phase boundary, critical point, deconfinement, hadronization

news from SQM2022 and experimental outlook

new data from all experimental collaborations

- phase boundary and critical endpoint:
  hadron yields, fluctuations, (higher) moments, rapidity correlations

- deconfinement:
  universal aspects of production of light and charm hadrons
  importance of resonance decays
  direct measurements with heavy quarks

- hadronization:
  universal hadronization of mesons and baryons
  composite hadrons: coalescense vs direct production

- outlook: the next decade

pbm
SQM2022
Summary 4
Friday, June 17, 2022

ISOQUANT SFB1225

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

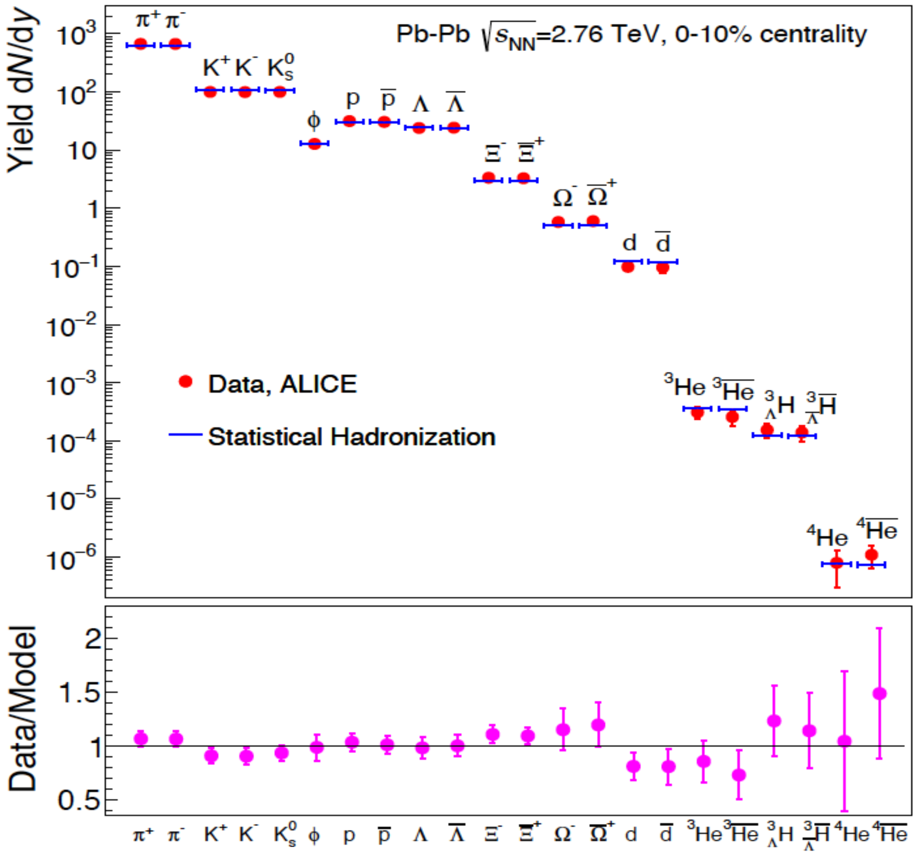
EMMI

GSI

(u,d,s) hadrons and the QGP phase boundary

statistical hadronization of (u,d,s) hadrons

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561 (2018) 321



Best fit:

$T_{CF} = 156.6 \pm 1.7$ MeV

$\mu_B = 0.7 \pm 3.8$ MeV

$V_{\Delta y=1} = 4175 \pm 380$ fm^3

$\chi^2/N_{df} = 16.7/19$

S-matrix treatment of inter-actions (non-strange sect.)

"proton puzzle" solved

PLB 792 (2019) 304

data: ALICE coll., Nucl. Phys. A971 (2018) 1

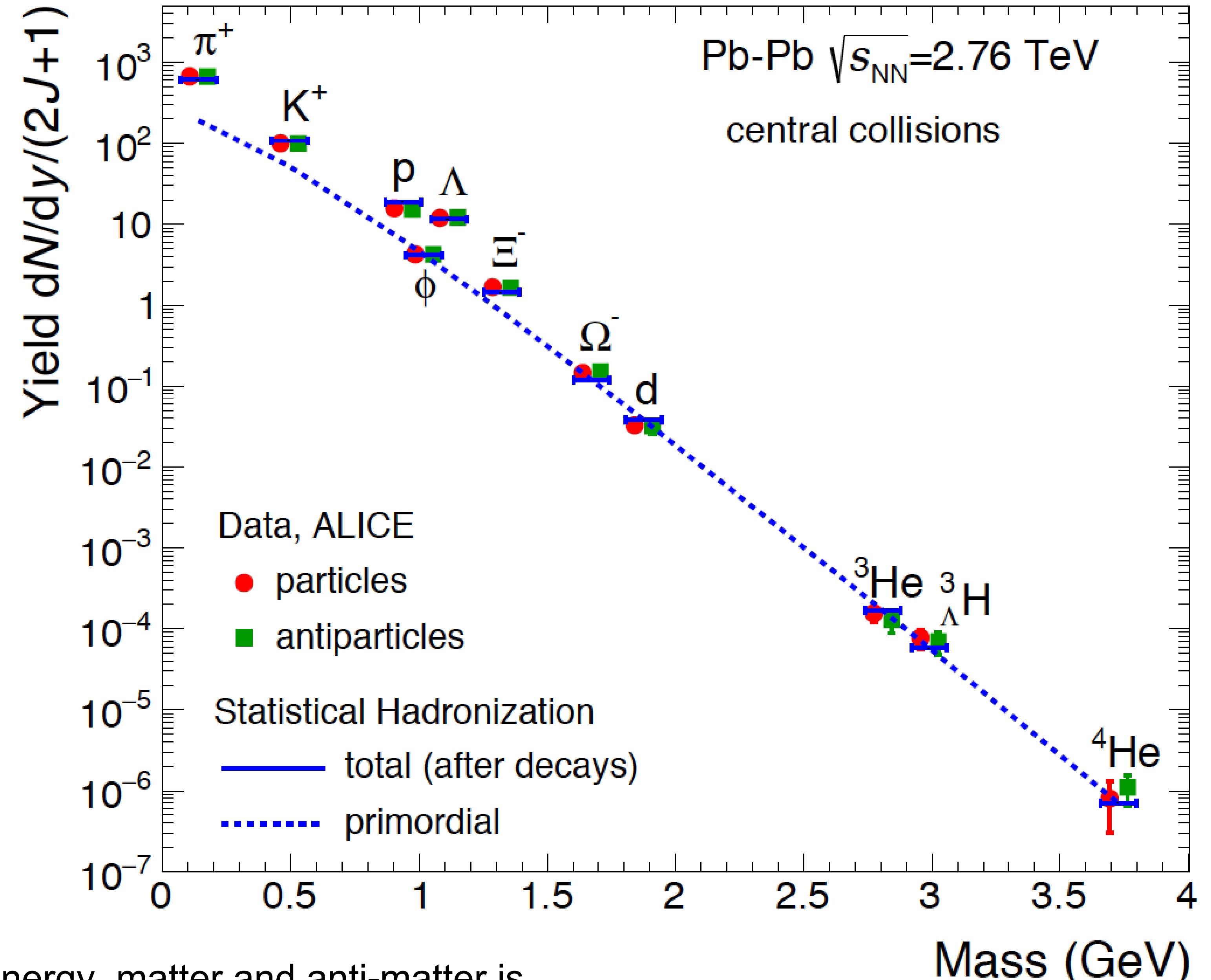
agreement over 9 orders of magnitude with QCD statistical operator prediction
(- strong decays need to be added)

- matter and antimatter formed in equal portions
- even large very fragile (hyper) nuclei follow the systematics

similar results at lower energy, each new energy yields a pair of (T, μ_B) values

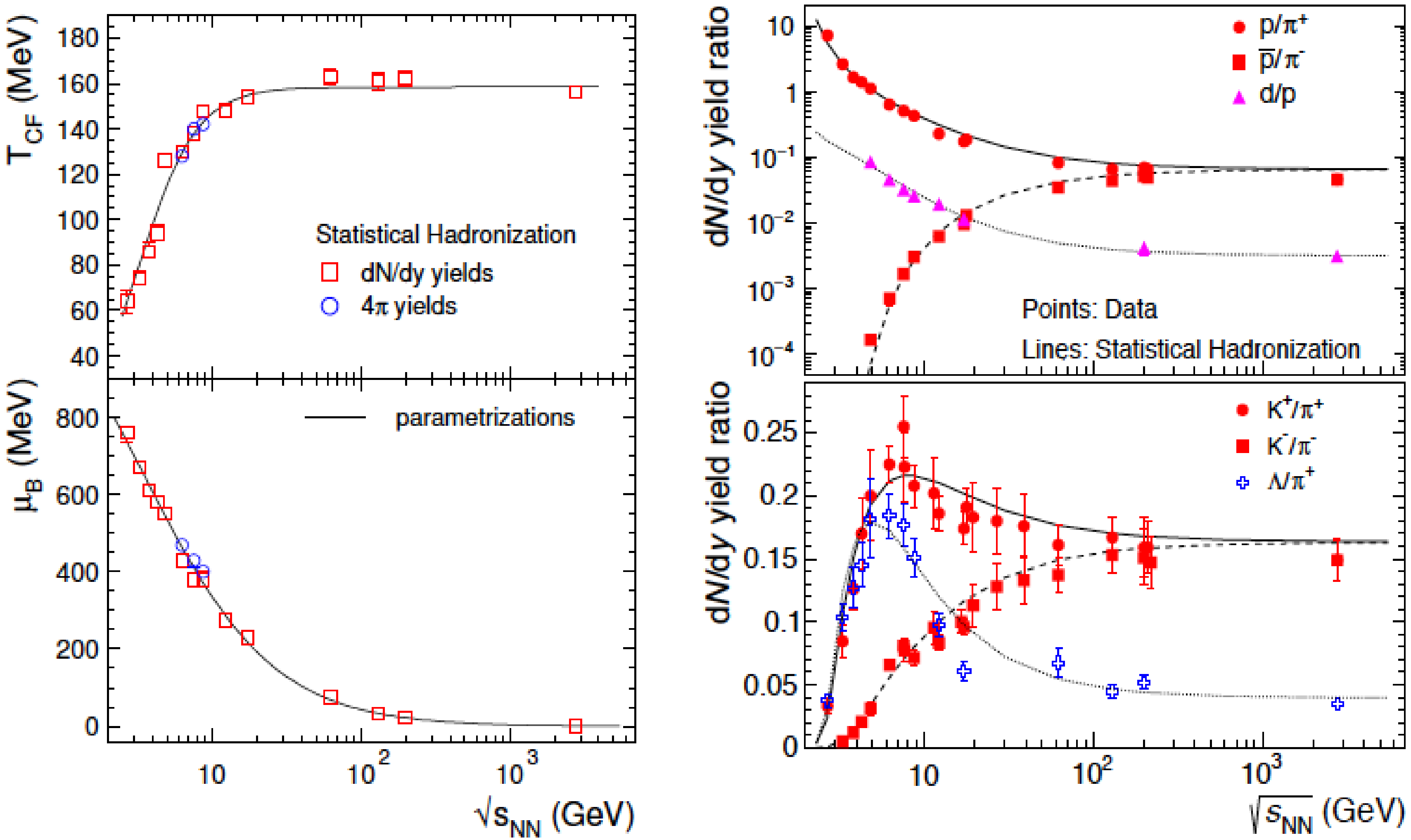
connection to QCD (QGP) phase diagram?

at LHC energy, production of (u,d,s) hadrons is governed
by mass and quantum numbers only
quark content does not matter



at LHC energy, matter and anti-matter is
produced with equal yields

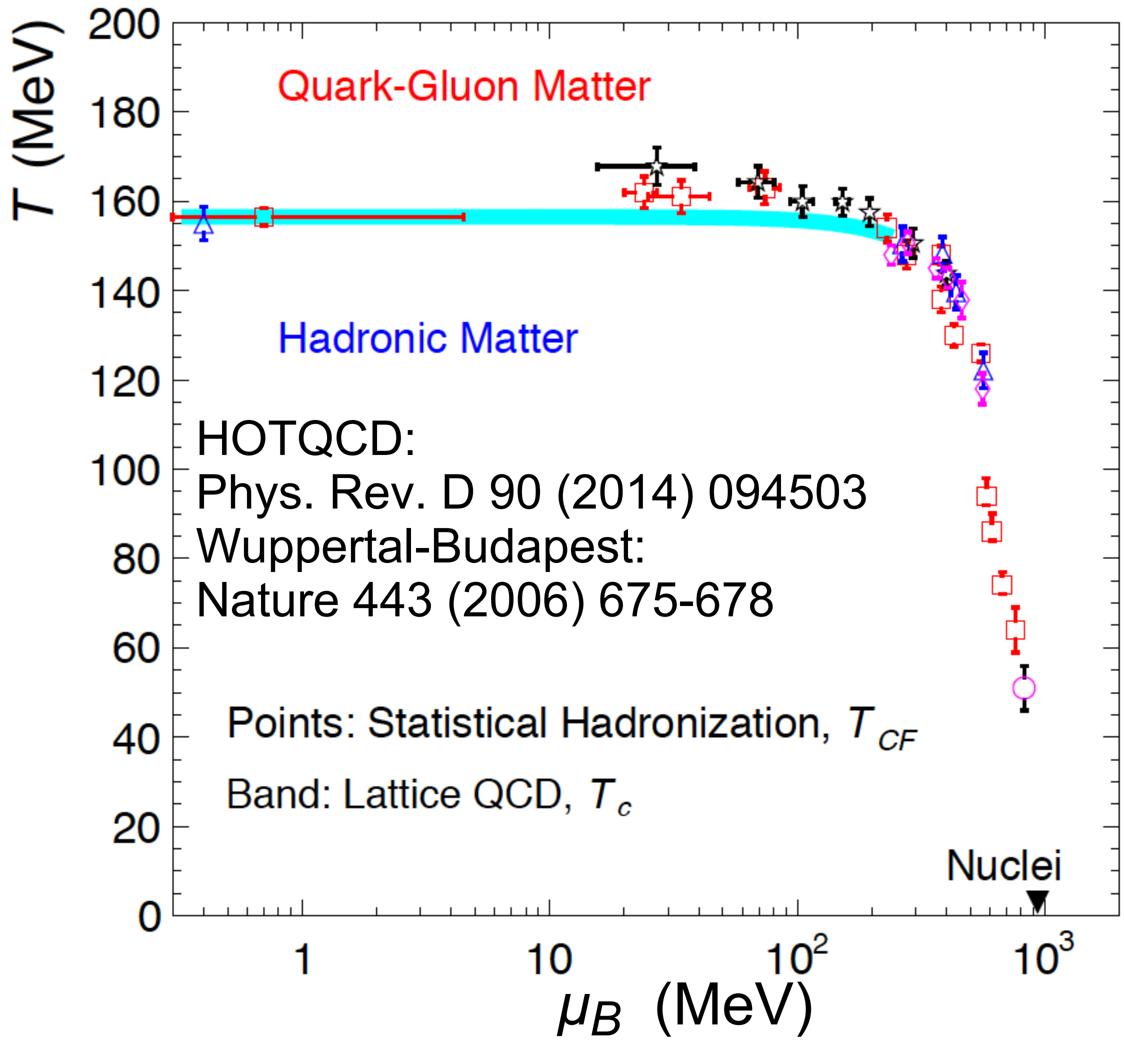
energy dependence of hadron production described quantitatively



together with known energy dependence of charged hadron production in Pb-Pb collisions we can predict yield of all hadrons at all energies with < 10% accuracy

the QGP phase diagram, LatticeQCD, and hadron production data

note: all coll. at SIS, AGS, SPS, RHIC and LHC involved in data taking
each entry is result of several years of experiments, variation of μ_B via variation of cm energy



experimental determination of phase boundary at
T_C = 156.6 ± 1.7 (stat.) ± 3 (syst.) MeV and μ_B = 0 MeV
Nature 561 (2018) 321

quantitative agreement of chemical freeze-out parameters with most recent LQCD predictions for baryo-chemical potential < 300 MeV

cross over transition at μ_B = 0 MeV, no experimental confirmation

should the transition be 1st order for large μ_B (large net baryon density)?

