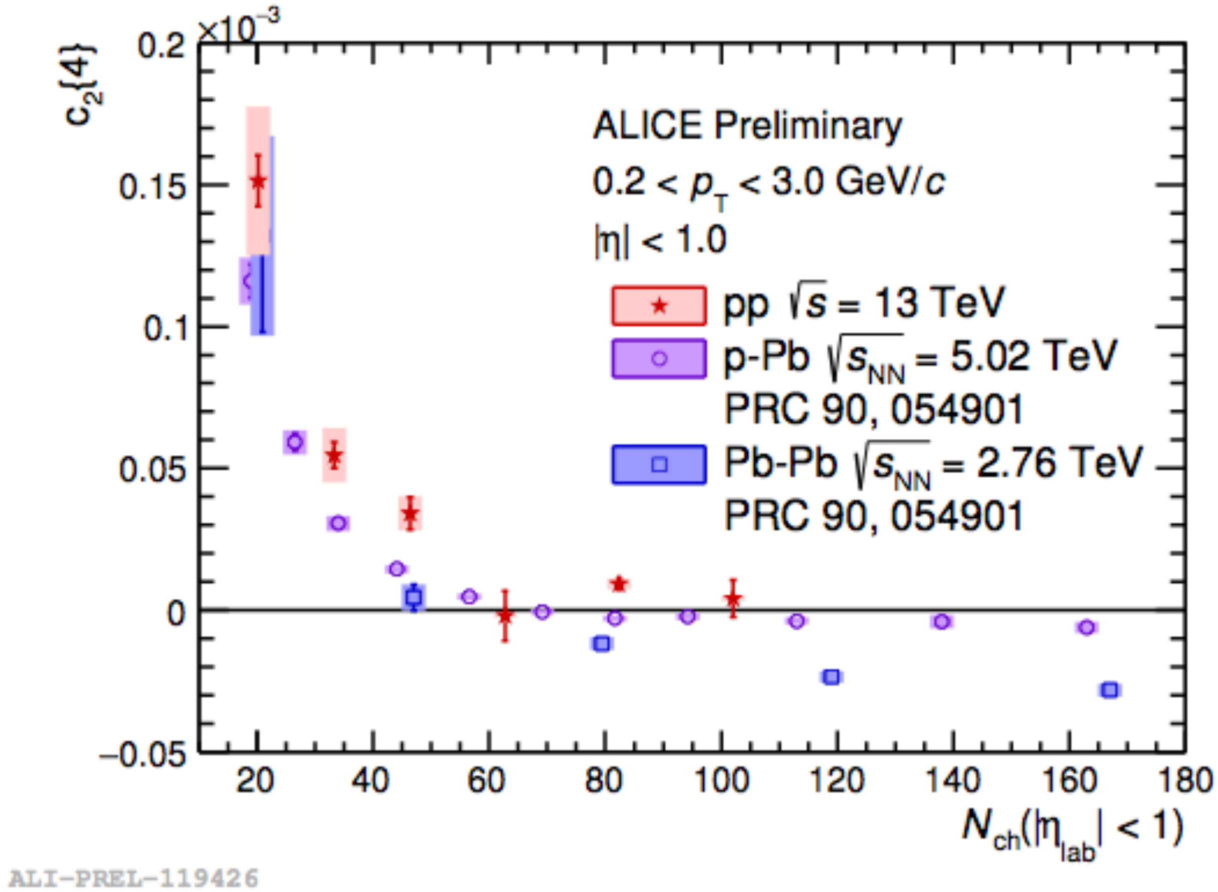
pp physicist **HI physicist**

Picture:
Credit Michele Floris

Interpretations should rely on a rich phenomenology, exploiting also the interplays between different underlying mechanisms

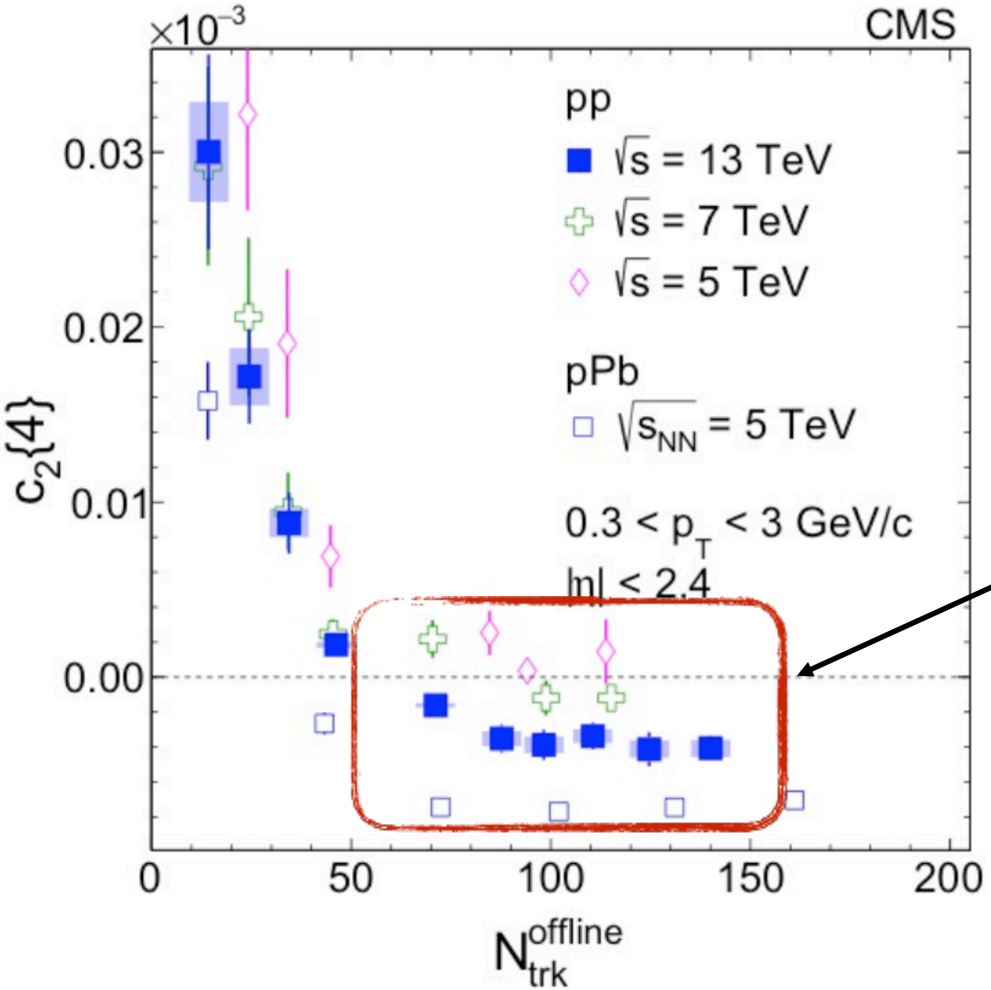
- Correlations vs Multiplicity

ALICE: Searches for azimuthal flow in pp collisions at √s = 13 TeV



- Negative four-particle cumulant $c_2\{4\}$ indicates collective behaviour *arXiv:1701.03830v1*
  ✓ No definitive evidence seen in pp by ALICE within uncertainties

CMS: Searches for azimuthal flow in pp and p-Pb collisions



Energy dependence?

Negative $c_2\{4\}$ reported by CMS

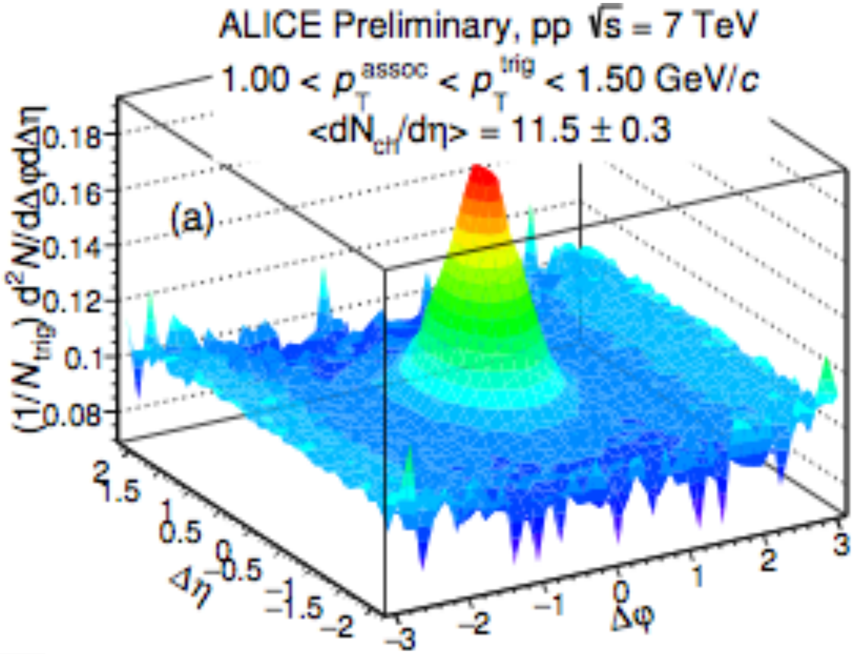
Z. Chen, CMS, QM17

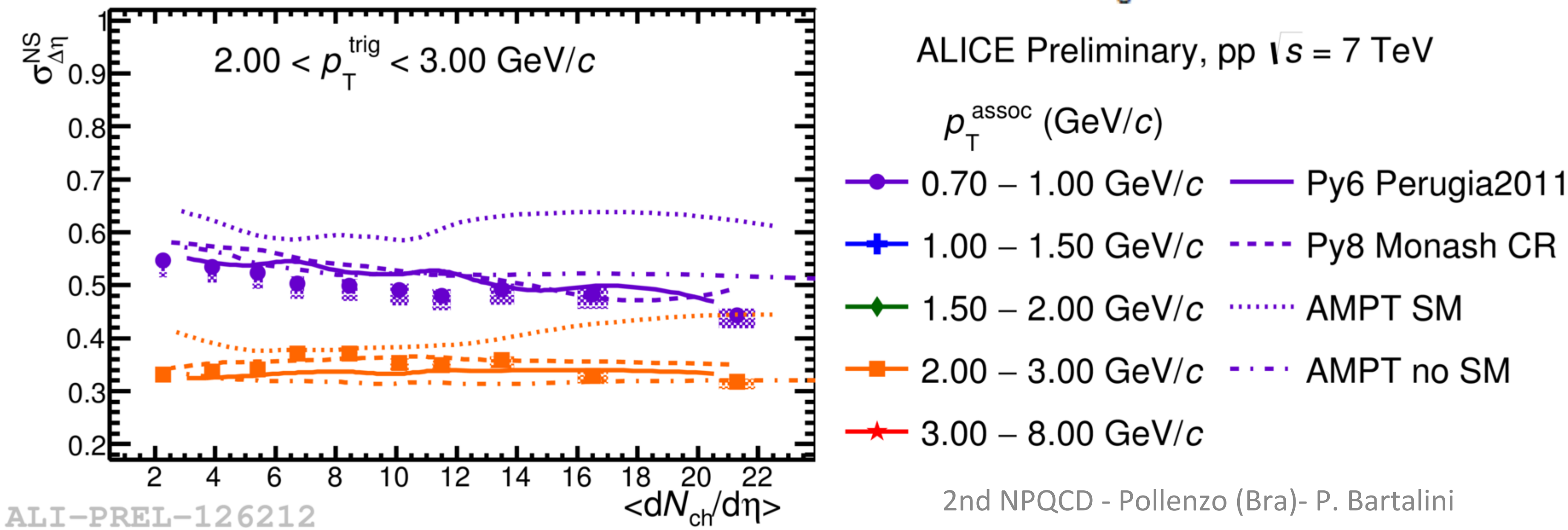
- Jet Shapes vs Multiplicity

ALICE: Nearside peak in two-particle correlations vs multiplicity in pp at √s = 7 TeV

- Is jet fragmentation altered in high multiplicity pp collisions?

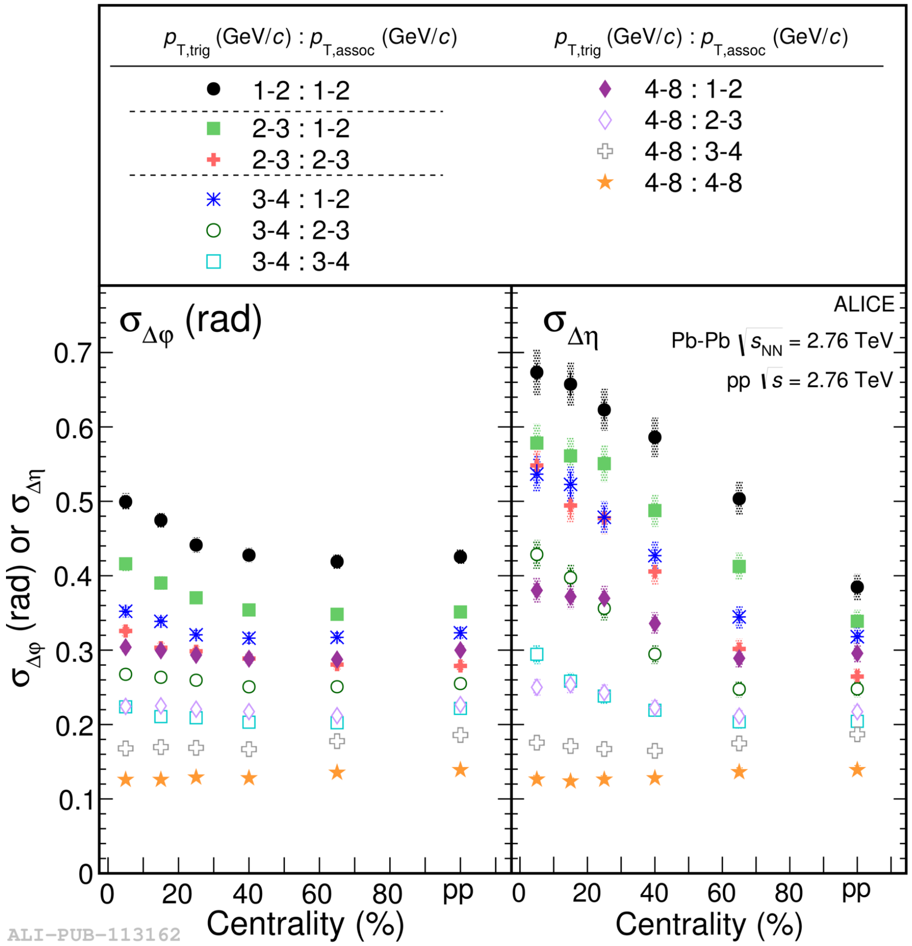
- Jet peak shape shows little to no dependence on multiplicity

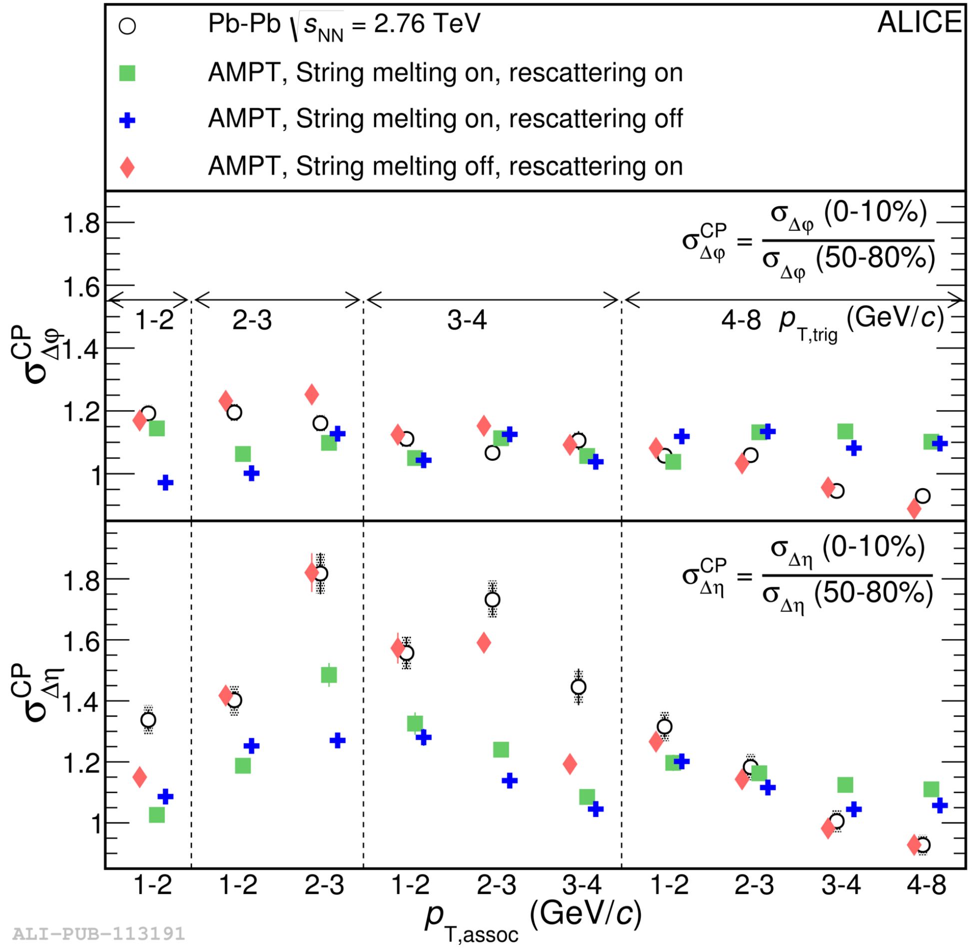




ALICE: Nearside peak in two-particle correlations vs multiplicity in Pb-Pb at √s = 2.76 TeV

arXiv:1609.06643, submitted to PRL





- Ordering of the width according to p_T
- Small broadening in Δφ , significant broadening in Δη
- AMPT description insufficient; best with melting off and re-scattering on

- Event shapes vs Multiplicity

ALICE: Transverse Sphericity (S_T) analysis

Eur.Phys.J. C72 (2012) 2124

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

Where λ_1 and λ_2 are the eigenvalues of S_{xy}:

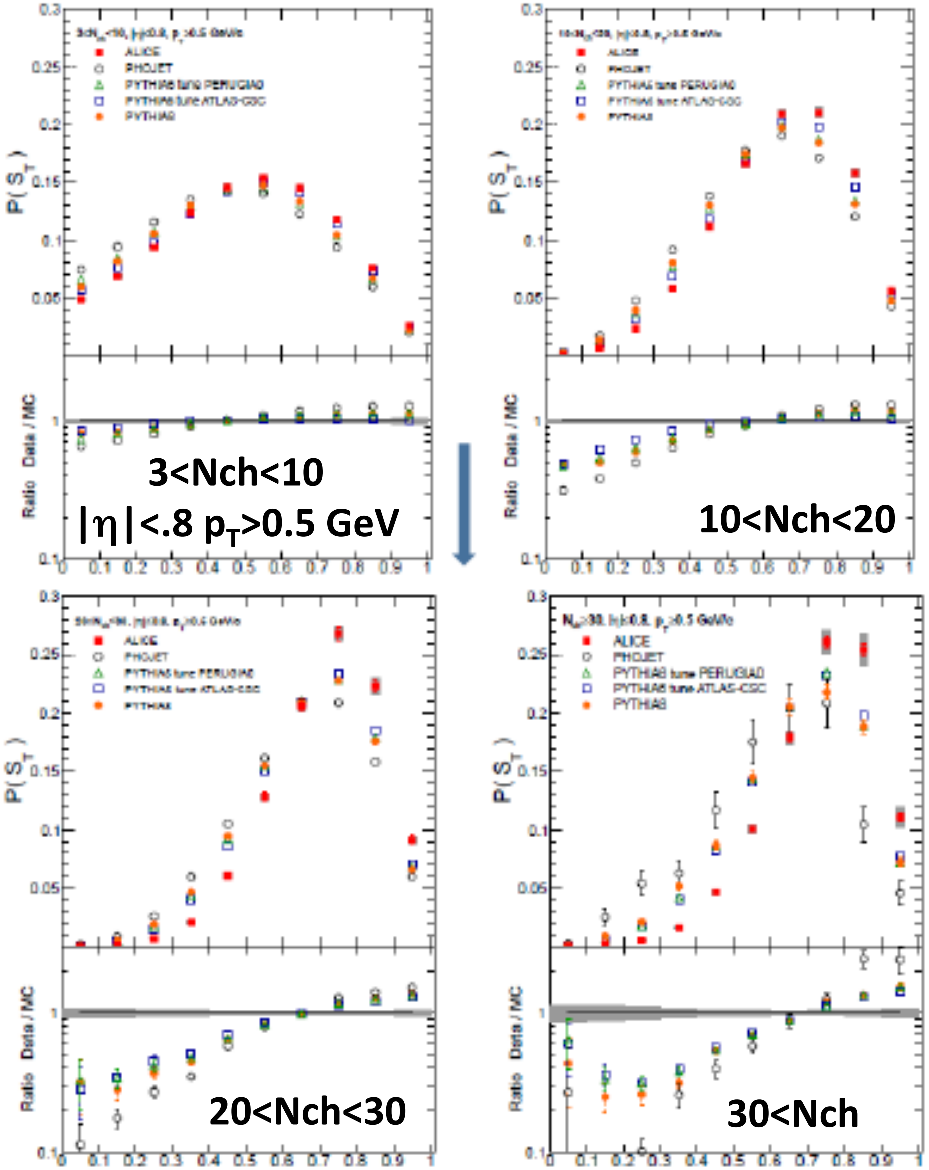
$$\mathbf{S_{xy}} = \frac{1}{\sum_j p_{T_j}} \sum_i \frac{1}{p_{T_i}} \begin{pmatrix} p_{x_i}^2 & p_{x_i} p_{y_i} \\ p_{y_i} p_{x_i} & p_{y_i}^2 \end{pmatrix}$$

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

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

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

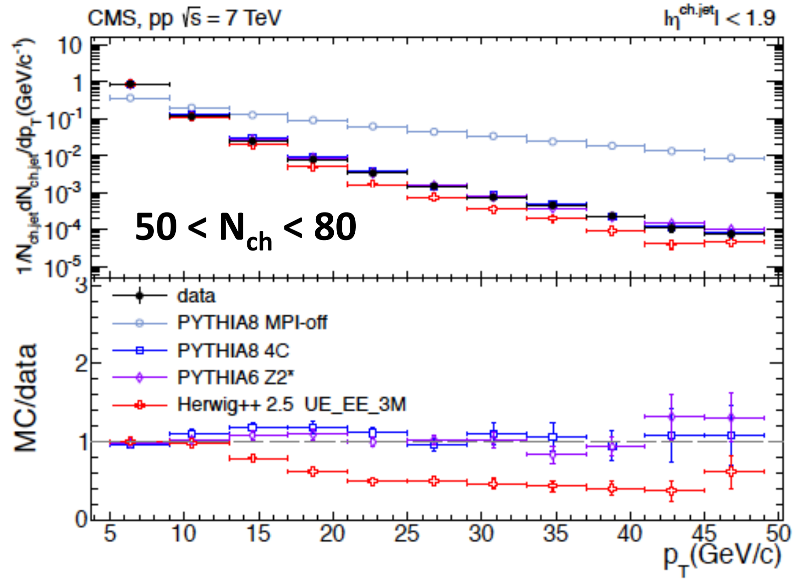
Sphericity observables may provide additional handles to study large multiplicity features.



- Jet p_T vs Multiplicity

CMS: jet p_T vs N_{ch}

Eur.Phys.J. C73 (2013) 2674



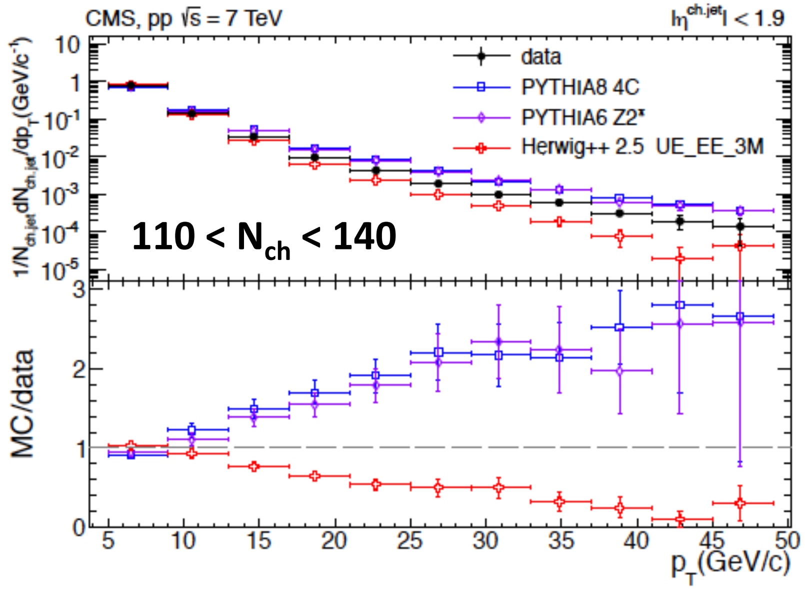
- Similarly to the centrality classification of events in nuclear collisions, events are sorted according to their charged particle multiplicity:

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

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

Really not much

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



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

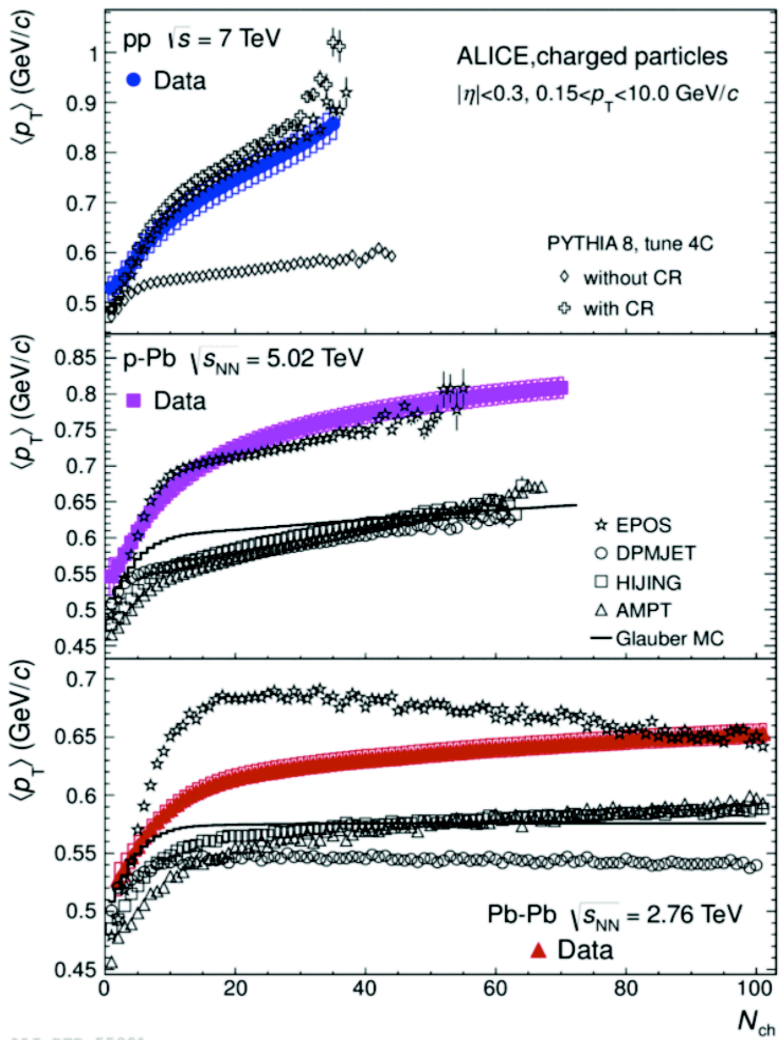
1. In each event, jets are found with anti-kT algorithm using charged particles only. The charged particles falling within a jet are further called "intra-jet" particles.

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

- $<p_T>$ vs Multiplicity
- $<p_T>$ fluctuations vs Multiplicity

ALICE: Charged particles: <p_T> vs multiplicity

Phys. Lett.B B727 (2013) 371



pp:

Naïve picture: if MPIs uncorrelated expect flat <p_T> vs N_{ch}

→ Ruled out by data!

