A Large Ion Collider Experiment

ALICE

ALICE Upgrade and Physics Topics (II)

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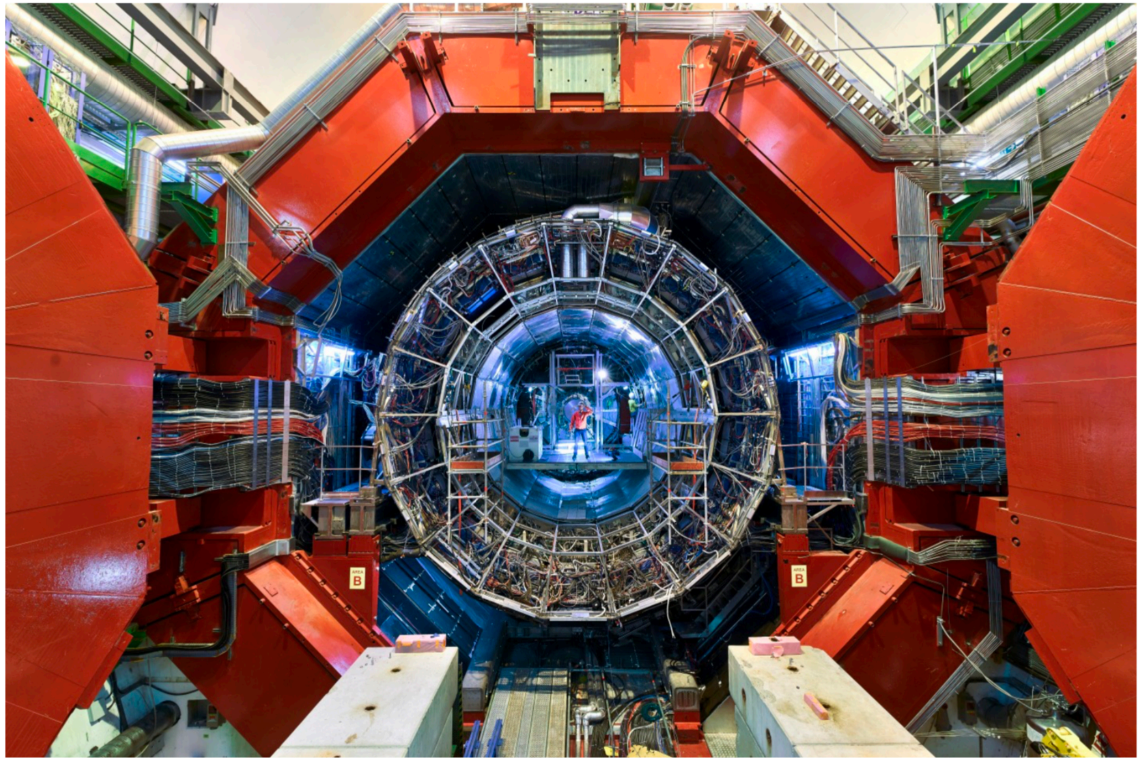
Outline

- Central barrel upgrade
- ITS and GEM-TPC upgrade
- New DAQ system upgrade
- ALICE and LHC plans
- ALICE Physics Goals
- Selected Physics Topics and Prospects
    - (Anti)nucleosynthesis in the laboratory
- Summary and outlook



Current status of ALICE cavern

Central barrel upgrade

New Inner Tracking System (ITS2)

- Complementary Metal-Oxide-Semiconductor (CMOS) Monolithic Active Pixel Sensor (MAPS) technology
- Improved resolution, less material, faster readout

New TPC Readout Chambers (ROCs)

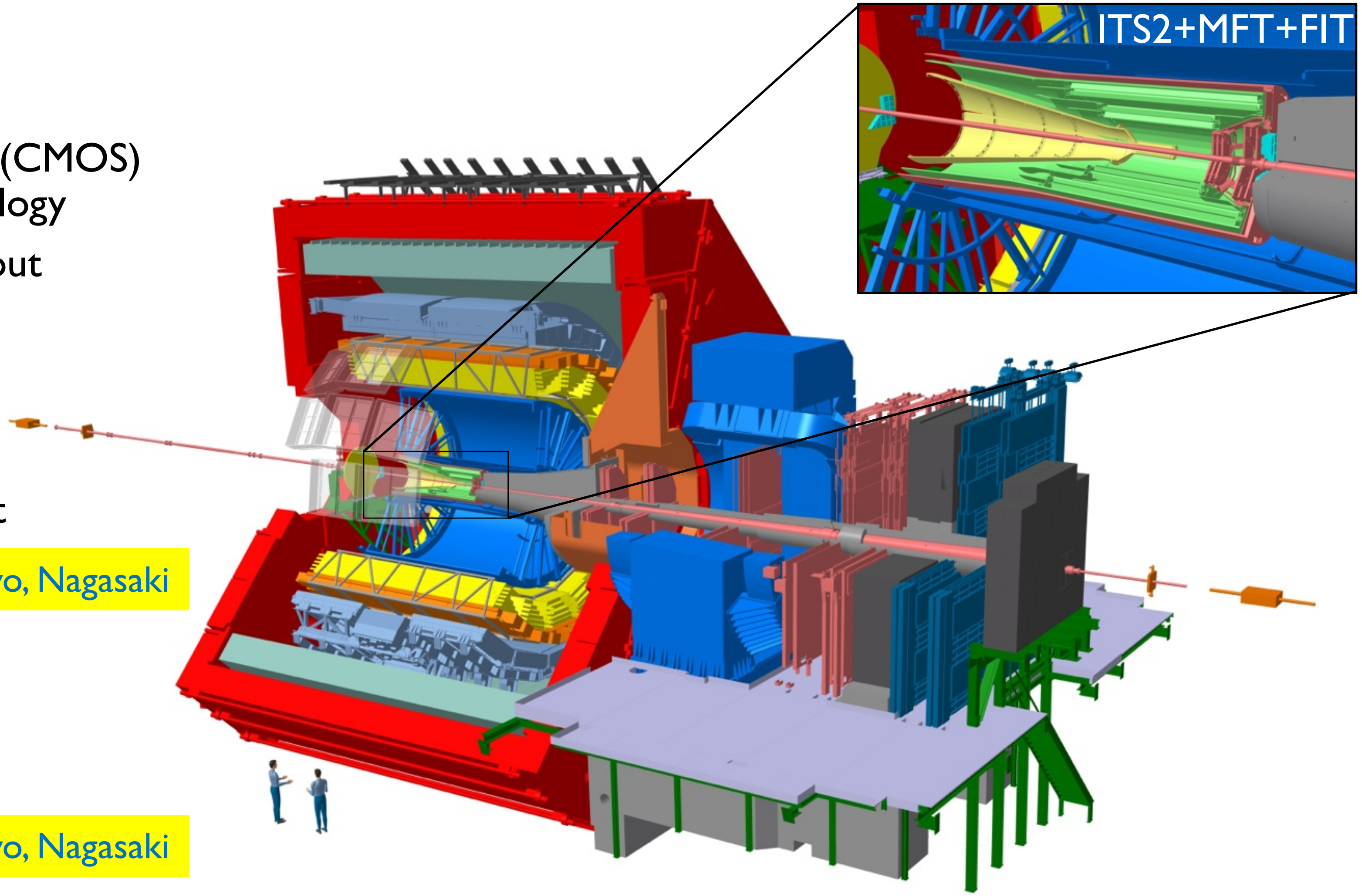
- Gas Electron Multiplier (GEM) technology
- New electronics (SAMPA), continuous readout

Tokyo, Nagasaki

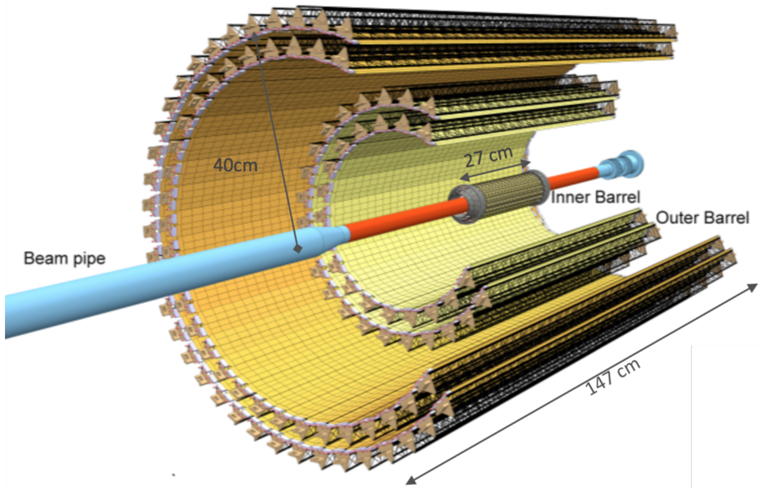
Integrated Online-Offline system (O^2)

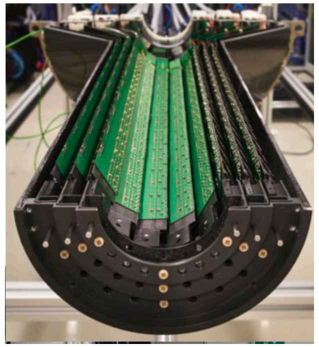
- Record MB Pb-Pb data at 50 kHz
- Online data processing to cope with 3 TB/s

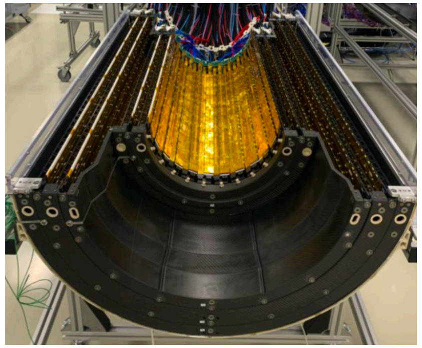
Tokyo, Nagasaki

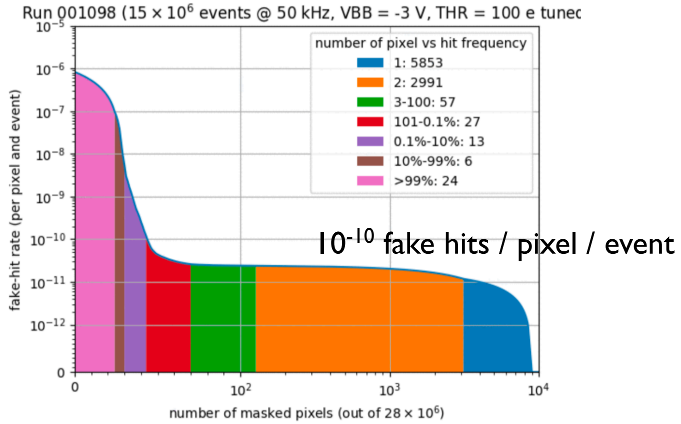


ALICE ITS upgrade - status



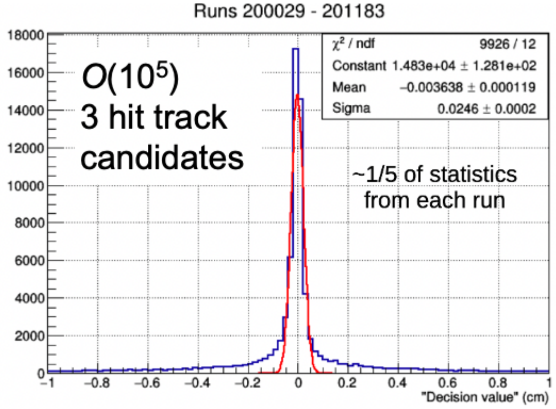




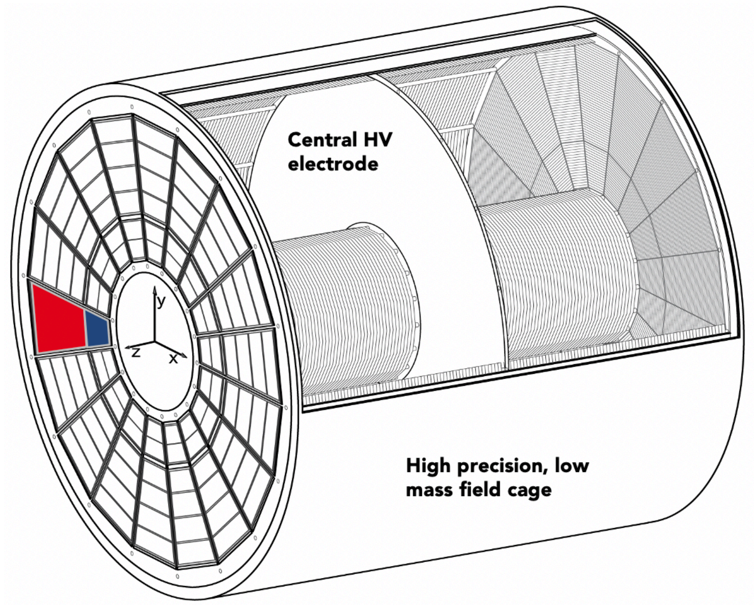


ALPIDE (ALICE Pixel Detector)

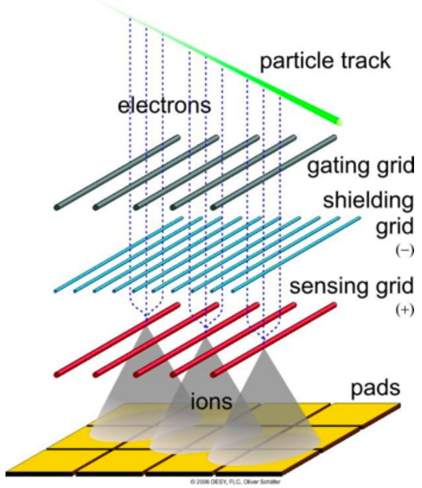
- Developed for the ALICE upgrade (ITS and MFT)
- Thinner: for innermost layers ~0.30% X_0
- Smaller pixels: 27 × 29 μm²
- Readout rate: 100 kHz
- 130 000 pixels/cm²
- Max. particle rate: ~100 MHz/cm²
- Spatial resolution: ~5 μm
- Thickness: 50 μm for the inner layers
- Fake-hit rate: < 10^{-9} per pixel per event

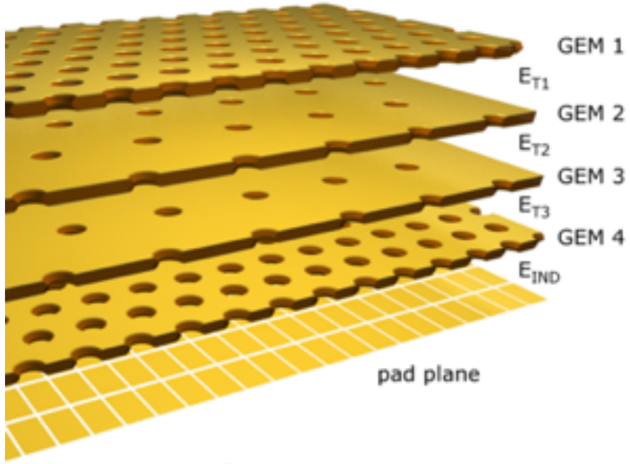


ALICE GEM-TPC upgrade

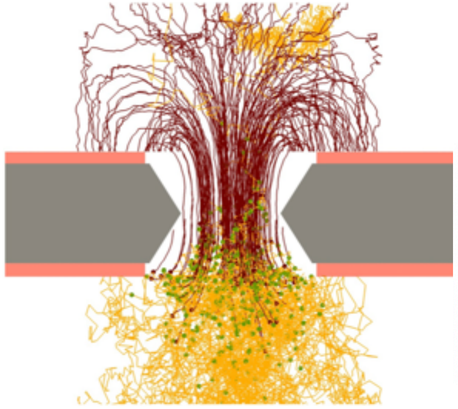


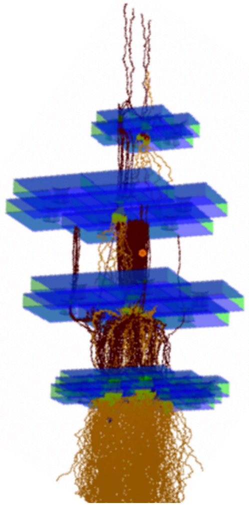
Operate TPC at 50 kHz
⟶ no gating grid. 4 GEMs and continuous readout





- Diameter: 5 m, length: 5 m
- Gas: Ne-CO_2-N_2, Ar-CO_2
- Max. drift time: ~100 µs
- 18 sectors on each side
- Inner and outer read out chambers: IROC, OROC
- Current detector (Run 1, Run 2):
  - 72 MWPCs, ~550 000 readout pads
  - Wire gating grid (GG) to minimize Ion Back-Flow (IBF)
  - Rate limitation: few kHz





Using 4 GEM stacks with different pitches (S-LP-LP-S)
- GEM is good at IBF
- Fast signals and no ion tails

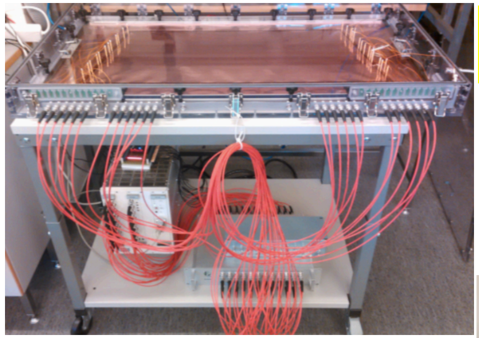
Many R&D efforts by CNS to optimize the GEM configurations and search for the alternative options

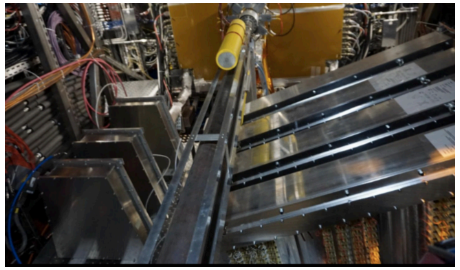
(新学術領域「クラスター階層」「量子ビーム応用」合同検出器ワークショップ)

