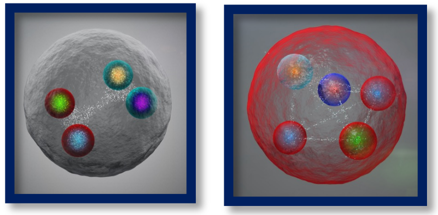
QCD Measurements in pp collisions

Sarah Porteboeuf Houssais
UCA LPC CNRS

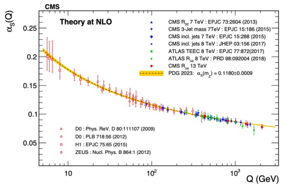
On behalf of the LHC Collaborations

Outline

- The quark model toward tetraquark and pentaquark



Presented by P. Gandini
Monday 03/06 at 17:36

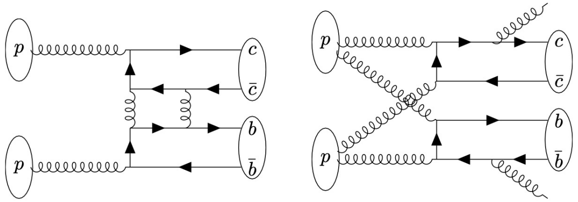


- The strong force: running of α_s and υ from FASER

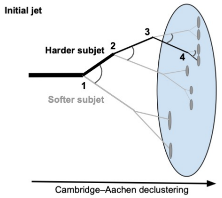
- Factorization approach in QCD, measurements of PDFs and TMDs

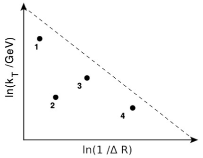
$$\frac{d\sigma^{pp\to h+X}}{dp_T d\eta} = \sum_{abc} f_{a/p} \otimes f_{b/p} \otimes \hat{\sigma}_{ab\to c}(z,\mu) \otimes D_c^h(z,\mu)$$

- Insight on multi-parton scattering with associated production

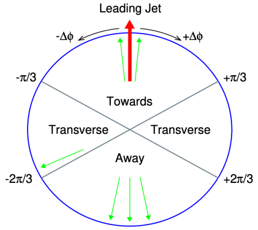


- Jet fragmentation and substructure





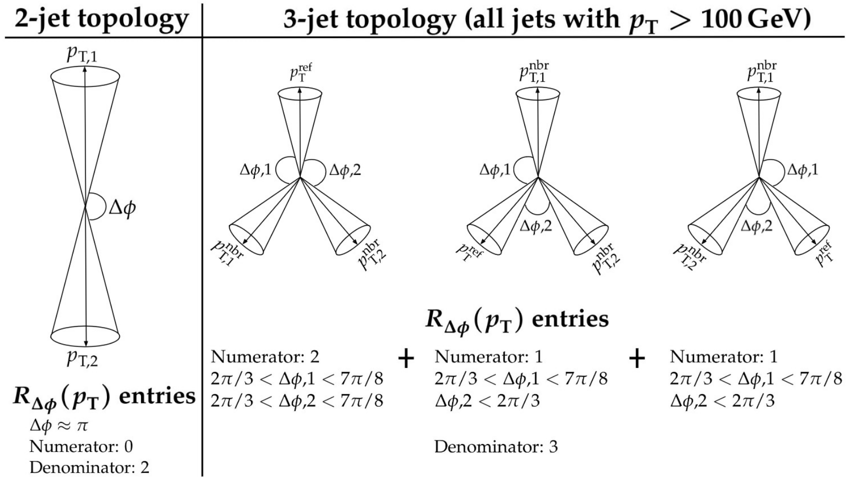
- Hadronization in hadronic environment

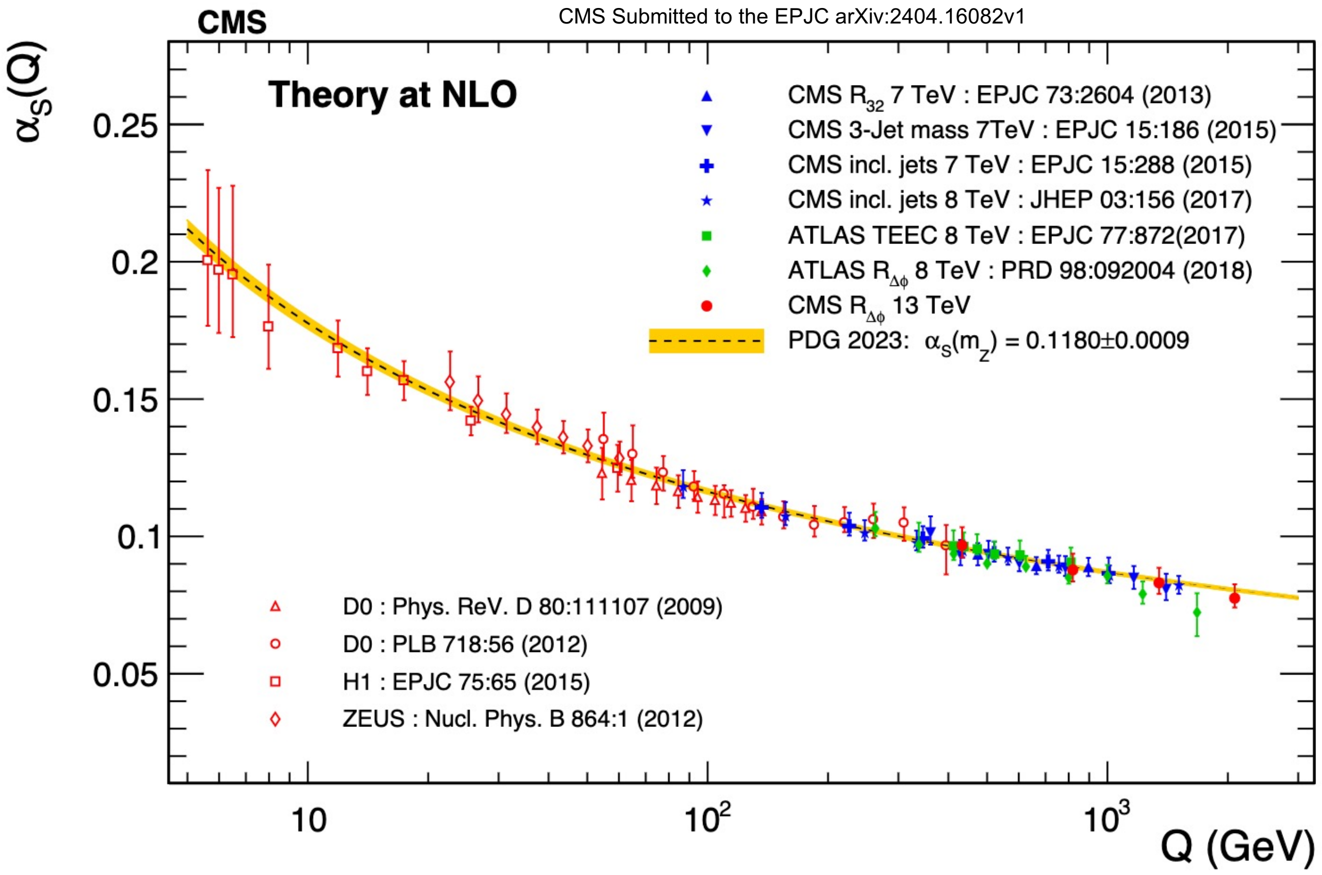


α_s with multi-jet

Azimuthal correlations among jets allow to probe α_s running up to 2 TeV

$$R_{\Delta\phi}(p_{\mathrm{T}}) = \frac{\sum_{i=1}^{N_{\mathrm{jet}}(p_{\mathrm{T}})} N_{\mathrm{nbr}}^{(i)}(\Delta\phi, p_{\mathrm{Tmin}}^{\mathrm{nbr}})}{N_{\mathrm{jet}}(p_{\mathrm{T}})},$$





NLO pQCD behaviour confirmed up to 2 TeV

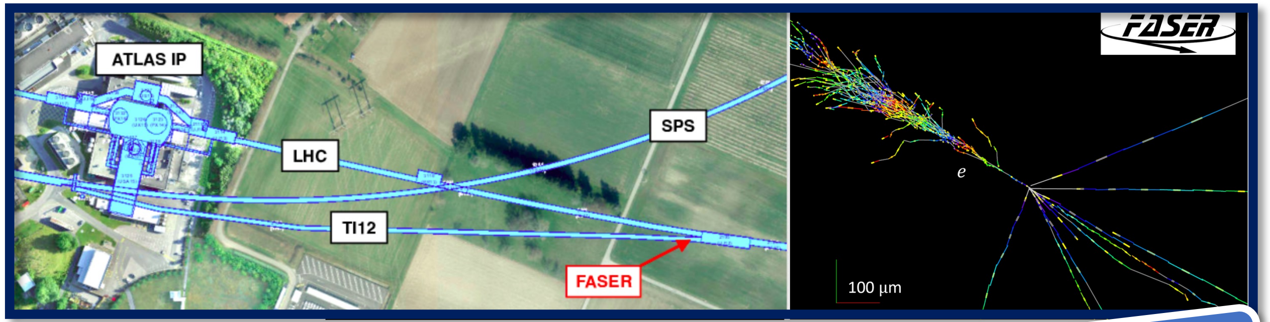
More from J. Roloff Thursday 06/06 at 14:18

sarah.porteboeuf@clermont.in2p3.fr

Neutrino cross section with FASER & SND

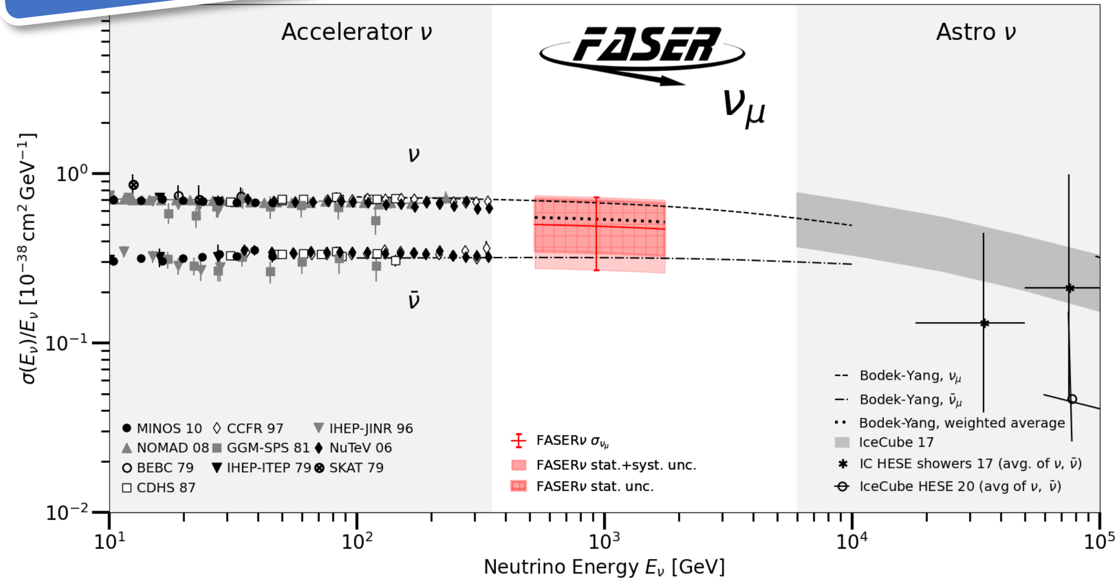
FASER Forward Search Experiment
SND Scattering and Neutrino Detector
480 m from ATLAS IP on both sides

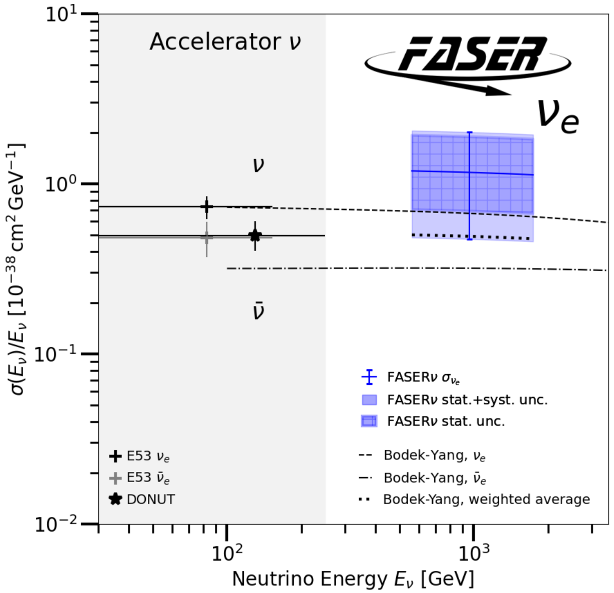
Neutrinos coming from the decay of very forward hadrons
light-flavour and charm



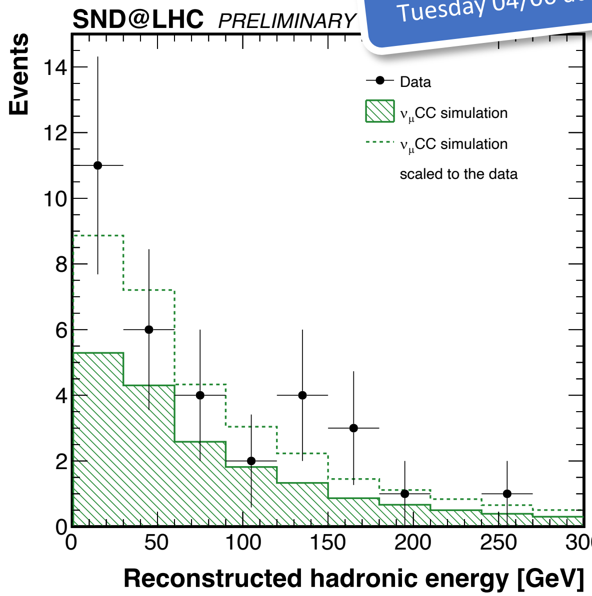
More from D. Koeck
Tuesday 04/06 at 14:18

FASER arXiv:2403.12520





More from C. Betancourt
Tuesday 04/06 at 14:36



Observation of ν_μ interactions the LHC by SND

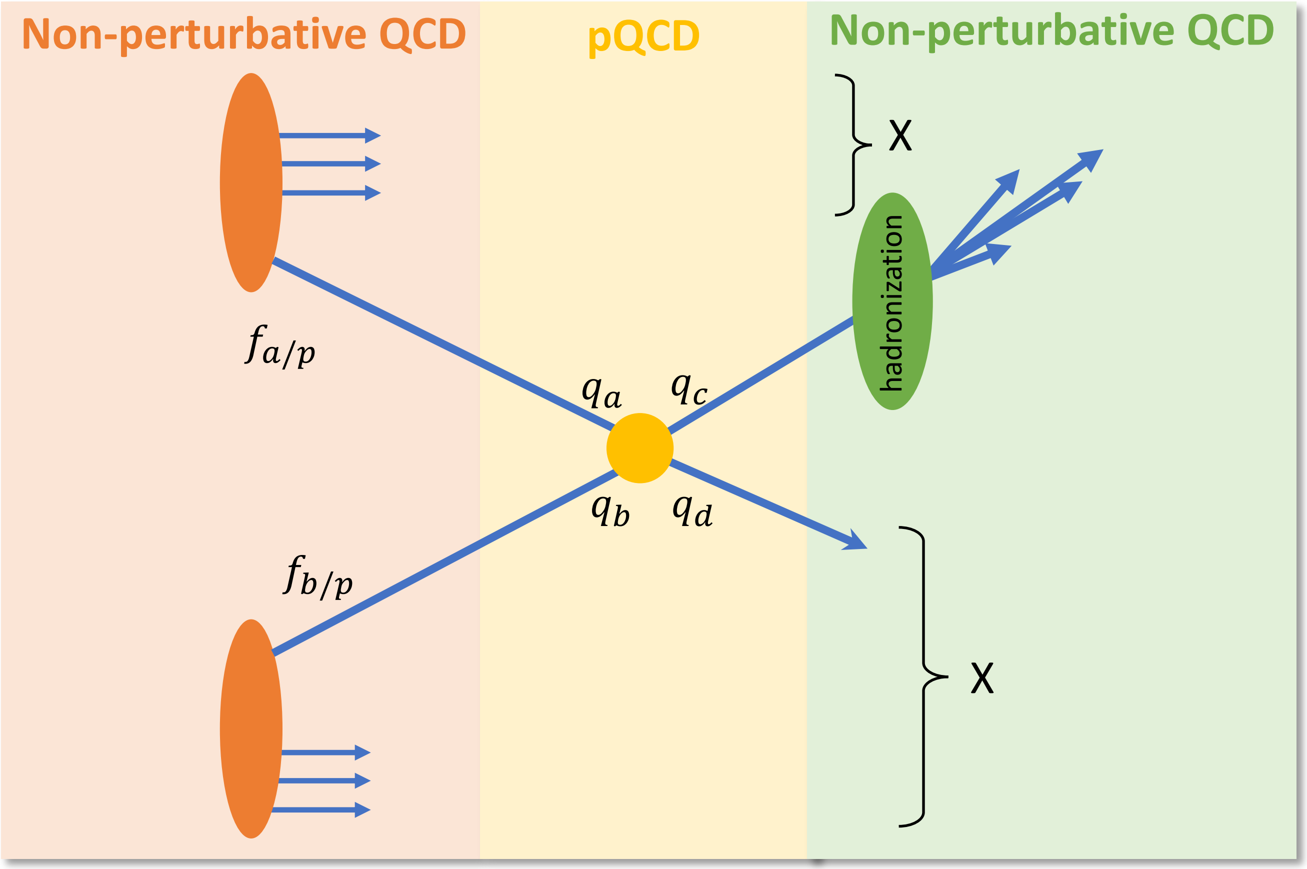
First neutrino cross-section measurement at a collider, in an unexplored energy regime from FASER

Factorization in QCD

Factorization of the perturbative and non perturbative component of the interaction

$f_{a/p}$

one-dimensional parton distribution functions (PDFs) parameterize the longitudinal momentum fraction distributions of partons inside the proton



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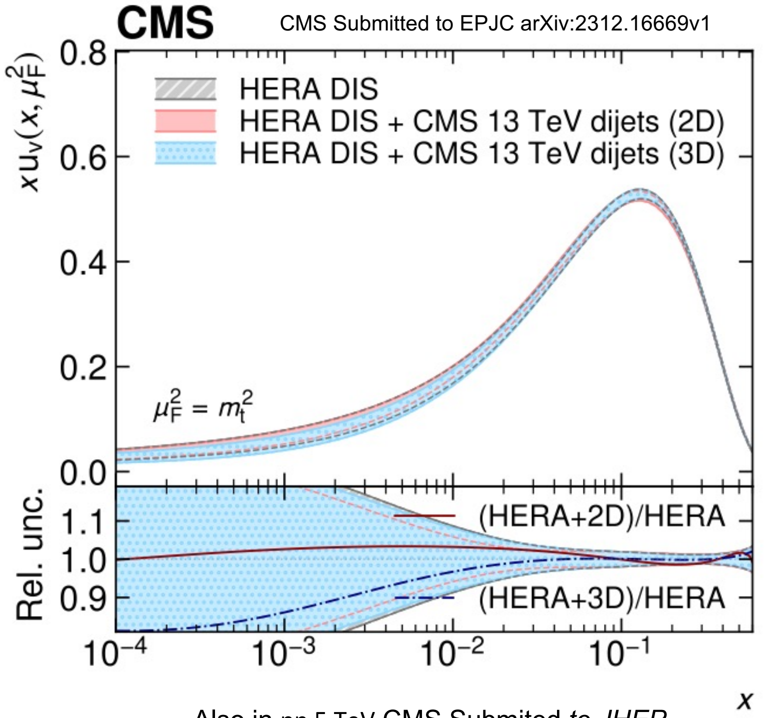
Recent results on PDFs

PDF from di-jet cross section

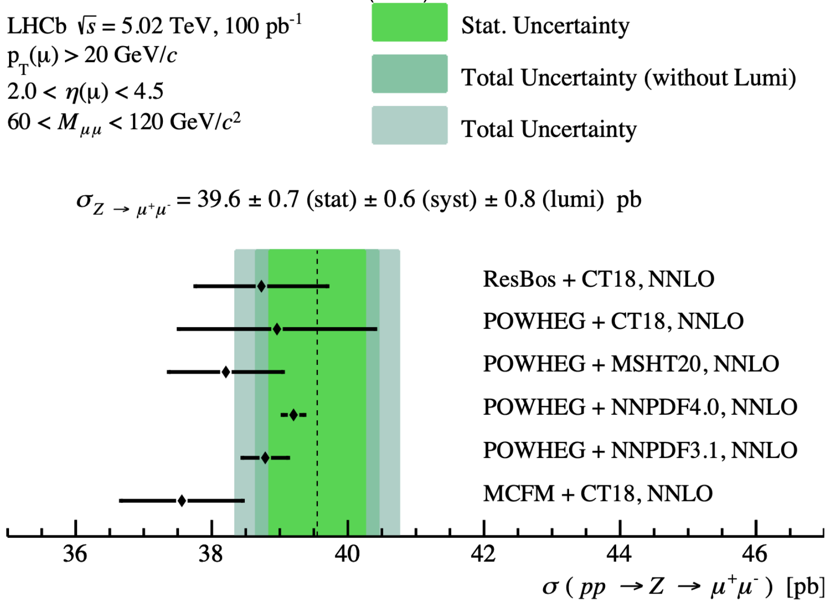
CMS Submitted to EPJC arXiv:2312.16669v1