→ Color Reconnection (CR) in MPI unavoidable to describe the <p_T> vs N_{ch} correlations.

(√s scaling: all the properties are driven by N_{ch})

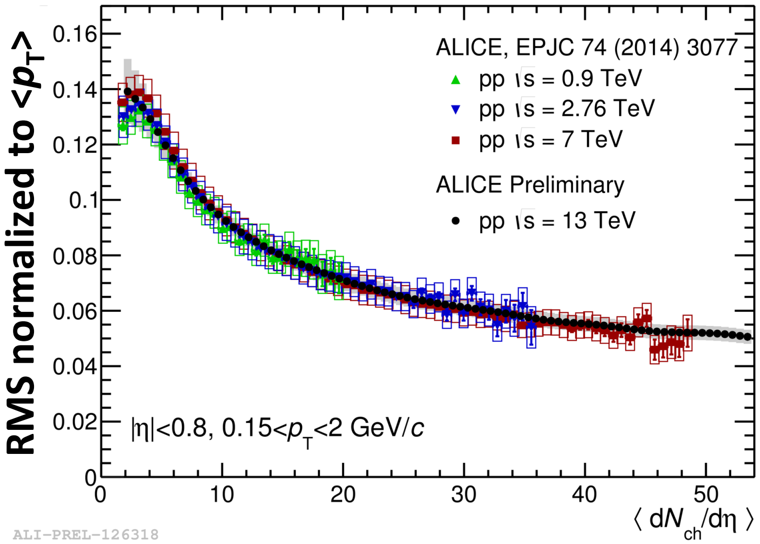
p-Pb:

EPOS OK, however shape qualitatively similar to the Pythia 8 predictions for tune 4C CR (i.e. with Color Reconections).

Pb-Pb:

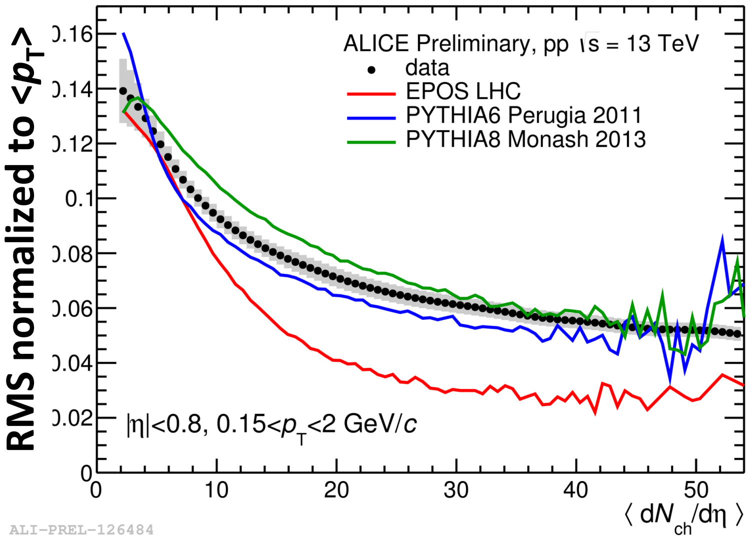
HI MCs are not able to provide a sufficient description, agreement with Pythia 8 predictions for tune 4C NOCR (i.e. with no Color Reconnections).

ALICE: Charged particles in pp collisions <p$_T$> fluctuations vs multiplicity



- <p_T> fluctuations: yet another multiplicity dependent observable that scales with √s!
  - Good inclusive description achieved by Pythia, fluctuations underestimated by EPOS LHC
- However, worse description of "spherical" events

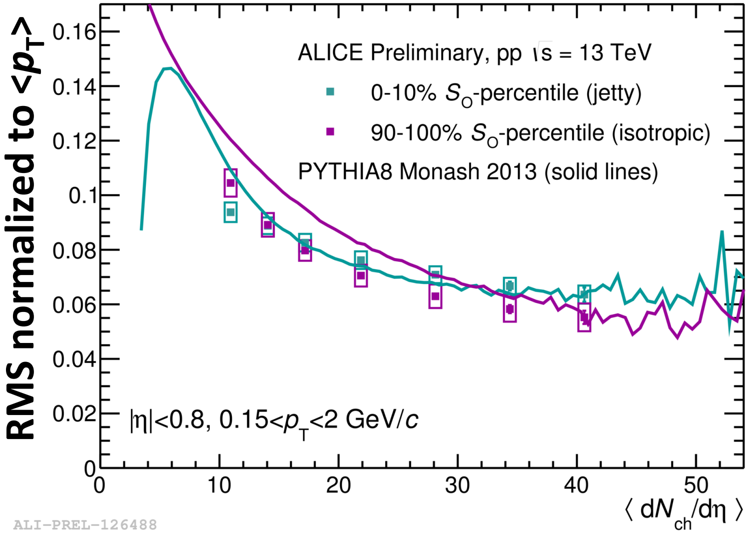
(On the other hand we know already that at HM the rate of spherical events is underestimated by Pythia *Eur.Phys.J. C72 (2012) 2124*)



See

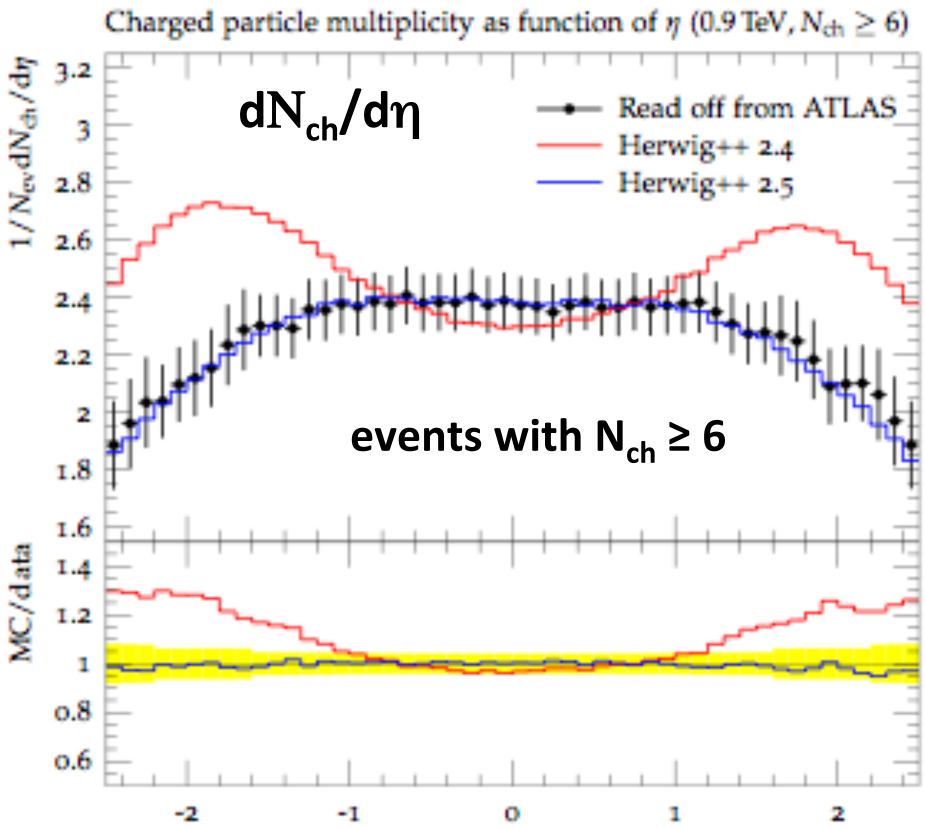
Irais Bautista QM'17

arXiv 1705.02056



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

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. *arxiv 1102.1672*

→ Color reconnection unavoidable to describe basic observables like the shape of the pseudorapidity distribution

Conclusions

- Huge progress on MPI studies from LHC RUN I & II
- Soft and Hard MPI pictures getting more and more consistent
- High Multiplicity final states of small systems
  - interpretation of the results still controversial: MPI, QGP, CGC, interplays, …
  - Nice scaling properties → N_{ch} more important than √s…

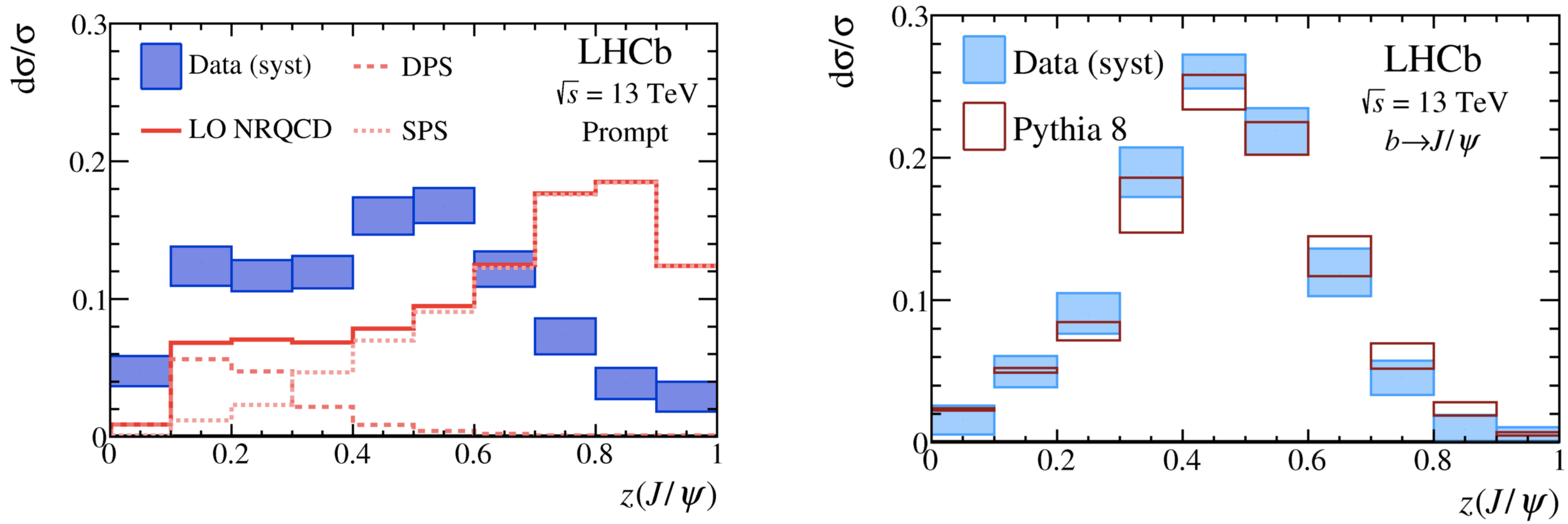
BACK-UP

Recent HF production

LHCb: J/ψ production in jets in pp collisions at √s = 13 TeV

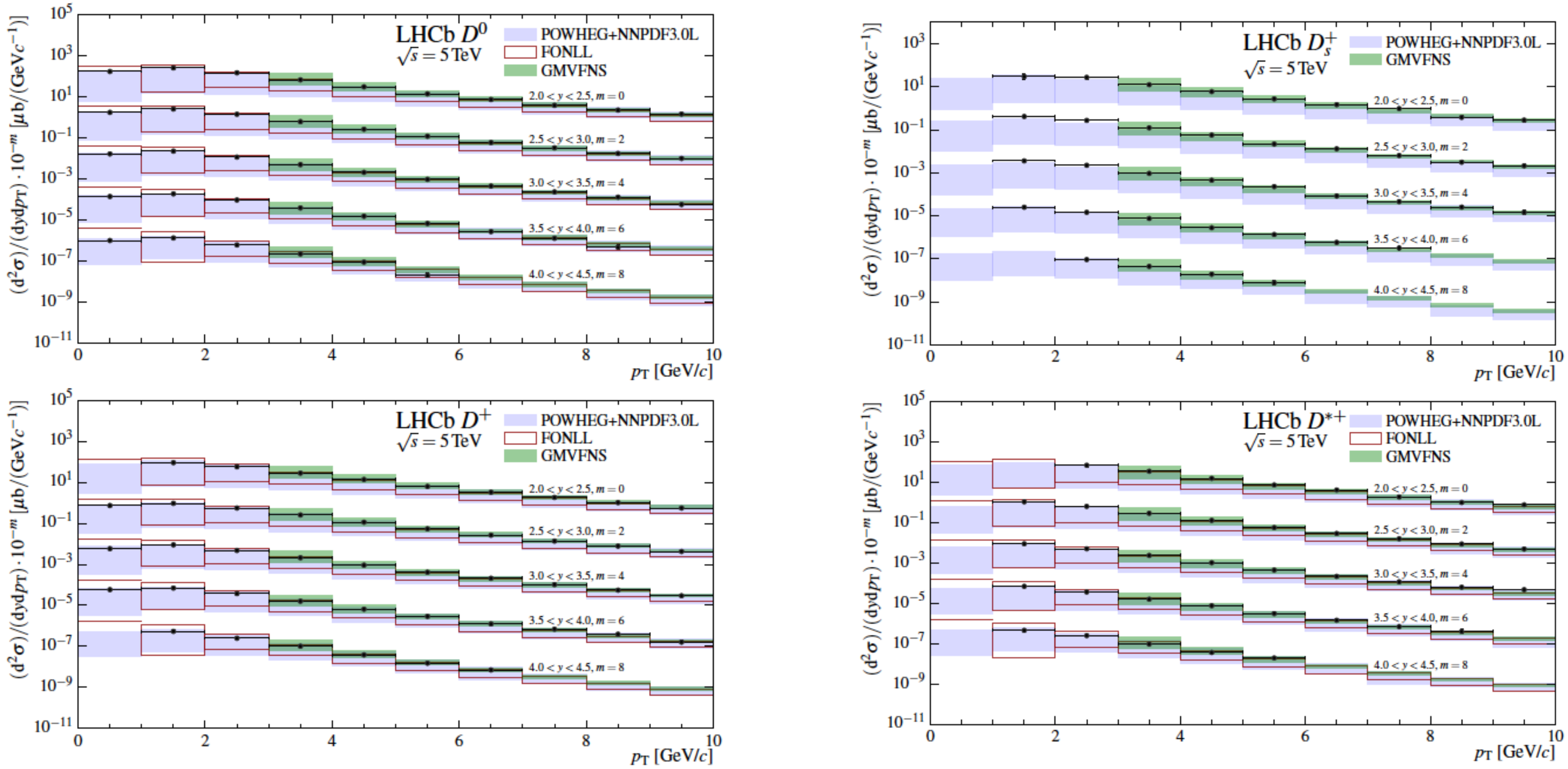
Phys. Rev. Lett. 118, 192001 (2017)

- Physics with jets at LHCb covers a wide range of QCD topics: Set important constraints in proton PDFs and probe hard QCD in a unique environment
  - Nice example, brand new analysis: Measurement of the fraction of p_T carried by J/ψ when reconstructed within a jet.
  - Clear difference comparing prompt and J/ψ production from *b*!



LHCb: Prompt charm production differential cross sections in pp at √s = 5 TeV

arXiv 1610.02230 **(Forward rapidity!)**



0 < p_T < 10 GeV/c for D_0 and D^+ **1 < p_T < 10 GeV/c for D_s^+ and D^{*+}**

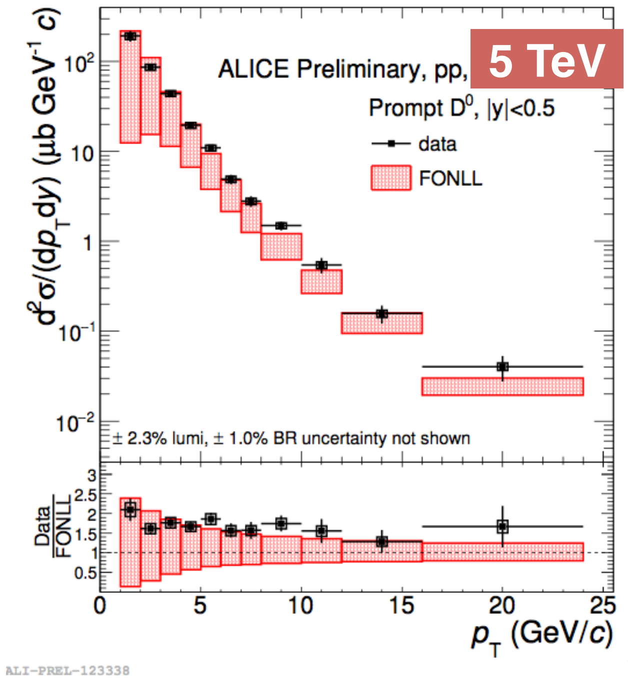
2.0 < y < 4.5

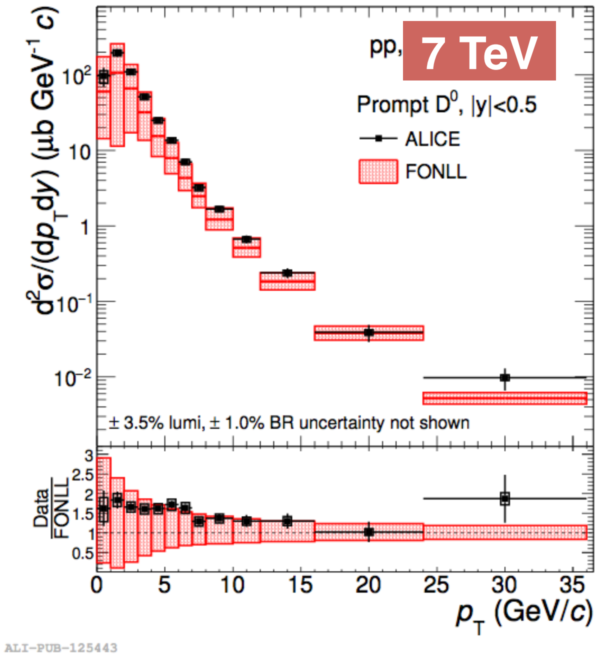
The measured values tend to lie at the upper edge of the predictions

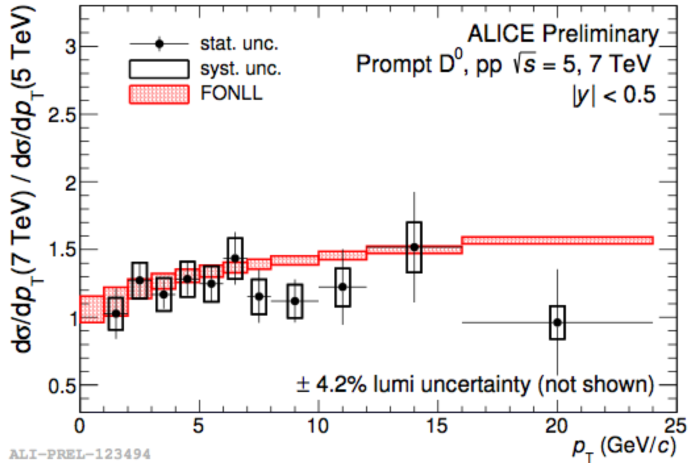
ALICE: Prompt charm production differential cross sections in pp at √s = 5 and 7 TeV

(Central rapidity!)

arXiv:1702.00766







New D^0 cross section measurement at 5 TeV

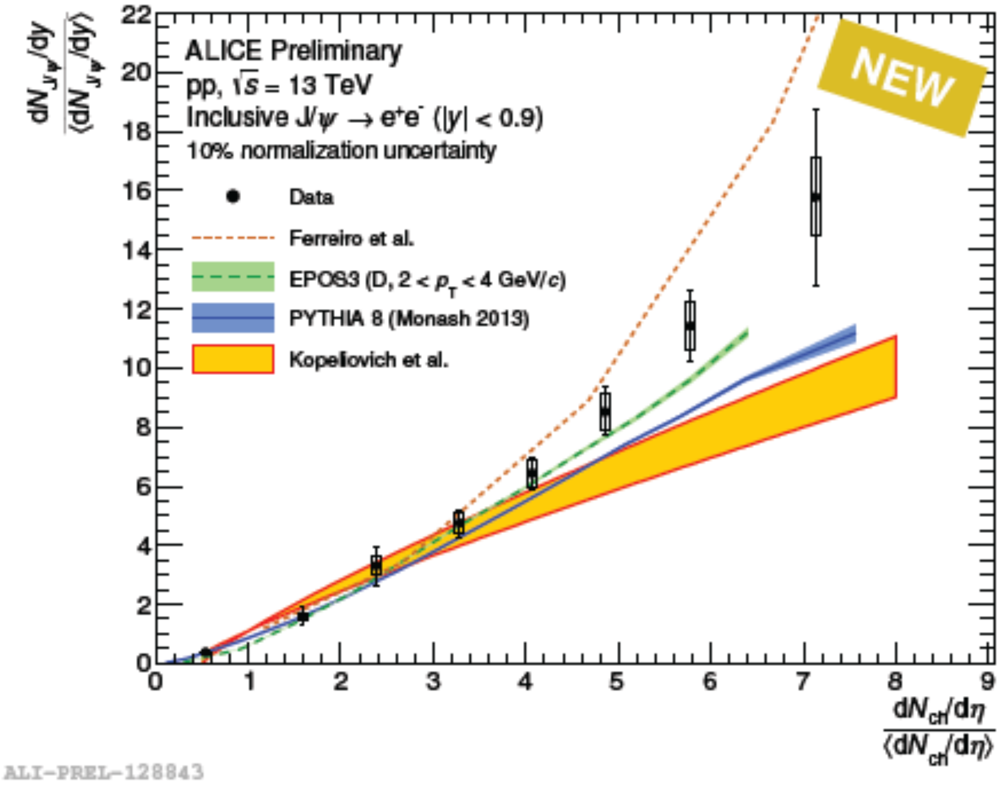
Measurement down to zero p_T at 7 TeV

Ratio compatible with pQCD-based model

The measured values tend to lie
at the upper edge of the FONLL predictions

ALICE: *J/ψ* production vs charged multiplicity in pp

Model comparison   J/ψ



Qualitative agreement with models except for PYTHIA 8 and Kapeliovich at high multiplicity

Important role of MPI in hadronic collisions

Percolation Model
[Phys.Rev. C86 (2012) 034903; arXiv:1501.03381 (2015)]

Mimic MPI via interactions of color sources with finite spatial extension

EPOS 3 for D (with Hydro)
[Phys.Rept. 350 (2001) 93–289; Phys.Rev. C89 (2014) 064903]

Parton based Gribov-Regge formalism, MPI proportional to multiplicity

PYTHIA 8
[Comput.Phys.Commun. 178 (2008) 852–867]

Hard processes in MPI
(new w.r.t. PYTHIA6)

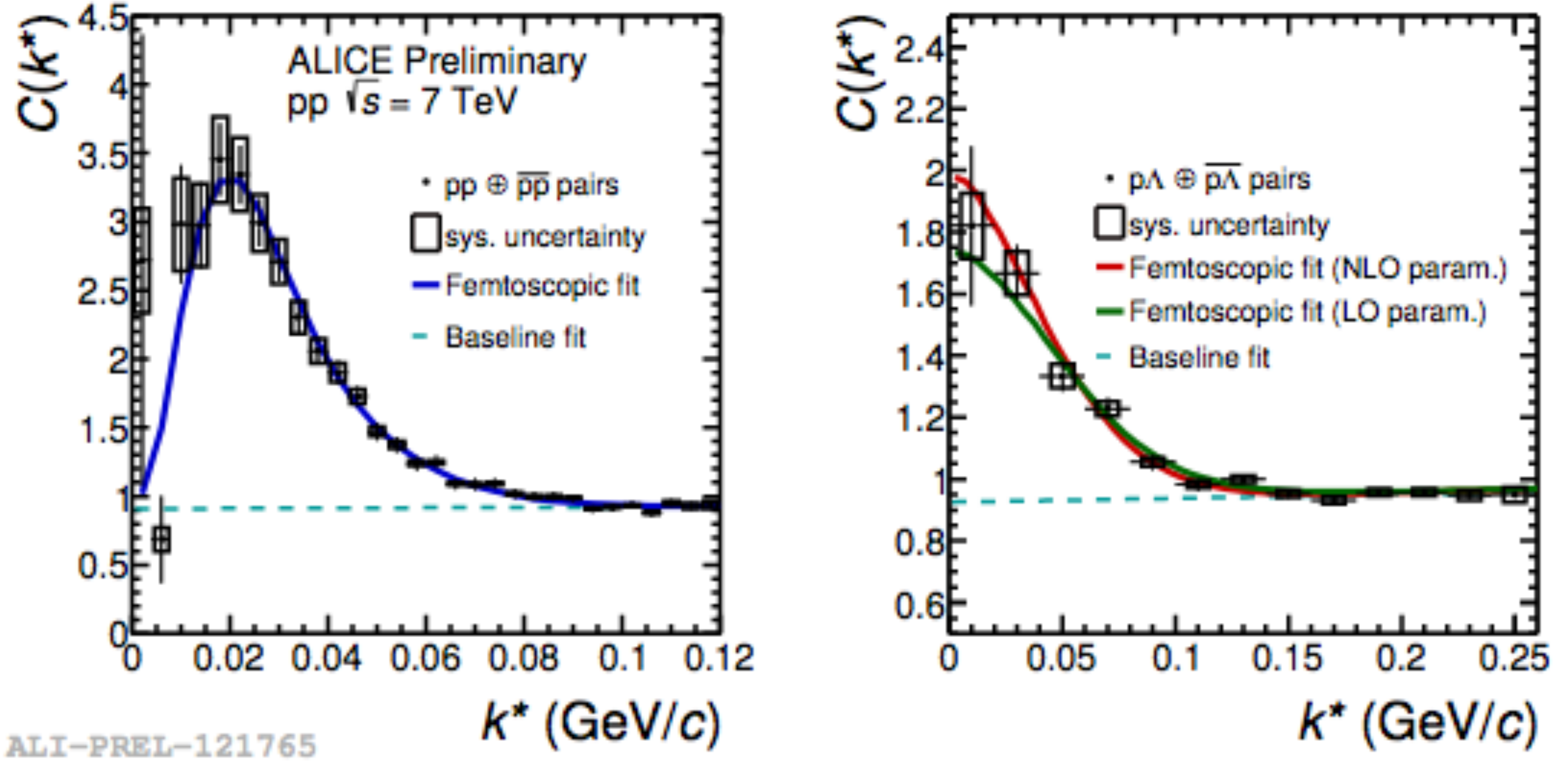
Kopeliovich et al.
[Phys. Rev. D 88, 116002 (2013)]

High multiplicities in pp collisions can be reached by contributions of higher Fock states

→ **A. Lardoux**

Baryon femtoscopy

ALICE: Baryon femtoscopy in pp 7 TeV collisions



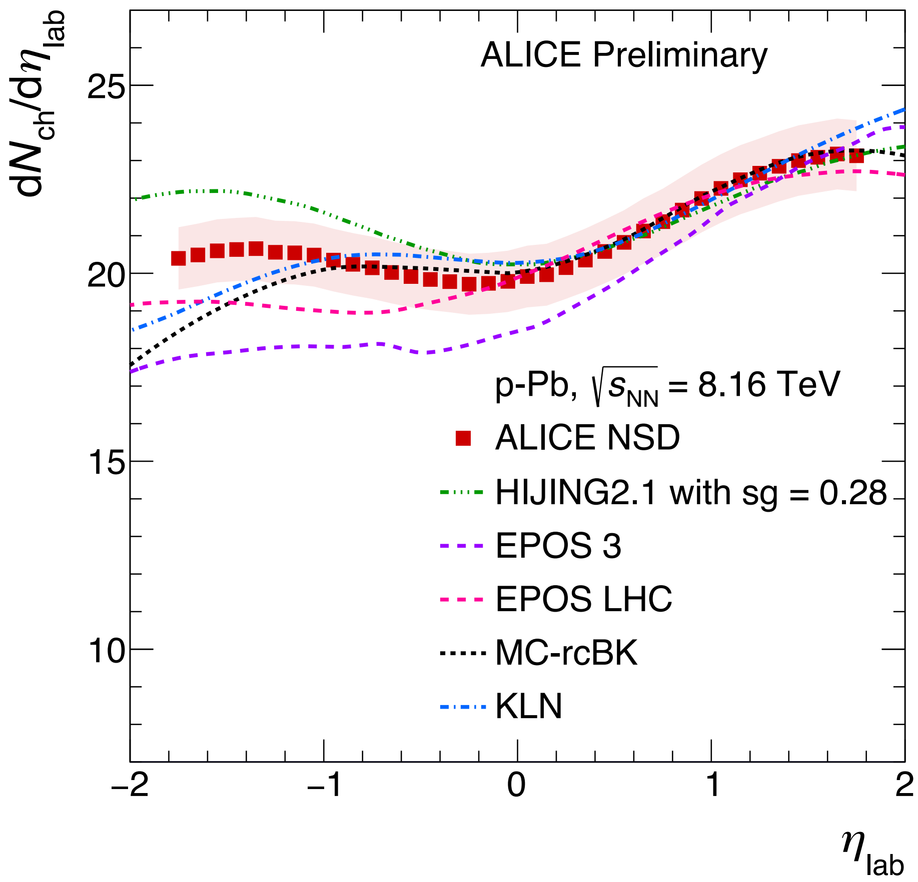
- Correlation functions in pp collisions dominated by final state strong interactions
- Scattering parameters derived from fits and compared to chiral effective field theory

