A Large Ion Collider Experiment

ALICE

ALICE physics highlights and perspectives

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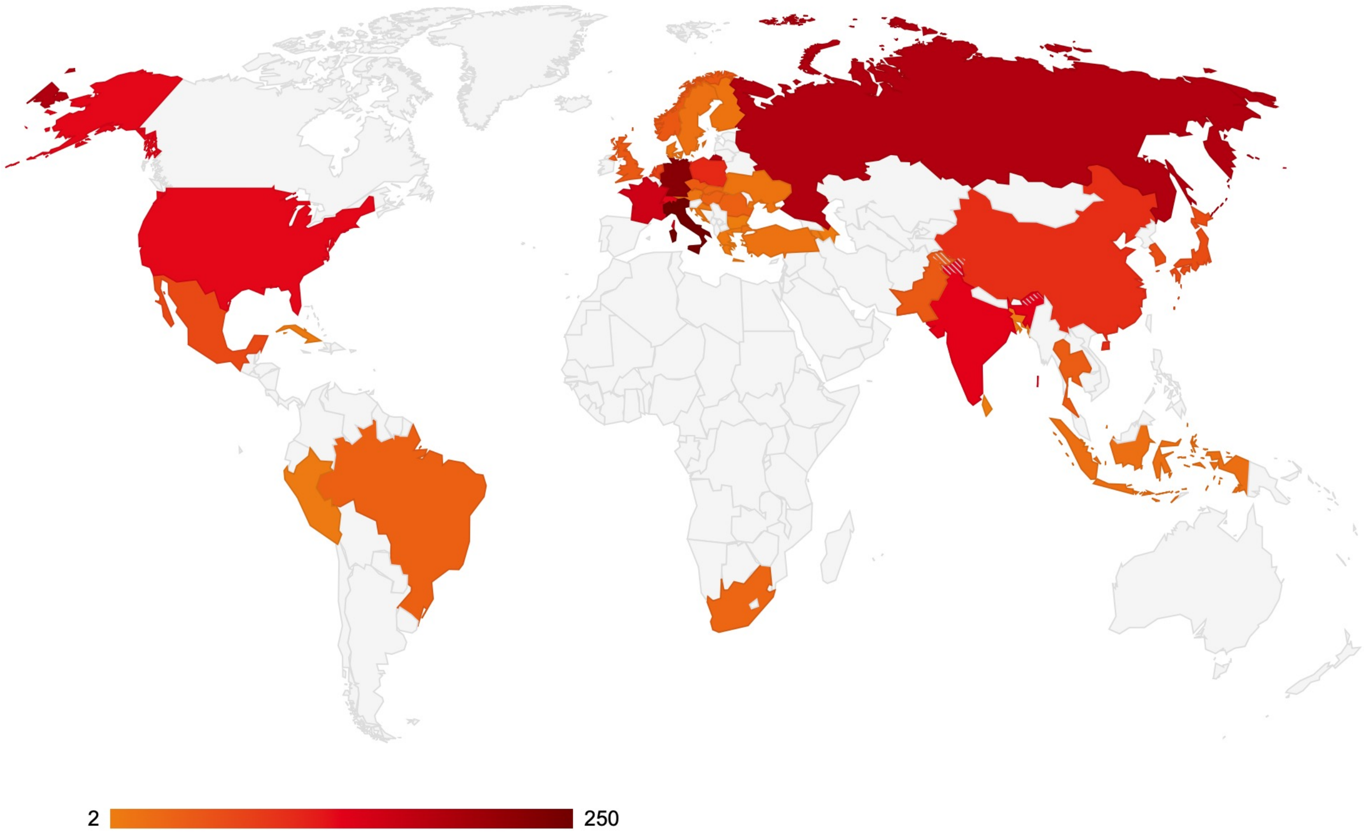
Workshop on Standard Model and Beyond

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

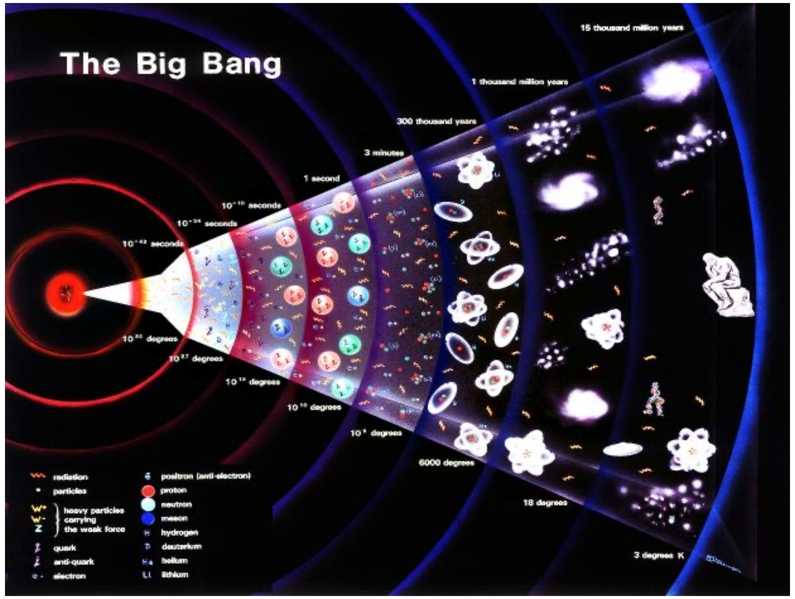
- 1992: Expression of interest
- 1997: ALICE approval
- 2000 – 2007: construction
- 2002 – early 2008: Installation
- 2009 – 2018: physics campaign