Also in pp 5 TeV CMS Submited *to JHEP*
arXiv:2312.16669v1 arXiv:2401.11355

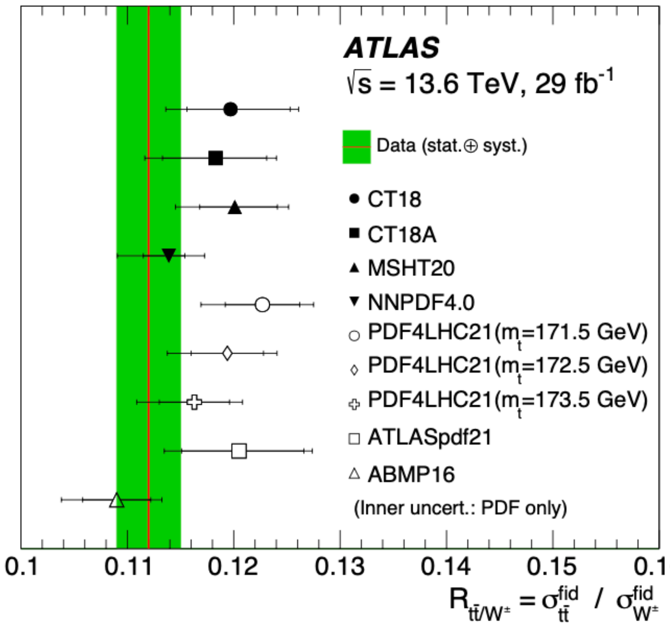
PDF from Z cross section

LHCb JHEP 02 (2024) 070 arXiv:2308.12940v4



PDF from $W^{\pm}$ and Z-bosons
Ratio with $t\bar{t}$ pair

ATLAS Phys. Lett. B 854 (2024) 138725. arXiv:2403.12902v2



More from J. Roloff & Tim Martin
Thursday 06/06

sarah.porteboeuf@clermont.in2p3.fr

Testing pQCD with jet cross section ratio

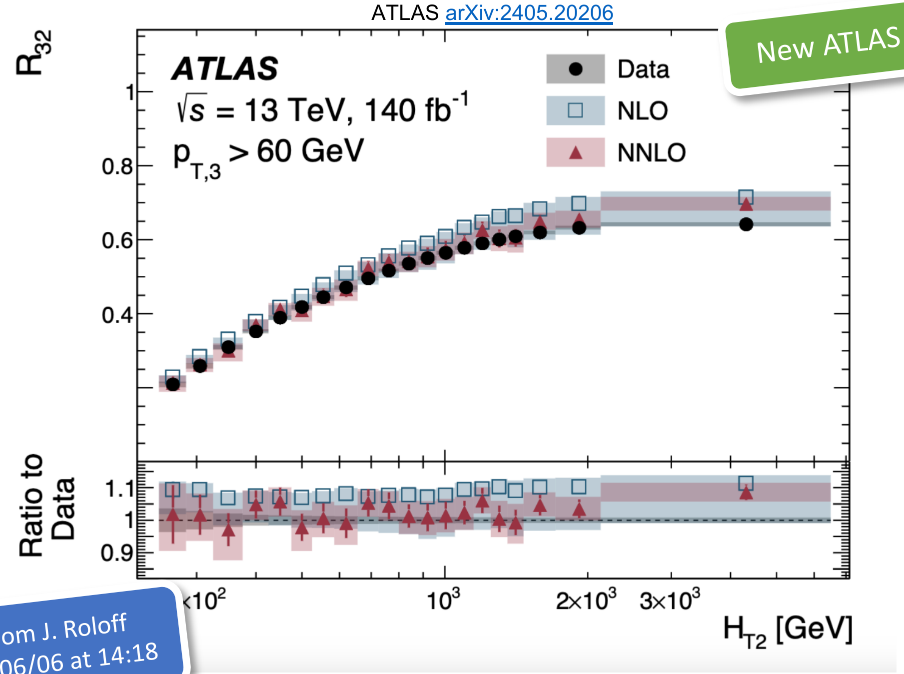
Events with multiple jets

Scalar sum of the transverse momenta of the leading two jets

$$H_{T2} = p_{T,1} + p_{T,2}$$

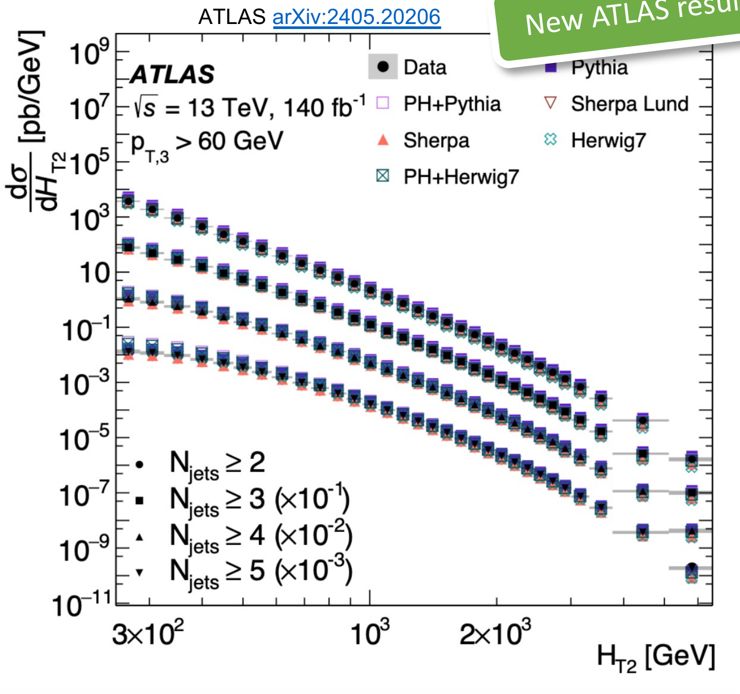
$$H_{T2} \geq 250 \text{ GeV}$$

Proxy for the energy scale of the hard-scattering interaction



New ATLAS result

More from J. Roloff Thursday 06/06 at 14:18



New ATLAS result

NNLO computations better described 3-to-2 cross section ratio, R_{32}, than NLO (ratios reduce uncertainties from PDF)

Importance of the higher-order predictions in describing multijet production

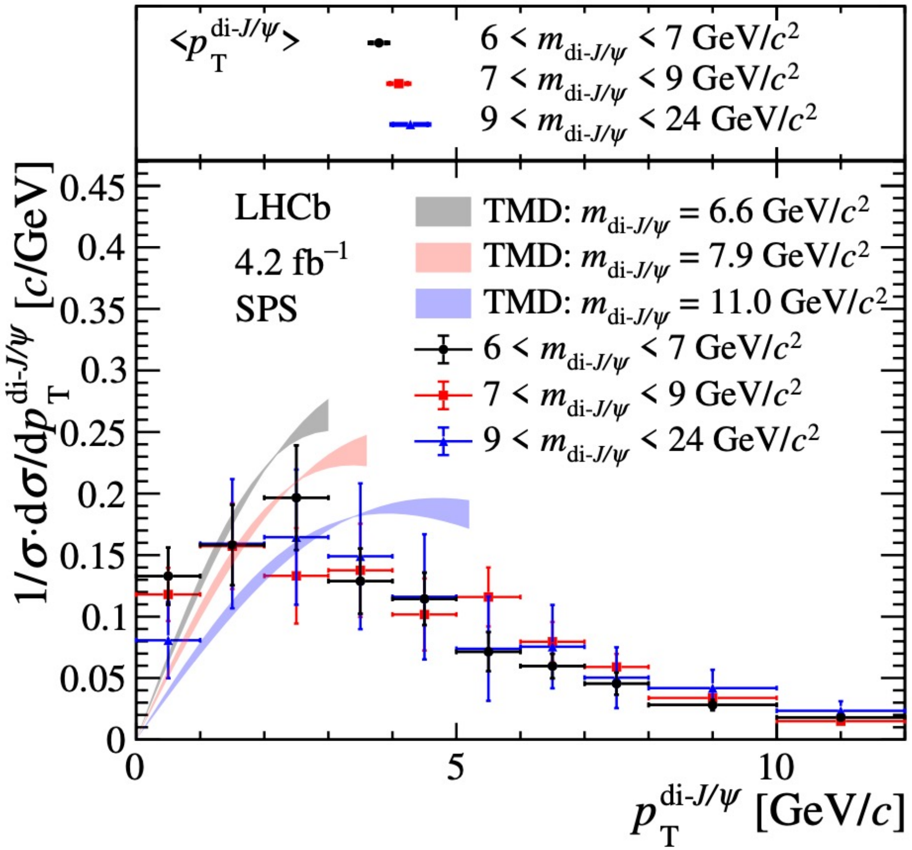
sarah.porteboeuf@clermont.in2p3.fr

Di-J/ψ to access TMDs

Transverse-Momentum Dependent Parton Distribution Functions

3 dimensional imaging of hadrons including transverse momentum and polarization degrees of freedom

LHCb JHEP 03 (2024) 088 arXiv:2311.14085v2



Di-J/ψ produced with **one hard process** (Single Parton Scattering) as a **golden channel to probe gluon TMDs** $f_1^g(x, k_T^2, \mu)$

No obvious broadening of the p_T spectrum can be seen in the TMD region

Di-J/ψ to access TMDs

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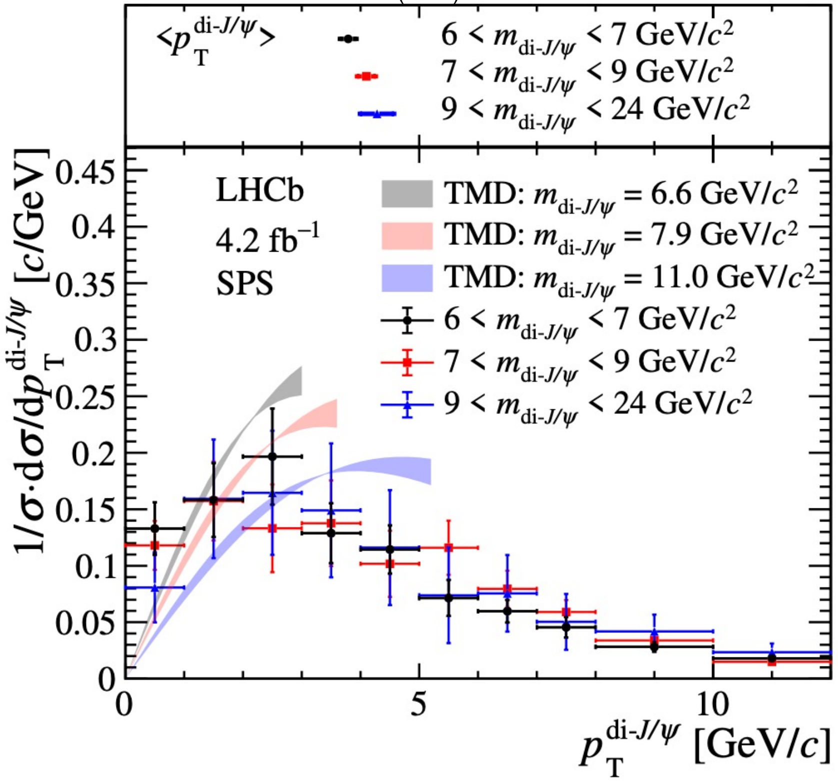


No obvious broadening of the p_T spectrum can be seen in the TMD region

The **azimuthal asymmetry of J/ψ pairs** is measured to probe the TMD function $h_1^{\perp g}(x, k_T^2, \mu)$

$$\langle \cos 2\phi_{CS} \rangle = -0.029 \pm 0.050\ (\text{stat}) \pm 0.009\ (\text{syst}),$$
$$\langle \cos 4\phi_{CS} \rangle = -0.087 \pm 0.052\ (\text{stat}) \pm 0.013\ (\text{syst}),$$

LHCb JHEP 03 (2024) 088 arXiv:2311.14085v2

Measurement consistent with 0

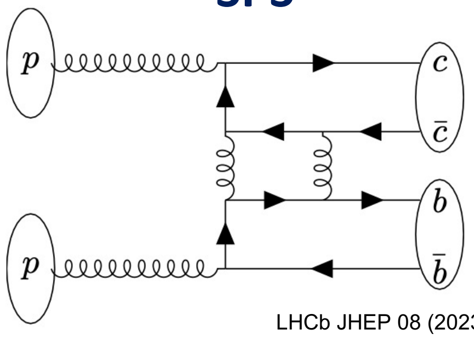
Presence of an azimuthal asymmetry at a few percent level is allowed

First experimental measurement of linear polarization of gluons inside unpolarized protons

sarah.porteboeuf@clermont.in2p3.fr

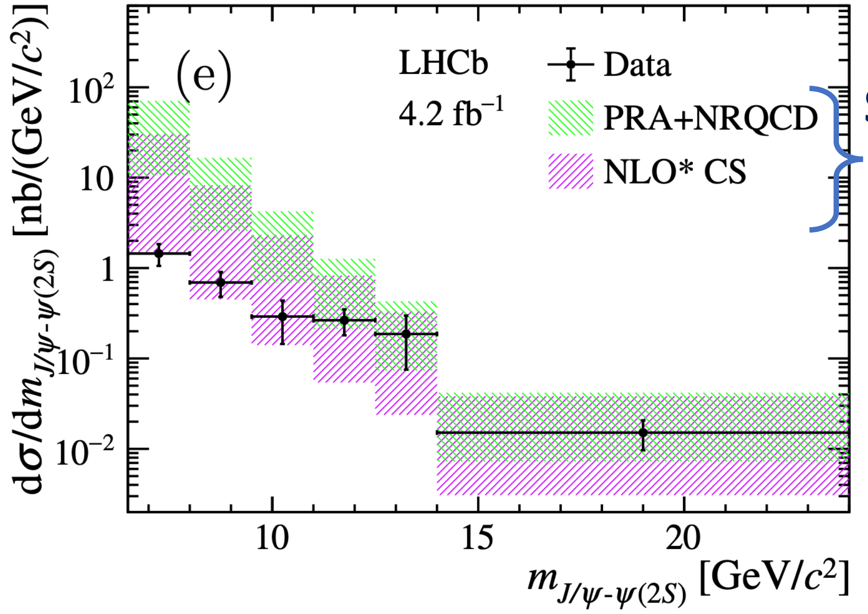
Double parton scattering: J/ψ + ψ(2S) or Υ(ns)

SPS



LHCb JHEP 08 (2023) 093 arXiv:2305.15580v2

LHCb JHEP 05 (2024) 259 arXiv:2311.15921v1

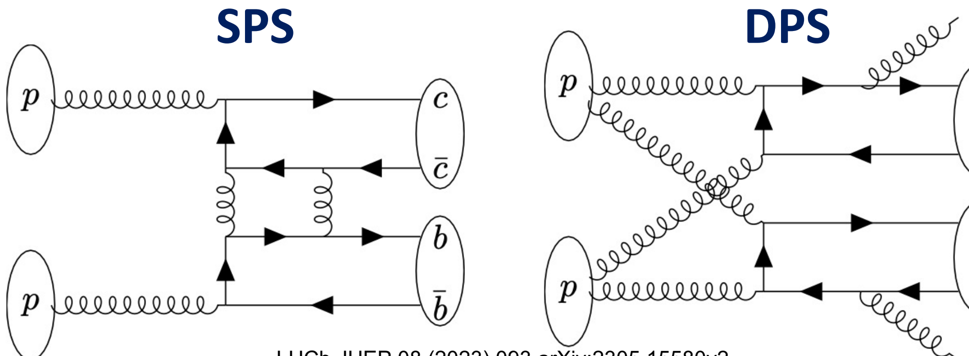


SPS

sarah.porteboeuf@clermont.in2p3.fr

LHCP Boston 2024

Double parton scattering: J/ψ + ψ(2S) or Υ(ns)

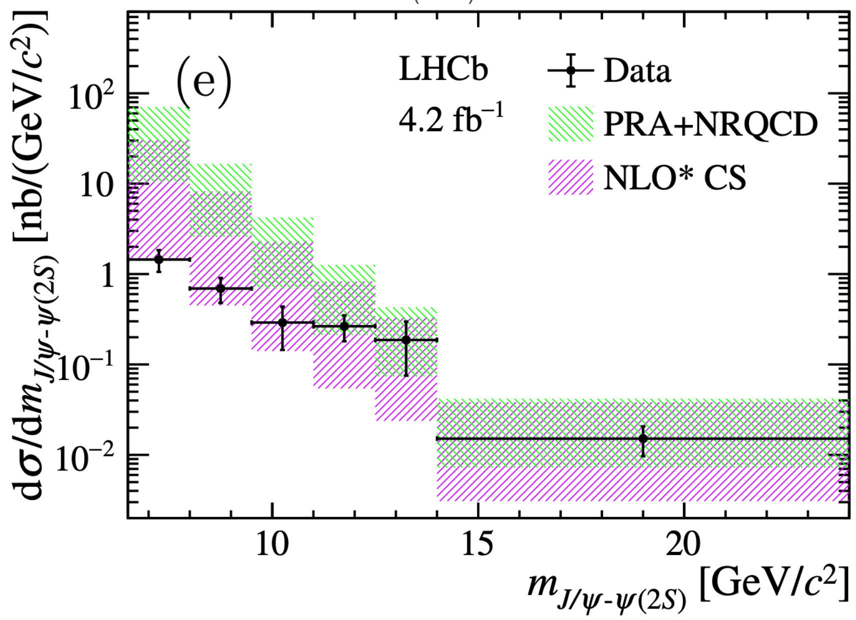


LHCb JHEP 08 (2023) 093 arXiv:2305.15580v2

$$\sigma_{DPS}^{AB} = \frac{m}{2}\frac{\sigma_{SPS}^{A}\sigma_{SPS}^{B}}{\sigma_{eff}}$$

m=2 when A and B are distinguishable
m=1 when indistinguishable

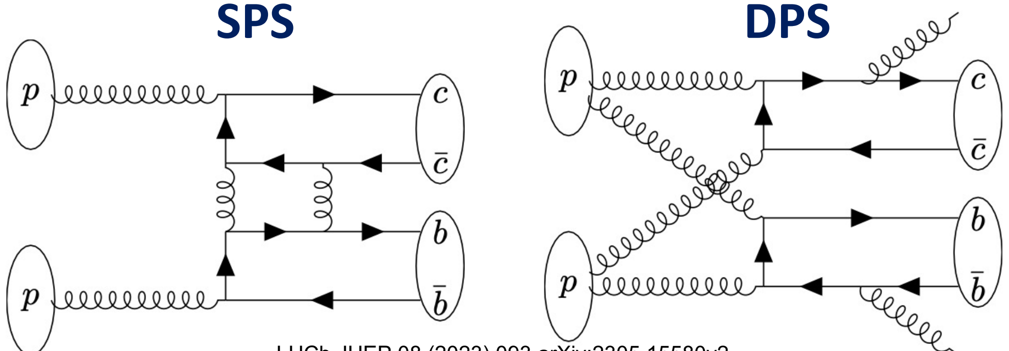
LHCb JHEP 05 (2024) 259 arXiv:2311.15921v1



Assume PDF factorization
Expected properties of σ_{eff}:
- collision energy independent
- process independent

sarah.porteboeuf@clermont.in2p3.fr

Double parton scattering: $J/\psi + \psi(2S)$ or $\Upsilon(ns)$



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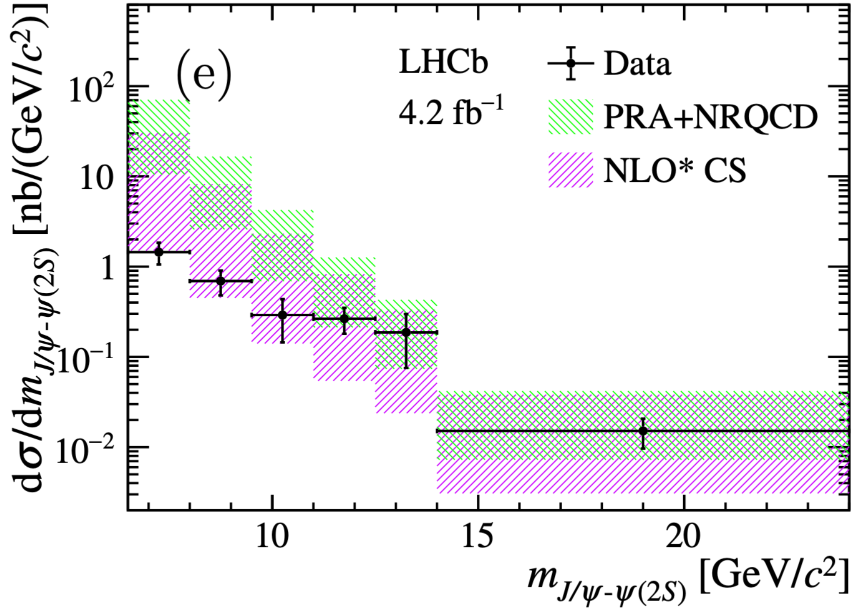
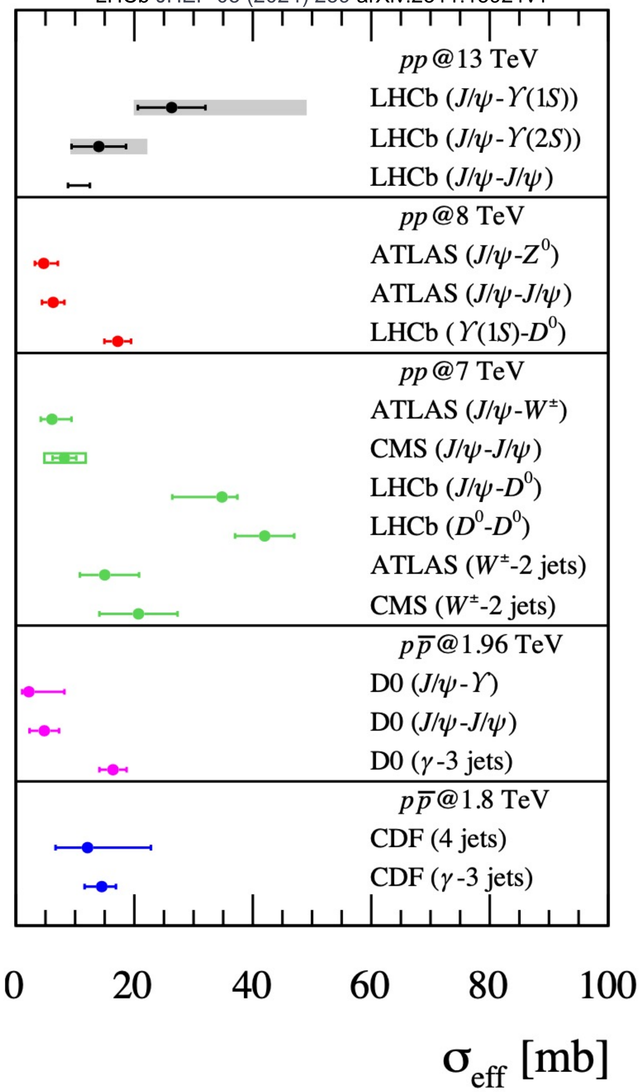


ALICE di-J/ψ

$$\sigma_{eff} = 6.7 \pm 1.6(\text{stat}) \pm 2.7\ (\text{syst})\text{mb}$$

ALICE Phys. Rev. C 108, 045203 (2023) arXiv:2303.13431

LHCb JHEP 05 (2024) 259 arXiv:2311.15921v1



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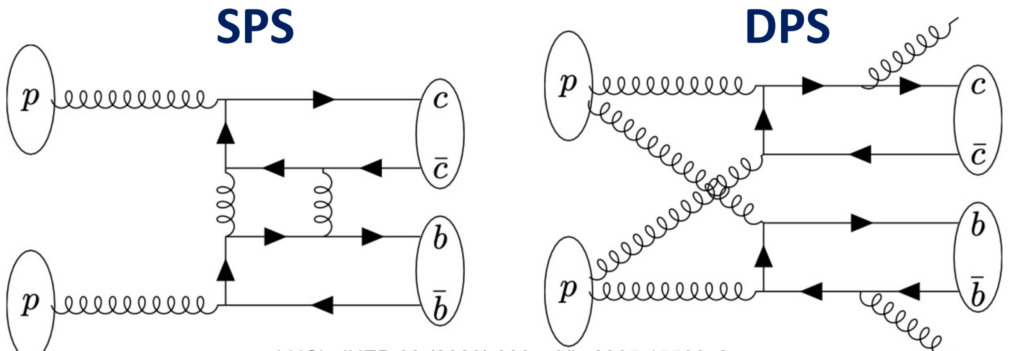
Double parton scattering: J/ψ + ψ(2S) or Υ(ns)



