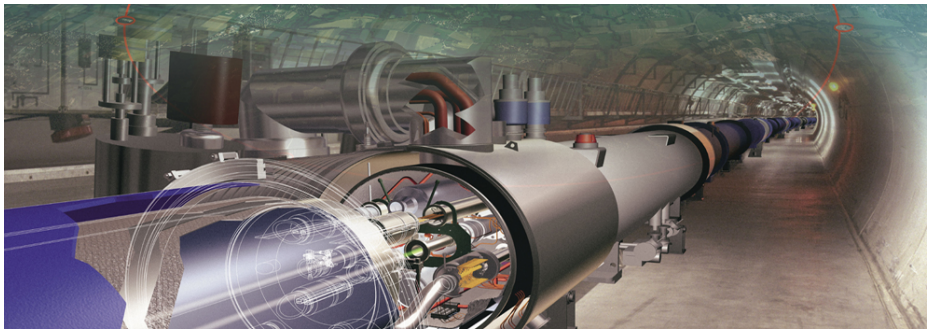
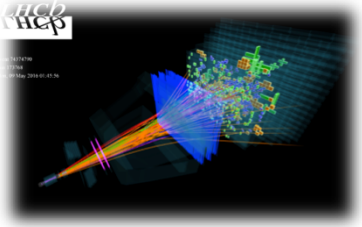
Soft QCD

Šárka Todorova-Nová on behalf of LHC experiments (ALICE,ATLAS,CMS,LHCB,TOTEM)



Shanghai
Jiao Tong University

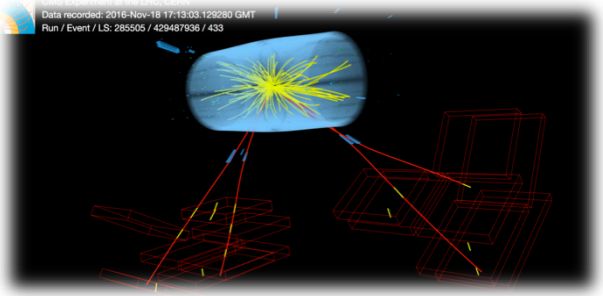
May 16th, 2017



Soft QCD – a common term to refer to

- *nonperturbative region of parton shower development /parton scattering*
- *hadronization process*

Field driven by phenomenology



Measurements

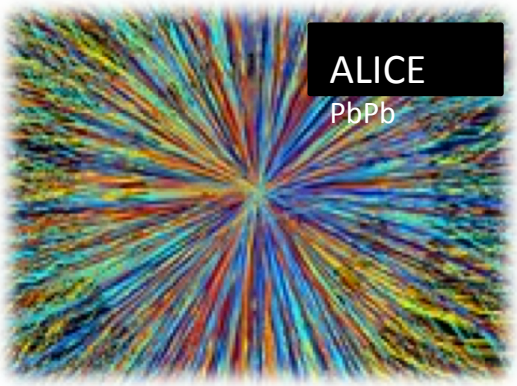
- *Inclusive cross-sections (7 TeV -> 13 TeV)*
- *Charged particle spectra (7 TeV -> 13 TeV)*
- *Identified particle spectra*
- *Particle correlations*

Similarities observed in pp / pPb / PbPb

Phenomenological modeling

- *Multi-parton interactions*
- *Colour coherence / reconnection*
- *Hydrodynamical models / collective effects*
- *Hadronization*

Effective quantization effects in string fragmentation



Inclusive x-section measurements in pp

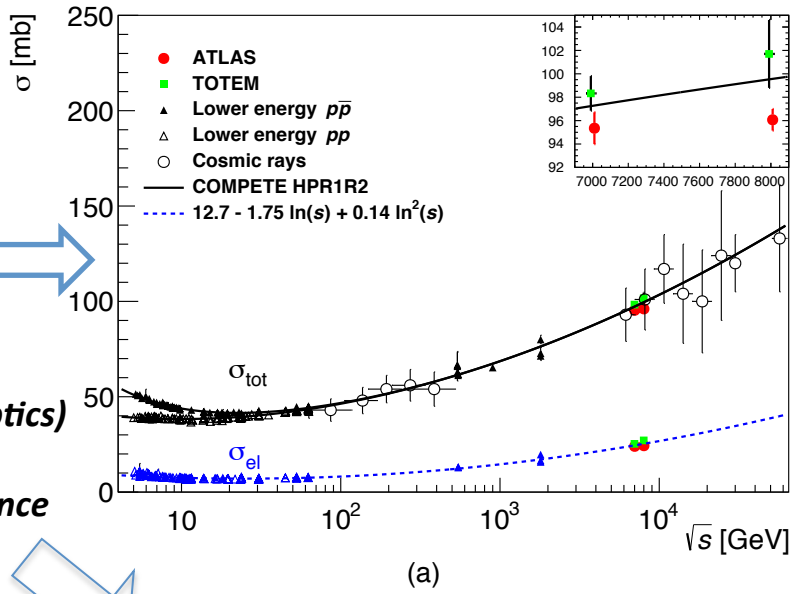
$\sigma_{tot} = \sigma_{el}(pp\to pp) + \sigma_{inel}(pp\to X\neq pp)$

Elastic and total x-section measurement by ATLAS (ALFA) and TOTEM @ 7 and 8 TeV

very forward proton spectrometer (z > 200 m from IP)
0.014 GeV² < \|t\| < 0.1 GeV² (ALFA)
6.10⁻⁴ GeV² < \|t\| < 0.2 GeV² (TOTEM with special beam optics)

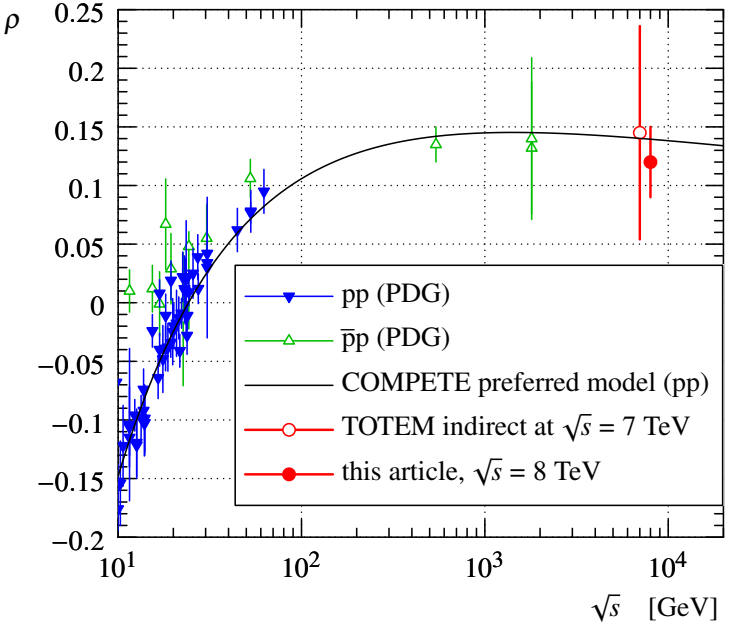
$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2}\left.\frac{d\sigma_{el}}{dt}\right|_{t\to 0},$$

ρ = 0.12 ± 0.03
from Coulomb-nuclear interference



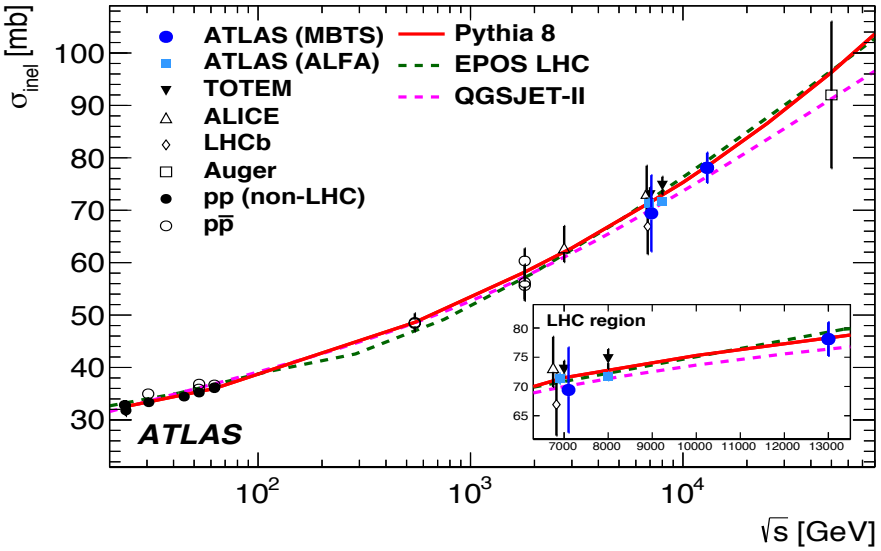
[Phys.Lett.B761(2016)158]

