Study of Exotic Particles using Heavy Ion Collisions

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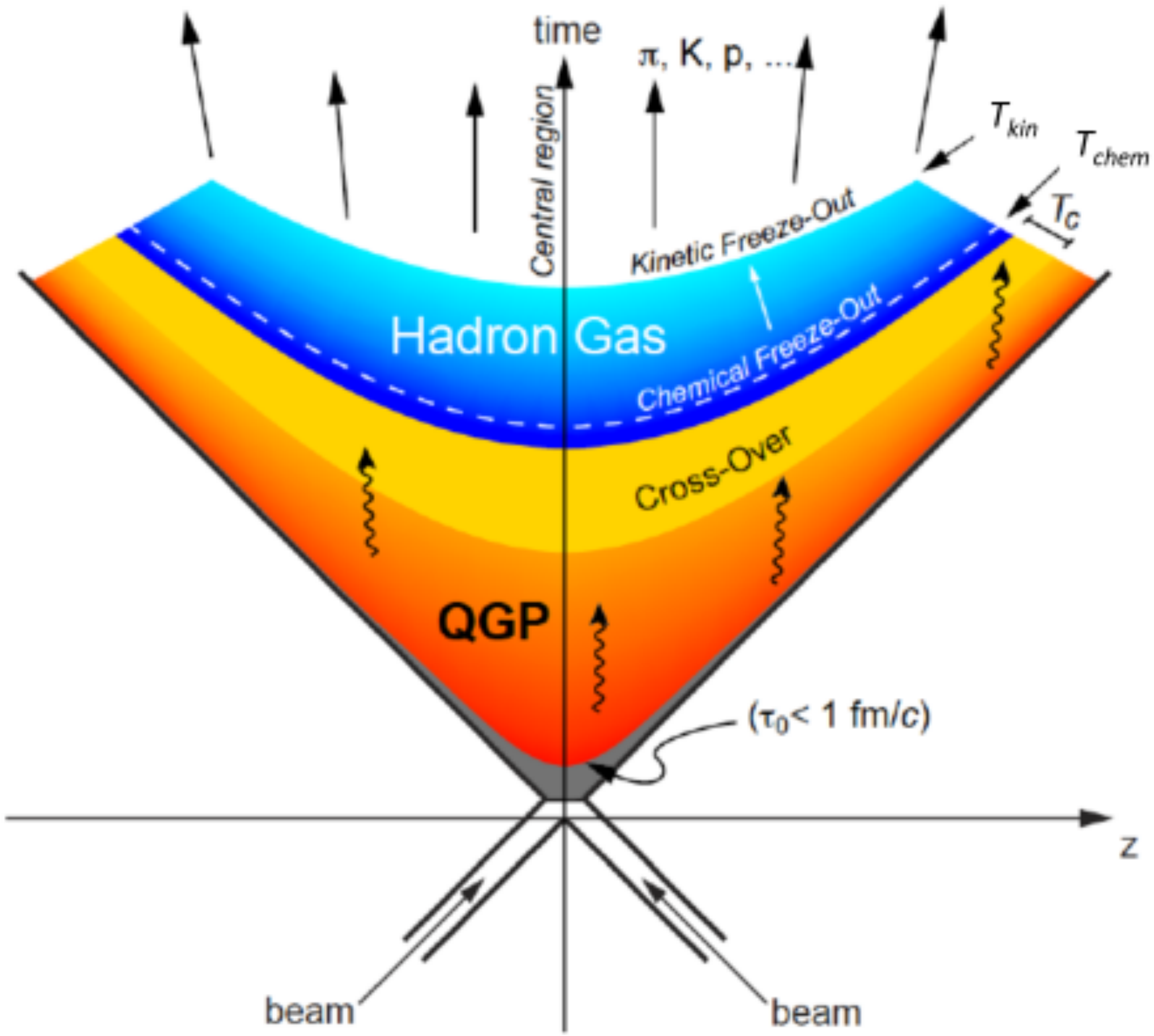
Menu

- Introduction
- Light nuclei and Hypernuclei
- Di-baryon and Baryon Interactions
- Heavy Flavour
- Thermal Photons and Lepton Pairs
- Outlook

INTRODUCTION

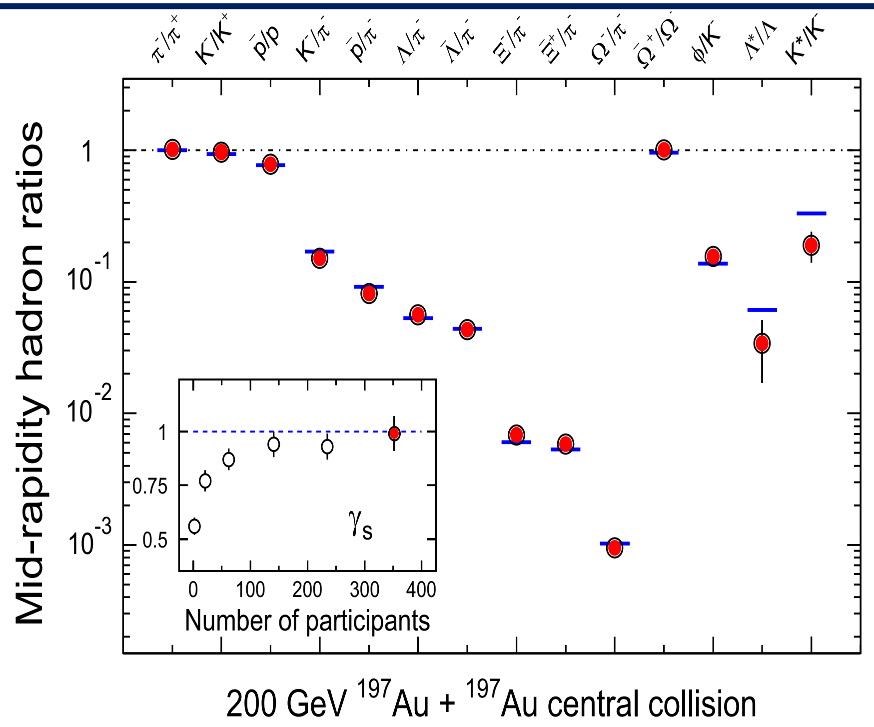
A Simplified View of Space Time Evolution of Heavy Ion Collisions



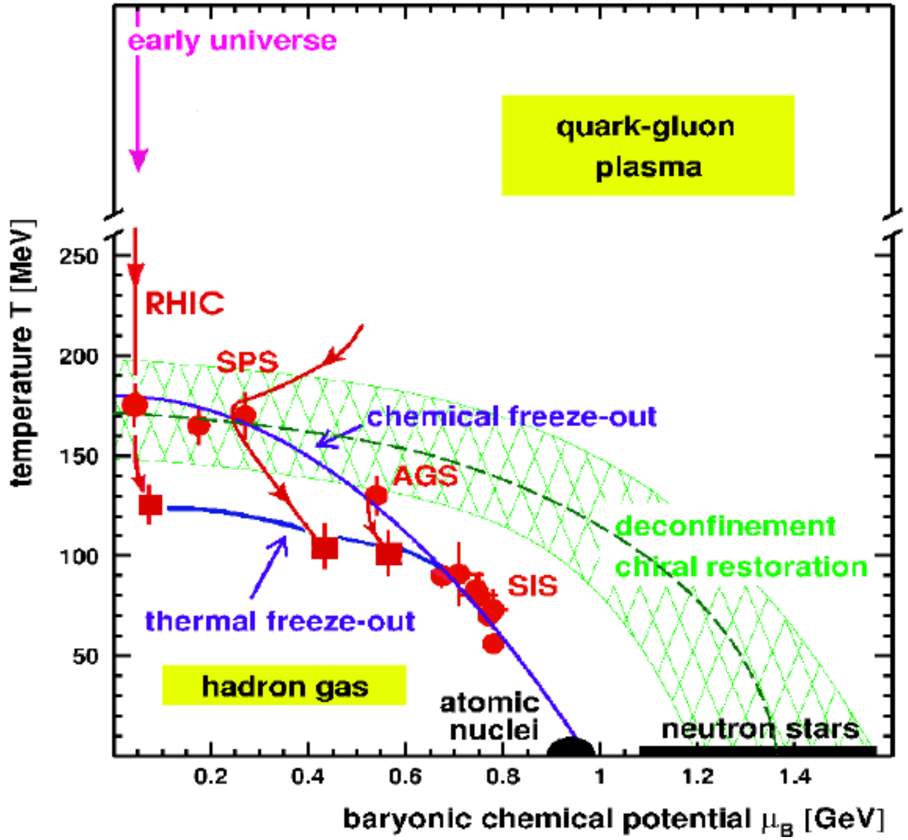
- QGP is formed in less than 1 fm/c after the collision of two nuclei
- QGP behaves as near-perfect hydro
- Transition from QGP phase to Hadron phase is "cross-over" around $T = T_C$
- Soon after the transition (or even during the cross-over transition), yield of hadrons is fixed (at $T = T_{ch}$; chemical freezeout = cease of inelastic scattering)
- Evolution ends at T_{kin} (kinetic freezeout = cease of elastic scattering)

Hadron Yields and Chemical Freezeout

$$N_A \approx g_A V(\pi T_{CH} m_A/2)^{3/2} \exp[(A\mu_B - m_A)/T_{CH}]$$



Heinz & Kestin; Eur.Phys.J.ST 155:75-87,2008



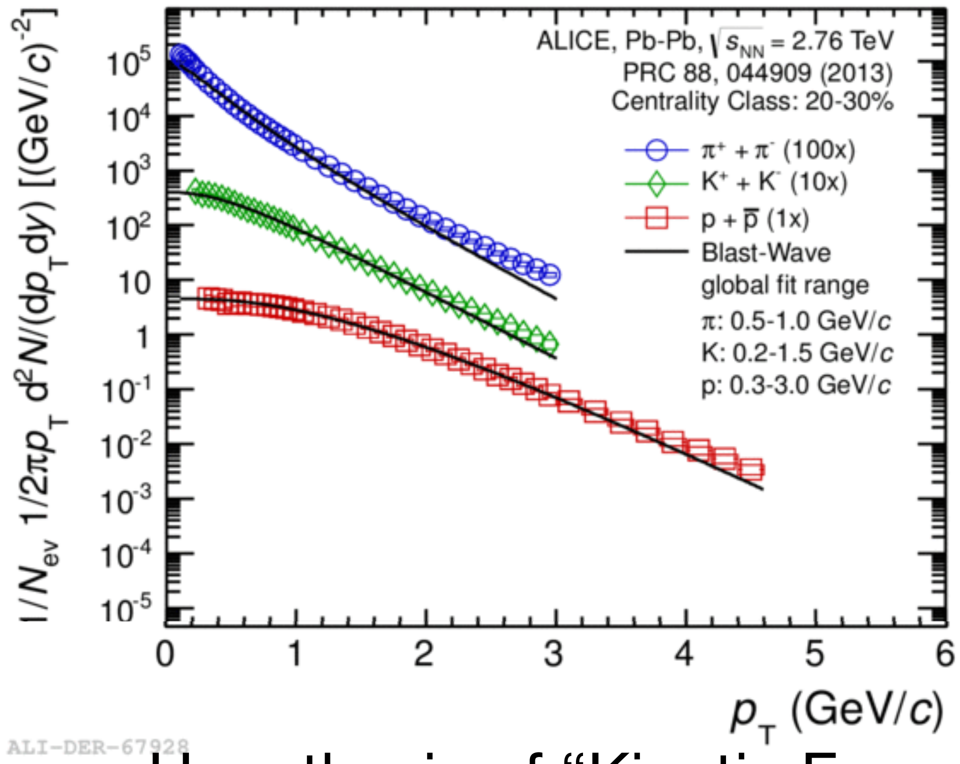
- Hypothesis of "Chemical Freezeout" works rather well to describe hadron yields in heavy ion collisions over wide colliding energies.
- T_{CH} is very close to T_C at RHIC and LHC

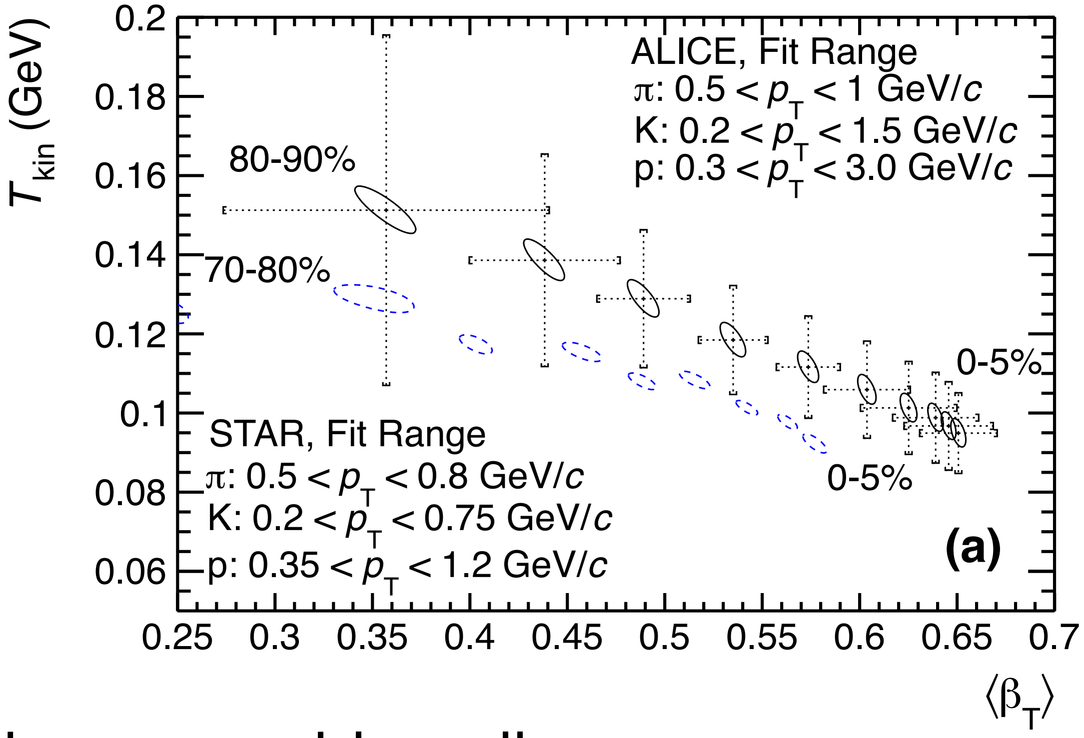
Kinetic Freezeout Hypothesis

$$\frac{dn}{m_T dm_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$

$$\beta_r(r) = \beta_s\left(\frac{r}{R}\right)^n \qquad \rho = \tanh^{-1}\beta_r$$

ALICE Col: PRC.88 (2013) 044910.



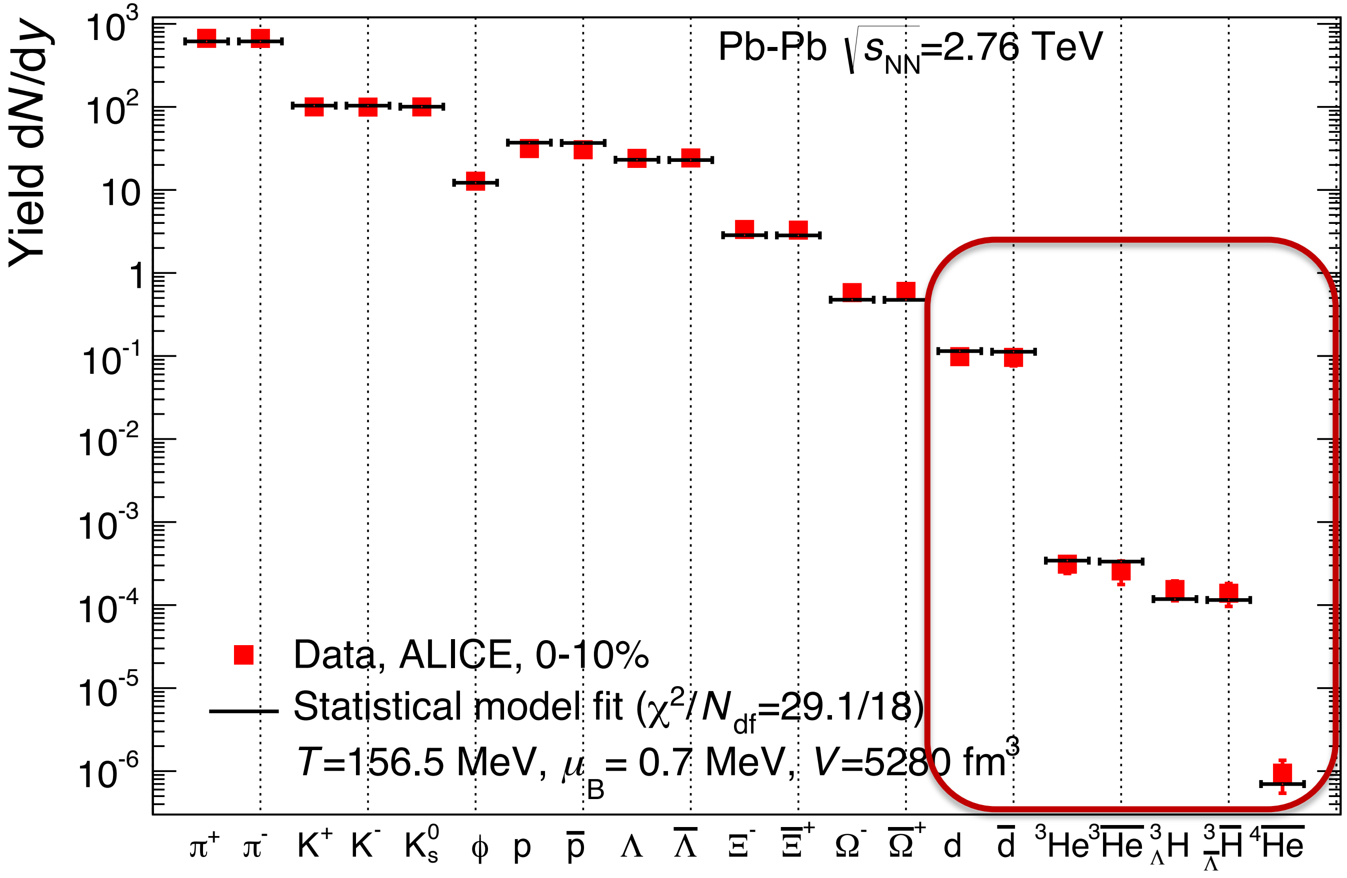


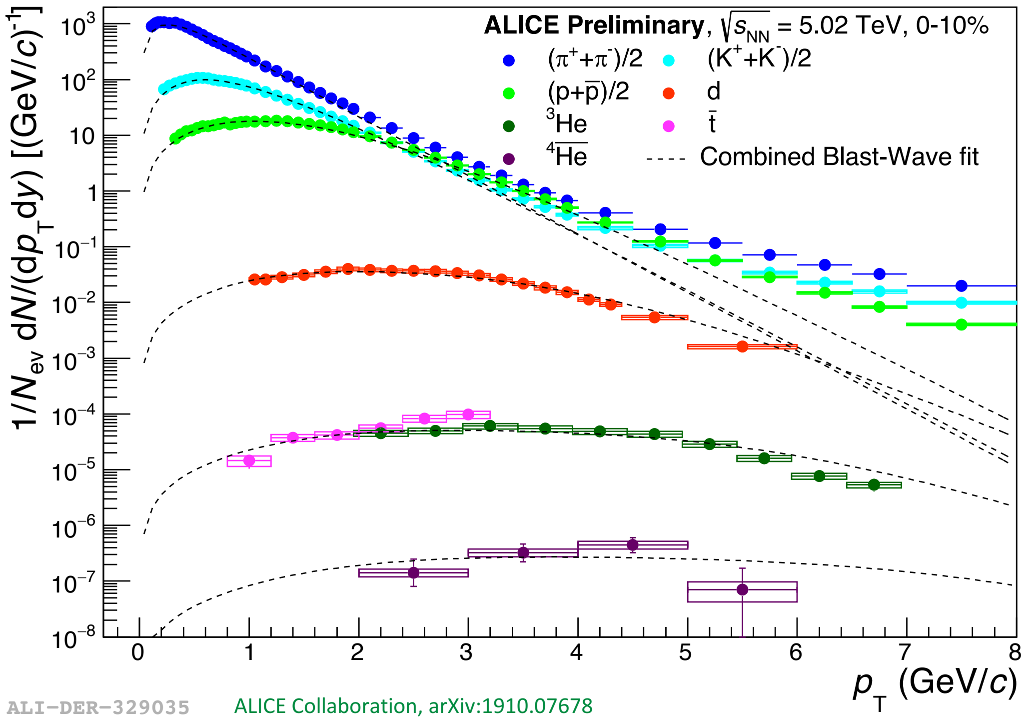
- Hypothesis of “Kinetic Freezeout” works reasonably well
- Blast-Wave fit (with T_{kin} = 100 – 150 MeV) can describe simultaneously the momentum spectra of π, K, p, (Λ, Ξ, Ω)

