Soft QCD

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ALICE

CMS

TOTEM

ATLAS EXPERIMENT

LHCb

What is this talk 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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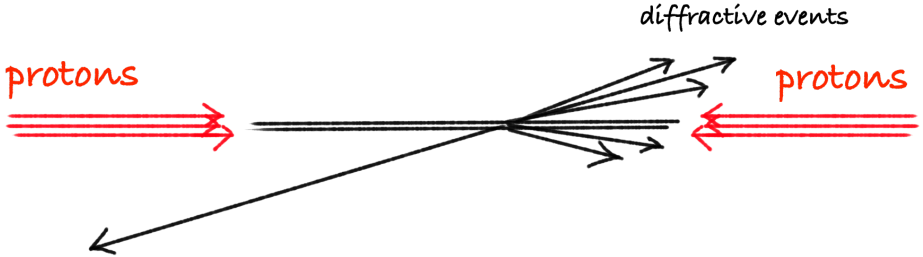
1. Diffractive events/processes



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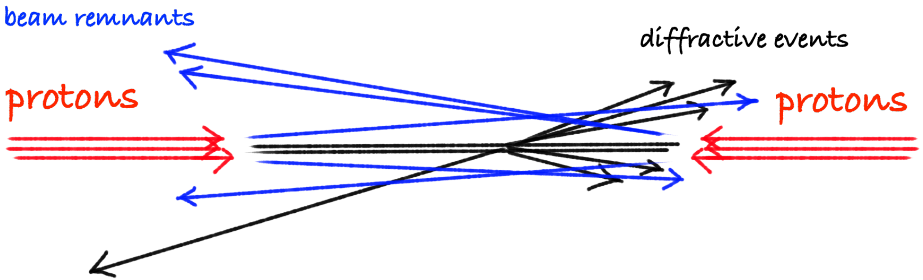

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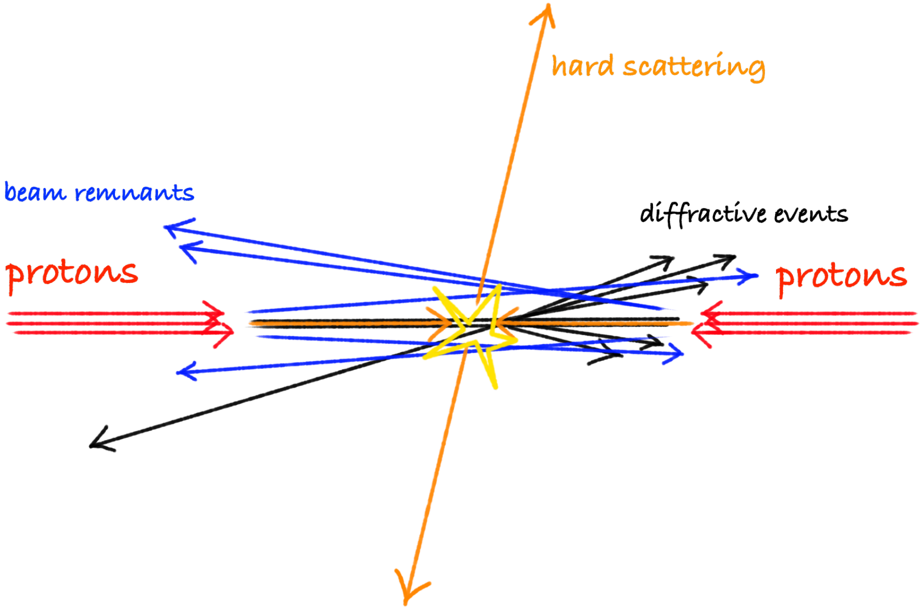

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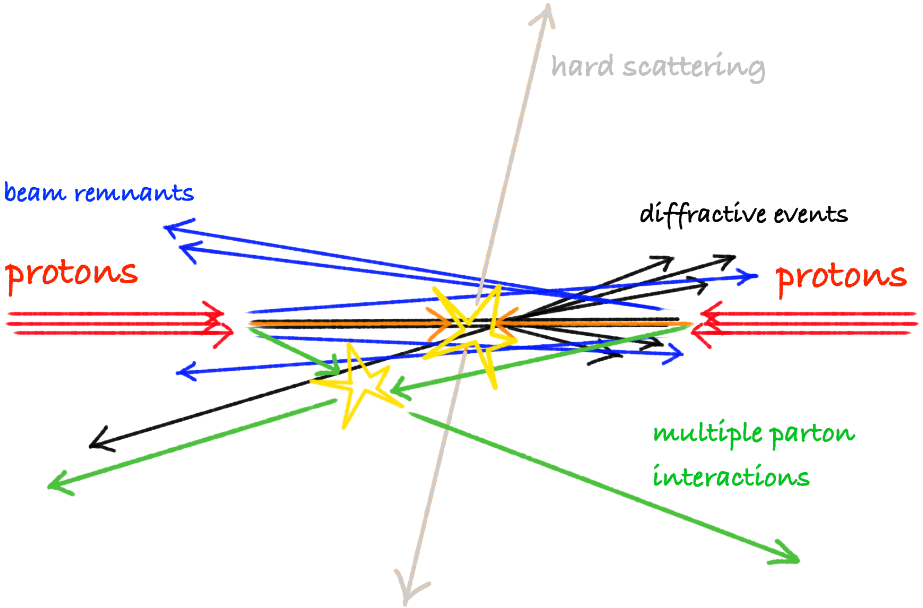
1. Diffractive events/processes
2. Multiple parton interactions (MPI)



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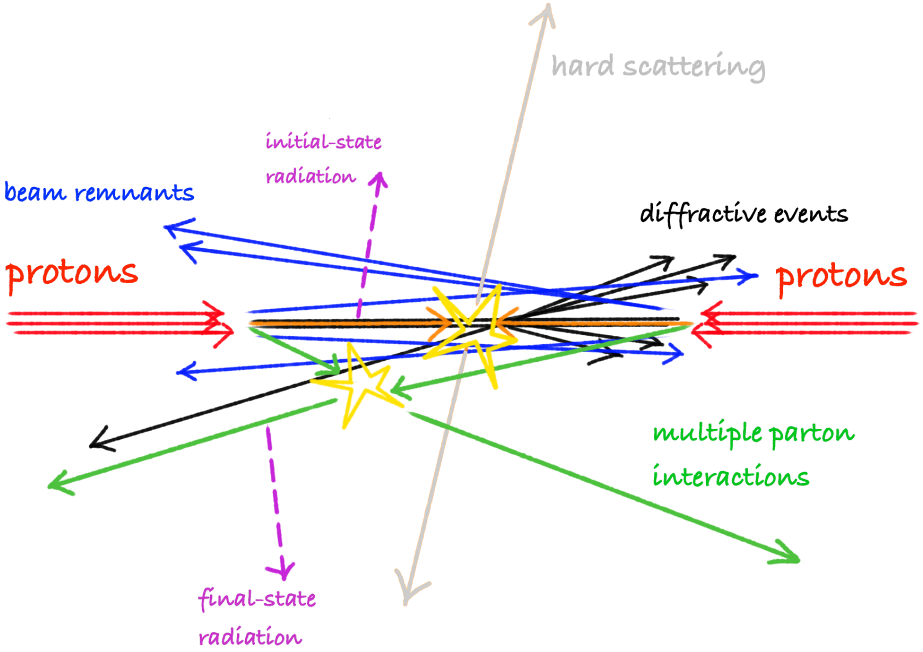
1. Diffractive events/processes
2. Multiple parton interactions (MPI)
3. Underlying events (UE)



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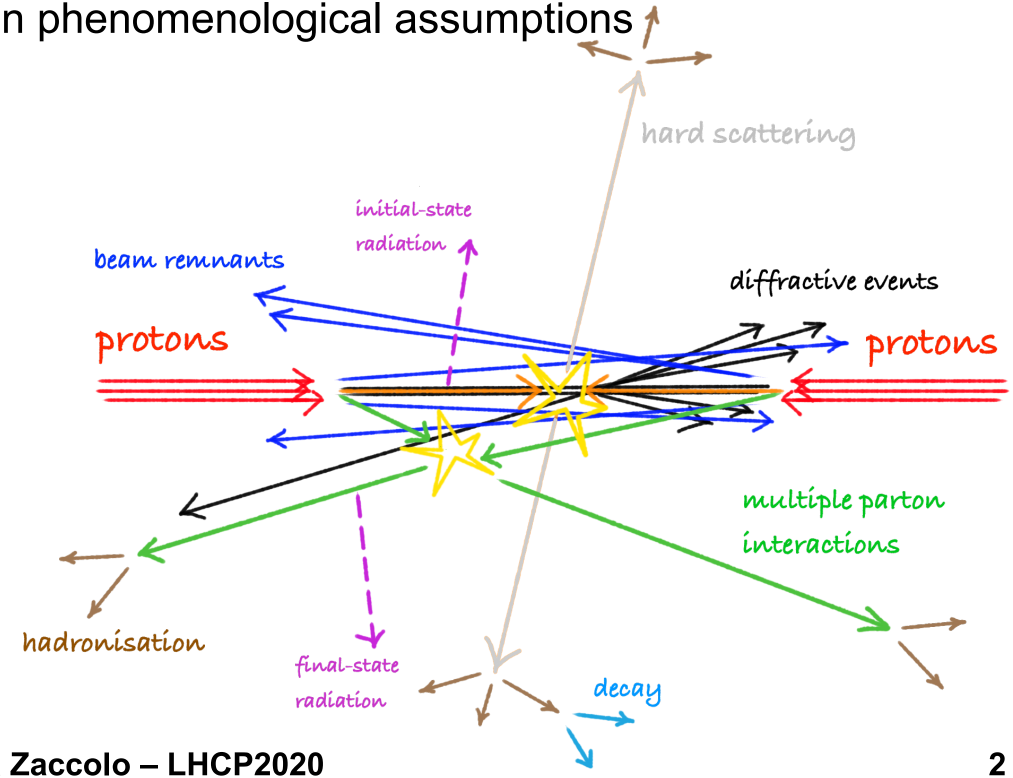
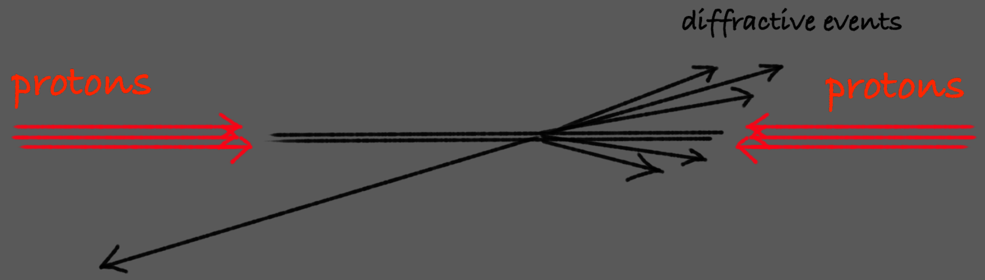
Soft QCD

