Study of Exotic Particles using High Energy Heavy Ion Collisions

Hideki Hamagaki

(hamagaki_hideki@pilot.nias.ac.jp)

Institute for Innovative Science and Technology
Nagasaki Institute of Applied Science
（IIST@NIAS）

Menu

- Introduction
- Pentaquark and Tetraquark
- Dibaryon and Baryon Interactions
- Bound and Slightly Unbound Dibaryons?
- ALICE Upgrade during LS2 (Long Shutdown 2)
- Summary and Outlook

Recently at colliders, BNL RHIC and CERN LHC, interesting studies have been performed; one on the di-baryons with strangeness and the other on the tetraquarks and pentaquarks.

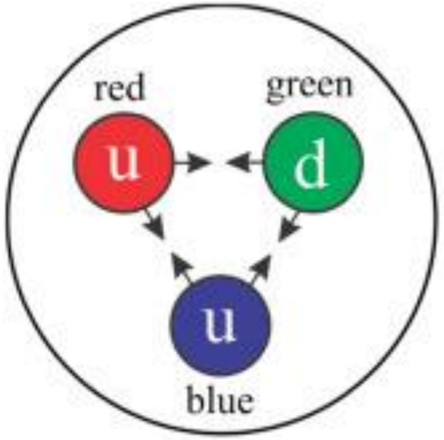
In this seminar, after brief historical introduction of the old studies, I will mainly concentrate on the recent progress on these studies.

I will also mention on the possible studies at ALICE in near future.

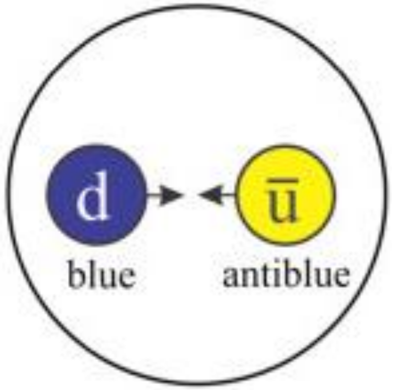
INTRODUCTION

Baryons, Mesons and Beyond

- The quark model allows for the existence of exotic hadrons such as tetraquarks ($qq\bar{q}\bar{q}$) and pentaquarks ($qqq\bar{q}\bar{q}$)
- Until very recently, we have had no evidence on the existence of hadrons beyond baryons (qqq) and mesons ($q\bar{q}$)
- Further larger number of quarks together → dibaryons, strangelet, …, core of neutron star
- Historically, in heavy ion collisions, we started research to find out exotic matter rather than exotic particles at LBL Bevalac.

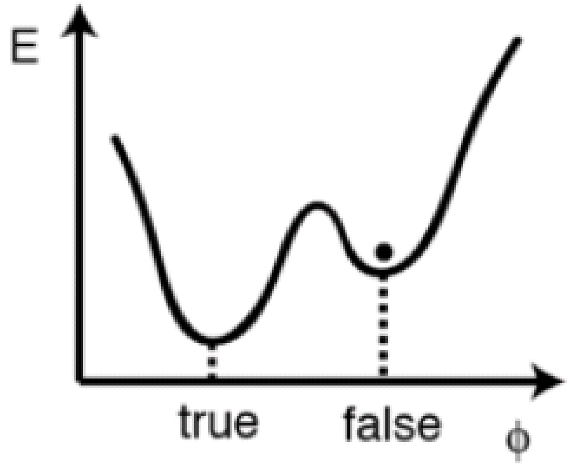


Baryon
(proton, p^+)

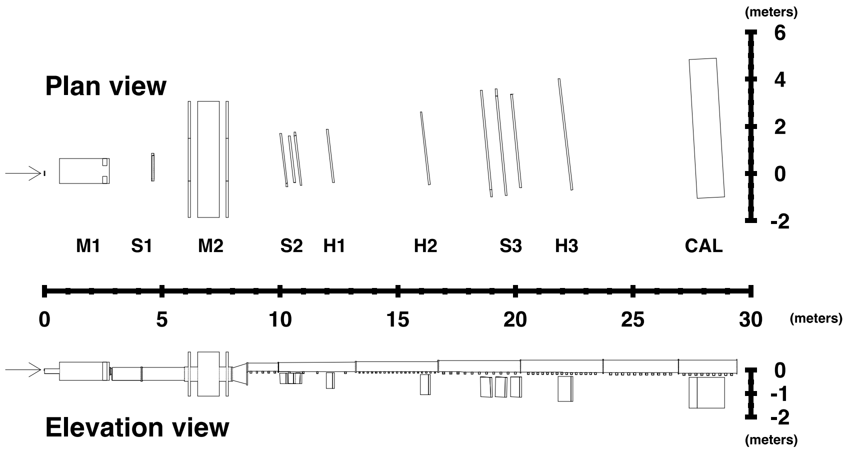


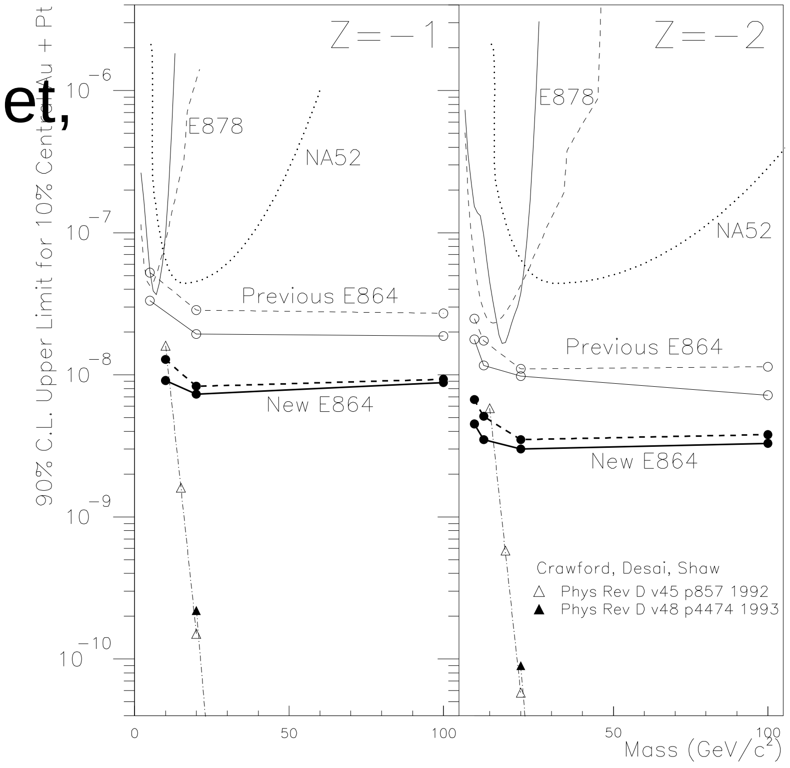
Meson
(negative pion, π^-)

Old History in Brief



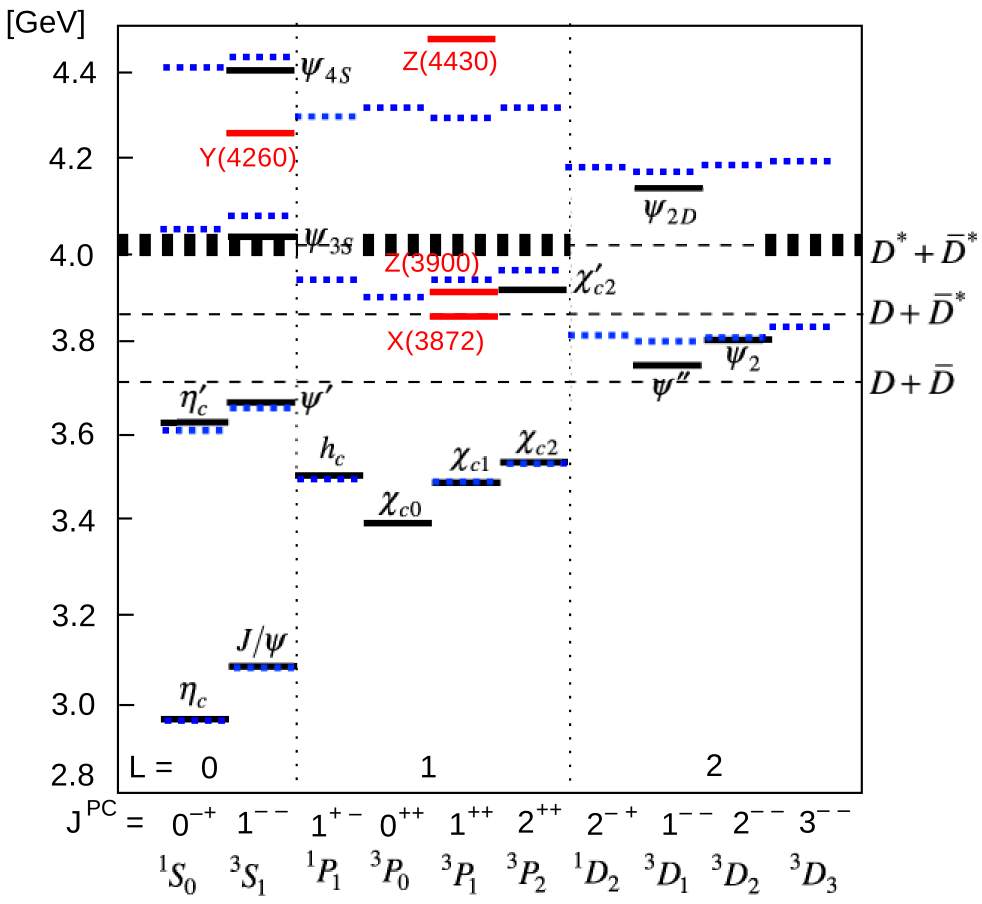
- Studying exotic matter realized under extreme conditions has been the major goal of study with high-energy heavy-ion collisions since LBL-BEVALC (more than 40 years ago)
  - "Exotic Hadronic Matter", such as Lee-Wick matter
  - Interim of neutron star; Pion condensate, Color superconductor
- At BNL-AGS, attempts were made for searching strangelet, an ultimate form of dense nuclear matter.
  - arXiv-9811049v1





Surprise Finding; X, Y, Z

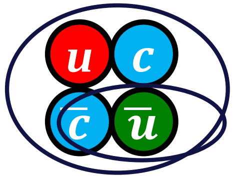
- 20+ new states containing $c\bar{c}$ named as X, Y, Z, have been found since 2003, starting with X(3872) (Belle Collaboration, PRL 91 (2003) 262001)
  - – High statistics e+e− collision data accumulated by B-factory experiments, with original aim of comprehensive study of the CP violation in B meson decays.
- Some X, Y, Z states (red solid bars) and charmonium states (black solid bars) in comparison with a conventional quark model results for $c\bar{c}$ states (blue dashed bars) (PTEP 2016 (2016) no.6, 062C01)



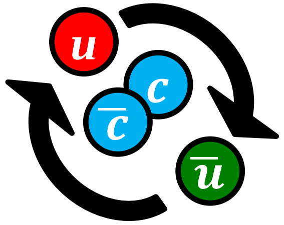
Possible Structure of Exotic $c\bar{c}$ States; XYZ

- X, Y , Z are thought to be candidates of exotic hadrons, which have been attracting a lot of attentions to reveal unvisited areas of QCD.

Compact tetraquark/pentaquark

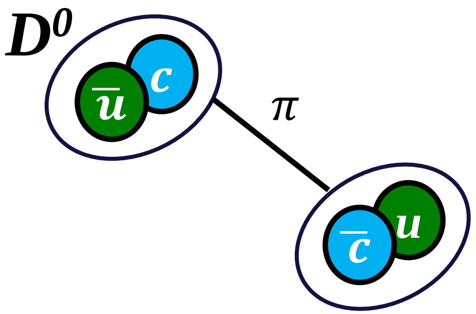


Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



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

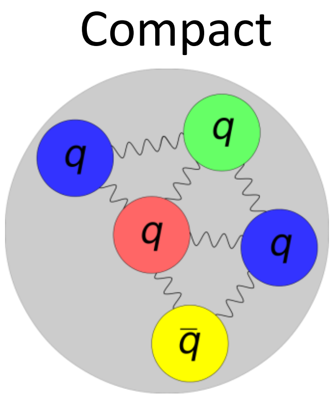
$$X = a\left|c\bar{c}\right\rangle + b\left|c\bar{c}q\bar{q}\right\rangle$$

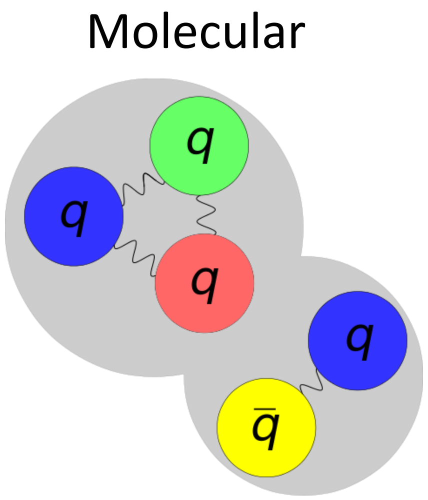
PLB 578 365 (2004)
PRD 96 074014 (2017)

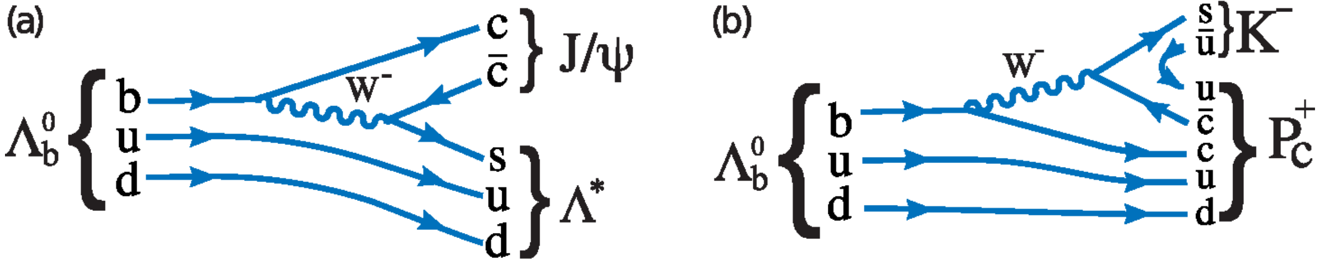
PENTAQUARKS AND TETRAQUARKS

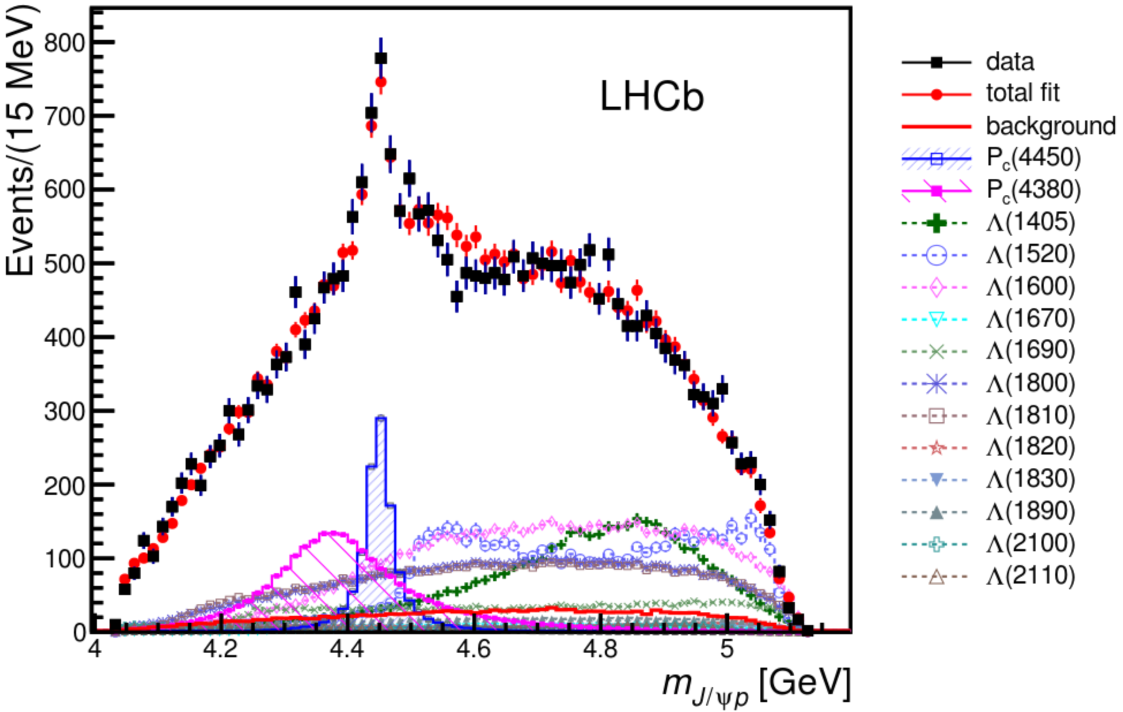
Pentaquarks

- First claim of pentaquark Θ$^+$ ($uudd\bar{s}$) (1540 MeV/c2 (4.6 σ)) from a LEPS experiment in Japan in 2003 (PRL 91, 012002, 2003)
- Several experiments in the mid-2000s also reported discoveries of other pentaquark states (J. of Phys. G. 33, 1–1232)
- Pentaquark with $c\bar{c}$ ($duuc\bar{c}$), reported by LHCb in 2015 (PRL 115 072001 (2015); arXiv1507.03414)
  - $\Lambda_b^0 \to J/\psi\, K^- p$



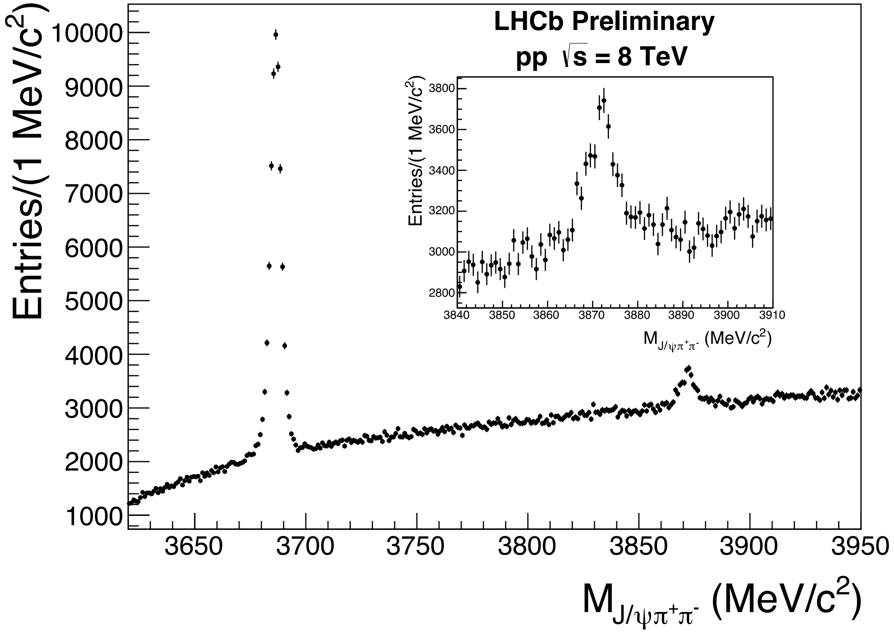


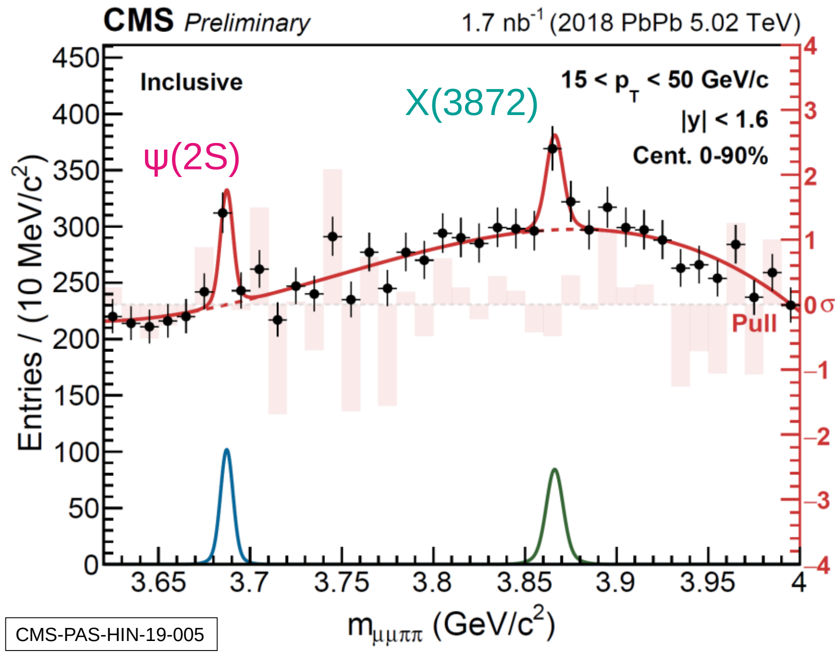




X(3872) at LHC

- Seen in both p+p and Pb+Pb collisions in the decay channel, $J/\psi\,\pi^{+}\pi^{-}$
- Same decay channel for $\Psi(2S)$