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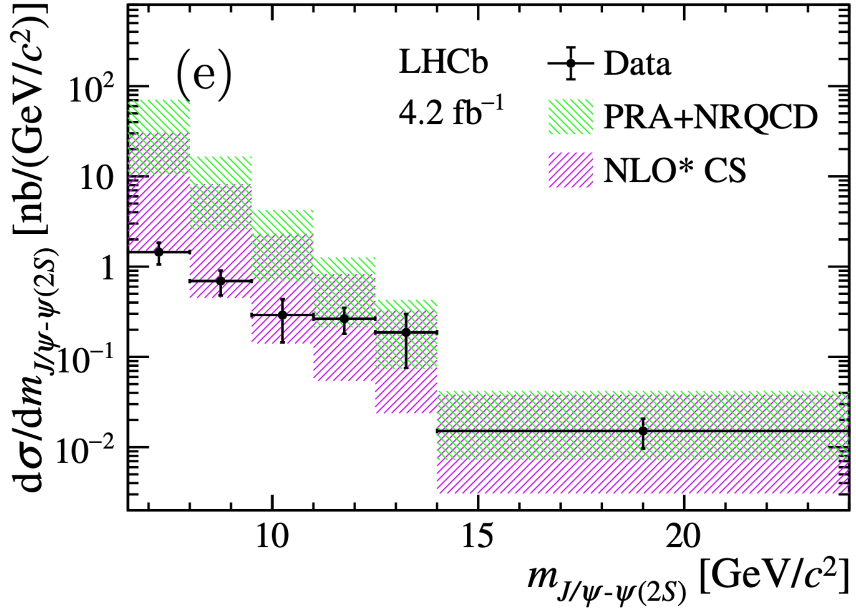
LHCb JHEP 05 (2024) 259 arXiv:2311.15921v1



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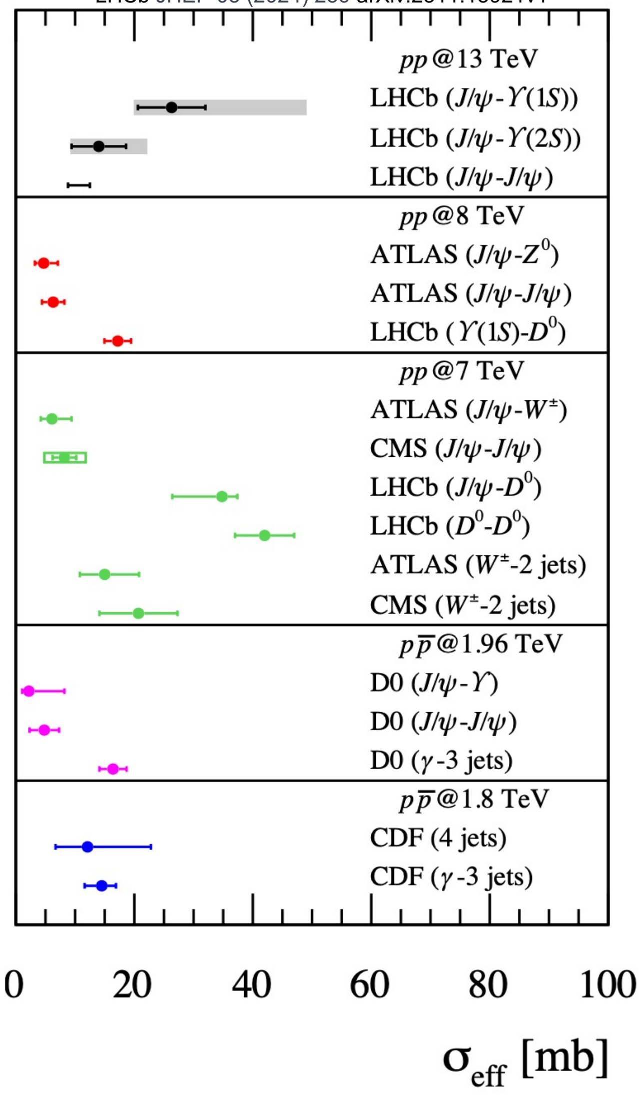
ALICE Phys. Rev. C 108, 045203 (2023) arXiv:2303.13431

Observed properties of σ_{eff}
Process dependent
Kinematic dependent
Energy dependent

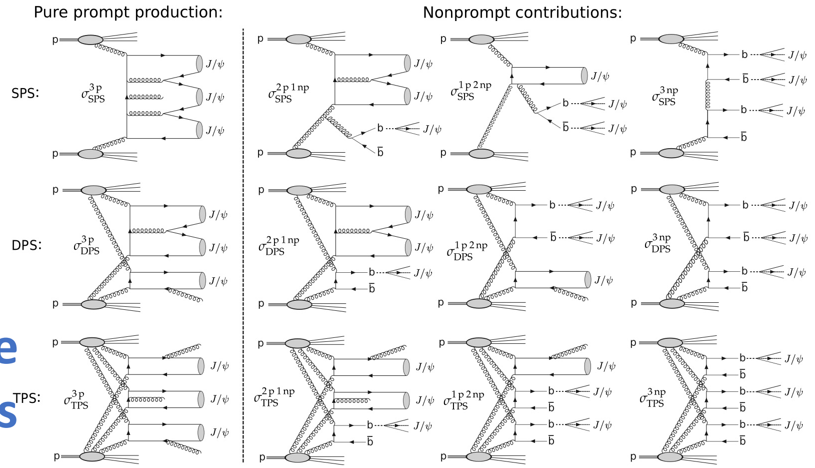
LHCb JHEP 05 (2024) 259 arXiv:2311.15921v1

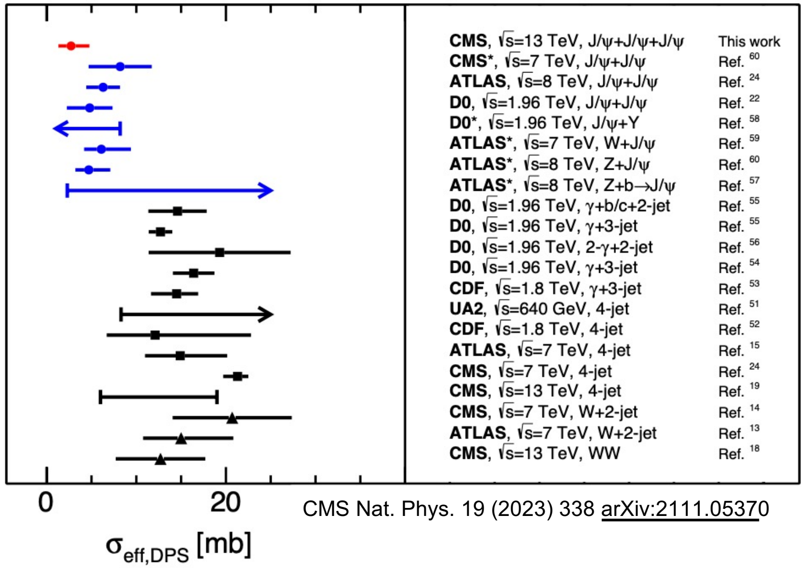


sarah.porteboeuf@clermont.in2p3.fr

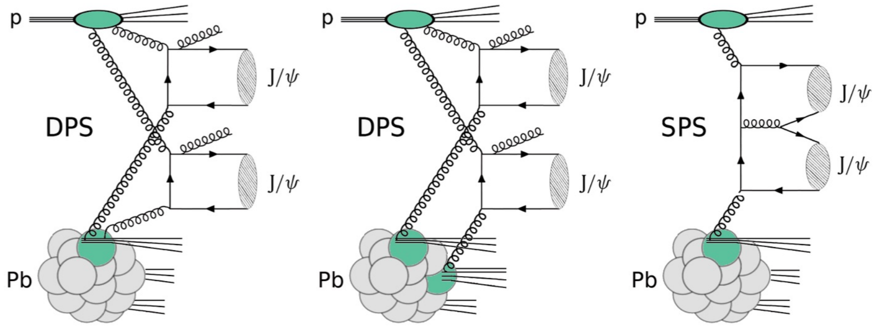
Next orders: tri-J/ψ in pp and di-J/ψ in p-Pb

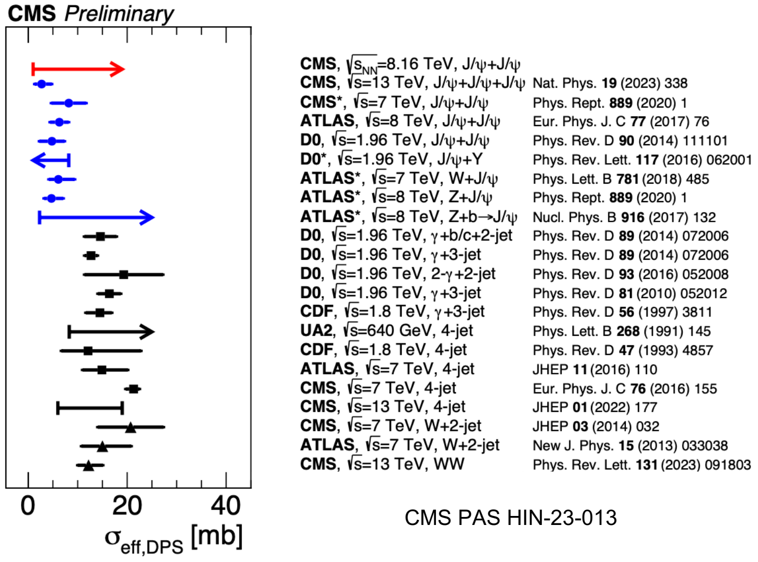
Confirm the dependence of the effective DPS cross section on the relevant parton species and *x* fractions probed





CMS Nat. Phys. 19 (2023) 338 arXiv:2111.05370



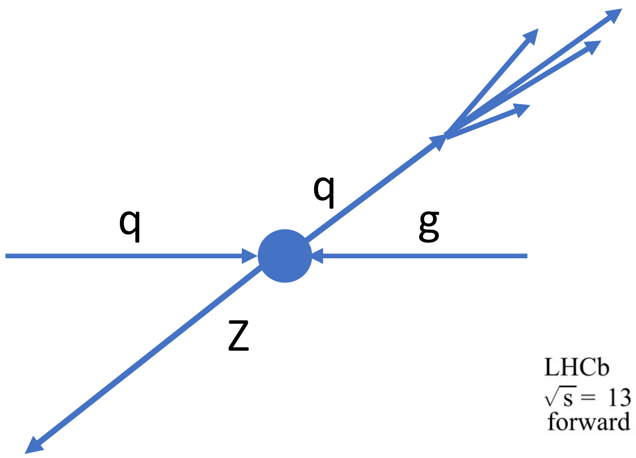


CMS PAS HIN-23-013

Also extracted from p-Pb collisions

sarah.porteboeuf@clermont.in2p3.fr

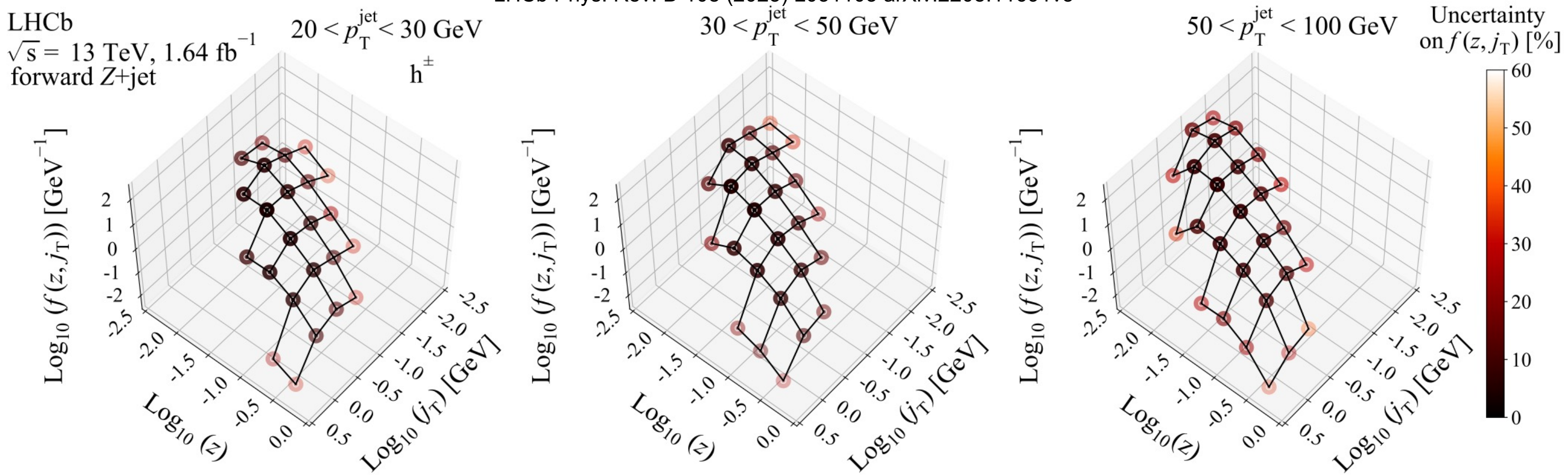
Jet Fragmentation Function of charged hadrons



Extraction of the **double differential JFFs** in j_T and z, in 3 jet p_T intervals for unidentified charged hadrons

Probe the longitudinal and transverse profiles of identified charged pions, kaons, and protons inside predominantly light-quark-initiated jets

LHCb Phys. Rev. D 108 (2023) L031103 arXiv:2208.11691v3



z longitudinal momentum fraction of the jet carried by the hadron
j_T transverse component of the hadron momentum with respect to the jet axis

More from S. Caletti & T. Martin Thursday 06/06

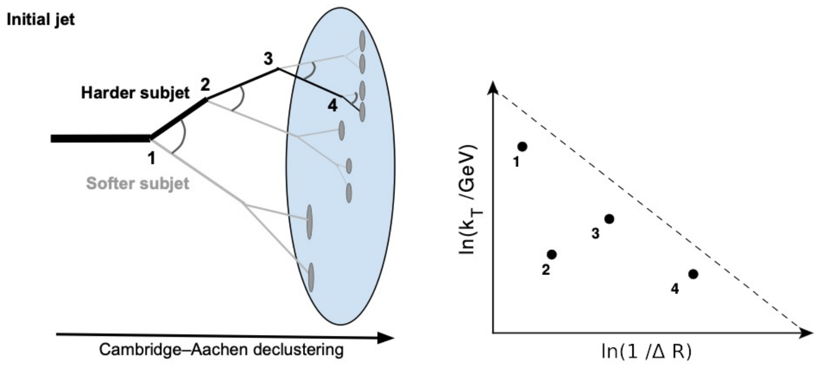
Probe the 3D picture of FF in the collinear and transverse dimension with respect to the jet axis

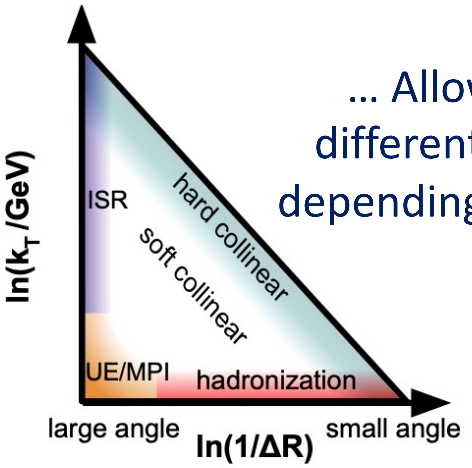
sarah.porteboeuf@clermont.in2p3.fr

More from I. Chahrour
Thursday 06/06 at 14:36

Lund sub-jet multiplicities

Two-dimensional representation of the phase space of emissions inside a jet …





… Allow to probe different mecanisms depending on kinematic

Lund sub-jet multiplicities

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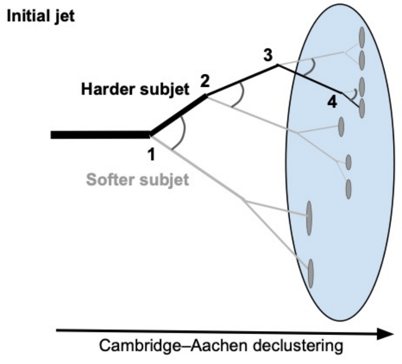
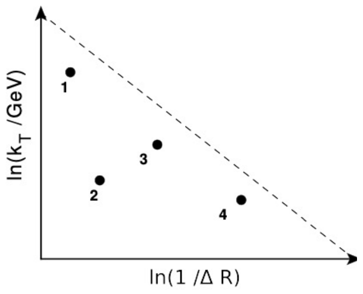
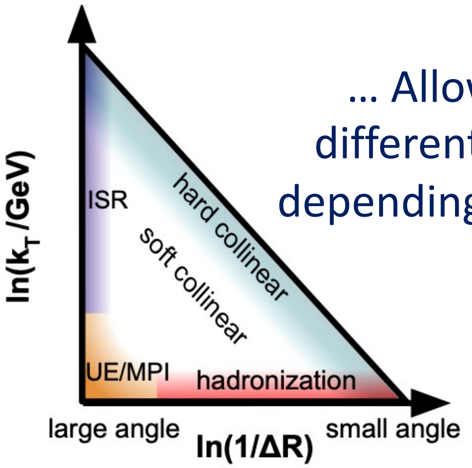




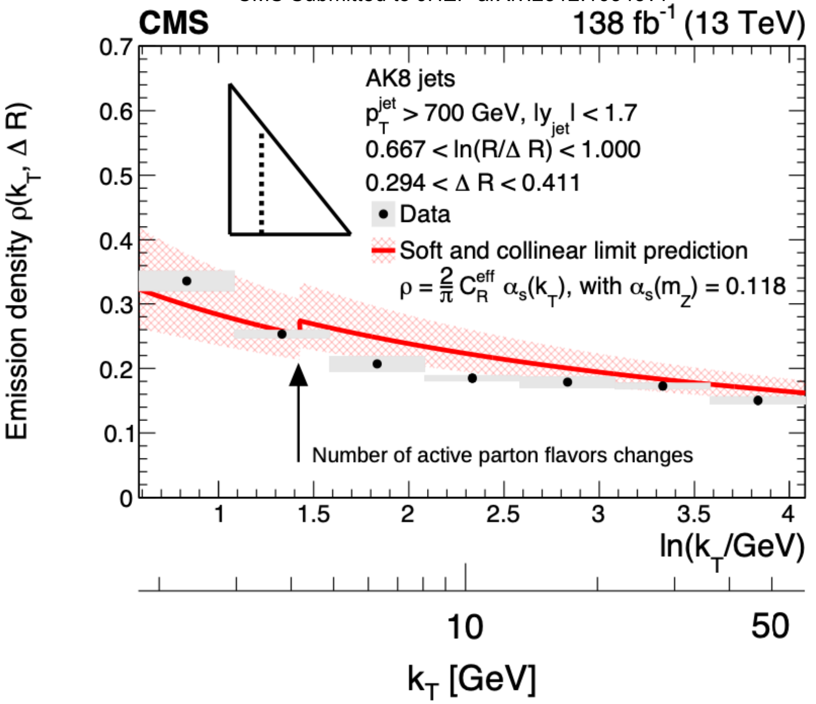


… Allow to probe different mecanisms depending on kinematic

Running of α_s in the jet shower

dominant mechanism responsible for the rise of the LJP density at low k_T (k_T characteristic energy scale in α_s evolution)

CMS Submitted to JHEP arXiv:2312.16343v1



Testing QCD with jet substructure

LHCP Boston 2024

Lund sub-jet multiplicities

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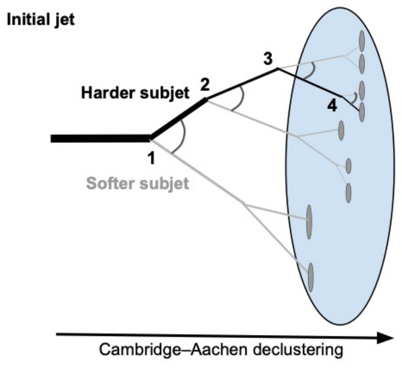
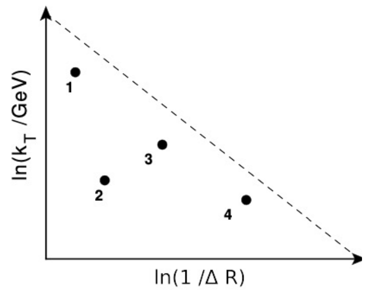
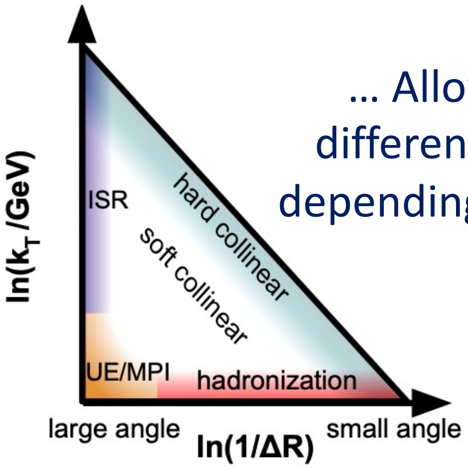
Two-dimensional representation of the phase space of emissions inside a jet …