The ALICE Scientific Mission

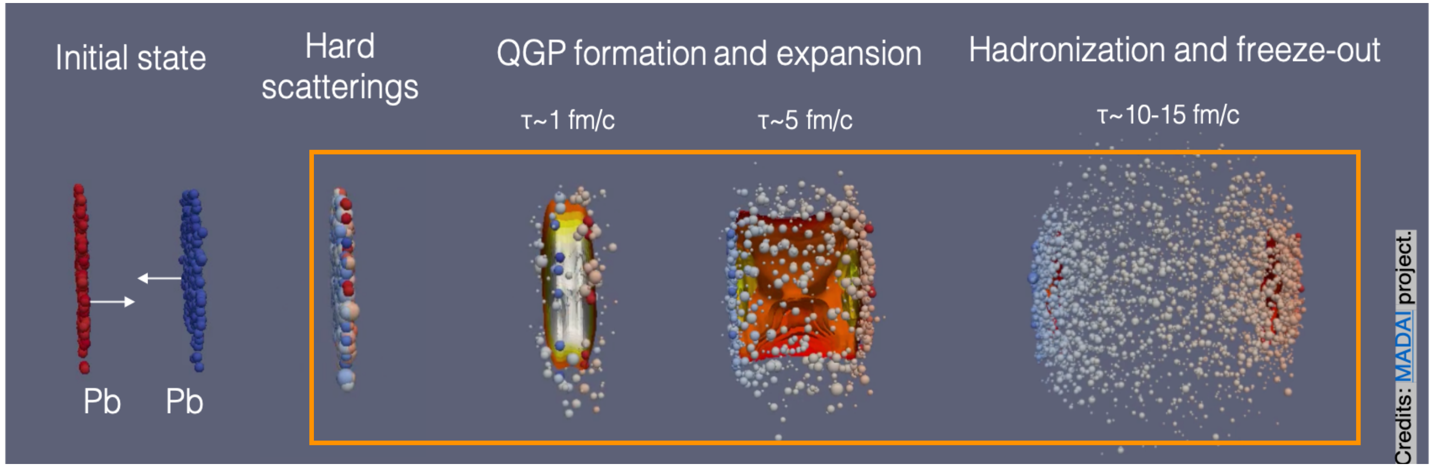
Characterize the physical properties of the **Quark-Gluon Plasma (QGP),** a **state of strongly-interacting** (colored) **matter** formed at extremely high energy densities

⇨ 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

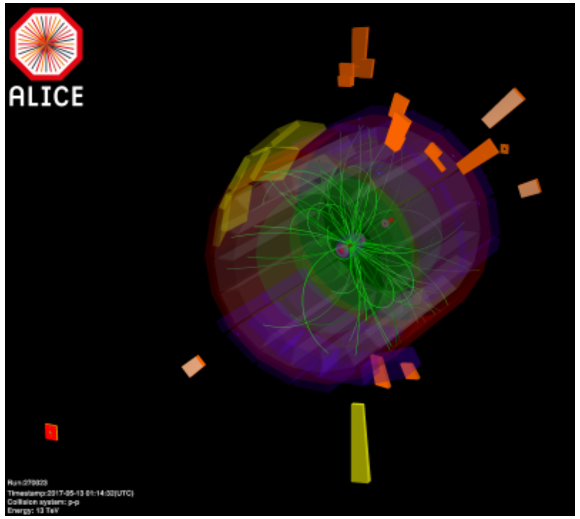


1 fm/c = 3x10^{-24} s, 1 MeV ~ 10^{10} K

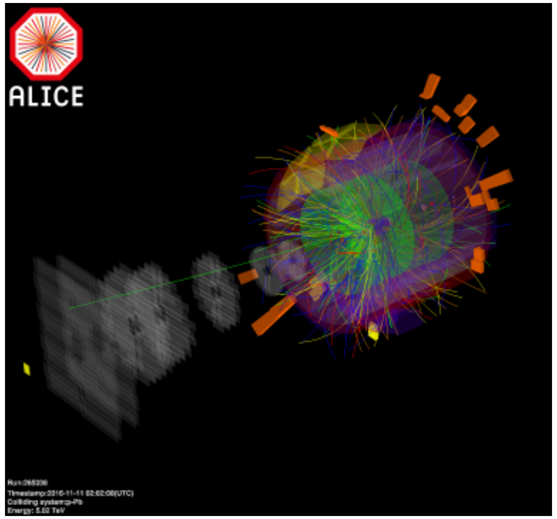
Heavy Ion Collisions at the LHC

- 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)