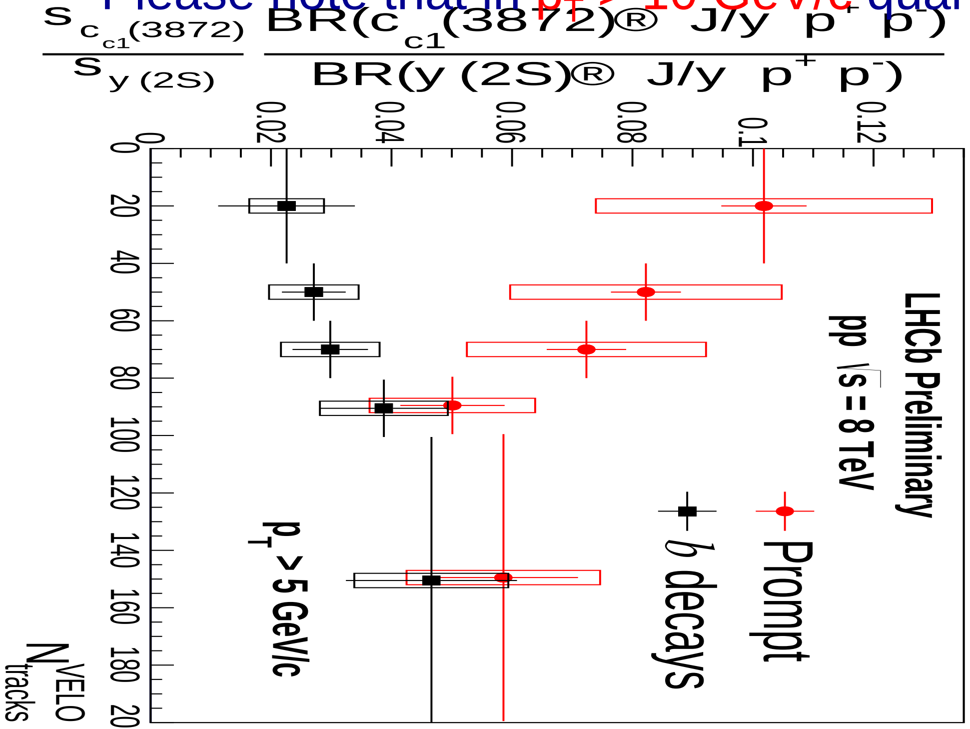


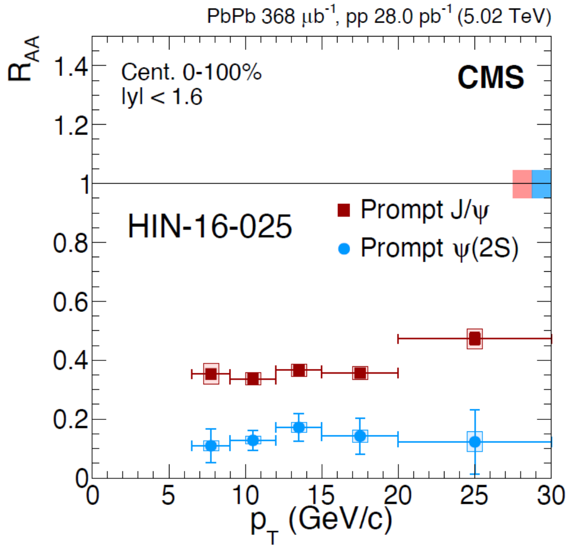


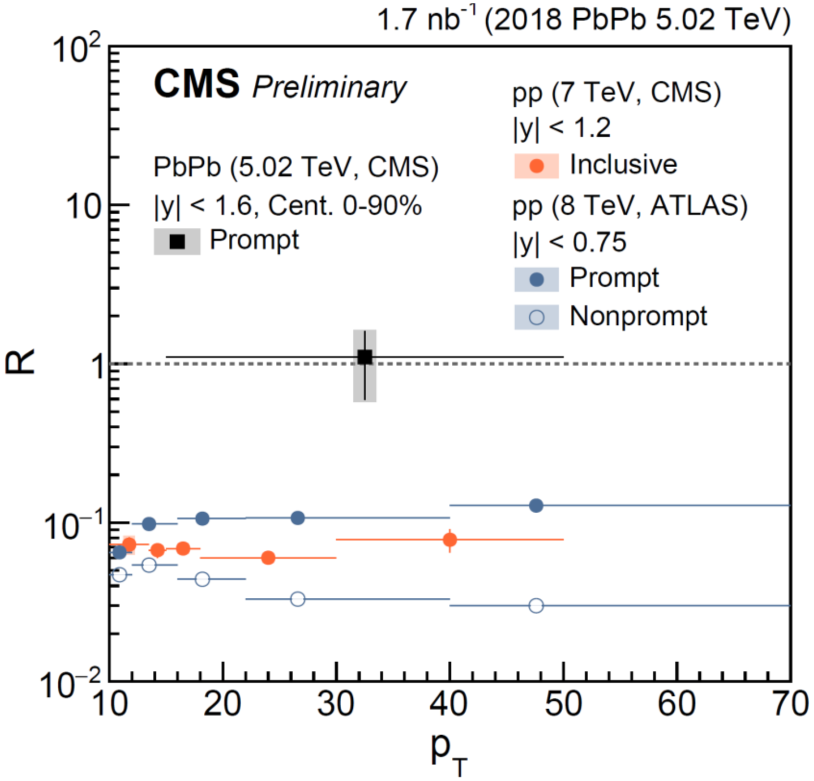
CMS-PAS-HIN-19-005

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

- In pp: $X(3872)/\psi(2S)$ ratio ~ 0.1 or less; larger suppression at higher 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

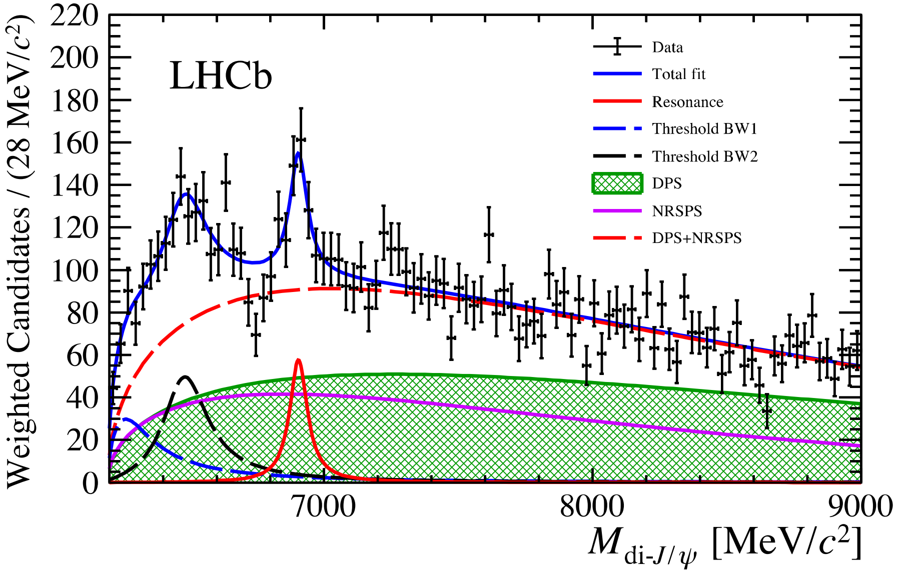


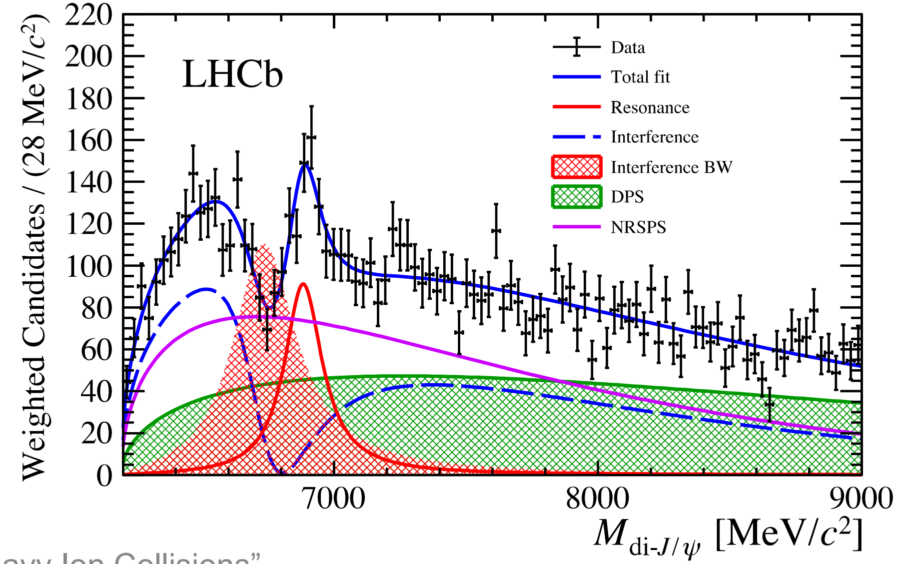




New Tetraquark; X (6900)

- Tetraquark states comprising only bottom quarks, T_{bbbb}, have been searched for by LHCb (JHEP 10 (2018) 086, arXiv:1806.09707) and CMS (arXiv:2002.06393), with no significant signals so far.
- X(6900); four-charm state, T_{cccc}, was reported by LHCb (arXiv:2006.16957), which disintegrate into a pair of charmonium states such as J/ψ mesons, with each consisting of a cc pair.
- Mass and Width obtained with the two models:
  - m[X (6900)] = 6905 ± 11 ± 7 MeV/c2, with Γ[X(6900)] = 80 ± 19 ± 33 MeV,
  - m[X (6900)] = 6886 ± 11 ± 11 MeV/c2, with Γ[X(6900)] = 168 ± 33 ± 69 MeV.





DIBARYON AND BARYON INTERACTION

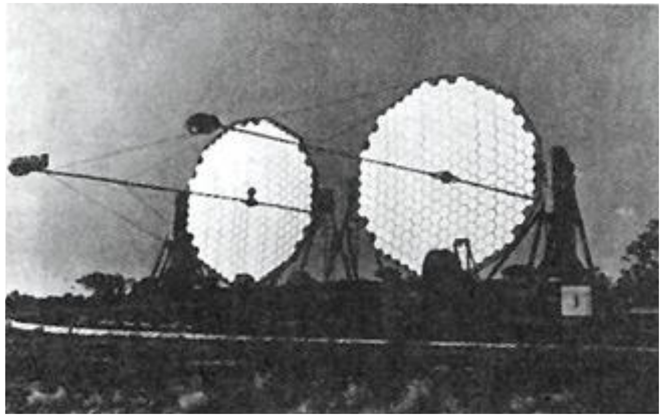
DiBaryon; a Type of Exotic Particle

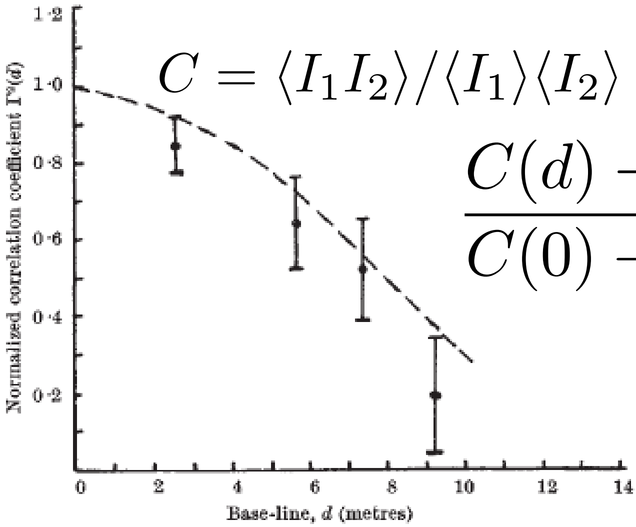
- Deuteron = First and still a unique dibaryon so far confirmed
- H-particle: 6-quark state (uuddss = Λ+Λ or Ξ+N)
  - Predicted by Jaffe ('77))
  - Suggested to be a resonance by the experiment (Yoon+ ('07))
  - Could be a bound state of Ξ+N (by HAL QCD ('16))

- Di-Baryon search and studies of baryon-baryon interaction in the extended space of flavor SU(3), that is, ΛN, ΣN, ΛΛ, ΞN ..., is drawing strong attention recently
  - Large push coms from the recent lattice QCD; baryon interaction can be calculated at almost physical point
  - Pioneering works by STAR experiment at BNL RHIC
  - LHC ALICE experiment is catching up very quickly

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

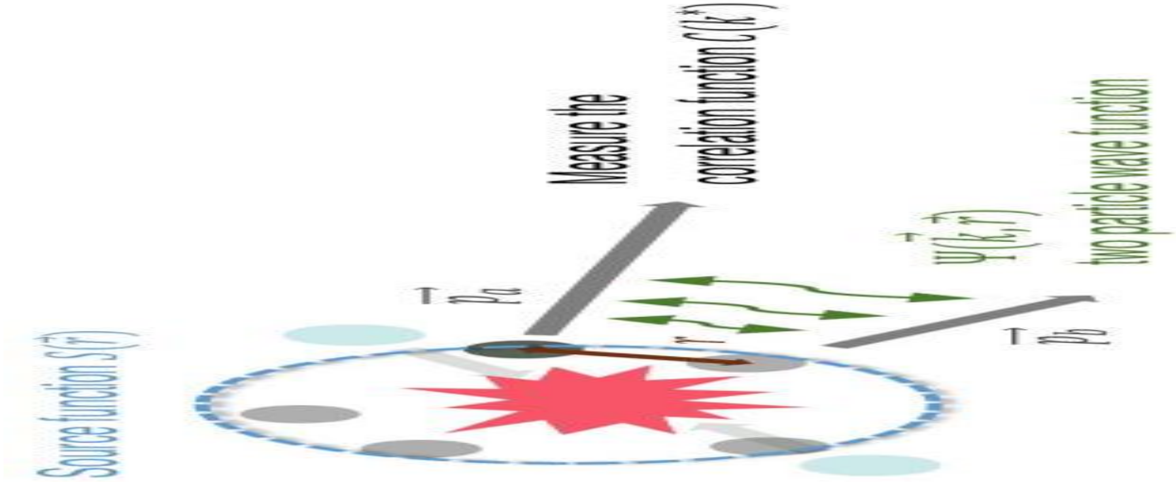


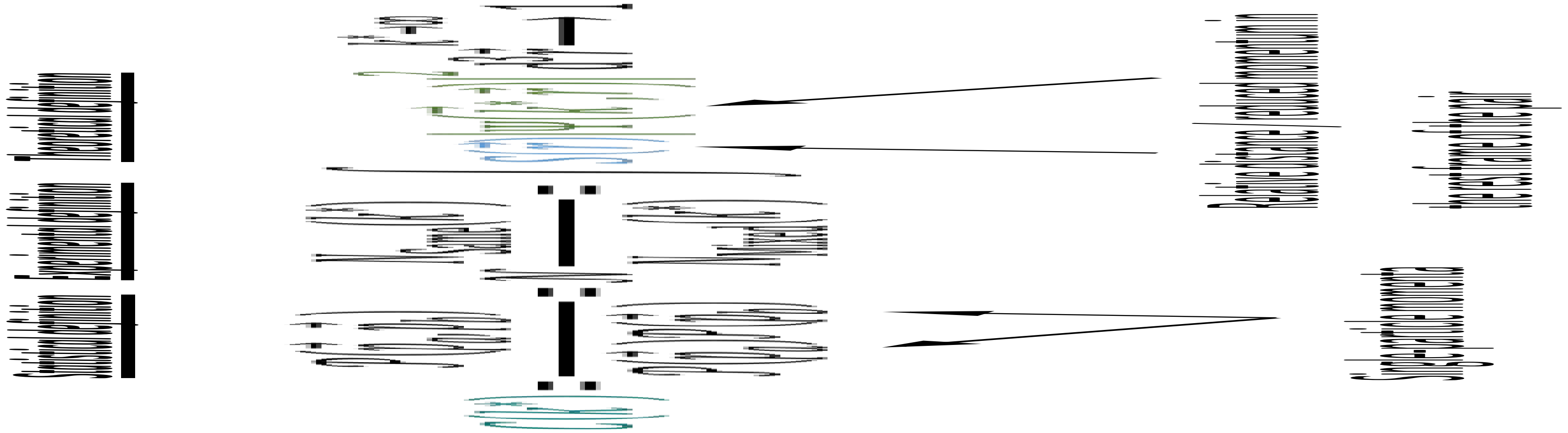


$$C = \langle I_1 I_2 \rangle / \langle I_1 \rangle \langle I_2 \rangle$$

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

Two Particle Correlation





Static/Spherical Source:

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

Asymptotic wave function:

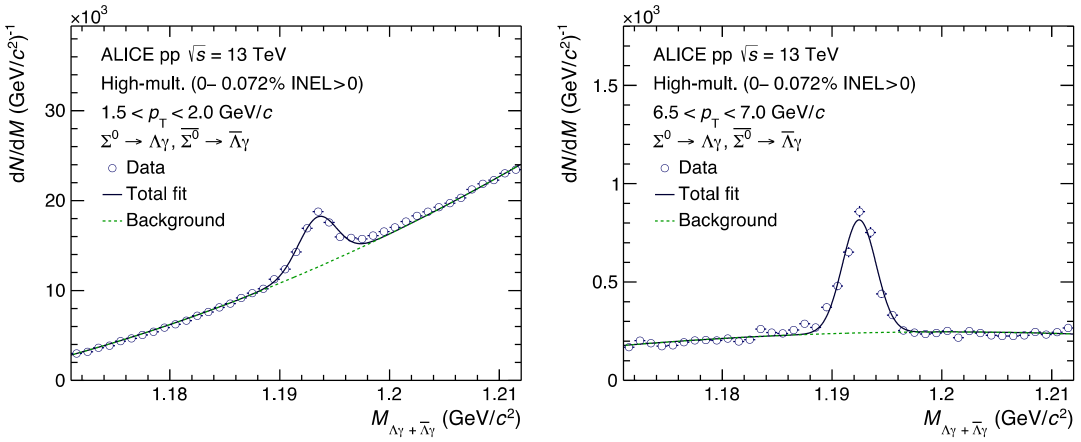
$$c_Q(r) \sim \sin(Qr + \delta)/(Qr)$$

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

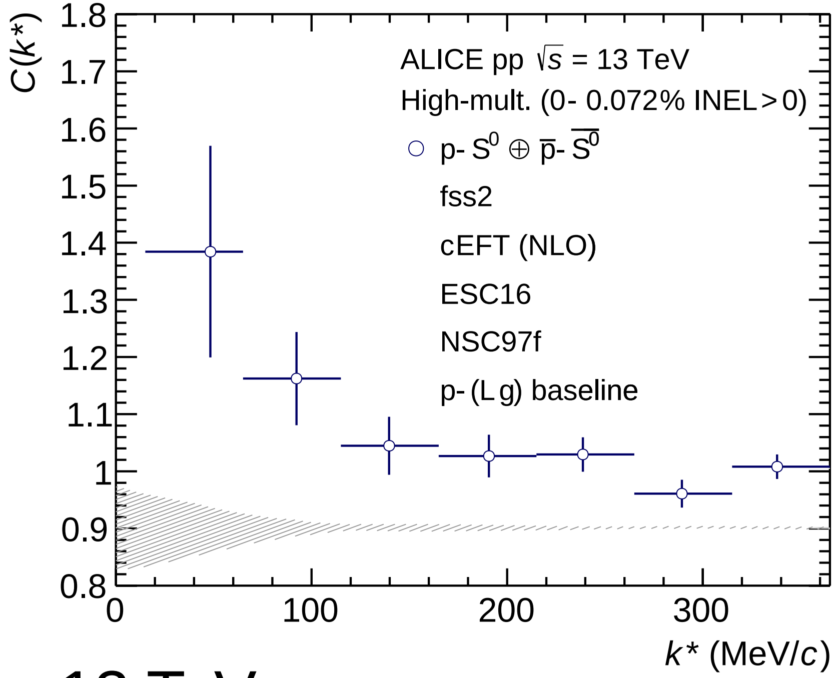
R. Lednický, VL Lyuboshitz;
Sov. J. Nucl. Phys. 35 (1982)
770−778

