Highlights from QM2022 from a hadron physics perspective

Zoltan Varga

NFO Seminar

2022.05.09.

Parallel sessions in 15 different categories

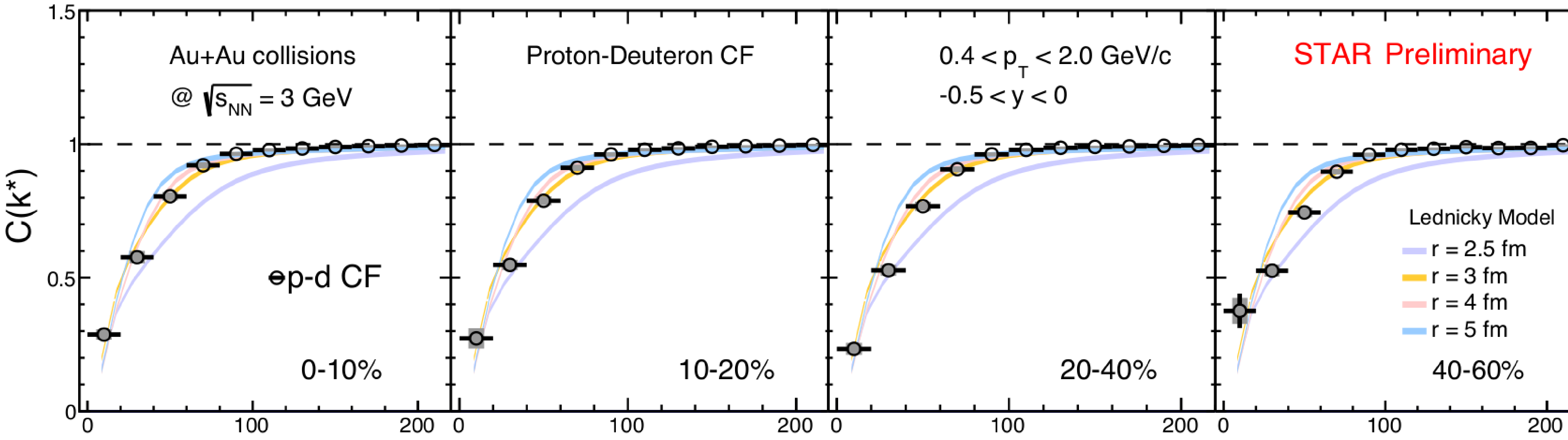
- T01: Initial state physics and approach to thermal equilibrium
- T02: Chirality, vorticity and spin polarization
- T03: QCD matter at finite temperature and density
- T04: Jets, high-pT hadrons, and medium response
- T05: QGP in small and medium systems
- T06: Lattice QCD and heavy-ion
- T07: Correlations and fluctuations
- T08: Strongly coupled systems
- T09: Ultra-peripheral collisions
- T10: Baryon rich matter, neutron stars, and gravitational waves
- T11: Heavy flavors, quarkonia, and strangeness production
- T12: New theoretical developments
- T13: Electroweak probes
- T14: Hadron production and collective dynamics
- T15: Future facilities and new instrumentation

Parallel sessions in 15 different categories

- T01: Initial state physics and approach to thermal equilibrium
- T02: Chirality, vorticity and spin polarization
- T03: QCD matter at finite temperature and density
- **T04: Jets, high-pT hadrons, and medium response**
- **T05: QGP in small and medium systems**
- T06: Lattice QCD and heavy-ion
- **T07: Correlations and fluctuations**
- T08: Strongly coupled systems
- T09: Ultra-peripheral collisions
- T10: Baryon rich matter, neutron stars, and gravitational waves
- **T11: Heavy flavors, quarkonia, and strangeness production**
- T12: New theoretical developments
- T13: Electroweak probes
- **T14: Hadron production and collective dynamics**
- T15: Future facilities and new instrumentation

Correlations and fluctuations

Proton-Deuteron Femtoscopy in Au+Au Collisions at 3 GeV



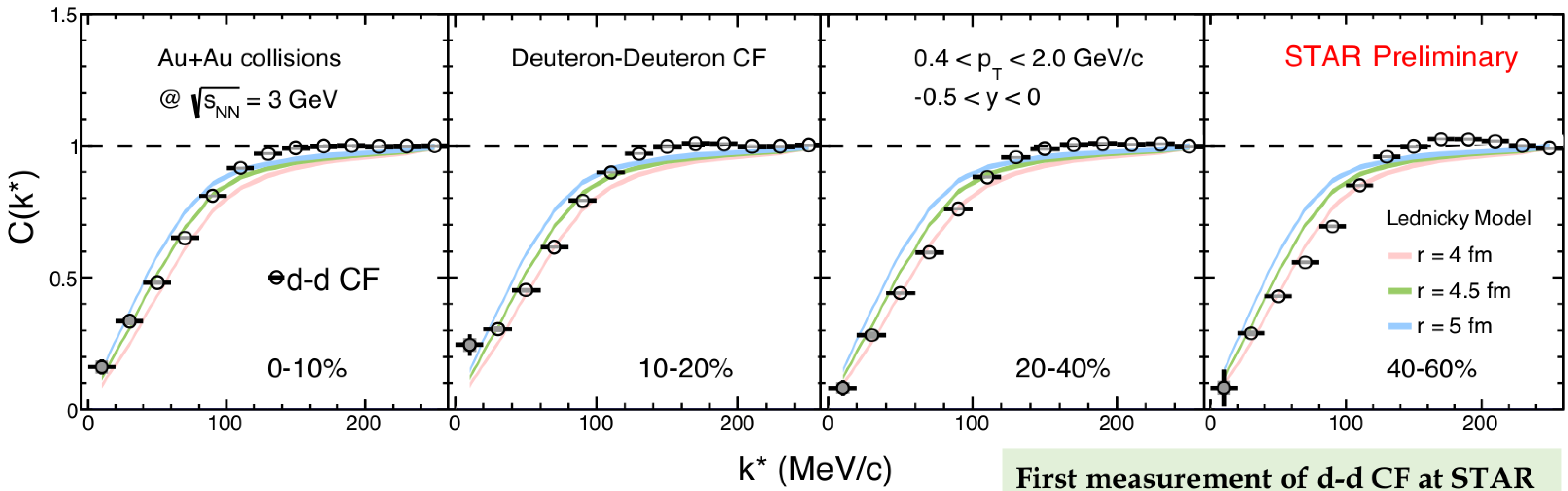
$$C(k^*) = \frac{\mathcal{P}(\vec{p}_a, \vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)}$$

First measurement of p-d CF at STAR

- Depletion for small k* range is observable
- Data can be described by Lednicky & Lyuboshitz model[1,2], assuming a spherical source size of r=3-4 fm.

1. Lednický R, Lyuboshitz V. Sov. J. Nucl. Phys. 35:770 (1982)
2. J. Arvieux, Nucl. Phys. A 221 (1974) 253–268

Deuteron-Deuteron Femtoscopy in Au+Au Collisions at 3 GeV



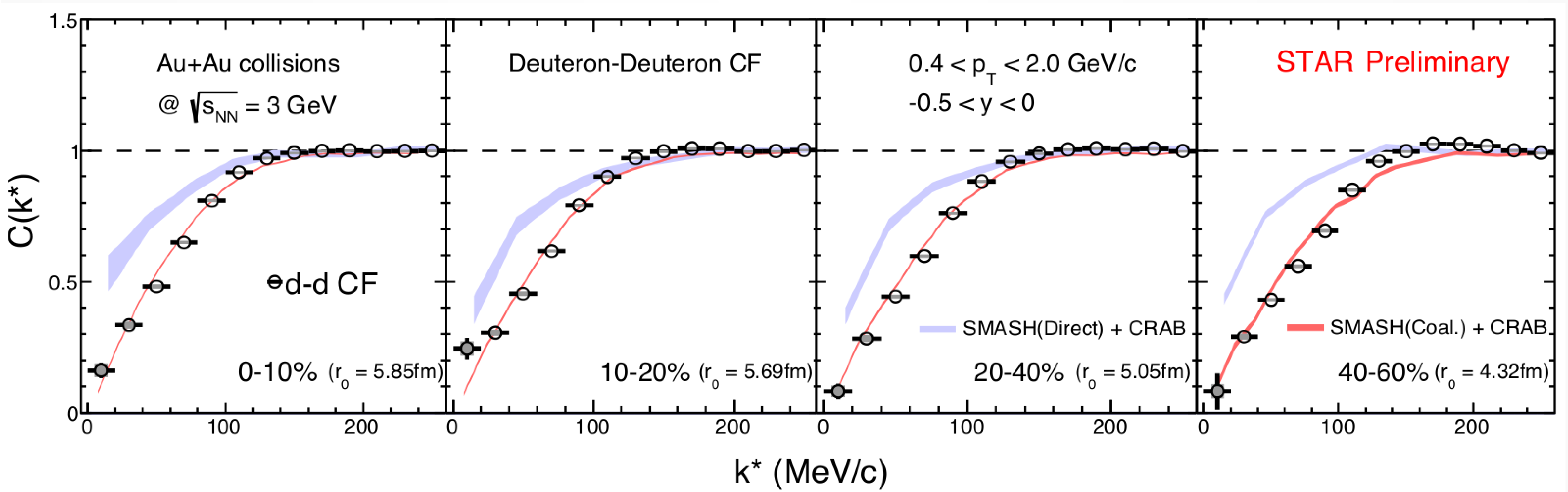
First measurement of d-d CF at STAR

- Depletion for small k* range is observable
- Data can be described by Lednicky & Lyuboshitz model[1,2], assuming a spherical source size of r=4-5 fm → larger compared to p-d!

1,I.N. Filikhin and S.L. Yakovlev, *Phys. Atom. Nucl.* 63, 55 (2000)
2,I.N. Filikhin and S.L. Yakovlev, *Phys. Atom. Nucl.* 63, 216 (2000)

Talk: Ke Mi (STAR)

Deuteron-Deuteron Femtoscopy in Au+Au Collisions at 3 GeV



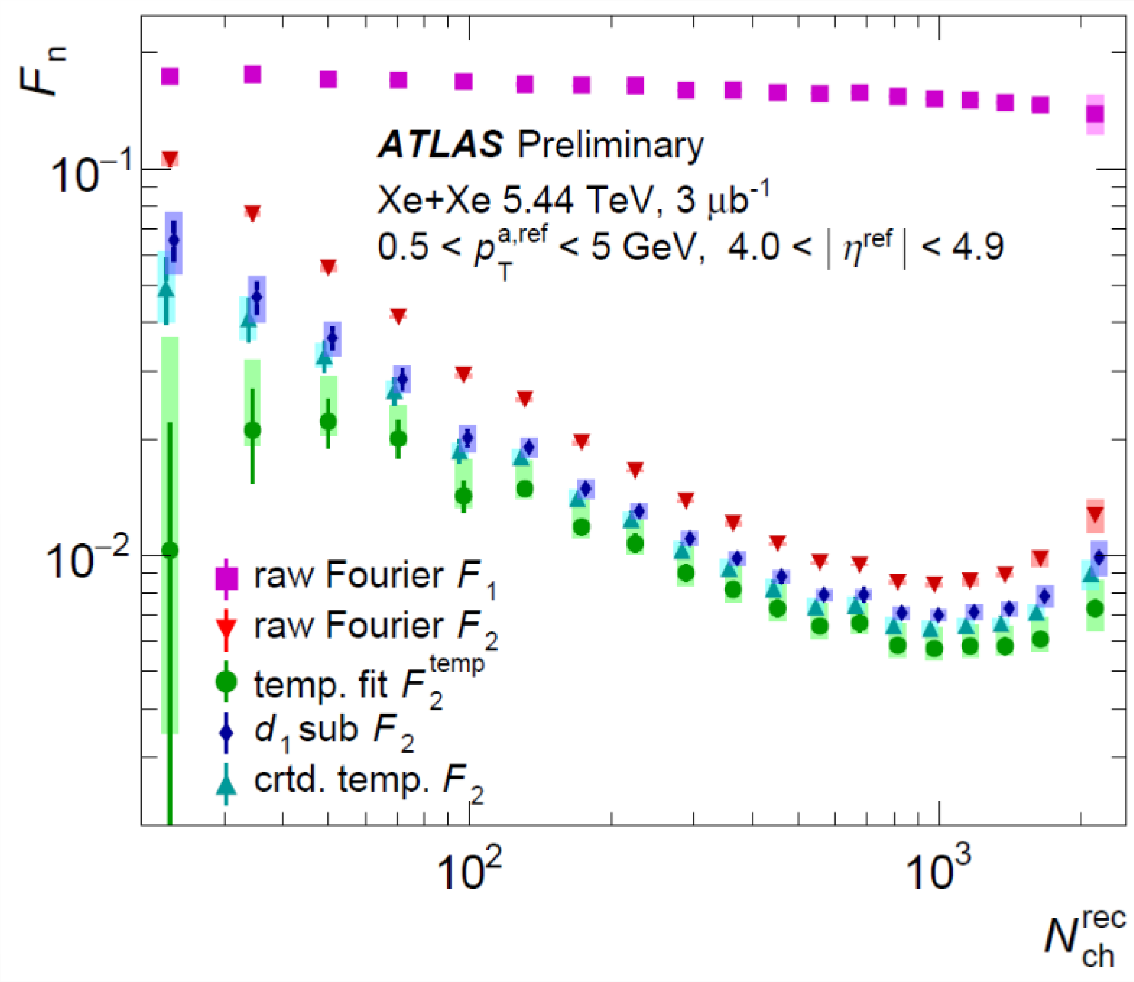
- Compare data with SMASH + CRAB (Correlation After Burner) model!
- Calculating CF with coalescence of deuterons gives better agreement with data → supports that deuteron formation at 3 GeV is dominated by coalescence
- SMASH source size: (4.3 – 5.9) fm from peripheral to central collisions
- **Light nuclei are likely to form via coalescence!**

Talk: Ke Mi (STAR)

SMASH: J. Weil et al. Phys.Rev.C 94 (2016) 5, 054905
Coalescence: W.Zhao et al. Phys. Rev. C.98 (2018) 5,054905

First measurement of longitudinal decorrelation in pp and peripheral Xe+Xe

- **Larger decorrelation** in **pp** compared to **Xe+Xe**
- Results sensitive to non-flow subtraction methodology
- **Disfavors** such **string models** of initial state, where nucleon-nucleon collision is simulated by a **low number of long strings**



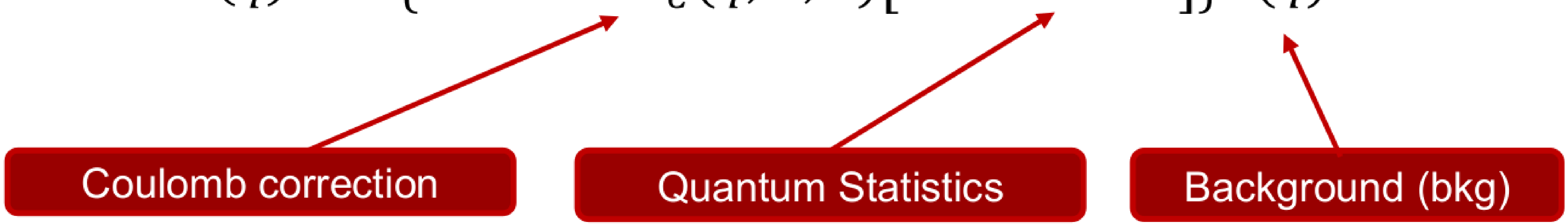
Talk: Blair D. Seidlitz (ATLAS)

Femtoscopic correlations at CMS

- **Femtoscopic correlation functions** are important tools to study the space-time structure of the hadron production from the sQGP
- Correlation functions are often assumed to be Gaussian/Exponential → correct description: **generalized Gaussian**
- α parameter of the correlation function might be **connected to** the **anomalous diffusion** in the final state.

