A Large Ion Collider Experiment

ALICE physics highlights and perspectives

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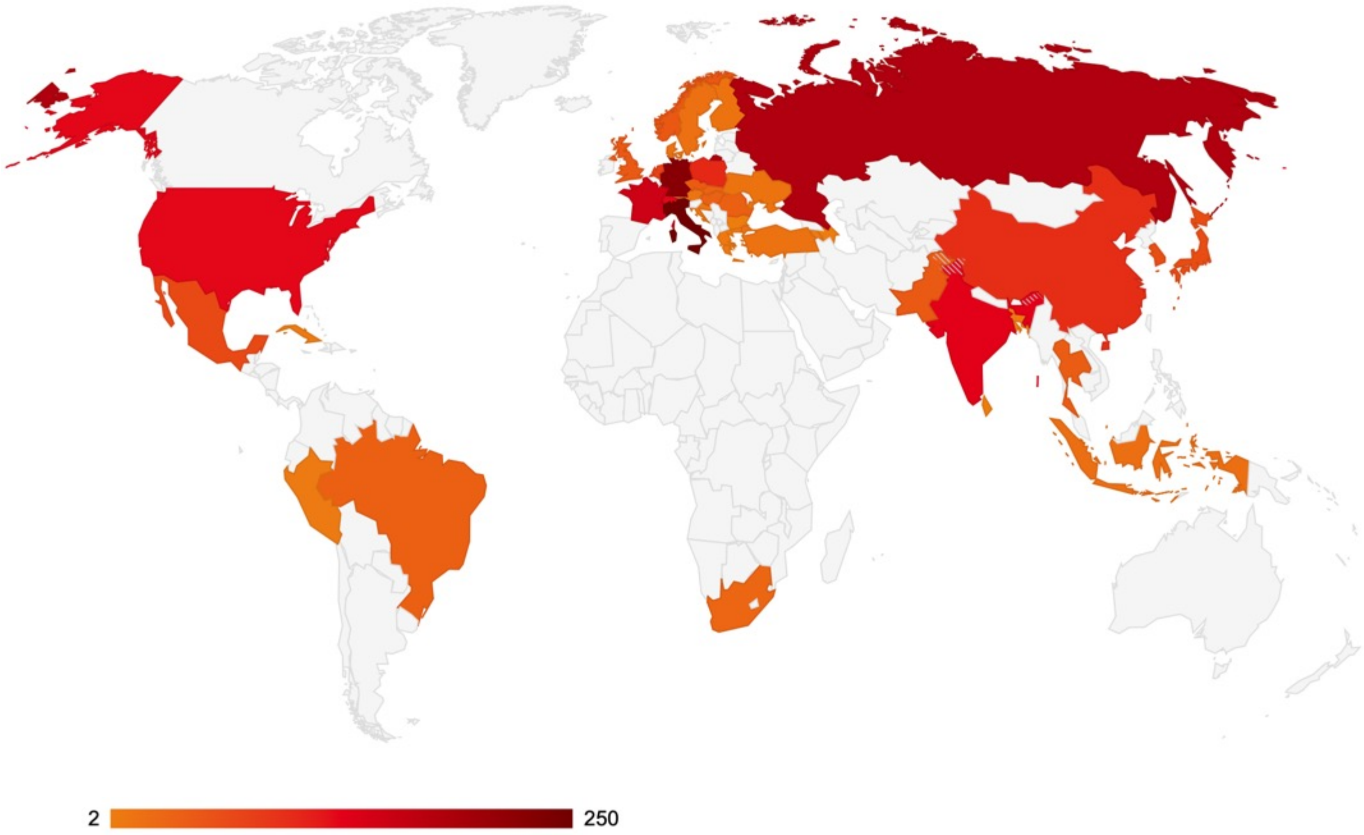
Workshop on Standard Model and Beyond

Corfu 2021, September 5

Outline

1. Introduction
2. Physics highlights
3. Preparations for Run 3
4. Future perspectives

The ALICE Collaboration



42 Countries, 173 Institutes

1946 Members

about **1000 signing authors**

Main stages

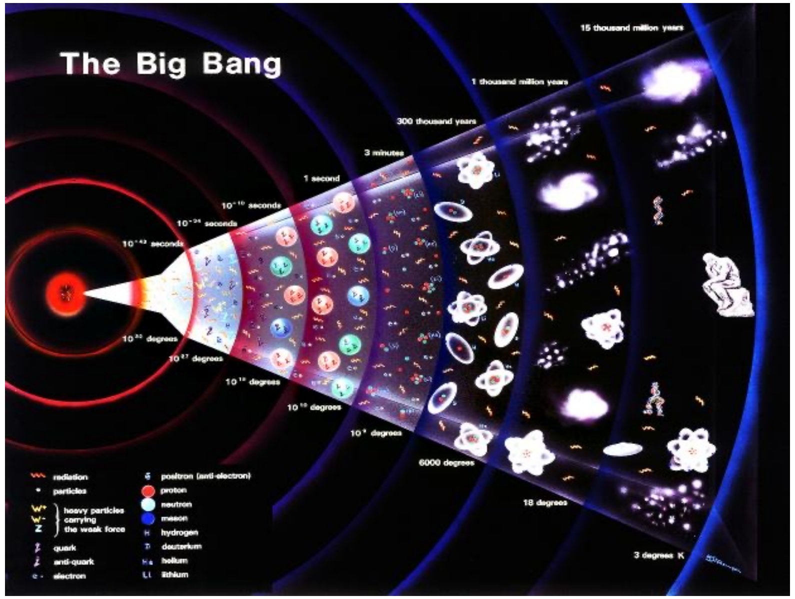
- 1992: Expression of interest
- 1997: ALICE approval
- 2000 – 2007: construction
- 2002 – early 2008: Installation
- 2009 – 2018: physics campaign

The ALICE Scientific Mission

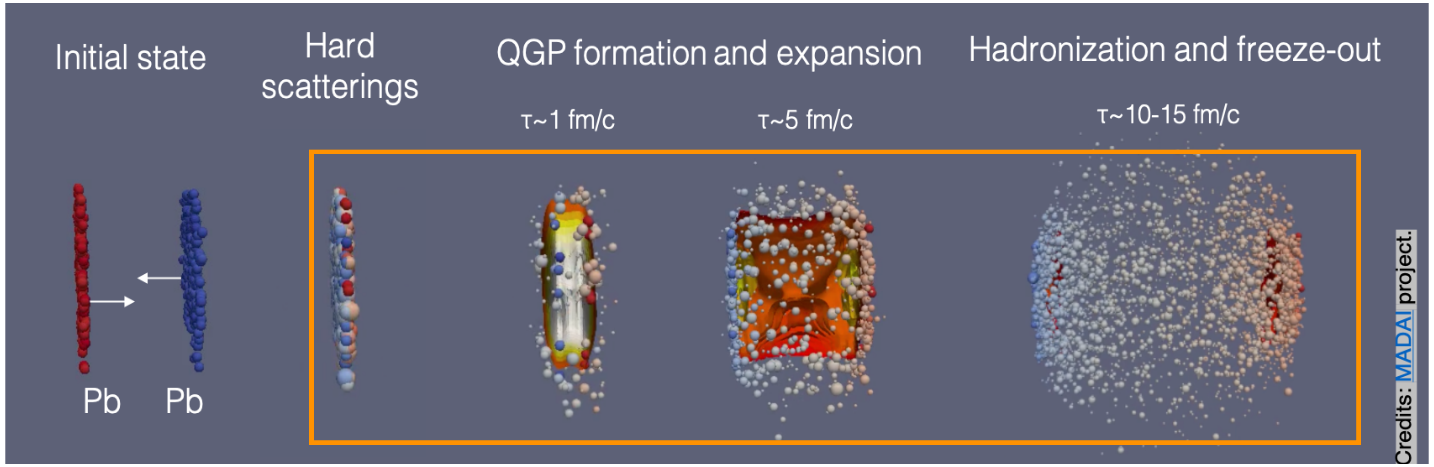
Characterize the physical properties of the **Quark-Gluon Plasma (QGP),** a **state of strongly-interacting** (colored) **matter** formed at extremely high energy densities

➩ in the collisions of heavy ions at the LHC, temperature O(10^{12} K): 10^5 x T at centre of Sun

➩ in the Universe O(1-10 μs) after the Big Bang



The mini Big Bang: a hot fireball generated by nuclear collision at the LHC

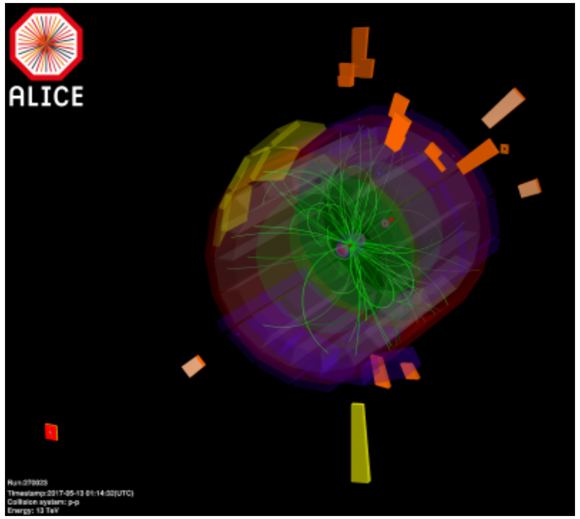


1 fm/c = 3×10^{-24} s, 1 MeV ~ 10^{10} K

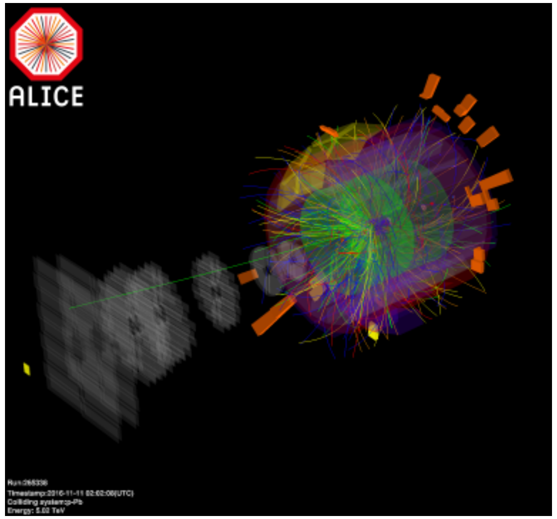
Heavy Ion Collisions at the LHC

- The LHC collides most of the time protons on protons
- Approximately one month of running time is dedicated to heavy-ions each year (primarily Pb ions)

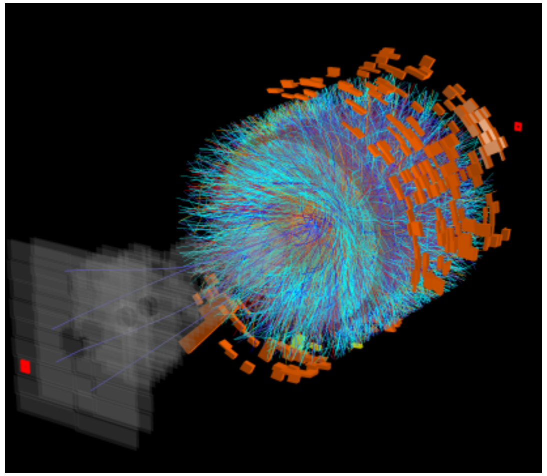
pp



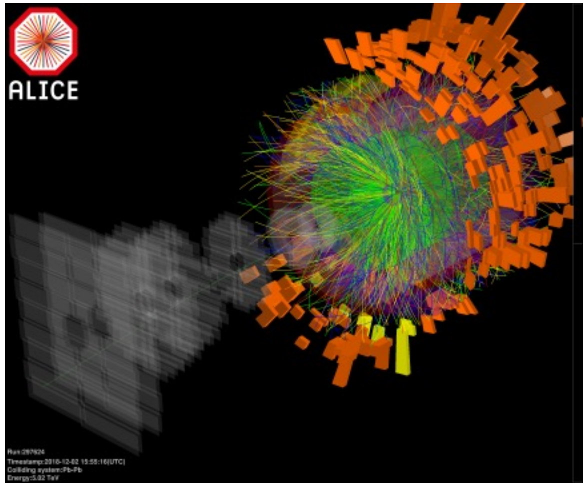
p-Pb



Xe-Xe



Pb-Pb



Pb-Pb collisions at the LHC

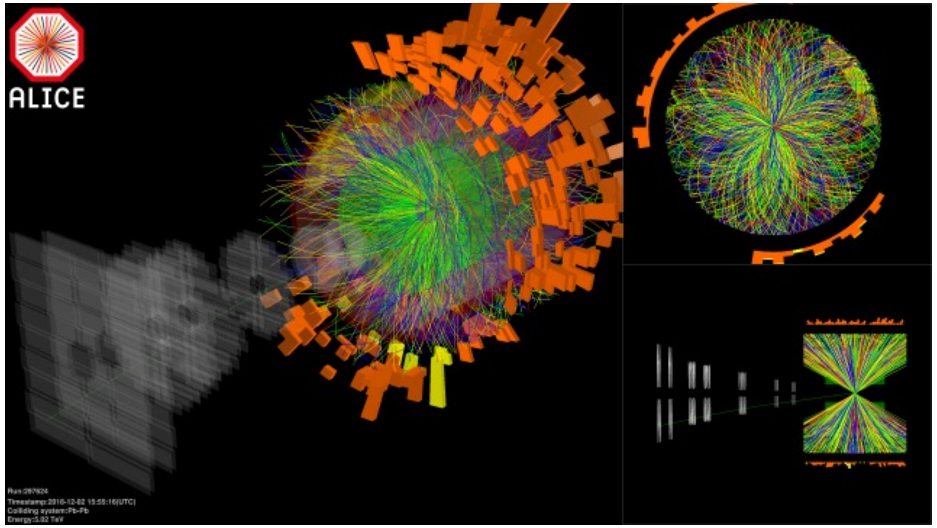
Energy per nucleon in a ${}^{208}_{82}$Pb-Pb collision at the LHC (**Run 2**)

- beam energy in pp E_{beam} = 6.5 TeV
- pp collision energy √s = 13 TeV
- Beam energy per nucleon in a Pb nucleus
  $E_{beam,PbPb}$ = 82/208 * 6.37 TeV = **2.51 TeV**
- Collision energy per nucleon in
  Pb-Pb: $\sqrt{s_{NN}}$ = **5.02 TeV**

- Total collision energy in Pb-Pb:
  √s = 1.04 PeV

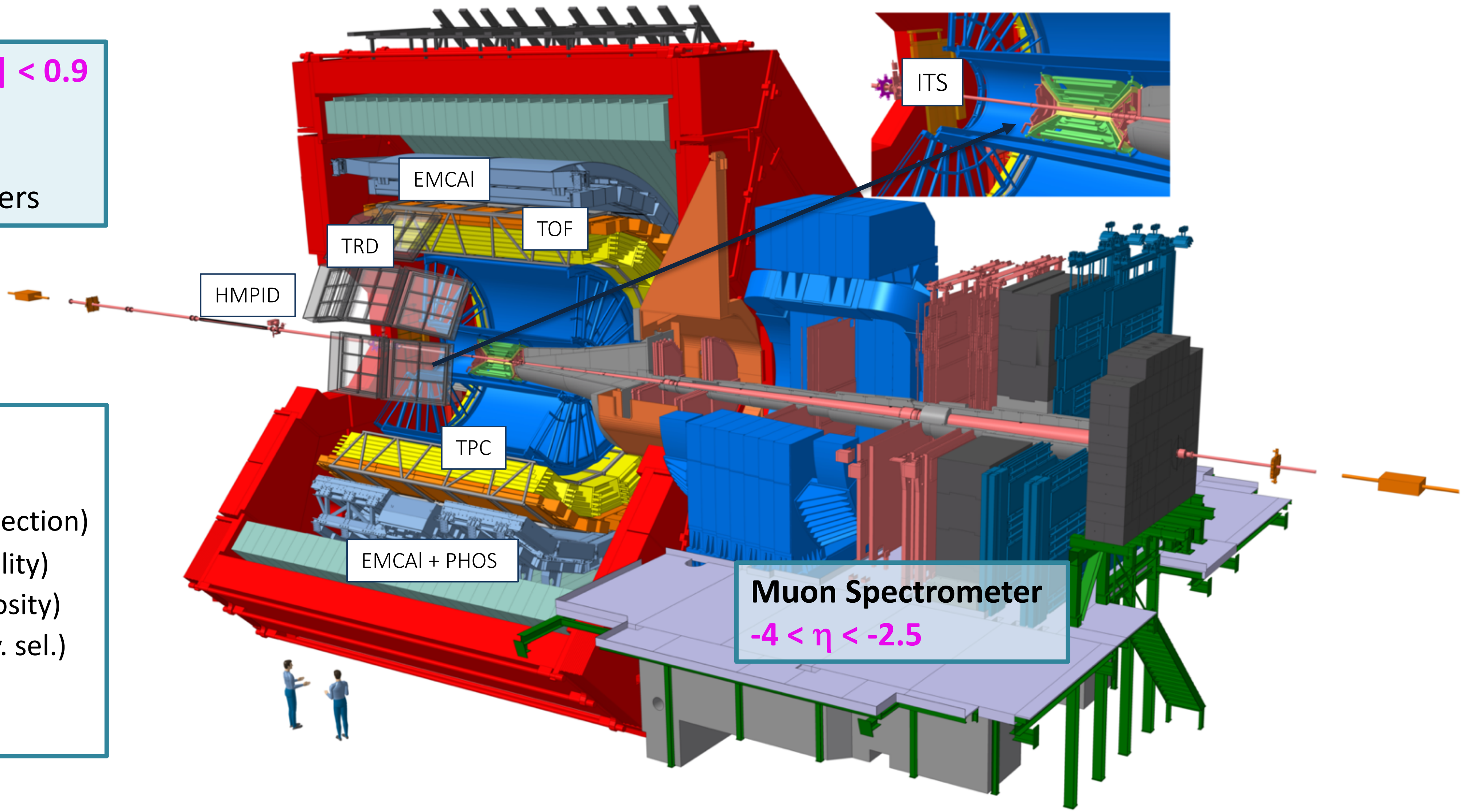
⇨ What can we learn from these massive interactions?

$$\sqrt{s_{\mathrm{NN}}} \approx 2c\,p_p\sqrt{\frac{Z_1 Z_2}{A_1 A_2}} \approx 2c\,p_p \begin{cases} 1 & \text{p-p} \\ 0.628 & \text{p-Pb} \\ 0.394 & \text{Pb-Pb} \end{cases}$$



The ALICE detector (version 1: Run 1 + Run 2)

Central Barrel **$|\eta| < 0.9$**
- Tracking
- PID
- EM-Calorimeters



Muon Spectrometer
$-4 < \eta < -2.5$

ACORDE (cosmics)

Forward detectors:
- AD (diffraction selection)
- V0 (trigger, centrality)
- V0 (timing, luminosity)
- ZDC (centrality, ev. sel.)
- FMD (N_{ch})
- PMD ($N\gamma$, Nch)

ALICE data taking and publications

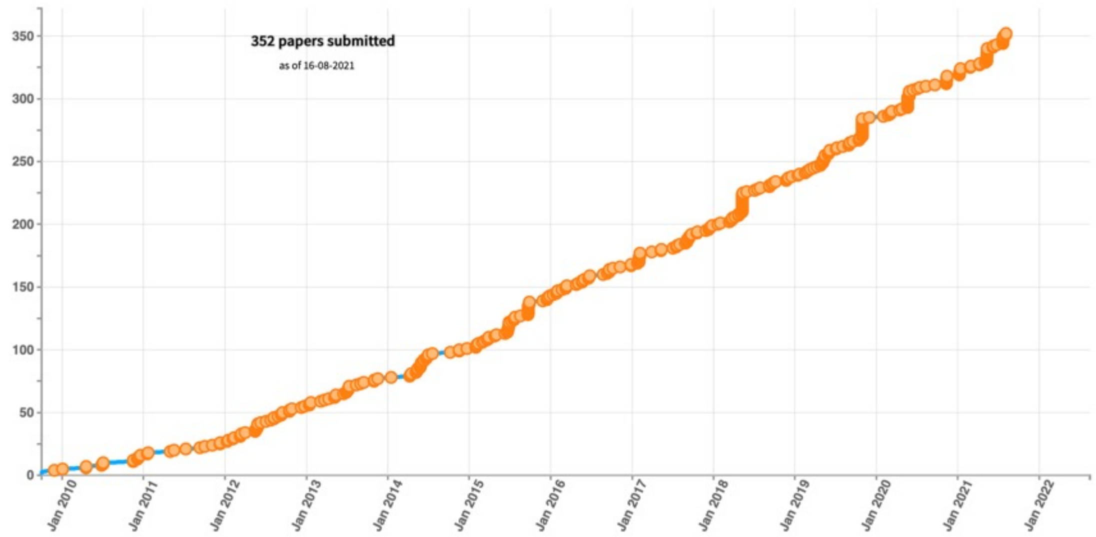
Run 1 (2009 – 2013) LS1 **Run 2** (2015 – 2018) **LS2** **Run 3** (2022 – 2024) LS3 **Run 4** (2027 – 2029)

← ALICE I → ← ALICE 2 →

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02	~75 μb^{-1} ~800 μb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13	~200 mb^{-1}, ~100 nb^{-1} ~1.5 pb^{-1}, ~2.5 pb^{-1} ~1.3 pb^{-1} ~36 pb^{-1}

Run 1 Run 2

352 ALICE papers on arXiv so far



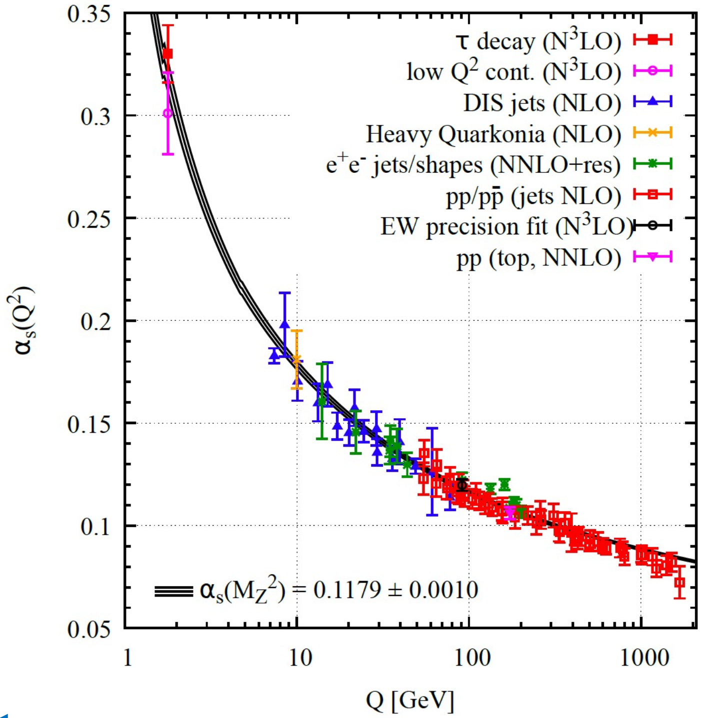
http://alice-publications.web.cern.ch/submitted

Strongly interacting (colored) matter

… a brief introduction

QGP: asymptotic state of QCD

Quark Gluon Plasma (QGP): at extreme temperatures and densities quarks and gluons behave quasi-free and are not localized to individual hadrons anymore



NB: free regime is reached only asymptotically!

