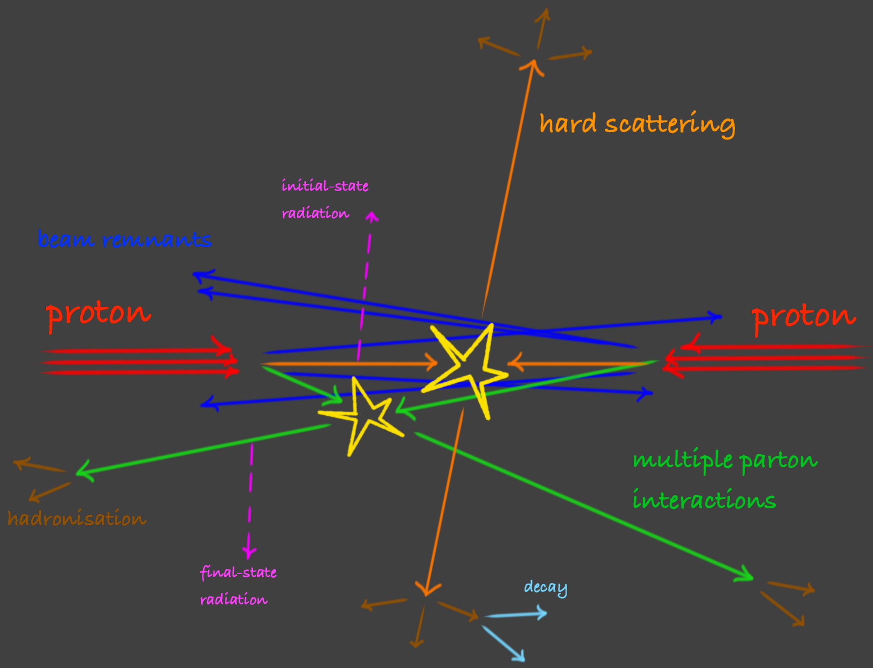
Soft QCD



Seminar
25th August 2021

Valentina Zaccolo
University and INFN – Trieste

ALICE

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What is this seminar about?

Soft QCD

- processes where effective α_S is large → low transverse momenta
- perturbative QCD fails → theory relies on phenomenological assumptions

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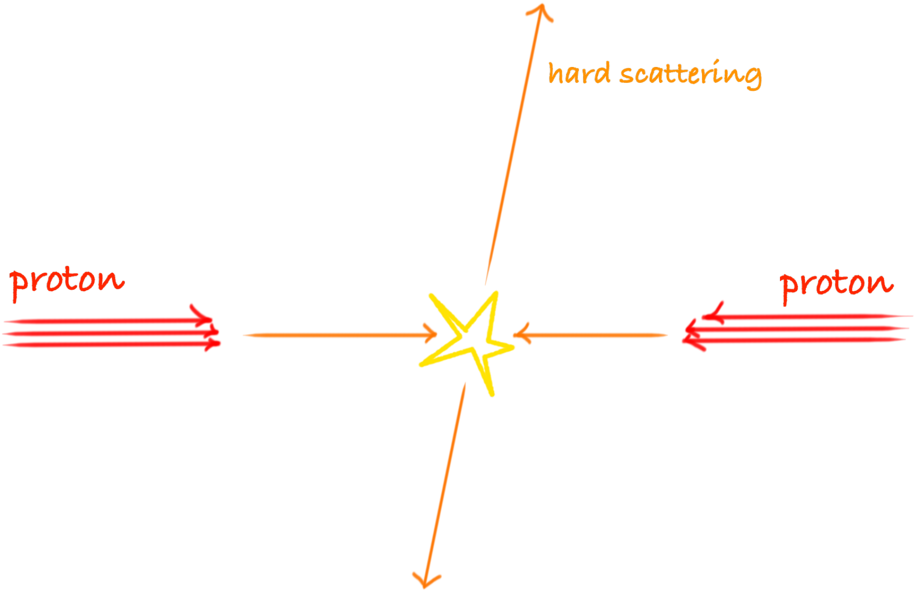

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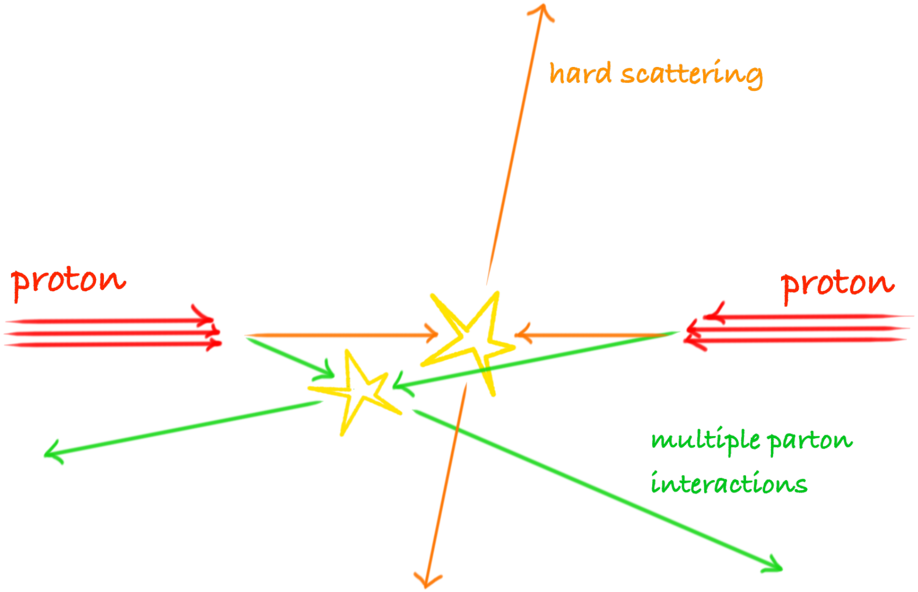
1. Multiple parton interactions (MPI)



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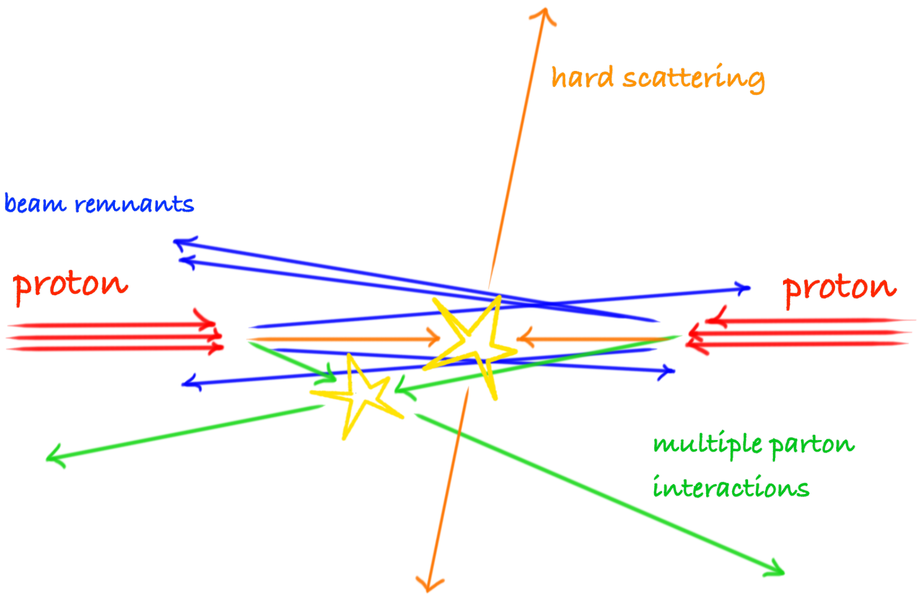

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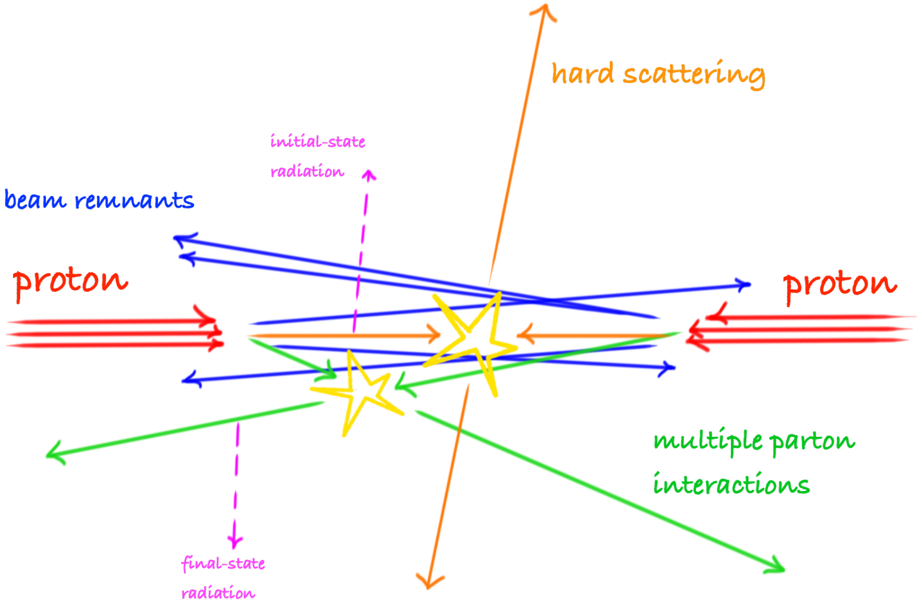
1. Multiple parton interactions (MPI)
2. Beam remnants
3. Initial- and final-state radiation

Underlying event



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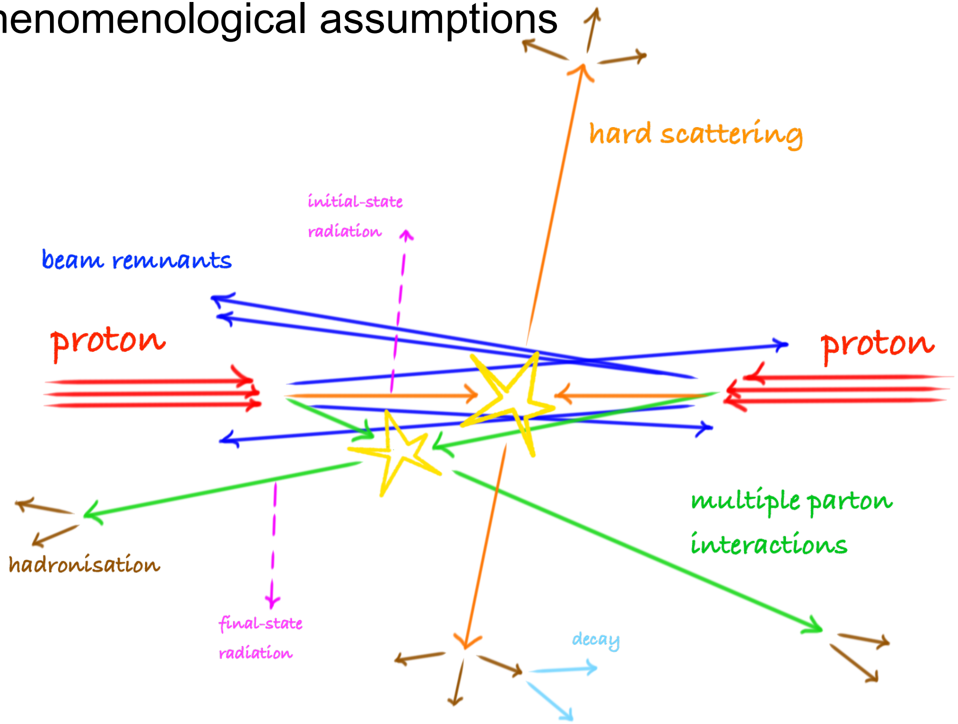
   Underlying event

4. Hadronisation + decay products



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First part

1. Multiple parton interactions (MPI)
2. Beam remnants
3. Initial- and final-state radiation

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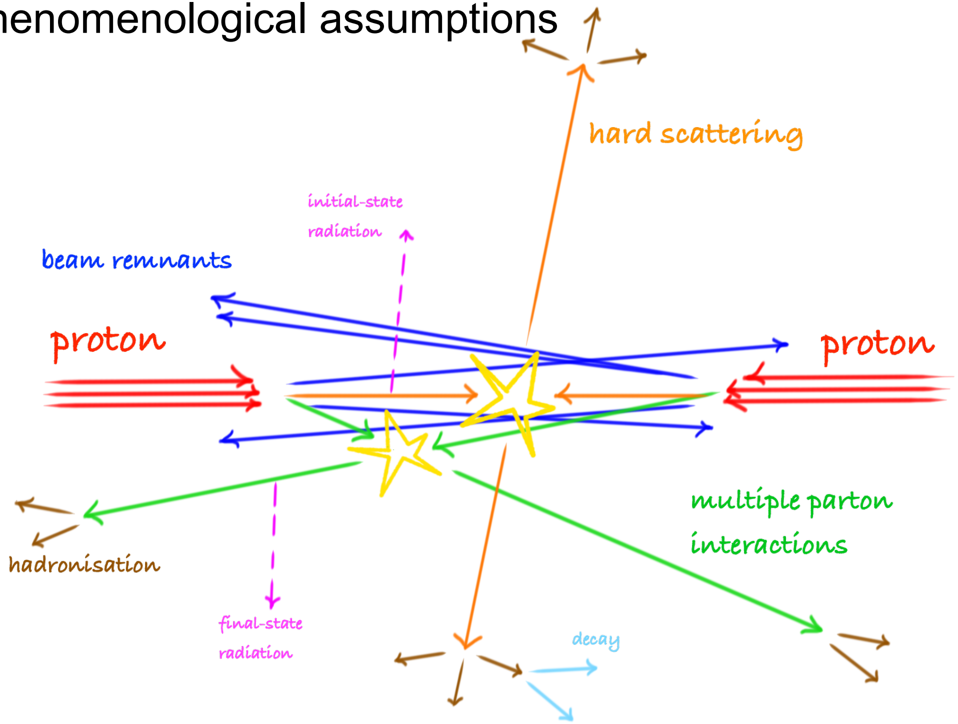

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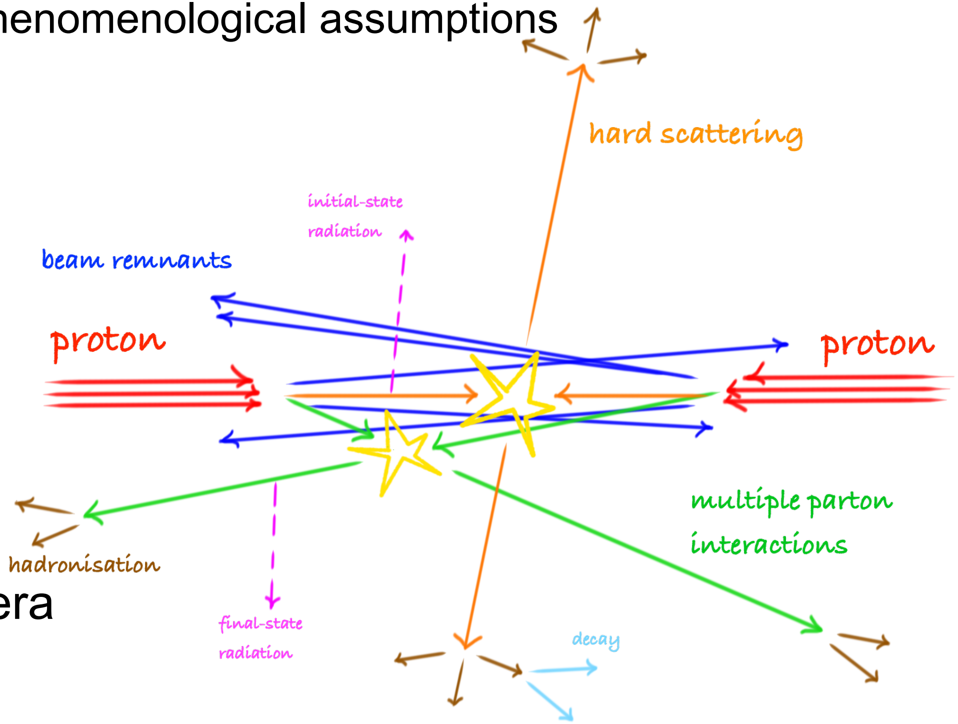
First part

1. Multiple parton interactions (MPI)
2. Beam remnants
3. Initial- and final-state radiation

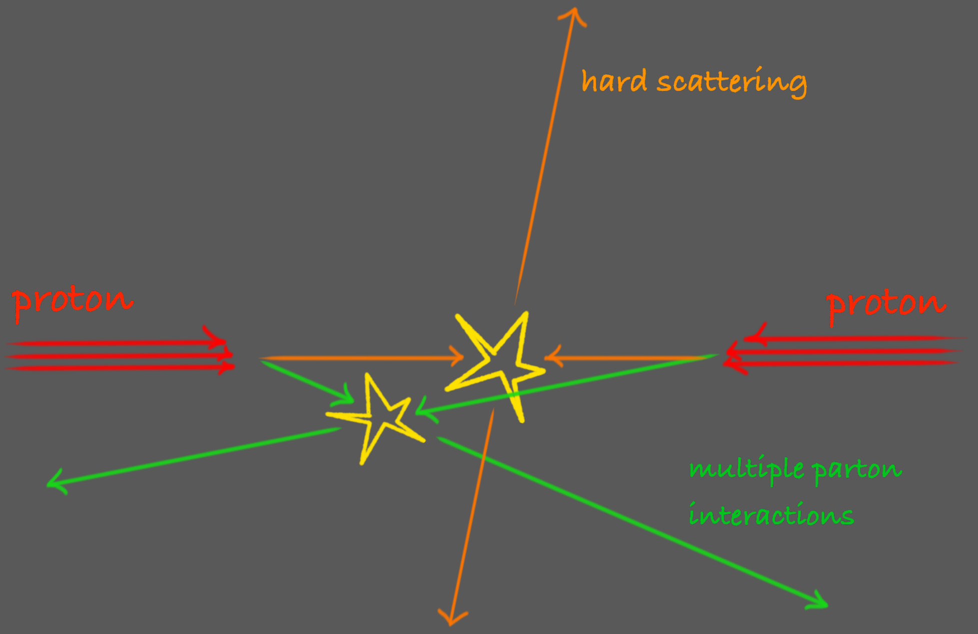
   Underlying event (items 1–3)
4. Hadronisation + decay products

Second part

→ some ways to move towards precision era



Multiple parton interactions



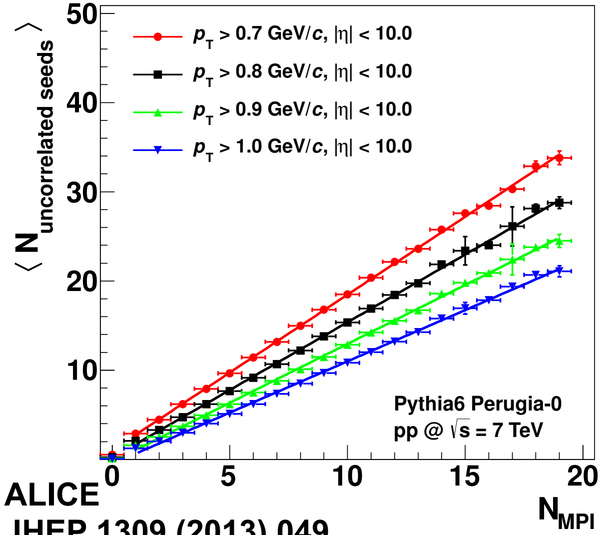
Study the number of MPI

Definition of uncorrelated seeds

- parton-parton hard scattering → partons back-to-back in ϕ
- two minijets (lower p_T) α N_{MPI}
- N_{MPI} α N_{ch} and underlying event characterization

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

α N_{MPI} in PYTHIA



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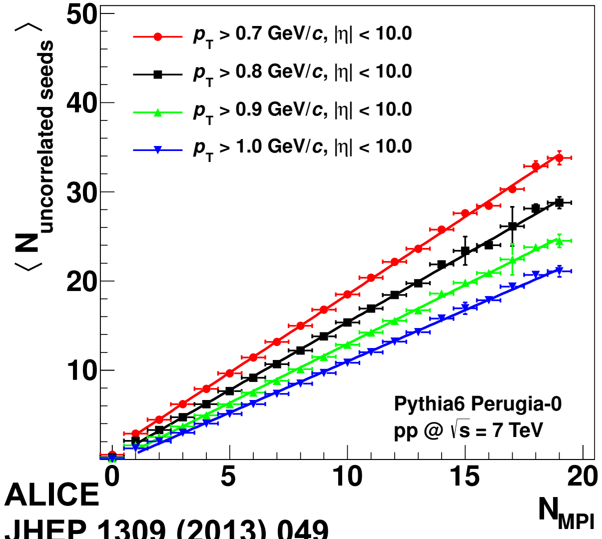

