CPOD
Workshop on Critical Point and Onset of Deconfinement
selected impressions

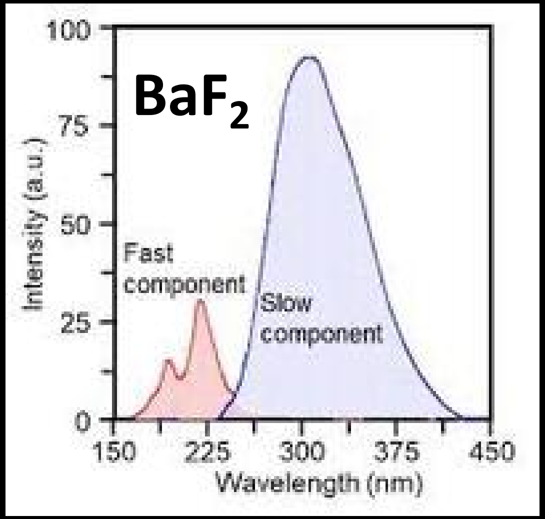
online, November 28^{th}- December 2^{nd}, 2022

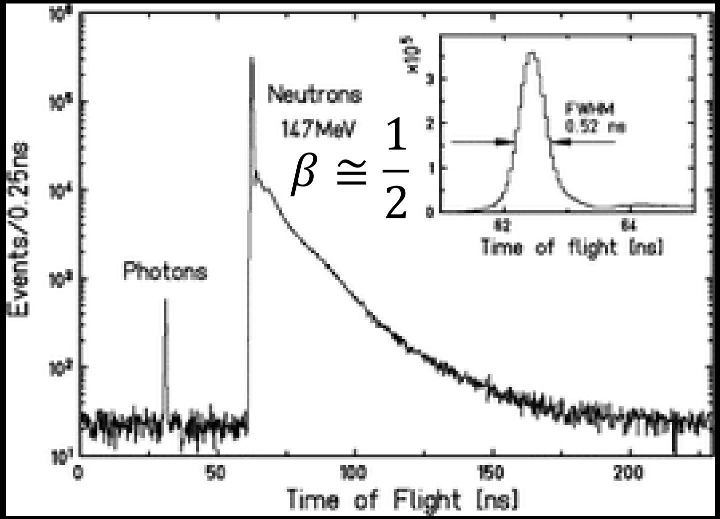
Tomasz Matulewicz

Seminarium ZFJ ------   12 I 2023

Profesor Marek Moszyński
1928-2022

18 stycznia 13:00 kościół akademicki św. Anny





CPOD-22: slides taken from presentations by:

- Igor Altsybeev (ALICE)
- Jacqueline Noronha-Hostler (BEST)
- Maja Maćkowiak-Pawłowska (NA61/SHINE)
- Marek Gaździcki (NA61/SHINE)
- Norbert Herrmann (CBM)
- Simon Spies (HADES)
- Travis Dore (BEST)
- Volodymyr Vovchenko (HRG)
- Xiujun Li (STAR)

CPOD – 2022 – selected impressions

- CPOD = Critical Point & Onset of Deconfinement
- Landscape of CPOD (QM, SQM, ICPAQGP, WWND, …)
- Phase diagram(s) and the statistical model of hadronization – more precise temperature and baryochemical potential @LHC , problem with the proton yield
- Fluctuations and the role of acceptance
- Hypernuclei (HADES, STAR)
- Future of FAIR
- Extras

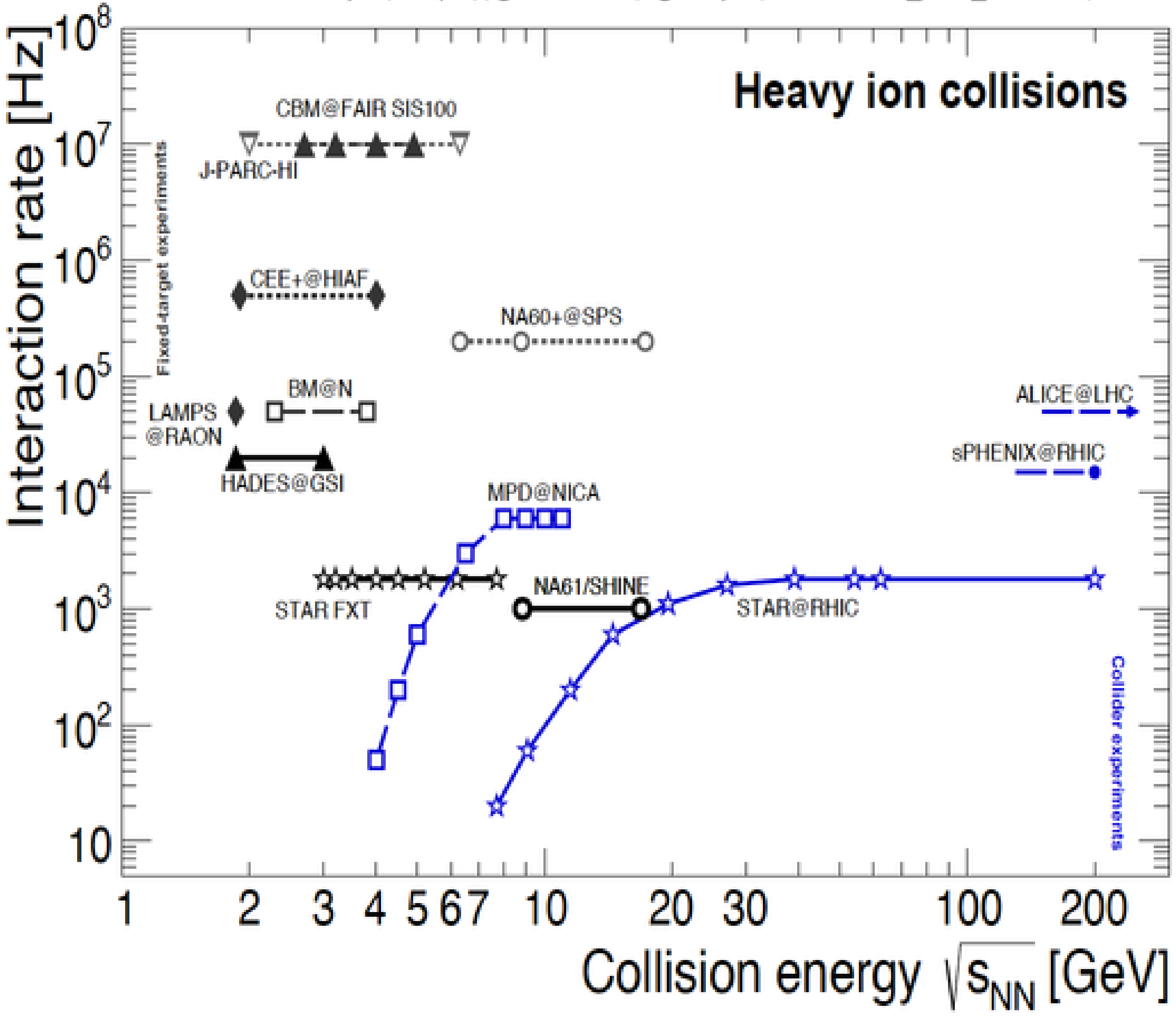
CPOD

online, November 28th- December 2nd, 2022

The International Advisory Committee has decided that the CPOD 2022 is closed for participants having appointments in RU, BE institutions, and JINR.

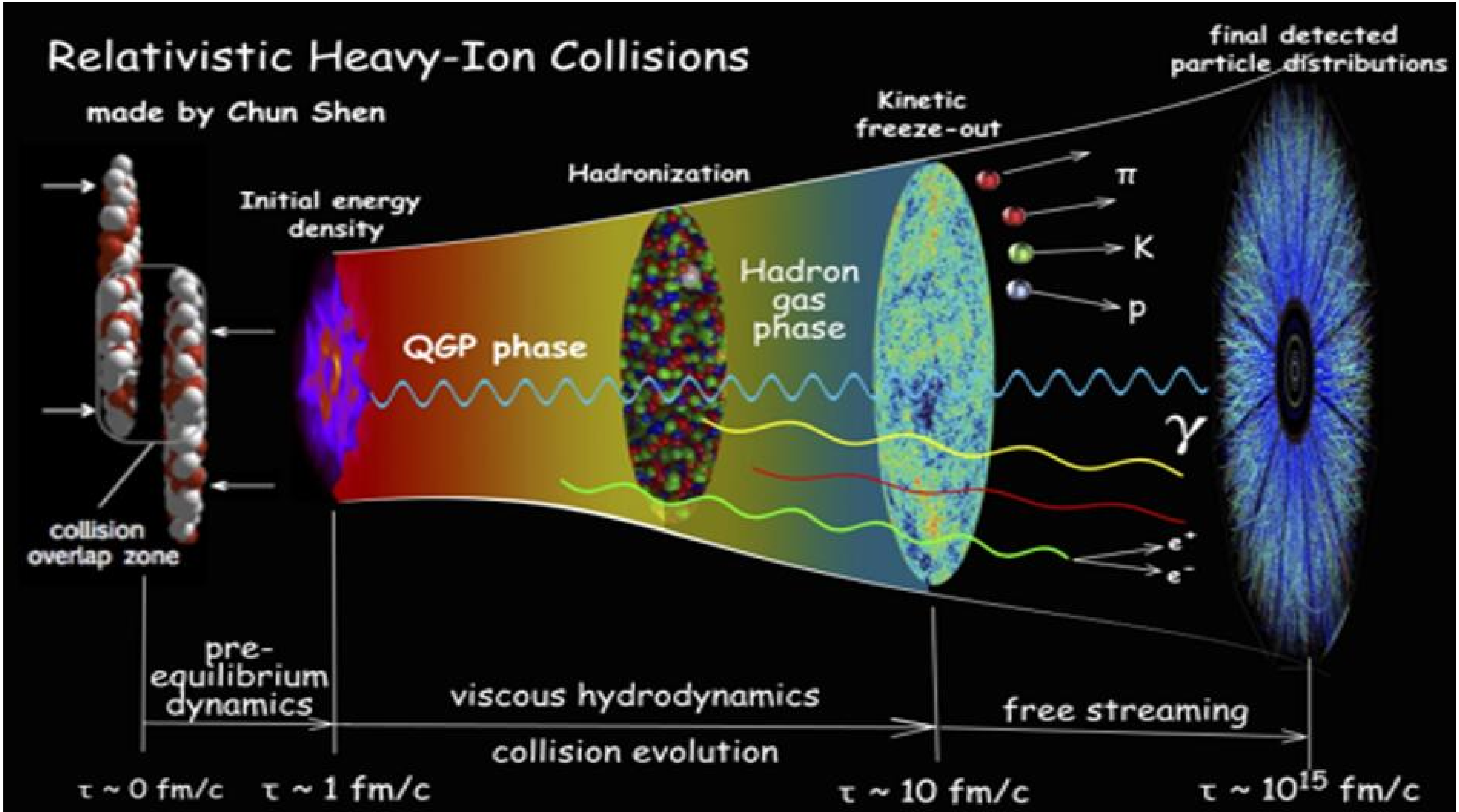
- QM – Quark Matter (18 months, Kraków 2022)
- SQM – Strangeness in Quark Matter (Busan 2022)
- CPOD
- ICPAQGP – International Conference of Physics and Astrophysics of QGP
- WWND – Winter Workshop on Nuclear Dynamics (Mexico 2023)
- ….

T. Galatyuk, https://github.com/tgalatyuk/interaction_rate_facilities, 2022



Phase diagram(s) and the statistical model of hadronization

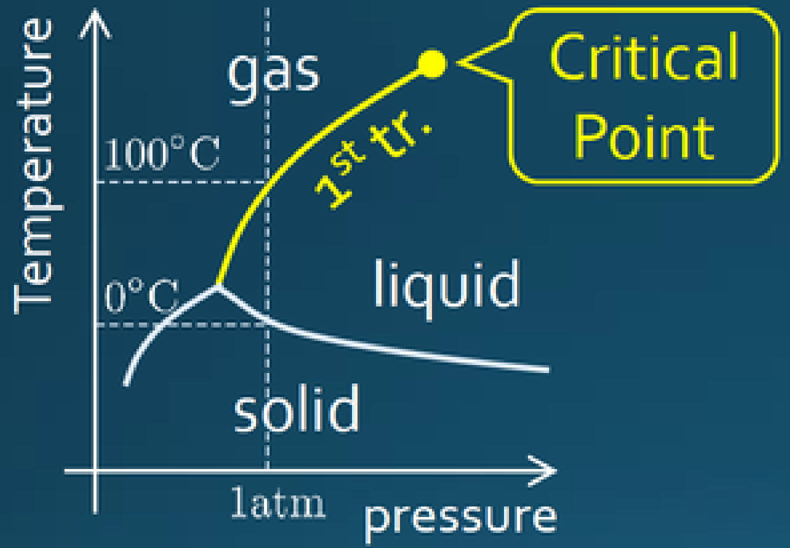
0. short introduction
1. more precise temperature and baryochemical potential @LHC
2. problem with the proton yield



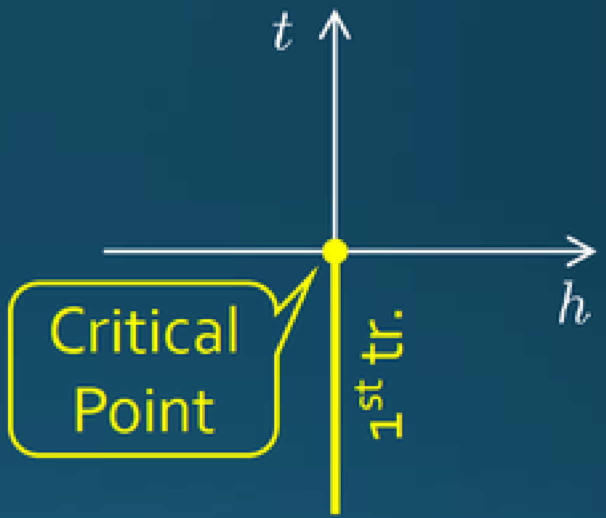
Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
QGP phase
Hadron gas phase
π
K
p
γ
e+
e-
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

Critical Points

- **Water**



- **Ising Model**



- CP: Second-order transition point.
- Singularities in thermodynamic quantities.
- These CPs belong to the same universality class (Z_2).

→ Common critical exponents. Ex. $C \sim (T - T_c)^{-\alpha}$

Thermal model for pedestrians

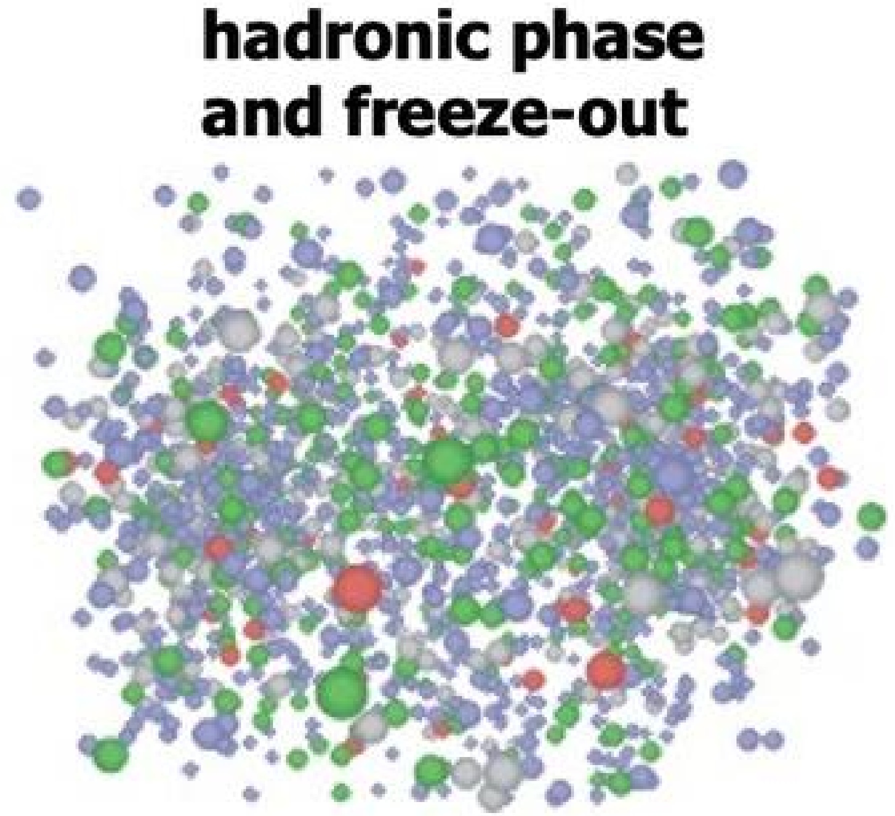
$$n_i = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp\left[(E_i - \mu_i)/T\right] \pm 1}$$