LIGHT NUCLEI AND HYPERNUCLEI

Hypothesis of "Chemical ad Kinetic Freezeout" seems to work well for loosely-bound Nuclei

Naturevolume 561, pages321–330 (2018)
A Andronic, P Braun-Munzinger, K Redlich & J Stachel





- Simultaneous blast-wave fit to π, K, p, d, t, ^{3}He and ^{4}He

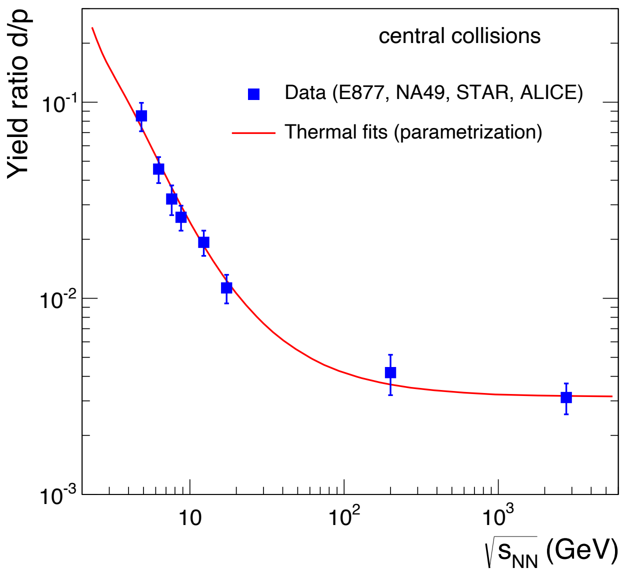
Why Thermal Model works for Loosely Bound Nuclei?

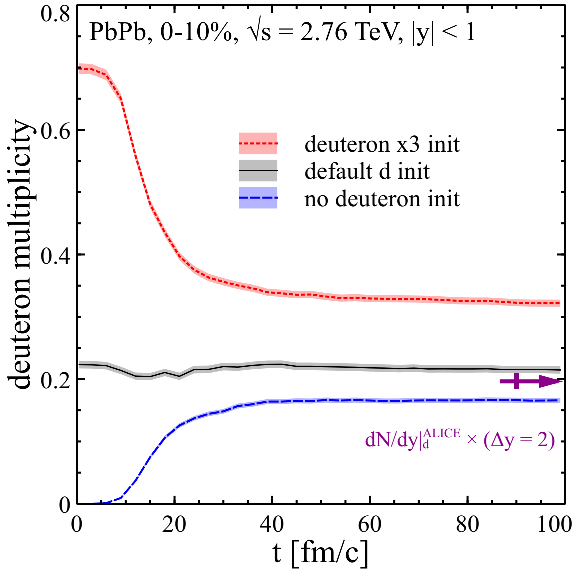
Understanding this will be relevant to study exotics which might have "molecular structure"

Plausible assumption: Particle yields are fixed → Total entropy is conserved after chemical freezeout state

Explanation?

- **Intuitive explanation:** A very dilute phase is realized directly after chemical freezeout stage
- **Recent proposal:** An isentropic expansion in partial chemical equilibrium (PCE) at $T < T_{ch}$
  – **mesons play a similar role as the photons in the early universe, which drive the entropy conservation during the expansion.**
    - Xu, Rapp, Eur. Phys. J. A55 (2019) no.5, 68;
    - Vovchenko et al, arXiv:1903.10024;
    - Oliinychenko, Pang, Elfner, Koch, PRC 99 (2019) 044907

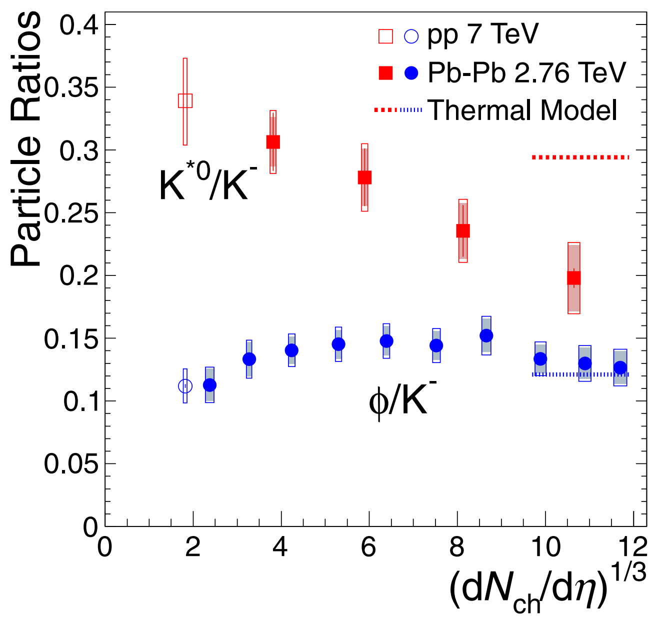


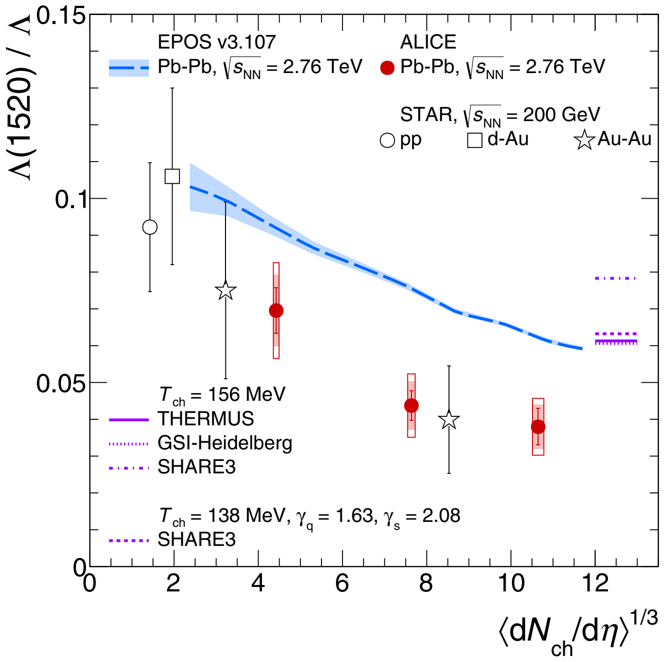


How about Short-lived Hadrons?

With respect to study exotics, understanding systematics of the yield of unstable hadrons as well as stable particles are important

- K*(892)^0, ϕ and Λ(1520) in Pb+Pb collisions
  - **K*(892)^0 (τ~3.9 fm/c):** K*/K- yield ratio (PRC **91**, 024609 (2015))
  - **ϕ(1020) (τ~46.5 fm/c):** ϕ/K- yield ratio
  - **Λ(1520) (τ~12.6 fm/c):** Λ(1520)/Λ yield ratio (PRC **99**, 024905 (2019))
- Yield ratio of short-lived hadrons, with lifetime comparable to or shorter than collision lifetime, changes with $dN_{ch}/d\eta$, while significant fraction survives
- Further works are needed to understand fully the production of (stable and unstable) hadrons and nuclei





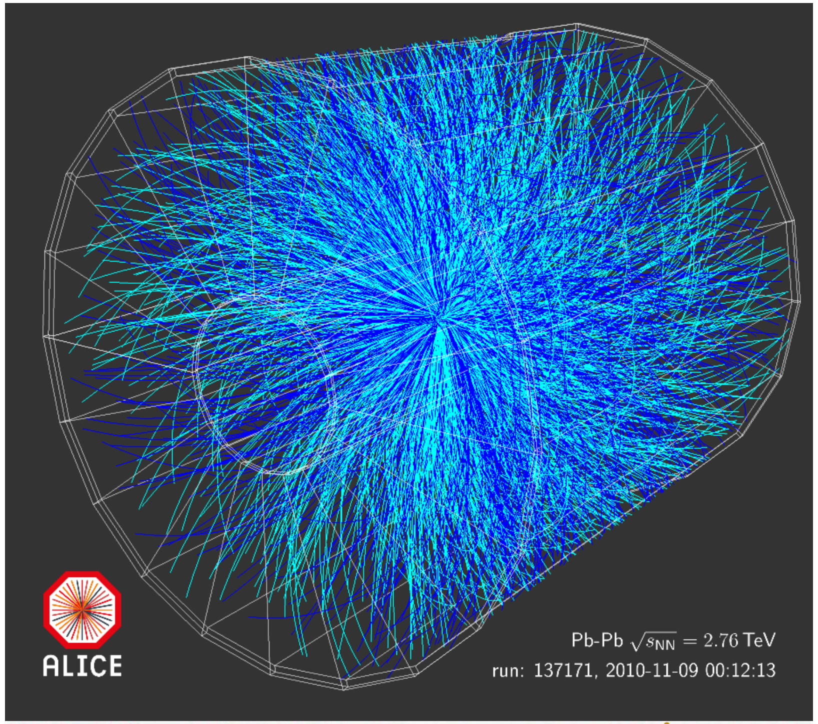
Hypertriton (and anti-hypertriton)

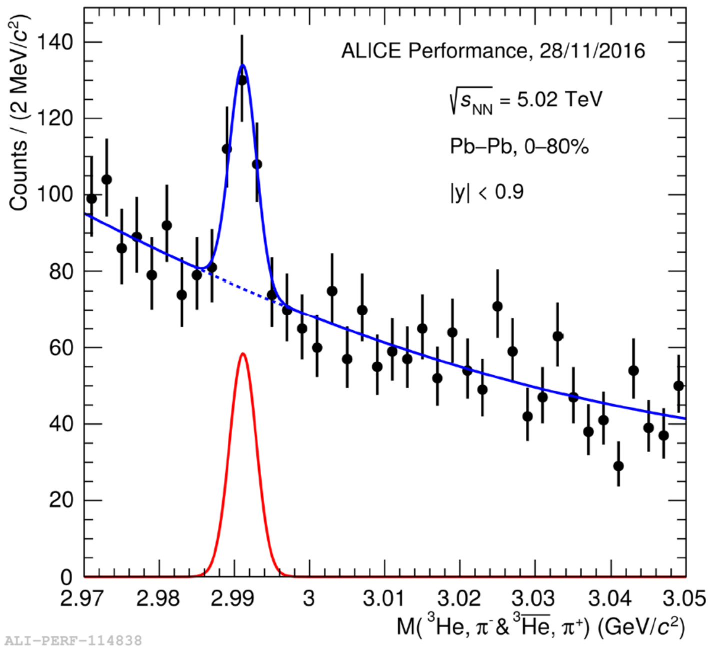
- Loosely bound state of Λ, p and n, with m = 2.991 GeV/c^2 and B_Λ = 130 keV; with rms-radius = 10.6 fm
- ${}^{3}_{\Lambda}\mathrm{H}$ yield is described by the thermal model

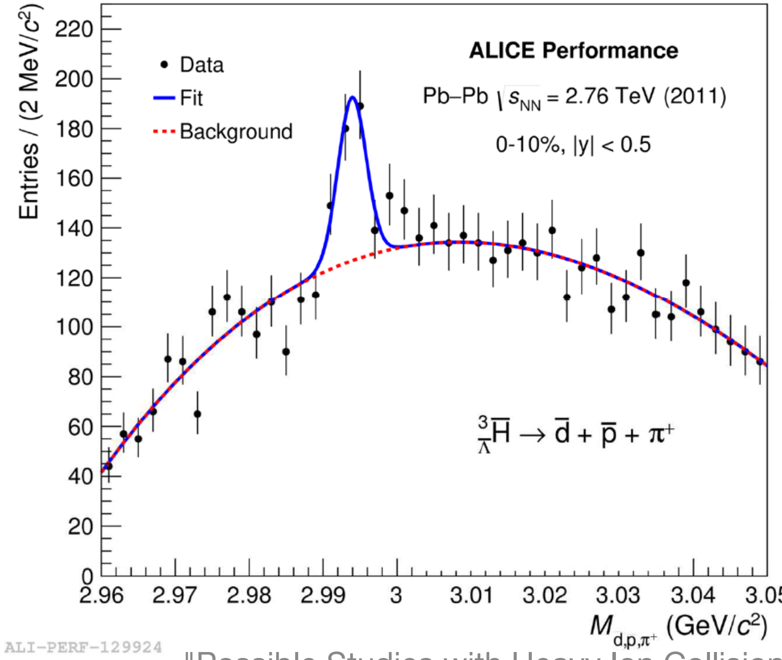
$-\,{}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$

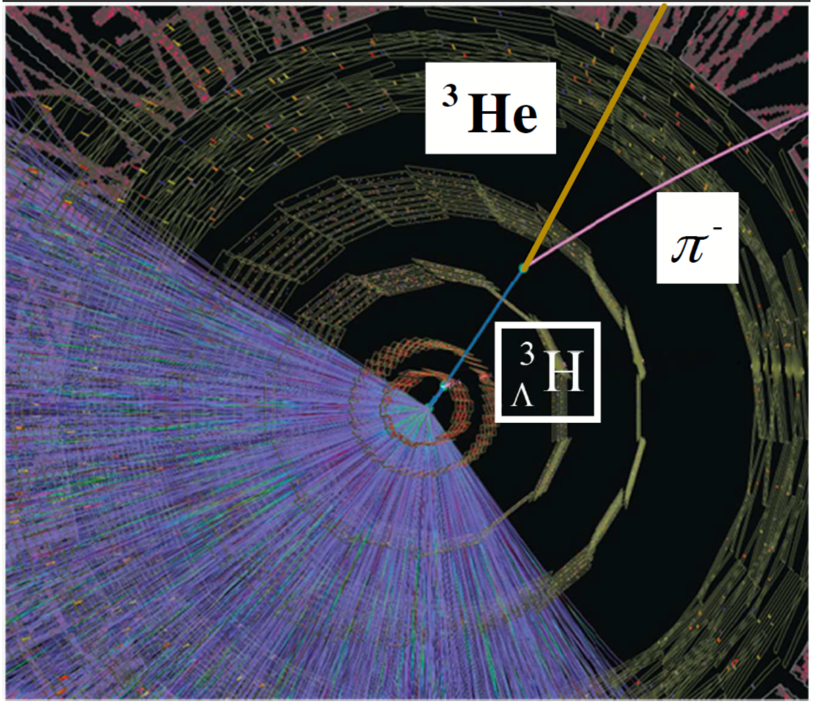
$-\,{}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$

