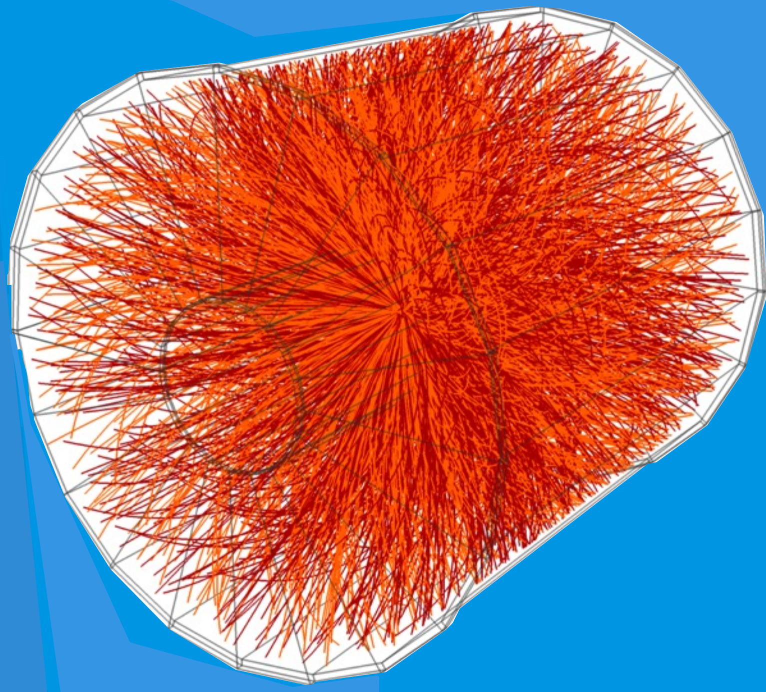
Charm production: constraints to transport models and charm diffusion coefficient with ALICE

Luuk Vermunt* (Universität Heidelberg),
for the ALICE Collaboration



QUARK MATTER
KRAKÓW
2022

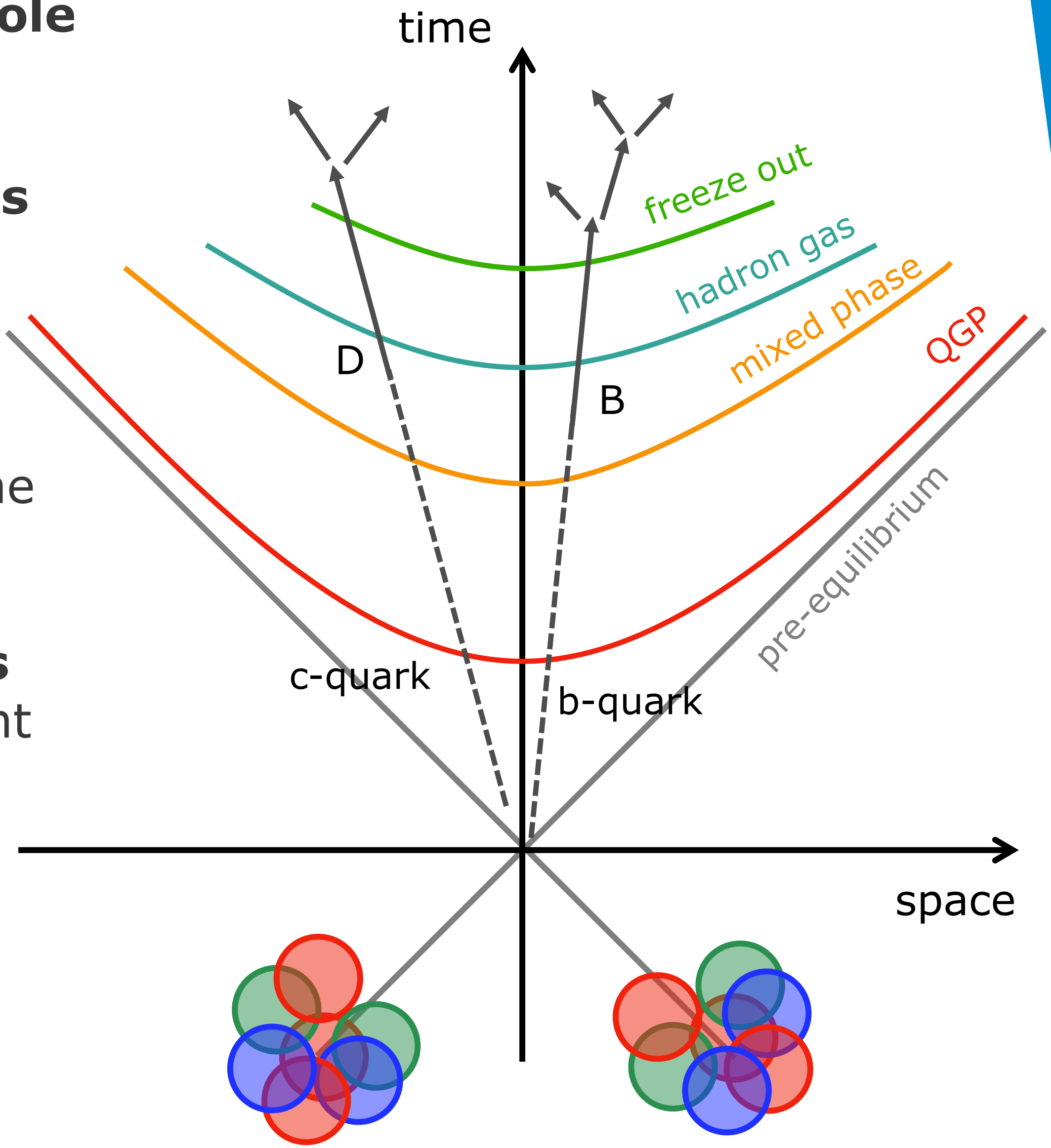
07/04/2022

* luuk.vermunt@cern.ch

Open heavy-flavour production

Open heavy-flavour production plays a **unique role** in heavy-ion physics:

- Production restricted to **early collision stages** and **retain a "memory"** of their evolution through the QGP
- Good theoretical control on the production (**perturbative QCD**) and transport through the medium (**diffusion treatment**)
- Heavy quarks **retain their flavour and mass identity**; can be "tagged" by the measurement of heavy-flavour hadrons



A Large Ion Collider Experiment

Charm-hadron analyses conducted in the central barrel ($|y|<0.5$), using:

Inner **T**racking **S**ystem
Time **P**rojection **C**hamber
Time-**o**f-**F**light detector
V0 detectors

Charm measurements in Pb–Pb collisions:

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

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

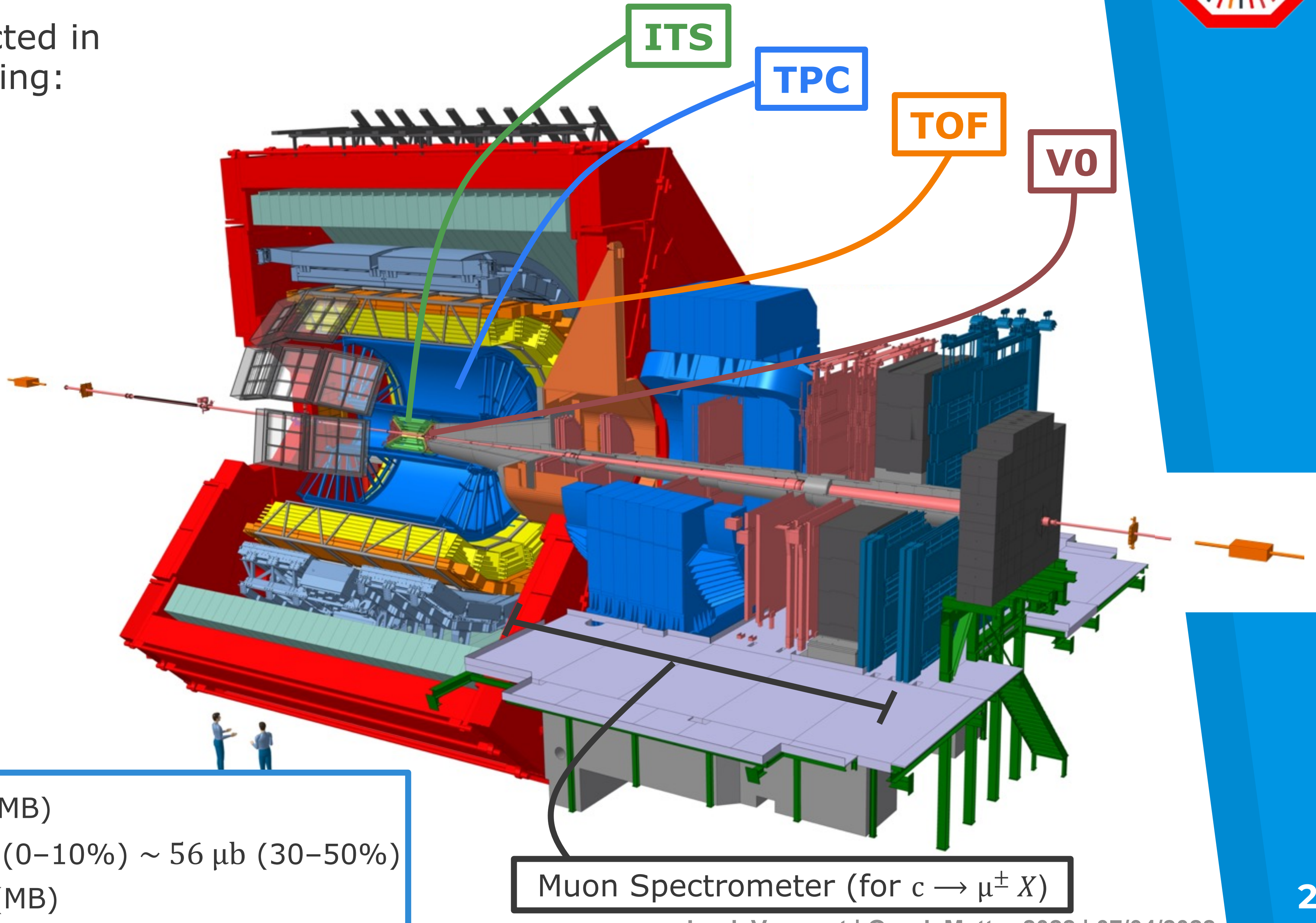
$D^{*+} \longrightarrow D^0\pi^+ \longrightarrow K^- \pi^+ \pi^+$

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

$c \longrightarrow \mu^\pm X$

Data samples used:

Pb–Pb 5.02 TeV 2015: $\mathcal{L}_{int} \sim 13\ \mu b$ (MB)
2018: $\mathcal{L}_{int} \sim 130\ \mu b$ (0–10%) $\sim 56\ \mu b$ (30–50%)
Xe–Xe 5.44 TeV 2017: $\mathcal{L}_{int} \sim 0.3\ \mu b$ (MB)



Regions of interest

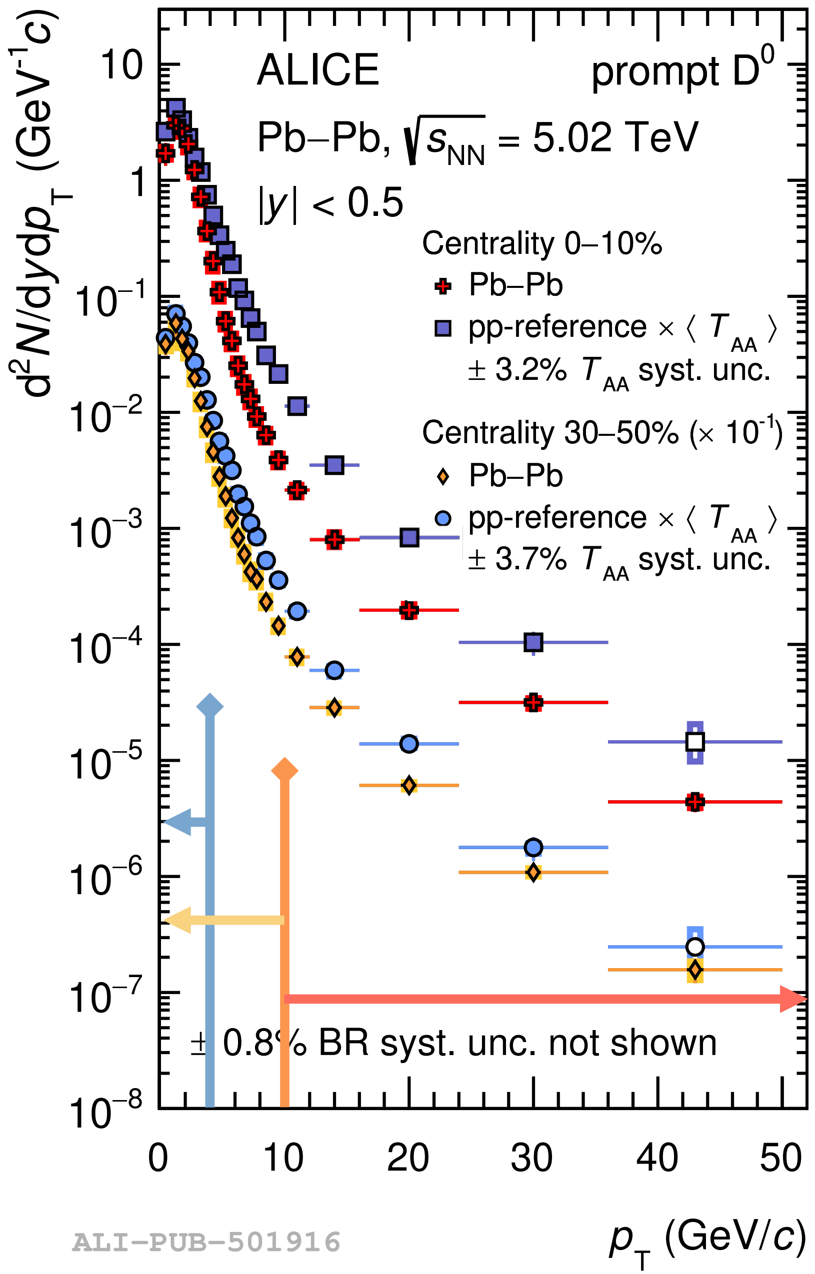
New: JHEP 01 (2022) 174

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

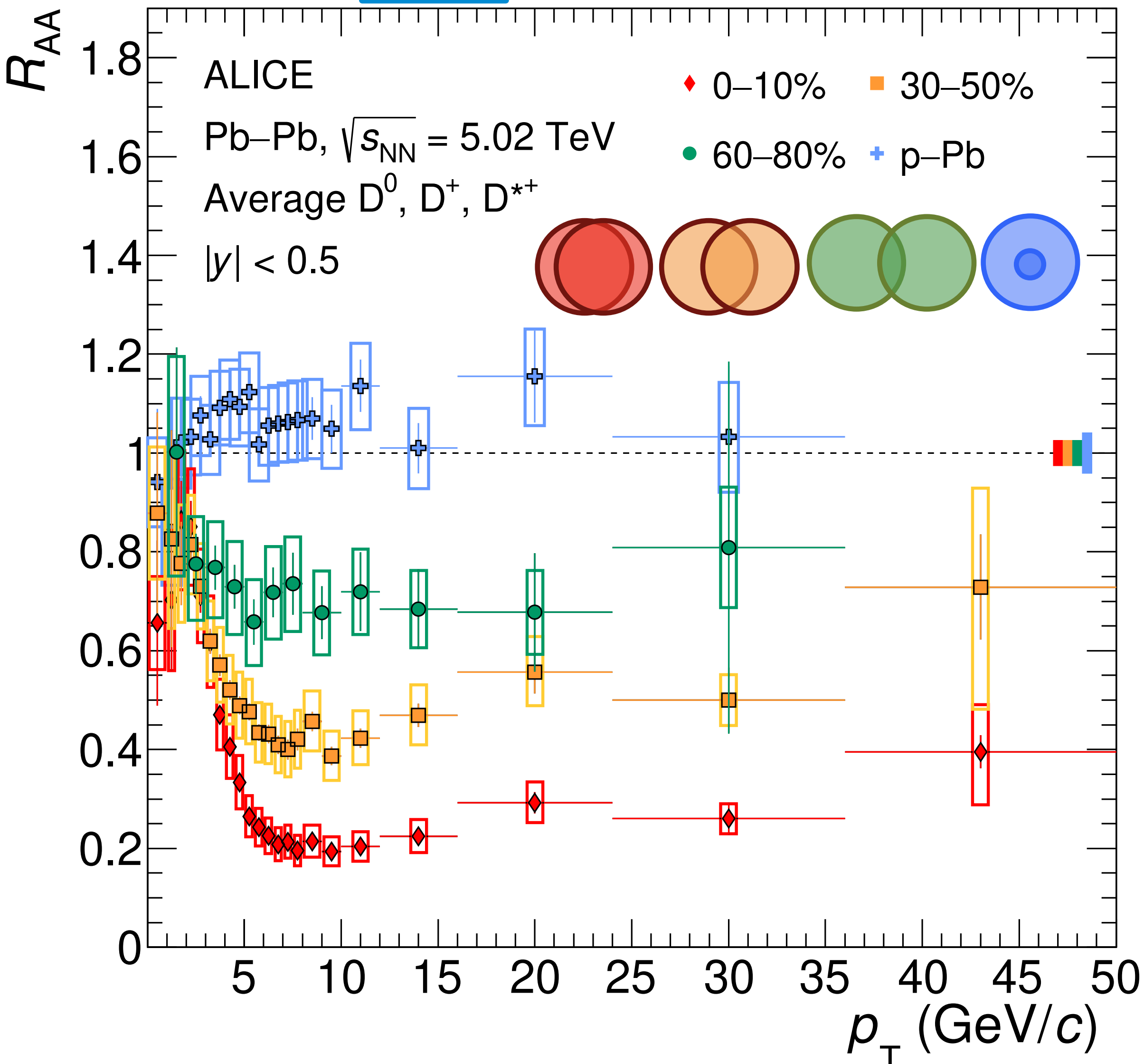
- Heavy quarks interact via gluon radiation
- Quark mass and path-length dependence?

