Recent results from the ALICE experiment

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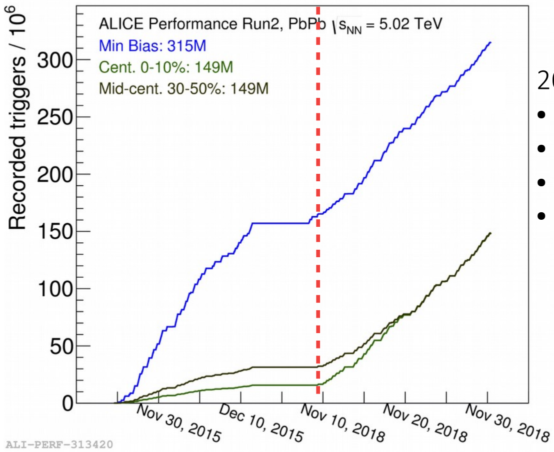
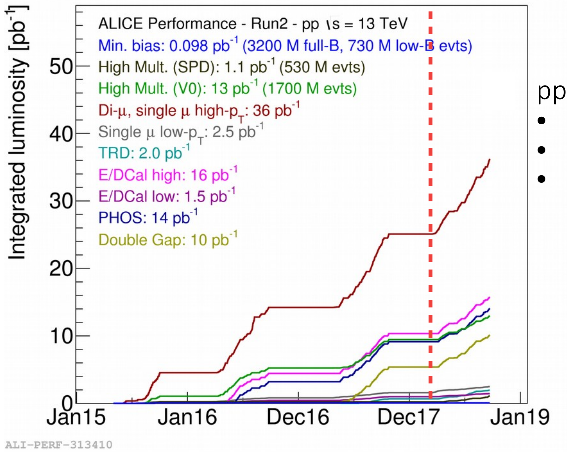
Run 2 statistics

system	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	0.9	$\sim 200\ \mu b^{-1}$
	2.76	$\sim 100\ nb^{-1}$
	5.02	$\sim 1.3\ pb^{-1}$
	7	$\sim 1.5\ pb^{-1}$
	8	$\sim 2.5\ pb^{-1}$
	13	$\sim 25\ pb^{-1}$
p–Pb	5.02	$\sim 15 + 3\ nb^{-1}$
	8.16	$\sim 25\ nb^{-1}$
Xe–Xe	5.44	$\sim 0.3\ \mu b^{-1}$
Pb–Pb	2.76	$\sim 75\ \mu b^{-1}$
	5.02	$\sim 0.25 + 1\ nb^{-1}$

- **Data taking efficiency in 2018:**
  - ~ 92% for pp in 2018
  - ~ 87% for Pb-Pb



2018 Pb-Pb data taking:
- Minimum Bias ~2015 Pb-Pb run
- Central 0-10% ~ 9 x 2015
- Mid-central 30-50% ~ 4 x 2015
- Delivered luminosity ~ 2 x 2015

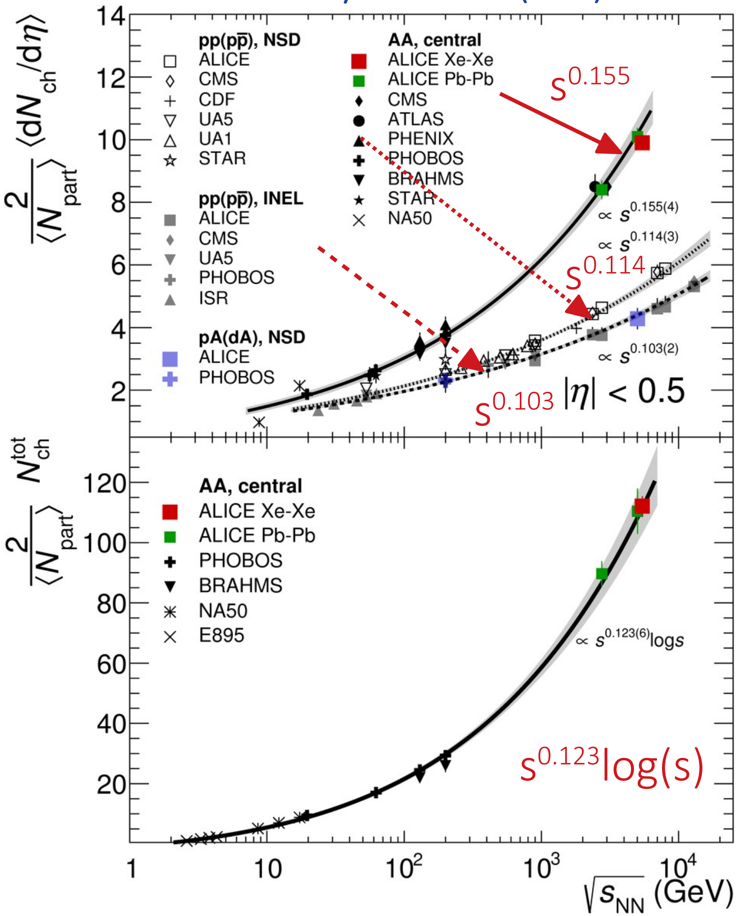


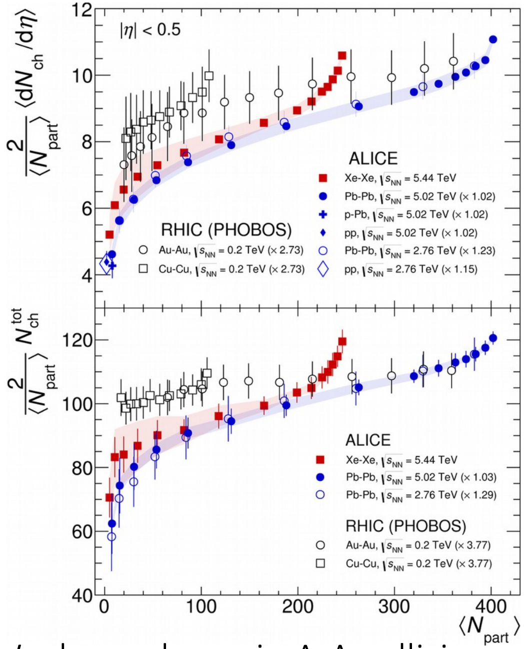
pp@13TeV total statistics:
- Minimum bias
- High multiplicity (V0 and SPD)
- Rare triggers: Muon, EMCAL/DCAL, PHOS, TRD, diffractive

Light flavor physics, flow and femtoscopy

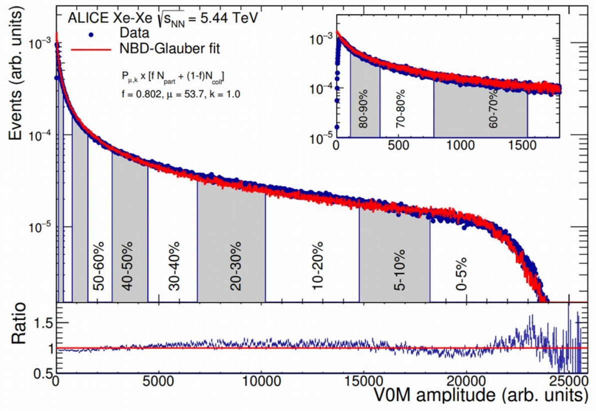
Charged-particle multiplicity in pp,p-Pb, Pb-Pb and Xe-Xe

ALICE Collaboration Phys.Lett. B 790 (2019) 35





Ts



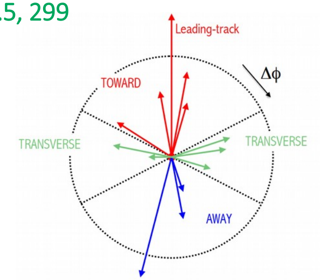
ALICE-PUBLIC-2018-003

- √s dependence in A-A collisions differs from pp and p-Pb (no universal scaling)
- Charged particle multiplicity density and total multiplicity as a function of centrality:
  - Deviations from N_{part} scaling
- Steeper rise in most central Xe-Xe and Pb-Pb collisions due to upward fluctuations

Transverse/toward p_T spectra in pp

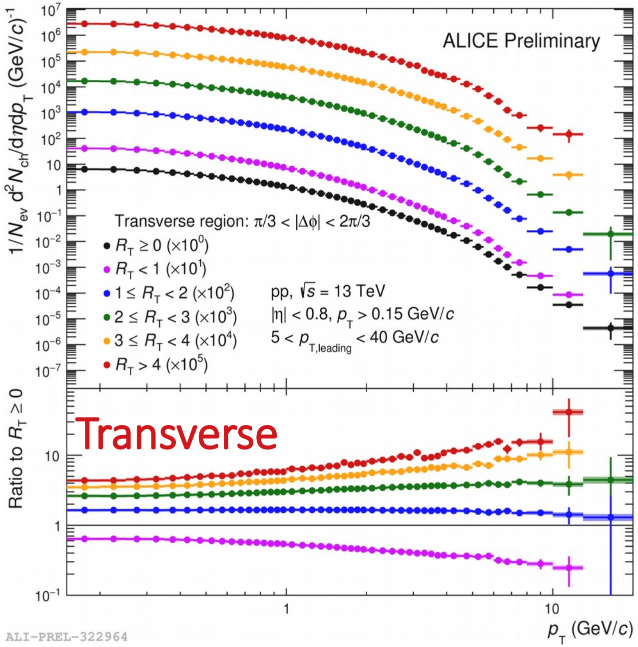
Ts

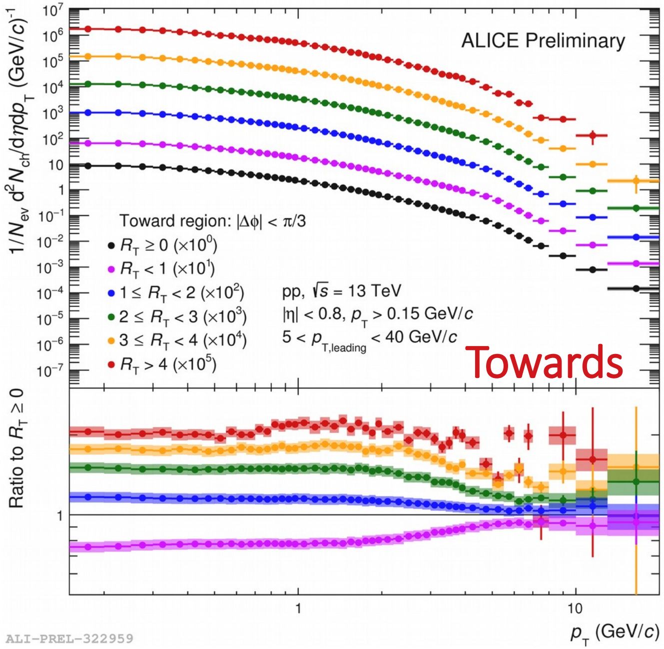
Eur. Phys. J. C76 (2016) no.5, 299



Transverse activity classifier R_T in the plateau region (jet pedestal)

$$R_T = \frac{N_{inclusive}}{\langle N_{inclusive} \rangle}$$

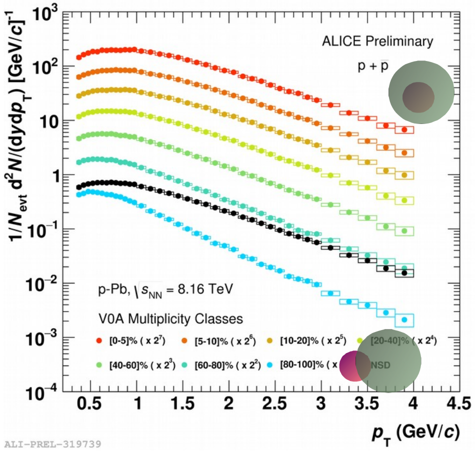




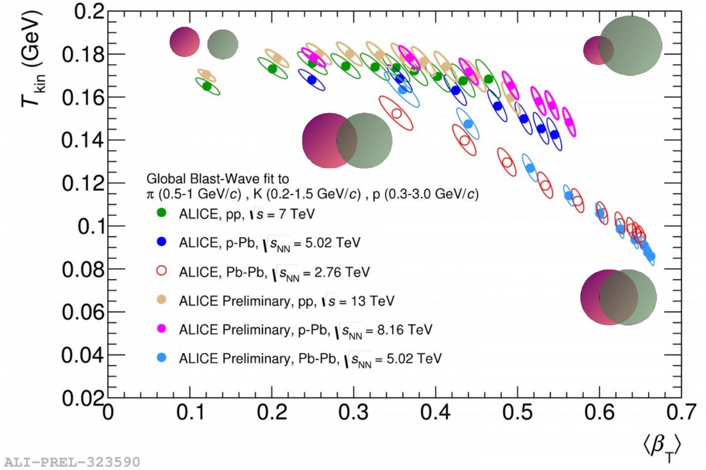
- p_T spectra in multiplicity intervals are biased due to correlations between low- and high-p_T particles → harder spectra in higher multiplicity events (ALICE, arXiv:1905.07208)
- R_T selection (jet free multiplicity estimator) can be used to reduce biases and help to understand these correlations
- Opposite trend at high p_T for transverse and toward spectra
  - Convergence to the inclusive jets for the toward spectra at high p_T → separation between soft (UE) and hard (jet) of the spectrum

p_T spectra of identified hadrons

Ba,Bo, Ca, Ct, LNF, To



Simultaneous BW fit to π ,K and p spectra

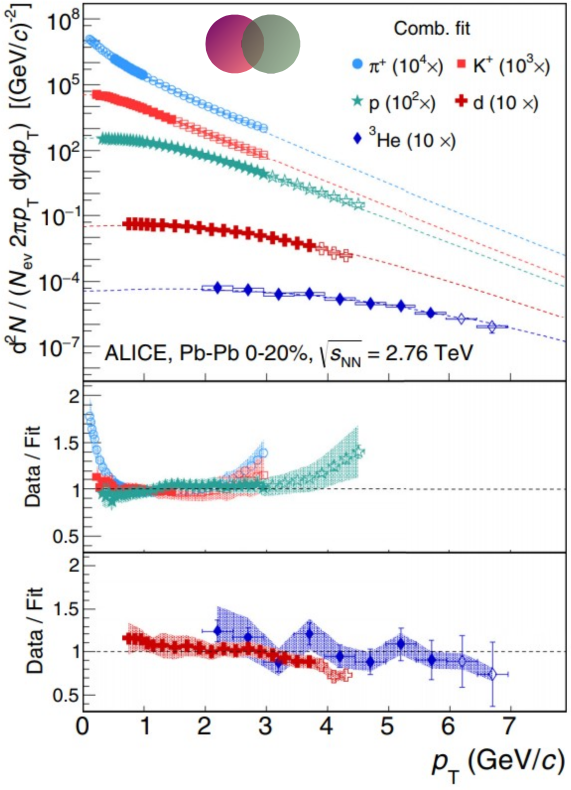


- Measured and identified with different analysis techniques: ITS, TPC, TOF, HMPID and topological identification
- Mass dependent hardening of the spectra with increasing centrality
  - Collective radial expansions
- Blast-Wave [1] (simplified hadrodynamic) model used to fit all the collected collision systems:
  - Similar trend observed in pp, p-Pb and Pb-Pb collisions
  - Large systems (Pb-Pb and Xe-Xe):
    - larger β_T for central Pb-Pb collisions
    - comparable T_{kin} and $\langle\beta_T\rangle$ in collisions at a similar $\langle dN_{ch}/d\eta\rangle$
  - Small systems p-Pb & pp vs A-A:
    - similar increase of $\langle\beta_T\rangle$ consistent with the presence of radial flow in p-Pb collisions.

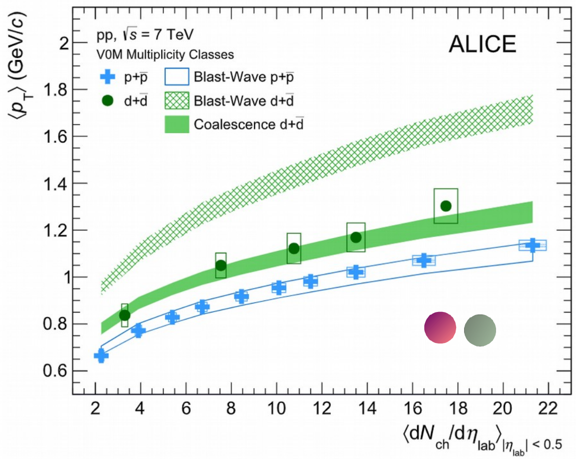
[1] Phys. Rev. C 48 (1993) 2462

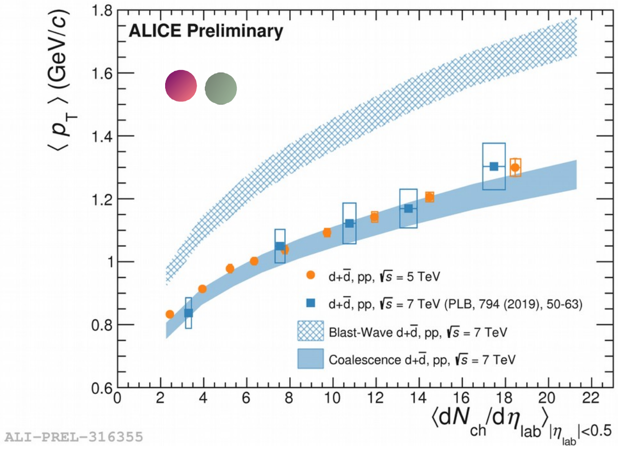
Blast-Wave fit including nuclei

ALICE Collaboration Phys. Rev. C 93.024917



ALICE Collaboration, Phys. Lett. B 794 (2019) 50–63



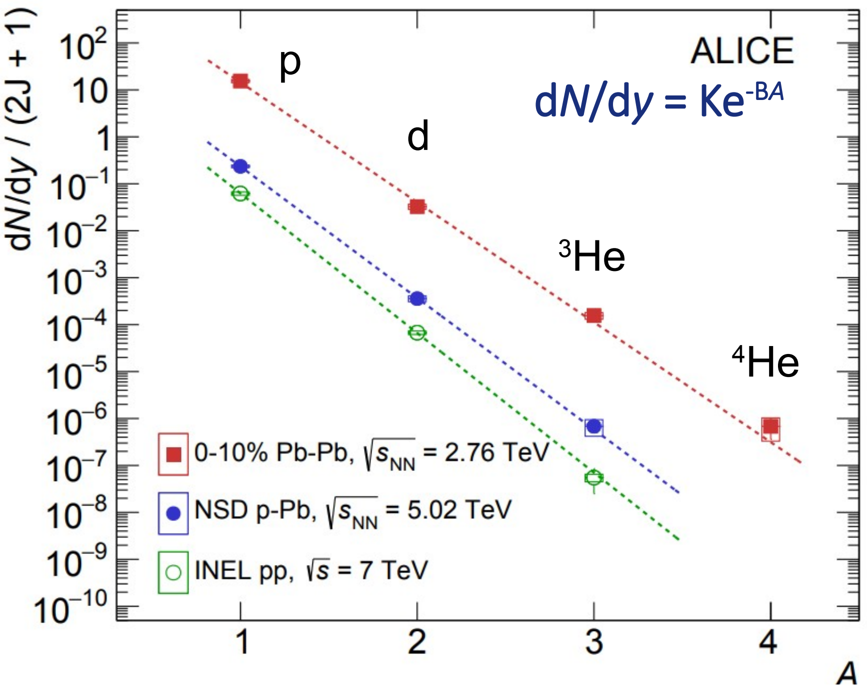


- In Pb-Pb collisions nuclei participate in collective expansions with $\langle\beta_T\rangle$ ~ 0.63 and T_{kin} ~ 113 MeV (consistent with π,K, p)
- In pp and p-Pb Blast-Wave model does not reproduce $\langle p_T\rangle$ of (anti-)deuteron
  - Coalescence scenario favored for deuteron production in pp

Bo,To,Ts

Nuclei production : penalty factor

ALICE Collaboration arXiv:1906.03136



ALICE Collaboration:
pp: Phys. Rev. C97 no. 2, (2018) 024615; arXiv:1709.08522
Pb-Pb: NPA 971, 1 (2018); arXiv:1710.07531,
p-Pb : arXiv:1906.03136

- Thermal model prediction: exponential dependence of the yield

$$\frac{dN}{dy} \propto \exp\left(-\frac{m}{T_{chem}}\right)$$

- The density ratio of a particle with the next heavier one:

$$\frac{n_i}{n_{i+1}} \approx \exp\left(-\frac{\Delta m}{T_{chem}}\right)$$

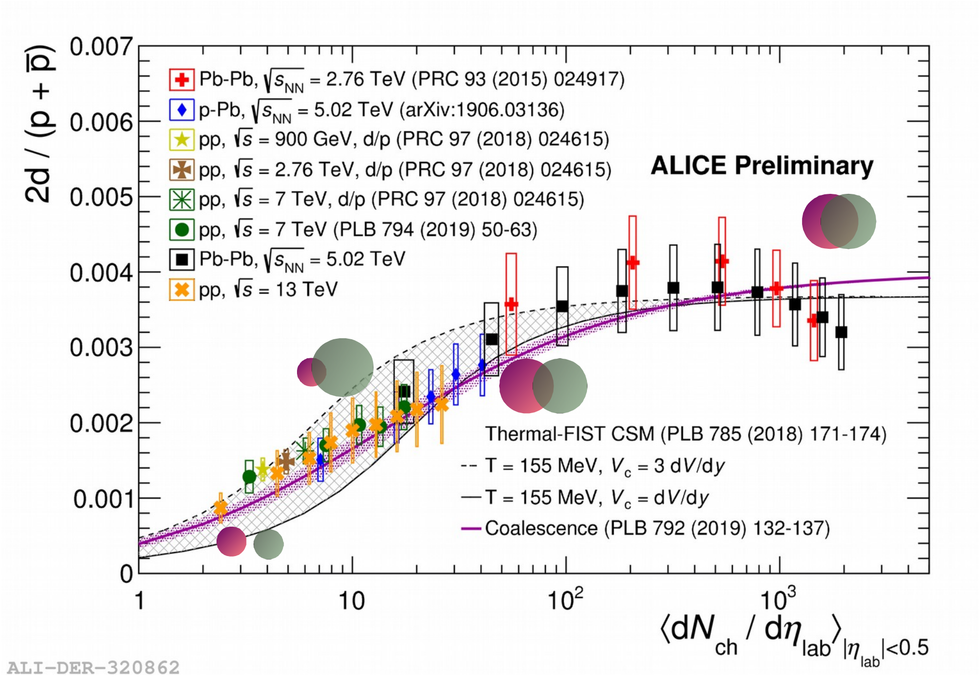
- Exponential decrease as expected from thermal model predictions
  - Pb-Pb : 359±41
  - p-Pb : 635±90
  - pp : 942±107

Production mechanisms: thermal vs coalescence?

