Soft QCD Measurements at LHC

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On behalf of the LHC experiments

(ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM)

Soft QCD :

- ➢ characterized by a soft scale (low p_T)
- ➢ applied to describe
  - the part of the scattering that dominates at soft scale
  - hadronization
- ➢ not uniform description, variability in modeling

Measurements

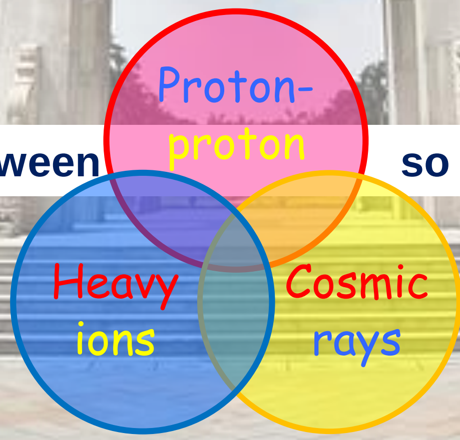
Soft scale → processes with large cross sections:

- ❑ Inclusive cross sections
- ❑ Inclusive & Identified particle spectra
- ❑ Underlying event
- ❑ Particle correlations
- ❑ Similarities between pp / pPb / PbPb

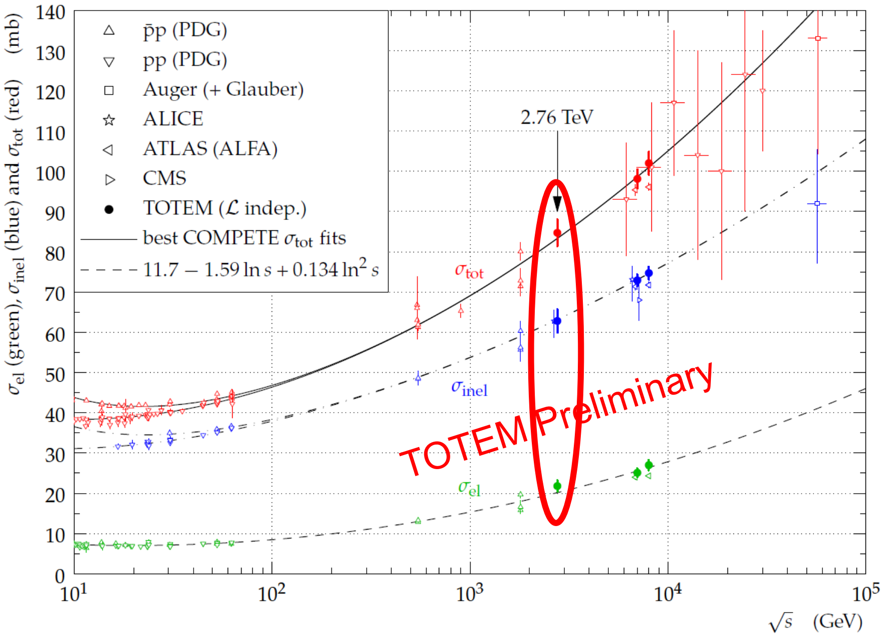
Phenomenology

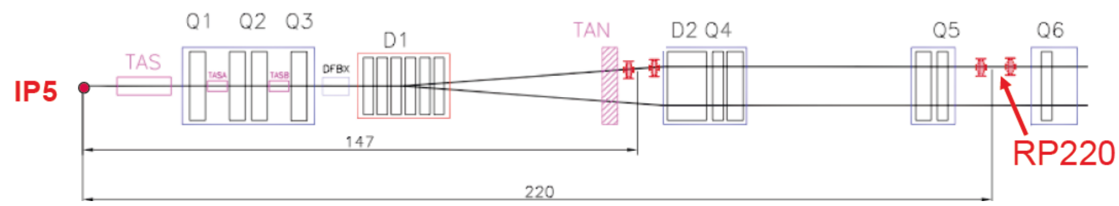
Multi-parton interactions (MPI)
Colour coherence / reconnection
Hadronization (line, ropes, helix)
Hydrodynamics / Gluon saturation

Very interesting links between **so different fields**



Inclusive (total & elastics) pp cross-sections



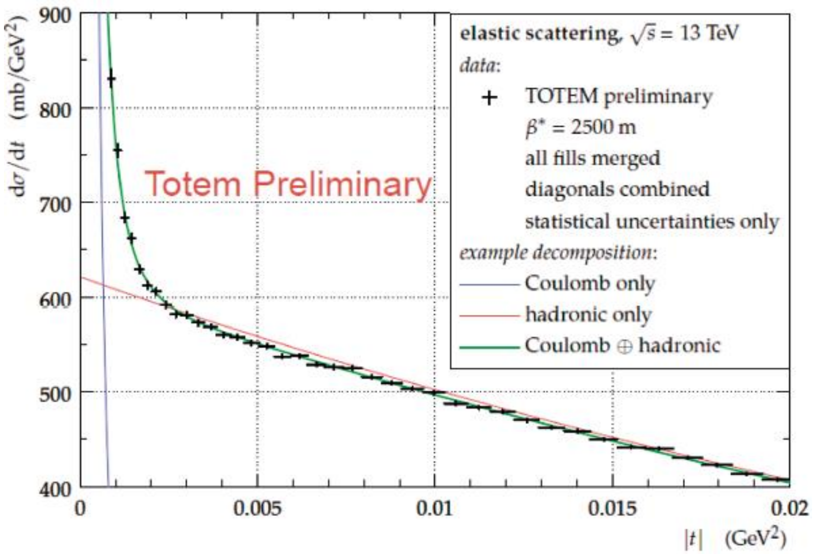


TOTEM, ALFA(ATLAS): dedicated forward proton detectors (~220-240 m from interaction point)

- very close to beam (~few mm dep. on LHC optics (β^*))
- the larger β^*, the lower t
- dedicated runs: various collision energies, negligible pile-up

β^* range: 11m - 2500m → $0.0006 < |t| < 2$ GeV²

TOTEM, NPB 899 (2015) 527   ATLAS, PLB 761 (2016) 158



13 TeV: β^* = 2500m, $0.0006 < |t| < 0.2$ GeV²

- Coulomb-Nuclear Interference region → ρ can be measured
- ρ = Real to imaginary part of forward amplitude

TOTEM, EPJC 76 (2016) 661

σ_{tot} input to model
- amount of pile-up at LHC
- interactions in cosmic rays

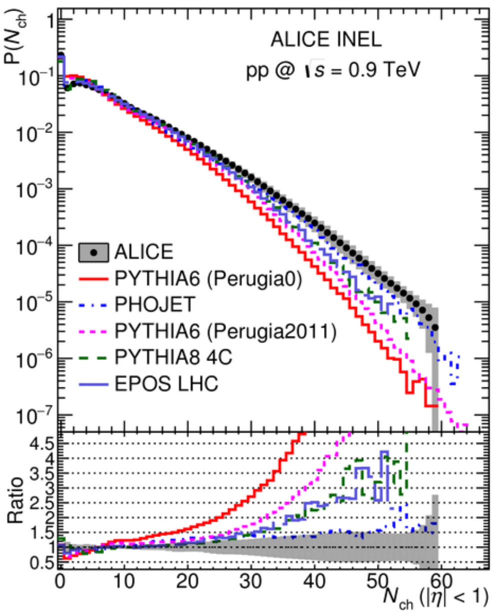
Inclusive charged particles in pp (0.9-13 TeV)

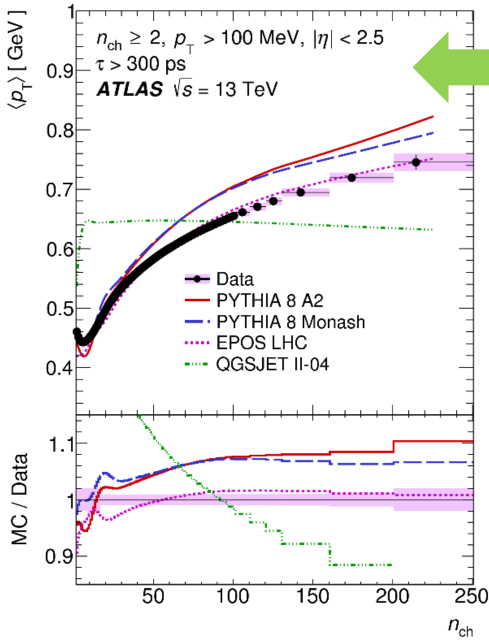
$\sqrt{s}$ = 0.9, 2.36, 2.76, 7, 8 TeV
|η| < 2, p_T > 0.1 GeV

INEL = all (MB) events
NSD = Non Single Diffraction

(ALICE, PbPb: PRL 116 (2016) 222302)

ALICE, EPJC77 (2017) 33





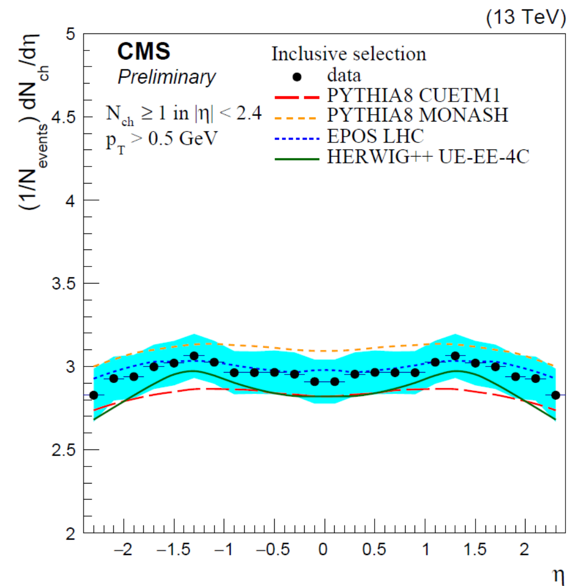
ATLAS, EPJC76 (2016) 502

QGSJET: no colour coherence
PYTHIA 8: colour reconnection
EPOS: hydrodynamical evolution

CMS-PAS-FSQ-15-008

Difficulties of all models to describe larger multiplicities

EPOS overall best description (specialized soft QCD model)



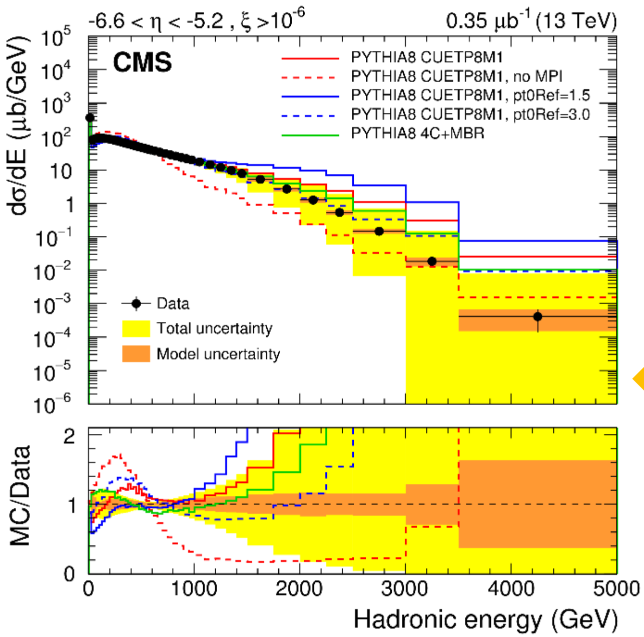
ALICE:

- Measurement of dN_{ch}/dη (η=0)($\sqrt{s}$) ~ s^{δ}: δ=0.114(INEL) (δ=0.15 for central PbPb)
- Alternatively: normalized q-moments $C_q = \frac{<N_{ch}^q>}{<N_{ch}>^q}$

For NSD events and three |η| intervals:
C_2 constant over $\sqrt{s}$ = 0.9-8.0 range
C_3, C_4, C_5 increase with $\sqrt{s}$ and with increasing Δη at given $\sqrt{s}$ → **KNO scaling violation**

In general: all models need to be retuned for every energy

Very forward energy flow



CASTOR (-6.6 < η < -5.2) with EM and HAD calorimeters
- Inclusively EM particles (e^+, e^-, γ)
- Inclusively hadrons (mainly π^+, π^-)

CMS, CERN-EP-2016-313

Measurements suitable to tune:

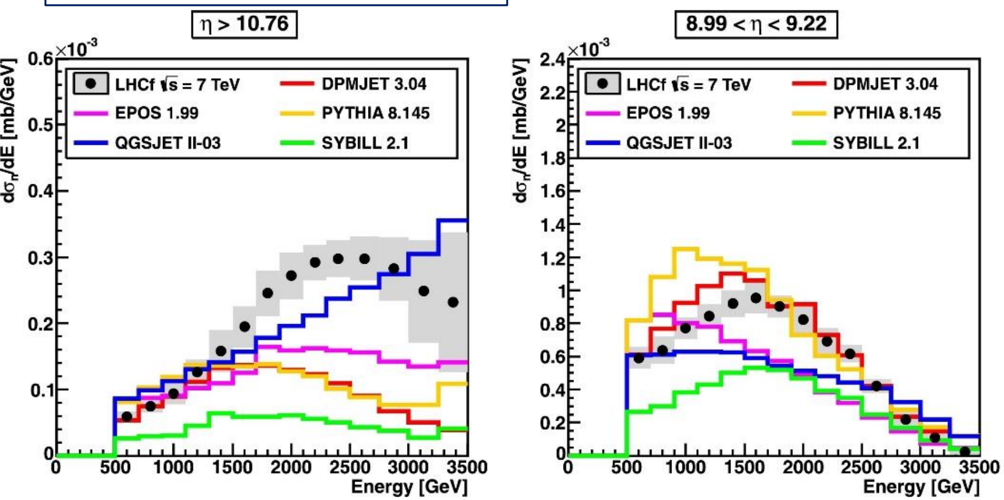
1) Multi-Parton Interaction models in MC generators for pp collisions

2) MC generators modeling HE cosmic ray air showers

$\sqrt{s}$ – evolution of model parameters is unknown
Again: MC generators need to be retuned for every energy point

Neutrons at **7** TeV, **pp**

LHCf, PLB 750 (2015) 360



❑ X_{max} (shower maximum position) modeling: σ_{inel}^{p-air} & forward identified particle spectra