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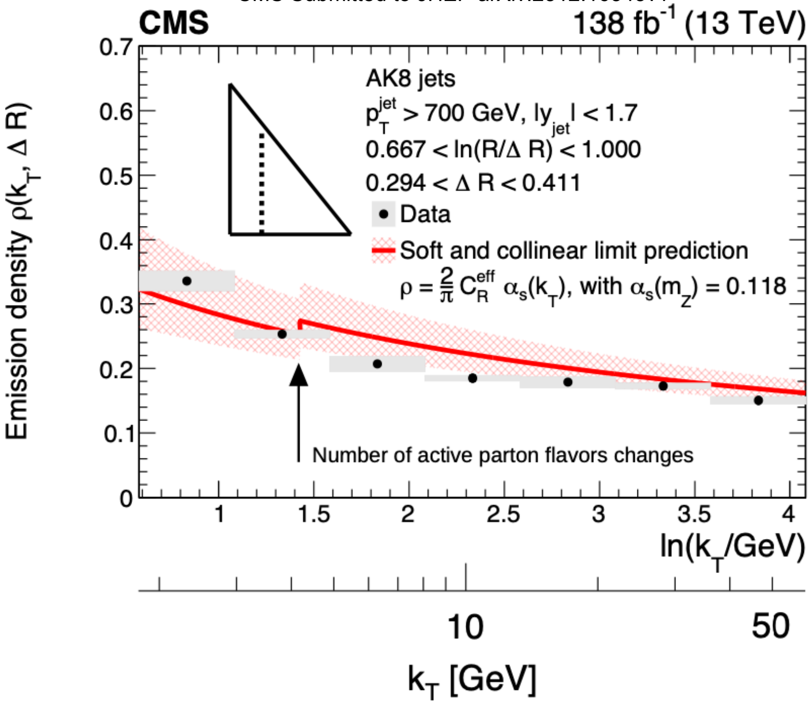
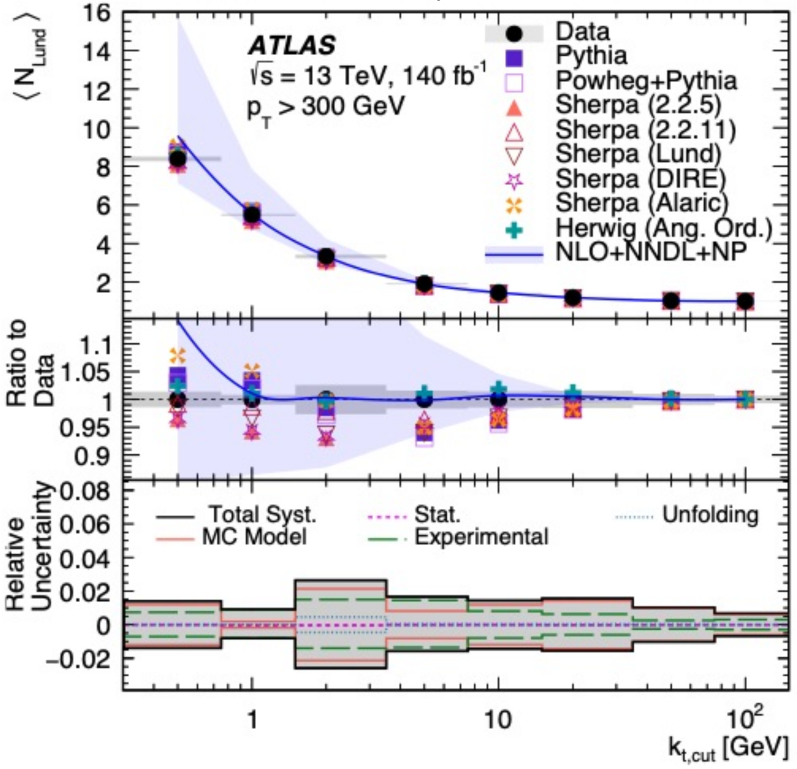
CMS Submitted to JHEP arXiv:2312.16343v1



Measurement of average number of Lund subject multiplicities

to constrained models

ATLAS Submitted to: Phys. Lett. B arXiv:2402.13052v1



Testing QCD with jet substructure

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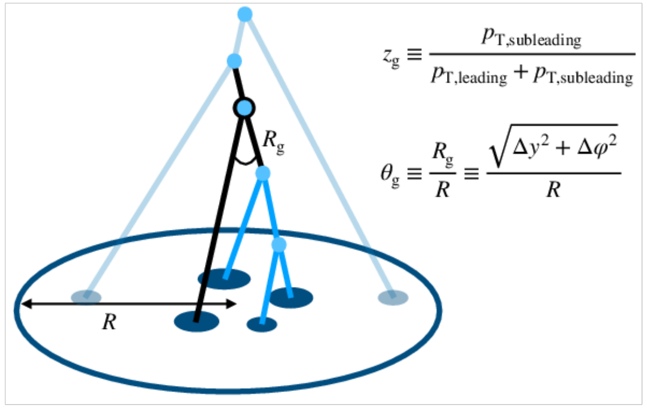
Substructure of D_0 tagged jets



More from S. Caletti
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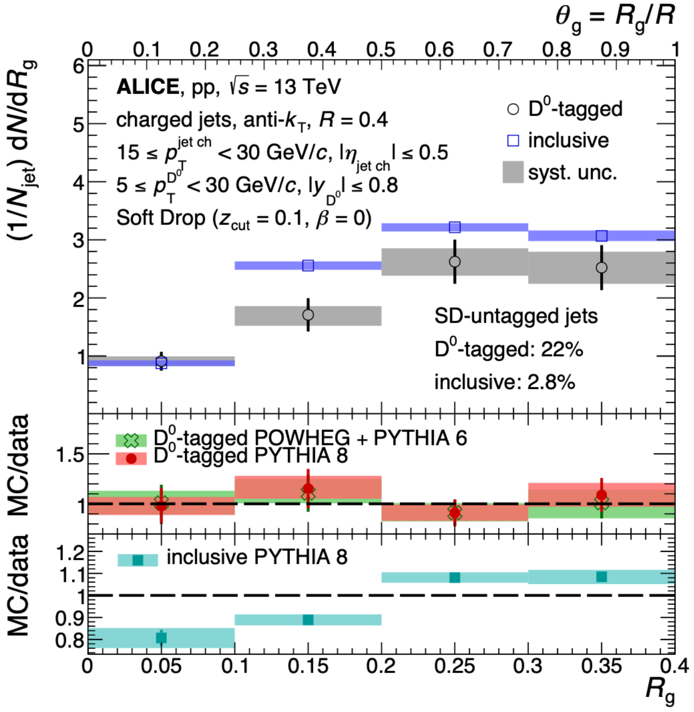
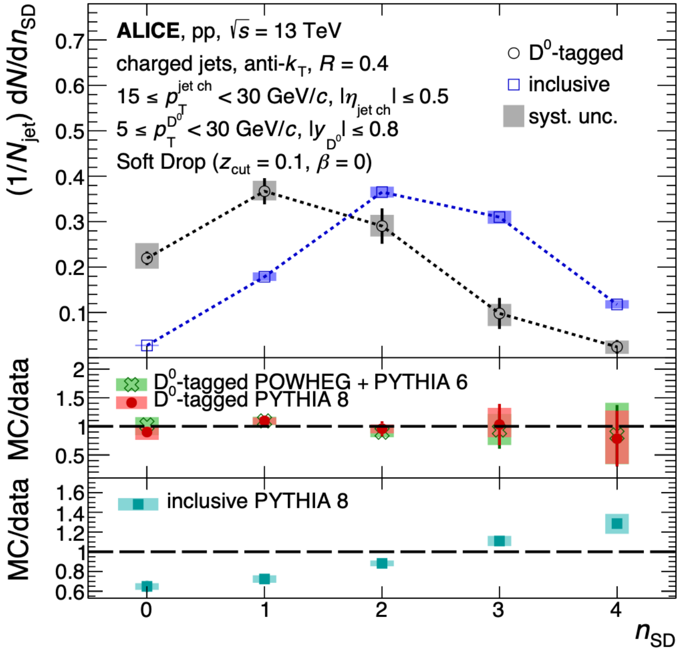
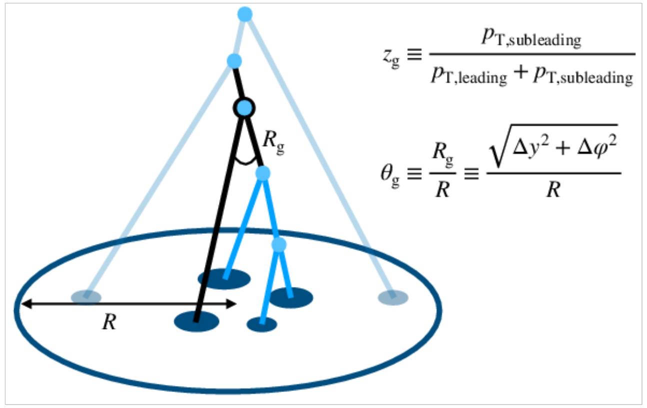
ALICE Phys. Rev. Lett. 131 (2023) 192301 arXiv:2208.04857





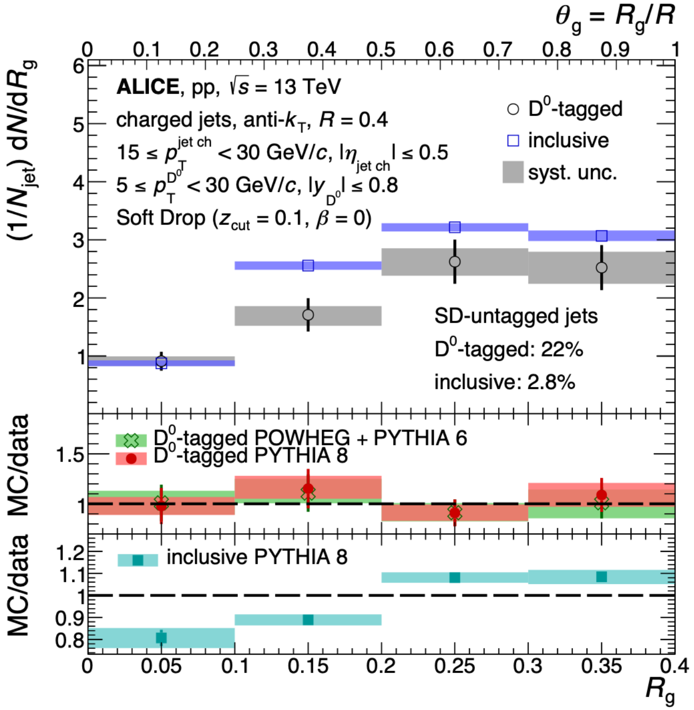
Direct experimental constraint of the splitting function of heavy-flavour quarks

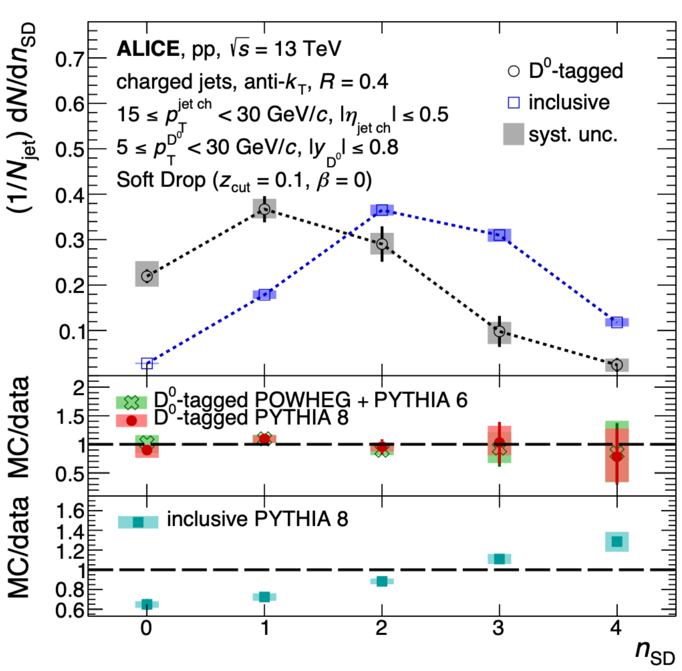
Substructure of D_0 tagged jets



More from S. Caletti
Thursday 06/06 at 14:00

ALICE Phys. Rev. Lett. 131 (2023) 192301 arXiv:2208.04857





➢ **Charm quarks R_g distribution**: **reduction at large-angles**. Inclusive sample with larger-angle perturbative emissions (gluon)

Direct experimental constraint of the splitting function of heavy-flavour quarks

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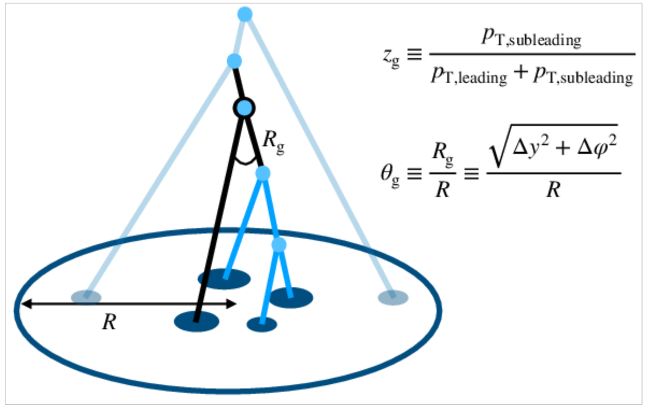

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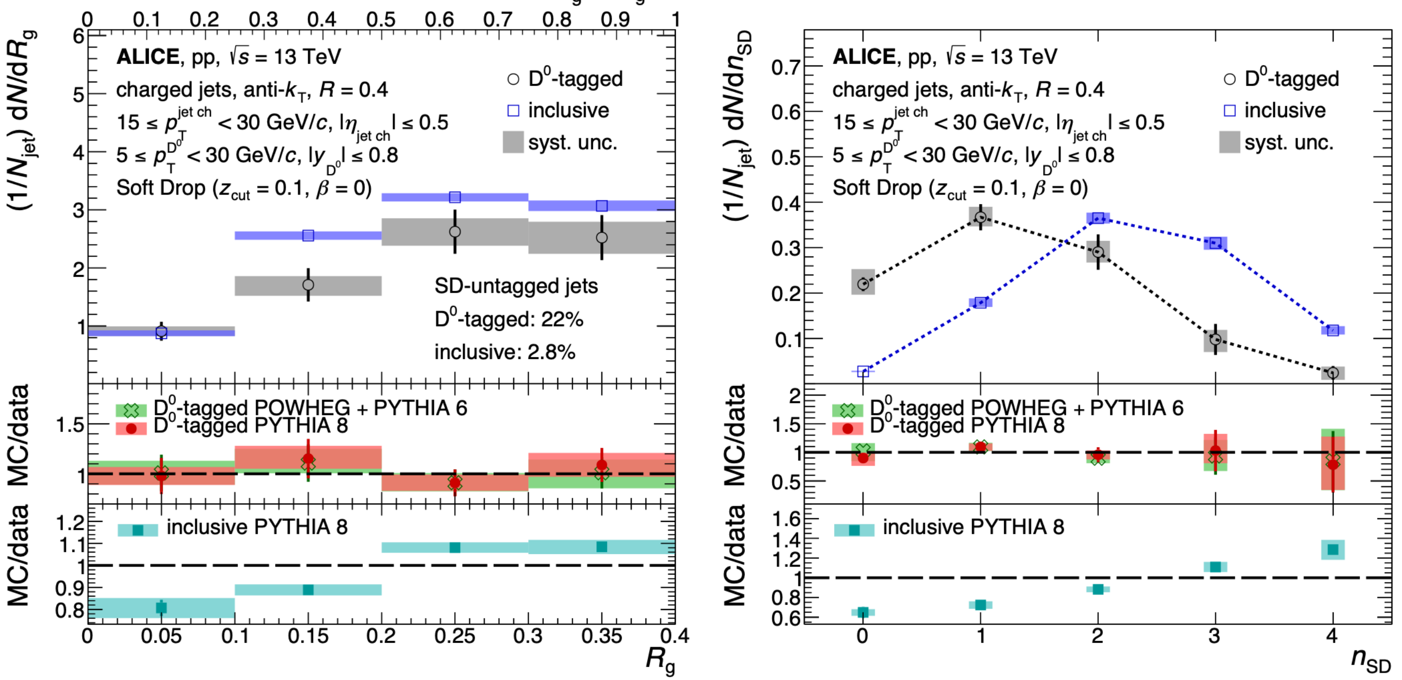


- **Charm quarks R_g distribution**: **reduction at large-angles**. Inclusive sample with larger-angle perturbative emissions (gluon)
- **n_{SD} distribution** (number of emissions of the charm quark satisfying the Soft Drop condition): **shift to smaller values for the charm-tagged jets**. **Charm quarks on average emit fewer gluons**. Consistent with dead cone effect for charm quark.
- Different characteristics of heavy-quark emissions vs. light quarks and gluons: **constrain the roles of quark mass and Casimir colour factors** in the parton shower.

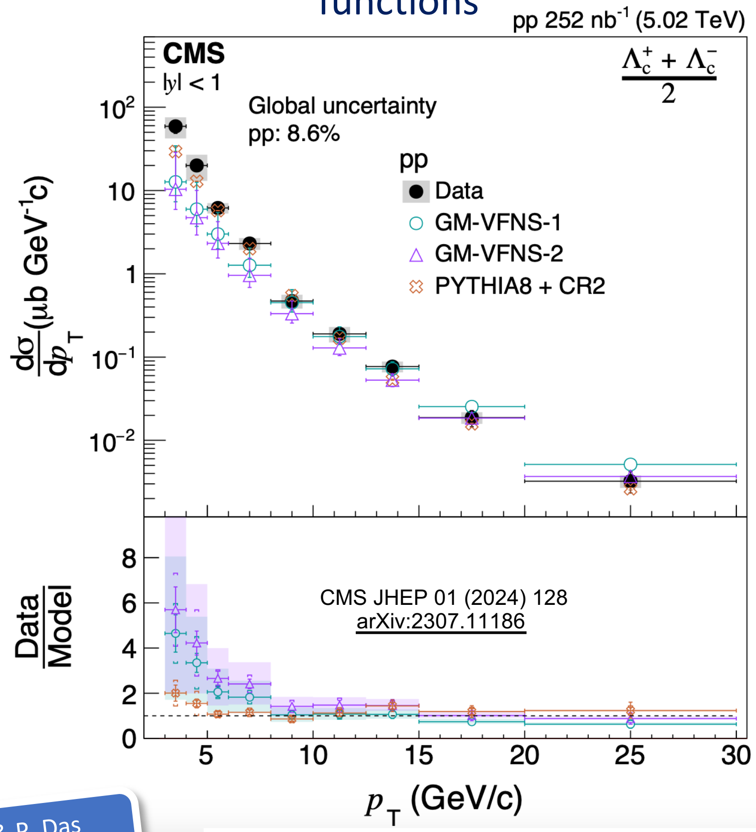
Direct experimental constraint of the splitting function of heavy-flavour quarks

Charm fragmentation at LHC

Λ_c^+-baryon yields much higher than predicted

(general-mass variable-flavor-number scheme with FF from OPAL and Belle fits)

Breakdown of the universality of charm quark fragmentation functions



More from V. Feuillard & P. Das
Wednesday 05/06 & Thursday 06/06

Charm hadronization is different in hadronic environment and in e^+e^-

LHCP Boston 2024

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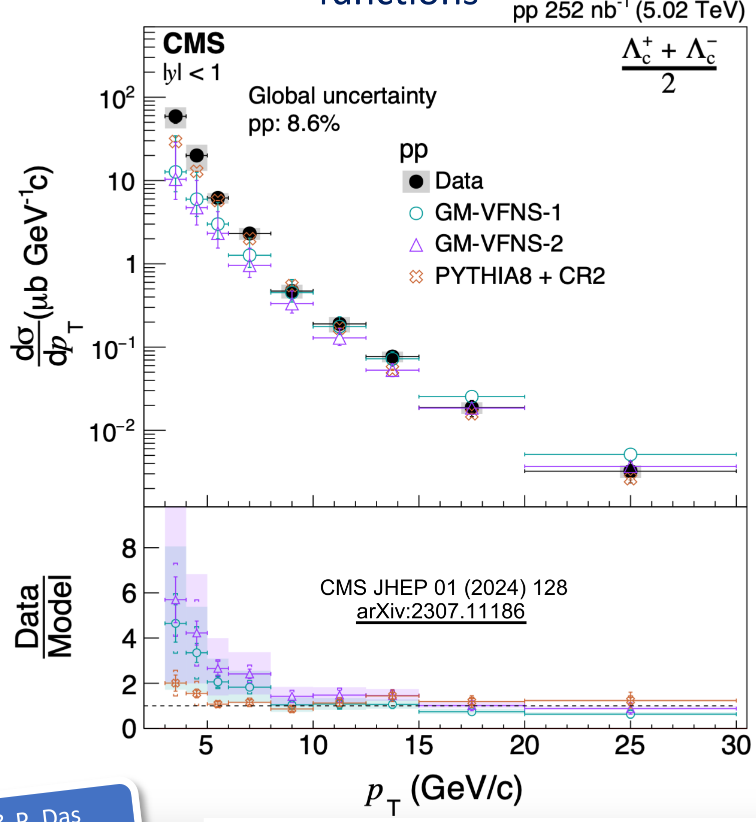
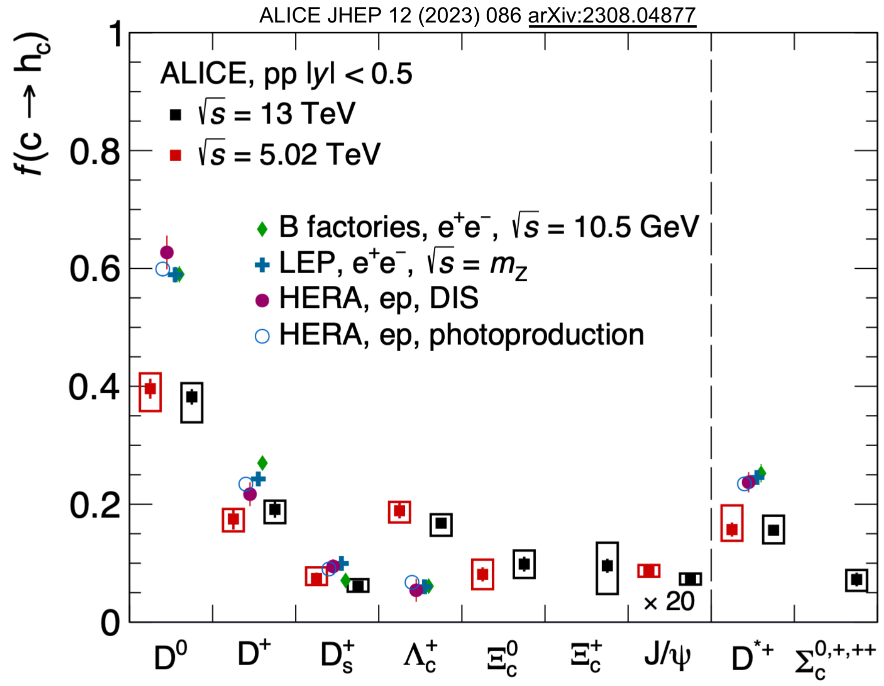


ALICE measured several charm hadron species

Prompt Λ_c^+-baryon fragmentation fraction in pp is ~3x larger than in e^+e^- and ep

Imply an overall reduction of the relative D-meson abundance (charm fragmentation function sum up to 1)



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sarah.porteboeuf@clermont.in2p3.fr

LHCP Boston 2024

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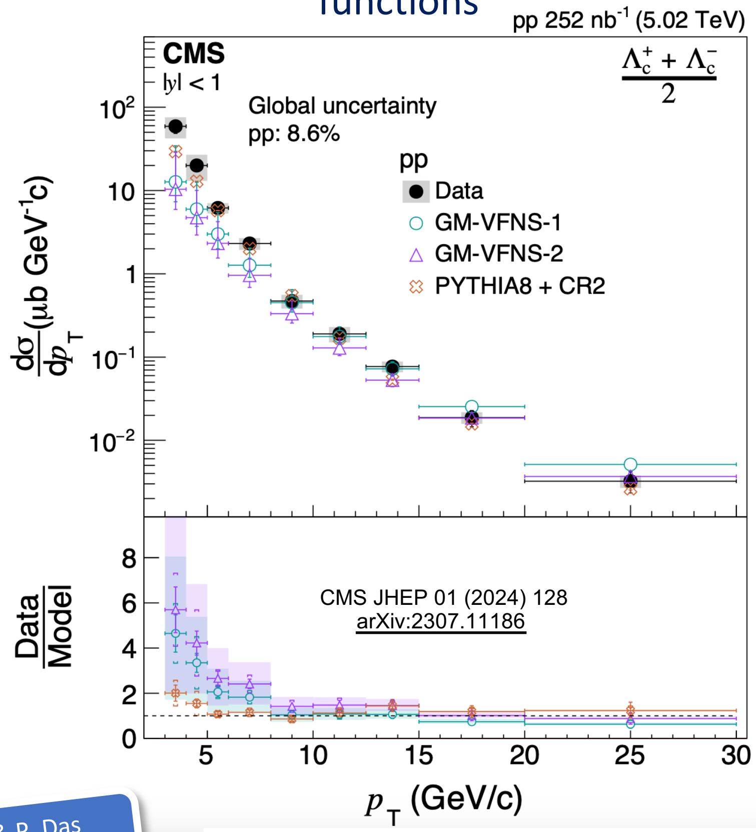

