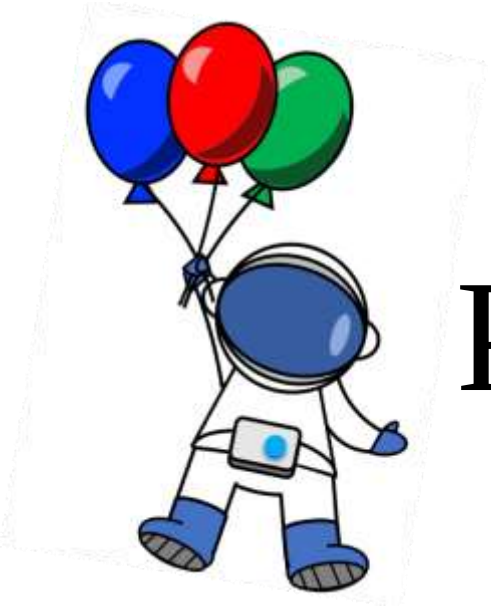


Physics of Small Systems

An experimental summary

Jiayin Sun
INFN Cagliari

Small systems are the baseline for QGP studies

Assuming no QGP is formed in small systems

pp collisions:
Baseline in vacuum
QCD studies

*p*A collisions:
Cold Nuclear Matter (CNM) effects:
small-*x* physics and initial states:
nPDF and/or gluon saturation?
interactions with cold/dilute medium

Effects considered as signatures of QGP formation are found in small systems:
- ✓ collectivity
- ✓ strangeness enhancement
- ✓ baryon/meson enhancement
- ✓ quarkonia breakup in medium
- ✗ energy loss

CNM effects are the baseline for QGP studies

Small-*x* physics and initial states:
nPDF and/or gluon saturation?

Hadronization
fragmentation?
coalescence?
Strangeness enhancement
Baryon enhancement

Correlations and collectivity
origin of flow in small system?

A QGP droplet formation in small systems?

Quarkonia breakup
comover effects?

Jet production and properties
Energy loss and transport in medium?

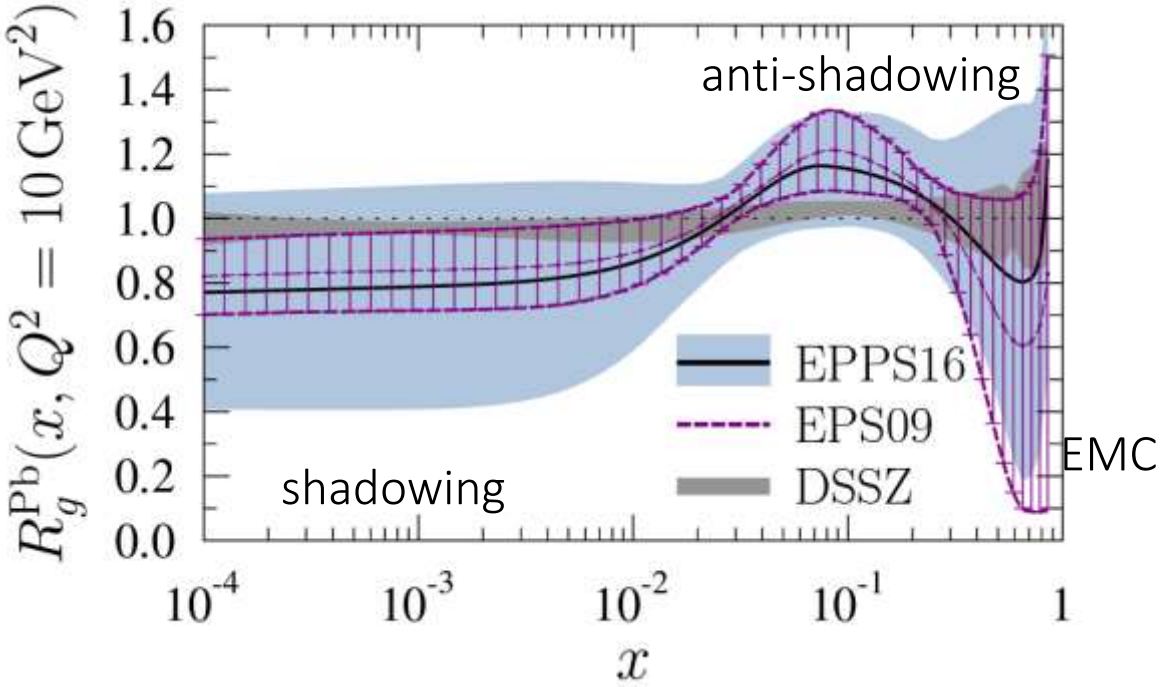
QCD and astrophysics

The big questions…

Small-*x* physics and initial states:
nPDF and/or gluon saturation?

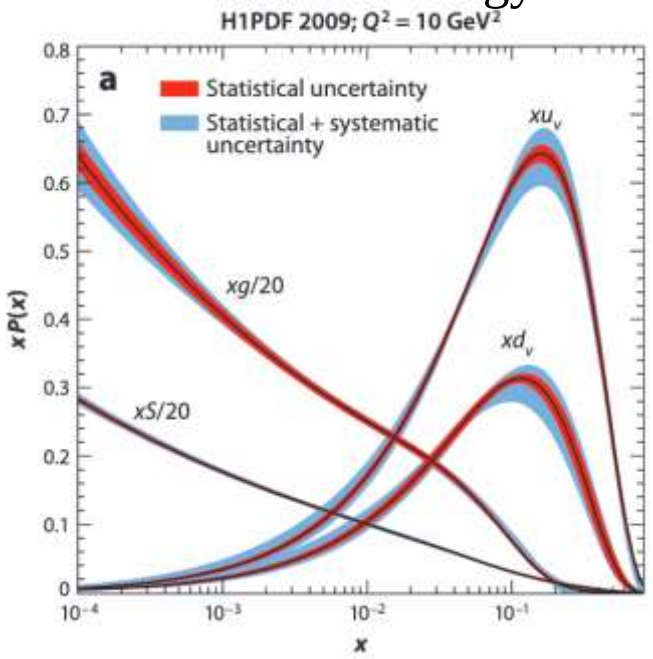
Initial state effects

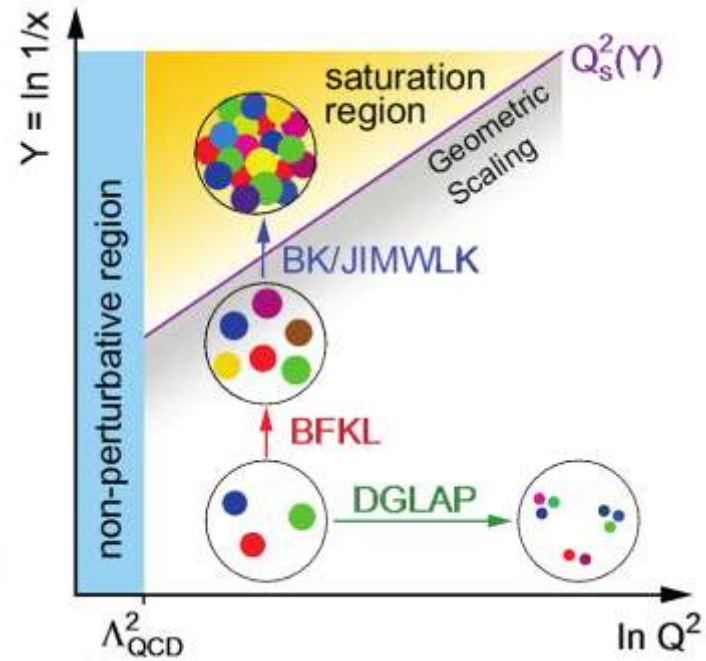
- Parton densities are modified in nuclei
  - Shadowing: depletion of the effective number of gluons in low-*x*.
  - Antishadowing, EMC effects…
  - Poorly constrained from previous data



arXiv:1612.05741

- Large number of small-*x* gluons, leading to a very dense saturated wave function known as the Color Glass Condensate (CGC)
  - Saturation scale $Q_s^2 \propto A^{1/3}$ (Lorentz contraction)
  - Expected in small *x* and small Q^2 region
- Initial state energy loss



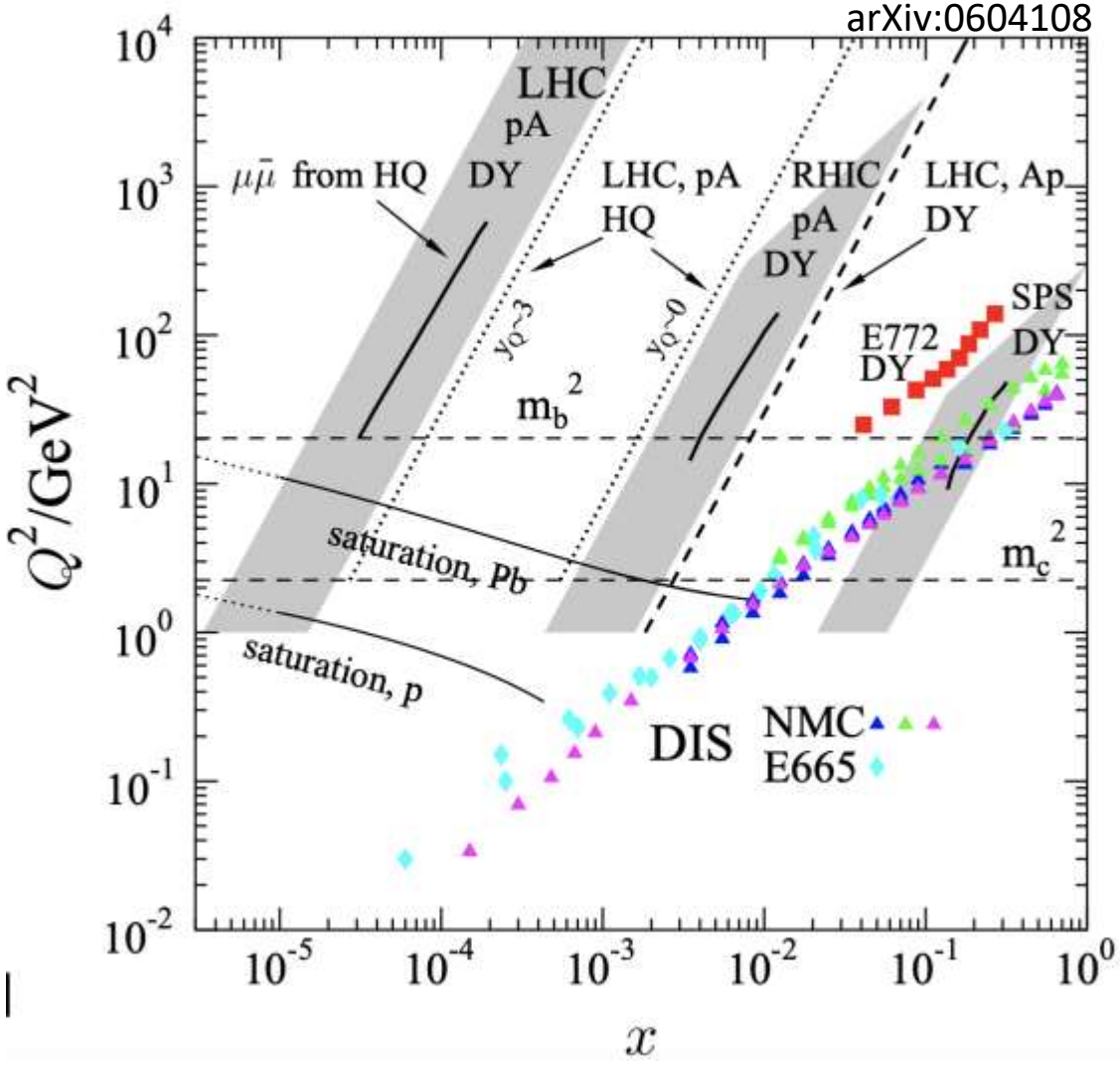


Annu. Rev. Nucl. Part. Sci. 60:463-89

Experimental approach

- Studied using pA collisions/γA collisions
- Probes:
  - Dijets
  - Top quark
  - W/Z, Drell-Yan
  - Heavy flavor
  - Light hadrons
  - Direct photons
  - VM in Ultra-Peripheral AA Collisions
- Observables:
  - $R_{p\mathrm{Pb}}$, R_{FB}, production cross-section, angular correlations…

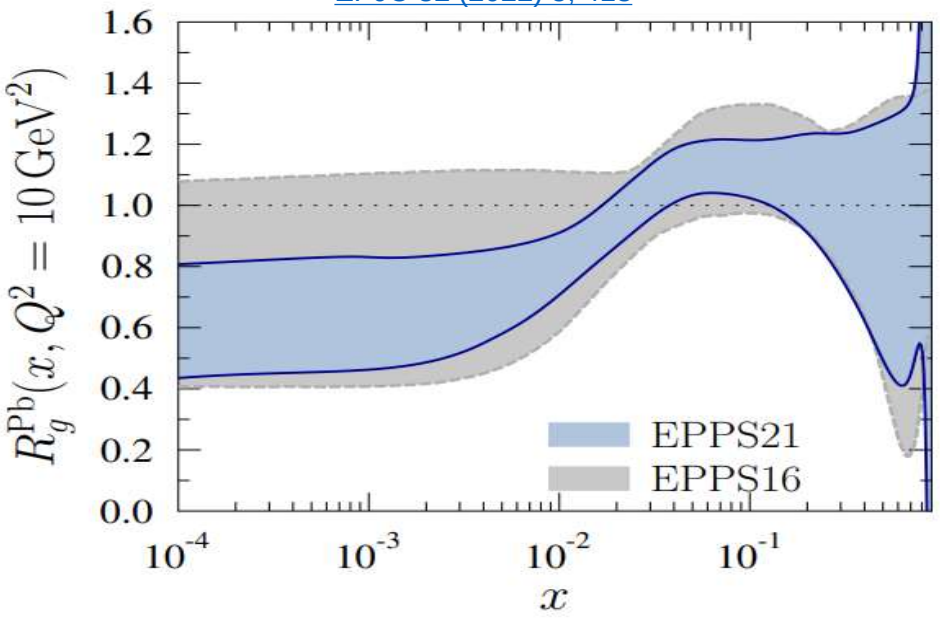
arXiv:0604108



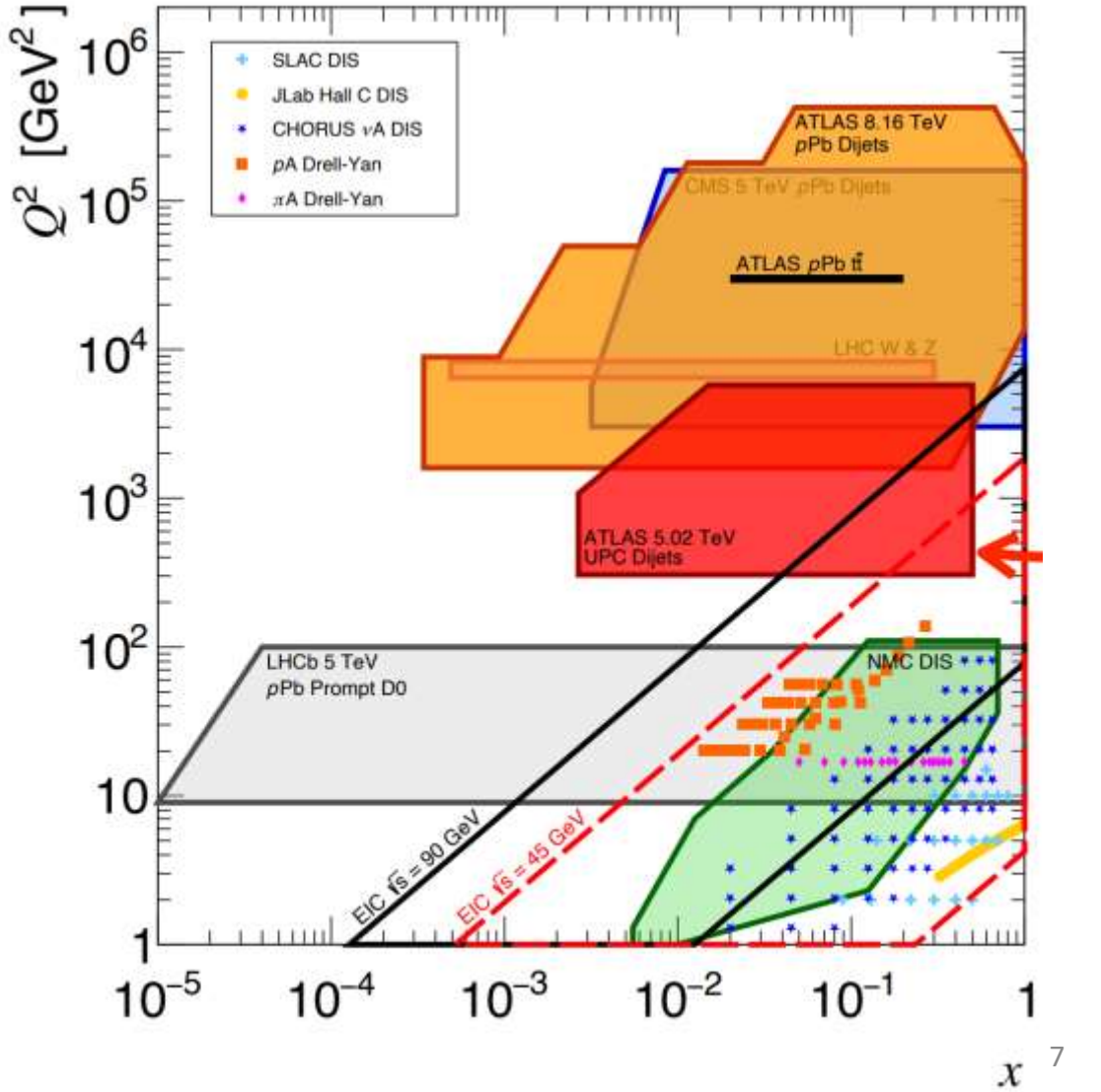
Experimental approach

- EPPS21 vs. EPPS16
- EPPS21 includes CMS dijets and LHCb D^0 at 5 TeV
- Significant progress on constraining nPDF