ρ parameter s dependence



[Eur.Phys.J.C76(2016)661]

Inelastic x-section : (78.1±2.9) mb @ 13 TeV



[Phys.Rev.Lett.117,182002(2016)]

Inclusive very forward energy measurements

Energy deposit in CASTOR calorimeter
$-6.6 < \eta < -5.2$

Reference for MC/model development

dashed lines: tune to the Tevatron data
full lines : LHC data (up to sqrt(s)=7 TeV) included

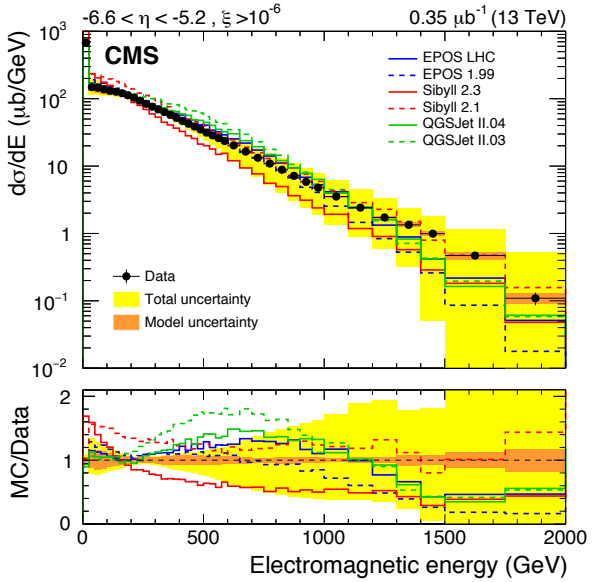
Sensitive to multi-parton interactions

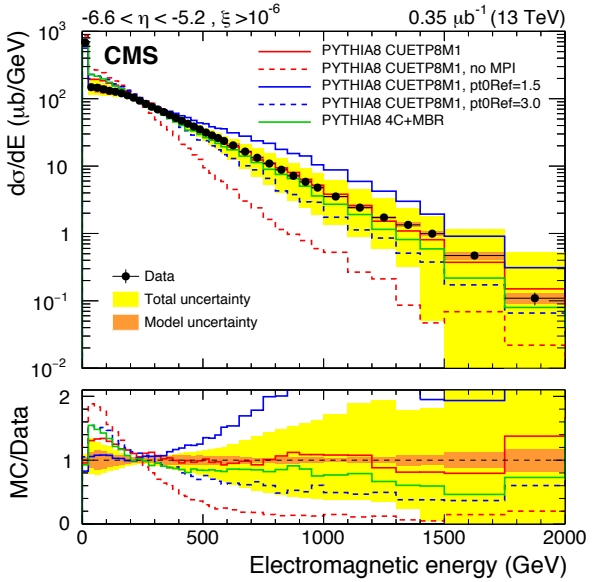
[arXiv:1701.08695], submitted to JHEP

cosmic rays modeling

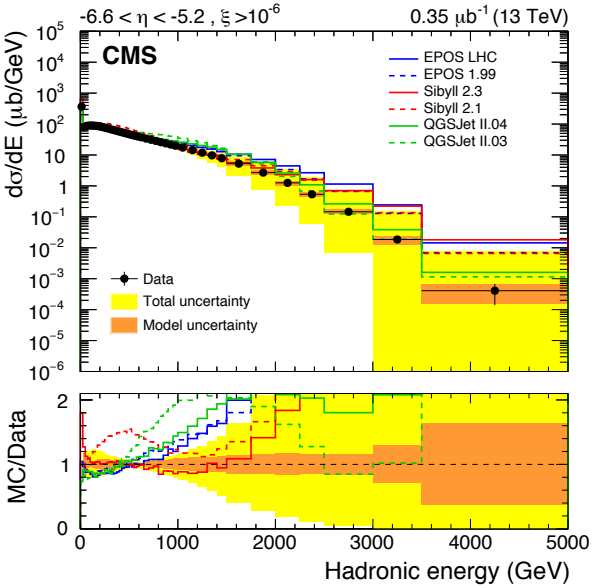
HEP modeling

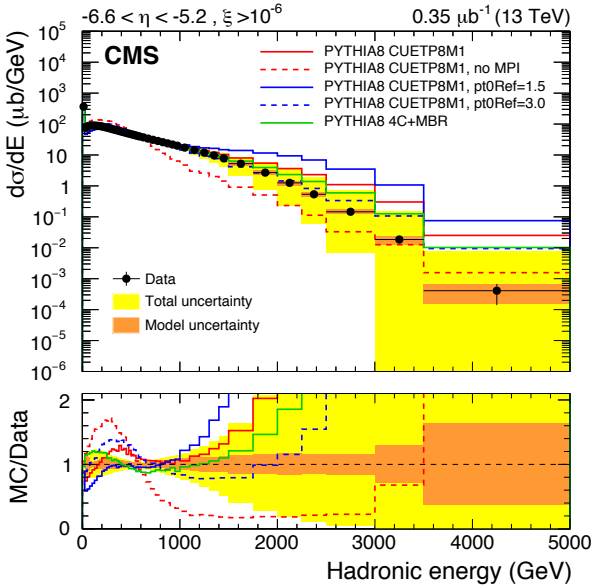
electromagnetic





hadronic





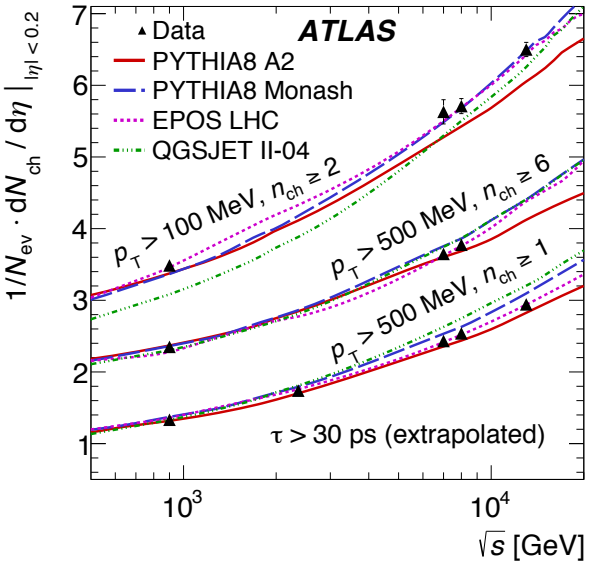
Inclusive charged particle spectra in pp @ 13 TeV

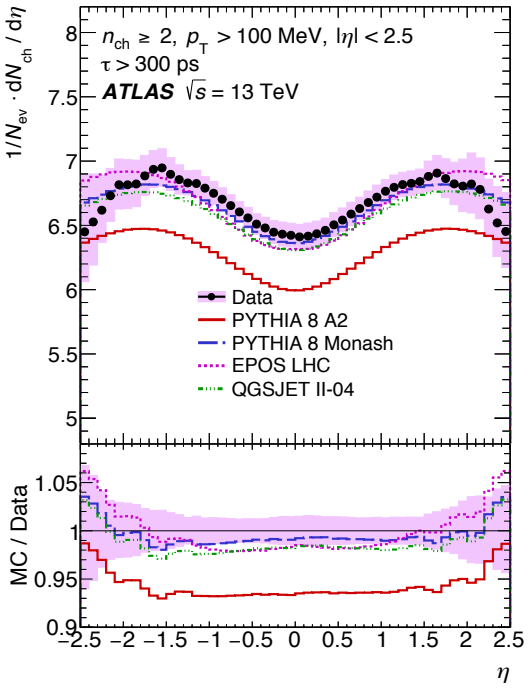
[Eur.Phys.J.C76 (2016) 502]

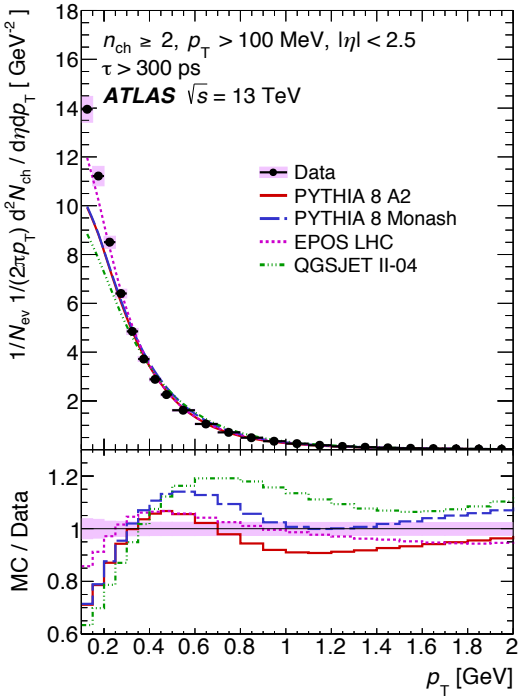
Minimum bias trigger, $|\eta|< 2.5$, $p_T> 100$ MeV

