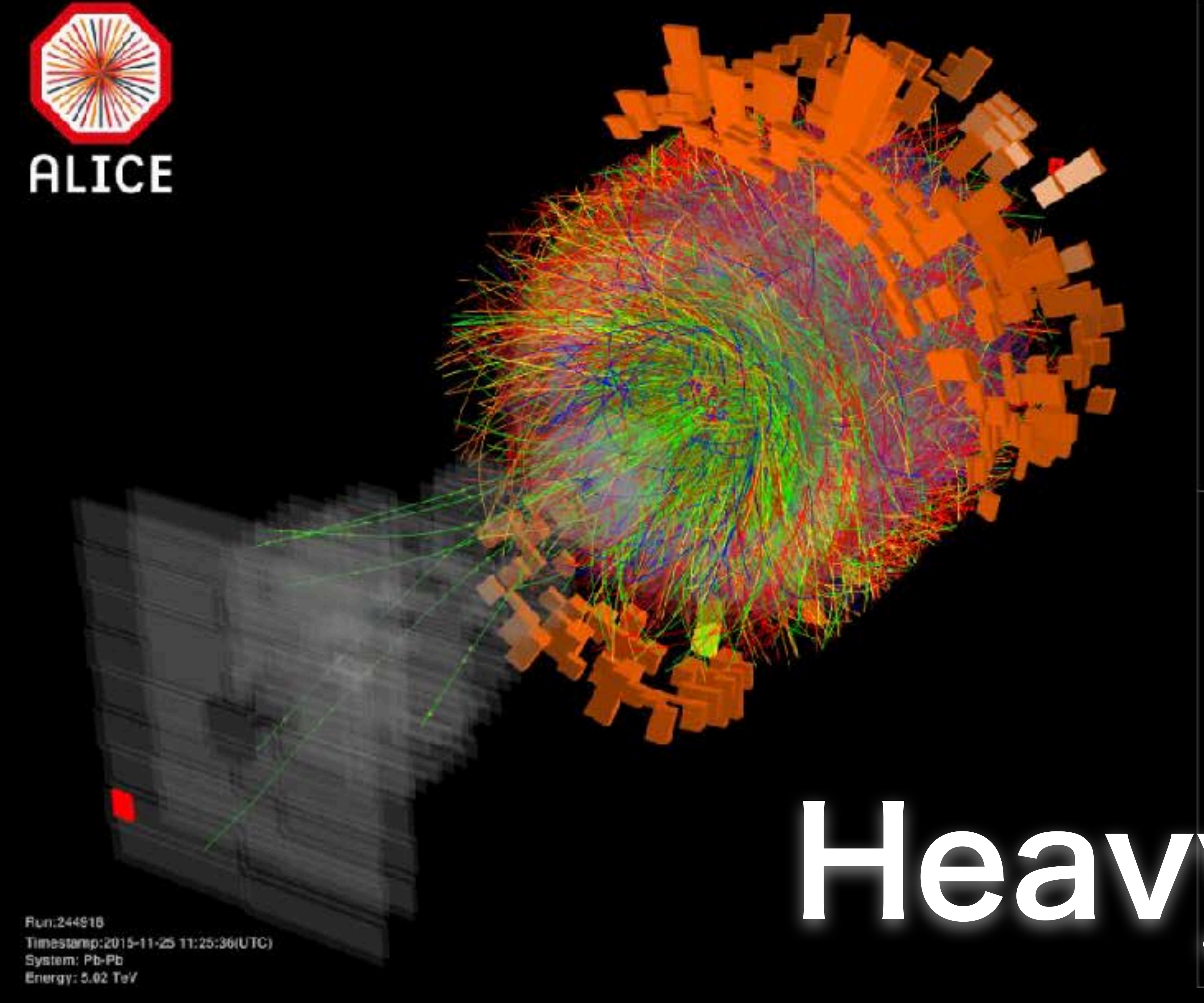
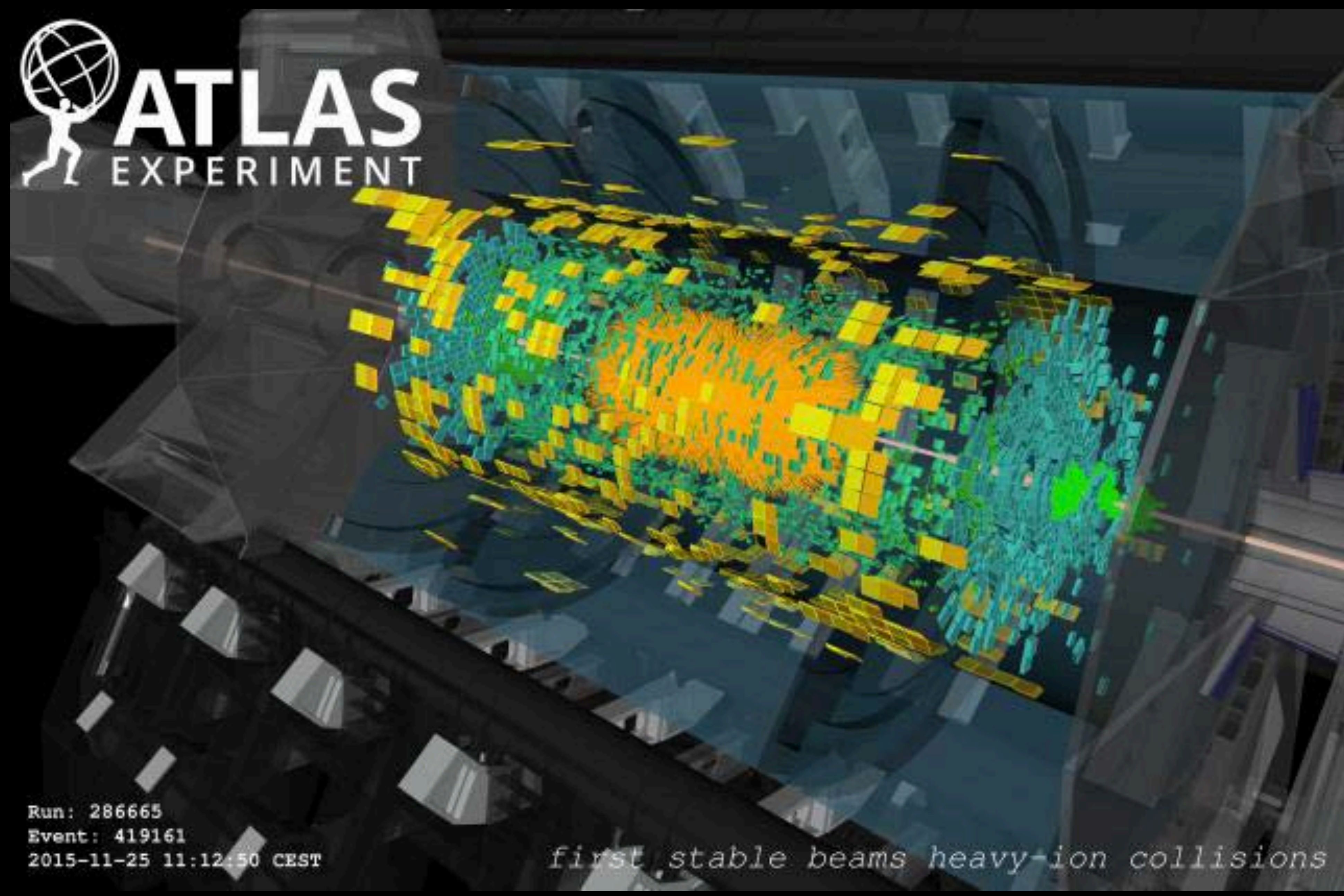
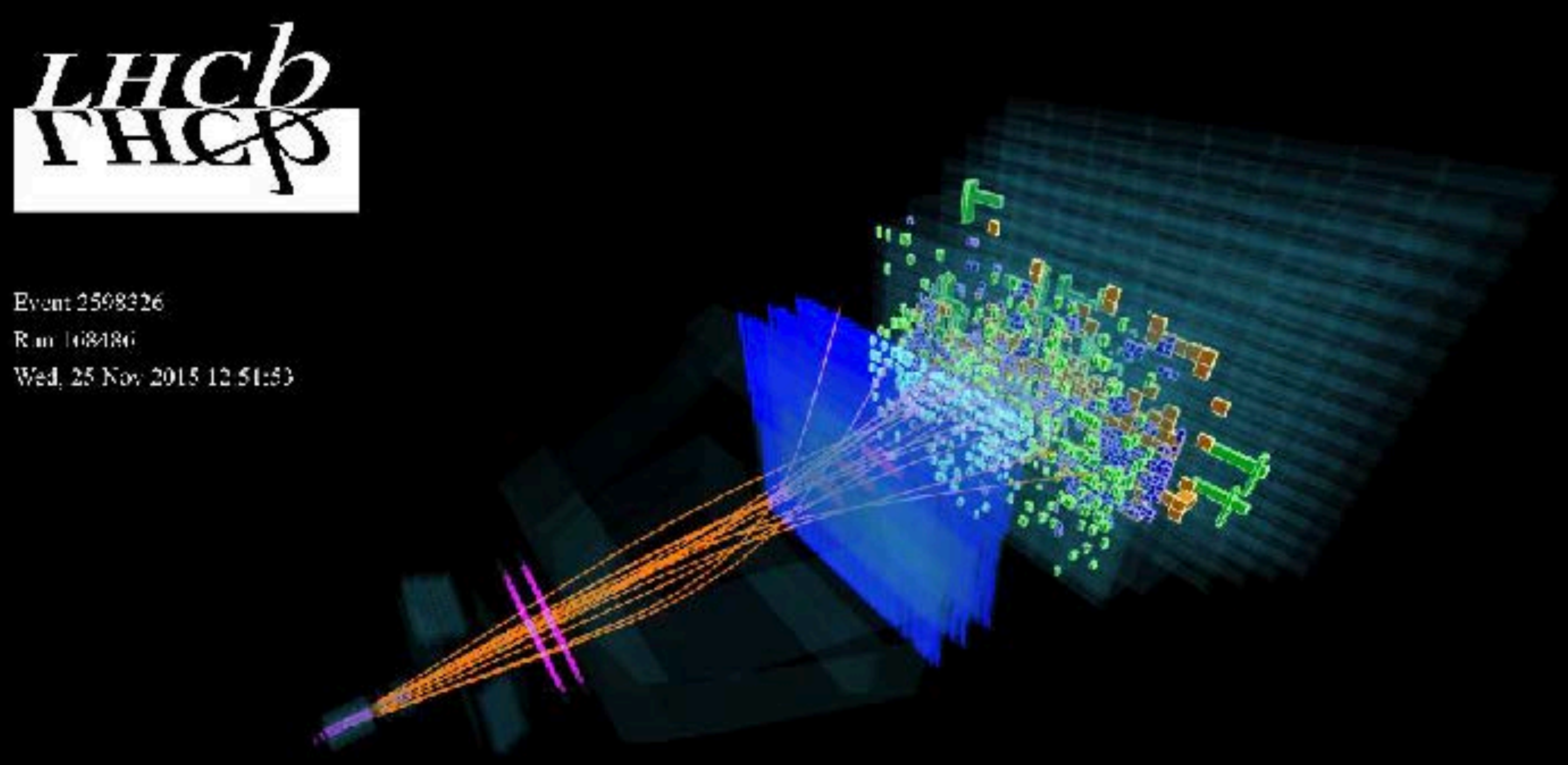
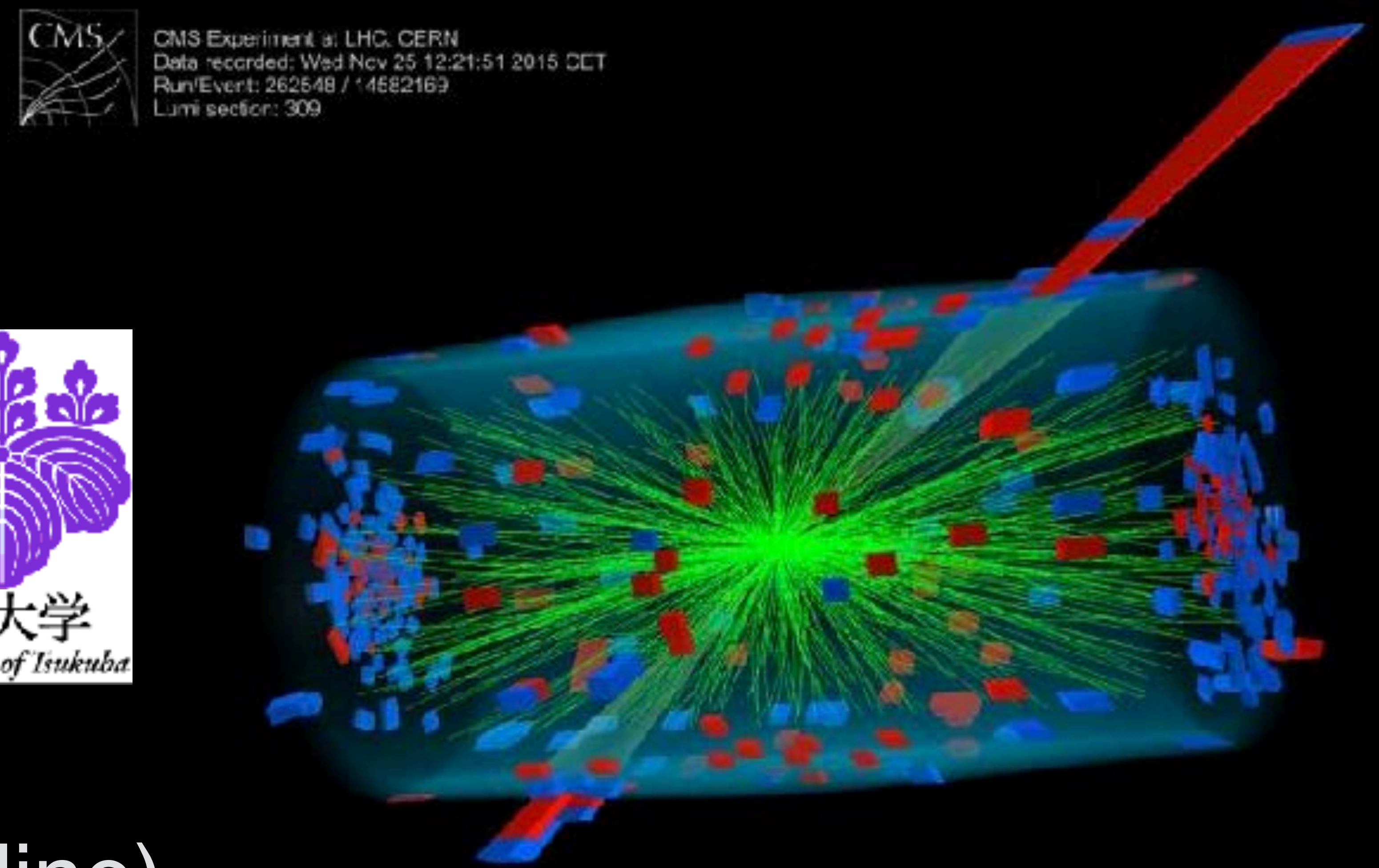




Heavy Ion Physics at LHC

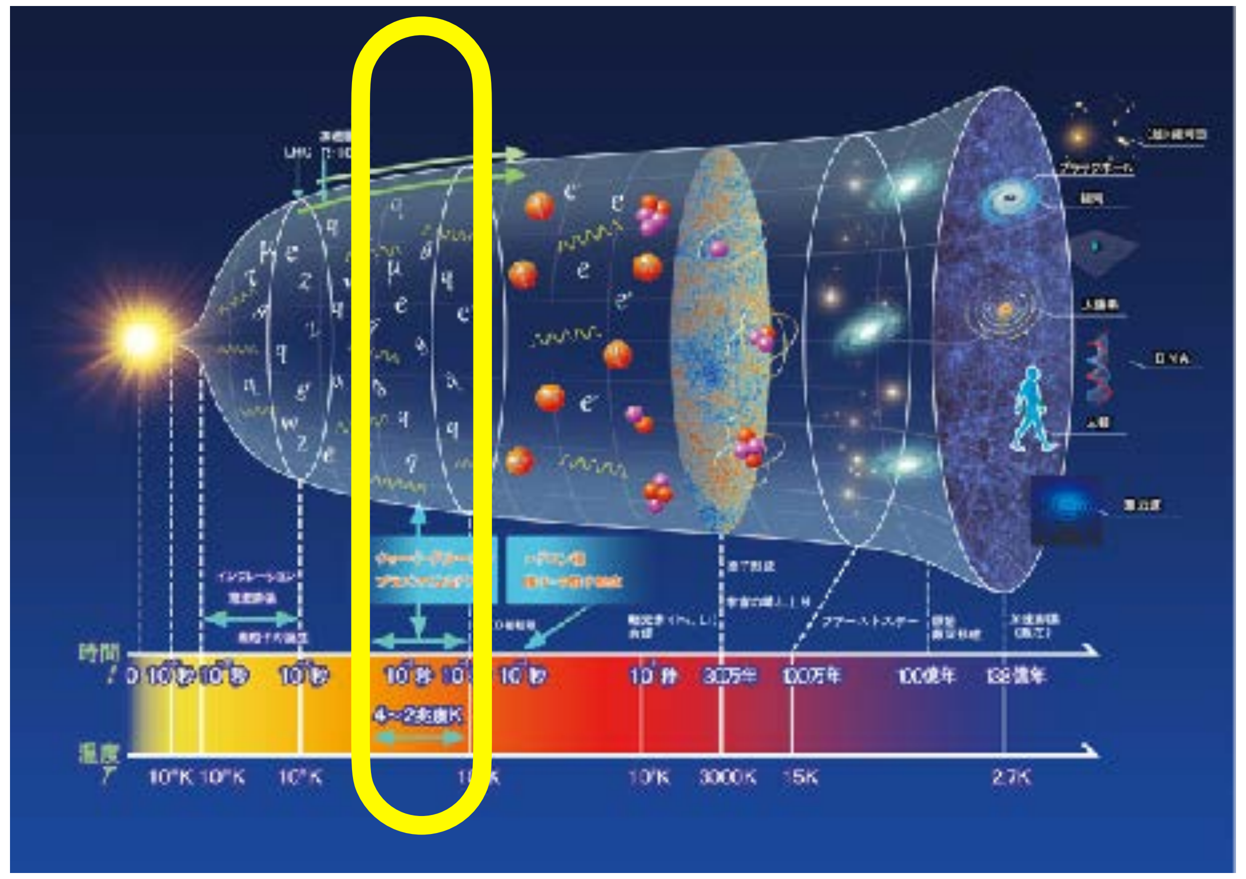


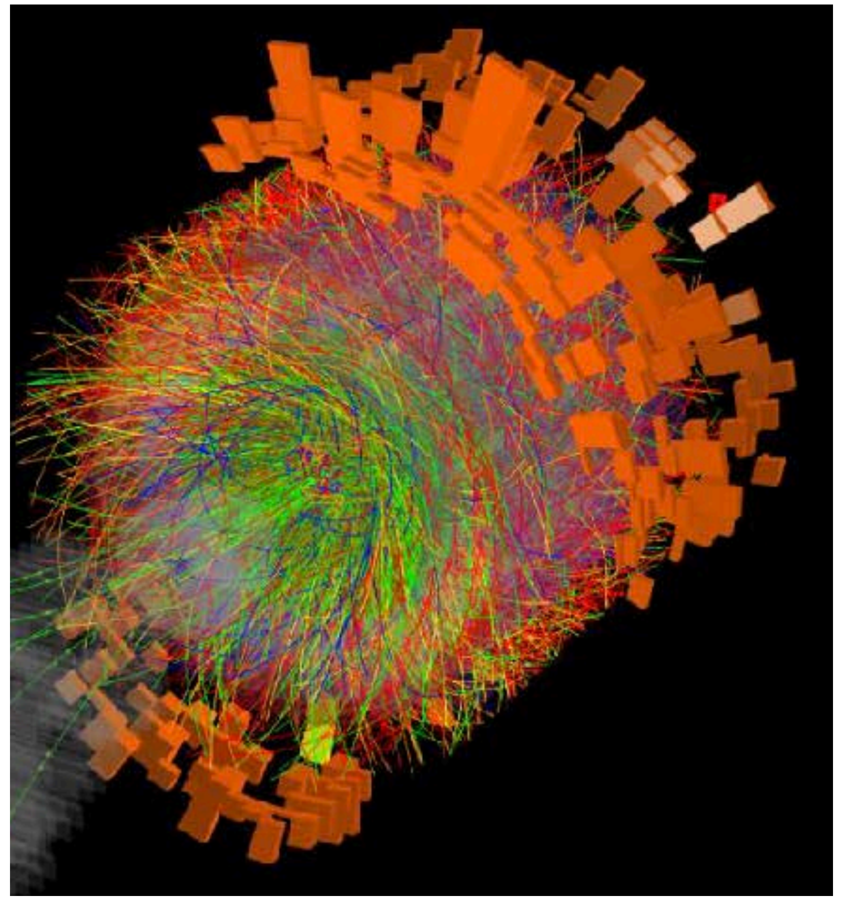


Tatsuya Chujo
Univ. of Tsukuba

TCHoU workshop, 2022, March 24 (online)

Phase transition in the universe

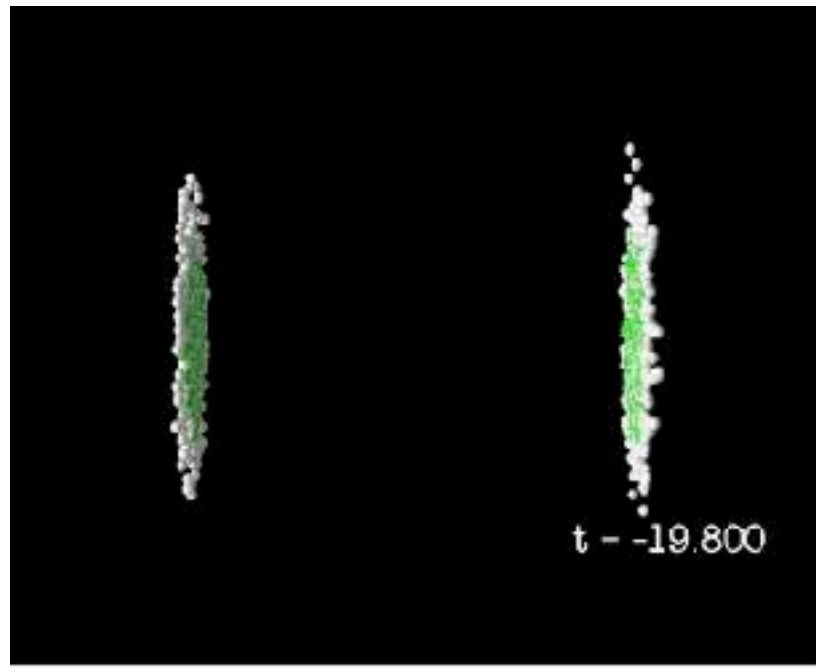


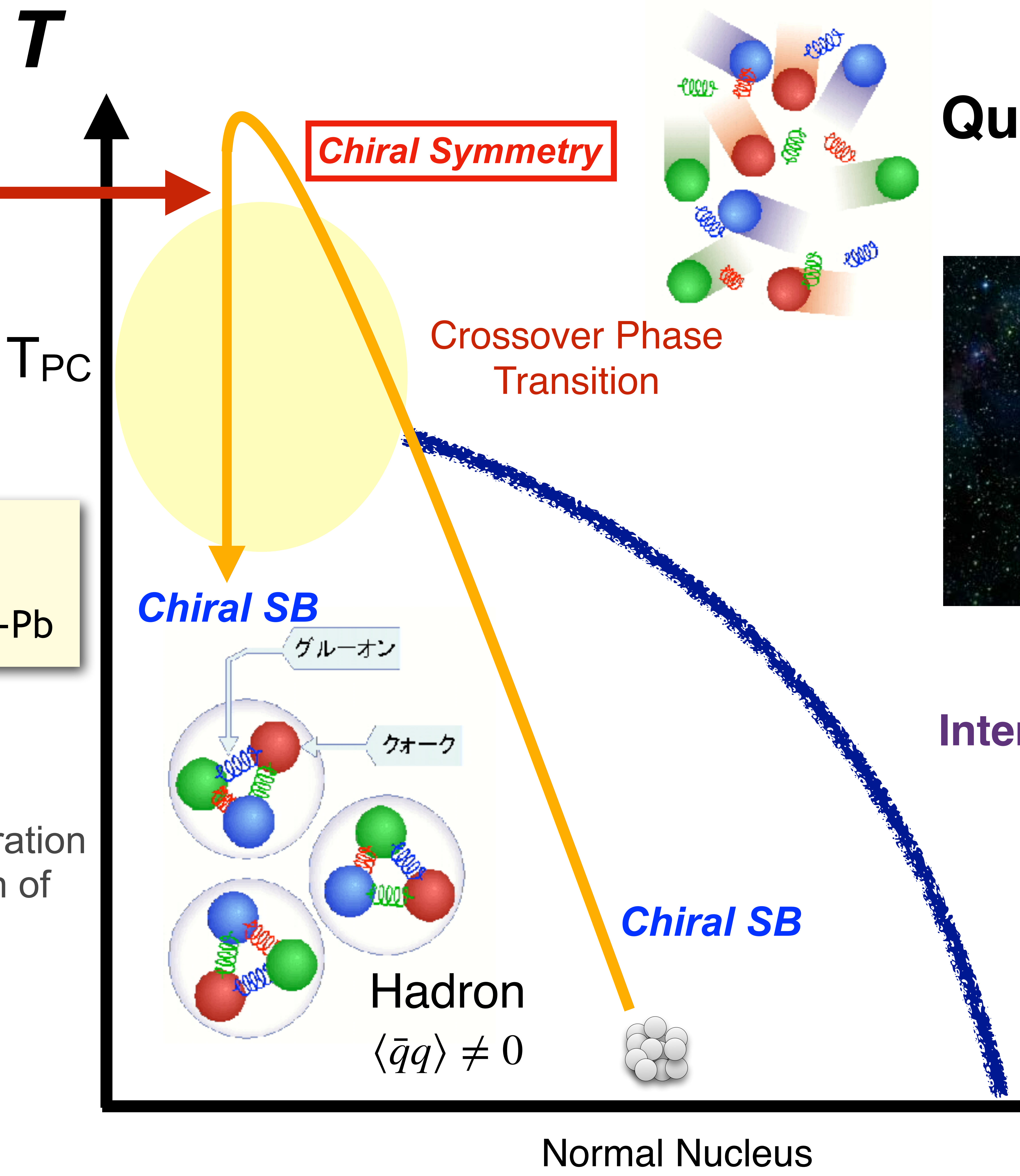


High Energy Nucleus-Nucleus Collisions

CERN (Switzerland)
LHC (2009-), 27 km
$\sqrt{s_{NN}}$ = 2.76, 5.02 TeV Pb-Pb

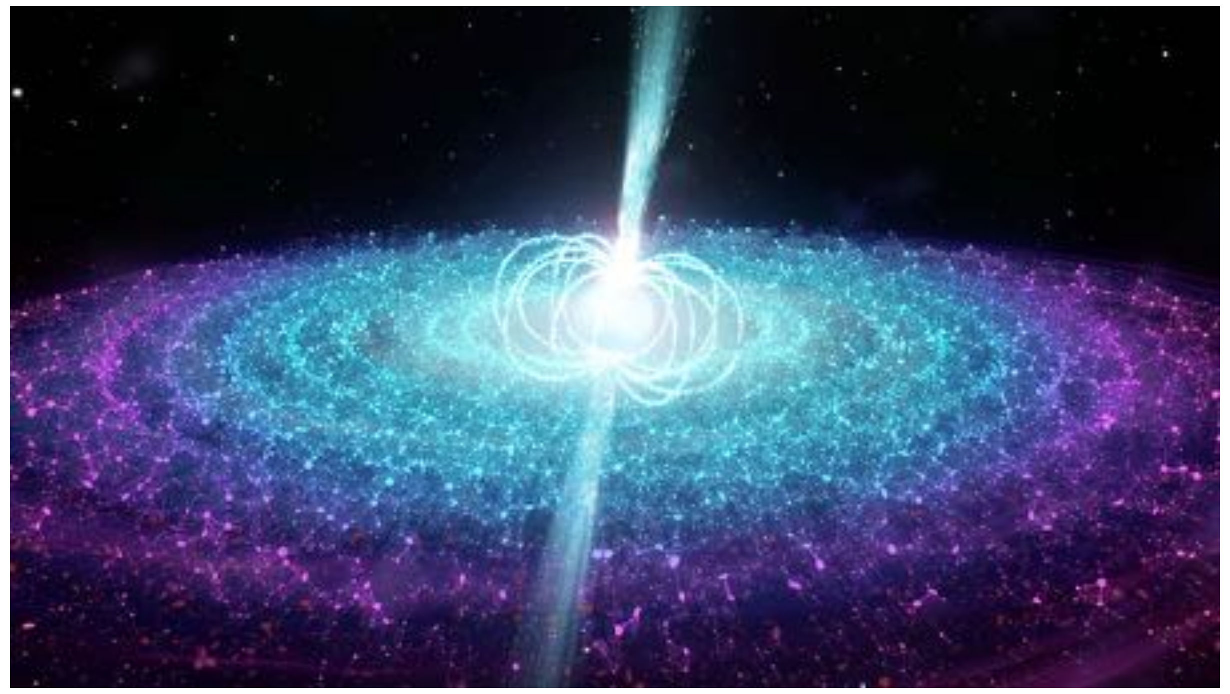
- Creation of QGP in the laboratory
- Properties of QGP, Restoration of Chiral Symmetry, Origin of nucleon mass





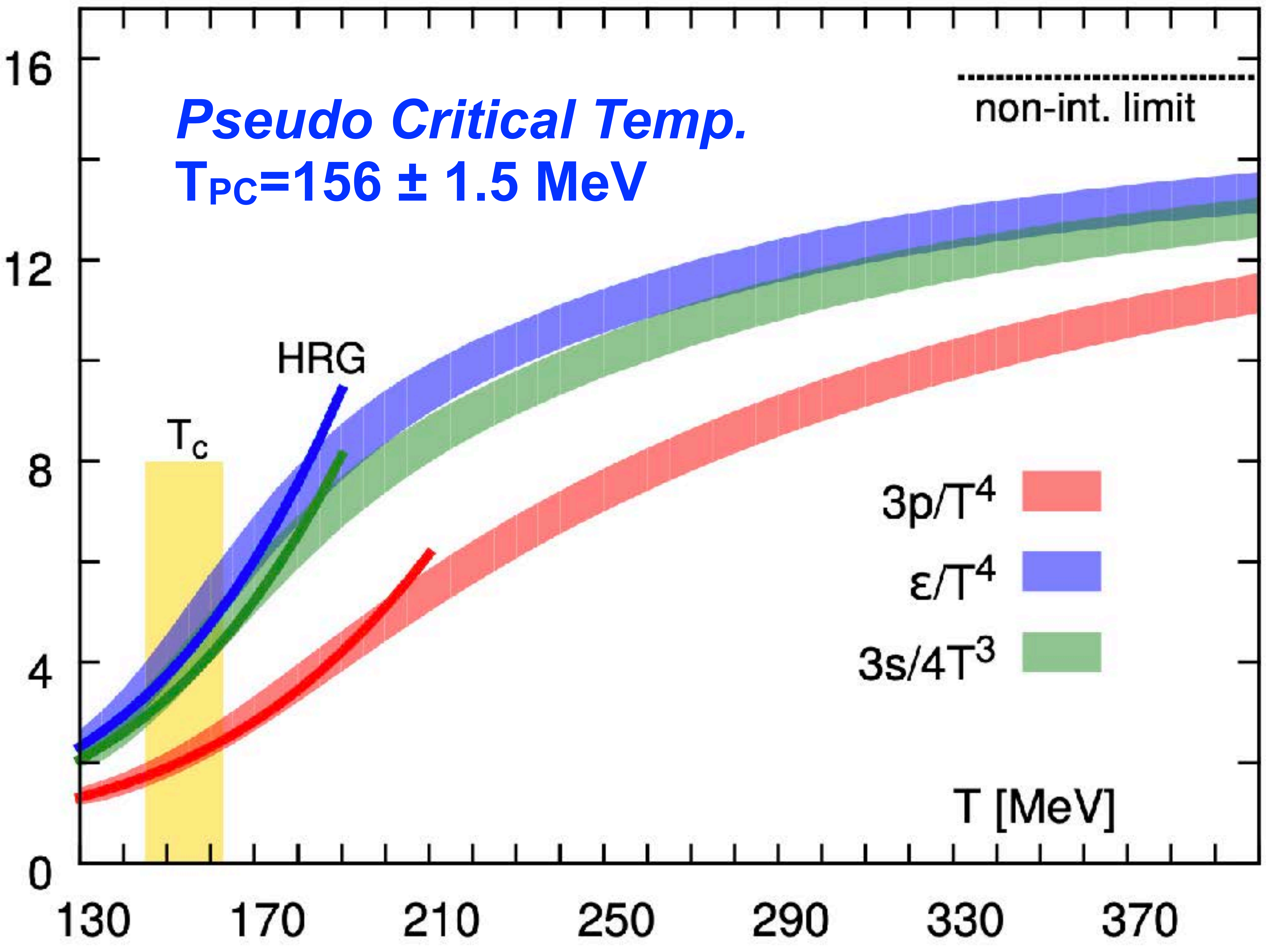
Neutron Star Merger

Interior of Neutron Star



* Neutron star image: https://phys.org/news/2018-09-neutron-star-jets-theory.html

Lattice QCD prediction



HotQCD Collaboration, PRD 90 (2014) 094503, arXiv:1407.6387 [hep-lat]

Crossover phase transition from hadronic phase to partonic phase

$$\epsilon = g\frac{\pi^2}{30}T^4$$

Ideal Stephan-Boltzmann Eq.

ε: energy density
T: temperature
g: degrees of freedom
(3: hadrons, 37: u, d quarks & gluon (spin, color, flavor))

To produce QGP, we need:

T_{pc} ~ 160 MeV

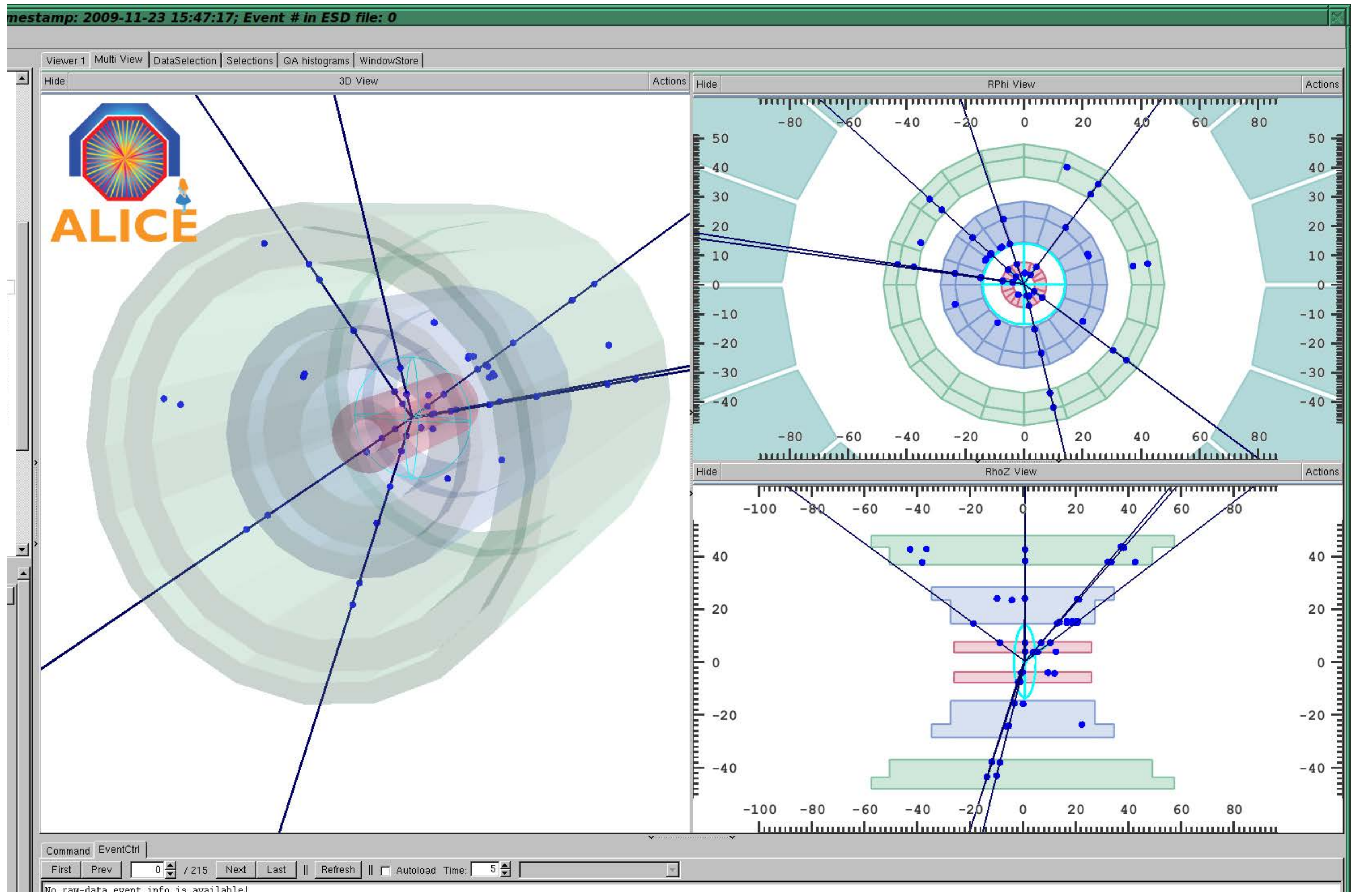
ε ~ 1 GeV/fm^3

Manifestation of dof for quarks and gluons

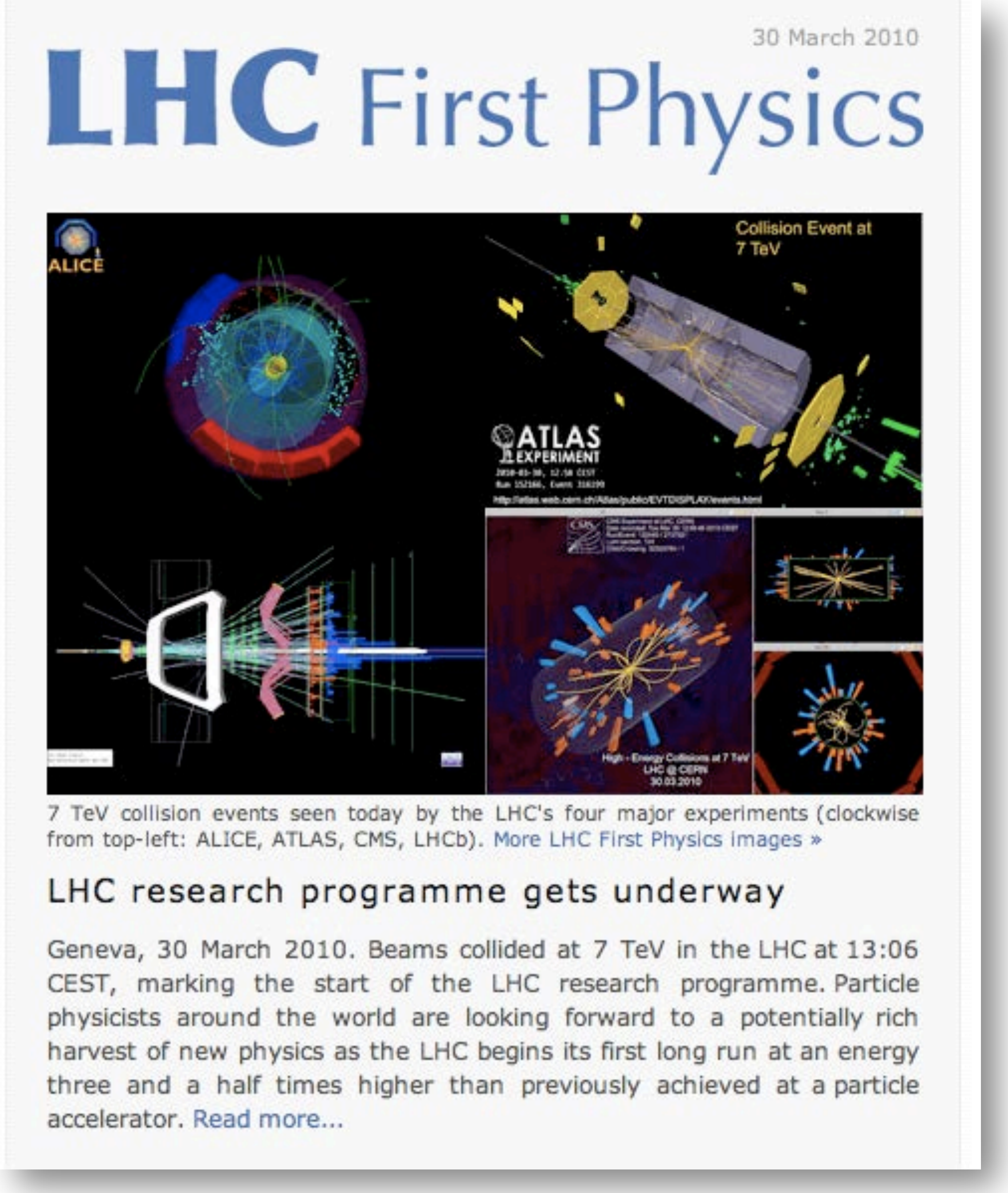
Part 1.
Experimental results from LHC heavy ion experiments

First Collisions (2009 - 2010)

Nov. 23, 2009
First p-p collisions at
$\sqrt{s}$= 900 GeV (ALICE)



Jan. 2010
First ALICE paper


30 March 2010

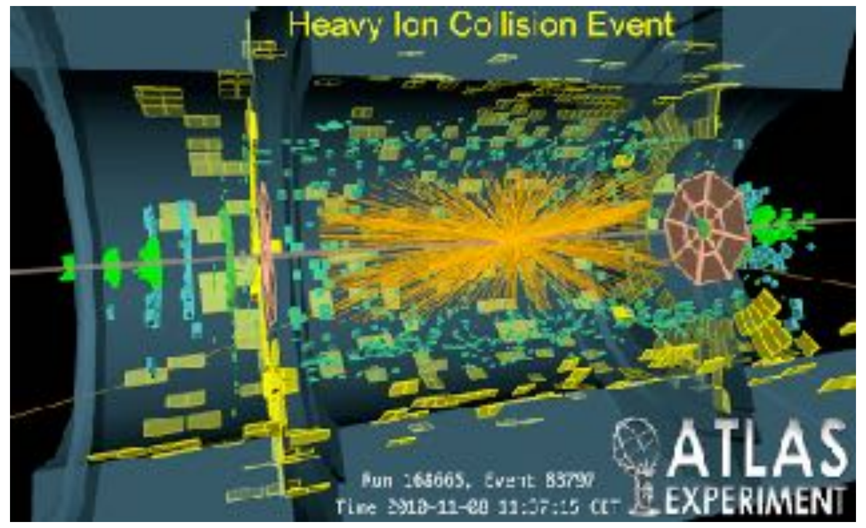
LHC First Physics

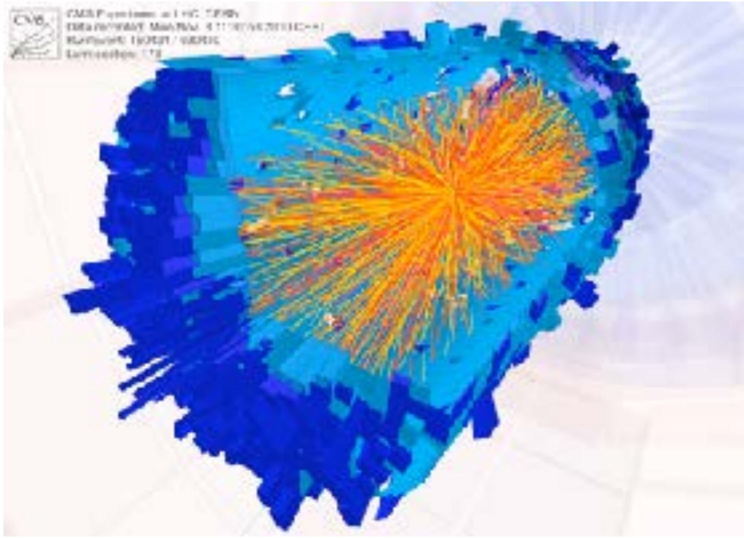
7 TeV collision events seen today by the LHC's four major experiments (clockwise from top-left: ALICE, ATLAS, CMS, LHCb). More LHC First Physics images »

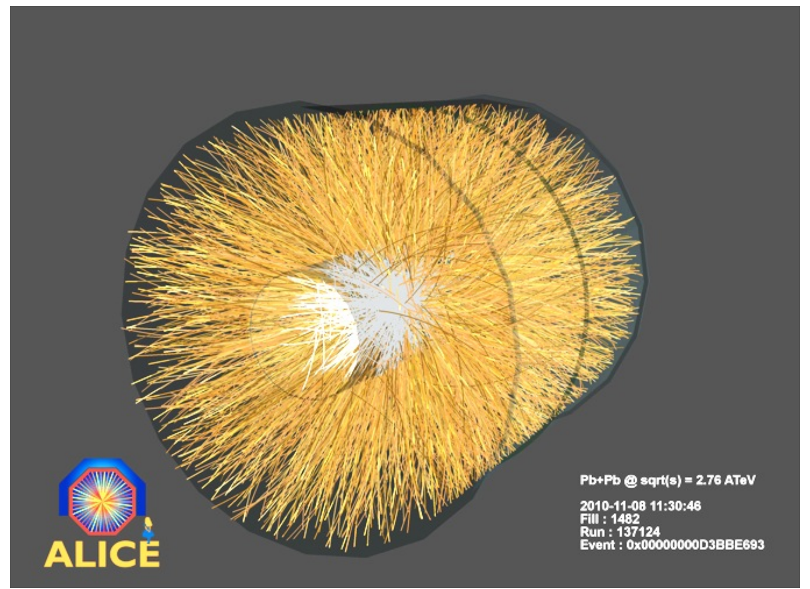
LHC research programme gets underway

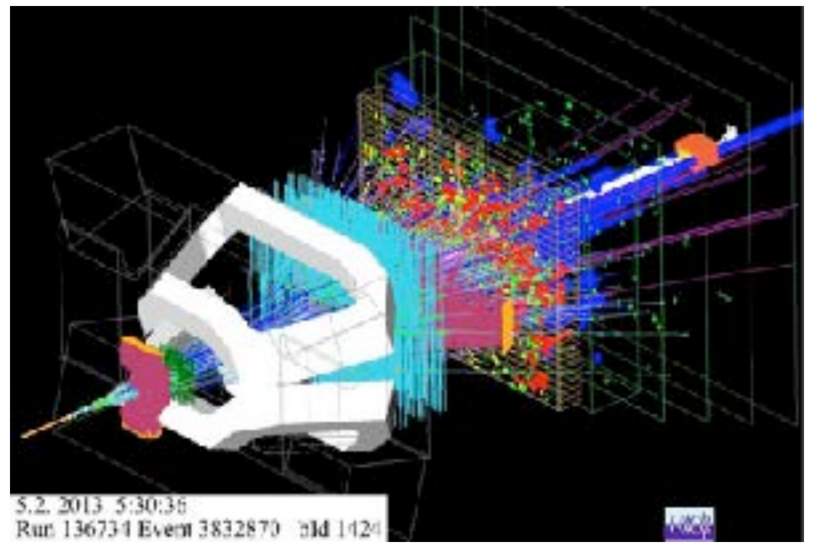
Geneva, 30 March 2010. Beams collided at 7 TeV in the LHC at 13:06 CEST, marking the start of the LHC research programme. Particle physicists around the world are looking forward to a potentially rich harvest of new physics as the LHC begins its first long run at an energy three and a half times higher than previously achieved at a particle accelerator. Read more...

Mar. 30, 2010
First p-p collisions
at $\sqrt{s}$ = 7 TeV





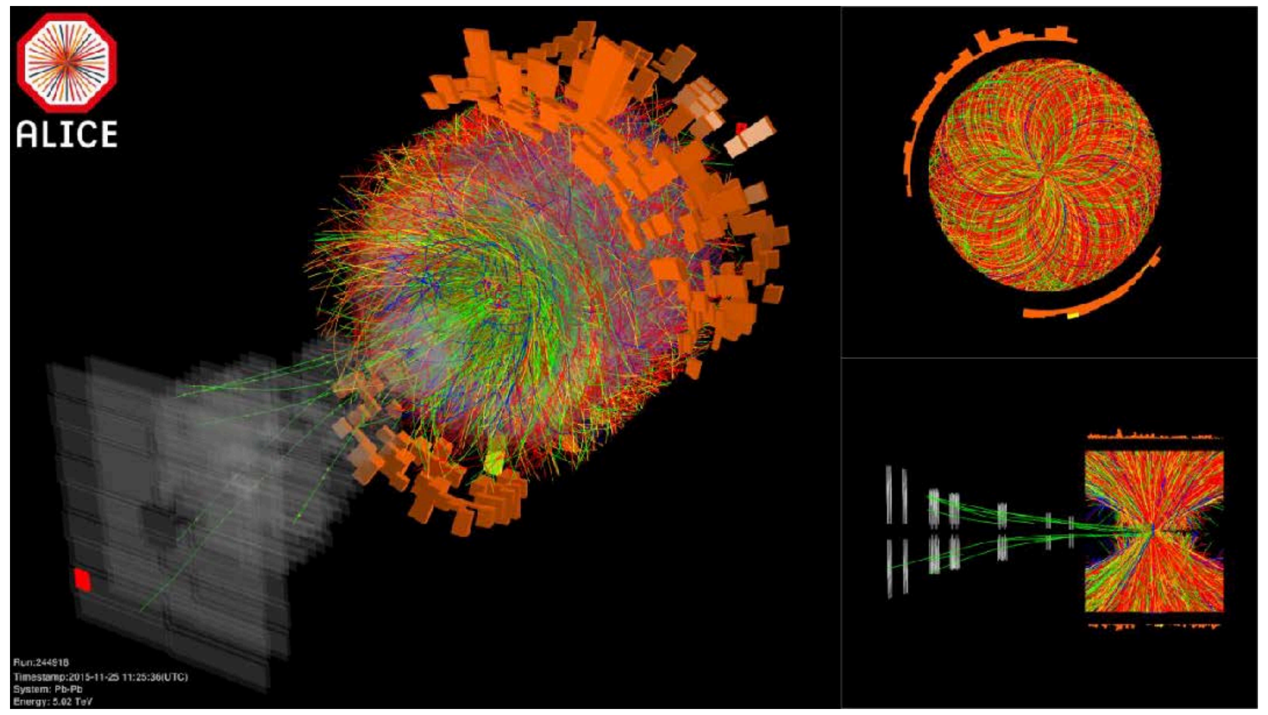




Nov. 8, 2010
First Pb-Pb collisions at
$\sqrt{s_{NN}}$ = 2.76 TeV

ALICE data collection

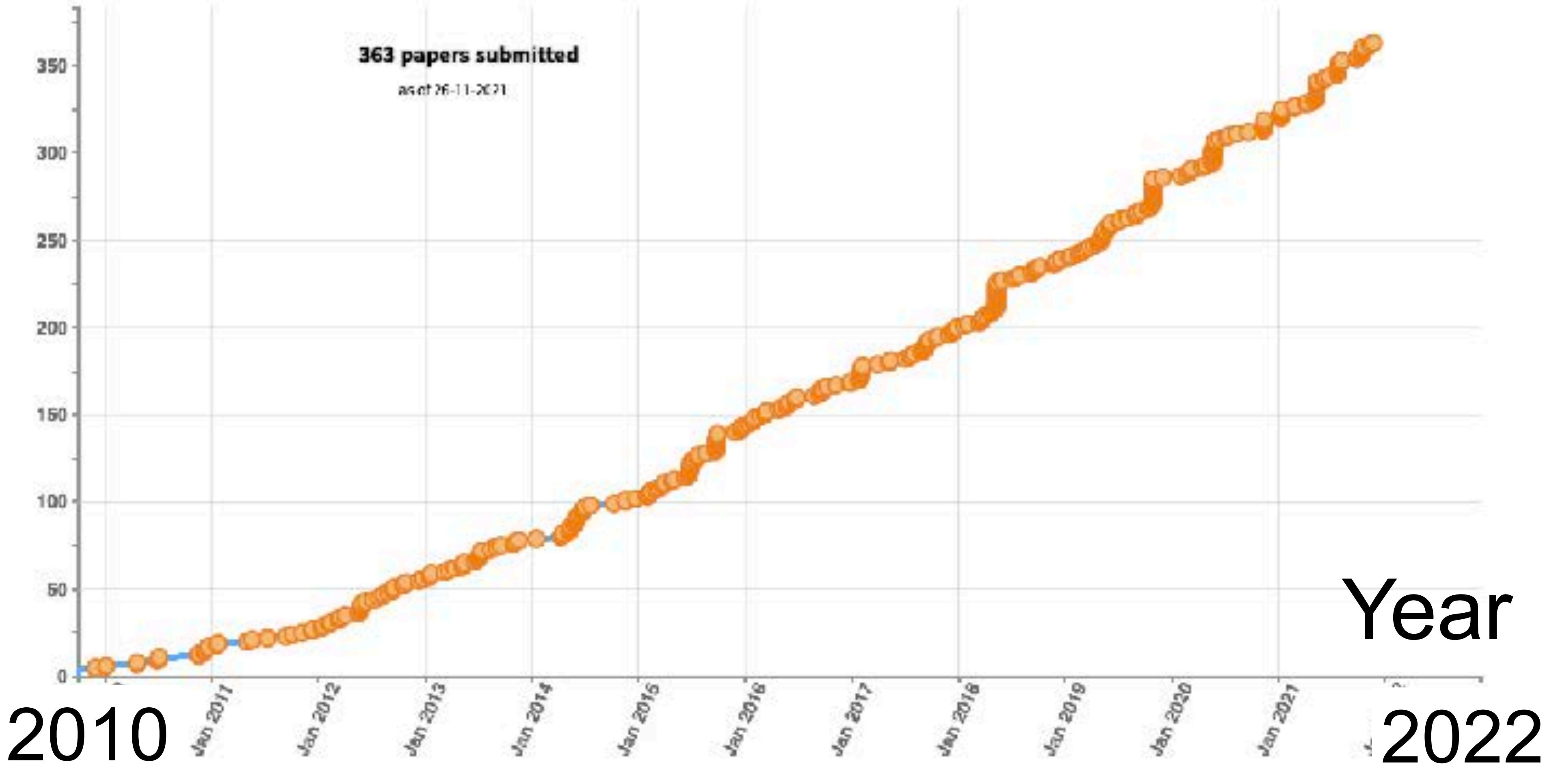
System	Year	Beam energy $\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2018	5.02	0.9 nb^{-1}
	2015	5.02	250 μb^{-1}
	2010-2011	2.76	75 μb^{-1}
Xe-Xe	2017	5.44	0.3 μb^{-1}
p-Pb	2016	8.16	25 nb^{-1}
		5.02	3 nb^{-1}
	2013	5.02	15 nb^{-1}
pp	2015-2018	13	59 pb^{-1}
		5.02	1.3 pb^{-1}
	2009-2013	8	2.5 pb^{-1}
		7	1.5 pb^{-1}
		2.76	100 μb^{-1}
		0.9	200 μb^{-1}



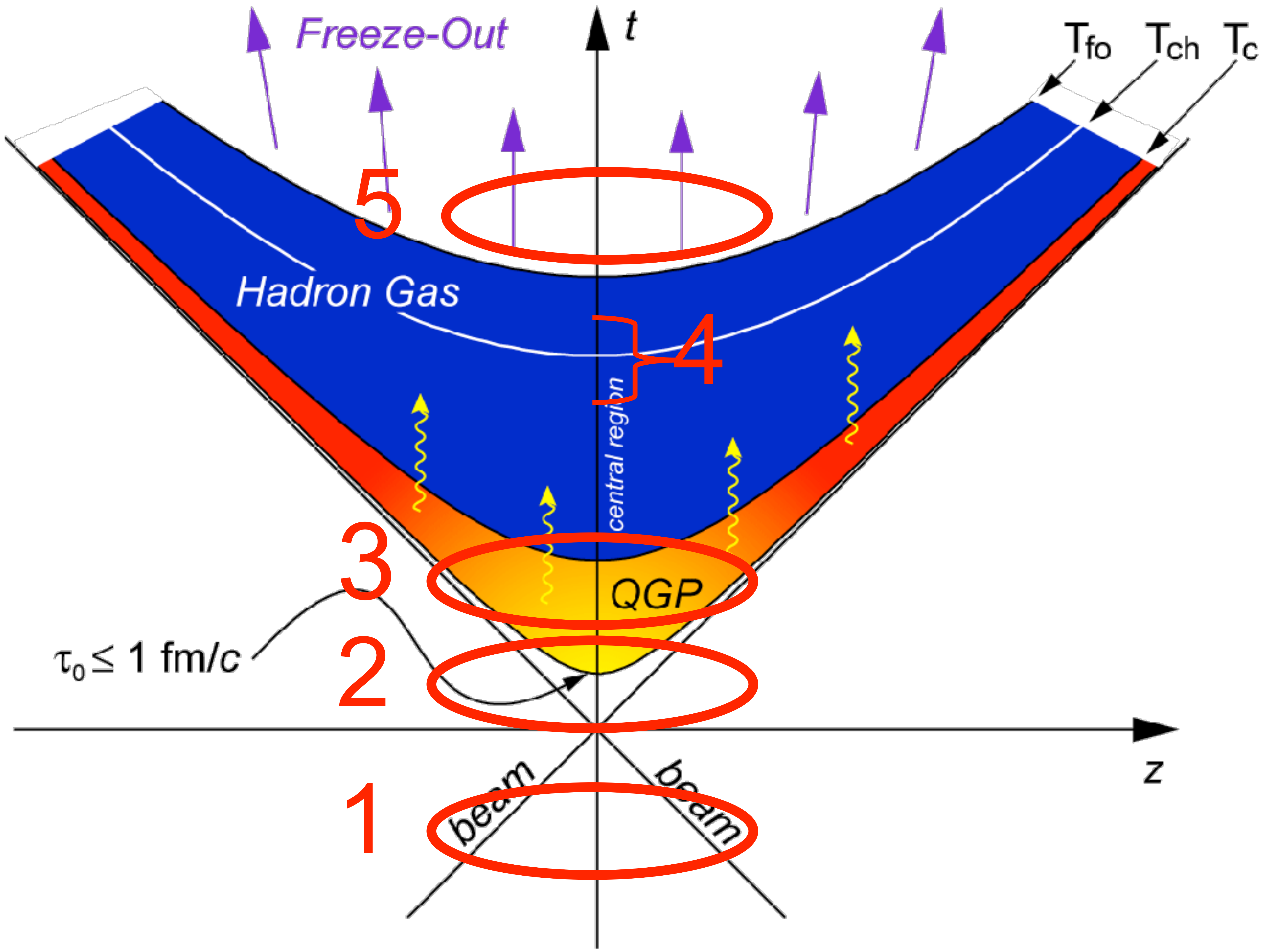
Run-1: 2009 - 2013

Run-2: 2015 - 2018

ALICE publications (2010-2021): **363 papers!**



Space-time evolution of Heavy Ion Collisions



5. Kinetic freeze-out (momenta are fixed)
4. Chemical freeze-out (Hadronization)
3. Local thermal equilibrium and QGP
2. Glasma

Collision!