Bo,To,Ts

Light nuclei production: Deuteron to proton ratio

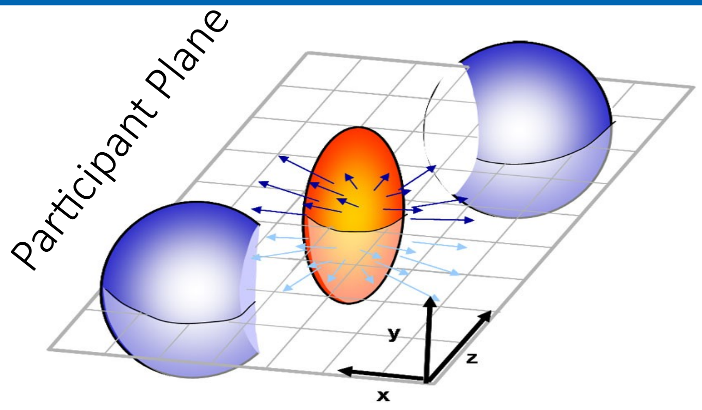
Bo,To,Ts



- d/p increases with multiplicity going from pp to peripheral Pb-Pb : consistent with simple coalescence ($d \propto p^2$)
- No significant centrality dependence in Pb-Pb : consistent with thermal model (yield fixed by T_{chem})
- How the two models are connected is not yet fully understood: **is there a single particle production mechanism?**

- Increasing trend at low and intermediate multiplicities:
  - SHM: Canonical suppression
  - Coalescence: increasing phase space
- No dependence of the ratio on multiplicity for high multiplicities
  - In agreement with both SHM and coalescence

Anisotropic flow



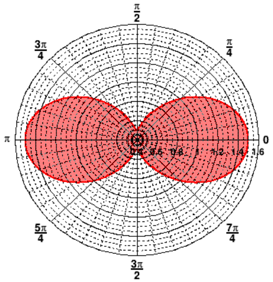
Angular distribution of reconstructed charged particles can be expanded into a Fourier series w.r.t. symmetry plane $\Psi_{\{n\}}$:

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

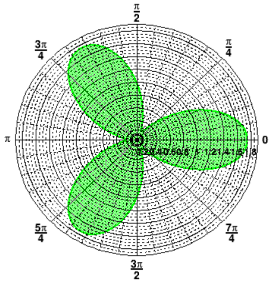
$$v_n=\left\langle\cos\left(n\left(\phi-\Psi_{\{n\}}\right)\right)\right\rangle$$

- The measurement of light nuclei v_2 will help in the understanding of particle production mechanisms
  - Do light nuclei follow the mass ordering observed for lighter particles?
  - Do light nuclei follow a quark/baryon number scaling (coalescence) or follow mass scaling (hydro)?

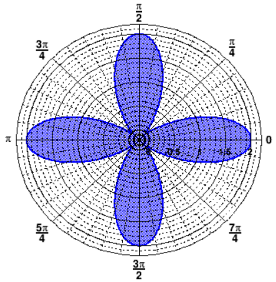
v_2



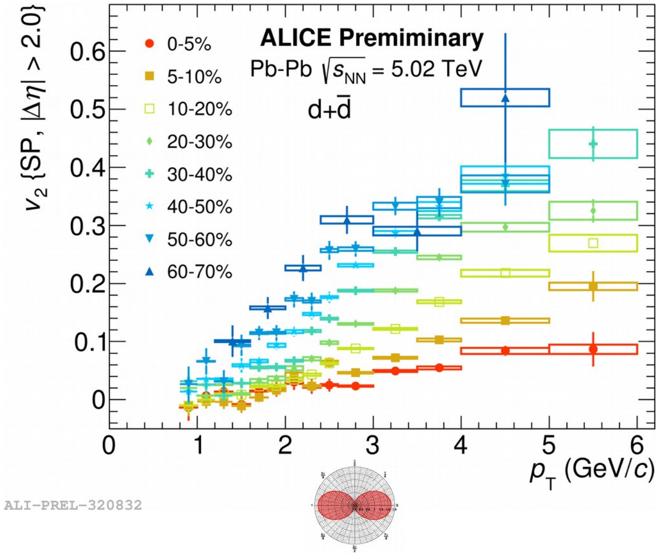
v_3

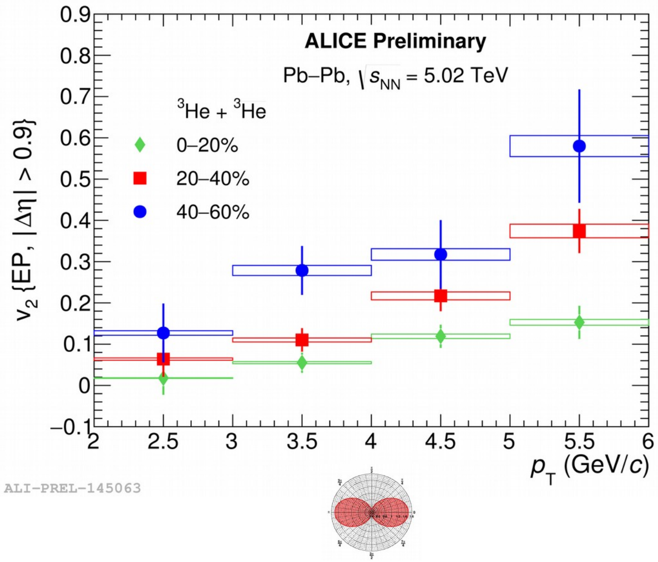


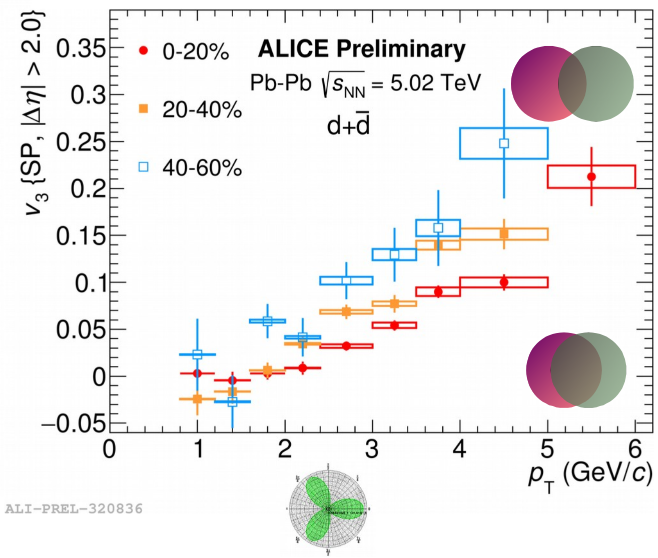
v_4



Light nuclei v_n for different centralities



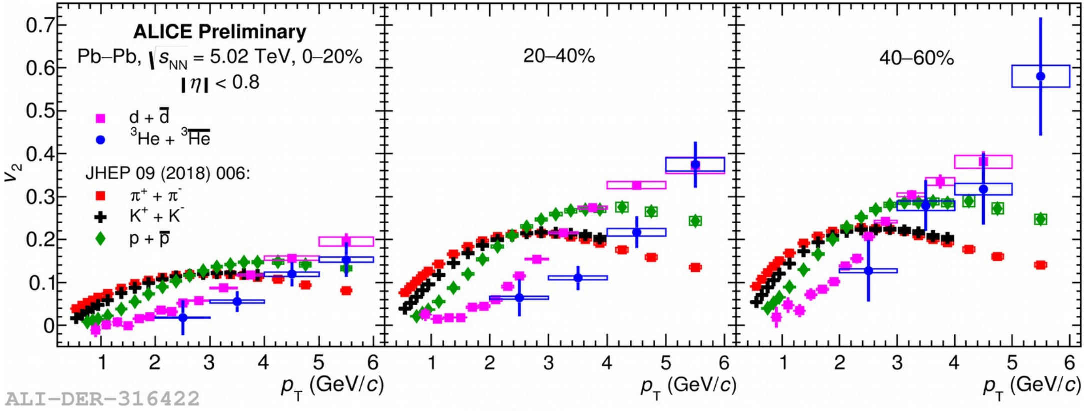


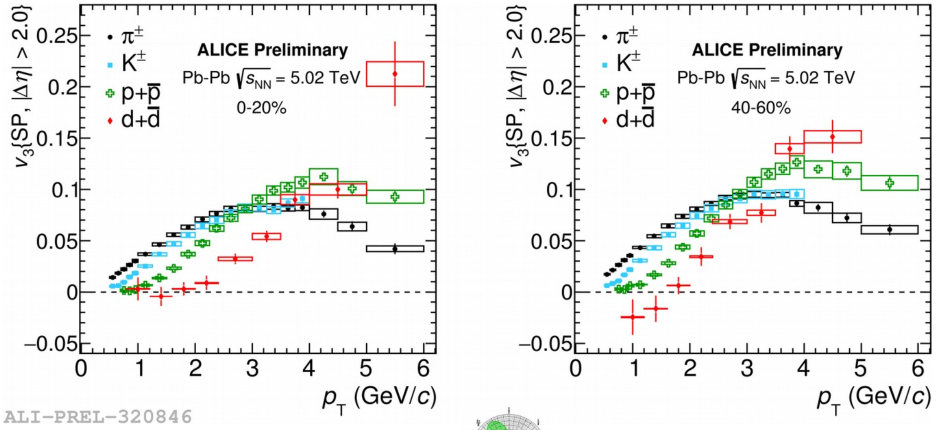


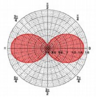
- v_2 of (anti-)deuterons and (anti-)^{3}He:
  - Centrality & p_T dependence as expected from relativistic hydrodynamics
- v_3 of (anti-)deuterons:
  - **First measurement** ever in ultra-relativistic heavy-ion collisions
  - Effects of initial state fluctuations of energy density in the colliding nuclei visible also for (anti-)deuterons

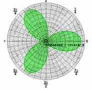
Ts

v_n of light (anti-)nuclei vs. v_n of π, K and p









- v_2:
  - Mass ordering at low p_T & slower rise for heavier particles
    - as expected from relativistic hydrodynamics
- v_3:
  - Centrality & p_T dependence of the (anti-)deuteron v_3 consistent with expectations based on the v_3 of identified hadrons
  - Mass ordering is observed at low p_T

Ts

Femtoscopy technique

- Femtoscopy: technique of measuring the distribution of relative momenta of pairs of particles
- This distribution depends on the shape and **size of the source** and on the **interactions** between those particles.

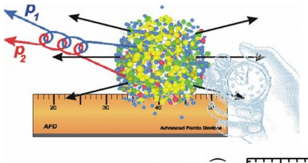
$$C(k^*) = \int S(\boldsymbol{r}, k^*) |\Psi(\boldsymbol{r}, k^*)|^2 d\vec{r}$$

$$k^* = \frac{|\boldsymbol{p}_a^* - \boldsymbol{p}_b^*|}{2}$$

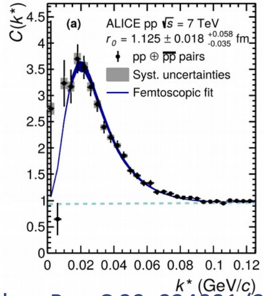
$$p_a^* + p_b^* = 0$$

Measured correlation — Emission Function (source size/shape) — Pair wave function

Scott Pratt, Mike Lisa

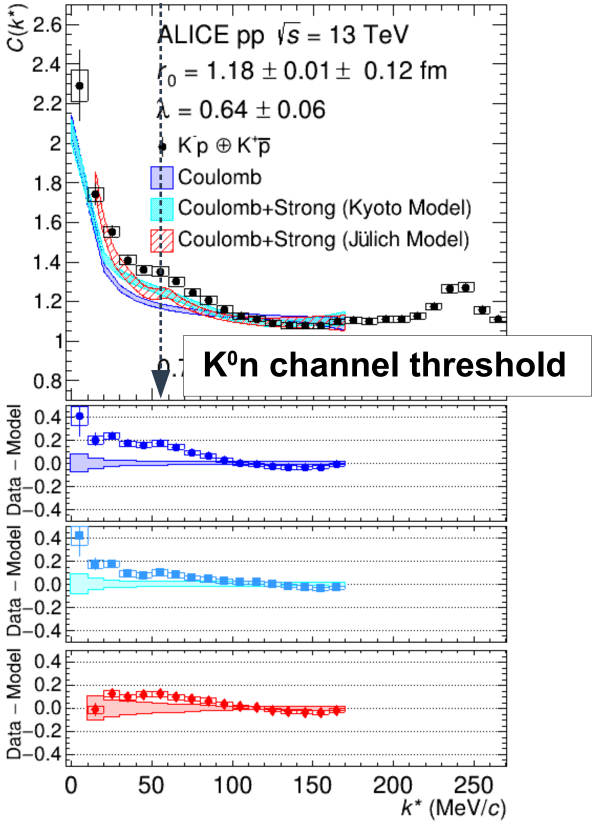


- **"Traditional" use of femtoscopy:**
  - Measure space-time characteristics of the particle emitting source ($S(\boldsymbol{r},k^*)$) assuming a particular form of the two particle interaction (HBT)
- **"Alternative" use of femtoscopy :**
  - Assume a common source and study the interaction between particles by computing the wave functions → **Unique too to study the interaction between YN and YY which is crucial to solve the "hyperon puzzle" and understand neutron stars!**



ALICE Collaboration,Phys. Rev. C 99, 024001 (2019)

Study of Kp strong interaction using femtoscopy

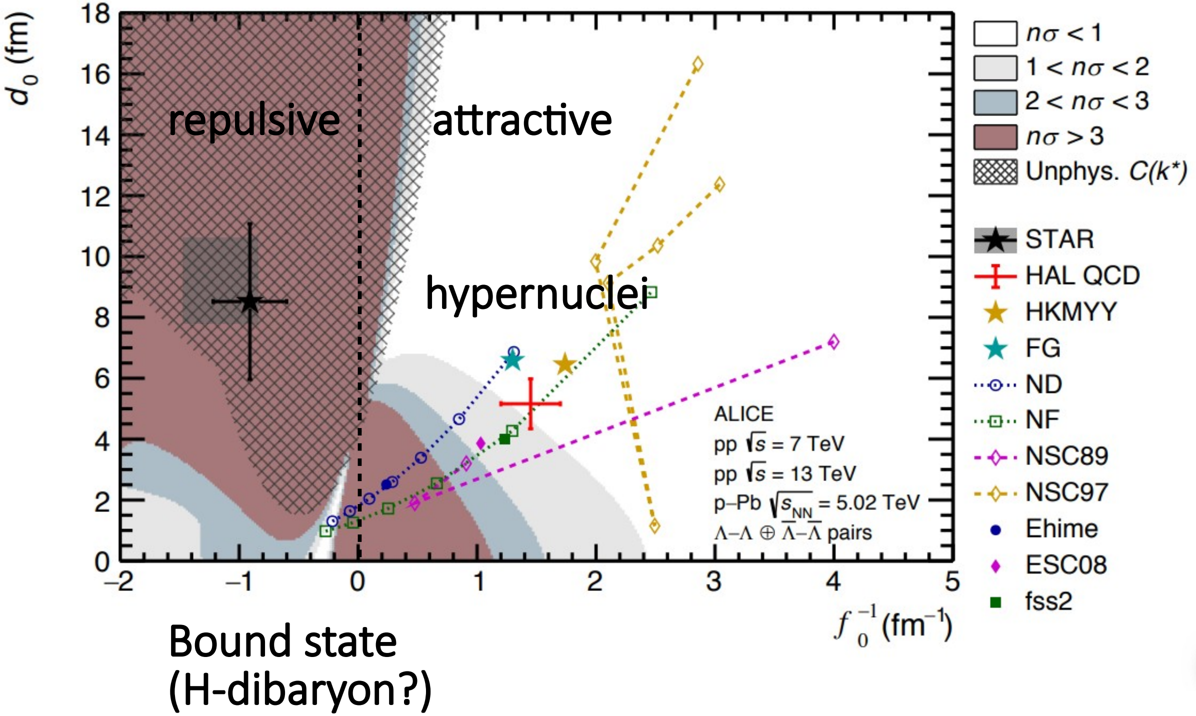


ALICE Collaboration, arXiv:1905.13470 [nucl-ex]

- Observation of a bump close to the K^0n threshold (89 MeV/*c* in the lab frame → 58 MeV/*c* in the CM frame)
  - **First** experimental **evidence** of the opening of the K^0n ($\bar{K^0}\bar{n}$) isospin breaking channel → femtoscopy is a unique tool to study the Kp scattering, where the conventional scattering experiments at fixed target are difficult to perform
- Comparison with model
  - Coulomb potential only
  - Chiral Kyoto model
  - Jülich strong potential recently updated to reproduce the SIDDHARTA results
  - → The correlation functions at low k* **cannot be reproduced** by any of the considered potentials

Study of ΛΛ interaction

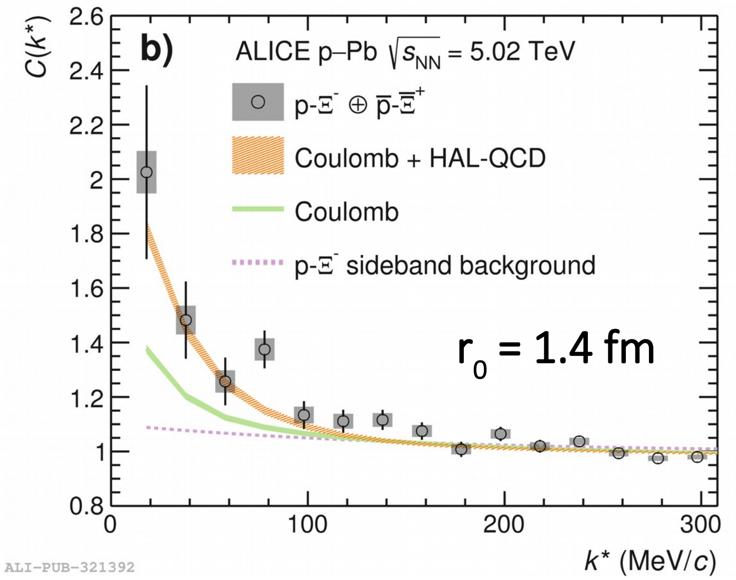
- Theoretical models and experimental measurements cover a wide range in the scattering parameter phase space
- Combined of all analyses data-set
  - pp 7 & 13 TeV
  - p-Pb 5.02 TeV
- Test the agreement between data and the prediction by the Lednický model in nσ
  - Under the hypothesis of a common Gaussian source
    - Small source size limits the prediction power of the Lednický model