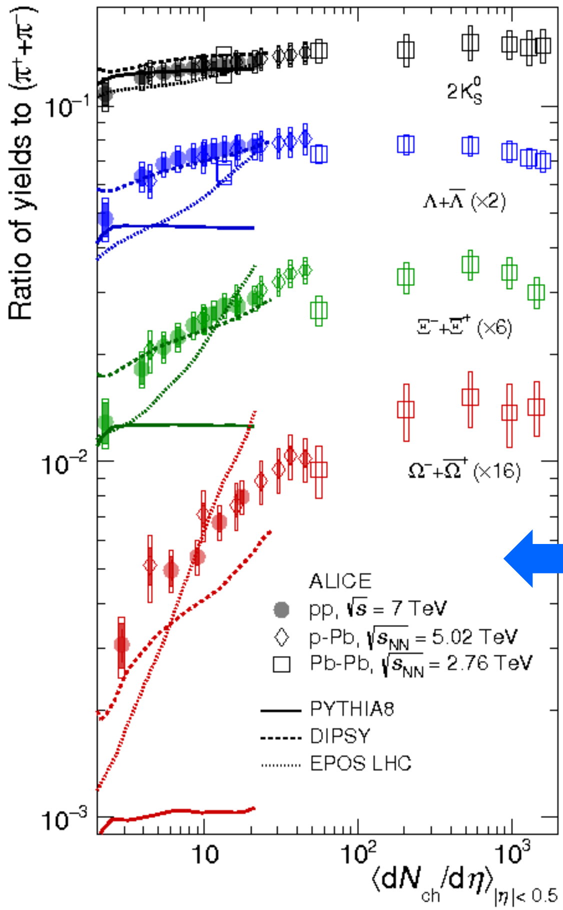
❑ hadronic interaction modeling: correlation central-forward particle production (ATLAS vs LHCf or CMS vs TOTEM)

LHCf: calorim. measuring soft neutral (n,π^0,γ) particles
- 140m from ATLAS, |η| > 8.4

PRD 94 (2016) 032007, CERN-EP-2017-051

Identified particle spectra (PbPb, pPb, pp)

ALICE, Nat. Phys. 13 (2017) 535



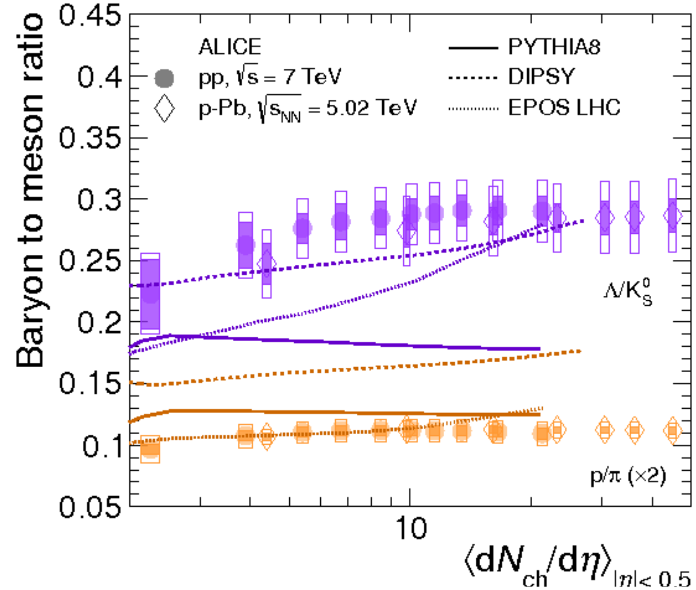
Enhanced strangeness = signature of QGP formation in heavy-ion collisions

- for the 1st time observed in pp
- similar dependence on particle multiplicity in PbPb, pPb, pp

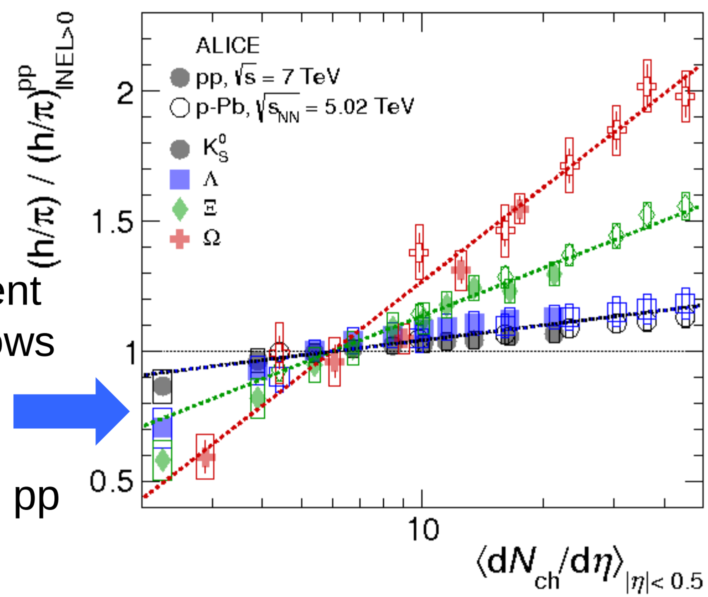
DIPSY closest to data (color ropes)

Strangeness enhancement wrt inclusive sample follows strangeness hierarchy:

- the same for pPb and pp

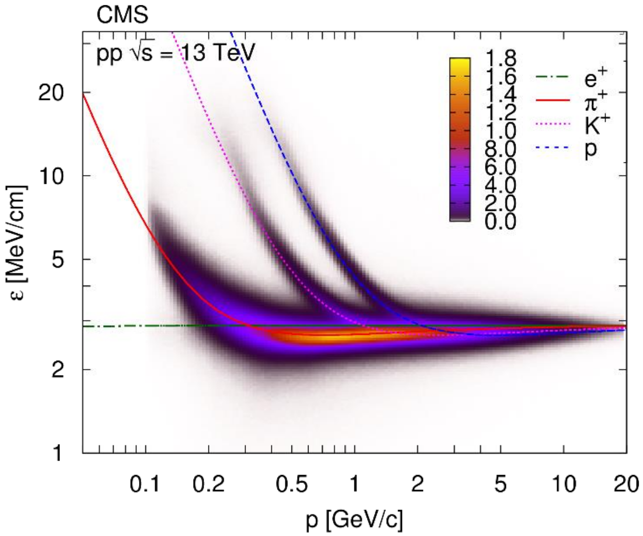


Details not described by any model



➢ See also talk by A. Kalweit

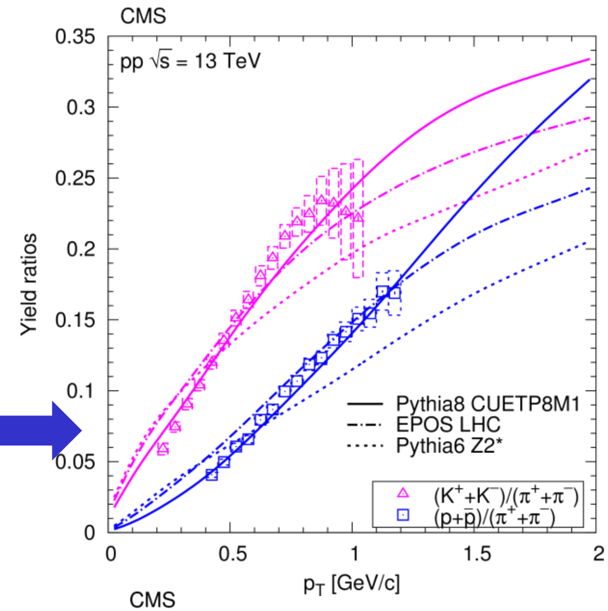
Identified particle spectra in pp (13 TeV)

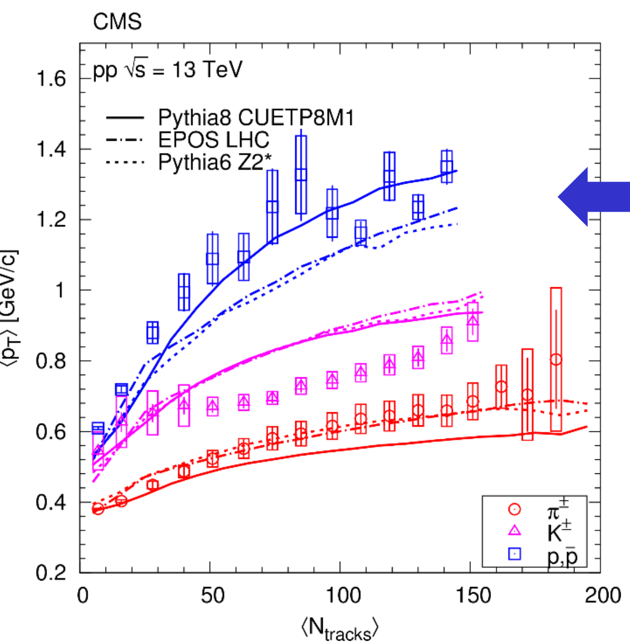


CMS, CERN-EP-2017-091

- ❑ Negligible pile-up
- ❑ Identification via dE/dx
- ❑ π, K, p: p < 1.2,1.05, 1.7 GeV
- ❑ |y| < 1.0 (2.4 for N_{tracks})

Ratio of particle yields K/π & p/π correctly described by PYTHIA 8

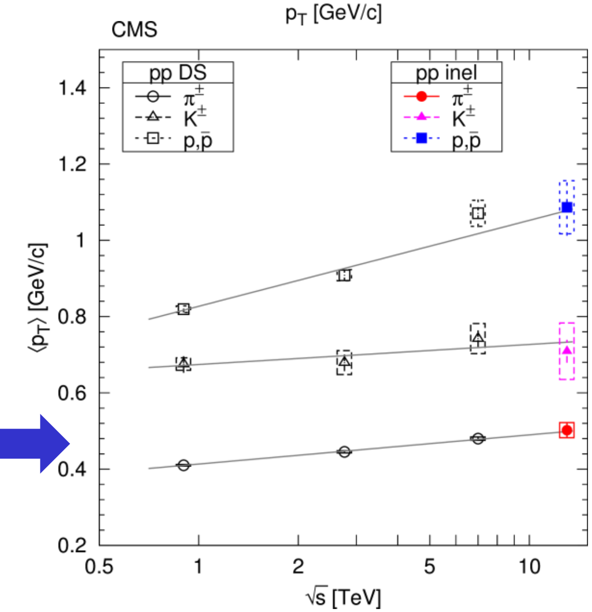




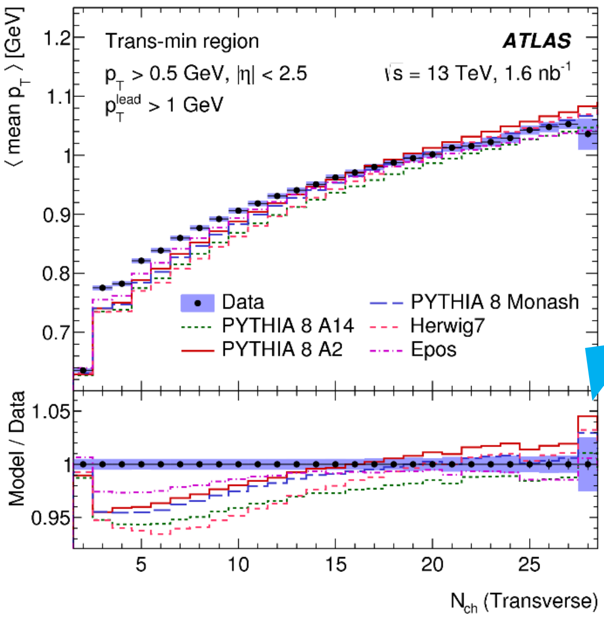
- ○ Low-multiplicity region well described
- ○ High-multiplicity region needs tuning of baryon and/or strangeness prod.

<p_T> increases with $m_{particle}$ & N_{tracks}

$\sqrt{s}$ - evolution connected with saturation scale of gluons in proton



Underlying Event study (13 TeV)



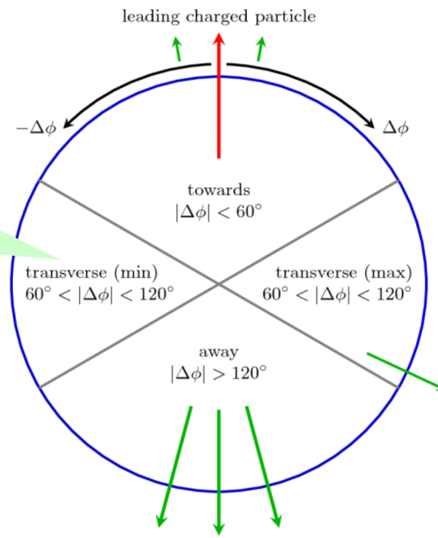
ATLAS, JHEP03 (2017) 157, also CMS tunes for UE/DPS in EPJC76 (2016) 155

Min.Bias events, leading track

|η| < 2.5, p_T > 0.5 GeV

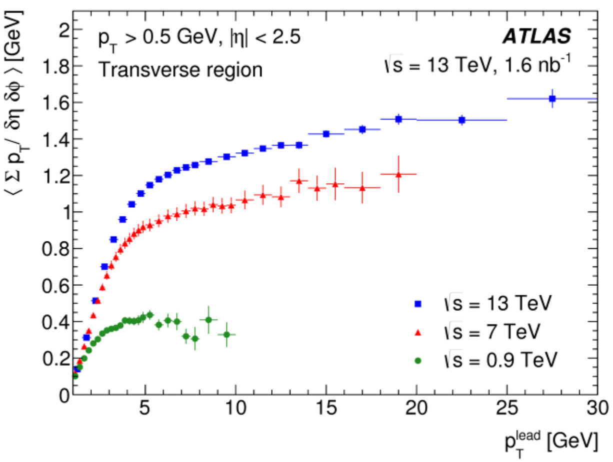
Most sensitive to MPI+CR

- Balance between two soft QCD properties
- affected by color reconnection



UE = everything except the hard scattering

- Initial state radiation
- Finale state radiation
- Multi-parton interactions
- Color reconnection

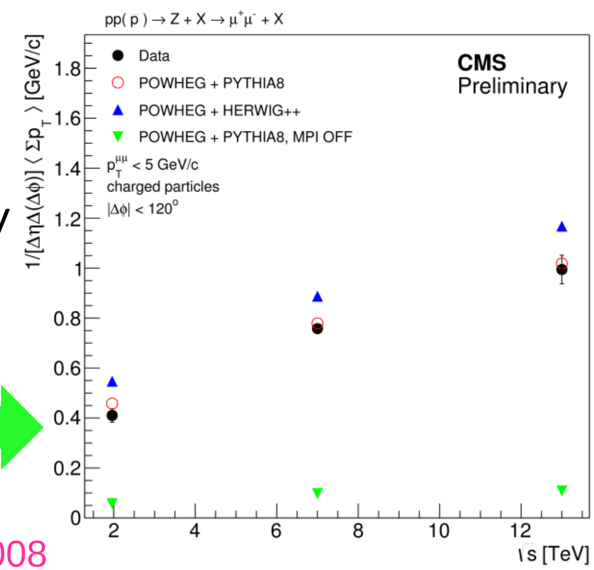


EPOS overall fine but not good for p_T (leading) > 10 GeV

Drell Yan events, leading $\mu^+\mu^-$ pair

|η| < 2, p_T > 0.5 GeV

High sensitivity to MPI

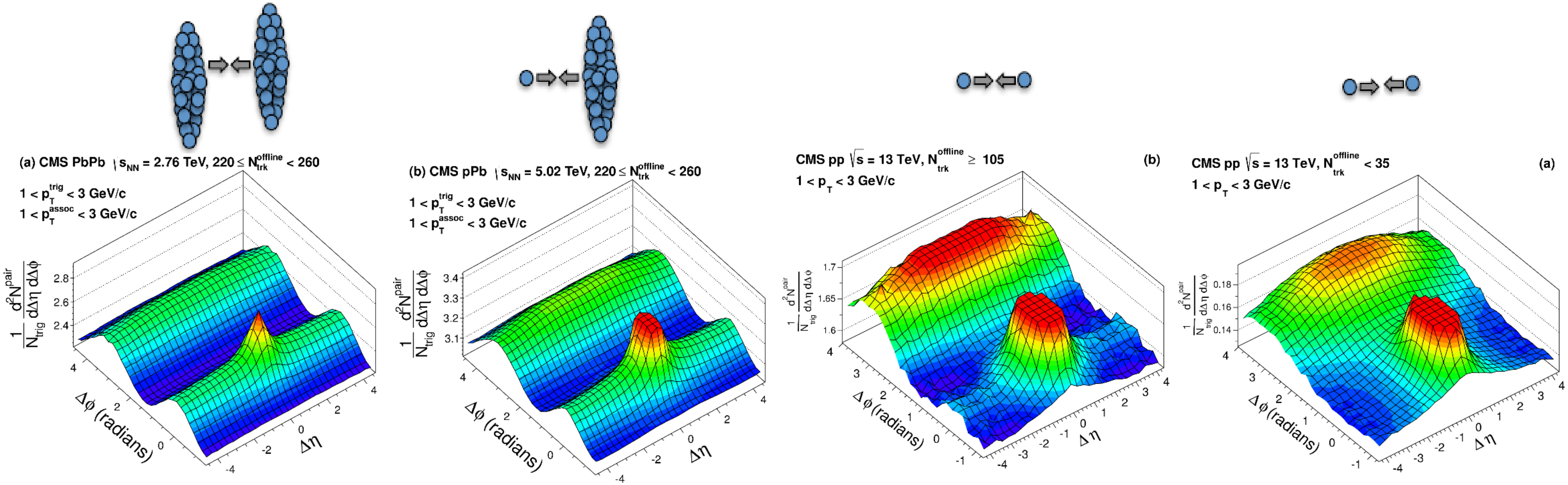


More collision energy → more UE activity.

