LHC-ALICEにおけるエキゾチック系探索の現状と今後の可能性

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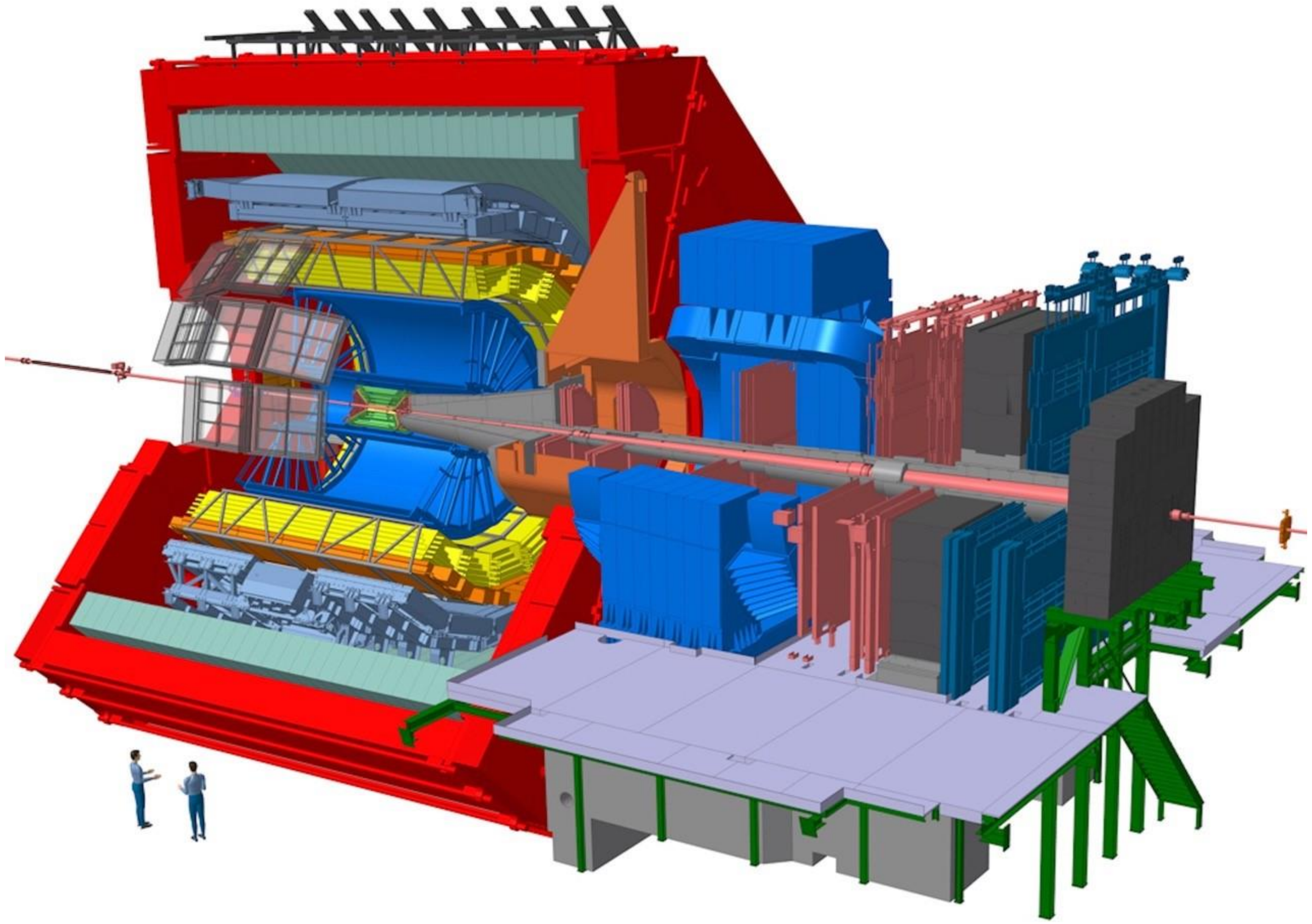
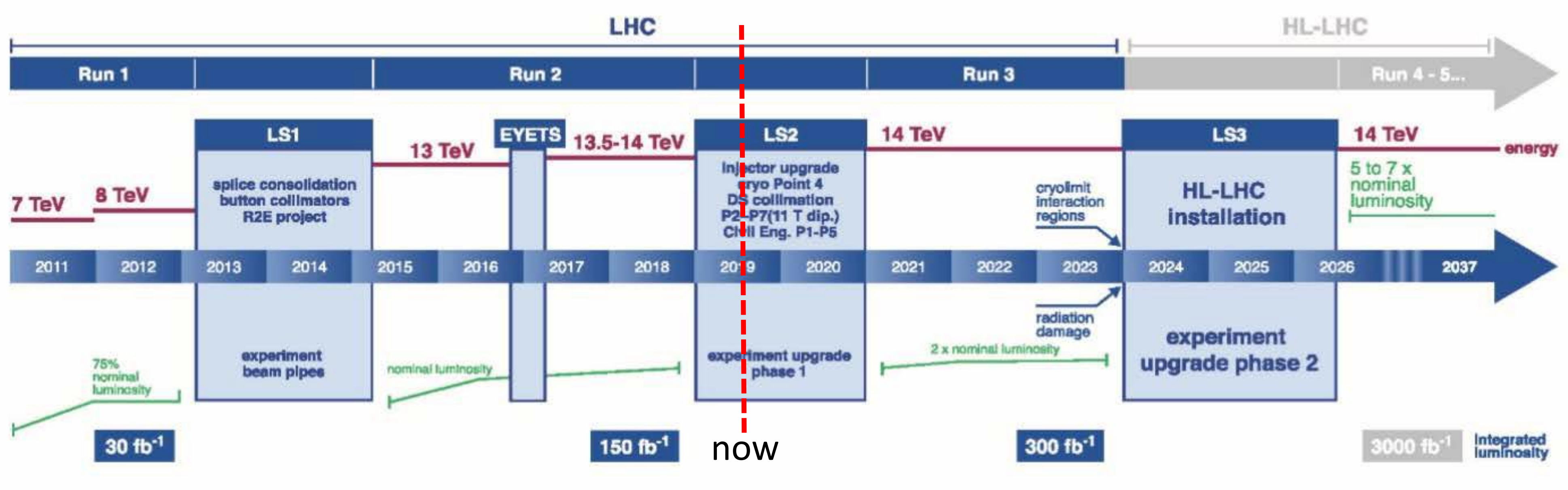
Aug.8, 2019 第 5 回「物質階層を横断する会」〜ハドロン・原子核・原子・分子合同ミーティング：軽いグザイハイパー核の構造と生成 @ RIKEN

ALICE@LHC upgrades for Run3

- New Inner Tracking System (ITS)
  MAPS: improved resolution, less material, faster readout
- New Forward Muon Tracker (MFT)
  vertex tracker at forward rapidity
- New TPC Readout Chambers
  4-GEM detectors
- New trigger detectors (FIT, AD)
  + centrality, event plane determination
- Upgraded read-out for TOF, TRD, MUON, ZDC, EMCal, PHOS, integrated Online-Offline system (O2)
  record minimum-bias Pb-Pb data at 50 kHz



LHC long term plan

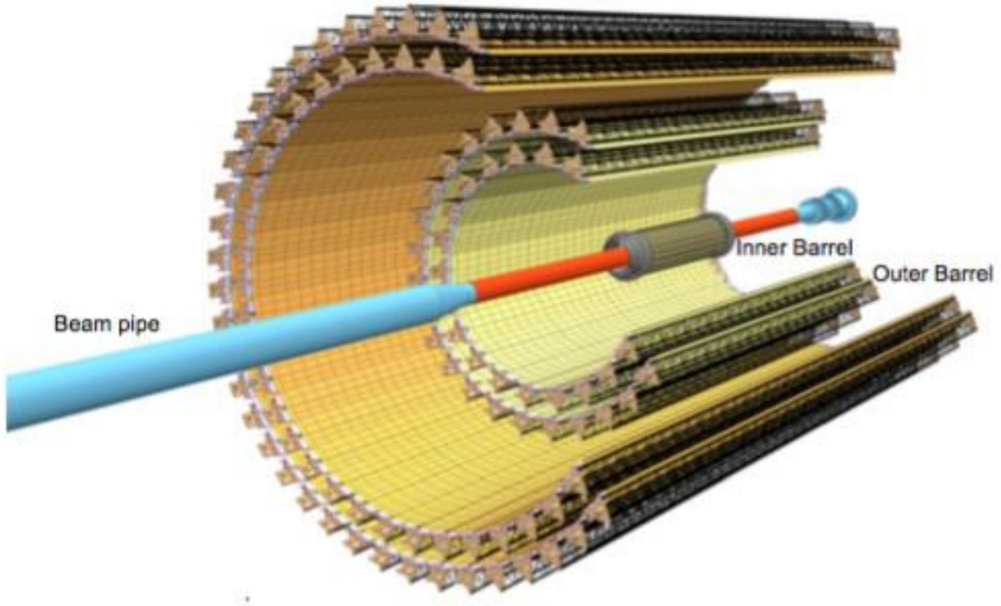


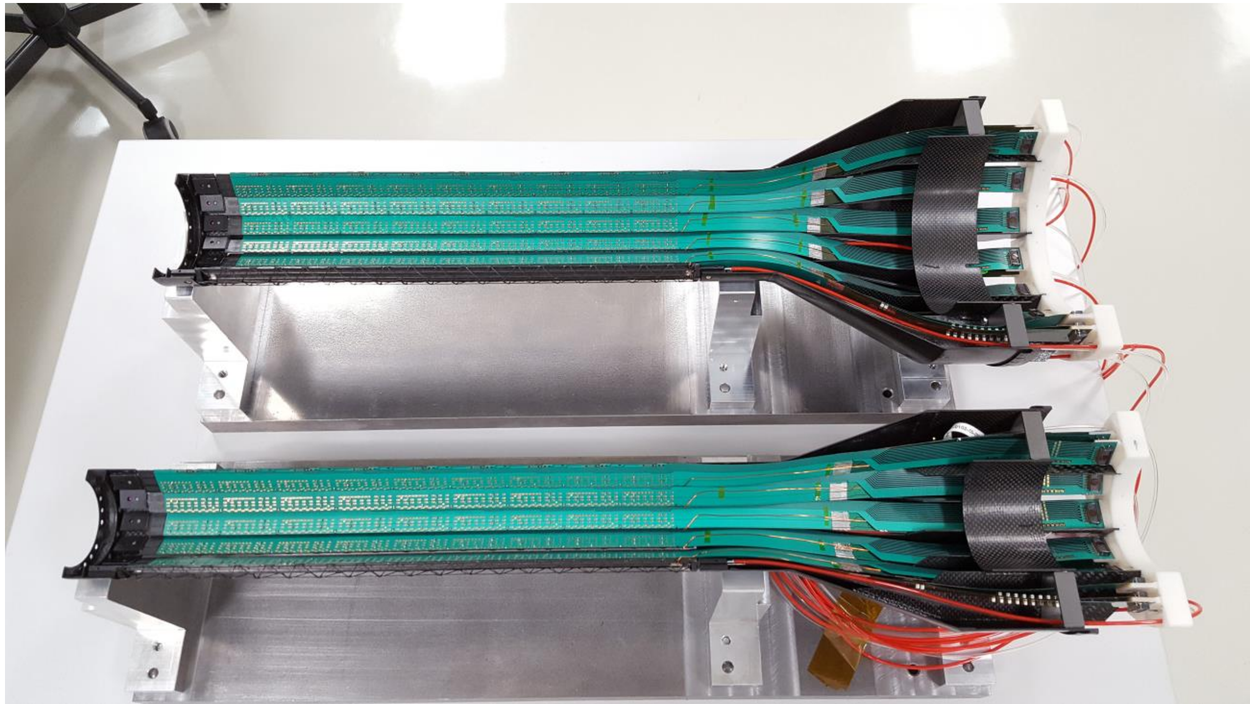
- LS2 : 2019 – 2020
  - Experiments upgrade phase 1
  - Injector upgrade
  - Civil engineering for HL-LHC at ATLAS, CMS
  - Magnet and cryogenics
- LS3 : 2024 – 2026
  - Experiments upgrade phase 2
  - HL-LHC preparation
- Run3 : 2021 – 2023
  - x2 pp nominal luminosity
  - x6 PbPb nominal luminosity → 50 kHz
- Run4 : 2026 – with HL-LHC
  - x5 to x7 nominal luminosity
  - x7 PbPb nominal luminosity
- after
  - HE-LHC (27 TeV) and FCC at 100 TeV (~2040)

see more detail in Frederick Bordry's talk in LHCP 2018

Inner Tracking System

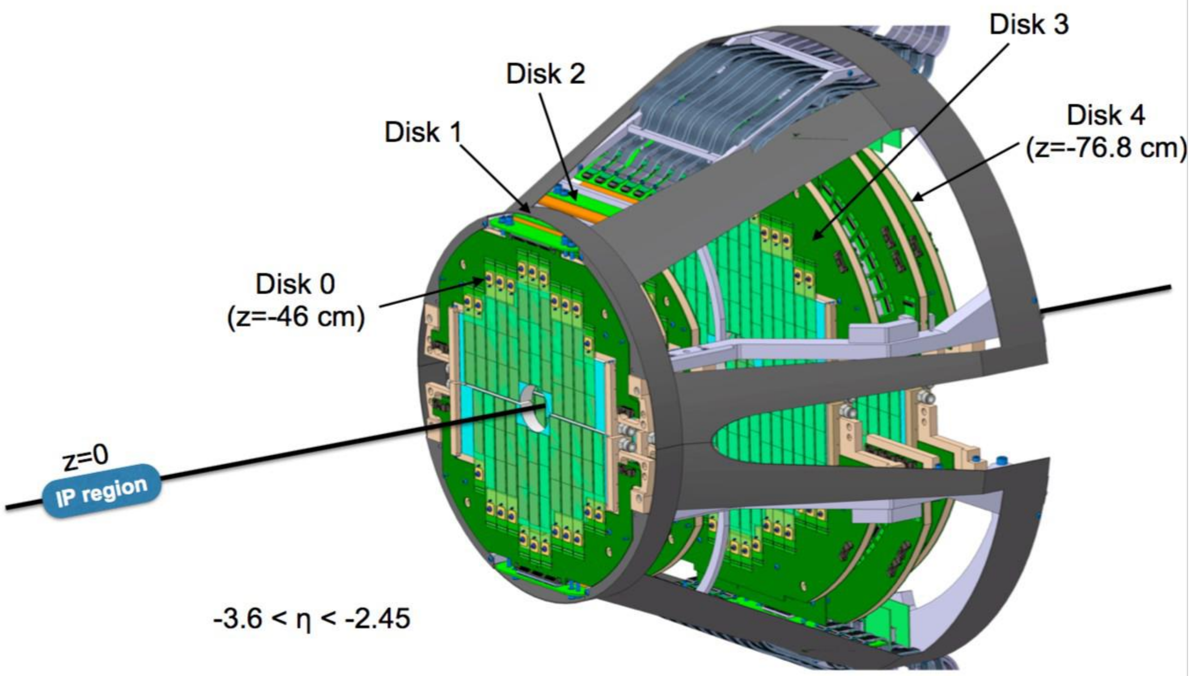
- Replaces old silicon detectors with new sensors
  - CMOS Monolithic Active Pixel Sensor (MAPS)
  - 7 layers full pixel detector
    (before combination of strip, drift, and pixel)
  - Light weight with carbon structure
  - Larger area (10 m^2)
  - More pseudo rapidity coverage ($-1.22 < \eta < 1.22$)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