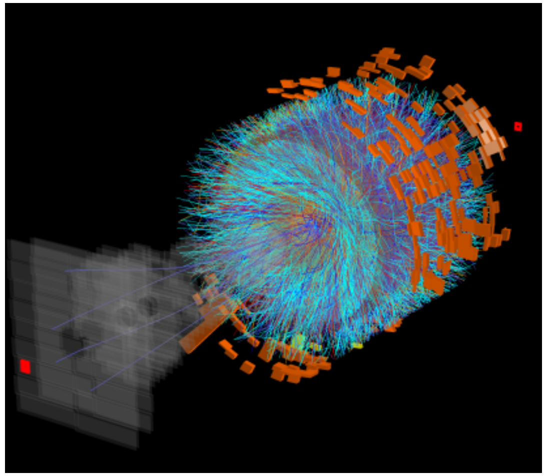
pp



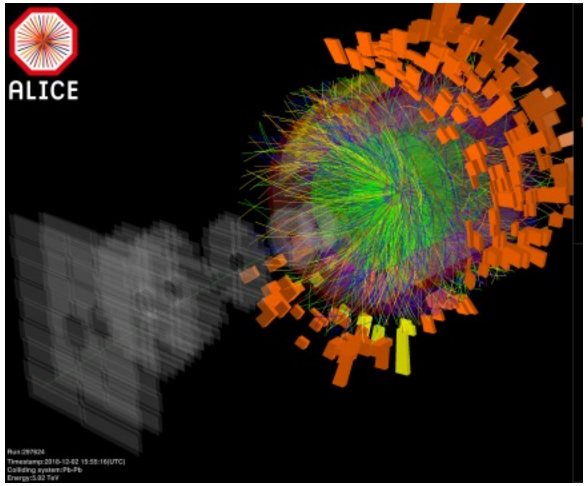
p-Pb



Xe-Xe



Pb-Pb



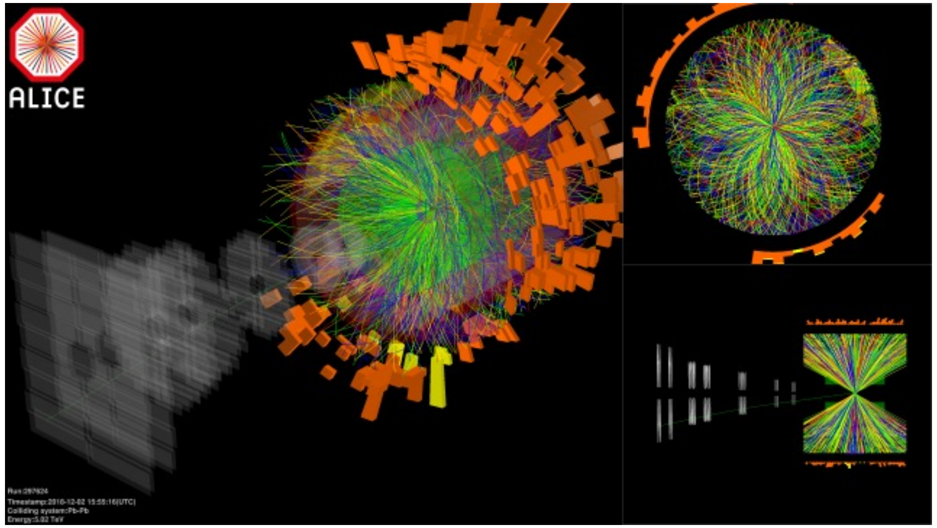
Pb-Pb collisions at the LHC

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 $\sqrt{s}$ = 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:
  $\sqrt{s}$ = 1.04 PeV

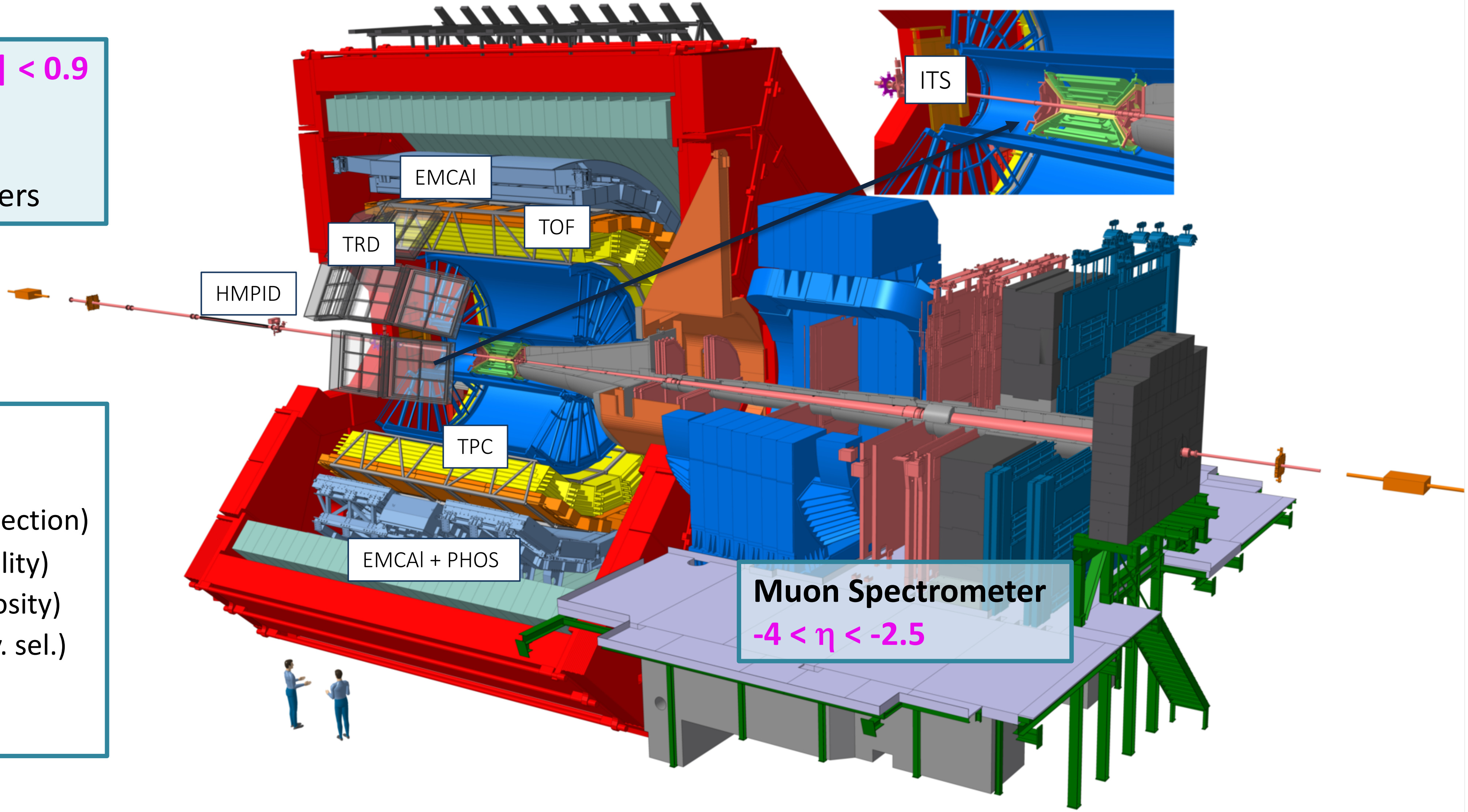
⇨ What can we learn from these massive interactions?