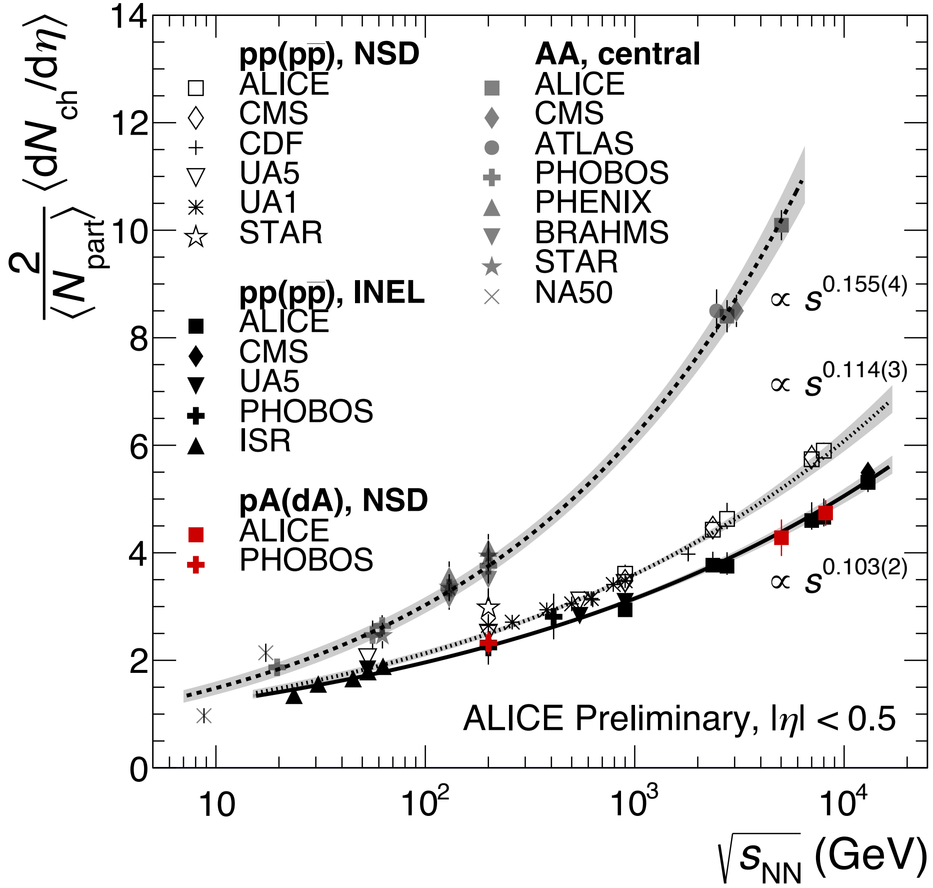
Recent η measurements

Pseudorapidity (η) and transverse momentum (p_T) distributions of charged particles

- Observables:
  - Differential distributions $\mathbf{d}N_{ch}/\mathbf{d}\eta$, $\mathbf{d}N_{ch}/\mathbf{d}p_T$, …
  - N_{ch} = number of primary charged particles
    - Primary particles are defined as prompt particles produced in the collision, including all decay products, with the exception of those from weak decays of strange particles.
- Detector performance
  - Count charged tracks for p_T > 50 MeV/c, reconstruct them for p_T > 150 MeV/c
  - → Corrections / uncertainties small
- Physics Programme
  - Test of Soft QCD: low x in collinear factorization and alternative descriptions
  - Tuning of the Monte Carlo the models
  - Constrain Multiple Parton Interaction (MPI) rates, correlations
  - Reference pp data to study nuclear effects in nucleus-nucleus and in proton-nucleus collisions
- **Key input to multiplicity-dependent measurements**

ALICE: dN_{ch}/dη measurement in p-Pb at √s_{NN} = 8.16 TeV





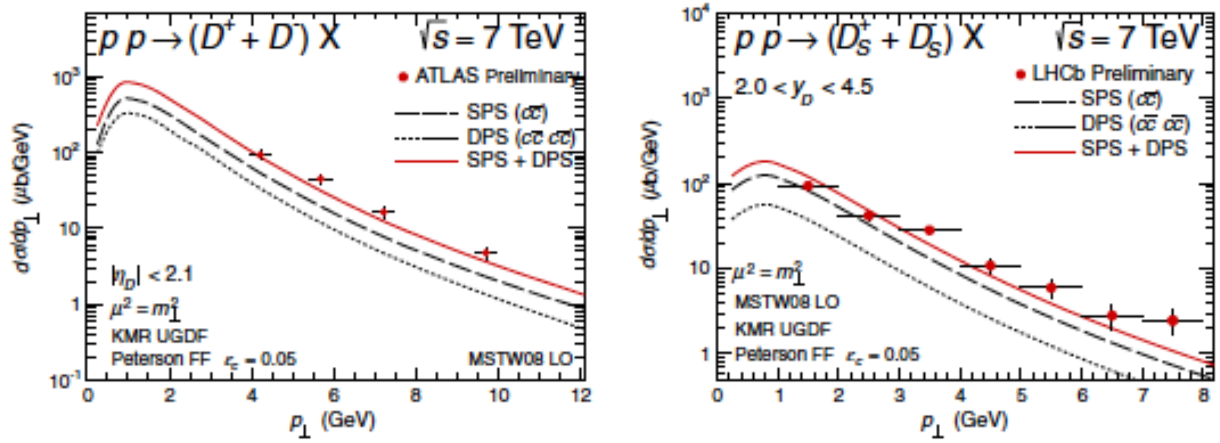
✓ MC generators close to data, in particular HIJING
- ~ 10-15% agreement.
- Effective tuning effort on Run 1 data

✓ The NSD pA measurements seem to match the inelastic pp data

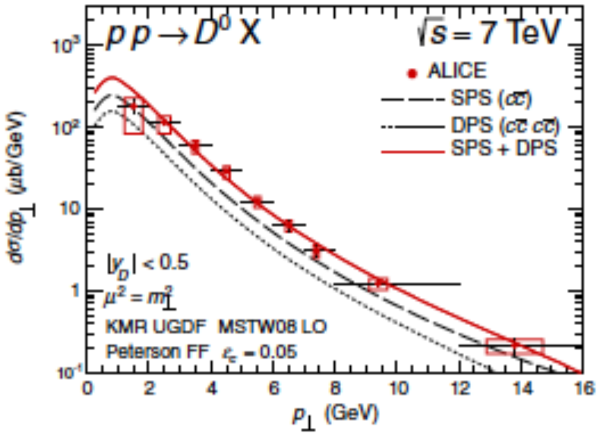
✓ Good performance of saturation-based models

Back-up DPS

DPS & Open charm production at the LHC



P(DPS) = (P(SPS))^2 * ($\sigma_{INEL}/2\sigma_{eff}$)

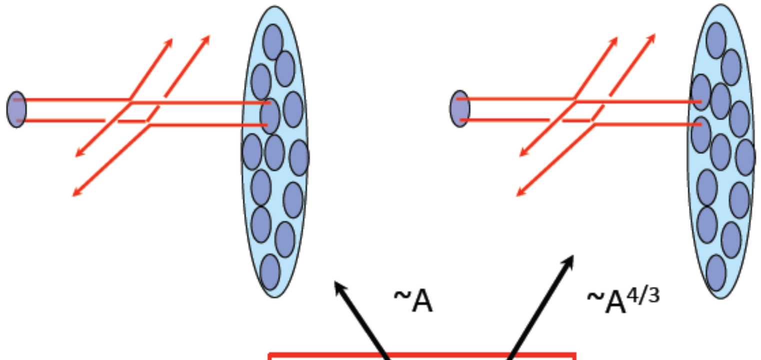


R.Maciula and A.Szczurek
Phys. Rev. D87, 074039 (2013)
assuming σ_{eff} = 14.5 mb

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

→ DPS essential to describe HF x-sections (in particular for multiple HF production)

DPS in pA collisions: W(→lν)+2jet



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

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

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

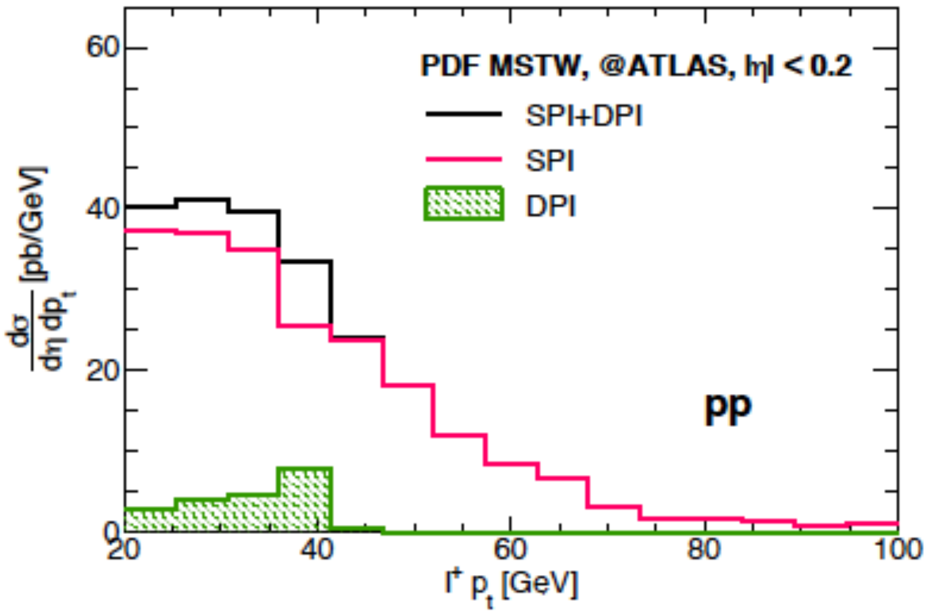
anti-shadowing contribution

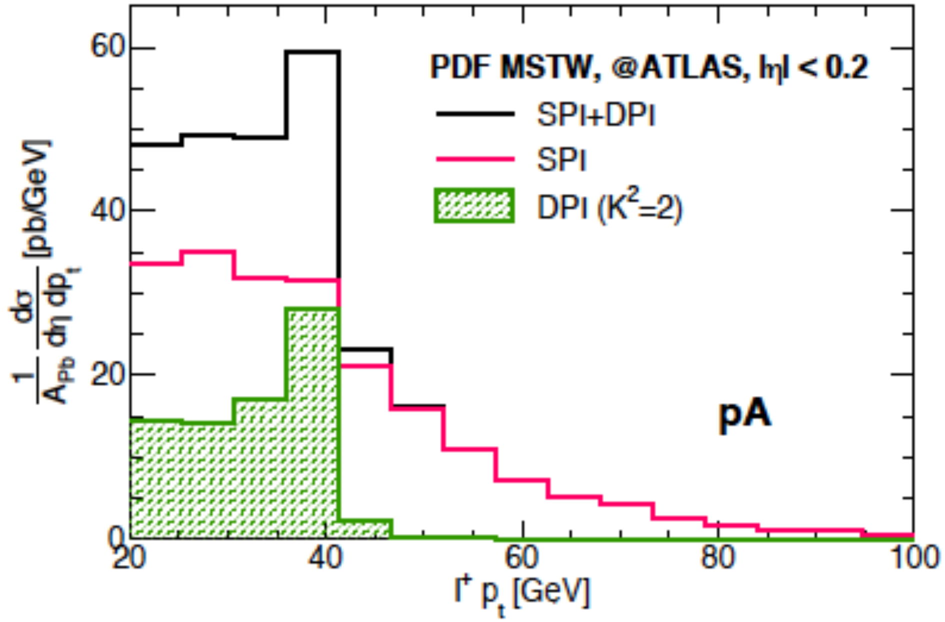
short range nuclear correlation

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

nuclear density => growth as A

[D.Treleani, 5th MPI@LHC]





Enhanced shoulder at ≈ 40 GeV in pA interactions

→ LHC Analysis feasible in RUN II ?

DPS/SPS ratios turn out to be enhanced of a factor $A^{1/3}$ in pA with respect to the corresponding ones in pp

UE in DY

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

UE Measurements in charged Jets:

Double scale picture

→ Coherent with the GPDF predictions

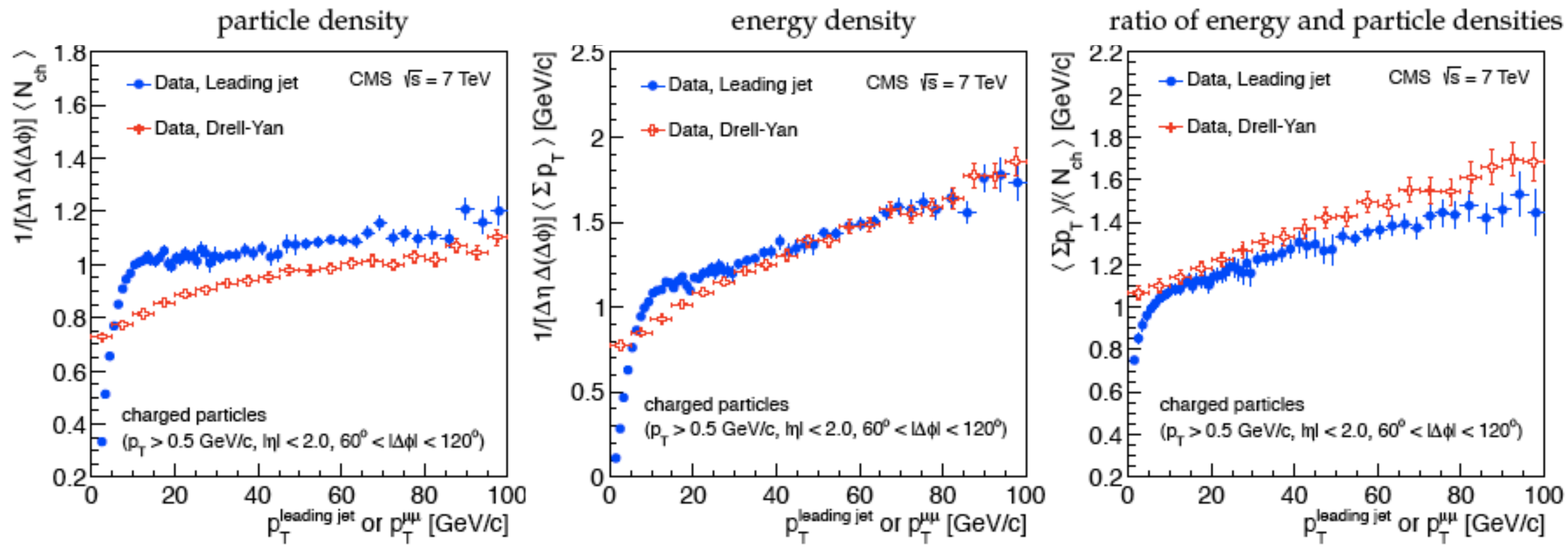
UE Measurements in Drell-Yan:

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

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

Min activity around 75% with respect to the plateau in jet events

→ Coherent with the GPDF predictions



Transverse

81 GeV < Mμμ < 101 GeV

JHEP 1109, 109 (2011).

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

ALICE results on Strangeness enhancement in small systems

Space time evolution of the particle production in an hadronic interaction

Hyperbola lines represent particles with the same proper time.

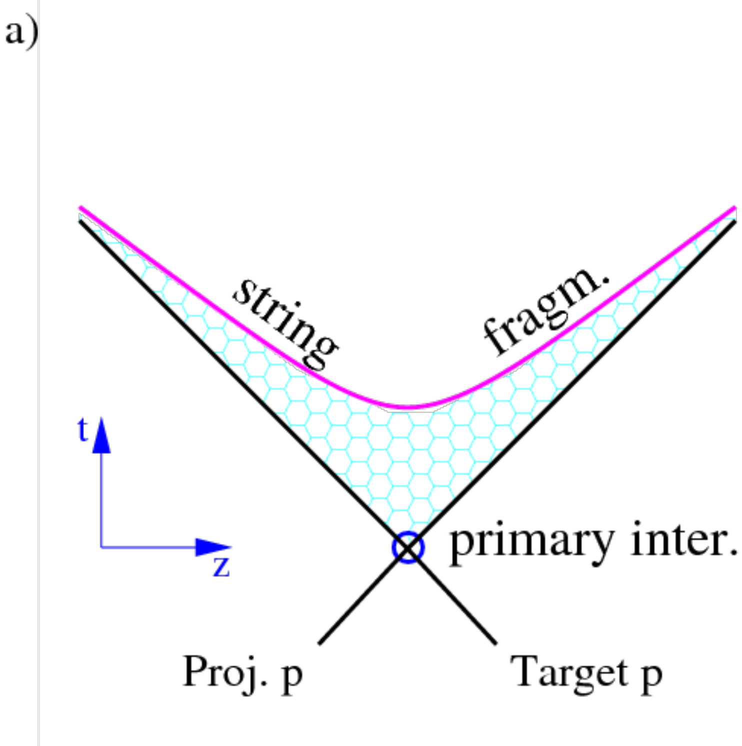


Figure a - The standard view of pp interactions

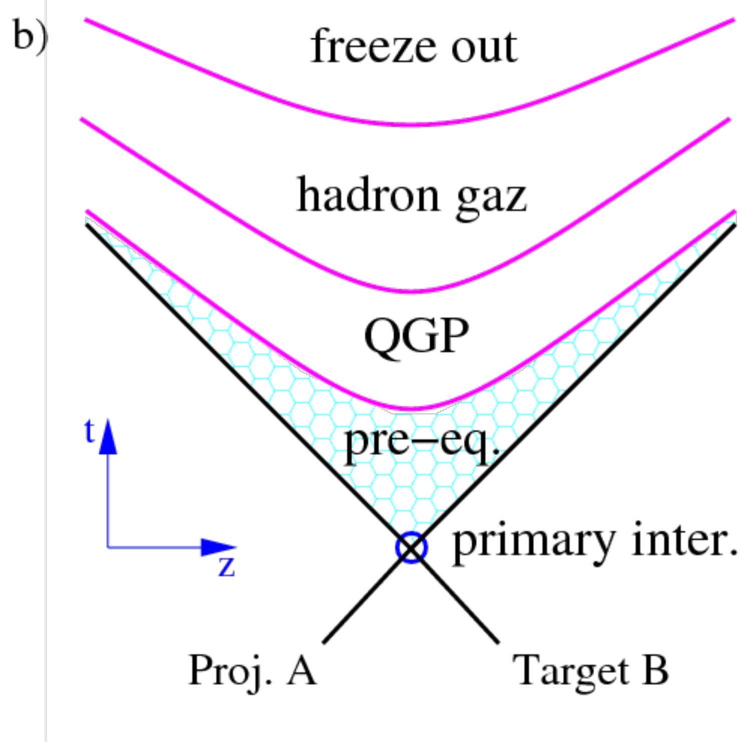


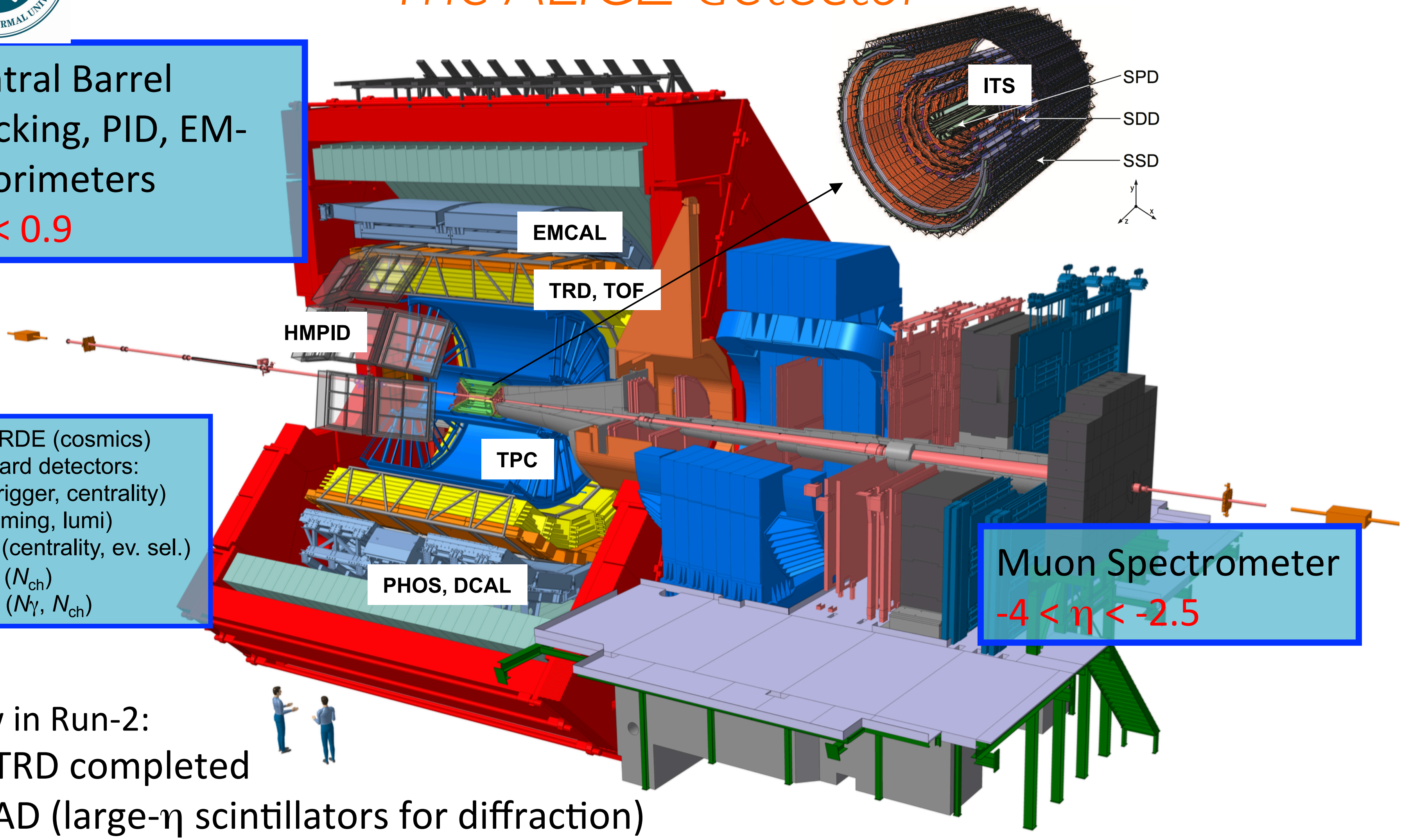
Figure b – HI collisions.

→ expect strange suppression

QGP is formed ($T > T_c = 154 \pm 9$ MeV)
→ don't expect strange suppression

The ALICE detector

Central Barrel
Tracking, PID, EM-Calorimeters
$|\eta| < 0.9$



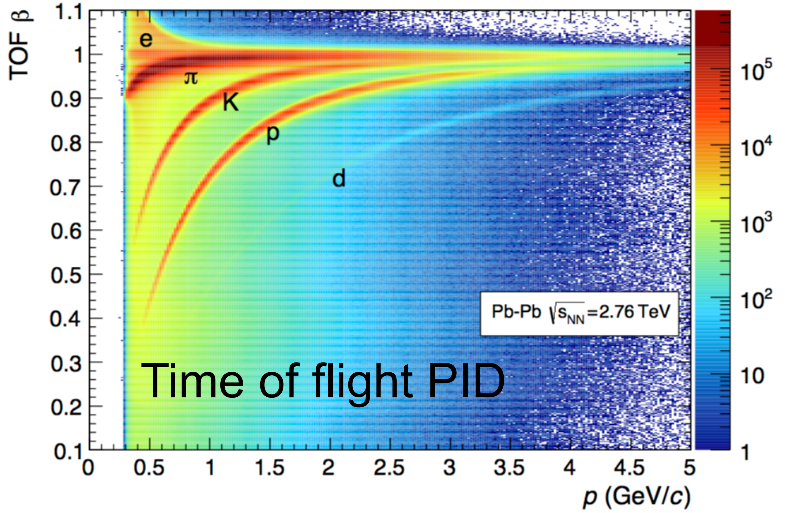
ACORDE (cosmics)
Forward detectors:
V0 (trigger, centrality)
T0 (timing, lumi)
ZDC (centrality, ev. sel.)
FMD (N_{ch})
PMD (N_{γ}, N_{ch})

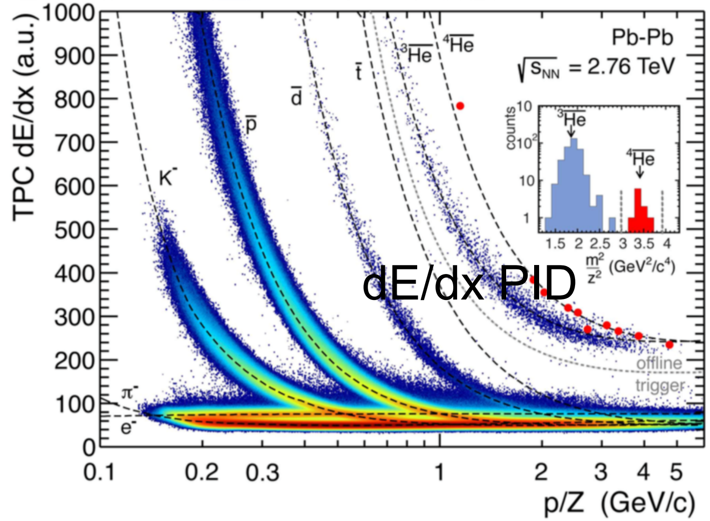
Muon Spectrometer
$-4 < \eta < -2.5$

New in Run-2:

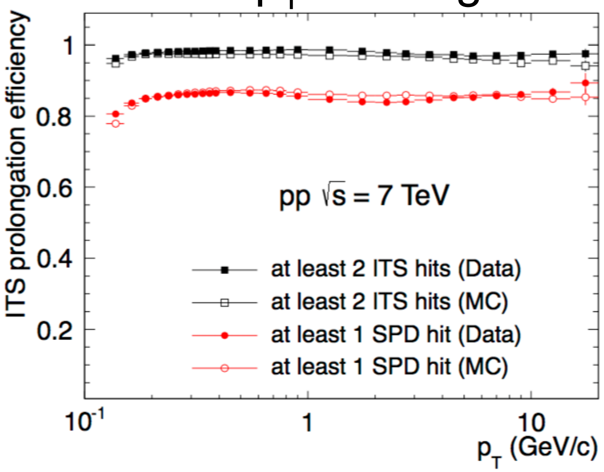
- ✓ TRD completed
- ✓ AD (large-η scintillators for diffraction)
- ✓ EMCal acceptance extended (DCAL)
- ✓ PHOS (γ e.m.cal) completed, also with Charged Particle Veto

ALICE's house specials (a selection)