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

1. Diffractive events/processes
2. Multiple parton interactions (MPI)
3. Underlying events (UE)
4. Hadronisation products
   (particle spectra and correlations)



Diffractive events

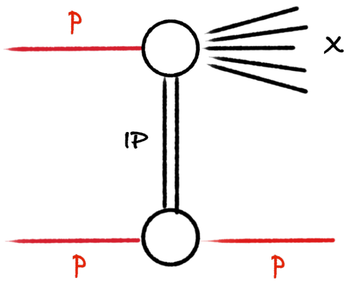


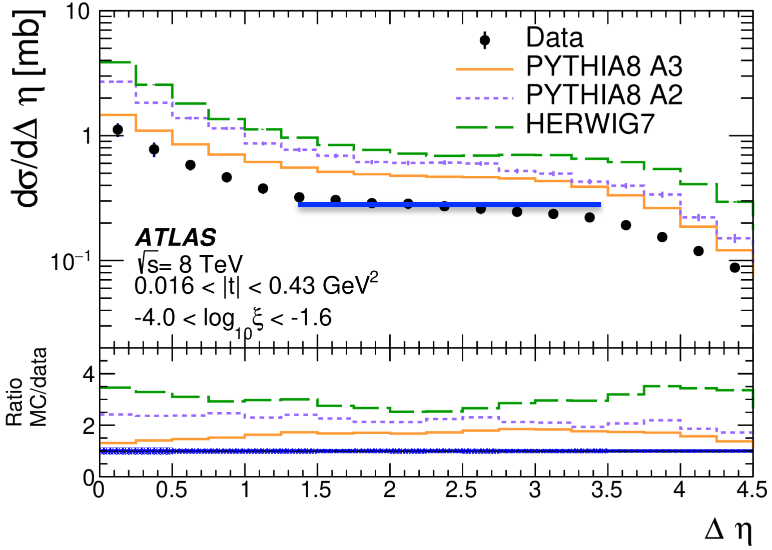
Starting from the softest events

New paper

Single-diffractive dissociation cross sections

Diffractive studies done using large rapidity gap techniques
→ distinction from double- and non-diffractive events with intact final-state proton in ATLAS forward spectrometer (ALFA)





- Measurement vs visible rapidity gap $\Delta\eta$ plateau

P. Bussey 28th at 3.20 pm

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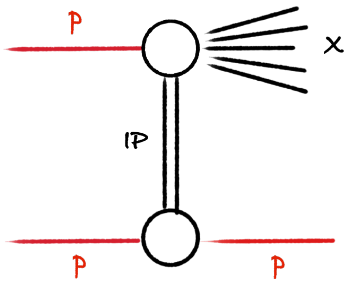
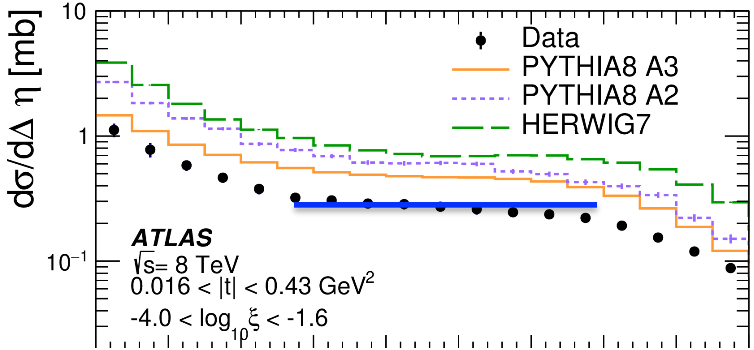
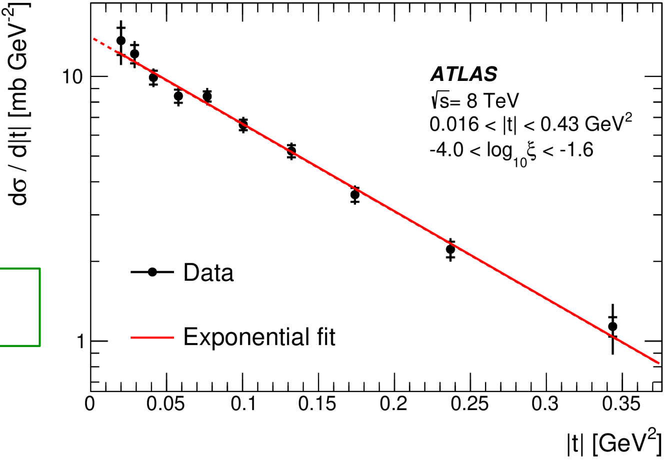
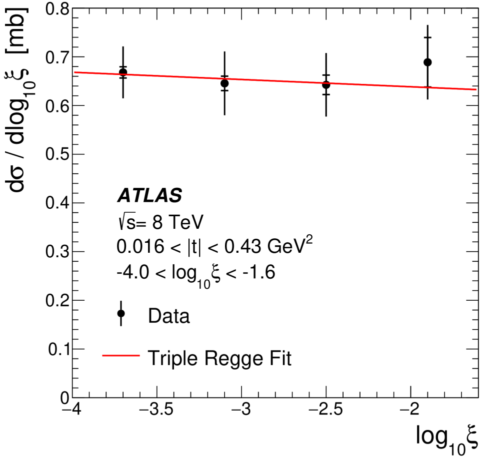




- Measurement vs visible rapidity gap Δη plateau
- vs proton transverse momentum t exponential fit
- vs proton energy loss $\xi = M^2_X/s$ independent





$\sigma^{fiducial(\xi,t)}_{SD}$ = 1.59 ± 0.13 mb

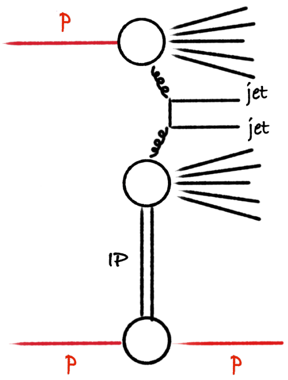
P. Bussey 28th at 3.20 pm

Hard diffractive processes

New paper

Single-diffractive dijet production

Diffractive system with 2 jets



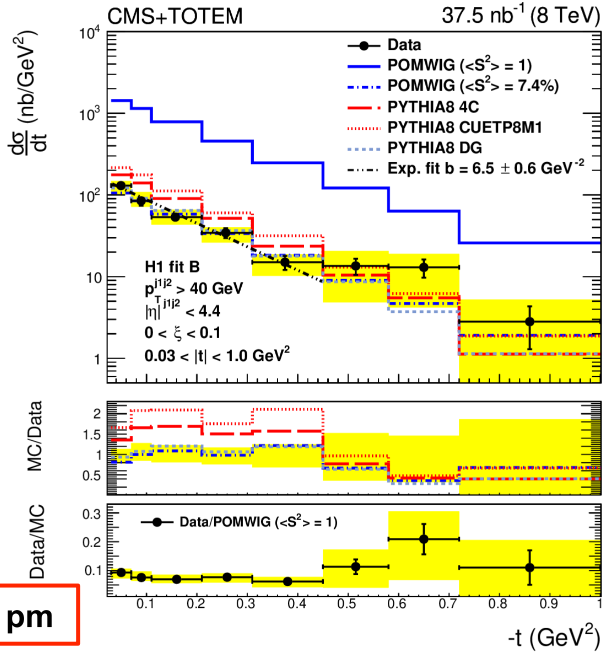
POMWIG

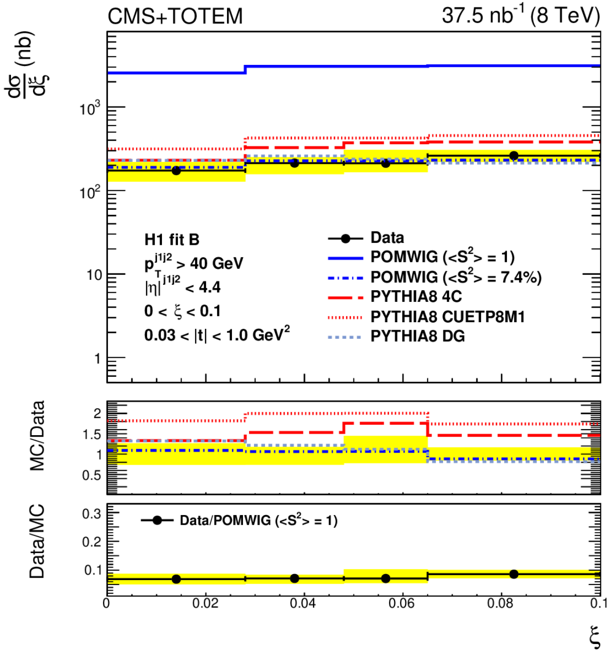
- pIP, pIR, IPIP
- good with $\langle S^2 \rangle$ correction