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



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

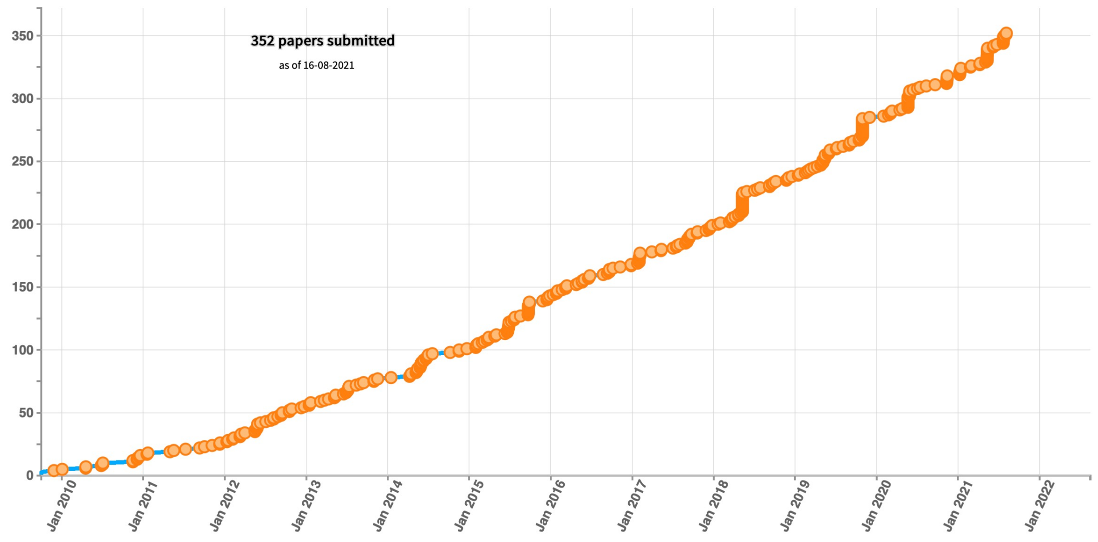
Run 1 (2009 – 2013) LS1 Run 2 (2015 – 2018) LS2 Run 3 (2022 – 2024) LS3 Run 4 (2027 – 2029)

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



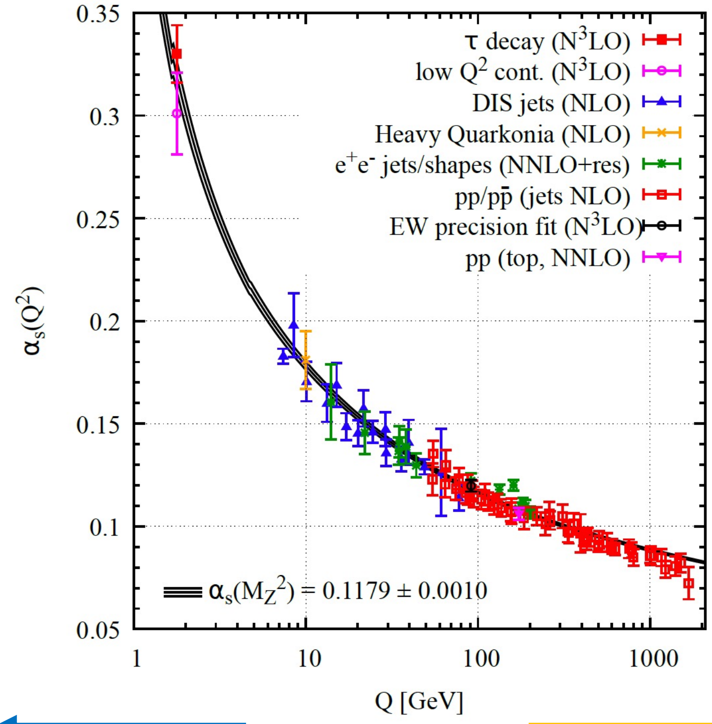
http://alice-publications.web.cern.ch/submitted

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



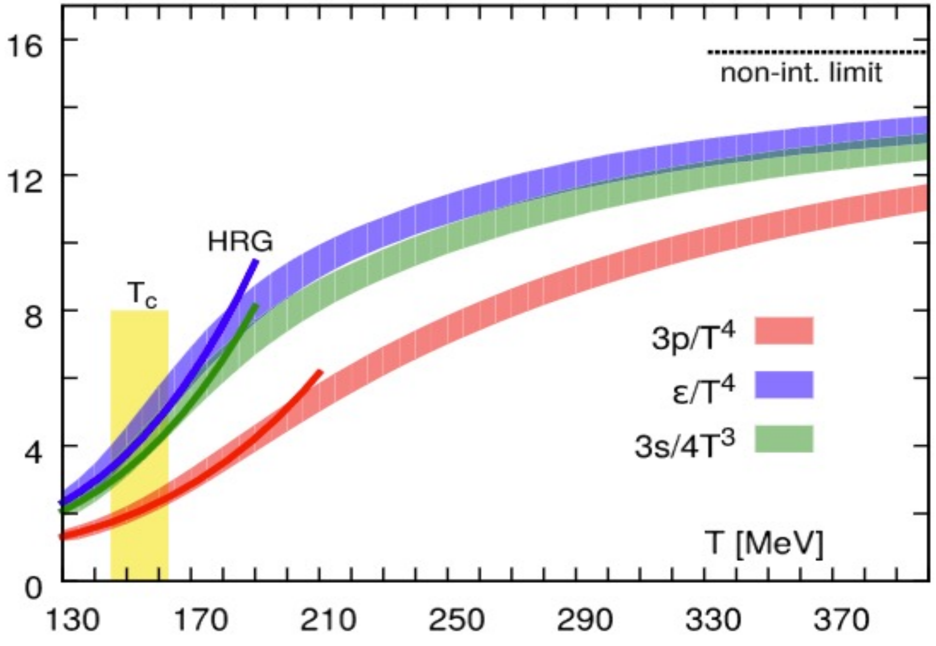
← Confinement

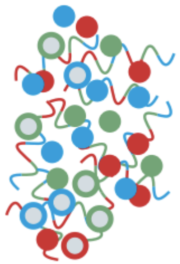
Asymptotic freedom →

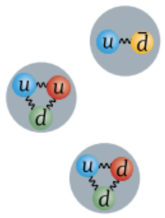
NB: free regime is reached only asymptotically!