pp: JHEP 05 (2021) 220

Nuclear modification factor: non-strange D

- Increasing suppression (for p_T > 3 GeV/c) for more central collisions due to **increasing density**, **size**, and **lifetime** of the medium
- Because of interplay of many different effects, **model comparison required** to interpret these single D-meson measurements

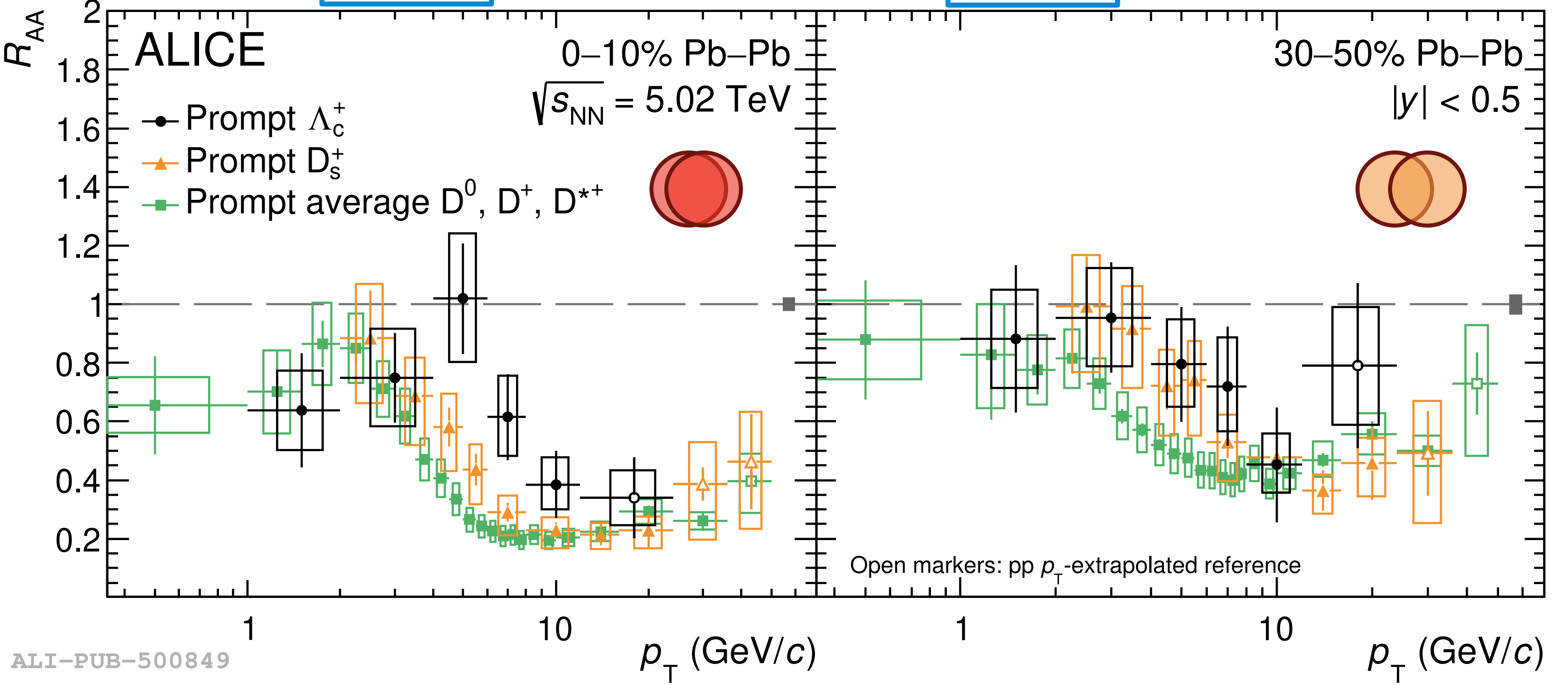
New: JHEP 01 (2022) 174



Pb-Pb 60-80%: JHEP 10 (2018) 174
p-Pb: JHEP 12 (2019) 092

Nuclear modification factor: D_s^+ and Λ_c^+

New Λ_c^+: arXiv:2112.08156 **New D_s^+:** PLB 827 (2022) 136986



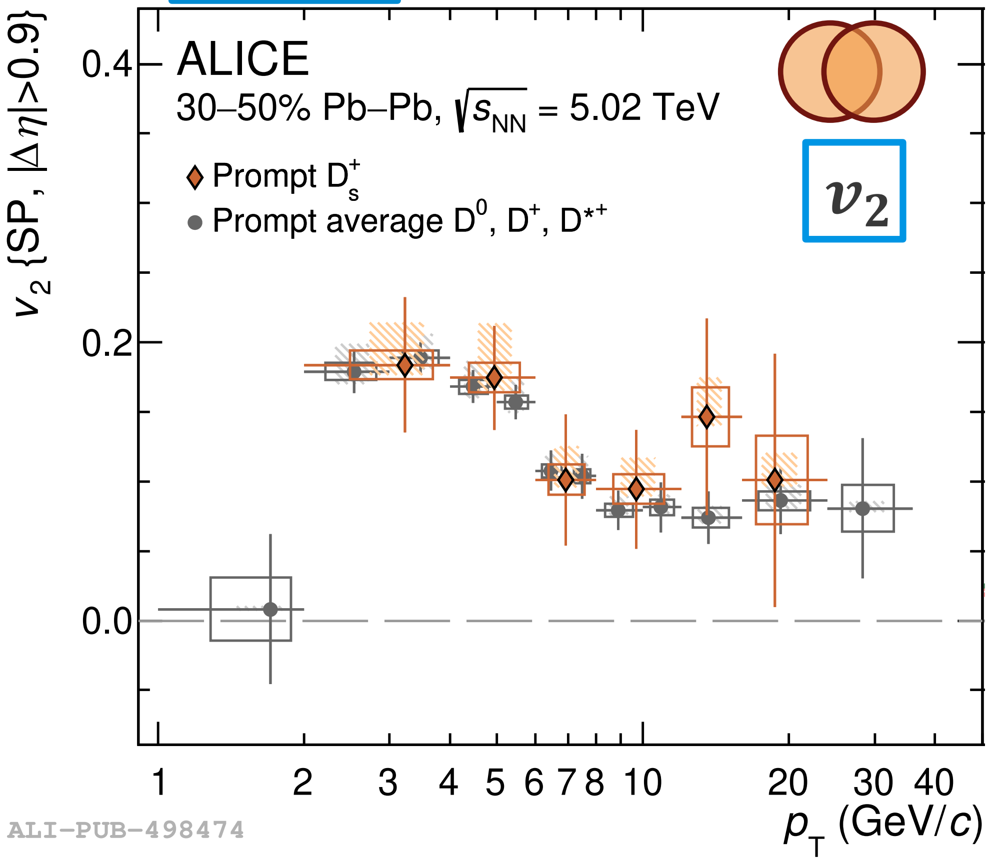
Hint of hierarchy, $R_{AA}(\Lambda_c^+) > R_{AA}(D_s^+) > R_{AA}(D)$ for $p_T > 4$ GeV/c in most central collisions

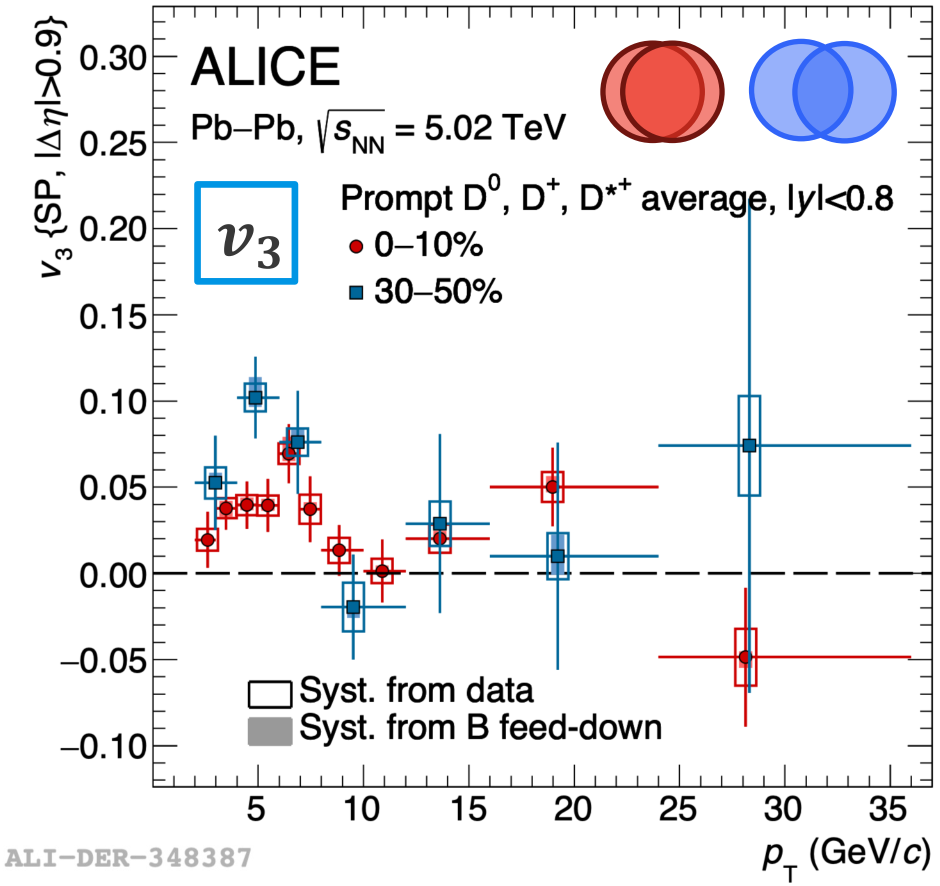
→ Indication of modified hadronisation mechanisms; interplay with radial flow?

Non strange D: JHEP 01 (2022) 174

Azimuthal anisotropies: D mesons

New D_s^+: PLB 827 (2022) 136986





Positive D v_2 and v_3 in 0–10% and 30–50%

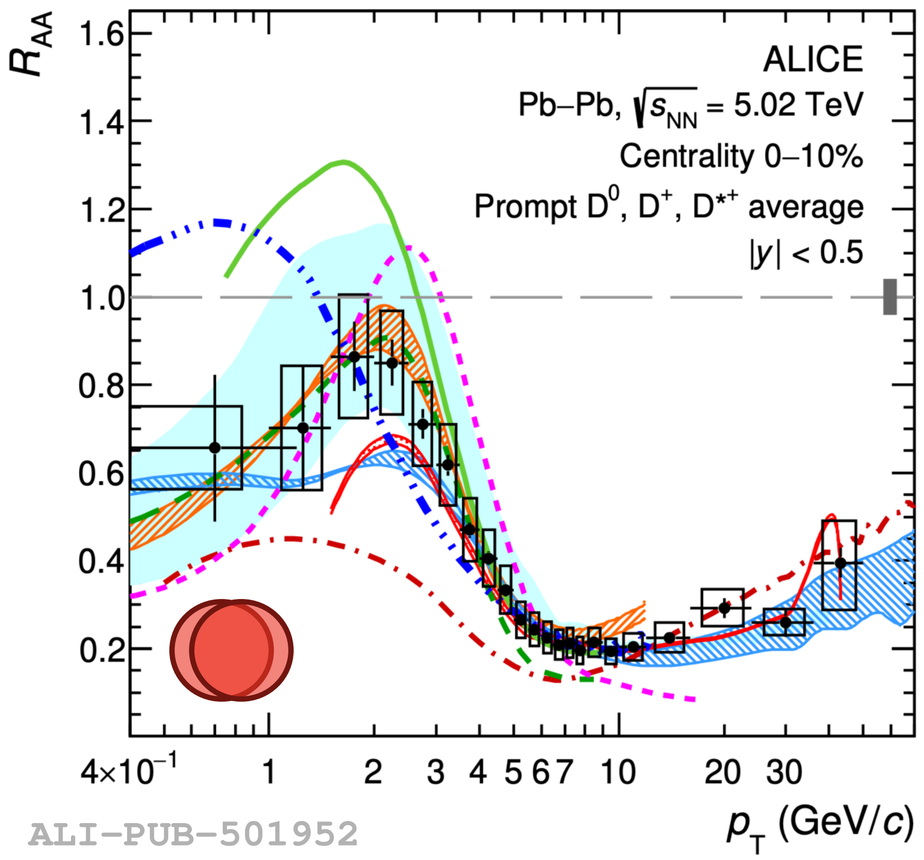
→ Charm participates in collective expansion

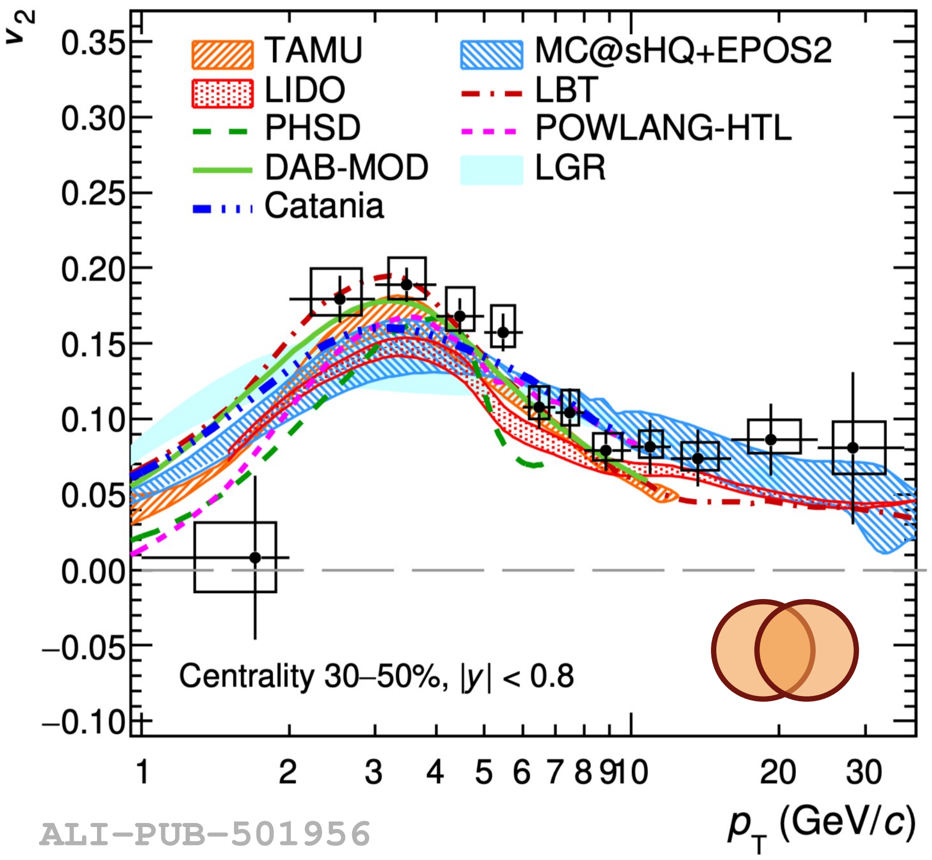
Positive D_s^+ v_2 in 2 < p_T < 8 GeV/c in 30–50% with **significance of 6.4σ**

→ Current uncertainties too large to draw conclusion about potential difference w.r.t. non-strange D

Non strange D: PLB 813 (2021) 136054

Charm-quark transport models





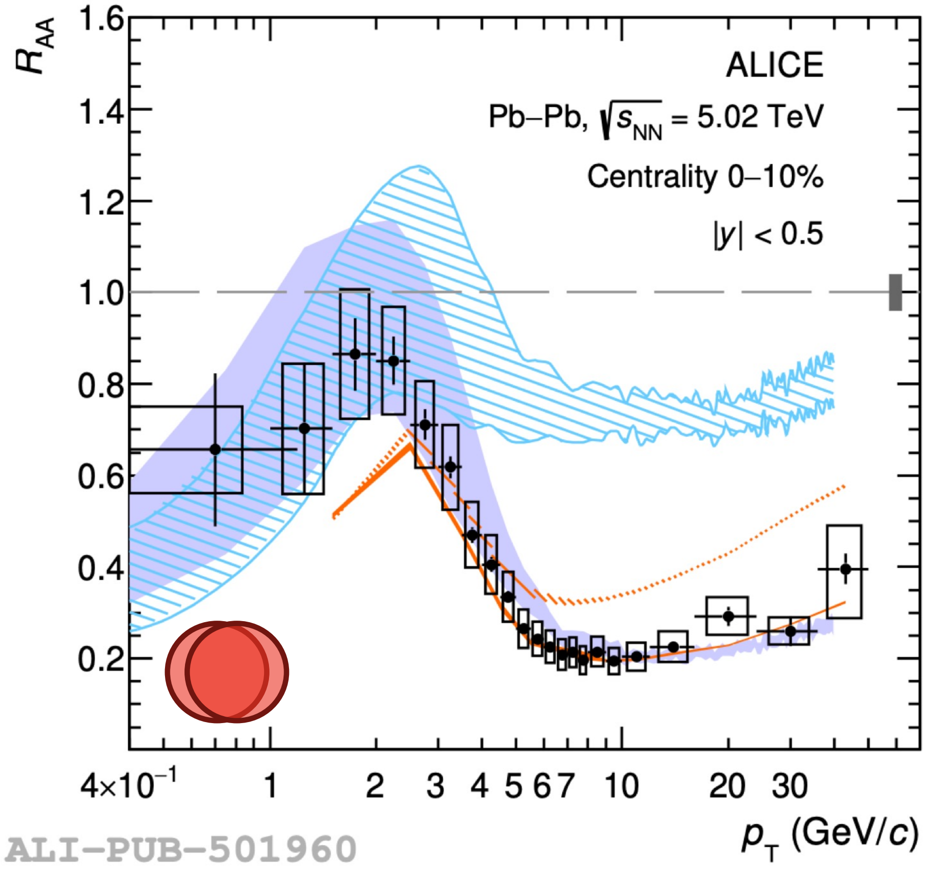
Most charm-quark **transport models** able to describe both the R_{AA} and v_2