One-dimensional fit to correlation function for charged hadrons (Lévy-type)

$$C(q) = N\{1 - \lambda + \lambda K_C(q; R, \alpha)\left[1 + \lambda e^{-|qR|^{\alpha}}\right]\}\Omega(q)$$

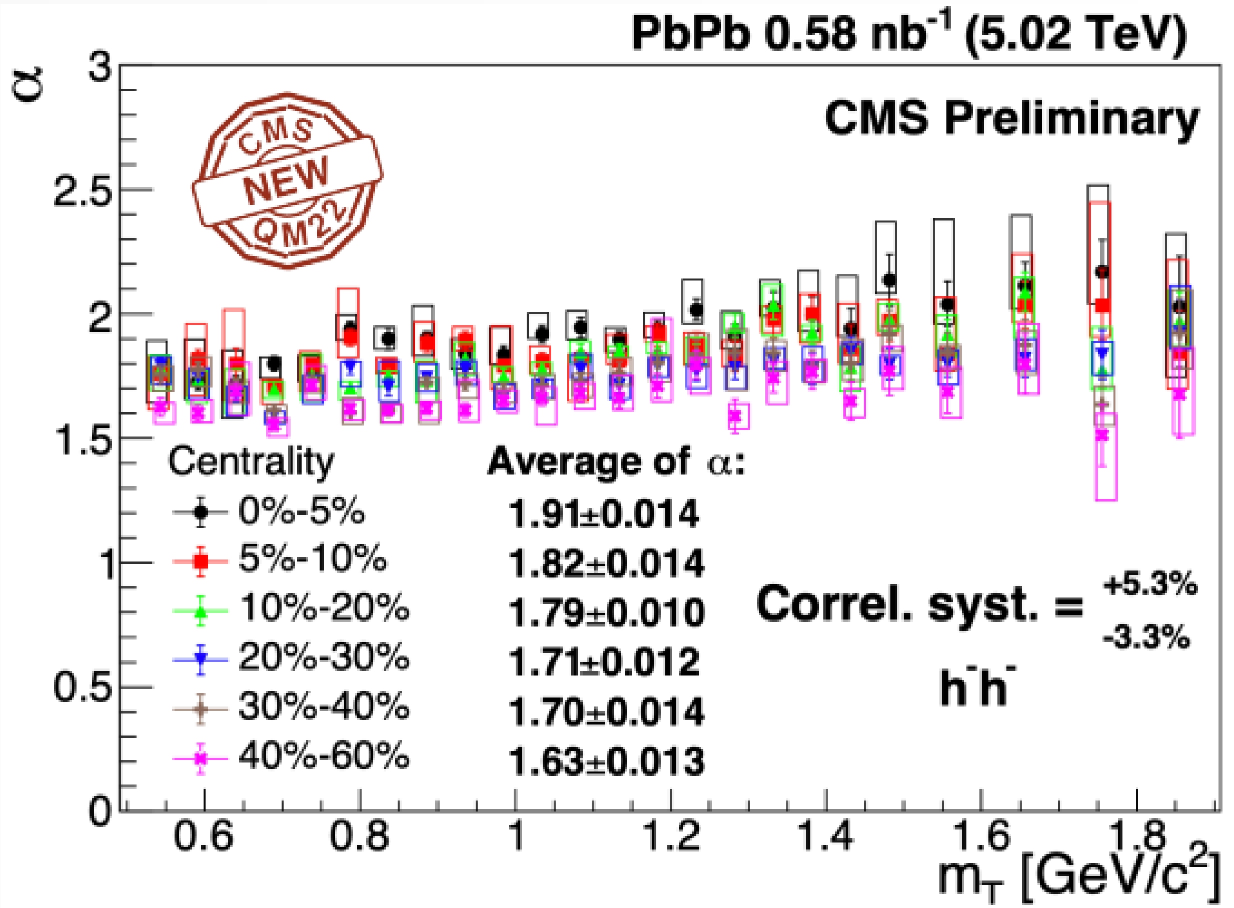


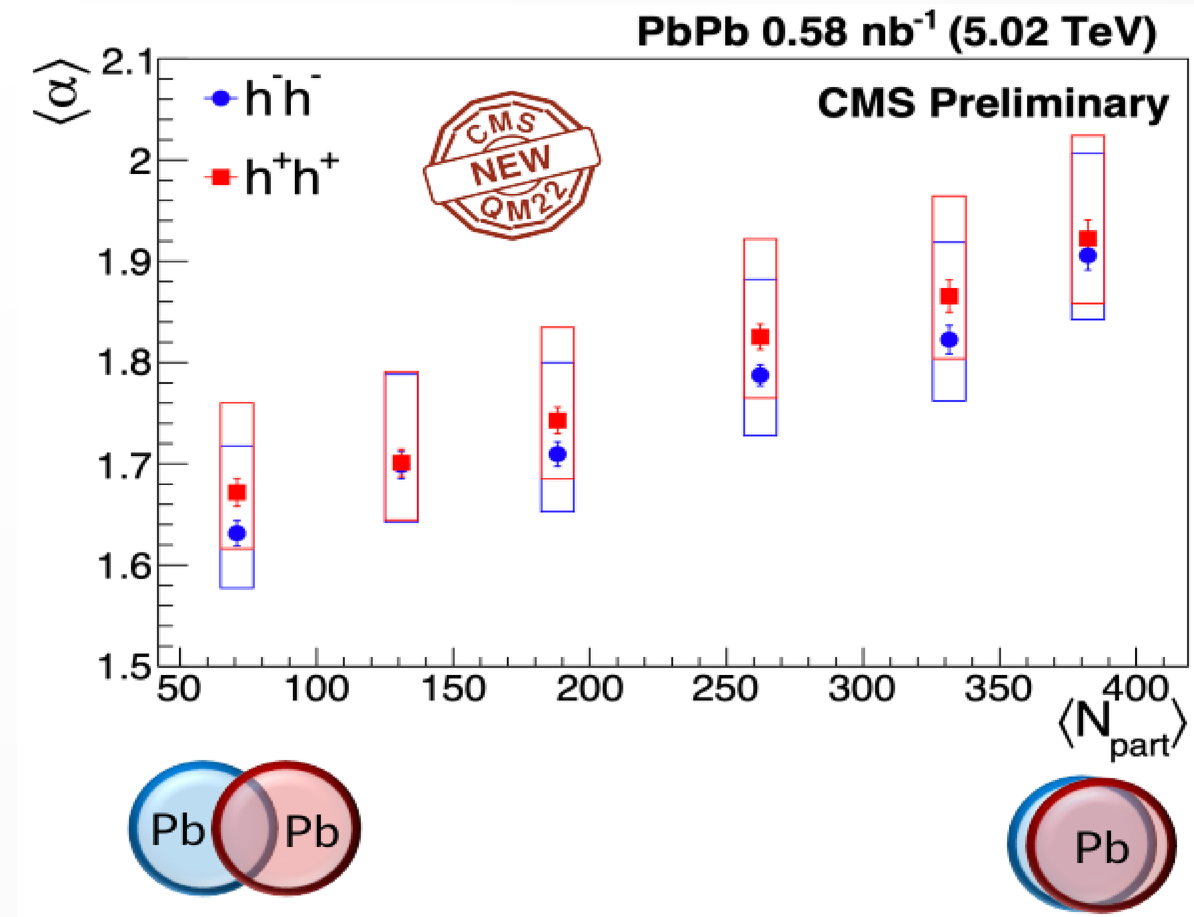
- Lévy stability parameter **α**: describing the shape of the source
- Lévy slace parameter **R**: spatial scale
- Correlation strength **λ**: core-halo ratio

Talk: Dener S. Lemos (CMS) Poster: Balázs Kórodi (CMS)

SMASH: J. Weil et al. Phys.Rev.C 94 (2016) 5, 054905
Coalescence: W.Zhao et al. Phys. Rev. C.98 (2018) 5,054905

Dependence of Lévy stability index α in function of m_T and multiplicity





- **The index α was first measured at LHC energies! → Non-Gaussian, centrality dependent behavior is observed.**
- α does not depend strongly on m_T .
- Challenge for phenomology: Centrality dependence is not modeled so far.

Heavy flavors, strangeness and quarkonia production

Charm production studies in ALICE

Open heavy-flavor production provides a unique opportunity for physics measurements:

- Production restricted to early stages of the collisions, and has a memory of its evolution through QGP
- Under good theoretical control:
  1) pQCD for production mechanism
  2) Diffusion treatment for the transport through the medium
- Heavy-flavor quarks retain their identity: flavor and mass → can be "tagged" by heavy-flavor measurements

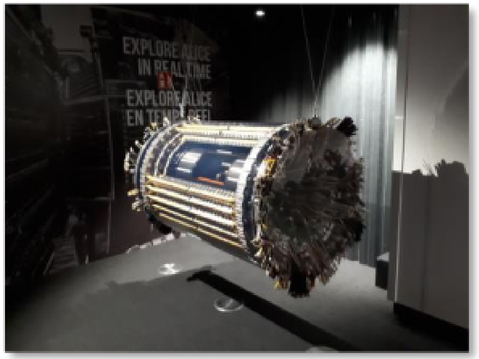
ALICE upgrade program for LHC Run 3&4 is crucial for HF measurements:

Run 3: ITS2 (installed in 2021)
Run 4: ITS3 (in prep.)

Promising future:

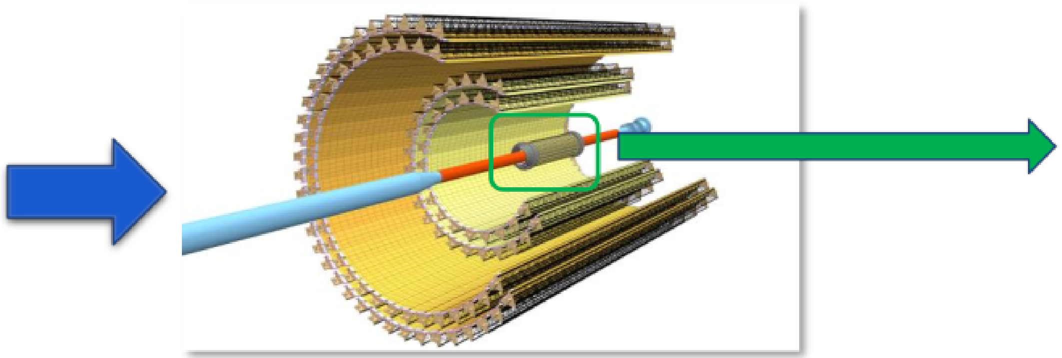
New precise HF measurements down to low p_T !

ITS 1 (ALICE exhibition)



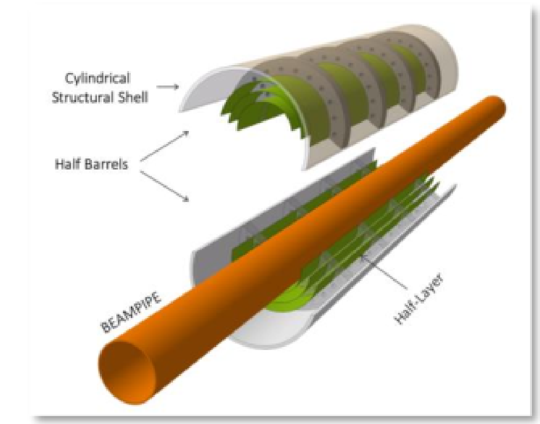
6 layers:
- 2 layers of Silicon Pixel Detector (SPD)
- 2 layers of Silicon Drift Detectors (SDD)
- 2 layers of Silicon Strip Detectors (SSD)

ITS 2



7 layers of ALPIDE Monolitic Active Pixel Sensors
→ 10 m^2 active silicon area
→ 12.6×10^9 pixels

ITS 3



3 truly cylindrical Si pixel layers
→ ultra-thin wafer-sized curved sensors
→ no external connections air-flow cooling

Charm production studies in ALICE

Different regions of interest:

See Luuk Vermunt's talk (ALICE)!