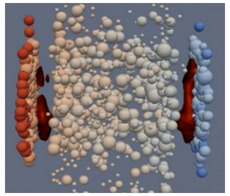
Where is the phase transition?
→ Lattice QCD

[PRD 90 094503 (2014)]

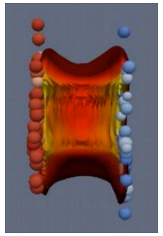








Hadron gas ← $\sim 10^{12}\ K$ → Quark Gluon Plasma



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

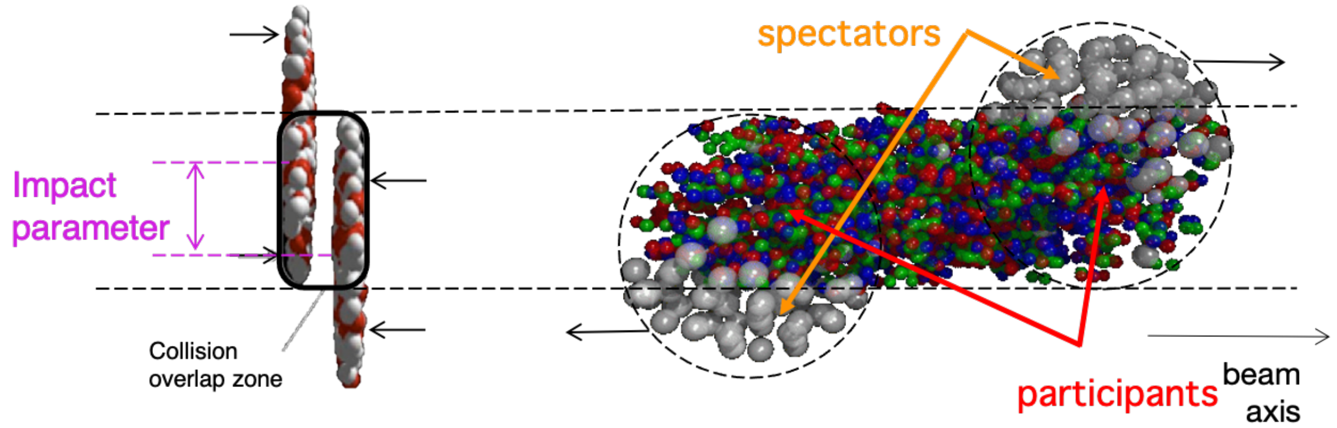
➪ Collide **heavy nuclei** (multiple, ~simulataneous, nucleon-nucleon collisions)

➪ **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)

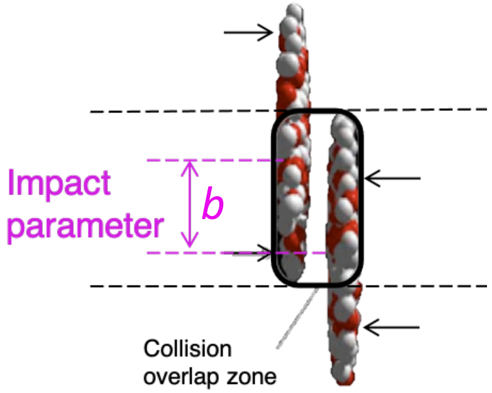
Impact parameter ***b*** not directly measurable

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

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



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

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

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

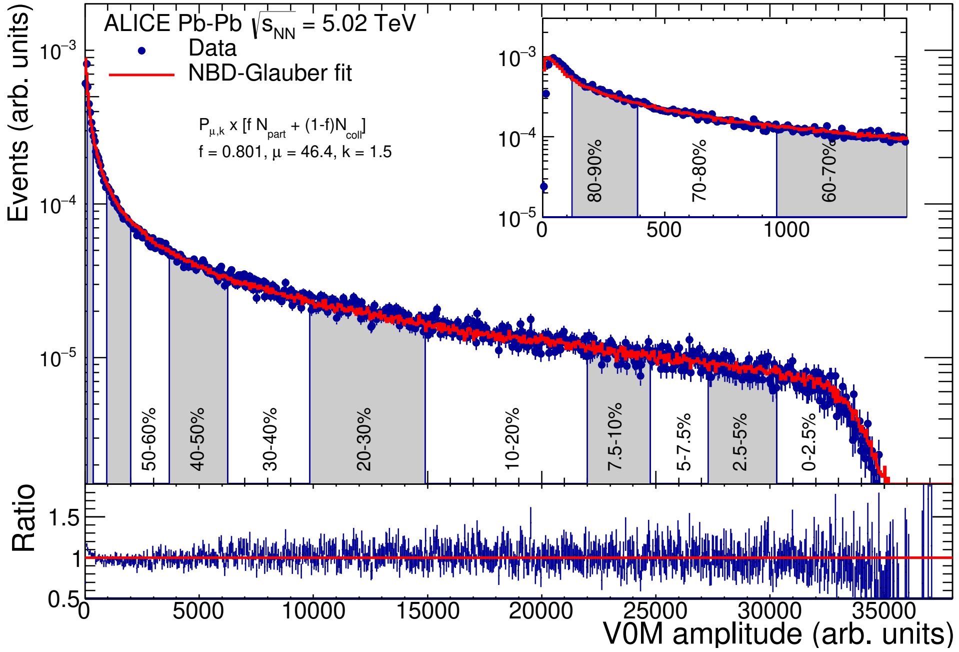
For example: sum of the **amplitudes in the ALICE V0 scintillators**