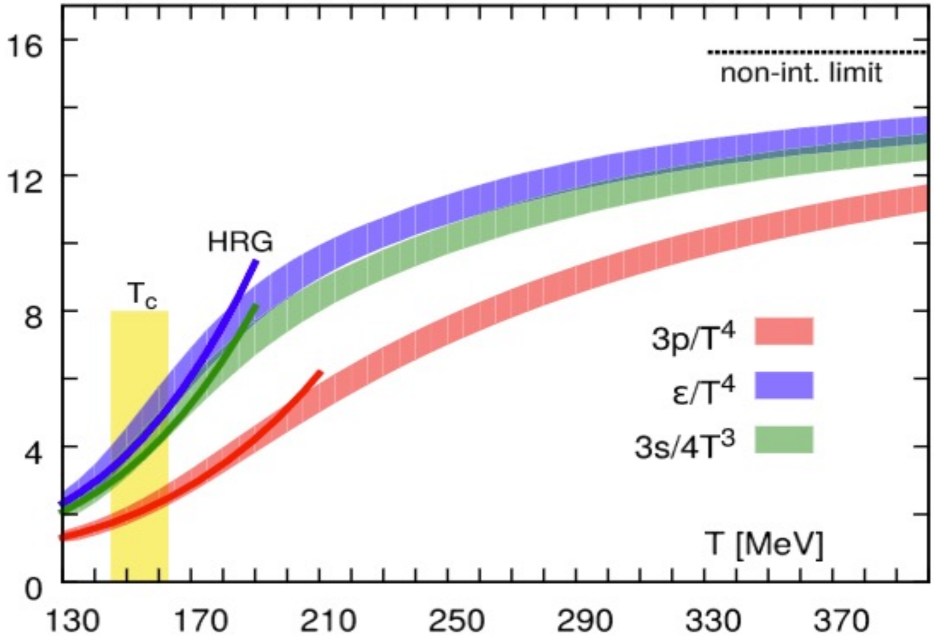
Confinement

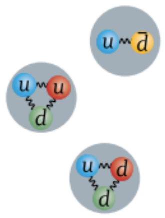
Asymptotic freedom

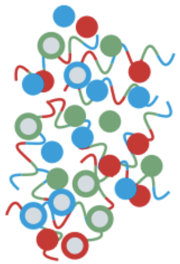
Where is the phase transition?

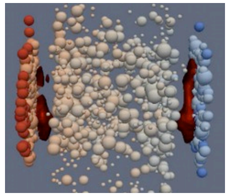
→ Lattice QCD

[PRD 90 094503 (2014)]

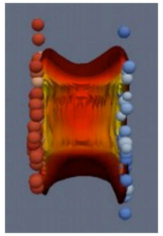








Hadron gas ← $\sim 10^{12}\ K$ → Quark Gluon Plasma



QGP in the laboratory: Pb-Pb collisions at the LHC

QGP can be formed by compressing large energy in a small volume

According to LQCD, the QGP is formed when

$$\varepsilon_c = (0.42 \pm 0.06)\ GeV/fm^3$$ critical energy

$$T_c = (156.5 \pm 1.5)\ MeV$$ critical temperature

For comparison
T=156 MeV ≙ $1.8 \cdot 10^{12}$ K
Sun core: $1.5 \cdot 10^7$ K
Sun surface: 5778 K

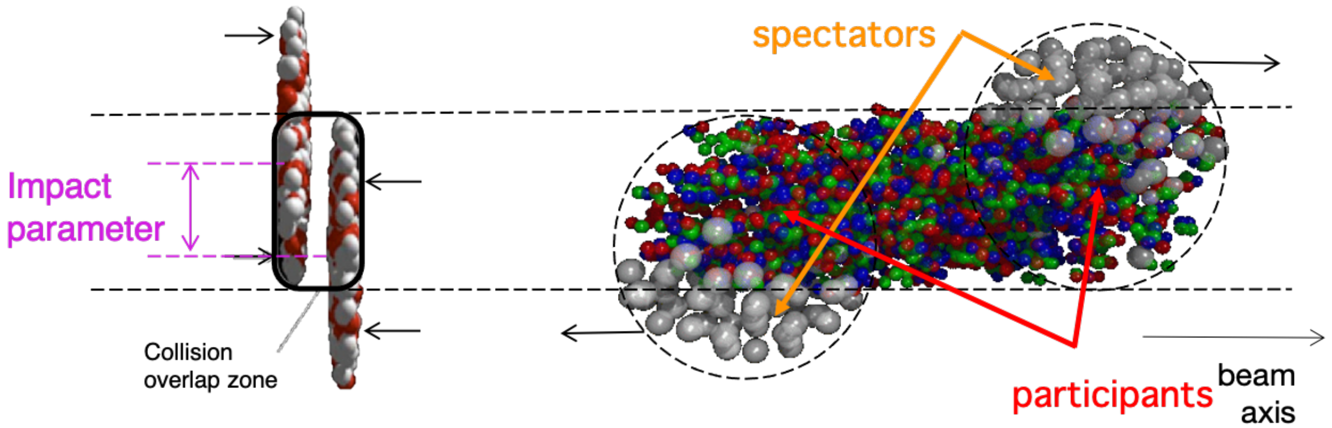
➪ Collide **heavy nuclei** (multiple, ~simulataneous, nucleon-nucleon collisions)

➪ **Control/vary the energy deposited** in the collision region by varying the collision system

- Impact parameter/centrality, nuclear species, p-Pb, pp
- Classify events based on final-state charged particle multiplicity

➪ **No direct observation** of the QGP is possible a rely on emerging particles as probes

Geometry of heavy-ion collisions



In the “lab frame” each incident nucleus is a **Lorentz-contracted disc**

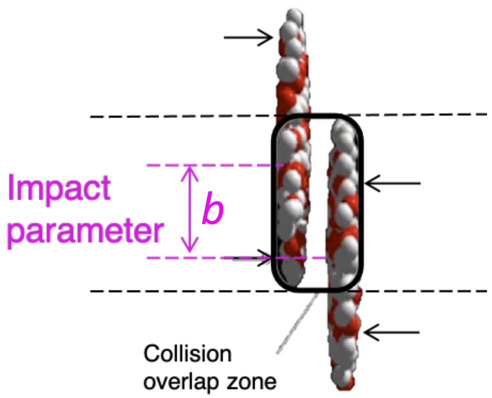
For large nuclei (e.g. Pb)

- disc diameter ~ **15 fm**
- thickness ~ **15/γ fm**
- γ = ~ 2500 @LHC (beam rapidity y=8.5)

Central collisions (e.g. 0-10%)
→ small impact parameter
→ many binary collisions
→ high particle multiplicity

Peripheral collisions (e.g. 70-80%)
→ large impact parameter
→ few binary collisions
→ low particle multiplicity

Centrality of heavy-ion collision



Impact parameter ***b*** not directly measurable

Centrality expressed in percentiles of total nucleus-nucleus cross-section corresponding to a particle multiplicity, or energy deposited, measured in ALICE

$$c \approx \frac{1}{\sigma_{AA}} \int_{N_{ch}^{THR}}^{\infty} \frac{d\sigma}{dN'_{ch}} dN'_{ch} \approx \frac{1}{\sigma_{AA}} \int_{0}^{E_{ZDC}^{THR}} \frac{d\sigma}{dE'_{ZDC}} dE'_{ZDC}.$$

$\sigma_{PbPb} = (7.67 \pm 0.16^{syst})\ b$

for Pb-Pb @ $\sqrt{S_{NN}} = 5.02\ TeV$

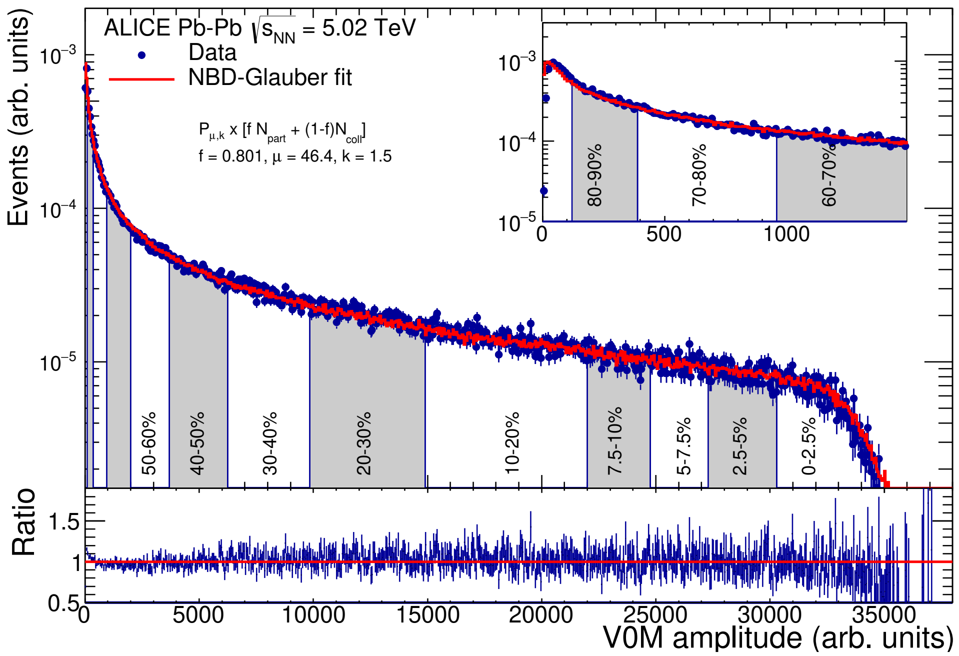
For example: sum of the **amplitudes in the ALICE V0 scintillators** →

Reproduced by **Glauber model** fit (red)

- Random relative position of nuclei in transverse plane
- Woods-Saxon distribution inside nucleus
- Simple particle production model (NBD)

⇨ $\langle N_{coll} \rangle, \langle N_{part} \rangle$ for each centrality class

ALICE-PUBLIC-2018-011



Energy density in the collision

The volume-averaged energy density can be estimated from the total produced transverse momentum

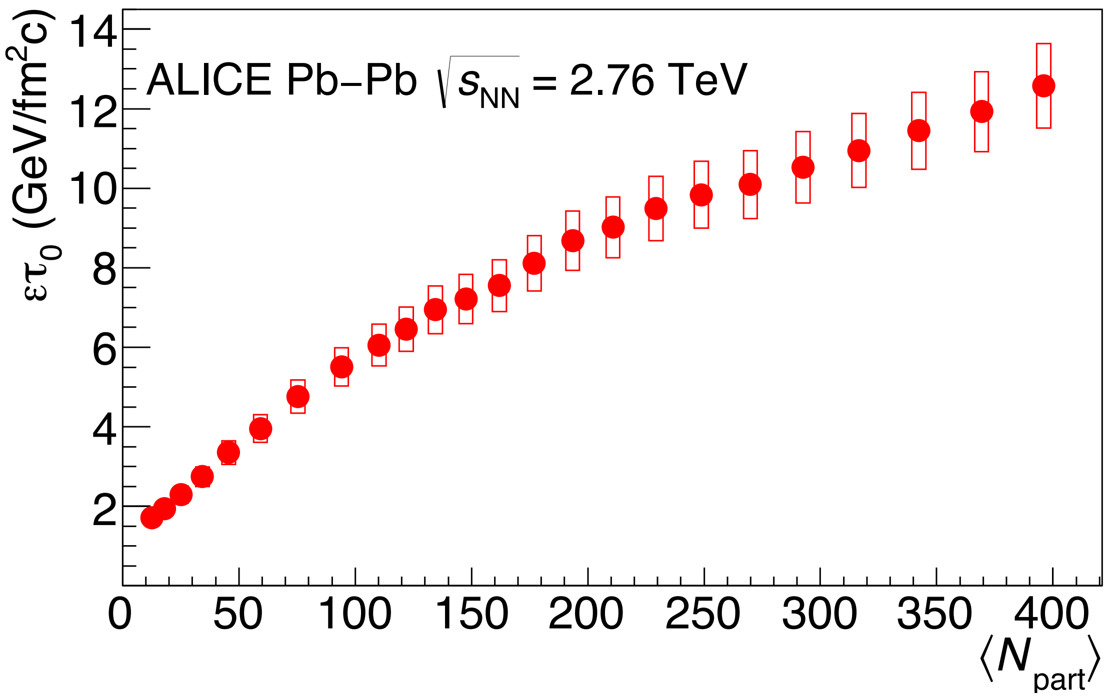
J. D. Bjorken
Phys. Rev. D **27**, 140

$$\varepsilon_{\mathrm{Bj}}(\tau) = \frac{1}{S_{\mathrm{T}}\tau}\frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}y}$$

$$E_{\mathrm{T}} = \sqrt{p_{\mathrm{T}}^2 + m^2}$$

S_T: transverse size of the interaction region at time τ

Phys. Rev. C **94**, 034903



Lower bound for “energy density” x “formation time”

$\varepsilon \equiv volume - averaged\ energy\ density$

$\tau_0 \equiv system\ formation\ time\ (model\ dependent)$

O(10) increase from peripheral to central Pb-Pb

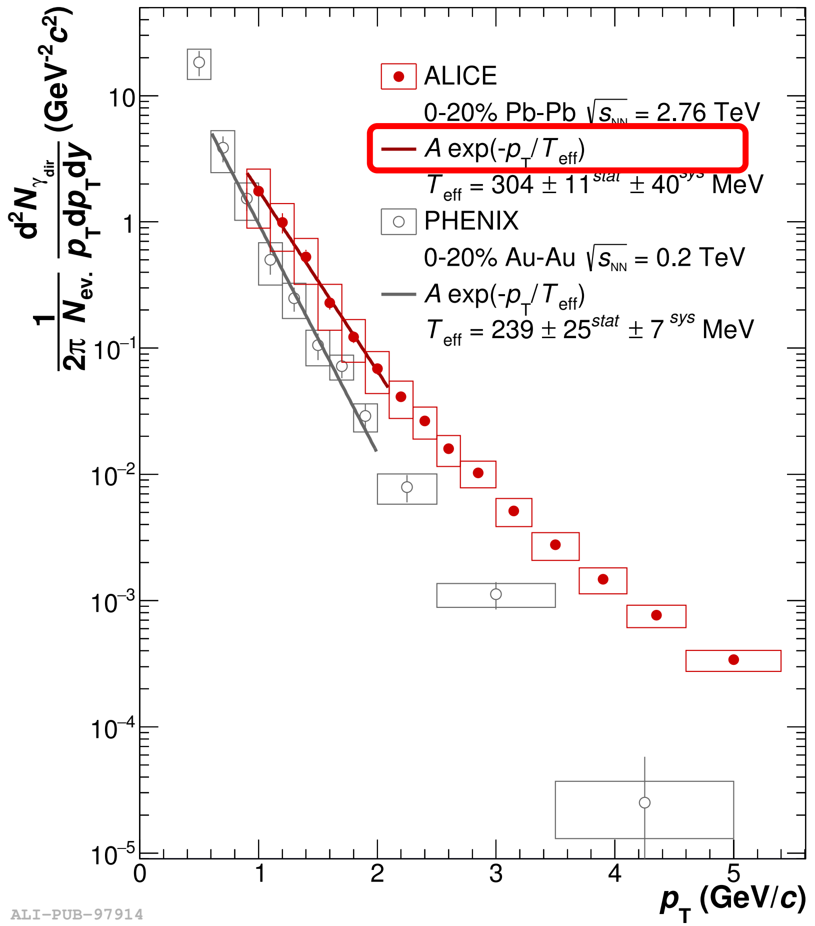
Assuming $\tau_0 = 1 fm/c$ → **$\varepsilon = 12.3 \pm 1\ GeV/fm^3$**

Spectra of direct photons in Pb-Pb collisions

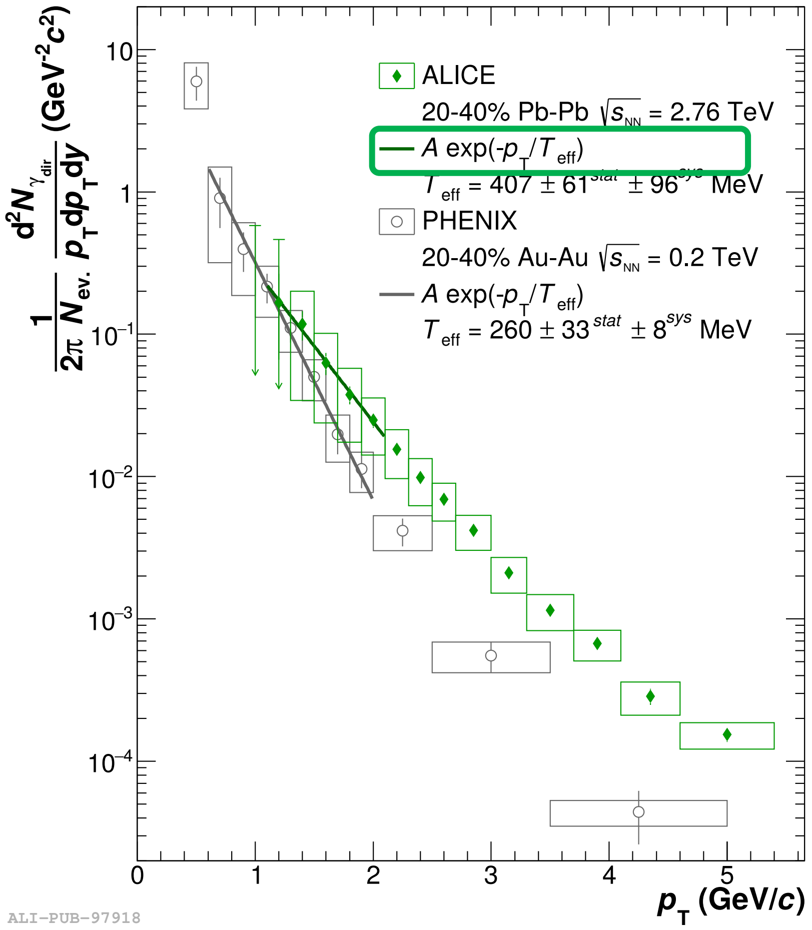
Effective temperature (T_{eff}) is extracted from the inverse logarithmic slope of the low-p_T region of the spectrum

$$d^2N_{\gamma_{dir}}/(p_T dp_T dy) \propto e^{-p_T/T_{eff}}$$

PLB 754 (2016) 235



PLB 754 (2016) 235



Harder photon spectra at LHC compared to RHIC

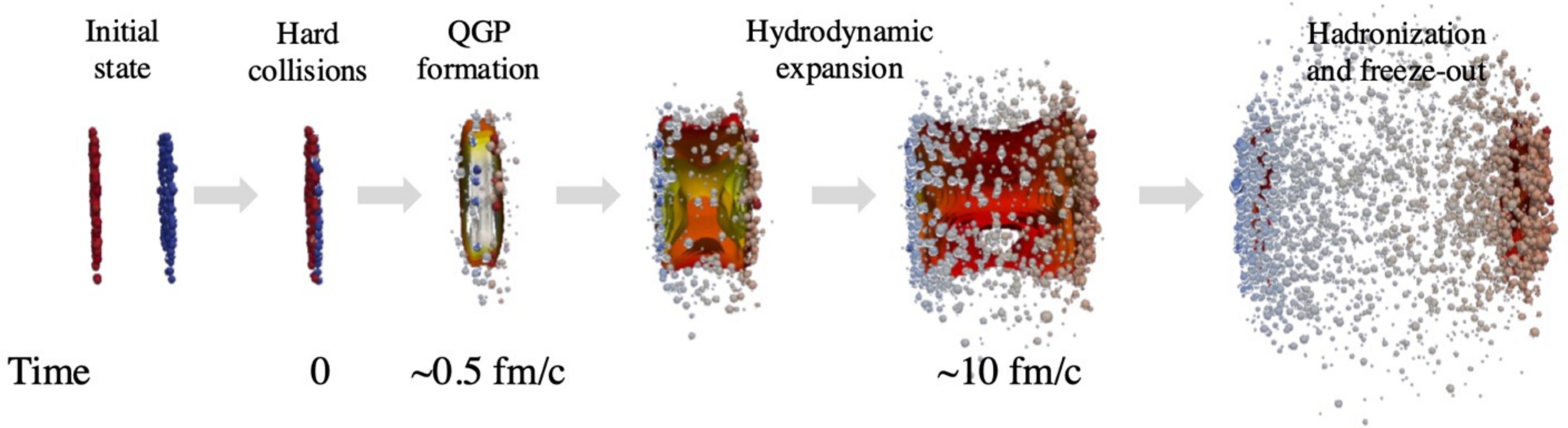
Increase temperature T_{eff} from RHIC to LHC