EPJC 82 (2022) 5, 413

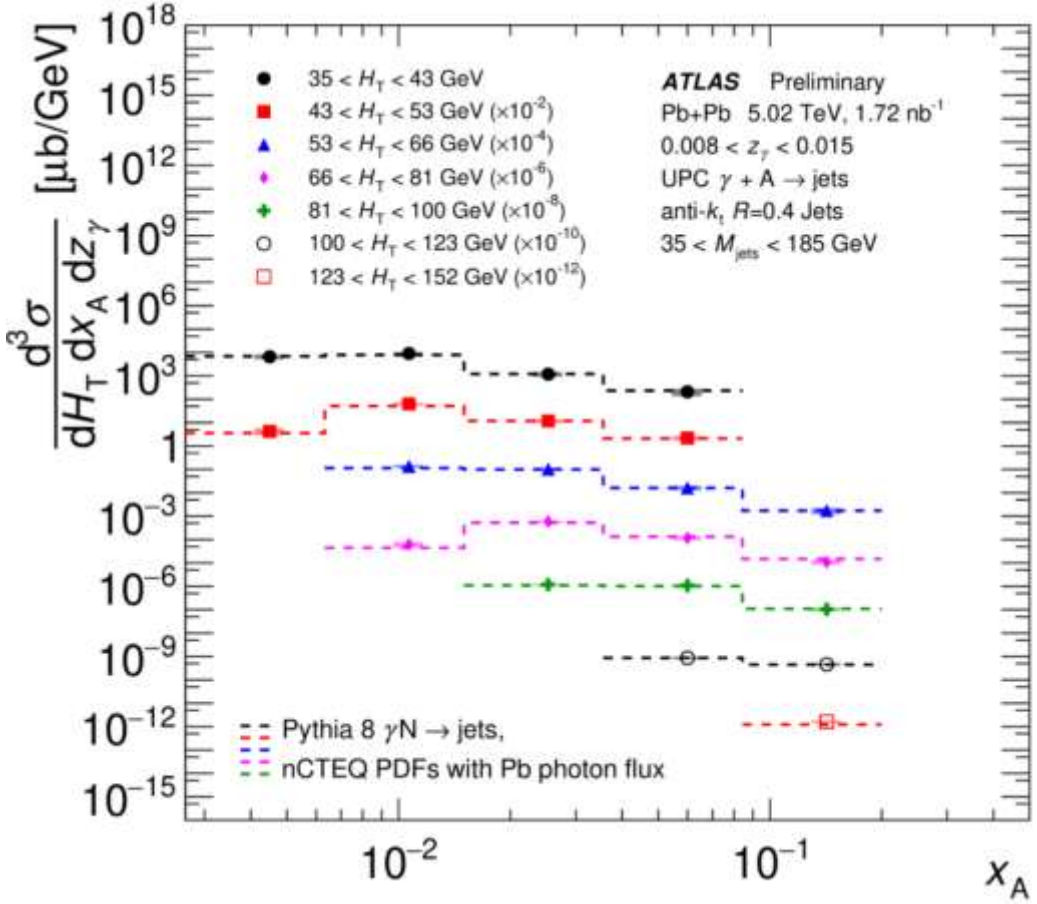


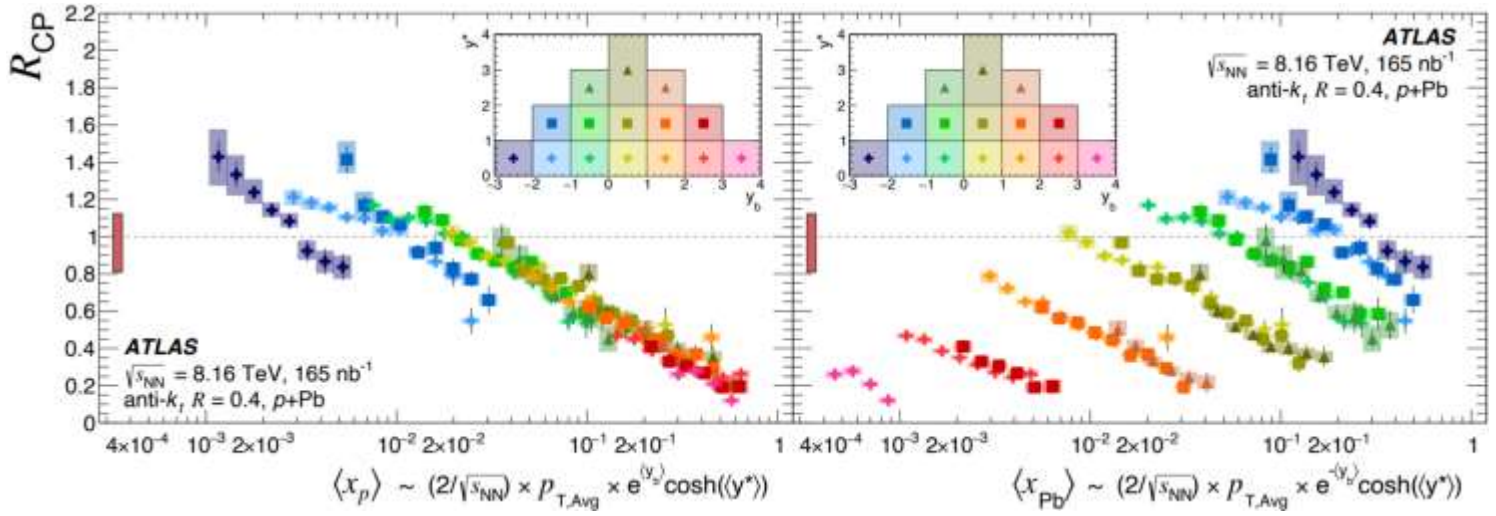
B. Gilbert, QM23 talk



Dijets in pPb and γPb collisions

B. Gilbert, QM23 talk

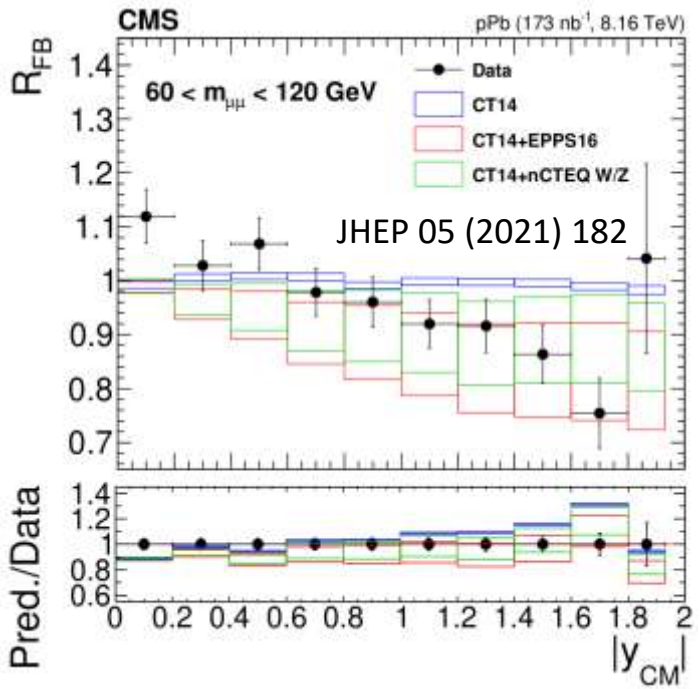


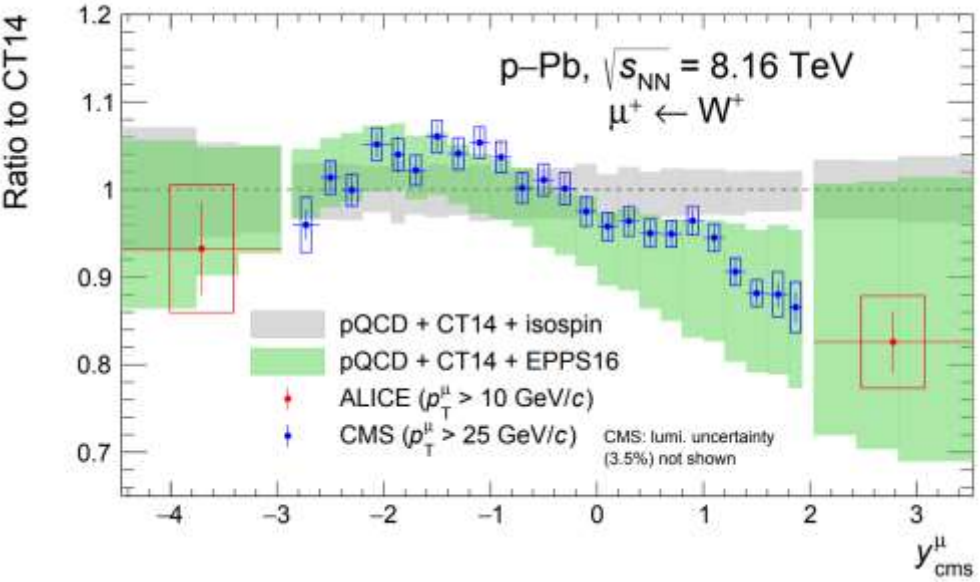


- γPb collisions
  - Photon energy allows access to low-x shadowing region
  - Results consistent with theoretical model
- pPb collisions
  - Measured centrality dependence of dijet yields
  - Triple-differential dijet yields → detailed studies of partonic system
  - Trend R_{CP} consistent with model

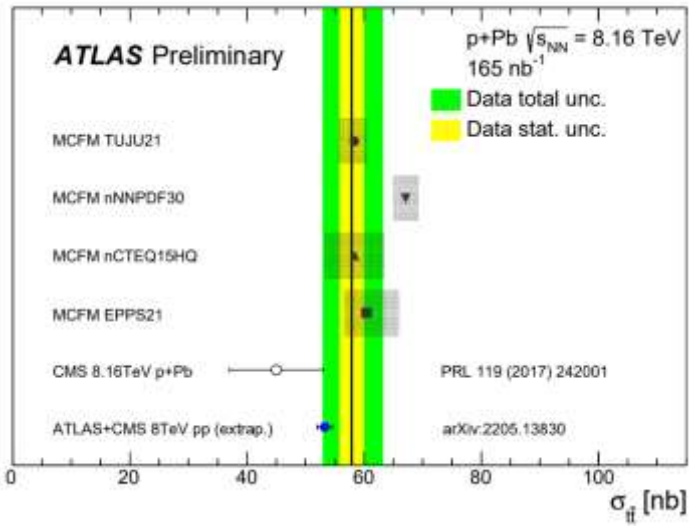
W/Z, $t\bar{t}$, Drell-Yan production

- W measurement reaches large |y| region ($x \sim 10^{-4}$ at forward region)
- W suppression at large rapidity
  - extending into EMC region
  - Support shadowing of the nuclear PDFs
- Data more precise than nPDFs
- New measurement of the top-quark pair production cross section in *p*Pb

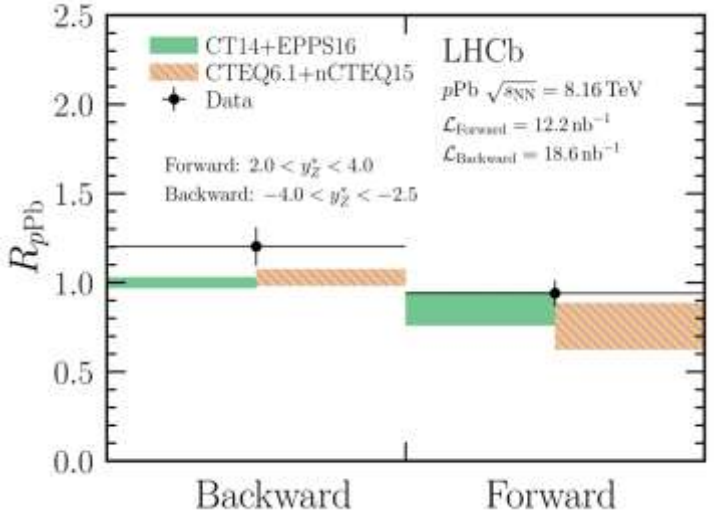




JHEP05(2023)036



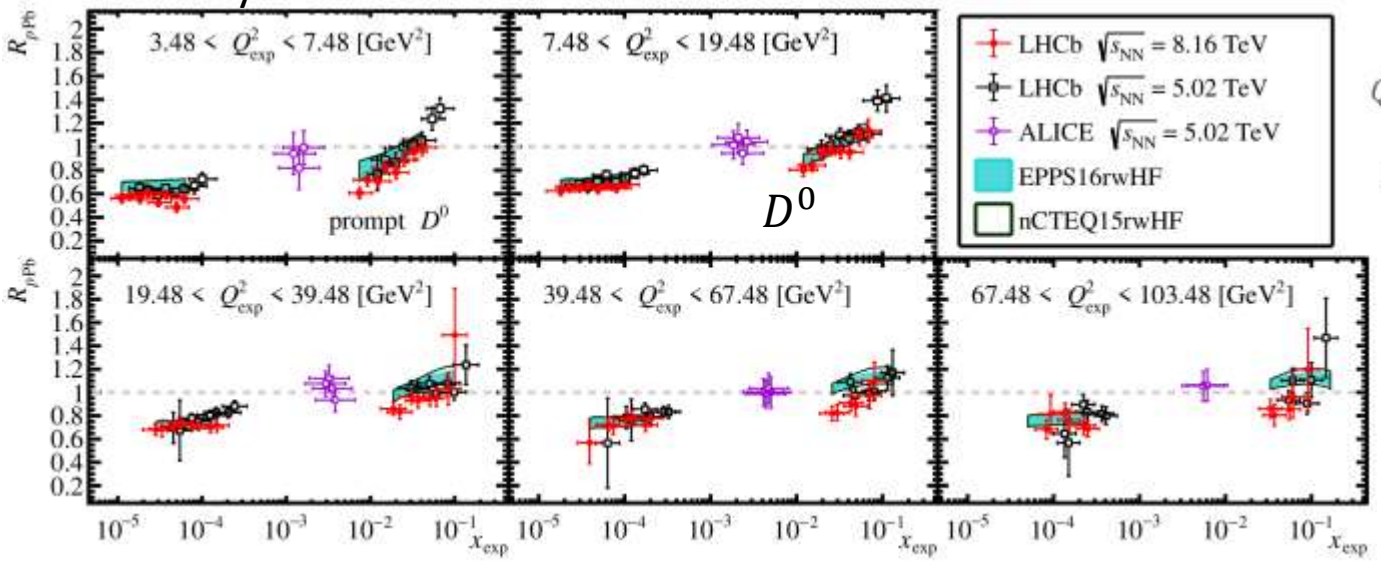
ATLAS-CONF-2023-063



JHEP 06 (2023) 022

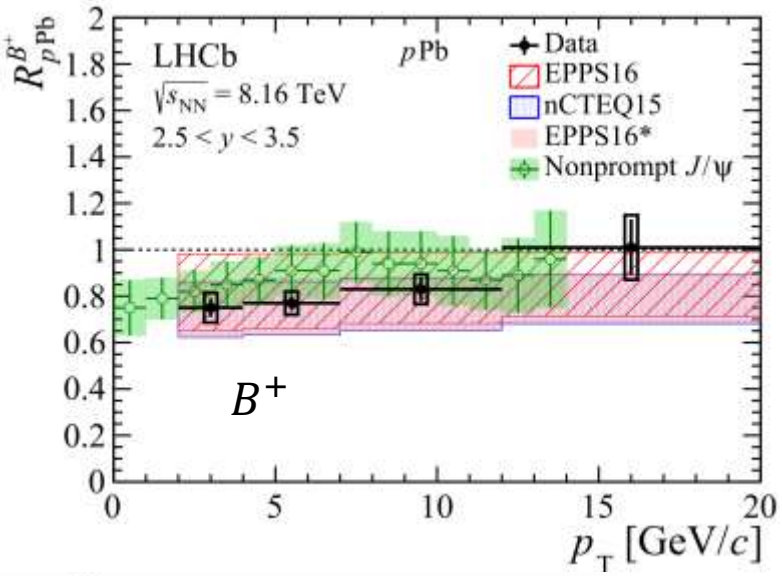
Heavy flavor production *p*Pb collisions

PhysRevLett.131.102301

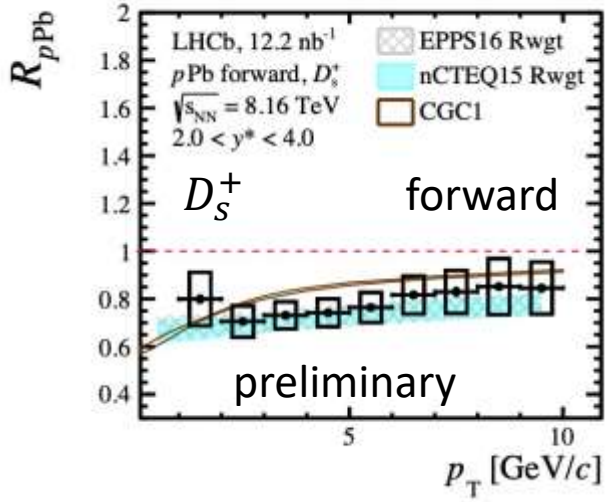


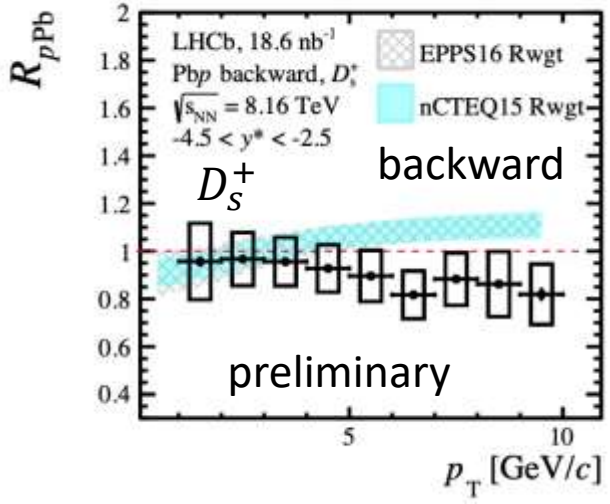
$$Q^2_{exp} \equiv m^2_{D^0} + p^2_T$$

$$x_{exp} \equiv 2\frac{Q_{exp}}{\sqrt{s_{NN}}}e^{-y^*}$$



Data < nPDF in the backward?