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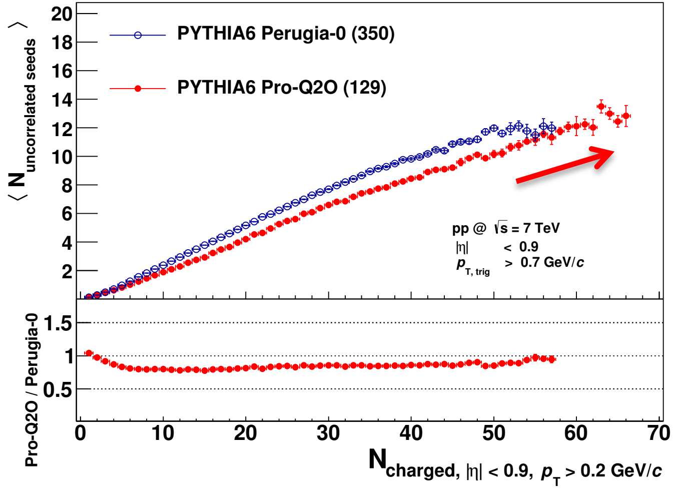
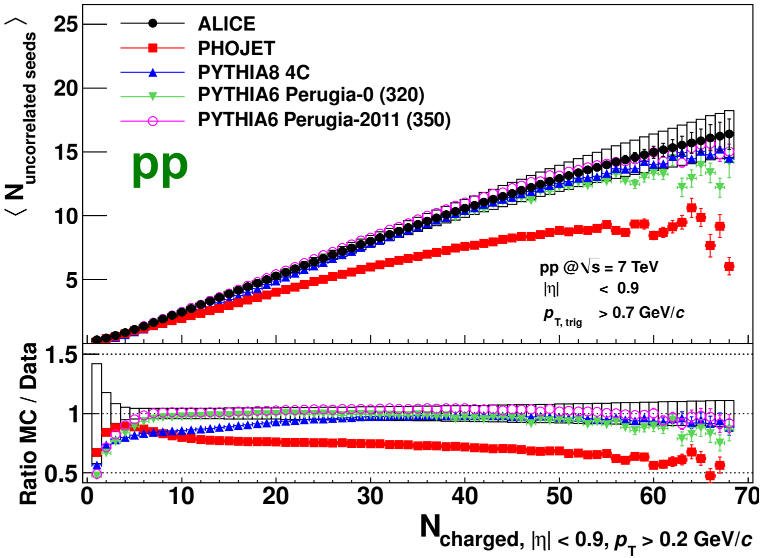
high multiplicities
number fragments
per parton
increase with N_{MPI}



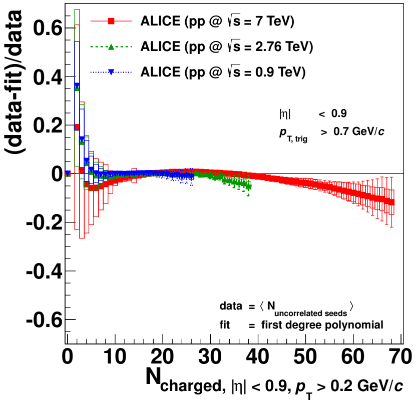
Saturation of N_{MPI}

Two-particle correlations in pp and p-Pb



pp linear fit →

limit in increasing N_{MPI} ⟶



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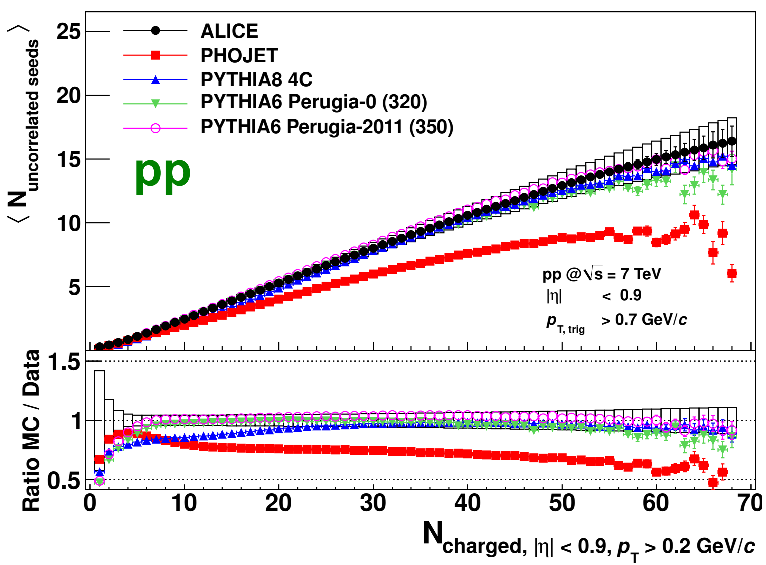
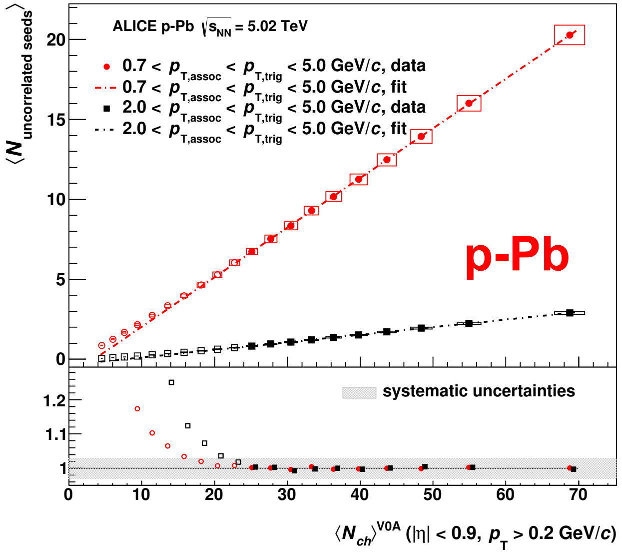


p-Pb linear fit →
no saturation
of the N_{MPI}



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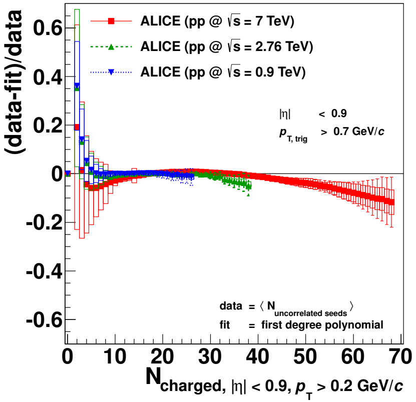

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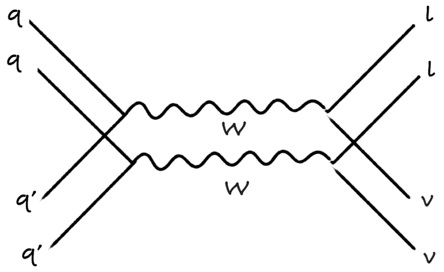
Directly targeting MPI

First evidence of WW from DPS

Clean final state

leptonic decay $e^{\pm}\mu^{\pm}$ or $\mu^{\pm}\mu^{\pm}$

$$\sigma_{AB}^{DPS} = \frac{n}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$



σ_{eff} parton distribution in the plane orthogonal to the direction of the protons

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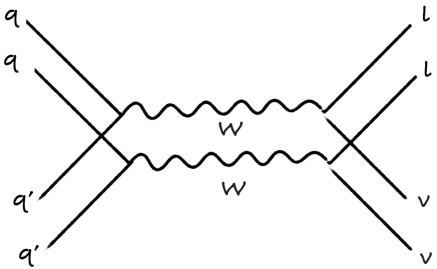

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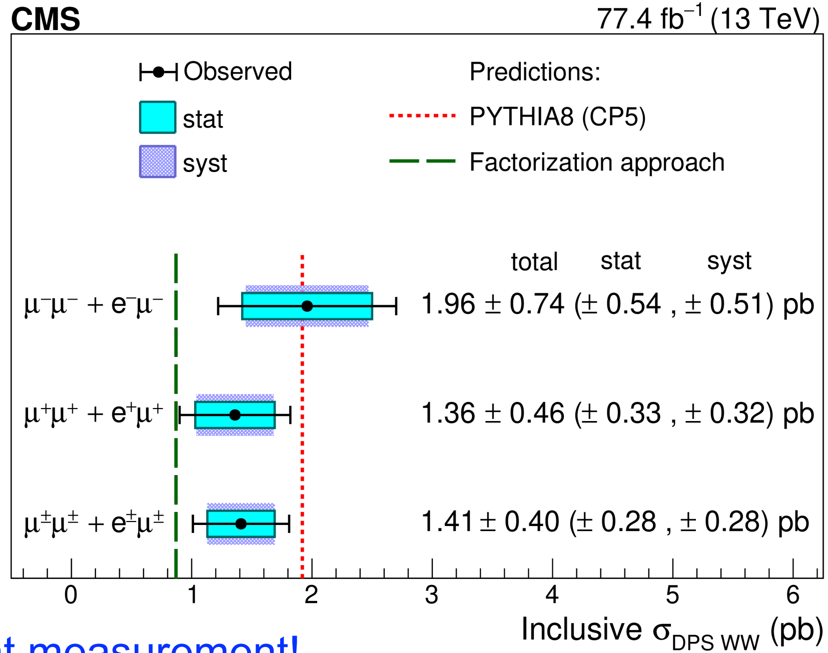
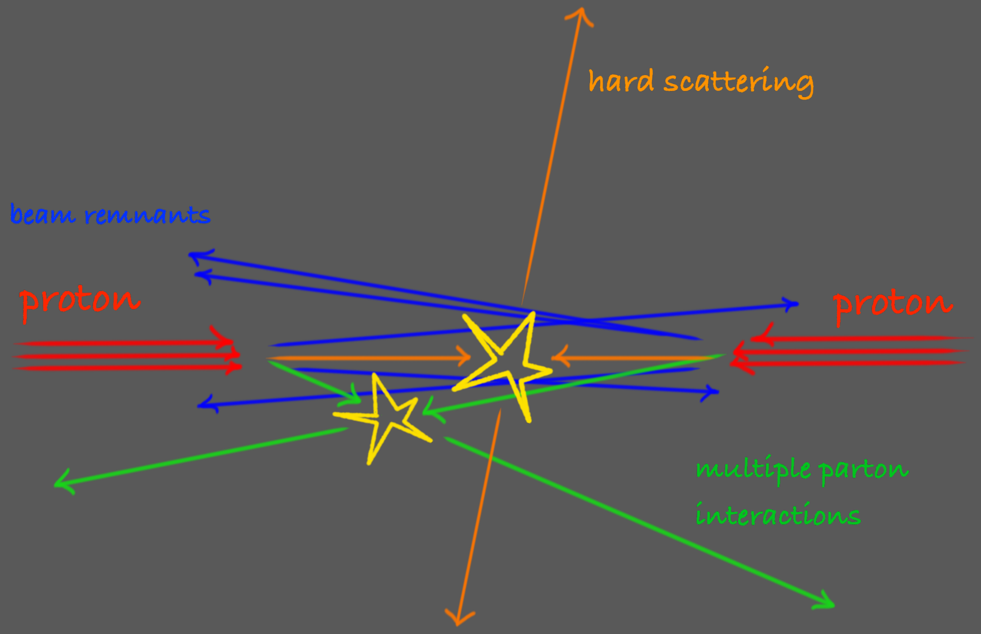


Predictions have large uncertainties → important measurement!

- Factorisation approach: from σ_{eff}
- PYTHIA: UE description

Beam remnants

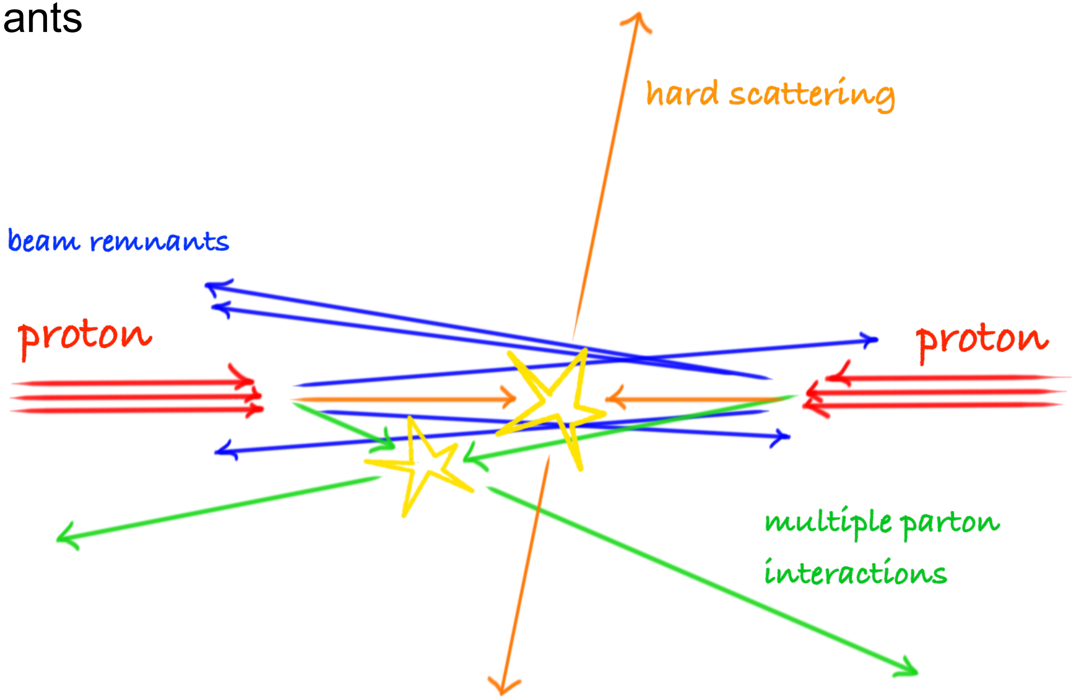


QCD properties in pp

Very forward energy vs. midrapidity activity

Fundamental insights into soft-QCD processes:

- midrapidity activity related to products of hard scatterings + showers + hard MPI
- very forward energy from beam remnants



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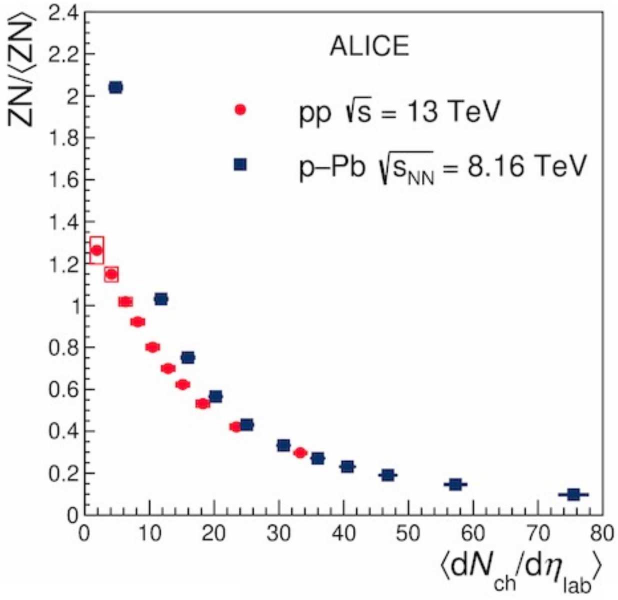
pp and p-Pb in agreement at high multiplicity



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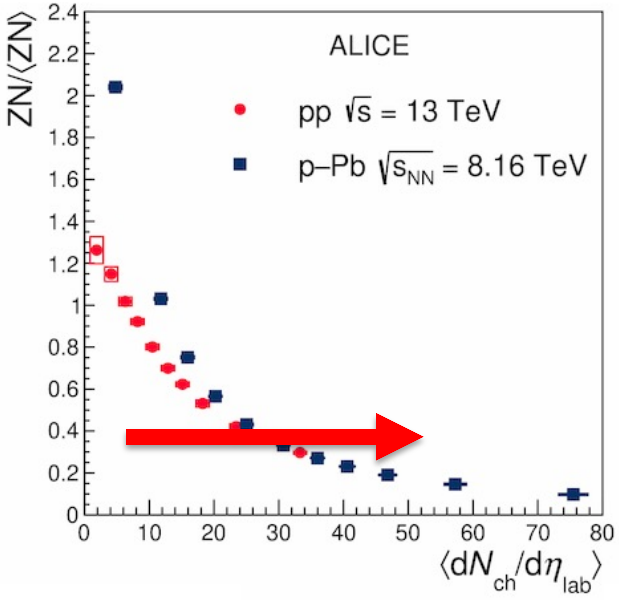
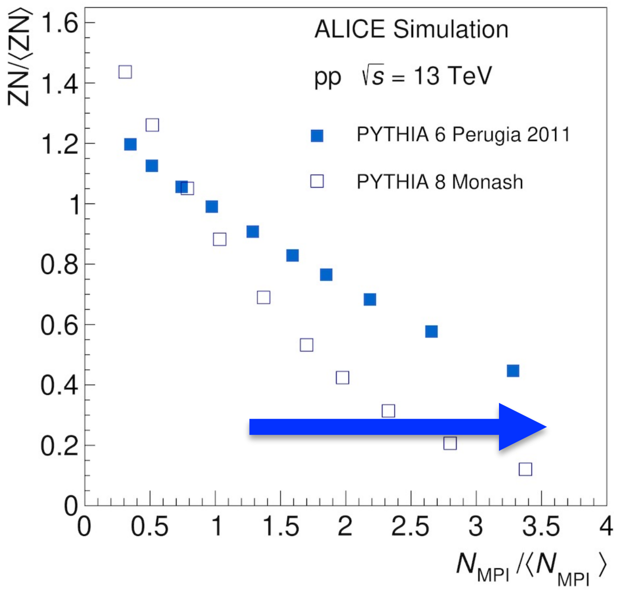
Small forward energy:
→ high midrapidity activity and low impact parameter
→ larger than average MPI





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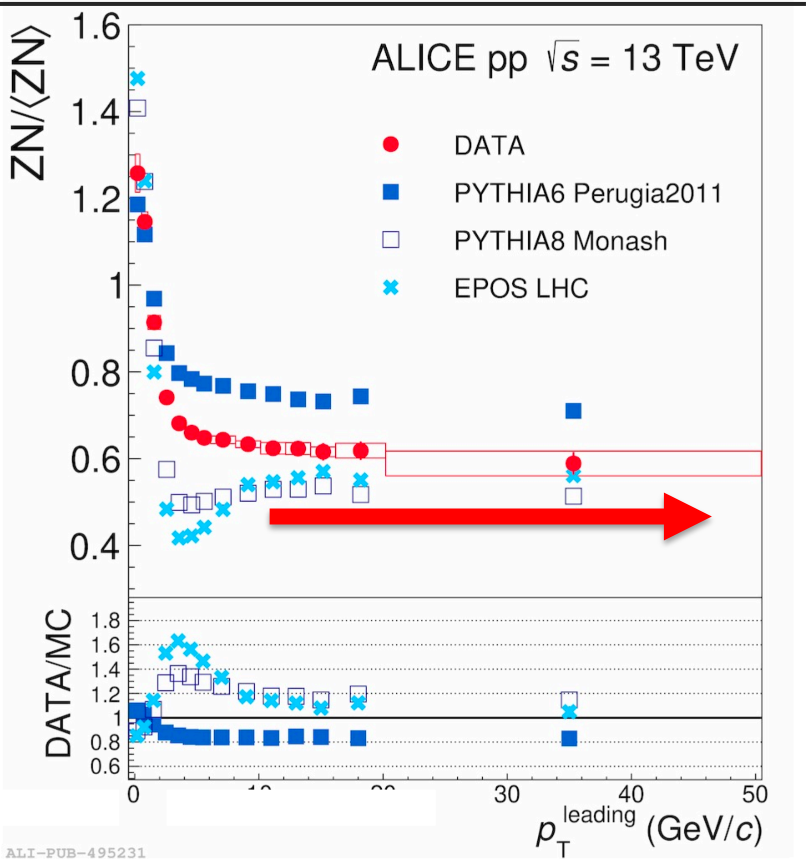
QCD properties in pp