$D^0 \longrightarrow K^- \pi^+$ $\quad D^+ \longrightarrow K^- \pi^+ \pi^+$

$D_s^+ \longrightarrow \phi \, \pi^+ \longrightarrow K^+ K^- \pi^+$

$D^{*+} \longrightarrow D^0 \pi^+ \longrightarrow K^- \pi^+ \pi^+$

$\Lambda_c^+ \longrightarrow K_S^0 \, p \longrightarrow \pi^+ \pi^- p$

$c \longrightarrow \mu^{\pm} X$

Low momenta

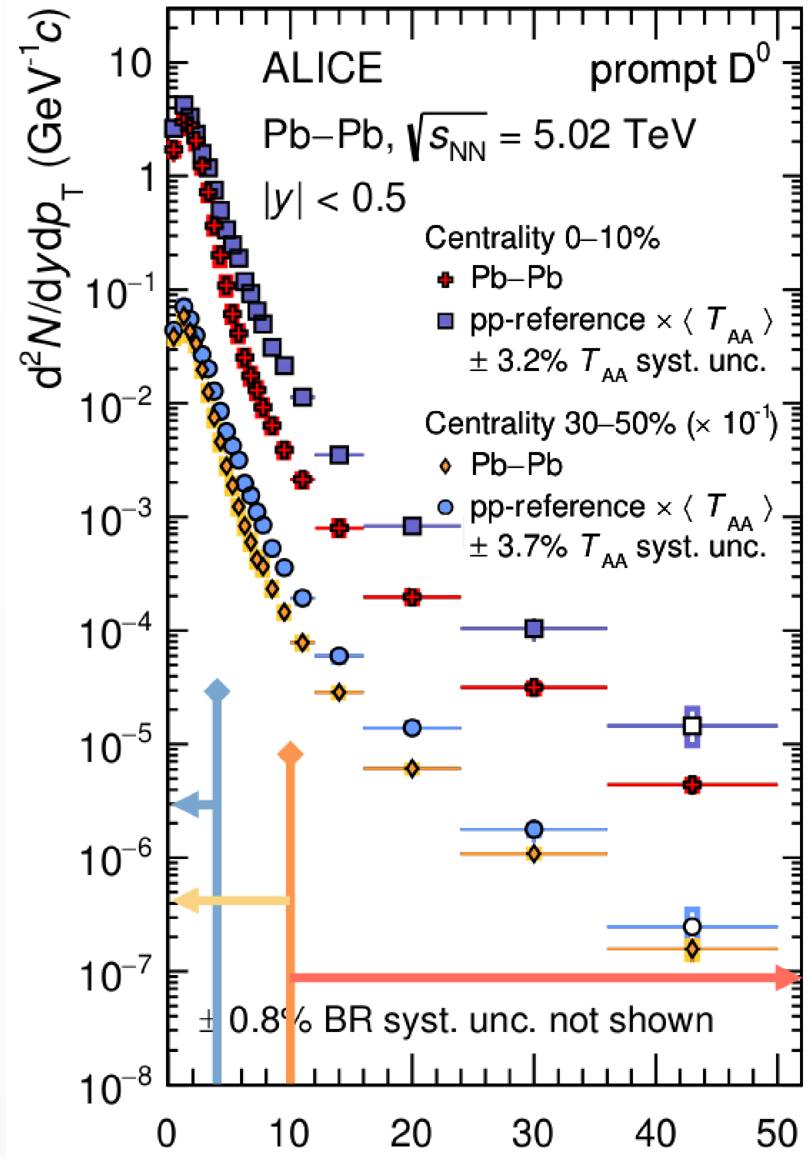
- Heavy quarks interact via elastic rescatterings
- Diffusion approach via Langevin dynamics
- Approach thermalisation
- nPDF and shadowing

Intermediate momenta

- Probes the heavy quark hadronisation mechanisms
- Via fragmentation and/or recombination?

High momenta

- Heavy quarks interact via gluon radiation
- Quark mass and path-length dependence?



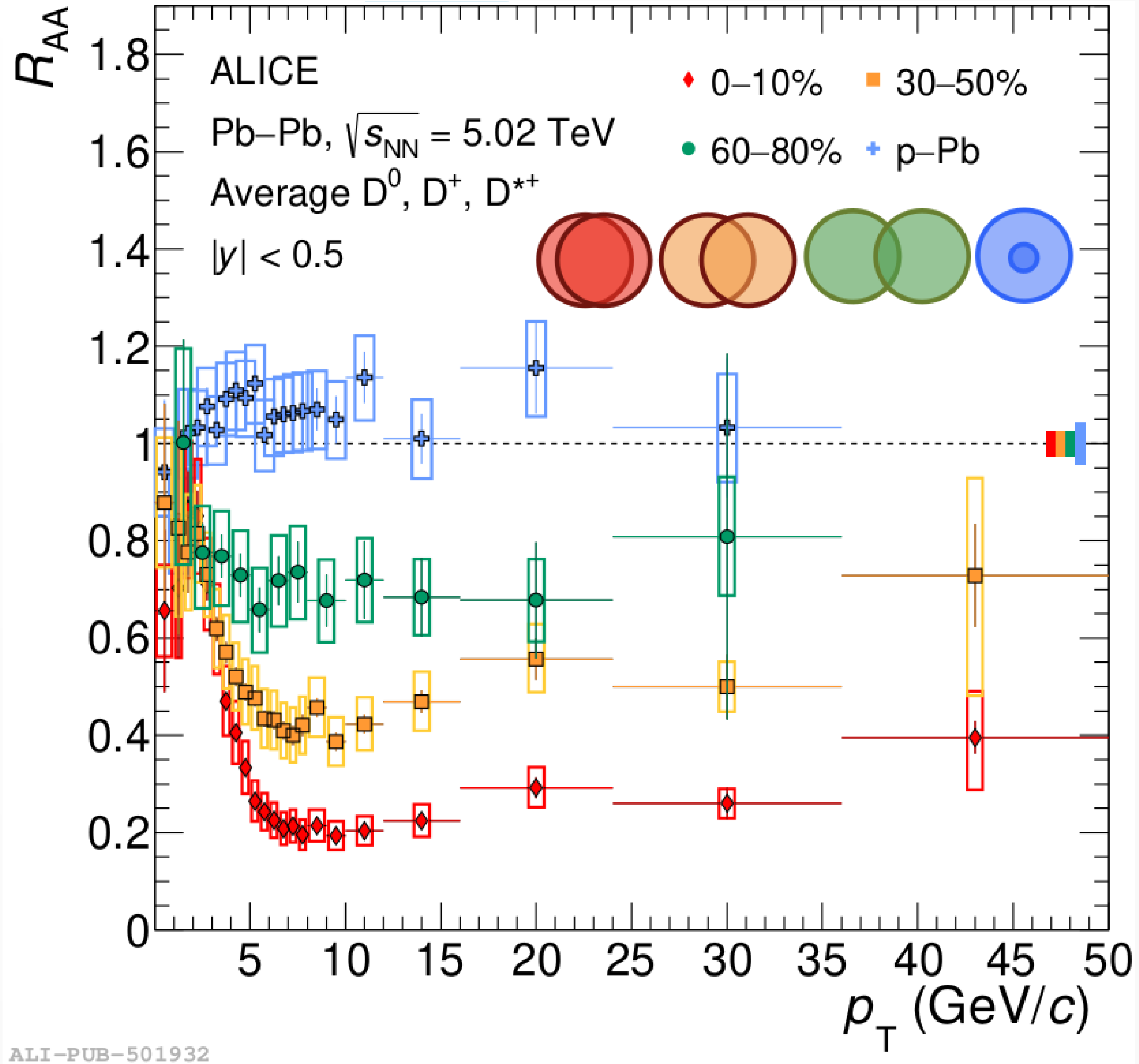
JHEP 01 (2022) 174 NEW!

Nuclear modification factor: non-strange D

<u>Lessons:</u>

There is an increasing suppression (p_T > 3 GeV/c) for more central collisions, due to increasing **density**, **size** and **lifetime** of the medium

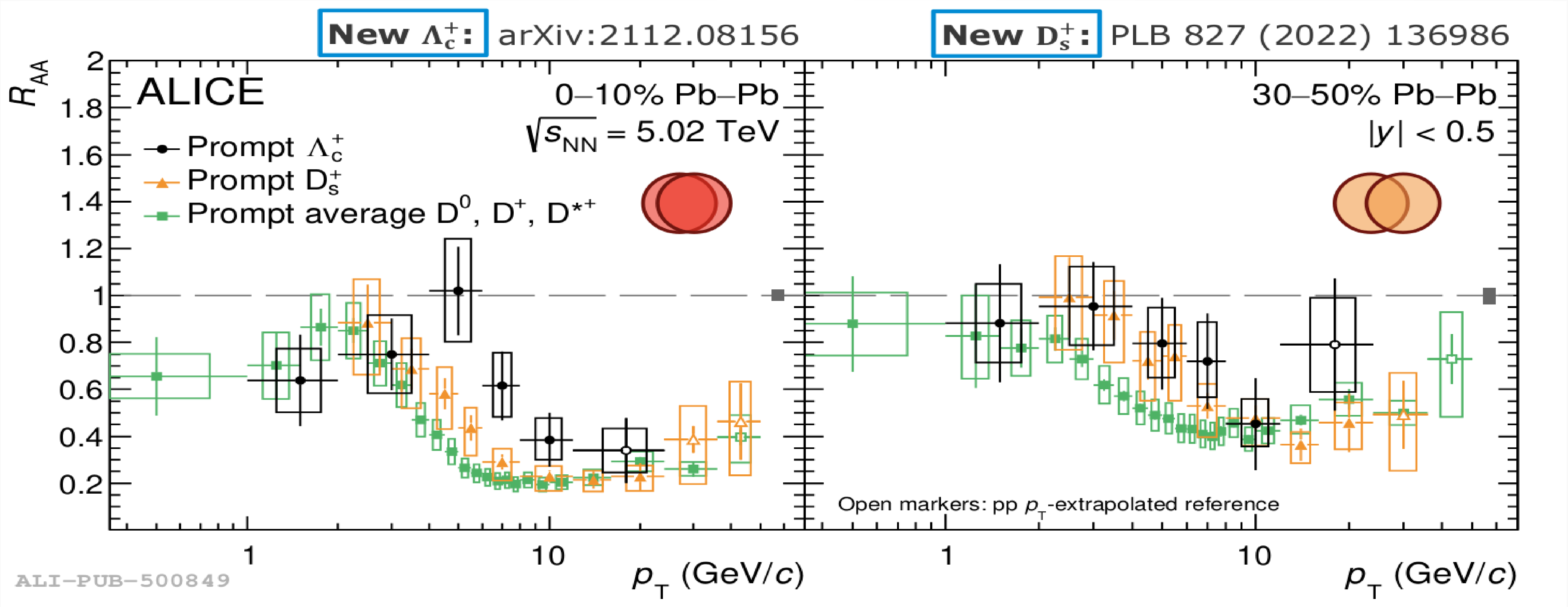
Due to the interplay of so many different effects → **model comparison required** to interpret even these single D-meson measurements



JHEP 01 (2022) 174 NEW!

Talk: Dener S. Lemos (CMS)

Nuclear modification factor: D_s^+ and Λ_c^+



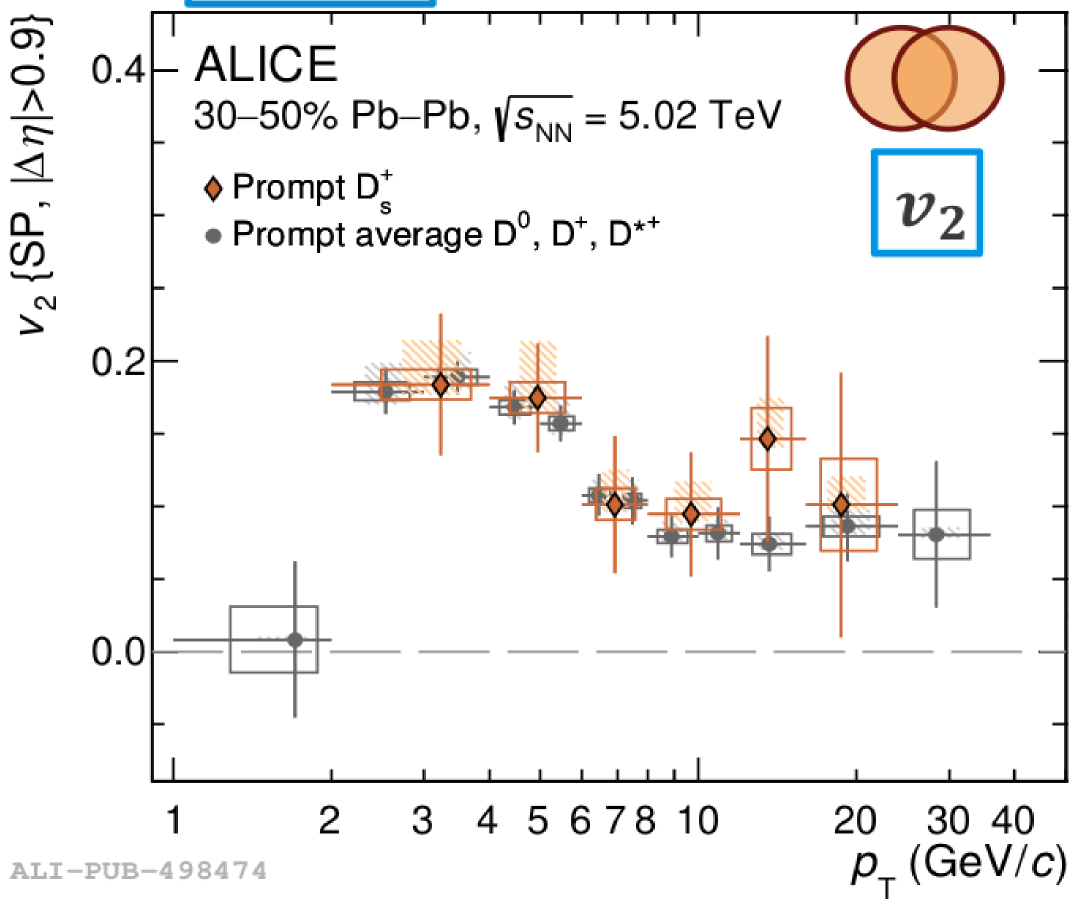
$R_{AA}(\Lambda_c^+)>R_{AA}(D_s^+)>R_{AA}(D)$ for p_T>4 GeV/c in the most central collisions

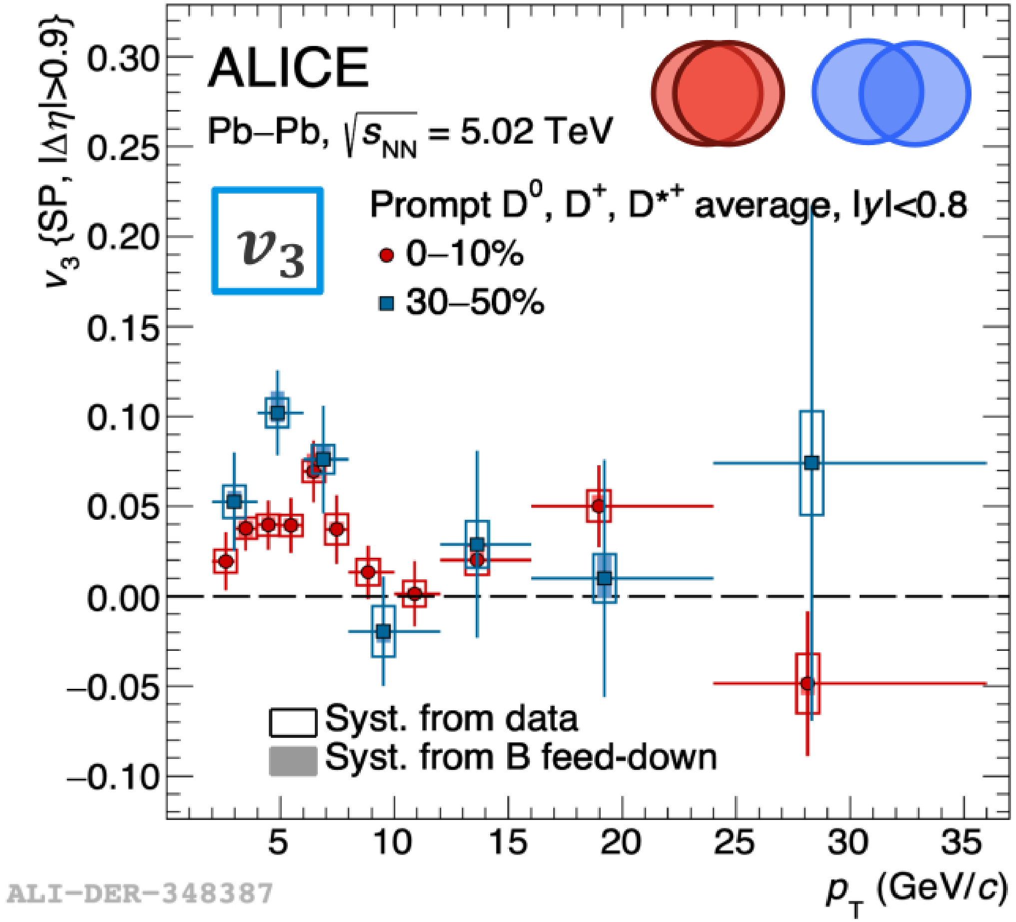
→ **Hint of hierarchy!** → Indication of modified hadronisation mechanism → Interplay with radial flow?