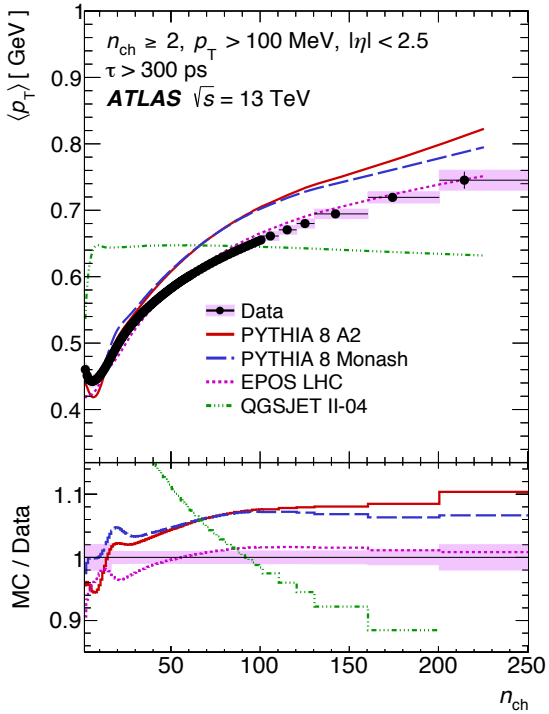
$\langle p_T \rangle$ vs. N_{ch} : QGSJET lacks colour coherent effects
(colour reconnection in PYTHIA, hydrodynamical evolution in EPOS)

Best overall description obtained with EPOS









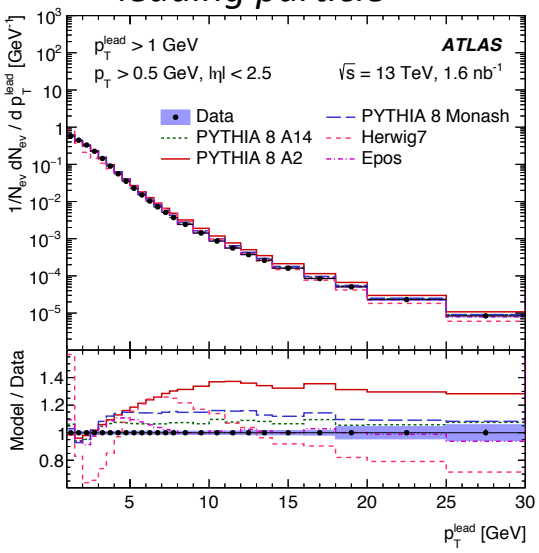
Underlying event spectra in pp @ 13 TeV

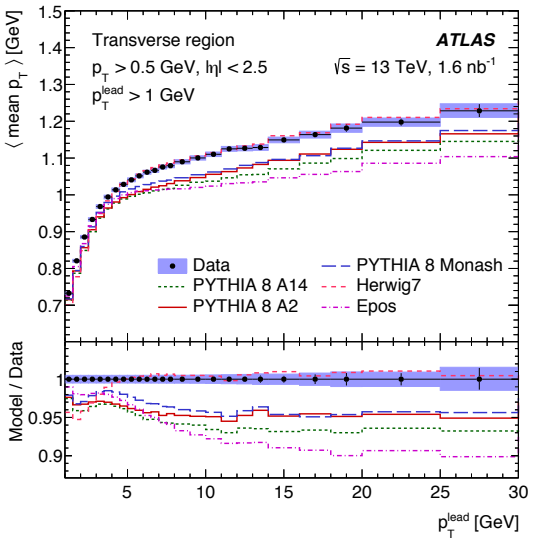
[JHEP03 (2017) 157] ***Minimum bias trigger, $|\eta|<2.5$, $p_T>500$ MeV***

(see also CMS tunes [Eur.Phys.J.C76(2016) 155 for UE/DPS)

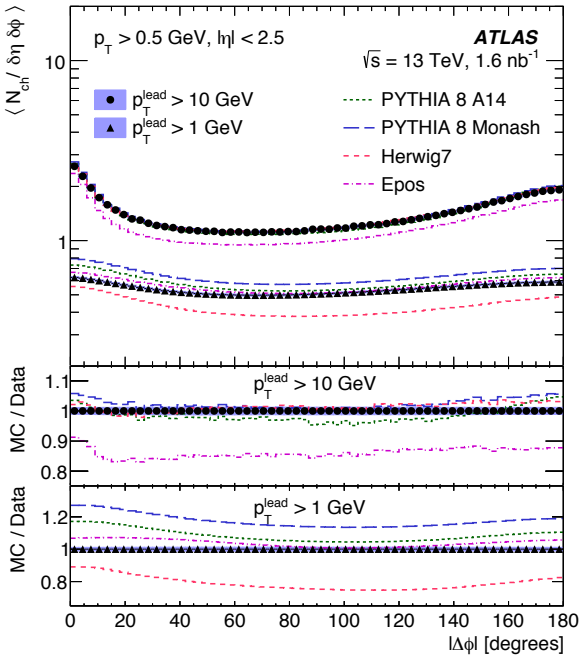
Tunes differ mostly in MPI and color reconnection/coherence model

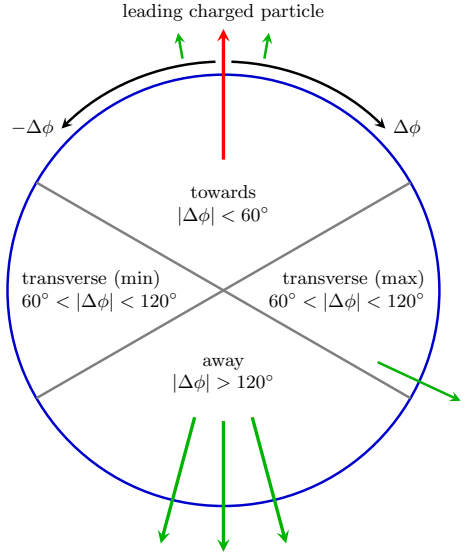
leading particle

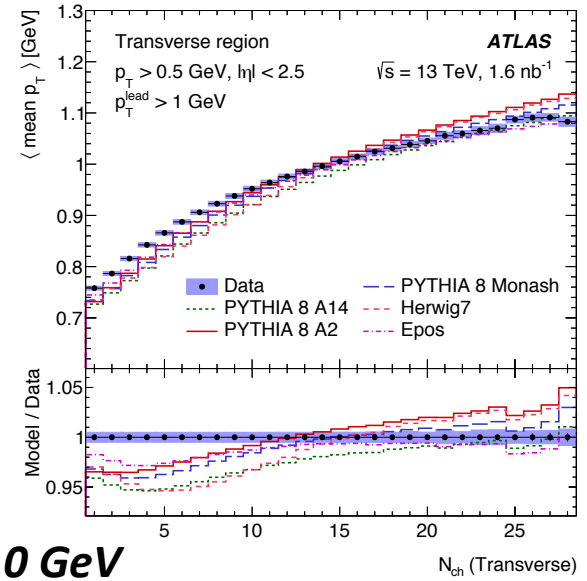




particle yield in Δϕ



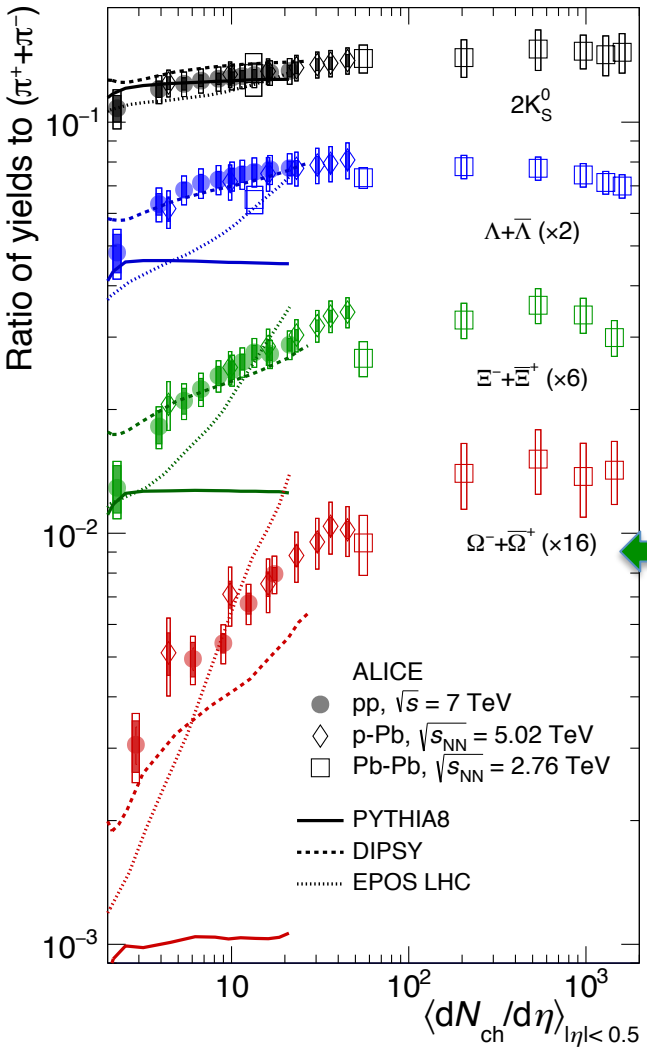




Epos looks fine for p_T^{lead}>1 GeV
but fails to describe data for p_T^{lead}>10 GeV
Herwig describes <p_T> vs. p_T^{lead}… but only for p_T^{lead}>5 GeV
All models fail to describe the charged multiplicity dependence of <p_T> in the transverse region