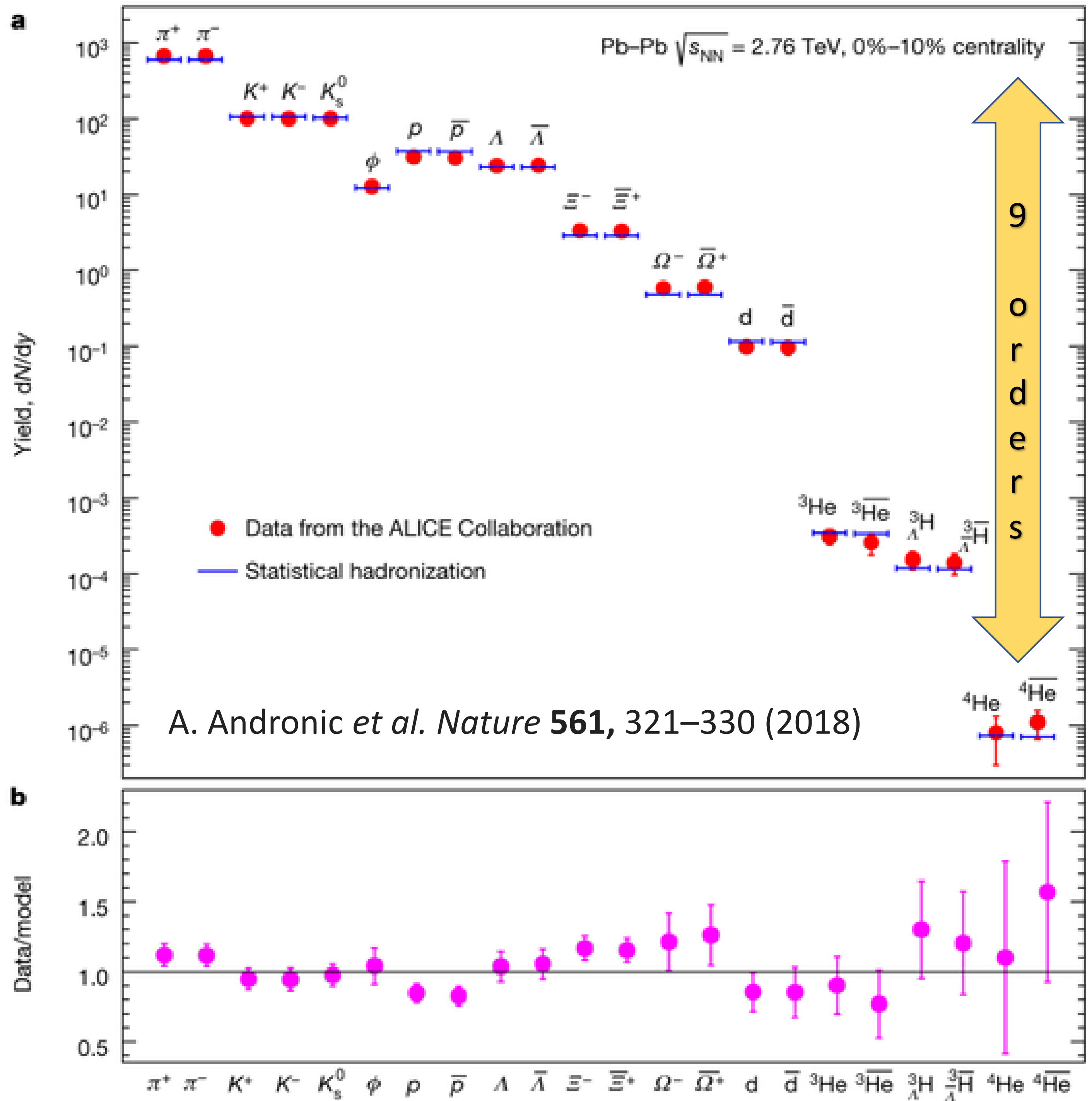
- The system formed in AA collision has to exist long enough for particles to interact several times, on the way to equilibrium
- The ratio of antiparticle to particle emission determines μ/T

$$\frac{\bar{p}}{p} = \frac{e^{-(E+\mu)/T}}{e^{-(E-\mu)/T}} = e^{-2\mu/T}$$

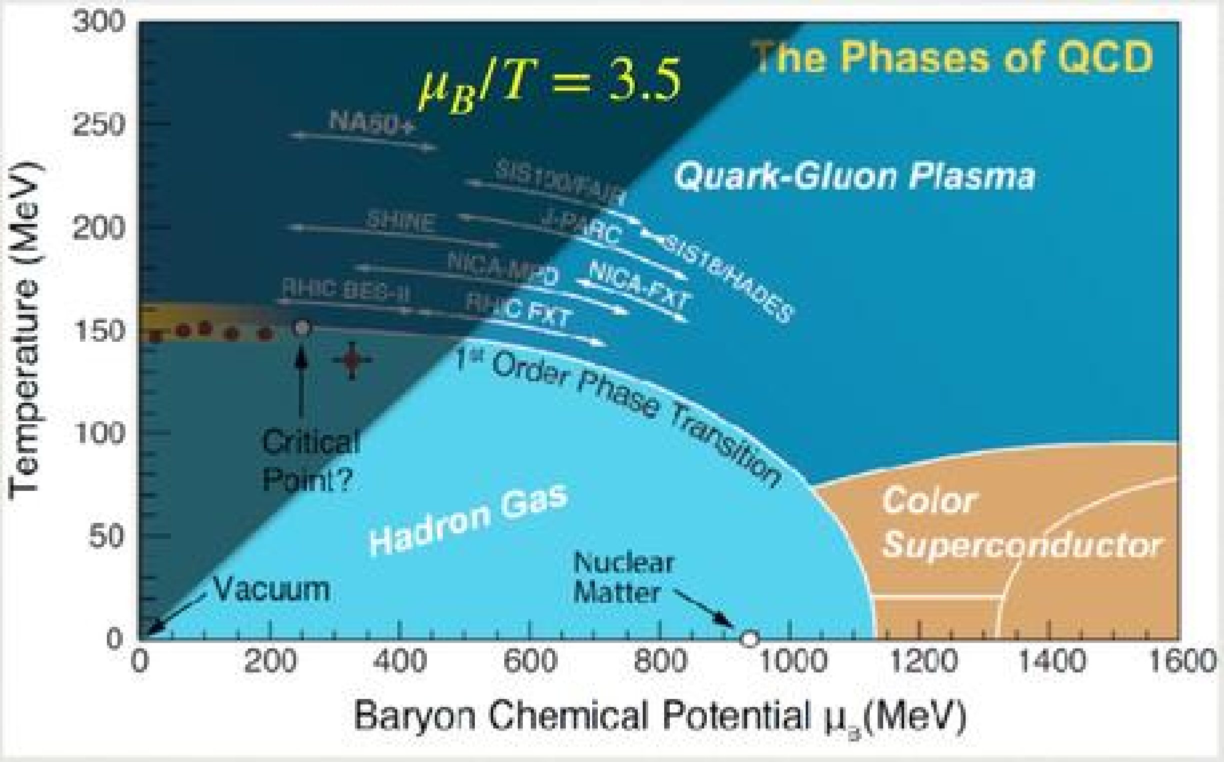
- From this μ/T ratio and the second relative yield μ and T are obtained
- The real model is much more complex (isospin, conservation of quantum numbers, conservation of energy, volume etc.). Selection: microcanonical, canonical, grand canonical (→ seminar by Krzysztof Piasecki 21 X 2021)