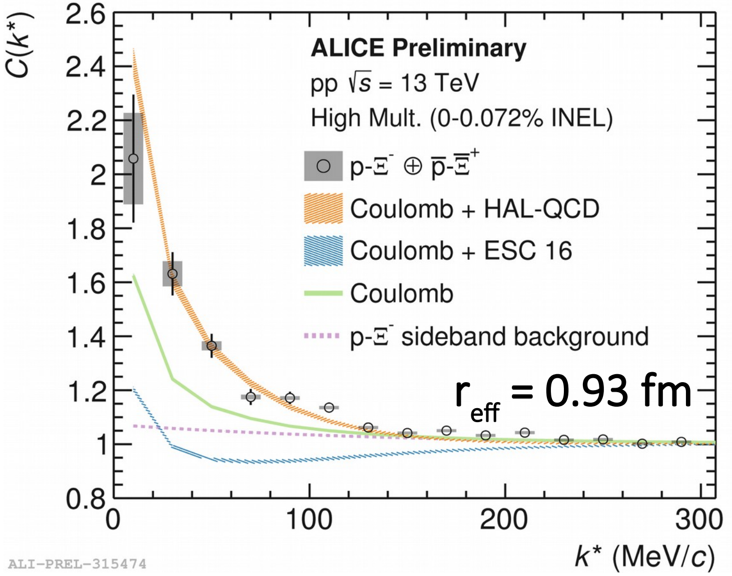


ALICE Collaboration arXiv:1905.07209

Study of the pΞ^- interaction

ALICE Collaboration, arXiv:1904.12198 [nucl-ex]





- Coulomb-only excluded at 4-5 σ level
- HAL-QCD correlation is compatible with data

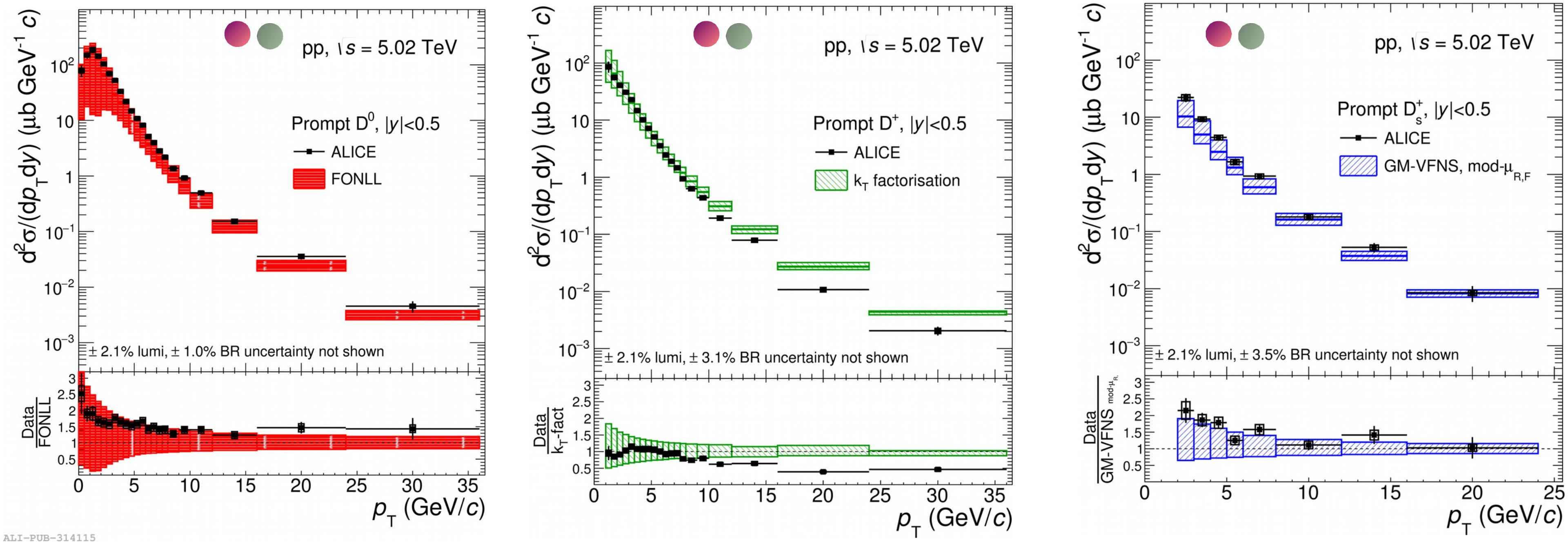
First experimental evidence of pΞ^- attractive potential

- Coulomb-only excluded at > 5.7 σ level
- HAL-QCD potential: compatible within (1.3-2.5)σ
- ESC 16 potential excluded at > 16 σ level

Charmed meson and baryons and quarkonia production

Heavy-flavour production in pp collisions

- D-meson production cross section in pp collisions at √s= 5.02 TeV at mid-rapidity
  - crucial reference, measured with high precision, at the same energy as Pb-Pb and p-Pb measurements



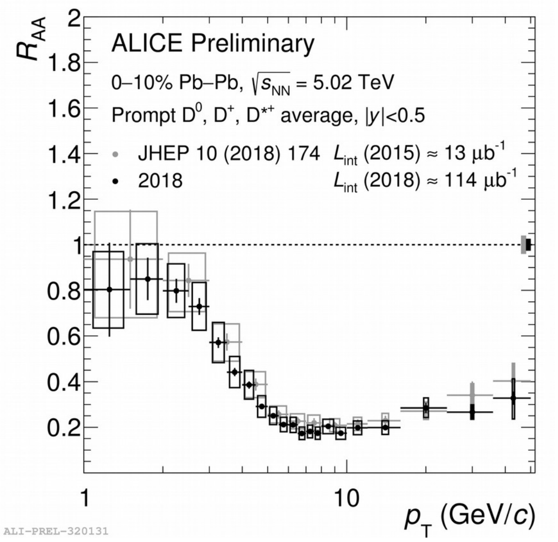
ALICE Collaboration Eur.Phys.J. C79 (2019) no.5, 388 arXiv:1901.07979v1

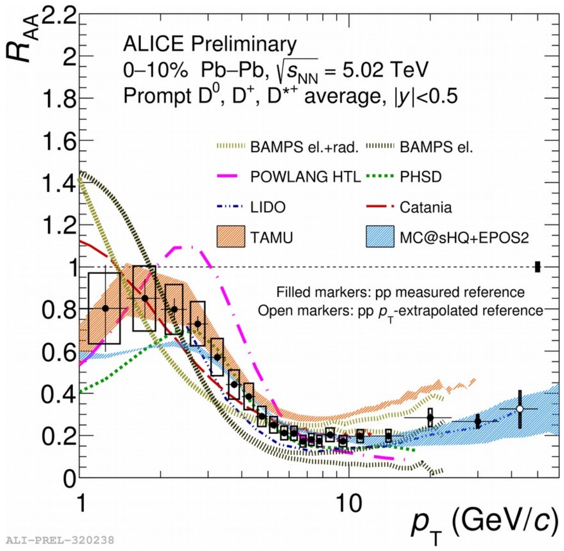
Bs-Pv, Pd, To

D-meson R_{AA} in Pb-Pb collisions

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll}^{AA} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

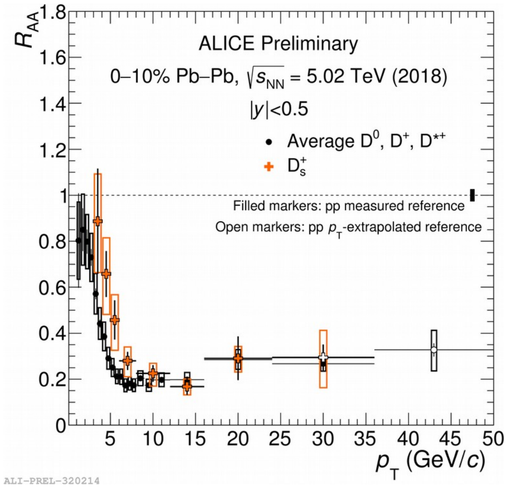
Pd, To

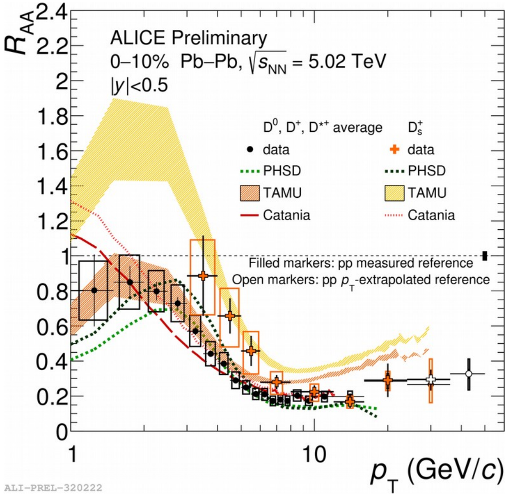




- 2018 data sample: reduced uncertainties → more p_T-differential
  - better constrain steeply decreasing R_{AA} trend at low p_T
  - Increasing suppression from peripheral (60-80%) to central (0-10%) Pb-Pb collisions
  - Data precision nailing down description of charm-interaction and diffusion in the medium at low transverse momenta

D_s^+ R_{AA}





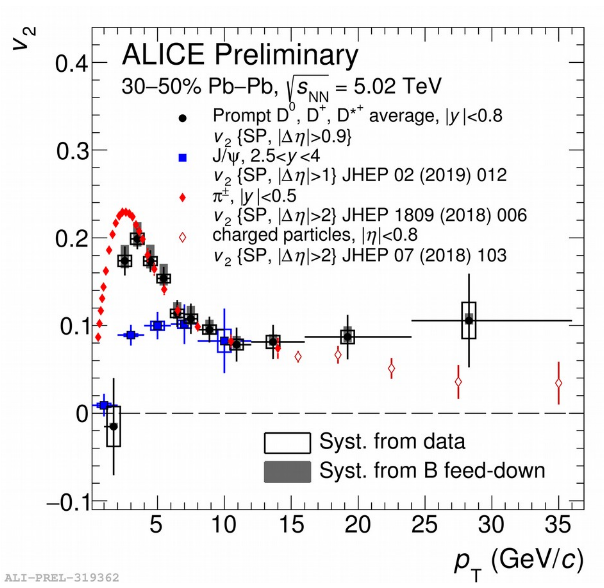
Pd, To

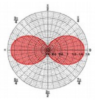
[1]Phys. Rev. C 93, 034906 (2016)
[2]Phys. Lett. B 735, 445 (2014)
[3]Eur. Phys. J. C (2018) 78: 348

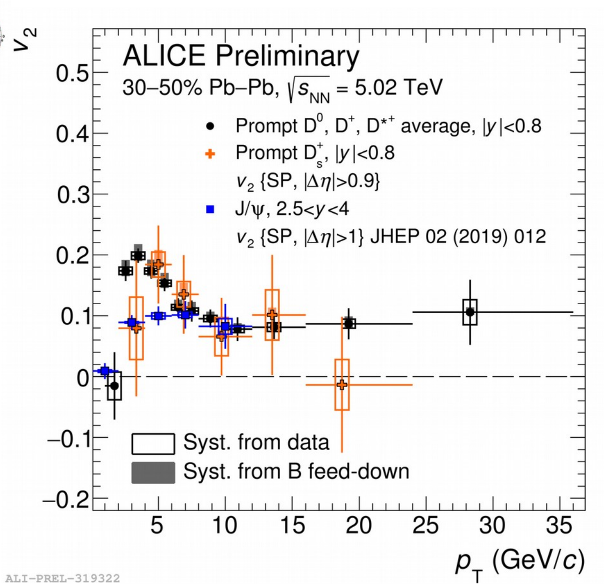
- Similar patter of **strange** and **non-strange** charmed mesons
- R_{AA} of **strange**-charmed mesons higher than the one of **non-strange**-charmed mesons
  ➔ enhancement of strangeness as expected in the QGP
- Comparison of R_{AA} of **strange**-charmed mesons to theoretical models of charm-quark transport in a hydrodynamically expanding medium: the used models [1,2,3] predict an increase of the D_s^+ with respect to **non-strange**-charmed mesons especially for $p_T < 5$ GeV/c as observed in data

D meson v_2 measurement

ALICE



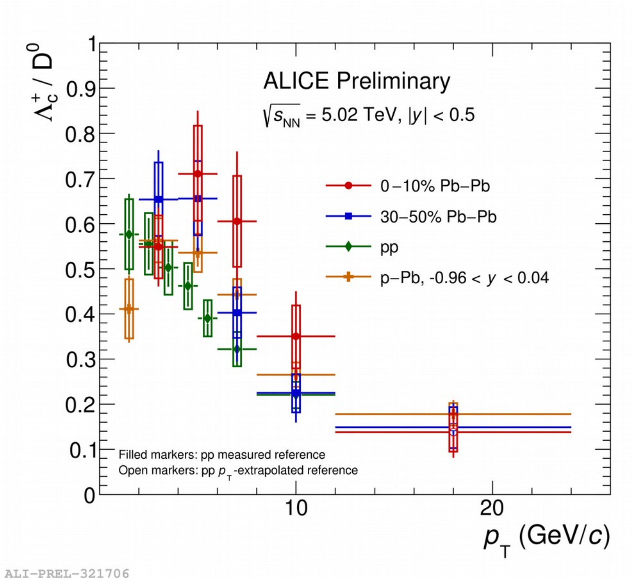


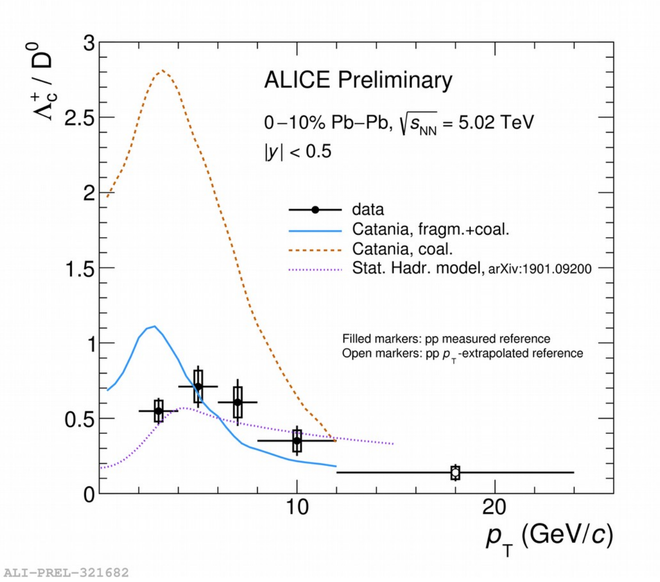


Pd, To, Ts

- Similar v_2 magnitude for strange and non-strange D mesons, but large uncertainties.
- D-meson $v_2 \geq J/\psi\ v_2 > 0$
  - charm quarks flow + possible enhancement of open charm v_2 from hadronisation via coalescence with flowing light-flavour quarks
- D_s v_2: similar magnitude for strange and non-strange D mesons, but large uncertainties.

Λ_c^+ production



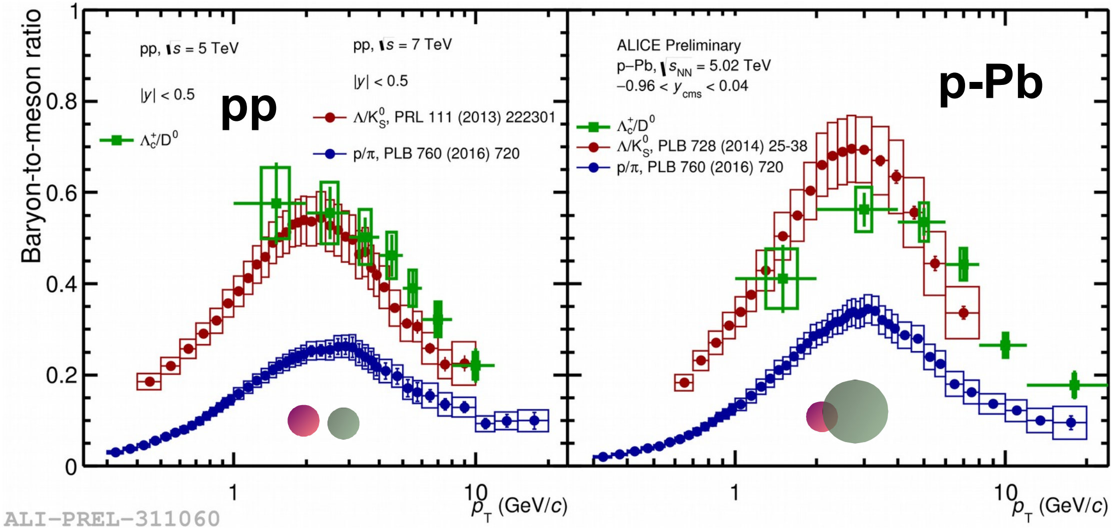


Bo, Pd, Sa

- Central collisions show a higher ratio than peripheral collisions, with a hint of decrease in the ratio at low p_T, but the uncertainties are large to draw a firm conclusion.
- Hint to a higher Λ_c^+/D^0 in Pb-Pb collisions than in pp (especially at intermediate p_T). Same behaviour with respect to p-Pb.
- Comparison to Catania[1] theory favors a scenario where both coalescence and fragmentation are present, for both centrality ranges.
- Good agreement with statistical hadronization model.

[1] Eur. Phys. J. C (2018) 78: 348

Baryon-to-meson ratio



Λ_C^+/D^0

Λ/K^0_s

p/π

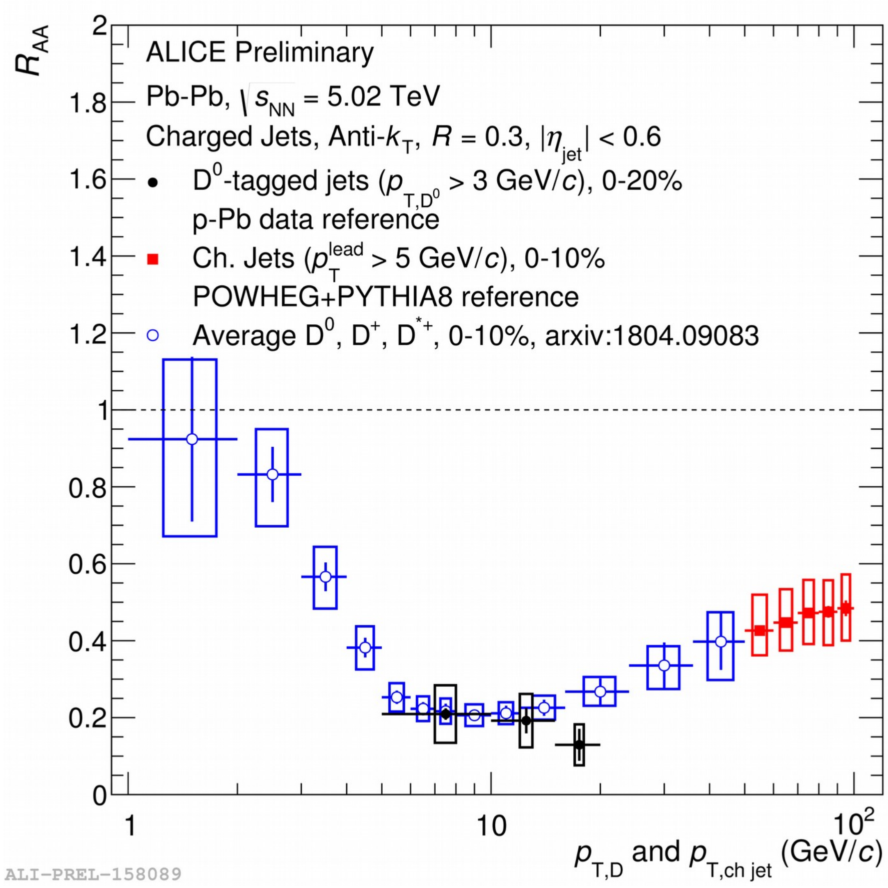
- Baryon-to-meson ratios are not flat vs p_T:
  - Enhancement in the intermediate p_T region
    - Not reproduced by model and not seen in e+e- collisions
- Intriguing similarity with p_T trend of baryon-to-meson ratios in light-flavor sector in pp and p-Pb collisions

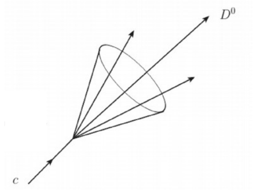
→ **Charm hadronisation not fully understood even in pp collisions**

- Multiplicity-dependent studies in pp are ongoing

Bo, Pd, Sa

D-meson production in jets in Pb-Pb collisions





Charged jets

D-meson tagged jets

D mesons (JHEP 1810 (2018) 174)