S = -1 system: p-Σ^0 Correlation

arXiv:1910.14407



γ: measured via external conversion



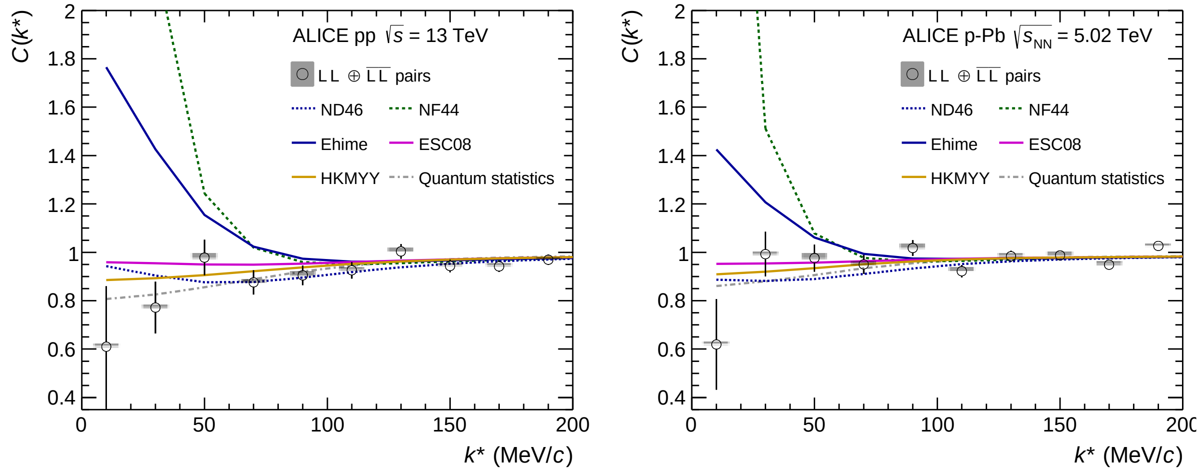
- p–Σ^0 interaction in high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV
- p–Σ^0 correlation function is consistent with the p–(Λγ) baseline ((0.2−0.8)σ)
  → indicating the presence of an overall shallow potential
- Present data cannot discriminate between the different models

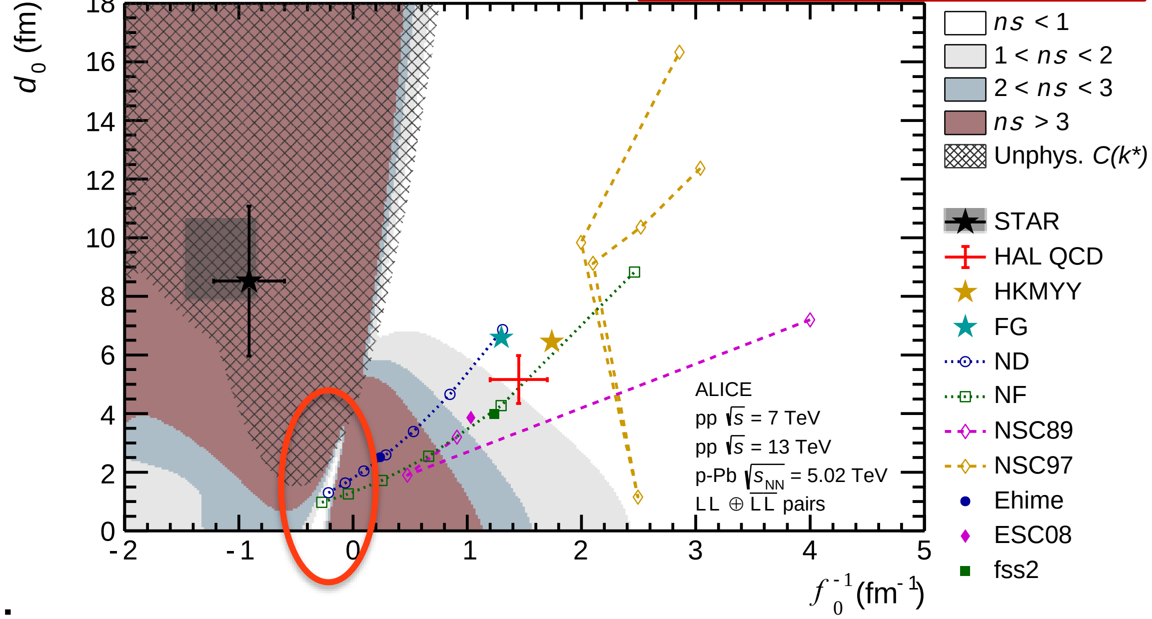
→ Two orders of magnitude larger data samples (expected from Run3&4) will provide tighter constraint to the models on the N–Σ sector

S = -2: ΛΛ Correlation in p+p & p+Pb Collisions

Phys. Lett. B797 (2019) 134822.

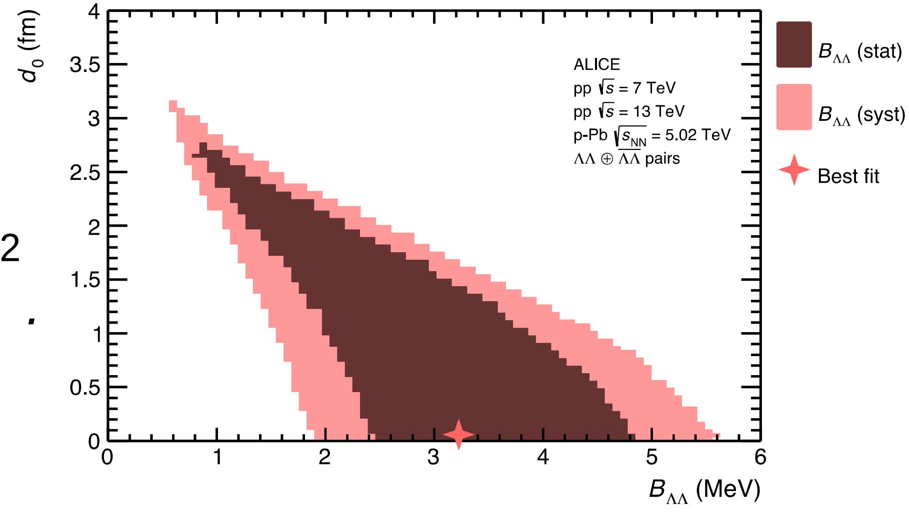
Phys. Rev. C 99, 024001 (2019)





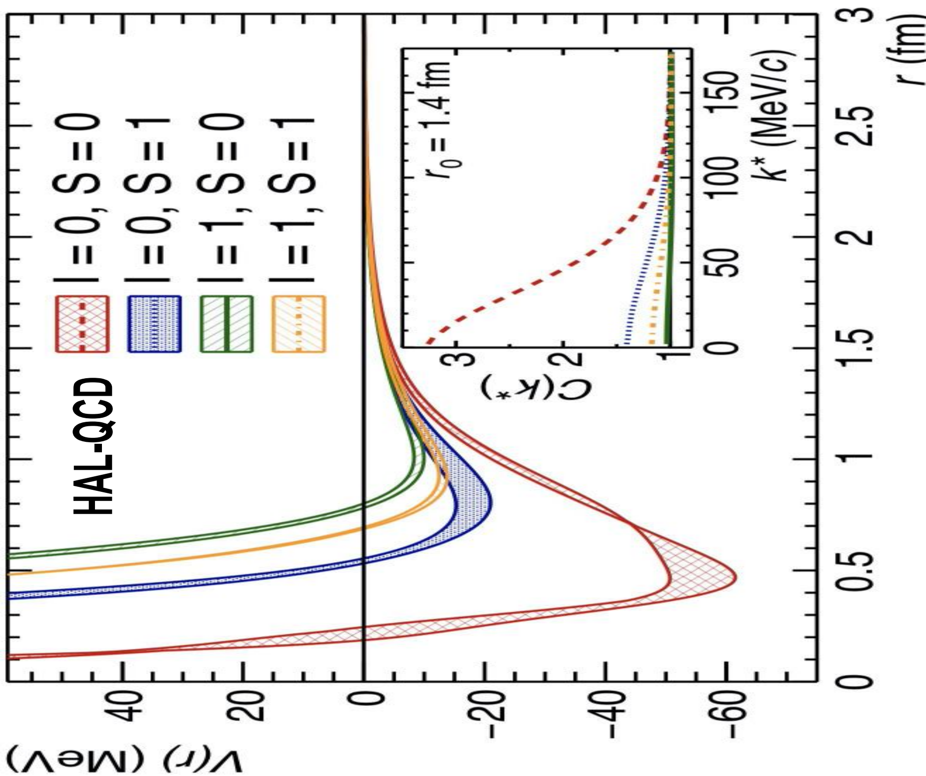
- Pioneering work by STAR collaboration
- Correlation function is very flat → allowed region for scattering parameters, d_0 and f_0^{-1},is very large
- Possible bound state in the region at slightly negative f_0^{-1} and $d_0 < 4$

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

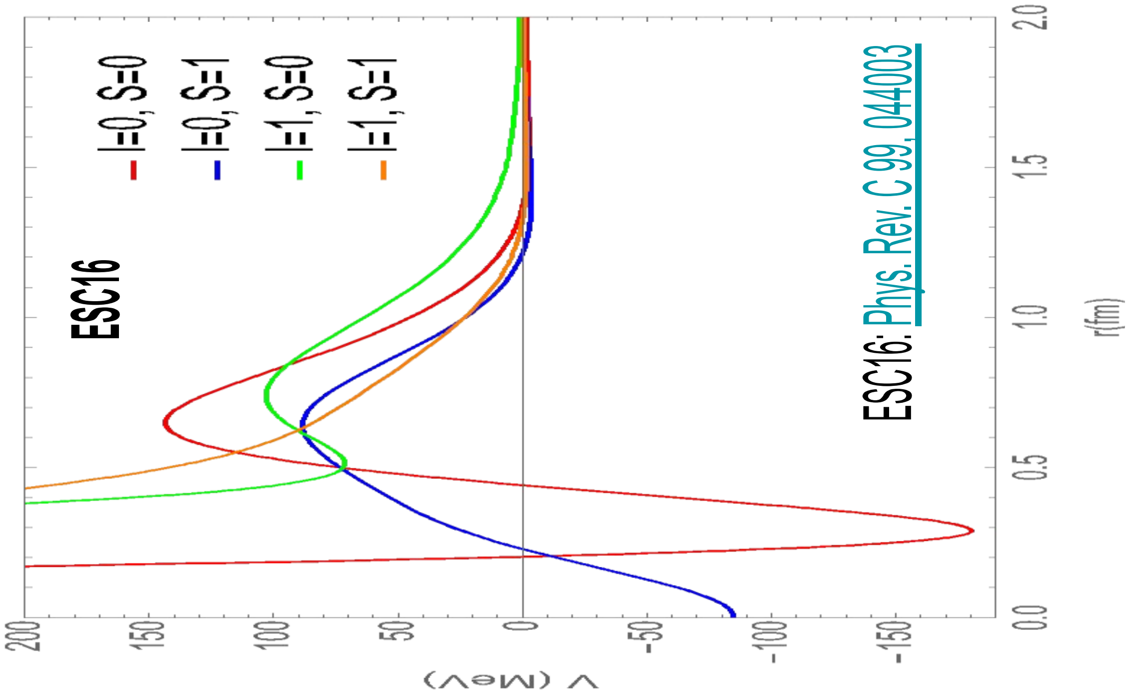


- Higher statistics at low k* region in Run 3

S = -2 System: p-Ξ$^-$ Correlation



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



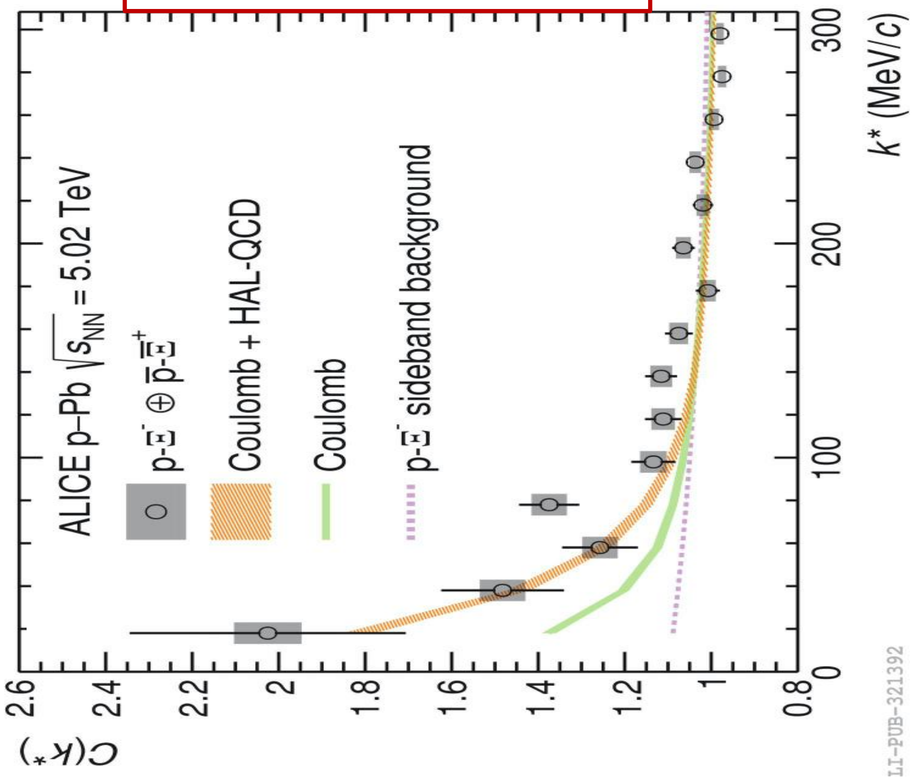
ESC16: Phys. Rev. C 99, 044003

ESC16: Potential by Nijmegen group

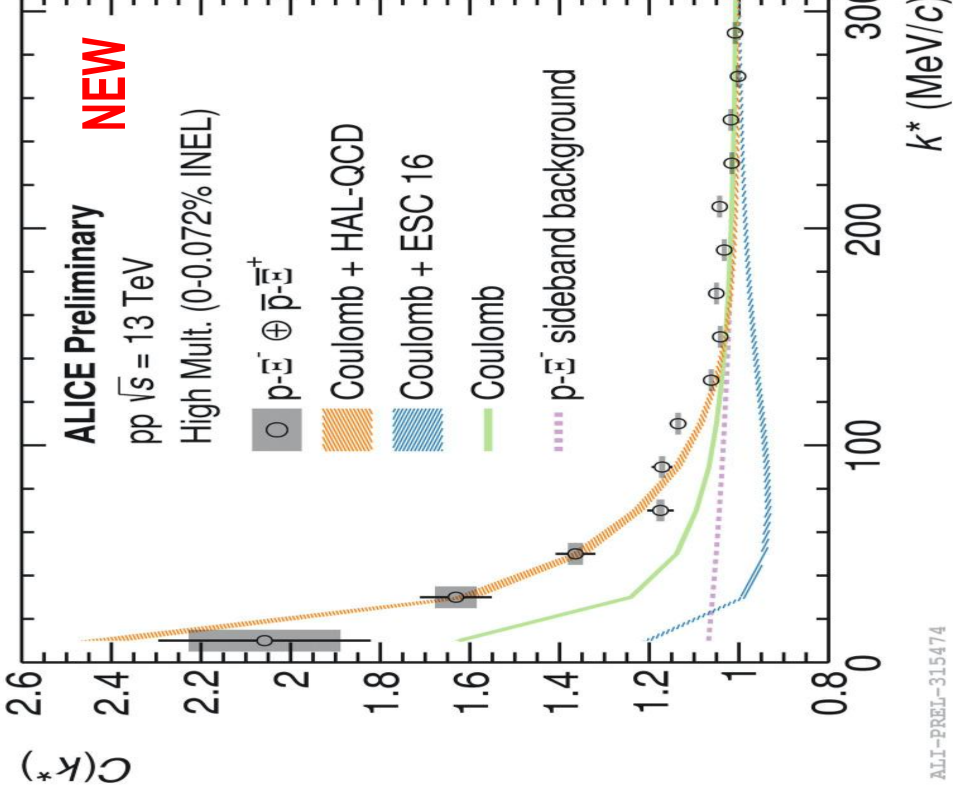
$$
\begin{aligned}
C_{\mathrm{p}-\Xi^-} &= \frac{1}{8} C_{\mathrm{N}-\Xi}\left(\mathrm{I}=0,\, \mathrm{S}=0\right) + \frac{3}{8} C_{\mathrm{N}-\Xi}\left(\mathrm{I}=0,\, \mathrm{S}=1\right) \\
&\quad + \frac{1}{8} C_{\mathrm{N}-\Xi}\left(\mathrm{I}=1,\, \mathrm{S}=0\right) + \frac{3}{8} C_{\mathrm{N}-\Xi}\left(\mathrm{I}=1,\,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

S = -2 System: p-Ξ^- Correlation

Phys. Rev. Lett. 123, 112002

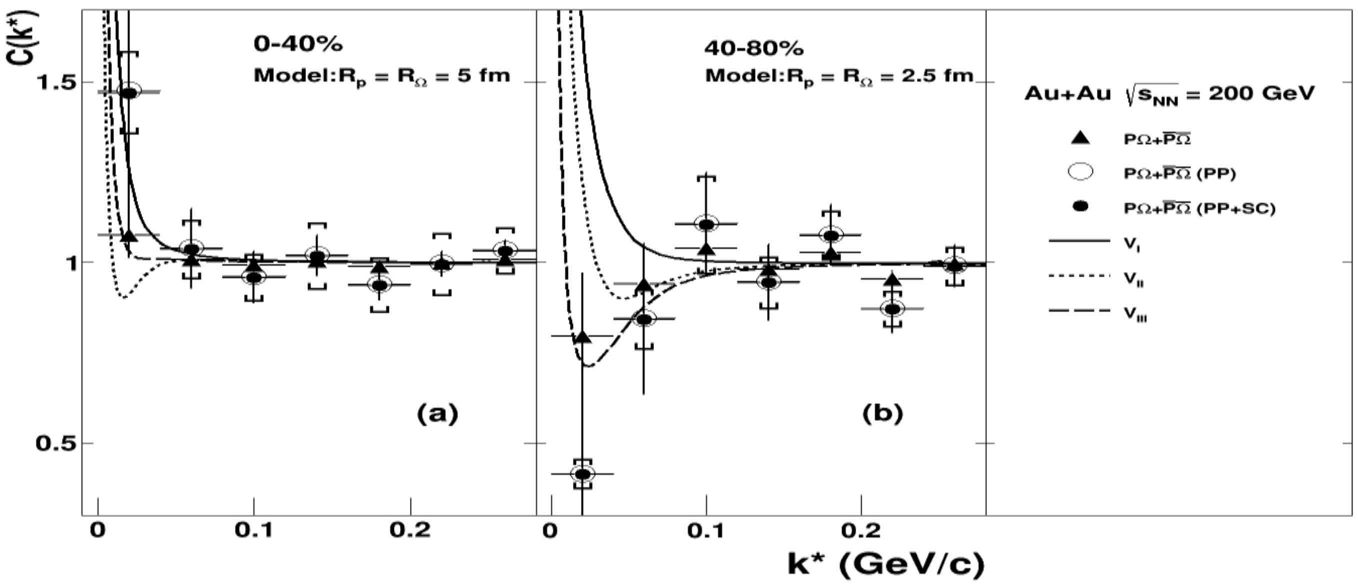


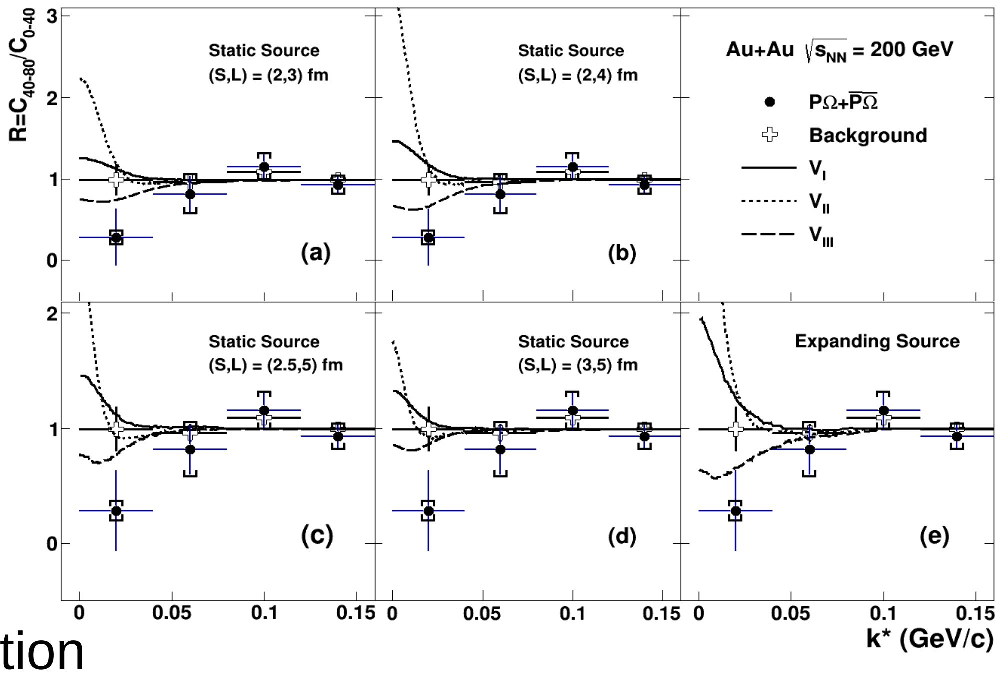
Presented in QM2019@Wuhan



- 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

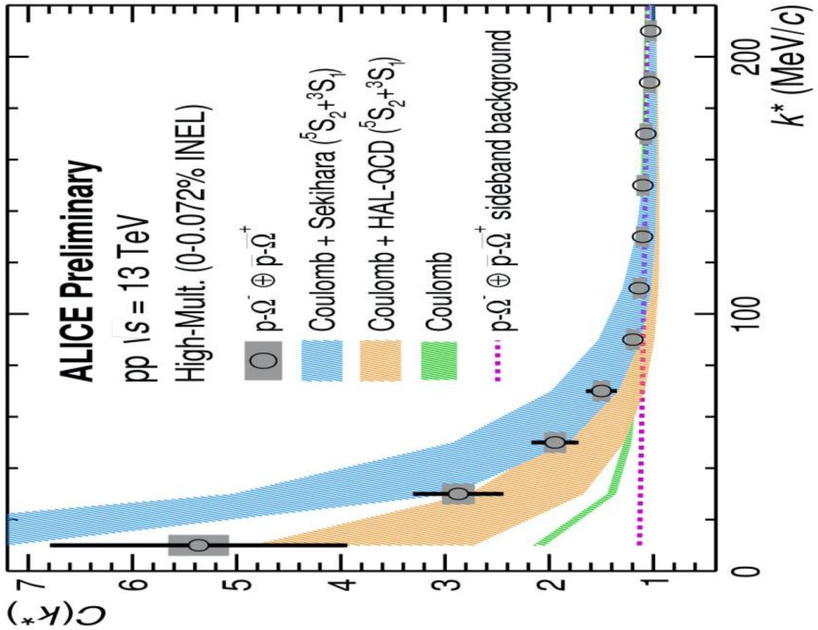
S = -3 System: STAR $p\Omega^-$ Correlation in Au+Au