Non strange D: JHEP 01 (2022) 174

Azimuthal anisotrophies for D mesons

New D_s^+: PLB 827 (2022) 136986

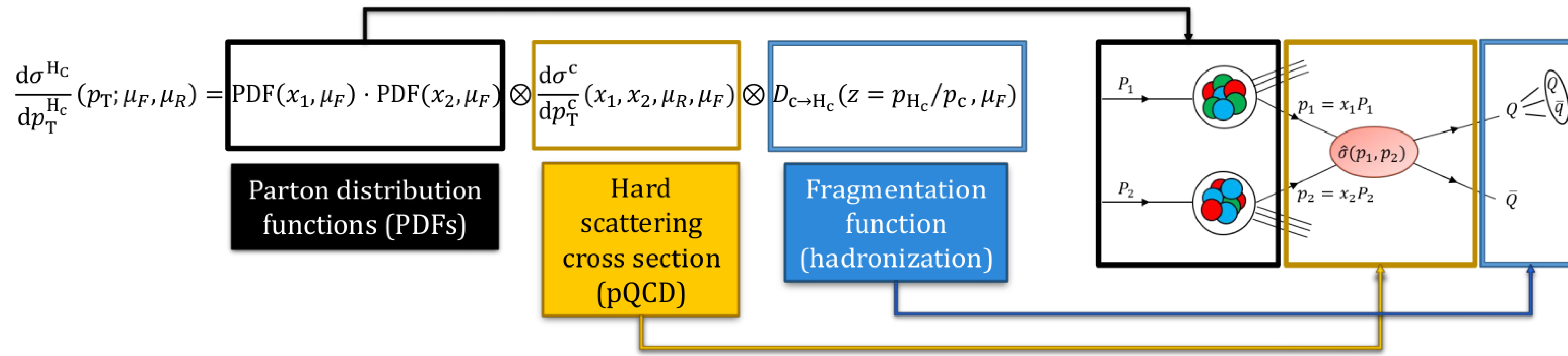




- **Positive D v_2 and v_3** in 0-10% and 30-50% → Charm participates in collective expansion!
- **Positive D_s^+ v_2** in $2<p_T<8$ GeV/c and 30-50% with significance of 6.4σ → Potential difference w.r.t. non-strange D? (Uncertainties too large atm…)

Non strange D: PLB 813 (2021) 136054

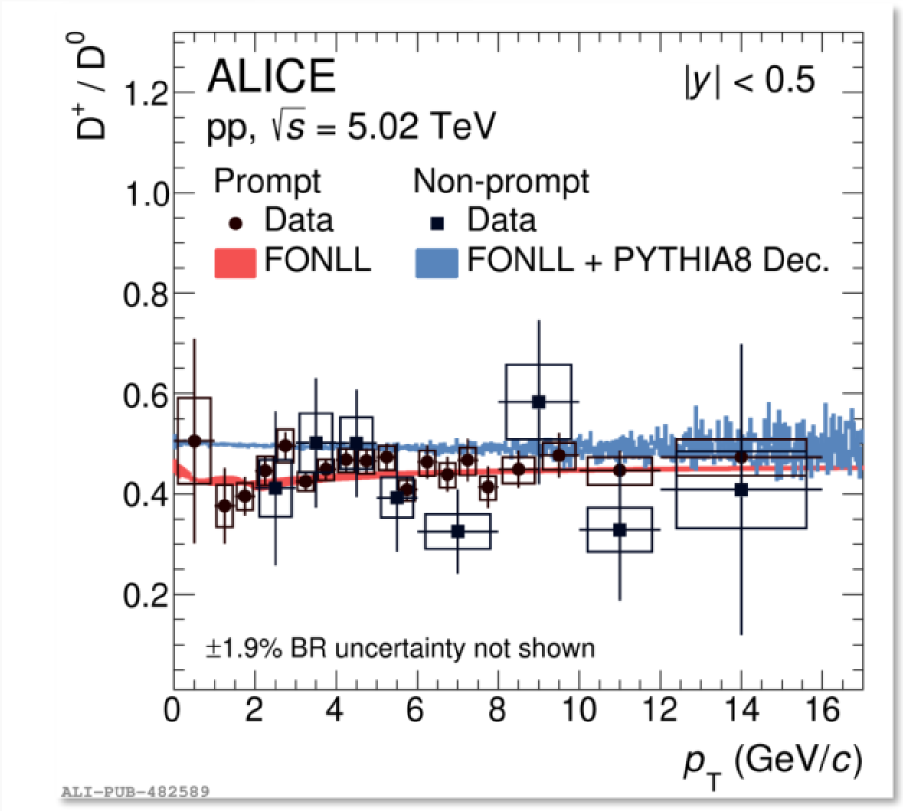
Heavy flavor production in pp collisions

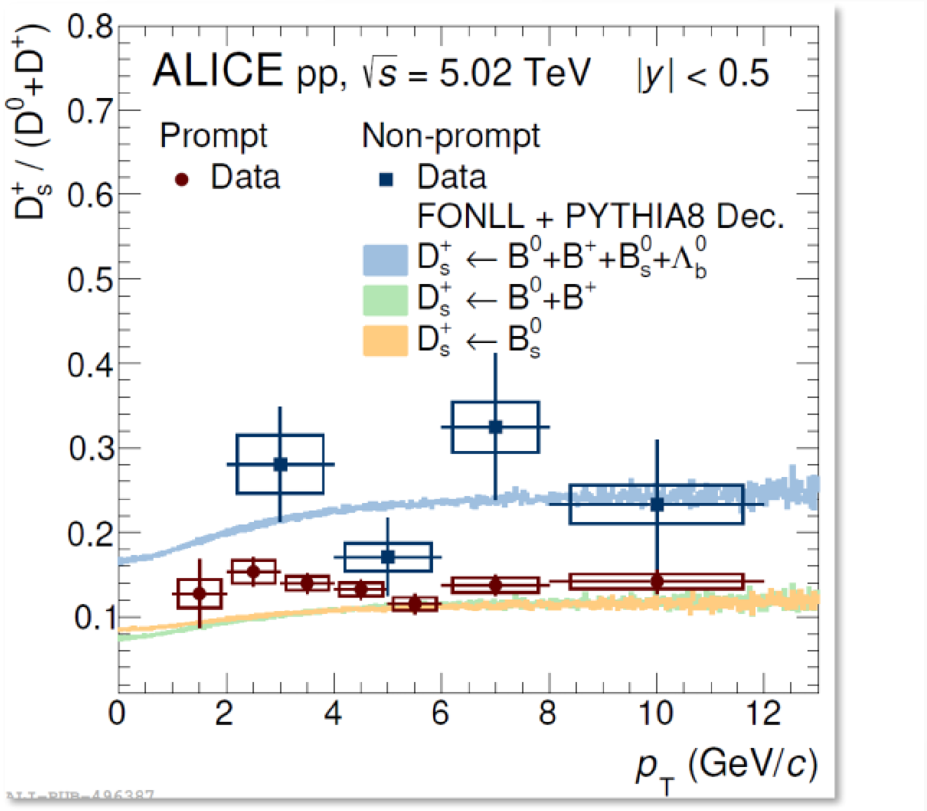


- Heavy flavor hadron production measurements are fundamental tests of pQCD
- Standard description of pp collisions: based on the factorization approach, i.e. fragmentation functions are assumed to be universal among collisions systems (can be constrained by e^+e^- and e^-p measurements)
- The ratios of particle species: ratios of fragmentation functions, they are sensitive to HF quark hadronization

TAMU: PRL 124, 042301 (2020)
Catania: PRC 96, 044905 (2017)
LGR: EPJC 80 (2020) 7, 671
PHSD: PRC 93, 034906 (2016)

Charm meson production in pp collisions

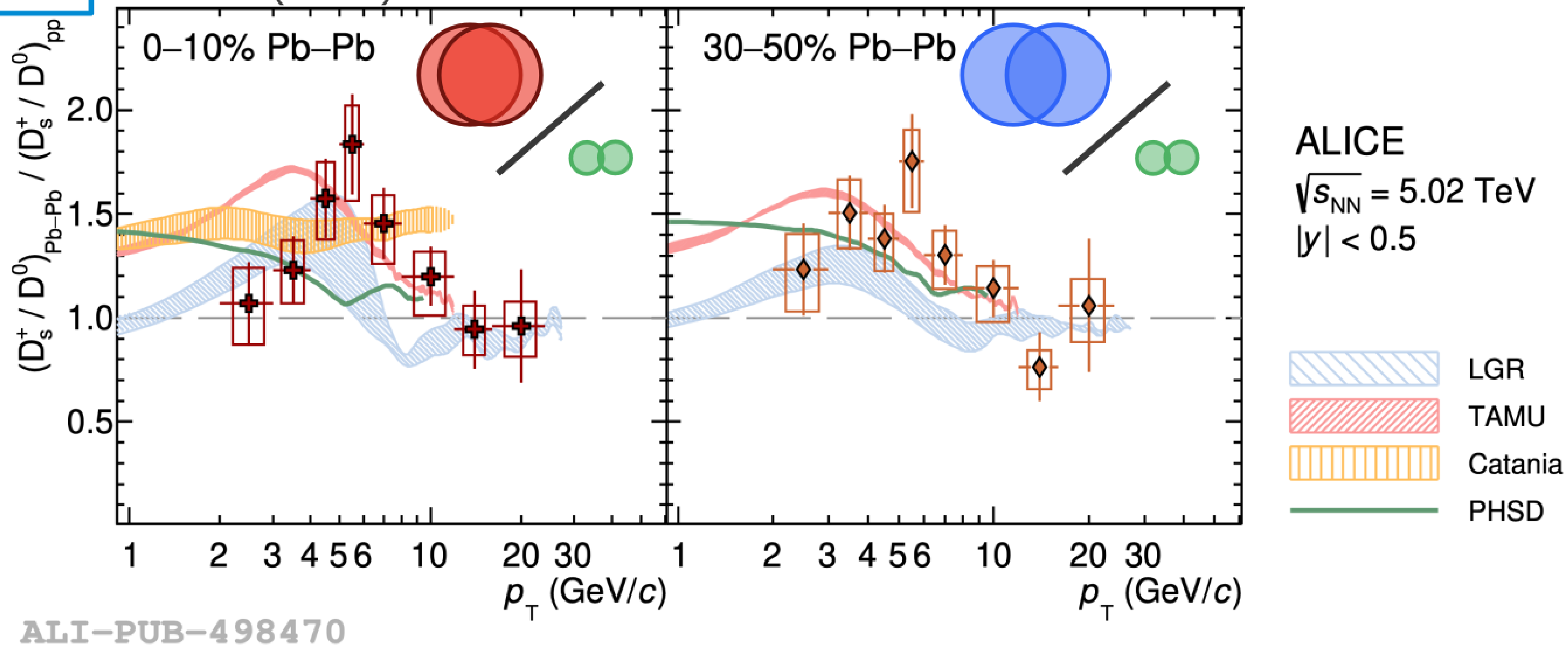




- Meson/meson ratios independent of meson p_T and collision system
- Agreement with model calculations (FONLL) based on the factorization approach and relying on universal fragmentation functions (e^+e^- and e^-p) and with e^+e^-, e^-p measurements
- $D_s^+/(D^0+D^+)$ is higher for non-prompt mesons → substantial B_s^0-decay contribution
- **Further hadronization mechanisms? Non-universal fragmentation functions?**

Probe hadronisation with charm-strange

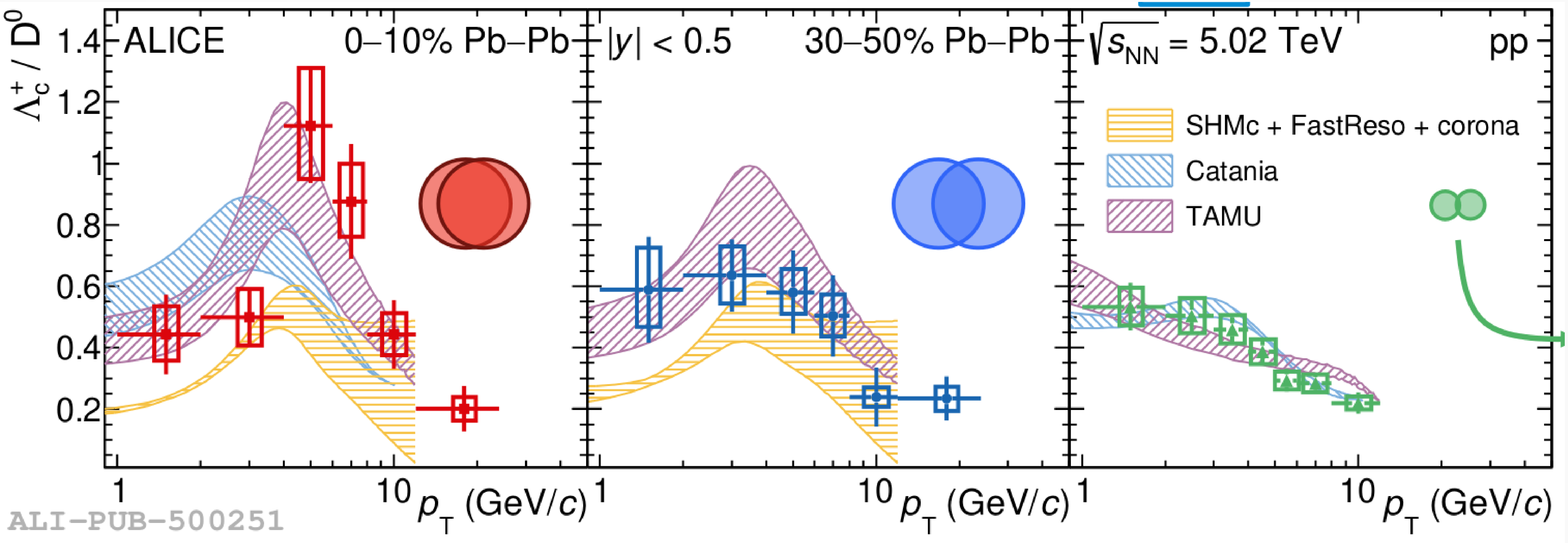
New: PLB 827 (2022) 136986



- The ratio is higher in the $2<p_T<8$ GeV/c region for 0-10% and 30-50% Pb-Pb.
- Described by models that include strangeness enhancement and fragmentation + recombination.