PYTHIA 8 DG

(diffractive event only if no MPI)

- only pIP
- no correction needed





D. Cerci 28th at 3.40 pm

arXiv: 2002.12146 [hep-ex]

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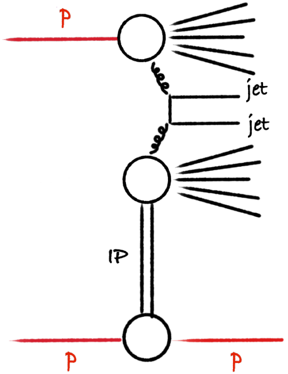
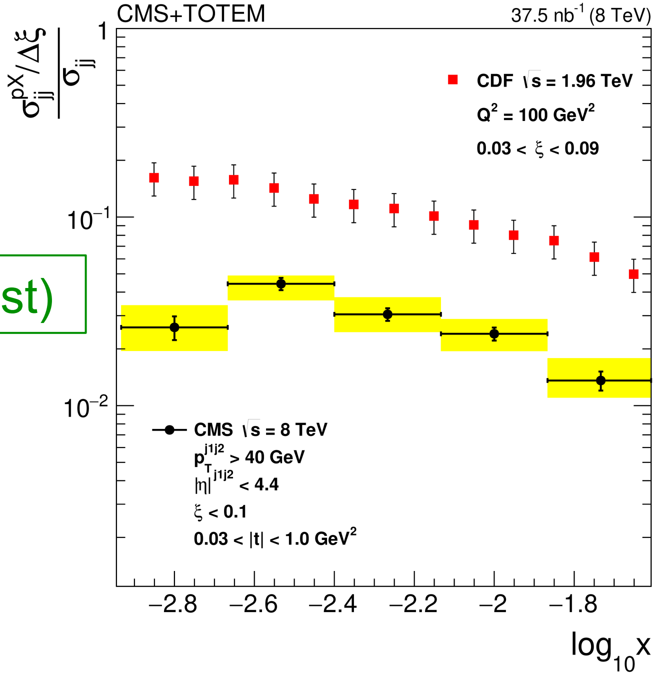


Ratio of single diffractive to inclusive dijet σ vs parton momentum fraction x
lower than CDF result

R = 0.025 ± 0.001 (stat) ± 0.003 (syst)



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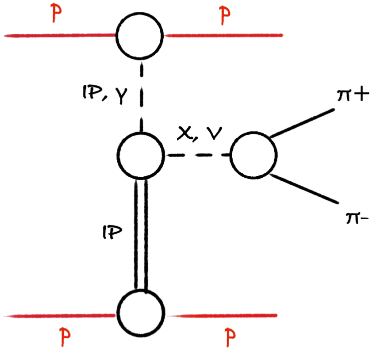
Central exclusive production

New paper

$\pi^+ \pi^-$ production

CEP events selected

- vetoing energy in the calorimeters
- requiring two charged pions in the tracker



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arXiv: 2003.02811 [hep-ex]

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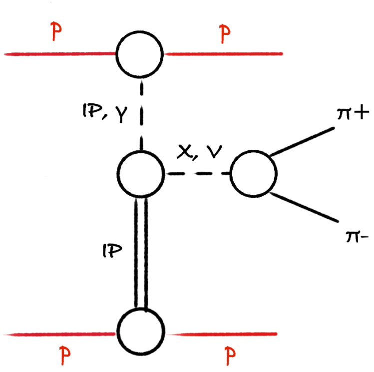
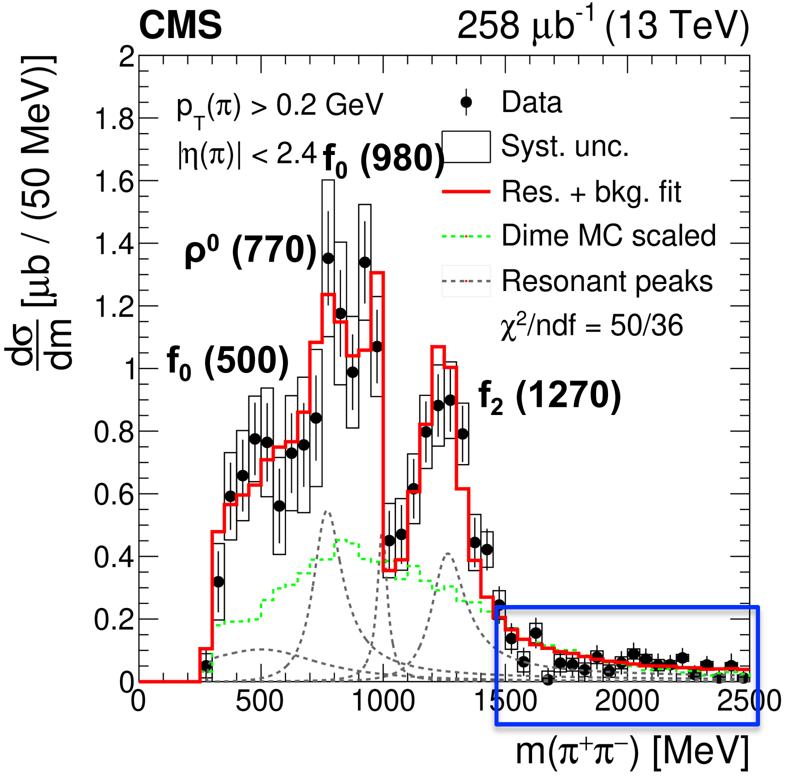


Fit

- interfering Breit-Wigner functions
- continuum contribution by DIME MC (DPE)

Above 1500 MeV fit overestimates data

- DIME MC mismodeling of the continuum shape
- further resonances



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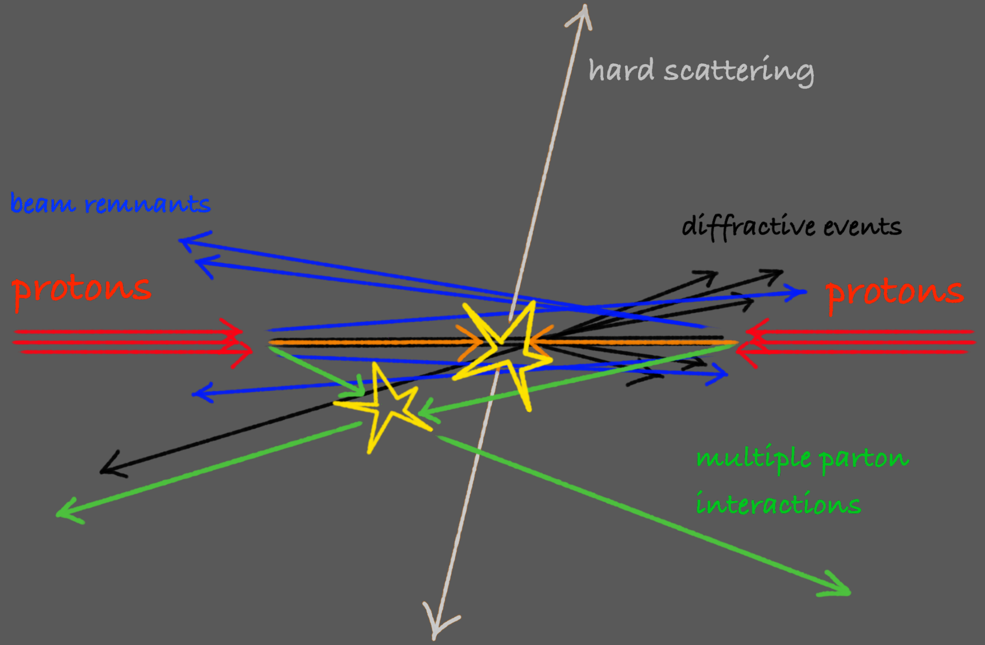
Multiple parton interactions



Directly targeting MPI

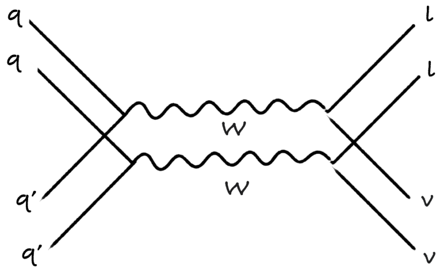
New paper

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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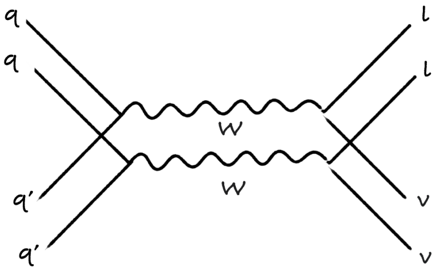