Very forward energy vs. $p_T^{leading}$

Forward energy saturates for $p_T^{leading}$ > 5 GeV/c



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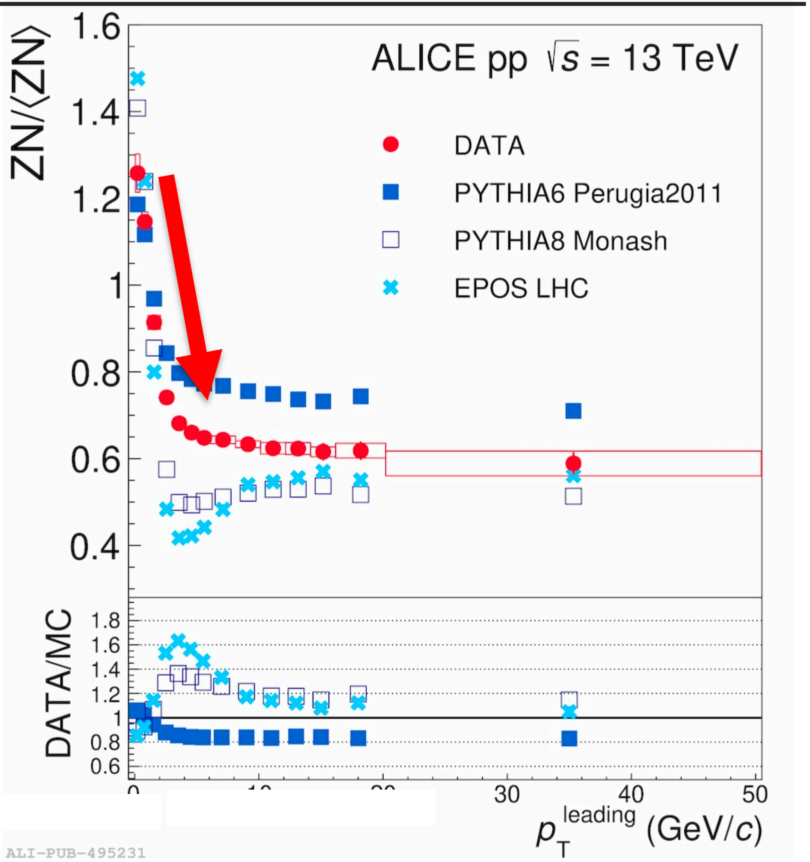
Strong anti-correlation between $p_T^{leading}$ and ZN at low $p_T^{leading}$ built in the initial stages of the collisions:
the two observables are causally disconnected in the evolution stages



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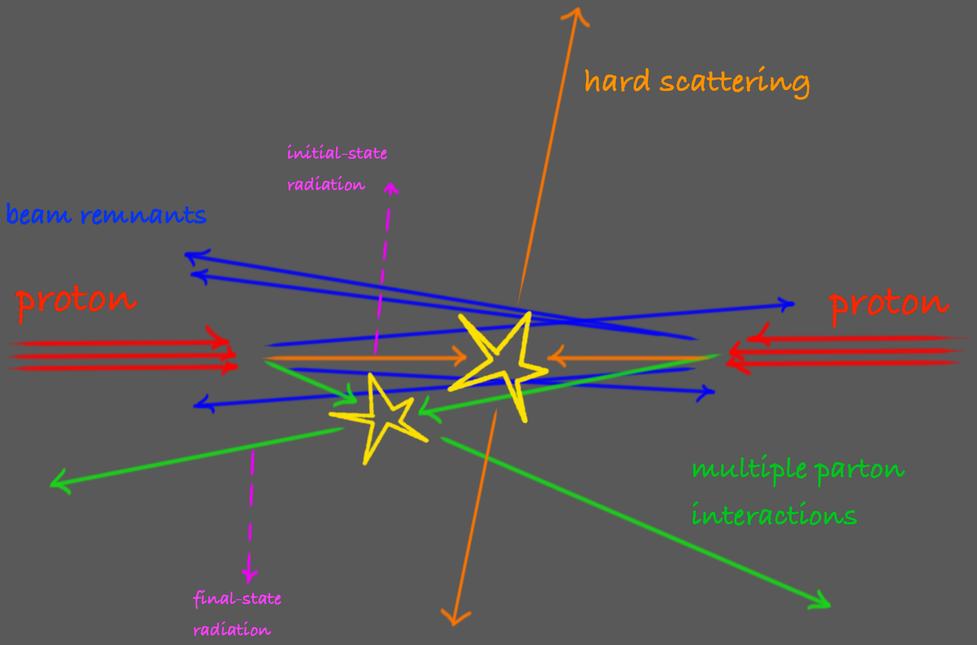
Underlying event



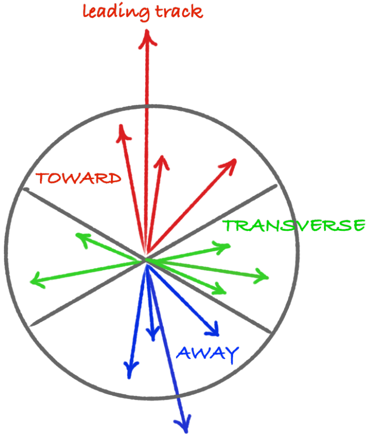
UE characterisation

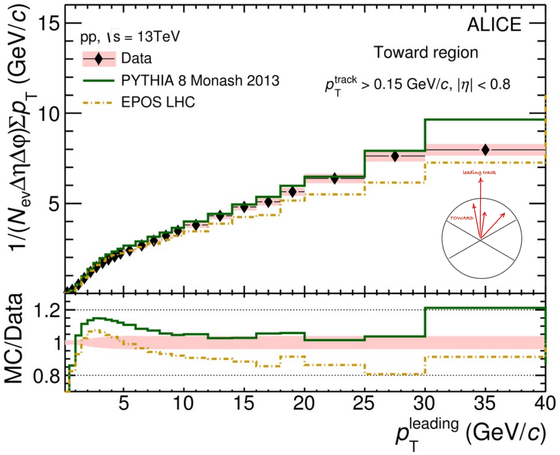
As a measurement wrt leading track

Summed p_T vs. $p_T^{leading}$

Toward and Away regions
collect fragmentation products from hard scattering

- increases monotonically





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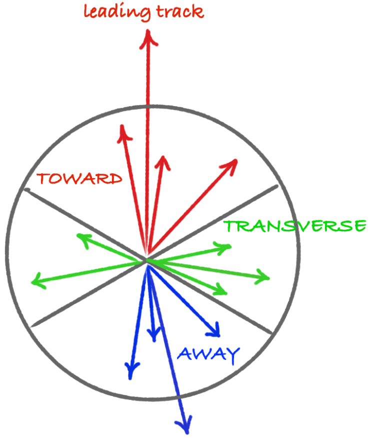
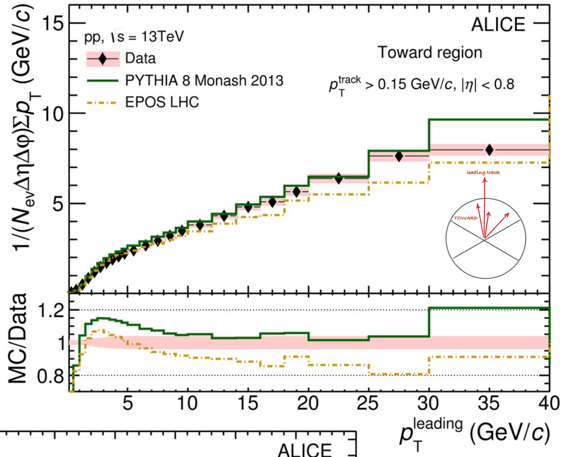
Transverse region

underlying event

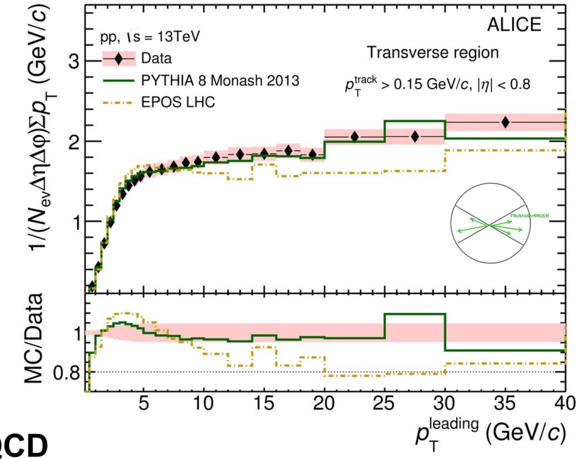
- first increases -> **MPI increase**
- flattens -> **MPI saturation**





PYTHIA 8 performs better

- good MPI description



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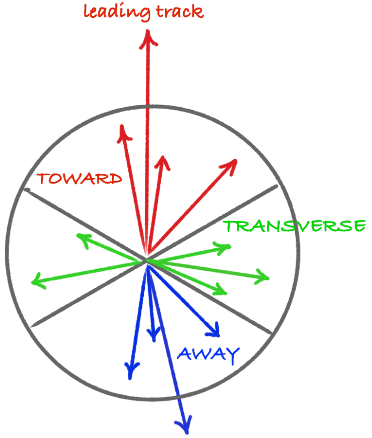
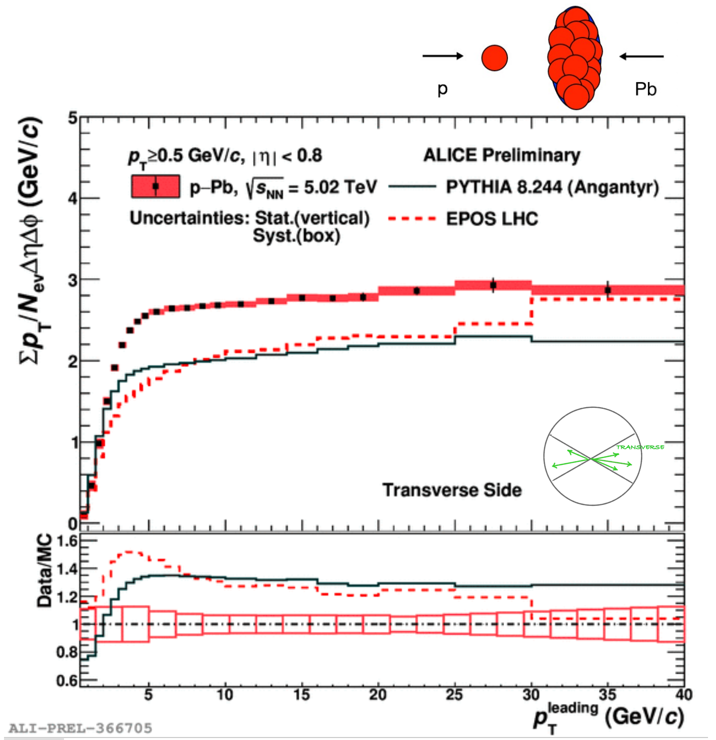


- Larger UE magnitude in p-Pb collisions
- Both models fail in describing the UE activity

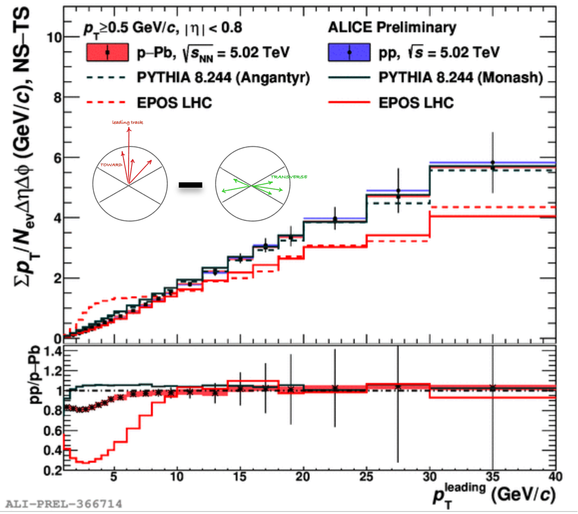


UE characterisation
Study of jet-like regions

Summed p_T vs. $p_T^{leading}$

Assuming transverse-side activity is flat:

- towards – transverse-side
  → depletion at low $p_T^{leading}$ in pp/p-Pb
- collective flow effect?
- EPOS LHC reproduces the depletion, but overestimates the effect



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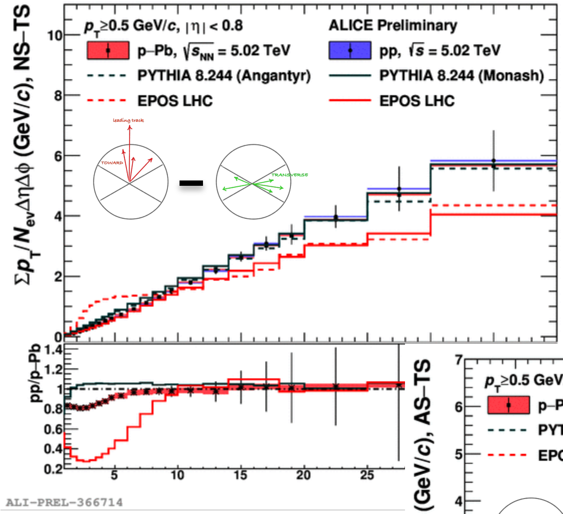
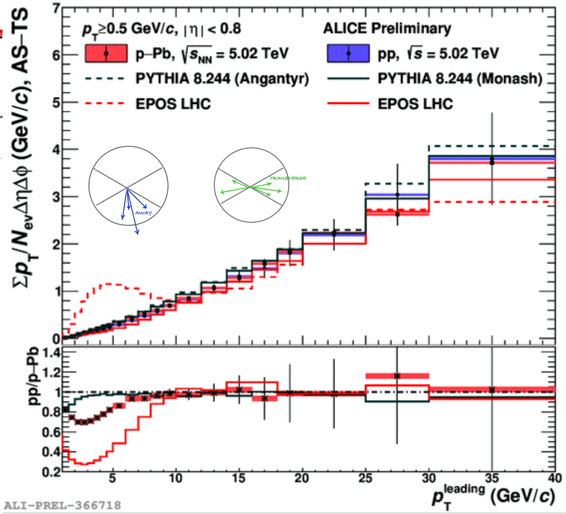


- away – trasverse-side
  → no jet-like modification in away side for p-Pb collisions



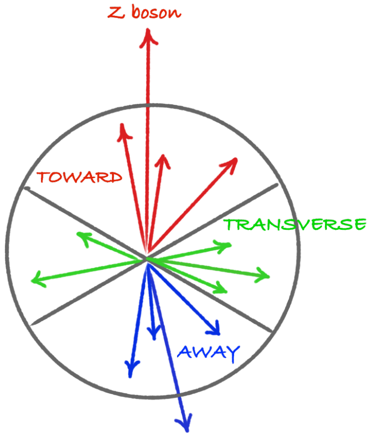
UE characterisation
As a measurement wrt Z boson

Using Z boson

→ very clean UE definition (no FSR)

Measurement done vs Thrust

$$T_{\perp} = \frac{\sum_i |\vec{p_{\mathrm{T},i}} \cdot \hat{n}|}{\sum_i |\vec{p_{\mathrm{T},i}}|}$$



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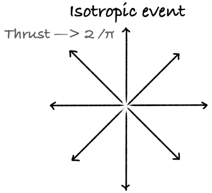
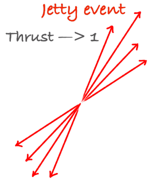
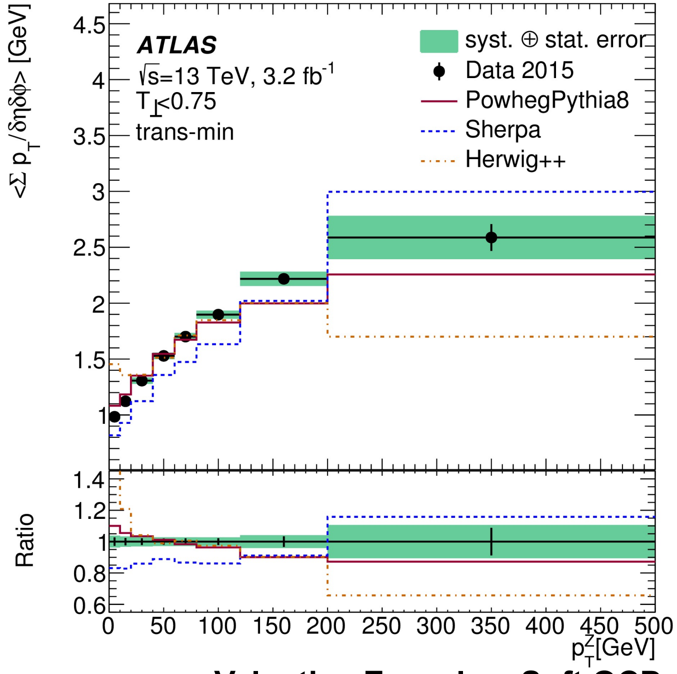
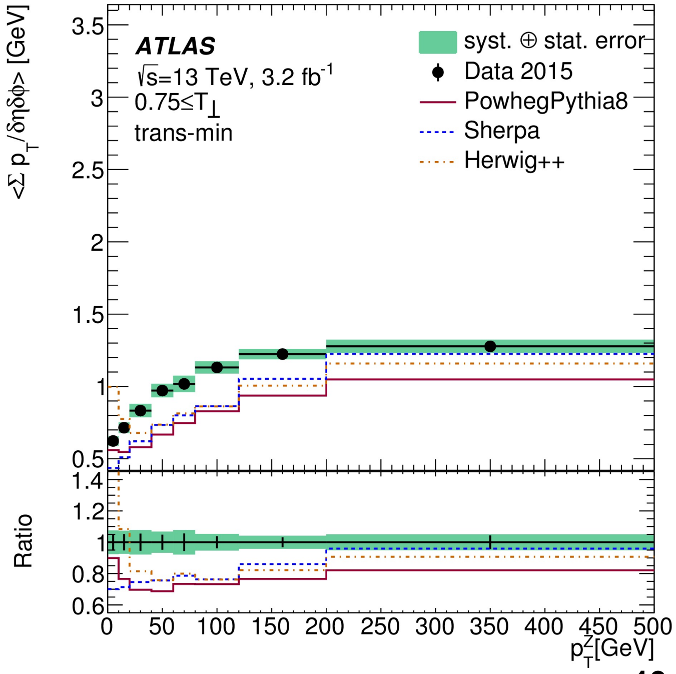
- isotropic event dominated by MPI
  - PowhegPythia8 works better
- jetty event dominated by ISR
  - all generators underestimate data









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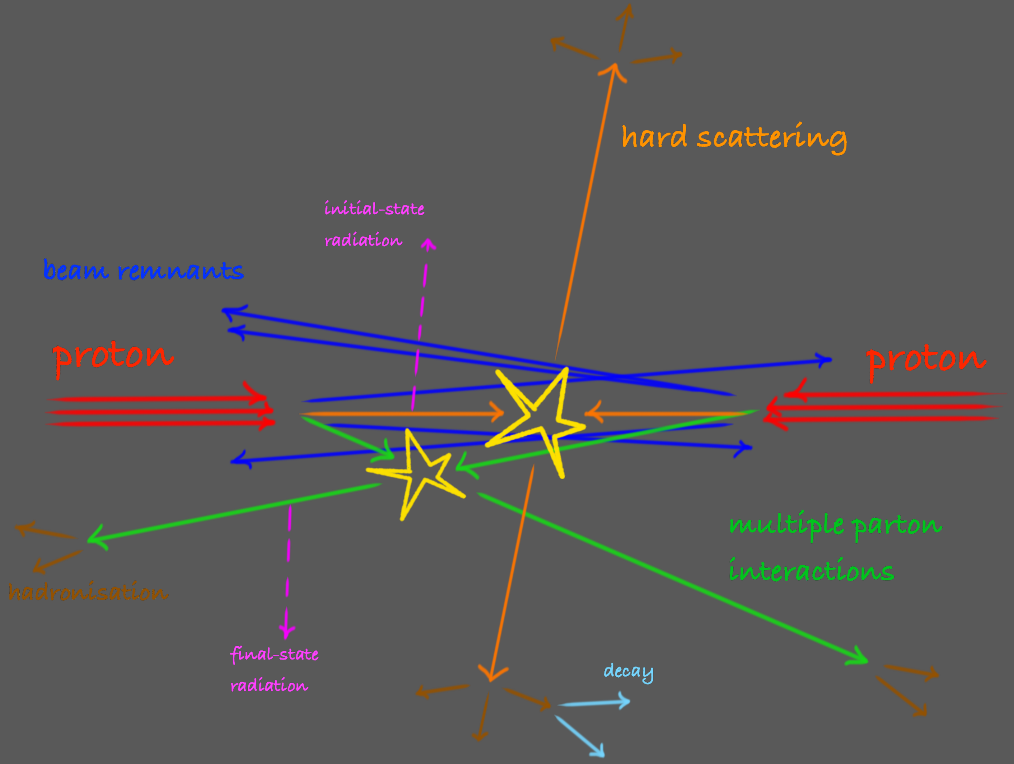
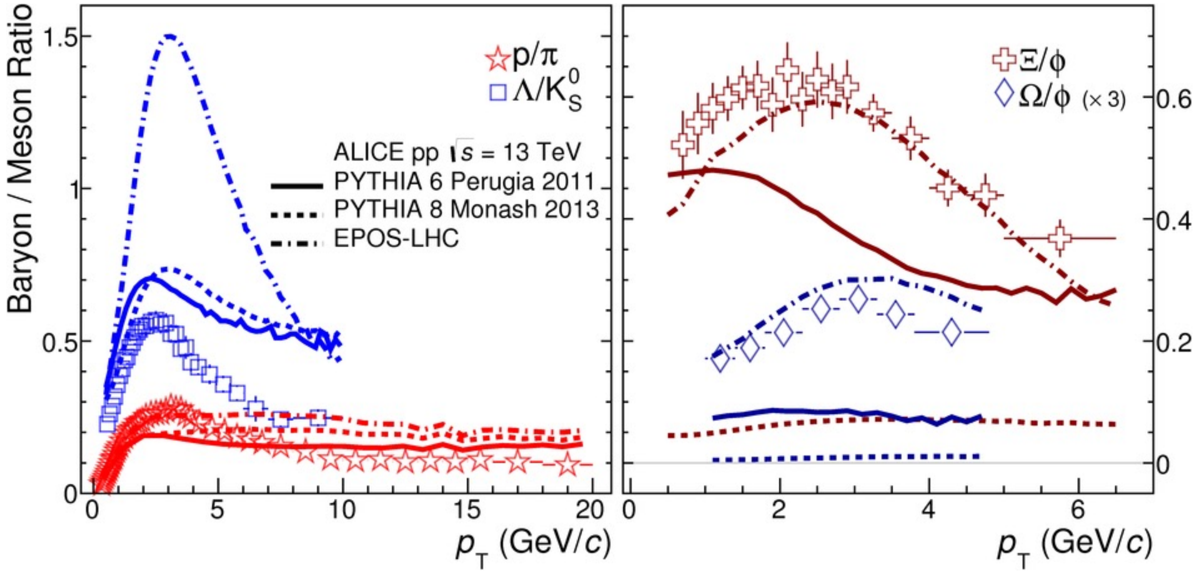
Final-state products



Baryon hadronisation
Baryon-to-meson ratios…

Modelling baryons is difficult due to their colour topology
- ➢ are not included in leading-colour approximations → interesting probes!