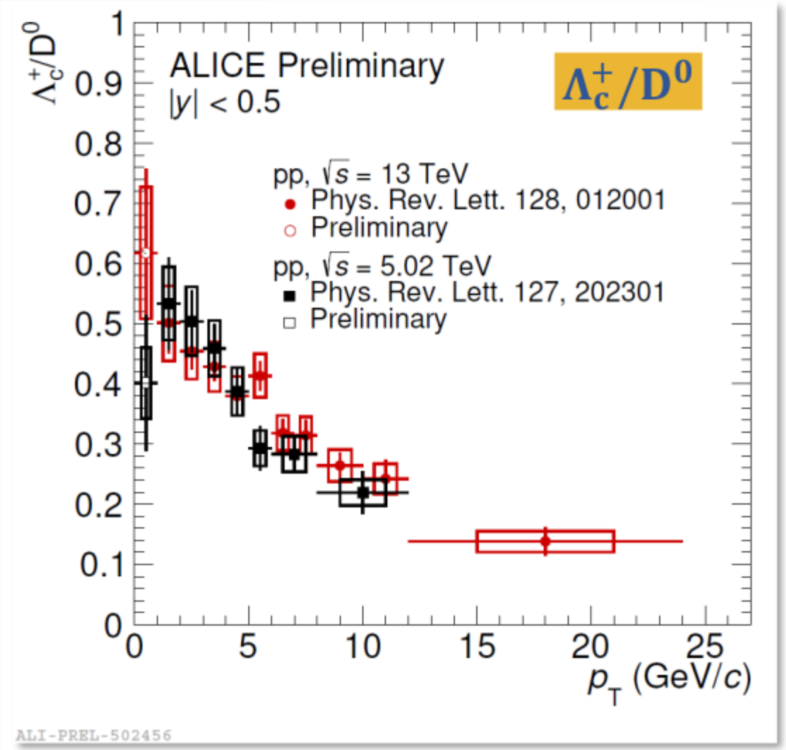
TAMU: PRL 124, 042301 (2020)
Catania: PRC 96, 044905 (2017)
LGR: EPJC 80 (2020) 7, 671
PHSD: PRC 93, 034906 (2016)

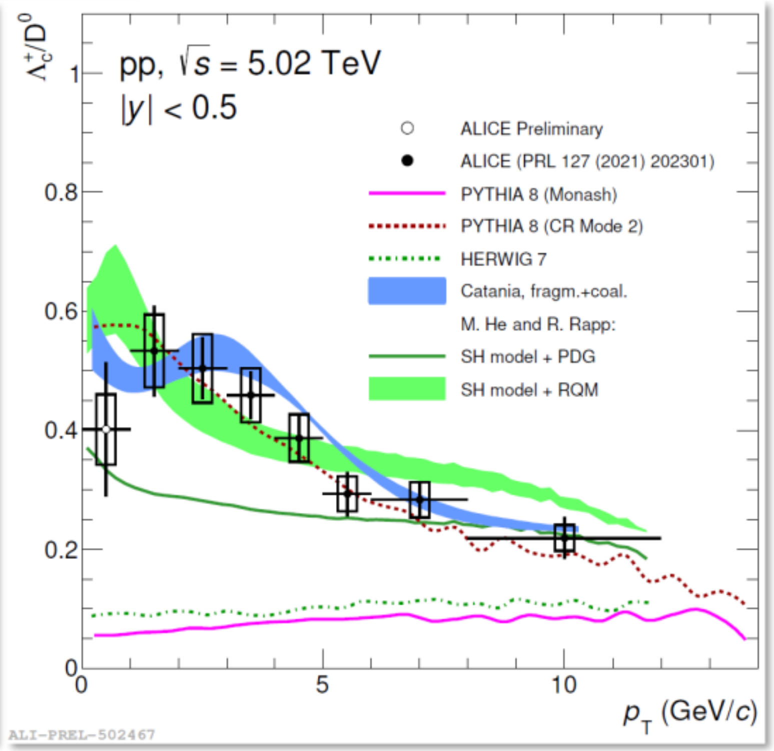
Probing hadronisation with charm baryons



- The ratio is enhanced in the 4<p_T<8 GeV/c region for 0-10% Pb-Pb w.r.t. pp collisions.
- Catania and SHMc only agree qualitatively. TAMU describes data quantitatively!
- We also studied the Λ_c^+/D^0 ratio enhancement with enhanced CR modes, and the role of the underlying event: arXiv:2111.00060 [hep-ph].

Λ_C^+/D^0 in pp collisions



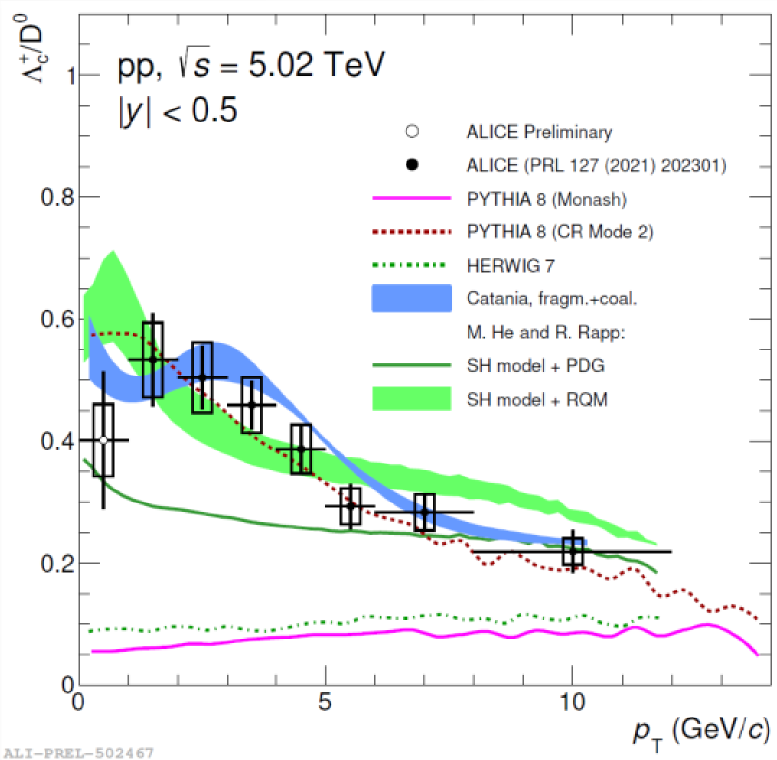


First Λ_c measurement at p_T=0!

Phys. Rev. Lett. 128, 012001
Phys. Rev. Lett. 127, 202301

- Strong p_T dependence observed for prompt Λ_C/D^0 → same as non-prompt Λ_C/D^0
- No energy dependence between √s=13 TeV and √s=5.02 TeV (within uncertainties)
- Ratio is significantly higher for pp than e^+e^- and e^-p collisions → x2-5 factor of enhancement!

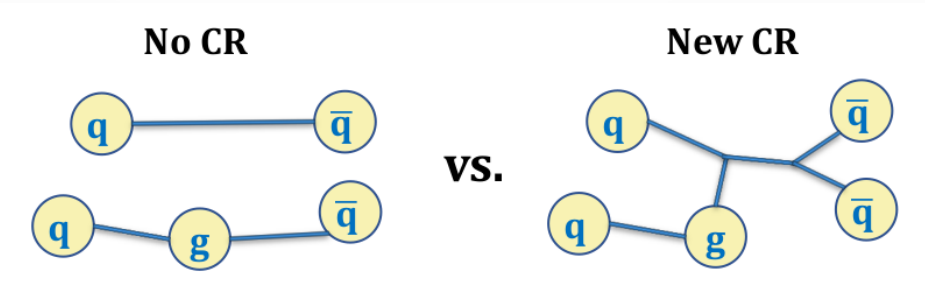
Λ_C^+/D^0 in pp collisions – what kind of models?



PYTHIA 8 with updated Colour Reconnection (CR) modeling

- CR with SU(3) weights and string length minimization
- **"junction"** topology **enhances charm baryon production**

J.P. Christiansen, P. Z. Skands: JHEP 1508 (2015) 003

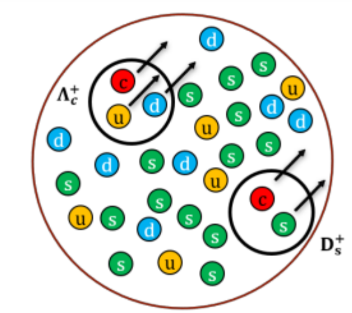


Our study with CR modes:

arXiv:2111.00060 [hep-ph]

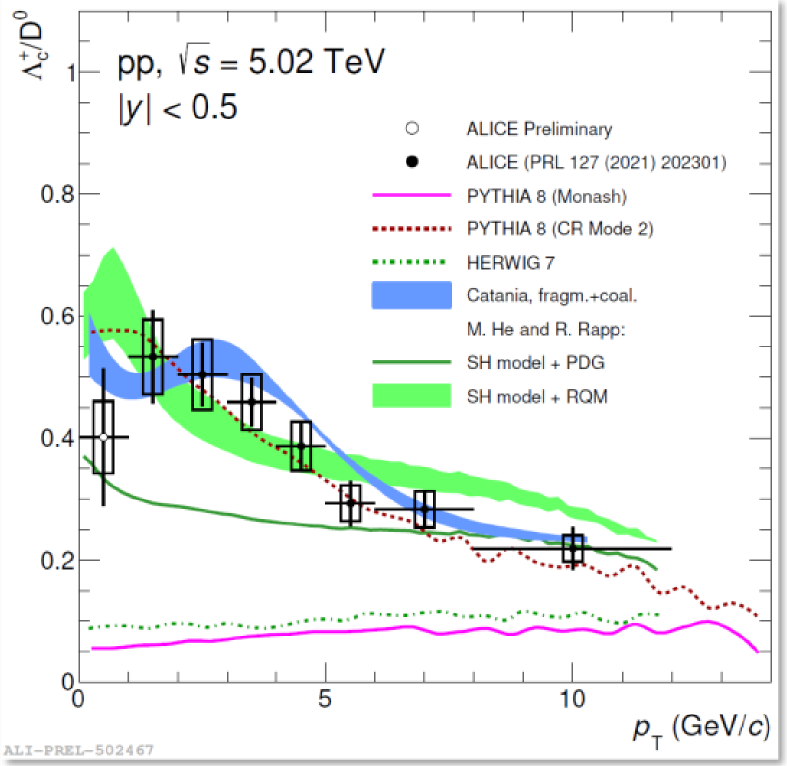
Catania model

- **Thermalised system** of u,d,s and gluons assumed
- Mixed hadron formation
  a. **Fragmentation**
  b. **Coalescence** → imposed to be the only mechanism for $p \to 0$



Coalescence

Λ_c^+/D^0 in pp collisions – what kind of models?

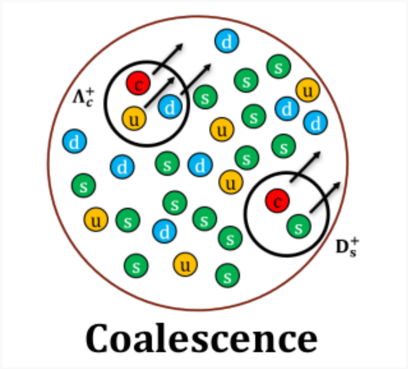


Statistical Hadronization Model and Relativistic Quark Model (SHM + RQM)

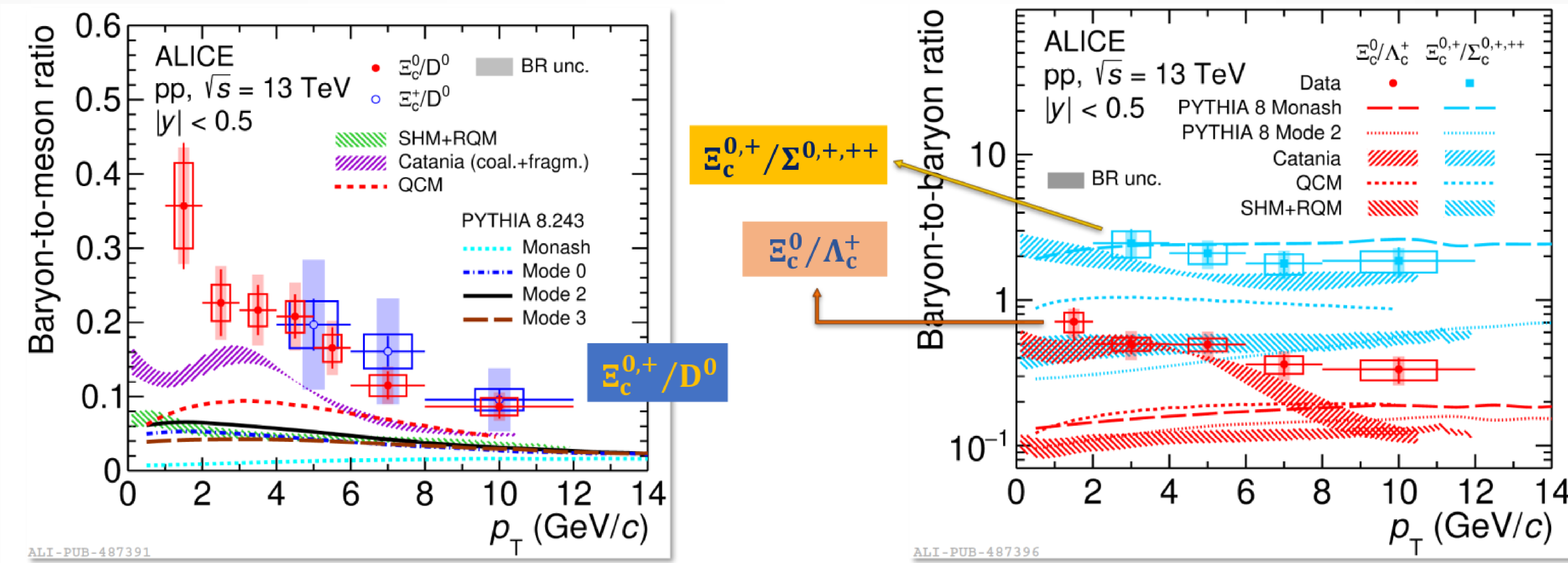
- **Hadronization** driven by statistical weights **governed by hadron masses** ($n_i \sim m_i^2 T_H K_2(m_i/T_H)$) at a hadronization temperature T_H
- Strong **feed-down** from an **augmented set of excited charm baryons**
  - → PDG: 5 Λ_c, 3 Σ_c, 8 Ξ_c, 2 Ω_c
  - → RQM: additional 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c (not yet measured)