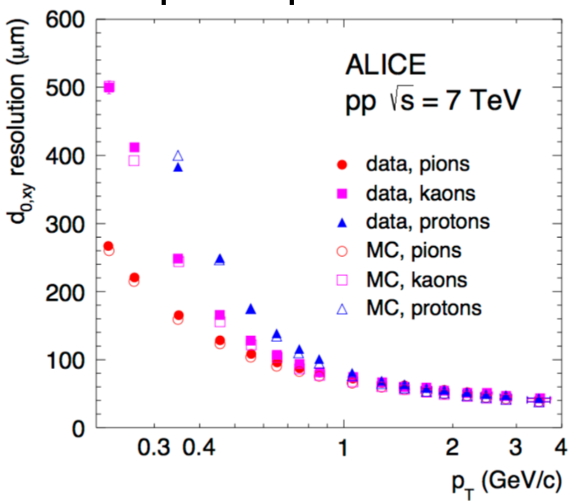




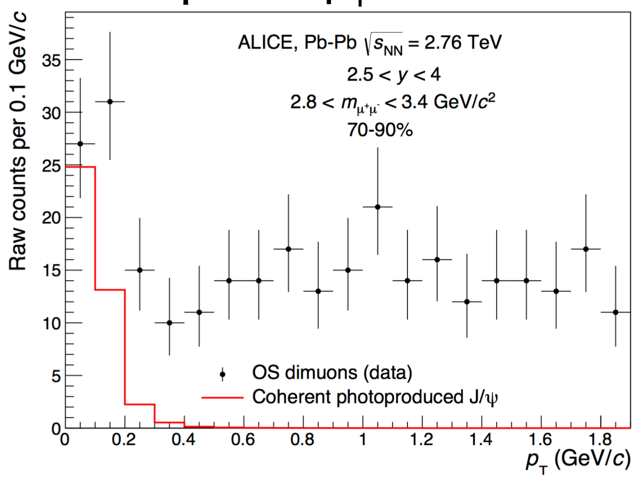
Low-p_T tracking



Spatial precision



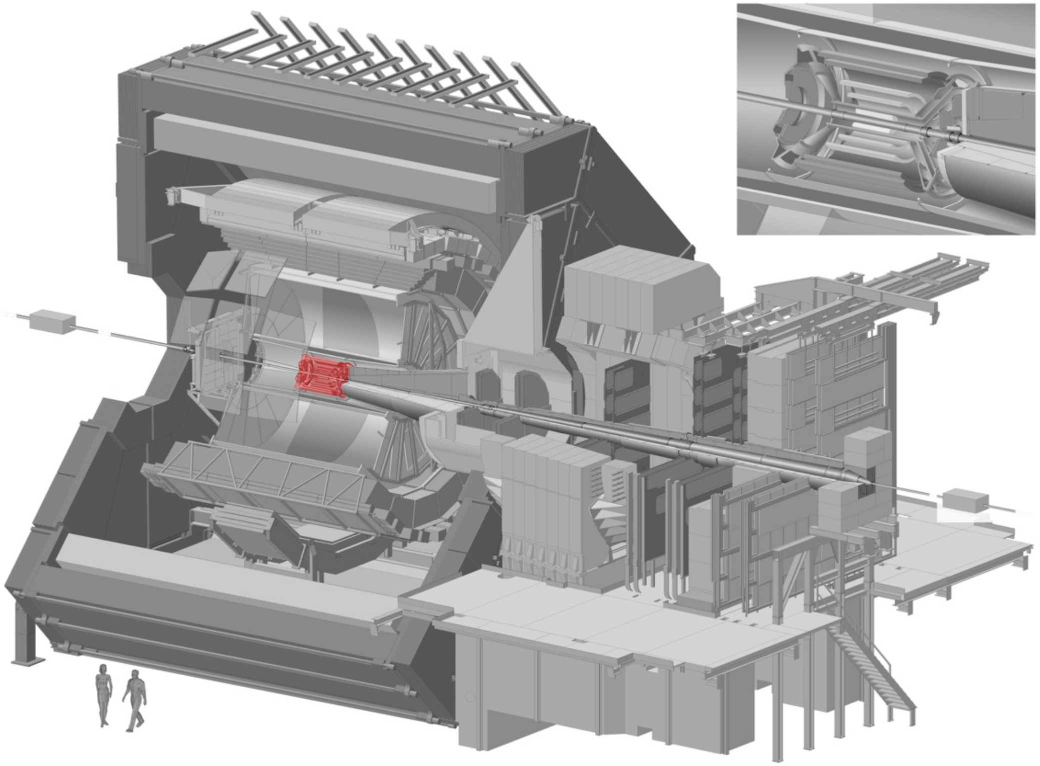
J/ψ from p_T=0



Int. J. Mod. Phys. A 29, 1430044 (2014)

PRL116 (2016) no.22, 222301

ALICE: Reconstructing charged particles in the central region



ITS ($|\eta|$<0.9)
- 6 Layers of silicon detectors!
- Trigger, **Tracking**, **Vertex**, PID (dE/dx)

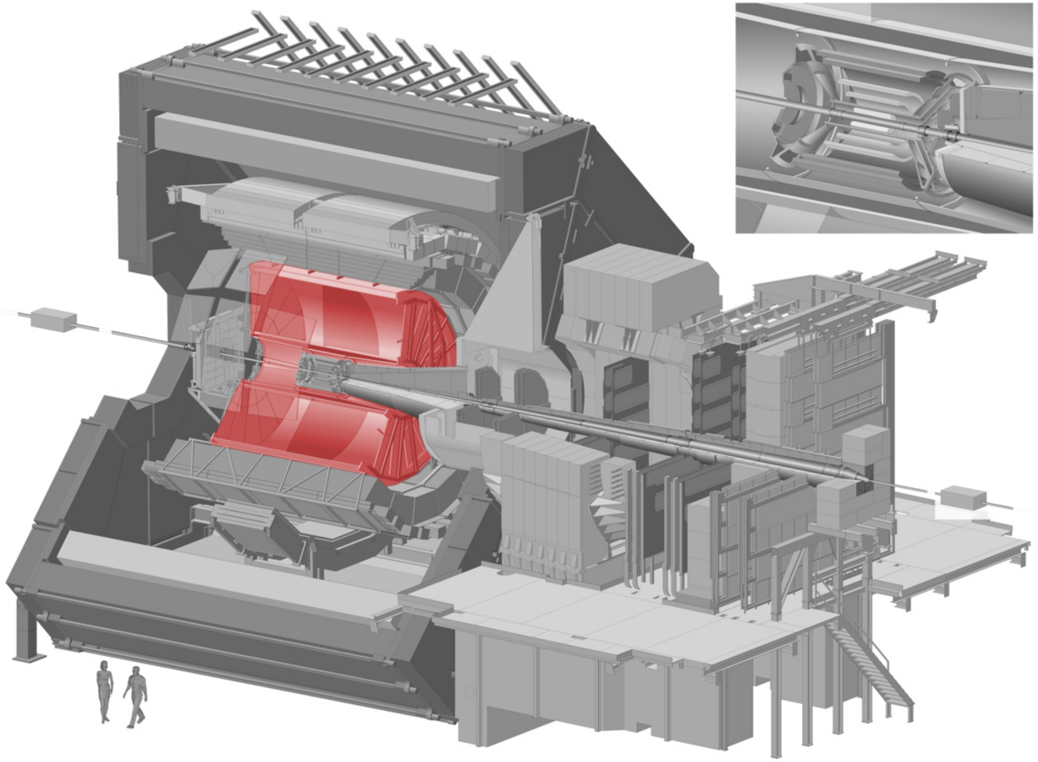
SPD tracklet

Used for the $\mathbf{d}N_{\mathrm{ch}}/\mathbf{d}\eta$ measurement

→ No p_T info, however it allows to count tracks from a very low $p_T \approx 50$ MeV

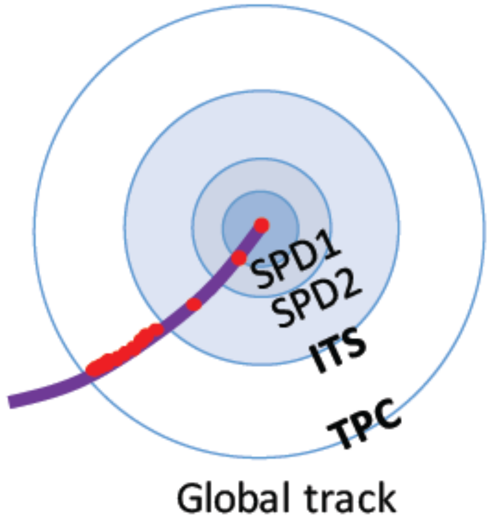
→ Using the spread of the vertex allows to extend the coverage to $|\eta|$<1.8

ALICE: Reconstructing charged particles in the central region



ITS ($|\eta|<0.9$)
- 6 Layers of silicon detectors!
- Trigger, **Tracking**, **Vertex**, PID (dE/dx)

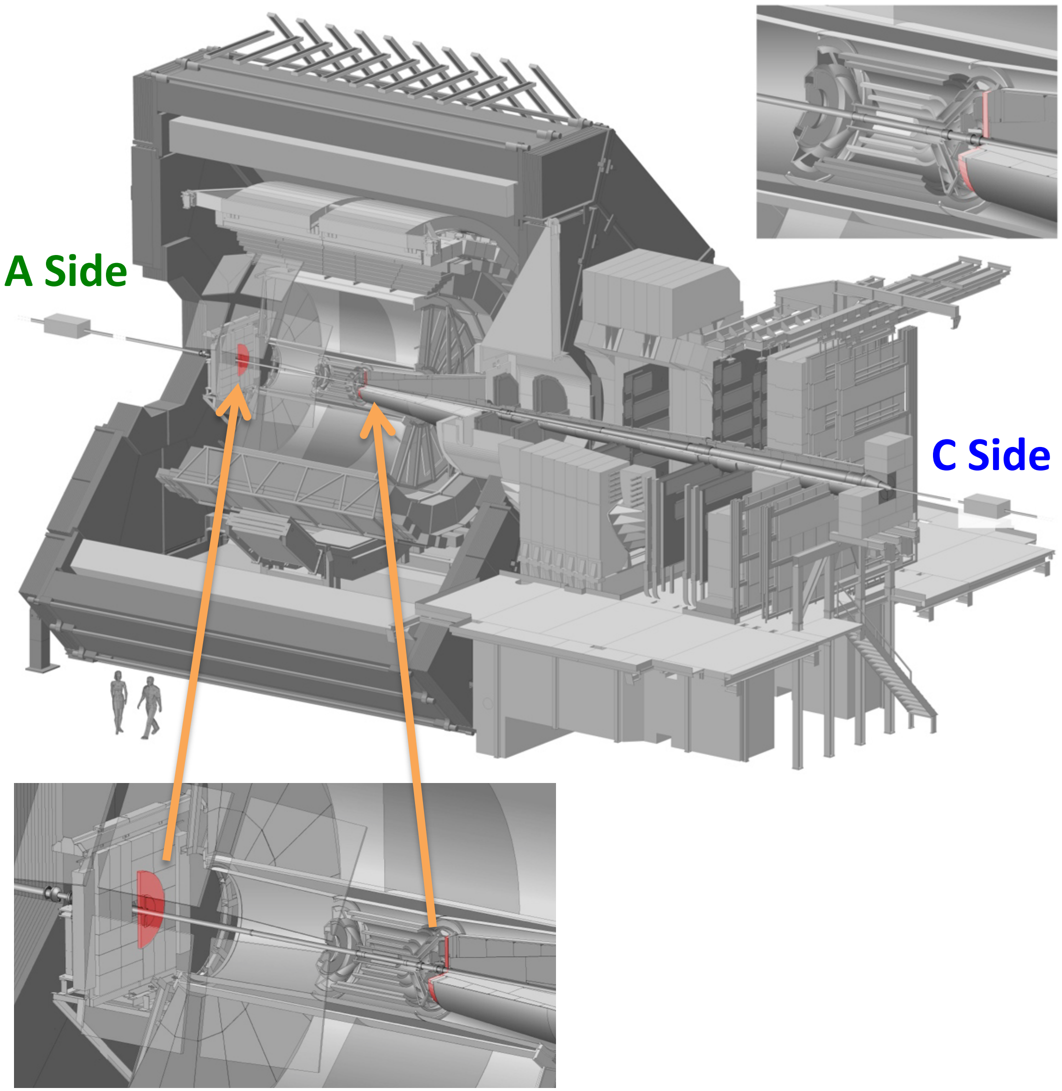
TPC ($|\eta|<0.9$)
- Gas-filled ionization detection volume
- **Tracking**, **Vertex**, PID (dE/dx)



Used for the $\mathbf{d}N_{ch}/\mathbf{d}p_T$ measurement

→ Reconstructed from ITS + TPC info
→ $\mathbf{p_T}$ information for $|\eta|<0.8$; p_T > 150 MeV

ALICE: Minimum Bias trigger and event selection



V0 [V0A (2.8<η<5.1) & V0C (-3.7<η<-1.7)]

- Forward arrays of scintillators
- **Trigger, Beam gas rejection**
- (Also event multiplicity estimator)

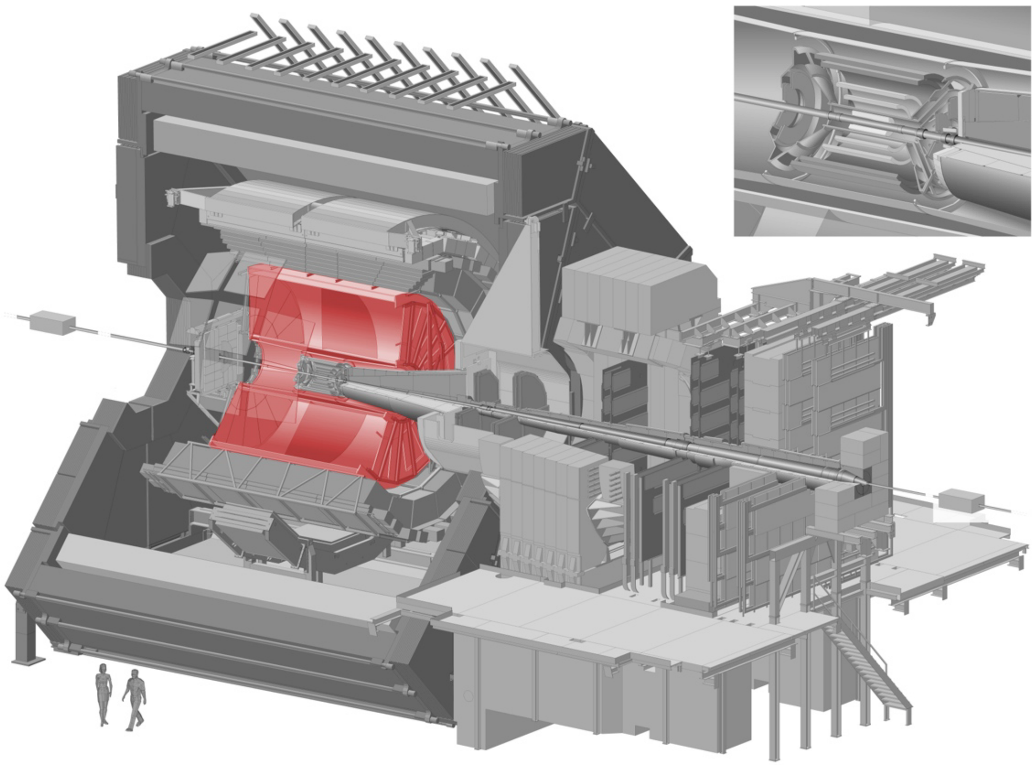
AD (Alice Diffractive detectors)

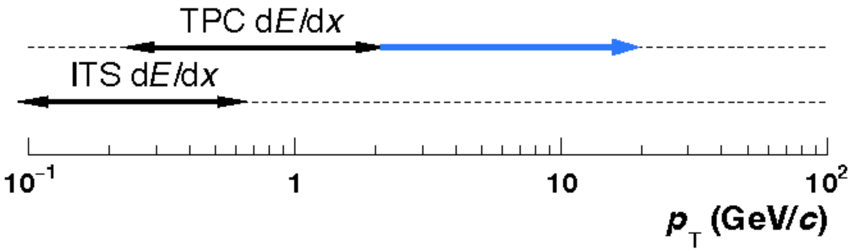
- Scintillation counters
- Integrated for RUN II
- Located at z=17, -19.5 m

→ Events are collected with various Minimum Bias triggers, the looser one being a logical OR of detector hits defined as (V0A || V0C || ADA || ADC)

- **INEL** : inelastic events
- **INEL>0** : inelastic events with at least 1 charged particle in $|\eta| < 1$

ALICE: Reconstructing the strange hadrons

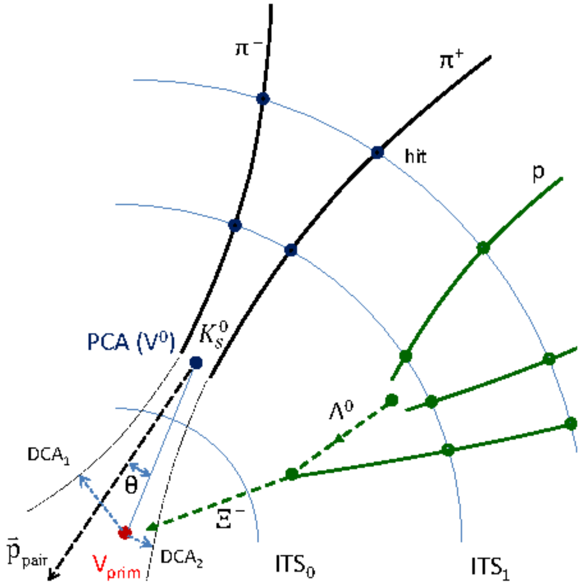




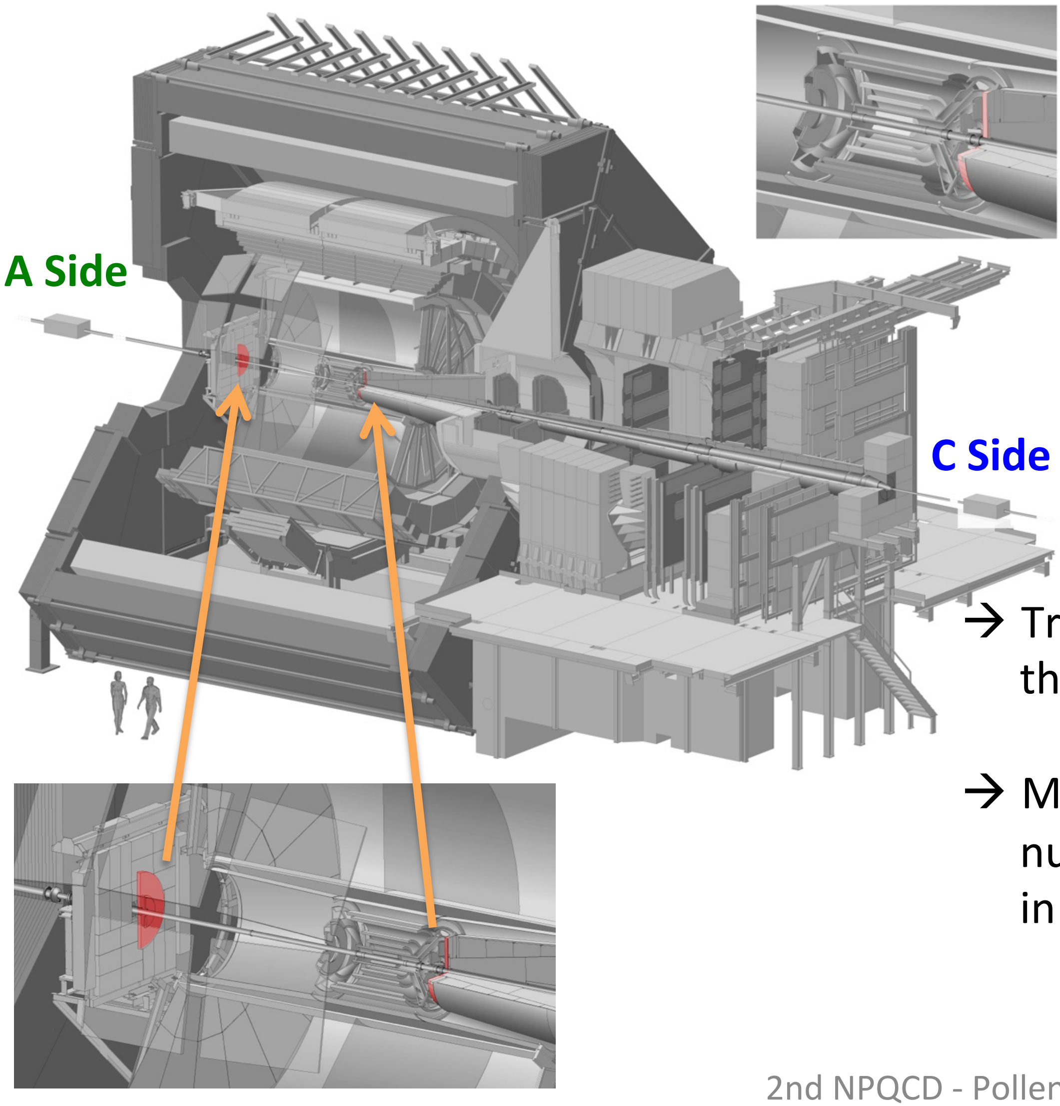
ITS ($|\eta|$<0.9)
- 6 Layers of silicon detectors!
- Trigger, tracking, vertex, PID (dE/dx)

TPC ($|\eta|$<0.9)
- Gas-filled ionization detection volume
- Tracking, vertex, PID (dE/dx)
- Reconstruction of weak decays

$$\Xi^- \rightarrow \Lambda + \pi^-$$



ALICE: Strangeness vs multiplicity: trigger and event selection



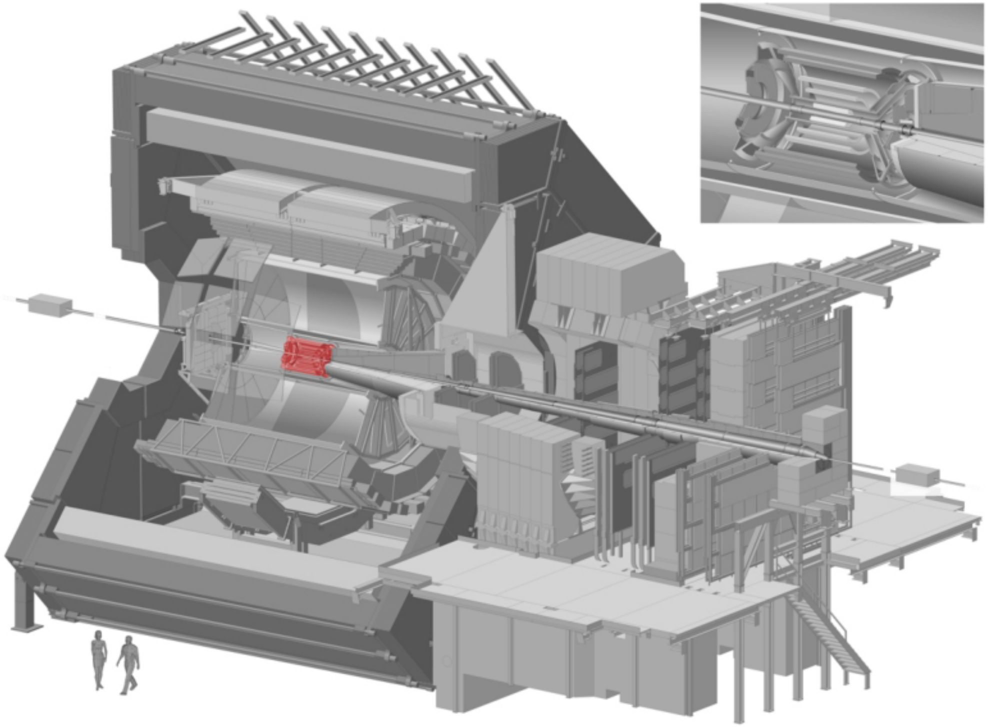
V0 [V0A (2.8<η<5.1) & V0C (-3.7<η<-1.7)]

- Forward arrays of scintillators
- Trigger, beam gas rejection
- (Also event multiplicity estimator)

→ Trigger based on total charge deposited in the V0A and V0C detectors ("V0M”)

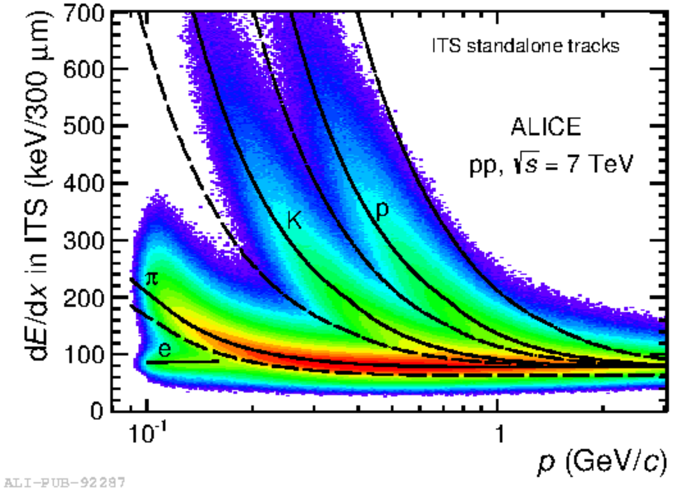
→ Multiplicity class defined as the average number of primary charged primary tracks in $|\eta|$<0.5 (exploiting the $\mathbf{d}N_{ch}/\mathbf{d}\eta$ analysis)

The ALICE Detector (PID)



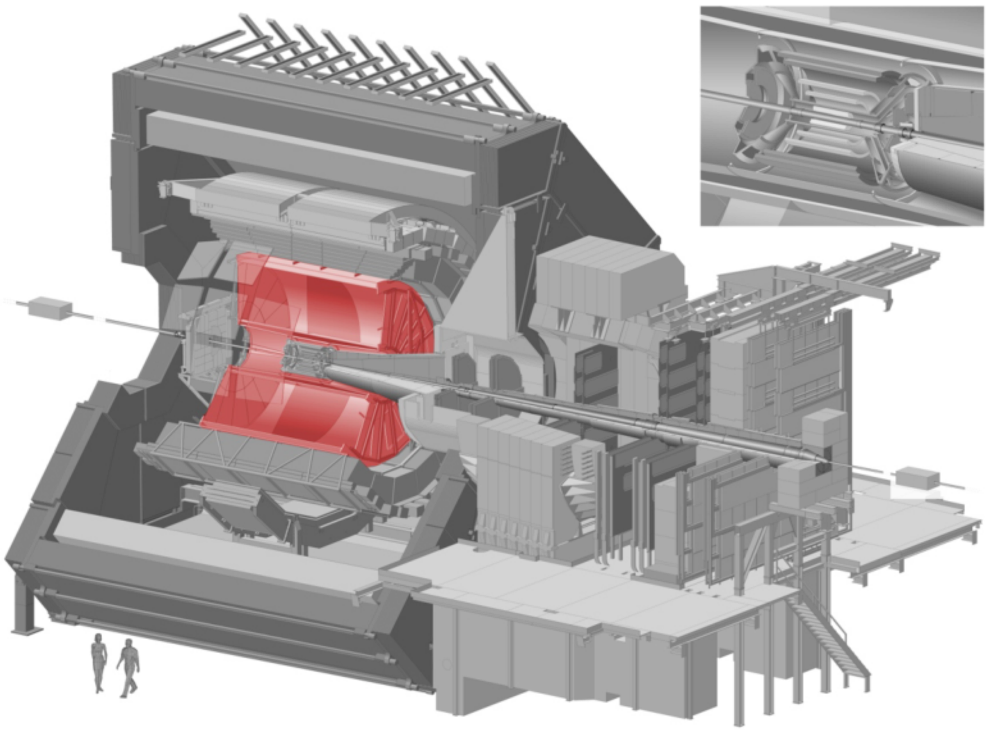
ITS (|η|<0.9)

- 6 Layers of silicon detectors
- Trigger, tracking, vertex, PID (d*E*/d*x*)