then there must be a critical endpoint in the phase diagram

search for critical phenomena by measuring higher moments of net proton (baryon) distributions along the phase boundary

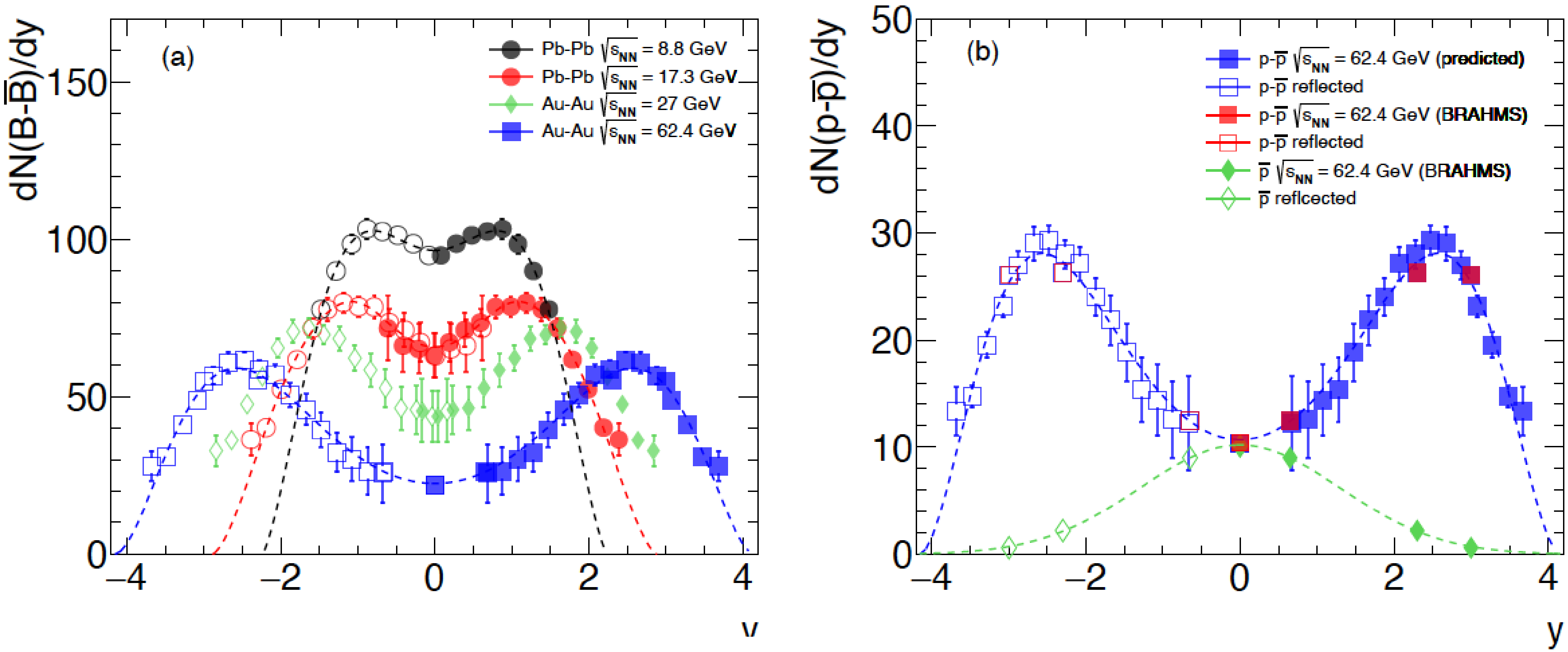
pbm, B.Friman, K. Redlich, A. Rustamov, J. Stachel,
Nucl.Phys. A 1008 (2021) 122141, 2007.02463 [nucl-th]
pbm, Rustamov, Stachel, Nucl.Phys. A 982 (2019) 307-310, 1807.08927 [nucl-th]
V. Vovchenko, V. Koch, arXiv:2204.00137 [hep-ph]
X. An et al, BEST coll., Nucl.Phys.A 1017 (2022) 122343, arXiv:2108.13867 [nucl-th]

comparison of experimental data of (mostly) STAR and ALICE with predictions of noncritical base line using canonical thermodynamics to impose baryon number conservation and otherwise assuming uncorrelated baryon and anti-baryon emission

make use of experimentally established energy dependence of phase space distributions (over 4π in rapidity and transverse momentum) of protons and anti-protons and baryons and anti-baryons)

net baryon distributions, event-by-event fluctuations and chemical freeze-out

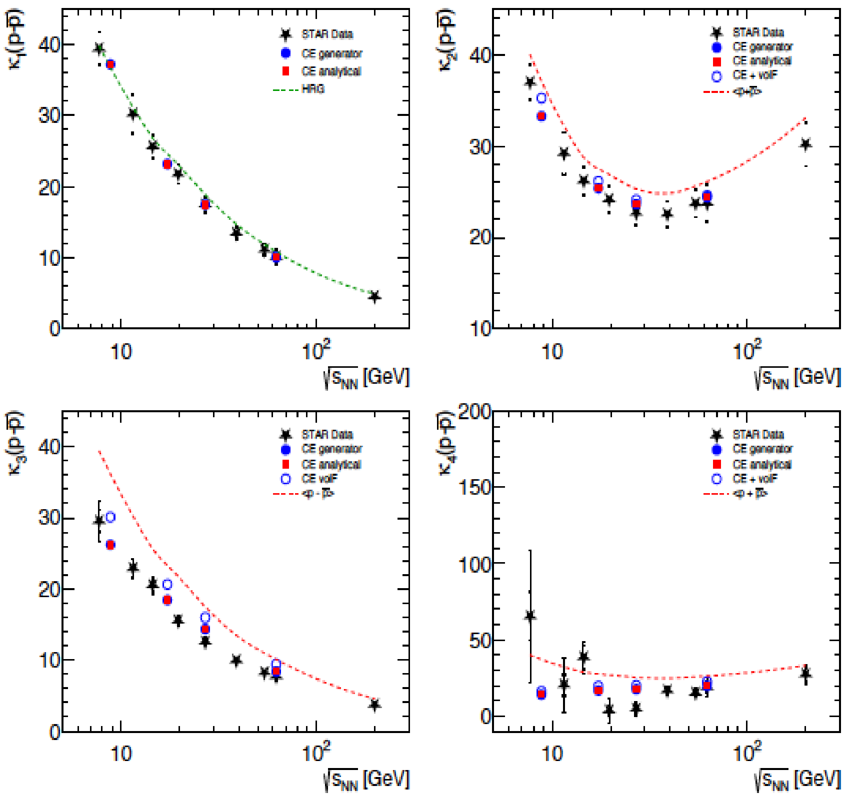
P.Braun-Munzinger, B.Friman, K.Redlich, A.Rustamov and J.Stachel,
Relativistic nuclear collisions: Establishing a non-critical baseline for fluctuation measurements,
[arXiv:2007.02463 [nucl-th], Nucl.Phys. A (in print)].

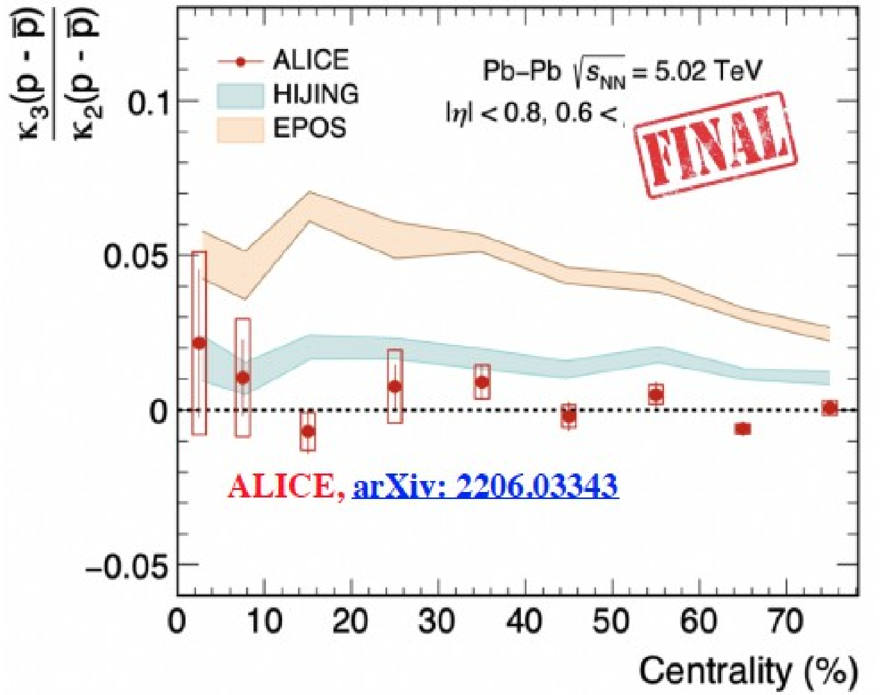


(a): Rapidity distributions of net baryons at $\sqrt{s_{NN}} = 8.8$ and 17.3 GeV (measured distributions from NA49) and 27 and 62.4 GeV (constructed using the limiting fragmentation concept described in the text). (b): Constructed (blue symbols) and BRAHMS measured (red symbols) rapidity distributions of net-protons at $\sqrt{s_{NN}} = 62.4$ GeV.

comparison of experimental cumulants (STAR collaboration, PRL 126 (2021) 092301) with predictions using the non-critical baseline, 2007.02463

3rd moment data from ALICE Mesut Arslandok, SQM22, Wed. morning session





good agreement, no evidence for critical behavior
expect factor 10 improvement in statistics with STAR BES2 and ALICE Run 3
4th - 6th cumulants should be available for comparison with LQCD predictions

global and local baryon number conservation

so far, comparison to fluctuation data in canonical ensemble assumes global baryon number conservation

in principle, local conservation, i.e. short range correlation in rapidity space, is possible and, indeed, a strong prediction of a string models for particle production, see below.

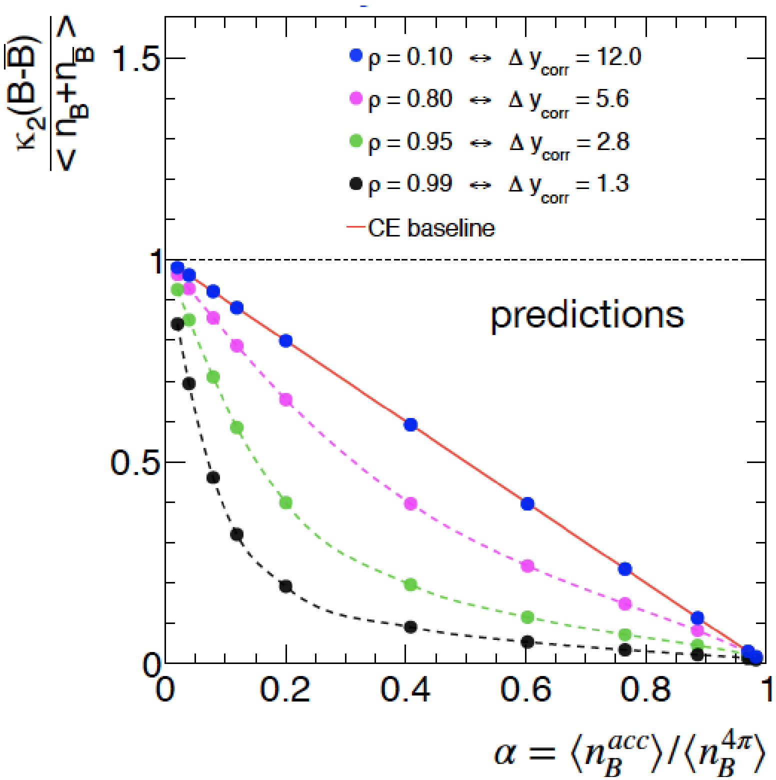
to take this into account, the following developments too place*:

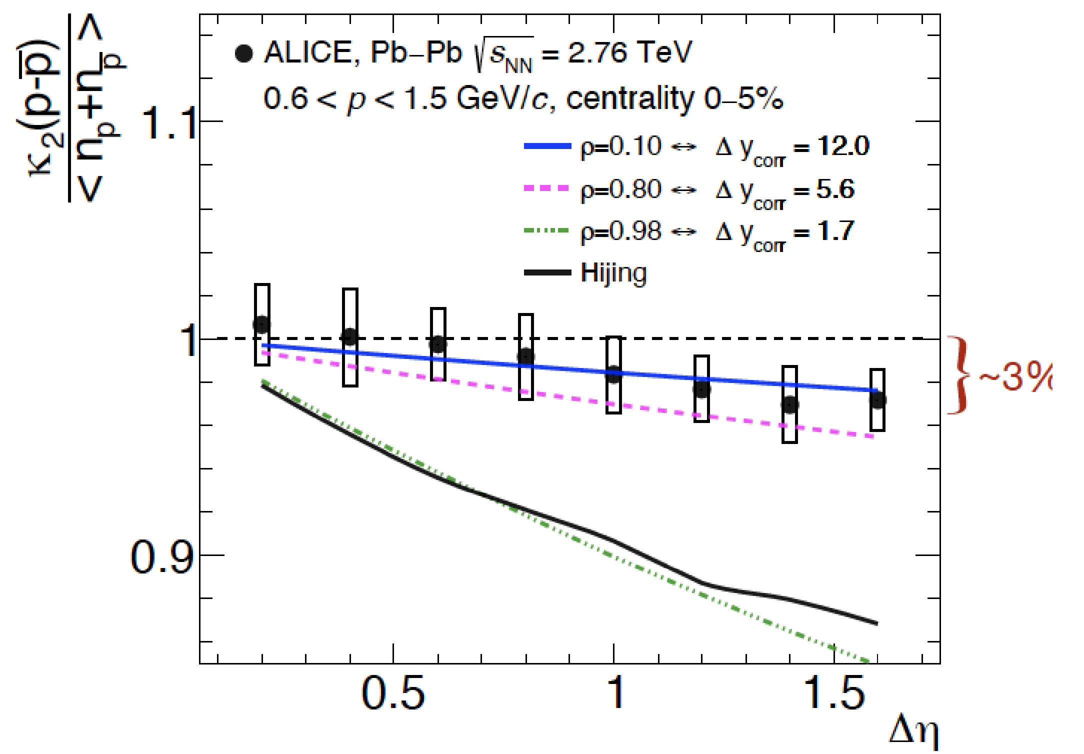
(i) a schematic model of local conservation