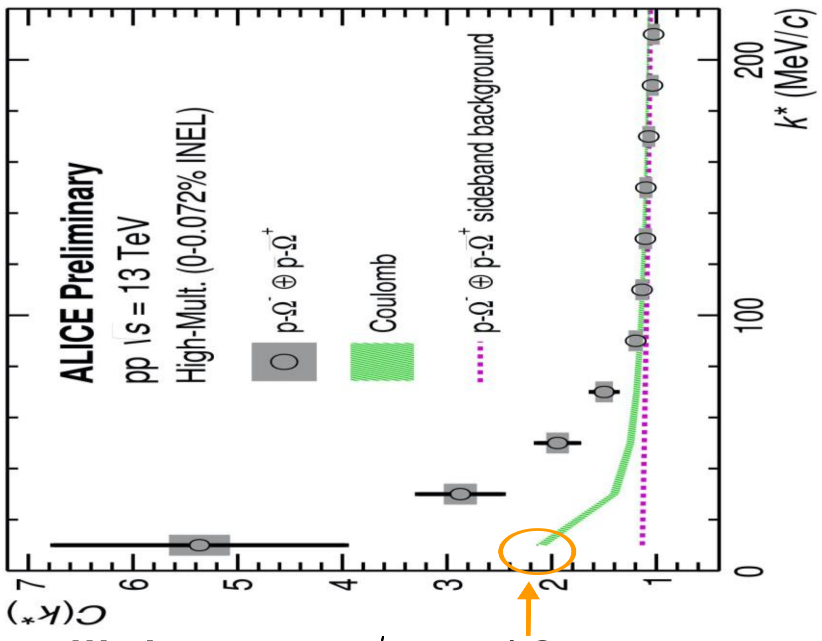


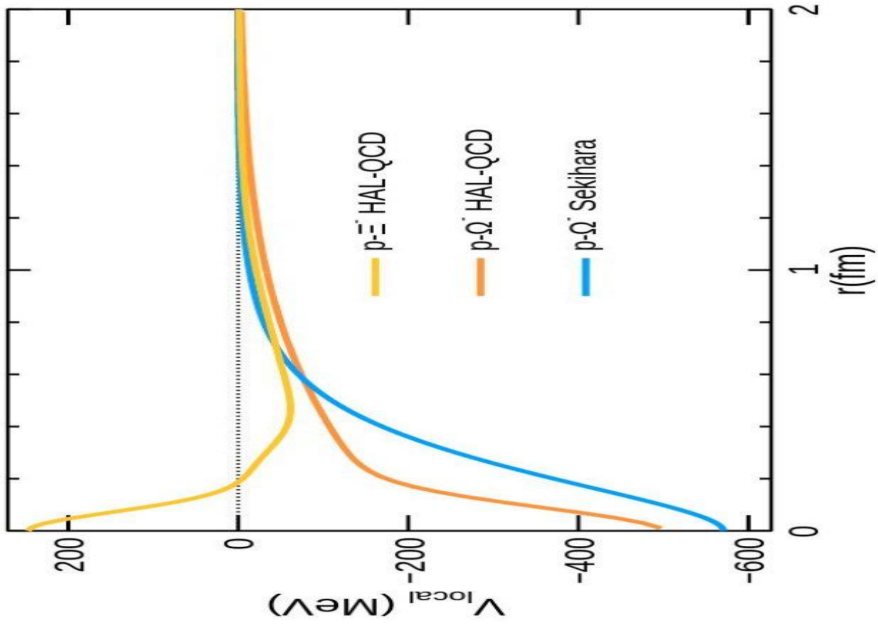


- Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, by STAR collaboration
  - arXiv:1808.02511 [hep-ex]
- Correlation pattern depends on the collision centrality → The ratio between central to peripheral
  - K. Morita, A. Ohnishi, F. Etminan and T. Hatsuda, PRC 94, 031901(R) (2016)
- The ratio is less than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

S = -3 System: ALICE pΩ^- Correlation





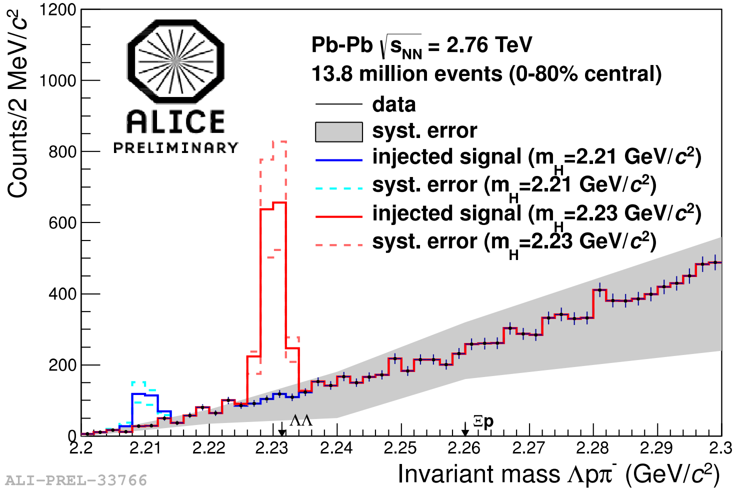


- pΩ^- correlation in p+p collisions at $\sqrt{s}$ = 13 TeV
- Compared with the two theoretical calculations: HAL-QCD (PLB 792 (2019) 284) & meson exchange (by Sekihara; PRC 98, 015205 (2018))
- More attractive than pΞ^-
- Theoretical uncertainty due to $^3S_1$

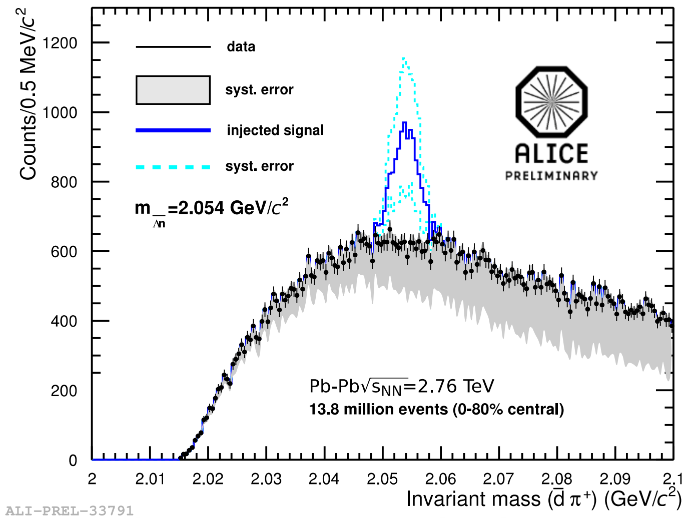
BOUND AND SLIGHTLY UNBOUND DIBARYONS?

Direct Search of ΛΛ and ΛN Bound State

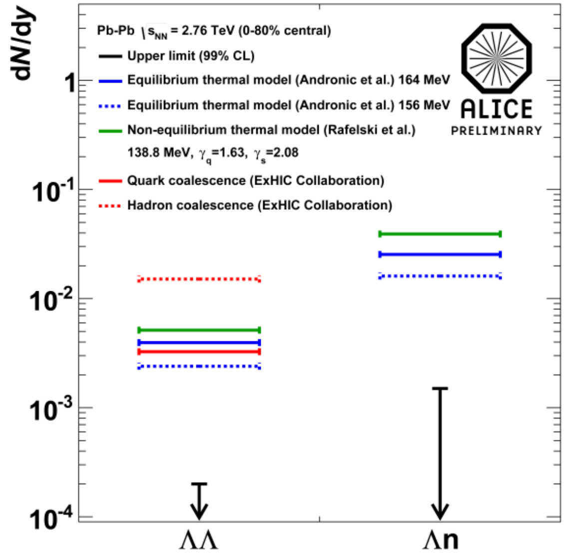
ALICE Coll.: EPJ Web of Conferences **97**,00013 (2015)



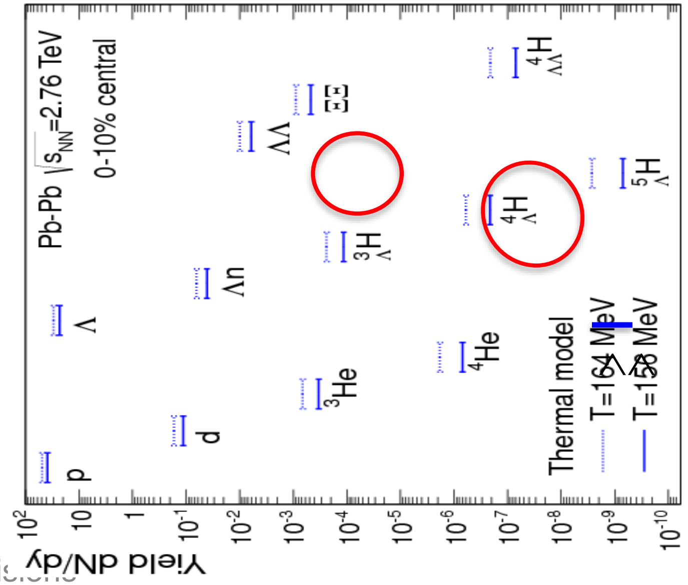
Invariant mass of Λpπ (ΛΛ→Λ+p+π⁻)



Invariant mass of dπ (Λn→d+π⁻)



- Searching ΛΛ bound state: channel $\Lambda+\pi^+\pi^-$ was chosen
- Searching Λn bound state: channel $d+\pi^-$ was chosen
- Comparison with the model calculations
  - Equilibrium thermal model
  - Non-equilibrium thermal model
  - Coalescence predictions



Hadron Production in Pb+Pb at LHC

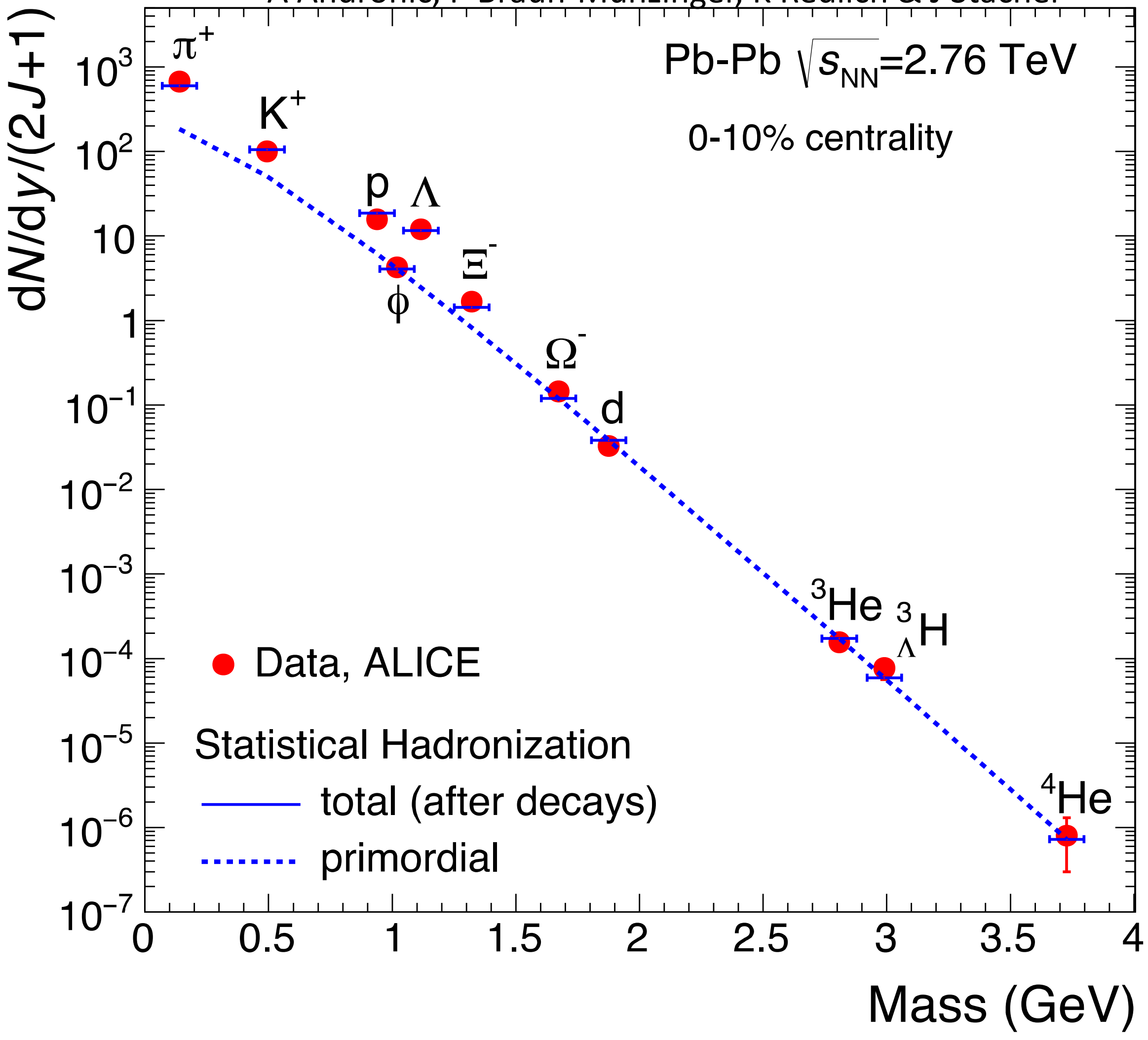
Yields are described rather well with the statistical hadronization (thermal) model,

- 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

$$\rho_i = \gamma_s^{|s_i|} \frac{g_i}{2\pi^2} T_{ch}{}^3 \left(\frac{m_i}{T_{ch}}\right)^2 K_2(m_i/T_{ch})\ \lambda_q{}^{Q_i}\ \lambda_s{}^{s_i}$$

$$\lambda_q = \exp(\mu_q/T_{ch}),$$
$$\lambda_s = \exp(\mu_s/T_{ch})$$

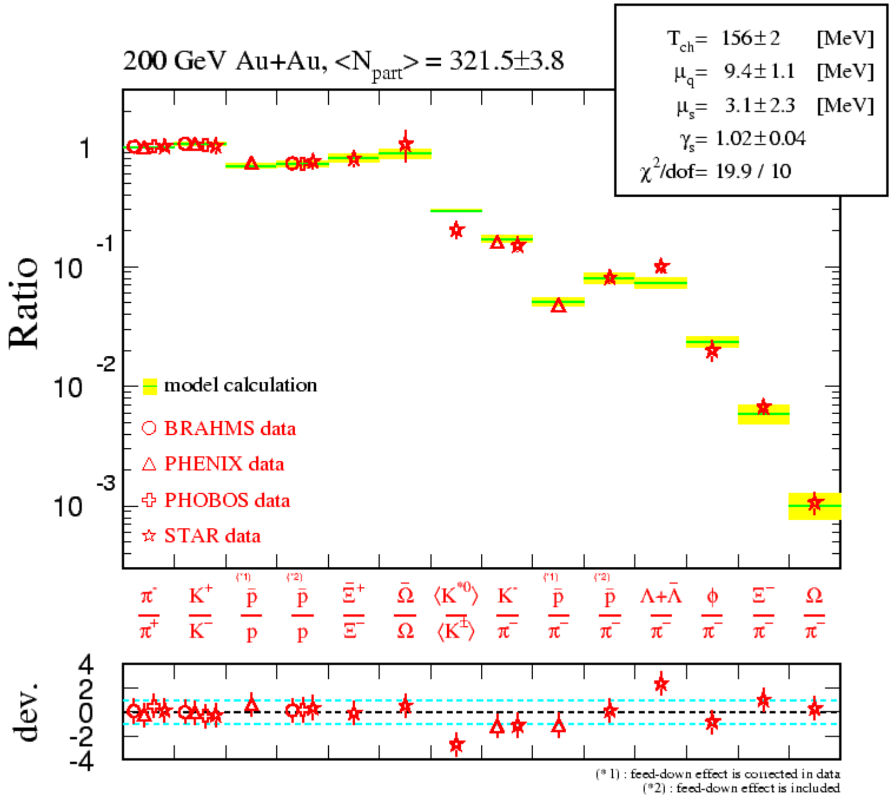
Q_i : 1 for u and d, -1 for u and d
s_i : 1 for s, -1 for s
g_i : spin-isospin freedom
m_i : particle mass

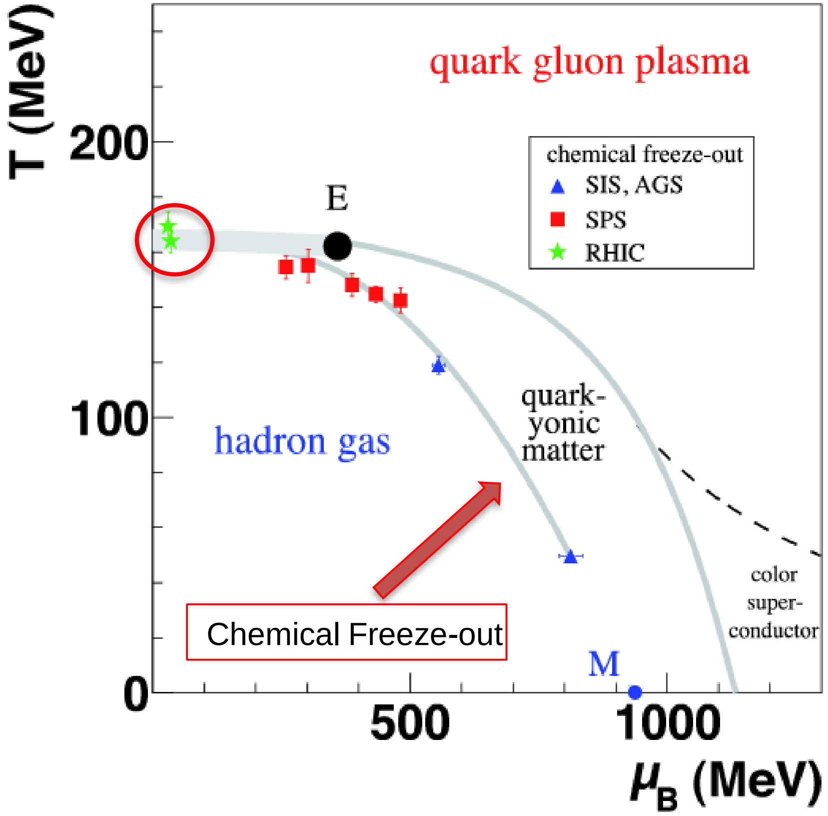
global parameters
T_{ch} : chemical freeze-out temperature
μ_q : light-quark chemical potential
μ_s : strangeness chemical potential
γ_s : strangeness saturation factor

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

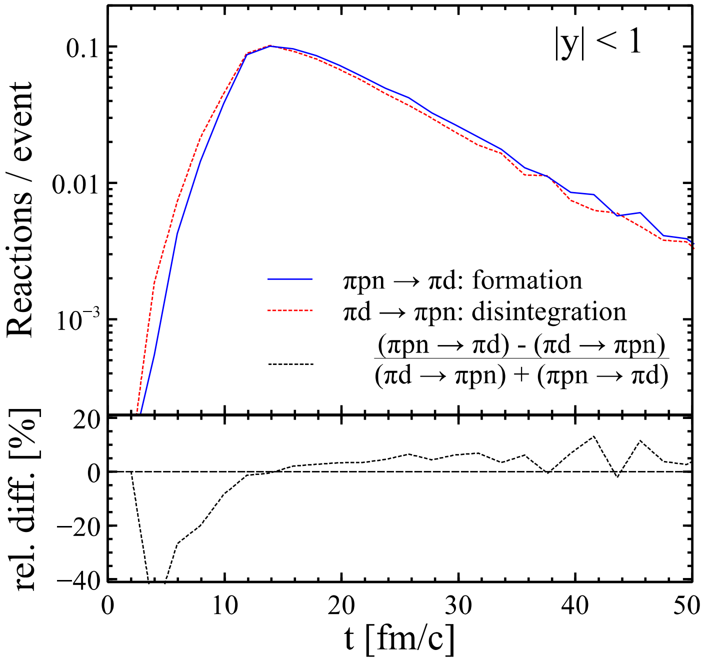


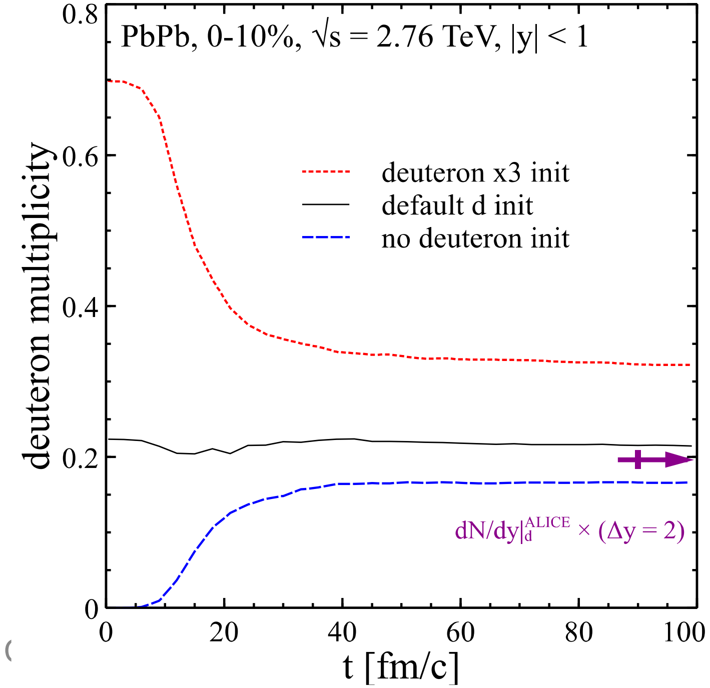


Why Thermal Model works for light nuclei yields?

