Study of Hadron Interactions and Exotic Hadrons in the ALICE Experiment at CERN LHC

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INTRODUCTION

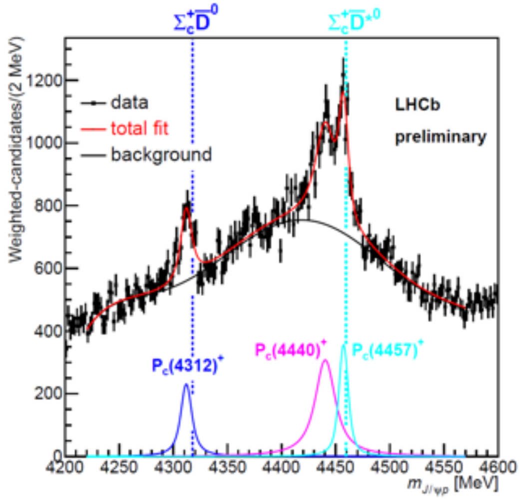
Exotica

- Having configuration different from baryon (qqq) & meson ($q\bar{q}$)
  - No intrinsic reason why only baryons and mesons are the stable configuration

Particle	m (MeV)	g	I	J^P	$2q/3q/6q$	$4q/5q/8q$	Mol.	$\omega_{\mathrm{Mol.}}$ (MeV)	Decay mode
Mesons									
$f_0(980)$	980	1	0	0^+	$q\bar{q}, s\bar{s}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$	67.8(B)	$\pi\pi$ (Strong decay)
$a_0(980)$	980	3	1	0^+	$q\bar{q}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$	67.8(B)	$\eta\pi$ (Strong decay)
$K(1460)$	1460	2	1/2	0^-	$q\bar{s}$	$q\bar{q}q\bar{s}$	$\bar{K}KK$	69.0(R)	$K\pi\pi$ (Strong decay)
$D_s(2317)$	2317	1	0	0^+	$c\bar{s}(L=1)$	$q\bar{q}c\bar{s}$	DK	273(B)	$D_s\pi$ (Strong decay)
T_{cc}^{1}[a]	3797	3	0	1^+	—	$qq\bar{c}\bar{c}$	$\bar{D}\bar{D}^*$	476(B)	$K^+\pi^- + K^+\pi^- + \pi^-$
$X(3872)$	3872	3	0	$1^+, 2^-$[c]	$c\bar{c}(L=2)$	$q\bar{q}c\bar{c}$	$\bar{D}D^*$	3.6(B)	$J/\psi\pi\pi$ (Strong decay)
$Z^+(4430)$[b]	4430	3	1	0^-[c]	—	$q\bar{q}c\bar{c}(L=1)$	$D_1\bar{D}^*$	13.5(B)	$J/\psi\pi$ (Strong decay)
T_{cb}^{0}[a]	7123	1	0	0^+	—	$qq\bar{c}\bar{b}$	$\bar{D}B$	128(B)	$K^+\pi^- + K^+\pi^-$
Baryons									
$\Lambda(1405)$	1405	2	0	$1/2^-$	$qqs(L=1)$	$qqqs\bar{q}$	$\bar{K}N$	20.5(R)–174(B)	$\pi\Sigma$ (Strong decay)
$\Theta^+(1530)$[b]	1530	2	0	$1/2^+$[c]	—	$qqqq\bar{s}(L=1)$	—	—	KN (Strong decay)
$\bar{K}KN$[a]	1920	4	1/2	$1/2^+$	—	$qqqs\bar{s}(L=1)$	$\bar{K}KN$	42(R)	$K\pi\Sigma, \pi\eta N$ (Strong decay)
$\bar{D}N$[a]	2790	2	0	$1/2^-$	—	$qqqq\bar{c}$	$\bar{D}N$	6.48(R)	$K^+\pi^-\pi^- + p$
$\bar{D}^*N$[a]	2919	4	0	$3/2^-$	—	$qqqq\bar{c}(L=2)$	$\bar{D}^*N$	6.48(R)	$\bar{D} + N$ (Strong decay)
Θ_{cs}[a]	2980	4	1/2	$1/2^+$	—	$qqqs\bar{c}(L=1)$	—	—	$\Lambda + K^+\pi^-$
BN[a]	6200	2	0	$1/2^-$	—	$qqqq\bar{b}$	BN	25.4(R)	$K^+\pi^-\pi^- + \pi^+ + p$
B^*N[a]	6226	4	0	$3/2^-$	—	$qqqq\bar{b}(L=2)$	B^*N	25.4(R)	$B + N$ (Strong decay)
Dibaryons									
H[a]	2245	1	0	0^+	$qqqqss$	—	ΞN	73.2(B)	$\Lambda\Lambda$ (Strong decay)
$\bar{K}NN$[b]	2352	2	1/2	0^-[c]	$qqqqqs(L=1)$	$qqqqqq\,s\bar{q}$	$\bar{K}NN$	20.5(T)–174(T)	ΛN (Strong decay)
$\Omega\Omega$[a]	3228	1	0	0^+	$ssssss$	—	$\Omega\Omega$	98.8(R)	$\Lambda K^- + \Lambda K^-$
H_c^{++}[a]	3377	3	1	0^+	$qqqqsc$	—	$\Xi_c N$	187(B)	$\Lambda K^-\pi^+\pi^+ + p$
$\bar{D}NN$[a]	3734	2	1/2	0^-	—	$qqqqqq\,q\bar{c}$	$\bar{D}NN$	6.48(T)	$K^+\pi^- + d, K^+\pi^-\pi^- + p + p$
BNN[a]	7147	2	1/2	0^-	—	$qqqqqq\,q\bar{b}$	BNN	25.4(T)	$K^+\pi^- + d, K^+\pi^- + p + p$

ExHIC collaboration;
PRC 84 (2011) 064910

Studies at LHC (I)



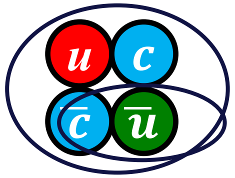
LHCb

- Z(4430)$^-$ ($c\bar{c}d\bar{u}$)
  - Confirmation of the result by Belle (Phys. Rev. D 92, 112009 (2015))
- Pentaquarks ($duuc\bar{c}$)
  - Recent analysis → three states; Pc+(4312), Pc+(4440), Pc+(4457)
  - Interpretations; tightly bound pentaquark state to loosely bound molecular baryon-meson state.
- χ_{c1}(3872) ($c\bar{c}u\bar{u}$)
  - X(3872): found in 2003 by Belle
  - hadronic molecules?
  - decay channel: J/$\psi\pi^+\pi$ (same as ψ(2S))

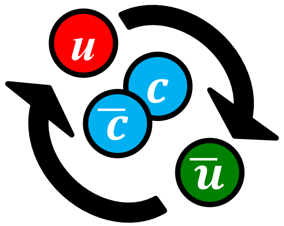
CMS

- χ_{c1}(3872) ($c\bar{c}u\bar{u}$) in Pb+Pb

Compact tetraquark/pentaquark

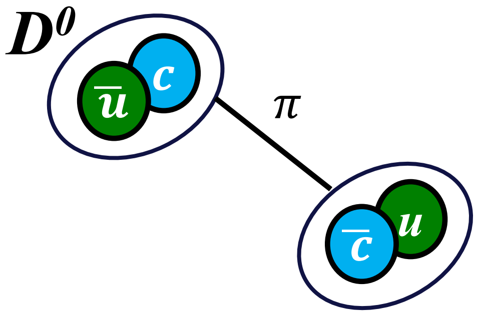


Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



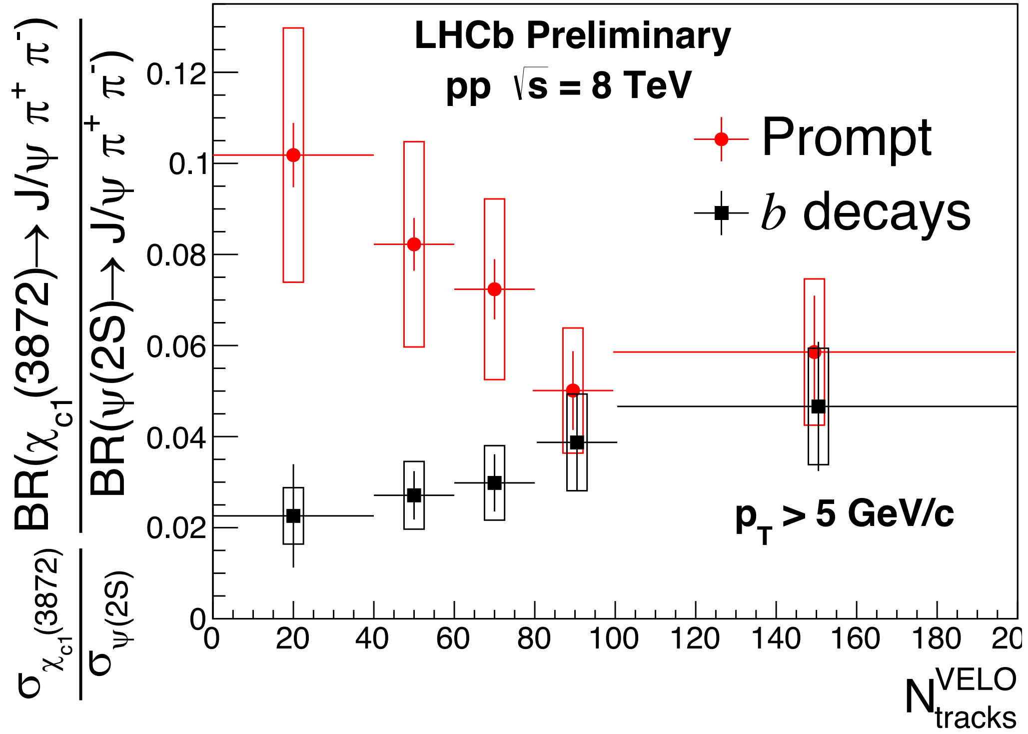
Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

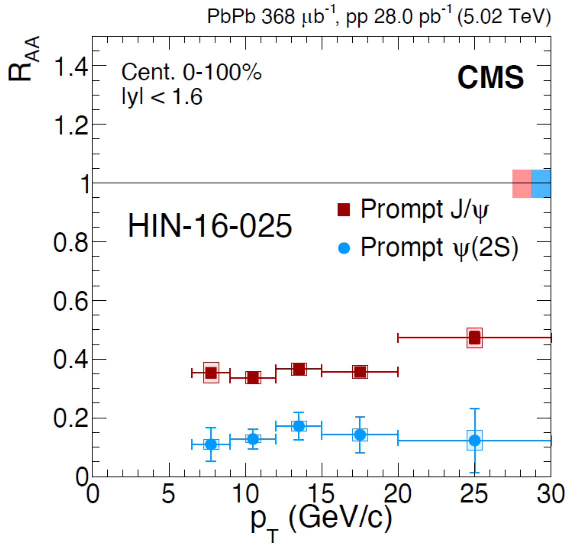
Hadronic Molecules
PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)

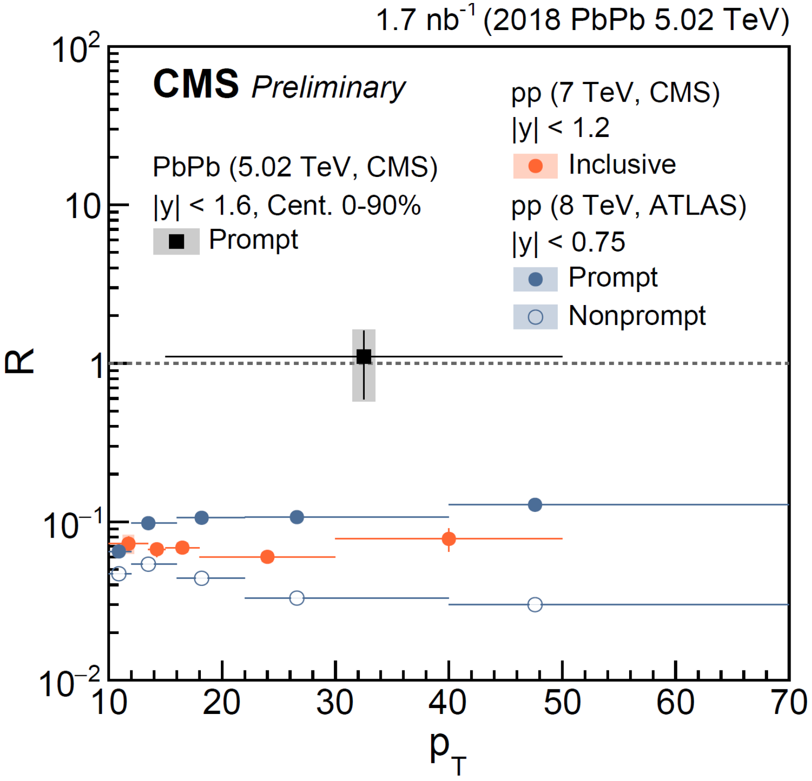


Puzzling X(3872)/$\psi(2S)$ in PbPb

- In pp: Increasing suppression of $X(3872)/\psi(2S)$ ratio with increase of event activity
- In PbPb: The $X(3872)/\psi(2S)$ yield 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







Studies at LHC (II)

ALICE

- Light (anti-)Nuclei
  - d, t, ^{3}He, ^{4}He
- Hypernuclei
  - $^3_\Lambda$H
- Baryon interaction & dibaryon search
  - p-Λ, Λ-Λ, p-Σ, p-Ξ, p-Ω

ALICE Upgrade during LS2

- Currently, LHC has been off for 2 years; long shutdown 2 (LS2)
  - 50 kHz minimum-bias Pb+Pb collisions
- ALICE has been doing significant upgrade of the detector and data taking system, to make it possible to record all 50 kHz minimum-bias Pb+Pb collision data at Run3
- When realized, extensive studies of (exotic) hadrons, baryon interactions and di-baryon search will become possible in the ALICE experiment

LIGHT NUCLEI AND HYPERNUCLEI

Hadron Production in Pb+Pb at LHC

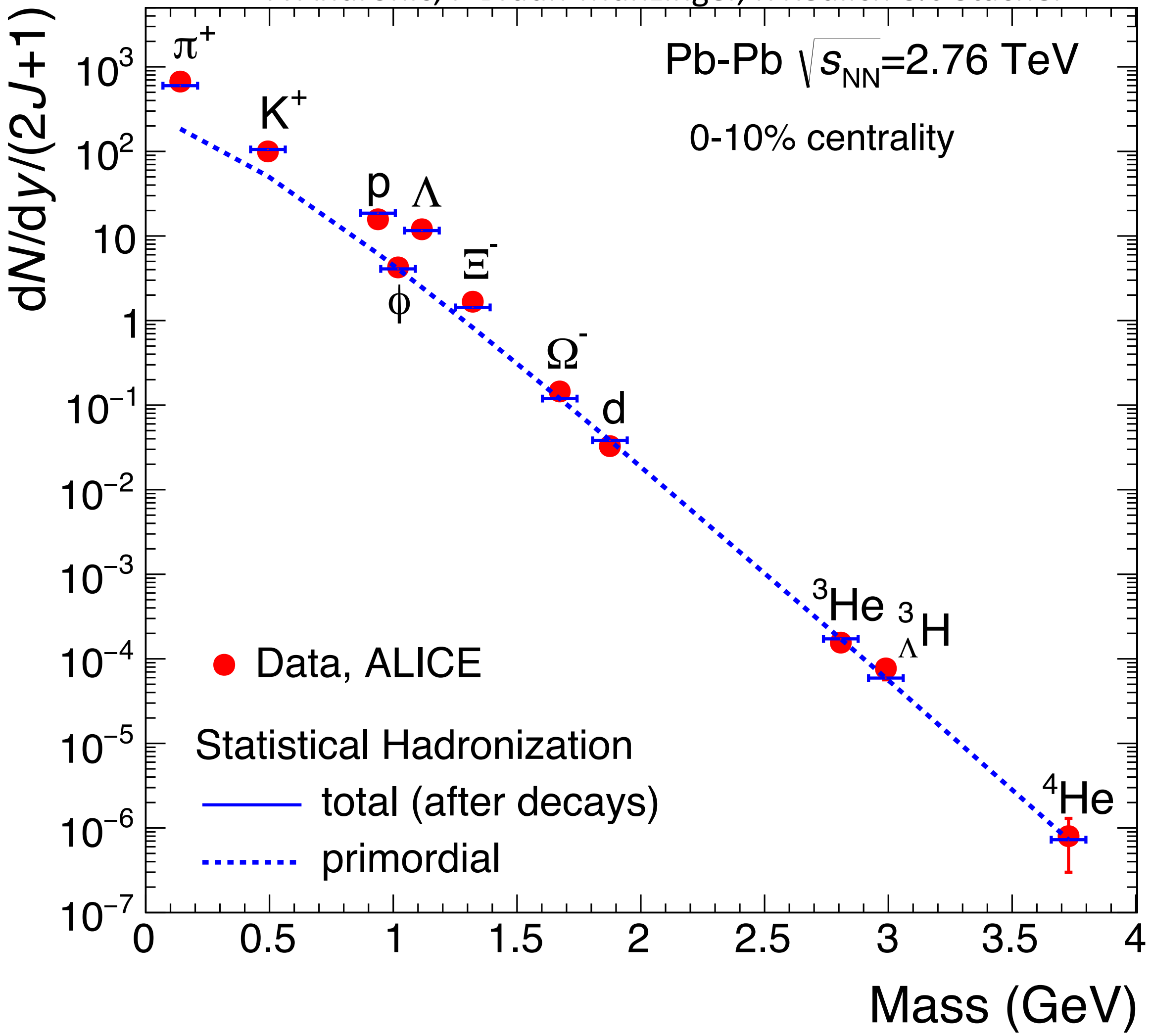
Yields are described rather well with the statistical hadronization (thermal) model,

- Chemical freeze-out temperature, T_{CF} ~ 155 MeV, for $\sqrt{s_{NN}}$ = 2.76 TeV Pb+Pb

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

- Blast-Wave fit (with T_F = 100 – 115 MeV) describe simultaneously the momentum spectra of π, K, p,Λ, Ξ, Ω, d, ^{3}He, $^3_\Lambda$H, and ^{4}He in central Pb+Pb collisions
- It is not obvious why the light nuclei and $^3_\Lambda$H follows the trend of hadron yield

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



Chemical Freezeout Hypothesis

- Hadron yields are fixed at a certain time in the space-time evolution of heavy ion collisions (chemical freezeout = end of inelastic scattering)
  - thermalized system complying hadrons with u, d, s quarks
  - hadron yields are determined with the few global parameters

$$\rho_i = \gamma_s^{|s_i|} \frac{g_i}{2\pi^2} T_{ch}^{\ 3} \left(\frac{m_i}{T_{ch}}\right)^2 K_2(m_i/T_{ch})\ \lambda_q^{\ Q_i}\ \lambda_s^{\ s_i} \qquad \begin{aligned}\lambda_q &= \exp(\mu_q/T_{ch}),\\ \lambda_s &= \exp(\mu_s/T_{ch})\end{aligned}$$

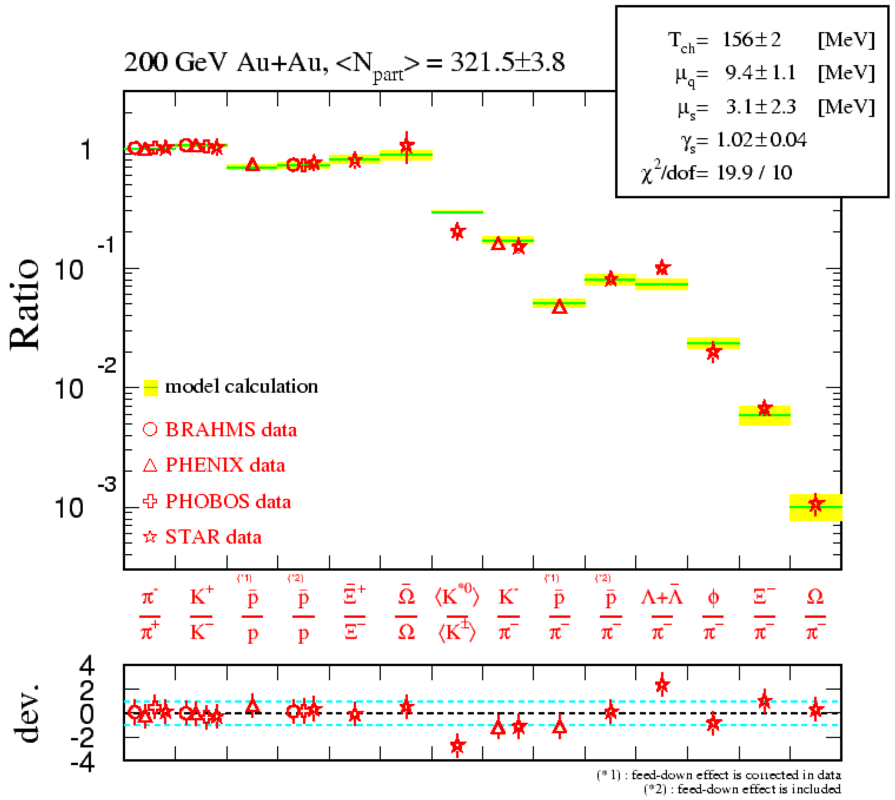
Q_i : 1 for u and d, -1 for u and d
s_i : 1 for s, -1 for s
g_i : spin-isospin freedom
m_i : particle mass

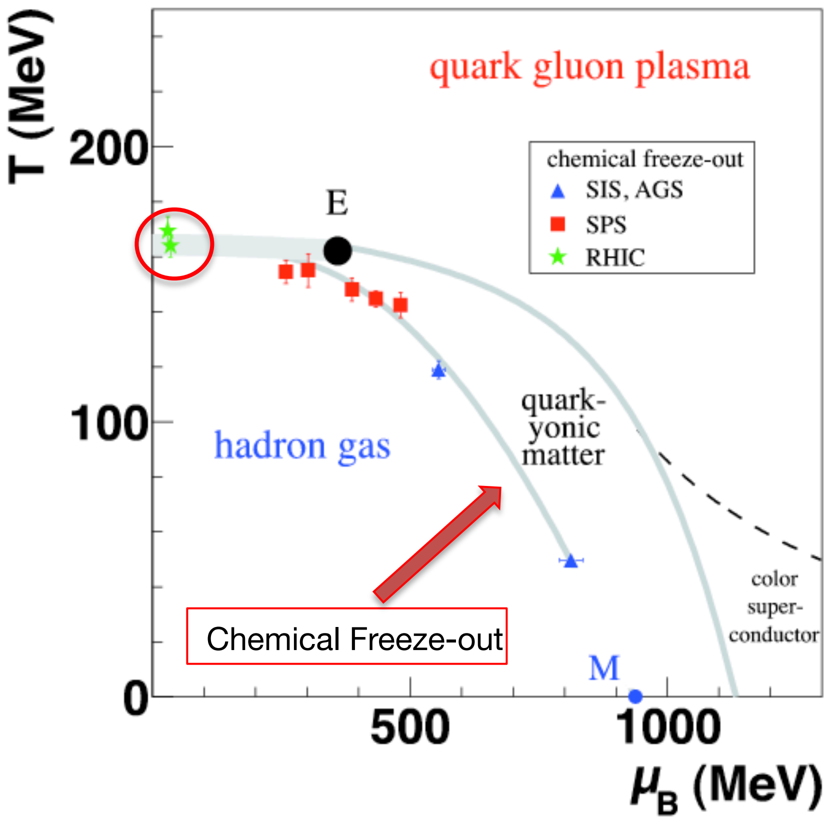
global parameters
T_{ch} : chemical freeze-out temperature
μ_q : light-quark chemical potential
μ_s : strangeness chemical potential
γ_s : strangeness saturation factor

Hadron Yields → Determine Temperature (T_{cf}) and Chemical Potential (μ_{cf}) at Chemical Freezeout

Hadron Yields and Chemical Freezeout

- Hypothesis of "Chemical Freezeout" works reasonably well to describe hadron yields for nuclear collisions in wide colliding energies.
- This property can be utilized to predict yield of specific particles

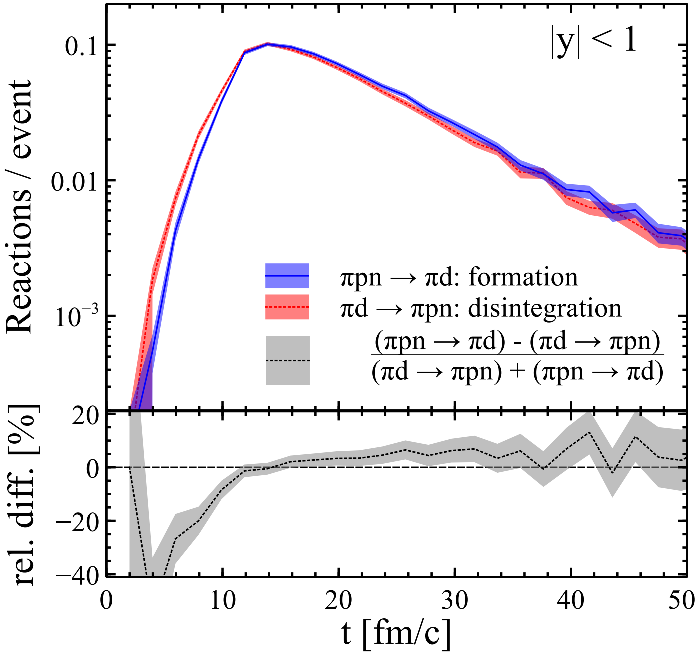


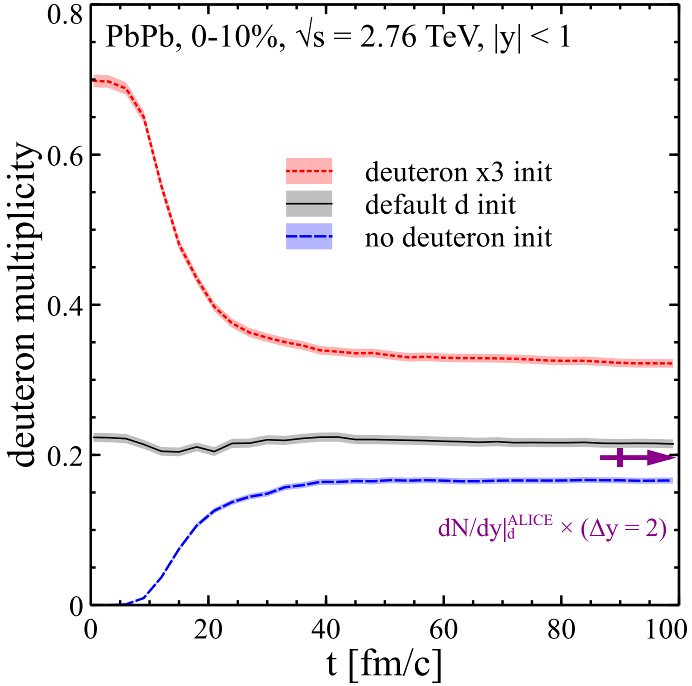


Why Thermal Model works for light nuclei yields?

