Overview of results from ALICE

- Particle production and collective flow
- Correlations and Fluctuations
- Summary and Outlook

UJ 22.03.2021 (virtual ☹)

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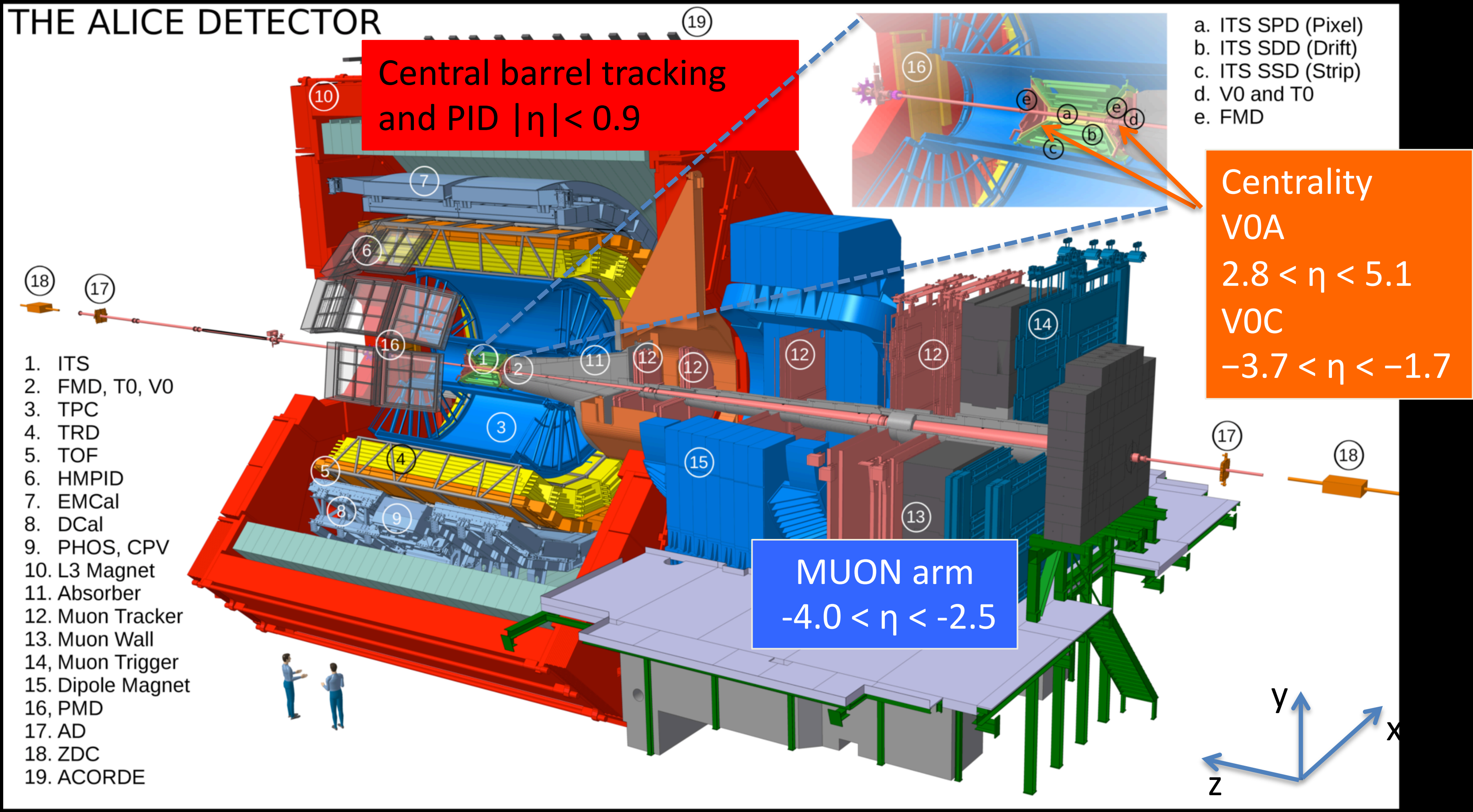
On behalf of the ALICE Collaboration

A Large Ion Collider Experiment

- Excellent particle identification capabilities over a wide p_T range 0.1-20 GeV/c
- Good momentum resolution ~1-5% for p_T = 0.1-50 GeV/c

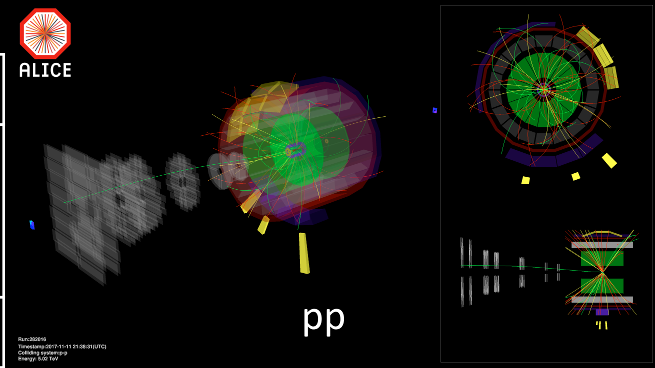


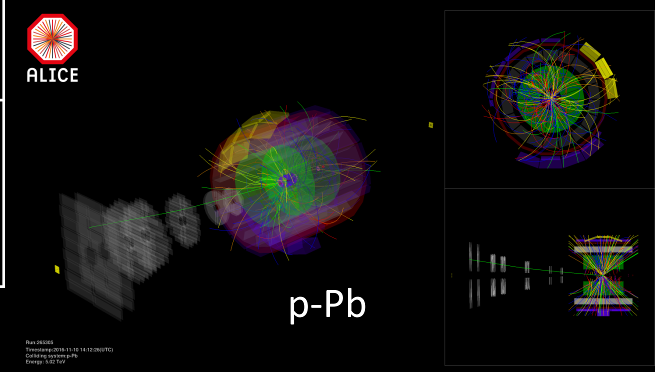
ALICE at work since 2009

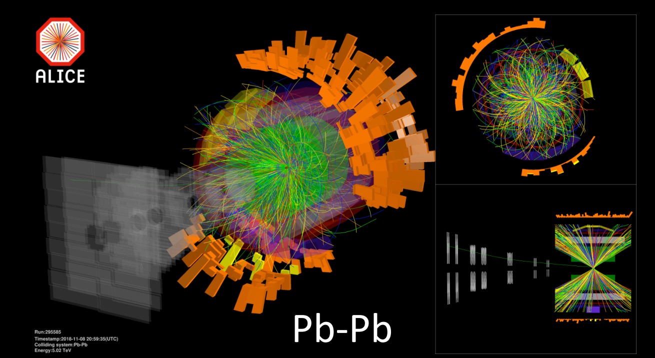
System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011 2015 2018	2.76 5.02 5.02	~75 μb^{-1} ~250 μb^{-1} ~0.9 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013 2015-2018	0.9, 2.76, 7, 8 5.02, 13	~200 μb^{-1}, ~100 μb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1} ~1.3 pb^{-1}, ~59 pb^{-1}

- Energy and system dependence studies of particle production are possible
- Large statistics of pp, p-Pb and Pb-Pb collisions at the same $\sqrt{s_{NN}}$
  → **Precise comparison studies**

Study of the quark-gluon plasma

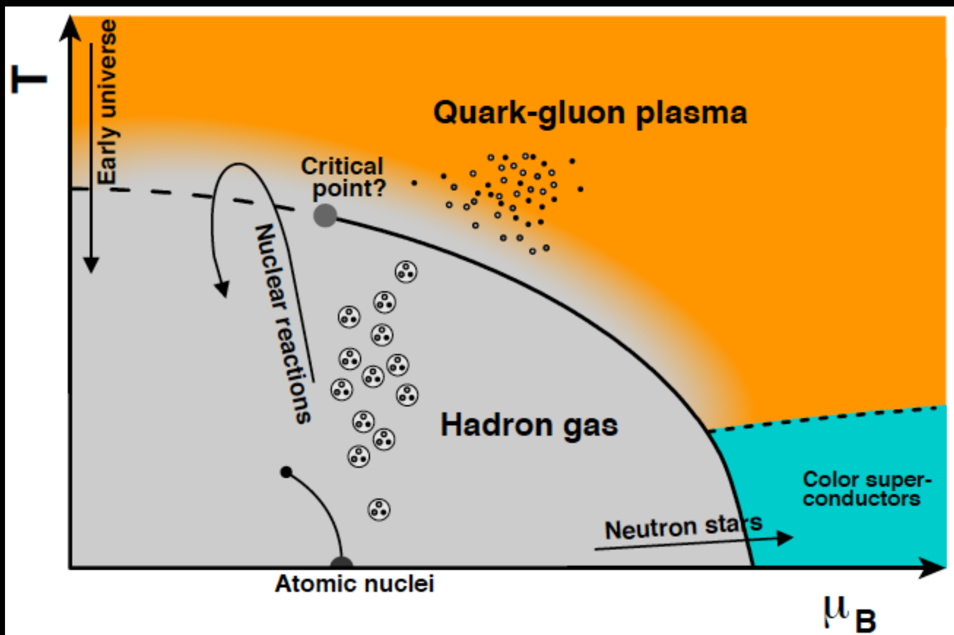


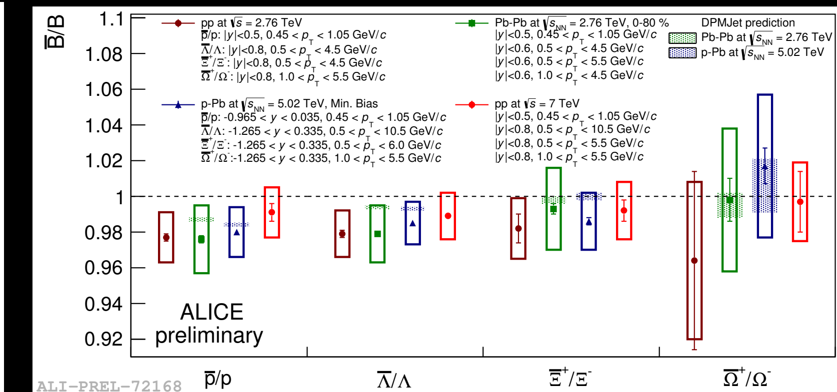




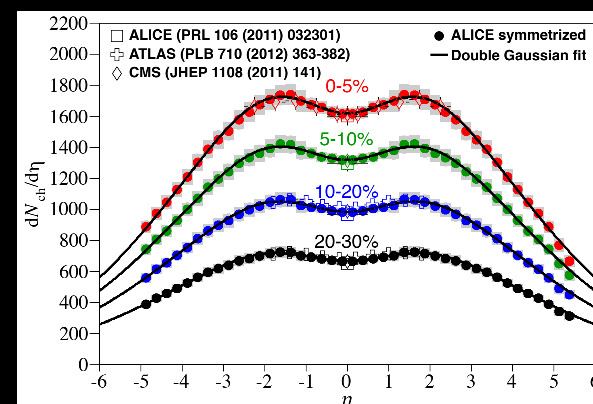
ALICE case

ALICE probes nuclear matter at μ_B ~ 0 and high temperature



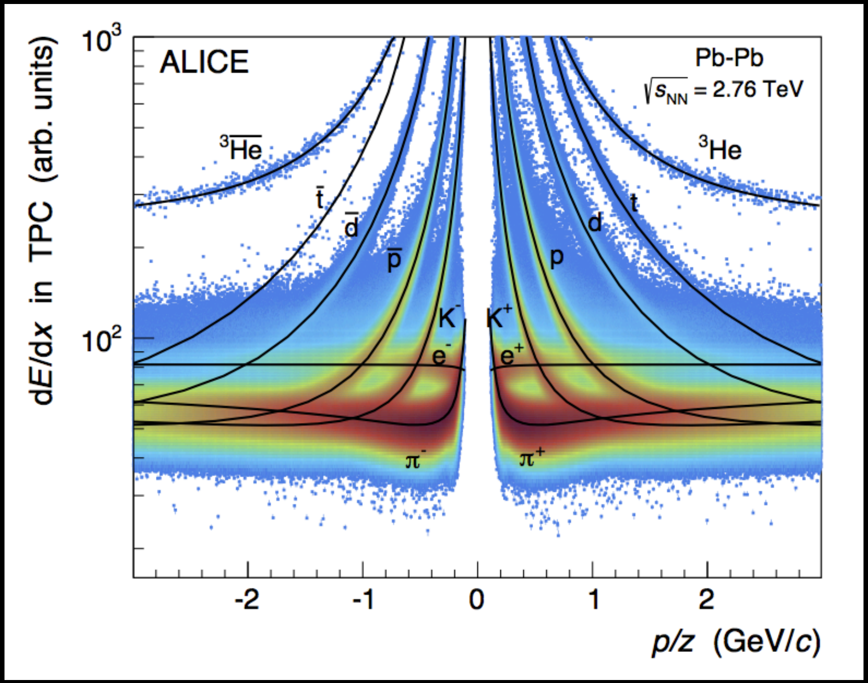


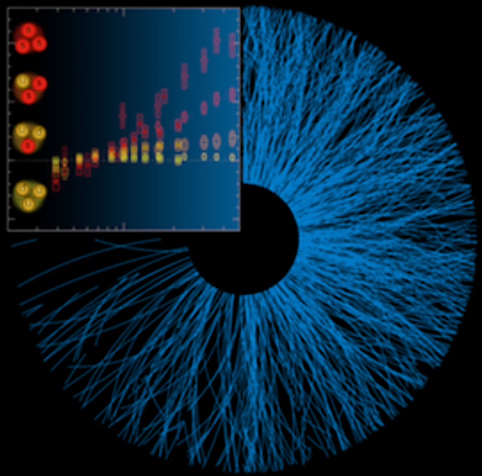
Phys. Lett. B 726 (2013) 610-622



Lattice QCD: Hadron gas to quark-gluon plasma
(μ_B = 0, T_C = 156.5 ± 1.5 MeV,
ε_C = (0.42 ± 0.06) GeV/fm^3, smooth crossover)
A. Bazavov et al. Phys. Lett. B 795 (2019) 15

Central collisions:
ε ~ 14 GeV/fm^3 >> ε_c

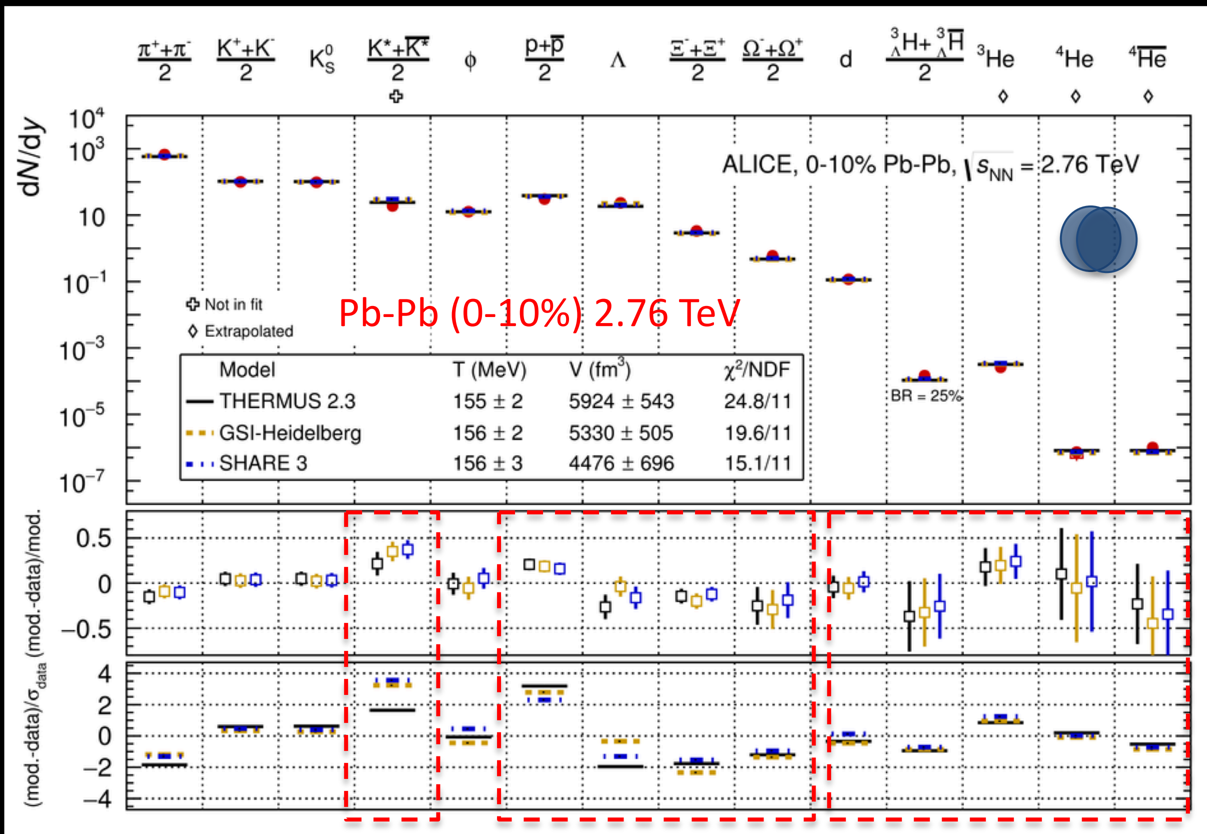




PARTICLE PRODUCTION

Hadron yields vs thermal models in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

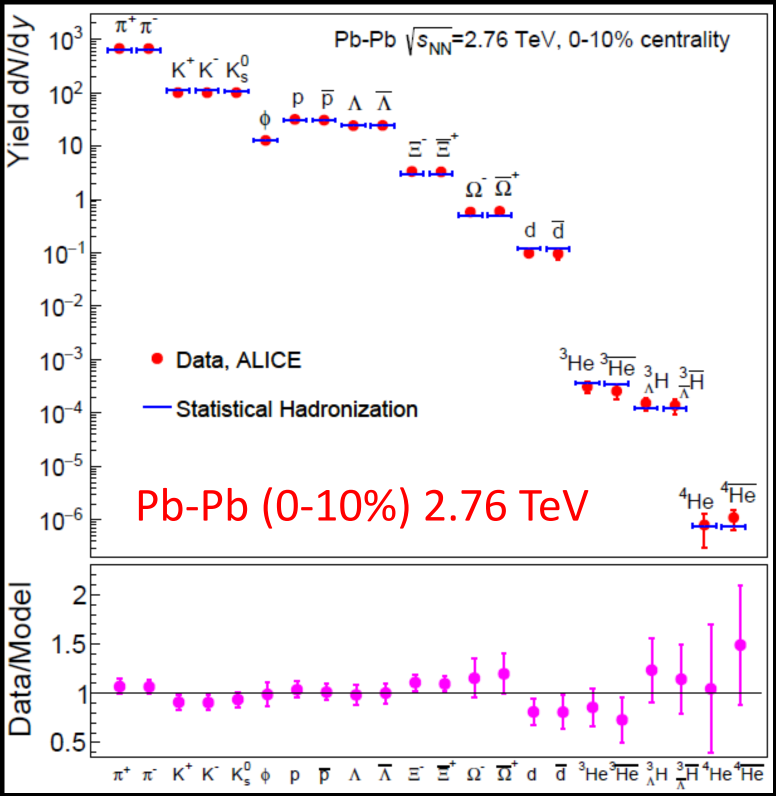
Nucl. Phys. A 971 (2018) 1



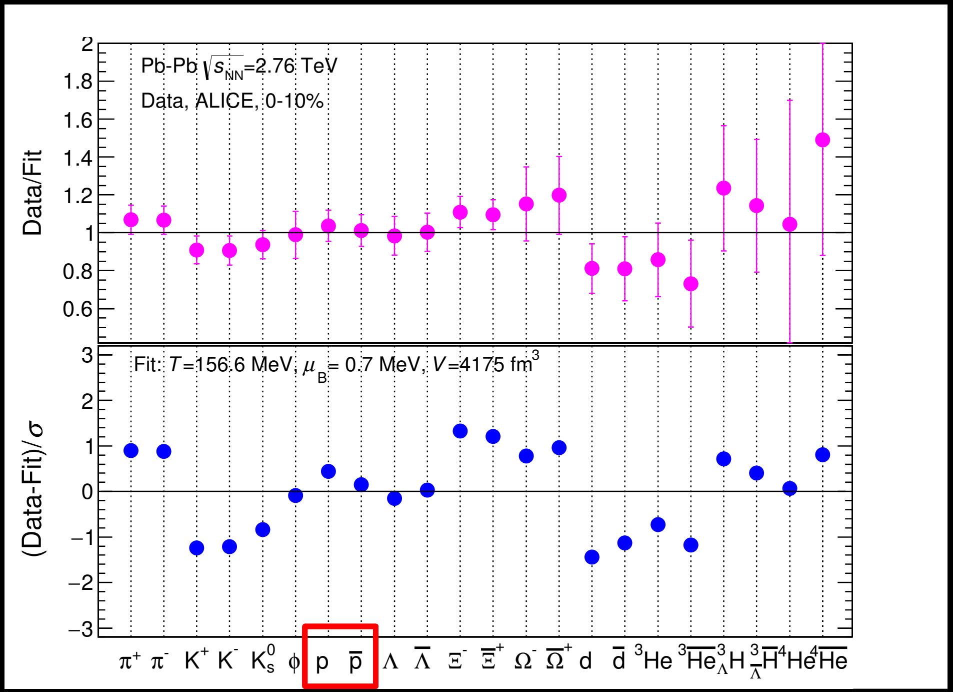
- Production of (most) hadrons well described at freezeout temperature T_{ch} ~ 156 MeV
- K*0 resonance (not included in the fit): production overestimated by thermal models
- Tension for protons and multi-strange baryons
- Light nuclei production described by thermal models (binding energy << T_{ch})?

