Experimental highlights of heavy-flavor production in heavy-ion collisions

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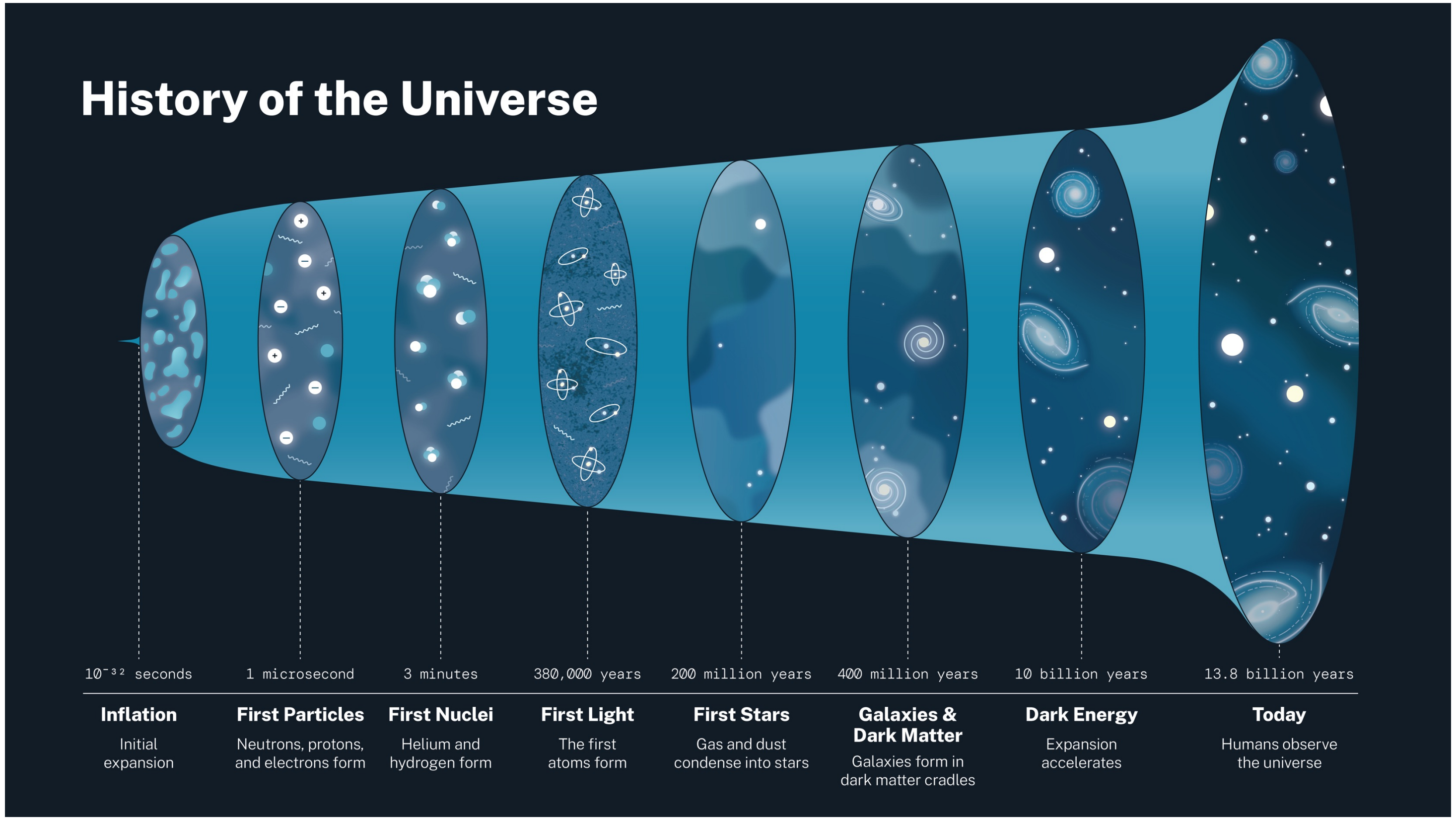
18th September 2025

Photo credit: West of Sicilly

The Big Bang

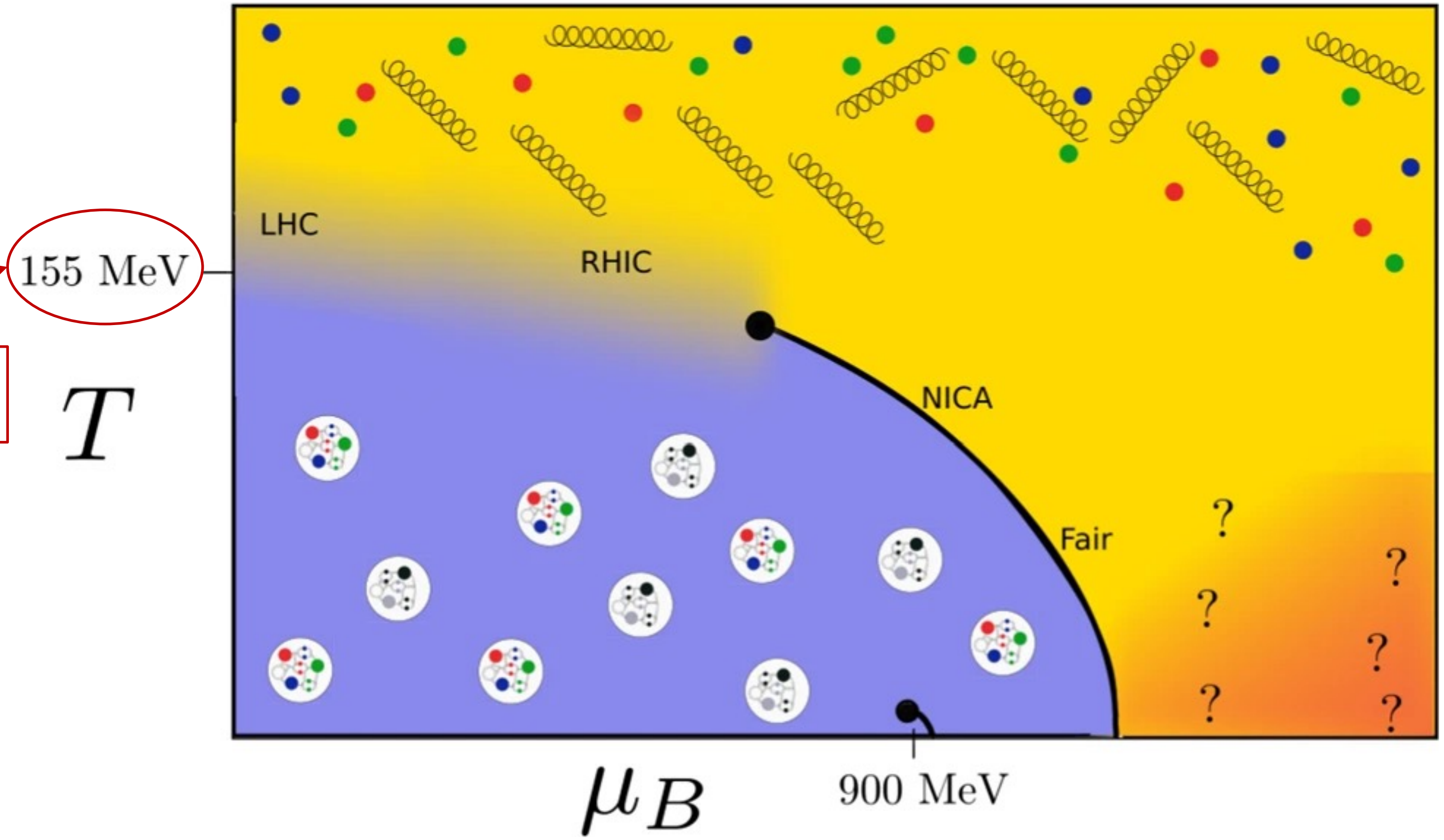


- Above a critical temperature, T_C, quarks and gluons are no longer confined
- This state of matter is the "Quark-Gluon Plasma"
- Believed the universe was above T_C for the first few microseconds after the Big Bang

Image credit to NASA

Phase diagram for QCD

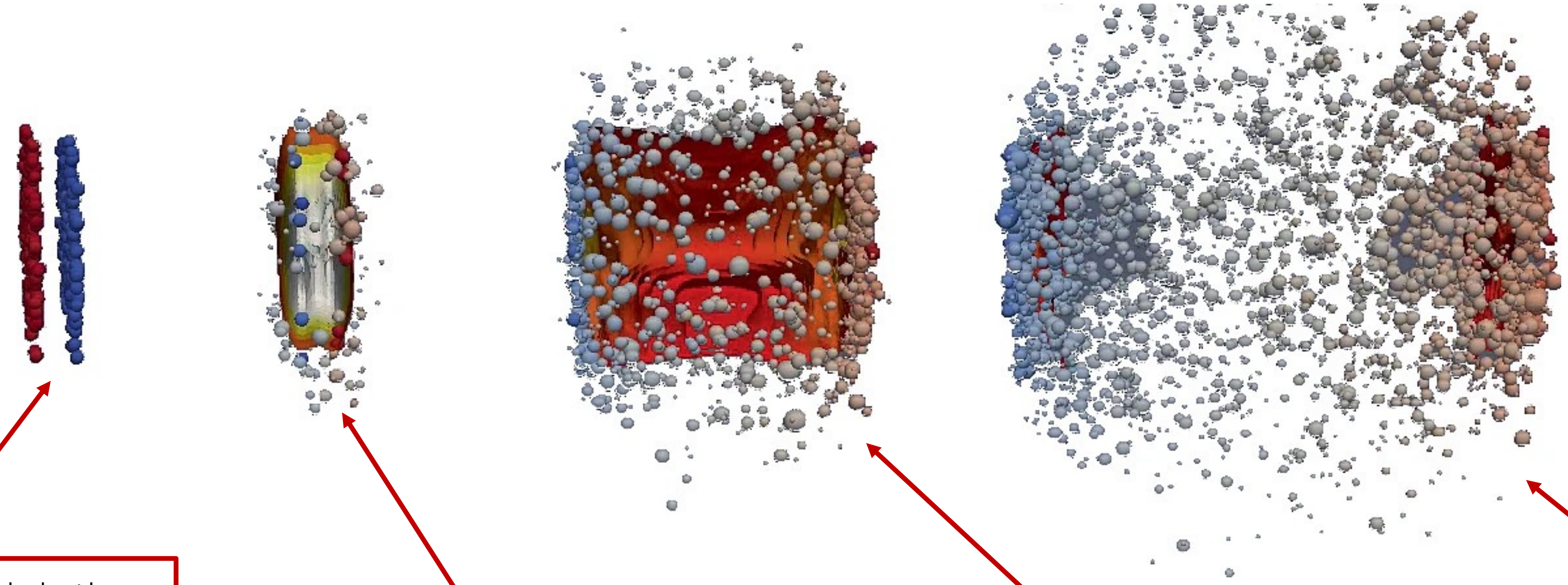
> 1 trillion Kelvin!



- Phase transition for low μ_B is not discrete but continuous
- Observatories and telescopes cannot probe this era of the universe

Eur. Phys. J. A 57, 136 (2021)

Fundamentals of heavy ion collisions



Nuclei at relativistic energies become Lorentz contracted (from about 15 fm at rest to less than 1 fm)

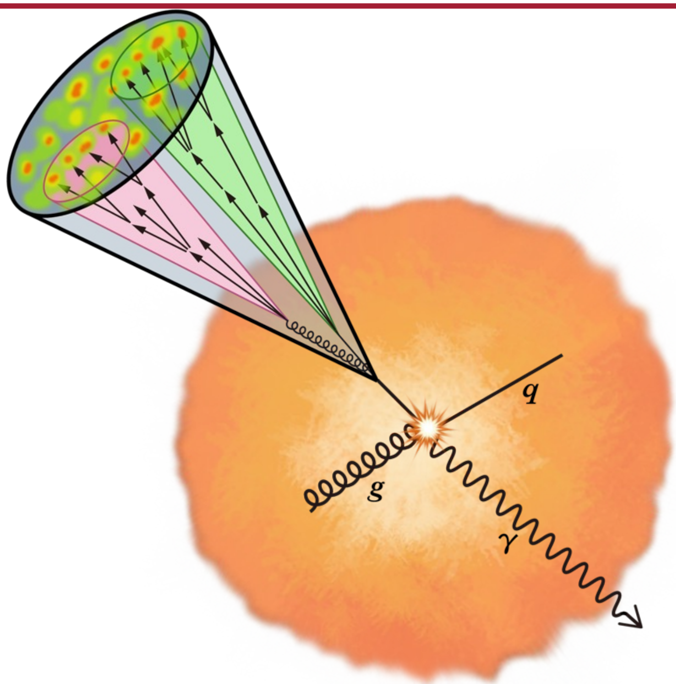
Initial quark production followed by QGP formation

Expansion of dense hydrodynamic matter

Energy-density is low enough for complete hadronization

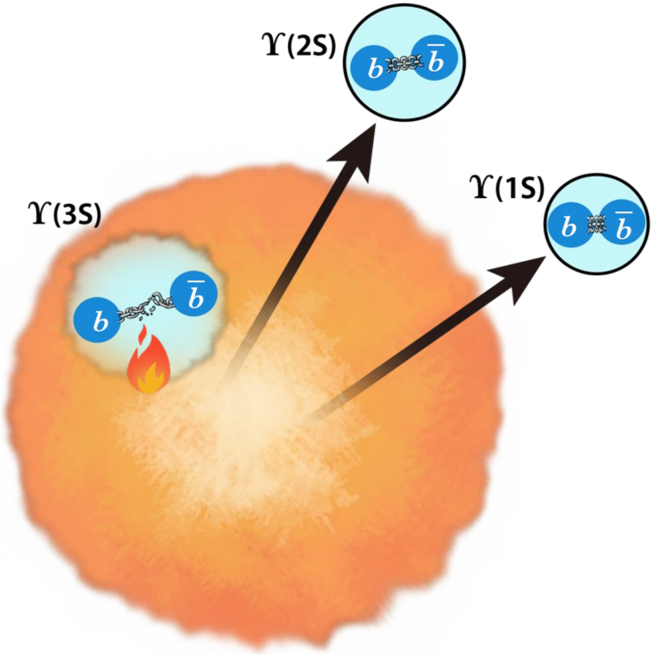
[Vorticity and Polarization in Heavy-Ion Collisions: Hydrodynamic Models]

Heavy flavor probes of QGP



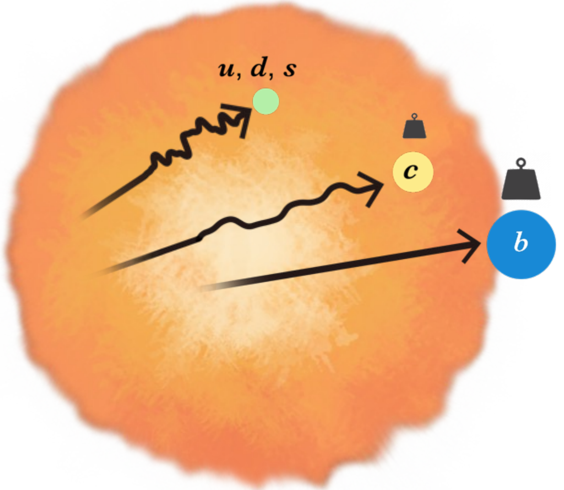
Jets and color-neutral particles

You need good calorimetry (electromagnetic and hadronic)



$BE[\Upsilon(3S)] < BE[\Upsilon(2S)] < BE[\Upsilon(1S)]$ *

You need good calorimetry and good tracking



Hard probes

$m_{u,d,s} < T_C < m_c < m_b$

You need good tracking

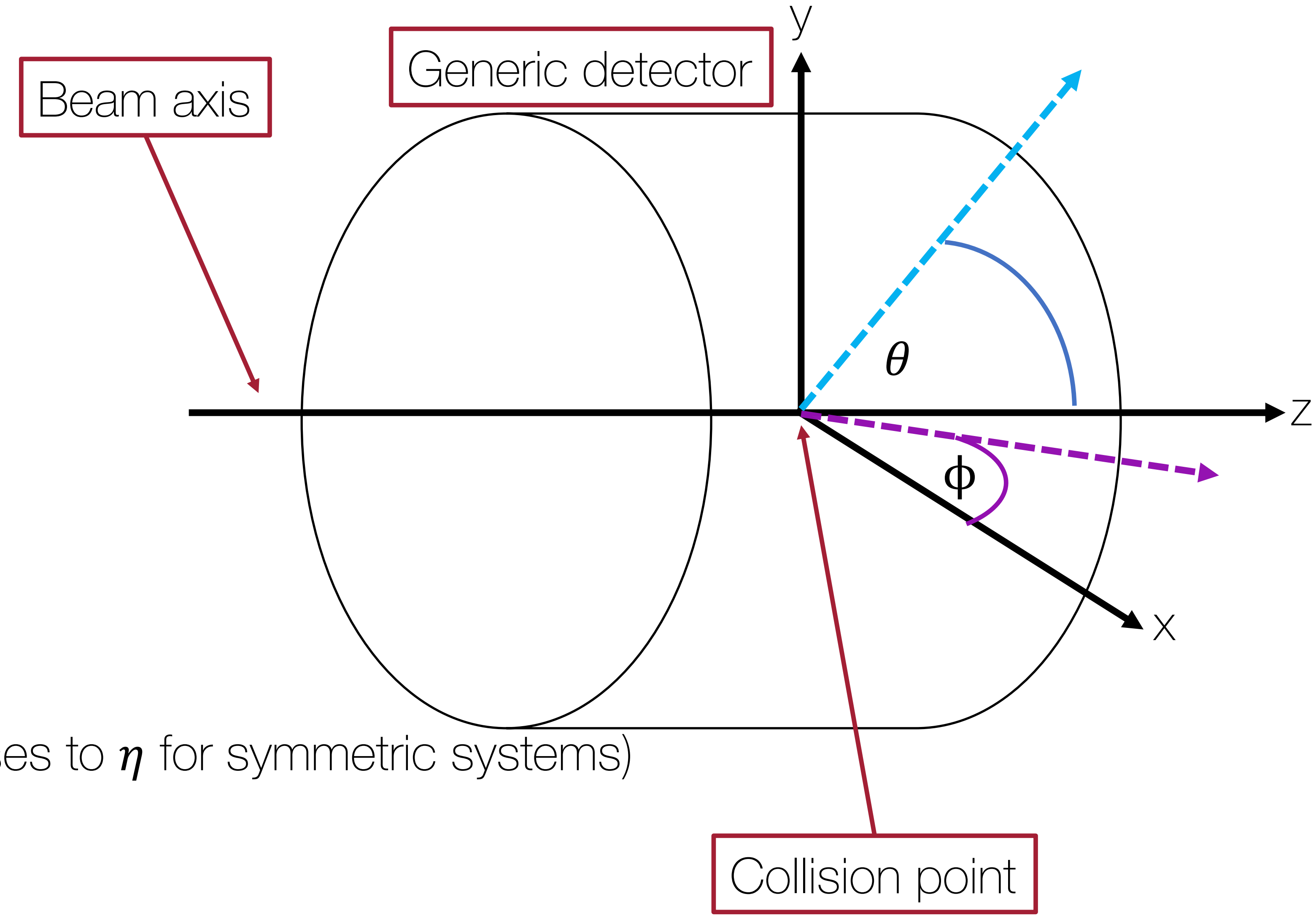
Credit to M. Ouchida

** Binding energy*

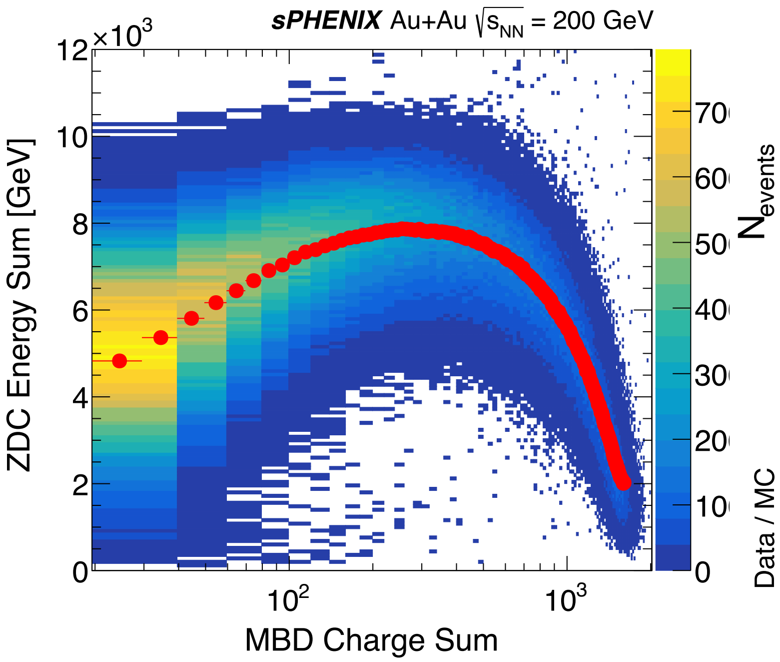
Making measurements at detectors

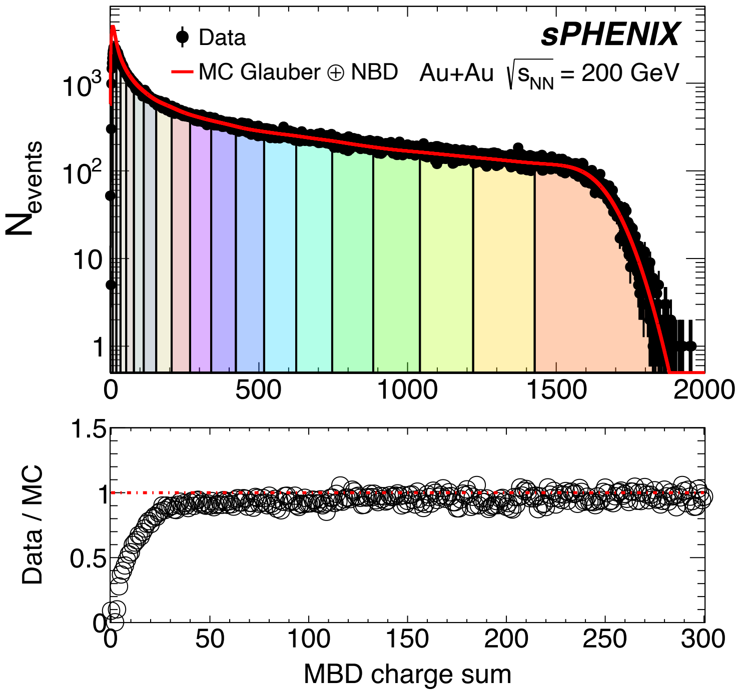
Making measurements, frames

- Transverse momentum
  $p_T = \sqrt{p_x^2 + p_y^2}$
- Azimuthal angle
  $\phi = \tan^{-1}\frac{y}{x}$ (or $\phi = \tan^{-1}\frac{p_y}{p_x}$)
- Longitudinal angle
  $\theta = \tan^{-1}\frac{p_z}{p}$
- Pseudorapidity
  $\eta = \frac{1}{2}\ln\left(\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z}\right) = -\ln(\tan\frac{\theta}{2})$
- Rapidity (mass dependent, collapses to η for symmetric systems)
  $y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$



Making measurements, centrality





- Centrality should not be measured in the same region as your physics signal
  - Use charge deposited in endcaps
- ZDC has increase then decrease in charge sum with increasing centrality
  - More peripheral, more fragments get swept away. More central, less spectator neutrons

Making measurements, nucl. modification factor

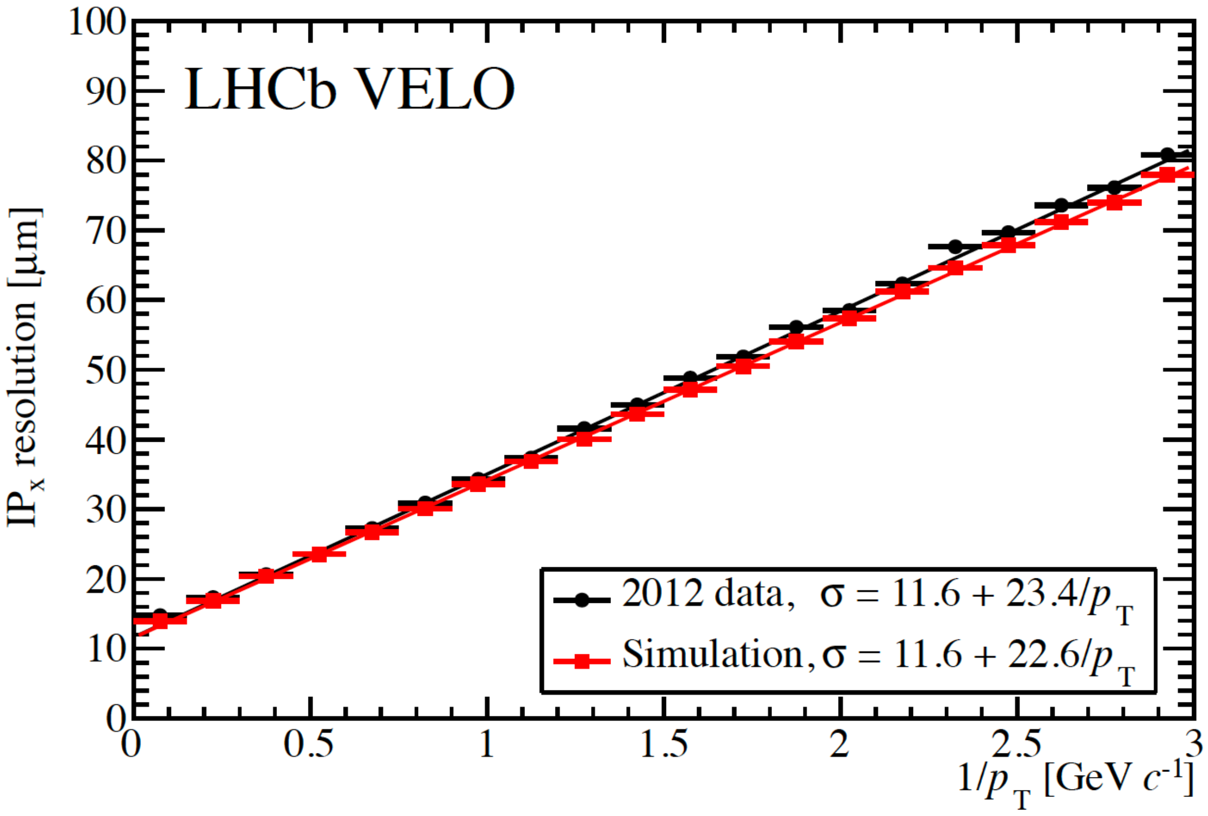
JINST 9 P09007

- $R_{AA}(p_T) = \frac{1}{\langle T_{AA}\rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$ where $\langle T_{AA}\rangle$ is the nuclear overlap function
- Depends on
  - Centrality/multiplicity
  - Momentum resolution
  - Impact parameter resolution
- Momentum resolution driven by
  - Alignment, magnetic field, measurement points & length
- Impact parameter resolution:

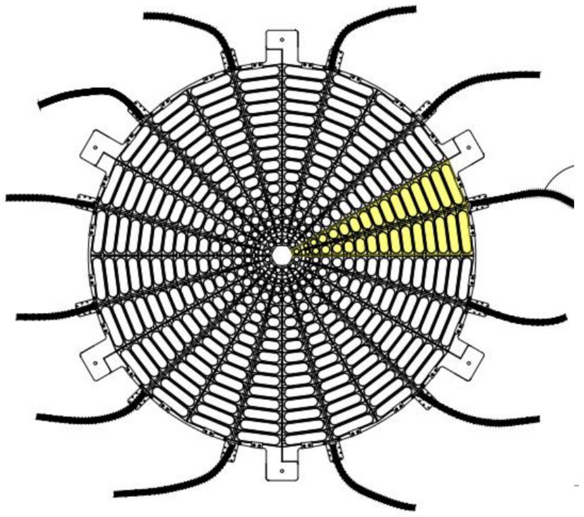
$$\sigma_{IP} \propto \frac{r_1^2}{p_T^2}\left[0.136\sqrt{\frac{x}{X_0}}\left(1 + 0.038\ln\frac{x}{X_o}\right)\right]^2$$

r_1 is the distance to the first measurement point

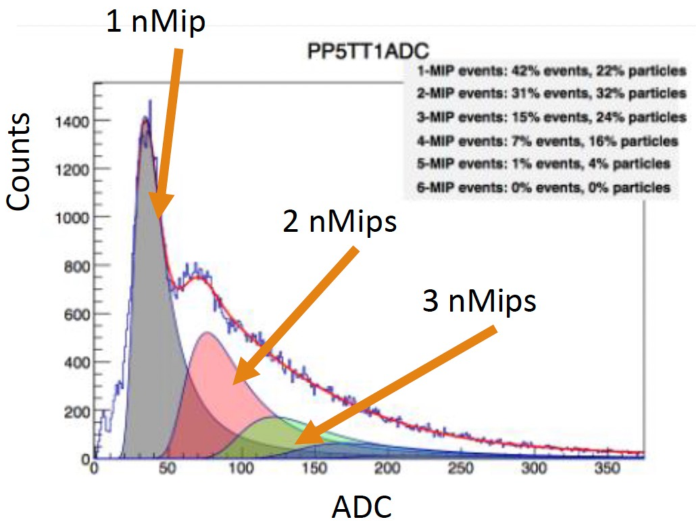
x/X_0 is the material budget (thickness in radiation lengths)