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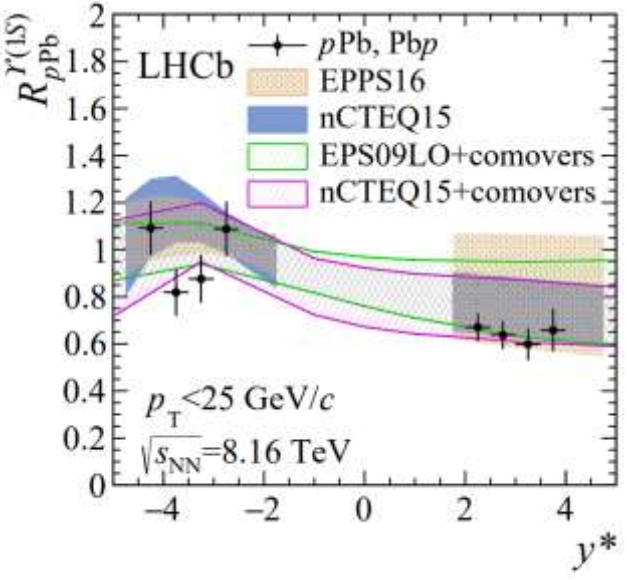
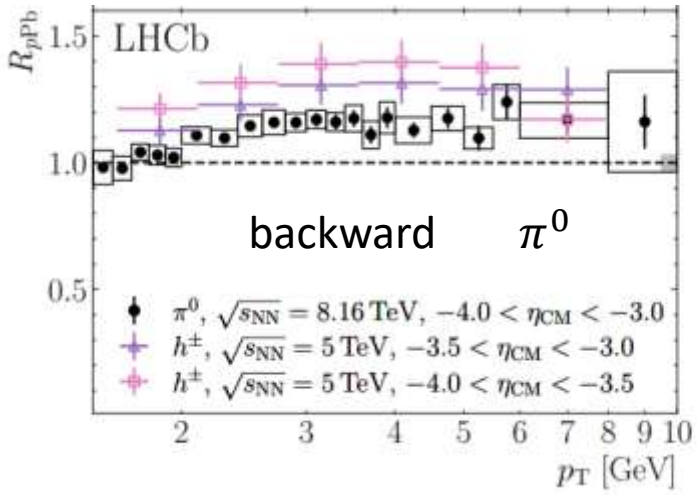
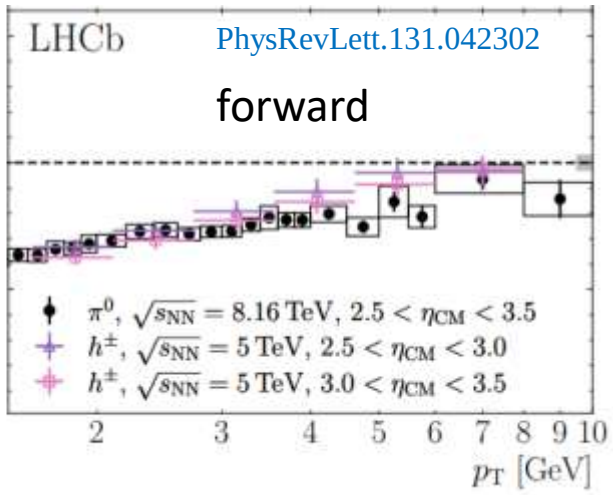
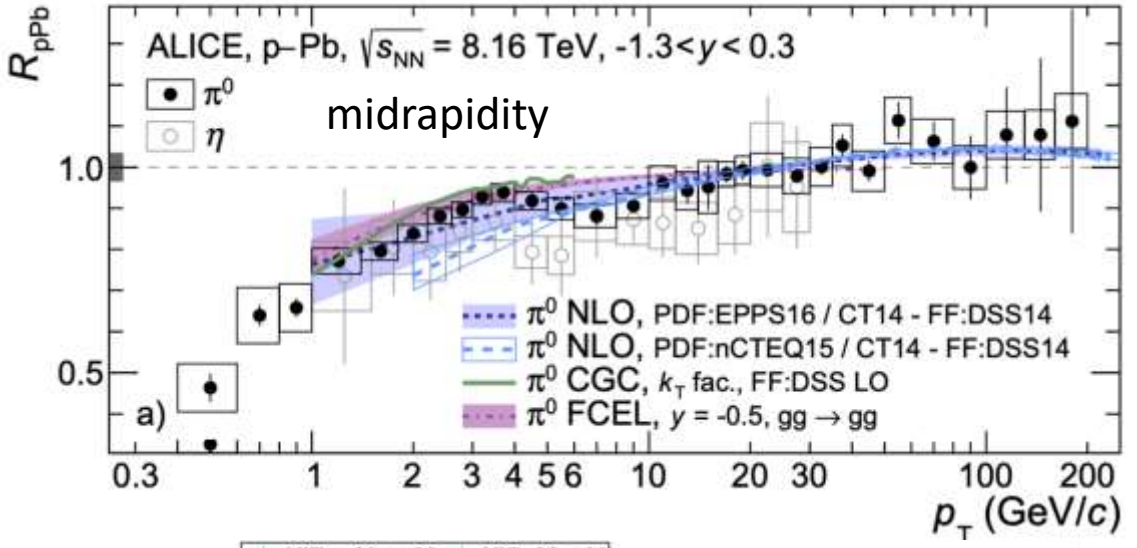


Light hadrons in *p*Pb collisions

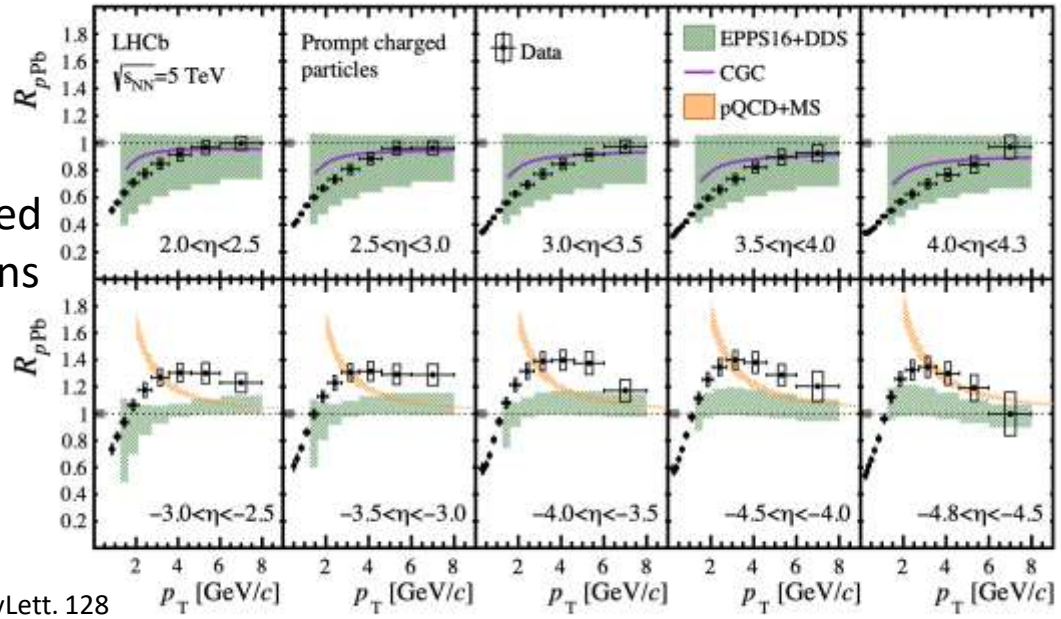
Phys. Lett. B 827 (2022) 136943







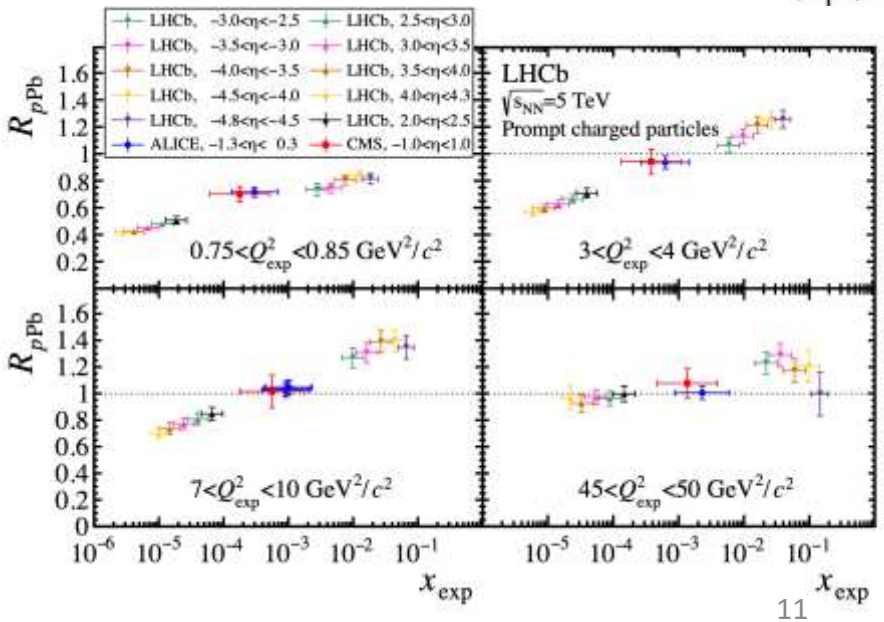
Charged hadrons



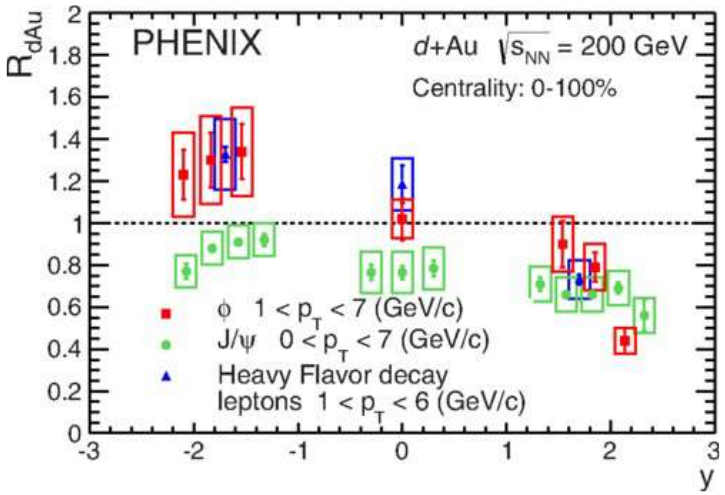
PhysRevLett. 128 (2022)142004

Forward: suppression
Backward: enhancement?

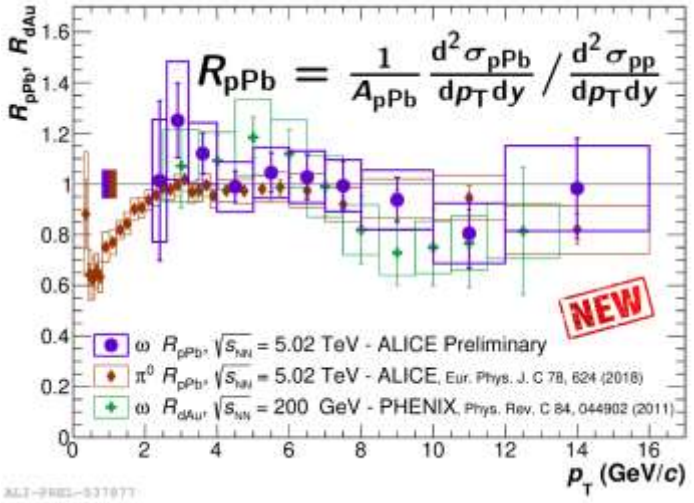
$$x_{exp} \equiv \frac{Q_{exp}}{\sqrt{s_{nn}}} e^{-\eta}$$
$$Q^2_{exp} \equiv m^2 \backslash + p_T^2$$



New light hadrons in dAu/*p*Pb collisions

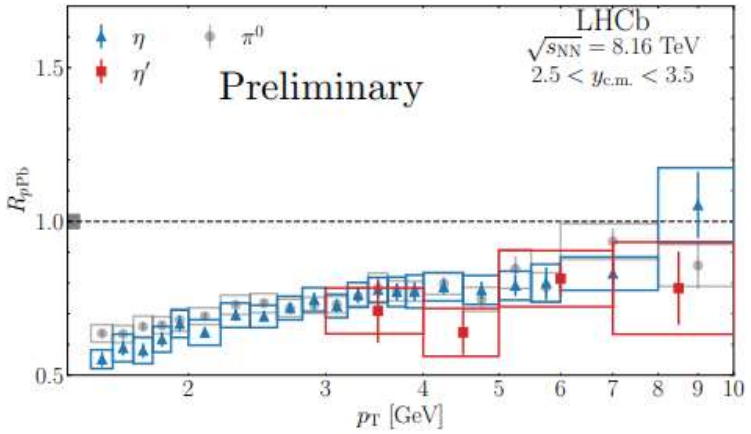


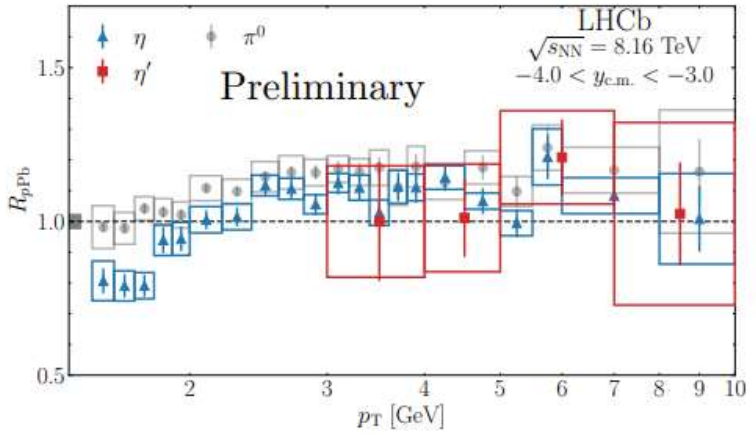
Hiden strange ϕ meson in dAu at $\sqrt{s_{NN}} = 200$ GeV
Enhancement in Au going direction



First measurement of ω meson in *p*Pb collisions at LHC

No nuclear modification observed



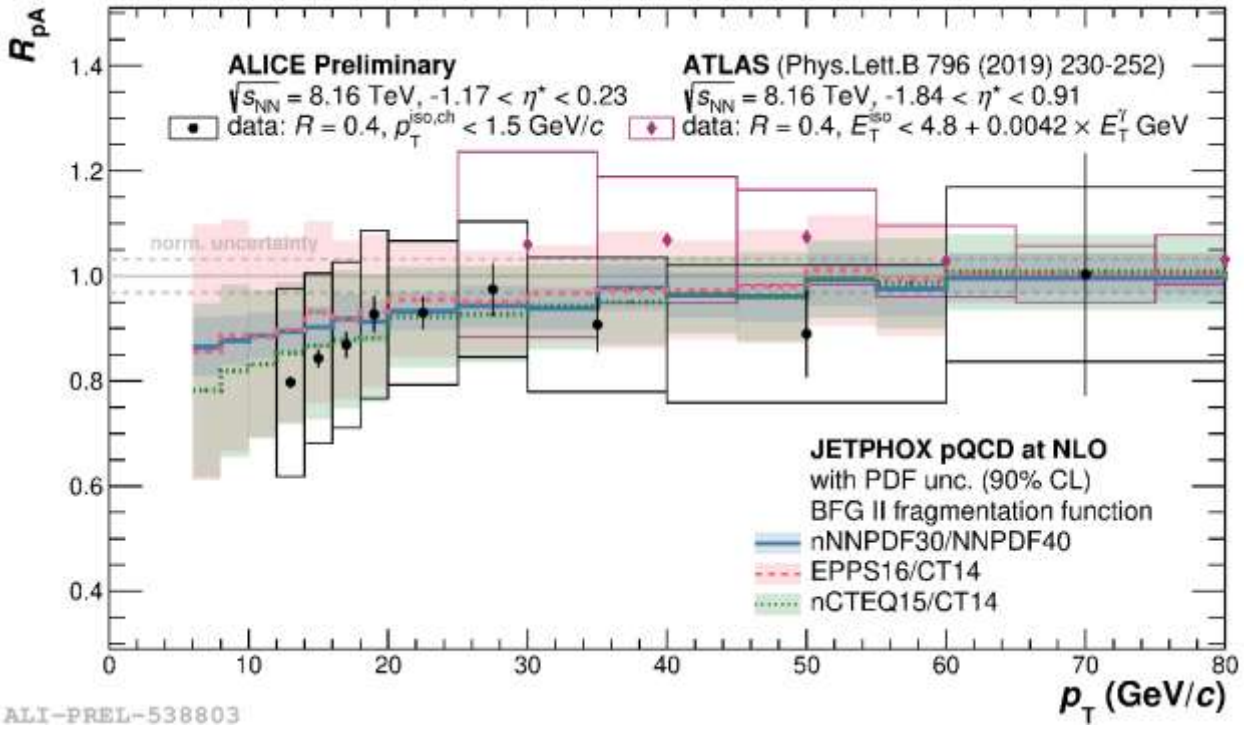


π^0, η, and η' nuclear modification factors agree
No evidence of mass-dependent effects
First η meson production measurement at forward rapidity
First measurement of η' meson nuclear modification factor