THERMUS: Wheaton et al., Comput. Phys. Commun, 180 (2009) 84
GSI-Heidelberg: Andronic et al., Phys. Lett. B 673 142
SHARE: Petran et al., Comp. Phys. Commun. 195 (2014) 2056

Hadron yields vs improved thermal model in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

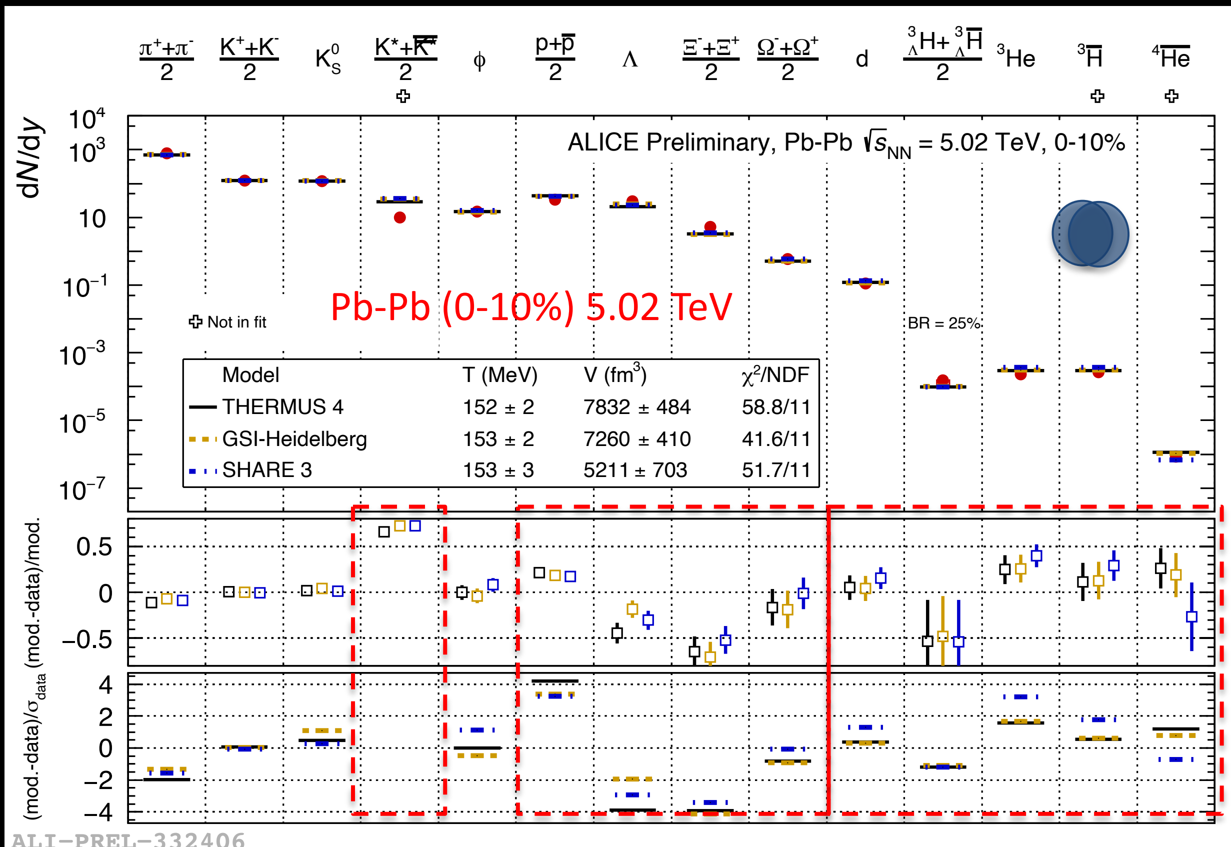


A. Andronic et al. Phys. Lett. B792 (2019) 304



- Resonant and non-resonant pion-nucleon and multi-pion-nucleon interactions included in the model (S-matrix approach)
- Production of hadrons well described at freezeout temperature T_{ch} = 156.6 ± 1.7 MeV → consistent with critical temperature T_c from the lattice QCD calculations

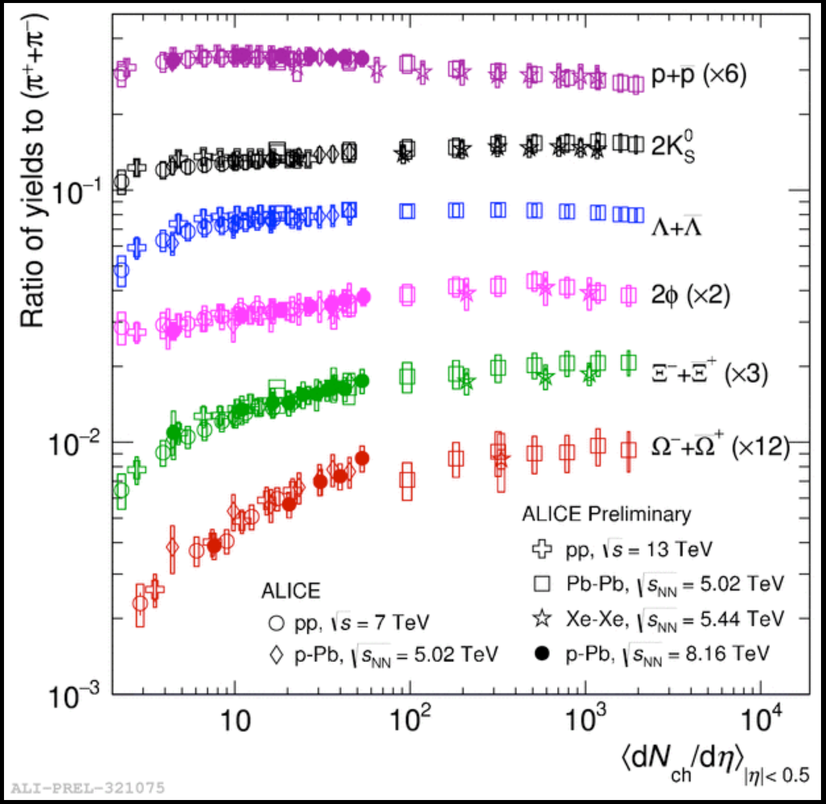
Particle yields vs thermal models in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



- Production of (most) hadrons well described at freeze-out temperature T_{ch} ~ 153 MeV (different than at 2.76 TeV)
- K^{*0} resonance (not included in the fit): production overestimated by thermal models
- Tension for protons and multi-strange baryons (new approach is currently studied)
- Light nuclei production described by thermal models (binding energy << T_{ch})?

THERMUS: Wheaton et al., Comput. Phys. Commun, 180 (2009) 84
GSI-Heidelberg: Andronic et al., Phys. Lett. B 673 142
SHARE: Petran et al., Comp. Phys. Commun. 195 (2014) 2056

Relative particle production in pp, p-Pb, Pb-Pb and Xe-Xe

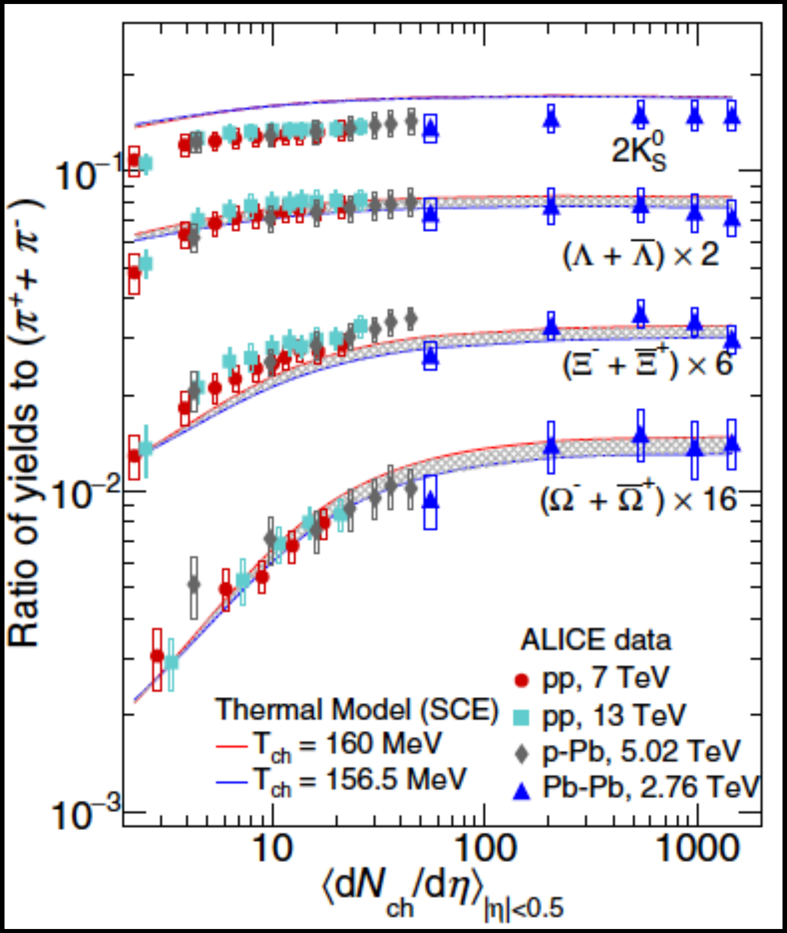


- Smooth evolution from pp to Pb-Pb
- No significant energy and system dependence is observed at similar multiplicity
- Relative strangeness production increases with multiplicity and strangeness content in small systems

→ Hadron production is driven by the characteristics of final state

pp 7 TeV: Nature Physics 13 (2017) 535
pp 7 and 13 TeV: arXiv:2005.11120
p-Pb 5.02 TeV: Phys. Lett. B728 (2014) 25, Phys. Lett. B758 (2016) 389
Xe-Xe 5.44 TeV: arXiv:2101.03100
pp and Pb-Pb 5.02 TeV: Phys. Rev. C 101, 044907 (2020)

Relative particle production in pp, p-Pb, Pb-Pb and Xe-Xe



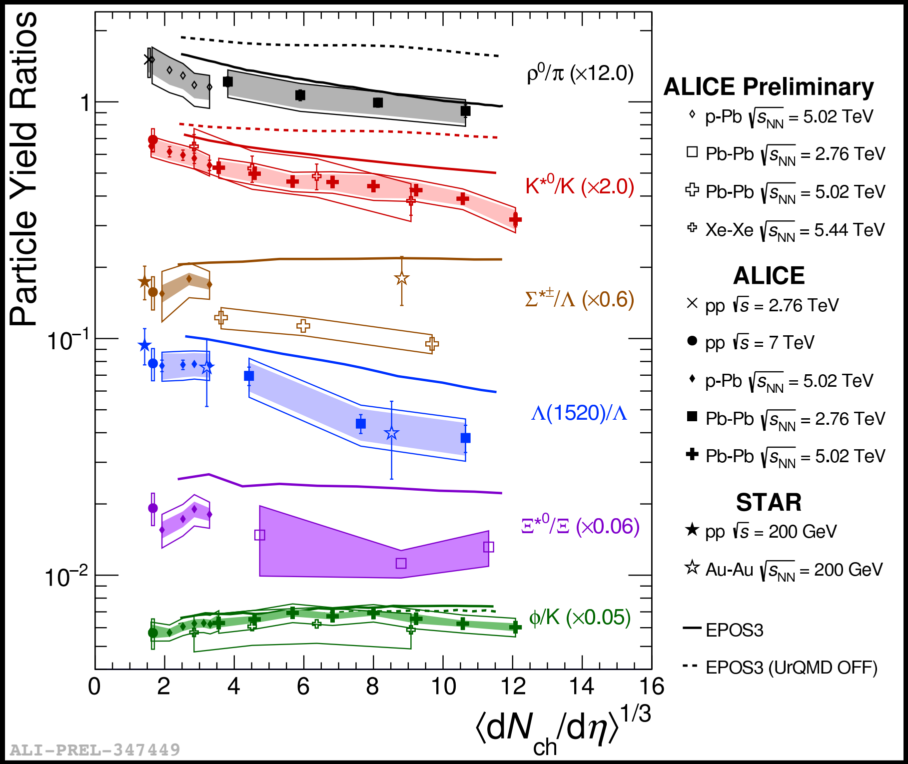
- Smooth evolution from pp to Pb-Pb
- No significant energy and system dependence is observed at similar multiplicity
- Relative strangeness production increases with multiplicity and strangeness content in small systems

- Thermal model (SCE) including interaction between hadrons (S-matrix approach) and exact strangeness conservation J. Cleymans et al. Phys. Rev. C103 014904 (2021)

pp 7 TeV and Pb-Pb 2.76 TeV: Nature Physics 13 (2017) 535
pp 7 and 13 TeV: arXiv:2005.11120

Relative resonance production in pp, p-Pb, Pb-Pb and Xe-Xe collisions

Resonance	ρ^0	K^{*0}	$\Sigma^{*\pm}$	$\Lambda(1520)$	Ξ^{*0}	ϕ
Lifetime (fm/c)	1.3	4.16	5.5	12.6	21.7	46.2



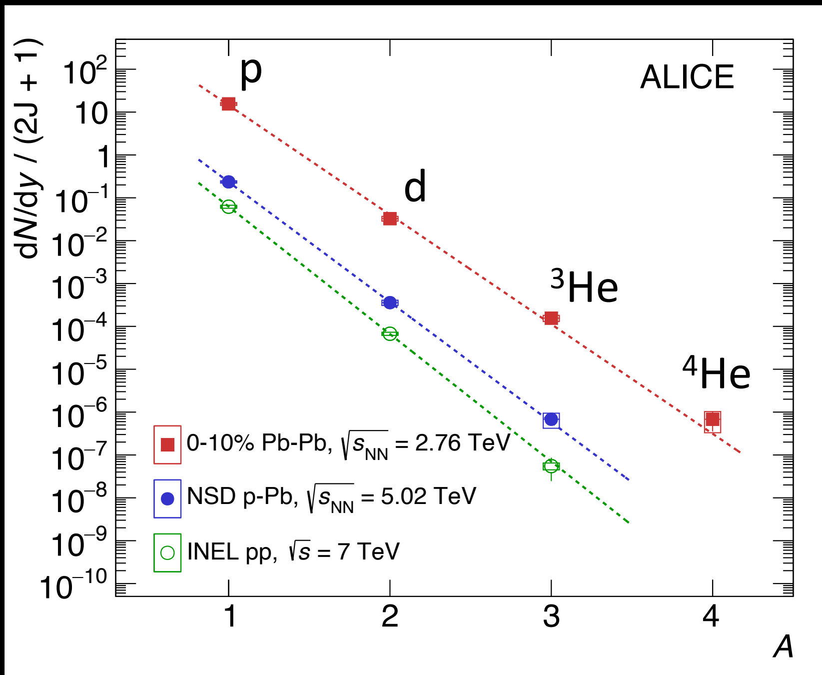
- Relative suppression of ρ^0, K^{*0}, $\Lambda(1520)$ with increasing multiplicity
- Σ^*/Λ, Ξ^*/Ξ, ϕ/K is independent of multiplicity
- Similar trend seen in all collision systems
- EPOS3 + UrQMD describes the trend of data

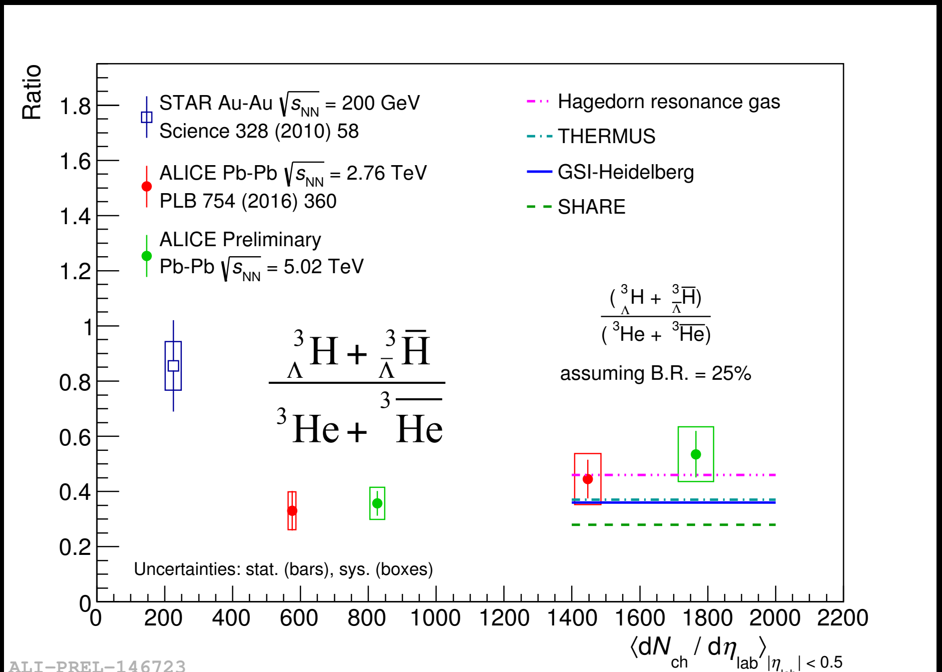
ρ^0: Phys. Rev. C99, (2019) 064901
K^{*0}: Phys. Rev. C95, (2017) 064606
$\Lambda(1520)$: Phys. Rev. C99, (2019) 024905
STAR, Phys.Rev.C78 (2008) 044906
STAR, Phys. Rev. Lett. 97 (2006) 132301
ϕ: Phys. Rev. C91 (2015) 024609
Σ^*, Ξ^*: Eur. Phys. J. C 77 (2017) 389

→ Dominance of rescattering over (re)combination in hadronic phase

Nuclei production in pp, p-Pb and Pb-Pb

p-Pb: Phys. Lett. B 800 (2019) 135043





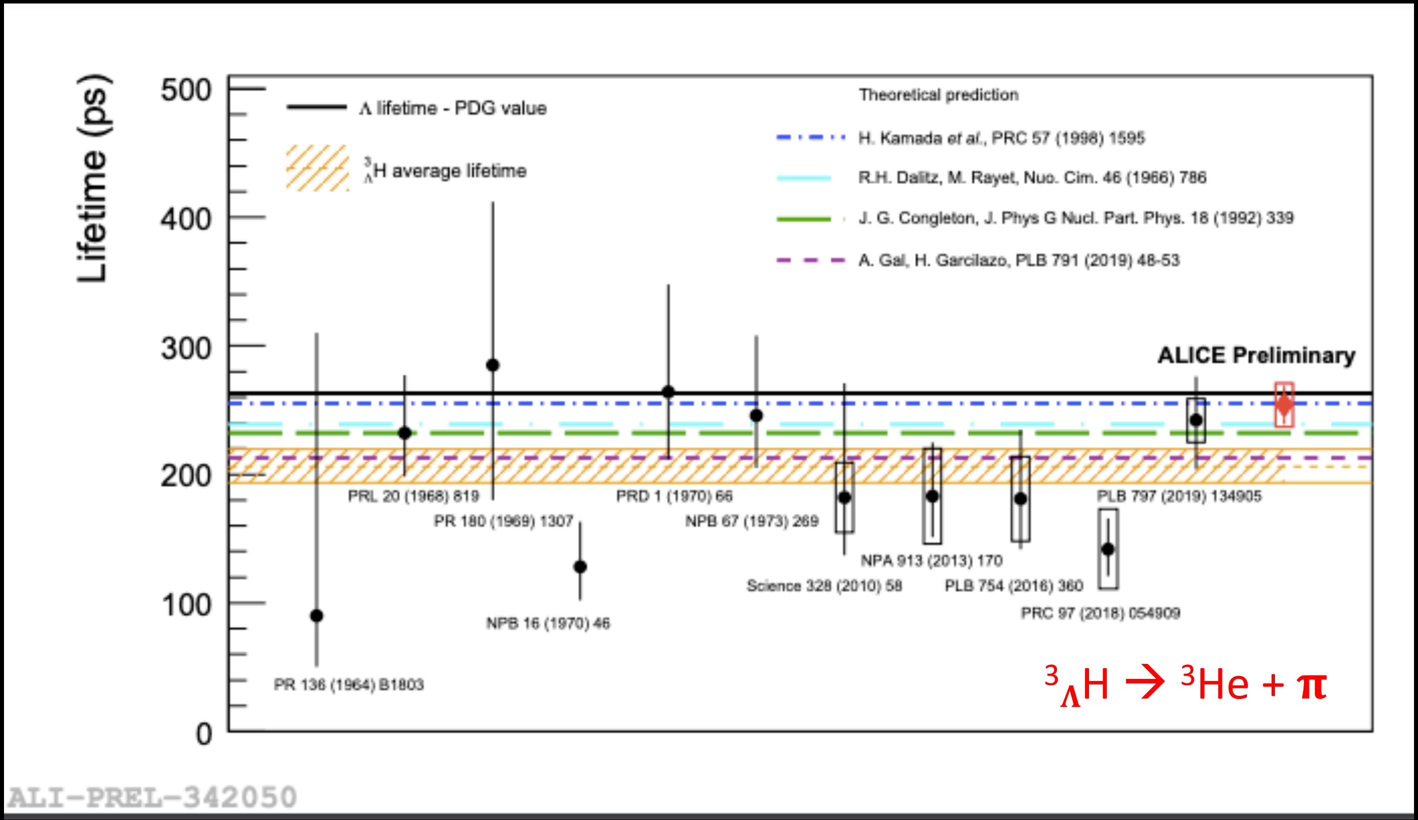
- Exponential decrease in nuclei rate described by thermal model
- Nuclei production rate decreases by factor of ~300 (Pb-Pb), ~600 (p-Pb) and ~1000 (pp) for each additional nucleon
- $^3_\Lambda$H production consistent with thermal model (binding energy ~0.13 MeV << T_{ch})