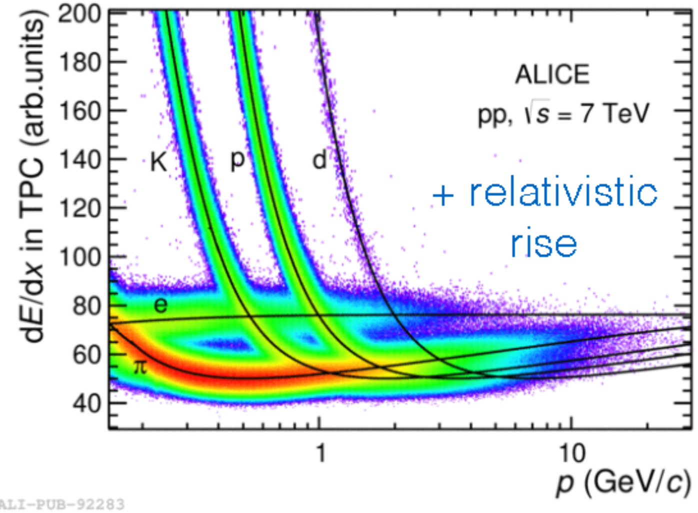
ITS d*E*/d*x*

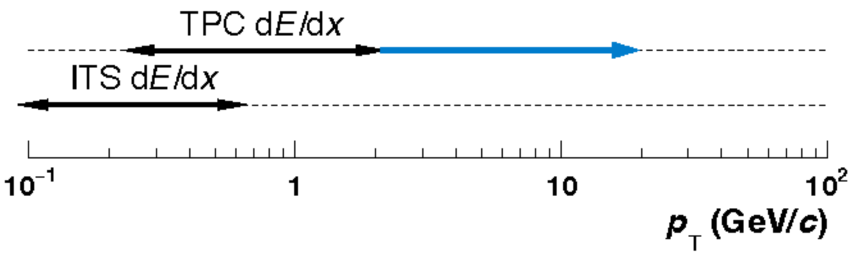
The ALICE Detector (PID)



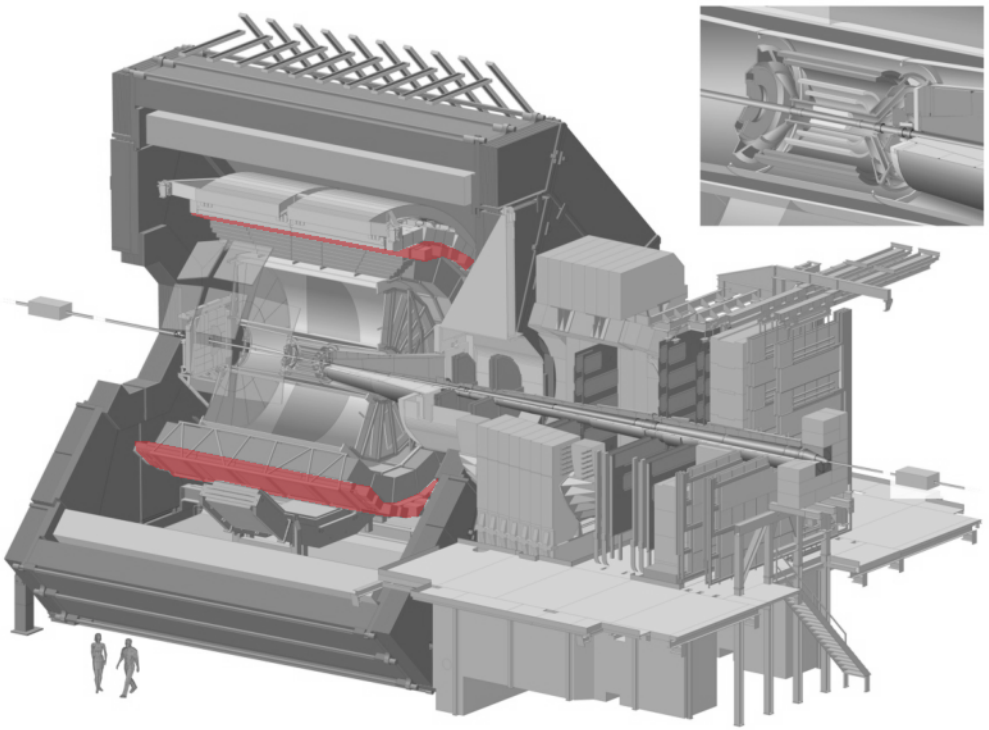
ITS (|η|<0.9)
- 6 Layers of silicon detectors
- Trigger, tracking, vertex, PID (dE/dx)

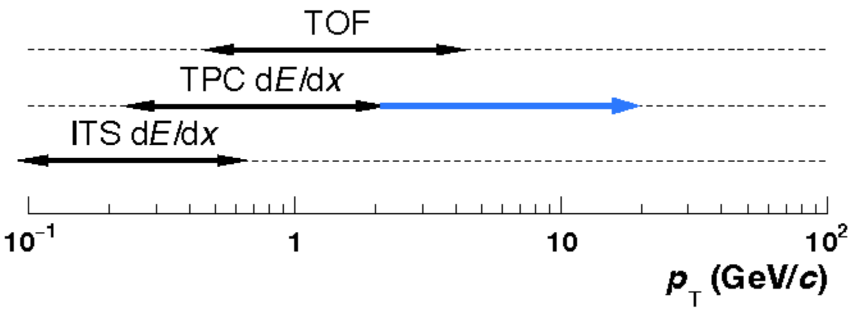
TPC (|η|<0.9)
- Gas-filled ionization detection volume
- Tracking, vertex, PID (dE/dx)





The ALICE Detector (PID)

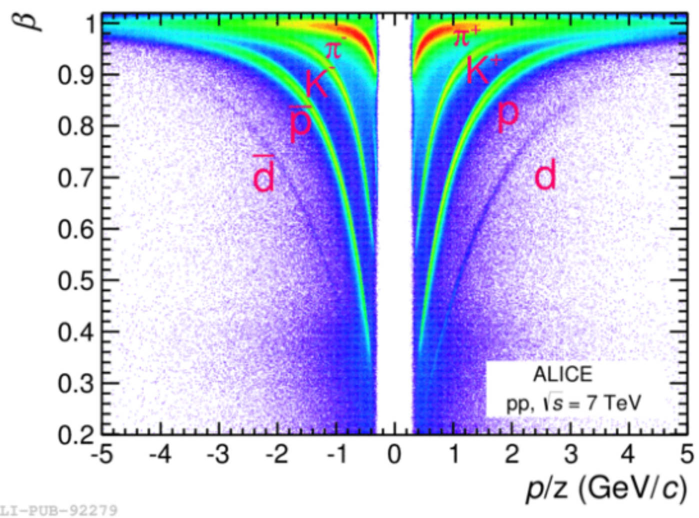




ITS (|η|<0.9)
- 6 Layers of silicon detectors
- Trigger, tracking, vertex, PID (dE/dx)

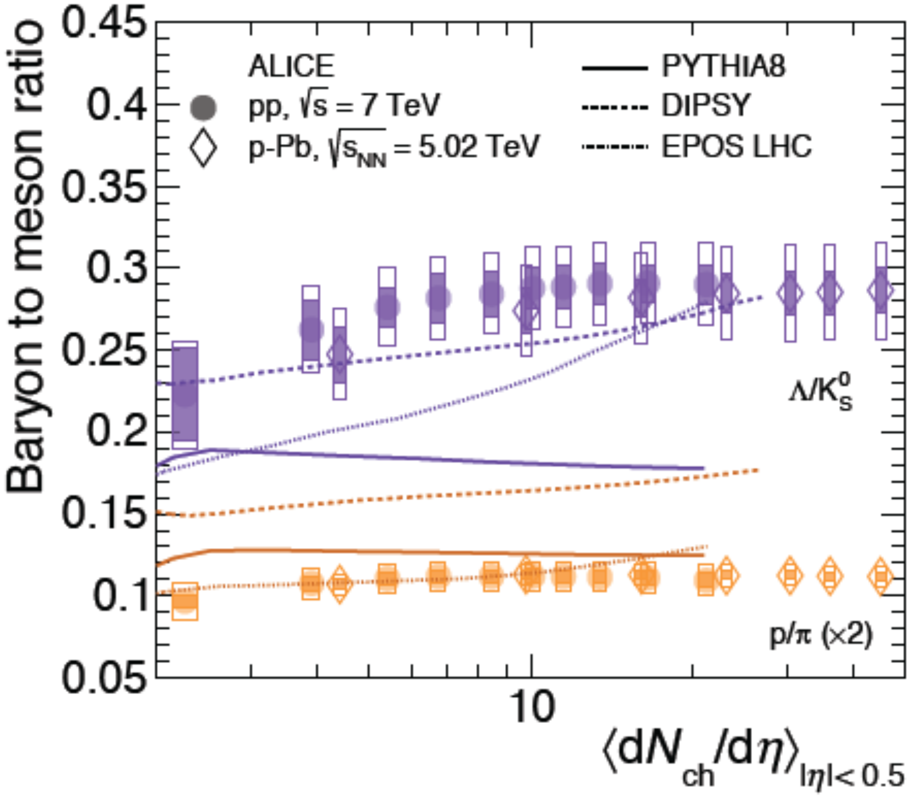
TPC (|η|<0.9)
- Gas-filled ionization detection volume
- Tracking, vertex, PID (dE/dx)
- Weak decay reconstruction (topological)

TOF (|η|<0.9)
- Multi-gap resistive plate chambers
- PID via velocity determination



Study of strangeness production vs charged multiplicity in pp collisions at √s = 13 TeV

barion/meson ratios

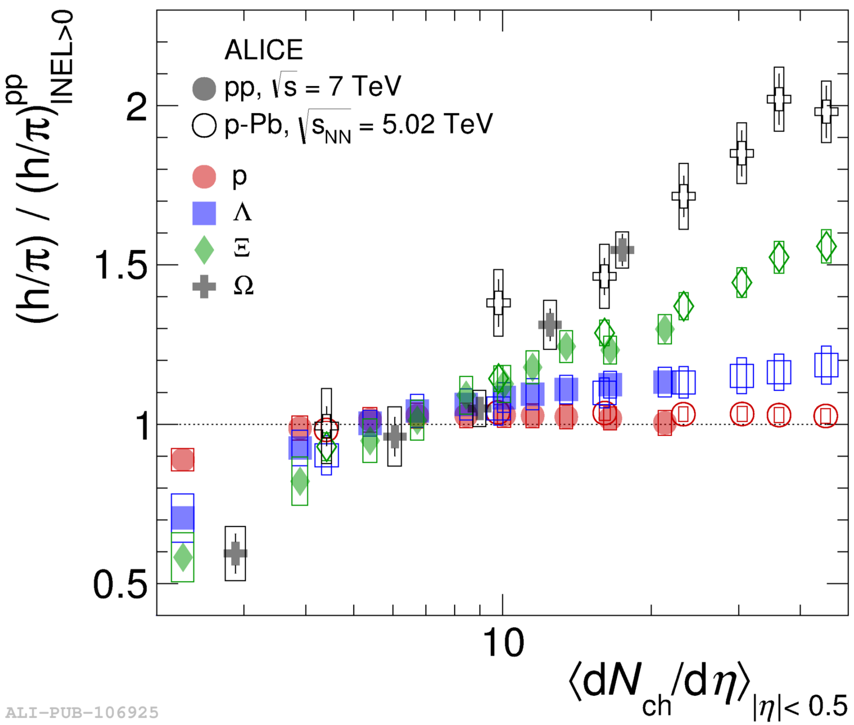


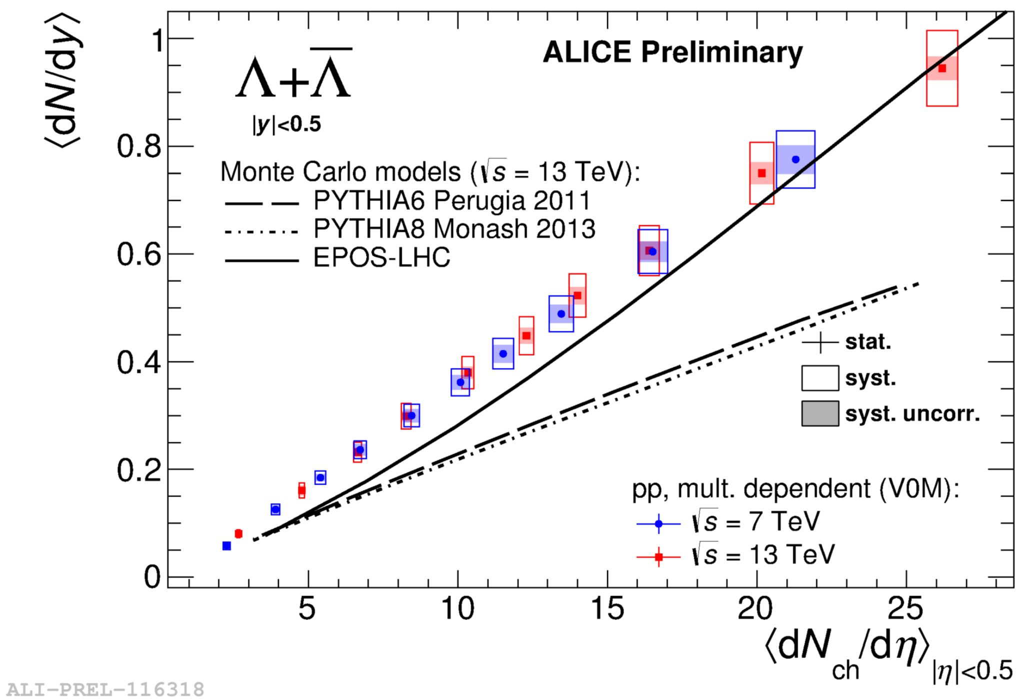
- "no strange" hadrons don't show any enhancement at High Multiplicities, in contrast to the predictions of DIPSY

pp results: *Nature 2017*

p-Pb results: *Phys. Lett. B 758 (2016) 389-401*

ALICE: Study of strangeness production vs charged multiplicity in pp collisions: dependence on strangeness content and center of mass energy





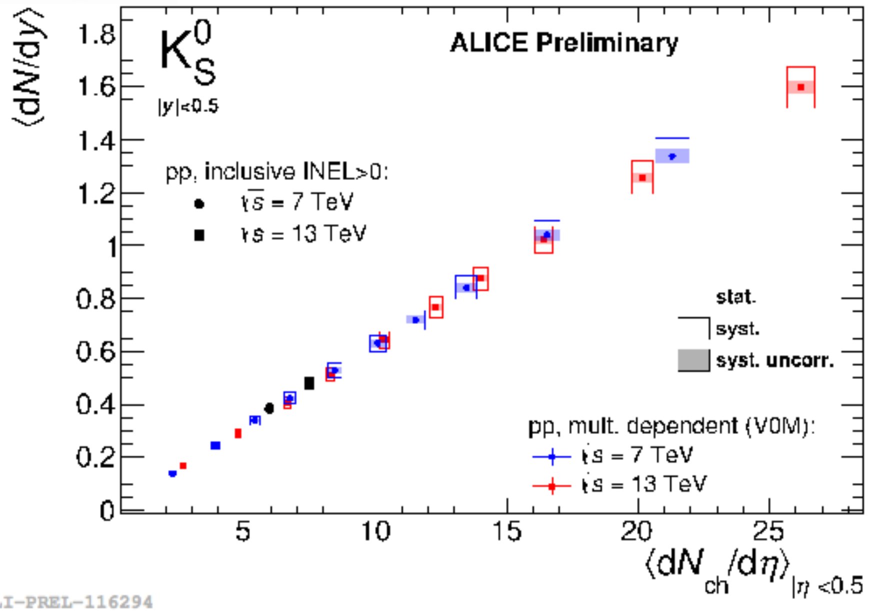
- The Observed increase is **even more pronounced** for **baryons with higher strangeness content**.

- Measurements at different center of mass energies as a function of multiplicity indicate that the **hadrochemistry is driven by event activity regardless of √s**

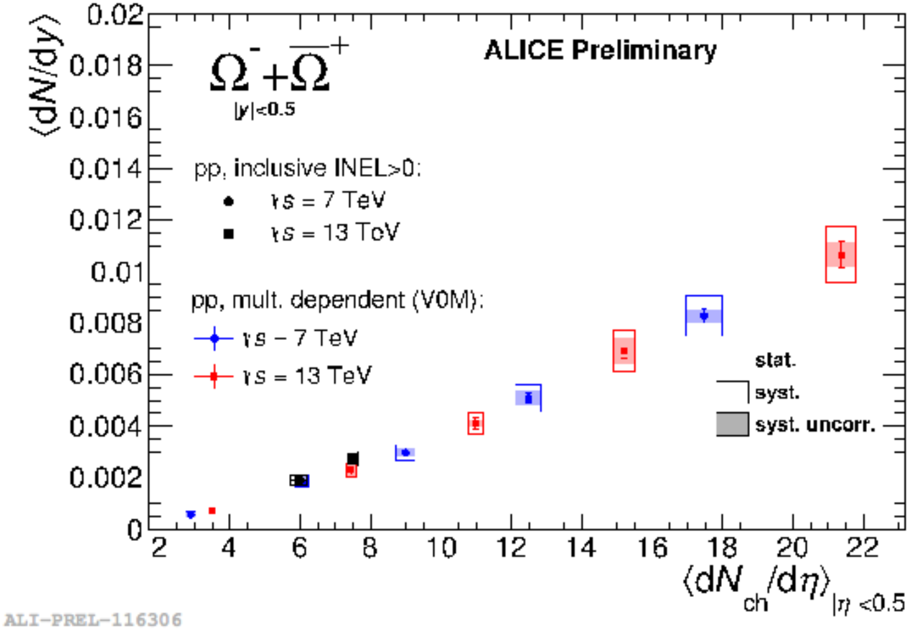
→ Scaling not reproduced by the tested models

pp results: *Nature 2017*
p-Pb results: *Phys. Lett. B 758 (2016) 389-401*

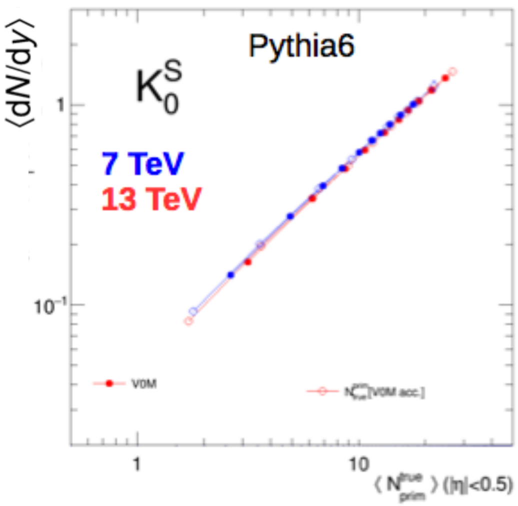
ALICE: Energy (in) dependence of strangeness

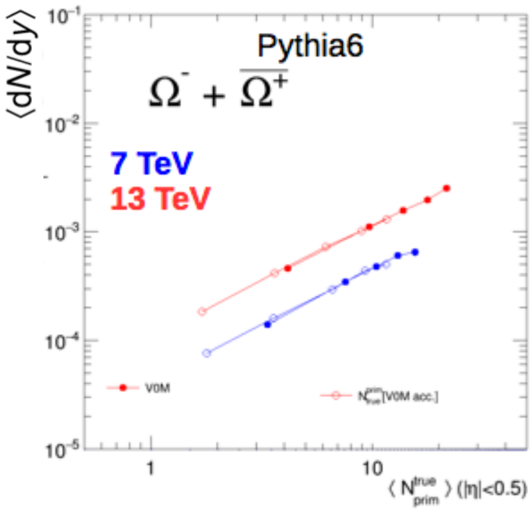


ALI-PREL-116294



ALI-PREL-116306





Strangeness depends on **multiplicity**, **not √s**

Not reproduced by Pythia!

ALICE: Study of strangeness production vs charged multiplicity in pp collisions

- Bottom line
  - An enhanced production of strange and multi-strange particles has been observed in high-multiplicity pp collisions.
  - The multiplicity dependence of strangeness production is strikingly similar in pp and p-Pb, and approaches values similar to those in central Pb-Pb.
  - Strangeness yields driven by event activity, independent from √s.
  - None of the current MC models are successful at fully describing these observations, although DIPSY and EPOS LHC turns out to reproduce at least the qualitative aspects of the strangeness yields evolution with the charged multiplicity.
  - Does the strangeness production in small systems eventually saturate at higher multiplicities?

Concepts

Mechanisms

Phenomenological Consequences

Observables

Multiple Parton Interactions (MPI)
Color Reconnection, Color Ropes, Thermal Strings, …

Quark Gluon Plasma (QGP) Hydro, Deconfinement, Canonical Suppression, …

Saturation
Color Glass Condensate (CGC), Glasma, …

Hadrochemistry

Hard processes

Flow-like patterns ("Collectivity")

Thermal radiation

PID Spectra

J/ψ

Jets

Correlations

Di-electrons

…

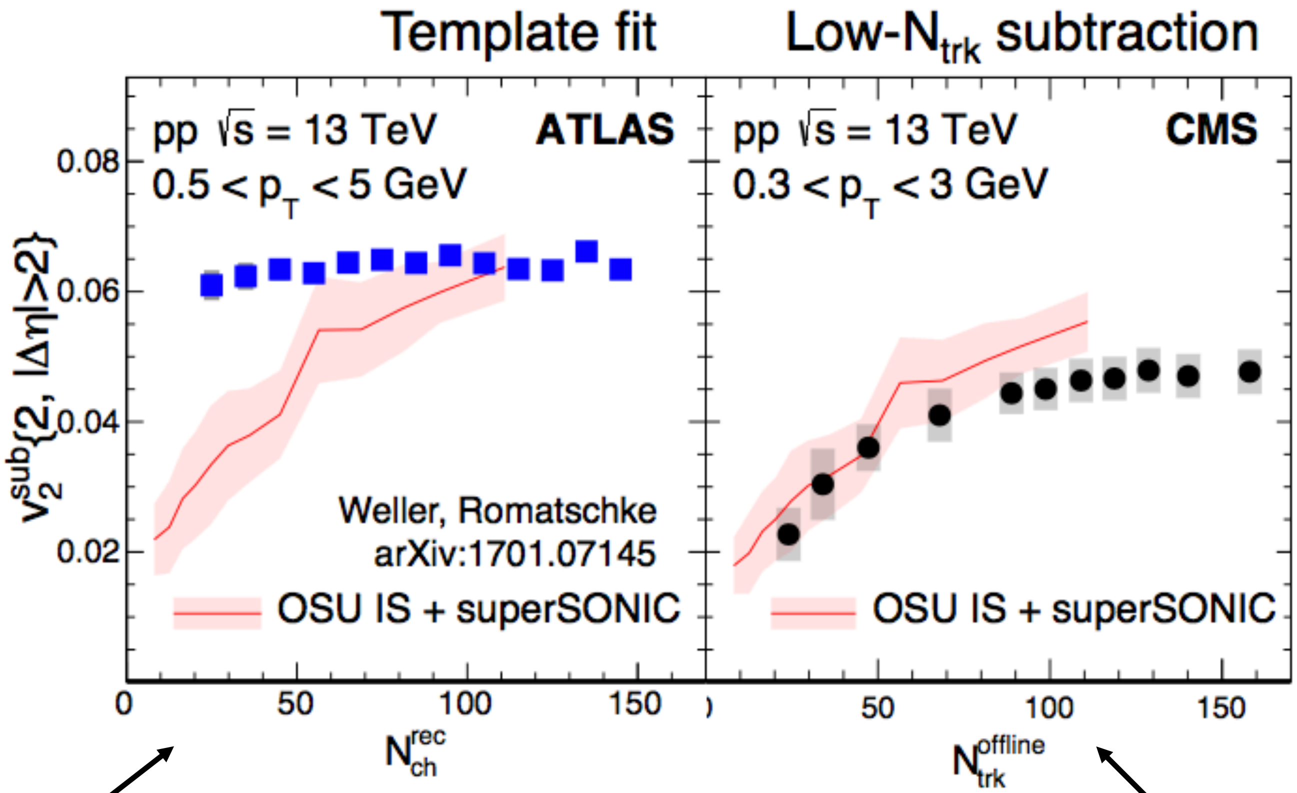
Interpretations should rely on a rich phenomenology, exploiting also the interplays between different underlying Mechanisms

Diagram:
Credit Michele Floris

Discussion on Correlations
What can we infer from $c_2\{4\}$?

- *Slides from Michele Floris*

Ambiguities in the subtraction method

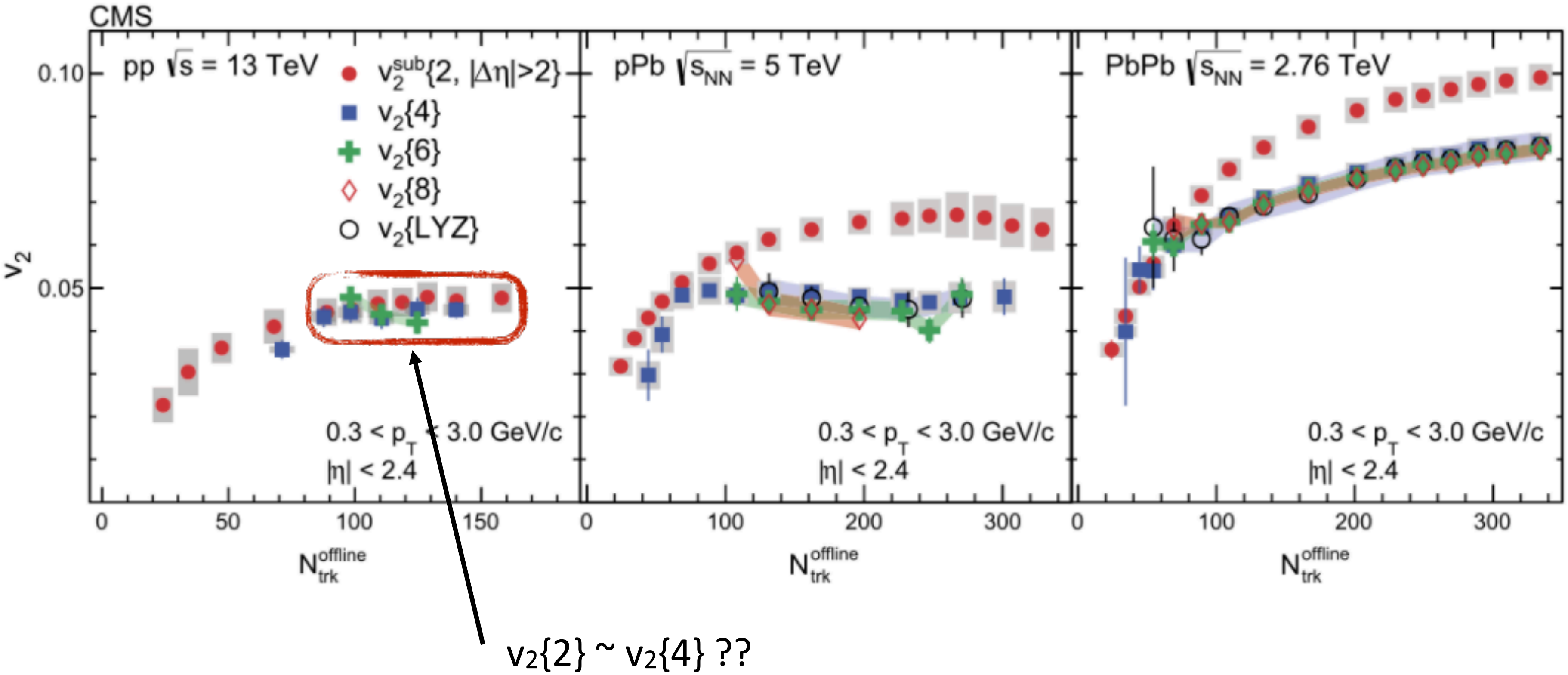


flow in bin n and n+1 equal

no flow in peripheral collisions

Comparison to theory?