Typical plateau observed

CMS-PAS-FSQ-16-008

2-Particle azimuthal correlations



CMS, PLB 724 (2013) 213 *Similar illustrations also by ALICE, ATLAS & LHCb* CMS, PRL 116 (2016) 172302

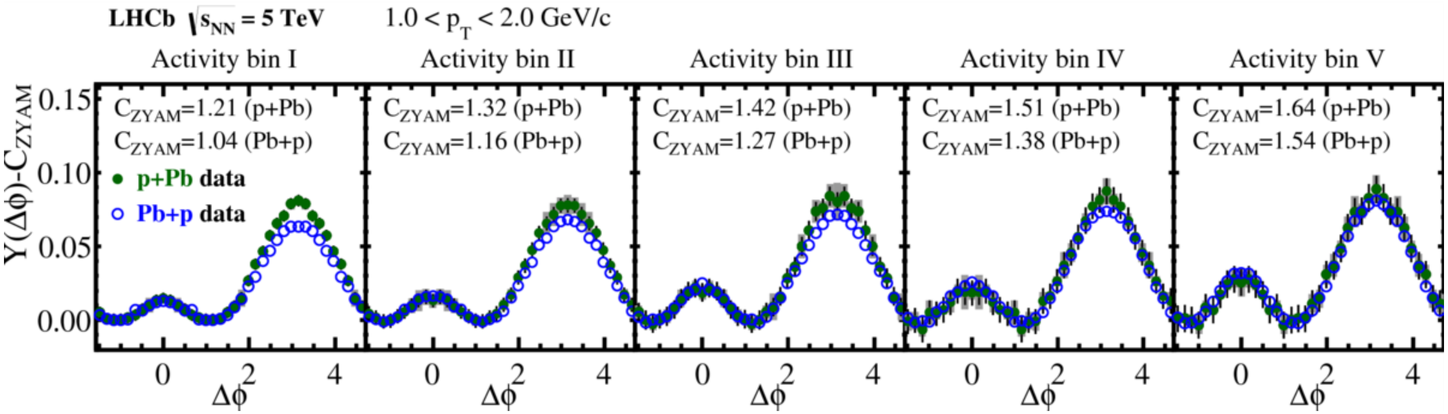
Long-range (|Δη|>2) ridge in 2-PC on near side (Δφ~0) observed in large systems (central AA coll.)
- described by Fourier decomposition ~ $1 + 2v_n\cos(n\Delta\varphi)$, v_n= single-particle anisotropy harmonics
- result of collective hydrodynamic expansion of hot and dense nuclear matter created in the overlap region

But long-range ridge seen also in pPb (much smaller system) and even in pp at high multiplicity!

- **Origin of the ridge in small systems still under debate**: hydrodynamics like for QGP? Initial state fluctuations (Color Glass Condensate/gluon saturation) ? Hadronization using ropes? Thin flux tubes?
- Ridge = testing ground to study complementarity between dynamical and hydrodynamical models

➢ See also talk by A. Kalweit

2-Particle azimuthal correlations



pPb 5 TeV:

LHCb, PLB 762 (2016) 473
(ALICE, CERN-EP-2016-228)

- Size of near-side ridge & away-side ridge increases with multiplicity
- Size of near-side ridge maximal for 1 < p_T < 2 GeV

Size of correlations in PbPb/pPb/pp:
~ linear grow with charged multiplicity

Ridge separation from non-flow (resonance decays, dijets) using:

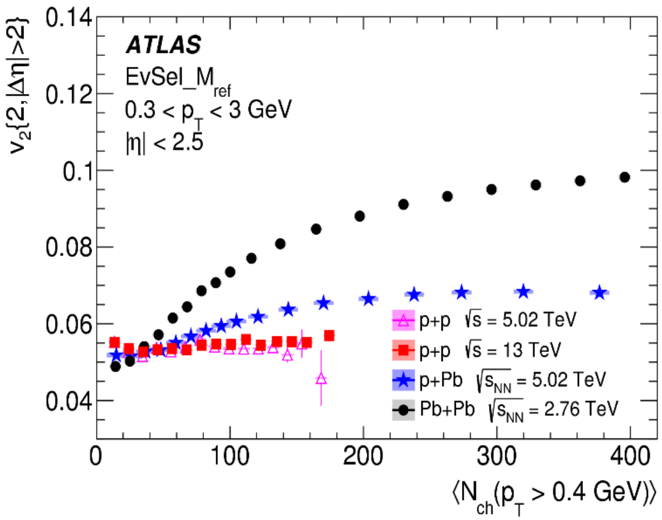
- low-multiplicity events

(e.g. ATLAS, PRL 116 (2016) 172301)

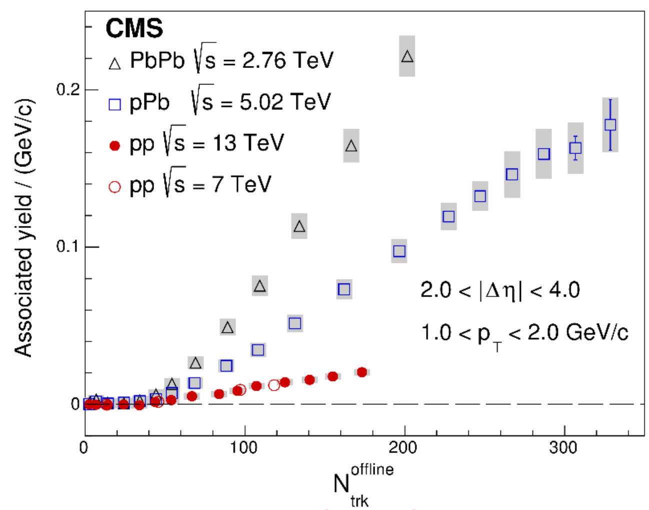
- three-subevent method (next slide)

$v_2\{2\}$(pp) < $v_2\{2\}$(pPb) < $v_2\{2\}$(PbPb)

Expected: $v_2\{2\}$(pPb) << $v_2\{2\}$(PbPb)



ATLAS, EPJC77 (2017), 428

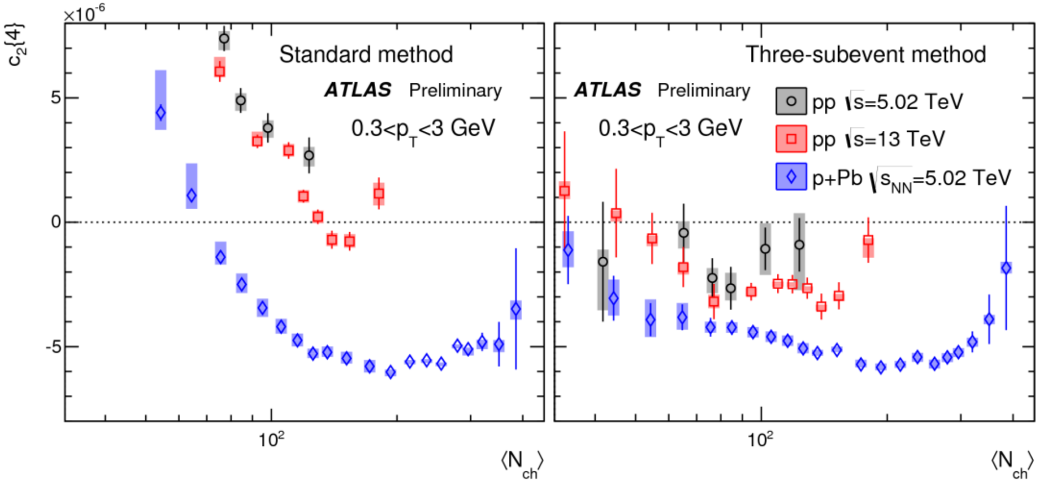


CMS, PRL 116 (2016), 172302

Multi-particle azimuthal correlations

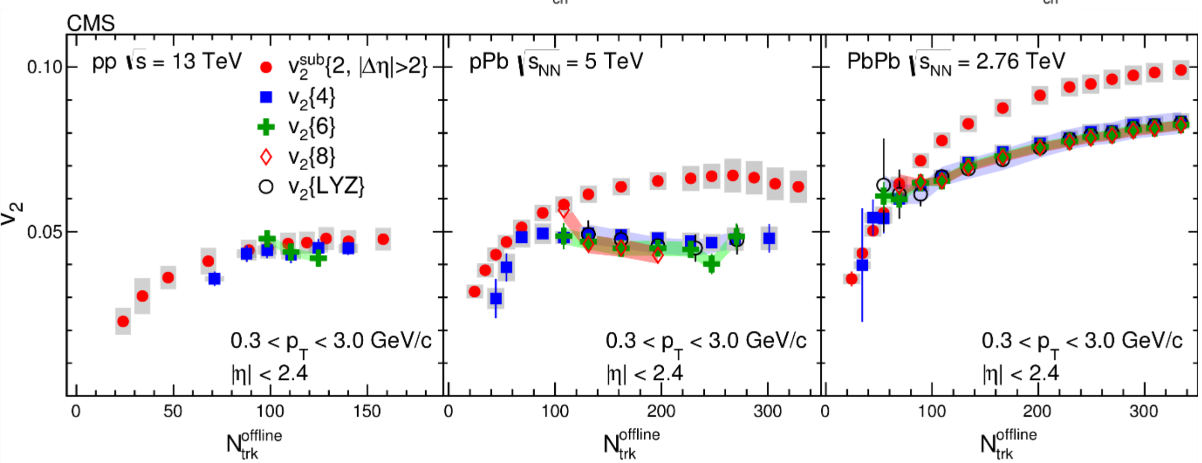
- ❑ 2-particle correlations suffer from non-flow. Multi-particle correlations are more robust against non-flow effects. But also more statistically demanding.
- ❑ Method: build cumulants $c_n\{2k\}$ and calculate flow harmonics $v_n\{2k\}$
- ❑ Extraction of collective flow in pp depends strongly on:
  - Event classification
  - Purity of non-flow subtraction

ATLAS-CONF-2017-002



Three-subevent method: reduces well the non-flow and gives 4-particle cumulant $c_2\{4\} < 0$ in all three collision systems

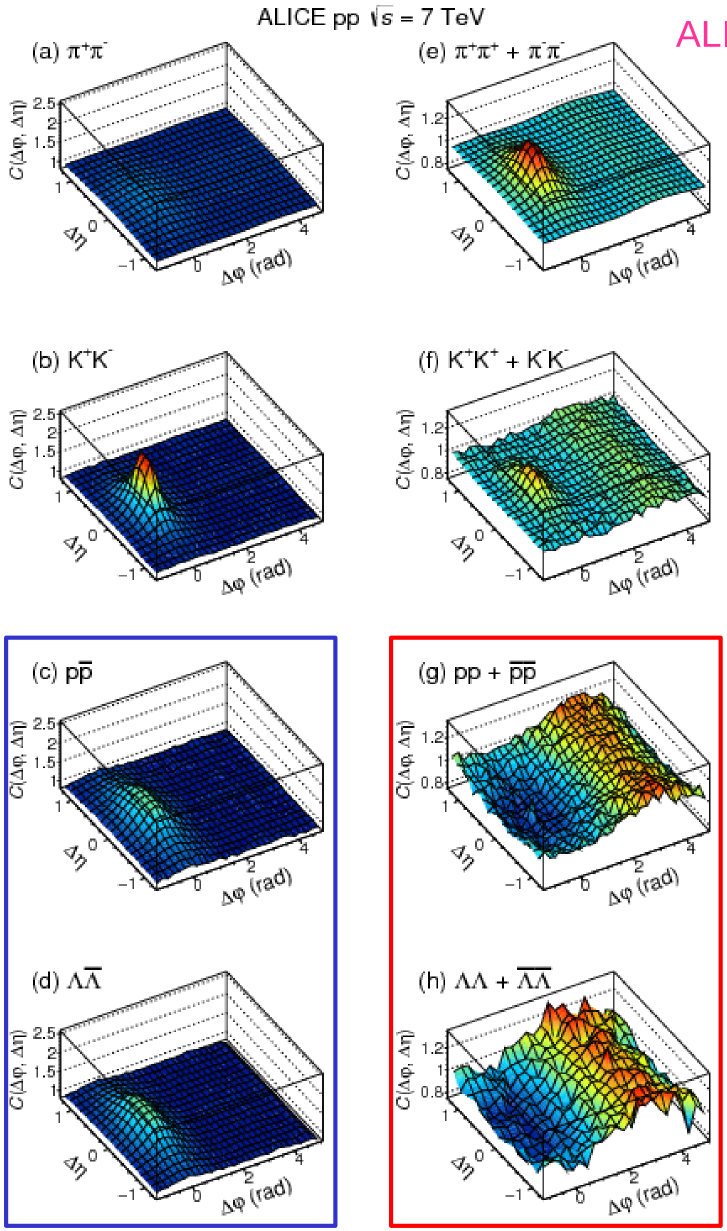
$$v_2\{4\} = \sqrt[4]{-c_2\{4\}}$$



- $v_2\{4\} < v_2\{2\}$ in pPb and PbPb as expected for a long-range collective effect
- $v_2\{4\} \leq v_2\{2\}$ also in pp ($v_2\{4\}$ smaller for three-subevent method)
- $v_2\{4\} \sim v_2\{6\}$ in all three systems: Collective nature of ridge also in pp!