Intial temeprature of the fire ball can be obtained invoking model calculations that incorporate the evolution of the QGP medium as well as radial flow effects blue-shift the direct photon spectra

Not yet attempted

Characterization of the time evolution of the collision

LHC Pb-Pb ➪ **large energy density** (initial ε > 15 GeV/fm^3) & **large volume** (~5000 fm^3)



Visualization by J.E. Bernhard, arXiv:1804.06469

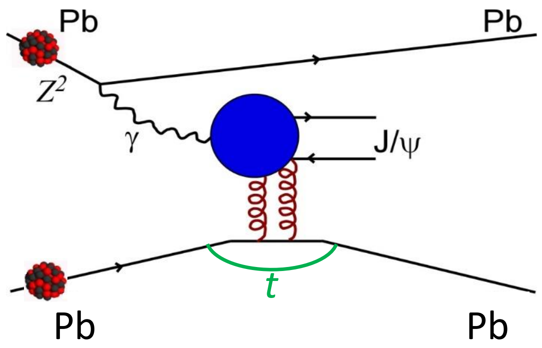
Study the time evolution of the collision

- Initial stage
- Macroscopic properties
- Colour deconfinement
- Parton interactions
- Expansion dynamics
- Hadronic phase

➪

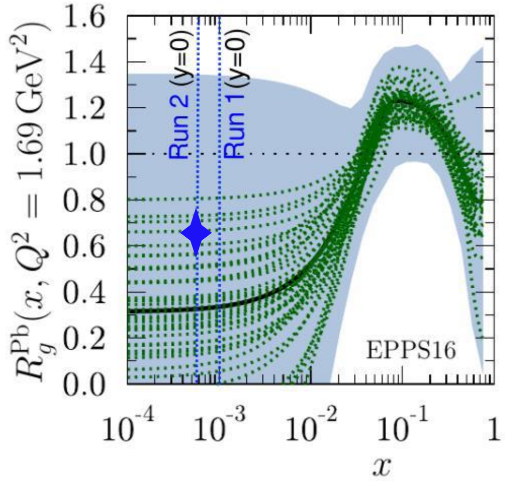
- Light flavour (including light-nuclei) production
- Heavy flavour production
- Quarkonia
- Photons, low-mass dileptons
- Jets
- Ultra Peripheral Collisions

Coherent J/ψ photoproduction in Pb-Pb ultra peripheral collisions



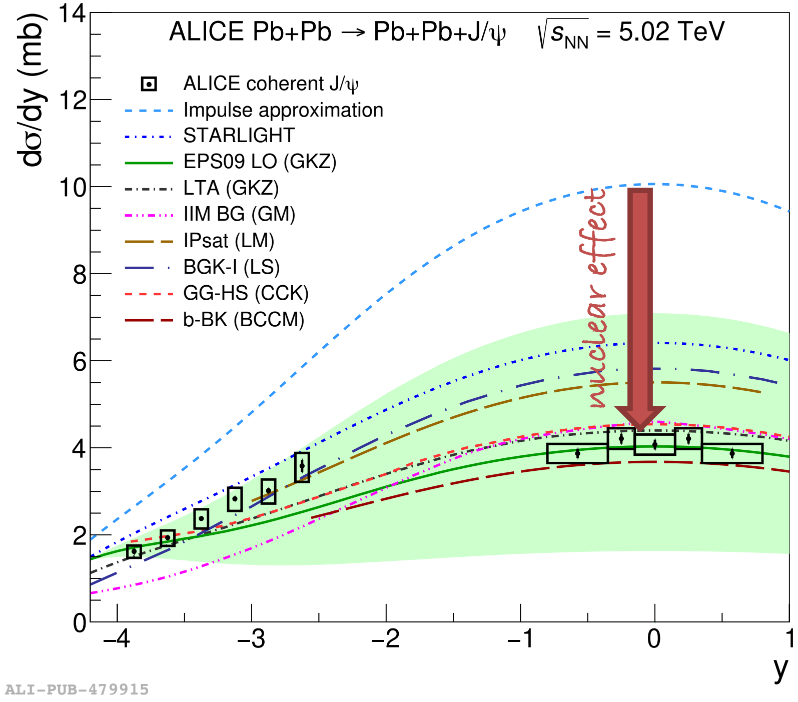
$$\left.\frac{d\sigma_{\gamma A\to J/\psi A}}{dt}\right|_{t=0} = \frac{M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{em}Q^8}\left[xg_A(x,Q^2)\right]^2$$

Eskola et. al., EPJC 77 (2017) 163

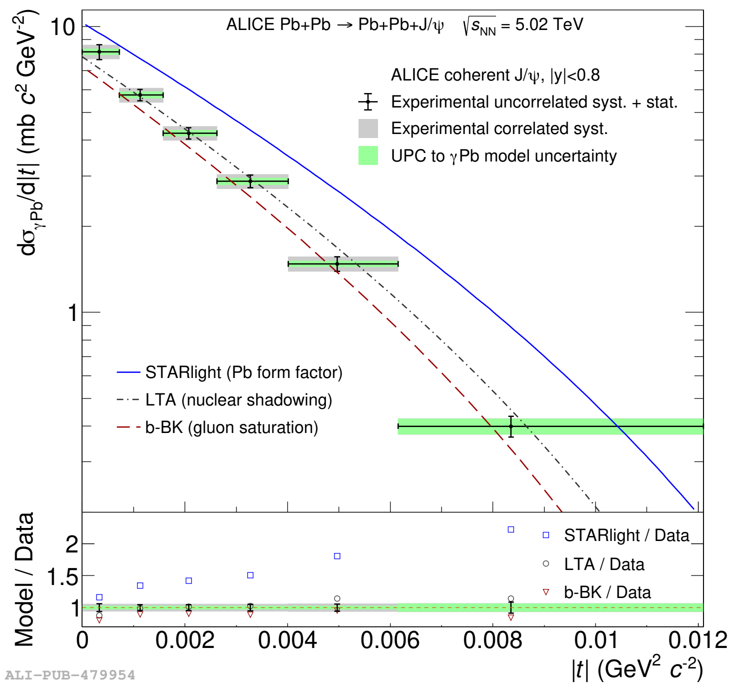


$$R_g^A(x,Q^2) = \frac{g_A(x,Q^2)}{Ag_p(x,Q^2)}$$

arXiv:2101.04577



arXiv:2101.04623

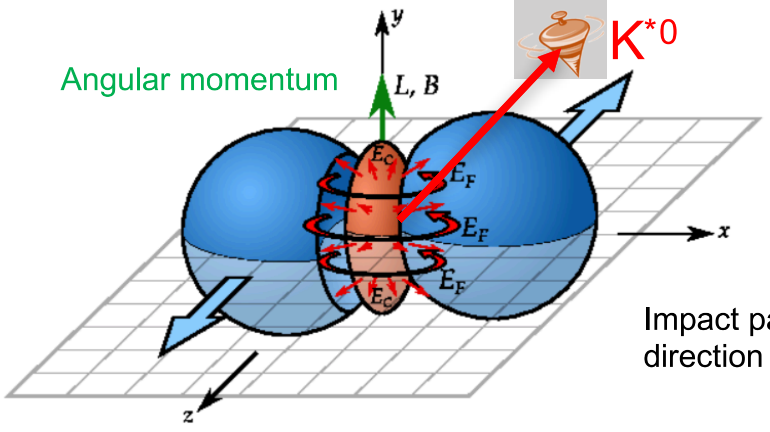


$|t| \approx p_T^2$

New measurment probing low-x gluon nuclear PDFs

- Comparison with the impulse approximation (no nuclear effects) allows for extraction of the gluon shadowing factor: **$R_g \sim 0.65$ at $x \sim 10^{-3}$**
- **First measurement** of t-dependence: sensitive to transverse gluon distribution

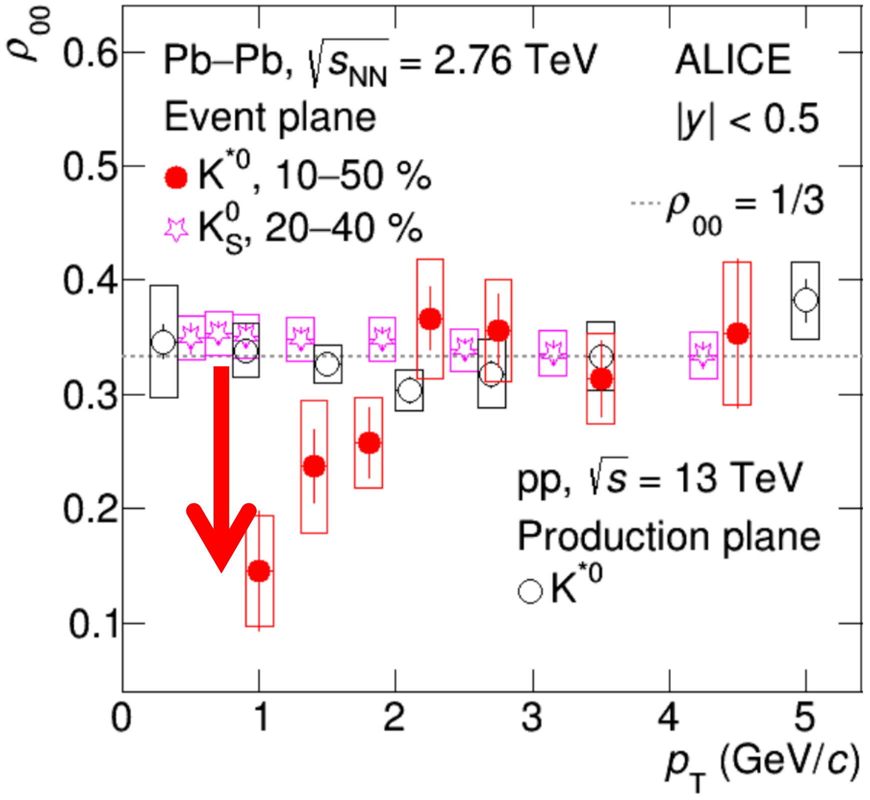
Spin alignment of vector mesons in rotating QGP



PRL 125 (2020) 012301

EDITORS' SUGGESTION

Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions



- Large angular momentum **L** in non-central collisions → **rotating QGP** (~ **10^{21}** revolutions per second)
- spin-orbit interactions expected to polarize quarks
- If quarks recombine to produce vector mesons (spin=1), **spin alignment** could appear
- Measurement using **K^{*0}** → **Kπ** decays shows a **3σ effect** at low momentum (Run 1 data)
- **Confirmed with higher significance** with preliminary measurement with Run 2 data

The nuclear modification factor R_{AA}

AA collision (e.g. Pb-Pb): many NN (binary) collisions

$$dN_{AA}/dp_T = N_{coll} \times dN_{pp}/dp_T$$

Without *nuclear effects* (interaction with the QCD medium), AA collision would be just the superposition of independent NN collisions with incoherent fragmentation

RAA = 1 at high p_T

→ the medium is transparent to the passage of partons

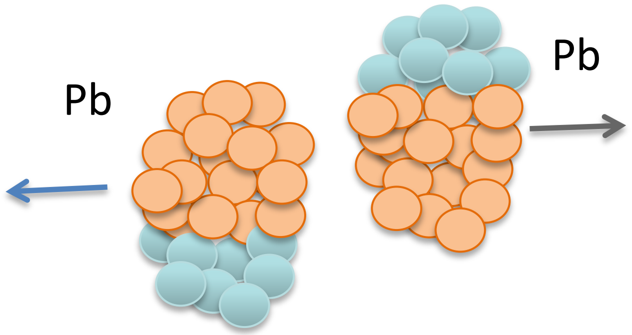
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll}\rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

If RAA < 1 at high pT

→ The medium is opaque to the passage of partons

→ parton-medium final state interaction

→ Energy loss, modification of FFs in the strongly interacting QGP



NB: at lower p_T, soft, non perturbative regime **R_{AA} not a good observable**

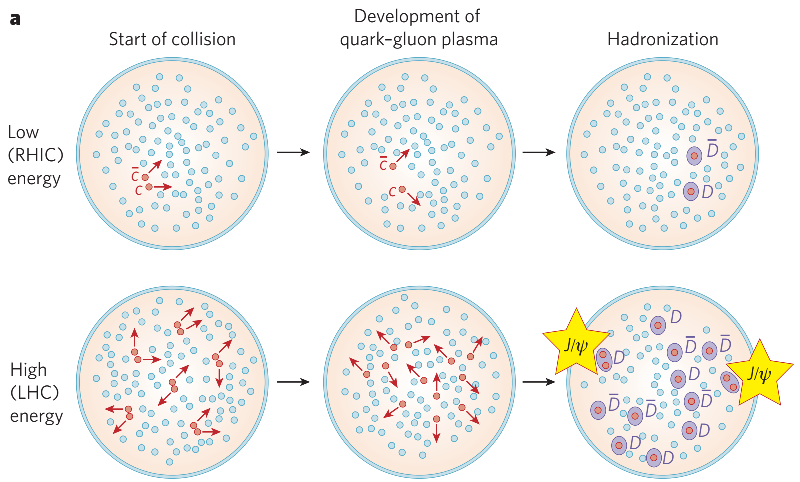
Quarkonia at the LHC

Suppression of quarkonium as QGP signature

→ $q\bar{q}$ pairs are suppressed due to **color screening in the QGP**

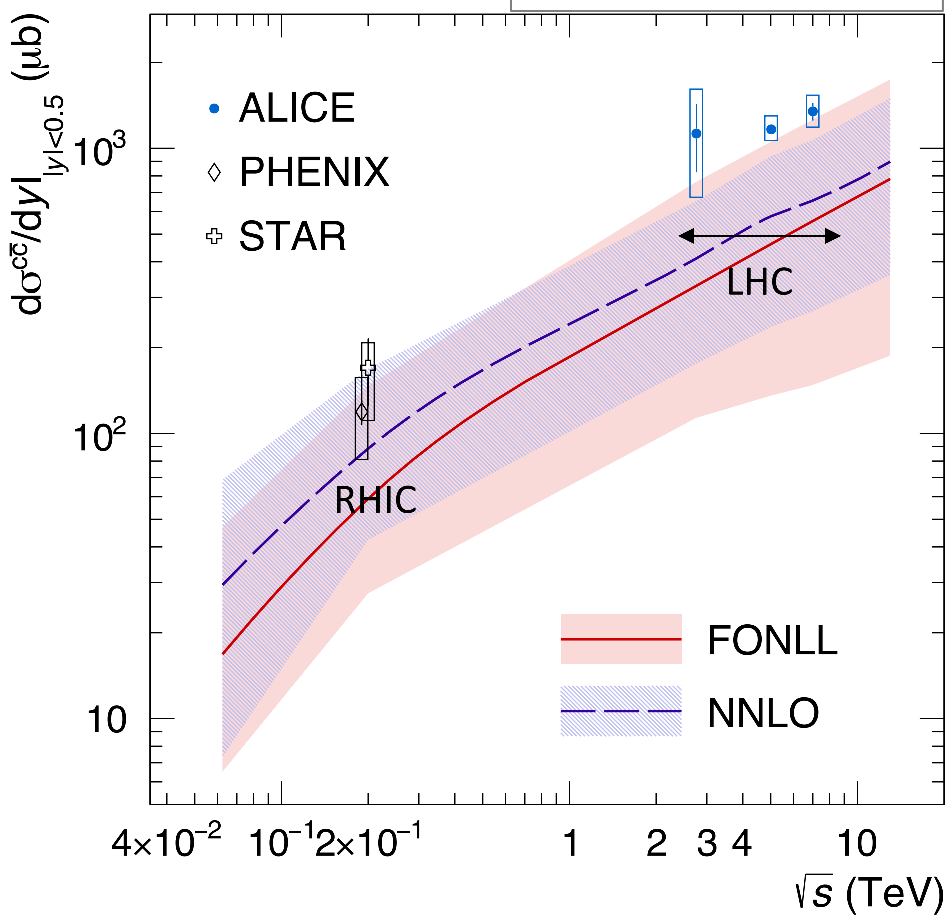
→ lattice QCD predicts the effective $q\bar{q}$ coupling to decrease in medium with increasing T

$c\bar{c}$ cross-section increase with $\sqrt{s}$:
$\sim$100 $c\bar{c}$ per central Pb-Pb event at the LHC vs $\sim$10 $c\bar{c}$ at RHIC
→ **(re)generation of charmonium** and charmed hadron production takes place at the phase boundary or in QGP



cartoon from:
P. Braun-Munzinger, J. Stachel
[Nature 448, 302–309(2007)]

charm cross-section



J/ψ dissociation and (re)generation at the LHC

recombination picture confimred by LHC data ➪ signature of de-confinement

R_{AA}(LHC) > R_{AA} (RHIC)

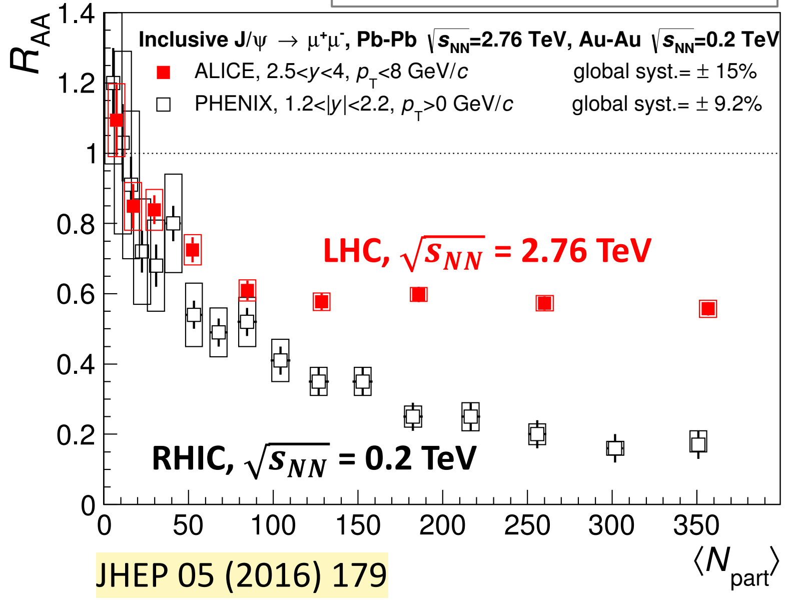
- cc regeneration counterbalances the suppression by screening in the QGP

R_{AA}(mid-rapidity) > R_{AA}(forward rapidity)

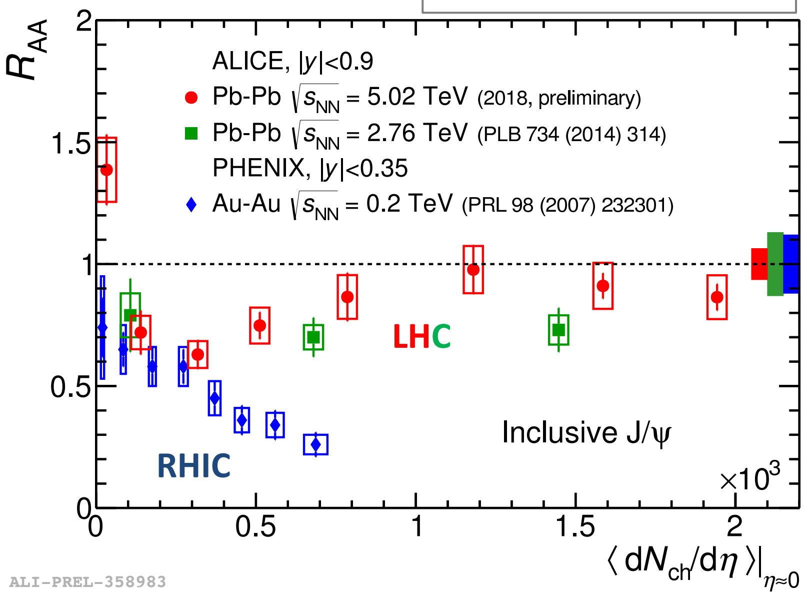
- At low p_T, modification decreases from **forward** to **central** rapidity
- reflects rapidity dependence of the cc cross-section (➪ regeneration probability)