(ii) a model for arbitrary rapidity correlations
this is based on the Choleski decomposition and the Metropolis algorithm

* work performed in collaboration with Anar Rustamov and Johanna Stachel
Nucl.Phys.A 960 (2017) 114-130, 1612.00702 [nucl-th] vol. fluct. and bar. # cons.
Nucl.Phys.A 982 (2019) 307-310, 1807.08927 [nucl-th] can. thermo. and local cons.
1907.03032 [nucl-th]
QM2022 presentation, to be published,
https://indico.cern.ch/event/895086/timetable/#20220406.detailed

model predictions and comparison to data, see Anar Rustamov, overview talk, SQM22, Monday session





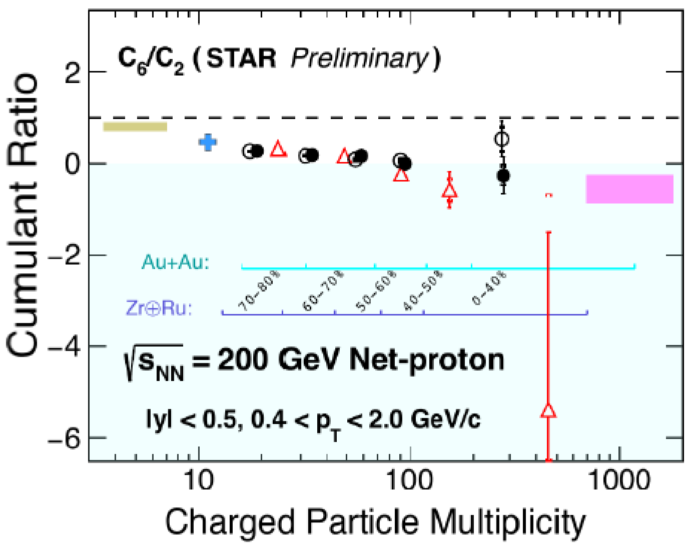
predictions are very sensitive to correlation coefficient ρ
ρ < 0.8 strongly preferred, in conflict with HIJING predictions and Lund string model

RHIC Beam Energy Scan and comments on STAR data

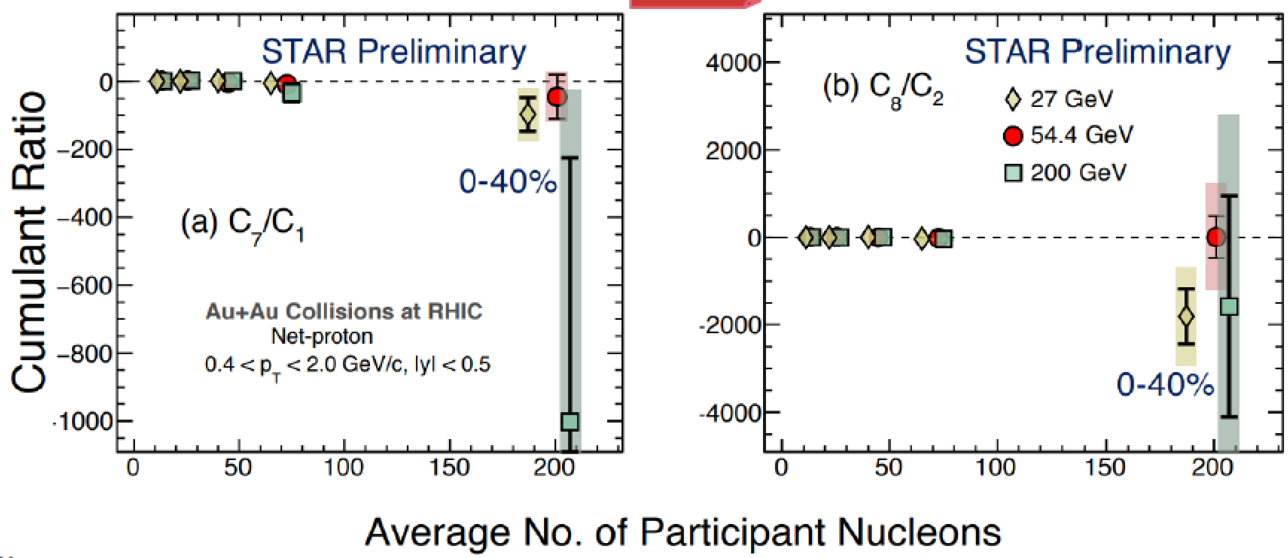
1st exploration of 6th, 7th and 8th moment distributions, an experimental tour de force

Higher-order net-proton cumulants

- Cumulants of conserved quantities (Q, B, S) sensitive to the correlation length



New



STAR: Phys. Rev. C 104 (2021) 024902; Phys. Rev. Lett 127 (2021) 262301

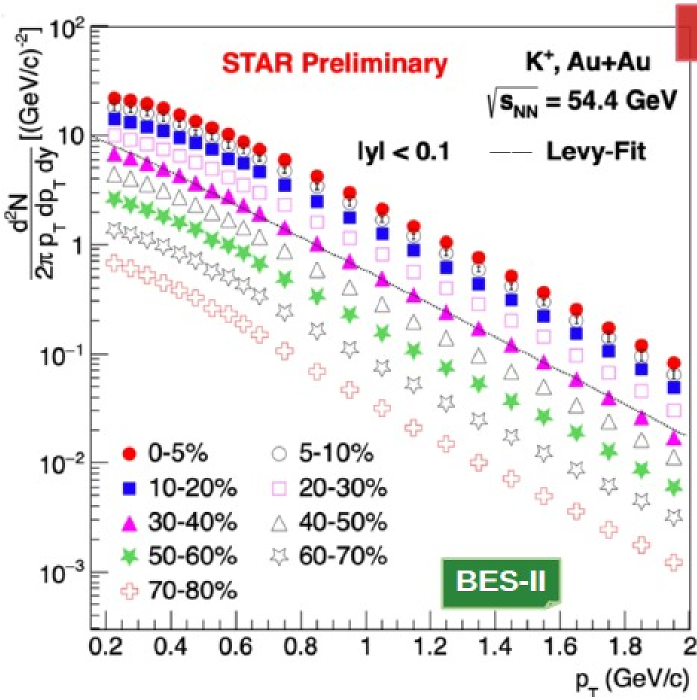
→ **200 GeV C_6/C_2 < 0**: systematic decreasing trend with multiplicity, consistent with lattice QCD results that predict **crossover** at μ_B =0

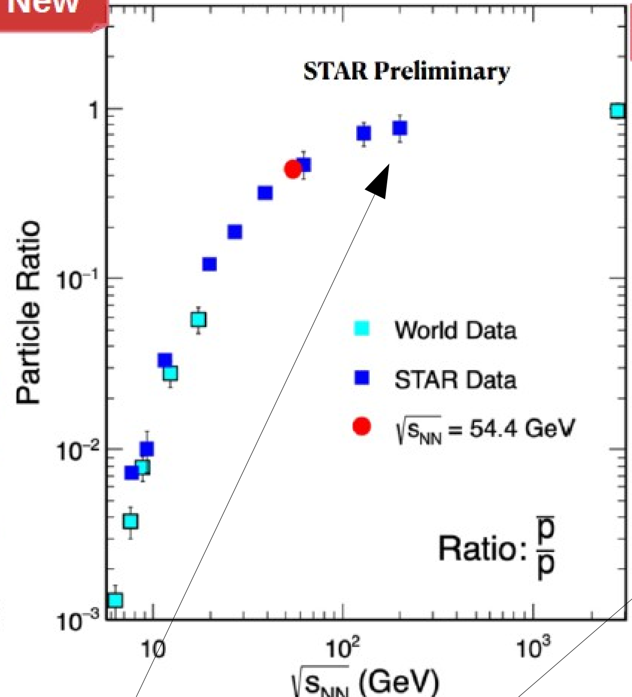
→ C_7/C_1 and C_8/C_2: hint of < 0 at high multiplicity, but with large uncertainties

Particle production at 54.4 GeV

- p_T spectra and ratios of $\pi^{+/-}$, $K^{+/-}$, p and anti-p

New





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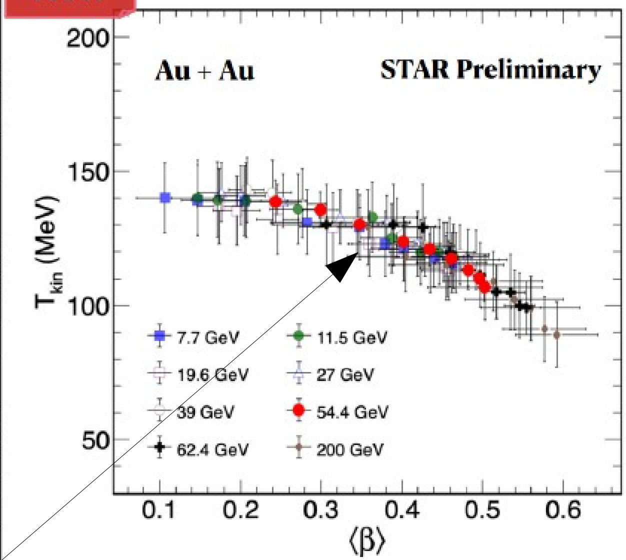
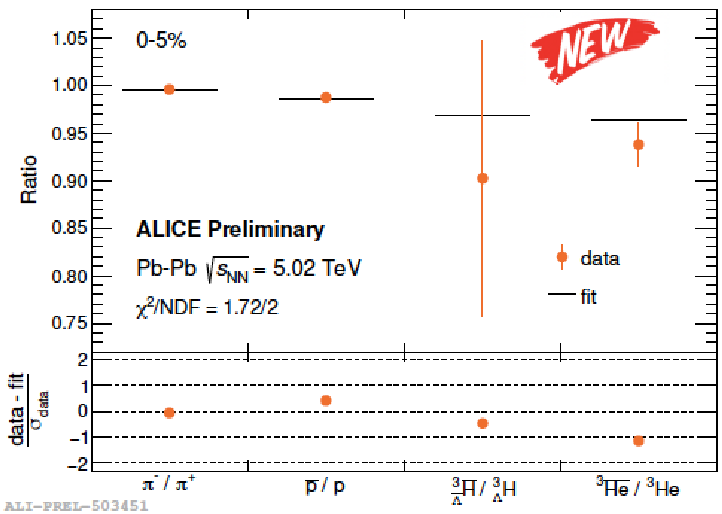


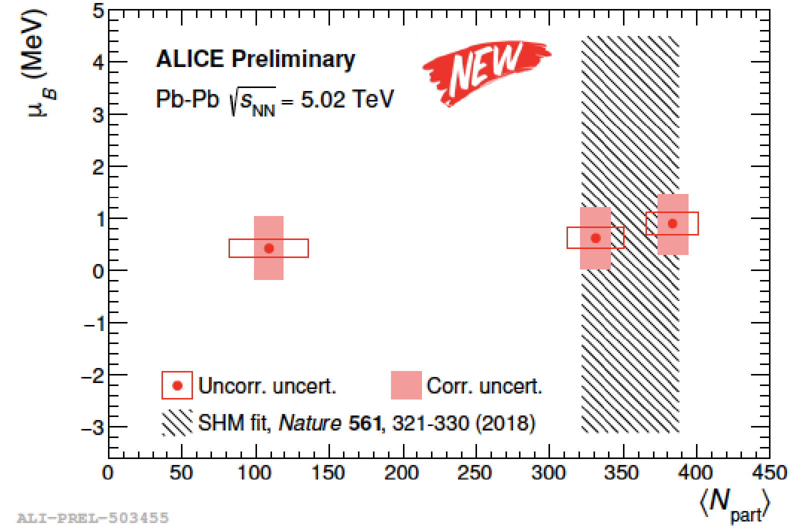
- Particle ratios follow global energy dependence trend
  - anti-p/p decreases with decreasing with $\sqrt{s_{NN}}$ → baryon stopping
- Kinetic freeze-out parameters extracted from fits to p_T spectra

Krishan Gopal
14.6 12:10pm

high precision data, μ_B decreases with increasing beam energy
analysis needs to be redone with resonance decays included
see Mazeliauskas et al., Nucl.Phys.A 1005 (2021) 121988

first precision measurement of μ_B at LHC energy





❖ Fitting the ratio with SHM equation

- $\overline{h}/h \propto \exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$
- Extract μ_B and μ_{I3} from the fits

	π^+	p	^{3}He	$^3_\Lambda$H
B+S/3	0	1	3	8/9
I_3	1	1/2	1/2	0

14 Jun 2022, 10:50, Mario Ciacco
@ Light-flavor and Strangeness

❖ Consistent with previous studies but with ***O(10) improvements*** in precision

- Most precise measurements of μ_B at the TeV scale!

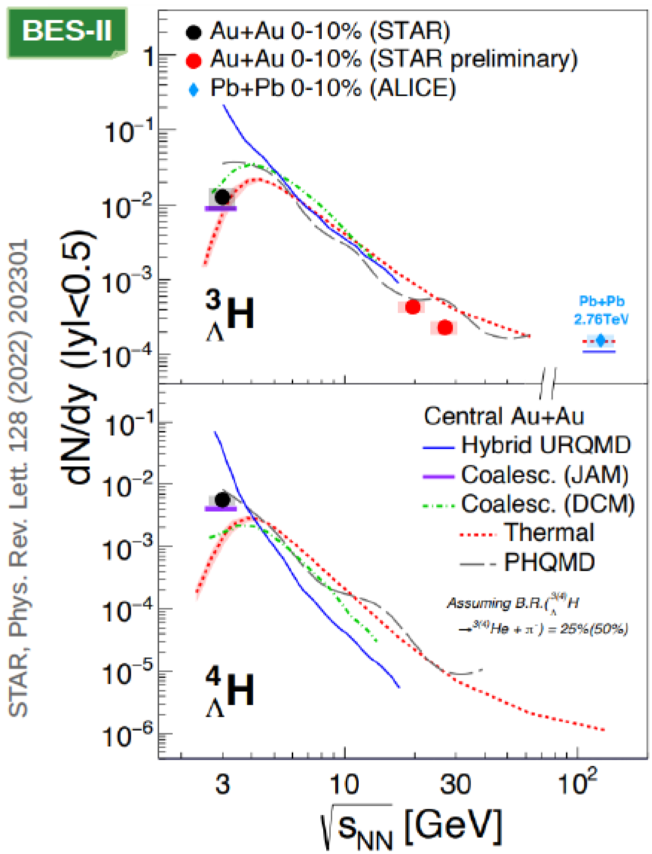
❖ A decreasing trend from central to peripheral collision, because of baryon stopping, is not observed.