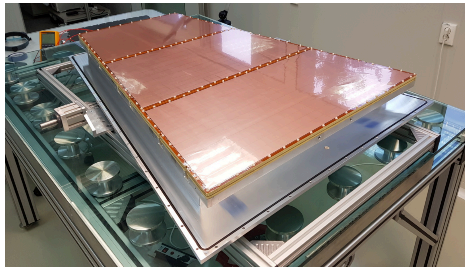
ALICE GEM-TPC upgrade - status

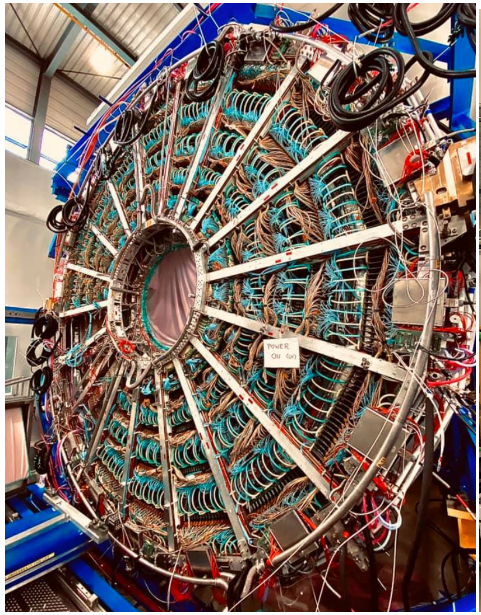
2019-2020

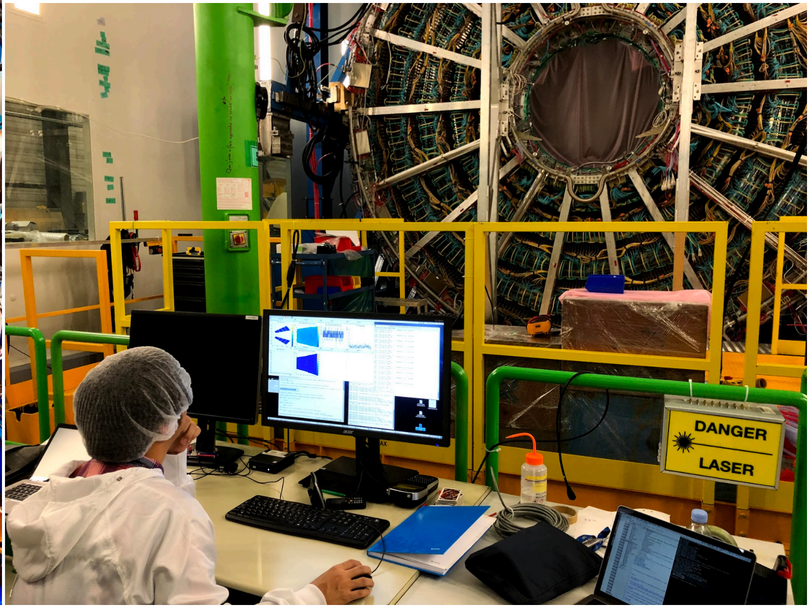
2017-2018



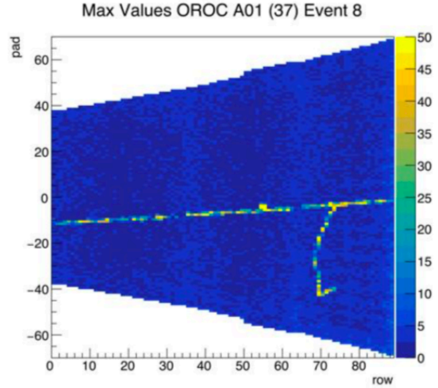


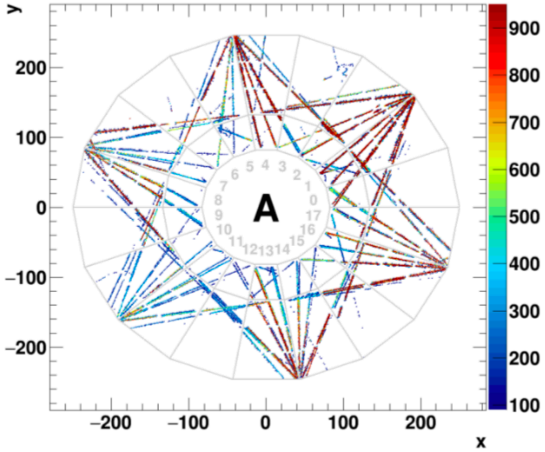




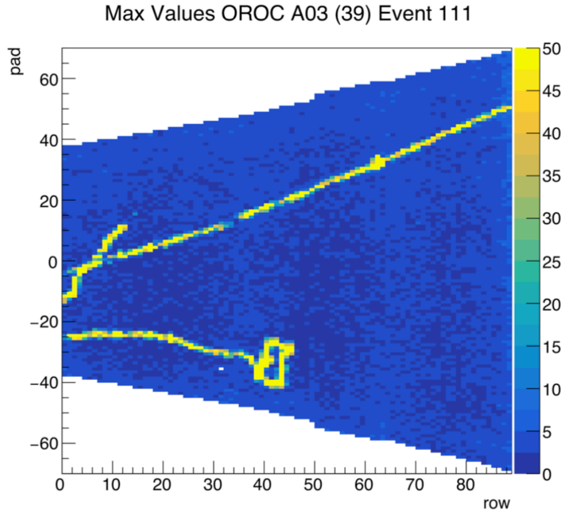


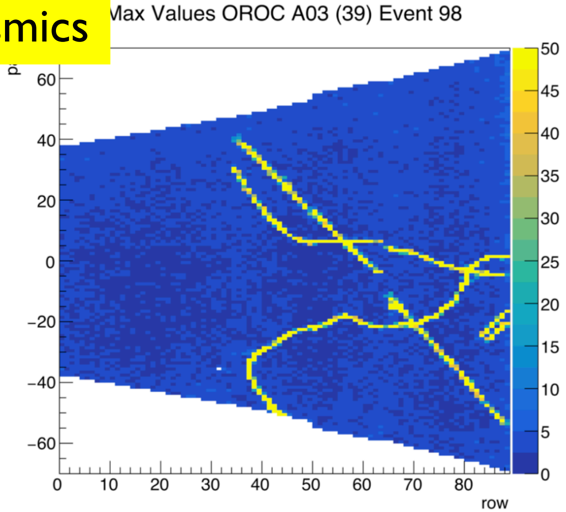
Laser tracks



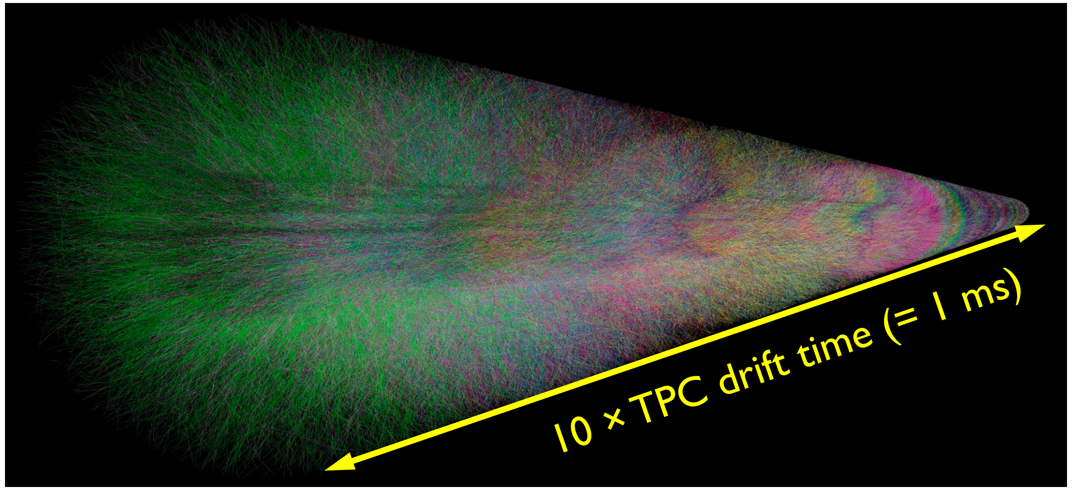


cosmics





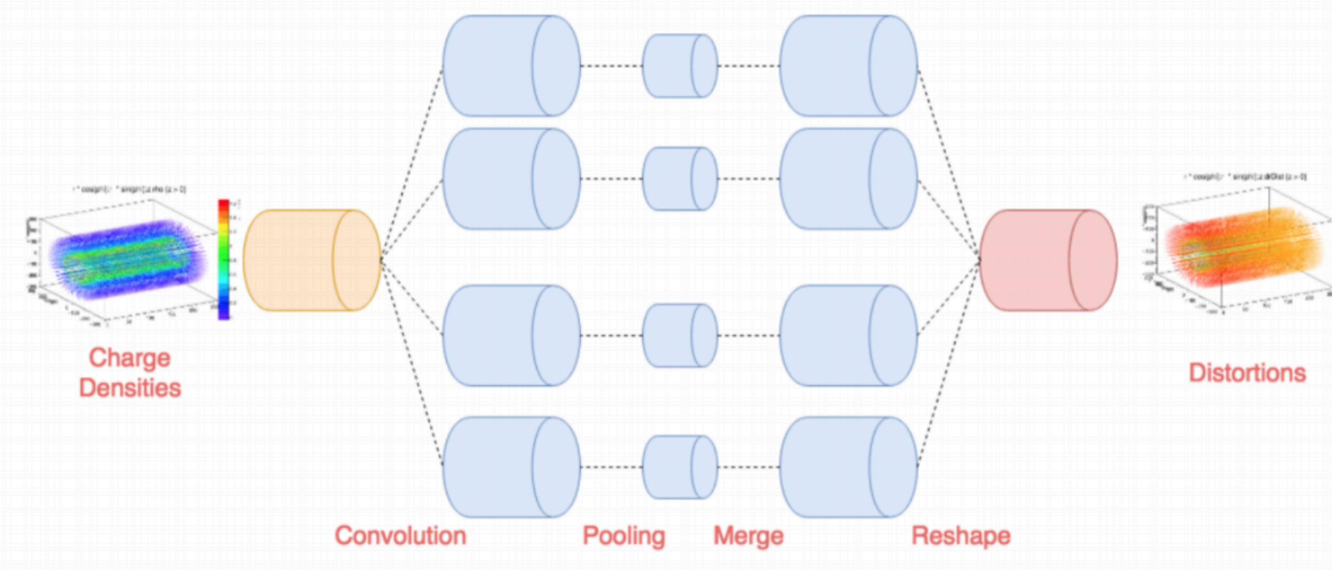
TPC space-charge distortion correction

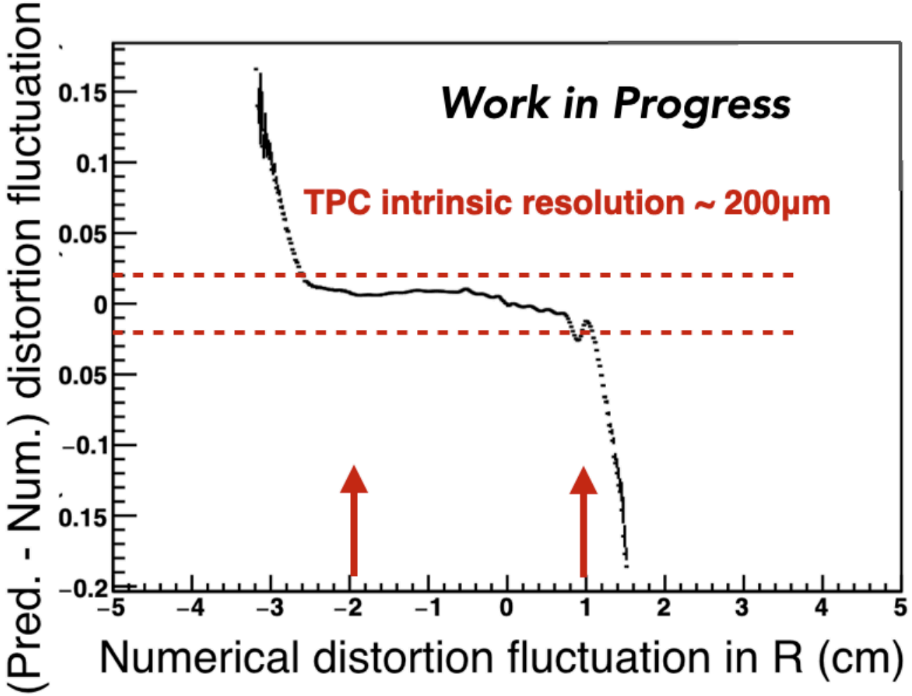


- 50 kHz Pb-Pb MC events
- Tracks/Clusters from different collisions are shown in different colors.

- $t_{d,ion}$ = 160 ms → ion pileup from 8000 events at 50 kHz Pb-Pb collisions
- Distortions up to dr ~ 20 cm, $dr\phi$ ~ 8 @ Gain=2000, IBF=1%
  - Final calibration to 10^{-3} required
- ML-based framework development in CNS using GPUs

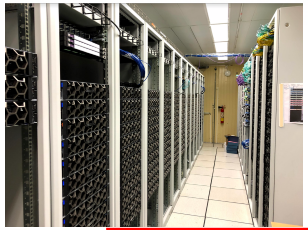
High resolution currents on GEM electrode
→ space-charge density → distortion correction

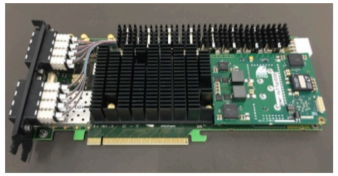




New DAQ system "O2"

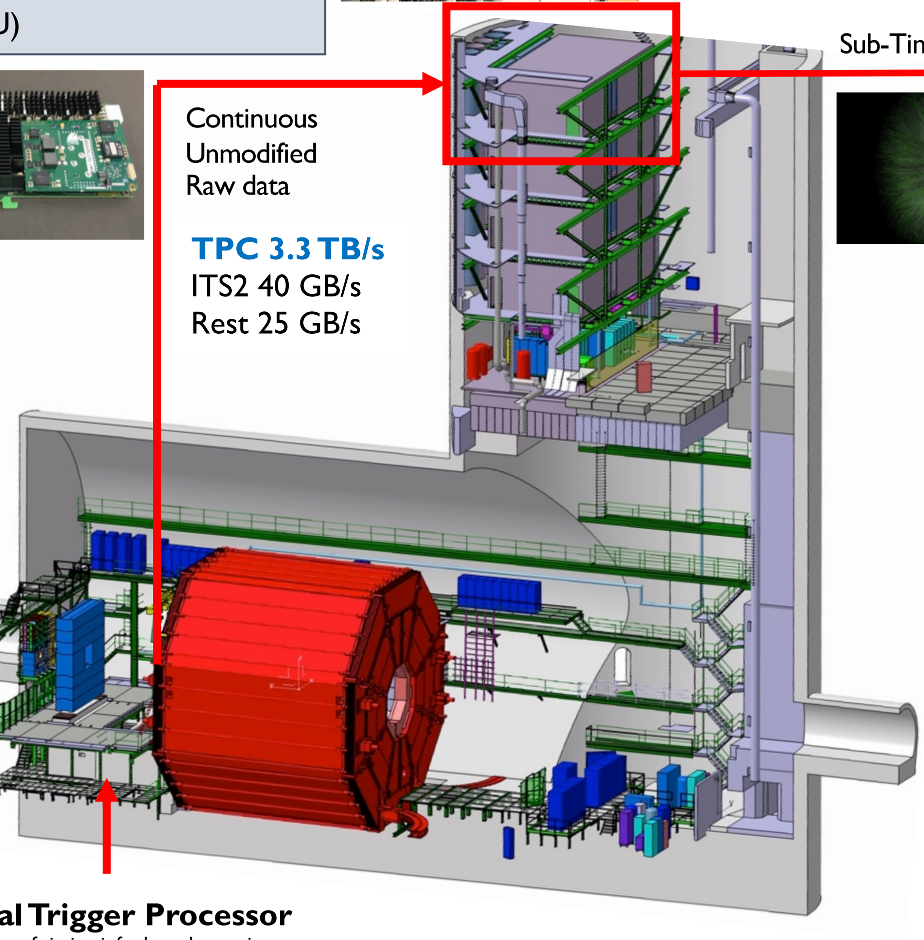
O2/FLP
CR1 – First Level Processors
Receive detector data and processing on PCIe-based FPGA board (CRU)





Continuous
Unmodified
Raw data

TPC 3.3 TB/s
ITS2 40 GB/s
Rest 25 GB/s

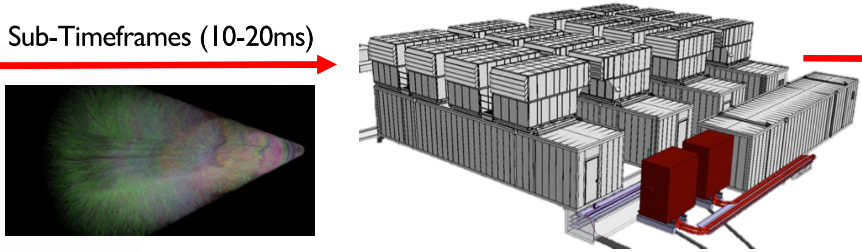


CTP
Central Trigger Processor
Distribution of timing info, heartbeat trigger

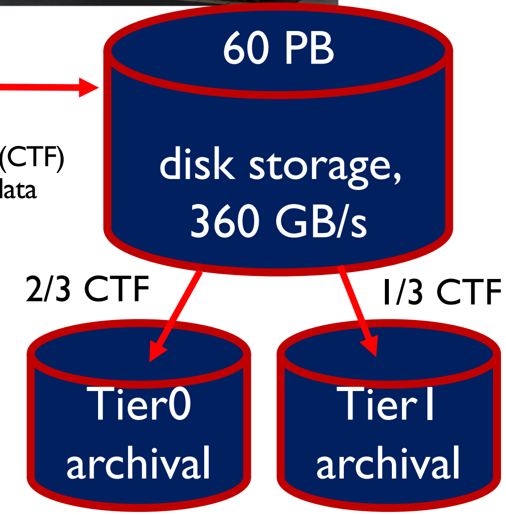
TPC 570 GB/s
ITS 40 GB/s
Rest 5 GB/s

Sub-Timeframes (10-20ms)

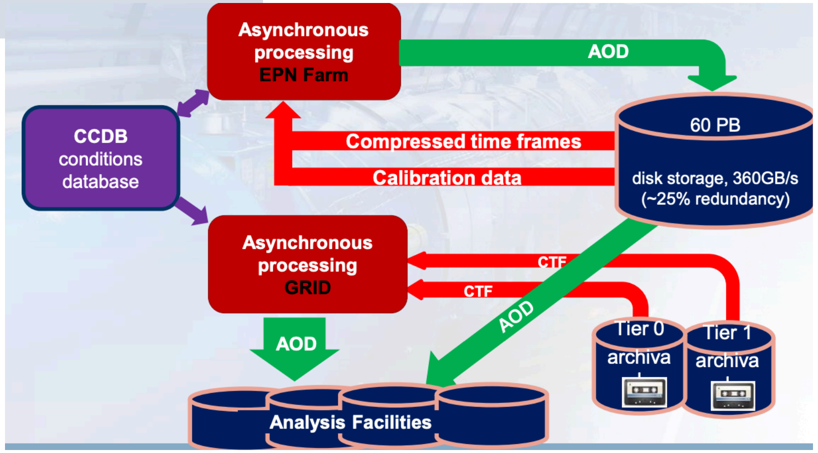
O2/EPN
CR0 - Event Processing Nodes
~2000 GPU & CPU