- p/π^0 (|S|=0)
  - models are flatter than data
- Λ/K^0_S (|S|=1)
  - EPOS LHC off
  - PYTHIA overestimates data by factor 3
- Ξ/ϕ (|S|=2) and Ω/ϕ (|S|=3, all s)
  - EPOS LHC good
  - PYTHIA off



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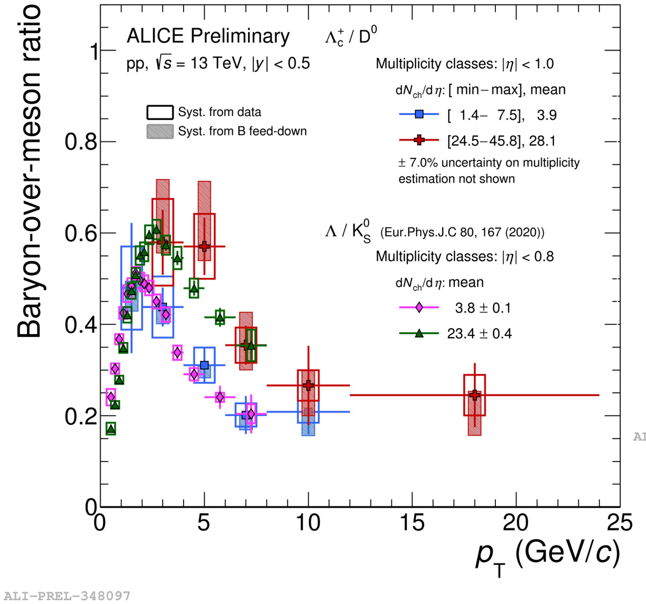
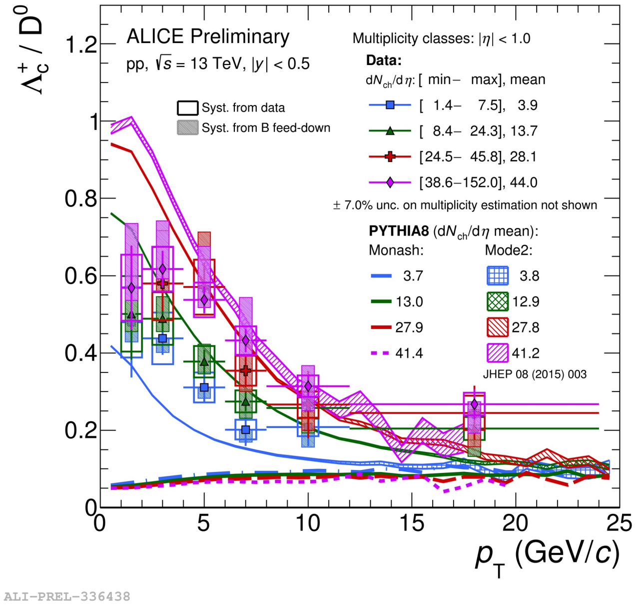
Same trend for Λ_C/D^0 (|C|=1)

- ○ is mid-p_T enhancement a baryon/meson feature?
- ○ PYTHIA Mode2 (QCD-CR) works for Λ_C/D^0…





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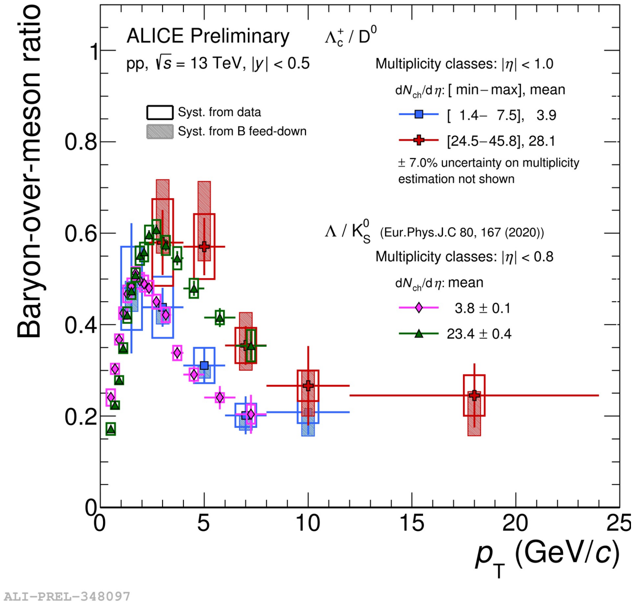
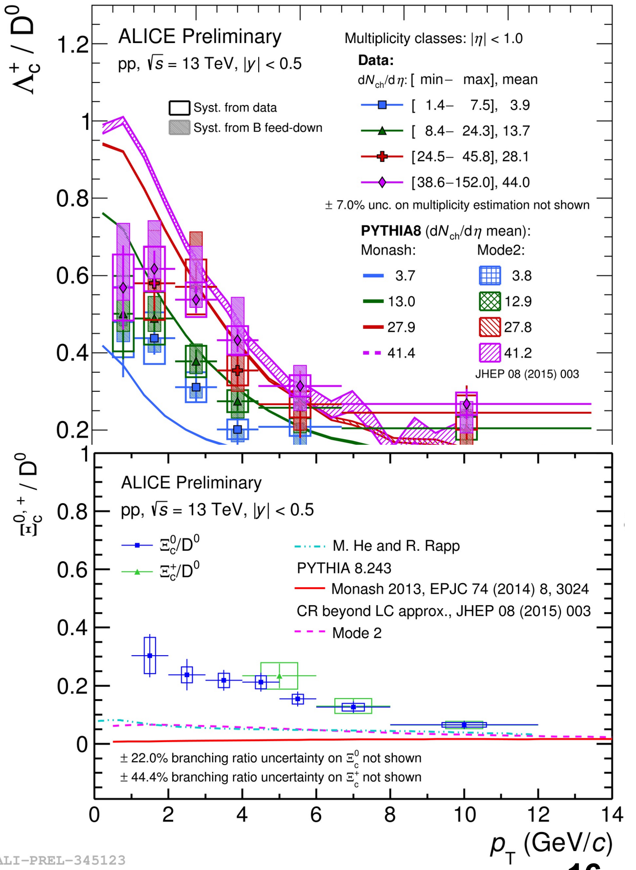
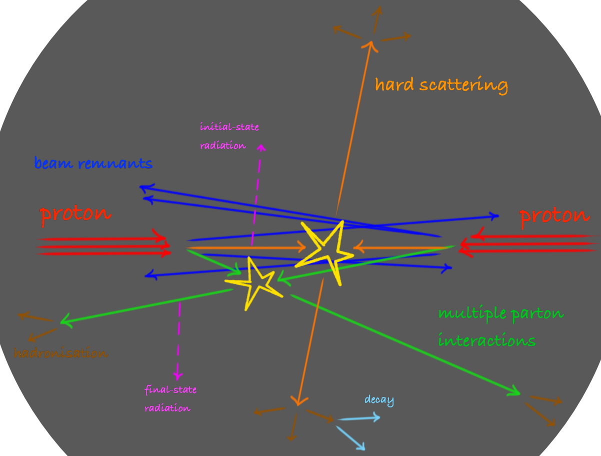
- ○ …but not for Ξ_C/D^0!



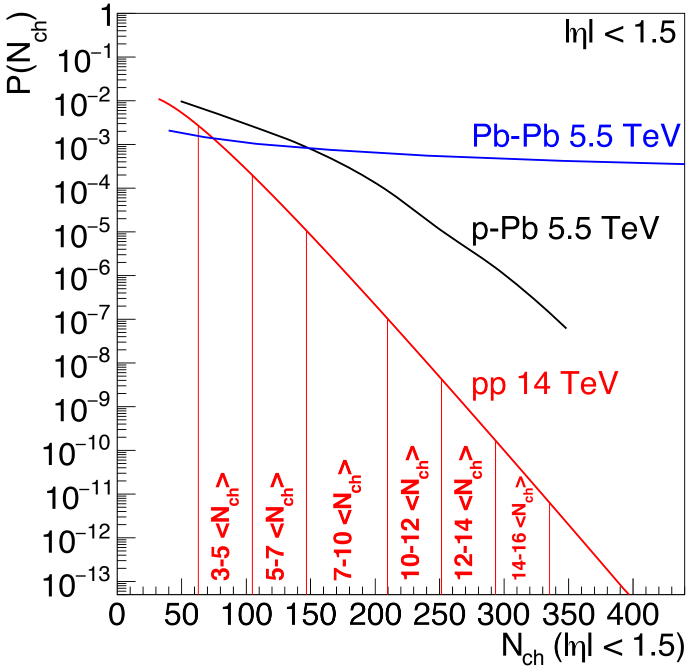


Towards precision era



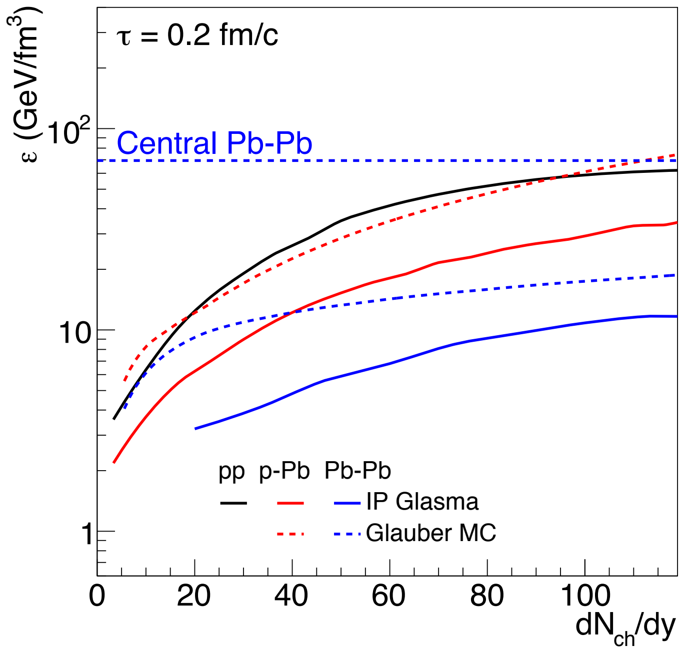
Yields as a function of multiplicity
Why is multiplicity so important?

Multiplicity



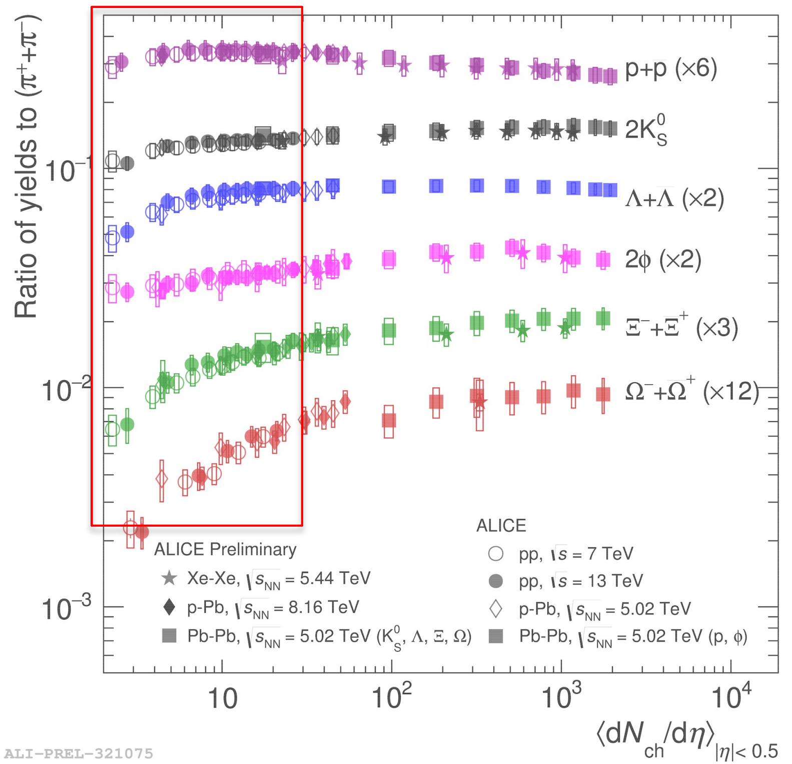
$$\epsilon = \frac{1}{A\tau}\langle E\rangle\frac{3}{2}\frac{dN_{ch}}{dy}$$

Energy density



Yields as a function of multiplicity
Strangeness enhancement

- In pp, the production of strange hadrons is suppressed relative to hadrons containing only light quarks due to quark s mass



Yields as a function of multiplicity
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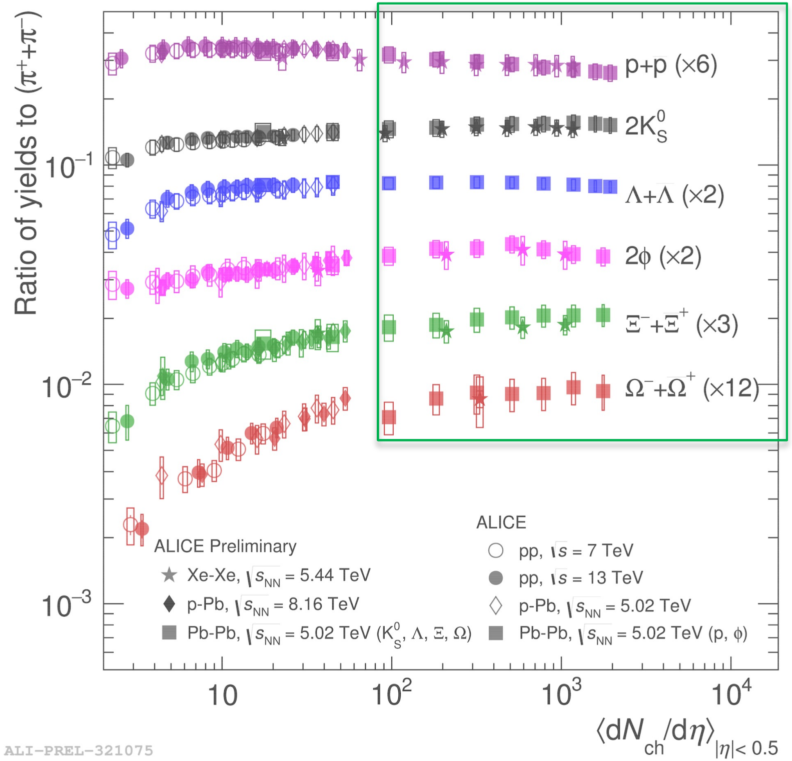


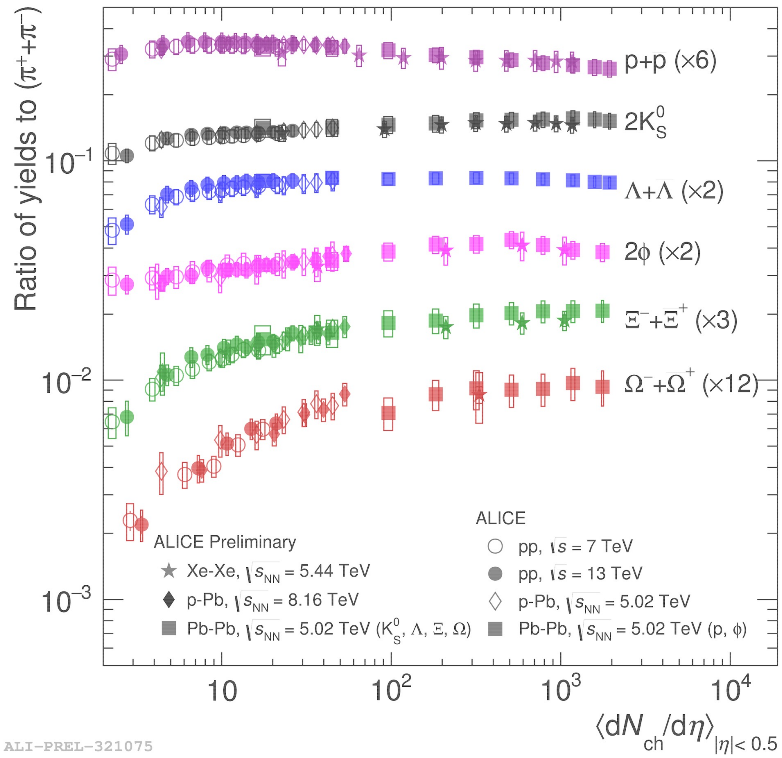
Yields as a function of multiplicity

Strangeness enhancement

- In pp, the production of strange hadrons is suppressed relative to hadrons containing only light quarks due to quark s mass

- In AA, particle ratios are described by a grand-canonical approach within the statistical hadronsation model

➢ What is the microscopic mechanism that explains strangeness enhancement?



Yields as a function of multiplicity

Heavy-flavour and high-p_T particle production

Non-linear heavy-flavour and high-p_T particle production increase with multiplicity

- effect of multiplicity saturation?
- interplay between multiplicity fluctuations of individual parton interactions and decrease of MPI?