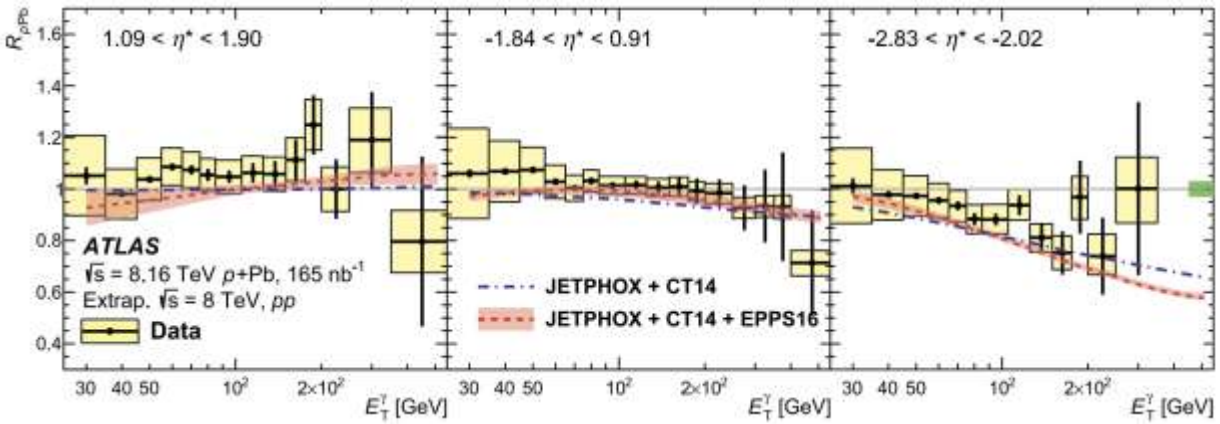
LHCb-PAPER-2023-030

Direct photons in *p*Pb collisions

- Hints of suppression at lower p_{T}
- Agreement between ALICE and ATLAS results
- Comparable suppression in nPDFs including gluon shadowing

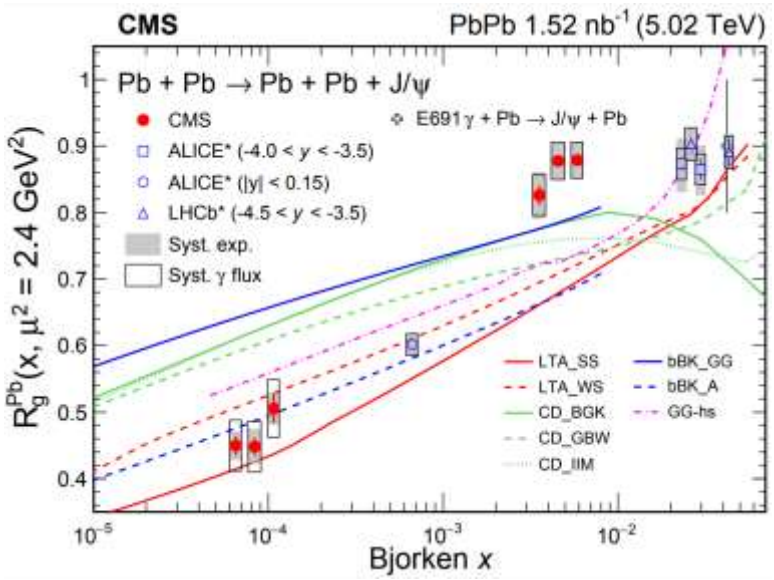


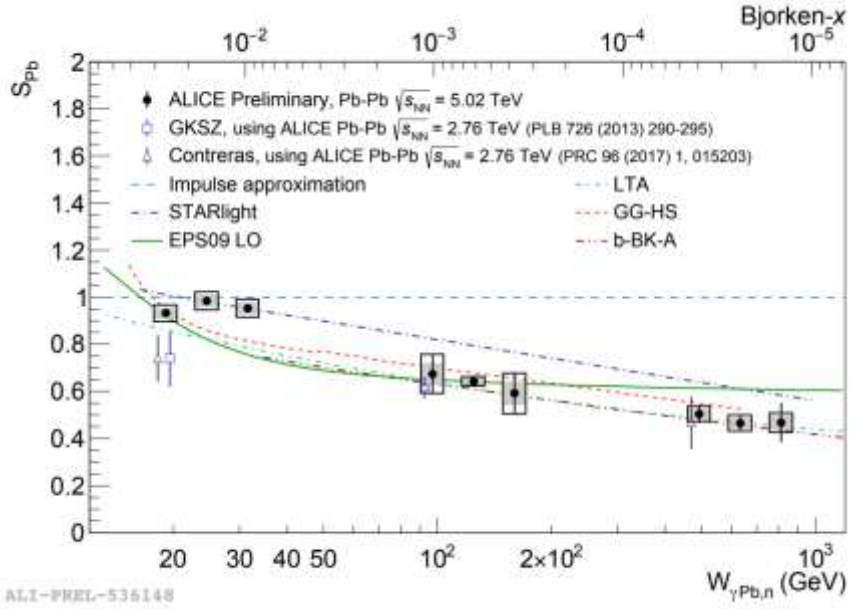
- $20 < E_{\mathrm{T}}^{\gamma} < 500$ GeV/c $\quad 3 \times 10^{-3} < x < 4 \times 10^{-1}$

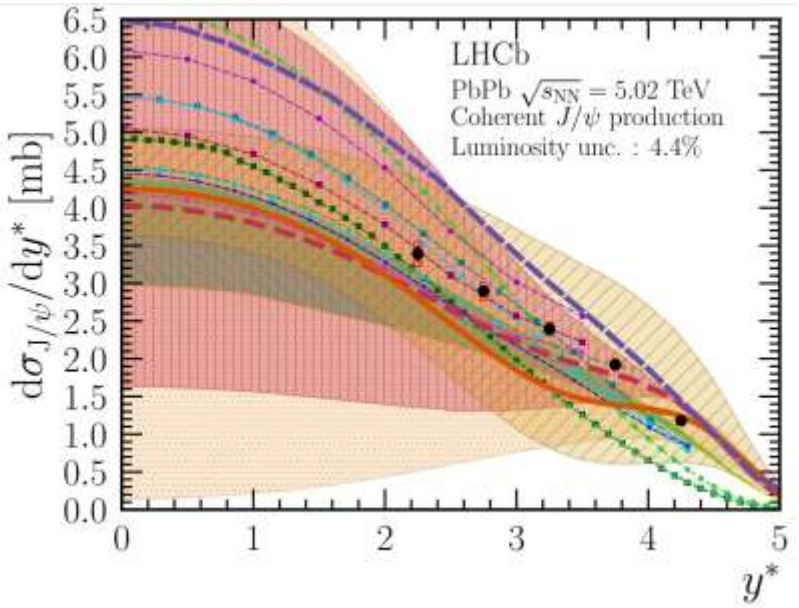


Physics Letters B 796 (2019) 230–252

Charmonia in PbPb ultraperipheral collisions







- Nuclear suppression factor at Bjorken-*x* of O(10^{-5}) in UPC PbPb with neutron emission
- Strong constraint on nPDF at small Bjorken-*x*

The big questions…

Hadronization

fragmentation?

coalescence?

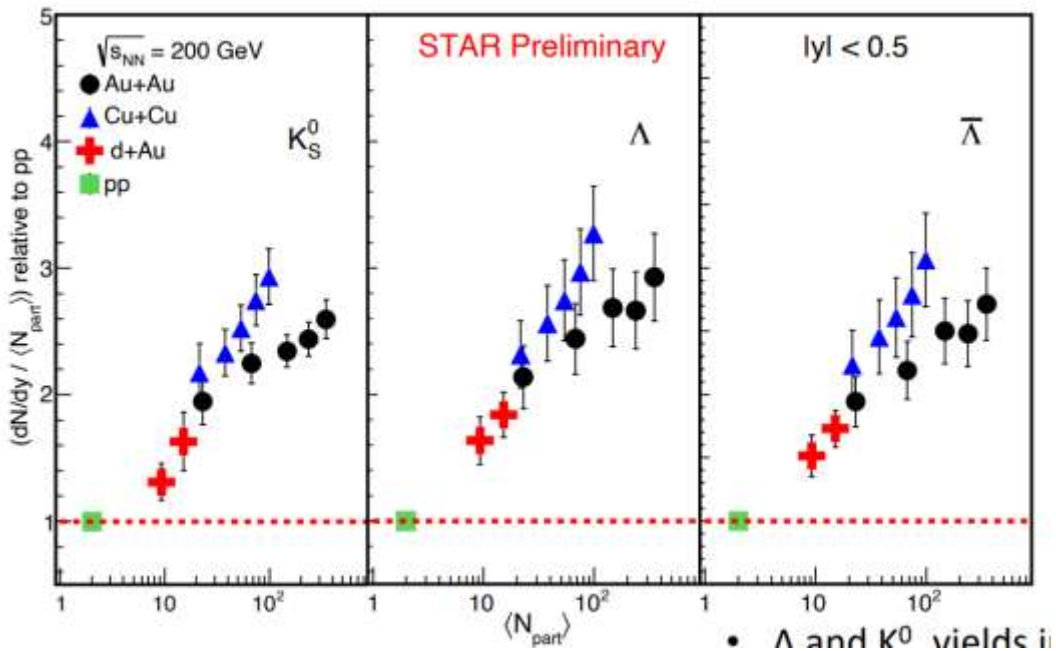
Strangeness enhancement

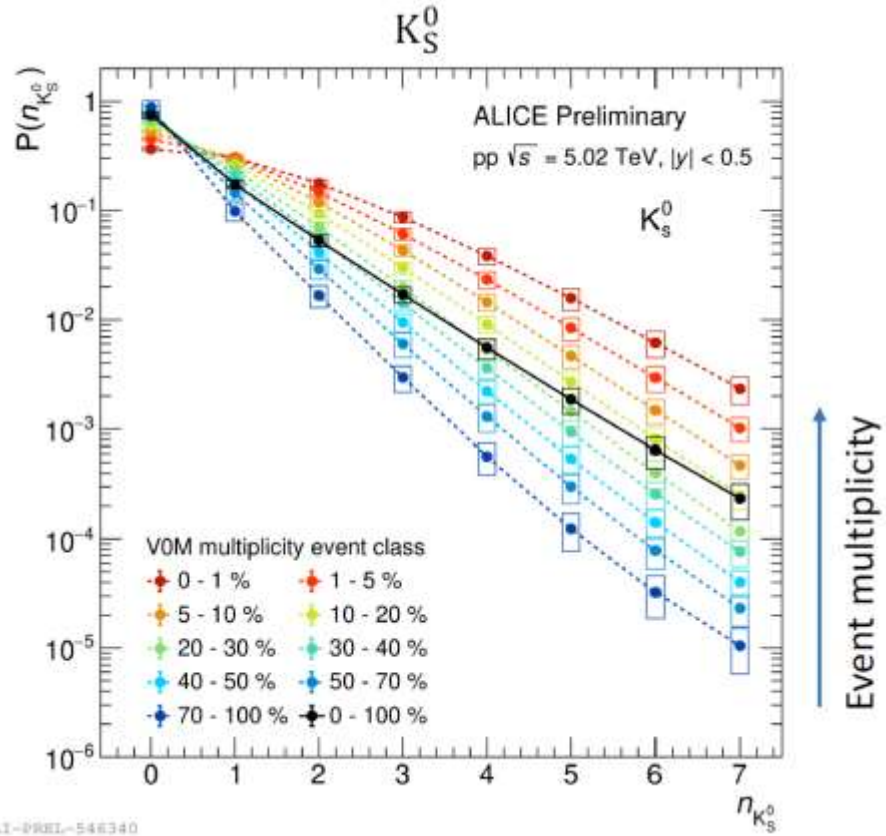
Baryon enhancement

Strangeness enhancement in small systems

- Λ and K_s^0 production in dAu collisions are enhanced

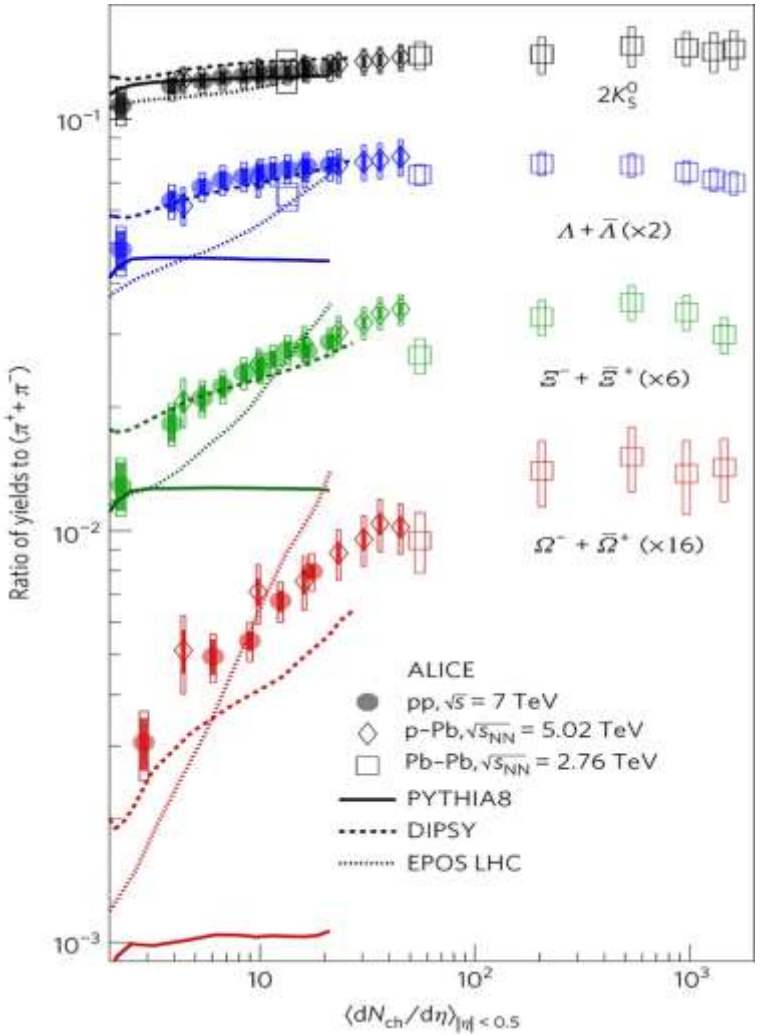
- The full Probability Density Function (PDF) for (multi-)strange hadrons is measured in *pp* collisions
- The PDF expresses the probability to produce n particles of a given species per event
- The probability to produce $n \geq 1$ strange hadron per event increases with the event charged-particle multiplicity



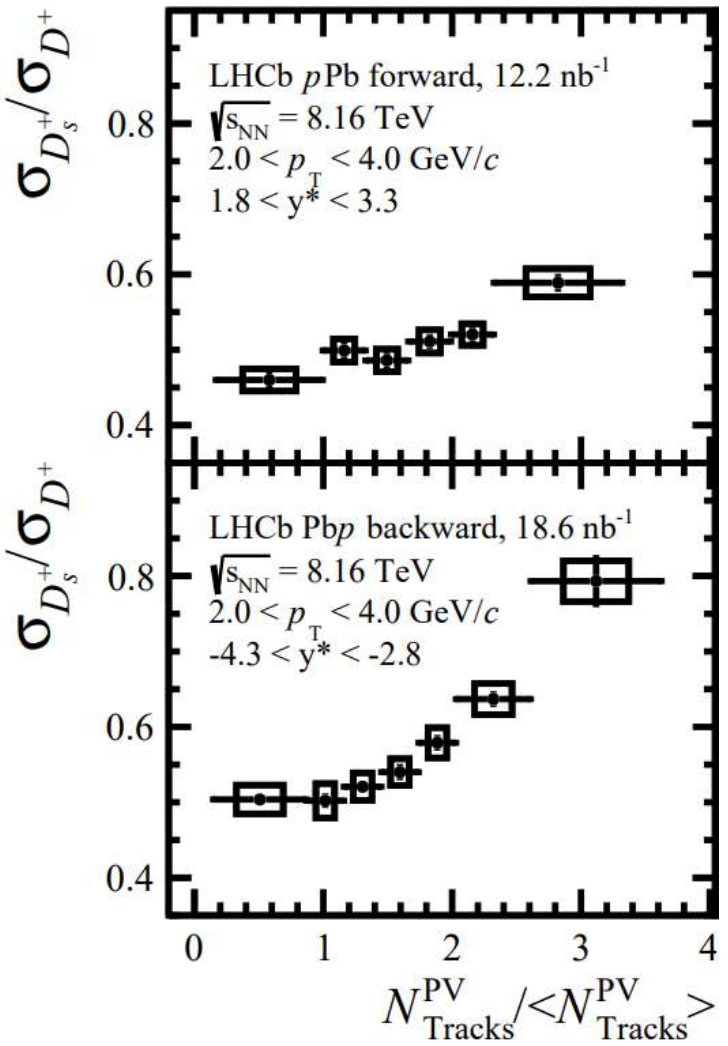


Strangeness enhancement with heavy flavor

- Observed with light flavor, charm and beauty



Nature Phys 13, 535–539 (2017)