  → Production mechanisms: thermal vs coalescence?

pp: Phys. Rev. C97 (2018) 024615

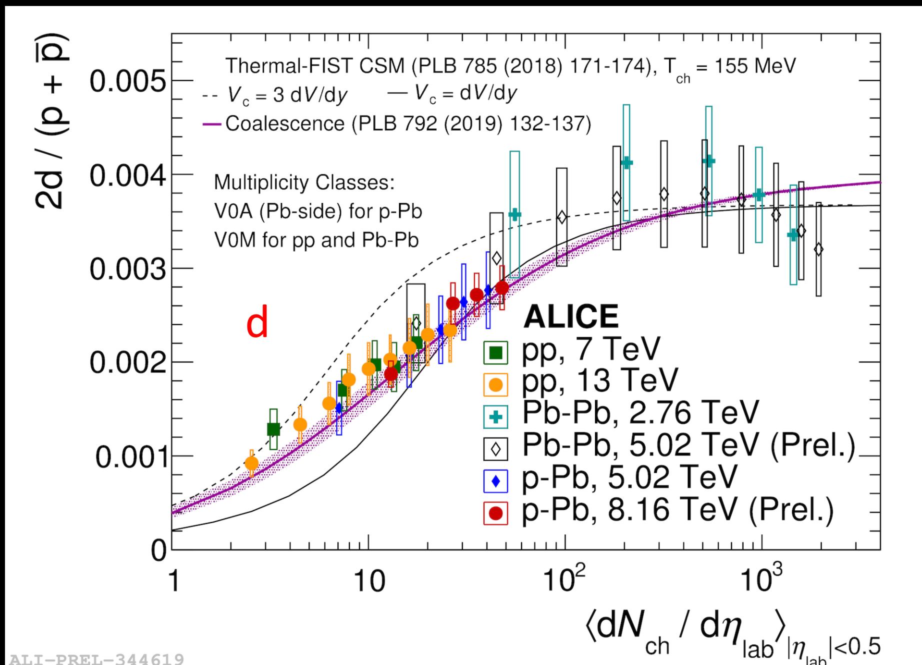
Pb-Pb: Nucl. Phys. A 971 (2018) 1

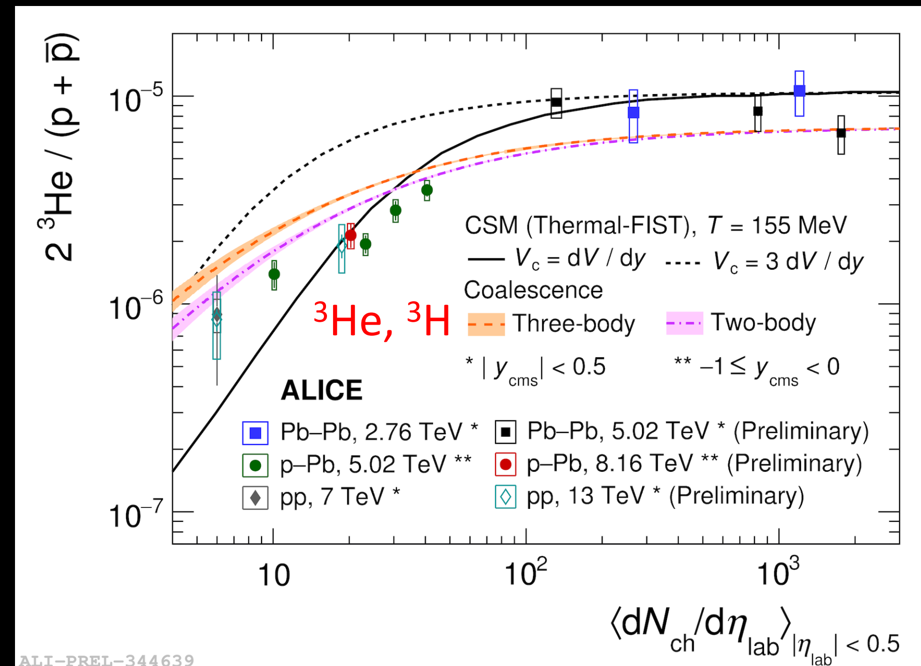
Hypertriton lifetime



- The most precise measurement of hypertriton lifetime
- Two body $^{3}_{\Lambda}$H decay channel has been used
- $^{3}_{\Lambda}$H lifetime consistent with the free Λ lifetime (not included in the average)
  → binding energy ~0.13 MeV
- Large discrepancy between recent World results

Formation of light nuclei





- Increase from pp to peripheral Pb-Pb
- No centrality dependence in high multiplicity Pb-Pb
- Data described qualitatively by coalescence and thermal models

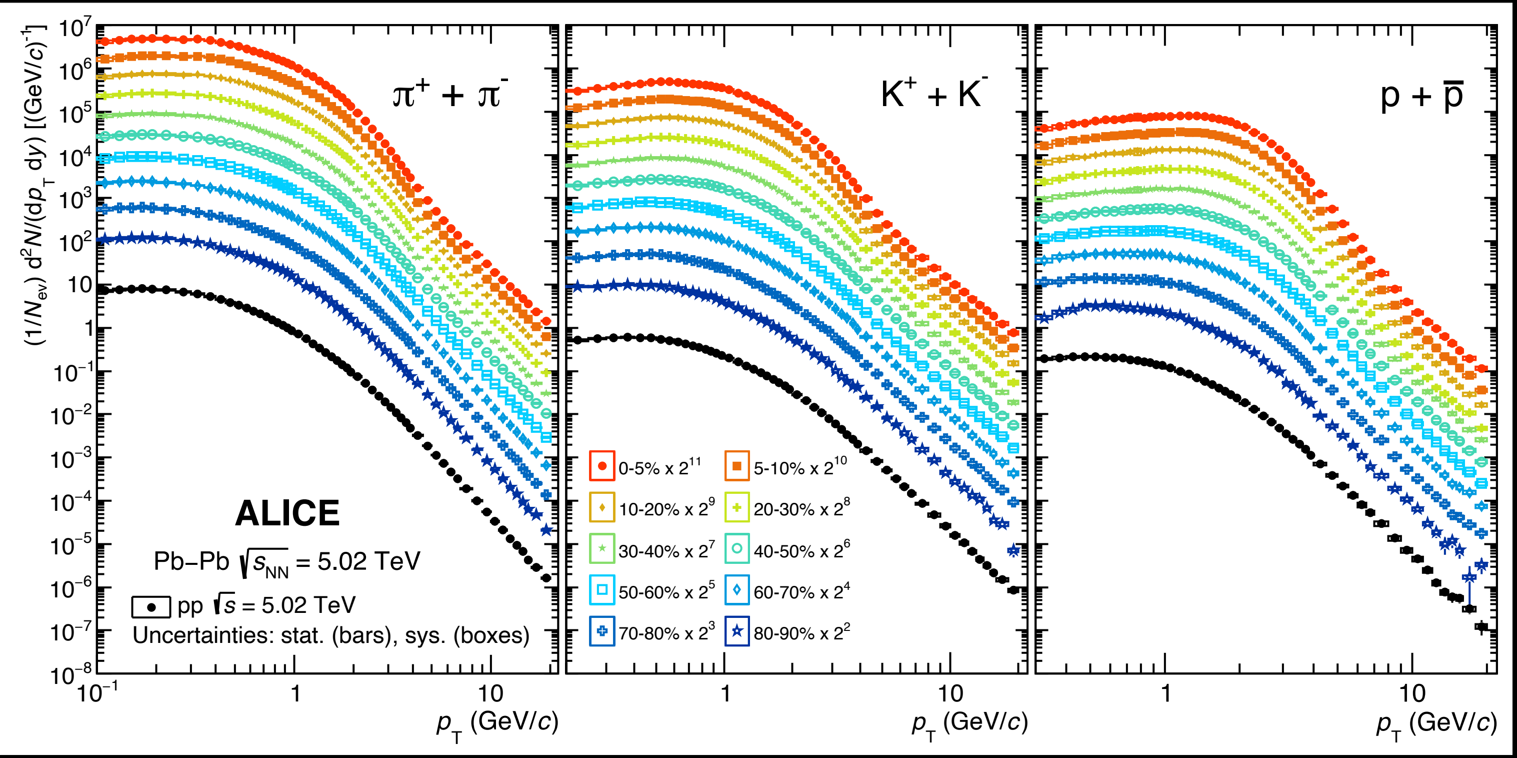
→ Production mechanisms: thermal vs coalescence?

Thermal- FIST CSM: V. Vovchenko et al., Phys. Lett. B 785 (2018) 171
Coalescence: K.-J. Sun et al., Phys. Lett. B 792 (2019) 132

SPECTRA

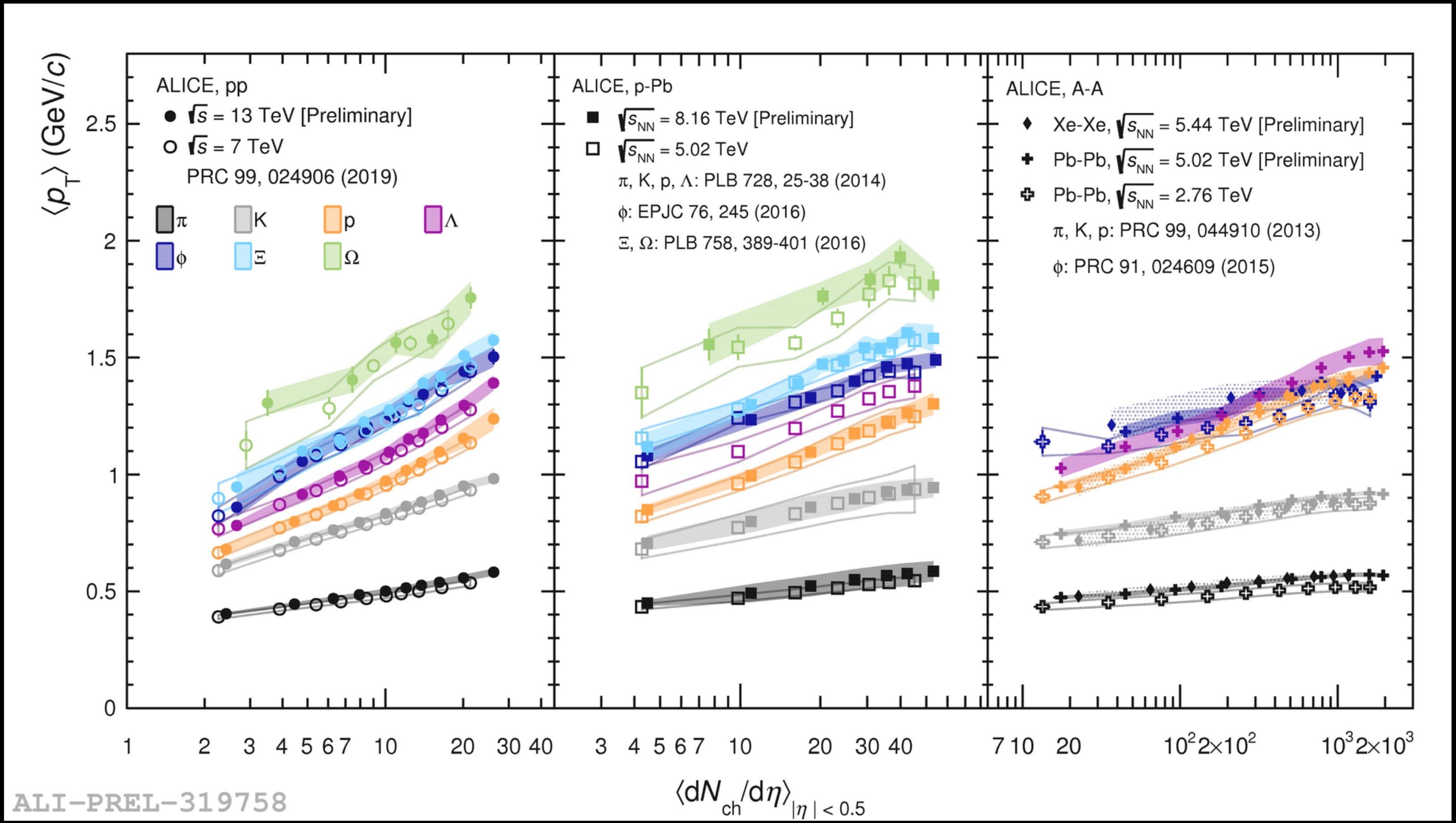
Transverse momentum spectra of charged π, K and p in Pb-Pb

Phys. Rev. C 101, 044907 (2020)



- Particle identification with different analysis techniques: ITS, TPC, TOF, HMPID and topological identification of decaying charged kaons
- Mass dependent hardening of the spectra with increasing centrality
  → Collective radial expansion

<p_T> vs centrality of hadrons in pp, p-Pb, Pb-Pb and Xe-Xe



- <p_T > increases with increasing centrality and mass
- Larger increase in smaller systems
  - → Collective radial expansion

pp 13 TeV: arXiv:2005.11120
Xe-Xe 5.44 TeV: arXiv:2101.03100
Pb-Pb 5.02 TeV: PRC 101, 044907 (2020)

Blast-Wave fit to hadron p_T spectra

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

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

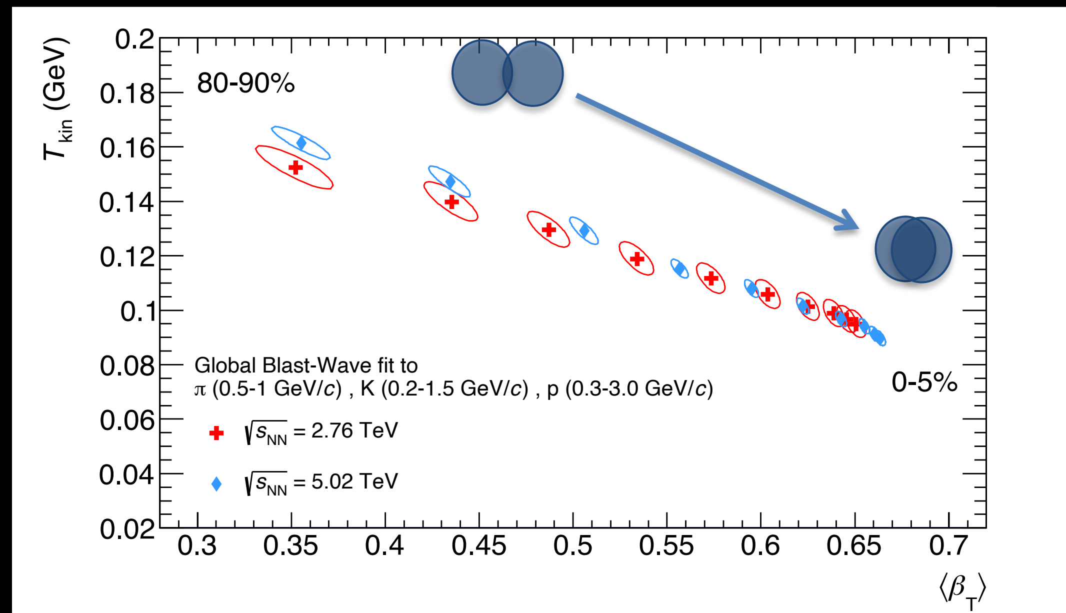
Schnedermann, Sollfrank and Heinz Phys. Rev. C 48, 2462

Simplified hydrodynamic model with 3 parameters:

- β_T - radial expansion velocity
- T_{kin} – kinetic freeze-out temperature
- n – velocity profile

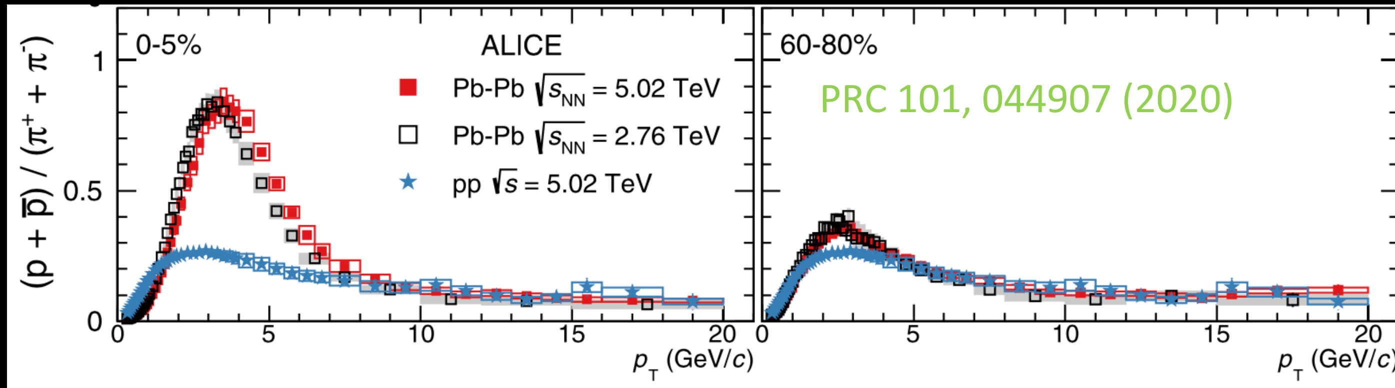
Phys. Rev. C 101, 044907 (2020)

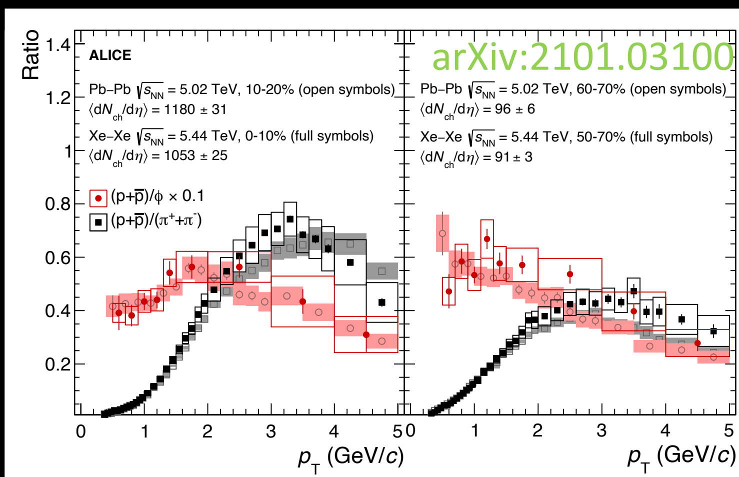
Simultaneous fit to the π, K, p spectra

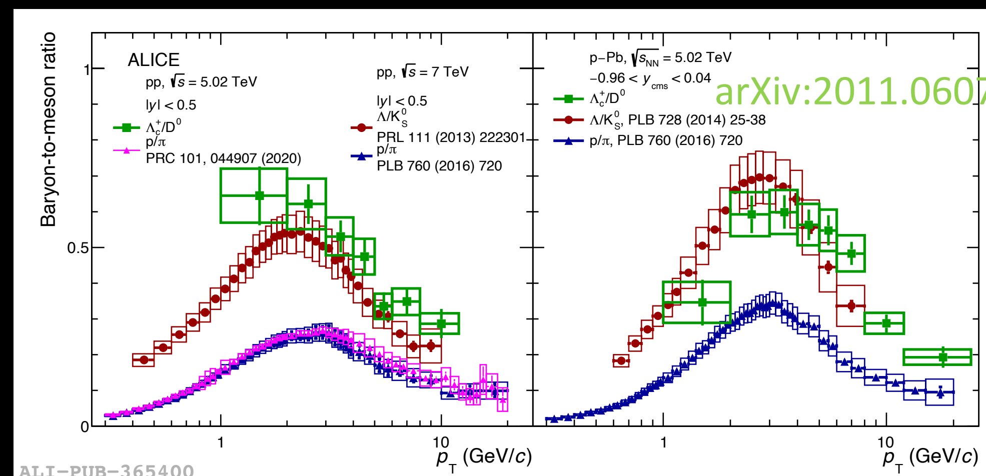


- $\langle\beta_T\rangle$ reaches ~0.65*c* in central Pb-Pb collisions
- T_{kin} decreases with collision centrality

Baryon-to-meson ratios





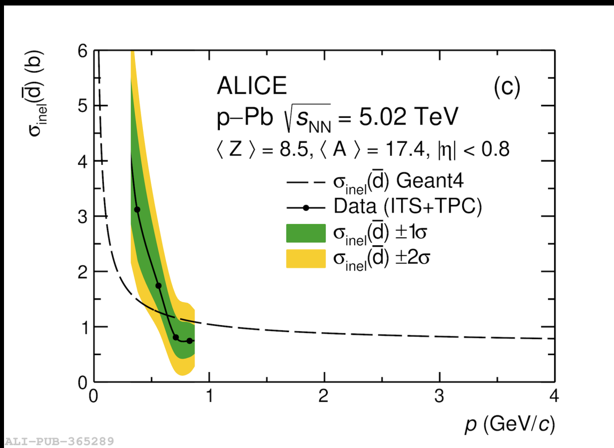


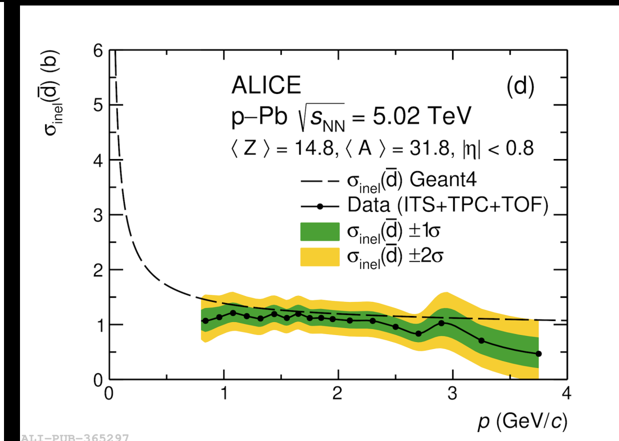
- Similar trends independent of collision system for the same multiplicity
- Λ_C/D_0 show similarities with those for light-flavor p/π and Λ/K^0s