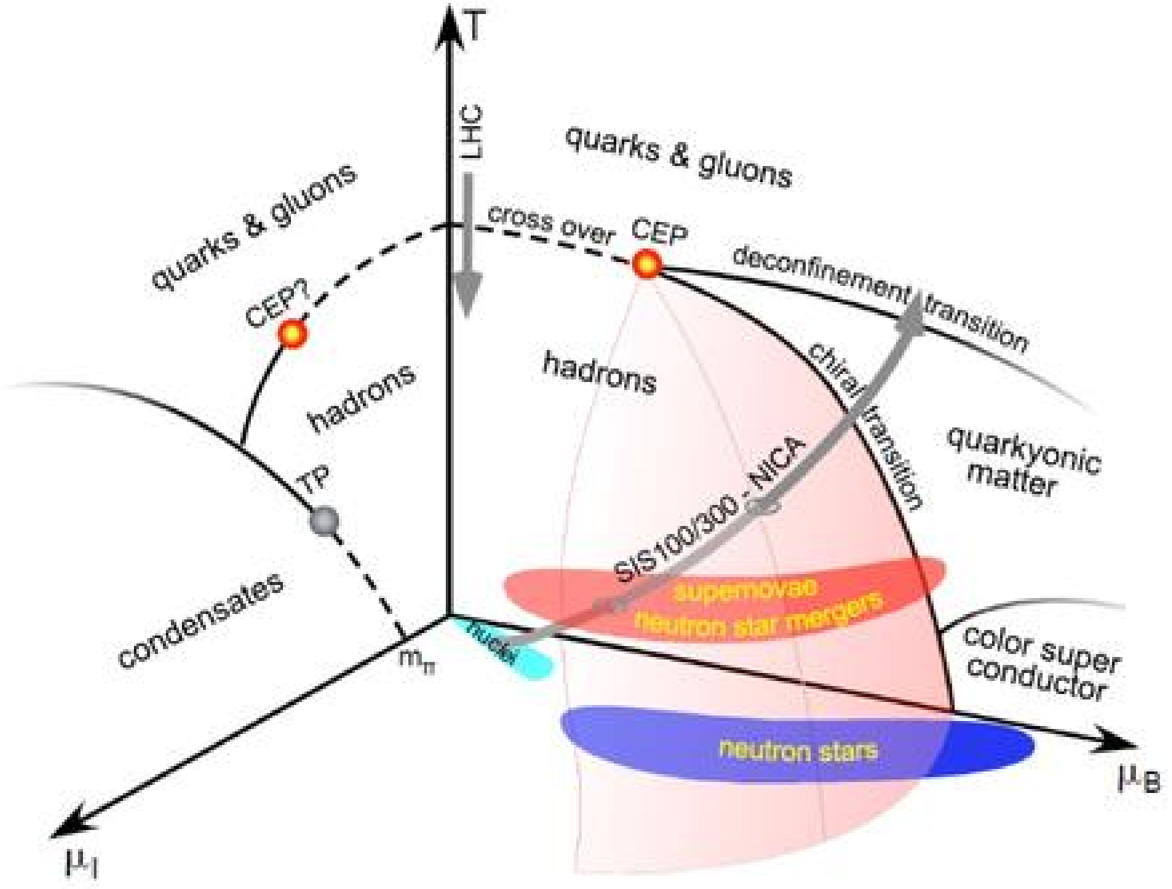
Thermal model in AA





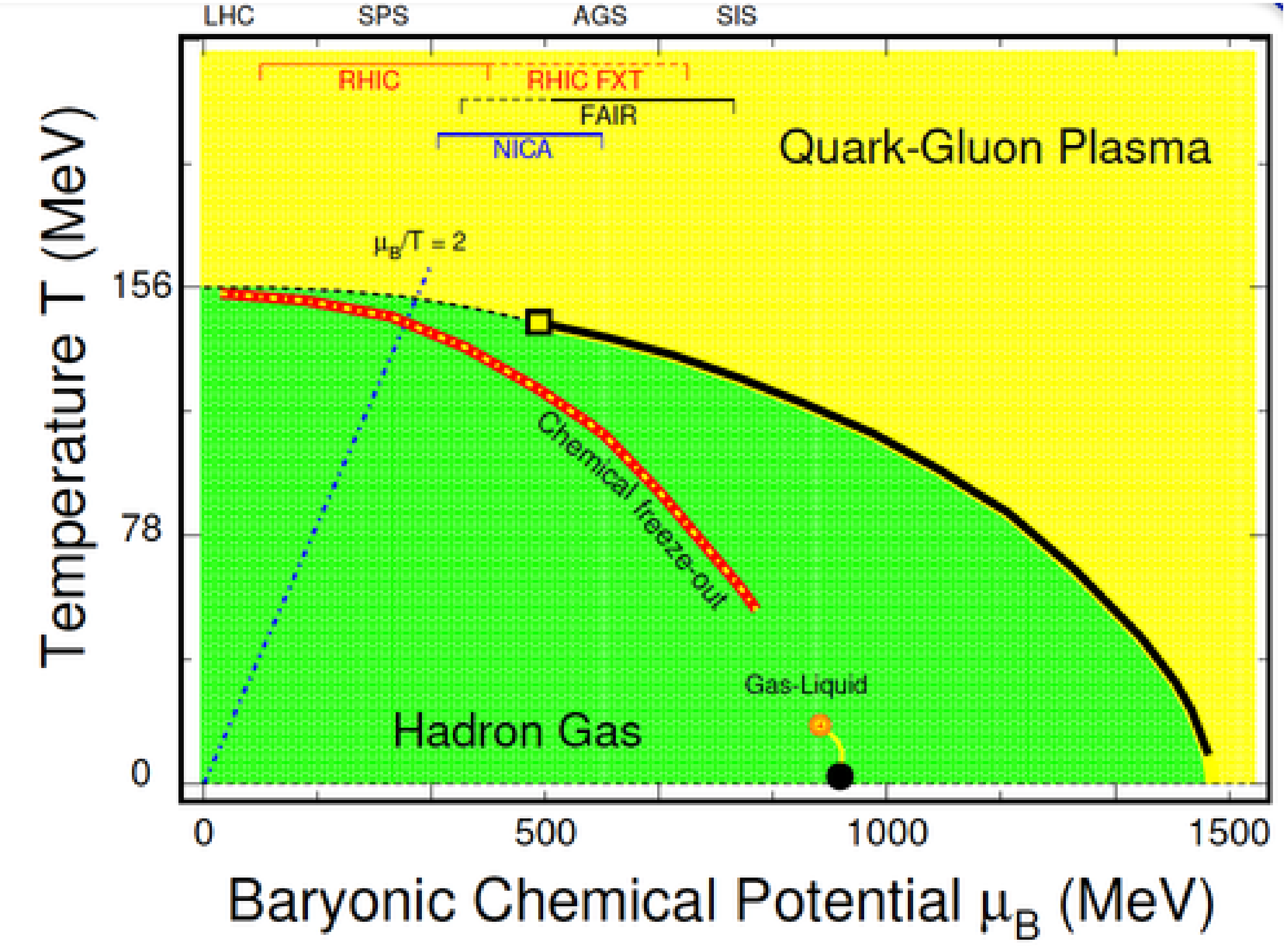
Phase diagram(s) - I

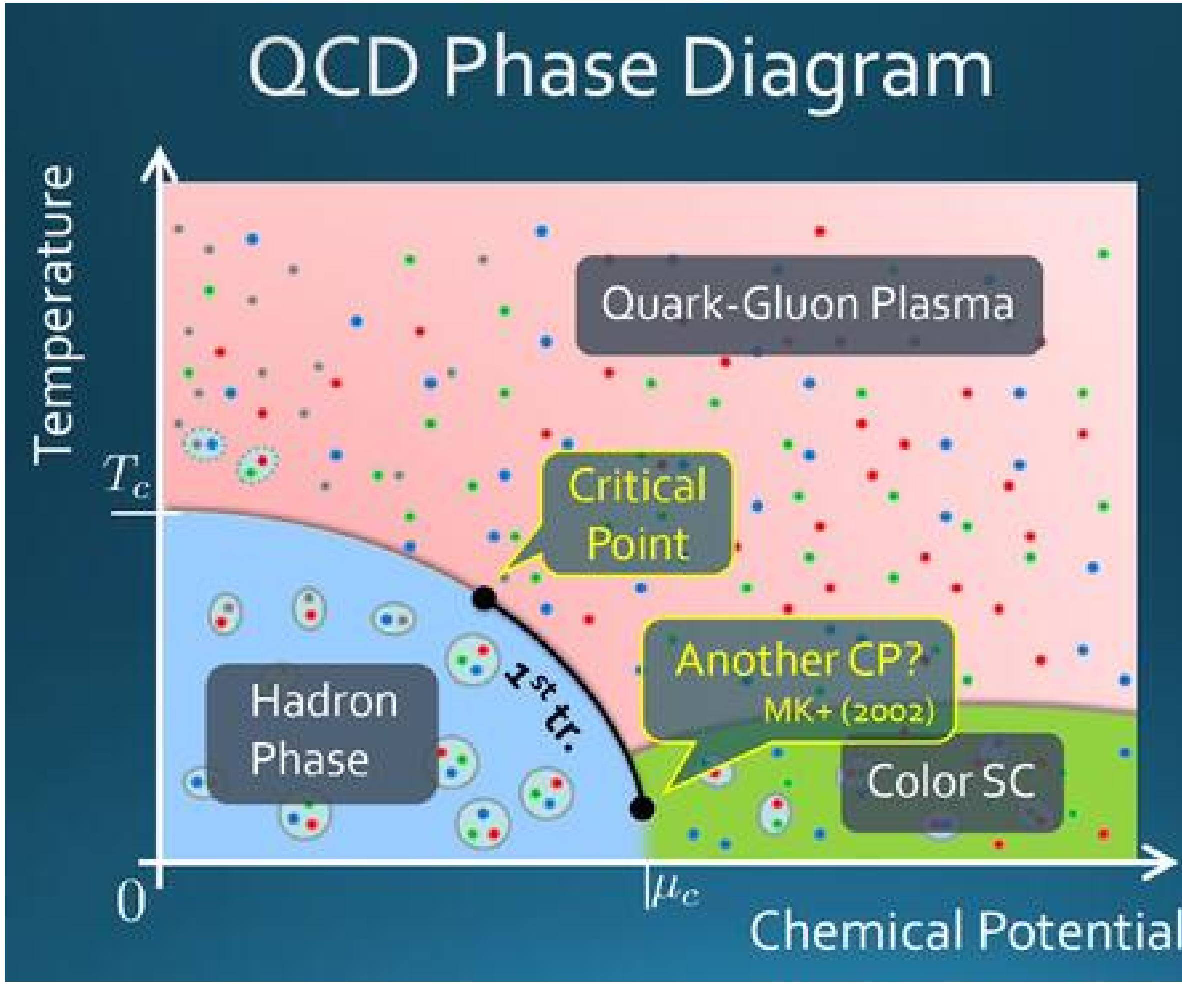




NUPECC Long Range Plan 2017

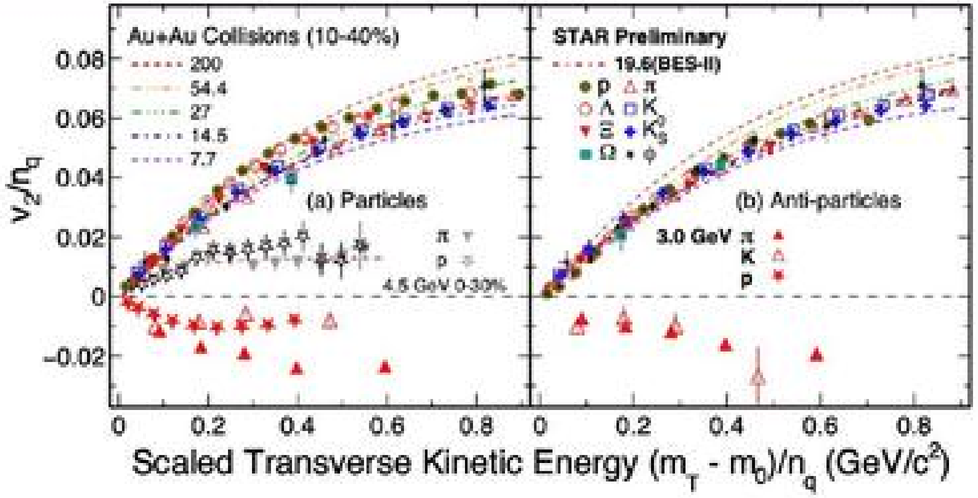
Phase diagram(s) - II



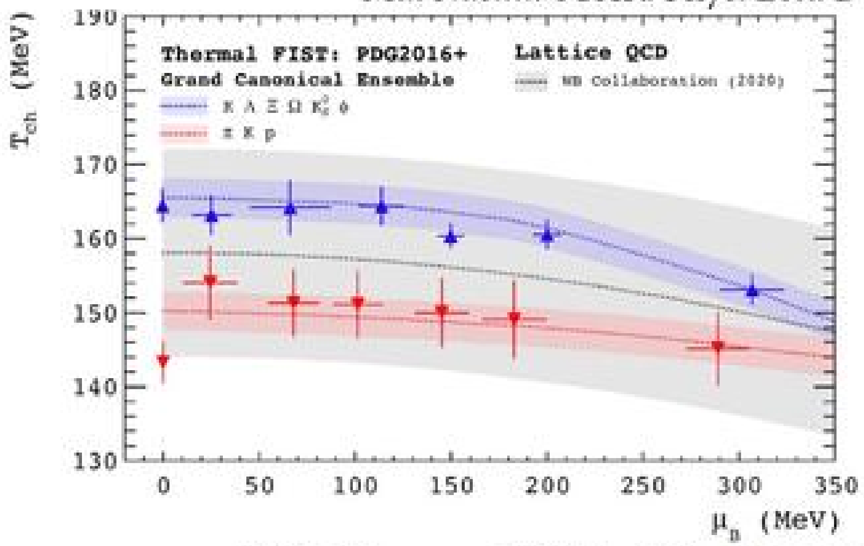


Where is the Onset of Deconfinement?

- What we know:
  - QGP Signatures observed at low μ_B (high $\sqrt{s_{NN}}$)
    - Partonic Collectivity, Enhanced Strangeness Production, Jet Quenching, etc.
  - Intuitively, at higher μ_B values (low $\sqrt{s_{NN}}$), we expect the absence of said signatures
    - Exhibit 1: NCQ Scaling at STAR
    - Exhibit 2: Flavor Heirachy at freeze-out?
- What we would like to know:
  - Precise value of $\sqrt{s_{NN}}$ at the onset of deconfinement
  - What about smaller systems?
  - Further Considerations (next contributions)
    - Additional onsets?
    - Acceptance as key experimental challenges

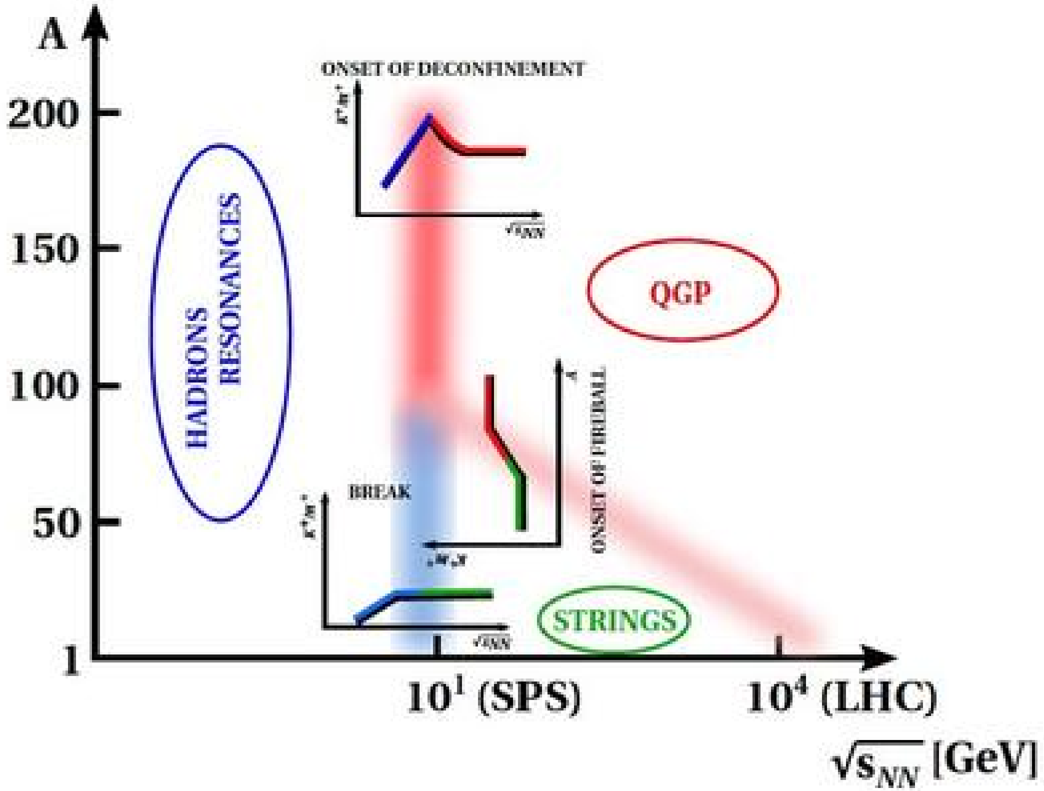


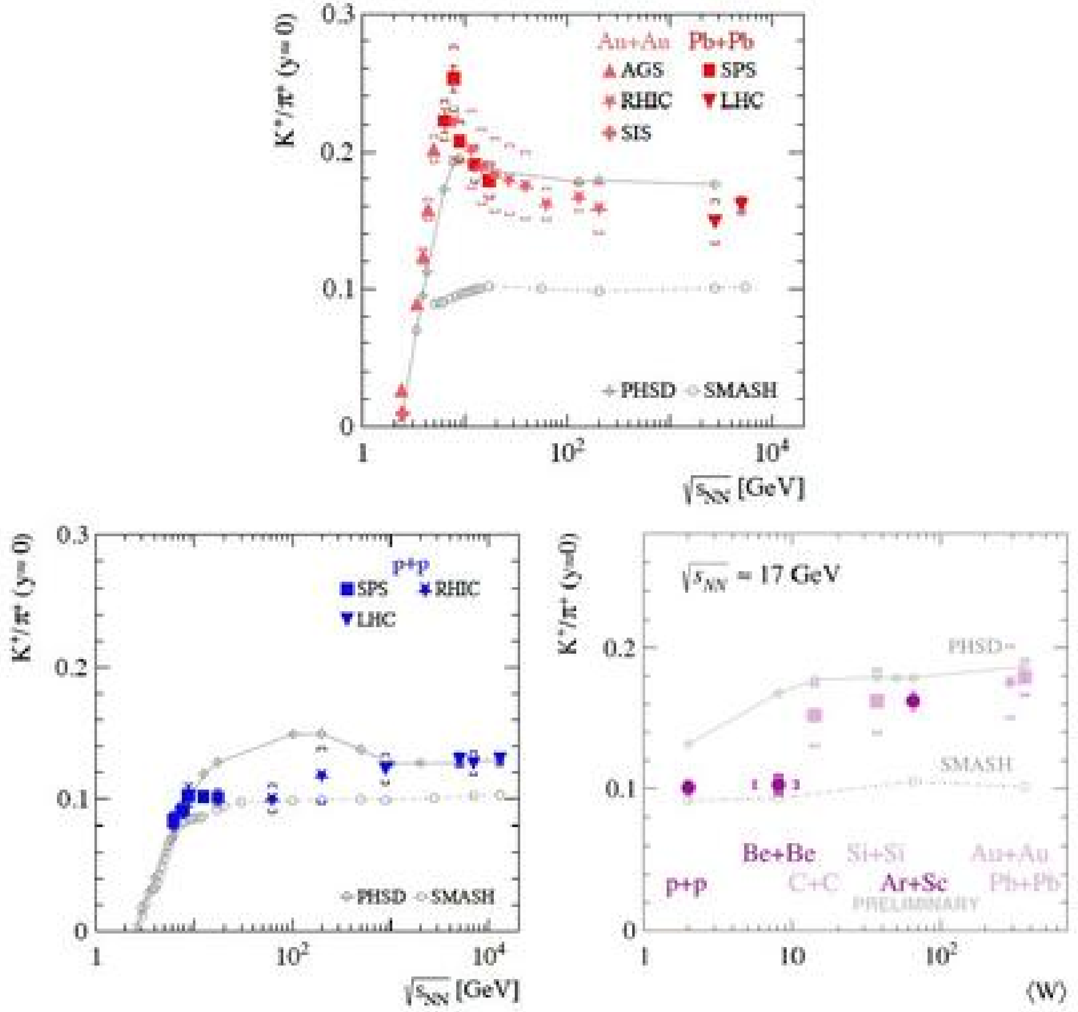
Md. Nasim. STAR: Phys. Lett. B **827** (2022) 137003



FAF, Olinger and Bellwied. Phys. Lett. B **814** (2021) 136098

Possible interpretation of the data

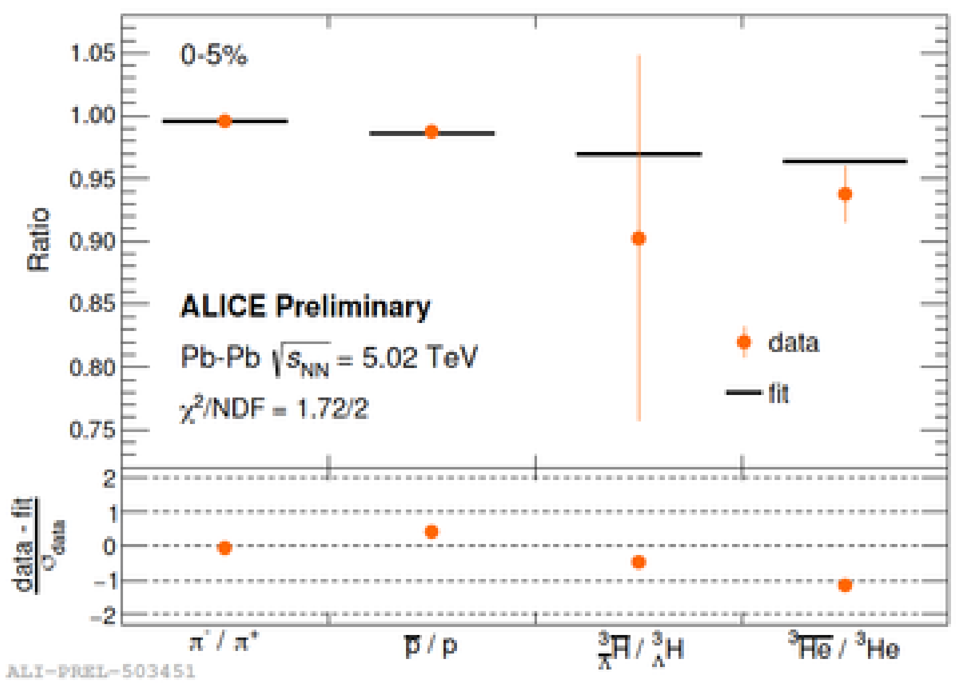


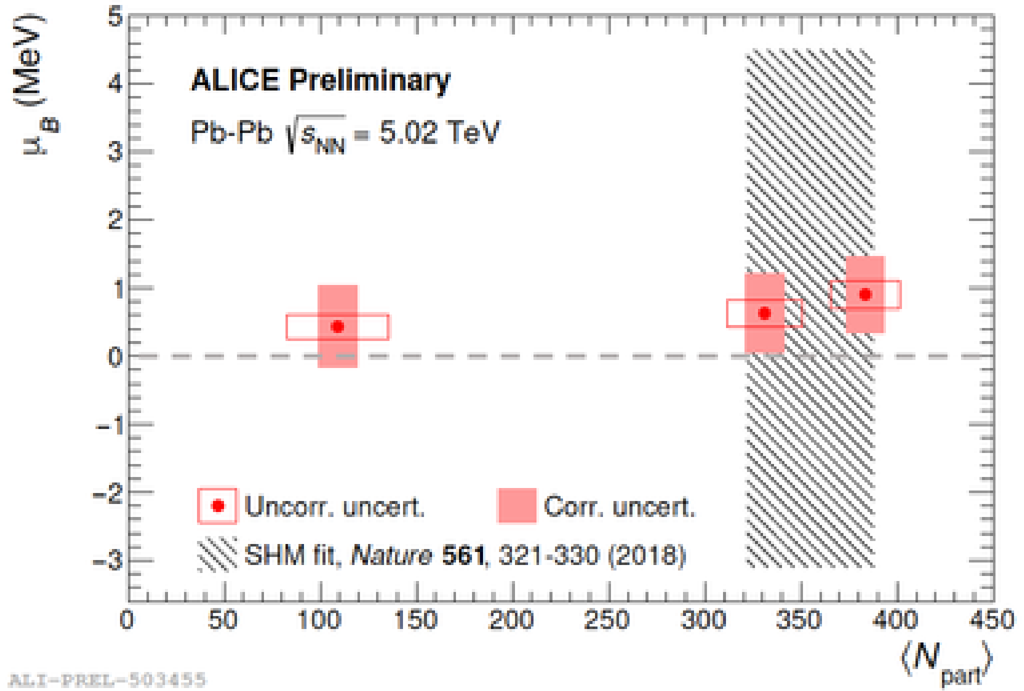


The onset of deconfinement and others –

- **changeover strings - QGP,**
- **changeover resonances - strings**

Centrality dependence of μ_B in Pb–Pb 5.02 TeV





Using *particle-antiparticle ratios*:

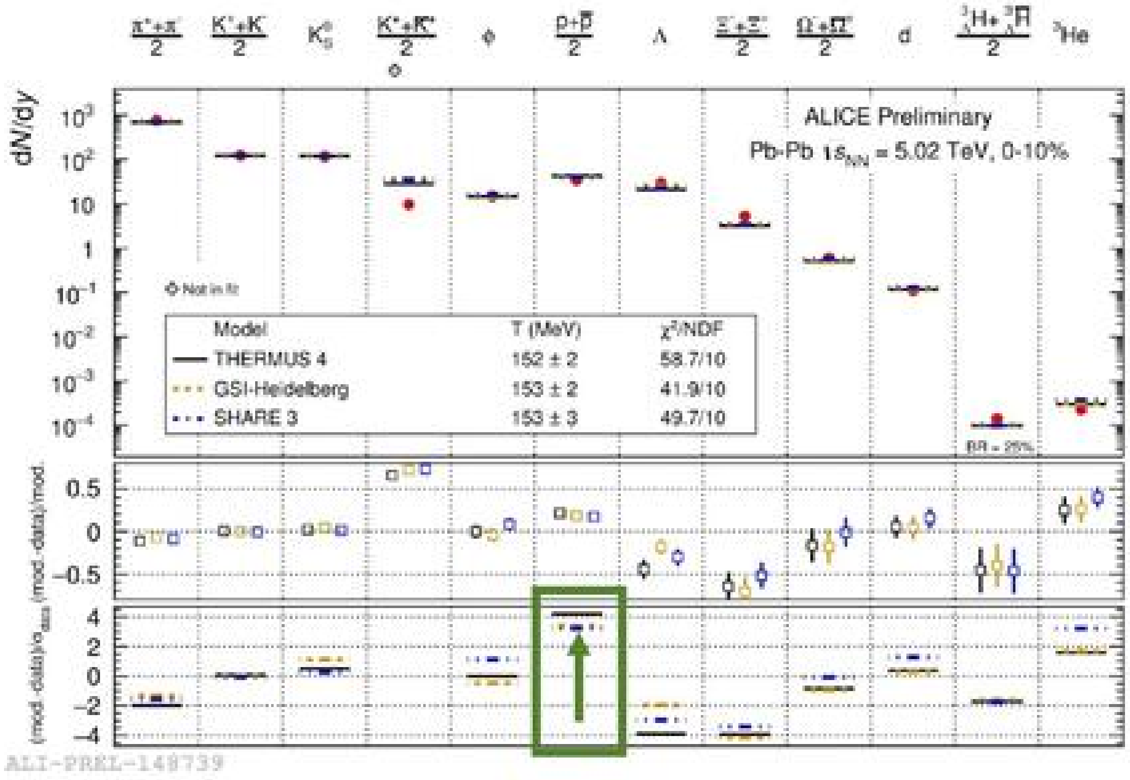
$$\frac{\bar{h}}{h} \propto exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$$