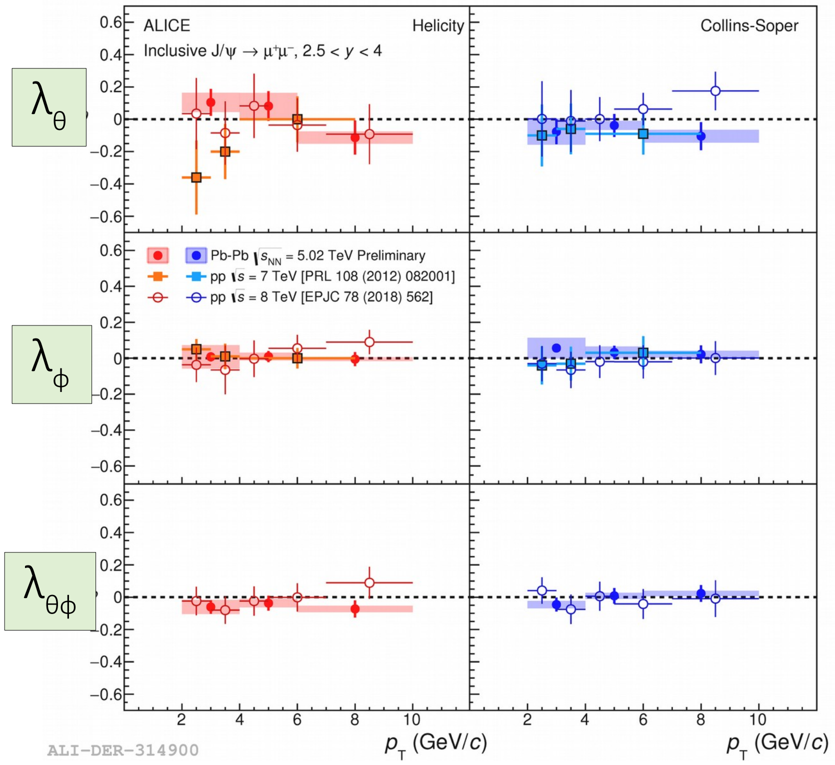
- Hint of smaller R_{AA} for low-p_T D-meson tagged jets compared to higher p_T charged jets
- Similar R_{AA} for D-meson tagged jets and D mesons

Ba, Pd

J/ψ polarization

$$W(\cos\vartheta,\varphi) \propto \frac{1}{3+\lambda_\vartheta}\cdot\left(1+\lambda_\vartheta\cos^2\vartheta+\lambda_\varphi\sin^2\vartheta\cos 2\varphi+\lambda_{\vartheta\varphi}\sin 2\vartheta\cos\varphi\right)$$

helicity Collins-Soper

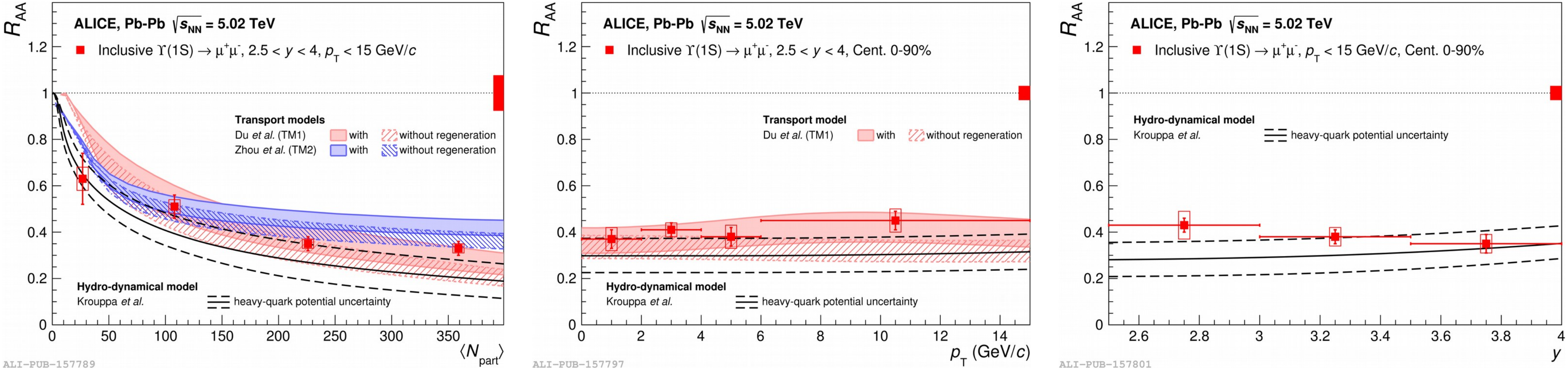


- J/ψ polarization measured for the **first time** in AA collisions at colliders
- Only 2015 data analyzed
  - Compatible with zero and with pp-collision data in both Helicity and Collin-Soper frames
- Outlook: possible future studies with different polarization axes to probe potential effects from vorticity and EM field

To

Υ(1S) nuclear-modification factor

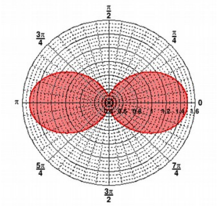
ALICE Collaboration Phys. Lett. B790 (2019) 89

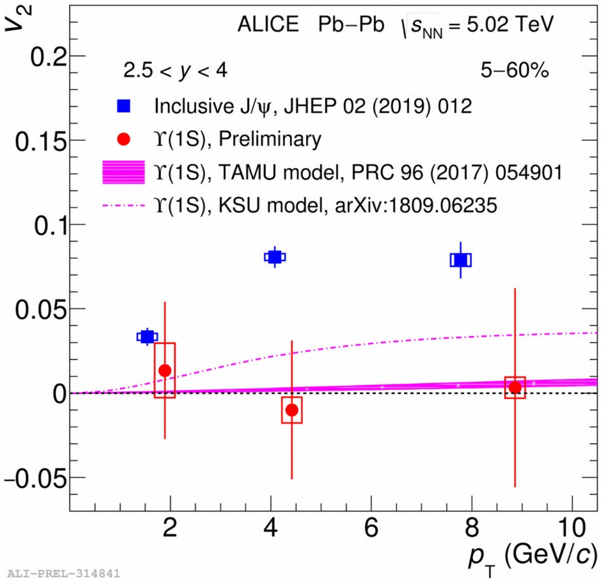


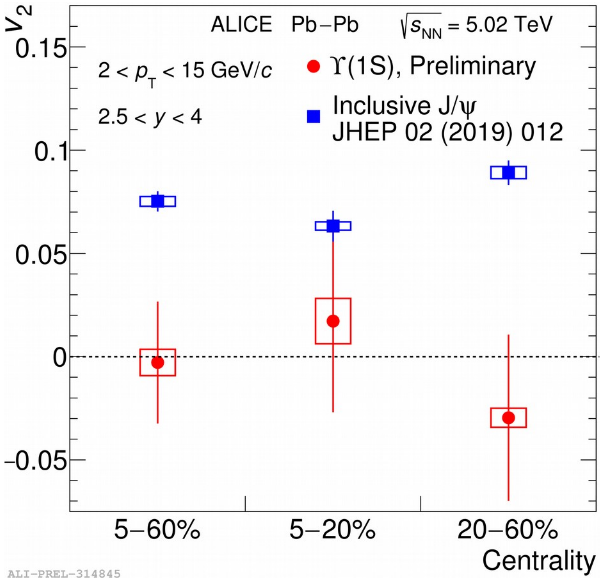
- Significant Υ(1S) suppression, increasing from peripheral to central collisions
- No significant variation observed as a function of p_T and rapidity
- Transport models reproduce data within uncertainties
- Stronger suppression measured for Y(2S) in 0-90% :

$$R_{AA}\Upsilon(2s) \,/\, R_{AA}\Upsilon(1s)AA = 0.28 \pm 0.15(\text{stat.}) \pm 0.03(\text{syst.})$$

Υ (non) anisotropy (Pb-Pb 2018)



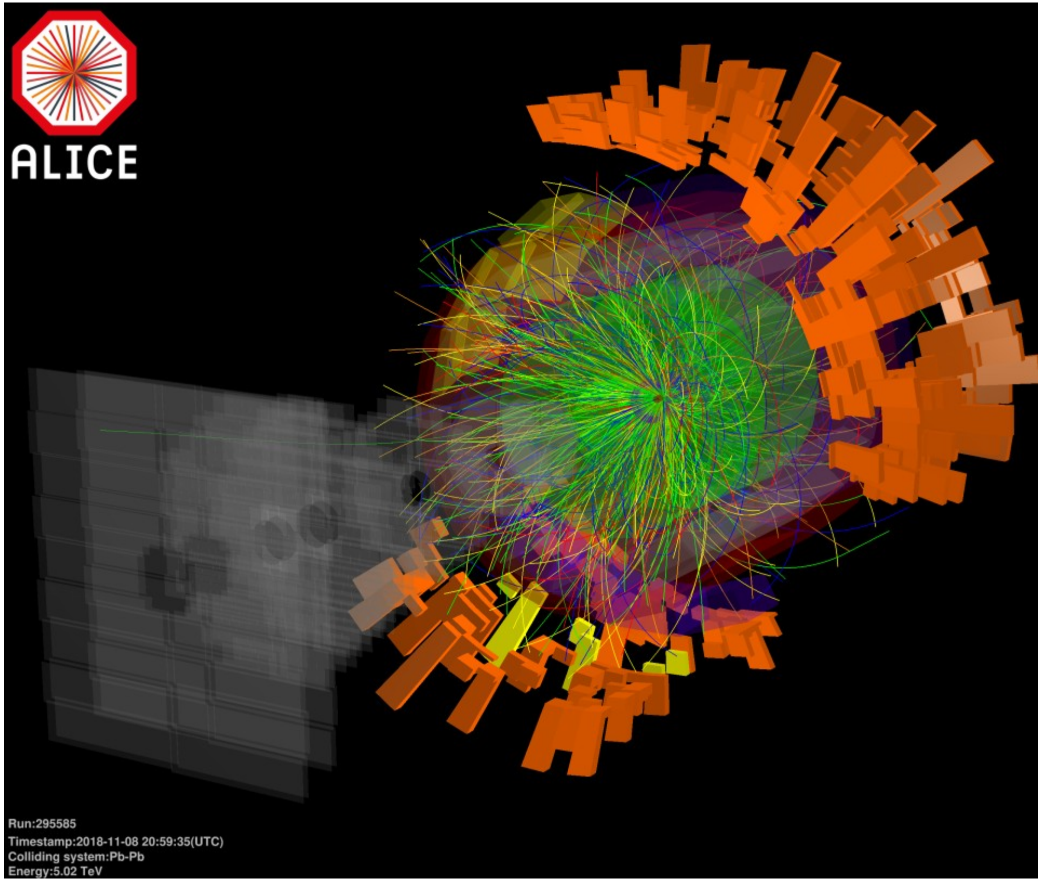




- First measurement of v_2 for $\Upsilon(1s)$ at forward rapidity: compatible with 0
  - ➔ **first particle measured not to have flow!**
- not dragged along by flow of medium,
  - ➔ not produced by recombination
- **Indication of lower v_2 than inclusive J/ψ (2.6 σ) in 3 < p_T < 15 GeV/c**

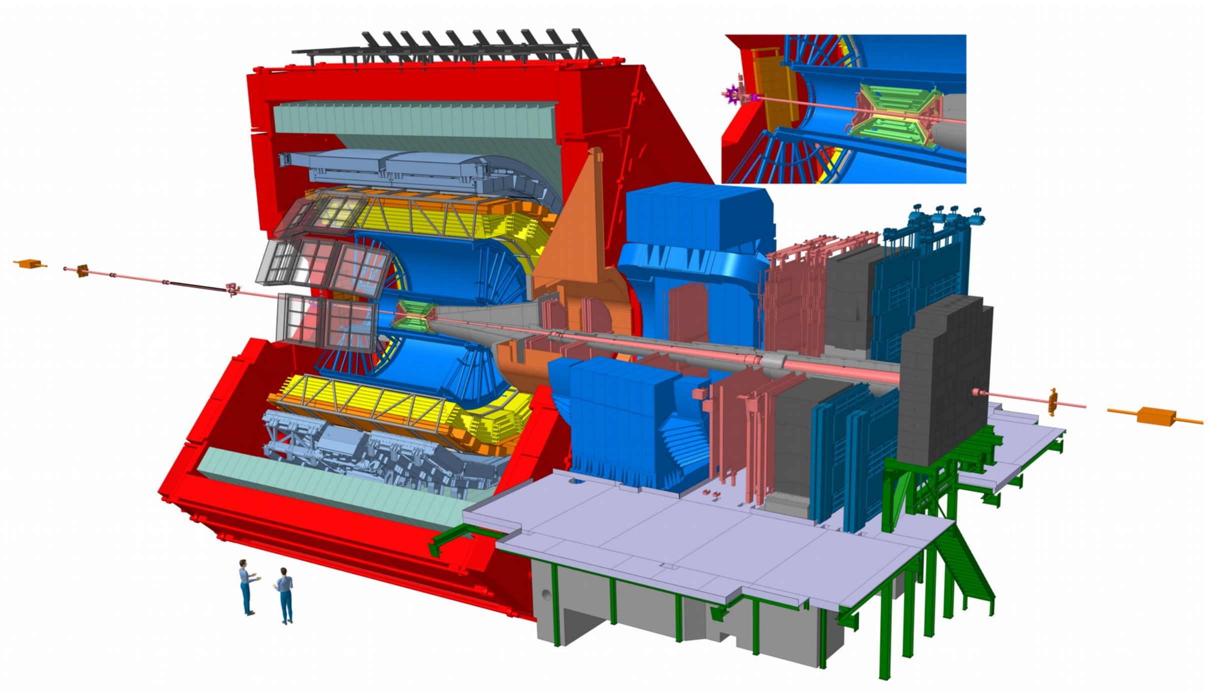
Conclusions

- End of Run 2 Data taking
- Lots of new results! In particular
  - Nuclei production, elliptic and triangular flow measurements in pp, p-Pb and Pb-Pb collisions
  - Femtoscopy measurements in small system
  - Strange and non-strange D-Meson RAA and v_2 measurement
  - p_T-differential results for Λ_c^+
  - J/ψ polarization
  - Anisotropy Υ(1S) in heavy-ion collisions



A Large Ion Collider Experiment

- ALICE particle identification capabilities are unique. Almost all known techniques are exploited: specific energy loss (dE/dx), time of flight, transition radiation, Cherenkov radiation, calorimetry and decay topology (V_0, cascade).



Inner Tracking System (ITS) :
- Primary vertex
- Tracking
- Particle identification via dE/dx

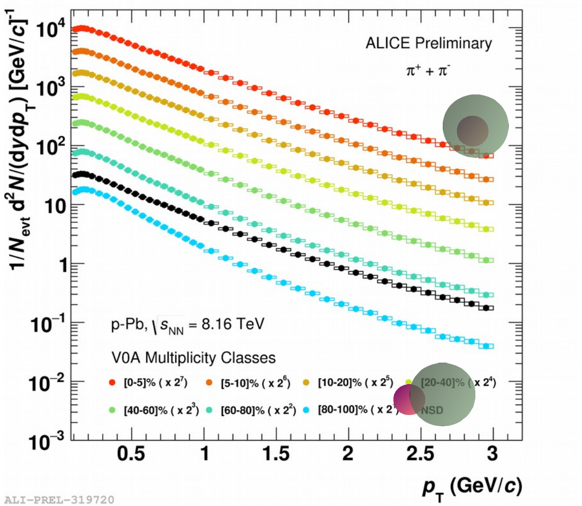
Time Projection Chamber (TPC):
- Global tracking
- Particle identification via dE/dx

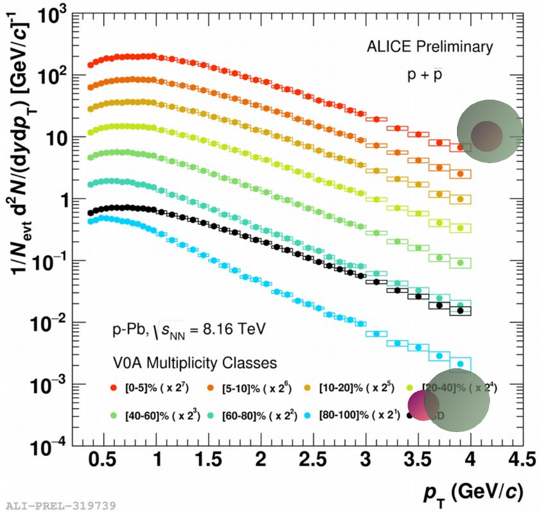
Time Of Flight (TOF):
- Particle identification via velocity measurement

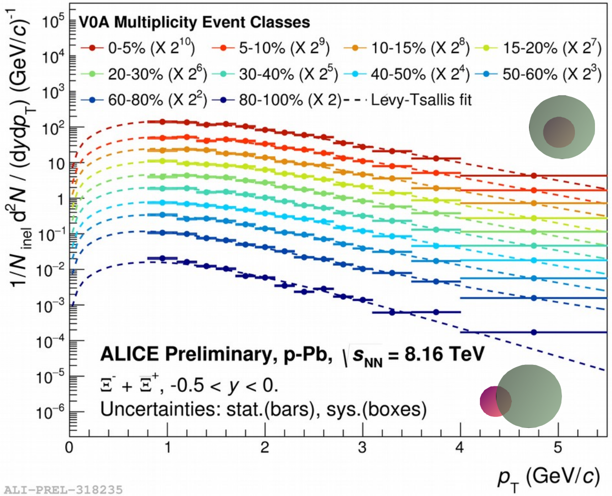
High Momentum PID (HMPID):
- particle identification via ring imaging Cherenkov

V0 (A-C): Trigger, beam-gas event rejection, centrality, multiplicity classes

p_T spectra of identified hadrons in p-Pb collisions







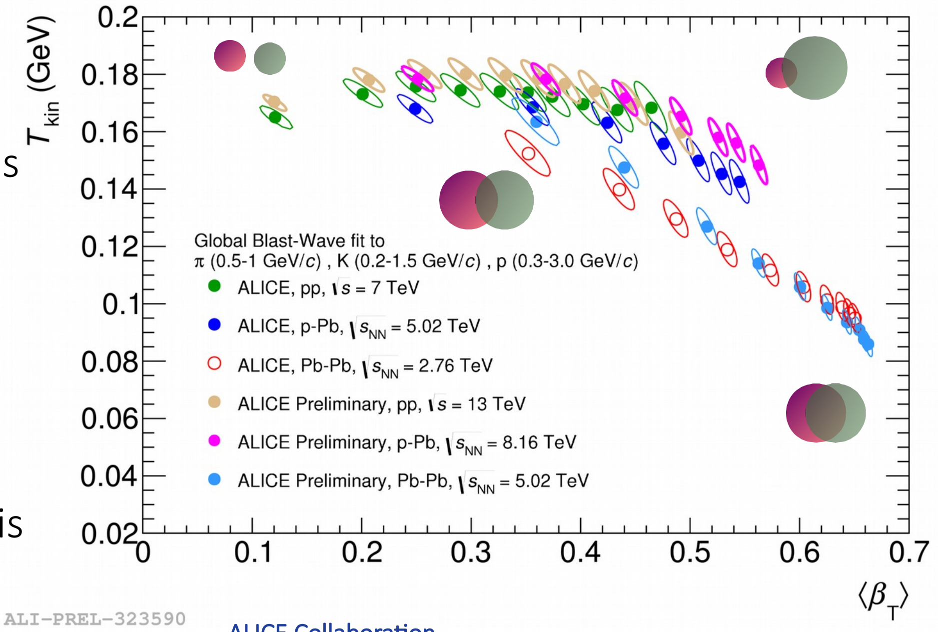
- Measured and identified with different analysis techniques: ITS, TPC, TOF, HMPID and topological identification
- Mass dependent hardening of the spectra with increasing centrality
  - ➔ Collective radial expansions
  - ➔ New spectra in p-Pb: spectra become harder as the multiplicity increases. The change is most pronounced for heavier particles
  - ➔ Spectra fit with a Lévy-Tsallis function

Ba,Bo, Ca, Ct, LNF, To

Blast-Wave fit to hadrons p_T spectra

- Similar trend observed in pp, p-Pb and Pb-Pb collisions
  - Large systems:
    - Larger β_T for central Pb-Pb collisions
    - Comparable T_{kin} and $\langle\beta_T\rangle$ in Pb-Pb and Xe-Xe collisions at a similar $\langle dN_{ch}/d\eta\rangle$
  - Small systems
    - p-Pb & pp vs A-A
    - p-Pb and Pb-Pb show a similar increase of $\langle\beta_T\rangle$ consistent with the presence of radial flow in p-Pb collisions. At similar $\langle dN_{ch}/d\eta\rangle$
      - comparable T_{kin} for p-Pb and Pb-Pb, whereas $\langle\beta_T\rangle$ is significantly higher in p-Pb
      - pp and p-Pb show a similar trend and values are comparable
      - Higher T_{kin} in p-Pb 8.16 TeV wrt 5.02 TeV