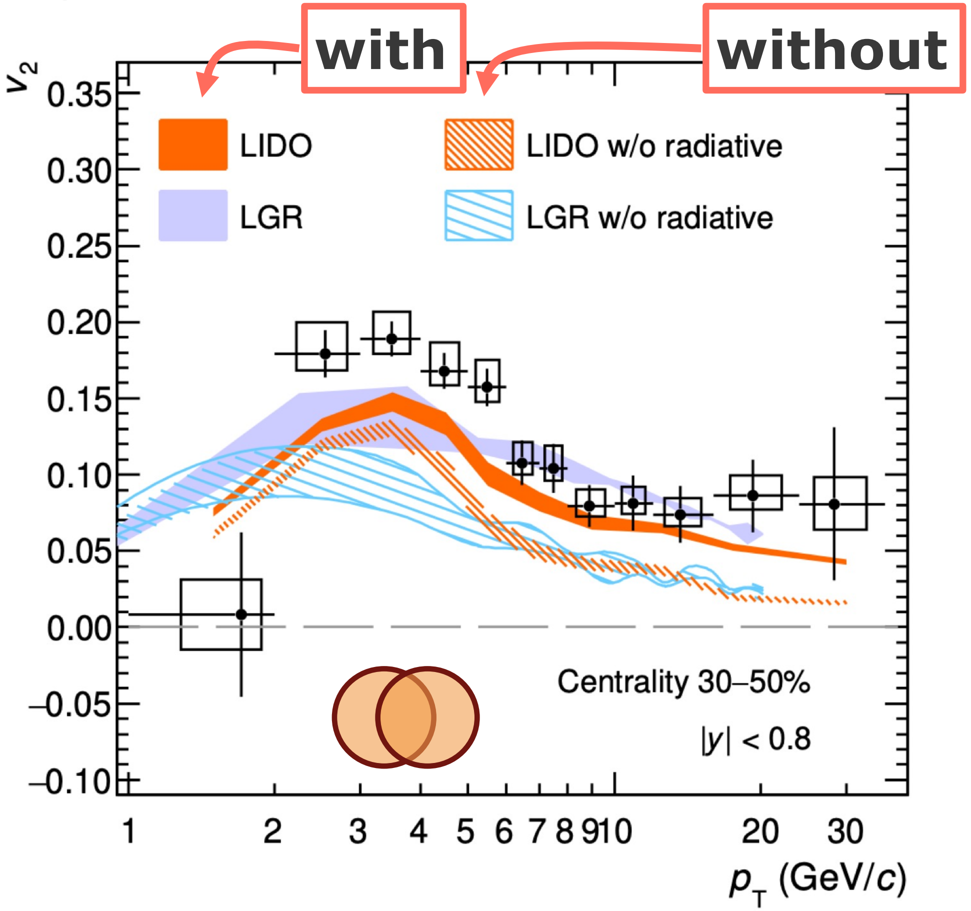
→ Use comparison to understand which physics effects are relevant

→ Use comparison to estimate the spatial diffusion coefficient

TAMU: PRL 124, 042301 (2020)
LIDO: PRC 98, 064901 (2018)
PHSD: PRC 93, 034906 (2016)
DAB-MOD: PRC 96, 064903 (2017)
Catania: PRC 96, 044905 (2017)
MC@sHQ: PRC 91, 014904 (2015)
LBT: PLB 777 (2018) 255-259
POWLANG: EPJC 75 (2015) 3, 121
LGR: EPJC 80 (2020) 7, 671
R_{AA}: JHEP 01 (2022) 174
v_2: PLB 813 (2021) 136054

Physics effects in models





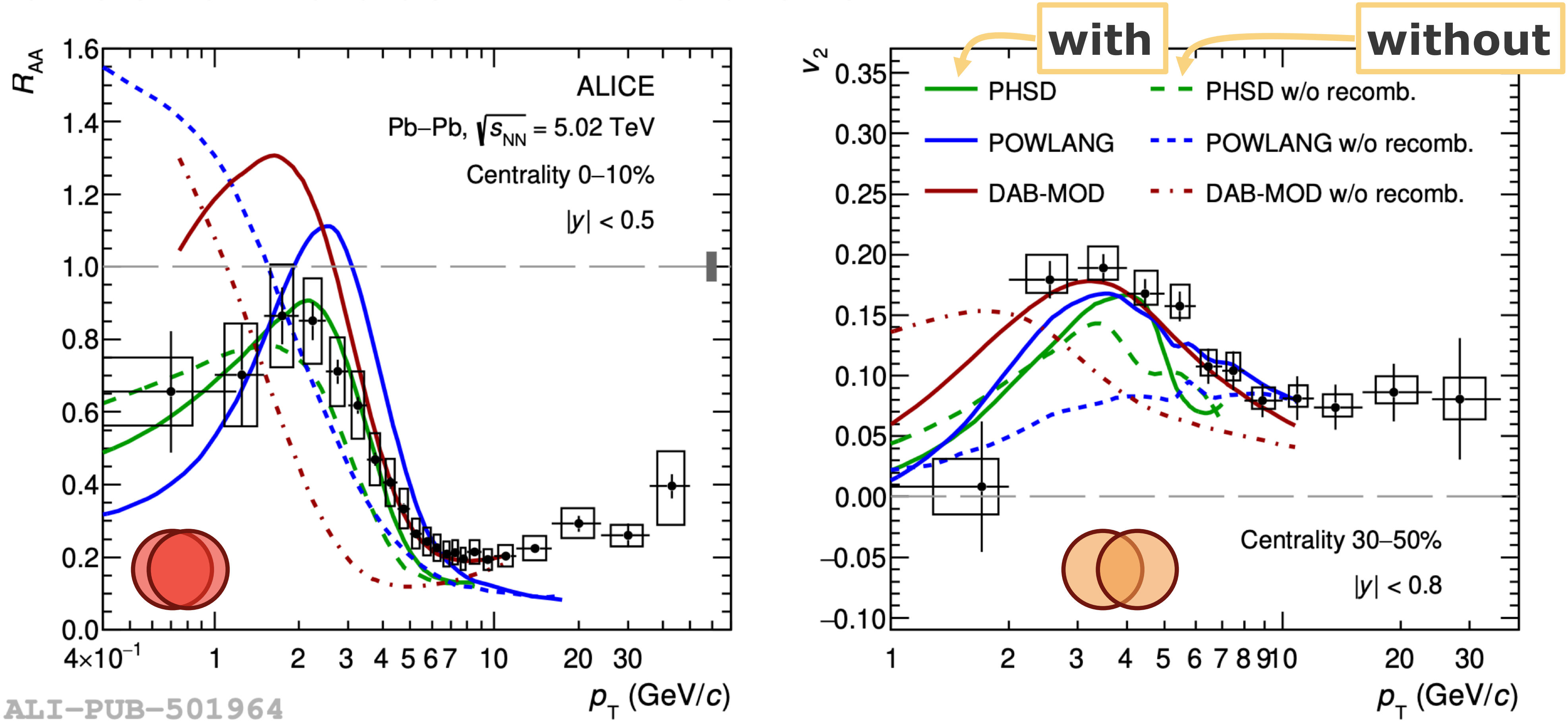
Radiative energy loss important to describe intermediate and high p_T

→ Small impact on low p_T region

LIDO: PRC 98, 064901 (2018)
LGR: EPJC 80 (2020) 7, 671

R_{AA}: JHEP 01 (2022) 174
v_2: PLB 813 (2021) 136054

Physics effects in models



Hadronisation via recombination important to describe low and intermediate p_T

→ D meson "picks up" the v_2 of the light quark

PHSD: PRC 93, 034906 (2016)
POWLANG: EPJC 75 (2015) 3, 121
DAB-MOD: PRC 96, 064903 (2017)

R_{AA}: JHEP 01 (2022) 174
v_2: PLB 813 (2021) 136054

Spatial diffusion coefficient

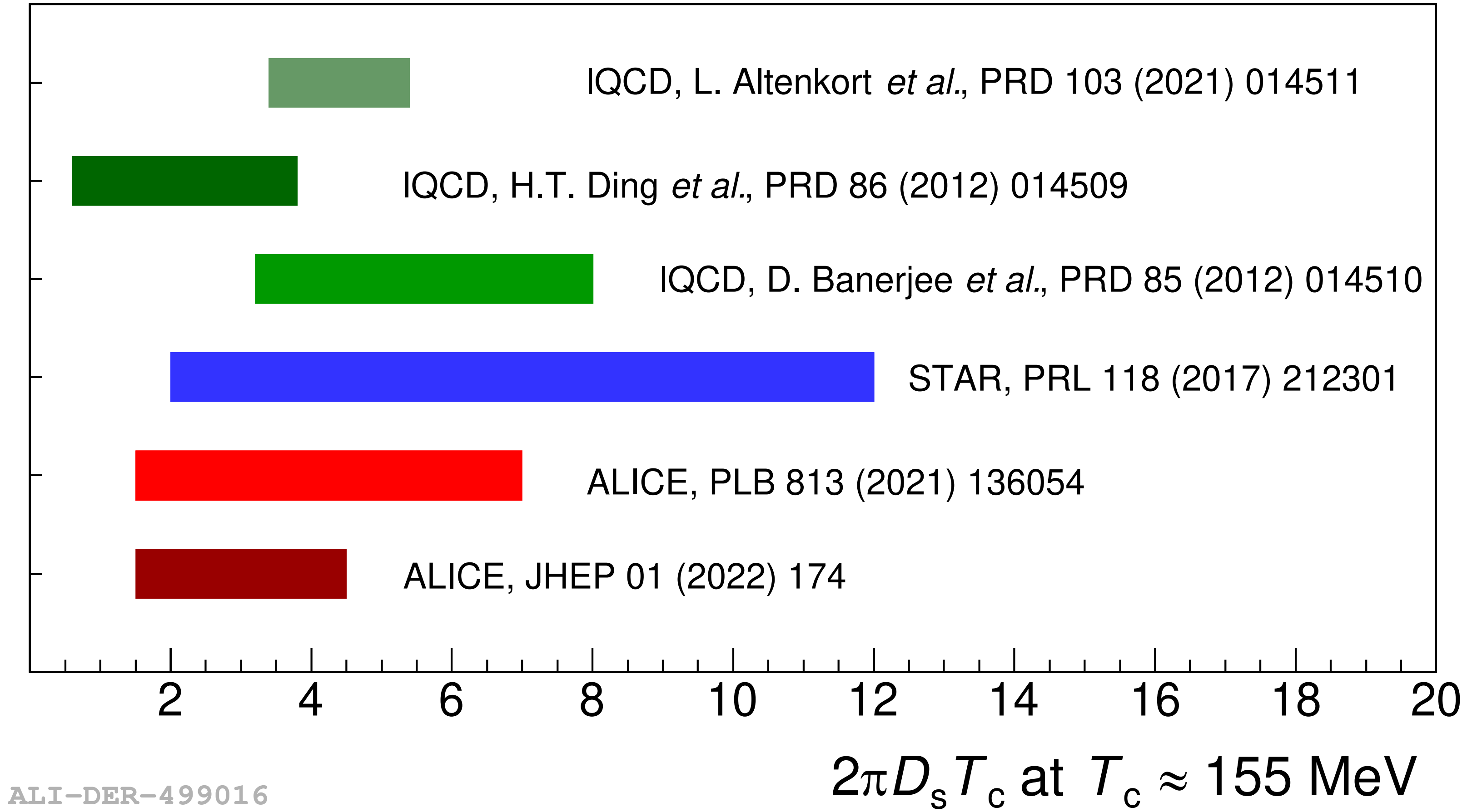
Constraining the spatial diffusion coefficient via the **data-to-model agreement**

→ Using R_{AA} (with $\chi^2/\mathrm{ndf} < 5$) and v_2 (with $\chi^2/\mathrm{ndf} < 2$) non-strange D measurements

→ TAMU, MC@sHQ, LIDO, LGR, and Catania "selected"

→ $1.5 < 2\pi D_s T_c < 4.5$
→ $\tau_{\mathrm{charm}} \simeq$ 3–8 fm/c

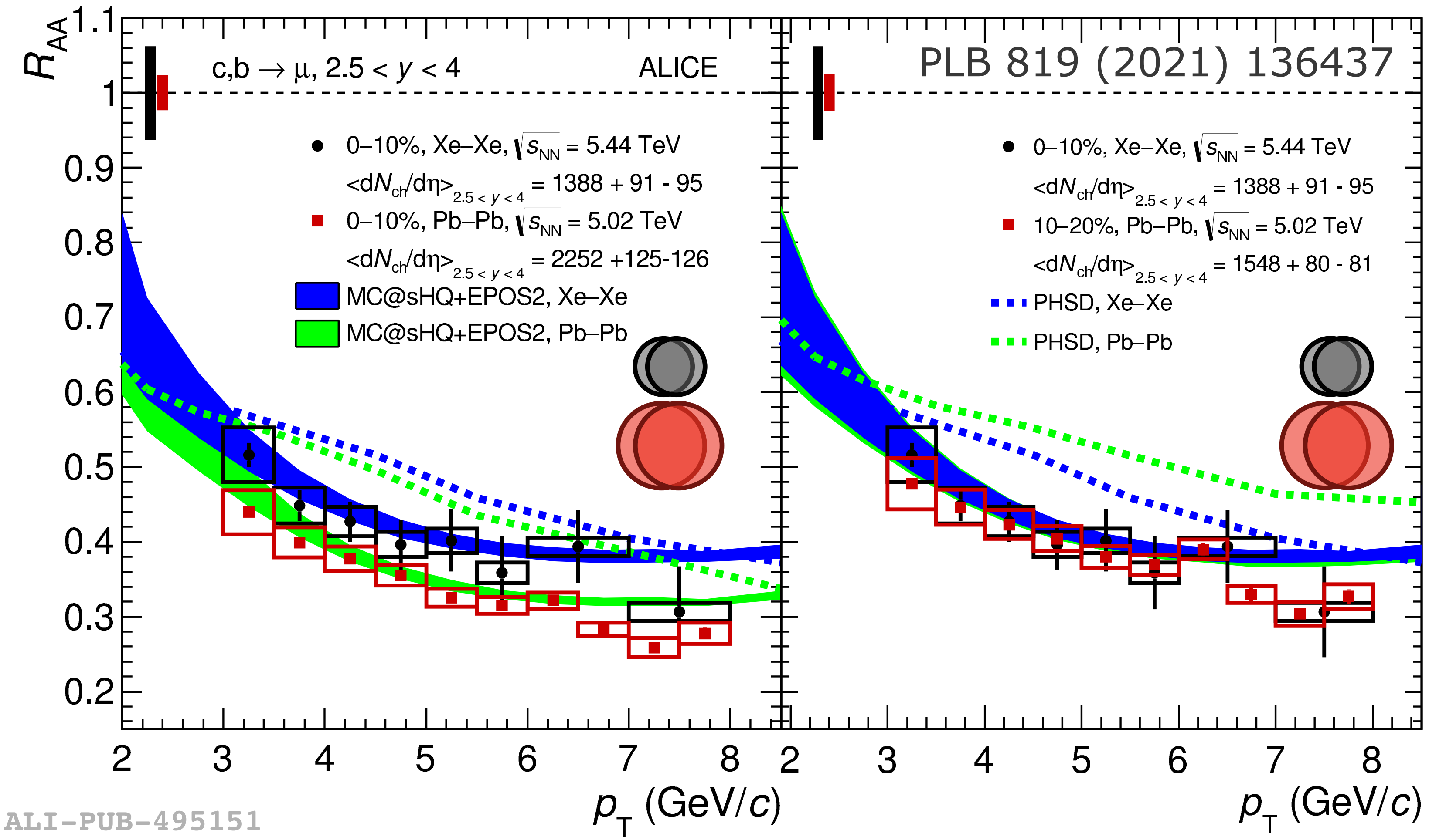
New



What do leptons from HF decays teach us?

R_{AA} of HF decay $\mu^{\pm}$ and $e^{\pm}$ (see backup) **reasonably well described** by transport models

→ Some tension for PHSD (no radiative e-loss) with forward muons, but describes $e^{\pm}$ at midrapidity



Similar R_{AA} for $\mu^{\pm}$ from heavy-flavour decays in Pb–Pb and Xe–Xe collisions **at similar $\langle dN_{ch}/d\eta \rangle$**

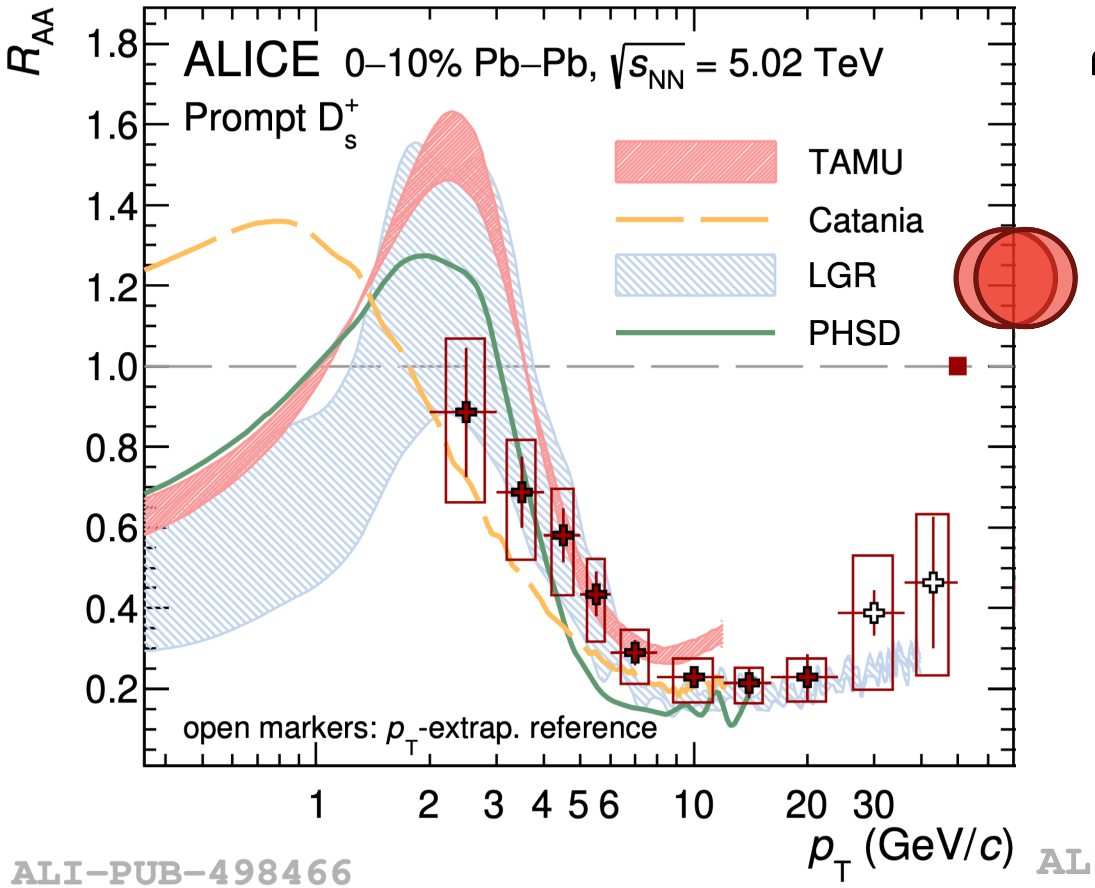
→ Possibility to further constrain model calculations