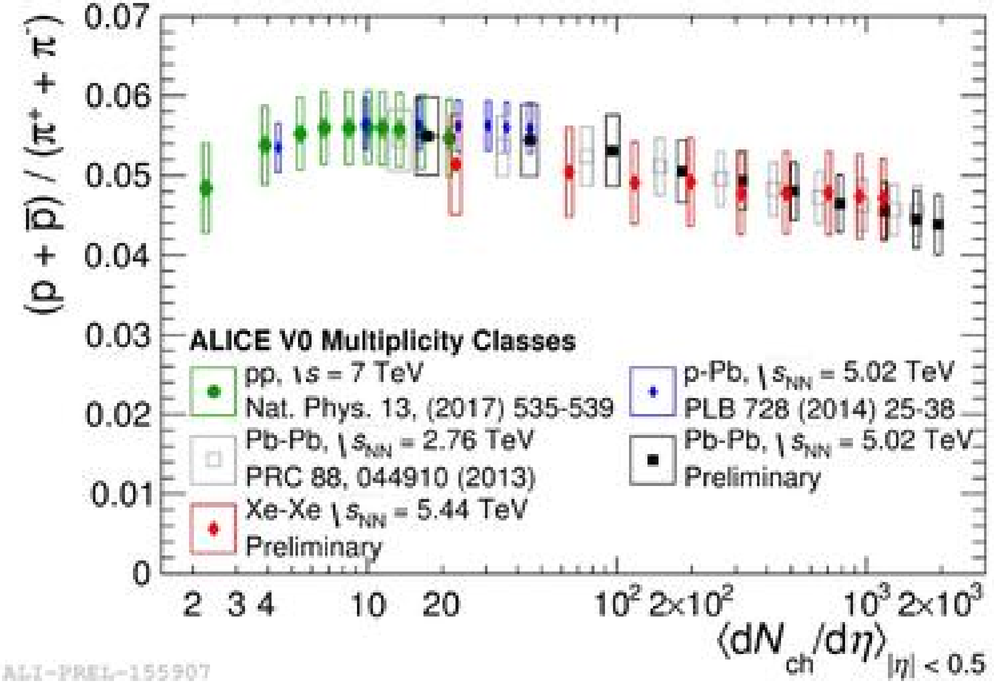
- T = 156.5 ± 1.5 MeV, fixed from SHM studies
- μ_B and μ_{I3} as free fit parameters

A. Andronic et al., Nature 561, (2018) 321

- **Most precise measurement in Pb-Pb at LHC**
  – taking ratios allows to cancel uncertainties
  – 6x improvement in precision with respect to Run 1 estimate
- Small but non-zero $\mu_B \approx 0.7$ MeV at LHC energies

Proton yields at the LHC





- Proton yield overestimated in standard thermal models
- The effect is larger in central collisions, hint of centrality dependence

Mechanisms affecting the proton yield

- Re-evaluating the chemical equilibrium proton abundance
  - Baryonic excluded volume [VV et al., PLB 775 (2017) 71]
  - Finite resonance widths [VV, Gorenstein, Stoecker, PRC 98 (2018) 034906]
  - S-matrix approach to πN scattering [Andronic et al., PLB 792 (2019) 304]

  centrality-independent

- Multiple freeze-out scenario (strange vs light)

  e.g. Flor, Olinger, Bellwied, PLB 814, 136098 (2021)

  centrality-independent

- **Effects of the hadronic phase** Steinheimer, Aichelin, Bleicher, PRL 110 (2013) 042501
  - Baryon annihilation, $N\bar{N} \to 5\pi$
  - No backreaction*, $5\pi \to N\bar{N}$. Some baryons will regenerate

  centrality-dependent

  Rapp, Shuryak, PRL 86 (2001) 2980;
  Pan, Pratt, PRC 89 (2014) 044911

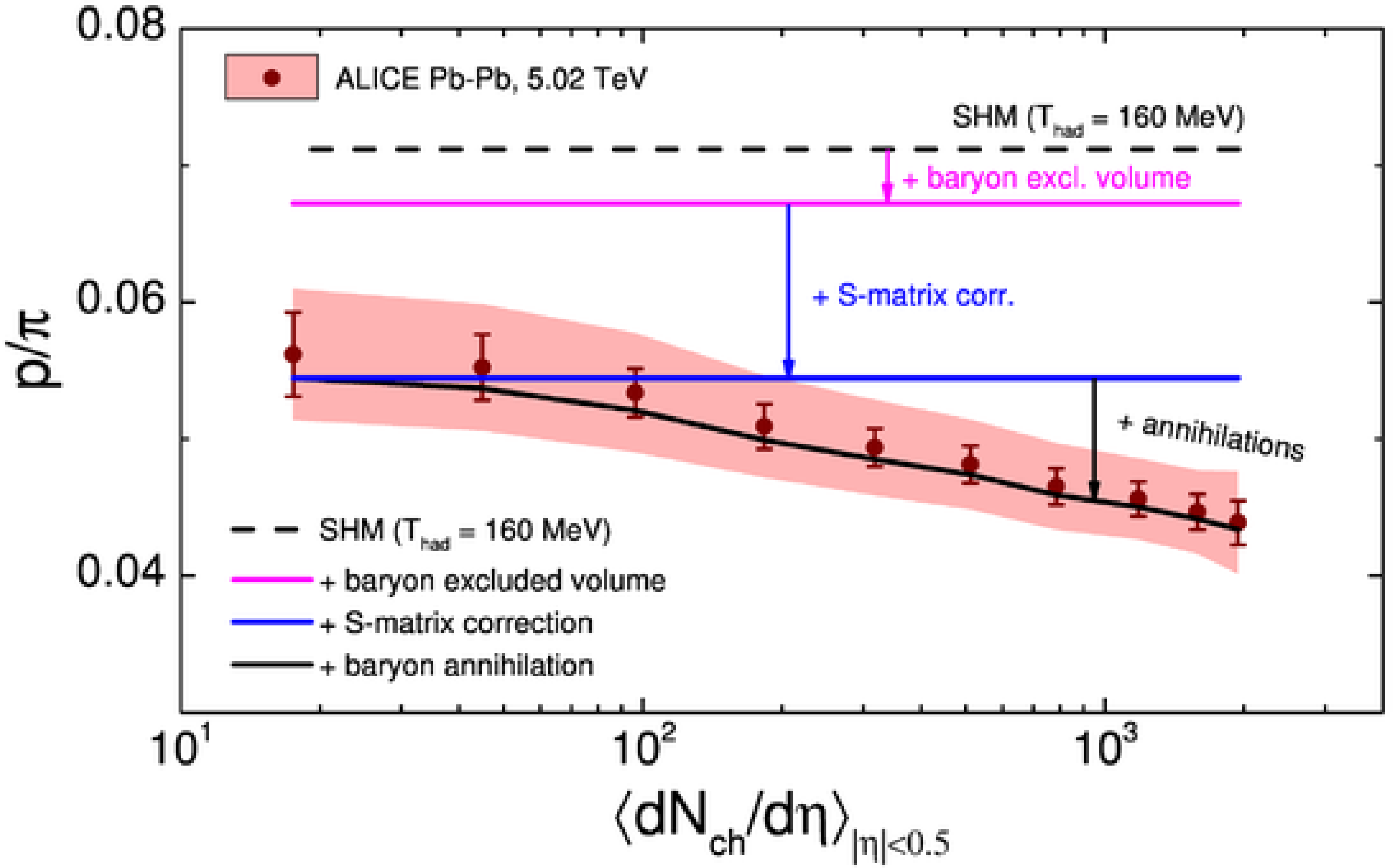
Annihilation vs other mechanisms affecting the p/π ratio

SHM: Thermal-FIST
[VV, Stoecker, Comput.Phys.Commun. 244 (2019) 295]

Baryon excl. volume
(baryon-baryon int.)
[VV et al., PLB 775 (2017) 71]

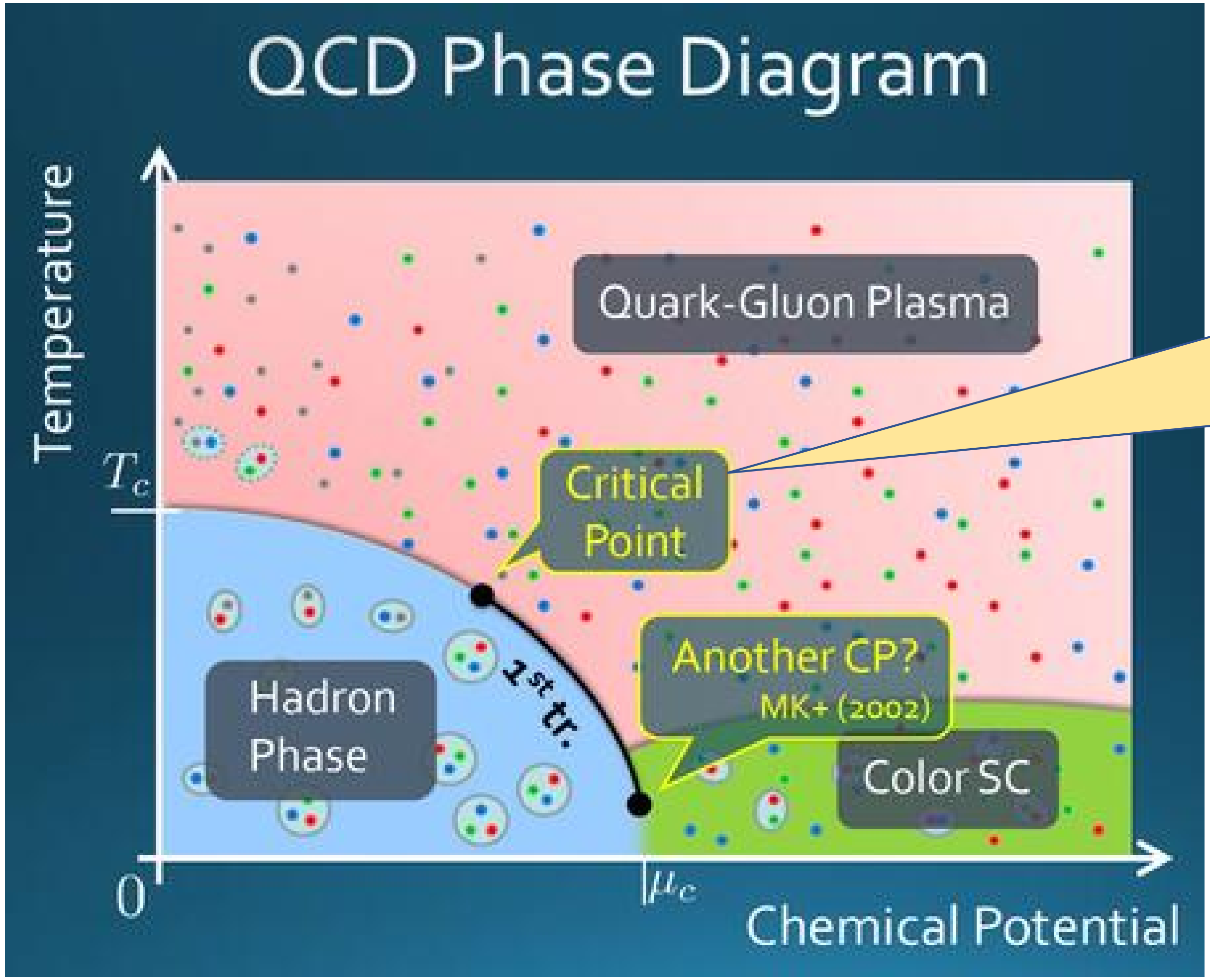
S-matrix correction
(meson-baryon int.)
[Andronic et al., PLB 792 (2019) 304]

Baryon annihilation
(baryon-antibaryon int.)
[VV, Koch, PLB 835 (2022) 137577]



Baryon annihilation and other mechanisms are complementary

Fluctuations and the role of acceptance

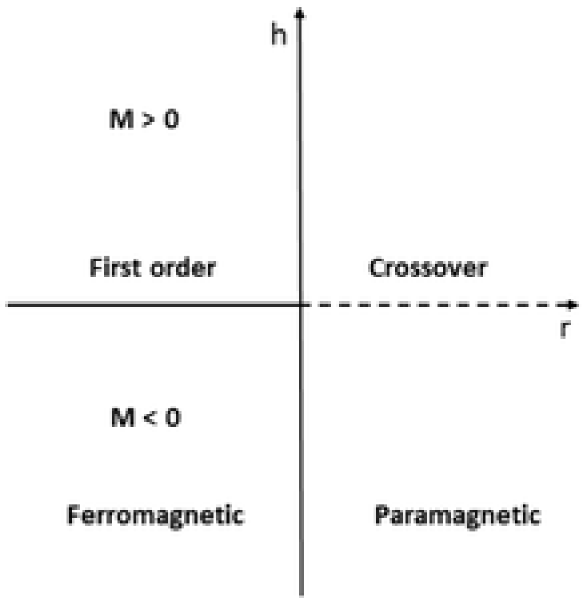


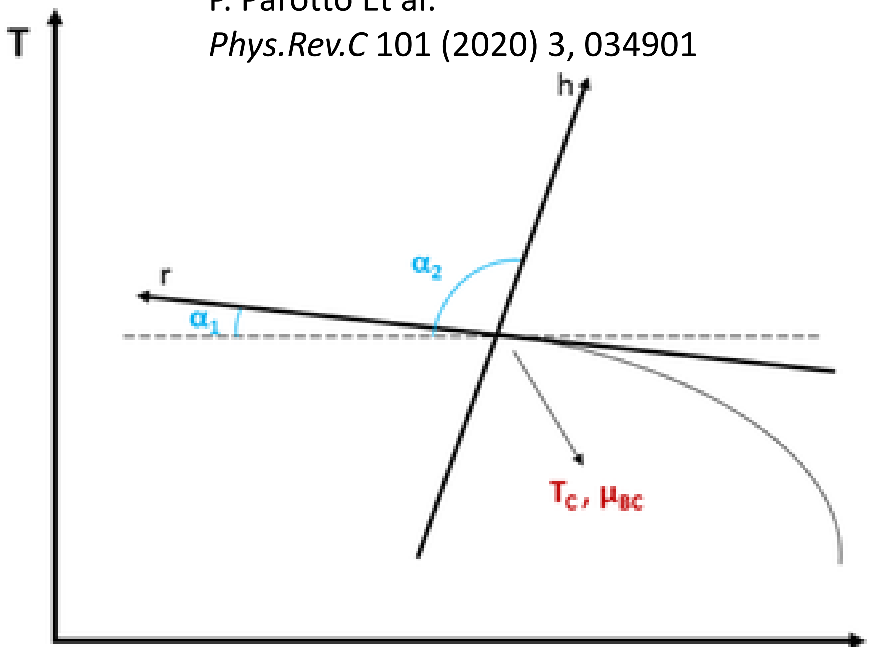
Non-statistical fluctuations expected around the critical point

Mapping the 3d ising model to qcd

P. Parotto Et al.
Phys.Rev.C 101 (2020) 3, 034901

Due to its symmetries, QCD is expected to be in the 3D Ising universality class





3D Ising

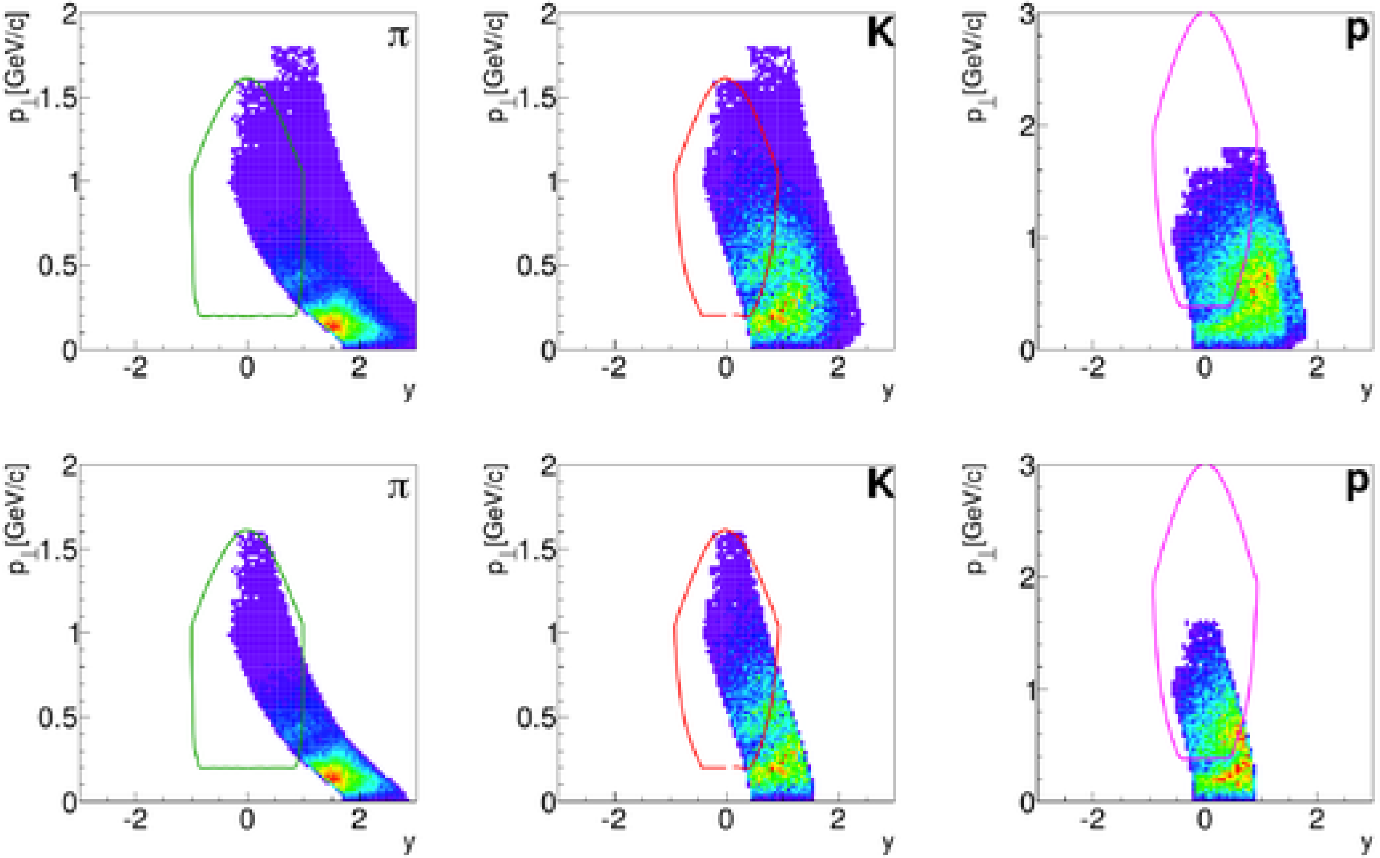
$$\xi \sim \left|\frac{T-T_c}{T_c}\right|^{-\nu} \quad \chi \sim \left|\frac{T-T_c}{T_c}\right|^{-\gamma}$$