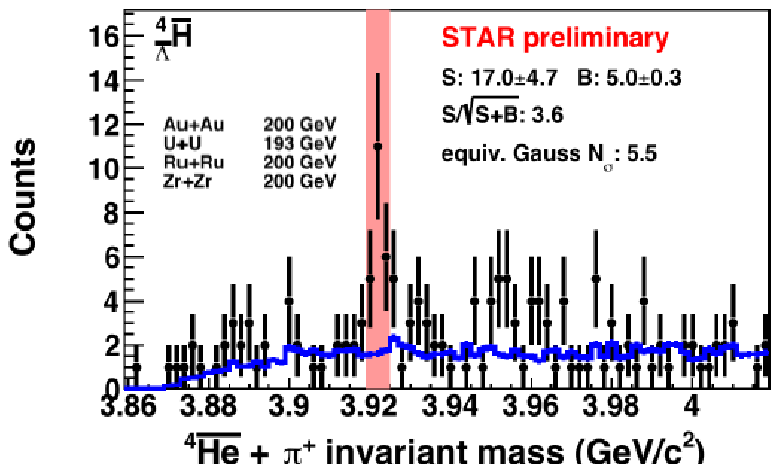
comment: great progress, no centrality dependence of μ_B, no baryon transport from the LHC beams to the central region, none of the current event generators describes this well!

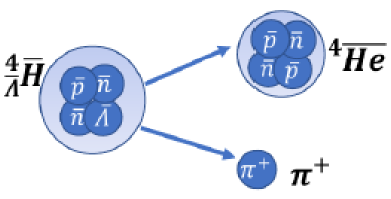
New Star results on anti-hypernuclei

Production of (anti-)light hypernuclei

- Hyperon-Nucleon (Y-N) interactions → EOS of neutron stars and the hadronic phase of heavy-ion collisions





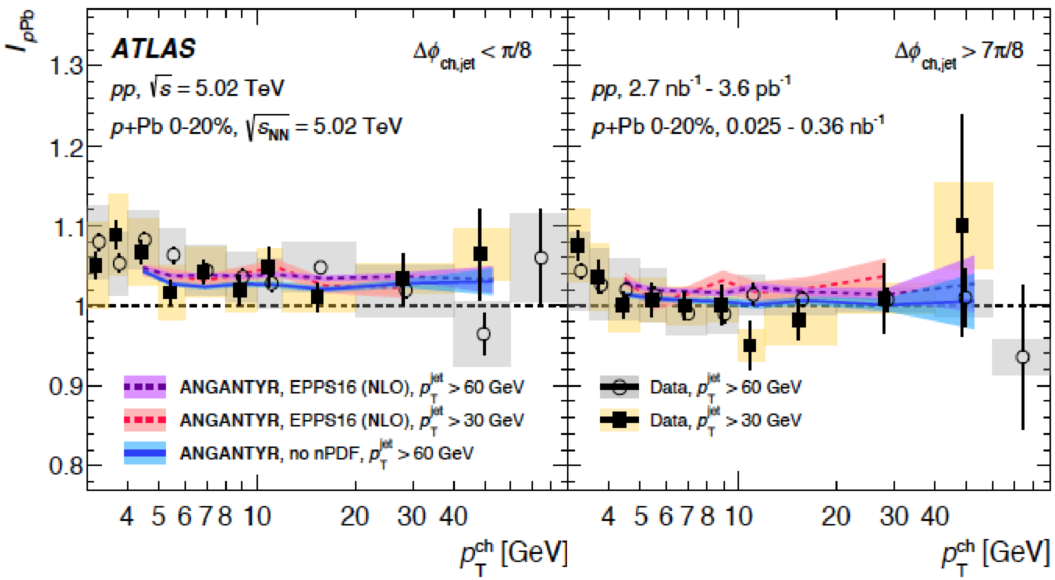


➔ Precision measurements of production yields of hypernuclei at 3, **19.6 and 27 GeV** → constraints on hypernuclei production models at high μ_B

➔ The first observation of **Anti-Hyper-Hydrogen-4**

high precision measument of jet quenching in pPb collisions by the ATLAS collaboration

arXiv:2206.01138 [nucl-ex]



the new ATLAS data essentially rule out the presence of parton energy loss in central pPb collisions, implying no QGP there

from the ATLAS paper

In conclusion, this Letter reports a measurement of charged-hadron yields in the azimuthal directions away from and near to jets in p+Pb collisions, compared with those in pp collisions, using data collected with the ATLAS detector at the LHC. Central p+Pb collisions, where the effects of a quark–gluon plasma are expected to be largest, are selected in an unbiased way by detecting forward spectator neutrons. The per-jet yields on the near-side indicate a modest, of order 5%, enhancement for $p_{\mathrm{T}}^{\mathrm{ch}} > 4$ GeV that is well described by the MC generator Angantyr. The per-jet yields on the away-side are consistent with unity for all $p_{\mathrm{T}}^{\mathrm{ch}} > 1$ GeV, with uncertainties that are particularly small for $p_{\mathrm{T}}^{\mathrm{ch}} > 4$ GeV. These data serve as a sensitive probe of jet quenching effects and place strong limits on the degree to which the propagation and fragmentation of hard-scattered partons is modified in small hadronic collisions. The results in this Letter heighten the challenge to the theoretical understanding of the quark–gluon system produced in p+Pb collisions.

now results on charmed hadrons

the mechanism for SHM with charm in more detail

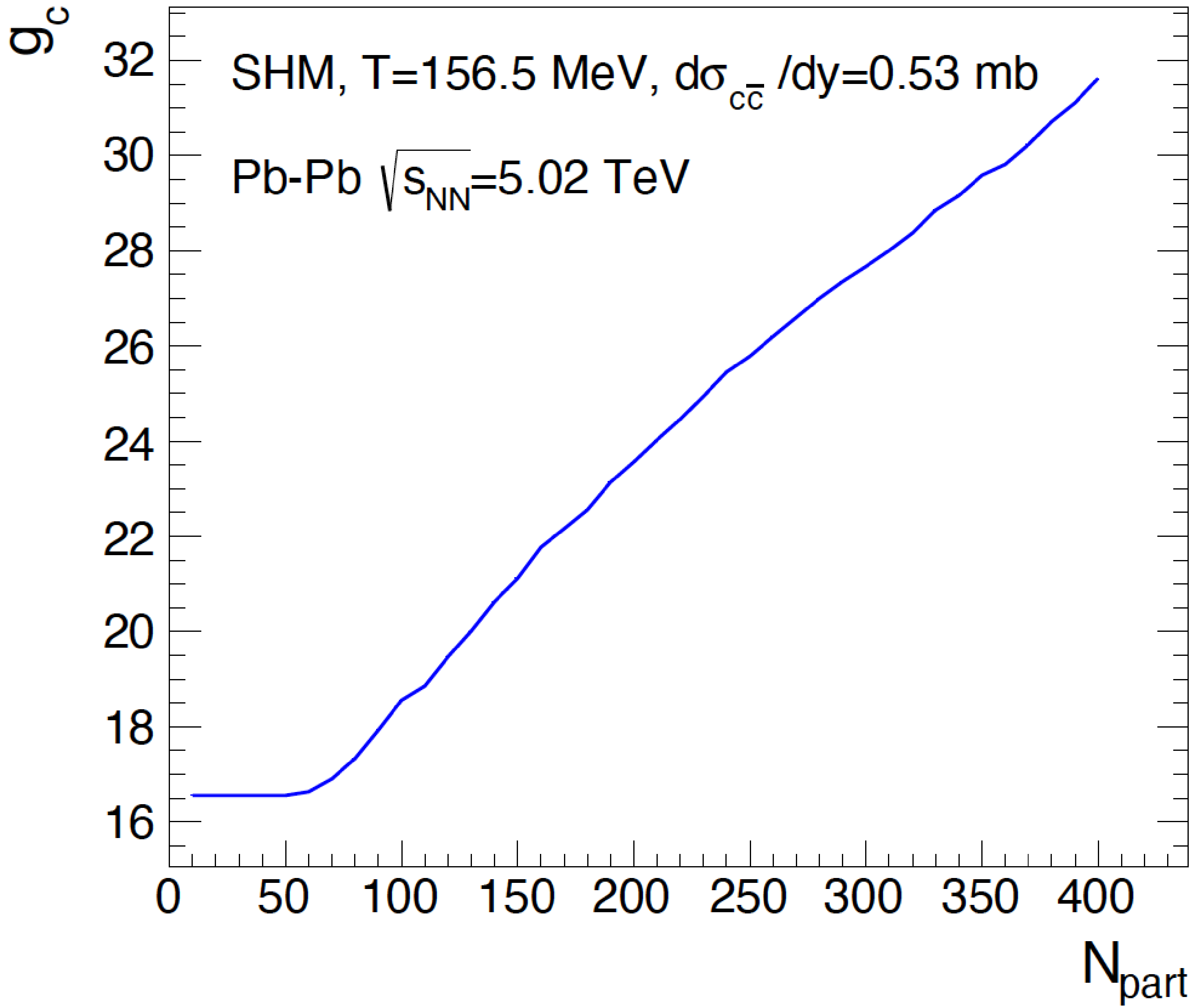
[Braun-Munzinger and Stachel, PLB 490 (2000) 196]
[Andronic, Braun-Munzinger and Stachel, NPA 789 (2007) 334]

- Charm quarks are produced in initial hard scatterings ($m_{c\bar{c}} \gg T_c$) and production can be described by pQCD ($m_{c\bar{c}} \gg \Lambda_{QCD}$)
- Charm quarks survive and *thermalise* in the QGP
- Full screening before T_{CF}
- Charmonium is formed at phase boundary (together with other hadrons)
- Thermal model input ($T_{CF}, \mu_b \to n_X^{th}$)

$$N_{c\bar{c}}^{dir} = \underbrace{\frac{1}{2} g_c V \left(\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th} + \cdots \right)}_{\text{Open charm}} + \underbrace{g_c^2 V \left(\sum_i n_{\psi_i}^{th} + n_{\chi_i}^{th} + \cdots \right)}_{\text{Charmonia}}$$

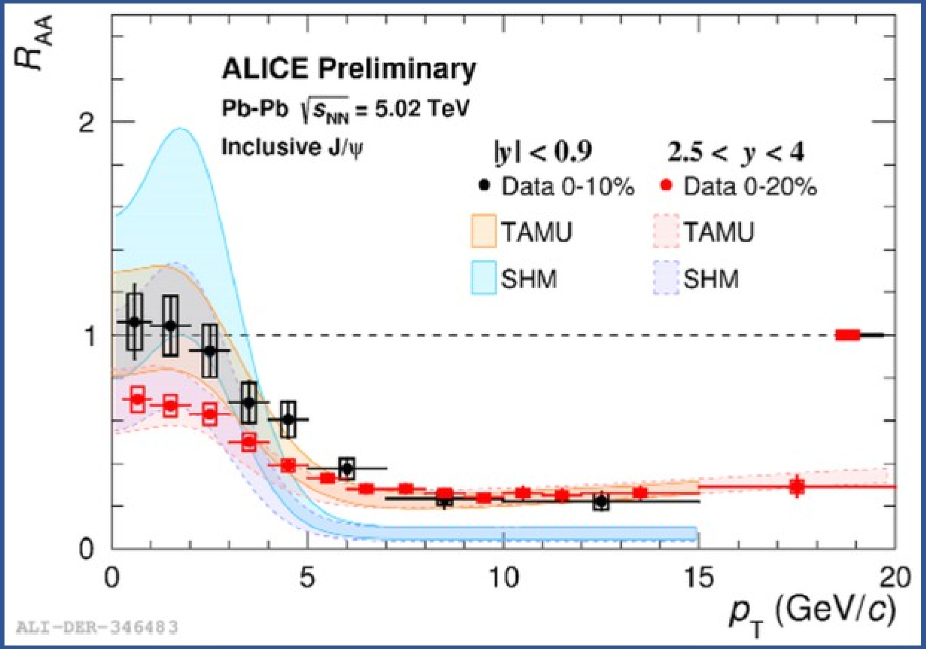
- Canonical correction is applied to n_{oc}^{th}
- Outcome $N_{J/\psi}, N_D, \ldots$

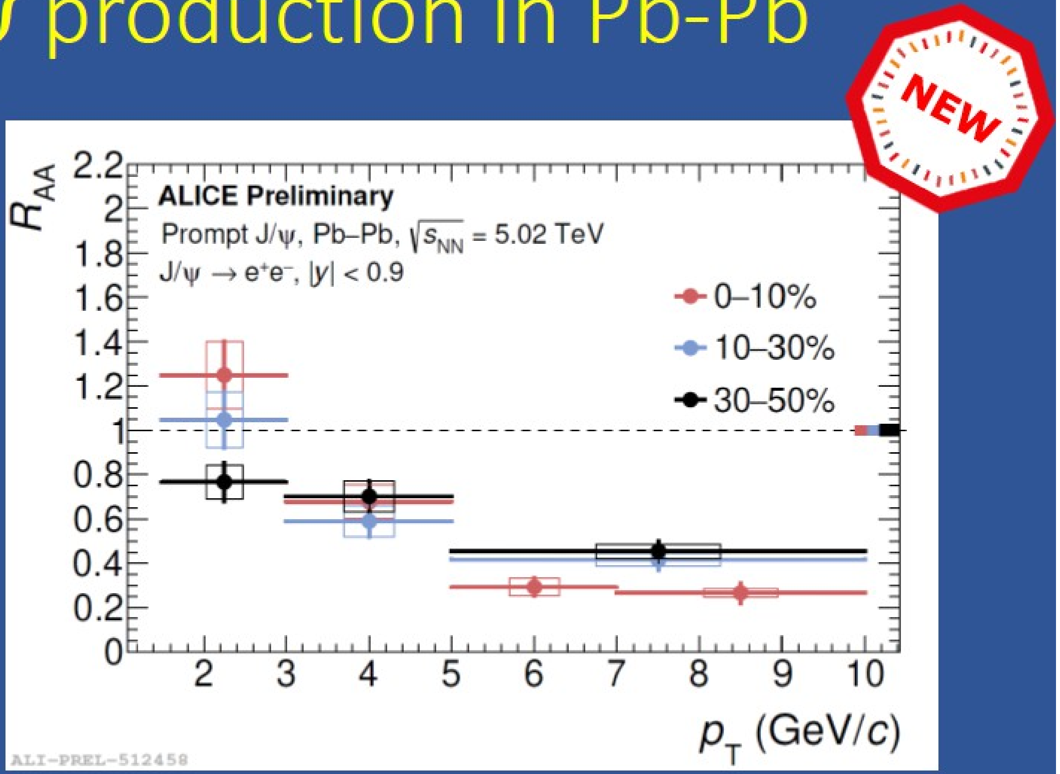
centrality dependence of charm fugacity g_c at LHC energy