Simultaneous fit to π ,K and p spectra



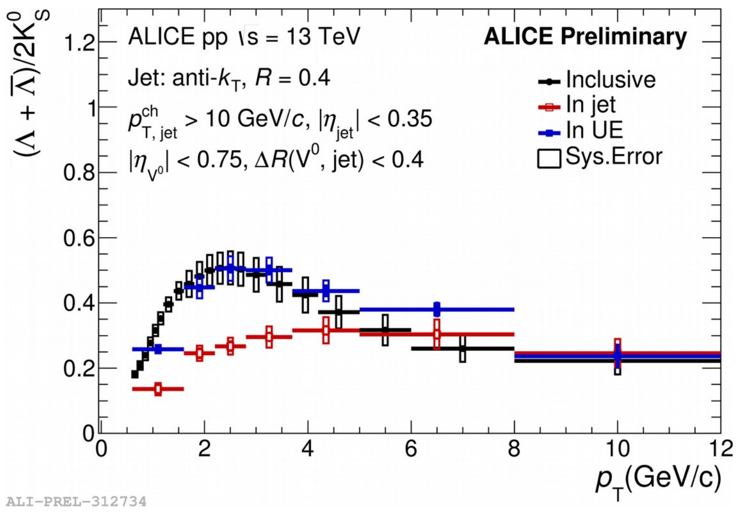
ALICE Collaboration
pp 7 TeV: Eur. Phys. J. C75(2015) 226
p-Pb 5.02 TeV: Phys.Lett. B 760(2016) 720
Pb-Pb 2.76 TeV: Phys. Rev. C88(2013) 044910

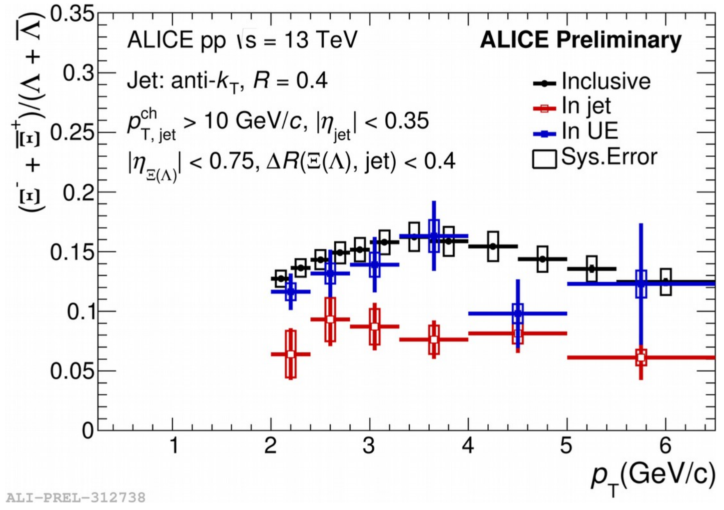
[1] Phys. Rev. C 48 (1993) 2462

Ba,Bo, Ca, Ct, LNF, To

Strangeness production: particle ratios in jets

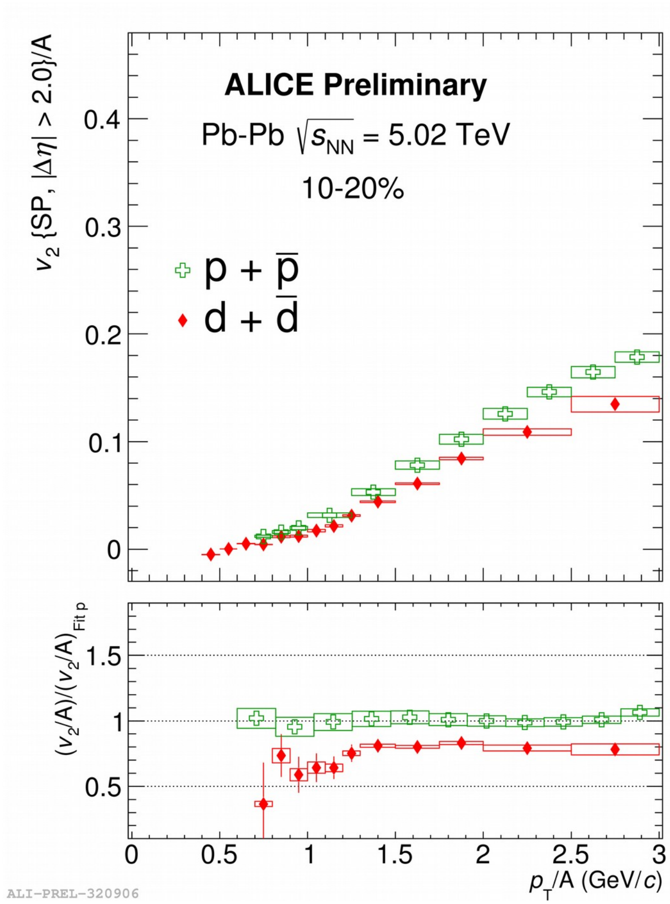
- Baryon-to-meson enhancement: is it also due to a modification of jet fragmentation in medium?
  - Separate hadrons produced in hard processes (jets) from hadrons produced in soft processes (underlying event UE).
- Production ratio of Λ/K^0_S and Ξ/Λ in pp collisions $\sqrt{s}$ =13TeV:
  - ratio in jets is significantly smaller than the inclusive ratio at low and intermediate p_T
  - small bump in inclusive similar to that of UE dynamics

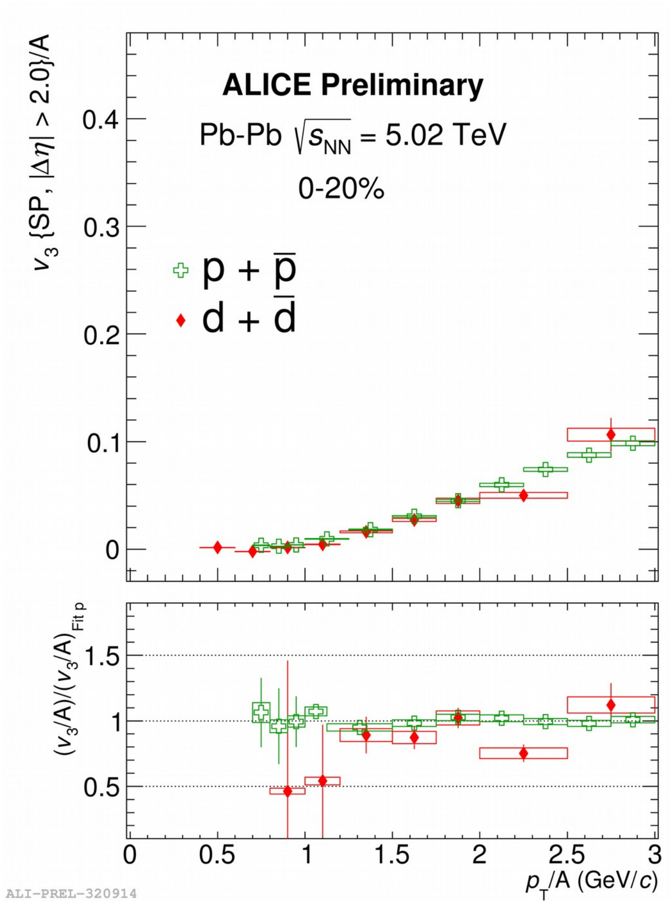




Different production mechanisms inside jets w.r.t. UE

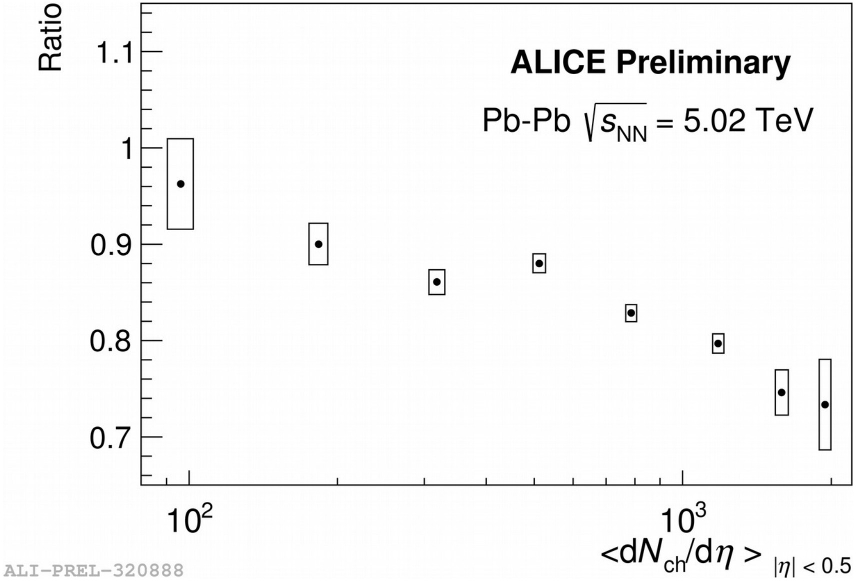
A-scaling of v_n of (anti-)deuterons





Ts

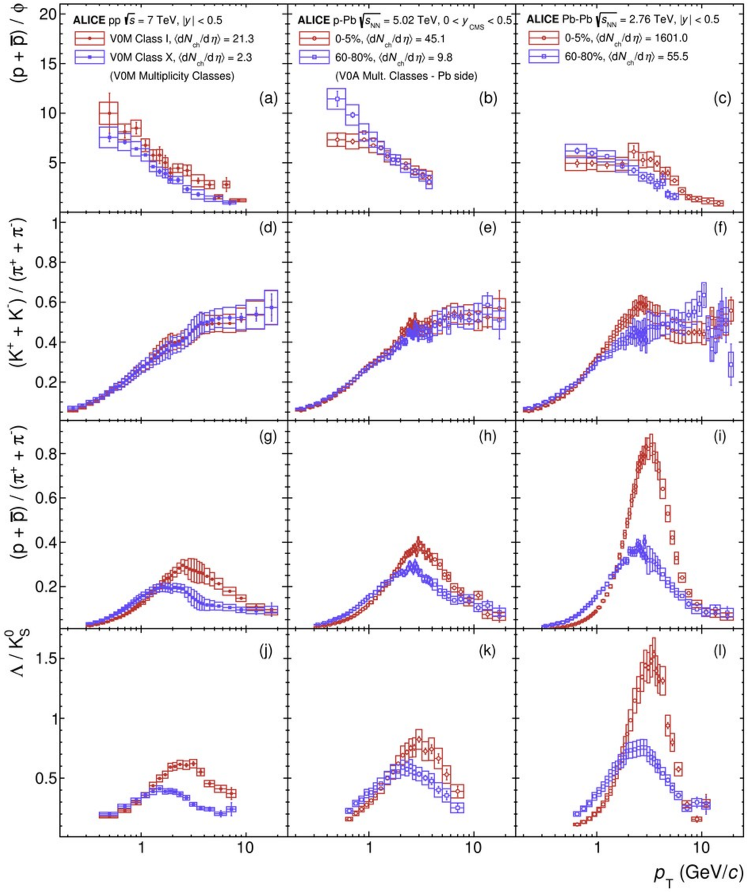
A-scaling of v_2 of (anti-)deuterons

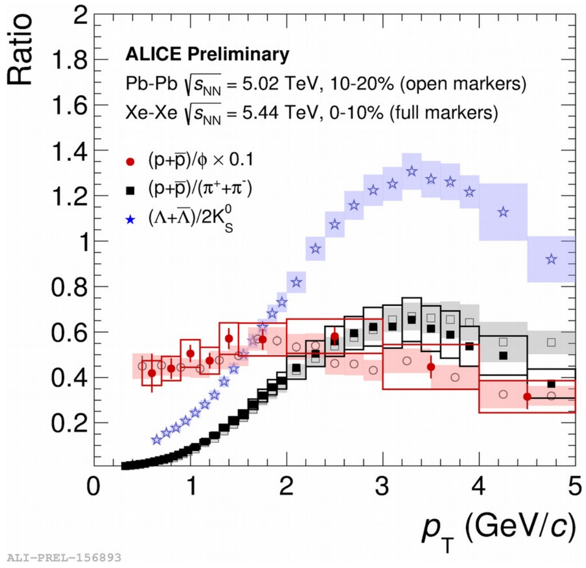


A trend of the A-scaling is observed as a function of multiplicity of the event

Particle ratios in pp, p-Pb and AA

ALICE Collaboration, Phys. Rev. C 99, 024906





- Similar evolution pattern of particle ratios from pp to AA
- Similar values for Pb-Pb and Xe-Xe at similar multiplicity
- p/ϕ consistent with radial flow but also with (re)combination
  - ➔ Particle production is driven by the characteristics of final state
  - ➔ Spectra at intermediate p_T determined by flow or recombination?

Blast-Wave fit to hadrons p_T spectra

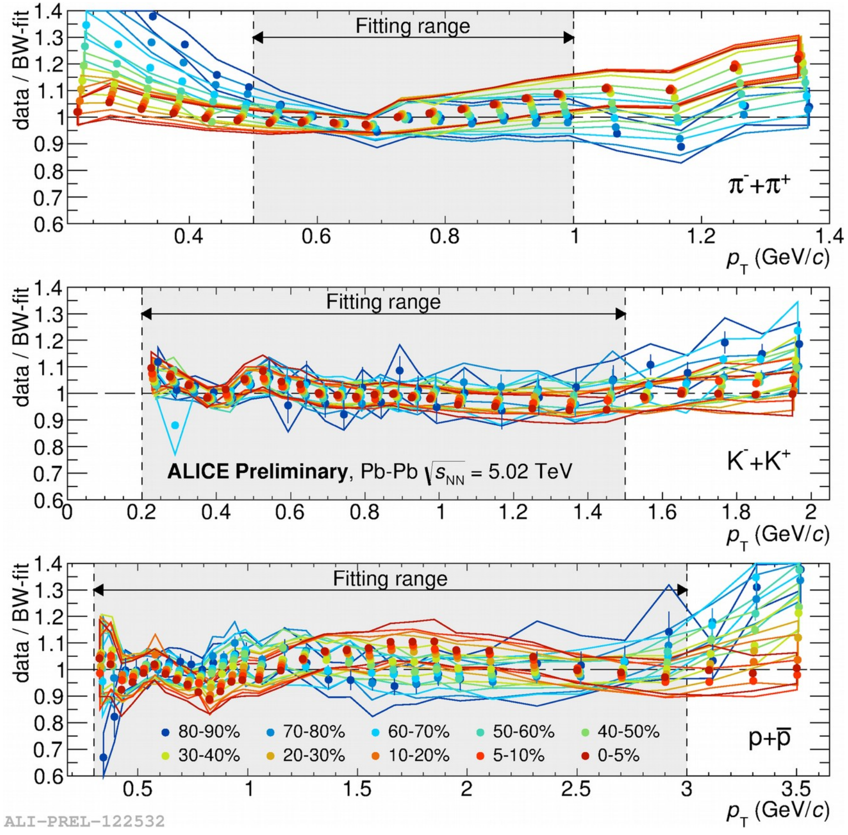
- Boltzmann-Gibbs Blast-Wave model: a 3-parameter simplified hydrodynamics model [1]

$$E\frac{d^3N}{dp^3} \propto \int_0^R m_T I_0\left(\frac{p_T\sinh(\rho)}{T_{kin}}\right) K_1\left(\frac{m_T\cosh(\rho)}{T_{kin}}\right) r\, dr$$

$$m_T = \sqrt{m^2 + p_T^2} \quad \rho = \tanh^{-1}(\beta_T) \quad \beta_T = \beta_s\left(\frac{r}{R}\right)^n$$

- β_T : Radial expansion velocity
  - β_S : surface velocity
  - ρ : boost angle
- T_{kin} : kinetic freeze-out temperature
- n : velocity profile

Simultaneous fit to π ,K and p spectra



[1] Phys. Rev. C 48 (1993) 2462

⟨p_T⟩ vs centrality of hadrons in pp, p-Pb and A-A

Ω(1672)

Ξ(1322)

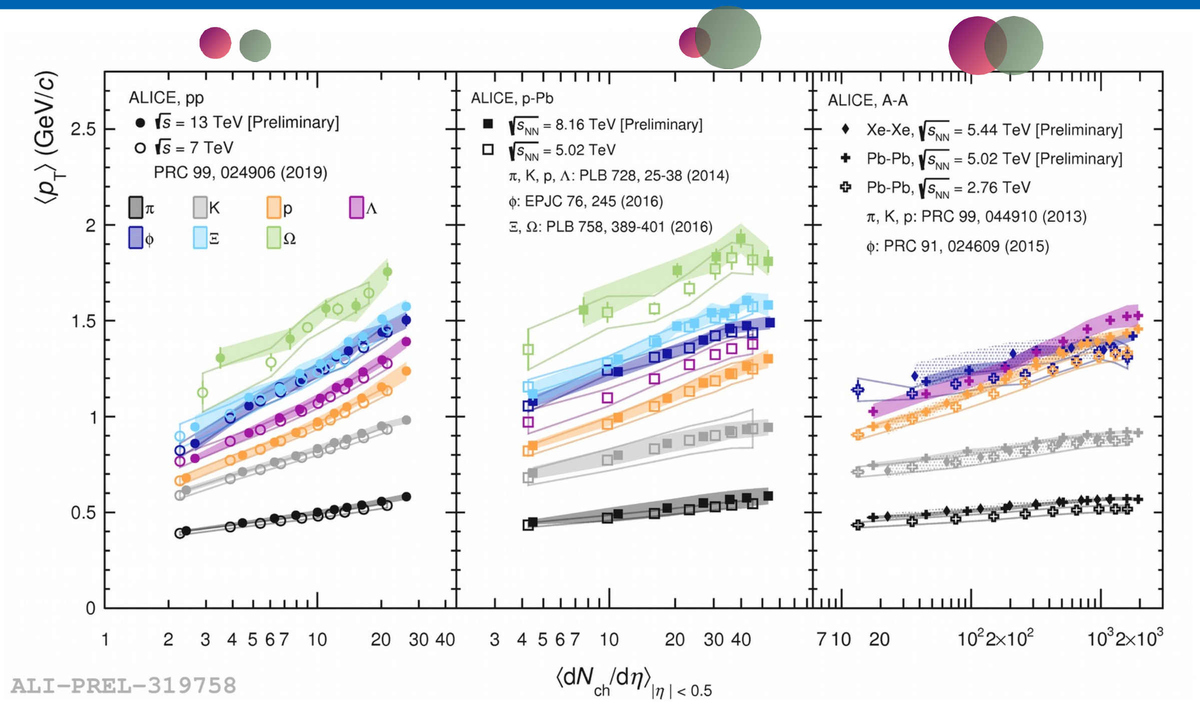
ϕ(1020)

Λ(1116)

p(938)