B. Dönigus, Nuclear Physics A 904–905 (2013) 547c–550c
Phys. Lett. B 754 (2016) 360-372





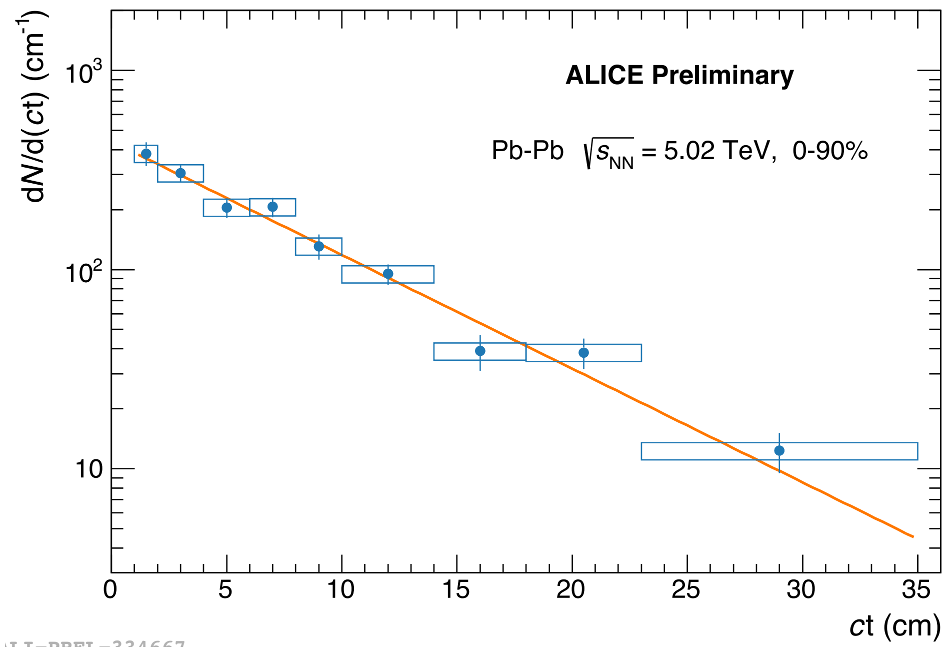


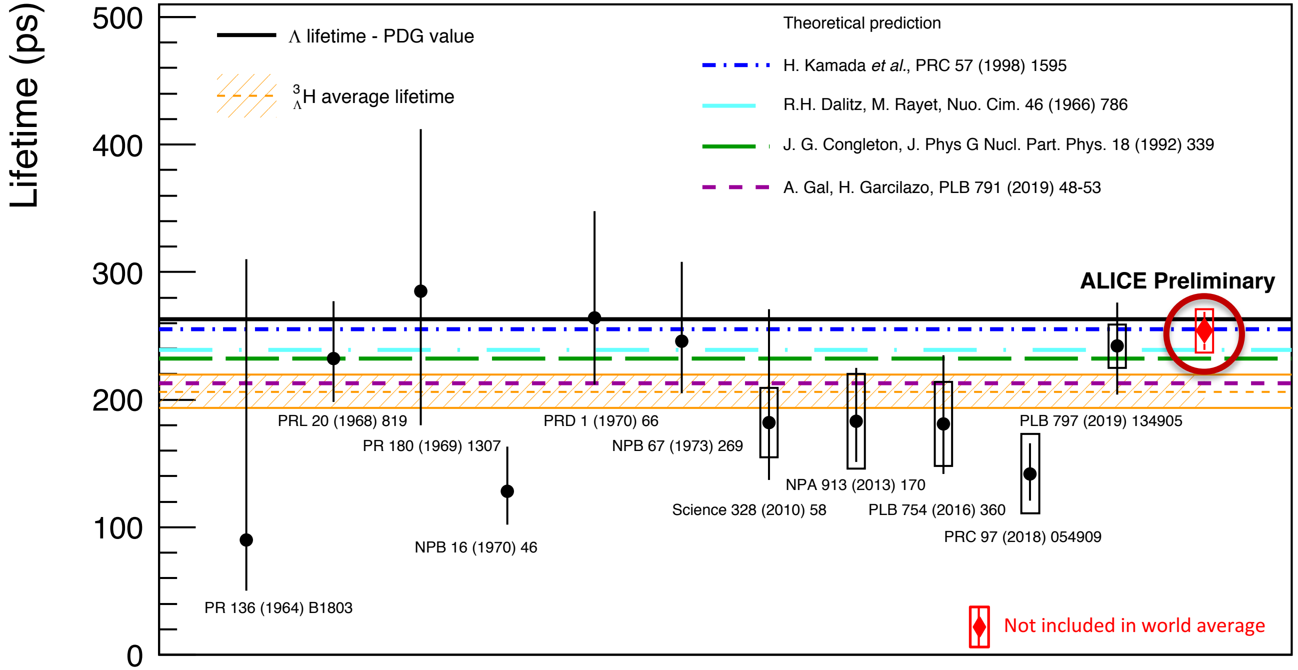


Lifetime of Hypertriton $^{3}_{\Lambda}H$

- Determination of lifetime of $^{3}_{\Lambda}H$ has been made by the several groups using the heavy Ion collisions, providing shorter lifetime than free Λ lifetime, though error bars were not small

- Recent ALICE measurement (red) is the most precise determination of hypertriton lifetime, with lifetime consistent with the free Λ lifetime





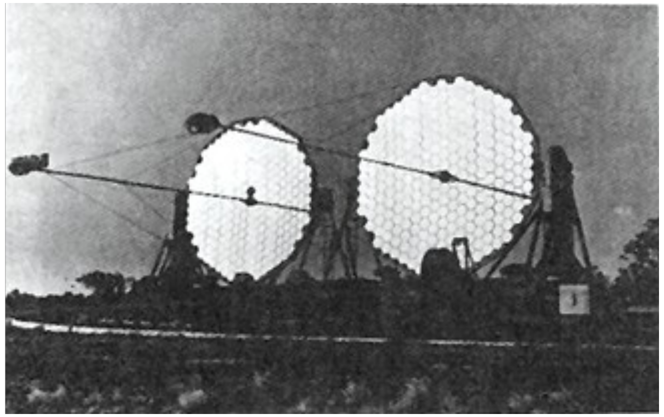
DI-BARYON SEARCH

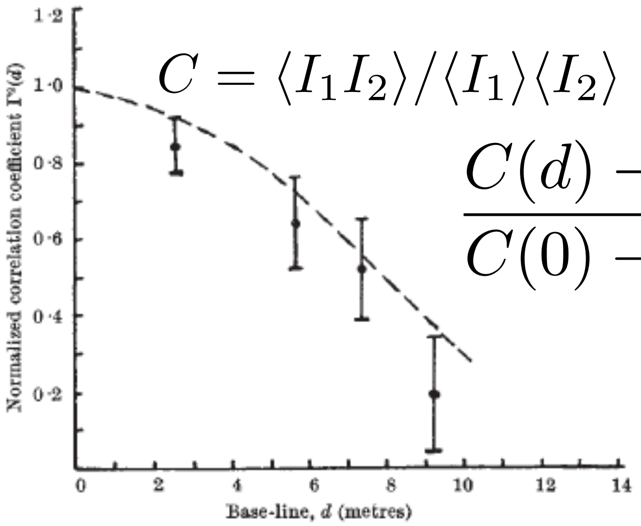
Di-Baryon; a Type of Exotic Particle

- Deuteron = First and still a unique dibaryon so far confirmed
- H-particle: 6-quark state (uuddss = Λ+Λ or Ξ+N)
  - Predicted by Jaffe ('77))
  - Suggested to be a resonance by the experiment (Yoon+ ('07))
  - Could be a bound state of Ξ+N (by HAL QCD ('16))
- Di-Baryon search and studies of baryon-baryon interaction using Heavy Ion collisions in the extended space of flavor SU(3); that is, ΛN, ΣN, ΛΛ, ΞN ..., is getting very popular
  - Pioneering works by STAR experiment at BNL RHIC
  - LHC ALICE experiment is catching up very quickly
- Encouraging is that the baryon interactions can be calculated using the lattice QCD at almost physical point

Methods in Heavy Ion Collisions

- Direct method: Construction of Invariant mass from the possible daughter particles
  - Bound state
  - Unbound resonance state with small decay width
- Two particle correlation（femtoscopy）
  - Origin: HBT (Hanbury Brown and Twiss) Intensity Interferometry
    - “A TEST OF A NEW TYPE OF STELLAR INTERFEROMETER ON SIRIUS”: Hanbury Brown & Twiss, Nature 10 (1956), 1047
    - Angular diameter of Sirius = 6.3 msec
  - Two particle correlation function provides the information of final state interaction of two particles at the kinetic freezeout stage
  - Wide variety of combinations including unstable hadrons

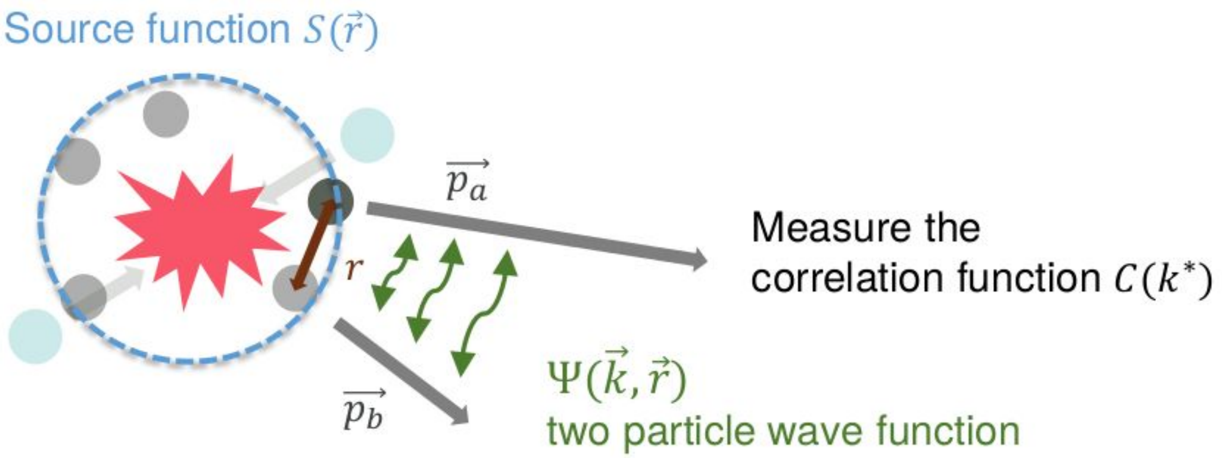




$$C = \langle I_1 I_2 \rangle / \langle I_1 \rangle \langle I_2 \rangle$$

$$\frac{C(d) - 1}{C(0) - 1}$$

Two Particle Correlation Function



R. Lednický, VL Lyuboshitz; Sov. J. Nucl. Phys. 35 (1982) 770–778

Static/Spherical Source:

$$S^{\rm rel}(r) \sim (\pi R^2)^{3/2} \exp\left(-\frac{r^2}{4R^2}\right)$$

Asymptotic wave function:

$$\chi_Q(r) \sim \sin(Qr+\delta)/(Qr)$$

$$Q\cot\delta = -\frac{1}{a_0} + \frac{1}{2} r_{\rm eff} Q^2$$

Statistical definition ***Experimental definition*** ***Theoretical definition***

$$C(k^*) = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \mathcal{N}\frac{N_{\rm Same}(k^*)}{N_{\rm Mixed}(k^*)} = \int S(\vec{r})\left|\Psi(\vec{k}^*,\vec{r})\right|^2 \mathrm{d}^3\vec{r} \xrightarrow{k^*\to\infty} 1$$

Single-particle momenta

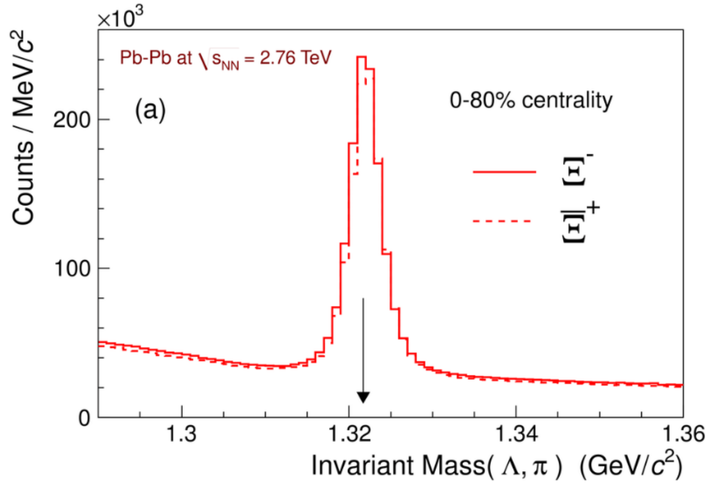
Relative distance / reduced momentum in the rest frame of the pair

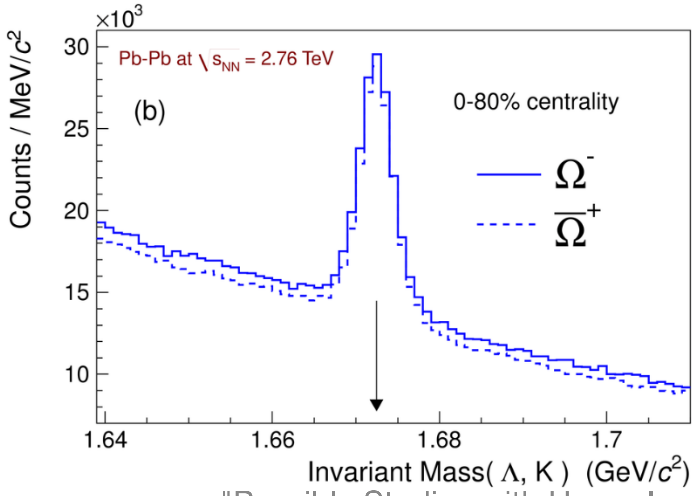
[Phys. Lett. B 728 (2014) 216-227](http://alice-publications.web.cern.ch/node/604)
http://alice-publications.web.cern.ch/node/604

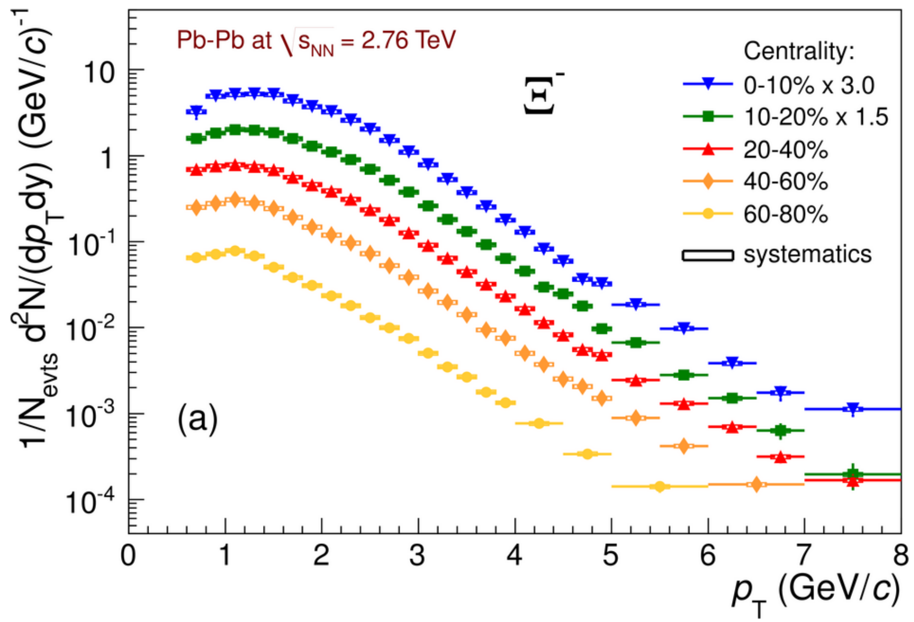
Multi-strange baryons

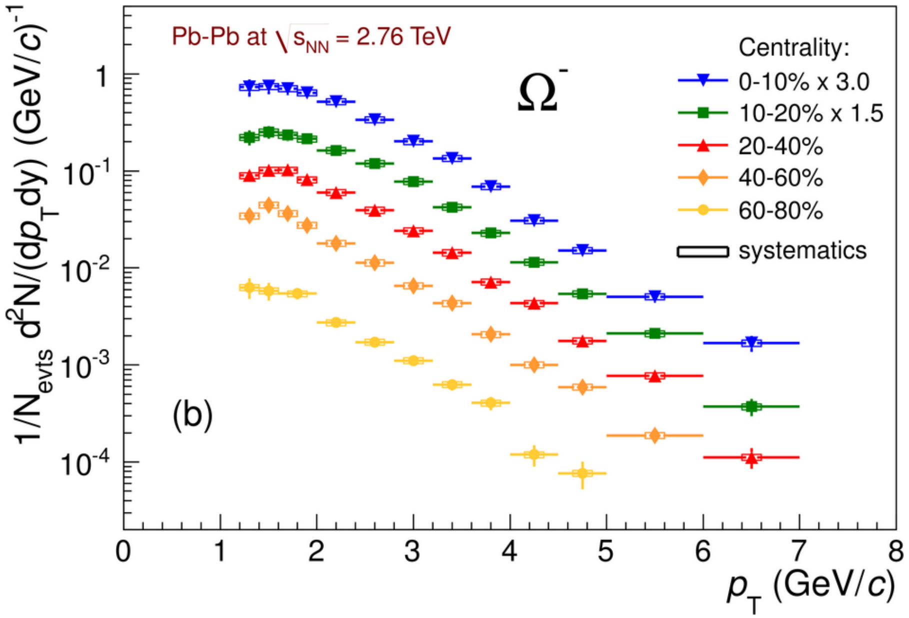
Pb+ Pb at $\sqrt{S_{NN}} = 2.76\ TeV$

Centrality	0-10%	10-20%
$\langle N_{part} \rangle$	356.1 ± 3.6	260.1 ± 3.9
Ξ^-	$3.34 \pm 0.06 \pm 0.24$	$2.53 \pm 0.04 \pm 0.18$
$\overline{\Xi}^+$	$3.28 \pm 0.06 \pm 0.23$	$2.51 \pm 0.05 \pm 0.18$
$\Xi^- + \overline{\Xi}^+$	$6.67 \pm 0.08 \pm 0.47$	$5.14 \pm 0.06 \pm 0.36$
Ω^-	$0.58 \pm 0.04 \pm 0.09$	$0.37 \pm 0.03 \pm 0.06$
$\overline{\Omega}^+$	$0.60 \pm 0.05 \pm 0.09$	$0.40 \pm 0.03 \pm 0.06$
$\Omega^- + \overline{\Omega}^+$	$1.19 \pm 0.06 \pm 0.19$	$0.78 \pm 0.04 \pm 0.15$