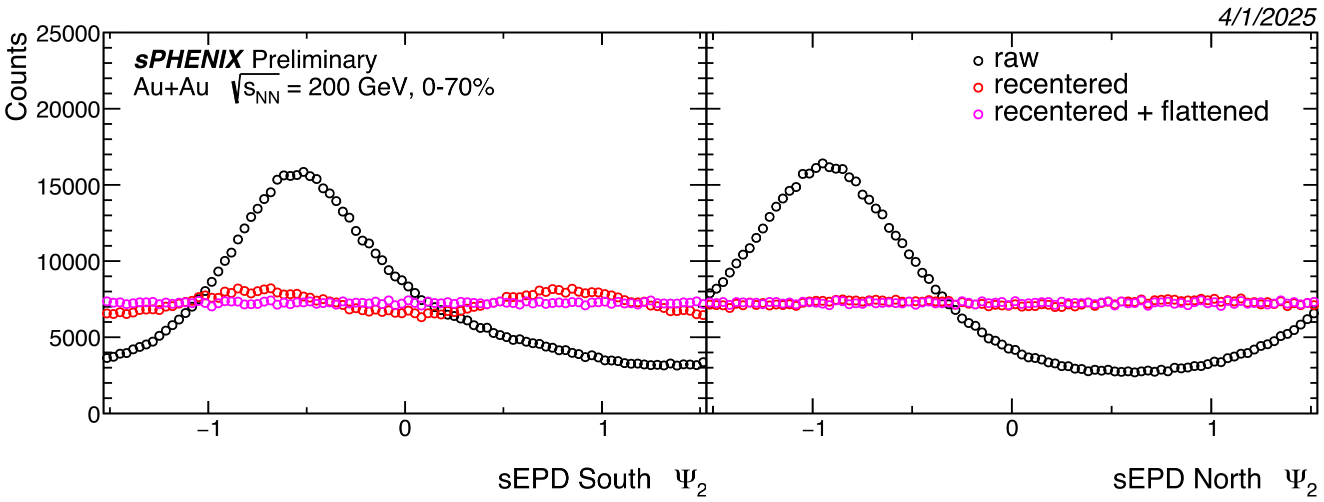


Making measurements, flow from event plane



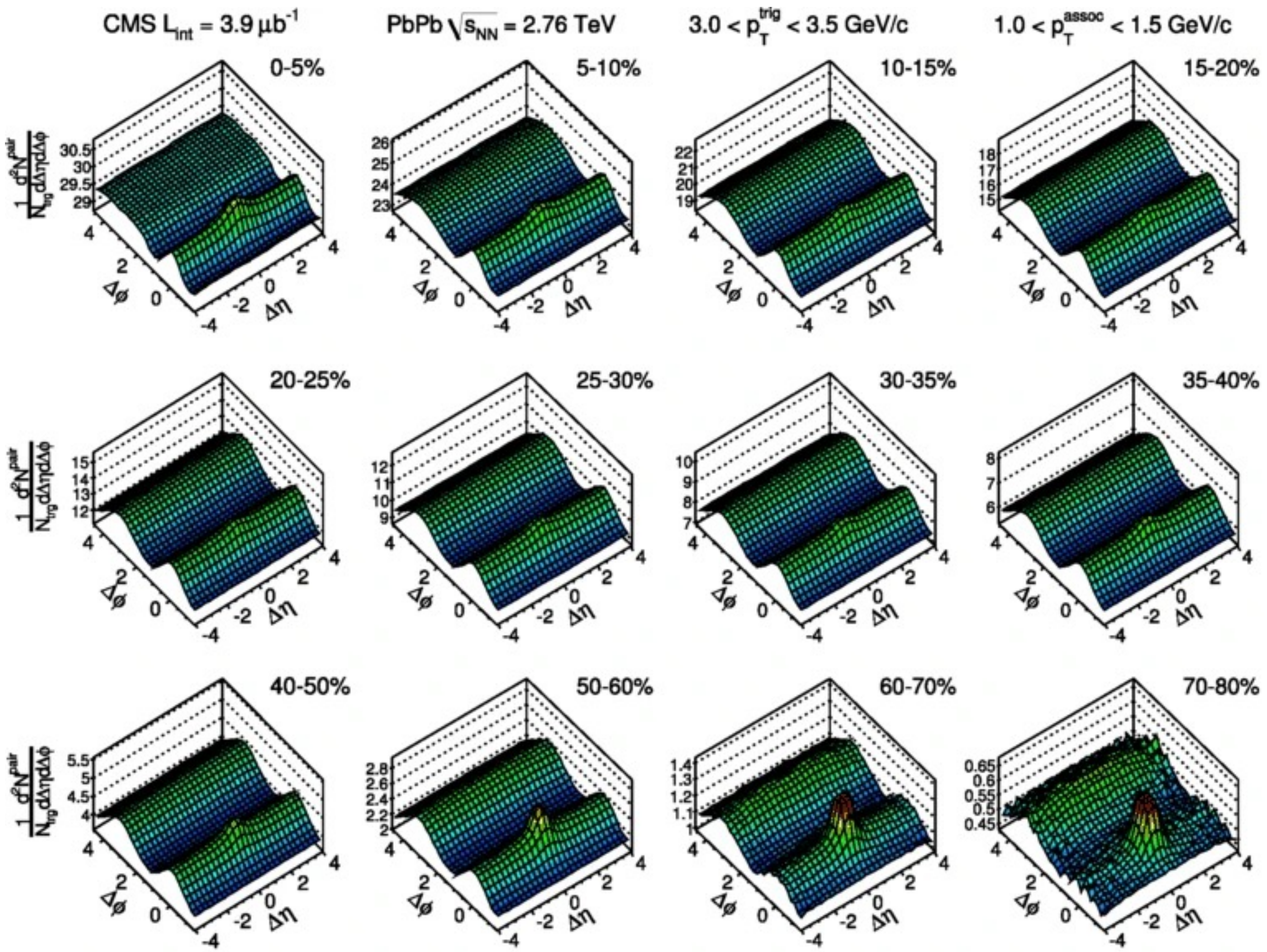
- Number of particles in area is proportional to number of minimal ionizing particles (nMips)
  - nMips derived from Analogue-to-digital conversion (ADC) count
- For STAR and sPHENIX event plane detectors, we can read each oval
- Hence signal responses define event plane
- Requires correction around phi to correct for different ADC response
  - Assumption is response should be uniform over a whole run





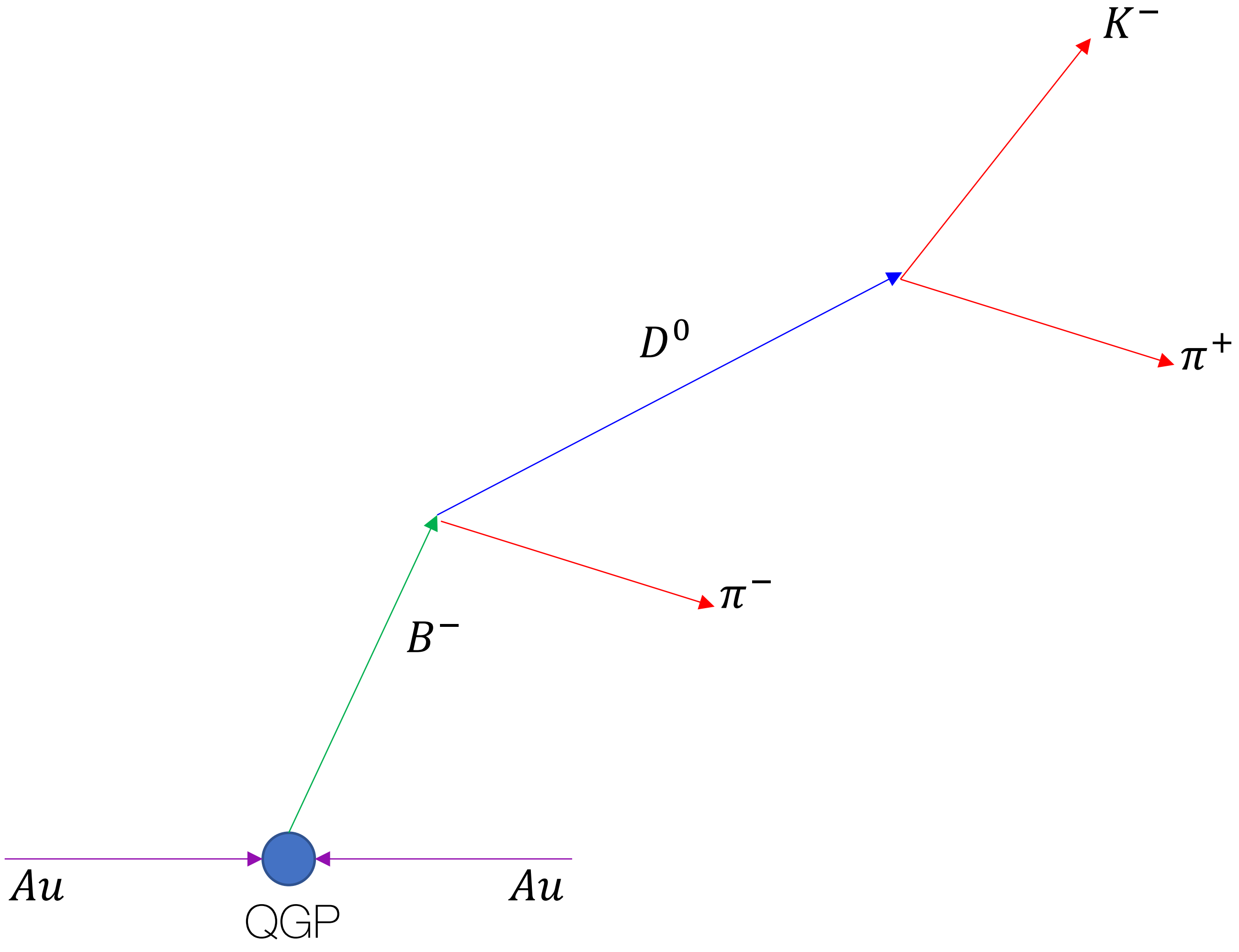
Making measurements, flow from correlations

- 2PC's are well established
- In HF sector, can we determine flow this way
- People discuss using $D^0/\overline{D}^0$ for this
  - Problems:
    - Yield decreases to the power 2
    - Two-track efficiency becomes four-track efficiency



[Eur. Phys. C 72 (2012) 10052]

Making measurements, particle reconstruction



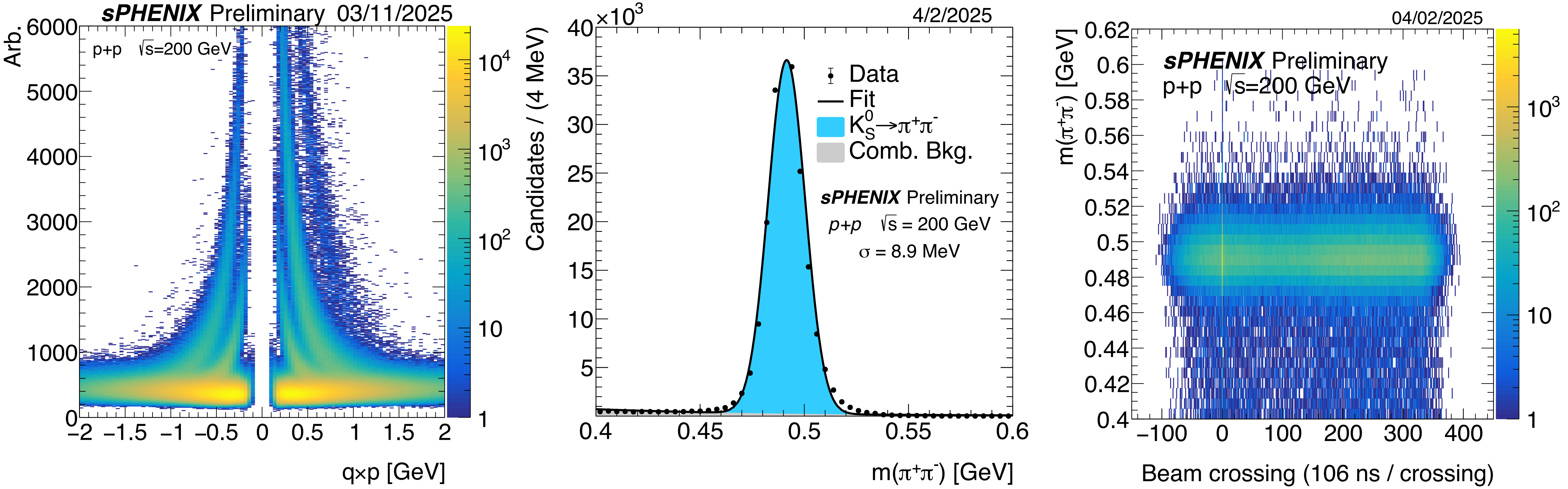
- Green and blue lines are ~mm long
  - Can't be seen in detectors
- Red lines are meters long
  - All leave signals in trackers
- Momentum conservation of red lines gives D^0 and B^- mass

$$\vec{p} = (p_x, p_y, p_z, E)$$

where

$$E = \sqrt{p_x^2 + p_y^2 + p_z^2 + m^2}$$

Making measurements, particle reconstruction

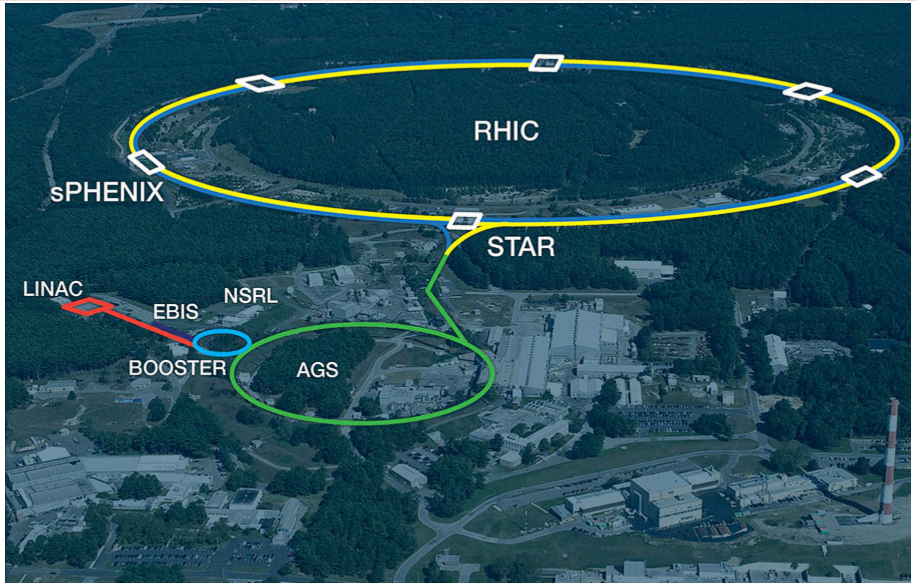


Left - dE/dx of tracks, middle - K_S^0 particle, right - $\pi^+\pi^-$ invariant mass / crossing

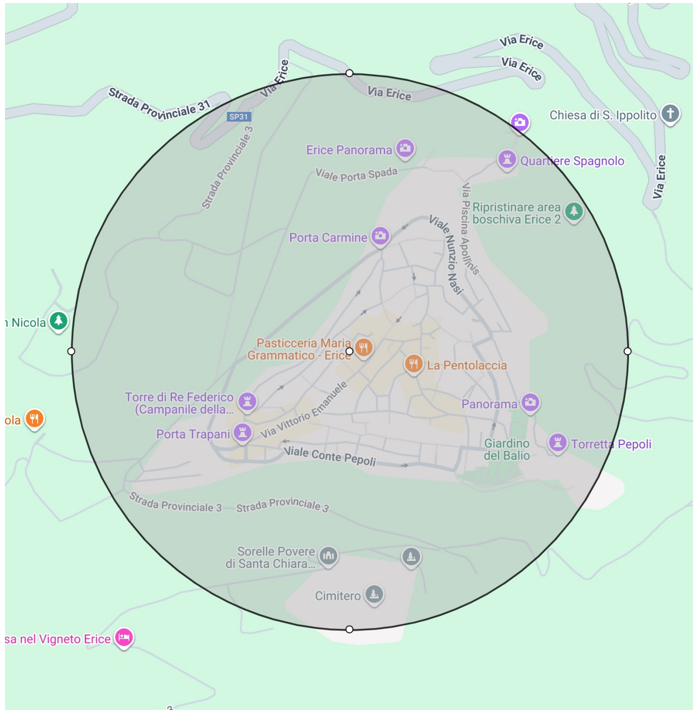
Detectors and Accelerators

Relativistic Heavy Ion Collider

- In operation, 2000 – 2025 (?)
- 5 major experiments
  - STAR, 2000 – now
  - PHOBOS, 2000 – 2005
  - BRAHMS, 2000 – 2006
  - PHENIX, 2000 – 2016
  - sPHENIX, 2023 – now



Max. particle energy	100 GeV/nucleon
Nominal. beam energy	550 kJ*
Max. bunches per beam	111
Particles per bunch	10^{10} for protons, 10^{9} for Au
Max. collision rate	3 MHz for pp, 25 kHz for AuAu

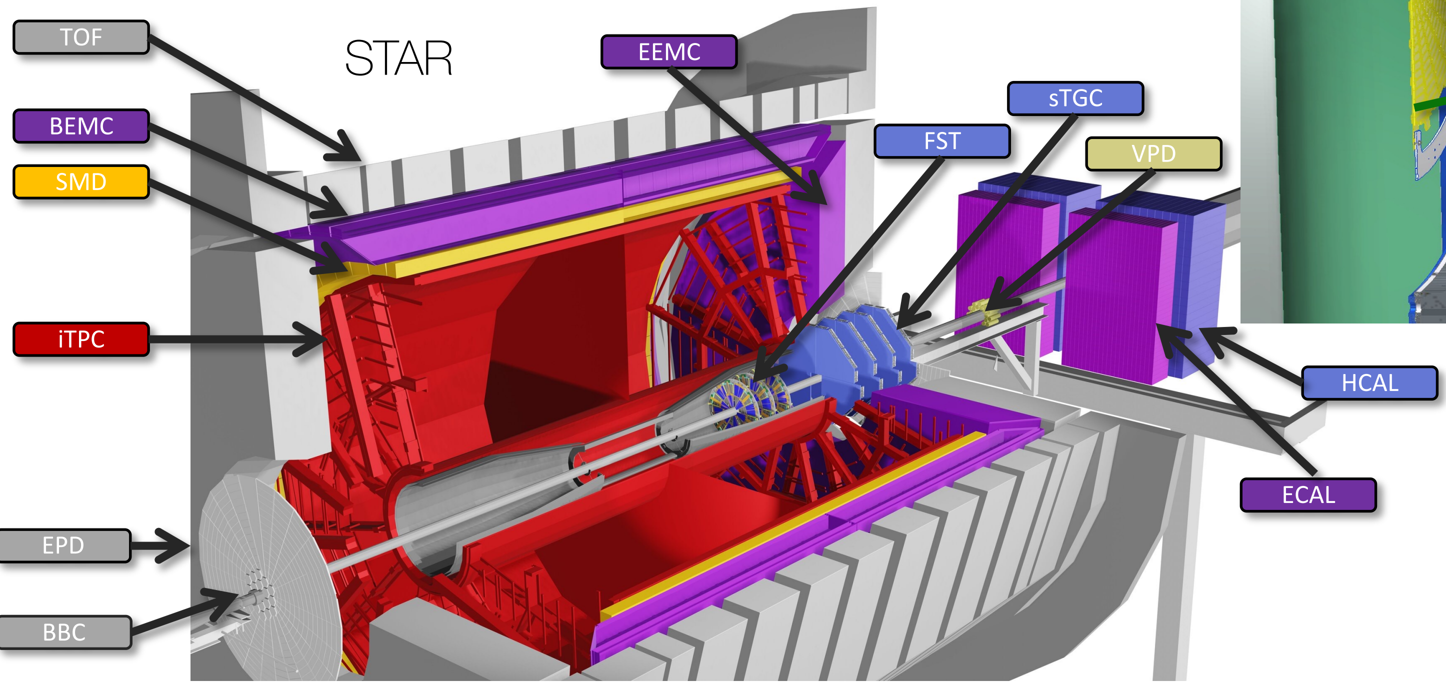


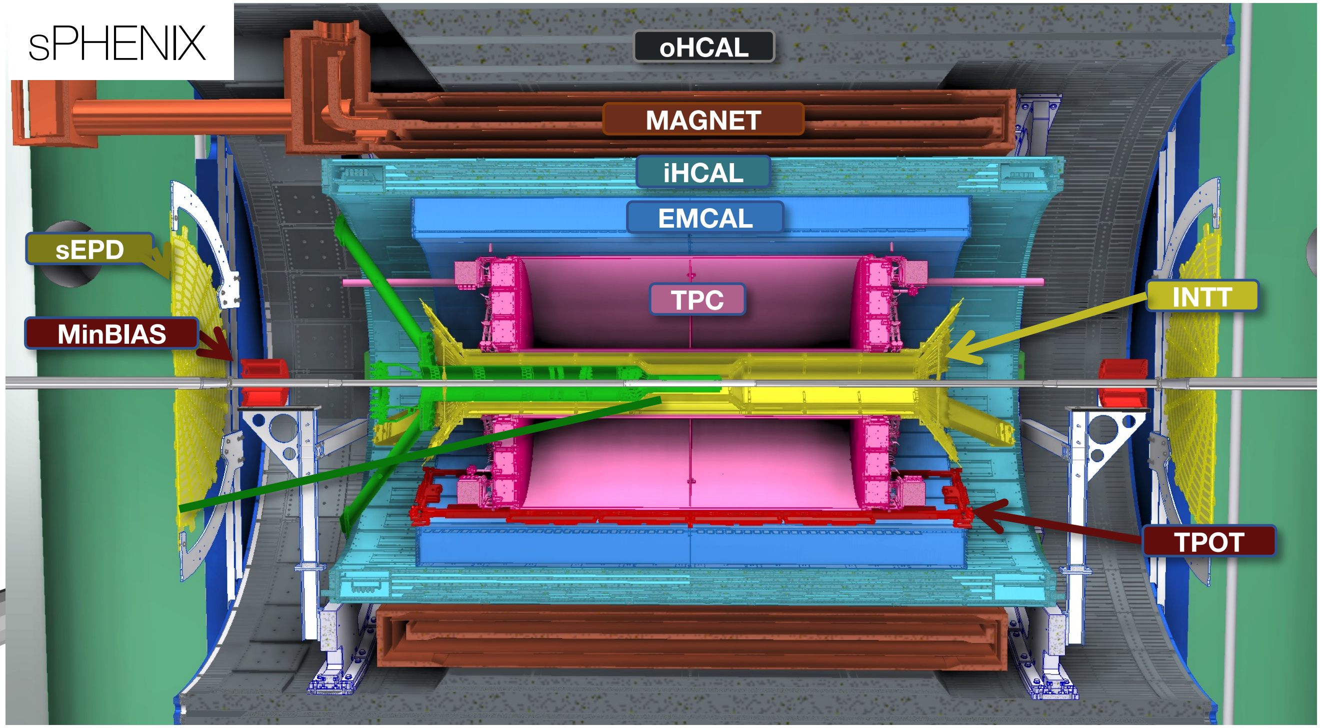
The size of RHIC, overlayed over Erice

*Equivalent of around 28 Erice cable cars traveling at 5 ms^{-1}

[NIM-A 499 (2003) 245–263]

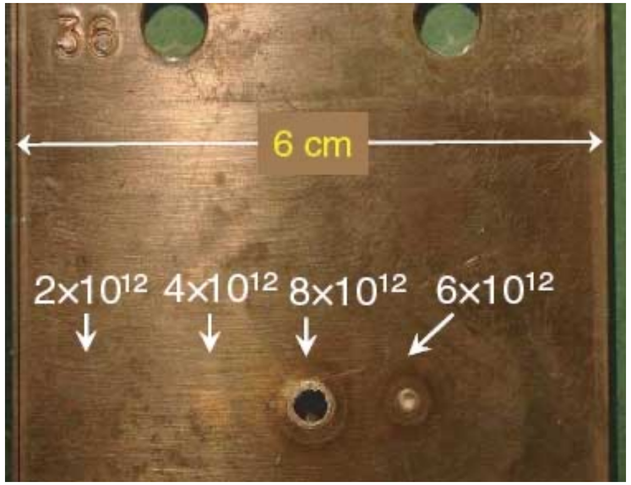
The RHIC detectors



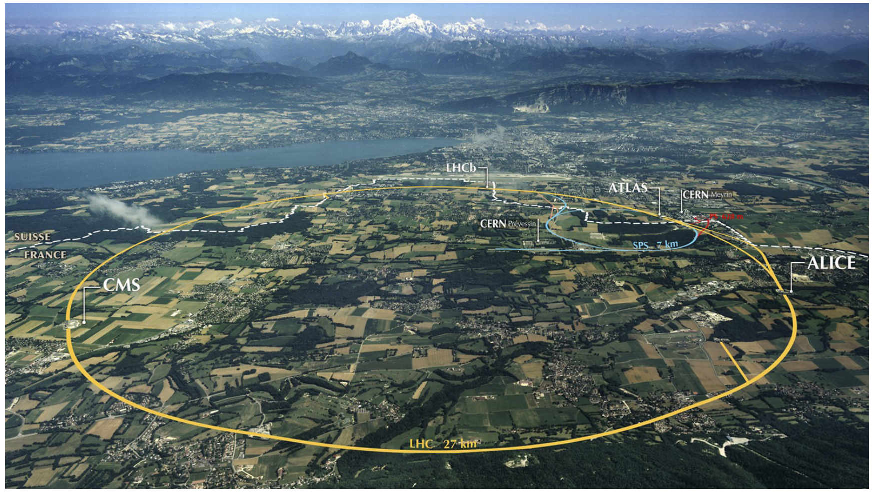


The Large Hadron Collider

- In operation, 2009 – now
- 4 major experiments
  - ALICE
  - ATLAS
  - CMS
  - LHCb



Left - 450 GeV beam shots from the SPS. The numbers refer to the no. of protons
Right – Outline of the LHC in Geneva



Max. particle energy	5.4 TeV/nucleon
Nominal. beam energy	362 MJ*
Max. bunches per beam	2808
Particles per bunch	10^{11} for protons, 10^{8} for PbPb
Max. collision rate	40 MHz for pp, 8 kHz for PbPb

*Equivalent of around 18000 Erice cable cars traveling at 5 ms^{-1}

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- In operation, 2009 – now
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  - ALICE
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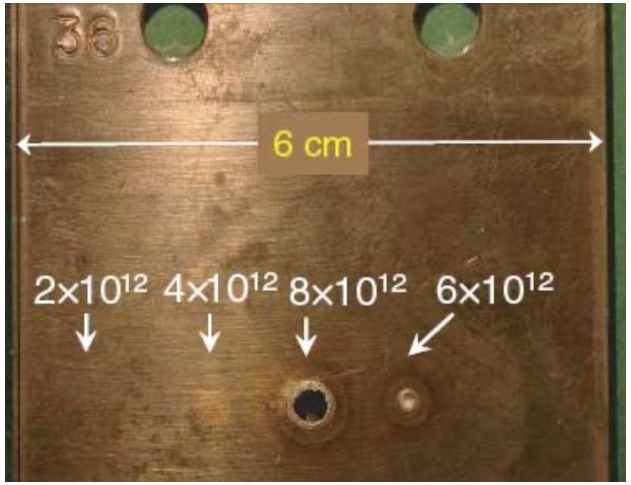

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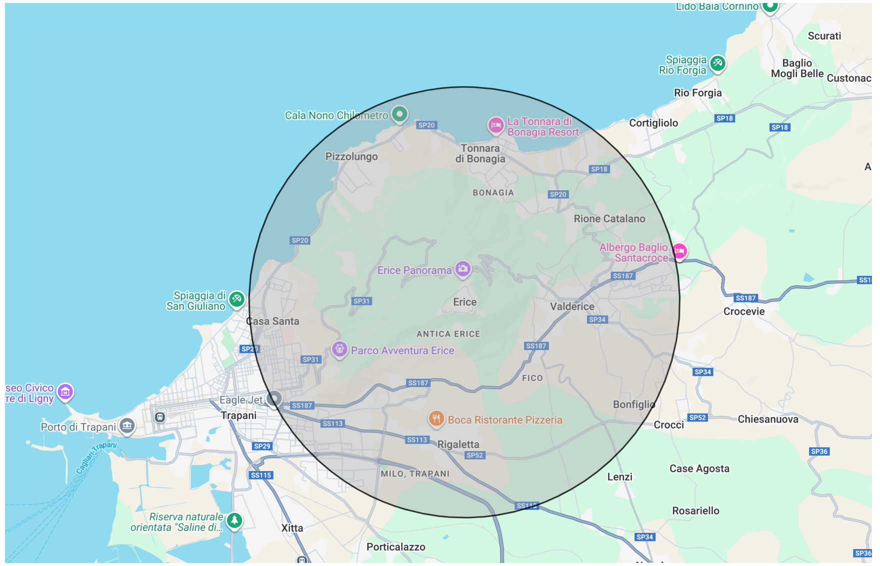