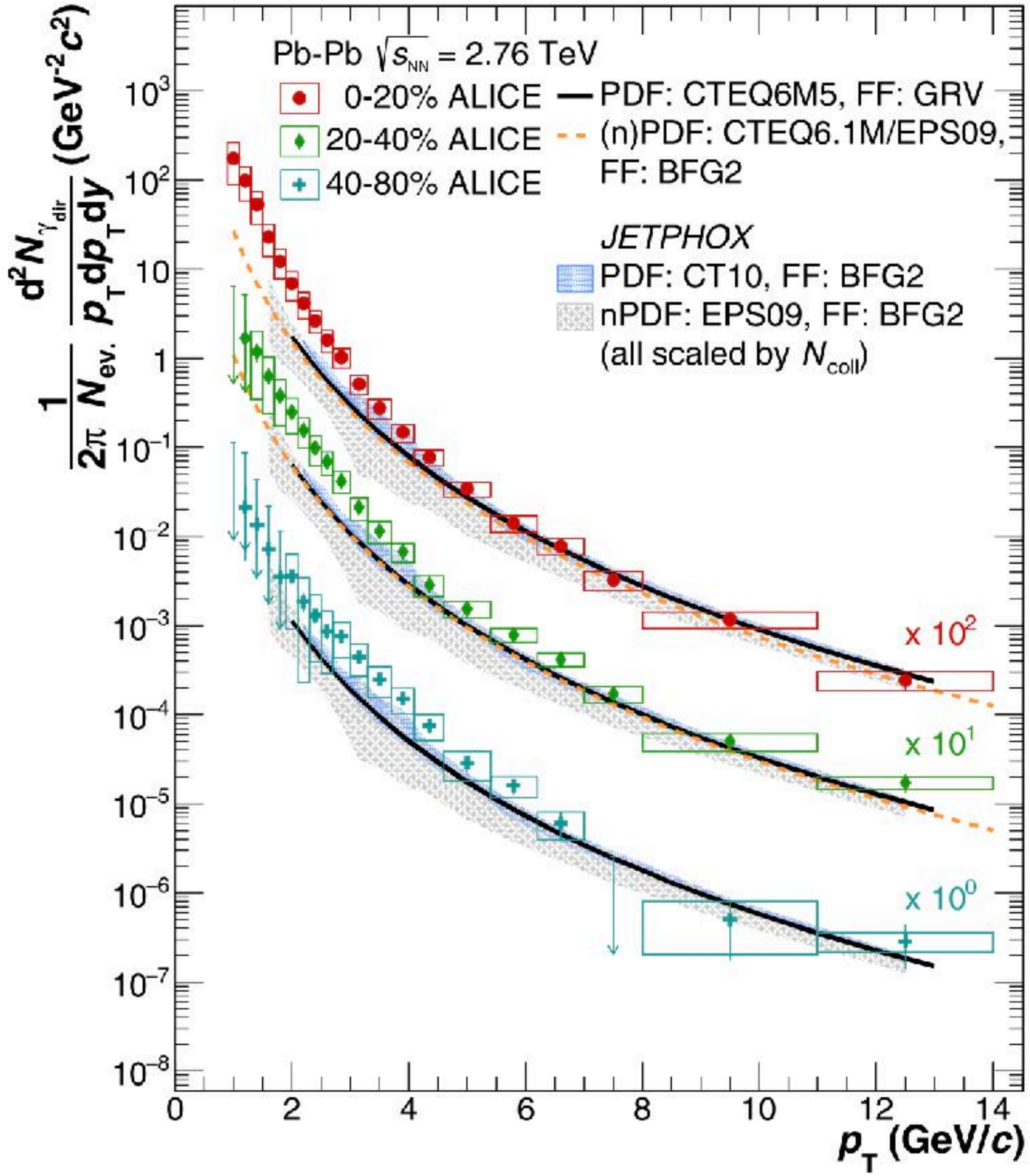
1. Initial Condition (CGC?)

arXiv:1804.06469v1, Jonah E. Bernhard

$T_{init.}$

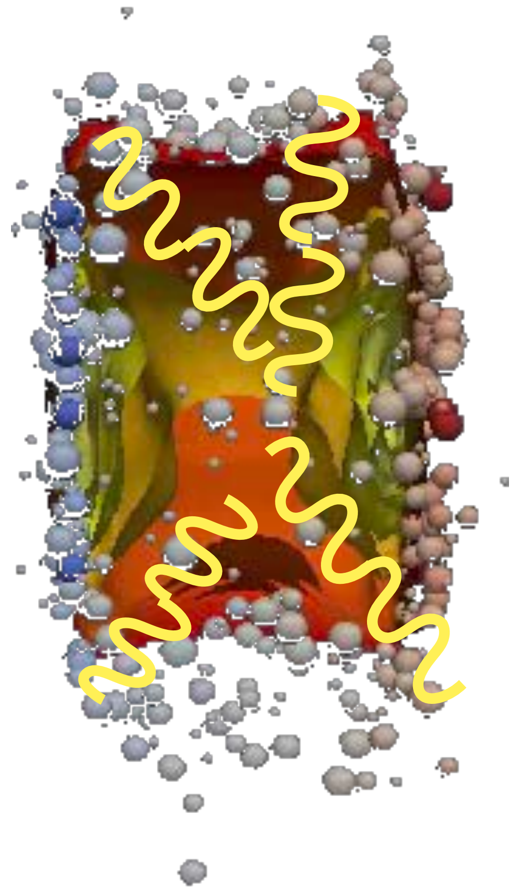
Pb-Pb

Initial temperature



ALICE, PLB 754 (2016) 235, arXiv: 1509.07324 [nucl-ex]

- Thermal radiation
- Observed an excess at low p_T over the pQCD expectation
- T_{eff} = 304 ± 11(stat.) ± 40 (syst.) MeV
- 3.4 trillion K



$T_{init.}$ ~ 300 MeV

Highest artificial temperature

Who	What
CERN, LARGE HADRON COLLIDER	5X10^12 DEGREE(S) KELVIN
Where	**When**
SWITZERLAND ()	13 AUGUST 2012

On 13 August 2012 scientists at CERN's Large Hadron Collider, Geneva, Switzerland, announced that they had achieved temperatures of over 5 trillion K and perhaps as high as 5.5 trillion K. The team had been using the ALICE experiment to smash together lead ions at 99% of the speed of light to create a quark gluon plasma – an exotic state of matter believed to have filled the universe just after the Big Bang.

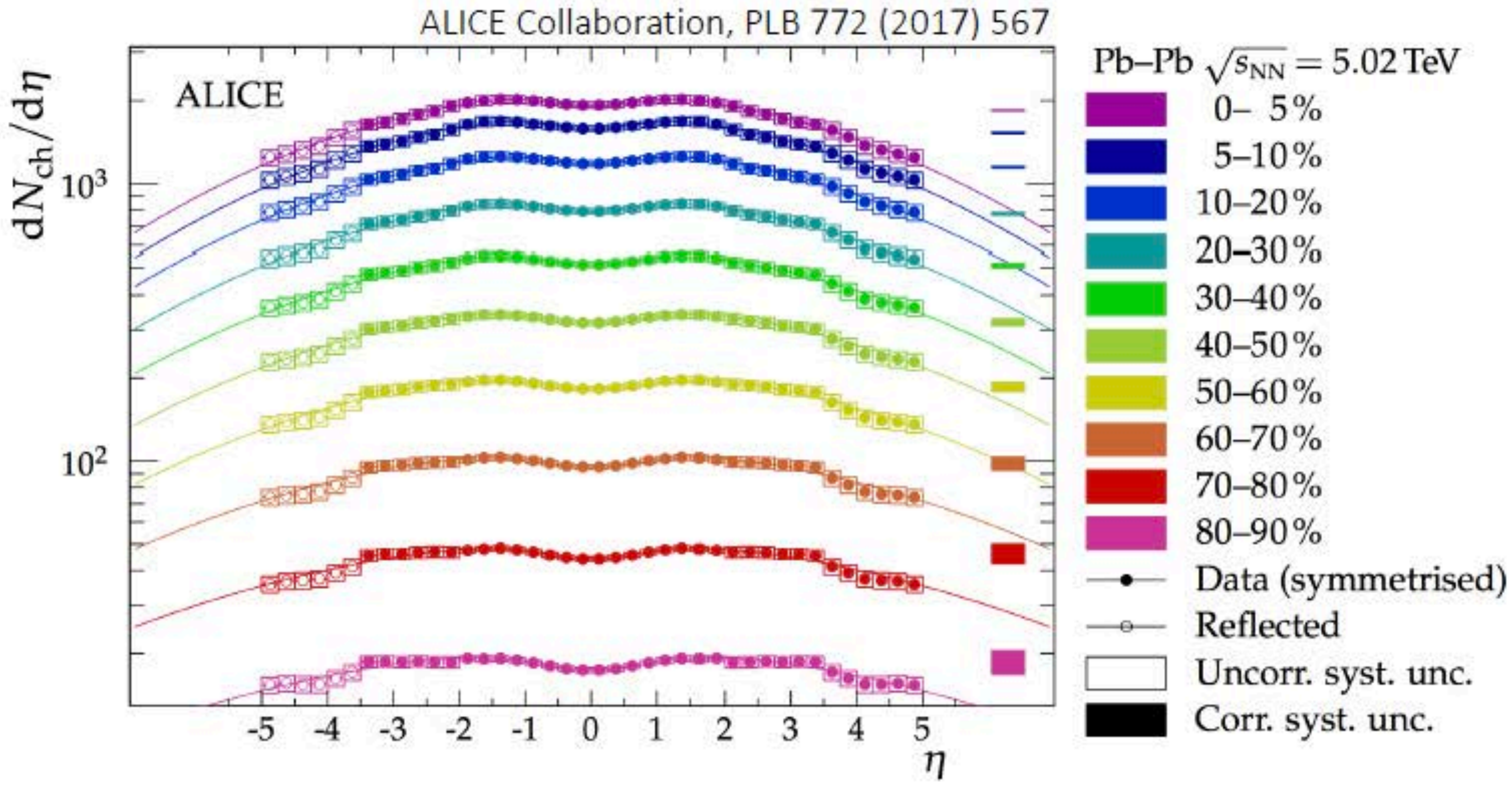
link

ε

Energy Density

Bjorken Energy Density

$$\langle \epsilon(t) \rangle = \frac{\text{Energy}}{\text{Volume}} = \frac{\langle E \rangle dN}{V} = \frac{1}{tA}\frac{dN(t)}{dy}\langle m_T \rangle(t)$$

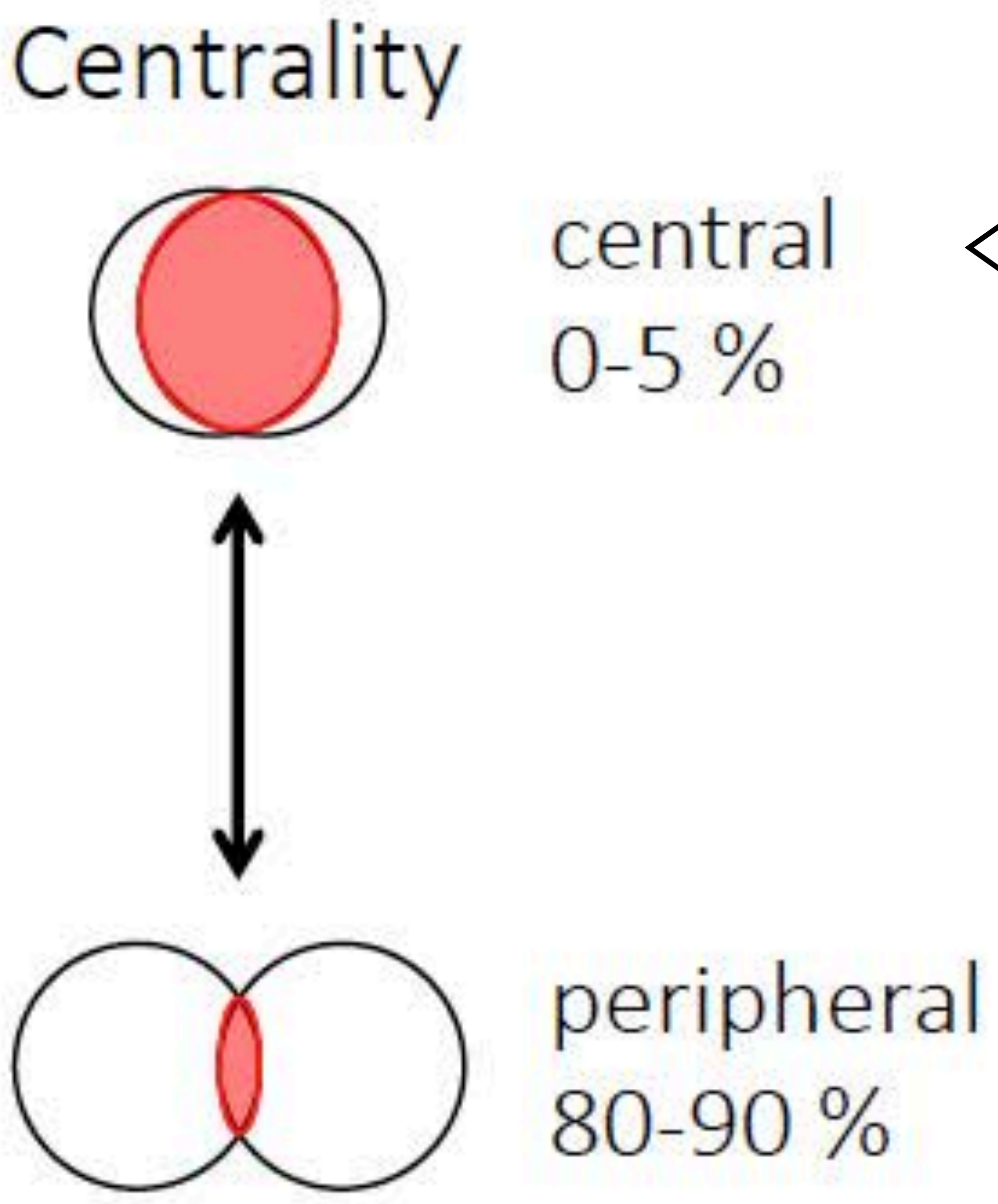


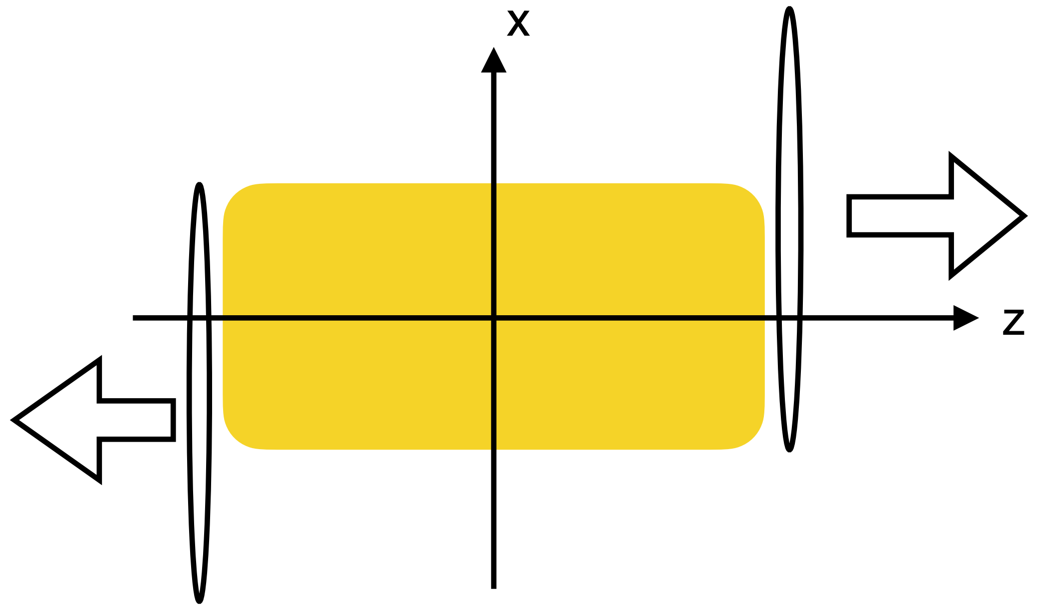
Pb-Pb

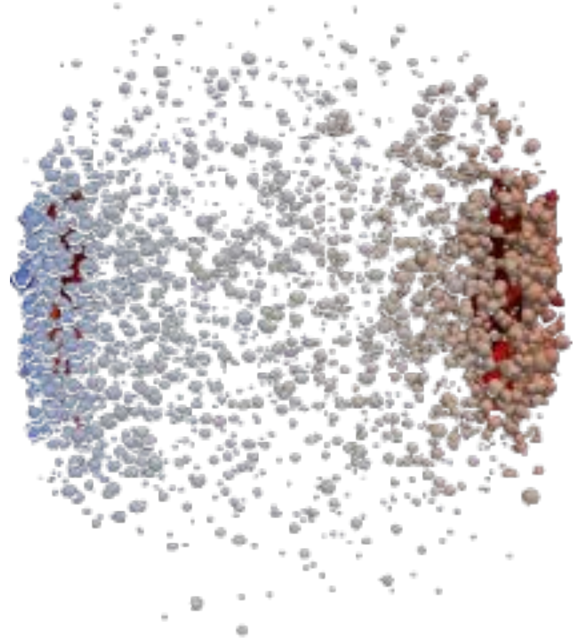
Volume, Duration time

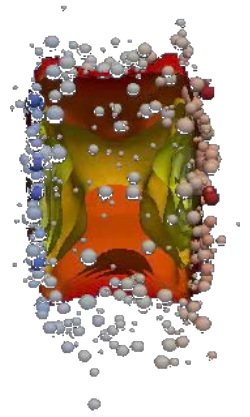
$V \sim 300\ \text{fm}^3$

$\tau \sim 10\ \text{fm/c}$





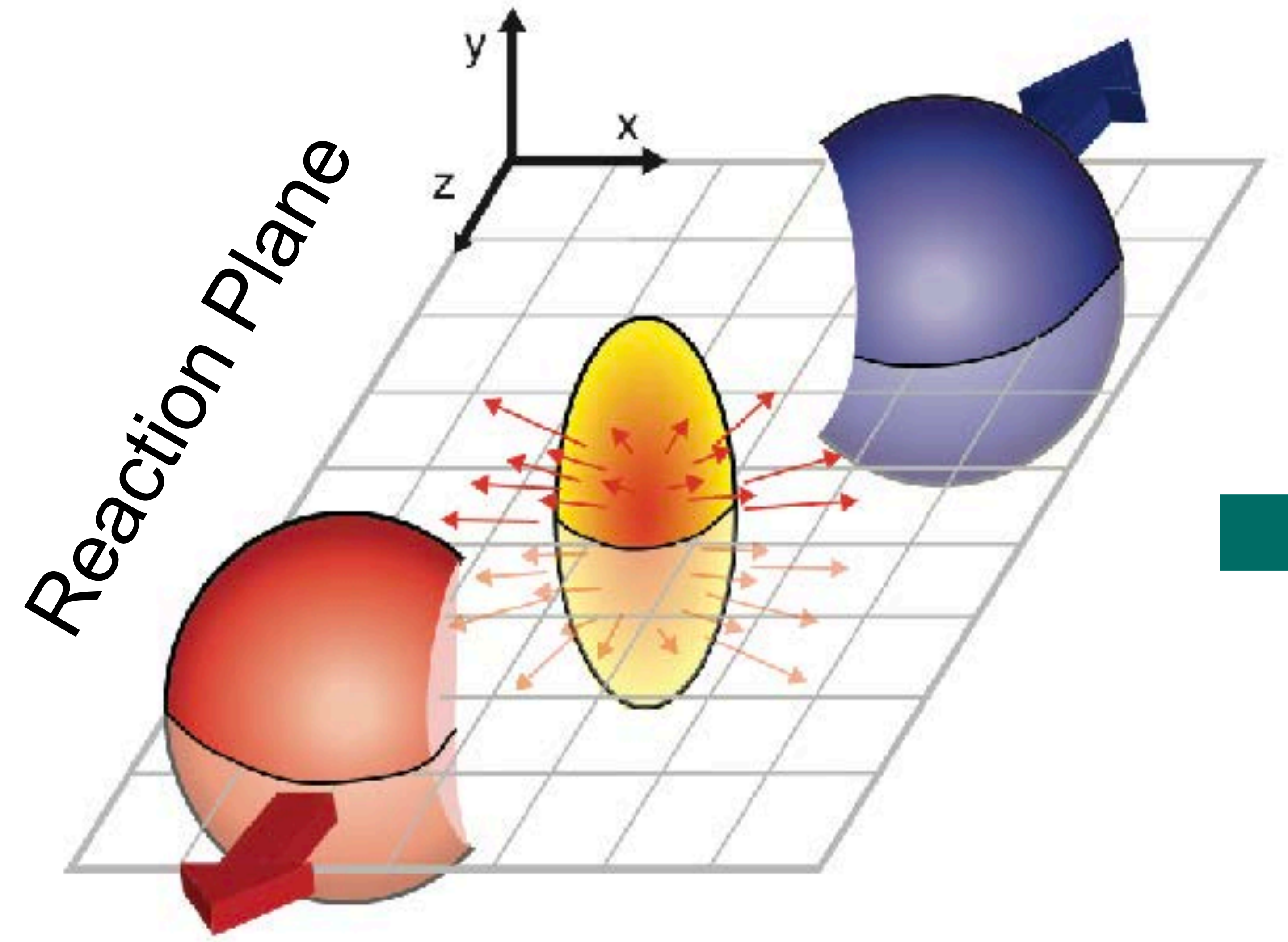




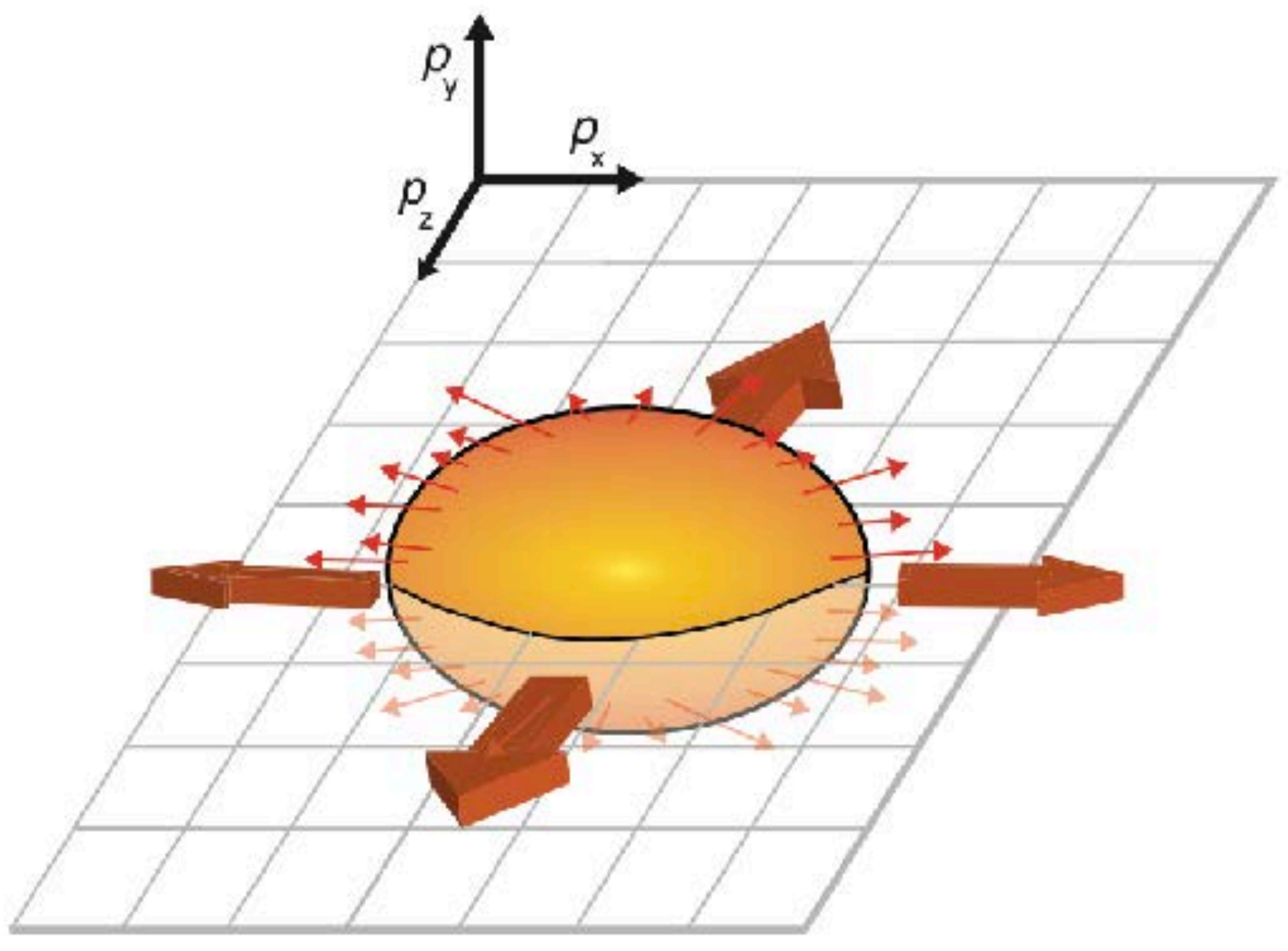
$\varepsilon \sim 16\ \text{GeV/fm}^3$

Collectivity of the system

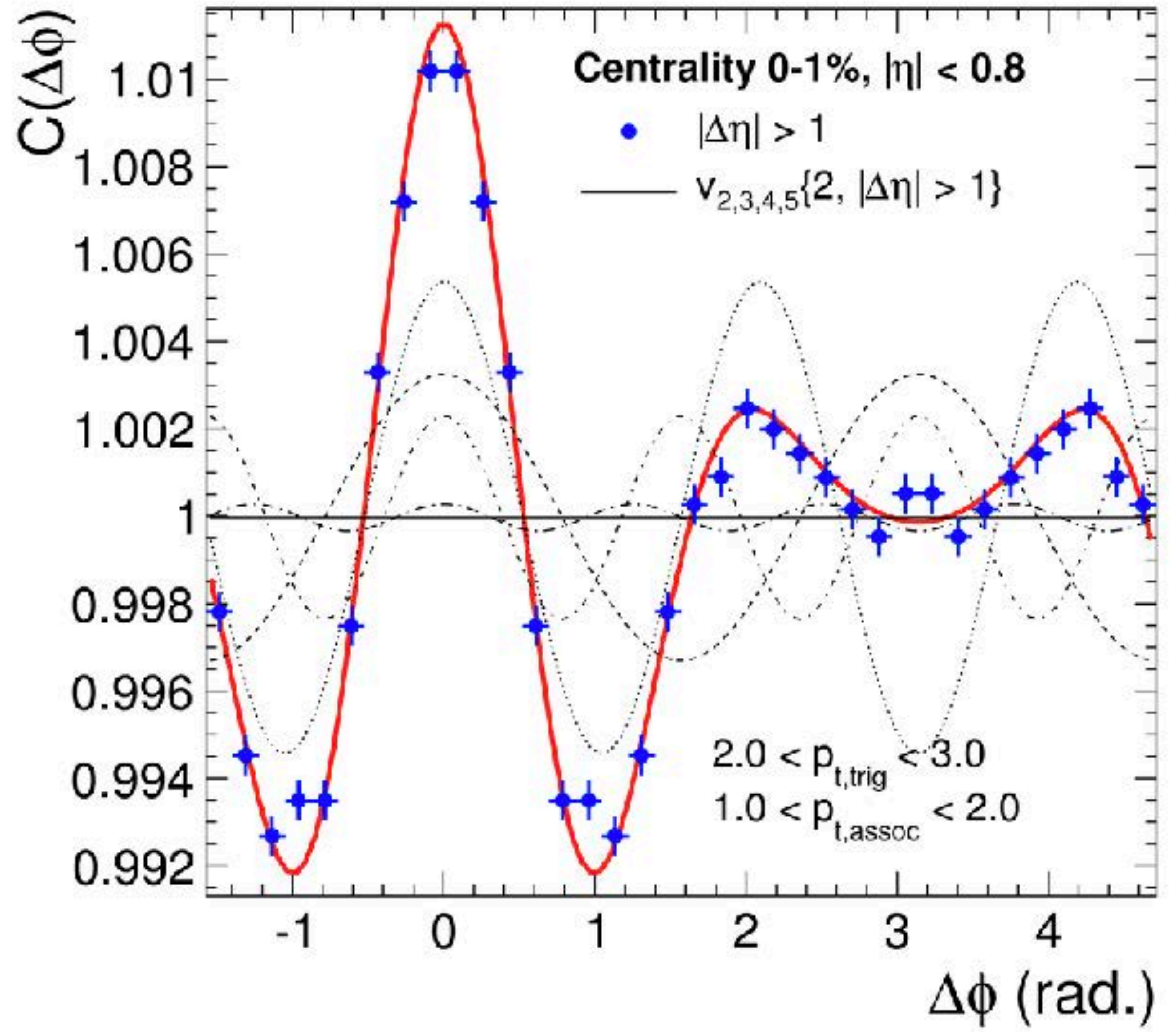
ALICE, Phys. Rev. Lett. 107 (2011) 032301

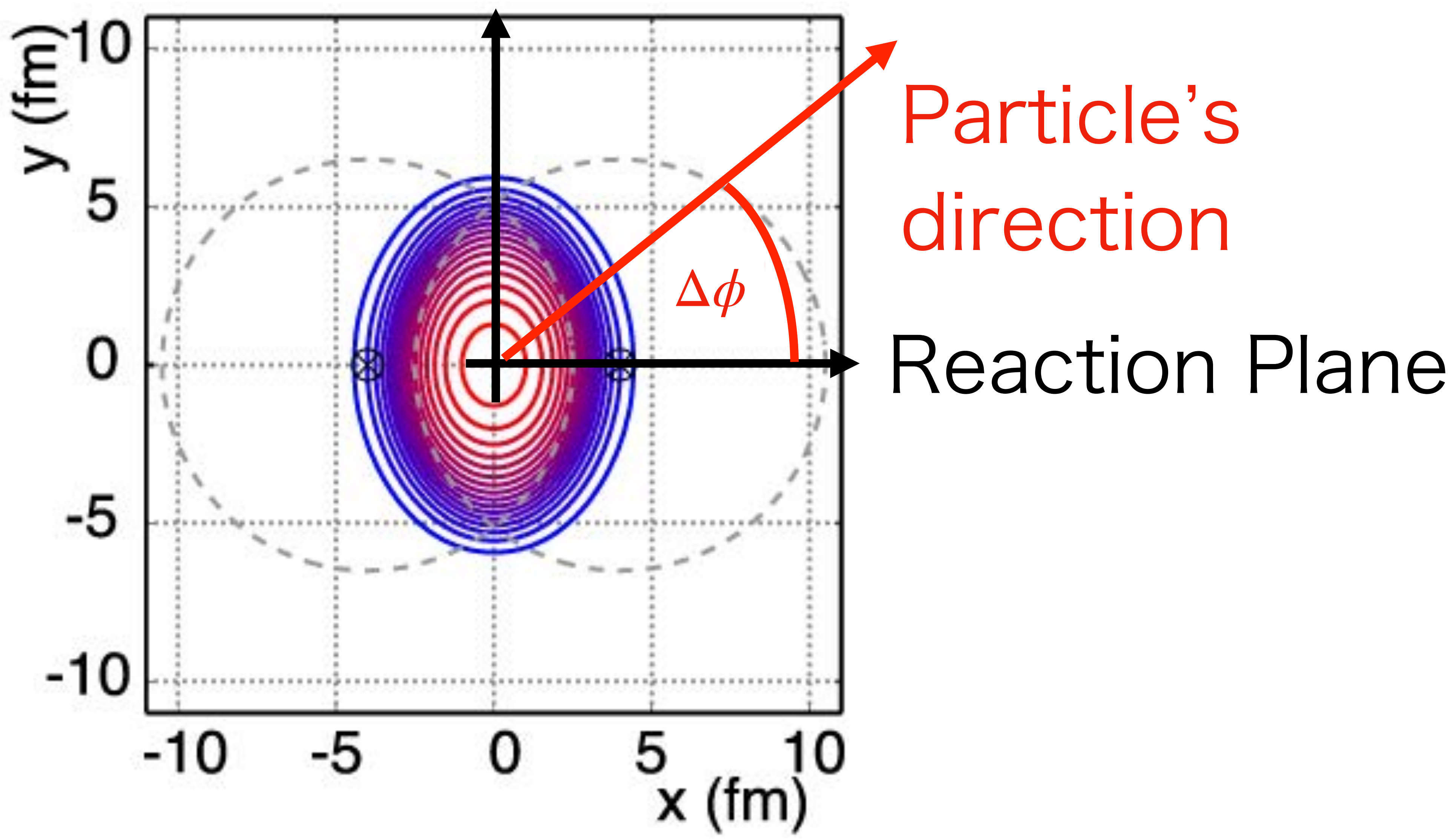


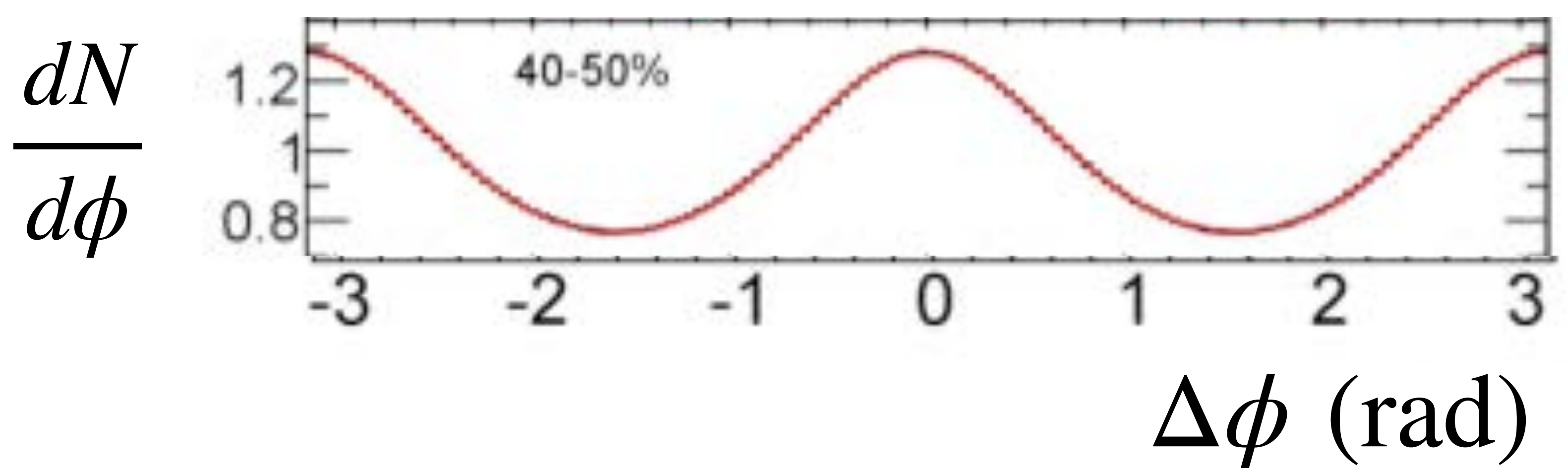
Geometrical Anisotropy



Momentum Anisotropy



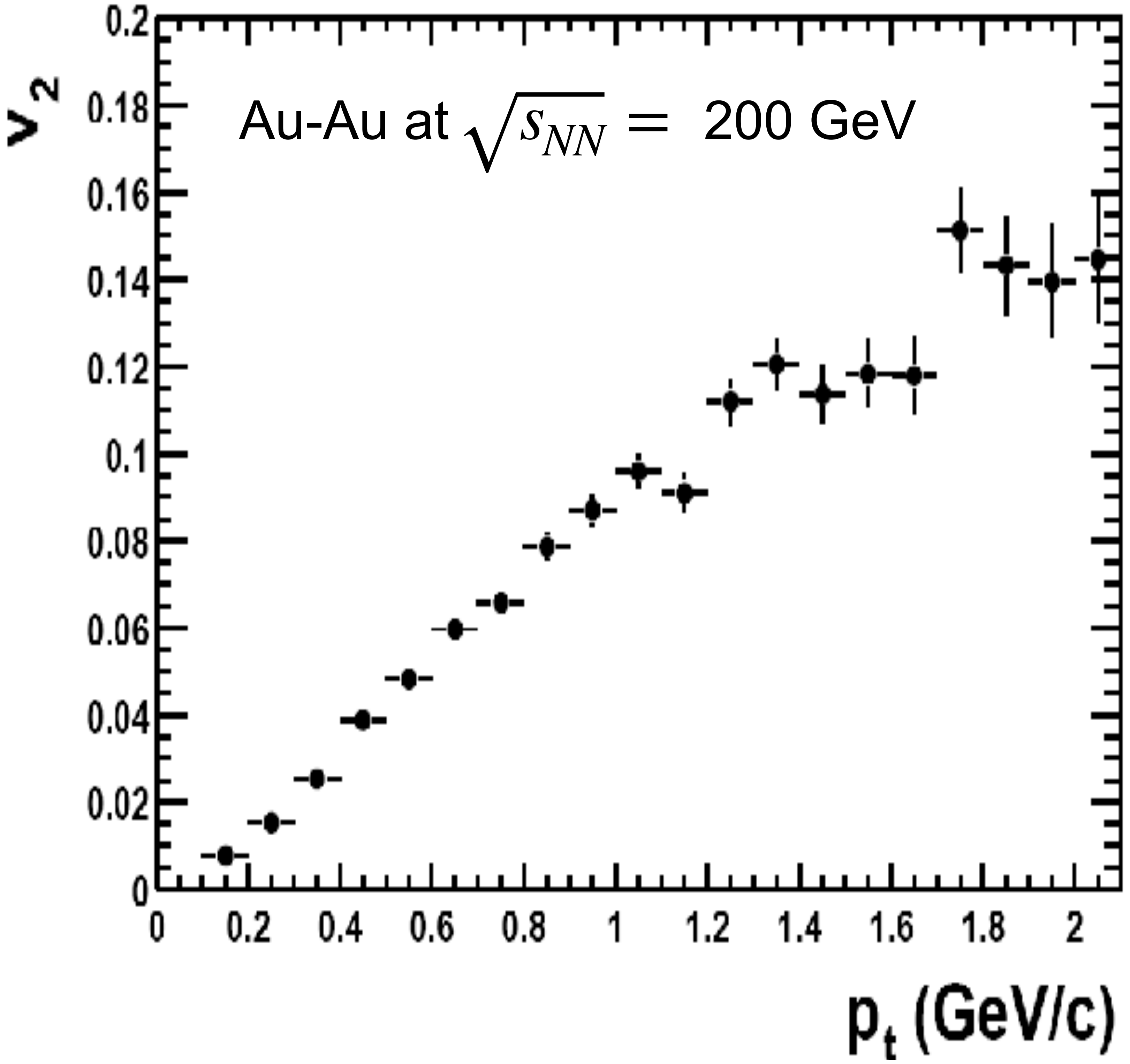




$$\frac{dN}{d\phi} \propto (1 + 2v_2 \cos(2\Delta\phi) + \ldots)$$

2nd coefficient of Fourier expansion : v_2 （elliptic flow）

STAR PRL86,402 (2001)

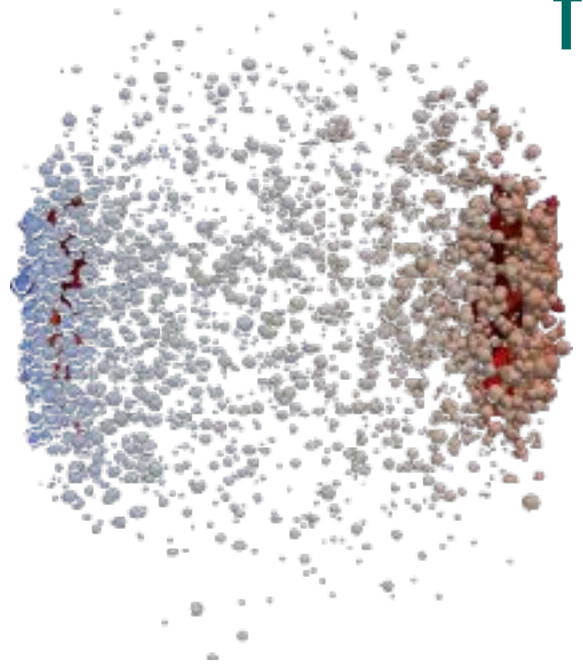


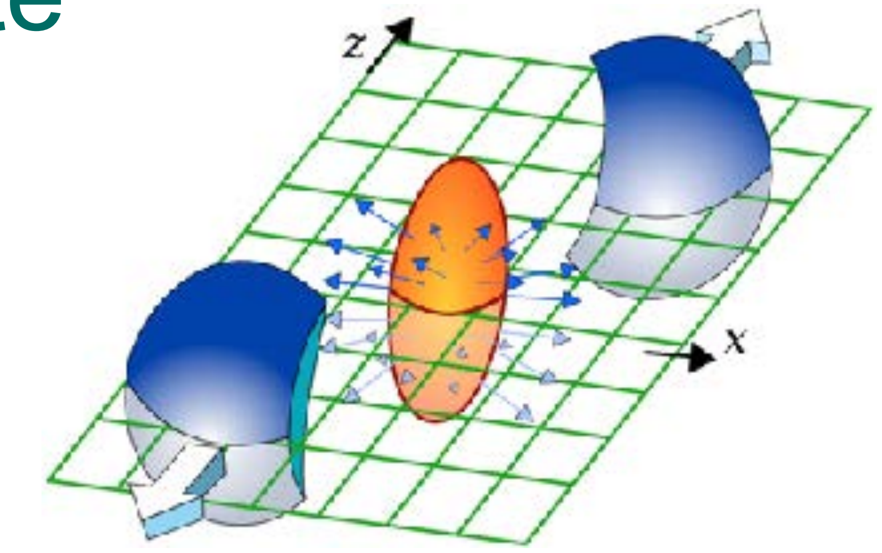
- **Large v_2 at RHIC and LHC**
- **To produce large v_2, it needs two conditions in Hydro cal.**

  (1) Early thermalization ～ 0.6 fm/c

  (2) Very small η/s

Extraction of properties from the final state





Because at early stage of collisions:

１）Reaction zone is elliptic

→ Different pressure gradient between short and long axis

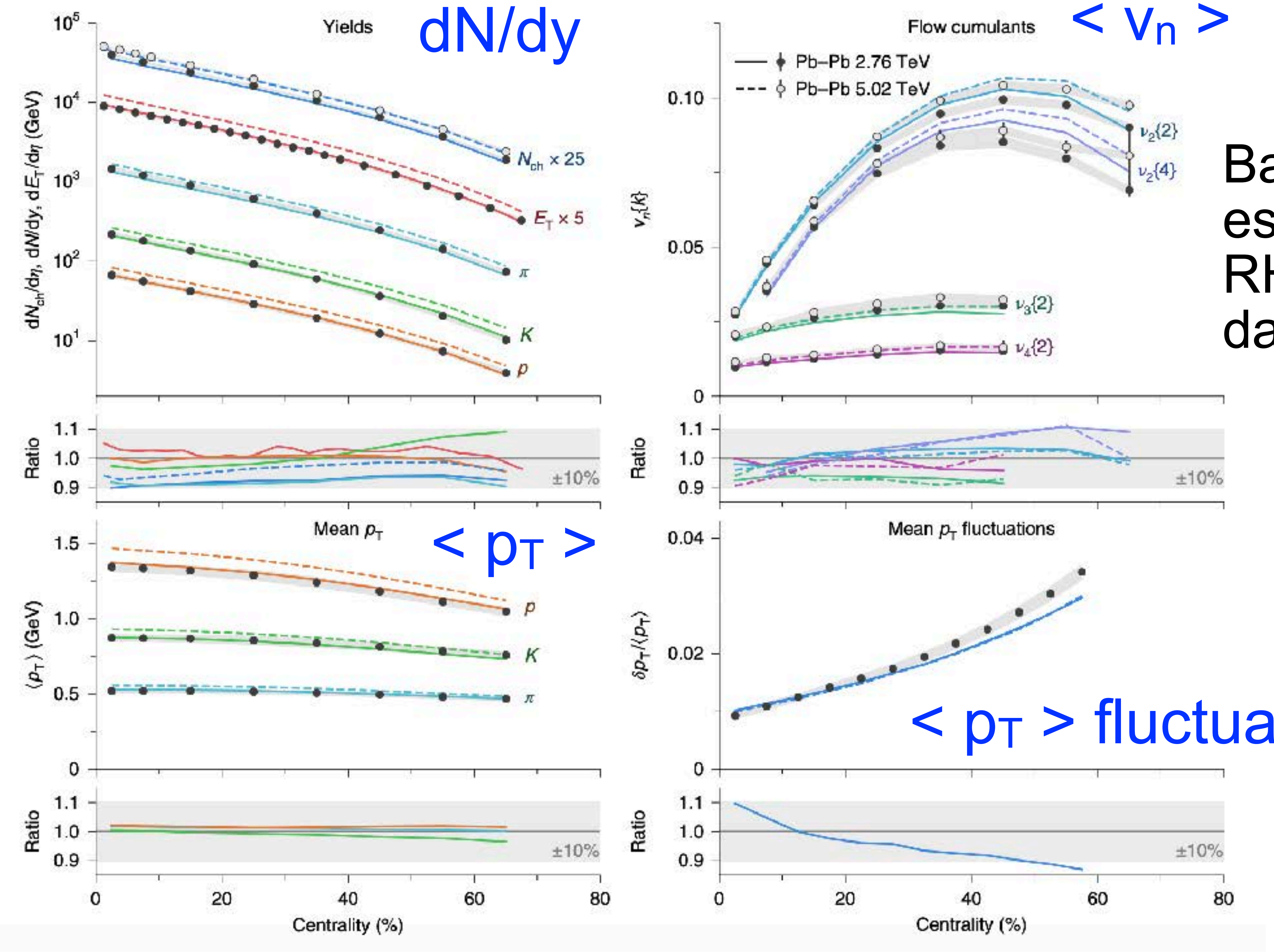
→ Elliptic flow (v_2) generation

２）Hydrodynamic equation works for QGP at a very early time (~0.6 fm/c) and also needs a small η/s (= strong coupling)

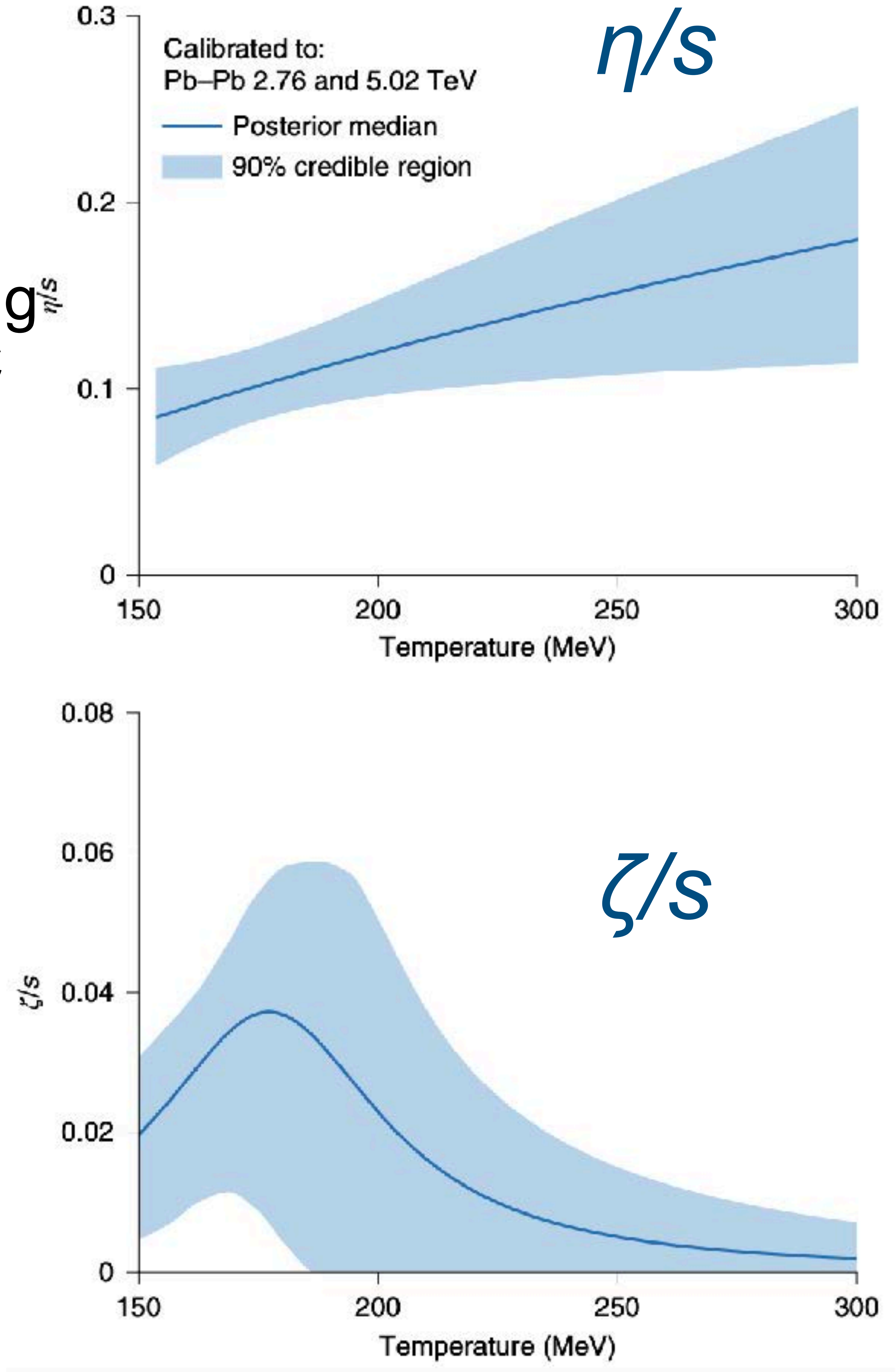
“strongly” coupled QGP (sQGP) with early thermalization

η/s ζ/s

Viscosity



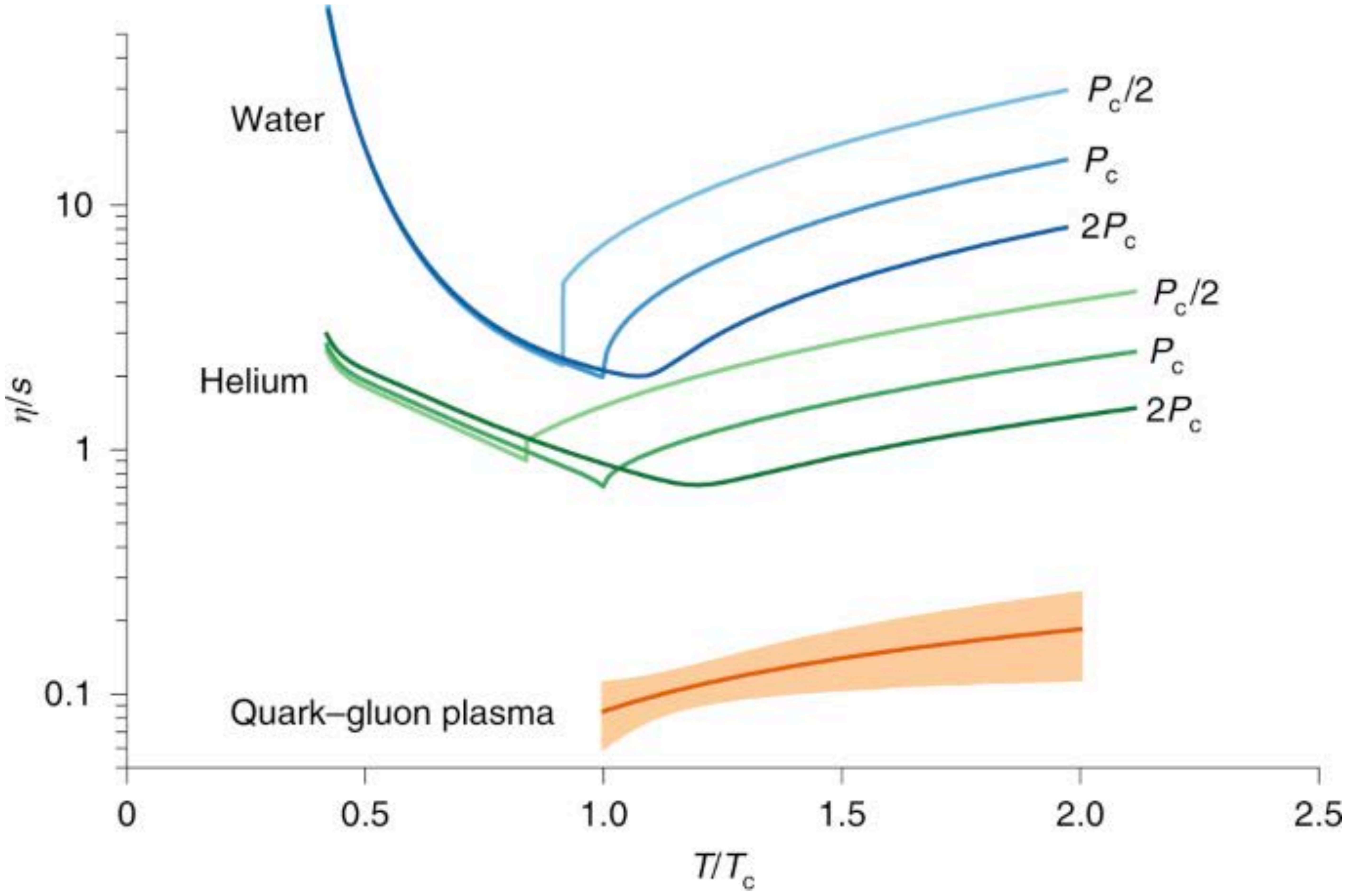
Bayesian estimation using RHIC and LHC data



J. S. Moreland, J. E. Bernhard, S. A. Bass, PRC 101 (2020) 024911, arXiv:1808.02106 [nucl-th]

Trajectum [PRL 126 (2021) 202301, arXiv:2010.15130], JETSCAPE [PRL 126 (2021) 242301, arXiv:2010.03928]

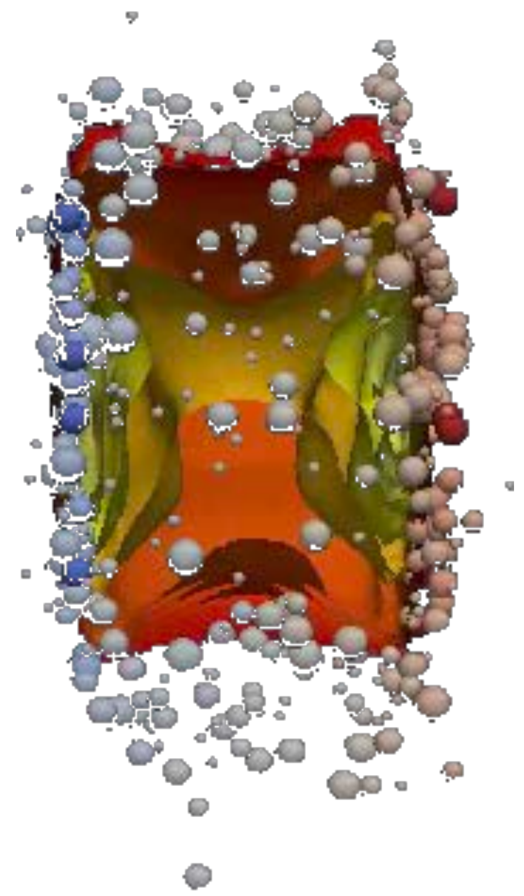
η/s Extracting QGP properties with flow



J. E. Bernhard et al. Nature Phys. 15 (2019) 1113

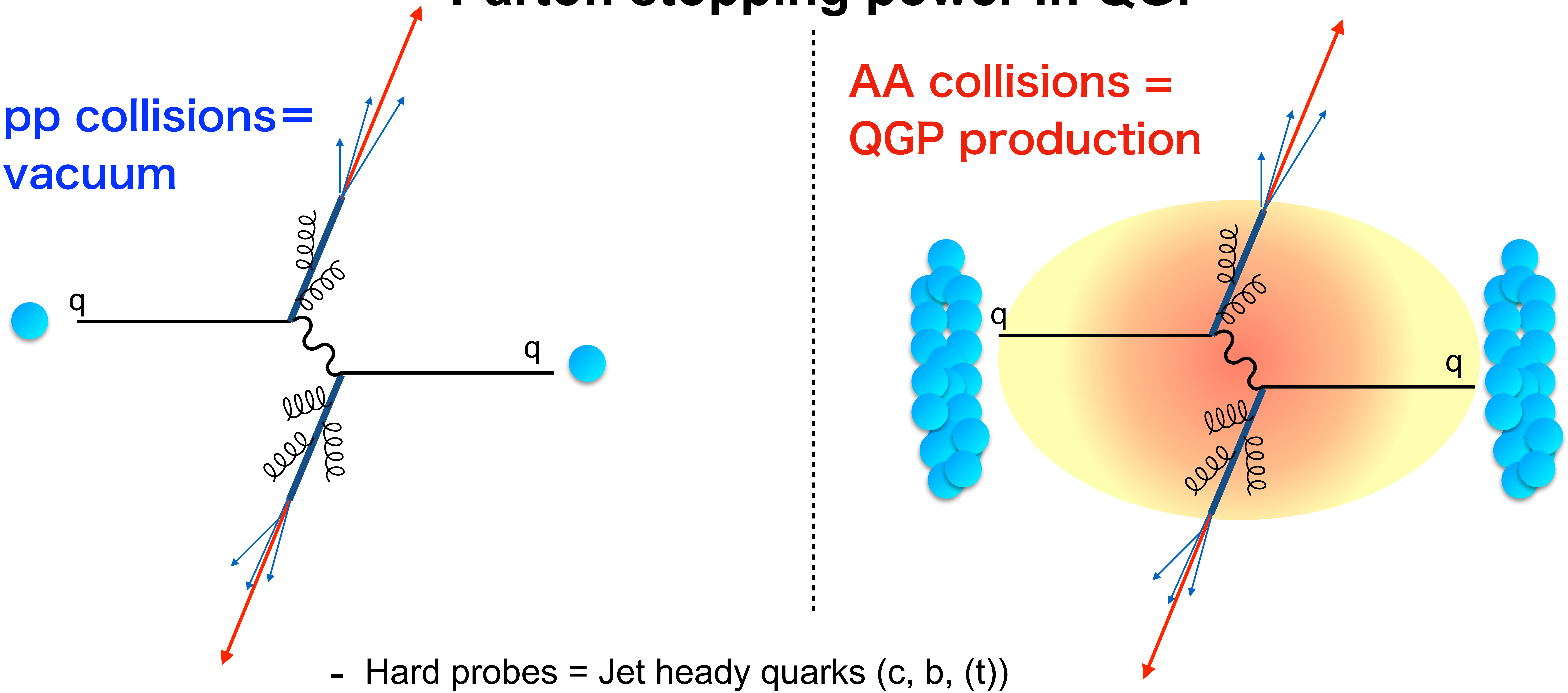
Shear viscosity (η/*s*) *is near the quantum lower bound (1/4π)*