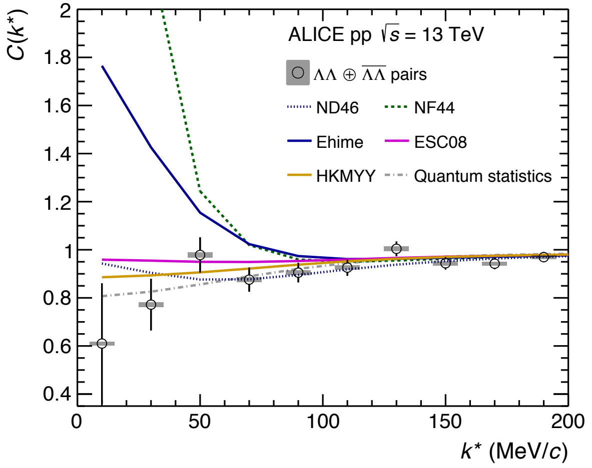


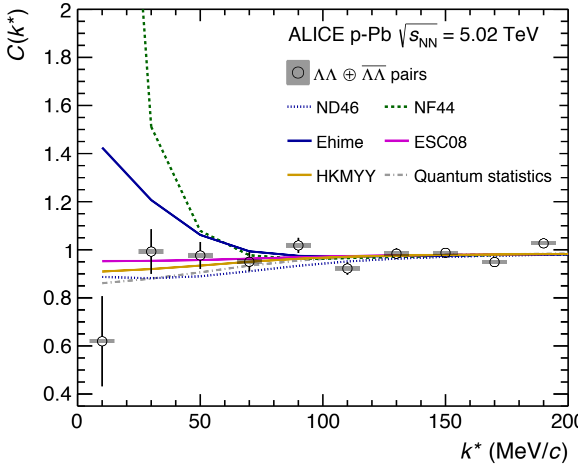


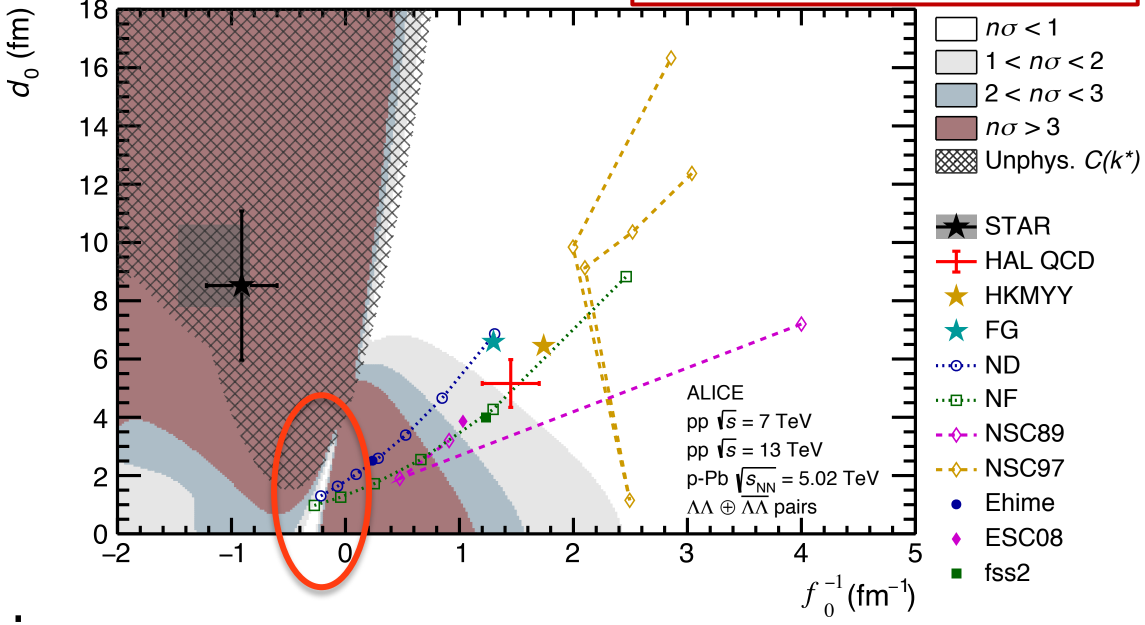
ΛΛ Correlation in p+p & p+Pb Collisions

Phys. Lett. B797 (2019) 134822.

Phys. Rev. C 99, 024001 (2019)

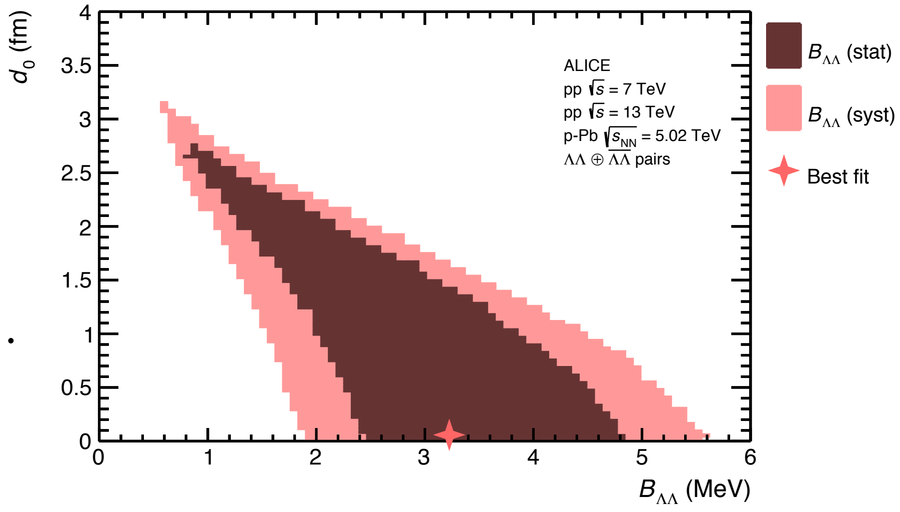




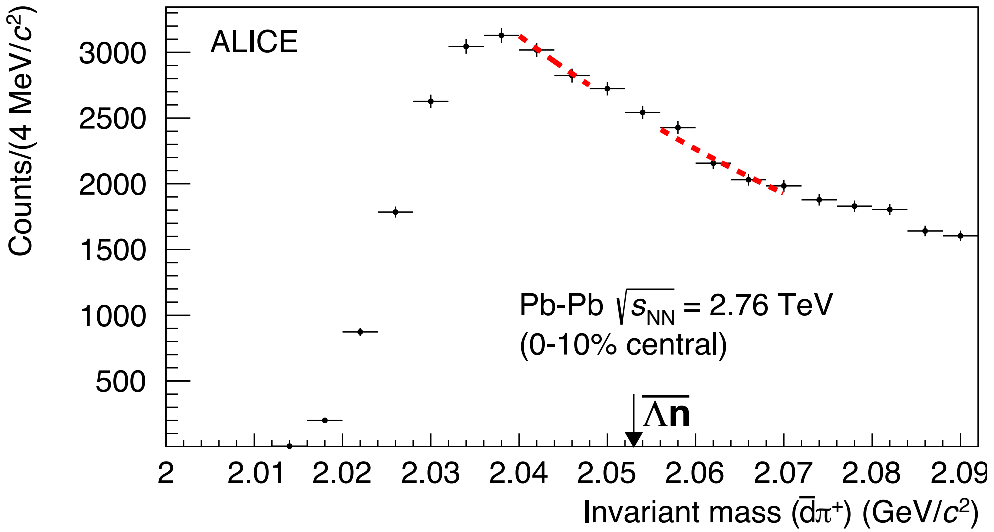


- Preceeding study by STAR collaboration
- Correlation function is very flat → Allowed region for scattering parameters, d_0 and f_0^{-1},is very large
- Possible bound state in the region at slightly negative f_0^{-1} and $d_0 < 4$

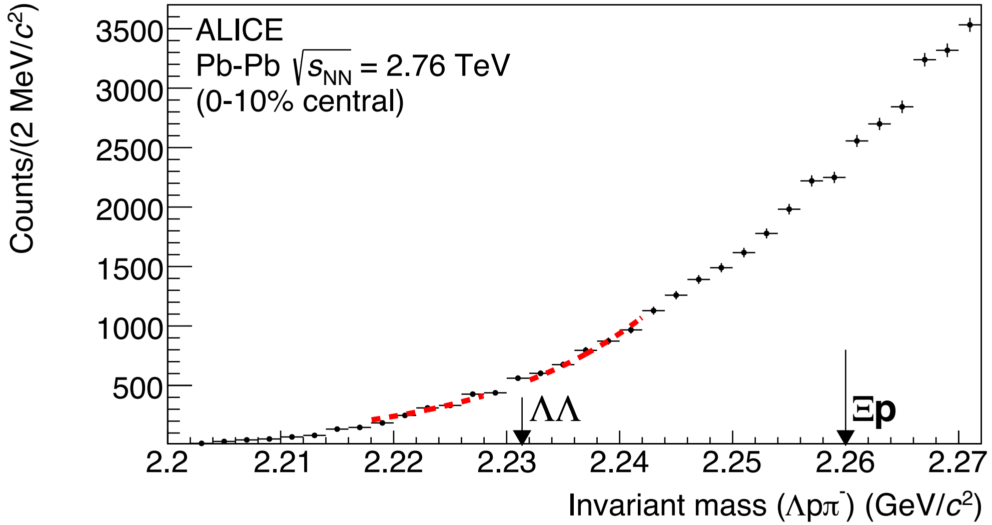
$$B_{\Lambda\Lambda} = \frac{1}{m_\Lambda d_0^2}\left(1-\sqrt{1+2d_0 f_0^{-1}}\right)^2.$$



Search of ΛN and ΛΛ Bound State



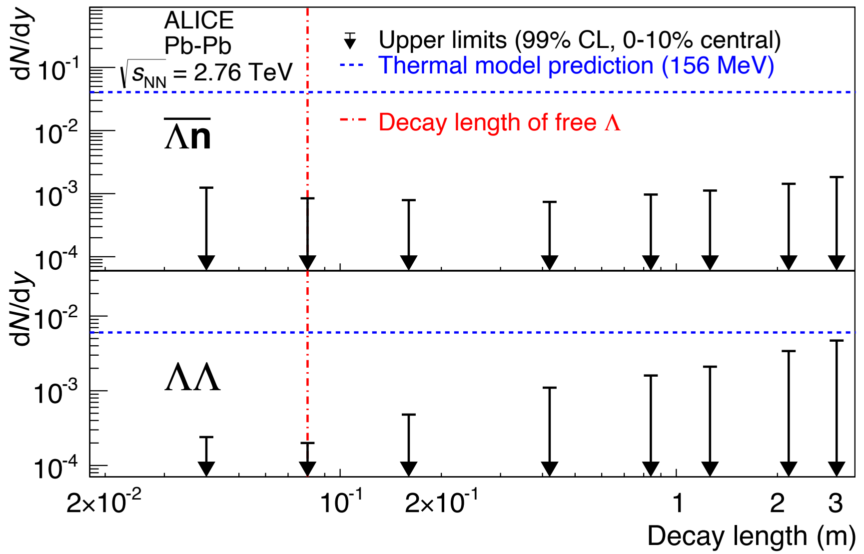
ALICE Coll.:Phys. Lett. B 752 (2016) 267-277



- Invariant mass of plausible combinations of daughter particles

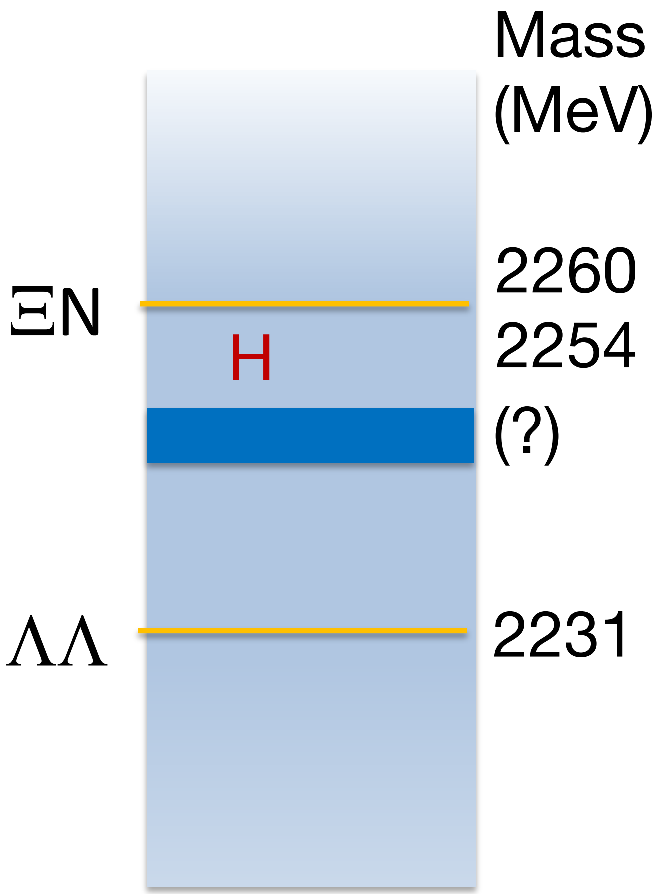
$$\overline{\Lambda N}: \bar{d} + \pi^+ \qquad H(\Lambda\Lambda): \Lambda + p + \pi^-$$

- Analysis was made by assuming long lived bound states with lifetime comparable to free Λ → No hint of such states



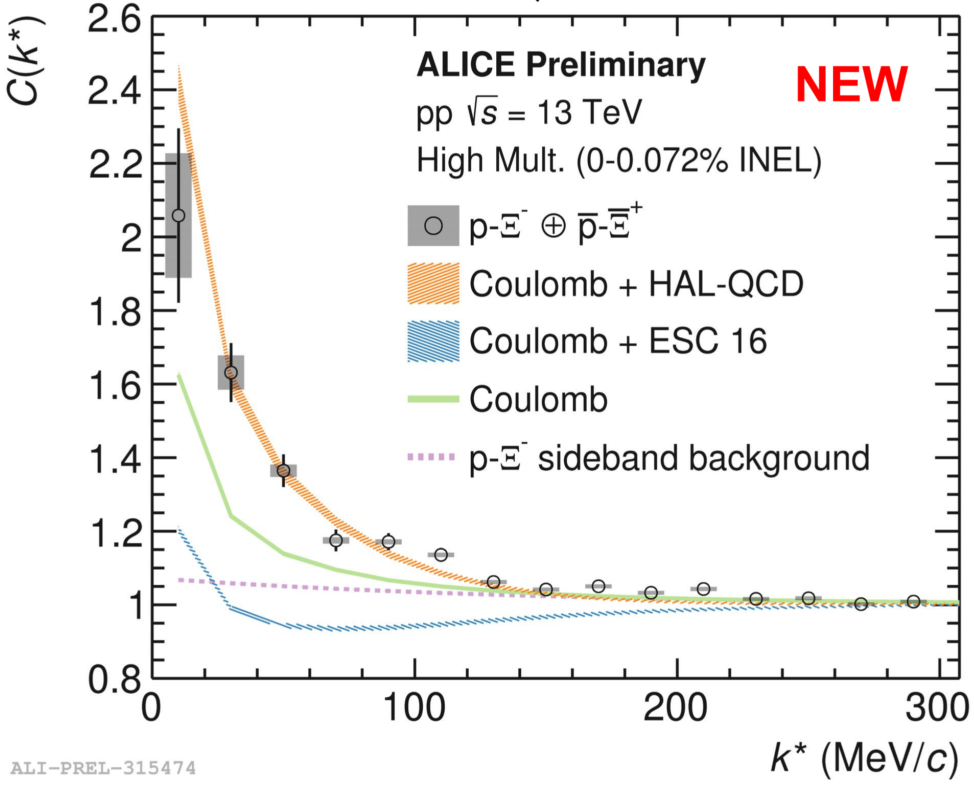
How to detect H?

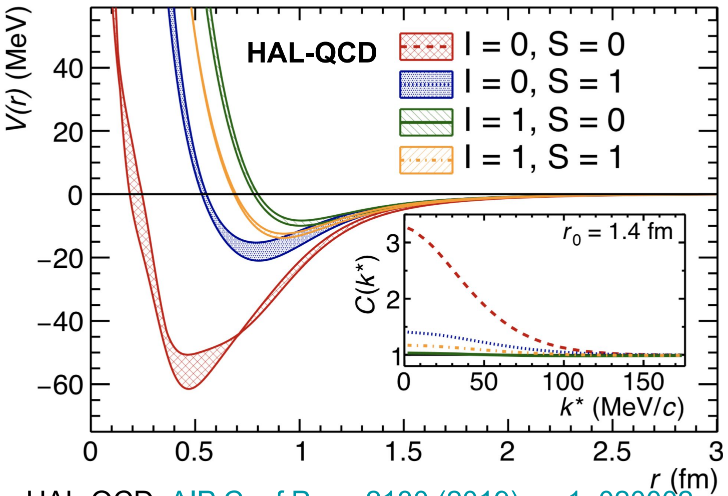
- Recent HAL-QCD suggests that H has ΞN configuration instead of ΛΛ, with mass slightly below ΞN or slightly unbound (arxiv 1912.08630)
- H may survive the violent space-time evolution
  - It is so, if H behaves similar to other short-lived particles
  - it itself is an interesting question
- Need to change the criterion to accept the candidates which decay promptly at the primary collision point
  - If unbound, it will strongly decay to ΞN
  - If bound, then it will strongly decay to ΛΛ
- Caveat: Depending on the lifetime of the resonance and background situation, much larger statistics may be needed