- 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



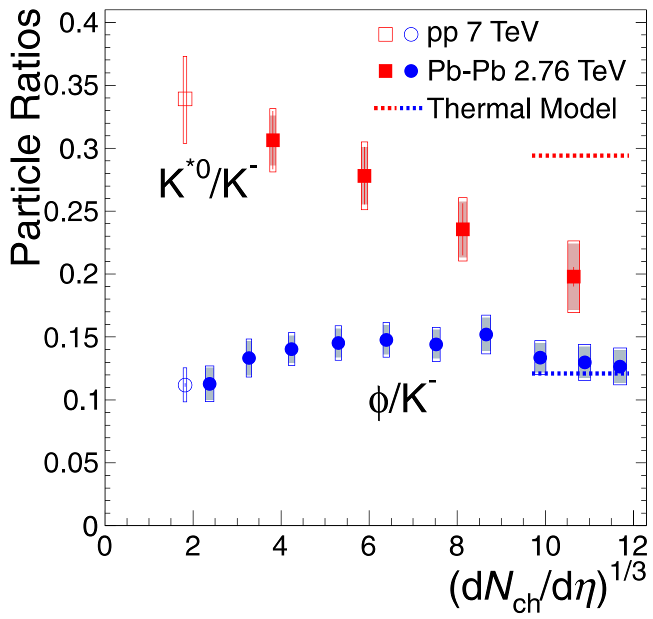


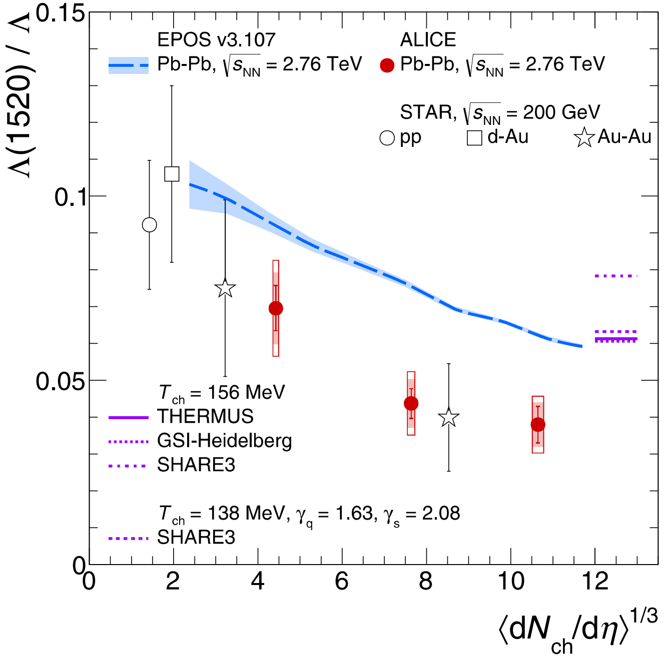
Survival of Short-lived Hadrons

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

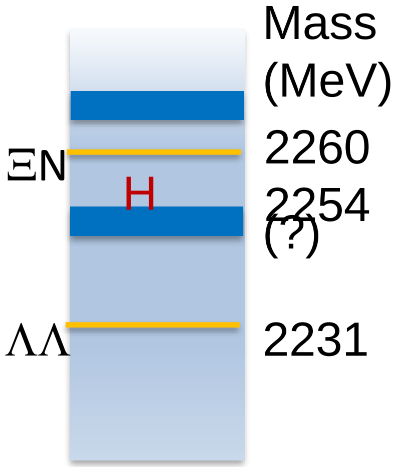




Dibaryons with Multi-strangeness

S = -2:

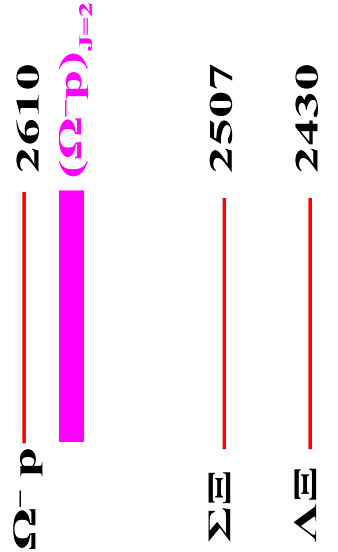
- Recent HAL-QCD suggests that H has ΞN configuration instead of ΛΛ, with mass slightly below ΞN or slightly unbound (arxiv 1912.08630)



S = -3:

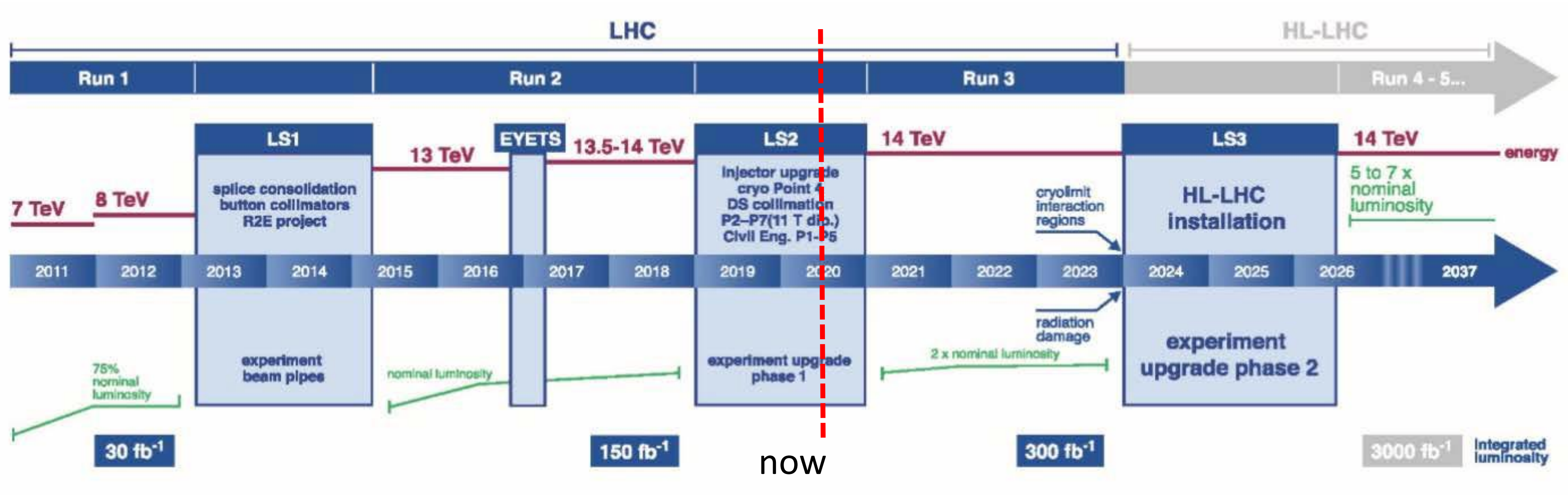
- Ω^-p is more attractive than Ξ^-p:
- HAL-QCD predicts that $^5S_2$ is a bound state
- Coupling between Ω^-p (S-state) and ΣΞ, ΛΞ (D-state) may not be big → small decay width

- They may survive the violent space-time evolution, if H behaves similar to other short-lived particles



ALICE UPGRADE DURING LS2 (LONG SHUTDOWN 2)

LHC Long Term Plan



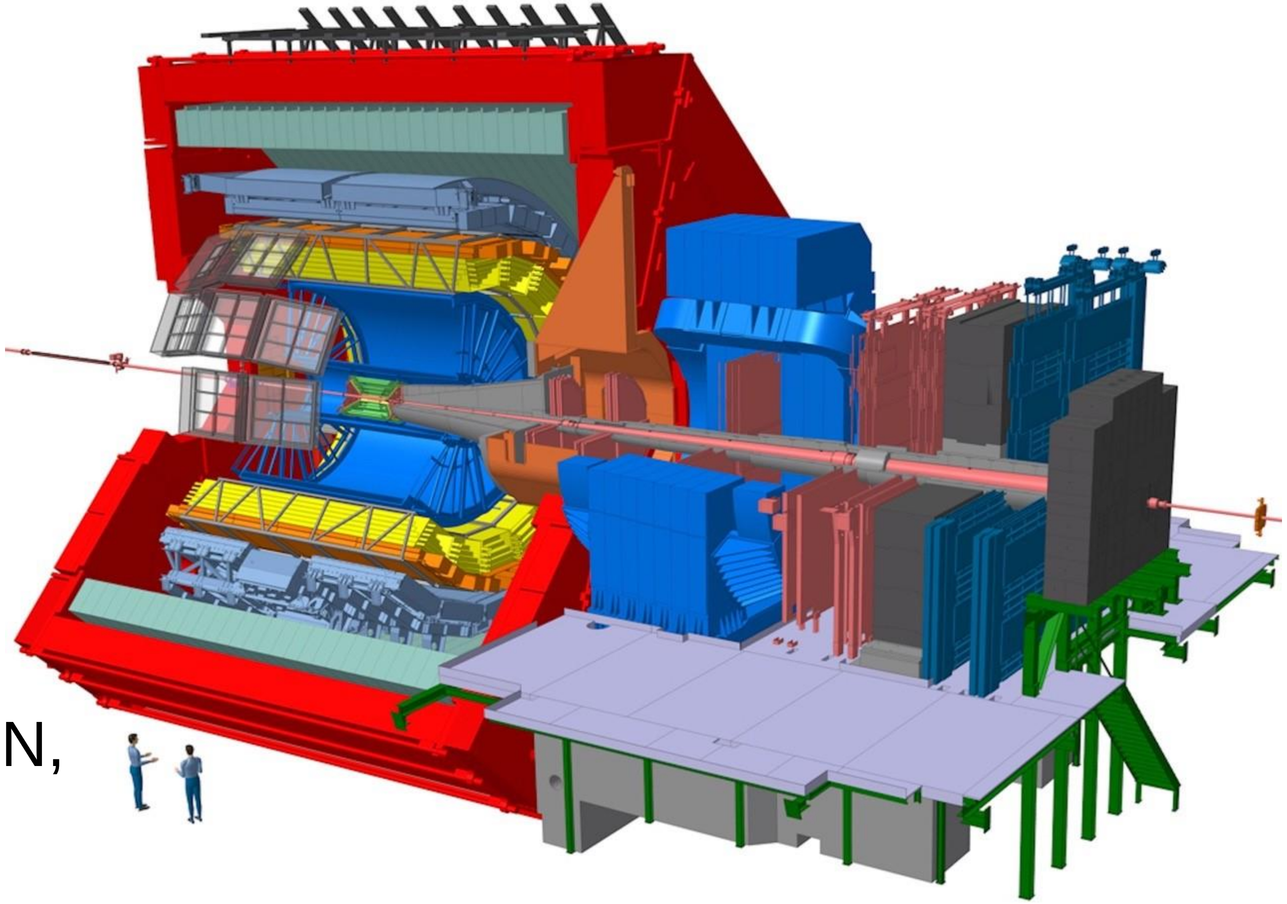
- LS2 : 2019 – 2021May
  - Experiments upgrade phase 1
  - Injector upgrade
  - Civil engineering for HL-LHC at ATLAS, CMS
  - Magnet and cryogenics
- LS3 : 2025 – 2027(?)
  - Experiments upgrade phase 2
  - HL-LHC preparation

- 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

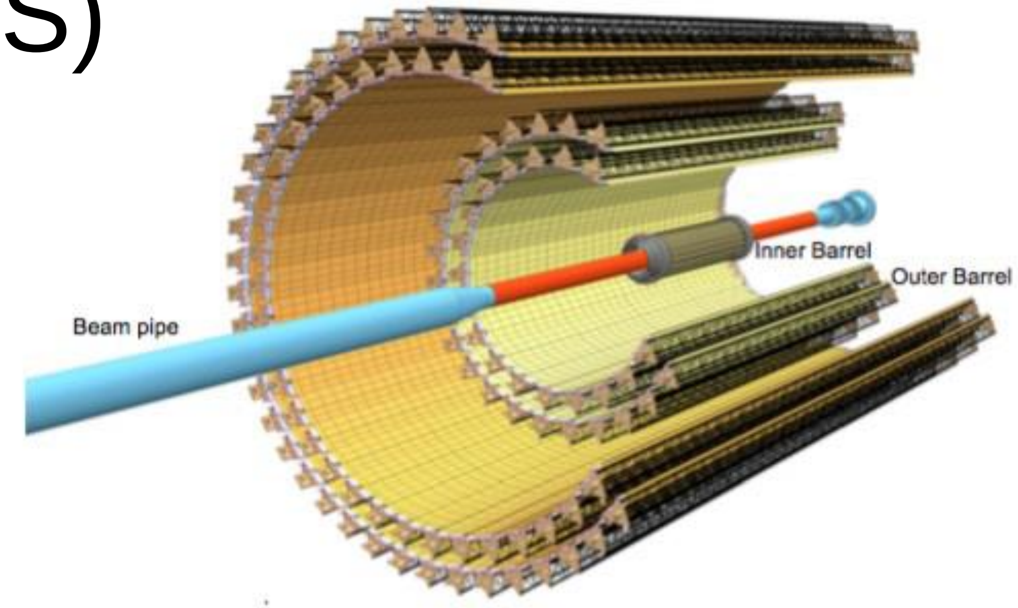
Purpose: Record minimum-bias Pb-Pb data at 50 kHz

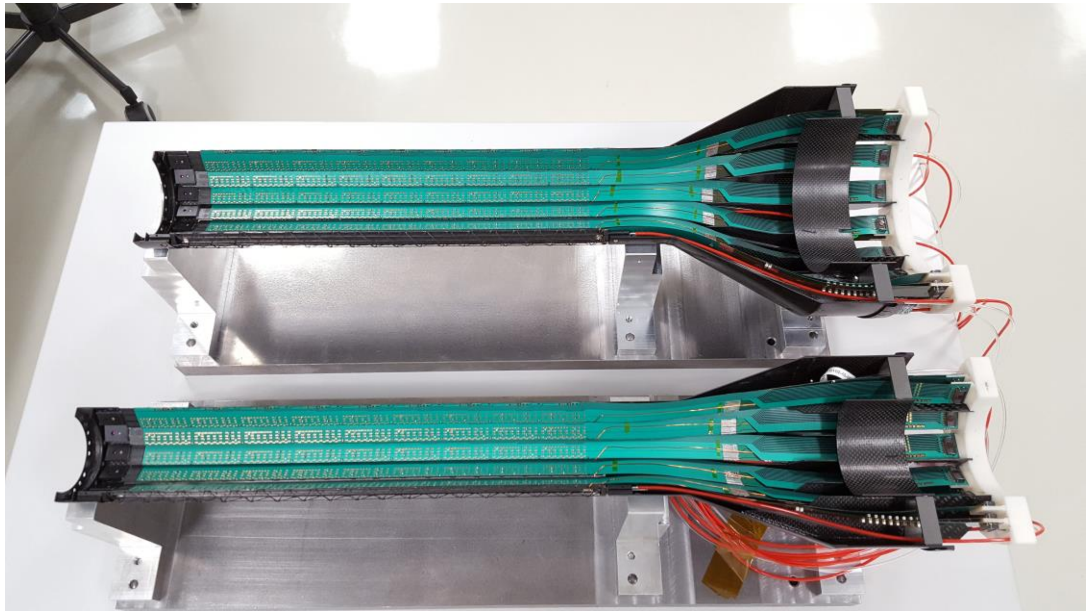
- New Inner Tracking System (ITS)
  - 7 layers of MAPS
- New TPC Readout Chambers
  - 4-GEM detectors
- New Forward Muon Tracker (MFT)
  - vertex tracker at forward rapidity
- New trigger detectors (FIT, AD)
  - centrality, event plane determination
- Upgraded read-out for TOF, TRD, MUON, ZDC, EMCal,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



Inner Tracking System (ITS)

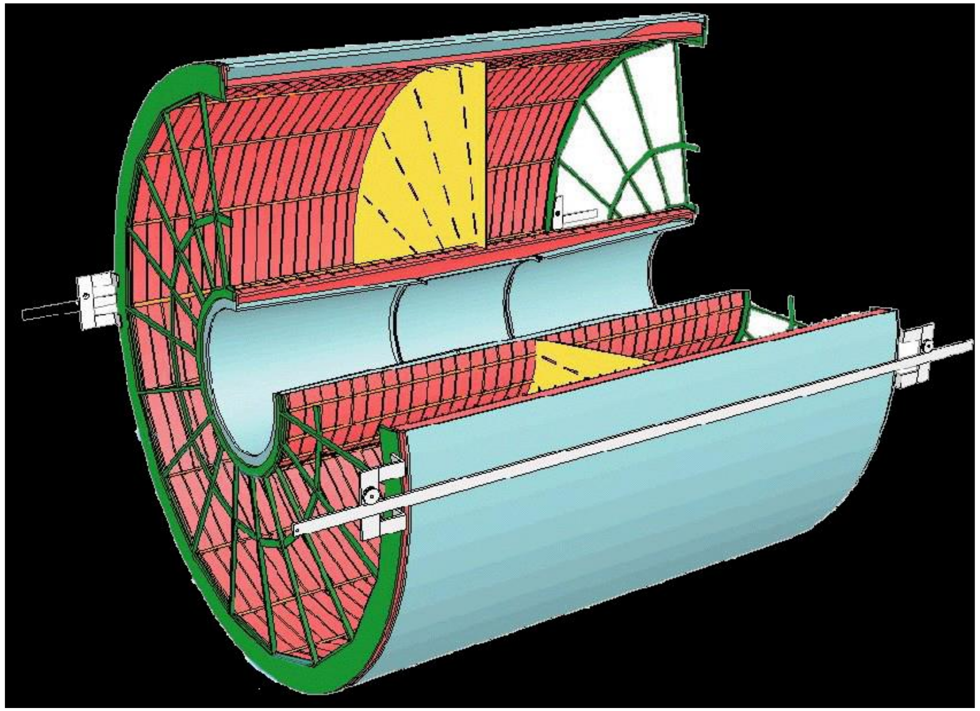
- CMOS Monolithic Active Pixel Sensor (MAPS)
  - – 7 layers full pixel detector
    (old = combination of strip, drift, and pixel)
  - – Light weight with carbon structure
  - – Larger area (10 m^2)
  - – More pseudo rapidity coverage ($-1.22 < \eta < 1.22$)
  - – First layer closer to interaction point
    (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))