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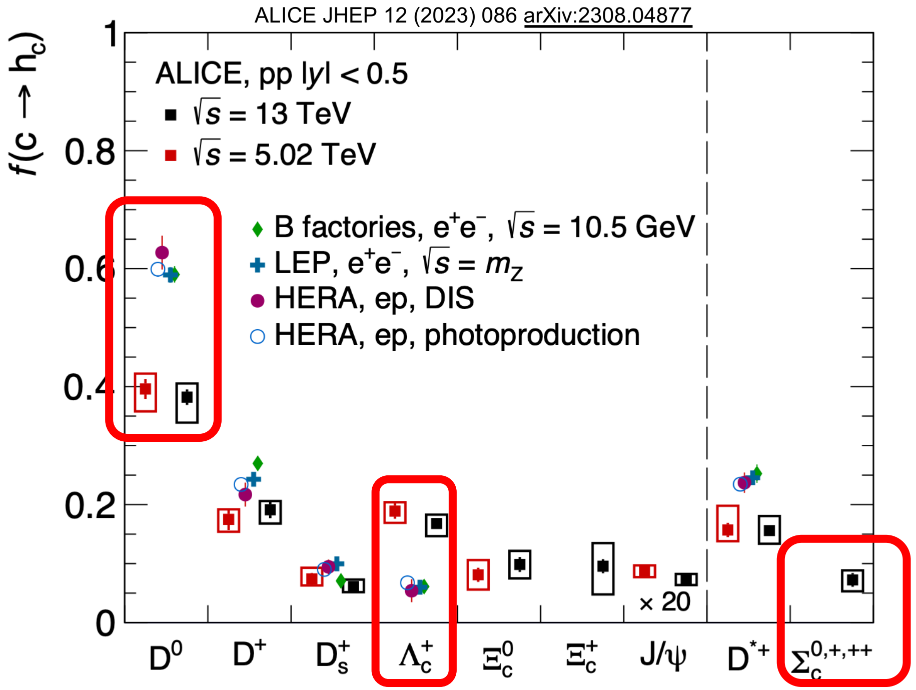


More from V. Feuillard & P. Das Wednesday 05/06 & Thursday 06/06

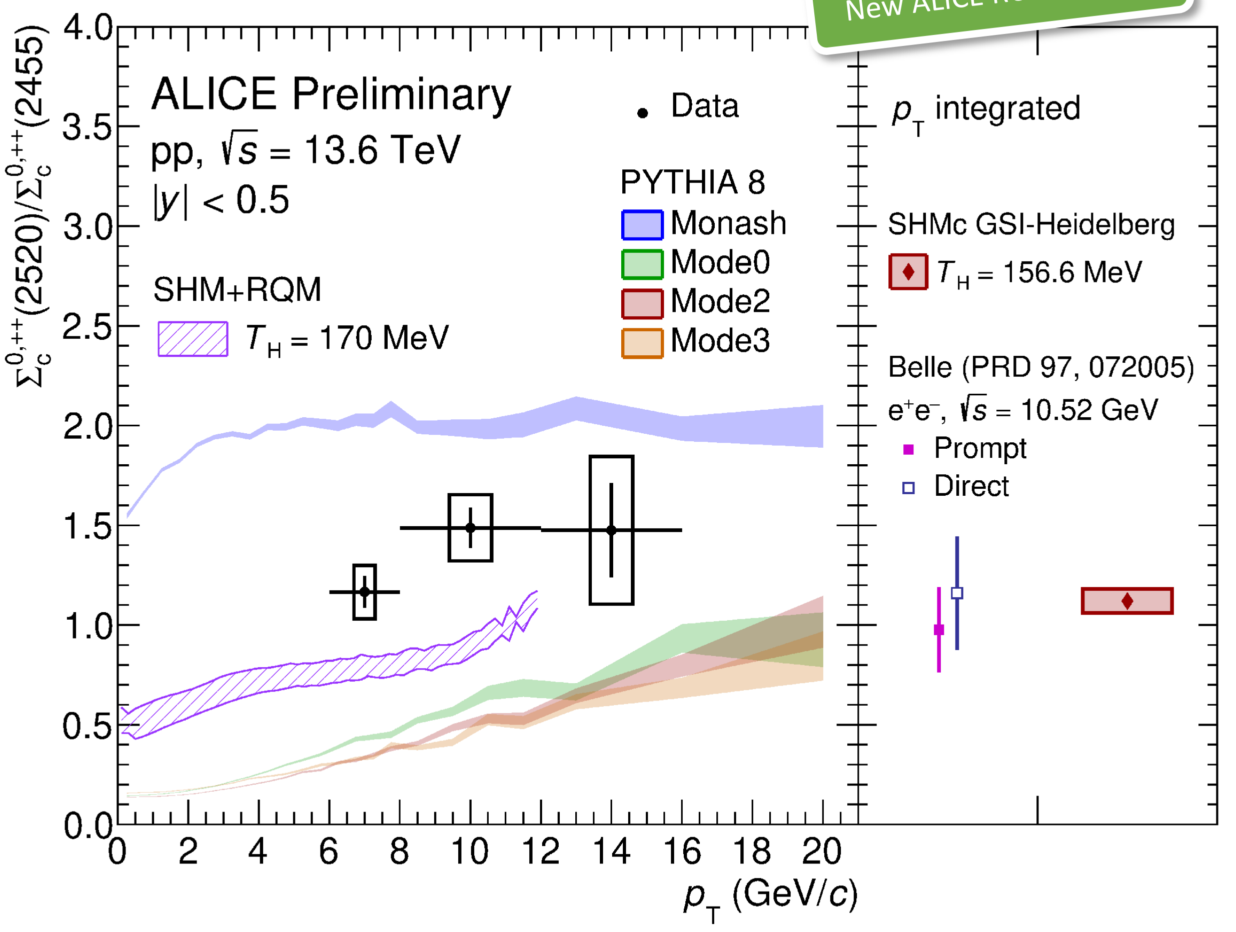
Charm hadronization is different in hadronic environment and in e^+e^-

sarah.porteboeuf@clermont.in2p3.fr

Charm fragmentation at LHC

- **First measurement of the $\Sigma_c^{0,++}(2520)$ relative production at the LHC**
- ALICE measurement in p_T range 6-14 GeV/c compatible with e^+e^- p_T integrated within uncertainties
- SHMc reproduces the ratio p_T integrated
- PYTHIA 8 (Monash + Mode 0/2/3) and Statistical Hadronization Model + RQM do not describe the data (feed-down from higher states under discussion)

New ALICE RUN 3 result



Charm abundance in pp under study

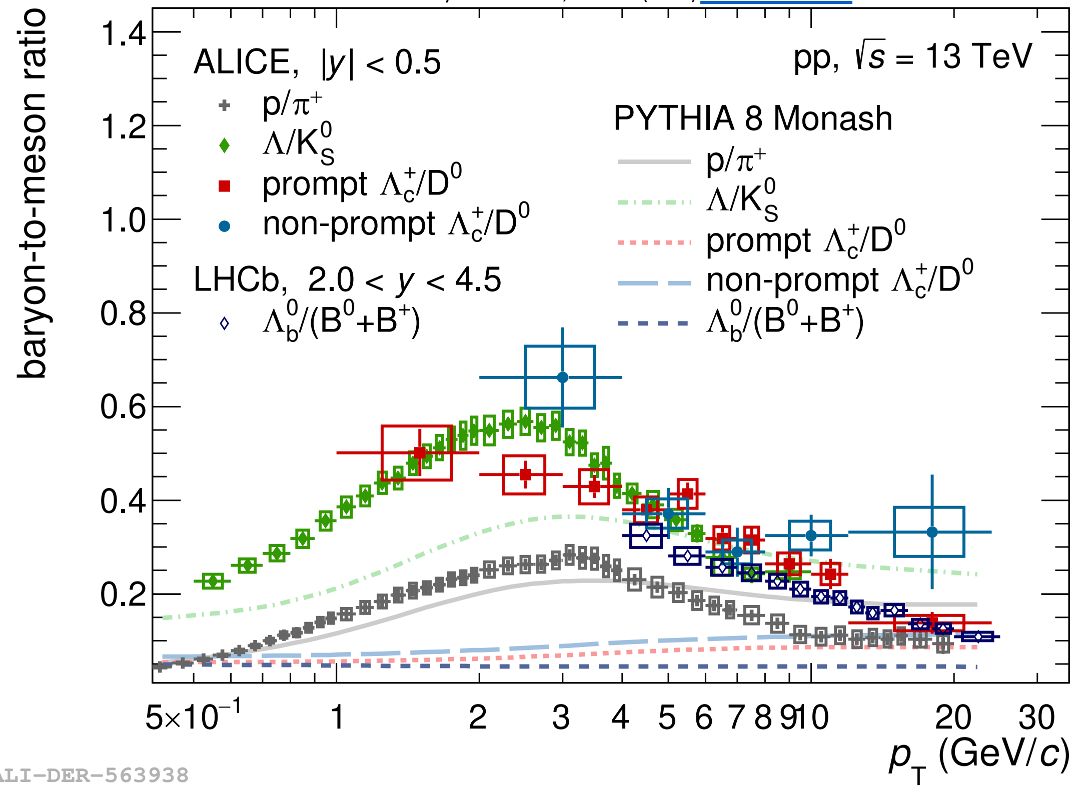
More from V. Feuillard Wednesday 05/06 at 14:18

sarah.porteboeuf@clermont.in2p3.fr

Beauty fragmentation at LHC

Beauty, charm, and strange hadrons show a similar trend as a function of p_T

ALICE Phys. Rev. D 108, 112003 (2023) arXiv:2308.04873



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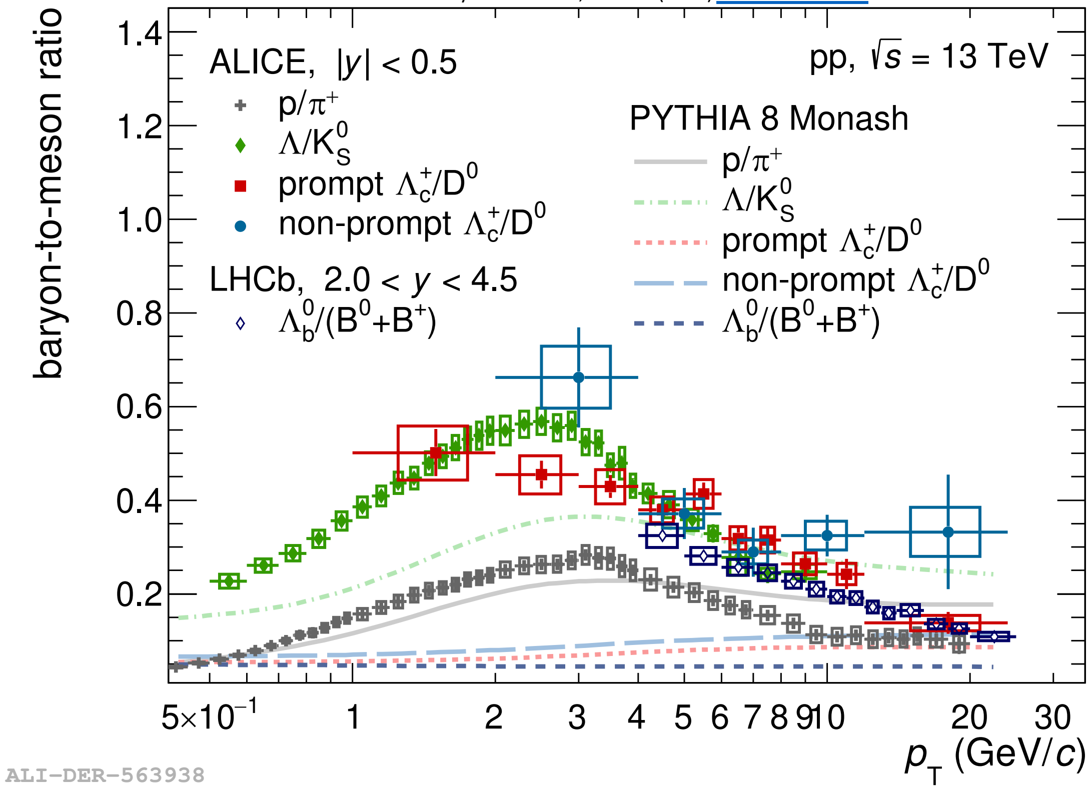
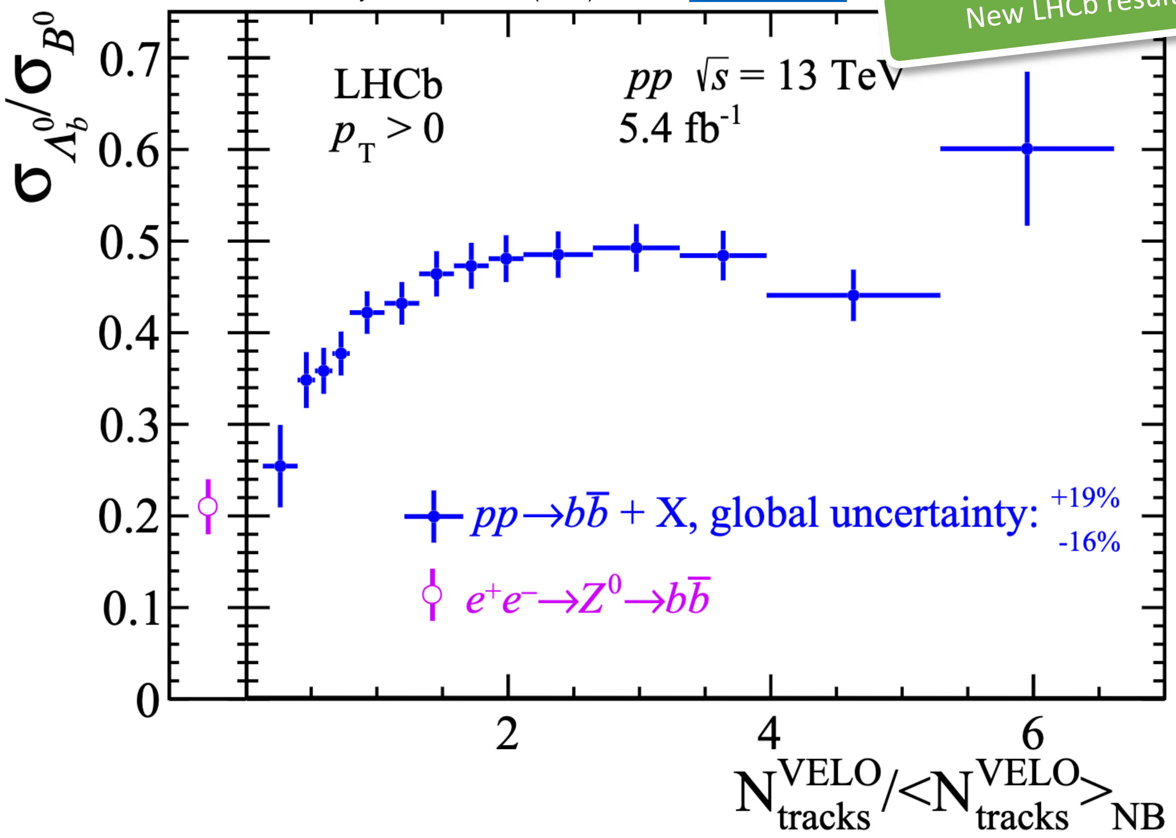


LHCb Phys. Rev. Lett. 131 (2023) 061901 arXiv:2204.13042

New LHCb result



Beauty hadronization is different in hadronic environment and in e^+e^-

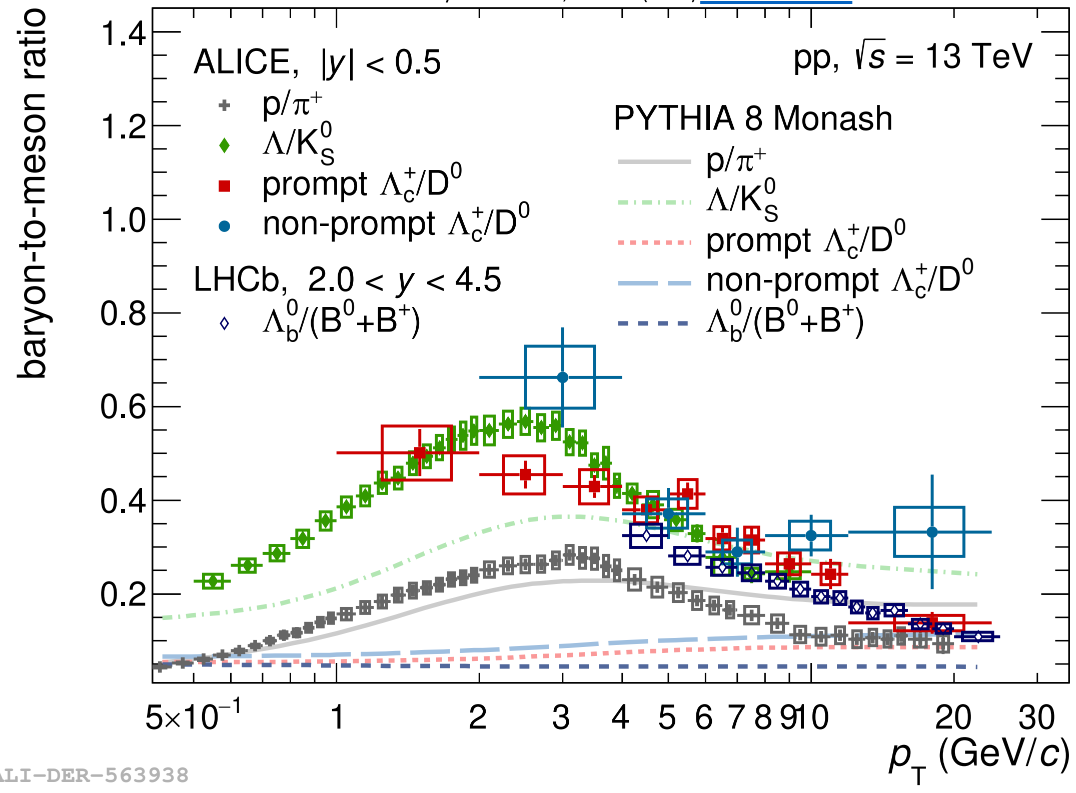
sarah.porteboeuf@clermont.in2p3.fr

Beauty fragmentation at LHC

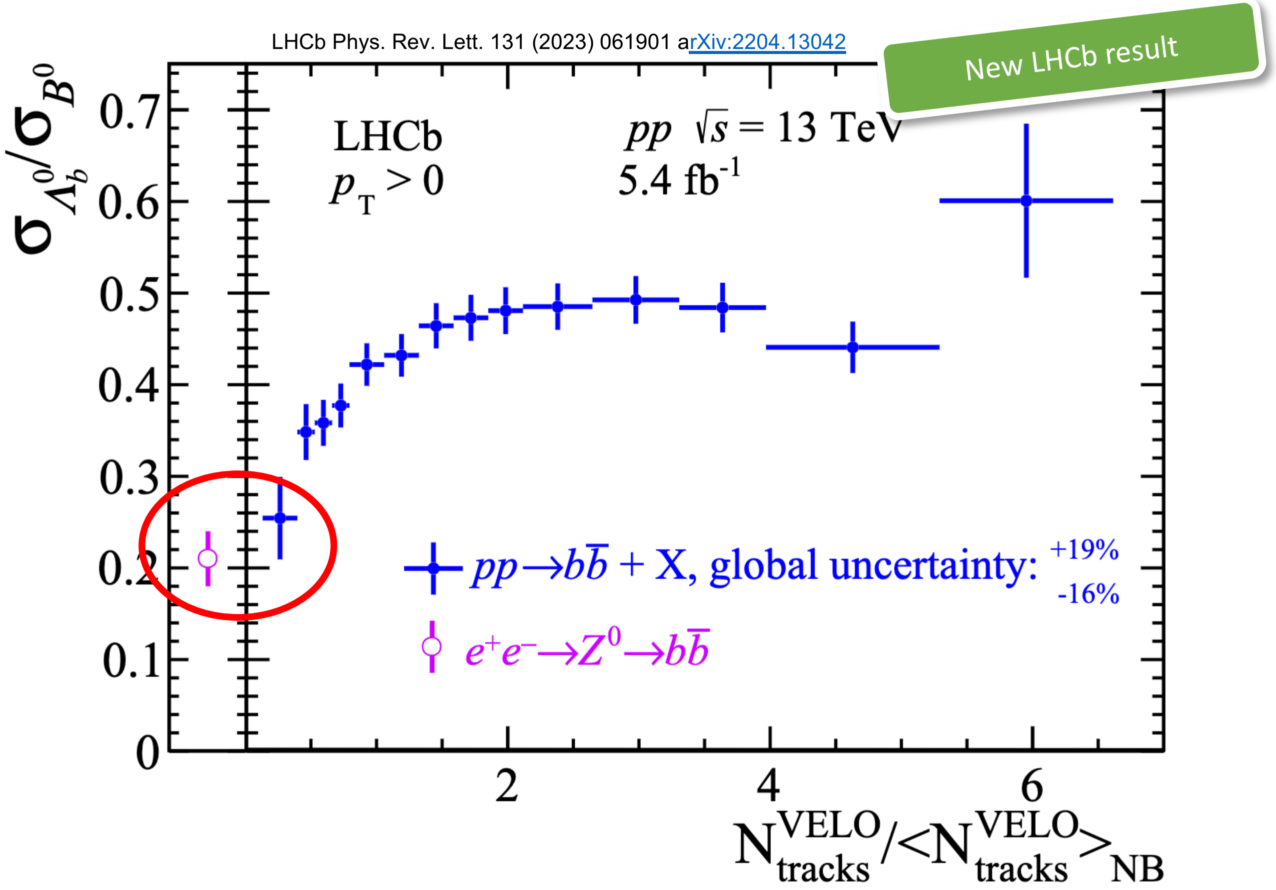
Beauty, charm, and strange hadrons show a similar trend as a function of p_T

Lowest multiplicity bins: pp data ~ e^+e^- data at LEP => fragmentation in vacuum