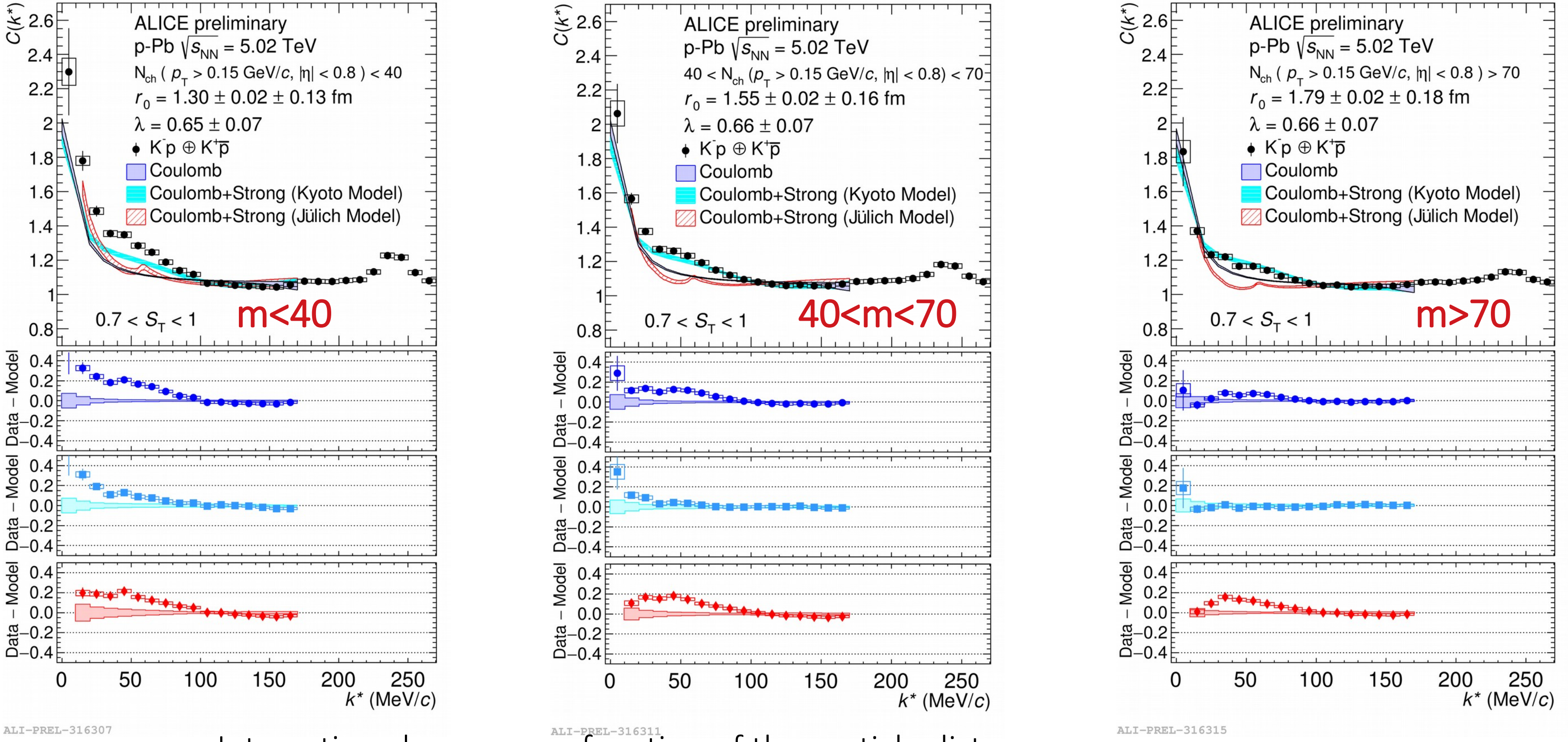
K(494)

π(140)



- ⟨p_T⟩ increases with increasing centrality and mass
- Similar hierarchy is observed in pp, p-Pb and peripheral A-A
  - in central A-A collisions particles with similar masses have similar ⟨p_T⟩ (as expected from hydrodynamics)
  - ϕ ⟨p_T⟩ is above Λ and p, and close to Ξ: mass ordering violated in pp, p-Pb and peripheral Pb-Pb
- The increase vs multiplicity is attributed to collective flow

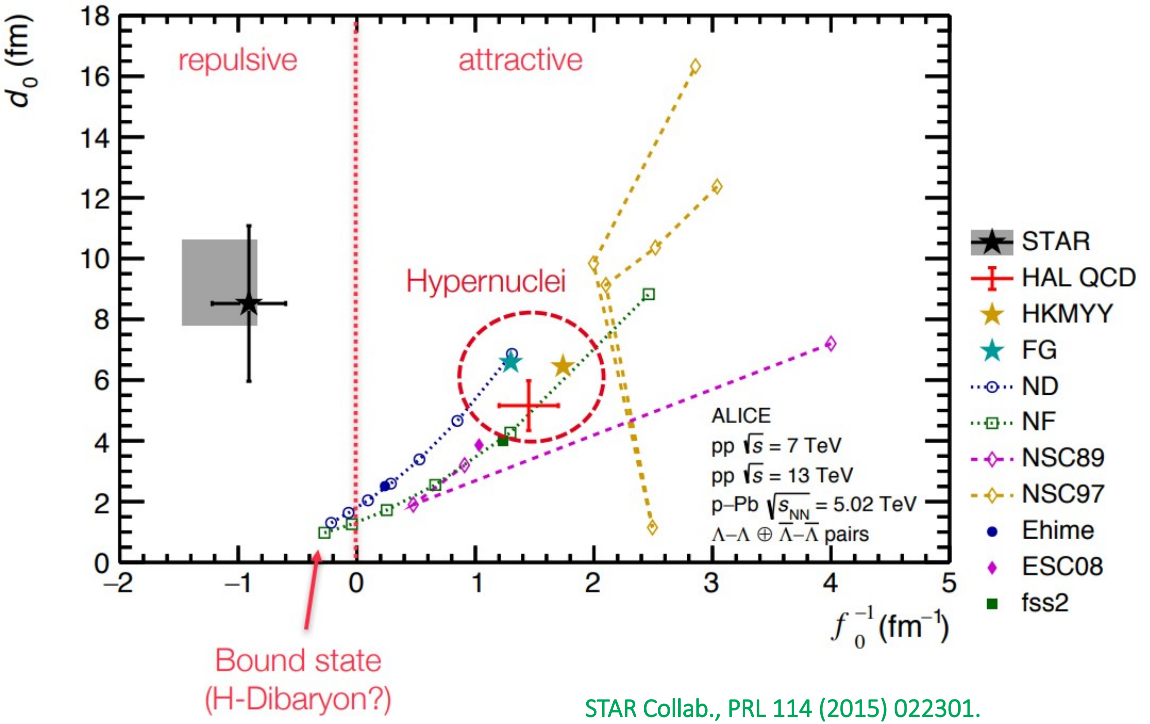
Kp interaction in p-Pb collisions



- Interaction changes as a function of the particle distance
  - Model can be tested and constrained in a more differential way

Study of ΛΛ interaction

- Theoretical models and experimental measurements cover a wide range in the scattering parameter phase space



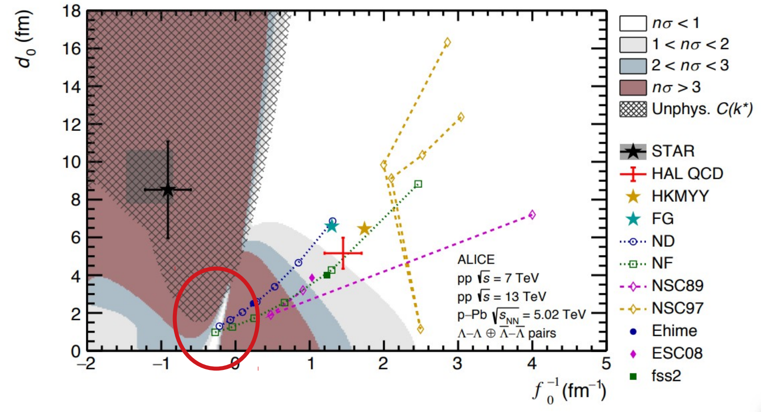
STAR Collab., PRL 114 (2015) 022301.
K. Morita et al., PRC 91 (2015) 024916.
HAL QCD: K. Sasaki and T. Hatsuda (HAL QCD Collab.), private communication.

Study of ΛΛ interaction

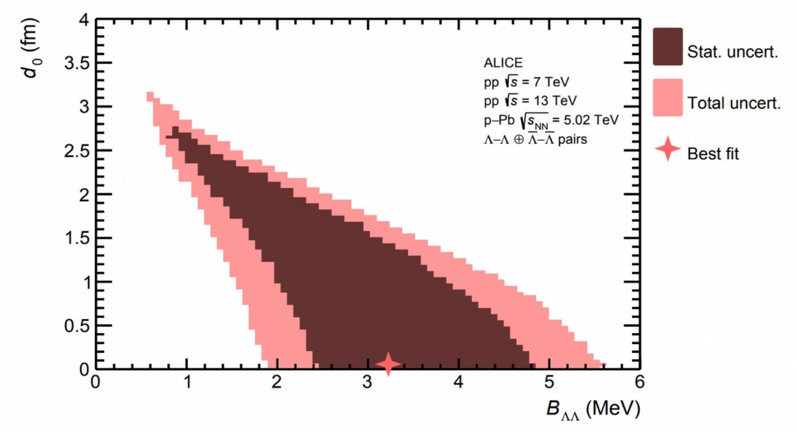
$$B_{\Lambda\Lambda}=\frac{1}{m_{\Lambda}d_0^2}\left(1-\sqrt{1+\frac{2d_0}{f_0}}\right)^2$$

S. Gongyo et al., PRL 120 (2018) 212001

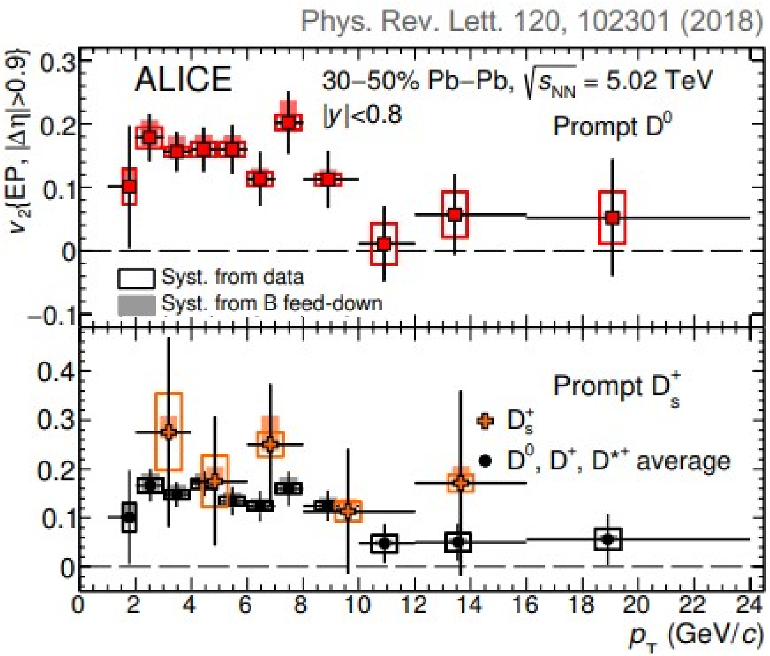
P. Naidon and S. Endo, Rept. Prog. Phys. 80 (2017) 056001



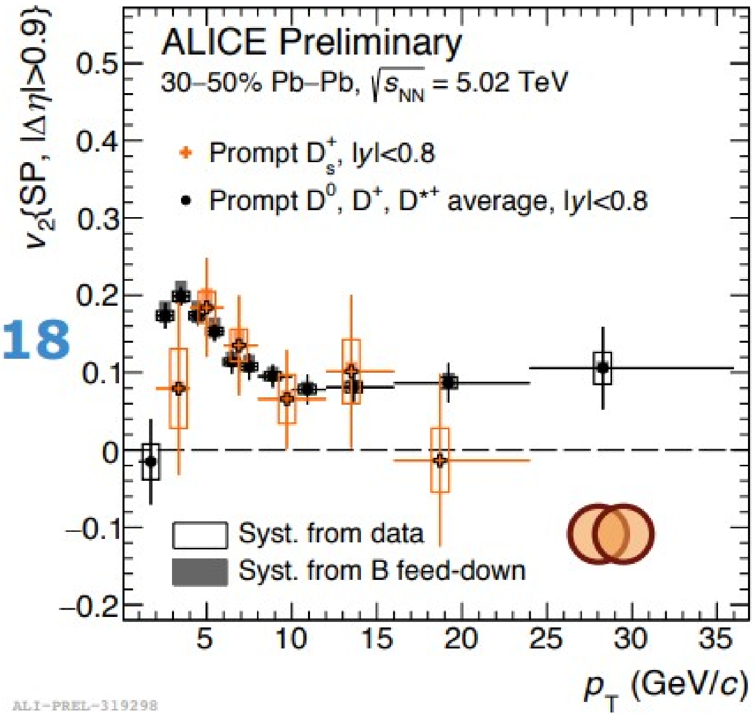
- H-Dibaryon: Tight constraints on the allowed binding energy
  - $B_{\Lambda\Lambda}=3.2^{+1.6}_{-2.4}(stat.)^{+1.8}_{-1.0}(syst.)$
  - More stringent than previous measurements



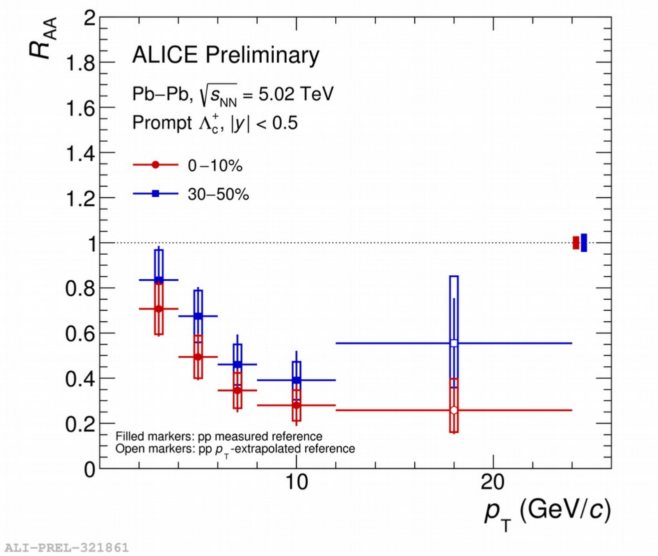
D_s v_2 :Comparison of the obtained results

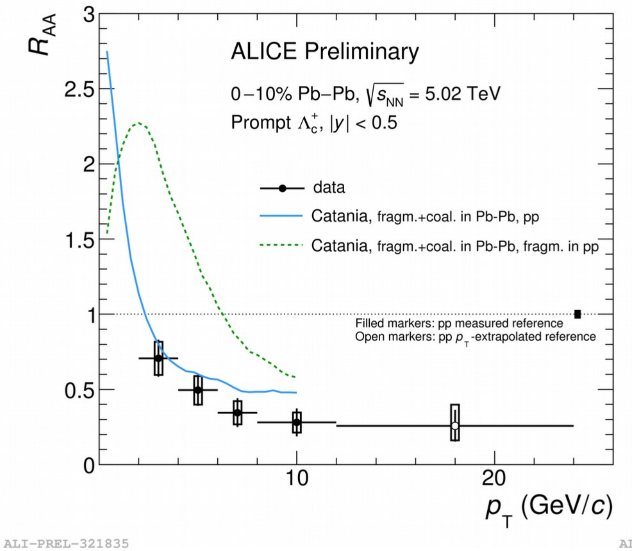


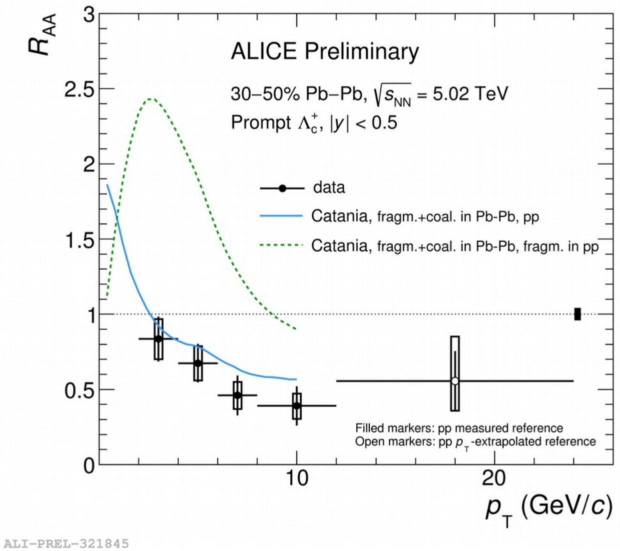
'15 → '18



$\Lambda_c^+ R_{AA}$

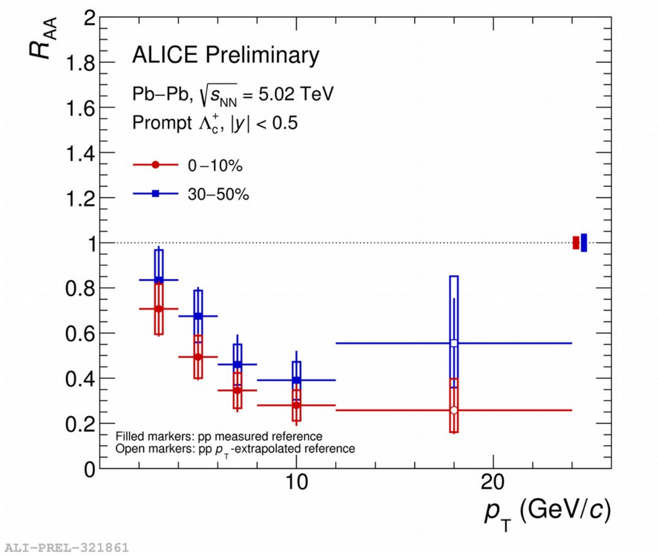


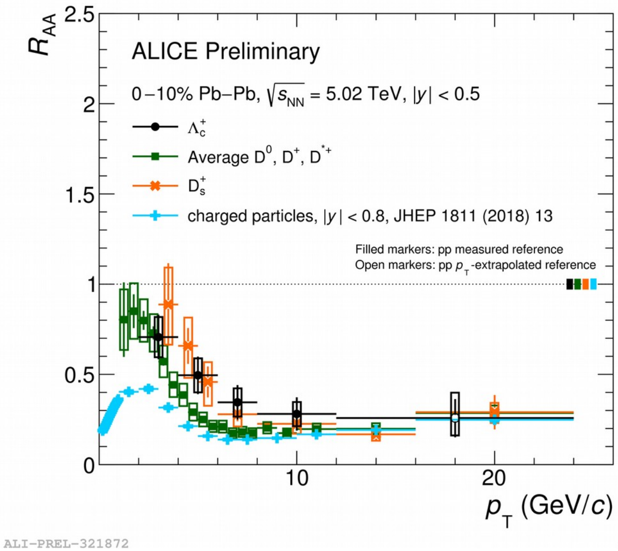


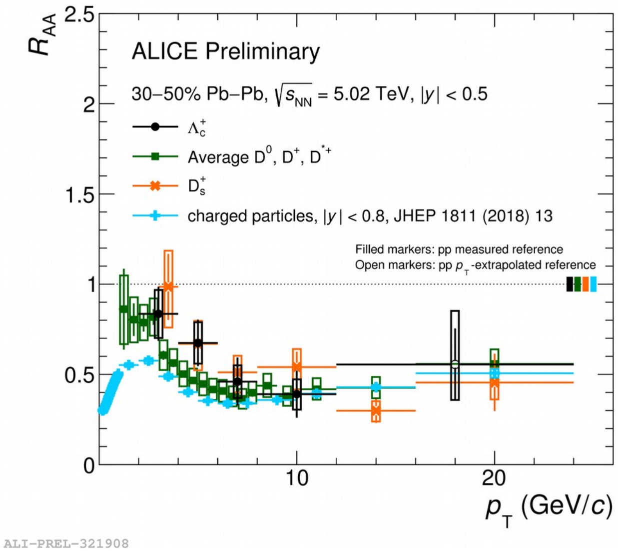


- Despite compatibility within uncertainties, hint to a nuclear modification factor smaller for central collisions by ~1.5x up to p_T = 12 GeV/*c*.
- Agreement within ~2σ with results from 2015 Pb-Pb data (PLB793 (2019) 212-223), but different centrality intervals
- Similarly to Λ_c^+/D^0 , the comparison to theory favours a scenario where both coalescence and fragmentation are present, for both centrality ranges.

$\Lambda_c^+ R_{AA}$







- Despite compatibility within uncertainties, hint to a nuclear modification factor smaller for central collisions by ~1.5x up to p_T = 12 GeV/*c*.
- Agreement within ~2σ with results from 2015 Pb-Pb data (PLB793 (2019) 212-223), but different centrality intervals

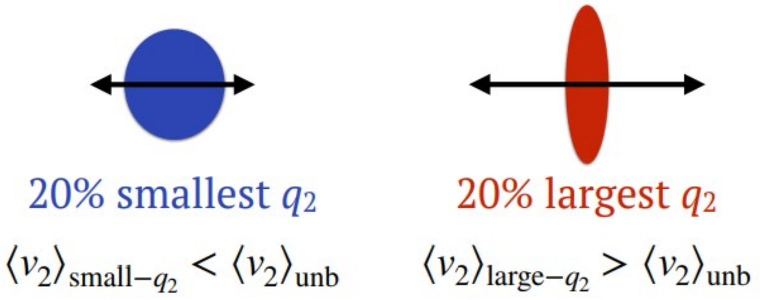
- Comparison to charged particles and non-strange D mesons suggests a higher $\Lambda_c^+ R_{AA}$.
- Comparison to D_s less straightforward due to uncertainties.