MC@sHQ: PRC 89, 014905 (2014)
PHSD: PRC 93, 034906 (2016)

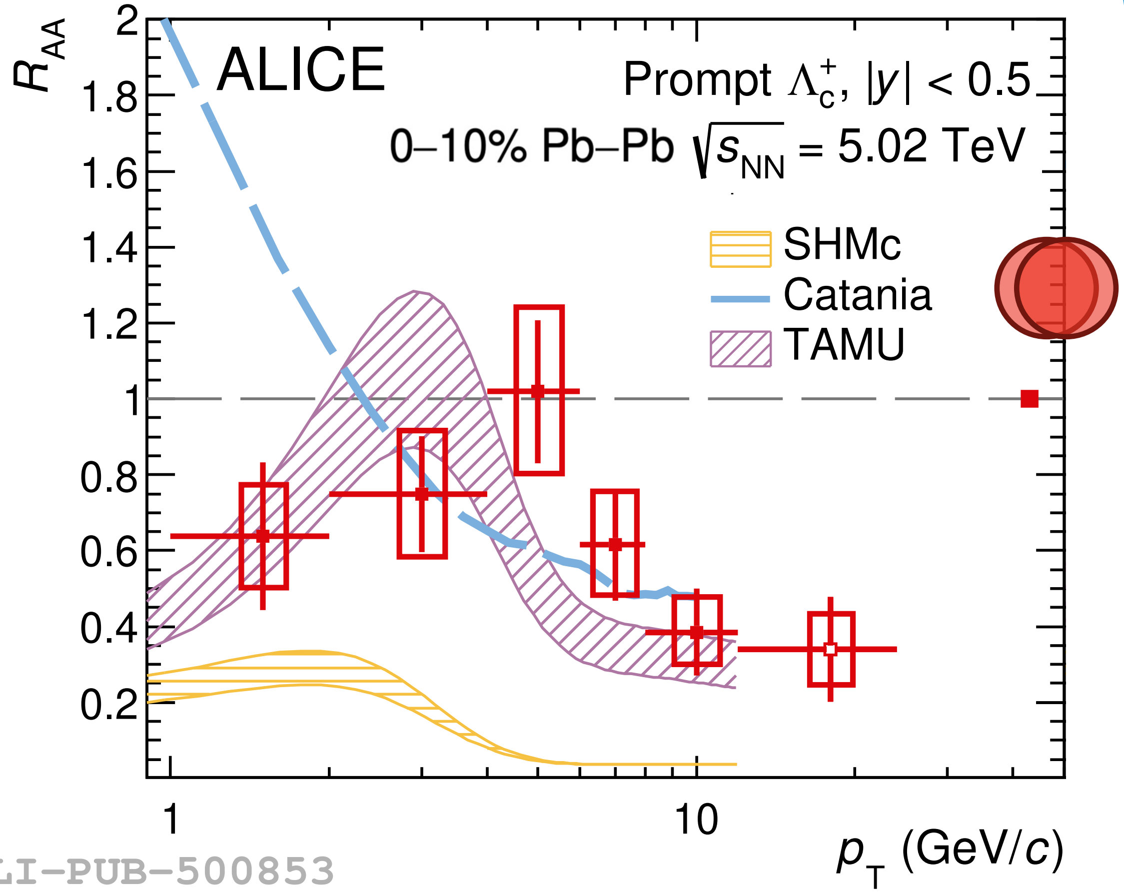
What do D_s^+ and Λ_c^+ teach us?

R_{AA} of D_s^+ and Λ_c^+ reasonably well described by models including charm recombination

→ Tension SHMc due to somewhat schematic corona description



ALI-PUB-498466



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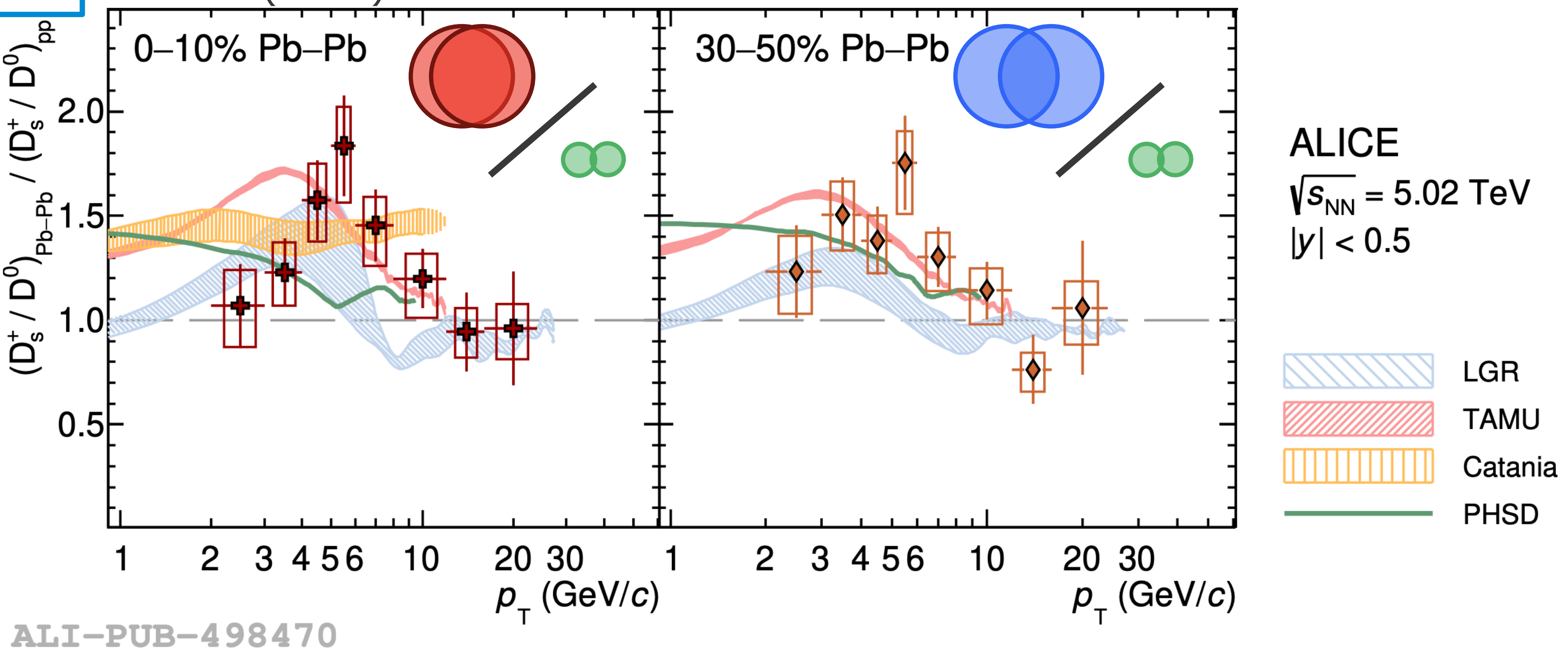
TAMU: PRL 124, 042301 (2020)
Catania: PRC 96, 044905 (2017)
LGR: EPJC 80 (2020) 7, 671
PHSD: PRC 93, 034906 (2016)
SHMc: JHEP 07 (2021) 035

D_s^+: PLB 827 (2022) 136986
Λ_c^+: arXiv:2112.08156

Charm-strange to probe hadronisation

New: PLB 827 (2022) 136986



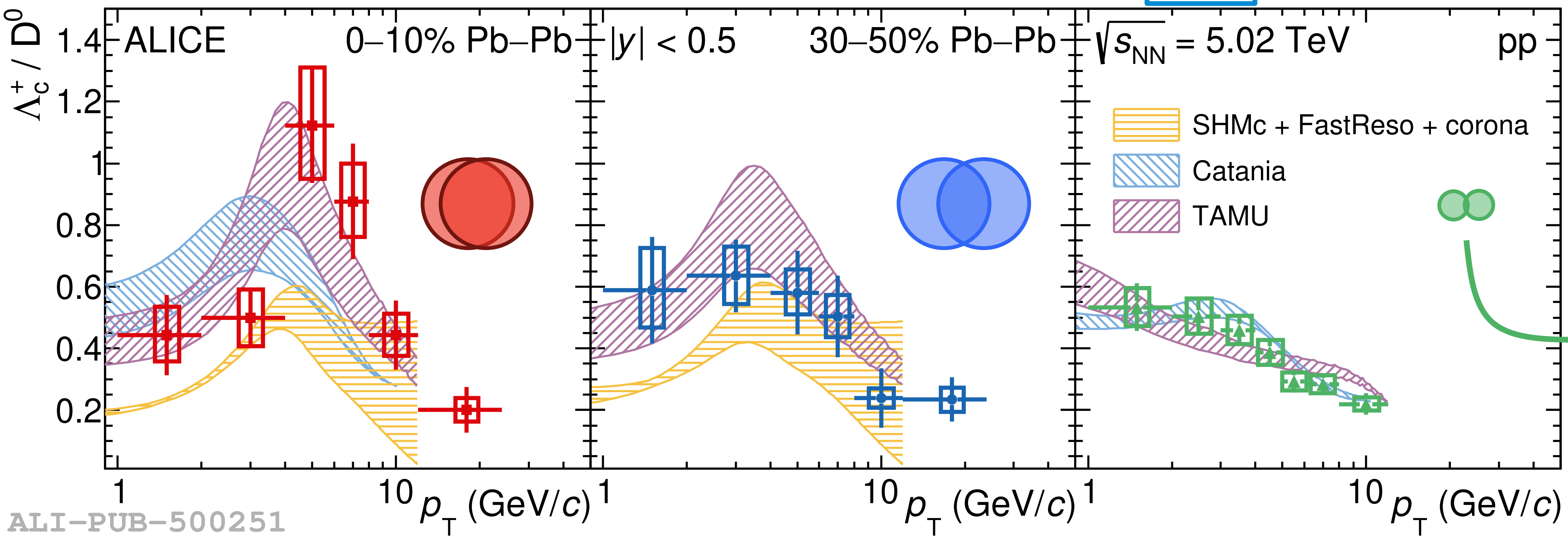
The D_s^+/D^0 ratio is **higher** in $2 < p_T < 8$ GeV/c in 0–10% (30–50%) Pb-Pb by **2.3σ** (**2.4σ**)

Described by models including 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)

Charm baryons to probe hadronisation

New: arXiv:2112.08156



M. Faggin 07/04/21 11:10

The Λ_c^+/D^0 ratio is **enhanced** in $4 < p_T < 8$ GeV/c for central Pb–Pb wrt pp collisions by **3.7σ**

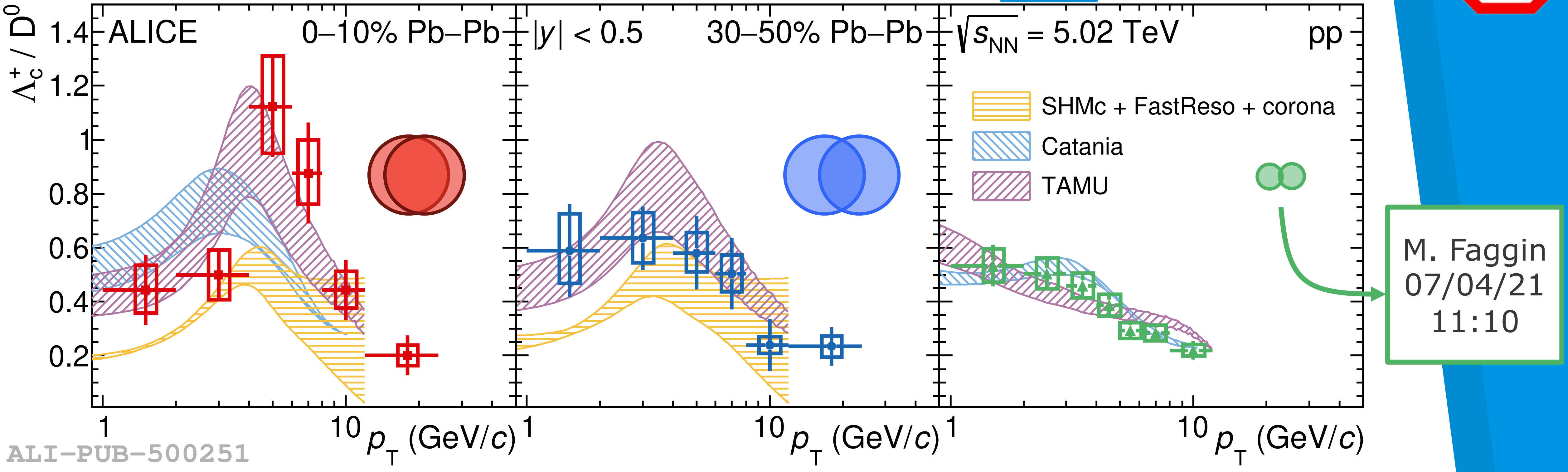
→ Also seen for baryon-to-meson ratios with **light-flavour particles**

→ Data is described by TAMU. The shapes of the Catania and SHMc predictions agree qualitatively

TAMU: PRL 124, 042301 (2020) Catania: PRC 96, 044905 (2017) SHMc: JHEP 07 (2021) 035

Charm baryons to probe hadronisation

New: arXiv:2112.08156



The Λ_c^+/D^0 ratio is enhanced in $4 < p_T < 8$ GeV/c for central Pb–Pb wrt pp collisions by 3.7σ

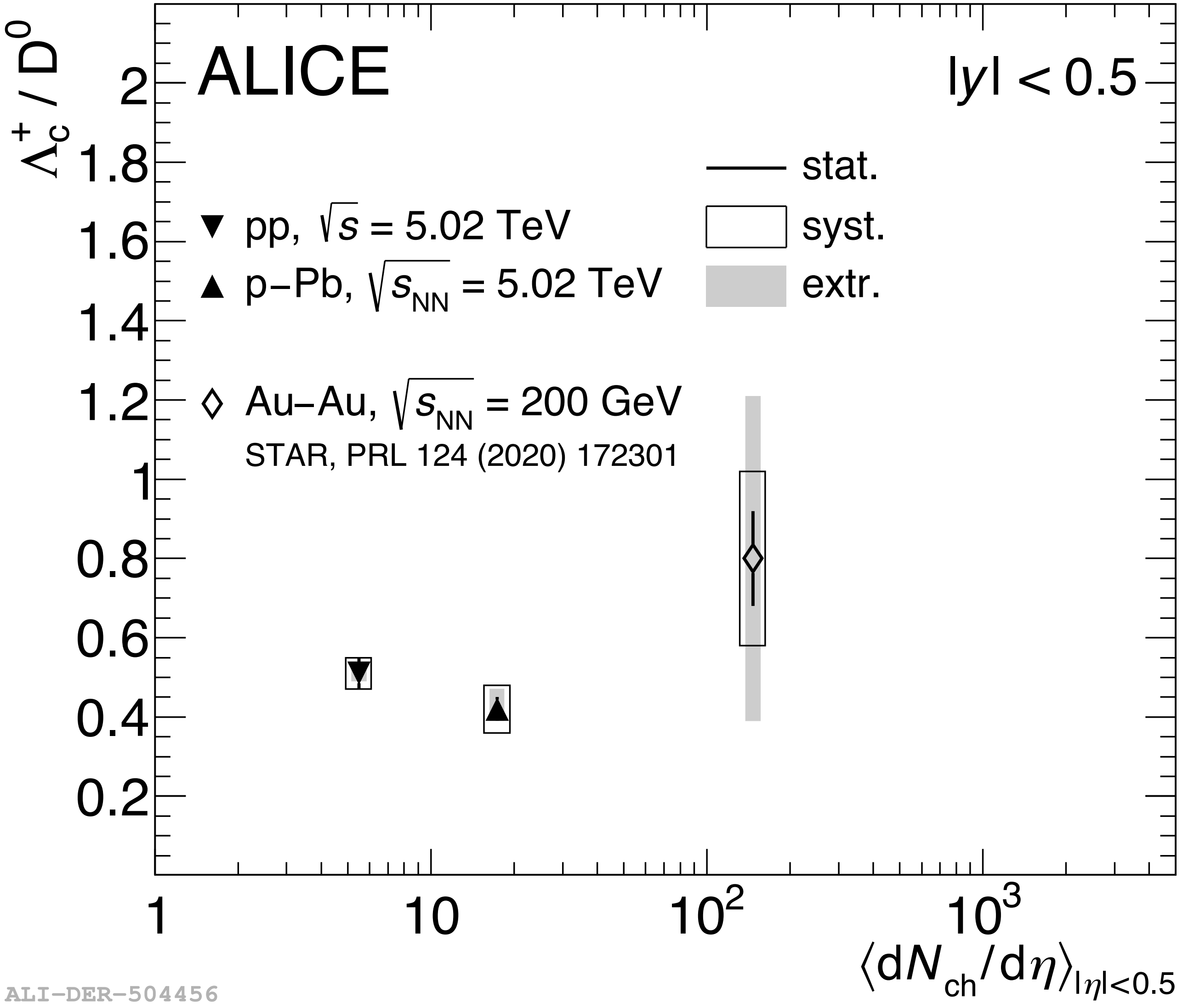
→ Also seen for baryon-to-meson ratios with light-flavour particles

→ Data is described by TAMU. The shapes of the Catania and SHMc predictions agree qualitatively

Can the enhancement be explained as an **interplay between radial flow & recombination**, i.e. a different redistribution of p_T between baryons and mesons?