Z. Chen, CMS, QM17

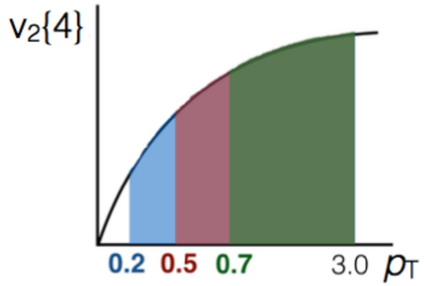


Multi particle cumulants measured in pp/p-Pb/Pb-Pb
In Pb-Pb: $v_2\{2\} > v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$:
non-flow suppressed almost completely?

taken as a proof of collectivity

Z. Chen, CMS, QM17

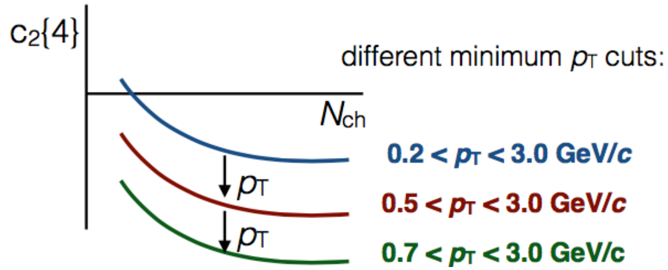
p_T dependence of cumulants



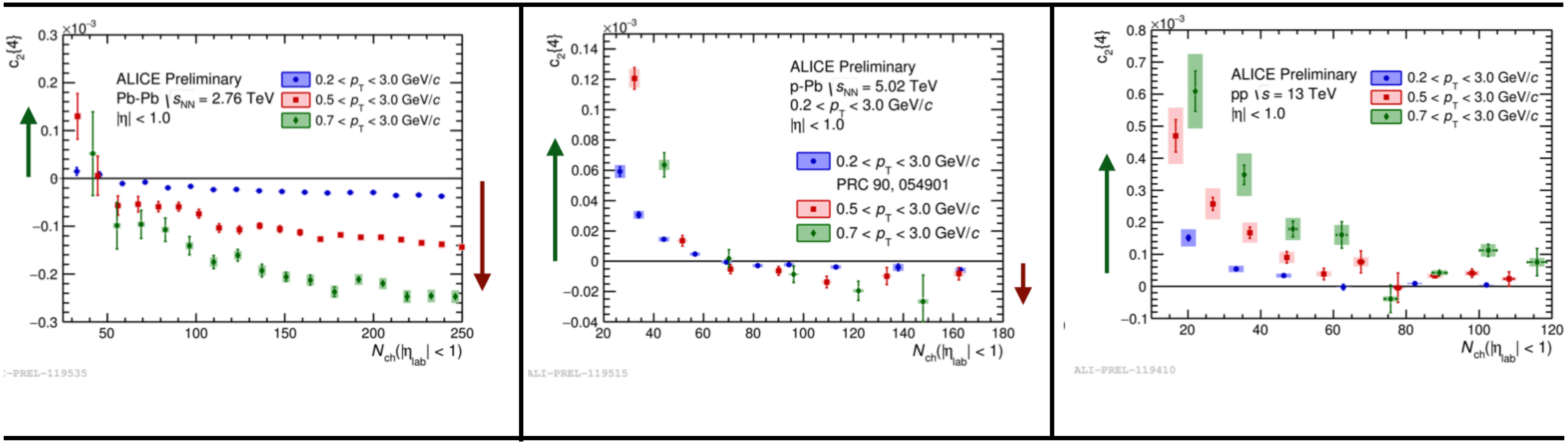
$$c_n\{4\} = -v_n\{4\}^4$$

increase of p_T - decrease of flow

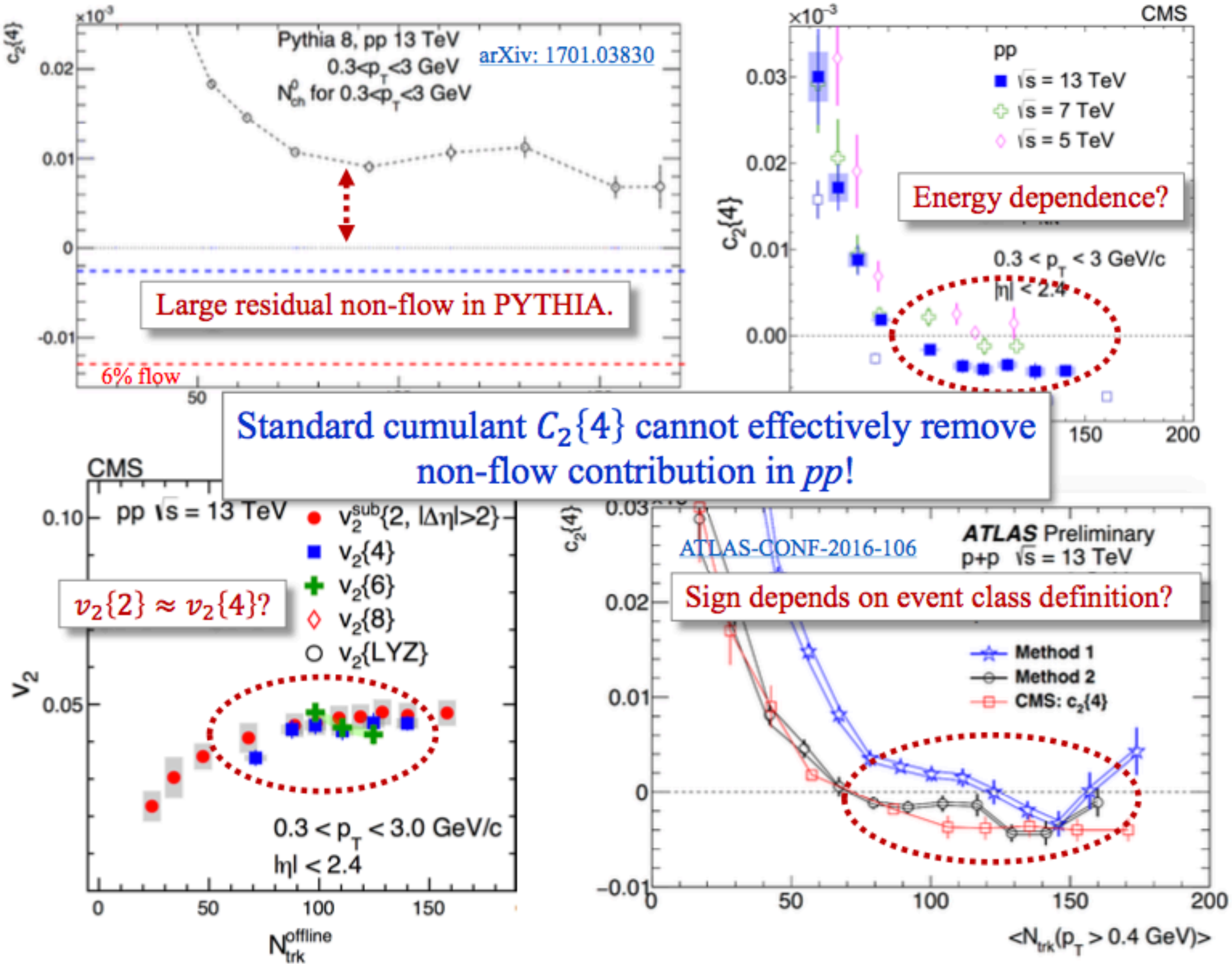
increase of p_T - increase of non-flow



K. Gajdosova, ALICE, QM17



Pb-Pb p-Pb p-p



Standard cumulant $C_2\{4\}$ cannot effectively remove non-flow contribution in *pp*!

M. Zhou, ATLAS, QM17

Cumulants, non-flow and fluctuations

$$C_2\{4\} \equiv \langle \text{nonflow} + \text{flow} \rangle_{evt}$$

Non-flow changes greatly EbyE

Flow changes little EbyE

Large system ⇒ many sources ⇒ Gaussian fluctuations
Small systems ⇒ few sources ⇒ fluctuations?
Non-Gaussian fluctuations may produce any c2{4} (including negative)!

$$p(\boldsymbol{q}_n) = p(\boldsymbol{v}_n) \otimes p(\boldsymbol{s}_n) \otimes p(\boldsymbol{s}_{\mathrm{n}}^{\mathrm{stat}})$$

flow e-by-e

non-flow

limited number of particles

Negative c2{4} for collective events if gaussian flow ebye

M. Zhou, ATLAS, QM17

Cumulants, non-flow and fluctuations

$$C_2\{4\} \equiv \langle \text{nonflow} + \text{flow} \rangle_{evt}$$

Non-flow changes greatly EbyE

Flow changes little EbyE

Large system ⇒ many sources ⇒ Gaussian-like fluctuations
Small systems ⇒ few sources ⇒ non-flow fluctuations?

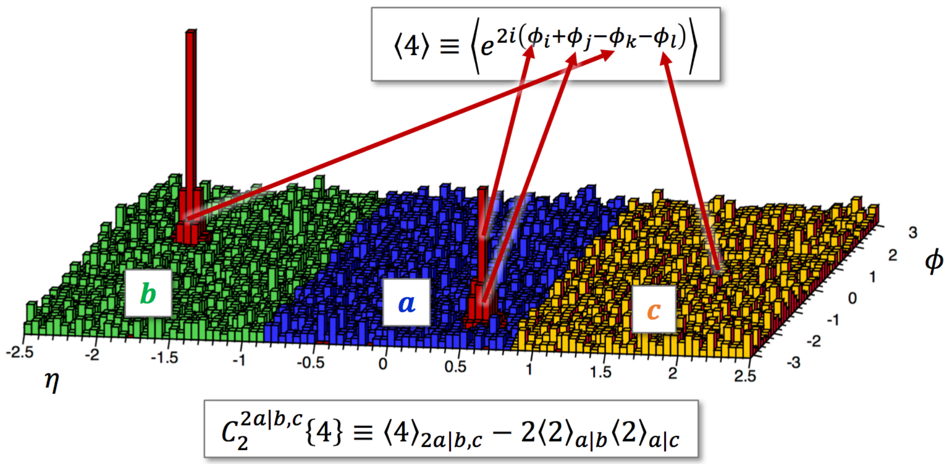
Non-Gaussian fluctuations of non-flow may produce any $c_2\{4\}$ (including negative)!

More effective way to suppress non-flow?

M. Zhou, ATLAS, QM17

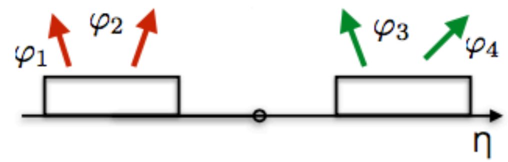
Suppressing non-flow

Atlas: 2 and 3 sub-events

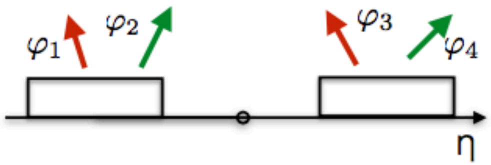


K. Gajdosova, ALICE, QM17

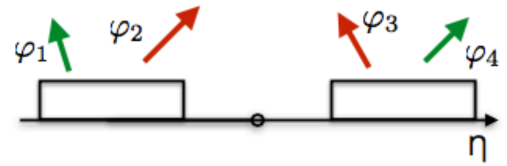
ALICE: sub events with eta gaps



$$\langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle \ldots \langle\langle 4 \rangle\rangle_{|\Delta\eta|}$$



$$\langle\langle \cos n(\varphi_1 - \varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle \ldots \langle\langle 2 \rangle\rangle^2_{|\Delta\eta|}$$



$$\langle\langle \cos n(\varphi_2 - \varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_1 - \varphi_4)\rangle\rangle \ldots \langle\langle 2 \rangle\rangle^2_{|\Delta\eta|}$$

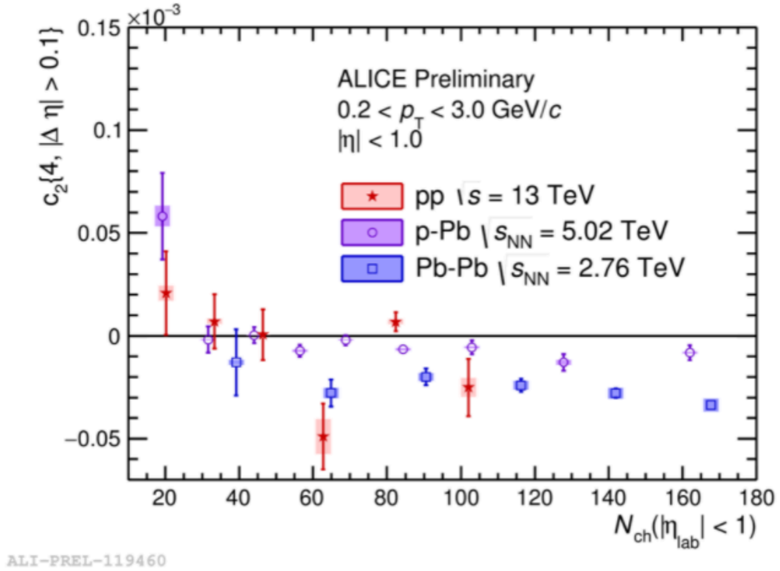
cumulants

$$c_n\{4, |\Delta\eta|\} = \langle\langle 4 \rangle\rangle_{|\Delta\eta|} - 2 \cdot \langle\langle 2 \rangle\rangle^2_{|\Delta\eta|}$$

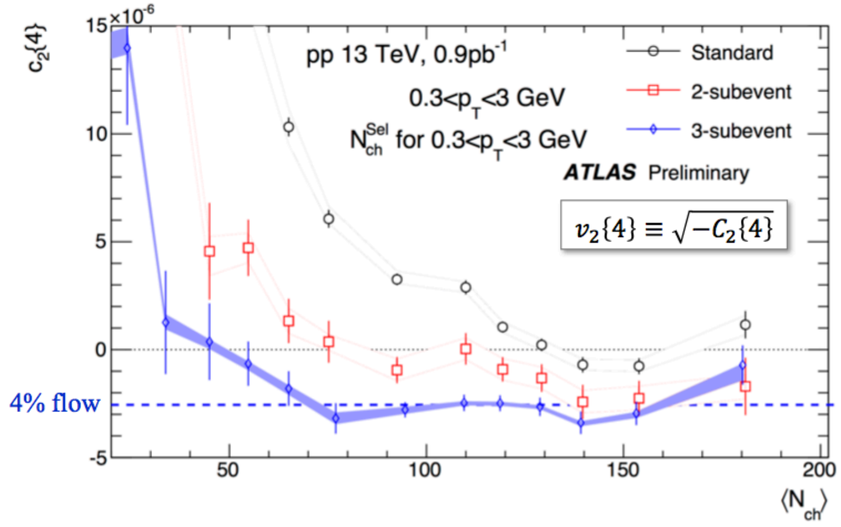
M. Zhou, ATLAS, QM17

Results

ALICE



ATLAS



2 sub-events with eta gap: Negative $c_2\{4\}$ at N_{CH} ~40 in p-Pb and Pb-Pb

3-subevents more effective in suppressing non-flow, statistics penalty comparable to 2-subev.

pp results limited by statistics

4% real flow?

M. Zhou, ATLAS, QM17

K. Gajdosova, ALICE, QM17

Saturation and UPC

PLB, 766, 186–191 (2016)

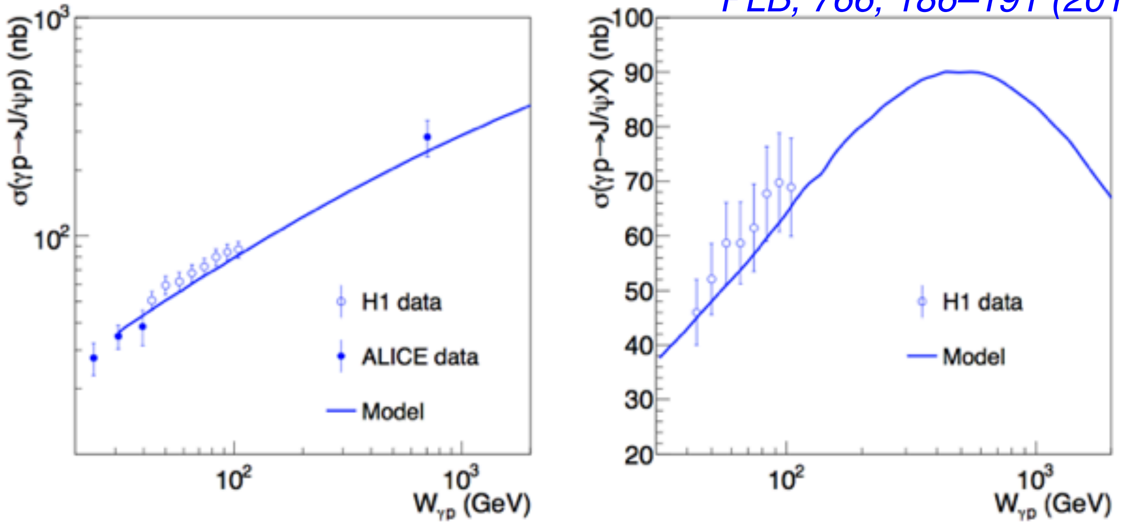


Figure 3: Comparison of the model (solid lines) to data on the $W_{\gamma p}$ dependence of the cross section for exclusive (left) and dissociative (right) photoproduction of J/ψ as measured by H1 [11] and ALICE [6] (open and solid bullets, respectively).

Maximum in the cross section of dissociative J/ψ production predicted **in presence of saturation**

→ Energy dependence of dissociative J/ψ production **can be measured in p-A**

Complementary **indication of saturation** &
constraint on **fluctuations pattern** in incoming nucleons

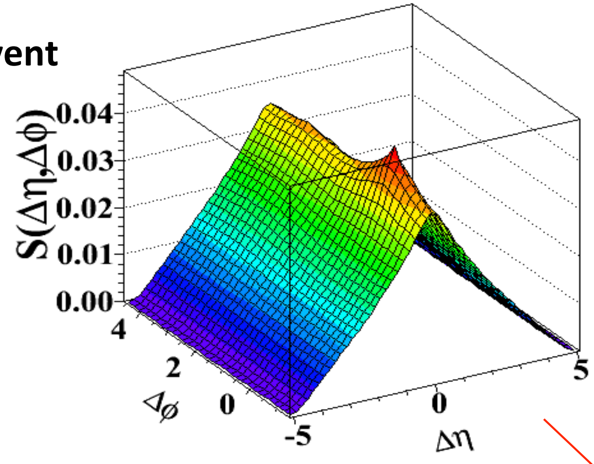
Ridge and other Multiplicity Dependent results in RUN I

Definition of di-hadron correlation function

Signal distribution:

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

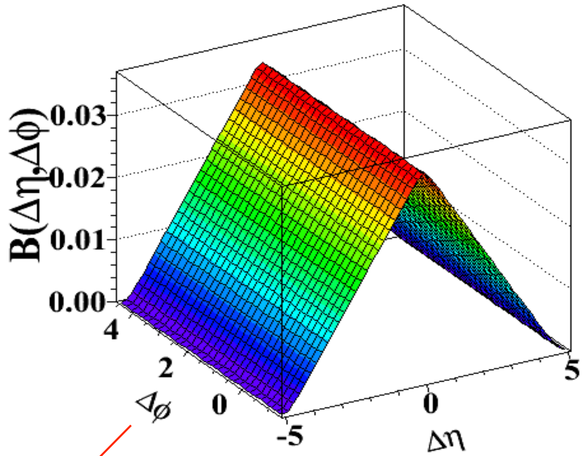
Particle pairs from same event



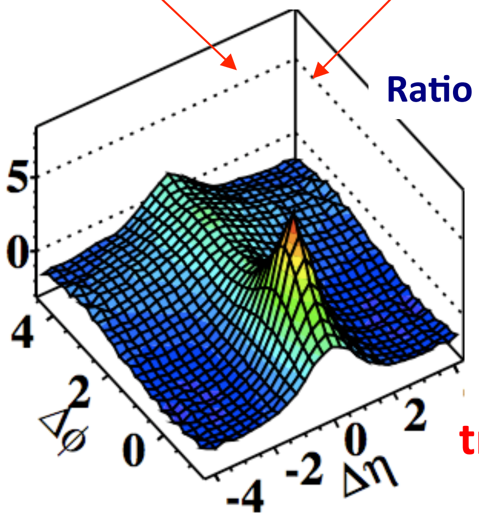
Background distribution:

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

Pairs from mixed events



$$\Delta\eta=\eta_1-\eta_2$$
$$\Delta\varphi=\varphi_1-\varphi_2$$



Ratio Signal/Background = Associated 2D Yields:

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

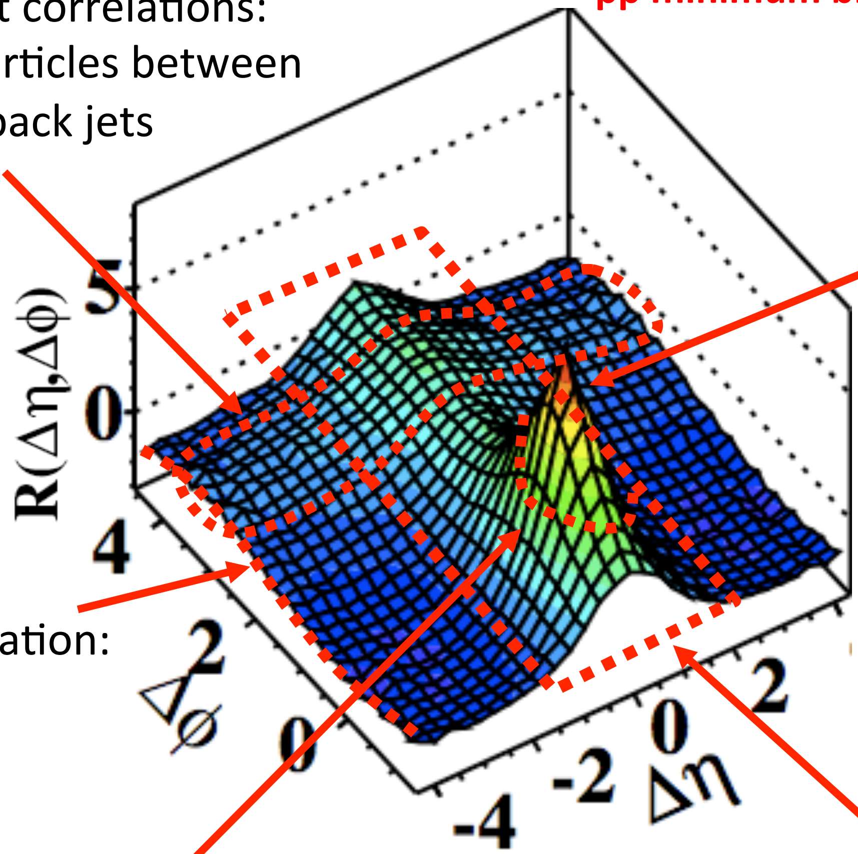
Can specify selected pair of trigger (p_T^{trig}) and associated (p_T^{assoc}) particle p_T ranges.

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)

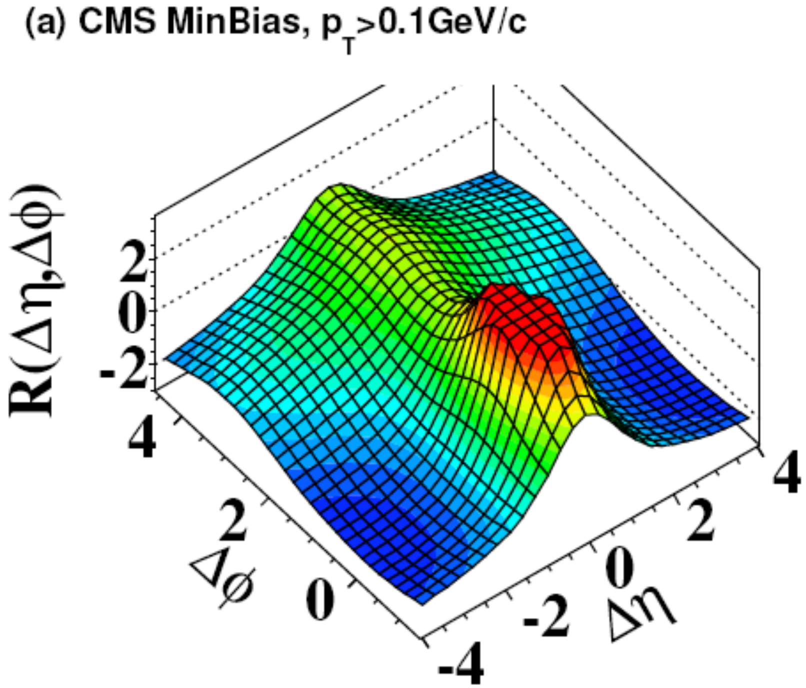
“Near-side”, Δϕ~ 0 jet peak:
Correlation of particles
within a single jet

Short-range correlations
Resonances, string or cluster fragmentation

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

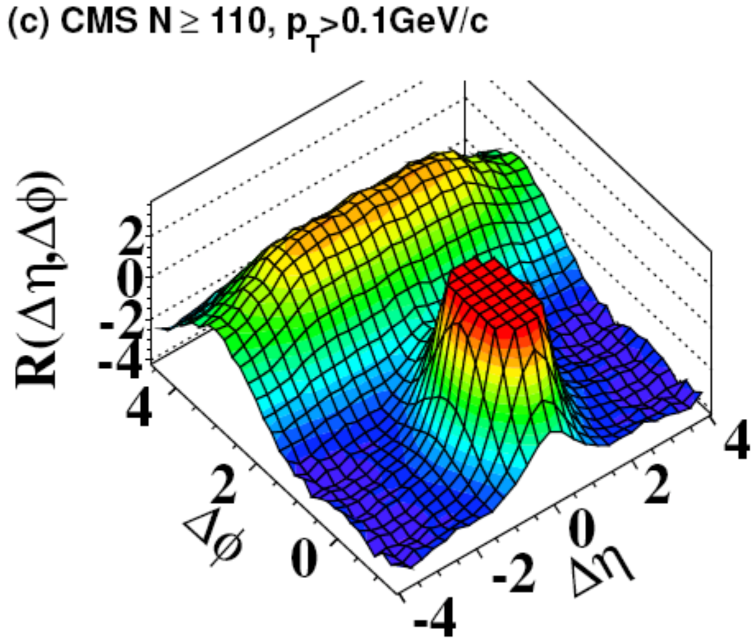
pp interactions at 7 TeV

MinBias



High Multiplicity (N>110)

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

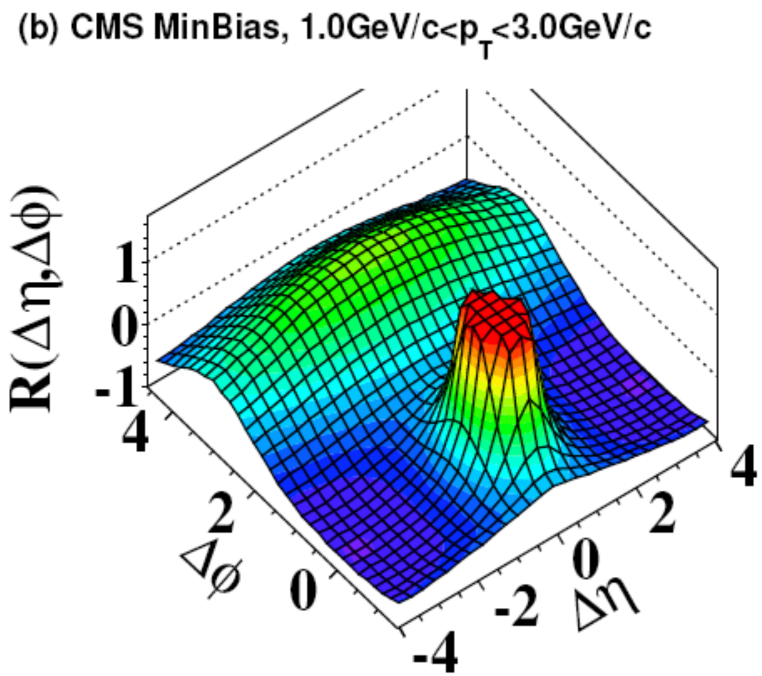


- The jet peak is cut for better visibility of the correlations.
- Jet peak correlations with away-side – stronger in the high multiplicity events
- No significant "new" structure seen in the high multiplicity events.