Eur. Phys. J. C (2018) 78: 348

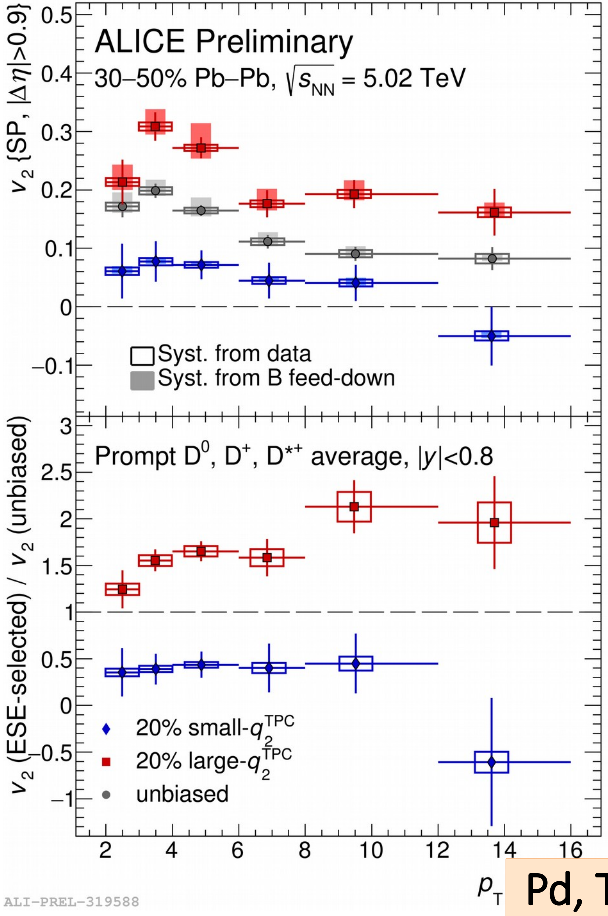
D-meson v_2 with Event-Shape Engineering

- The Event-shape engineering (ESE) technique relies on the classification of events according to their eccentricity, using the magnitude of the second-harmonic reduced flow vector q_2

$$q_2=\frac{|\vec{Q_2}|}{\sqrt{M}}, Q_{2,x}=\sum_{i=1}^{M}\cos(2\varphi_i), Q_{2,y}=\sum_{i=1}^{M}\sin(2\varphi_i)$$



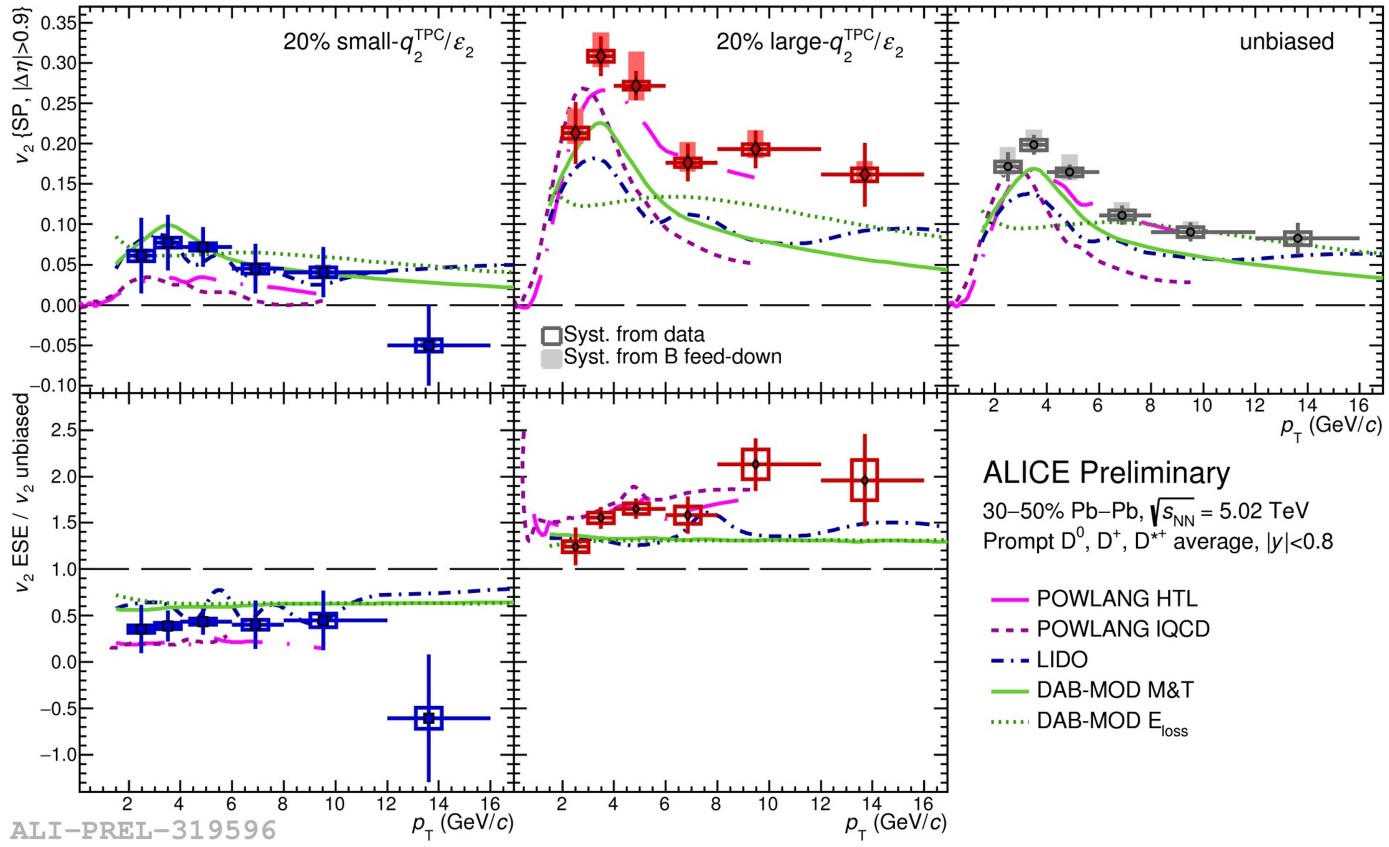
- **Measurement of D-meson v_2 in ESE-selected samples indicate a positive correlation between the D-meson v_2 and the light-hadron v_2**



Pd, To

D-meson v_2 with Event-Shape Engineering

Pd, To



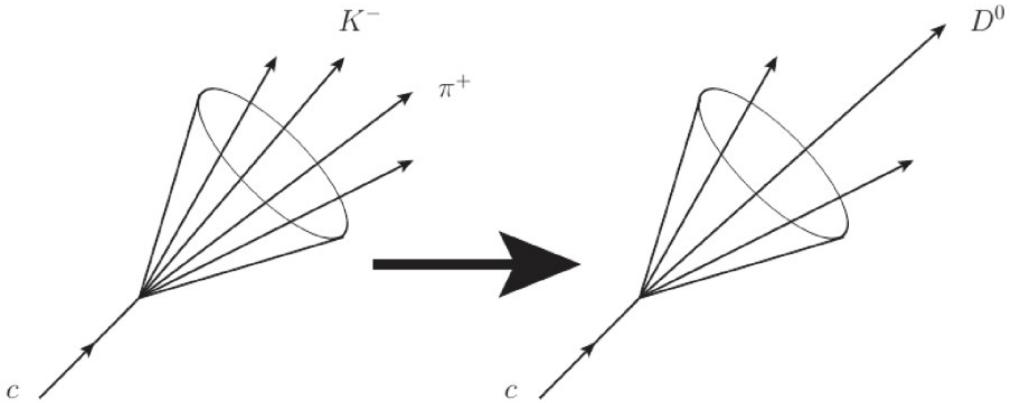
- Models based on charm quark transport in an hydrodynamically expanding medium describe reasonably q_2 dependence of elliptic flow
- D-meson v_2 variation predicted by models similar for different parameters (e.g. POWLANG HLT vs. lQCD)

POWLANG: EPJC 75,121(2015); LIDO: arxiv 1810.08177; DAB-MOD: PRC 96 064903 (2017)

D^0-tagged jets: Reconstruction

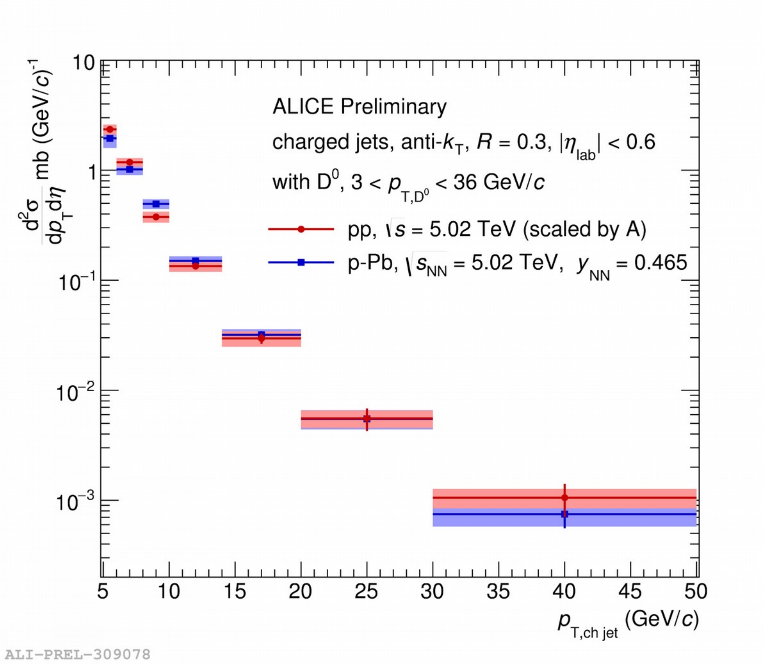
- D^0 meson selection:
  - Decay channel: $D^0 \rightarrow K^- \pi^+$ (BR = 3.89%)[PDG PRD 98 (2018) 030001]
  - K/π PID via d*E*/d*x* of TPC and TOF
  - Topological selection (secondary vertex)
  - p_{T}, D > 2 GeV/*c*
- D^0-meson candidates replace their decay products (K and π) in the jet reconstruction

- Jet finding:
  - Track-based jet reconstruction
    - Anti-kT , R= 0.3, 0.4
    - $p_{T,ch}$ jet > 5 GeV/*c*

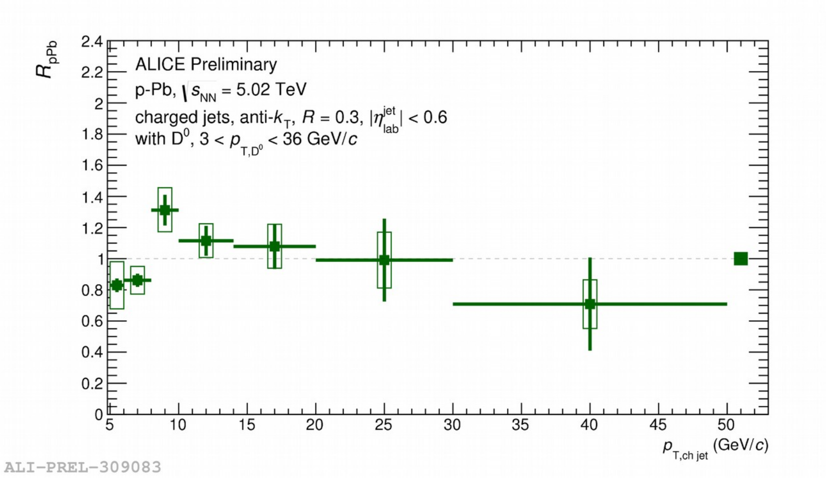


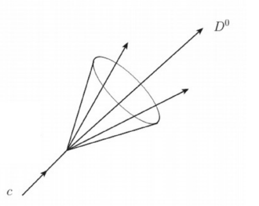
Ba, Pd

D^0-tagged jets: pp vs. p-Pb at 5.02 TeV



$$R_{pA}(p_T) = \frac{1}{A}\frac{d\sigma_{pA}/dp_T}{d\sigma_{pp}/dp_T}$$



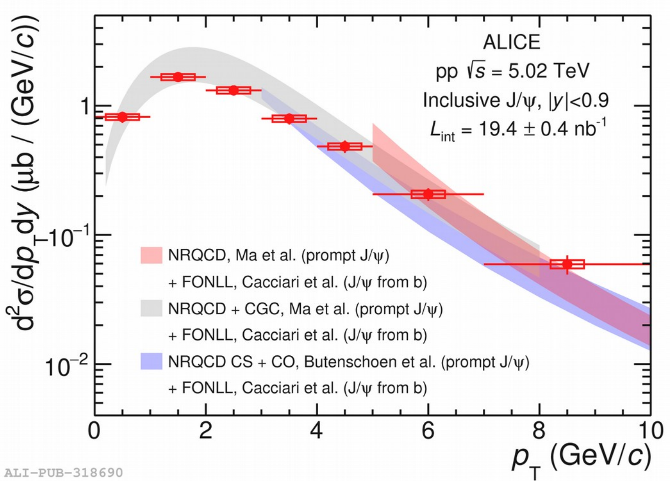


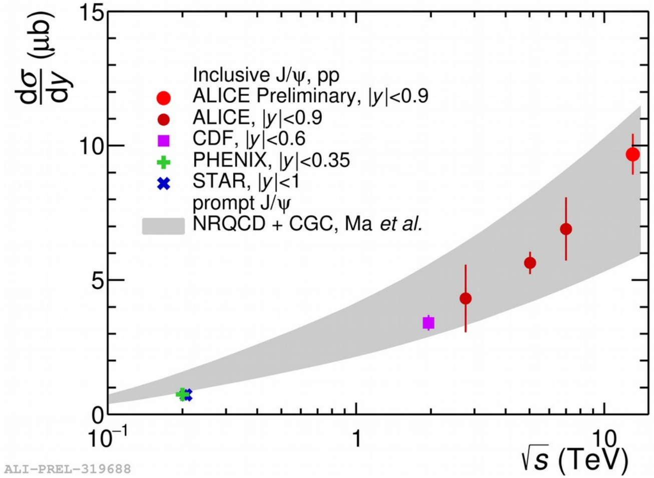
- Compatibility of p_T-differential cross section among the pp and p-Pb systems
- R_{pPb} compatible with unity within the current uncertainty
- No modifications among the two systems
- No evidence of CNM effects

Ba, Pd

J/ψ production at mid rapidity

ALICE Collaboration arxiv 1905.07211



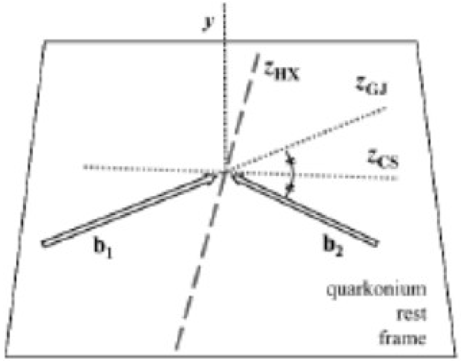


- J/ψ p_T-differential cross section down to p_T=0 at mid-rapidity at 5 and 13 TeV
  - New pp reference + important constraints to understand J/ψ production mechanism
- NRQCD+CGC describes data down to p_T=0, as well as the cross section vs. √s
- **Run 1,2 ALICE legacy on charmonia: double p_T,y differential view on J/ψ (and forward ψ(2S)) production down to p_T=0 from √s = 2.76 to 13 TeV**

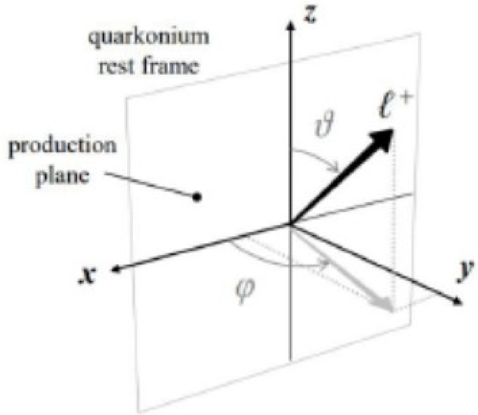
LO-NRQCD+CGC: Y.-Q. Ma and R. Venugopalan: PRL. 113 (2014) 192301;
NLO-NRCQD: Y.-Q. Ma et al., PRL 106 (2011) 042002;
NLO-NRQCD CS+CO: M. Butenschoen and B.A. Kniehl, PRL 106 (2011) 022003

J/ψ polarization

Helicity frame: z_{HX} along J/ψ momentum in collision center-of-mass frame
Collin-Soper: z_{CS} defined by bisector of the angle defined by a beam momentum vector and the opposite of the other beam momentum vector seen in the J/ψ rest frame



Figures from P.Faccioli et al. EPJ C69 (2010) 657-673



$$W(\cos\vartheta,\varphi) \propto \frac{1}{3+\lambda_\vartheta} \cdot \left(1+\lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi\right)$$

$(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi}) = (0,0,0) \rightarrow J/\psi$ is not polarised

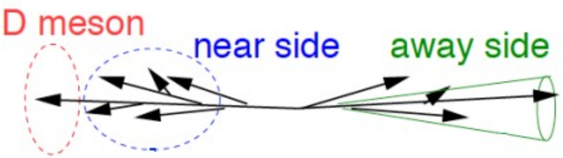
$(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi}) = (-1,0,0) \rightarrow J/\psi$ is longitudinally polarised

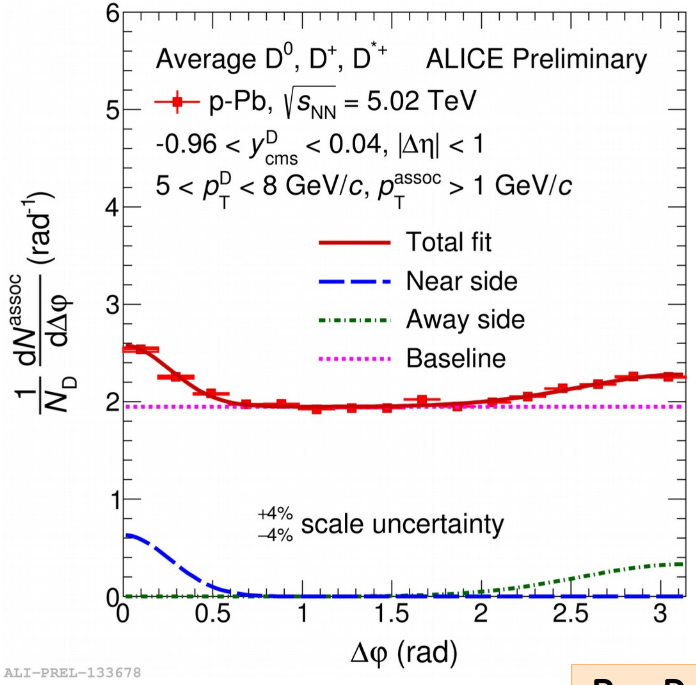
$(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi}) = (+1,0,0) \rightarrow J/\psi$ is transversally polarised

To

D-h correlations

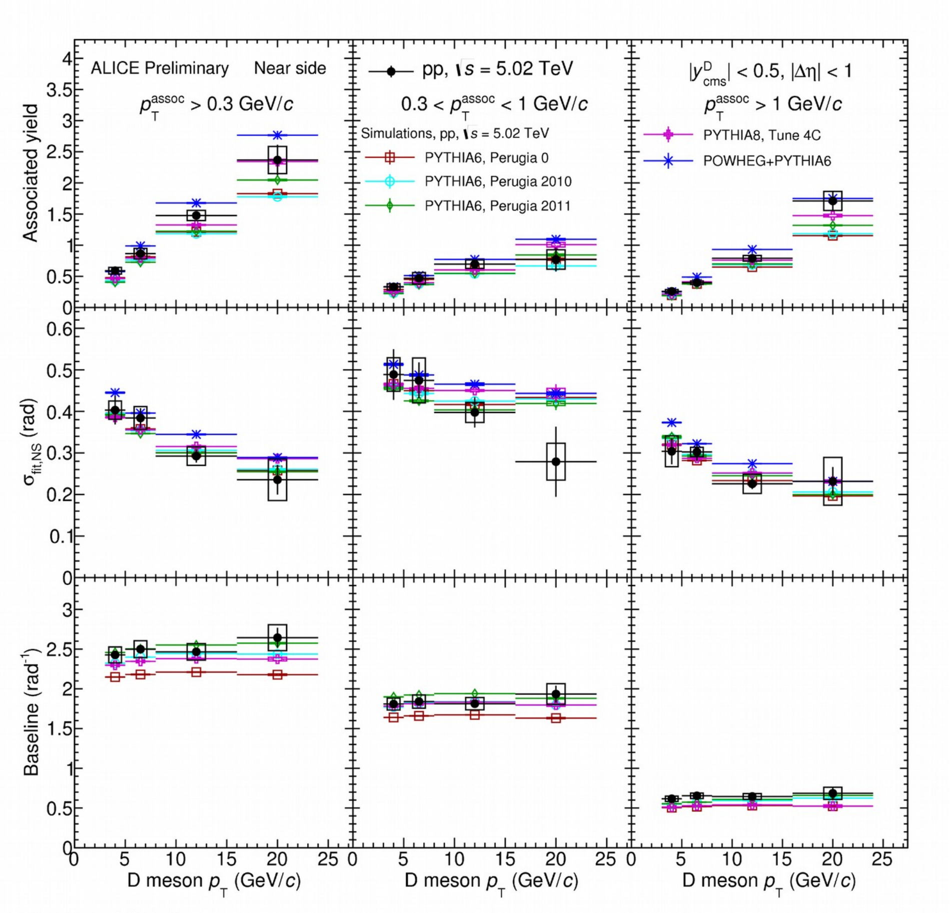
- Complementary to jet studies:
  - internal composition, spatial profile
- D^0, D^{*+}, D^+-meson (trigger particle) correlated with primary charged tracks (associated particles)
- Corrections:
  - Limited detector acceptance and spatial inhomogeneities → Event mixing
  - Trigger and associated particle efficiencies
  - Subtraction of B feed-down contribution (FONLL based)
  - Residual secondary particle contamination
- Fit to weighted average of D^0, D^{*+}, D^+ correlation distributions to extract quantitative observable (near- and away-side peak yields and widths, baseline height)