ALICE Phys. Rev. D 108, 112003 (2023) arXiv:2308.04873



LHCb Phys. Rev. Lett. 131 (2023) 061901 arXiv:2204.13042



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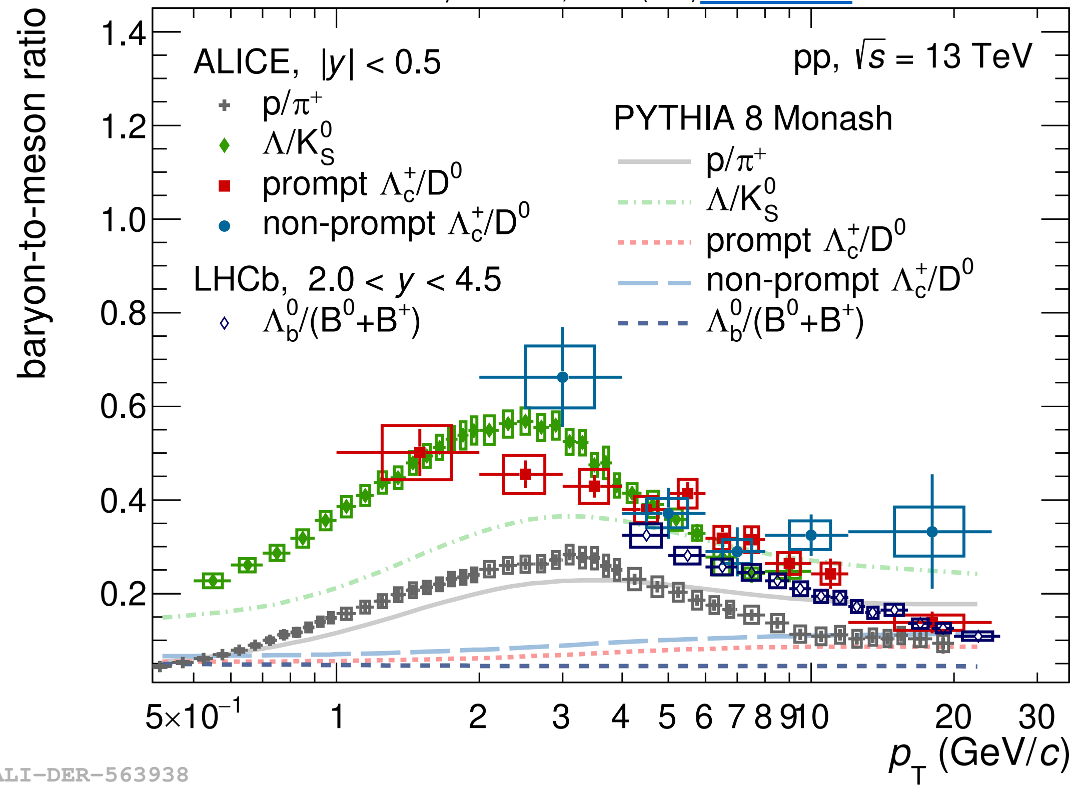
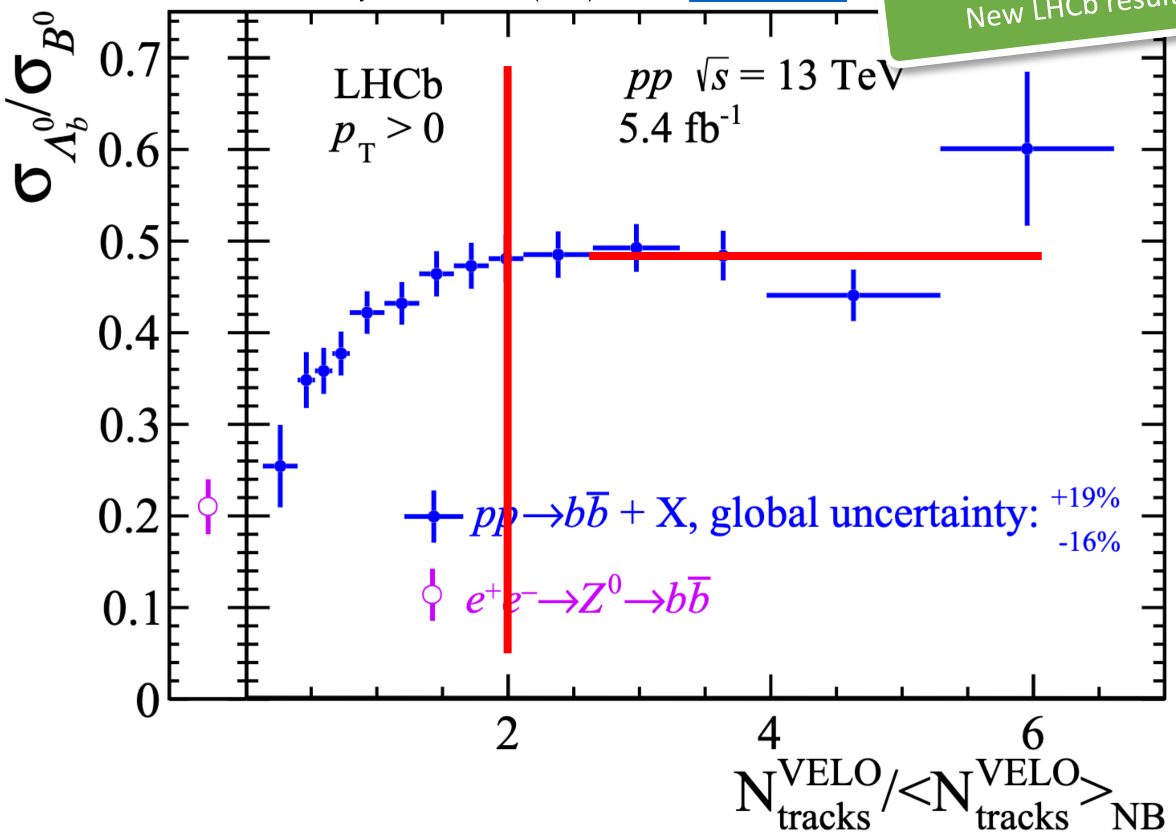


Rise of the baryon fraction with multiplicity, plateaus for collisions > 2x average number of VELO tracks

LHCb Phys. Rev. Lett. 131 (2023) 061901 arXiv:2204.13042

New LHCb result



Beauty hadronization is different in hadronic environment and in e^+e^-

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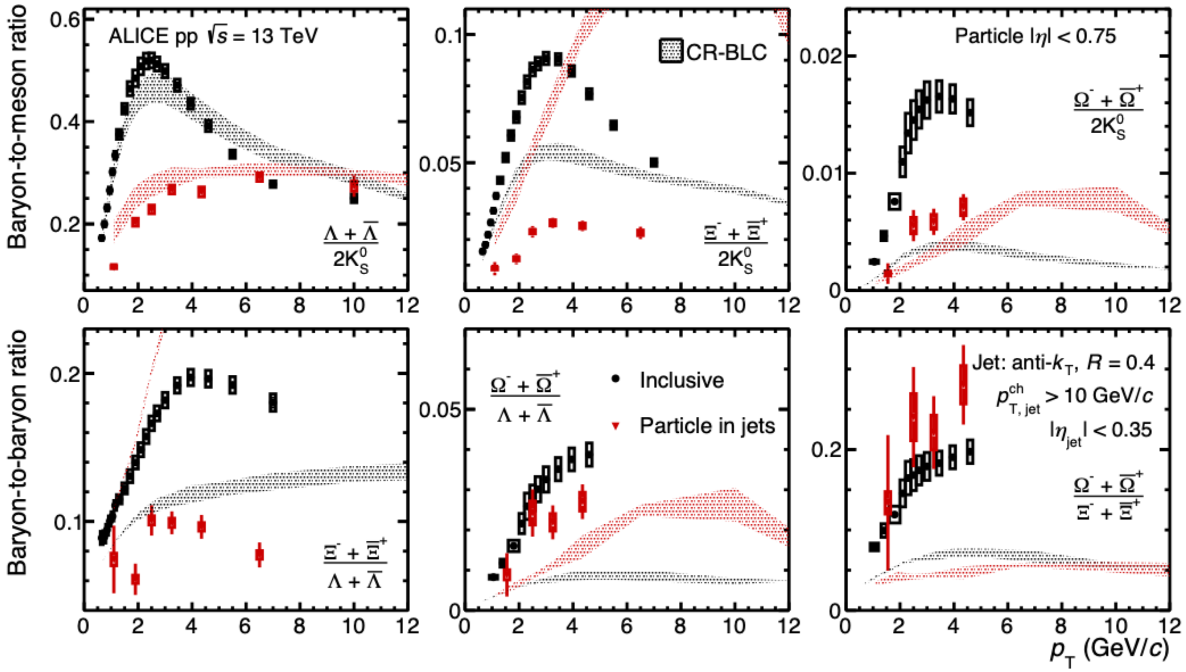
Hadronization in and out of jets

Strange baryon-to-meson and baryon-to baryon ratios suppressed by a factor ~ 2 in jets
w.r.t inclusive measurements

ALICE JHEP 07 (2023) 136 arXiv:2211.08936



Hadronic environment (in jet vs. out of jet) impact hadronization

More from P. Das
Thursday 06/06 at 15:12

sarah.porteboeuf@clermont.in2p3.fr

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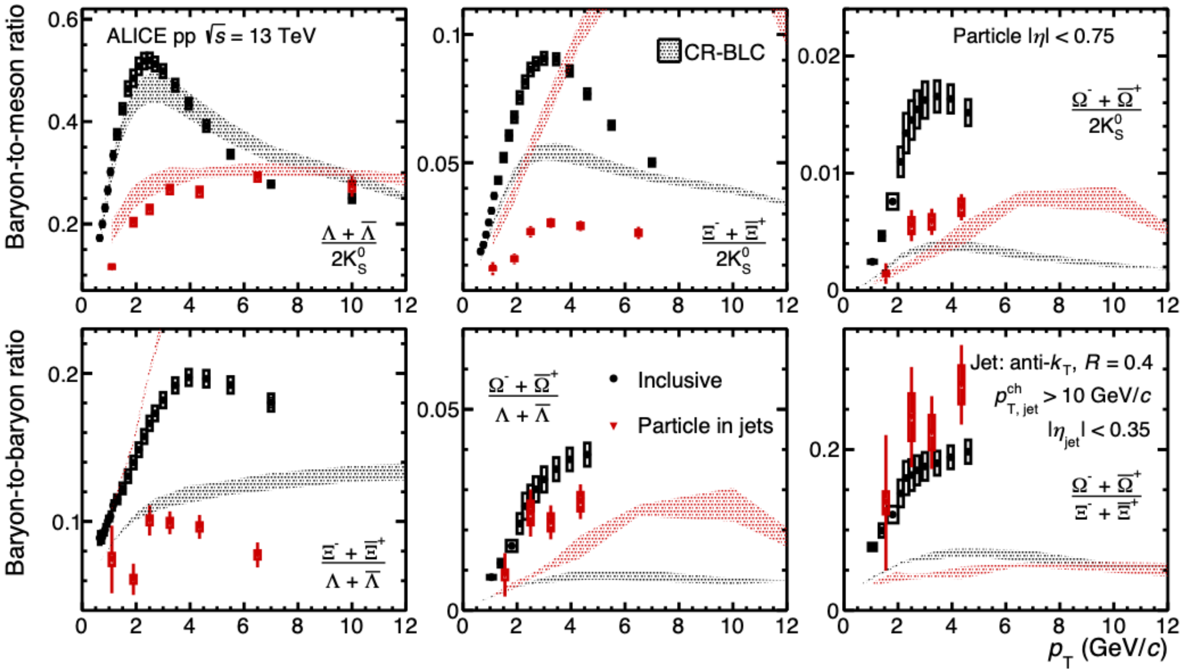
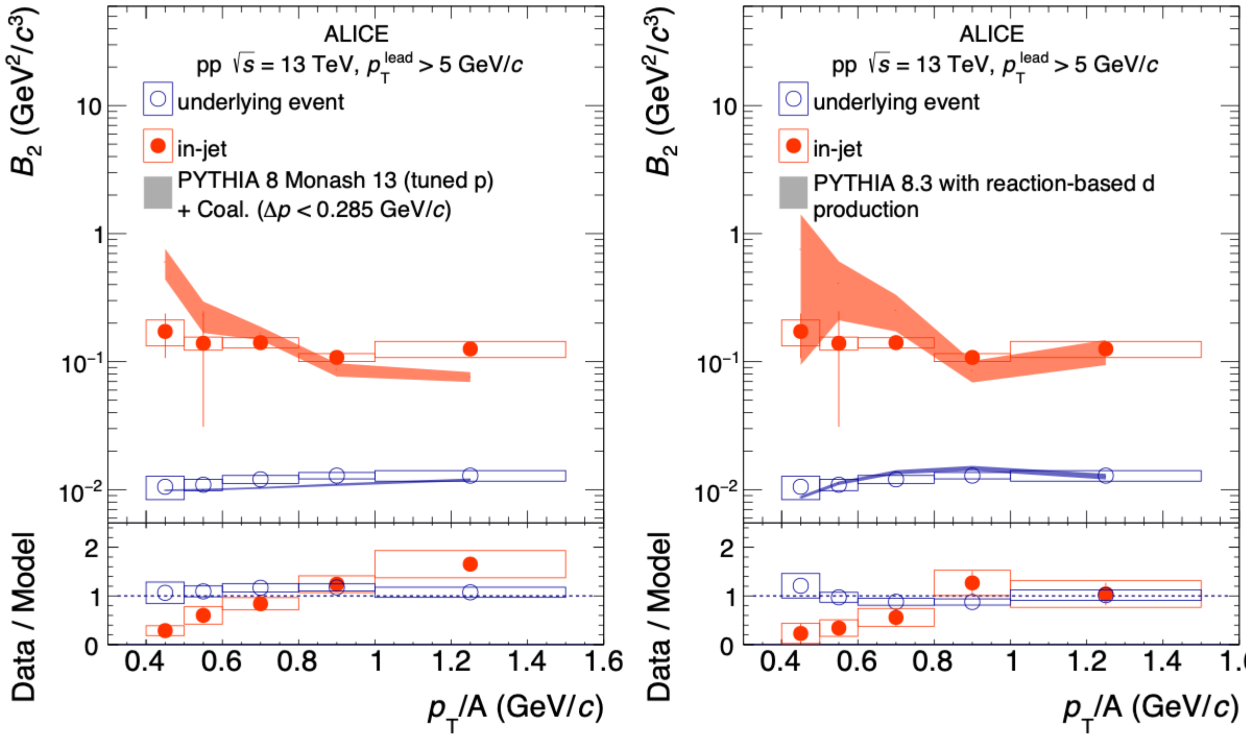


Deuteron coalescence probability in jets x 10
vs. underlying event
Nucleons have a smaller average phase-space distance

ALICE Phys. Rev. Lett. 131 (2023) 042301 arXiv:2211.15204



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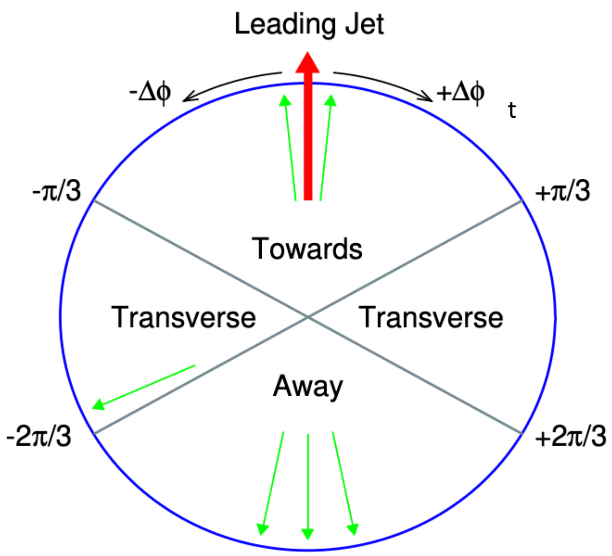
Underlying event study with strangeness production

- **Phase space divided in 3 regions**
  - Toward the leading jet: dominated by jet fragmentation
  - Away from the leading jet (back-to-back)
  - Transverse region: dominated by underlying event, MPI and soft processes



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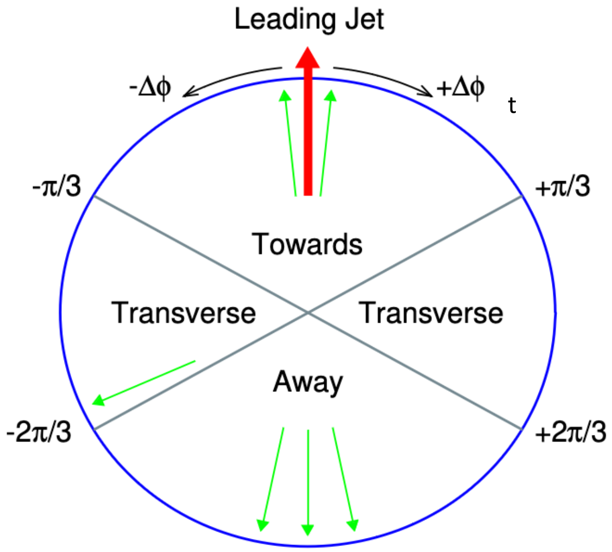
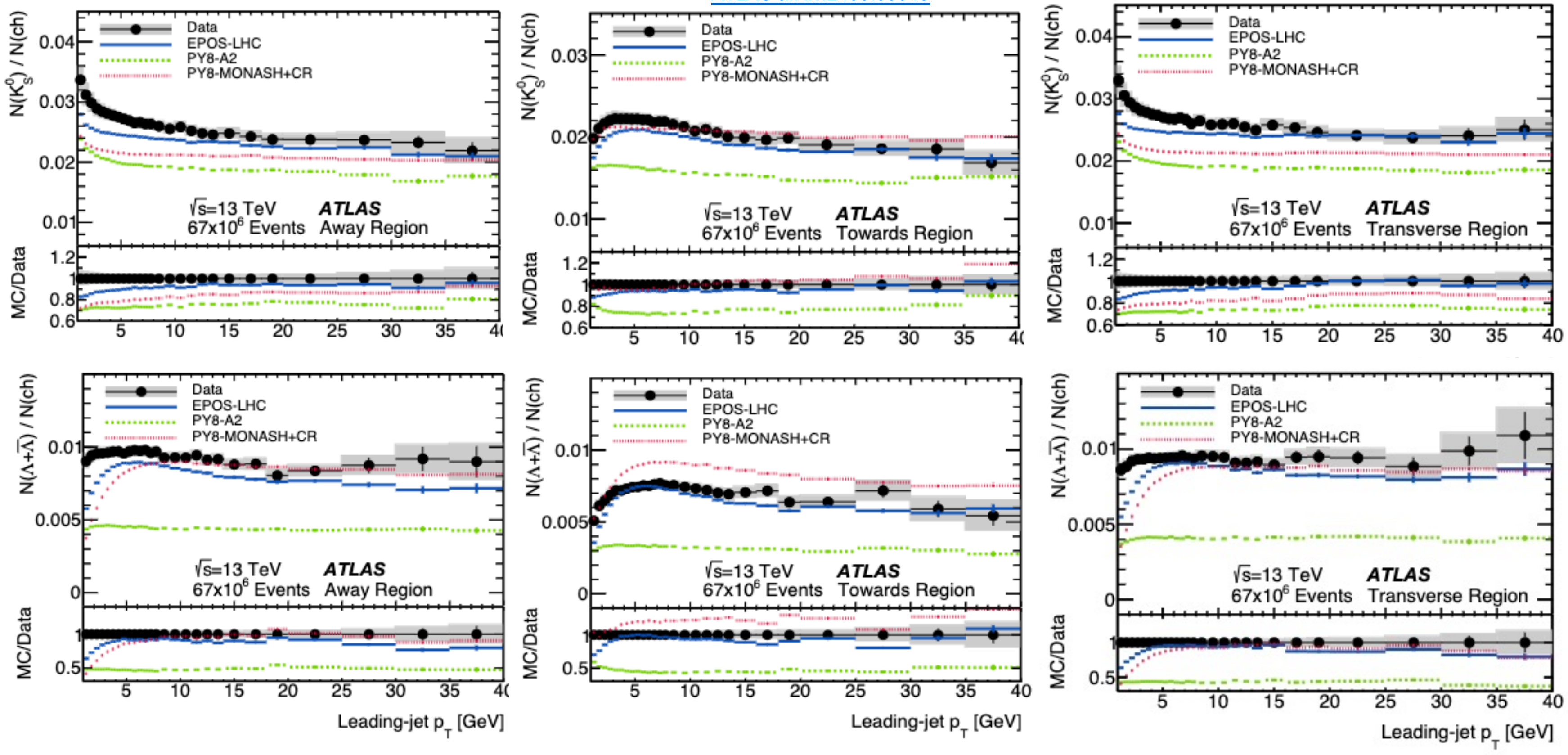


ATLAS arXiv:2405.05048



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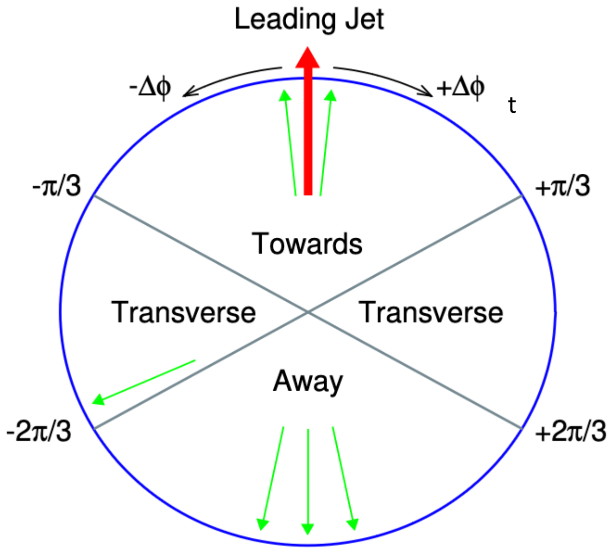