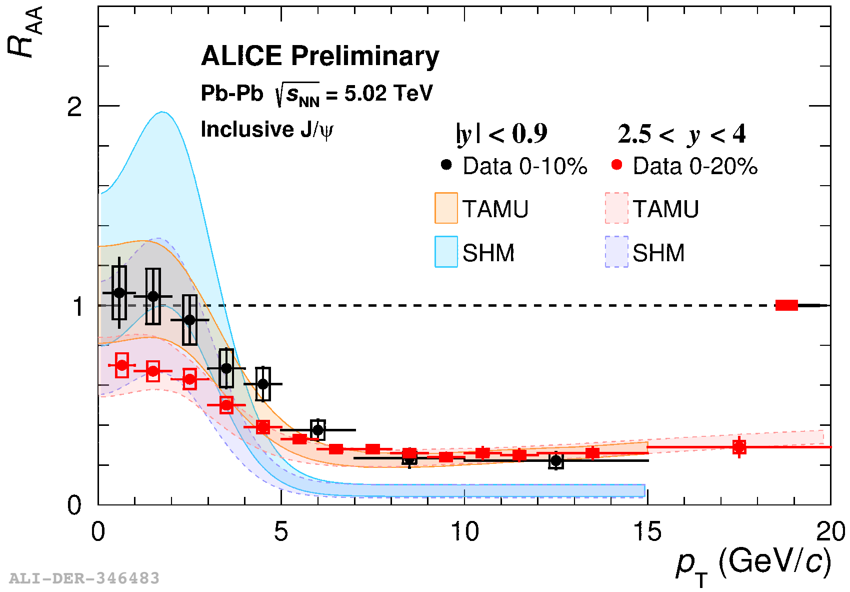
J/ψ at forward rapidity

J/ψ at mid rapidity

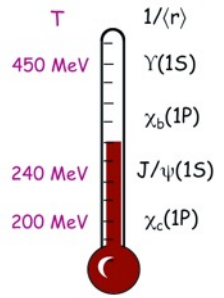


JHEP 05 (2016) 179





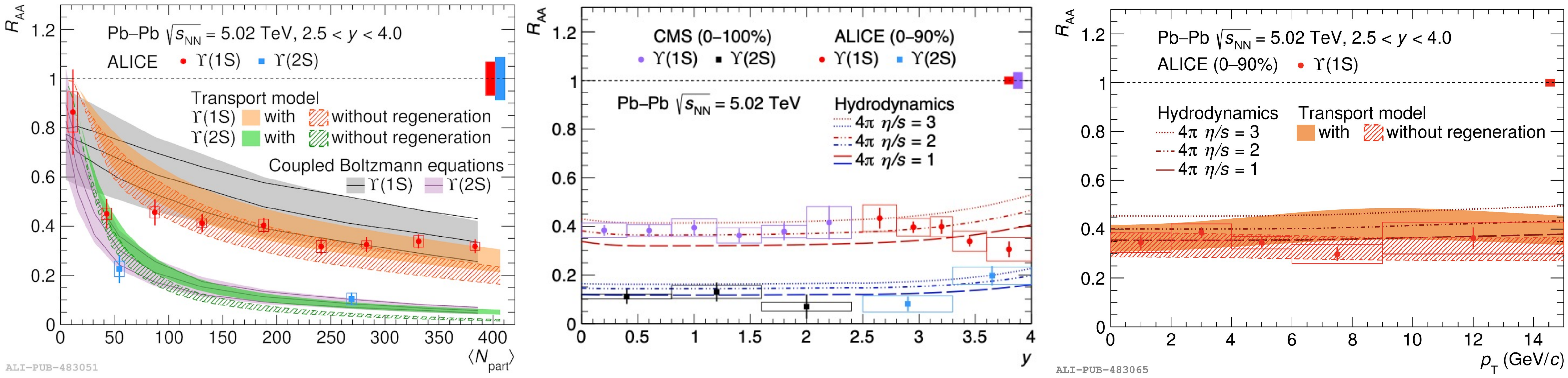
Suppression of bottomonia in Pb-Pb collisions



Varying the binding energy: ψ(2S) < Υ(2S) < J/ψ < Υ(1S)

0.05 0.55 0.65 1.1 GeV

arXiv:2011.05758



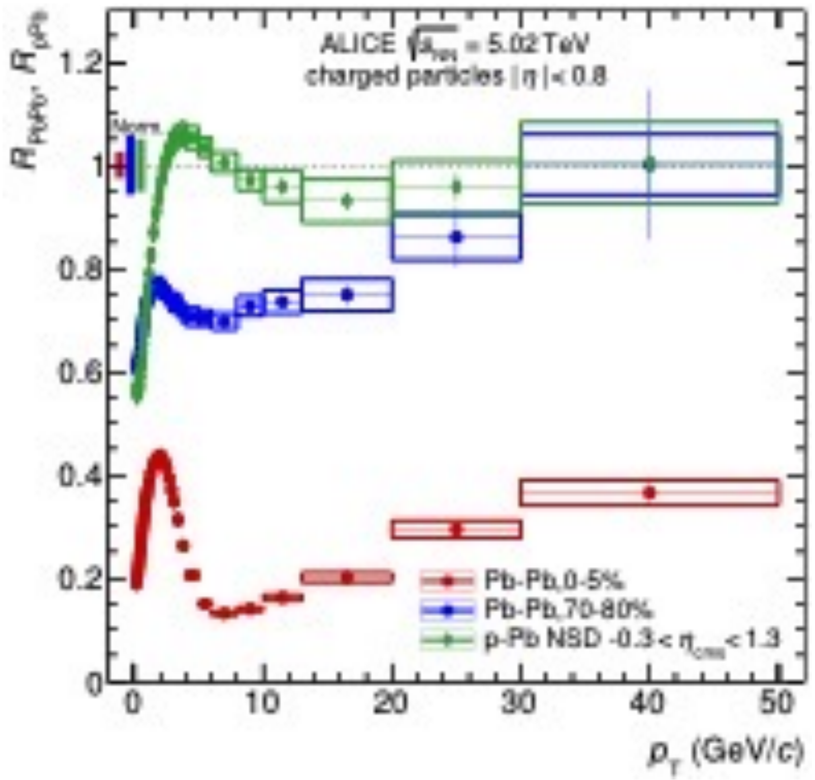
- Centrality dependence consistent with progressive suppression in a hotter medium
- Υ(2S) at forward rapidity - a suppression stronger wrt Υ(1S) consistent with lower binding energy
- Screening induces a strong suppression of Υ production, flat vs p_T ⇨ recombination effects small

The nuclear modification factor R_{AA}

High precision measurements in a broad p_T range and vs centrality

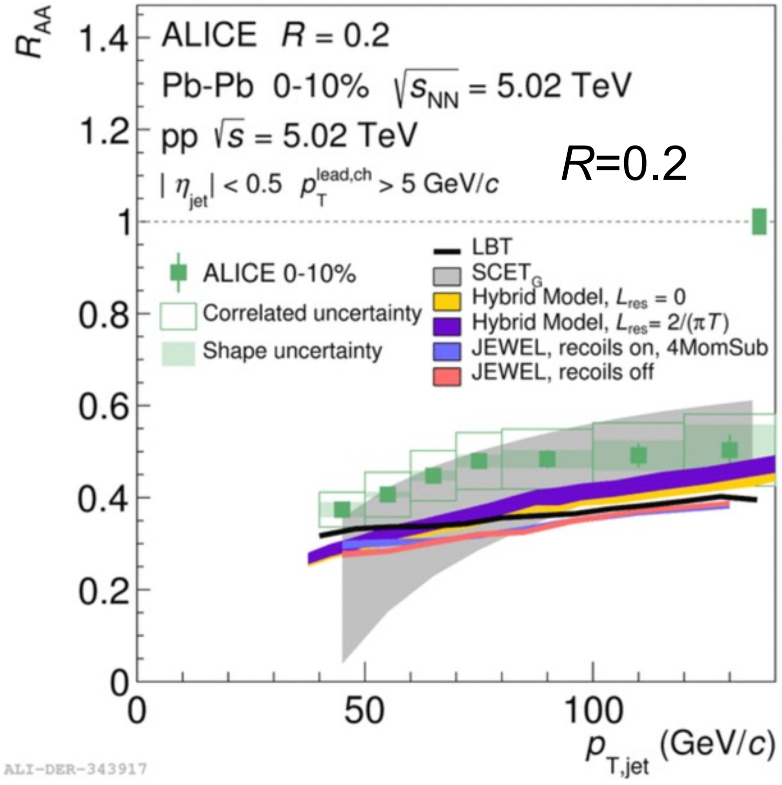
Strong suppression observed in central heavy-ion collisions up to very high p_T

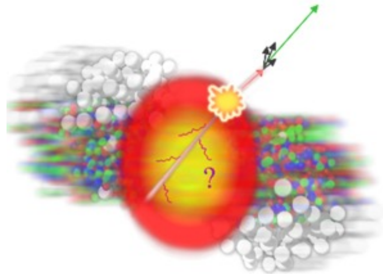
⇨ **suppression due to parton energy loss**

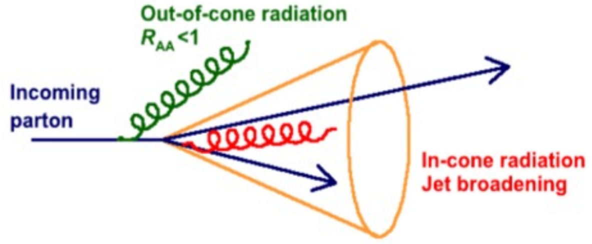


PRC 101 (2020) 3, 034911

with area-based background subtraction







Large reduction of jet yields down to 40 GeV/c

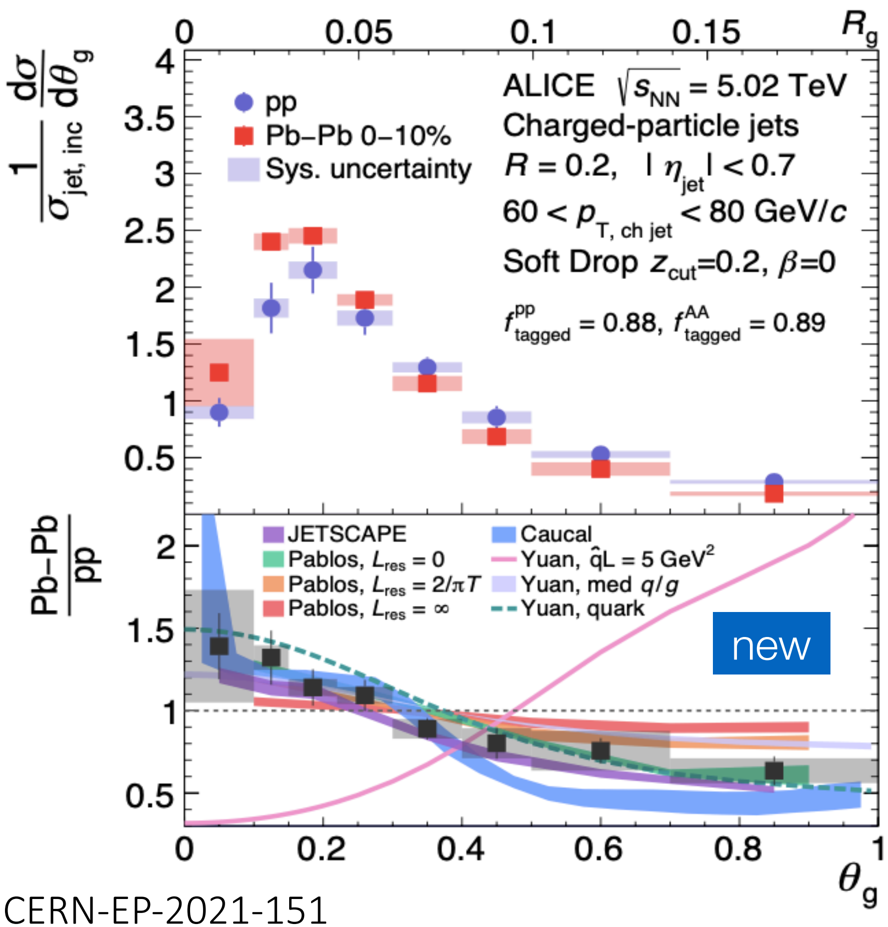
Lost energy not recovered within the jet “cone” (similar suppression for R = 04)

→ large angle QGP-induced gluon emission

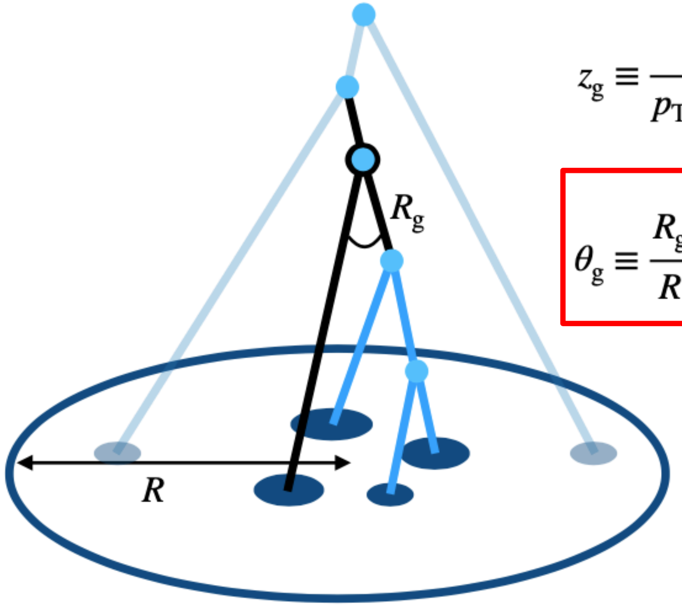
Exploring the QGP with jets

Study medium-modified parton shower

e.g.: grooming: find first hard splitting (Soft Drop)



CERN-EP-2021-151

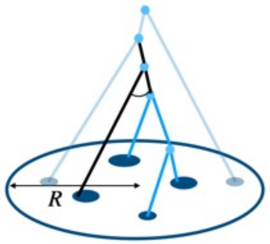


$$z_g \equiv \frac{p_{T,subleading}}{p_{T,leading} + p_{T,subleading}}$$

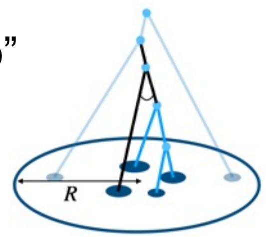
$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

⇨ Jet core is more collimated in Pb-Pb than in pp

Cartoon: “pp”

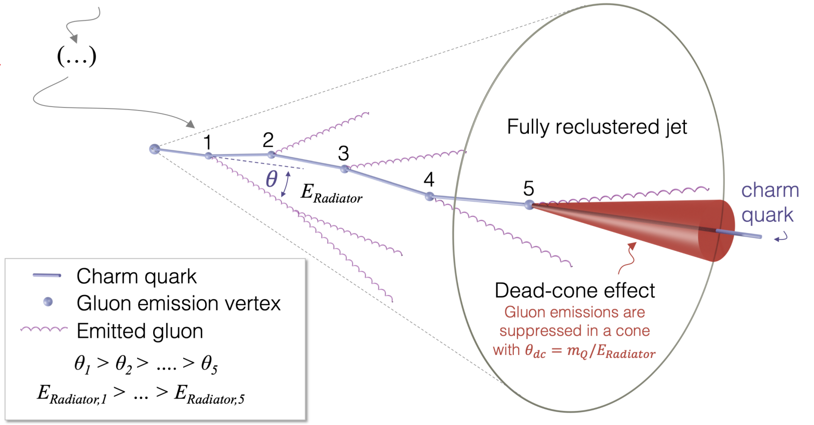


“Pb-Pb”



QCD interlude: dead-cone effect now 'seen' in pp

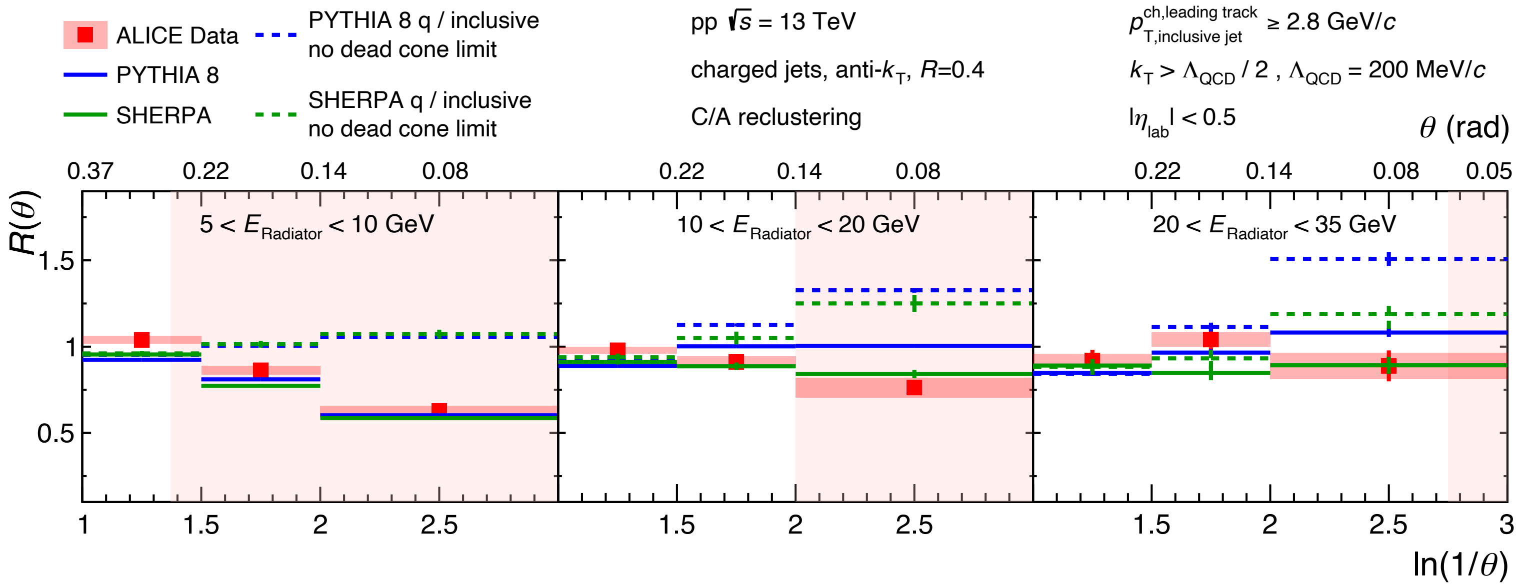
by measuring D^0-meson tagged jets in hadronic collisions (pp 13 TeV)



Follow a heavy quark through the primary Lund Plane & suppress hadronization effects/non pert. (at small K_T)

Ratio of the splitting angle (θ) distributions for D^0-meson tagged jets and inclusive jets, in bins of $E_{radiator}$

$$R(\theta) = \frac{1}{N^{D^0\,\text{jets}}} \frac{dn^{D^0\,\text{jets}}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{\text{inclusive jets}}} \frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)} \Bigg|_{k_T, E_{\text{Radiator}}}$$



Radiation suppressed in the expected angular region (shaded)

Suppression lifted as $mass_Q << E_{radiator}$

arXiv: 2106.05713 [nucl-ex]