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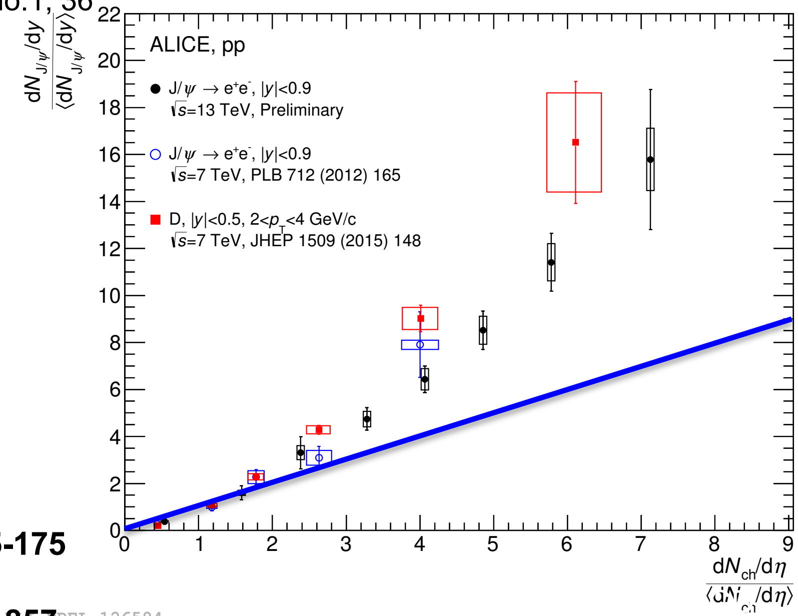

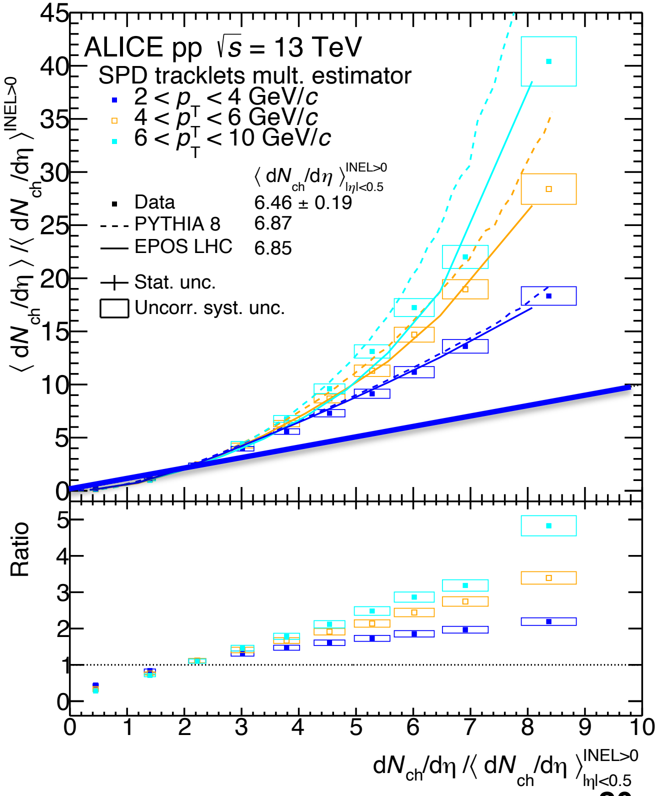

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Phys.Lett. B712 (2012) 165-175
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Eur.Phys.J.C 79 (2019) 10, 857

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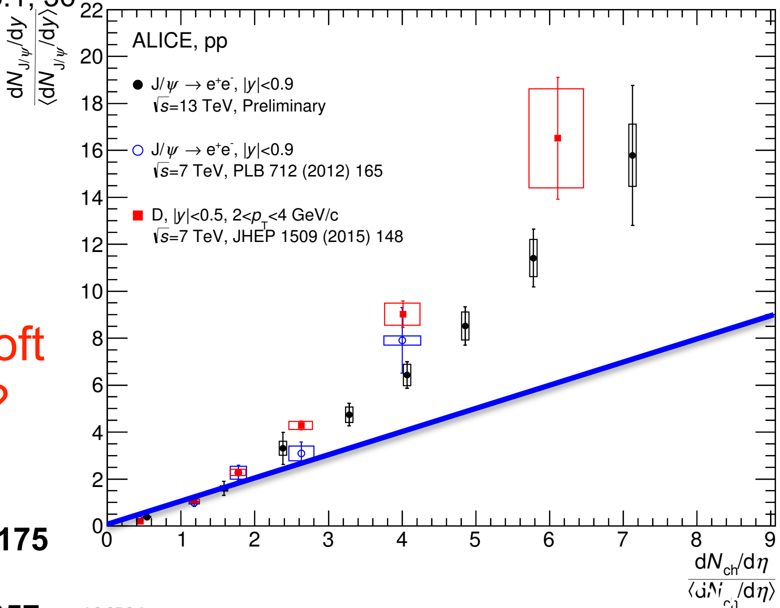
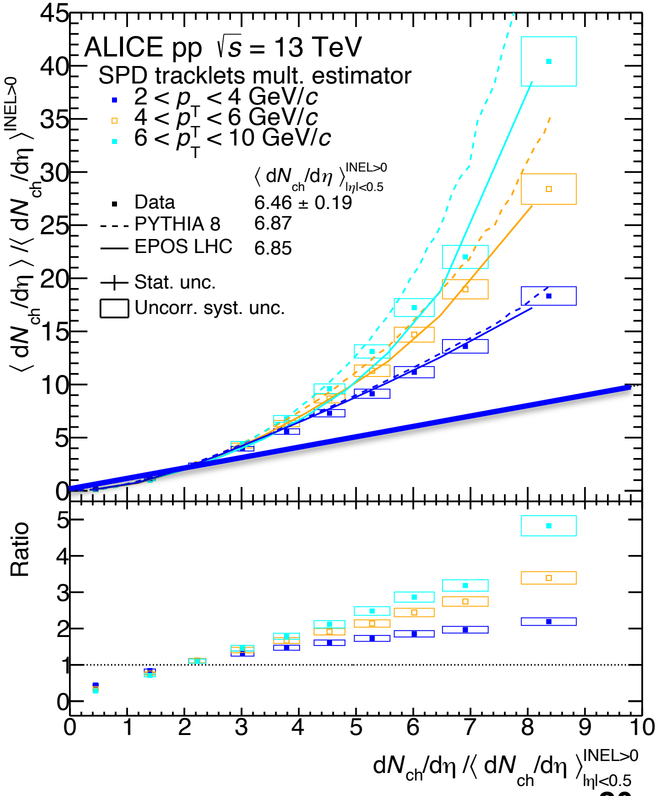
➢ Could a **jet free multiplicity estimator** help to understand soft QCD dynamics?





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A jet–free multiplicity estimator

What is R_T?

We look for a variable that

1. is not influenced by the initial hard parton scattering
2. can discriminate among soft and hard events

A jet–free multiplicity estimator

What is R_T?

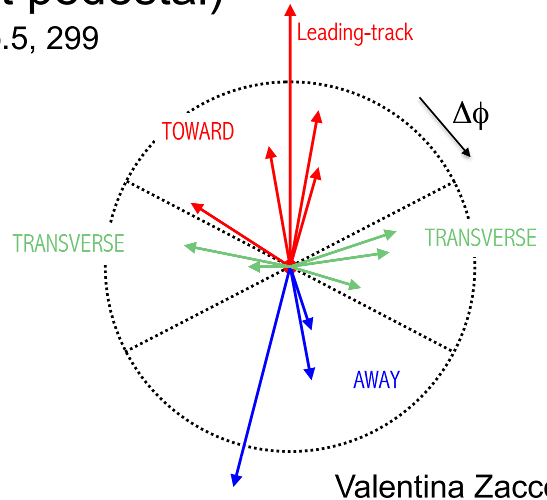
We look for a variable that

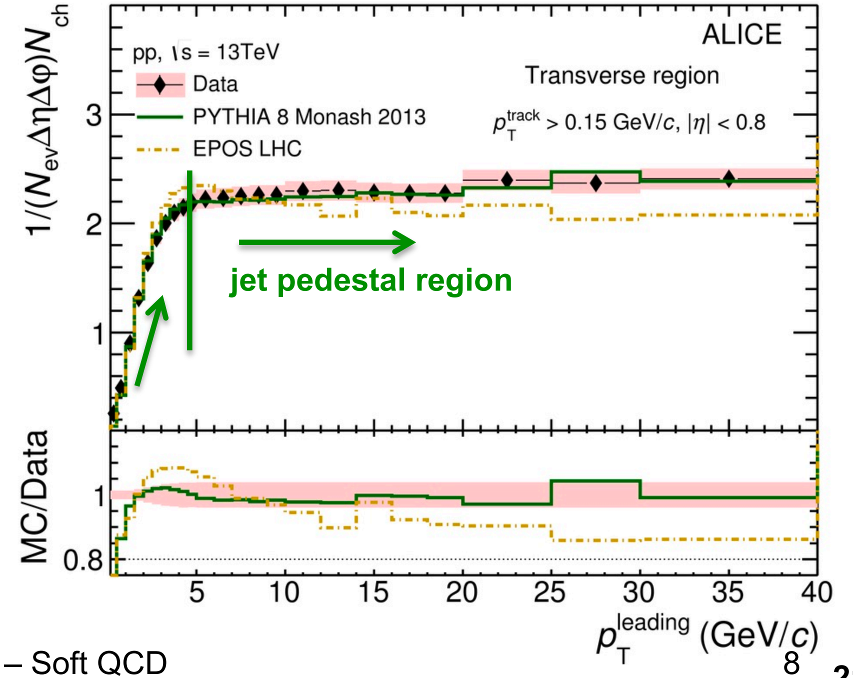
1. is not influenced by the initial hard parton scattering
2. can discriminate among soft and hard events

➢ define the relative transverse activity classifier R_T in the plateau region (jet pedestal)

Eur.Phys.J. C76 (2016) no.5, 299

$$R_T = \frac{N_{inclusive}}{\langle N_{inclusive} \rangle}$$





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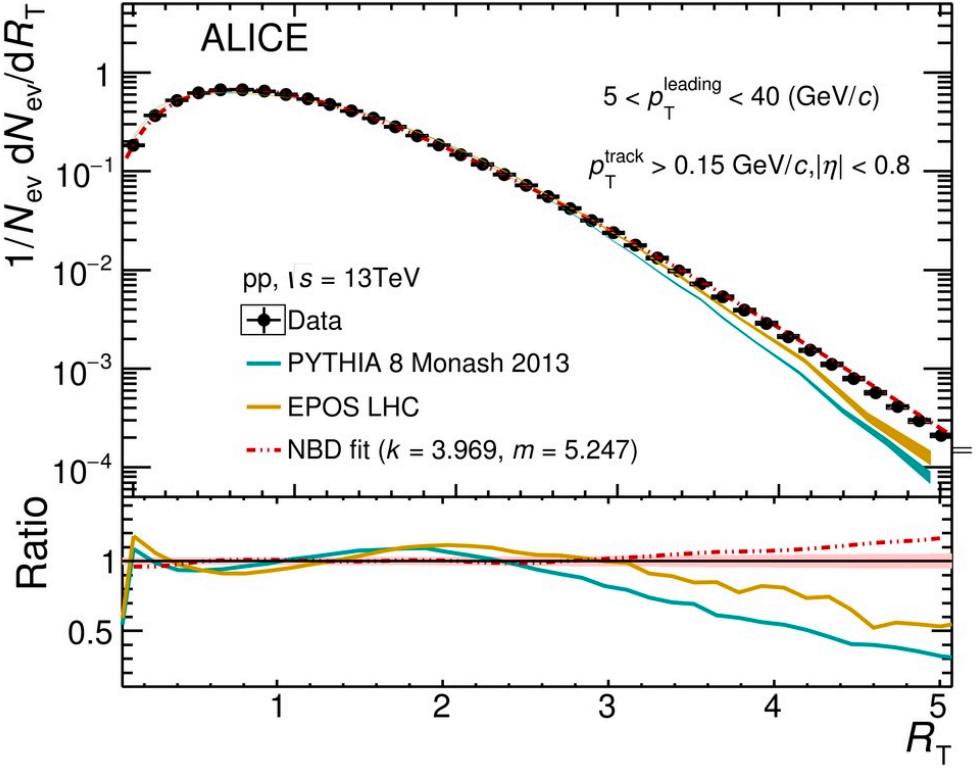
A jet–free multiplicity estimator
R_T distribution

Selection done in:

- transverse multiplicity
- plateau region $5 < p_T^{\text{leading}} < 40$ GeV/c



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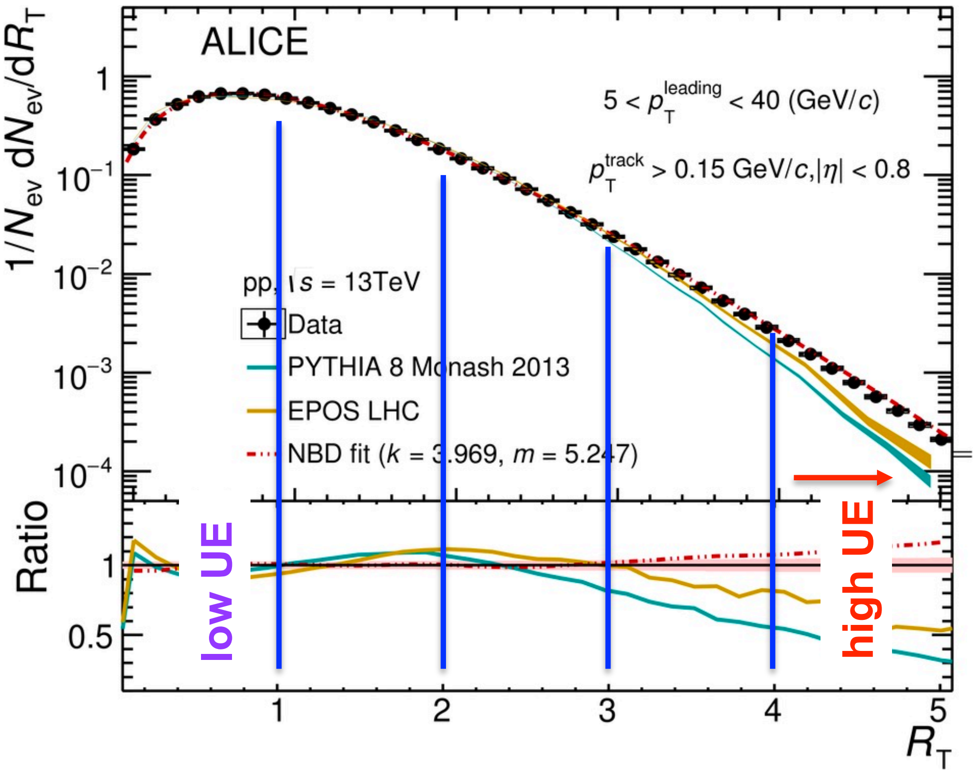
JHEP 04 (2020) 192

A jet–free multiplicity estimator
R_T distribution

Selection done in:

- transverse multiplicity
- plateau region $5 < p_T^{leading} < 40$ GeV/c
- several R_T bins to allow to distinguish among low and high UE activity



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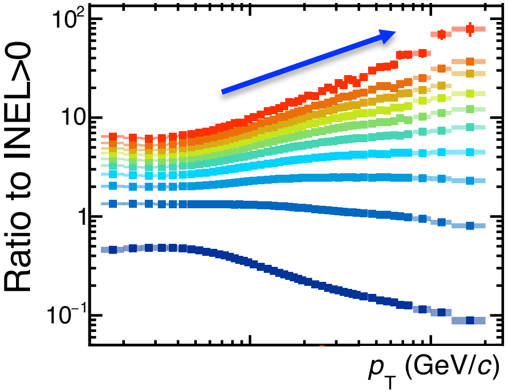
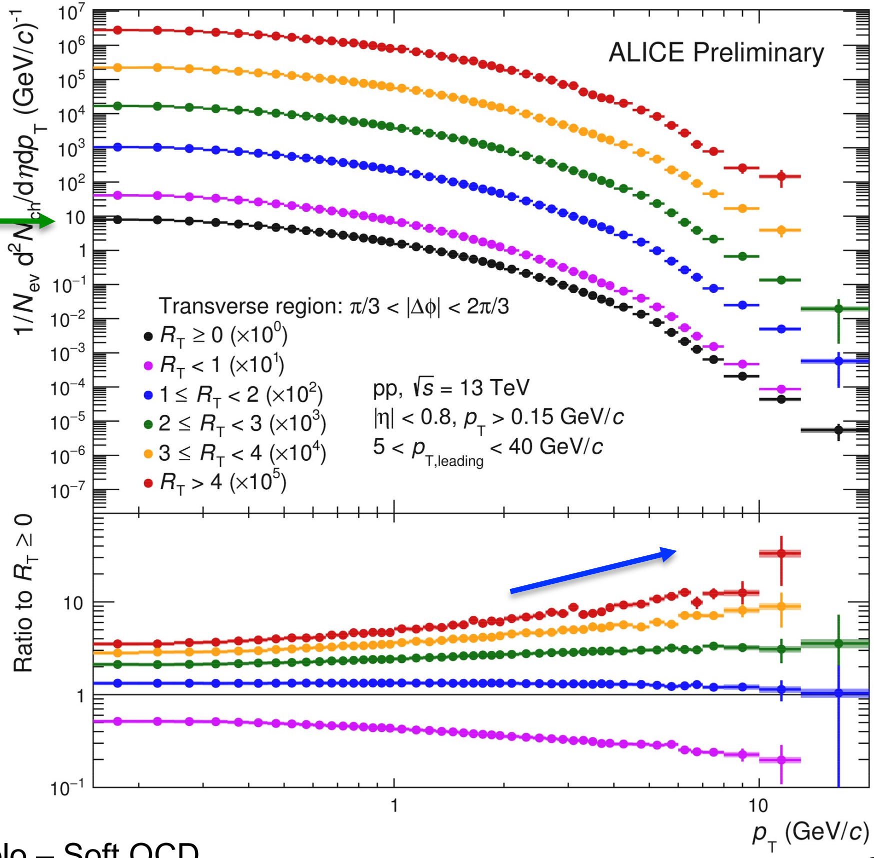
JHEP 04 (2020) 192

Transverse p_T distributions

Comparison to inclusive transverse spectra

- clear p_T hardening at high multiplicity in the transverse region → same trend observed for the midrapidity-based multiplicity estimator





Transverse p_T distributions

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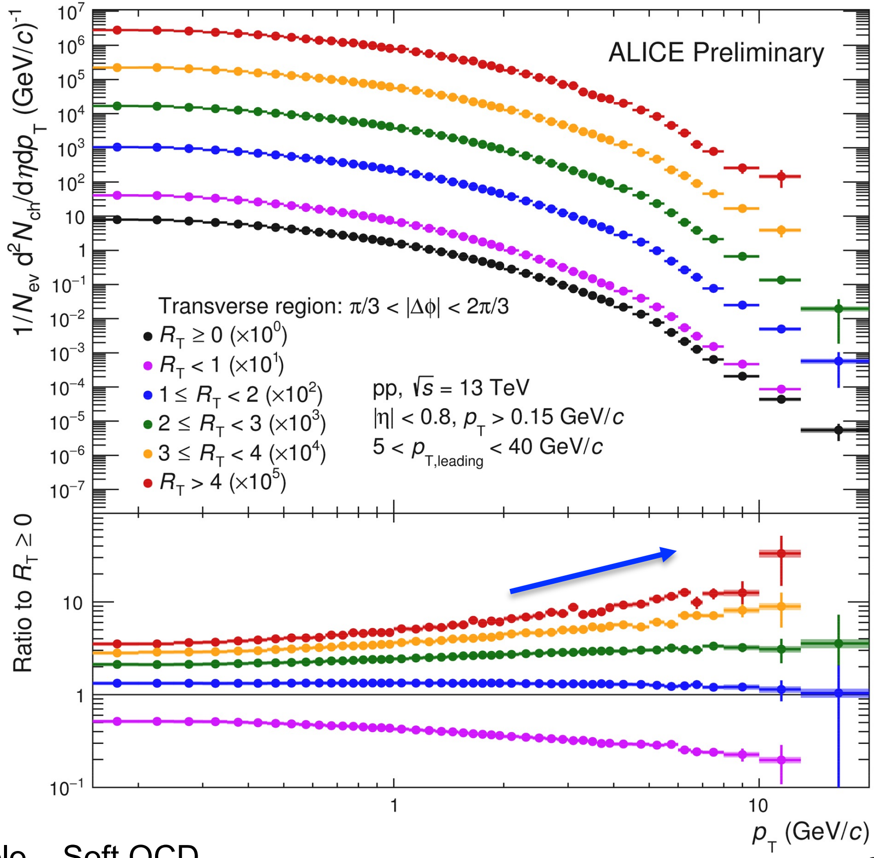
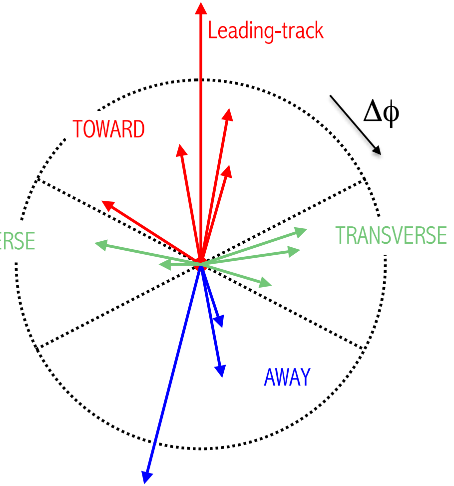
- measurement (p_T) and selection (multiplicity) are done in the same pseudorapidity region