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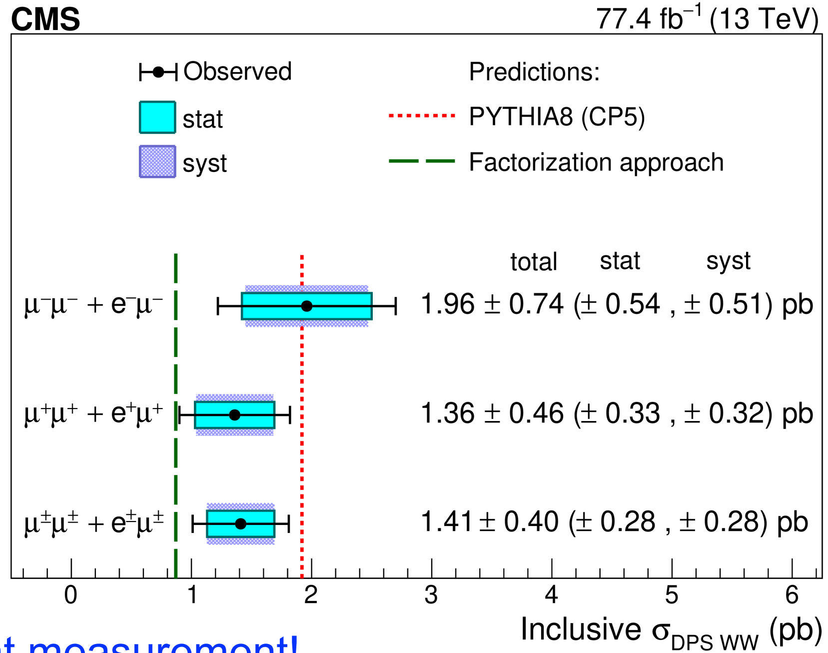
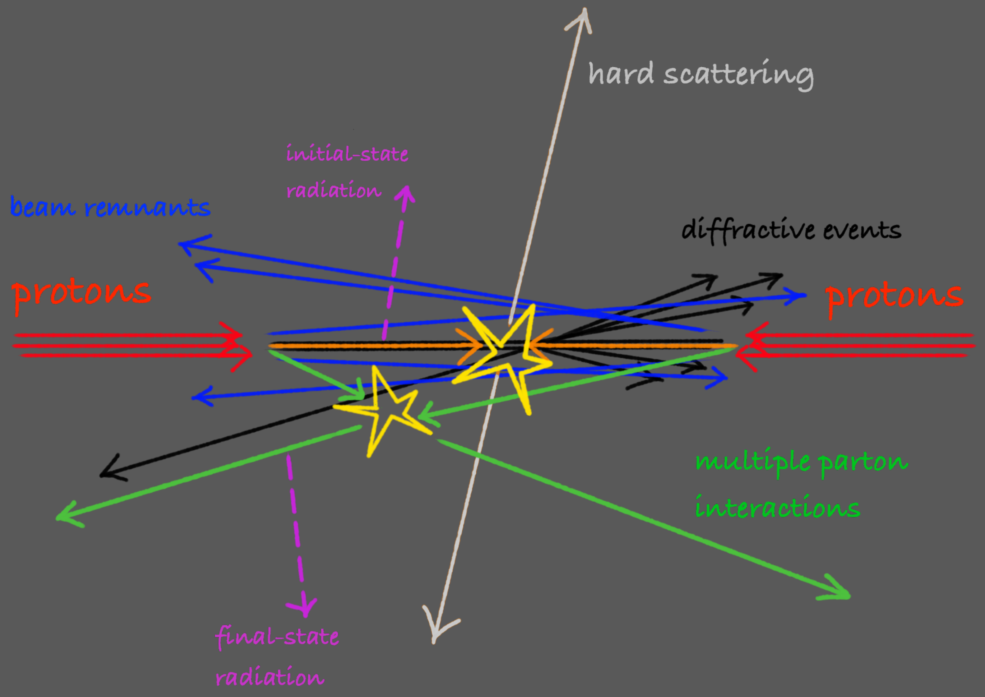


Predictions have large uncertainties → important measurement!

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

Underlying events



UE characterisation

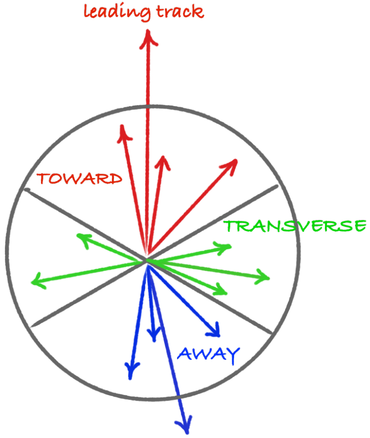
New paper

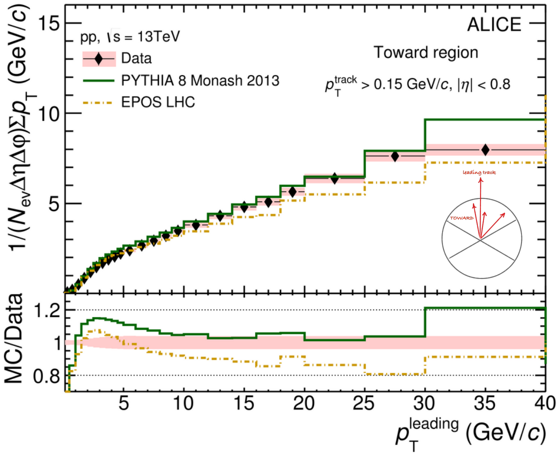
As a measurement wrt leading track…

Summed p_T vs. $p_{T,LT}$

Toward and Away regions
collect fragmentation products from hard scattering

- increases monotonically





L. Bianchi 27th at 2 pm
A. Calivà 28th at 3 pm

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As a measurement wrt leading track…

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collect fragmentation products from hard scattering
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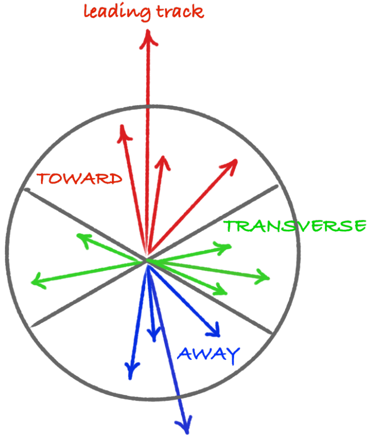
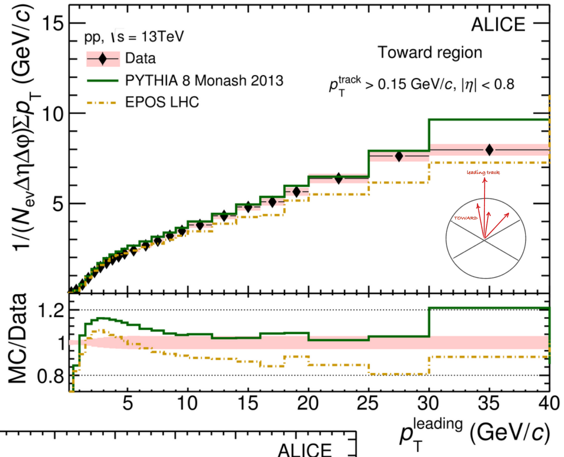
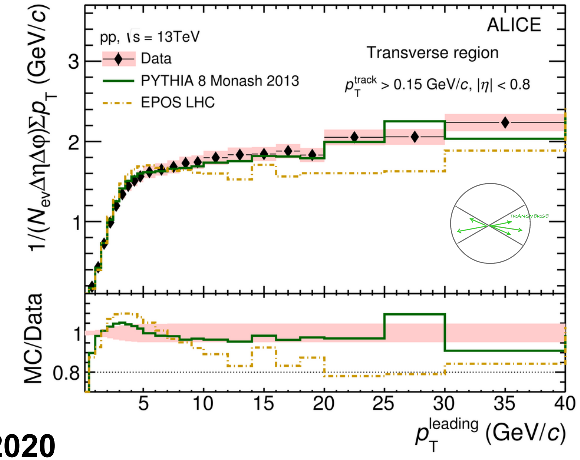
Transverse region
underlying event
- first increases -> **MPI increase**
- flattens -> **MPI saturation**







PYTHIA 8 performs better
- good MPI description

L. Bianchi 27th at 2 pm
A. Calivà 28th at 3 pm

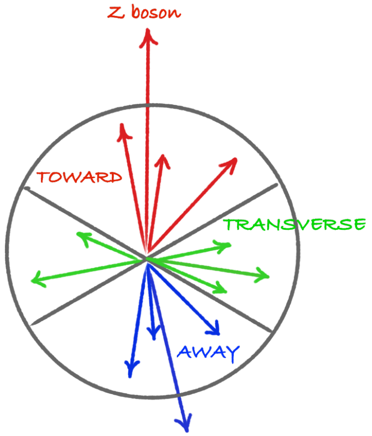
UE characterisation
…as a measurement wrt Z boson…

Using Z boson

→ very clean UE definition (no FSR)

Measurement done vs Thrust

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



P. Bussey 28th at 3.20 pm

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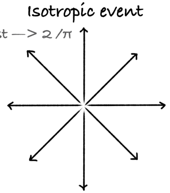
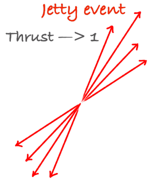
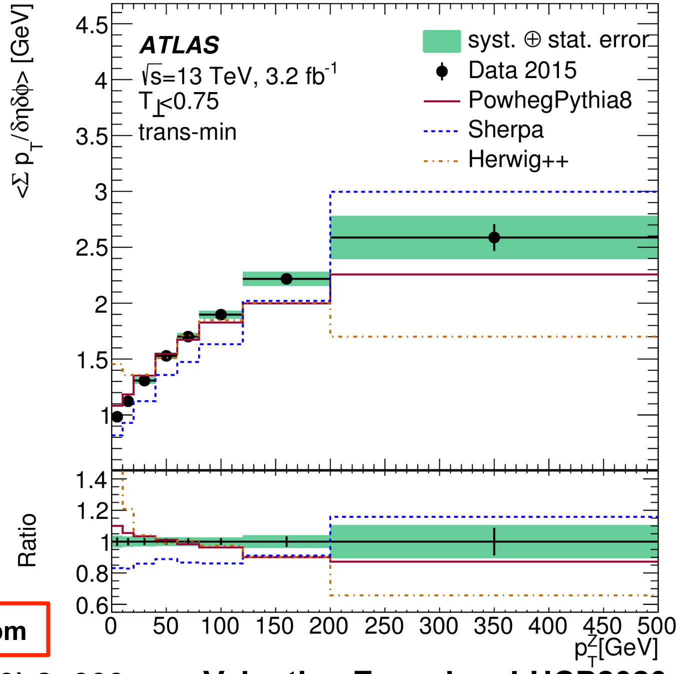
Measurement done vs Thrust