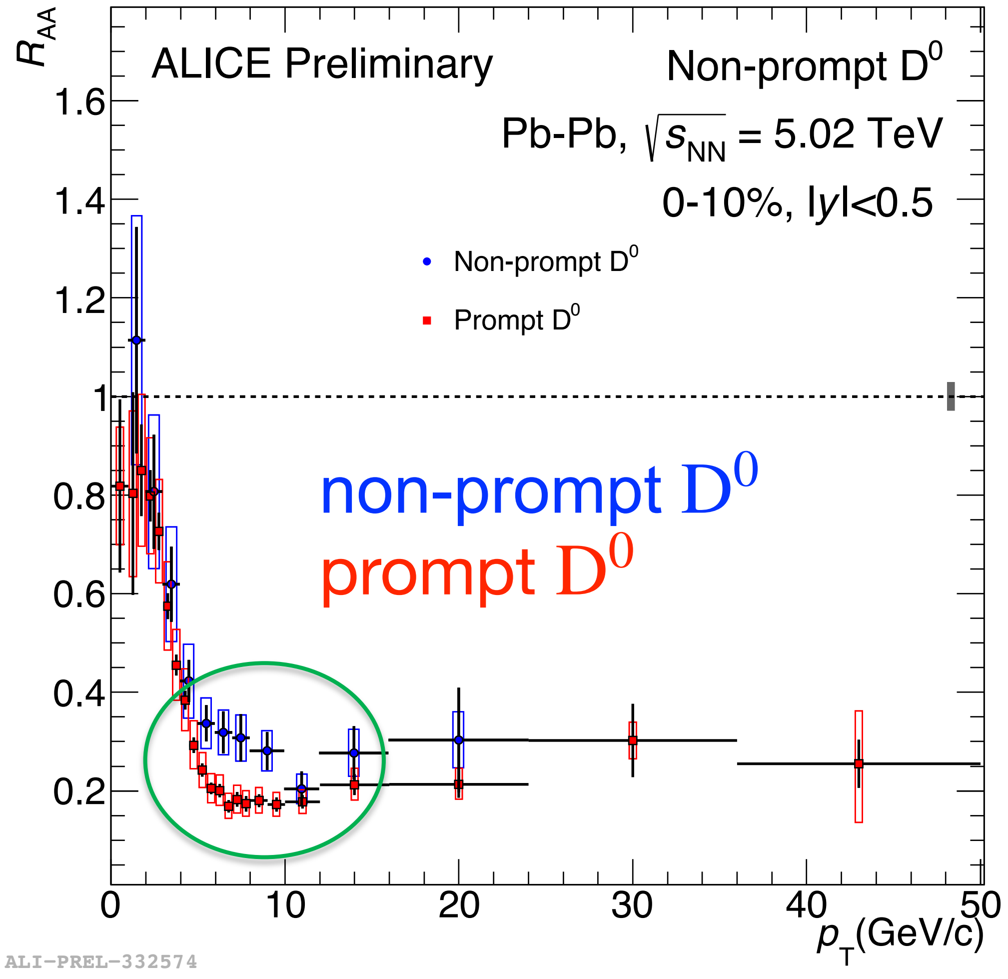
Energy loss of c and b quarks in the QGP

Less suppression for (non-prompt) D mesons from B decays than prompt D mesons

- Quarks and gluons lose energy while traversing the QGP (**R_{AA} < 1**)
- Energy loss predicted to depend on QGP density, but also on quark mass
- "Dead cone effect" reduces gluon radiation for high-mass quarks

radiation suppressed for $\theta_C < m_Q/E$

- Also note: first measurement of D meson production down to zero p_T in Pb-Pb
- More precise measurement with new ITS in Run 3



Hydrodynamic expansion - flow

Flow picture: a collective motion of particles superimposed to the thermal motion

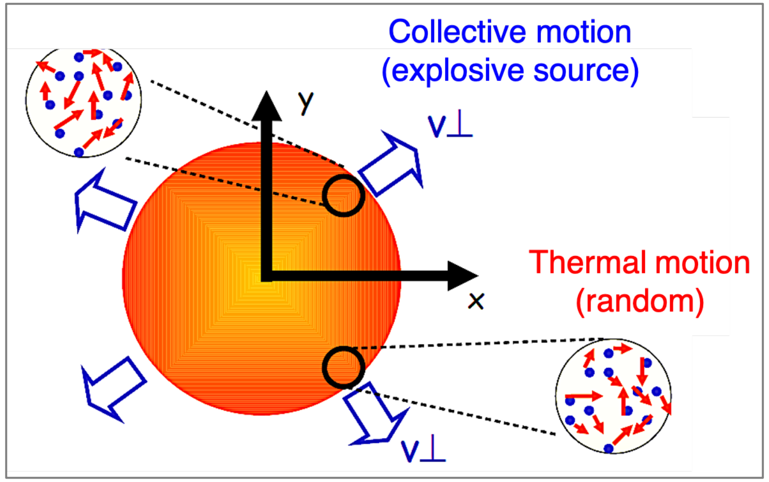
Isotropic Radial flow is a natural consequence of any interacting system expanding into the vacuum under a common velocity field

- Affects transverse momentum distributions of hadrons, particle rations, …

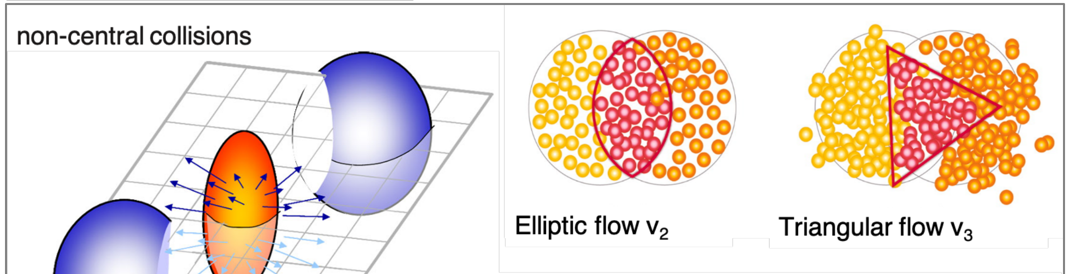
Anisotropic flow:
Pressure gradients convert spatial anisotropy into observable **momentum anisotropies**

- Anisotropy in azimuthal angle described by Fourier series
- Stronger in non-central collisions
- v_n describes how initial fluctuations propagate in a viscous fluid

Isotropic Radial Flow

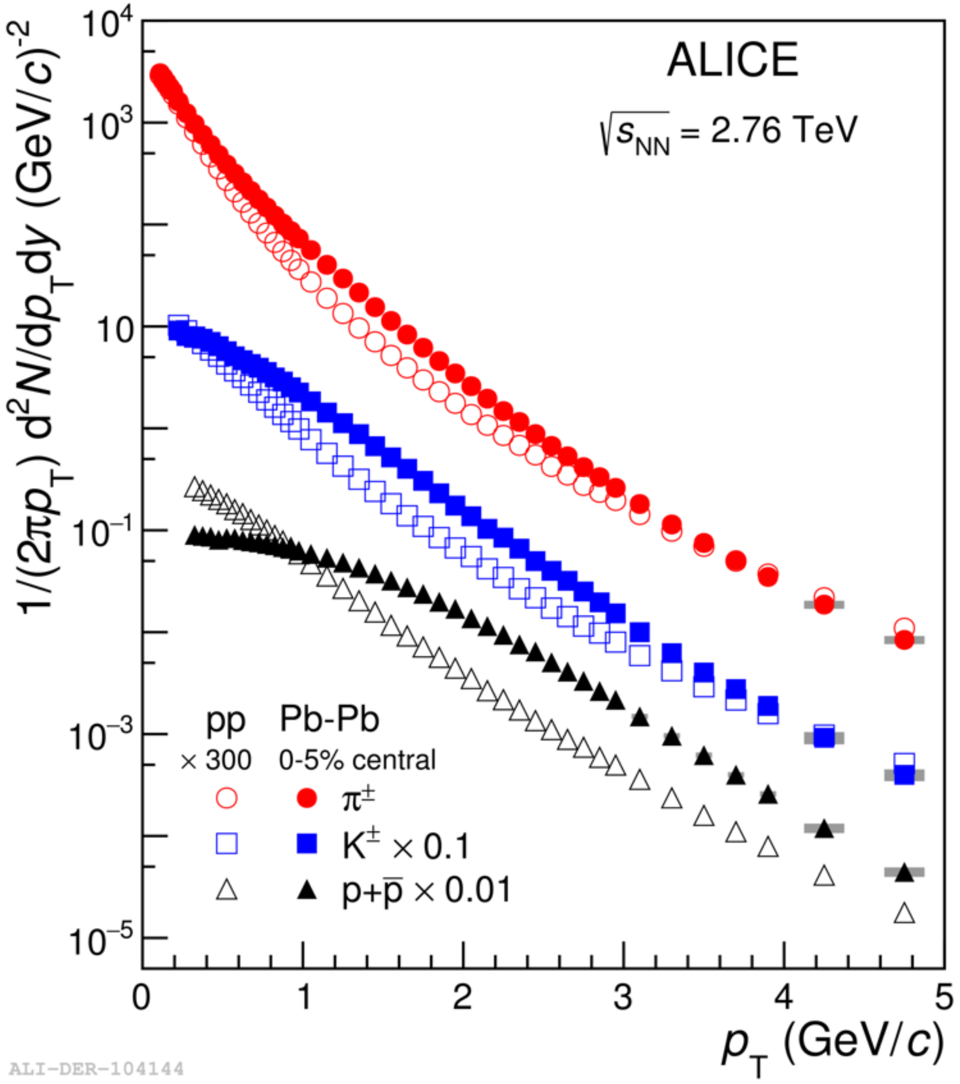


Anisotropic flow



$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

Radial flow in AA collisions



Radial hydrodynamic expansion leads to a modification of the spectral shape ➪ **mass dependent *boost***

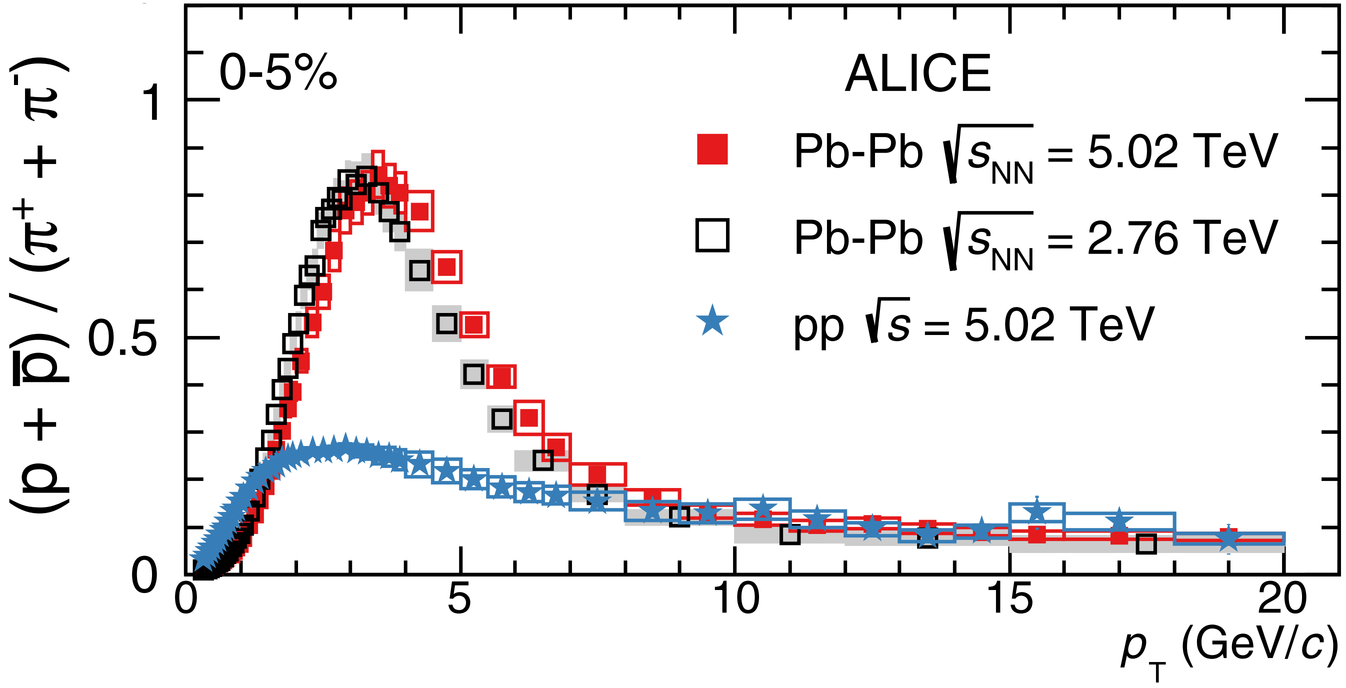
- p_T-spectra harden with centrality
- more pronounced for heavier particles (e.g.: $p > K > \pi$) as *velocities* become equalized in the flow field (p = βγ·m)
- Hydrodynamic models show a good agreement with the data.

Radial flow in AA collisions

Transverse expansion of the QGP

- Light flavour hadron spectra and baryon/meson ratios reveal the presence of a **strong radial flow**
- Radial flow increases with **centrality** pushing heavier particles to higher p_T
- Agreement with expectations based on **hydrodynamic expansion** of QGP

PRC **101**, 044907 (2020)

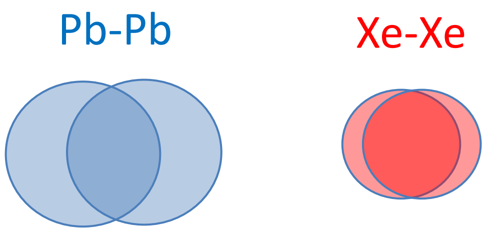


Radial and elliptic flow in AA collisions

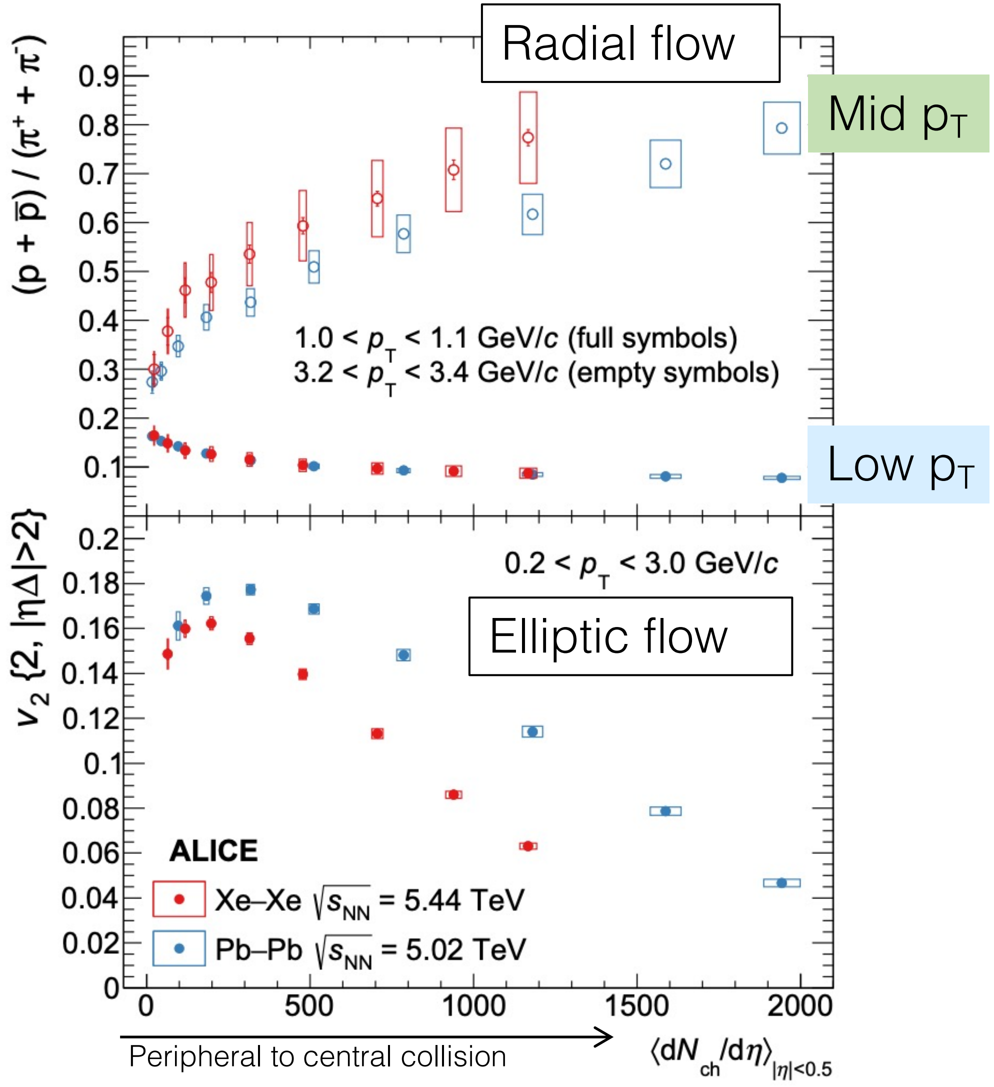
Transverse expansion of the QGP

Radial flow depends only on the **final-state charged particle multiplicity** (system size)

Elliptic flow depends on multiplicity and on the eccentricity (intial **geometry**)



EPJC 81 (2021) 7, 584



ALICE

Elliptic flow of hadrons … and also light nuclei

Nearly all particles species partcipate in collective flow, even A=2 and A-3 light nuclei

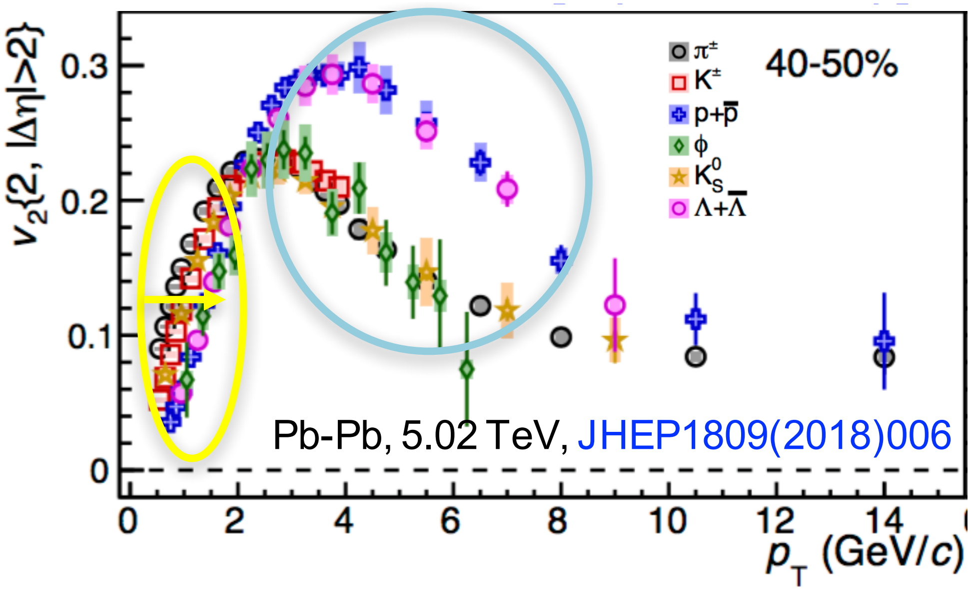
Mass ordering at low p_T (π, K, p, d, ^{3}He) ➪ hydrodynamic flow, very small viscosity

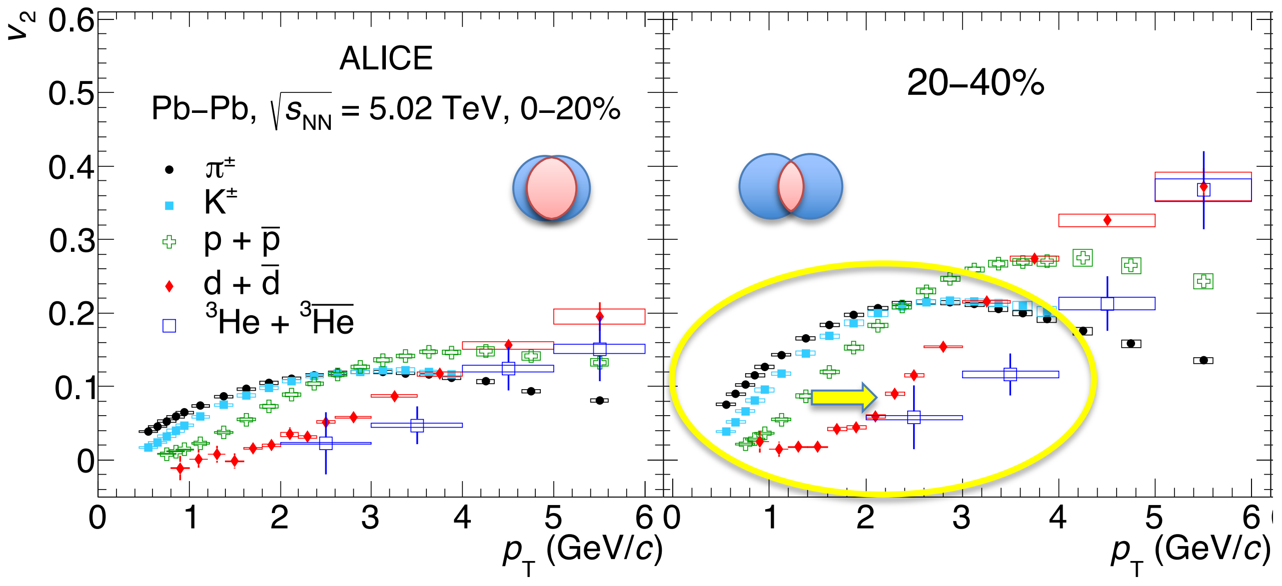
p_T < 2-3 GeV/c - from collective dynamics during hydro expansion (heavier hadrons shifted to higher p_T by radial flow