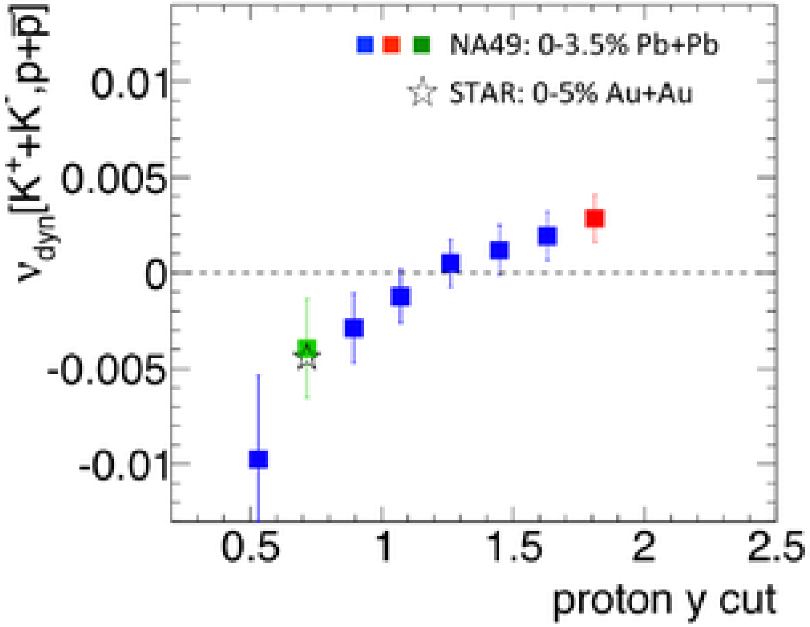
QCD

$$\chi_2^B \sim \xi^2 \quad \chi_4^B \sim \xi^{11}$$

M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011)

Acceptance – source of potential discrepency





line - STAR acceptance; distribution - NA49 acceptance

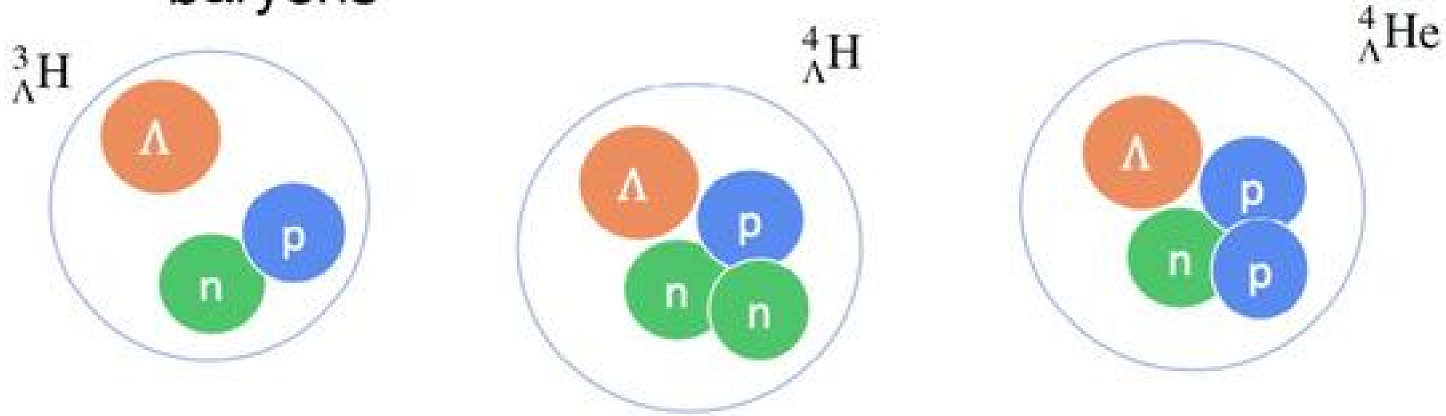
NA49, Phys. Rev. C 89, 054902 (2014)

Analysis performed in a wider acceptance can be restricted to smaller ones

Hypernuclei (HADES, STAR)

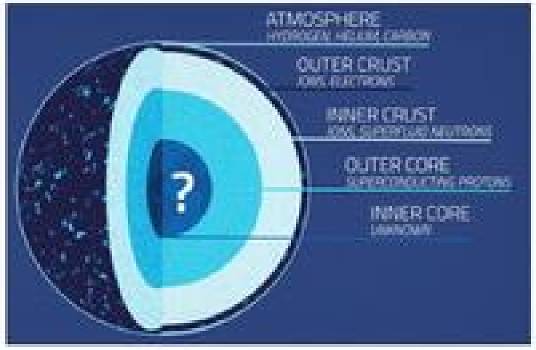
Introduction: what and why

- What are hypernuclei?
  - Bound nuclear systems of non-strange and strange baryons

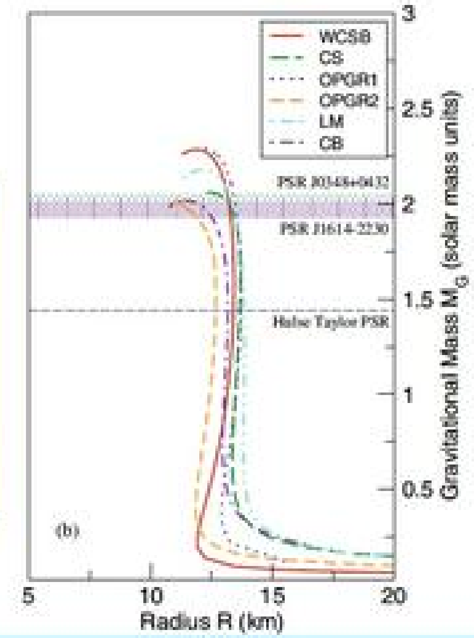


Marian Danysz (right) and Jerzy Pniewski (left) discovered hypernuclei in 1952

- Why hypernuclei?
  - Probe hyperon-nucleon (Y-N) interaction
  - Strangeness in high density nuclear matter
    - Equation-of-State (EoS) of neutron star



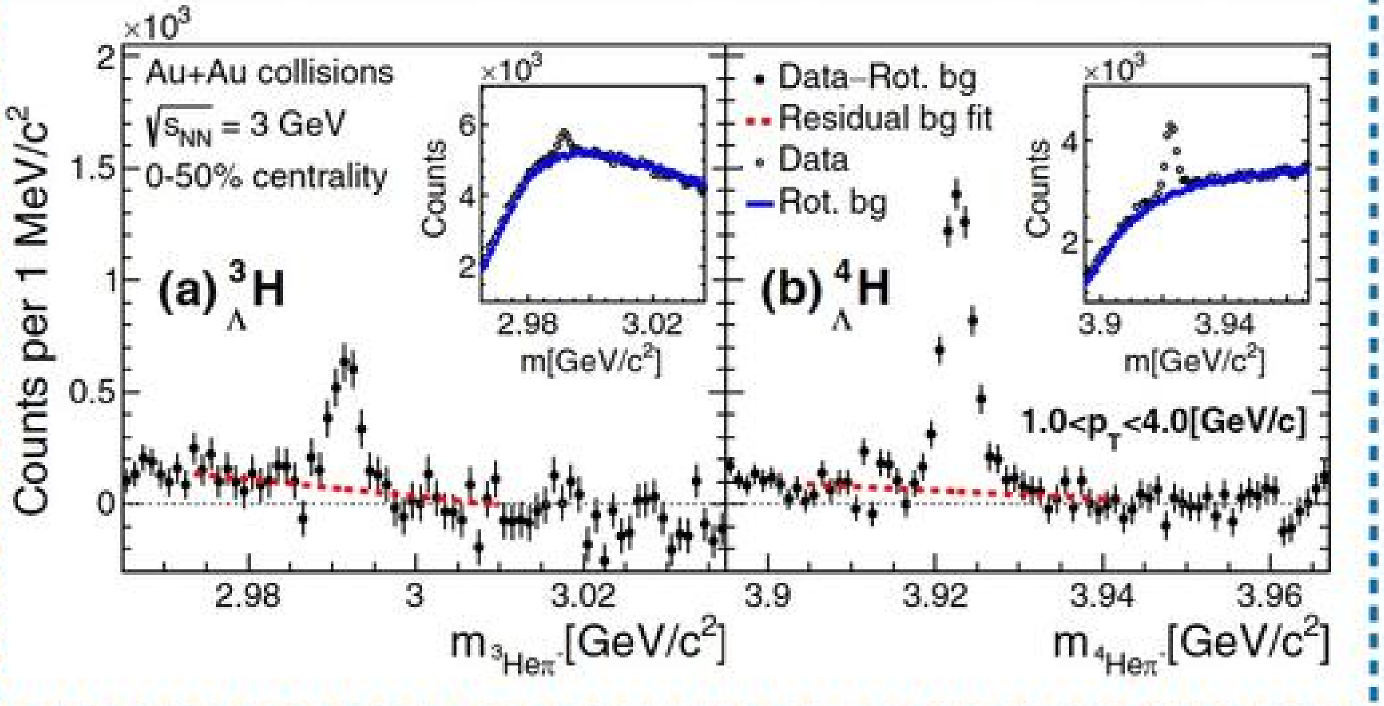
neutron star



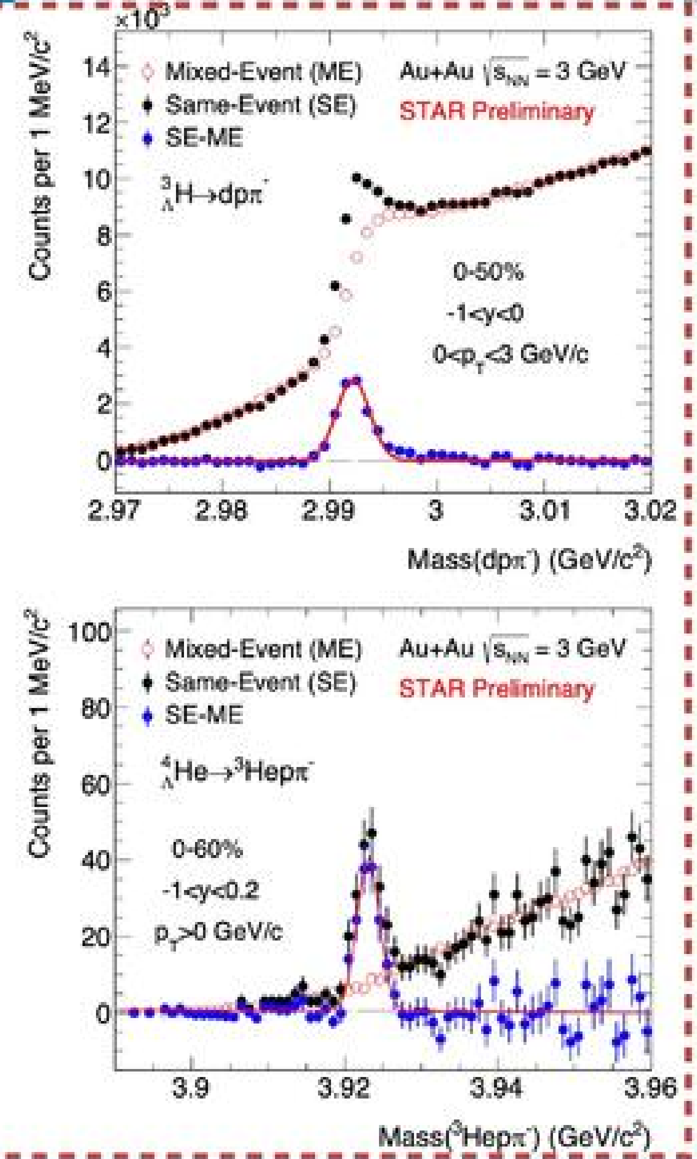
D. Chatterjee, Eur. Phys. J. A (2016) 52: 29

Hypernuclei signal reconstruction

2-body decay channels: STAR, PRL 128, 202301(2022)



3-body decay channels:

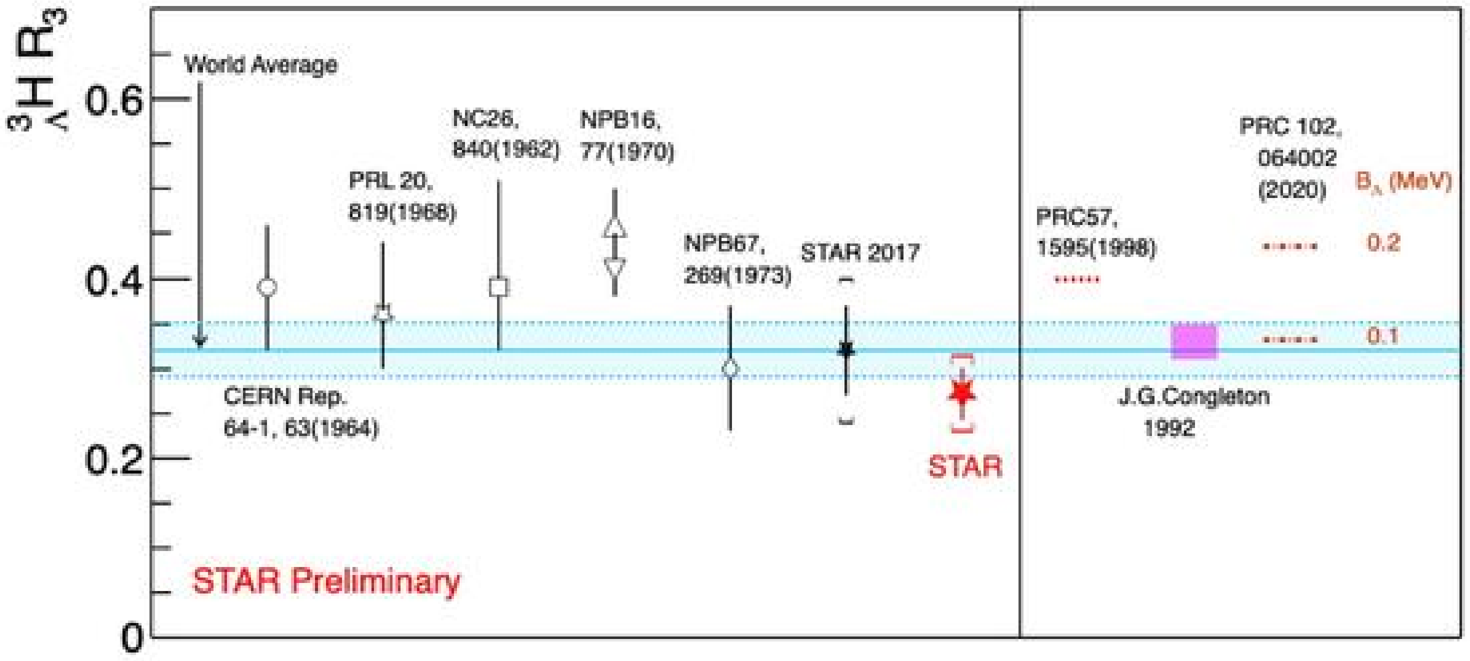


- Combinatorial background estimated via:
  - Rotating pion tracks for 2-body decay channels
  - Event mixing for 3-body decay channels

${}^{3}_{\Lambda}$H branching ratio R_3

Relative branching ratio: $R_3 = \frac{B.R.({}^{3}_{\Lambda}H \rightarrow {}^{3}He\pi^-)}{B.R.({}^{3}_{\Lambda}H \rightarrow {}^{3}He\pi^-) + B.R.({}^{3}_{\Lambda}H \rightarrow dp\pi^-)}$