TAMU: PRL 124, 042301 (2020) Catania: PRC 96, 044905 (2017) SHMc: JHEP 07 (2021) 035

p_T-integrated Λ_c^+/D^0 ratio



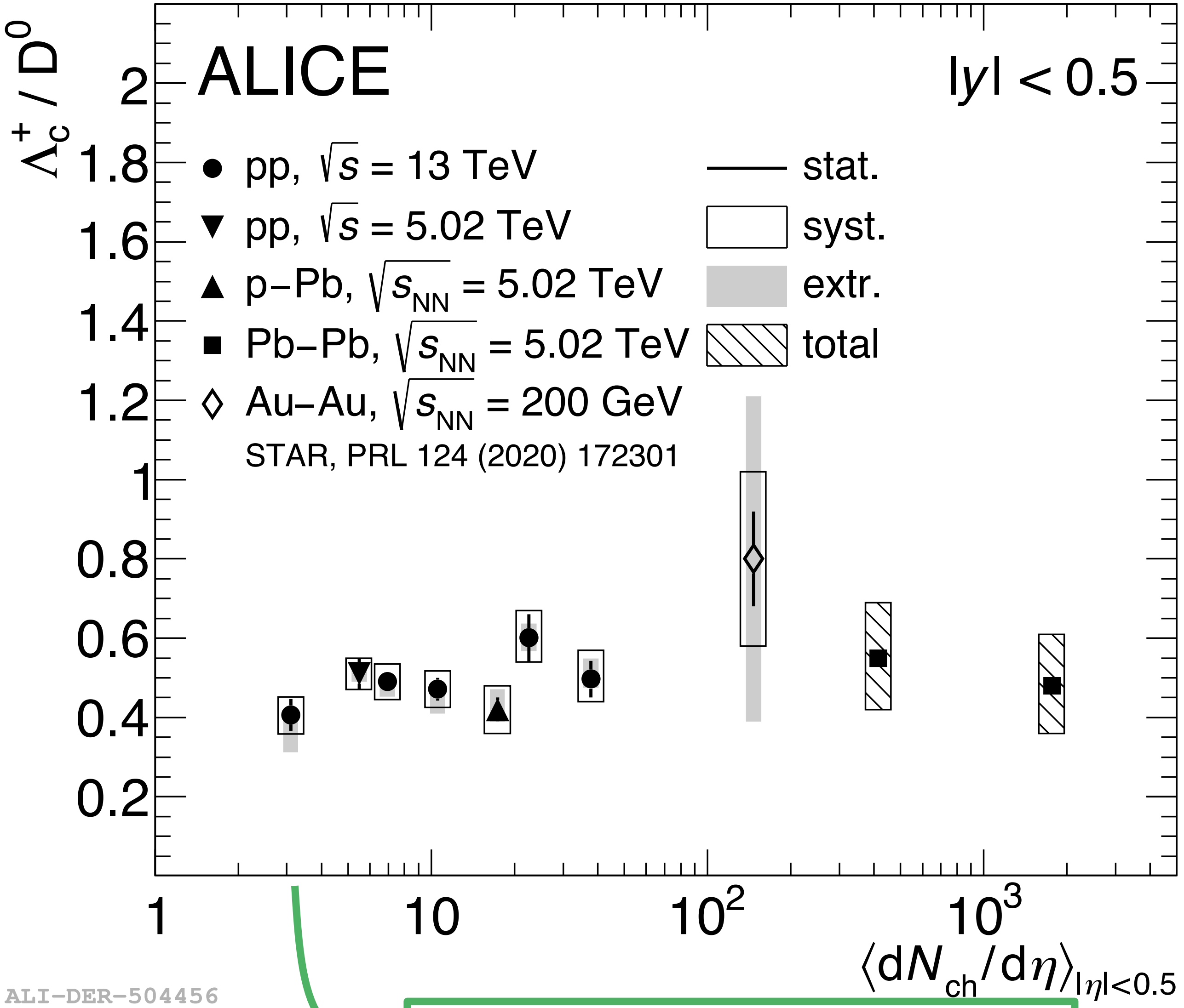
p_T-integrated Λ_c^+/D^0 ratio

New Pb–Pb: arXiv:2112.08156

New pp: arXiv:2111.11948

New and precise estimates by ALICE at **low and high multiplicities**

Hint of **flat trend with multiplicity**



ALI-DER-504456

L. Stritto, 07/04/21, 16:00

p_T-integrated Λ_c^+/D^0 ratio

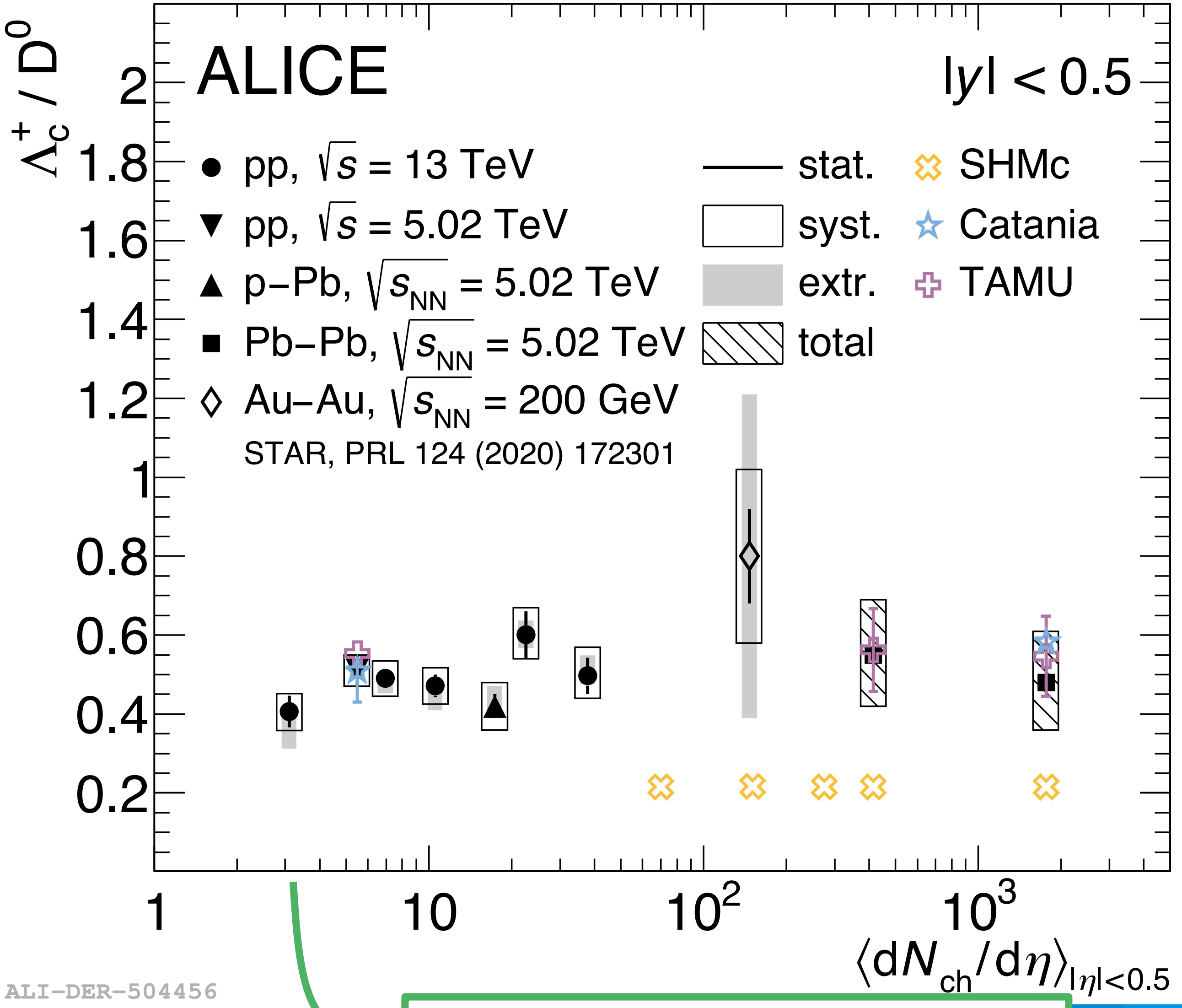
New Pb–Pb: arXiv:2112.08156

New pp: arXiv:2111.11948

New and precise estimates by ALICE at **low and high multiplicities**

Hint of **flat trend with multiplicity**

→ Reproduced by fragm+recomb and SHM predictions (including new charm-baryon states for the latter)



L. Stritto, 07/04/21, 16:00

TAMU: PRL 124, 042301 (2020)
Catania: PRC 96, 044905 (2017)
SHMc: JHEP 07 (2021) 035

p_T-integrated Λ_c^+/D^0 ratio

New Pb–Pb: arXiv:2112.08156

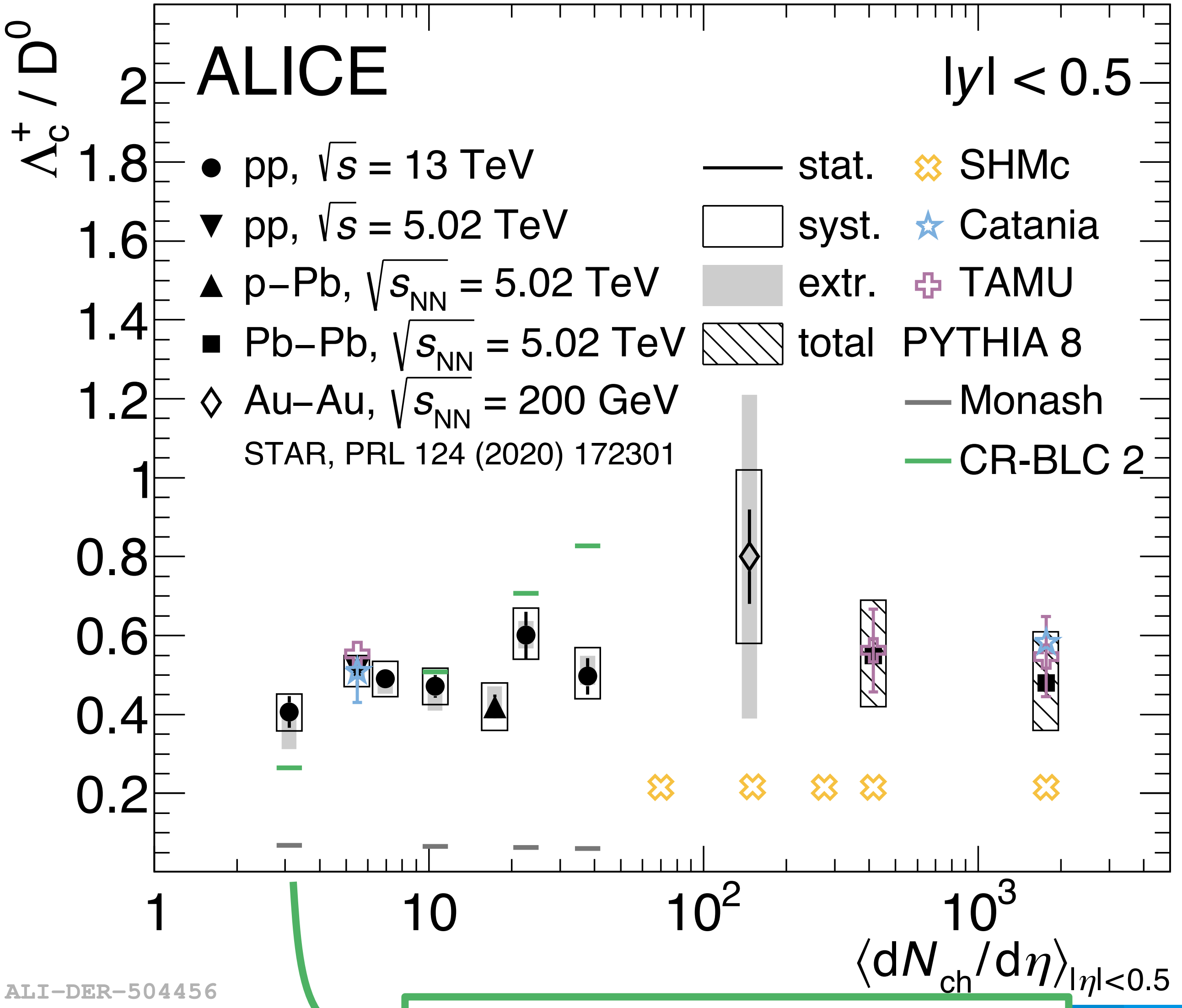
New pp: arXiv:2111.11948

New and precise estimates by ALICE at **low and high multiplicities**

Hint of **flat trend with multiplicity**

→ Reproduced by fragm+recomb and SHM predictions (including new charm-baryon states for the latter)

Is the p_T differential Λ_c^+/D^0 enhancement just a consequence of **radial flow and recombination**?



L. Stritto, 07/04/21, 16:00

TAMU: PRL 124, 042301 (2020)
Catania: PRC 96, 044905 (2017)
SHMc: JHEP 07 (2021) 035
Monash: EPJC 74 (2014) 3024
CR-BLC 2: JHEP 08 (2015) 003

Statistical hadronisation of charm

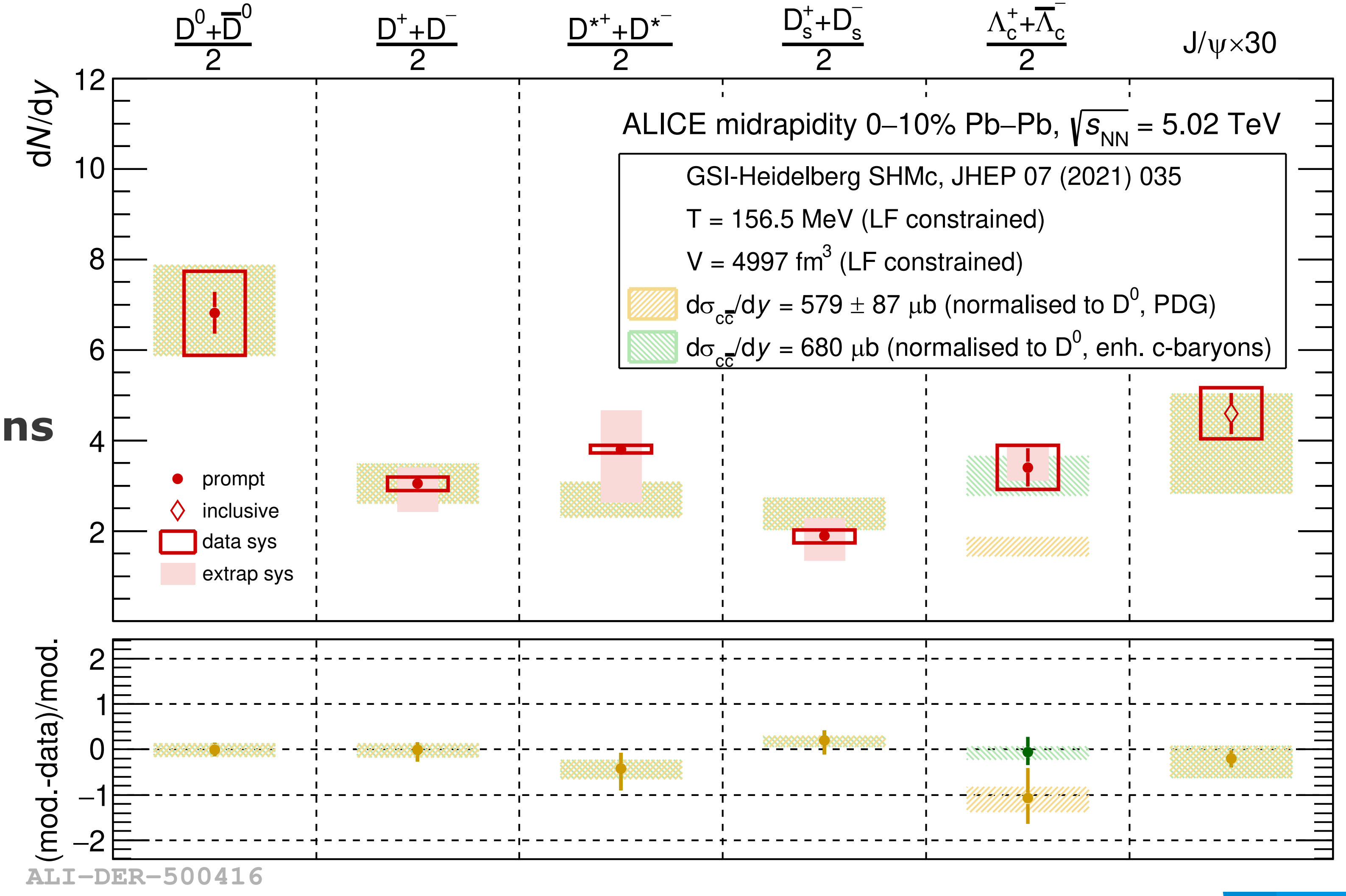
SHMc (charm quarks fully thermalised in the QGP)

→ Distributed into hadrons at phase boundary according to **thermal weights**

Measured yields of **open-charm mesons compatible** with SHMc

Measured yield of Λ_c^+ **underestimated**

→ Described in case of an enhanced charm-baryon resonance spectrum



Conclusion

ALICE performed precise heavy-flavour measurements with Run 2 Pb–Pb data

→ Charm mesons **down to p_T = 0**

→ **Charm-strange** mesons and **charm baryons** to low p_T

→ No p_T integrated Λ_c^+/D^0 enhancement with multiplicity

→ Beauty production also accessed, via non-prompt D mesons and $e^{\pm}$ from beauty decays

X. Peng, 06/04/21, 12:10

What did we learn so far?

→ Charm quarks interact with medium via **collisional and radiative processes**

→ Charm quarks participate in the collective motion, i.e. are **thermalised**

→ Charm quarks hadronise via **recombination** (in addition to fragmentation)

What's next?