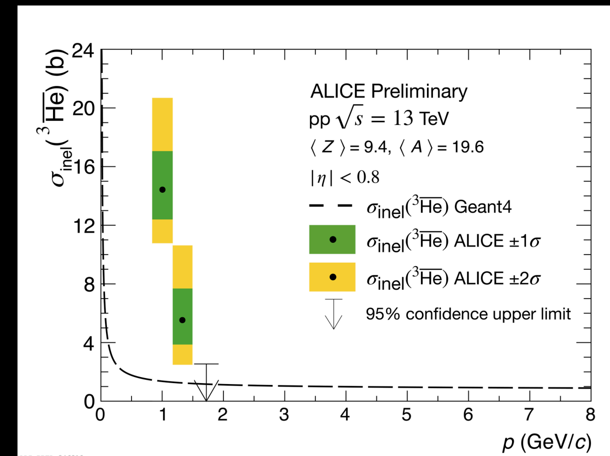
  → hint for the common production mechanism of light- and heavy-flavor baryons (coalescence vs. fragmentation)

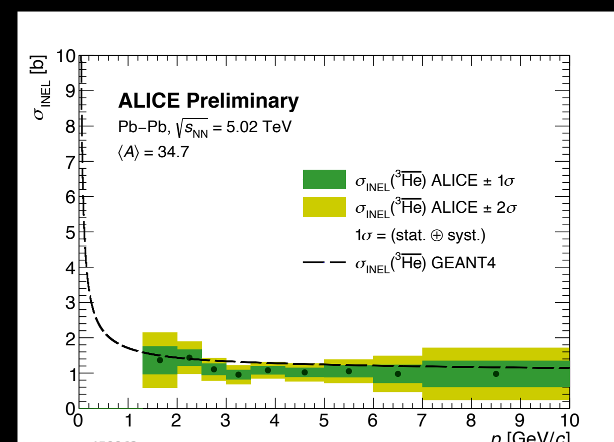
Antinuclei interaction cross sections

Phys. Rev. Lett. 125 (2020) 162001





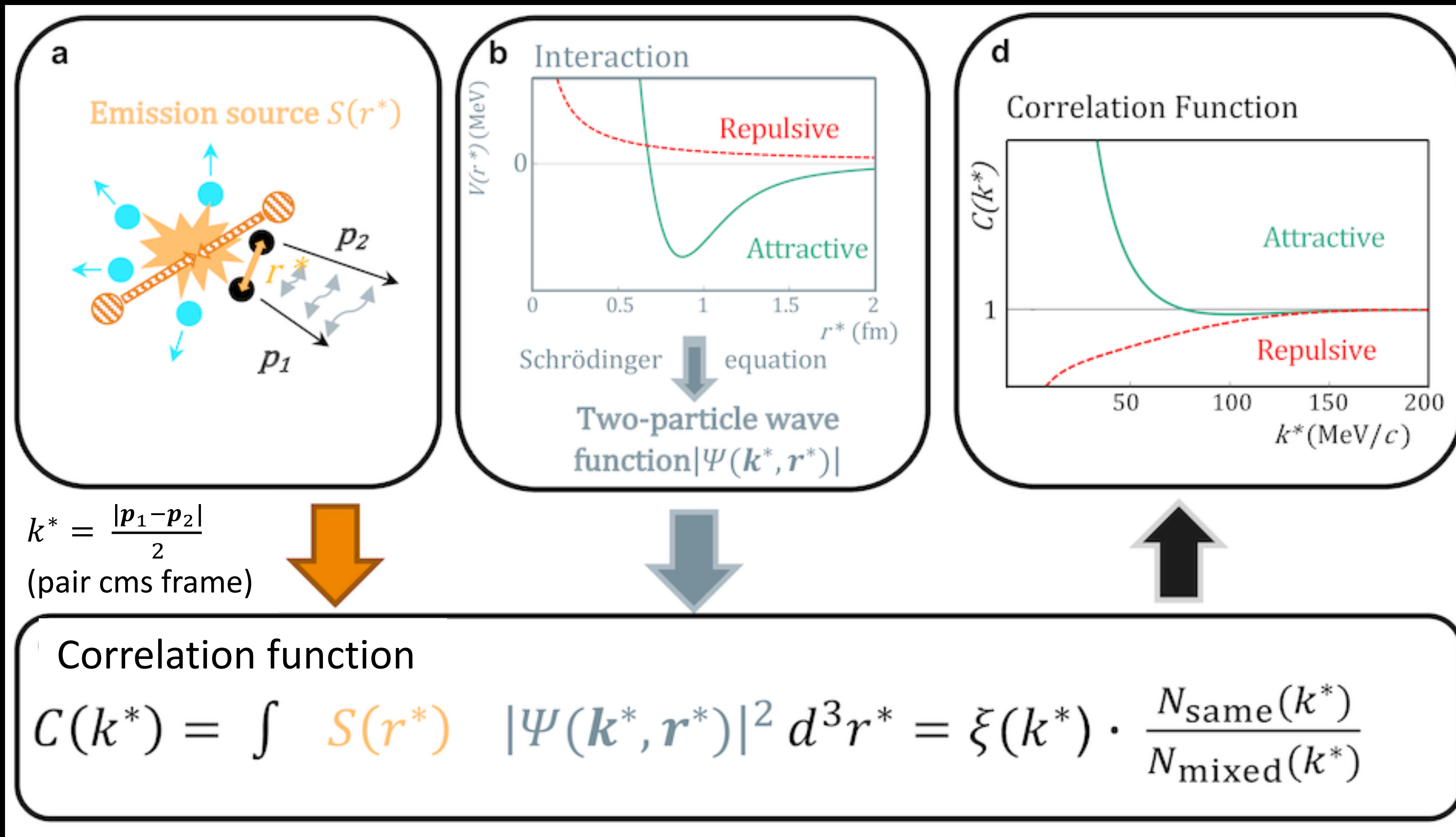




- Studies relevant for understating anti-nuclei absorption in the galactic medium (dark matter searches)
- First measurement of anti-deuteron and anti-^{3}He INEL cross section at low momentum
- ALICE detector material used as target to study anti-nuclei absorption

FEMTOSCOPY CORRELATIONS

Femtoscopy correlations to study stable and unstable hadron interactions

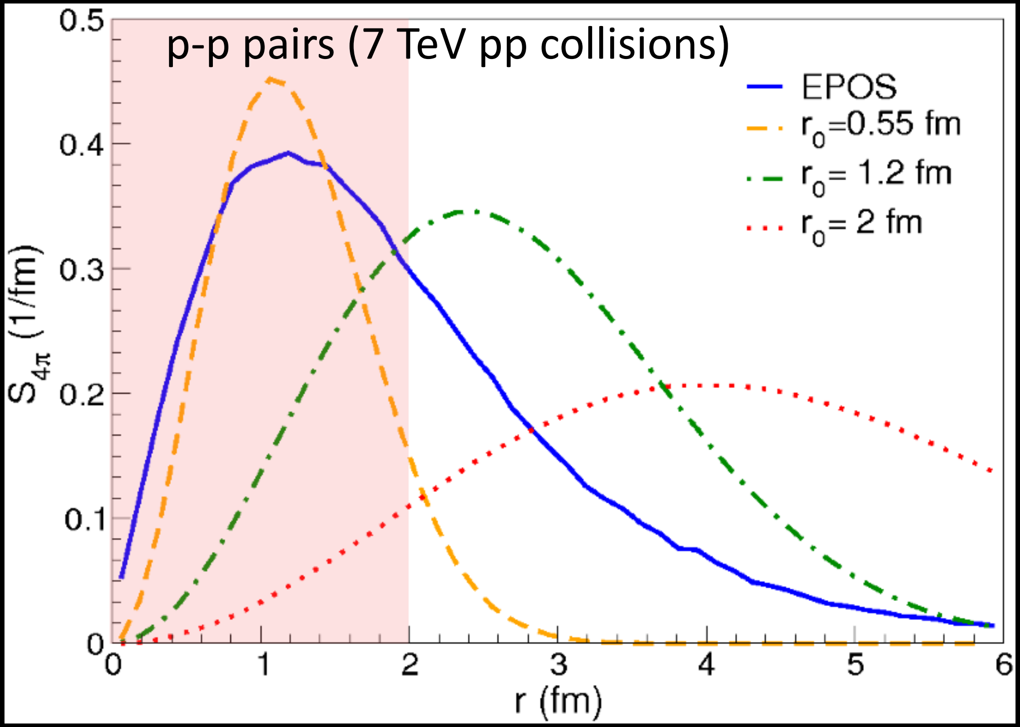


- Origin of correlations: quantum interference, resonances, conservation laws or final-state interactions
- Final-state interactions dominate at small k^*

Pioneering by HADES Coll.
Phys. Rev. C 94, 025201 (2016)

Femtoscopy in small systems

CATS, D. Mihaylov et al., Eur. Phys. J. C78 (2018) 394



Gaussian emission source:

$$S(r^*) = \frac{1}{(4\pi r_0^2)^{3/2}} \exp\left(-\frac{r^{*2}}{4r_0^2}\right)$$

Pair emission probability:

$$S_{4\pi}(r^*) = 4\pi r^2 S(r^*)$$

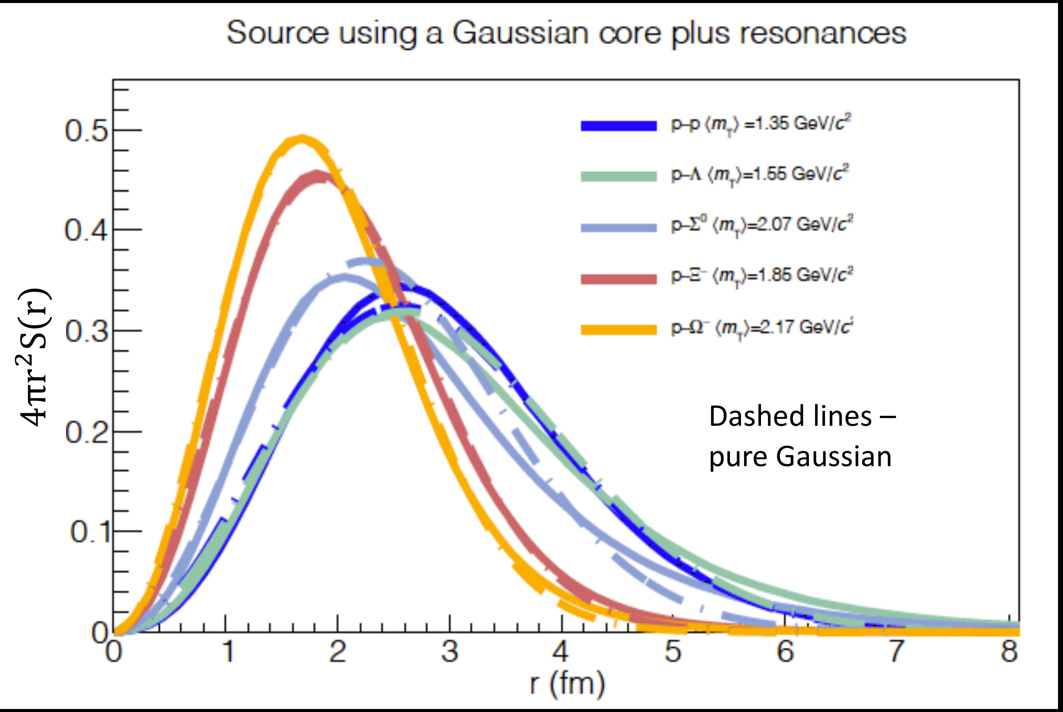
EPOS model predicts non-Gaussian emission source

T. Pierog et al. PRC 92 (2015) 034906

- A lot of pairs is emitted from the source at distance below ~2 fm (typical range of strong interaction)

→ Small particle emission source in pp and p-Pb collisions is essential to study the strong interaction!

Common baryon source



ALICE PLB 811 (2020) 135849

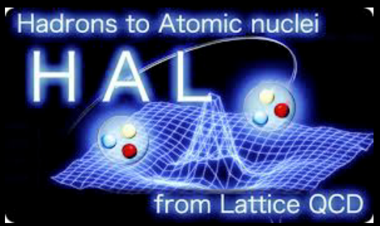
Pair	r_{Core} [fm]	r_{Eff} [fm]
p-p	1.1	1.2
p-Λ	1.0	1.3
p-Σ^0	0.87	1.02
p-Ξ^-	0.93	1.02
p-Ω^-	0.86	0.95

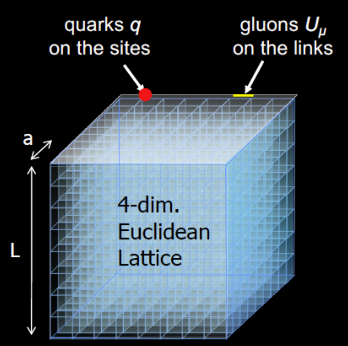
$$S(r^*) = G(r^*, r_{core}(m_T)) = \frac{1}{\left(4\pi r_{core}^2\right)^{3/2}} \exp\left(-\frac{r^{*2}}{4r_{core}^2}\right) \otimes E(r^*, M_{res}, \tau_{res}, p_{res})$$

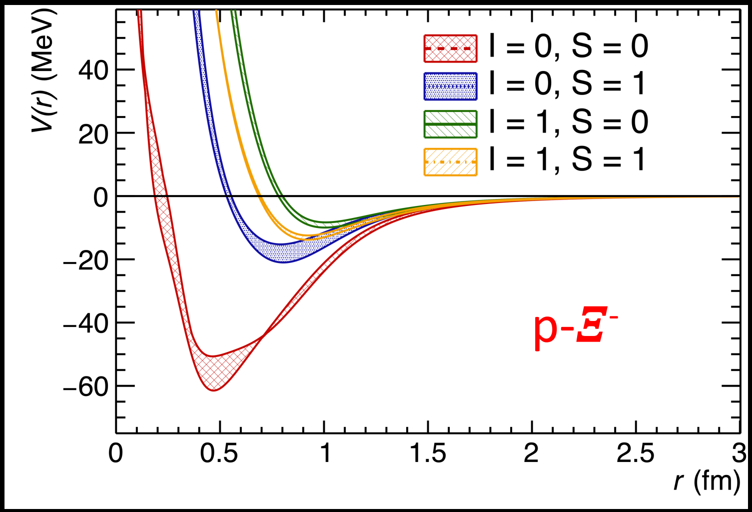
- Emission source for heavier pairs using p-p correlation function plus resonances
- Gaussian source with r_{eff} = 1.02±0.05 (0.95±0.06) fm used for the p-Ξ (p-Ω) emission

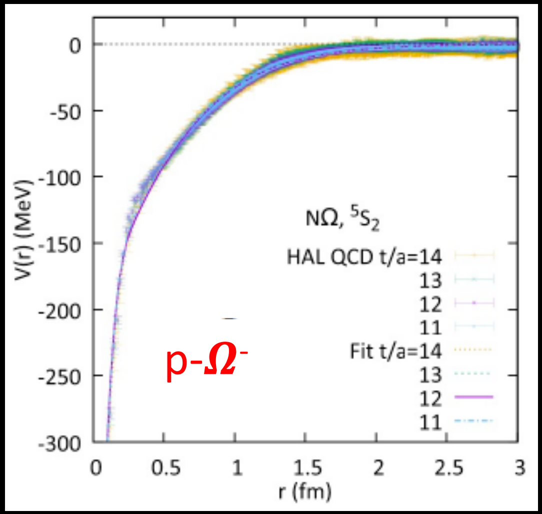
The strong interaction for p-Ξ and p-Ω on lattice

HAL QCD Coll., NPA 998 (2020) 121737, PLB 792 (2019) 284







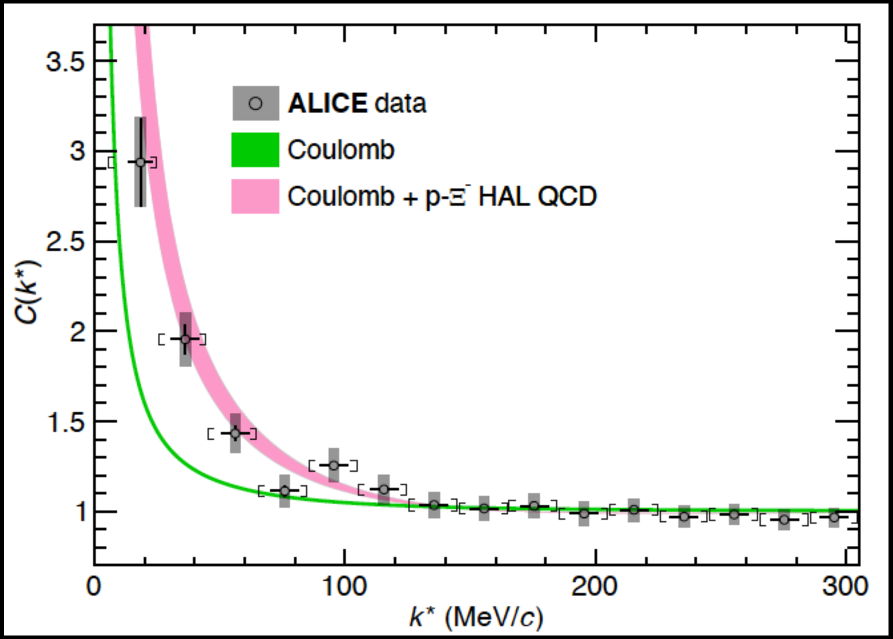


- a = 0.085 fm
- L = 8.1 fm
- m_π = 146 MeV/c²
- m_K = 525 MeV/c²

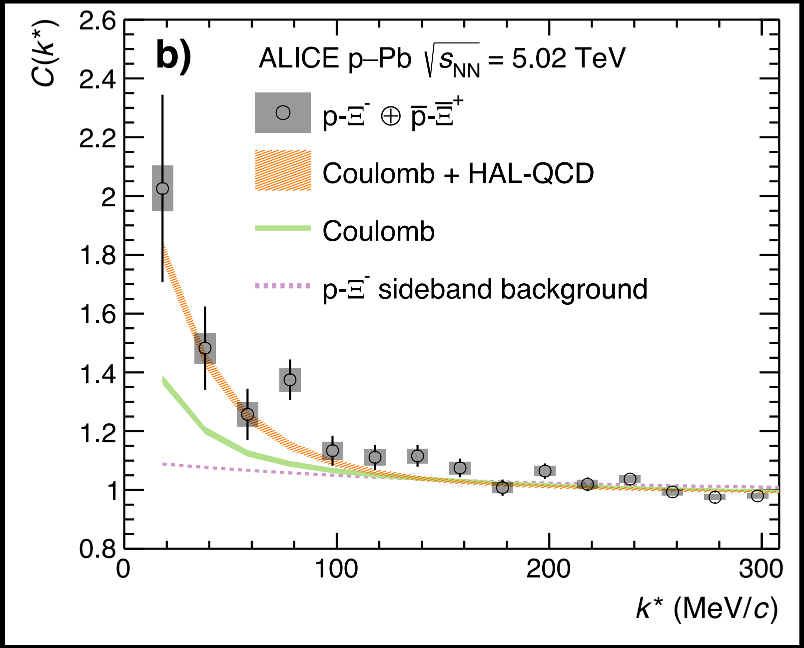
- p-Ξ interaction in four channels: isospin (I = 0,1) and spin (S=0,1)
  - Attractive with repulsive core at small distances
- p-Ω interaction in $^5S_2$ (I=1/2, S=2) channel
  - Attractive in the whole range
  - After inclusion Coulomb interaction prediction of bound state with binding energy ~ 2.5 MeV
- p-Ω interaction in $^3S_1$ channel does not include yet inelastic channels (e.g. p$\Omega \rightarrow \Lambda\Xi$)

p-Ξ correlation function in pp and p-Pb

Nature 588 (2020) 232



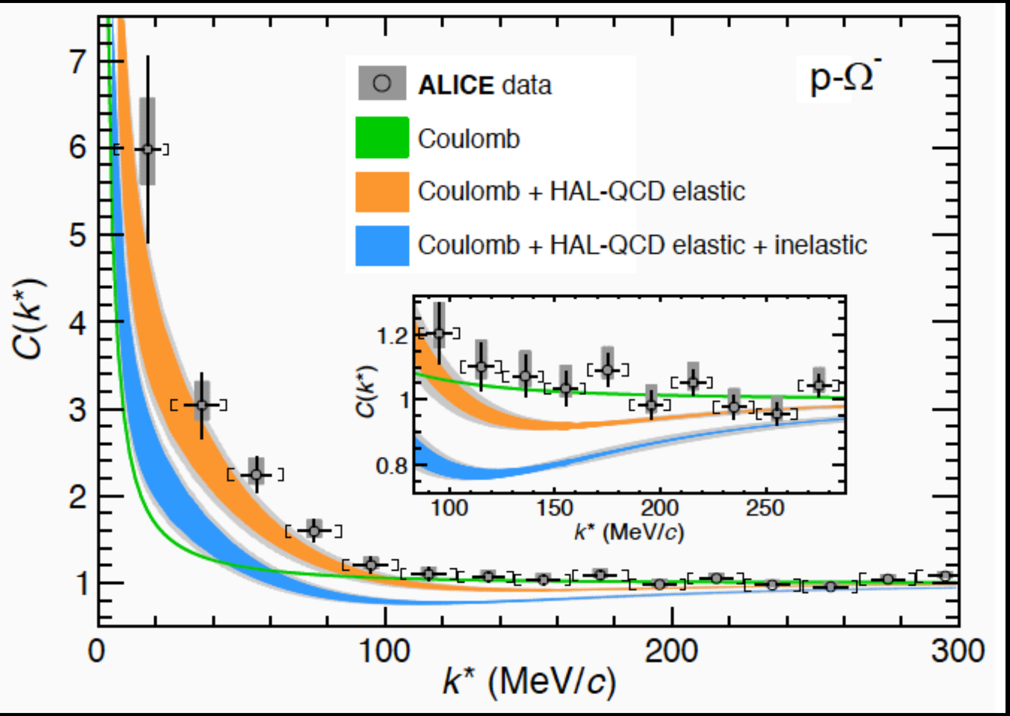
Phys. Rev. Lett. 123, 112002 (2019)