- Theoretical works:
  - Xu, Rapp, Eur. Phys. J. A55 (2019) no.5, 68
  - Vovchenko et al, arXiv:1903.10024
  - Oliinychenko, Pang, Elfner, Koch, PRC 99 (2019) 044907
- An isentropic expansion of a hadron resonance gas (HRG) in partial chemical equilibrium (PCE) at $T < T_{ch}$
  - Mesons play a similar role as the photons during the evolution of the early universe – they drive the entropy conservation during the expansion.
  - Nuclei are kept in partial (relative) equilibrium as long as the cross sections are large from CF stage to KF stage
- *Small entropy production between T_{ch} to T_{KF} ?*

DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907

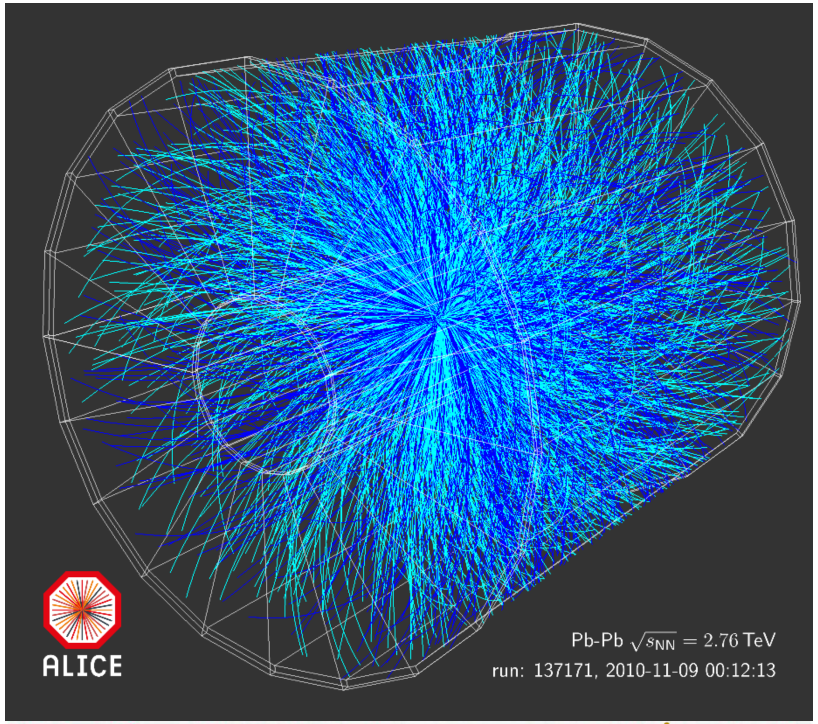


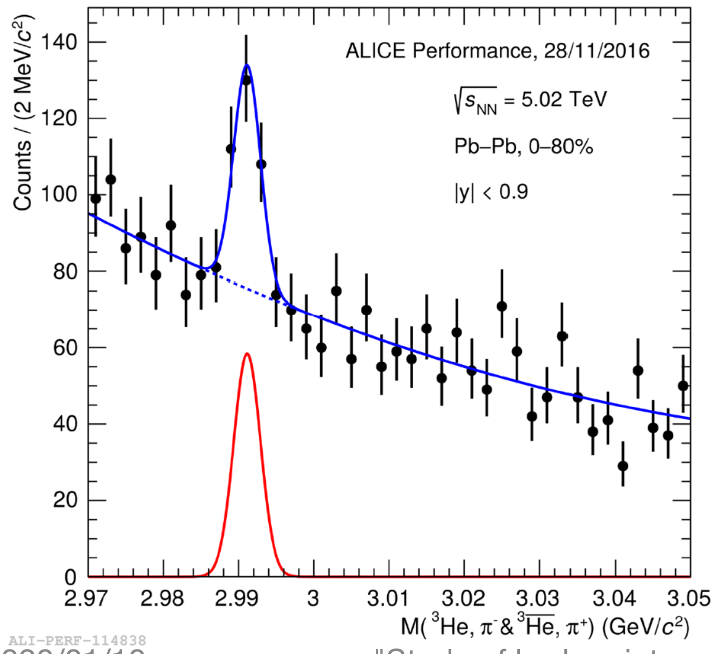


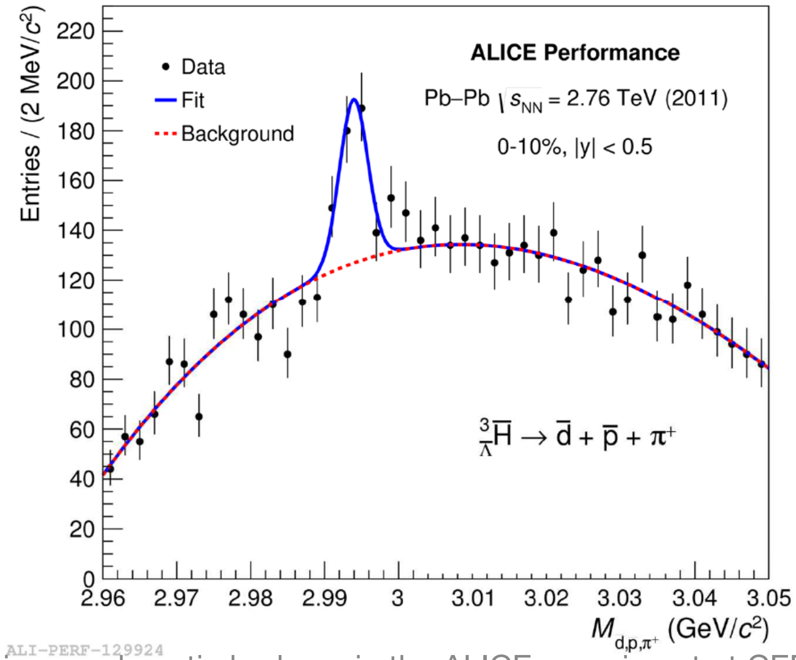
Hypertriton (and anti-hypertriton)

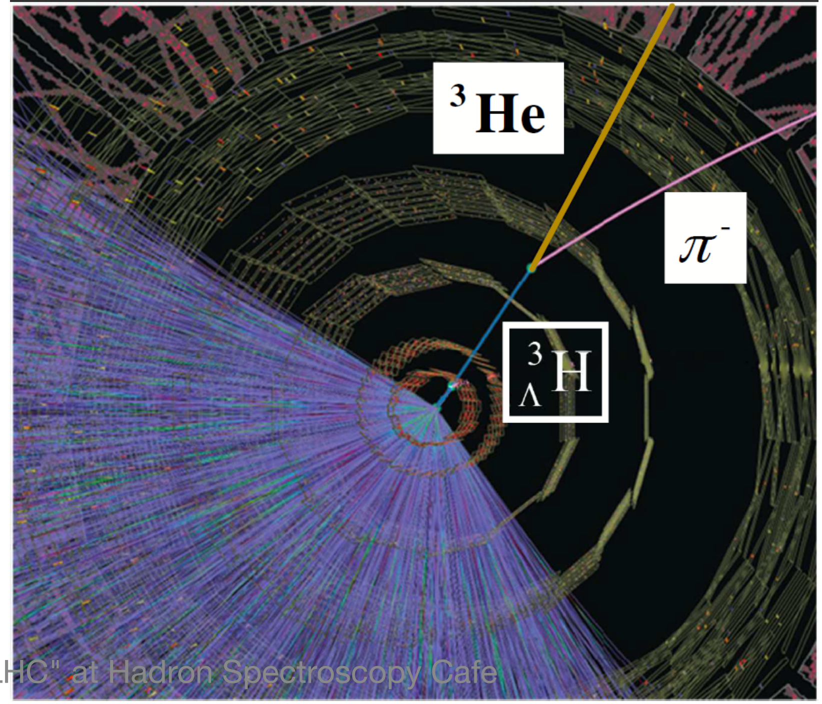
- Weakly bound state of Λ, p and n, with m = 2.991 GeV/c^2 and B_Λ = 130 keV; with rms-radius = 10.6 fm
  - $^3_\Lambda H \rightarrow {}^3He + \pi^-$ … 25% B.R.
  - $^3_\Lambda H \rightarrow {}^3H + \pi^0$
  - $^3_\Lambda H \rightarrow d + p + \pi^-$
  - $^3_\Lambda H \rightarrow d + n + \pi^0$

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





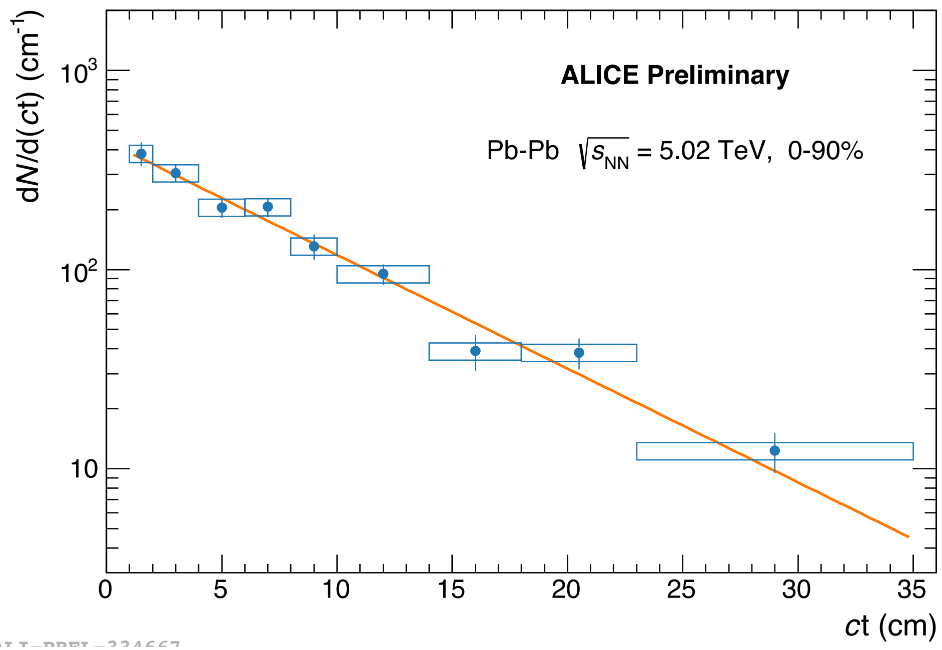


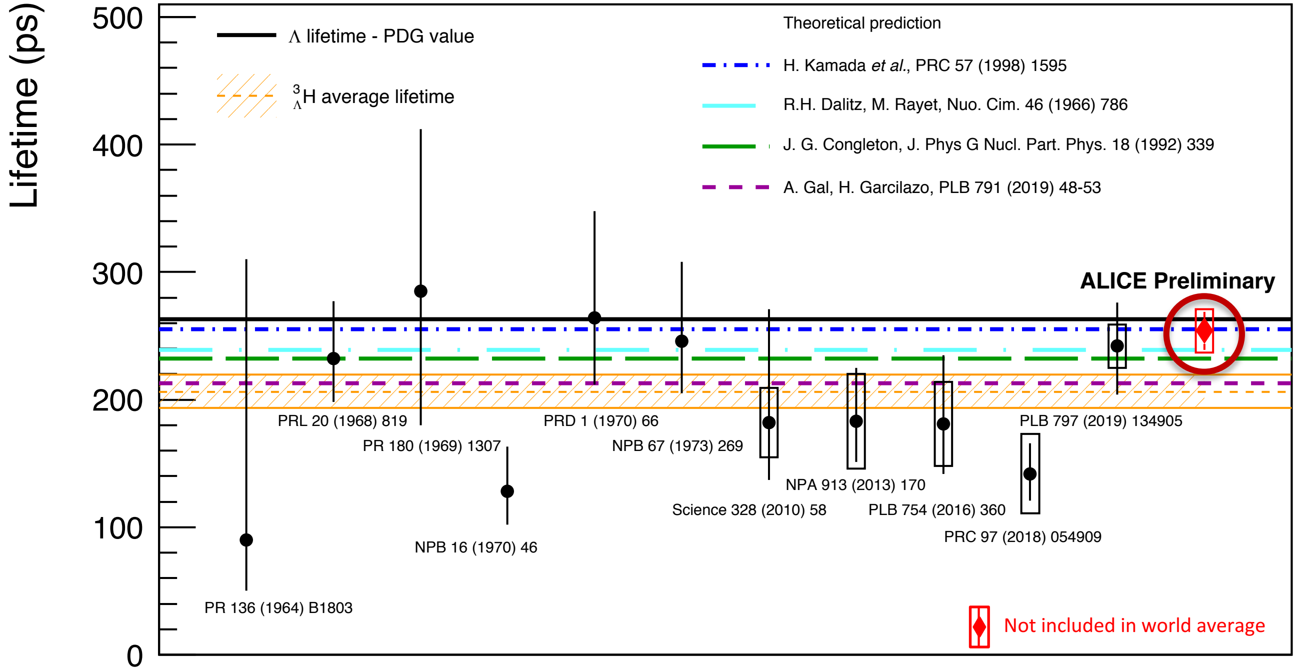


Lifetime of Hypertriton $^{3}_{\Lambda}H$

- Determination of lifetime of $^{3}_{\Lambda}H$ has been made by the several groups using the heavy Ion collisions
  - Heavy-ion experiments had provided consistently a shorter lifetime than free Λ lifetime, although the error bar was not small; deviations were less than 3 sigma.

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





DI-BARYON AND BARYON INTERACTION

Di-Baryon and Baryon Interaction

- Studies using Heavy Ion collisions is getting very popular recently
  - Pioneering works by STAR experiment at BNL RHIC
  - LHC ALICE experiment is catching up very rapidly
- Baryon interaction is the basic building block of nuclear physics
- Extended to the flavor SU(3) space
- It is very encouraging that the baryon interactions can be calculated using the lattice QCD at almost physical point

Methods of Dibaryon/Interaction Study

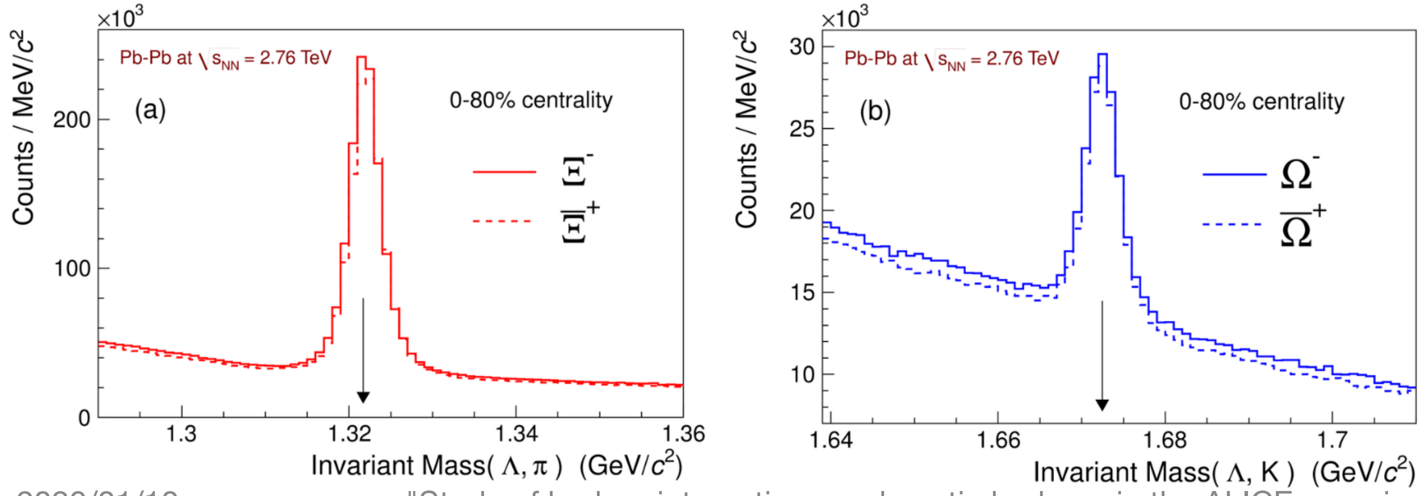
- Binary scattering with a fixed target
  - Only stable target can be used → limited combination
- Measurement of Invariant mass for final products in the collisions
  - Bound state
  - Unbound resonance state with small decay width
- Two particle correlation（femtoscopy）
  - Final state interaction of two particles in the collisions
  - HBT (Hanbury Brown and Twiss) Intensity Interferometry
  - Wider variety of combinations compared to the binary scattering with a fixed target

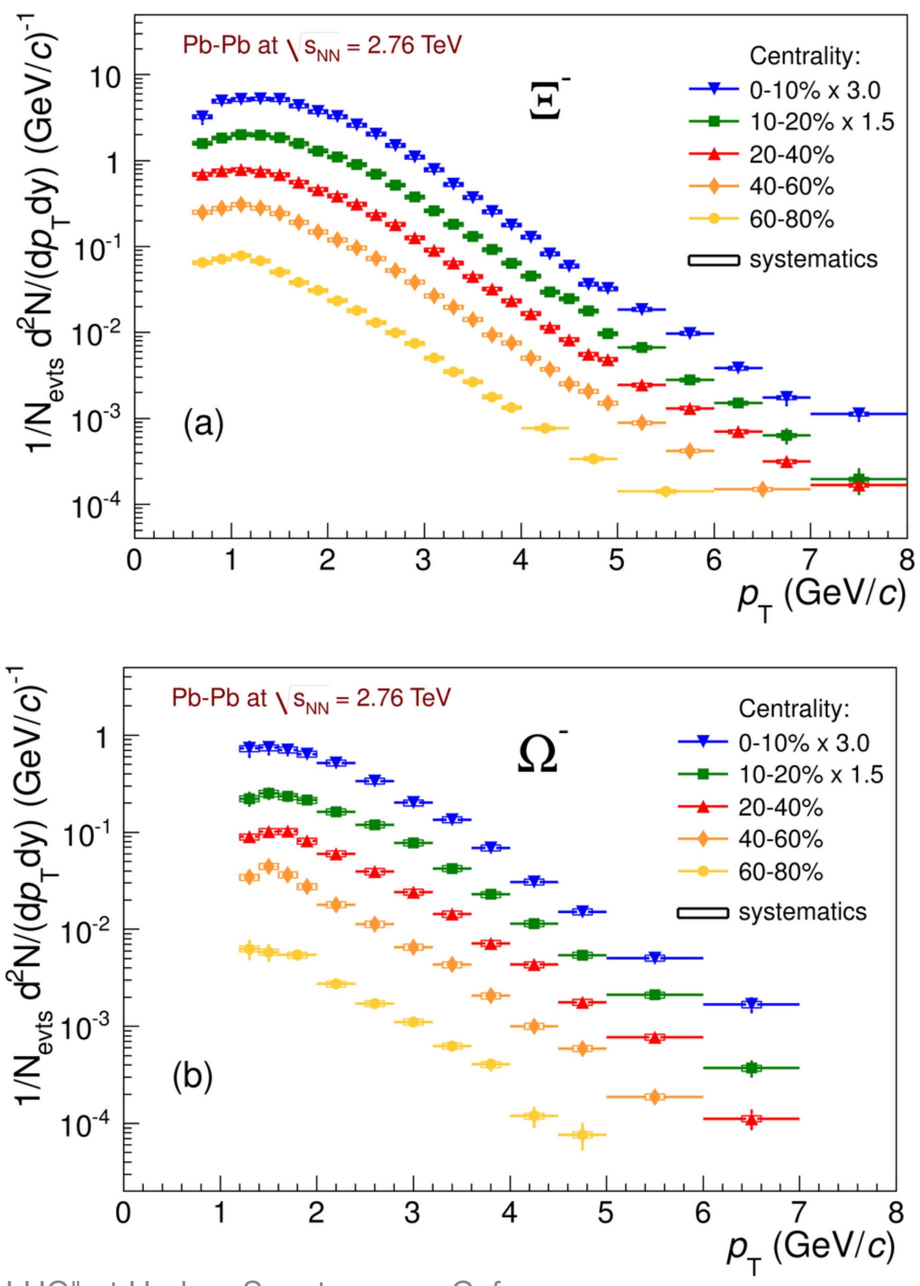
Phys. Lett. B 728 (2014) 216-227
http://alice-publications.web.cern.ch/node/604

Multi-strange baryons

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

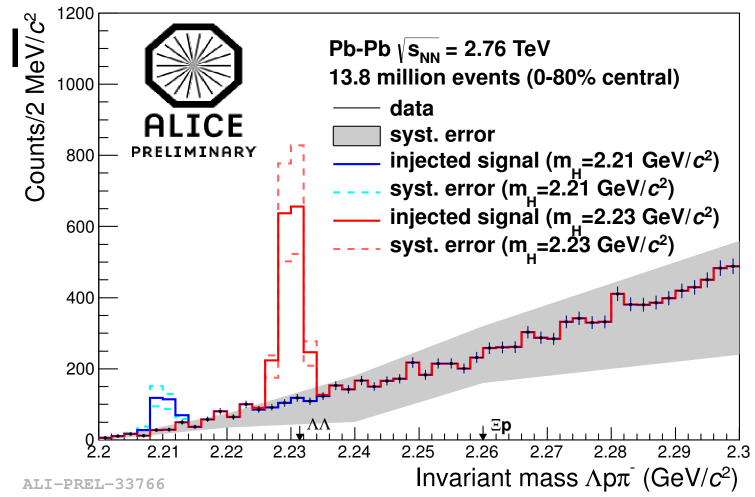
Centrality	0-10%	10-20%
$\langle N_{\mathrm{part}} \rangle$	356.1 ± 3.6	260.1 ± 3.9
Ξ^-	$3.34 \pm 0.06 \pm 0.24$	$2.53 \pm 0.04 \pm 0.18$
$\overline{\Xi}^+$	$3.28 \pm 0.06 \pm 0.23$	$2.51 \pm 0.05 \pm 0.18$
$\Xi^- + \overline{\Xi}^+$	$6.67 \pm 0.08 \pm 0.47$	$5.14 \pm 0.06 \pm 0.36$
Ω^-	$0.58 \pm 0.04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