Wide ALICE upgrade program for LHC Run 3 and 4, crucial for HF measurements

→ Continuous readout **at 50 kHz interaction rate** for Pb–Pb collisions

→ **Improved tracking precision** by a factor 3–6

→ New silicon Inner Tracking System

Run 3: ITS2 (**installed in 2021**)

Run 4: ITS3 (**TDR in preparation**)

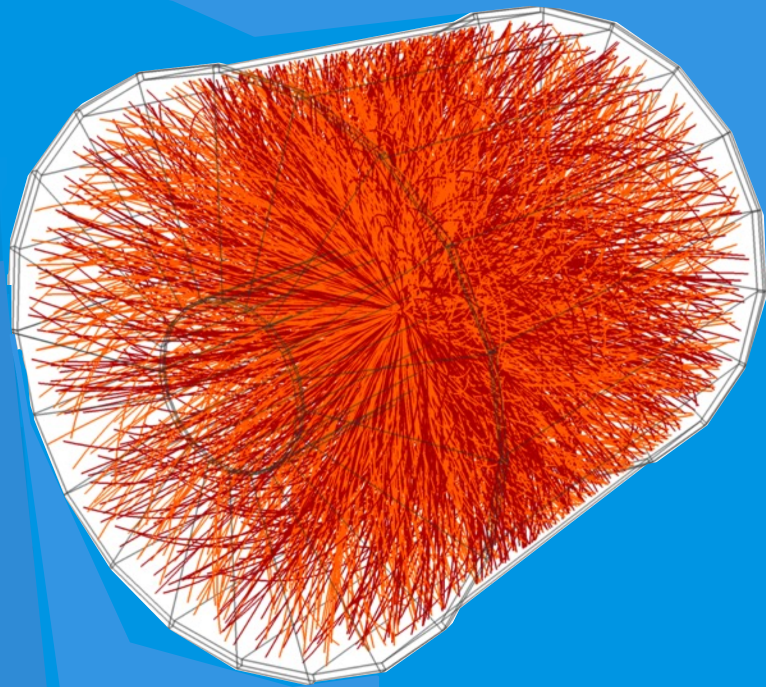
A. Alkin, 07/04/21, 15:40
S. Scheid, 07/04/21, 16:00

The near future will bring us **new** and **more precise** HF measurements down to **low p_T**, stay tuned…

Thank you for your attention!

ITS2: CERN-LHCC-2013-024 ITS3: CERN-LHCC-2019-018

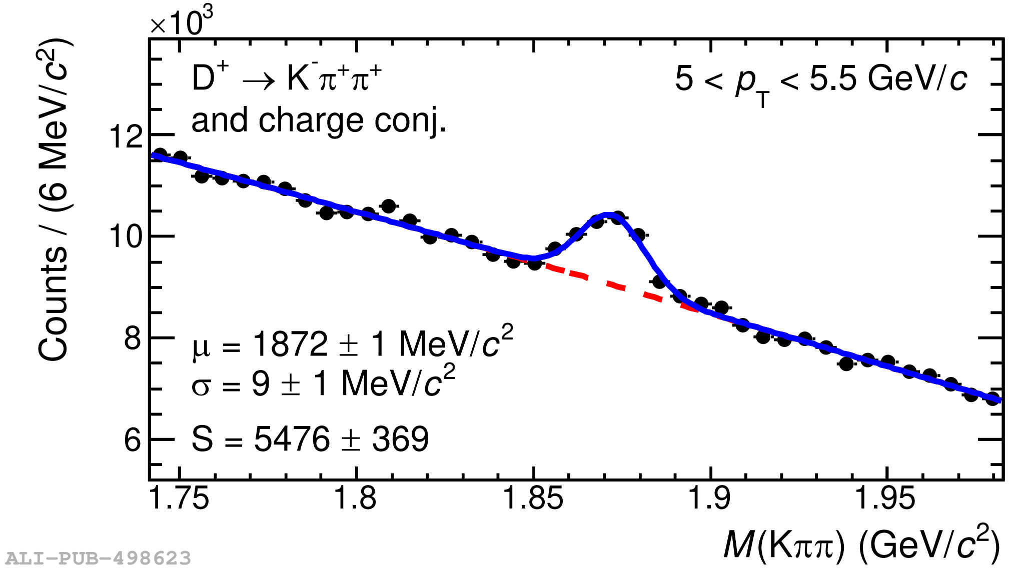
Additional slides

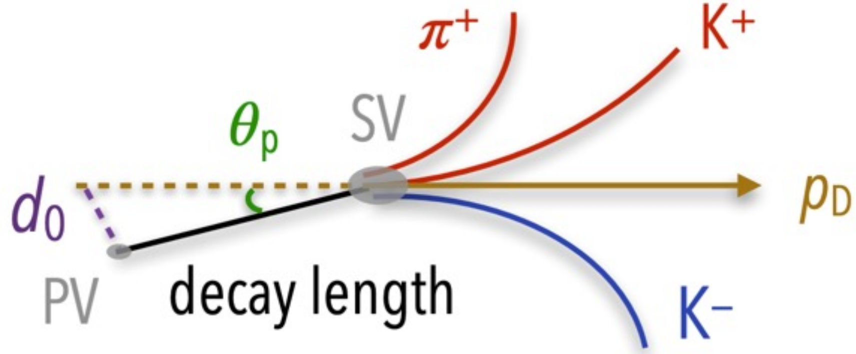


Experimental techniques: charm hadrons

Fully reconstructed charm hadrons (in ALICE):

1. Heavy-flavour candidates defined by combining **pairs/triplets of charged tracks** at midrapidity.
2. Apply **kinematical** and **geometrical** selections on displaced decay-topology.
3. Selections based on **particle identification** of decay tracks.
4. Signal extracted via an **invariant-mass analysis**.
5. Yield corrected for **efficiency** (MC simulations) and **feed-down from b-hadron decays** (pQCD predictions).



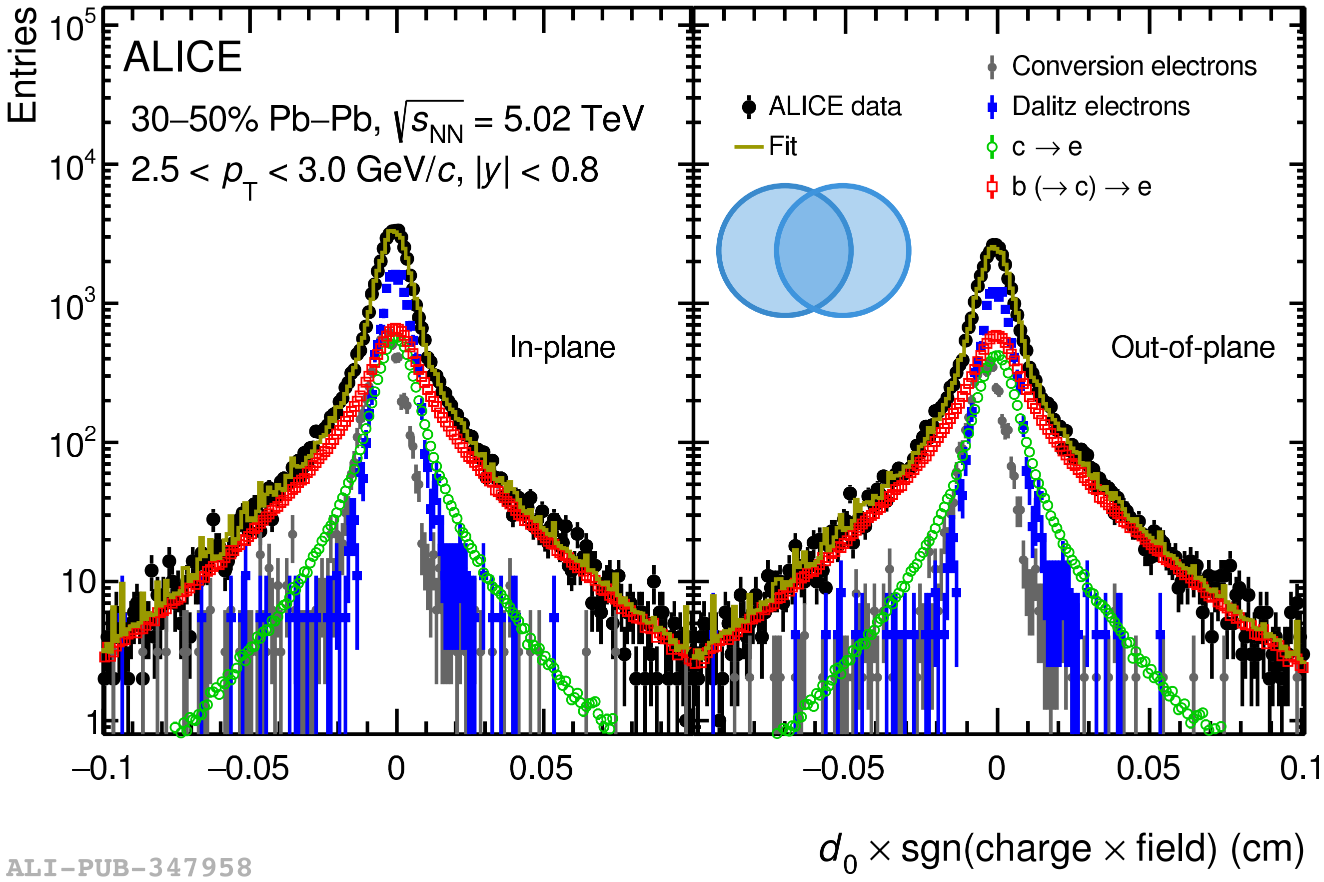


D^+: 311.8 μm
D_s^+: 151.2
D^0: 122.9
Λ_c^+: 60.7
D^{*+}: $2.4 \cdot 10^{-6}$

Experimental techniques: HF leptons

- Partial reconstruction **via semileptonic decays**
  - $\rightarrow$ c, b $\rightarrow e^{\pm}X$
  - $\rightarrow$ c, b $\rightarrow \mu^{\pm}X$

- Exploiting
  - $\rightarrow$ identification of $e^{\pm}$ at midrapidity
  - $\rightarrow$ tracking of $\mu^{\pm}$ at forward rapidity
  - $\rightarrow$ subtraction of hadron contamination and non-HF leptons
  - $\rightarrow$ separation of charm and beauty $e^{\pm}$ viia impact parameter d_0



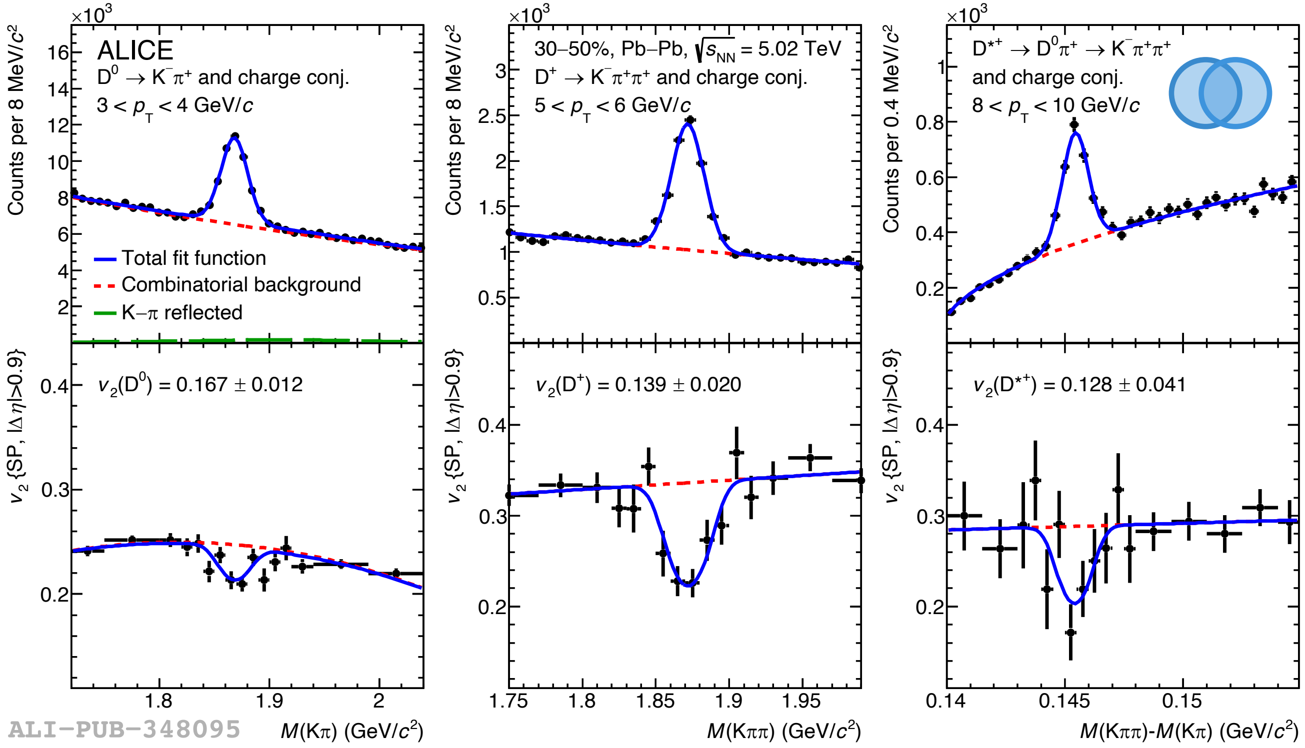
Experimental techniques: azimuthal anisotropies

v_2 measured with the **Scalar-Product** (SP) method

$$v_n\{\mathrm{SP}\} = \left\langle\left\langle \mathbf{u}_\mathrm{n} \cdot \mathbf{Q}_\mathrm{n}^{\mathrm{A}*} \right\rangle\right\rangle \Big/ \sqrt{\frac{\langle \mathbf{Q}_\mathrm{n}^\mathrm{A} \cdot \mathbf{Q}_\mathrm{n}^{\mathrm{B}*} \rangle \langle \mathbf{Q}_\mathrm{n}^\mathrm{A} \cdot \mathbf{Q}_\mathrm{n}^{\mathrm{C}*} \rangle}{\langle \mathbf{Q}_\mathrm{n}^\mathrm{B} \cdot \mathbf{Q}_\mathrm{n}^{\mathrm{C}*} \rangle}}$$

$$\mathbf{Q}_\mathrm{n} = \left(\Sigma_{k=0}^{N_\mathrm{tracks}} \cos(\mathrm{n}\varphi_k),\ \Sigma_{k=0}^{N_\mathrm{tracks}} \sin(\mathrm{n}\varphi_k)\right)$$

$$\mathbf{u}_\mathrm{n} = (\cos(\mathrm{n}\varphi_\mathrm{D}),\ \sin(\mathrm{n}\varphi_\mathrm{D}))$$



- Since per-particle identification of D mesons not possible, two component (signal, background) **fit of v_n vs. invariant mass** performed:

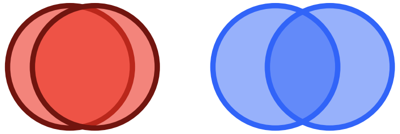
$$v_\mathrm{n}^\mathrm{tot}(M) = \frac{S}{S+B}(M) \cdot v_n^\mathrm{signal} + \frac{B}{S+B}(M) \cdot v_n^\mathrm{bkg}(M)$$

Azimuthal anisotropies (v_2)

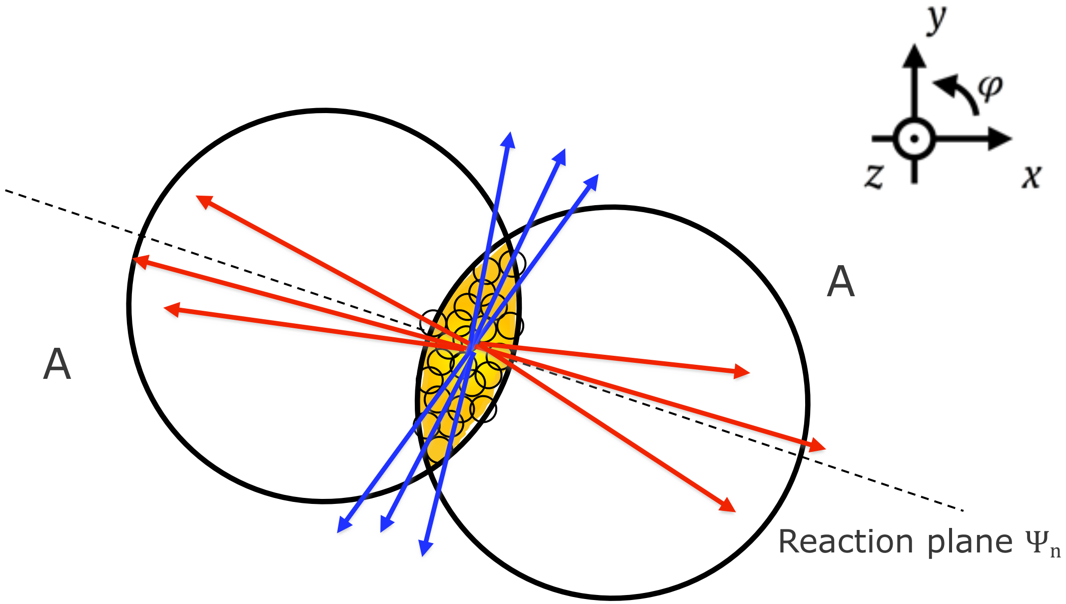
$$E\frac{d^3N}{dp_T} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left\{1 + \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right\}$$