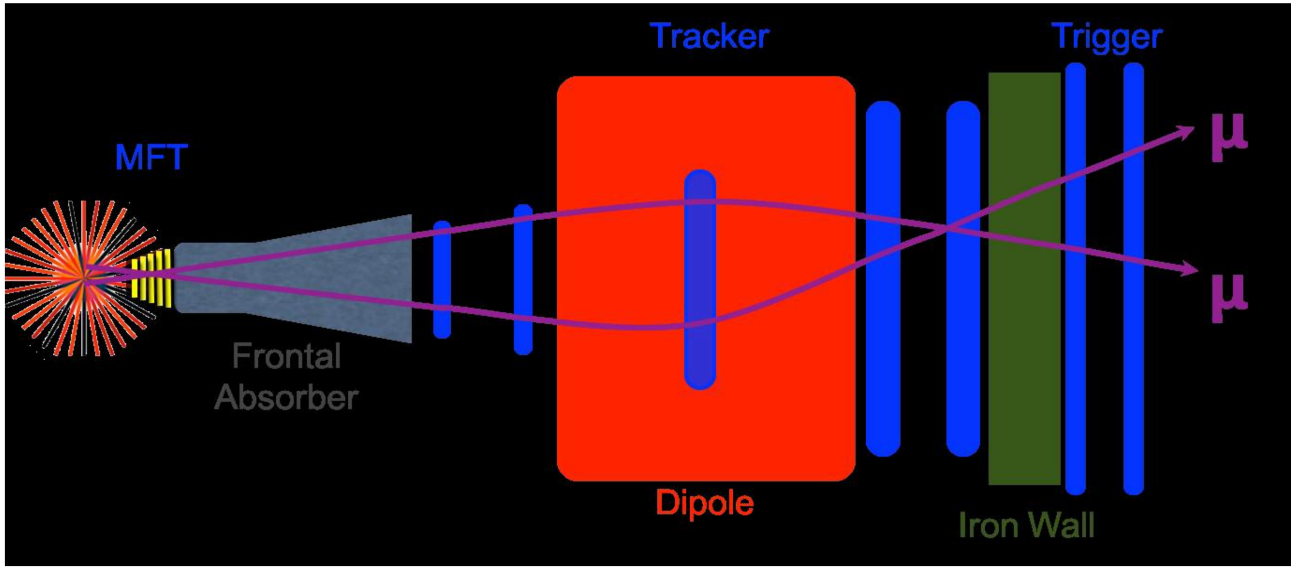




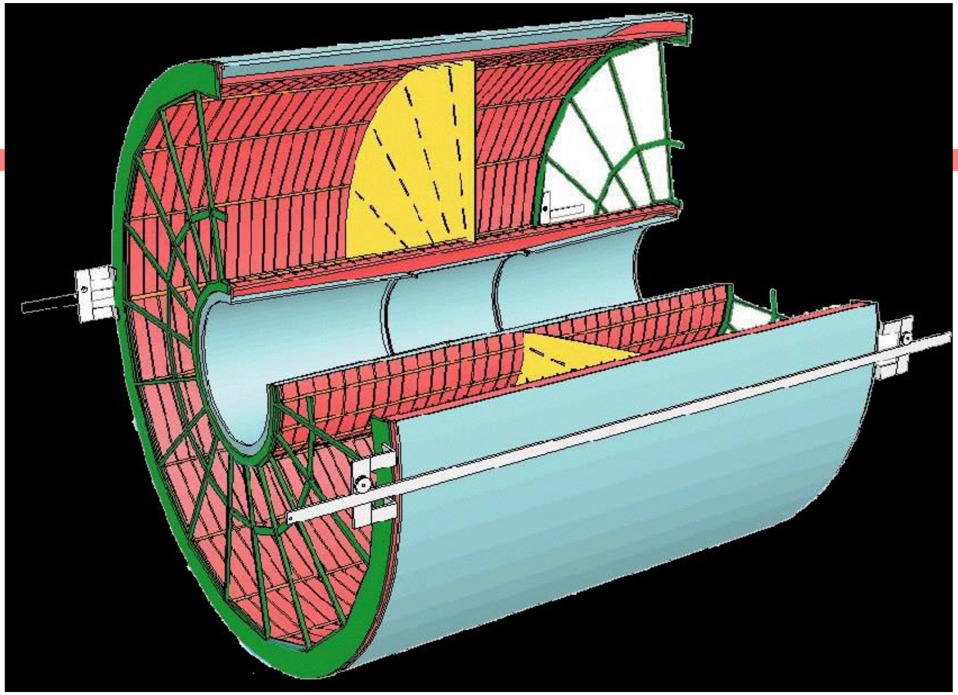
MFT as a new detector

- New detector in ALICE
  - Add vertexing capability in muon spectrometer system
    - Distinguish prompt J/ψ from B decay
  - 5 layer silicon pixels (ITS technology)
  - 0.4 m^2 area

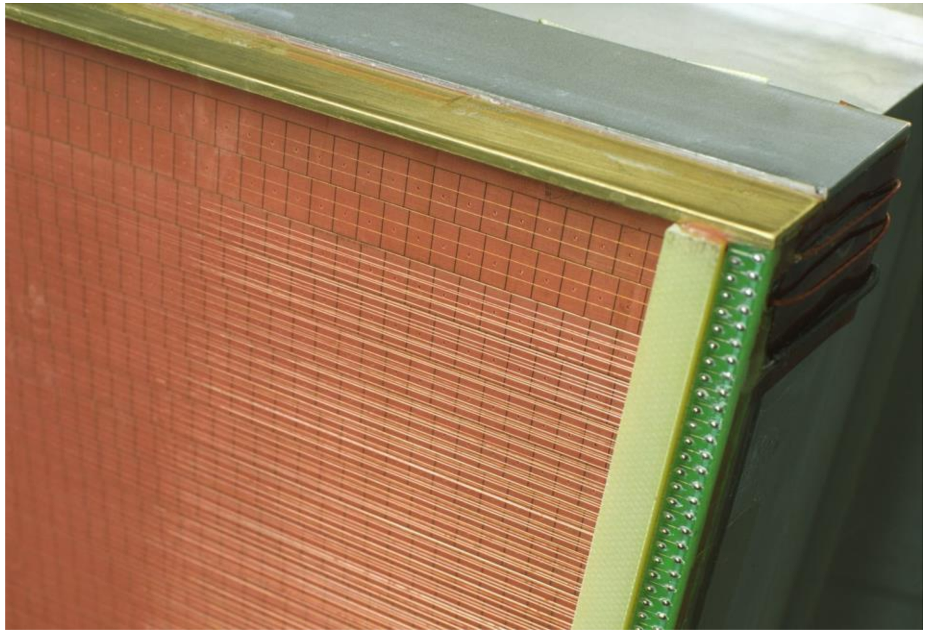


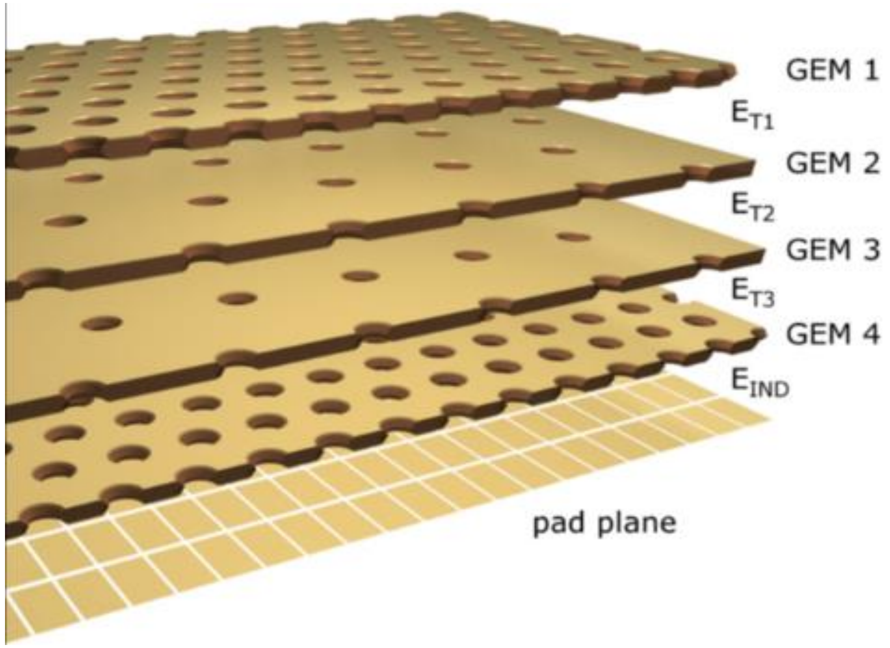


TPC Upgrade

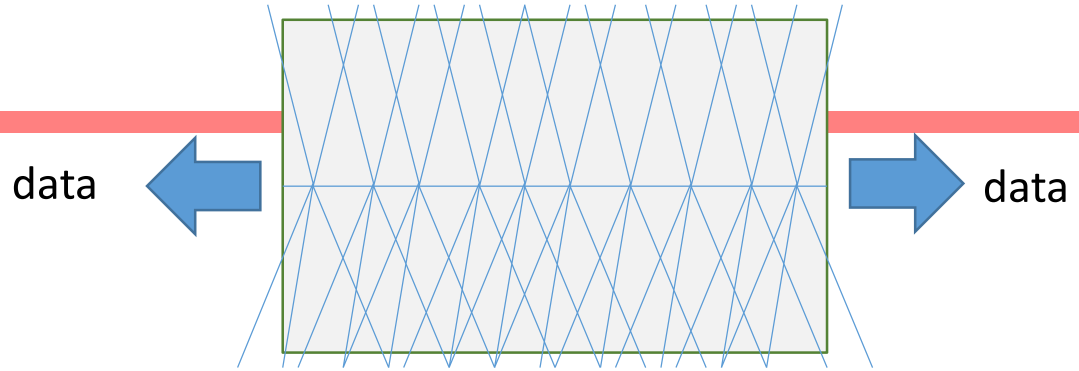


- The most important and challenging upgrade in ALICE
  - 4 GEM system replaces traditional wire amplification system
  - decrease “dead-time” due to ion absorption time
    - 500 ns down to **zero** → data rate from 2 kHz to ∞
    - 530k channels, 200 ns sampling ADC data come out
      - 3.5 TB/s continuous data rate
      - massive online computing power required
    - CNS-Tokyo, Nagasaki-IAS from Japan

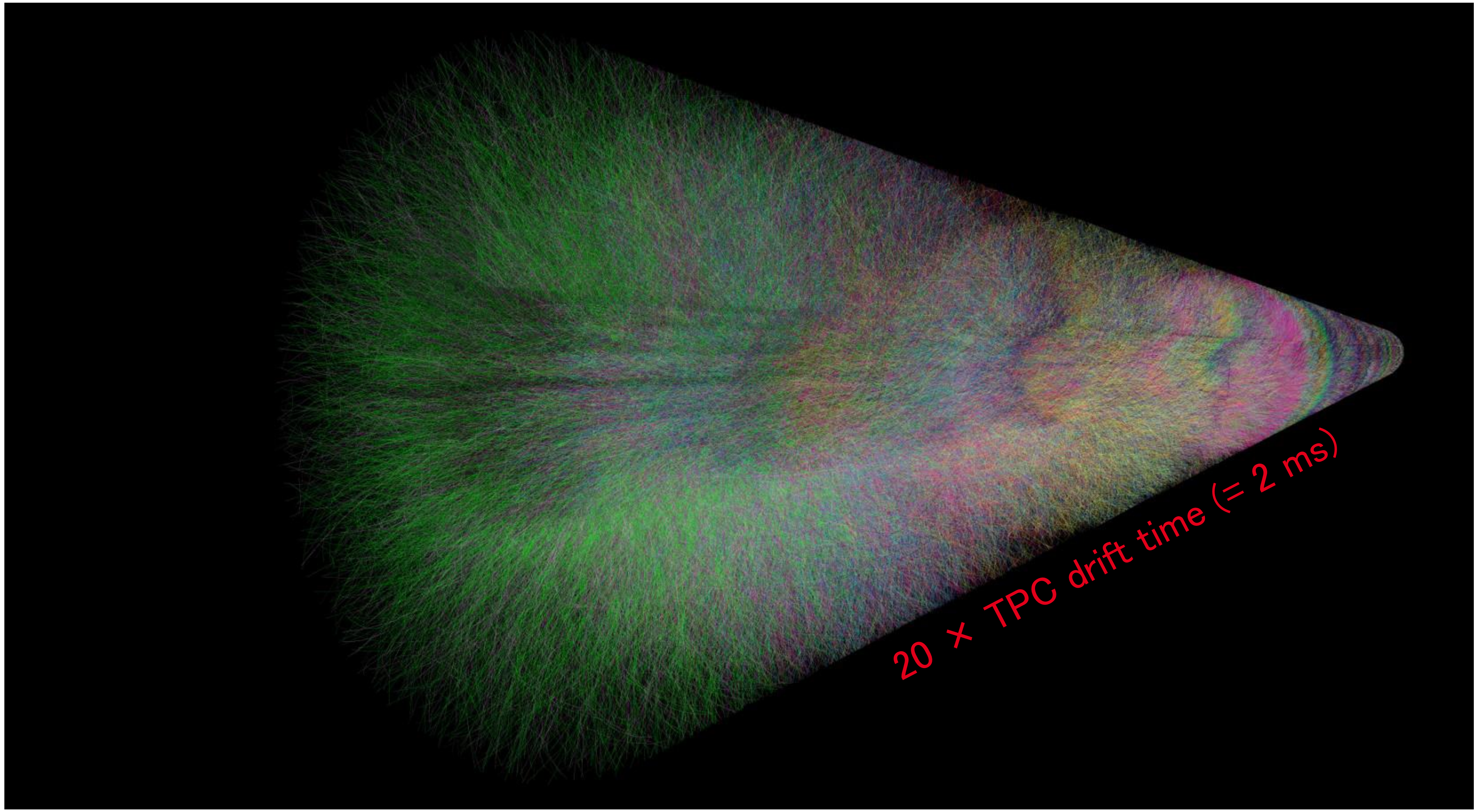




TPC Upgrade (cont.)

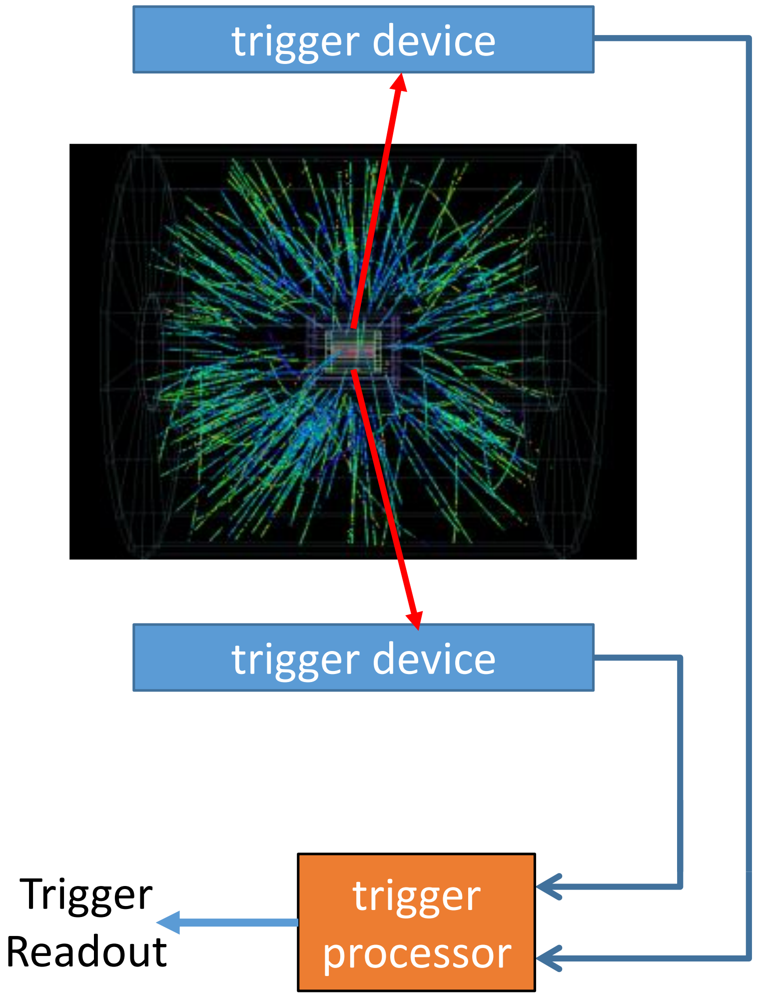


- LHC may provide above 50 kHz event rate after upgrade
- Means 3.5 TB/s data rate
- TPC drift time (100 μs)



Data taking upgrade without hardware trigger

- What's hardware trigger?
  1. find interesting event such as high momentum particle, jet, etc
  2. initiate detector data readout
  3. readout time (TPC case: 500 μs) → deadtime (loss of luminosity)
- Triggering to rare particles such as low p_T heavy flavor multi-particle decay from exotic particles in high multiplicity event is impossible
  - decreasing threshold → trigger to all garbage
  - non-simple threshold type trigger → full data analysis (a dilemma)
  - also 50 kHz for ALICE TPC means always ~5 events overlapping in data
    - event-by-event data taking no longer possible