Identified particle spectra (pp,pPb,PbPb)

[Nature Physics(2017), arXiv:1606.07424]

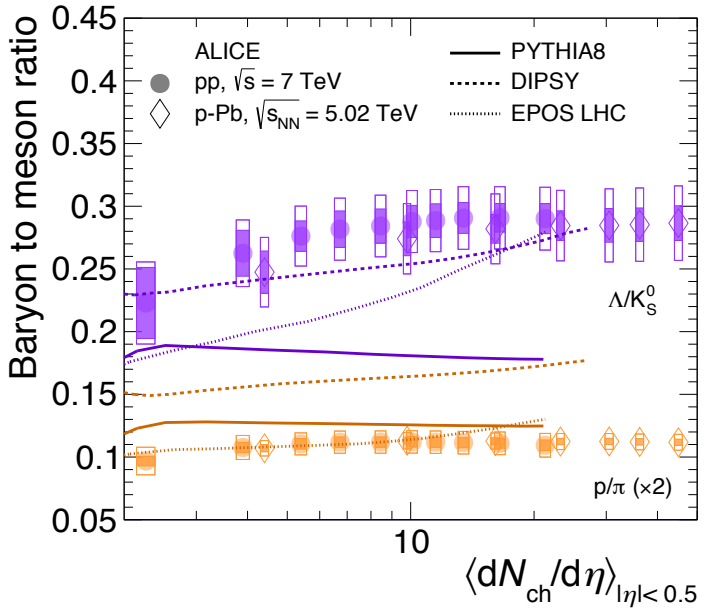


Enhanced production of strange and multi-strange particles has similar charged multiplicity dependence in PbPb, pPb and pp

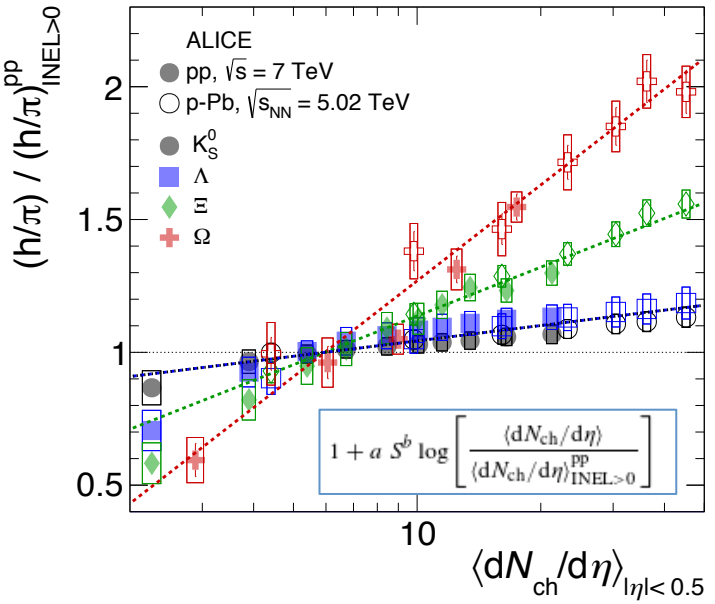
Relative particle/π yields integrated over p_T

DIPSY doing best job in modelling (color ropes)

Will be discussed in more detail by Paolo Bartolini later in this session

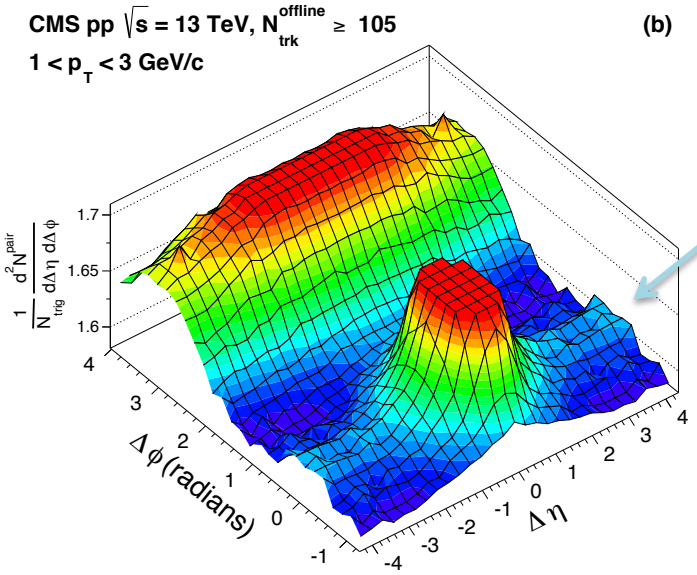


(particles from weak decay not included in N_{ch})



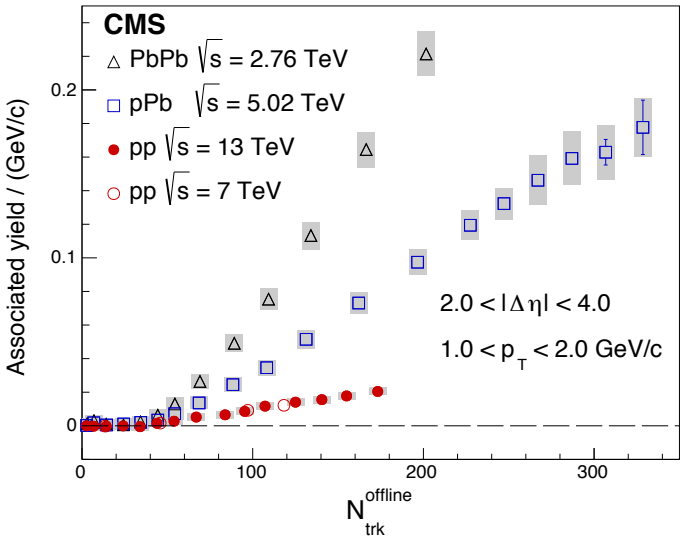
Two-particle azimuthal correlations

[Phys.Rev.Lett. 116, 172302 (2016)]
(also see: Phys.Rev.Lett.116,172301(2016) by ATLAS
Phys.Lett.B762(2016) 473-483 by LHCb,
CERN-EP-2016-228 by ALICE)

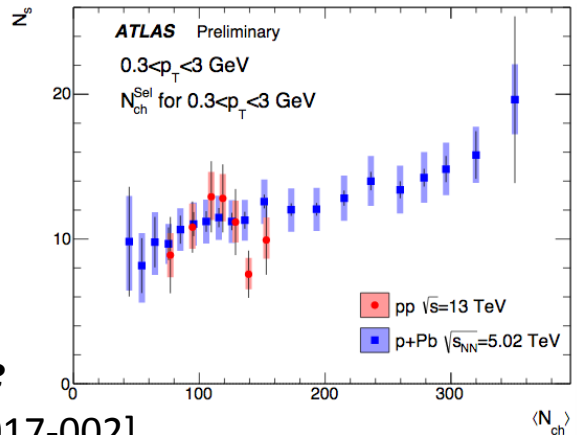


Near-side structure emerging at high multiplicities at Δφ~0

Magnitude of correlations approx. linear increase with charged multiplicity



Related : subevent cumulant analysis with better separation of long-range (collective flow) and short-range (jets) correlations



Extracts number of particles sources in the initial state

[ATLAS-CONF-2017-002]

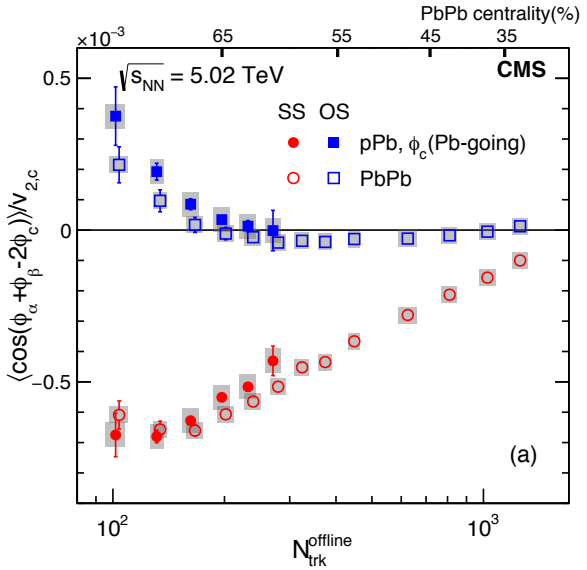
Possible explanation: collision of thin flux tubes / line-like source