Catania model

- **Thermalised system** of u,d,s and gluons assumed
- Mixed hadron formation
  - a. **Fragmentation**
  - b. **Coalescence** → imposed to be the only mechanism for $p \to 0$



We can look at heavier charmed baryons: $\Xi_C^{0,+}$



- Clear p_T dependence and larger than Monash
- Significantly underestimated by models
- Catania model is fairly close to the data

- $\Xi_C^{0,+}/\Sigma_C^{0,+,++}$ is in agreement with Monash

First D^0-tagged jet measurement at RHIC energies

Observation: **Jet energy is redistributed to large distances from the jet axis in the presence of QGP**

$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jet}}\frac{\sum_{\text{track}\in(r_a,r_b)} p_{\text{T,track}}}{p_{\text{T,jet}}}$$

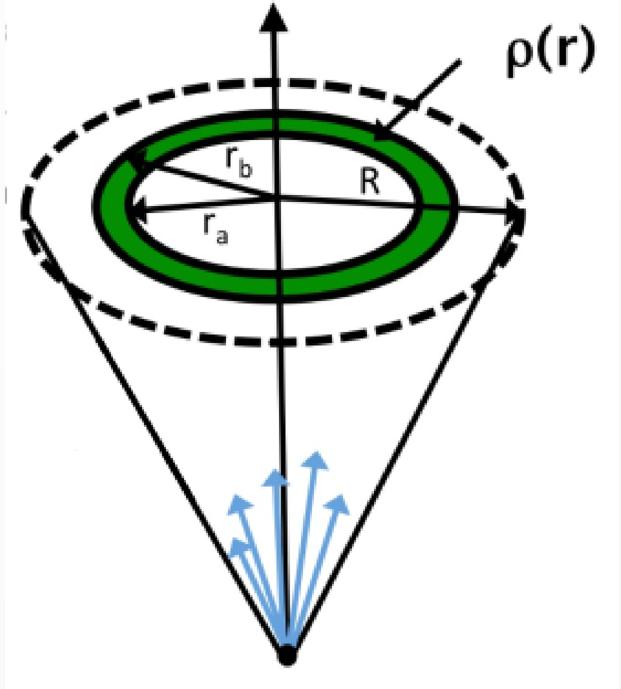
$$r = \sqrt{(\eta_{\text{track}} - \eta_{\text{jet}})^2 + (\phi_{\text{track}} - \phi_{\text{jet}})^2}$$

Possible mechanisms:

- Multiple scattering
- Medium-induced Bremsstrahlung
- Medium response

↓

Dependent on the mass of the underlying parton → **Motivation to study heavy-flavor jets**

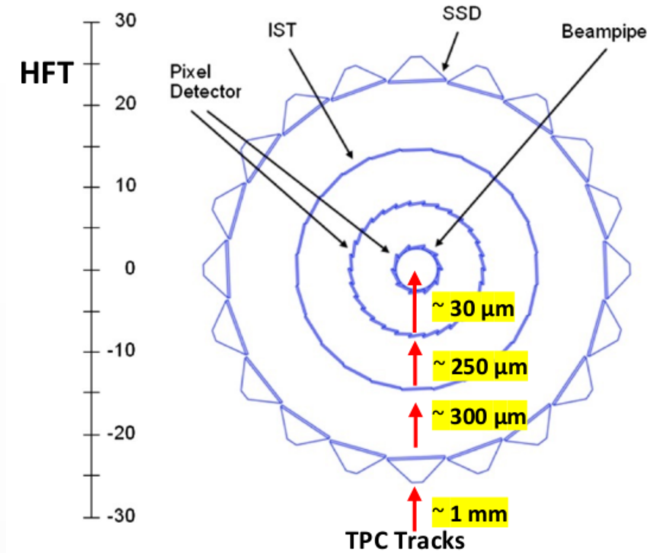


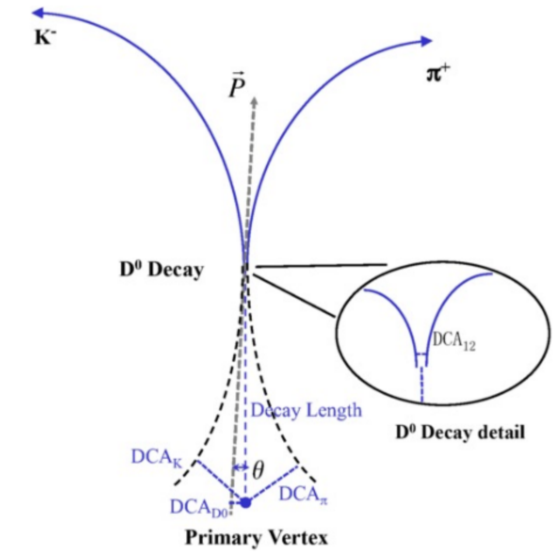
Talk: Diptanil Roy (STAR)

First D0-tagged jet measurement at RHIC energies

D reconstruction:

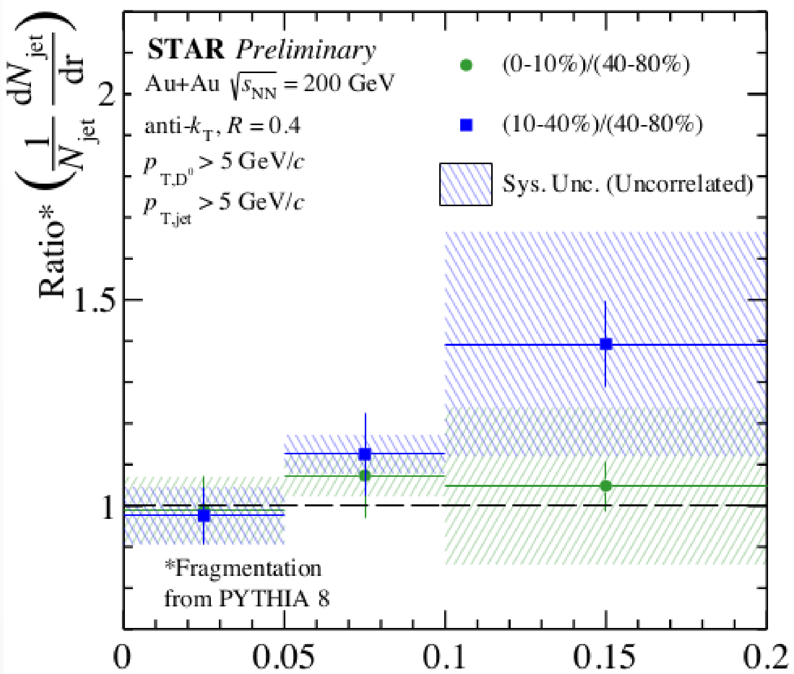
- Kaons and pions are identified using TPC and TOF
- Decay length of D^0 ~ 123 μm
- HFT can reconstruct D^0 candidates based on decay topology

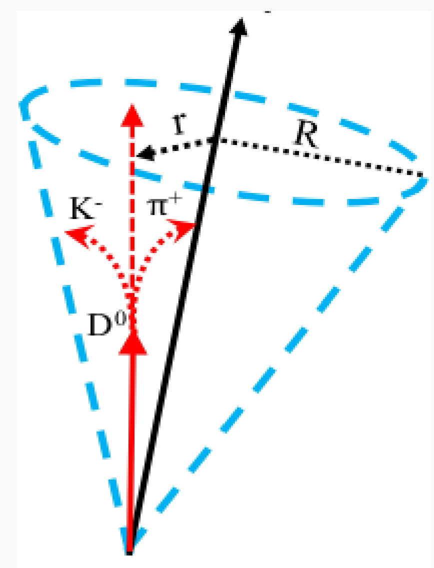




Correction to jet yield:

- Response matrix for pp √s = 200 GeV from PYTHIA and GEANT3 to mimic the detector response
- Single Particle (SP) embedding in heavy ion event to model fluctuations in area-based background subtraction
- Reweight PYTHIA with c-quark distribution from FONLL [1] to modify the shape of the jet p T spectra
- Heavy-flavor jet fragmentation modeled using PYTHIA
- Systematics from variation in fragmentation model will be studied later





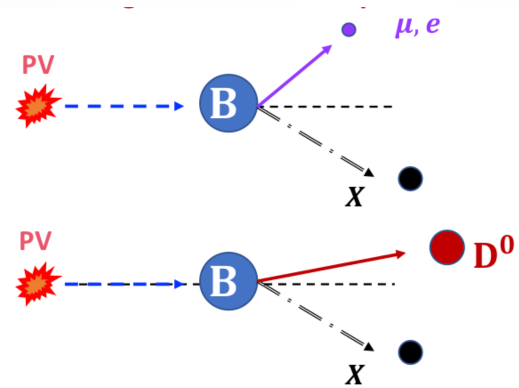
Talk: Diptanil Roy (STAR)

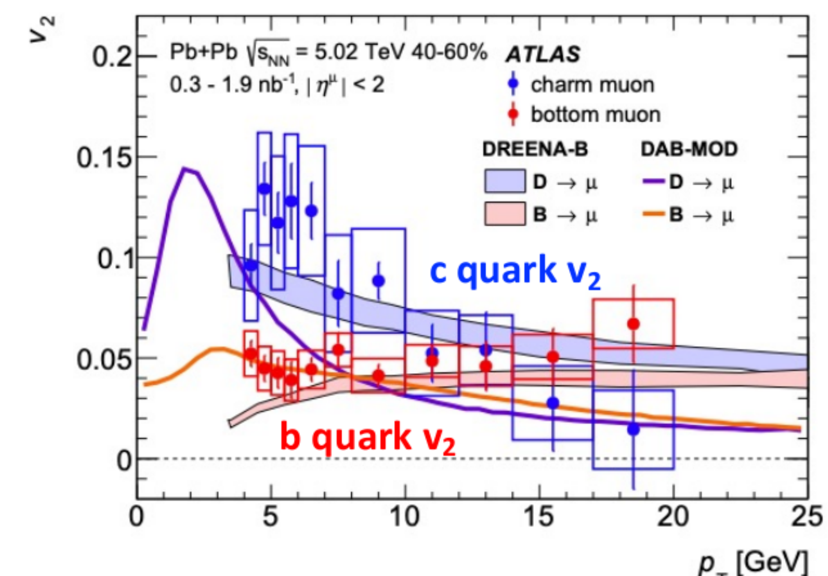
First measurement of b→D^0 azimuthal anizotrophy in PbPb collisions

b quark anisotropy:

- ATLAS $b \to \mu$
- ALICE $b \to e$
- CMS $b \to J/\psi$

❖ Non-zero v_2!
❖ v_3 consistent with zero

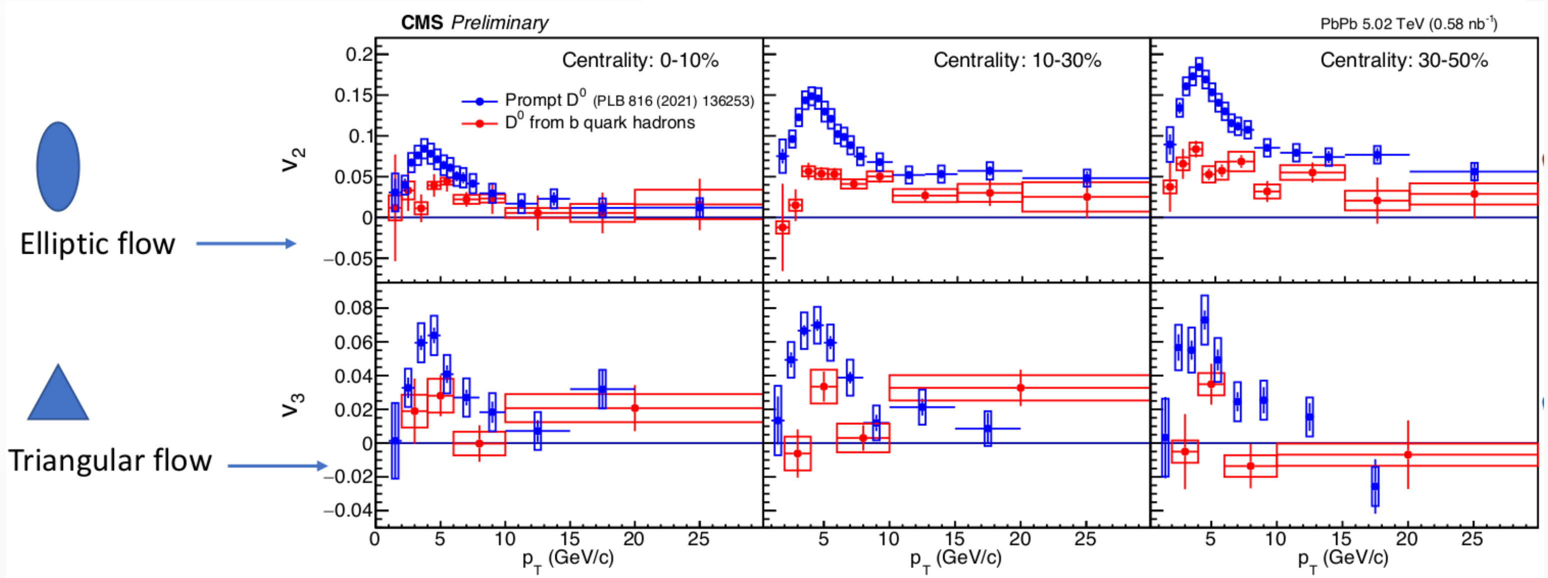




PLB 807 (2020) 135595

- ❑ **Advantages of $b \to D^0$ channel**
  - ✓ Larger branching ratio wrt $b \to J/\psi$
  - ✓ Higher mass than leptons: less diluted signal