CMS, PLB 765 (2017) 193

Angular correlations of identified particles

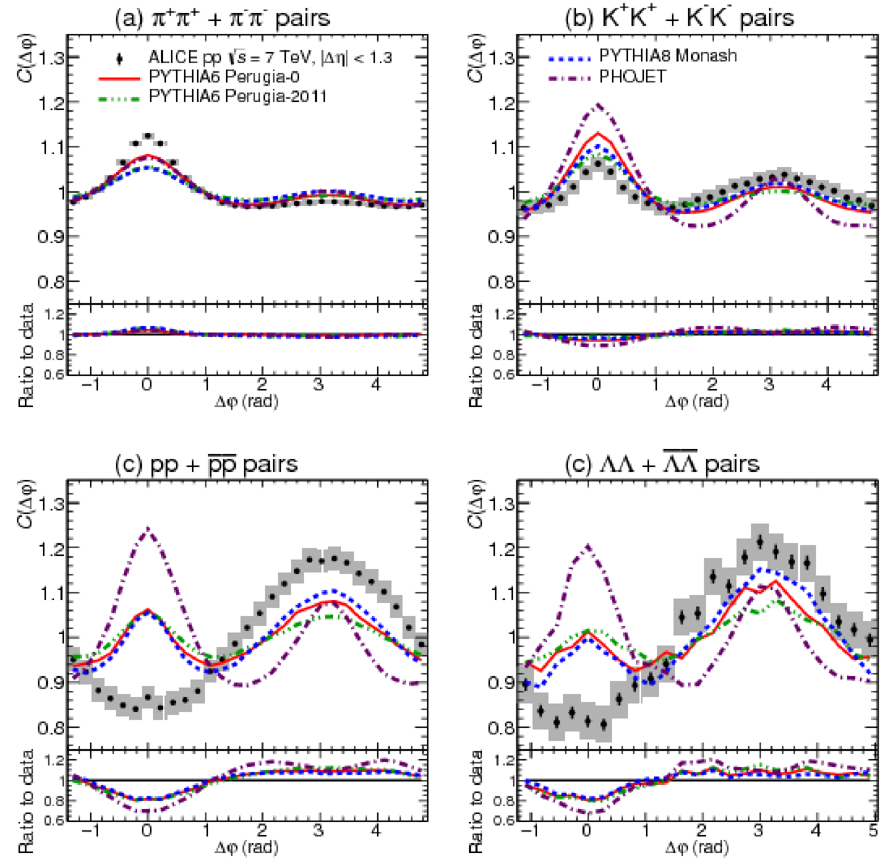


ALICE, CERN-EP-2016-322

Study of near-side peak (Δη~0,Δφ~0)

Baryon-(Anti)Baryon correlation

(Anti)Baryon-(Anti)Baryon **anticorrelation**



Depression not explained by:

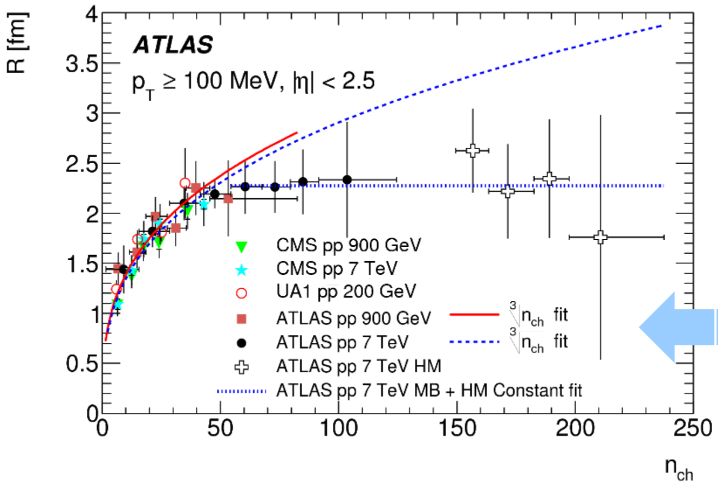
- Fermi-Dirac Quant.Stat (since depression seen also for pΛ+$\bar{p}\bar{\Lambda}$)
- Strong final state interactions
- Local baryon nr. conservation

Not reproduced by MC (Pythia 6, Pythia 8, Phojet - conserve local baryon nr., do not include quantum stat. effects).
Something essential missing in string fragmentation.

Bose-Einstein correlations in pp, pPb, PbPb

Min.Bias pp events, |η| < 2.5, p_T > 0.1 GeV

ATLAS, EPJ C75 (2015) 466



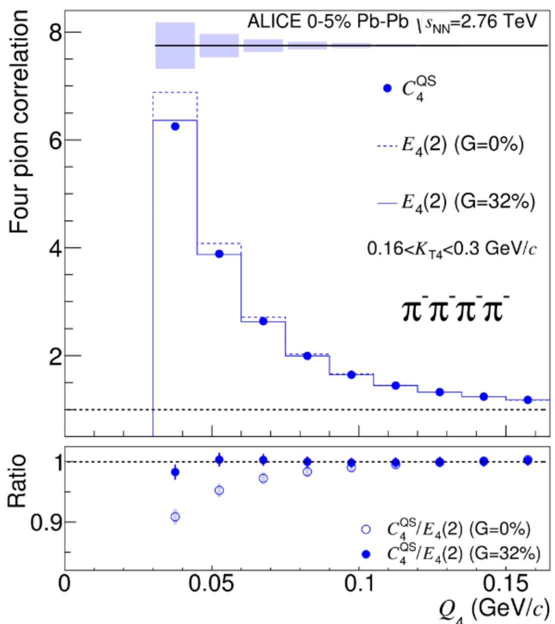
2-PC (C_2) of identical particles: Same-sign/Opposite-sign double ratio Data/MC

$C_2 = C_0[1 + \Omega(\lambda, R)](1 + \varepsilon Q)$
λ = correlation strength
R = correlation source size

Saturation of R at high-mult.
- observed for the 1st time

❑ Decrease of R with k_T measured (as in pPb: ATLAS, CERN-EP-2017-004)

R (λ) increasing (decreasing) with n_{ch}
↓
Larger sources appear more coherent (pp, LHCb-PAPER-2017-025)



Multi-pion BEC in PbPb: ALICE, PRC 93 (2016) 054908

❑ Ratio measured multi-π / expected multi-π from 2-π:
- pp, pPb: no suppression observed
- PbPb: suppression at low Q_4, Q_3

4-π: explained by 32% of coherent correlations
(but 3-π: not explained by 32% of coherent correlations)

(PbPb: ALICE, PRL 118 (2017) 222301)

SUMMARY

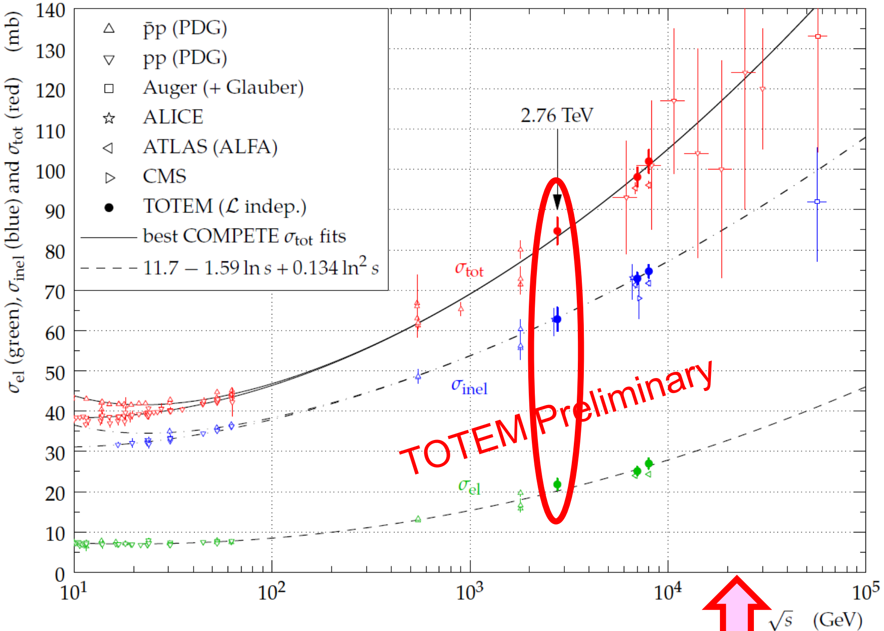
- ❑ Soft QCD measurements important in many aspects:
  - σ_{tot} as input for modelling pile-up at LHC and extensive air showers caused by cosmic rays
  - Very forward flow (also vs central flow) to model interactions in cosmic rays
  - Underlying event non-negligible in many LHC analyses
  - Particle correlations as a powerful tool to study multihadron production
  - To understand hadronization process

- ❑ All collision systems useful for soft QCD studies, complementing each other
- ❑ Performant LHC @ experiments provide high-statistics & high-precision data samples → estimate reliably many sources of systematics
- ❑ Sophisticated techniques (low p_T ~ 100 MeV, efficient background subtraction, unfolding…)
- ❑ Precision data help faster understand unexplained phenomena and develop/reject models

- ❑ Necessity to retune MC models to describe data at every energy
- ❑ Similar phenomena observed in PbPb / pPb / pp (high multiplicity) collisions: strangeness enhancement, collectivity effects. Why in small systems (pPb, pp)? Currently lively discussed
  - Near-side ridge as testing ground to study complementarity between hydrodynamics/QGP and dynamics model (CGC/saturation/ropes)
- ❑ Intensive works on improving the hadronization models (lines/ropes/helices)

BACKUP SLIDES

Inclusive (total) pp cross-sections



TOTEM, ALFA(ATLAS): dedicated forward proton detectors (~220-240 m from interaction point)

- very close to beam (~few mm dep. on LHC optics (β^*))
- the larger β^*, the lower t
- dedicated runs (special LHC optics, negligible pile-up)

New TOTEM results for 2.76 TeV
β^*= 11m, 0.08 < |t| < 0.4 GeV²

1) elastic observables only, ρ=0.145 from COMPETE, optical theorem

$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2}\frac{1}{\mathcal{L}}\frac{dN_{el}}{dt}(0)$$

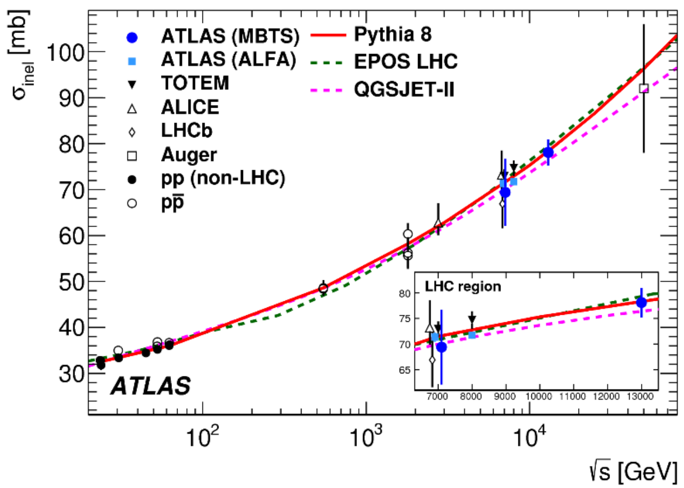
2) no ρ, no optical theorem

$$\sigma_{tot} = \frac{1}{\mathcal{L}}(N_{el} + N_{inel})$$

3) no $\mathcal{L}$, optical theorem

$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2}\frac{\frac{dN_{el}}{dt}(0)}{N_{el}+N_{inel}}$$

σ_{tot}



New ATLAS 8 TeV results
β^*= 90m, 0.014 < |t| < 0.1 GeV²
ATLAS, PLB 761 (2016) 158

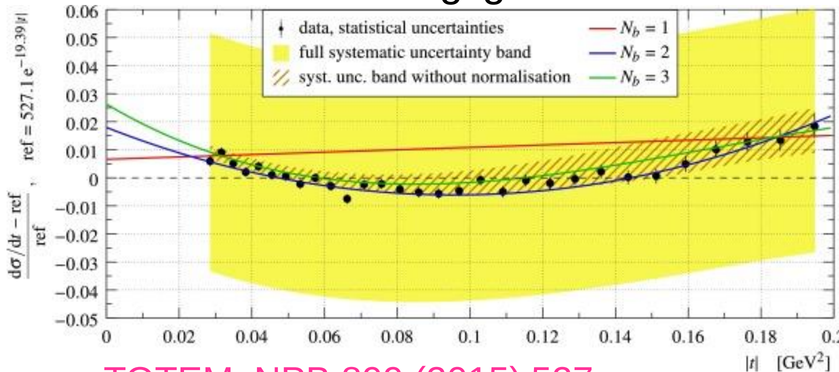
New ATLAS result for 13 TeV
- Central detector only

ATLAS, PRL 117 (2016) 182002

σ_{tot} input to model
- amount of pile-up at LHC
- interactions in cosmic rays

Inclusive (elastic) pp cross-section

8 TeV, β^* = 90m, 0.027 < |t| < 0.2 GeV²
- Coulomb effects negligible



TOTEM, NPB 899 (2015) 527

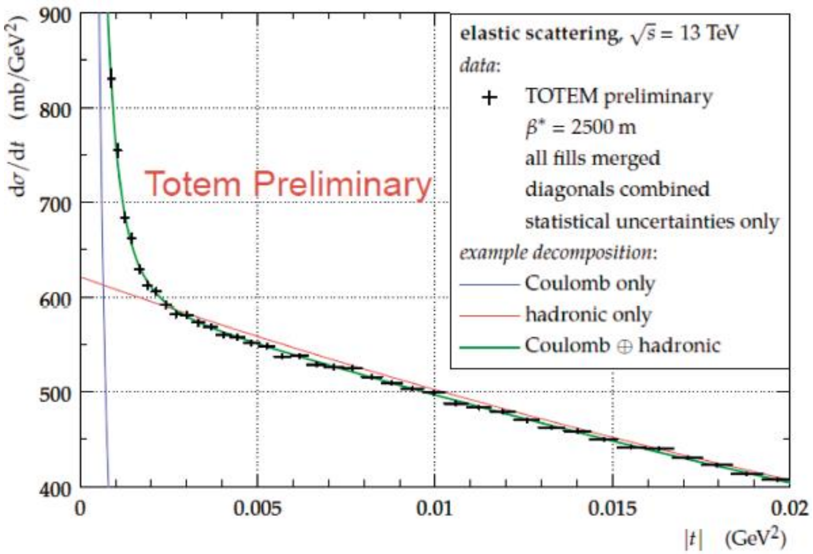
$$\frac{d\sigma}{dt}(t) = \left.\frac{d\sigma}{dt}\right|_{t=0} \exp\left(\sum_{i=1}^{N_b} b_i\, t^i\right),$$