Baryon vs. meson grouping at higher p_T ➪ **quark-level flow + recombination?**

3 < p_T < 8-10 GeV/*c* - **baryons flow more than mesons** consistent with hadronisation by coalescence

arXiv: 2005.14639





Going heavy (flavour): charm and beauty also flow

D mesons and J/ψ exhibit large flow

- At intermidiate p_T, J/ψ < D < pions

⇨ consistent with contribution of recombination

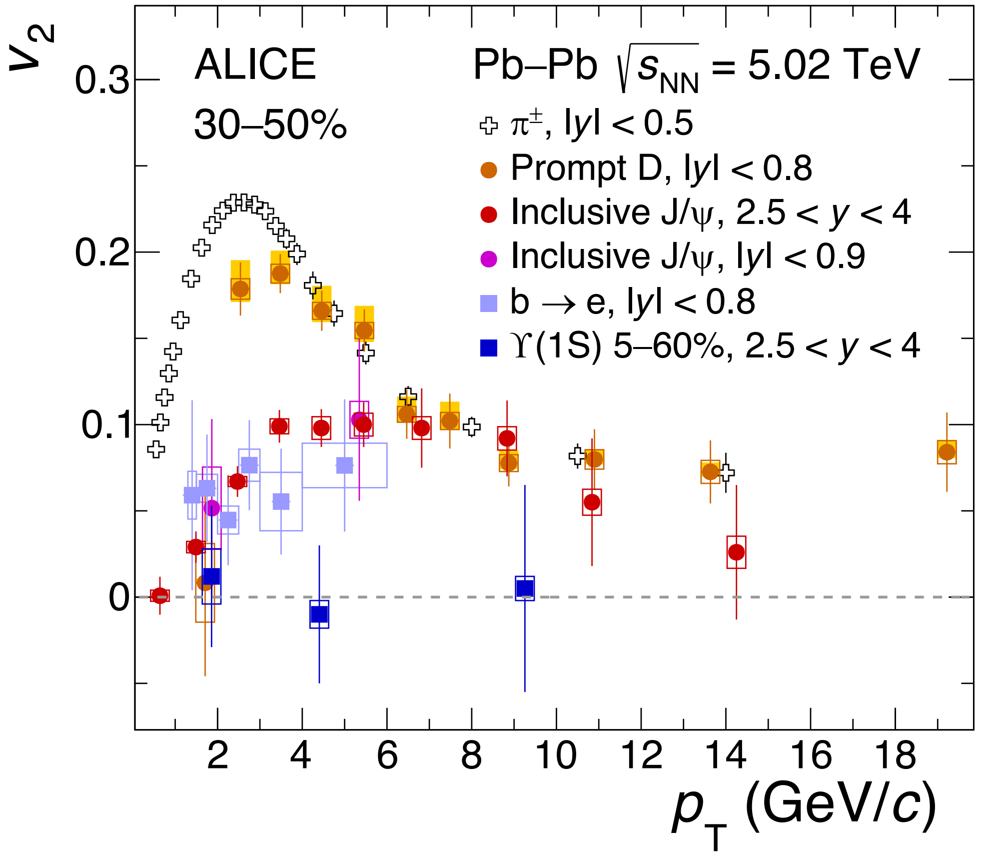
Model description indicates c quark thermalisation time ~3-8 fm/c < QGP lifetime

B mesons also flow

- Model description indicates smaller flow for b than for c

No indication of Y(1S) flow

- Consistent with large Y mass and small $b\bar{b}$ recombination



π: JHEP 1809(2018)006 D: arXiv: 2005.11131 J/ψ: CERN-EP-2020-094

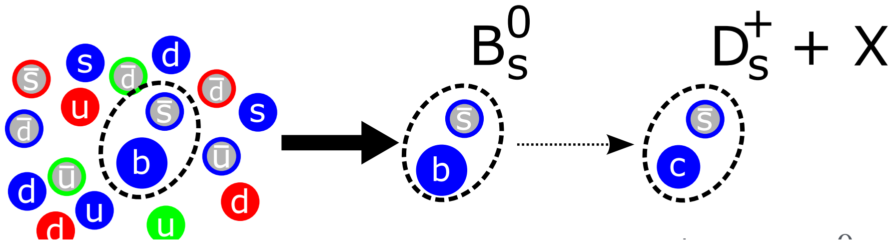
b → e: arXiv: 2005.11130 Y(1S): PRL 123(2019)192301

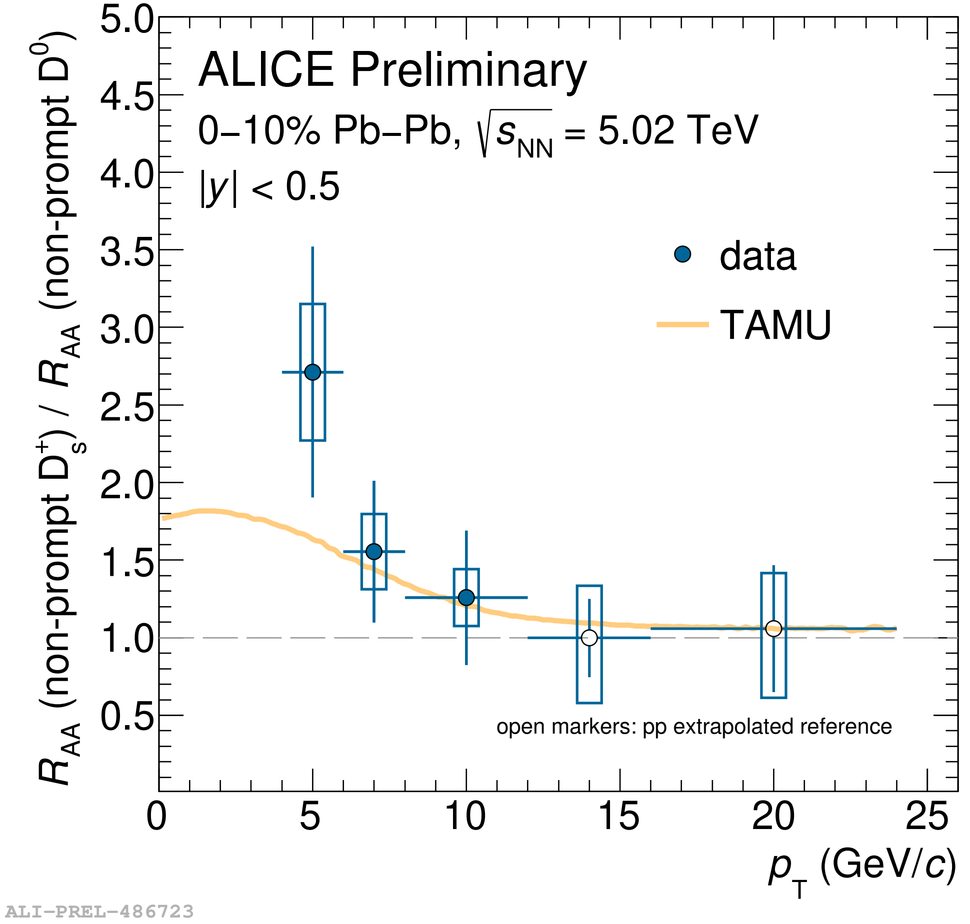
Energy loss and hadronization of c and b quarks in the QGP

R_{AA}(non-prompt D^{+}_{s}) > R_{AA}(non-prompt D^0) consistent with coalescence picture

- non-prompt D^{+}_{S} less suppressed than non-prompt D^0 at low p_T

- enhanced production of B^{0}_{s} from beauty hadronization via coalescence (50% of D^{+}_{s} from B^{0}_{s})



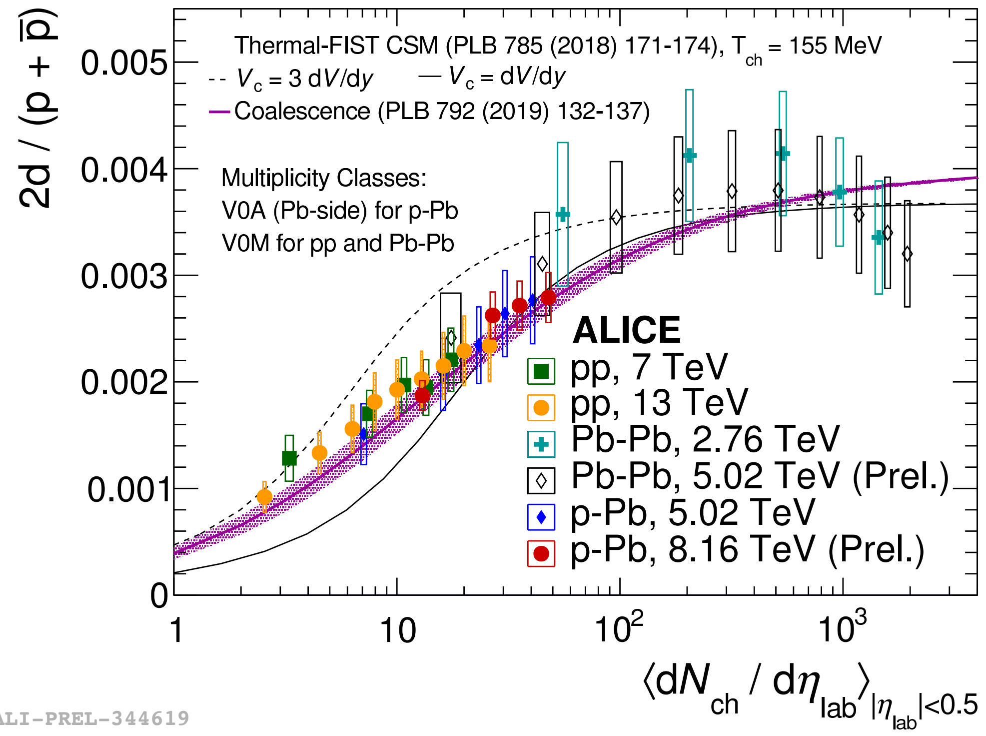


From hadrons to light nuclei

Smooth evolution of production of rare light nuclei as a function of the system size

➪ puzzle of the survual of loosely bound states ($E_B \sim$ 2MeV) in the hot hadron gas (T ~ 150-100 MeV) produced in heavy-ion collisions

➪ constrain models of nucleosynthesis in hadronic collisions: **statistical hadronization vs coalescence**



Coalescence

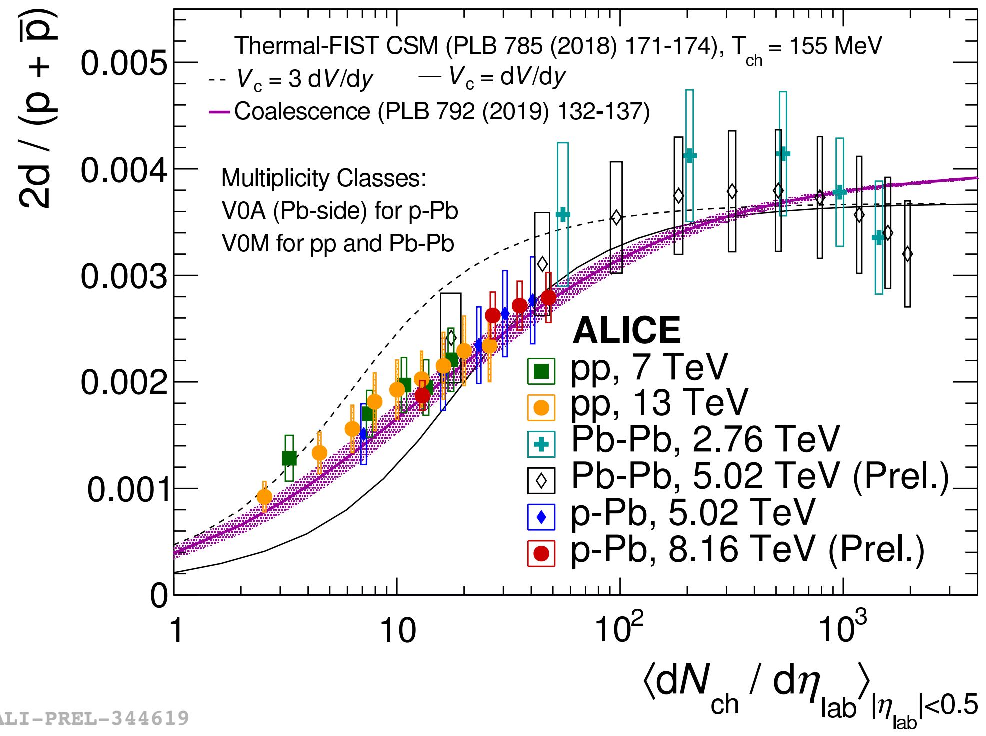
- cluster forms when nucleons are close in phase space
- dependence on the source size
- dependence on the nucleus internal structure

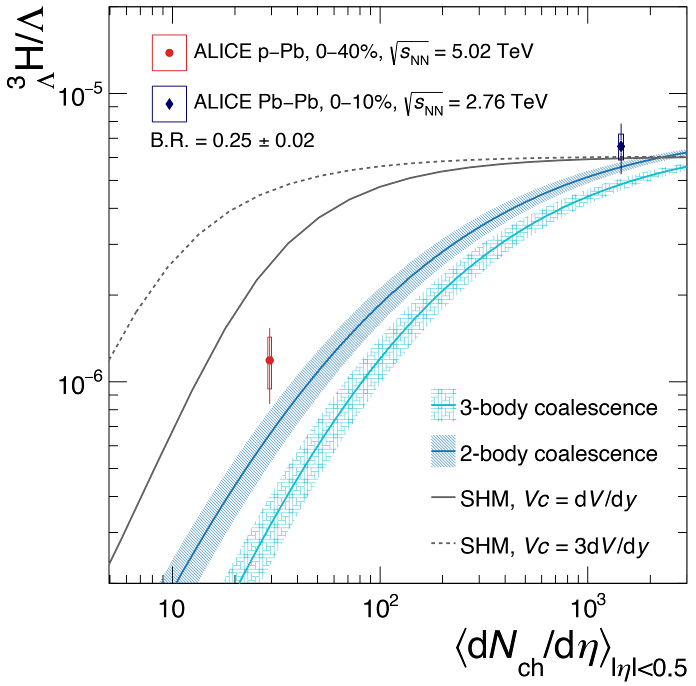
➪ test with **hypertriton** (Λpn):
loosely bound ($B_\Lambda \sim$ 130 keV) and large (r ~ 10-14 fm)

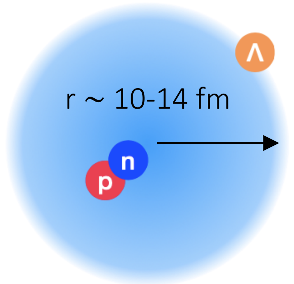
From hadrons to light nuclei

Smooth evolution of production of rare light nuclei as a function of the system size

- ➪ puzzle of the survual of loosely bound states ($E_B \sim$ 2MeV) in the hot hadron gas (T ~ 150-100 MeV) produced in heavy-ion collisions
- ➪ constrain models of nucleosynthesis in hadronic collisions: **statistical hadronization vs coalescence**
- ➪ demonstrated by **first measurment of hypertriton in small system** (favours coalescence)







Systematic and precise measurements as function of system size and momentum in Runs 3 and 4

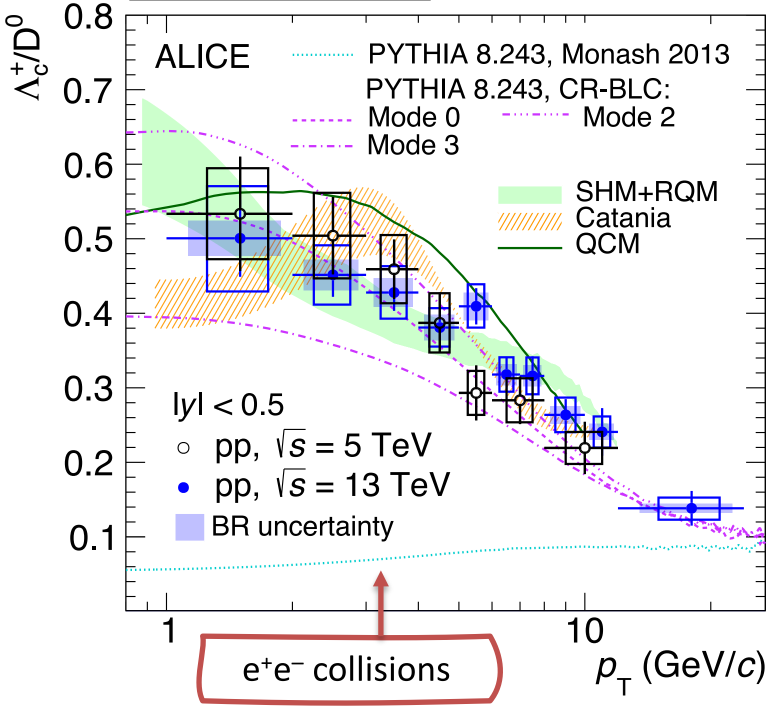
Beyond QGP physics

… a few examples

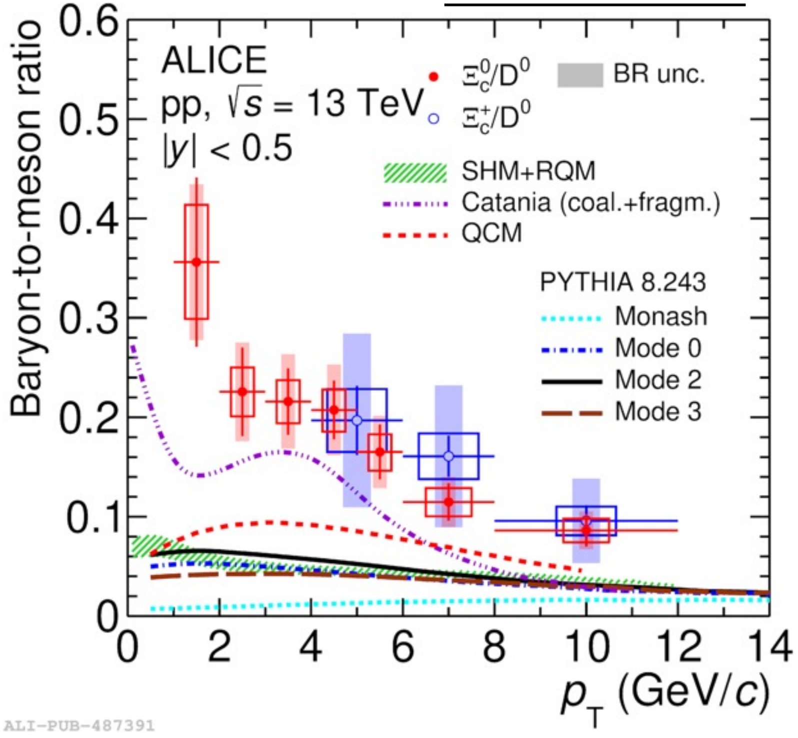
Charm baryon/meson measurements in pp collisions

Charm hadronization differs at the LHC

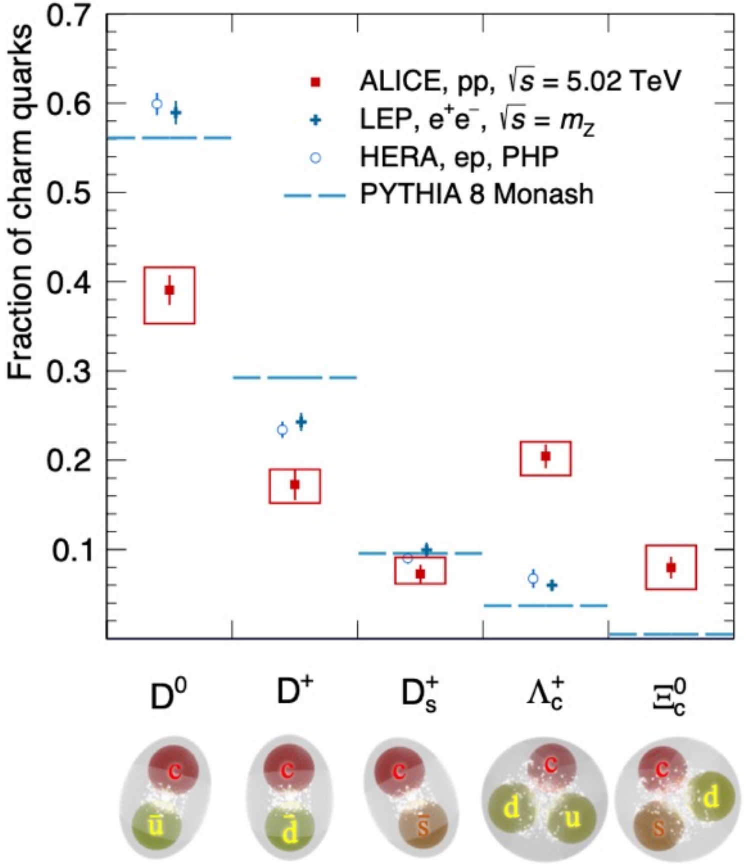
arXiv:2011.06078 arXiv:2106.08278



arXiv:2105.05187



arXiv:2105.06335



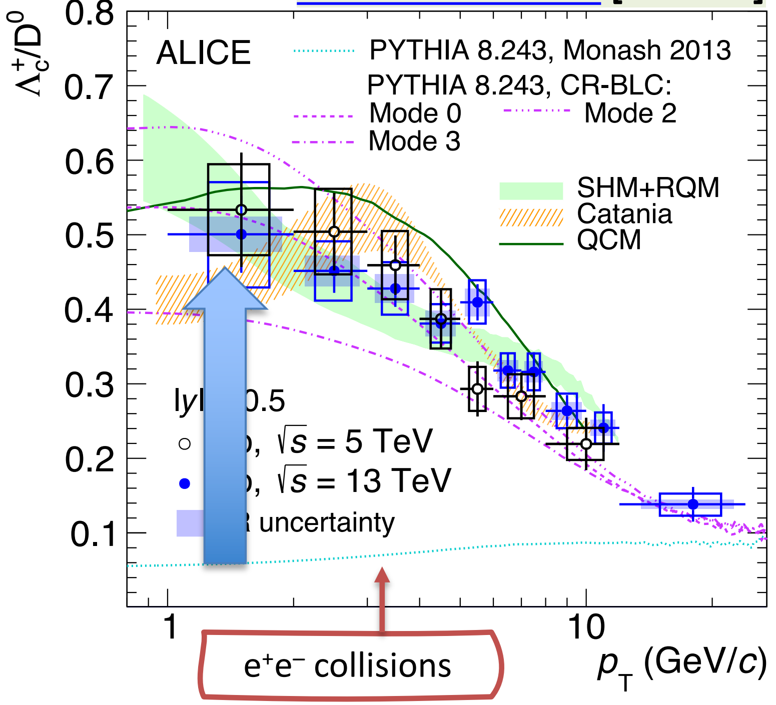
- unique measurements (at low-momenta) of Λ_c (also Ξ_c and Ω_c)
- cross section (fragmentation fraction) larger than expected (ee and ep)