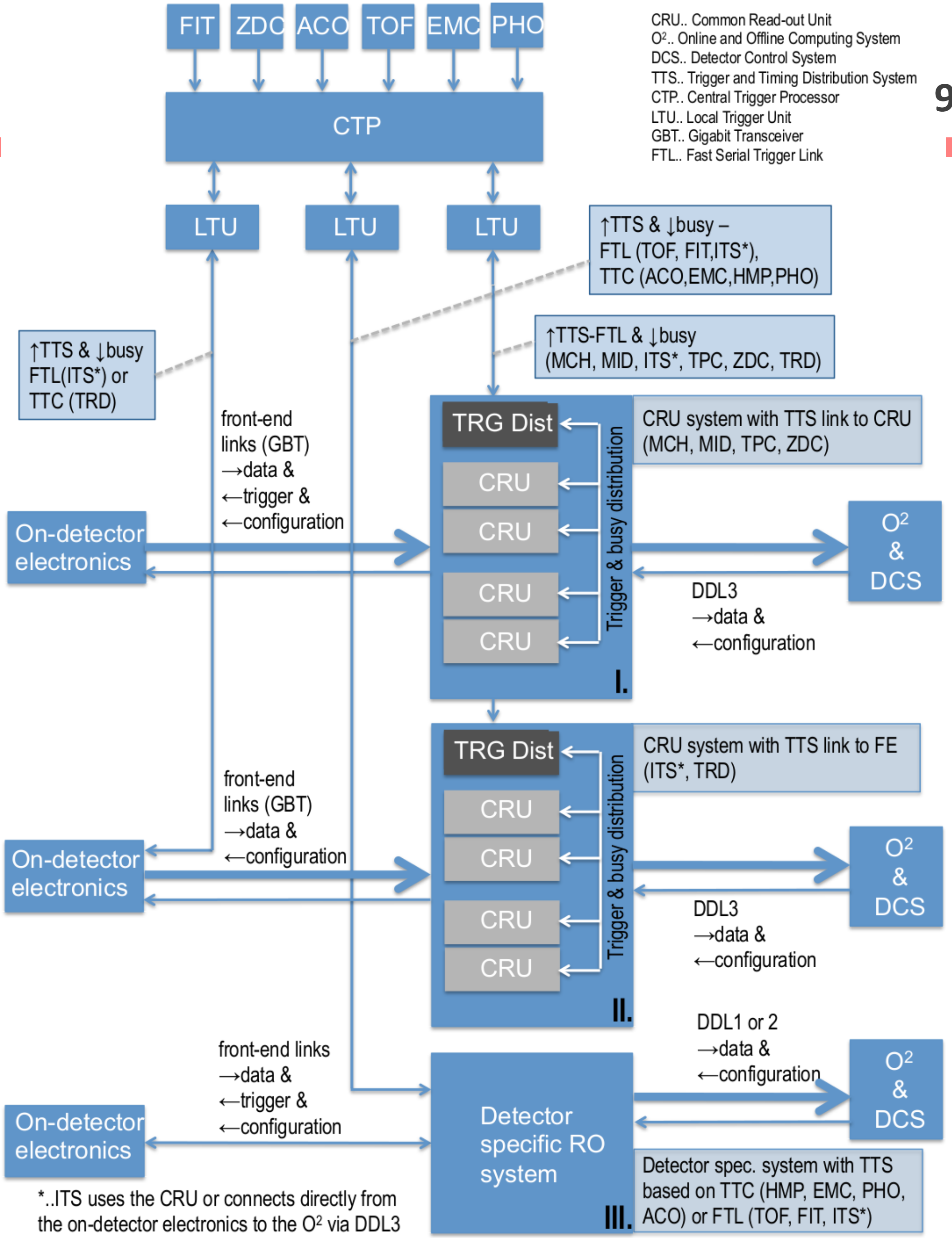


- The biggest decision for Run3 → abandon "hardware trigger"
  - TAKE ALL DATA, STORE ALL without trigger
    → continuous readout
    - data compression, online analysis are key technology

ALICE readout system

Common Readout Unit (CRU)

- common design for at least "major" and "new" detectors
- Detector Control System
- trigger and timing distribution
- data readout and processing with **O(10) faster** than CPUs
  - sorting, online processing
    - clustering (large **FPGA**), tracking (commercial **GPU**)
  - deploy ~350 for TPC (~6M CHF project)



Conclusive table of performance of upgraded ALICE

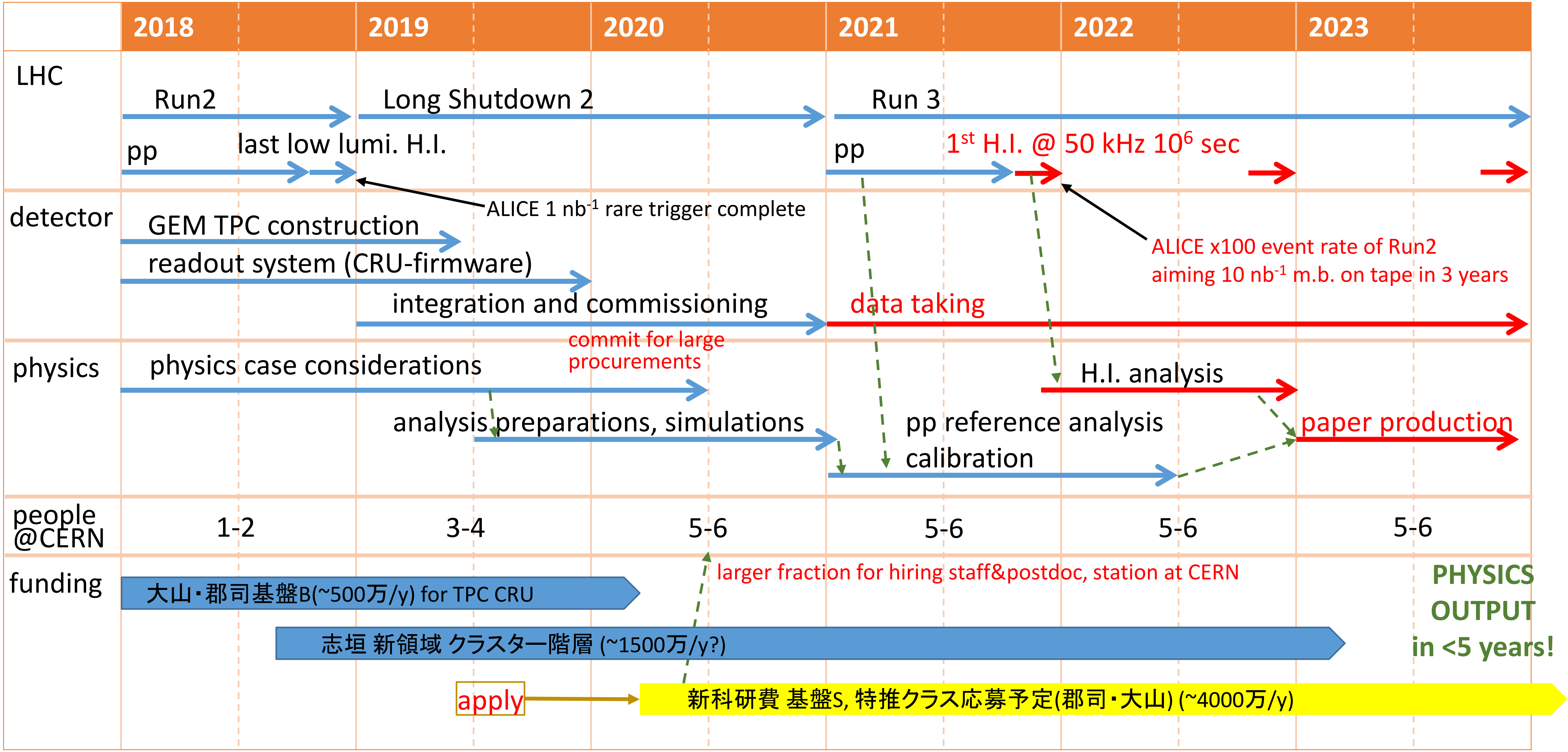
central barrel case

	Run1+2	Run3	typical signals, physics

minimum bias event
&
untriggerable rare event
	~ 10^9 events (recorded)
	~ 0.1 nb^{-1}
		x100 statistics = 10^{11} (recorded)
		~10 nb^{-1}
			• any kind of single particle analysis
			• e^+e^- low invariant mass
			• such as anti-nuclei (/^{4}He) (already visible)
			• low-pT multi-particle decay
			  • open heavy flavor baryons as tools
			    • 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}** (recorded) ~10 nb^{-1}	• high p_T jet related observables • high p_T gamma, electron • such as Υ and maybe top-quark related?

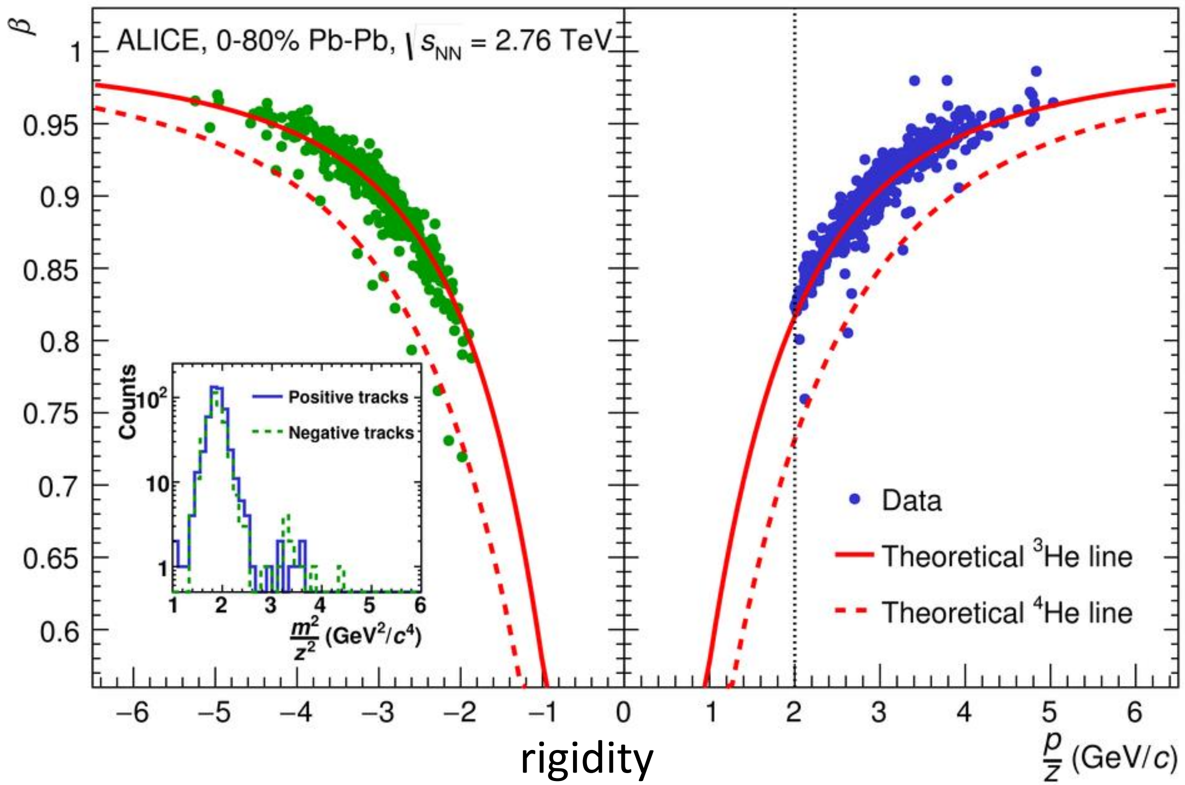
Roadmap


2018
2019
2020
2021
2022
2023
LHC
Run2
Long Shutdown 2
Run 3
pp
last low lumi. H.I.
pp
1st H.I. @ 50 kHz 10^6 sec
ALICE 1 nb-1 rare trigger complete
ALICE x100 event rate of Run2
aiming 10 nb-1 m.b. on tape in 3 years
detector
GEM TPC construction
readout system (CRU-firmware)
integration and commissioning
data taking
physics
physics case considerations
commit for large
procurements
H.I. analysis
analysis preparations, simulations
pp reference analysis
calibration
paper production
people
@CERN
1-2
3-4
5-6
5-6
5-6
5-6
funding
larger fraction for hiring staff&postdoc, station at CERN
大山・郡司基盤B(~500万/y) for TPC CRU
志垣 新領域 クラスター階層 (~1500万/y?)
apply
新科研費 基盤S, 特推クラス応募予定(郡司・大山) (~4000万/y)
PHYSICS
OUTPUT
in <5 years!

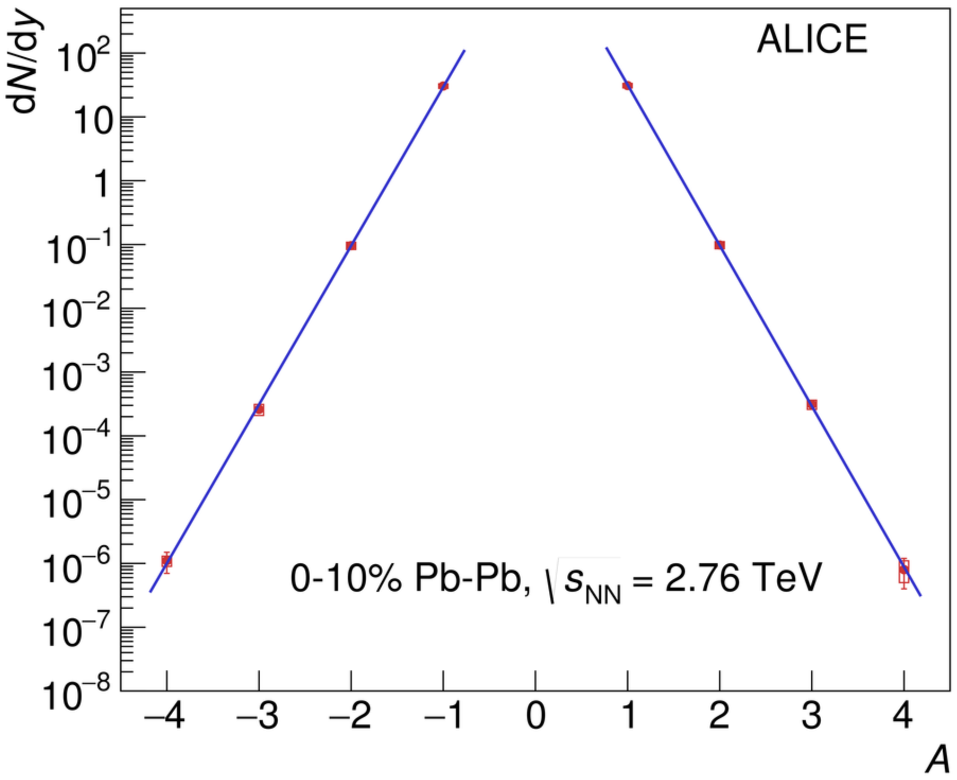
Light nuclei, anti-nuclei (performance check)

- 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 data (100 billion), we expect x2000 statistics → ~20k ^{4}He and 6M ^{3}He

time of flight



rigidity

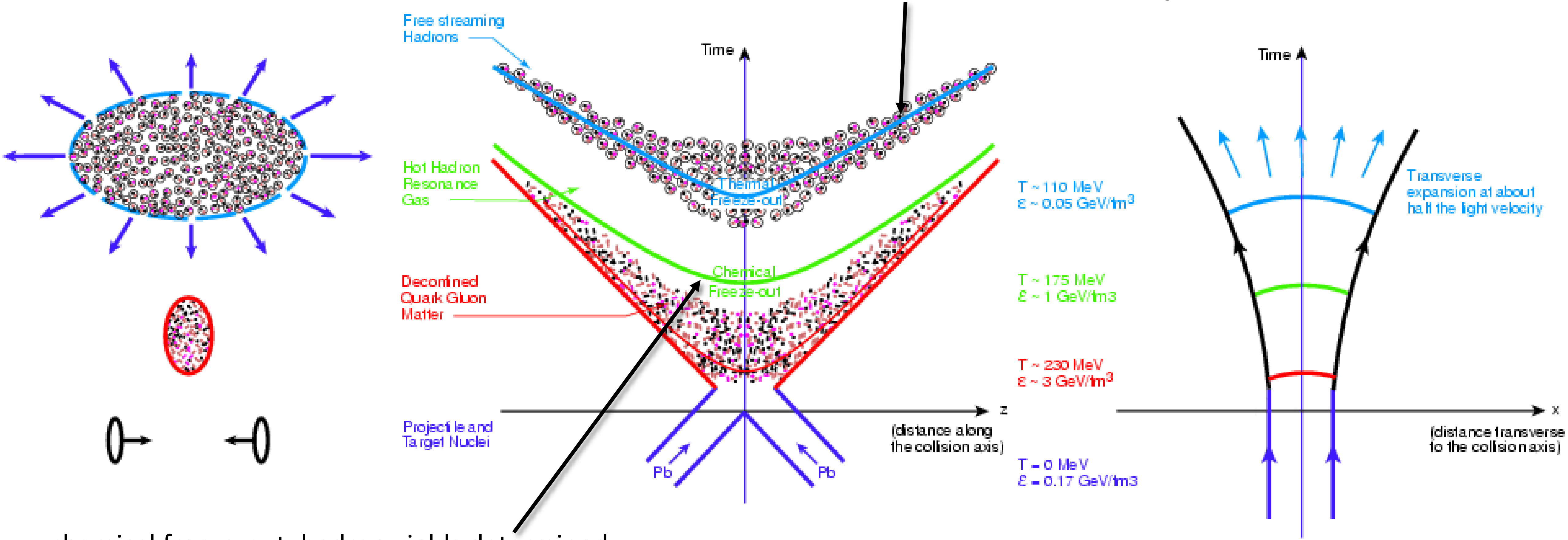


penalty factor ~ 300/nucleon

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

Space-time evolution in heavy ion collisions

residual interaction begins



chemical freeze-out: hadron yields determined

Drawings: http://na49info.web.cern.ch/na49info/Public/Press/findings.html

Chemical freeze-out hypothesis

- Hadron yields are fixed at a certain time in the space-time evolution of heavy ion collisions (=end of inelastic scattering)
  - thermalized system complying hadrons with u, d, s quarks .. i.e. GCE: $\rho = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp[(E-\mu)/T_{ch}]\pm 1}$
  - hadron yields are determined with the few global parameters