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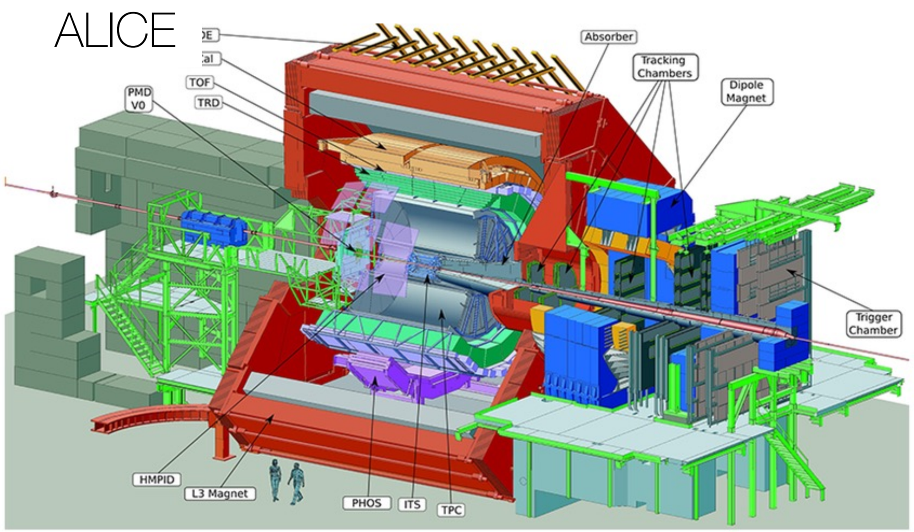
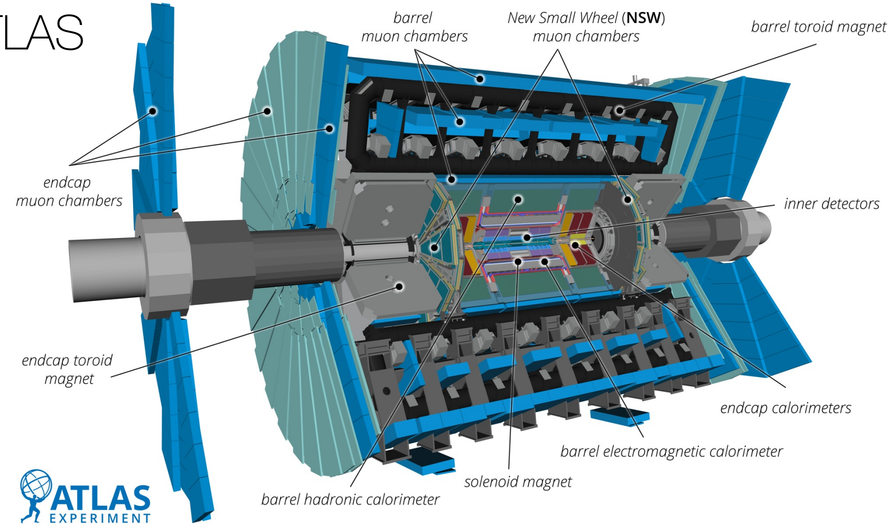
The LHC detectors

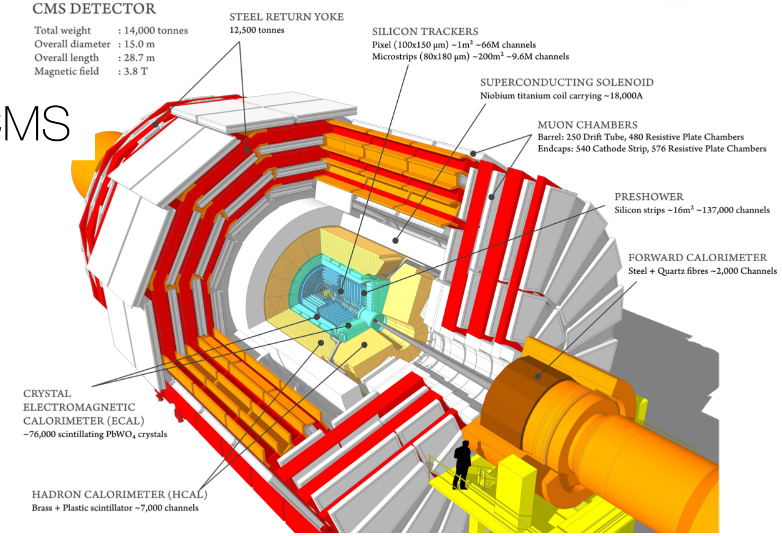
ALICE



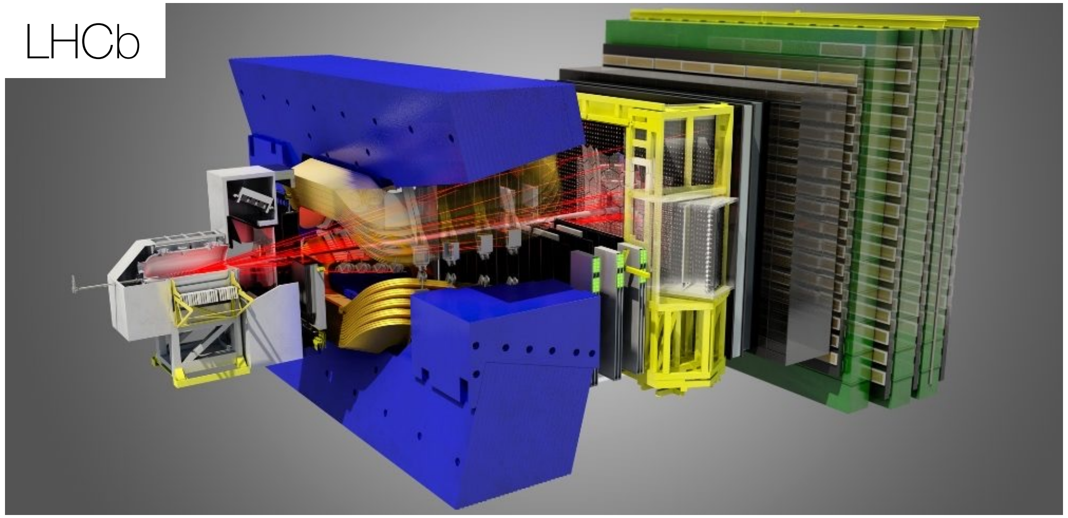
ATLAS



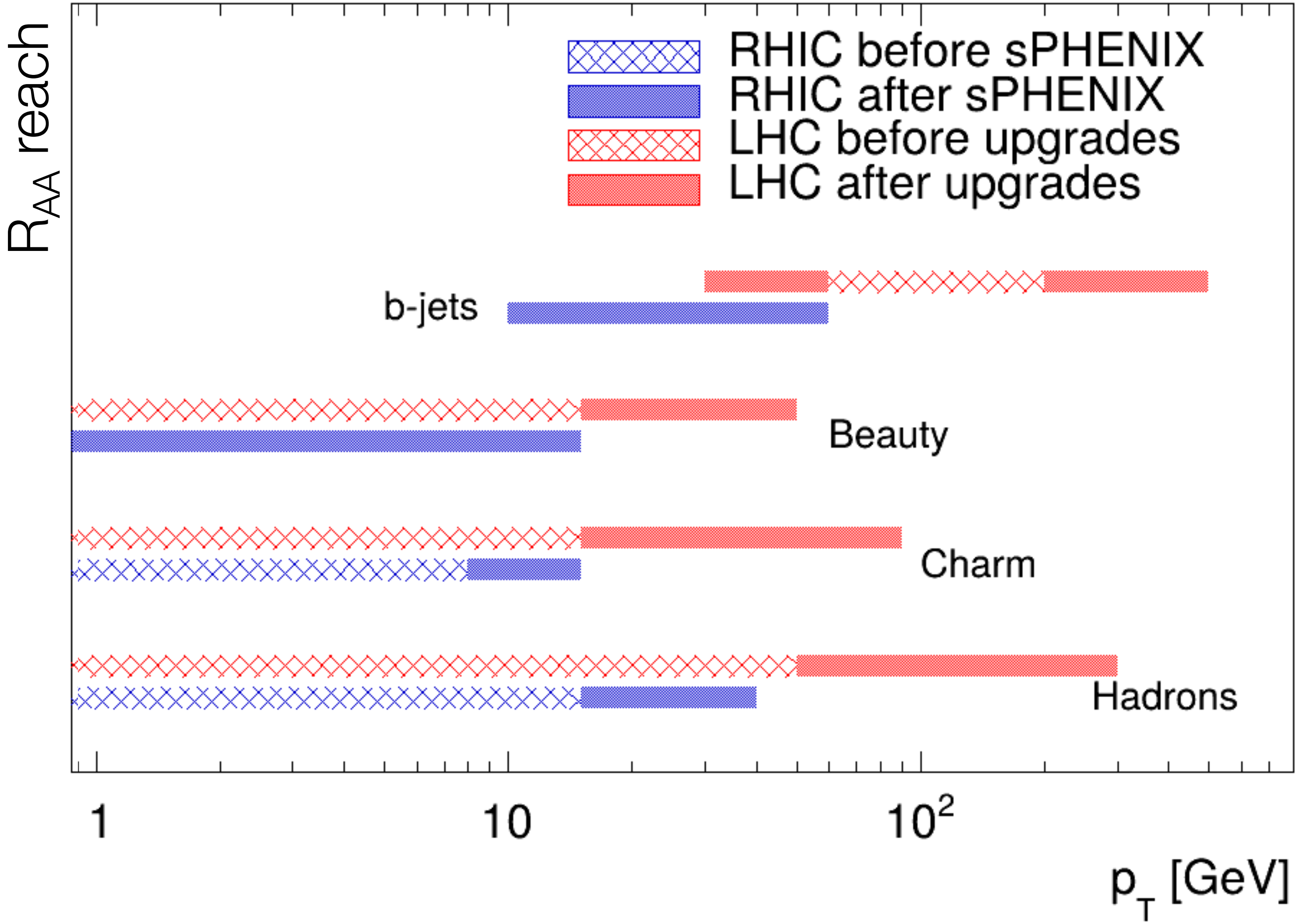
CMS



LHCb



RHIC vs LHC



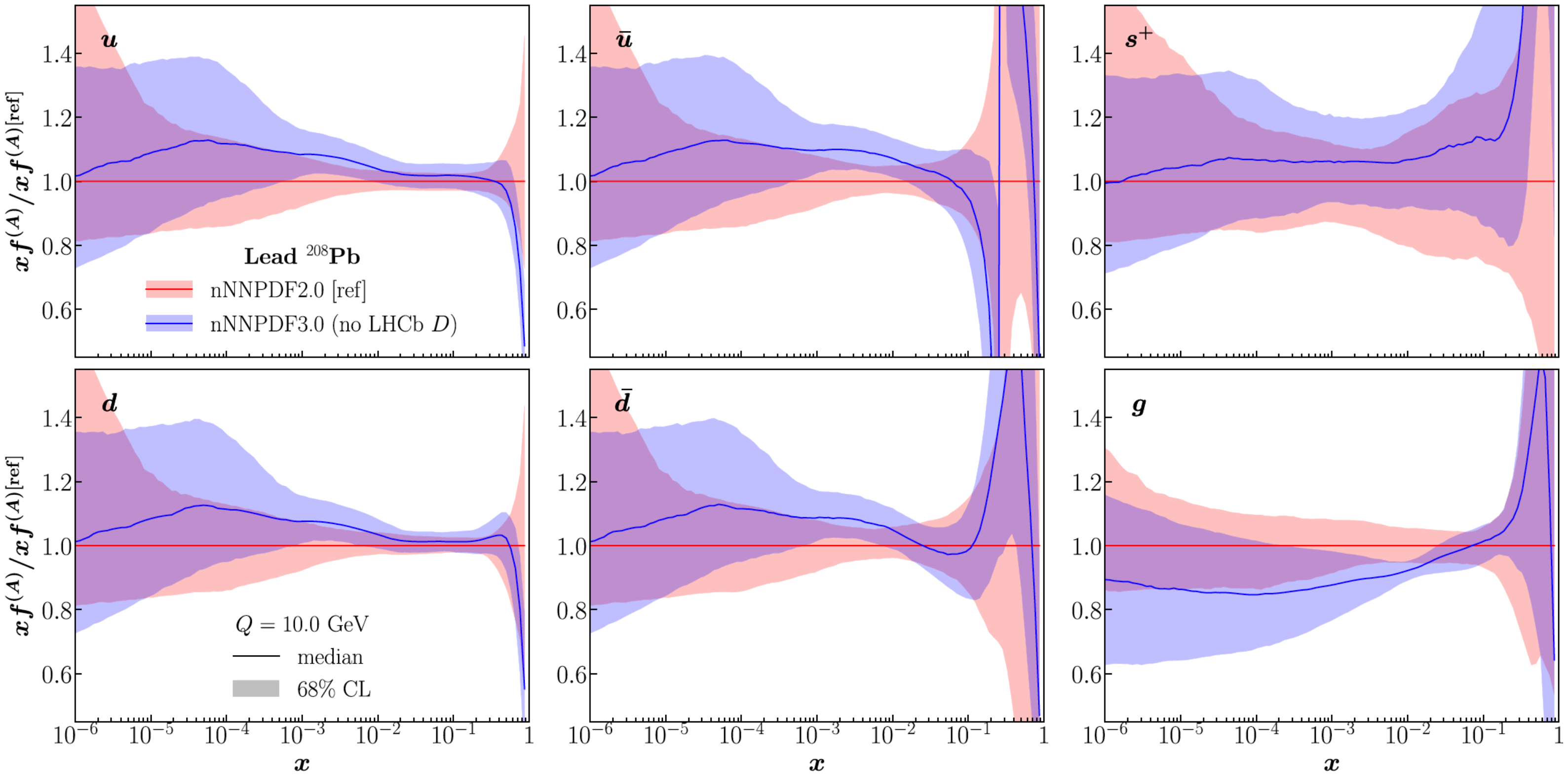
RHIC before sPHENIX
RHIC after sPHENIX
LHC before upgrades
LHC after upgrades
b-jets
Beauty
Charm
Hadrons
R_{AA} reach
1
10
10^2
p_T [GeV]

nPDF models and constraints

EPPS updates for nNNPDF's

EPJC (2022) 82: 507
A. Kusina, IS25

- New inputs for nNNDPF3.0:
  - *p*Pb D-meson data from LHCb (Run I)
  - *p*Pb prompt from ATLAS (Ru II)
  - *p*Pb Z data from CMS (Run II ALICE (Run I, Run II), LHCb (Run I)
  - *p*Pb W± data from ALICE (Ru I)
  - *p*Pb dijet data from CMS (Ru I)
  - Neutral current DIS data for deuteron



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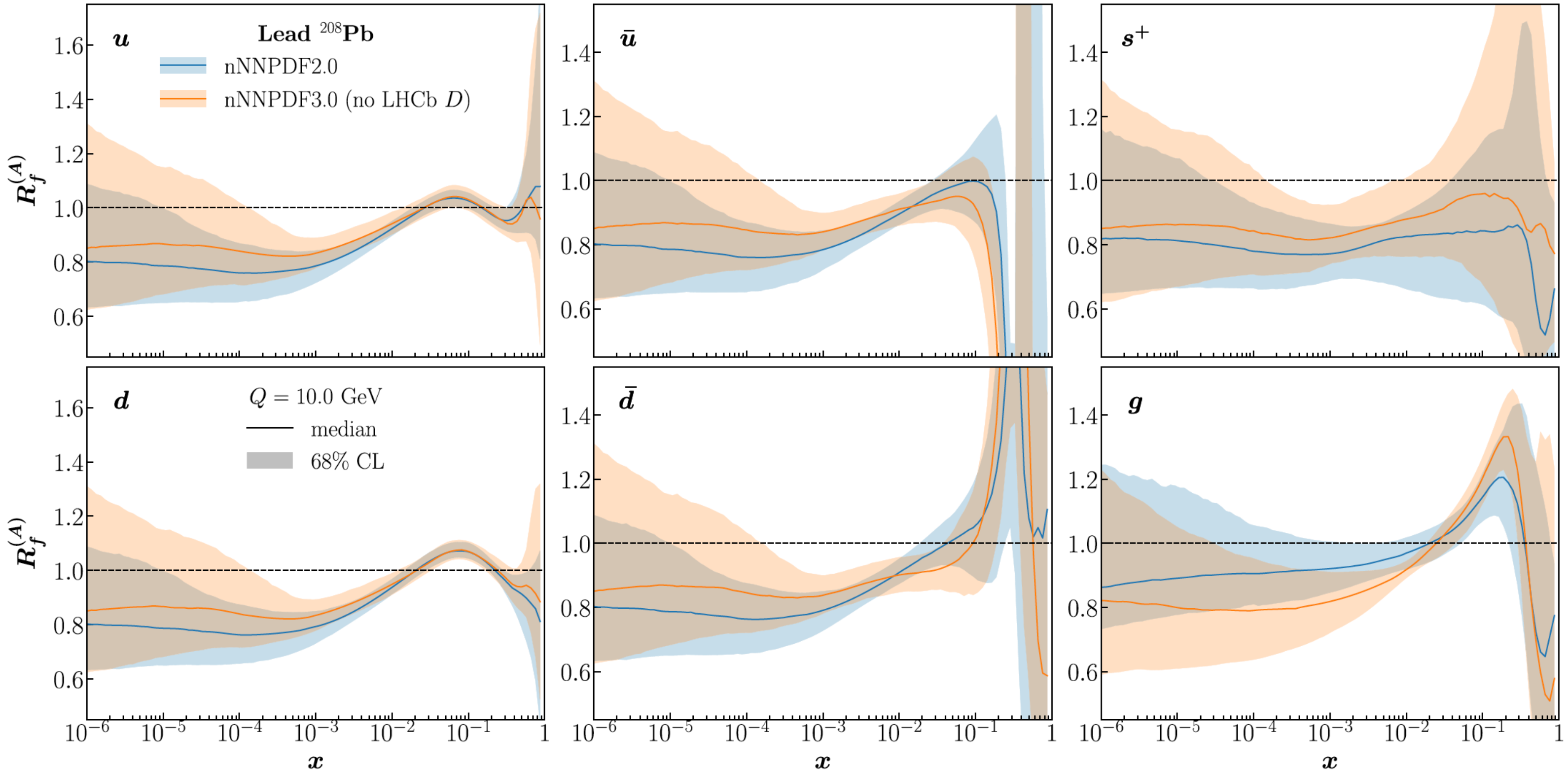
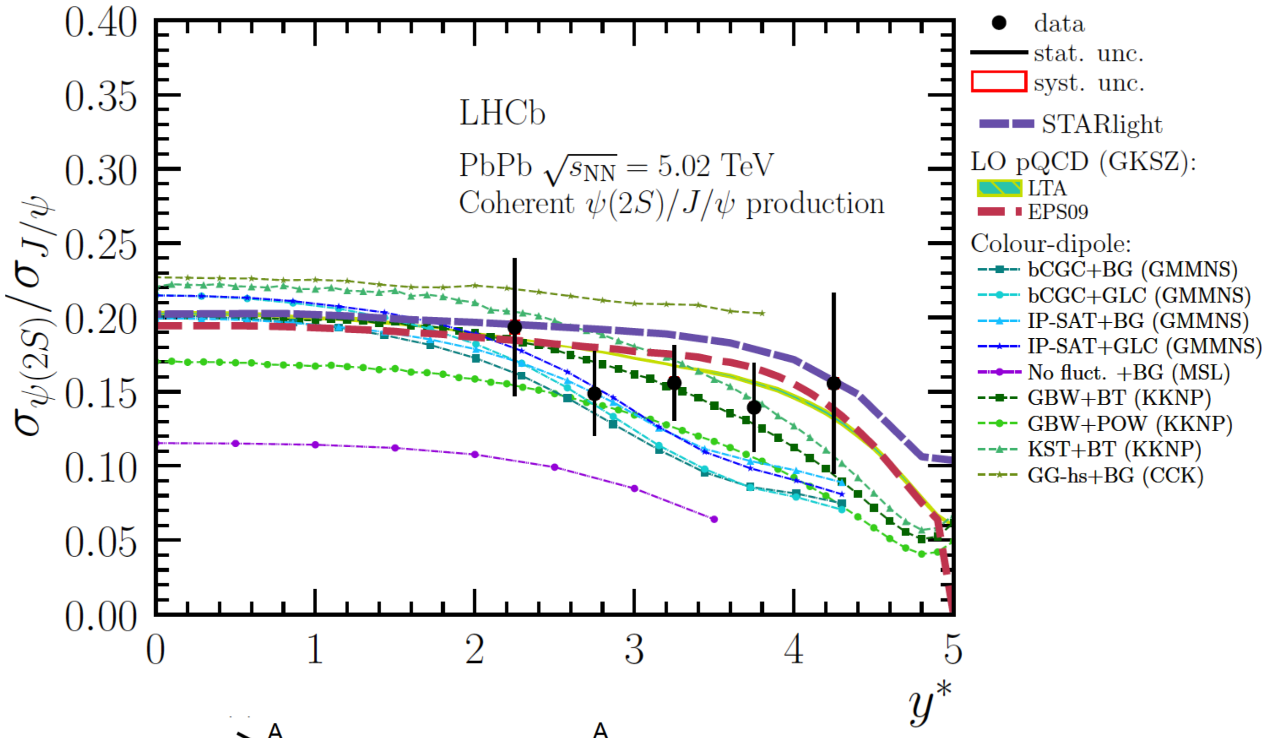
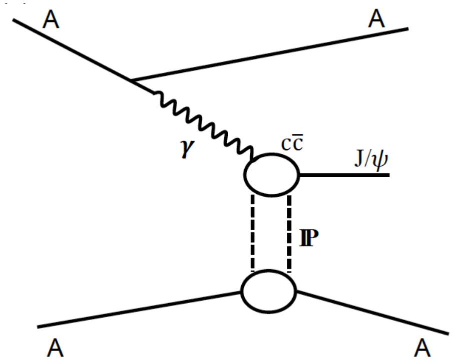


UPC J/ψ at LHCb

JHEP 06 (2023) 146

- Coherent charmonia production is a good probe of gluon distributions
- Twist approximation (LTA) and nPDF model (EPS09) show a decrease in relative coherent ψ(2S) production at high y
- Current results are statistically lacking to say whether this is the case