- p-Ξ interaction is attractive
- No indication of bound state in data
- p-Ξ interaction stronger than Coulomb → observation of strong interaction
- Coulomb + HAL QCD in agreement with p-Ξ measurements

p-Ω correlation function in pp at 13 TeV

Nature 588 (2020) 232

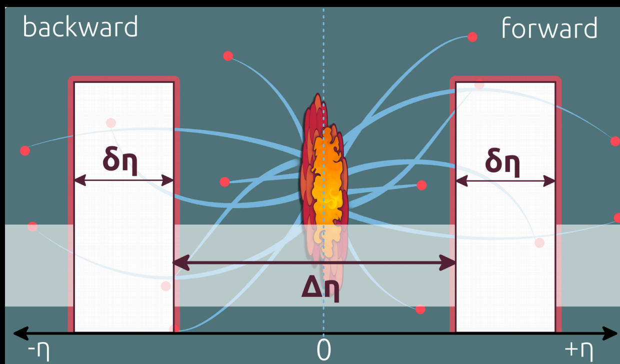


- p-Ω interaction is attractive
- No indication of bound state in data
- p-Ω interaction stronger than Coulomb → observation of strong interaction
- Calculations underestimate p-Ω measurements for both cases tested for missing p-Ω inelastic channels in $^3S_1$ state
  - Inelastic channel dominated by absorption
  - Neglecting inelastic channel

CORRELATIONS AND FLUCTUATIONS

Forward-backward correlations with strongly intensive quantity Σ

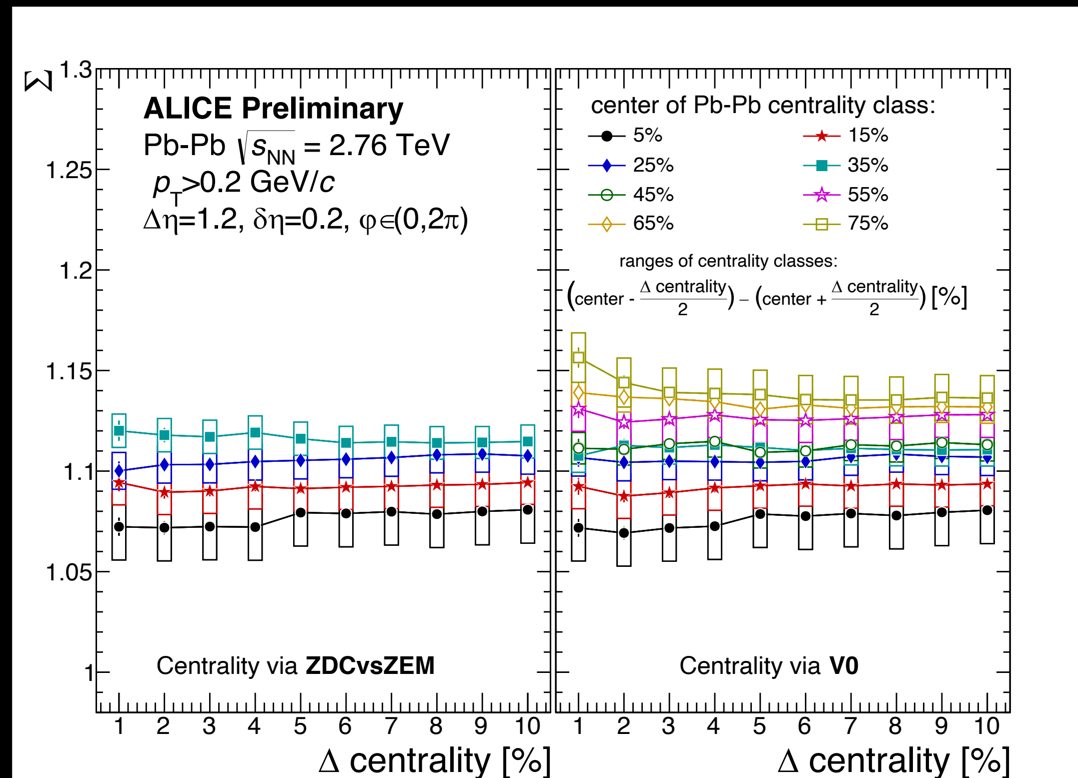
Σ provides information on the early collision dynamics



$$\Sigma = \frac{1}{\langle n_B \rangle + \langle n_F \rangle}\left[\langle n_F \rangle \omega_B + \langle n_B \rangle \omega_F - 2\,\mathrm{Cov}(n_F, n_B)\right]$$

$$\omega_{B(F)} = \frac{\mathrm{Var}(n_{B(F)})}{\langle n_{B(F)} \rangle}$$

M. Gaździcki and M. I. Gorenstein, PRC84 (2011) 014904



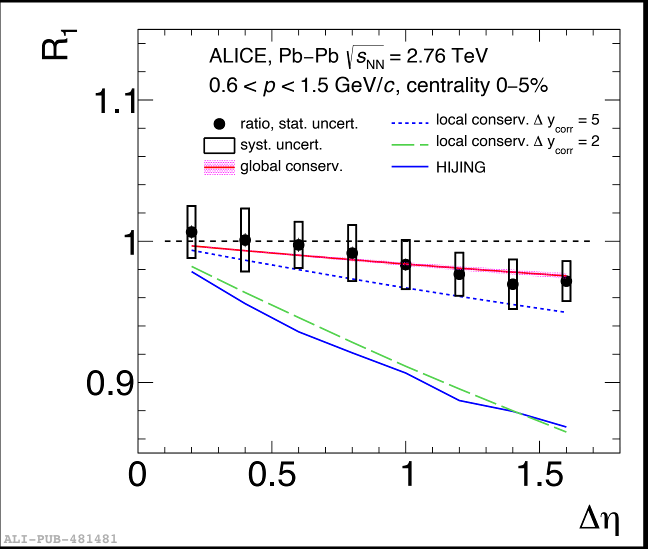
- Σ is independent from event centrality estimator and width of the centrality interval

Net-proton fluctuations in Pb-Pb at 2.76 TeV

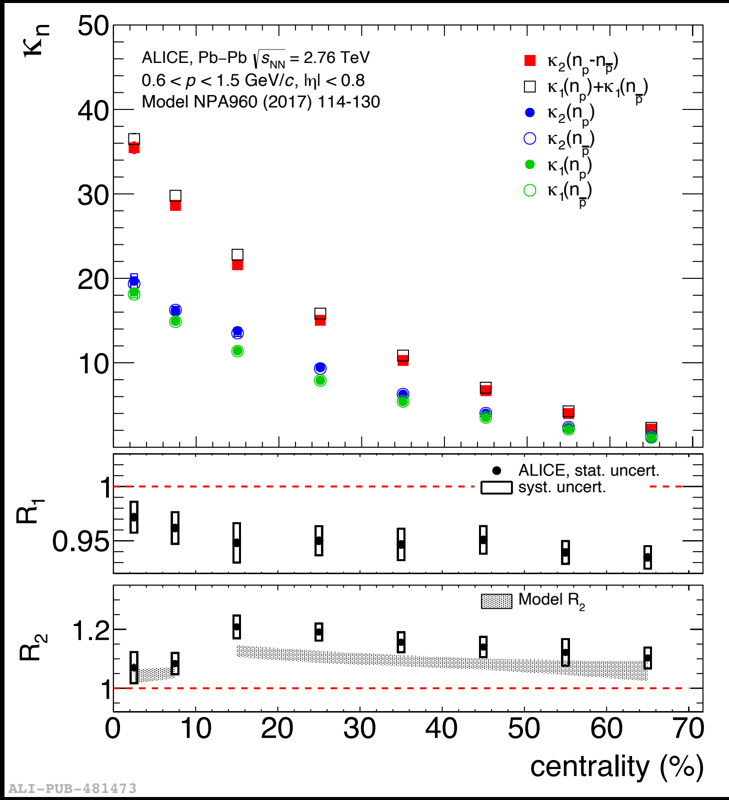
$$\kappa_1(\Delta n_B) = \sum_{\Delta n_B=-\infty}^{\infty} \Delta n_B P(\Delta n_B) = \langle \Delta n_B \rangle ,$$

$$\kappa_2(\Delta n_B) = \sum_{\Delta n_B=-\infty}^{\infty} (\Delta n_B - \langle \Delta n_B \rangle)^2 P(\Delta n_B) = \left\langle (\Delta n_B - \langle \Delta n_B \rangle)^2 \right\rangle$$

$$R_1 = \kappa_2(n_p - n_{\bar{p}}) / < n_p + n_{\bar{p}} >, \quad R_2 = \kappa_2(n_p) / < n_p >$$



Phys. Lett. B 807 (2020) 135564



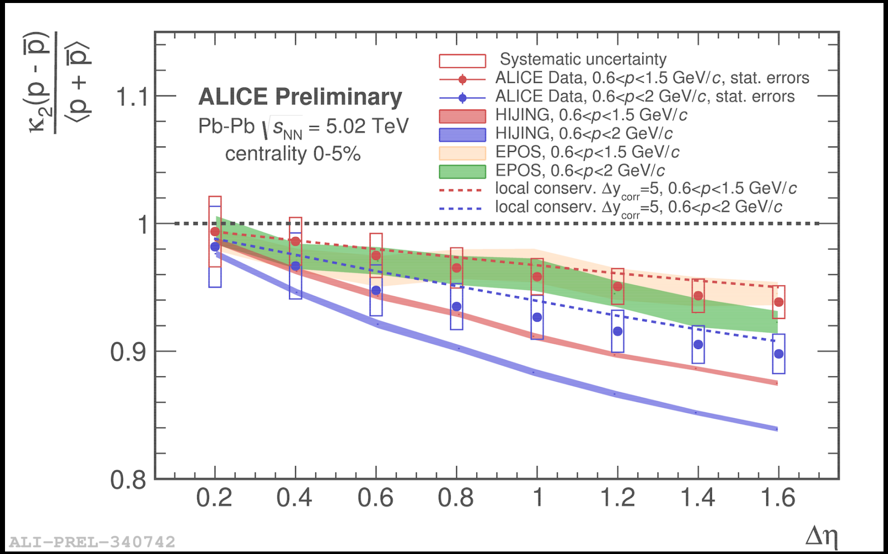
- Event-by-event baryon number conservation leads to subtle long-range correlations arising from very early interactions in the collisions
- Experimental tests of lattice QCD predictions on second and higher order cumulants of net-baryon distributions → critical behavior near QCD phase boundaries

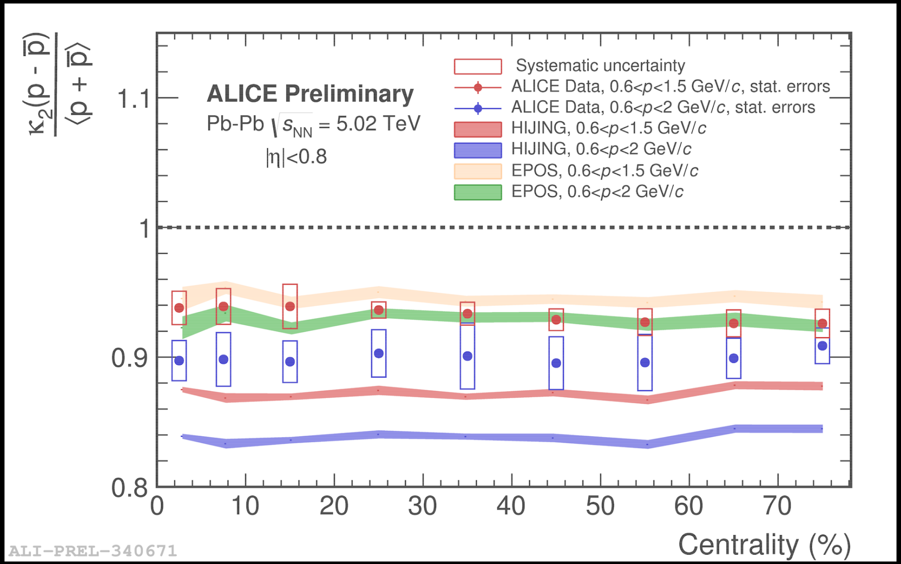
Net-proton fluctuations in Pb-Pb at 5.02 TeV

$$\kappa_1(\Delta n_B) = \sum_{\Delta n_B=-\infty}^{\infty} \Delta n_B P(\Delta n_B) = \langle \Delta n_B \rangle ,$$

$$\kappa_2(\Delta n_B) = \sum_{\Delta n_B=-\infty}^{\infty} (\Delta n_B - \langle \Delta n_B \rangle)^2 P(\Delta n_B) = \left\langle (\Delta n_B - \langle \Delta n_B \rangle)^2 \right\rangle$$

$$R_1 = \kappa_2(n_p - n_{\bar{p}}) / < n_p + n_{\bar{p}} >, \quad R_2 = \kappa_2(n_p) / < n_p >$$





- Event-by-event baryon number conservation leads to subtle long-range correlations arising from very early interactions in the collisions
- Experimental tests of lattice QCD predictions on second and higher order cumulants of net-baryon distributions → critical behavior near QCD phase boundaries

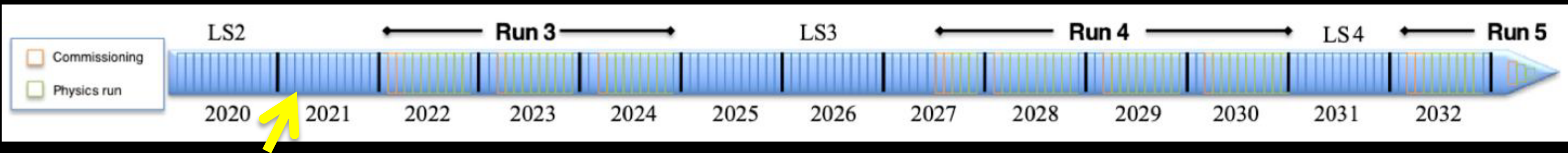
Summary

- Relative to pion particle production is driven by characteristics of final state
- Several mechanisms of hadron and nuclei production: (re)scattering, (re)combination, coalescence etc.
- Collective effects are observed in small and large systems

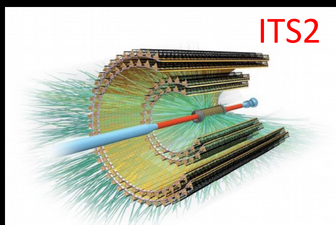
- The strong interaction between protons and hyperons (p-Ξ and p-Ω) is attractive (no indication of bound states)

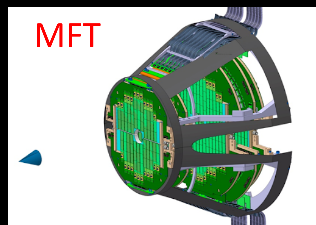
- Strongly intensive quantities allow for particle correlation studies free from volume size and volume fluctuations
- Baryon number conservation introduces a subtle long-range correlation in net-baryon correlation studies

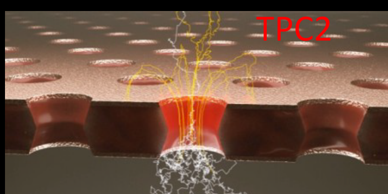
Outlook

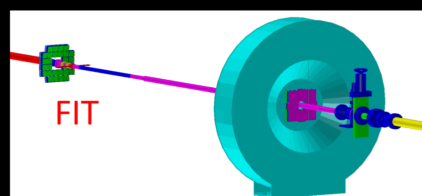


LS2: upgrades

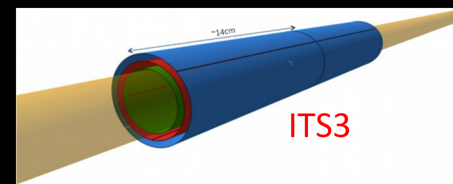


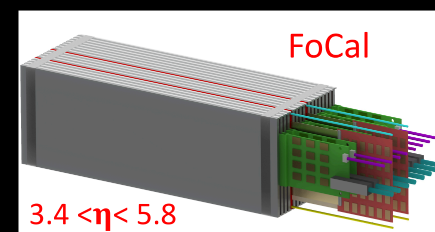




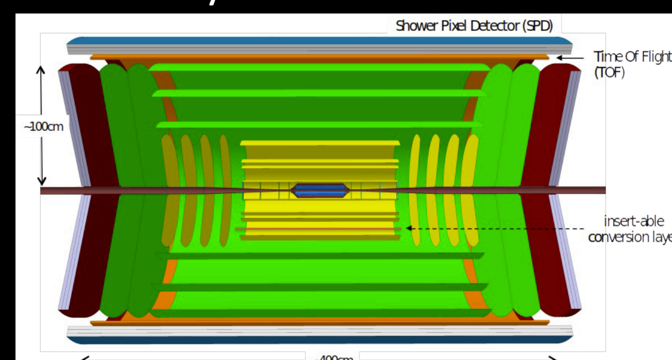


LS3: upgrades





LS4: Future heavy-ion detector arXiv:1902.01211

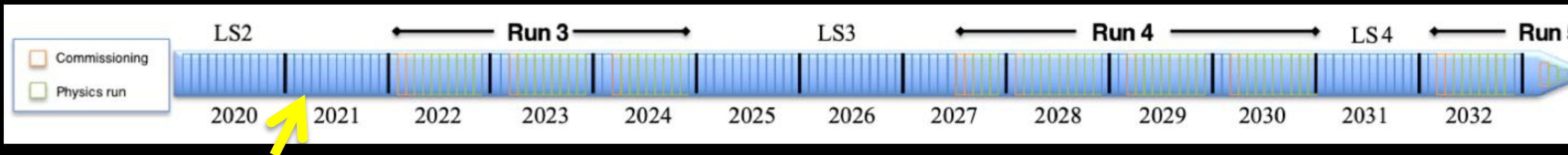


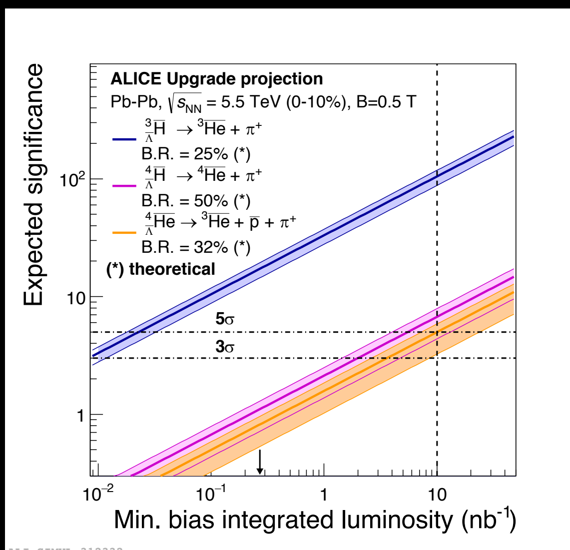
Continuous data taking

- Detector upgrade
- Online-offline computing system upgrade
- Readout electronics and trigger upgrade