→ *QGP is the "perfect liquid"*



$\eta/s \sim 0.1 \sim 1/4\pi$

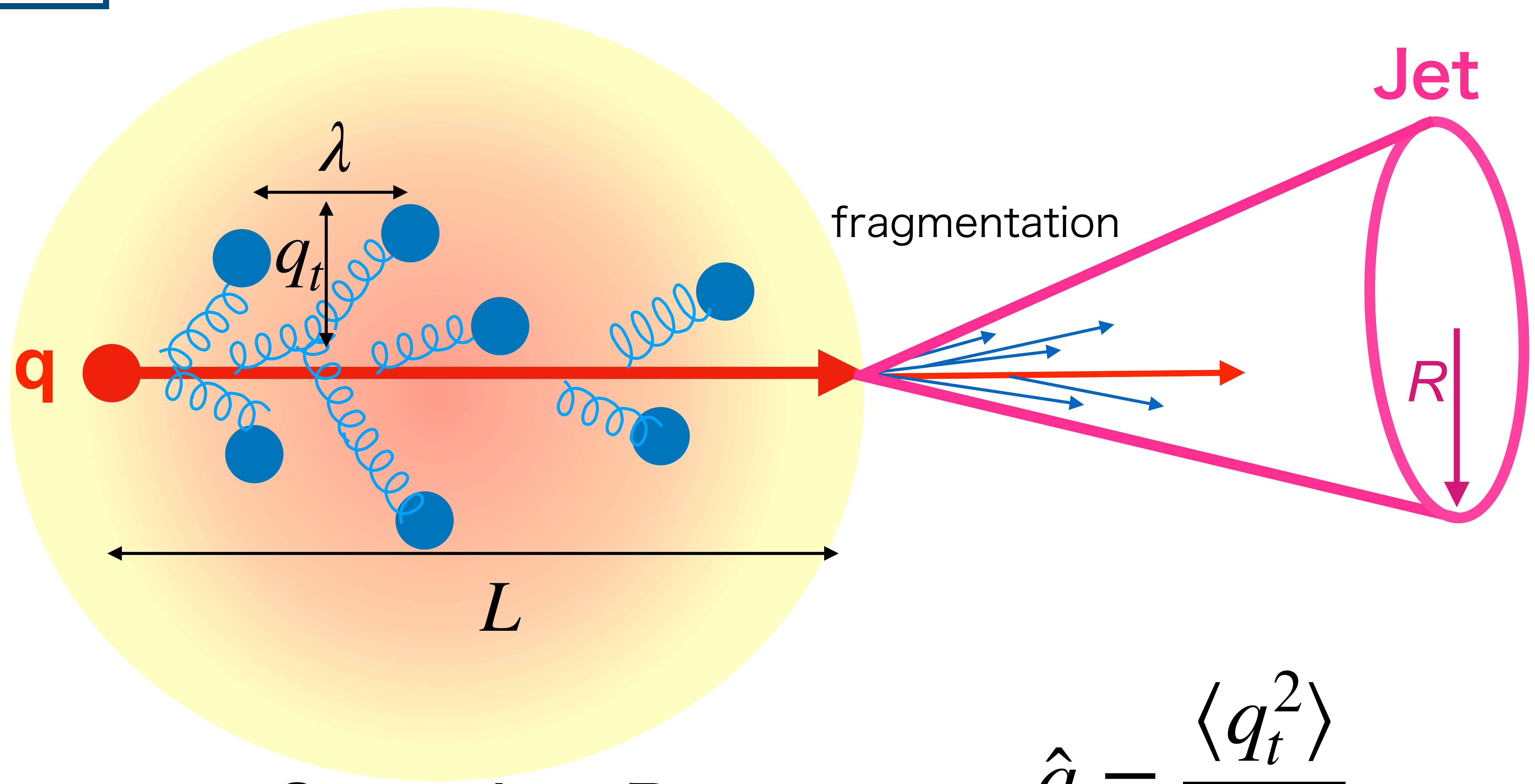
Parton stopping power in QGP



- Hard probes = Jet heady quarks (c, b, (t))
- Produced in early parton scattering at early stage with large Q^2
- Calculable by pQCD

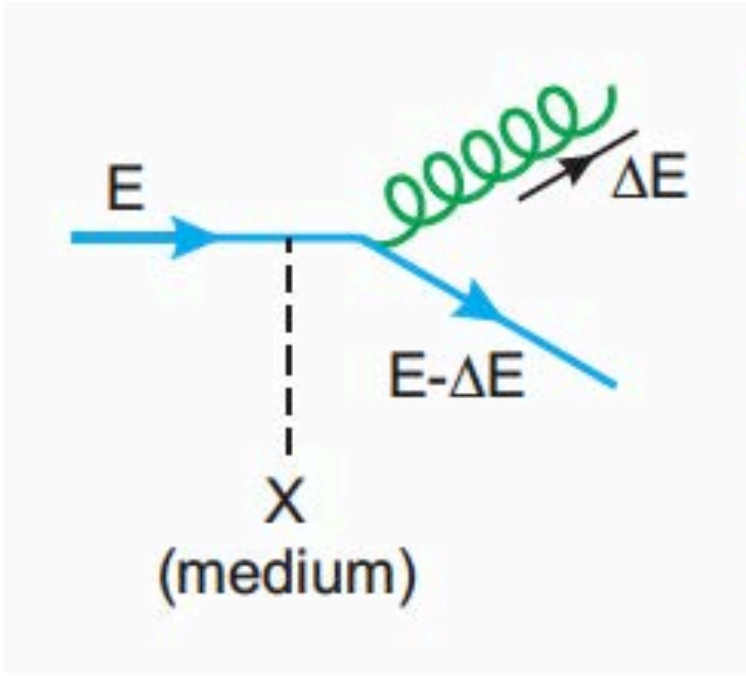
$\hat{q}$

Energy loss in QGP



Stopping Power $$\hat{q} = \frac{\langle q_t^2 \rangle}{\lambda}$$

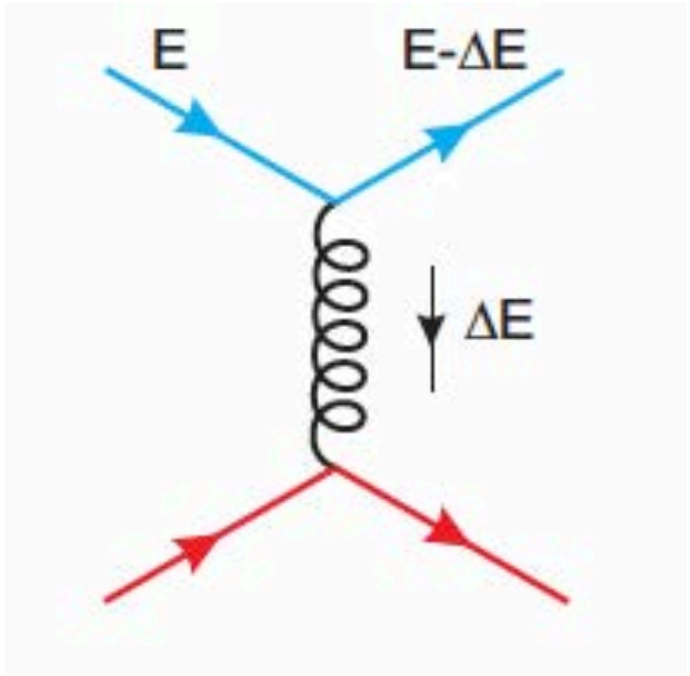
1） Gluon radiation (Radiative)



$$\Delta E \propto L^2$$

pQCD $$\Delta E \propto \alpha_s C_R \langle \hat{q} \rangle L^2$$

2） Elastic scattering (Collisional)



$$\Delta E \propto L^1$$

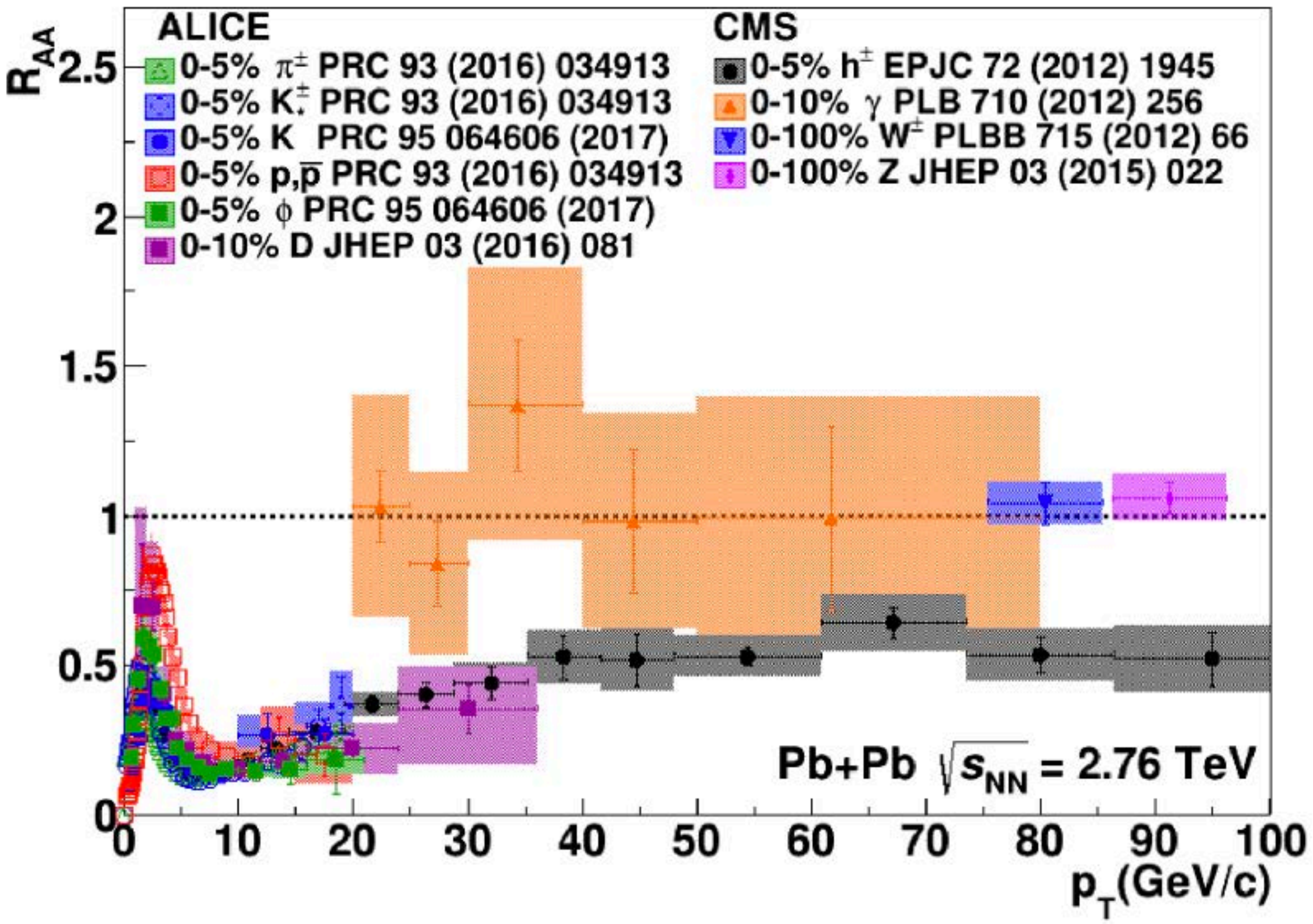
- **What is the mechanism of energy loss in QGP?**
- **How much the stopping power $\hat{q}$?**
- **Any difference between quark and gluon?**
- **Where the energy goes?**

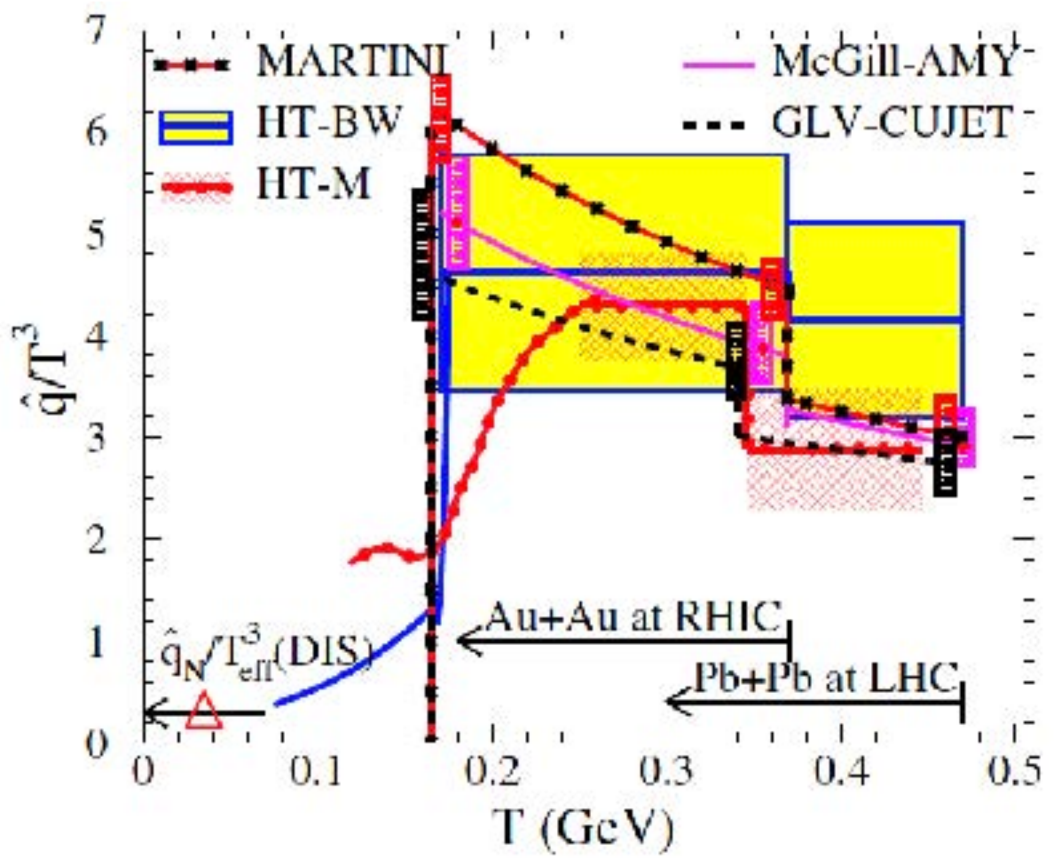
$\hat{q}$ Energy loss in QGP

$$R_{AA} = \frac{\text{Hot Dense QGP in Pb} - \text{Pb}}{\text{Vacumme in pp}}$$

- **Significant suppression of jet in AA**
- **Large energy loss is possible by QGP only**
- **Extract stopping power from model comparison**

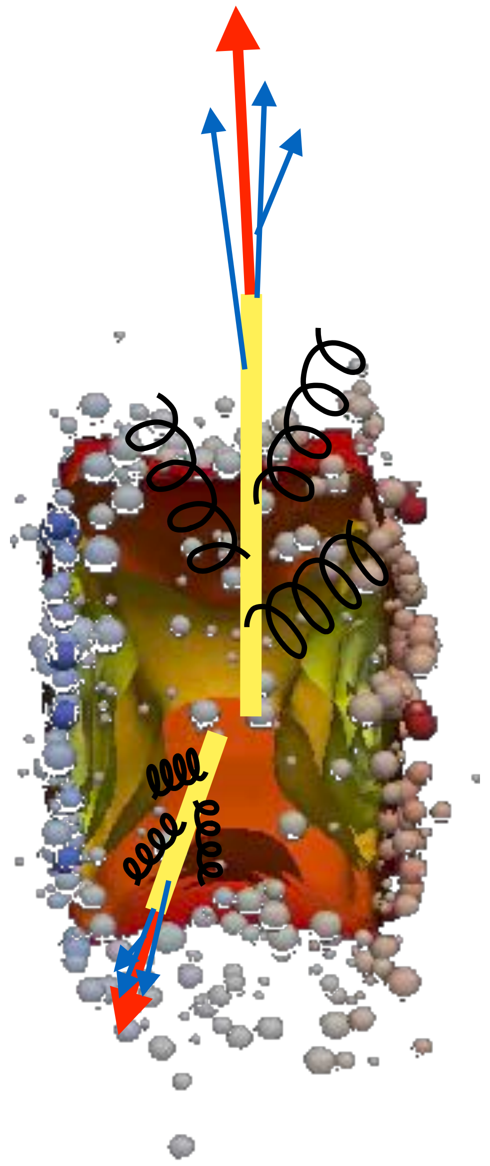
$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm at } \begin{matrix} \text{T=370 MeV,} \\ \text{T=470 MeV,} \end{matrix}$$

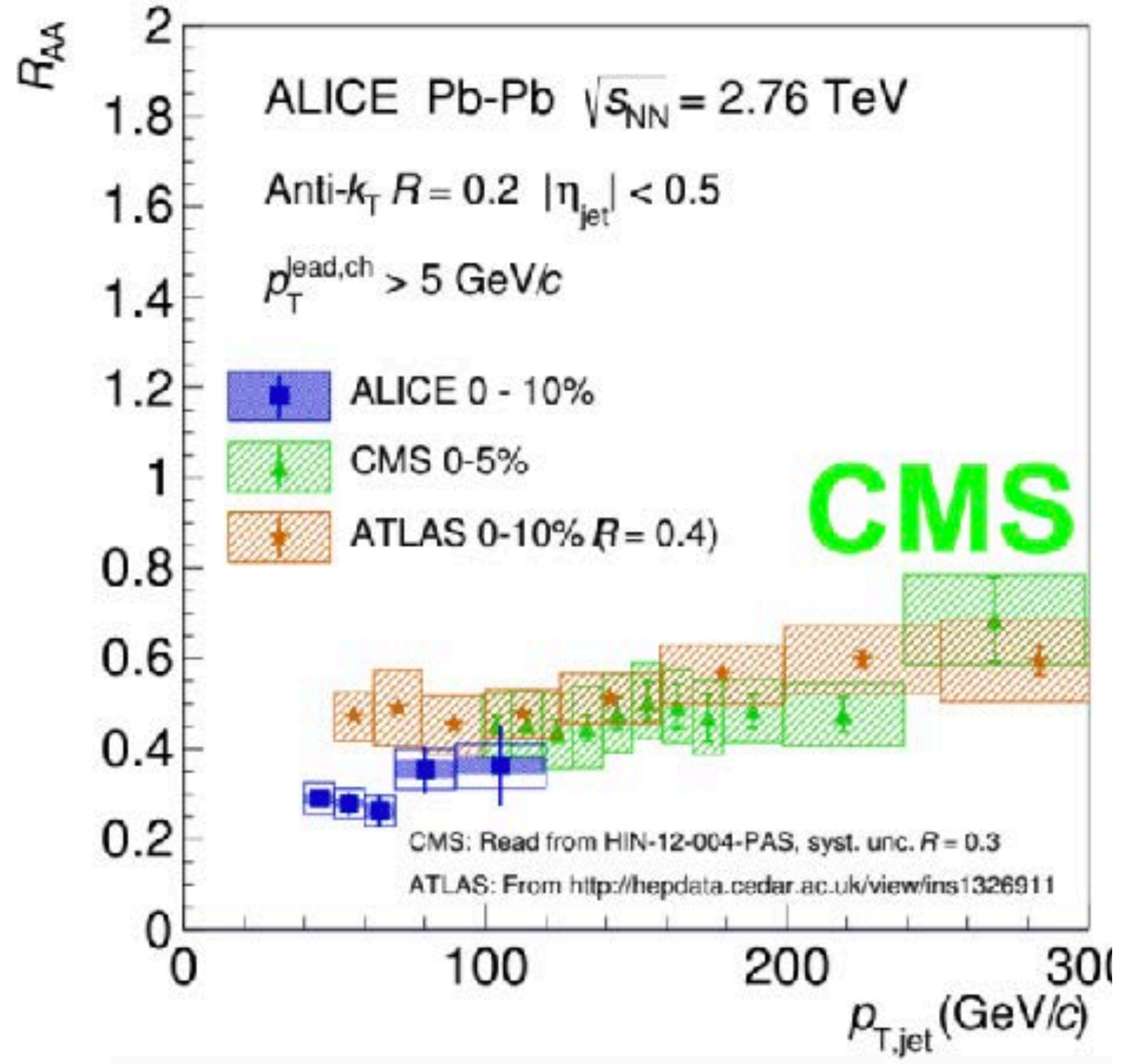




Burke et al., arXiv:1312.5003v2(JET collaboration)

$\hat{q}$ ~ 1-2 GeV²/fm





ALICE, PLB 746 (2015) 1 arXiv:1502.01689 [nucl-ex]

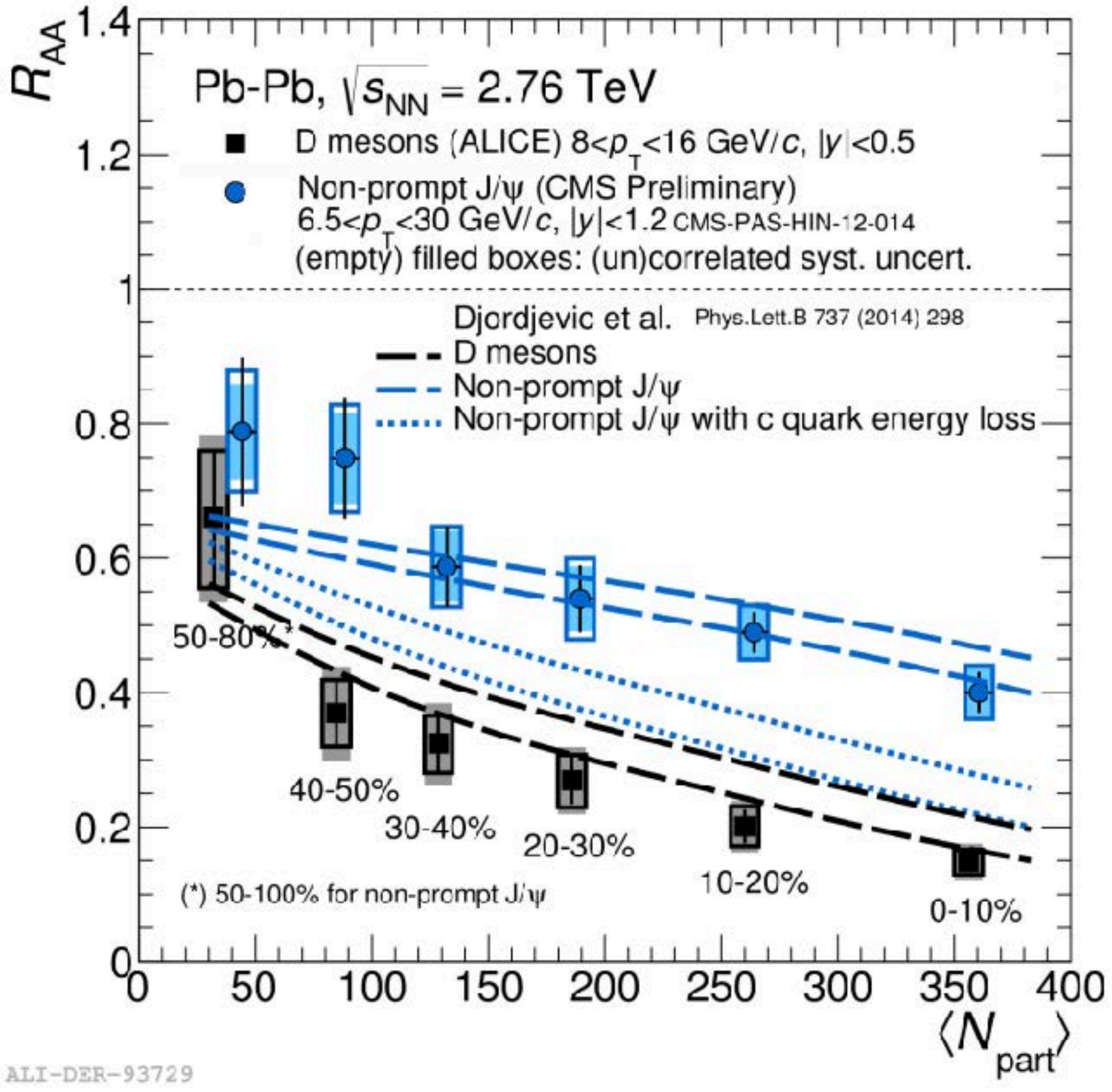
ATLAS, PRL 114 (2015) 072302arXiv:1411.2357 [hep-ex]

CMS HIN-12-004-PAS

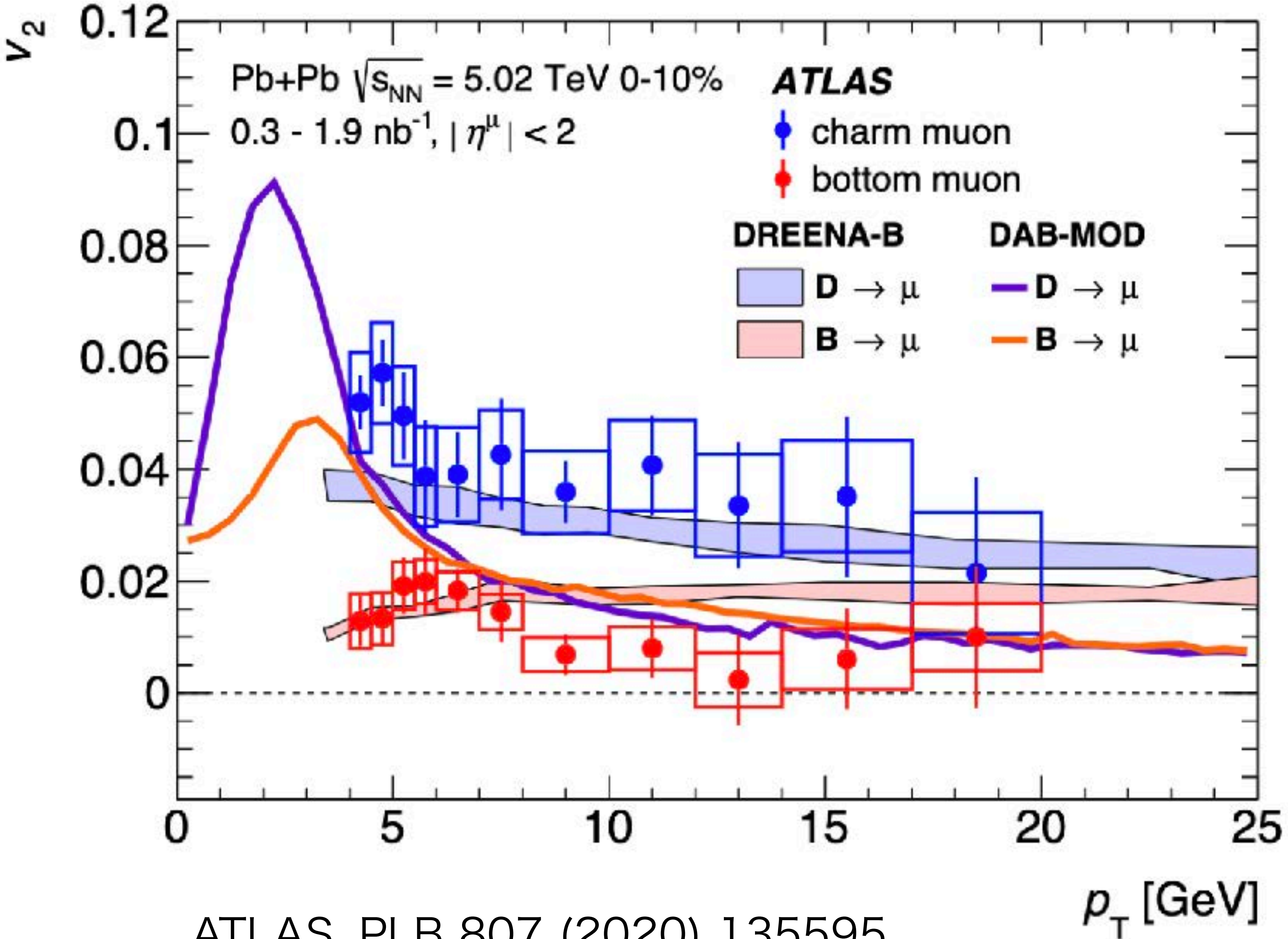
Hard probes: Heavy quarks

Mass-dependent suppression of D (c-hadron) and non-prompt J/ψ (from b-hadron)
→ dead cone effect

Hard probes also flow, mass-dependent v2 of muons from c and b decays



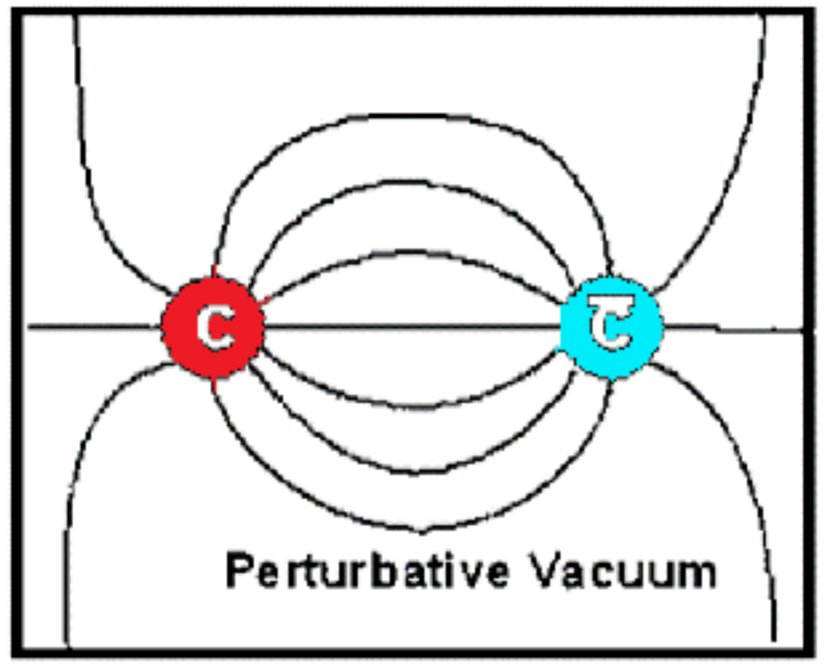
ALICE, JHEP 11 (2015) 205, arXiv:1506.06604 [nucl-ex]
CMS, EPJC 77 (2017) 252, arXiv:2003.03565 [nucl-ex]

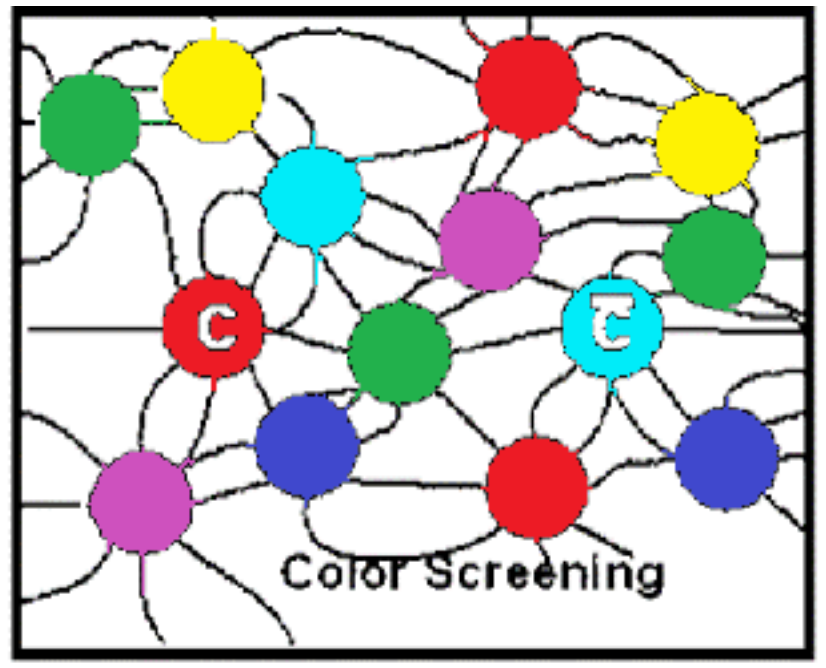


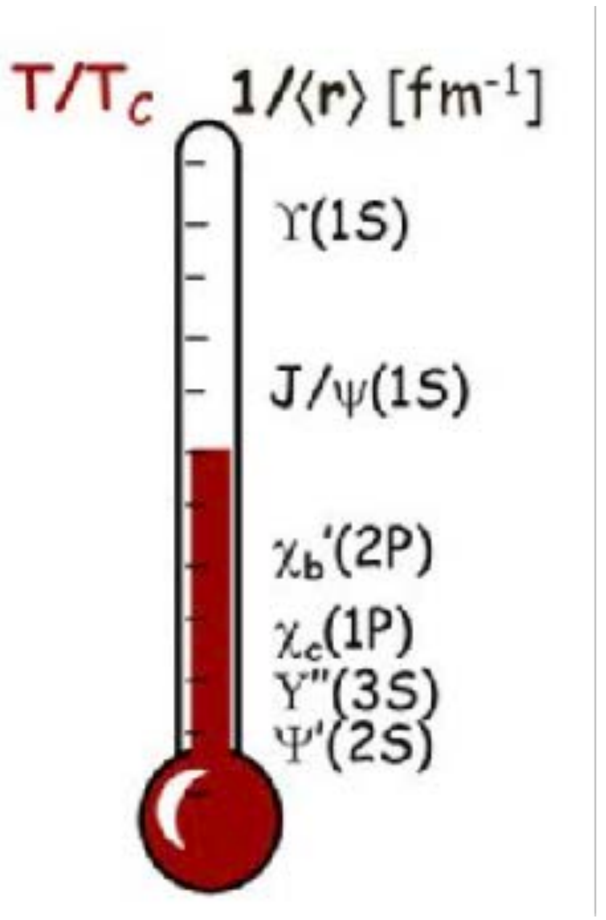
ATLAS, PLB 807 (2020) 135595,
arXiv:1610.00613 [nucl-ex]

Melting and regeneration of J/ψ

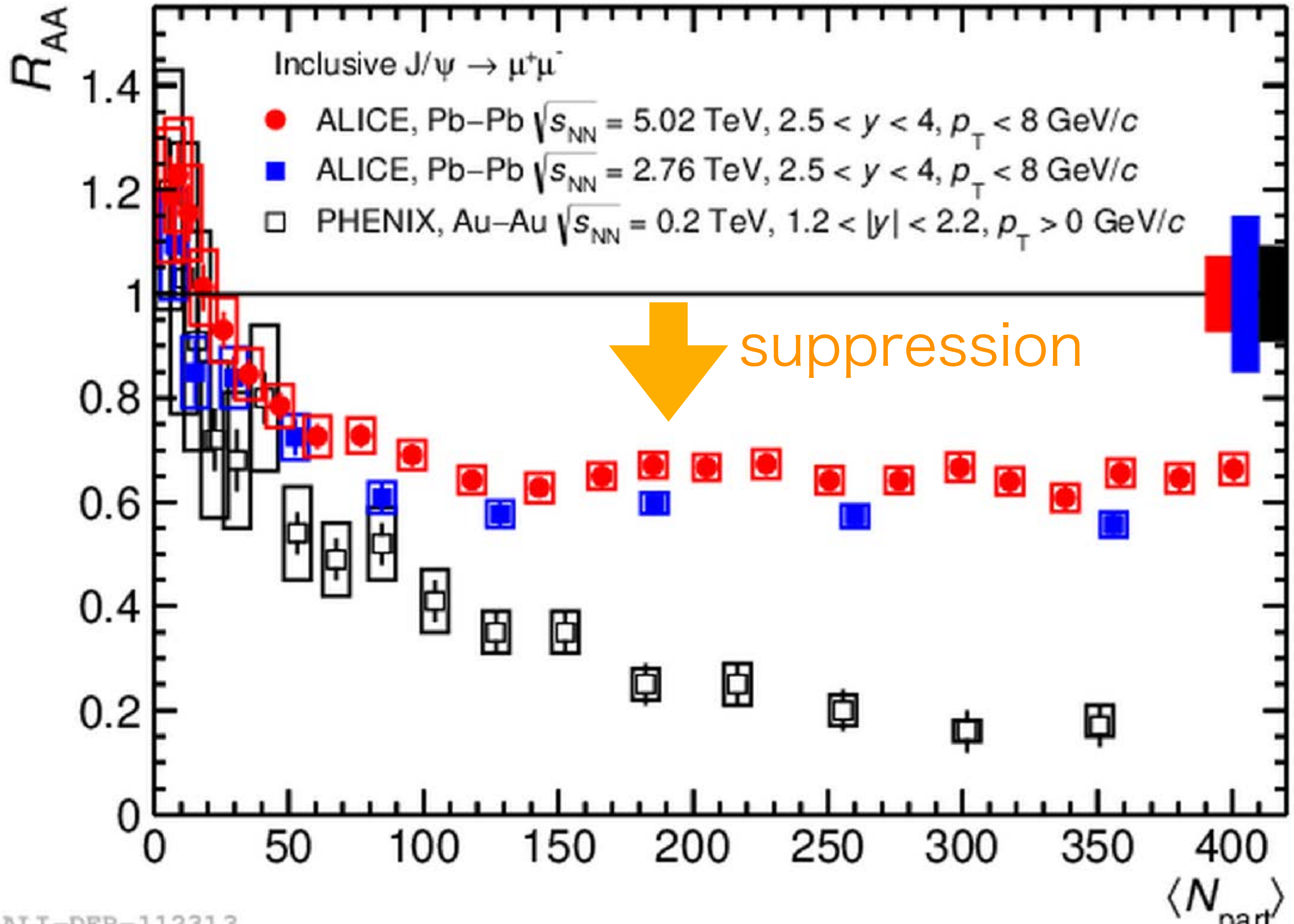
Quarkonia dissociate at high temperatures → suppression







T. Matsui, H. Satz, PLB 178 (1986) 416

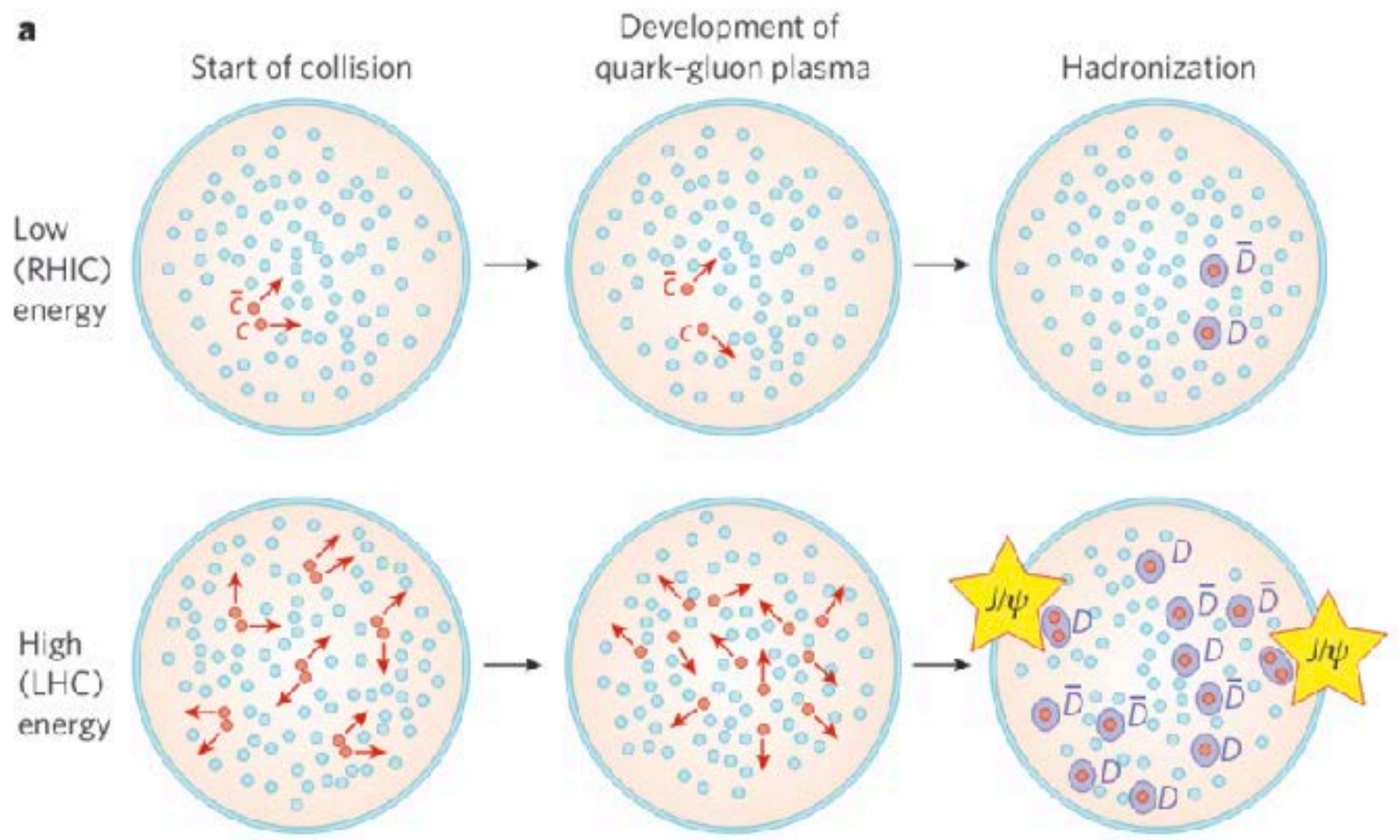


ALICE, PLB 766 (2017) 212, arXiv:1606.08197 [nucl-ex]

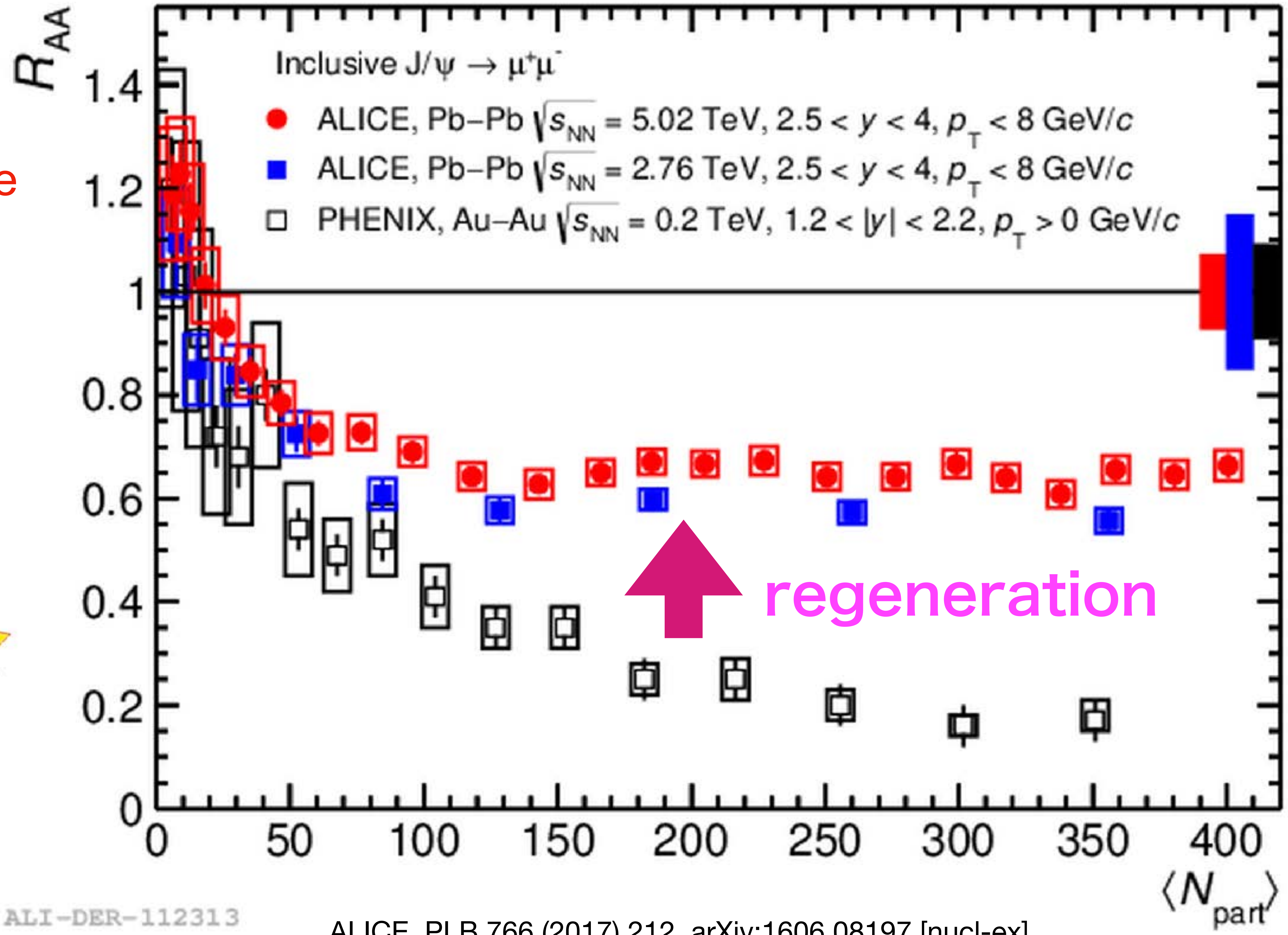
Melting and regeneration of J/ψ

Quarkonia dissociate at high temperatures → suppression
Clear evidence for recombination as new production mechanism

More charm quarks available at LHC compared to those at RHIC
→ regeneration
→ an evidence of de-confined state and thermalization

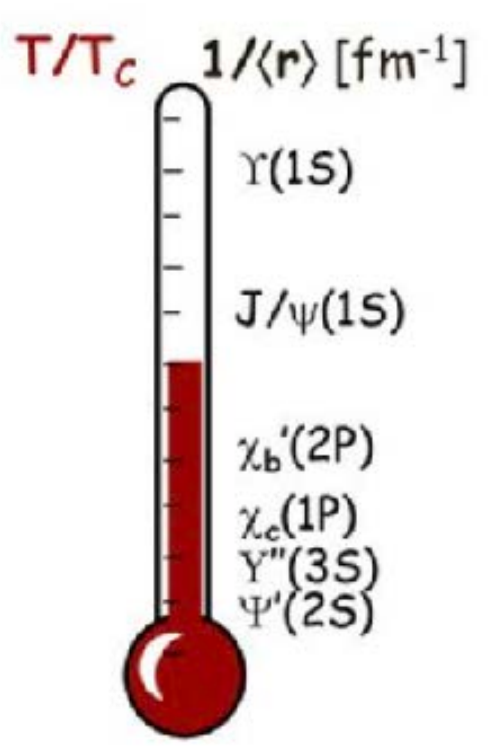


R. Thews, M. Schroedter, J. Rafelski, PRC 63 (2001) 054905, arXiv:hep-ph/0007323
P. Braun-Munzinger and J. Stachel, Nature 448 (2007) 302



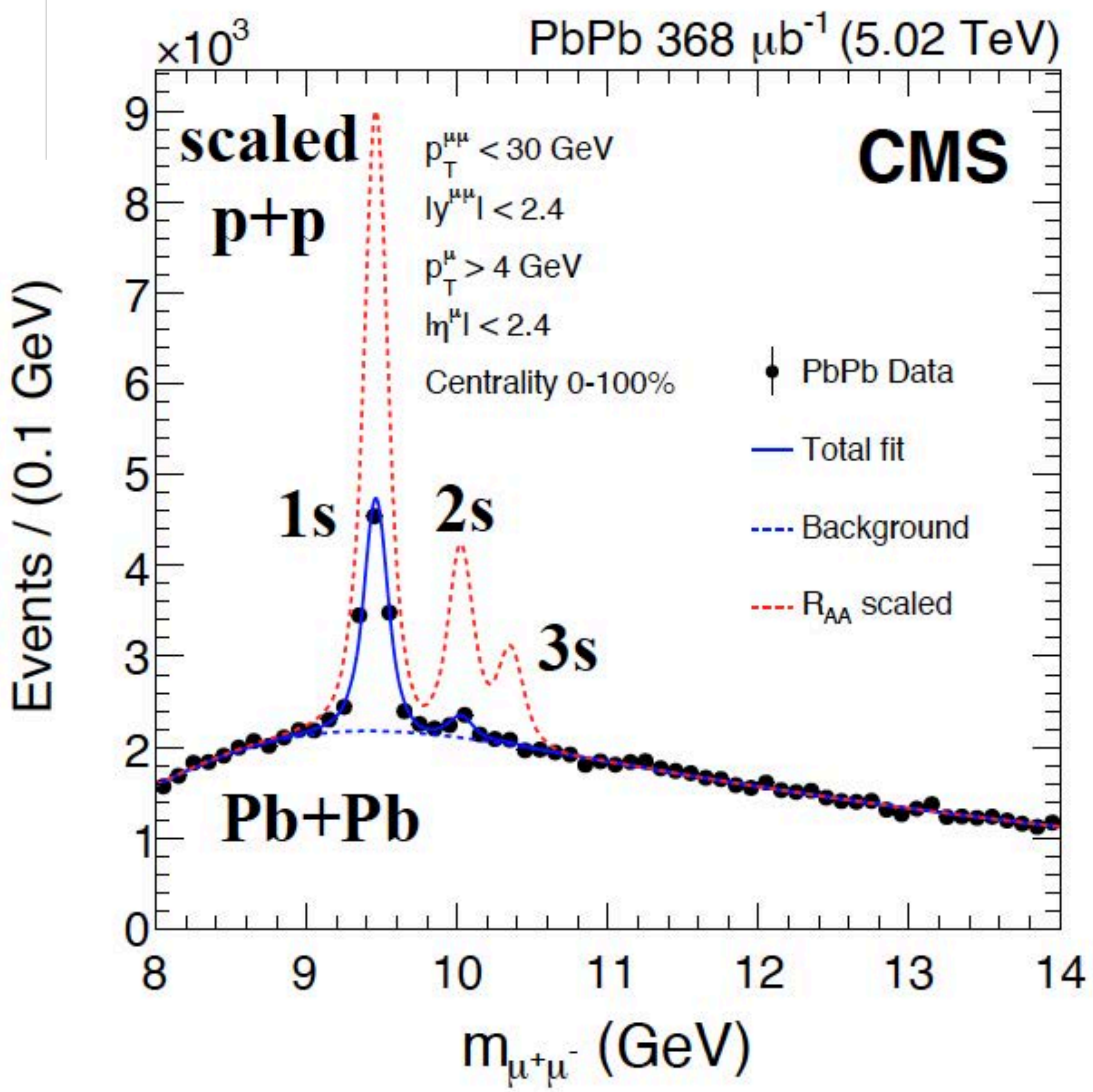
ALICE, PLB 766 (2017) 212, arXiv:1606.08197 [nucl-ex]

Thermometer: Melting of quarkonia: Υ

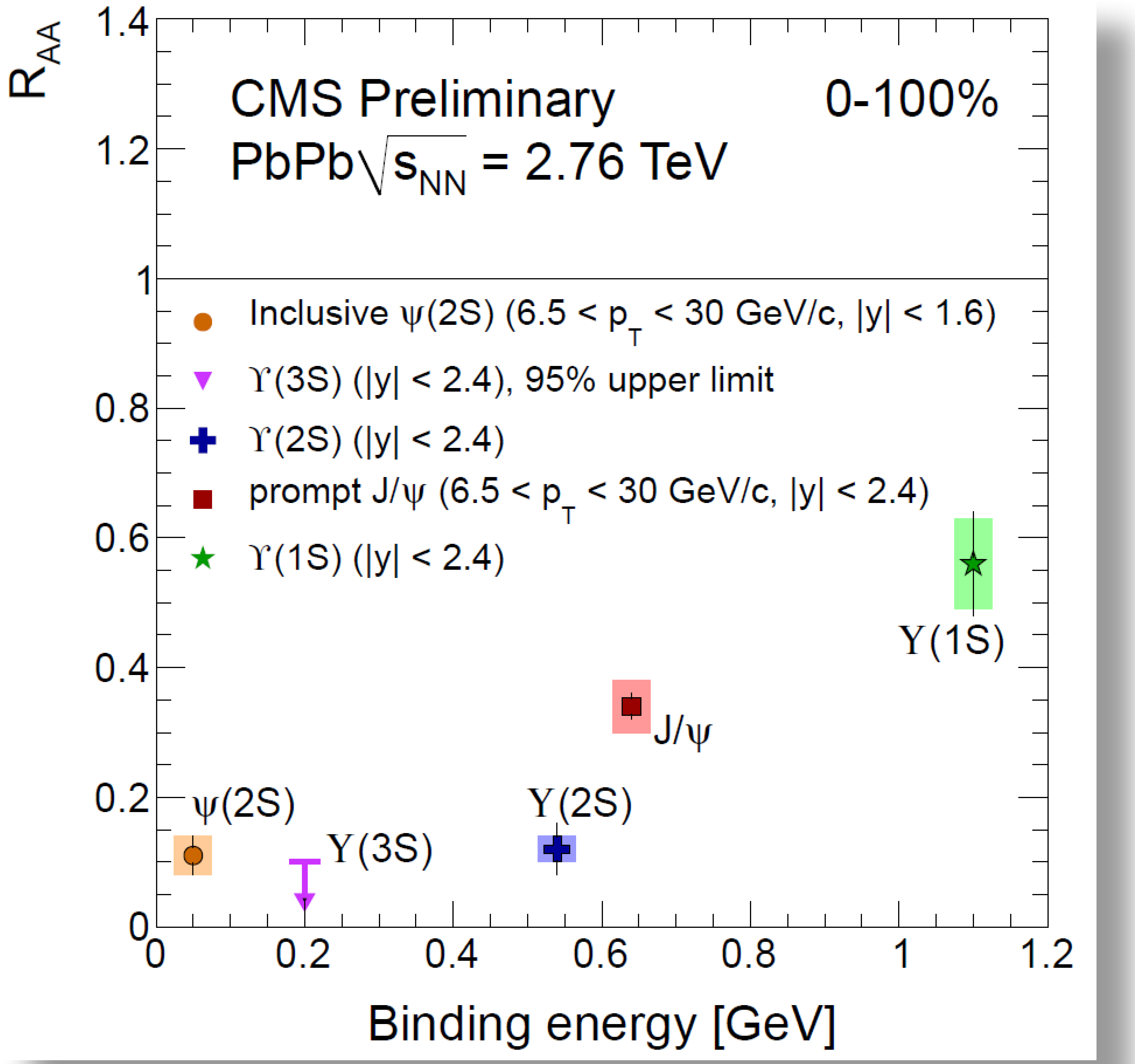


Melting excited ϒ states

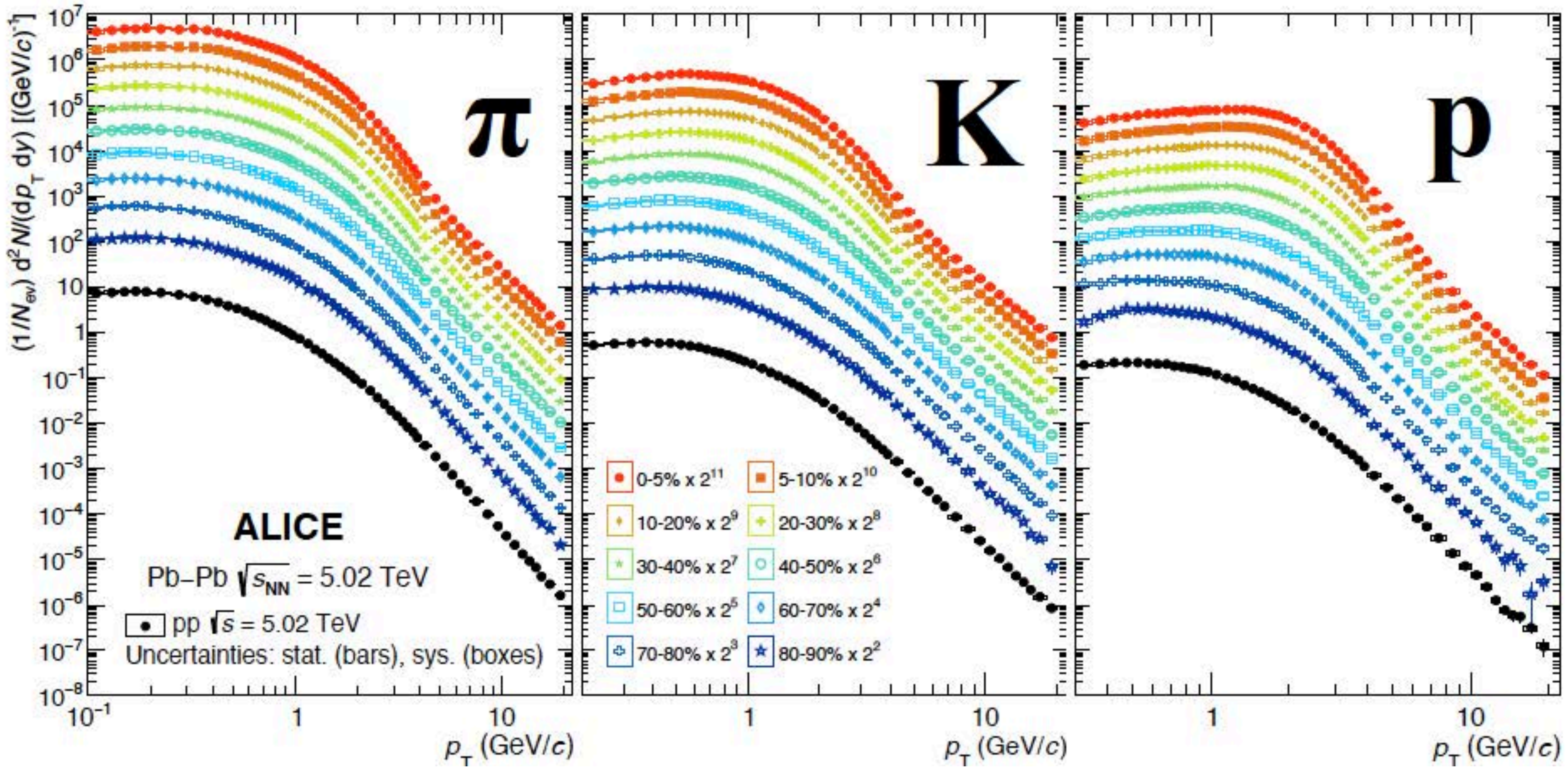
- Suppression of ground state Υ(1s), and excited states Υ(2S) and Υ(3S).
- **Sequential melting scenario, Υ(3S) > Υ (2S) > Υ (1S), which are more weakly bound in this order**