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

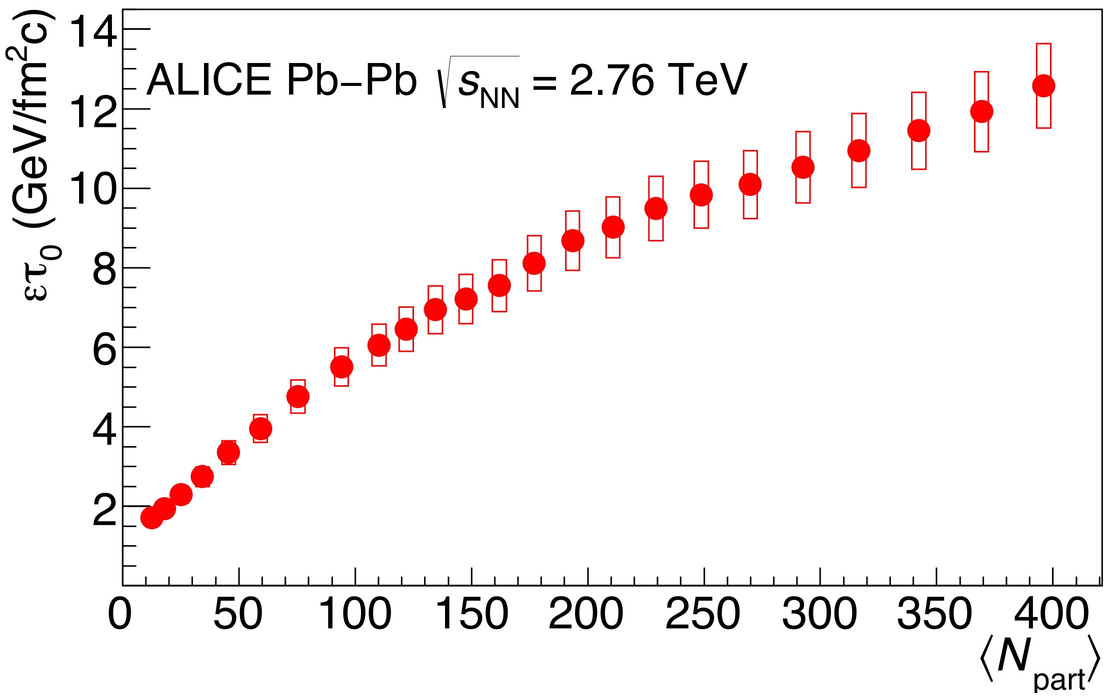
J. D. Bjorken
Phys. Rev. D **27**, 140

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

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

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

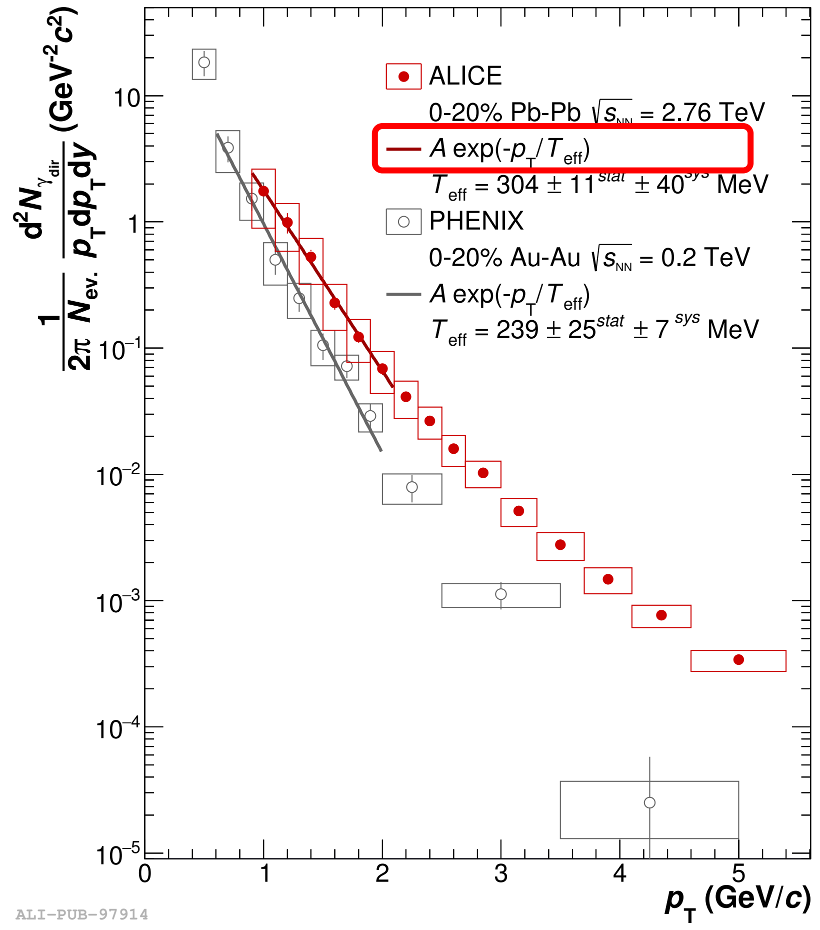
Assuming $\tau_0 = 1 fm/c$ ➡ $\boxed{\varepsilon = 12.3 \pm 1\ GeV/fm^3}$