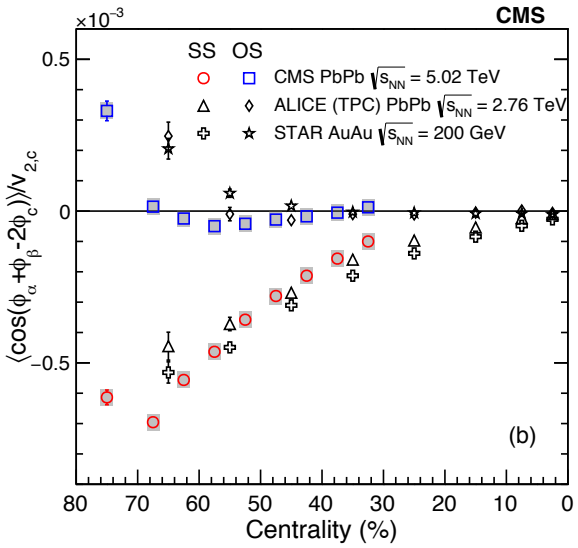
[Bjorken, Brodsky, Goldhaber,
Phys.Letter B726,344 (2013)]

Charge-dependent azimuthal correlations

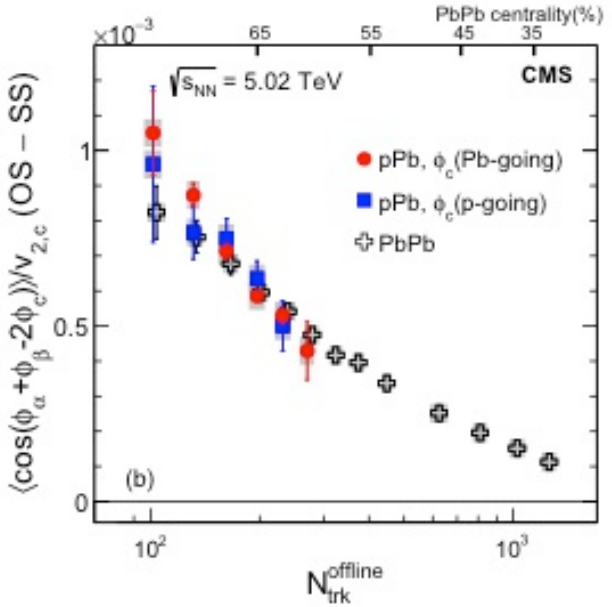
[Phys.Rev.Lett 118,122301(2017)]

Charge-dependent 3-particle correlations: same-sign (SS) or opposite-sign (OS) pair and 3rd particle in forward calorimeter





The (OS – SS) asymmetry has been interpreted as possible signature of a chiral magnetic effect in heavy ion collisions .. .. but the data are very similar in pPb and PbPb



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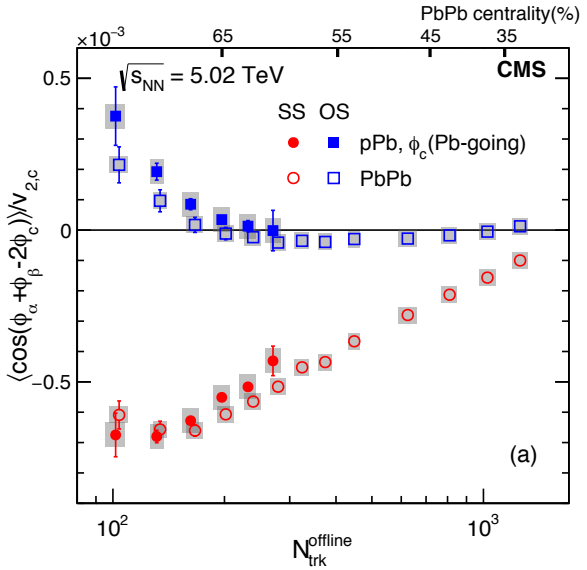

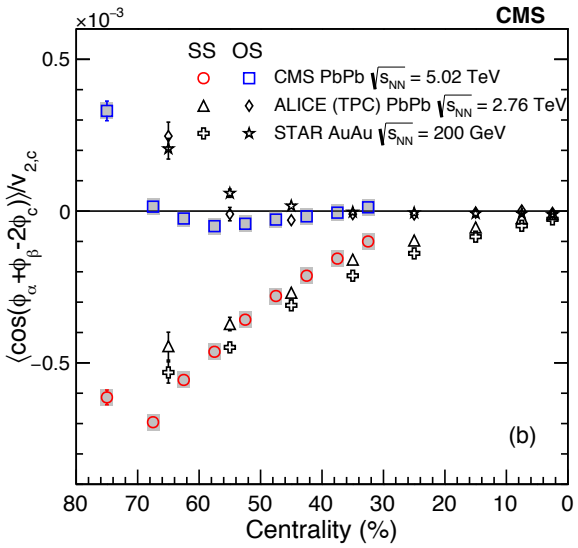

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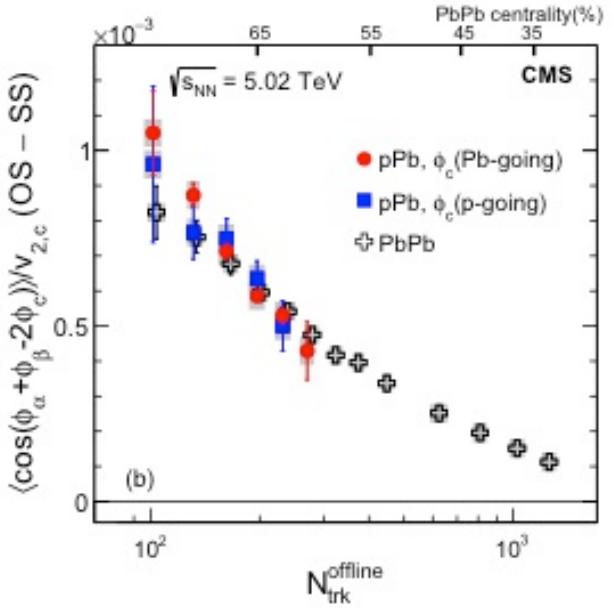
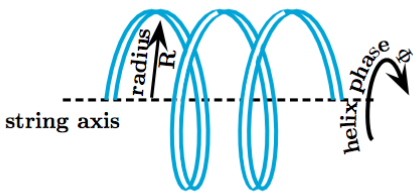
Besides : azimuthal correlations have been observed in very soft pp collisions and linked to <u>a hadronization effect</u> : possible signature of fragmentation of a helical QCD string

[Phys.Rev.D86, 052005 (2012)]



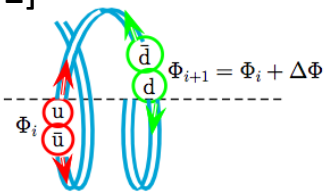
Hadronization / fragmentation of helical QCD string *[JHEP 9809(1998)014.]*

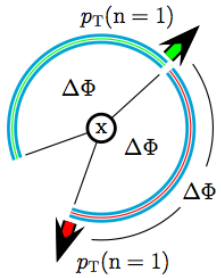


Bo Andersson et al. "Is there a screwiness at the end of the QCD cascades?"
helicity conservation-> no collinear q->qg, g->gg emissions
i.e. no soft collinear divergencies in QCD : natural regularization

Quantized (helix) QCD string [Phys.Rev.D89 (2014) 015002]

When imposing cross-talk between string breakup vertices (causality)
(along the string or across loops), hadron spectra follow a simple
effective quantization pattern : $m_T = n\,\kappa R\,\Delta\phi$, $m_T = n\,kR\,2\pi + \varepsilon$





$\kappa\xi$ [MeV]	κ R [MeV]	$\Delta\Phi$
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

TABLE I. Best fit of the parameters of the pion ground state obtained from the mass spectrum of light pseudoscalar mesons. The η mass is reproduced within a 3% margin which serves as the base of uncertainty for $R, \Delta\Phi$ parameters.

pseudoscalar mesons used to constrain string shape
(model becomes predictive)
Works for light vector mesons, too :
ω, ρ (n=4, decays into m π, m<n)