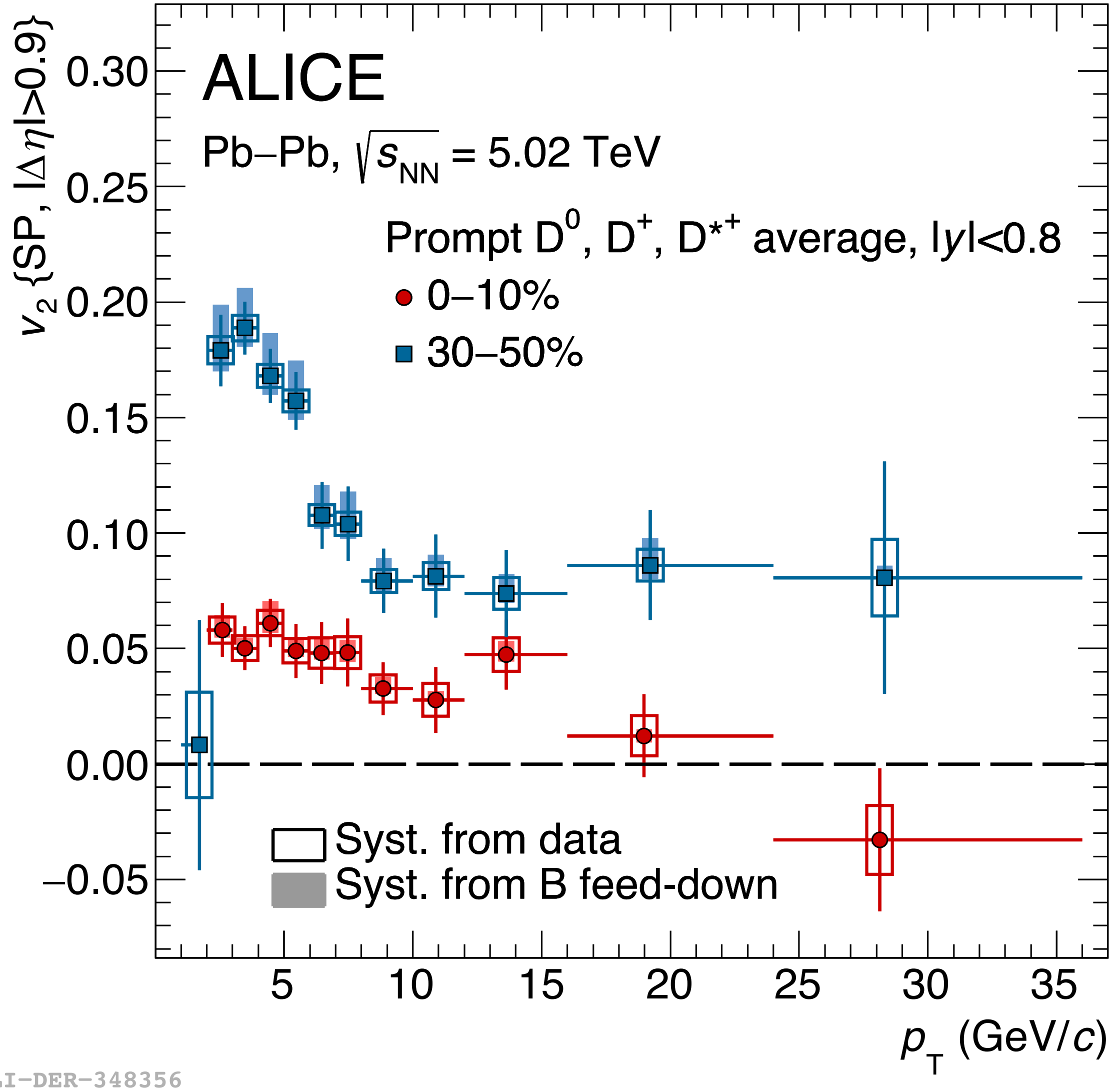
$$v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$$

second harmonic coefficient
elliptic flow



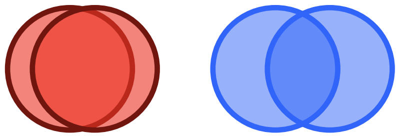
Asymmetry between the in-plane and out-of-plane directions.





PLB 813 (2021) 136054

Azimuthal anisotropies (v_3)



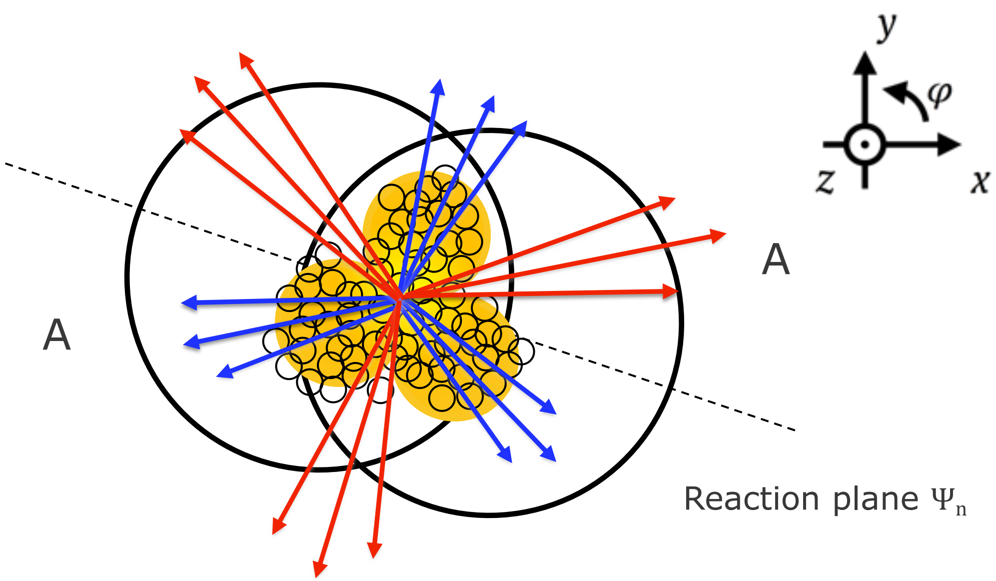
$$E\frac{d^3N}{dp_T} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left\{1 + \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right\}$$

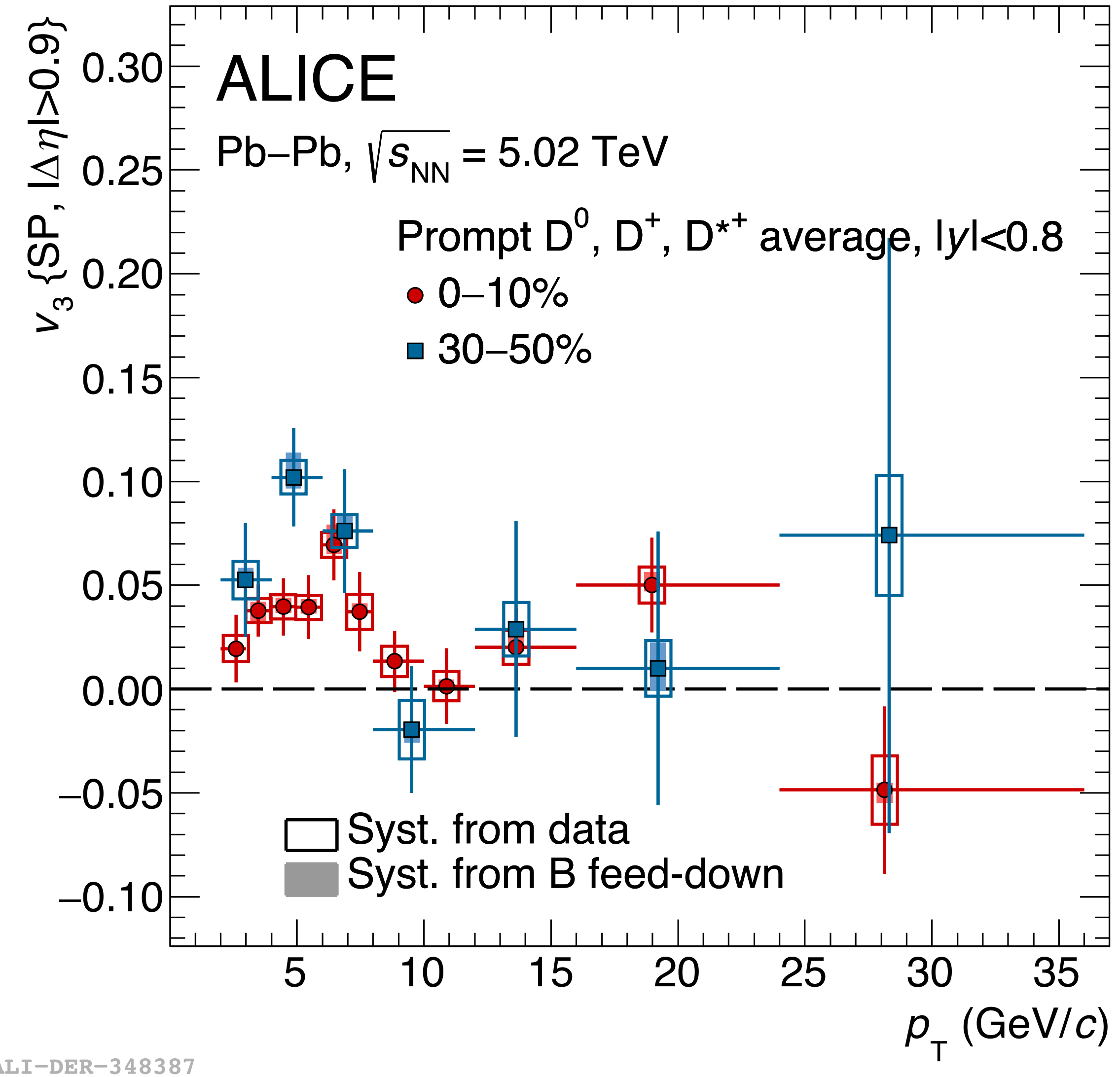
$$v_3 = \langle \cos[3(\varphi - \Psi_3)] \rangle$$

third harmonic coefficient
triangular flow

Event-by-event fluctuations in initial distributions of participant nucleons in the overlap region

- Sensitive to the shear viscosity over entropy density ratio, η/s.





ALI-DER-348387

PLB 813 (2021) 136054

Heavy versus light/charm versus beauty

p_T < 3-4 GeV/c: **Mass ordering**.

- $v_2(\Upsilon) \lesssim v_2(e \leftarrow b) \approx v_2(J/\Psi) < v_2(D) < v_2(\pi^\pm)$

→ Interplay between anisotropic flow and isotropic expansion of system (**radial flow**).

4 < p_T < 8 GeV/c: **No. constituent quark scaling**.

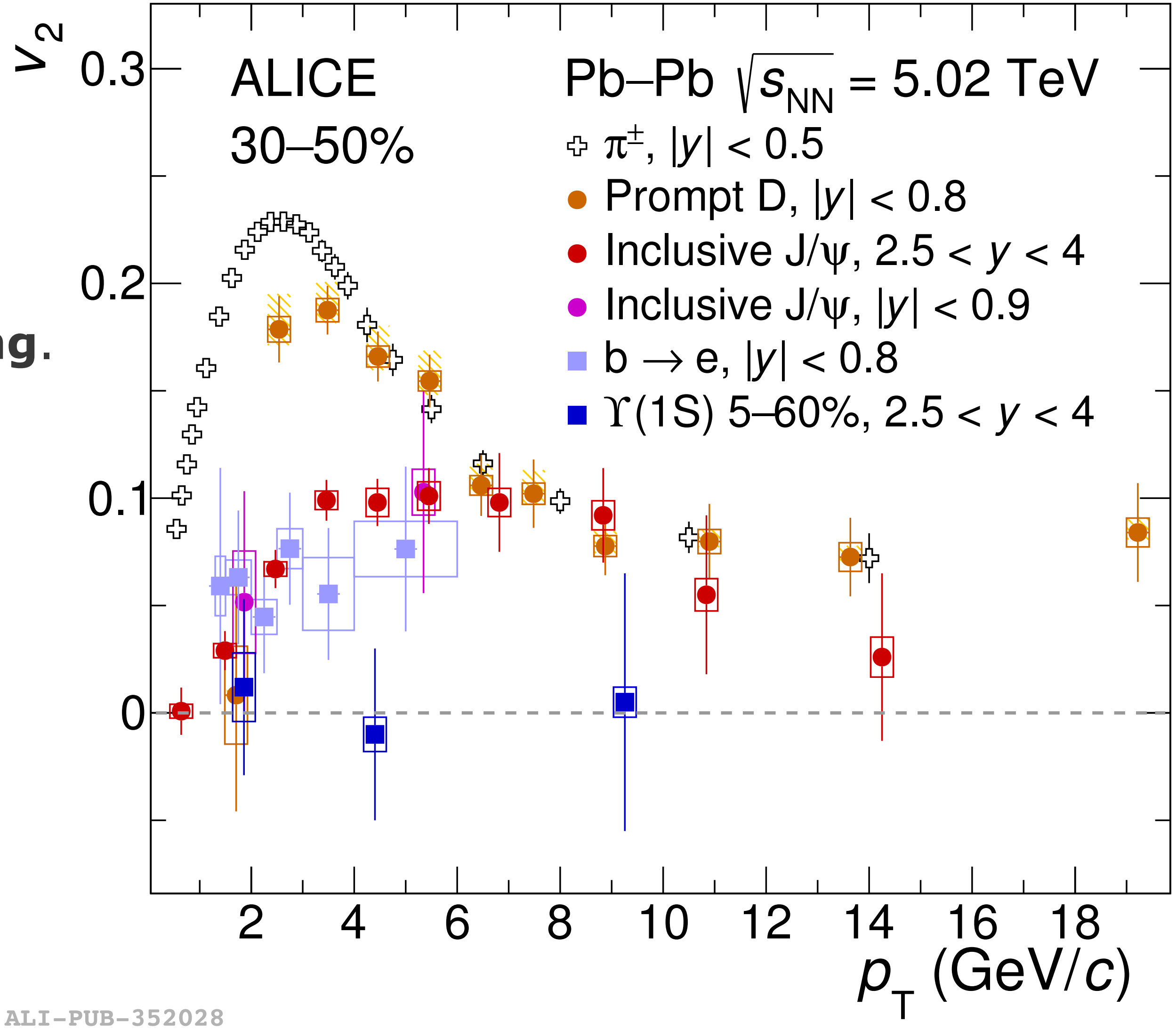
- $v_2(J/\Psi) < v_2(D) \approx v_2(\pi^\pm)$ $(< v_2(p))$
- $v_2(\Upsilon) < v_2(e \leftarrow b)$

→ Supports hypothesis of hadronisation via **quark coalescence**.

p_T > 8 GeV/c: **Compatible coefficients**.

- $v_2(J/\Psi) \approx v_2(D) \approx v_2(\pi^\pm)$ $(\approx v_2(p))$

→ Supports hypothesis of similar **path-length dependence** of in-medium energy loss.



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PRL 123, 192301 (2019)
PRL 126, 162001 (2021)

Charm-hadron flow carried by light quarks

Test of n-quark scaling and recombination mechanisms

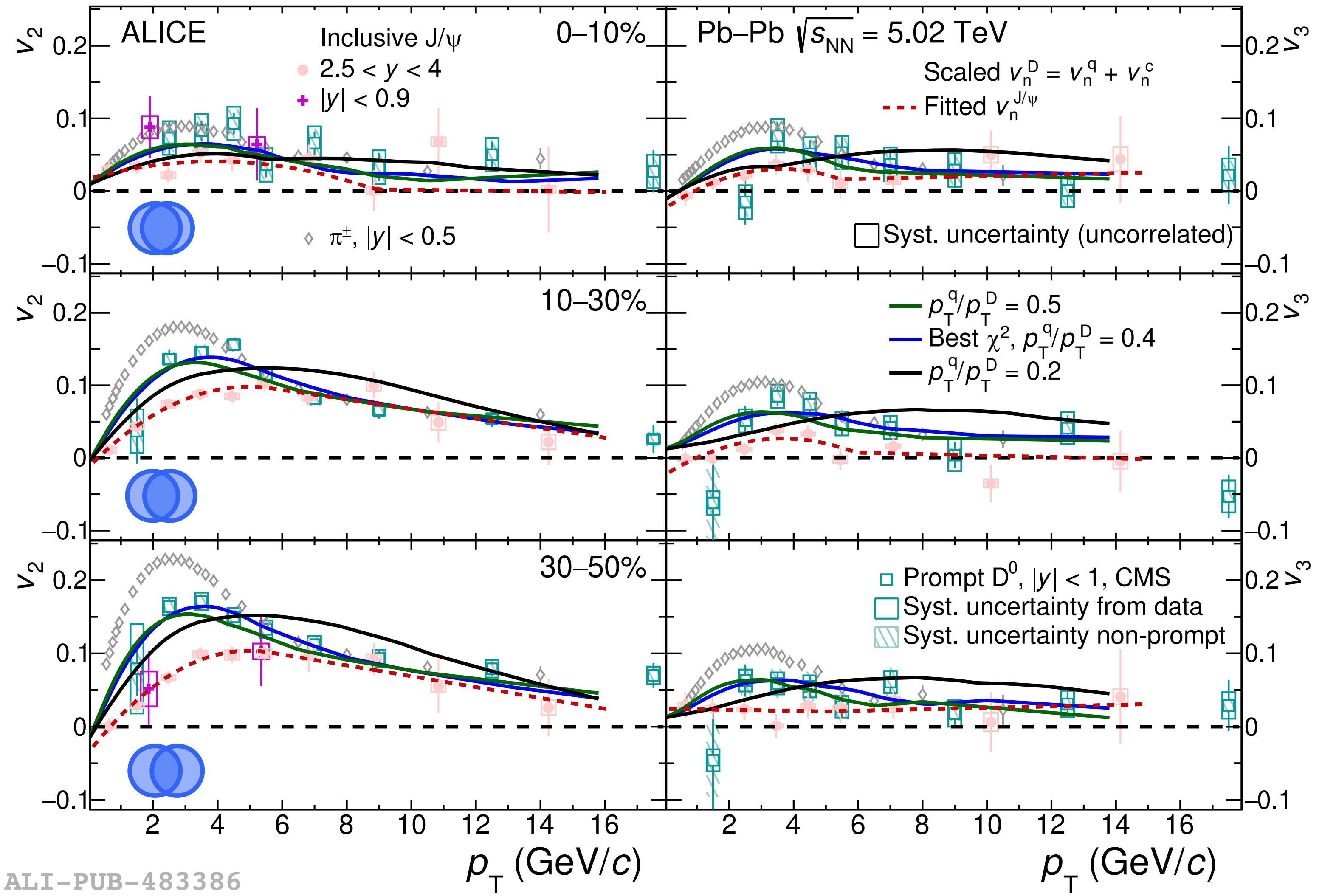
→ quark flow obtained by intepolating $v_n(\mathrm{J}/\Psi)$ and $v_n(\pi)$

→ assuming:

$$v_n^{\pi}(p_{\mathrm{T}}^{\pi}) = 2 * v_n^{q}(p_{\mathrm{T}}^{\pi}/2)$$

$$v_n^{\mathrm{D}}\left(p_{\mathrm{T}}^{\mathrm{D}}\right) = v_n^{q}\left(p_{\mathrm{T}}^{q}\right) + v_n^{\mathrm{c}}(p_{\mathrm{T}}^{\mathrm{c}})$$