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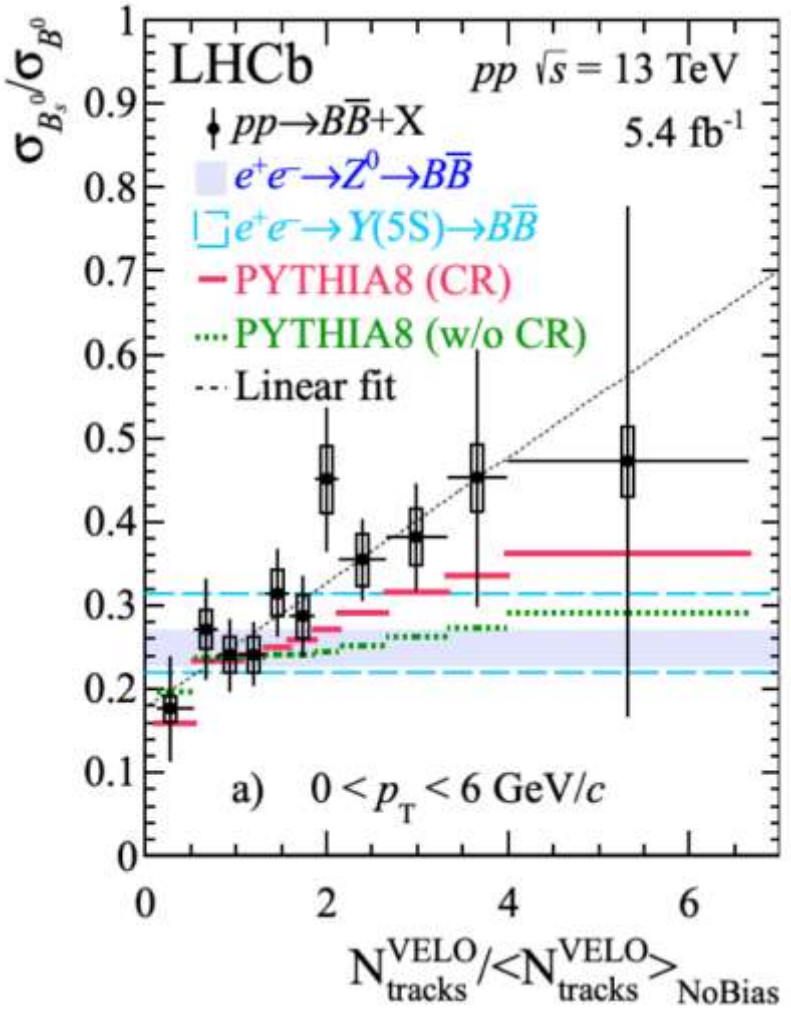
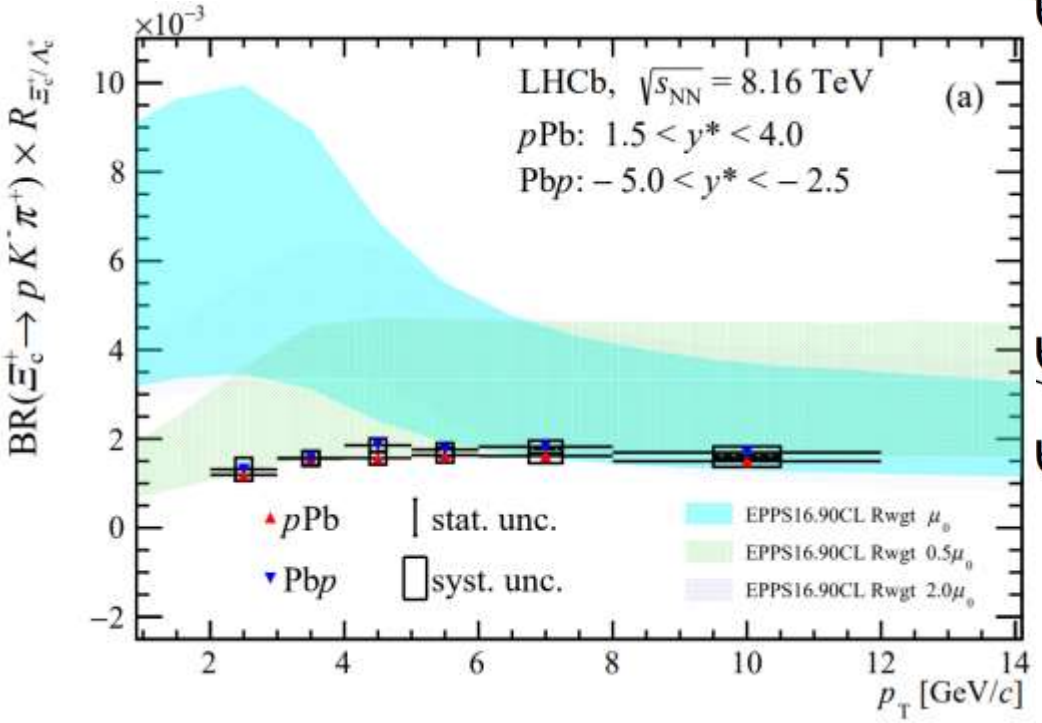


arXiv:2204.13042

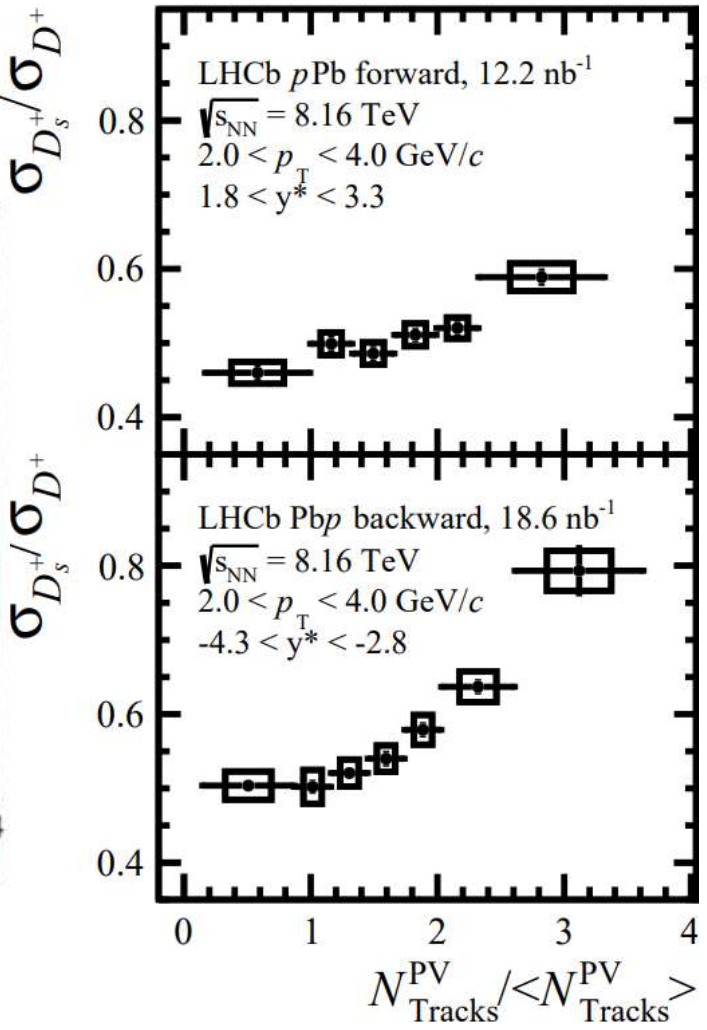
Strangeness enhancement with heavy flavor

- New observable: charm baryon ratio

$$\frac{\Xi_c^+(usc)}{\Lambda_c^+(udc)}$$



arXiv:2305.06711



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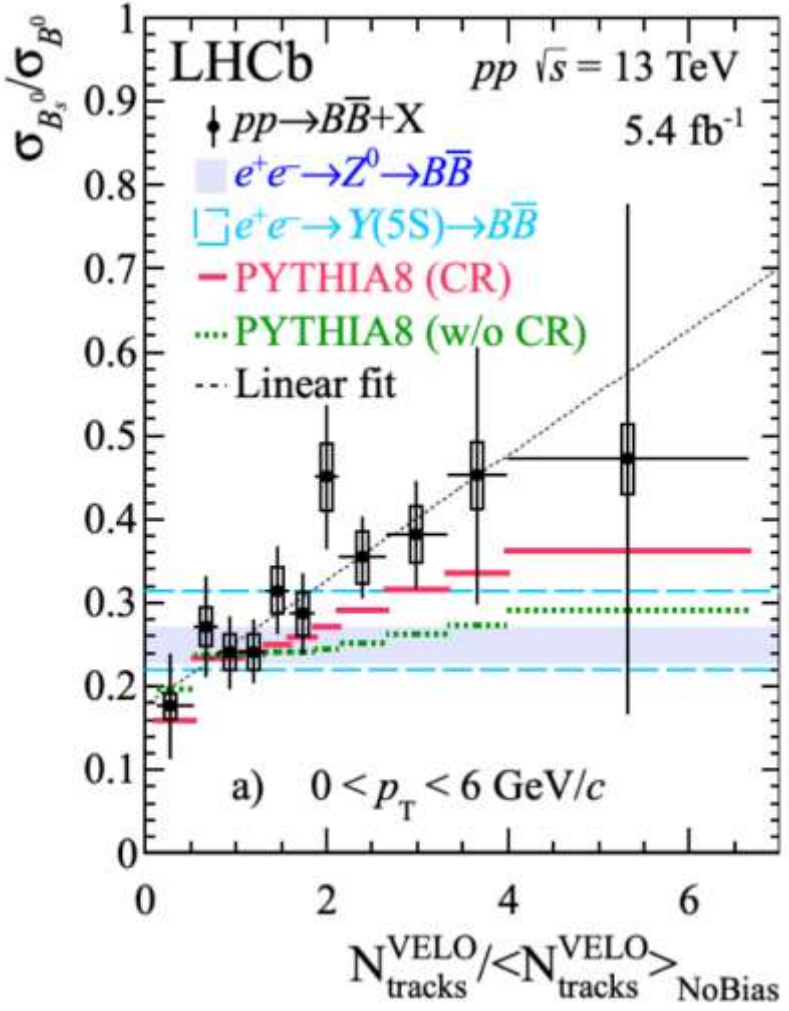
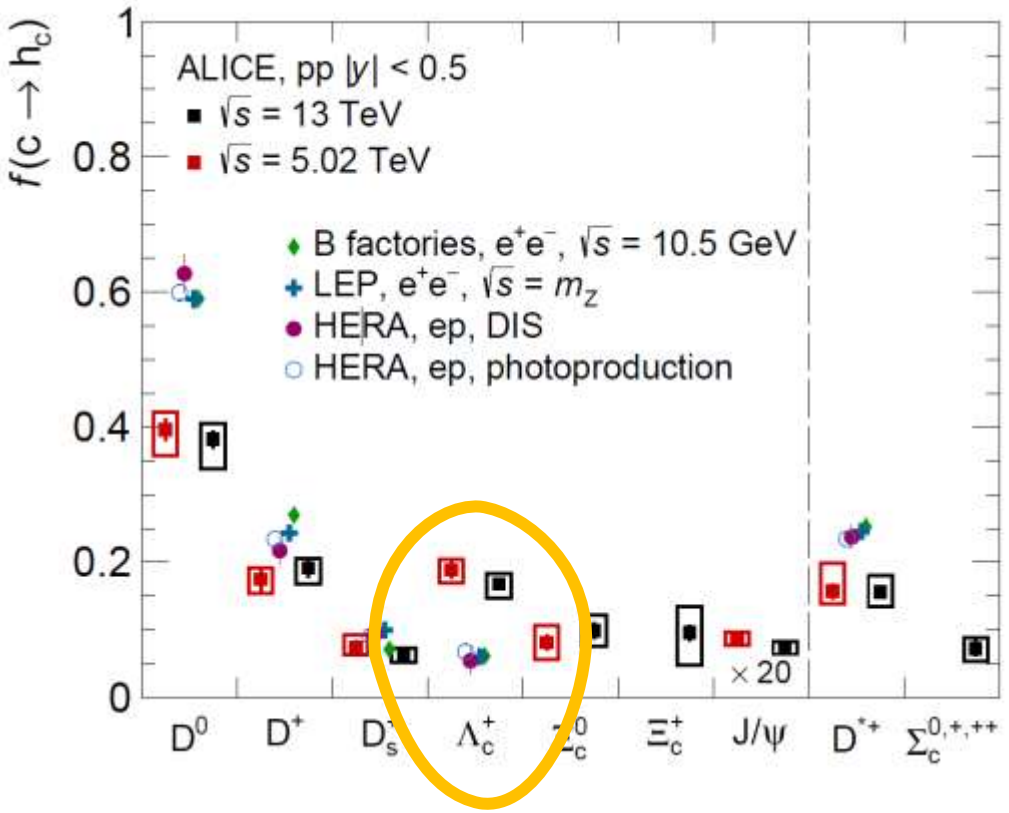
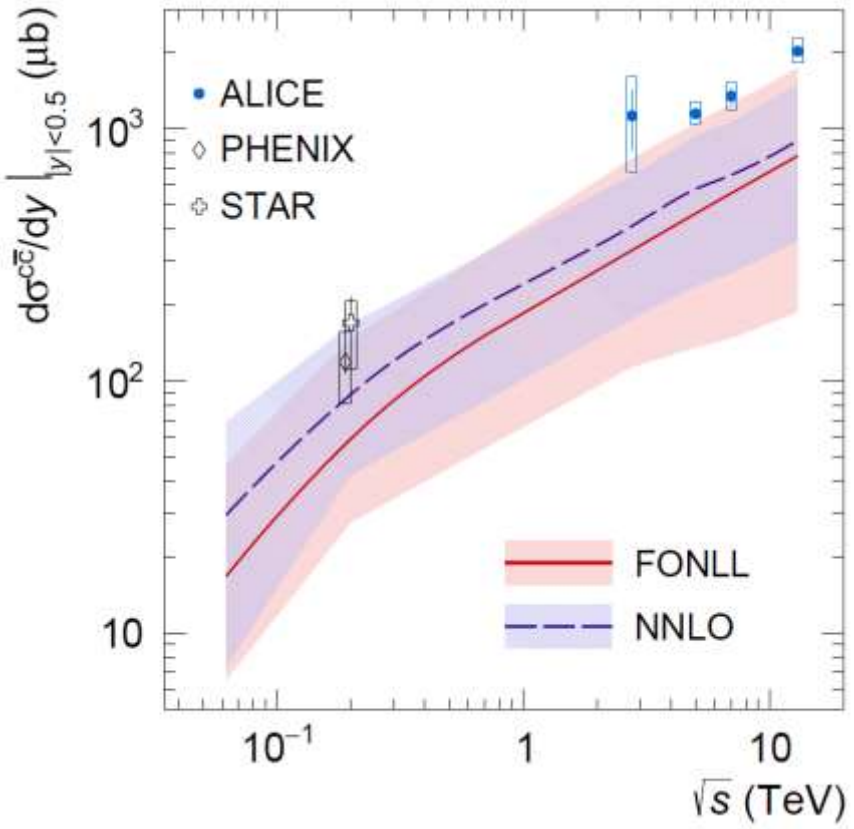


arXiv:2204.13042

Charm hadronization and production in *pp* collisions

- all ground-state charm hadron fragmentation fractions
  - Λ_c^+, Ξ_c^+ enhanced compared to e^+e^- and ep collisions
- $c\bar{c}$ cross section calculated from sum of D^0, D^+, D_s^+, J/ψ, Λ_c^+, Ξ_c^0, and Ξ_c^+ hadrons at midrapidity

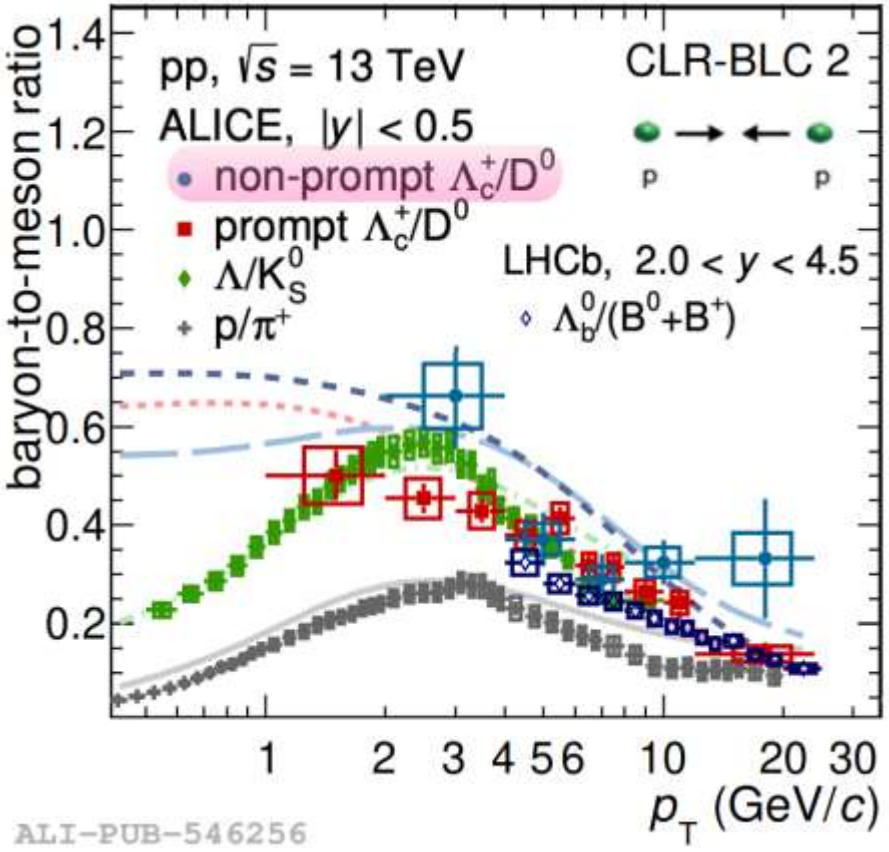




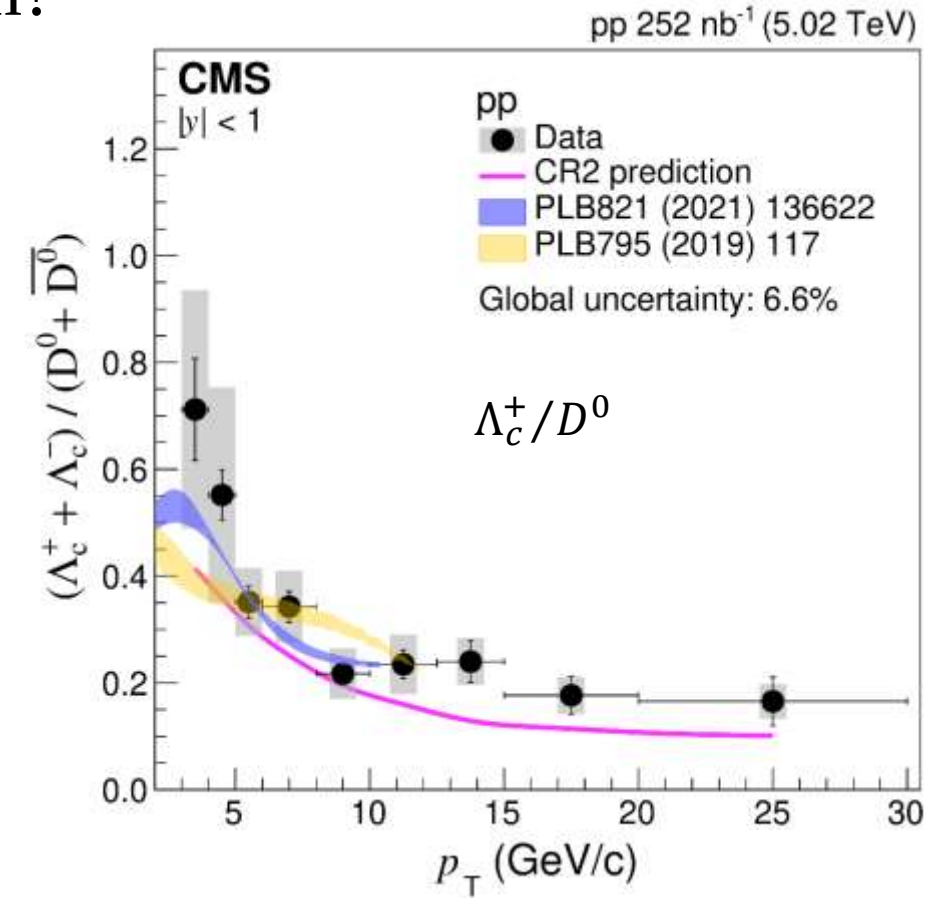
arXiv:2308.04877

Charm baryon enhancement in *pp* collisions

- Different baryon to meson ratio show similar shape
- → similar formation mechanism?