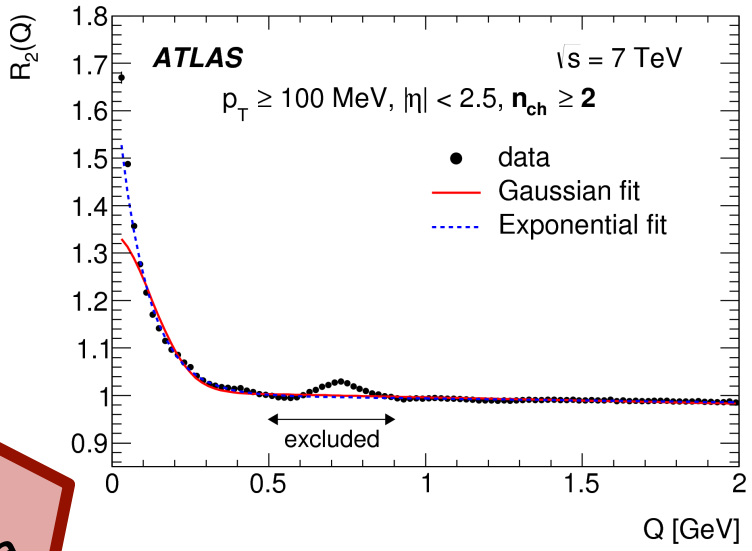
Effective quantization (2 parameters : κR , ΔΦ)
- ***hadron spectra***
- ***momentum difference $Q = \sqrt{-(p_i - p_j)^2}$ between hadrons in 'ground' state***
  -> particle correlations

Enhanced production of pairs of identical particles

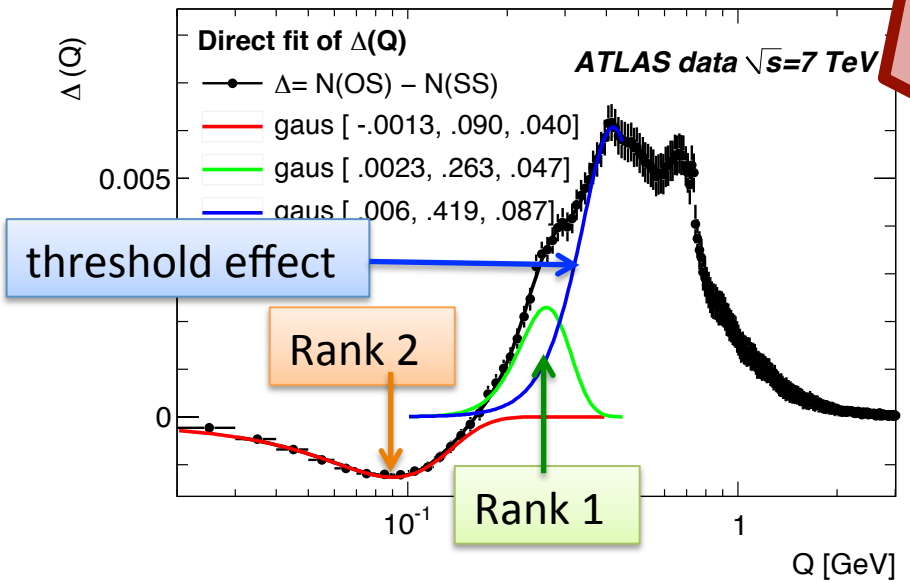
[Eur.Phys.J.C75(2015) 466]

- ***traditionally, attributed to Bose-Einstein interference / HBT effect***
- ***base of femtoscopy measurements in heavy ion experiments***
- *often measured as ratio SS/OS (R_2 double ratio data/MC)*

- ***also expected in <u>coherent</u> emission of chains of ground state pions in helix string fragmentation***



Identical input data



Subtraction OS – SS

$\Delta(Q) = [N(OS) - N(SS)] / N_{ch}$

Low Q spectrum agrees with expectations of quantized fragmentation
Data exhibit threshold effect in production of adjacent hadrons

Quantized helix string model prediction:

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

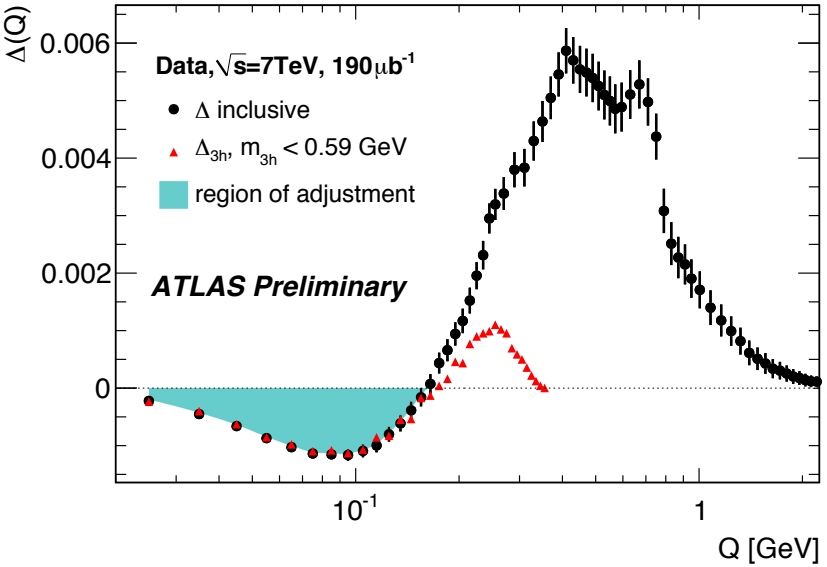
Enhanced production of identical particles : source

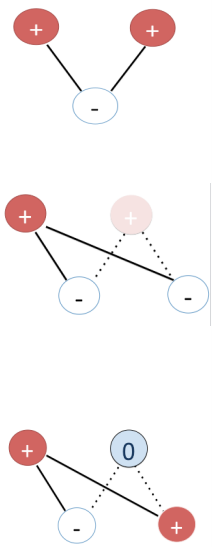
[CERN-EP-2017-092, ATLAS-STDM-2014-08]

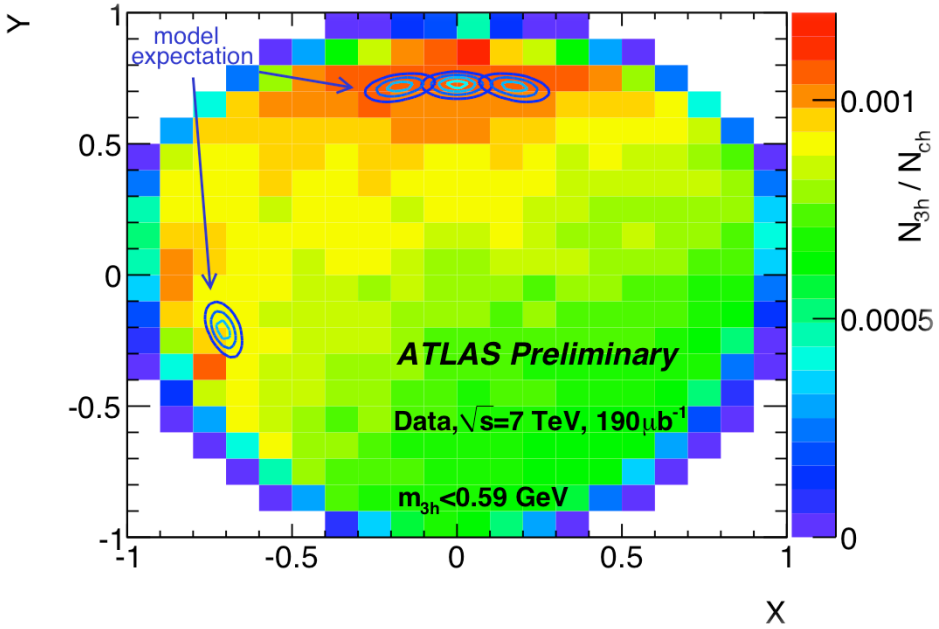
Selection of charge ordered hadron chains [+-+] [-+-] via mass minimization

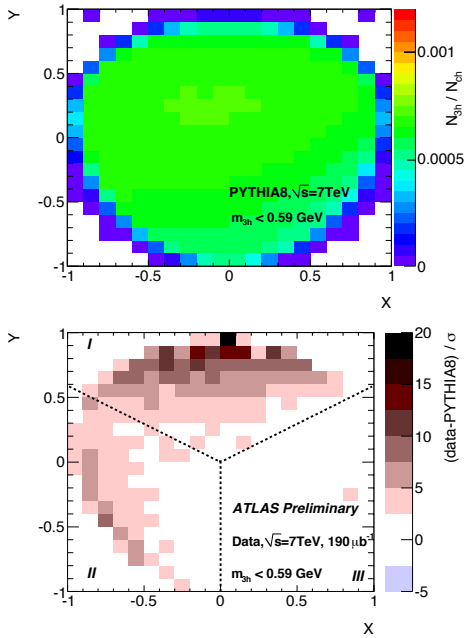
Source of correlations isolated:
3-hadron chain selection with properties predicted by the model (m_{3h}<0.6 GeV)

3-body decay conform to expectations
(signature of chain of ground state pions)