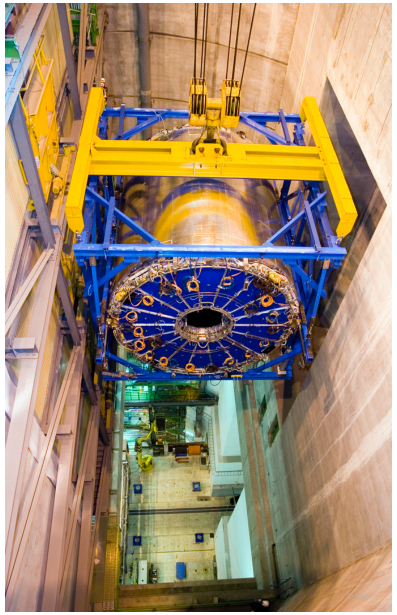
Compressed
Timeframes (CTF)
Calibration data



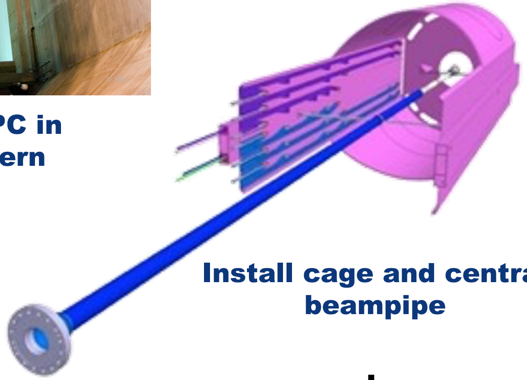
O2/PDP
Physics and Data Processing on EPN
- **Synchronous reconstruction**
- **Calibration & asynchronous reconstruction (and event selection only for pp)**
- **Utilize ~2000 GPU and HPC**



(Re-)installation sequence

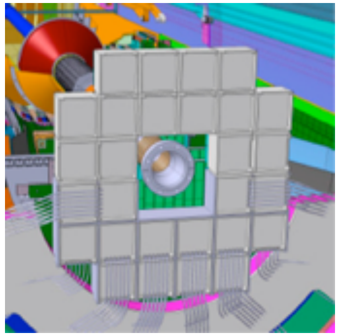


Reinstall TPC in ALICE Cavern

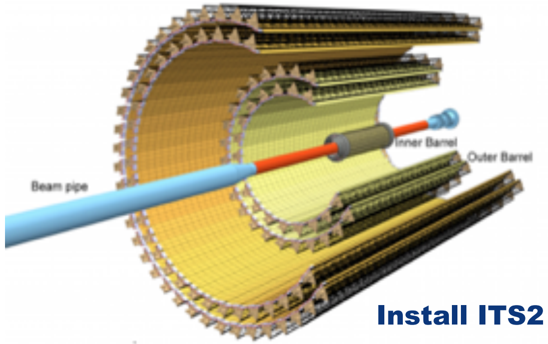


Install cage and central beampipe

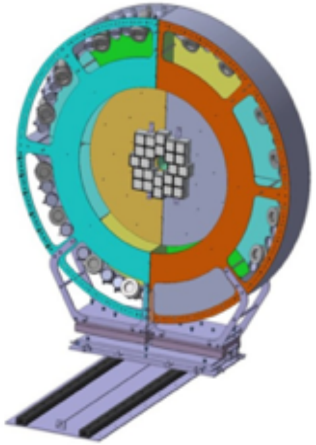
Reinstall Miniframe



Install MFT and FIT-C



Install ITS2



Install FIT-A

Global commissioning

LS2 ends

????

Jul-Aug '20

Aug-Sep '20

Oct '20

Nov-Dec '20

Jan-Mar '21

Apr '21

Aug '21

LHC and ALICE Run3 program

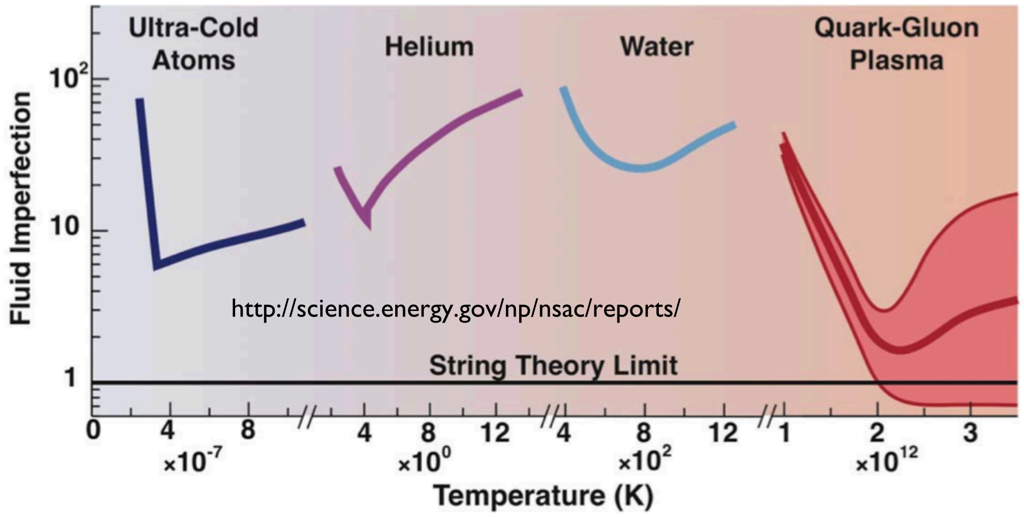
- Decision at the last December:
  - Extend LS2 by 2 month. Cavern closure on May 1st 2021.
  - Extend Run3 by one year (2021 – 2024). LS3 starts in 2025
  - Consider to drop one of the HI runs after 2021 (most likely 2022) and attach it to the HI run in 2024.
  - Decide on the final beam energy after the magnet training at the end of the extended LS2.
- ALICE's plan is to accumulate 200 pb^{-1} for pp and 6.2nb^{-1} for Pb-Pb (~x5 as Run2) in Run3.

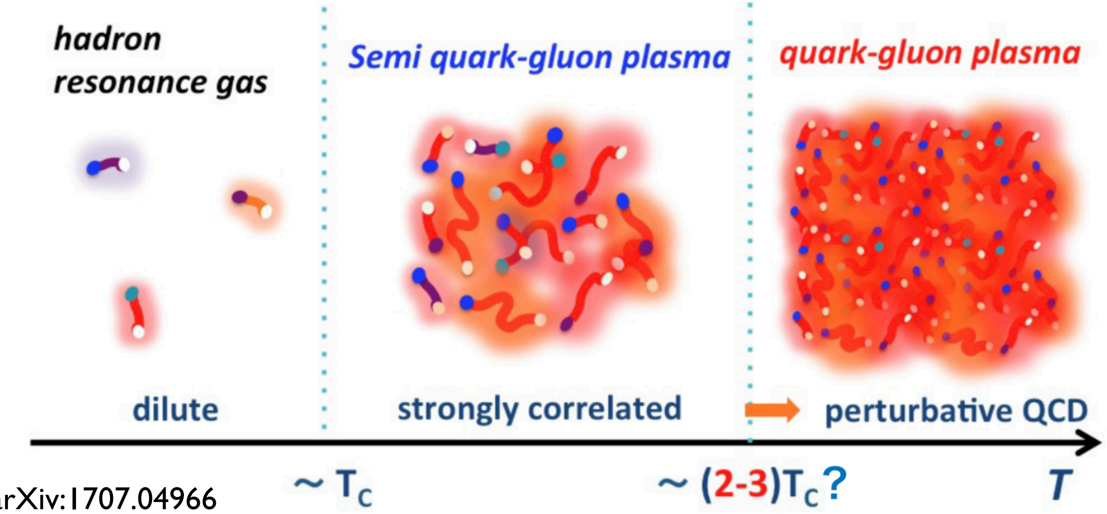
arXiv:1812.06772 (YR-WG05)

*** The COVID-19 pandemic has a huge impact on these plans ***
LHC and experiments are evaluating new schedules. First outcomes will come in June.

Main questions to be answered (personal view)

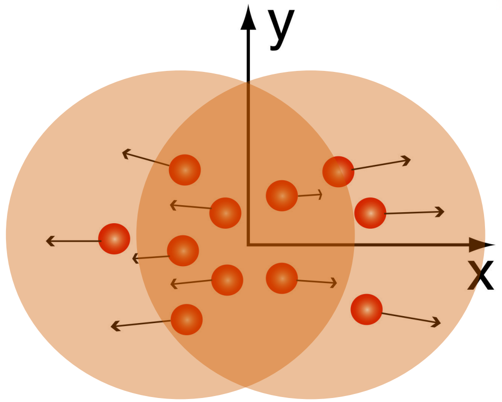
- Space-time evolution of the system is described by relativistic (viscous-)hydrodynamics.
  - Viscosity/entropy is found to be close to the limit of strongly interacting system
- What is the temperature dependence of medium properties?
  - strongly correlated system ⇆ weakly correlated system
- What is the characterization of the phase transition between hadron gas and QGP?
  - Deconfinement and chiral transition?
- What is the smallest droplets of the QGP?
  - Observation of collectivity in small systems (pp and p-Pb collisions). What is the origin? Hydro?

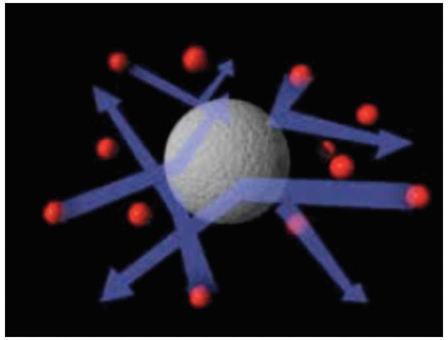




arXiv:1707.04966

Prospects – Transport properties





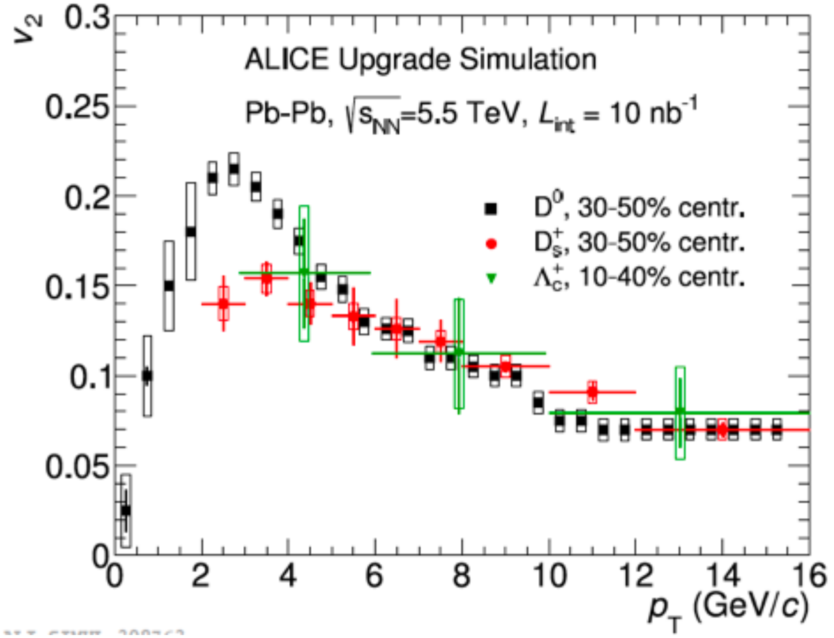
$$\frac{d\vec{p}}{dt} = -\eta_D(p)\,\vec{p} + \vec{\xi}$$

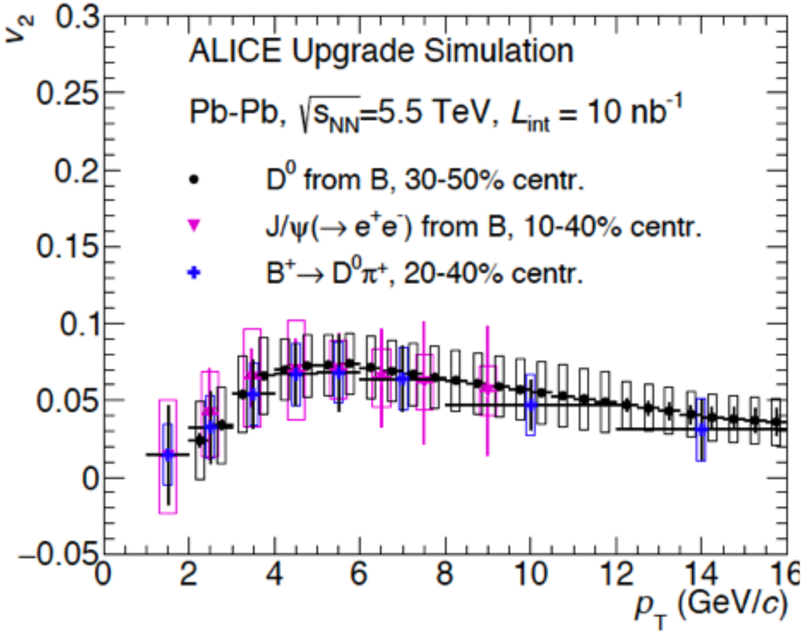
$$\langle \xi^i(t)\,\xi^j(t')\rangle = \kappa\,\delta^{ij}\,\delta(t-t')$$

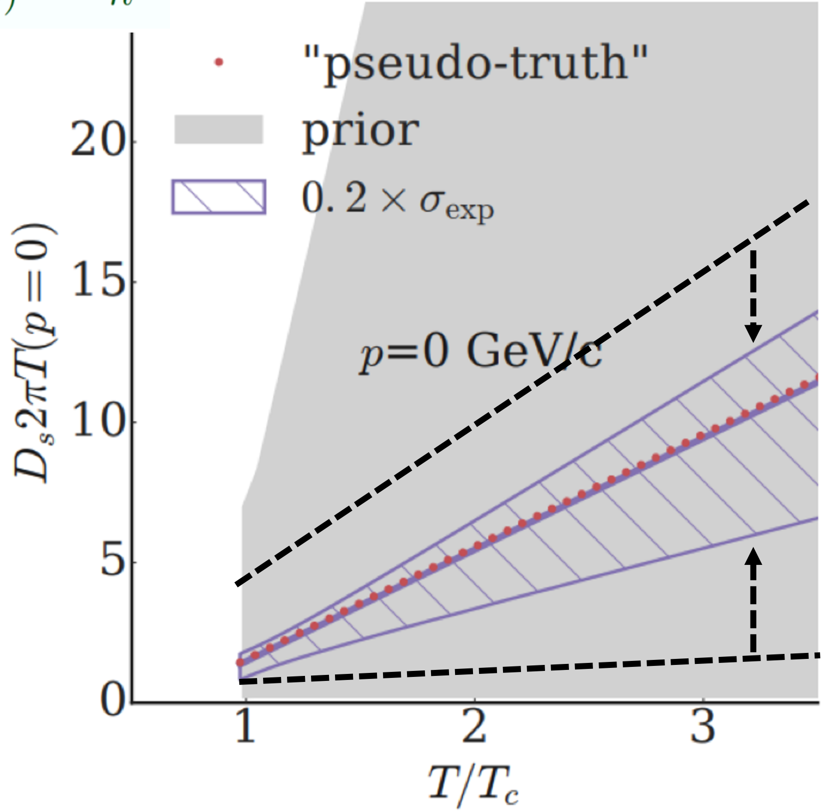
$$\eta_D(p) = \frac{\kappa}{2TE} \qquad D = \frac{t}{M\eta_D(0)} = \frac{2T^2}{\kappa}$$

Temperature dependence of transport properties

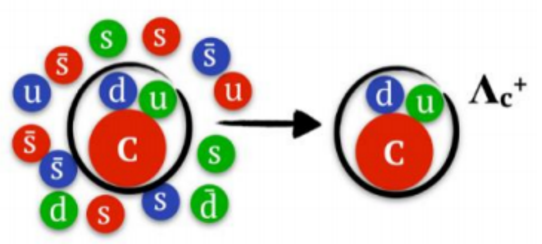
$v_2 = \langle \cos 2(\psi - \Psi_{EP}) \rangle$