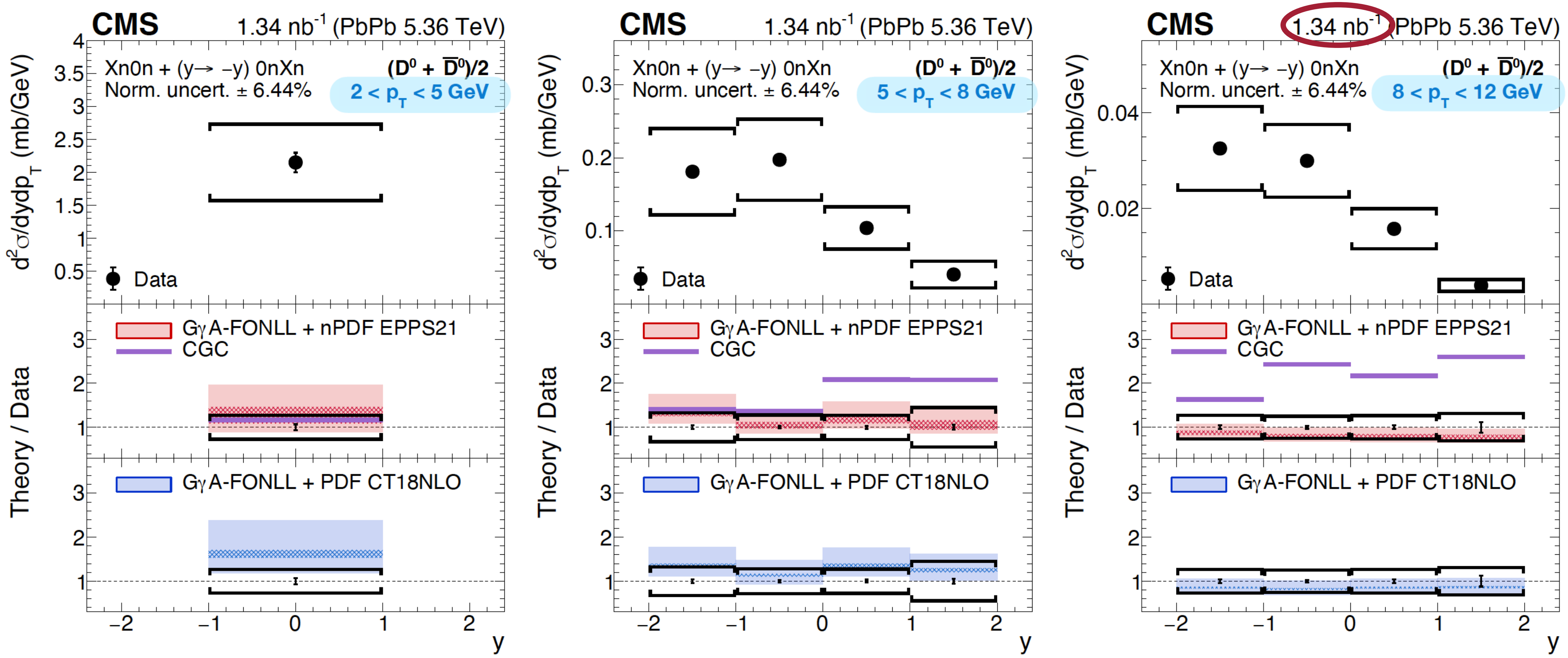




Coherent J/ψ production mechanism

UPC D^0 at CMS & TOTEM

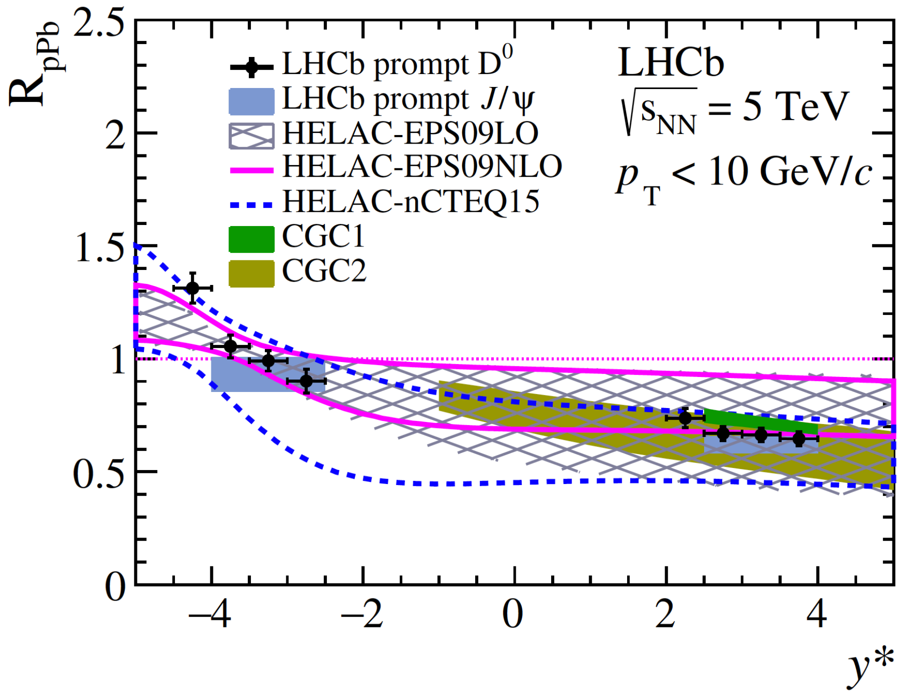
CMS-PAS-HIN-25-002
J. Lang, IS25

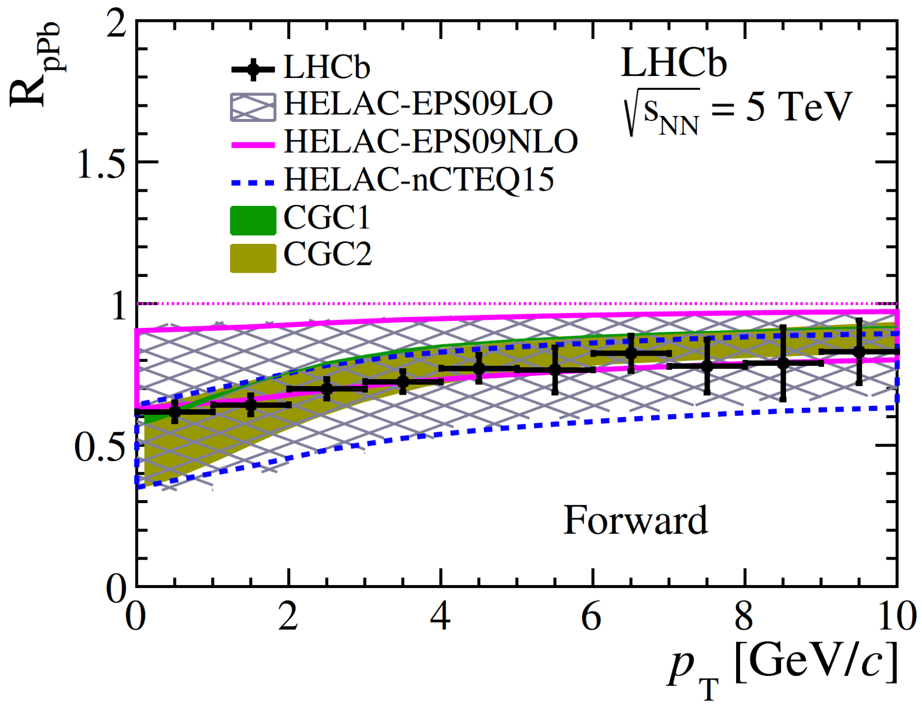


- Moving to higher D^0 p_T, disagreement with CGC models

LHCb nPDF in pPb

JHEP 1710 (2017) 090

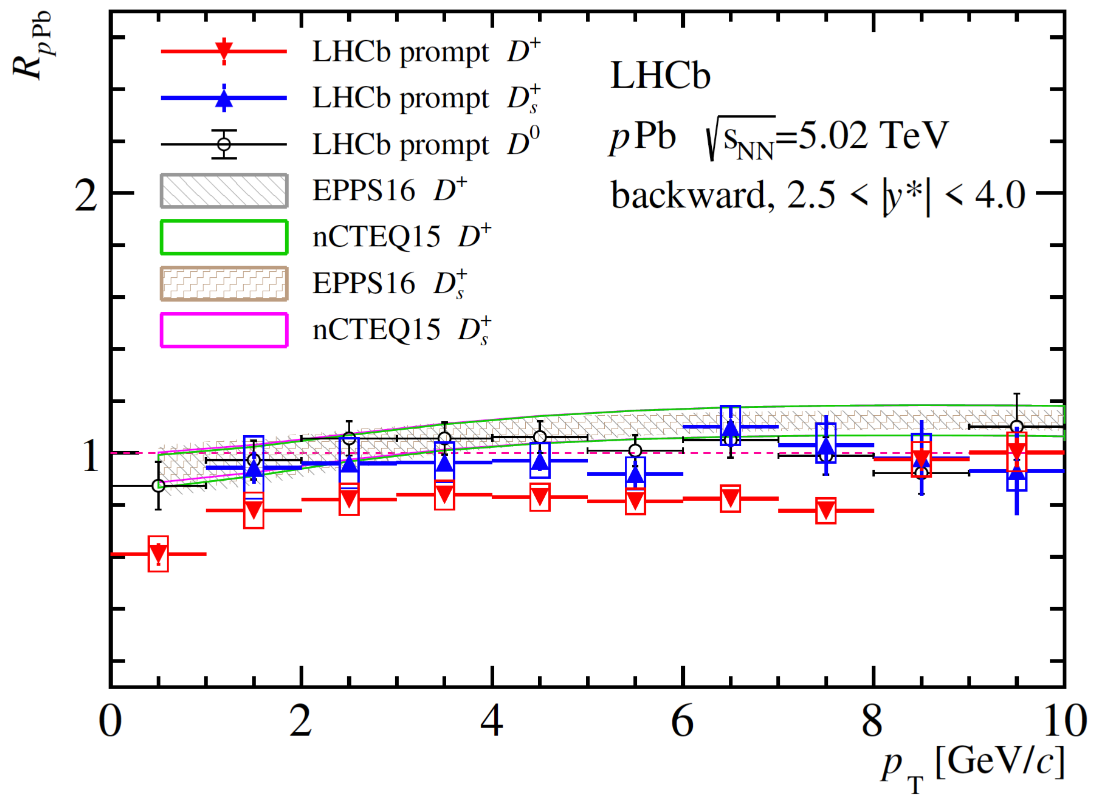


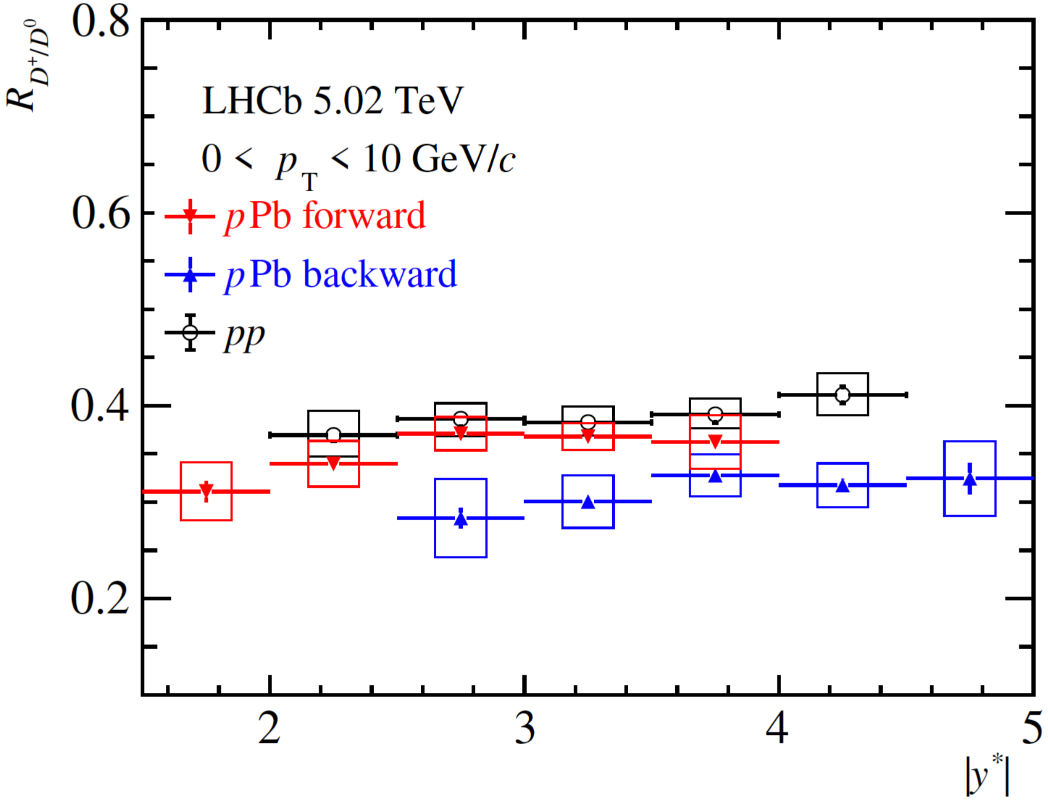


- D^0 data is consistent with several nPDF models (LO, NLO and nCTEQ15)
- Data points are compatible with CGC2 but consistently lower for CGC1
  - CGC1 uses large-x gluon splitting
  - CGC2 uses running Balitsky-Kovchegov equations

LHCb nPDF in pPb

[JHEP 01 (2024) 070]

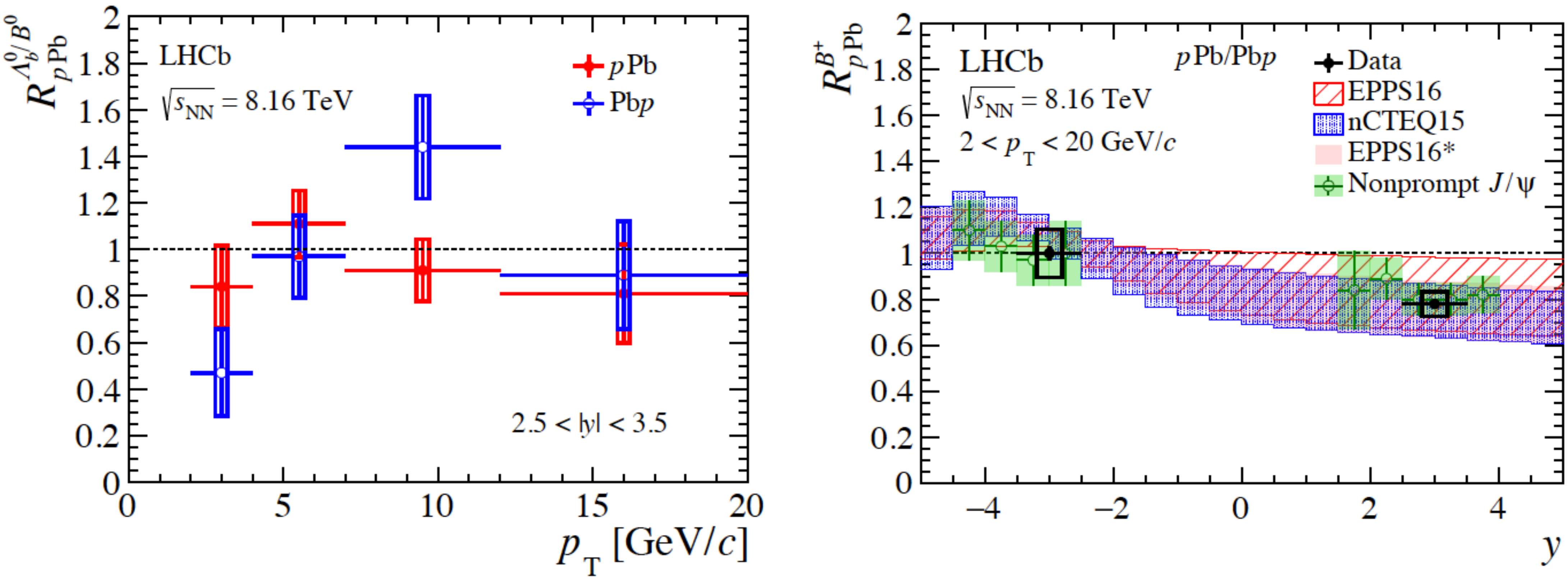




- New LHCb analysis shows consistent behaviour between D^0 and D_s^+
- However, D^+ shows consistently more suppression compared to D^0
- Possibly indicates different hadronization processes in open charm

LHCb nPDF in pPb

Phys. Rev. D99 (2019) 052011

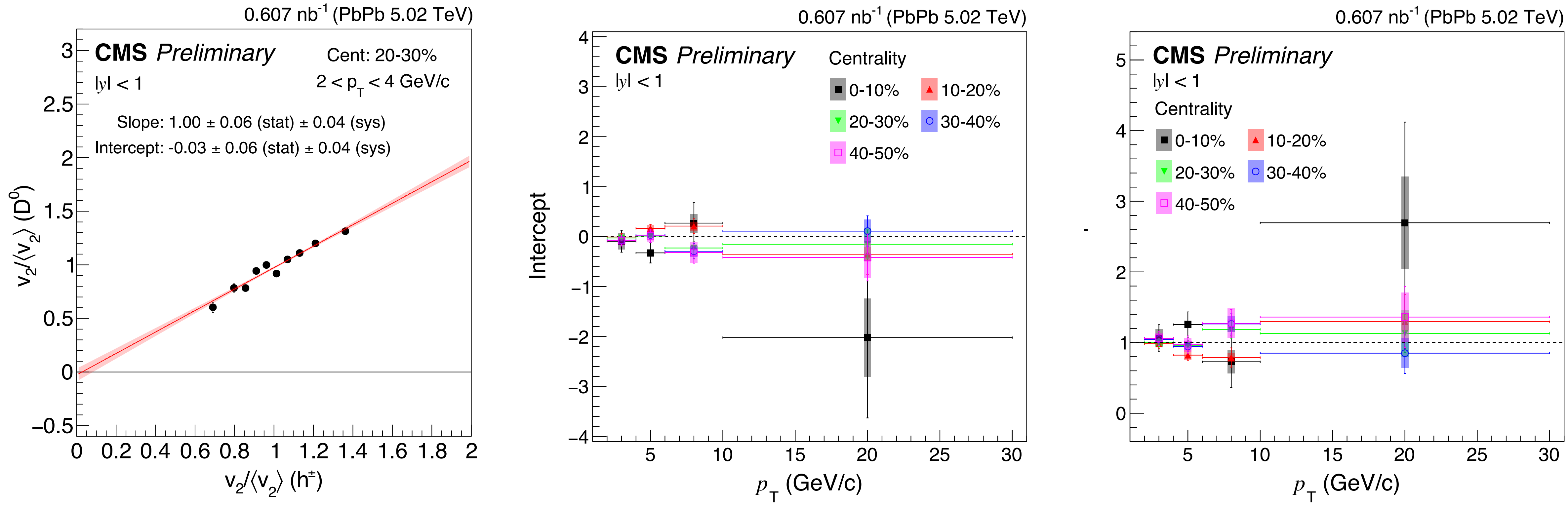


- Forward coverage of LHCb allows probes of nPDF at high rapidity
- Results show deviations > 2σ between beauty baryons and mesons in lead-going direction

Flow to constrain the initial state

D^0 vs $h^{\pm}$ v_2

[CMS-PAS-HIN-24-015](CMS-PAS-HIN-24-015)

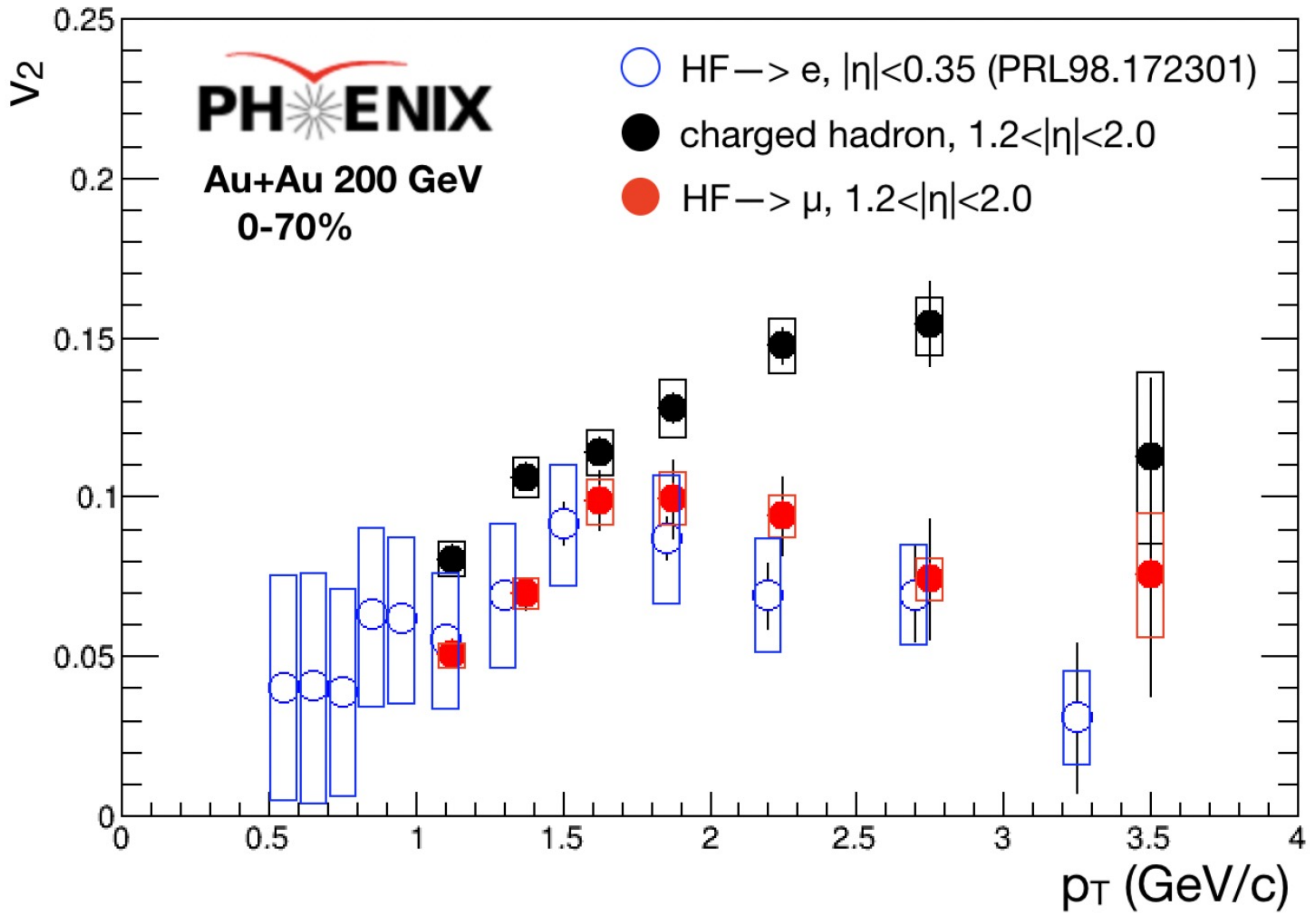


- Slope and intercept consistent with 1 & 0 respectively
- Initial geometry may define flow in charm

Heavy flavor electron flow

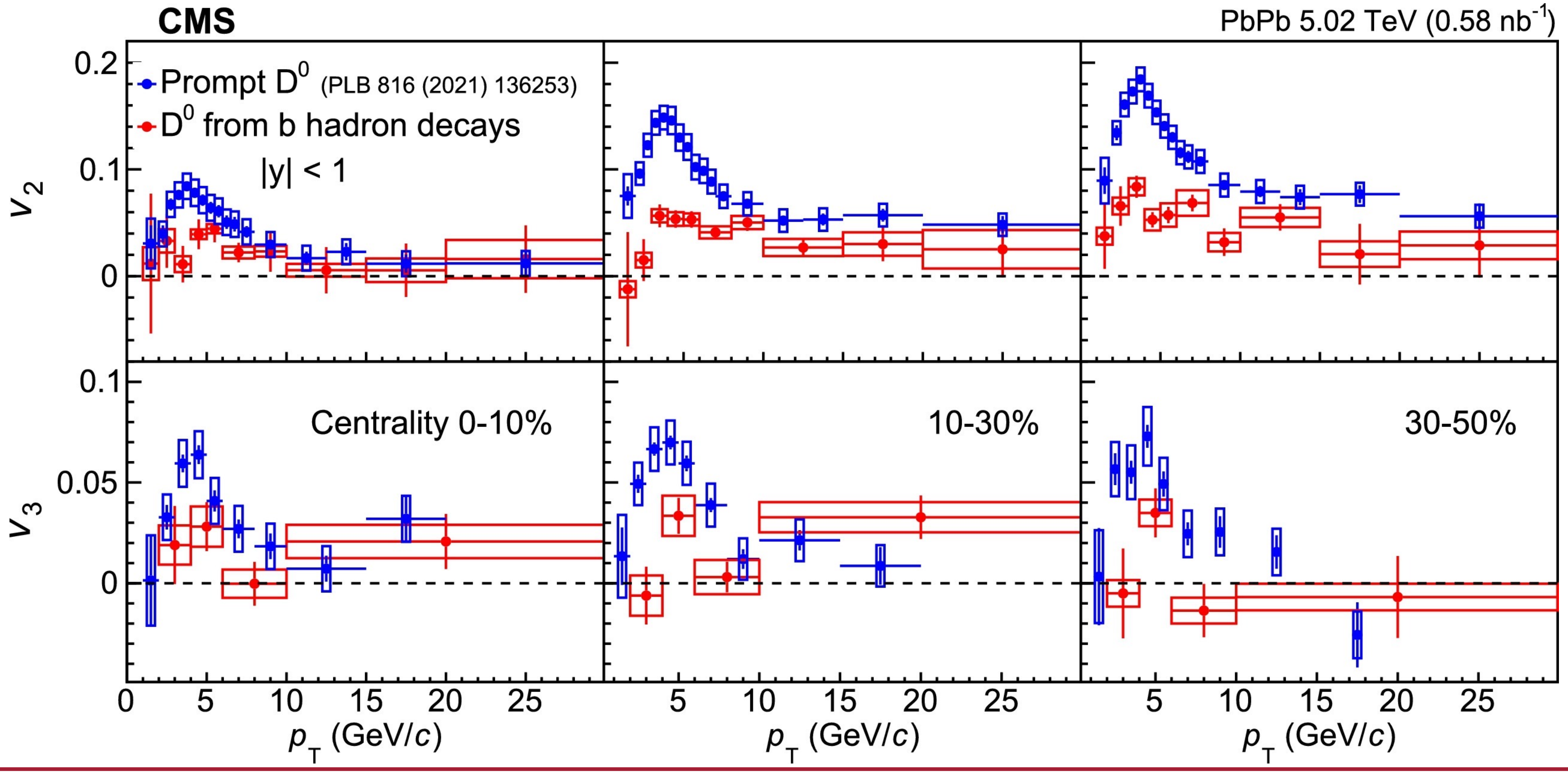
PRC 112 034902 (2025)

- Both lepton flavors exhibit similar flow characteristics
  - In different rapidity regions
- Clear mass hierarchy
- Secondary vertex tagging reduces charmonia contributions
- Hard to disentangle open charm and beauty contributions



Non-prompt D^0 flow

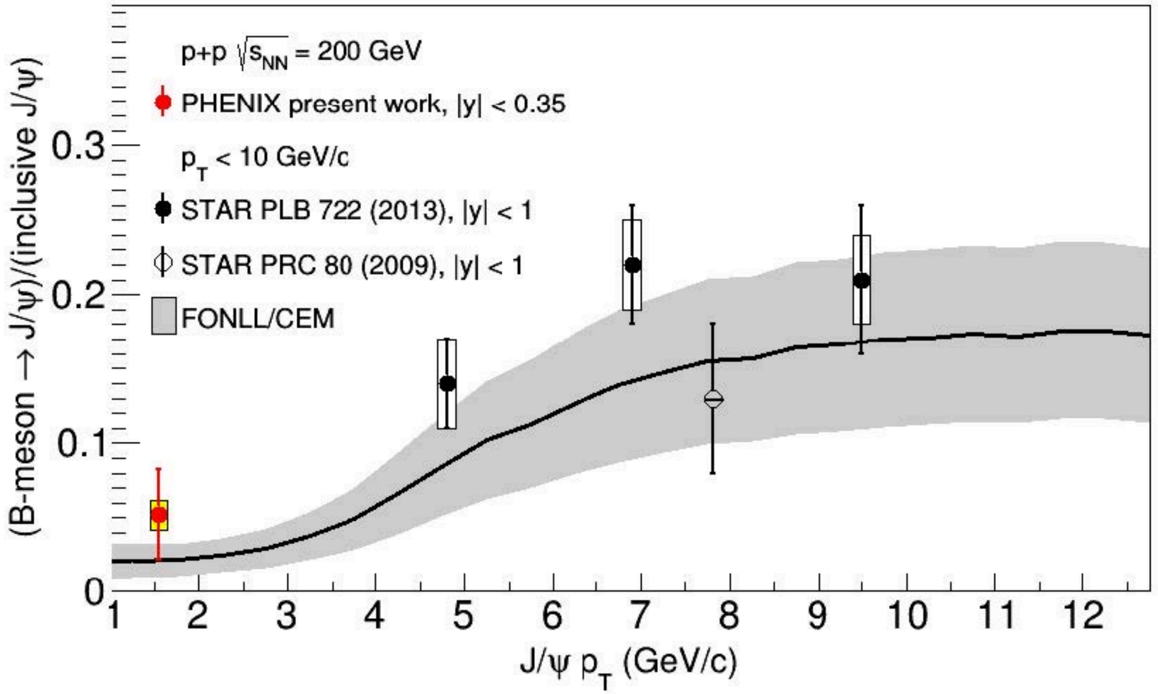
PLB 850 (2024) 138389

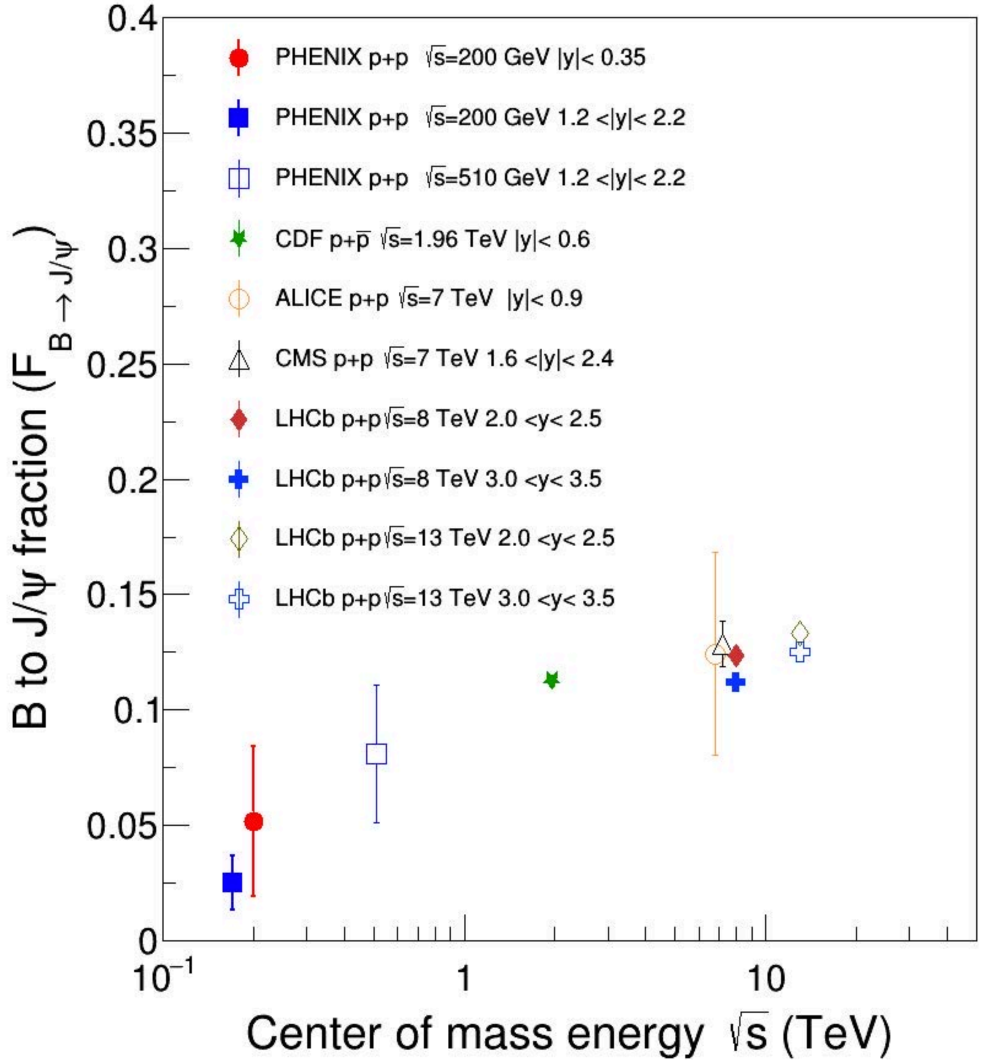


b-hadron mechanisms

$b \to J/\psi$ production

R. Nouicer, IS25



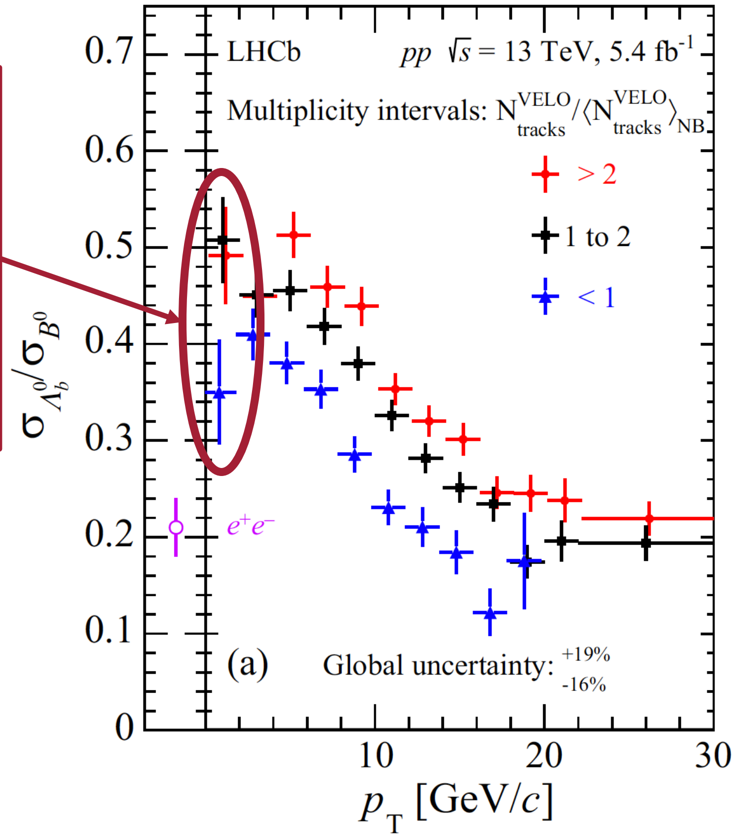


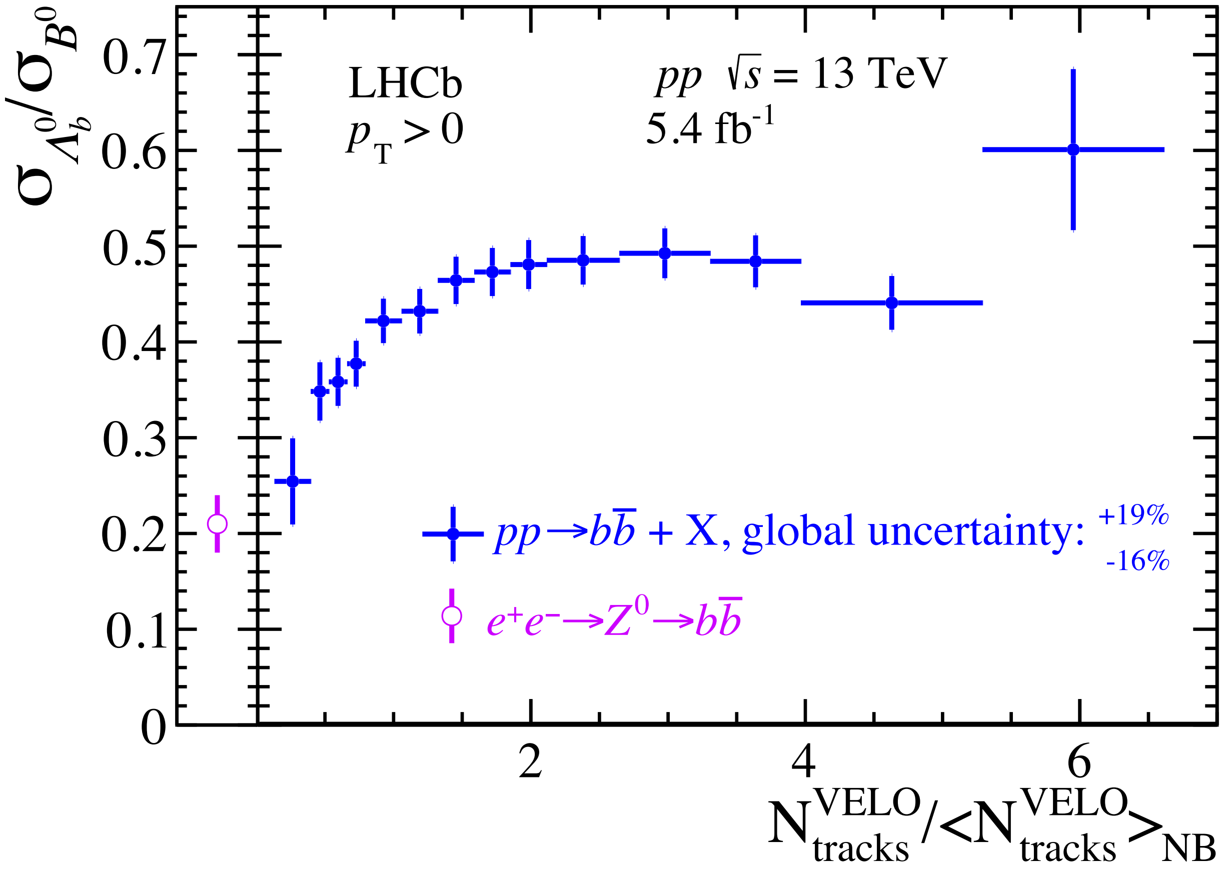
- Recent PHENIX measurement of non-prompt J/ψ fraction shows strong agreement with Fixed-Order-Next-to-Leading-Logarithm plus Color-Evaporation-Model predictions

Open-beauty ratios

PRL 132 (2024) 081901

Significant increase in b-baryon production





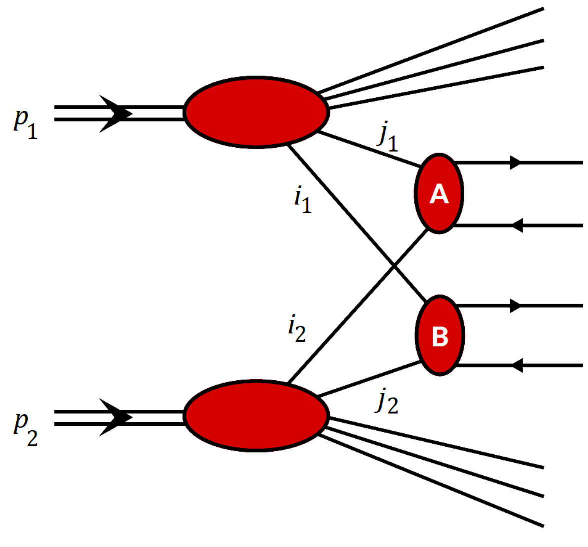
At low p_T, are we seeing coalescence with low momentum light quarks as a (dominant) production mechanism?