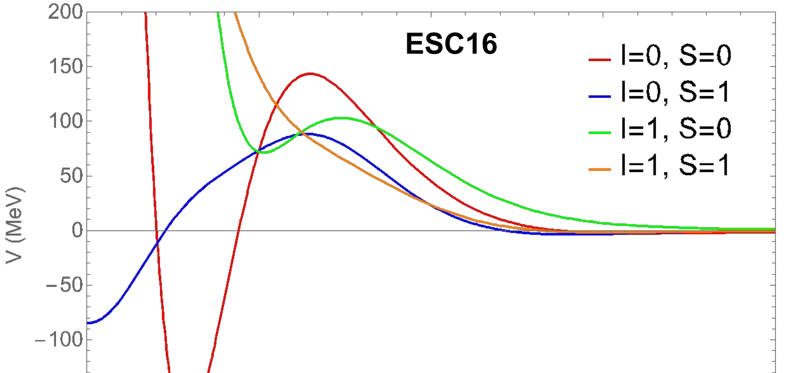
Ξ^-p Correlation

Presented in QM2019@Wuhan





HAL-QCD: AIP Conf.Proc. 2130 (2019) no.1, 020002

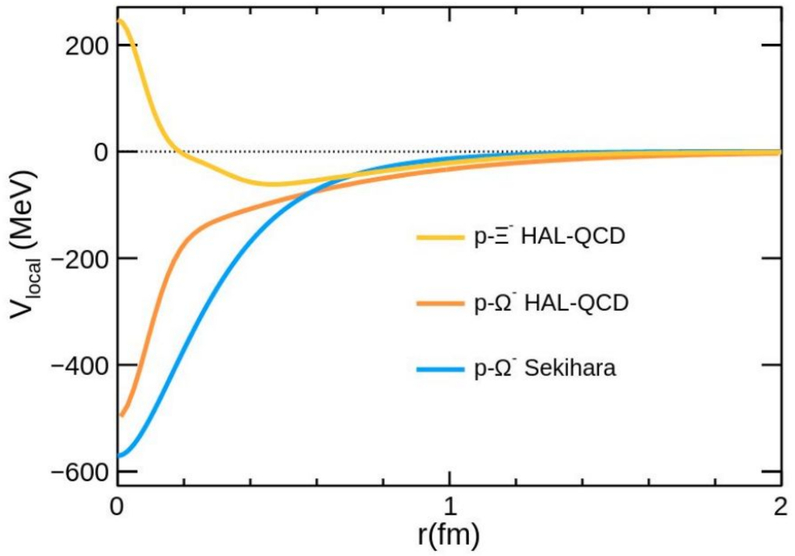


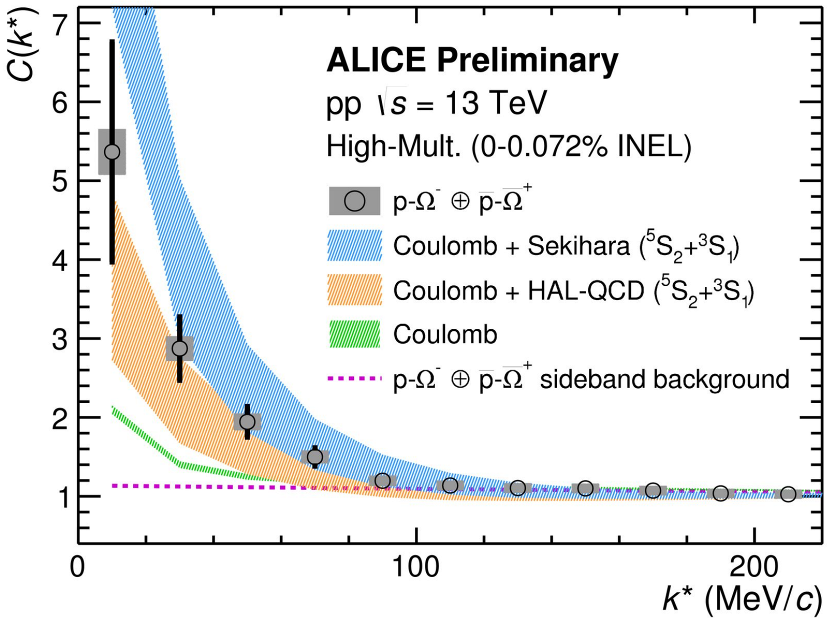
ESC16: Phys. Rev. C 99, 044003

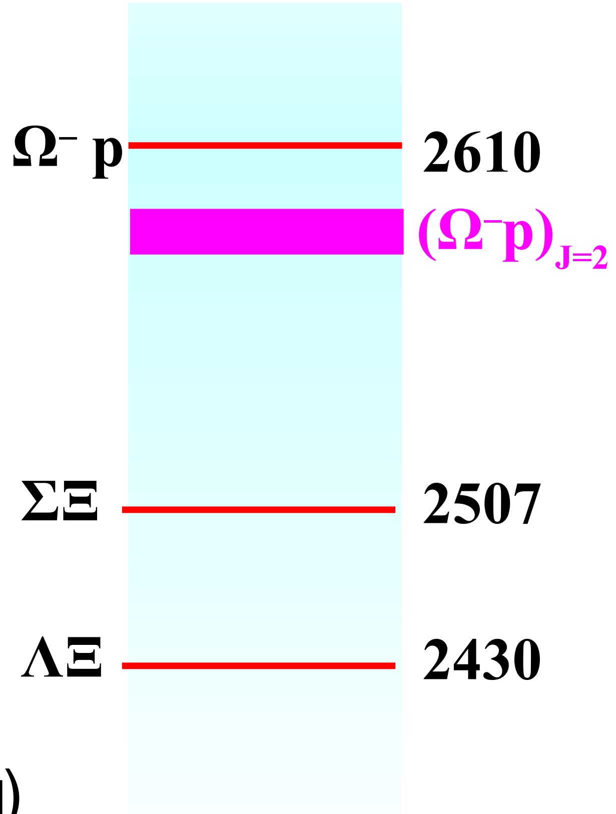
$$C_{p-\Xi^-} = \frac{1}{8}C_{N-\Xi}\,(I=0,S=0) + \frac{3}{8}C_{N-\Xi}\,(I=0,S=1) + \frac{1}{8}C_{N-\Xi}\,(I=1,S=0) + \frac{3}{8}C_{N-\Xi}\,(I=1,S=1).$$

- ALICE: pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV & pp collisions at $\sqrt{s}$ = 13 TeV
- Compared with HAL-QCD and ESC 16 (Potential by Nijmegen group)
  - ESC 16 will be excluded

$\Omega^{-}p$ Correlation





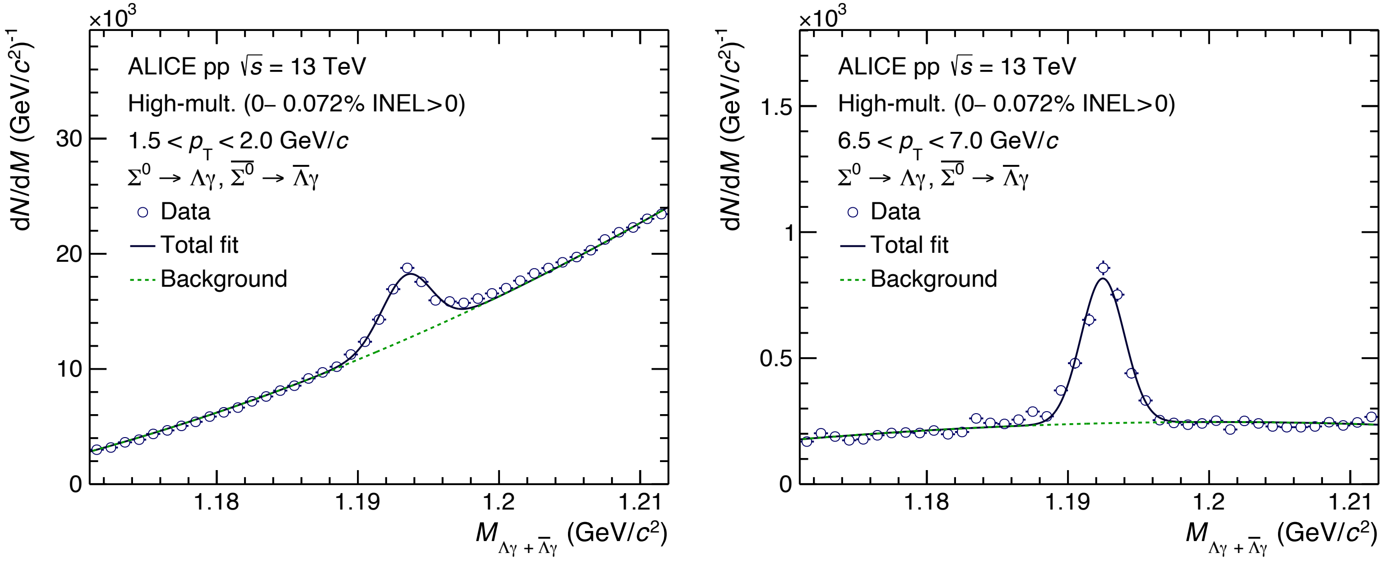


- Preceding work by STAR Collaboration (arXiv:1808.02511 [hep-ex])
- Two theoretical calculations: HAL-QCD (PLB 792 (2019) 284) & meson exchange (by Sekihara; PRC 98, 015205 (2018))
- $\Omega^{-}p$ is more attractive than $\Xi^{-}p$: HAL-QCD predicts that $^{5}S_{2}$ is a bound state
  - Coupling between $\Omega^{-}p$ (S-state) and $\Sigma\Xi$, $\Lambda\Xi$ (D-state) may not be big → small decay width

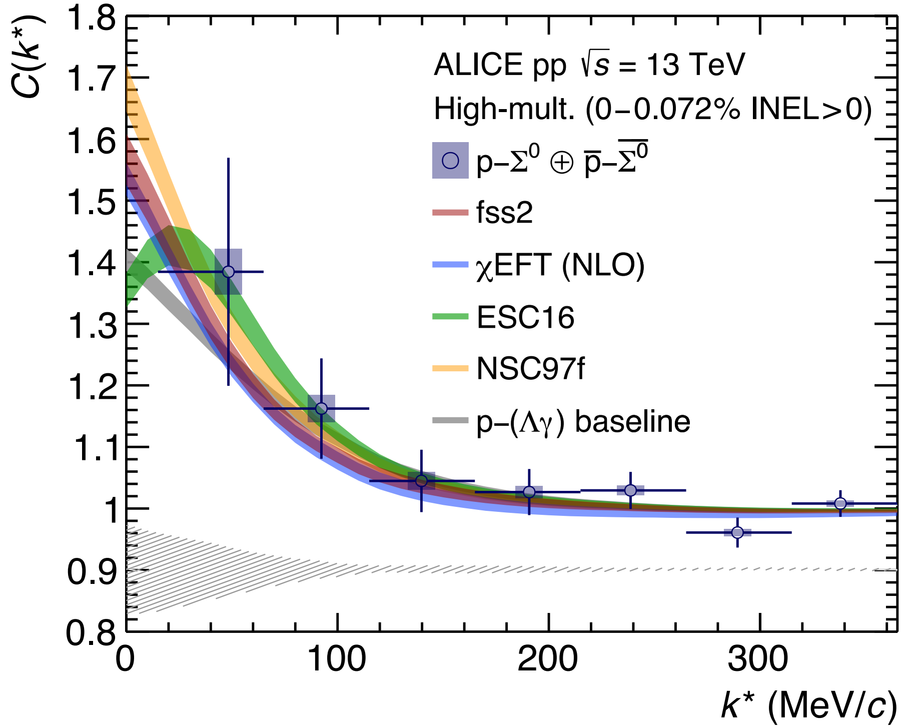
→ Why not try to make a direct measurement!

Σ^0p Correlation

arXiv:1910.14407



γ: measured via external conversion

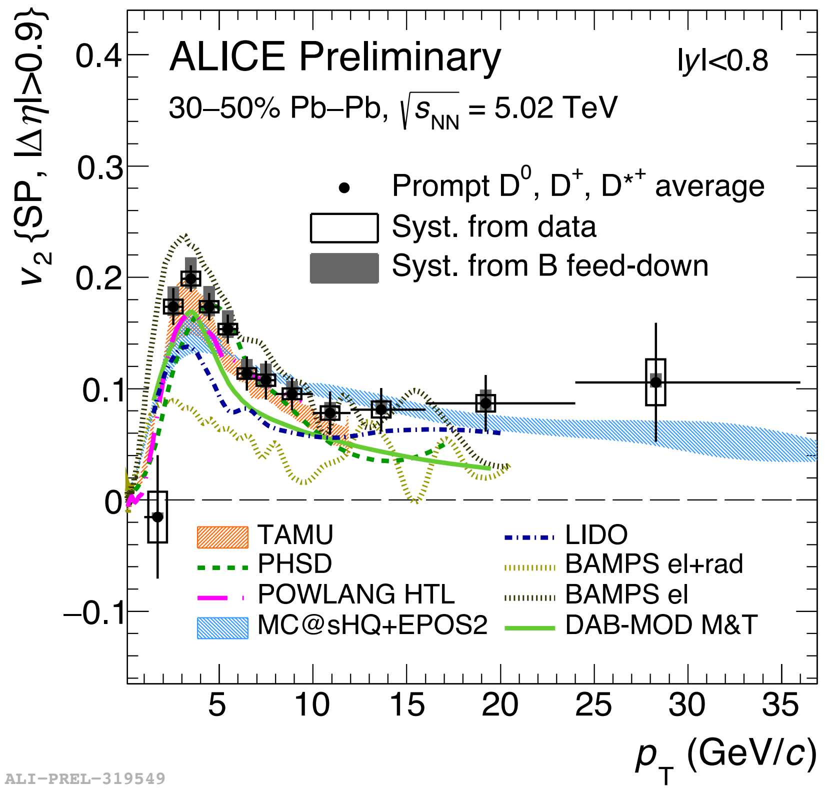


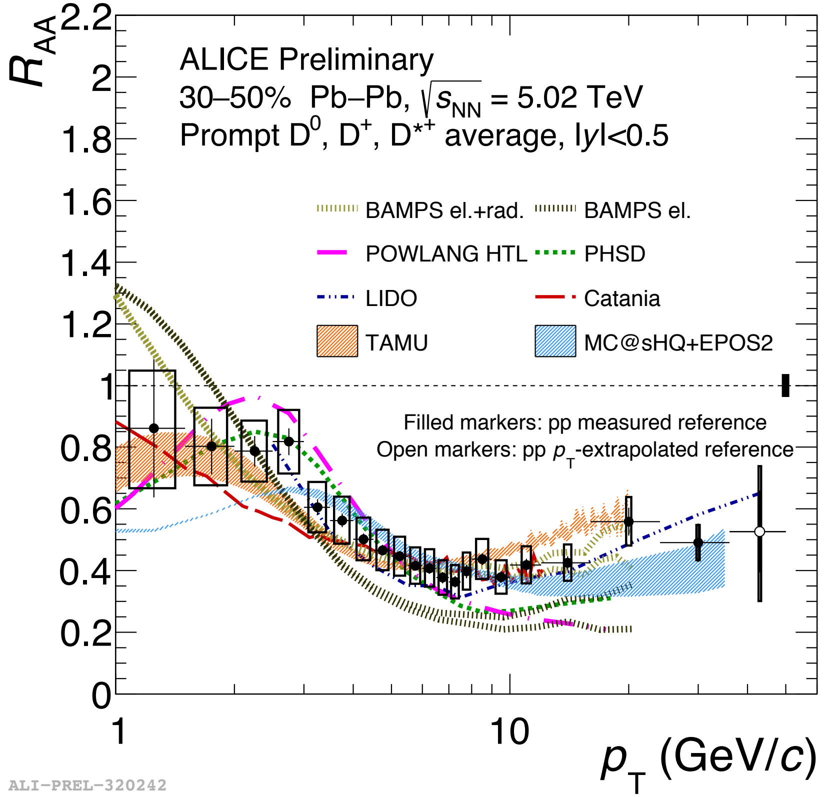
- Σ^0p interaction in high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV
- Σ^0p correlation function is consistent with the ($\Lambda\gamma$)p baseline ((0.2–0.8)σ) → indicating the presence of an overall shallow potential
- Present data cannot discriminate between the different models

HEAVY FLAVOUR

V_2 and R_{AA} of D mesons

- Both R_{AA} and v_2 at low p_T can be fairly well described by the models which employs elastic collisions in expanding hydrodynamic medium; BAMPS elastic, MC@sHQ+EPOS2, TAMU and POWLANG HTL

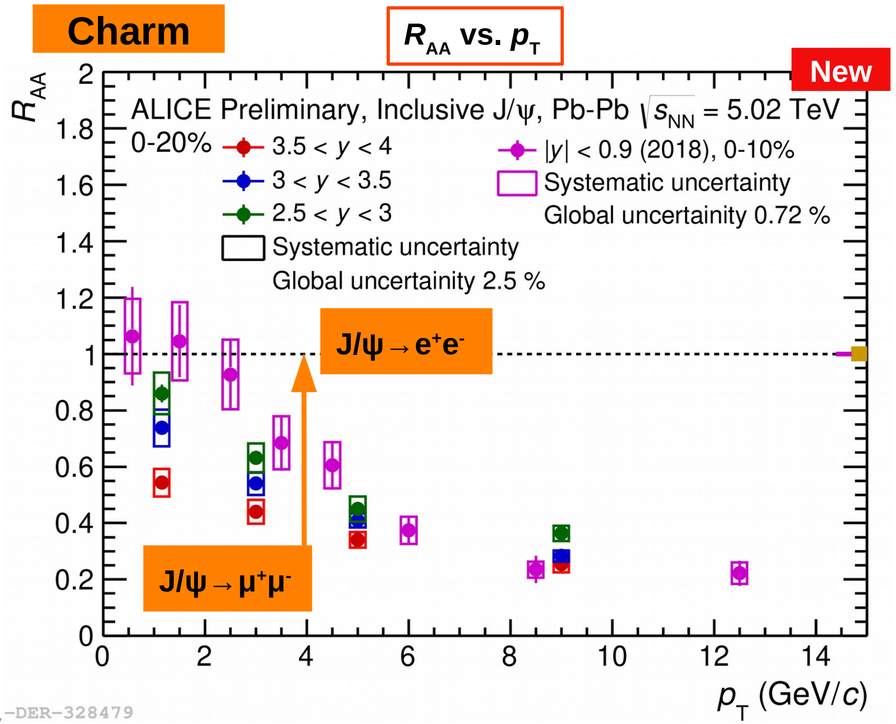


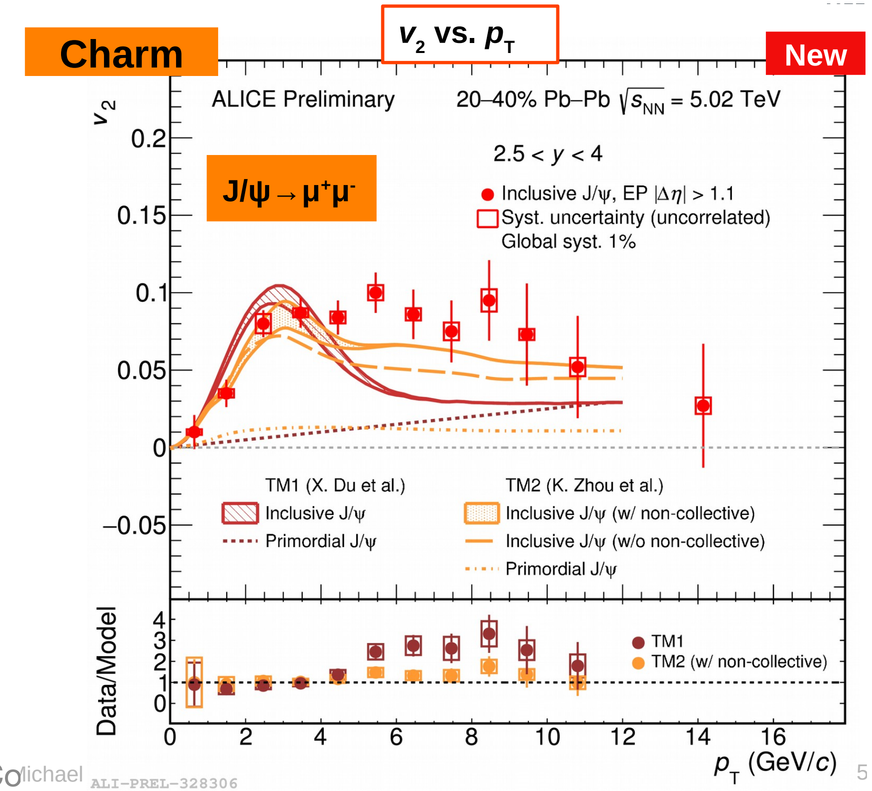


R_{AA} and v_2 of J/ψ

- At low p_T: Large yield at mid-rapidity due to quark coalescence
- At high p_T: R_{AA} gets smaller and rapidity dependence is smaller

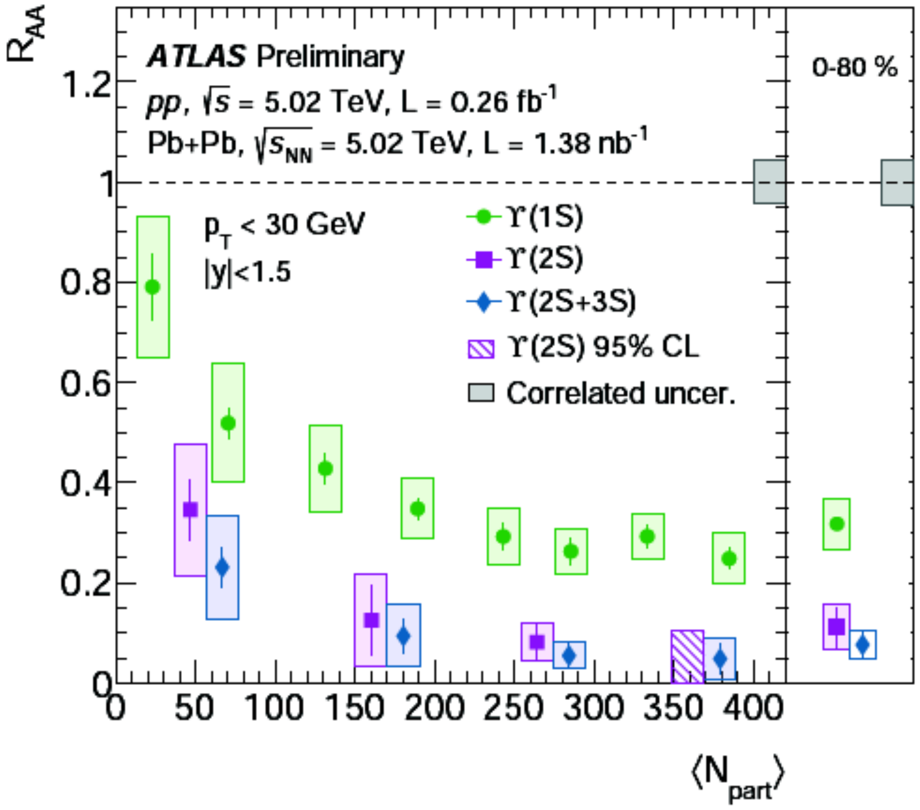
- Large J/ψ v_2 in wide p_T range
- J/ψ inherits elliptic flow of charm quarks
- Additional mechanisms may work for p_T > 4 GeV/c?