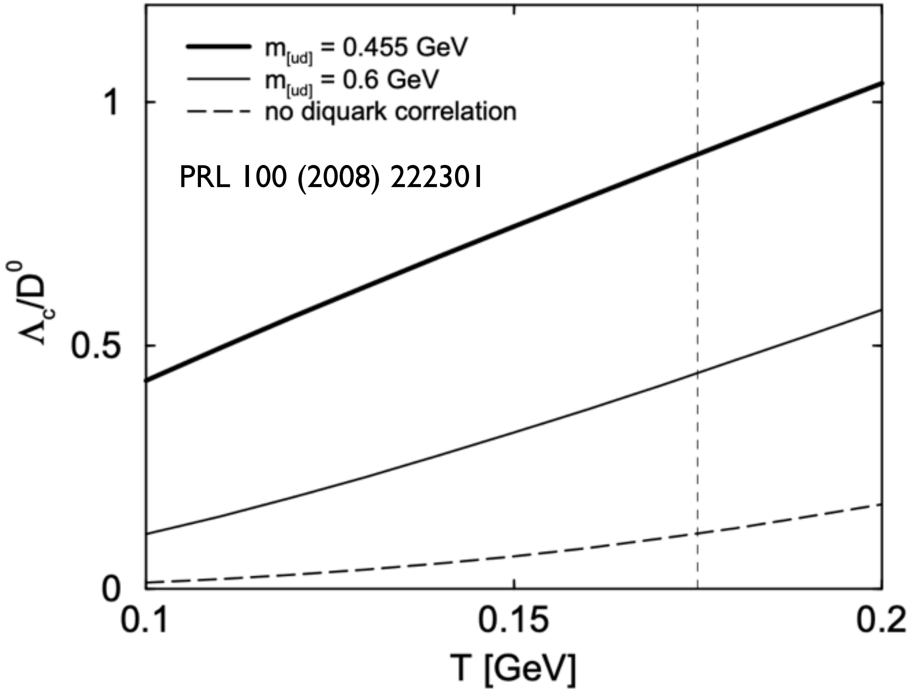
Prospects – di-quark correlations

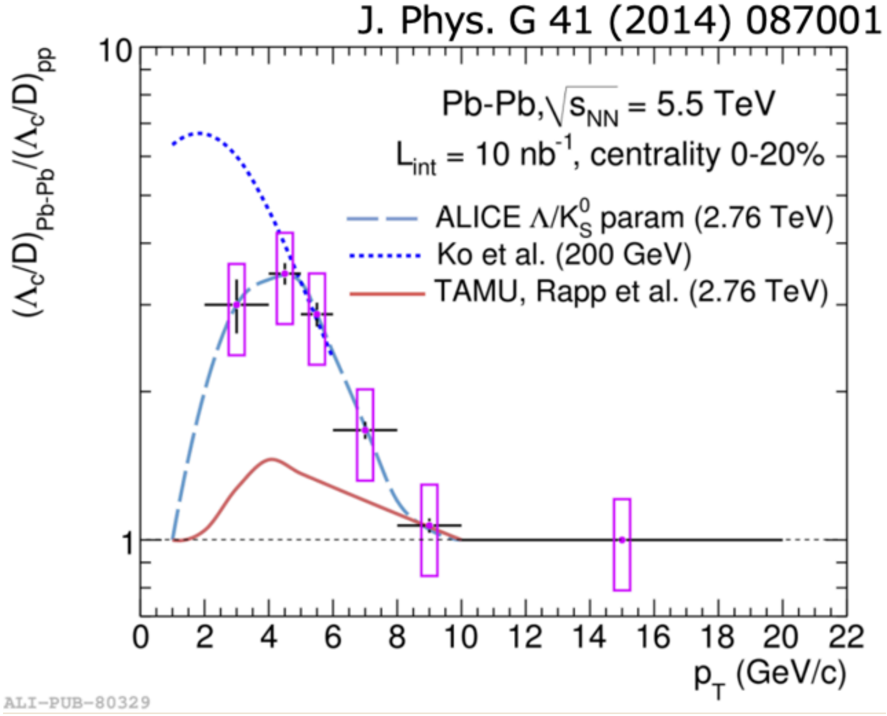


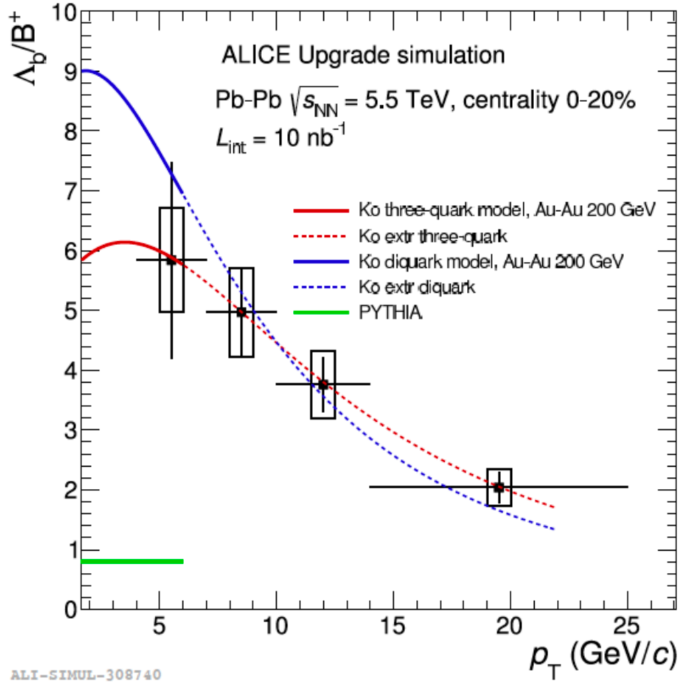
Enhanced production of charmed baryons relative to mesons
Sensitive also to the existence of [ud] diquarks in the QGP

Oh et al., PRC79 (2009) 044905
Ghosh at al., PRD 90 (2014) 054018
He, Rapp et al. arXiv:1905.9216

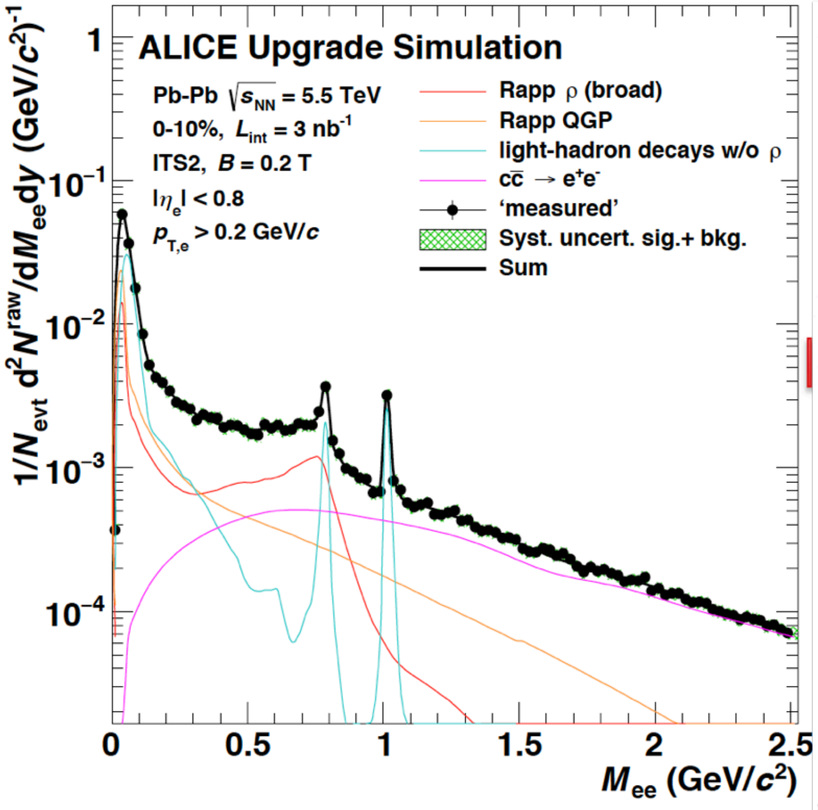
Di-quark as effective DoF

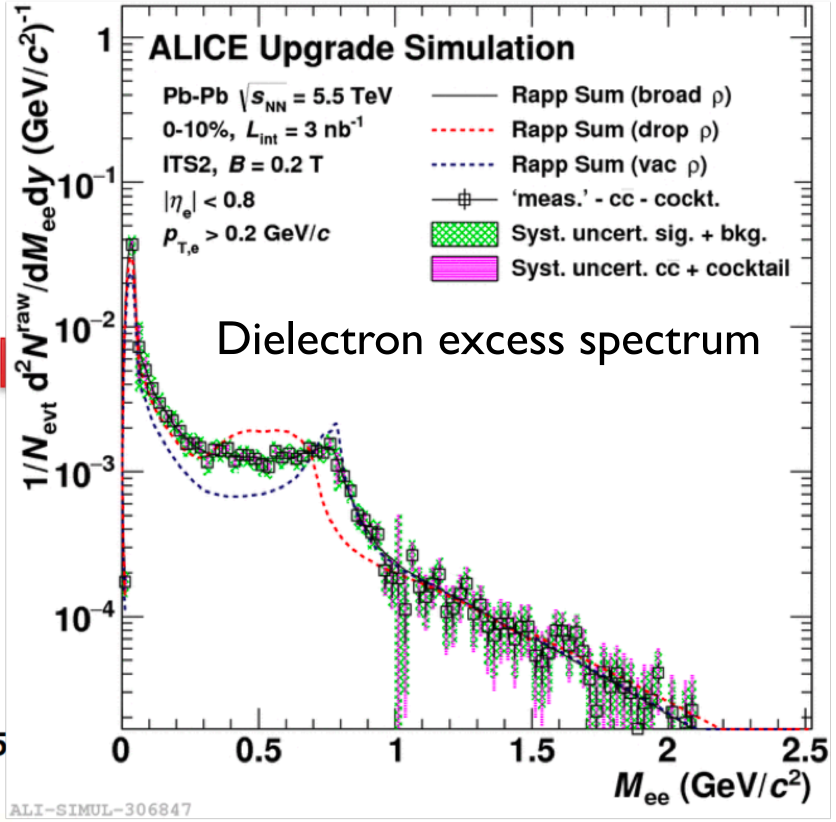




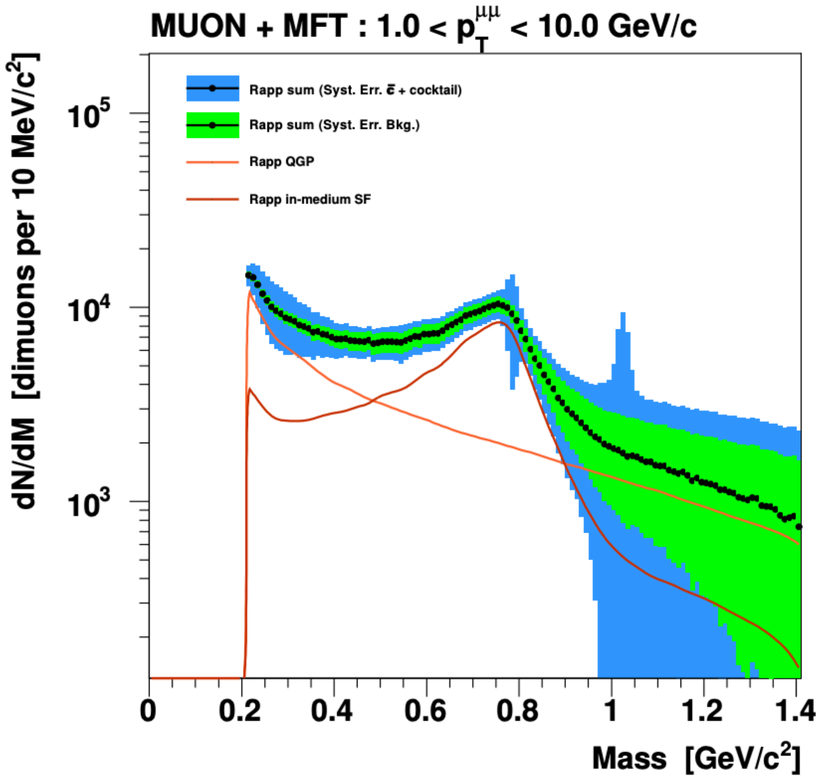


Prospects – spectrum functions, thermal radiation





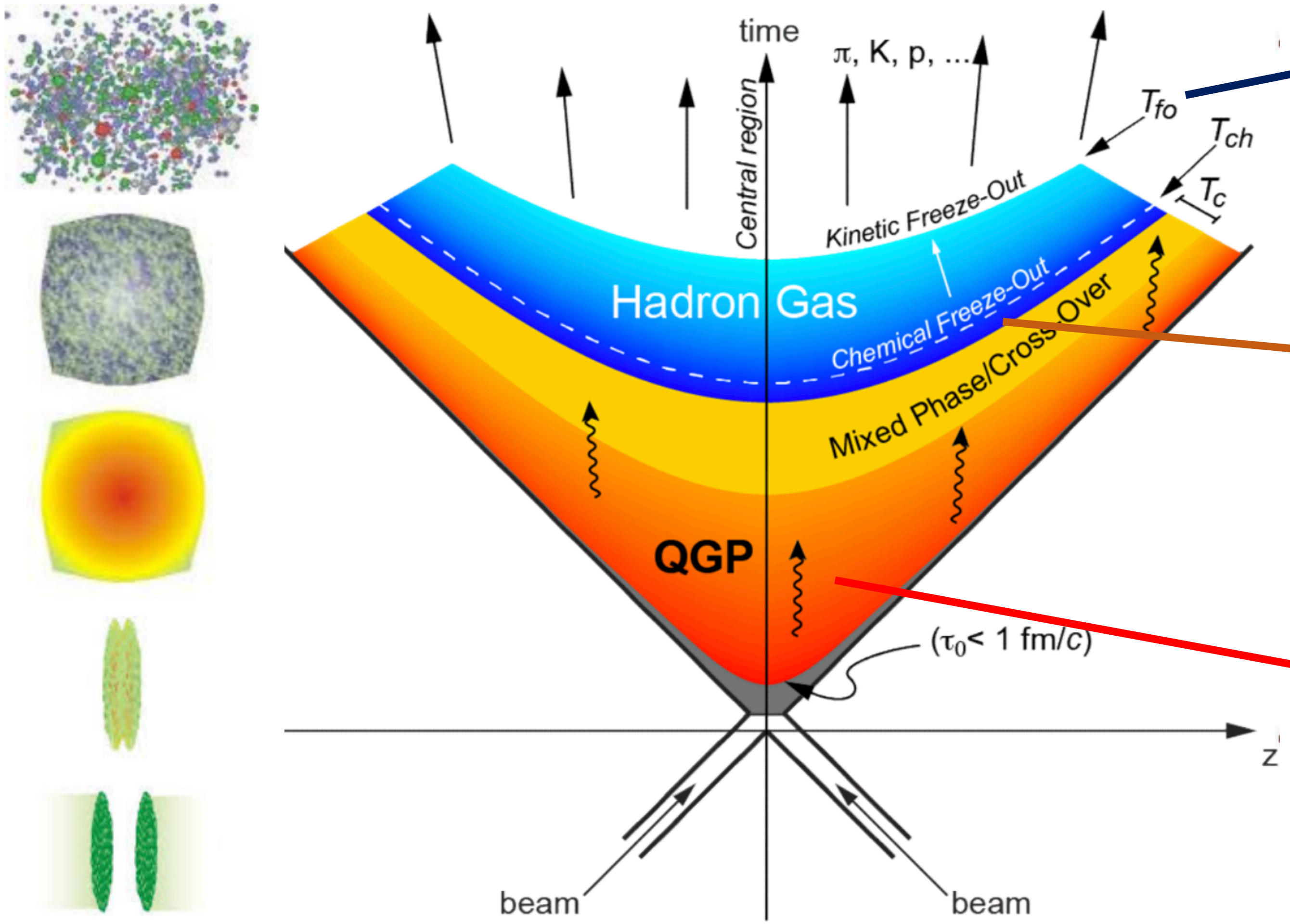
Dimuon excess spectrum with MFT upgrade



- In medium spectral function and link to chiral symmetry restoration
- Direct thermal radiation ($M_{ll} \propto T$): Differential view of space-time evolution, temperature dependence of medium properties, (for small systems) direct evidence of formation of thermalzed system
- p_T<<T: electric conductivity

$$\sigma_{EM}(T) = - e^2 \lim_{q_0 \to 0} \left[\partial/\partial q_0 \, \mathrm{Im}\, \Pi_{EM}(q_0, q=0; T) \right]$$

Hadronization



Thermal Freezeout (T ~ 100 MeV)

- Cease of elastic scattering
- Particle dynamics (momentum spectra) fixed

Chemical Freezeout (T ~ 150 MeV)

- Cease of inelastic interactions
- Particle abundances (“chemical composition”) are fixed

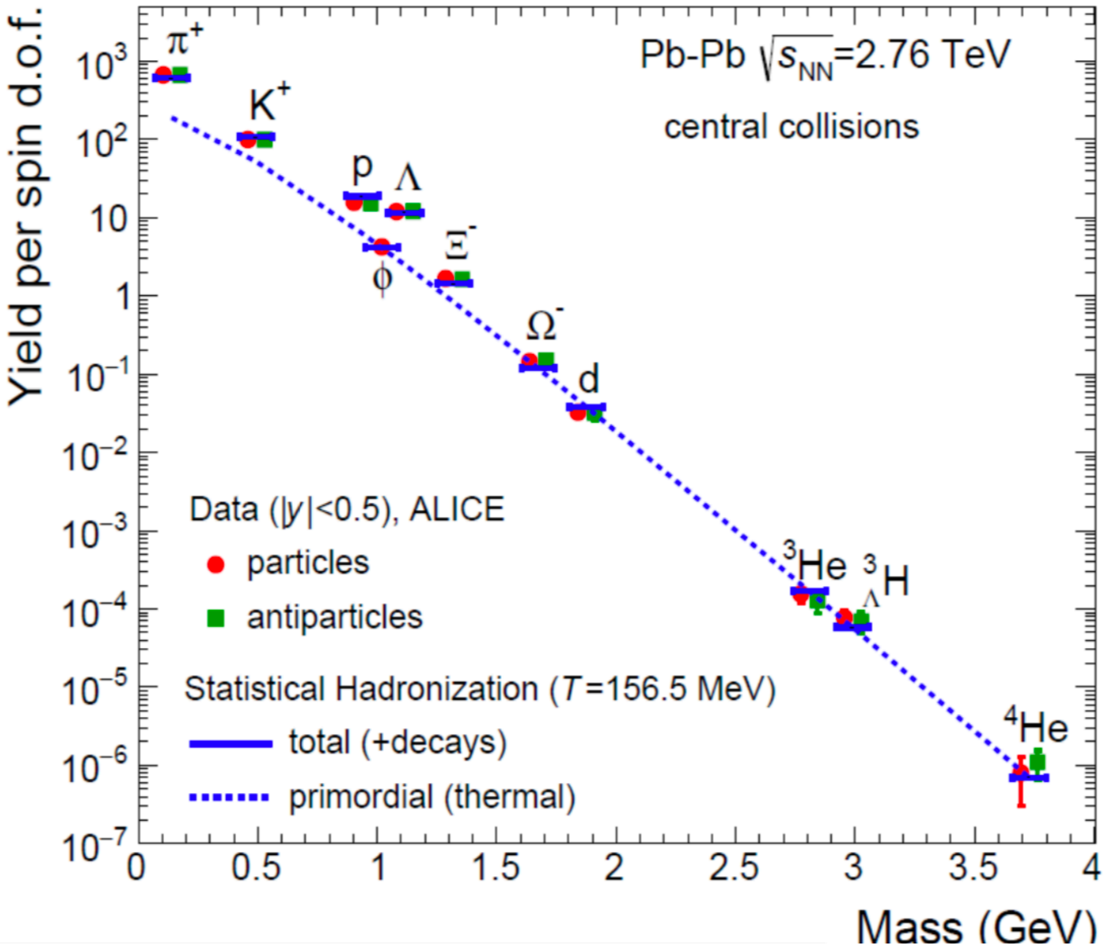
Quark-Gluon Plasma (T ~ 400-600 MeV)

- System reaches local equilibrium
- Evolution is described by hydrodynamics

(anti-)(hyper-)nuclei laboratory

ALICE

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



Yields of light hadrons from a chemically equilibrated system can be described by statistical-thermal models :

$$dN/dy \sim \exp\{-m/T_{ch}\}$$

1 free parameter: temperature T_{ch} (= 156.5 $\pm$ 1.5 MeV) can describe the yields over 9 orders of magnitude

Light (anti-)nuclei are also well described despite their low binding energy ($E_{b,d}$ = 2.2 MeV << T_{ch}).