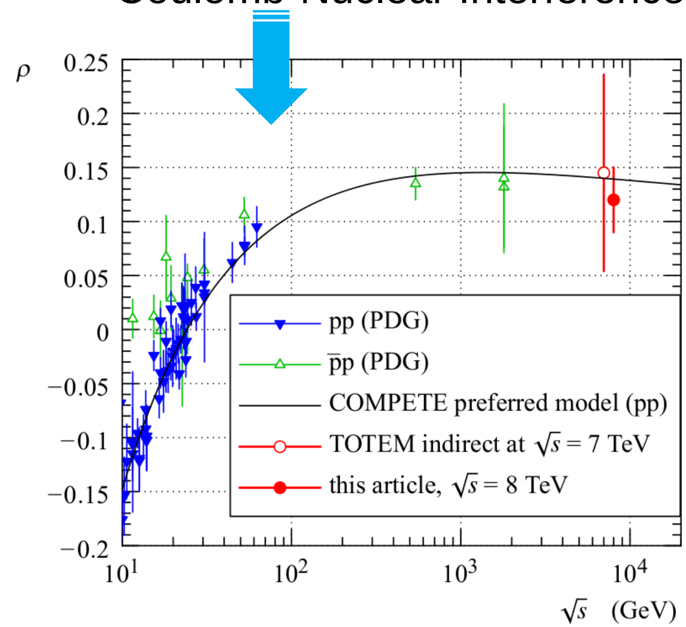
Pure exponential form (N_b=1) excluded at 7.2σ significance

Non-exponential form observed also at 7 and 13 TeV

8 TeV: β^* = 1.0km, 0.0006 < |t| < 0.2 GeV²
Coulomb-Nuclear Interference region

New (preliminary) results at 13 TeV: β^* = 2.5km, 0.0006 < |t| < 0.2 GeV²
- Coulomb-Nuclear Interference region





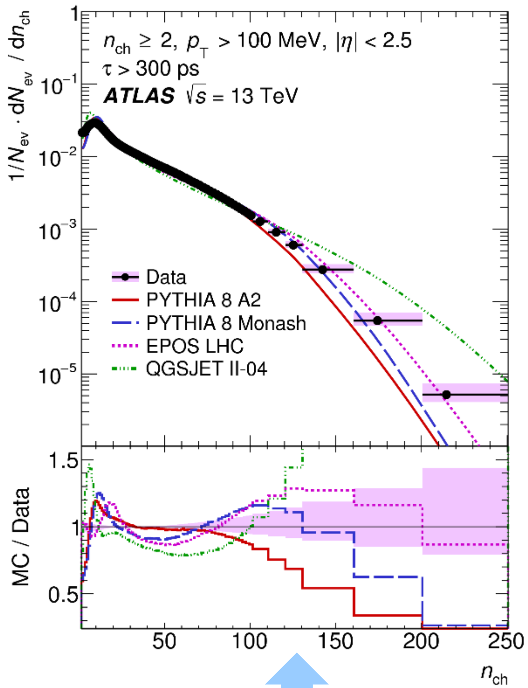
TOTEM, EPJC 76 (2016) 661

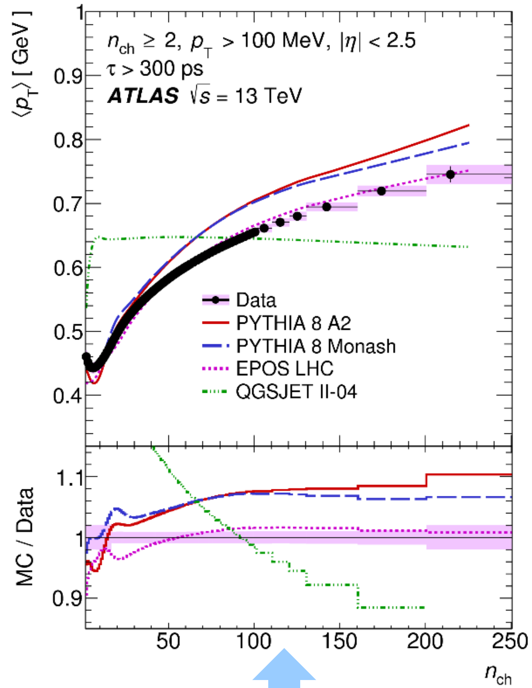
13 TeV point to come
2018 plan: 900 GeV

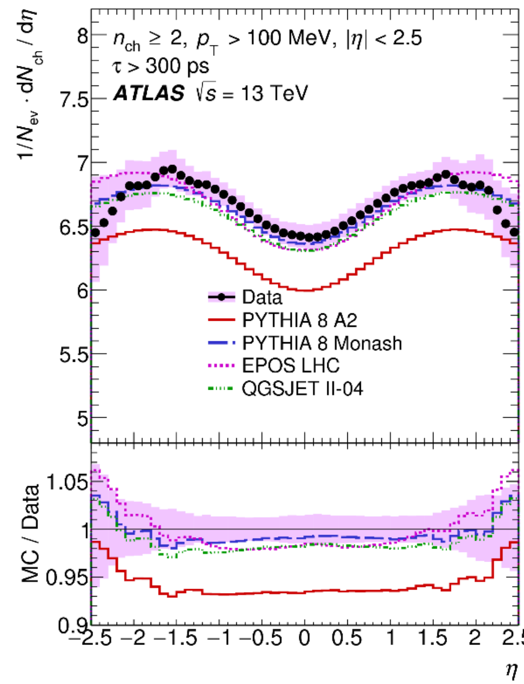
Inclusive charged particles in pp (13 TeV)

Min.Bias events:
at least two tracks with
|η| < 2.5, p_T > 0.1 GeV
↑
very low value:
special procedure

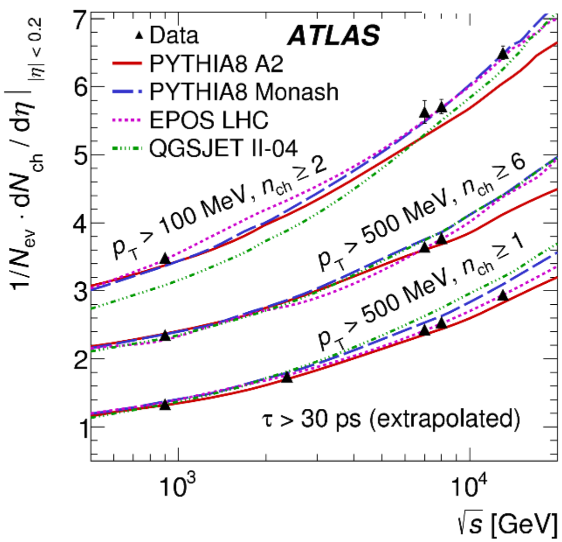
τ>300ps
(exclude strange baryons
due to low reconstruction
efficiency)







ATLAS, EPJC76 (2016) 502

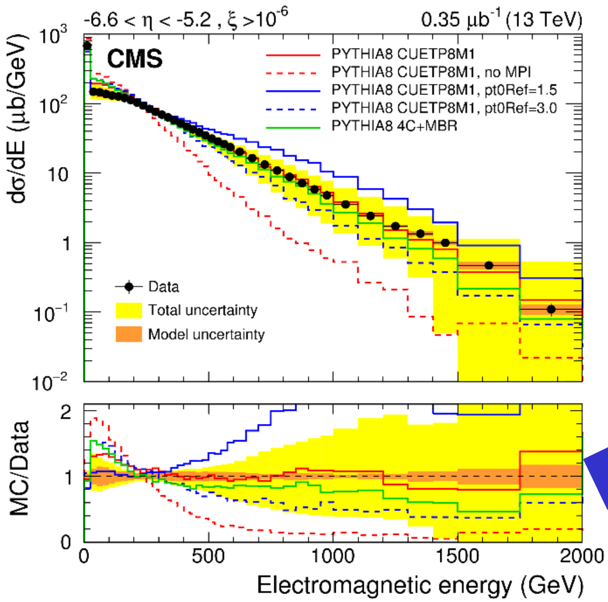


Multiplicity distribution
again not described
perfectly

<p_T> (N_{ch}):
QGSJET: no colour coherence
PYTHIA 8: colour reconnection
EPOS: hydrodynamical evolution

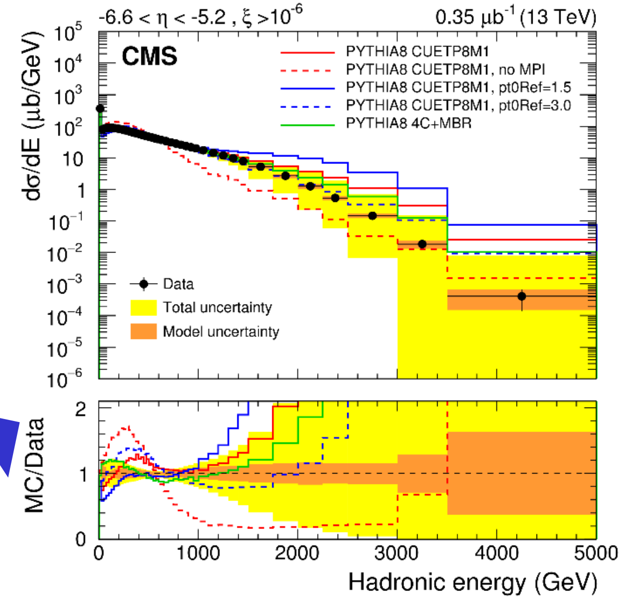
EPOS gives best overall description

Inclusive very forward energy flow (13 TeV)



CMS, CERN-EP-2016-313

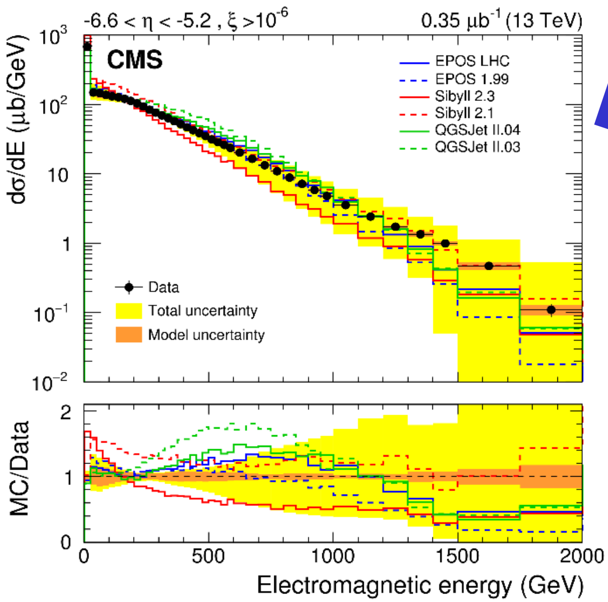
Energy measured in CASTOR calorimeter ($-6.6 < \eta < -5.2$)

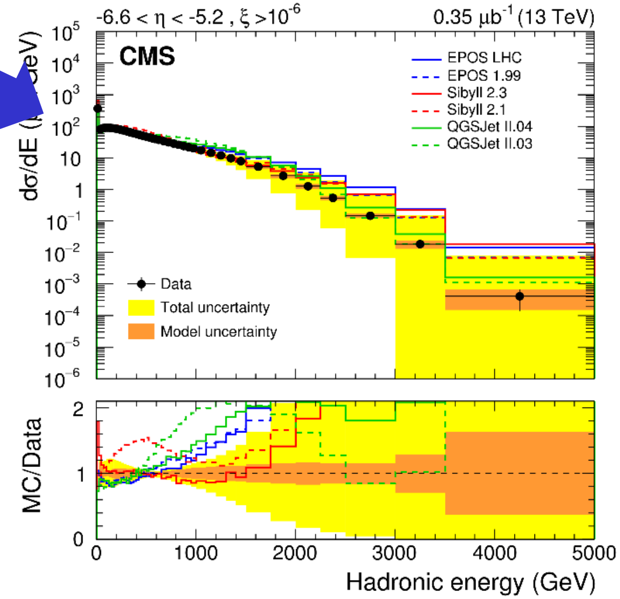


Measurements suitable to tune:

1) MPI models in MC generators for pp collisions

2) MC generators modeling HE cosmic ray air showers

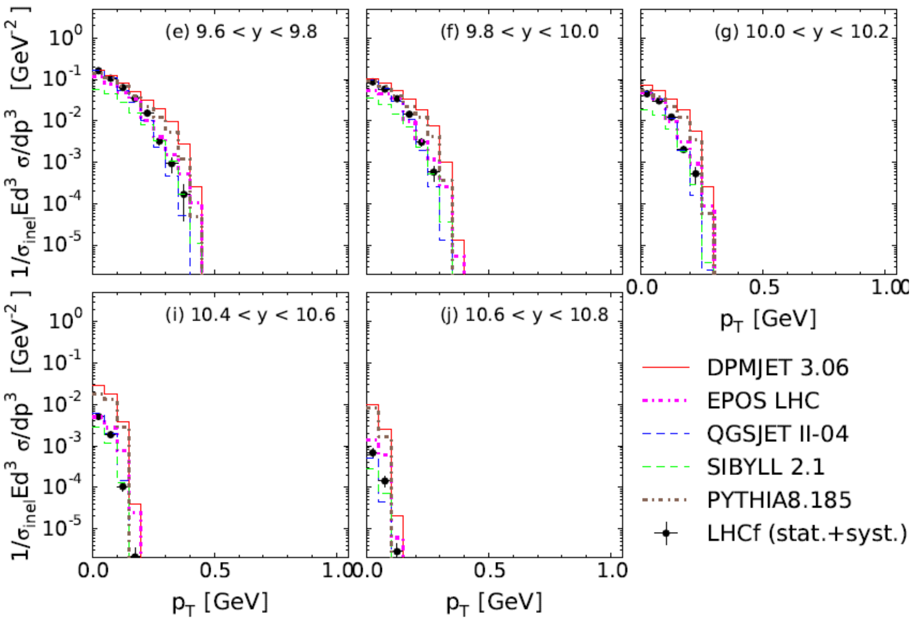




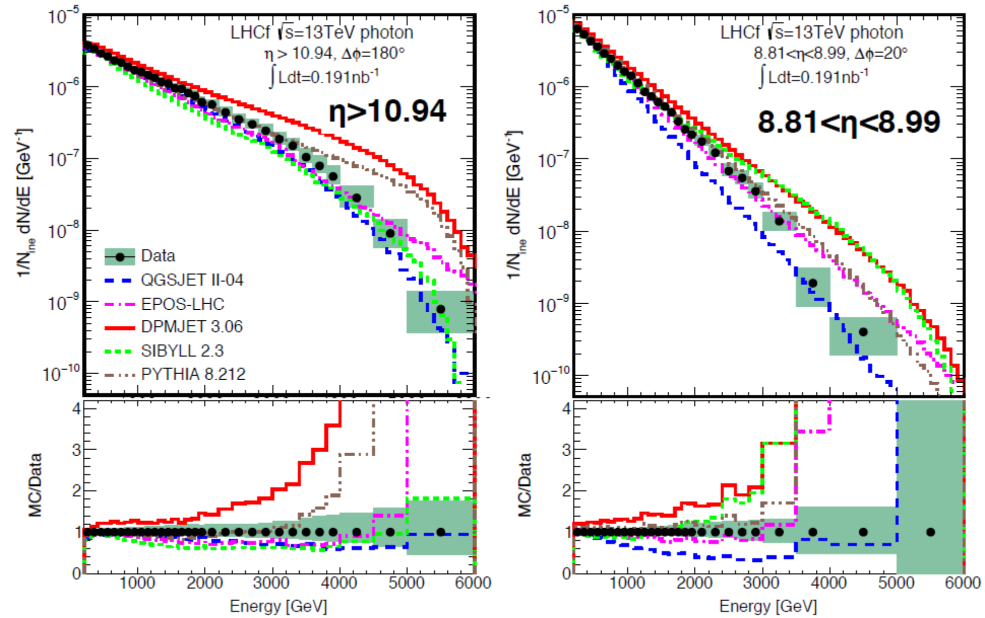
Dashed: tunes based on Tevatron data
Full: Tevatron + LHC ($\sqrt{s}$ = 7 TeV) data