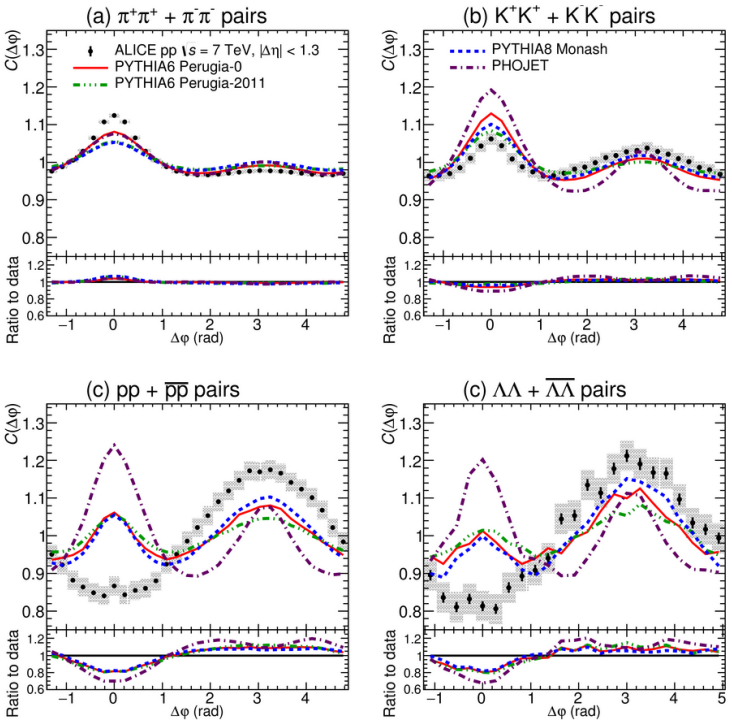


$$X = \sqrt{3}\frac{T_0 - T_2}{\Sigma T};\ Y = \frac{3T_1}{\Sigma T} - 1;$$ T_i kinetic energy in chain rest frame

(see talk by O.Kepka)

Angular correlations of identified particles

[arXiv:1612.08975, subm.to EPJC]

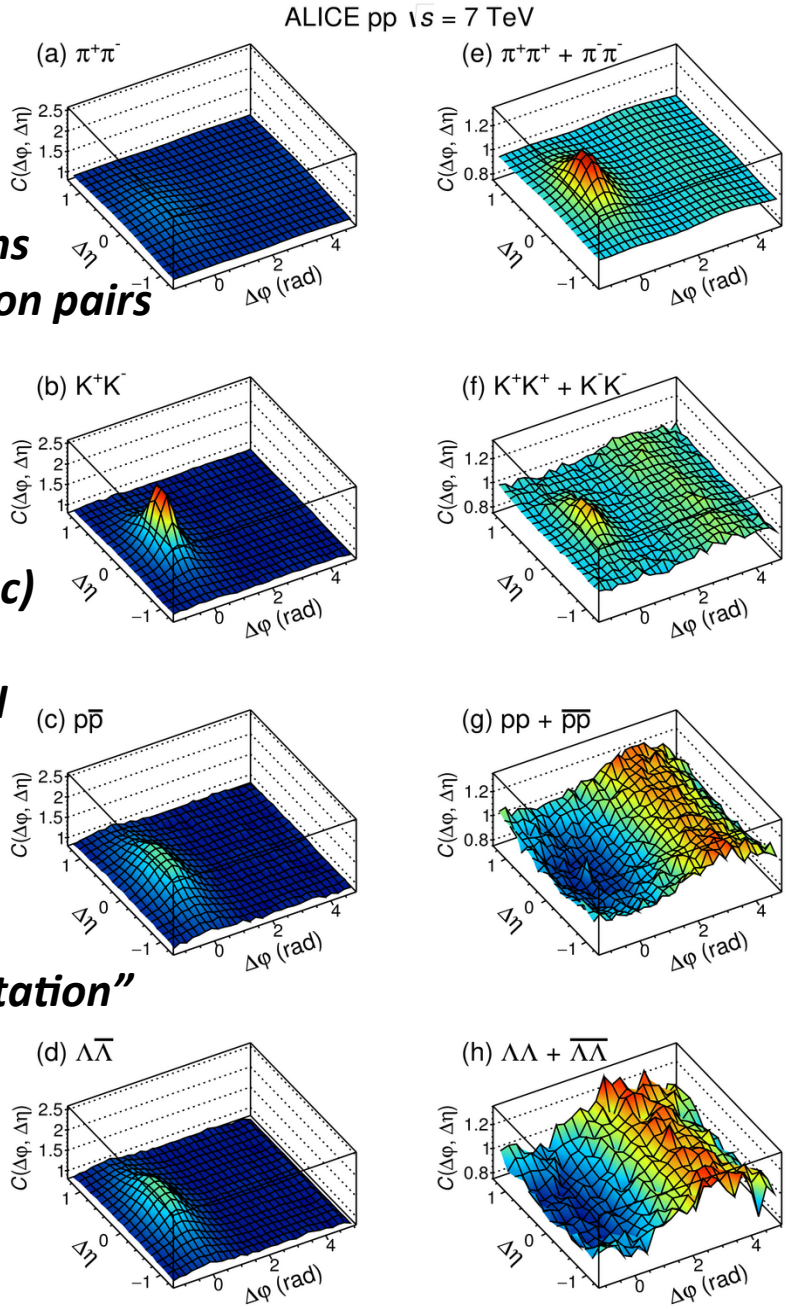


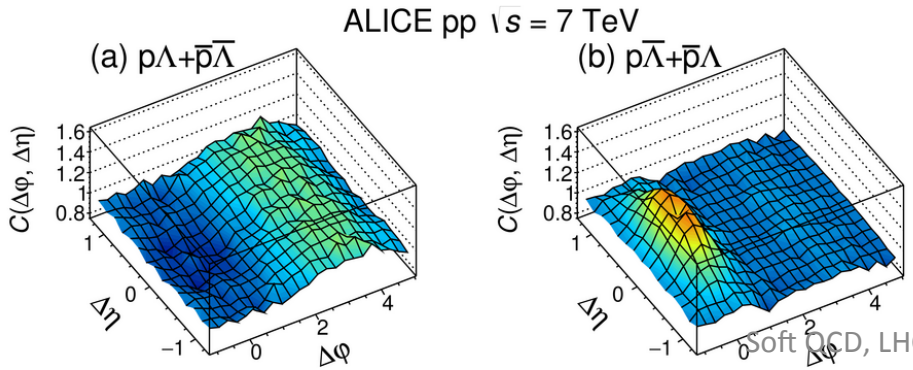
Anti-correlations of baryon-baryon pairs

Similar for pp, ΛΛ, pΛ + c.c. (not Fermi-Dirac)

Not reproduced by MC models

"something is missing in the string fragmentation"





Pledge : can we have this measured in Lorentz invariant quantities (Q)?

Summary & perspectives

- ✓ *Inclusive x-sections understood*
- ✓ *Inclusive particle spectra : modeling not quite predictive yet (typically, stepping into new region in energy or event topology requires retuning of generators)*
- ✓ *Identified particle rates and particles correlations :similar properties in pp,pPb,PbPb*

2 different approaches : "collective effects " - effective deconfinment & statistical description (hydrodynamical flow)

"detailed modelling of confinment" (flux tubes/ropes/ effective quantization)

The issue can be settled experimentally (for example : ground state pions should carry the intrinsic transverse momentum of ~130-140 MeV – w.r.t string axis)

Model of helical QCD string eliminates soft collinear divergencies and provides link between previously disconnected features of hadron production (mass spectra/correlations/properties of hadronic ground state)

? Is there a sort of a natural cut-off in the parton emission ?

? By measuring it (indirectly), can we build a non-divergent QCD theory ?