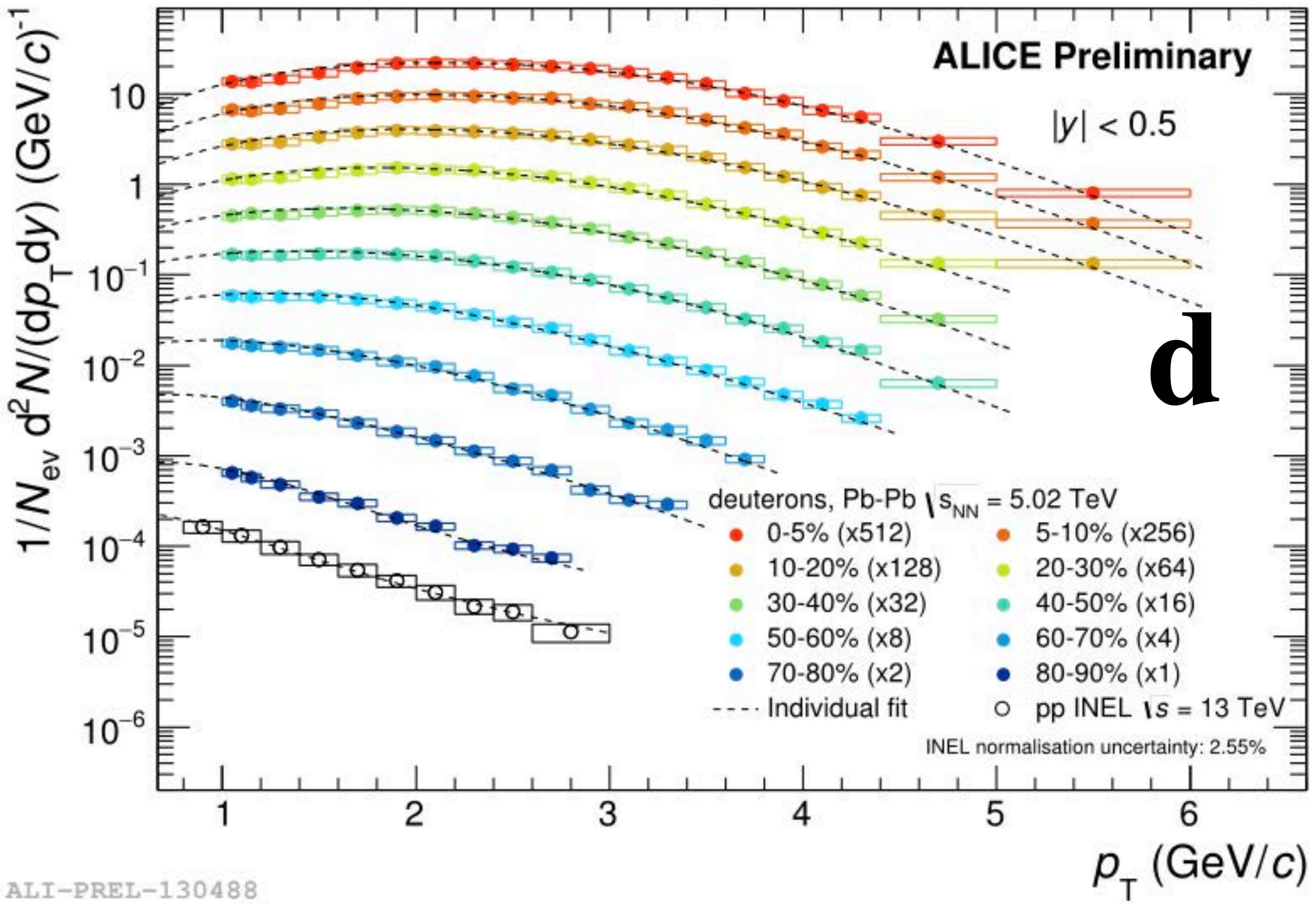


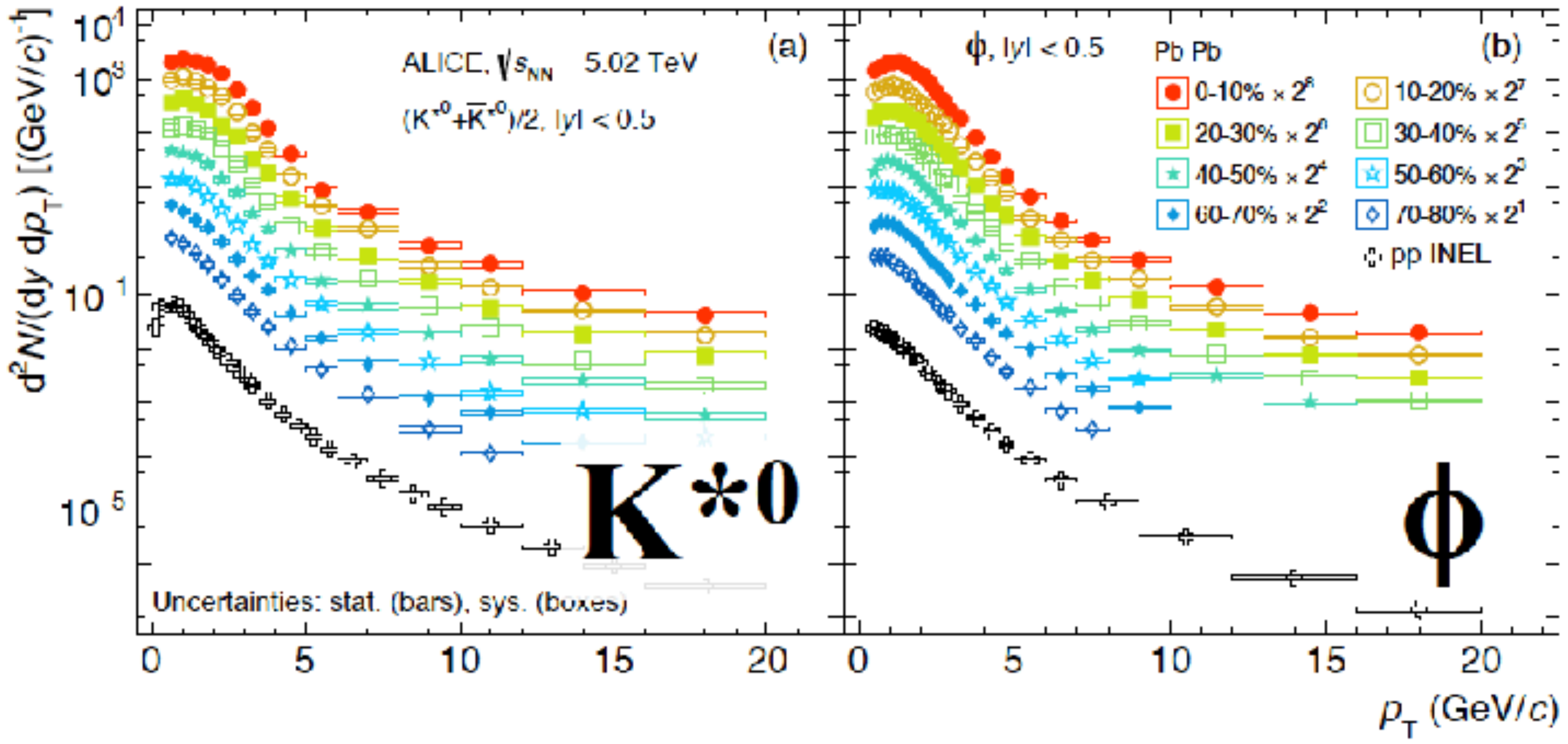
CMS, PLB 790 (2019) 270, arXiv:1805.09215 [hep-ex]

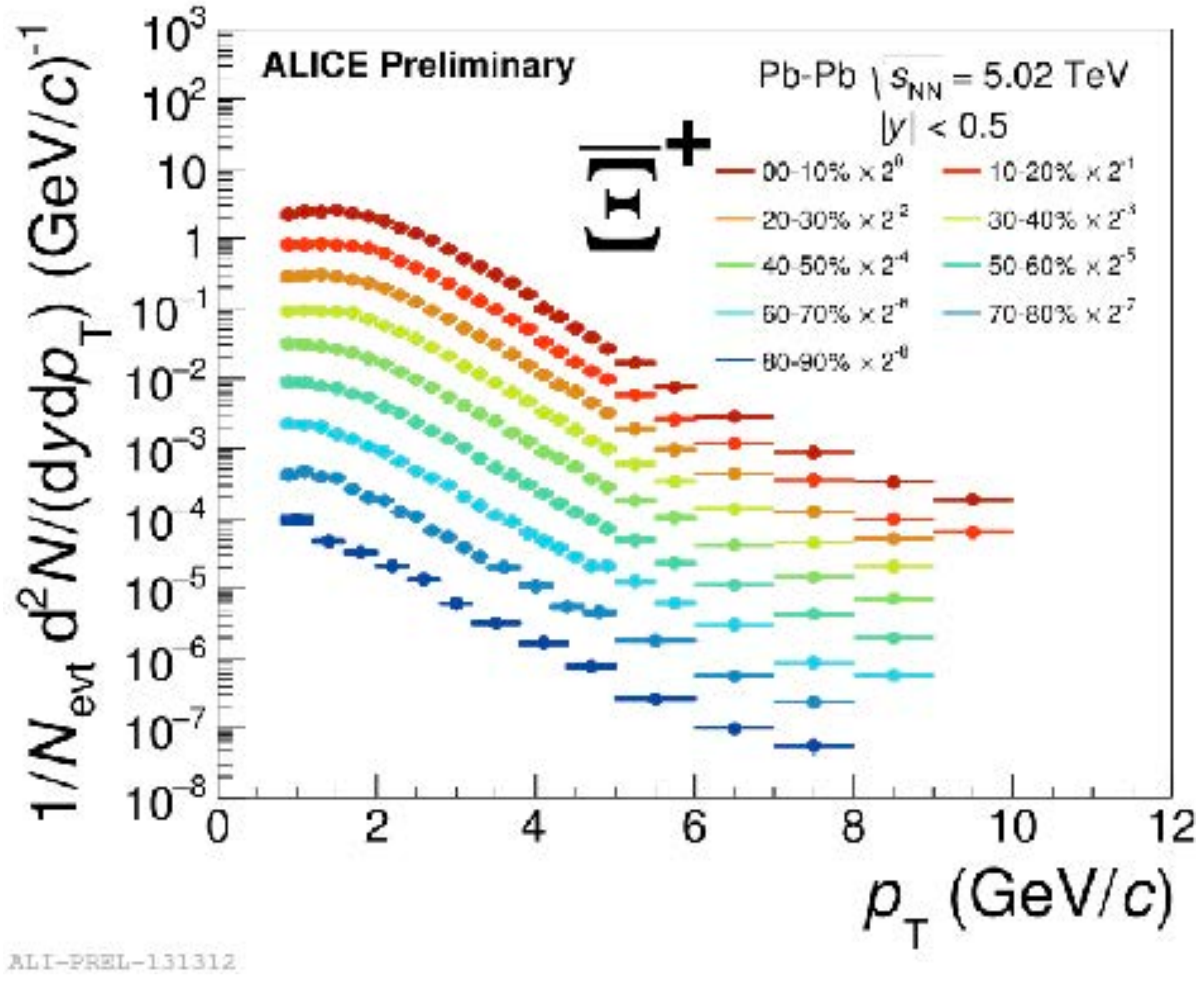


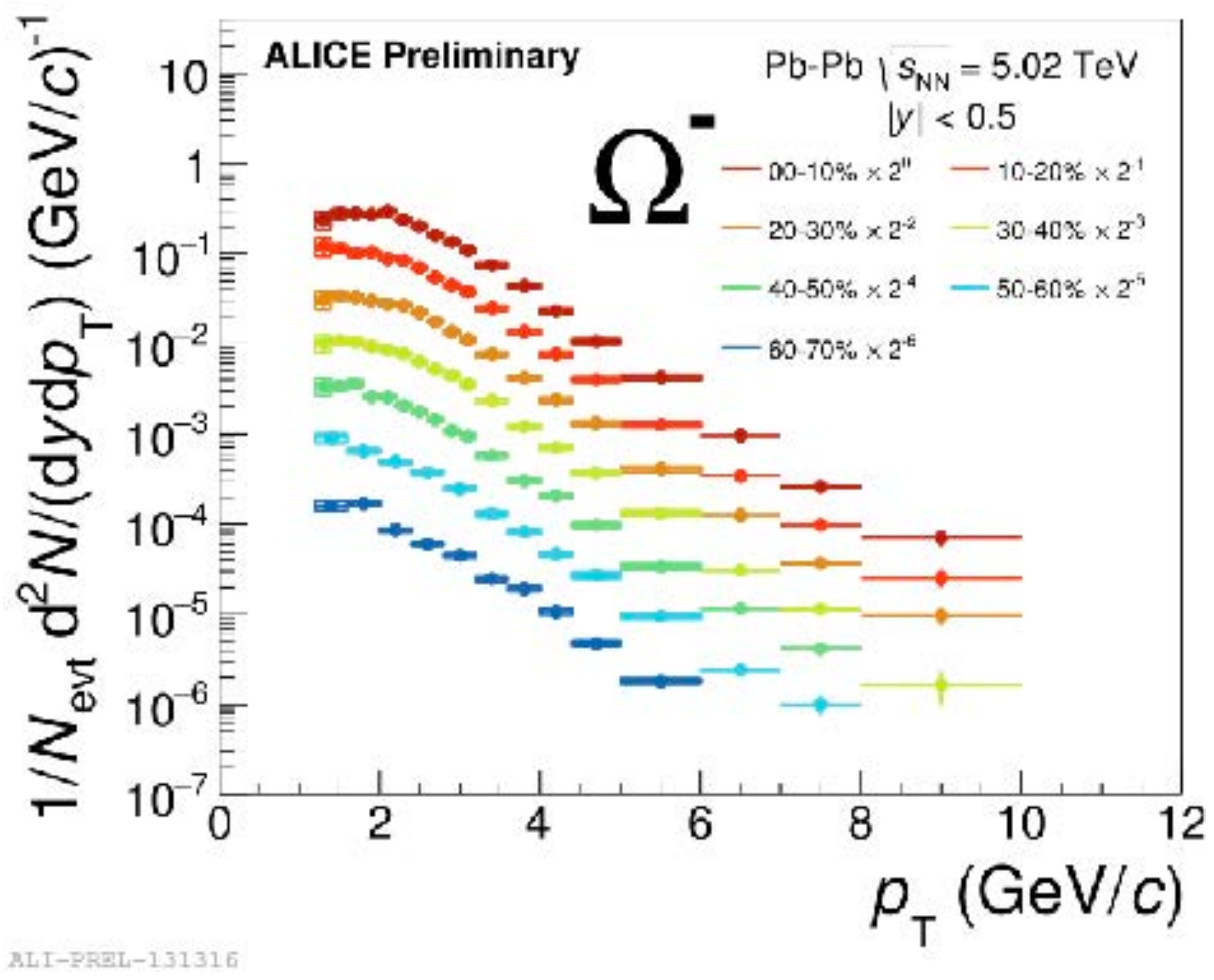
Identified Hadron p_T spectra in Pb-Pb











T_{ch}, μ_B Hadron Chemistry (with 22 species by T_{ch}, μ_B)

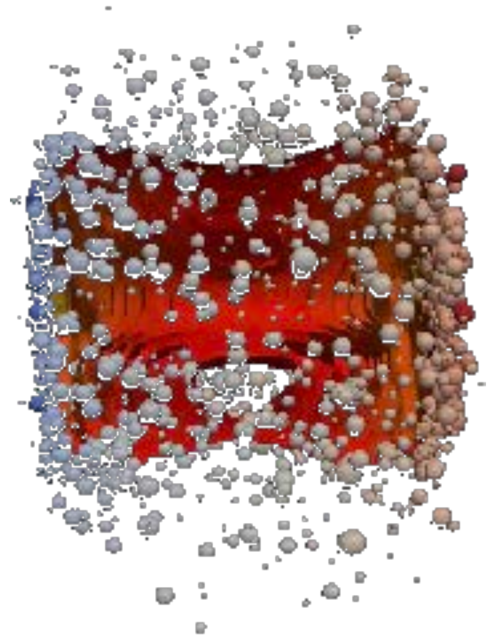
Hadron production:Bose, Fermi distributions

Statistical thermal model

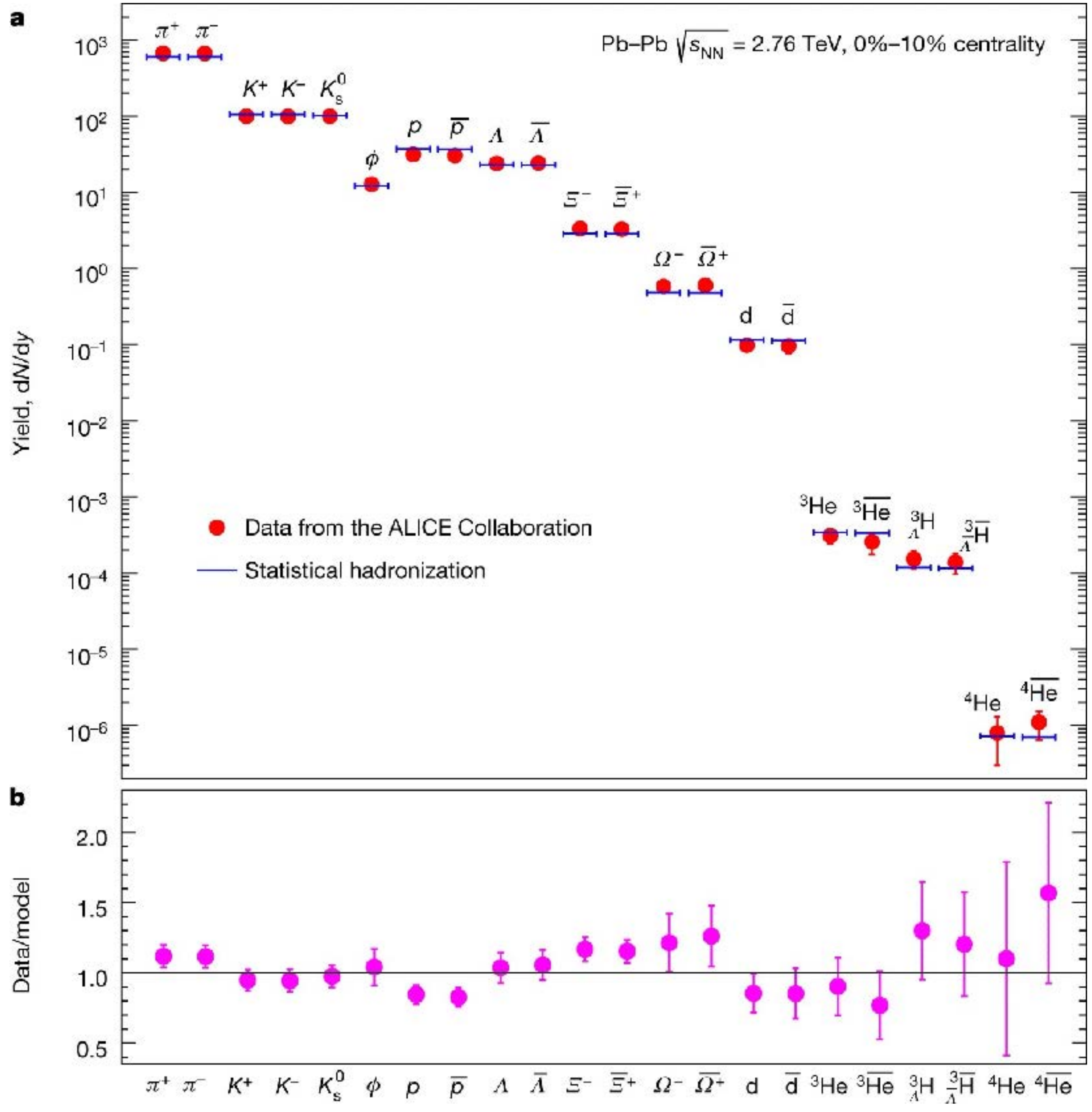
$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

Particle production assuming thermal equilibrium with a common chemical freeze-out temperature

→ excellent agreement with the data over nine orders of magnitude!

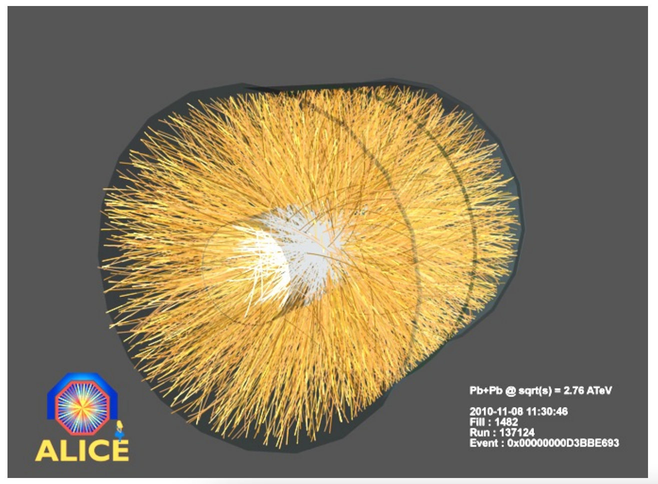


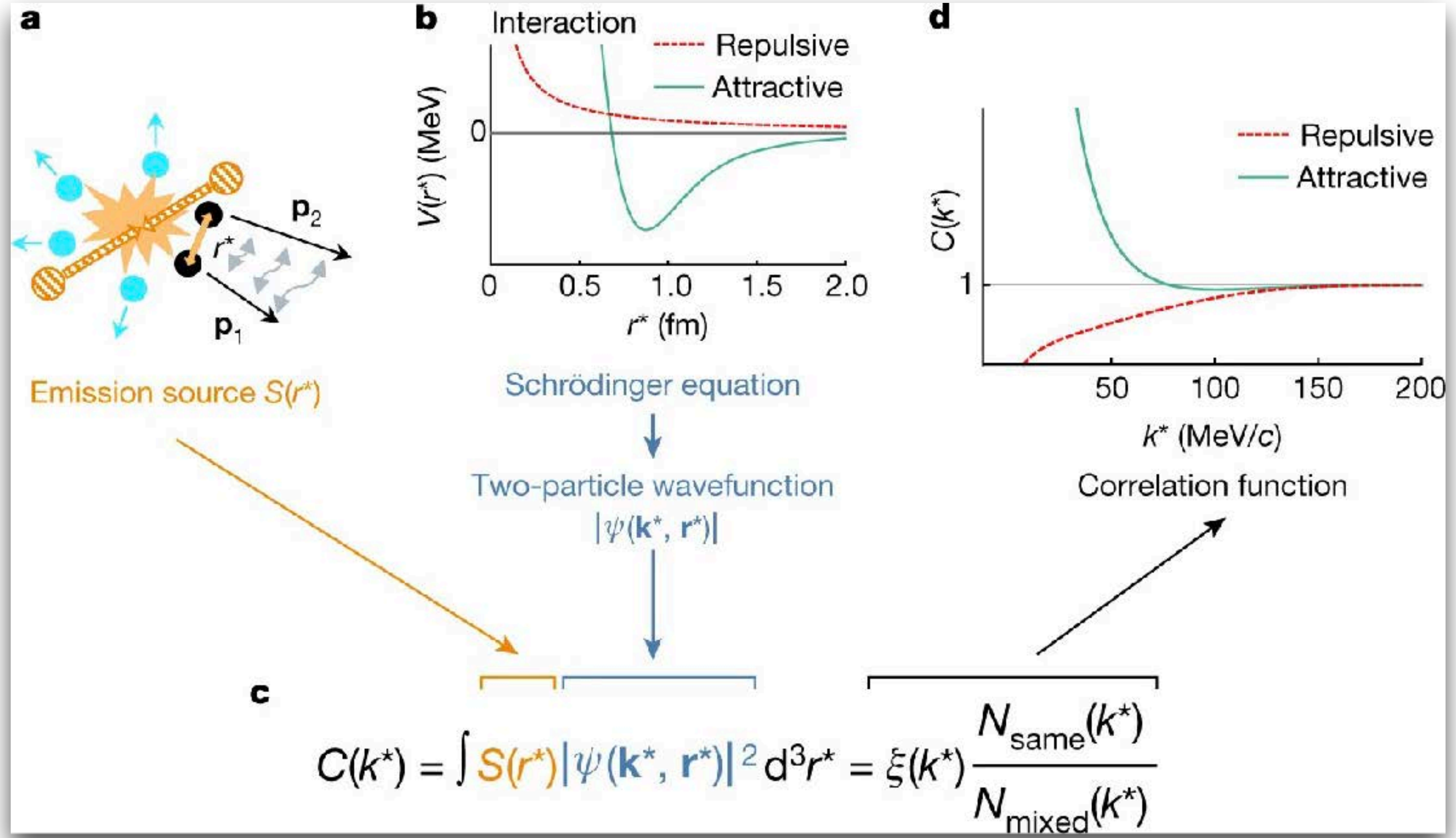
T_{ch} : 153 MeV, μ_B ~ 0

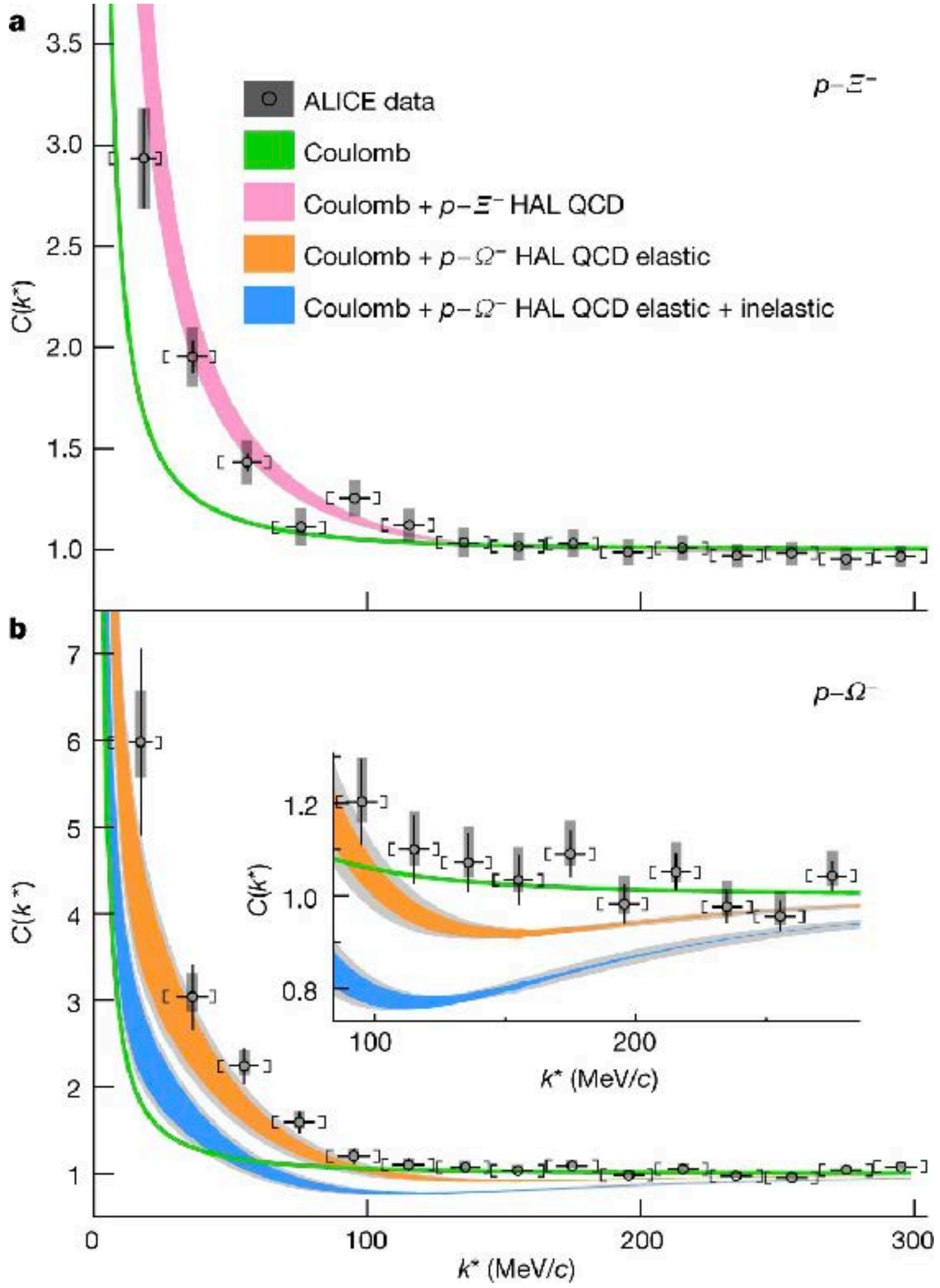


A. Andronic et al., Nature 561 (2018) 321

Laboratory for strong interaction





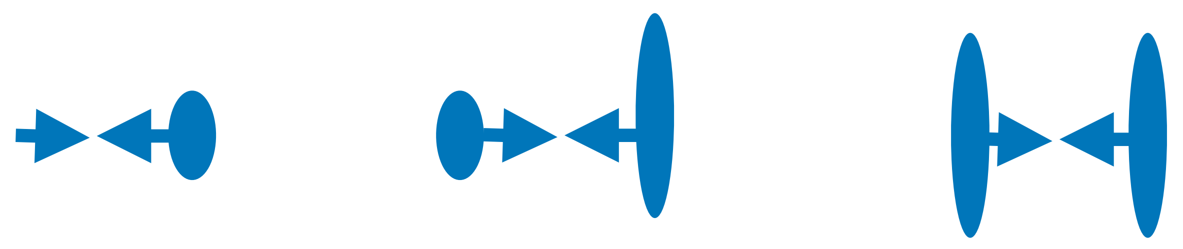


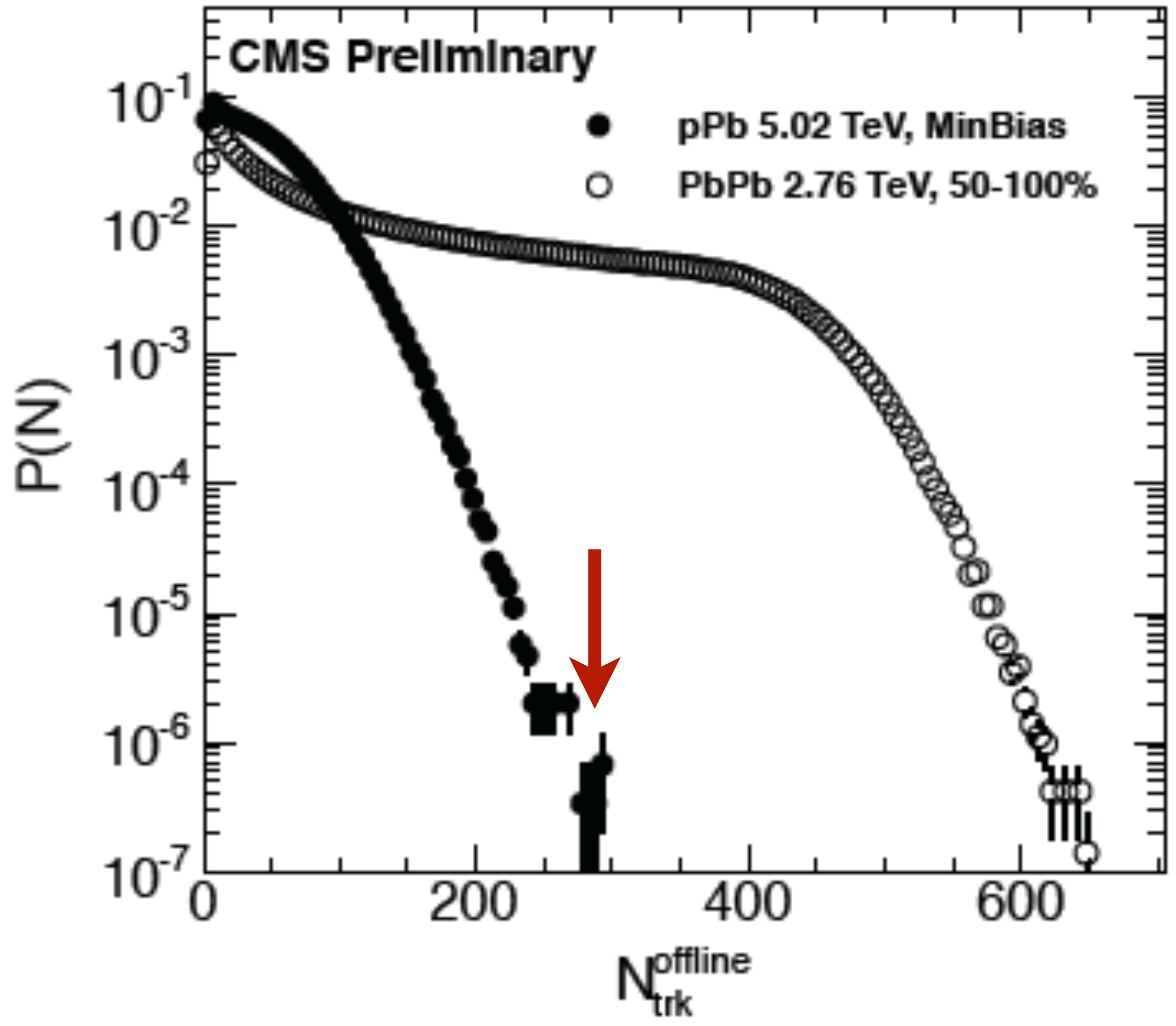
- Unveiling strong-interaction potentials among hadrons via femtoscopy
- Important test for lattice QCD, input for EOS of neutron stars

ALICE Nature 588 (2020) 232
ALICE Phys. Rev. Lett. 127 (2021) 172301
ALICE Phys. Lett. B822 (2021) 136708

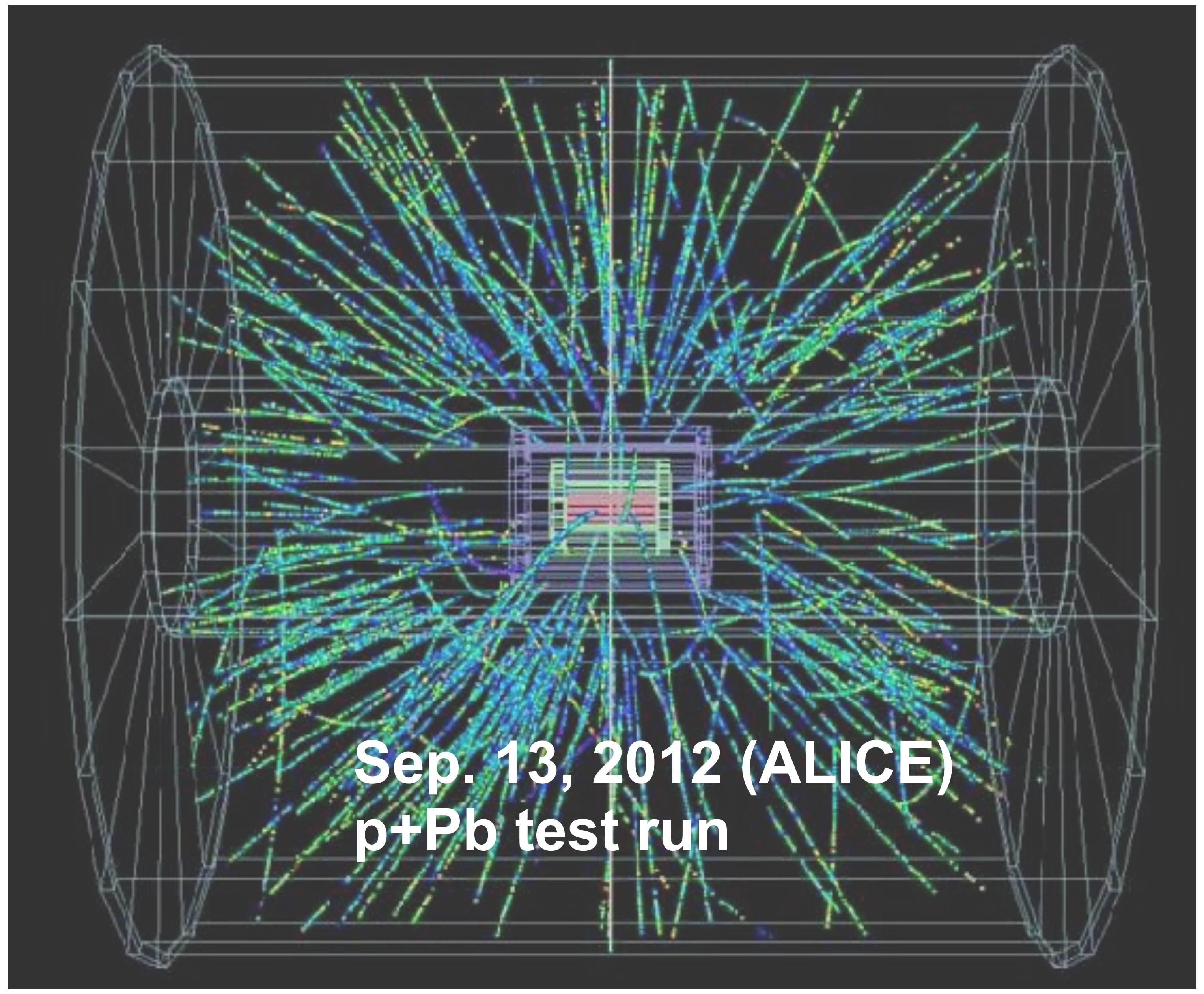
Small systems

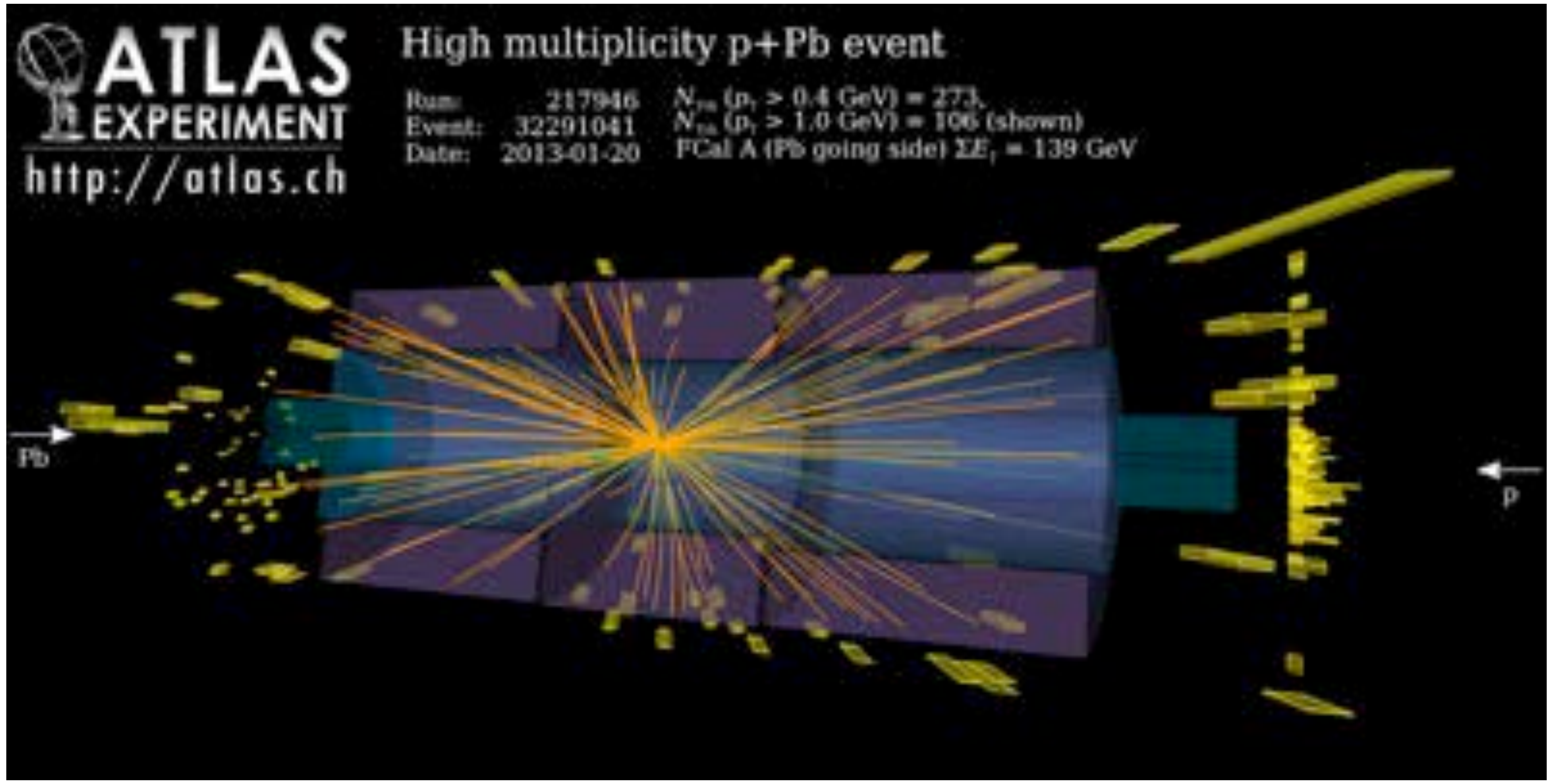
pp **p-Pb** **Pb-Pb**



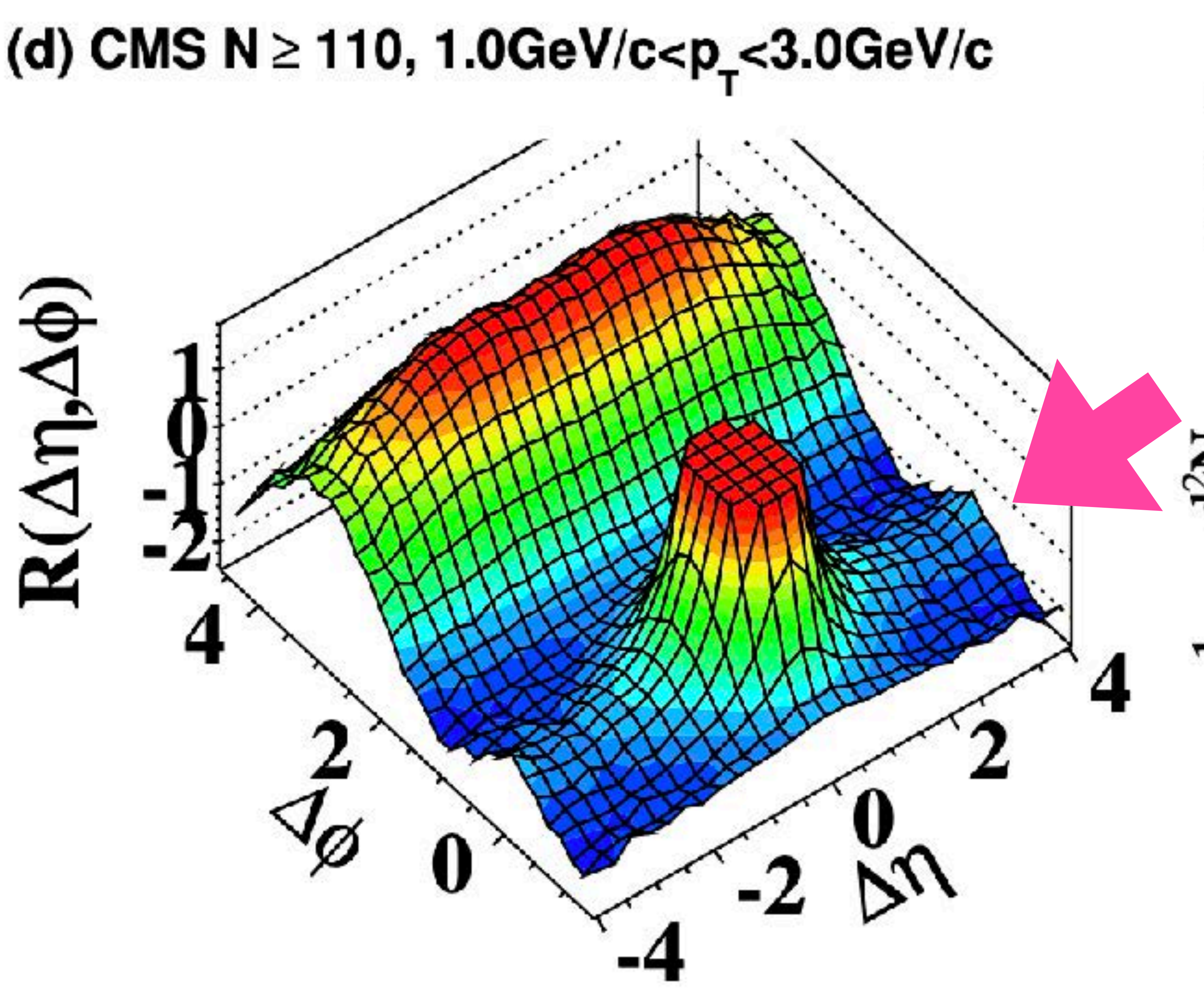


Highest p-Pb multiplicity ~ 55-60% Pb-Pb

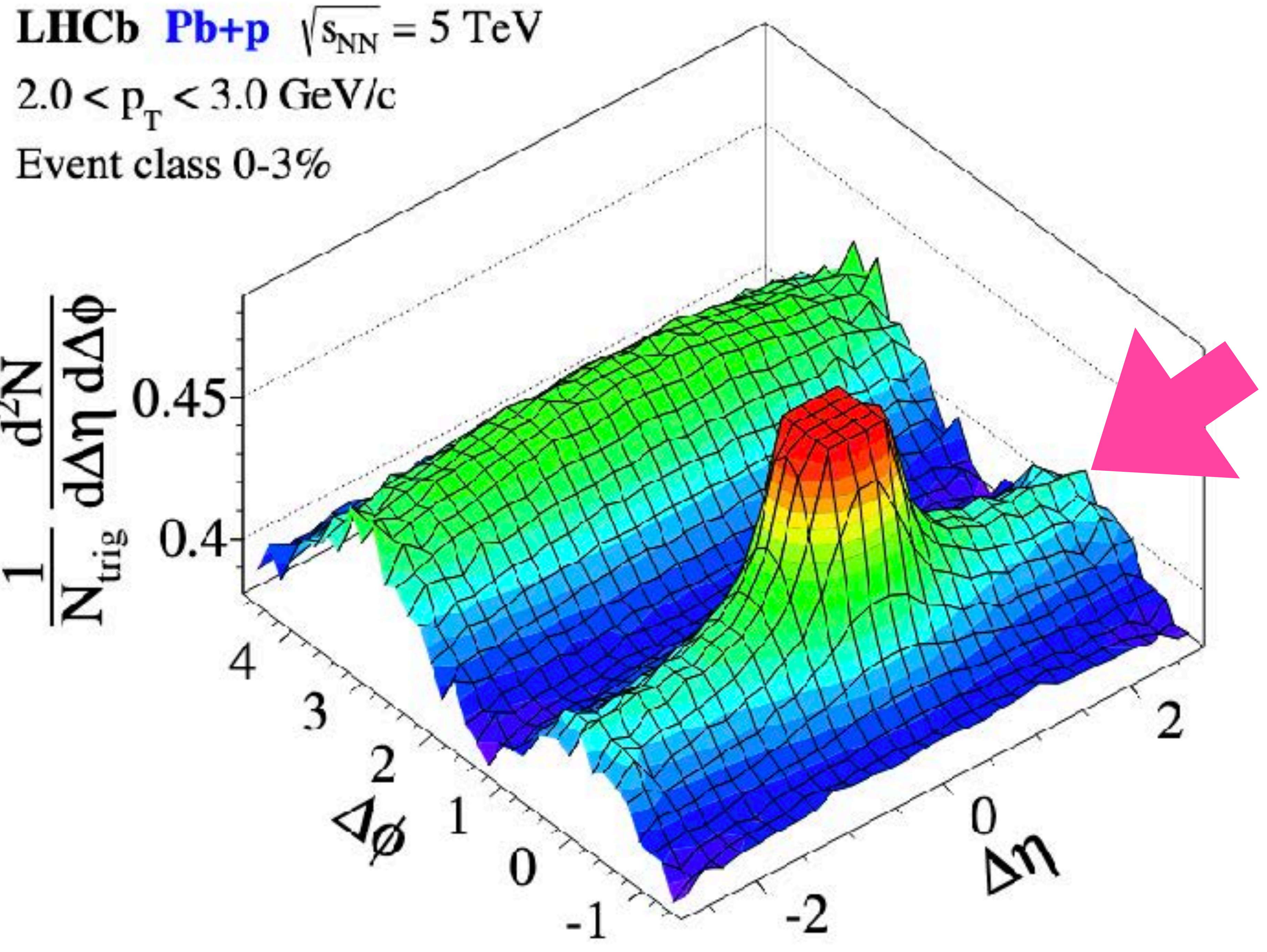




Collective behavior in small systems



pp



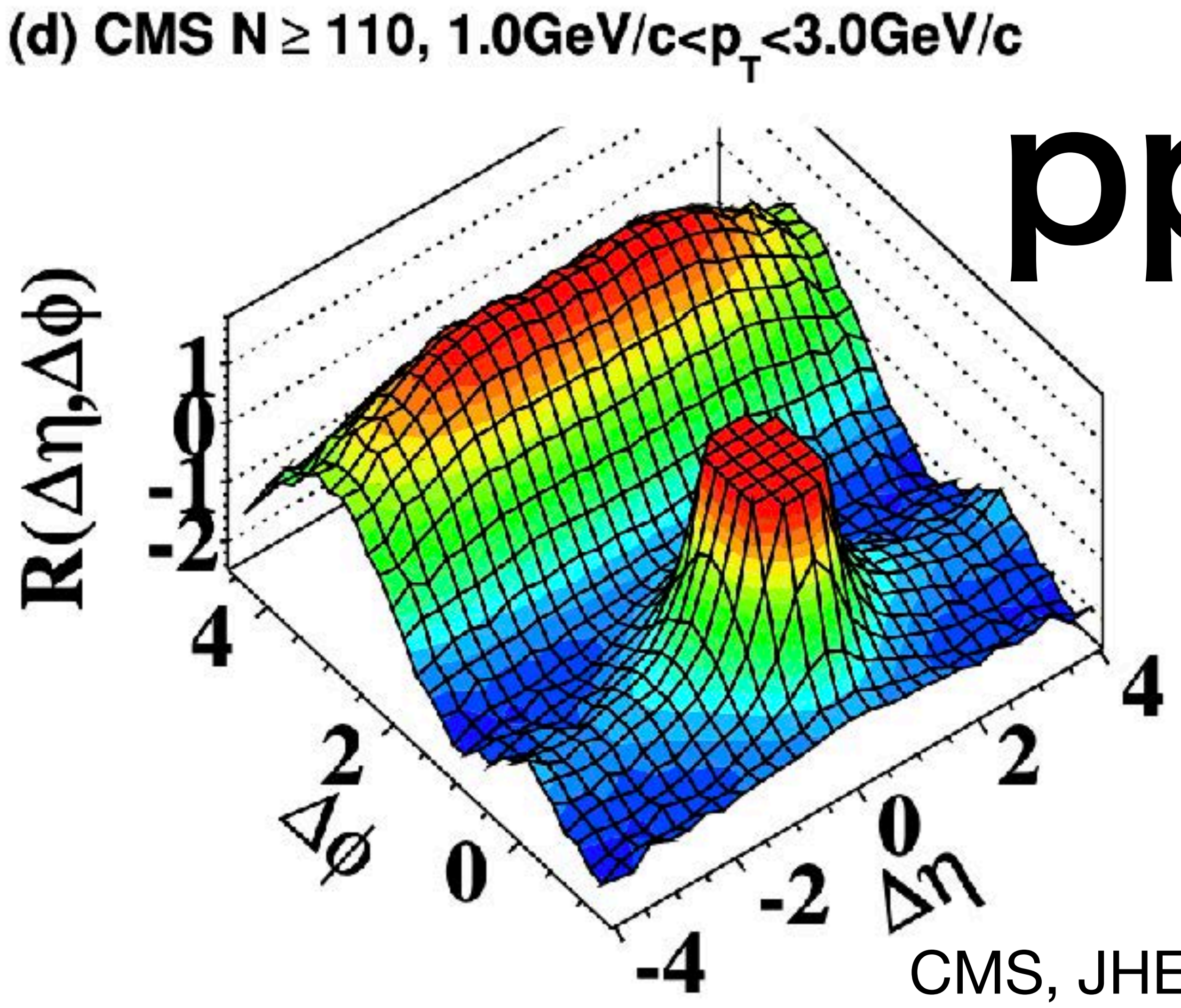
p-Pb

- Two particle correlations in η and φ spaces
- **In high multiplicity p-p and p-Pb, "ridge" structure in Δη direction are seen**

CMS, JHEP 1009 (2010) 91, arXiv: 1009.4122 [hep-ex]

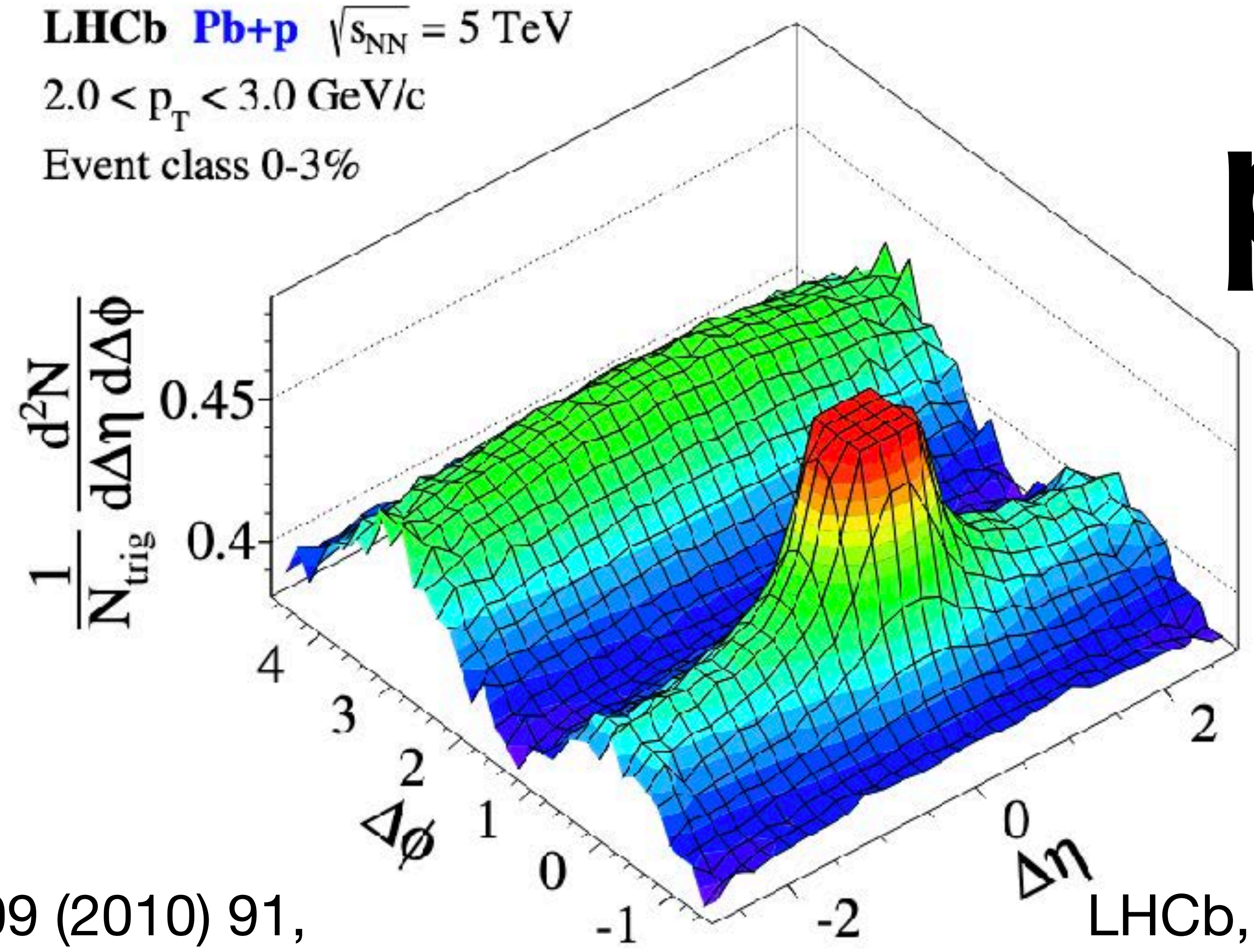
LHCb, PLB 762 (2016) 473, arXiv:1512.00439 [nucl-ex]

Collective behavior in small systems



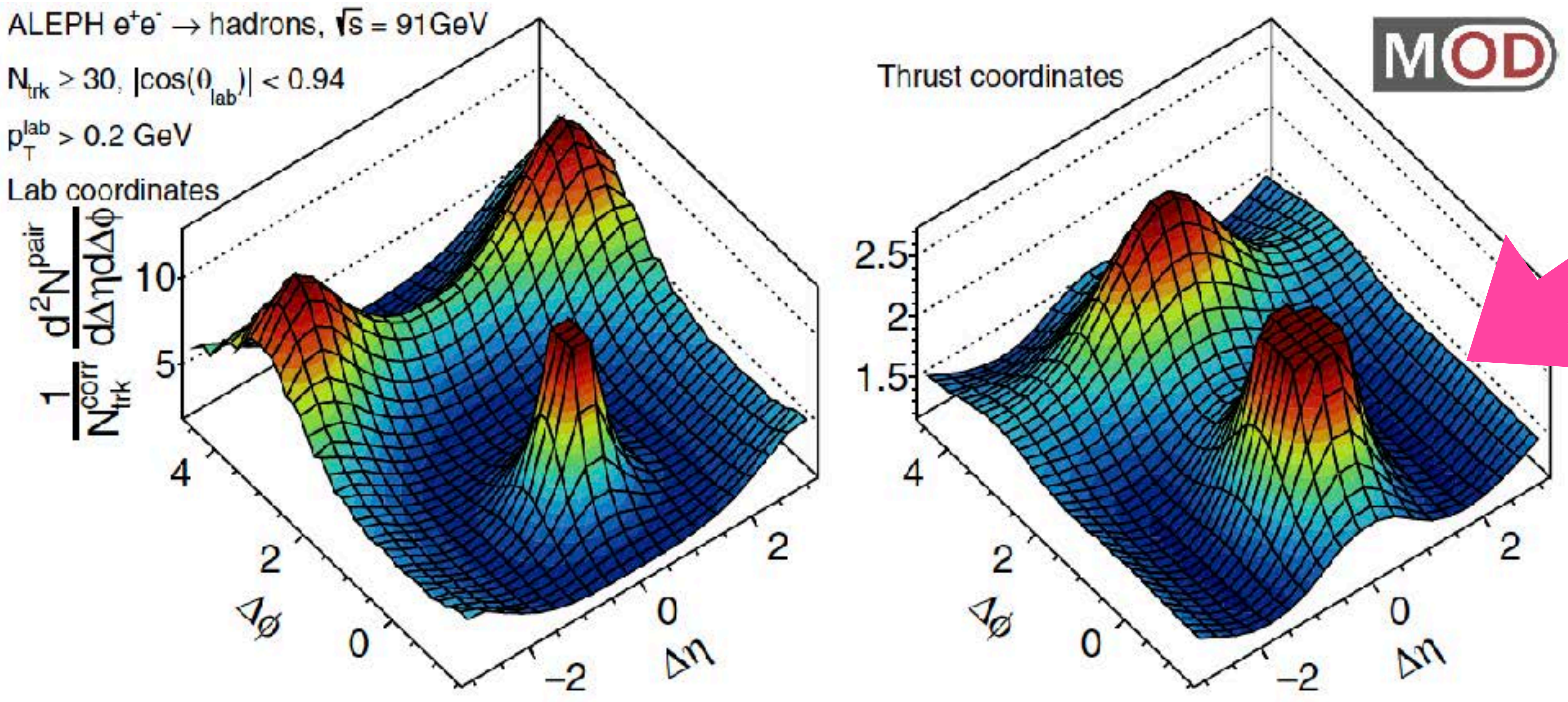
pp

CMS, JHEP 1009 (2010) 91, arXiv: 1009.4122 [hep-ex]



p-Pb

LHCb, PLB 762 (2016) 473, arXiv:1512.00439 [nucl-ex]



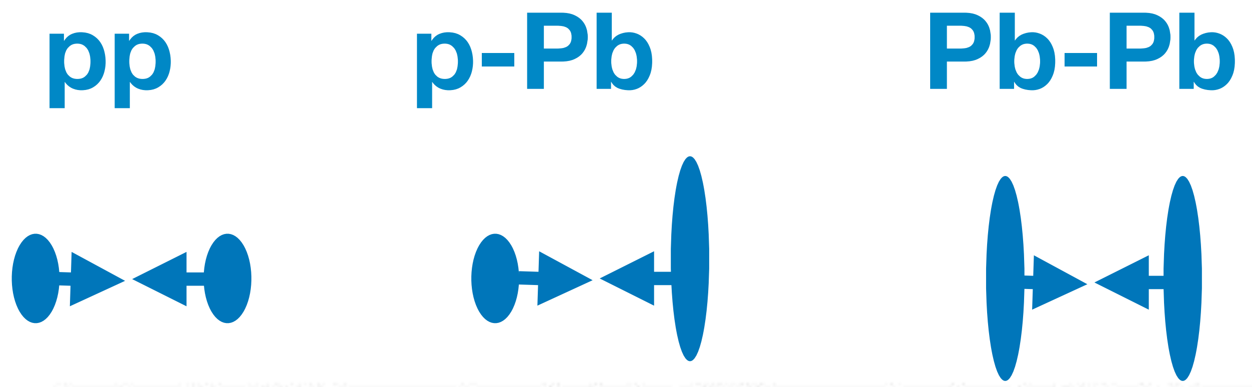
e+e-

no ridge

ALEPH Archived Data Phys. Rev. Lett. 123, 212002 (2019)

- Two particle correlations in η and φ spaces
- **In high multiplicity p-p and p-Pb, "ridge" structure in Δη direction are seen**
- **No ridge in e+e- data**
- Origin of the ridge structure is still unclear
- Initial stage (e.g. CGC) or small QGP?