F. Hildenbrand et al. PRC 102, 064002 (2020)



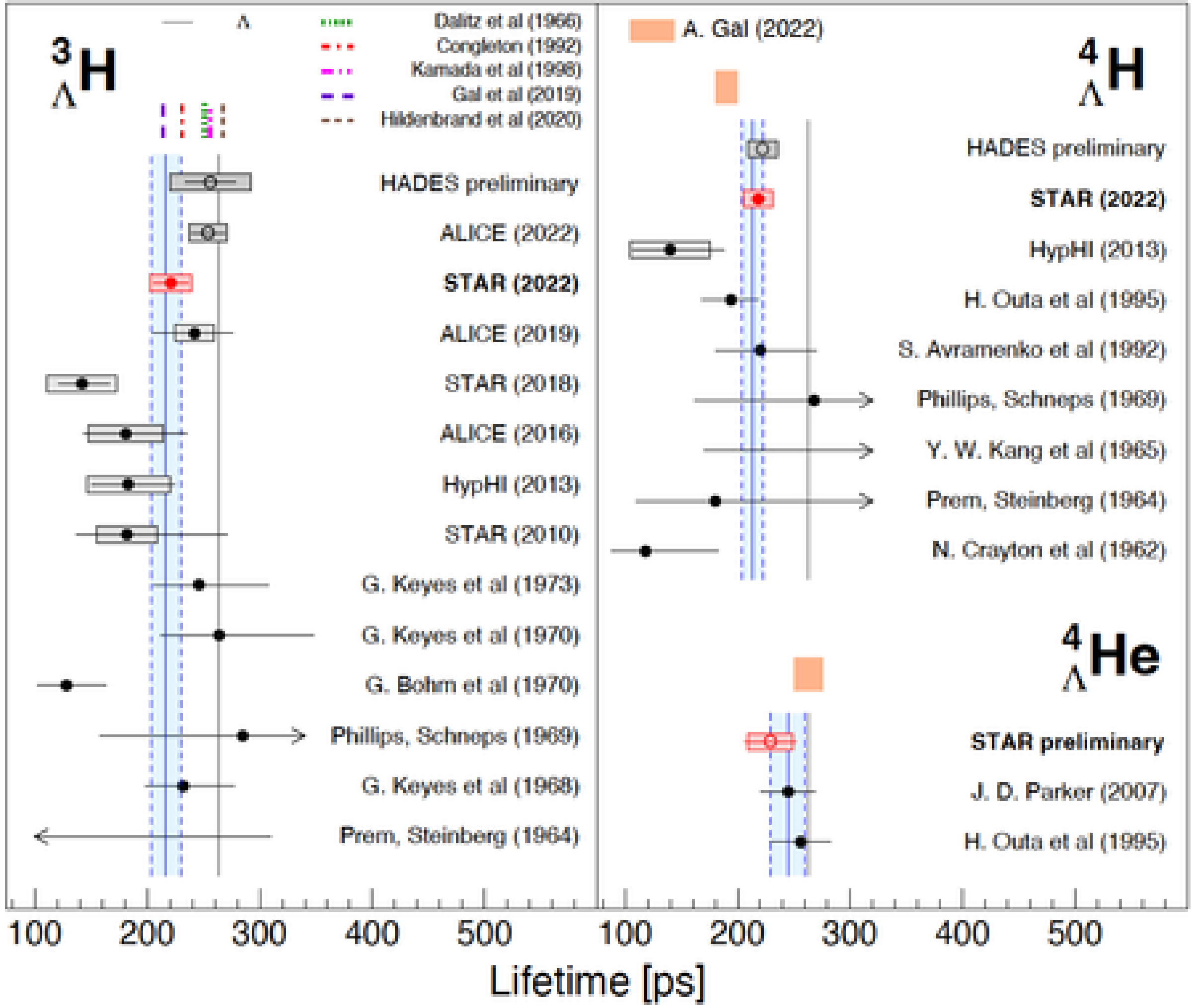
- Recent calculation shows that R_3 may be sensitive to the binding energy (B_Λ) of ${}^{3}_{\Lambda}$H
  - $B_\Lambda \rightarrow$ provide constraints to Y-N interaction

- Using $\sqrt{s_{NN}}$ = 3.0 GeV data:
  - $R_3 = 0.272 \pm 0.030(stat.) \pm 0.042(syst.)$
  - Updated world average R_3 (0.32 ± 0.03) is consistent with theoretical models assuming B_Λ~ 0.1 MeV

- Improved precision on R_3
  - Stronger constraints on absolute B.R.s and hypertriton internal structure models

${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He lifetimes

STAR, PRL 128, 202301(2022)



Using $\sqrt{s_{NN}}$ = 3.0 GeV and 7.2 GeV datasets:

${}^{3}_{\Lambda}$H: $\tau = 221 \pm 15(\text{stat.}) \pm 19(\text{syst.})[\text{ps}]$

${}^{4}_{\Lambda}$H: $\tau = 218 \pm 6(\text{stat.}) \pm 13(\text{syst.})[\text{ps}]$

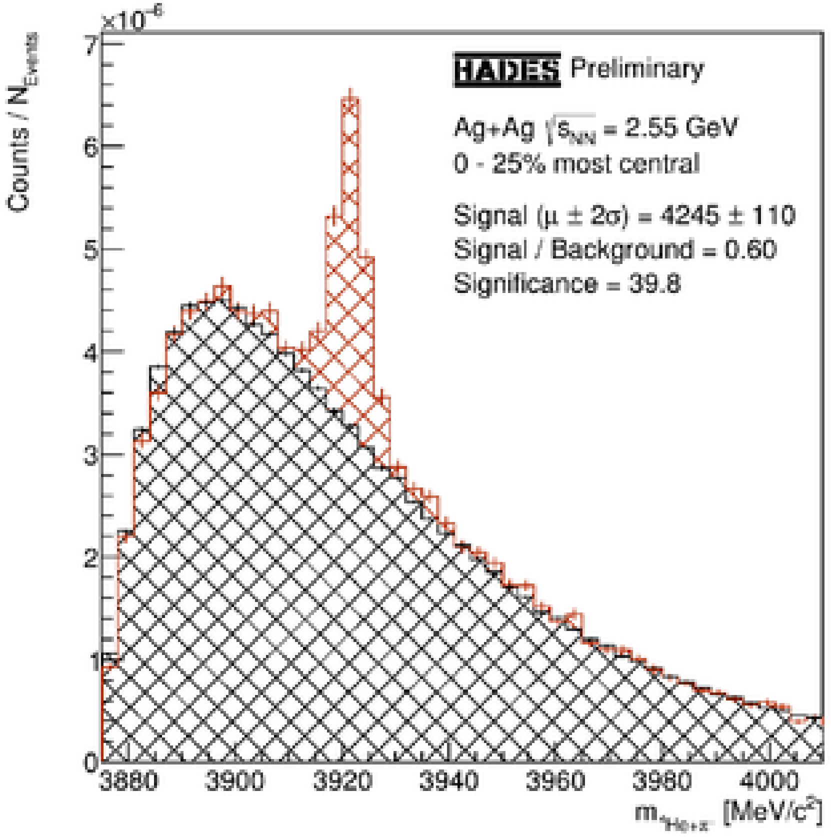
${}^{4}_{\Lambda}$He: $\tau = 229 \pm 23(\text{stat.}) \pm 20(\text{syst.})[\text{ps}]$

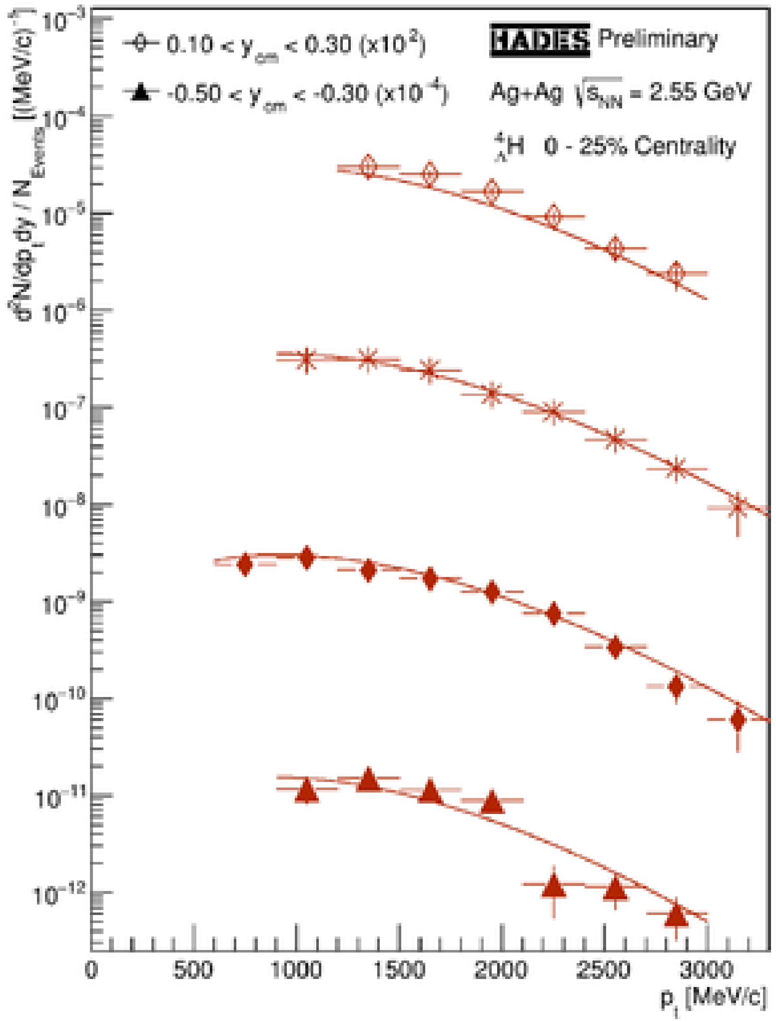
- Lifetimes of light hypernuclei ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He are shorter than that of free Λ (with 1.8σ, 3.0σ, 1.1σ respectively)
- Consistent with former measurements (within 2.5σ for ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H)
- $\tau_{{}^{3}_{\Lambda}\text{H}}$: consistent with calculation including pion FSI[1] and calculation with Λd 2-body picture[2] within 1σ
- $\tau_{{}^{4}_{\Lambda}\text{H}}$ and $\tau_{{}^{4}_{\Lambda}\text{He}}$: consistent with expectations from isospin rule

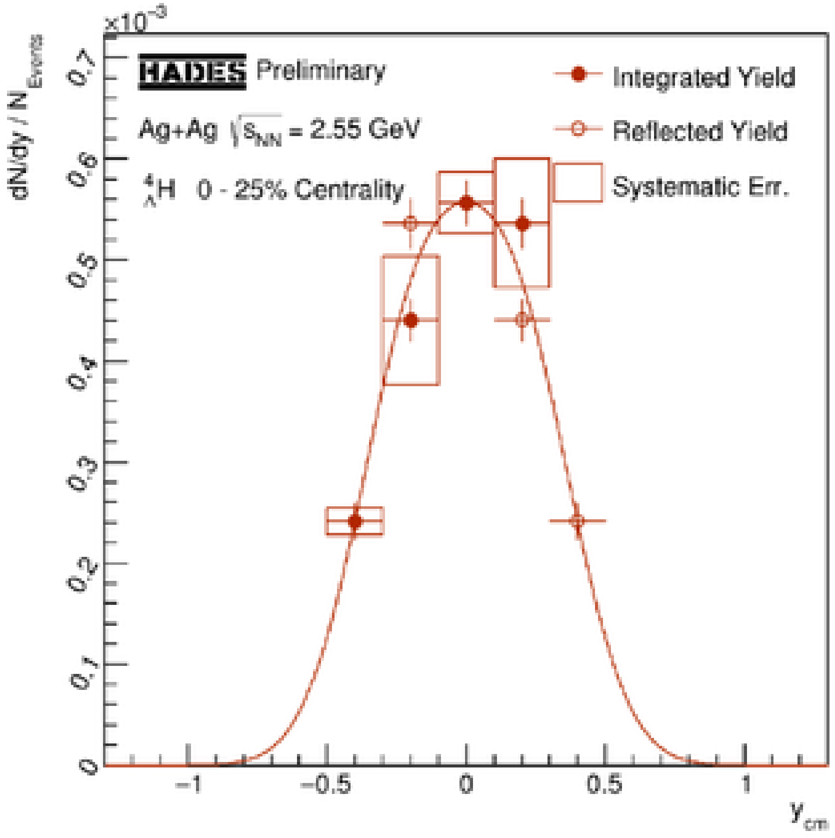
${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H results with improved precision
→ Provide tighter constraints on models.

[1]A. Gal and H. Garcilazo, PLB 791, 48 (2019)
[2]J.G. Congleton, J. Phys. G 18, 339 (1992)

$^{4}_{\Lambda}$H Two-Body Decay: $^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$



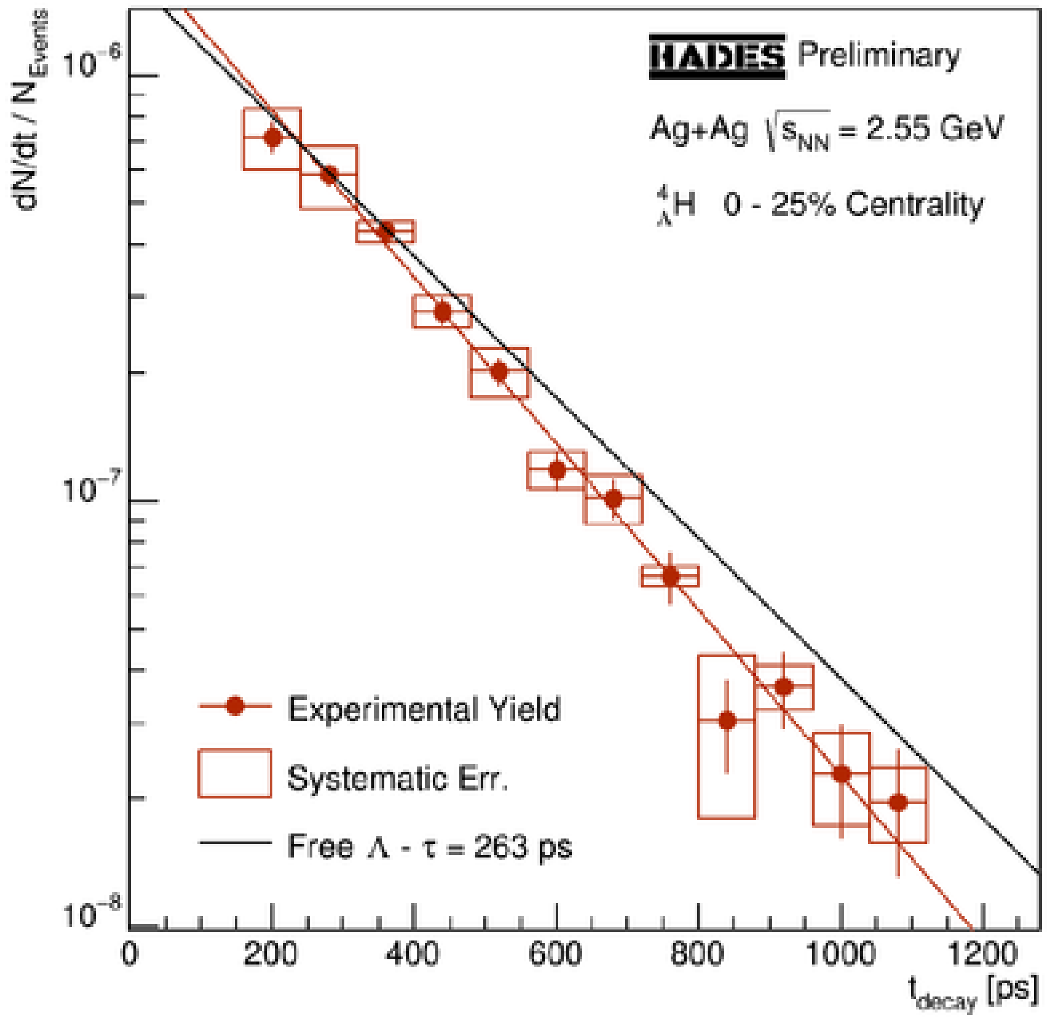




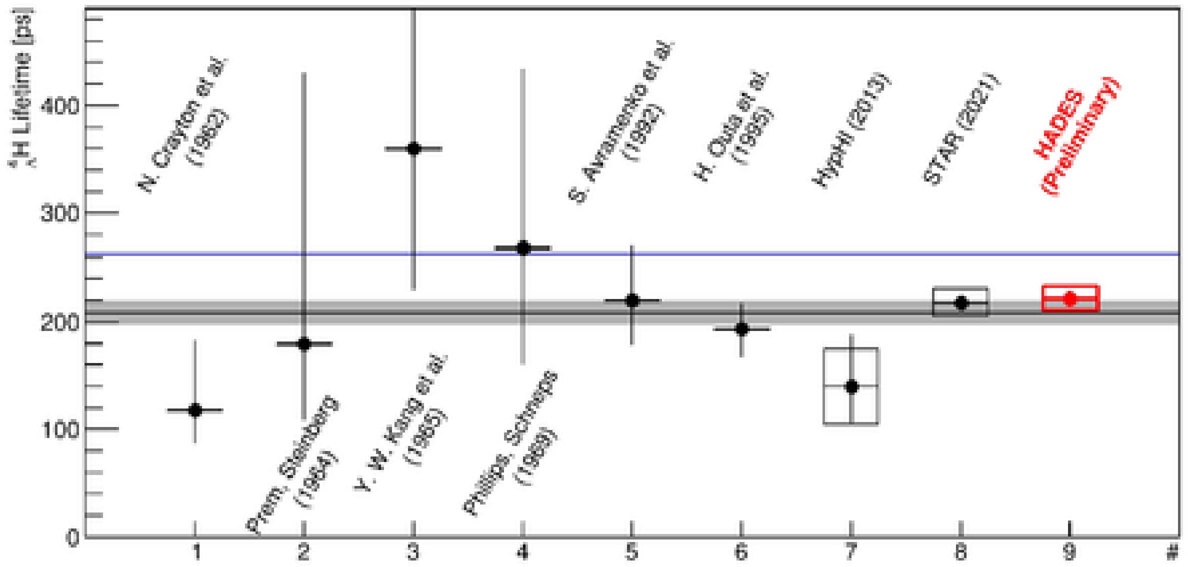
- Significant signal
- Multi-differential analysis of $^{4}_{\Lambda}$H production possible

- **First measurement at mid-rapidity at this energy**
- Systematic studies ongoing

$^{4}_{\Lambda}H$ Two-Body Decay: $^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$