- Mass ordering of flow magnitudes
- Weak p_T and centrality dependence
- Non-zero v_3



Talk: Milan Stojanovic (CMS)

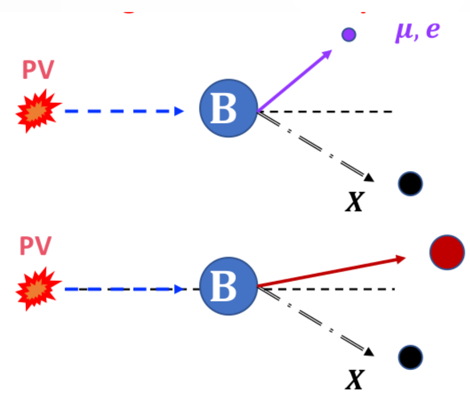
First measurement of b→D⁰ azimuthal anizotrophy in PbPb collisions

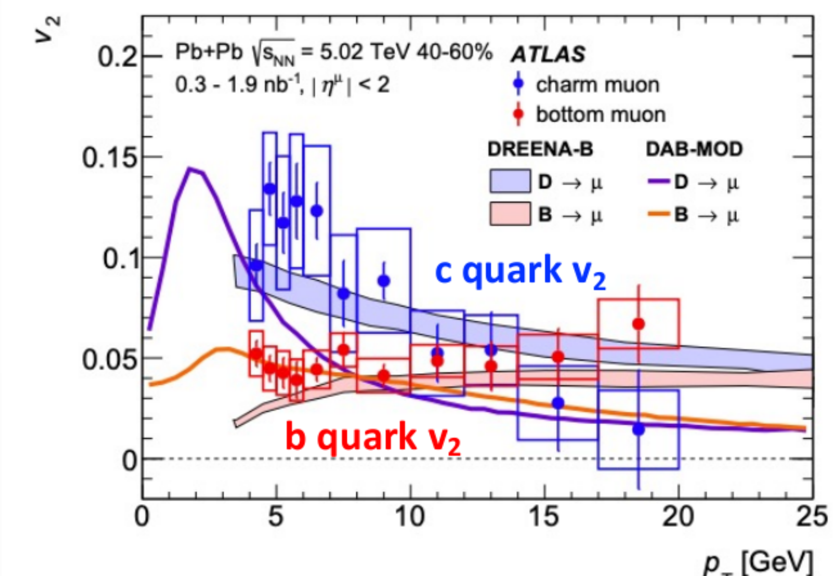
b quark anisotropy:

- ❑ ATLAS $b \to \mu$
- ❑ ALICE $b \to e$
- ❑ CMS $b \to J/\psi$

❖ Non-zero v_2!

❖ v_3 consistent with zero





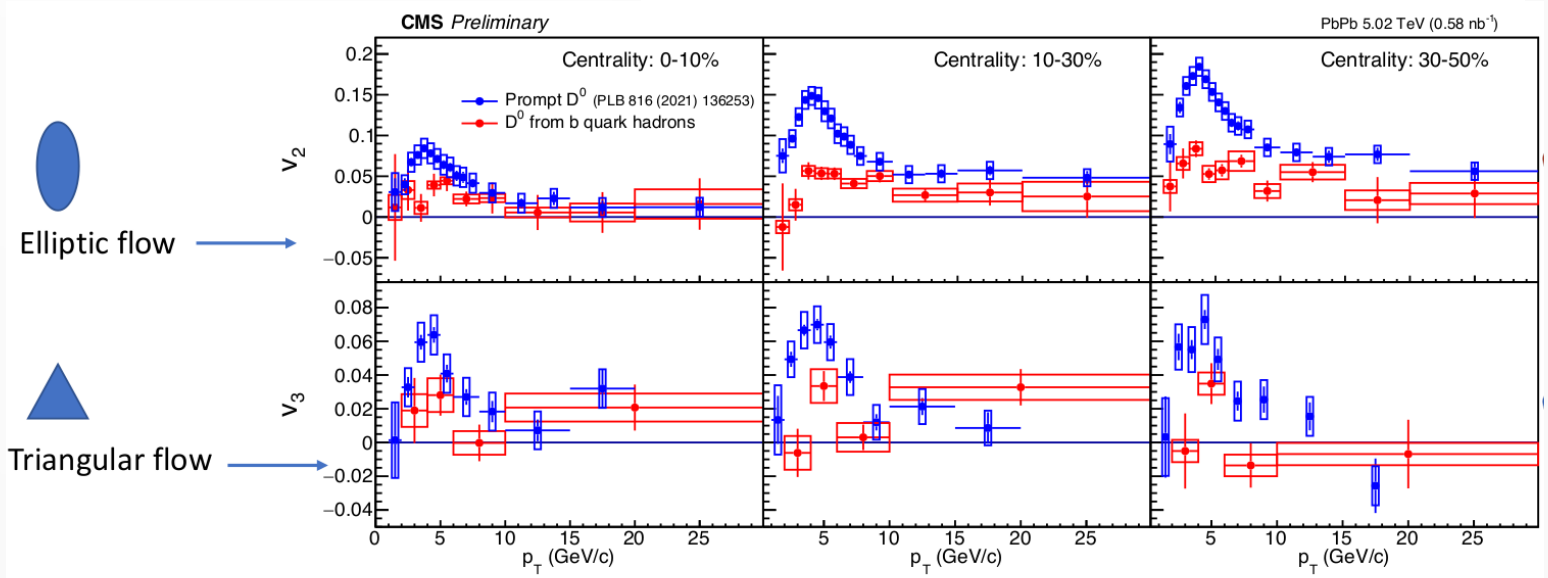
PLB 807 (2020) 135595

❑ **Advantages of $b \to D^0$ channel**

✓ Larger branching ratio wrt $b \to J/\psi$

✓ Higher mass than leptons: less diluted signal

- Qualitative agreement between theory and data
- PHSD magnitude similar as in data (position of maximum shifted towards higher p_T)



Talk: Milan Stojanovic (CMS)

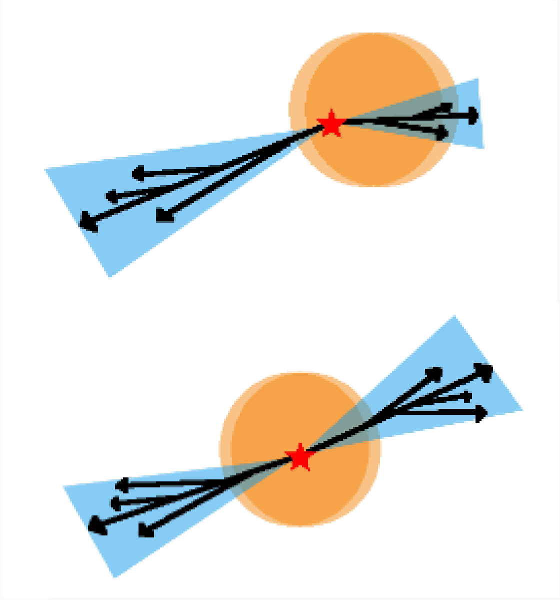
Jets, high-p_T hadrons and medium response

New measurement of dijet quenching (with ATLAS)

- Measuring back-to-back jet pairs provides access to asymmetric energy loss and
- Provides constraint on the contributions from:
  - Path length dependent energy loss
  - Energy loss functions
- Provides enhanced sensitivity to “small” amounts of jet quenching

$$x_j = \frac{p_T^{\text{subleading}}}{p_T^{\text{leading}}}$$

unbalanced dijet: low x_j



balanced dijet: high x_j

Pair normalized: $\frac{1}{N_{pair}}\frac{dN_{pair}}{dx_J}$ → enables comparison of the x_j shape across centrality in PbPb and pp

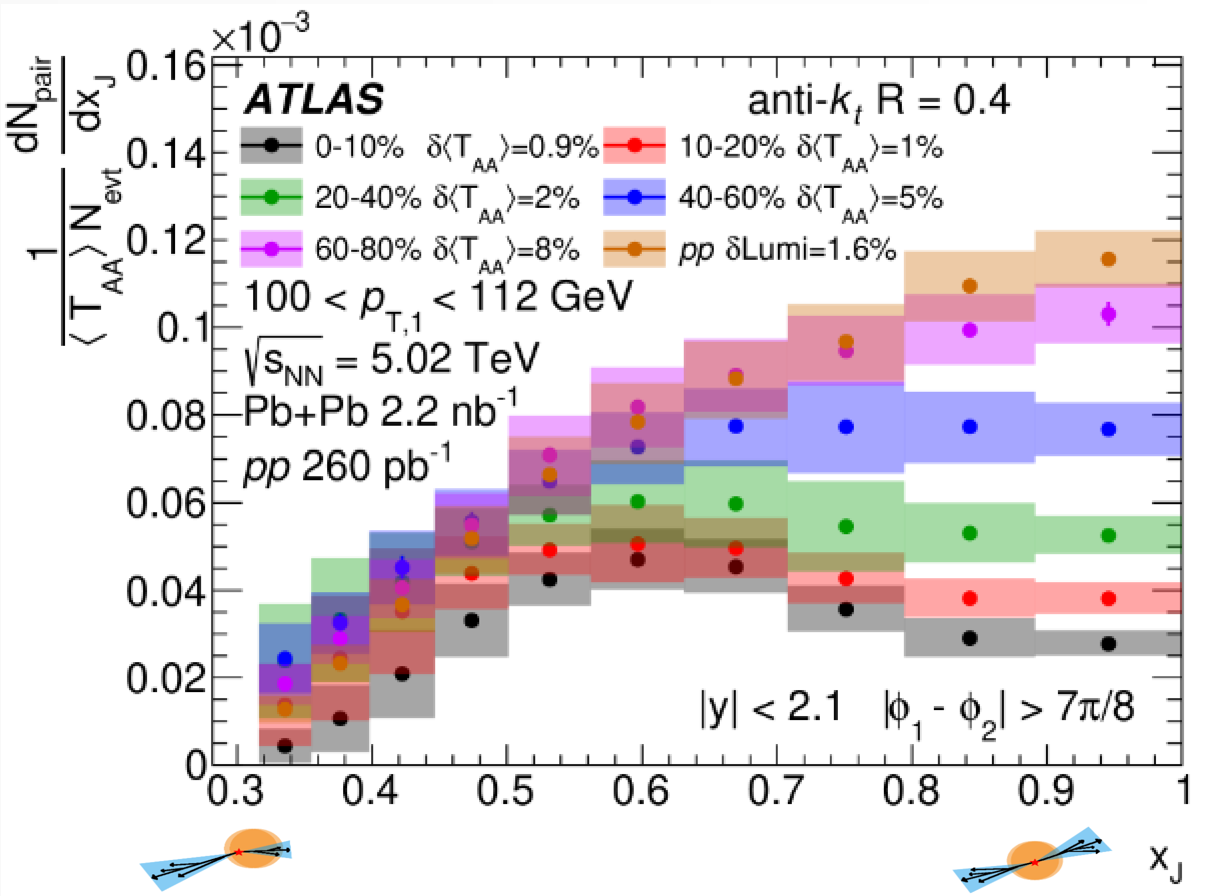
“Absolutely” normalized: $\frac{1}{N_{evt}\langle T_{AA}\rangle}\frac{dN_{pair}}{dx_J}$ NEW!

→ enables evaluation of the dijet per event yields as a function of x_j

→ Provides insight on the dynamics of the dijet energy loss

Talk: Timothy Rinn (ATLAS)

New measurement of dijet quenching (with ATLAS)