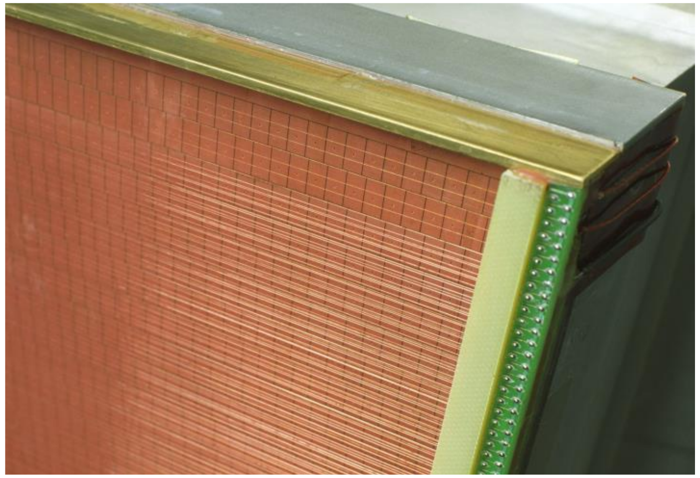


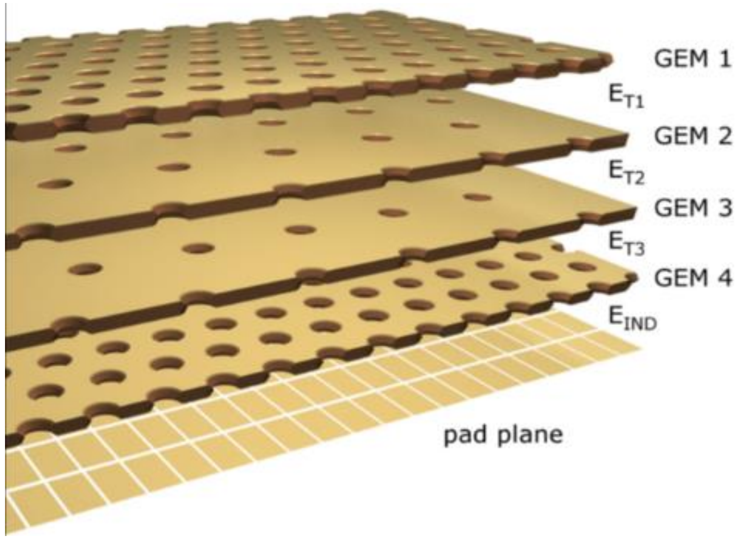


TPC Upgrade

- 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

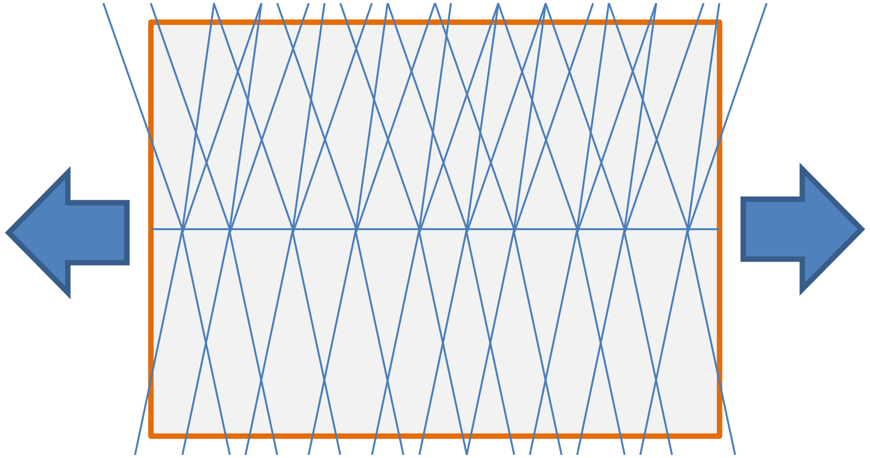


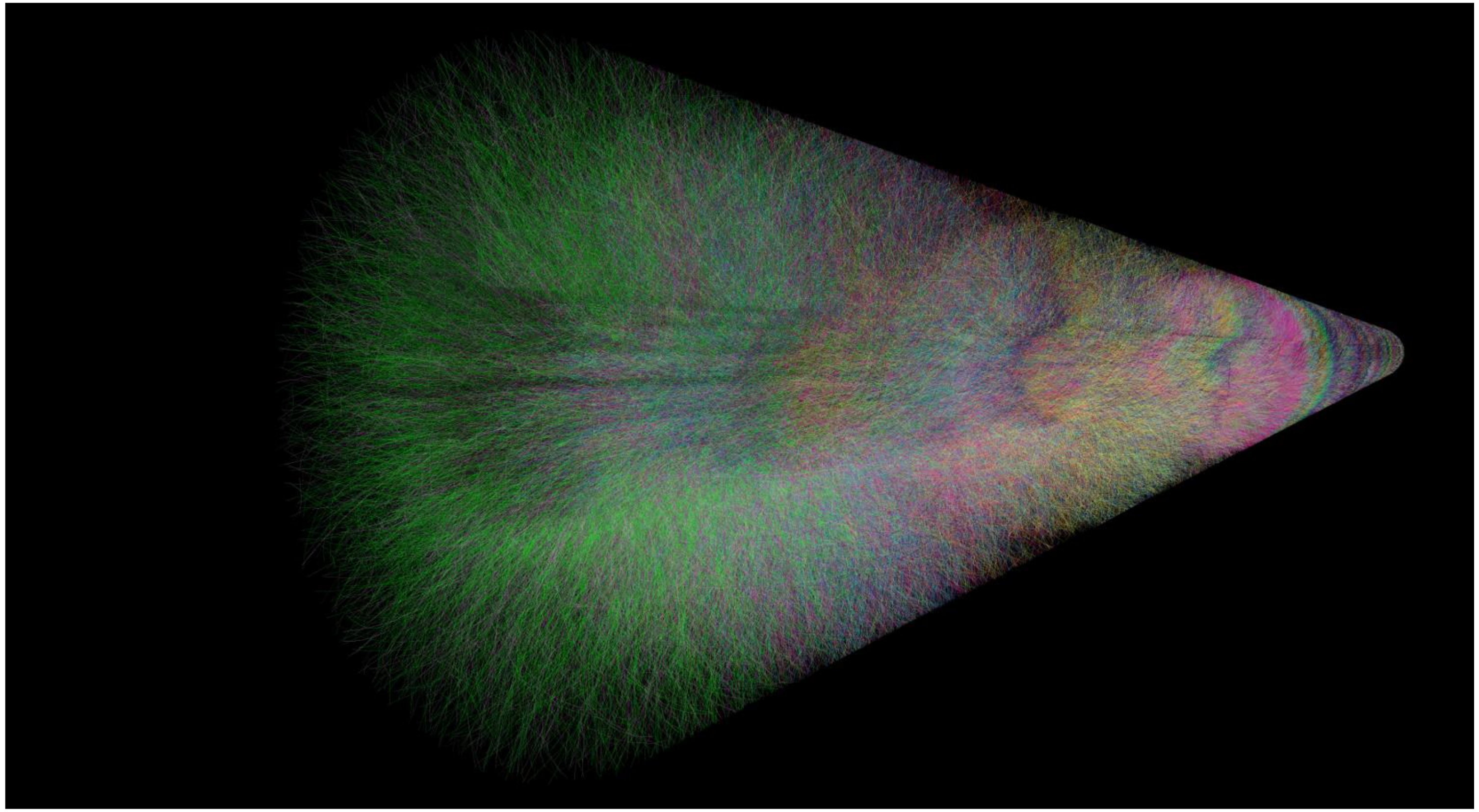




TPC Upgrade (cont.)

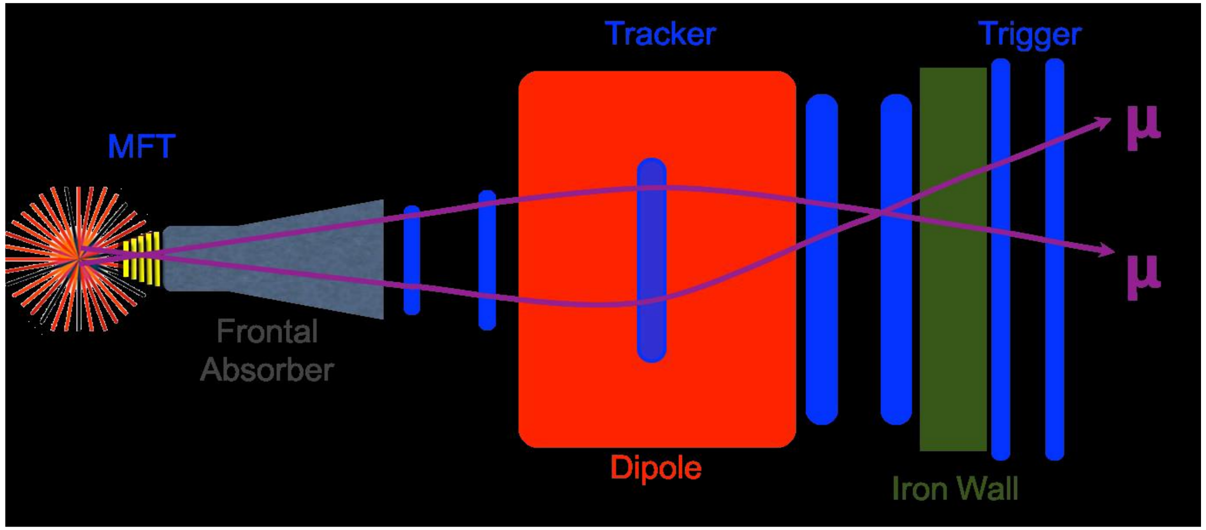
- LHC will provide ~50 kHz event rate in Pb+Pb collisions after LS2
- electron drift time in TPC =100 μs
- Overlapping events
  - 50 kHz = collision every 20 μs

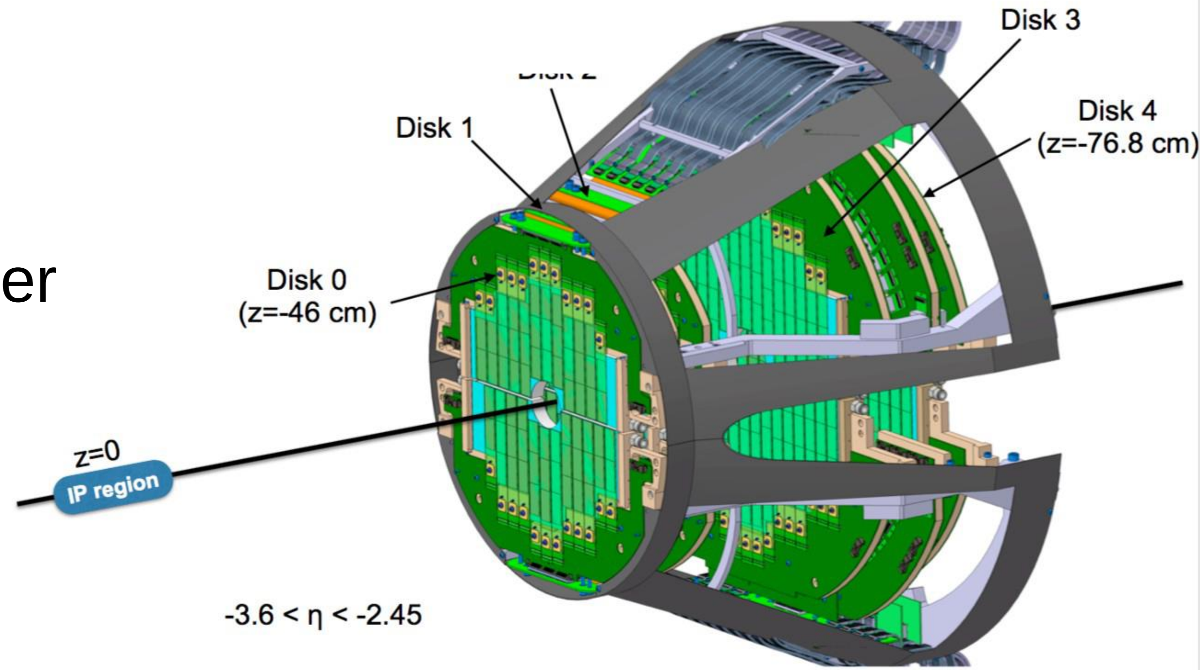




MFT (Muon Front Tracker)

- 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

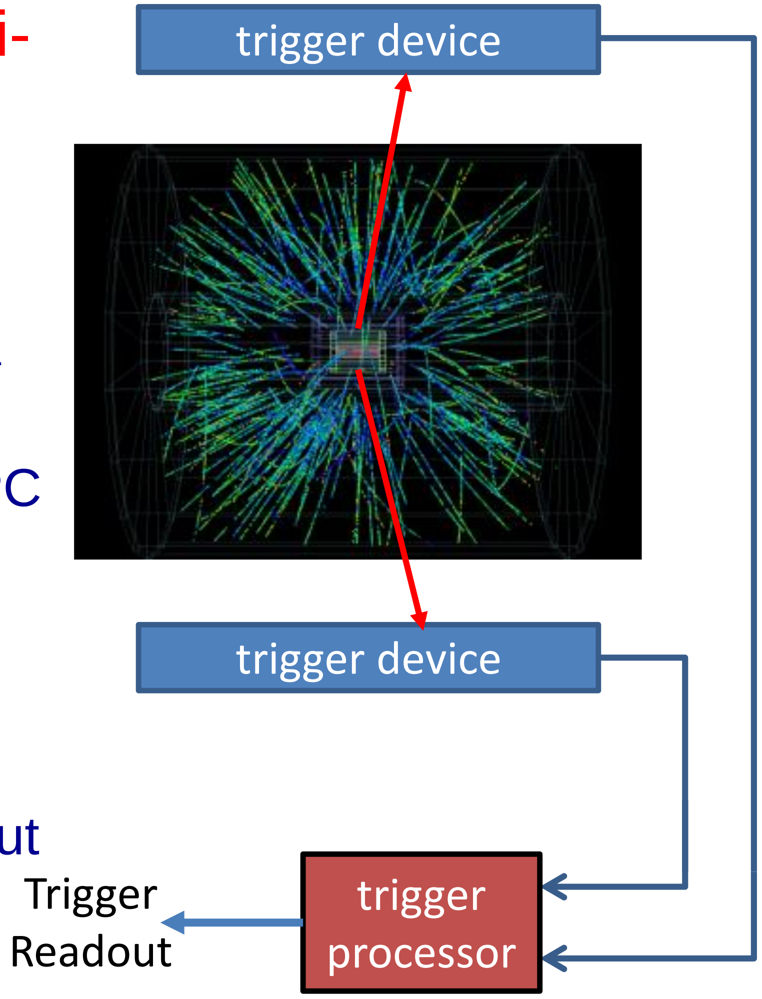




Hiroshima group is participating this project

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


trigger device

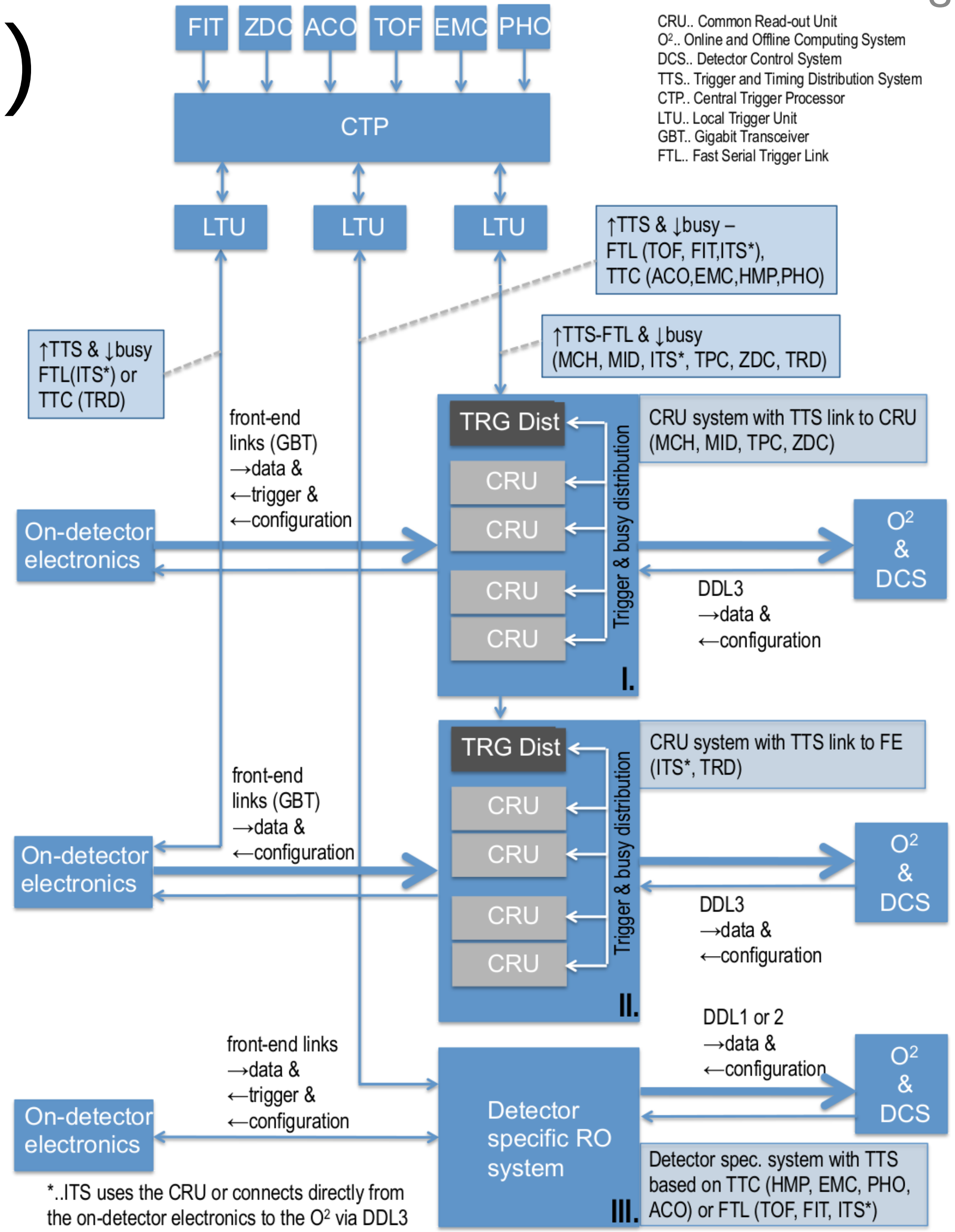
trigger device

trigger processor

Trigger Readout

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)



CRU.. Common Read-out Unit
O².. Online and Offline Computing System
DCS.. Detector Control System
TTS.. Trigger and Timing Distribution System
CTP.. Central Trigger Processor
LTU.. Local Trigger Unit
GBT.. Gigabit Transceiver
FTL.. Fast Serial Trigger Link

FIT
ZDC
ACO
TOF
EMC
PHO

CTP

LTU
LTU
LTU

↑TTS & ↓busy – FTL (TOF, FIT,ITS*), TTC (ACO,EMC,HMP,PHO)

↑TTS & ↓busy FTL(ITS*) or TTC (TRD)

↑TTS-FTL & ↓busy (MCH, MID, ITS*, TPC, ZDC, TRD)

front-end links (GBT) →data & ←trigger & ←configuration

On-detector electronics

TRG Dist
CRU
CRU
CRU
CRU
Trigger & busy distribution
I.

CRU system with TTS link to CRU (MCH, MID, TPC, ZDC)

DDL3 →data & ←configuration

O² & DCS

front-end links (GBT) →data & ←configuration

On-detector electronics

TRG Dist
CRU
CRU
CRU
CRU
Trigger & busy distribution
II.

CRU system with TTS link to FE (ITS*, TRD)

DDL3 →data & ←configuration

O² & DCS

front-end links →data & ←trigger & ←configuration

On-detector electronics

Detector specific RO system
III.

DDL1 or 2 →data & ←configuration

O² & DCS

Detector spec. system with TTS based on TTC (HMP, EMC, PHO, ACO) or FTL (TOF, FIT, ITS*)

*..ITS uses the CRU or connects directly from the on-detector electronics to the O² via DDL3

Performance of Upgraded ALICE

Central Barrel: ITS + TPC + …

	Run1+2	**Run3**	**typical signals, physics**

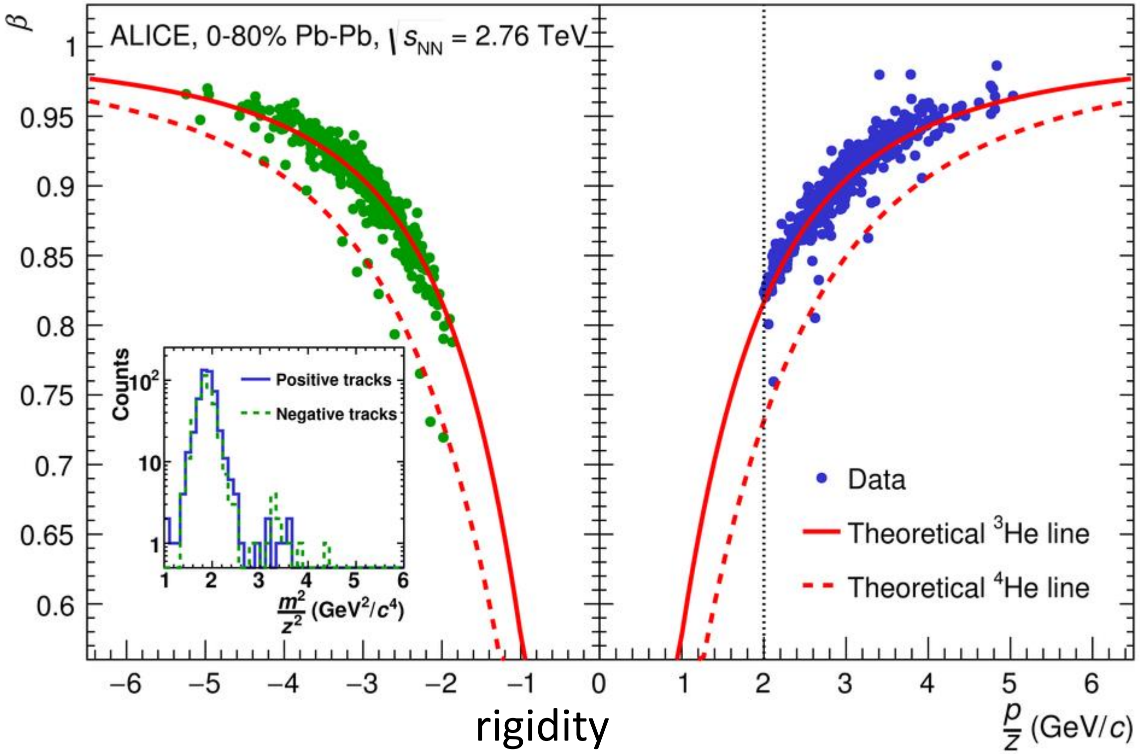
Minimum bias event
Untriggerable rare event
	~ 10^9 events (recorded)
	~ 0.1 nb^{-1}
		x100 statistics = 10^{11}
		~10 nb^{-1}
			• any kind of single particle analysis
			• e^+e^- low invariant mass
			• anti-nuclei (/^{4}He) (already visible)
			• low-pT multi-particle decay
			  • open heavy flavor 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?