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

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

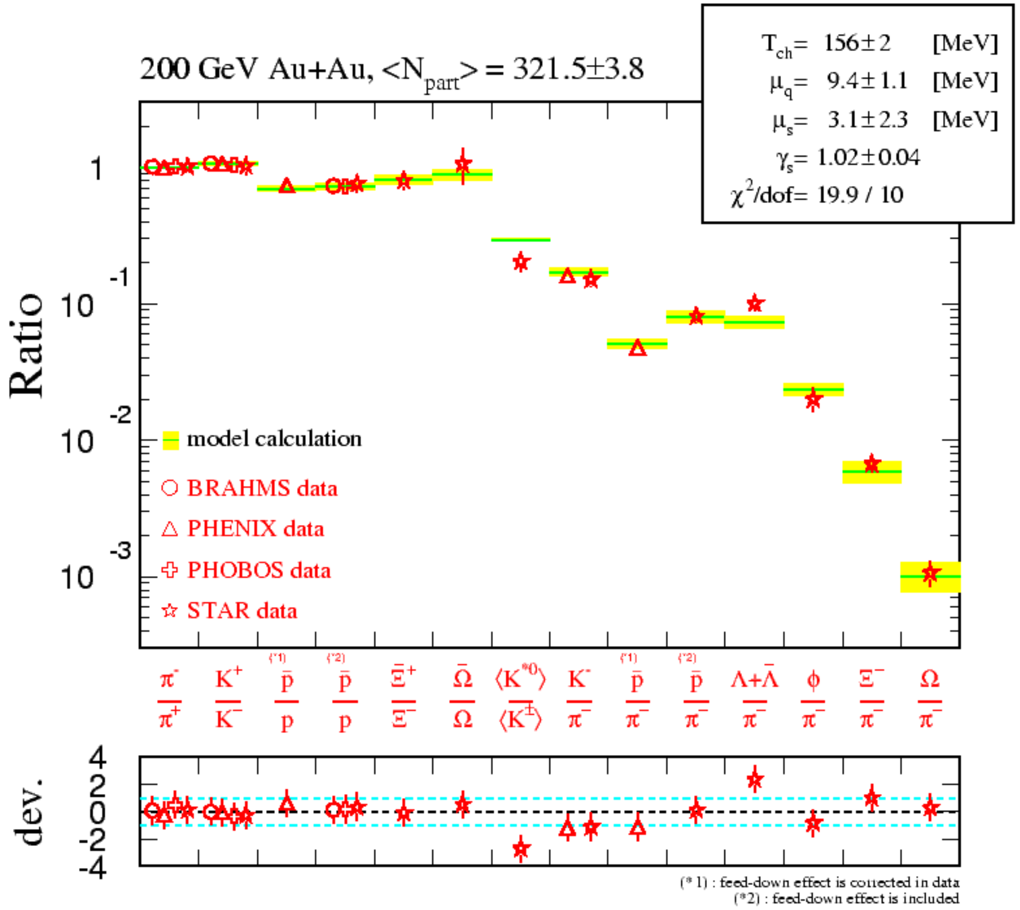
Q_i : 1 for u and d, -1 for $\bar{\mathrm{u}}$ and $\bar{\mathrm{d}}$
s_i : 1 for s, -1 for $\bar{\mathrm{s}}$
g_i : spin-isospin freedom
m_i : particle mass
K_2 : modified Bessel function

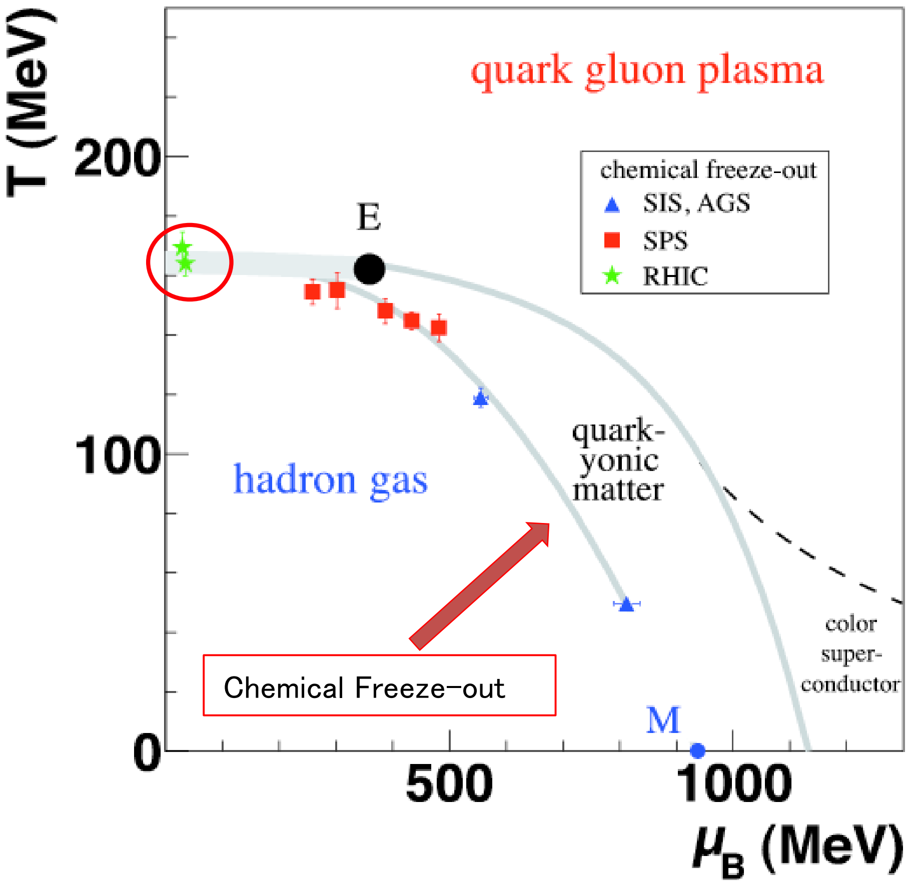
global parameters
T_{ch} : chemical freeze-out temperature
μ_{q} : light-quark chemical potential
μ_{s} : strangeness chemical potential
γ_{s} : strangeness saturation factor

Hadron yields → determine temperature and chemical potential at chemical freeze-out

Hadron yields and chemical freeze-out

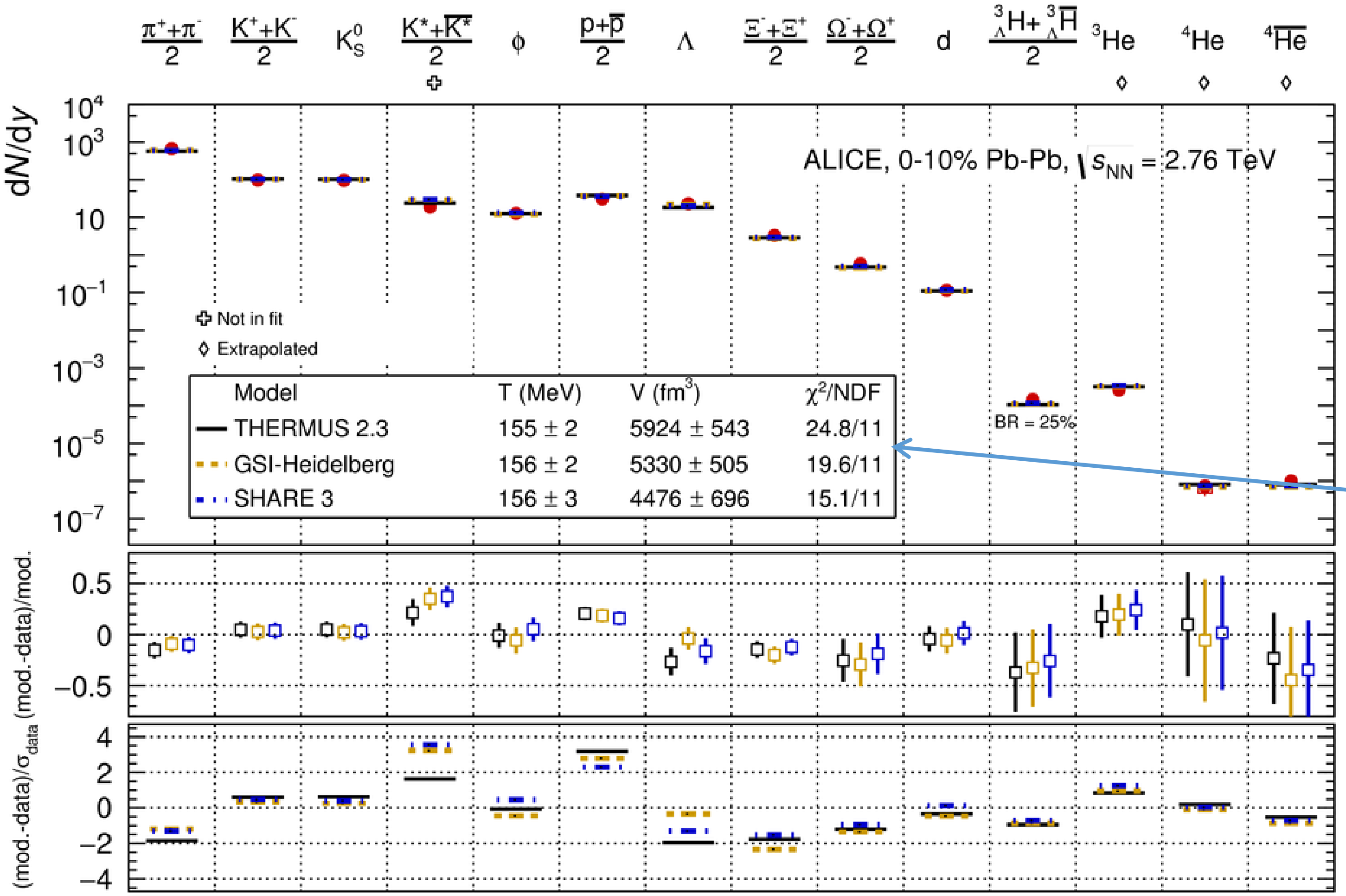
- Hypothesis of chemical freeze-out works reasonably well to describe hadron yields for nuclear collisions in wide colliding energies.
- Utilize this property to predict yield of specific particles





Thermal model at 156 MeV predicts yields well

- Pb-Pb $s_{NN}^{1/2}$ = 2.76 TeV, 10% central collisions
- Yields from pion to ^{4}He are fitted well with the CF models



NPA 971 (2018) 1–20
ALICE collaboration

Three CF models:
T_{CF} ~ 155–156 MeV

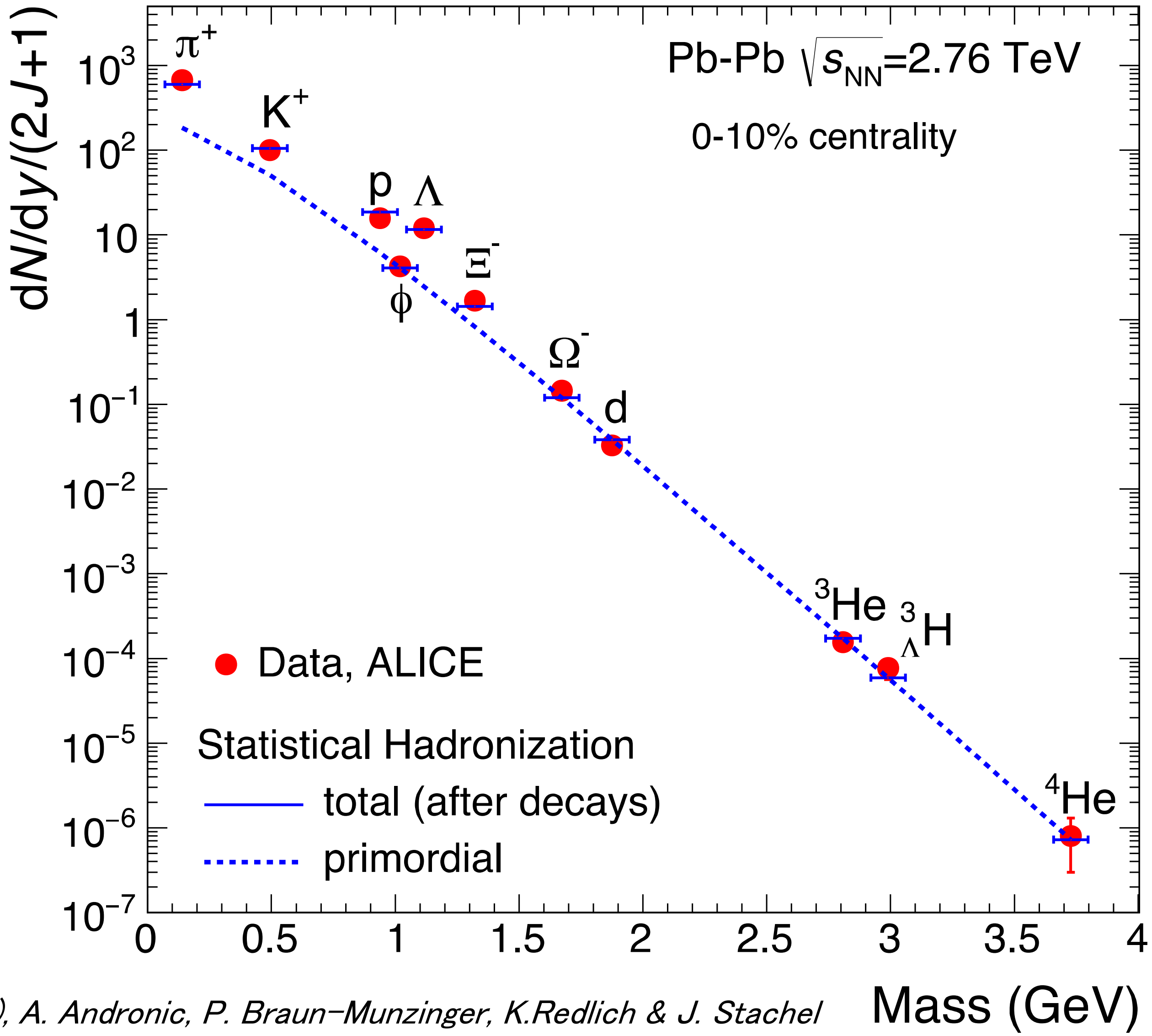
Yields are sensitive to the CF temperature

Hadron yields vs. mass

- Smooth trend with mass
- Why the simple chemical freeze-out model works so well covering not only mesons but also to light nuclei?