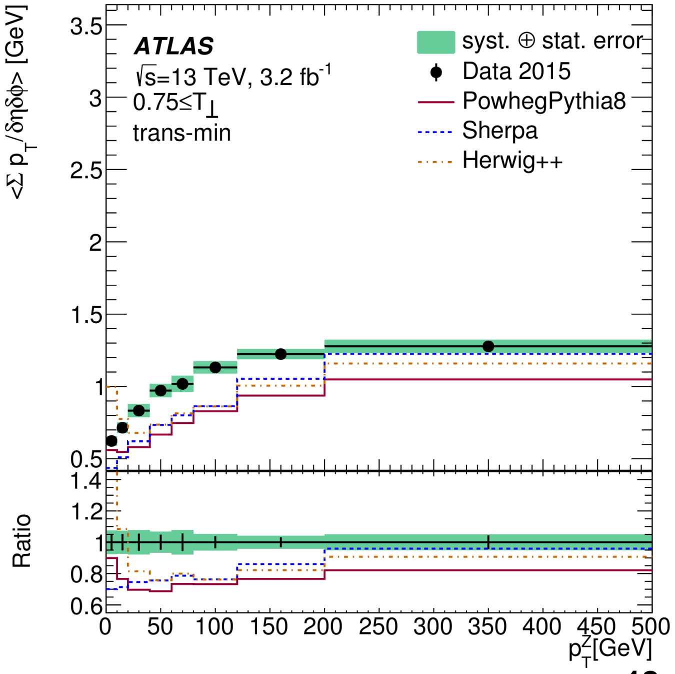
$$T_{\perp} = \frac{\sum_i |\vec{p_{T,i}} \cdot \hat{n}|}{\sum_i |\vec{p_{T,i}}|}$$

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







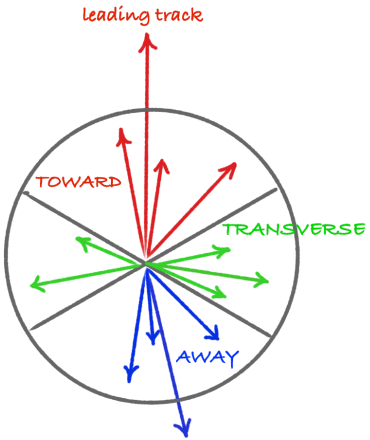


P. Bussey 28th at 3.20 pm

UE characterisation
...and as a tool

New paper

Define relative transverse activity classifier
in the plateau region
$5 < p_T^{leading} < 40$ GeV/c
Martin, Skands, Farrington
Eur.Phys.J.C 76 (2016) 5, 299



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

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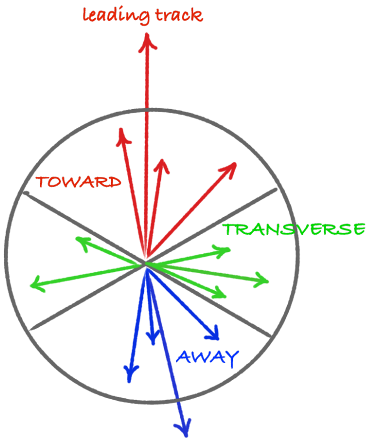
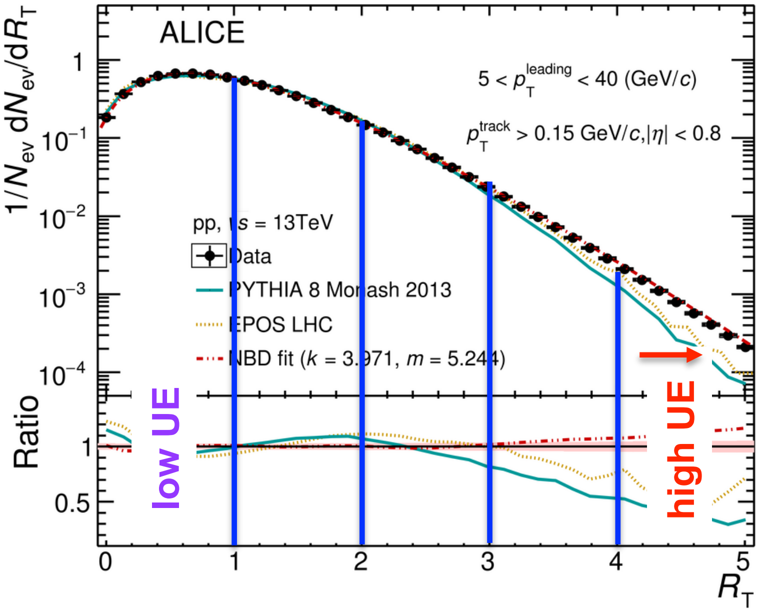




(almost) jet–free multiplicity estimator

➢ use it as tool for particle-production studies

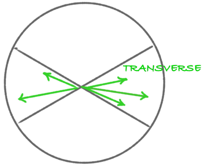
L. Bianchi 27th at 2 pm
A. Calivà 28th at 3 pm

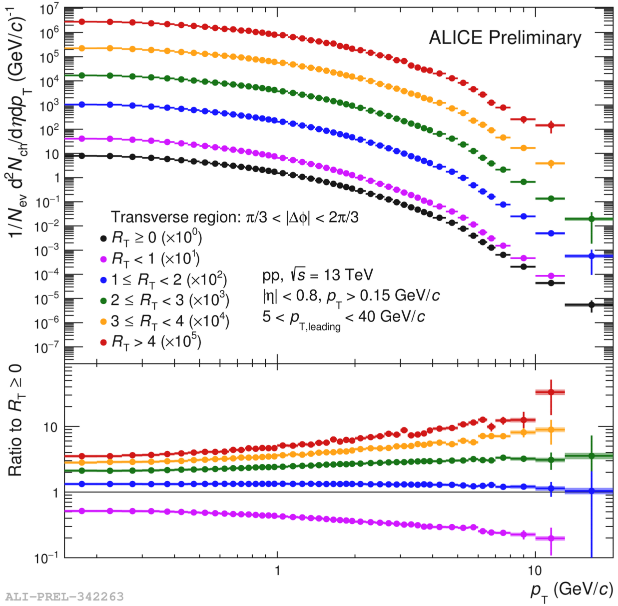
UE characterisation
...and as a tool

Particle production vs R_T

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

- transverse
  - clear p_T hardening at high multiplicity





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UE characterisation
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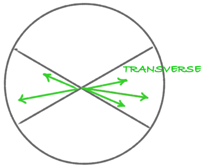
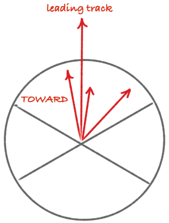
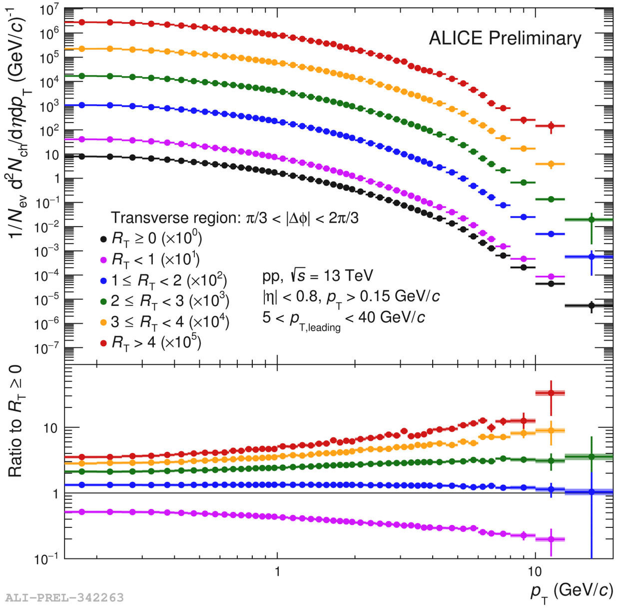
Particle production vs R_T

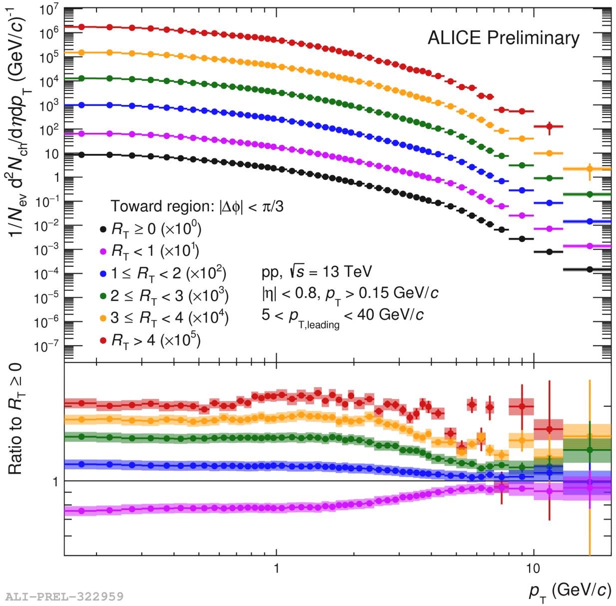
$$R_T = \frac{N_{ch}^{transverse}}{\langle N_{ch}^{transverse} \rangle}$$

- transverse
  - clear p_T hardening at high multiplicity
- toward
  - convergence to jet
  - separation among UE and jet at high p_T