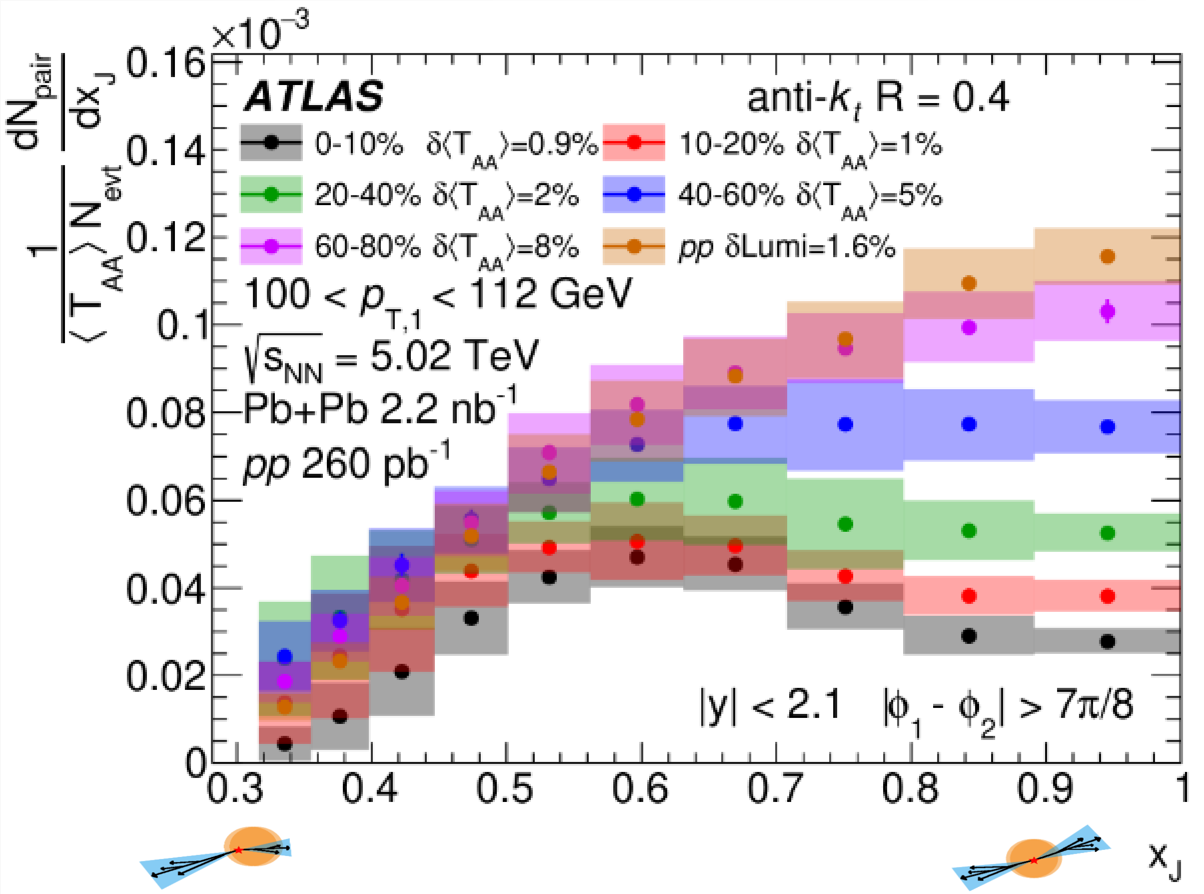


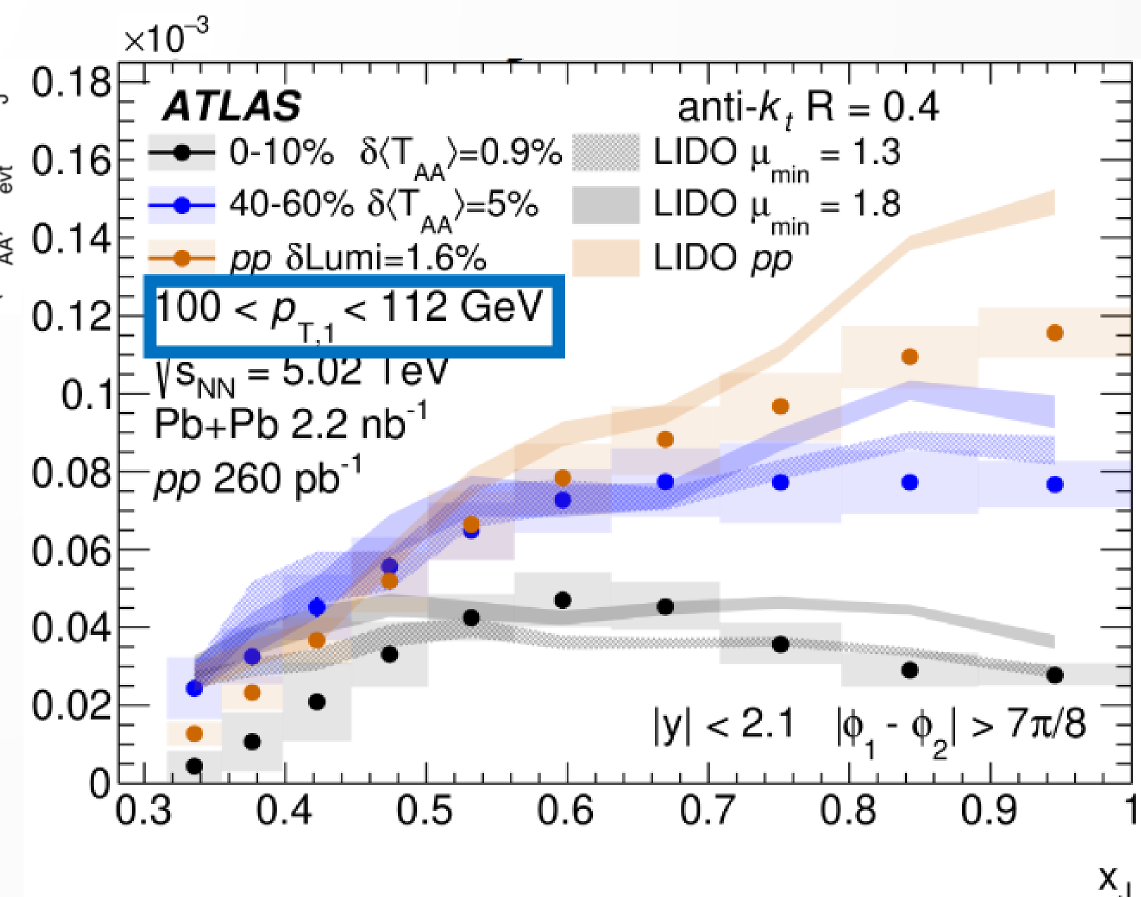
- Using absolute normalization enables the study of dijet yields as a function of x_J
- Observation: Peak structure at intermediate x_J → suppression of symmetric dijets
- No evidence for enhancement over pp in the intermediate x_J range

$$x_j = \frac{p_T^{\text{subleading}}}{p_T^{\text{leading}}}$$

Talk: Timothy Rinn (ATLAS)

New measurement of dijet quenching (with ATLAS)





$$x_j = \frac{p_T^{\text{subleading}}}{p_T^{\text{leading}}}$$

- Absolute yield of dijet pairs at low $p_{T,1}$ are overestimated by the theoretical calculations!

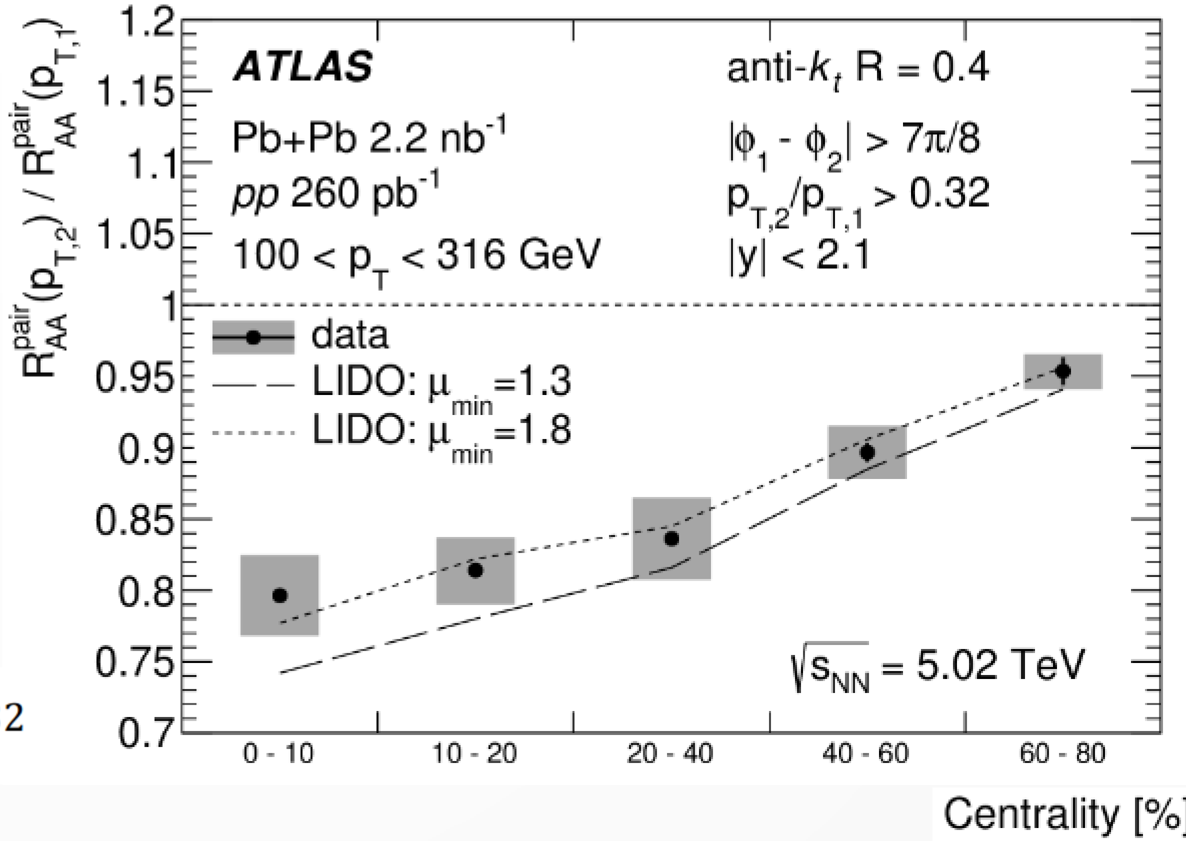
Talk: Timothy Rinn (ATLAS)

New measurement of dijet quenching (with ATLAS)

$$R_{AA}^{\text{pair}}(p_{T,1}) = \frac{\frac{1}{\langle T_{AA}\rangle N_{evt}^{AA}} \int_{0.32\times p_{T,1}}^{p_{T,1}} \frac{d^2N_{pair}^{AA}}{dp_{T,1}dp_{T,2}}\, dp_{T,2}}{\frac{1}{L_{pp}} \int_{0.32\times p_{T,1}}^{p_{T,1}} \frac{d^2N_{pair}^{pp}}{dp_{T,1}dp_{T,2}}\, dp_{T,2}}$$

$$R_{AA}^{\text{pair}}(p_{T,2}) = \frac{\frac{1}{\langle T_{AA}\rangle N_{evt}^{AA}} \int_{p_{T,2}}^{p_{T,2}/0.32} \frac{d^2N_{pair}^{AA}}{dp_{T,1}dp_{T,2}}\, dp_{T,1}}{\frac{1}{L_{pp}} \int_{p_{T,2}}^{p_{T,2}/0.32} \frac{d^2N_{pair}^{pp}}{dp_{T,1}dp_{T,2}}\, dp_{T,1}}$$

$$\frac{p_{T,2}}{p_{T,1}} > 0.32$$



- $R_{AA}(p_{T,1})$ → suppression of the leading jet in a dijet
- $R_{AA}(p_{T,2})$ → suppression of the subleading jet in a dijet

- Measurement of R_{AA} quantifies the suppression of leading and subleading jets
- Suppression of subleading jets to leading jets in peripheral PbPb

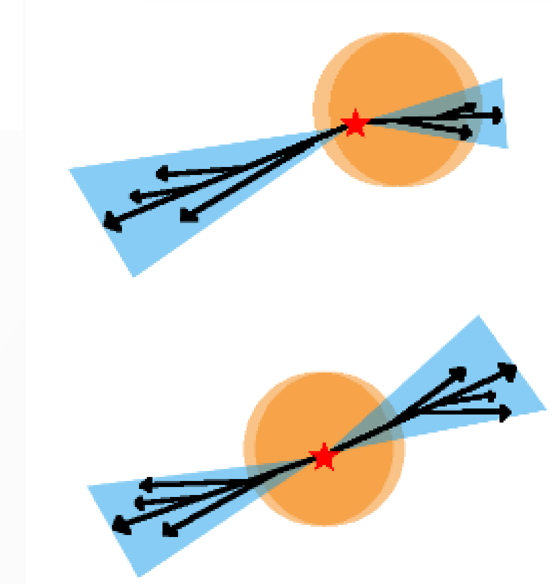
Talk: Timothy Rinn (ATLAS)

Dijet measurements

- Measured jet shapes for leading and subleading jets in dijet events as a function of x_j:
  - Leading jets are broadest in balanced events
  - Subleading jets show largest modification in unbalanced events

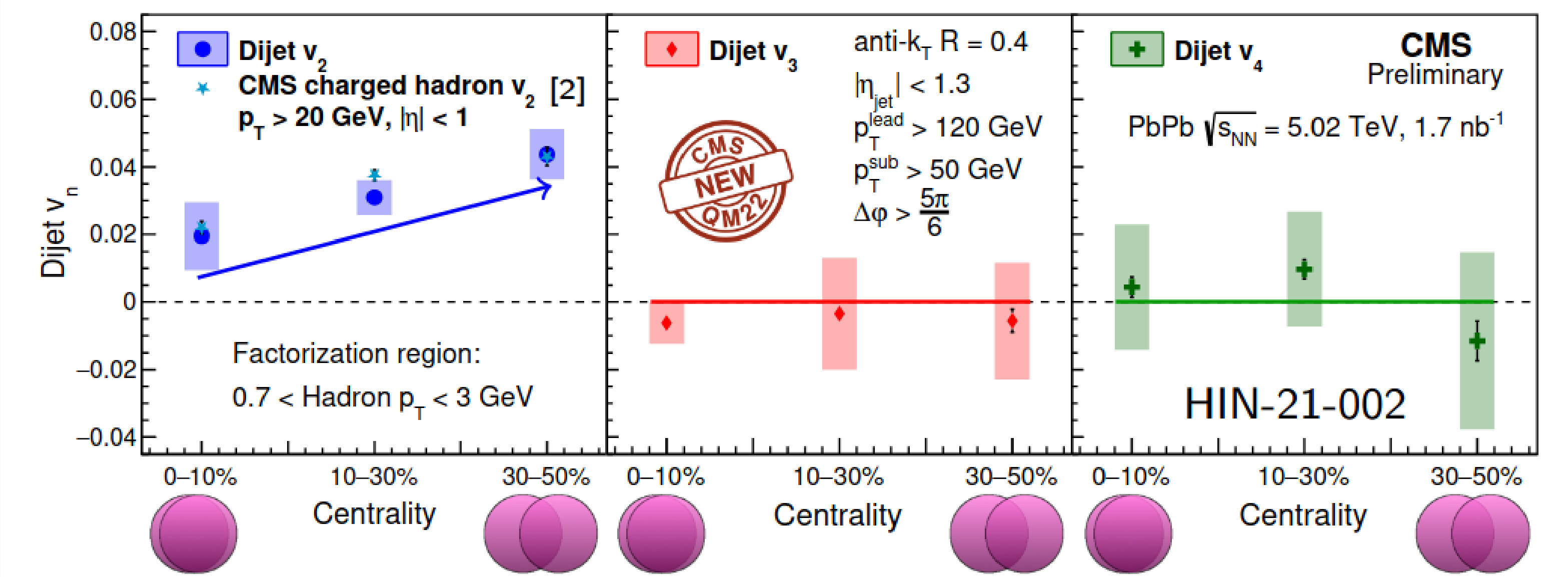
$$x_j = \frac{p_T^{\mathrm{subleading}}}{p_T^{\mathrm{leading}}}$$

unbalanced dijet: low x_j



balanced dijet: high x_j

Talk: Jussi Viinikainen (CMS)



- Dijet v_2 increasing towards more peripheral events → path length dependence
- Dijet v_3 and v_4 consistent with zero.

BACKUP

Charm quark transport models:

	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF
TAMU	✅	❌	✅	✅	✅
LIDO	✅	✅	✅	✅	✅
PHSD	✅	❌	✅	✅	✅
DAB-MOD	✅	✅	✅	✅	❌
Catania	✅	❌	✅	✅	✅
MC@sHQ+EPOS	✅	✅	✅	✅	✅
LBT	✅	✅	✅	✅	✅
POWLANG+HTL	✅	❌	✅	✅	✅
LGR	✅	✅	✅	✅	✅

But more importantly: different **implementations** and **input parameters**.