Enrico Scomparin, SQM2022, June 13, 2022

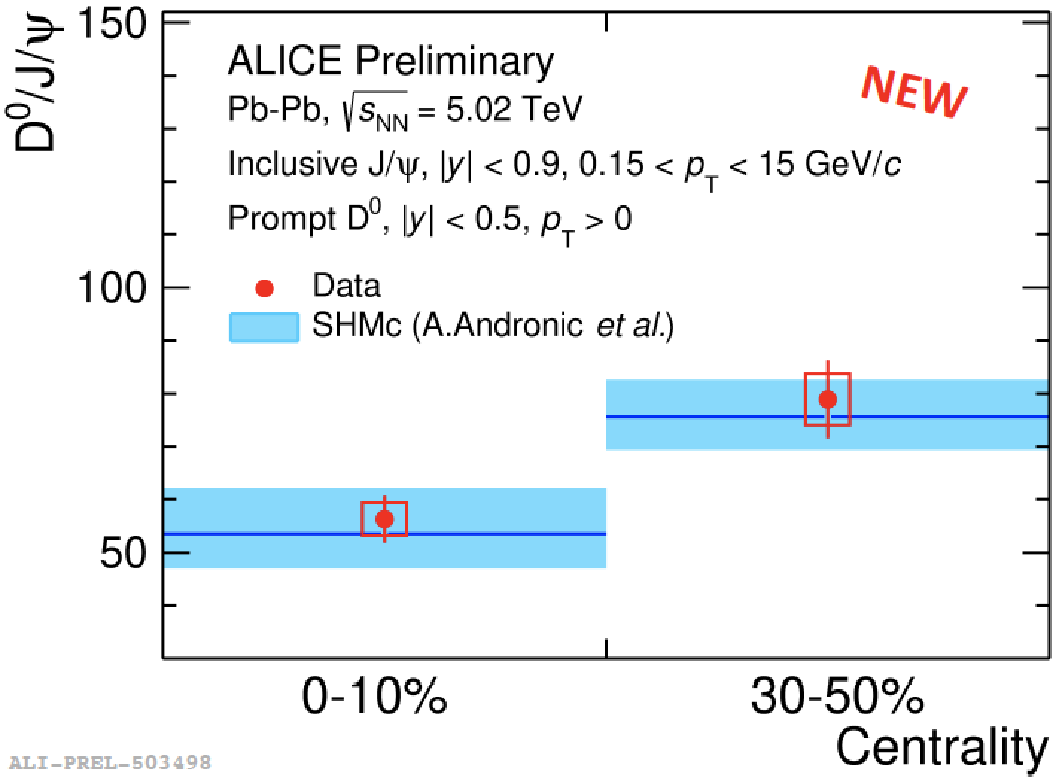
Inclusive and prompt J/ψ production in Pb-Pb





- Rise of inclusive J/ψ R_{AA} at low p_T, stronger effect at y=0 → decisive signature of recombination
- Models include regeneration either at the freeze-out (SHMc) or during the medium evolution (TAMU)
  → Both in agreement with data at low p_T
- Effect confirmed when looking at prompt J/ψ production at midrapidity, clear centrality dependence

Xiaozhi Bai, ALICE coll., June14, 2022, SQM2022



A. Andronic et al., JHEP07 (2021) 035

D^0 and J/ψ simultaneously reproduced, no free parameter

at the phase boundary, all processes producing J/ψ included,
even including D Dbar* --> J/ψ π with resonance feeding
no additional contribution to J/ψ production from confined hadronic phase

why are multi-charm hadrons important to measure?

these complex baryons or mesons (charmonia) are assembled at the QCD phase transition from the quarks in the fireball

in the SHMc the production probability scales as g_c^{nc} if charm quarks are deconfined over the volume of the fireball formed in the Pb-Pb collision, see below

it follows that the yield of the doubly charmed Ξ_{cc}^{++} or J/ψ should be strongly (by a factor 900, see below) enhanced

measurement of this enhancement is hence a clear proof of deconfinement of charm quarks over distances determined by the volume of the fireball

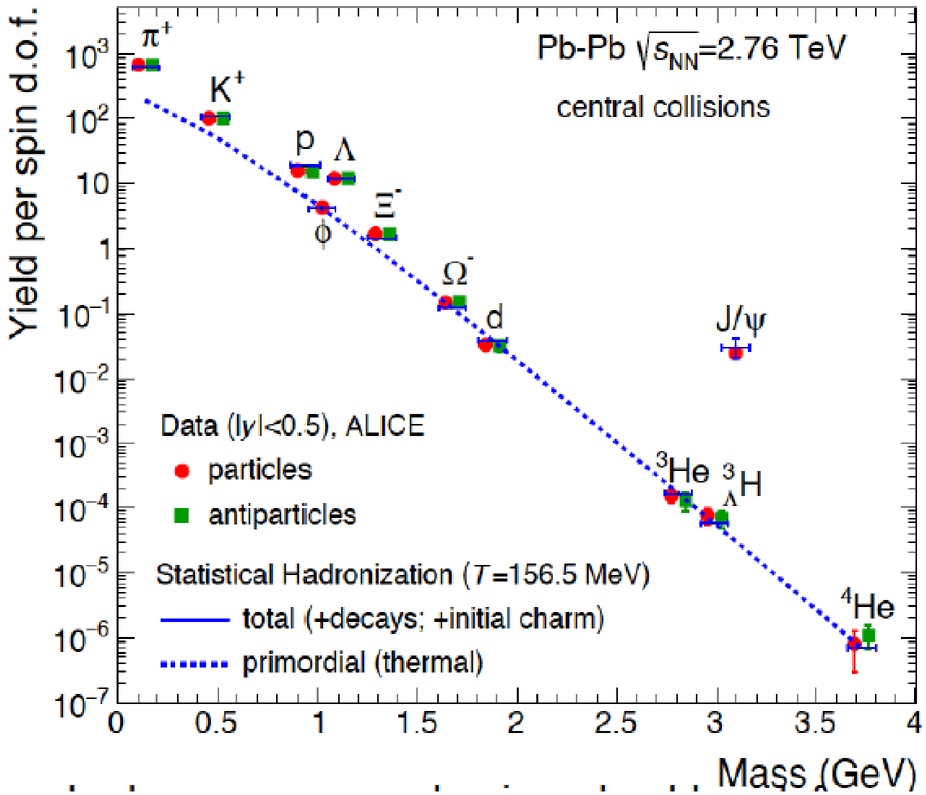
in central Pb-Pb collisions this volume is of order 5000 fm^3

this implies deconfinement of charm quarks over linear dimensions of order 10 fm much larger than the size of a (confined) nucleon (size of order 0.8 fm)
1st time direct experimental proof of deconfinement

future measurements inLHC Run3 and Run4 and especially ALICE 3 will test picture of universal hadronization at the phase boundary for all hadrons

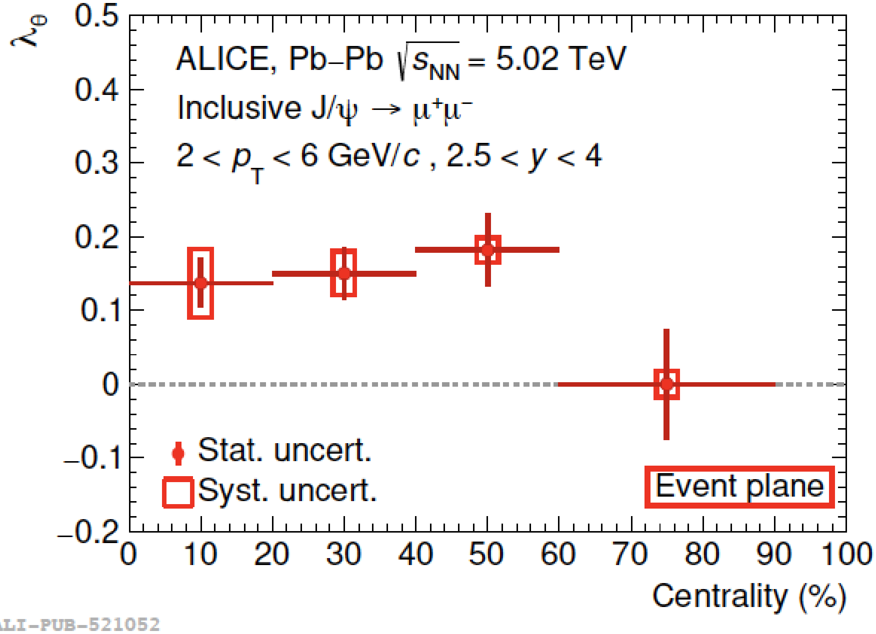
predicted g_c^2 enhancement from the SHMc is experimentally confirmed

enhancement factor is 900 for J/ψ



J/ψ polarization in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

arXiv:2204.10171



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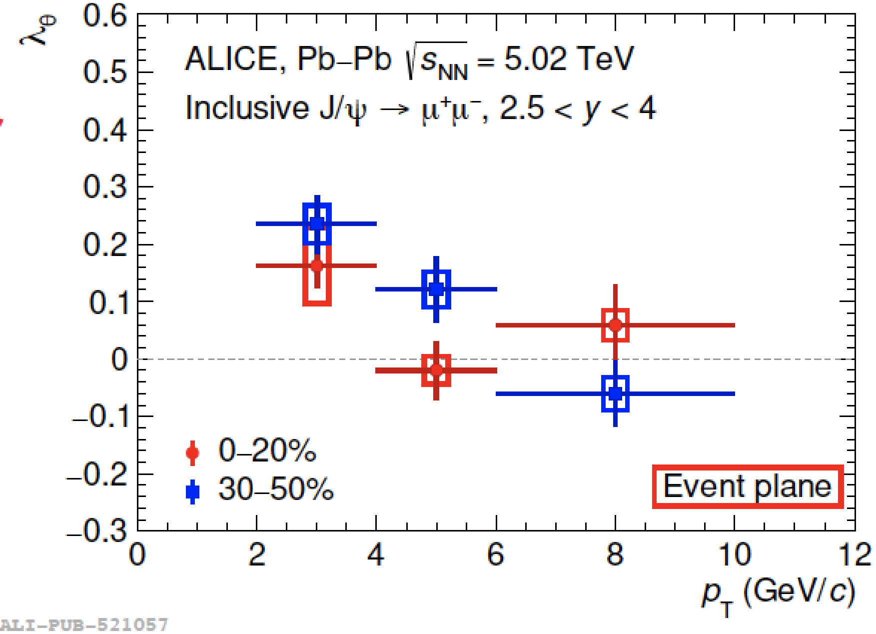
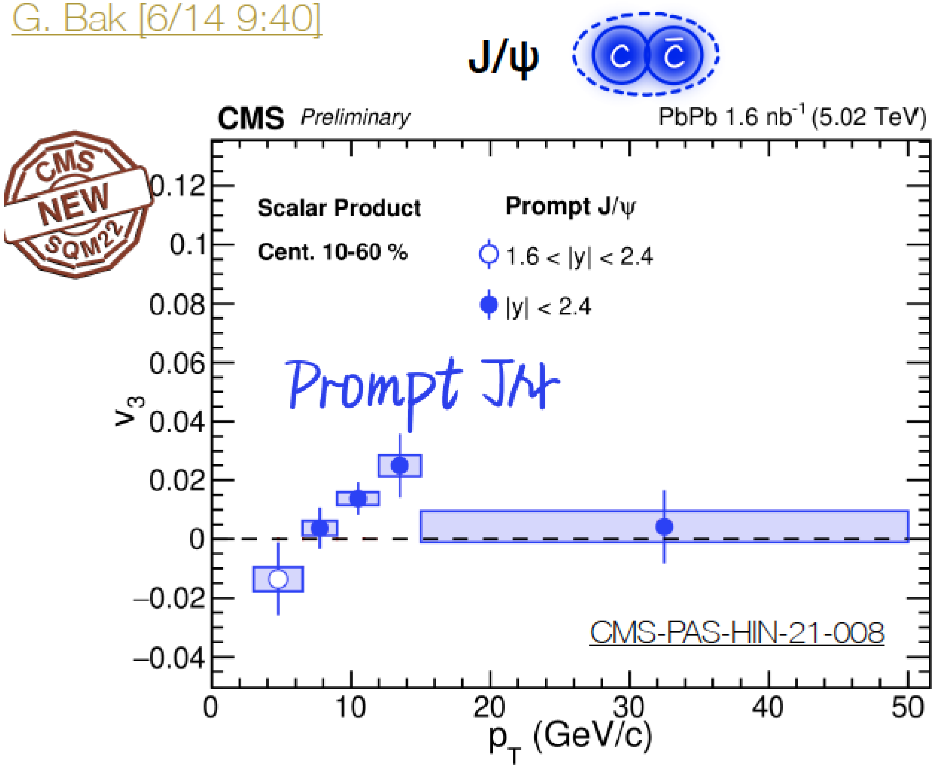