  - T_{CF} ~ 155 MeV
  - T_{KF} ~ 100 MeV

  - BE(d) ~ 2.22 MeV
  - BE($^{3}_{\Lambda}$H) = 0.13 ± 0.05 MeV [NPA 754, 3c (2005)]

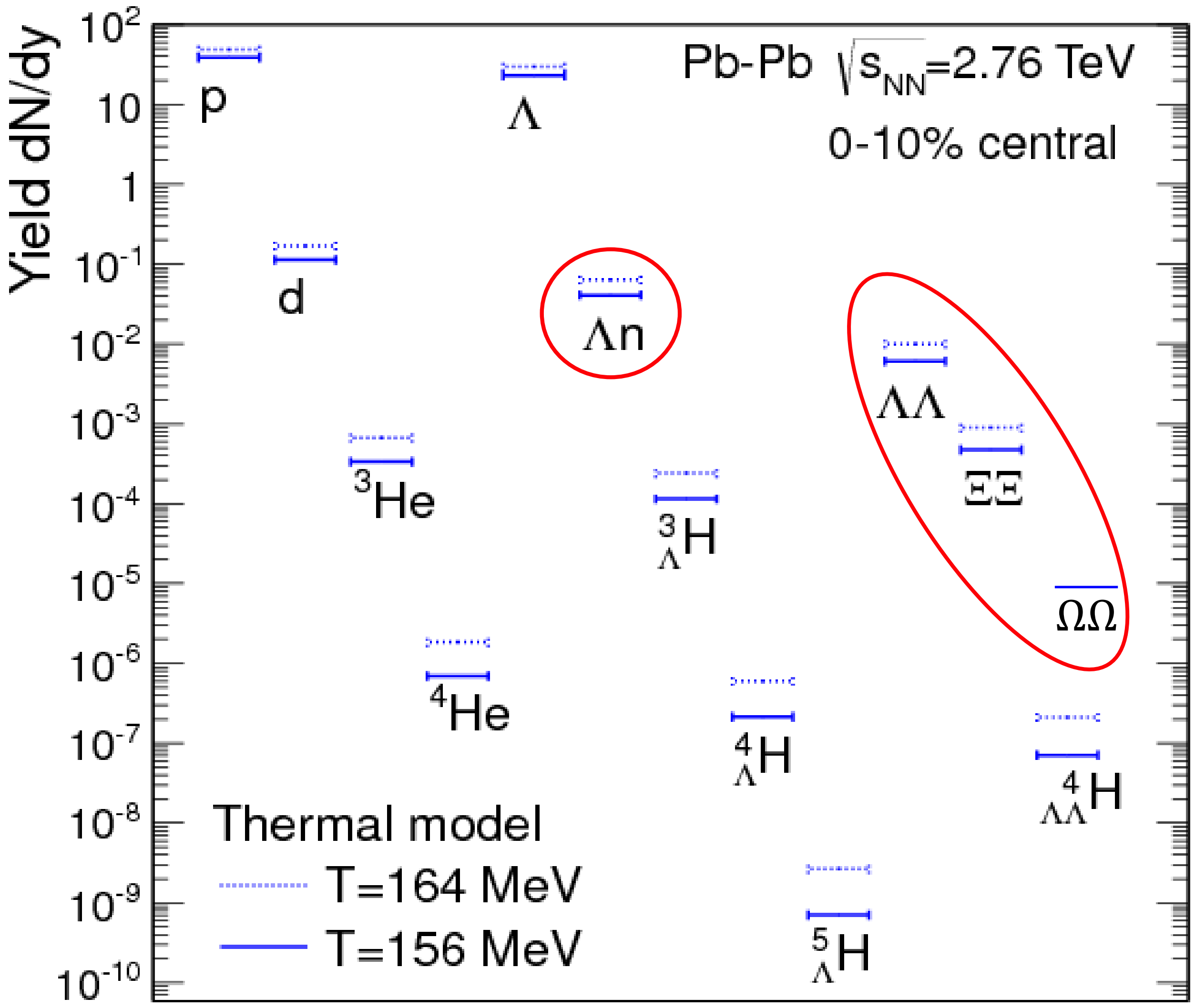


Naturevolume 561, pages321–330 (2018), A. Andronic, P. Braun-Munzinger, K.Redlich & J. Stachel

Expected yields for di-baryons

- We can expect enough statistics even for ΩΩ in the LHC RUN3

- In case when the yield deviate from the CF model expectation;
  - no bound state
  - production mechanism is different from those of normal nuclei
  - unique configuration



Expected yield

■ Run3 with x3000 statistics double-Λ hyper nuclei is in target

J. Phys. G 41 (2014) 087001

	Expected yields
Anti-α	30,000
$^{3}_{\Lambda}H$	300,000
$^{4}_{\Lambda}H$	800
$^{4}_{\Lambda\Lambda}H$	**34**
ΞΞ	150,000

10^{10} central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.5 TeV
8% efficiency per detected baryon is assumed

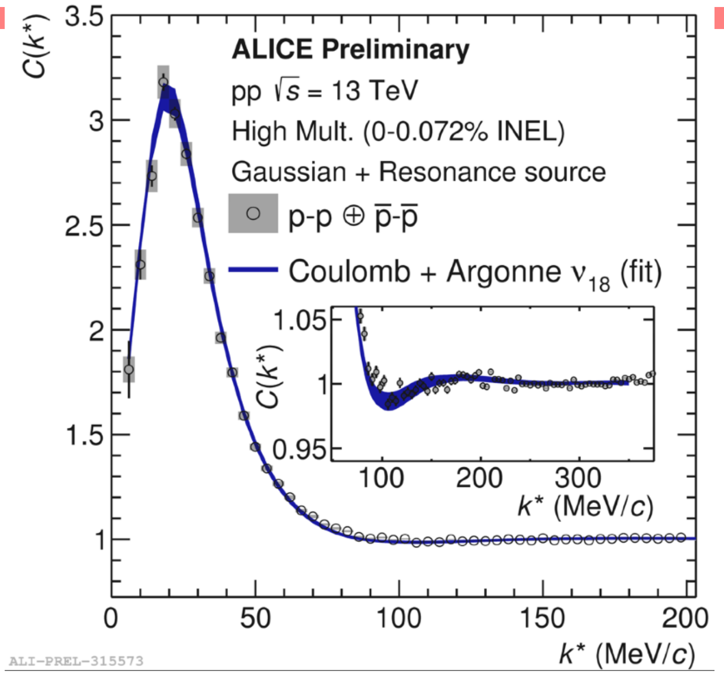
slide by Y. Watanabe in ExHIC2016

numbers from **Upgrade of the ALICE Experiment: Letter Of Intent**

Methods for searching exotica in ALICE

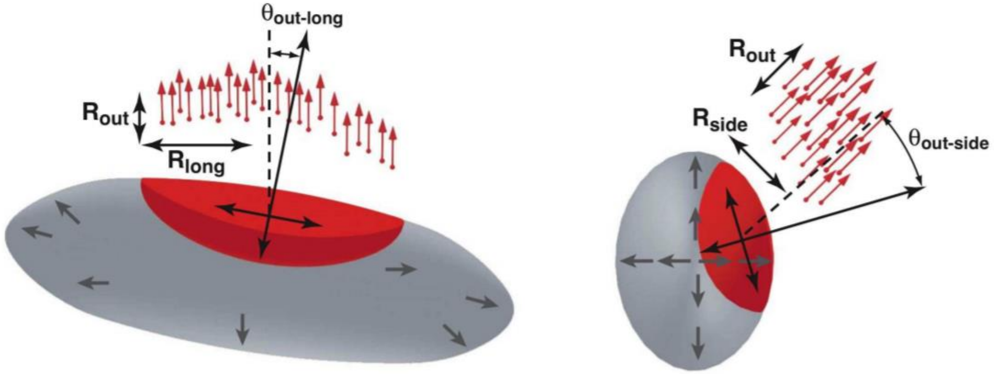
Its collider with dN/dy ~ O(1000)

→ 1. statistical production by chemical freezeout time
2. or final state interactions after thermal freezeout



- Direct measurement of invariant mass of two hadrons
  - finding bound state as a mass peak
  - unbound resonance state: useful for states with small decay width

- Two particle correlation（femtoscopy）
  - Extension of binary scattering method
  - Measurement of final state interaction of two particles
  - HBT (Hanbury Brown and Twiss) effect



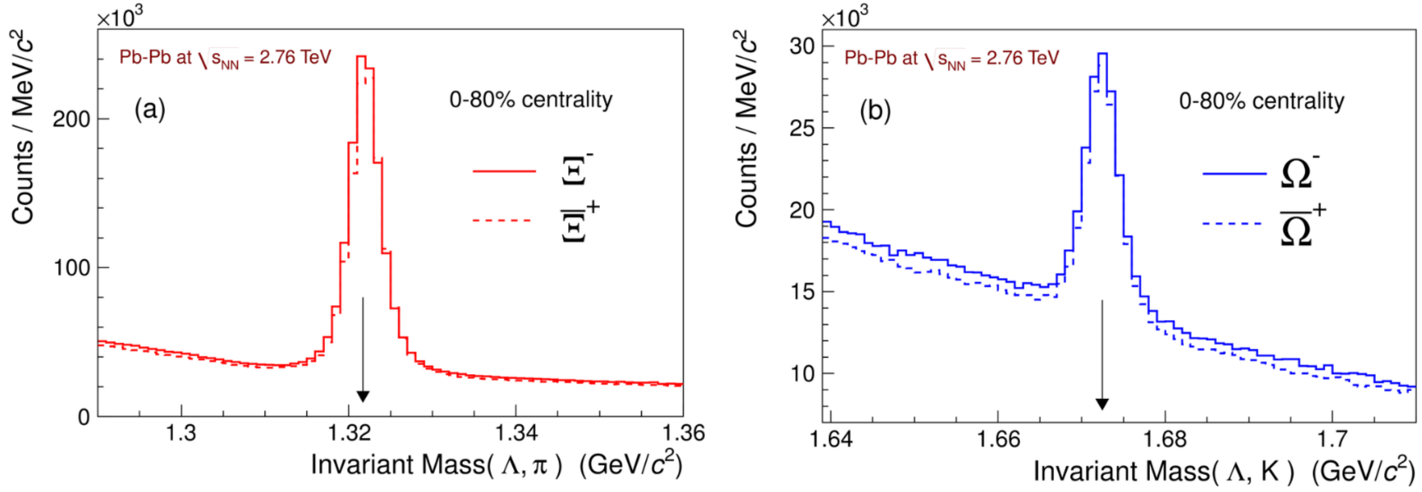
$$C(\boldsymbol{p}_1,\boldsymbol{p}_2) = \frac{P(\boldsymbol{p}_1,\boldsymbol{p}_2)}{P(\boldsymbol{p}_1)P(\boldsymbol{p}_2)} \to C(k^*) = \aleph \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

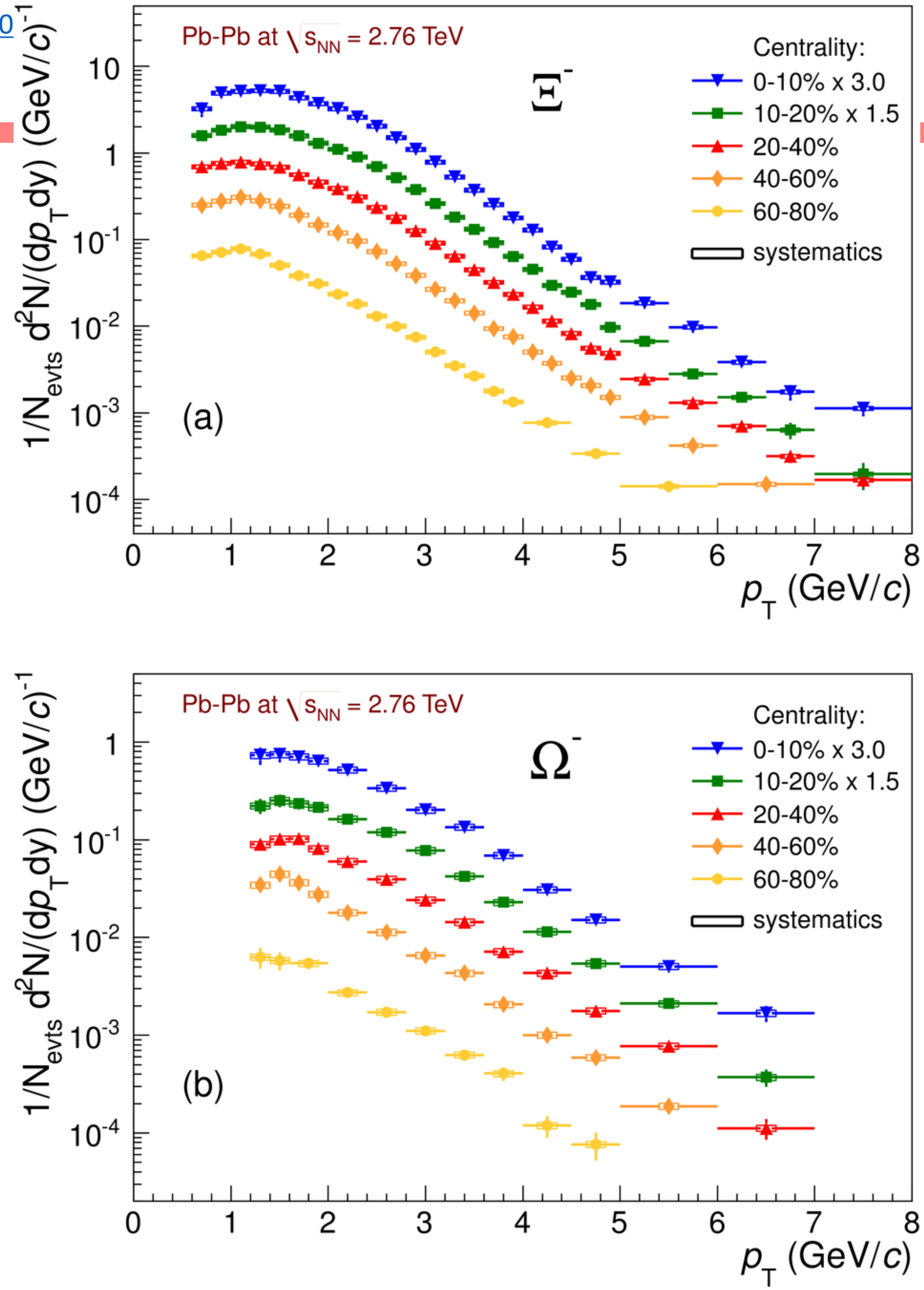
Phys. Lett. B 728 (2014) 216-227
http://alice-publications.web.cern.ch/node/60

Multistrange baryons

- are Ξ and Ω yield in ALICE enough for ΞΞ and ΩΩ studies?
- 15M 2.76 TeV Pb+Pb MB data give enough of them through
  - $\Xi^- \rightarrow \Lambda + \pi^-$ (99.9%)
  - $\Omega^- \rightarrow \Lambda + K^-$ (67.8%)
- p_T spectra available
  - <10 Ξ per event
  - <1 Ω per event
- Run3 statistics > x5000

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^-	$0.58 \pm 0.04 \pm 0.09$	$0.37 \pm 0.03 \pm 0.06$
$\overline{\Omega}^+$	$0.60 \pm 0.05 \pm 0.09$	$0.40 \pm 0.03 \pm 0.06$
$\Omega^- + \overline{\Omega}^+$	$1.19 \pm 0.06 \pm 0.19$	$0.78 \pm 0.04 \pm 0.15$



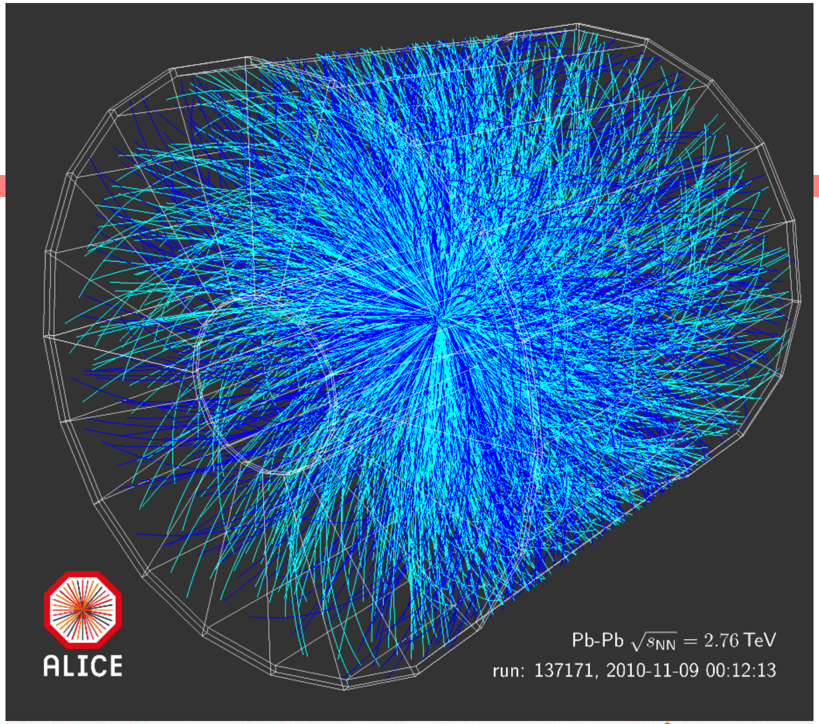


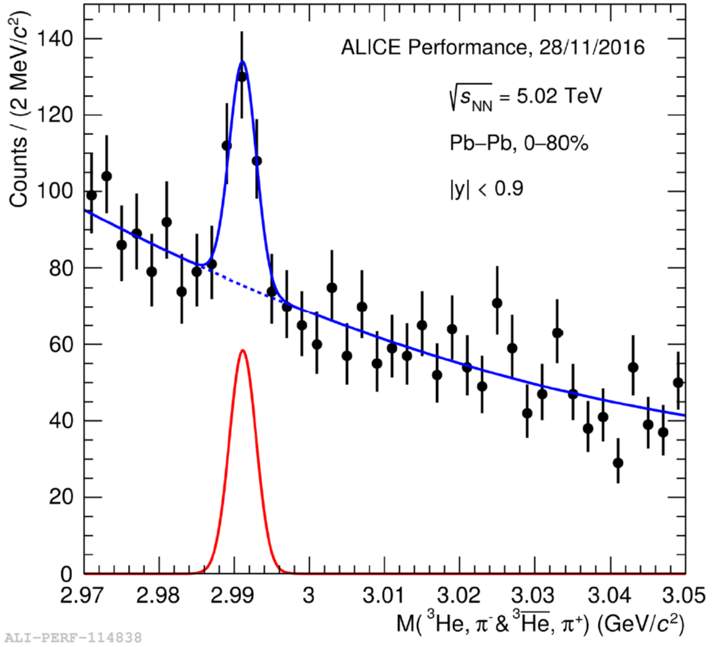
Hypertriton, anti-hypertriton

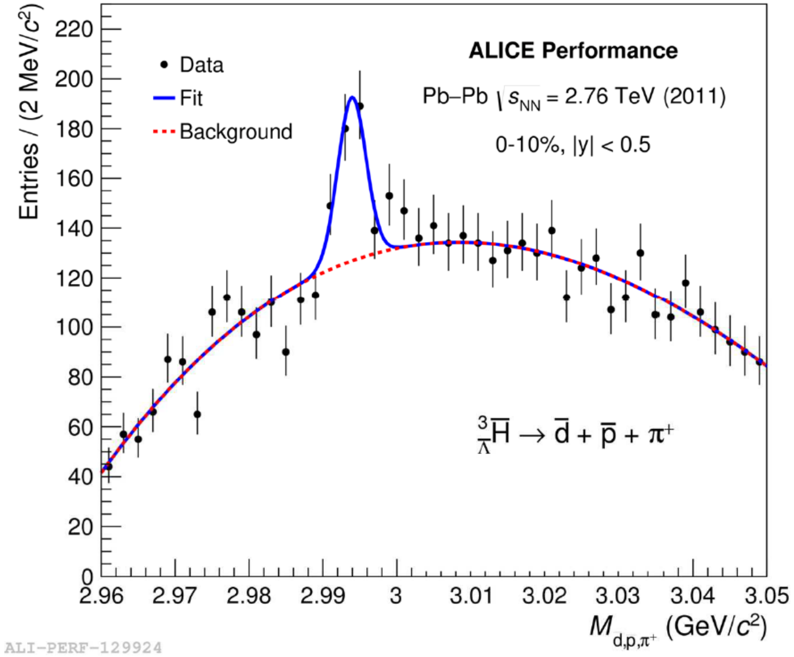
- Use (anti-)nuclei and hyperon as tools:
  - ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{+}$ … 25% B.R. (plenty found)
  - ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{H} + \pi^{0}$
  - ${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$
  - ${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{n} + \pi^{0}$