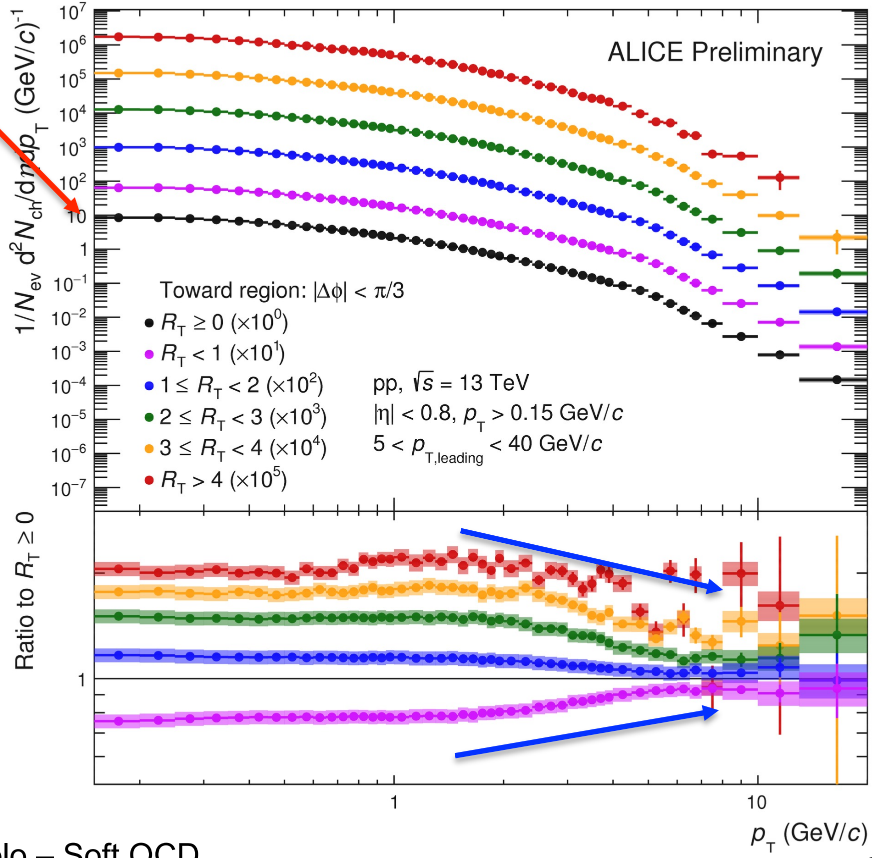


Toward p_T distributions

Comparison to inclusive toward spectra

- If the multiplicity is determined in the transverse region, the spectra in the toward (jet) region clearly show the opposite trend

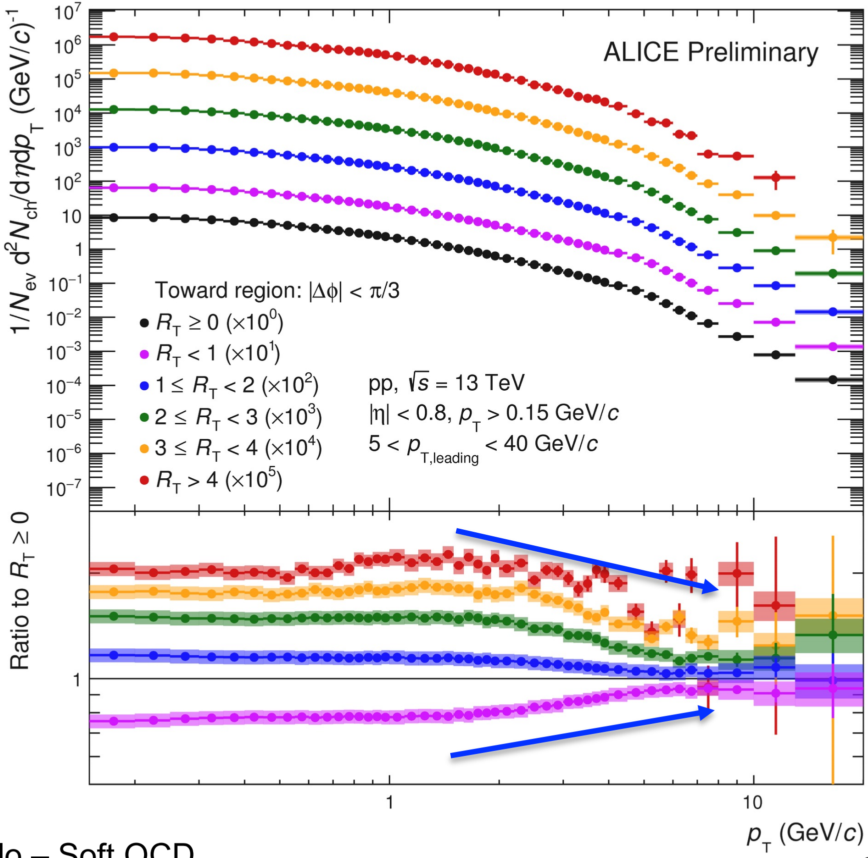




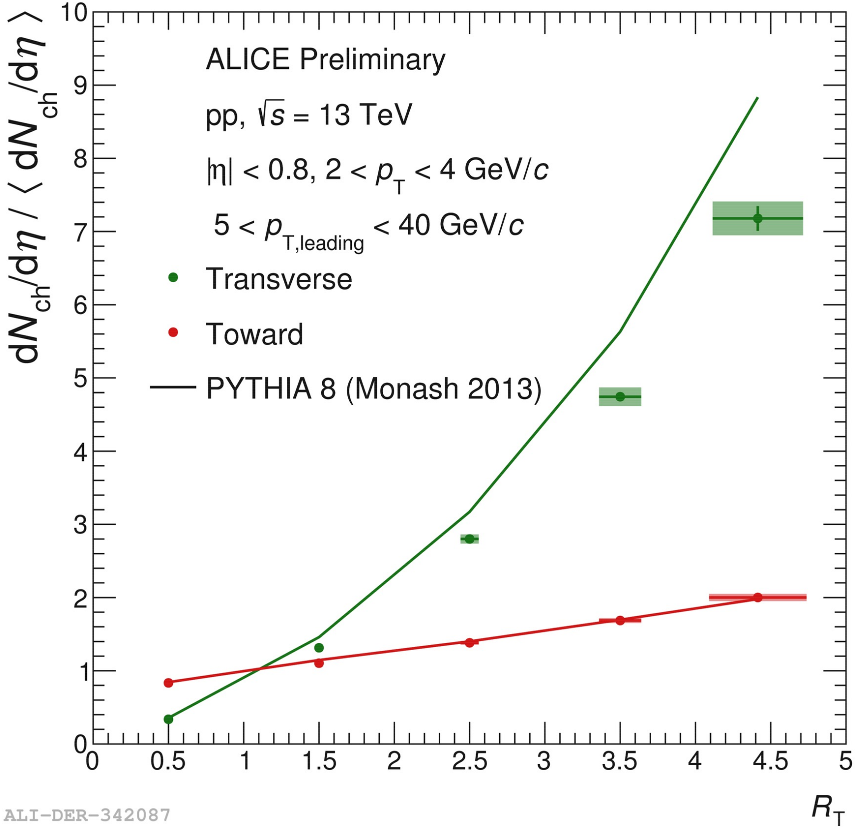
Toward p_T distributions

Comparison to inclusive toward spectra

- If the multiplicity is determined in the transverse region, the spectra in the toward (jet) region clearly show the opposite trend
- we observe convergence to the jet:
  - complete separation among soft (UE) and hard (jet) part of the event at high p_T
  - correlation effects are significantly reduced

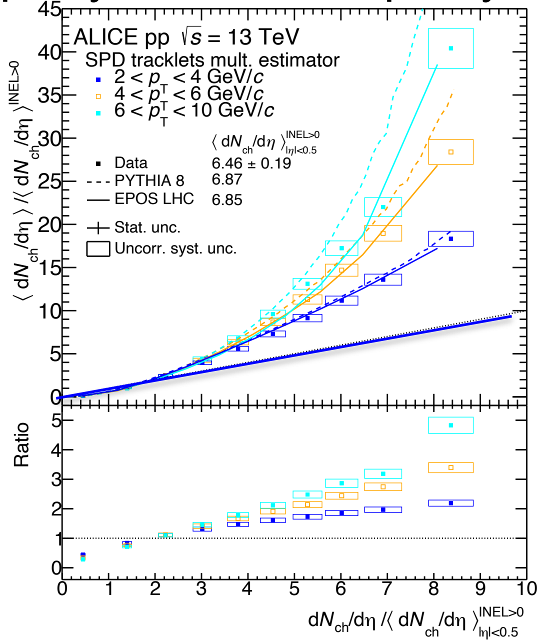


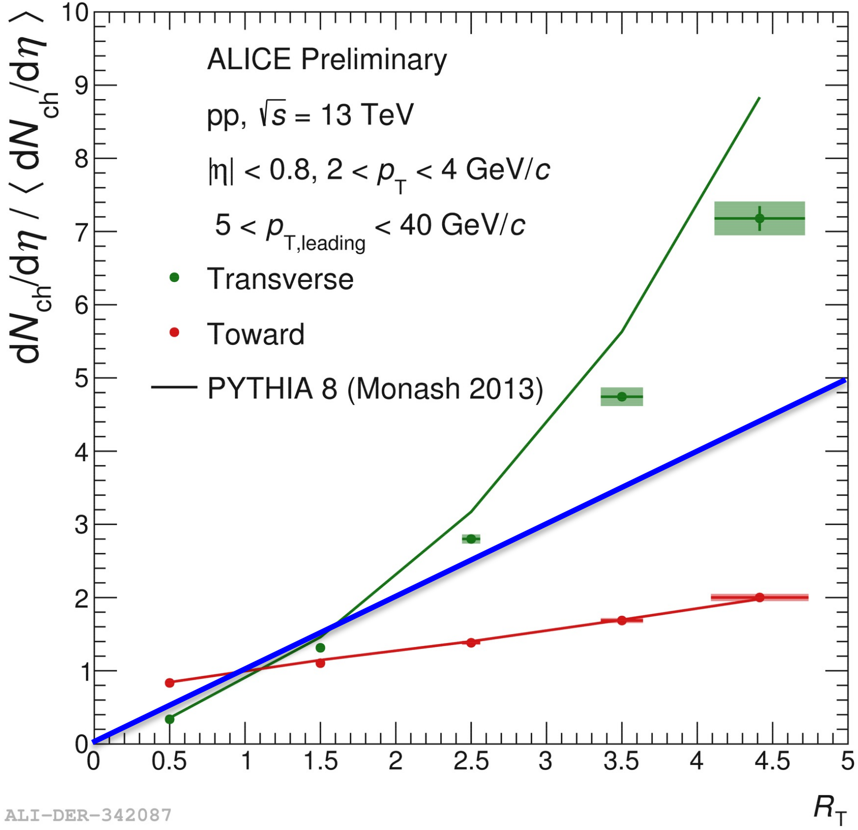
R_T dependence for transverse and toward



R_T dependence for transverse and toward

- yield in transverse vs R_T
  same behavior observed using the midrapidity–based multiplicity estimator





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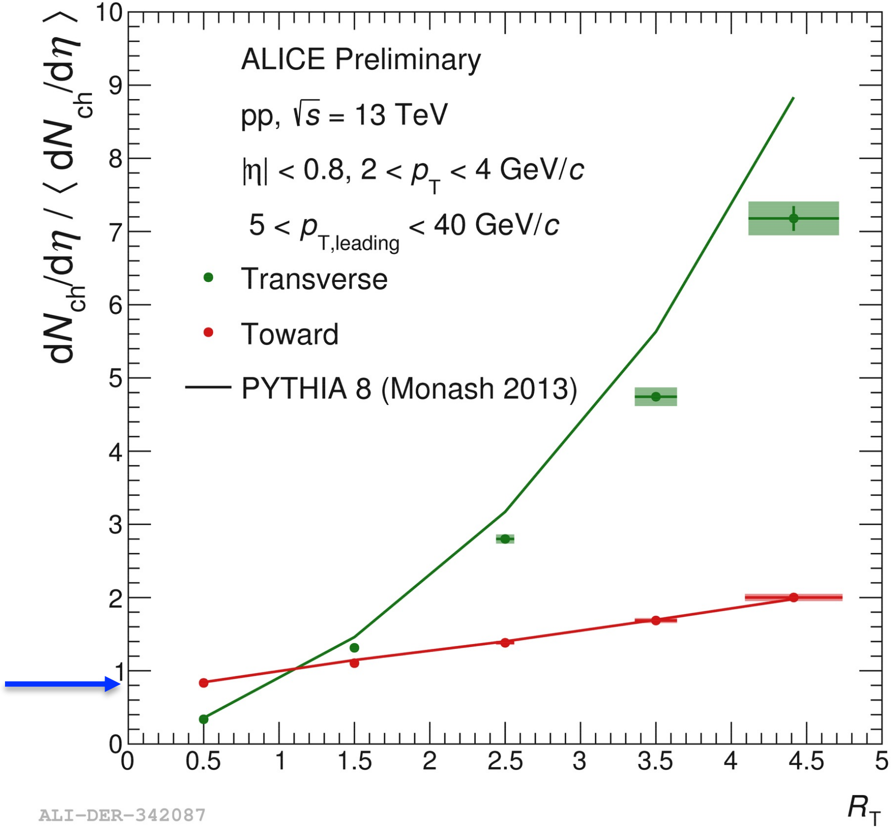
R_T dependence for transverse and toward

- yield in toward vs R_T
  - does not converge to 0
    → at R_T = 0 we can have a jet
    → possibility to study hard object with almost no UE activity!



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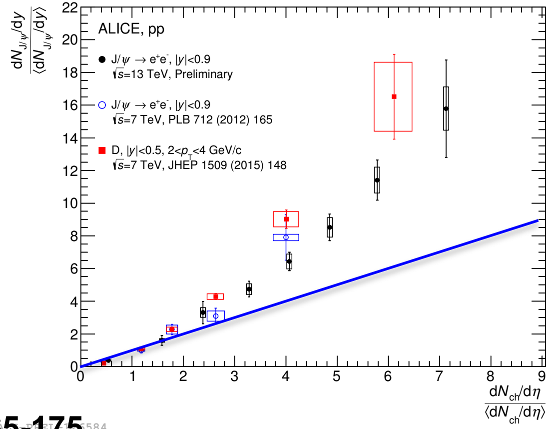
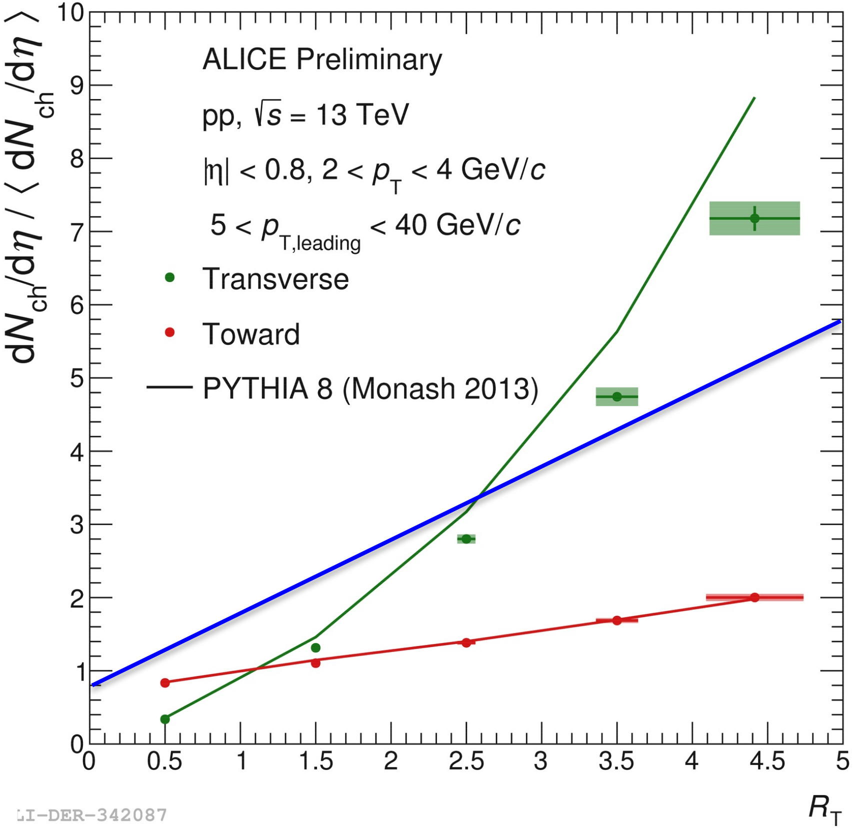
    → not the same as heavy flavours!





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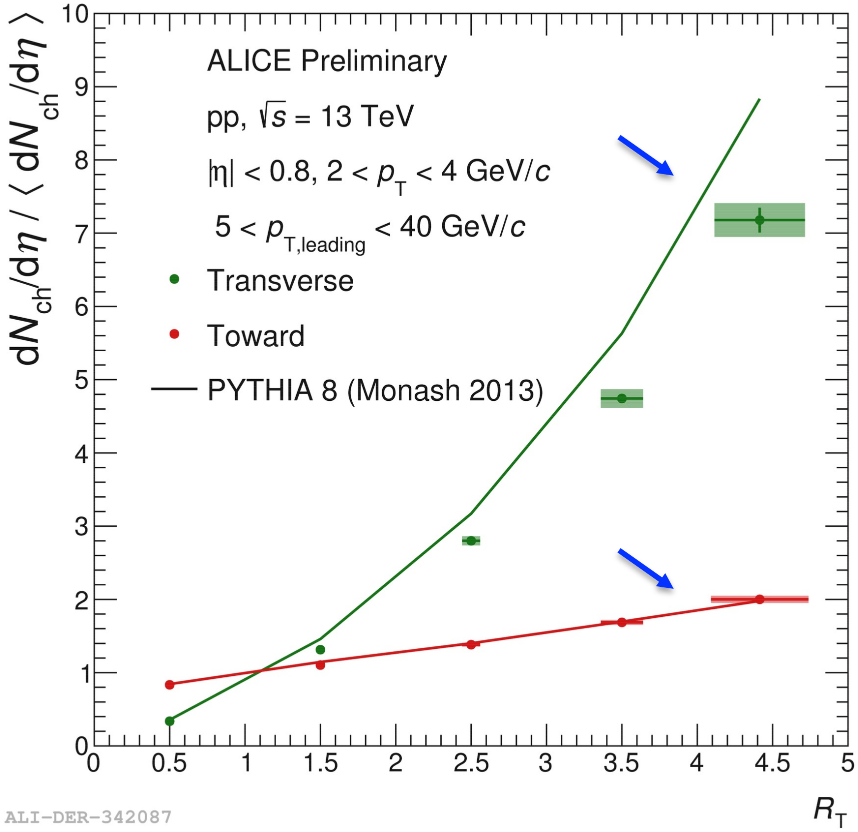
  - it is linear
    → not the same as heavy flavours!
  - PYTHIA 8.2 reproduces well the observed trends

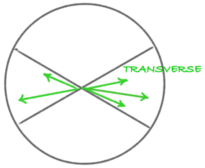


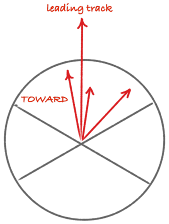
Yields as a function of the UE activity
Strangeness enhancement

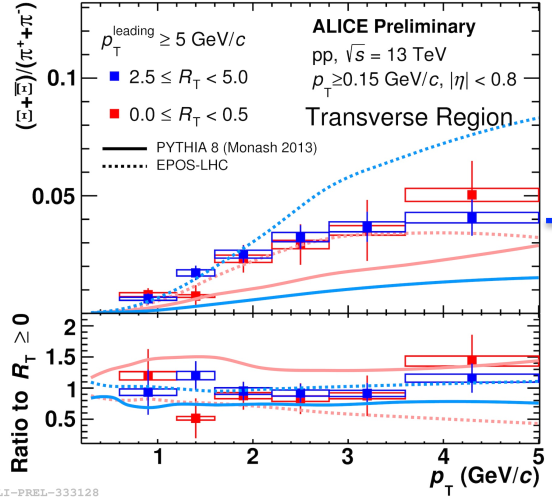
Particle production vs R_T

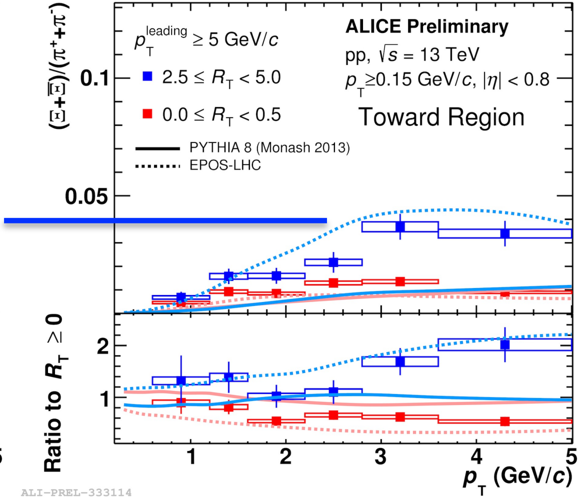
$$R_T = \frac{N_{ch}^{transverse}}{\langle N_{ch}^{transverse} \rangle}$$

- transverse
  - no enhancement
- toward
  - enhancement
  - for high R_T values → same ratio yields as transverse