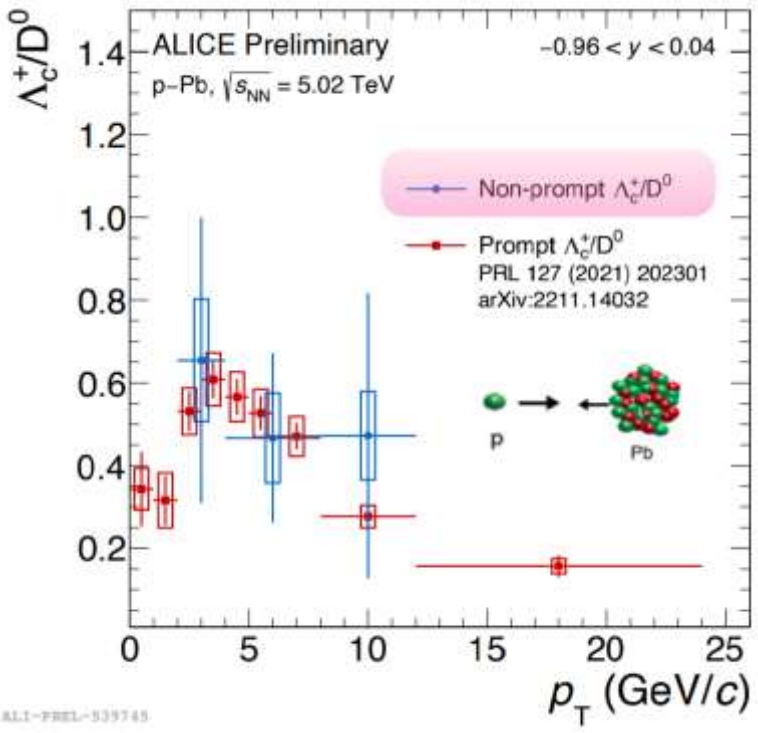
arXiv: 2308.04873

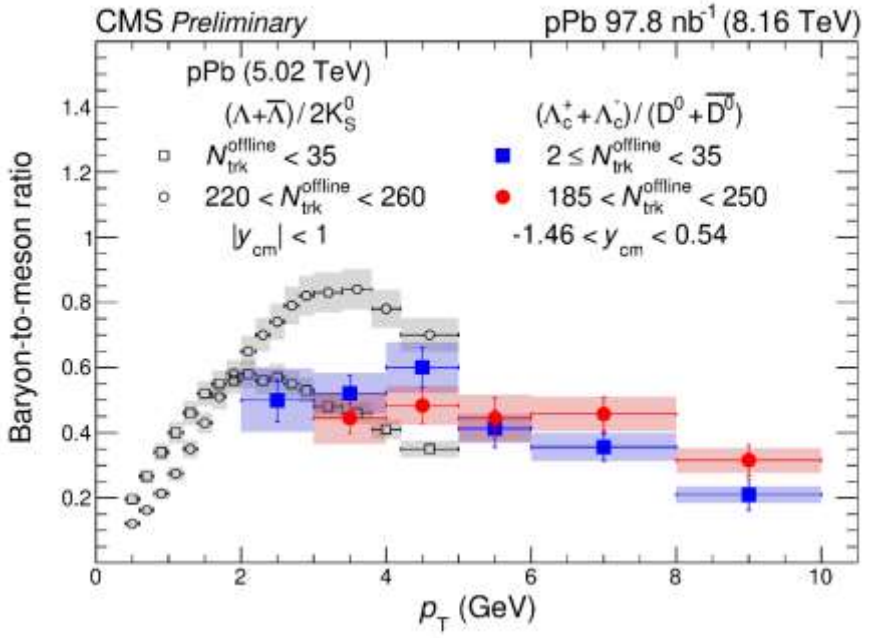


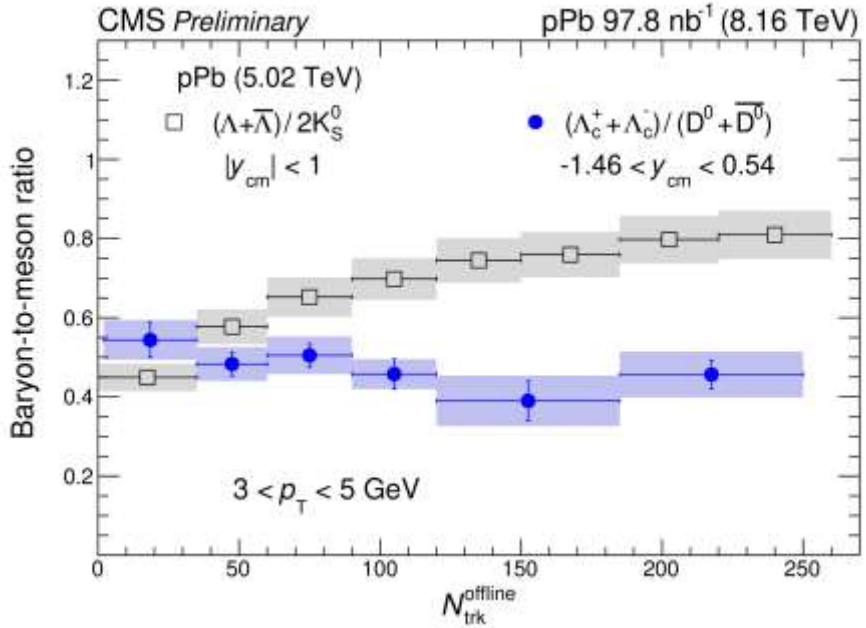
arXiv:2307.11186

Charm baryon enhancement in *p*Pb collisions

- Λ_c^+/D^0 ratio down to $p_T = 0$, prompt compatible with non-prompt ratio
- New CMS measurement consistent with ALICE result
- No multiplicity dependence observed



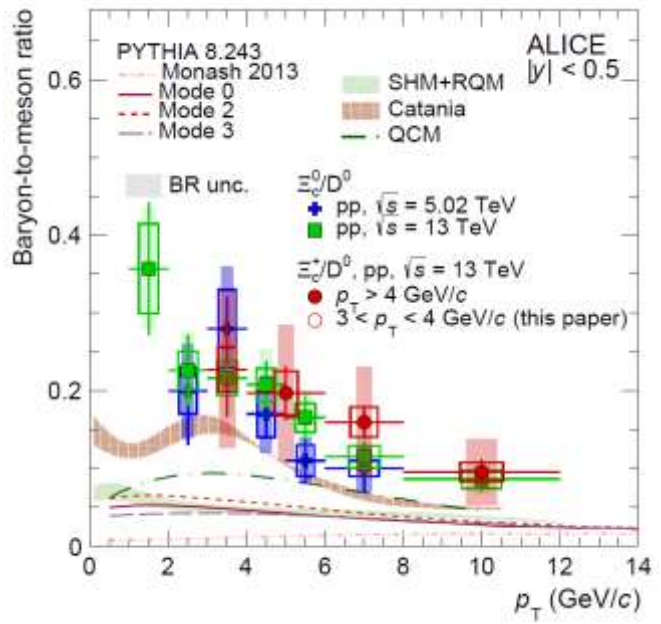


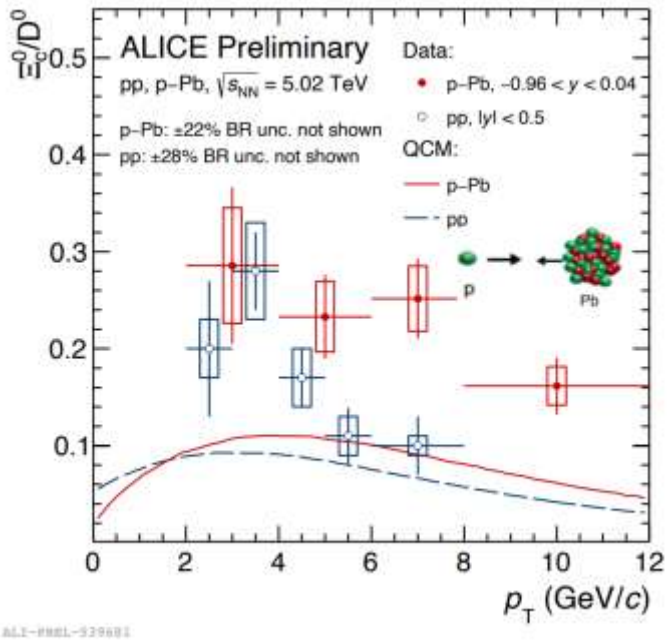


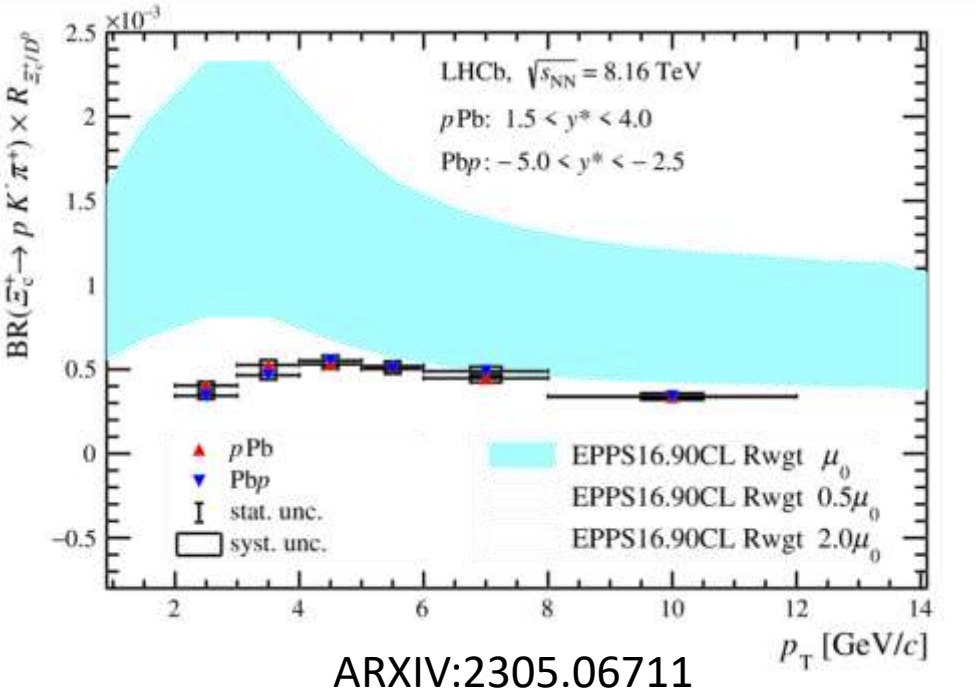
CMS-PAS-HIN-21-016

More charm baryons in *pp* and *p*Pb collisions

- First measurements of $\Xi_c^0(\mathrm{dsc})/D^0$ and $\Xi_c^+(\mathrm{usc})/D^0$ ratios in *p*Pb collisions
- Hint of enhancement of $\Xi_c^0(\mathrm{dsc})/D^0$ in *p*Pb compared to *pp*
- Ξ_c^+/D^0 ratio compatible between forward and backward rapidities



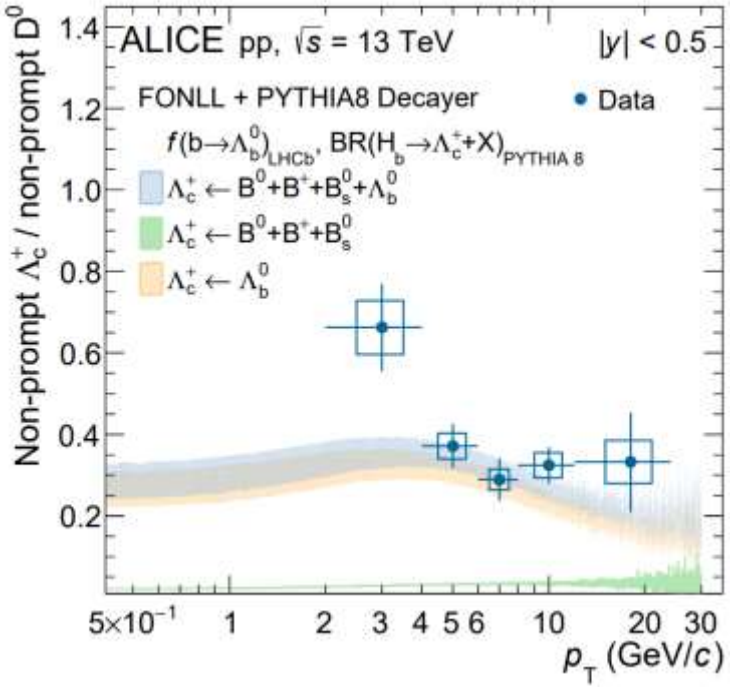


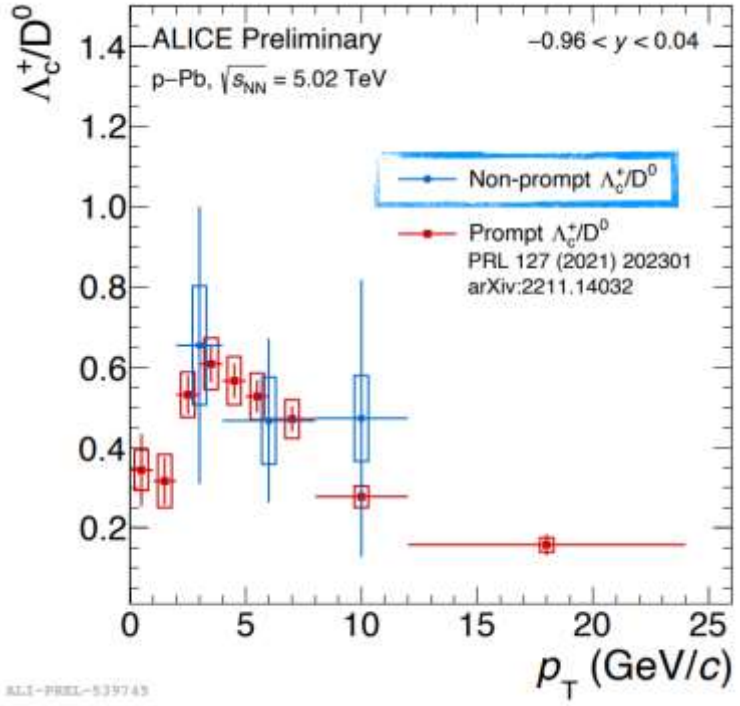


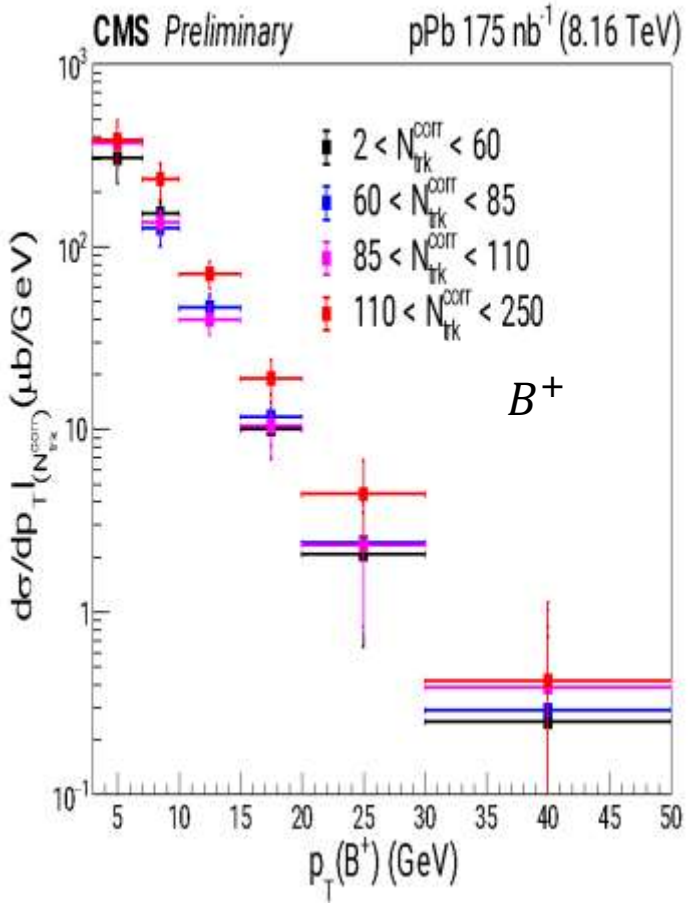
ARXIV:2305.06711

How about beauty?