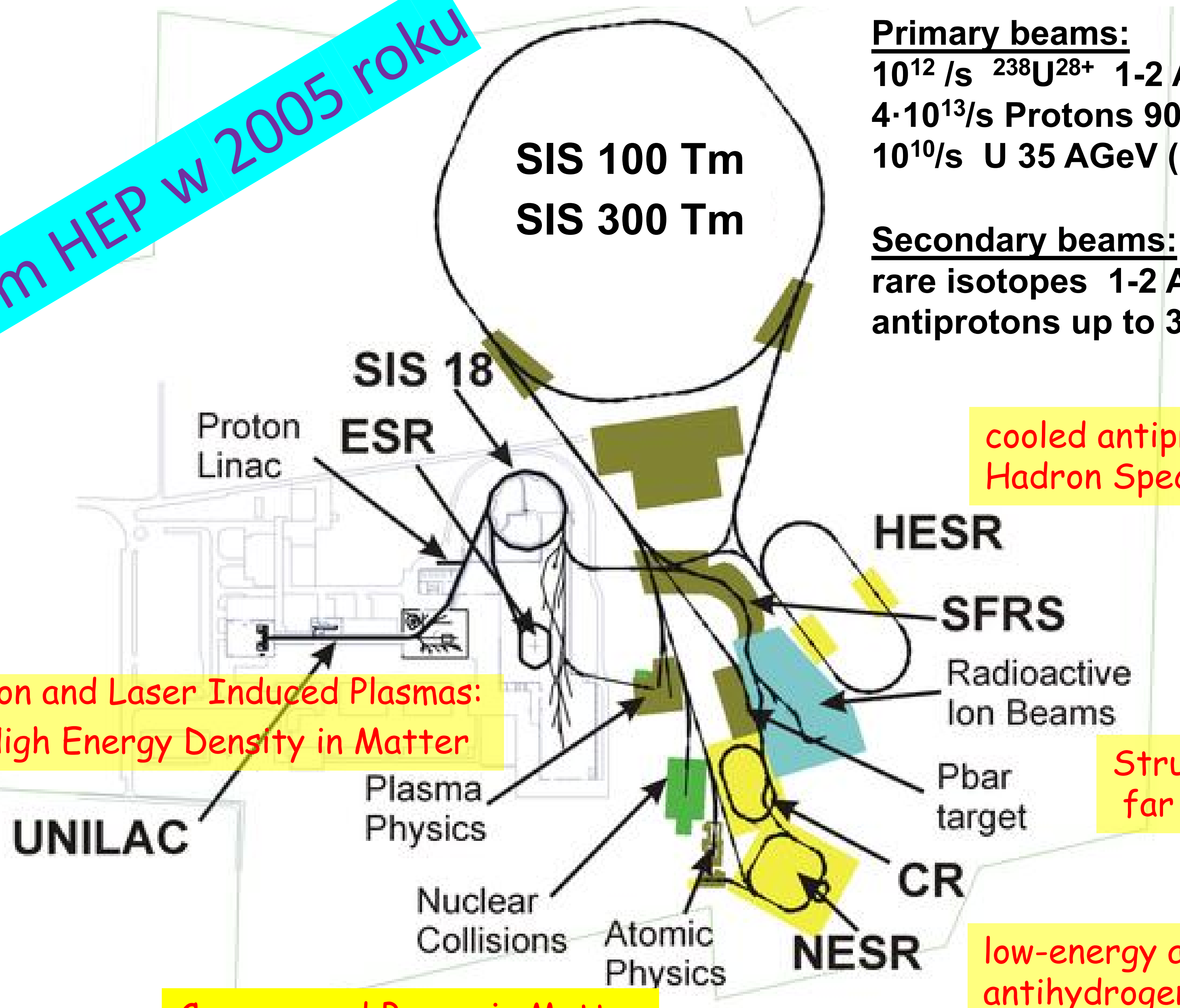
- $^{4}_{\Lambda}H$ lifetime measurement contribution to world data
- Lifetime of $(222 \pm 7_{stat} \pm 12_{sys})$ ps compatible with earlier measurements measured
  - ➢ 4.7σ deviation to free Λ lifetime
- Further systematic uncertainty analyses ongoing



Future of FAIR

The future Facility for Antiproton an Ion Research (FAIR)

z seminarium HEP w 2005 roku



Primary beams:
10^{12} /s $^{238}U^{28+}$ 1-2 AGeV
$4{\cdot}10^{13}$/s Protons 90 GeV
10^{10}/s U 35 AGeV (Ni 45 AGeV)

Secondary beams:
rare isotopes 1-2 AGeV
antiprotons up to 30 GeV

cooled antiproton beam:
Hadron Spectroscopy

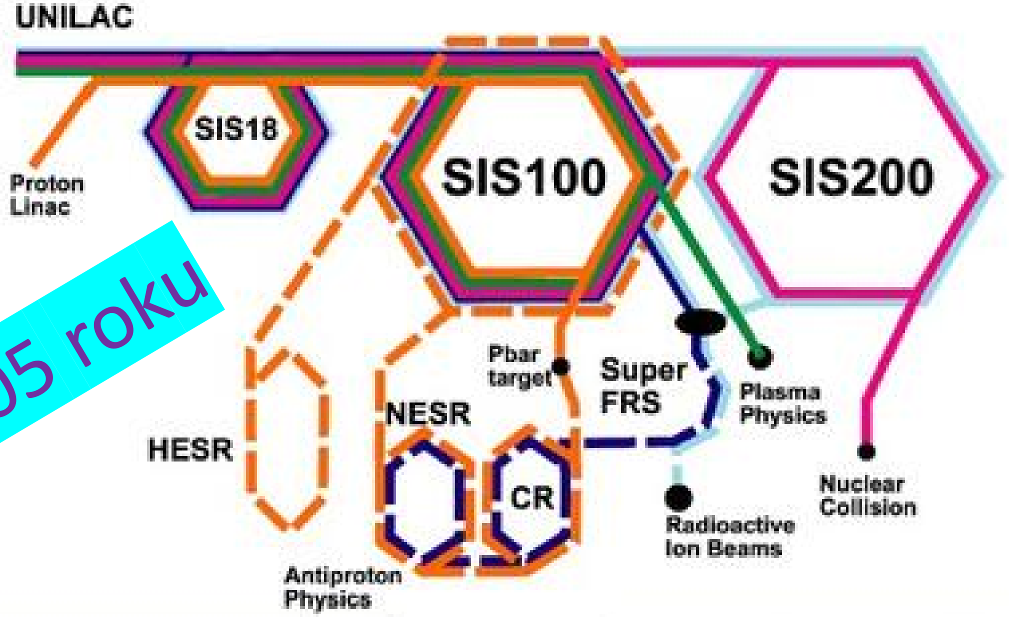
Ion and Laser Induced Plasmas:
High Energy Density in Matter

Structure of Nuclei
far from Stability

low-energy antiproton beam:
antihydrogen

Compressed Baryonic Matter

Parallel Operation



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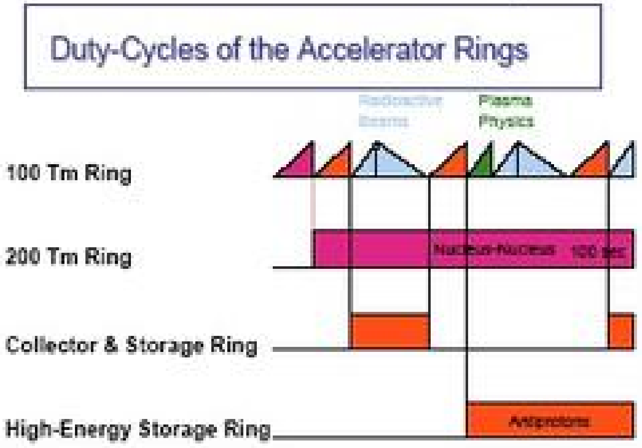
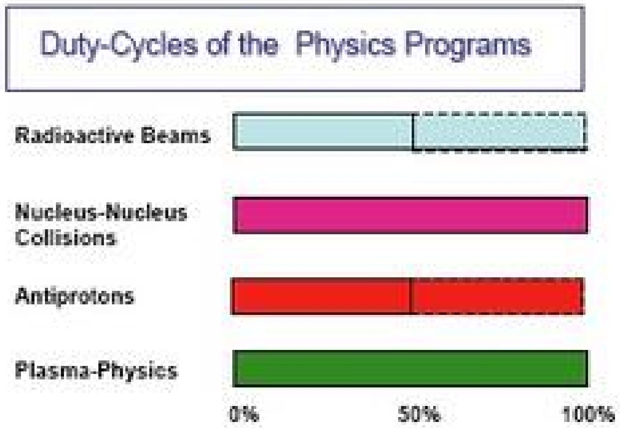




GSI

MINISTER
NAUKI I SZKOLNICTWA WYŻSZEGO

Warszawa, dnia 26.10 2007 r.

DWM/ 3856/FAIR/JC/07

Zgoda
Jarosław Kaczyński

Pan Jarosław KACZYŃSKI
Prezes Rady Ministrów
w miejscu

Szanowny Panie Premierze,

zgodnie z art. 5 ust. 1 ustawy z dnia 14 kwietnia 2000 r. o umowach międzynarodowych (Dz. U. Nr 39, poz. 443 oraz z 2002 r. Nr 216, poz. 1824) wnoszę o udzielenie zgody na rozpoczęcie negocjacji ***Konwencji w sprawie budowy i działania Europejskiego Ośrodka Badań Antyprotonów i Jonów*** **(FAIR - Facility for Antiproton and Ion Research in Europe)** oraz ***Aktu końcowego Konferencji delegatów Rządów Chińskiej Republiki Ludowej, Federalnej Republiki Niemiec, Królestwa Hiszpanii, Republiki Finlandii, Republiki Francuskiej, Zjednoczonego Królestwa Wielkiej Brytanii i Irlandii Północnej, Republiki Greckiej, Republiki Indii, Republiki Włoskiej, Rzeczypospolitej Polskiej, Republiki Rumuńskiej, Federacji Rosyjskiej oraz Królestwa Szwecji, reprezentowanych przez Przedstawicieli w pełni umocowanych przez swoje rządy do działania w sprawie utworzenia Europejskiego Ośrodka Badań Antyprotonów i Jonów (FAIR) sp. z o.o.***

Udział Polski: 23,7M€

- Infrastruktura akceleratorowa: 18M€ dostarczone jako wkład in-kind/gotówka
- Detektory do badań fizycznych: 5,7M€

1531

KONWENCJA

dotycząca budowy i funkcjonowania Ośrodka Badań Antyprotonami i Jonami w Europie,

sporządzona w Wiesbaden dnia 4 października 2010 r.

W imieniu Rzeczypospolitej Polskiej

PREZYDENT RZECZYPOSPOLITEJ POLSKIEJ

podaje do powszechnej wiadomości:

Dnia 4 października 2010 r. w Wiesbaden została sporządzona Konwencja dotycząca budowy i funkcjonowania Ośrodka Badań Antyprotonami i Jonami w Europie, w następującym brzmieniu:

Przekład

Konwencja Dotycząca Budowy i Funkcjonowania Ośrodka Badań Antyprotonami i Jonami w Europie[1]

Spis treści

481

USTAWA

z dnia 25 lutego 2011 r.

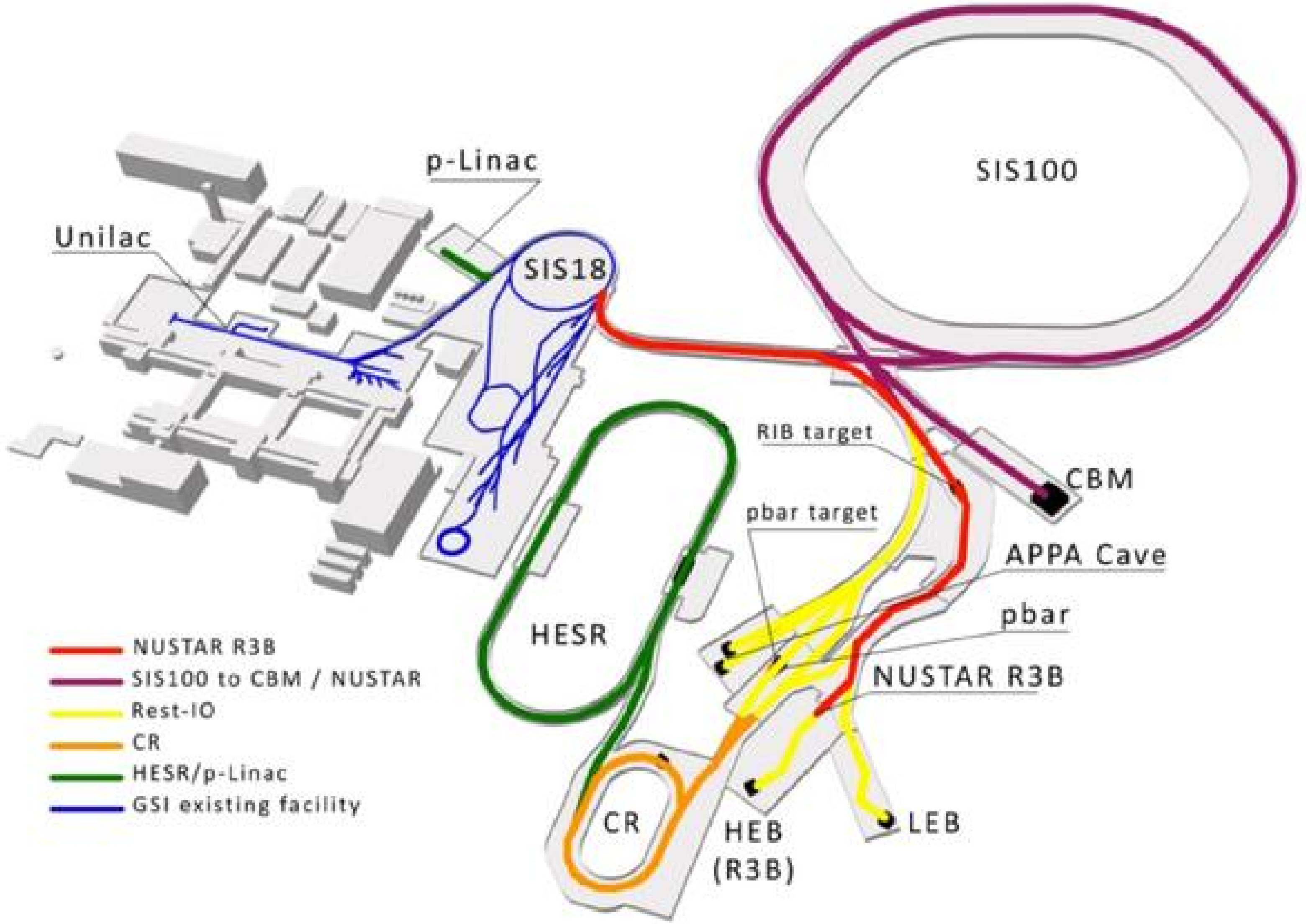
o ratyfikacji Konwencji dotyczącej budowy i funkcjonowania Ośrodka Badań Antyprotonami i Jonami w Europie, sporządzonej w Wiesbaden dnia 4 października 2010 r.

Art. 1. Wyraża się zgodę na dokonanie przez Prezydenta Rzeczypospolitej Polskiej ratyfikacji Konwencji dotyczącej budowy i funkcjonowania Ośrodka Badań Antyprotonami i Jonami w Europie, sporządzonej w Wiesbaden dnia 4 października 2010 r.

Art. 2. Ustawa wchodzi w życie po upływie 14 dni od dnia ogłoszenia.