Spectra of direct photons in Pb-Pb collisions

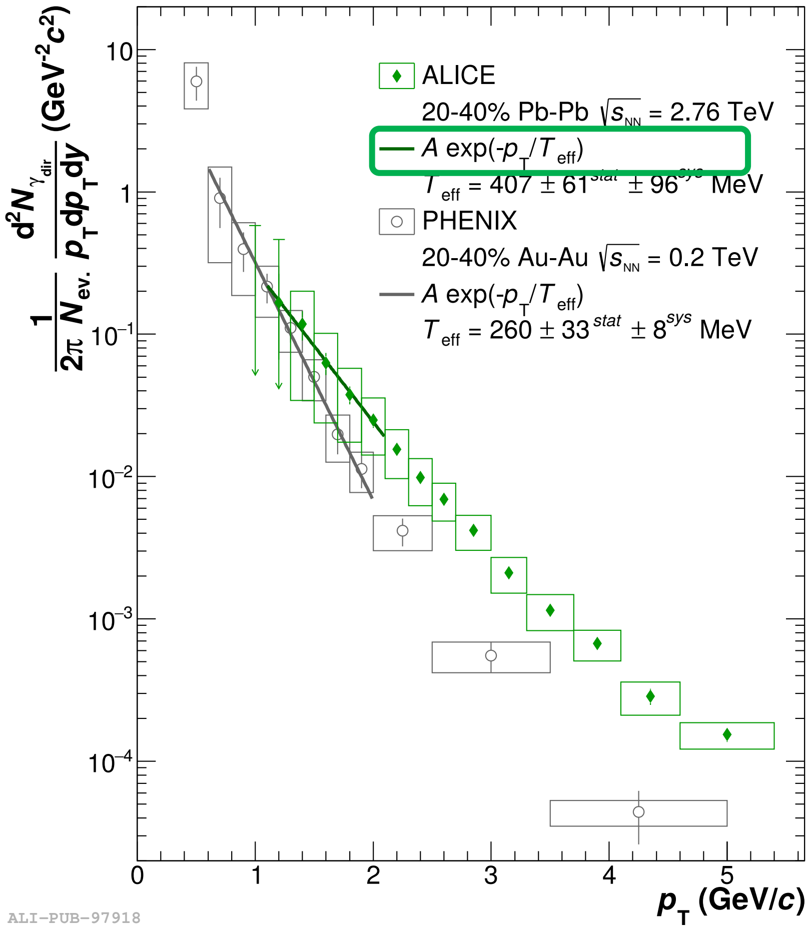
Effective temperature (T_{eff}) is extracted from the inverse logarithmic slope of the low-p_T region of the spectrum

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

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
⇨ model calculations that incorporate evolution of the QGP medium and radial flow effects (**blue-shift**)

Not yet attempted

Characterization of the time evolution of the collision

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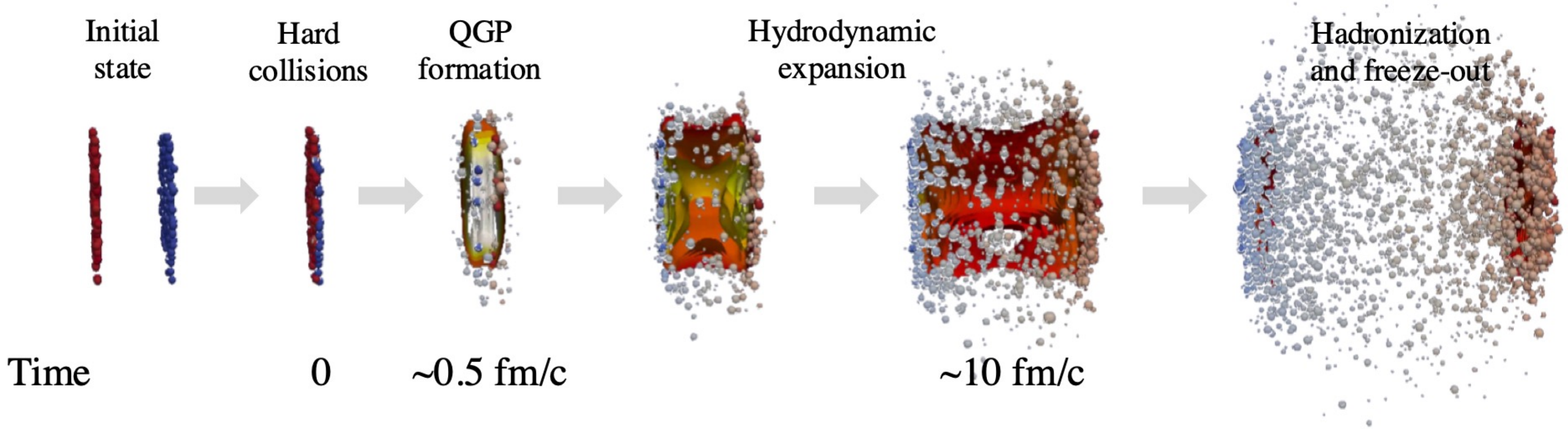
LHC Pb-Pb ⇨ **large energy density** (initial $\varepsilon > 15$ GeV/fm^3) & **large volume** (~5000 fm^3)



Visualization by J.E. Bernhard, arXiv:1804.06469

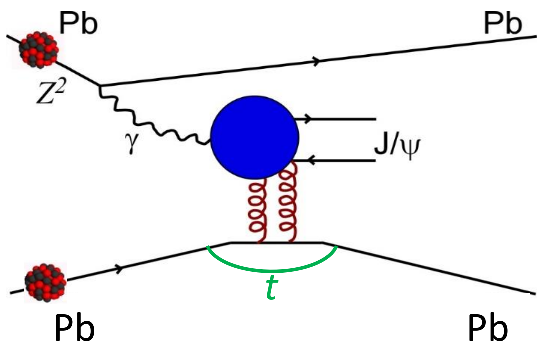
Study the time evolution of the collision

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

⇨

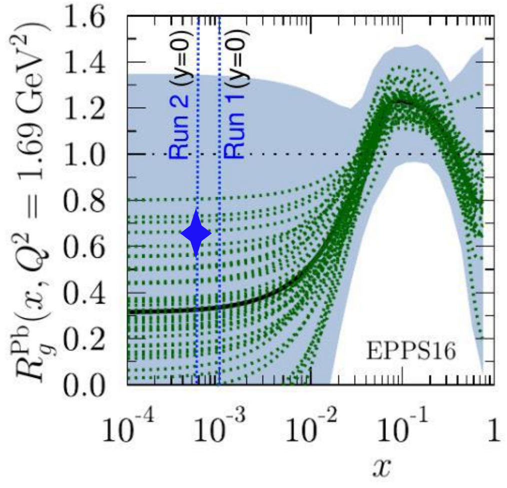
- Light flavour (including light-nuclei) production
- Heavy flavour production
- Quarkonia
- Photons, low-mass dileptons
- Jets
- Ultra Peripheral Collisions