Identified particles at very forward direction

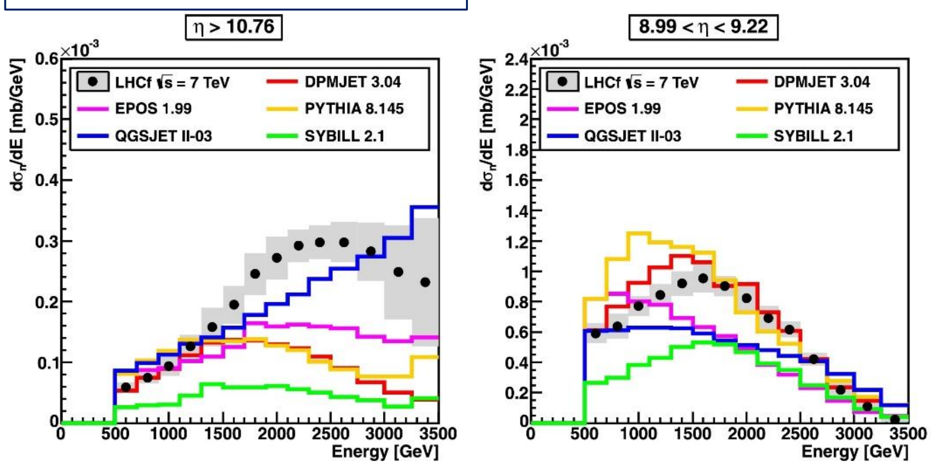
π^0 at 7 TeV, pp LHCf, PRD 94 (2016) 032007



Photons at 13 TeV, pp LHCf, CERN-EP-2017-051



Neutrons at 7 TeV, pp LHCf, PLB 750 (2015) 360



LHCf: soft neutral particles at very forward direction → constrains models for cosmic rays:

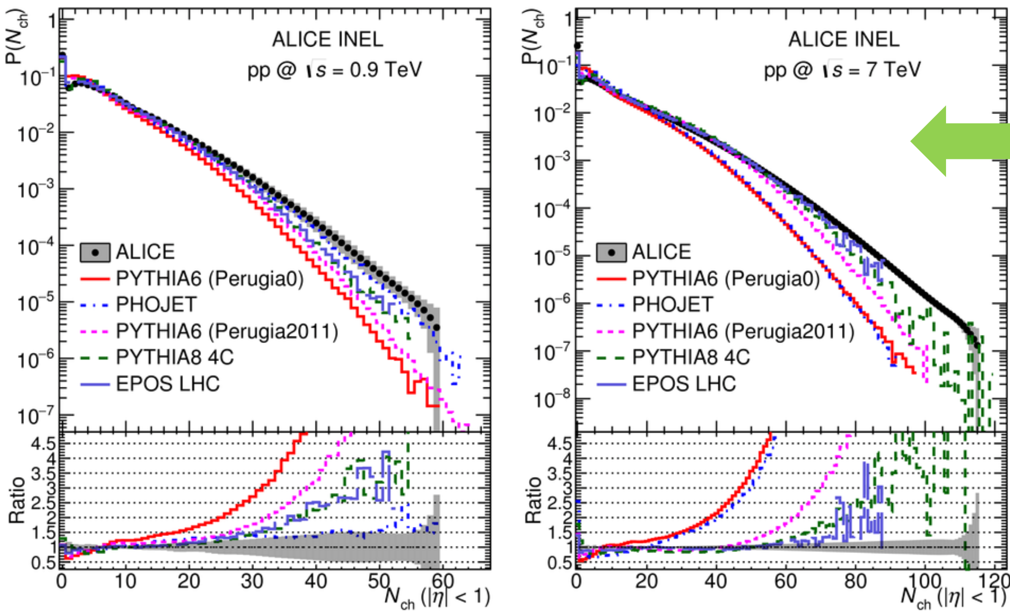
- ❑ X_{max} (shower maximum position) modeling needs: σ_{inel}^{p-air} & forward identified particle spectra
- ❑ hadronic interaction modeling needs: correlation between central and fw particle production (ATLAS vs LHCf or CMS vs TOTEM)

Inclusive charged particles in pp (0.9-8 TeV)

$\sqrt{s}$ = 0.9, 2.36, 2.76, 7, 8 TeV
|η| < 2, p_T > 0.1 GeV

INEL = all (MB) events
NSD = Non Single Diffraction

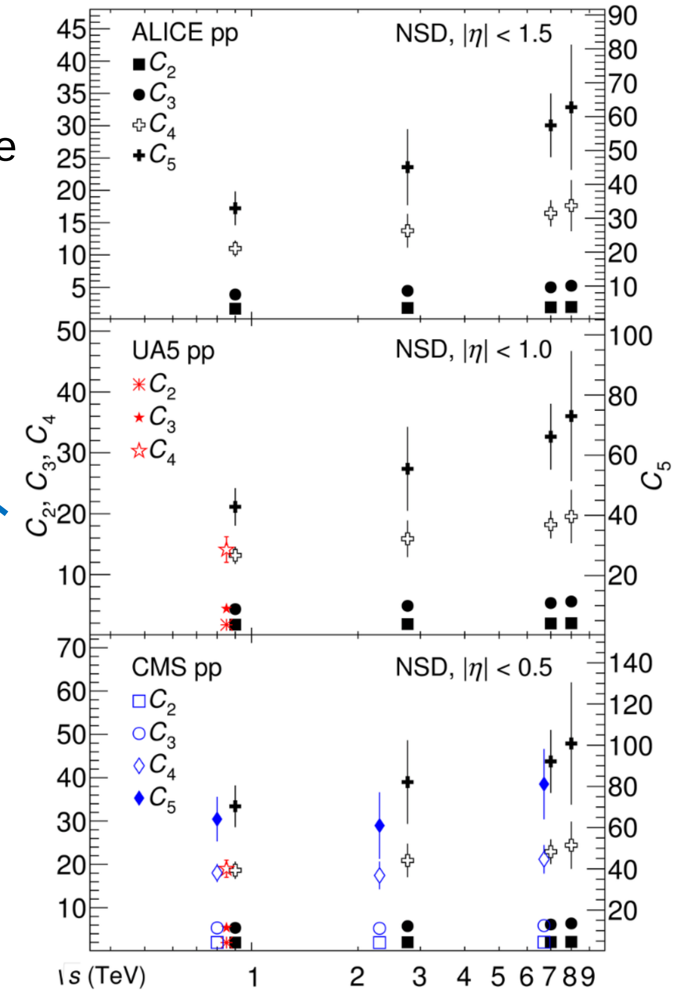
ALICE, EPJC77 (2017) 33
(PbPb: PRL 116 (2016) 222302)



Difficulties of all models to describe the data

Best agreement with EPOS

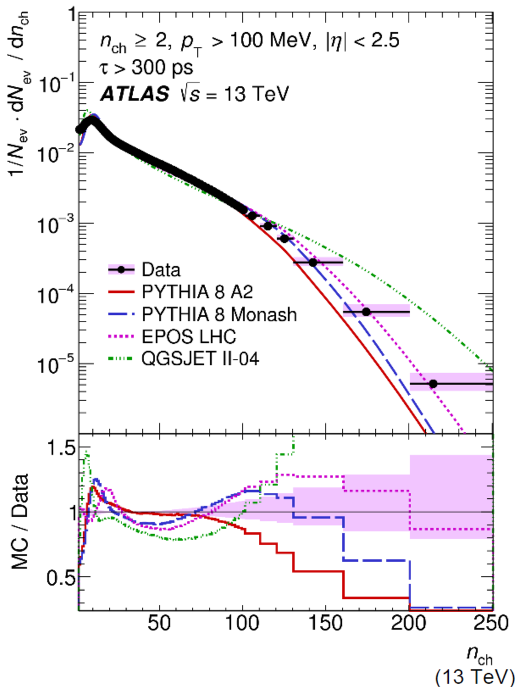
KNO scaling violation

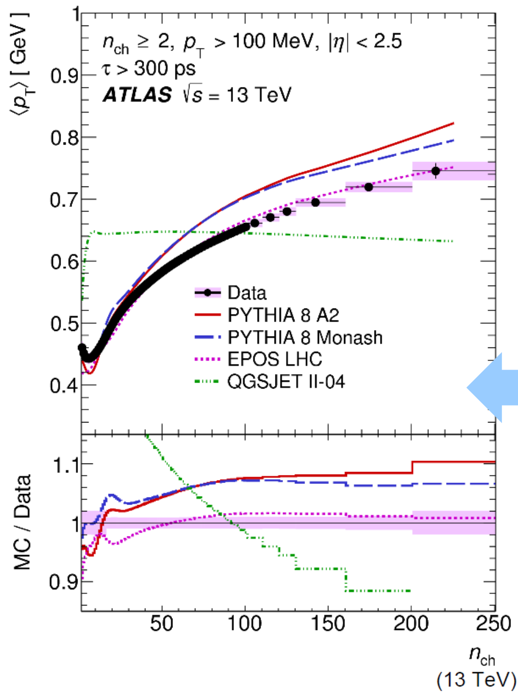


- Measurement of dN_{ch}/dη (η=0)($\sqrt{s}$) ~ s^{δ}: δ=0.114(INEL) (δ=0.15 for central PbPb)
- Alternatively: normalized q-moments $C_q = \frac{<N_{ch}^q>}{<N_{ch}>^q}$

For NSD events and three |η| intervals:
C_2 constant over $\sqrt{s}$ = 0.9-8.0 range
C_3, C_4, C_5 increase with $\sqrt{s}$ and with increasing Δη at given $\sqrt{s}$

Inclusive charged particles in pp (13 TeV)



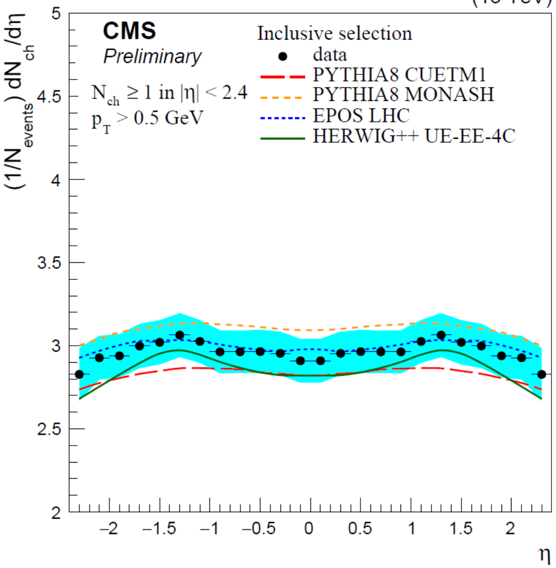


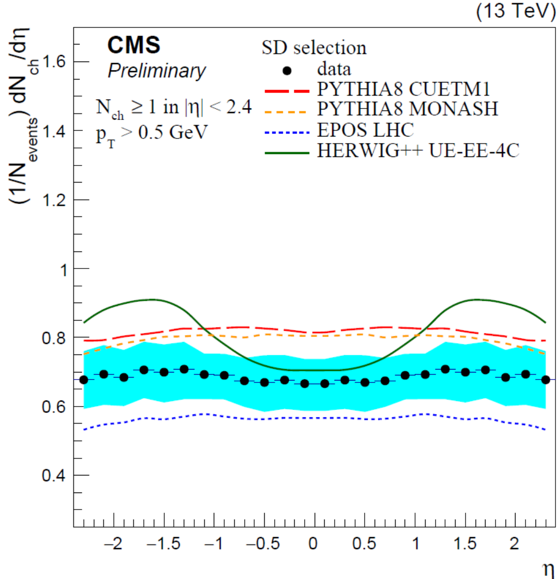
ATLAS, EPJC76 (2016) 502

Min.Bias events: at least two tracks with $|\eta| < 2.5$, $p_T > 0.1$ GeV

QGSJET: no colour coherence
PYTHIA 8: colour reconnection
EPOS: hydrodynamical evolution

Multiplicity distribution again not described perfectly





CMS-PAS-FSQ-15-008

$|\eta| < 2.4$, $p_T > 0.5$ GeV
SD = Single Diffraction

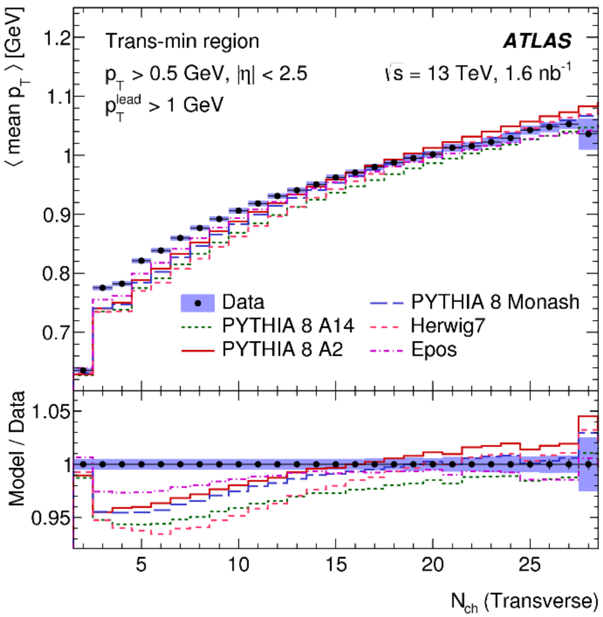
HERWIG++ deficient

EPOS gives best overall description (specialized soft QCD model)

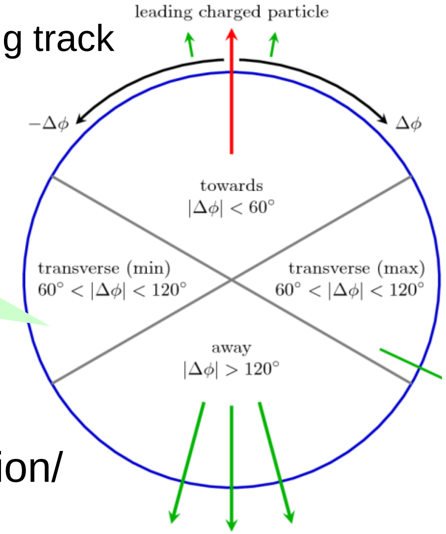
In general: all models need to be retuned for the 13 TeV energy