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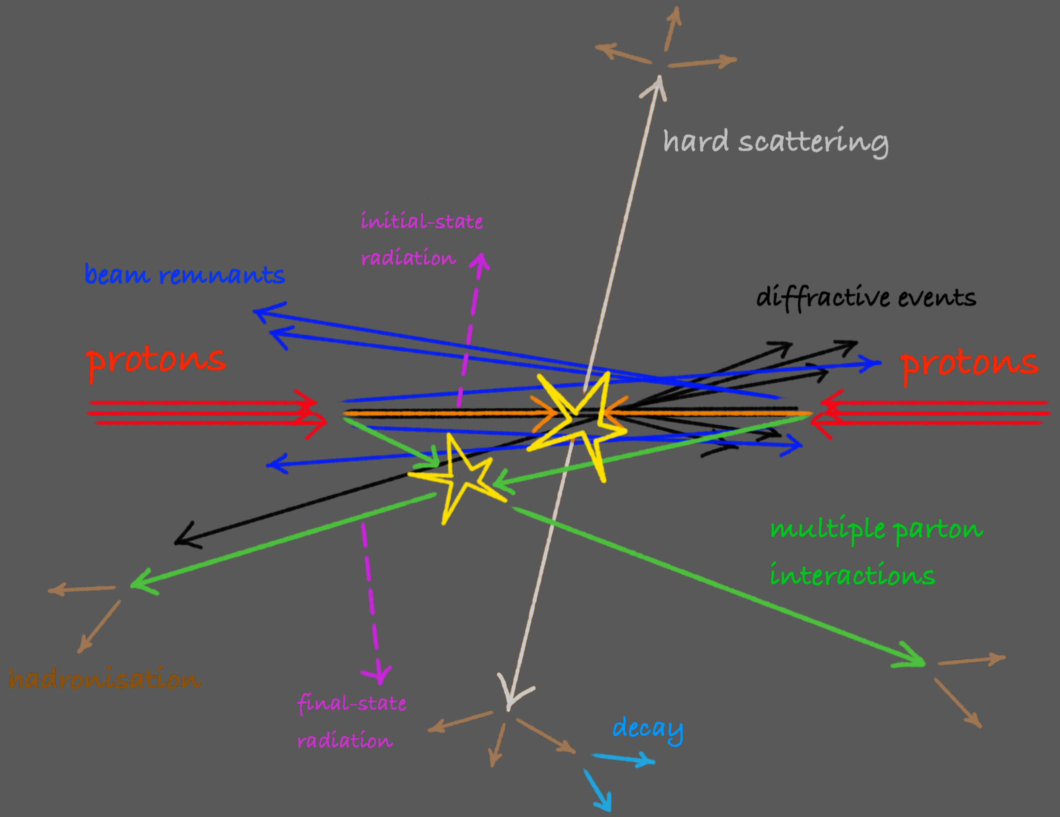
Final-state products



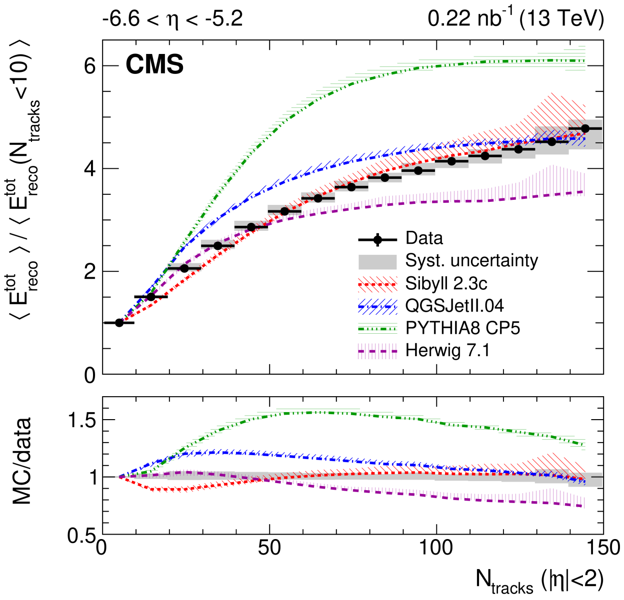
Soft particle production

New paper

Very forward energy vs mid-rapidity tracks

Energy deposited in the forward calorimeter
vs tracks at mid-rapidity

- total energy / few N_{ch} → challenging for all models!
  Diffraction (dominant at forward rapidities) still difficult to describe



D. Cerci 28th at 3.40 pm

Eur.Phys.J.C 79 (2019) 11, 893

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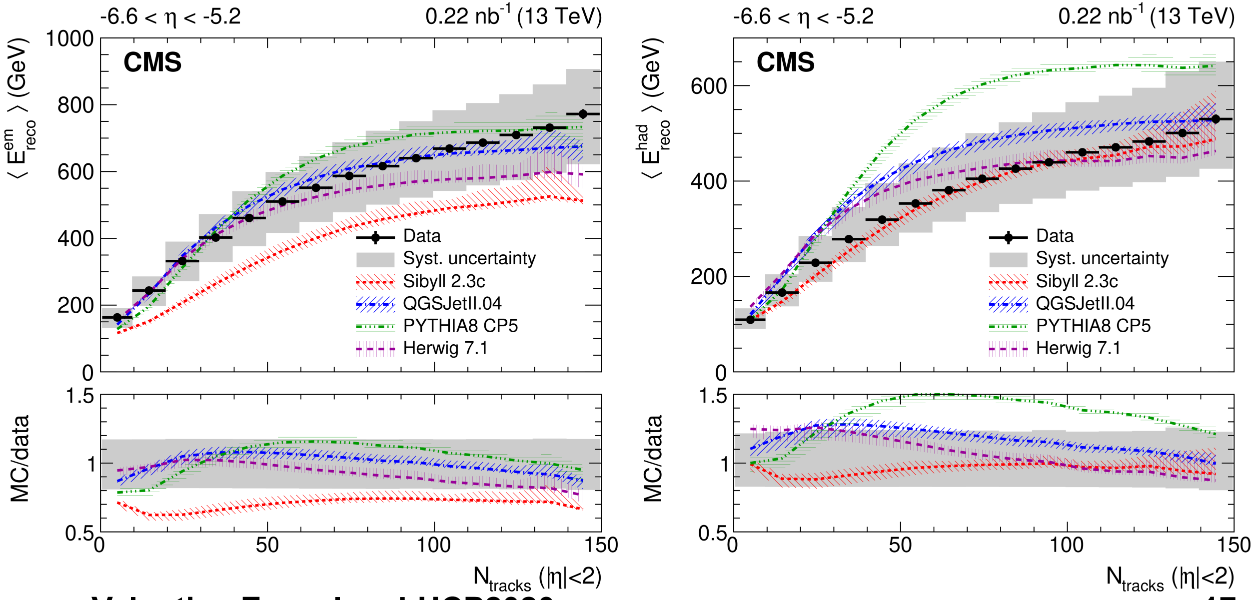
- electromagnetic component
  → underestimated by all predictions
  especially Sibyll 2.3c
  (model for air shower simulation)
- hadronic component
  → generally overestimated
  PYTHIA 8 CP5 (tuned to measured UE) off



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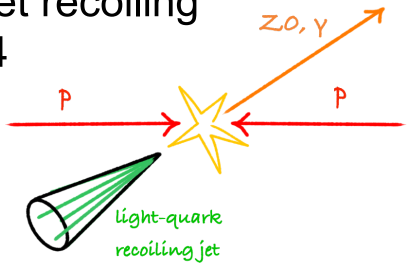
Soft jets at forward rapidities

Charged-hadron production in Z jets

Charged hadrons produced in jet recoiling against a Z boson in $2.5 < \eta < 4$

- probe light-quark jets
- test differences between quark and gluon hadronisation



W. Barter 26th at 5.30 pm

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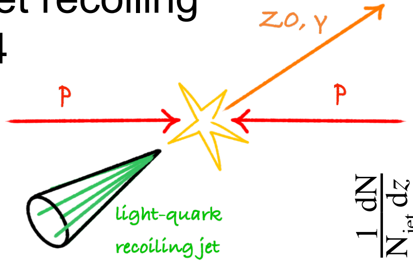
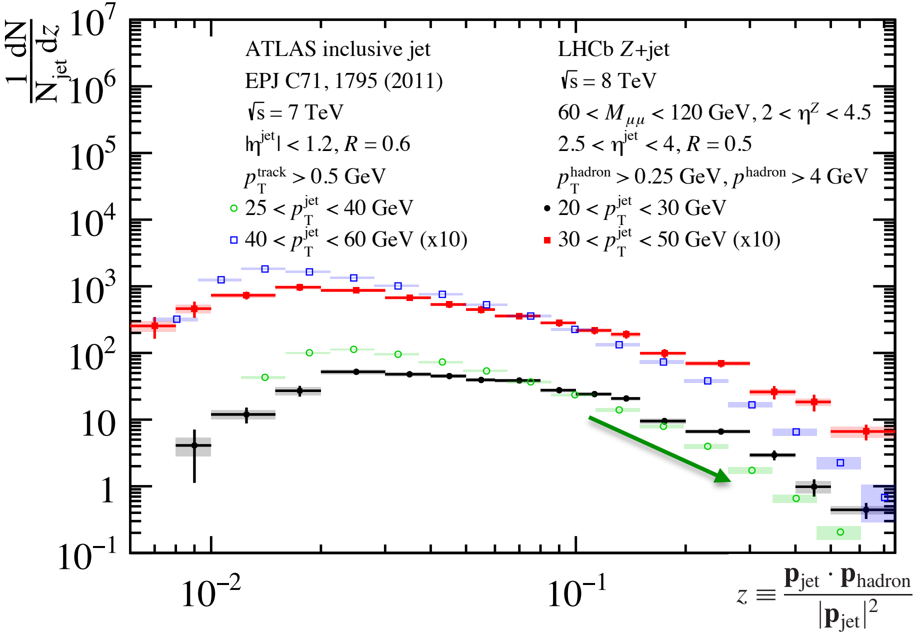


- Forward jets (LHCb) more collimated than mid-rapidity ones (ATLAS)
  - ○ difference in fragmentation functions for light quarks and gluons