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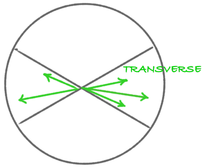
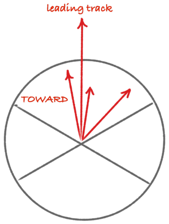
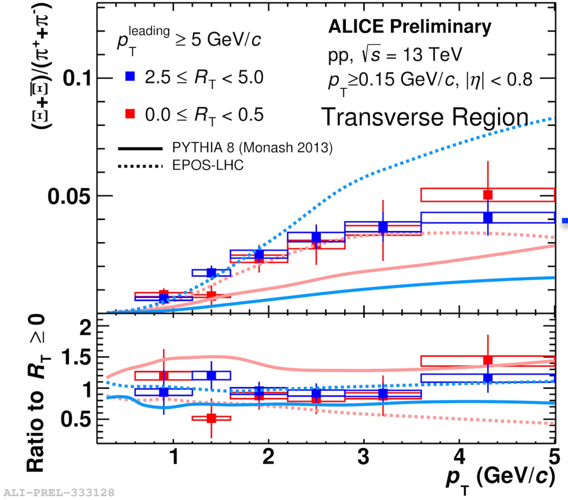
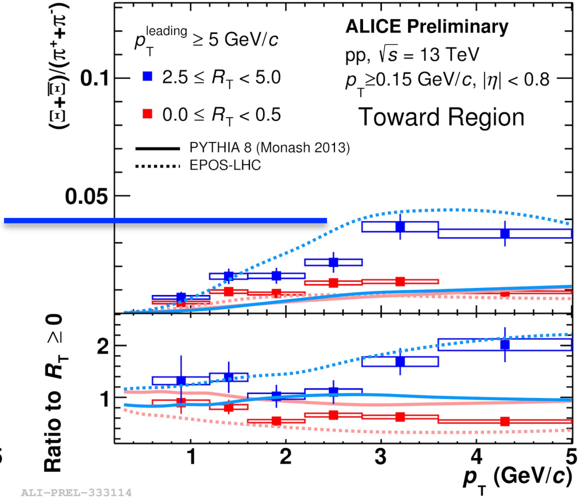
➢ Strangeness enhacement observed in
- jet+UE
- high UE activity









Yields as a function of the UE activity

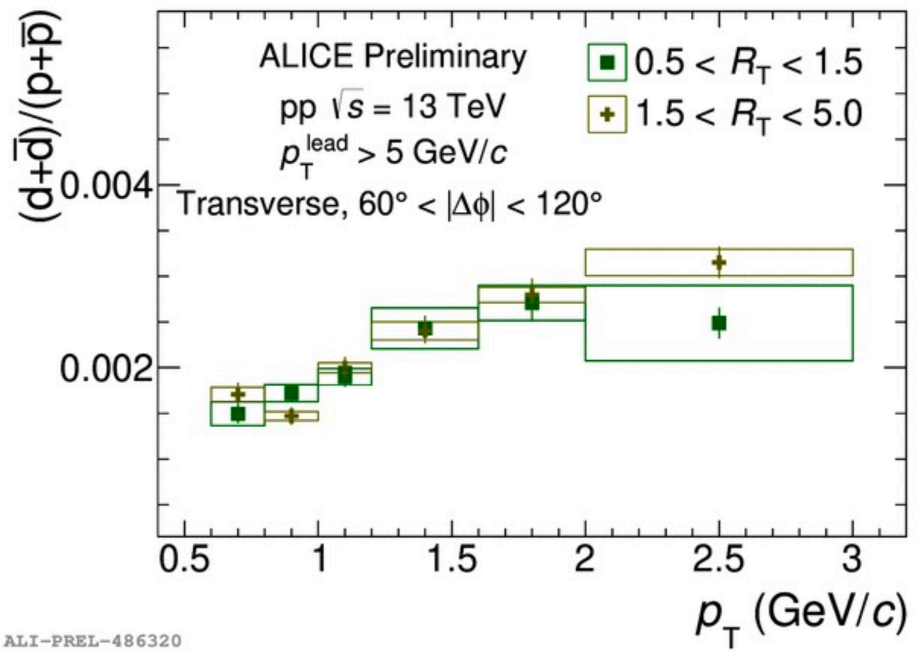
Deuteron production

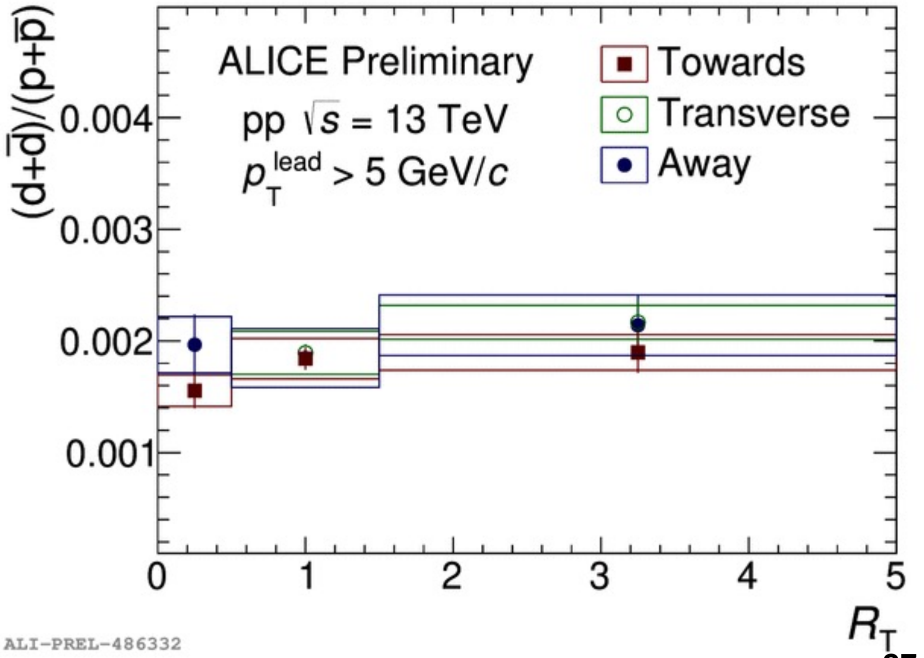
Particle production vs R_T

$$R_T = \frac{N_{ch}^{transverse}}{\langle N_{ch}^{transverse} \rangle}$$

d/p:

- no dependence on R_T





Yields as a function of the UE activity

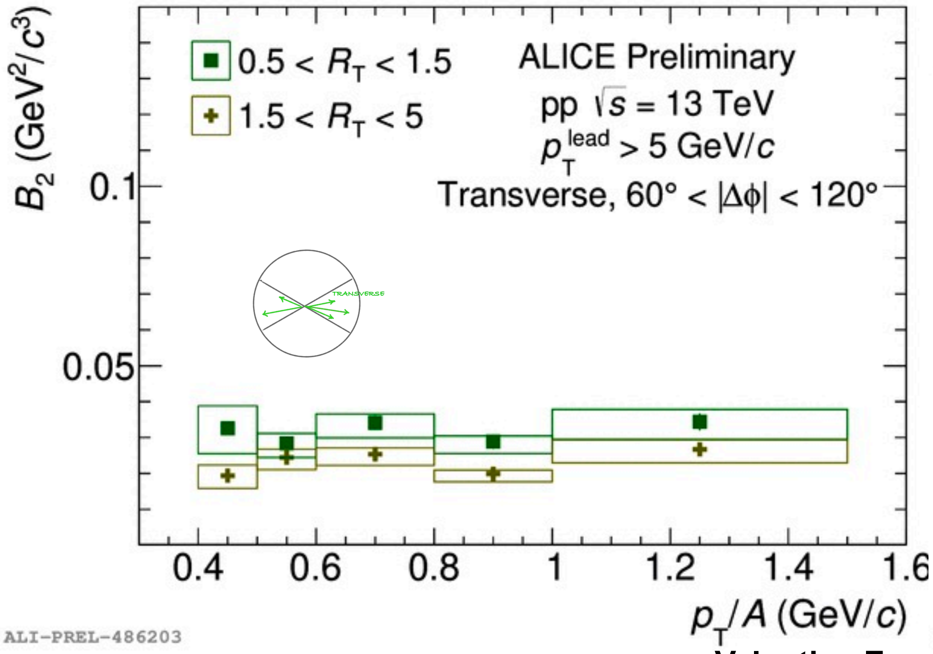
Deuteron production

Particle production vs R_T

$$R_T = \frac{N_{ch}^{transverse}}{\langle N_{ch}^{transverse} \rangle}$$

Coalescence parameter from → $E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A \Bigg|_{\vec{p}_p = \vec{p}_A / A}$

- flat vs p_T/ for all azimuthal regions



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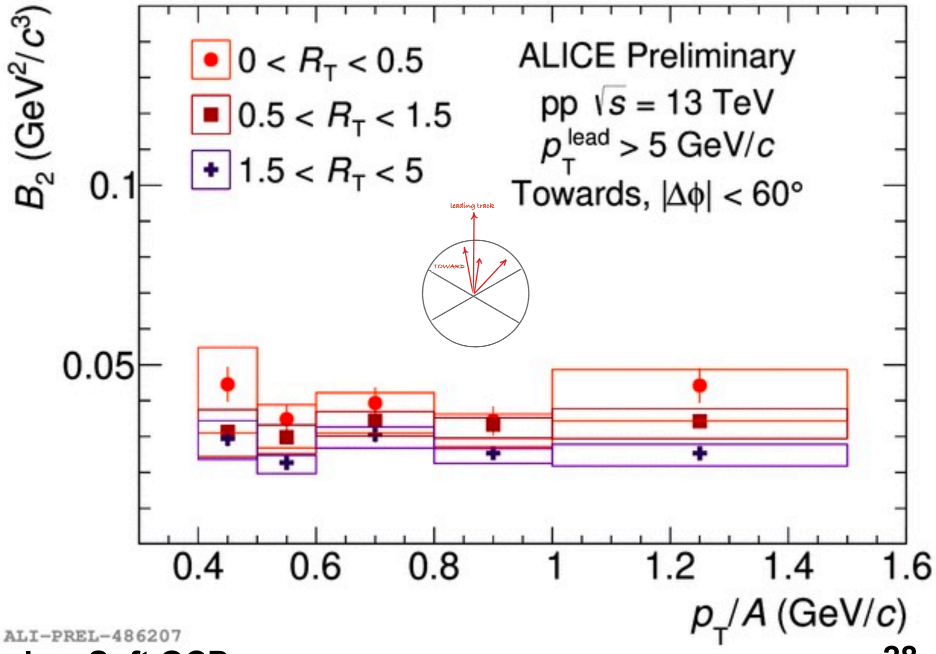

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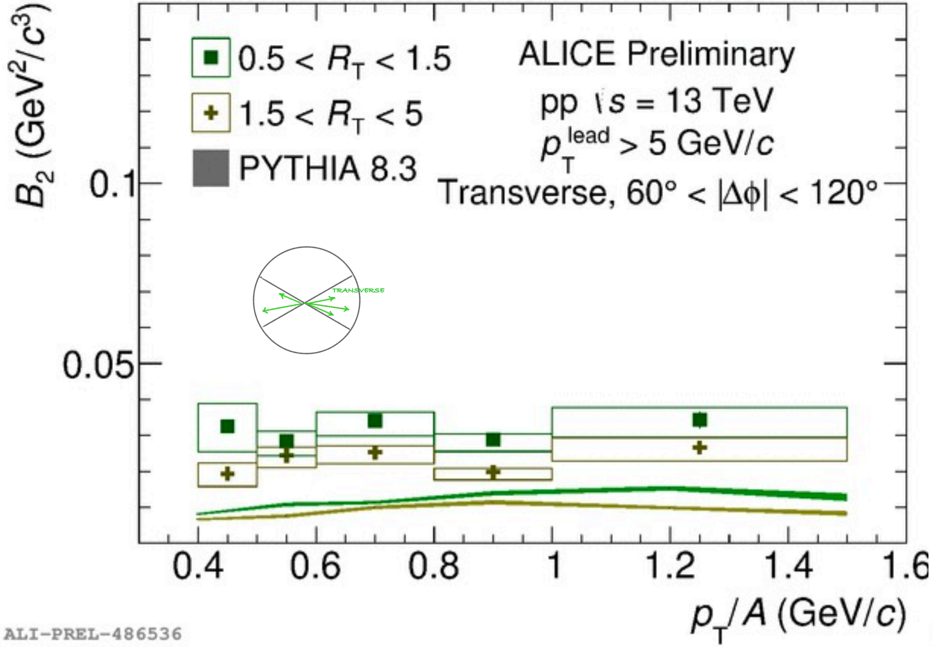
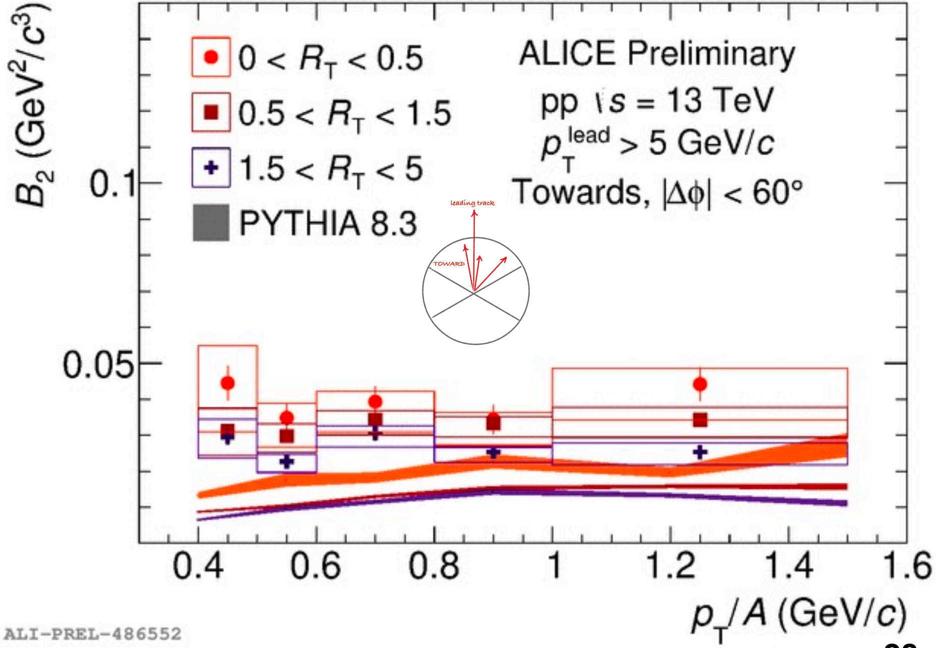
- flat vs p_T/ for all azimuthal regions
- Pythia 8.3 with d production via coalescence and reactions underestimates it



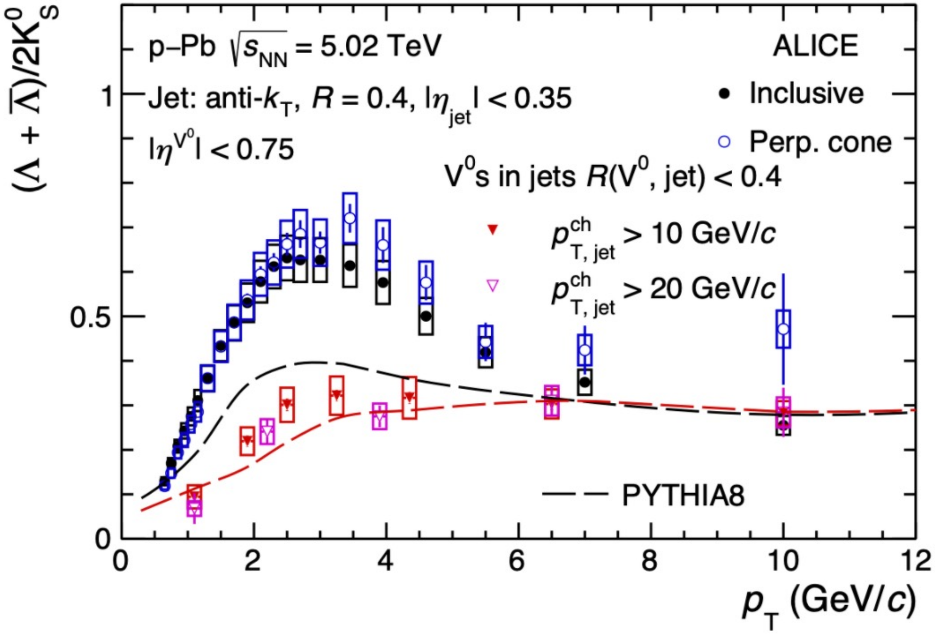


New ideas


hard scattering
initial-state radiation
beam remnants
proton
proton
multiple parton interactions
hadronisation
final-state radiation
decay

Why looking for UE characterisation?

Production of strange baryons (Λ) and mesons (K^0_s) is reported inside jets and in the event portion perpendicular to a jet (low energy processes)



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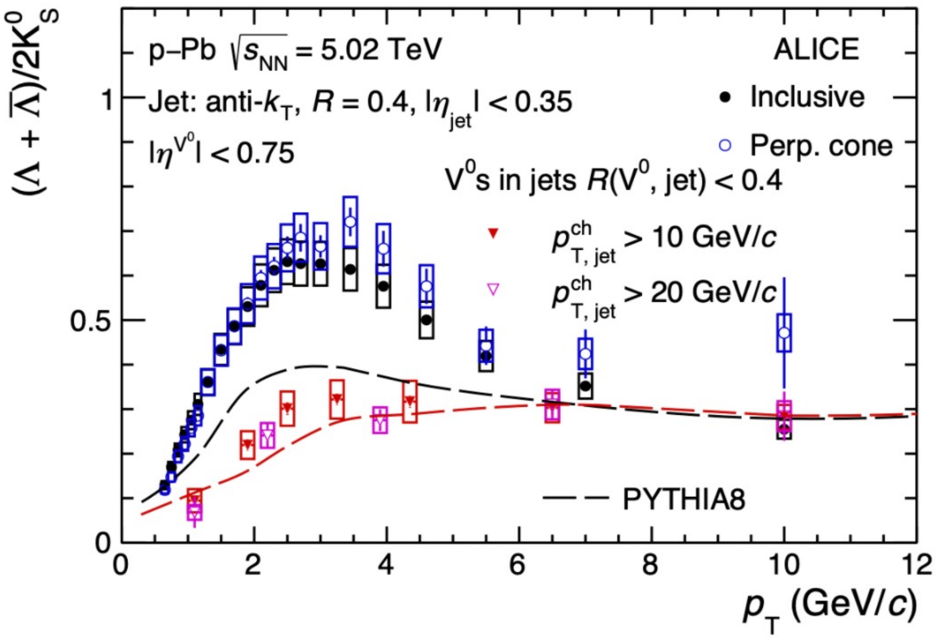
e-Print: 2105.04890 [nucl-ex]

Why looking for UE characterisation?

Production of strange baryons (Λ) and mesons (K^0_s) is reported inside jets and in the event portion perpendicular to a jet (low energy processes)

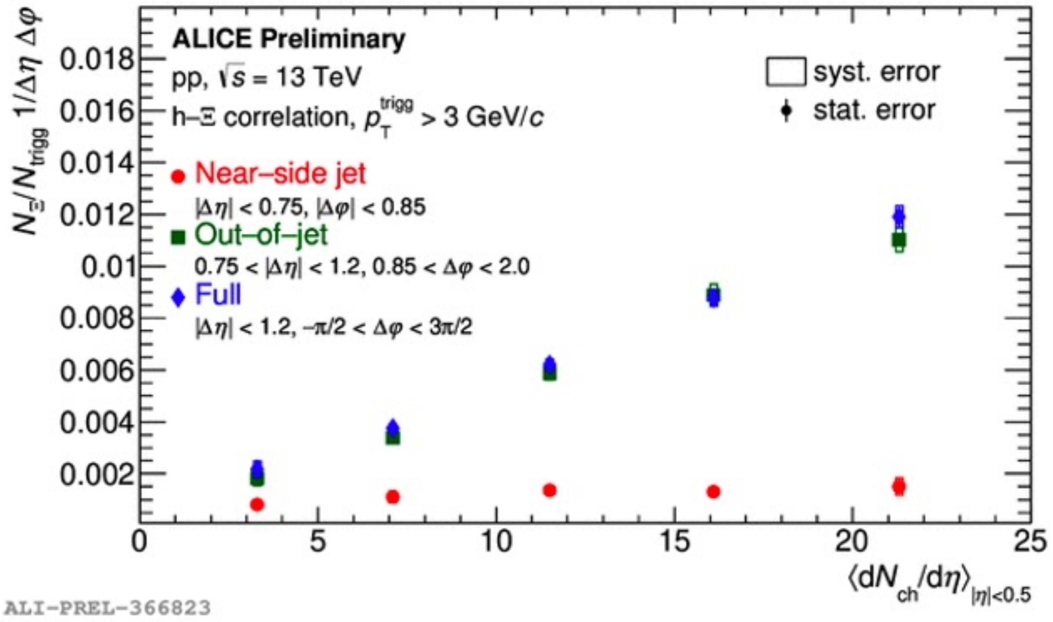
→ the particles away from jets show a large baryon-over-meson increase.