Prezydent Rzeczypospolitej Polskiej: *B. Komorowski*

Future of FAIR and CBM



Substantial cost increase surfaced in 2021,
Russian attack on Ukraine

Science evaluation in 2022
(chairs: R. Heuer, R. Tribble)

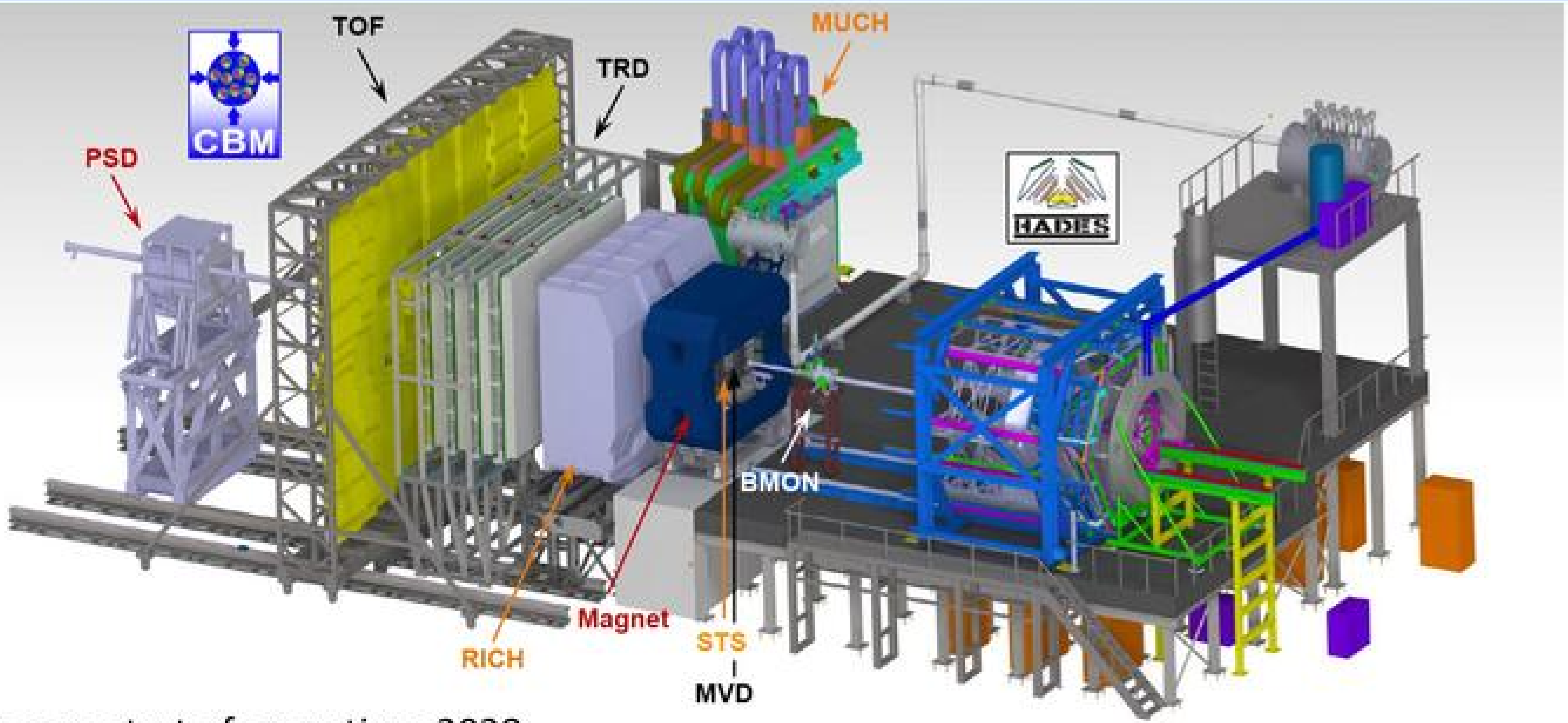
Recommendation:
downscope FAIR project

Suggested scenario:
FS+: SIS100 & SFRS/R3B & CBM

Decision by FAIR council
expected in Feb. 2023

https://www.gsi.de/fileadmin/oeffentlichkeitsarbeit/fair/FAIR-report_221025.pdf

Status and plans of CBM experiment



Key features of CBM

- Radiation hard detectors
- Tracking acceptance:
  $2^\circ < \theta_{lab} < 25^\circ$
- PID alternatives
  - electron/hadron: RICH, TRD, TOF
  - muon: MUCH, TRD, TOF
- Free streaming DAQ
- Software based event selection
- R_{int} = 10 MHz (Au+Au) with MVD
  R_{int} = 0.1 MHz (Au+Au)

Prepare start of operation: 2028

Replacements of former Russian contributions:

Magnet (urgent FAIR procurement item), PSD
(MUCH, RICH) gas system and mechanics
STS module production workforce

} covered by in-kind contracts, mitigation through FAIR resources
Missing STS funds got granted by BMBF on Dec. 1, 2022

Optimize setup for future extensions

Conclusion

Very successful STAR program is ending

- last run in 2025
- ultimate physics goal of BES not reached yet

High μ_B program with CBM@SIS100 is natural continuation

- explore QCD matter at neutron star core densities
- employ high statistics capability
  - to achieve high-precision of multi-differential observables
  - to enable rare processes as sensitive probes

T

~150 MeV

FAIR project and CBM need support of community

- start of operation unclear, optimistically 2028
- US-CBM white paper [arXiv:2209.05009] very helpful

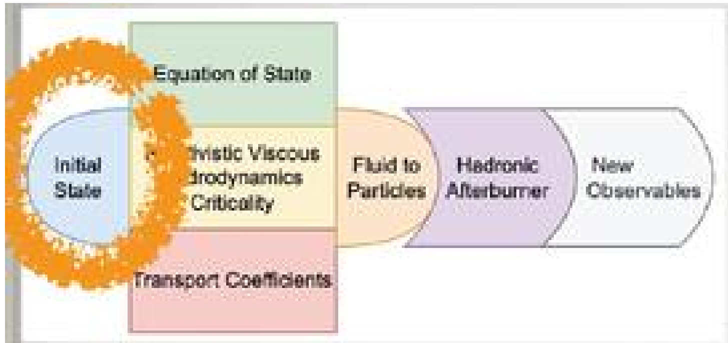
CBM Phase 0 activities: HADES, mCBM

- reference measurements possible with SIS18

CBM collaboration is open for additions and invites for participation.

Extras

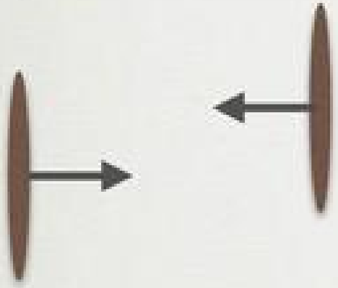
- Transition from high to low energies: the hadronic only phase is „new" observation
- 3-body femtoscopy
- Absorption of antinuclei in matter



Physics of $\sqrt{s} = 3 - 20$ GeV collisions

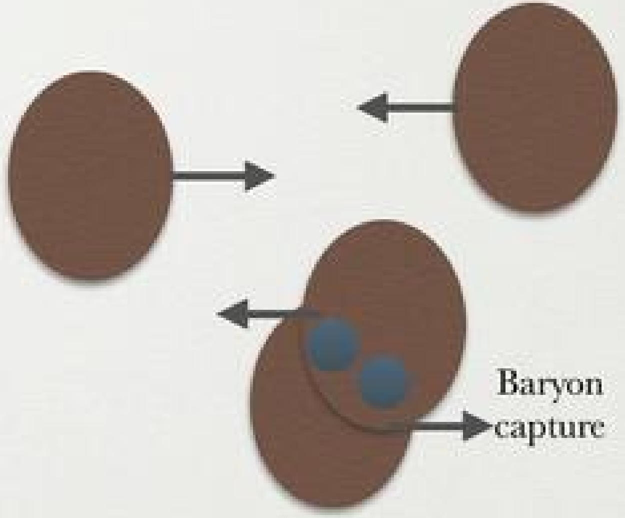
BEST = Beam Energy Scan Theory

Large $\sqrt{s_{NN}}$

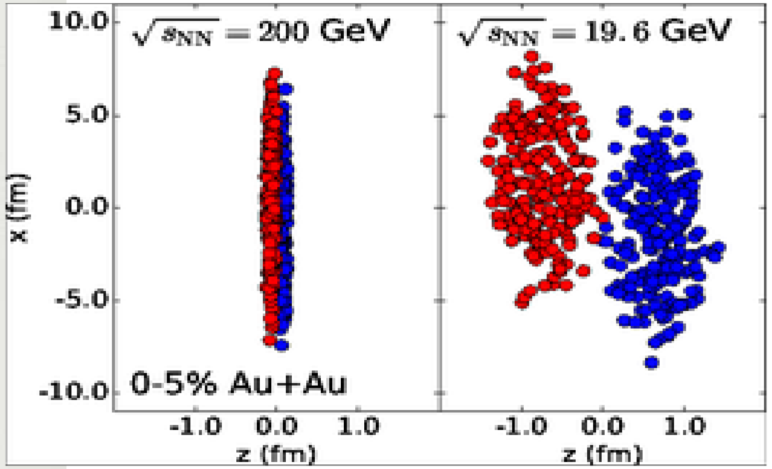


- Lorentz contracted (2D)
- Nuclei pass through instantaneously
- Too quick to capture baryons

Small $\sqrt{s_{NN}}$



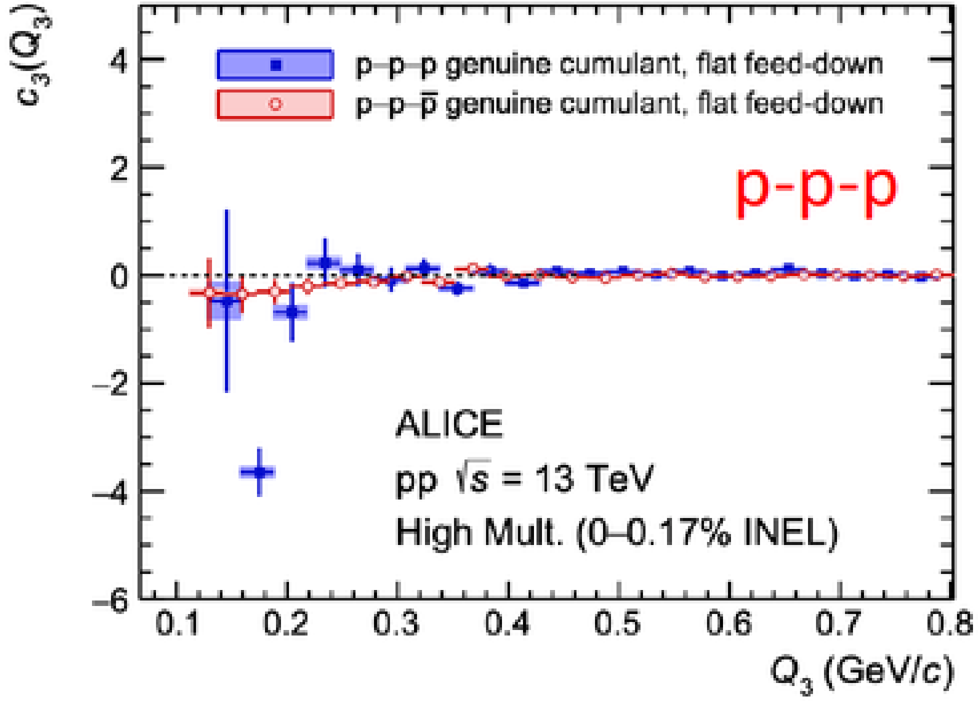
- 3D nuclei pass slowly
- Time to capture baryons

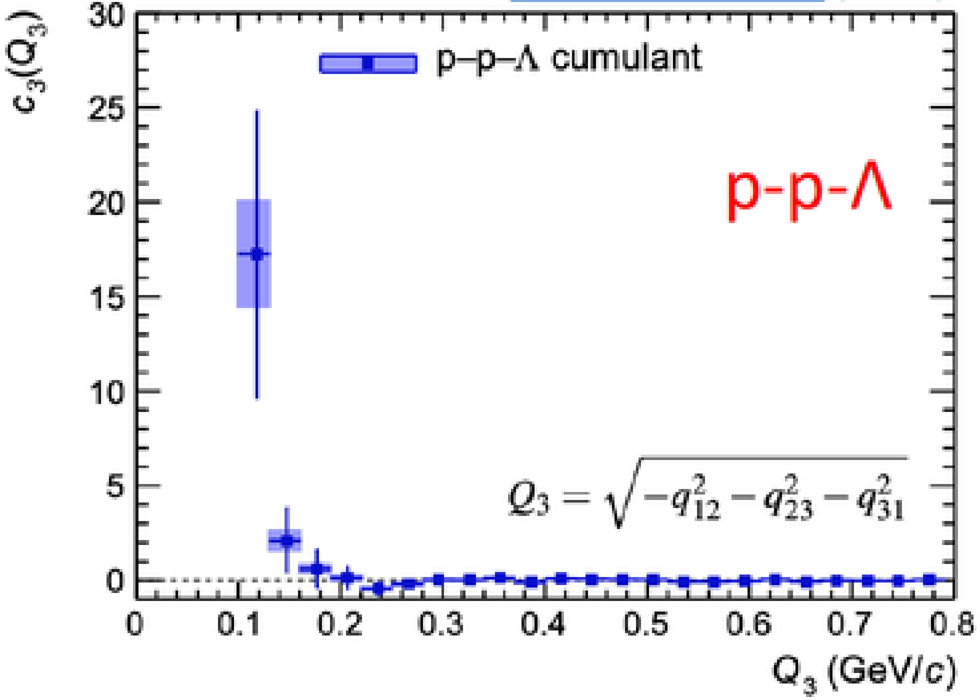


3-body femtoscopic correlations

Accepted by EPJ A

ALICE, arXiv:2206.03344 (2022)





- Measured 3-particle correlation functions deviate from lower-order contributions→ hint to **three-body effects**
- N-N-N and N-N-Λ interactions for the **EoS of neutron stars** *D. Lonardoni et al., PRL 114, 092301 (2015)*

Absorption of $^{3}\overline{\mathrm{He}}$ nuclei in matter

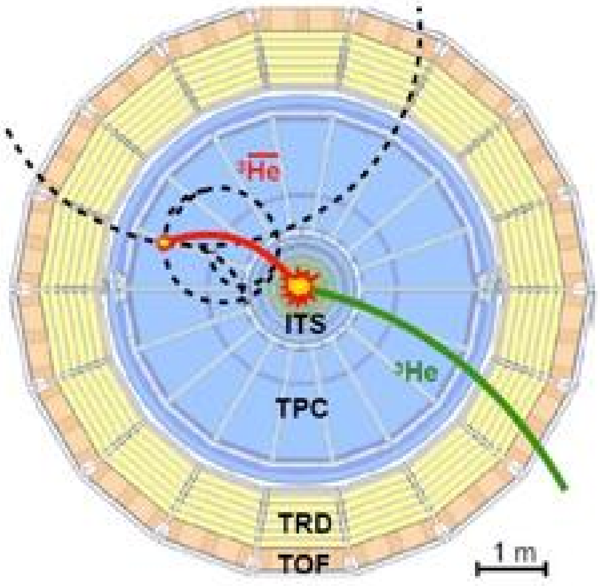
Measurements of antinuclei provide important input for astrophysics and dark-matter studies

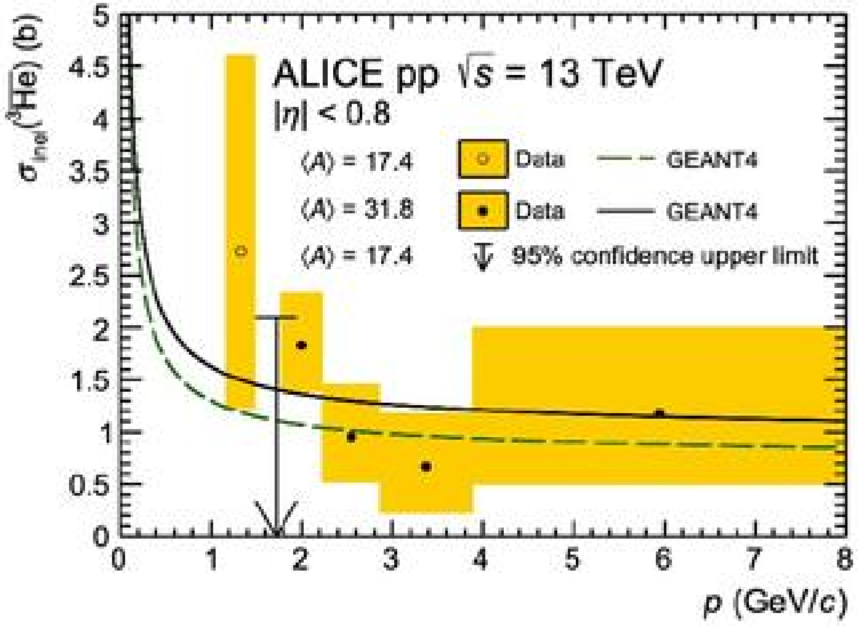
- One of dominant production mechanisms is **DM annihilation** (e.g. $\chi + \chi \rightarrow W^{+}W^{-} \rightarrow {}^{3}\overline{\mathrm{He}} + X$)
- **Disappearance probability** of antinuclei (quantified by σ_{inel}) is crucial for studying the galaxy transparency

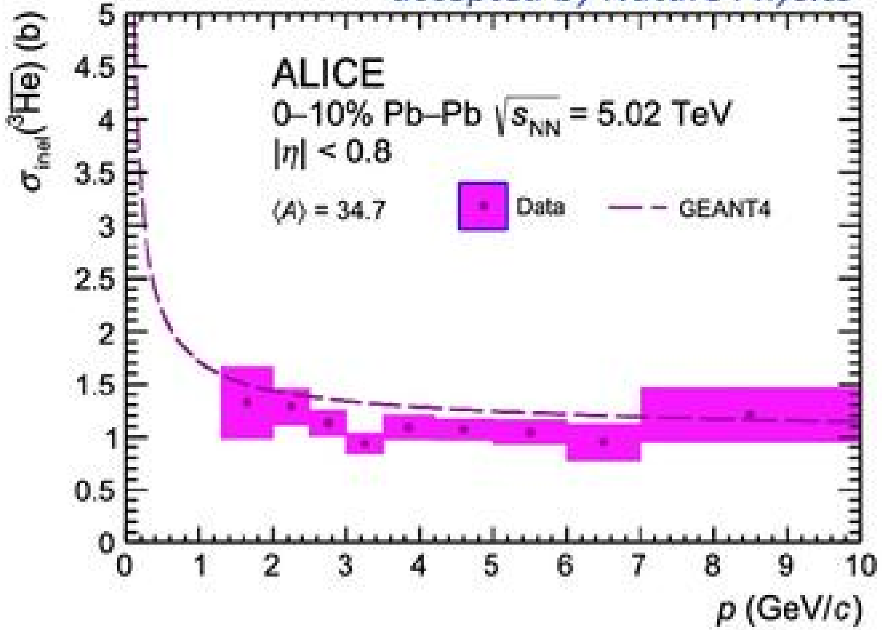
○ ALICE: antinuclei factory + interaction in detector material → measurement of σ_{inel} for $^{3}\overline{\mathrm{He}}$

○ via baryon/antibaryon ratio (pp), or TOF-to-TPC ratio (Pb–Pb)

ALICE, arXiv.2202.01549
accepted by Nature Physics







- GEANT4 modeling **consistent within 2σ** with data

1915
1927
1939
1951
1963
1975
1987
1999
2011
2023

FIREBALL by Deep Purple (1971)

Ritchie Blackmore (guitar)

Jon Lord (keyboard)

Roger Glover (bass)

Ian Paice (percussion)

Ian Gillan (frontman)