- First measurement of non-prompt Λ_c^+/D^0
- CMS B^+ production in multiplicity bins

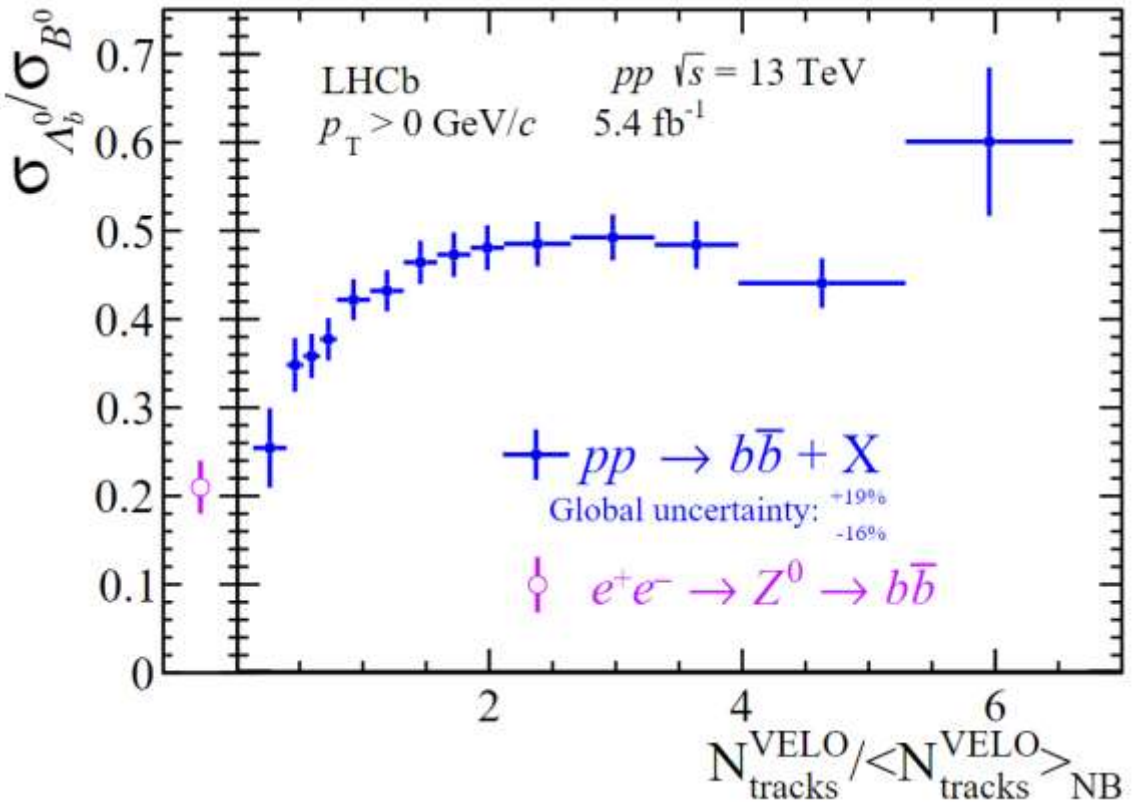




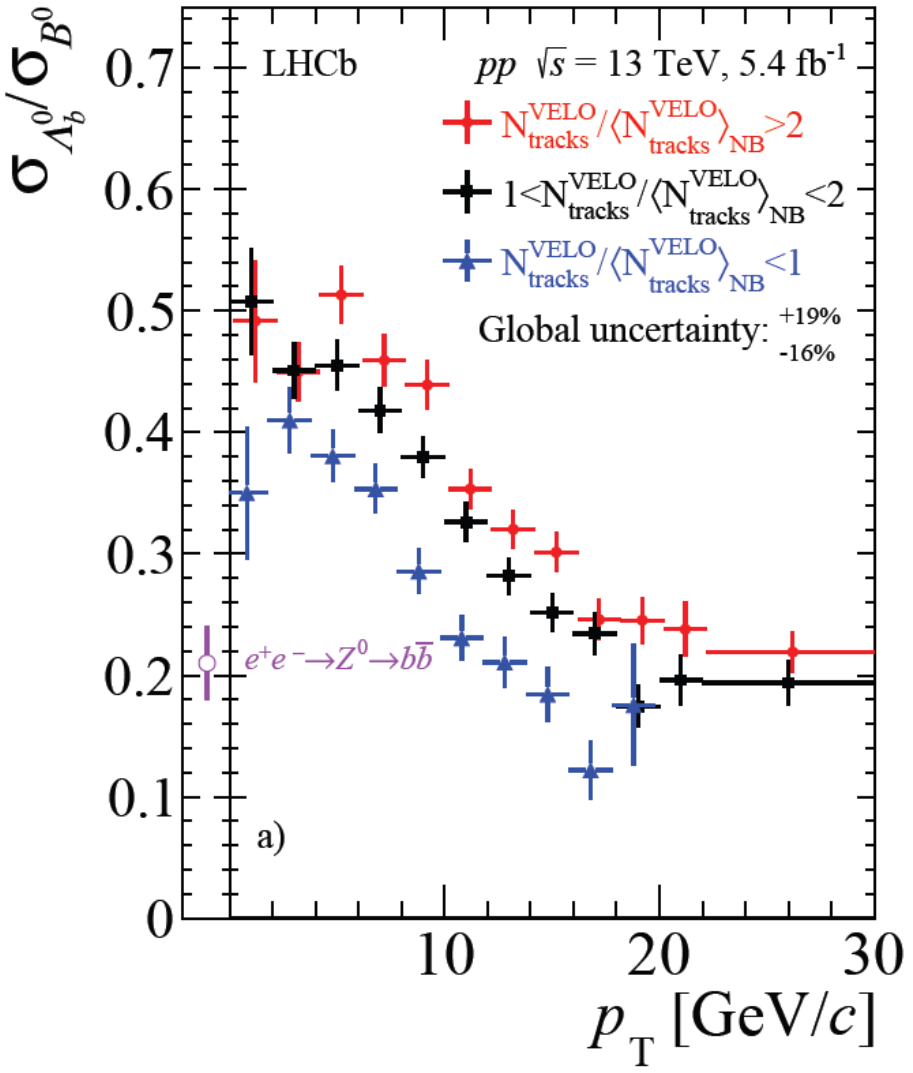


Λ_b^0/B^0 in pp collisions at 13 TeV

- Λ_b^0/B^0 ratio increases with multiplicity
- Higher than e^+e^- value at low p_T
- Consistent with e^+e^- value at lowest multiplicity and high p_T



LHCb-PAPER-2023-027



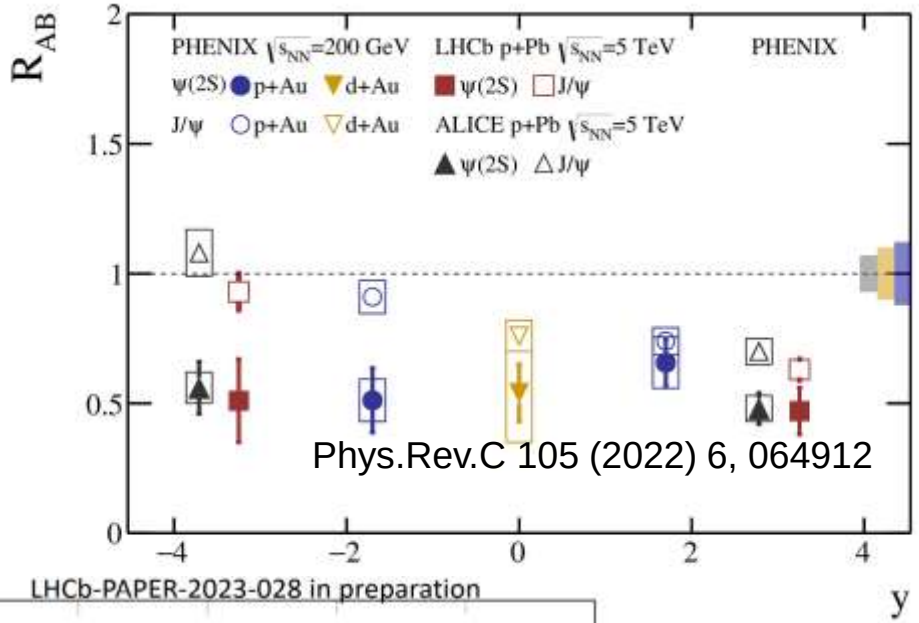
The big questions…

Quarkonia breakup

comover effects?

Quarkonia in pPb collisions

- First measurement: χ_{c1} + χ_{c2} measured in the $J/\psi\,\gamma$ decay channel.
- No final-state dissociation of χ_c states in pPb collisions



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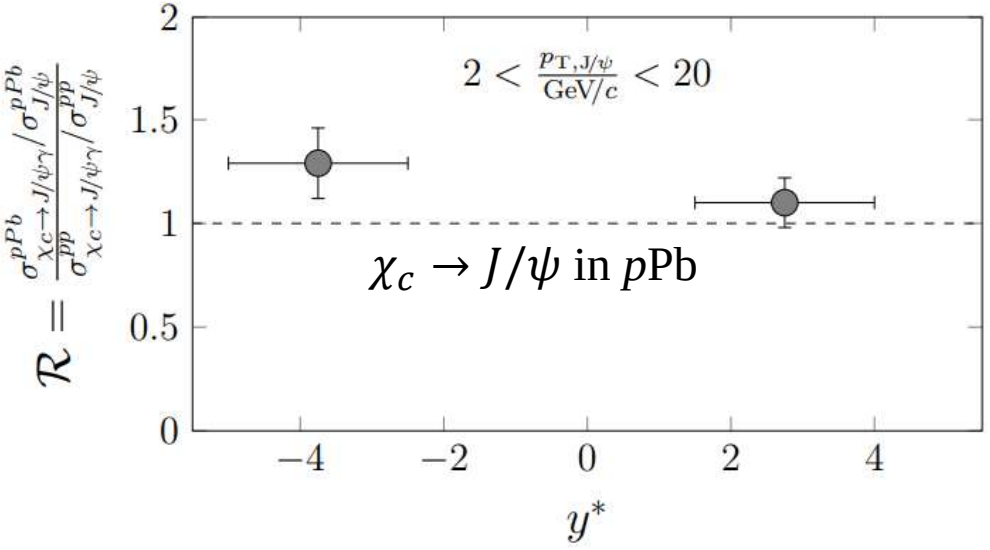
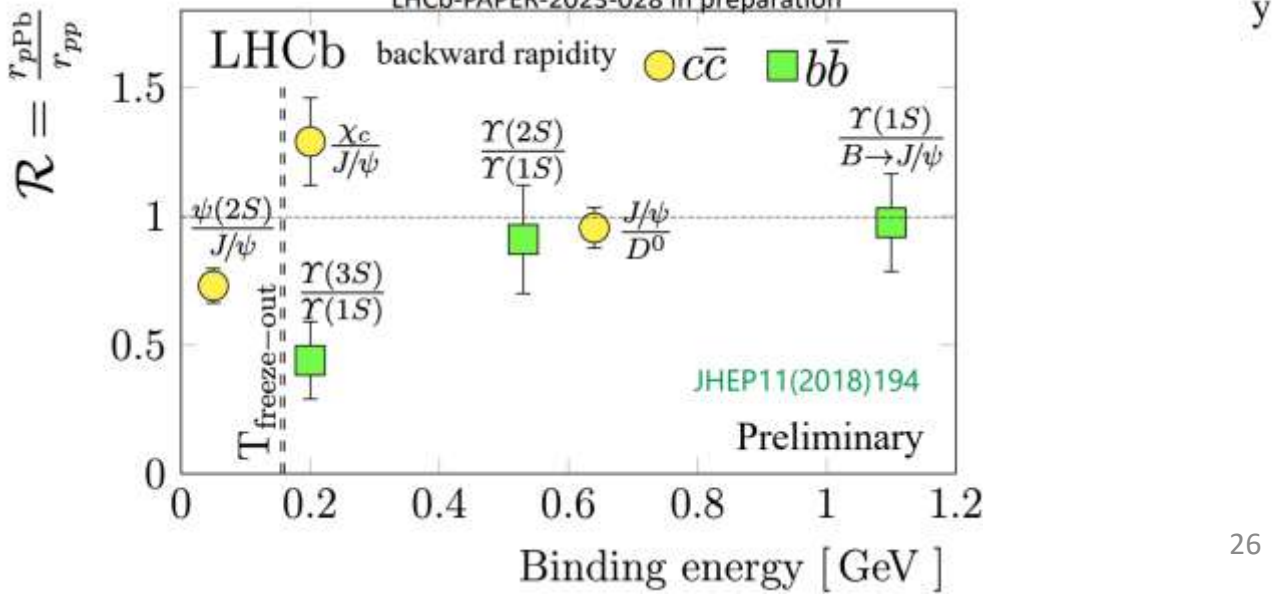


LHCb-PAPER-2023-028 in preparation



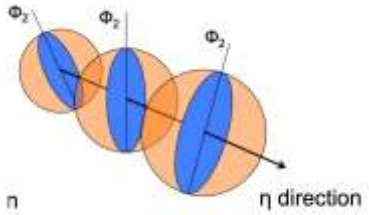
The big questions…

Correlations and collectivity

origin of flow in small system?

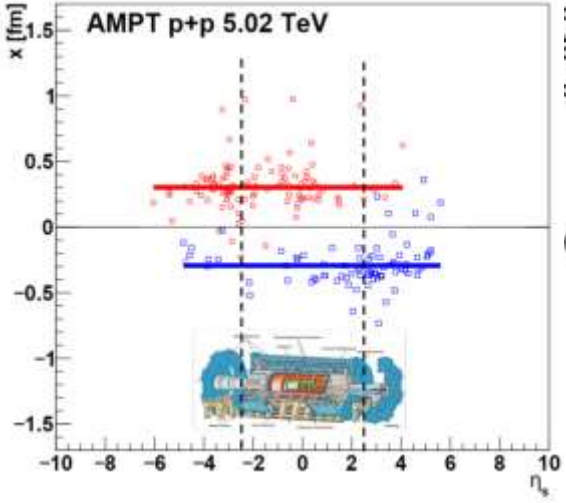
Flow in *pp* system suggests proton sub-nucleon structure

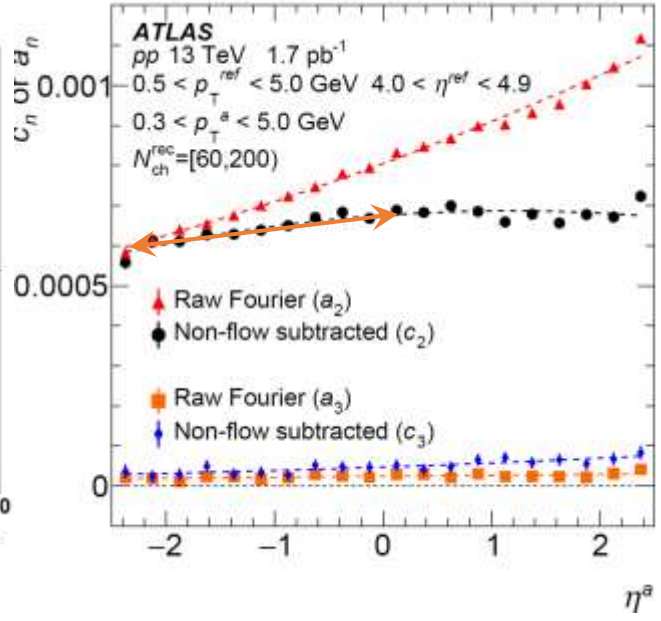
- Flow decorrelation in η
- Simple model of proton-proton collisions
  - A string per participant
  - No variation in geometry
  - No longitudinal decorrelation



$$\Psi_n(\eta_1) \neq \Psi_n(\eta_2)$$

- Need for sub-nucleonic structure to explain data

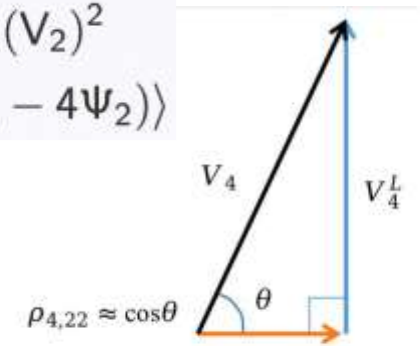




- Nonlinear flow response
- $\rho_{4,22}$ decreasing trend indicates sub-nucleon structure of proton