Thank you for your attention ! More info to be found in parallel sessions

backup info

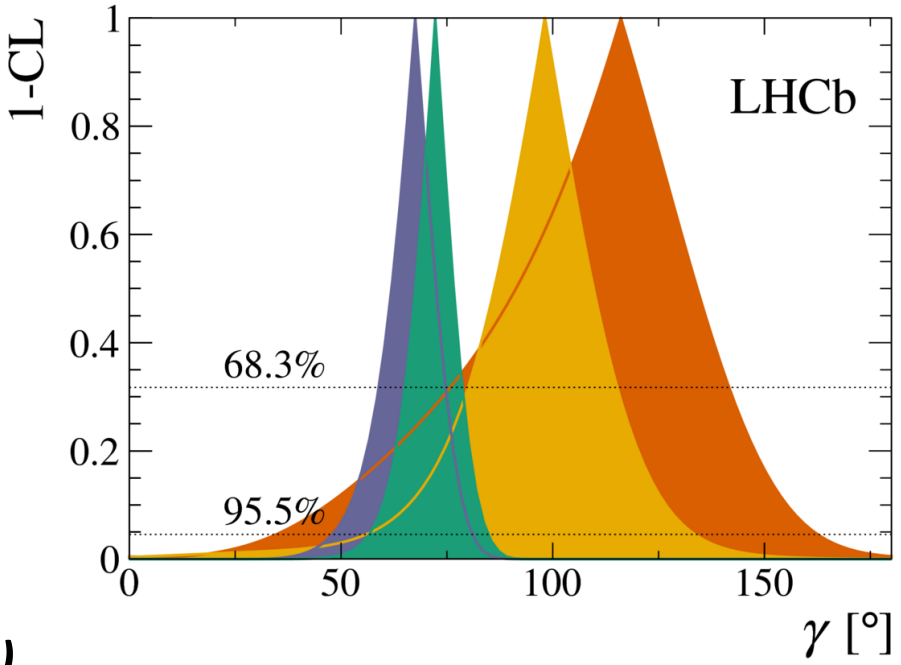
CKM matrix – direct measurements

[JHEP 12 (2016) 087]

Combination of B -> D K – like modes:

$$\gamma = (72.2\,^{+6.8}_{-7.3})^\circ$$ ***(B->Dh compatible)***

- ***most precise single experiment combination (Run 1)***
- ***projected precision ~ 4° (at the end of Run2)***



1-CL plots (profile likelihood method)

B decay	D decay	Method	Ref.	Status since last combination [28]
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS	[44]	Updated to 3 fb^{-1}
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[44]	Updated to 3 fb^{-1}
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[45]	New
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[46]	As before
$B^+ \to DK^+$	$D \to K^0_S K^-\pi^+$	GLS	[47]	As before
$B^+ \to Dh^+\pi^-\pi^+$	$D \to h^+h^-$	GLW/ADS	[48]	New
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[49]	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[50]	New
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[51]	New
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD	[52]	As before

B^0_s decays

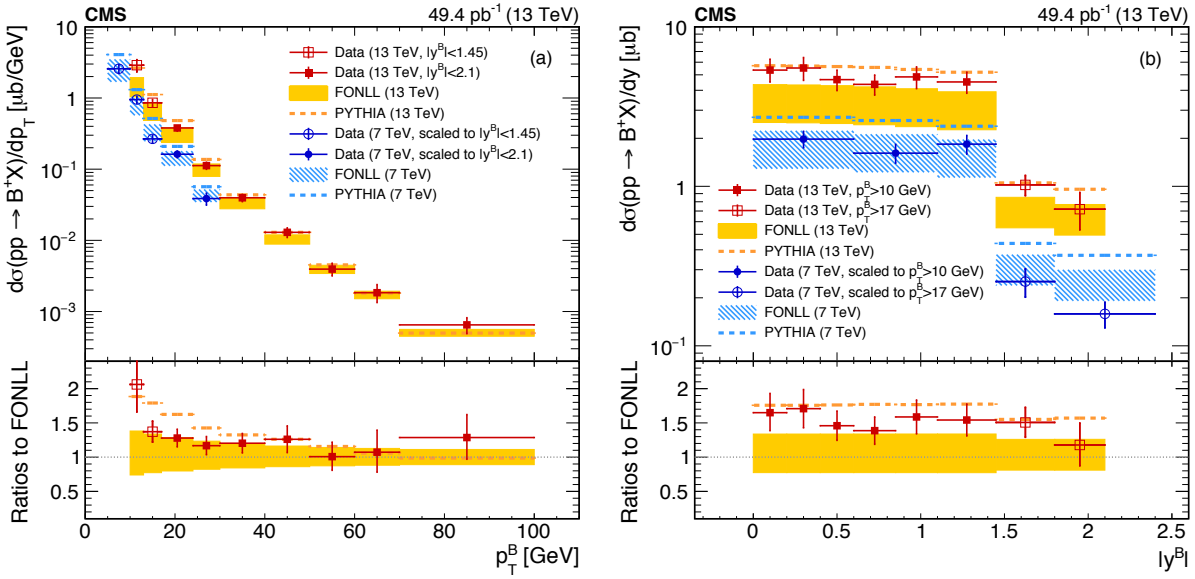
B^0 decays

B^+ decays

Combination

Inclusive b-quark production

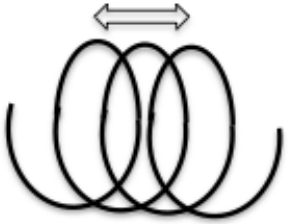
- ***inclusive B^+ production*** [arXiv:1609.00873, subm.to PLB]

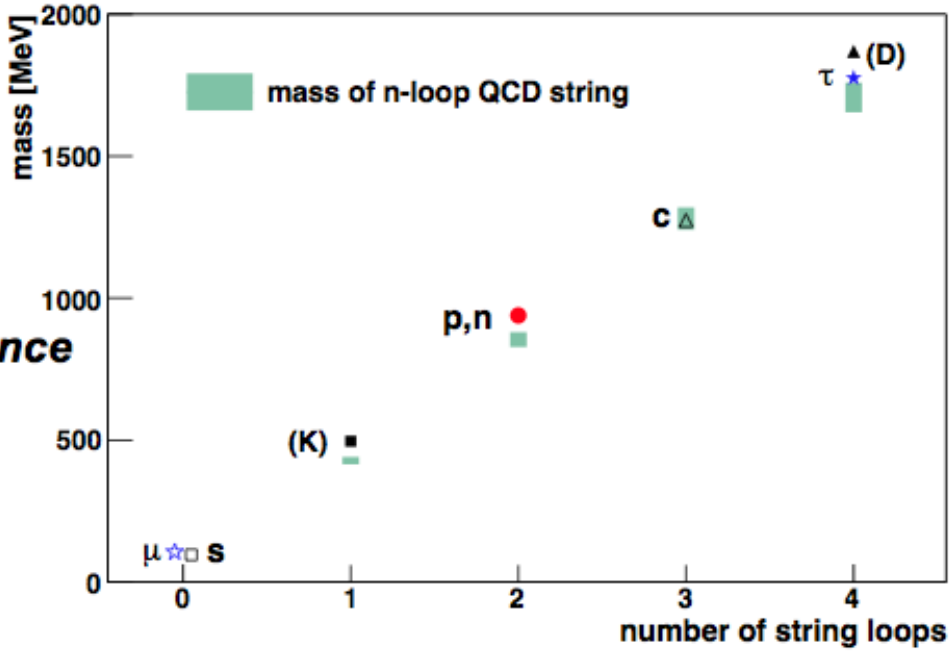


- ***published result of LHCb*** [Phys.Rev.Lett.118,052002(2017)]

  requires correction (not available yet)

Quantized helix string model has largephenomenological potential
What if the curly field interacts across loops ("knotting") ?





[arXiv:1406.3564]

The mass of the multiple string loop correlates with the emergence of new particles (new 'quantum' numbers)

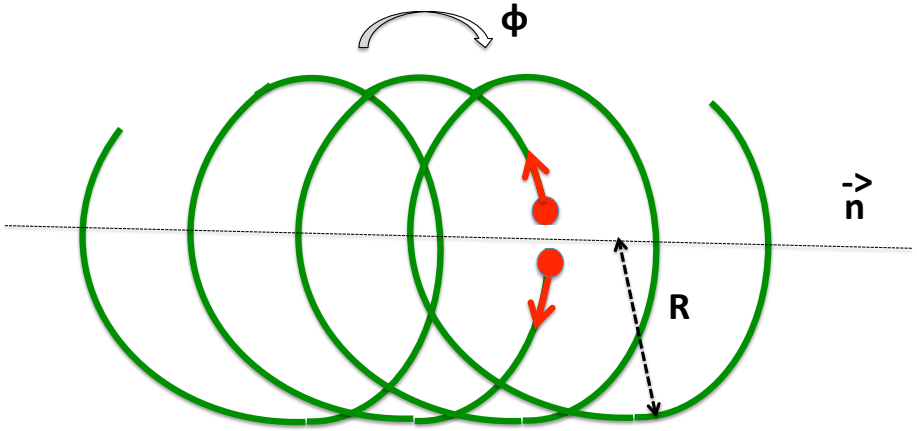
-> topological origin of mass spectrum ?
-> increasingly complex knots generate new particle properties ?

In the model, proton corresponds to the trefoil – the simplest non-trivial topological knot

Trajectory of parton under helix-string potential satisfies the uncertainty principle:

The particle appears at the classical trajectory

$$\vec{x}(t) = \vec{x}(0) + \beta\, c\, t\, \vec{n}$$



just once per the period for $\omega\,\Delta t = k\,2\pi$, $k = 1, 2, 3 \ldots$

And the corresponding action is

$$x(\Delta t)\, p(\Delta t) - x(0)\, p(0) = \kappa c\, (\Delta t / \gamma)^2 = \kappa c\, \tau^2 = \kappa\, (0.183 \pm 0.01)\ fm^2/c \approx \hbar$$

τ is the invariant period of parton rotation (spin)