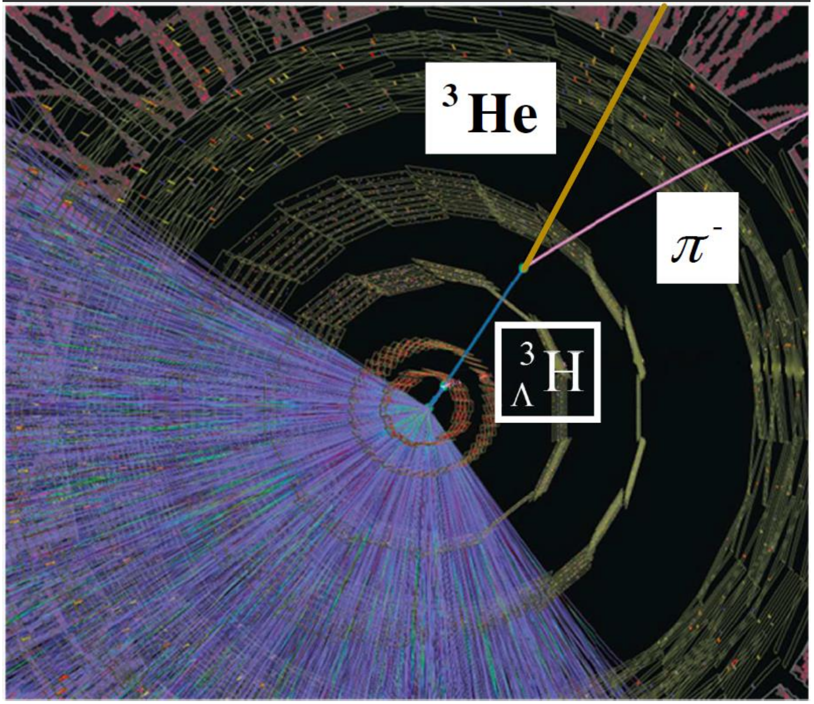
  \+ all anti-particle sets

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



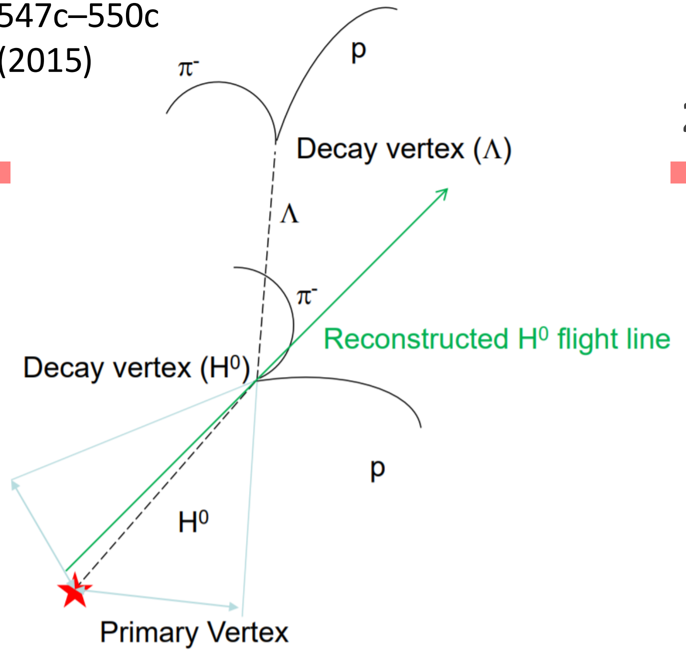






Dibaryon: direct search

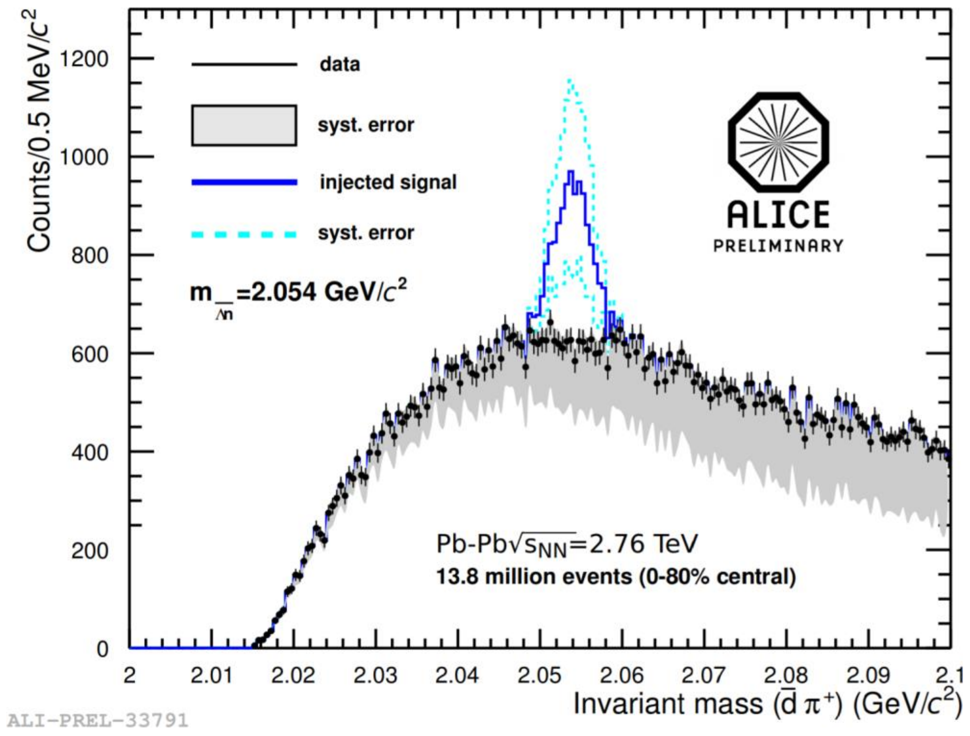
B. Dönigus, Nuclear Physics A 904–905 (2013) 547c–550c
ALICE Coll.: EPJ Web of Conferences 97,00013 (2015)

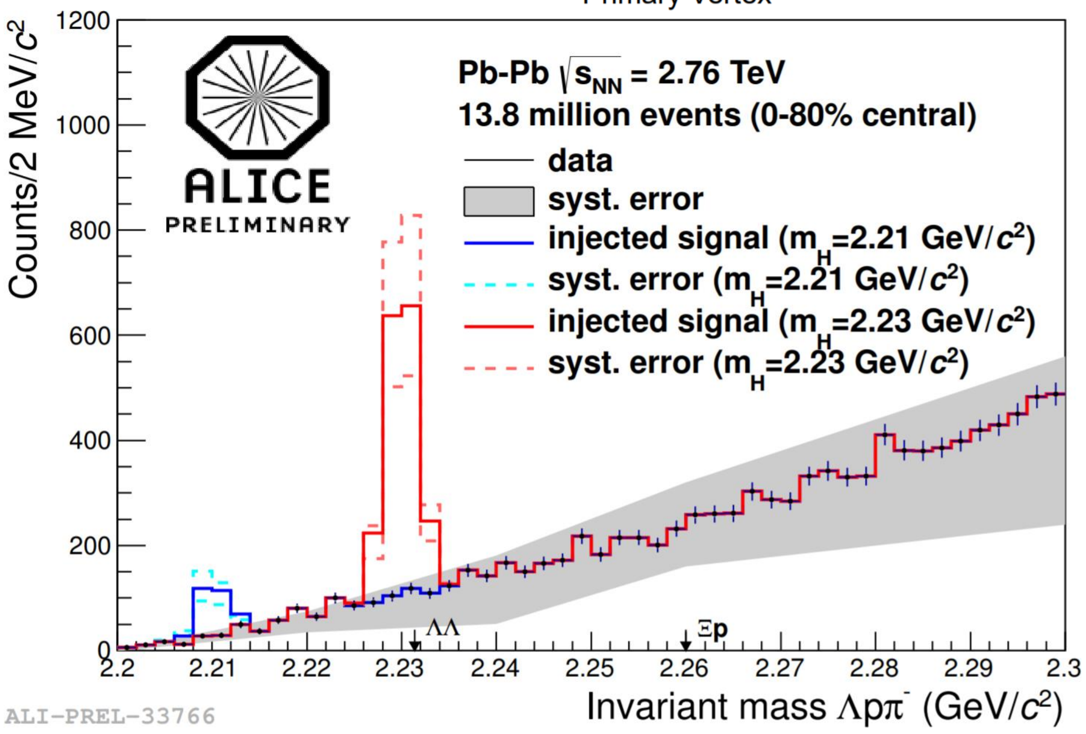


- $\Lambda n \rightarrow d + \pi^-$ mass spectrum … negative
- $\Lambda\Lambda \rightarrow \Lambda + p + \pi^-$ mass spectrum … negative