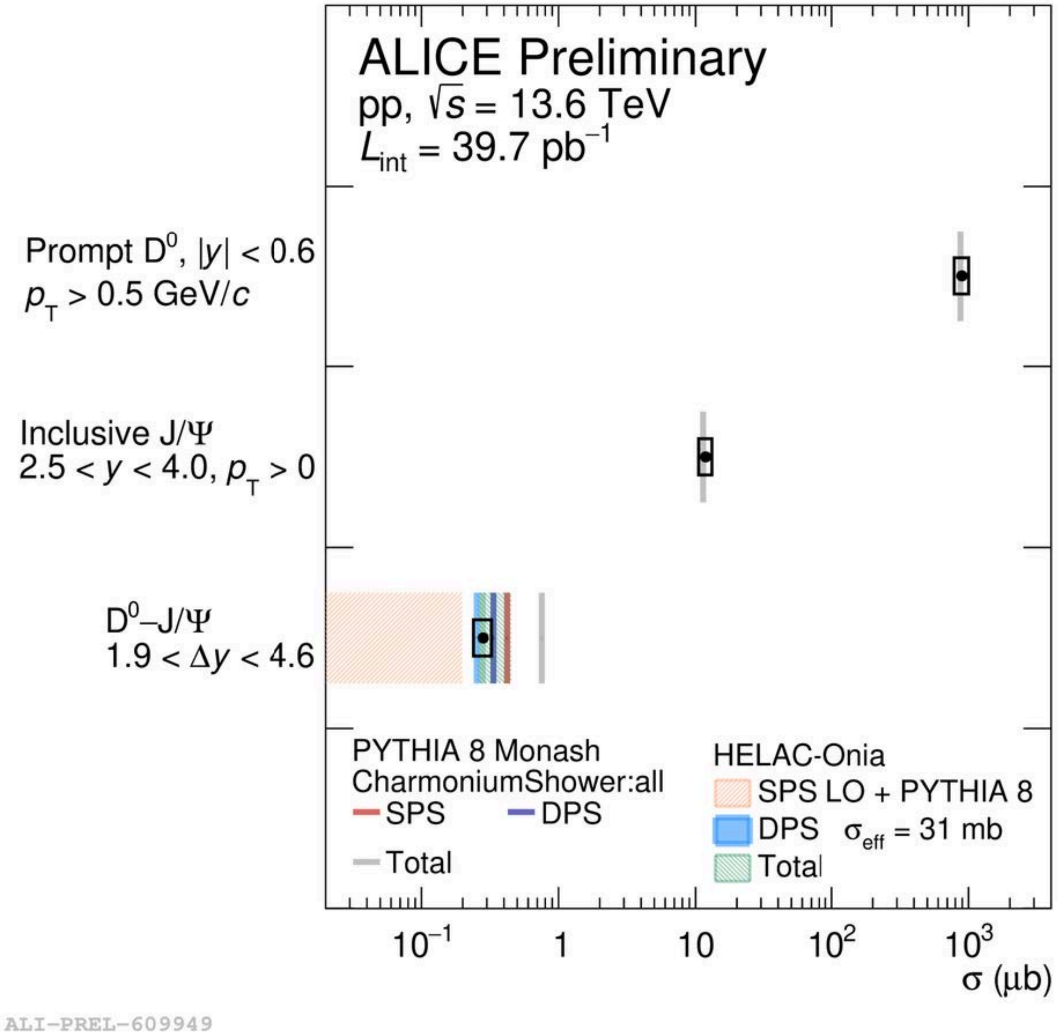
Production and polarization

MPI production on heavy flavour

A. Tavira García, IS25

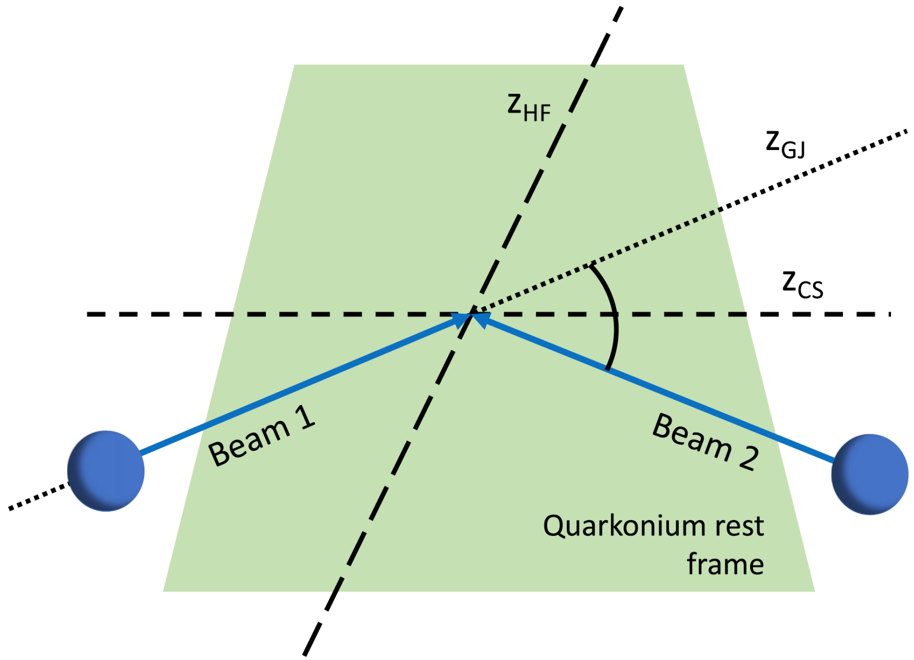
- New ALICE results on DPS production of J/ψ- J/ψ, D^0-D^0 & J/ψ-D^0 production
- Measurements of effective cross-section should be process-independent
- Observations indicate otherwise

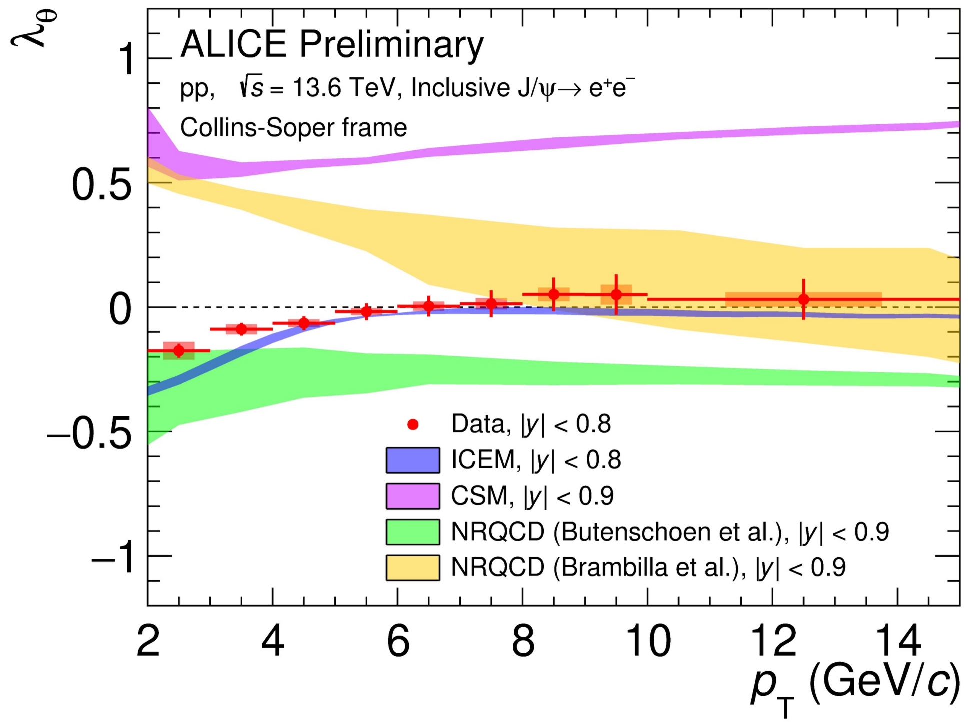




J/ψ polarisation

B. Sahoo, IS25

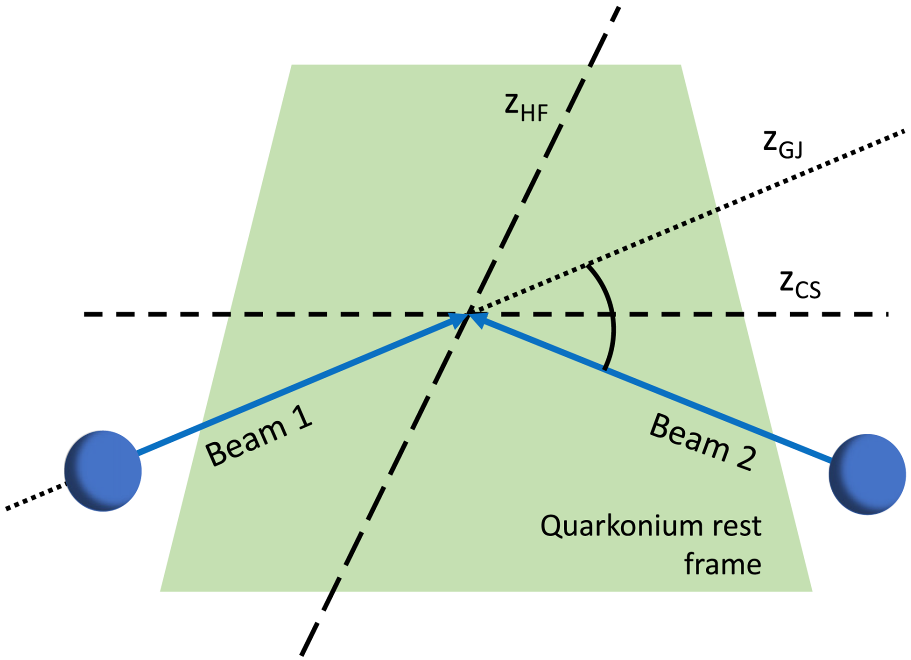


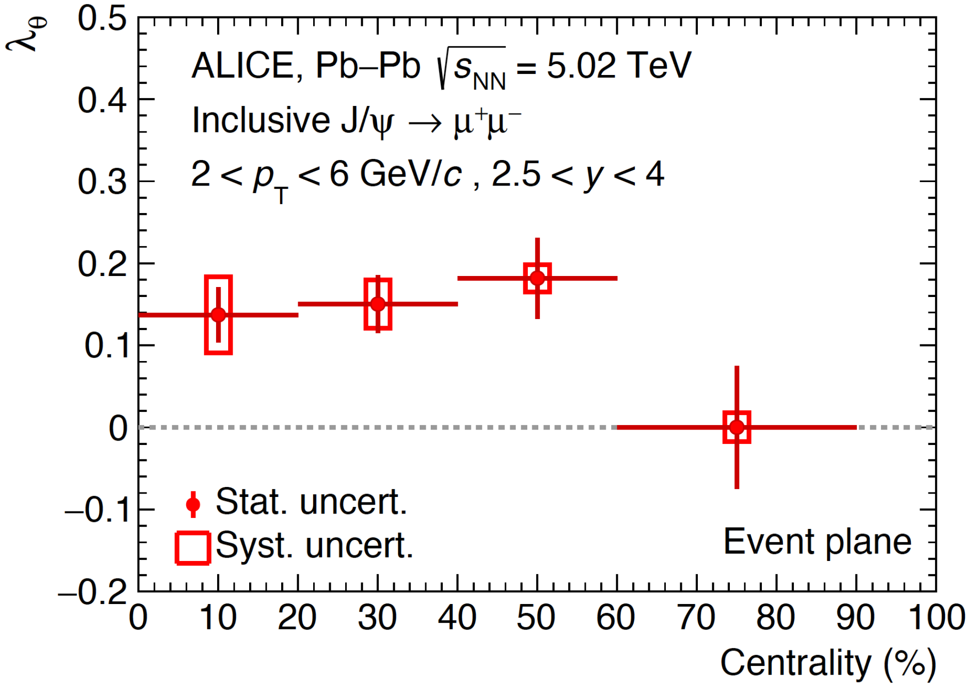


- Fast charmonia production could enable polarization from initial EM field
- Improved colour-evaporation model (ICEM) considers direct J/ψ production without feed-down
- Polarization experimentally consistent with 0 in *pp*

J/ψ polarisation

PRL 131, 042303 (2023)
B. Sahoo, IS25



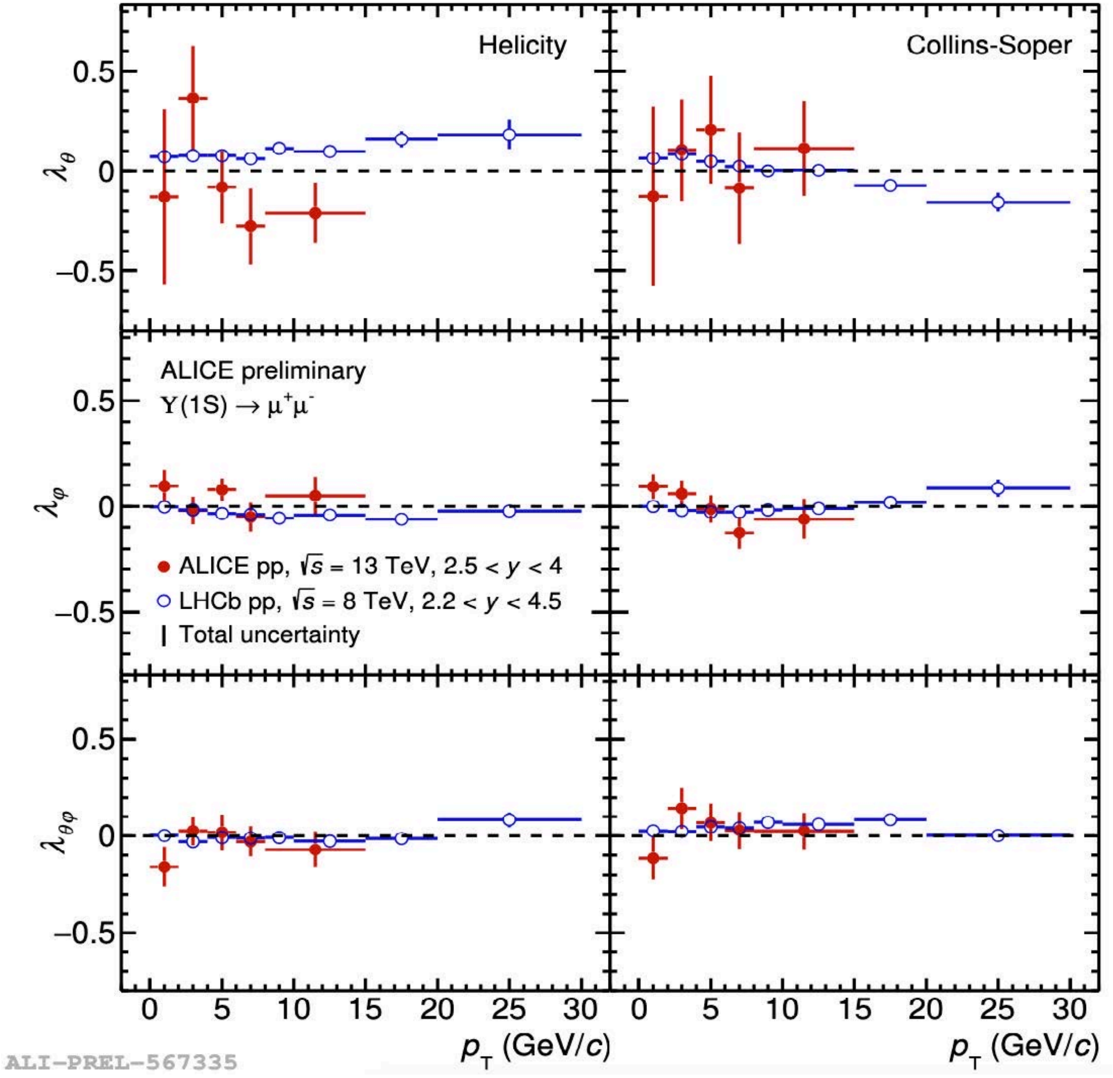


- Improved colour-evaporation model (ICEM) considers direct J/ψ production without feed-down
- 3.9σ deviation from 0 for polarization seen in heavy ion collisions

Υ polarisation

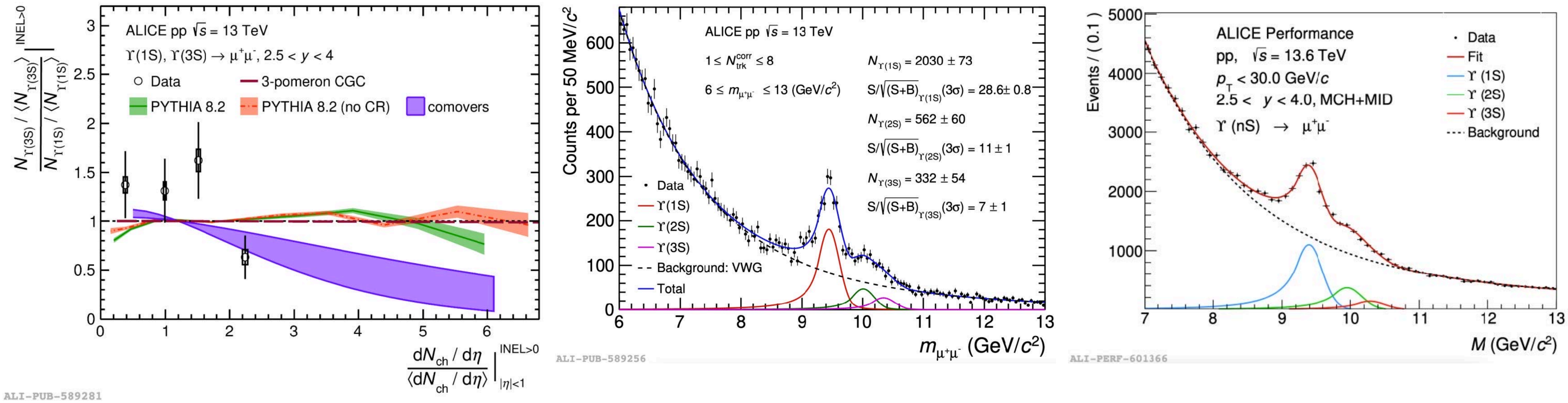
K. K. Pradhan, IS25

- ALICE measurement of polarization is consistent with 0
- Also consistent with LHCb results



ϒ production

K. K. Pradhan, IS25

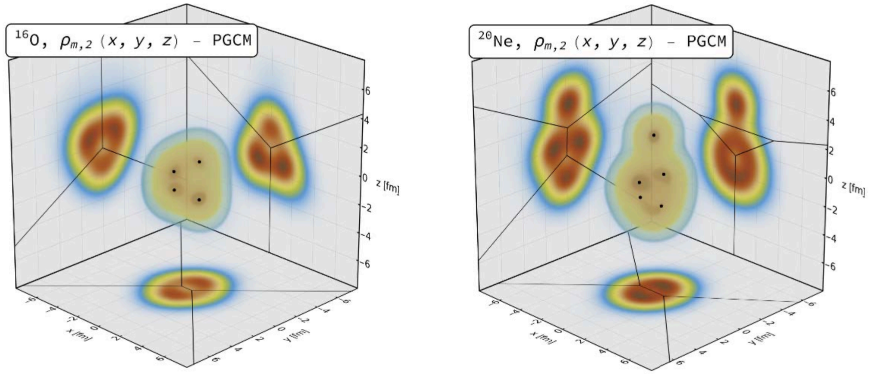


- ALICE measurement of production could favour comover model
- The full run 3 sample could shed light on this

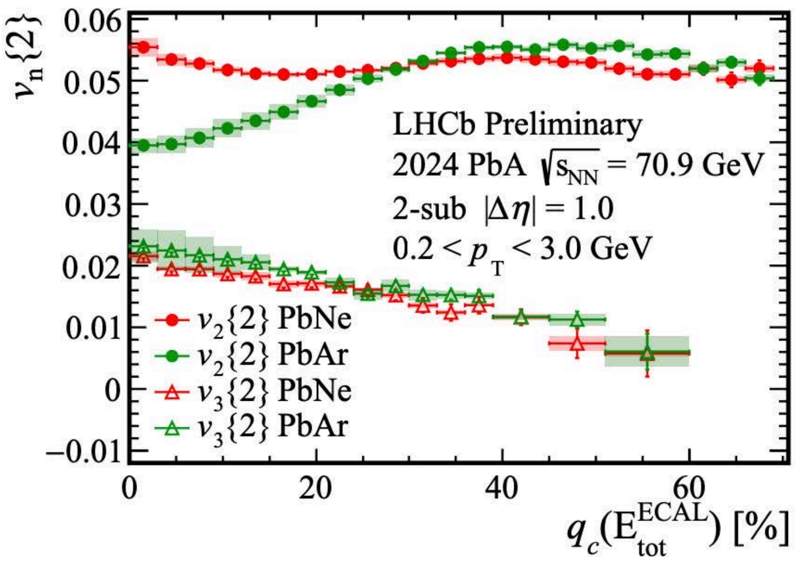
Using collision systems to constrain IS

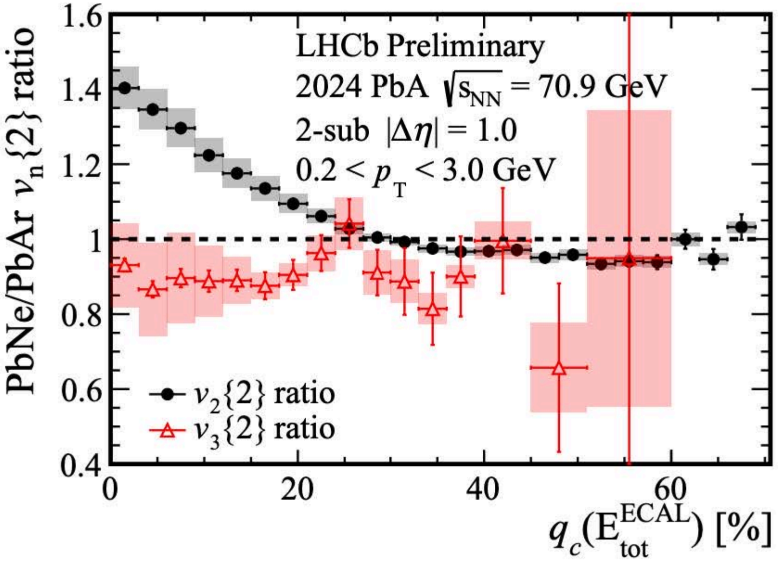
Nuclear shapes from SMOG

C.Shen, QM25
C. Lucarelli, IS25
W. Van der Schee, IS25

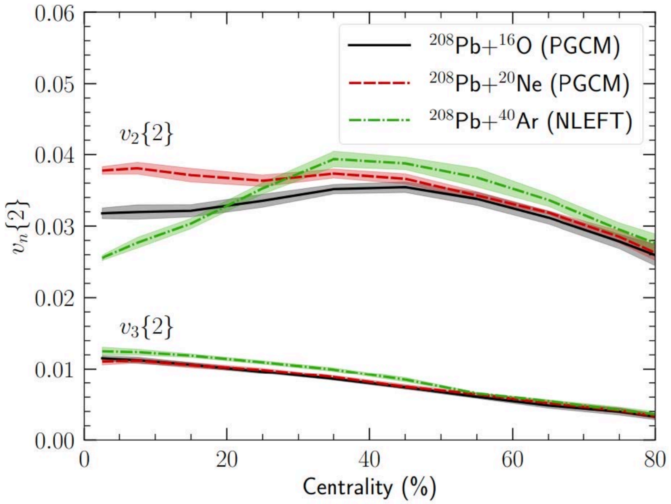


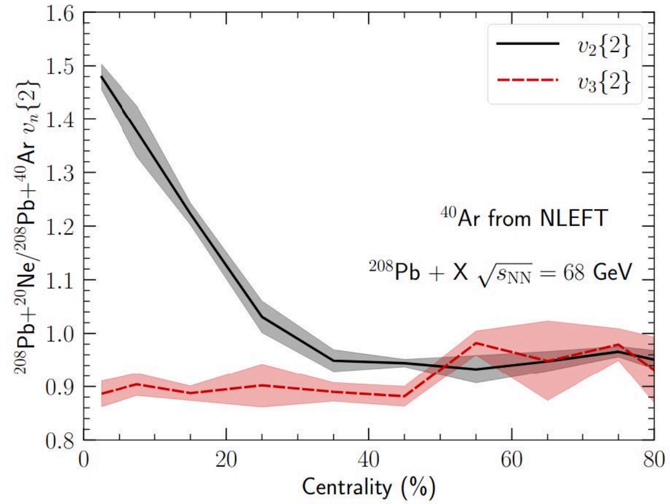
Predicted shape of ^{16}O (left) and ^{20}Ne (right)





- Ratio of flow coefficients between PbAr and PbNe
- Theory and experiment appear by-eye to agree very well

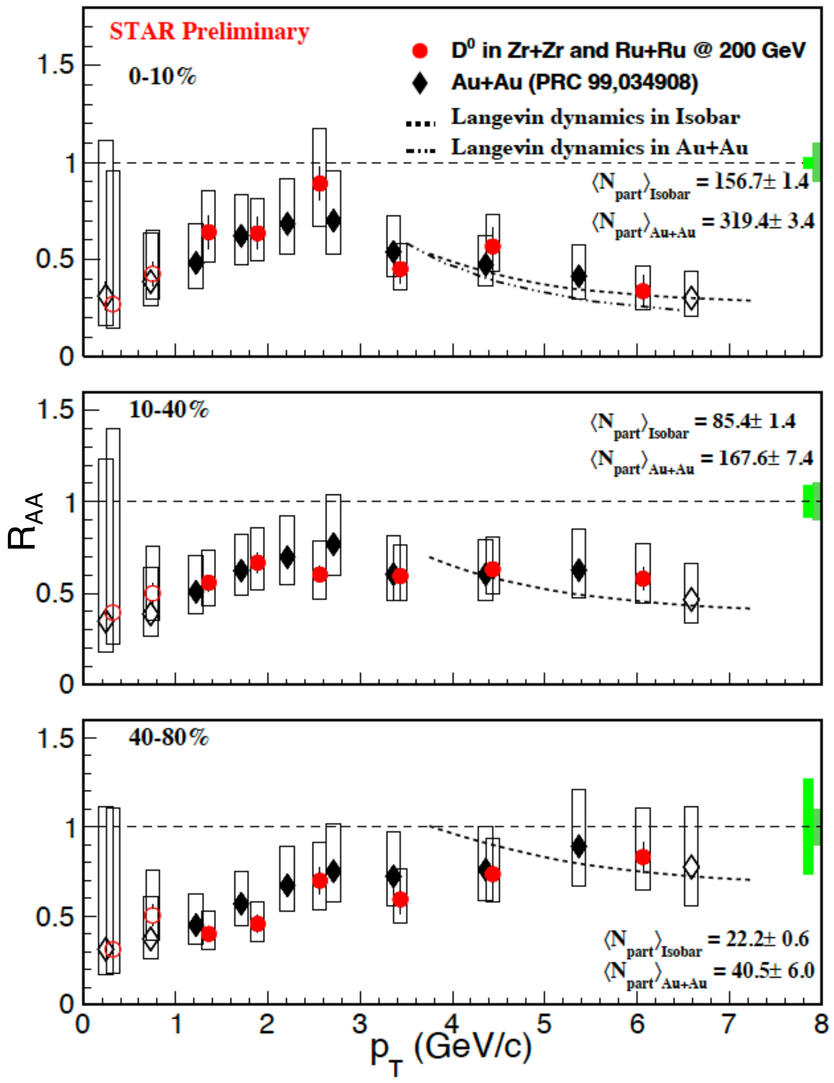




System size dependence

EPJ 296 (2024) 09003

- STAR observes no significant R_{AA} difference between isobar and AuAu collisions
- Observations consistent with radiative and collision losses
  - Little, if any, initial state dependence
- However, can we use isobars as probes of proton structure such as the baryon junction?