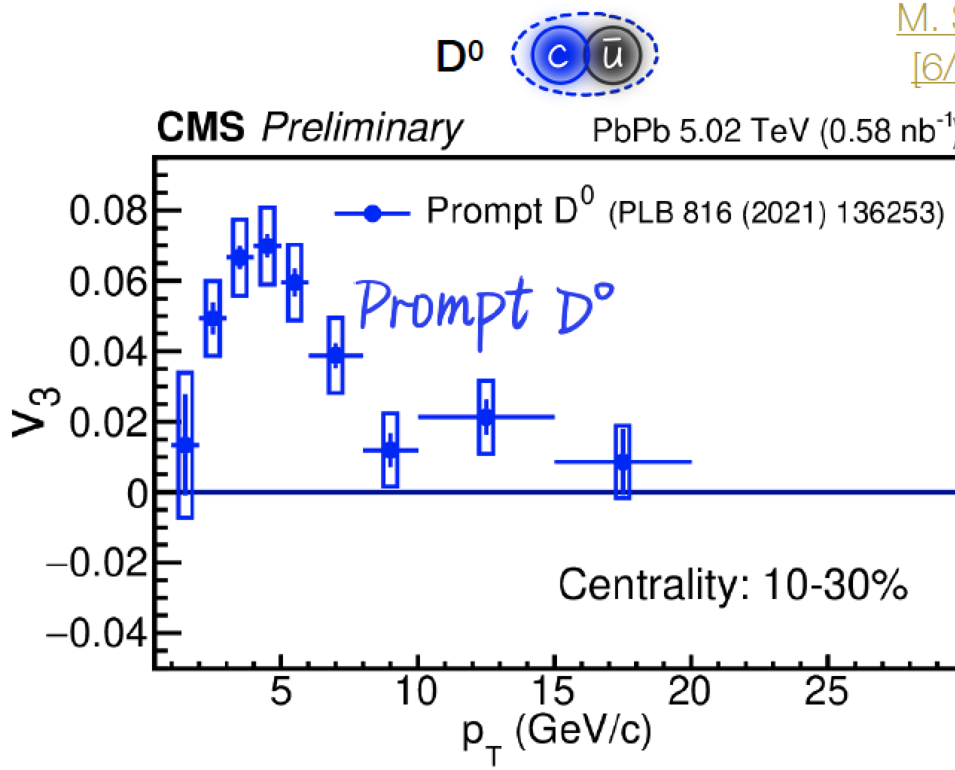
- First measurement of quarkonium polarization w.r.t the event plane
- Significant polarization (~$\mathbf{3.5\sigma}$) observed in semicentral collisions (40-60%) in $2 < p_T < 6$ GeV/c
- The deviation reaches ~$\mathbf{3.9\sigma}$ at low p_T ($2 < p_T < 4$ GeV/c) in 30-50%
- Interpretation of results requires inputs from theoretical models

new results on charmed hadrons with CMS

G. Bak [6/14 9:40]

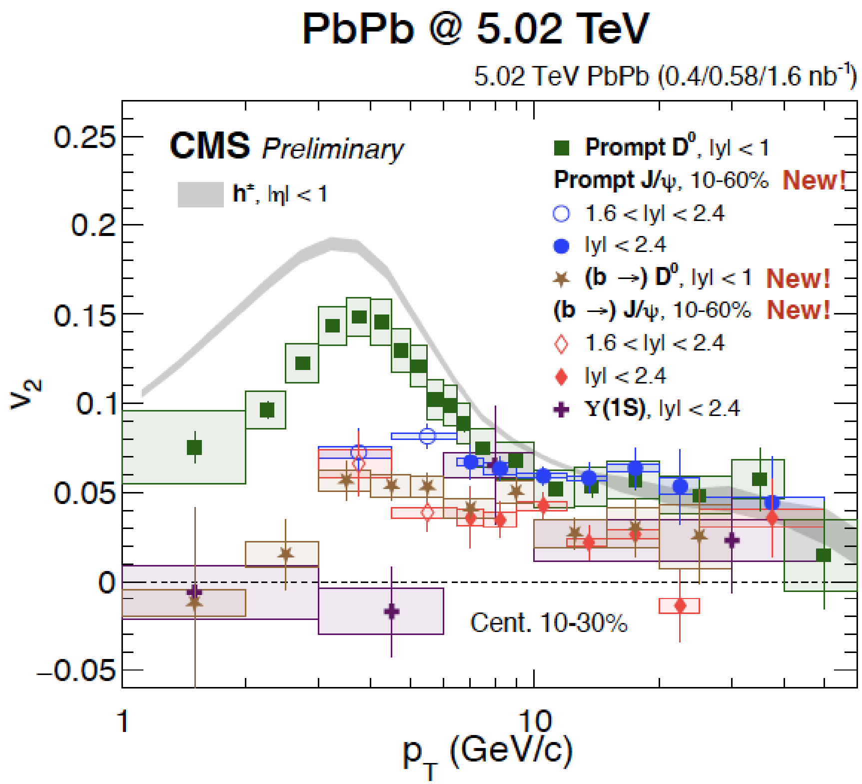


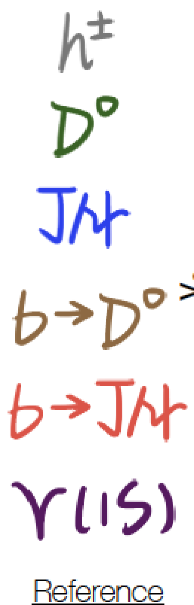
M. Stojanovic [6/14 10:50]

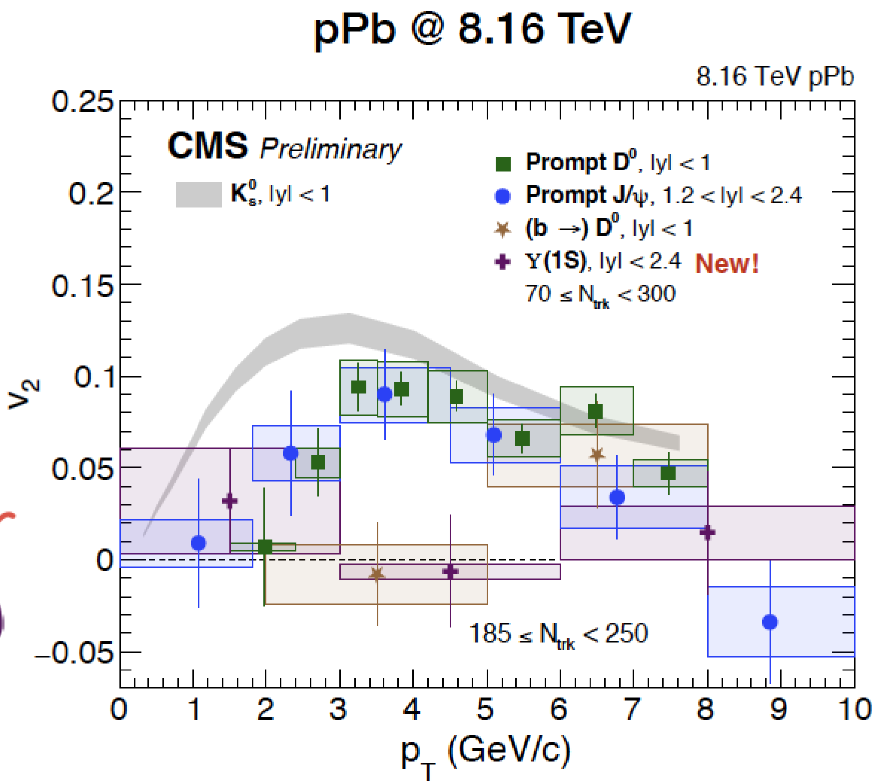


- First J/ψ v_3 measurement of prompt component
- Prompt D^0 v_3 > Prompt J/ψ v_3 ➜ charm is less sensitive to initial fluctuations than light quarks?

charm and beauty results from CMS (Jing Wang)



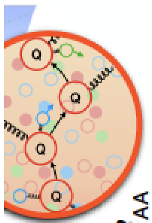




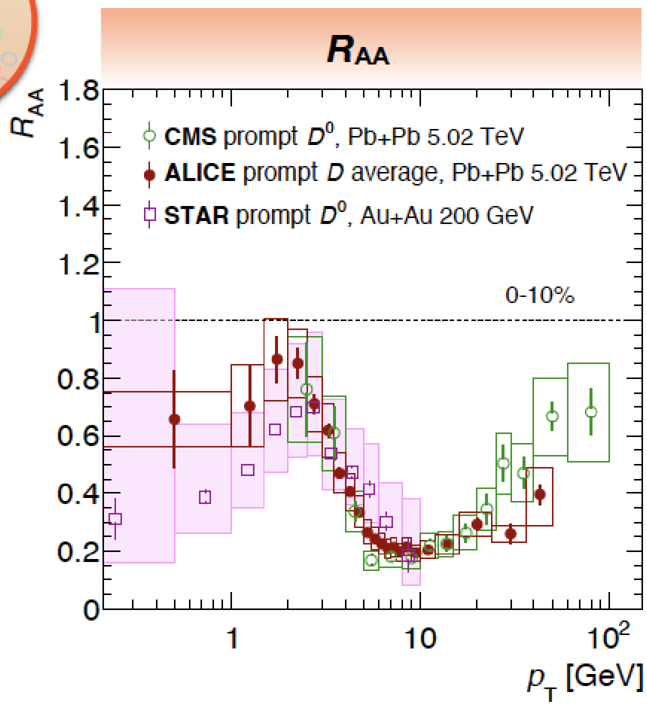
- Abundant physics behind these high precision and unique measurements from CMS!
- Strong constraint on theoretical calculations in different collision systems

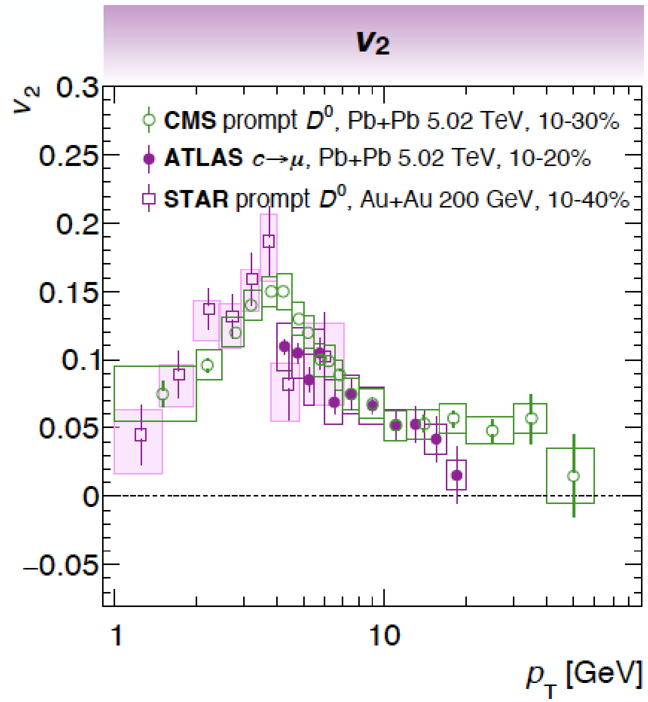
Hu Qipeng heavy flavor summary

ALICE talk: M. Völkl
CMS talk: M. Stojanovic
ATLAS talk: W. Zhou



Charm-hadron in medium

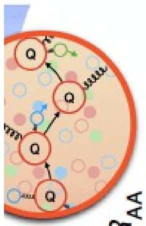


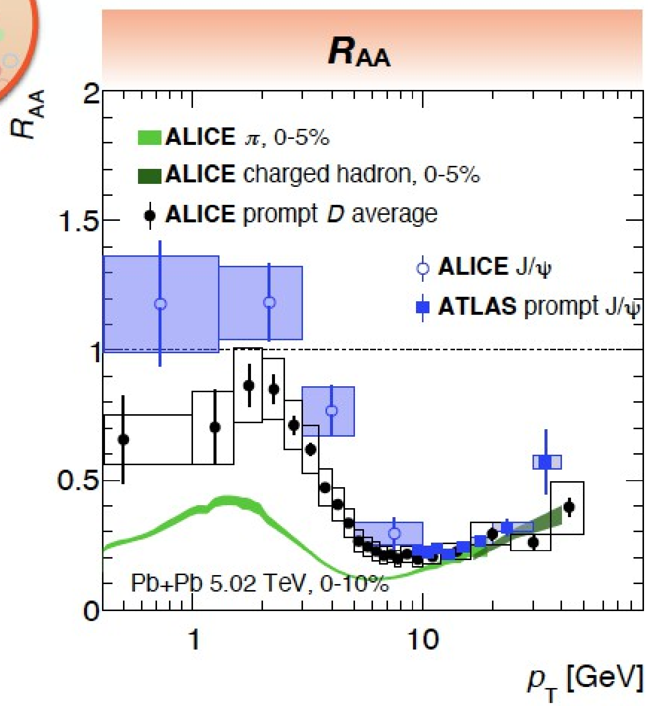


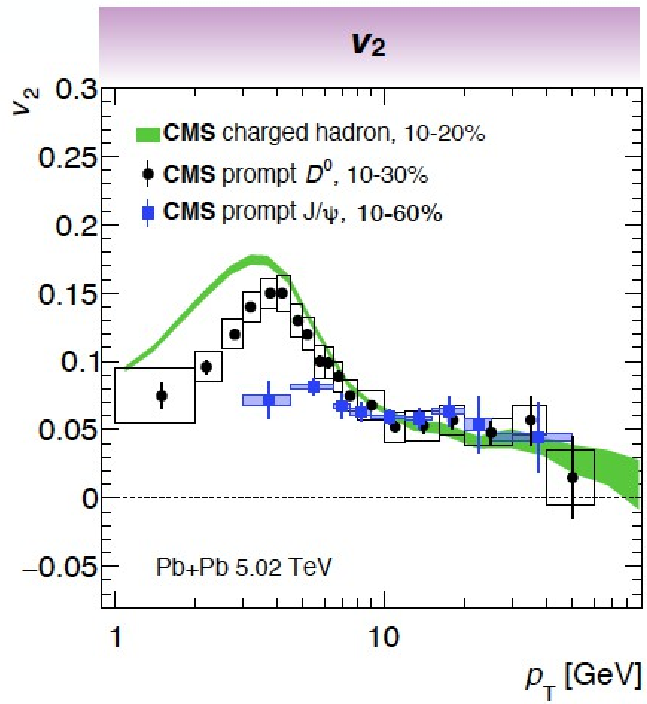
ALICE R_{AA}, JHEP 01 (2022) 174
CMS R_{AA}, PLB 782 (2018) 474
STAR R_{AA} PRC 99 (2019) 034908

- Precise R_{AA} and v_2 measured down to p_T ~ 0 GeV. Open charm is stronlgy modified in a p_T dpenent way
- Perfect consistency between LHC experiments: ALICE, CMS, ATLAS
- Similarity between LHC and RHIC

Charm vs. light / quarkonium







ALICE D R_{AA}: JHEP 01 (2022) 174
ALICE charged hadron R_{AA}: JHEP 11 (2018) 013
ALICE pion R_{AA}: PRC 101 (2020) 044907
ALICE J/ψ R_{AA}: PLB 805 (2020) 135434
ATLAS J/ψ R_{AA}: EPJC 78 (2018) 762

CMS D v_2: PLB 816 (2021) 136253
CMS charged hadron v_2: PLB 776 (2017) 195
CMS J/ψ v_2: CMS-PAS-HIN-21-008

Low p_T (p_T < 10 GeV):