How light (anti-)nuclei exist in the medium?

Mass number	Nucleus	Composition	Binding energy (MeV)	Spin	λ_A^{meas} (fm)
A = 2	d	pn	2.224575 (9)	1	2.1413 ± 0.0025
A = 3	^{3}H	pnn	8.4817986 (20)	1/2	1.755 ± 0.086
	^{3}He	ppn	7.7180428 (23)	1/2	1.959 ± 0.030
	$^3_\Lambda$H	pΛn	0.13 ± 0.05[a]	1/2	4.9–10.0

Statistical hadronization model

The **production mechanisms** of light (anti-)nuclei in high-energy physics are still not completely understood.

Two classes of models are available:

- the **statistical hadronization** model
  - Chemical and kinetic freezeout are decoupled.

thermal model for yields:

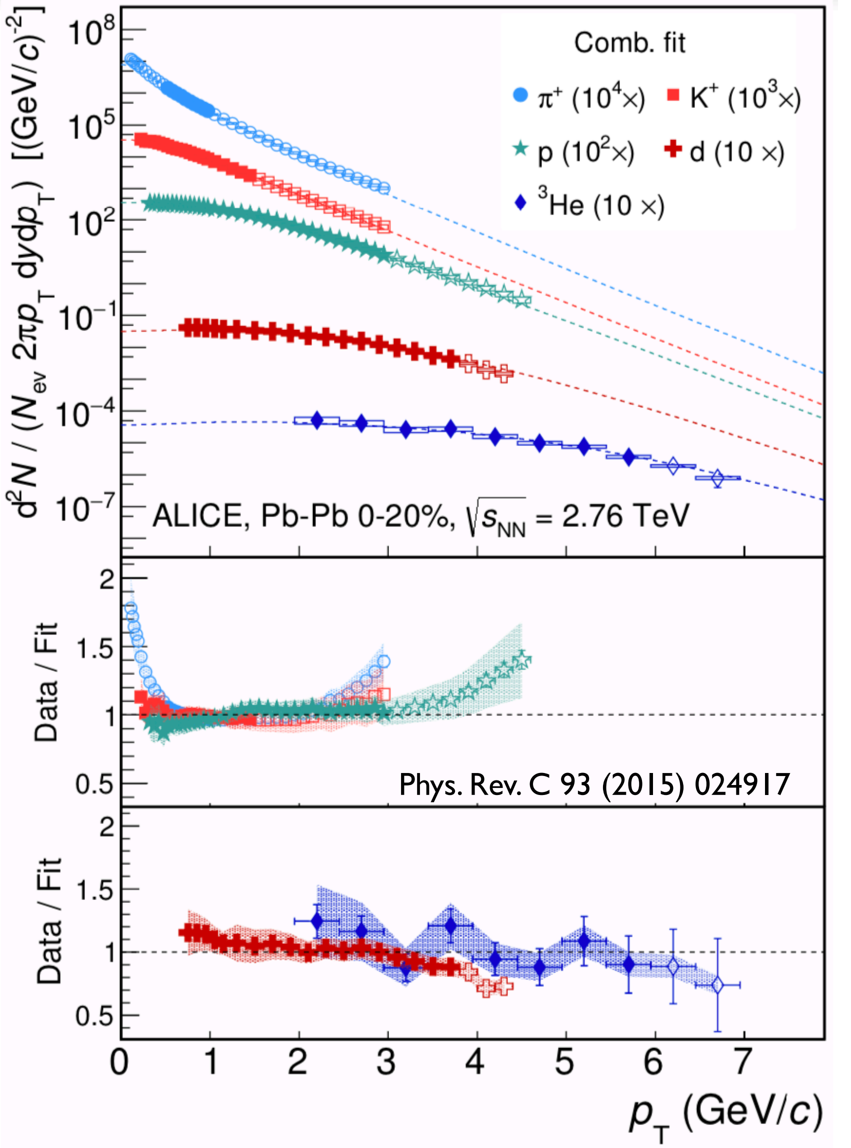
$$\frac{dN_d}{dy}\Big|_{y=0} = \frac{g_d V_{CFO}}{2\pi^2\hbar^3} T_{CFO}\, m_d^2\, K_2\left(\frac{m_d}{T_{CFO}}\right)$$

p_T spectra:

$$\frac{1}{p_T}\frac{\mathrm{d}N}{\mathrm{d}p_T} \propto \int_0^R r\,\mathrm{d}r\, m_T I_0\left(\frac{p_T \sinh\rho}{T_{\mathrm{kin}}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{\mathrm{kin}}}\right)$$

$$\rho = \tanh^{-1}\beta = \tanh^{-1}\left(\beta_S (r/R)^n\right)$$

T_{chem} = 160 MeV, T_{kin} ~113 MeV and β_s = 0.86

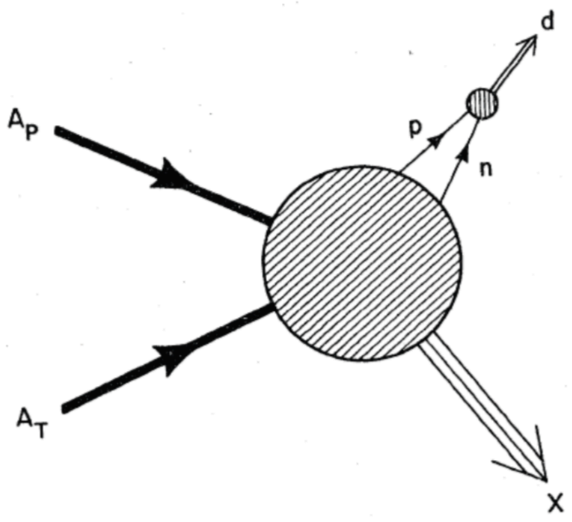


Coalescence model

The **production mechanisms** of light (anti-)nuclei in high-energy physics are still not completely understood.

Two classes of models are available:

- the **statistical hadronization** model
- the **coalescence** model
  - If baryons are close in phase space they can form a nucleus
  - Interplay between the configuration of the phase space of baryons and the wave function of the nuclei to be formed
  - Coalescence parameter $\mathbf{B_A}$
    - $\mathbf{B_A}$ is related to the **probability** to form a nucleus via coalescence



Parton distribution

Hadron Wigner function

$$\frac{dN_{meson}}{dp_T} \propto \int f_q(x_q, p_q) f_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}}) \boxed{f_W(x_a, x_{\bar{q}}; p_q, p_{\bar{q}})}$$

$$\boxed{B_A = E_A \frac{d^3N_A}{dp_A^3} \Big/ \left(E_p \frac{d^3N_p}{dp_p^3} \right)^A}$$

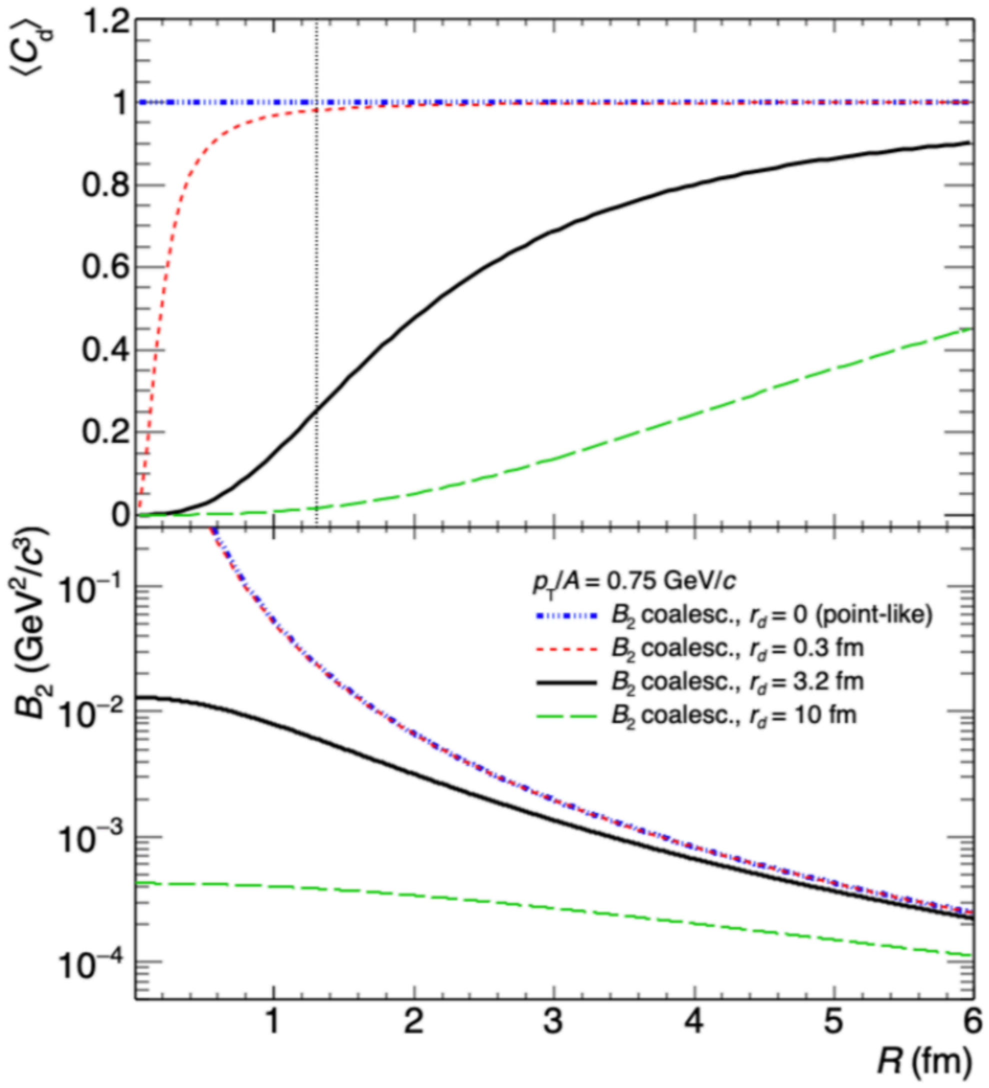
Coalescence models: Description of B_2

- Space-time distribution of nucleons (local equilibrium) and space-time evolution (collective expansion, HBT volume as effective volume) considered
  - overlap between nucleus wave-function (Wigner formalism) and nucleon phase-space distribution
  - Quantum mechanical correction factor which accounts for the internal structure of the deuteron cluster

U. Heinz et al. Phys Rev C.59.1585

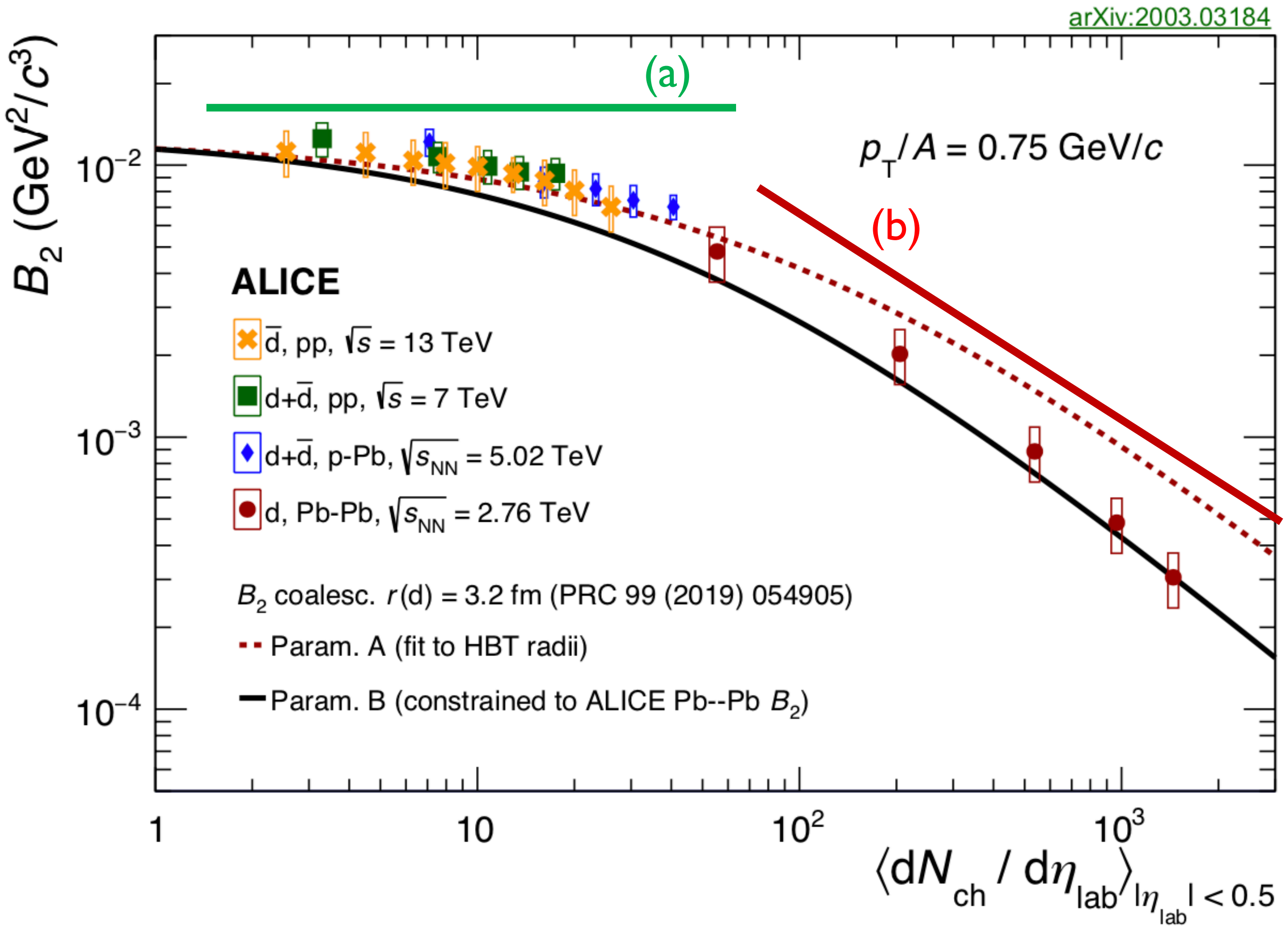
$$B_2 = \frac{3\pi^{3/2}\langle C_d\rangle}{2m_T R^3(m_T)} \quad \text{with} \quad \langle C_d\rangle \approx \left[1 + \left(\frac{r_d}{2R(m_T)}\right)^2\right]^{-3/2}$$

$$B_A = \frac{2J_A+1}{2^A\sqrt{A}}\frac{1}{m_T^{A-1}}\left[\frac{2\pi}{R^2(m_T)+\left(r_A/2\right)^2}\right]^{\frac{3}{2}(A-1)}$$



*F. Bellini, A. Kalweit PRC.99.054905

B_2 vs. multiplicity (pp – Pb-Pb)



The coalescence parameter evolves smoothly as a function of multiplicity

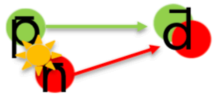
A possible parameterization using the system HBT radius R

$$B_A = \frac{2J_A + 1}{2^A\sqrt{A}} \frac{1}{m_T^{A-1}} \left[\frac{2\pi}{R^2(m_T) + \left(r_A/2\right)^2} \right]^{\frac{3}{2}(A-1)}$$

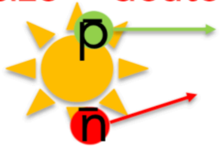
$$R = a \left\langle dN/d\eta \right\rangle^{1/3} + b$$

Interplay between R and r_A

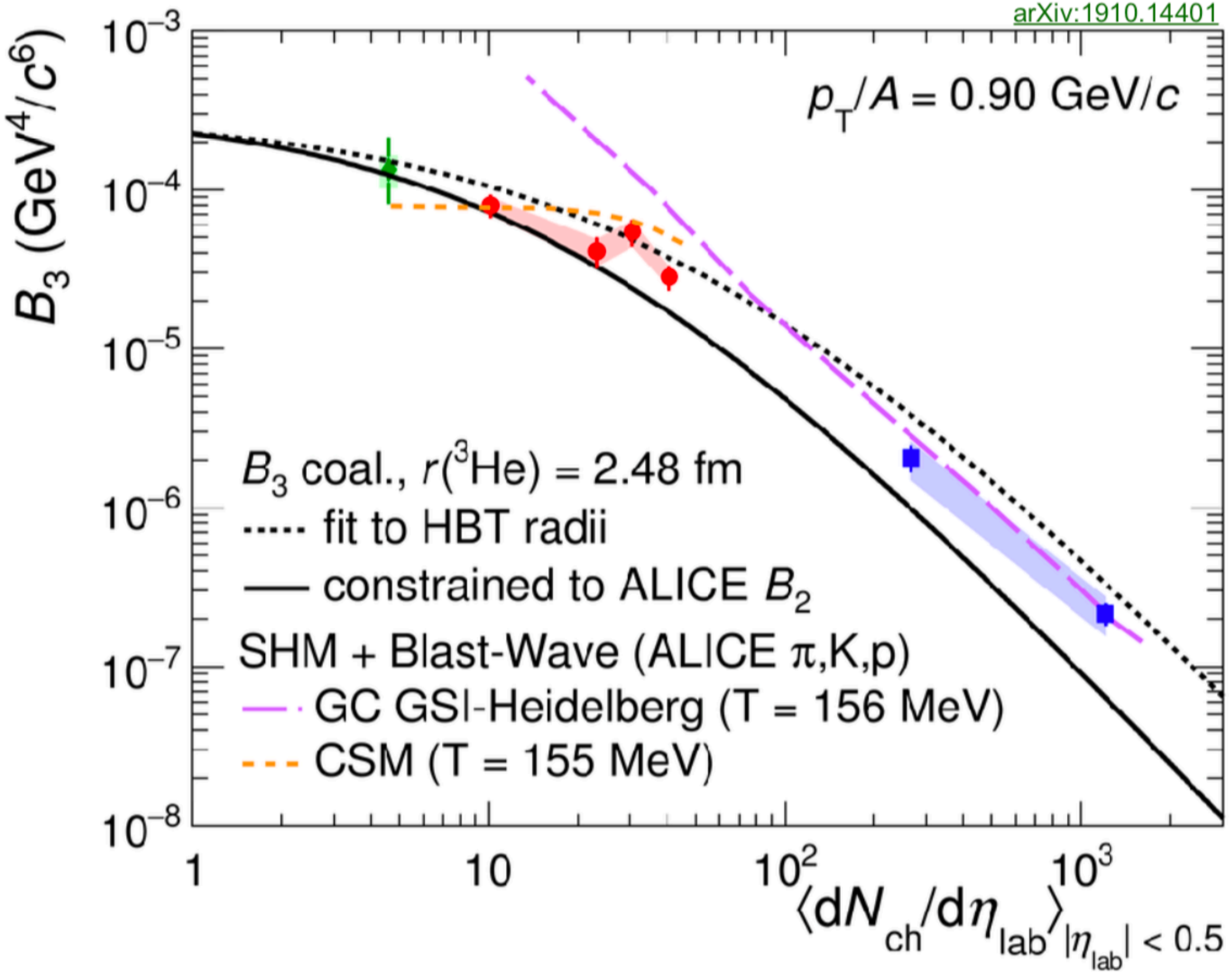
(a.) system size < deuteron size



(b.) system size > deuteron size



B_3 vs. multiplicity (pp – Pb-Pb)