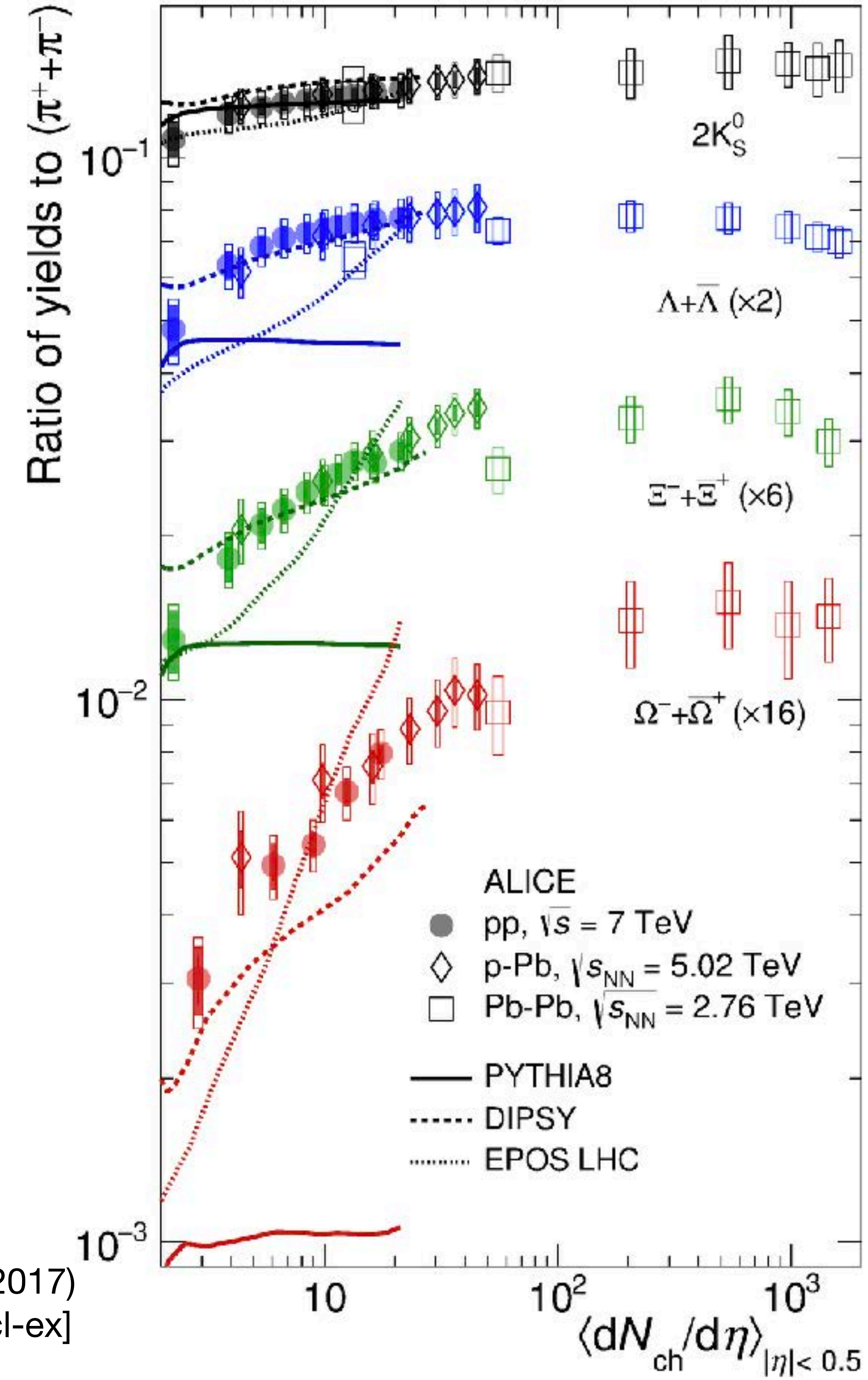
Strangeness enhancement in small systems



The smooth increase of strange particle yields (w.r.t. pions) as a function of multiplicity was observed from p+p to p+Pb to Pb+Pb

Data reproduce by Color reconnection and multi parton interaction (MPI)

Q) At the same multiplicity, physics is same for pp vs. p-Pb and p-Pb and Pb-Pb?



MPI

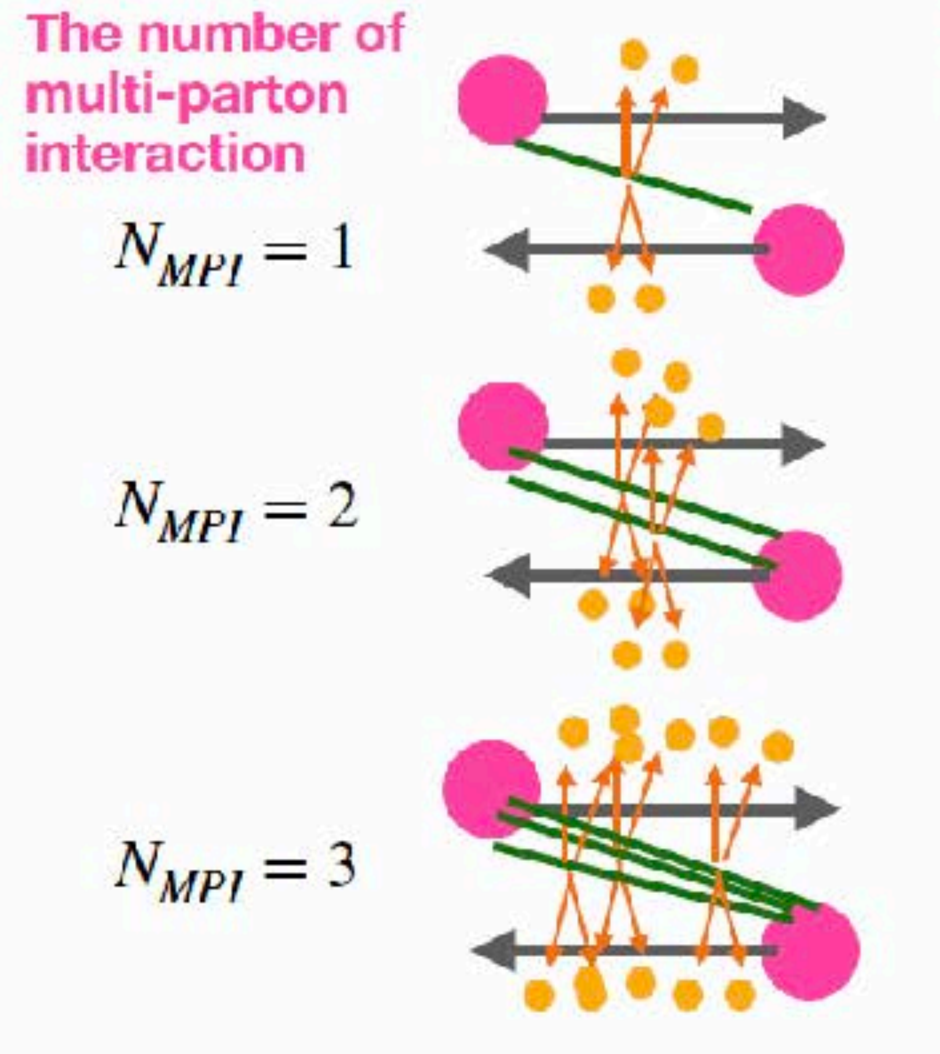


Figure by H. Menjo

Color Reconnection

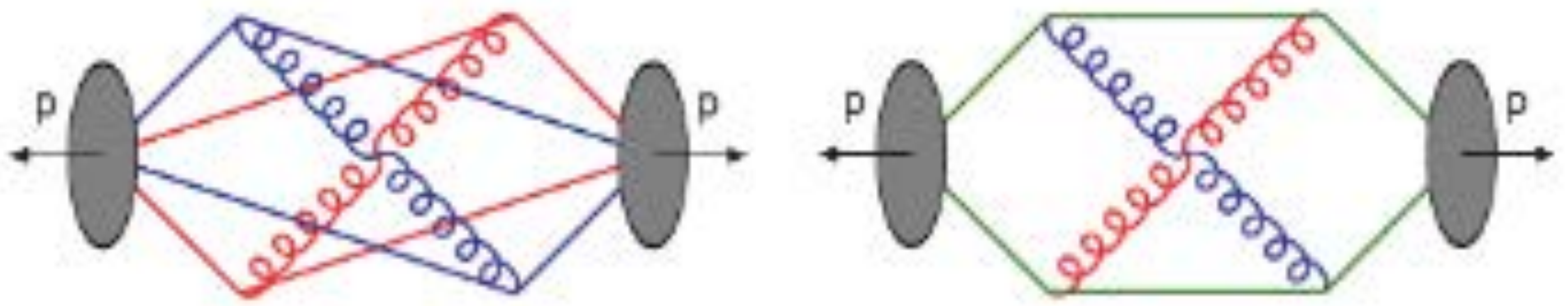


Figure by H. Menjo (Paolo Gunnellini, MPI@LHC 2017)

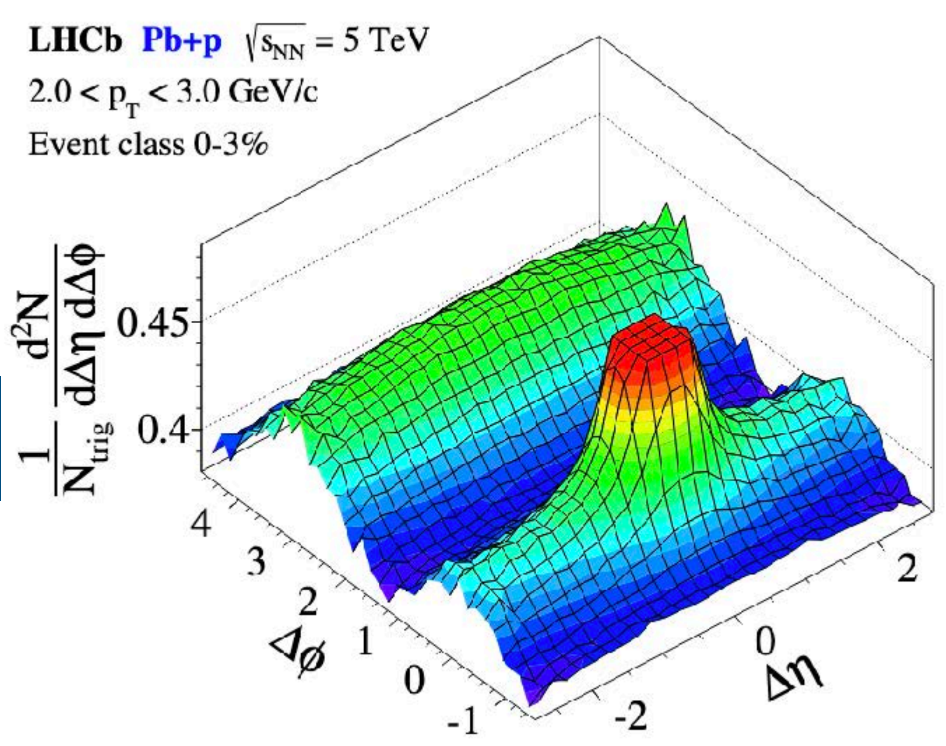
ALICE, Nature Physics 13 (2017) 535, arXiv: 1606.07424 [nucl-ex]

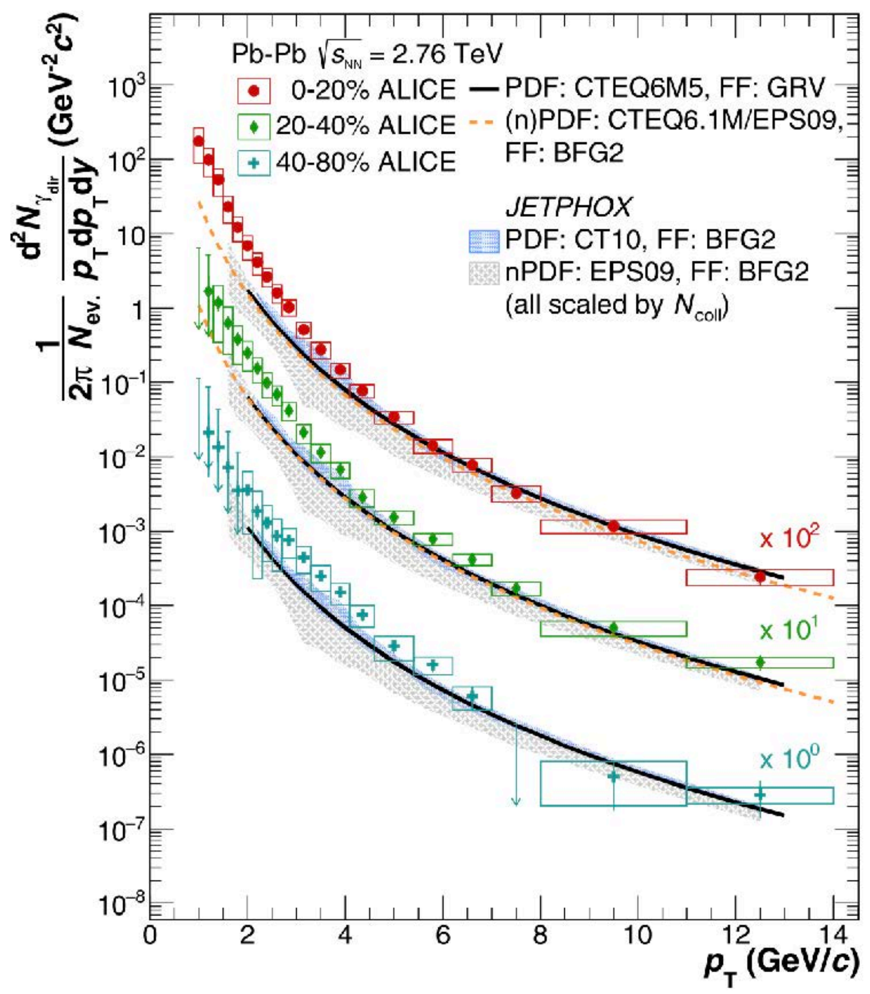
Part 2.
Open questions

List of (my) questions

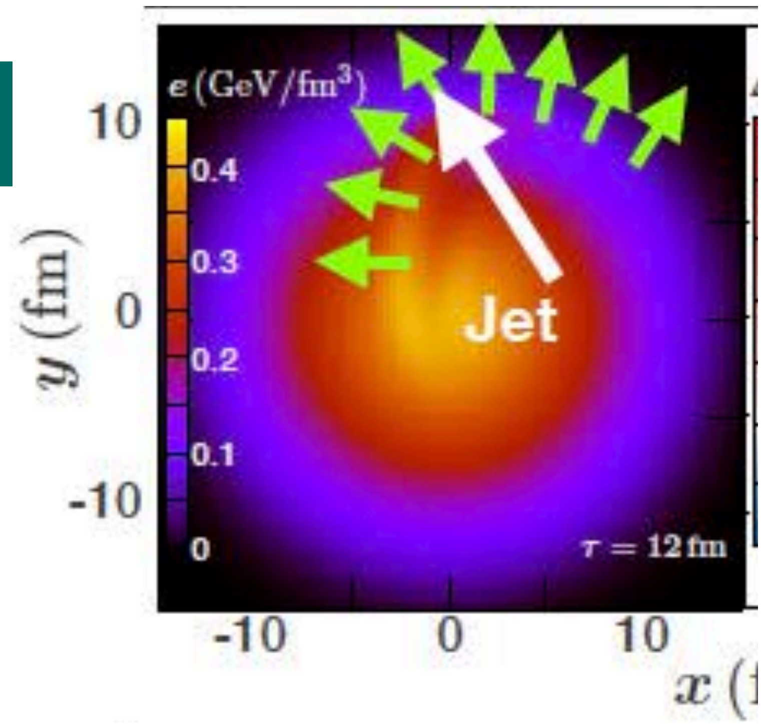
- What is the **origin of "collectivity" or ridge** in small systems?
- Color reconnection with multi-parton interaction vs. small QGP
- Same physics in pp, p-Pb and Pb-Pb if the all multiplicities are same?
- Why there is no jet quenching in high multiplicity in pp and p-Pb, but Pb-Pb does?
- What is the **initial condition, CGC** exists?
- Why **QGP thermalizes so quickly**?
- How QGP is created in heavy ion collisions?
- Is there a **critical end point** in QCD phase diagram?
- Thermal photons are coming from an early stage or late hadronic stage or both?
- What is the **diffusion coefficient D_s**?
- Medium response: is there a **Mach cone** shock wave?
- **Chiral symmetry restoration** at μ_B=0 and high temperature?
- QGP in heavy ion collisions is same as QGP in early universe?

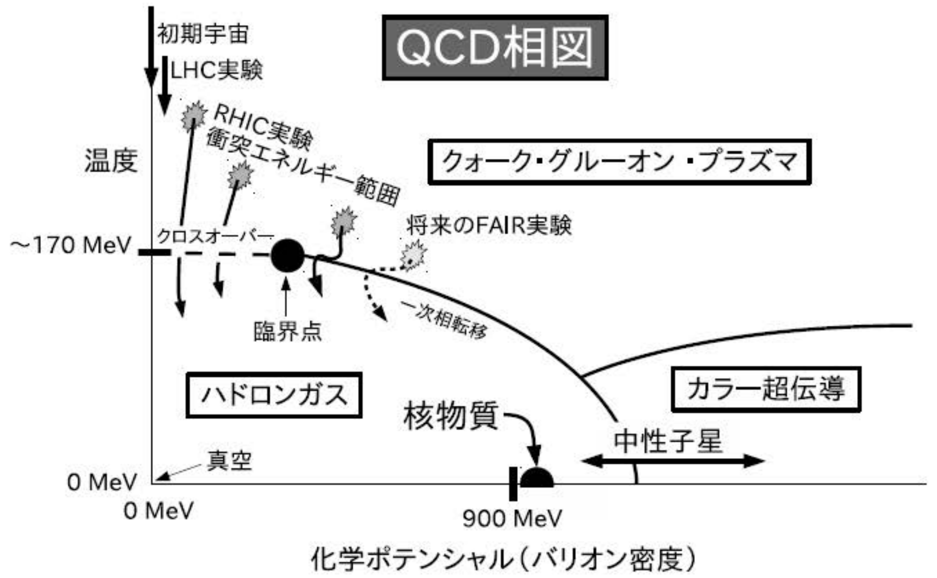
small system





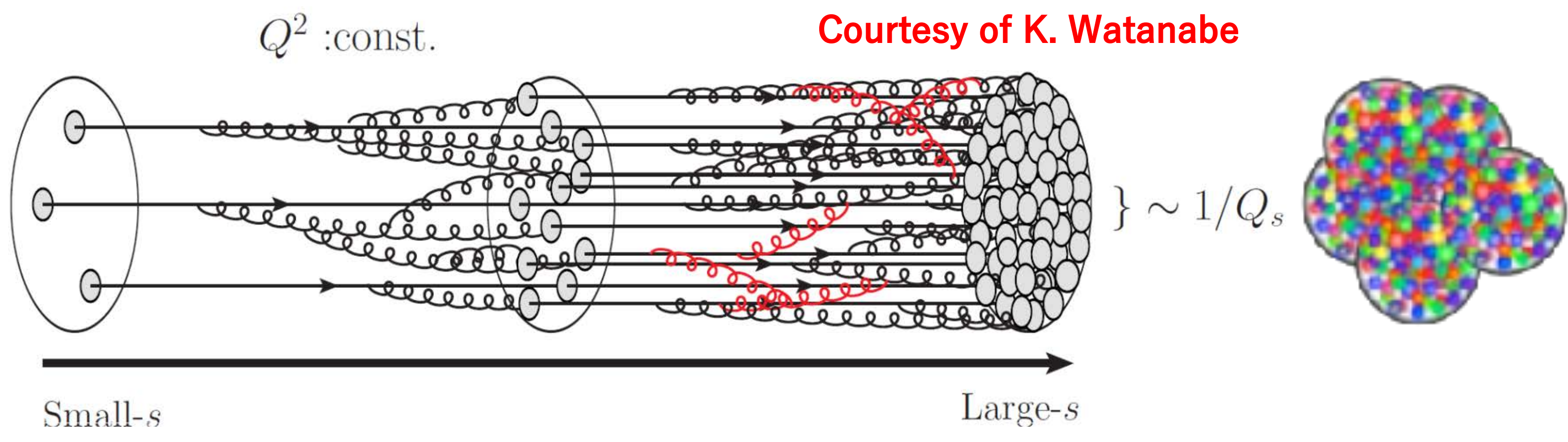
Initial condition





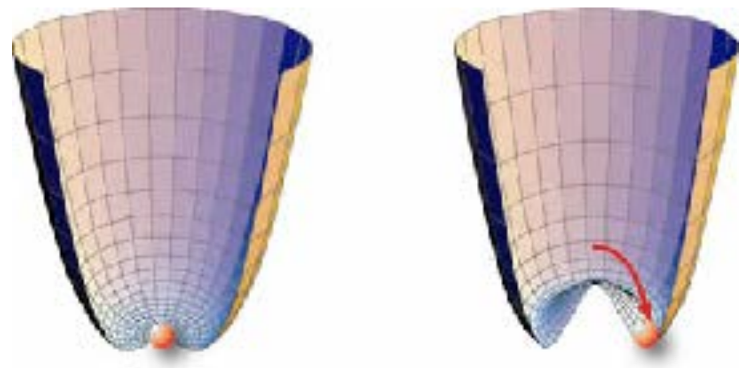
Phase diagram

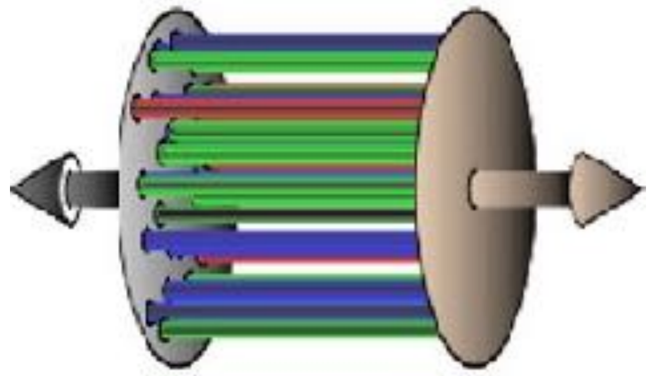
Matter properties



Medium responce

Chiral symmetry

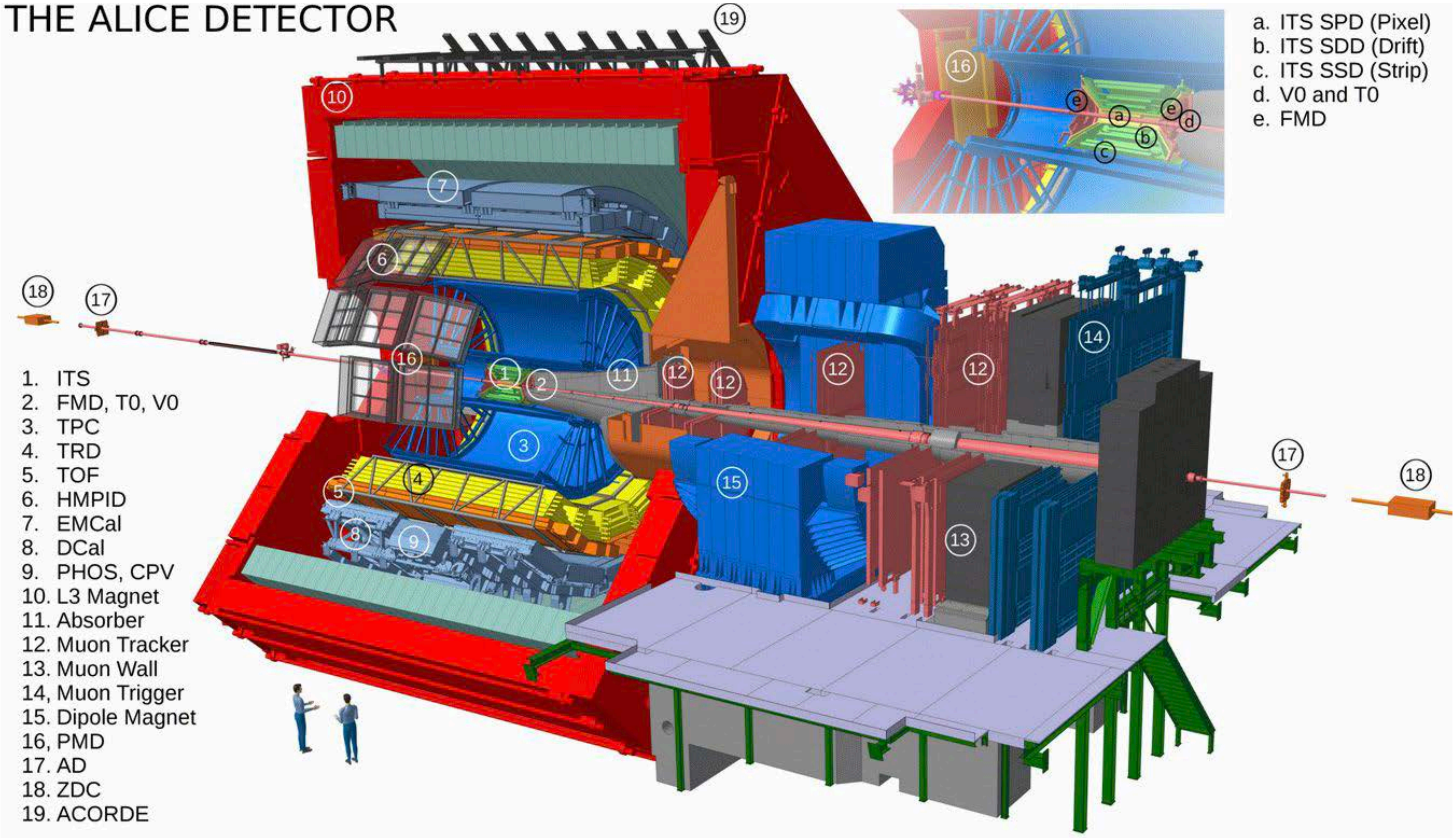




Early universe

Part 3.
Future of Heavy Ion Physics @ LHC (ALICE)

ALICE detecter in Run-2 (2025-2018)



ALICE upgrades and physics program

Run 3 (2022-2025)

New TPC (GEM), ITS, muon tracker (MFT), Fast online trigger (FIT) O² DAQ

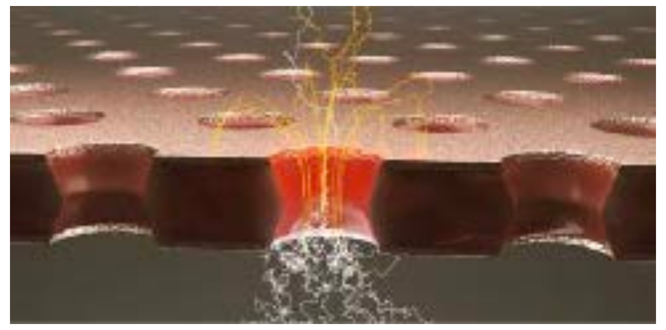
→ x100 statistics in Pb-Pb than Run-2

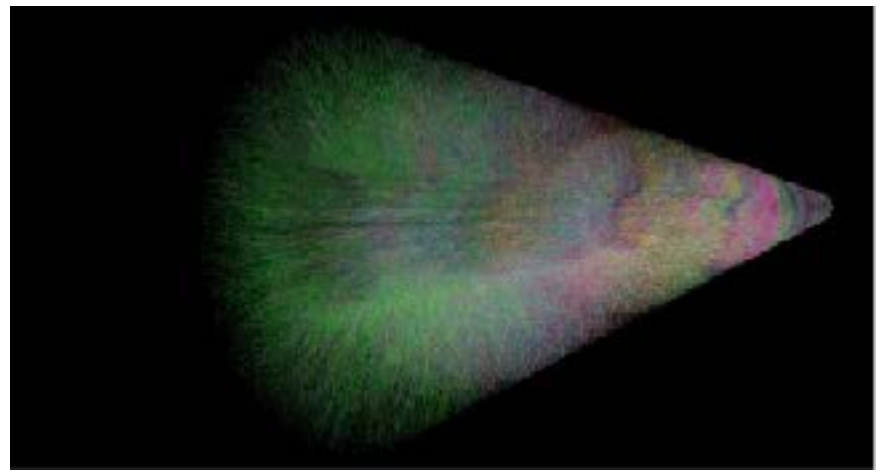
Run 4 (2029-2032)

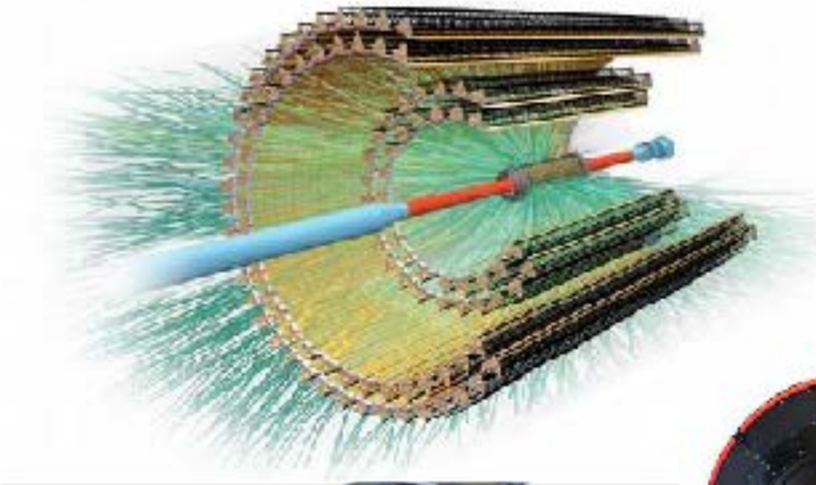
Forward Calorimeter (FoCal), new silicon tracker (ITS3)

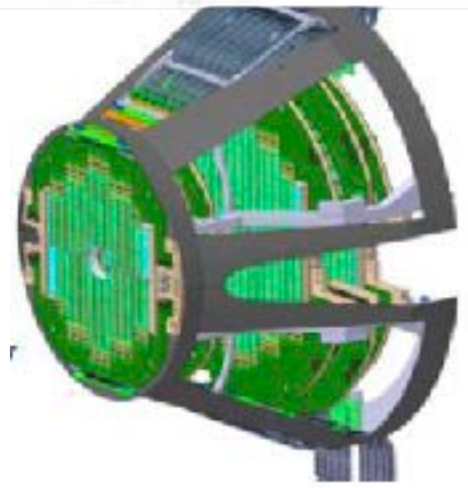
Run 5 (2035-2038)

ALICE3 (~all silicon)

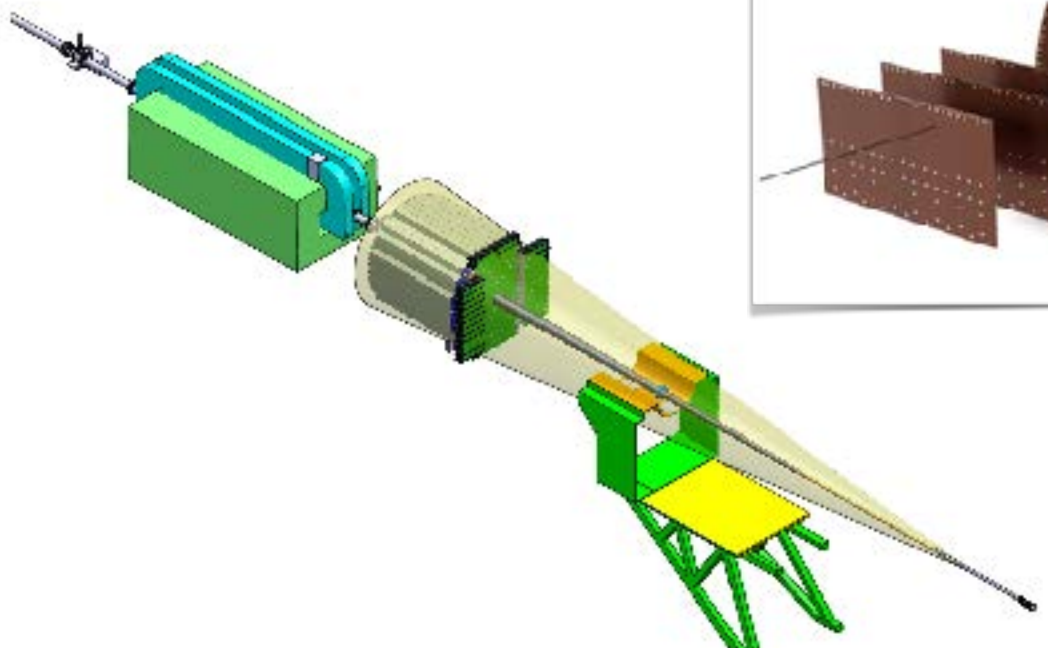


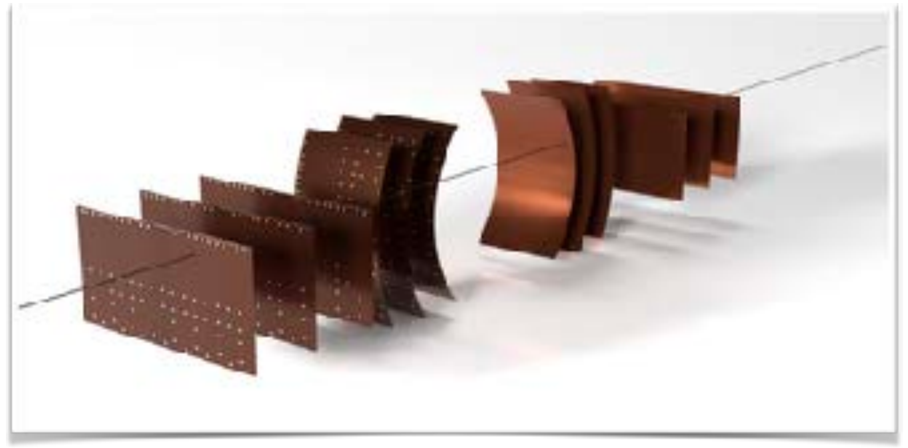




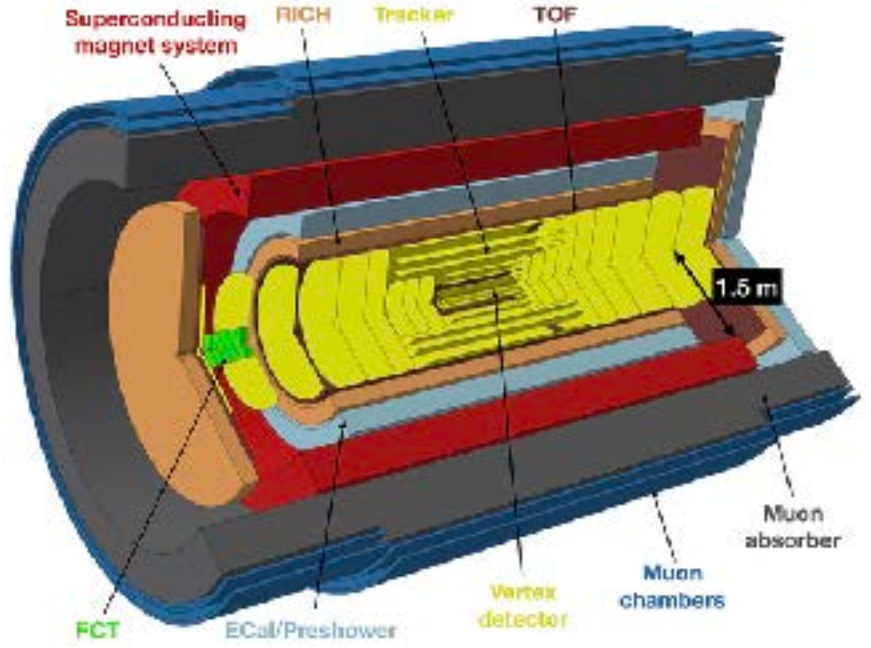


Heavy quark, jet, heavy nuclei, exotic hadron



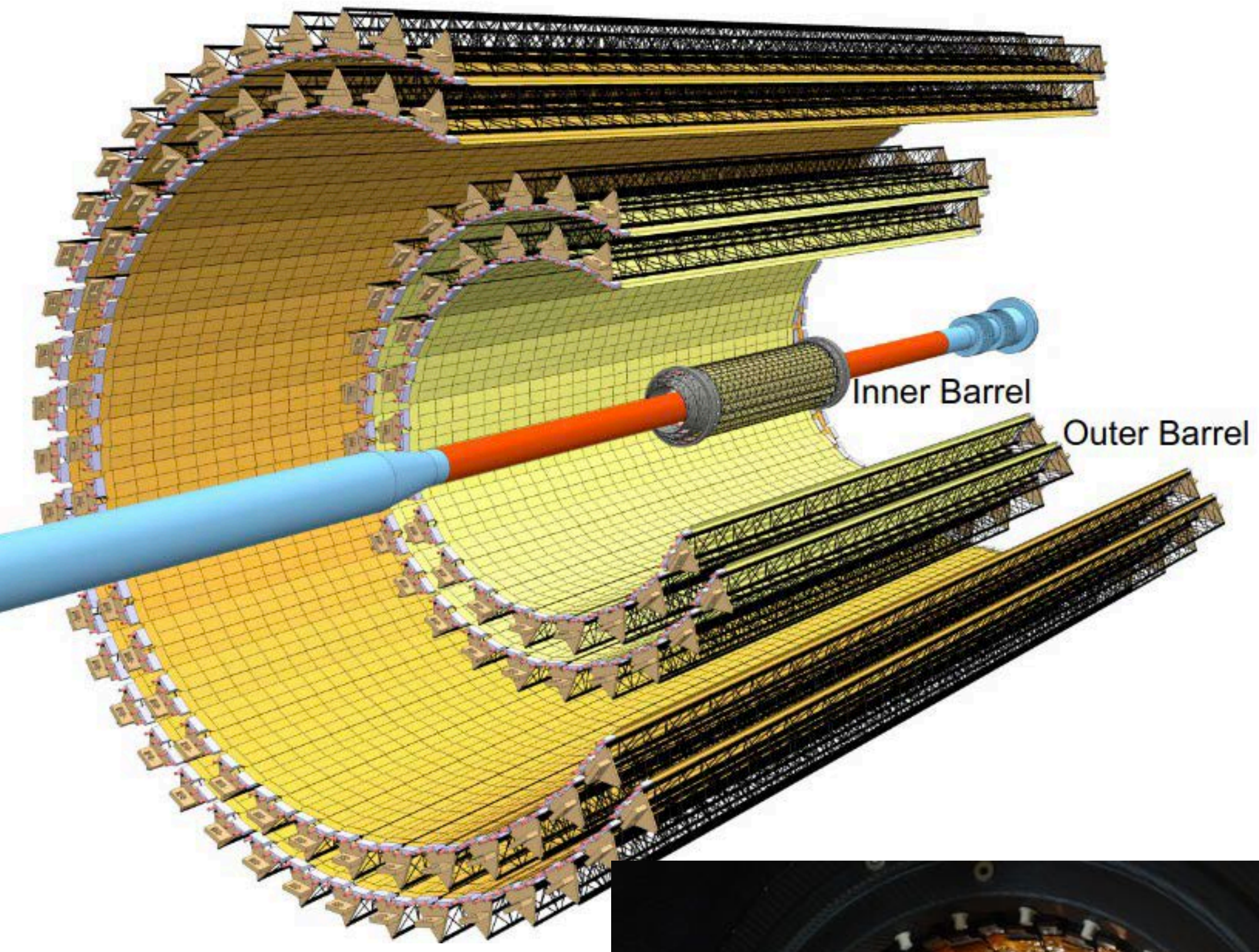


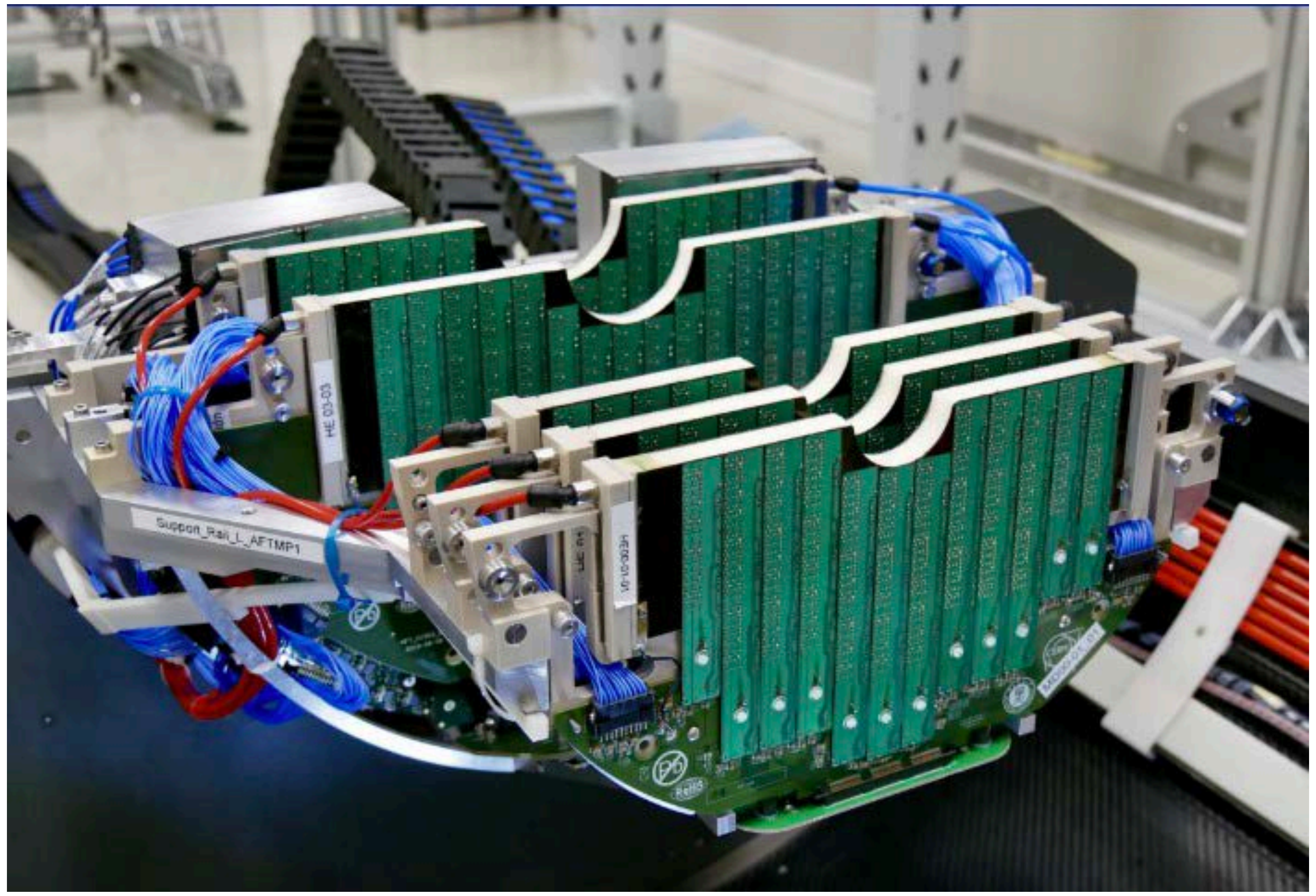
Color Glass Condensate, Gluon density (nPDF), Heavy quark



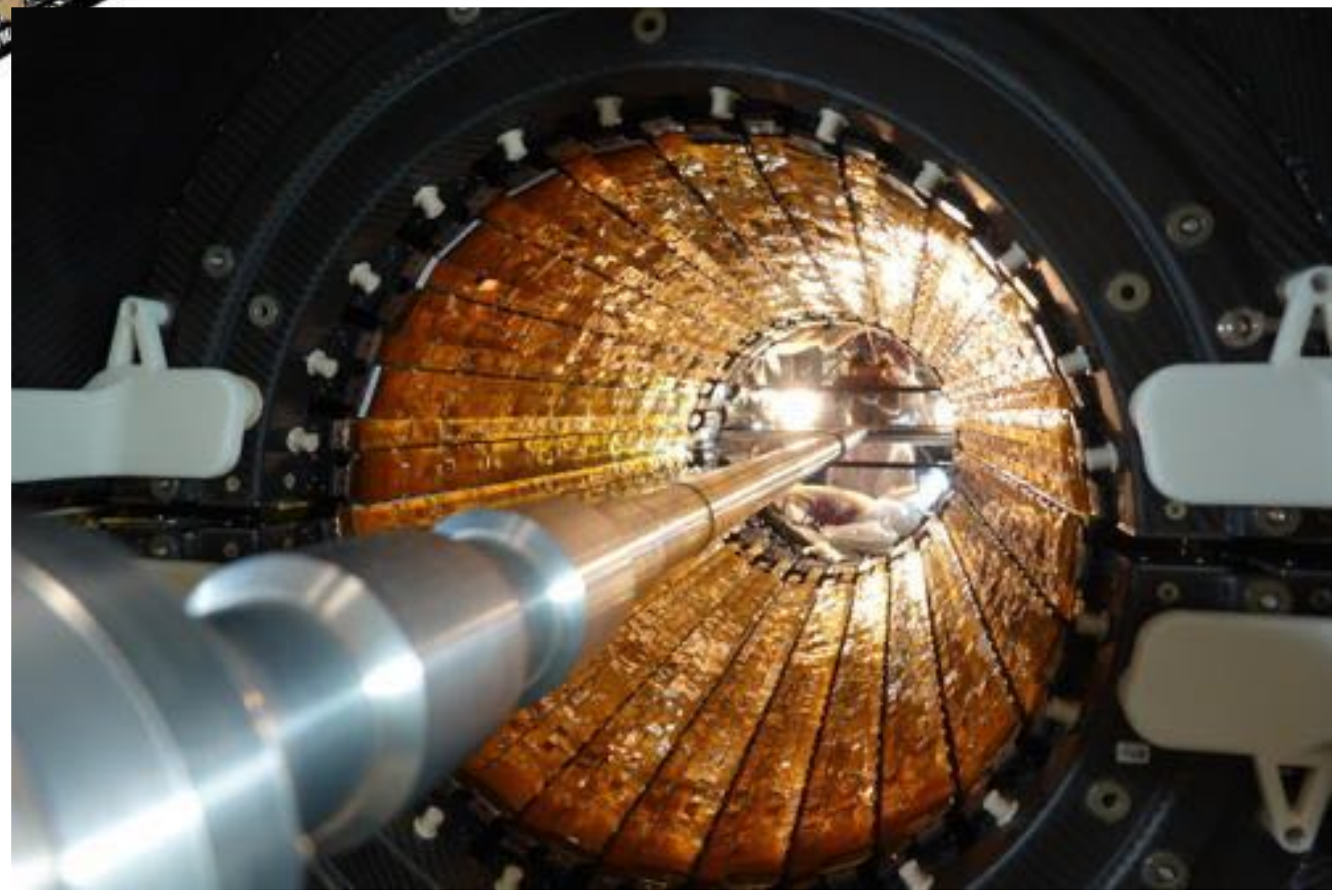
Chiral symmetry, Heavy quark, exotic hadron, thermal radiation

ALICE Run-3 upgrade during LS2 (2019-2021)

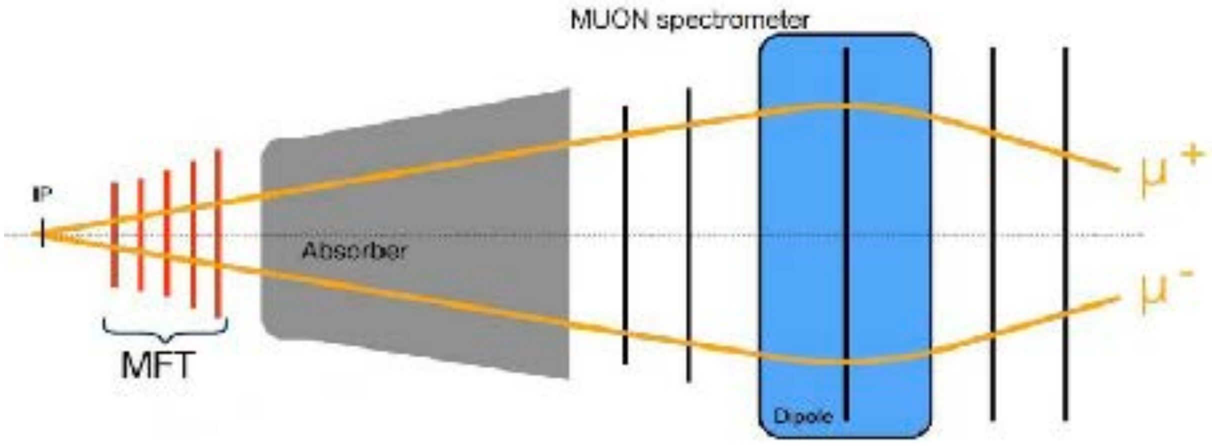


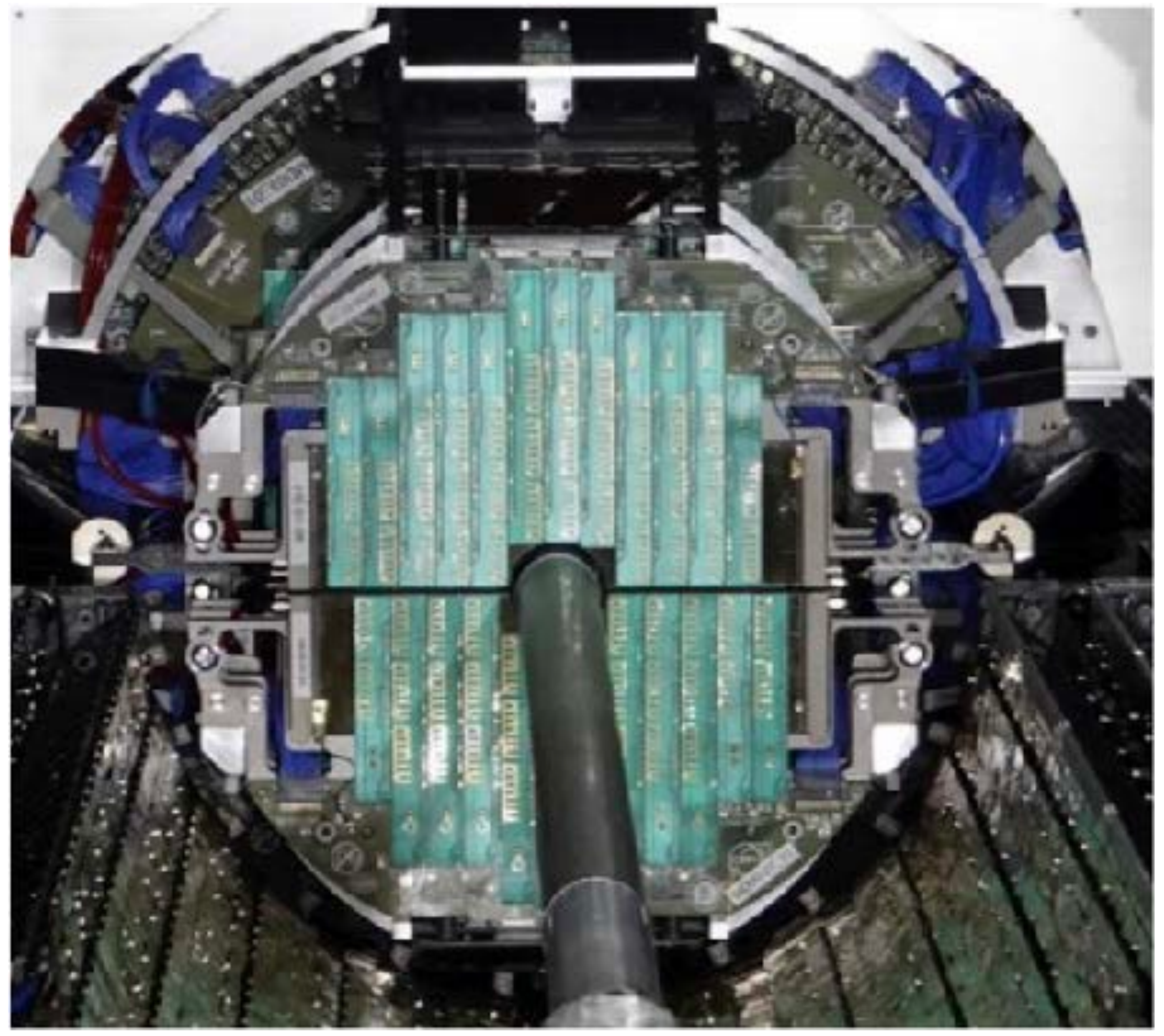


ITS2

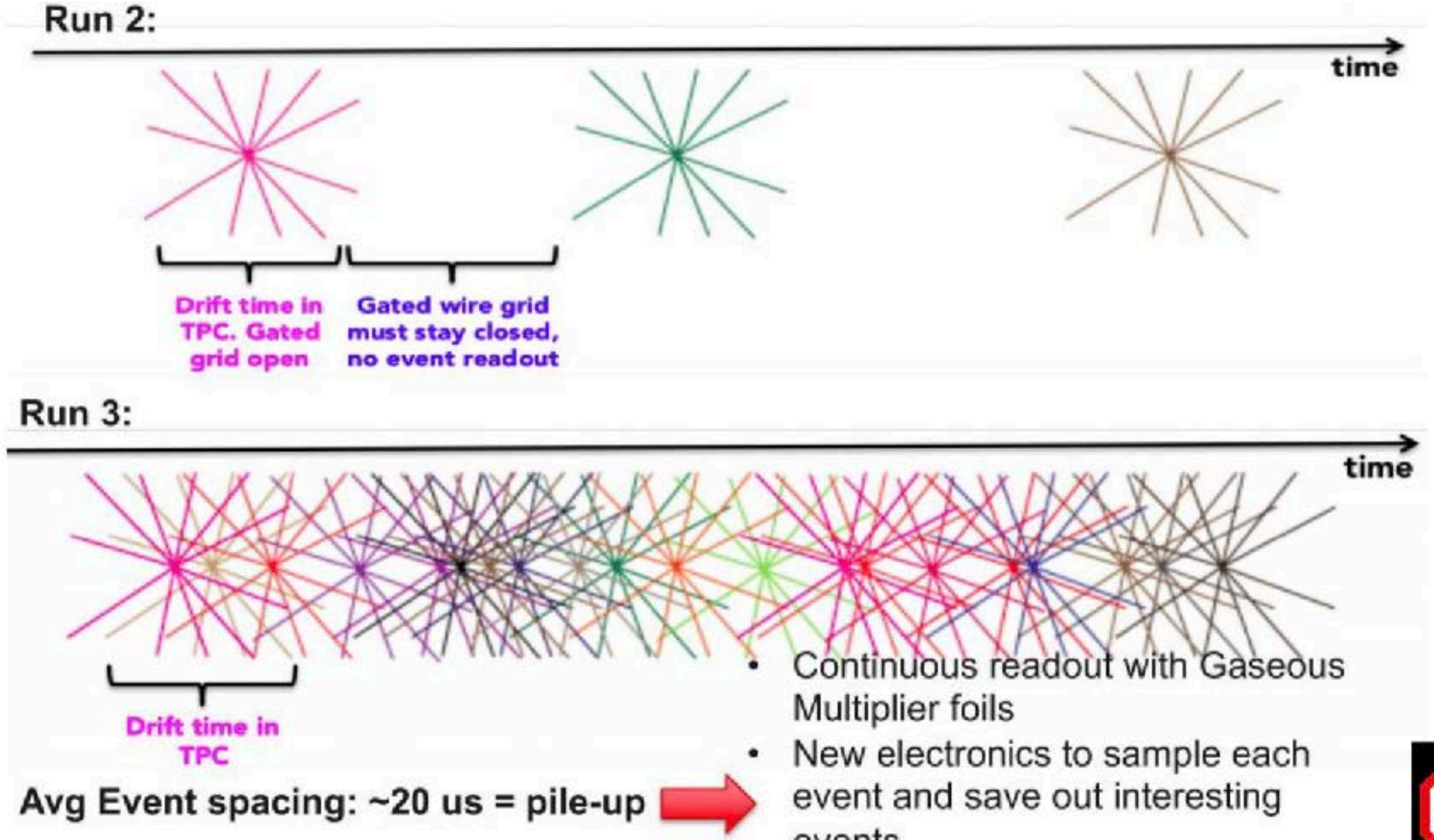


MFT

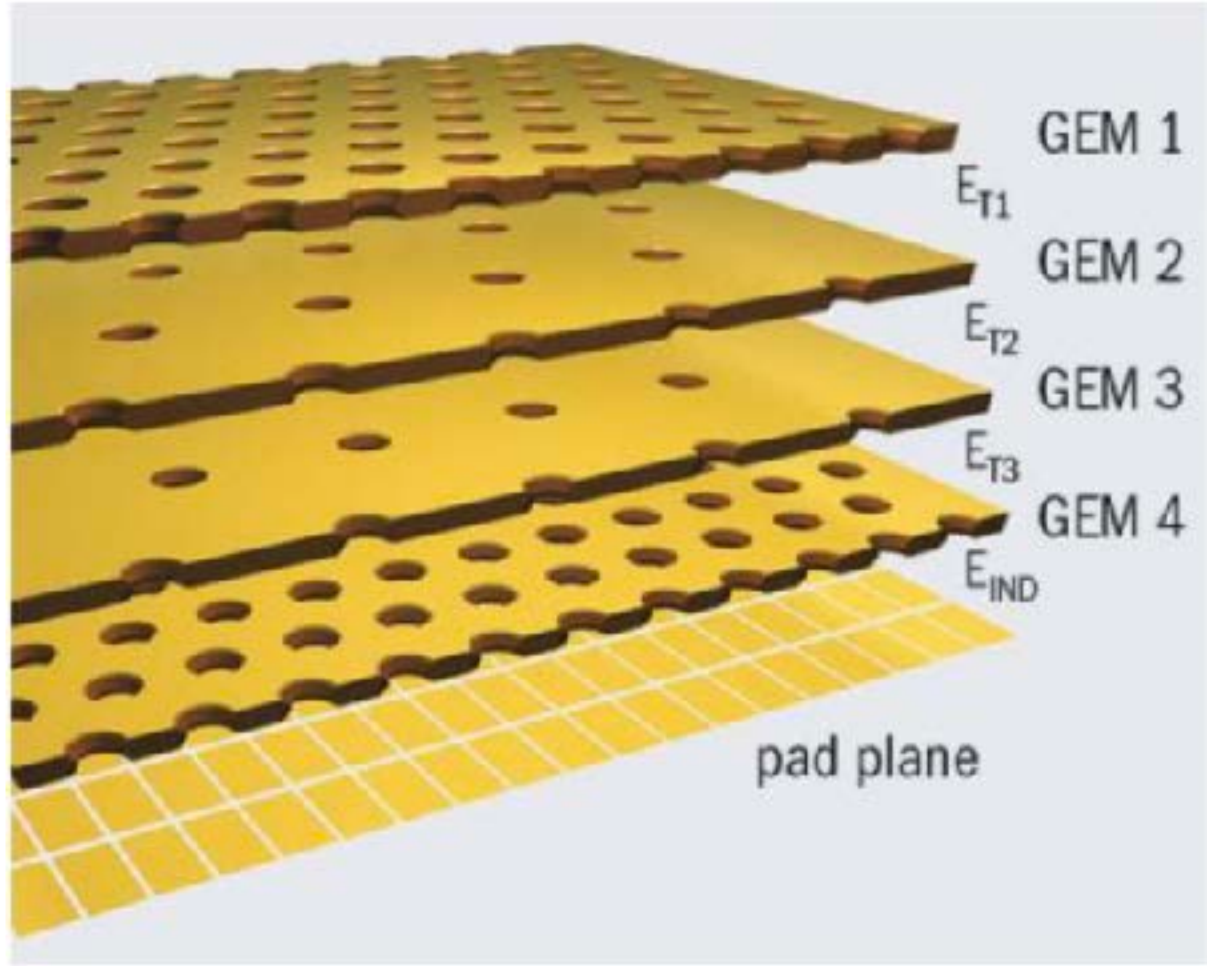


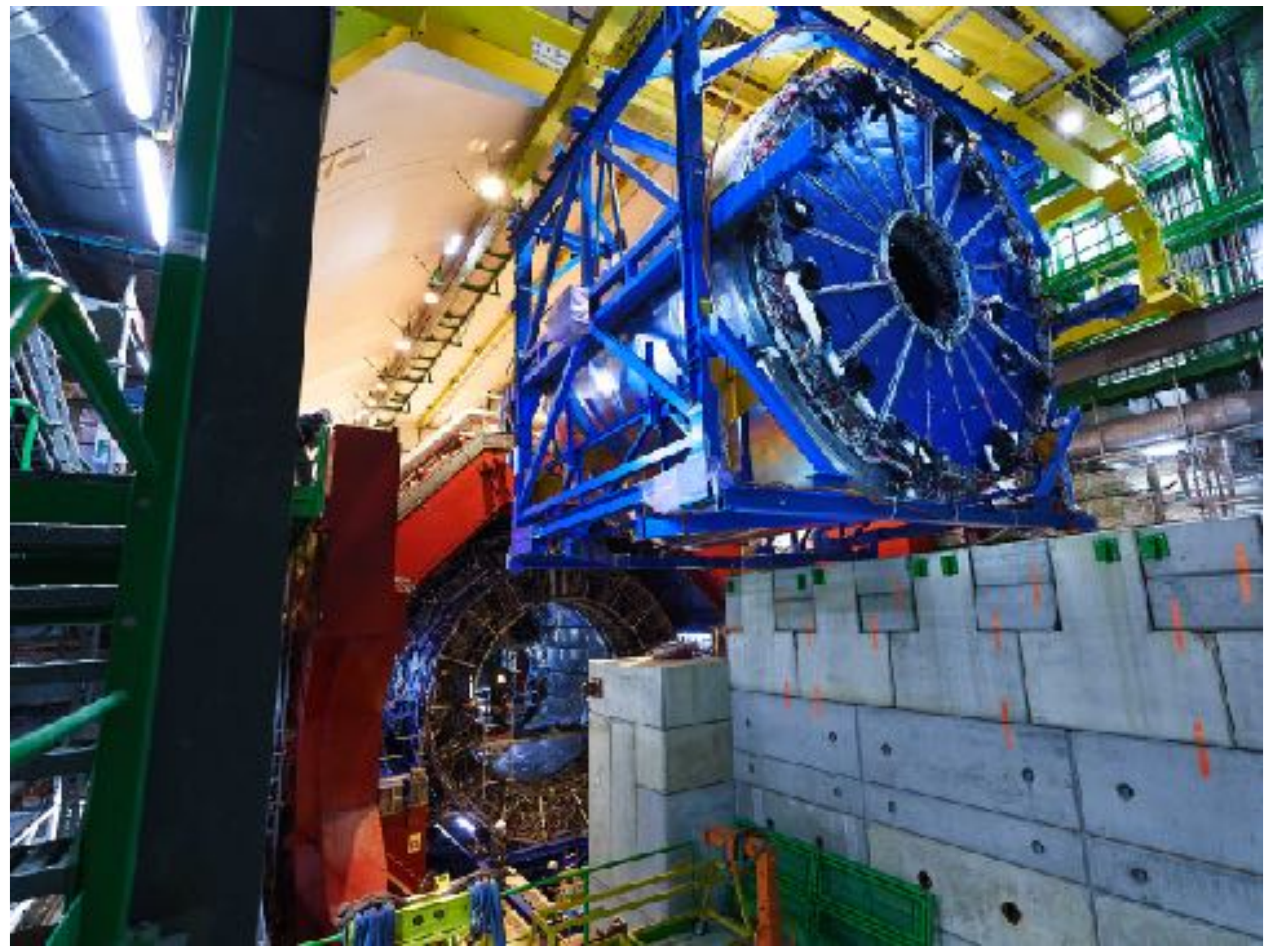


ALICE Run-3 upgrade during LS2 (2019-2021)