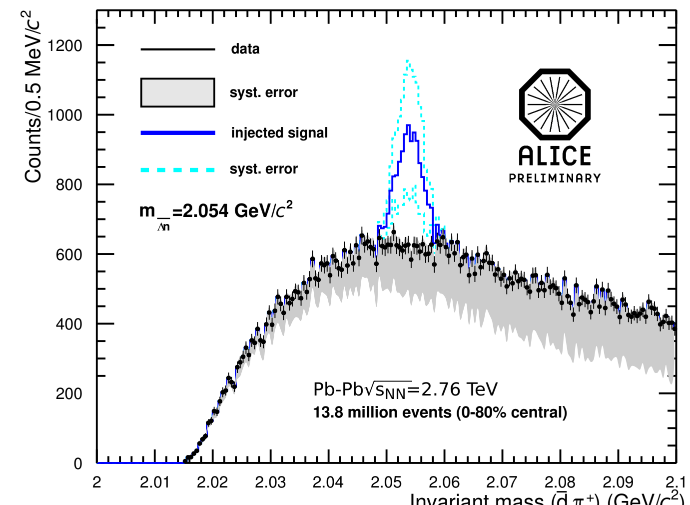


Direct Search of ΛΛ and ΛN Bound State

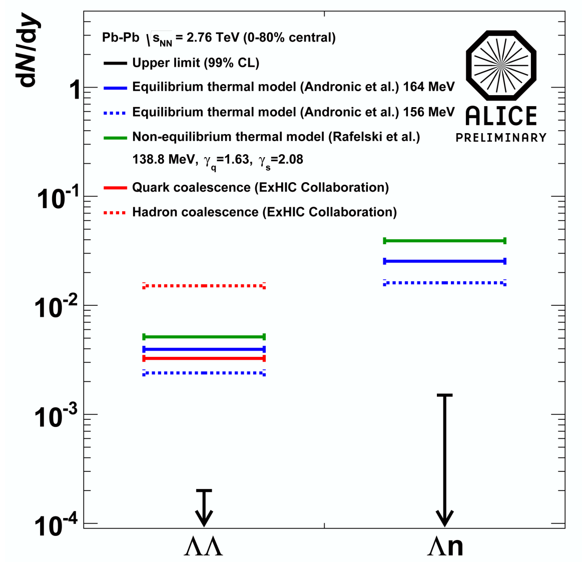
ALICE Coll.: EPJ Web of Conferences **97**,00013 (2015)



Invariant mass of Λpπ (ΛΛ→Λ+p+π⁻)

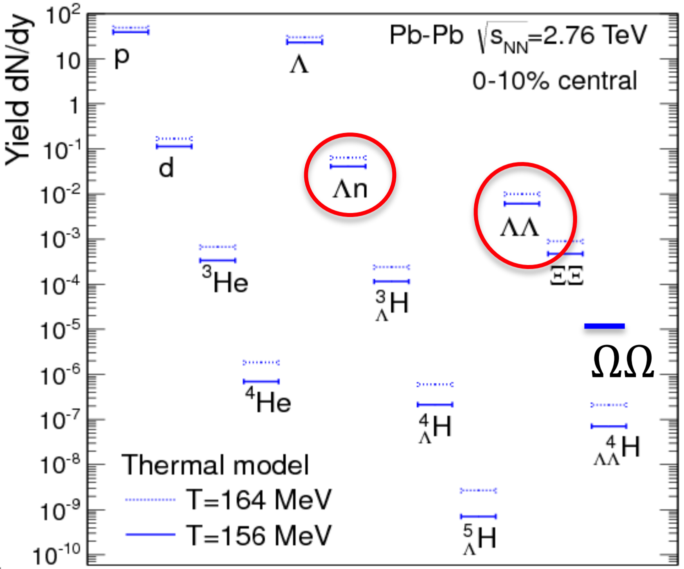


Invariant mass of dπ (Λn→d+π⁻)



Comparison with the model calculations

- Equilibrium thermal model
- Non-equilibrium thermal model
- Coalescence predictions

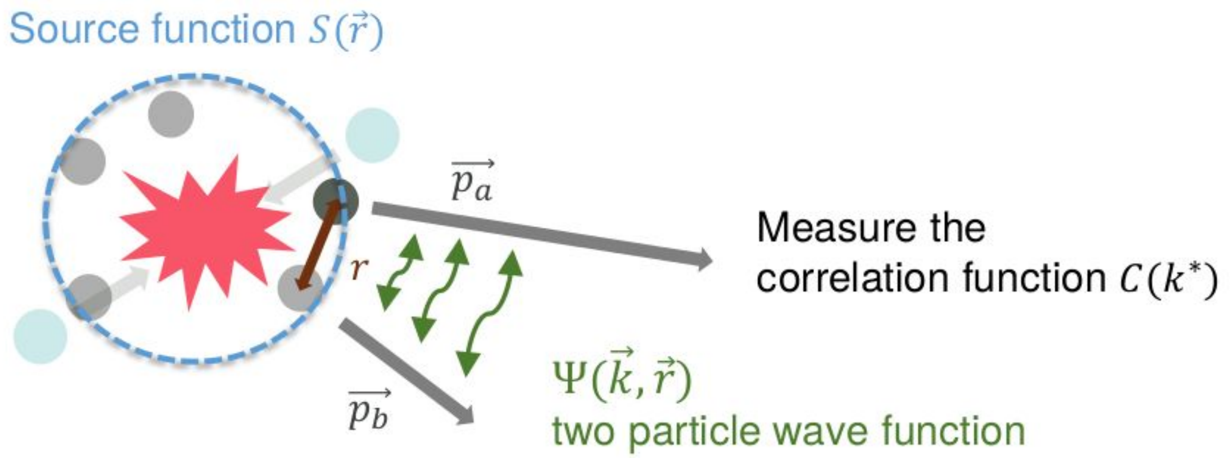


Current consensus: H (ΛΛ) is slightly unbound with mass between ΛΛ and pΞ⁻

- Continue study in the RUN3

Two Particle Correlation

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



Static/Spherical Source:

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

Asymptotic wave function:

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

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

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

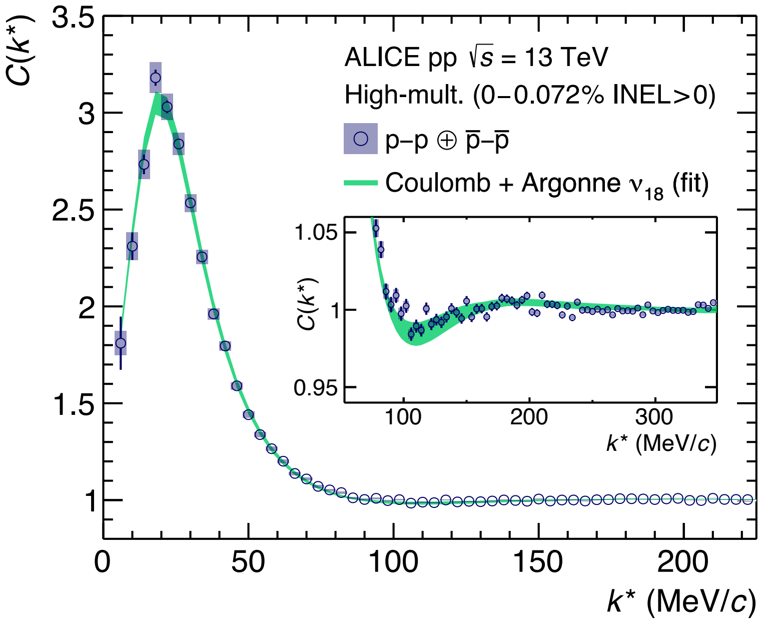
$$C(k^*) = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \mathcal{N}\frac{N_{\mathrm{Same}}(k^*)}{N_{\mathrm{Mixed}}(k^*)} = \int S(\vec{r})\left|\Psi(\vec{k}^*,\vec{r})\right|^2 \mathrm{d}^3\vec{r} \xrightarrow{k^*\to\infty} 1$$

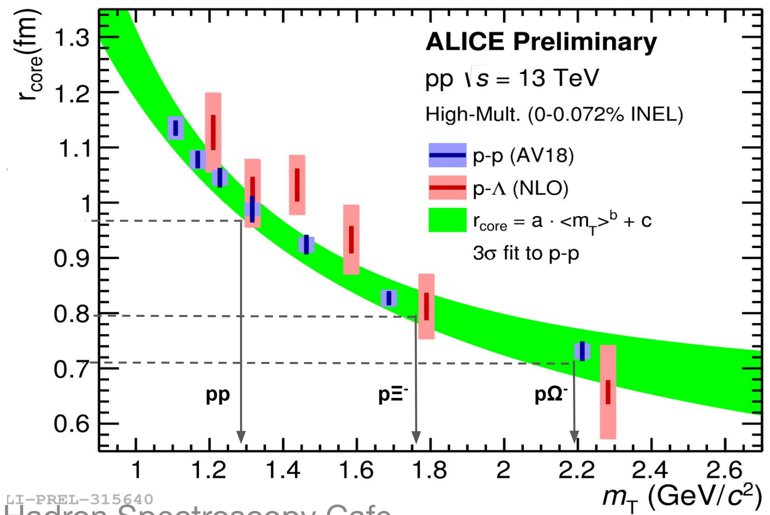
Single-particle momenta

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

Source Characteristics in Small Systems

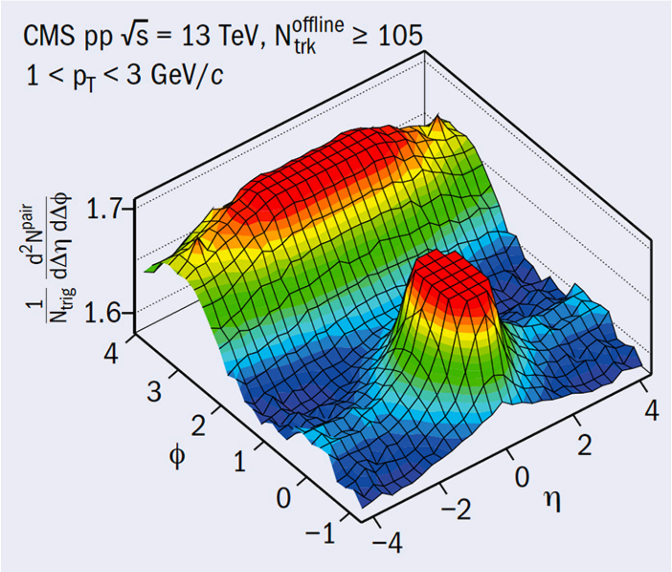
- p+p and p+A collisions are used for femtoscopy study
- Ansatz: The source is similar for all baryon pairs in small systems
  - The size of the source core is determined from the p-p correlation function, since the p-p interaction is well known
  - The p-p femtoscopic analysis is performed differentially in $\langle m_T \rangle$ bins
  - Another assumption: All baryon-baryon pairs have the same $\langle m_T \rangle$ dependence -- this may not be correct, in case where hydro effect is on
  - Effect of strong short-lived resonances are taken into account for all baryons (using statistical hadronization model)
- Cross-checked by p-Λ analysis

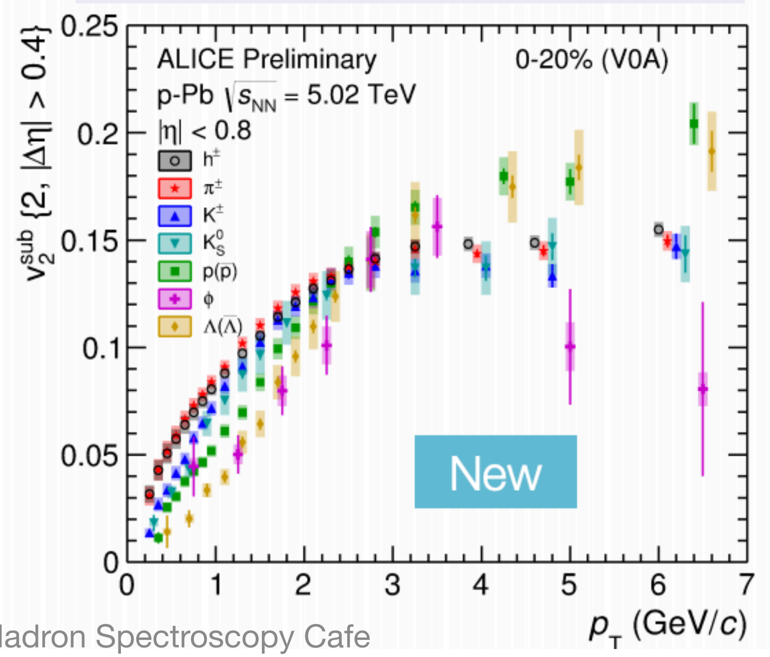




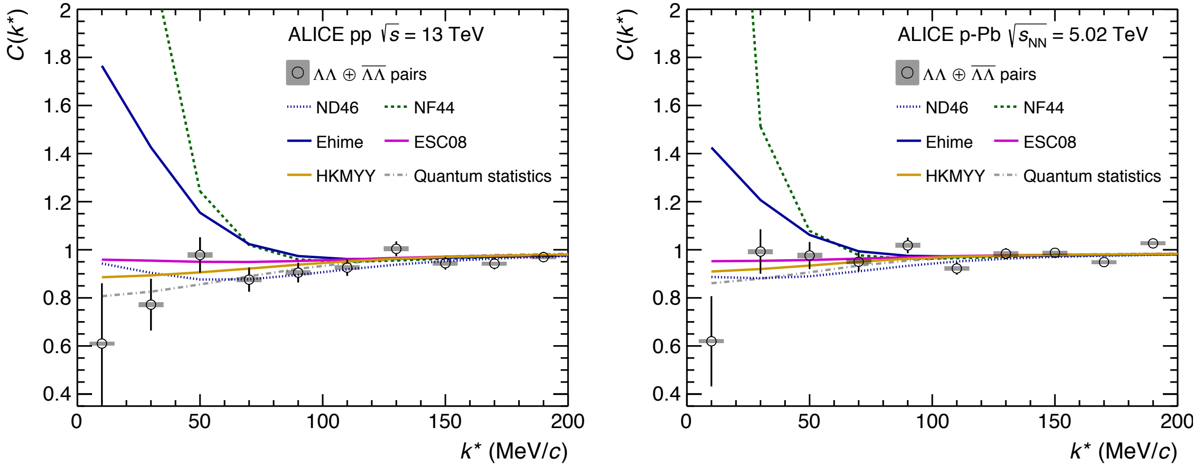
A Short Comment on Small System

- p+p and p+A collisions have been used in the study of baryon interaction via femtoscopy
- Behavior consistent to hydrodynamical fluid is seen in violent (high-multiplicity) p+p and p+A collisions
- Understanding the dynamics of small systems are relevant to the study of baryon interaction via femtoscopy



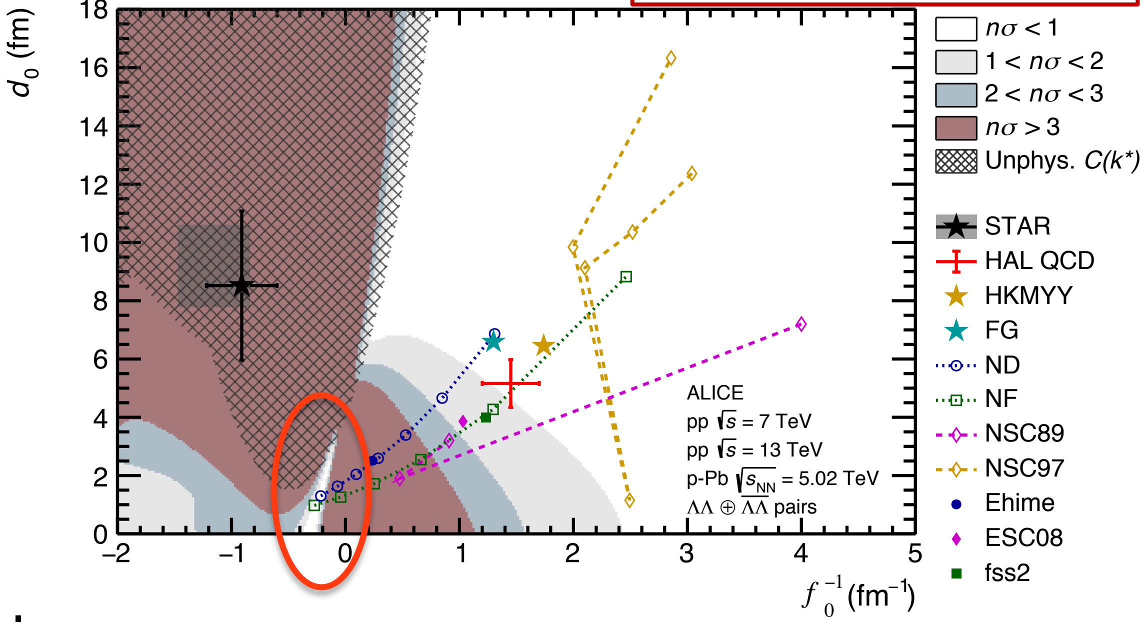


ΛΛ Correlation in p+p & p+Pb Collisions



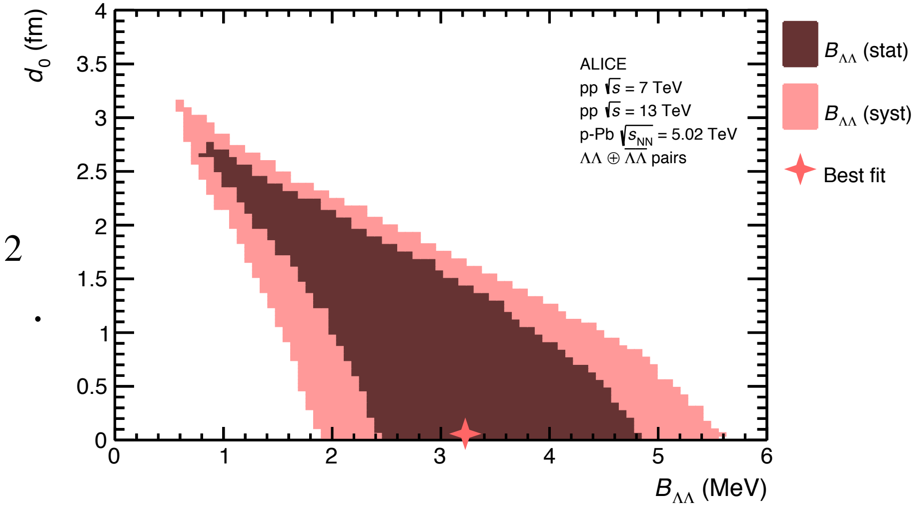
Phys. Lett. B797 (2019) 134822.

Phys. Rev. C 99, 024001 (2019)



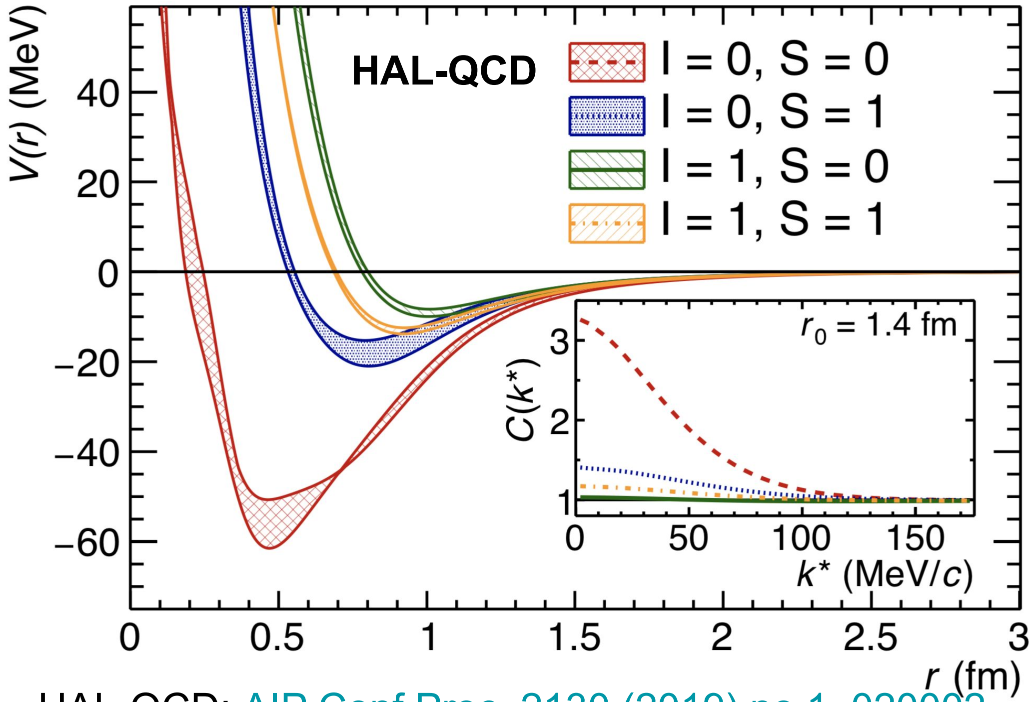
- Preceeding study by STAR collaboration
- Correlation function is very flat → Allowed region for scattering parameters, d_0 and f_0^{-1},is very large
- Possible bound state in the region at slightly negative f_0^{-1} and $d_0 < 4$

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

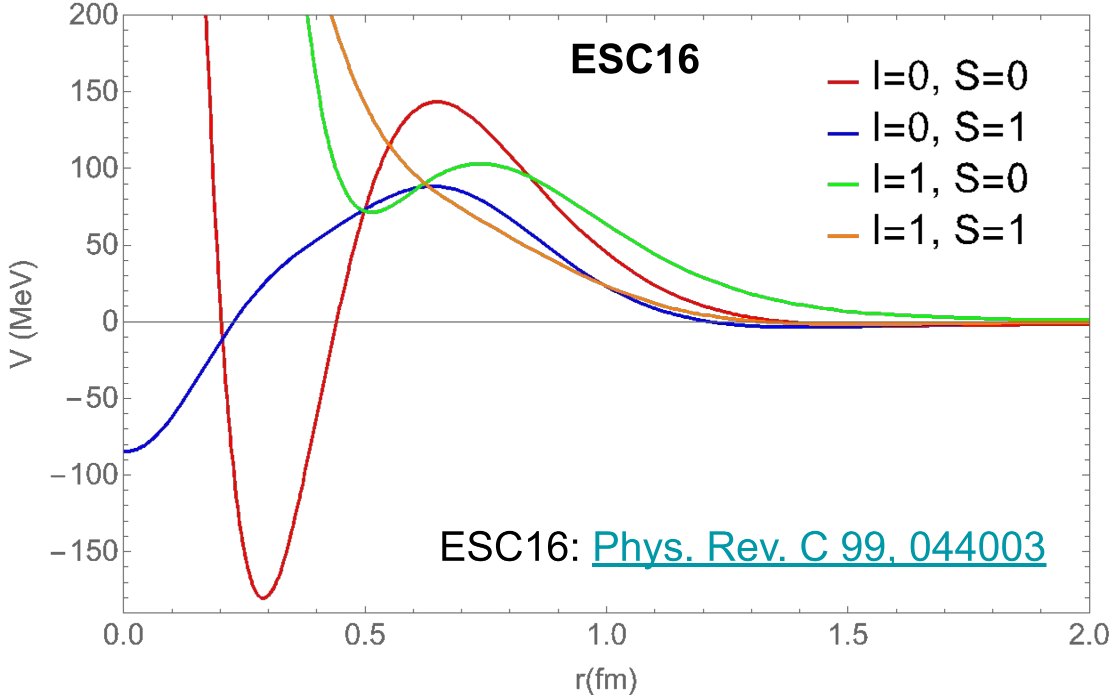


- Higher statistics at low k* region in Run 3

p-Ξ^- Correlation



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

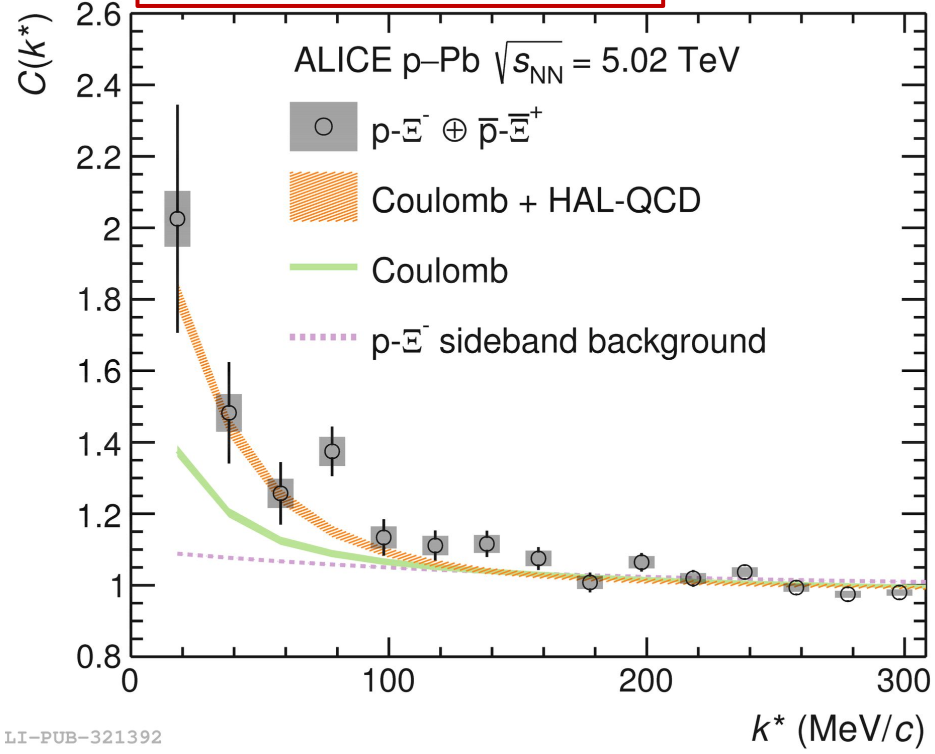


ESC16: Potential by Nijmegen group

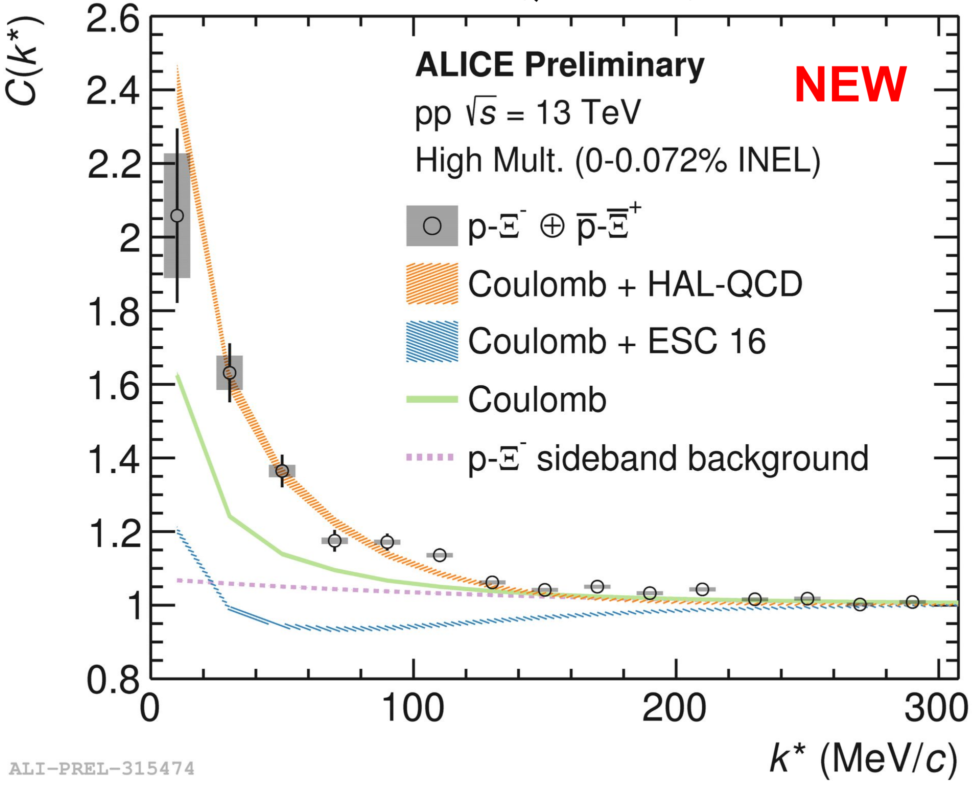
$$
\begin{aligned}
C_{\mathrm{p-\Xi^-}} &= \frac{1}{8} C_{\mathrm{N-\Xi}}\,(\mathrm{I}=0,\, \mathrm{S}=0) + \frac{3}{8} C_{\mathrm{N-\Xi}}\,(\mathrm{I}=0,\, \mathrm{S}=1) \\
&\quad + \frac{1}{8} C_{\mathrm{N-\Xi}}\,(\mathrm{I}=1,\, \mathrm{S}=0) + \frac{3}{8} C_{\mathrm{N-\Xi}}\,(\mathrm{I}=1,\, \mathrm{S}=1).
\end{aligned}
$$