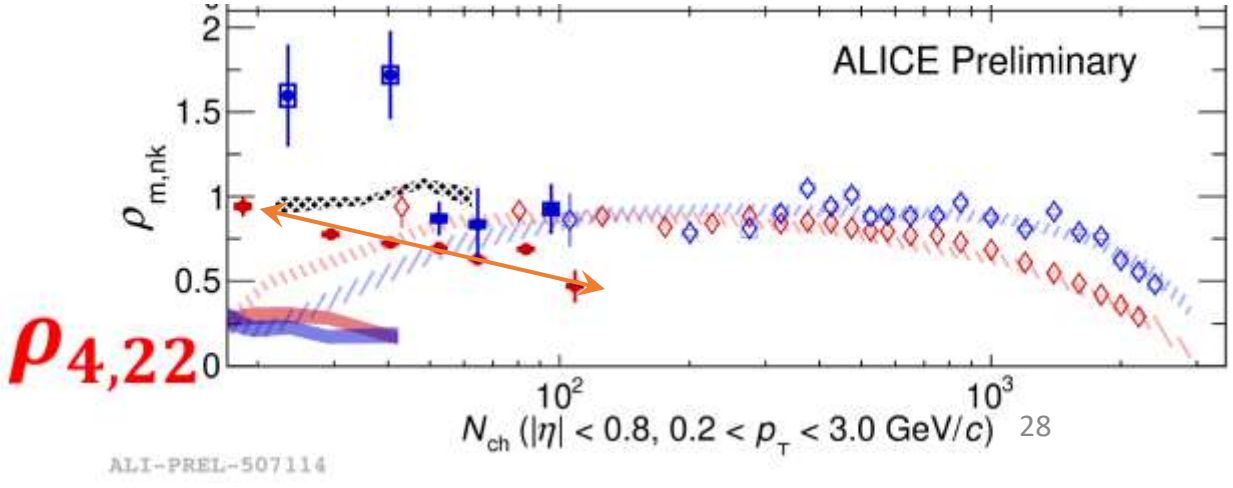
$$V_4 = V_4^L + V_4^{NL} = V_4^L + \chi_{4,22}(V_2)^2$$

$$\rho_{4,22} = v_{4,22}/v_4\{2\} = \langle\cos(4\Psi_4 - 4\Psi_2)\rangle$$



$$V_4^{NL} \approx \chi_{4,22}(V_2)^2$$

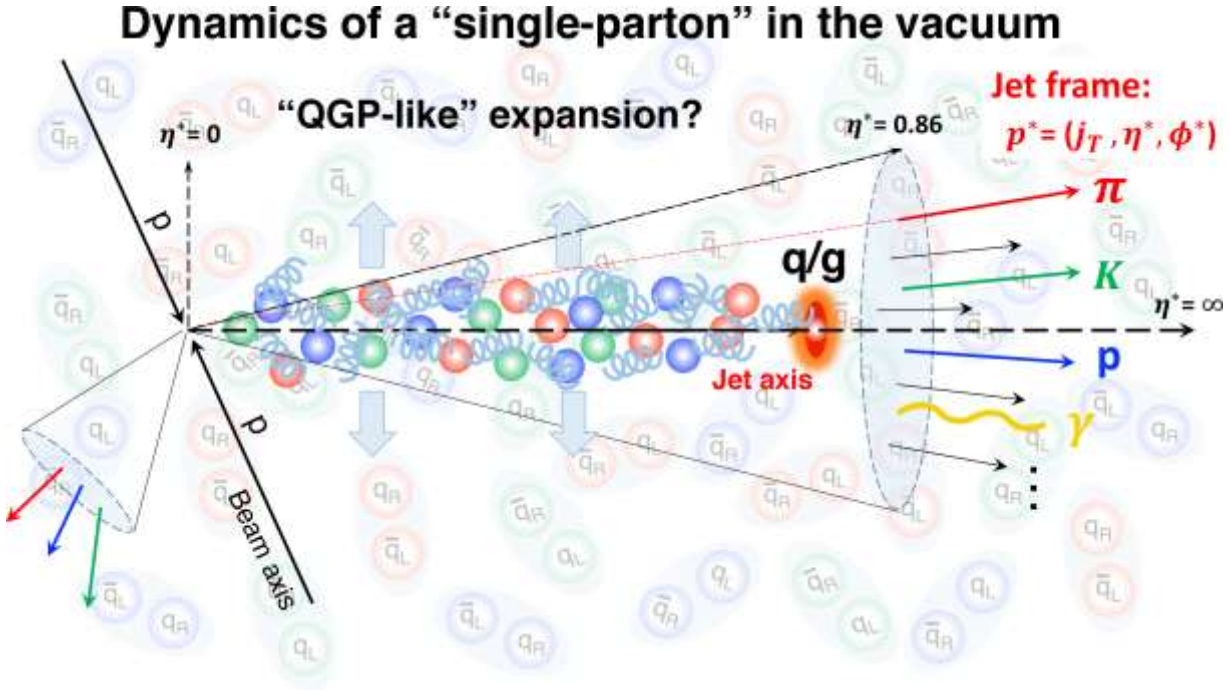
$$|V_4^{NL}| = v_{4,22}$$



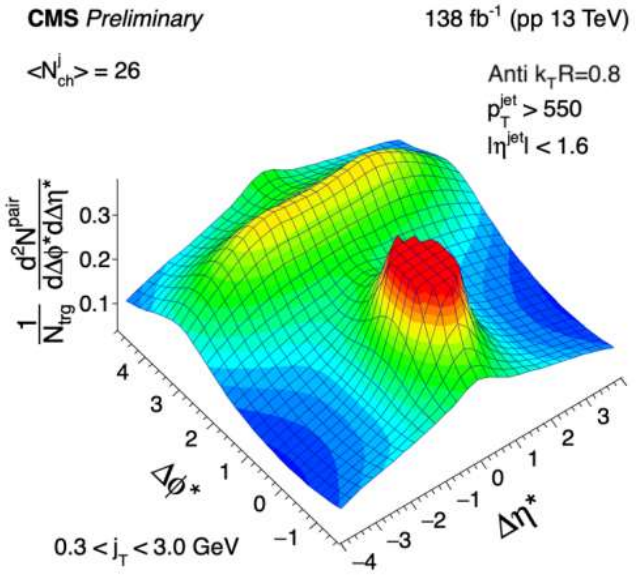
Flow in single jet (*pp*@13TeV)

Observation of enhanced long-range elliptic anisotropies inside high-multiplicity jets in pp collisions at the LHC

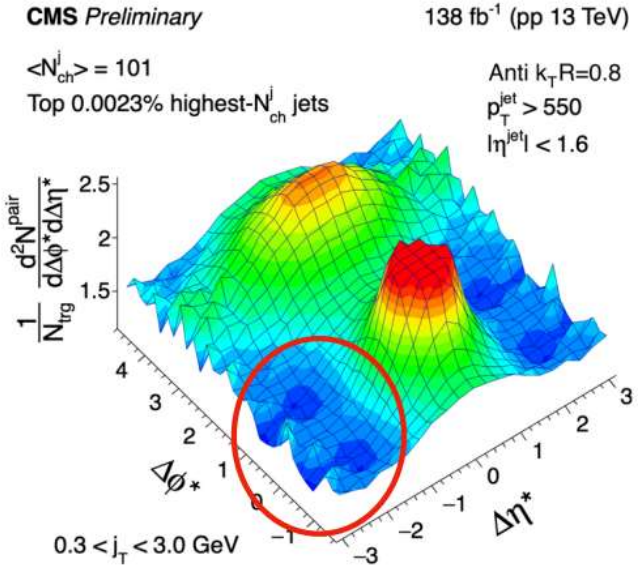
- From how small of a system can collectivity emerge?
- Collectivity from a fragmenting parton?



N_{ch} ~ 26

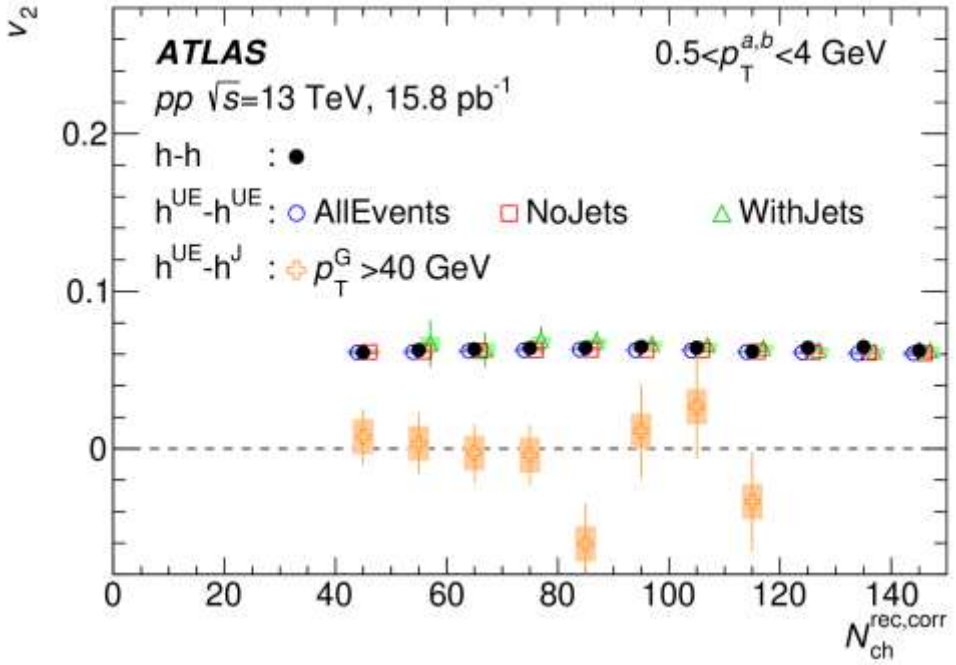


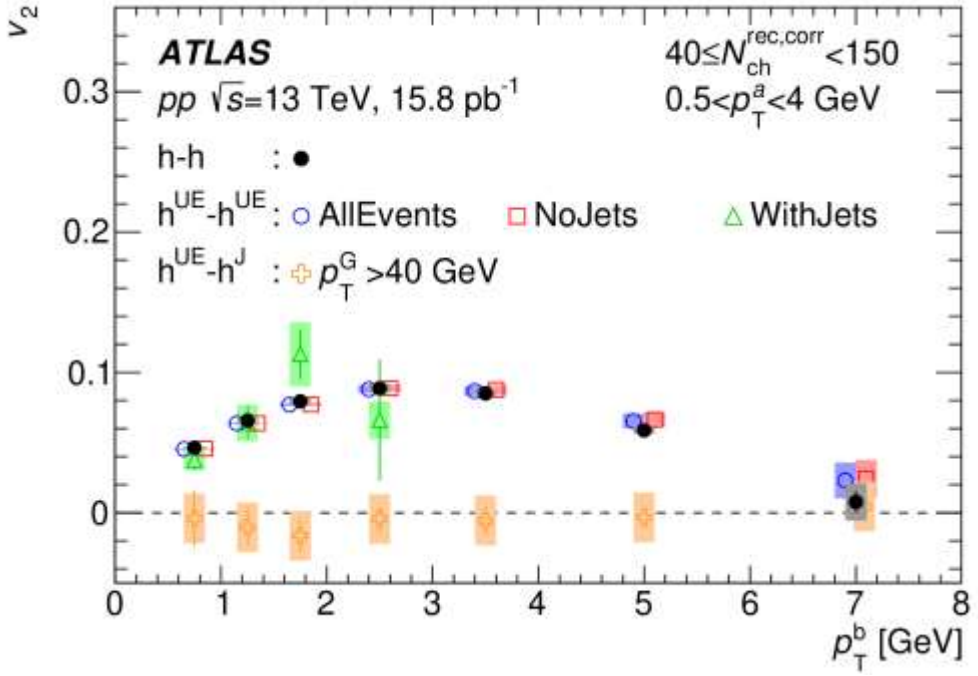
N_{ch} ~ 100



Hard-soft correlations:
2PC in *pp* with jets and Underlying Event (UE)

- Is the ridge associated with jet production?
- v_2 from jet-UE pairs and UE-UE pairs
- No significant correlation between jets and UE
  → ruling out hard processes contributing to the ridge





arXiv:2303.17357

The big questions…

Jet production and properties

Energy loss and transport in medium?

π^0 energy loss in dAu collisions?

- Experimental measure N_{coll} using direct photon

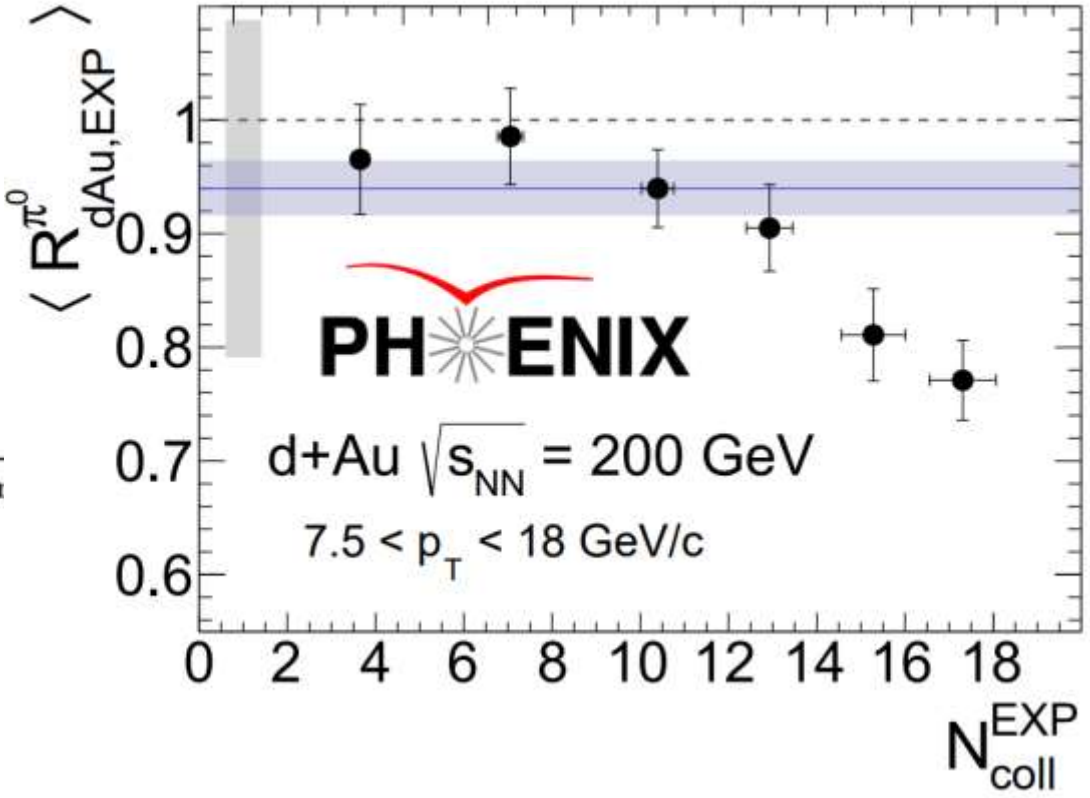
$$N_{\rm coll}^{\rm EXP}(p_T) = \frac{Y_{d\rm Au}^{\gamma^{\rm dir}}(p_T)}{Y_{pp}^{\gamma^{\rm dir}}(p_T)}$$

- π^0 Nuclear modification factor

$$R_{d\rm Au,EXP}^{\pi^0} = \frac{Y_{d\rm Au}^{\pi^0}}{N_{\rm coll}^{\rm EXP}\ Y_{pp}^{\pi^0}} = \frac{Y_{d\rm Au}^{\pi^0}/Y_{pp}^{\pi^0}}{Y_{d\rm Au}^{\gamma^{\rm dir}}/Y_{pp}^{\gamma^{\rm dir}}}$$

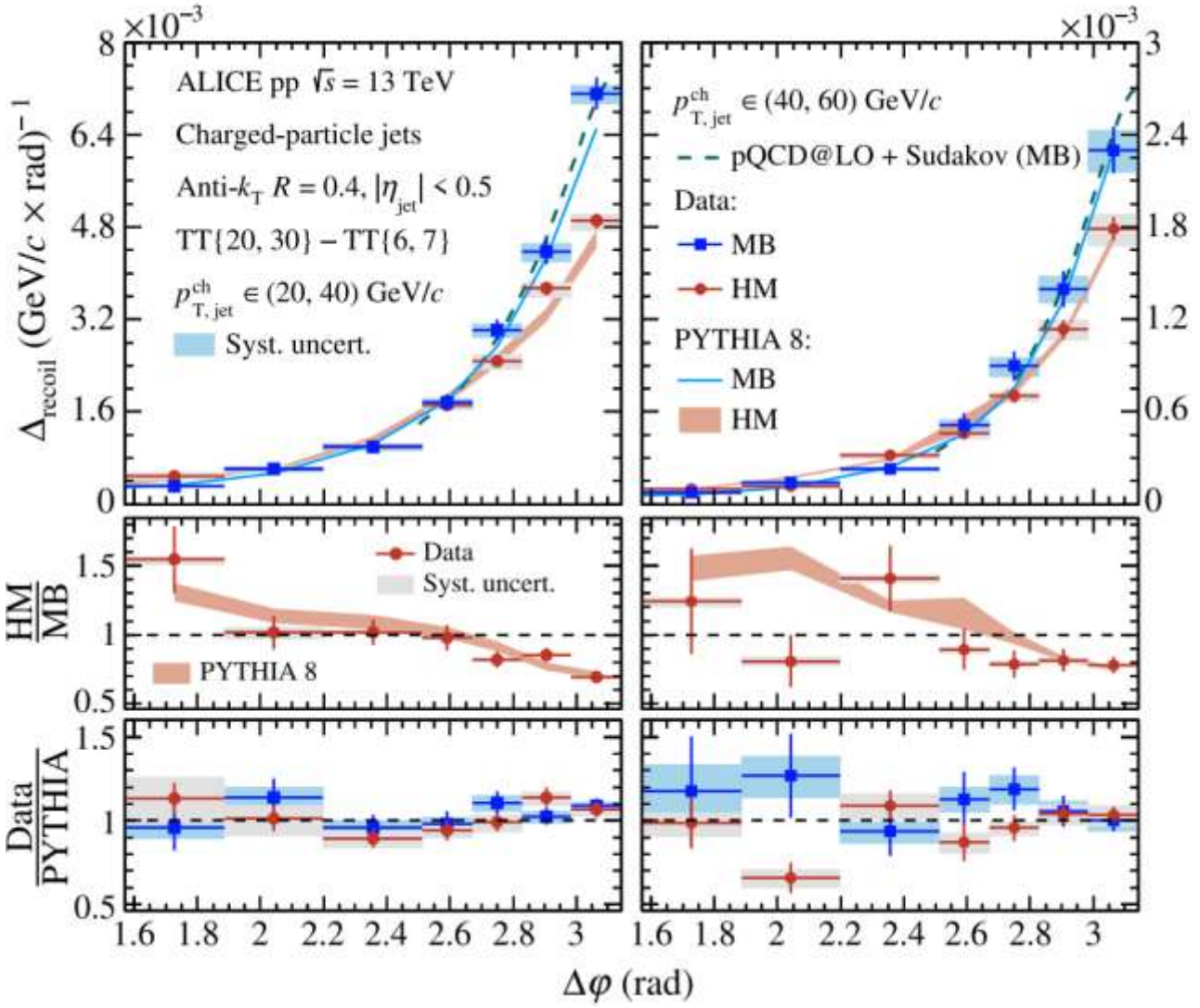
- Suppression in central collisions

arXiv: 2303.12899



Searching for jet quenching in small systems

- Recoil jet widening and yield suppression in HM events
- Pythia8 (without jet quenching) reproduces effects
- Originates from bias induced by the HM event selection
  - Multiplicity estimator in the forward + hard process in midrapidity
  - Bias towards multi-jet final states
- Effect of the bias mimics suppression



CERN-EP-2023-180-2

Summary

- Initial state:
  - Significant progress on constraining nPDF at small and large *x*
  - Tension with nPDF
  - Still looking for gluon saturation
- Strangeness enhancement:
  - D_s^+/D^+ ratio enhanced in high multiplicity *p*Pb collisions
- Baryon/meson ratio:
  - Λ_c^+/D^0 ratio flat dependence on multiplicity
  - Λ_b^0/B^0 ratio rises with increasing multiplicity
- Collectivity:
  - Ridge in HM single jet
- Energy loss: ?
- More

- What's next?
  - LHC Run3 + special OO run
  - LHCb SMOG2 program (high stat. proton-Gas data, *talk by Saverio Mariani*)
  - Electron-Ion Collider (*talk by Xuan Li*)