Ba, Pd

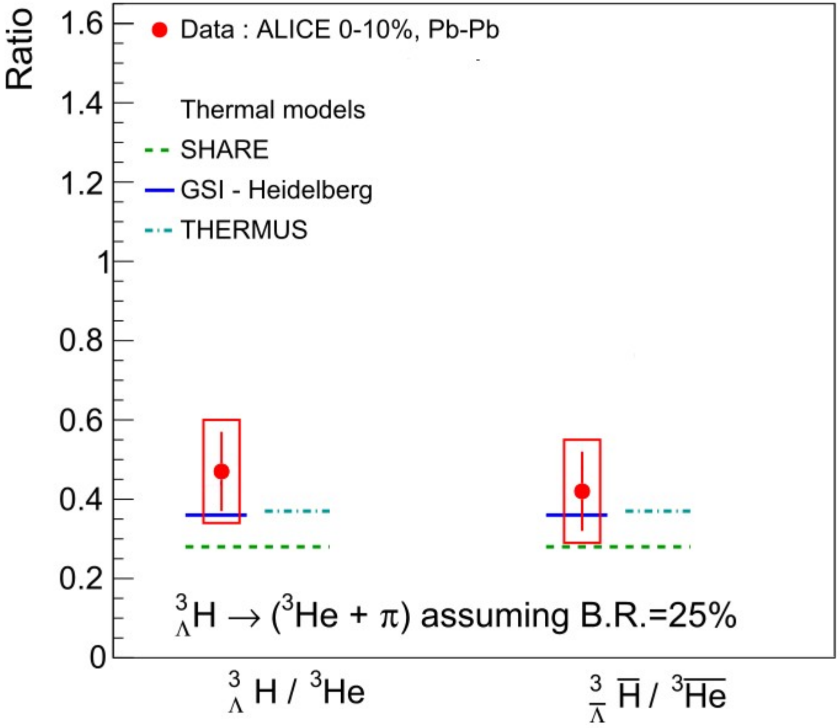
D-h correlations: Data (pp √s = 5 TeV) vs Model



- Yield and width vs. p_T(D) describe the charged- particle multiplicity and the spatial profile of the charm jet
- POWHEG+PYTHIA tends to generally predict larger associated yields and broader peaks than PYTHIA, describing better data yields
- Apart for Perugia-0 tune all the models catch well the baseline values and trend with current uncertainties

Ba, Pd

Thermal model comparison

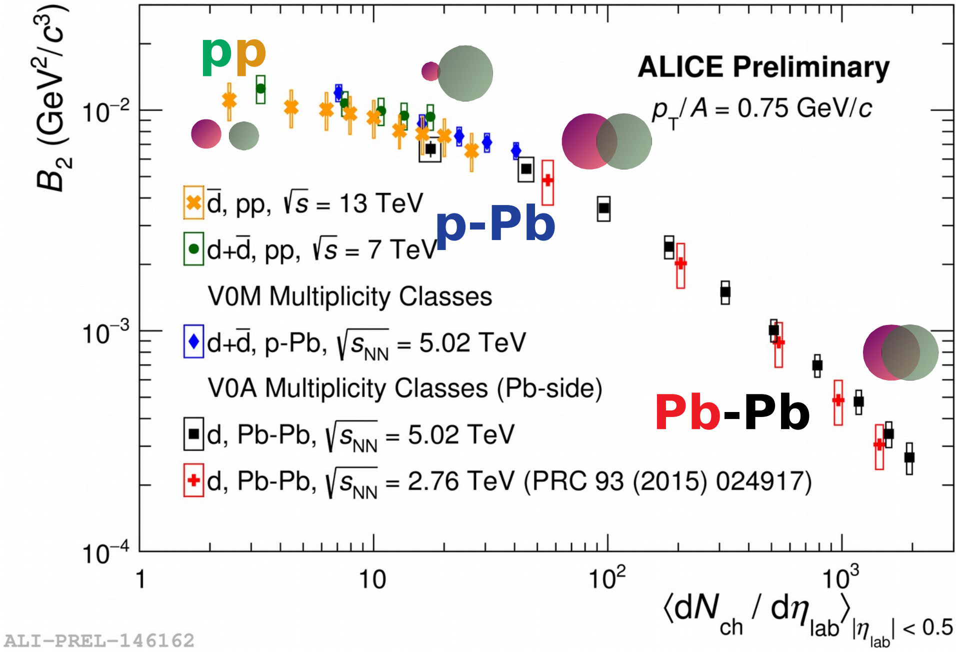


- $^{3}_{\Lambda}H/^{3}He$ ratio compared with different thermal models:
  - Extracted yield is in good agreement with equilibrium thermal model prediction for T_{chem} = 156 MeV, such as GSI-Heidelberg model [1] even if B_{Λ} is << T_{ch}

ALICE Collaboration Phys. Lett. B 754 (2016) 360-372

[1]A. Andronic et al., Phys. Lett. B 697, 203 (2011)

Coalescence parameter B_2



F.Bellini and A. P.Kalweit, arXiv:1807.05894 [hep-ph].
R. Scheibl, U. Heinz, PRC 59 (1999) 1585-1602
K. Blum et al., PRD 96 (2017) 103021

Simple coalescence model

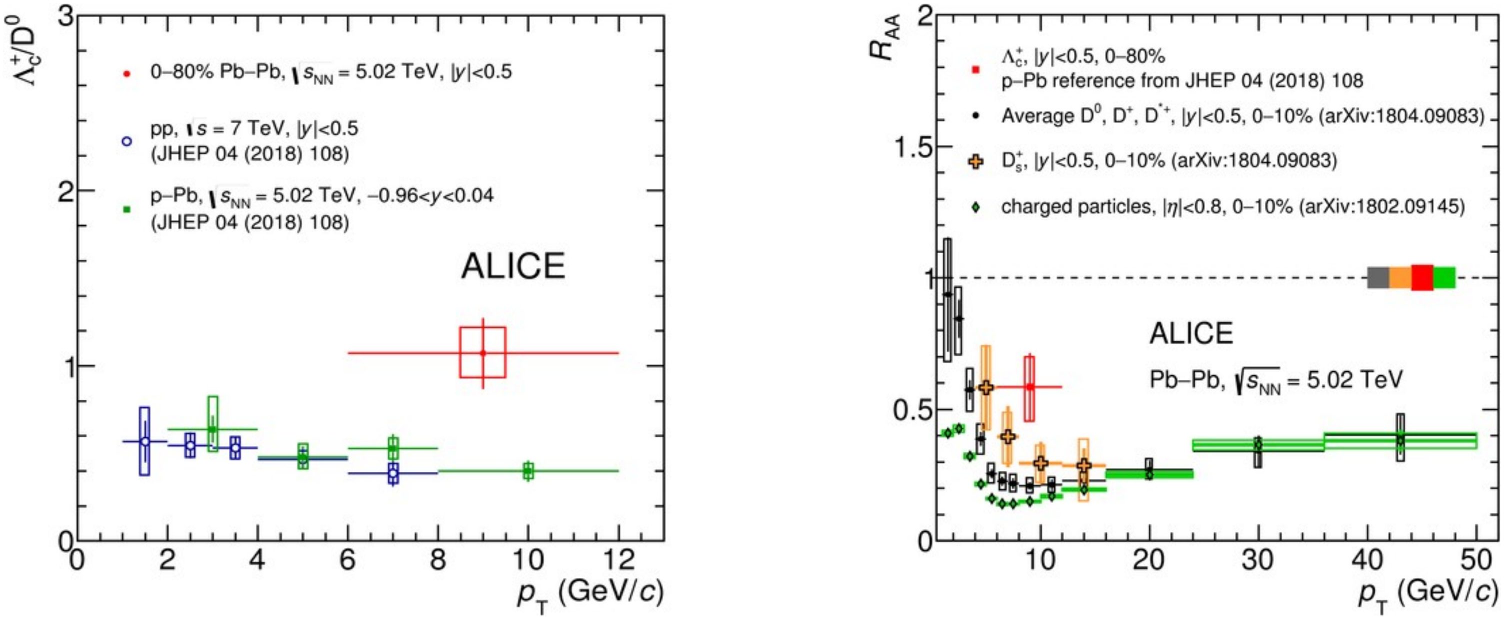
- Flat B_2 vs p_T and no dependence on multiplicity/centrality
  - ✔ Approximately observed in "small systems": pp, p-Pb and peripheral Pb-Pb

More elaborate coalescence model takes into account the volume of the source:

$$B_2 = \frac{3\pi^{3/2}\langle C_d \rangle}{2m_T R^3(m_T)}$$

- B_2 scales like HBT radii (R)
  - ➢ decrease with centrality in Pb-Pb is explained as an increase in the source volume
  - ➢ increase with p_T in central Pb-Pb reflects the k_T-dependence of the homogeneity volume (i.e. volume with similar flow properties) in HBT
  - ✔ Qualitative agreement in central Pb-Pb collisions

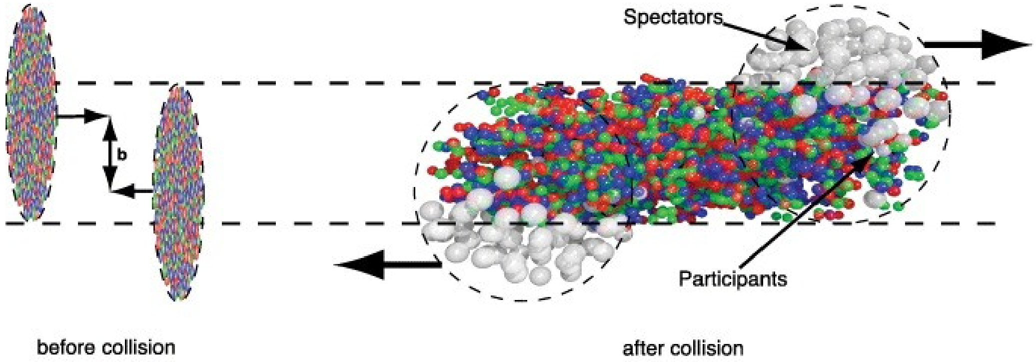
Λ_c production in heavy ion collisions



- ALICE measured Λ_c in Pb-Pb collisions at 5.02 TeV for 0-80% centrality class
  - ~2.5σ hint of Λ_c / D^0 ratio enhanced in Pb-Pb collisions w.r.t. pp and p-Pb collisions
  - ~2.0σ hint of larger R_{AA} of Λ_c than D mesons in 0-10% centrality class
    - Charm quark hadronization via **coalescence**:
      - hierarchy of the R_{AA} $\Lambda_c > D_s >$ Non-strange D-meson > pions

ALICE Collaboration arXiv:1809.10922
DOI: 10.1016/j.physletb.2019.04.046

Centrality of the collisions

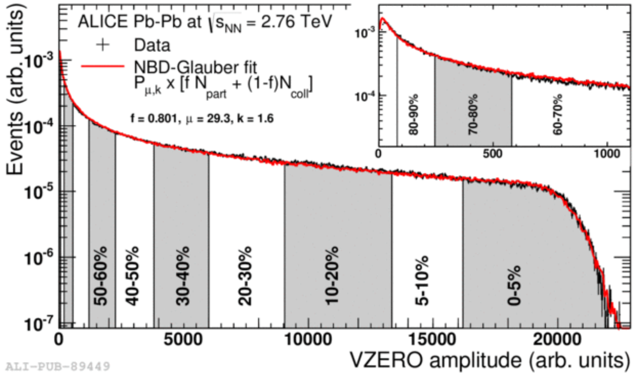


Centrality = degree of overlap of the 2 colliding nuclei

Central collisions:
- small impact parameter *b*
- high number of participant nucleons → high multiplicity

Peripheral collisions:
- large impact parameter *b*
- low number of participant nucleons → low multiplicity

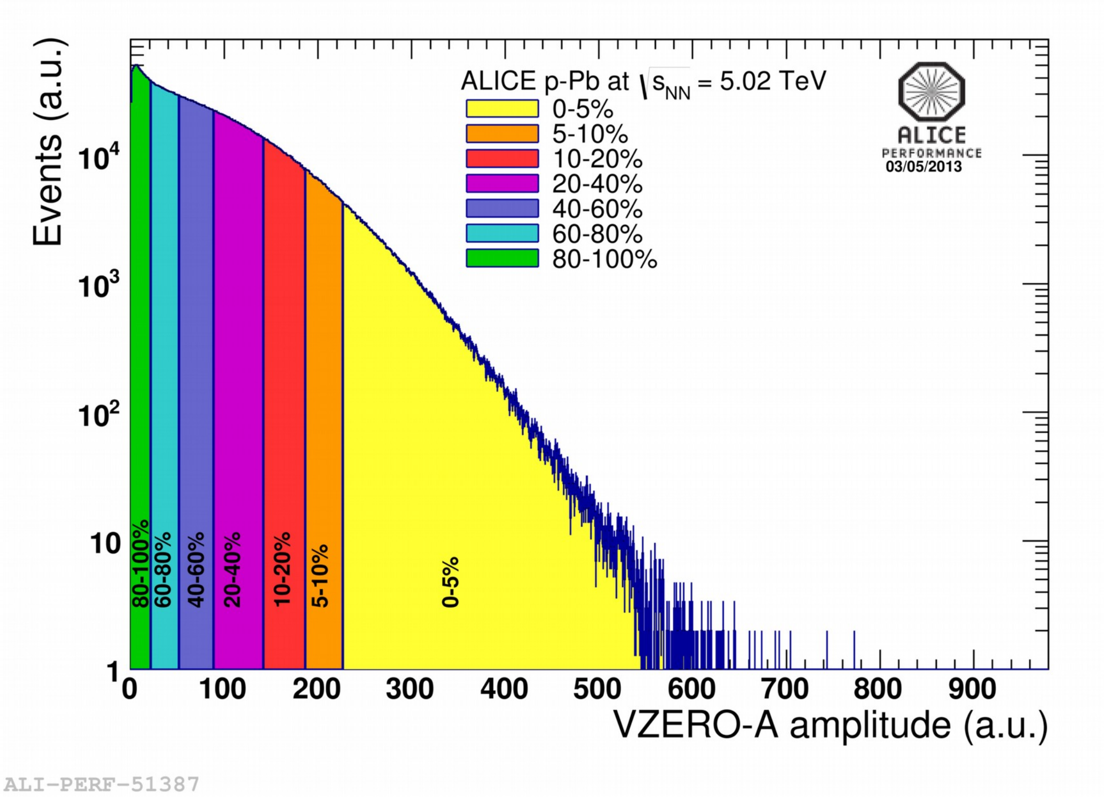
Centrality connected to observables via Glauber model



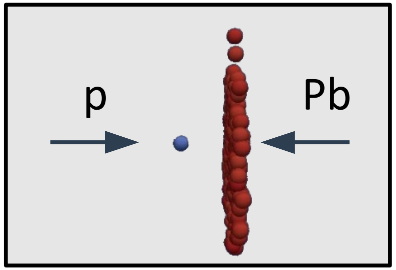
ALICE Collaboration, Phys. Rev. Lett. 106, 032301 (2011)

Centrality of the collisions: p-Pb and pp

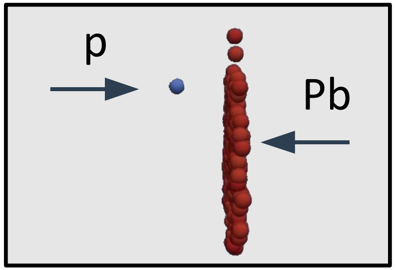
Multiplicity estimator: slices in VZERO-A (V0A) amplitude



Central collision



Peripheral collision

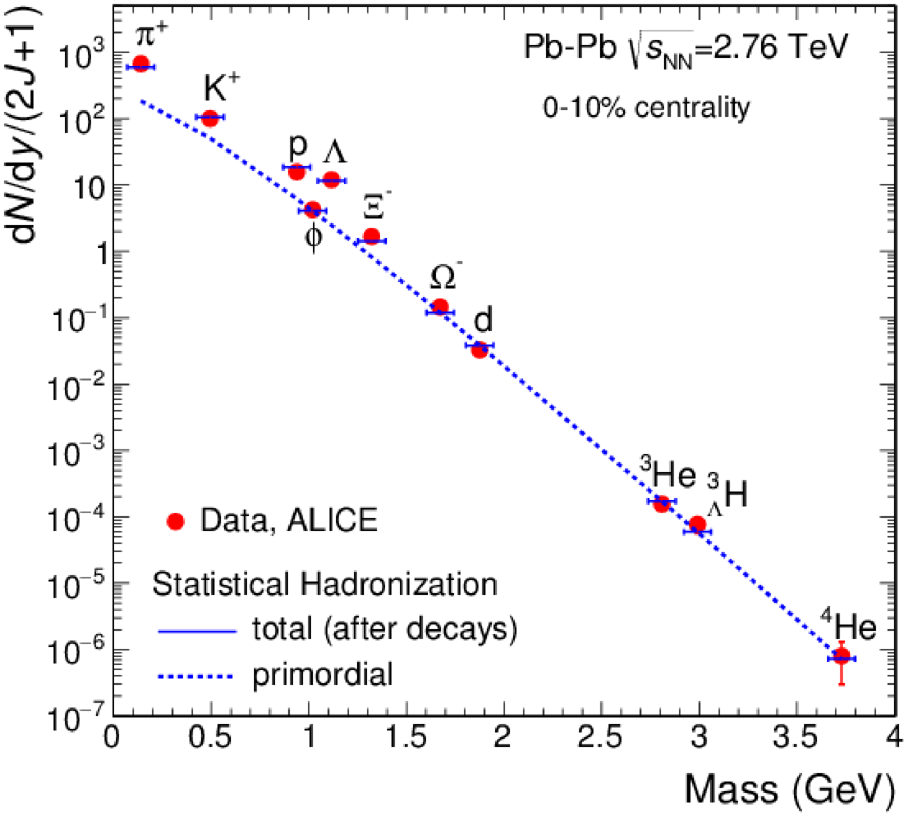


Correlation between impact parameter and multiplicity is not as straight-forward as in Pb-Pb

Statistical thermal model

- Thermodynamic approach to particle production in heavy-ion collision: all the particles are produced at chemical freeze-out
- Starting point: Grand Canonical partition function (Z) for a relativistic ideal quantum gas of hadrons of particle type i (i = pion, proton,... → full PDG)
- Thermal model can predict also the yields of any particle at chemical freeze-out
- Exponential dependence of the particle yield: $\frac{dN}{dy} \propto e^{\left(-\frac{m}{T_{chem}}\right)}$
- The thermal model predicts an exponential decrease of particle yields with increasing mass at a given temperature
- The density ratio of a particle with the next heavier one: $\frac{n_i}{n_{i+1}} \approx \exp\left(-\frac{\Delta m}{T}\right)$

Thermal model



Nature 561 (2018) no.7723, 321-330 arXiv:1710.09425 [nucl-th]

Statistical hadronization model: thermal emission from equilibrated source

Particle abundances fixed at chemical freeze-out

$$N_i = \frac{g_i V}{2\pi^2} \int_0^{+\infty} \frac{p^2 dp}{\exp\left[-\left(\frac{E-\mu_B}{T_{\mathrm{chem}}}\right)\right] \pm 1}$$

- Primordial yields modified by hadron decays:
  - Contribution obtained from calculations based on known hadron spectrum
  - Excellent agreement with data with only 2 free parameters: T_{chem} , V