W. Barter 26th at 5.30 pm

Baryon hadronisation

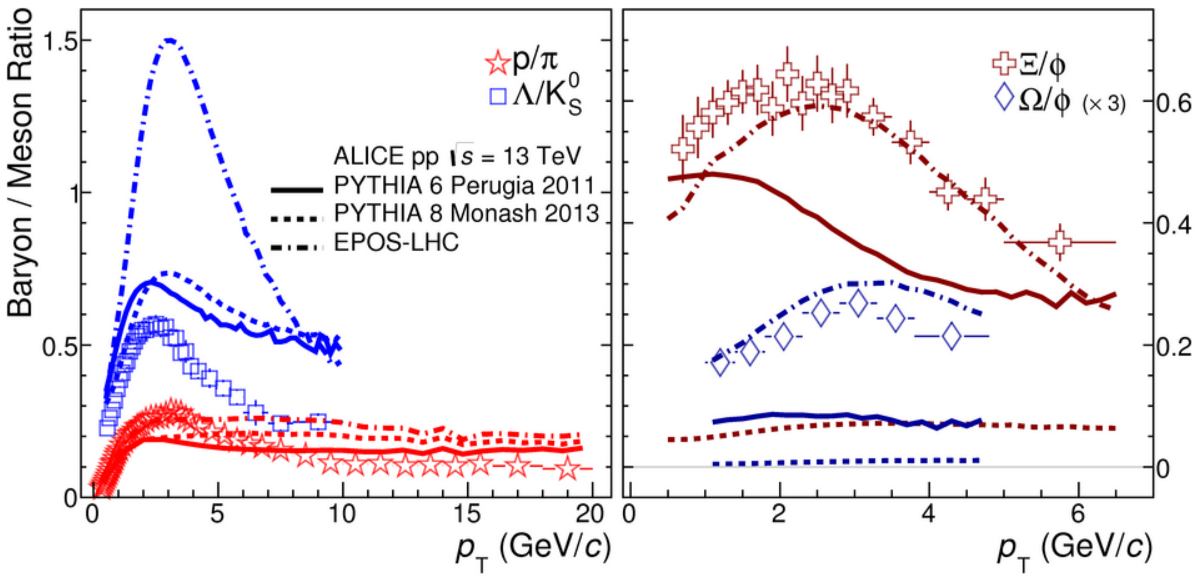
Baryon-to-meson ratios…

New paper

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



Baryon hadronisation

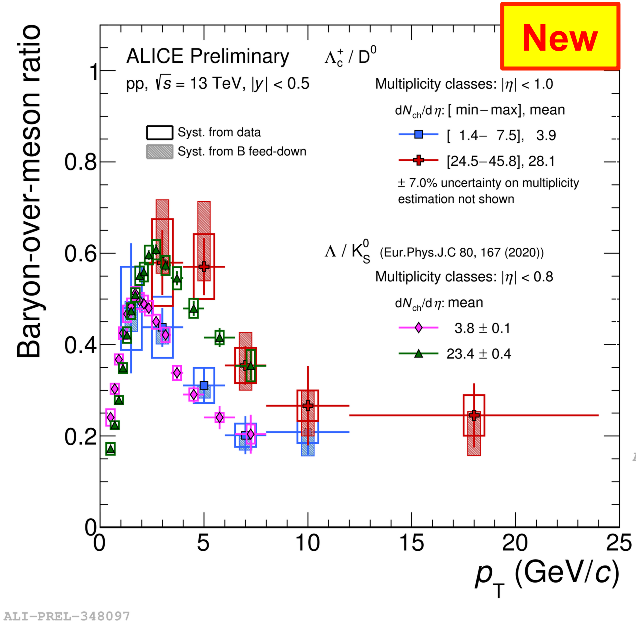
Baryon-to-meson ratios…

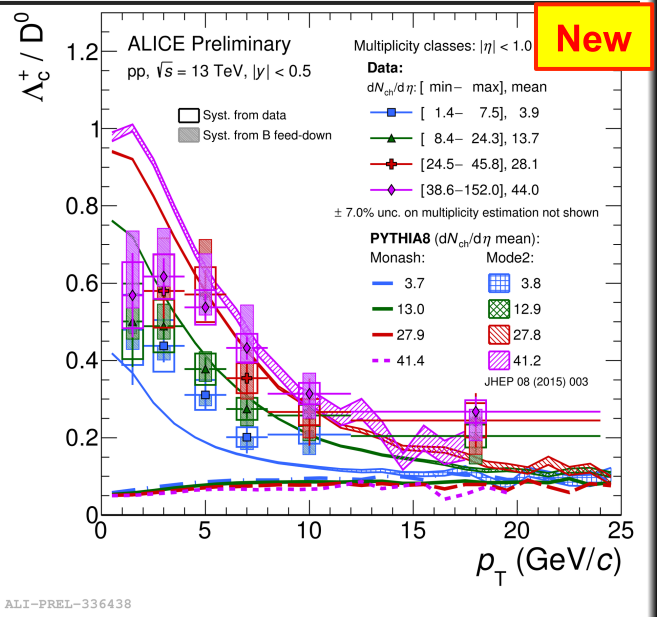
Modelling baryons is difficult due to their colour topology

- ➢ are not included in leading-colour approximations → interesting probes!

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…





A. Harlendova 25th at 3.30 pm
GM. Innocenti 27th at 1.30 pm
C. Terrevoli 29th at 2.30 pm

Baryon hadronisation

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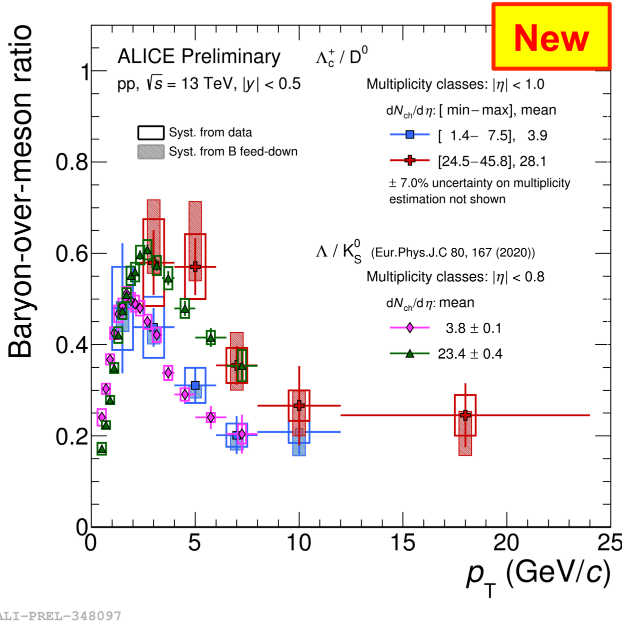
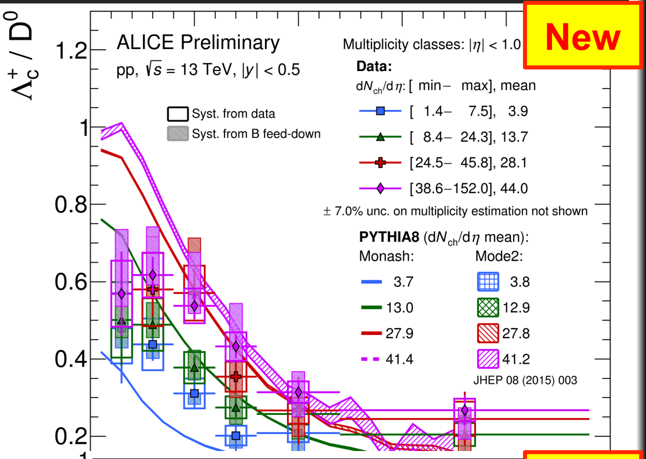
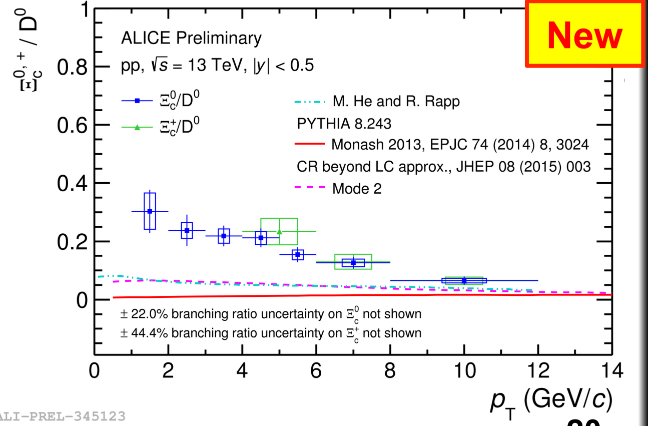
- is mid-p_T enhancement a baryon/meson feature?
- PYTHIA Mode2 (QCD-CR) works for Λ_C/D^0…
- …but not for Ξ_C/D^0!







A. Harlendova 25th at 3.30 pm
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Baryon hadronisation
...and correlations

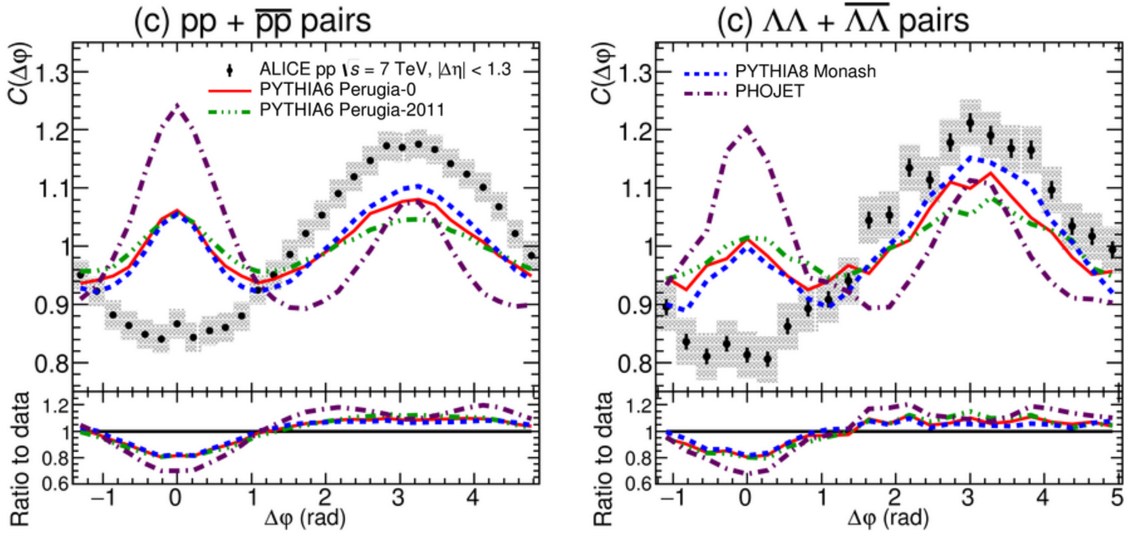
Angular correlations → valuable tool to test hadronisation