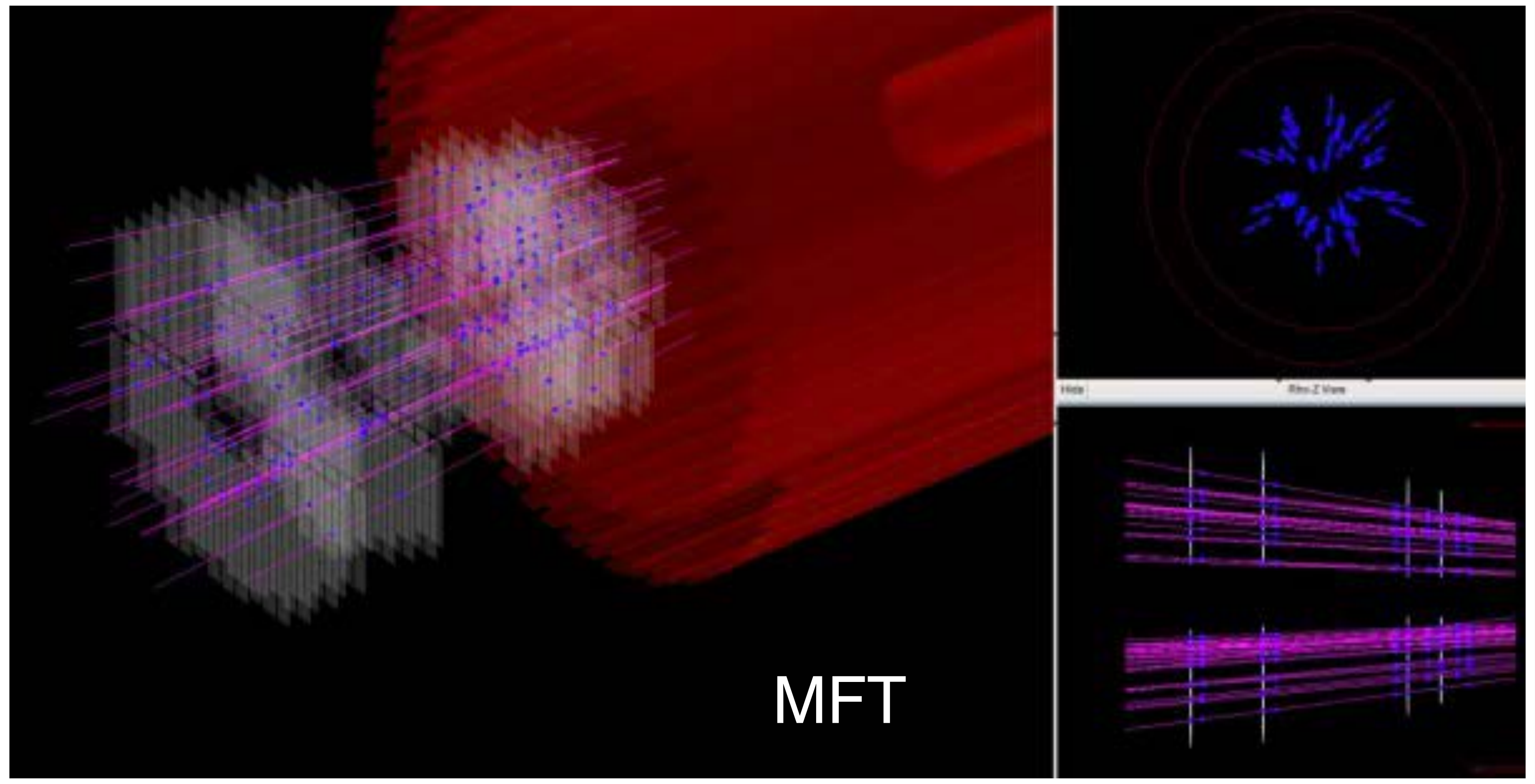


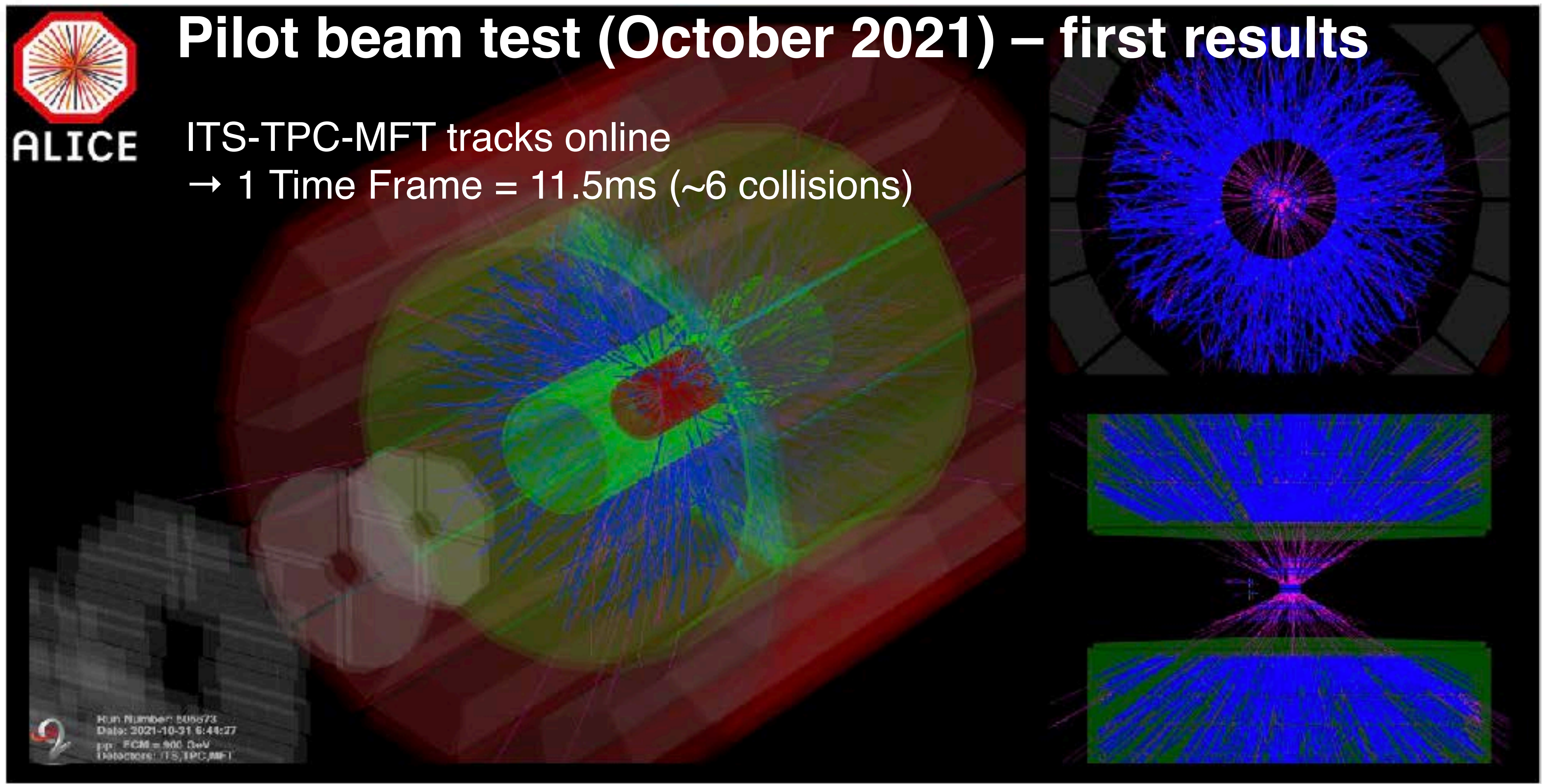
- Continuous readout with Gaseous Multiplier foils
- New electronics to sample each event and save out interesting events





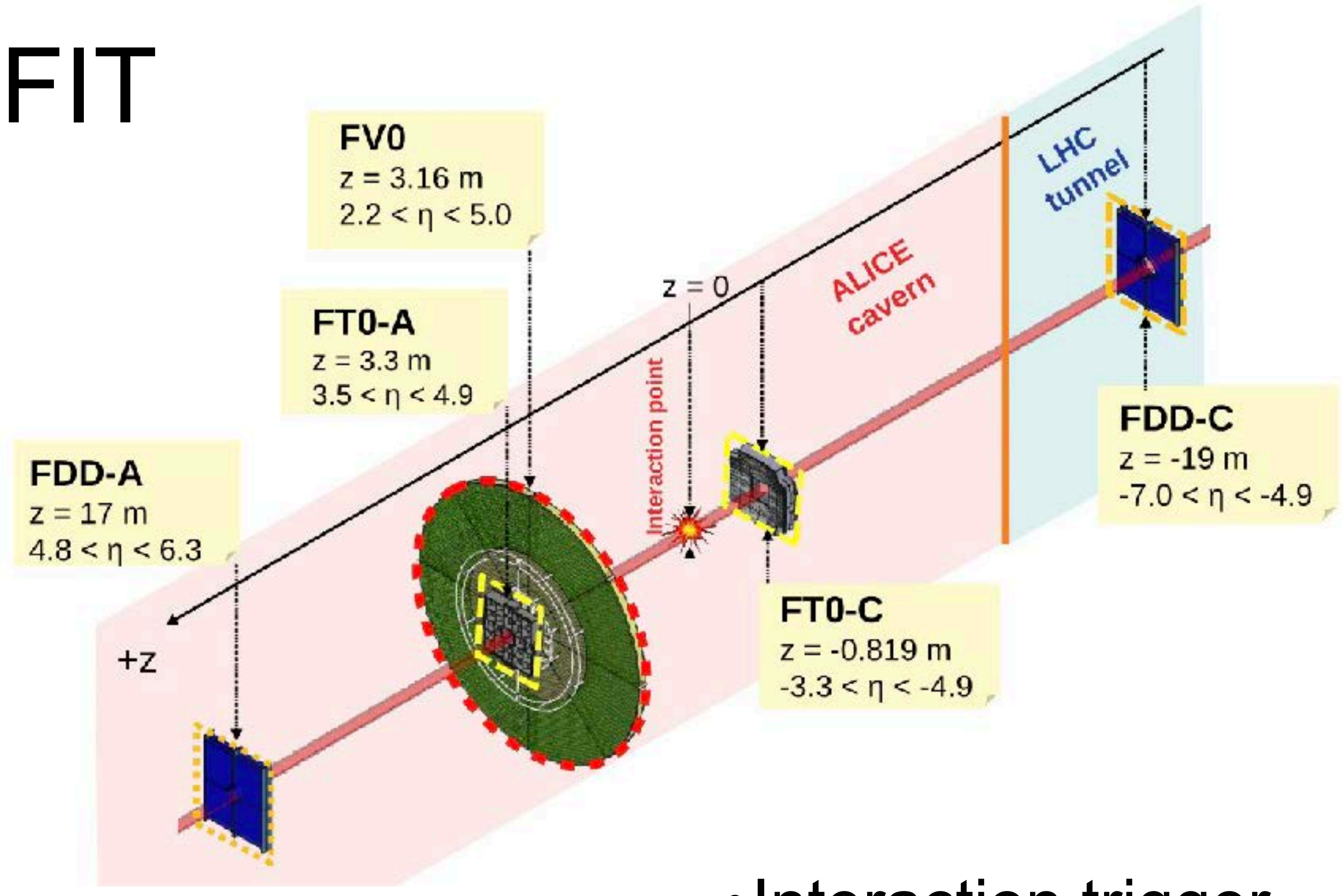
TPC

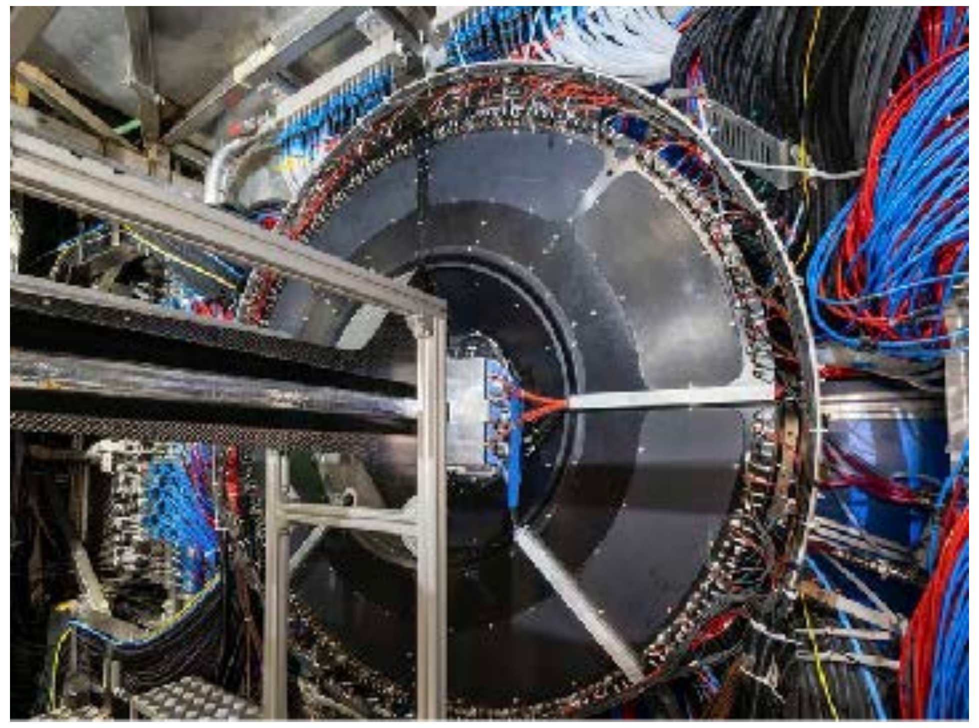




ALICE Run-3 upgrade during LS2 (2019-2021)

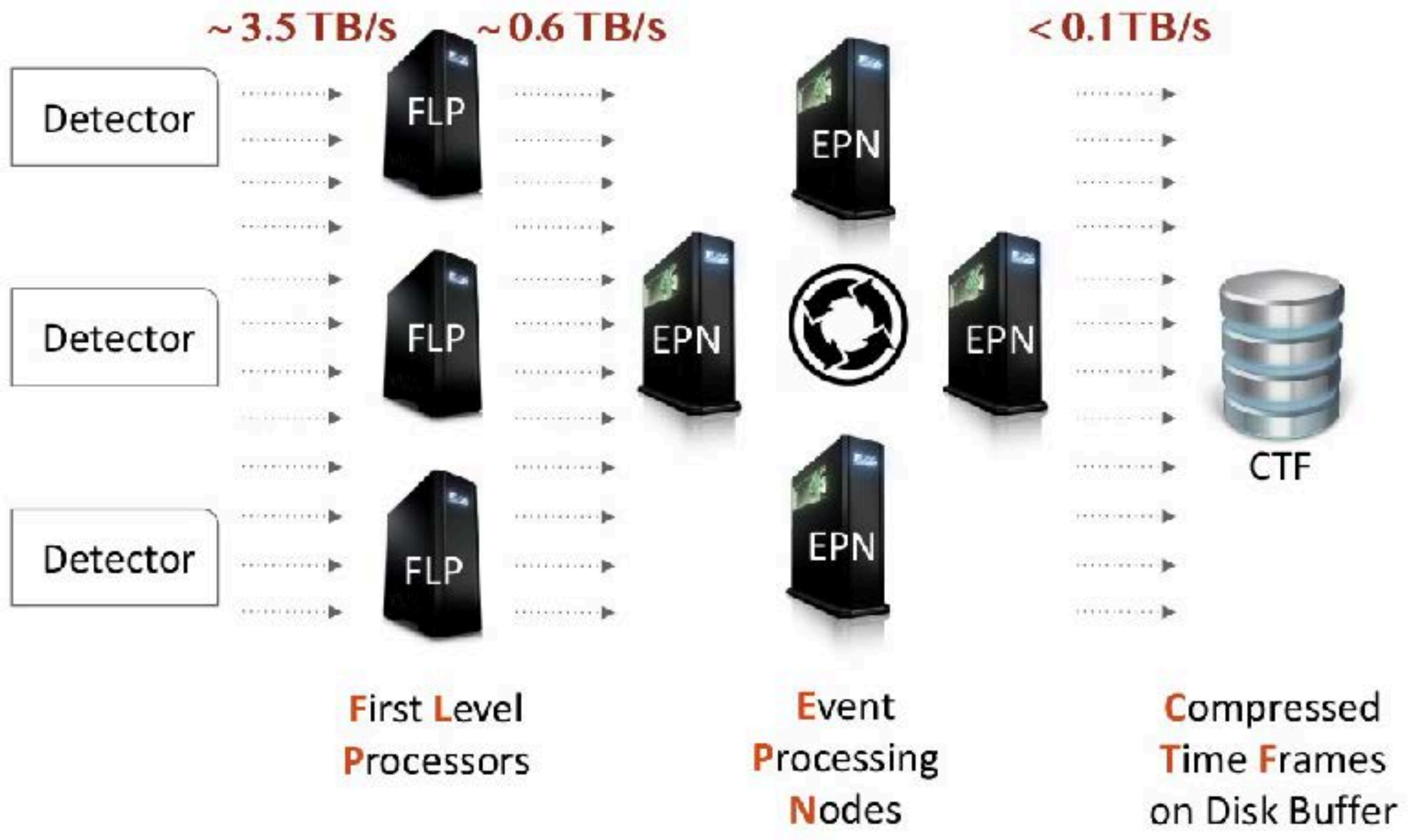
FIT





- Interaction trigger
- Event characterizations (e.g. charge particle multiplicity, vertex position, event plane, centrality)
- Collision time (TOF PID)

O^2

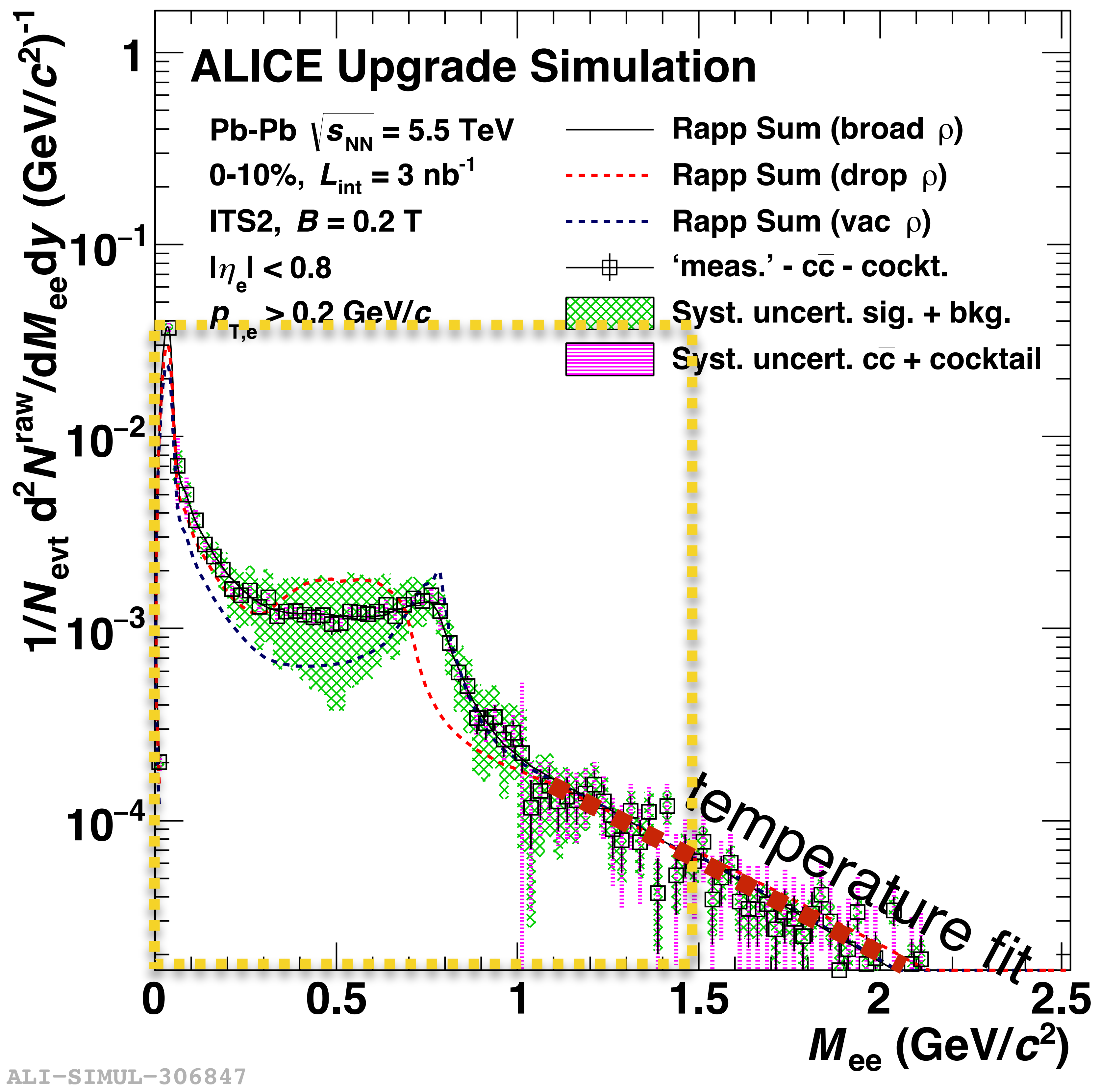


- 250 FLPs receive data from detectors → ~3.5 TB/s (TPC most relevant)
- 1500 EPN nodes process sub-timeframes (→ merged to complete Time Frames)
- Synchronous reconstruction, calibration and data compression → use of GPU mandatory
- Asynchronous stage: reconstruction with final calibration → Final Analysis Object Data (AOD)

Run-3 Physics (1)

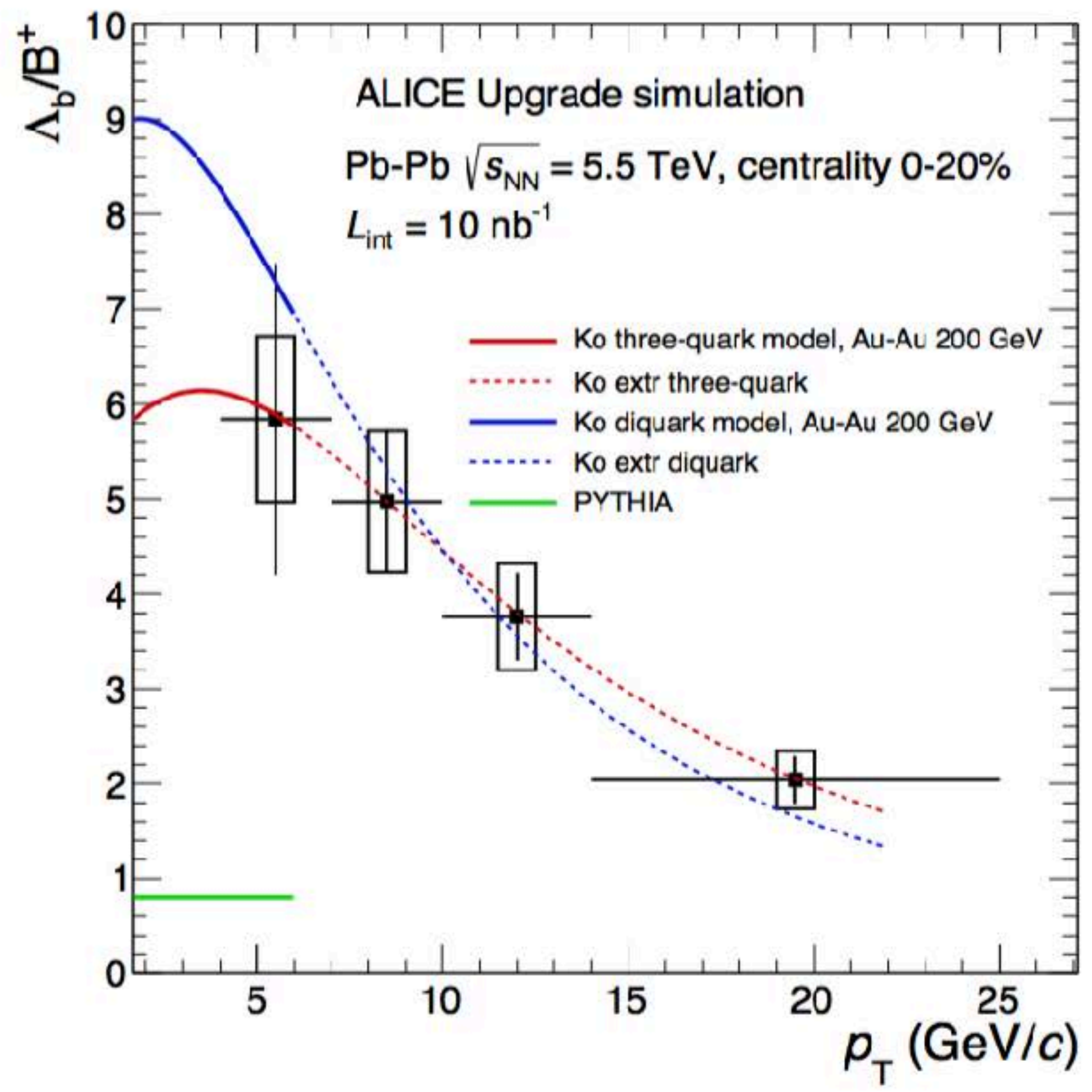
Thermal radiation

Di-electrons
(less material, better tracking, low-B run)



Heavy flavor recombination

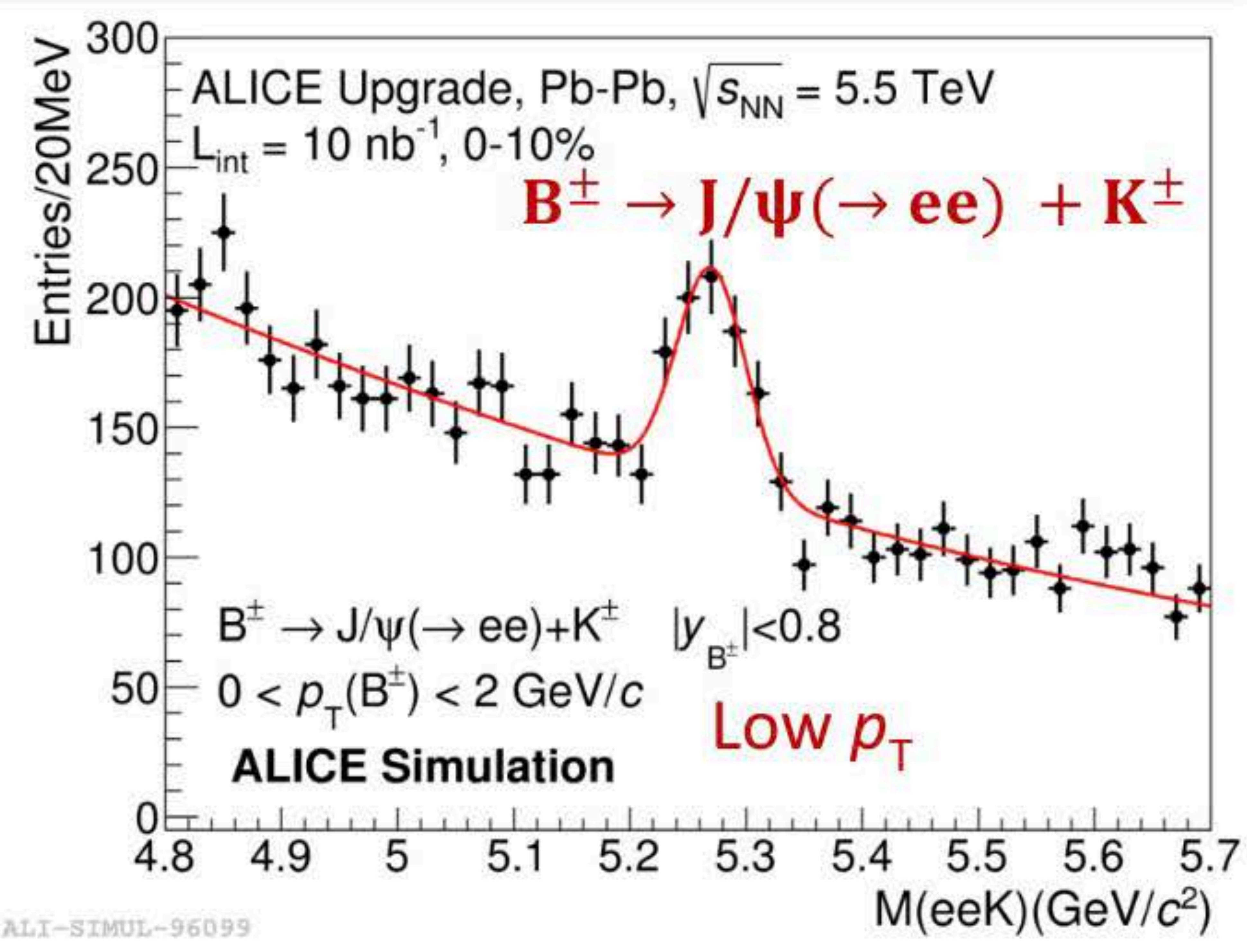
Recombination vs radial flow, also crucial for diffusion coefficient

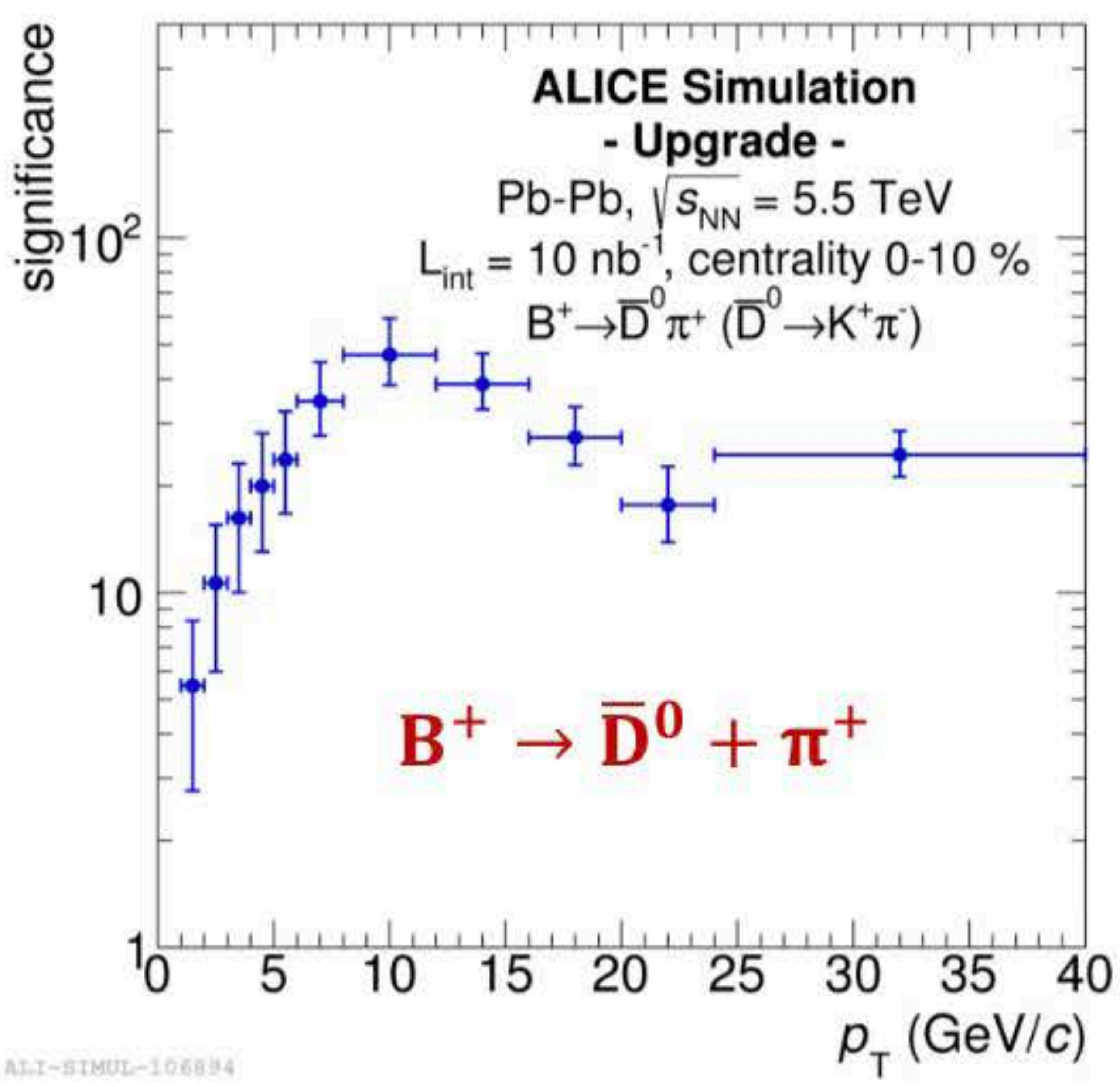


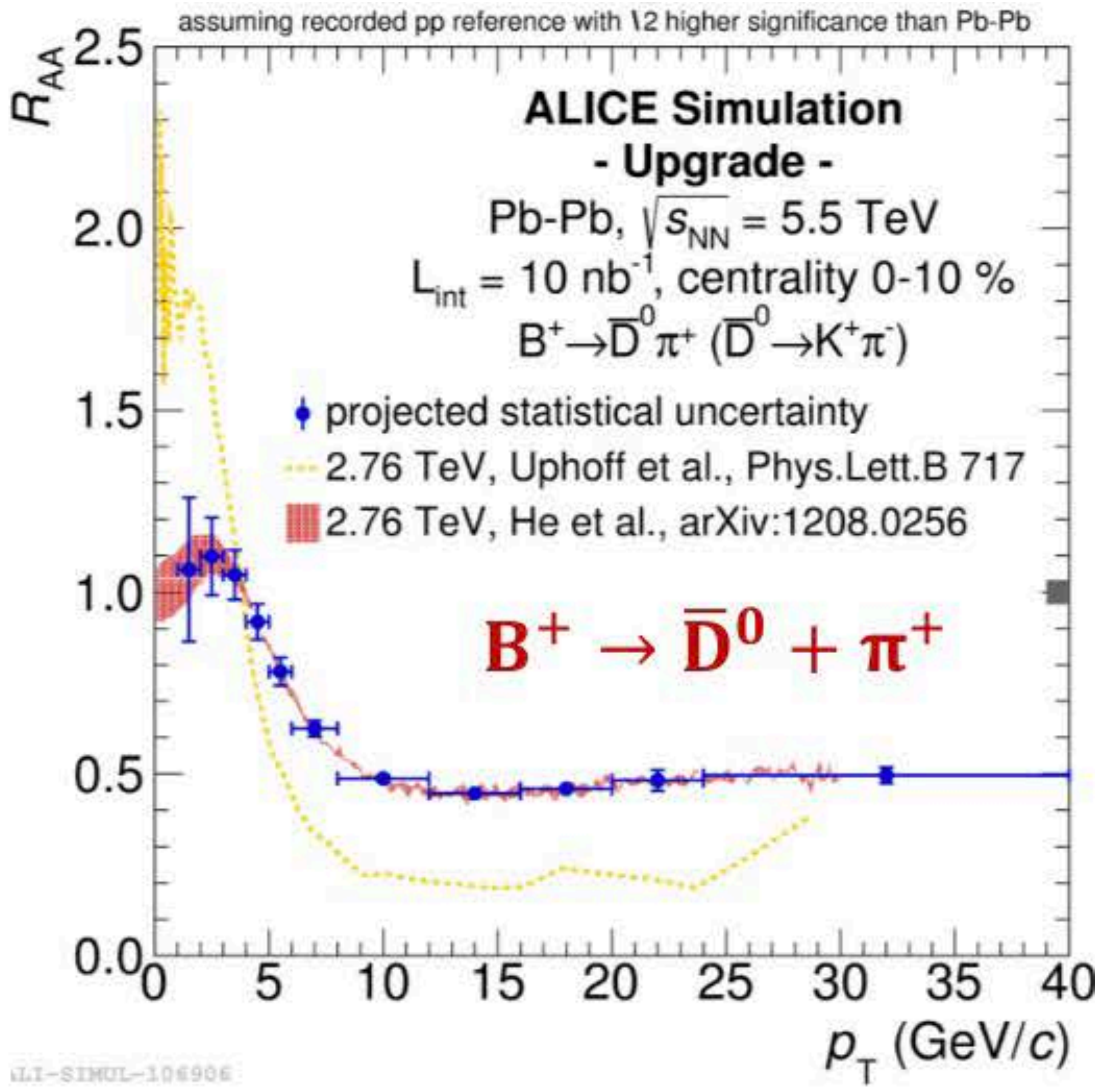
Run-3 Physics (2)

Access to beauty at low p_T

- <u>Not</u> achievable with Run 2 data





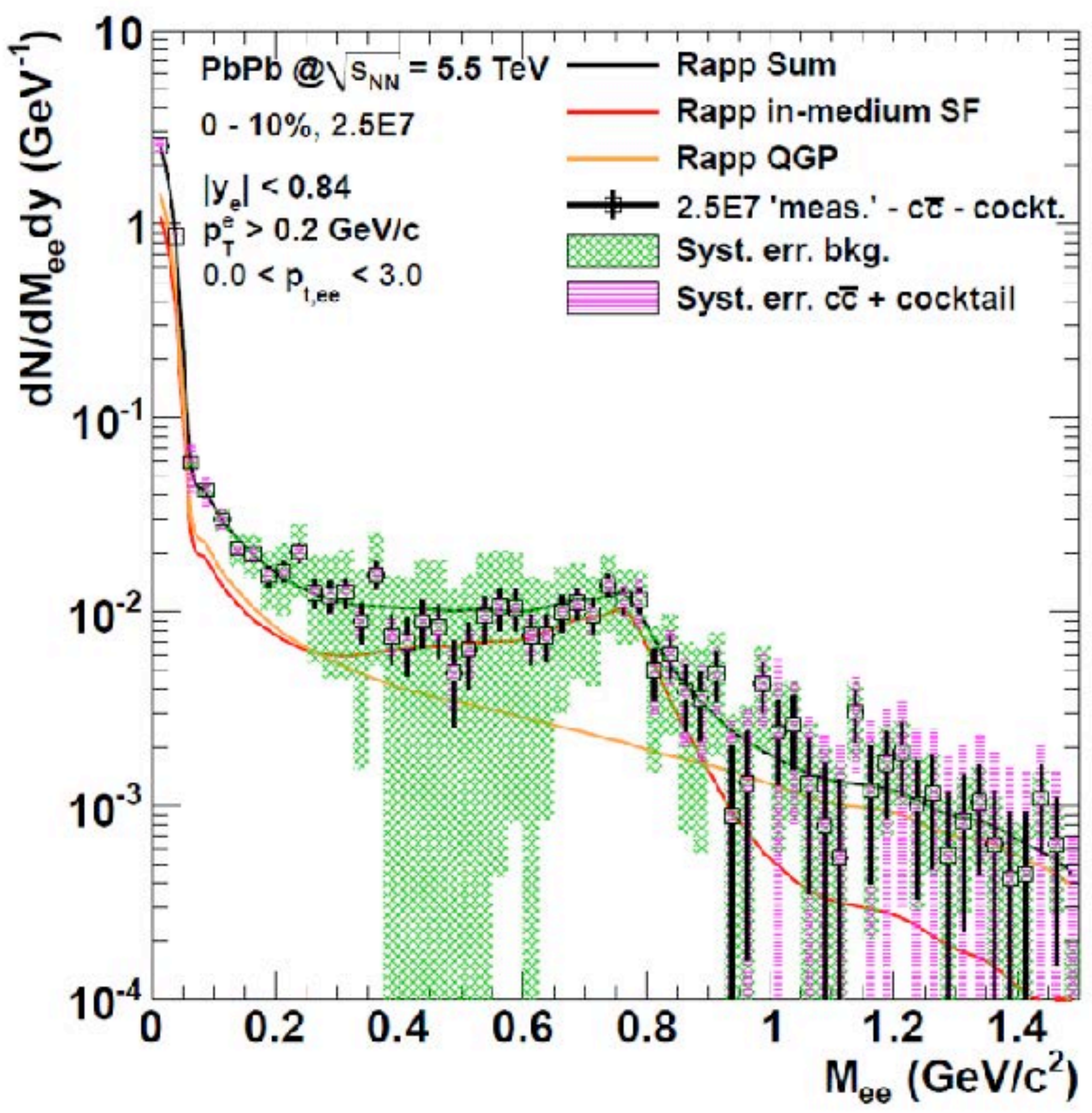


Run-3 Physics (3)

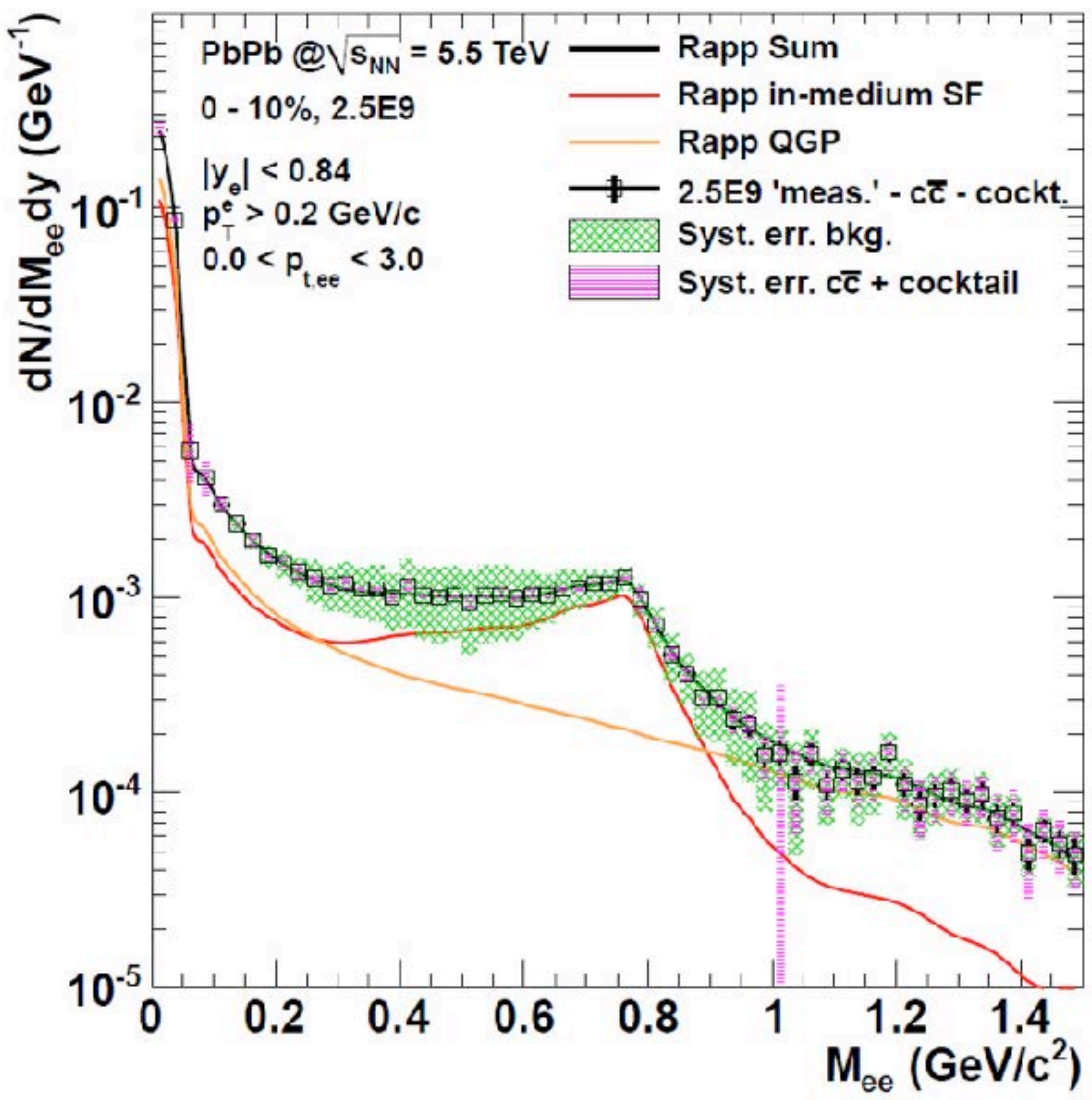
Search for Chiral symmetry restoration at high T and $\mu_B = 0$

Towards precision measurement of around ρ mass region

Before



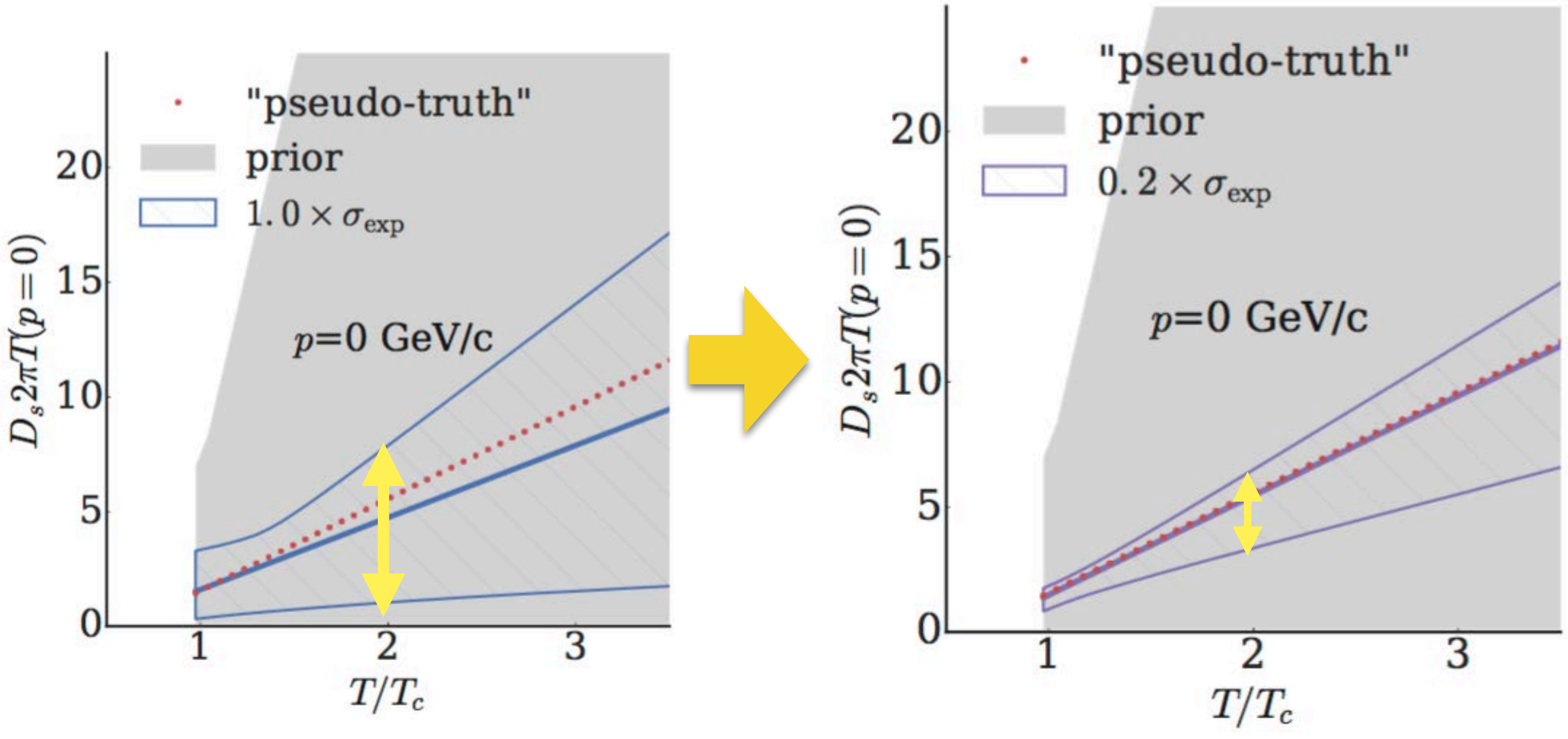
After

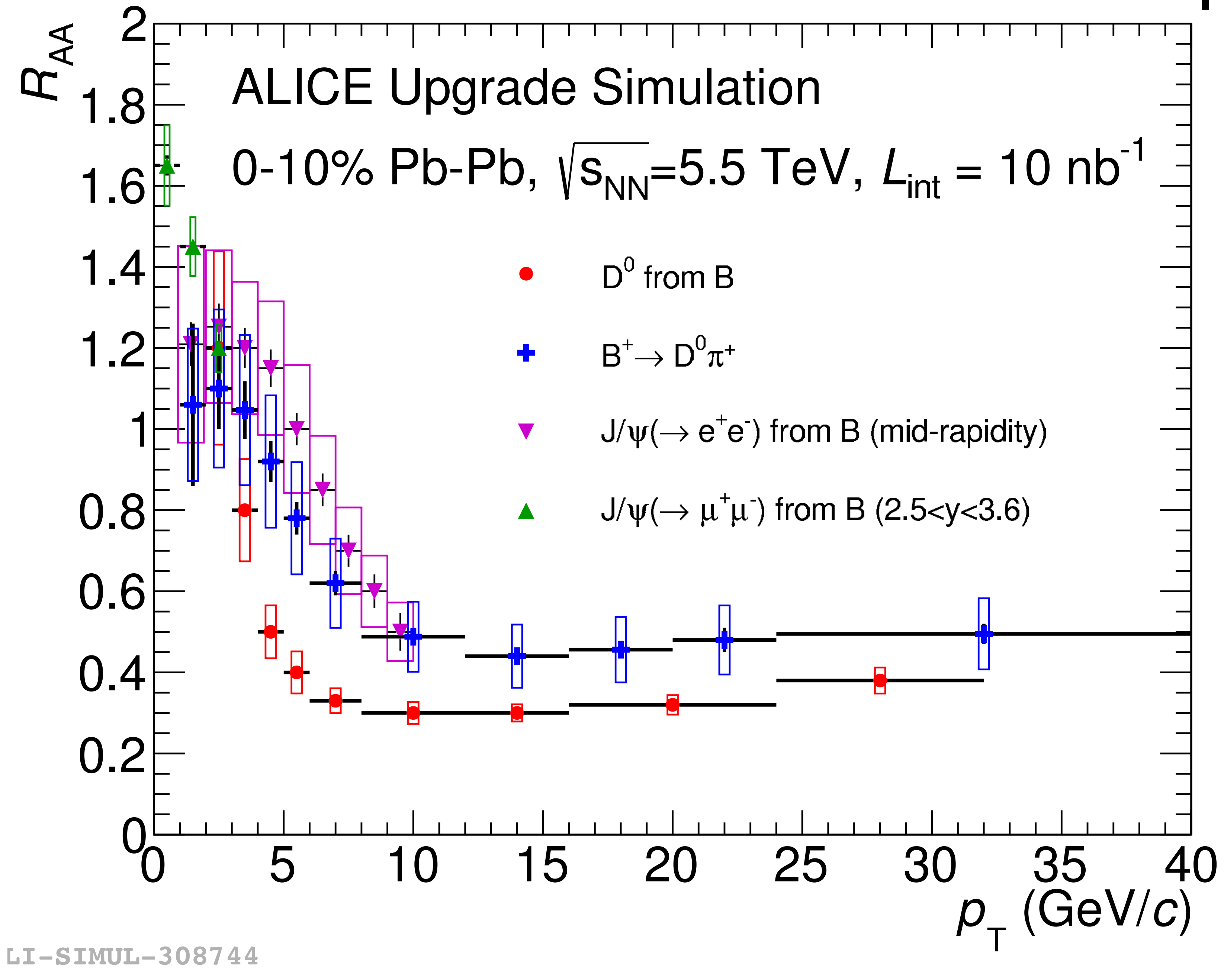


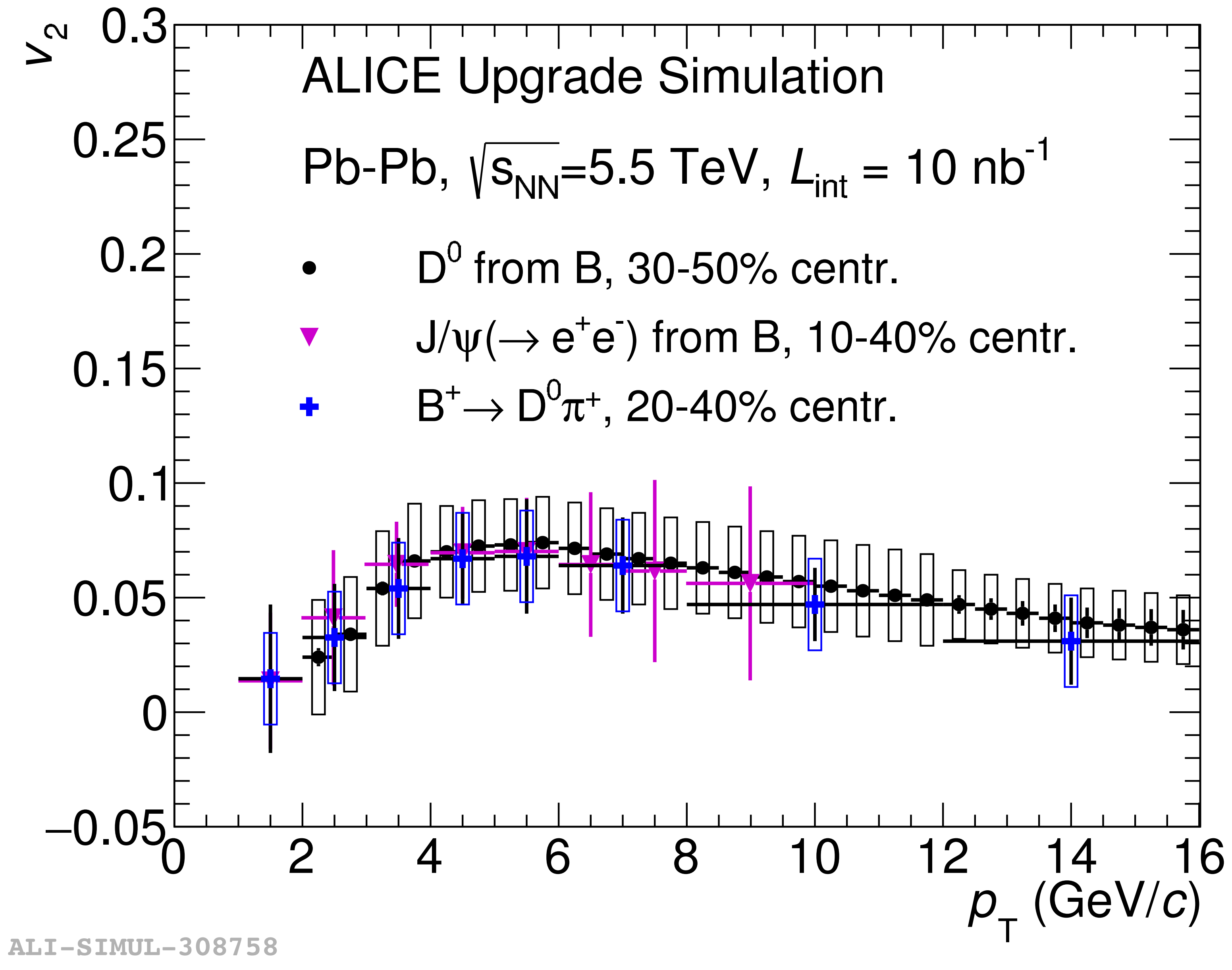
D_s Run-3 Physics (4)