J. High Energy Phys. 09 (2010) 091

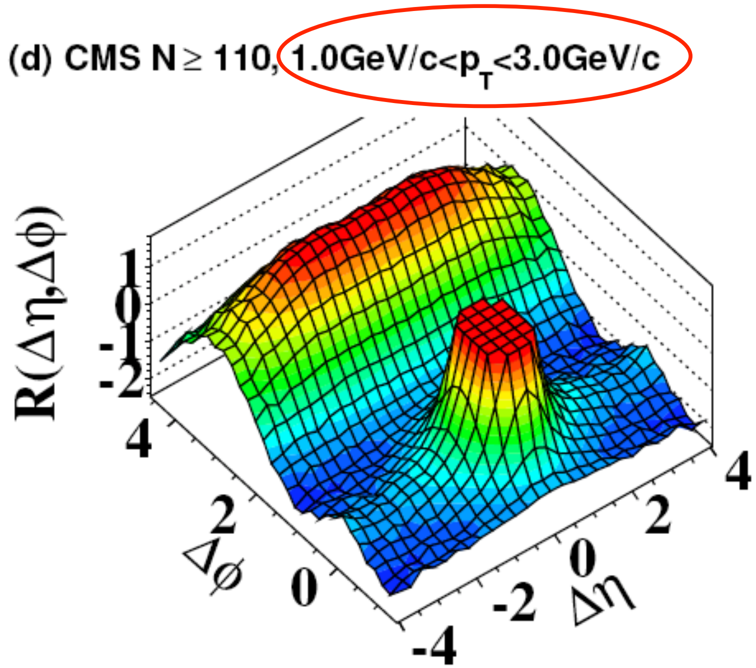
CMS: Associated 2D Yields for Particles with $1.0 < P_T < 3$ GeV

MinBias



High Multiplicity (N>110)

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



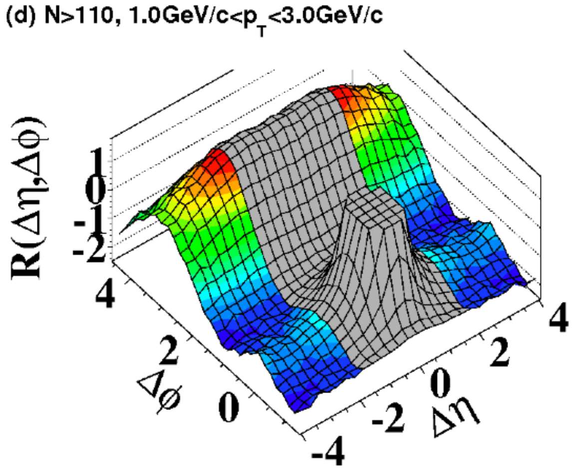
- **Limiting p_T of particles to $1<p_T<3$ GeV**
  → Gives a pronounced structure at large Δη around ΔΦ=0 in the high multiplicity events.

J. High Energy Phys. 09 (2010) 091.

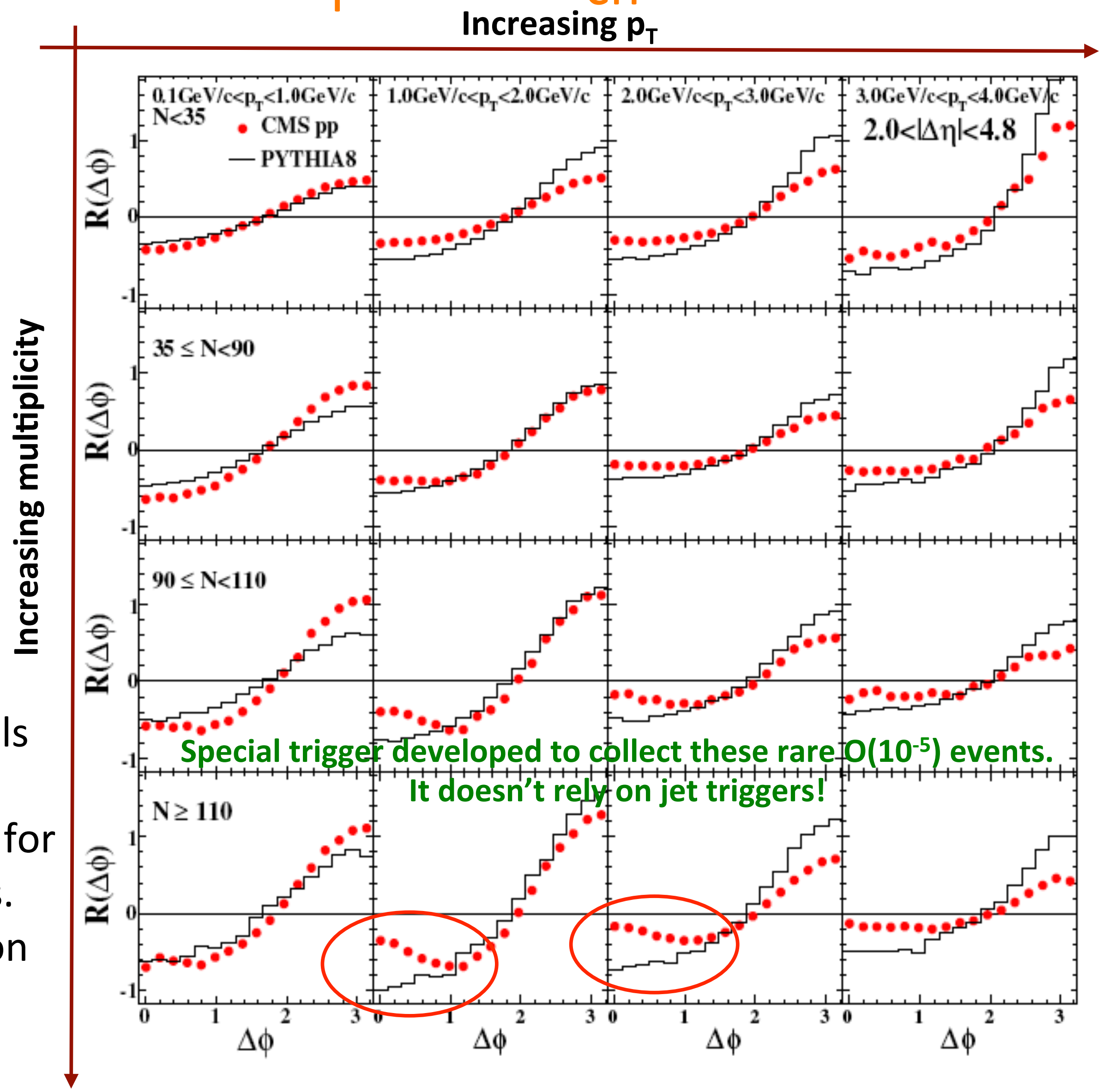
CMS: Associated 1D yields in bins of p_T and N_{ch}

Long range:

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



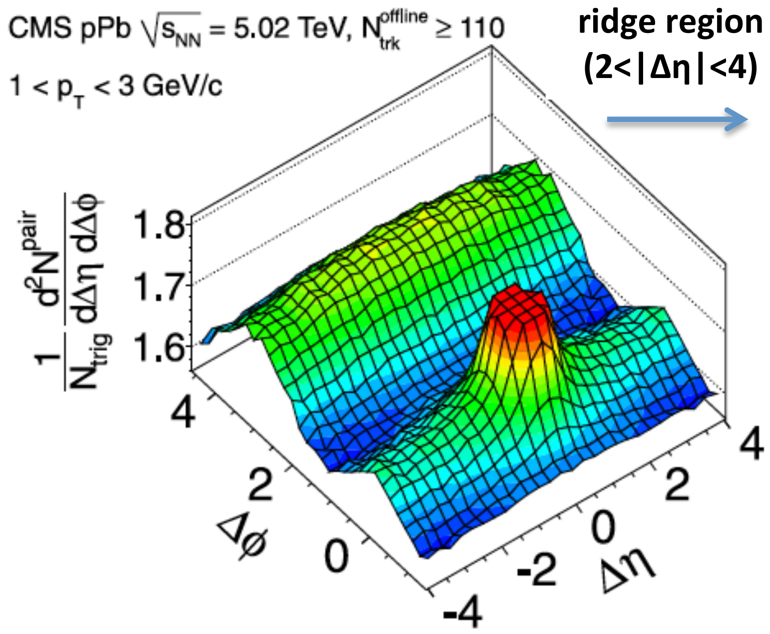
- **Ridge most pronounced for high multiplicity events and at $1 < p_T < 3$ GeV.**
- No ridge seen in tested MC models (Pythia 8, Pythia6, Herwig++, etc.)
- Several interpretations proposed for this HI-like effect in pp interactions.
- Clear major role of Multiple Parton Interactions.



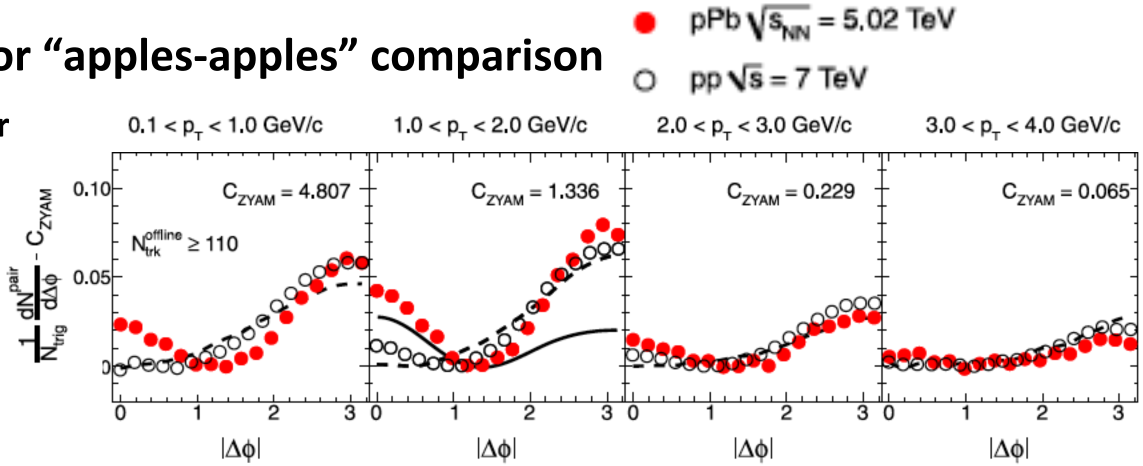
J. High Energy Phys. 09 (2010) 091.

CMS: Ridge in p-Pb interactions

Same approach as in pp ridge paper for "apples-apples" comparison



Average over ridge region (2<|Δη|<4)



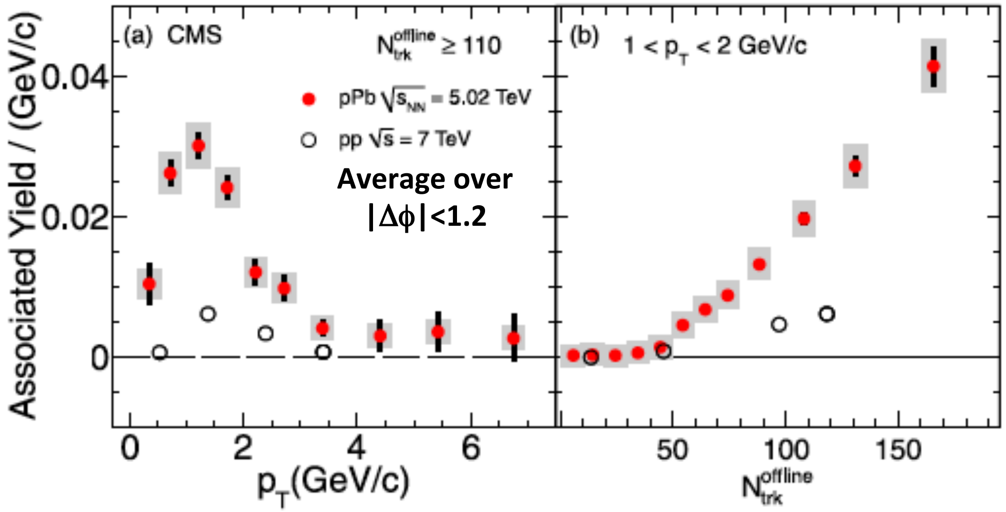
v_2=0.066, v_3=0.037

HIJING pPb

Neither HIJING nor the tested hydro model do describe the ridge

More successful models: AMPT, EPOS etc.

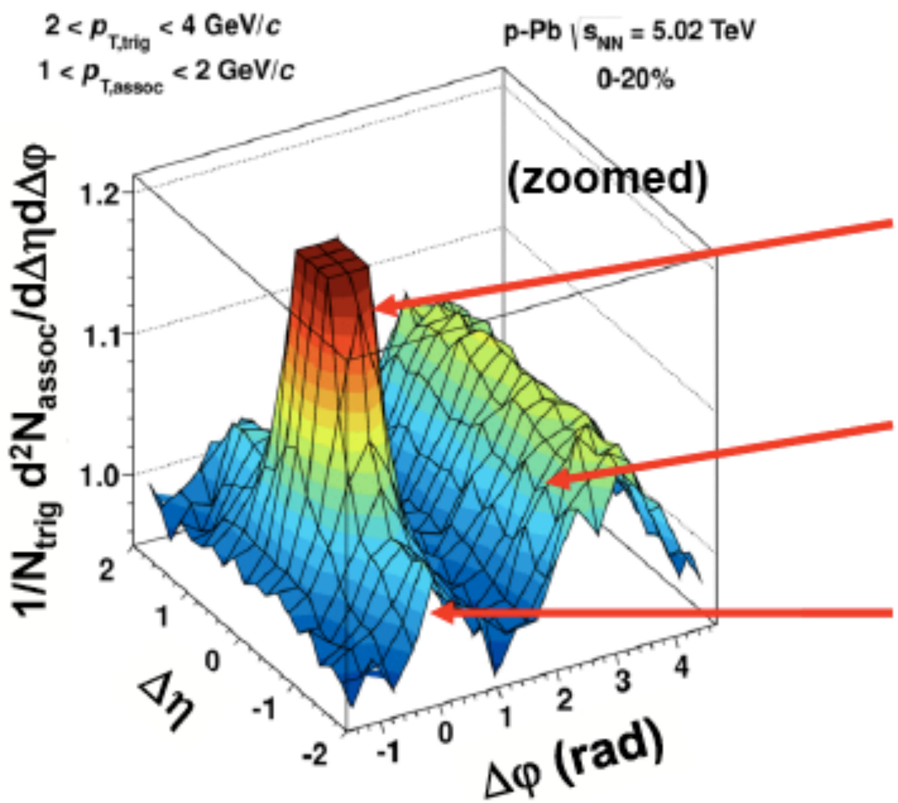
→ See the talk of Klaus Werner at QM2014



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

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
($\Delta\varphi$ ~ 0, $\Delta\eta$ ~ 0)

Away-side jet
($\Delta\varphi$ ~ π, elongated in $\Delta\eta$)

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

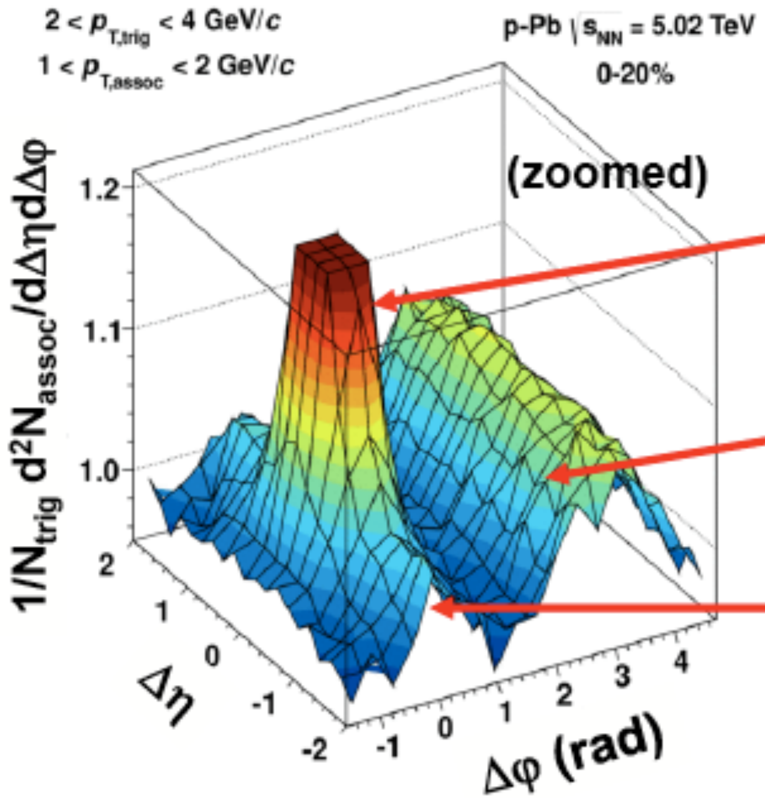
ALICE reports double "ridge" structure in p-Pb interactions at $\sqrt{s_{NN}}$ = 5.02 TeV.

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.

ALICE: Double Ridge in p-Pb interactions

Phys. Lett. B 719 (2013) 29.



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

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

Away-side jet
($\Delta\varphi$ ~ π, elongated in $\Delta\eta$)

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

ALICE reports 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.**

Bottom Line

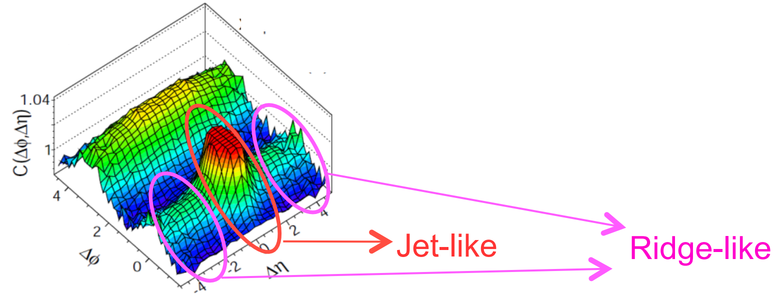
- Long-range correlations:
  - Significant ridge structures are observed in high multiplicity pp ($\sqrt{s}$ = 2.76, 7, 13 TeV), p-Pb ($\sqrt{s_{NN}}$ = 5.02 TeV) and Pb-Pb ($\sqrt{s_{NN}}$ = 2.76 TeV) collisions.
  - effect showing up in the intermediate momentum range: p_T = 1-4 GeV
  - Pb-Pb expected from the elliptic flow.
  - p-Pb and pp observations still controversial
  - The size of the effect is huge in p-Pb.
  - Second ridge structure also detected in p-Pb.
- Short-range (BE) correlations:
  - The radius of effective emission region (r) grows with N_{ch}
    - r vs N_{ch} scales with $\sqrt{s}$

Multiplicity dependent analyses focusing on High Multiplicity final states

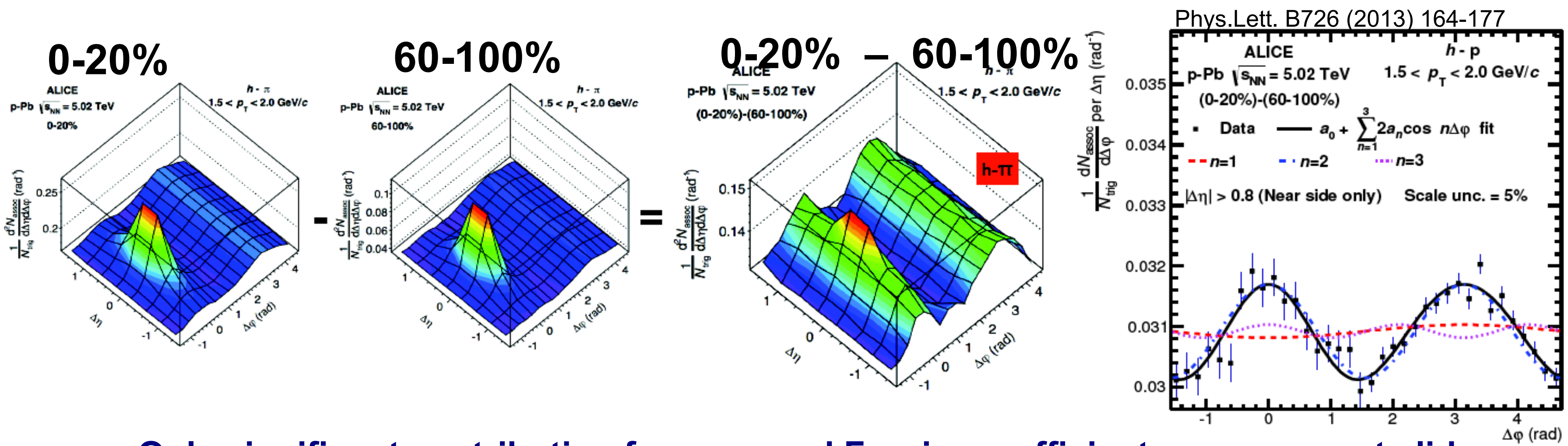
Also triggered by the observation of long range $\eta-\phi$ correlations in High Multiplicity events (ridge) reported in the previous slides.

ALICE: v_2 from h-(π, K, p) long range correlations in p-Pb

- **Two particle correlation function:**
  - **Trigger particle → unidentified hadron**
  - **Associated particle → identified hadron (π,**
  - **0.7 < p_T,ass < p_T,trigg < 5 GeV/c**



- **Double "ridge" like structures observed → in order to study the jet-like component, the ridge structures have been subtracted**

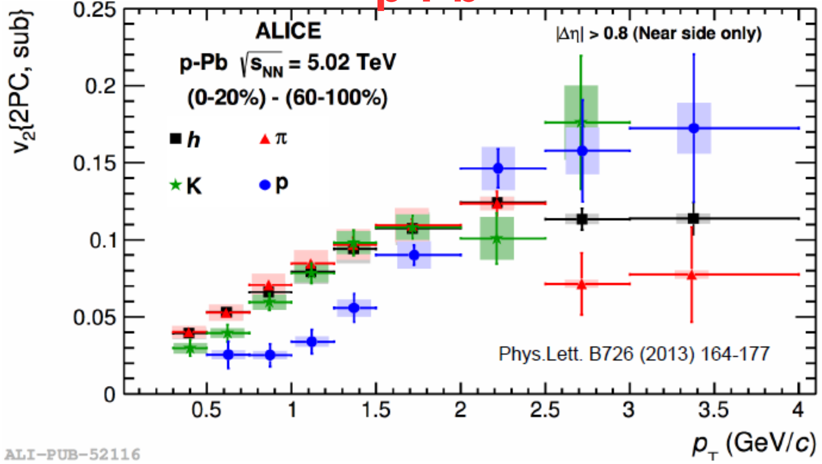


- **Only significant contribution from second Fourier coefficient v_2 → see next slide**
  - **First coefficient smaller w.r.t. the case without subtraction (up to ~10 times smaller)**
  - **Third coefficient still small**

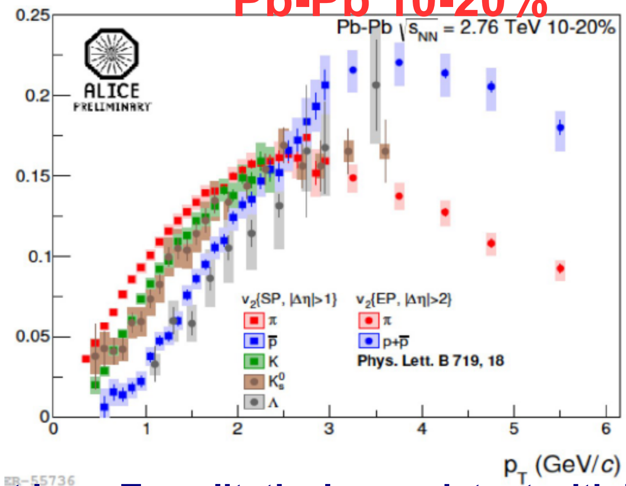
ALICE: v_2 from h-(π, K, p) long range correlations in p-Pb

- **Two particle correlation function:**
  - **Trigger particle → unidentified hadron**
  - **Associated particle → identified hadron (π, K, p)**
  - **Same p_T interval for trigger / associated particles**
- **Ridge like component isolated by subtracting low multiplicity correlations (60-100%) from high multiplicity correlations(0-20%):**
  - **Mostly jet contribution (i.e. no significant ridge) in low multiplicity p-Pb events**

p-Pb



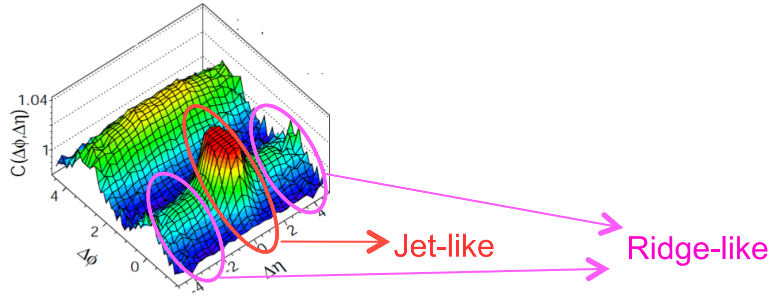
Pb-Pb 10-20%



- **Similar behaviour as in Pb-Pb collisions → mass ordering at low pT qualitatively consistent with hydro models**
  - **MPI + Color Reconnection also at the origin of flow-like pattern in p-Pb ? → still open question**

ALICE: di-hadron azimuthal correlations in p-Pb

- **Two particle correlation function:**
  - **Trigger particle → unidentified hadron**
  - **Associated particle → unidentified hadron**
  - **$0.7 < p_T$,ass $< p_T$,trigg < 5 GeV/c**



- **Double "ridge" like structures observed → in order to study the jet-like component, the ridge structures have been subtracted**

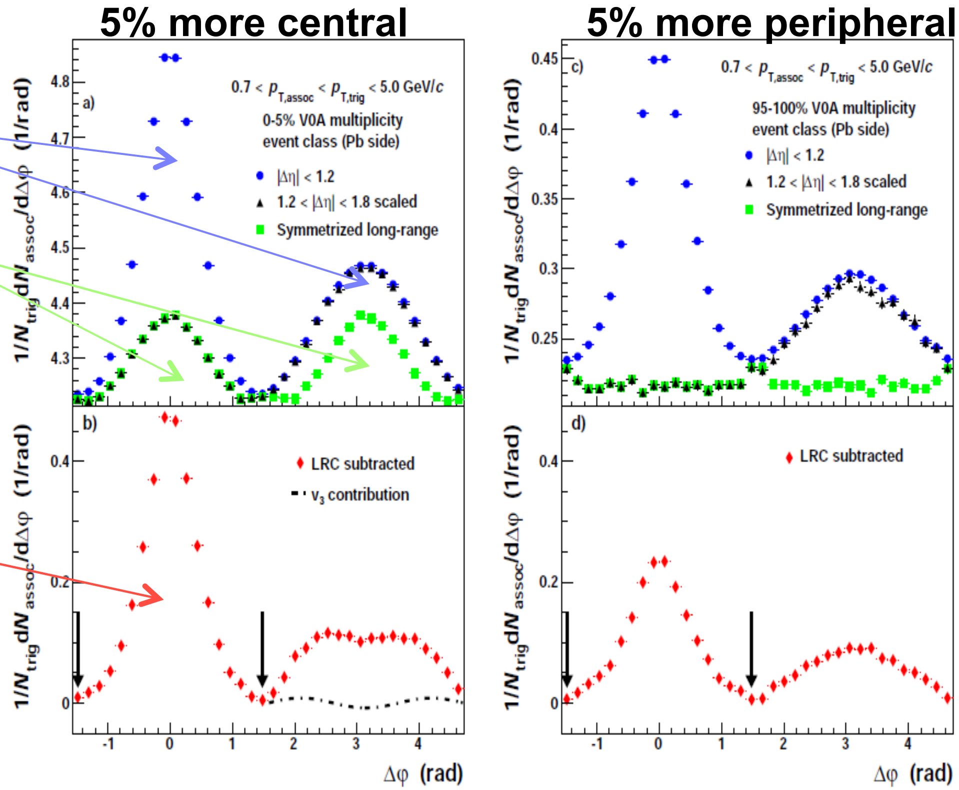
Phys. Lett. B 741 (2015) 38-50

Short range (|Δη|<1.2) near (away) side at Δϕ=0 (Δϕ=π)