■ analysis based on 2-3 % of already obtained data

■ need confirmation in Run3 data with x3000 statistics





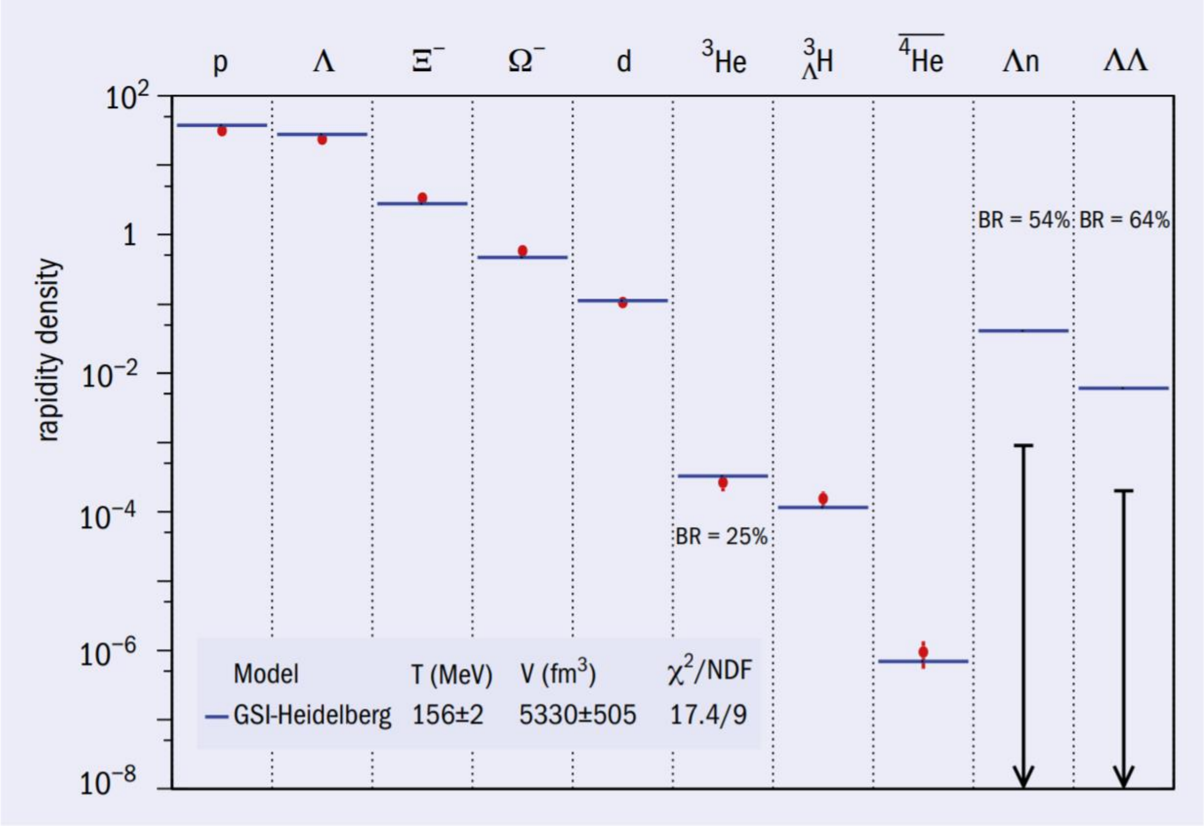
Dibaryon: direct search

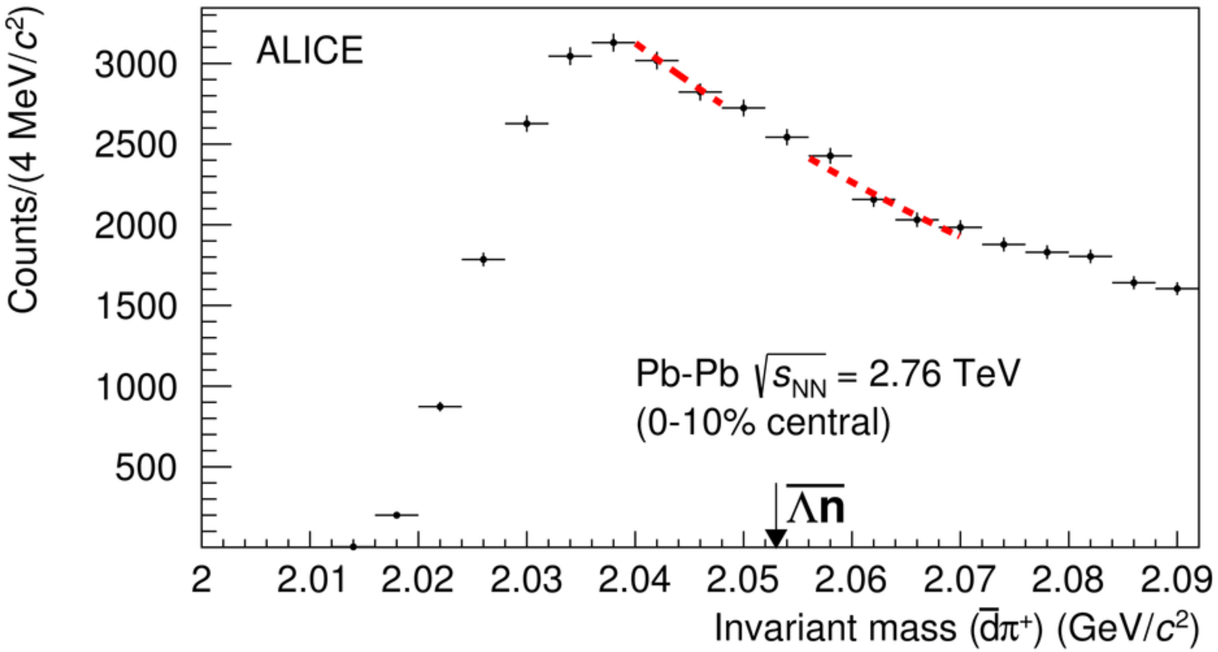
- 20M PbPb central data

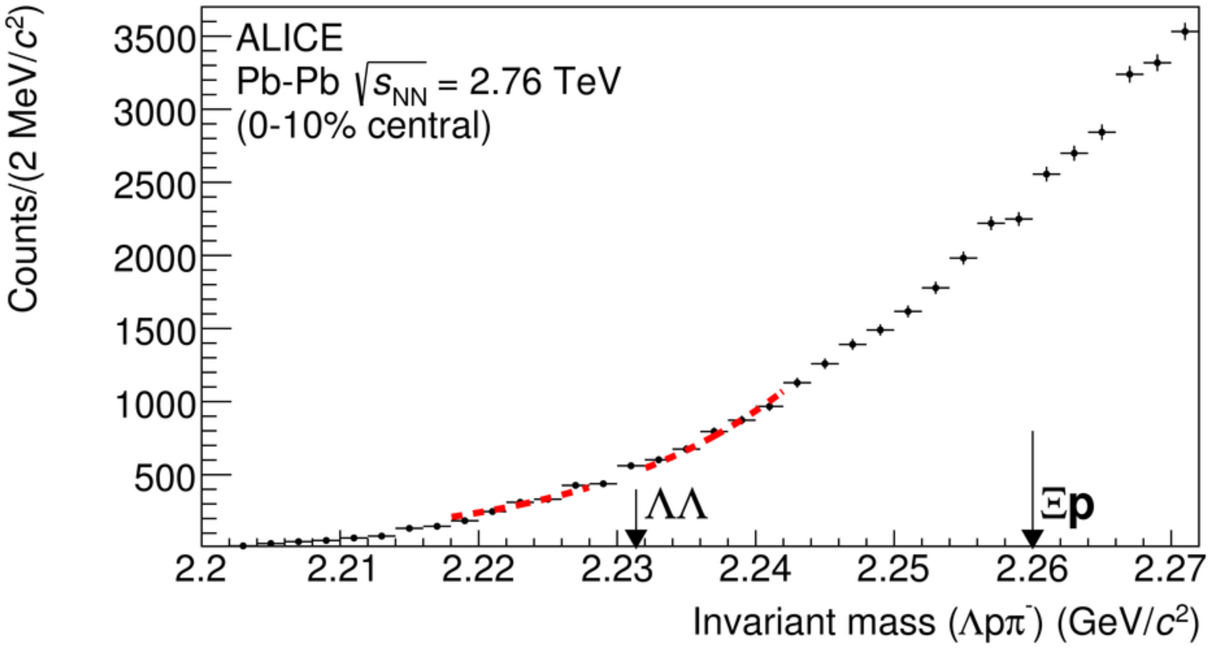
  Phys. Lett. B 752 (2016) 267-277

  http://alice-publications.web.cern.ch/node/1650

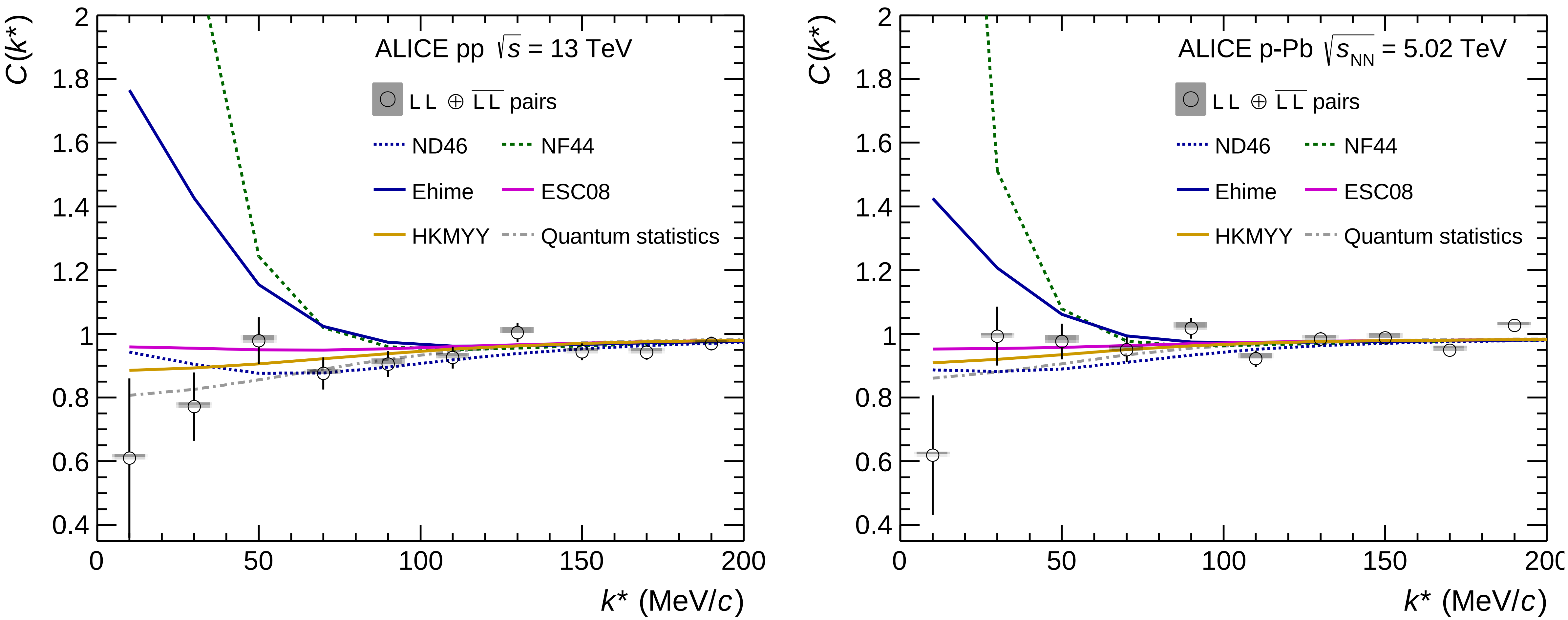
CERN Courier Sep. 2015





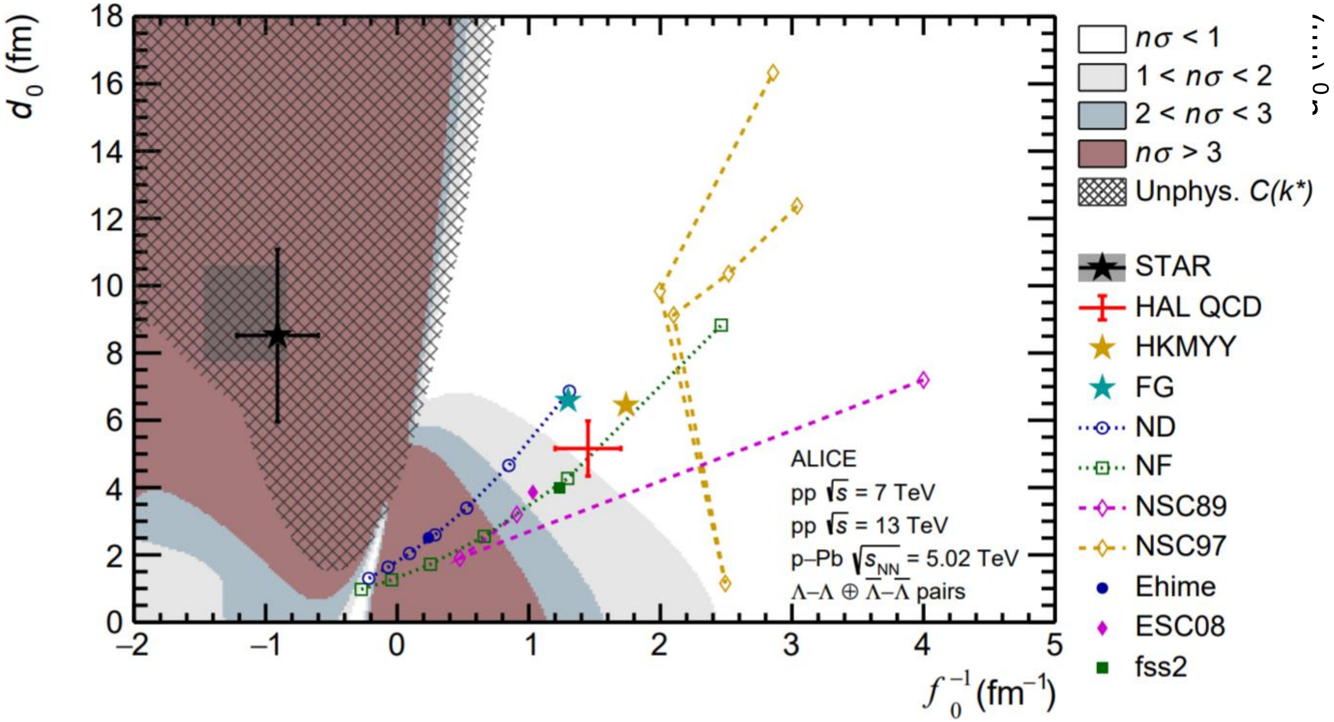


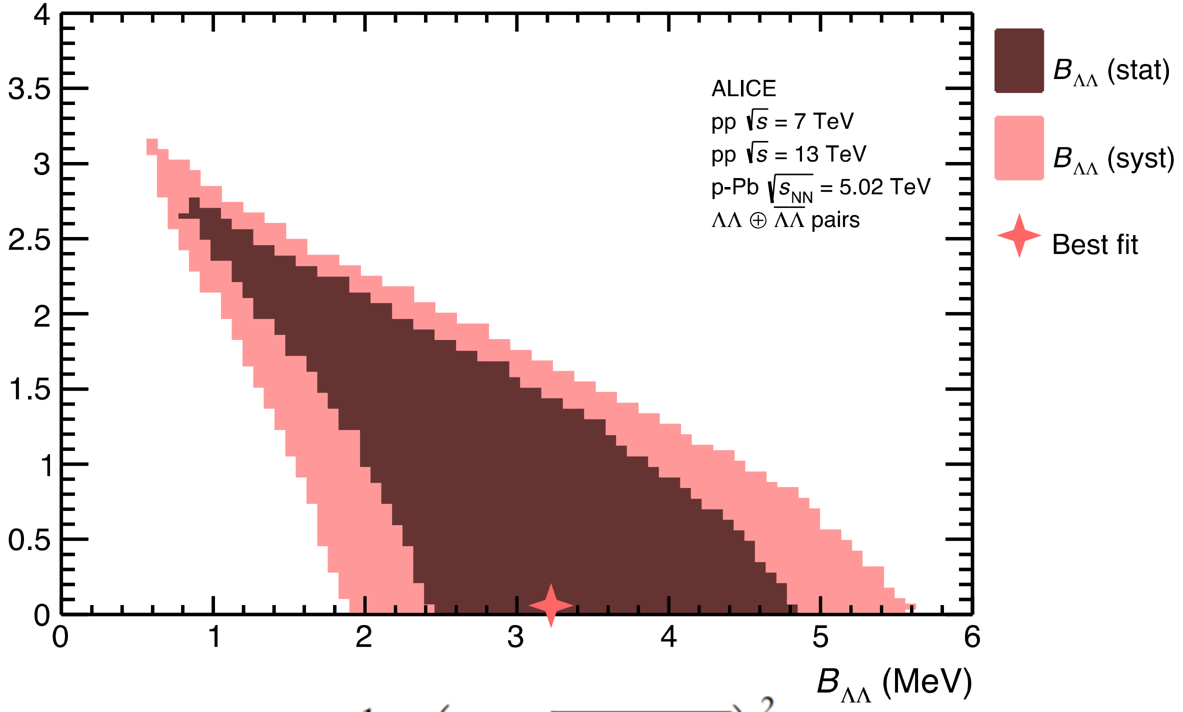
ΛΛ Correlation in pp & pPb (femtoscopy)



ΛΛ Correlation in pp & pPb (femtoscopy) cont.

- The scattering parameters, d_0 (effective range) and f_0^{-1},(inverse scattering length), have large ambiguity, because the correlation function is very flat
- Possible bound state in the region at slightly negative f_0^{-1} and $d_0 < 4$
- Paper accepted: arXiv:1905.07209



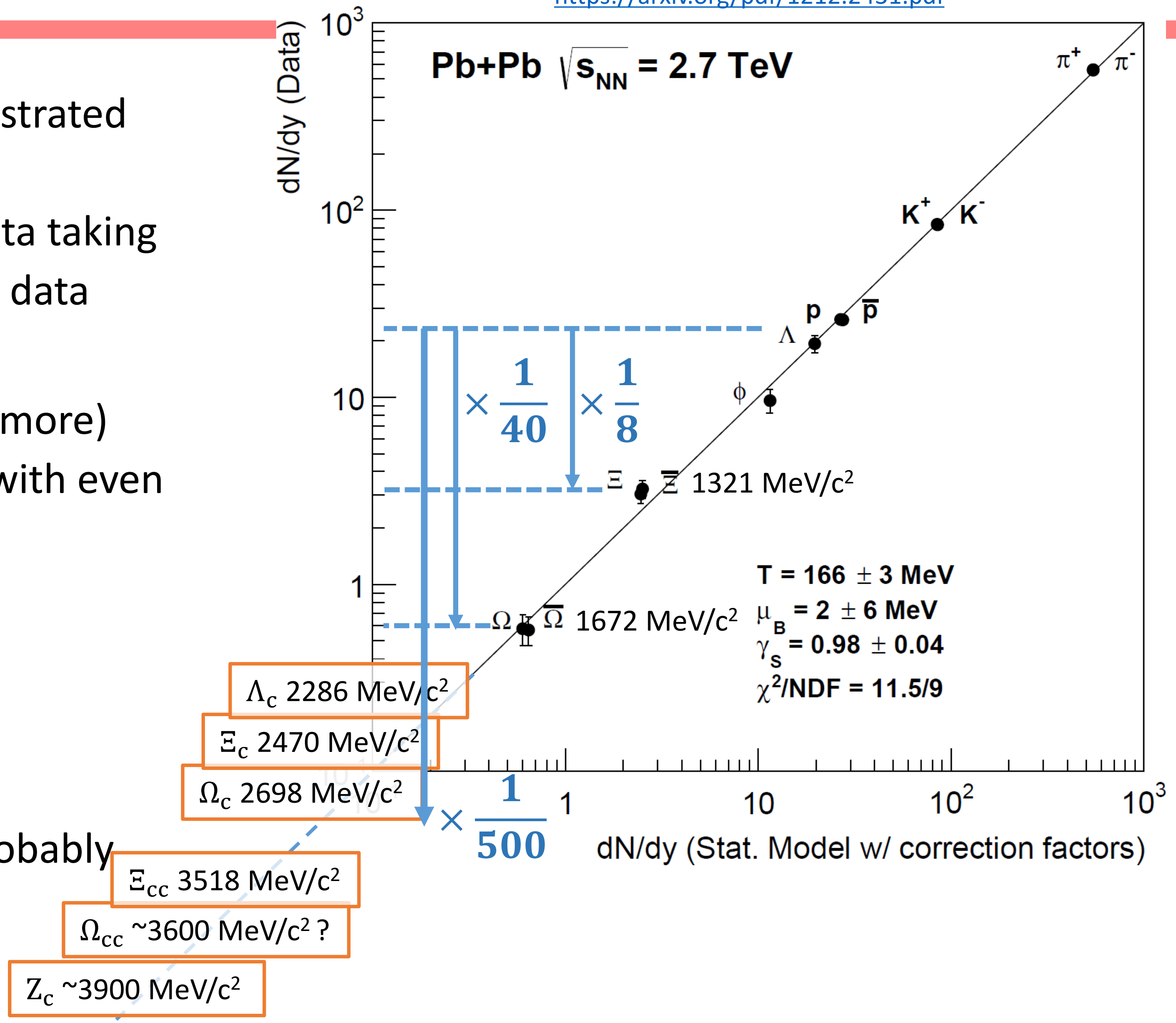


$$B_{\Lambda\Lambda} = \frac{1}{m_\Lambda d_0^2}\left(1 - \sqrt{1 + 2 d_0 f_0^{-1}}\right)^2$$