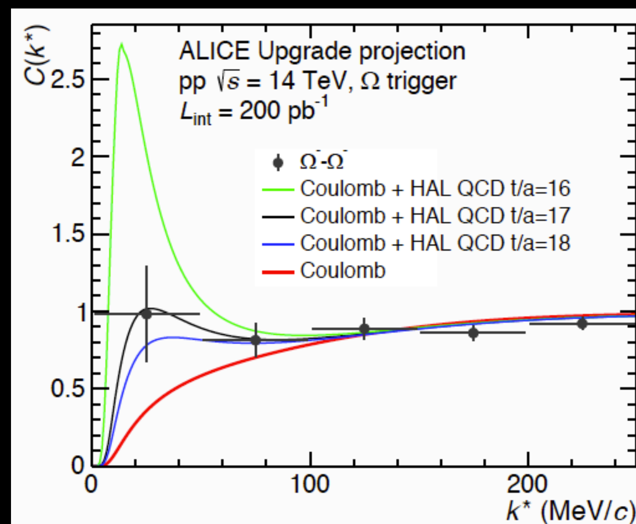
Outlook

LHC Run3 projected statistic

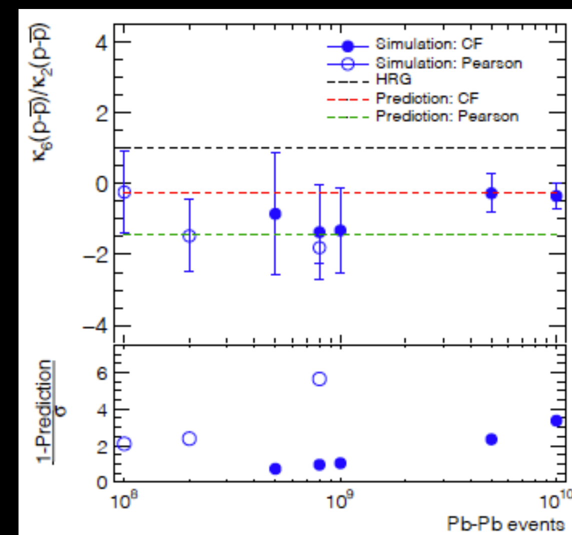




More than 3**σ** significance for ${}^{4}_{\Lambda}\overline{\mathrm{He}}$



Ω-Ω correlations

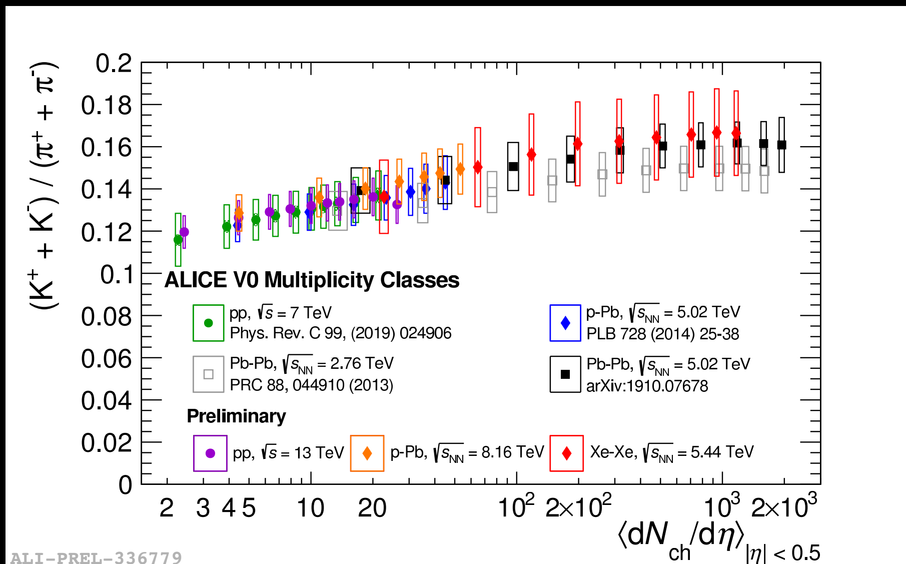


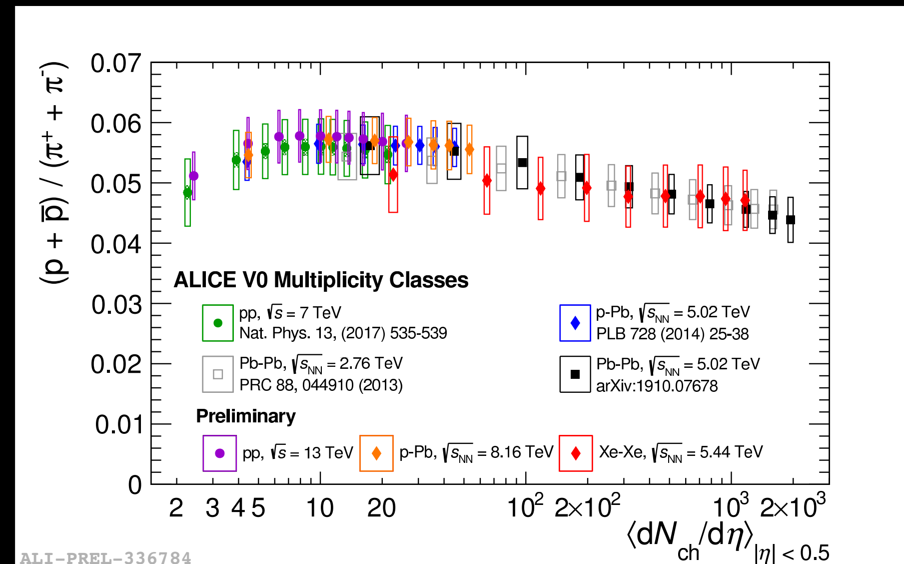
Net-proton 6th order cumulants

THANK YOU FOR YOUR ATTENTION!

Backup

K/π and p/π in pp, p-Pb, Pb-Pb and Xe-Xe

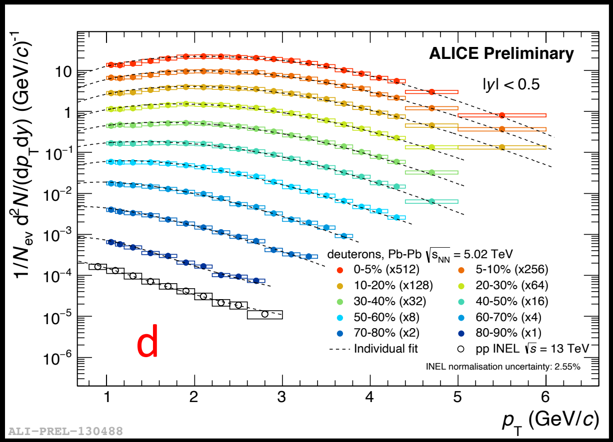


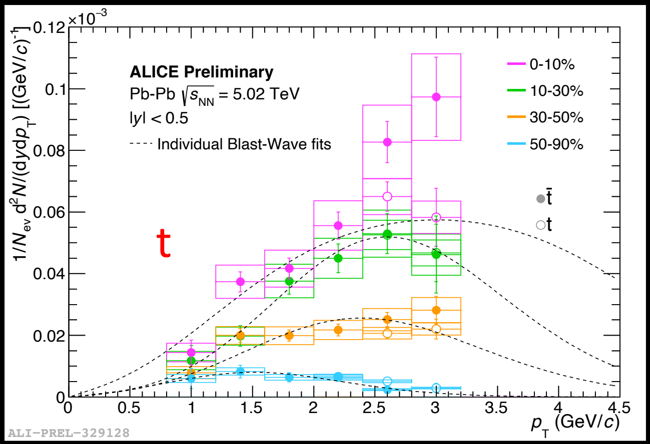


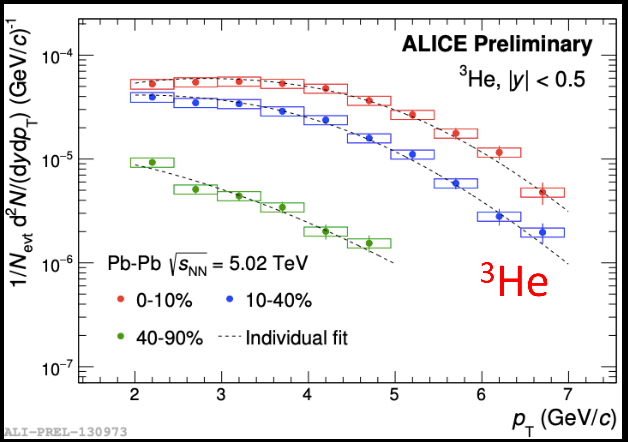
- No significant energy dependence is observed
- **K/π and p/π** are consistent for all collision systems at similar multiplicity

→ Particle production is driven by the characteristics of final state

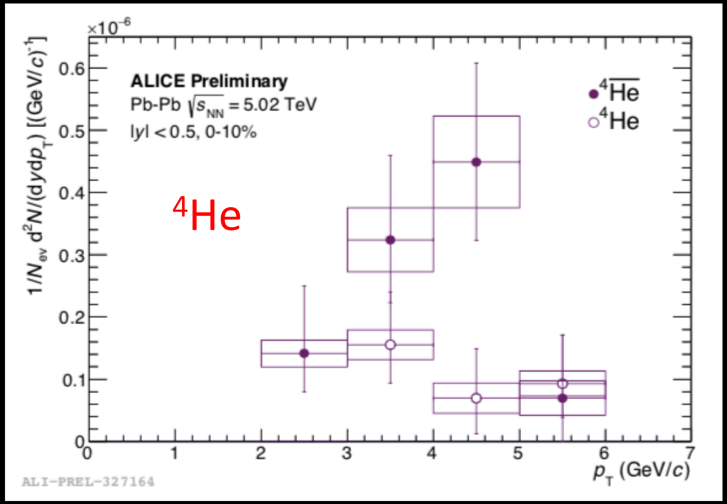
(Anti)nuclei p_T spectra in Pb-Pb





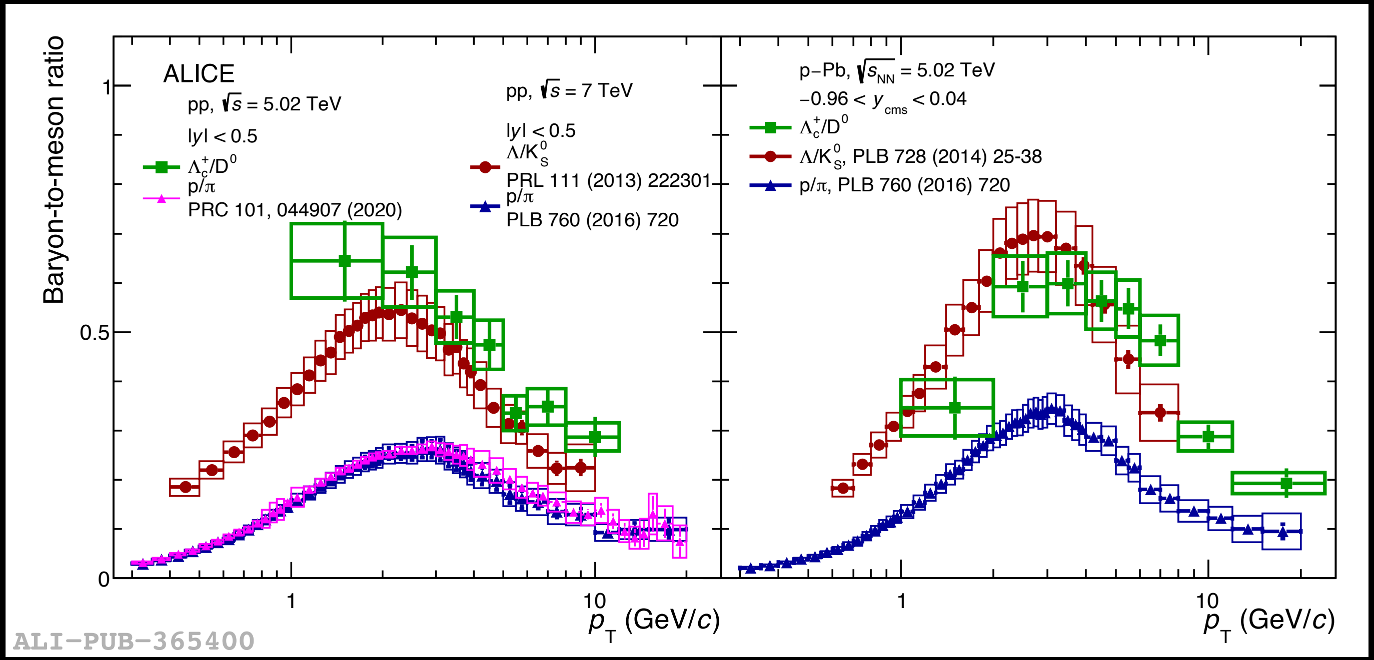


- Light nuclei p_T spectra are modified by radial flow



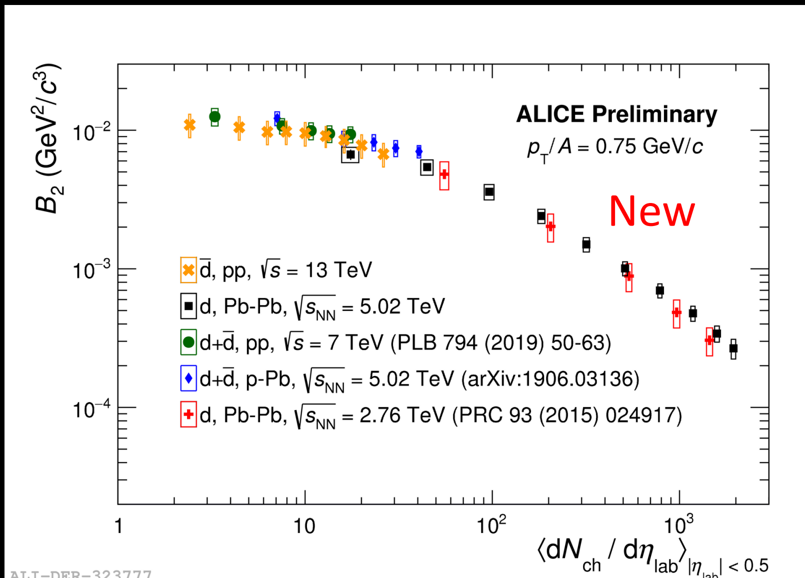
Baryon-to-meson ratios

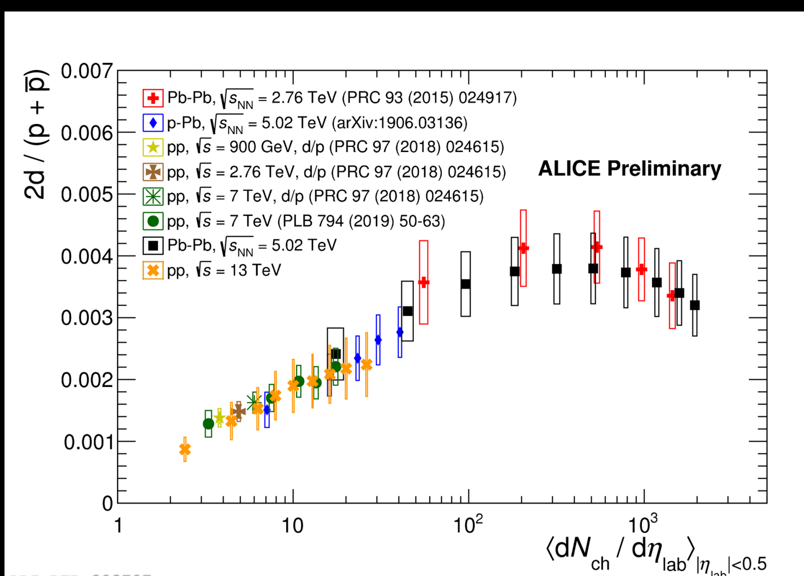
arXiv:2011.06078



- Baryon-to-meson ratio for Λ_C/D_0 show similarities with those for light-flavor p/π and Λ/K^0s
  → hint for the common production mechanism of light- and heavy-flavor baryons (coalescence vs. fragmentation)

Formation of light nuclei: (anti) deuterons





- Coalescence of baryons close in phase space (A - mass number)

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A$$

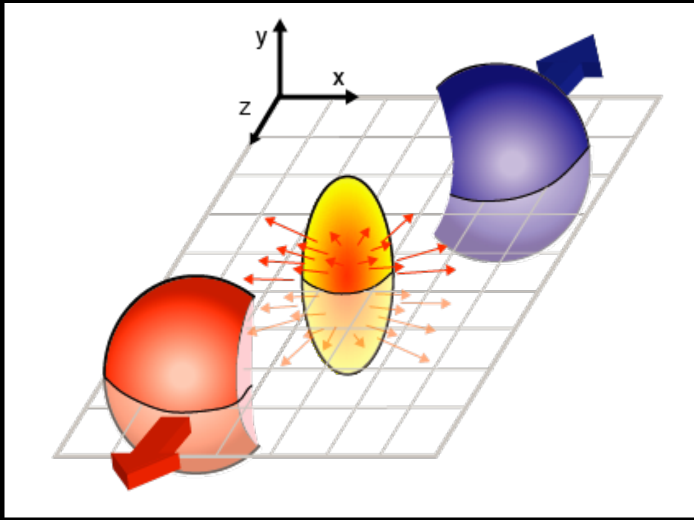
- B_2 shows dependence on multiplicity (no dependence on p_T)

- d/p vs multiplicity
  - Increase from pp to peripheral Pb-Pb consistent with coalescence model
  - No centrality dependence in high multiplicity Pb-Pb (yields consistent with thermal model)

→ Production mechanisms: thermal vs coalescence?

ANISOTROPIC FLOW

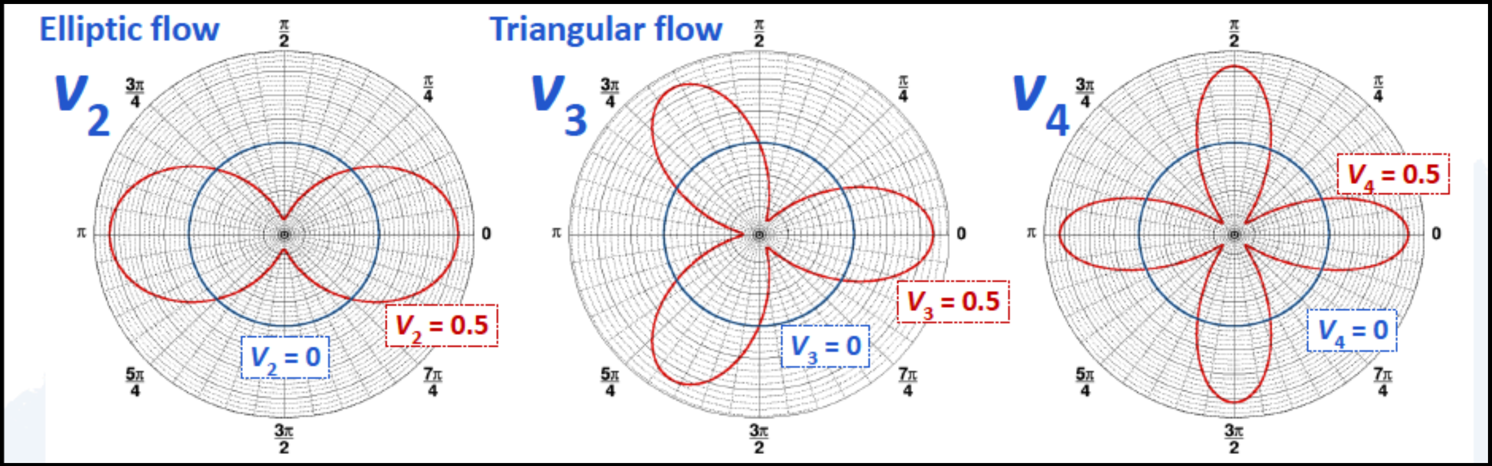
Anisotropic flow



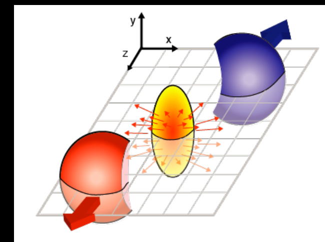
- Strongly interacting system:
  spatial anisotropy → momentum anisotropy
- Quantified in terms of Fourier coefficients v_n