Underlying Event study (13 TeV)

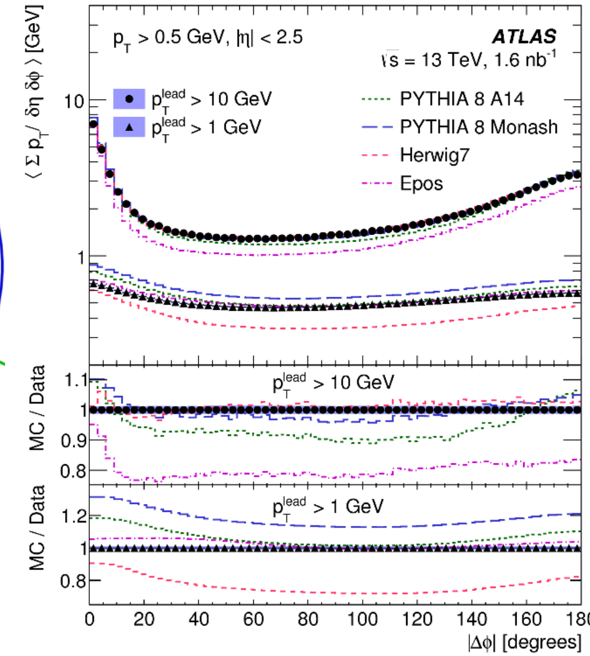
ATLAS, JHEP03 (2017) 157, also CMS tunes for UE/DPS in EPJC76 (2016) 155



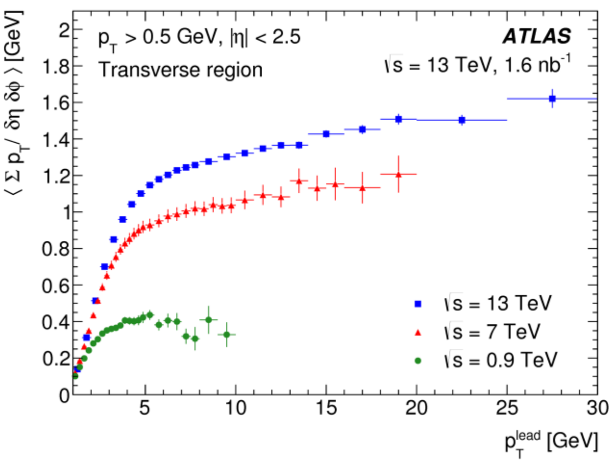
Min.Bias events, leading track
|η| < 2.5, p_T > 0.5 GeV



Most sensitive to UE



Models differ in MPI and color reconnection/ coherence model

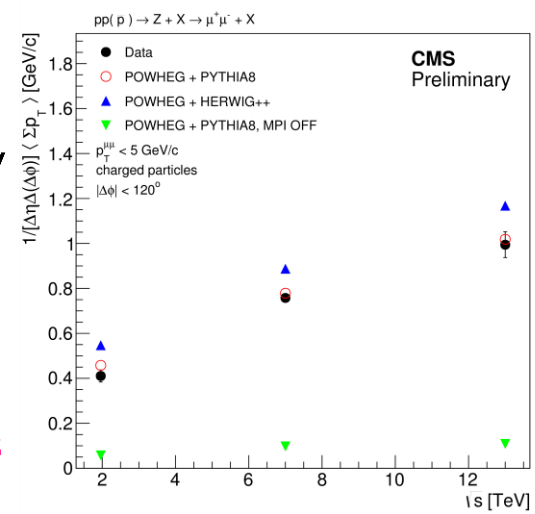


EPOS overall fine but not good for p_T (leading) > 10 GeV

All models fail to describe <p_T (N_{ch})> in transverse region

Drell Yan events, leading $\mu^+\mu^-$ pair
|η| < 2, p_T > 0.5 GeV

High sensitivity to MPI

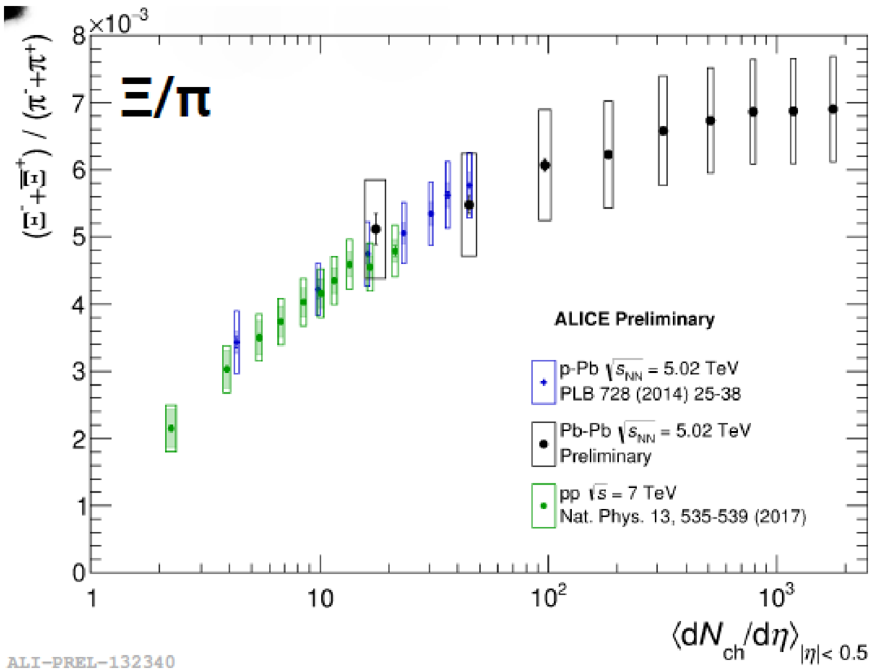


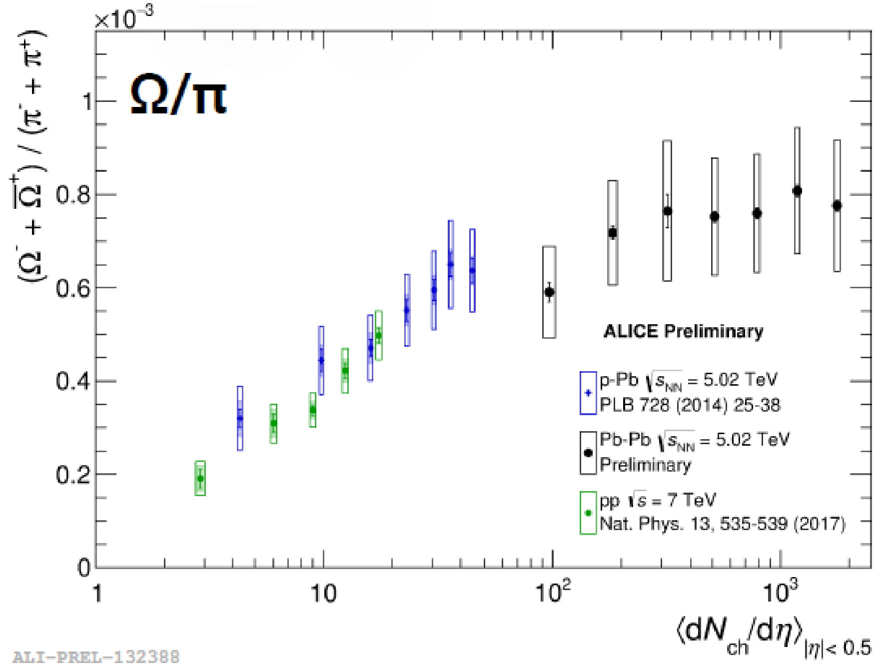
CMS-PAS-FSQ-16-008

More collision energy → more UE activity.
Typical plateau observed

Strangeness enhancement in PbPb (5 TeV)

New results from 5 TeV PbPb collisions:
√s closer to pPb and pp energies → PbPb points approach better the trend from pp and pPb points

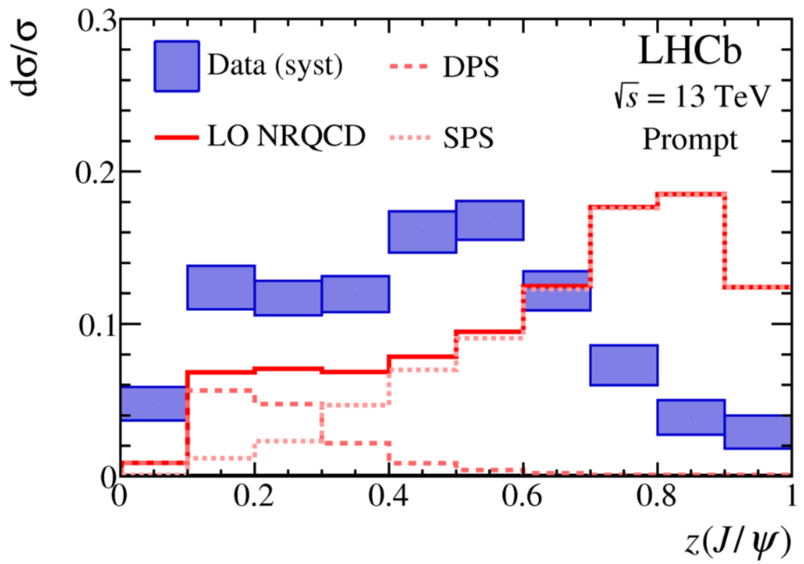


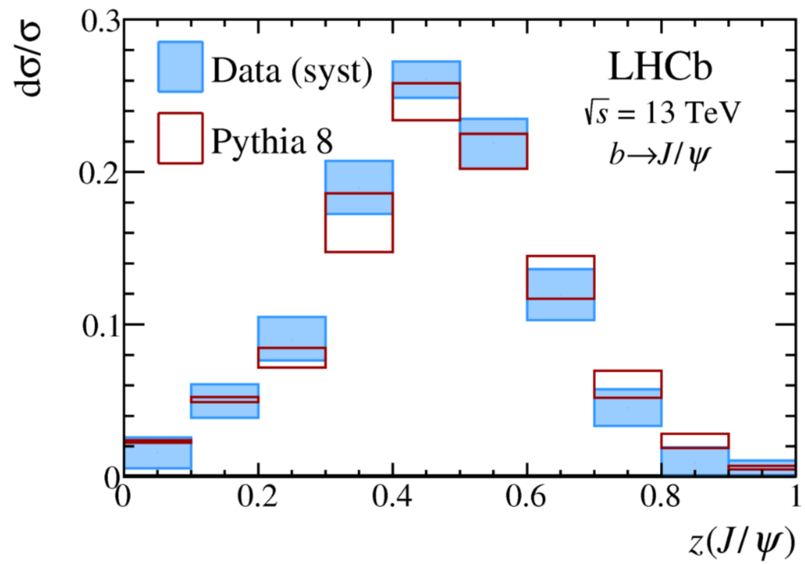


J/Ψ production in jets

- J/Ψ production occurs in transition between perturbative and non-perturbative QCD
- Measure z(J/Ψ) = p_T(J/Ψ) / p_T(jet) for prompt J/Ψ and those from b-hadron decays in jets
  - J/Ψ→$\mu^+\mu^-$, 2< η(J/Ψ,μ)< 4.5, $p_T(\mu)$ > 0.5 GeV
  - Jets: anti-kt, R=0.5, p_T > 20 GeV, 2 < η < 4.0

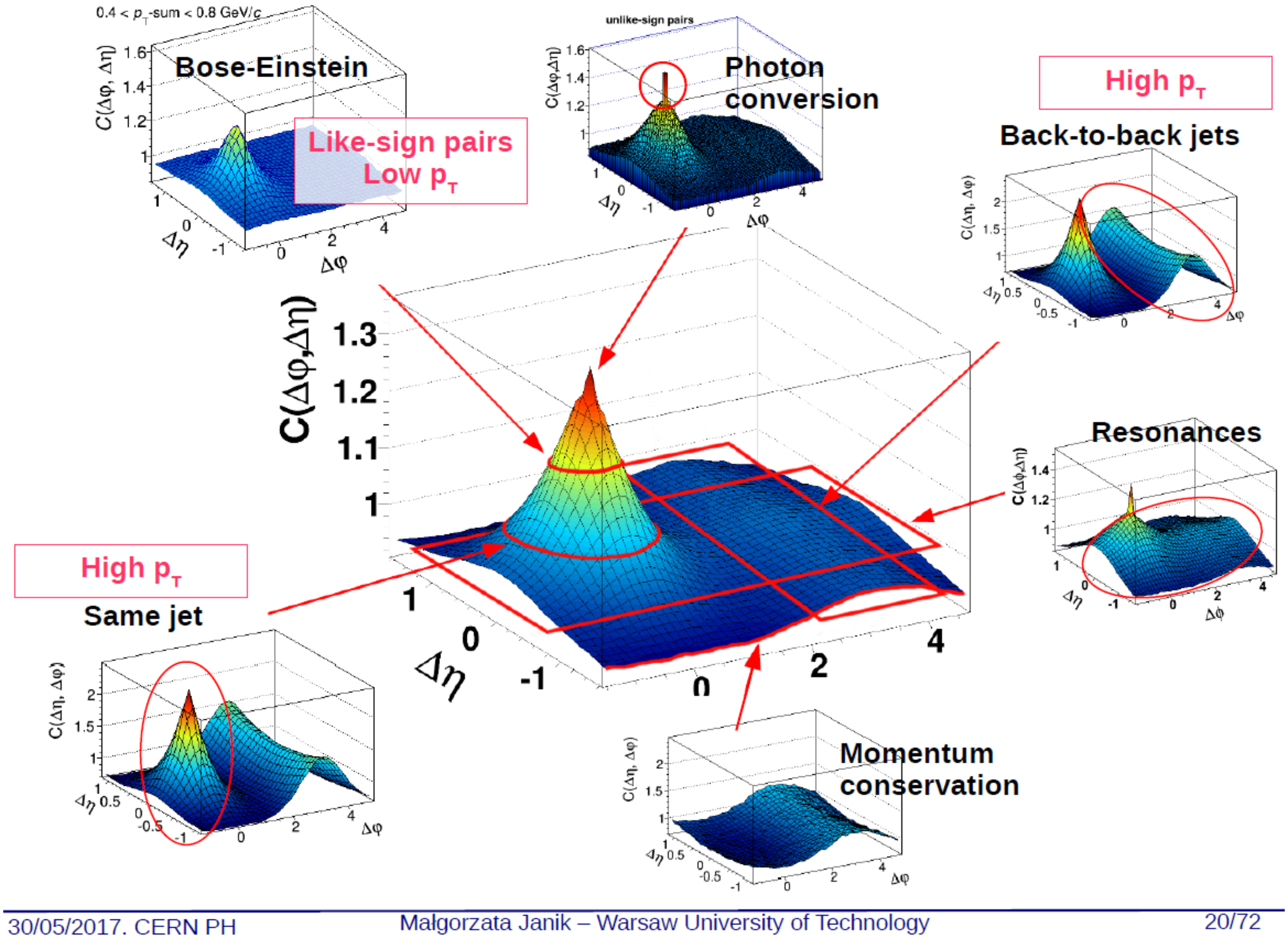
The 1st ever measurement of z(J/Ψ) for prompt J/Ψ!