p-Ξ⁻ Correlation

Phys. Rev. Lett. 123, 112002

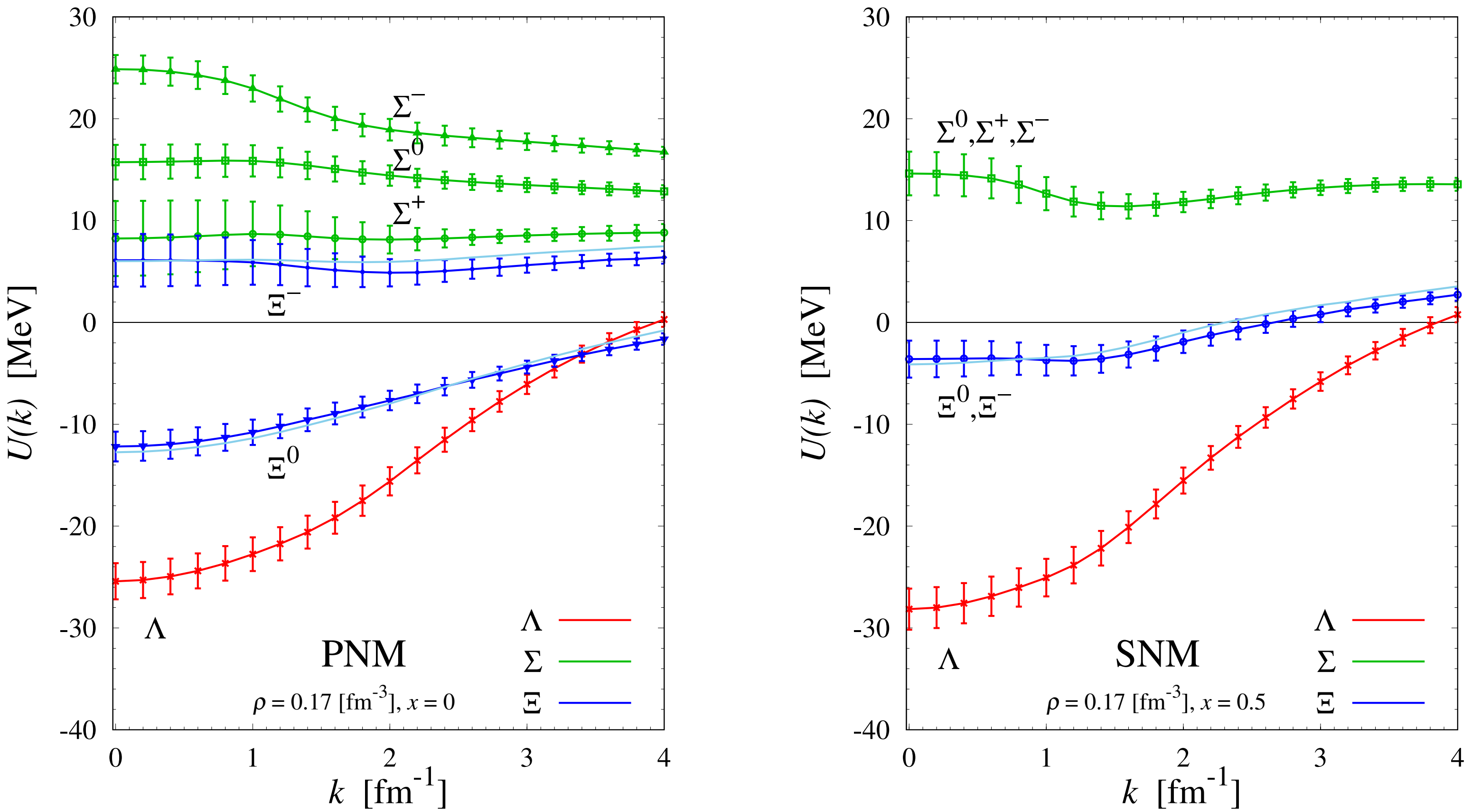


Presented in QM2019@Wuhan



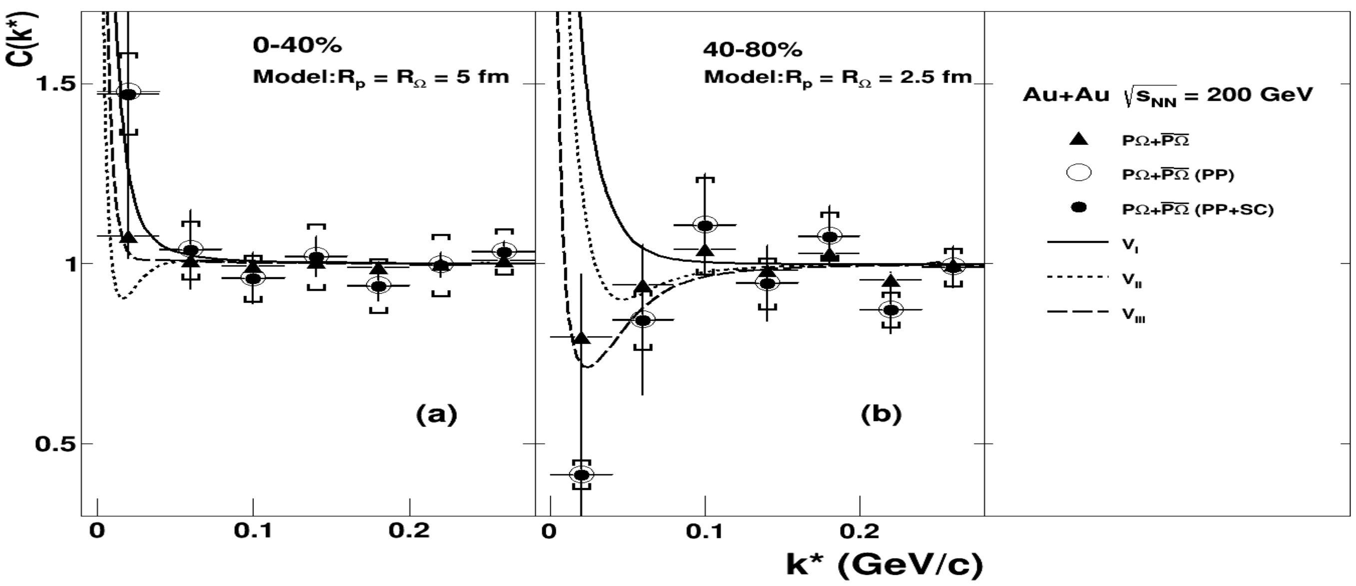
- ALICE: p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV & p-p collisions at $\sqrt{s}$ = 13 TeV
- ESC 16 may be excluded
- Data with higher statistics in RUN3

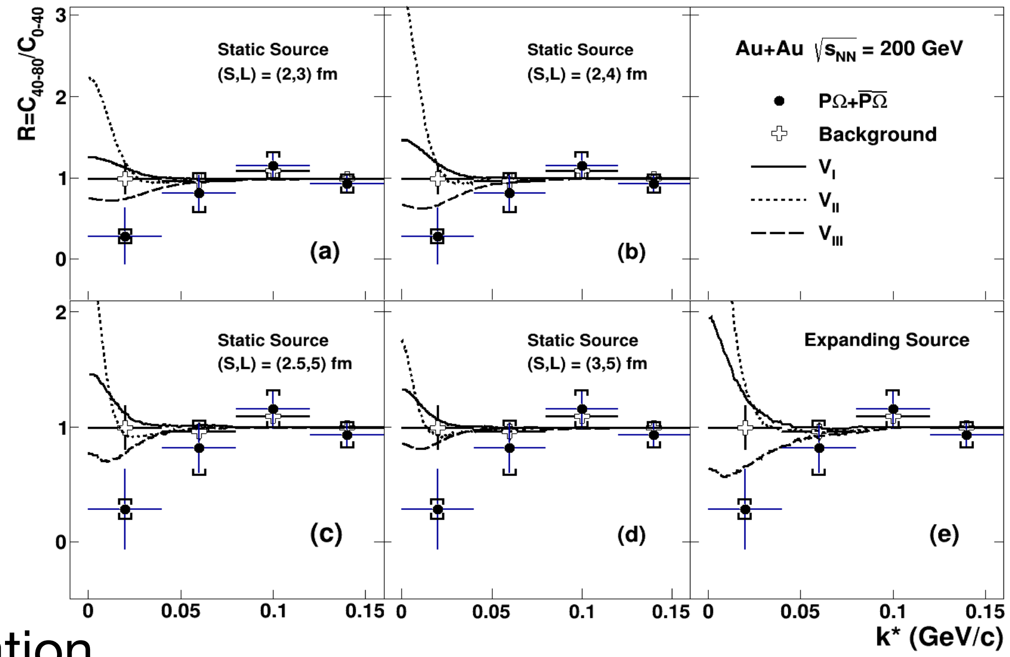
U(k) in Nuclear Matter by HAL-QCD



- PNM (pure neutron matter) & SNM (symmetric nuclear matter)
- Σ is repulsive in pure neutron matter (at normal nuclear density)

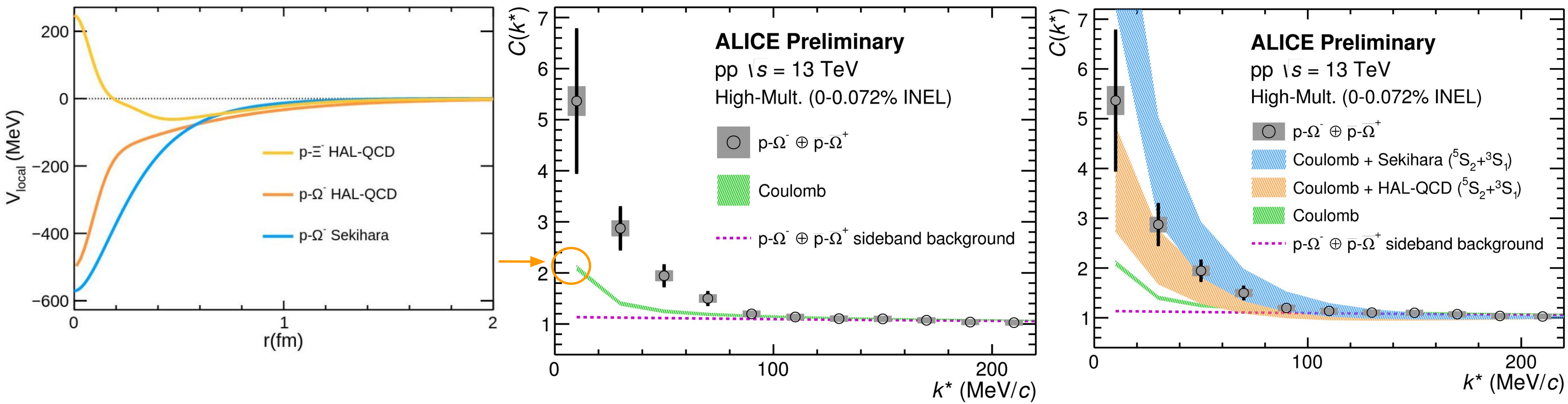
STAR: pΩ^- Correlation in Au+Au





- Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, by STAR collaboration
  - arXiv:1808.02511 [hep-ex]
- Correlation pattern depends on the collision centrality → The ratio between central to peripheral
  - K. Morita, A. Ohnishi, F. Etminan and T. Hatsuda, PRC 94, 031901(R) (2016)
- The ratio is less than 1 in k* < 40 MeV/c → Positive scattering length → Suggesting bound state of pΩ

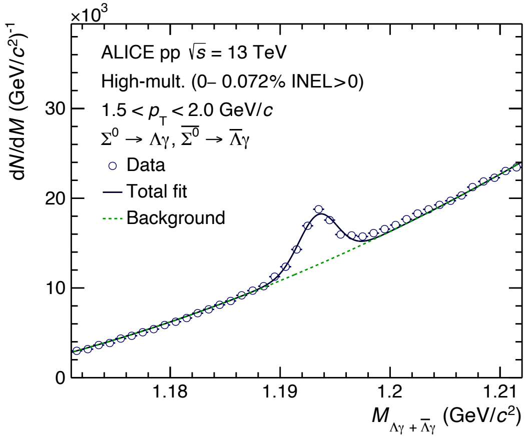
ALICE: pΩ^- Correlation

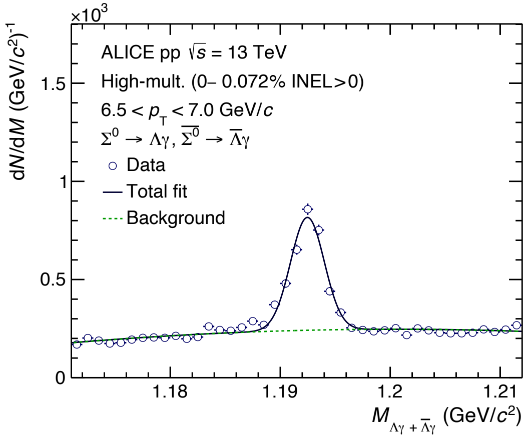


- pΩ^- correlation in p+p collisions at $\sqrt{s}$ = 13 TeV
- Compared with the two theoretical calculations: HAL-QCD (PLB 792 (2019) 284) & meson exchange (by Sekihara; PRC 98, 015205 (2018))
- More attractive than pΞ^-
- Theoretical uncertainty due to $^3S_1$

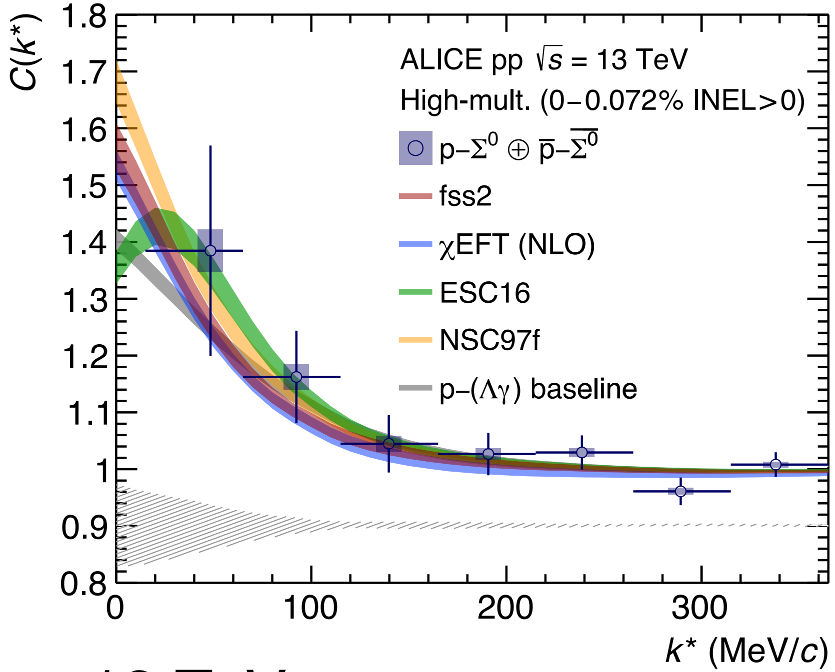
p-Σ^0 Correlation

arXiv:1910.14407





γ: measured via external conversion

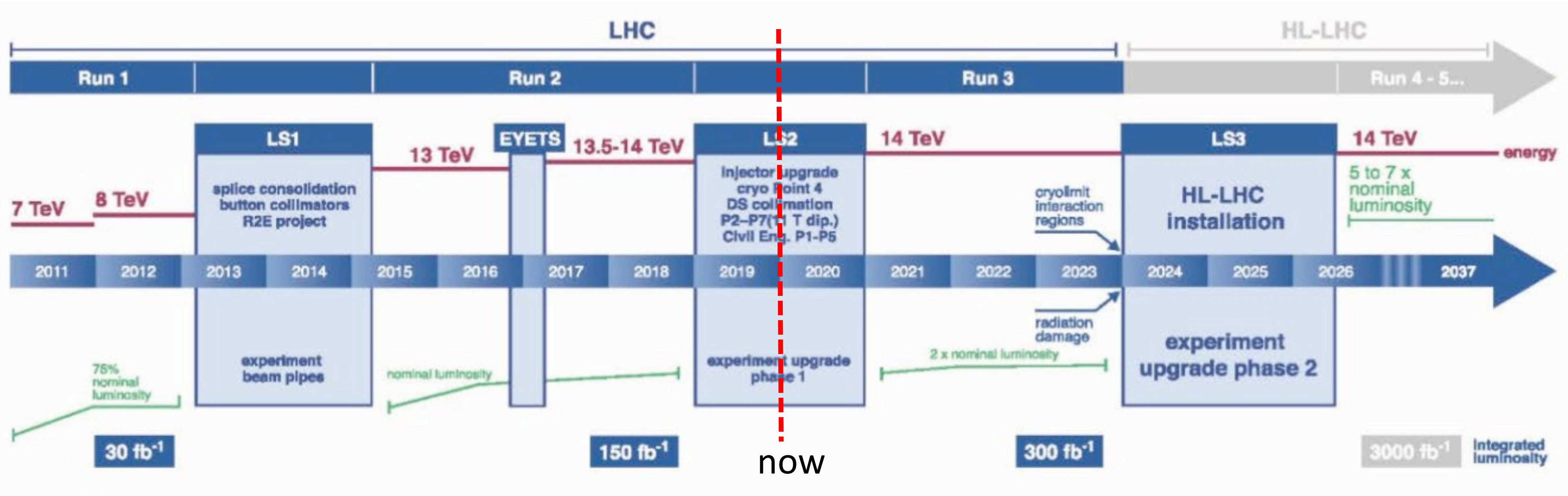


- p–Σ^0 interaction in high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV
- p–Σ^0 correlation function is consistent with the p–($\Lambda\gamma$) baseline ((0.2–0.8)σ) → indicating the presence of an overall shallow potential
- Present data cannot discriminate between the different models

→ Two orders of magnitude larger data samples (expected from Run3&4) will provide tighter constraint to the models on the N–Σ sector

ALICE UPGRADE DURING LS2

LHC Long Term Plan



- LS2 : 2019 – 2021May
  - Experiments upgrade phase 1
  - Injector upgrade
  - Civil engineering for HL-LHC at ATLAS, CMS
  - Magnet and cryogenics
- LS3 : 2025 – 2027(?)
  - Experiments upgrade phase 2
  - HL-LHC preparation

■ Run3 : 2021Jun – 2024
- x2 p-p nominal luminosity
- x6 Pb-Pb nominal luminosity = min.bias 50 kHz

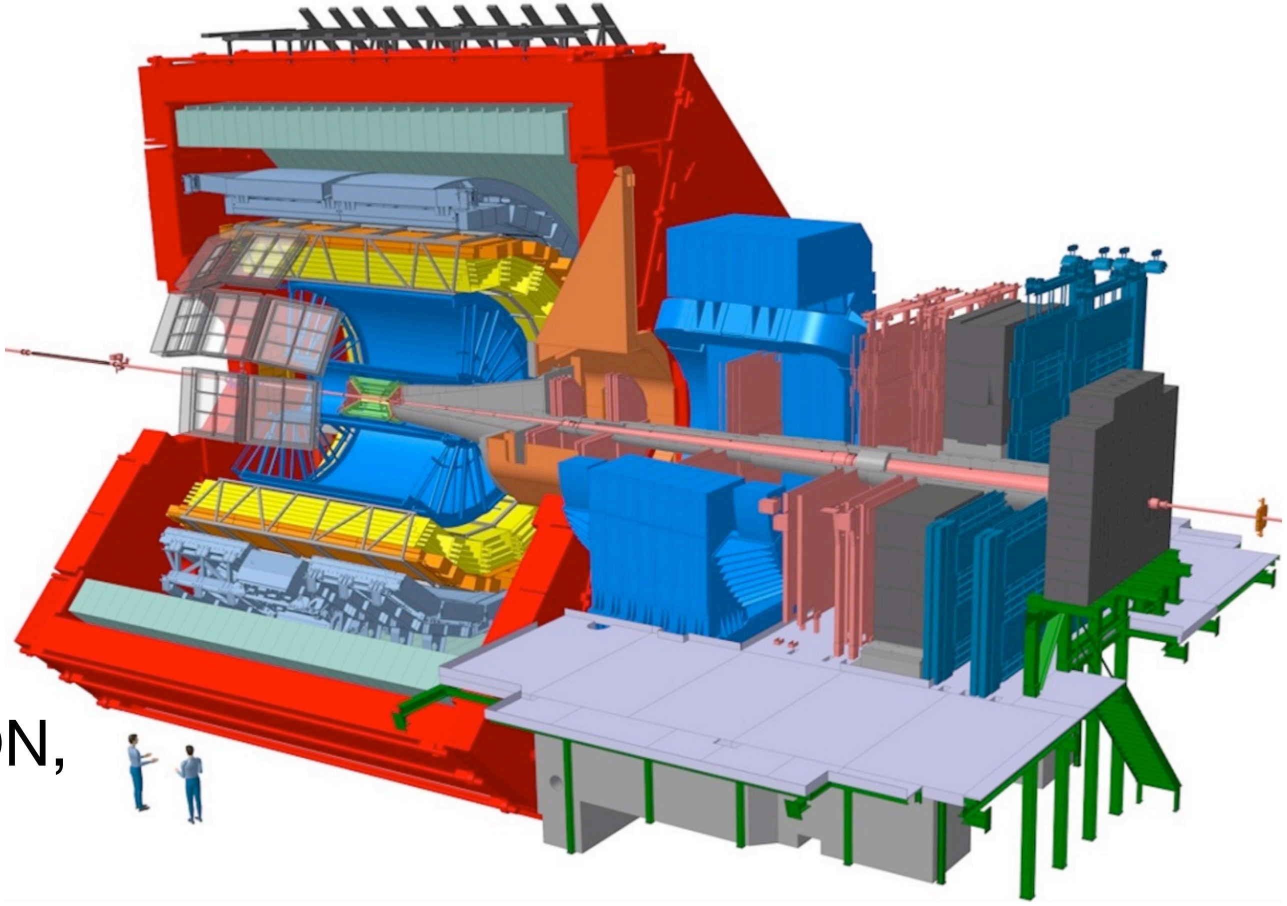
■ Run4 : 2028 – HL-LHC RUN
- x5 to x7 p-p nominal luminosity
- x7 Pb-Pb nominal luminosity