ALICE

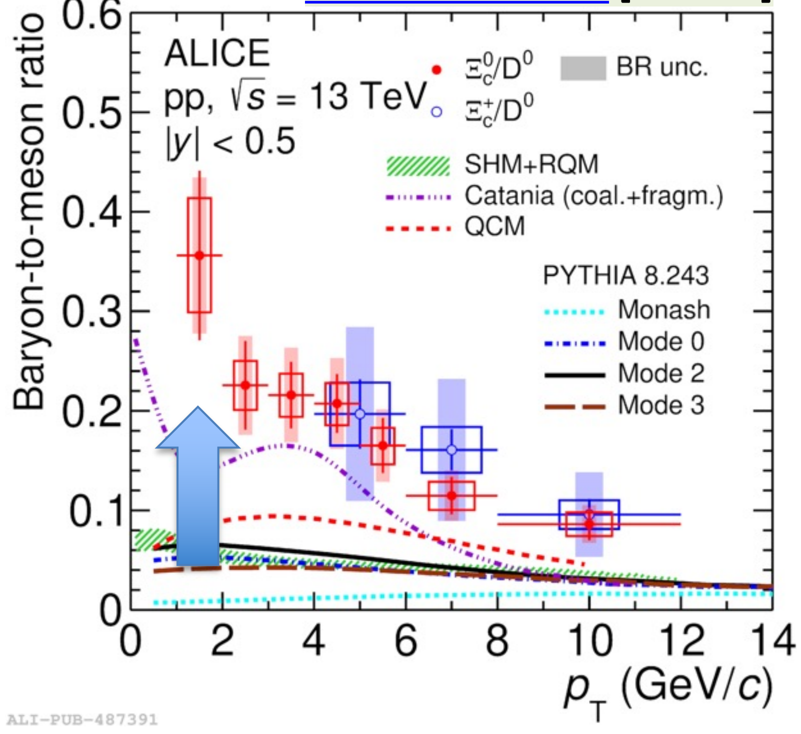
Charm baryon/meson measurements in pp collisions

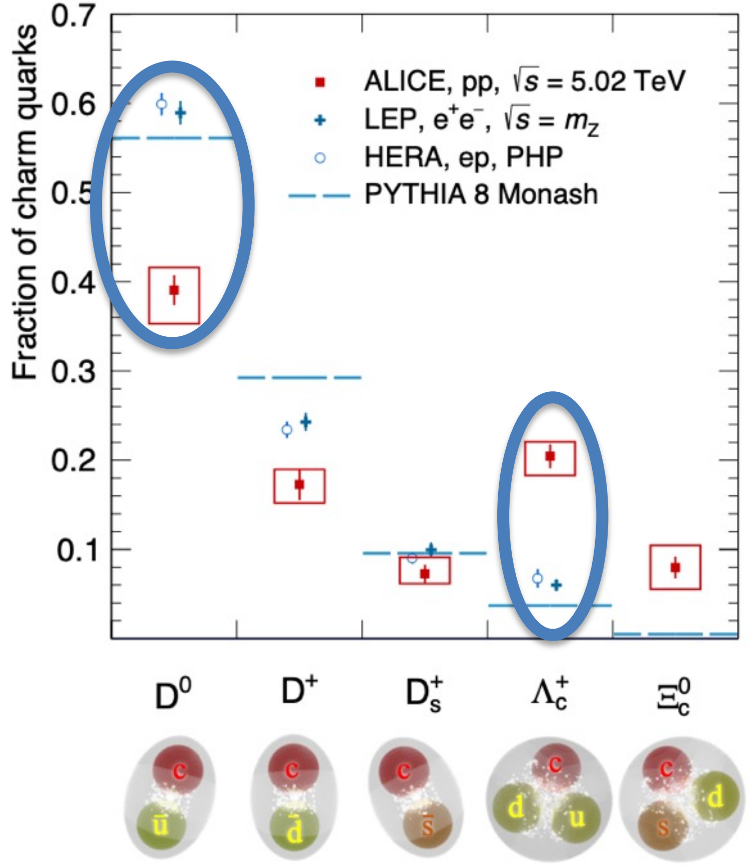
Charm hadronization differs at the LHC

arXiv:2011.06078 [nucl-ex]



arXiv:2105.05187 [nucl-ex]

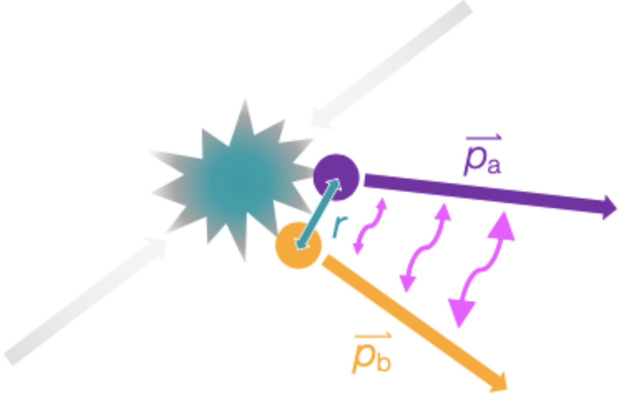




- unique measurements (at low-momenta) of Λ_c (also Ξ_c and Ω_c)
- cross section (fragmentation fraction) larger than expected (ee and ep)

Strong interaction between hadrons

Correlation function sensitive to interaction potential



1. **Fix source geometry**
2. **Measure correlation fct. C(k^*)**

→ study the strong interaction

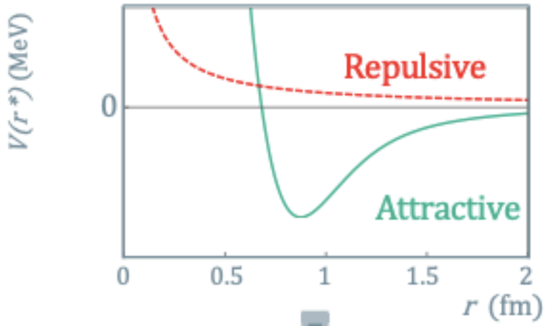
$$C(k^*) = \int S(r)\, \left|\psi(\vec{k}^*, \vec{r})\right|^2 d^3r$$

Emission source — Two-particle wave function

Source parametrisation

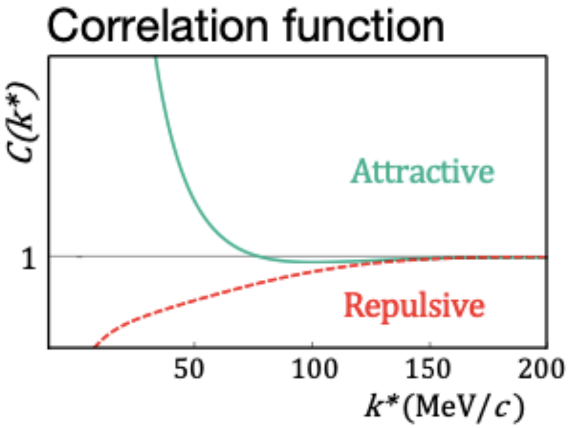
Gaussian source

Interacting potential



Schrödinger equation**

Two-particle wave function $|\Psi(k^*, r)|$



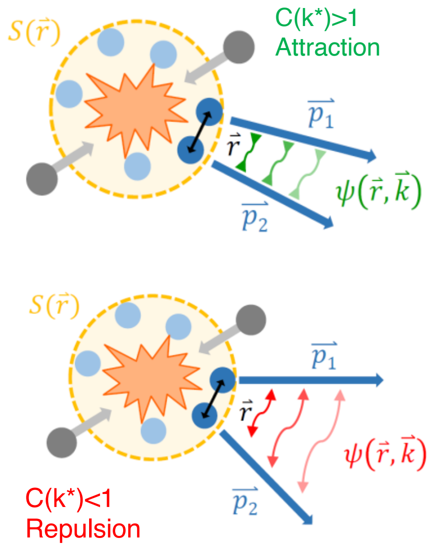
Strong interaction between hadrons

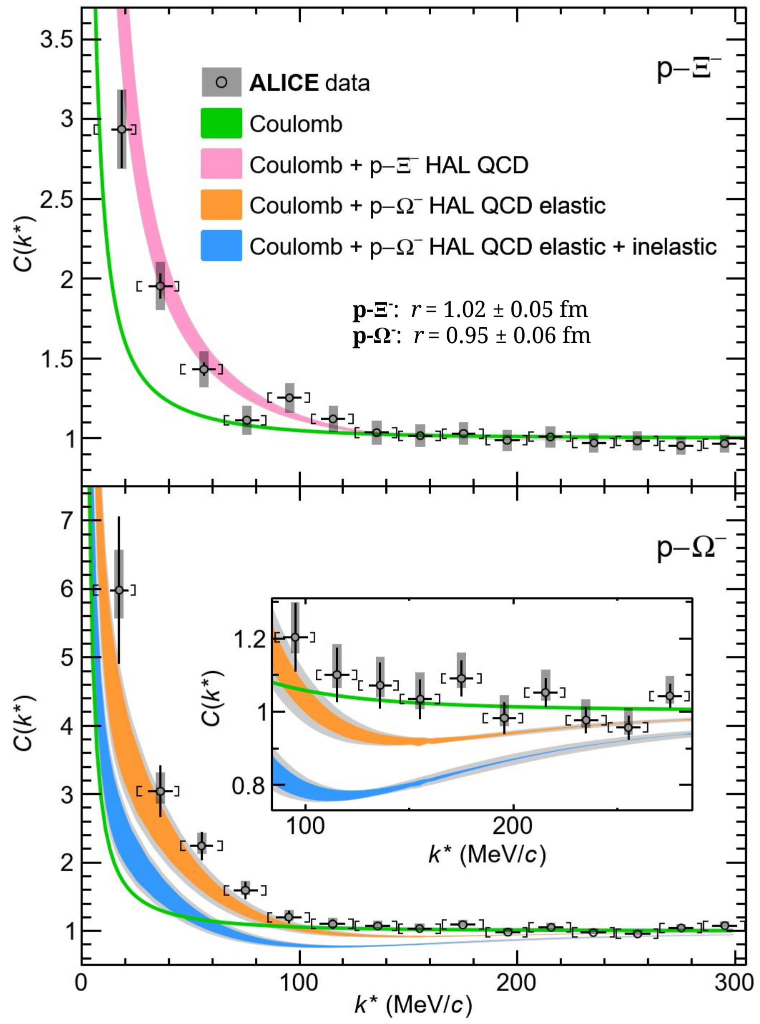
ALICE measurements on topic

Phys. Rev. C 99 (2019) 024001	p-p, p-Λ, Λ–Λ (pp)
Phys. Lett. B 797 (2019) 134822	Λ–Λ (p-Pb)
Phys. Rev. Lett. 123 (2019) 112002	p-Ξ^- (p-Pb)
Phys. Rev. Lett. 124 (2020) 092301	p-K (pp)
Phys. Letters B 805 (2020) 135419	p-Σ (pp)
Phys. Lett. B 811 (2020) 135849	source size in pp
Nature 588 (2020) 232-238	**p-Ω (pp)**
arXiv:2104.04427	NΛ – NΣ (pp)
arXiv: 2105.05578	p-ϕ (pp)
arXiv:2105.05683	**K-p (Pb-Pb)**
arXiv:2105.05190	p-/p, p-/Λ, Λ–/Λ (pp)

"Unveiling the strong interaction among stable and unstable"

Nature 588 (2020) 232-238





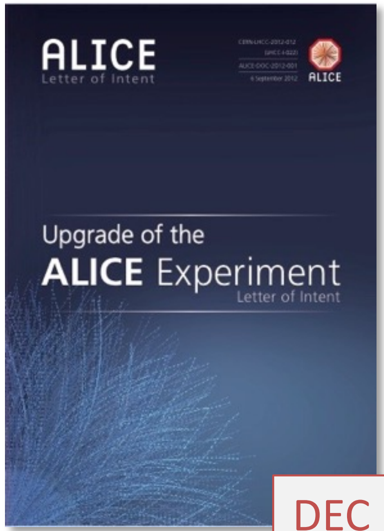
Proton-hyperon (p-Y) strong interaction poorly known

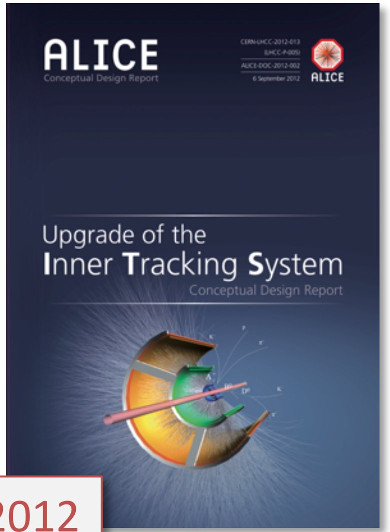
precise measurement of strong interaction for p-Ξ^- and p-Ω^-

- direct comparison to lattice QCD
- p-Ξ^- important for the EoS of neutron stars (which contain hyperon-rich matter)

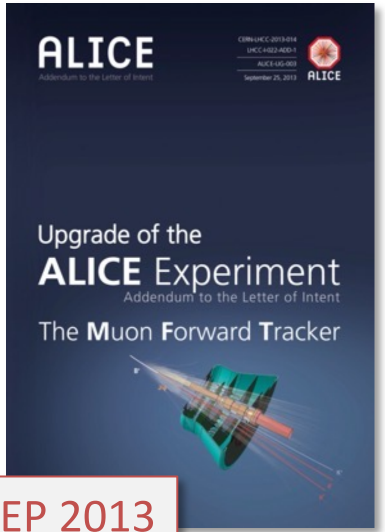
ALICE Upgrades
ongoing activties and future plans

ALICE Detector Version 2.0 (Upgrades for Run 3+)



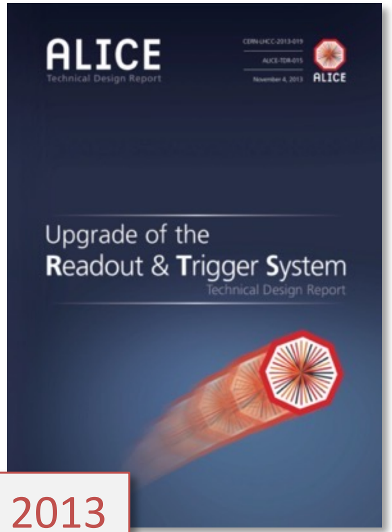


DEC 2012

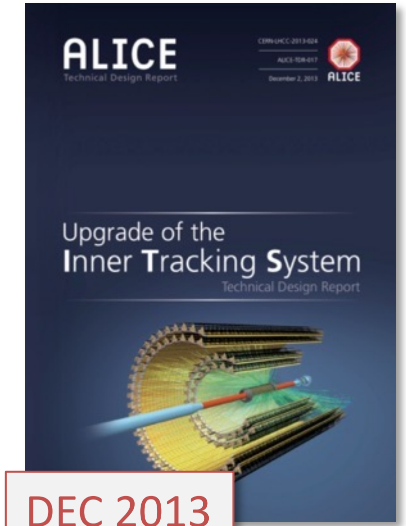


SEP 2013

- From LoI to last TDR: 2013 – 2015 ✓
- Construction: 2016 – 2019 ✓
- Installation: 2020 – 2021 ✓
- Global commissioning: ongoing



NOV 2013



DEC 2013

MAR 2014

MAY 2015

NOV 2015

ALICE Detector Version 2.0 (Upgrades for Run 3+)

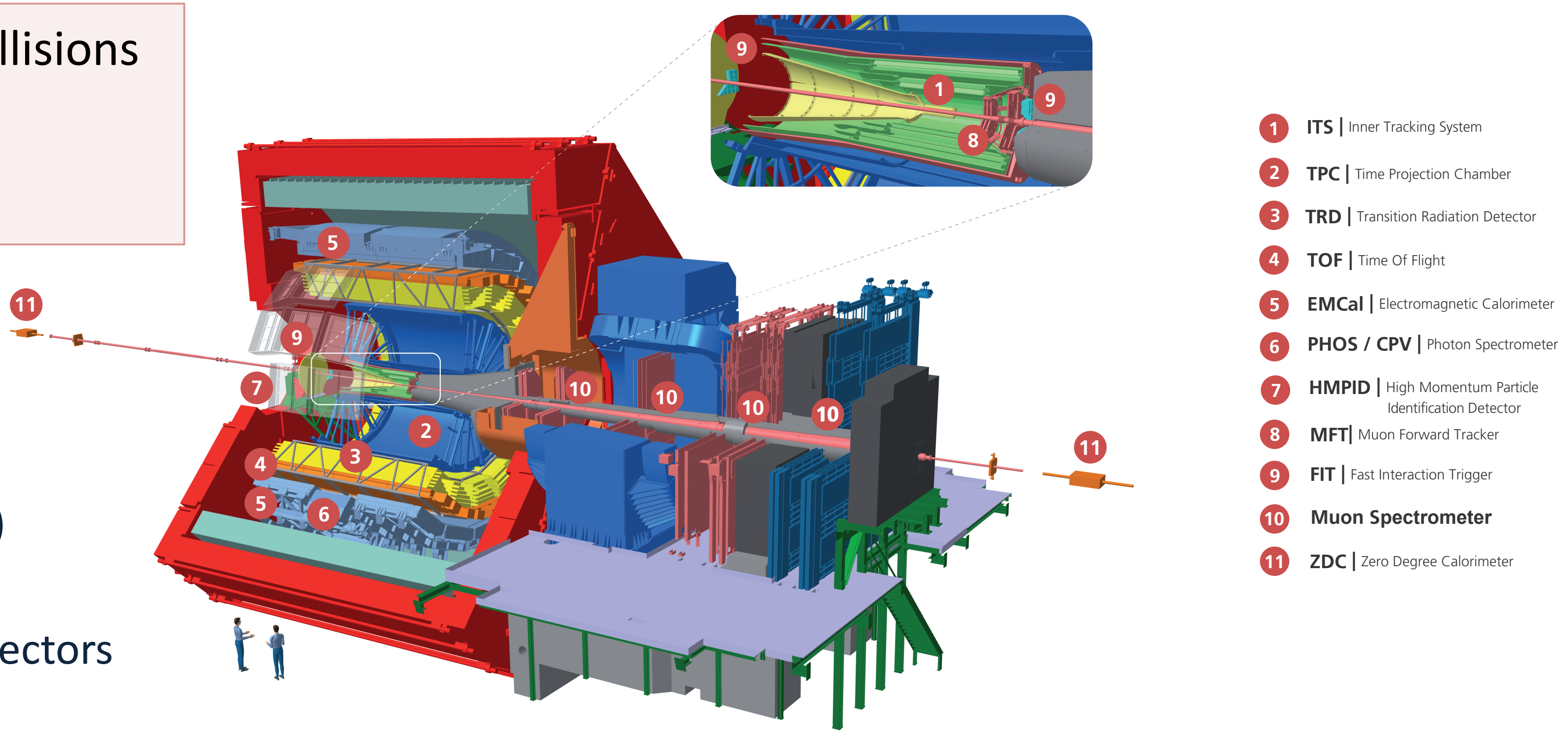
Runs 1 and 2: 1 nb^{-1} of Pb-Pb collisions