Transport coefficients (D_s)

heavy-quark diffusion coefficients



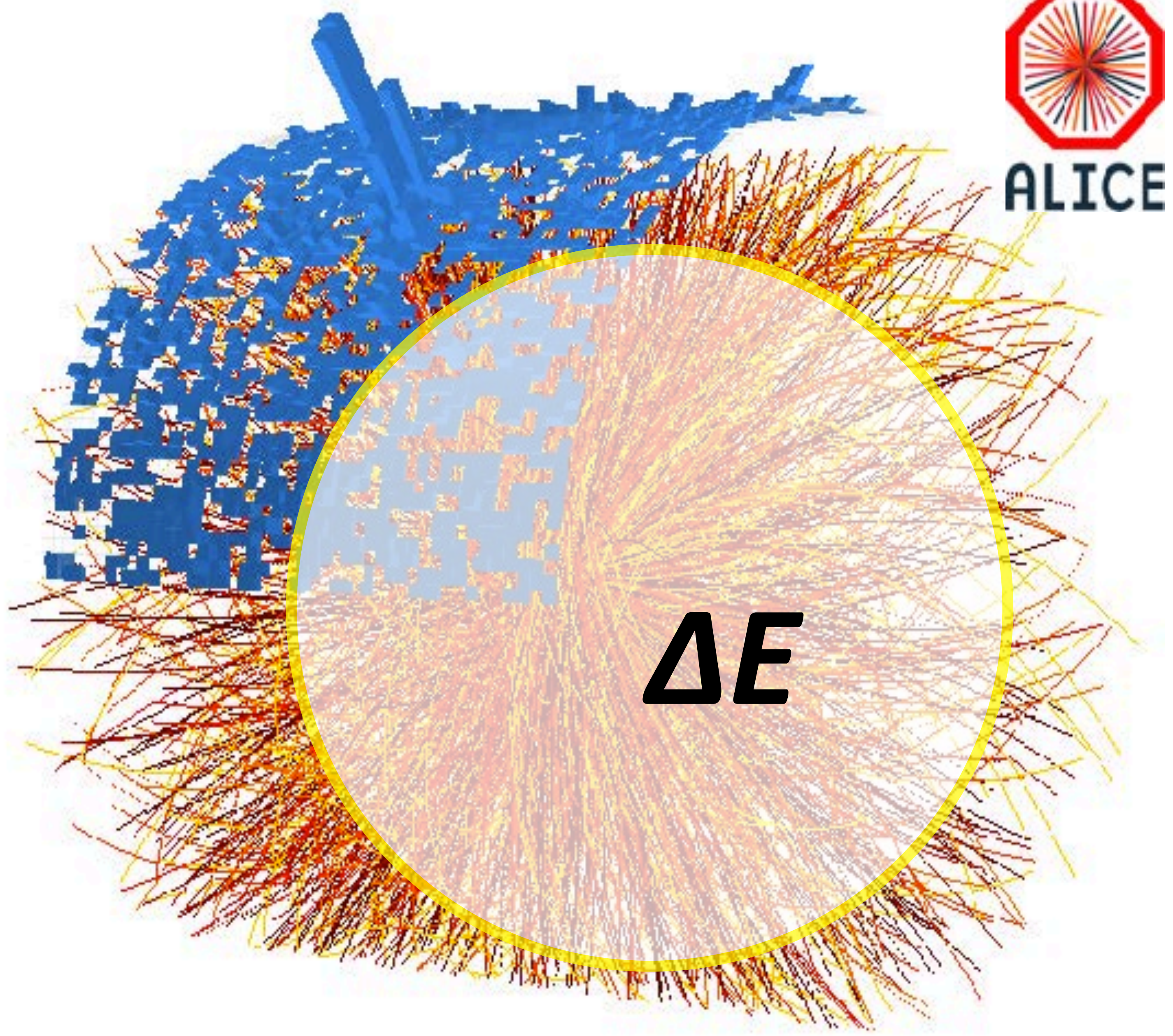




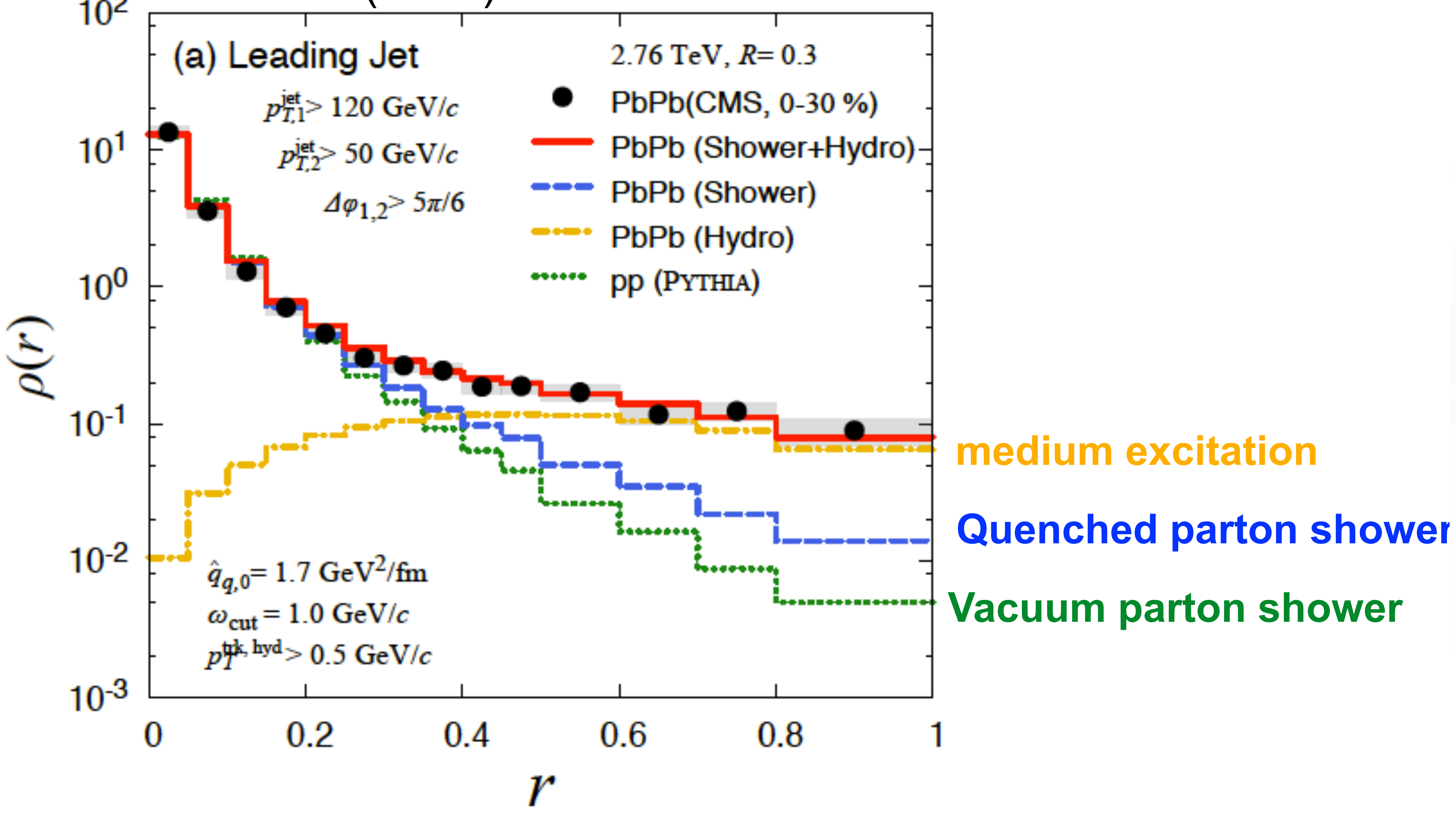
Open heavy-flavour R_{AA} and v_2 down to p_T=0

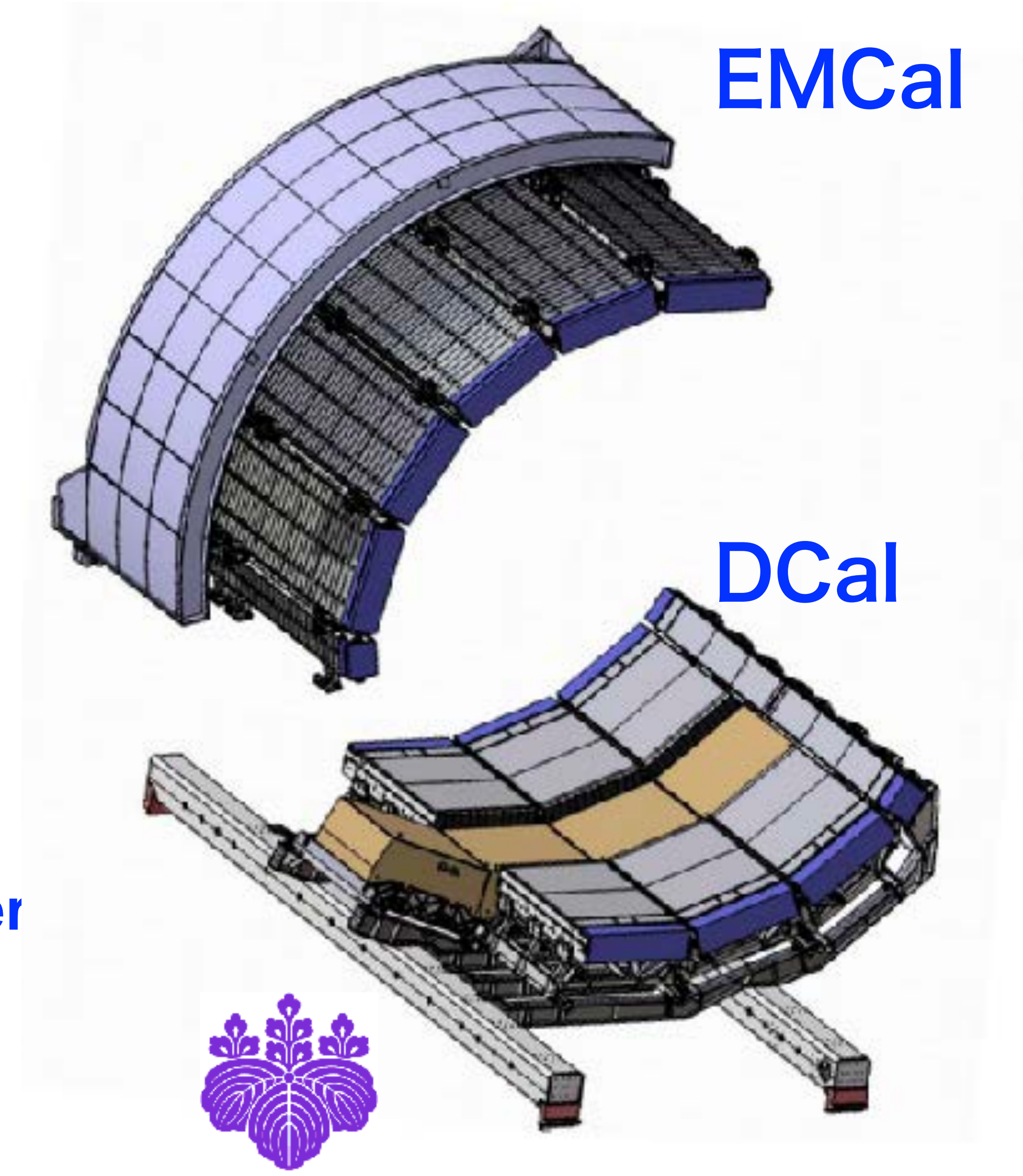
→Precise determination of $(2\pi T)D_s$ vs. T

Run-3 Physics (5)

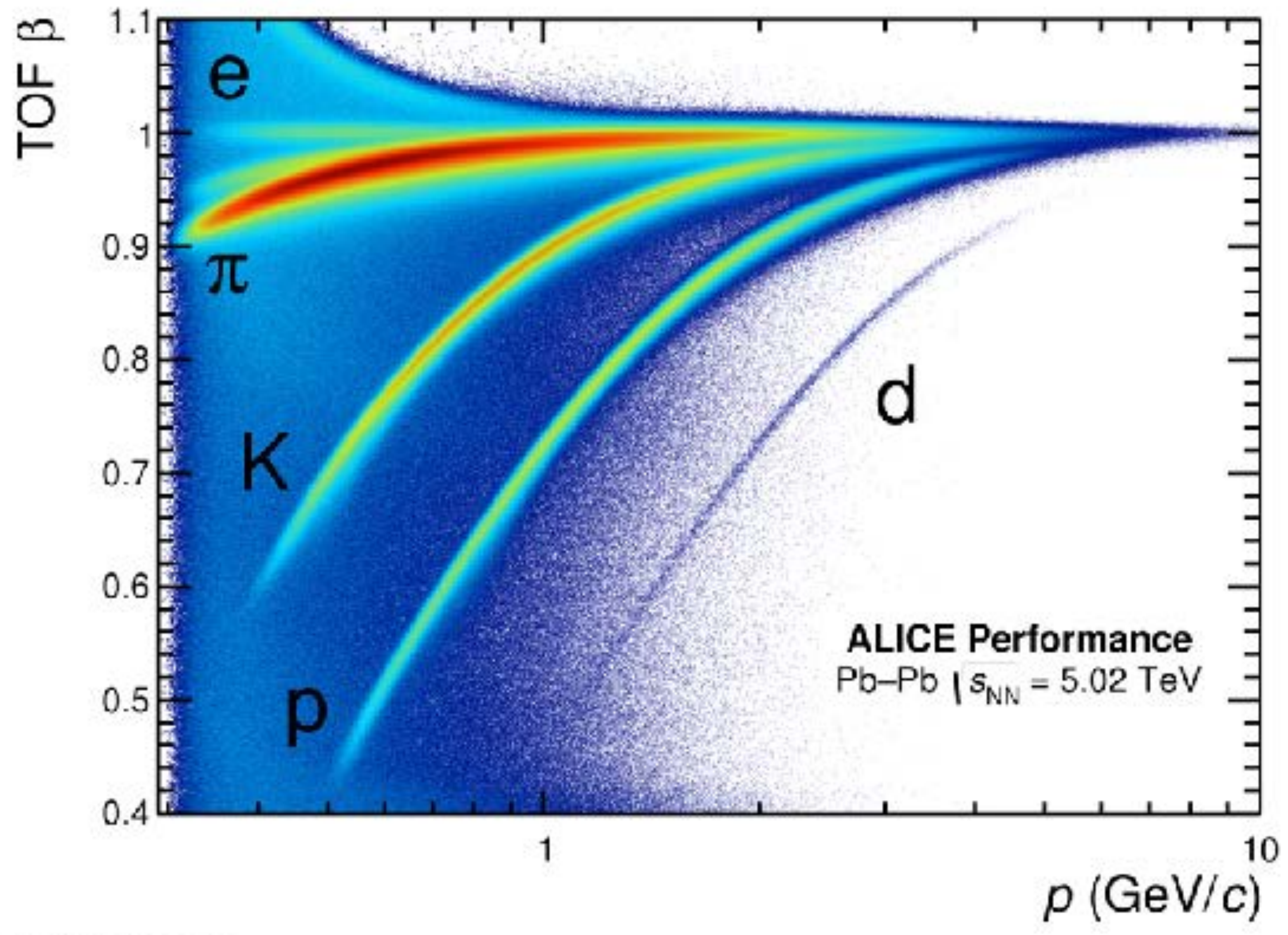


Tachibana, Phys.Rev.C 95, 044909 (2017)





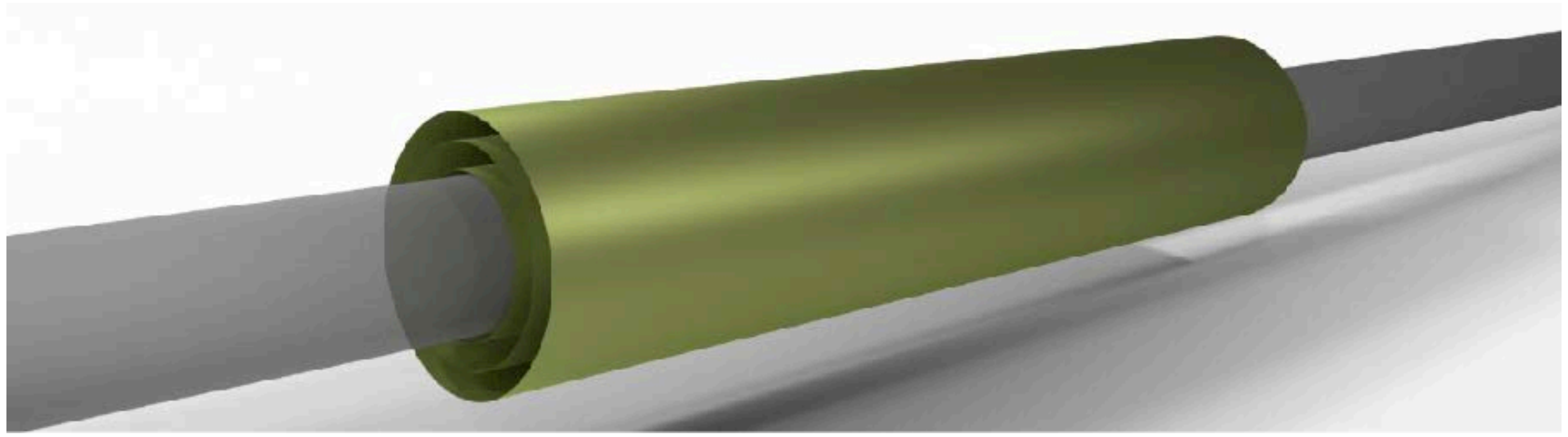
ALICE PID capability (TOF)



- Medium response, where the lost energy goes?
  → **Large angle soft hadron emission**
- **ALICE Run-3:**
  - **di-jet and γ-jet using DCal with PID**
  - **x100 MB statistics + EMCal trigger**
- Mach cone search, sound velocity in QGP, EOS (?)

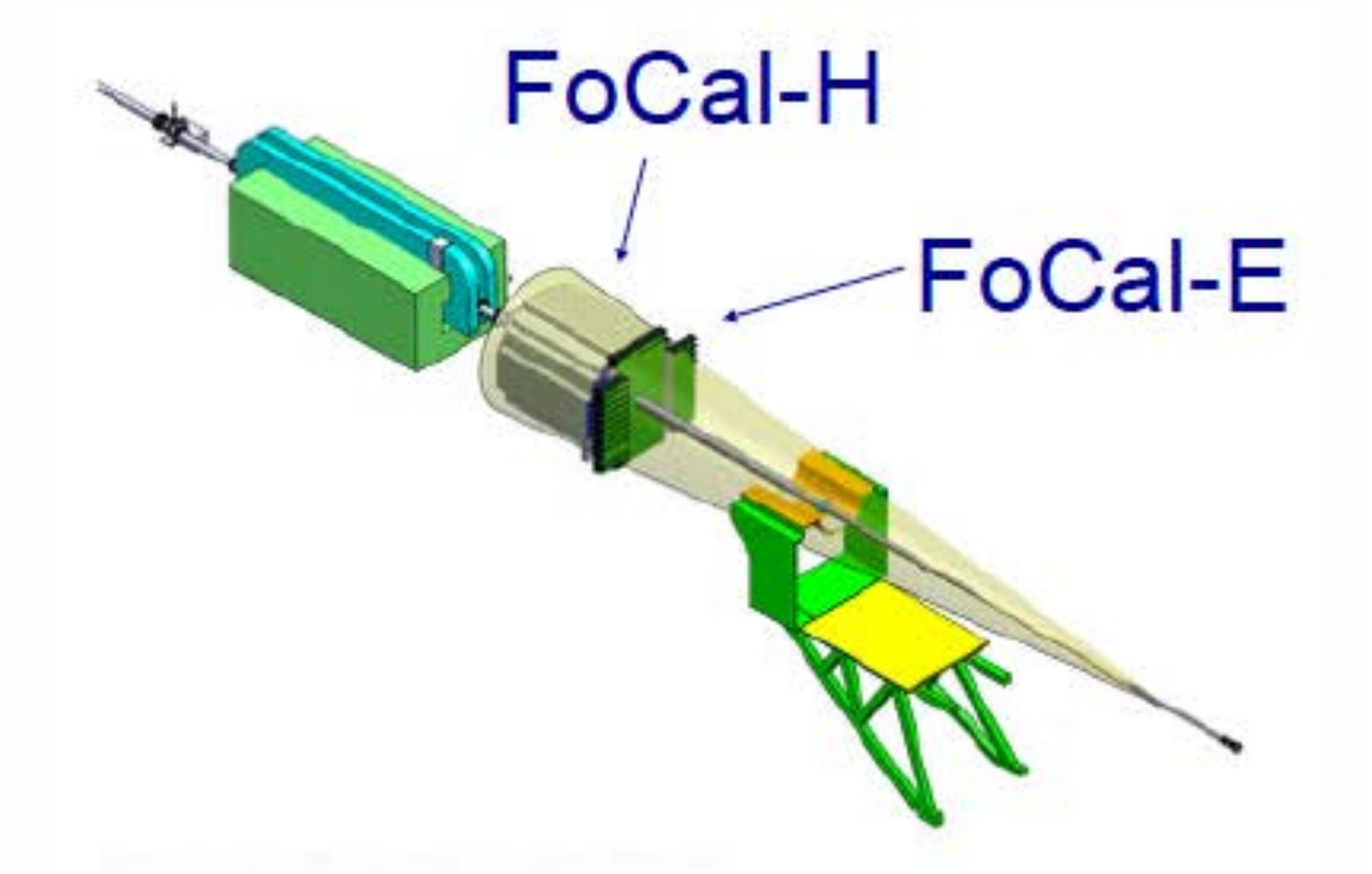
ALICE Run-4 upgrade during LS3 (2026-2028)

ITS3



New ITS Inner Barrel → ITS3
LoI (2019):
https://cds.cern.ch/record/2703140

FoCal



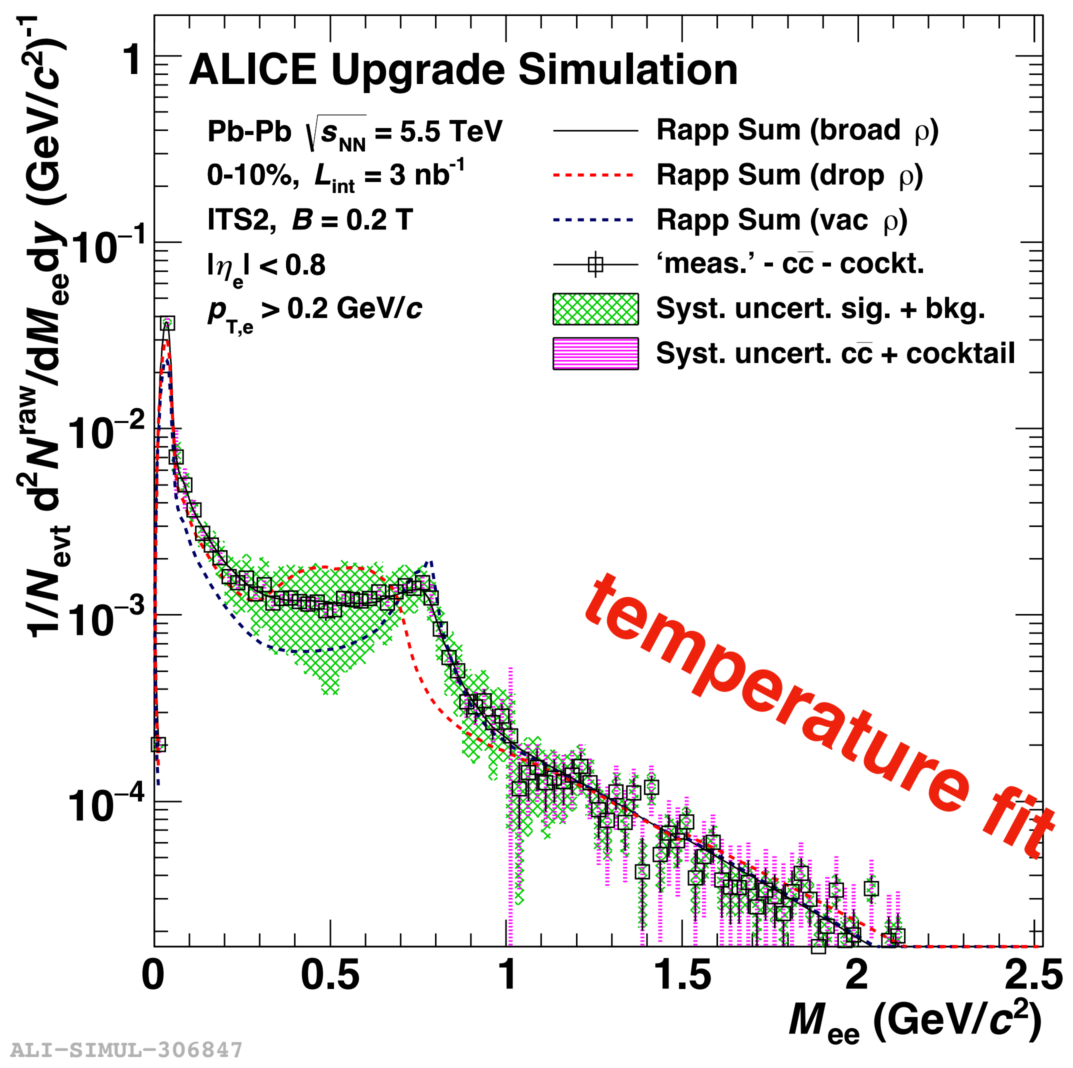
New Foward Calorimeter (FoCal)
LoI (2020):
https://cds.cern.ch/record/2719928

T_{init} Run-4 Physics (1)

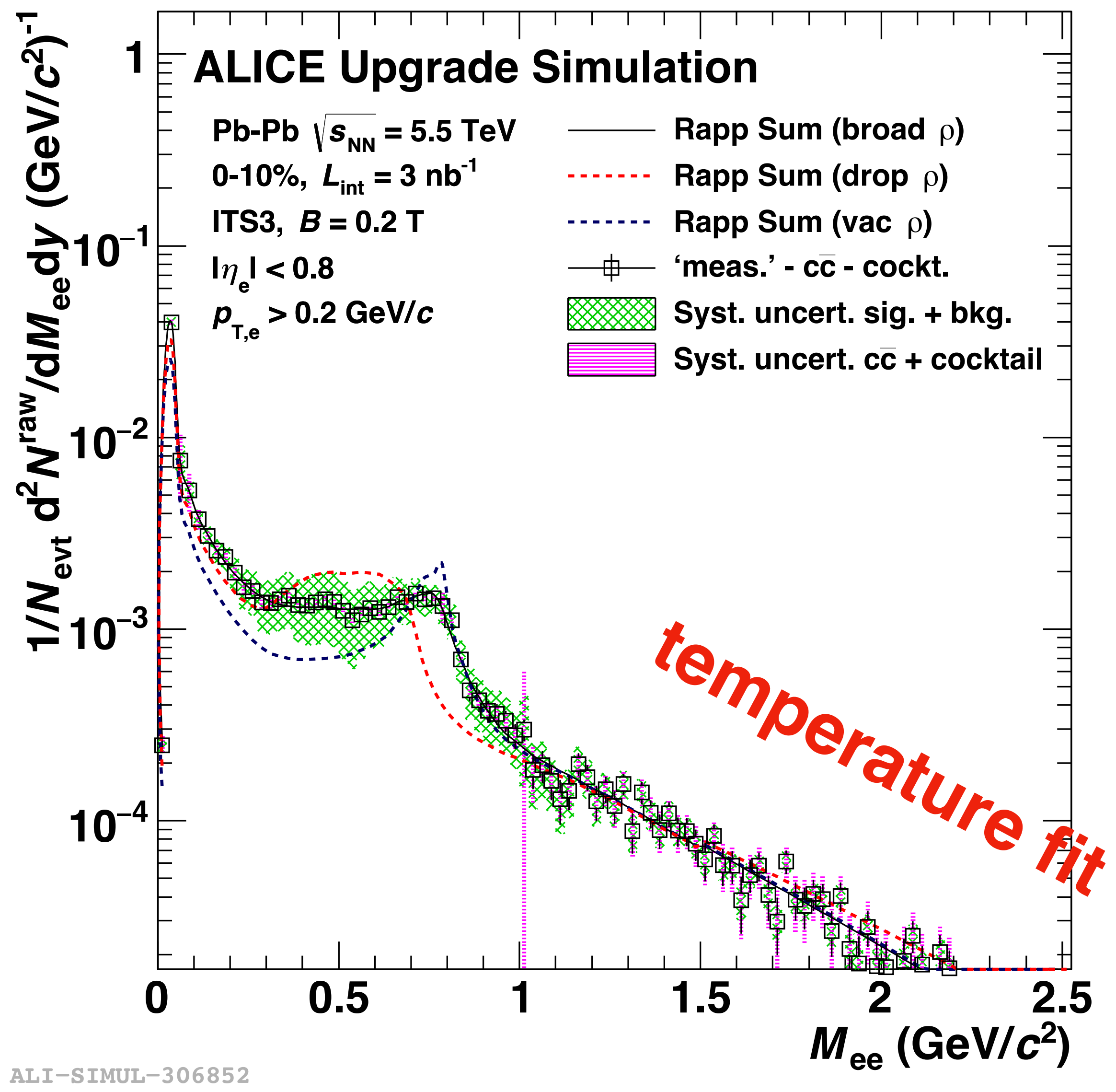
A new ultra-light inner barrel (ITS3)

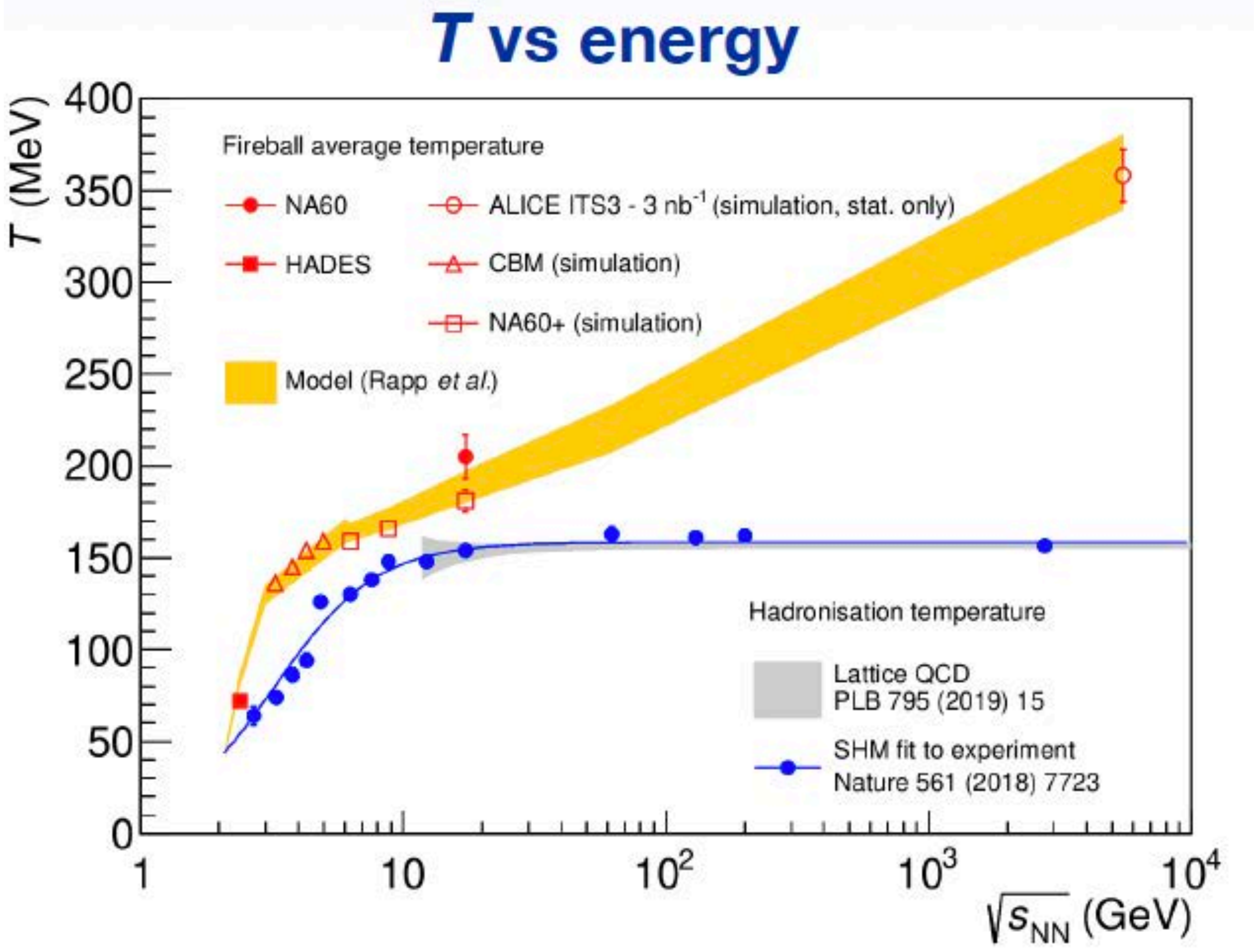
- **Low-mass di-electrons:**
  - Vertexing (better charm rejection)
  - Lower material thickness (less conversions)
  - Higher low-pT efficiency (better conv. rejection)

ITS2



ITS3

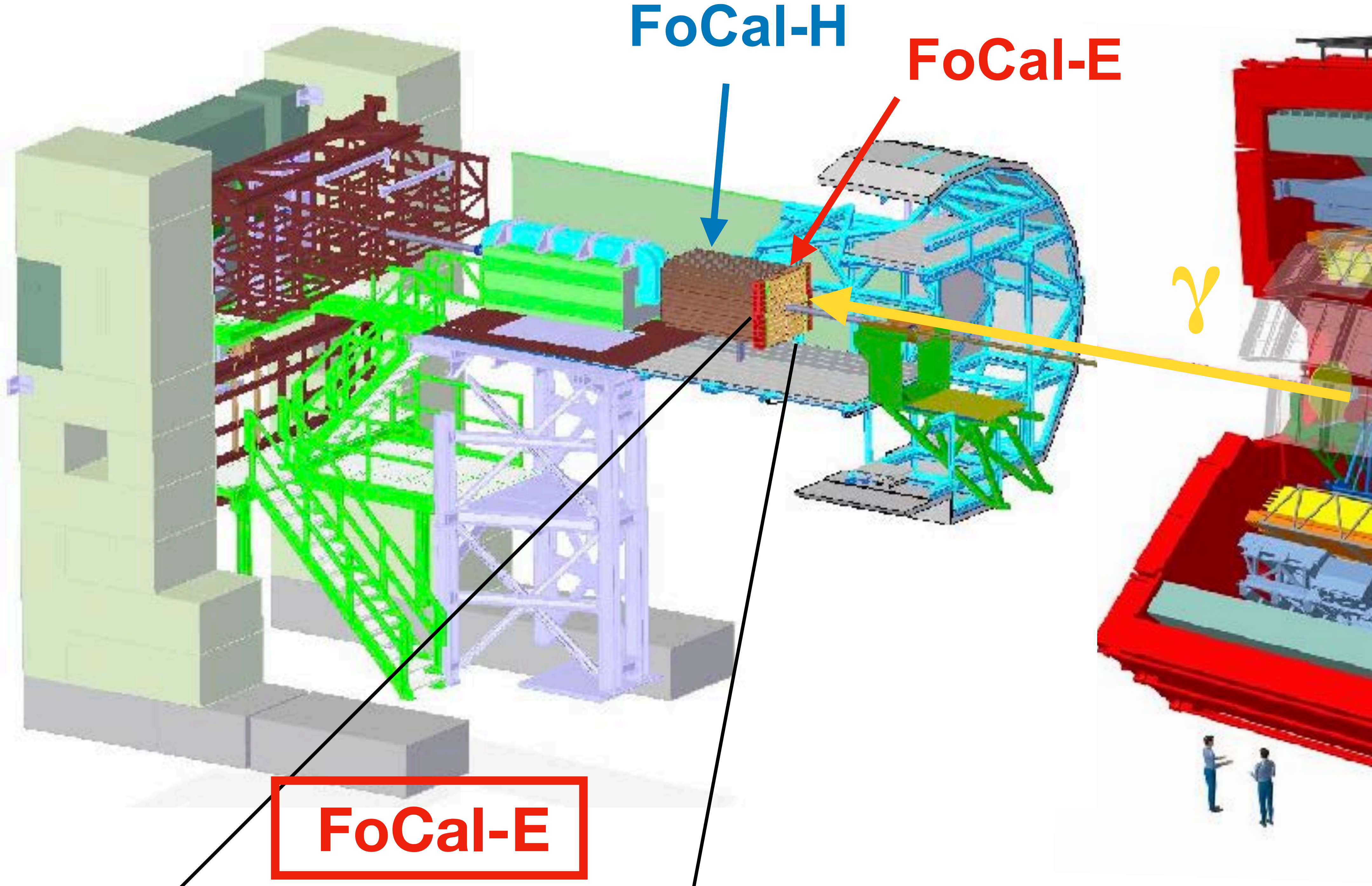




ρ_g Run-4 Physics (2)

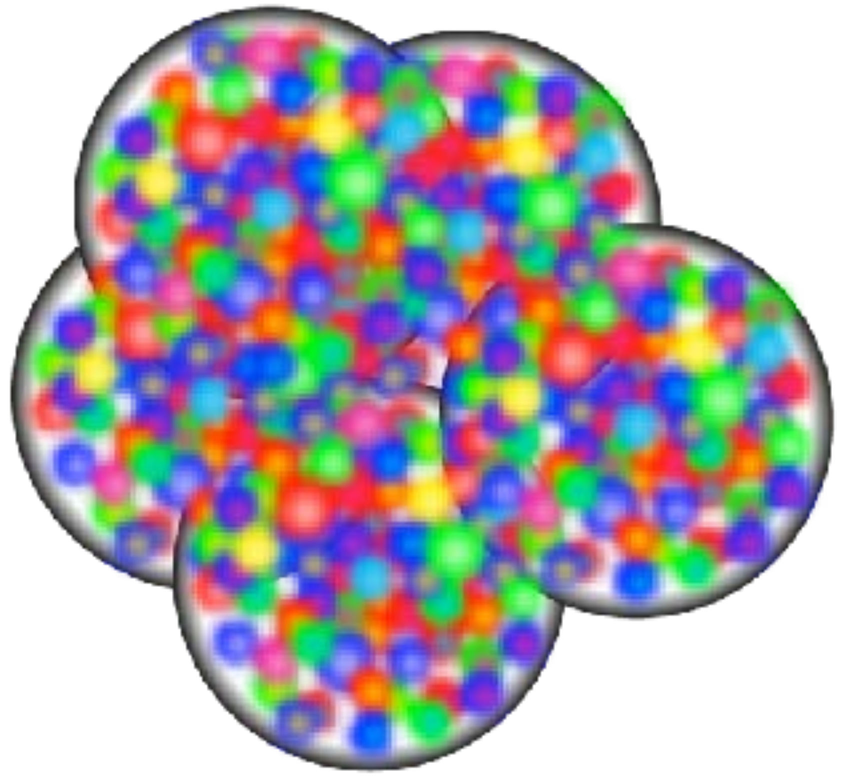
FoCal = Forward Calorimeter

- **FoCal-E**: High granularity Si-W sampling Electromagnetic Calorimeter (direct photon, π^0)
- **FoCal-H**: Hadron calorimeter (photon isolation, jet)
- Purposes : Gluon density down to very low x ($x \sim 10^{-6}$), CGC

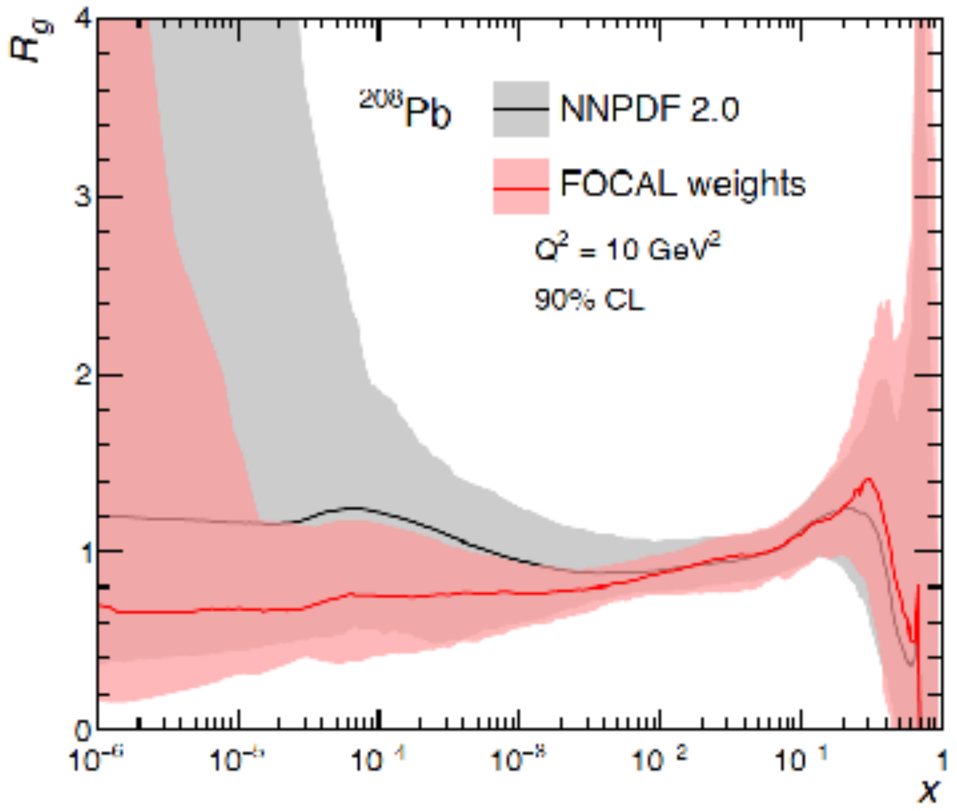


CERN EP newsletter (2022 March)

Color Glass Condensate (CGC)



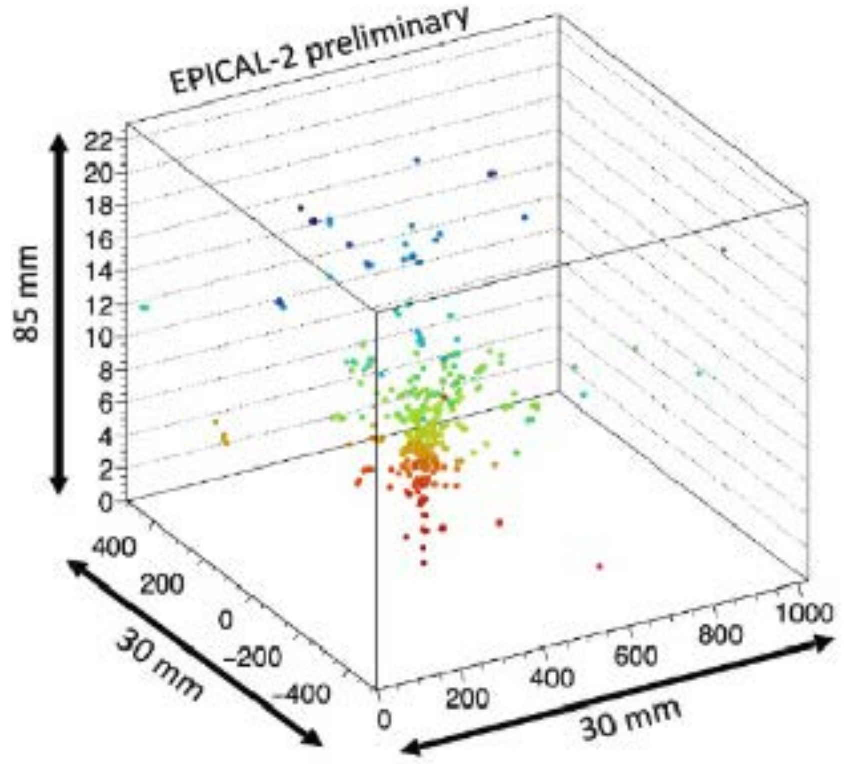
Gluon density in Pb nucleus

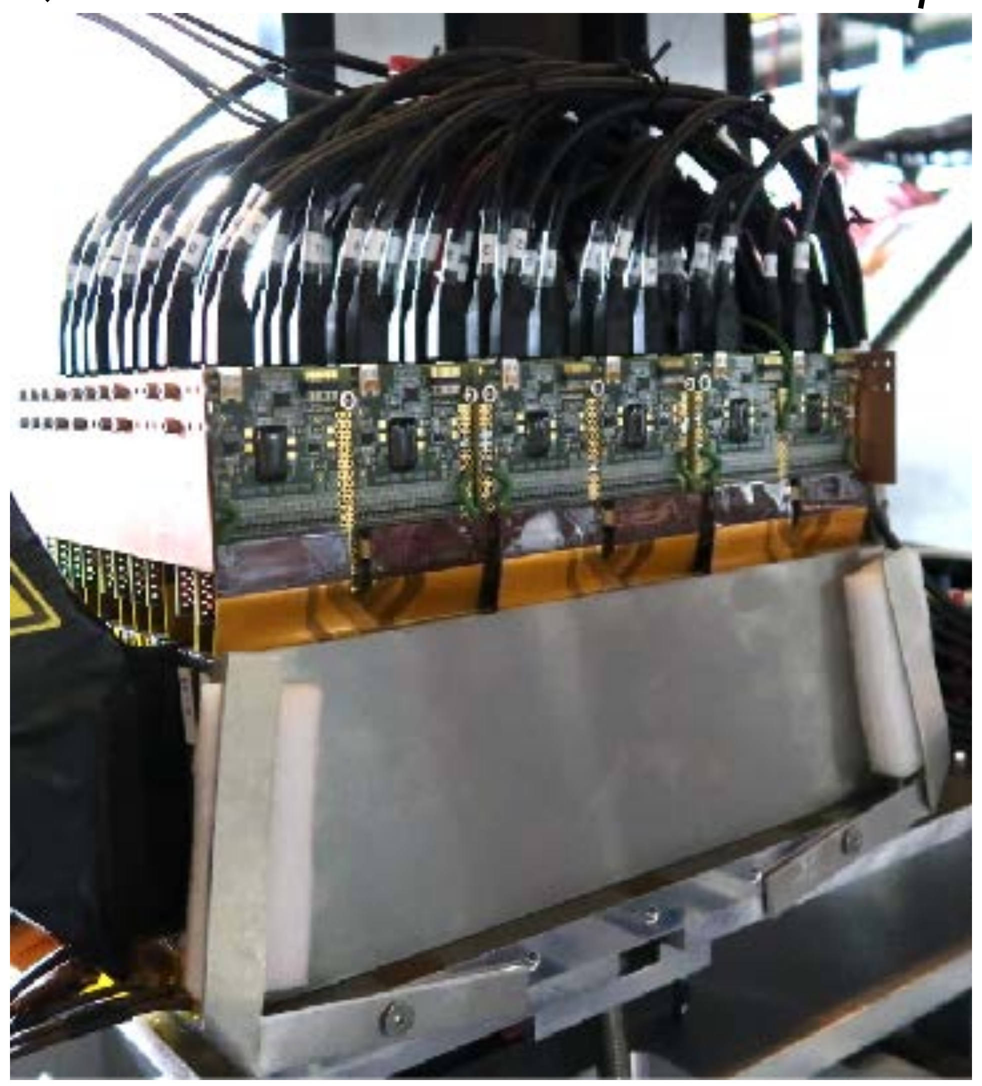


"FoCal-E PIXEL" photon position

2 layers

cell size: 30x30 μm²





"FoCal-E PAD" photon energy

18 layers

cell size: 1x1 cm²

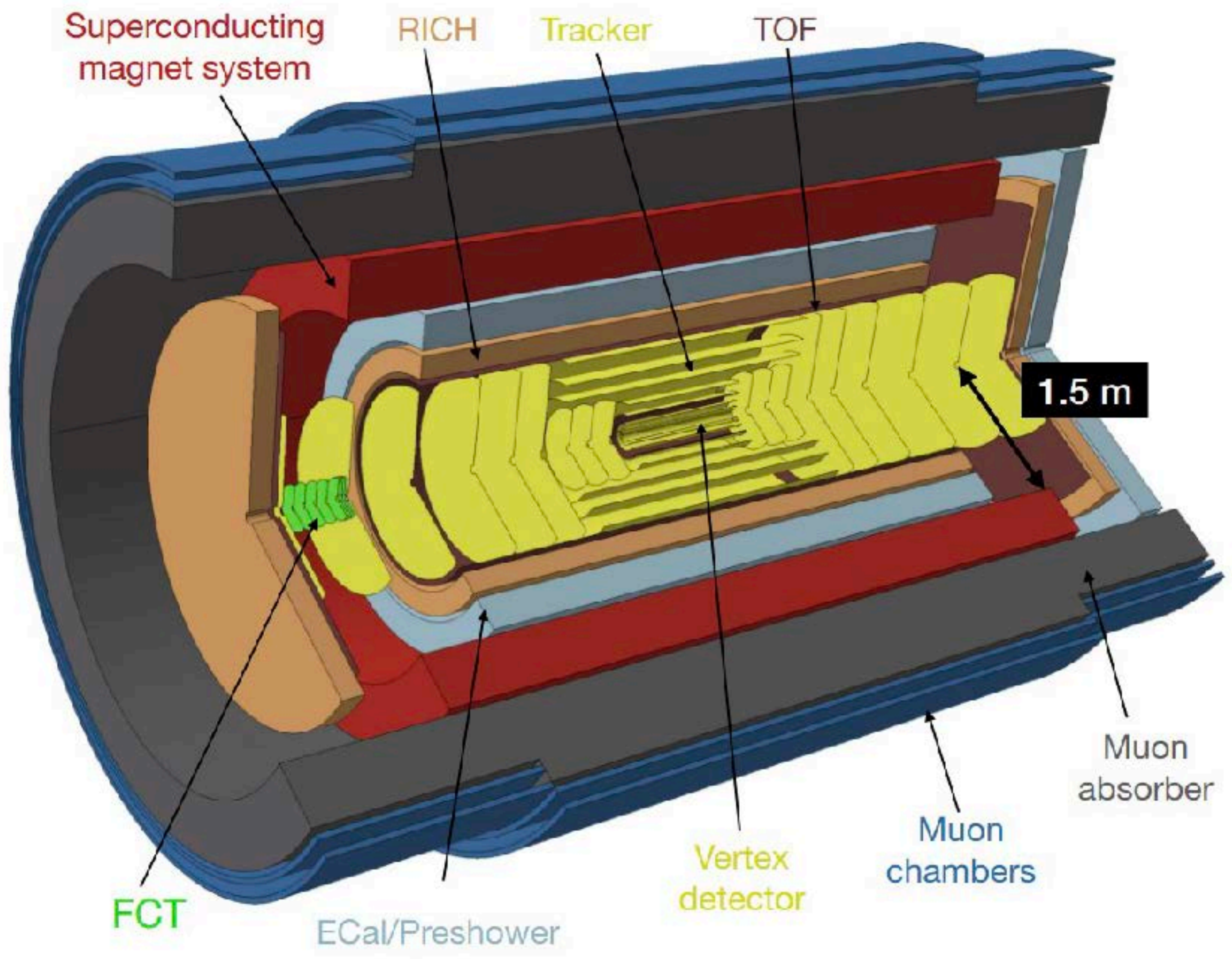
mini-FoCal (2018)

“ALICE3” in Run-5 (2035-2038)

Expression of Interest arXiv:1902.01211

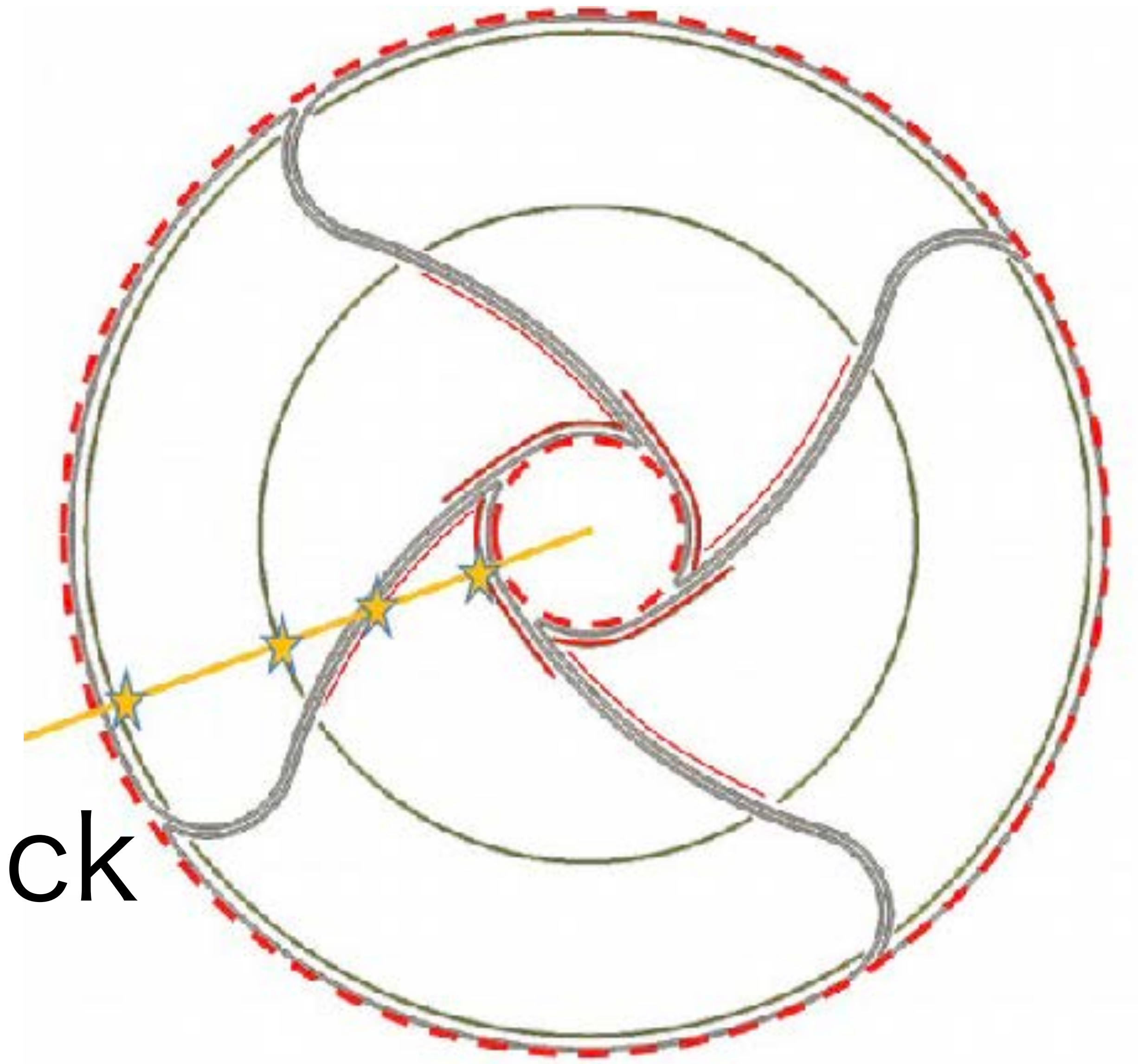
ALICE3 LoI @ CERN research board

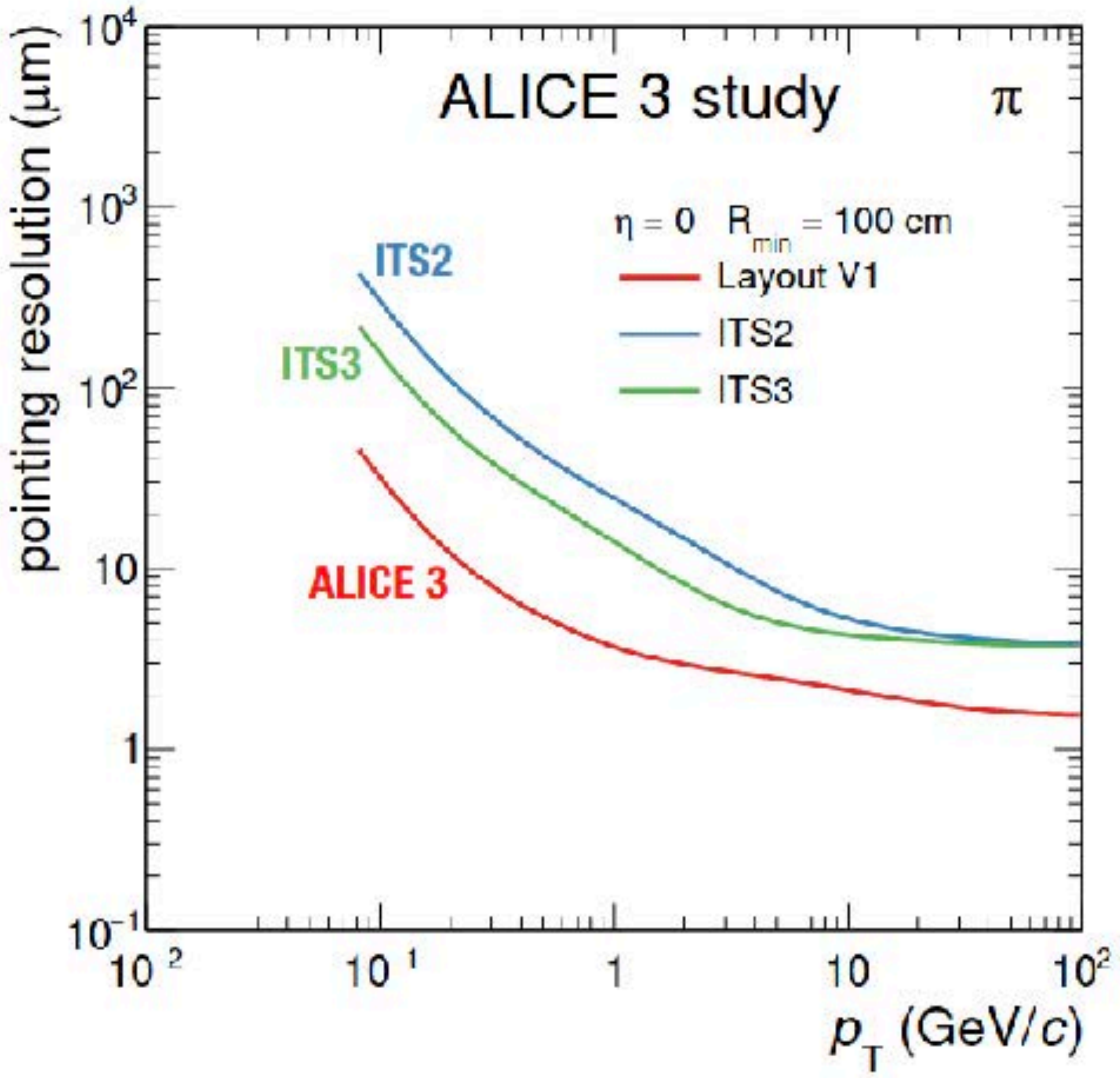
Recent workshop (Oct. 2021)
https://indico.cern.ch/event/1063724/