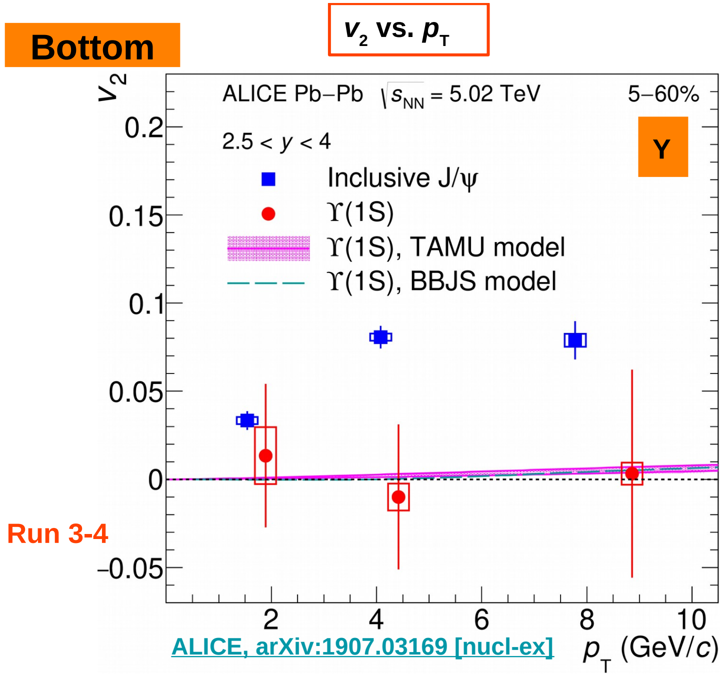




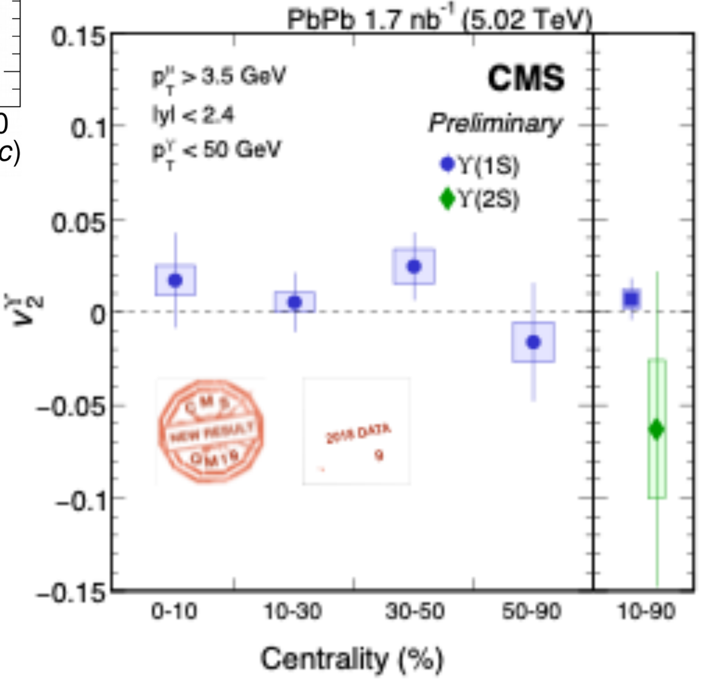
Bottomonium

- R_{AA} as a function of $<N_{part}>$ in Pb+Pb collisions

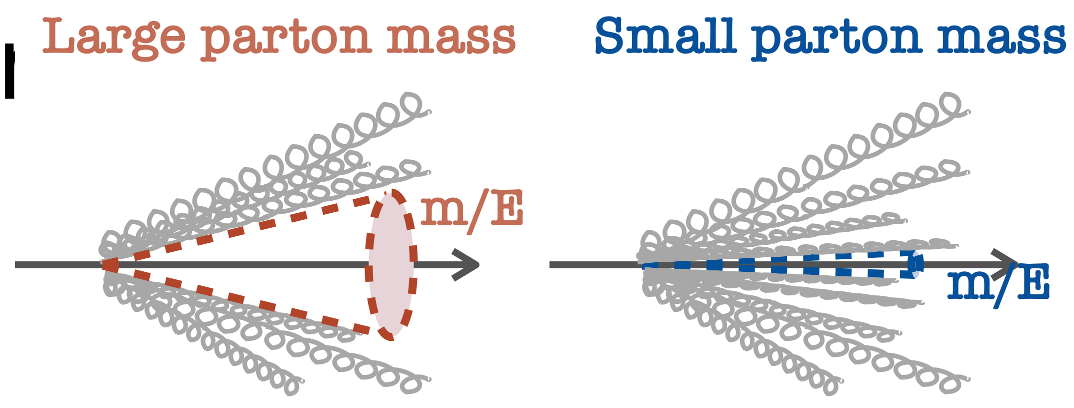




- v_2 of ϒ(1S) in Pb+Pb ~zero

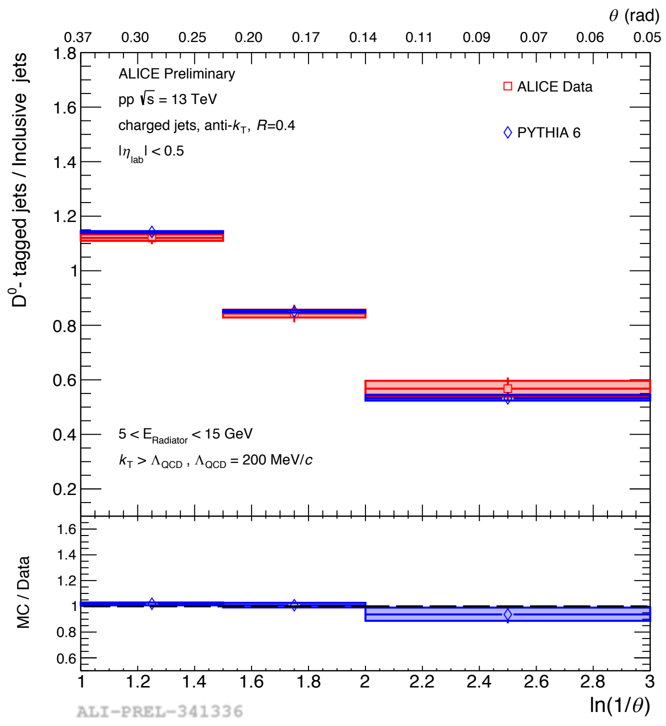


Dead Co

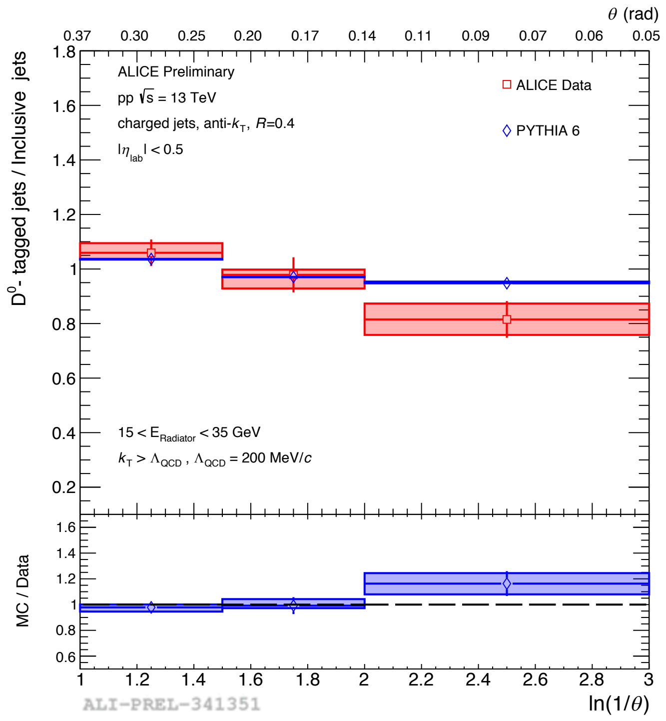


N. Zardoshti , 5 Nov 2019, 09:20

- A universal property of all radiations: Suppression of emissions from a radiator (quark) within $\theta < m_q/E_q$
  - Gluons radiated with a small k_T are suppressed
- Jet reclustering techniques allow for an accurate reconstruction of splitting kinematics
- Splitting initiated by charm quarks (via the D^0) is suppressed at small angles compared to inclusive jets



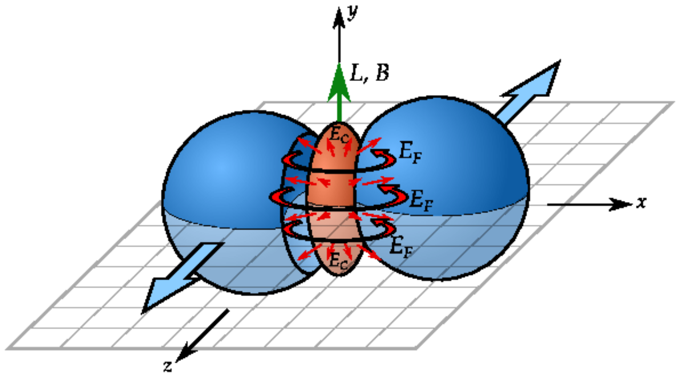
5 < $E_{Radiator}$ < 15 GeV

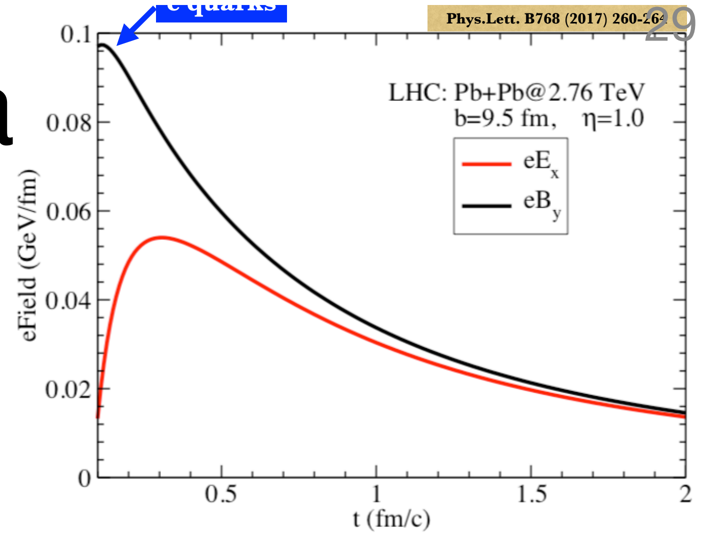


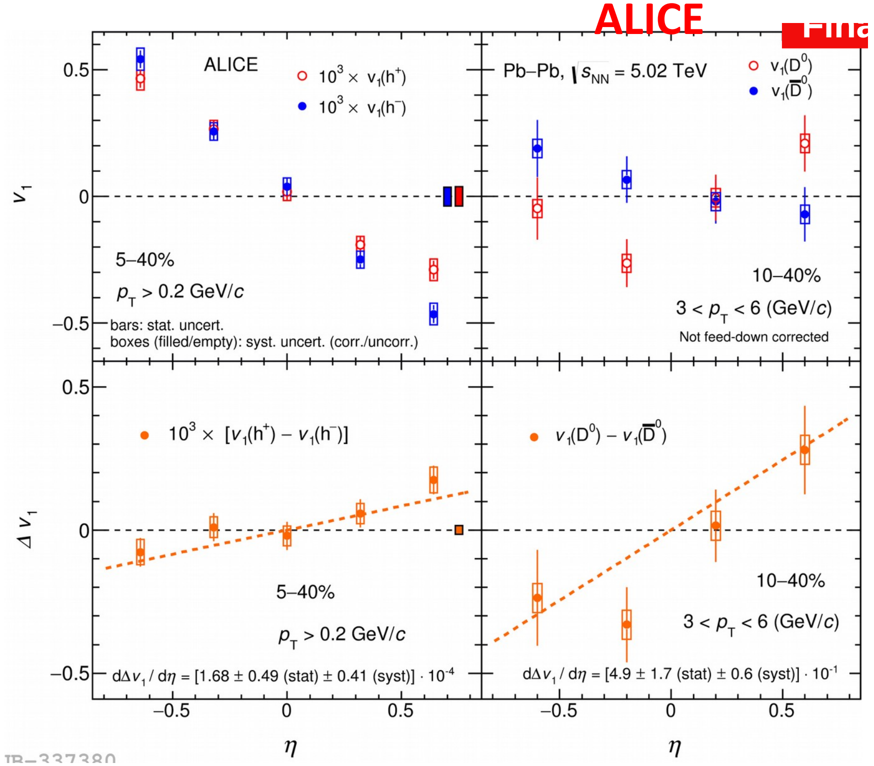
15 < $E_{Radiator}$ < 35 GeV

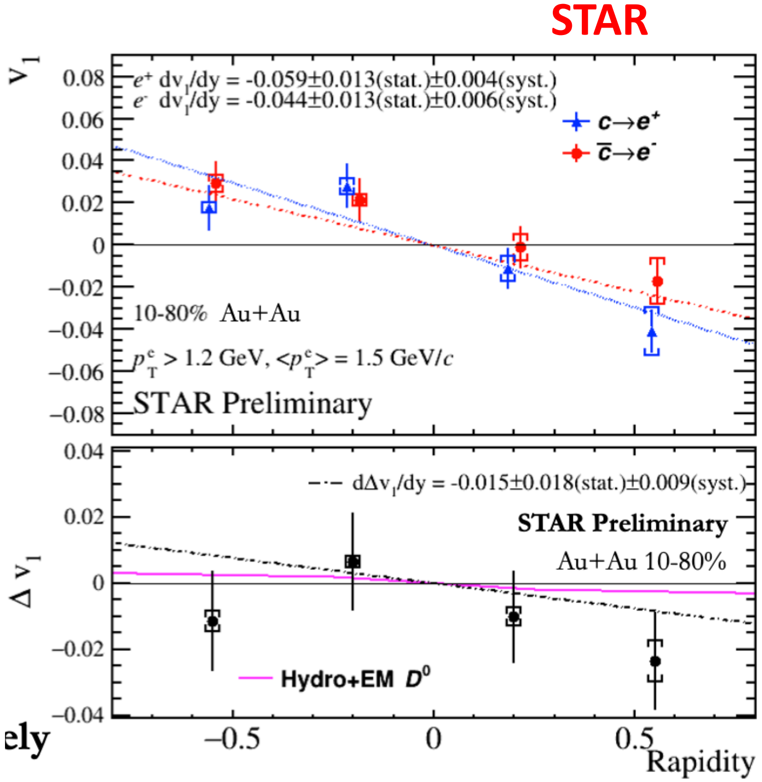
Strong EM Field at Initial Sta

- Strong magnetic field (~10^{18} G) is generated in non-central heavy-ion collisions
- Heavy quarks are suited to detect the EM effect at initial stage
- $d\Delta v1/d\eta$ slope: positive (LHC-ALICE) vs. negative (RHIC-STAR)?