Ξ, Ω dibaryon and further exotica

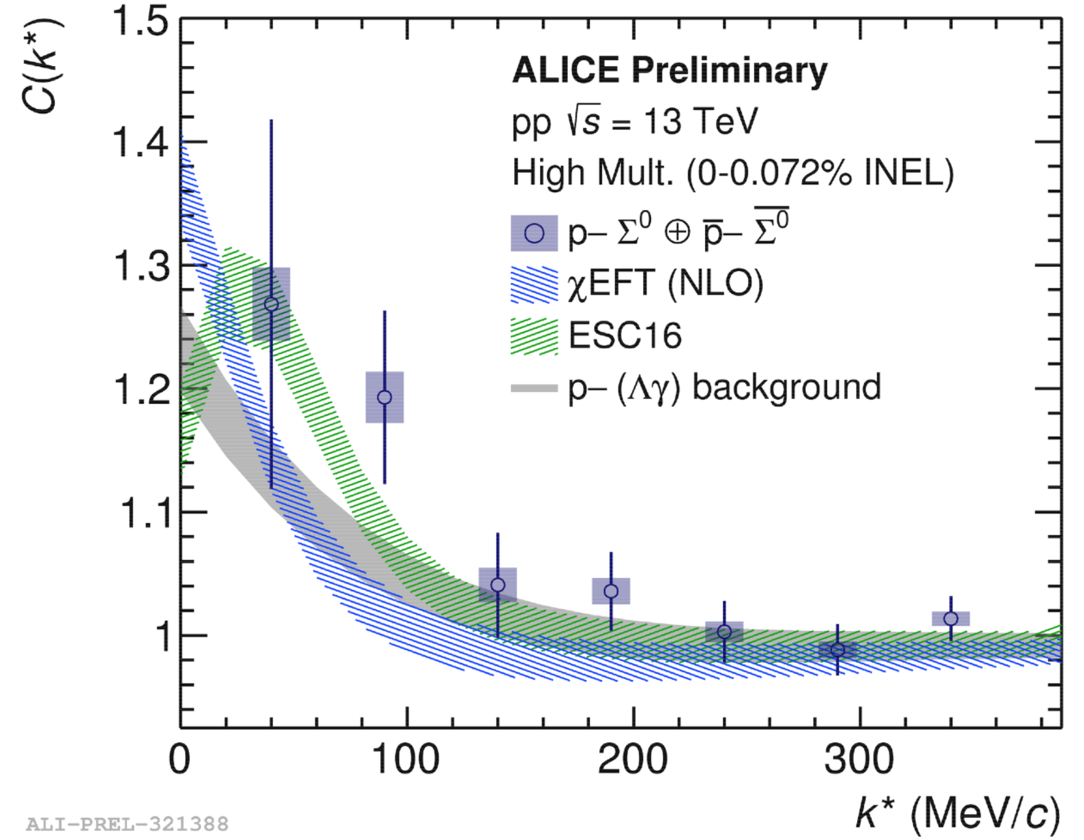
F.Becattini et al, PRL 111, 082302
https://arxiv.org/pdf/1212.2431.pdf

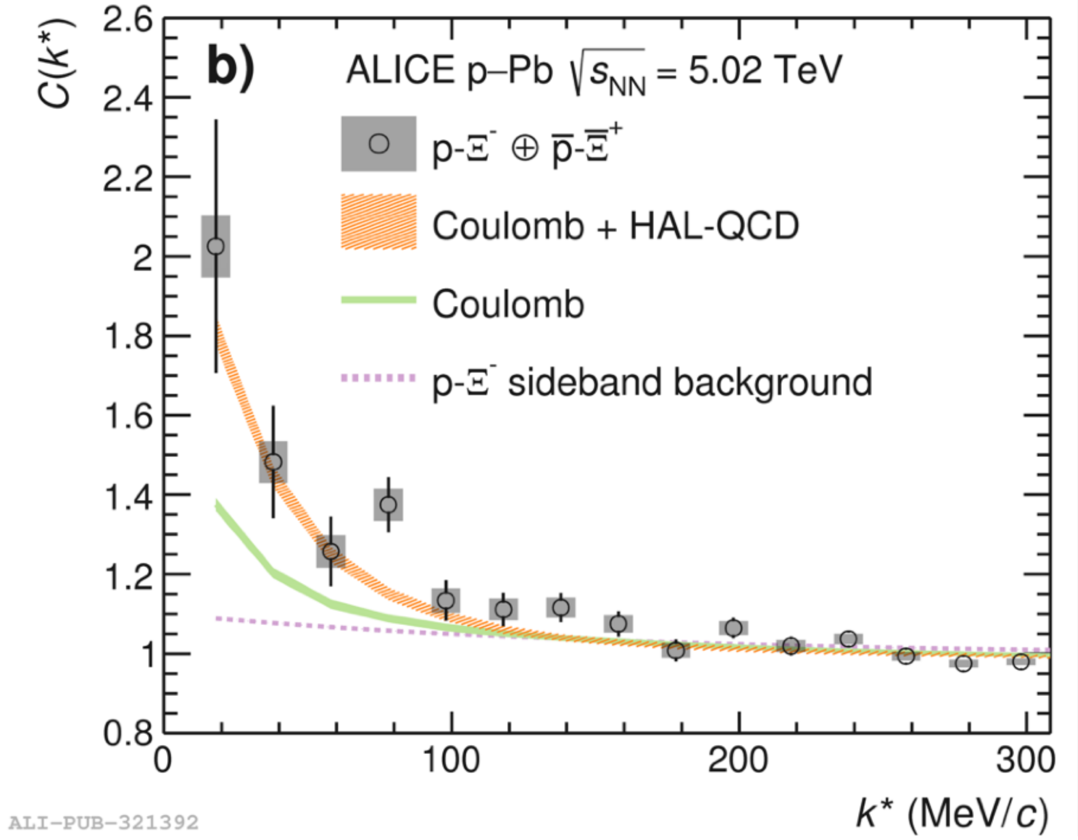
- ΛΛ mass spectra analysis for far ALICE demonstrated
  - with 20M central events
    - corresponds to 200M m.b. events data taking
    - run3, we can expect x500 equivalent data
- Run-3 expectation is 10^{11} min.bias
  - corresponds to 10G central events (x500 more)
  - NΞ , ΞΞ , NΩ , ΩΩ mass spectra analysis with even better statistics will be available
    - NΞ, NΩ : richly
    - ΩΩ : $\frac{dN}{dy} \lesssim 1$
  - Even heavier system will be possible?
    - $N\Lambda_c$, $N\Xi_c$, $N\Omega_c$
    - charm production cross section is probably too small?
    - tetraquark, mesonic atoms?



pΞ correlation in p-Pb

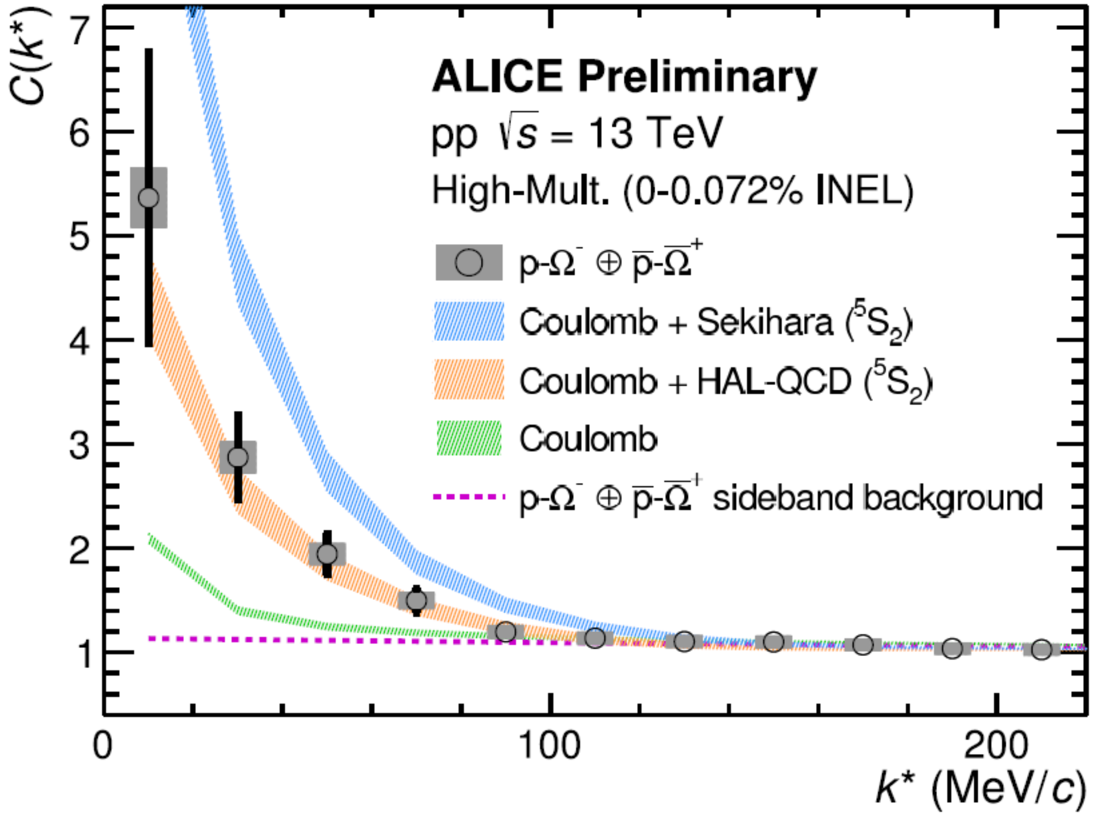
- pΞ correlation in p-Pb showed >>1 at low k* in p+Pb collision : hint for attractive nuclear force?
- in $p\Xi^-$ correlation, coulomb “only” is excluded at >4σ
- precise study with comparison among pp, pA, and AA, combining with phenomenology will be needed, and possible in Run3 (> x100 statistics)



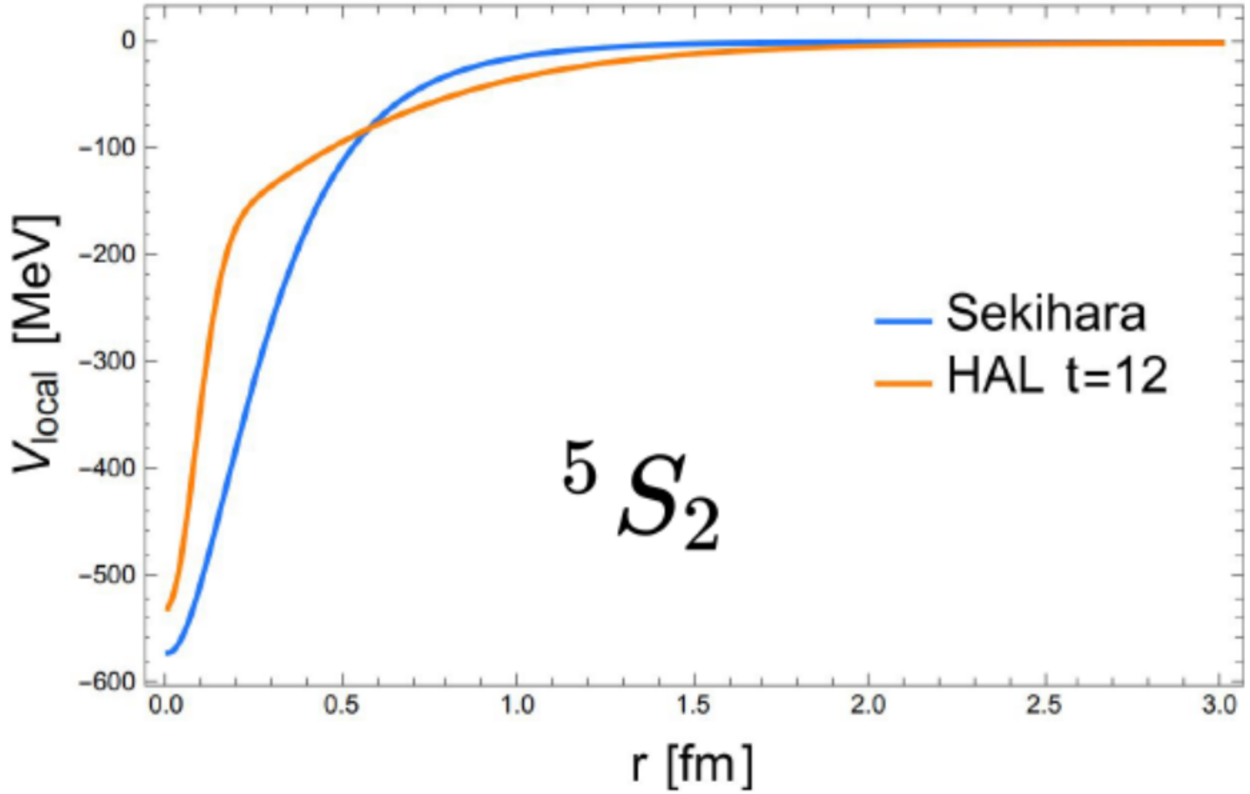


$p\Omega$ correlation

- new ALICE measurement (preliminary) shows that data agrees with Coulomb+strong attractive interaction (hint for bound state?)
- see detail in L.Fbbietti, SQM2019



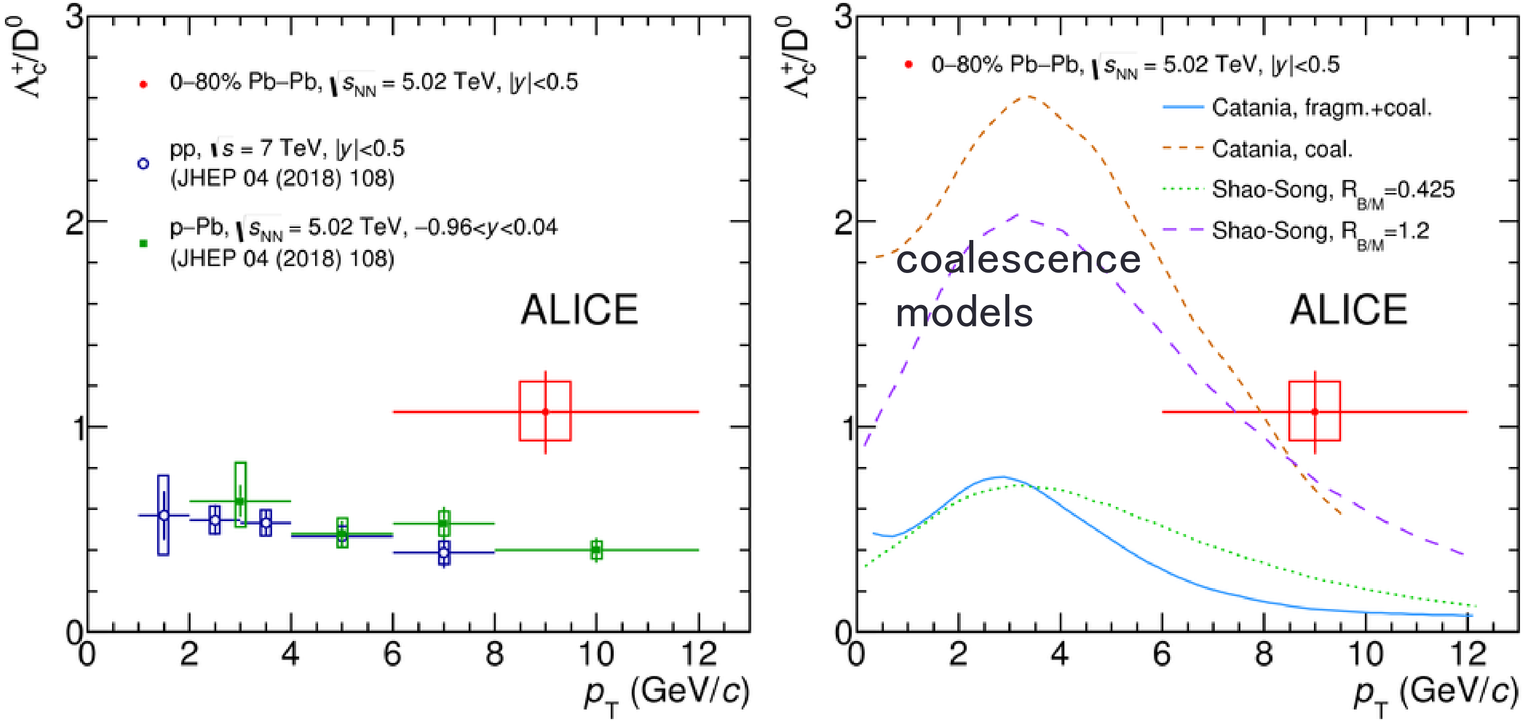
ALI-PREL-315620



charmed baryon?

arXiv: 1809.10922

- $\Lambda_c \rightarrow p + K^- + \pi^+$
- not well measured/understood even in pp collisions
- yield increases with temperature (x2 high in PbPb than pp,p+Pb)
- seem equal or more to D^0 yield (76 mb in p-Pb)
  - $3\text{x}10^{-2}$ per pA event → dN/dy = $O(10^{-2})$
  - in Pb+Pb, it could be O(1) ~ $O(10^{-1})$ (dN/dy=1.4 CERN-LHCC-201)
  - signal extraction not easy due to large background



Summary and Outlook

Summary

- Chemical freeze-out model reproduces rather well the hadron yields from pions to light nuclei
- Present status of di-baryon and (multi-)strange baryon searches was shown

Outlook

- Strange di-baryons: Studies with high statistics data at LHC RUN3 is expected; ΩΩ, ΞΩ, ΞΞ, ...
- ALICE may extend searches also for heavy flavor (di-)baryons

Total number of strangeness	Combination	Current status	LHC RUN3
1	N+Λ(N+Σ)	△ Au+Au 200GeV (STAR) p+Nb 3.2GeV (HADES) p+p 7TeV, 13TeV (ALICE)	○
2	Λ+Λ(Λ+Σ, Σ+Σ)	△ Au+Au 200GeV (STAR) p+p 7TeV, 13TeV (ALICE)	○
2	N+Ξ	△ p+p 13TeV (ALICE) △ p+Pb 5.02TeV (ALICE)	○
3	N+Ω	△ Au+Au 200GeV (STAR)	○
3	Λ+Ξ(Σ+Ξ)	×	○
4	Ξ+Ξ	×	○
5	Ξ+Ω	×	○
6	Ω+Ω	×	○