The coalescence parameter evolves smoothly as a function of multiplicity

A possible parameterization using the system HBT radius R

$$B_A = \frac{2J_A+1}{2^A\sqrt{A}} \frac{1}{m_T^{A-1}} \left[\frac{2\pi}{R^2(m_T) + (r_A/2)^2} \right]^{\frac{3}{2}(A-1)}$$

$$R = a\,\langle \mathrm{d}N/\mathrm{d}\eta \rangle^{1/3} + b$$

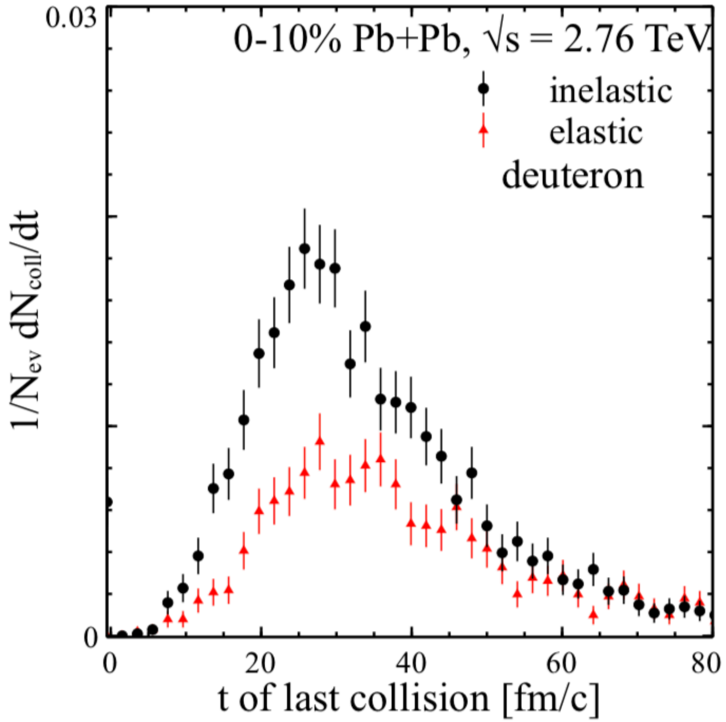
Neither of the two(coalescence, CSM+GC SHM) reproduces B_3 over the full range.

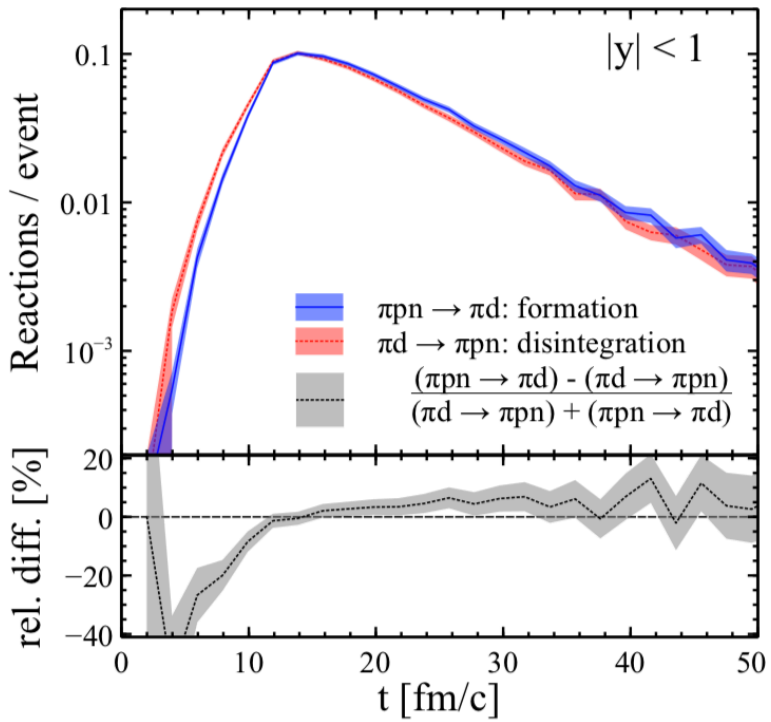
Dynamical Models

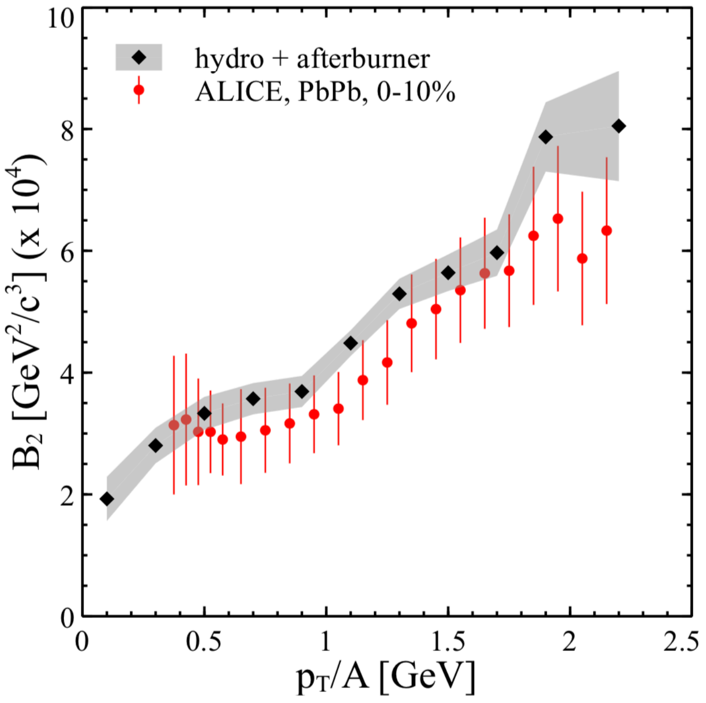
Hydro + Coalescence (hadronic rescattering)

Oliinychenko, Pang, Elfner, Koch, 1809.03071 (TRENTO+CLVisc+SMASH)

- Incorporate πd ⇆ πnp with detailed balance in the SMASH afterburner (“pion catalyzed coalescence”):



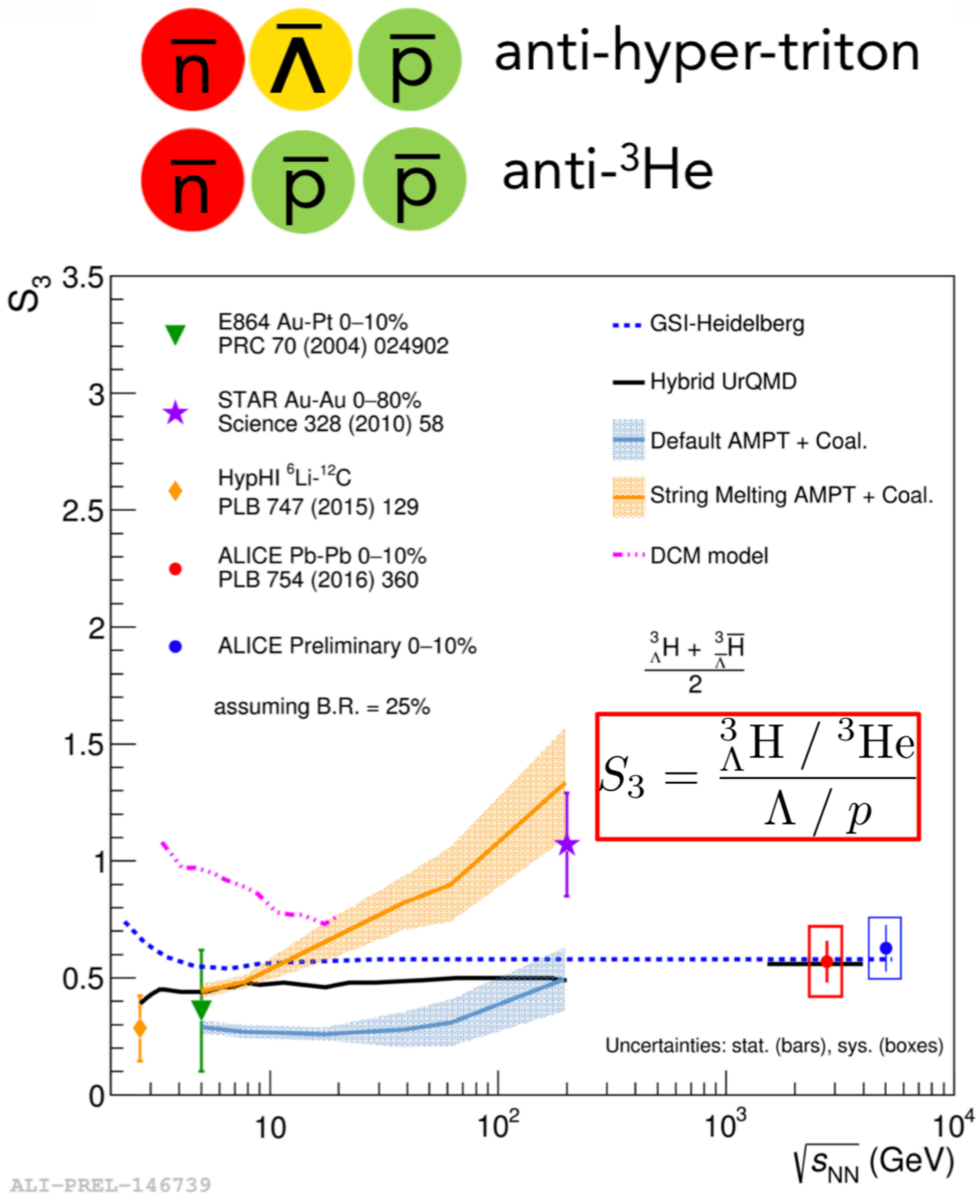




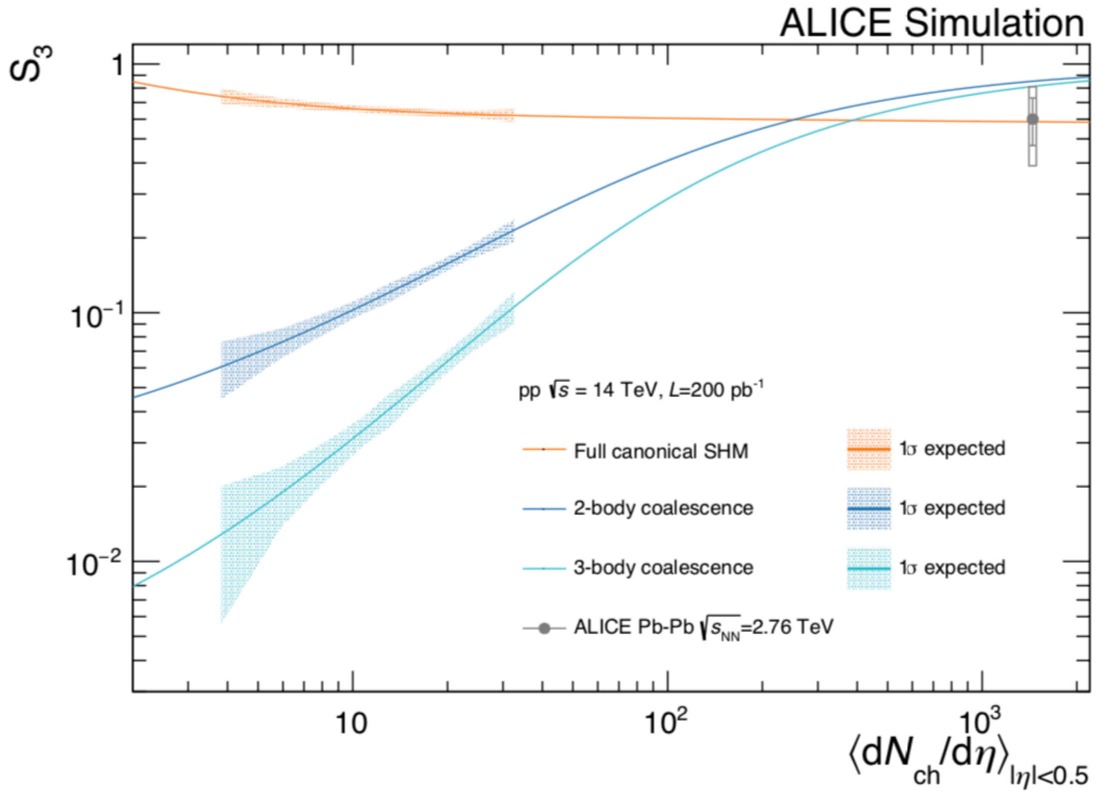
Deuteron freezes out at late time. Its chemical and kinetic freeze-outs roughly coincide

After about 12-15 fm/c within 5%, πd ⇆ πnp is equilibrated

Hypertriton production



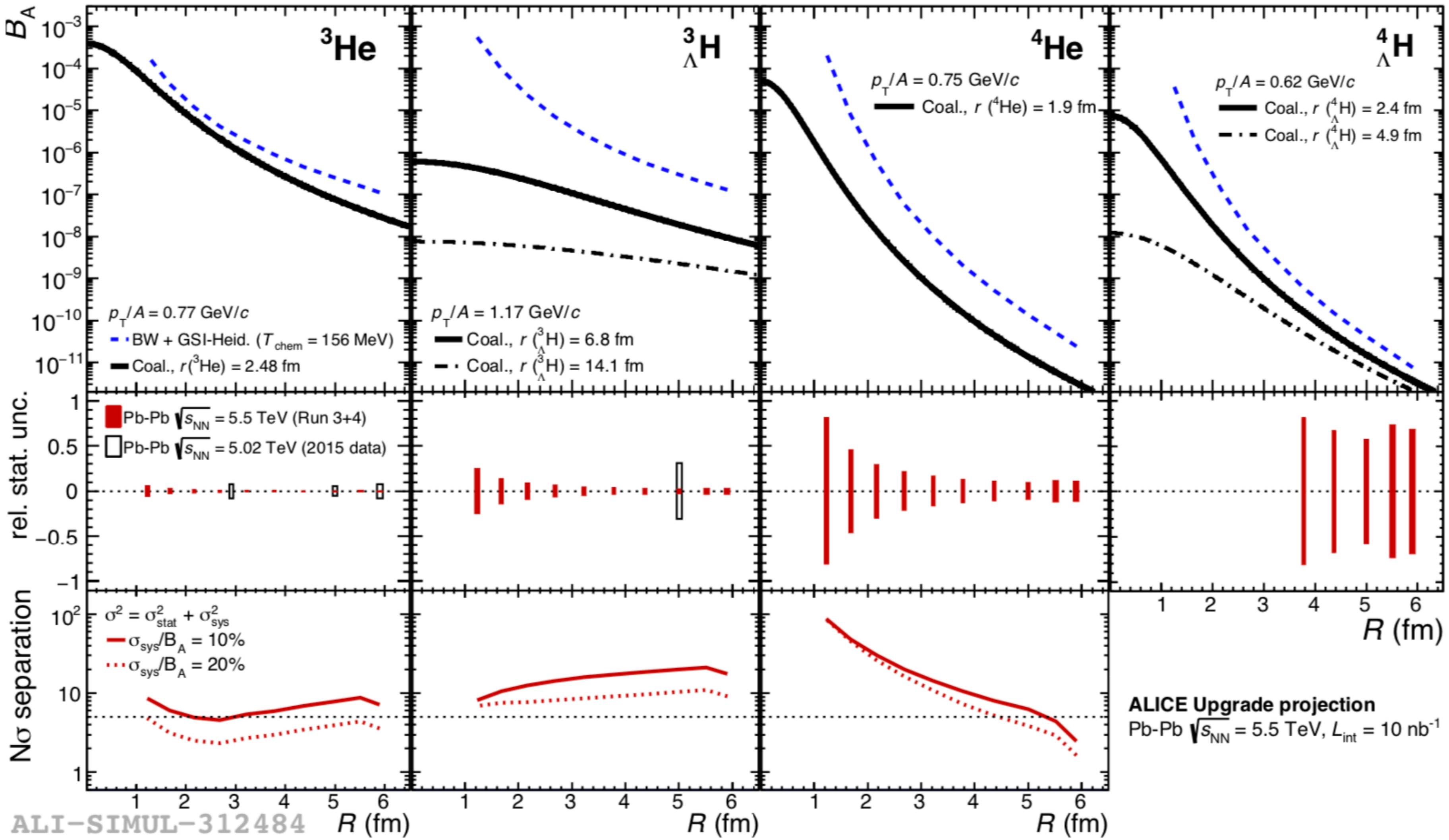
Yields of (hyper-)nuclei agree with SHM predictions at chemical freeze-out.
Final-state coalescence requires more detailed modelling (ex, local baryon-strangeness correlation):
simple coalescence ($S_3 \approx 1$) does not describe data.