■ after
- HE-LHC (27 TeV) and FCC at 100 TeV (~2040)

ALICE Upgrades during LS2

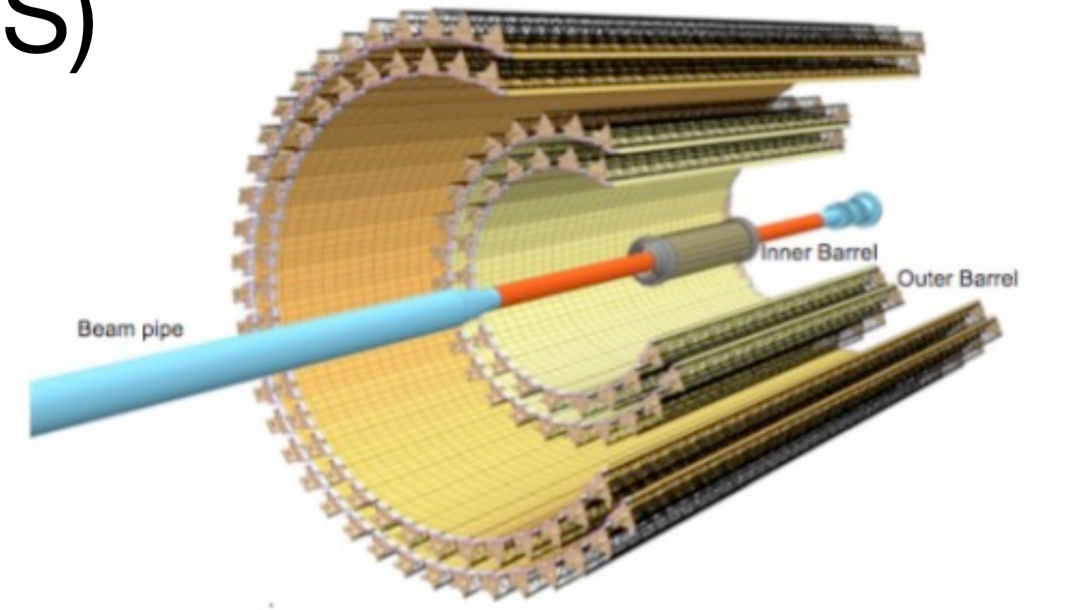
Purpose: Record minimum-bias Pb-Pb data at 50 kHz

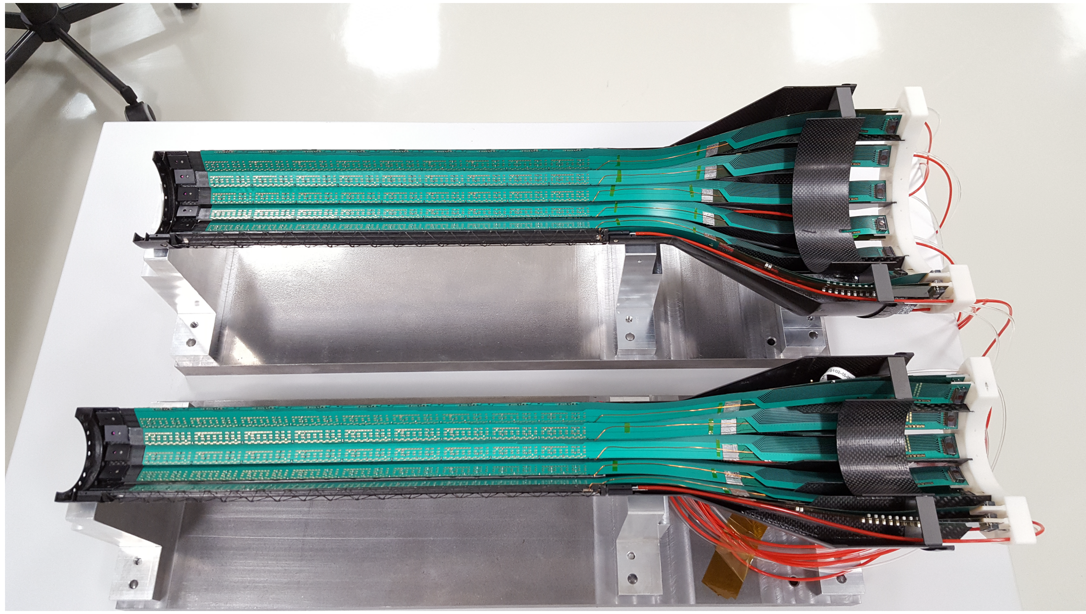
- New Inner Tracking System (ITS)
  - 7 layers of MAPS
- New TPC Readout Chambers
  - 4-GEM detectors
- New Forward Muon Tracker (MFT)
  - vertex tracker at forward rapidity
- New trigger detectors (FIT, AD)
  - centrality, event plane determination
- Upgraded read-out for TOF, TRD, MUON, ZDC, EMCal, PHOS
- Integrated Online-Offline system (O^2)



Inner Tracking System (ITS)

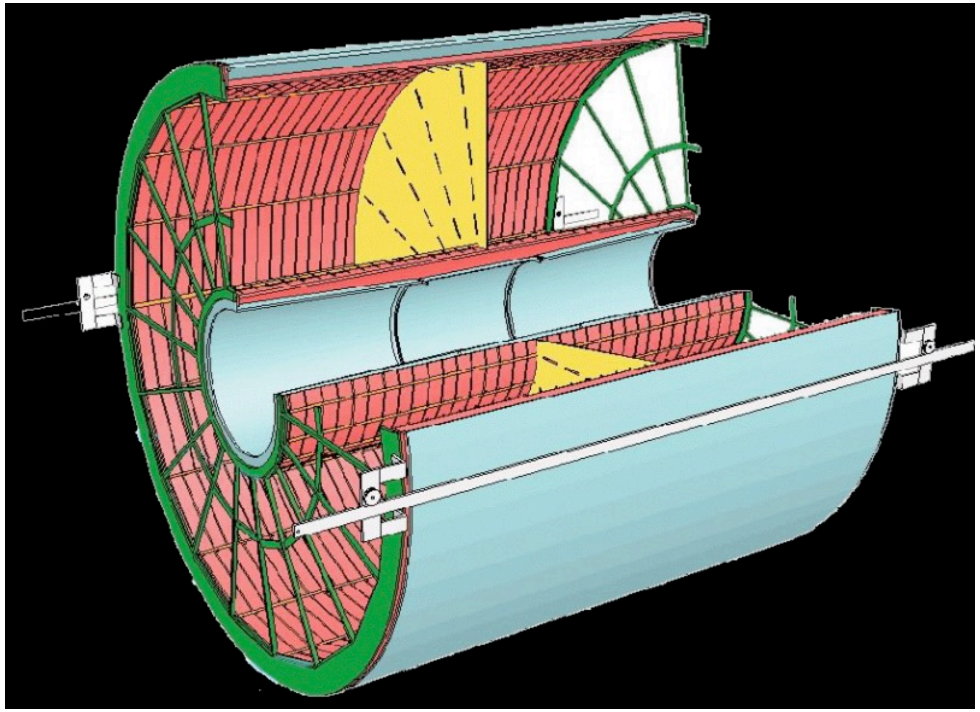
- CMOS Monolithic Active Pixel Sensor (MAPS)
  – 7 layers full pixel detector
    (old = combination of strip, drift, and pixel)
  – Light weight with carbon structure
  – Larger area (10 m^2)
  – More pseudo rapidity coverage ($-1.22 < \eta < 1.22$)
  – First layer closer to interaction point
    (39 mm → 22 mm)
    - New beam pipe
- Improved features
  – Low material (1.44% → 0.3% X_0)
  – Smaller pixel (50x425 μm^2 → 27x28 μm^2)
  – Faster readout (1 kHz (slowest) → 100 kHz))

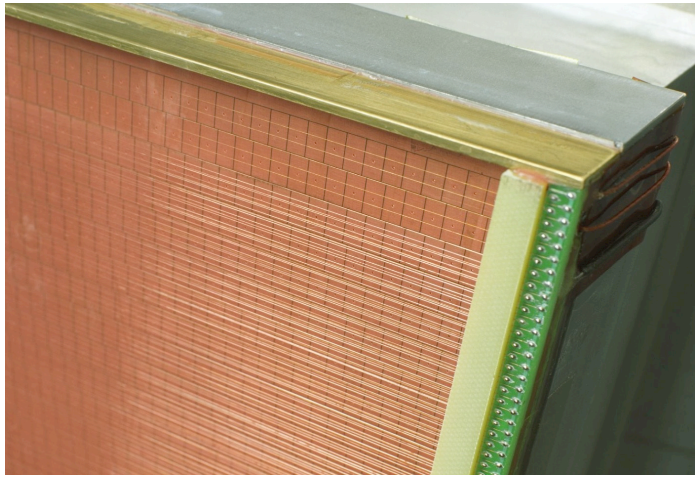


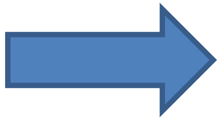


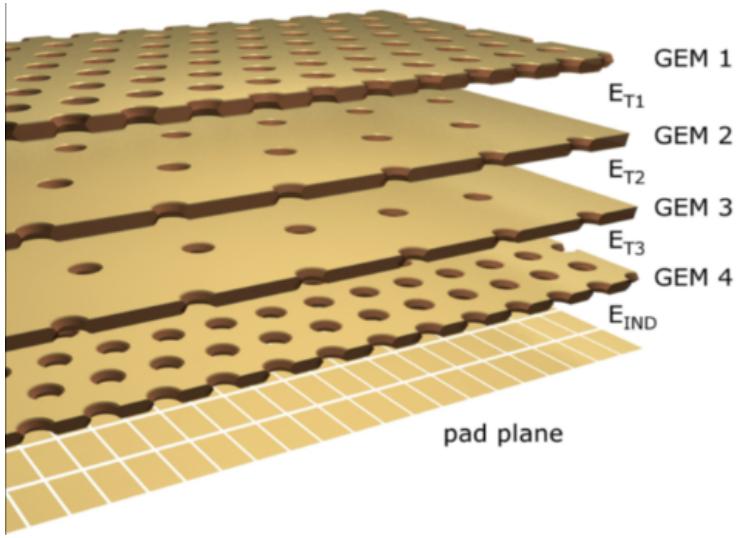
TPC Upgrade

- Most important and challenging upgrade
- Traditional wire chamber system → 4 GEM system
  - Deadtime-less reading by getting rid of Gating Grid
    - Old readout: deadtime per event = 500 μs
  - 530k channels, 200 ns sampling ADC data
    - continuous data rate = 3.5 TB/s
    - massive online computing power required
- CNS-Tokyo & NIAS from Japan



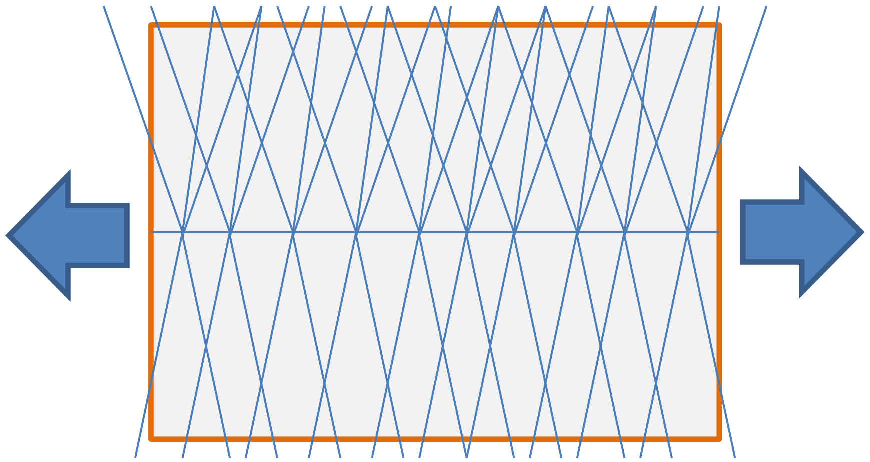


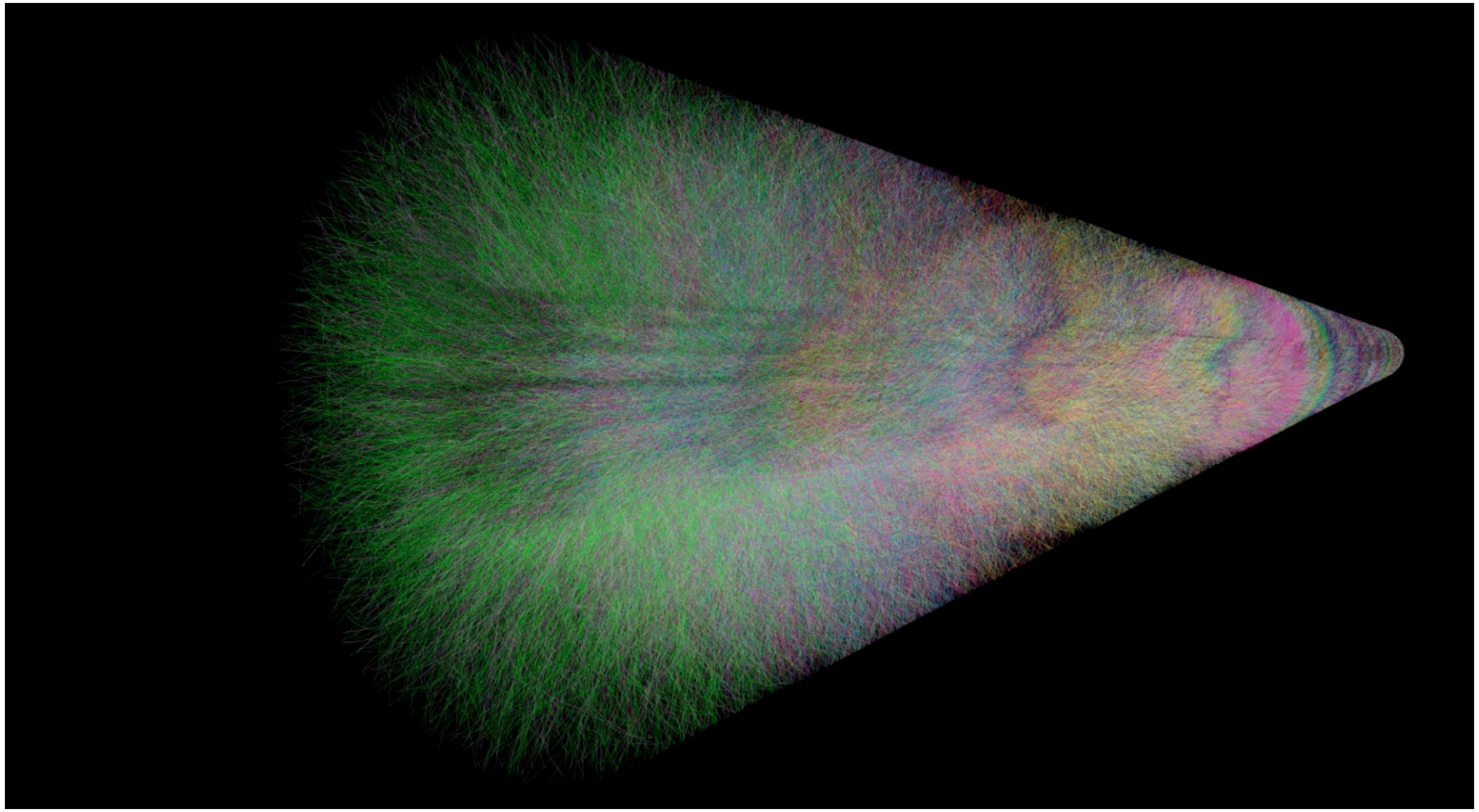




TPC Upgrade (cont.)

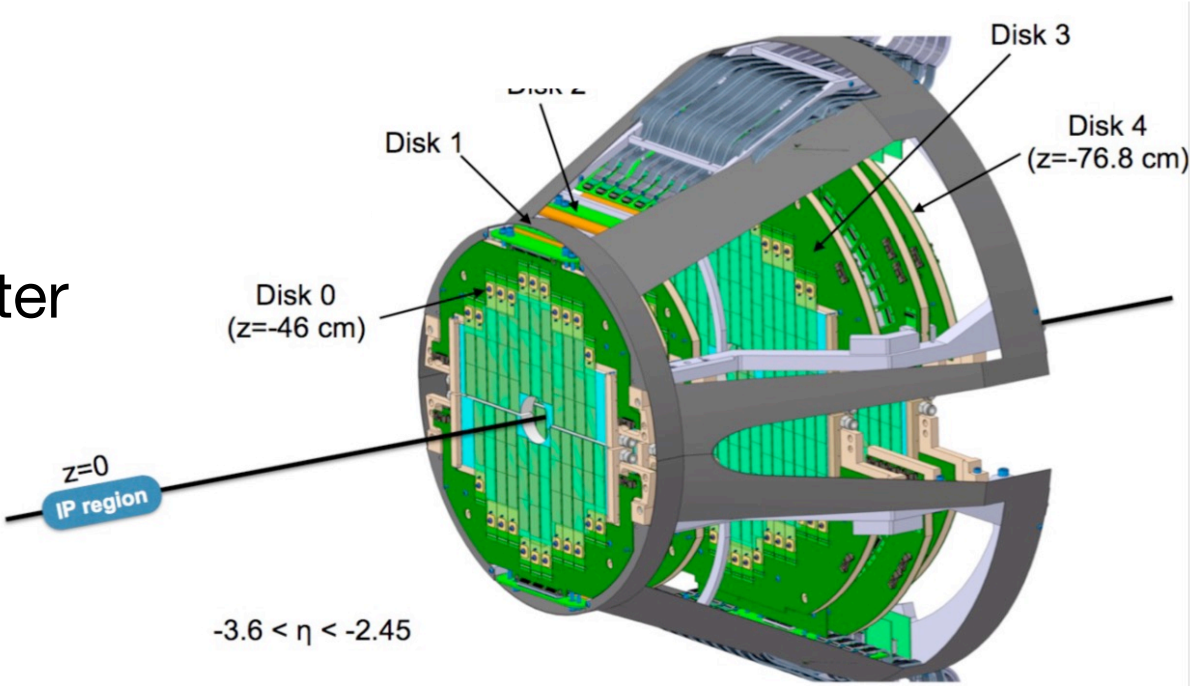
- LHC will provide ~50 kHz event rate in Pb+Pb collisions after LS2
- electron drift time in TPC =100 μs
- Overlapping events
  - 50 kHz = collision every 20 μs

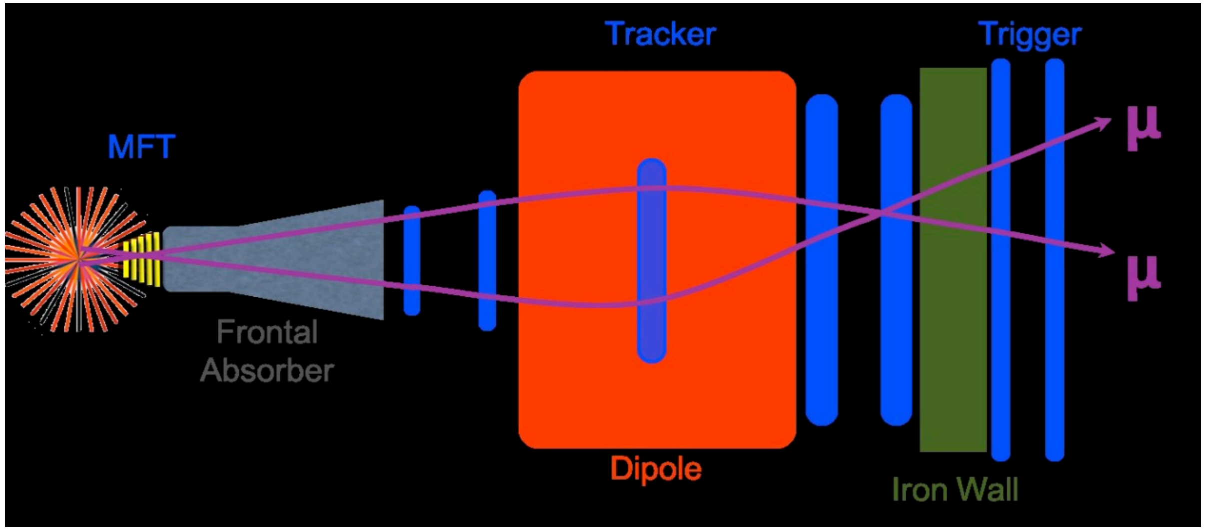




MFT (Muon Front Tracker)

- MFT: New detector in ALICE
  - 5 layer silicon pixels (ITS technology)
  - 0.4 m^2 area
- Add vertex capability to Muon Spectrometer
  - background rejection
  - distinguish prompt/charm-decay/bottom-decay
  - improve momentum resolution

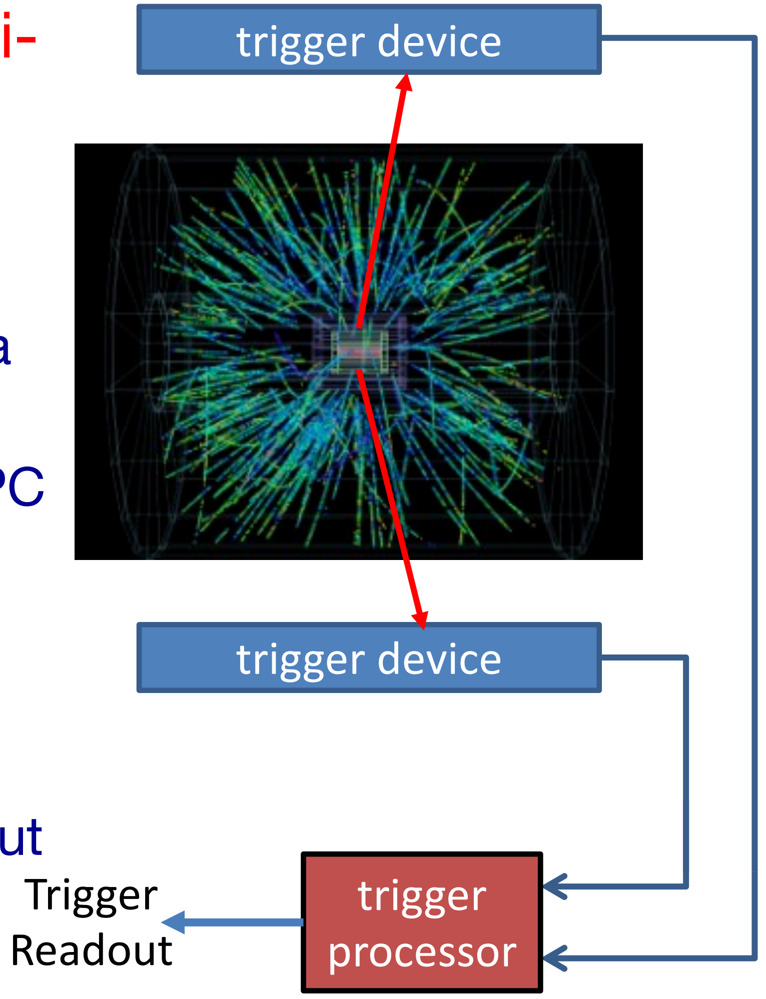




Hiroshima group is participating this project

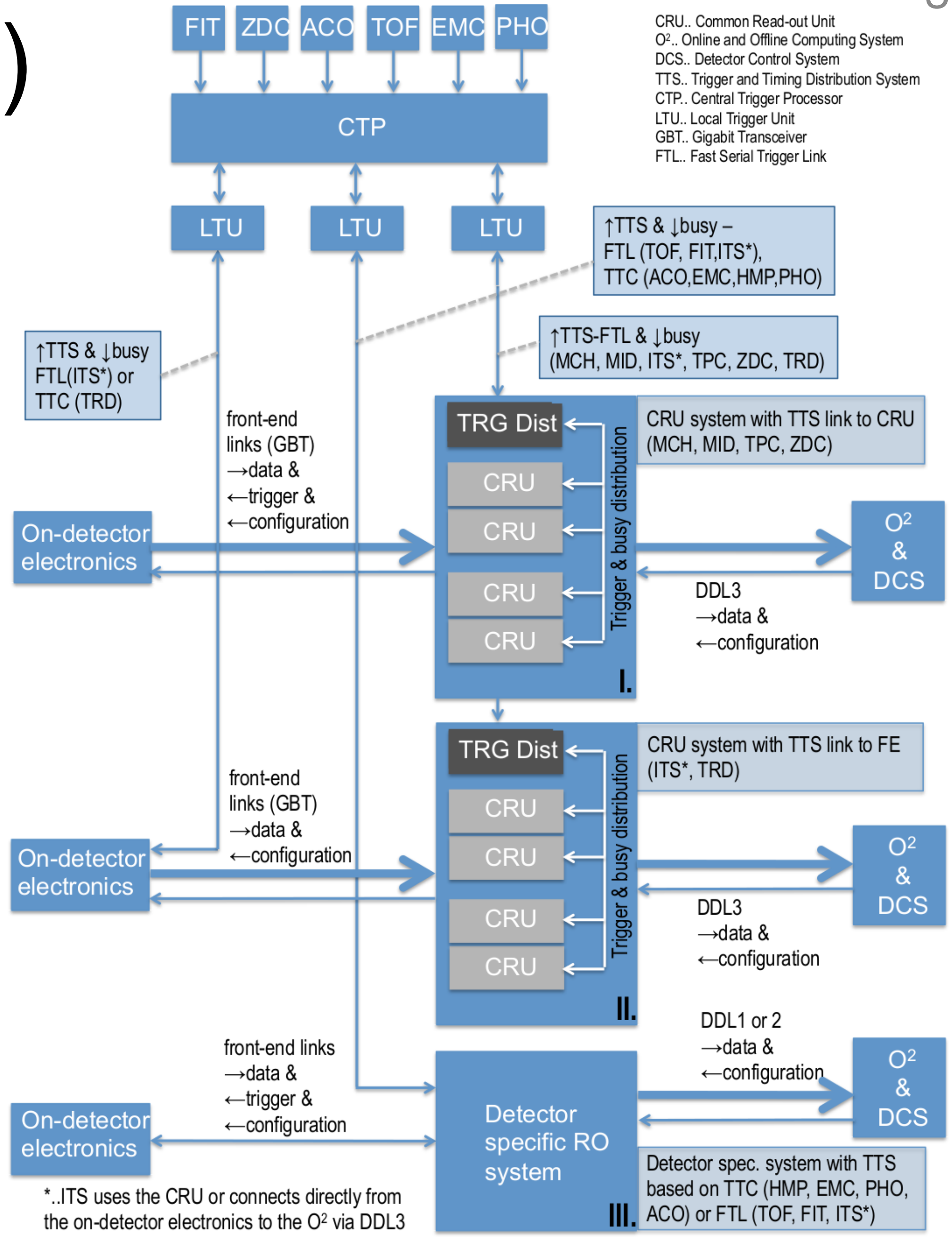
Data Taking Upgrade

- Triggering rare particles such as low p_T heavy flavor multi-particle decay from exotic particles in high multiplicity event is impossible
  - decreasing threshold → trigger all garbage
  - non-simple threshold type trigger → full data analysis I required (a dilemma)
  - 50 kHz means always ~5 events overlapping in data for ALICE TPC = event-by-event data taking no longer possible
- The biggest decision for Run3 = Abandon “hardware trigger” in Pb+Pb collisions
  - TAKE ALL DATA, STORE ALL without trigger → continuous readout
  - data compression & online analysis are key technology