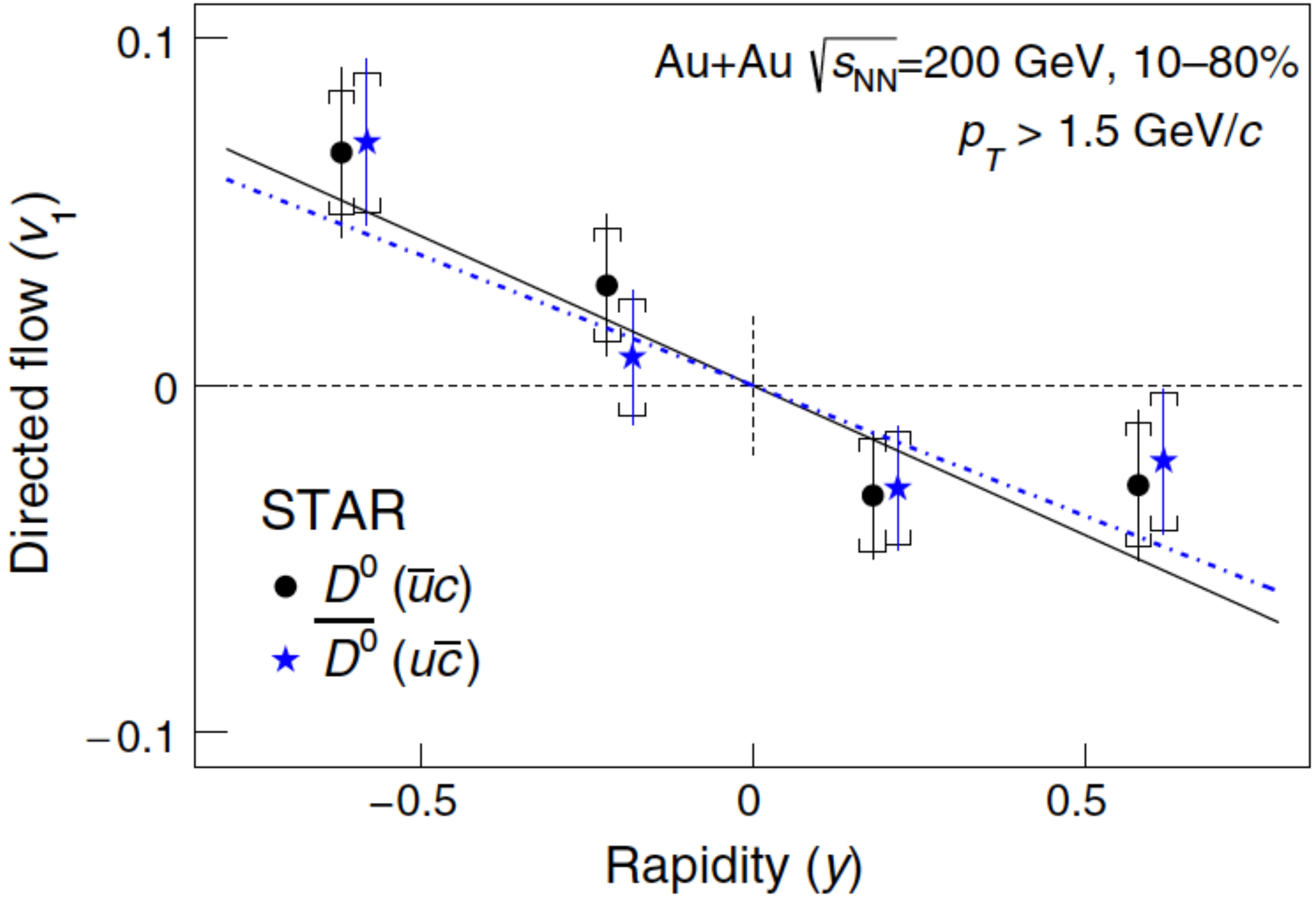


Probing the final state

v_1 probe of EM field

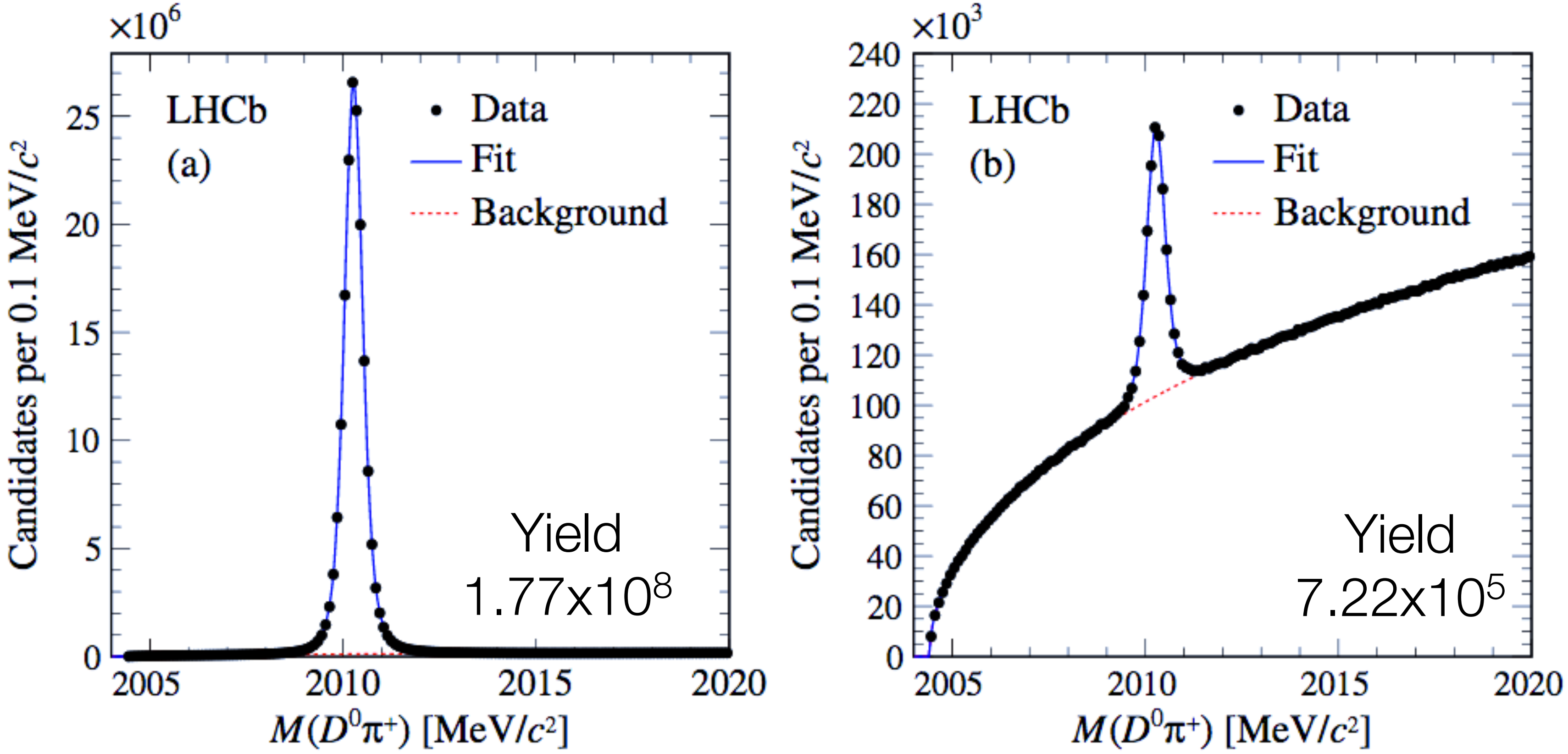
PRL 123, 162301 (2019)

- Lorentz force of an initial EM field can induce larger v_1 for heavy quarks compared to light
- Charge-conjugation operator induces a splitting between quarks and antiquarks
- Higher statistics samples needed to really probe initial EM field

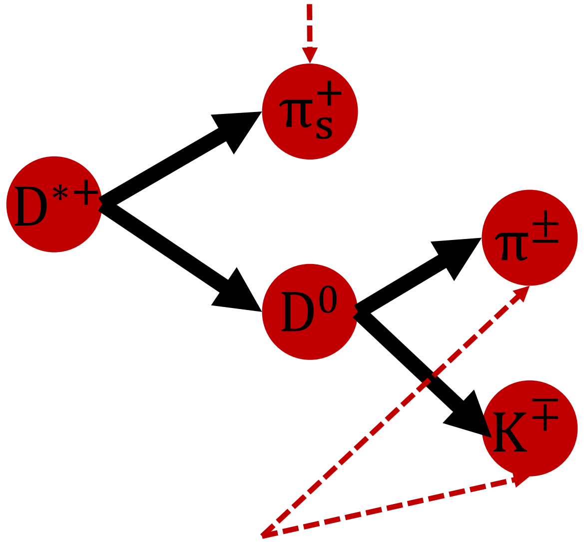


D^0 mixing and $D^0 \to K^+\pi^-$

Phys. Rev. D. 97,031101



D^0 tagged by pion charge

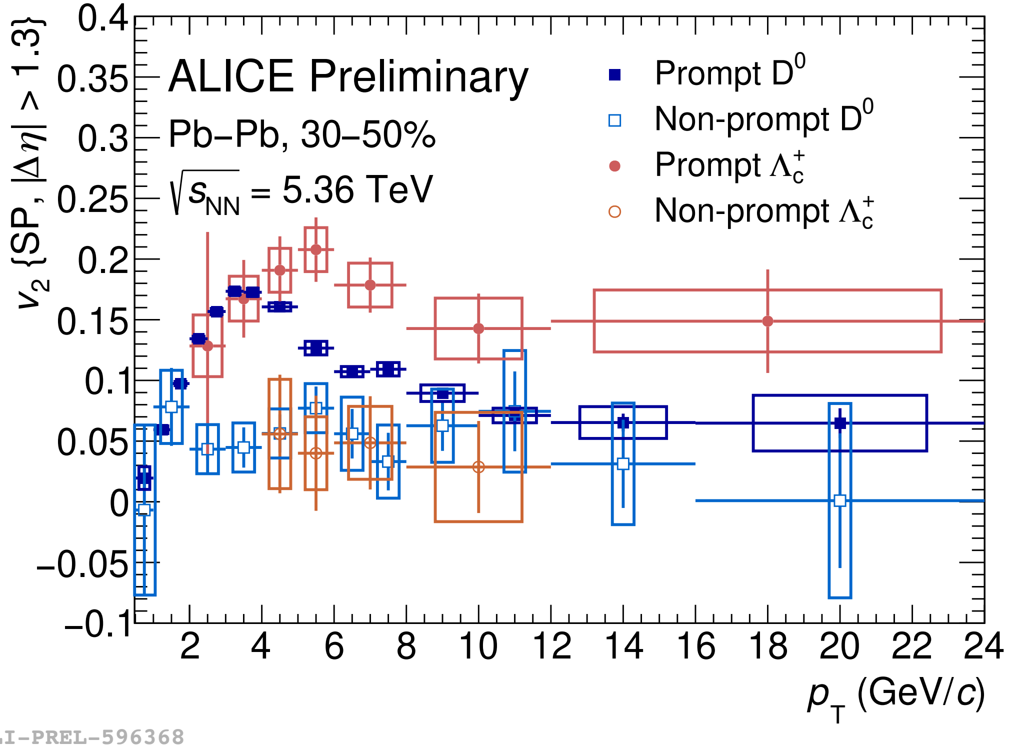


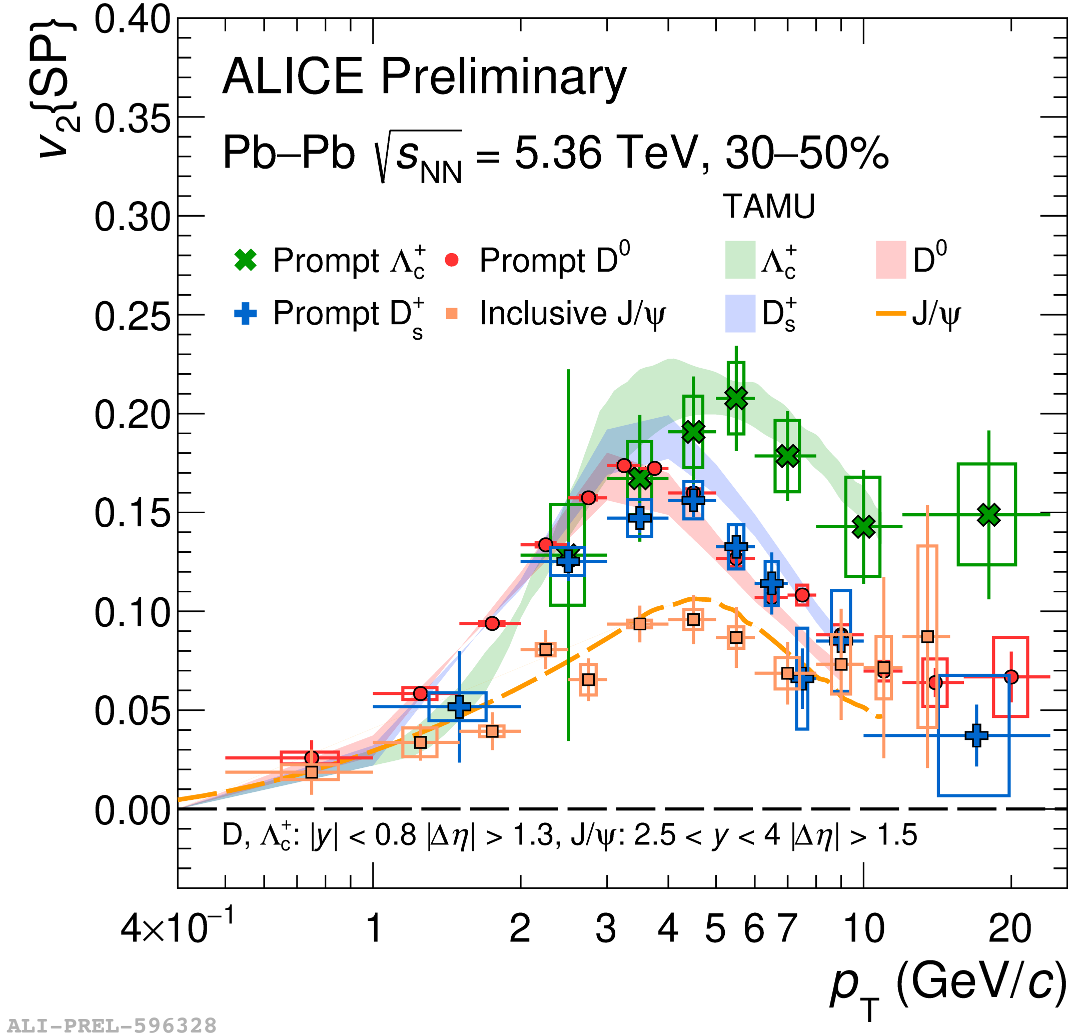
Right-Wrong sign by daughters charge

Left - Invariant mass distribution of right-sign ($D^0 \to K^-\pi^+$) decays
Right - Invariant mass distribution of wrong sign ($D^0 \to K^+\pi^-$) decays

Λ_c^+ flow

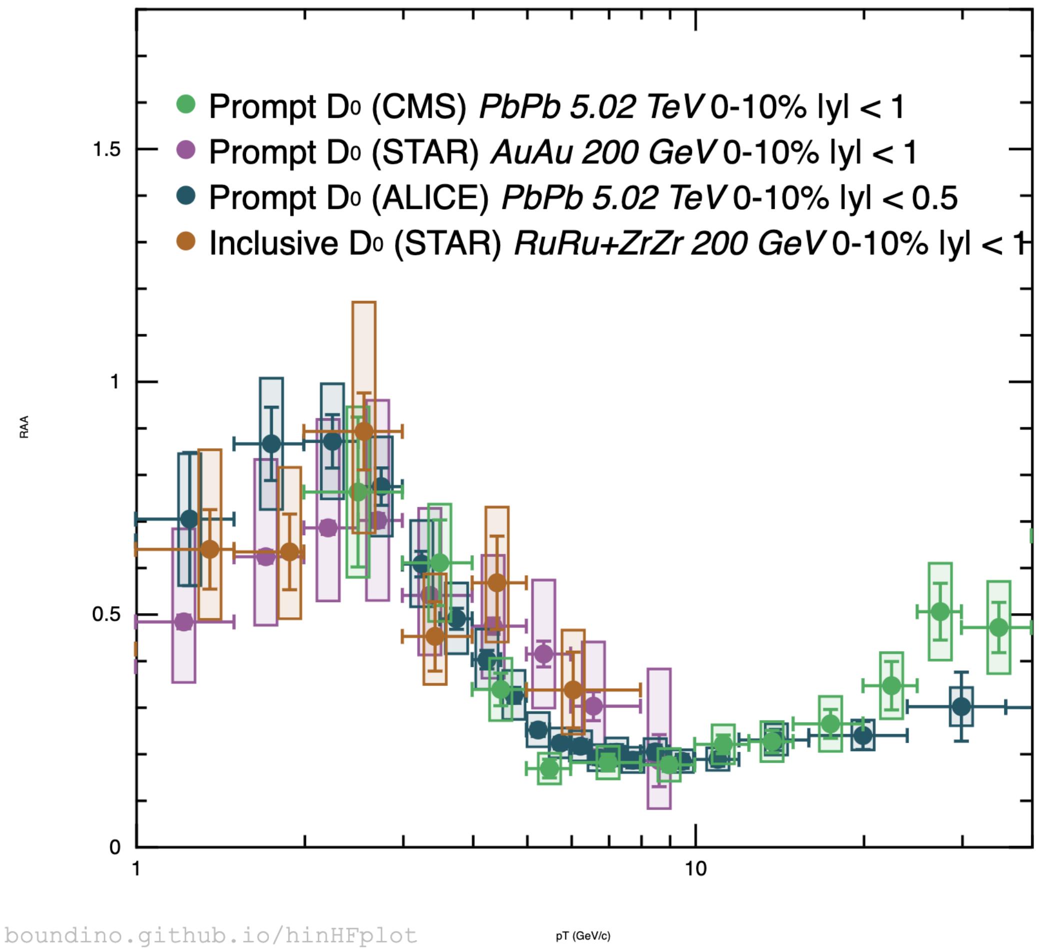
- Evidence for meson/baryon splitting in open charm
- Non-prompt flow is similar for Λ_c^+ and D^0

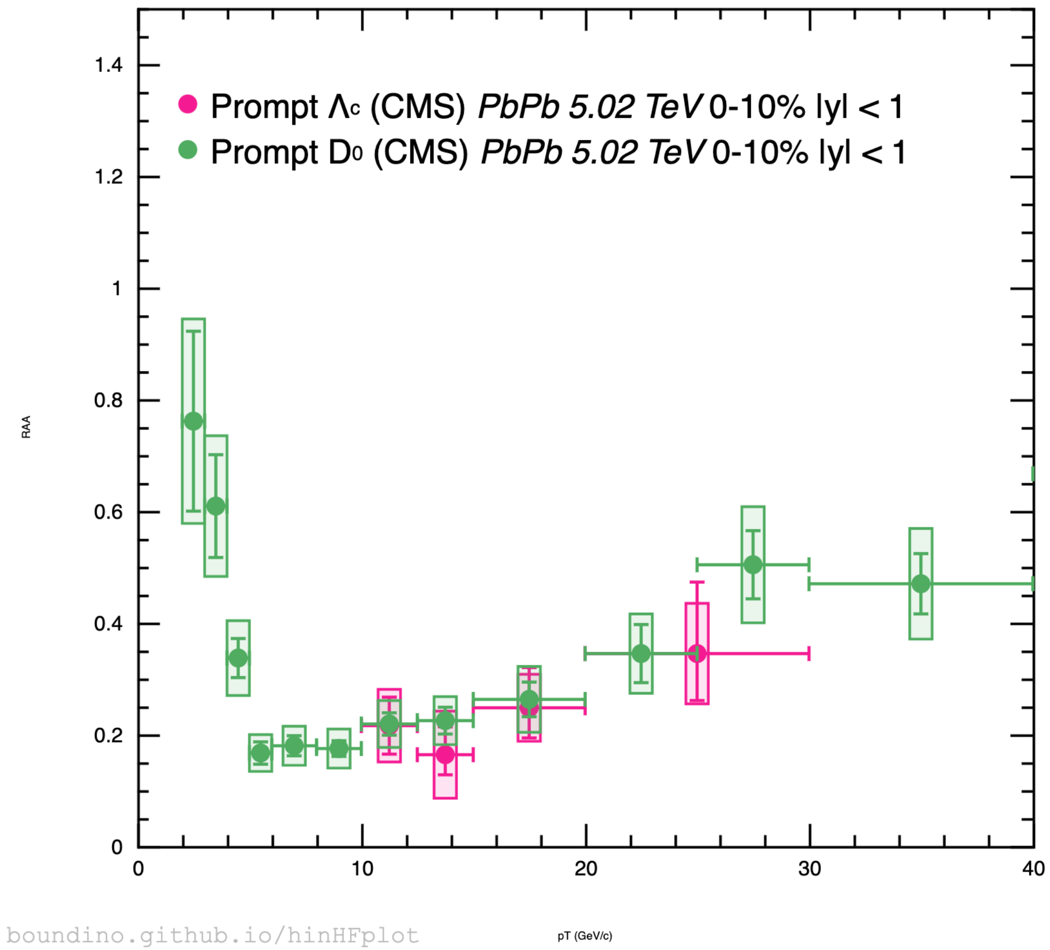




Baryon/meson comparisons

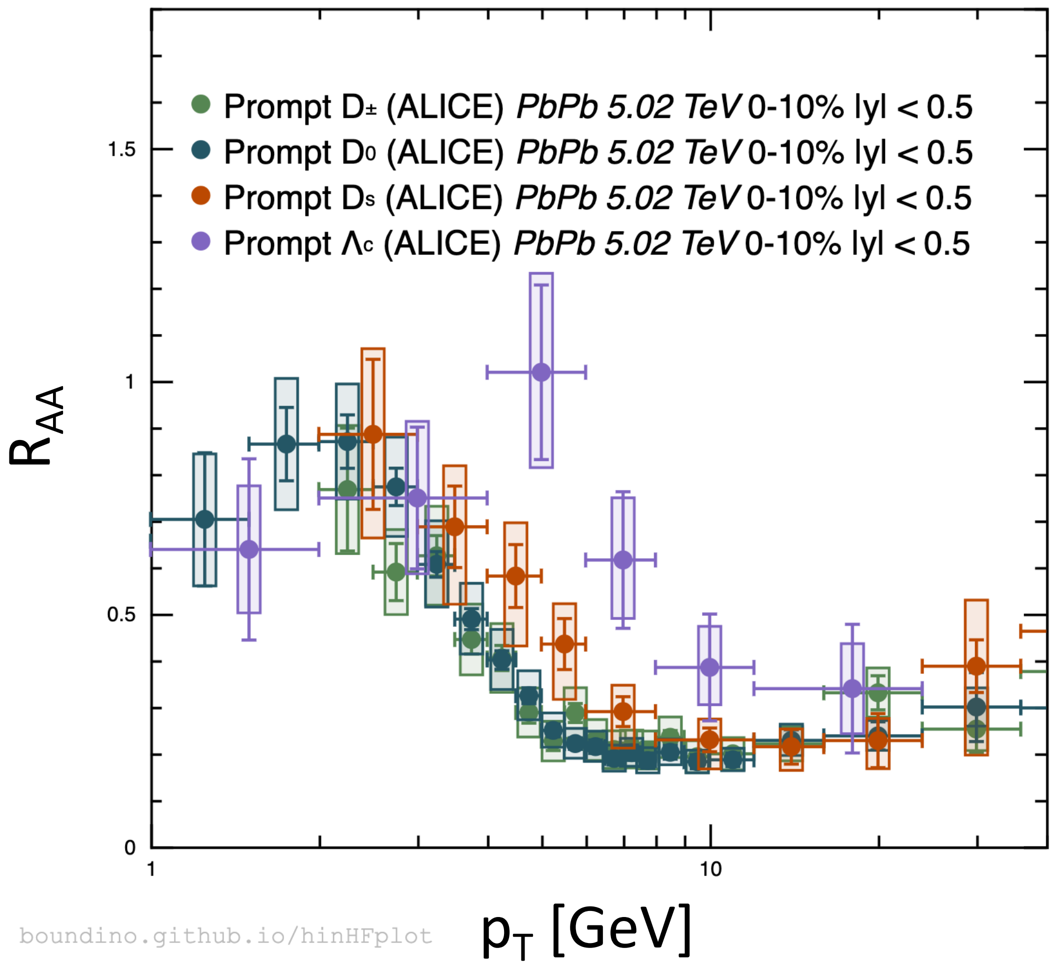
PRC 99 (2019) 034908
JHEP 01 (2022) 174
PLB 782 (2018) 474
STAR Preliminary