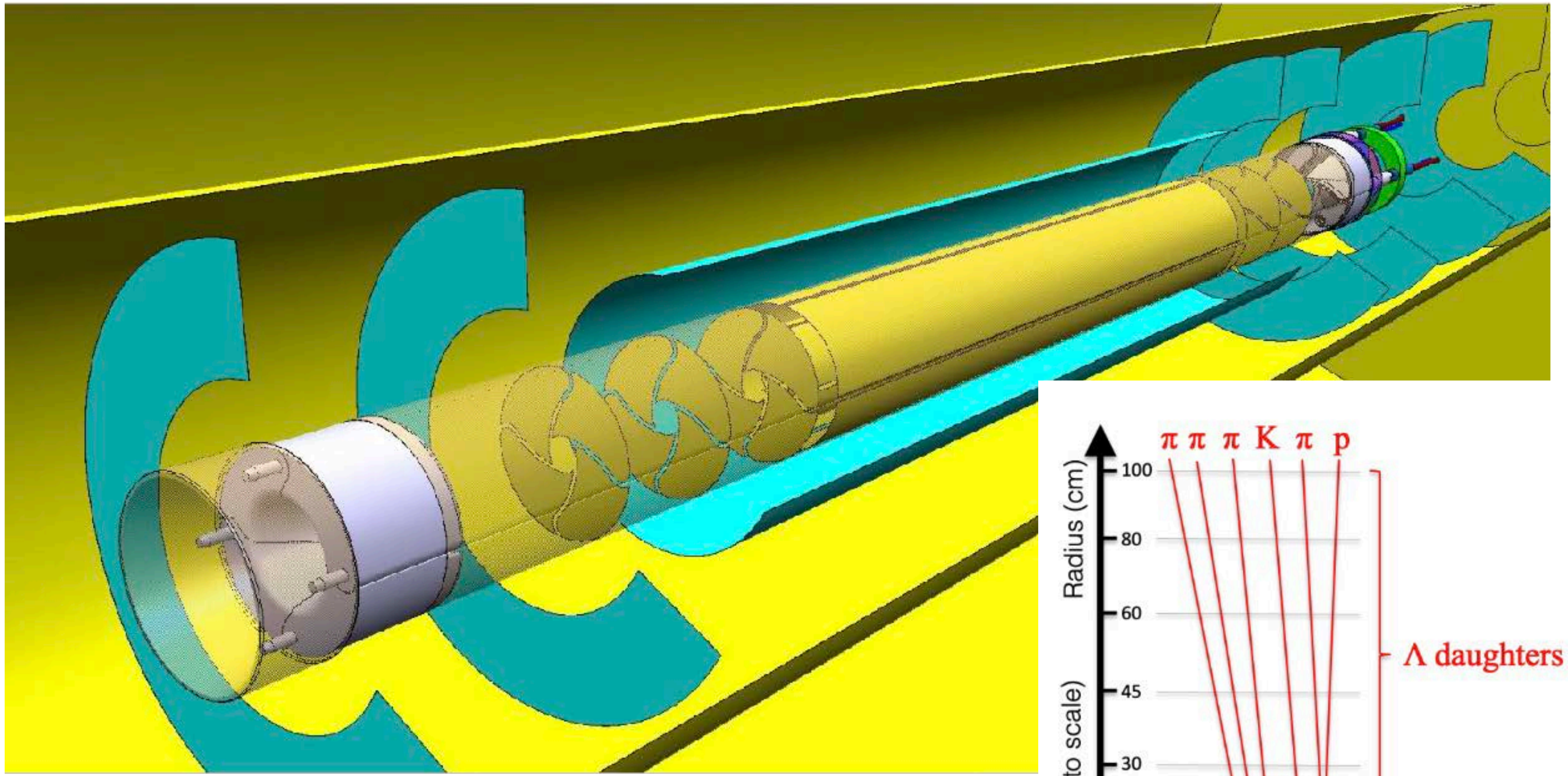


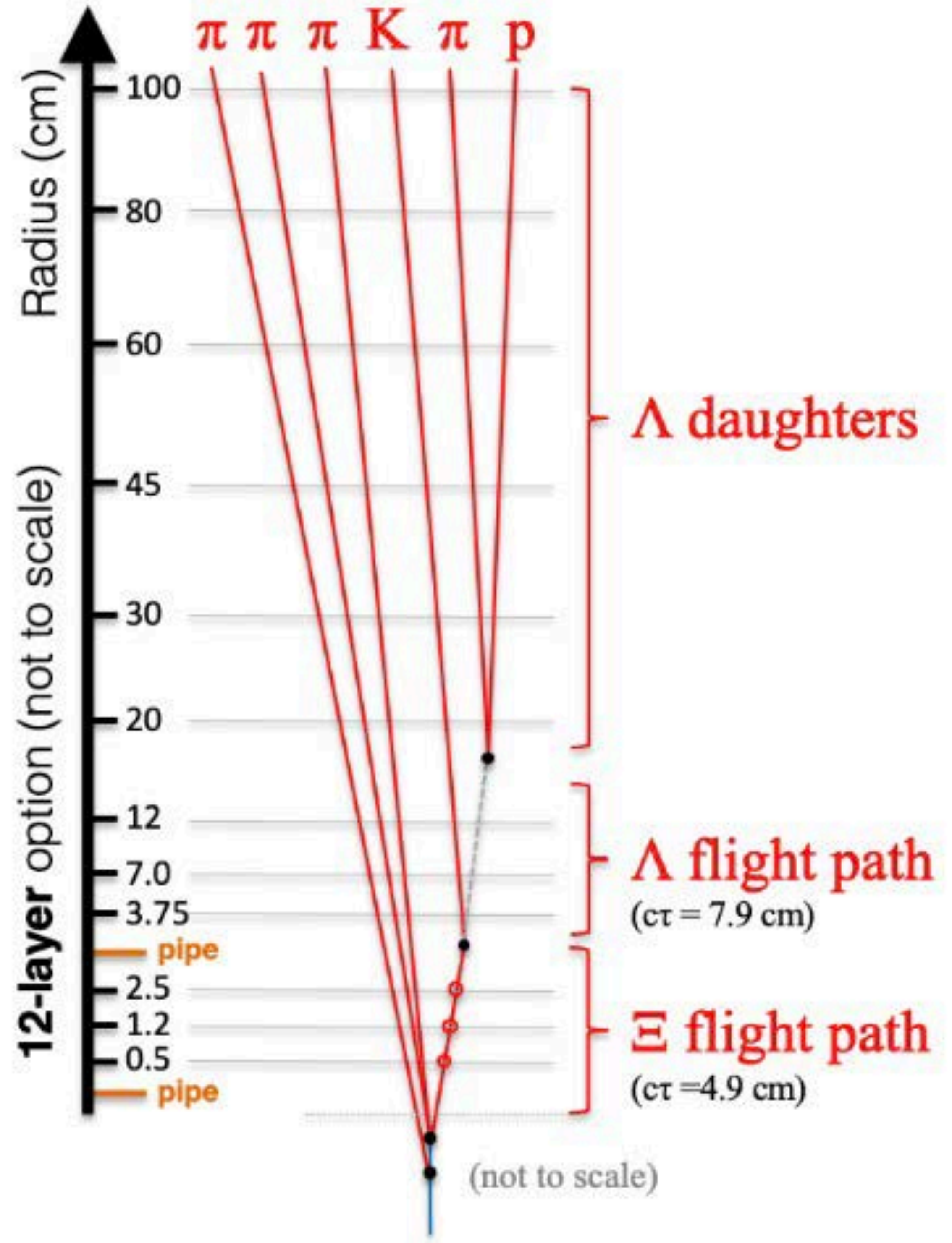
Novel measurements of electromagnetic and hadronic probes of the QGP at very low momenta

"ALICE3" in Run-5 (2035-2038)



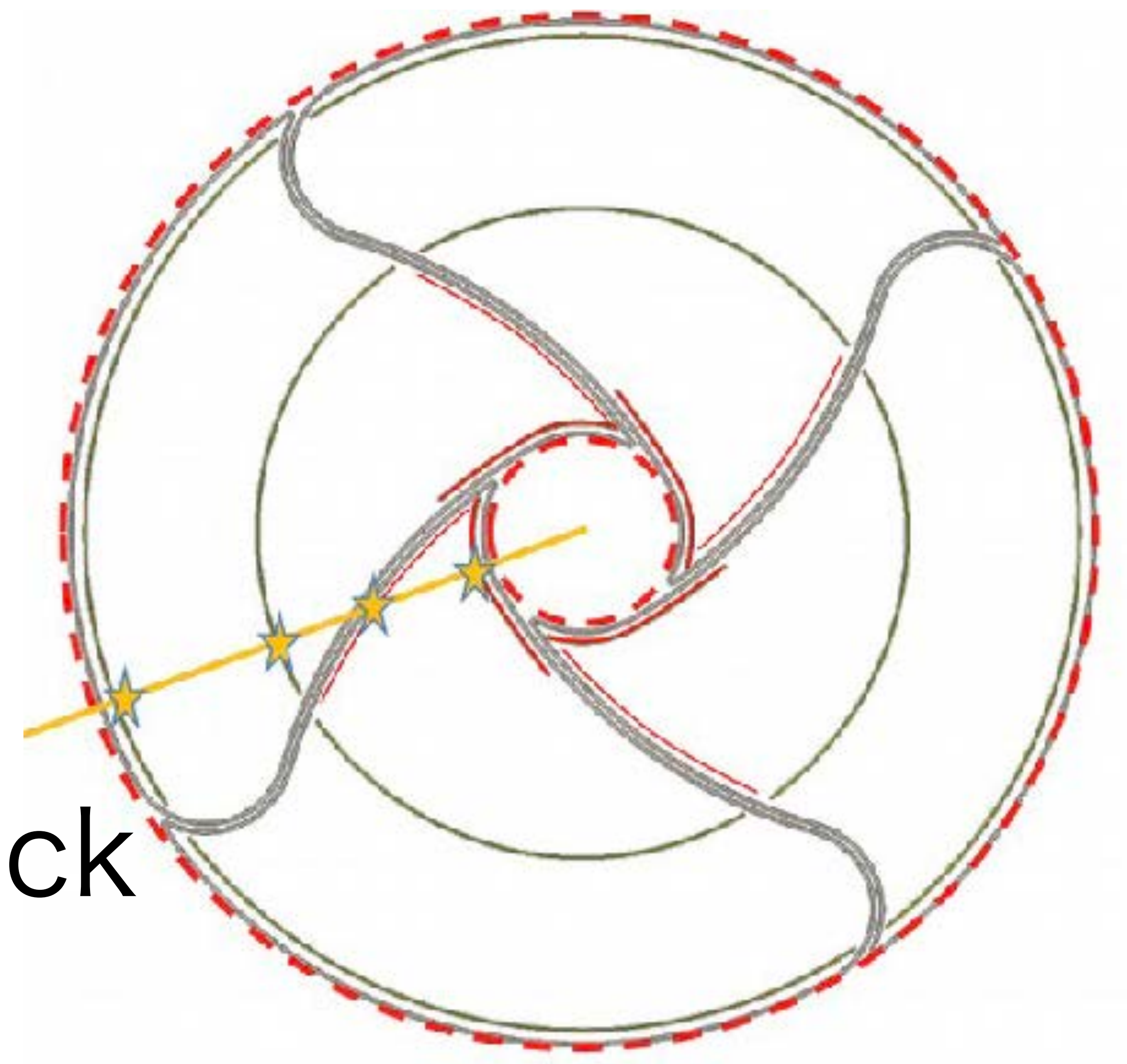




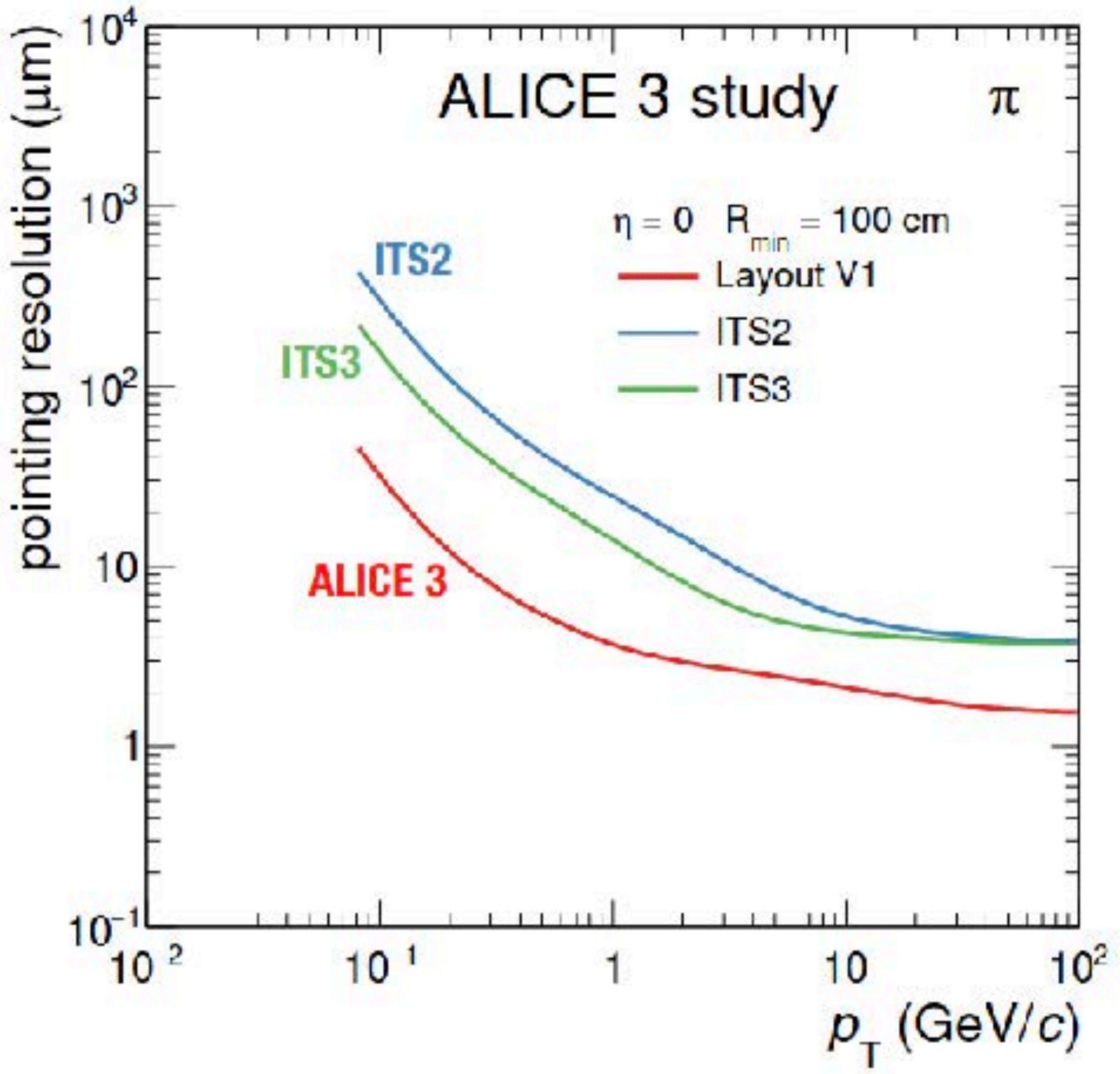


Si tracker inside the beam pipe!

“ALICE3” in Run-5 (2035-2038)



Track



Selection of key points of ALICE 3 physics

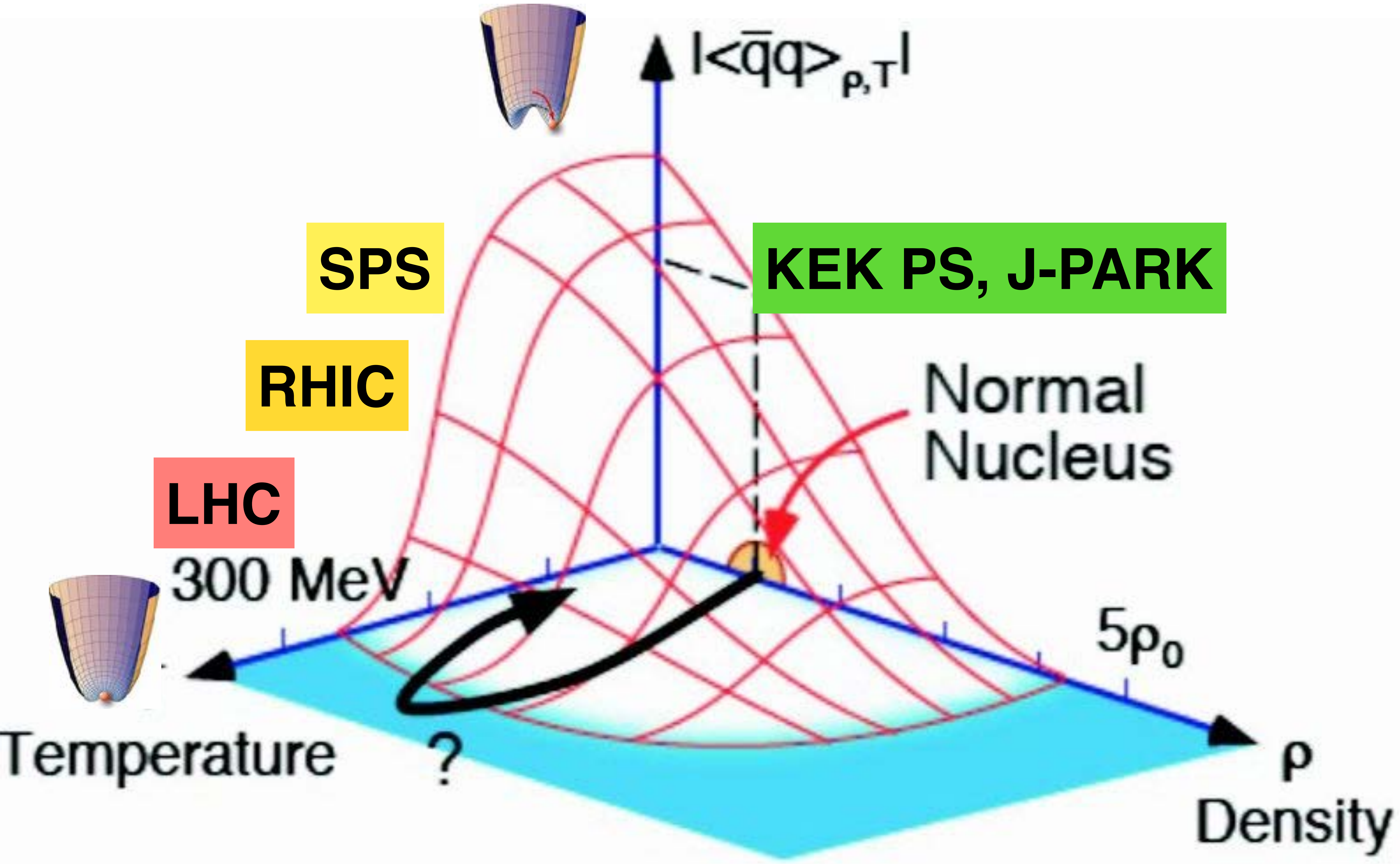
- **Precision measurements of di-leptons**
  - Characterization and evolution of the QGP
  - Chiral symmetry restoration

- **(multi-)heavy-flavoured hadrons**
  - Transport properties and diffusion in the QGP
  - Mechanisms of hadronization

- **Hadron correlation**
  - Interaction potentials
  - Fluctuations of conserved charges

ALICE3 : Chiral Symmetry Restoration

$\langle \bar{q}q \rangle$



Chiral SB $\langle \bar{q}q \rangle \neq 0$

Restoration of Chiral symmetry

$\langle \bar{q}q \rangle \approx 0$ @ high T
@ high ρ

Achieved highest temp. in ALICE

Vector mesons (ρ, ω, ϕ, a_1, ..)

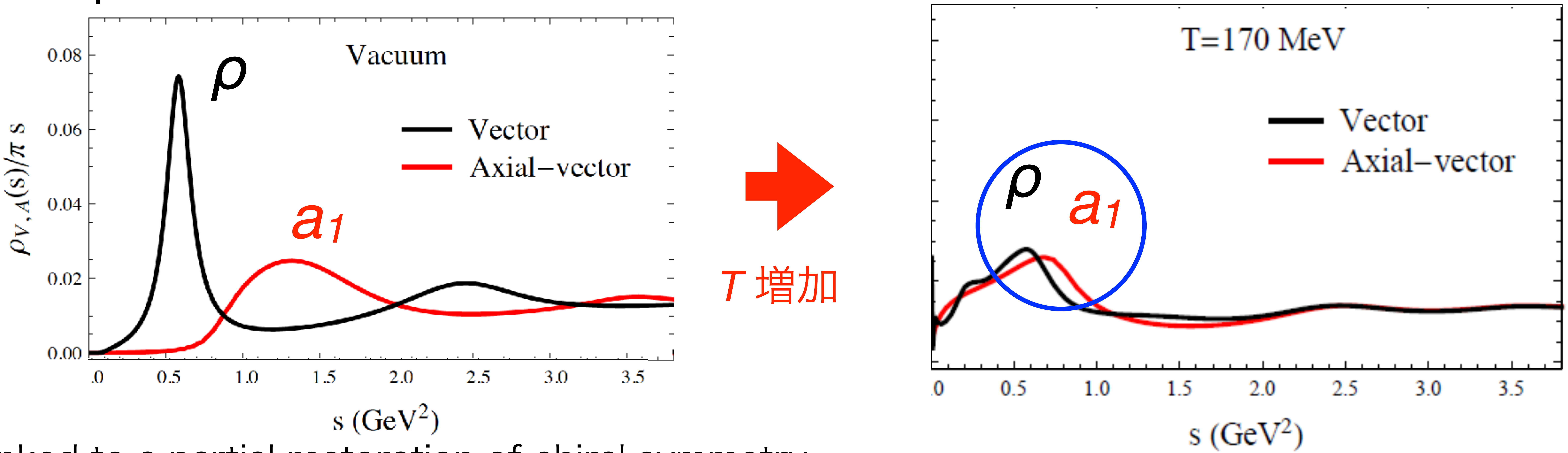
Low mass region (< 1 GeV/c^2)

Highest precision measurement for e^+e^- pairs

Increase of ρ meson width, ρ-a_1 mixing

P.M Hohler and R. Rapp, Phys. Lett. B 731 (2014) 103

spectral function



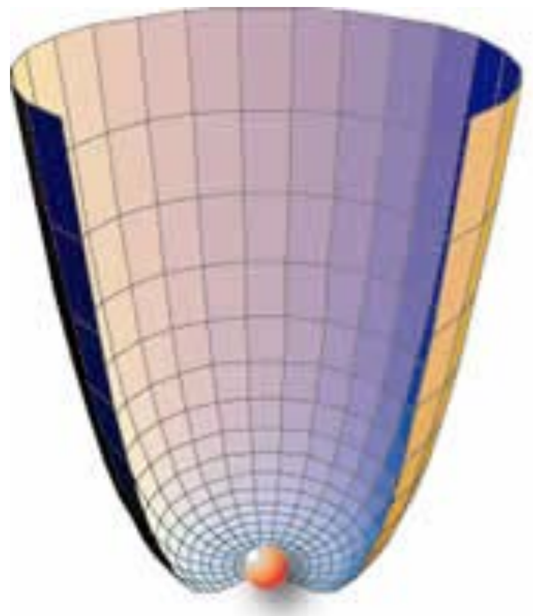
- Linked to a partial restoration of chiral symmetry
- Difficult to measure a_1 meson experimentally. Needed precision measurement below < 1 GeV/c^2
- At high temperature, in-medium modification of ρ meson and regeneration of a_1 meson

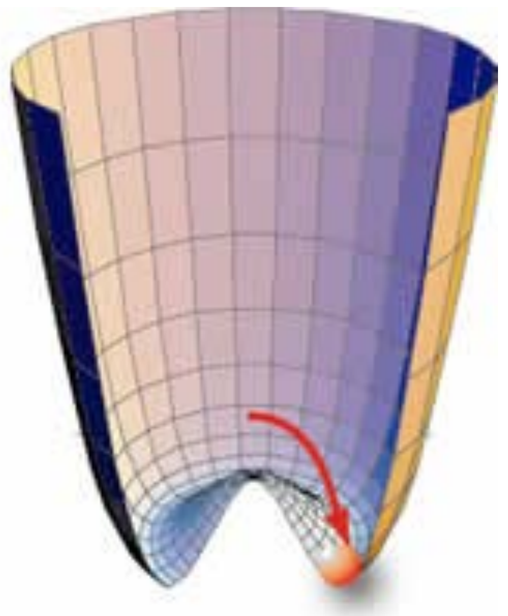
→**Look at this change!**

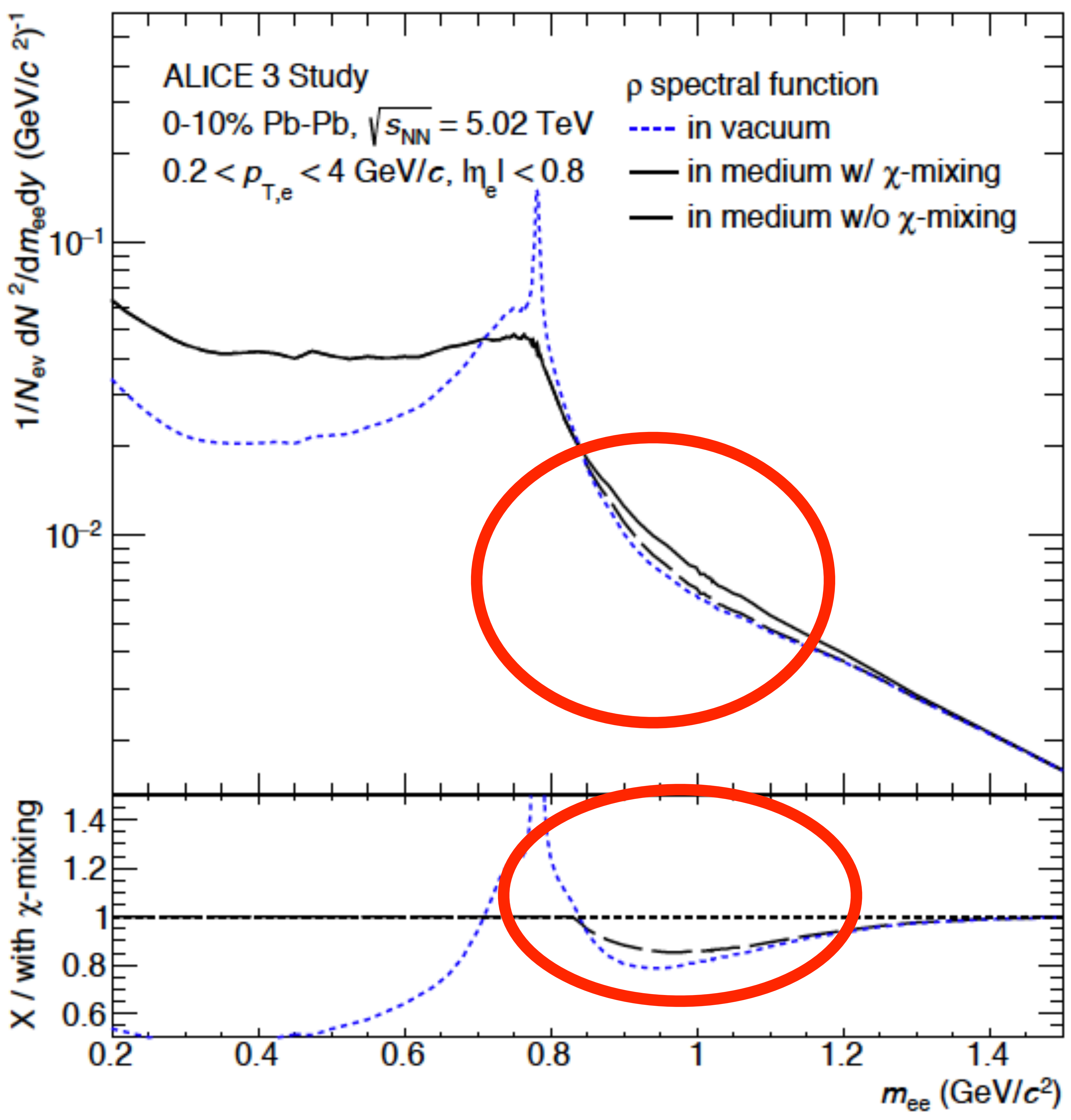
High precision measurement of e^+e^- pairs

Thermal dielectron spectrum for different spectral function *ρ function*

- M_{ee} ~ chage around 1 GeV/c^2 : ρ-a1 mixing!
- Needed an extremely high precision
- Cannot be achieved ALICE Run-3 (ITS2), Run-4 (ITS3)
- Need ALICE Run-5 ("ALICE 3")





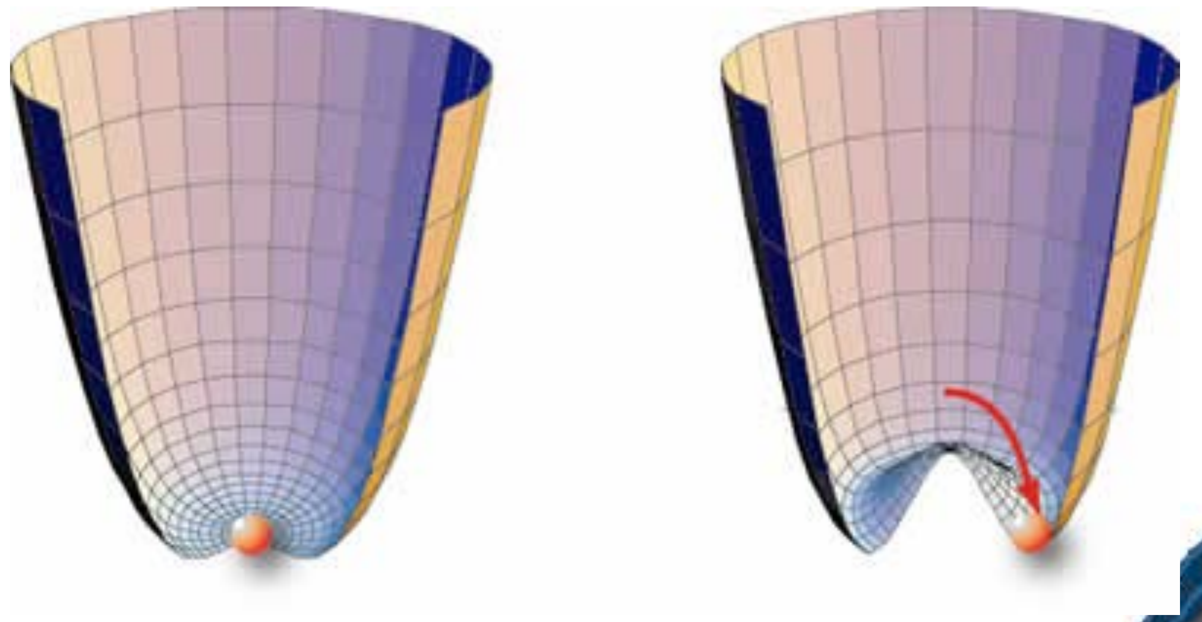


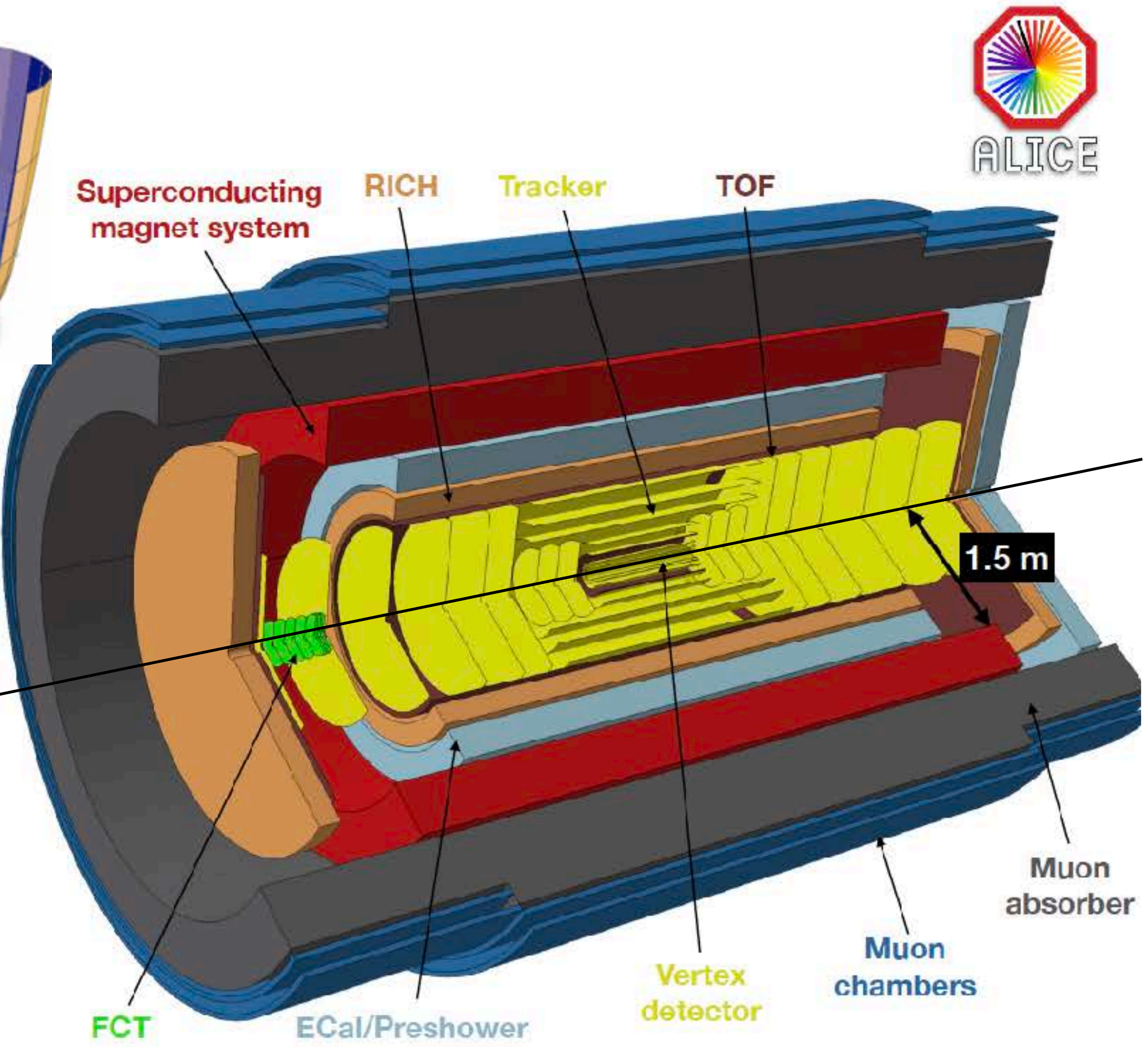
R. Rapp, Adv. High Energy Phys. 2013 (2013) 148253

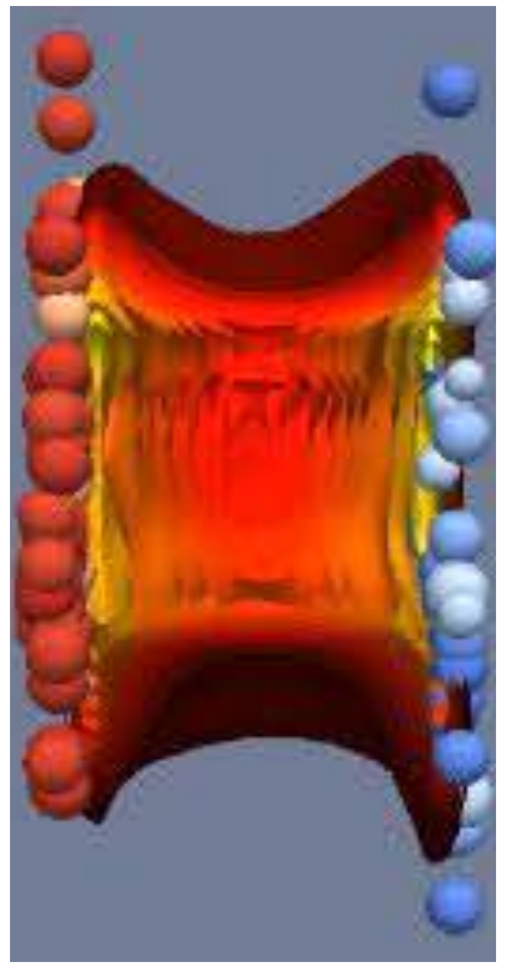
P.M Hohler and R. Rapp, Phys. Lett. B 731 (2014) 103

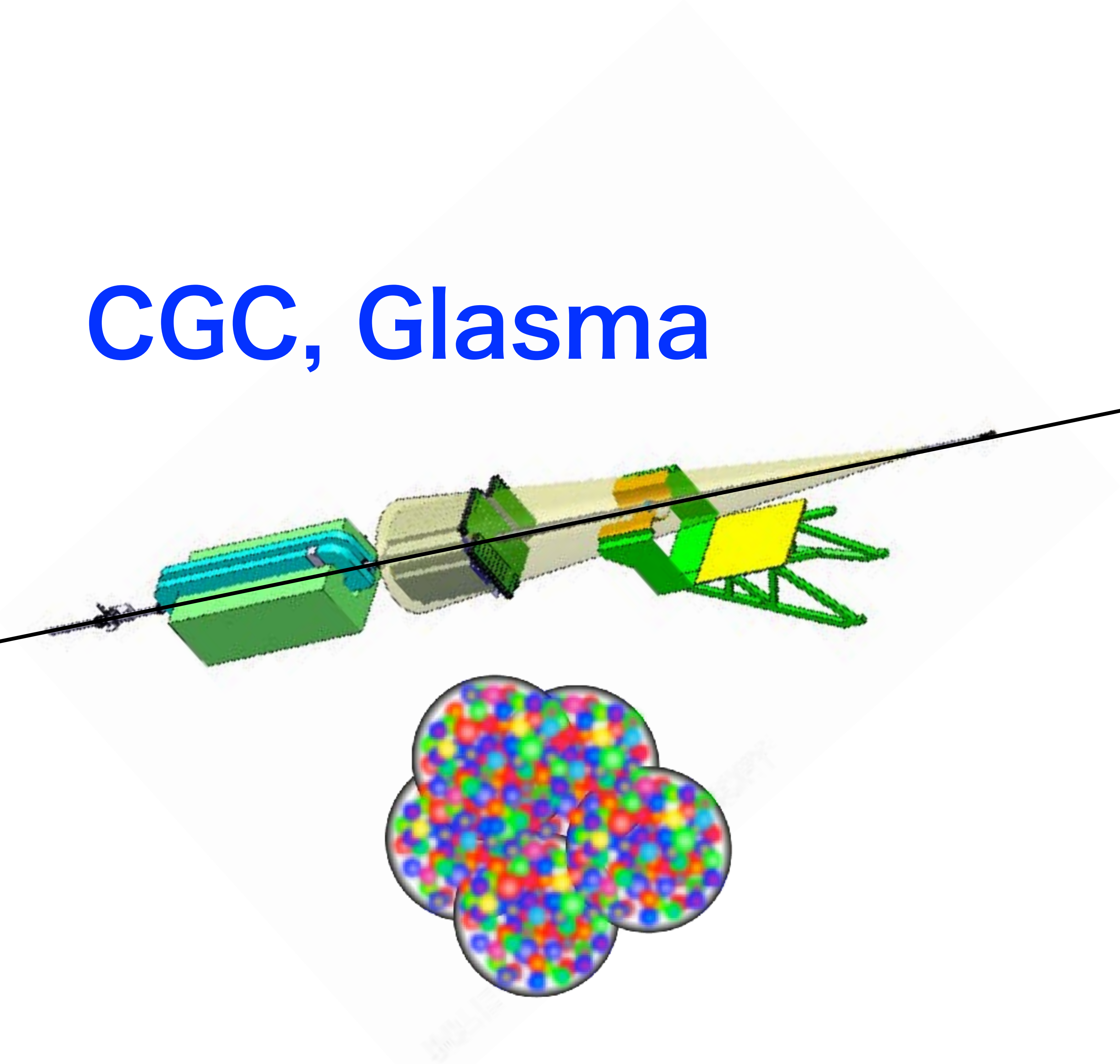
R. Rapp private communication

ALICE3 & FoCal+? (Run-5)





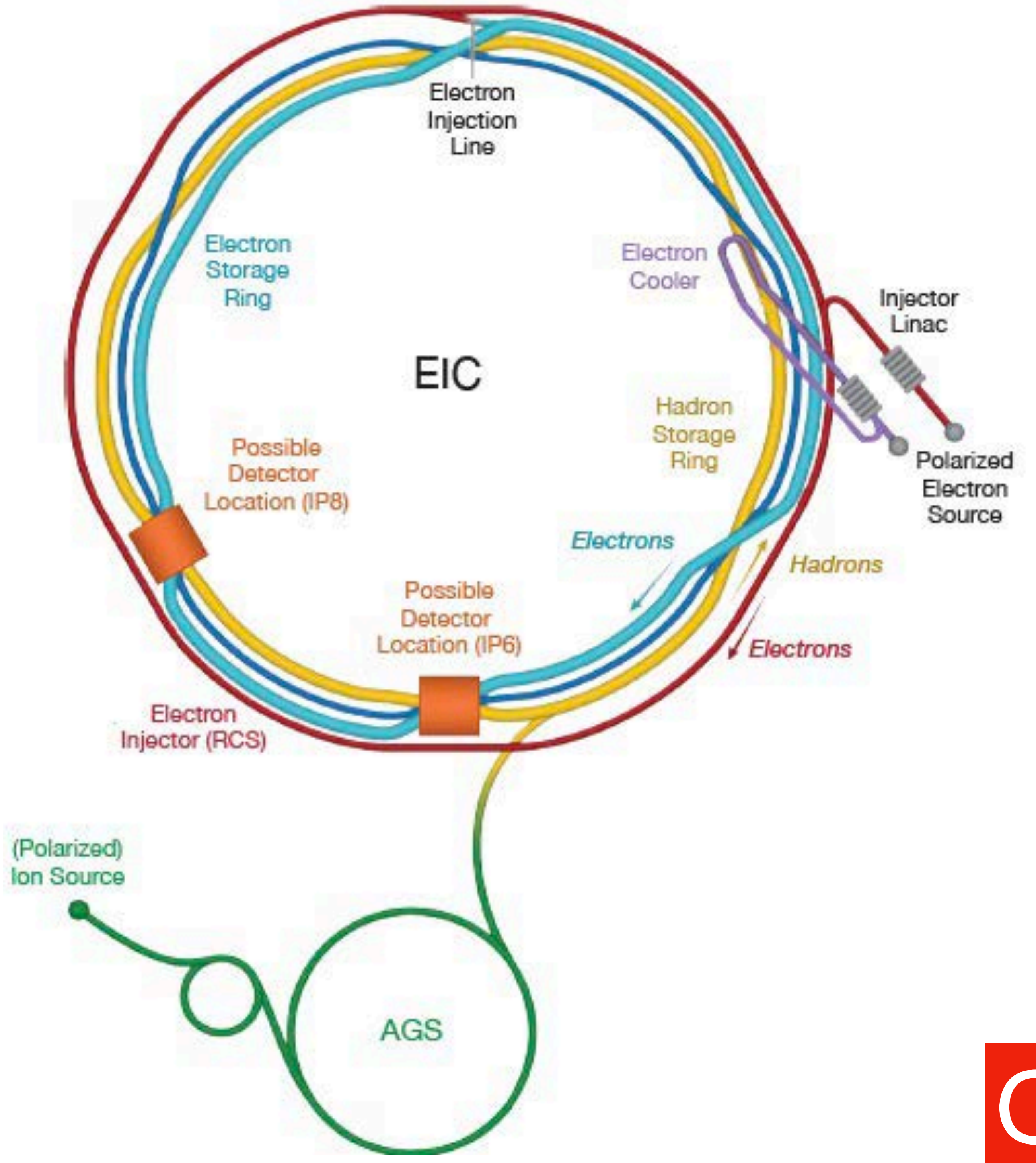




CGC, Glasma

QGP production, Chiral symmetry restoration @ high T

EIC eA vs. LHC HI



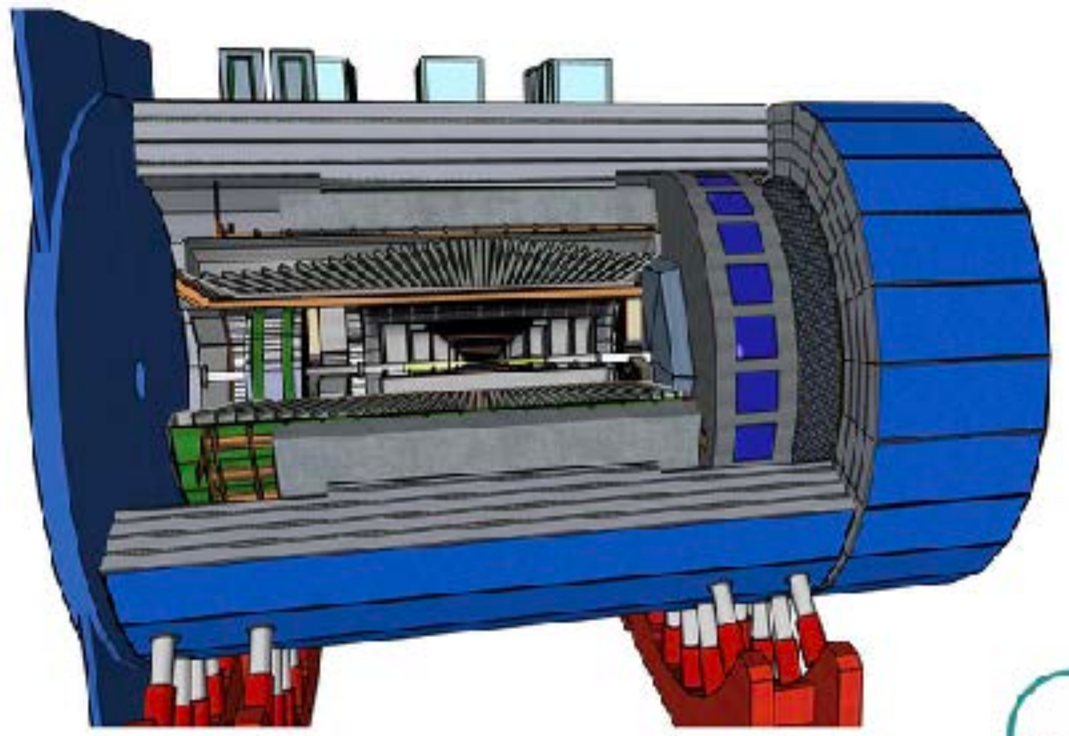
- At BNL, EIC will start to operate around 2030

- A high luminosity polarized e, p / ion collider at $\sqrt{s}$ = 28-140 GeV

- Factor 100 to 1000 higher luminosity as HERA

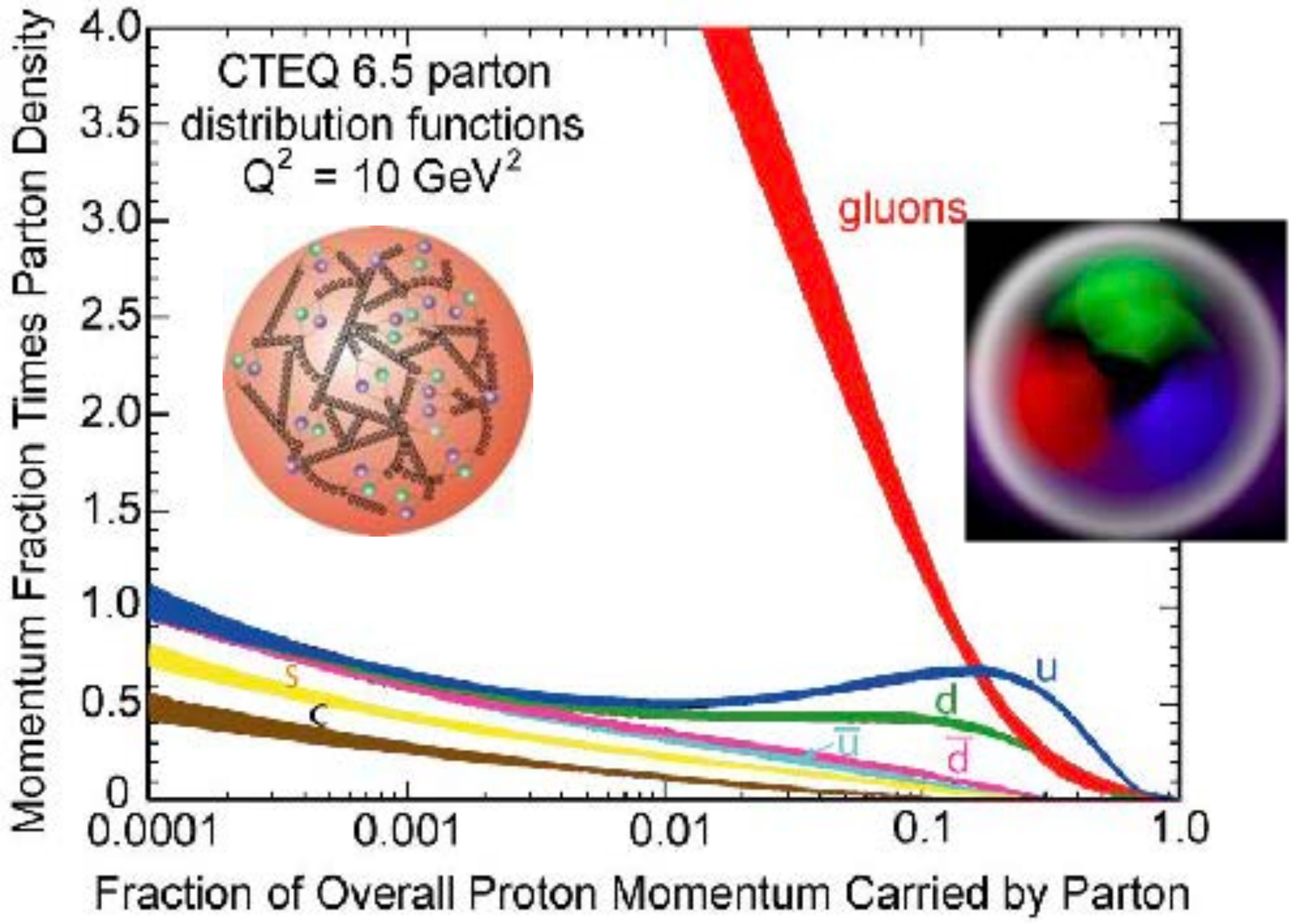
- ECCE has been recommended as “Detector-1” by DPAP (Mar. 2022)

Good synergies with EIC

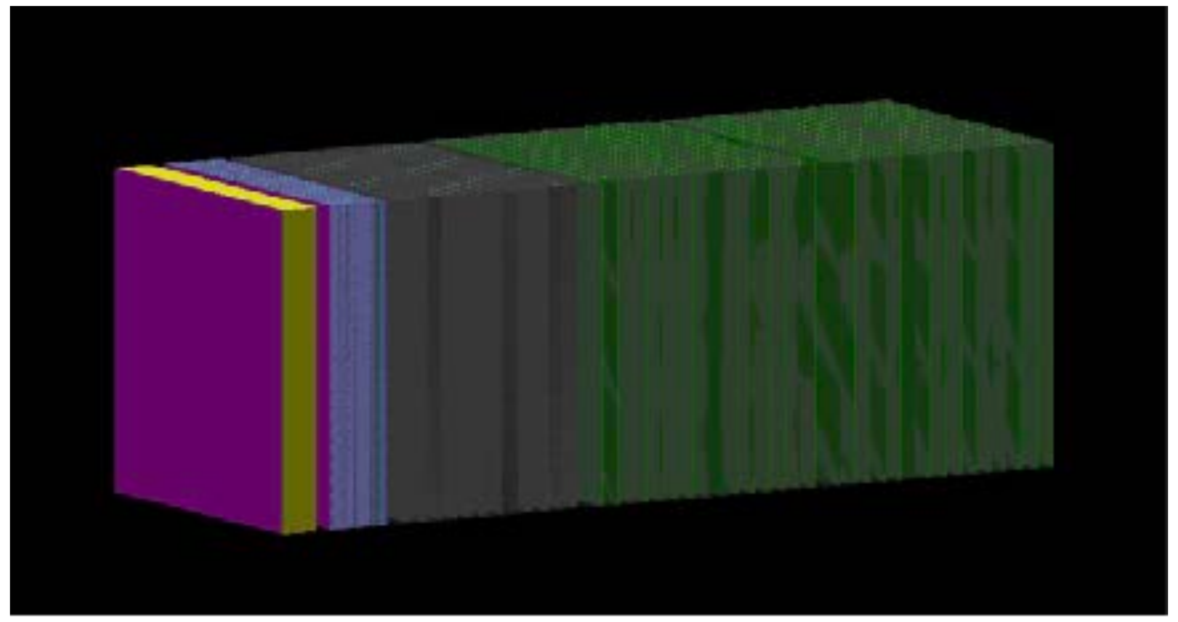


EIC Comprehensive Chromodynamics Experiment

CGC, initial condition of Heavy Ion



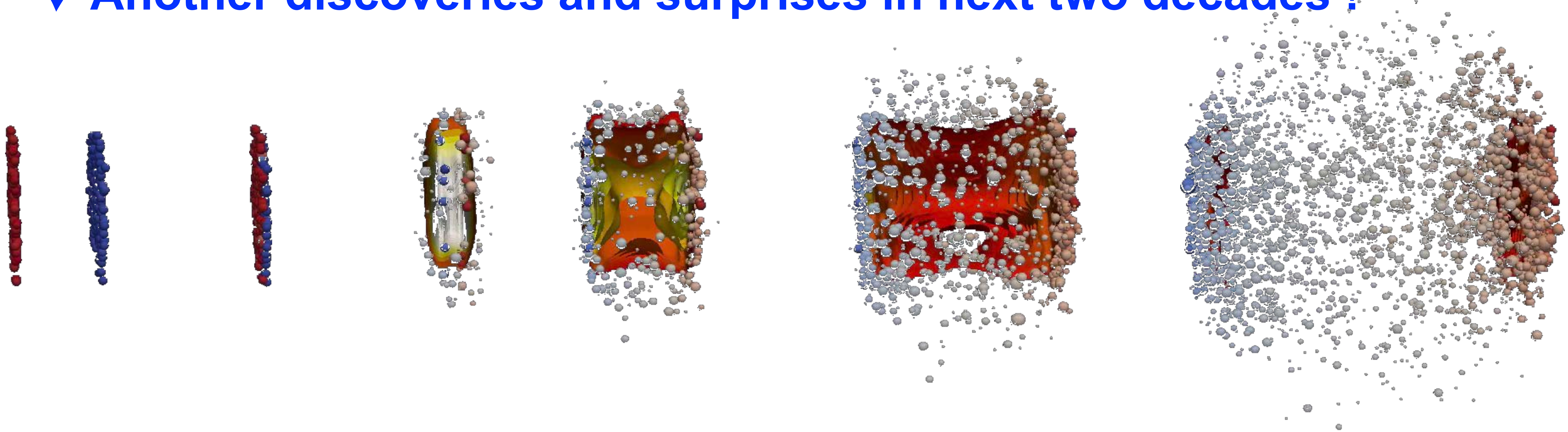
Detector Technology



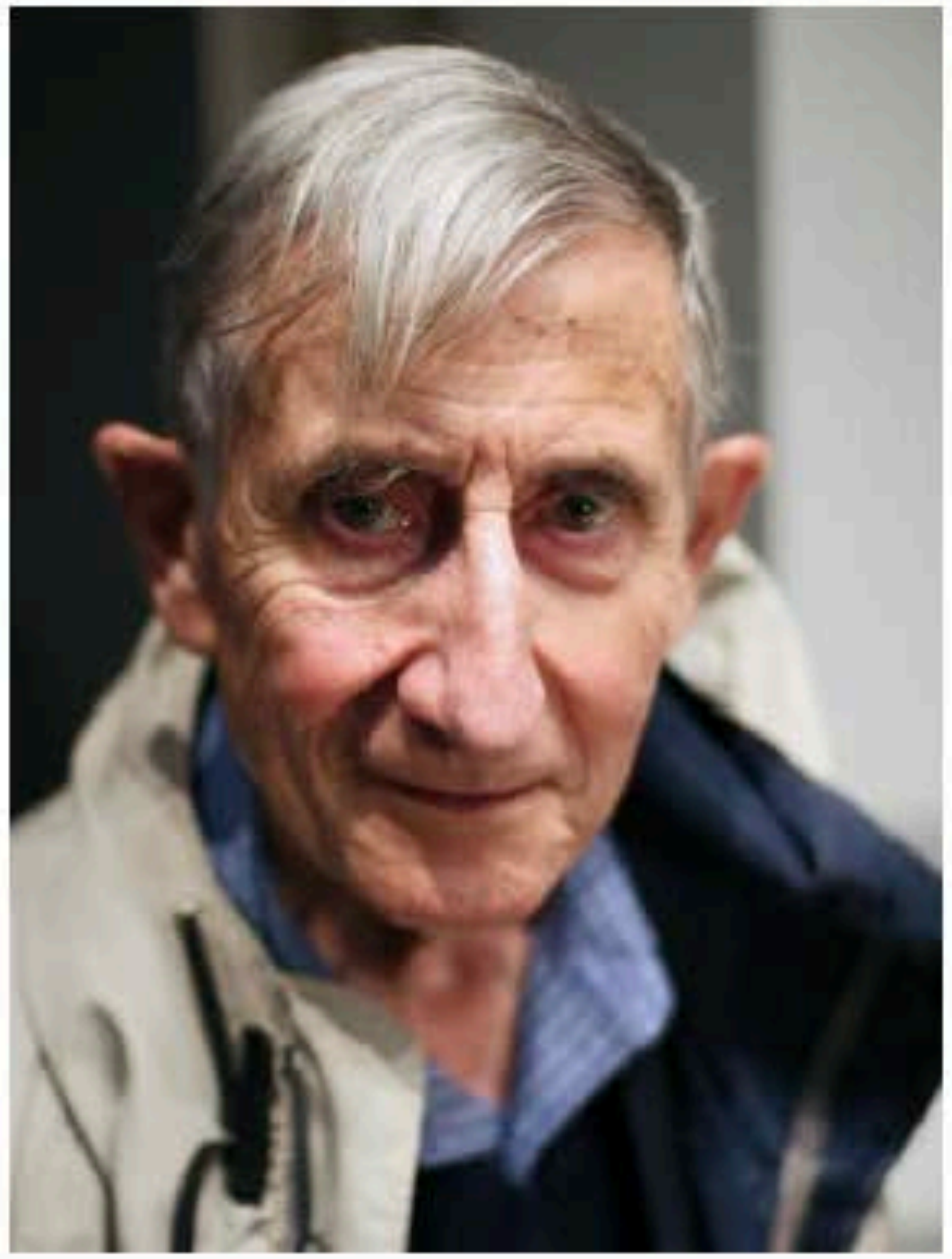
ZDC design for EIC, figure by S. Shimizu

Summary

- ✓ Since 2009, LHC HI program provides rich and new views on quark gluon plasma produced at LHC.
- ✓ Still there are remaining big questions.
- ✓ To answer these, upgrades are planed.
- ✓ Another discoveries and surprises in next two decades !



New directions in science by new tools



"New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained."

Freeman Dyson

Slide from K. Hanagaki (KEK), 2021

Thank you for your attention!