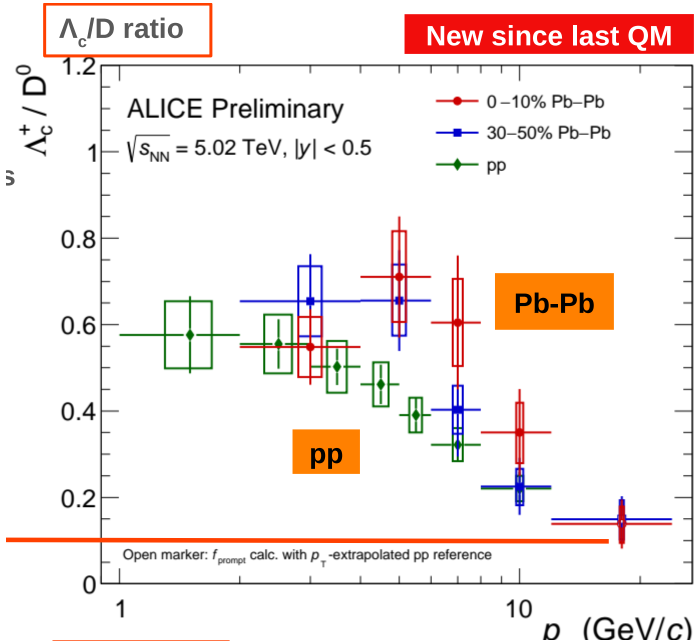


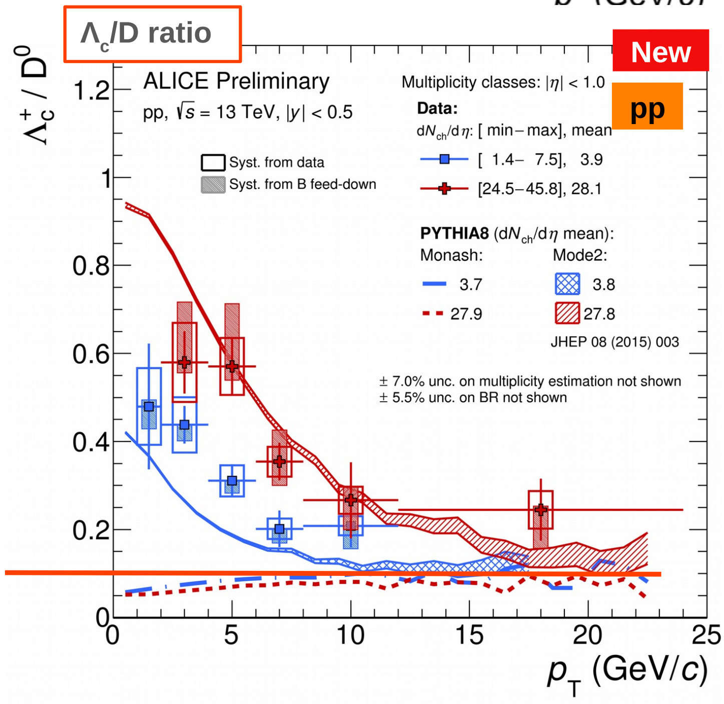




Λ_c/D Ratio in pp and Pb-Pb Collisions

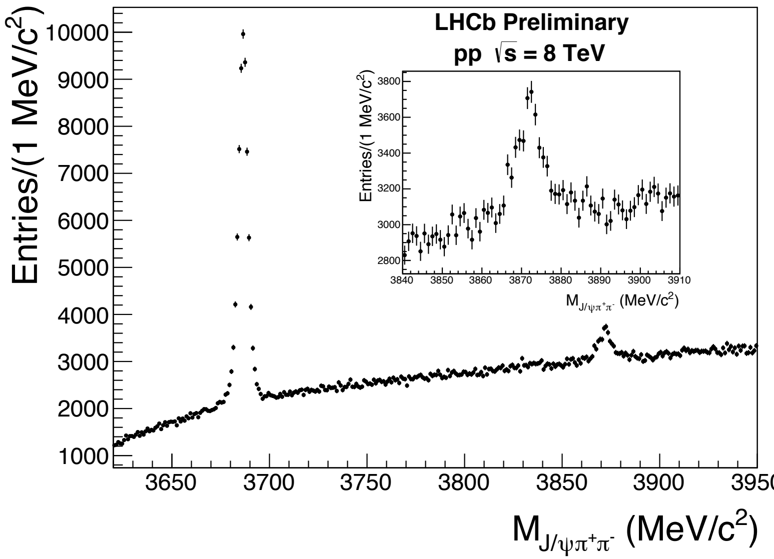
- Sensitive to quark-quark correlation in baryons (and in QGP?)
- Large enhancement in pp and Pb-Pb collisions compared to those in ee and ep collisions
  - We need higher statistics for Pb+Pb collisions
- Multiplicity dependence in pp collisions is compared with Pythia
  - Default Pythia provides the ratio similar to ee and ep data
  - Pythia with color reconnection describe the data (ratio) well, while cross sections are not reproduced



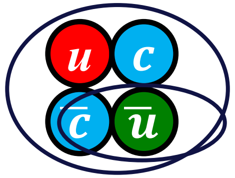


Exotic $c\bar{c}$ States XYZ

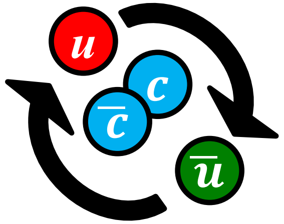
- 20+ new states containing $c\bar{c}$ have been discovered since 2003, which do not fit in the picture of normal charmonium



Compact tetraquark/pentaquark



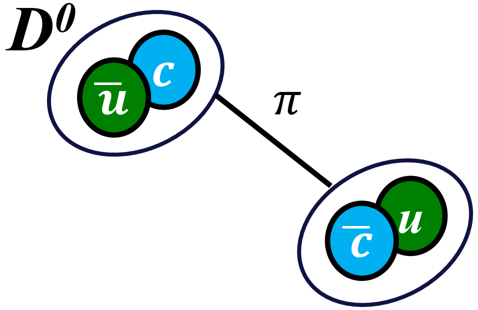
Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

Hadronic Molecules

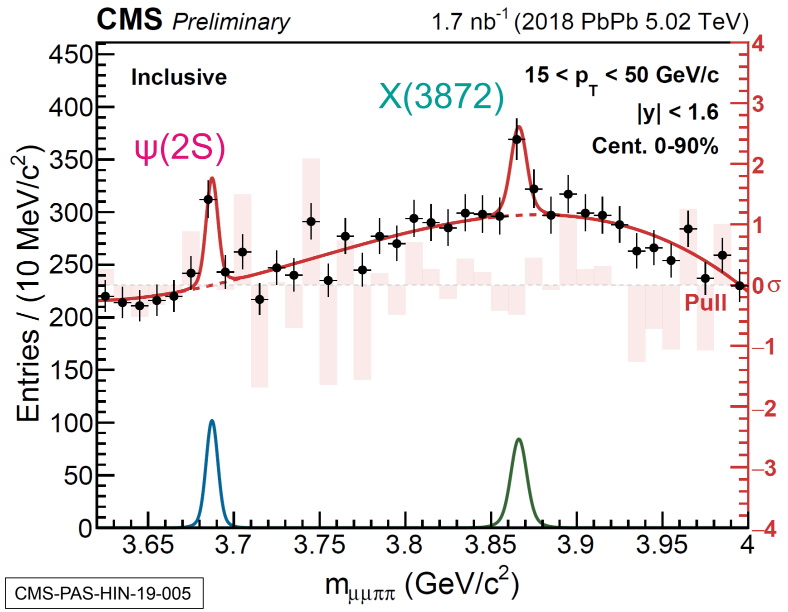
PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)



Mixtures of exotic + conventional states

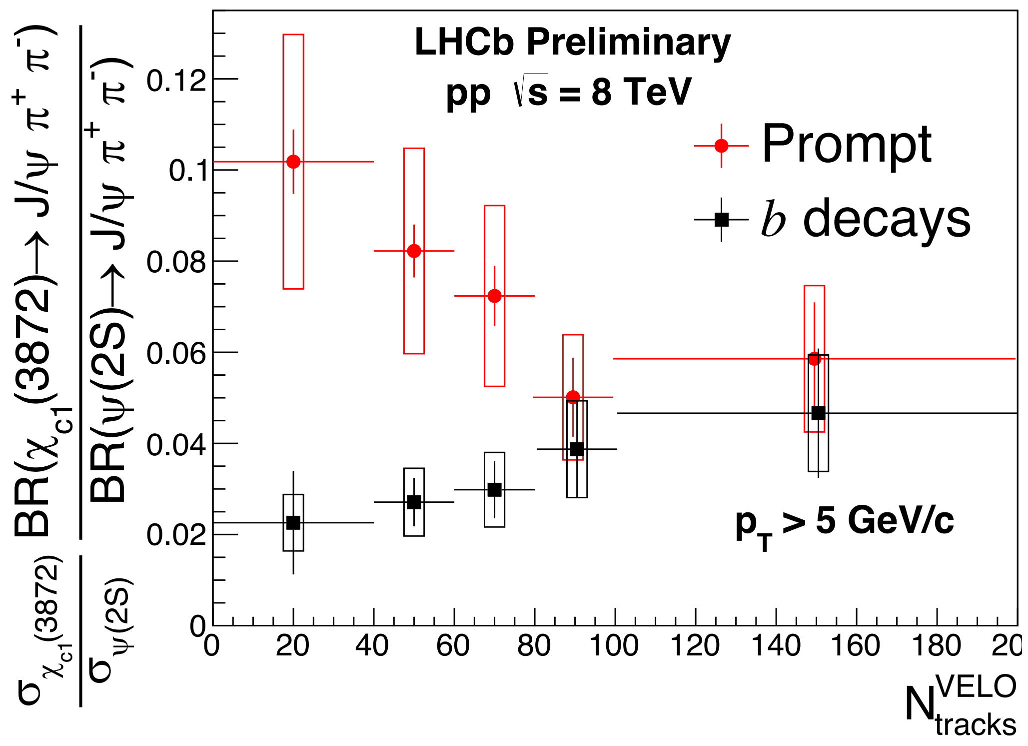
$$X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle$$

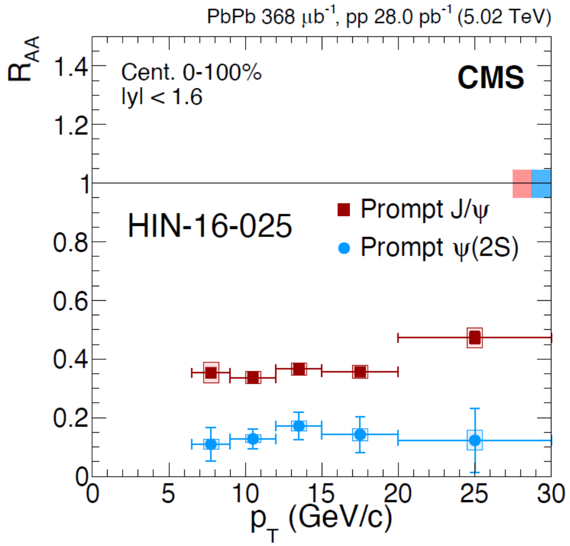
PLB 578 365 (2004)
PRD 96 074014 (2017)

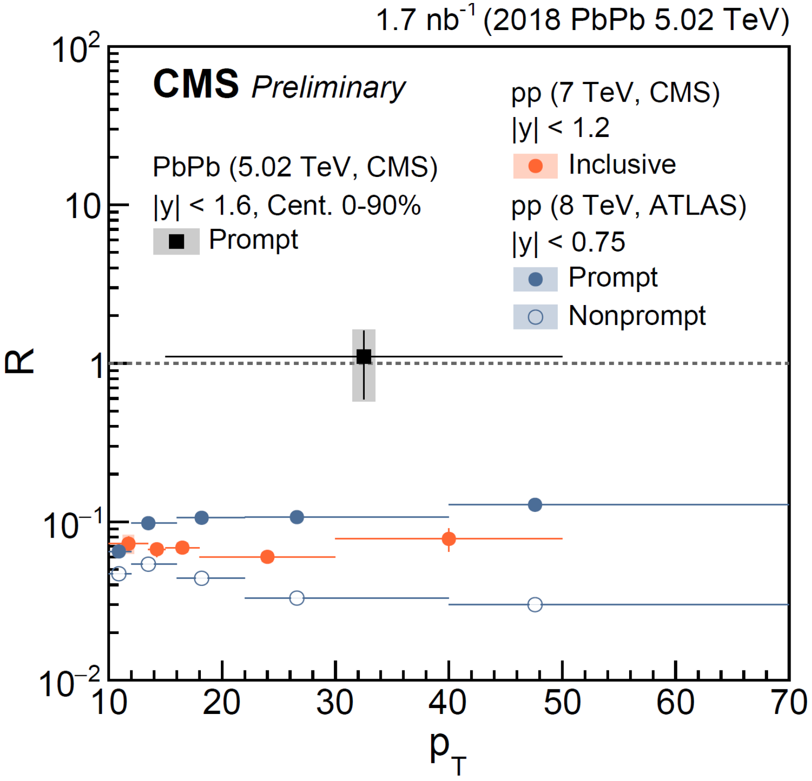


Puzzling X(3872)/$\psi(2S)$ in PbPb

- In pp: Increasing suppression of $X(3872)/\psi(2S)$ with increase of event activity
- In PbPb: the ratio ~ 1
  - $R_{AA}(\psi(2S))$ ~ 0.1 - 0.15 → R_{AA}(X3872) ~ 1 – 1.5 (= not suppressed or even enhanced)
  - Please note that in p_T > 10 GeV/c quark or hadron coalescence is NOT likely a dominant process



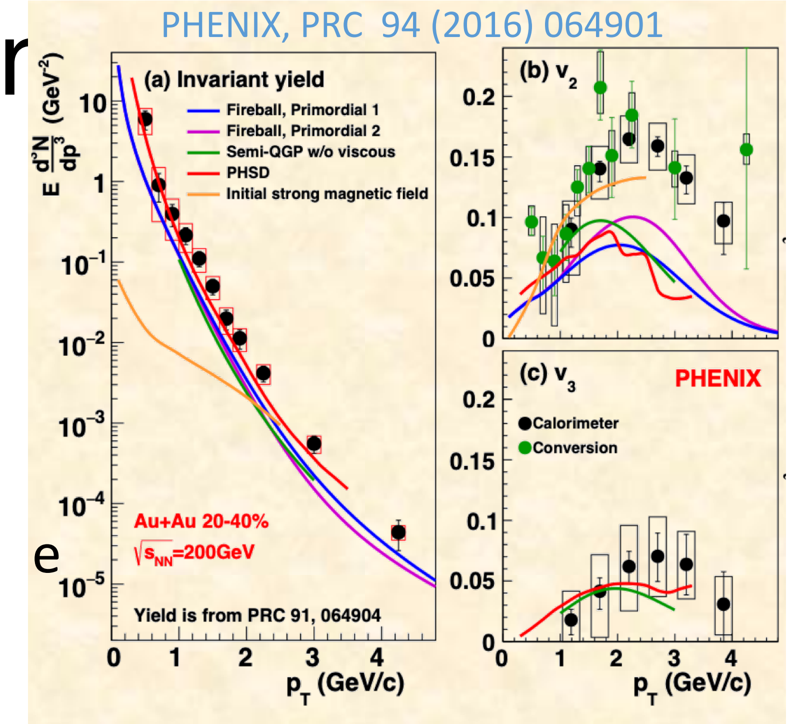


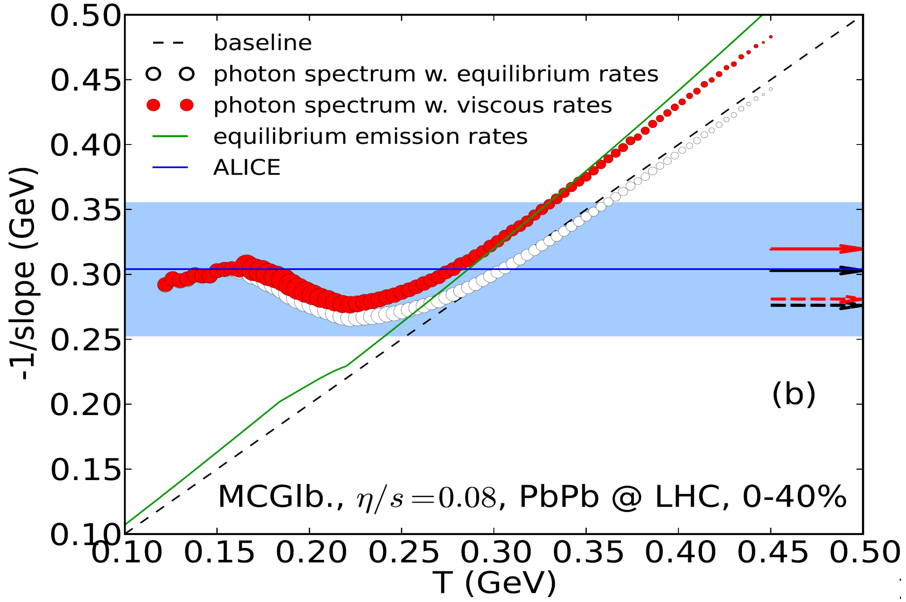


THERMAL PHOTON AND DILEPTON

Soft Direct Photon

- Large yields at low p_T
  - Suggesting emission at early stage
- Large flow
  - Suggesting emission at late stage
- Consensus
  - At RHIC & LHC energies, most photons are emitted from fireball regions with T ≈ Tc
  - large p_T slope = Blue-shifted due to radial flow: $T_{eff} = T\sqrt{\frac{1+v}{1-v}}$
- Quantitatively, still not very successful to reproduce both