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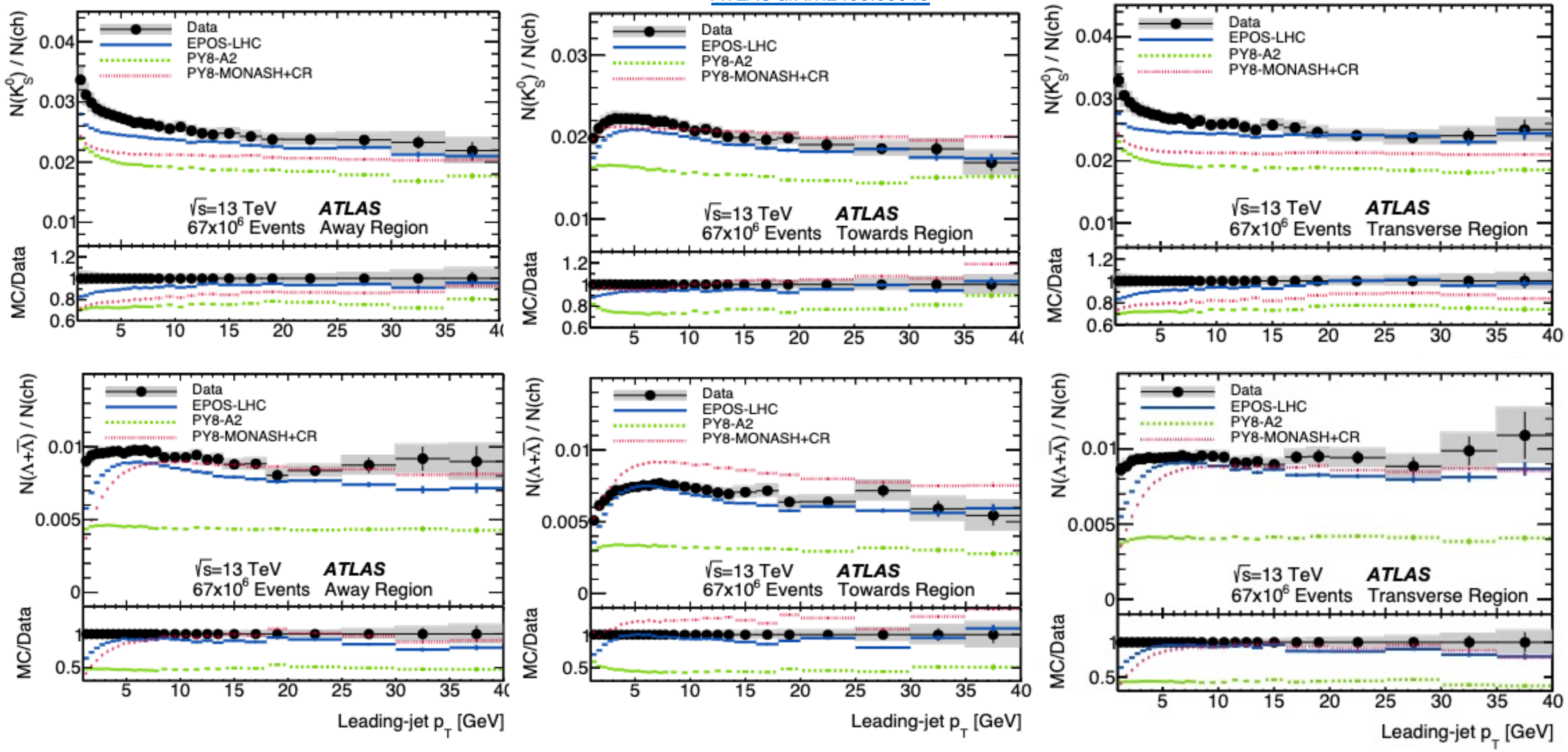


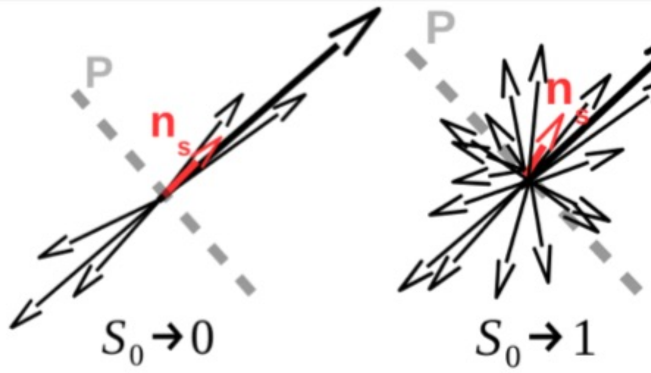
$\boldsymbol{\Lambda}$ **and** $\boldsymbol{K_s^0}$ production in 3 regions allow to understand **modelling of underlying event** from event generators

None tested can reproduce all aspects

Strangeness production to study underlying event dynamic

Event shape modeling

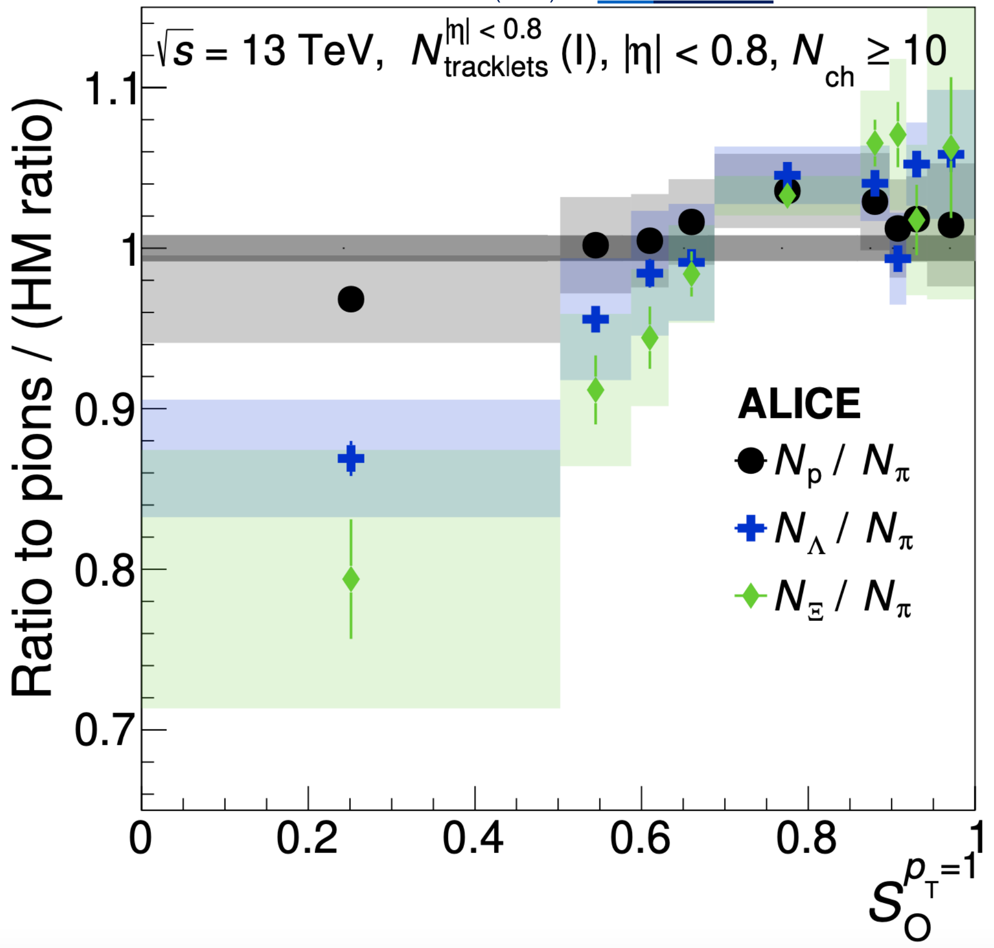
Strangeness production
Suppressed in events with **jet**-like topologies
Slightly **enhanced in** softer, **isotropic** event topologies



$$S_0 = \frac{\pi^2}{4} \min_{\vec{n}=(n_x,n_y,0)} \left(\frac{\sum_i |\vec{p}_{T_i} \times \hat{n}|}{\sum_i p_{T_i}} \right)^2$$

$$S_0 = \begin{cases} 0 \text{ "jetty" limit (hard events)} \\ 1 \text{ "isotropic" limit (soft events)} \end{cases}$$

ALICE JHEP05(2024)184 arXiv:2310.10236



Event shape modeling to understand strangeness production in pp collisions

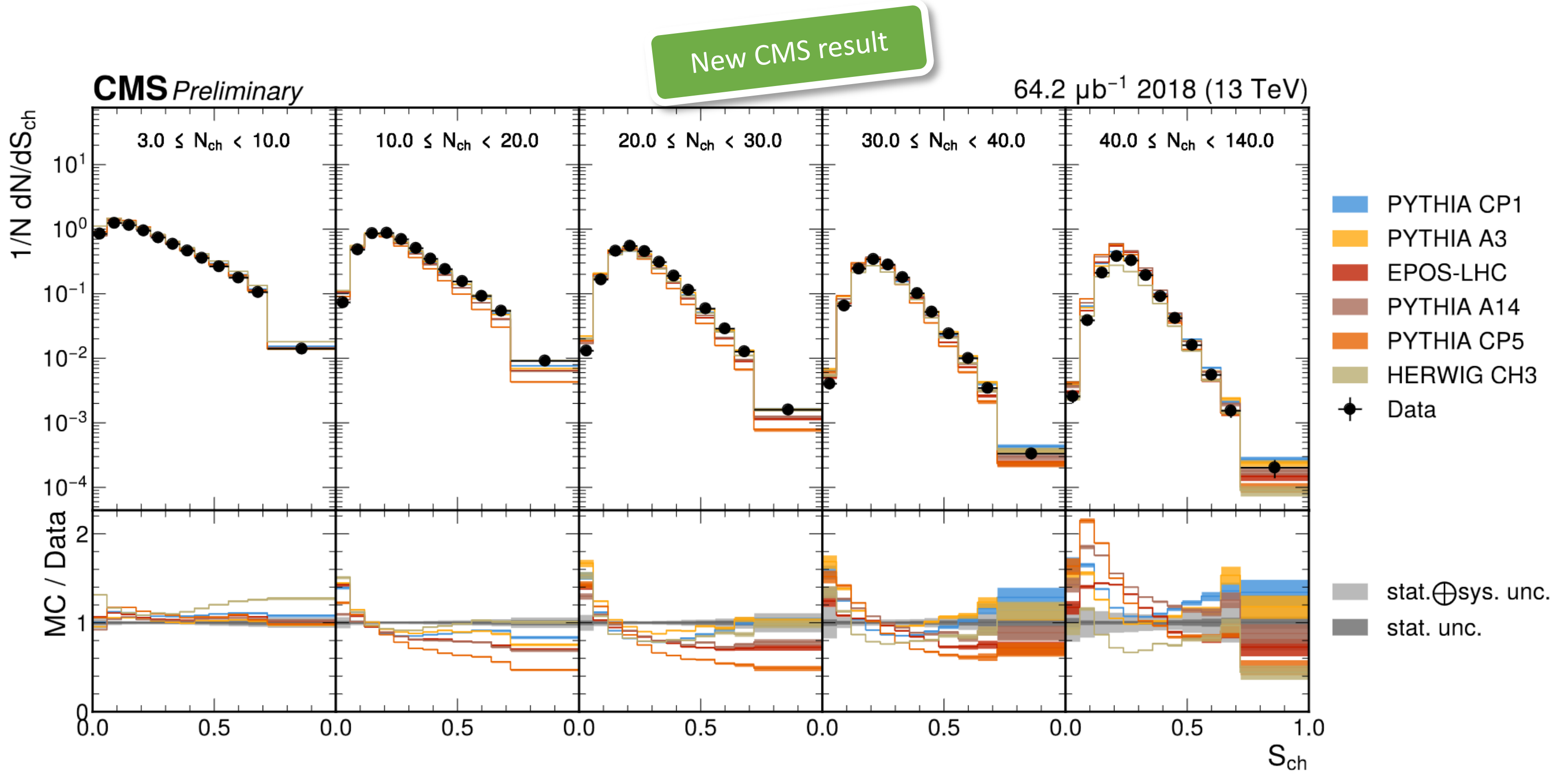
Event shape modeling

The tensor *S*

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p_i}|^2}$$

$\alpha, \beta \epsilon \{x, y, z\}$ cartesian coordinates
i is the index for the final-state charged particles that passed the selections based on the detector acceptance

Sphericity *S* from the two eigenvalues



Data more isotropic than the modeling in event generators

sarah.porteboeuf@clermont.in2p3.fr

LHCP Boston 2024

Conclusions

- **The strong force: running of α_s and υ from FASER**
  - **Running of α_s up to 2 TeV**
  - **First υ cross section at collider**
- **Factorization approach in QCD, measurements of PDFs and TMDs**
  - **Precision measurement with electroweak bosons**
  - **Jet cross section ration highlight the importance of NNLO computations**
  - **Accessing the transverse-Momentum Dependent Parton Distribution Function**
- **Insight on multi-parton scattering with associated production**
  - **DPS with charm and beauty show non universal σ_{eff}**
  - **Next orders : Tri-J/ψ in pp and** di-J/ψ in p-Pb
- **Jet fragmentation and substructure**
  - **Direct experimental constraint of the splitting function of heavy-flavour quarks**
  - **Testing QCD with jet substructure**
- **Hadronization in hadronic environment**
  - **Charm and beauty hadronization are different in hadronic environment and in e^+e^-**
  - **Hadronic environment (in jet vs. out of jet) impact hadronization**
  - **Underlying event dynamic and event shape modeling under study**

More in QCD,
Flavor Physics & Heavy Ion
parallel sessions

To be continued with A. Dobrin
Friday 07/06 at 09:00

sarah.porteboeuf@clermont.in2p3.fr

Backup

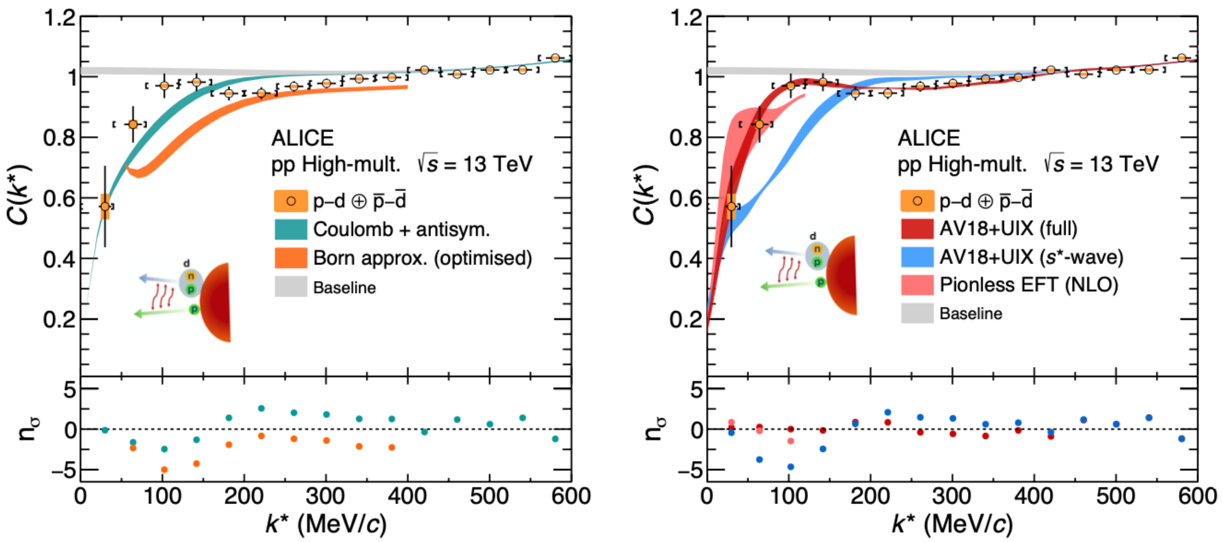
sarah.porteboeuf@clermont.in2p3.fr

Exploring the strong interaction of 3-body systems

Measuring correlation functions of 3-body systems with femtoscopic techniques in high multiplicity pp collisions at 13 TeV

Proton-deuteron correlations
Distance comparable to the proton radius

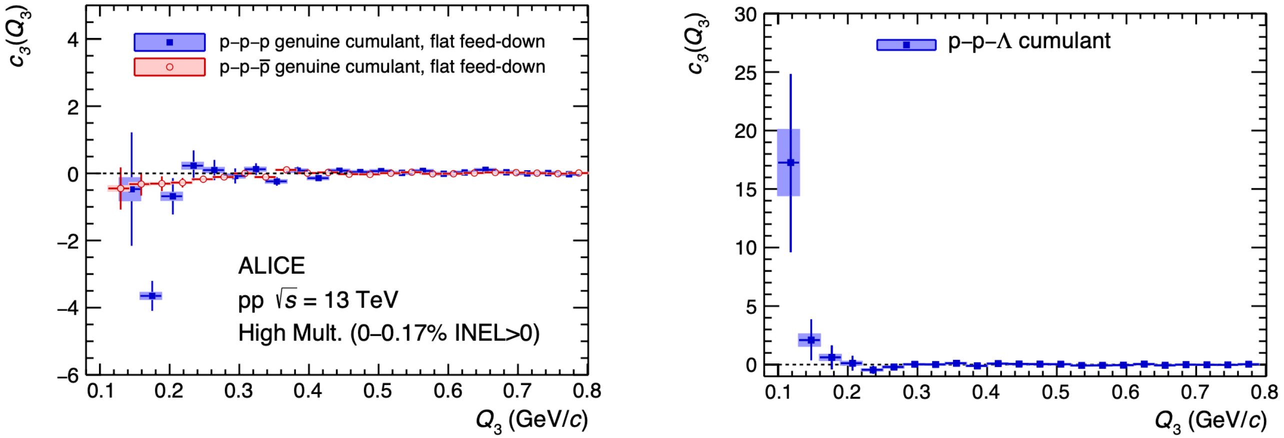
ALICE arXiv:2308.16120v1



Only a full 3-body calculation that accounts for the internal structure of the deuteron can explain the data (Av18+UIX full)

$\mathrm{p-p-p/\bar{p}}$ and $\mathrm{p-p-\Lambda}$

ALICE Eur. Phys. J. A 59 (2023) 145 arXiv:2206.03344



Non zero 3-particle cumulant hints for 3-body forces

More from D.L. Mihaylov
Friday 07/06 at 14:18

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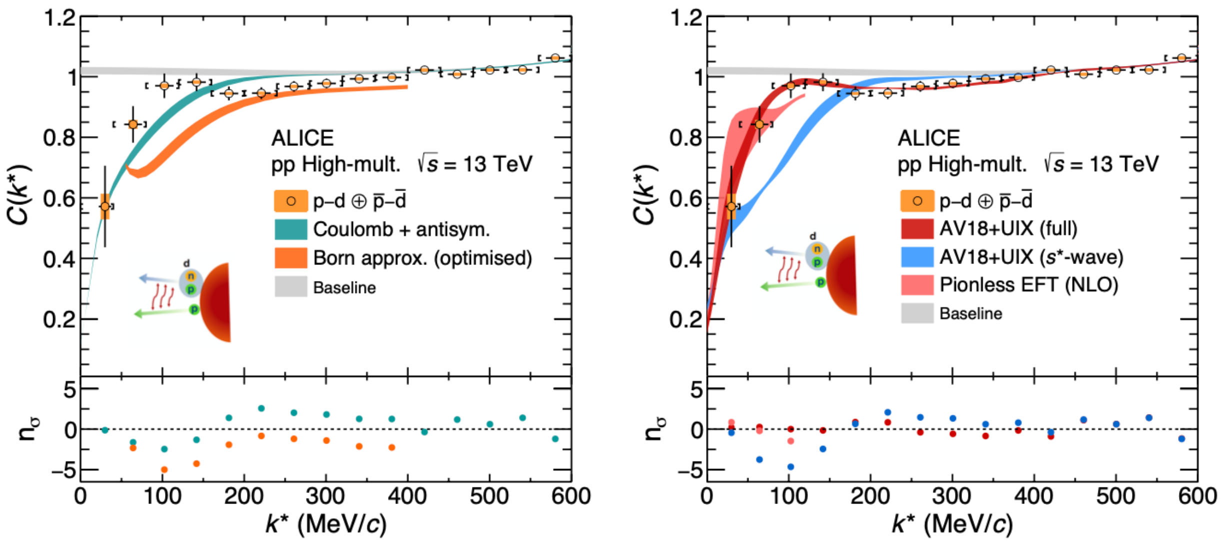
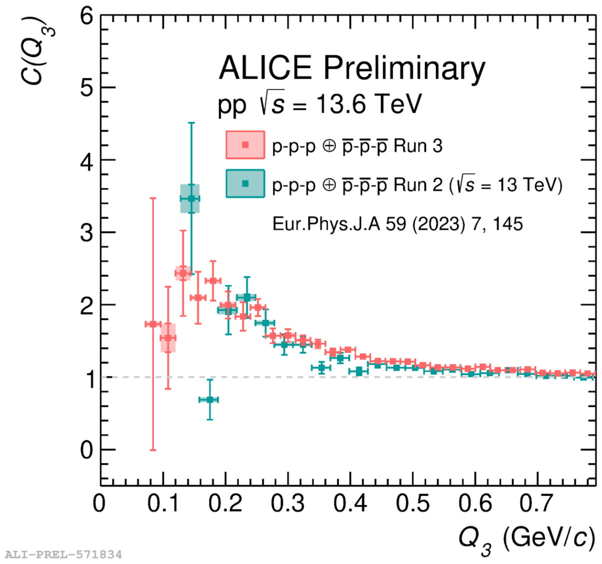
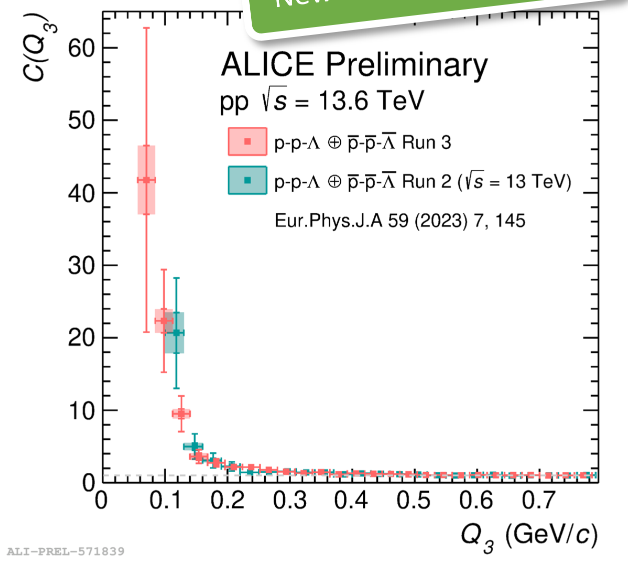


Only a full 3-body calculation that accounts for the internal structure of the deuteron can explain the data (Av18+UIX full)