Baryon-baryon correlations

$$\mathbb{C}(\Delta\eta, \Delta\varphi) = \frac{1}{N_{\mathrm{pairs}}} \frac{\mathrm{d}^2 N_{\mathrm{pairs}}}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\varphi}$$

near-side anti-correlations

- baryon production close in phase space disfavoured
- no model can reproduce it



Baryon hadronisation
…and correlations

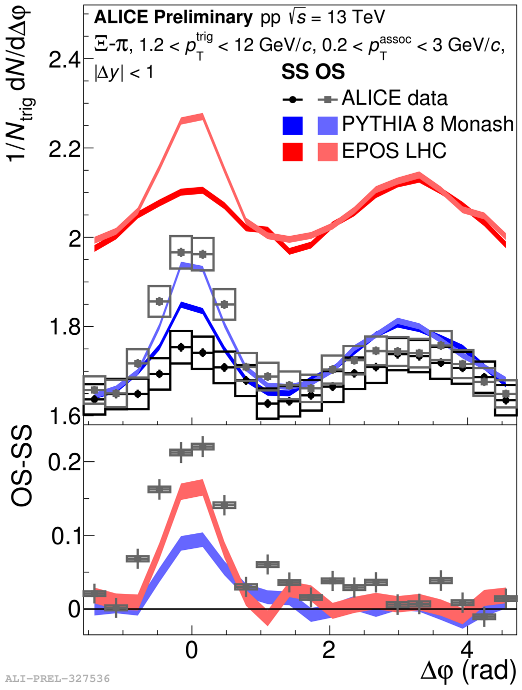
Angular correlations → valuable tool to test hadronisation

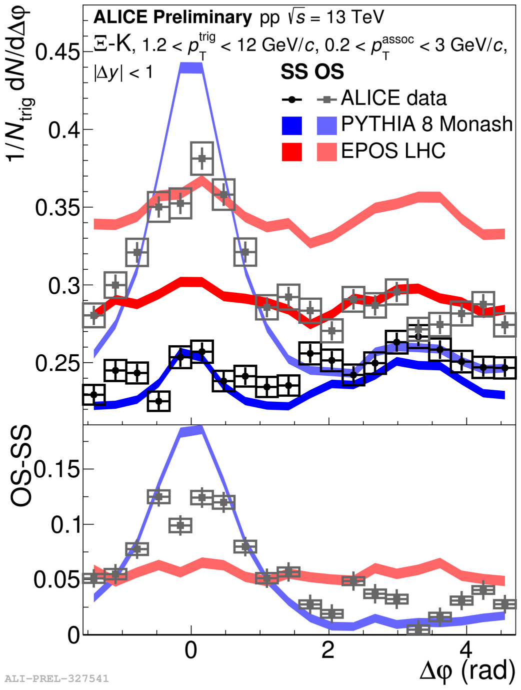
Baryon-meson per-trigger yield

$$\mathbb{Y}(\Delta y, \Delta\varphi) = \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{pairs}}}{\mathrm{d}\Delta y \mathrm{d}\Delta\varphi}$$

Ξ-π
- models reproduce correlation
- normalisation is off for EPOS LHC

Ξ-K
- stronger and wider near-side peak
- too much correlation for PYTHIA 8
- too little for EPOS LHC





Conclusions and outlook

Soft QCD modelling is crucial for understanding of hadronisation mechanisms and for high-precision SM and beyond measurements

- Observables related to MPI are well modelled
- Development needed to describe
  - diffraction
  - initial/final state radiation
  - hadronisation at forward rapidities
  - hadronisation of baryons

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Looking forward to development of precision tools (e.g. phase space subdivisions) to help modelling Soft QCD further

Run 3 data will help to reach the goal!

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More questions? Discussion?

Topic: Discussion on Soft-QCD talk - LHCP2020
Time: May 26, 2020 06:30 PM Rome
Join Zoom Meeting:
https://cern.zoom.us/j/96875900338?pwd=cCswSTdLb1ZDbkN0VzJlbFpIY0dKdz09
Meeting ID: 968 7590 0338
Password: same of this session

Looking forward to development of precision tools (e.g. phase space subdivisions) to help modelling Soft QCD further

Run 3 data will help to reach the goal!

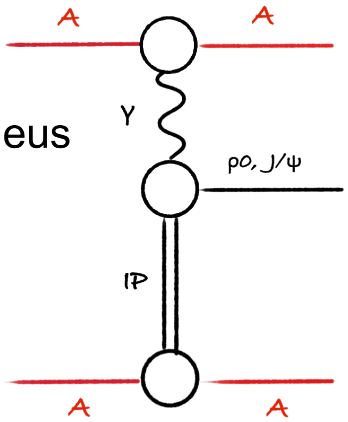
Backup slides

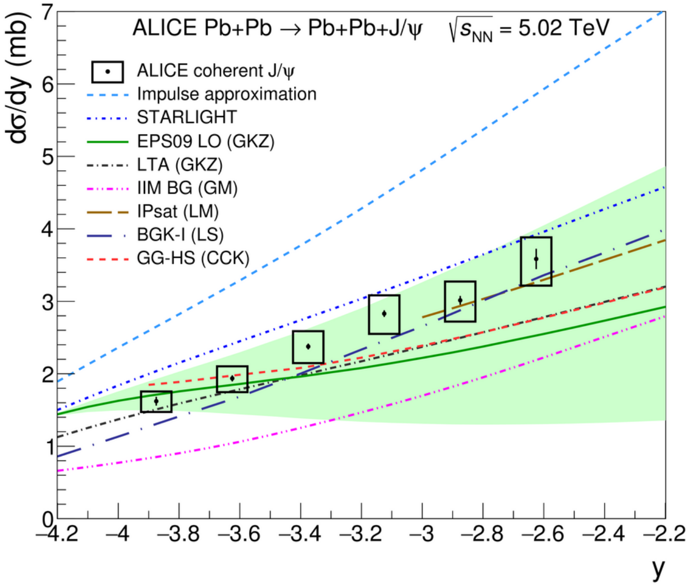
What about heavy ions?
Vector meson photoproduction with nuclei

Nucleus carry EM field → source of γ
UPC at very high impact parameter b → exchange of virtual γ
small x → important constraints
for the nuclear gluon shadowing models

J/Ψ coherent production

- γ interacts coherently with whole nucleus
- gluon shadowing needed
  to reproduce data





What about heavy ions?

Vector meson photoproduction with nuclei

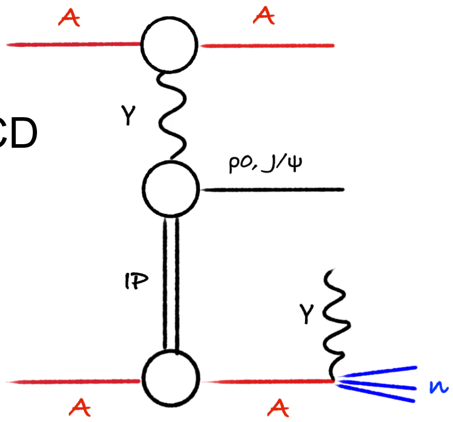
New paper

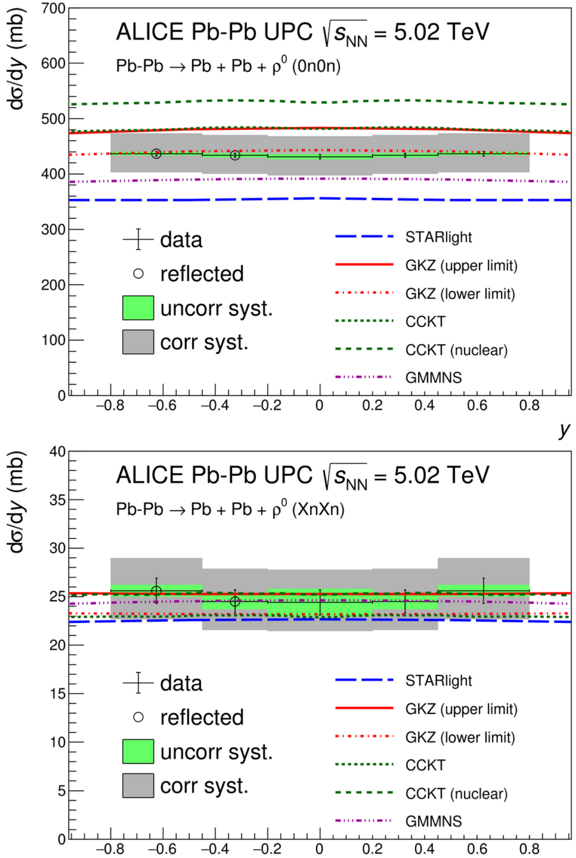
Nucleus carry EM field → source of γ
UPC at very high impact parameter b → exchange of virtual γ
small x → important constraints for the nuclear gluon shadowing models

ρ^0 coherent production

- approach to the black-disc limit of QCD
- EMD classes disentangle low and high energy contributions to γ-Pb cross section

D. Horak's poster





ALICE arxiv: 2002.10897 [nucl-ex]

UE characterisation
…and as a tool for heavy-ion studies

Particle production vs R_T

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

p-Pb similar to pp

- clear hardening of p_T spectra for transverse region

Pb-Pb

- same trend for all azimuthal regions
- effect of isotropic structure of AA collision

Models reproduce the spectra qualitatively but not quantitatively

- PYTHIA extension to HI as superposition of pp (Angantyr) performs better