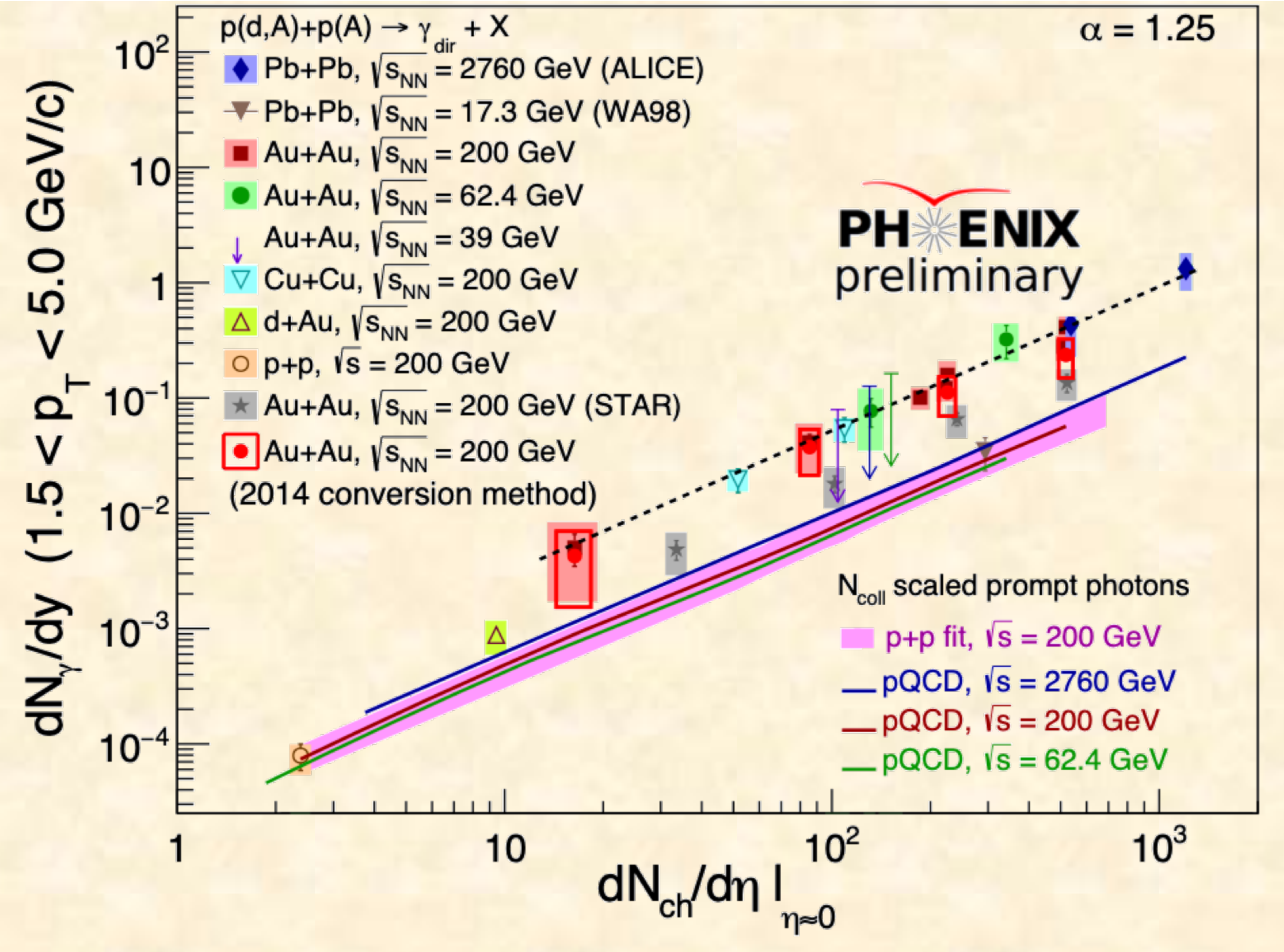


Scaling of Direct Photon Yield

- Scaling with $dN_{ch}/d\eta$

$$\frac{dN_\gamma}{dy} \propto \left(\frac{dN_{ch}}{dh}\right)^\alpha \qquad \text{with } \alpha = 1.25$$

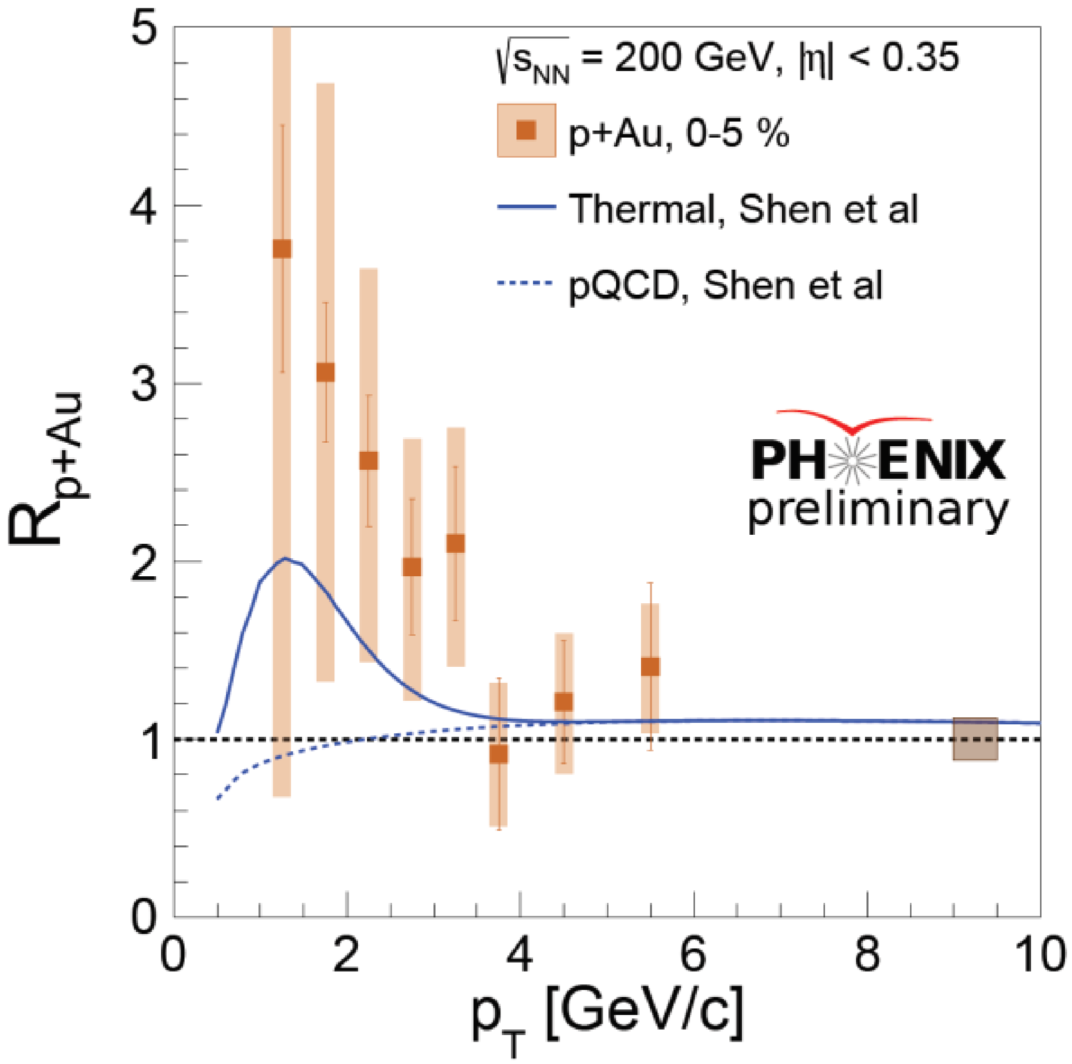
- Irrelevant to the colliding system and colliding energies
- Yields by STAR are significantly lower, although the scaling behavior is similar
- Scaling behavior extended to small system?



Thermal photons in small systems

- Preliminary result by PHENIX
- Enhancement of low p_T photons in central p+Au, although with very low statistics
- Consistent with expected thermal photon production (Chun Shen et al.; PRC 95 014906 (2017))

- Hope
  - High statistics
  - LHC

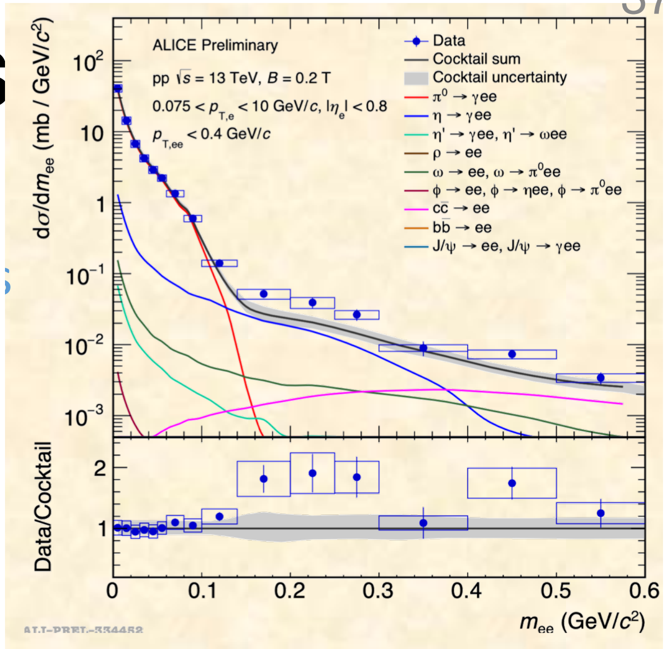


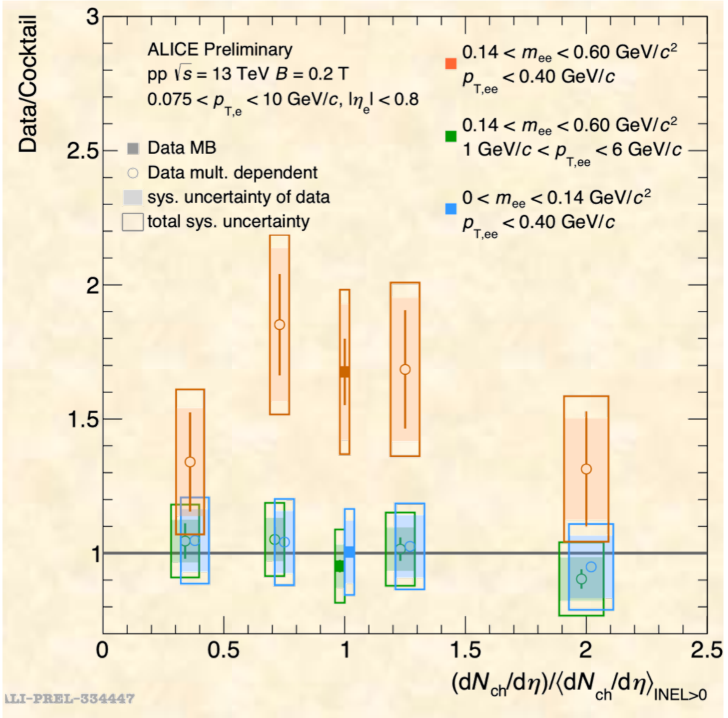
Revival of Soft Dielectrons

- Historical soft dielectrons: Reported first by the Axial Field Spectrometer collaboration at ISR in p+p@63GeV

- ALICE: Low magnetic field run in 13TeV p+p
- Enhancement in the limited mass and pT region
  – $0.14\ \mathrm{GeV}/c^2 < m < 0.60\ \mathrm{GeV}/c^2$ with $p_T < 0.40\ \mathrm{GeV}/c$

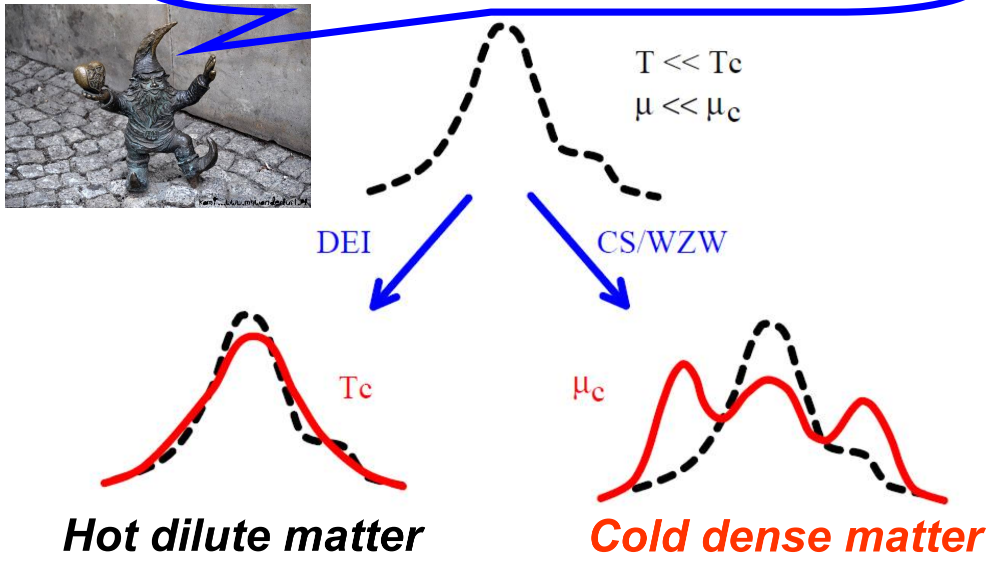
- So far, no explanation for this enhancement





Chiral Mixing

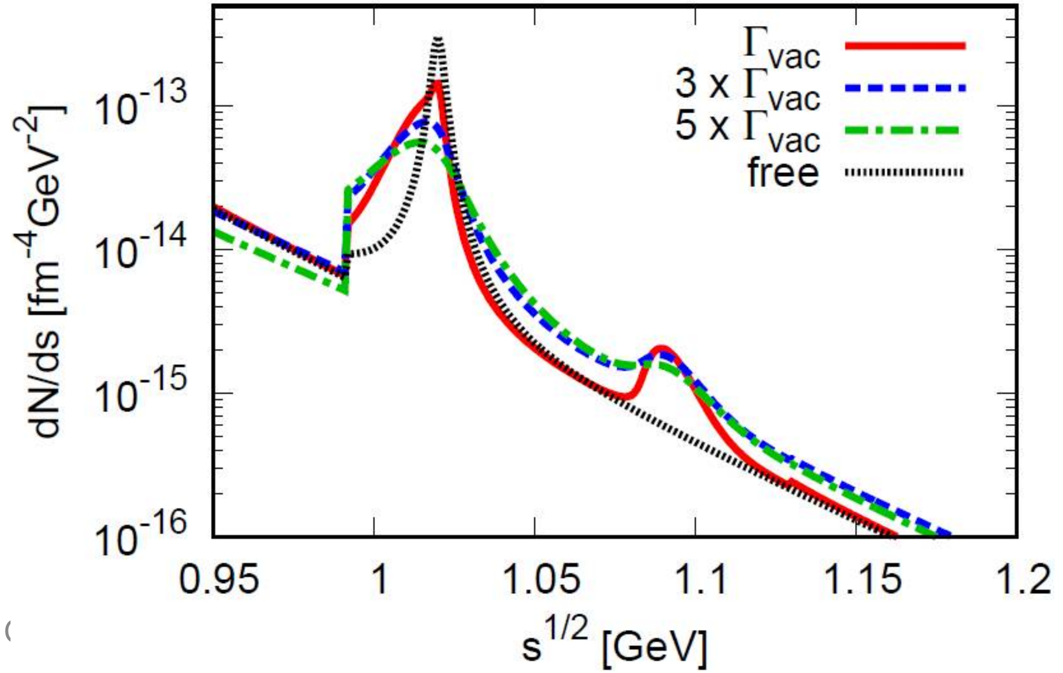
My fingers crossed,
HIAF/FAIR/J-PARC/NICA/RHIC-BES!



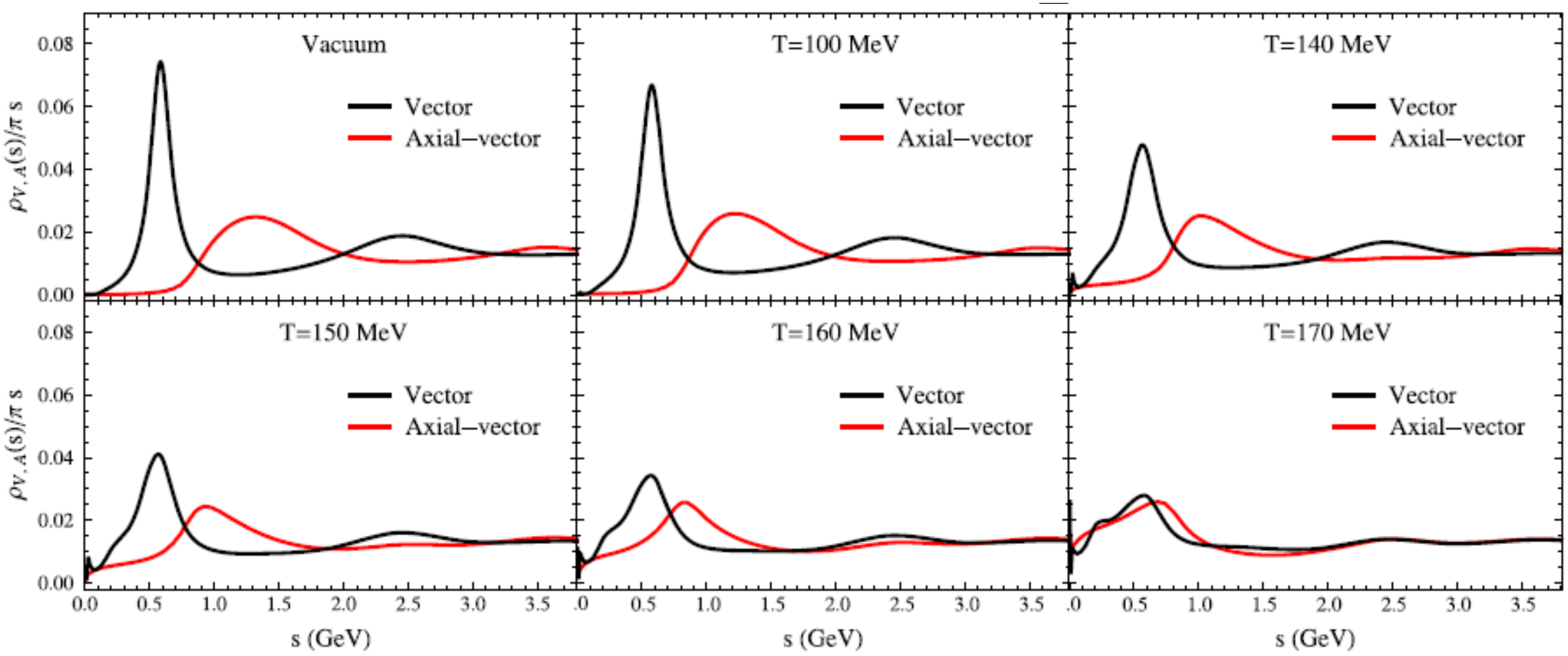
- It is important to measure vector and axial vector partner at the same time
- Difficult to measure axial vector partner → mixing: Axial-vector mesons can show up in vector spectrum in a medium!

<VV> ← chiral mixing → <AA>

- **C. Sasaki's bet:** Baryon dense matter is a better place for this study
- Mixing of ϕ meson and $f_1(1420)$



ρ - a_1 mixing; Temperature Dependence



[Hohler, Rapp ('14,'16)]

- Vector SF & ansatz for a_1 mass and width
- Reduction of a_1 mass, width broadening
- Role of higher-lying states: ρ', a1', ...

SUMMARY AND OUTLOOK

Outlook

Dibaryons:

- Good chance to discover $\Lambda\Lambda$ and Ωp, hopefully from the available dataset
- Even if not found, we will have much higher statistics in the coming RUN 3
- Reach $\Omega\Omega$, which is predicted to be a bound state by HAL-QCD.

Heavy Flavor (charm & bottom)

- Heavy baryon yield and Baryon/Meson ratio -- di-quark condensation
- Two particle correlations; D-D、Λ_c-D、Λ_c-N,,,
- XYZ, …

Thermal Photons and Lepton Pairs

- Understanding yield and azimuthal asymmetry of direct photon
- Chiral mixing using lepton pair measurements