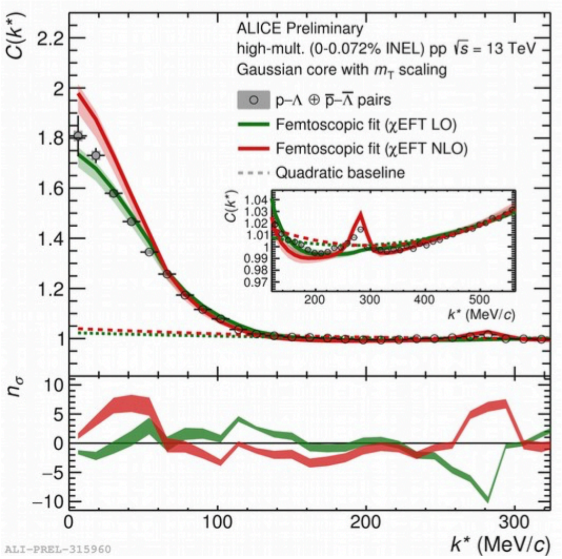
(anti-)(hyper-)nuclei - prospects

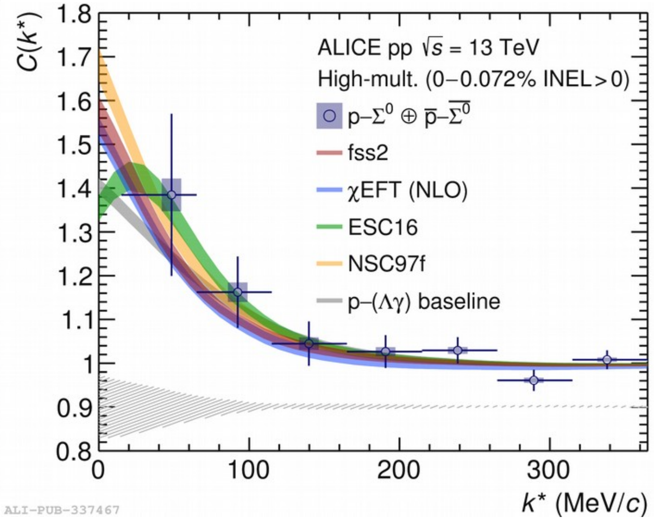
Utilize very different sizes of (hyper)nuclei vs radius of fireball

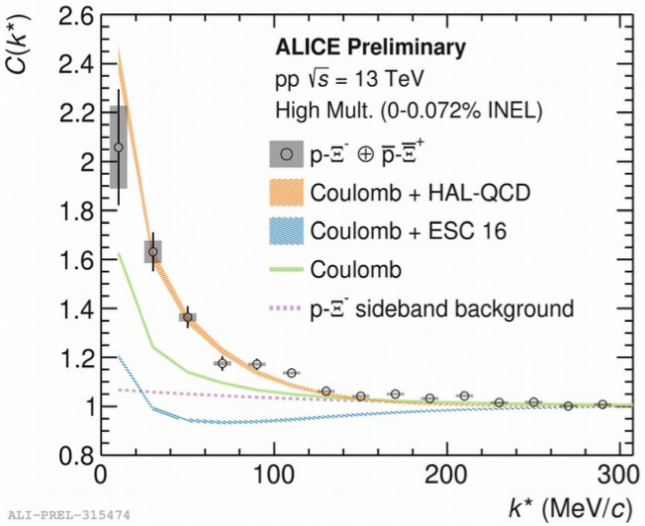
- Run 3 and Run 4 will allow us to measure in details the production of even ^{4}He and hyper nuclei
- Decisive test for probing the interplay between system size and (hyper)(anti)nucleus wave function

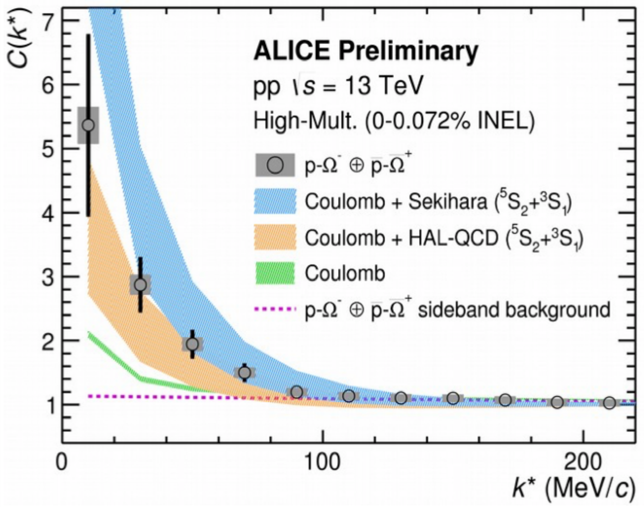


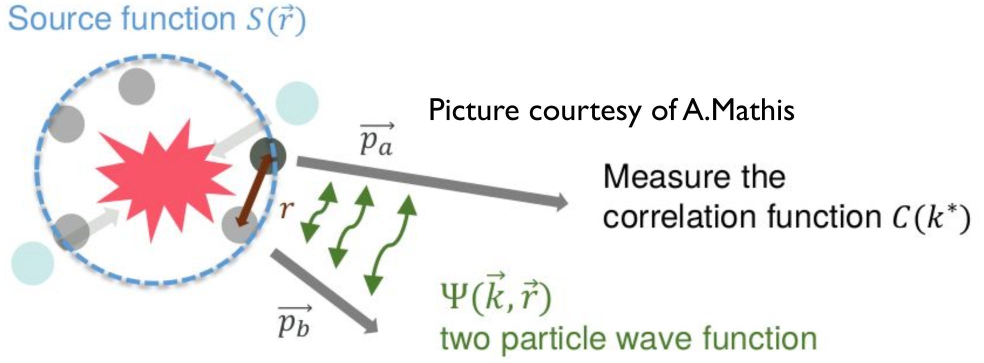
Correlation functions











Picture courtesy of A.Mathis

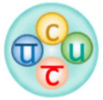
$$C(k^*) = \mathcal{N} \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)} = \int S(r)\ |\Psi(k^*,r)|^2\ d^3r$$

ALICE in investigating correlation functions for various pairs via femtoscopy technique.

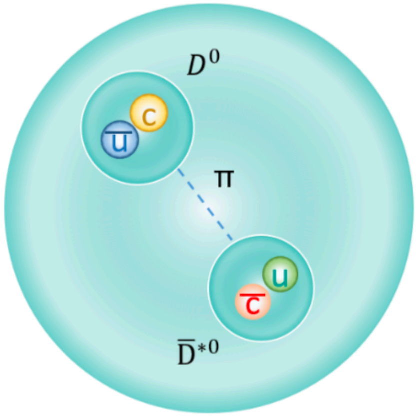
The formation of any exotic bound objects can be studied by studying correlation functions in ALICE Run3 and Run4.
For example, (d, Λ) → $^3{}_\Lambda$H and (^{3}He, Λ)→ $^4{}_\Lambda$He, (d, Λ_c)→ c-triton

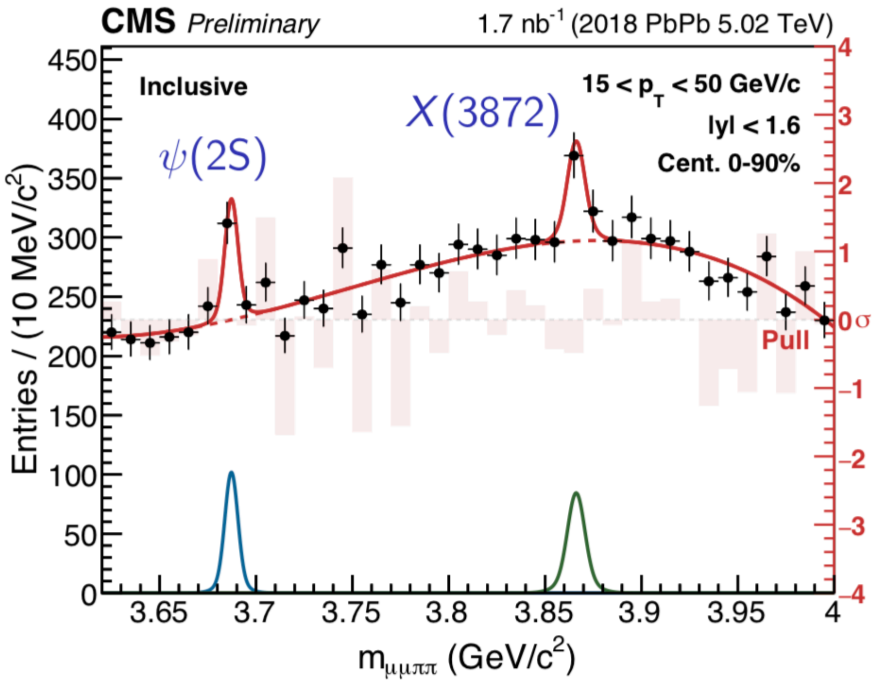
X(3872)

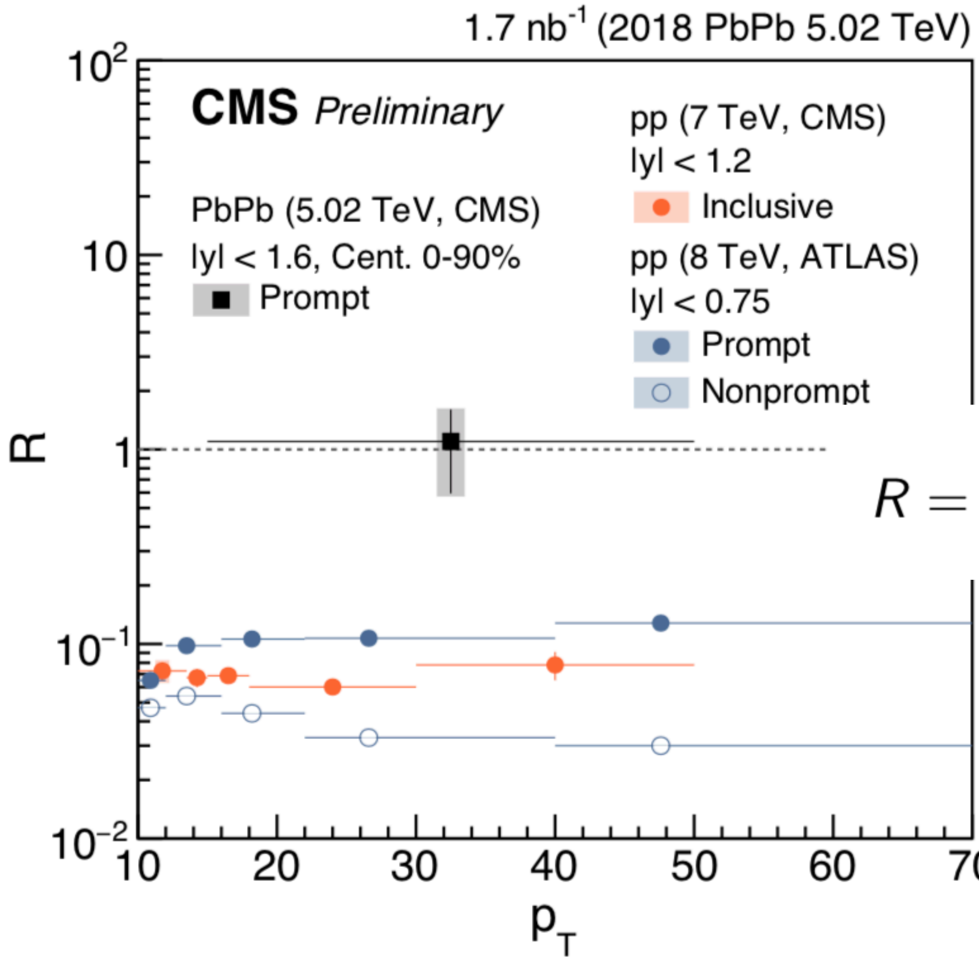
Tetraquark (4q)



$D^0 - \bar{D}^{*0}$ molecule



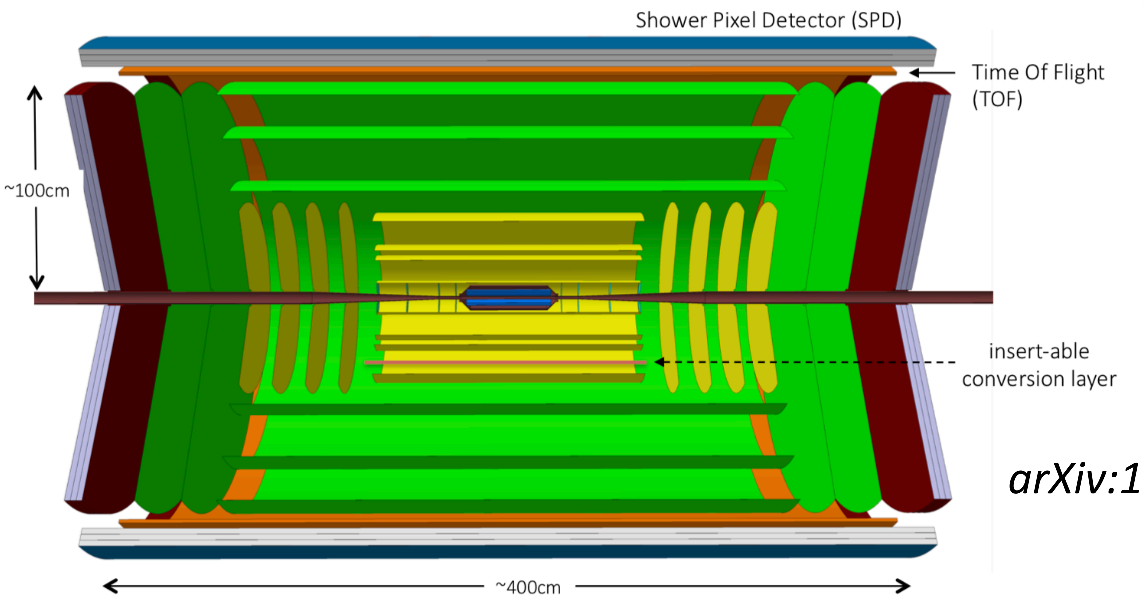




$$R = N^{(\mathrm{Corr})}_{X(3872)} / N^{(\mathrm{Corr})}_{\psi(2S)}$$

ψ(2S) is strongly suppressed in Pb-Pb.
X(3872) is less suppressed than ψ(2S)

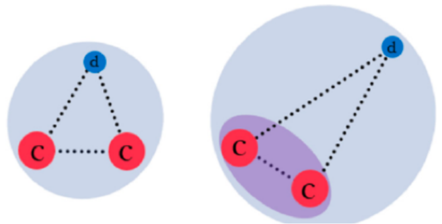
ALICE beyond 2030

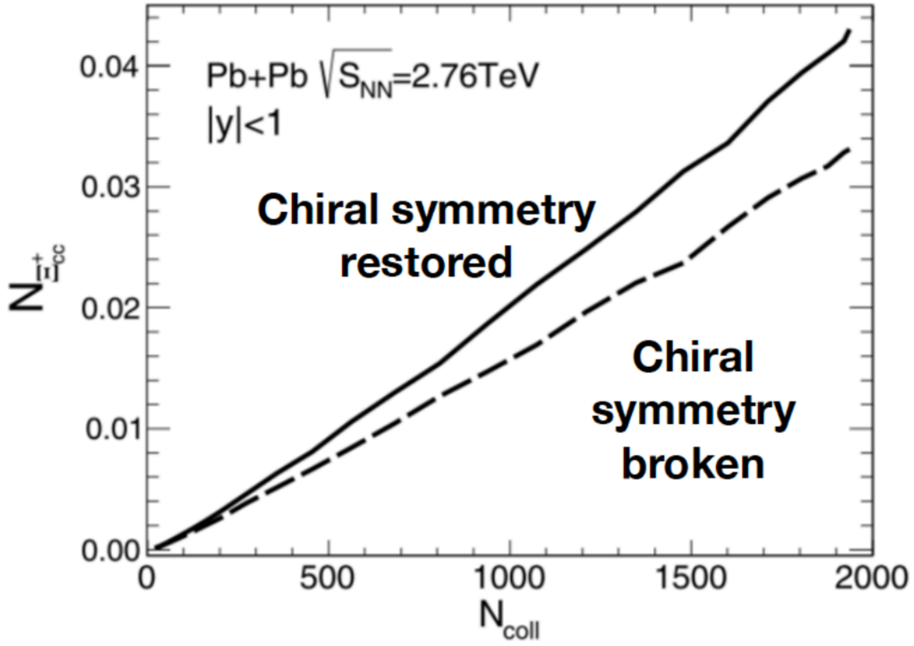


arXiv:1902.01211

Multiply Heavy Flavored hadrons. e.g.: Ξ_{cc}, Ω_{cc}, Ω_{ccc}

- Ultimate precision on B mesons at low p_T
- X, Y, Z charmonium-like states (e.g. X(3872))





[Zhao, He, Zhuang, PLB 771 (2017) 349-353]

Chiral symmetry restoration on the coalescence hyper surface:

- Ξ_{cc} mass: 3.58 GeV → 2.79 GeV
- Ξ_{cc} <radius>: 0.41 fm → 0.49 fm
- Distance between 2 c quarks and between cc pair and q: $\langle r_{cc}\rangle$=0.44 fm, $\langle r_{cc\text{-}q}\rangle$=0.53 fm → $\langle r_{cc}\rangle$=0.46 fm, $\langle r_{cc\text{-}q}\rangle$=0.97 fm

Chiral symmetry broken: Ξ_{cc} is a 3-quark state ccq
Chiral symmetry restored: Ξ_{cc} is a quark-diquark state

→ *production yield sensitive to coalescence happening between a 3-quark state and a diquark-quark state*

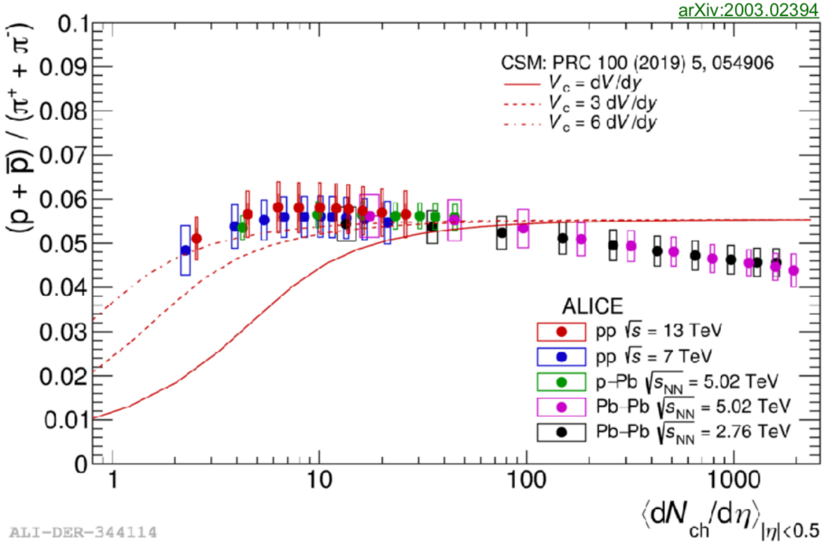
Summary and outlook

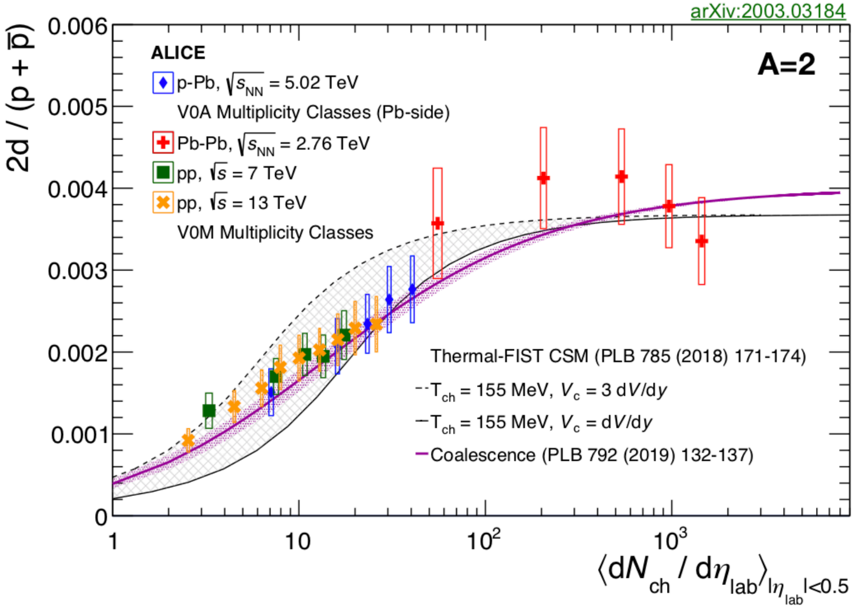
- ALICE upgrade is progressing well.
  - LHC and ALICE Run3+Run4 plans will be revisited due to COVID-19 crisis.
- With ALICE upgrade, more detailed understanding on:
  - Temperature dependence of medium properties
  - Di-quark correlations
  - Thermal dileptons, low mass vector meson spectral functions
  - Production of (anti-)(hyper-)nuclei in heavy-ion collisions
- ALICE upgrade beyond 2030.
  - Any inputs are very welcome!