$\mathrm{p-p-p}$ and $\mathrm{p-p-\Lambda}$

New ALICE RUN 3 results





Non zero 3-particle cumulant hints for 3-body forces

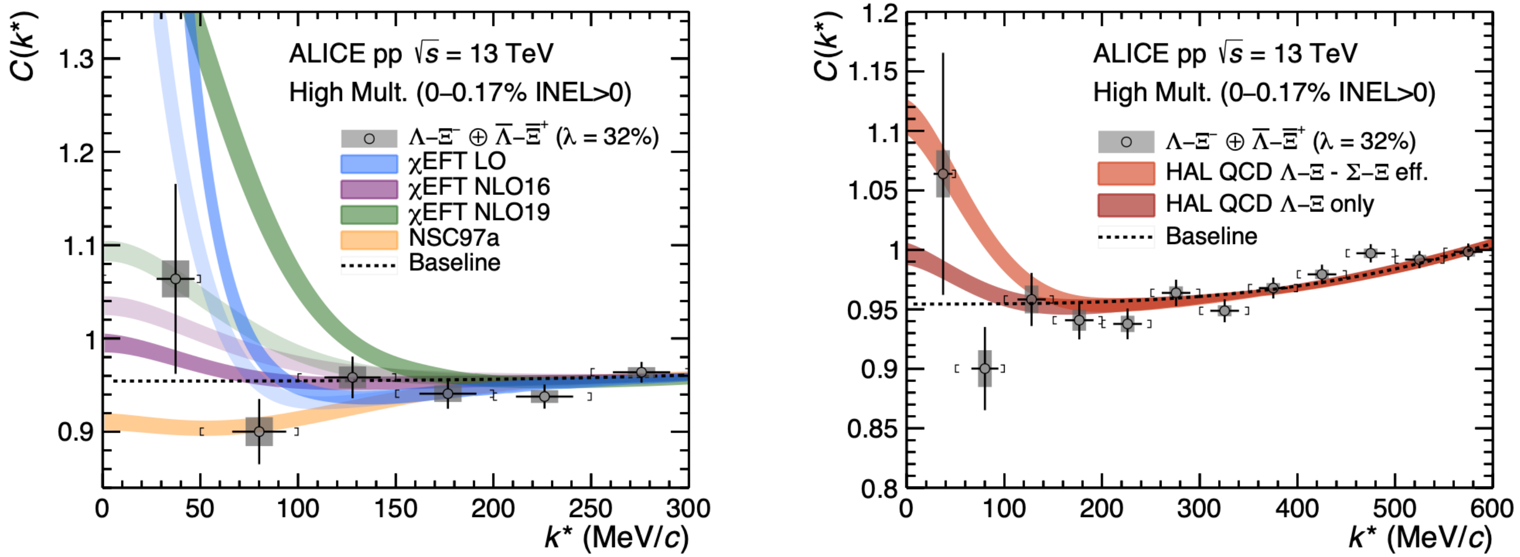
More from D.L. Mihaylov
Friday 07/06 at 14:18

sarah.porteboeuf@clermont.in2p3.fr

Testing L-QCD with strangeness

- Measurement of two-particle correlations as a function of the relative momentum to test the strong interaction among hadrons with strange quarks
- Comparisons with theoretical models:
  - including leading-order and next-to-leading-order chiral Effective Field Theory calculations
  - a meson exchange model
  - Lattice QCD calculations close to the physical point for systems rich in strangeness

ALICE Phys. Lett. B 844 (2023) 137223 arXiv:2204.10258

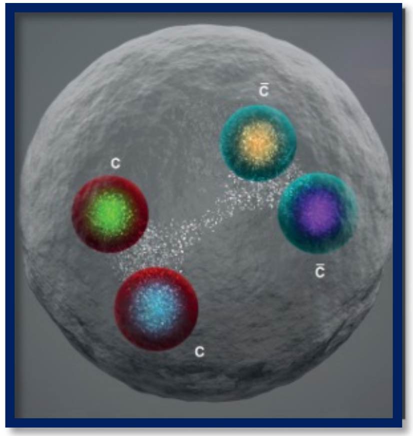


More from D.L. Mihaylov
Friday 07/06 at 14:18

Data more compatible with predictions of small scattering parameters and hence a weak $\Lambda - \Xi^-$ interaction

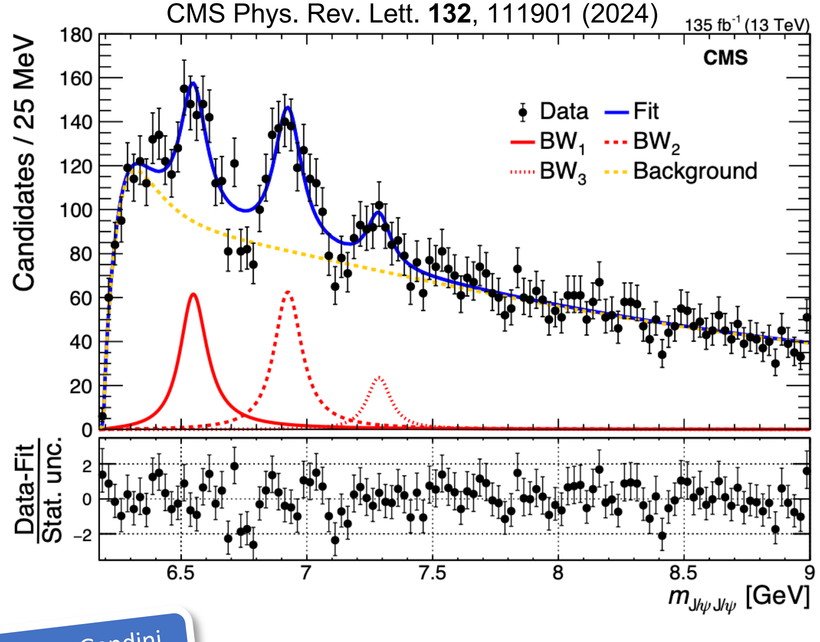
sarah.porteboeuf@clermont.in2p3.fr

Tetraquark with di-J/ψ spectrum

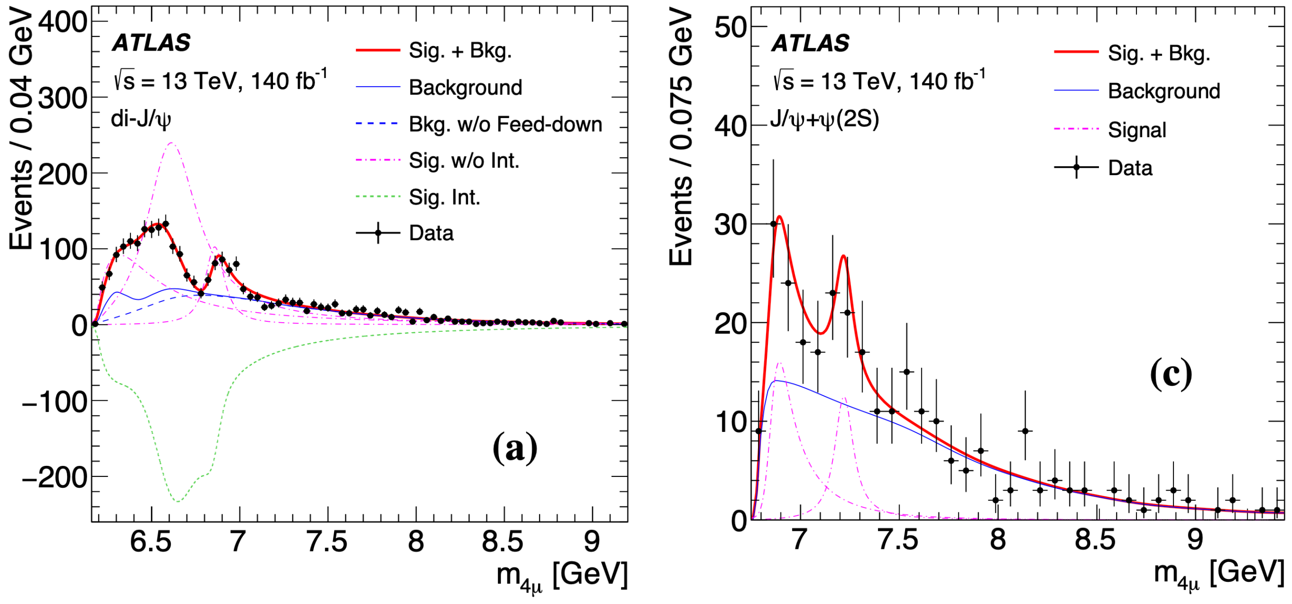


- Tetraquark candidate X(6900) first observed by LHCb in 2020 Sci. Bull. **65**, 1983 (2020)
- X(6900) confirmed by CMS and ATLAS in channel $T_{cc\bar{c}\bar{c}} \rightarrow J/\psi\, J/\psi$ and $T_{cc\bar{c}\bar{c}} \rightarrow J/\psi\psi(2s)$
- Structure observed by CMS in $J/\psi\, J/\psi$ spectrum, hint for X(6600) and X(7100)

CMS Phys. Rev. Lett. **132**, 111901 (2024)



ATLAS Phys. Rev. Lett. 131 151902 (2023)



Presented by P. Gandini
Monday 03/06 at 17:36

New charmed Tetraquark candidates

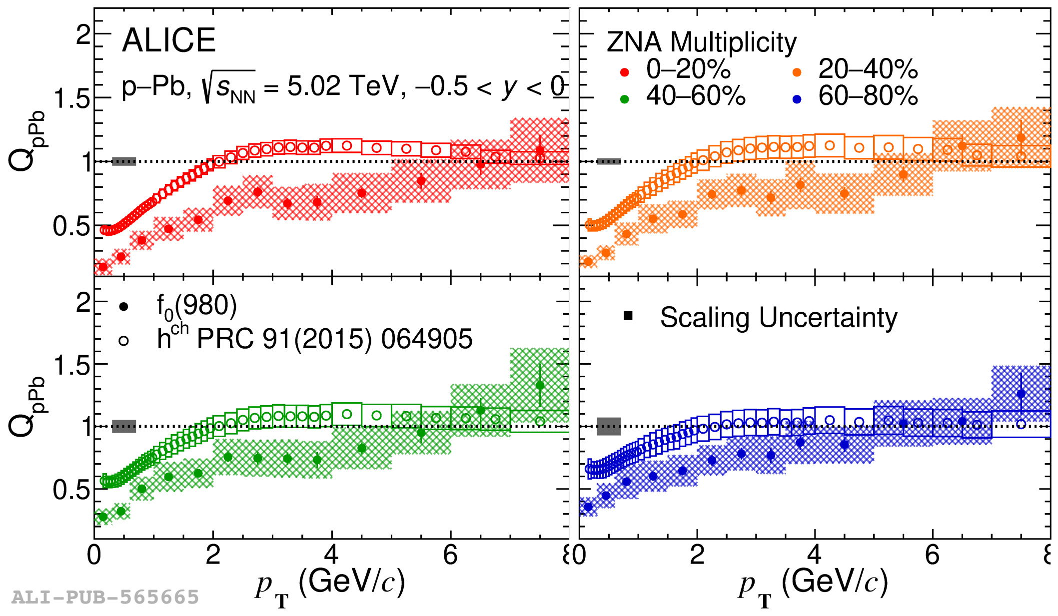
sarah.porteboeuf@clermont.in2p3.fr

f_0(980) : hint at a 2-quark structure with p-Pb collisions

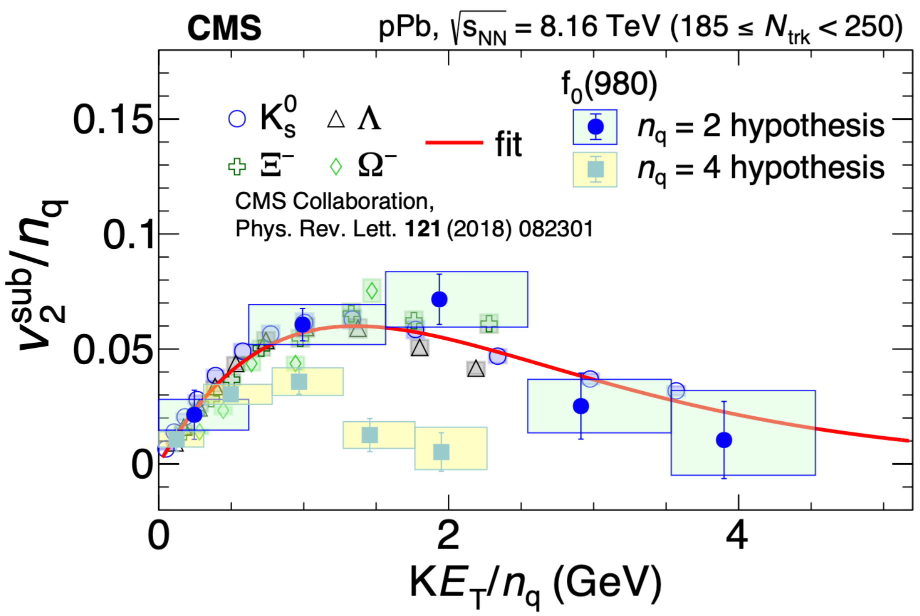
Presented by P. Gandini
Monday 03/06 at 17:36

- Is the f_0(980) a $q\bar{q}$ meson, a tetraquark state, a $K\bar{K}$ molecule or a $q\bar{q}$-gluon hybrid state ?
- Study of f_0(980) production and dynamic in p-Pb collisions

ALICE arXiv:2311.11786



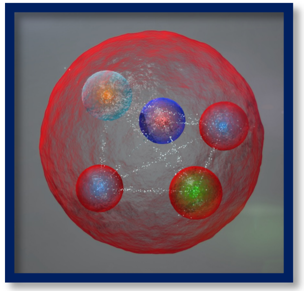
CMS Submitted to Nature Physics arXiv:2312.17092v1



Clear suppression of f_0 nuclear modification factor production suggests impact of final state scattering and meson like structure

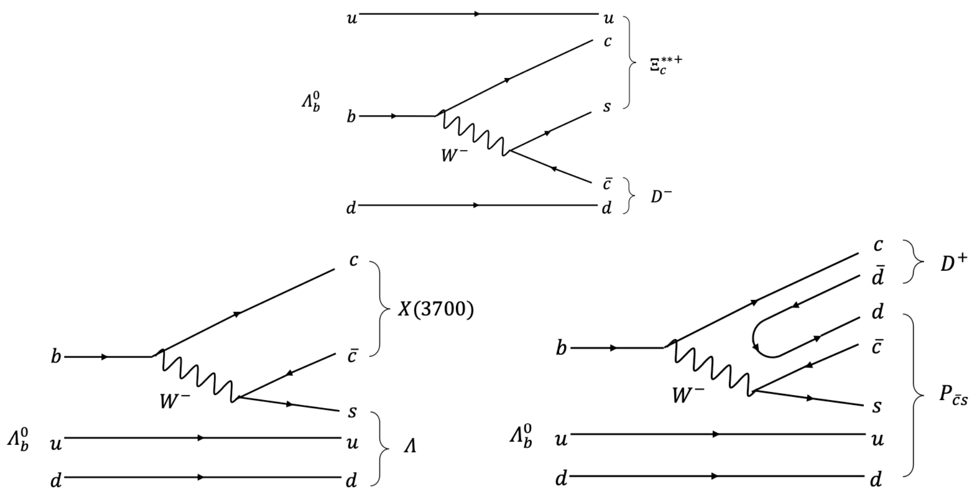
f0(980) is found to be a $q\bar{q}$ meson (number-of-constituent-quarks scaling hypothesis) Other hypothesis ruled out

Search for Pentaquark



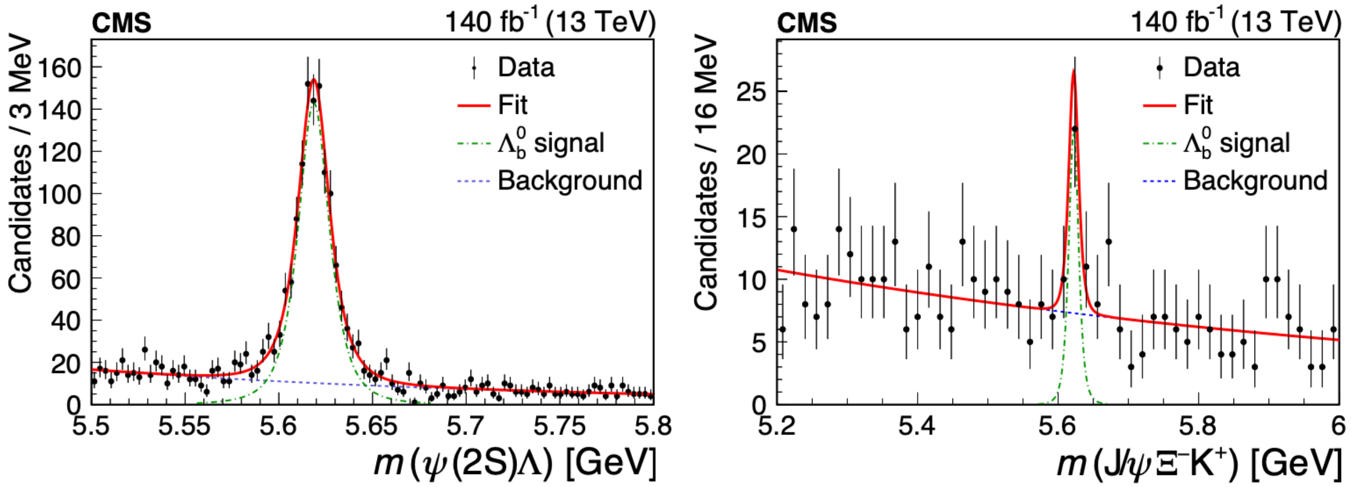
- **First observation of $\Lambda_b^0 \to D^+ D^- \Lambda$**

LHCb Submitted to JHEP arXiv:2403.03586v1



- **First observation of $\Lambda_b^0 \to J/\psi \Xi^- K^+$**

CMS Submitted to the EPJ C arXiv:2401.16303v1 (2024)



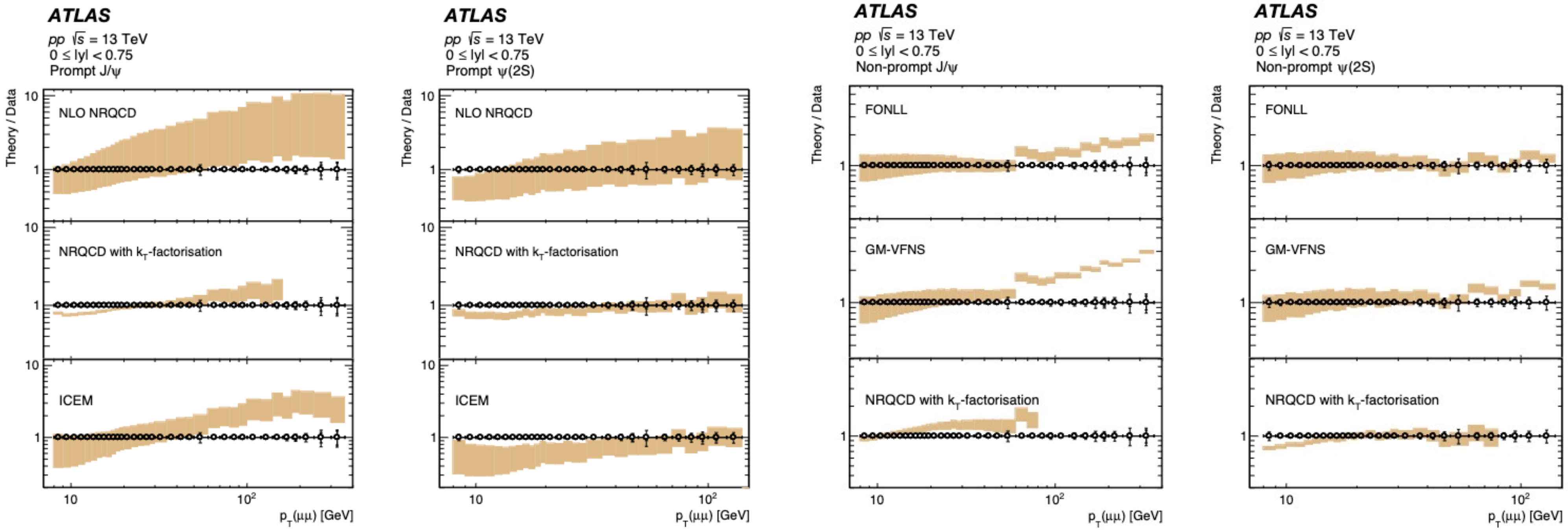
Presented by P. Gandini
Monday 03/06 at 17:36

Opens the possibility to search for doubly-strange hidden-charm pentaquarks

sarah.porteboeuf@clermont.in2p3.fr

J/ψ & $\psi(2S)$ (non-)prompt production cross section

- Cross sections measured up to 100 GeV
- Similar p_T-dependences for the prompt and non-prompt differential cross-sections
- Non-prompt fractions nearly constant for both J/ψ and $\psi(2S)$ states



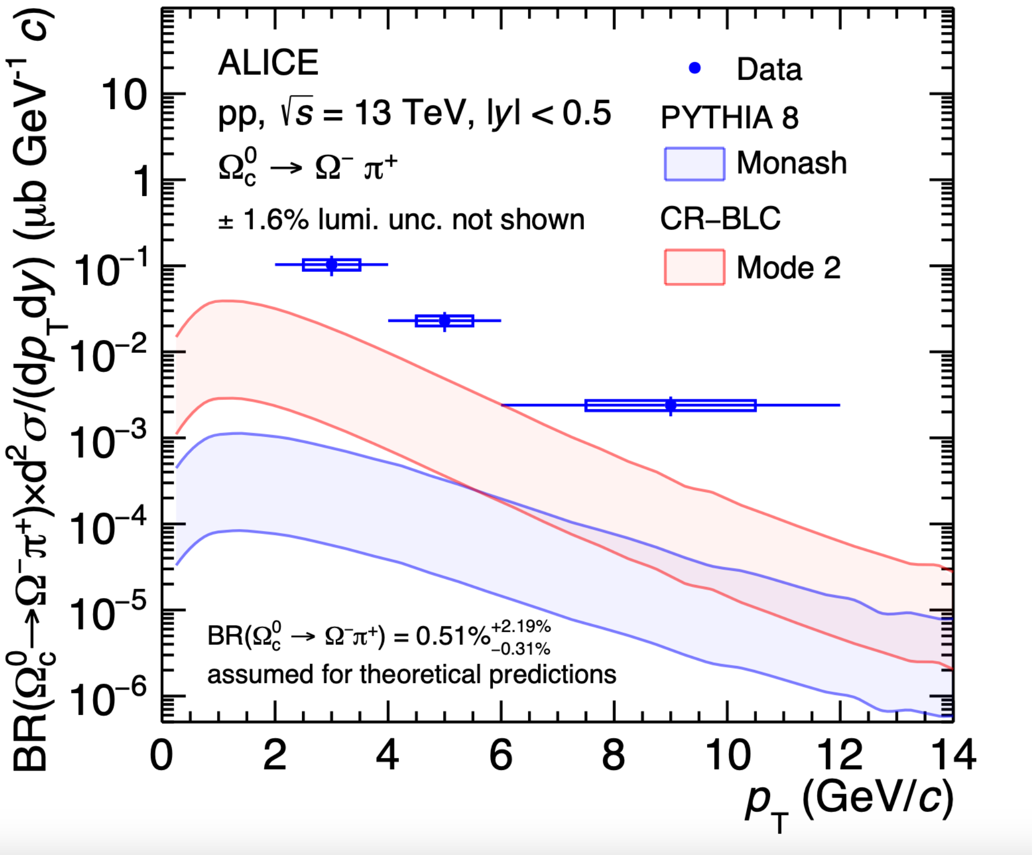
ATLAS Eur. Phys. J. C 84 (2024) 169 arXiv:2309.17177

Charmonia cross sections up to 100 GeV

More from V. Feuillard
Wednesday 05/06 at 14:18

Charm fragmentation at LHC

ALICE Phys. Lett. B 846 (2023) 137625 arXiv:2205.13993



More from P. Das
Thursday 06/06 at 15:12

Charm fragmentation is different in hadronic environment and in e^+e^-

sarah.porteboeuf@clermont.in2p3.fr