Common Readout Unit (CRU)

- Common to at least “major” and “new” detectors
- Detector Control System
- Trigger and timing distribution
- Data readout & processing with **O(10) faster** than CPUs
  - sorting, online processing: clustering (large **FPGA**), tracking (commercial **GPU**)
- deploy ~350 for TPC (~6M CHF project)



AFTER LS2 UPGRADE

Performance of Upgraded ALICE

Central Barrel: ITS + TPC + …

	Run1+2	Run3	typical signals, physics

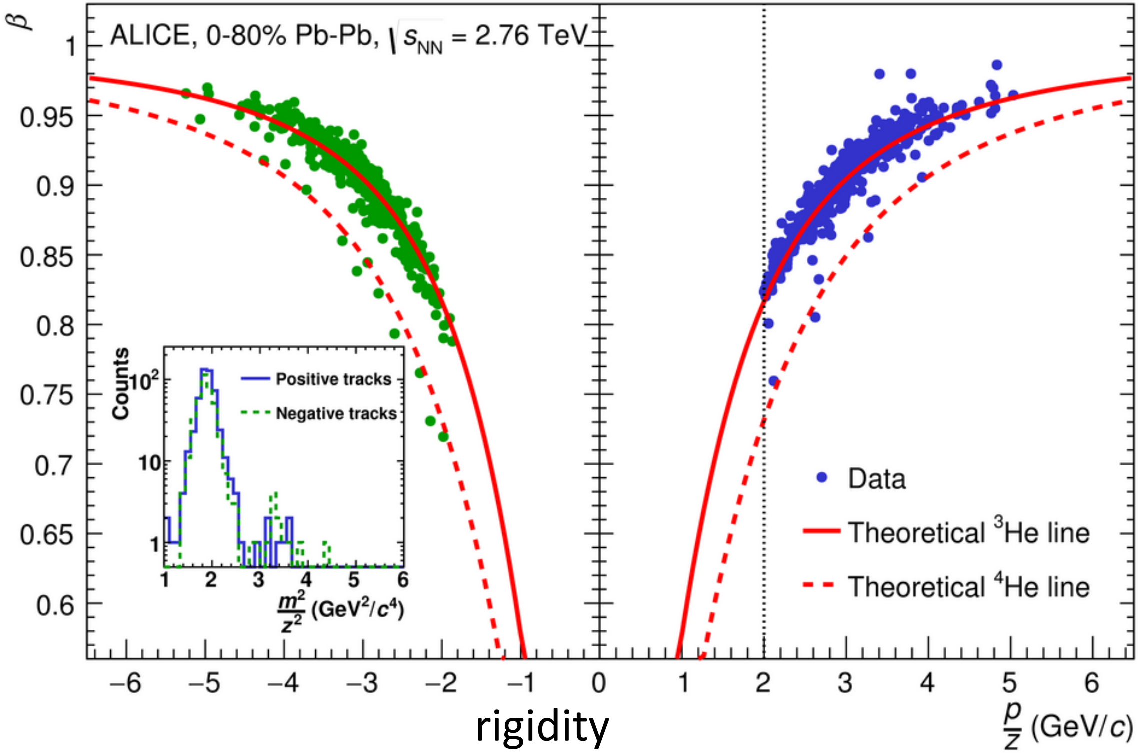
Minimum bias event
 	
Untriggerable rare event
	~ 10^9 events (recorded)
	
	~ 0.1 nb^{-1}
		x100 statistics = 10^{11}
		
		~10 nb^{-1}
			• any kind of single particle analysis
			• e^+e^- low invariant mass
			• anti-nuclei (/^{4}He) (already visible)
			• low-pT multi-particle decay
			  • open heavy flavor baryons: Λc, Ωc
			  • hyper-nuclei such as $^3{}_\Lambda H$
			  • dibaryons
			  • (muti-)hyper nuclei

Triggerable rare event	~10^{10} events (inspected) ~1 nb^{-1}	**x10 statistics = 10^{11}** ~10 nb^{-1}	• high p_T jet related observables • high p_T gamma, electron • such as Υ and maybe top-quark related?

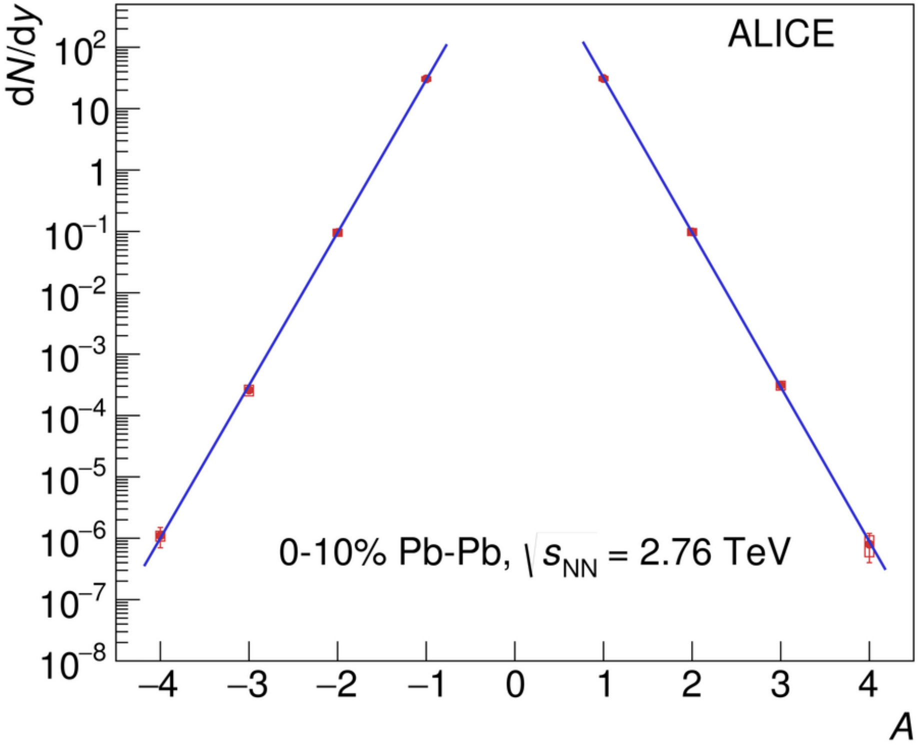
Performance after Upgrade: Light (anti-)nuclei

- ALICE can identify measure ALL charged particles, nuclei, and charged decay daughters, as well as photons
- Nuclei, anti-nuclei up to A=4 is measured in ALICE 2.76 TeV 40M Pb+Pb data in 2011
- In Run3: x2000 statistics (100 billion events) → ~20,000 ^{4}He and 6x10^{6} ^{3}He

time of flight



rigidity

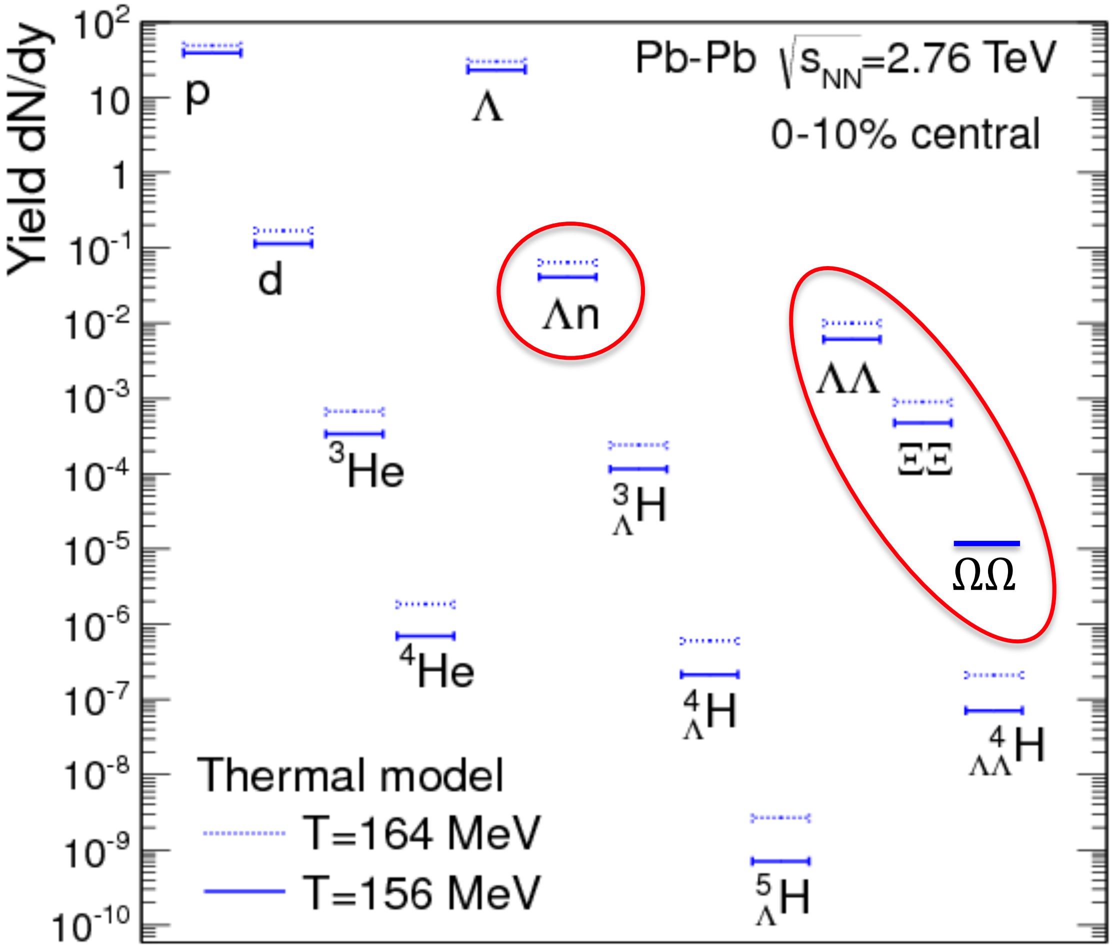


Nucl. Phys. A 971 (2018) 1-20 , arXiv:1710.07531

penalty factor ~ 300/nucleon

Expected Counts in Run3

^{3}He	6,000,000
^{4}He	20,000
$^{3}_{\Lambda}H$	300,000
$^{4}_{\Lambda}H$	800
$^{4}_{\Lambda\Lambda}H$	34
$\Xi\Xi$	150,000
$\Omega\Omega$	3,000



- Upgrade of the ALICE Experiment: Letter Of Intent (J. Phys. G 41 (2014) 087001)
- 10^{10} central Pb-Pb collisions at $\sqrt{S_{NN}} = 5.5\,TeV$
- Assume 8% efficiency per detected baryon

SUMMARY AND OUTLOOK

Summary and Outlook

Summary

- Present status of studying light nuclei and hypernuclei
- Present status of di-baryon search and study of baryon interaction
- ALICE upgrade

Outlook

- Light nuclei and Hypernuclei
- High statistics multi-strange dibaryon data; $\Omega\Omega$、$\Xi\Omega$、$\Xi\Xi$、…
- Extension to Heavy Flavor (not discussed in this presentation)
  - Heavy baryon yield and Baryon/Meson ratio -- di-quark condensation
  - Two particle correlations; D-D、Λ_c-D、Λ_c-N,,,
  - XYZ, …; feasibilities are to be studied

Summary and Outlook (Cont.)

Comment on femtoscopy of baryons

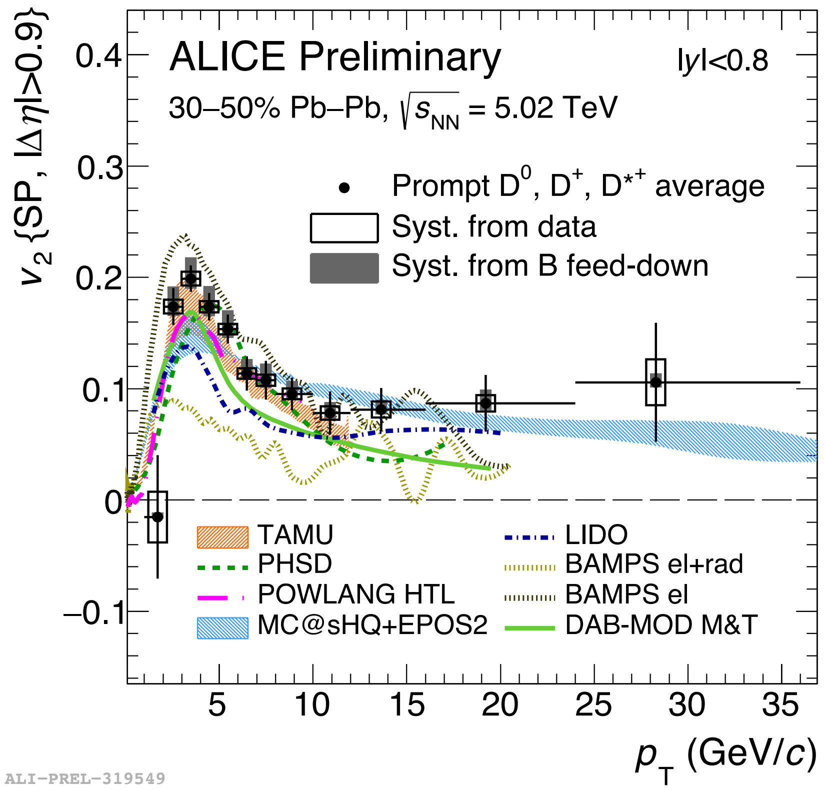
- Strange-baryons make weak decay, which means the angular asymmetry in the emitted particle (pion or Kaon)
- Whether is this information useful to constrain the spin of the mother nucleus?
  - How effective is it?

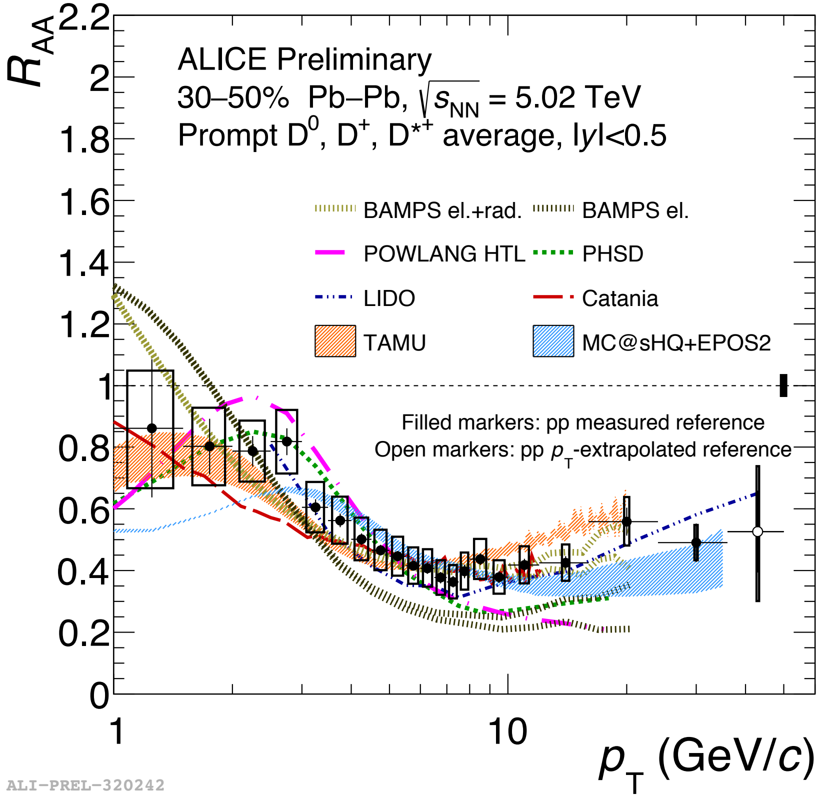
BACKUP

HEAVY FLAVOUR

V_2 and R_{AA} of D mesons

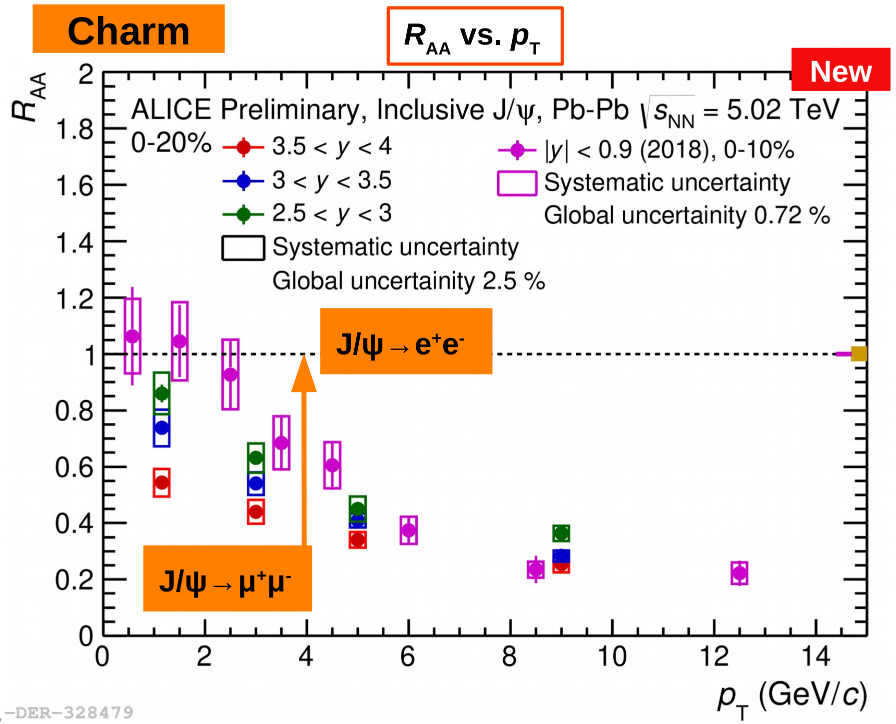
- Both R_{AA} and v_2 at low p_T can be fairly well described by the models which employs elastic collisions in expanding hydrodynamic medium; BAMPS elastic, MC@sHQ+EPOS2, TAMU and POWLANG HTL



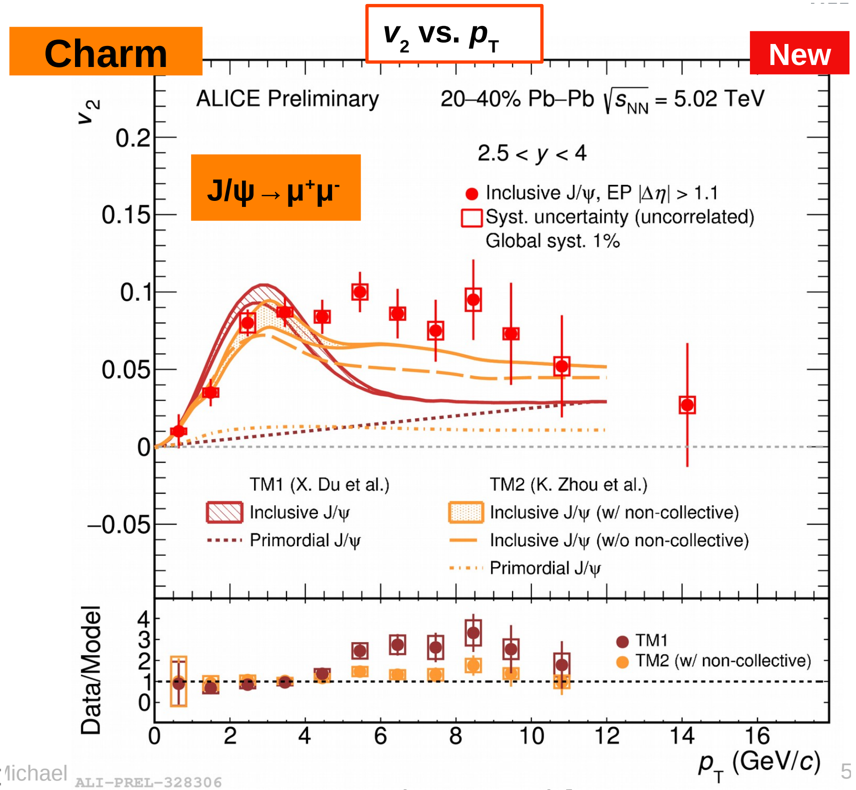


R_{AA} and v_2 of J/ψ

- 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

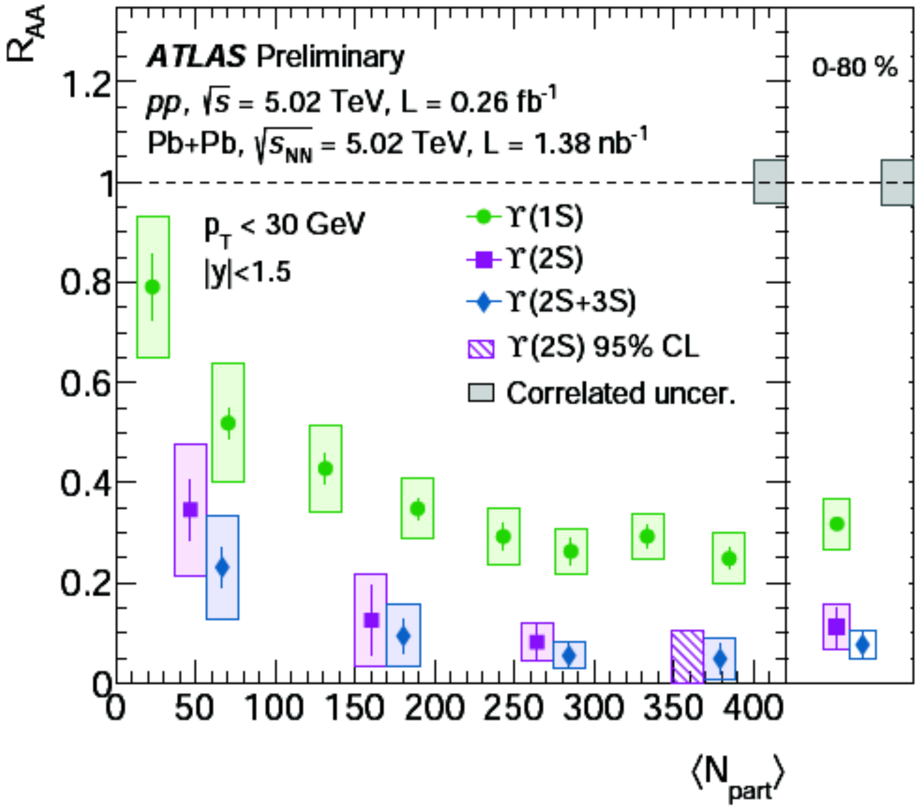


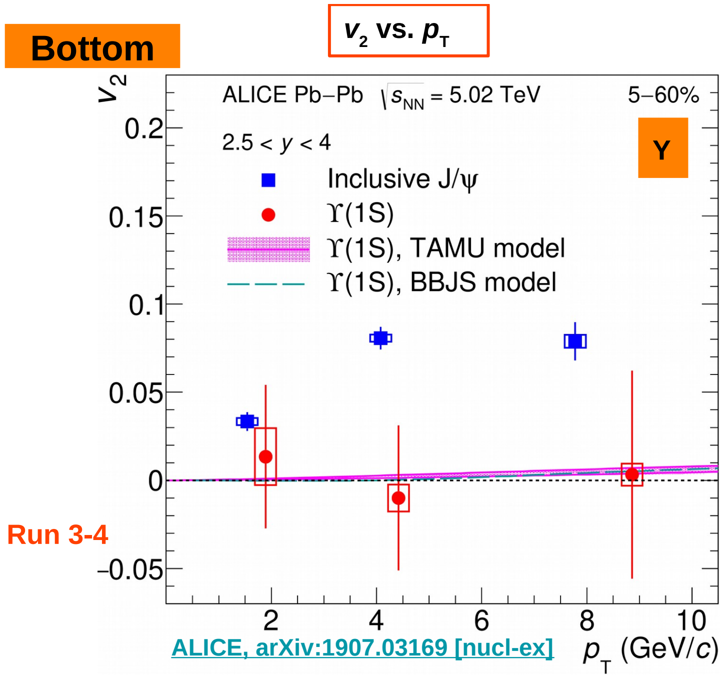
- Large J/ψ v_2 in wide p_T range
- J/ψ inherits elliptic flow of charm quarks
- Additional mechanisms may work for p_T > 4 GeV/c?