→ Good description of D^0 flow when light quark carries a large fraction (i.e. $p_{\mathrm{T}}^{q}/p_{\mathrm{T}}^{\mathrm{D}} = 0.4$) of D meson p_{T}



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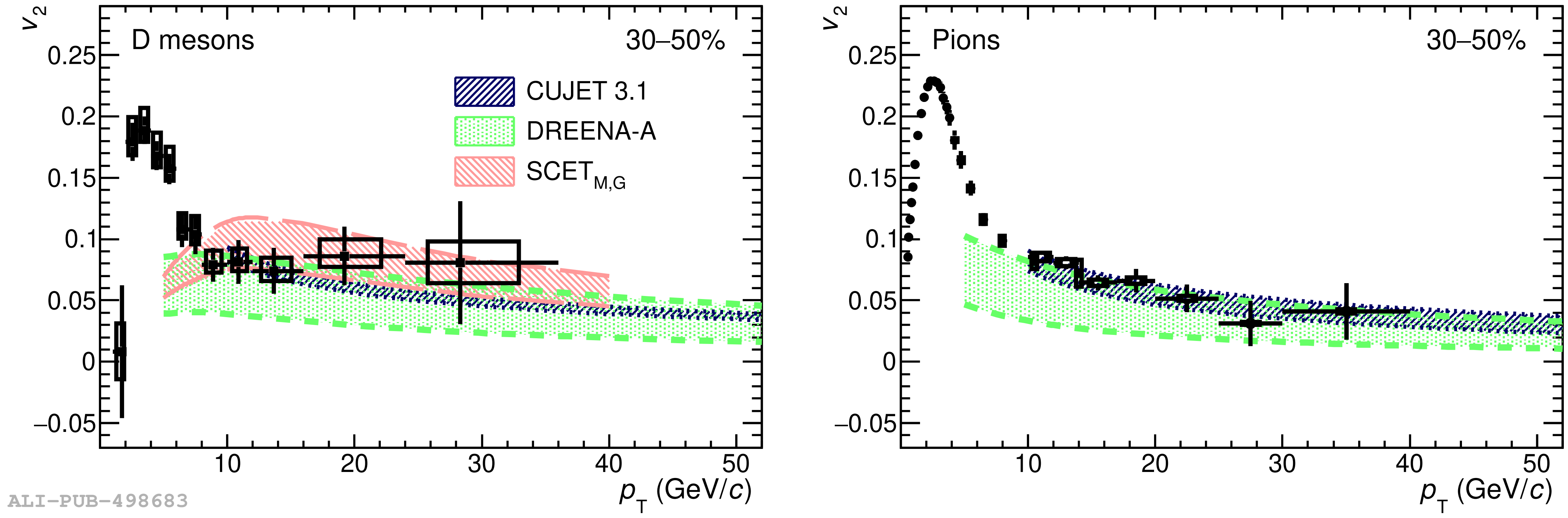
JHEP 1809 (2018) 006

Heavy versus light versus theory



Perturbative QCD calculations describe reasonably well the measured v_2, "confirming"

- the **quadratic path length dependence** of radiative energy loss;
- the expected mass dependence due to the **dead-cone effect**.

	Collisional en. loss	**Radiative en. loss**	**Coalescence**	**Hydro**	**nPDF**
CUJET 3.1	✅	✅	❌	✅	✅
DREENA-A	✅	✅	❌	✅	❌
SCET$_{M,G}$	✅	✅	❌	❌	✅

opacity expansion model

soft-collinear effective theory

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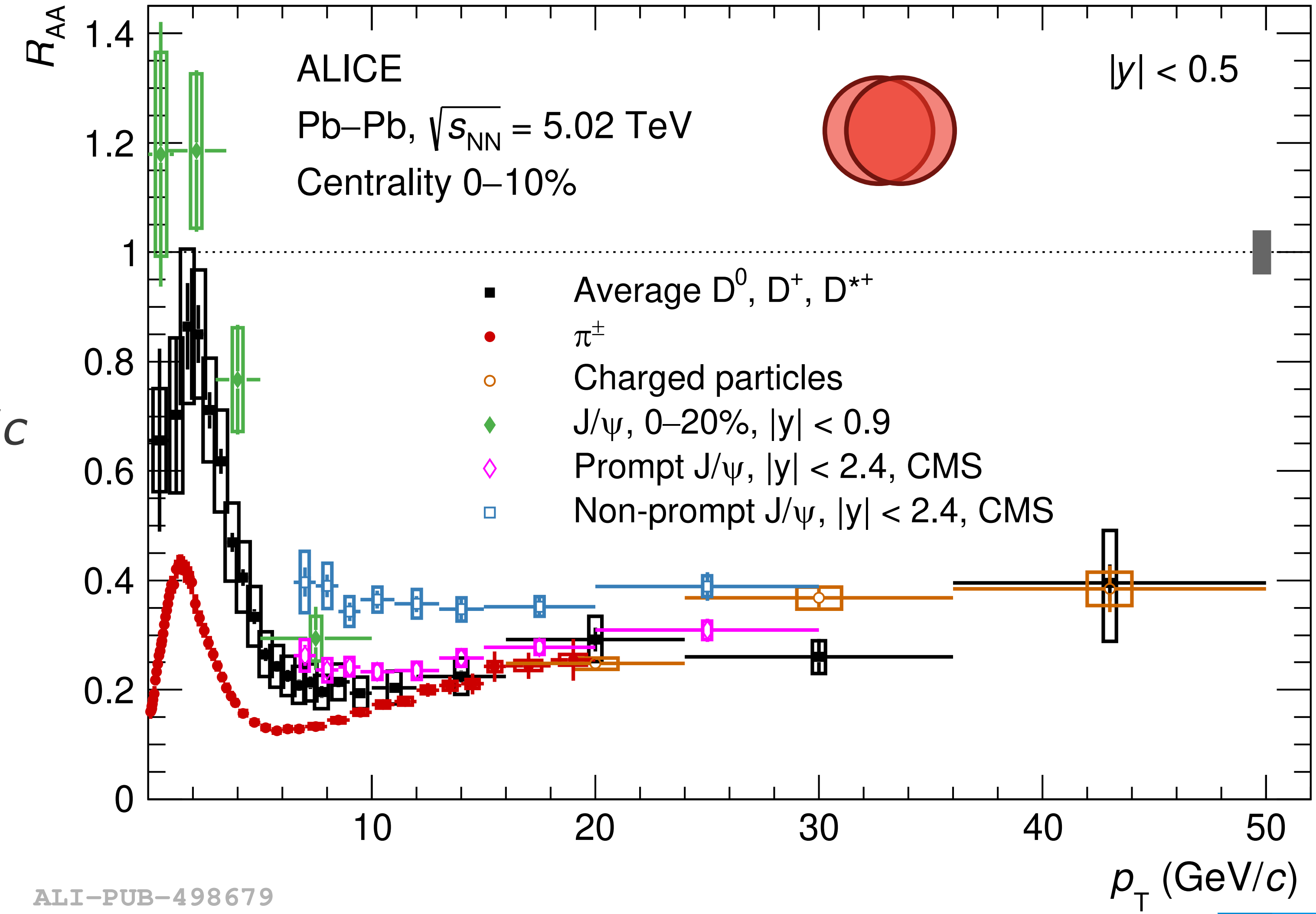
Heavy versus light/charm versus beauty

R_{AA}(**D**) > R_{AA}(**LF**) for $p_T < 8$ GeV/c

R_{AA}(**charm**) < R_{AA}(**beauty**)

R_{AA}(**D**) ≈ R_{AA}(**J/ψ**) for $p_T \gtrsim 10$ GeV/c

R_{AA}(**D**) ~ R_{AA}(**J/ψ**) for $p_T \gtrsim 2$ GeV/c



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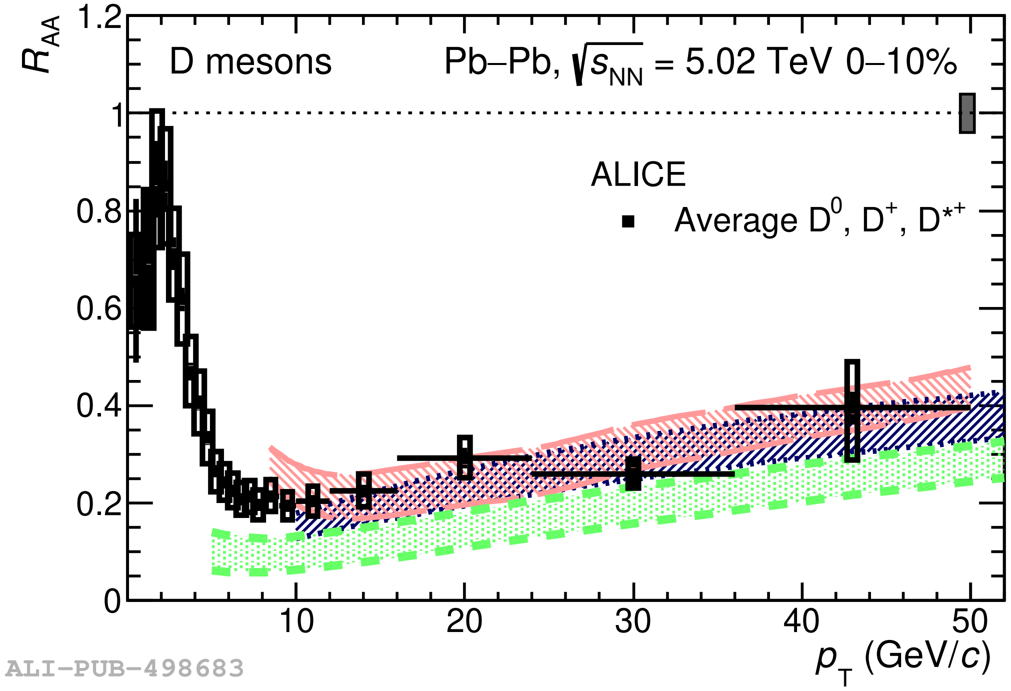
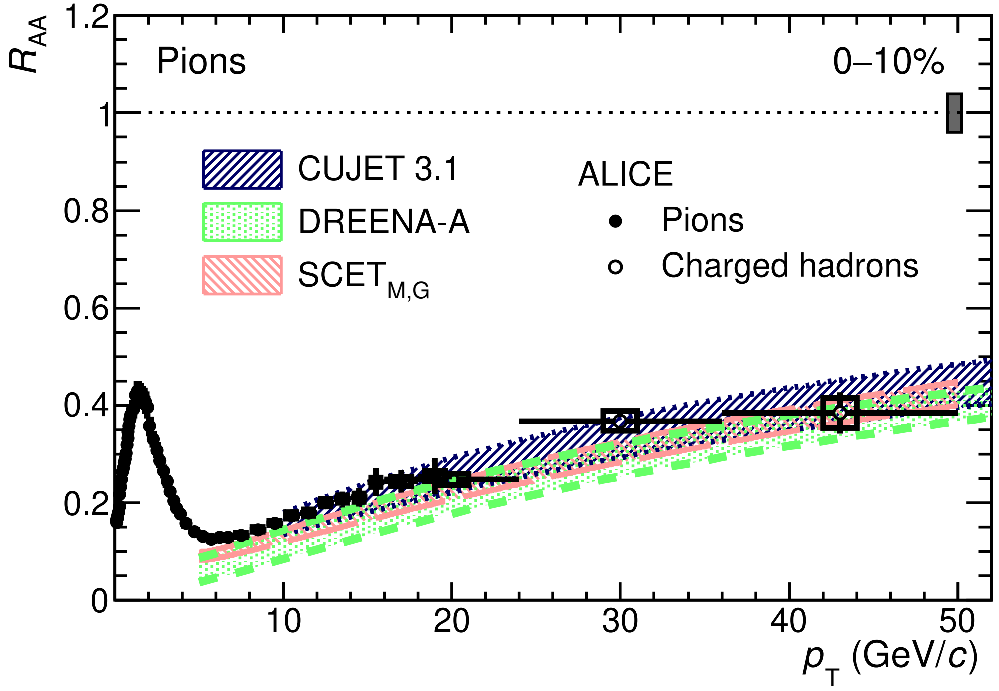
Heavy versus light versus theory





Perturbative QCD calculations describe reasonably well the measured R_{AA}, “confirming”

- the **quadratic path length dependence** of radiative energy loss;
- the expected mass dependence due to the **dead-cone effect**.

	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF
CUJET 3.1	✅	✅	❌	✅	✅
DREENA-A	✅	✅	❌	✅	❌
$SCET_{M,G}$	✅	✅	❌	❌	✅

opacity expansion model

soft-collinear effective theory

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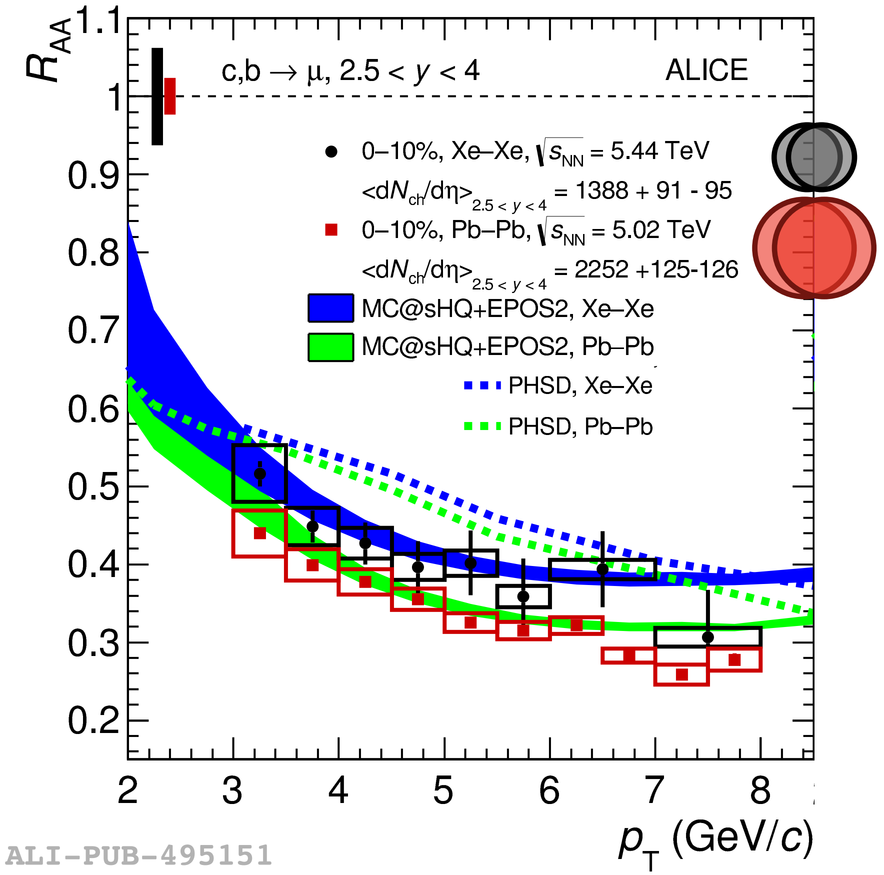
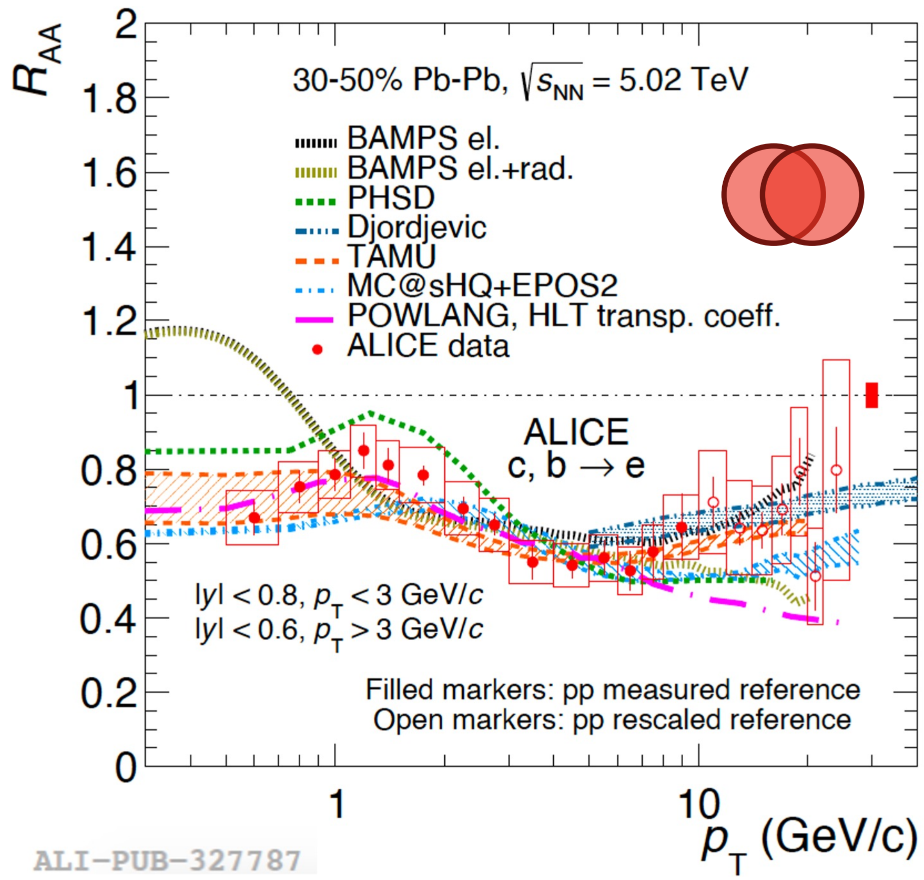
Heavy flavour decay leptons

R_{AA} of HF decay muons and electrons reasonably well described by most transport models

→ Some tension for PHSD (no radiative e-loss) with forward muons, but describes $e^{\pm}$ at midrapidity





$\mu^{\pm}$: PLB 819 (2021) 136437

$e^{\pm}$: PLB 804 (2020) 135377

MC@sHQ: PRC 89, 014905 (2014)

PHSD: PRC 93, 034906 (2016)

Djordjevic: PRC 92, 024918 (2015)

BAMPS: JPG 42 (2015) 11, 115106

TAMU: PLB 735 (2014) 445-450

POWLANG: EPJC 75 (2015) 3, 121

Charm-quark transport models: ingredients

	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**.