Interaction rate ~8 kHz

readout rate ≈ 1 kHz

LS2 upgrade

- New TPC R/O planes
- New silicon tracker (ITS & MFT)
- New Fast Interaction Trigger (FIT)
- New Online/Offline system (**O2**)
- Upgrade readout of all other detectors



> Improve tracking resolution at low p_T

x50 statistics increase for most observables

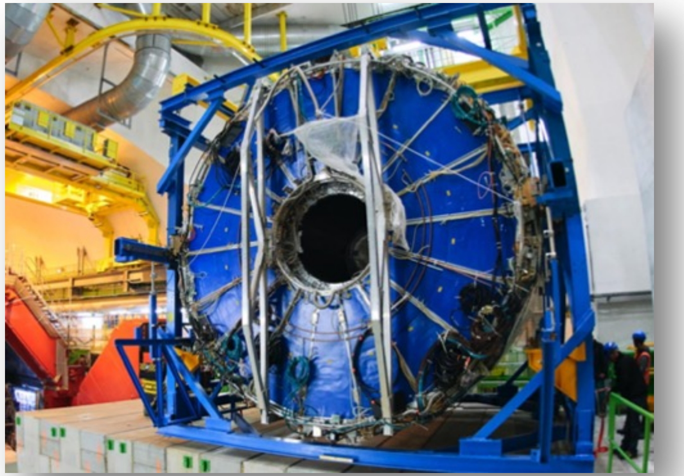
Run 3+Run 4: **13 nb^{-1} of Pb-Pb collisions**

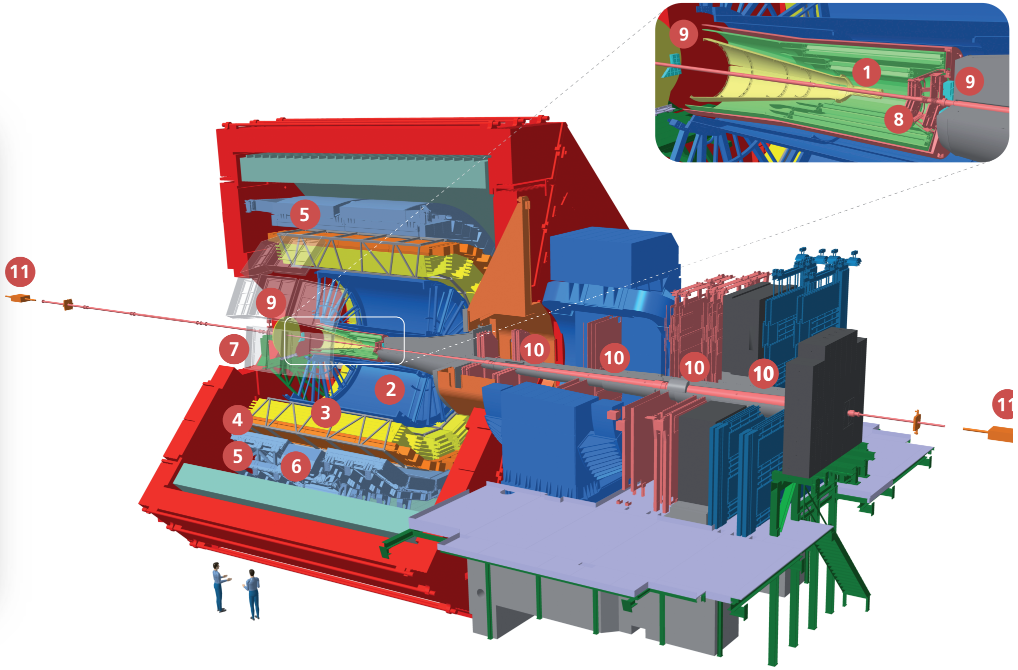
readout rate ≈ 50 kHz (Pb-Pb), ≈ 1 MHz (pp)

online reconstruction : all events to storage!

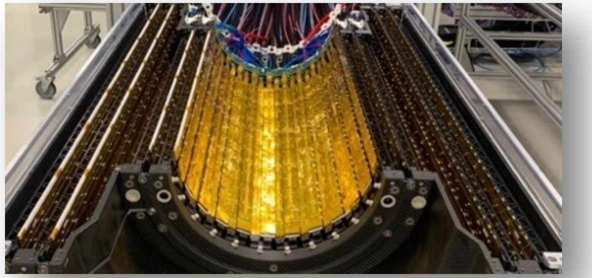
ALICE Detector Version 2.0 (Upgrades for Run 3+)

GEM-based TPC readout

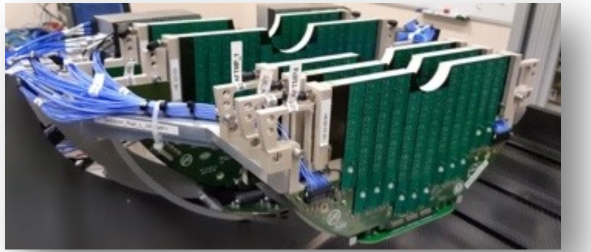




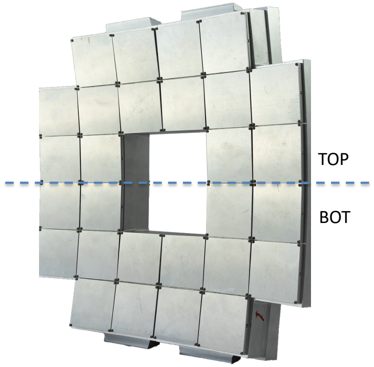
Monolithic-pixel - ITS2



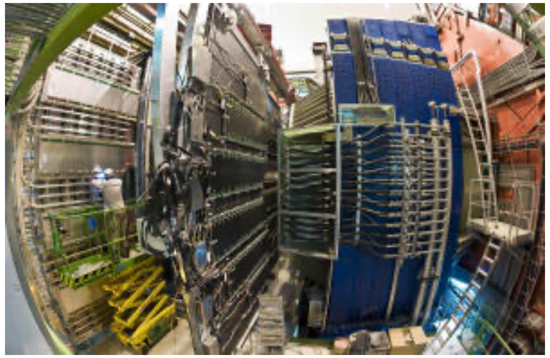
Pixel Muon Forward Tracker (MFT)



Fast Interaction Trigger FIT



Muon Spectrometer



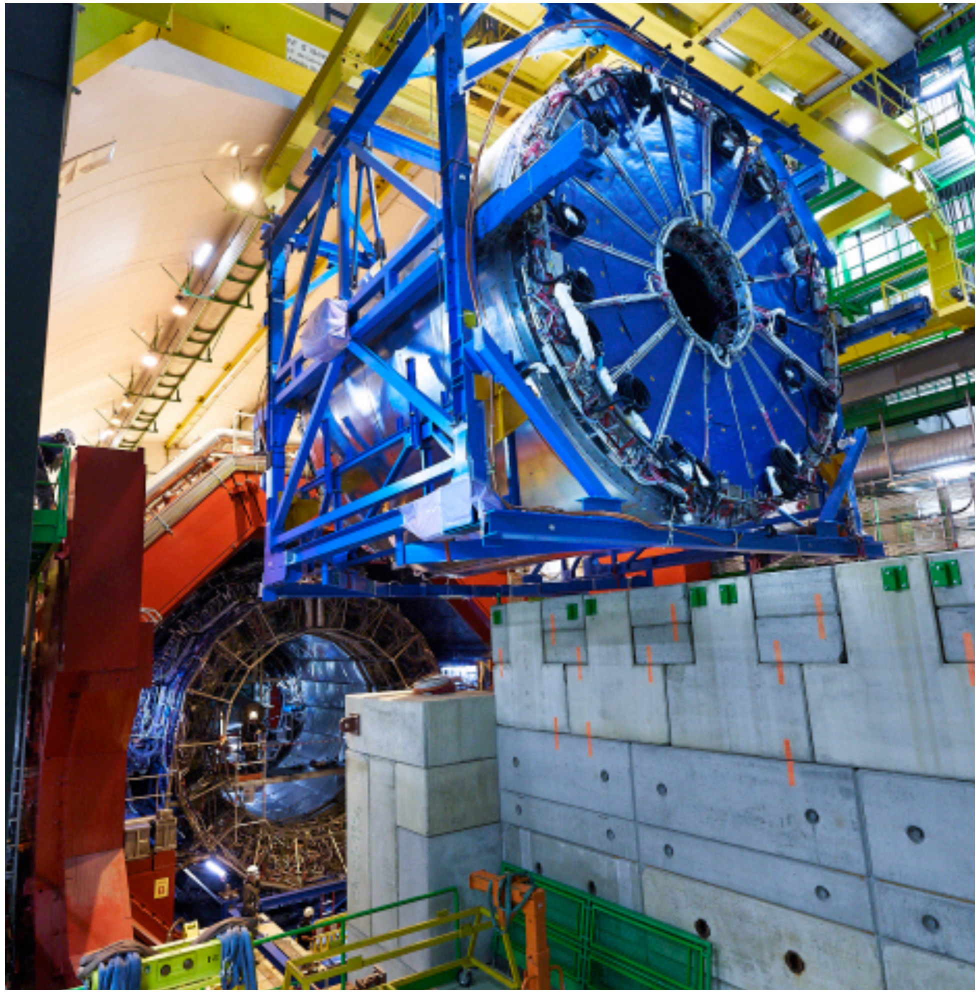
New Central Trigger Processor (CTP)

Upgrade of R/O for EMCal, PHOS, TRD, HMPID, ZDC

New Online/Offline (O2)

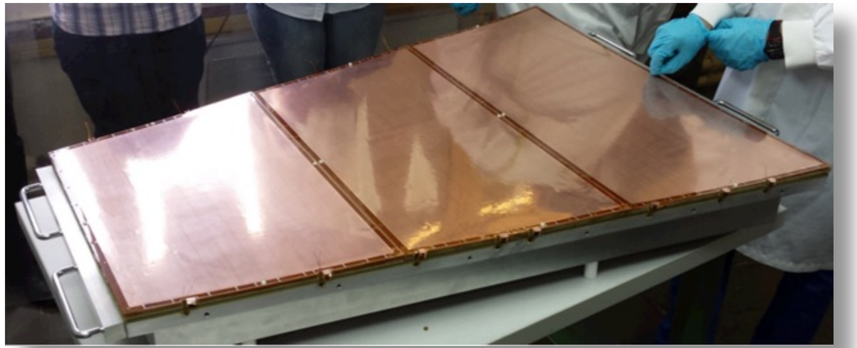
TPC Upgrade for continuous readout

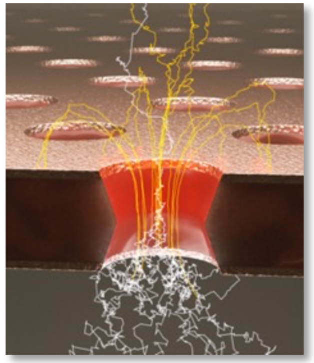
Goal: TPC continuous readout (➪ no gating grid)



Solution: Replace MWPC with 4-GEMs

100 m^2 single-mask foils GEM production



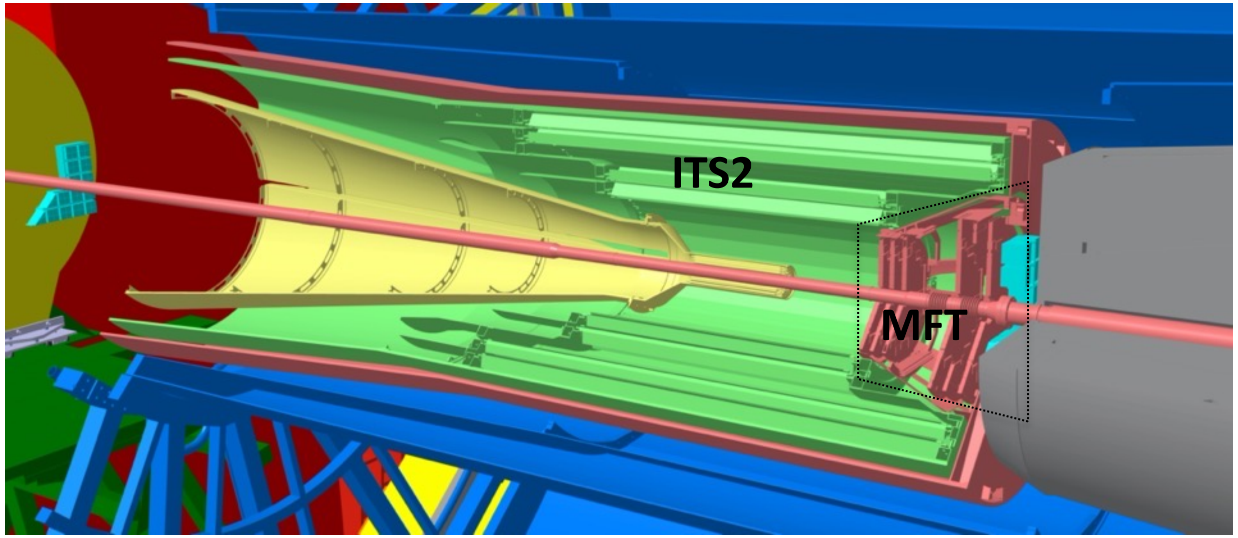


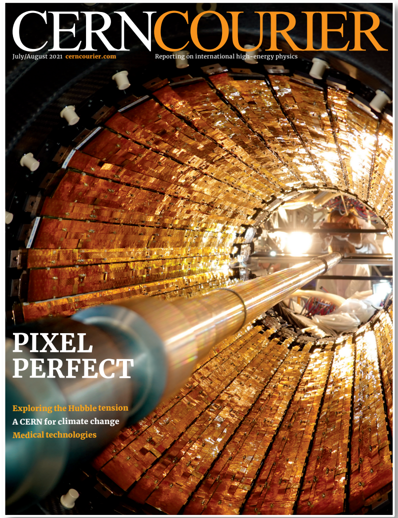
Read Out Chamber

➪ GEM provides ion backflow suppression to **< 1%**

➪ 524 000 pads readout continuously ➪ **3.4 TByte/sec**

New Inner Tracking System and Muon Froward Tracker





Based on MAPS technology (ALPIDE)

- **10 m²** active silicon area
- **12.5 G-pixels**
- **50 μm** thin sensor
- Spatial resolution **~5µm**
- Max particle rate ~ **100 MHz /cm²**

Inner Tracking System upgrade (ITS2)

- Closer to the IP: first layer at ≈22 mm
- Smaller pixels: 28 x 29 μm^2
- Lower material budget: 0.35% X_0

⇨ improved pointing resolution (**x 3**)

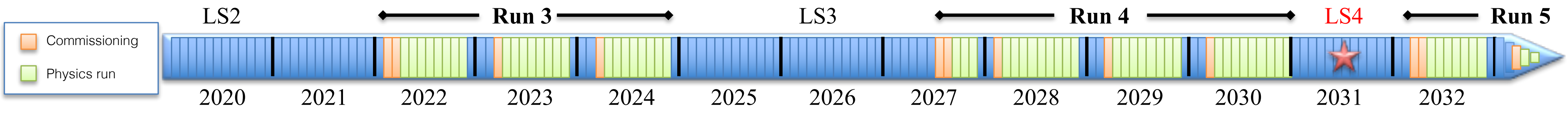
⇨ Improved tracking efficieny at low p_T

New Muon Forward Tracker (MFT)

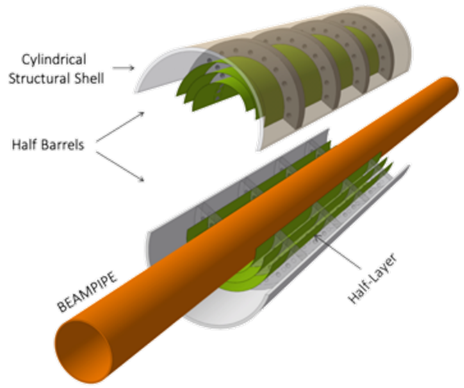
- New forward vertex detector upstream muon absorber

⇨ improved muon pointing resolution

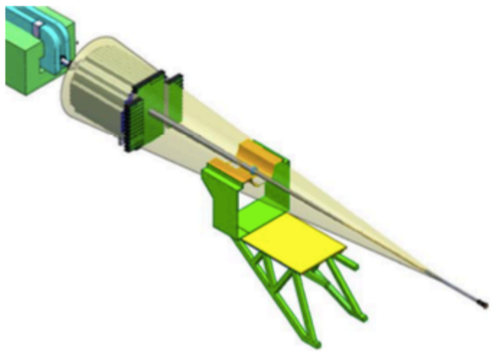
Perspectives: upgrades for Run 4, ALICE 3 for Run 5



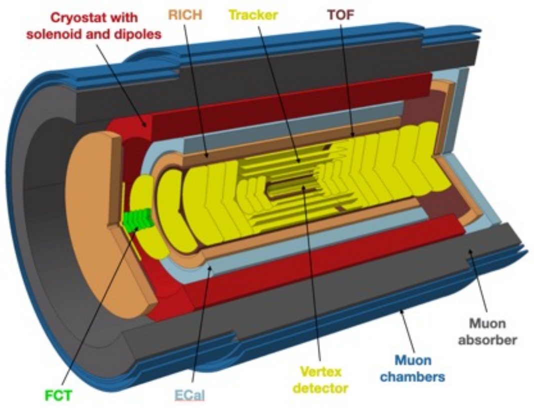
ITS3



FoCal



ALICE 3



ITS3: wafer-scale, ultra-thin, bent MAPS
improvement in the measurement of low p_T charm and beauty hadrons and low-mass dielectrons

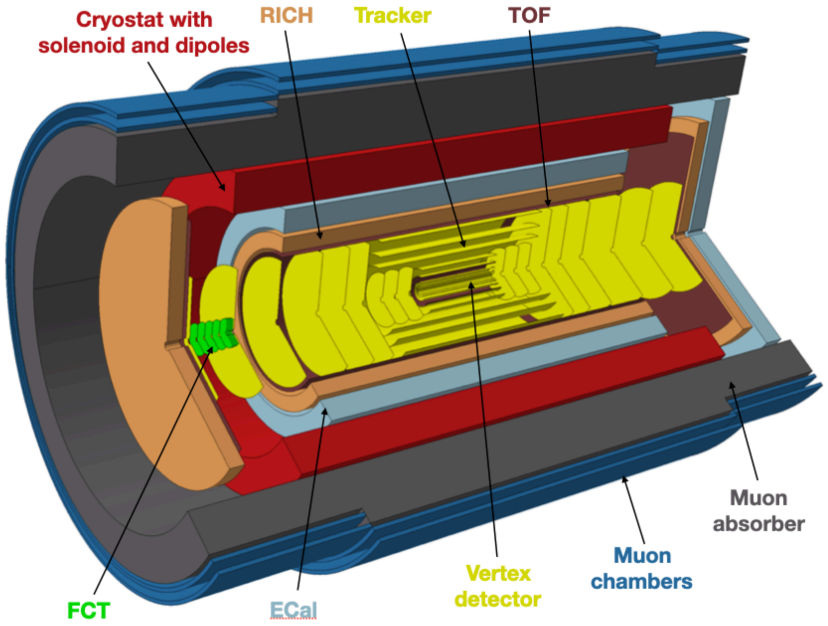
LoI: CERN-LHCC-2019-018

FoCal: forward EM calo with Si readout
for isolated γ measurement in $3.4 < \eta < 5.8$ in p-Pb

LoI ALICE-PUBLIC-2019-005

ALICE 3: a new dedicated heavy-ion detector for Run 5+ (> 2030)

Novel measurements of electromagnetic and hadronic probes of the QGP at very low momenta
⇨ mechanism of hadron formation in the QGP, QGP transport properties, QGP electrical conductivity, QGP radiation and access to the pre-hydrodynamization phase, Chiral Symmetry restoration, …

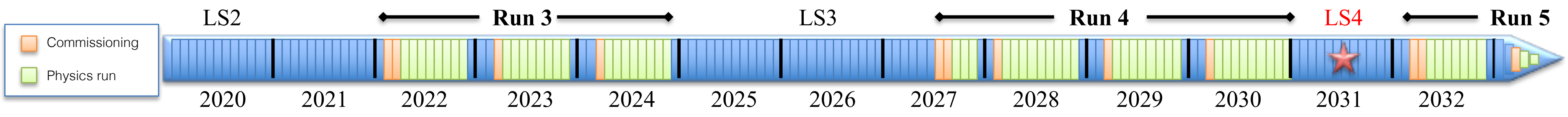


Expression of Interest arXiv:1902.01211

Also submitted as input to the European Strategy for Particle Physics Update (Granada, May 2019)

Timeline

- Conceptual studies ongoing 2019-2021
- Public workshop in October 2021
- Submit a LoI to the LHCC by 2021
- Construction and installation by LS4



Conclusions

A wealth of results based on full Run 2 samples offer:

- Detailed insights into **QGP workings and properties**
- plus a broader **and rich QCD programme**:
    - pQCD, hadron structure, formation of hadrons and nuclei

Underway and coming up:

- Major upgrade for Run 3 on track (ALICE v. 2.0)
- In preparation: ITS3, FoCal for Run 4 (ALICE v. 2.1)
- Plans for next generation dedicated HI experiment for Run 5+ (ALICE v. 3.0)