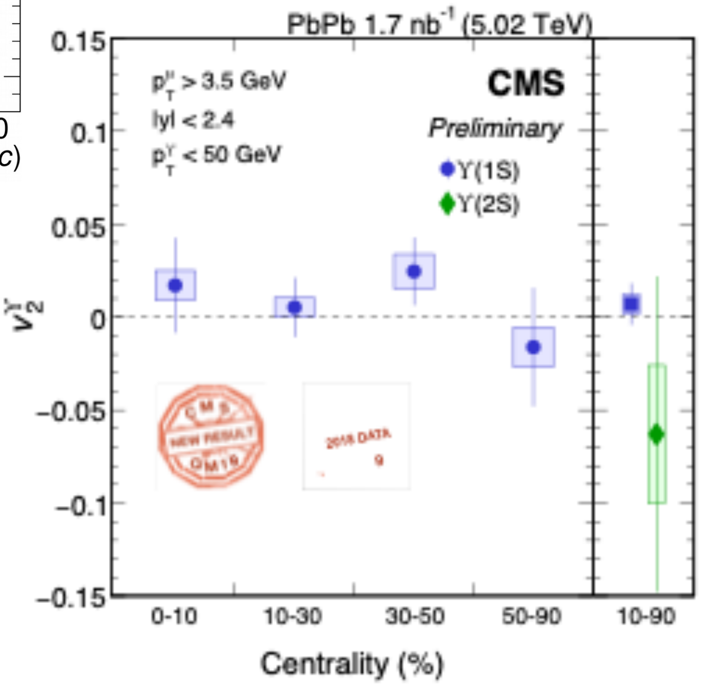
Bottomonium

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





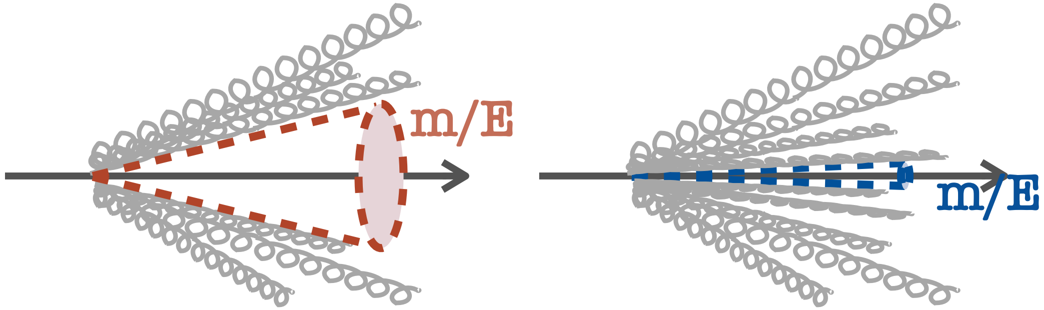
- v_2 of Υ(1S) in Pb+Pb ~zero



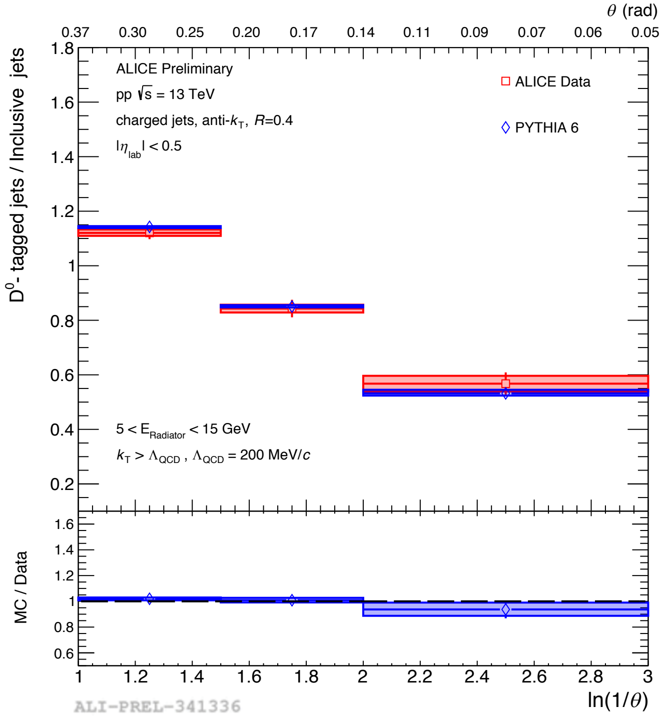
Dead Cone Effect

- 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

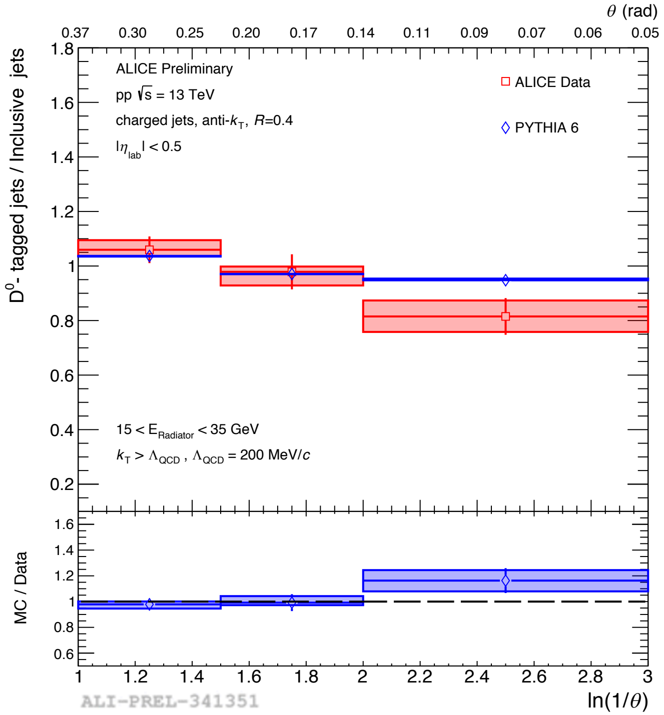
Large parton mass **Small parton mass**



N. Zardoshti , 5 Nov 2019, 09:20



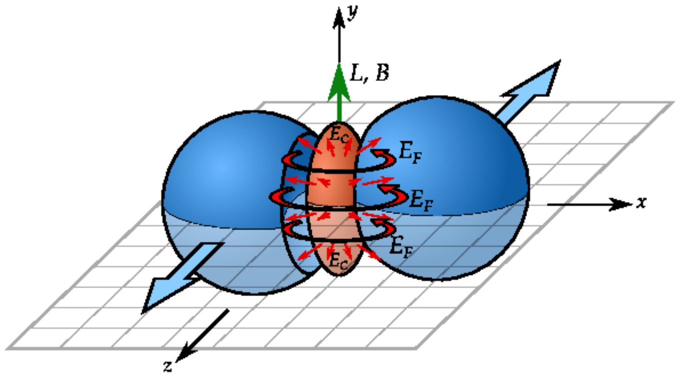
$5 < E_{Radiator} < 15$ GeV

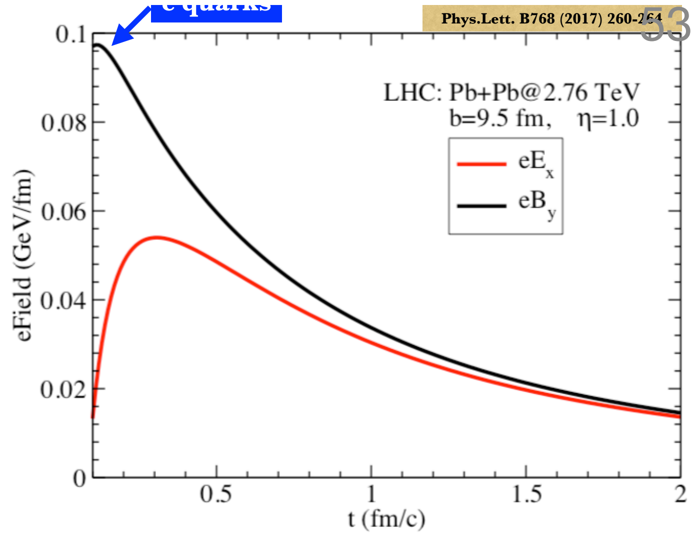


$15 < E_{Radiator} < 35$ GeV

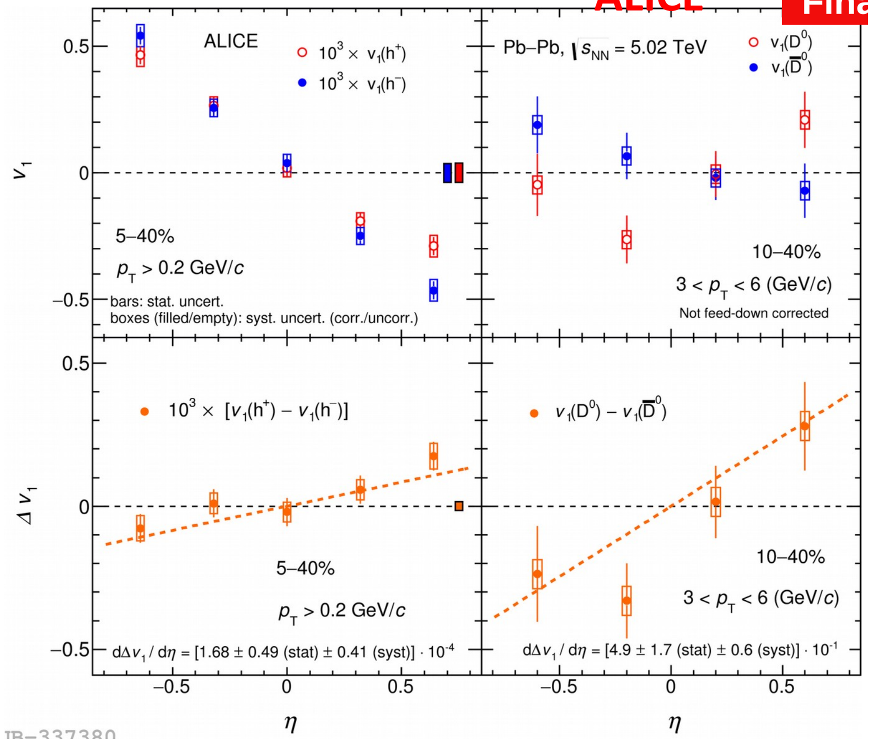
Strong EM Field at Initial Stage

- 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
- dΔv1/dη slope: positive (LHC-ALICE) vs. negative (RHIC-STAR)?

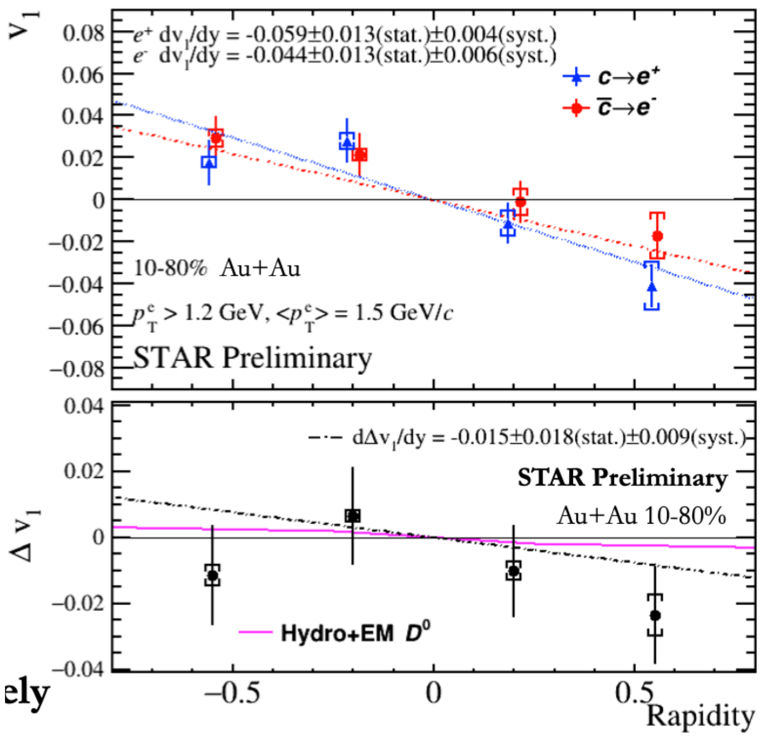




ALICE

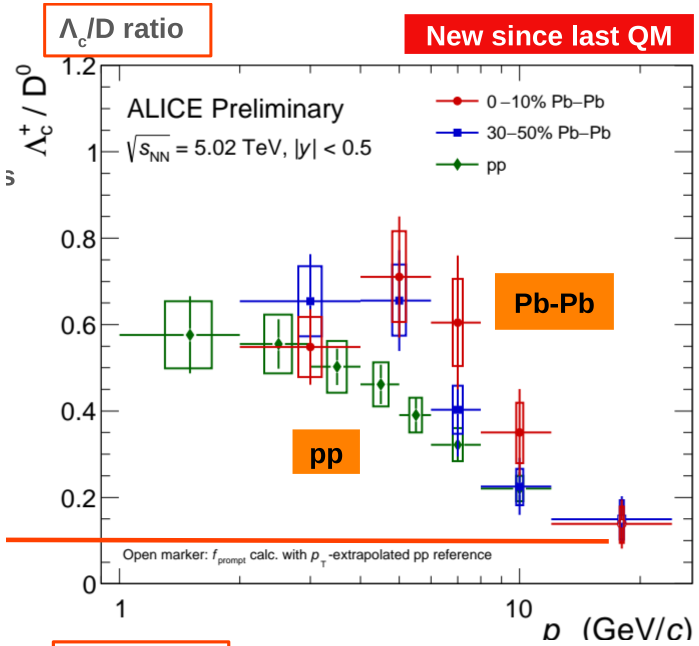


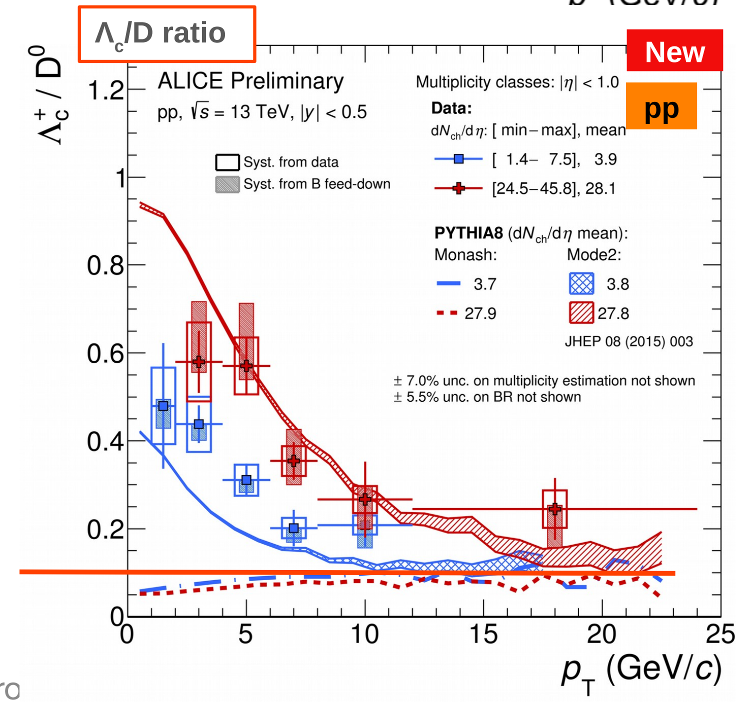
STAR



Λ_c/D Ratio in pp and Pb-Pb Collisions

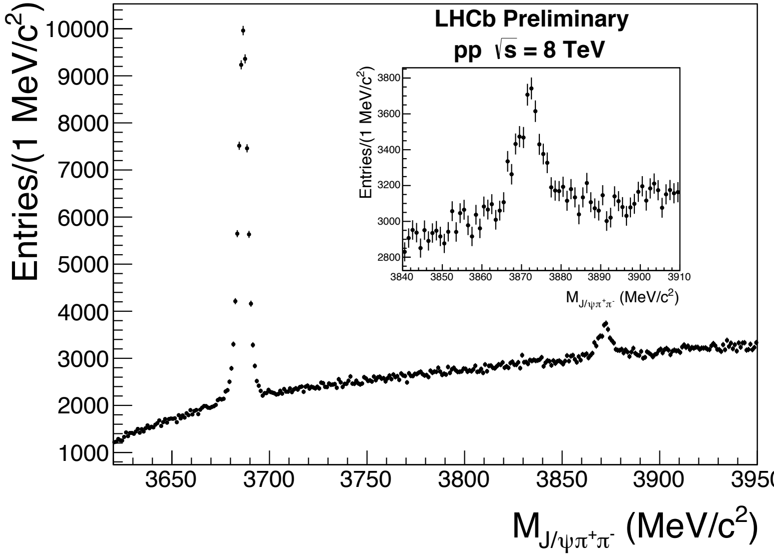
- Sensitive to quark-quark correlation in baryons (and in QGP?)
- Large enhancement in pp and Pb-Pb collisions compared to those in ee and ep collisions
  - We need higher statistics for Pb+Pb collisions
- Multiplicity dependence in pp collisions is compared with Pythia
  - Default Pythia provides the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



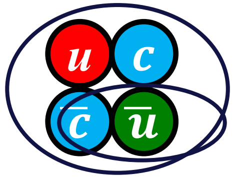


Exotic $c\bar{c}$ States XYZ

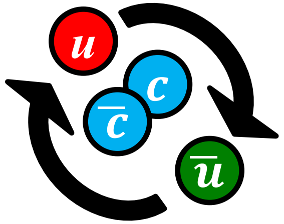
- 20+ new states containing $c\bar{c}$ have been discovered since 2003, which do not fit in the picture of normal charmonium



Compact tetraquark/pentaquark

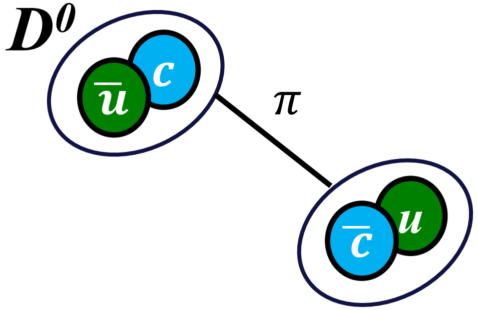


Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



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

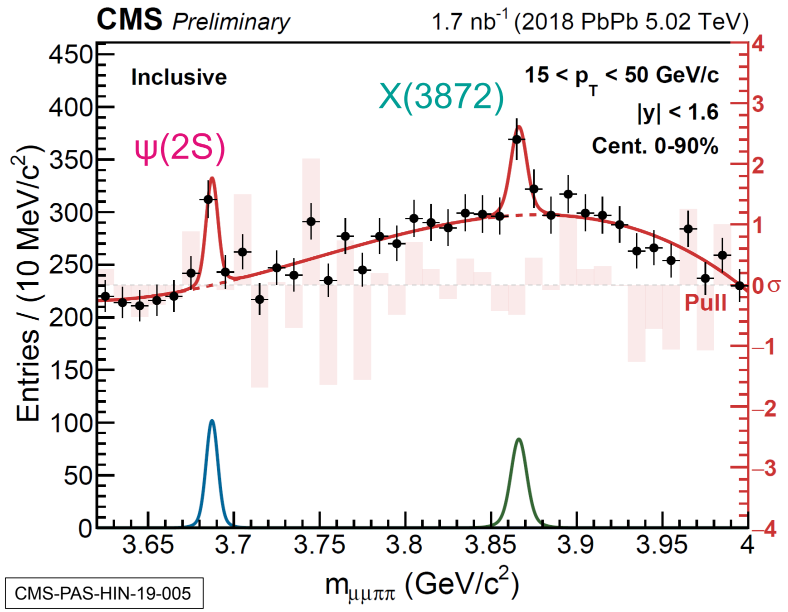
Hadronic Molecules
PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)



Mixtures of exotic + conventional states

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

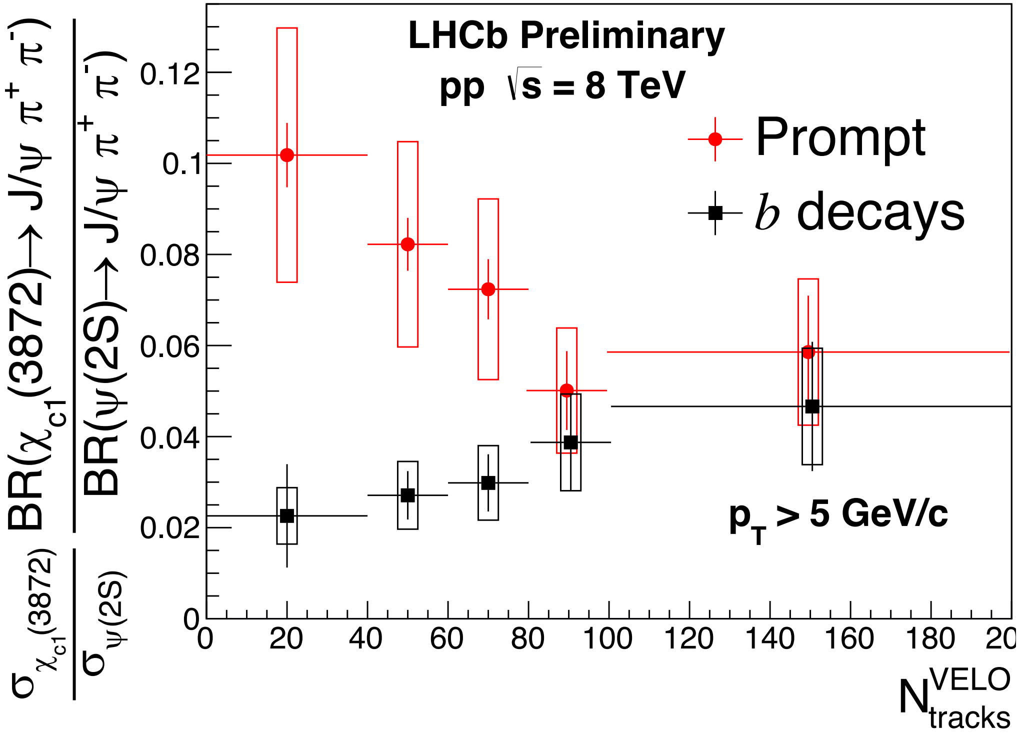
PLB 578 365 (2004)
PRD 96 074014 (2017)