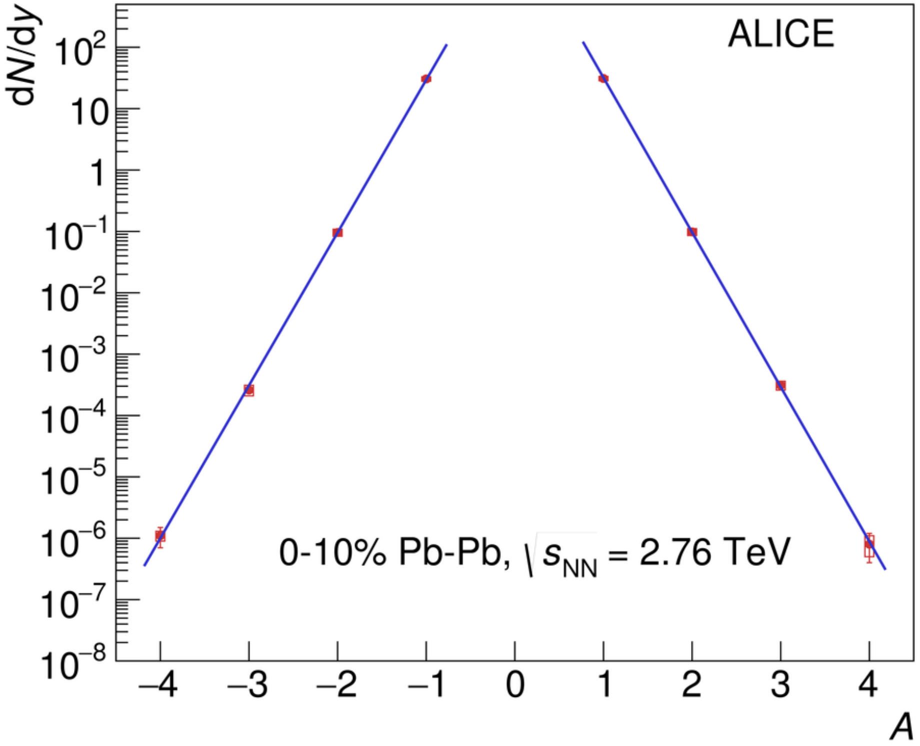
Performance after Upgrade: Light (anti-)nuclei

- 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

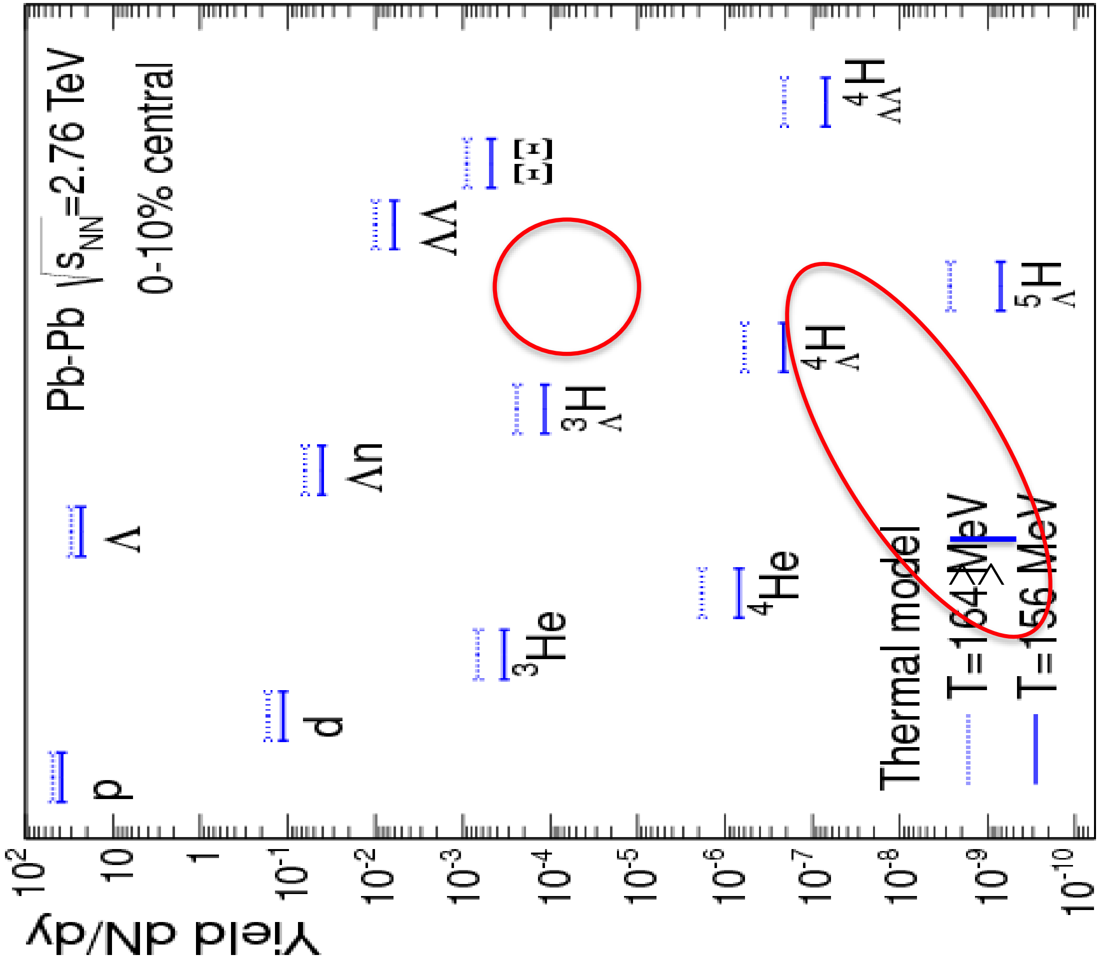


penalty factor ~ 300/nucleon

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

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 & Outlook

- Pentaquark and Tetraquark
- Di-baryon and baryon interaction
- ALICE upgrade

Outlook -- only ALICE experiment

- Extensive study of multi-strange dibaryon system, ΩΩ、pΩ、pΞ、□, using femtoscopy and direct measurement with high statistics data;
- Extension to Heavy Flavour (not discussed in this presentation)

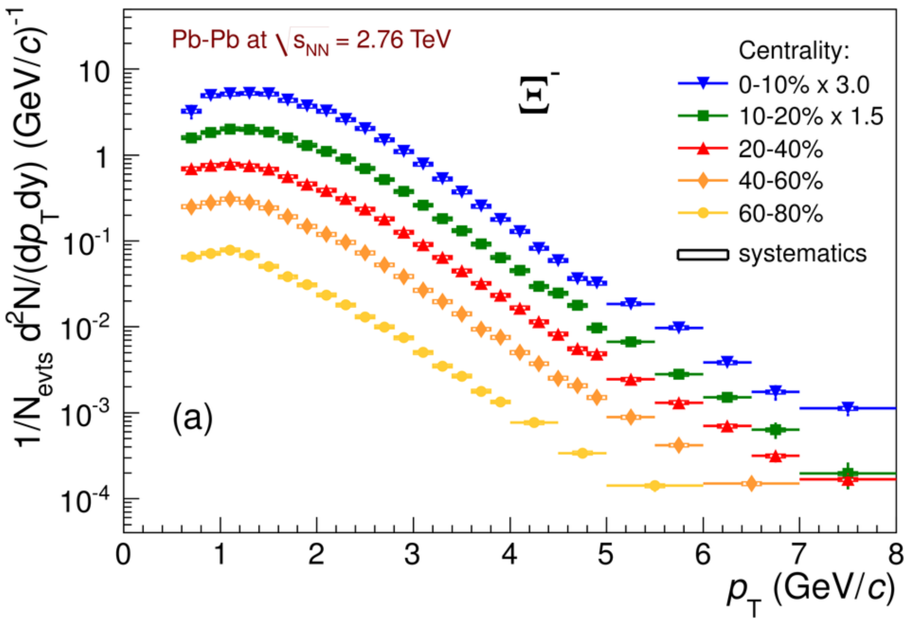
BACKUP

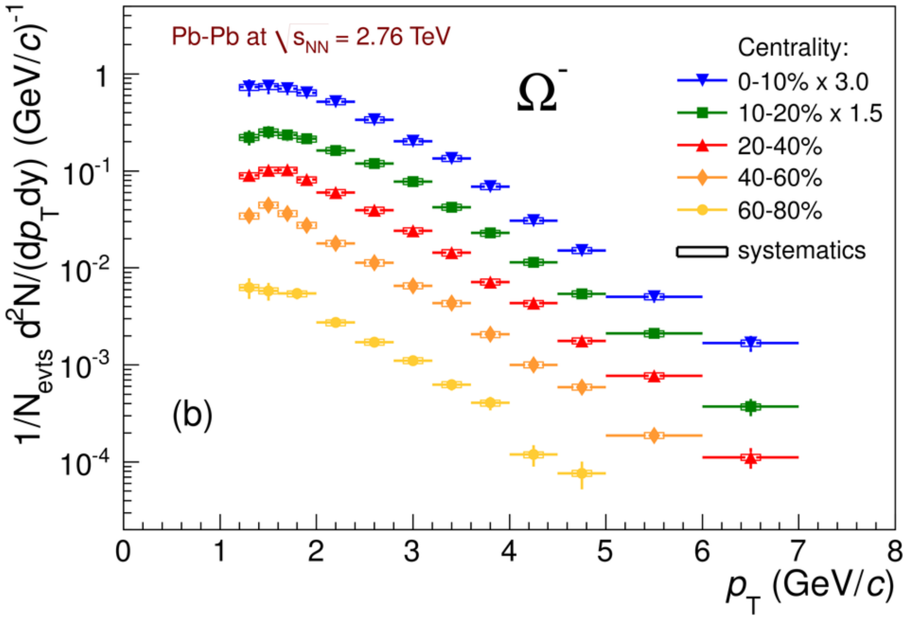
Multi-strange baryons

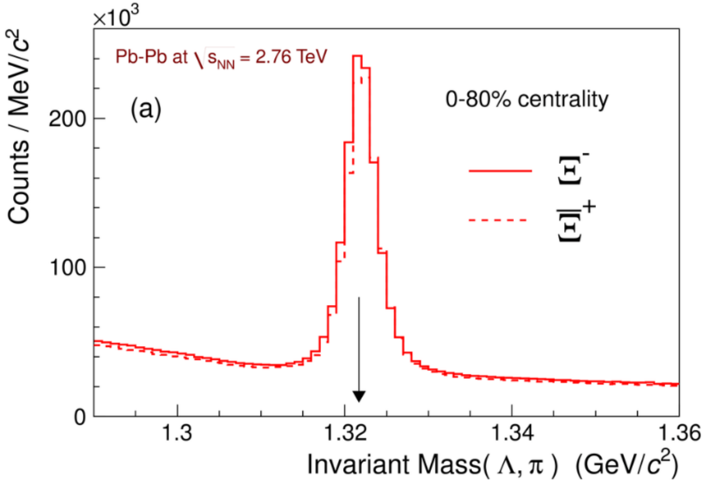
Phys. Lett. B 728 (2014) 216-227
http://alice-publications.web.cern.ch/node/604

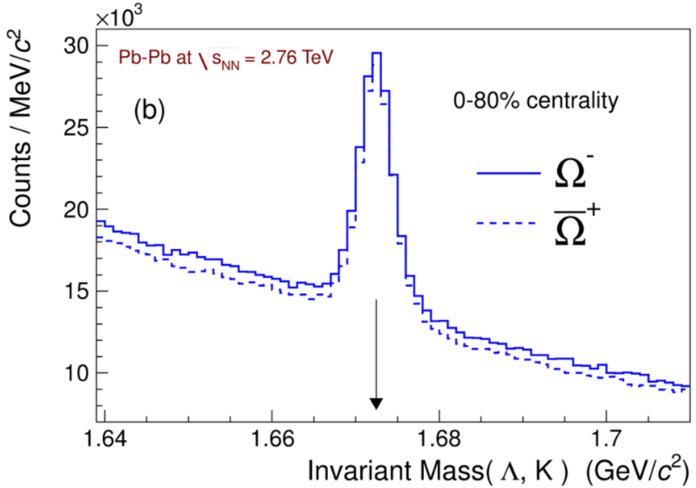
Pb+ Pb at $\sqrt{S_{NN}} = 2.76\,TeV$

Centrality $\langle N_{\rm part}\rangle$	0-10% 356.1 ± 3.6	10-20% 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^-	$0.58 \pm 0.04 \pm 0.09$	$0.37 \pm 0.03 \pm 0.06$
$\overline{\Omega}^+$	$0.60 \pm 0.05 \pm 0.09$	$0.40 \pm 0.03 \pm 0.06$
$\Omega^- + \overline{\Omega}^+$	$1.19 \pm 0.06 \pm 0.19$	$0.78 \pm 0.04 \pm 0.15$

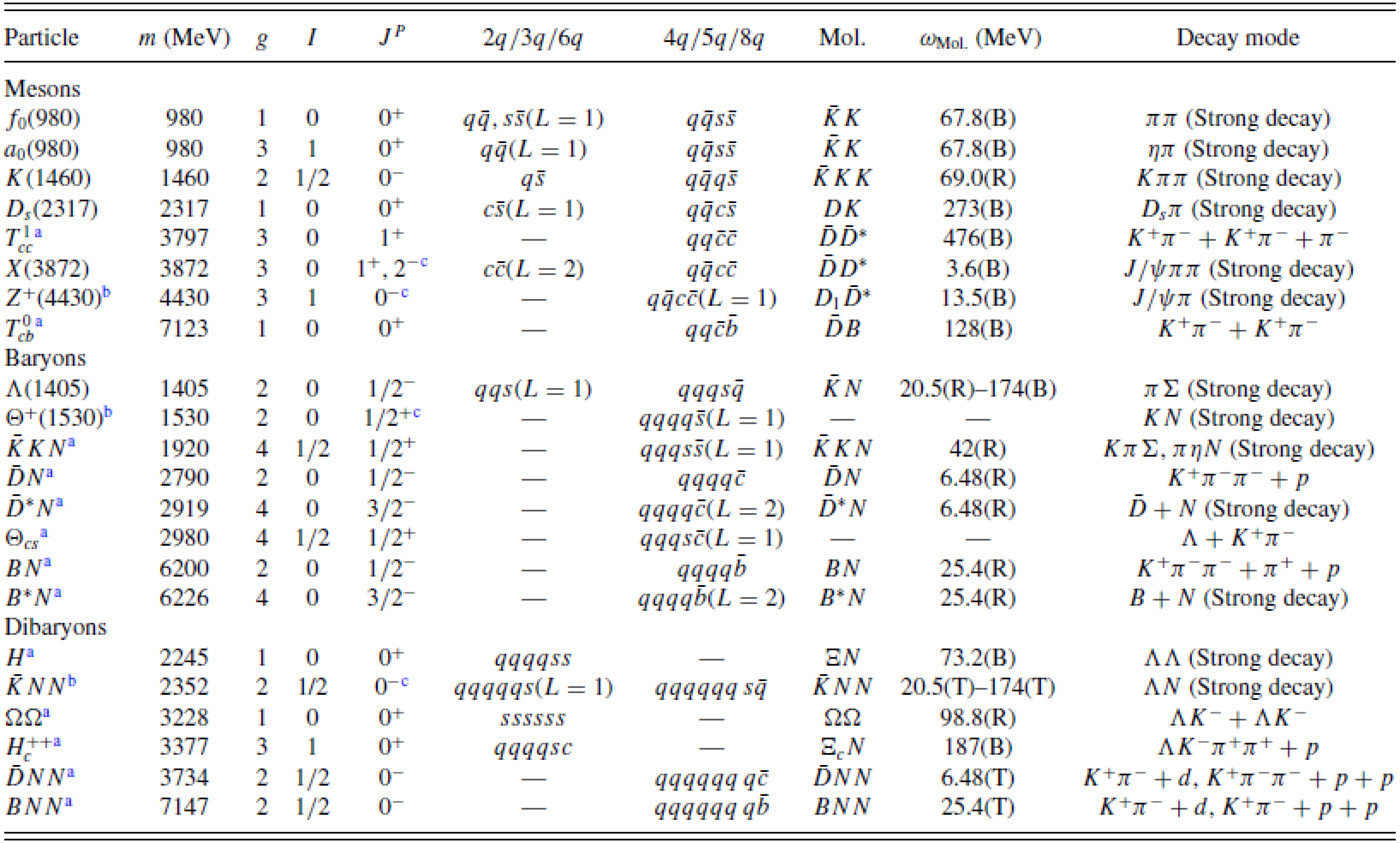








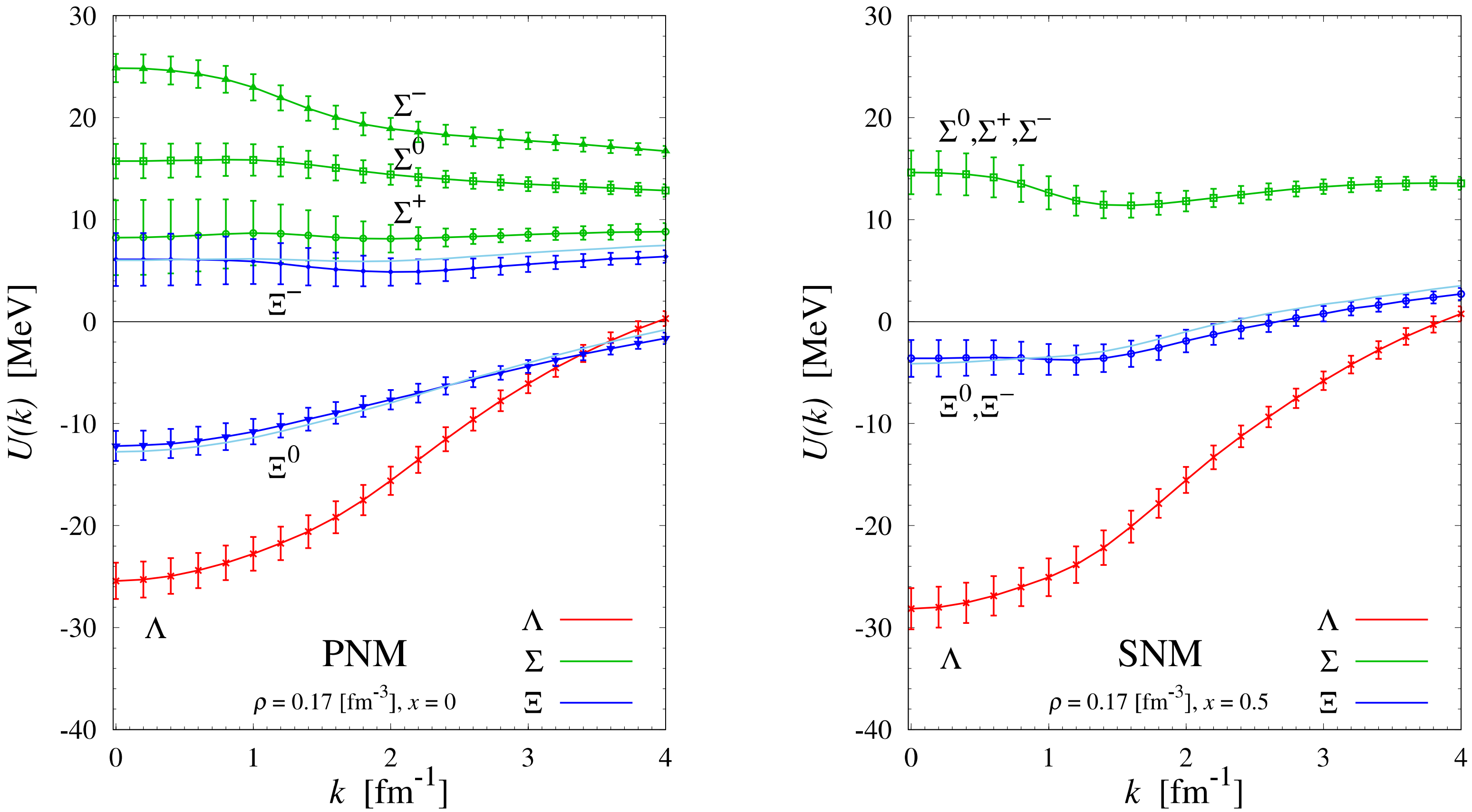
Exotica by ExHIC Collaboration



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)	$K^+\pi^- + d, K^+\pi^- + p + p$