- ❑ Prompt J/Ψ produced in parton showers
- ❑ z(J/Ψ) not described by LO non-relativistic QCD (includes color-octet+color-singlet mechanisms) as implemented in PYTHIA 8.
- ❑ Some soft component missing?

❑ z(J/Ψ) of J/Ψ from b-hadron decays described by PYTHIA 8.

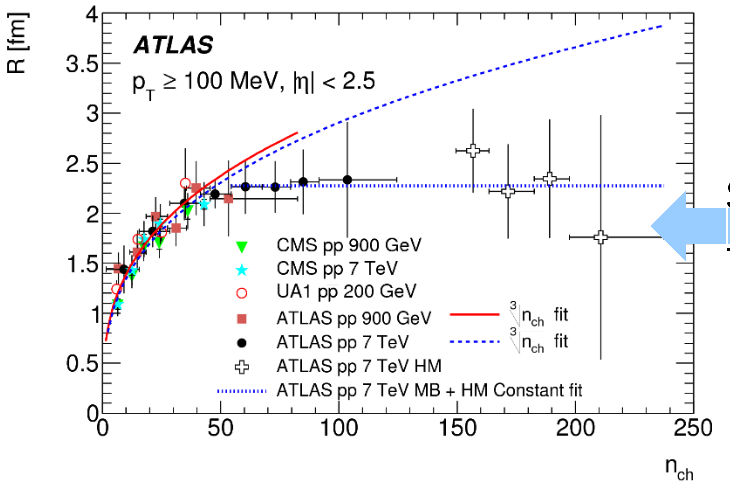


Bose-Einstein
Like-sign pairs
Low p_T
Photon conversion
unlike-sign pairs
High p_T
Back-to-back jets
Resonances
High p_T
Same jet
Momentum conservation
$C(\Delta\varphi,\Delta\eta)$
0.4 < p_T-sum < 0.8 GeV/c
30/05/2017. CERN PH
Małgorzata Janik – Warsaw University of Technology
20/72

Bose-Einstein correlations in pp, pPb, PbPb

Min.Bias events, |η| < 2.5, p_T > 0.1 GeV **2-PC (C_2) of identical particles**: SS/OS double ratio Data/MC

ATLAS, EPJ C75 (2015) 466



$C_2 = C_0[1 + \Omega(\lambda, R)](1 + \varepsilon Q)$

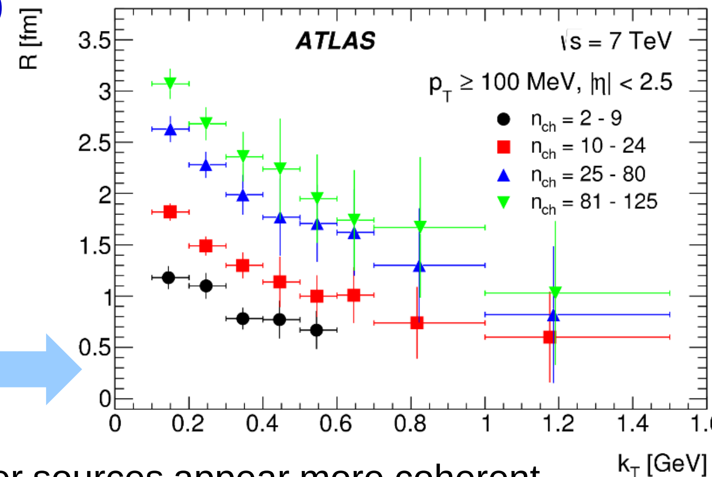
λ = correlation strength

R = correlation source size

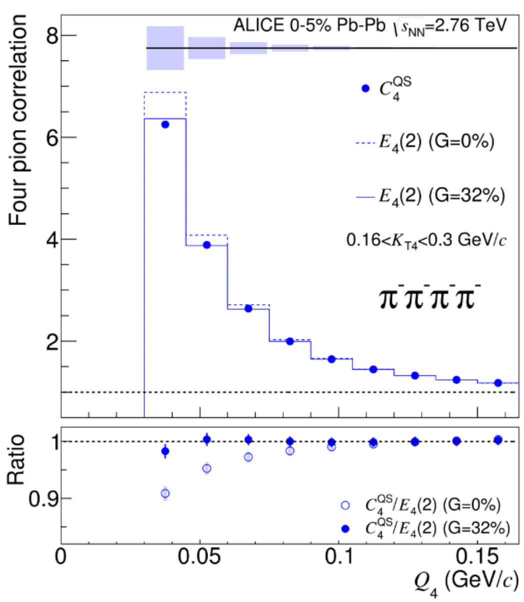
Saturation of R at high-mult.

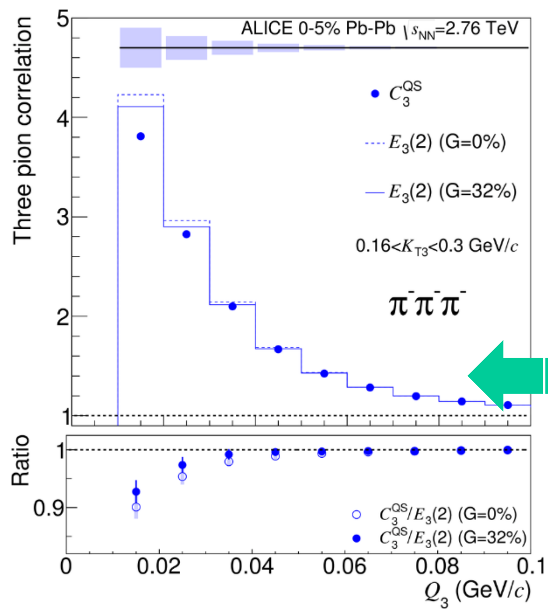
- observed for the 1st time

Decrease of R with k_T observed also in pPb (ATLAS, CERN-EP-2017-004)



Larger sources appear more coherent (pp, LHCb-PAPER-2017-025)





Multi-pion BEC: ALICE, PRC 93 (2016) 054908

- ❑ Corrected for Coulomb correlations
- ❑ Ratio measured multi-π / expected 2-π:

- pp, pPb: no suppression observed
- PbPb: suppression at low Q_4, Q_3

4-π: explained by 32% of coherent correlations

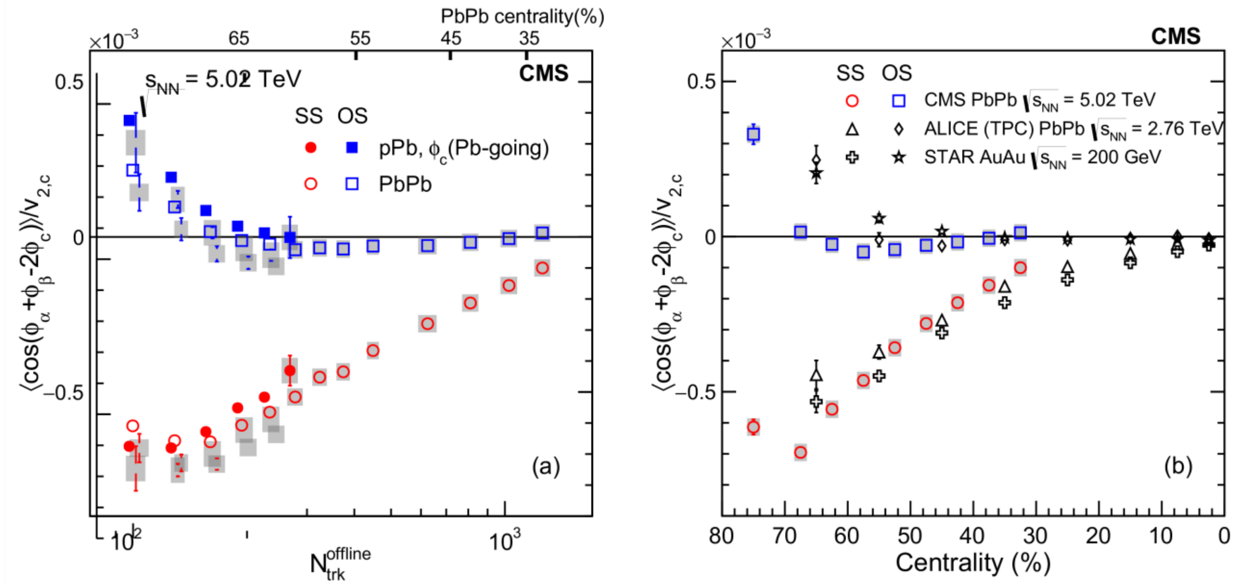
3-π: not explained by 32% of coherent corr's

(PbPb: ALICE, PRL 118 (2017) 222301)

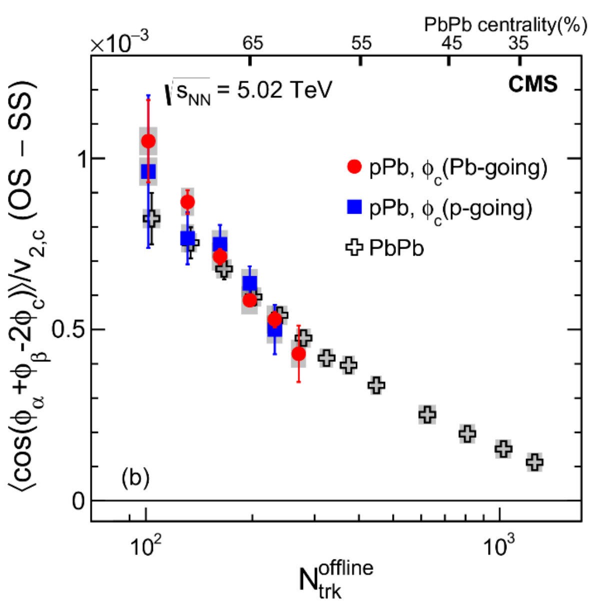
Charge-dependent azimuthal correlations

Charge-dependent 3-particle azimuthal correlations with respect to (2nd order) event plane:
Same sign (SS) and opposite sign (OS) particle pairs and 3rd particle in forward calorimeter (to probe the long-range correlations).

The (OS-SS) difference interpreted as possible signature of chiral magnetic effect (CME) in AA collisions.



CMS, PRL 118 (2017) 122301



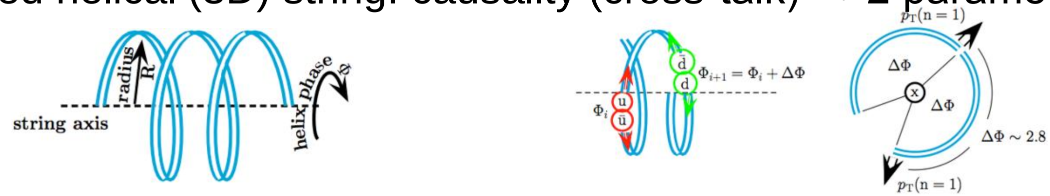
PbPb and pPb data show a similar effect.
BUT: in high-multiplicity pPb collisions a strong CME is not expected

- mag.field smaller than in peripheral PbPb collisions
- angle between mag.field and event plane randomly distrib.

- Slopes for PbPb and pPb different?
- Analogous effect produced by medium vorticity
- (Lambda polarization at STAR)

Hadronization of helical QCD string

- ❑ Lund string fragmentation: randomly broken 1D string, no cross-talk between break-up vertices
- ❑ Quantized helical (3D) string: causality (cross-talk) → 2 parameters (κR, ΔΦ):



κR, ΔΦ fixed using masses of pseudoscalar mesons:

κξ [MeV]	κ R [MeV]	ΔΦ
192.5 ± 0.5	68 ± 2	2.82 ± 0.06

meson	PDG mass [MeV]	model estimate [MeV]
π	135 - 140	137
η	548	565
η'	958	958

PR D89 (2014) 015002

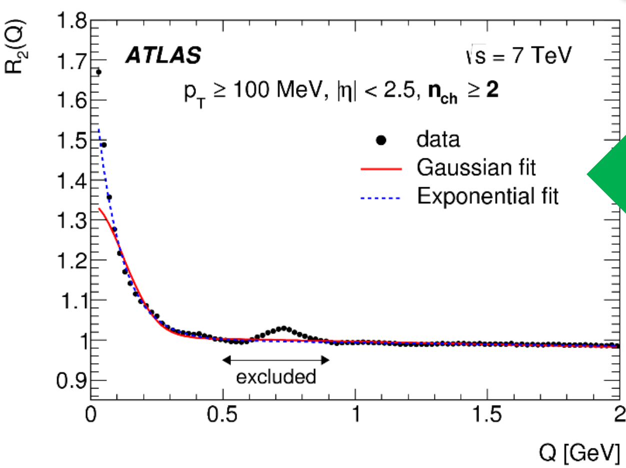
- Hadron spectra follow a simple quantized pattern: m_T = n κR ΔΦ
- Predicts momentum difference Q for pairs of ground-state hadrons

Pair rank difference r	1	2	3	4	5
Q expected [MeV]	266 ± 8	91 ± 3	236 ± 7	171 ± 5	178 ± 5

- Adjacent pions produced with p_T difference ~266 MeV. Low-Q region populated by SS pairs (r=2)

Enhanced production of identical pairs

Identical input data



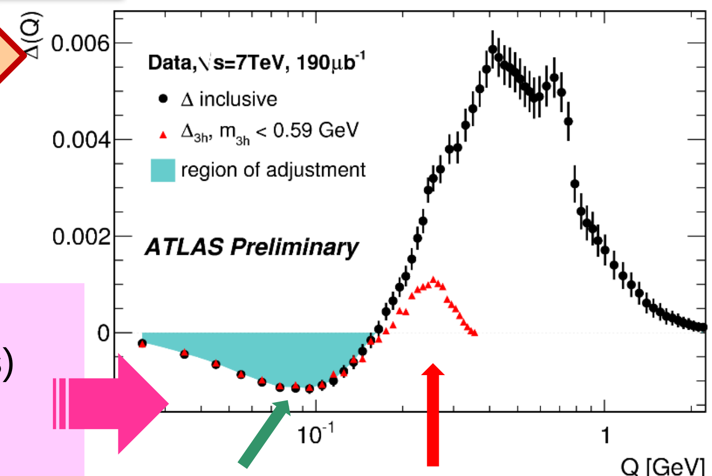
ATLAS, EPJ C75 (2015) 466

Bose-Einstein correlations (incoherent particle production)

Helical string fragmentation (coherent emission of chains of ground state pions)

- $\Delta(Q)$ = [N(OS)-N(SS)]/N_{ch}
- Describes the low-Q region
- Source of correlations: 3-hadron chains

ATLAS, CERN-EP-2017-092



Rank 2

Rank 1