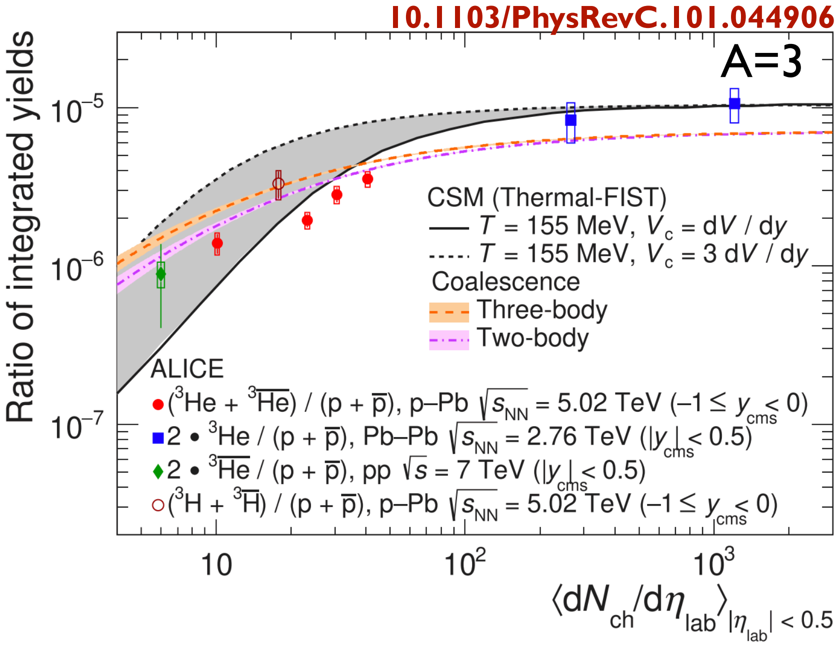
ALICE

Backup slides

Particle ratios vs. multiplicity



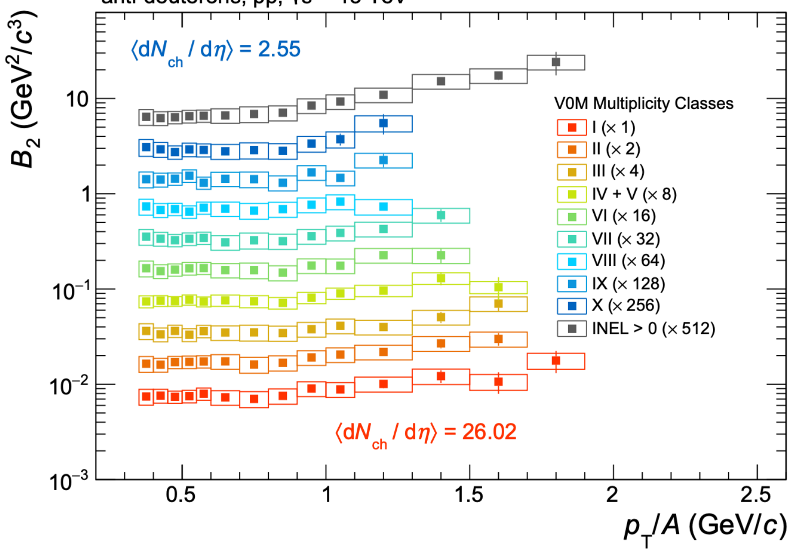




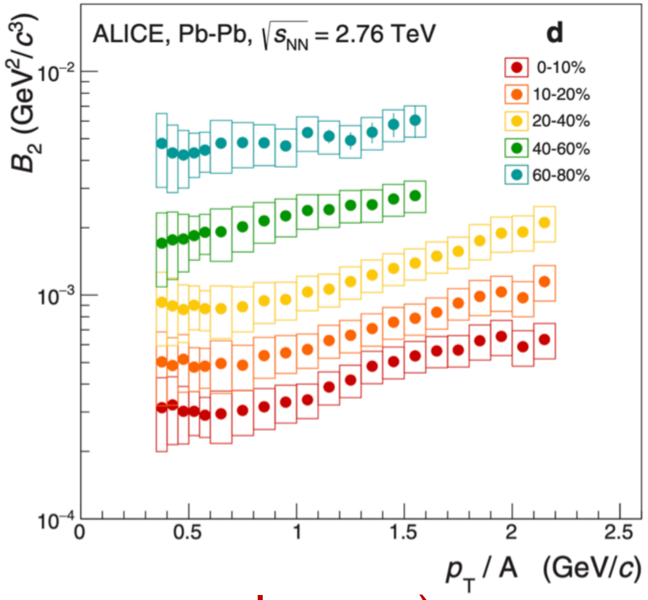
- Thermal model with canonical suppression gets the rise of the nucleus/proton ratio
  - However with the same parameters proton over pion ratio is not reproduced at low multiplicity
- Advanced nuclei coalescence can describe the d/p ratio but again struggle with the A=3 nuclei

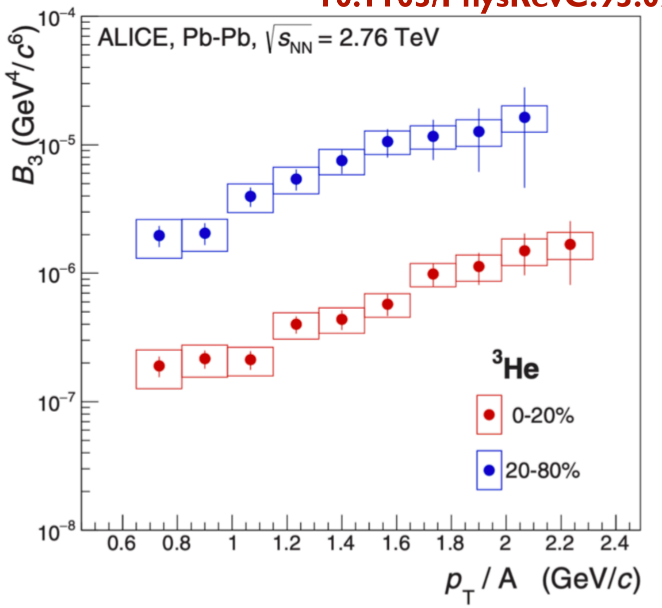
B_A vs. p_T and multiplicity

arXiv:2003.03184



10.1103/PhysRevC.93.024917

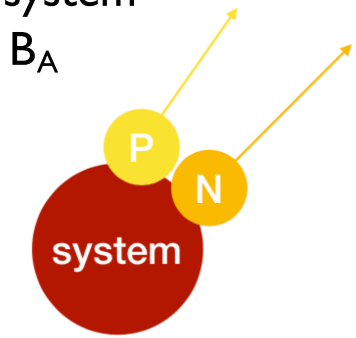




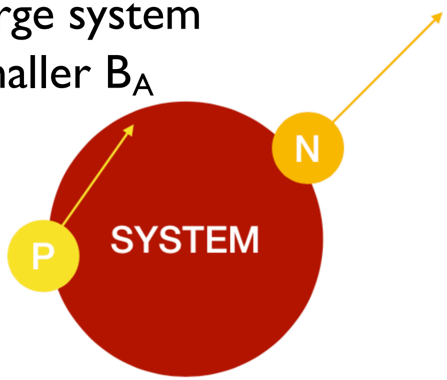
Smaller B_A as multiplicity becomes larger (more central events)

Small p_T dependence in pp and larger in Pb-Pb collisions

Small system
Large B_A

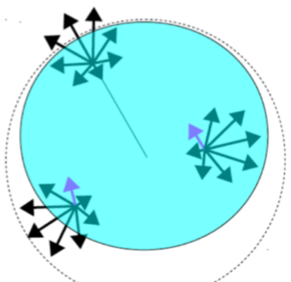


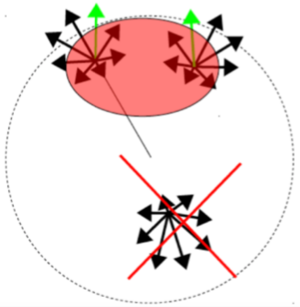
Large system
Smaller B_A



Due to radial expansion, as p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shift to the outside of the source

Small p_T
Smaller B_A





Large p_T
Larger B_A

HBT radii vs. multiplicity

- Measurements are carried out vs multiplicity
- Multiplicity → System size

- System size: **HBT radius R**

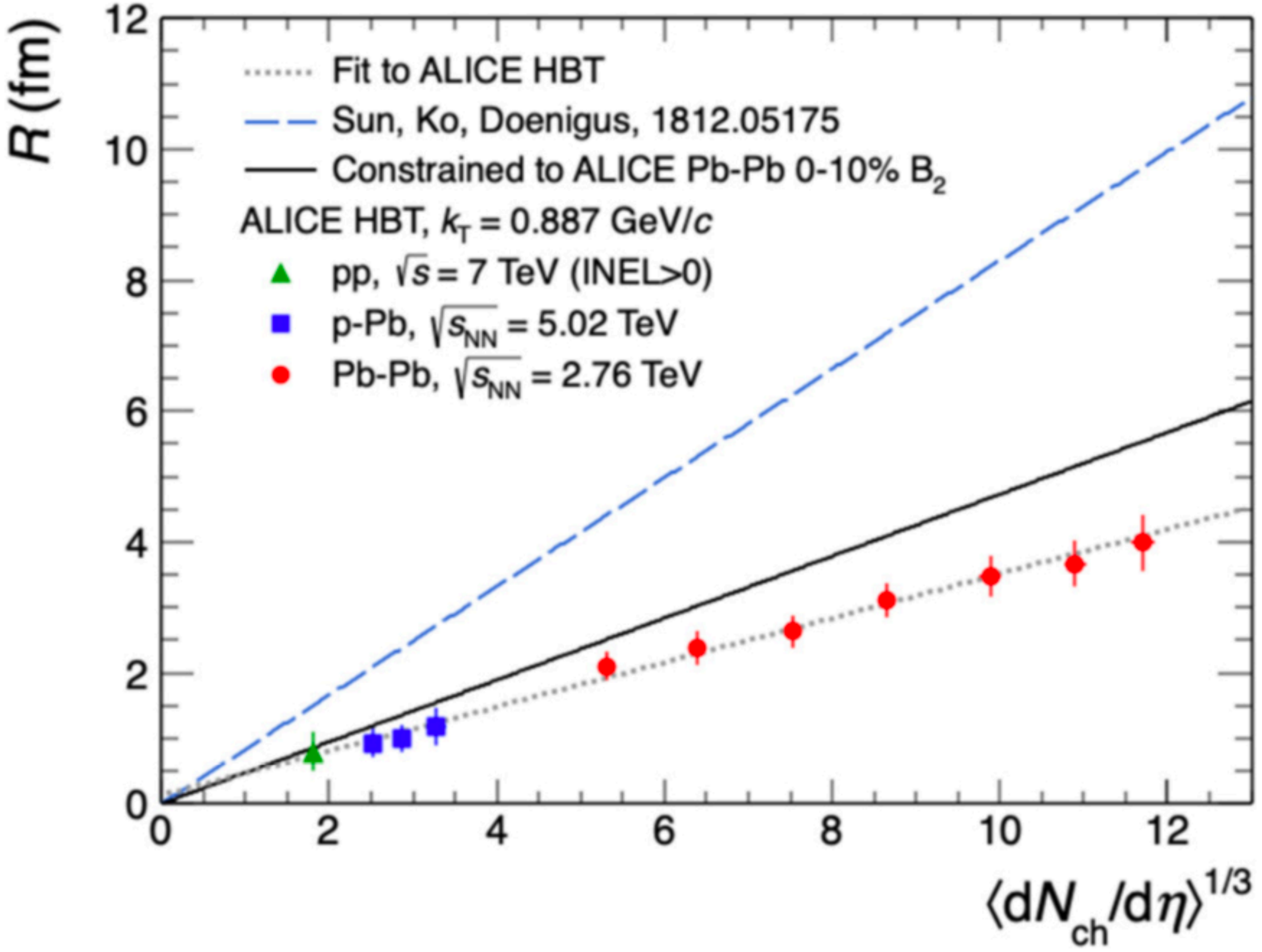
$$R = a \, \langle \mathrm{d}N/\mathrm{d}\eta \rangle^{1/3} + b$$

- **Two cases for B2 comparison:**

  A. *a* and *b* taken from a **fit** of R vs multiplicity

  B. *a* and *b* are **fixed** to reproduce B_2 in 0-10% Pb-Pb

. Bellini, A. Kalweit PRC.99.054905



From the correlation to the coalescence parameter

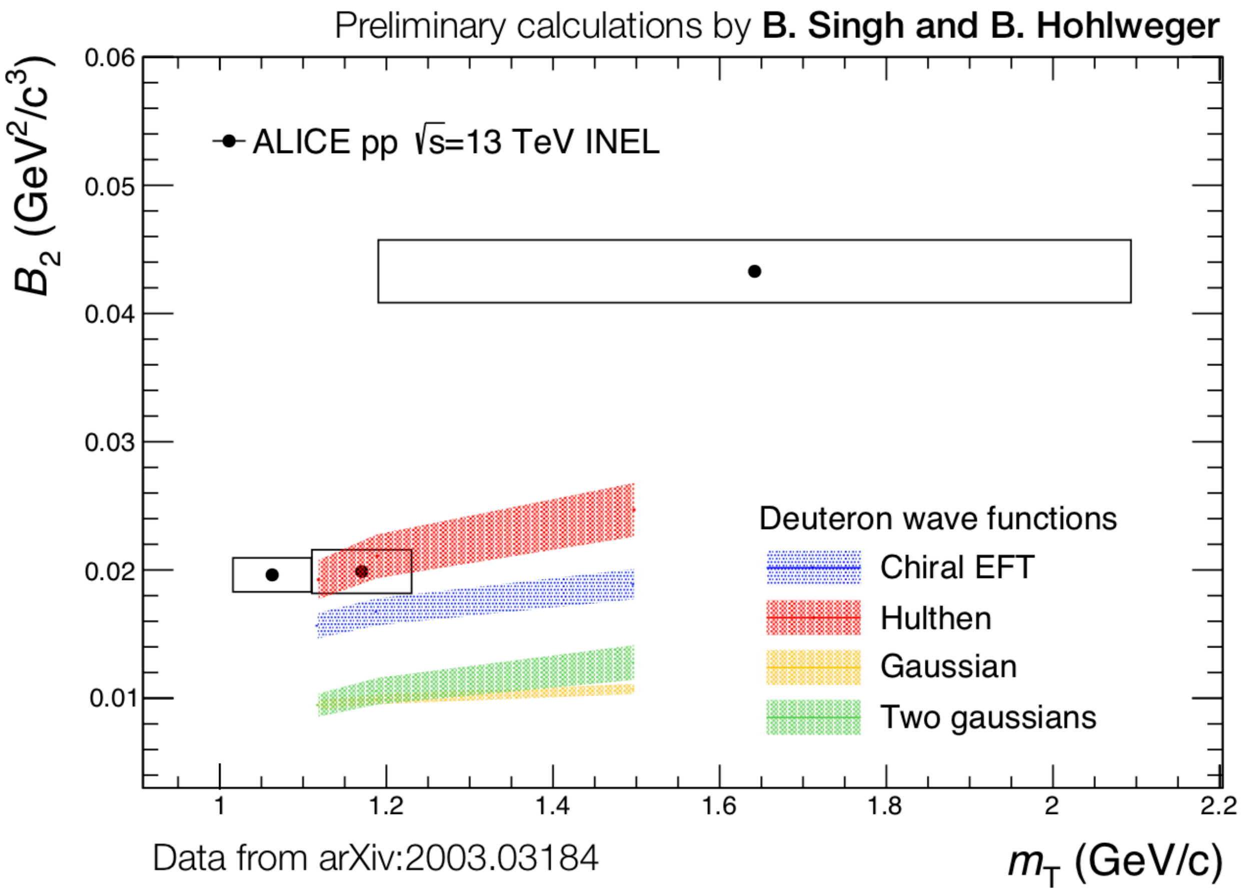
A new development that allows us to zoom into the production of nuclei through coalescence

$$B_2(p) \approx \frac{3}{2m} \int \mathrm{d}^3 q \underbrace{\boxed{\mathscr{D}(\vec{q})}}_{\text{Wigner density}} \overbrace{\boxed{\mathscr{C}_2^{\mathrm{PRF}}(\vec{p}, \vec{q})}}^{\text{Correlation radius}}$$

"Source Radius + Nucleus wave function -> B_2"

Different wave functions give very different expected coalescence parameter

*K. Blum, M. Takimoto PRC99, 044913 (2019)



Data from arXiv:2003.03184