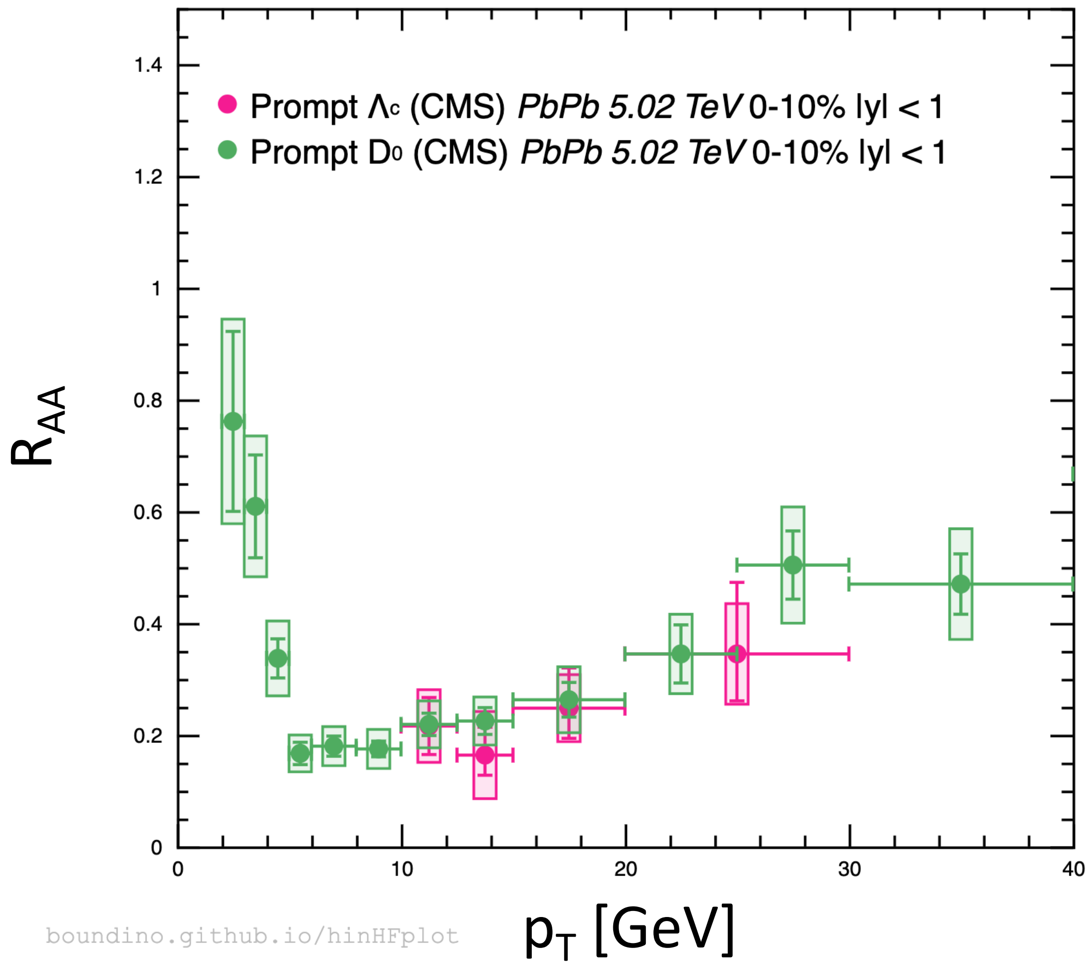




Baryon/meson comparisons

JHEP 01 (2022) 174
PLB 827 (2022) 136986
PLB 839 (2023) 137796





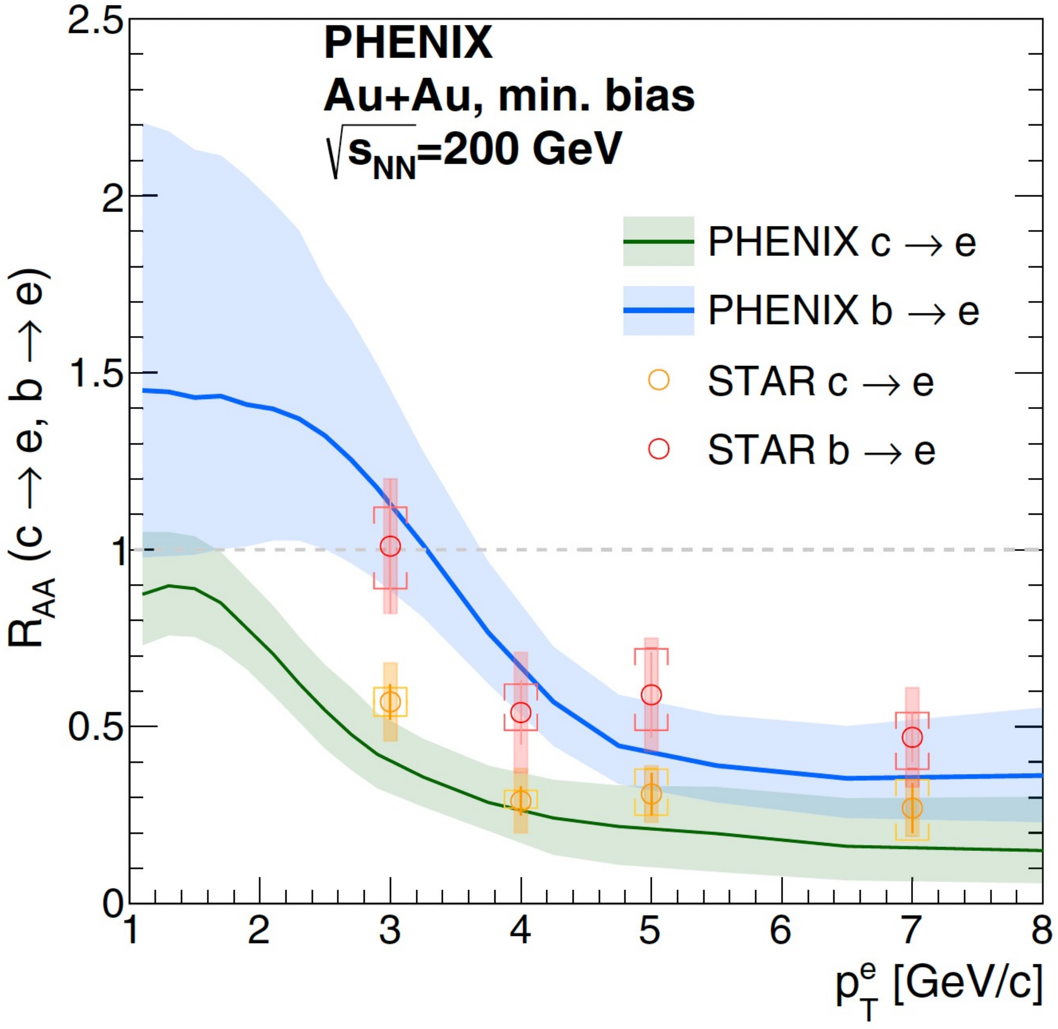
Non-prompt electron production

PRC 109 (2024) 044907

- Both STAR and PHENIX see less suppression in heavier b-quarks than c-quarks

$R_{AA}^{c\to e} = \frac{1-f_{AuAu}}{1-f_{pp}} R_{AA}^{HF}$ and $R_{AA}^{b\to e} = \frac{f_{AuAu}}{f_{pp}} R_{AA}^{HF}$

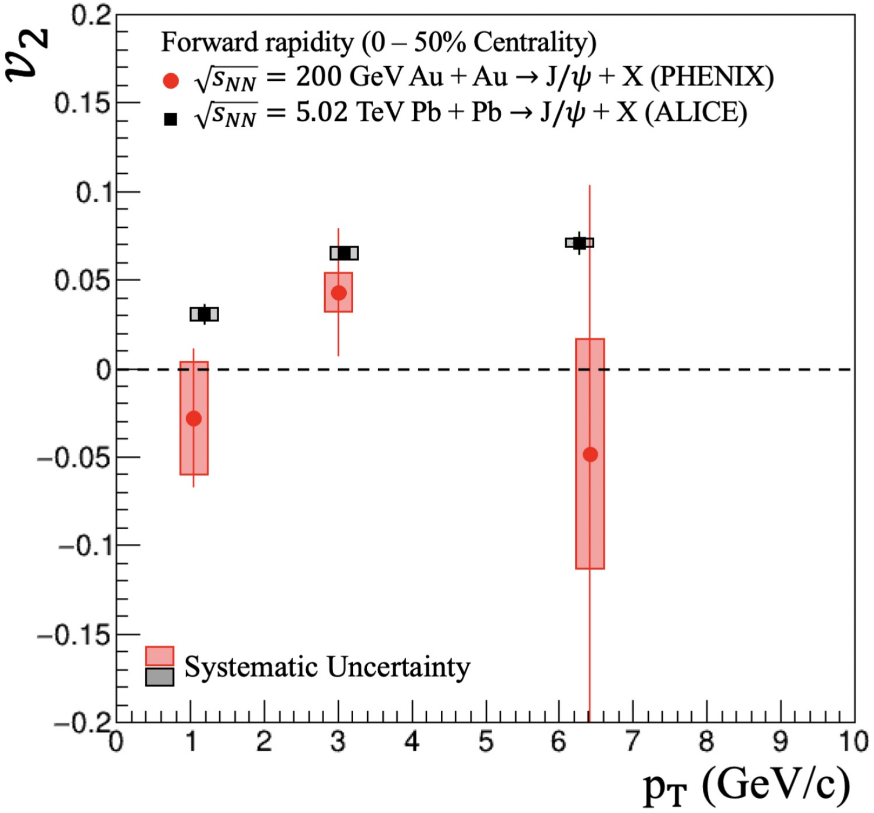
- Tricky analysis
  - Electrons identified by RICH and/or EMCal matching
  - Must be displaced from PV (transverse DCA)
  - Decay lengths of D^0 and B^0 used to separate charm and beauty
- sPHENIX could do well here with projective EMCal

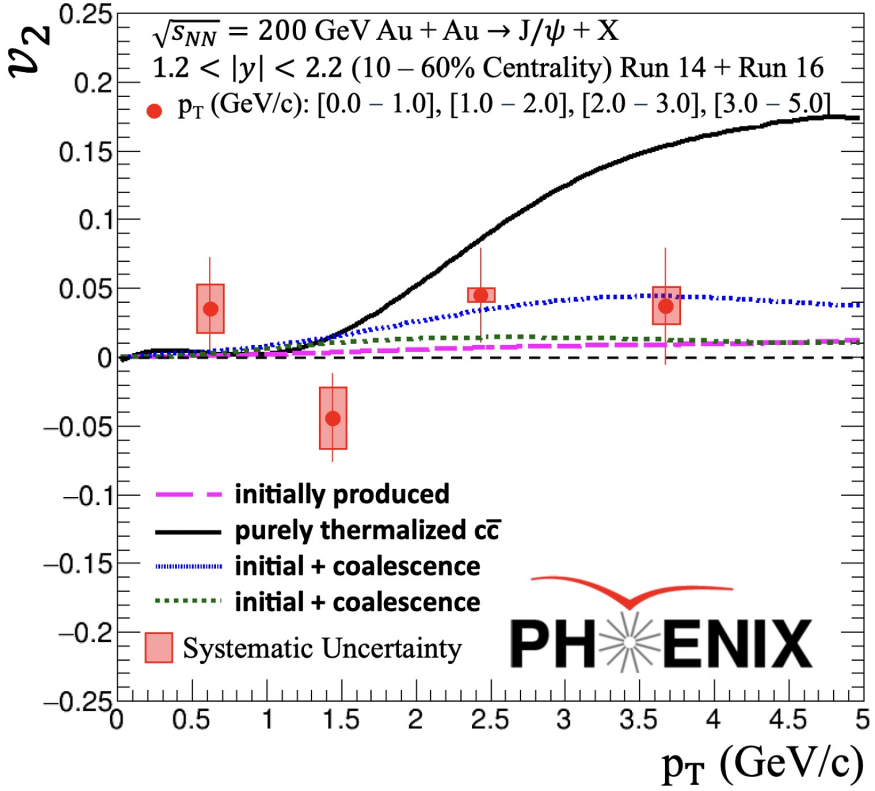


Charmonia flow

Phys. Rev. C 112, 014904

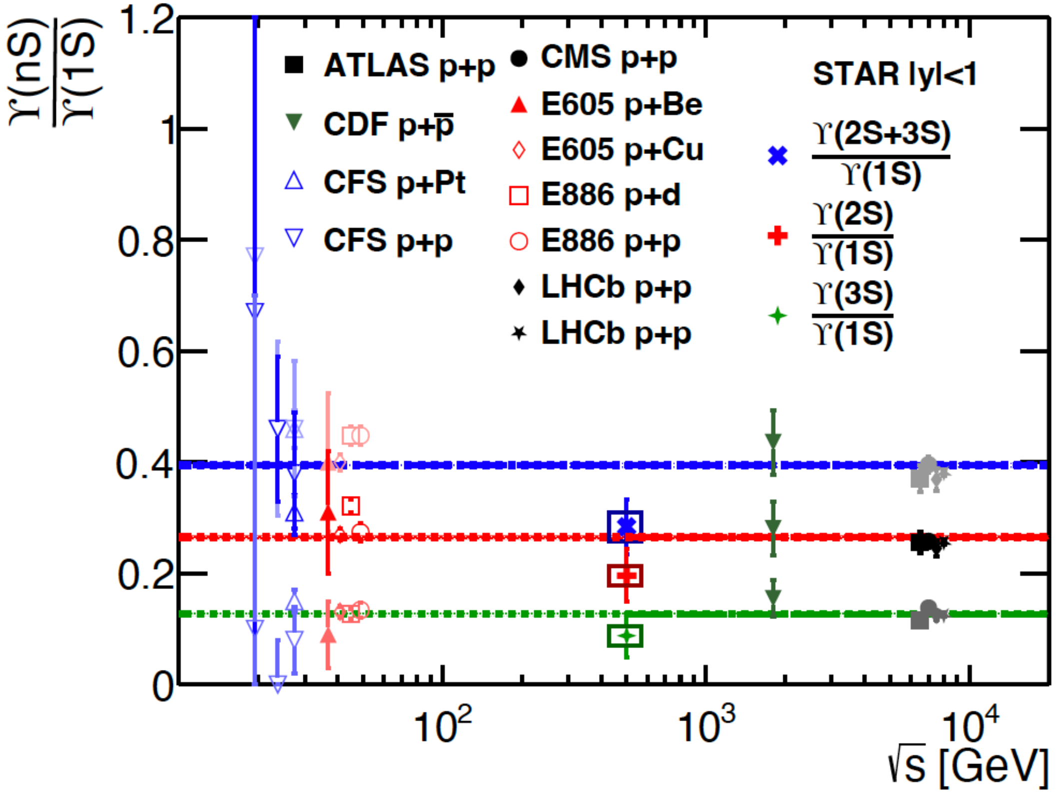
- PHENIX results consistent with no flow
- Consistent with STAR
- Contradicts ALICE
  - CoM dependence or statistics?
- PHENIX results favour coalescence

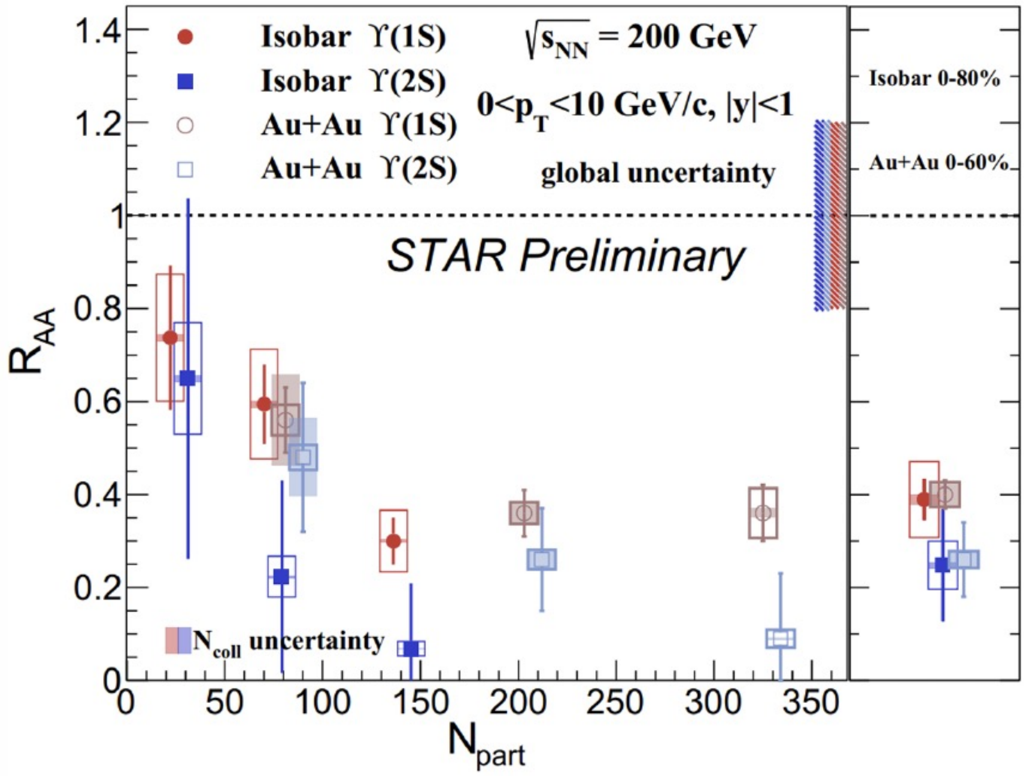




Upsilon production

PRL 130 (2023) 112301
Phys. Rev. D 112, 032004





- New STAR *pp* results show lower than average combined $\Upsilon(2S) + \Upsilon(3S)$ production
- Individual productions consistent with average

Conclusion

- Charm and beauty quark masses are above the critical temperature
  - Produced in the initial collision
  - Experience the full evolution of QGP
- Heavier *b*-quark mass compared to *c*-quark means less likely to be "pushed around" by QGP ("Brownian"-like motion)
- Experimental measurements are challenging
  - Small decay lengths mean close to the background
  - Small cross-section means lots of run time is required
- Experimental measurements are
  - Key inputs to theoretical models
  - Key tests of theoretical models

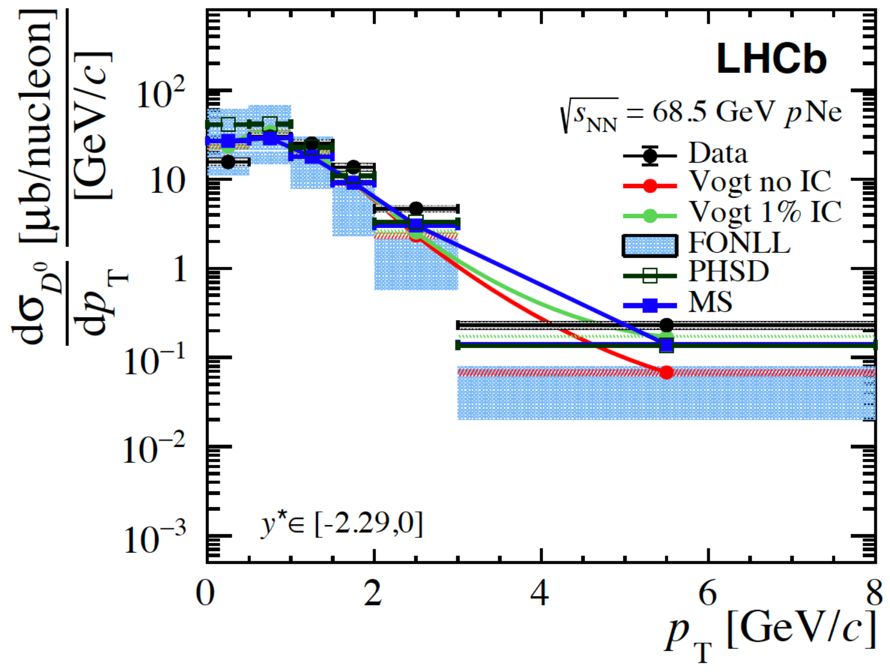
Backup

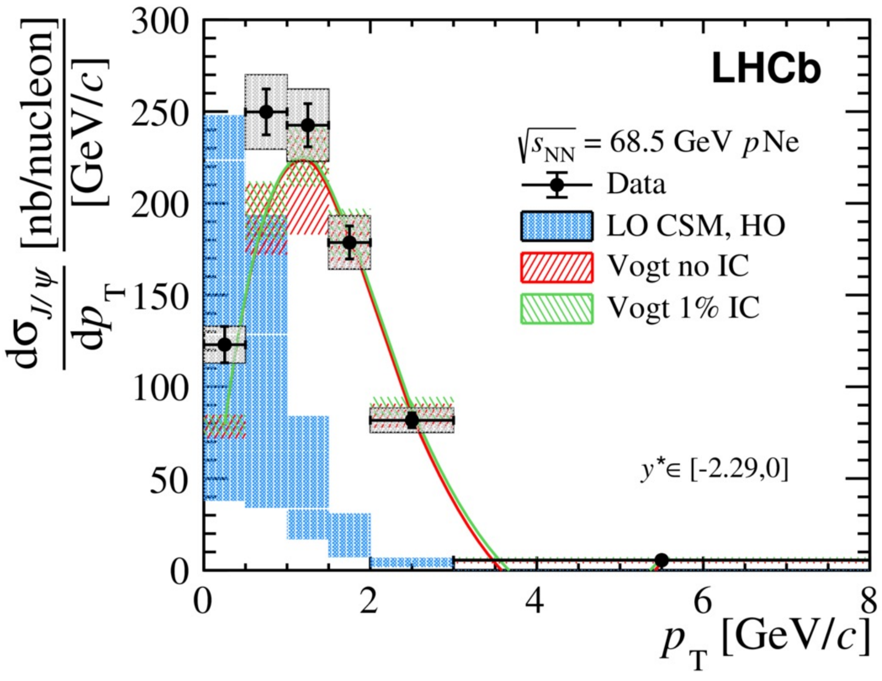
Open charm at SMOG

EPJ C83 (2023) 541
EPJ C83 (2023) 625

$pNe \rightarrow D^0 + X$

$pNe \rightarrow J/\psi + X$

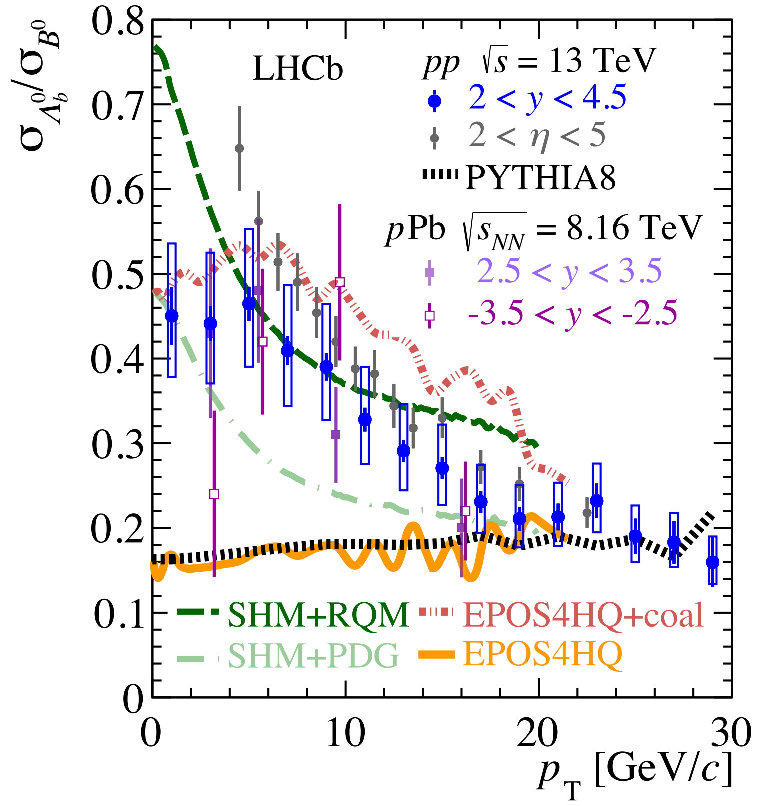


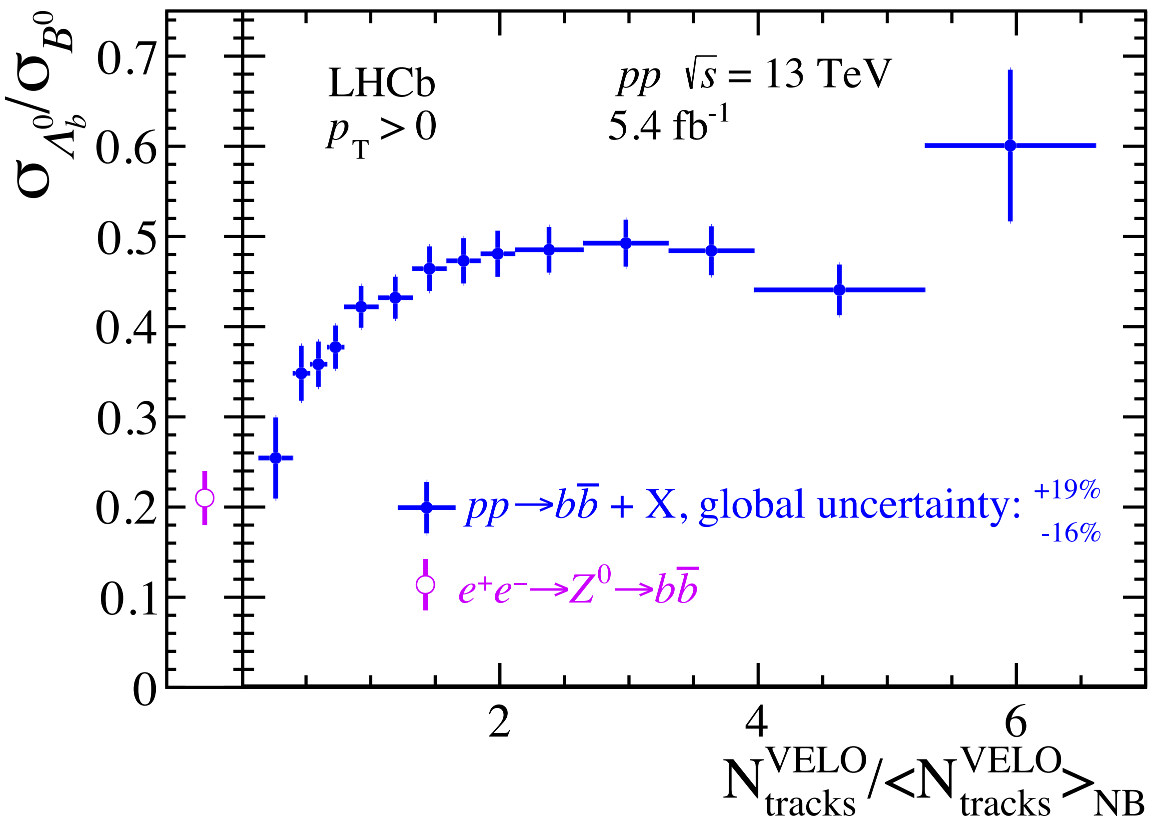


- LHCb's SMOG system allows low density gas injection into collision point
- SMOG1, at collision point, limited statistics, has to run when LHC is quiet
- SMOG2, before collision point, huge statistics, can run in parallel with LHC

Open-beauty ratios

[PRL 132 (2024) 081901](PRL 132 (2024) 081901)

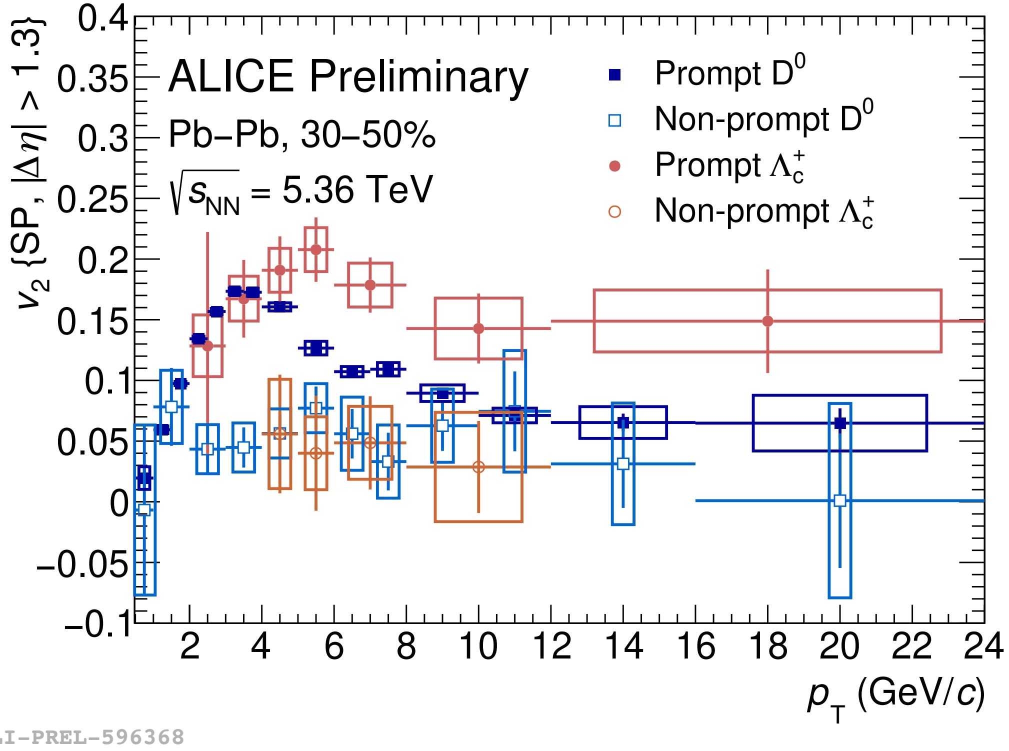


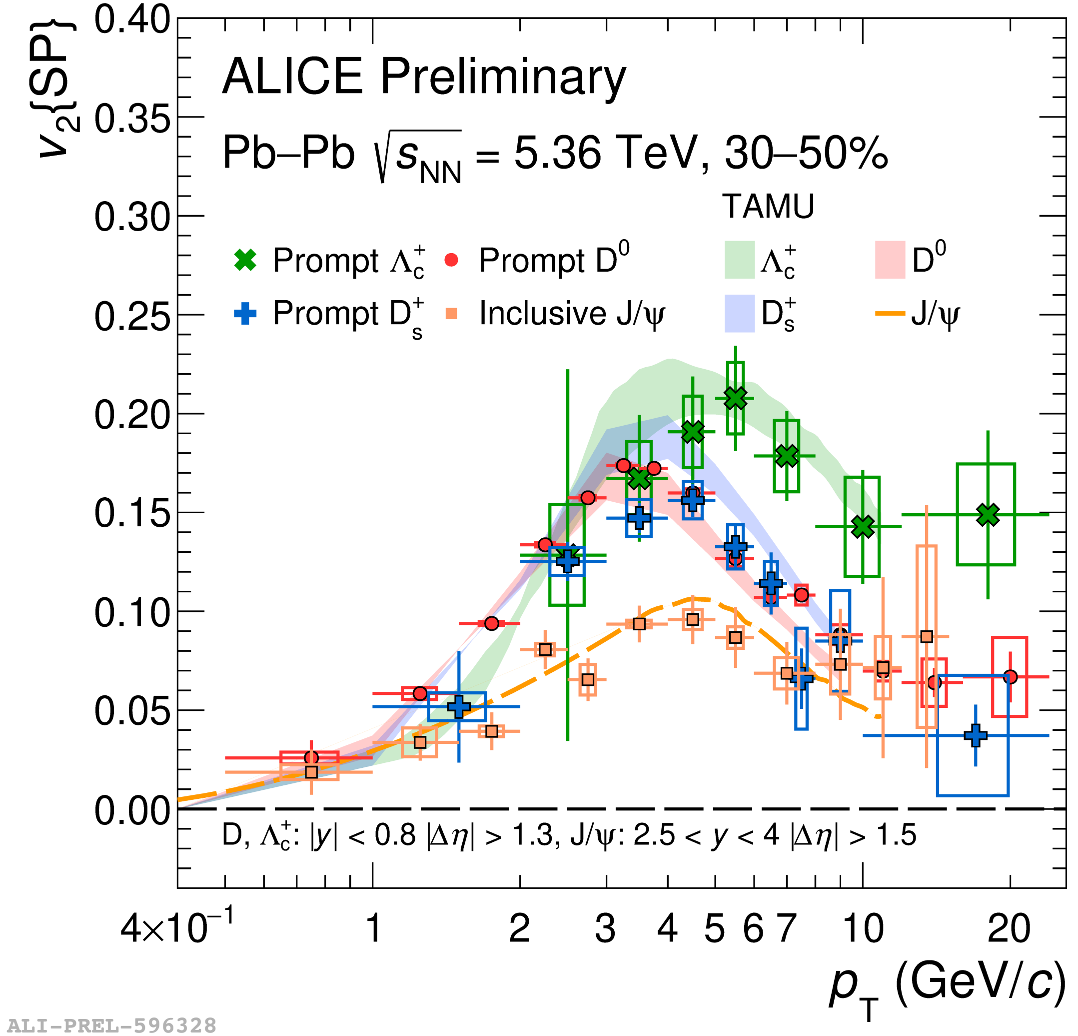


At low p_T and high charged-particle multiplicity, LHCb sees a higher cross-section ratio than in e^+e^- baselines