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

$$v_n(p_T, y) = \langle \cos[n(\varphi - \Psi_n)] \rangle$$



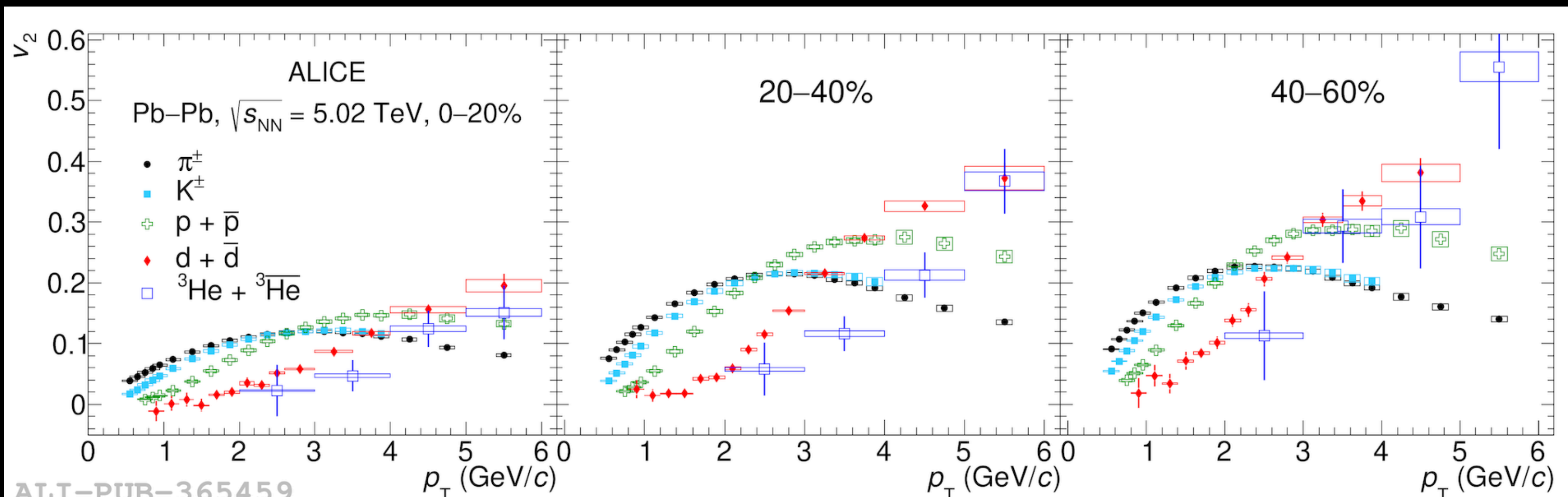
Hadron and nuclei v_2 in Pb-Pb



$$f(\varphi) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right]$$

$$v_n(p_T, y) = \langle \cos[n(\varphi - \Psi_n)] \rangle$$

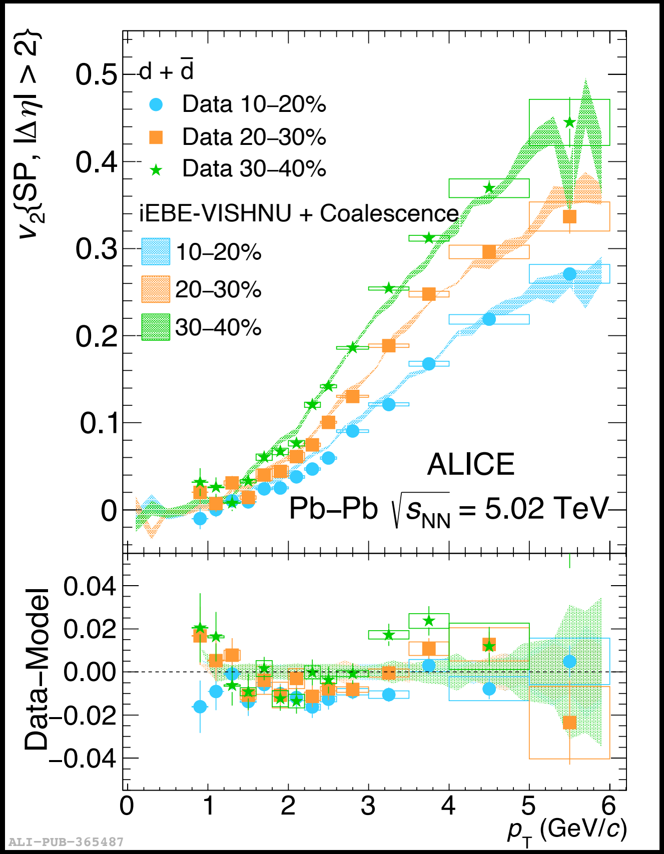
Phys. Rev. C 102 (2020) 055203

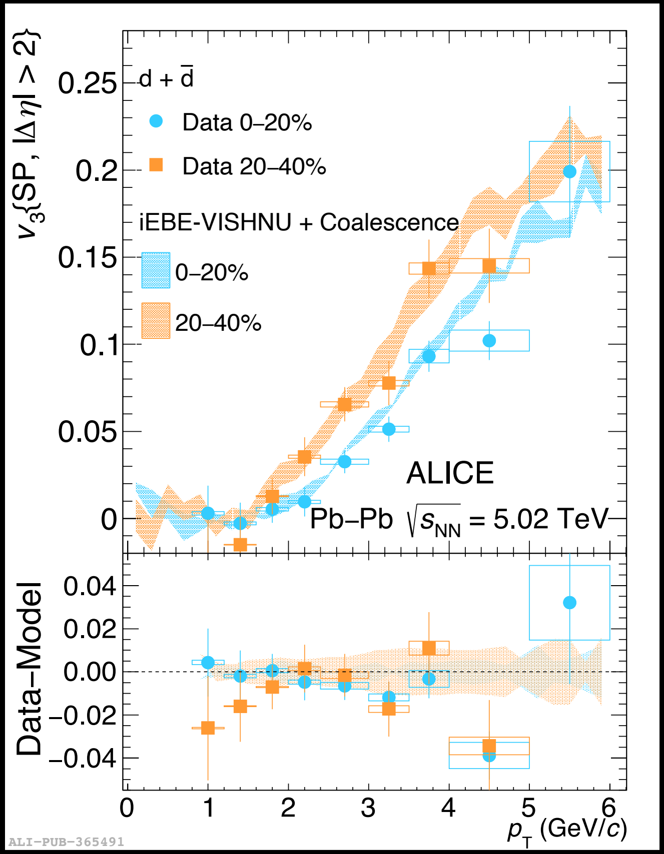


- p_T < 2 GeV/*c:* mass ordering
- p_T ~ 2.5 GeV/*c:* crossing between v_2 of baryons and mesons
- p_T > 2.5 GeV/*c*: baryons v_2 > mesons v_2 (flow driven by quark content)
- Light nuclei participating in flow

(Anti)deuteron v_2 and v_3 in Pb-Pb

Phys. Rev. C 102 (2020) 055203

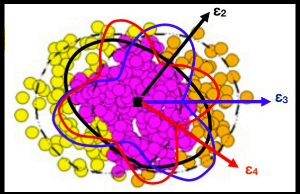




- Coalescence model with phase-space distributions of protons and neutrons from iEBE-VISHNU in agreement with data

Correlations between flow amplitudes

Observables sensitive to initial state and dynamical evolution of QGP



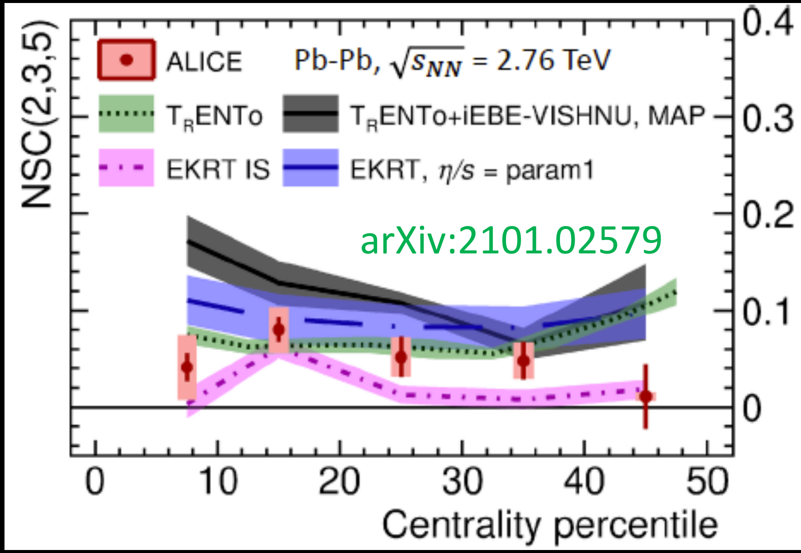
Symmetric cumulants

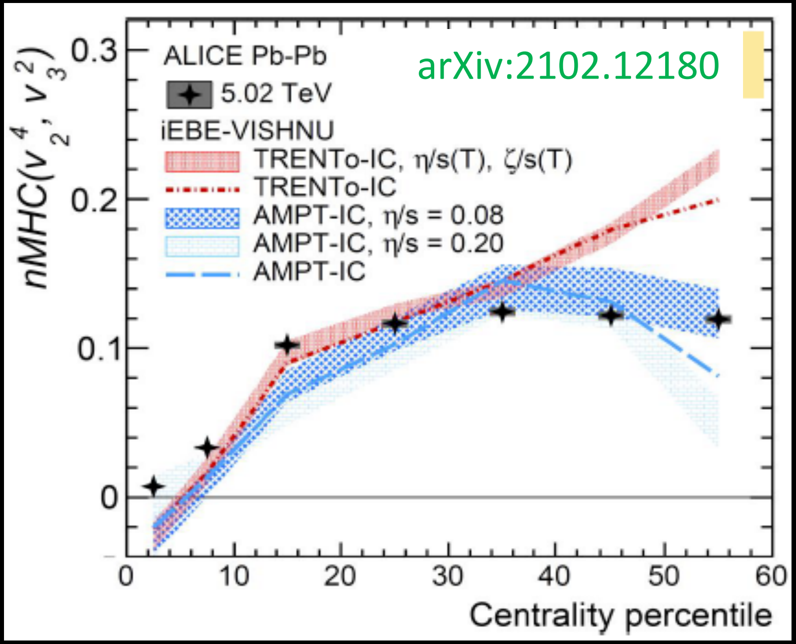
$$SC(k,l,m) \equiv \langle v_k^2 v_l^2 v_m^2 \rangle - \langle v_k^2 v_l^2 \rangle \langle v_m^2 \rangle - \langle v_k^2 v_m^2 \rangle \langle v_l^2 \rangle - \langle v_l^2 v_m^2 \rangle \langle v_k^2 \rangle + 2 \langle v_k^2 \rangle \langle v_l^2 \rangle \langle v_m^2 \rangle$$

$$NSC(k,l,m) \equiv \frac{SC(k,l,m)}{\langle v_k^2 \rangle \langle v_l^2 \rangle \langle v_m^2 \rangle}$$

Mixed harmonic cumulants

$$MHC(v_2^4, v_3^2) = \langle v_2^4 v_3^2 \rangle - 4 \langle v_2^2 v_3^2 \rangle \langle v_2^2 \rangle - \langle v_2^4 \rangle \langle v_3^2 \rangle + 4 \langle v_2^2 \rangle^2 \langle v_3^2 \rangle$$

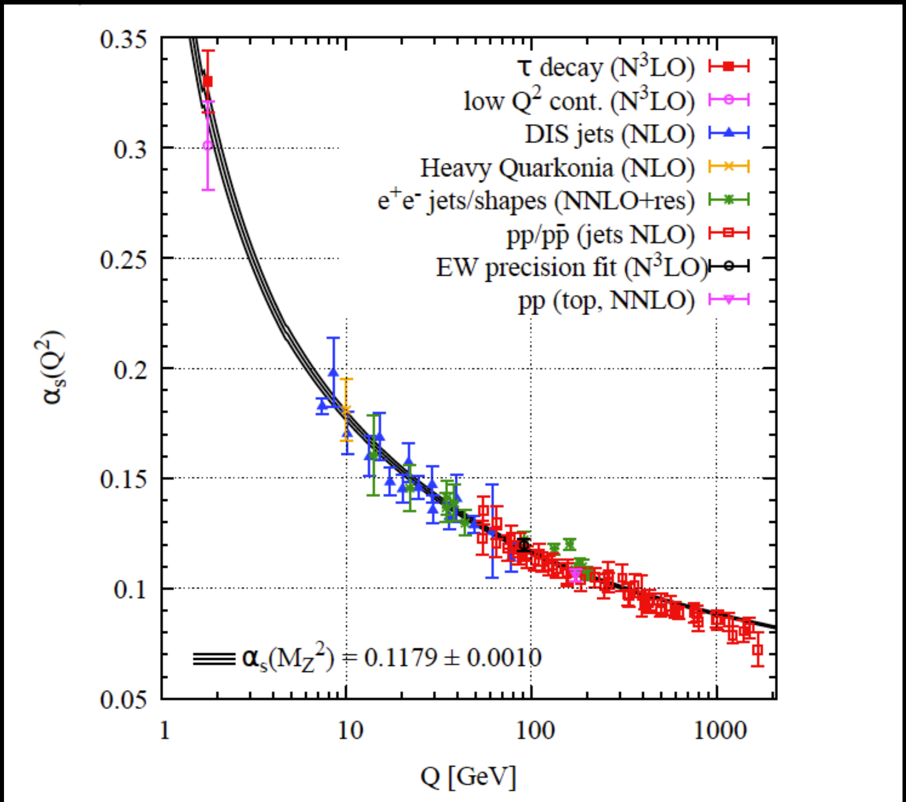




- Symmetric cumulants and mixed harmonic cumulants are insensitive to non-flow contributions

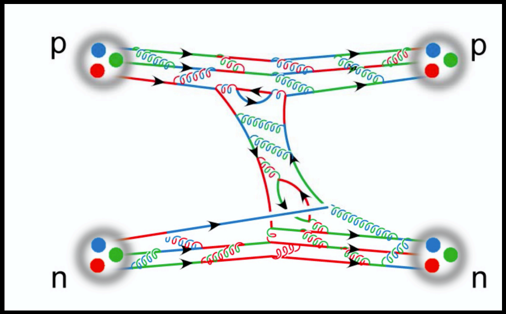
The strong interaction

PDG 2020



Running coupling constant α_s:

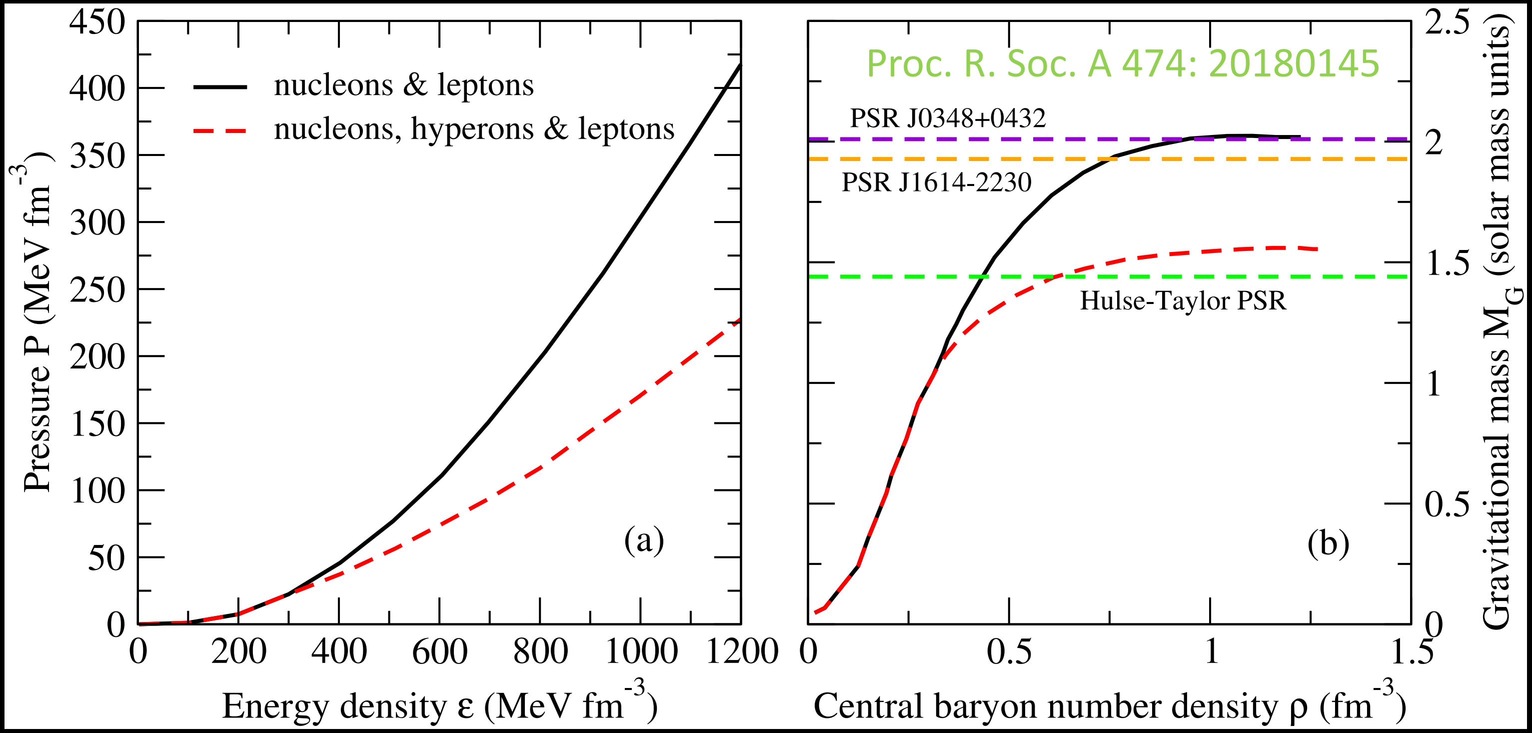
- Asymptotic freedom at small distance ($Q^2 >> \Lambda^2_{QCD}$)
- Confinement at large distance ($Q \lesssim 1$ GeV)
  → Perturbative methods not applicable
  → Effective theories with hadrons as degrees of freedom
  → Lattice QCD calculations



$$\alpha_s(Q^2) \equiv \frac{g_s^2(Q^2)}{4\pi} = \frac{12\pi}{(33-2N_f)\ln(Q^2/\Lambda_{QCD}^2)}$$

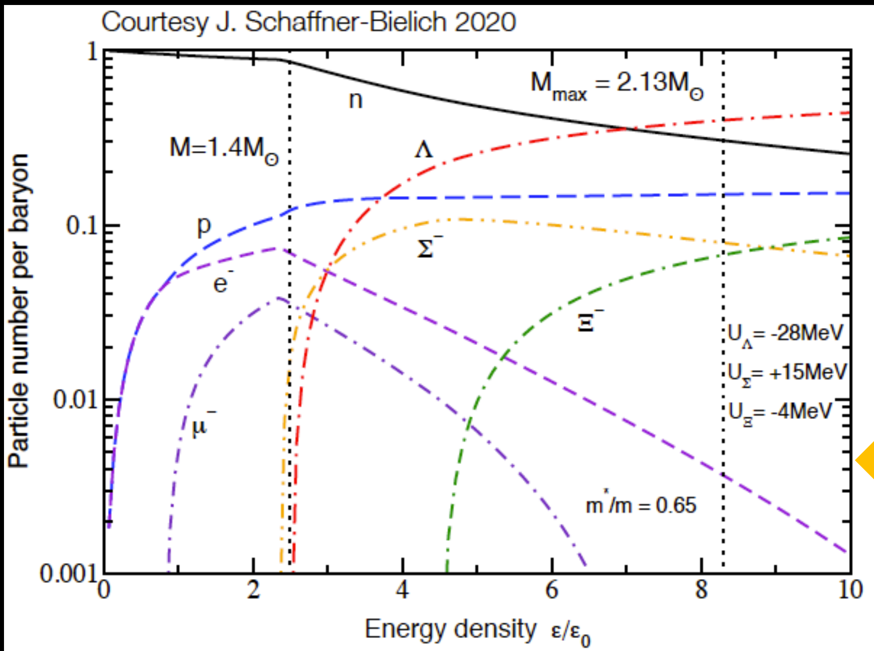
What is the strong interaction between different hadron species?

Hyperon puzzle

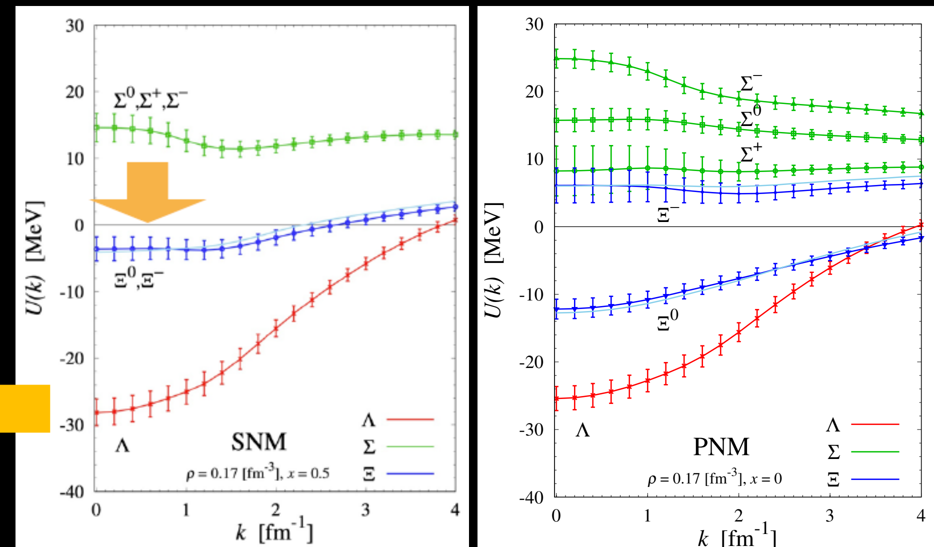


- Hyperons may appear in the inner core of neutron stars at densities of about 2–3ρ_0
- Their presence in the neutron star interior leads to a softening of the EoS and consequently to a reduction of the maximum mass (current predictions 1.4-1.8 $M_\odot$)
- Astrophysical observations of pulsars rule out almost all currently proposed EoS with hyperons…?
- Additional repulsion: Y-Y repulsive potential, hyperonic three-body forces (e.g. NNY, NYY, YYY), quark-gluon plasma below the hyperon threshold (hybrid neutron stars)…?