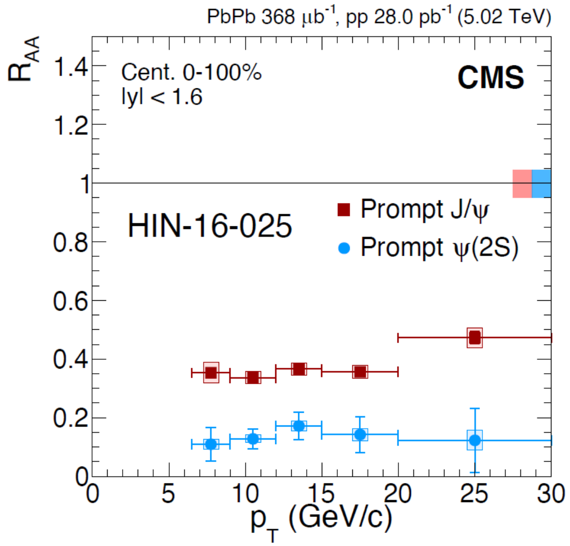


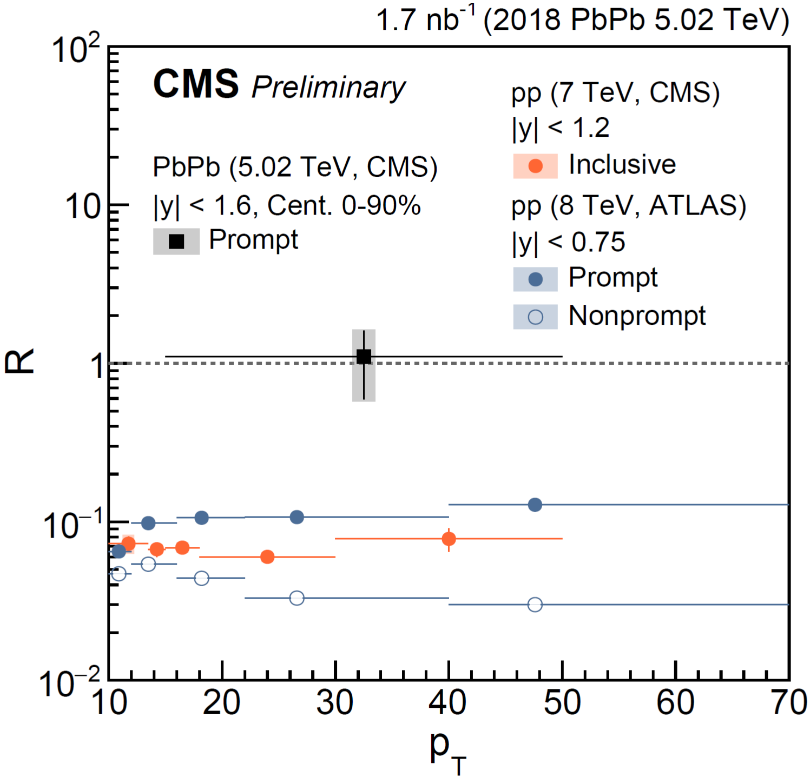
CMS-PAS-HIN-19-005

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



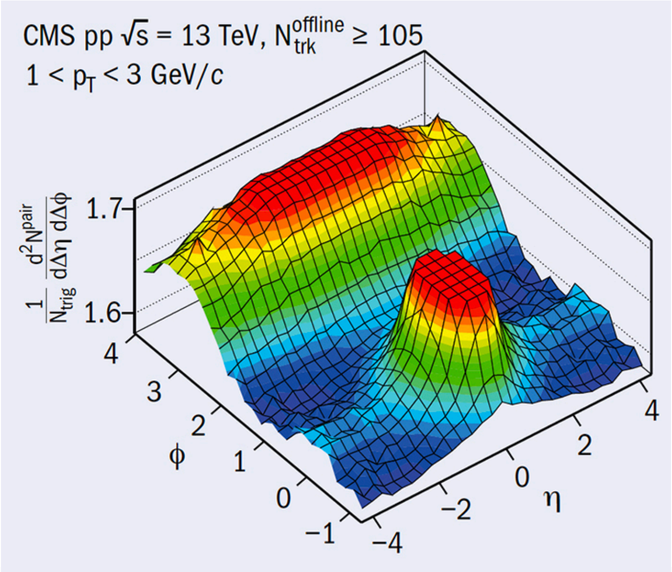


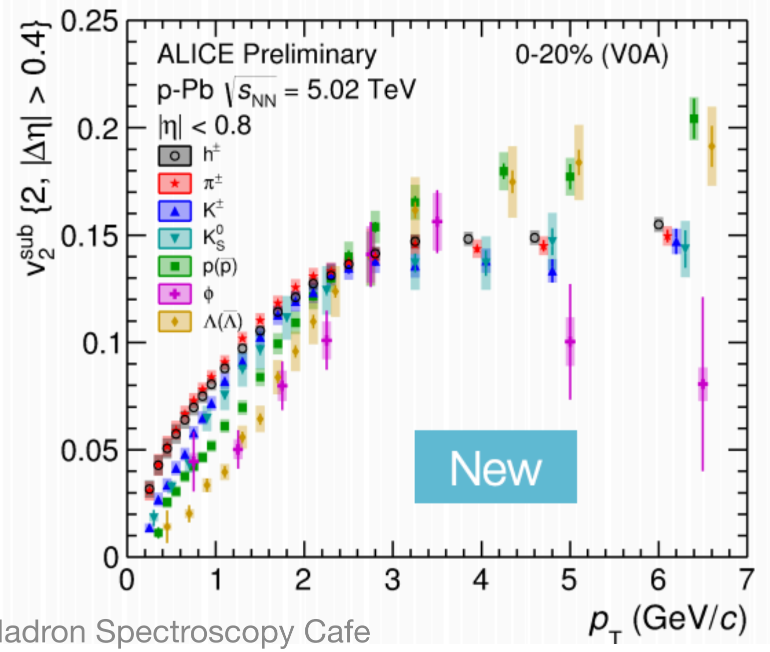


SMALL SYSTEM

A Short Detour to Small System

- p-p and p-A collisions have also been utilized in the study of baryon interaction via femtoscopy
- Behavior consistent to hydrodynamical fluid is seen in violent p-p and p-A collisions
- Understanding the dynamics of small systems are relevant to the study of baryon interaction via femtoscopy

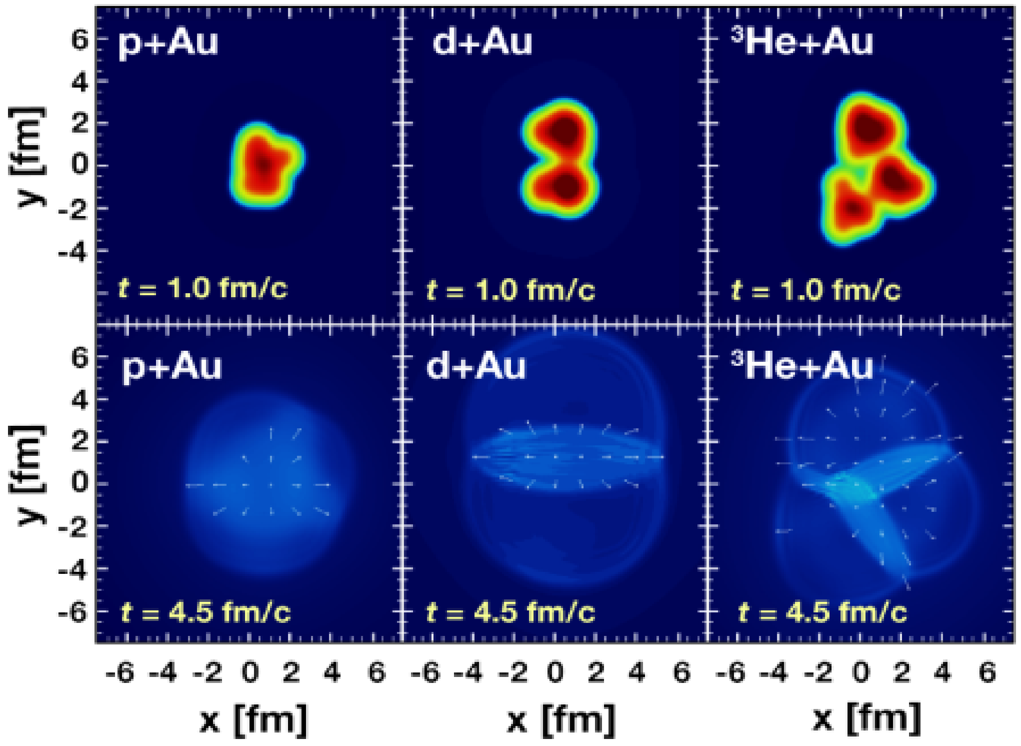




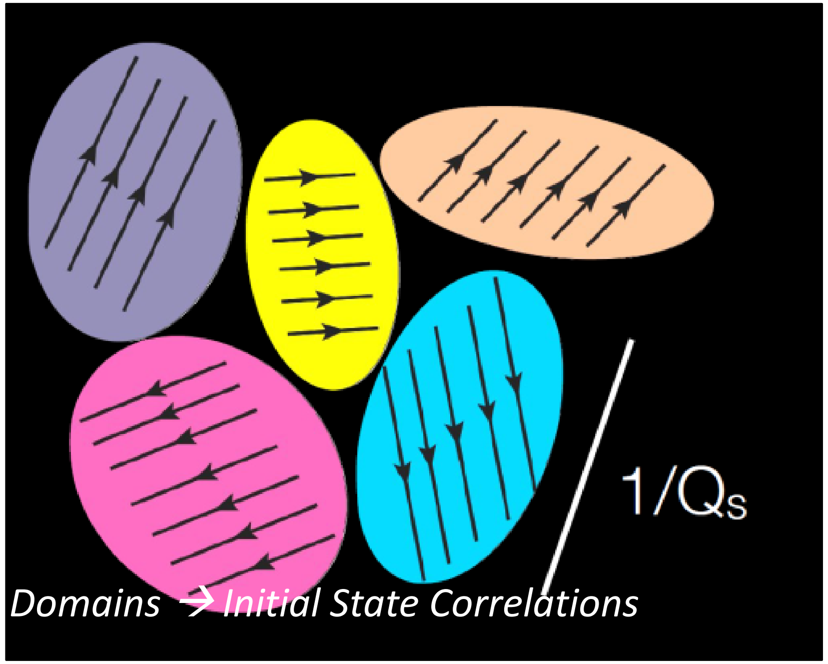
Spatial Correlations in Small Systems

- Two competing views on the origin of spatial correlations in small systems
  - Hydrodynamical fluid, starting from the initial geometry
  - Initial state correlations (due to color domains)

Geometry → Final State Flow

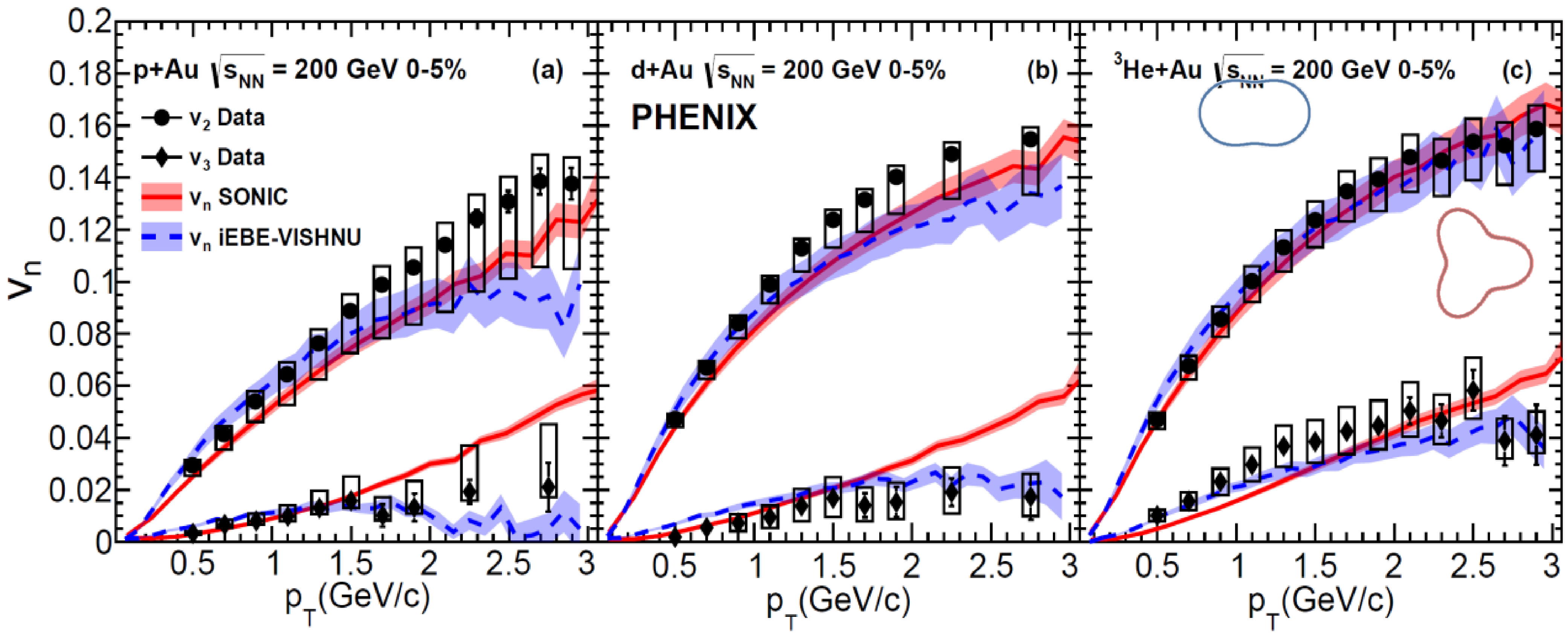


Color Domains → Initial State Correlations



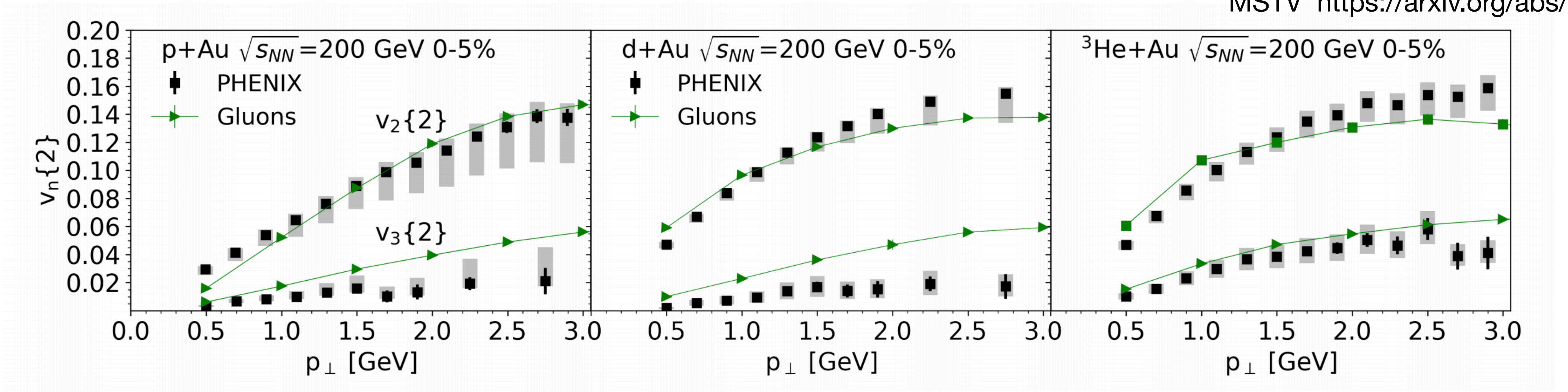
v_n in p+Au, d+Au and ^{3}He+Au by PHENIX

- Good agreement between the experimental results and hydro calculations, which backs up the interpretation with hydro



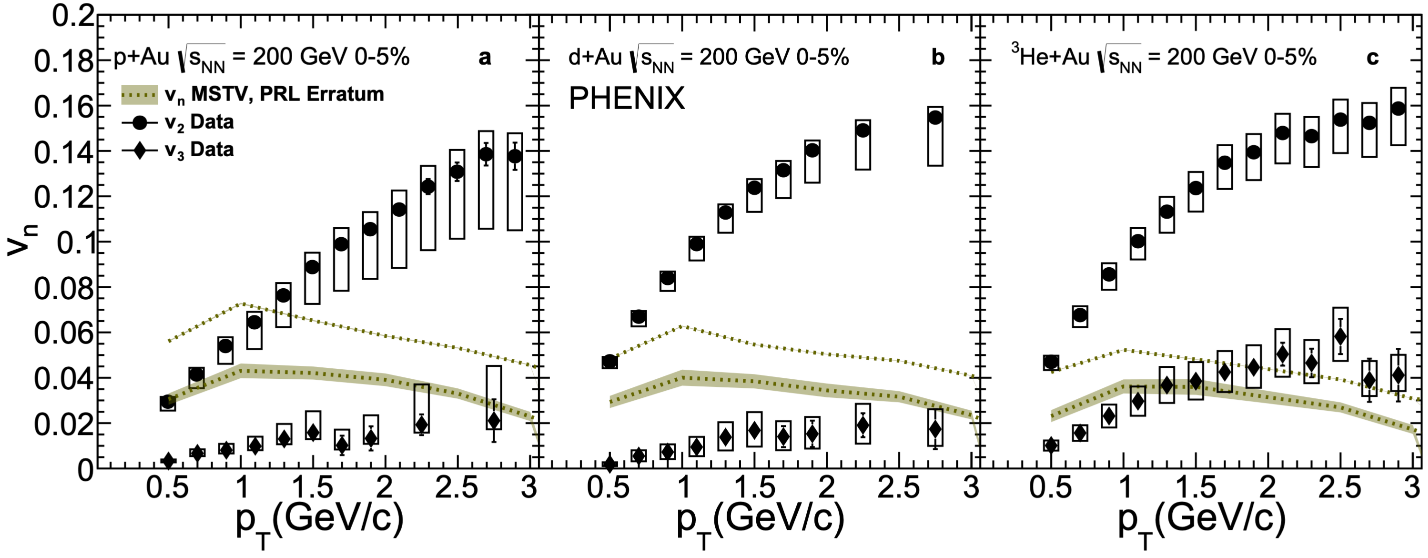
CGC Model

MSTV Phys.Rev.Lett. 121 (2018) no.5, 052301
MSTV Phys.Lett. B788 (2019) 161-165
MSTV https://arxiv.org/abs/1901.10506



Reported to work OK, but trivial erroı
was found in the code

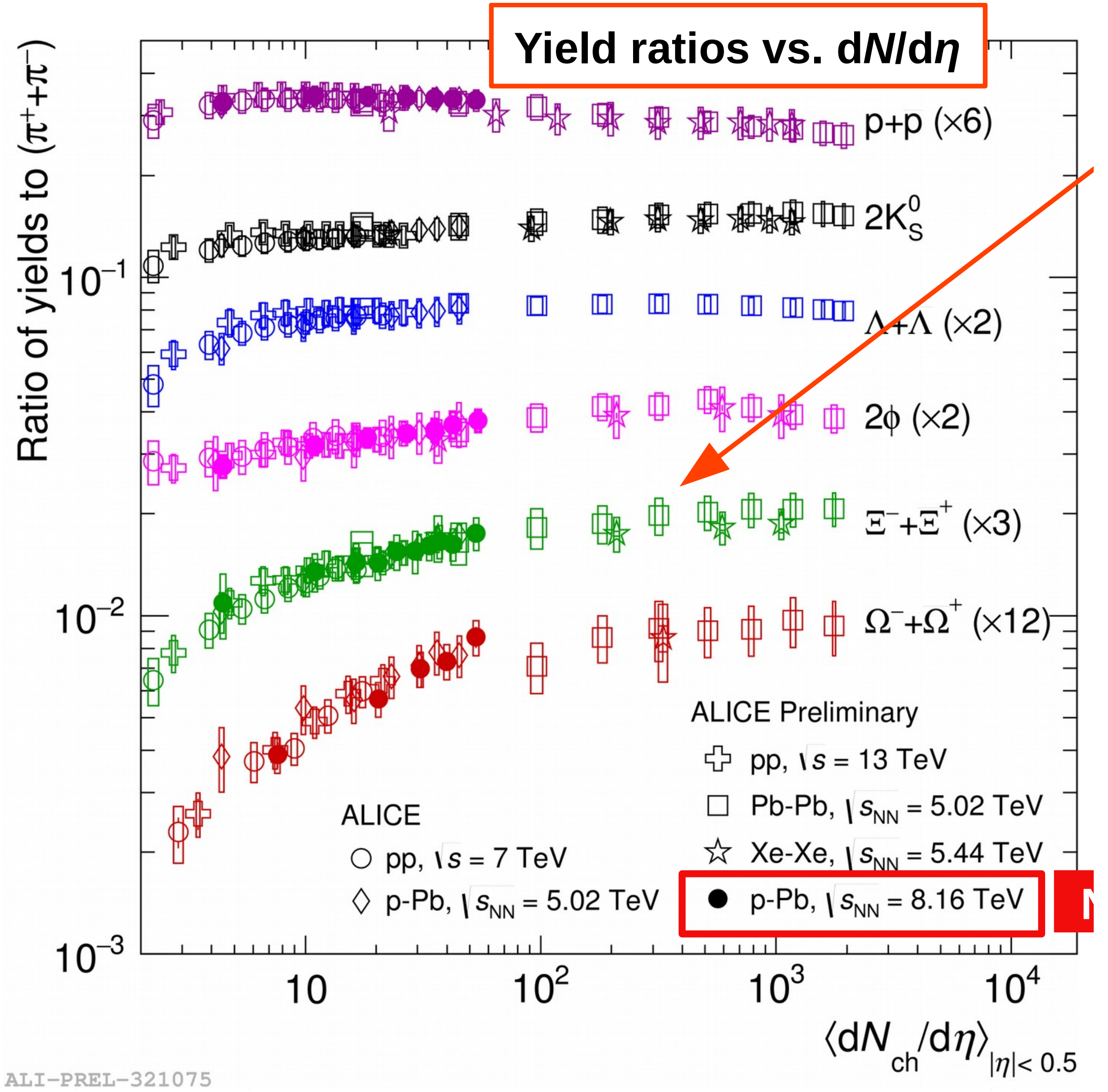
- Erratum: PRL 121 (2018) no.5, 05230
- Corrigendum: PLB788 (2019) 161-16



CGC alone is not enough

Particle Yield vs. $dN_{ch}/d\eta$

- Systematic trend of yield ratios as a function of charged particle multiplicity; from p+p, p+A to A+A
- Strong yield suppression of multi-strange baryons at low multiplicity, i.e. in small systems
  - could be a good probe to study the dynamics of small systems
- Trend is successfully reproduced by the hydro model with dynamical core-corona initialization by Hirano group



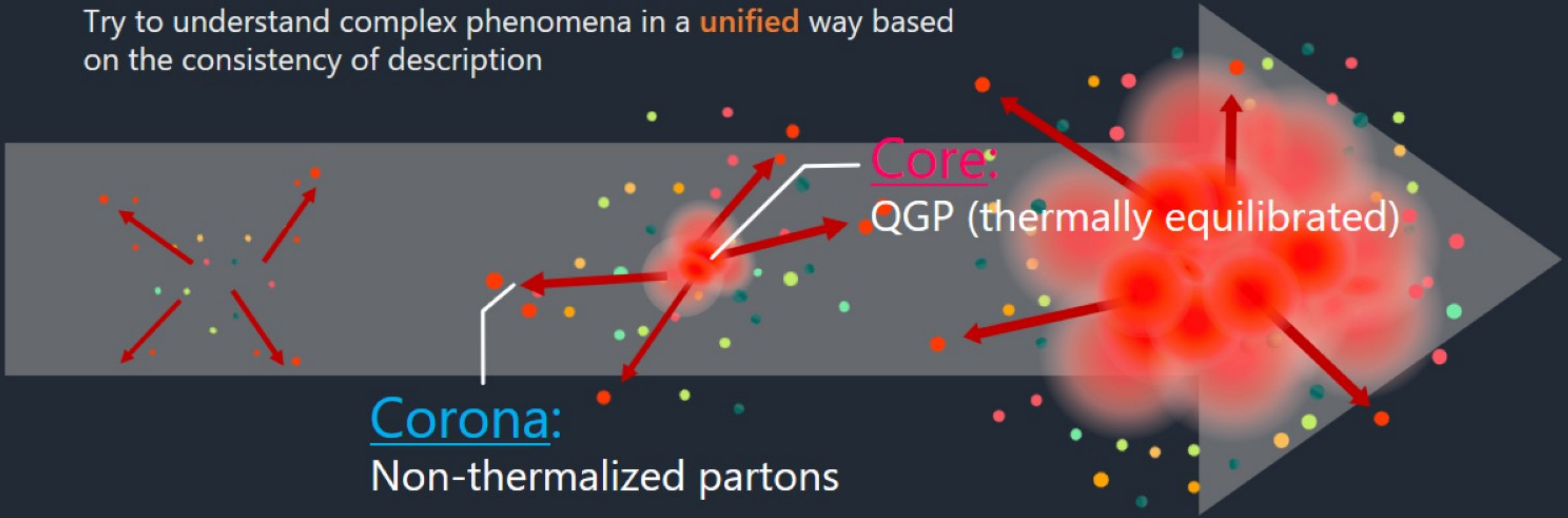
*Core-corona picture: P. Bozek, Acta Phys. Polon. B36, 3071 (2005), K. Werner Phys. Rev. Lett. 98, 152301 (2007)

Motivation

Dynamical core-corona initialization model

Y. Kanakubo *et al.*, arXiv:1910.10556 [nucl-th]
Y. Kanakubo, *et al.*, PTEP 2018 (2018) no.12, 121D01

Try to understand complex phenomena in a **unified** way based on the consistency of description



Current goal: To reveal the detail of QGP signals in small system
→ Have the same origin as ones observed in heavy-ion collisions?