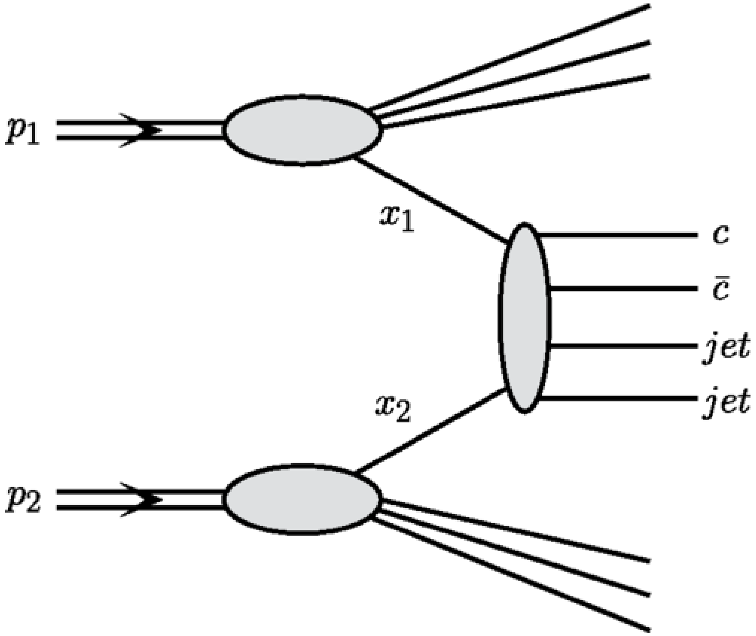
ExHIC collaboration;
PRC 84 (2011) 064910

U(k) in Nuclear Matter by HAL-QCD

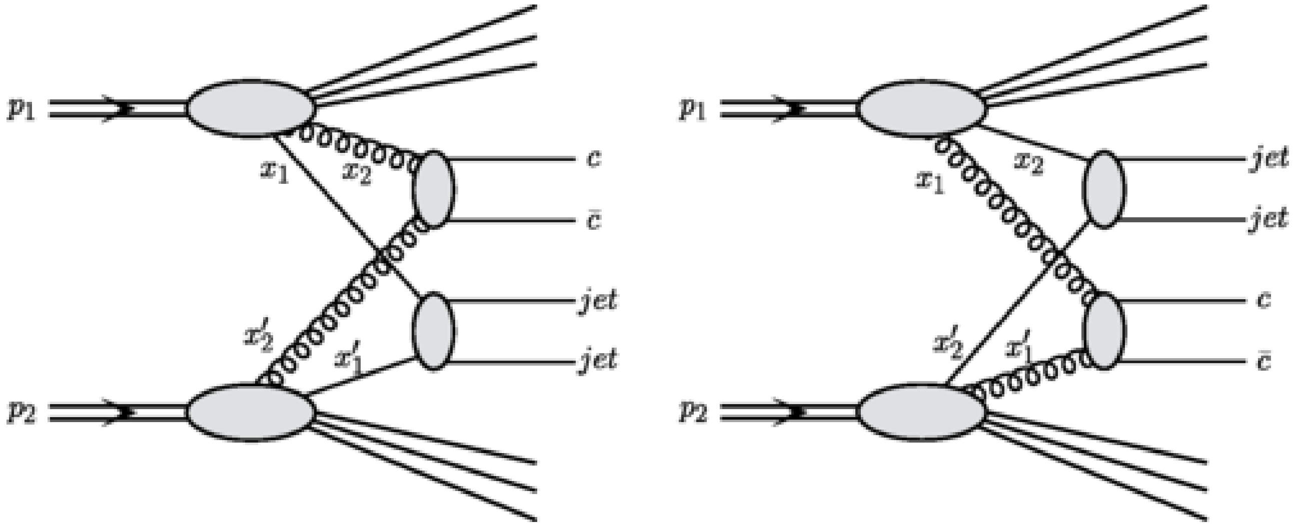


- PNM (pure neutron matter) & SNM (symmetric nuclear matter)
- Σ is repulsive in pure neutron matter (at normal nuclear density)

SPS (Single Parton Scattering) and DPS (Dual Parton Scattering)



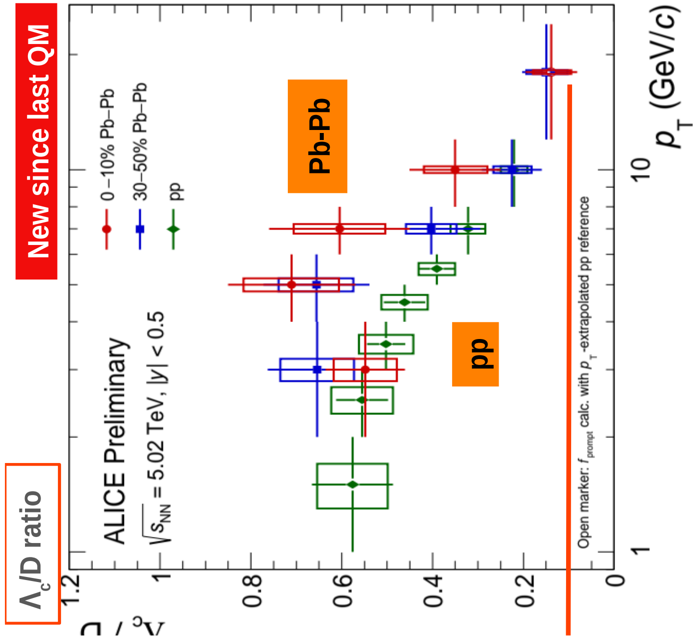
Single Parton Scattering

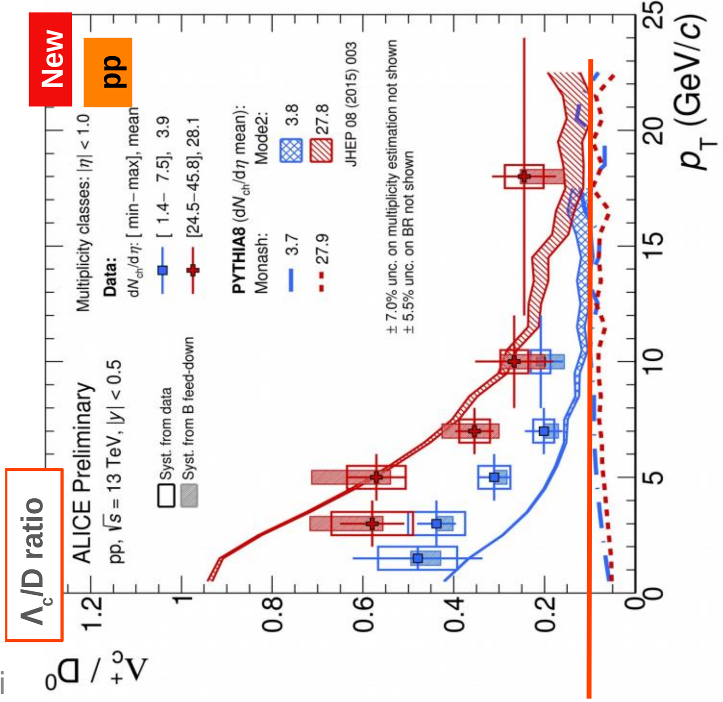


Dual Parton Scattering

Λ_c/D Ratio in pp and Pb-Pb Collisions

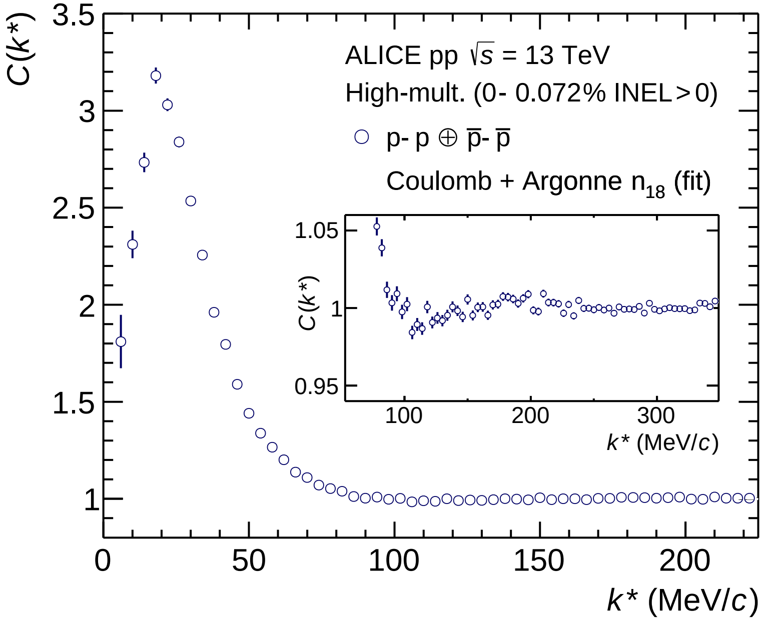
- Sensitive to quark-quark correlation in baryons (and in QGP?)
- Large enhancement in pp and Pb-Pb collisions compared to those in ee and ep collisions
  - We need higher statistics for Pb+Pb collisions
- Multiplicity dependence in pp collisions is compared with Pythia
  - Default Pythia provides the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

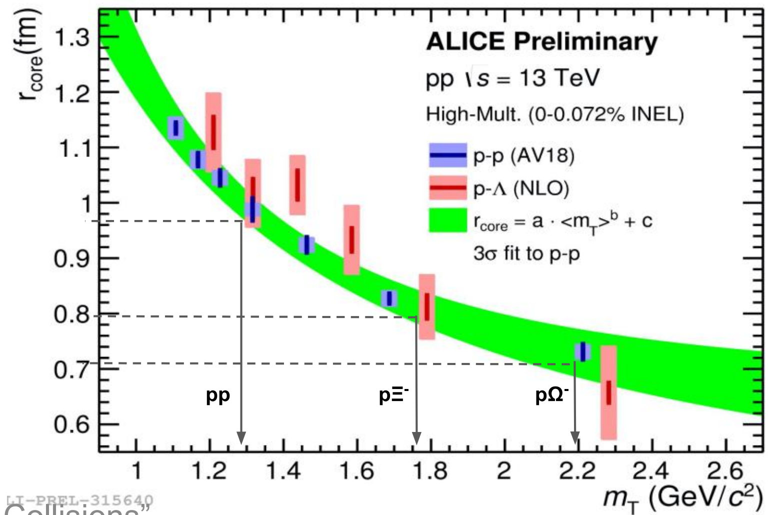




Source Characteristics in Small Systems

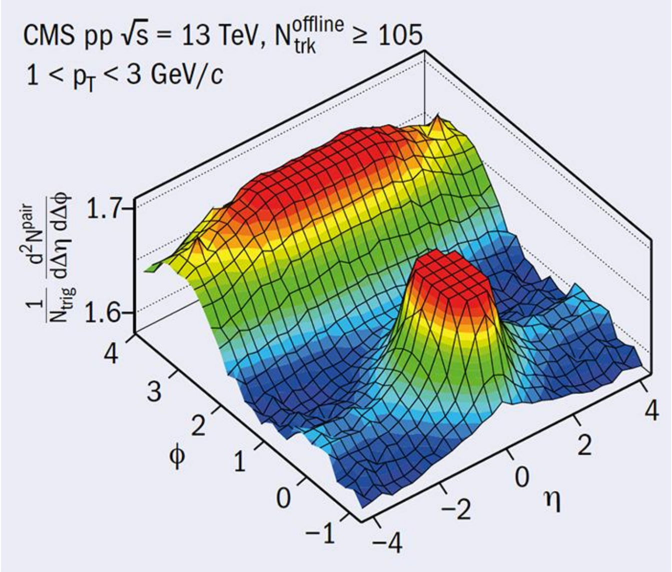
- p+p and p+A collisions are also used for femtoscopy study
- Ansatz: The source is similar for all baryon pairs in small systems
  - The size of the source core is determined from the p-p correlation function, since the p-p interaction is well known
  - The p-p femtoscopic analysis is performed differentially in $<m_T>$ bins
  - Another assumption: All baryon-baryon pairs have the same $<m_T>$ 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

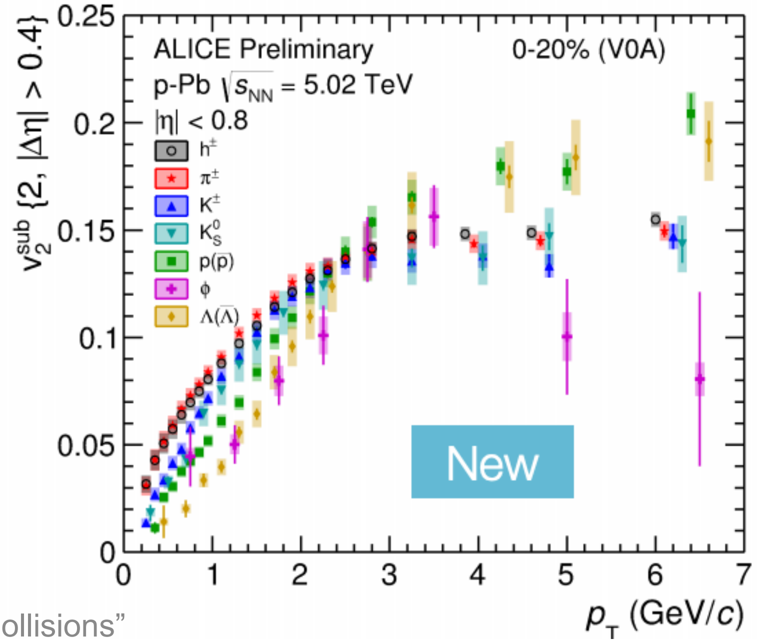




A Short Comment on Small System

- 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



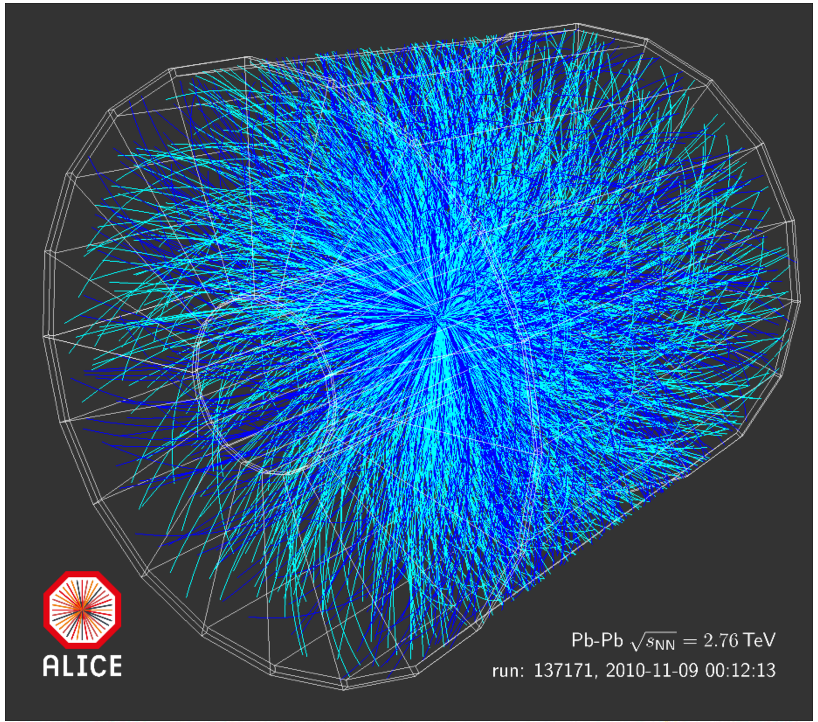


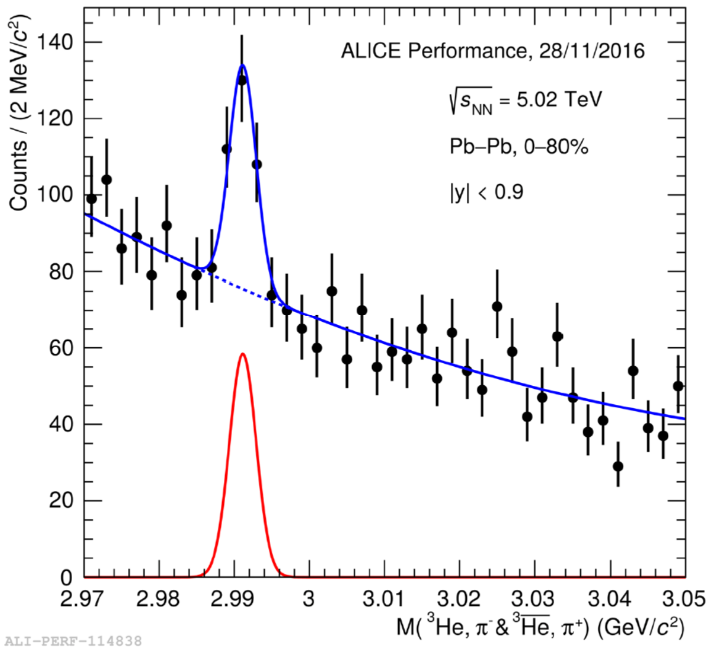
New

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
  - $^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$ … 25% B.R.
  - $^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{H} + \pi^{0}$
  - $^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$
  - $^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{n} + \pi^{0}$

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





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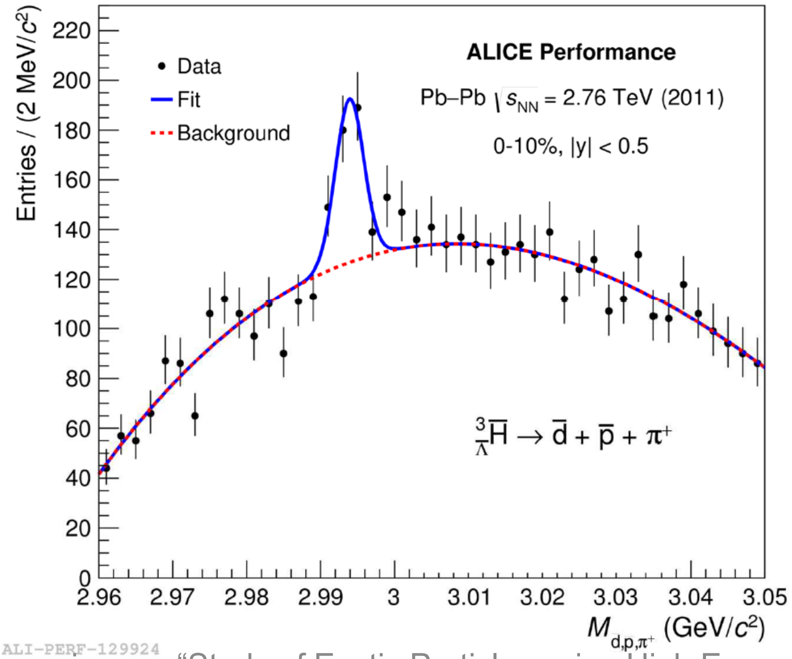

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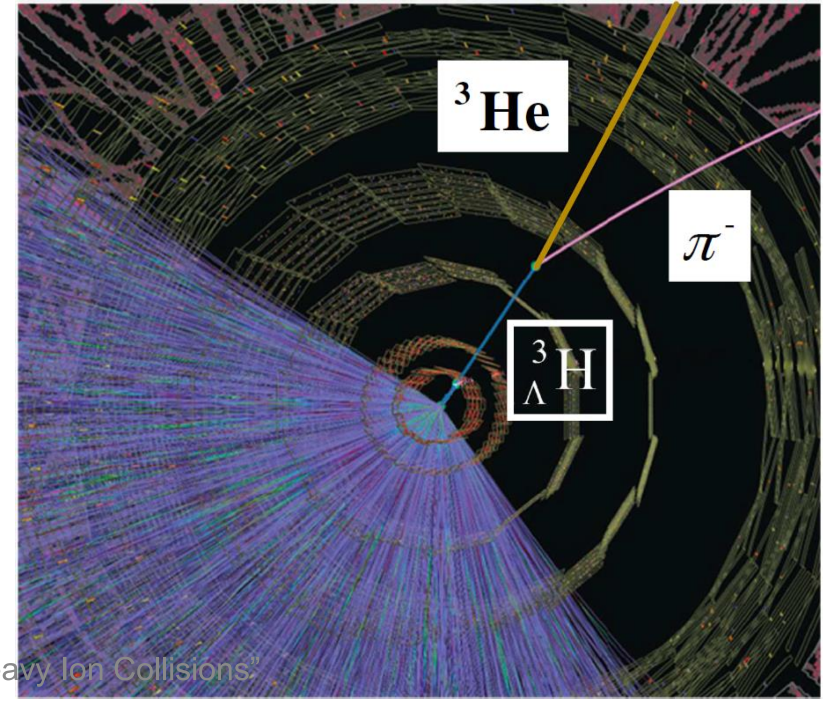

Lifetime of Hypertriton ${}^{3}_{\Lambda}$H

- 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