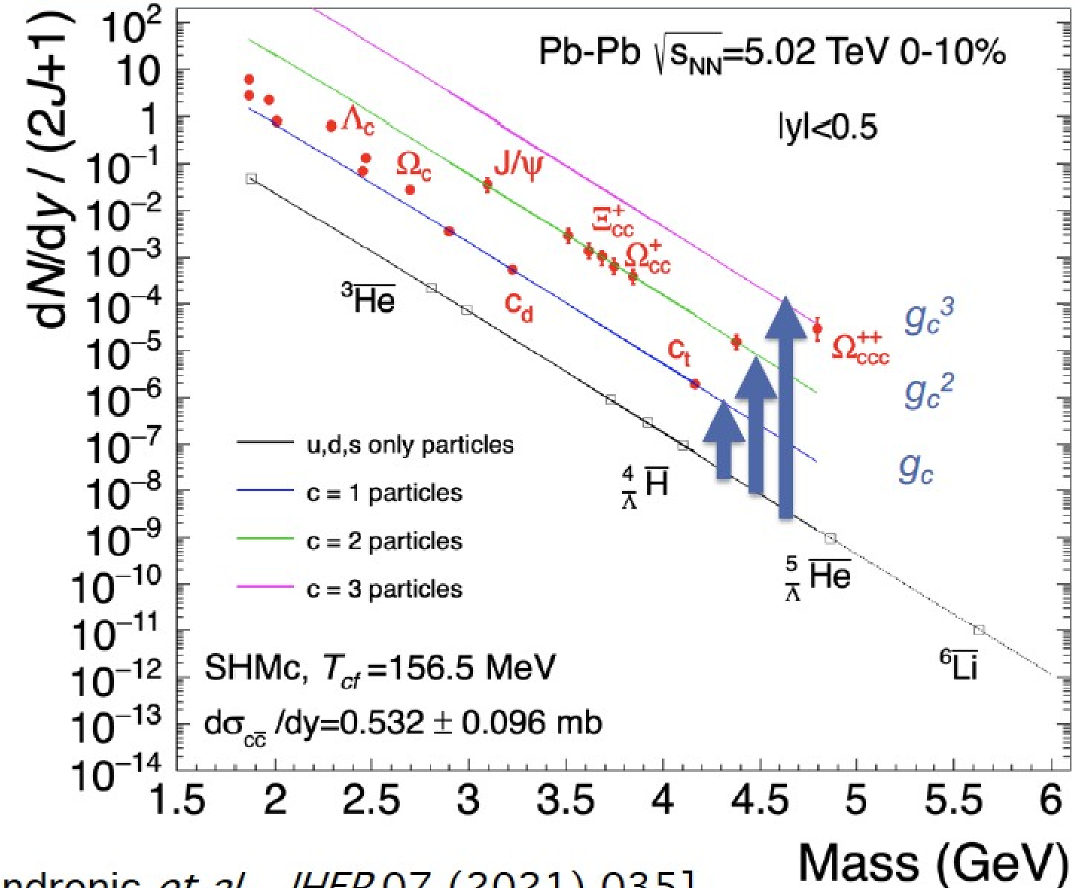
- R_{AA} : charged particle < prompt D < prompt J/ψ
- v_2: charged particle > prompt D > prompt J/ψ

High p_T (p_T > 10 GeV):

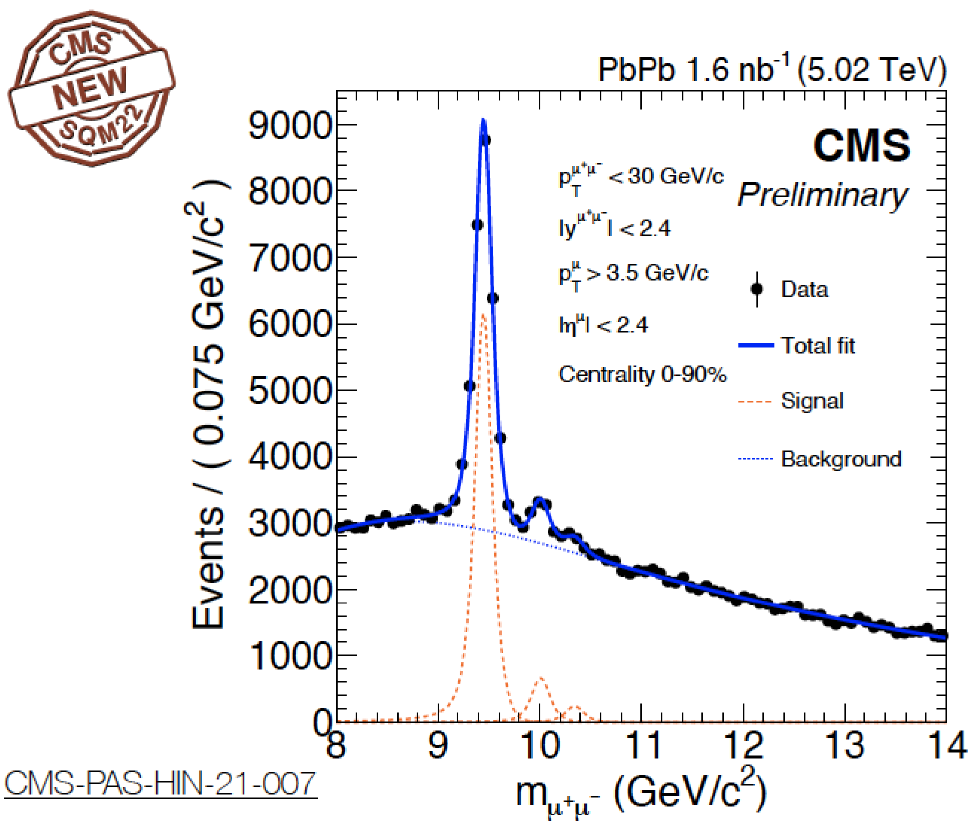
- R_{AA} : charged particle ~ prompt D ~ prompt J/ψ
- v_2: charged particle ~ prompt D ~ prompt J/ψ

Run3/Run4 and ALICE 3: a playground to test hadronization scenarios

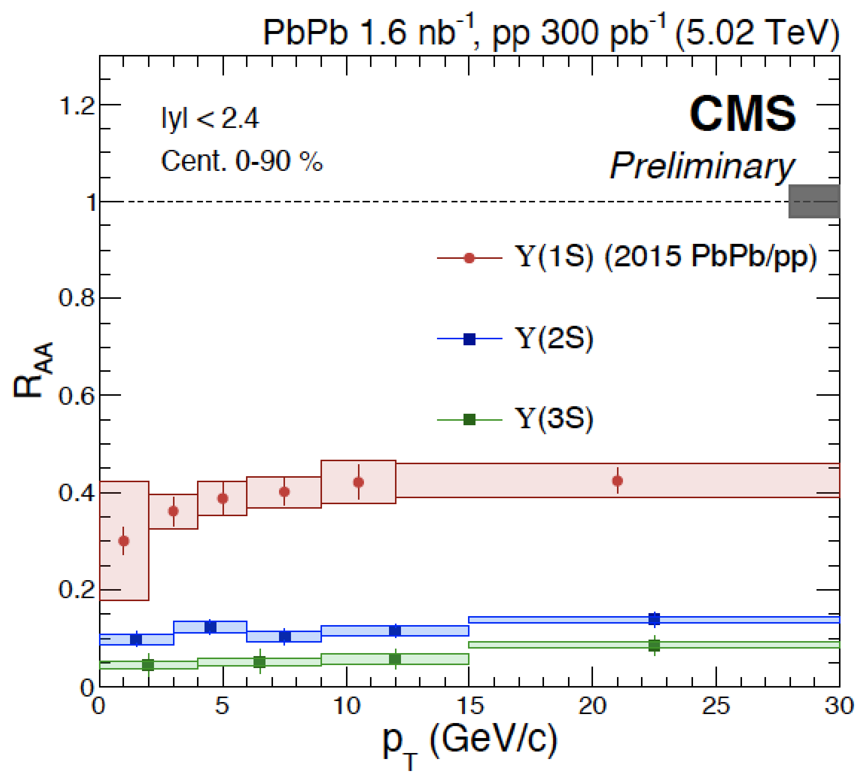
Predictions of statistical-thermal hadronization model



[A. Andronic *et al.*, *JHEP* 07 (2021) 035]



CMS-PAS-HIN-21-007



- First observation of Υ(3S) in PbPb!
- Signal significance > 5σ

- Smaller R_{AA} of Υ(3S) than Υ(2S)
- Strong constraint to theoretical models

the near future at the high lumi LHC -- Sarah Porteboeuf

LHC program

RUN 1 2009-2013	LS1	RUN 2 2015-2018	LS2	RUN 3 2022-2025	LS3	RUN 4 2029-2032
pp, pPb, Pb-Pb		pp, pPb, Xe-Xe Pb-Pb		pp, pO, O-O, pPb,Pb-Pb		pp, pPb, Pb-Pb

- **Pb-Pb luminosity limited** by LHC ~1-2·10^{27} cm^{-2} s^{-1} (beam losses)
- Several fills lost on beam dumps due to 10 Hz beam oscillation events; collimation efficiency

RUN 3

- **High Luminosity for ions** (~7·10^{27} cm^{-2} s^{-1})
- **Oxygen** (small to large system bridge, cosmic ray)
- Improved collimation systems
  ➞ lifted limitation in the LHC from bound-free pair production
  ➞ ion luminosities now limited by bunch intensities from injectors

LHC program

RUN 1	LS1	RUN 2	LS2	RUN 3	LS3	RUN 4
2009-2013		2015-2018		2022-2025		2029-2032
pp, pPb, Pb-Pb		pp, pPb, Xe-Xe Pb-Pb		pp, pO, O-O, pPb,Pb-Pb		pp, pPb, Pb-Pb

Total integrated Luminosity RUN 1+2
Pb-Pb: 1.5 nb^{-1} in ALICE, 2.54 nb^{-1} in ATLAS/CMS, 0.26 nb^{-1} in LHCb
p-Pb: 75 nb^{-1} in ALICE, ~220 nb^{-1} in ATLAS/CMS, 36 nb^{-1} in LHCb

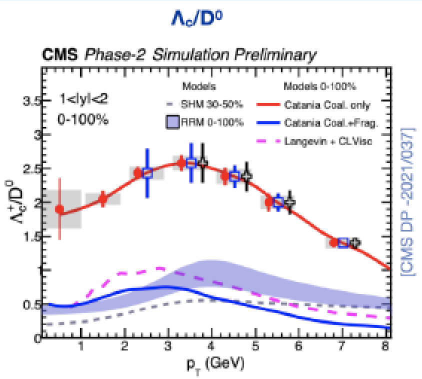
Target Luminosity RUN 3+4
Pb-Pb: 13 nb^{-1} in ALICE/ATLAS/CMS, 2 nb^{-1} in LHCb
p-Pb: 0,5 pb^{-1} in ALICE, 1pb^{-1} in ATLAS/CMS, 0.2 pb^{-1} in LHCb
To be continued in RUN 5, see talk by R. Bailhache

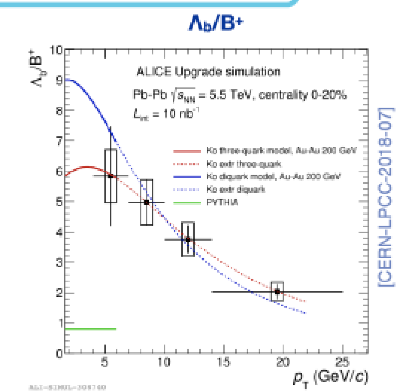
PHYSICS Outlook* – RUN 3+4

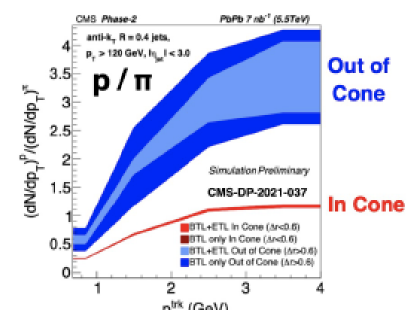
* Not an exhaustive overview

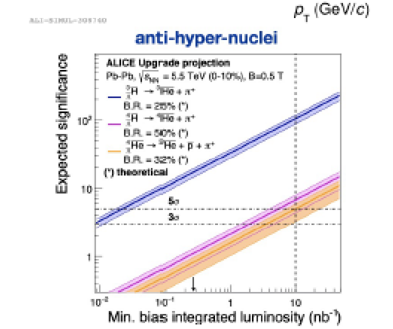
- **Upgraded machine:**
  - increase in energy and luminosity
  - Intermediate systems with Oxygen
- **Upgraded experiments**
  - To cope with the machine upgrade and collect more statistics
  - All experiments developed upgrade for HI physics

- **Initial State:**
  - Nuclear PDF and Nucleon structure, low-*x*
  - Reference systems (UPC, pA, pp), event characterization
  - Total c cross section
- **In-medium dynamics: thermalization and transport propertie**
  - Thermal radiation with photon and dielectron
  - Susceptibilities and net baryon fluctuations
  - Quenching mass and time dependance
  - Heavy flavor transport, precision measurement for R_{AA} and v_2, bottomonia
- **Onset of collective behavior from small to large systems**
  - Systematic measurements of QGP legacy probes vs. mult, vs. systems, vs. energy
  - Onset of energy loss and thermal radiation
  - High mult pp sample and new collision systems
- **Hadronisation**
  - Baryon/meson ratios, flow
  - Multi-charm baryons
  - Jets