Λ_c^+ flow

- Evidence for meson/baryon splitting in open charm
- Non-prompt flow is similar for Λ_c^+ and D^0

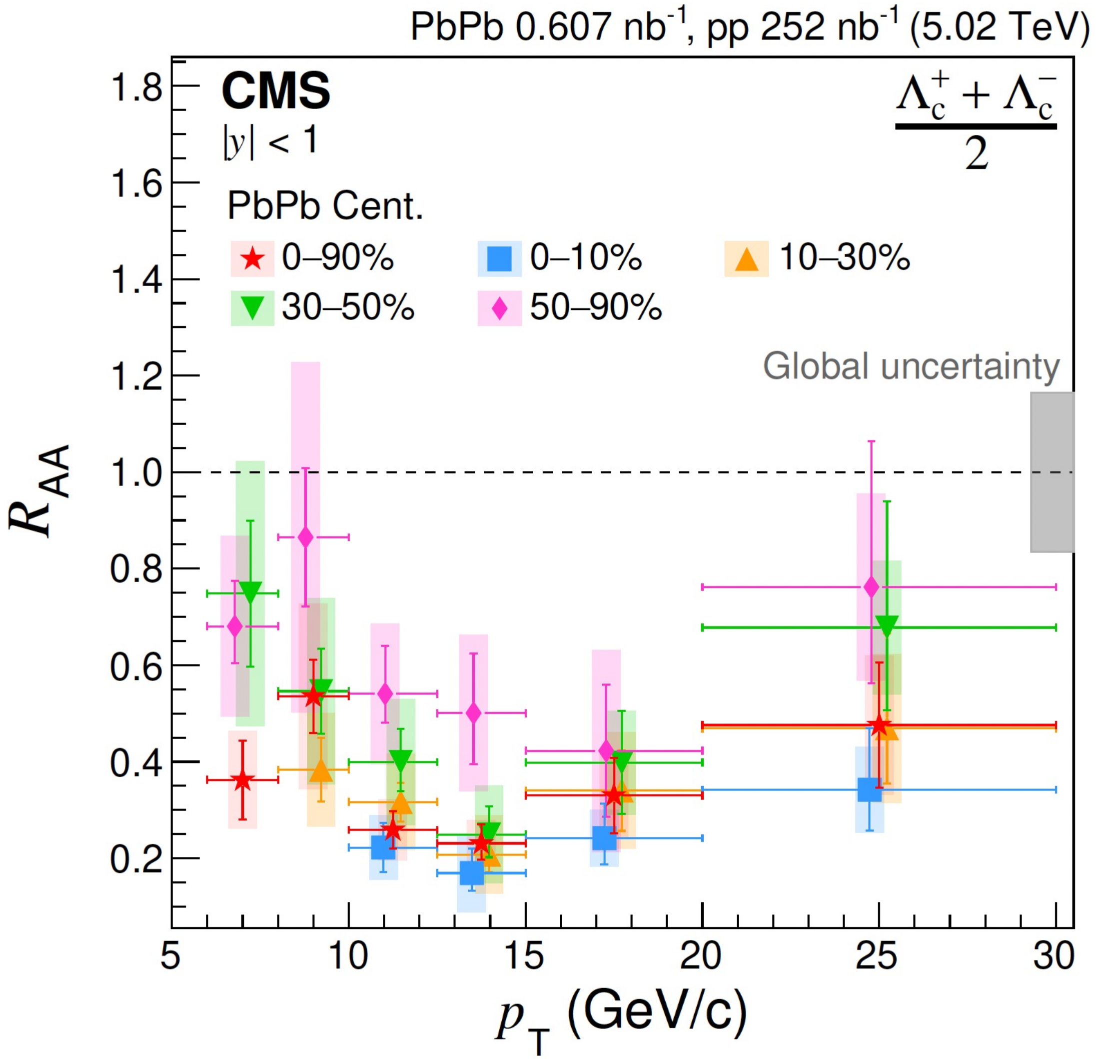




Λ_c^+ R_{AA}

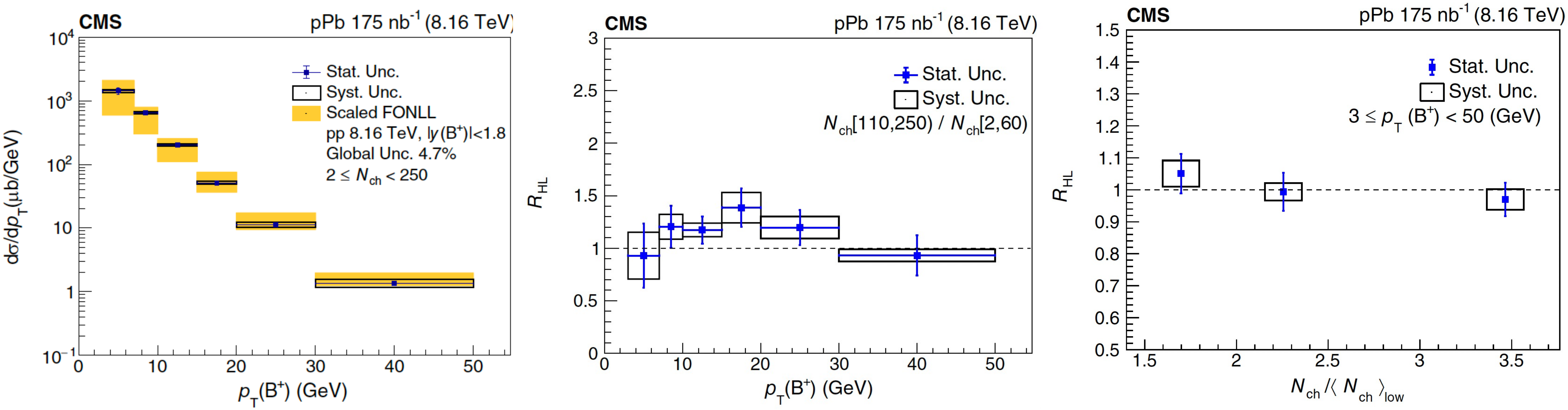
JHEP 01 (2024) 128

Good evidence of increasing suppression with more central events



b-hadron modification in pPb

PRL 134 (2025) 111903



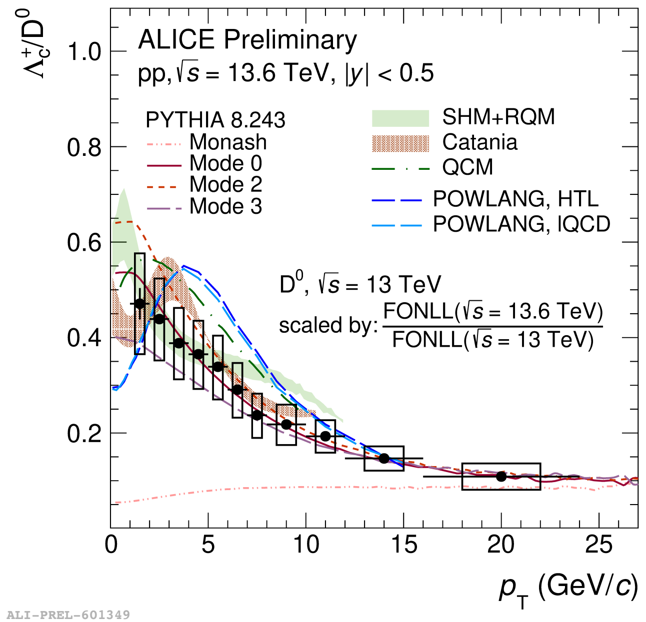
$$R_{HL} = \frac{(d\sigma_{B^+}/dp_T)_{high}}{(d\sigma_{B^+}/dp_T)_{low}} \Bigg/ \frac{(d\sigma_Z/dp_T)_{high}}{(d\sigma_Z/dp_T)_{low}}$$

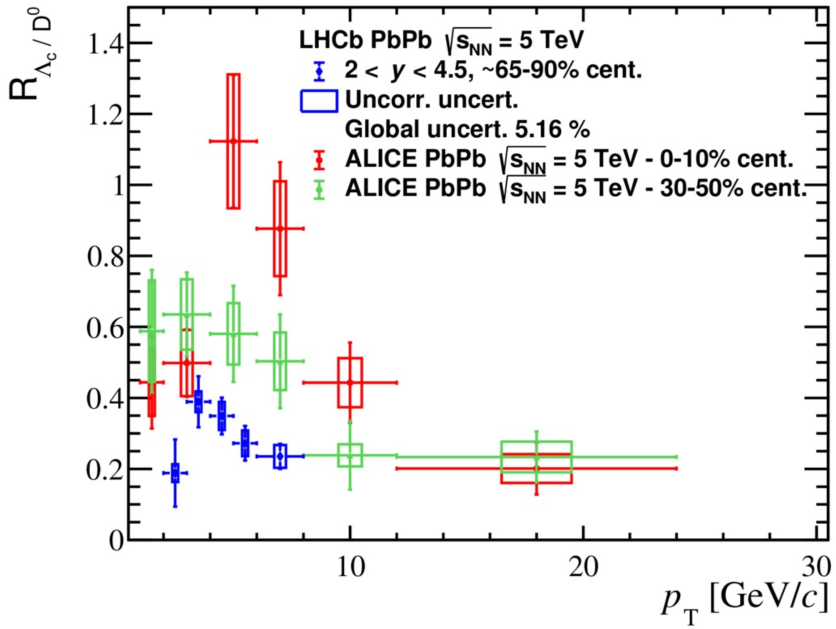
High & low refer to charged-particle multiplicities

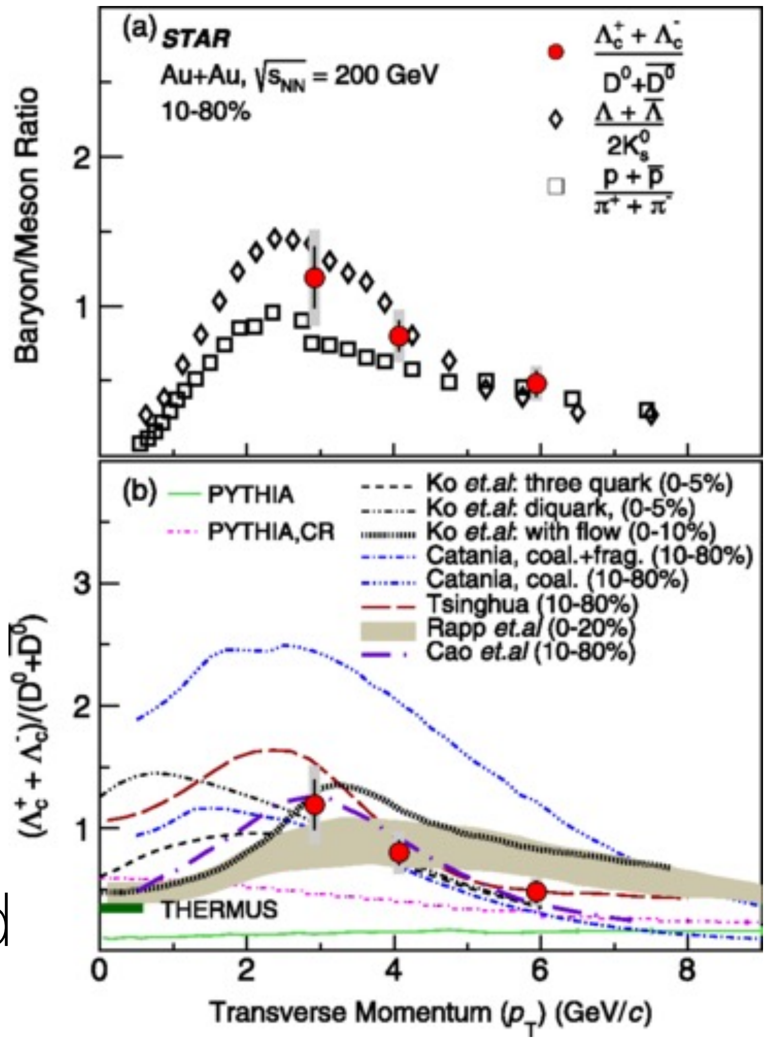
Z-boson production scales with N_{coll} and has no medium effect, clean probe

Λ_c^+/D^0 ratios

ALICE Figure
JHEP06 (2023) 132
PRL 124, 172301



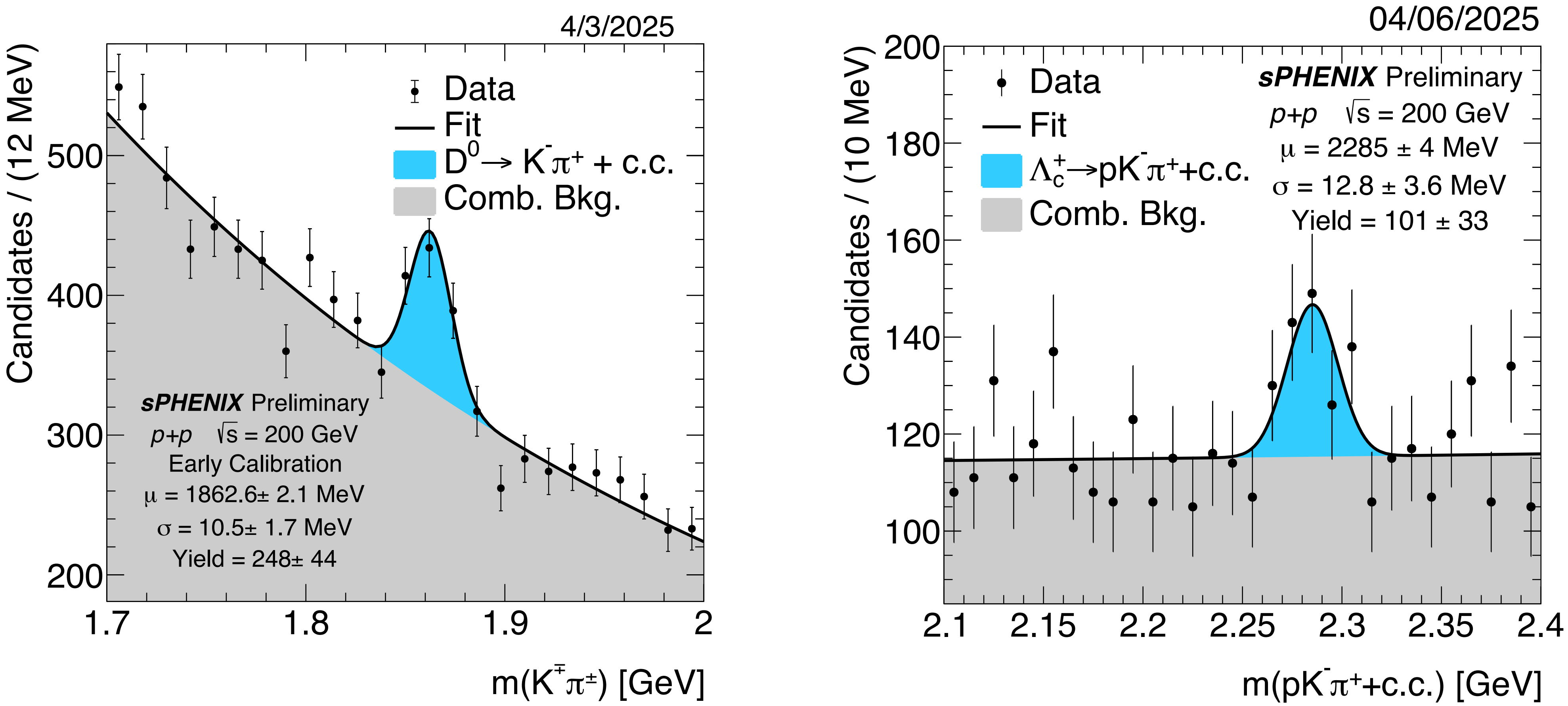




- Does baryon—to—meson ratio decrease with more peripheral events?
- Does *pp* data shed light on color-recombination?
- CMS results consistent with no coalescence but limited at low p_T

Λ_c^+/D^0 ratios

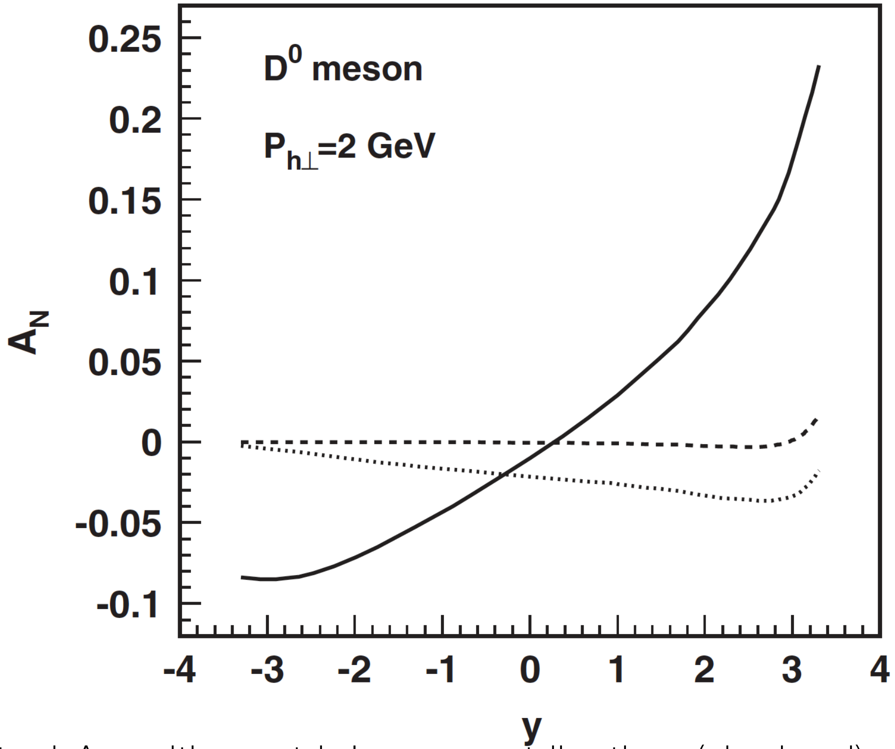
M. Peters, IS25



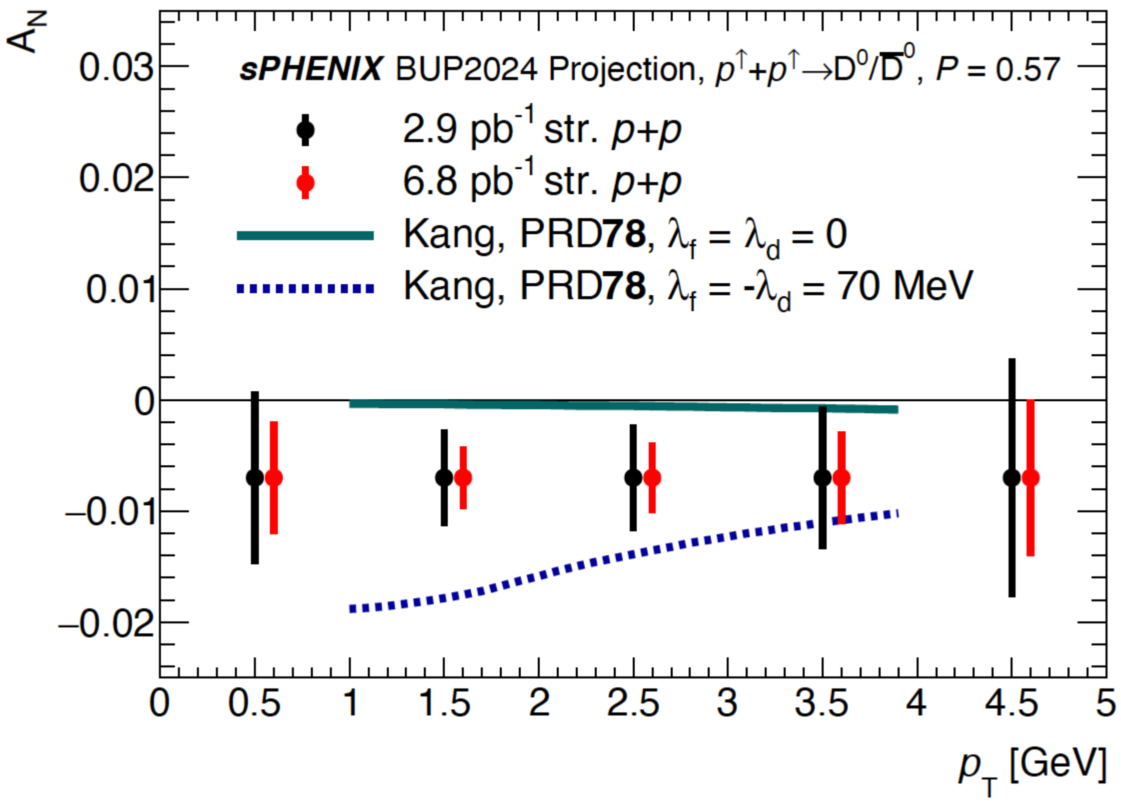
- sPHENIX has entered the heavy flavor game
- First Λ_c^+ in *pp* at RHIC

D^0 Transverse Single Spin Asymmetries

Phys. Rev. D78 (2008) 114013

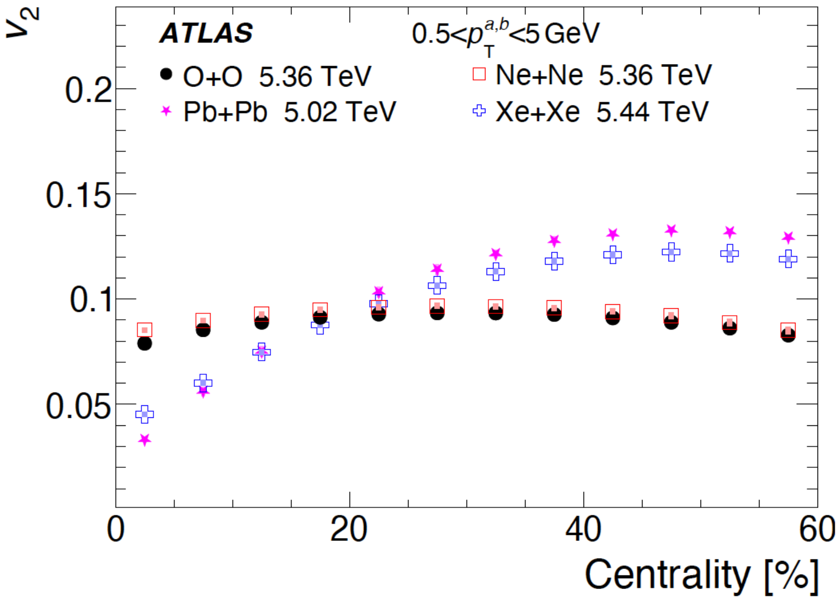


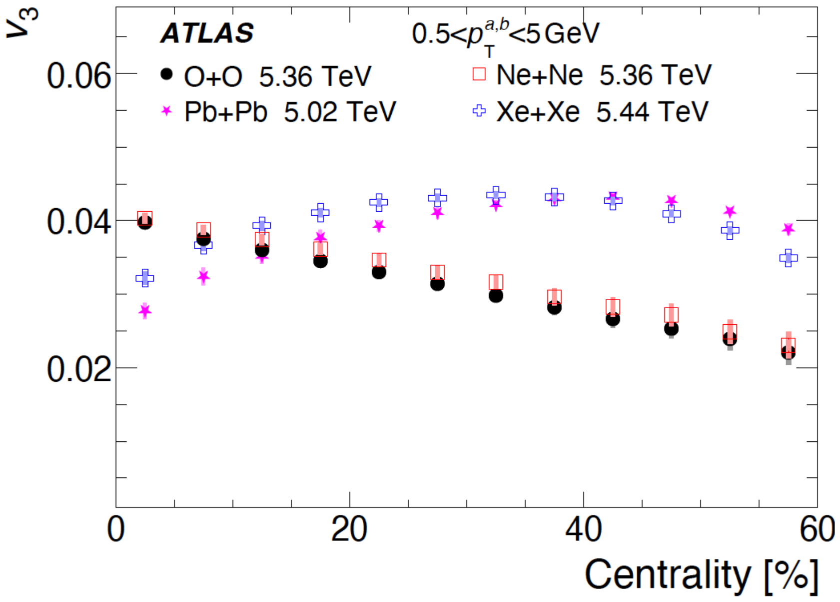
Predicted A_N with no trigluon contribution (dashed), trigluon contributions with positive (solid) and negative (dotted) correlations

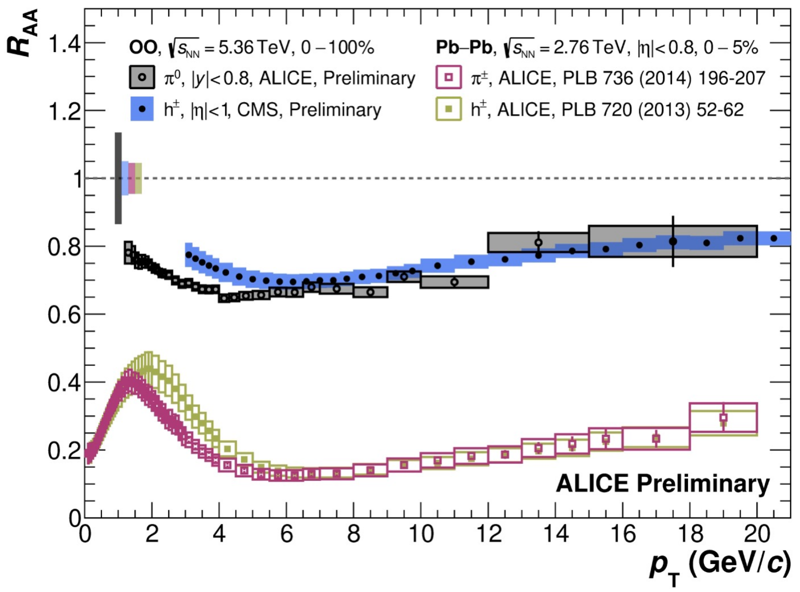


- Significant TSSAs (A_N) in D^0 would be a strong indication of trigluon correlations

Heavy flavor in oxygen systems







- Energy loss sensitivity at high p_T
- Momentum diffusion sensitivity at low p_T
- Predictions were
  - $v_2(OO) < v_2(PbPb)$
  - $v_3(OO) \sim v_3(PbPb)$

A. Mazeliauskas, IS25
N. Strangmann, IS25
A. Dimri, IS25
A. Baty, IS25
arXiv:2103.01939

$t\bar{t}$ as a new “heavy flavor”?

CMS-PAS-HIN-24-021
A. Ståhl, IS25

- Top quarks are not seen as heavy flavor due to lack of bound states
- However, can probe gluon PDF’s
- Cross-section is consistent with ATLAS measurements