Hyperon puzzle and lattice QCD



HAL QCD, T. Ionue et al.AIP Conf.Proc. 2130 (2019) 1, 020002



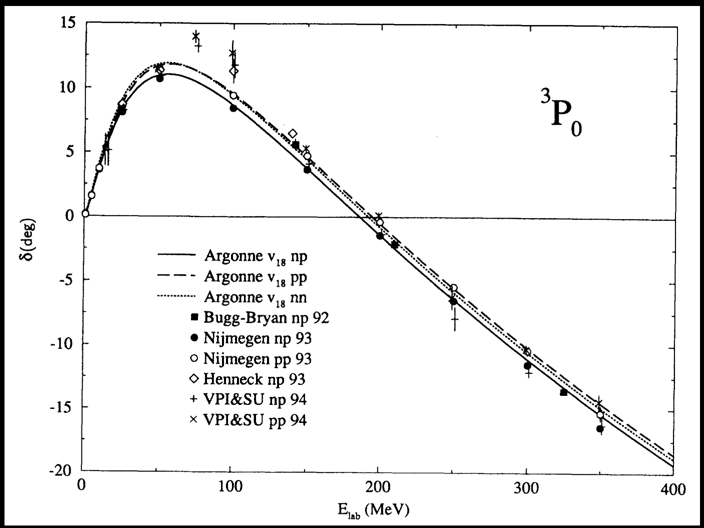
Hyperon single-particle potential

- Ξ^- attractive single-particle potential in symmetric nuclear matter (SNM) and repulsive in pure neutron matter (PNM)
- Ξ^- appears at larger densities in neutron stars

→ Resulting EoS of neutron stars is stiffer and matches astrophysical observation…

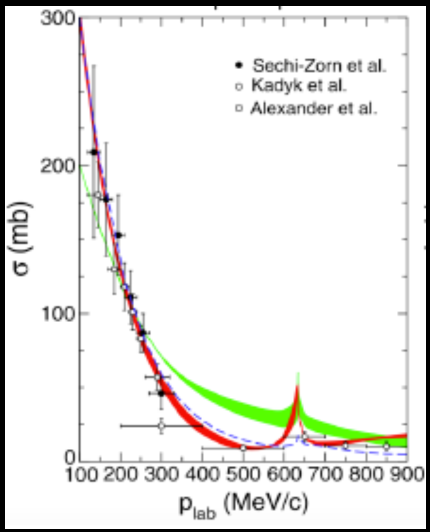
Experimental data to constrain the strong interaction

N+N → N+N



R. B. Wiringa et al., PRC 51 (1995) 38

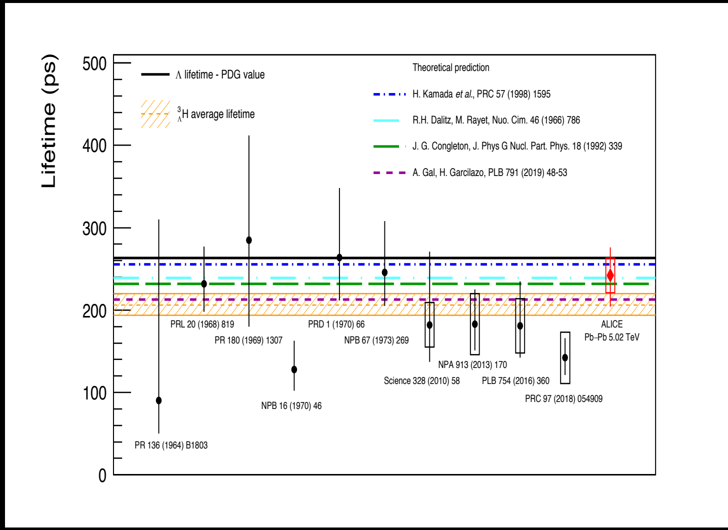
N + Λ → N + Λ



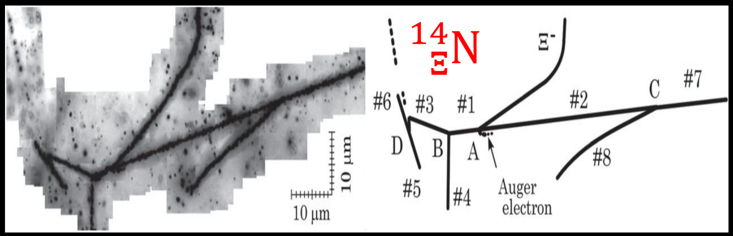
LO: H. Poinder et al. NPA 779 (2006) 244

NLO: J. Haindenbauer et al. NPA 915 (2013) 24

Hypertriton lifetime



ALICE PLB797 (2019) 134905

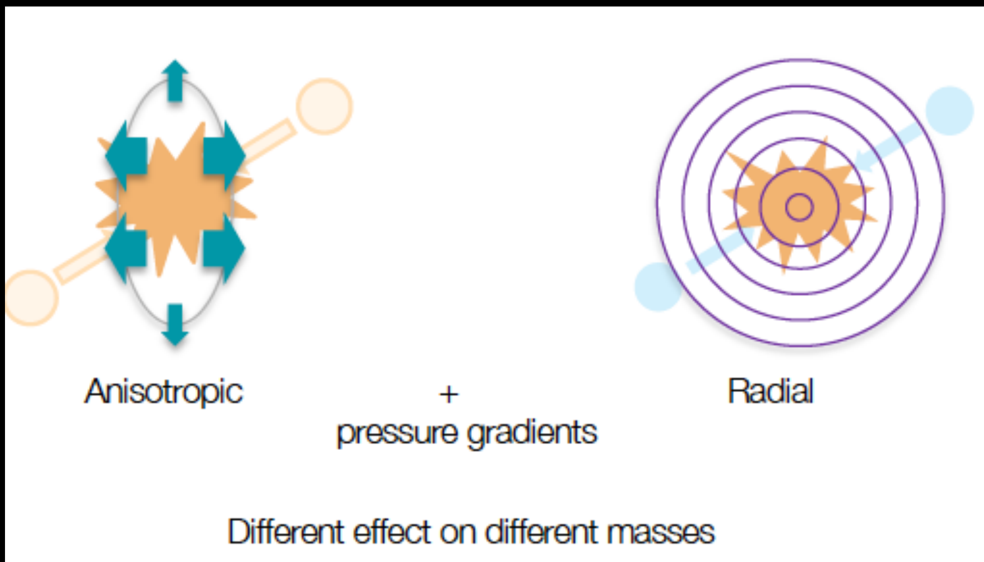


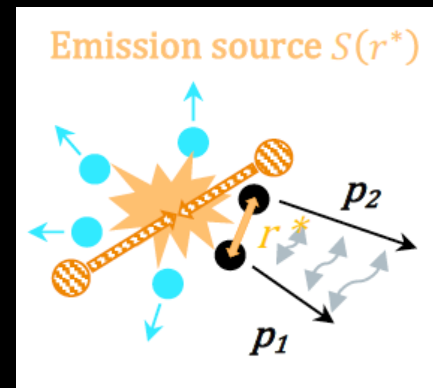
K. Nakazawa, PTEP 2015 (2015) 033D02

- Good constraints for NN interaction
- Small statistics of scattering data for hyperons
- ~1000 Λ-hypernuclei and one ${}^{14}_{\Xi}$N discovered by now

Common baryon source

Collective flow and feed-down from short lived resonances modify source size





Resonances with $c\tau \sim r_O \sim$ 1fm (Δ^{++},N^*,Σ^*)

Particle	Primordial fraction	Resonances <cτ>
Proton	33 %	1.6 fm
Lambda	34 %	4.7 fm

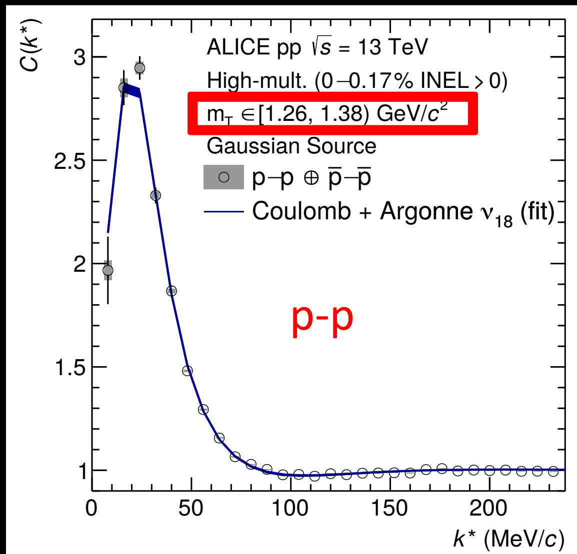
U. Wiedemann U. Heinz (PRC56 R610, 1997)

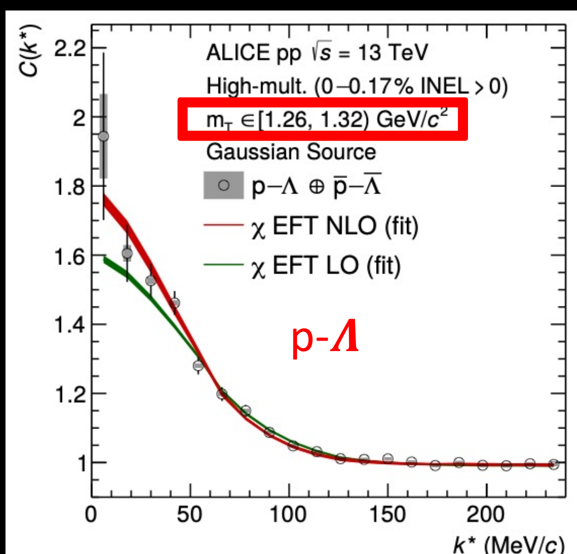
$$m_T = \sqrt{k_T^2 + m^2},\ k_T = \frac{1}{2}|p_{T1} + p_{T2}|$$

$$S(r^*) = G(r^*, r_{core}(m_T)) = \frac{1}{\left(4\pi r_{core}^2\right)^{3/2}} \exp\left(-\frac{r^{*2}}{4r_{core}^2}\right) \otimes E(r^*, M_{res}, \tau_{res}, p_{res})$$

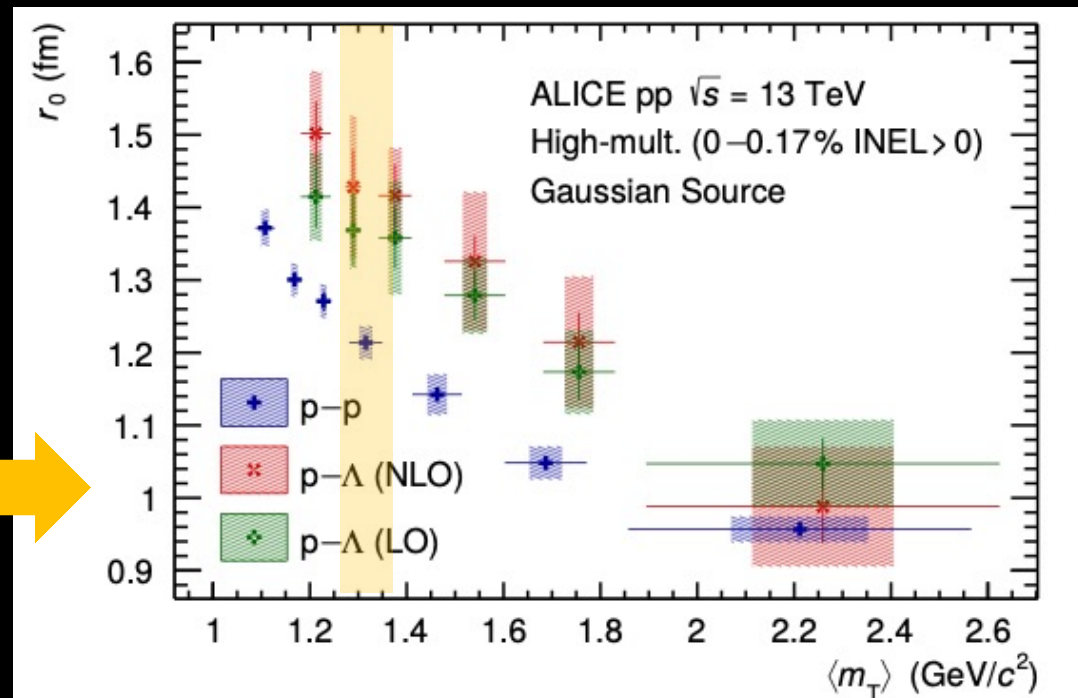
$$E(r^*, M_{res}, \tau_{res}, p_{res}) = \frac{1}{s} \exp\left(-\frac{1}{s}\right),\ s = \beta\gamma\tau_{res} = \frac{p_{res}}{M_{res}}\tau_{res}$$

Common baryon source





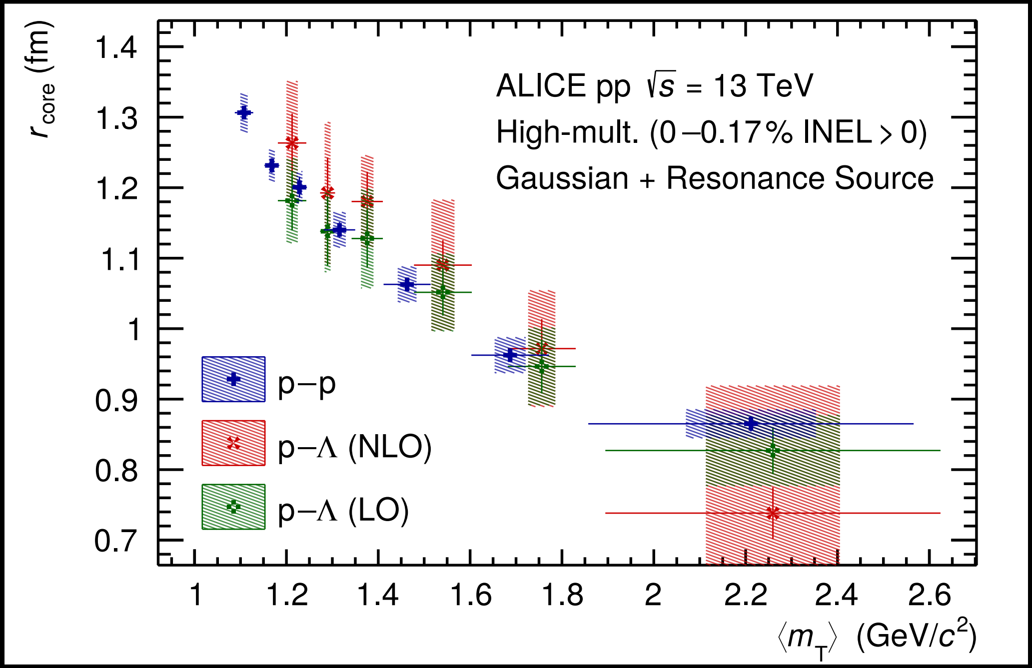
ALICE PLB 811 (2020) 135849

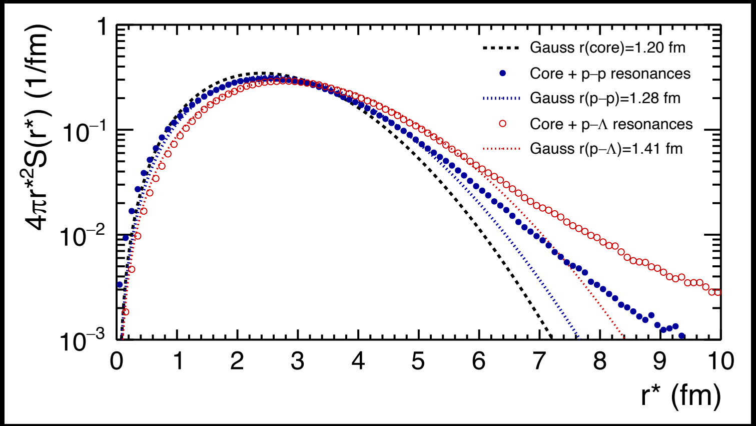


- Different source size depending on the baryon pair
- Gaussian source scales with m_T

Common baryon source

ALICE PLB 811 (2020) 135849





- Relative particle abundances from Statistical Hadronization Model *
- Kinematic distributions from EPOS **

- All baryon pairs with included resonances show common m_T scaling

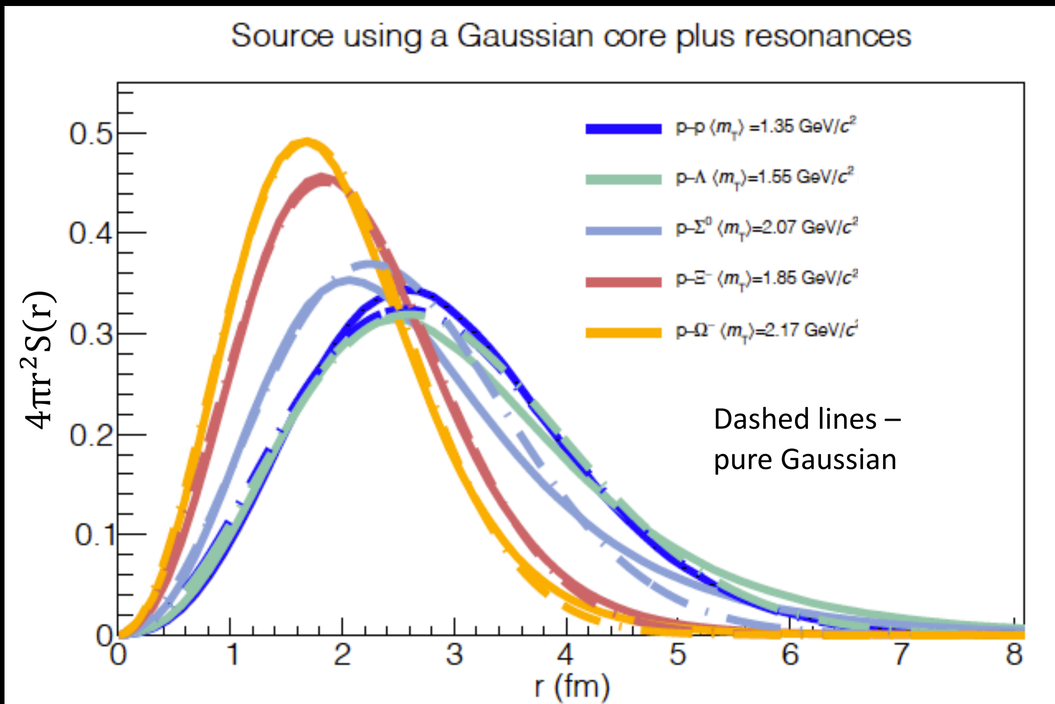
→ Indication of common baryon source

→ One can use p-p correlation to fix source size for other baryon pairs

* F. Becattini et al. J. Phys. G: Nucl. Part. Phys. **38** 025002

** T. Pierog et al. PRC 92 (2015) 034906

Common baryon source



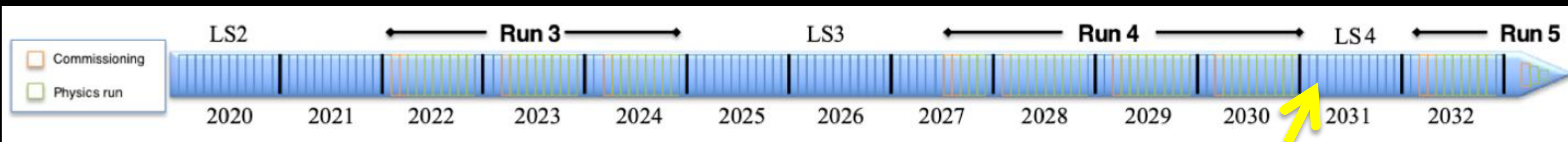
Pair	r_{Core} [fm]	r_{Eff} [fm]
p-p	1.1	1.2
p-Λ	1.0	1.3
p-Σ^0	0.87	1.02
p-Ξ^-	0.93	1.02
p-Ω^-	0.86	0.95

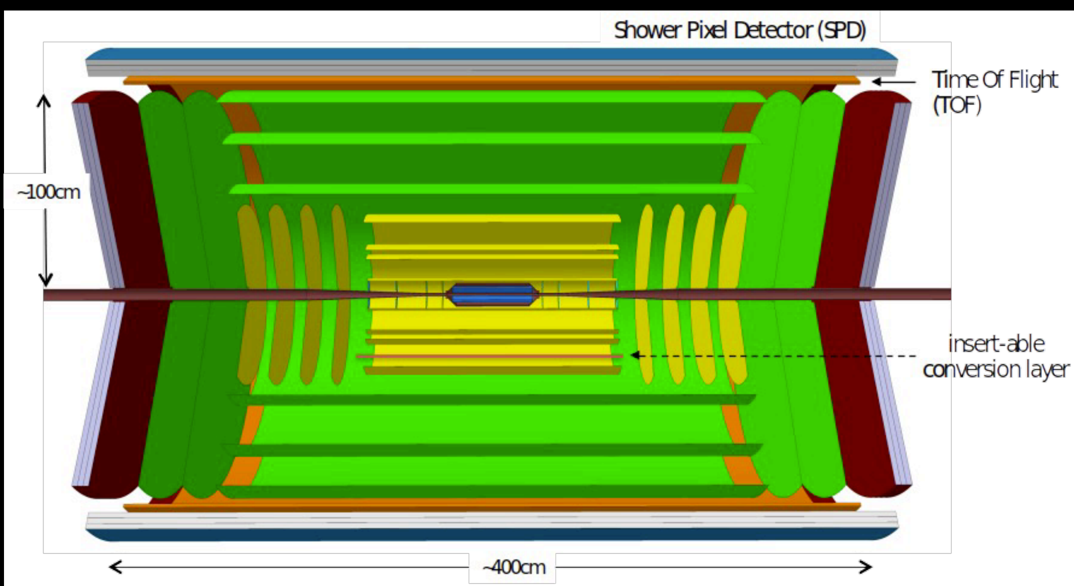
- Emission source for heavier pairs using p-p correlation function plus resonances
- Gaussian source with $r_{eff} = 1.02 \pm 0.05$ (0.95 ± 0.06) fm used for the p-***Ξ*** (p-***Ω***) emission

Future Heavy Ion Detector

Possibility to extend heavy ion measurements at the LHC beyond 2030

arXiv:1902.01211





Physics:

- Heavy flavor and quarkonia
- Low mass dielectrons
- Soft photons and hadrons
- BSM

Design guidelines:

- All silicon detector
- High rate capability: ~$10^{34}/cm^2/s$ (~50x Run3-4)
- Vertex spatial resolution: ~1 μm
- Tracking over wide kinematic range
  - 30 MeV/c < p_T < 10 GeV/c
  - $|\eta| < 4.0$