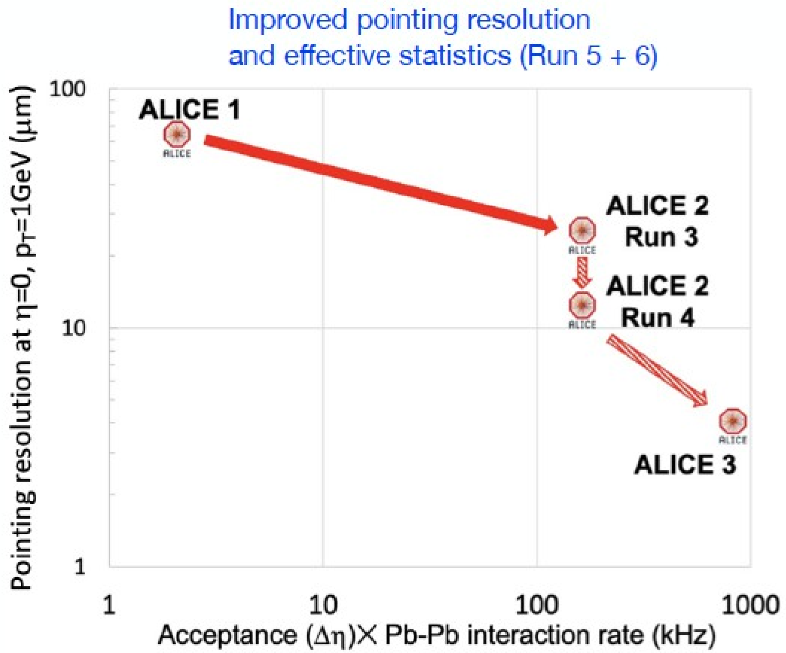


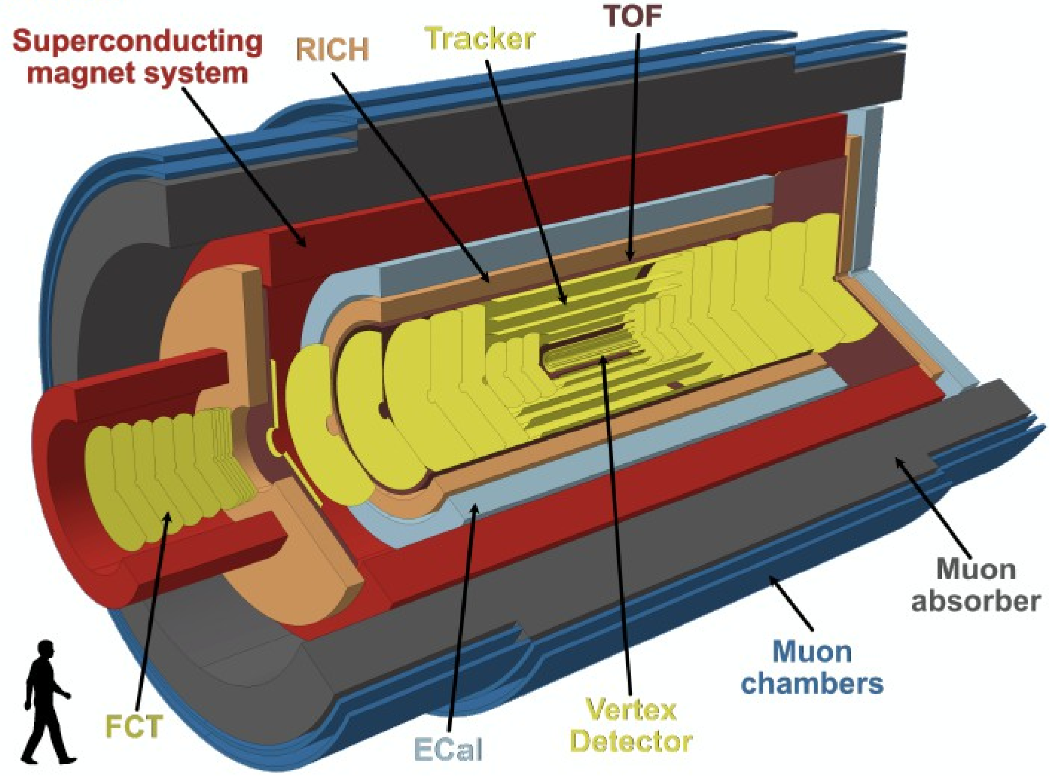




ALICE 3 detector concept

- Compact all-silicon tracker with high-resolution vertex detector
- Particle identification $\gamma, e^{\pm}, \mu^{\pm}, K^{\pm}, \pi^{\pm}$
  - Over large acceptance ($-4 < \eta < 4$)
  - Down to very low p_T



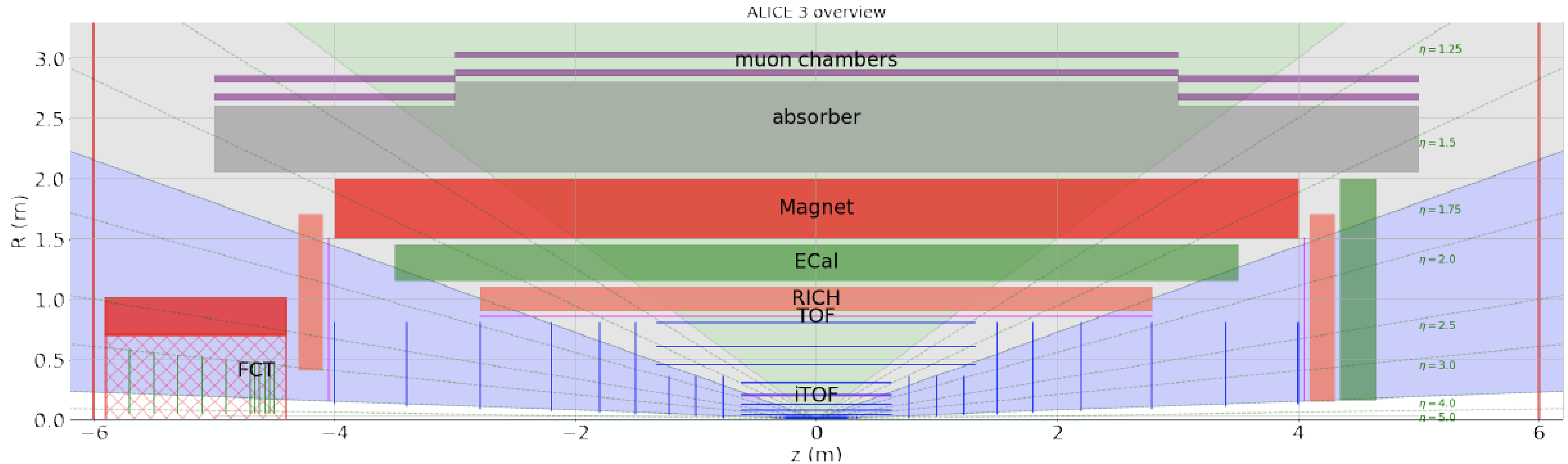


D.Adamova et al. ArXiv:1902.01211
ALICE CERN-LHCC-2022-009

Observables and detector requirements

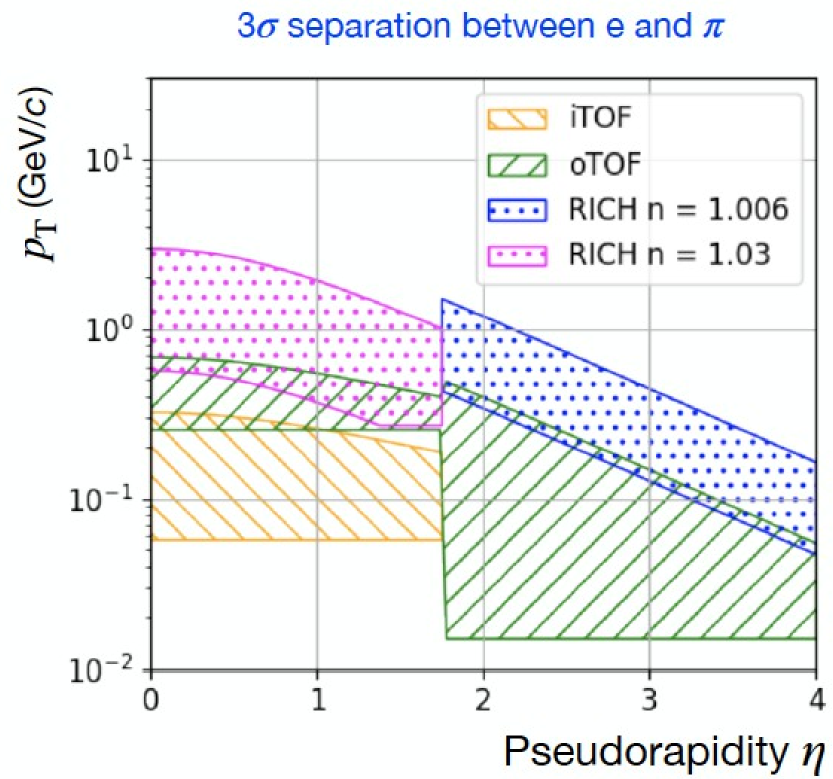
- **Heavy-flavour hadrons** ($p_T \rightarrow 0$, wide η range)
  → Vertexing, tracking, hadron identification
- **Quarkonia and Exotica** ($p_T \rightarrow 0$)
  → Muon and γ identification
- **Nuclei**
  → Identification of $z > 1$ particles
- **Dielectrons** ($p_T \sim 0.05 - 3$ GeV/c, $m_{ee} \sim$ 0.1 - 4 GeV/c^2)
  → Vertexing, tracking, electron identification
- **Photons** ($E_\gamma \sim$ 0.1 - 50 GeV/c, wide η range)
  → Photon conversion, electromagnetic calorimeter
- **Ultra-soft photons** ($1 \leq p_T \leq 10$ MeV/c)
  →Dedicated Forward Conversion Tracker detector (FCT)

Use Time-of-flight detectors, Ring-imaging Cherenkov detectors, Calorimeters, muon chambers, FCT

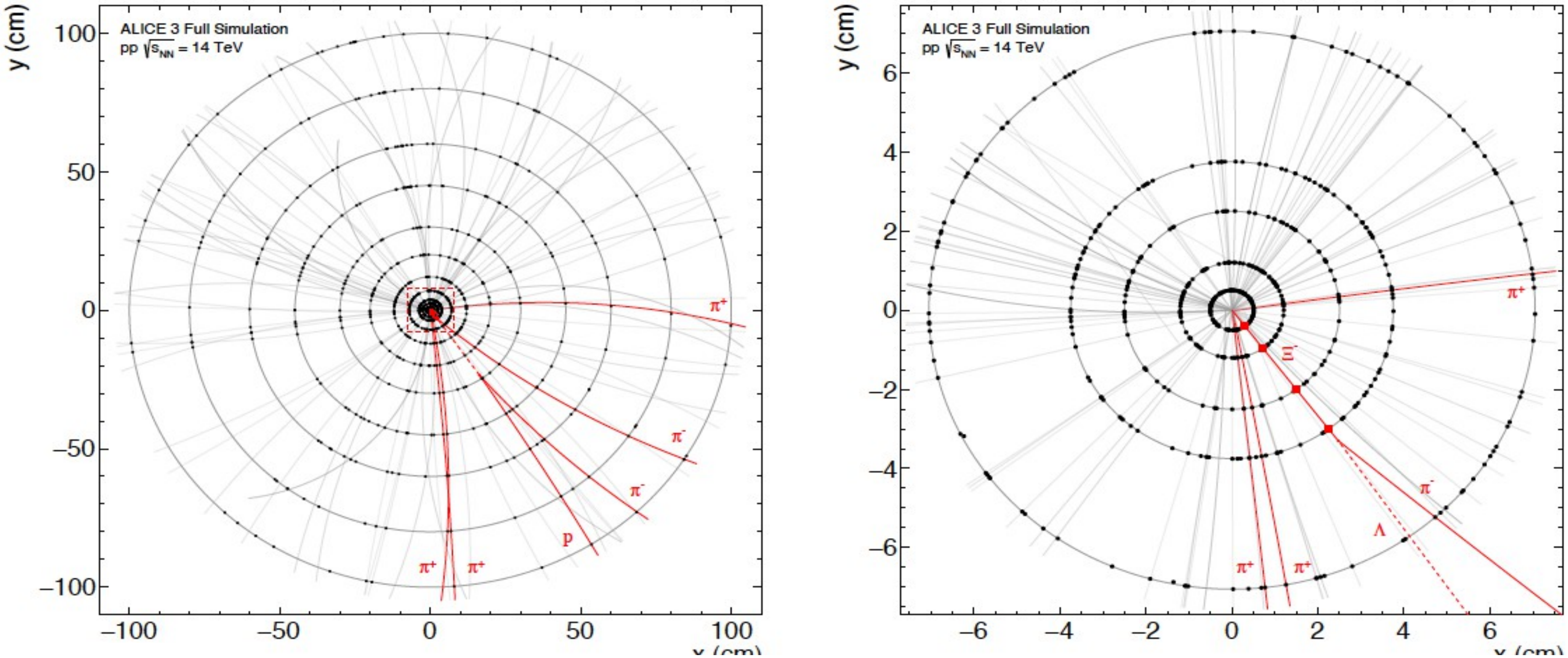


Particle identification

- **Time-of-light detectors**
  - 2 barrel + 1 forward TOF layers ($R = 19$ & $85\,\mathrm{cm}$, $z = 405\,\mathrm{cm}$)
  - With silicon timing sensors ($\sigma_{\mathrm{TOF}} \approx 20\,\mathrm{ps}$)
- **Ring-Imaging Cherenkov detectors**
  - 1 barrel + 1 forward layer
  - Aerogel radiators with continuous coverage from TOF
- **Large acceptance Electromagnetic calorimeter**
  - Pb-scintillator sampling calorimeter + at $\eta \approx 0$ crystal calorimeter
  - Photons + high p electrons identification
- **Muon Identifier**
  - Absorber + 2 layers of muon detectors
  - Muons down to $p_{\mathrm{T}} \geq 1.5\,\mathrm{GeV}/c$
- **Forward conversion tracker**
  - Thin tracking disks in $3 < \eta < 5$ in its own dipole field
  - Very low p_{T} photons ($\leq 10\,\mathrm{MeV}/c$)



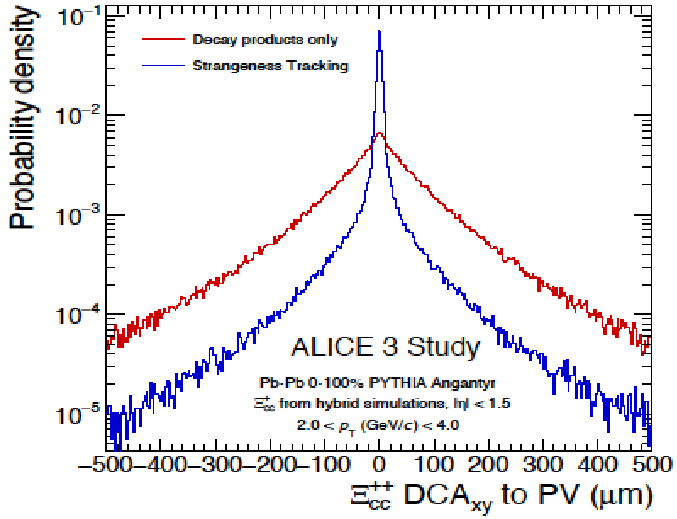
new ALICE development: strangeness tracking



(left) Illustration of strangeness tracking from full detector simulation of the Ξ_{cc}^{++} decay into $\Xi_c^+ + \pi^+$ with the successive decay $\Xi_c^+ \rightarrow \Xi^- + 2\pi^+$. (right) Close-up illustration of the region marked with a red dashed box in the left figure, containing the five innermost layers of ALICE 3 and the hits that were added to the Ξ^- trajectory (red squares).

Ξ^{++}_{cc} mass spectrum without (red) and with (blue) strangeness tracking

the power of ultra-thin, ultra-precise MAPS detectors for ALICE 3



Summary and outlook

ALICE 3 needed to unravel the microscopic dynamics of the QGP

Innovative detector concept to meet the requirements of the ALICE 3 physics program

Outlook:

- 2023-25: Selection of technologies, small-scale proof of concept prototypes (≈ 25% of R&D founds)
- 2026-27: Large-scale engineered prototypes (≈ 75% of R&D funds)
  →Technical Design Reports
- 2028-32: Construction and testing
- 2033-34: Preparation of cavern and installation of ALICE 3

Thanks to the full ALICE 3 team for the huge work
in particular Jochen Klein and Marco Van Leeuwen