Long range (1.2<|Δη|<1.8) near side (Δϕ=0) and away side (Δϕ=π) simmetrized

Subtraction: short range – long range (symmetrized) correlations

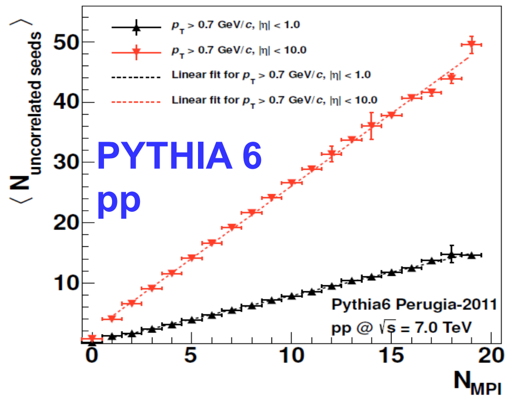
Number of associated particles in the near (<$N_{ass,nearside}$>) and away (<$N_{ass,awayside}$>) side calculated by integrating the subtracted Δϕ projection



ALICE: Number of uncorrelated seeds

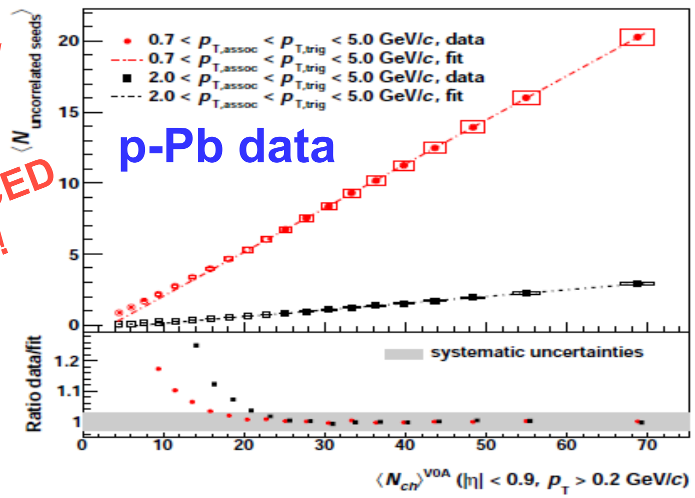
$$\langle N_{\text{uncorrelated seeds}}\rangle = \frac{\langle N_{\text{trig}}\rangle}{\langle N_{\text{correlated triggers}}\rangle} = \frac{\langle N_{\text{trig}}\rangle}{1+\langle N_{\text{assoc,nearside}}\rangle + \langle N_{\text{assoc,awayside}}\rangle}$$

- **provides the number of independent sources of particle production → in PYTHIA the uncorrelated seeds are found to be proportional to the number of the MPIs**

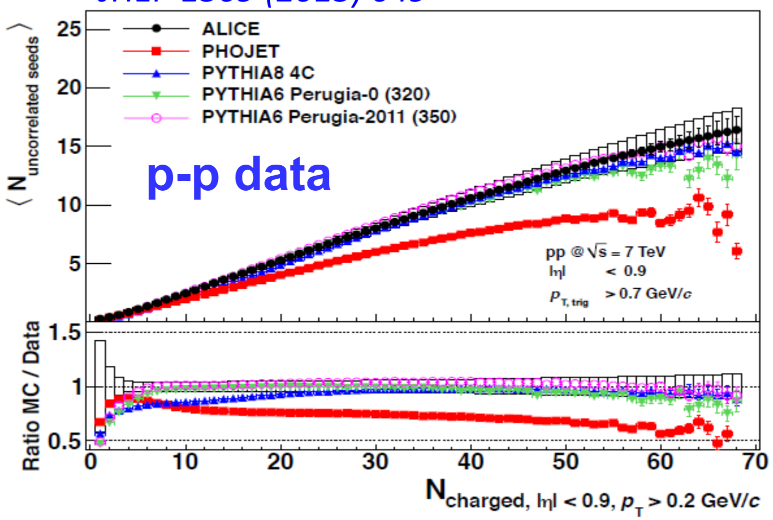


Phys. Lett. B 741 (2015) 38-50

FIRST INTRODUCED BY ALICE!

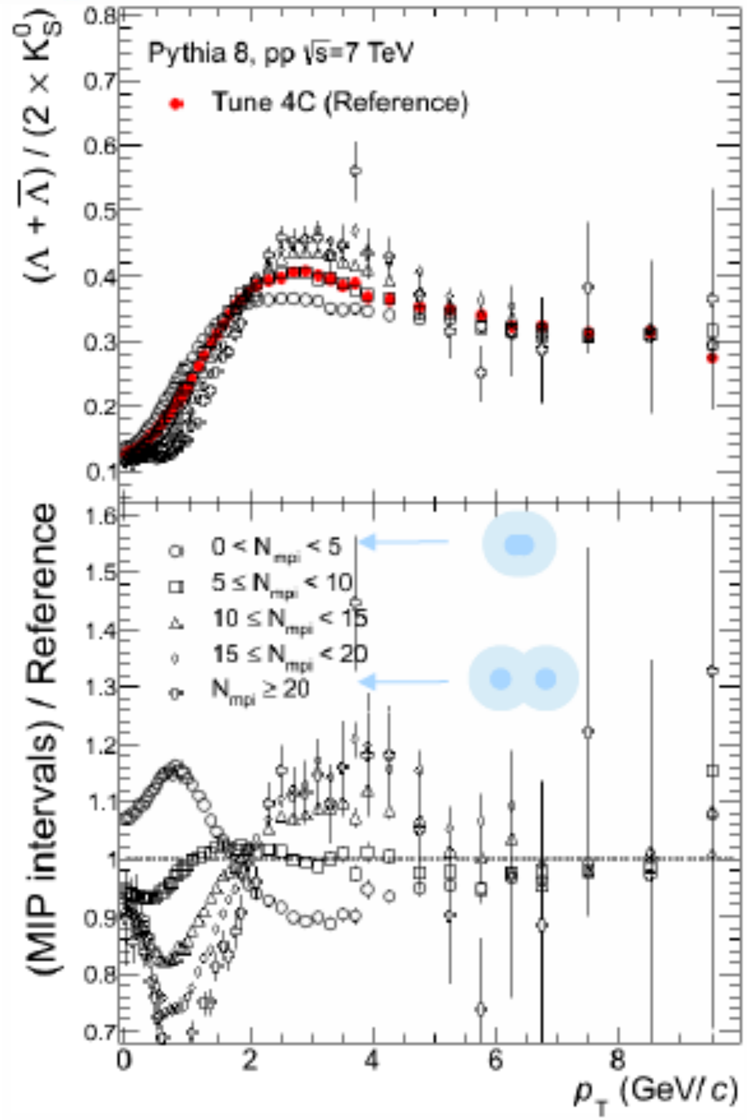


JHEP 1309 (2013) 049

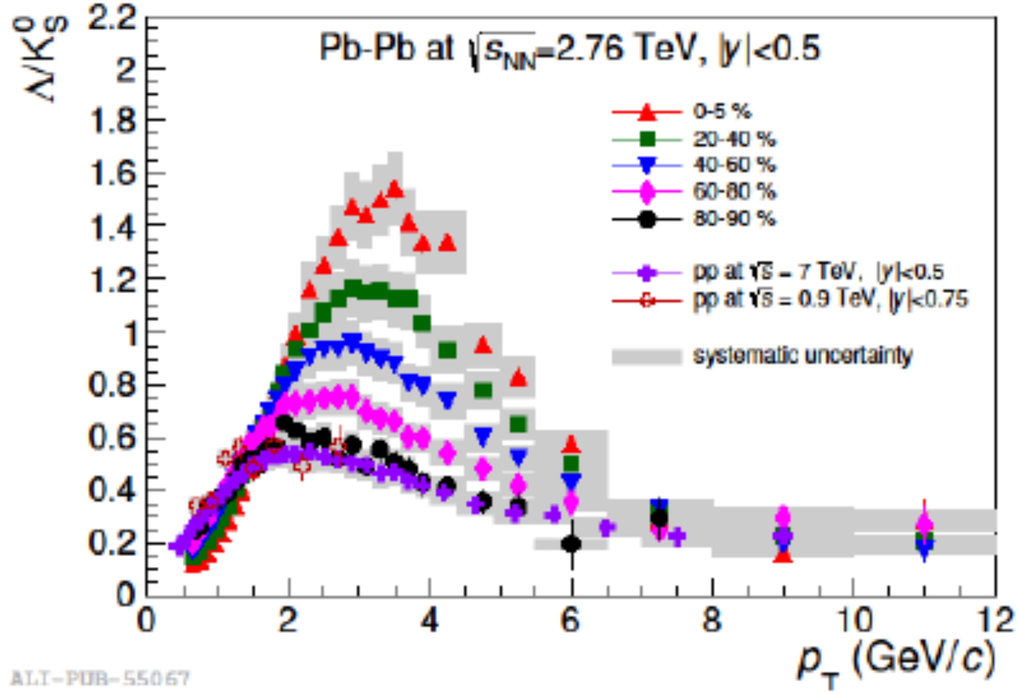


- **increases almost linearly with multiplicity (deviation observed at low multiplicity) → there is no evident saturation of nMPIs at high multiplicities in p-Pb**
- **In pp there is an indication of a limit in the increasing of the MPIs**

Color reconnection and flow-like patterns in pp



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

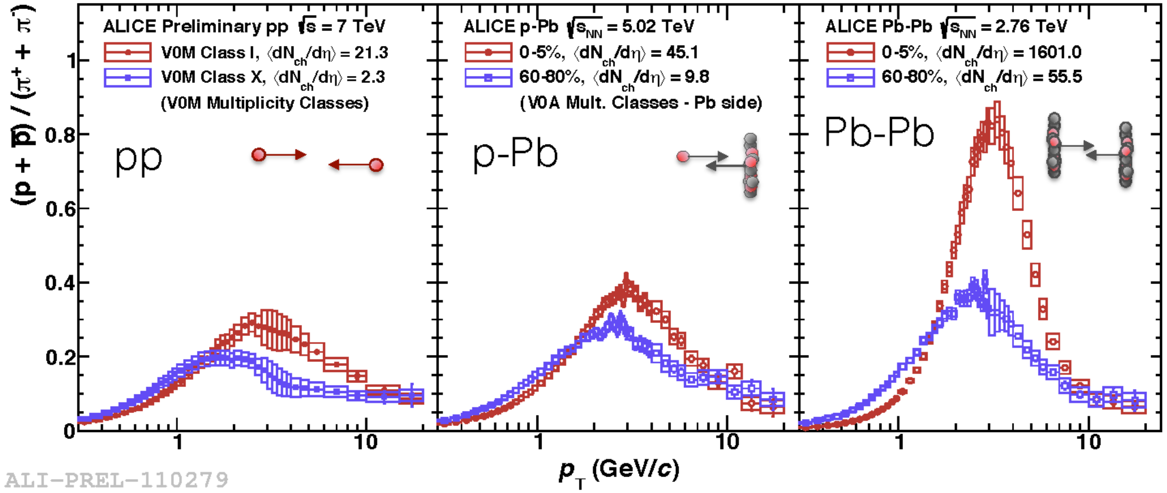


Nucl.Phys. A941 (2015) 78-86 2016

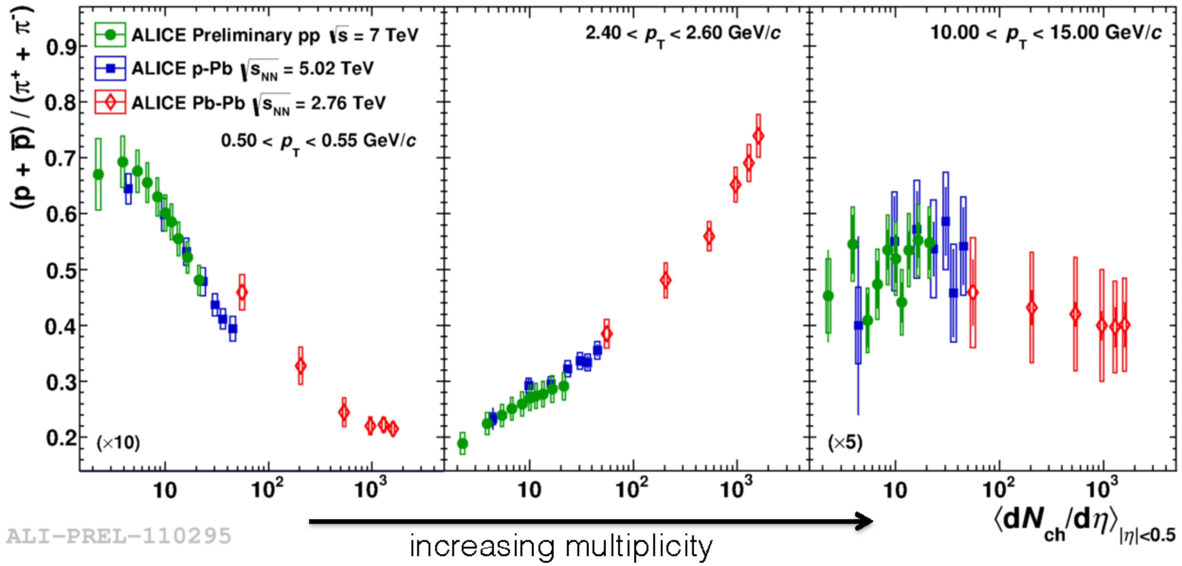
Color reconnection matters! Flat shapes otherwise.

ALICE: Baryon to Meson Ratios

pp / p-Pb / Pb-Pb



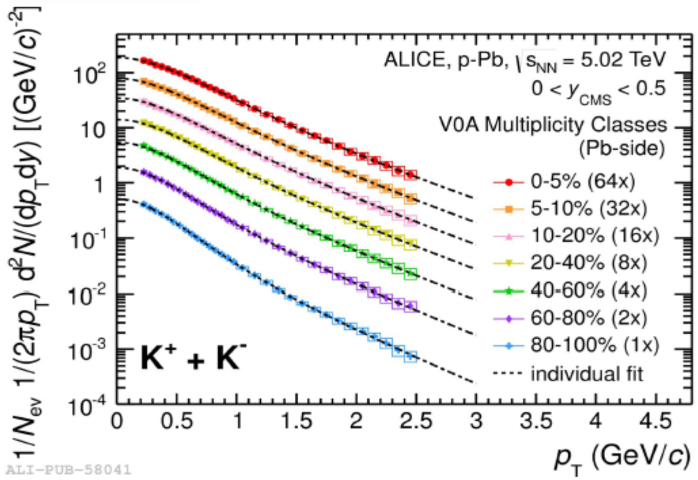
Similar qualitative behavior at High Multiplicities between pp, p-Pb, Pb-Pb



The trend of the ratios vs <$dN_{ch}/d\eta$> also appears to be independent from the system in all the investigated p_T slices

ALICE: Identified hadrons at low-p_T vs charged multiplicity (p-Pb)

ALICE, Phys. Lett.B 728 (2014) 25

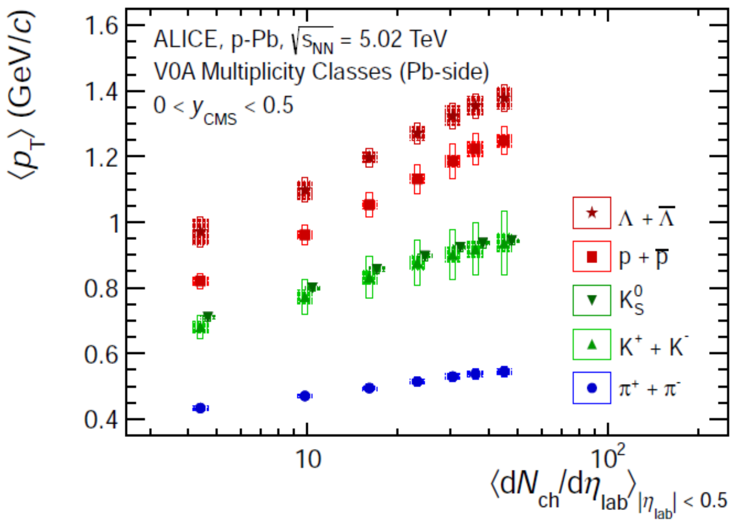


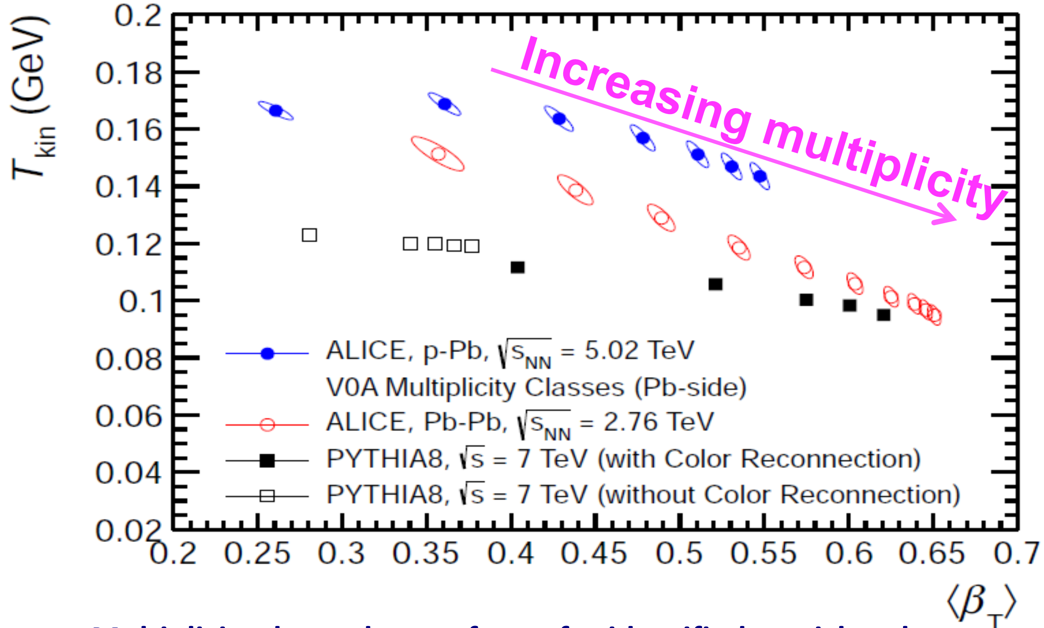
ALICE: Blast-wave model fit (thermal +collective)

$$\frac{1}{p_T}\frac{dN}{dp_T} \propto \int_0^R r\,dr\, m_T I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right)$$

$$\rho = \tanh^{-1}\beta_T$$

T_{kin} – kinetic freeze-out
β_T – transverse velocity





- **Multiplicity dependence of $\langle p_T \rangle$ for identified particles:clear mass ordering → indication for a collective expansion with a common velocity field.**
  - **The same kind of mass ordering is also qualitatively expected from colour re-connections** **[A. Ortiz Velasquez et al. Phys. Rev. Lett. 111 (2013) 4, 042001]**
- **Similar evolution of the blast–wave parameters with increasing multiplicity in p-Pb and Pb-Pb**
- **PYTHIA8 pp events (no hydrodynamic evolution) also show the same trend (albeit at a 30% smaller T_{kin})**
  - **MPI + Color Reconnection causes similar effect as radial flow**

Summary of ALICE RUN I HM Analyses (pp, p-Pb)

- Primary Seeds → Experimental progress in direct detection of soft MPI
  - Hints of saturation of Number of Primary Seeds vs N_{ch} in pp, no saturation in p-Pb.
  - Linear evolution of event yields in pp and pPb
- Transverse Sphericity analysis (pp).
  - At HM, events look more spherical with respect to the predictions of the QCD models.
  - In the context of the pQCD MPI models HM events can be regarded as the result of several soft MPI instead of being contributed by jet-like interactions.
- Multiplicity dependence of $\langle p_T \rangle$ of identified particles and p_T spectra
  - indication for a collective expansion with a common velocity field,
  - Pattern reproduced qualitatively by Pythia MPI with Color Reconnections.
- baryon/meson ratios
  - Similar qualitative behavior at High Multiplicities between pp, p-Pb, Pb-Pb
  - The trend of the baryon/meson ratios vs $\langle dN_{ch}/d\eta \rangle$ appears to be independent from the system in all the investigated p_T slices
- Several pending issues, exciting progress perspectives in the LHC RUN II, in particular for what concerns the data collected by the ALICE high multiplicity triggers.

MC

Pythia Color Reconnections

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

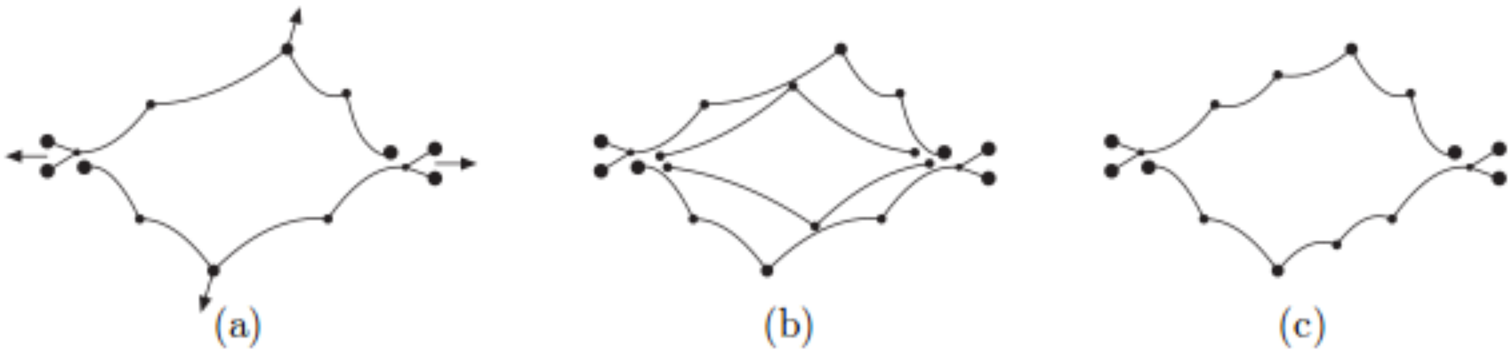


Fig. 2. (a) In a hard gluon-gluon subcollision the outgoing gluons will be colour-connected to the projectile and target remnants. Initial state radiation may give extra gluon kinks, which are ordered in rapidity. (b) A second hard scattering would naively be expected to give two new strings connected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

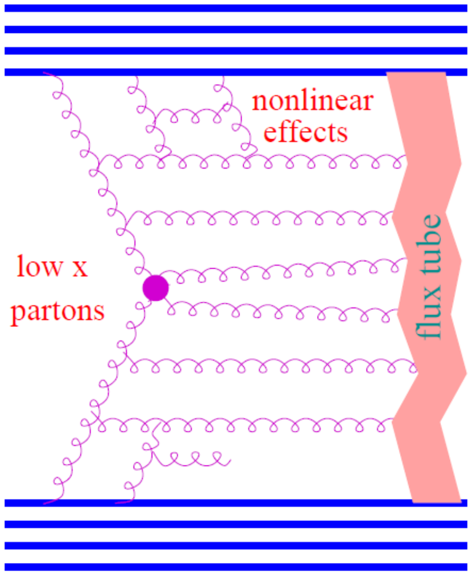
G. Gustafson, Acta Phys.Polon.B40:1981-1996,2009

EPOS

- The EPOS MC takes a Parton-Based Gribov Regge theory approach to event generation. String hadronisation in EPOS is treated differently based on the local density of string segments per unit volume with respect to a critical-density parameter. Each string is classified as being in either a low density coronal region or in a high density core region.
- Corona hadronisation proceeds via unmodified string fragmentation whereas the core is subjected to a hydrodynamic evolution; i.e. it is hadronised including additional contributions from longitudinal and radial flow effects. Core conditions are easily satisfied in ion collisions, however even for an average pp collision ($N_{ch} = 30$, $|\eta| < 2.4$) at $\sqrt{s} = 7$ TeV, around 30% of central particle production arises from the core region.
  - This rises to 75% for $N_{ch} = 100$.

MPI in EPOS

[Parton-based Gribov-Regge Theory, H. J. Drescher, M. Hladik, S. Ostapchenko, T.Pierog, and K. Werner, Phys. Rept. 350 (2001) 93-289]



- Many elementary scattering happening in parallel
- Elementary scattering = "parton ladder" + soft component
- Parton evolutions from the projectile and the target side towards the center (small x)
- Evolution equation DGLAP
- Parton ladder = quasilongitudinal color field ("flux tube")
- Well known problem with pQCD based Pomeron:
  - **Total cross section too high : MPI required**

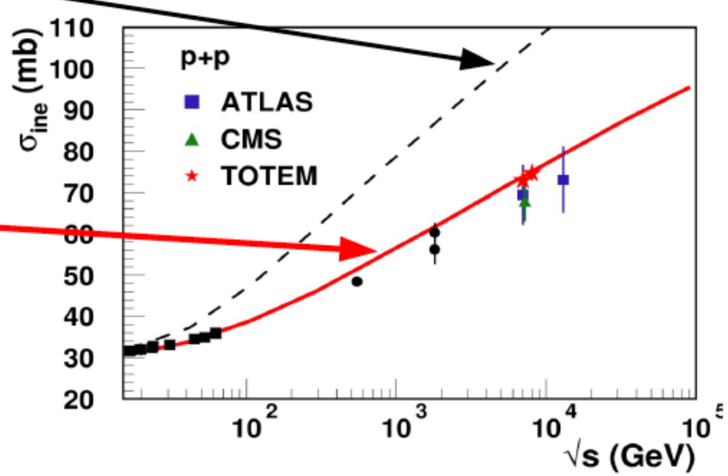
Non linear effects:
similarities with the
Pythia way of implementing
Color screening effects

No effective coupling

$$A_{\mathrm{pom}} \sim (x_1 x_2)^{\beta}$$

With effective coupling

$$A_{\mathrm{pom}} \sim x_1^{\beta} x_2^{\beta-\varepsilon}$$



Number of MPI fixed
by total cross section

DIPSY Event Generator

arXiv:1103.4321v2

DIPSY = Dipoles in Impact Parameter Space and Rapidity (Y)

- MC generator for pp, pA and AA minimum bias collisions
- Based on Muellers dipole formulation:
  - Includes sub-leading effects from energy conservation and running coupling.
  - Accounts for colour suppressed effects from pomeron loops via a dipole swing mechanism.
  - It also treat for a consistent treatment of non-perturbative confinement effects.

DIPSY

- DIPSY implements Mueller's dipole cascade model, which operates in transverse coordinate space (unlike conventional showers which operate in momentum space). Instead of conventional PDFs, the model starts from an explicit representation of each proton being composed of three colour dipoles in impact-parameter space and rapidity. These are then evolved in rapidity space via iterated gluon emission, forming a dipole cascade. The resulting partonic final states are hadronised using the Lund string model, via an interface to PYTHIA 8.
- The recently developed rope extension to DIPSY allows geometrically nearby strings to act as a combined "colour rope", which can hadronise with a higher intrinsic tension. The consequences are larger p_T kicks (relative to the string direction, which for soft-particle production in pp collisions largely coincides with the z-axis) and production of more strange hadrons and baryons, the latter via probabilistic collapses of ropes to string junctions. The model also incorporates a mechanism called final-state "swing", which acts to minimise the masses of final-state colour-dipoles via colour reconnections, driven by SU(3) colour rules combined with an ad-hoc probabilistic evolution kernel.

AMPT

Settings:

- string melting off, hadronic rescattering on
- string melting on, hadronic rescattering on
- string melting on, hadronic rescattering off

Monika Kofarago
HP'2016