→ modelling the baryon-over-meson has important constraint: the absence of the jet!



Why looking for UE characterisation?

Enhancement of strange baryon Ξ happens outside the energetic jet

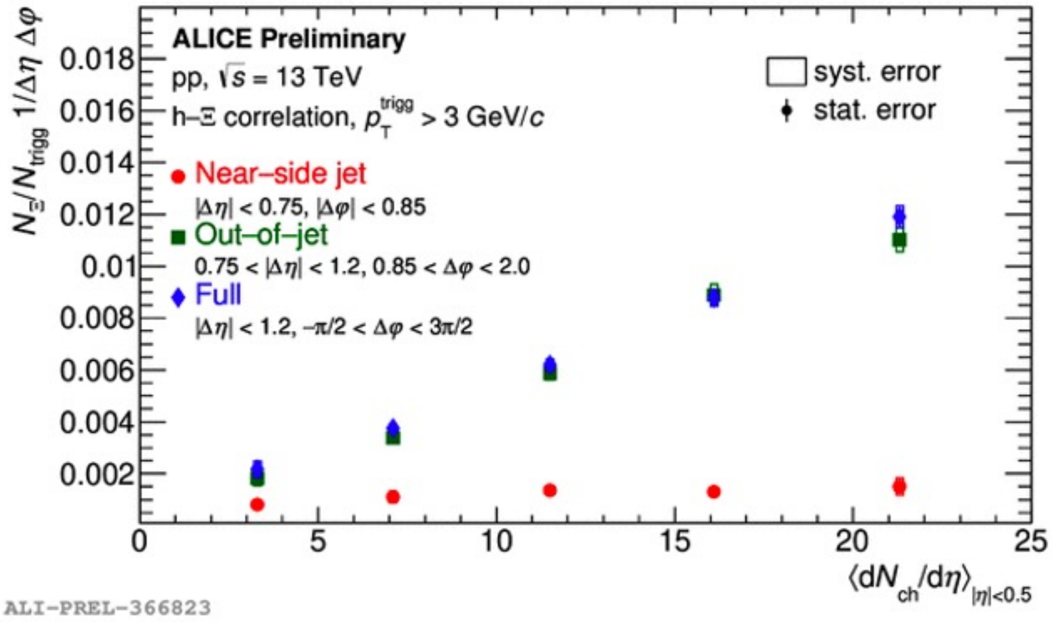


Why looking for UE characterisation?

Enhancement of strange baryon Ξ happens outside the energetic jet

→ strange particles away from jets show large strangeness enhacement

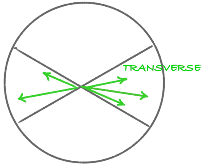
→ the absence of the jet is the important part to study!



Relative transverse activity classifier: what next?

The relative transverse activity classifier probes the softer region of the event: the transverse one with respect to the leading track in the UE plateau

$$R_T = \frac{N_{ch}^{transverse}}{\langle N_{ch}^{transverse} \rangle}$$



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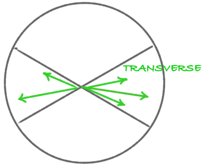
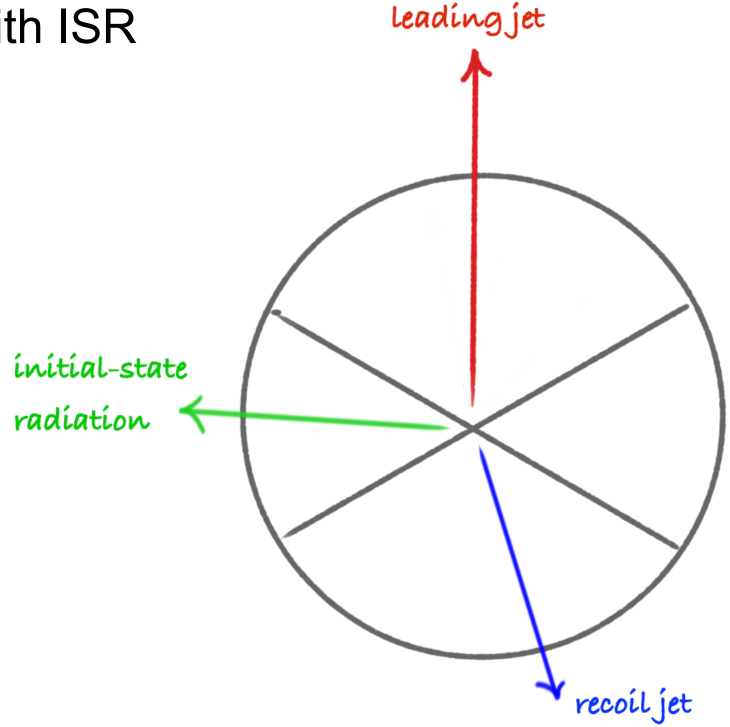


However, the R_T classifier still contains I/FSR and MPI

→ normally described in general purpose MC using pQCD extrapolated to low momentum transfer

A closer look at topologies

3-jet topology
with ISR



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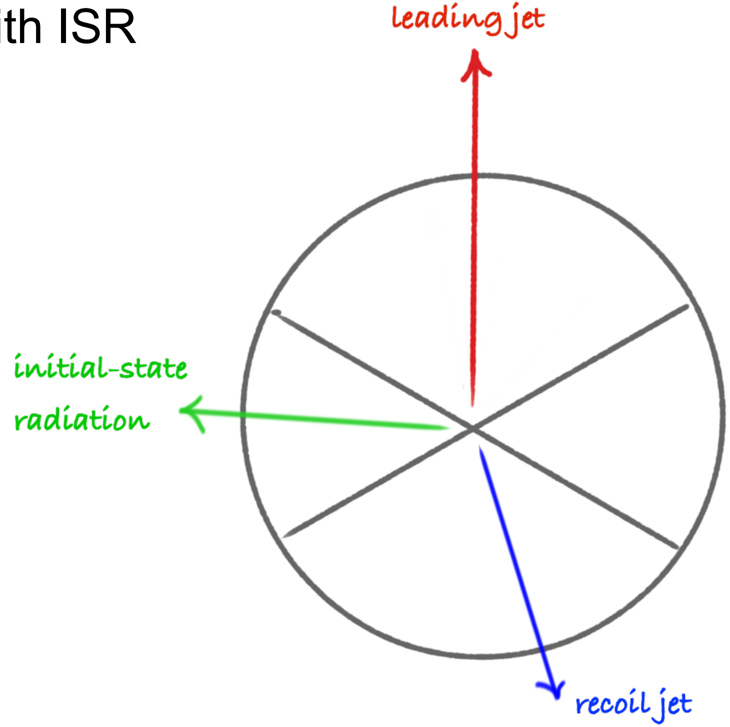
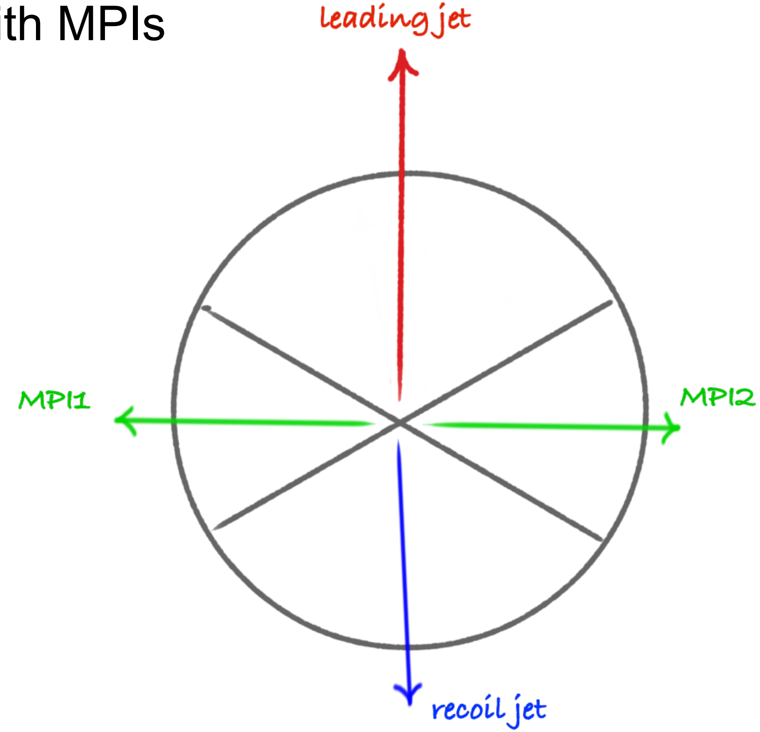


4-jet topology
with MPIs



Soft classifiers?

Jets and mini-jets can be removed to create a soft transverse activity classifier

A possible technique is to select track clusters formed by

- one track with p_T > 0.7 GeV/c
- at least one associated track with p_T > 0.4 GeV/c in a cone radius $\sqrt{\Delta\eta^2 + \Delta\varphi^2} = 0.7$
- in the transverse region with respect to $p_T^{leading}$

used by CDF to tag mini-jets Phys.Rev.D 65 (2002) 072005

These cones can be removed → R_T^{Soft} classifier

Other “clean” classifiers

1. Use Z boson as leading track → cleaner environment, no FSR

2. Resume uncorrelated seeds correlated to N_{MPI}

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

→ Many ways to move to precision era for soft-QCD hadronisation studies!

What happens after the experiment?

Experimental soft-QCD precision era craves soft-QCD precision modelling!

Between which partons confining potentials should be allowed to arise?
In the context of MPI, colour reconnections (CR) describe models that allow such potentials to form between partons produced in different MPI systems
(this affects dramatically the multiplicity, spectra, hadrons formed…)

What happens after the experiment?

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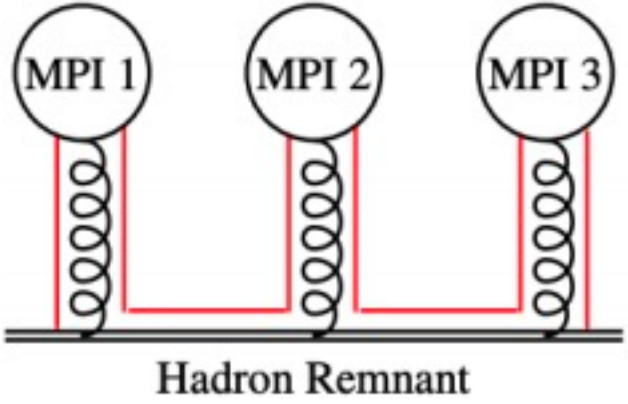
The default CR modeling in PYTHIA 8.3 is based on a simple measure of string-length minimisation

P. Skands, S. Carrazza, J. Rojo, Eur.Phys.J. C74 (2014) no.8, 3024

→ this model does not allow for changes to baryon/meson or strangeness ratios



What happens after the experiment?

Experimental soft-QCD precision era craves soft-QCD precision modelling!

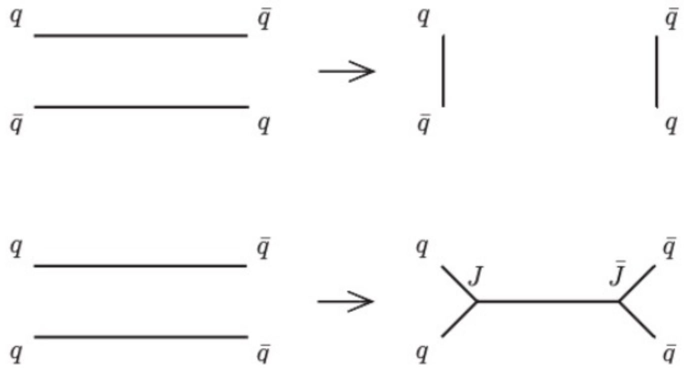
In the QCD-CR development

R. Christensen, P.Z. Skands, JHEP 1508 (2015) 003

CR are governed by a set of simplified QCD colour-algebra rules:

- uncorrelated colour-anticolour pairs have a chance to be in a colour singlet and to form a confining potential

→ The model then selects minimising the resulting string length



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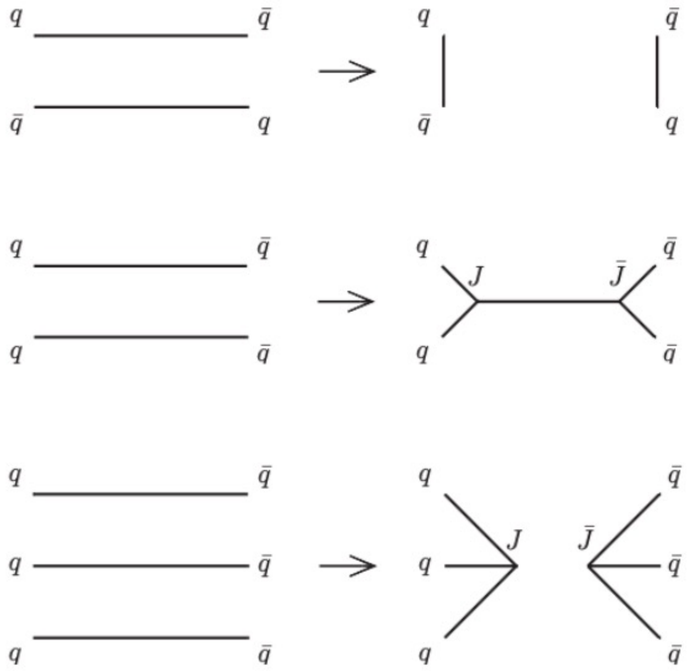
R. Christensen, P.Z. Skands, JHEP 1508 (2015) 003

CR are governed by a set of simplified QCD colour-algebra rules:

- uncorrelated colour-anticolour pairs have a chance to be in a colour singlet and to form a confining potential

→ The model then selects minimising the resulting string length

→ The QCD algebra also allows for three uncorrelated (anti-)triplets to form a singlet
- new source of (anti-)baryon production
- with the total baryon number still being conserved!



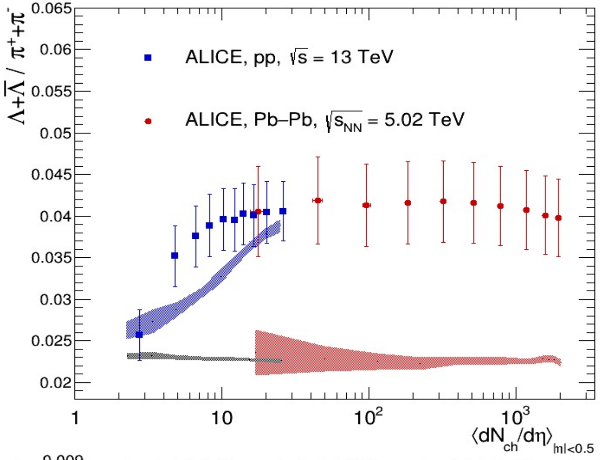
What happens after the experiment?

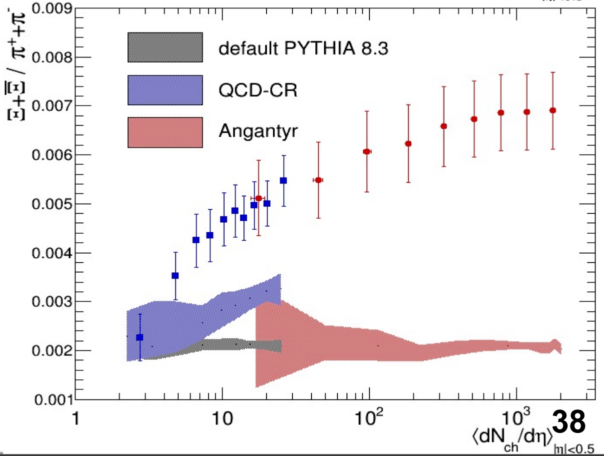
For microscopic (string) models like PYTHIA:
ALICE strange-particle yields are compared to different versions.

For pp collisions:
- default PYTHIA 8.3 model
- recent QCD-CR tune

→ For Λ/π the strangeness enhancement is impressively better described with the QCD-based model.

→ QCD-CR cannot reproduce the multi-strange ratio Ξ/π





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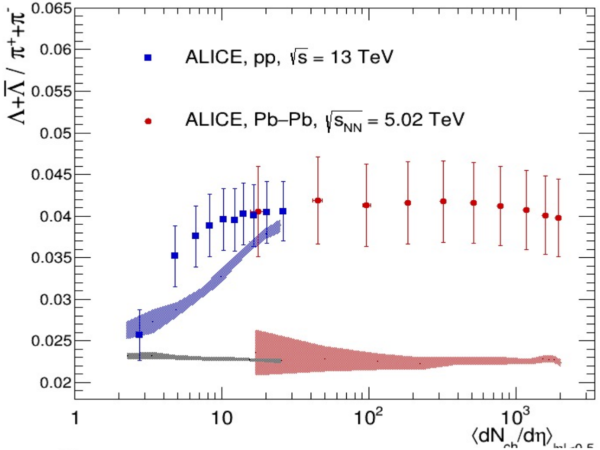
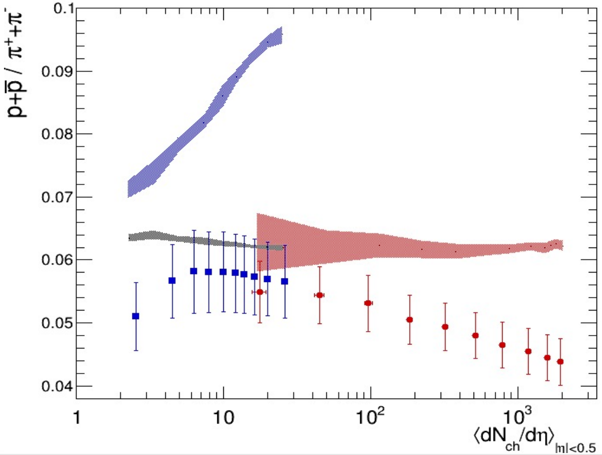
→ For Λ/π the strangeness enhancement is impressively better described with the QCD-based model.

→ QCD-CR overestimates the number of protons





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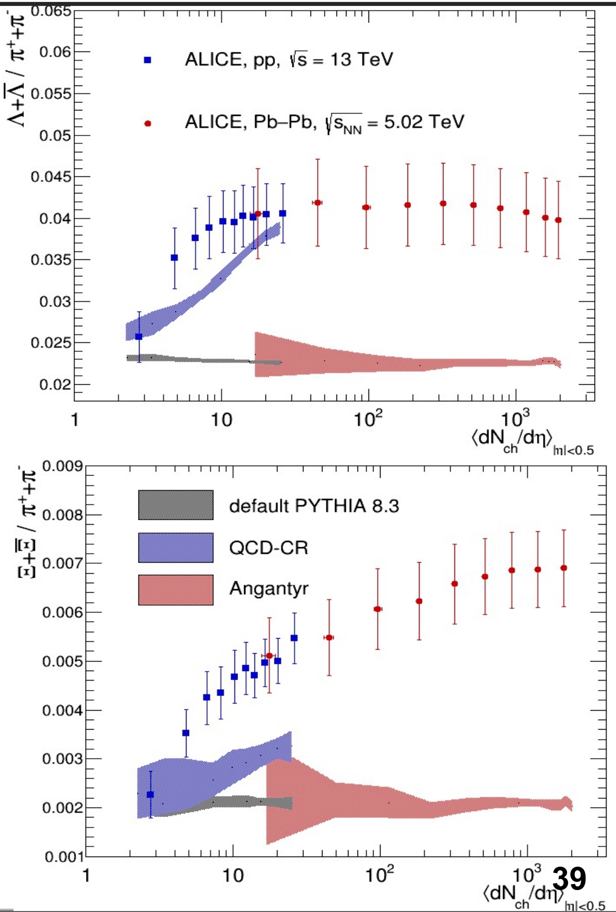
For microscopic (string) models like PYTHIA:
ALICE strange-particle yields are compared to different versions.

For AA collisions:

- Angantyr

→ strangeness enhancement is not described with the current implementation of Angantyr



Conclusions and outlook

Broad range of soft-QCD measurements exist
→ we are now entering the precision era!

Huge data statistics will be needed for some of the precision measurements proposed:

- strangeness enhancement: unknow microscopic origin
- especially for heavy-flavour: hadronisation still under study

Run3 (and beyond) data
will provide many new perspectives!