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



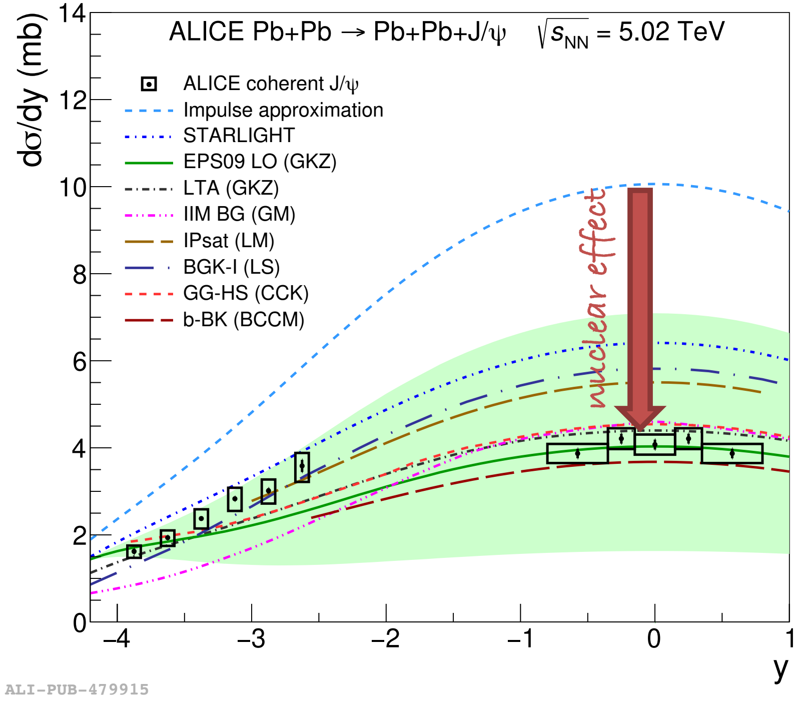
$$\left.\frac{d\sigma_{\gamma A\to J/\psi A}}{dt}\right|_{t=0} = \frac{M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{em}Q^8}\left[xg_A(x,Q^2)\right]^2$$

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

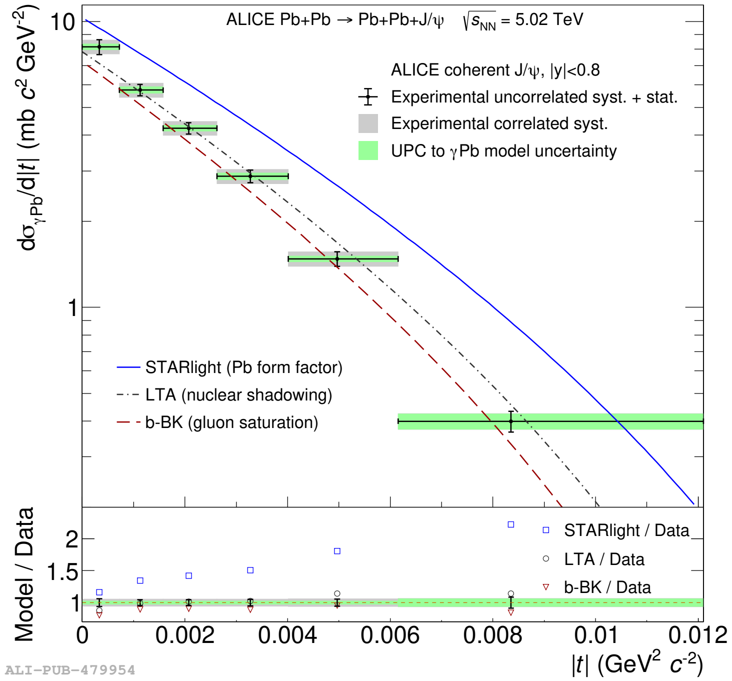


$$R_g^A(x,Q^2) = \frac{g_A(x,Q^2)}{Ag_p(x,Q^2)}$$

arXiv:2101.04577



arXiv:2101.04623

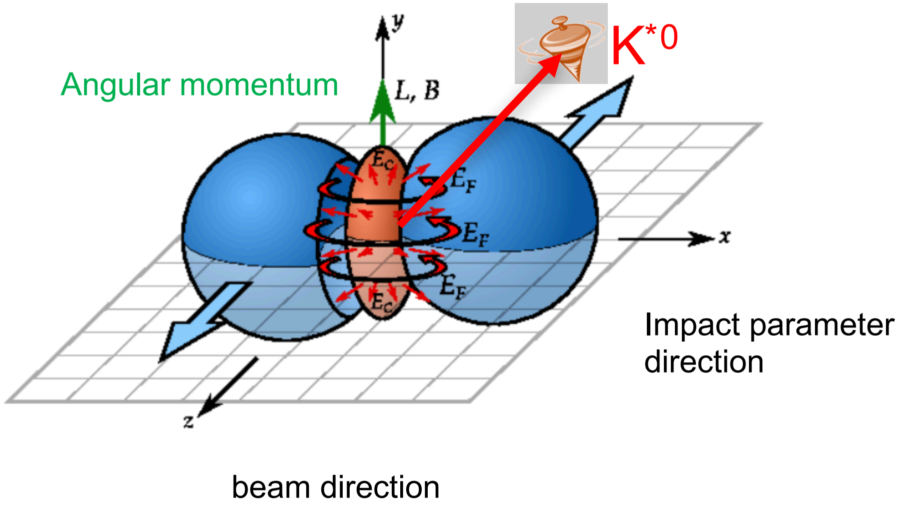


$|t| \approx p_T^2$

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

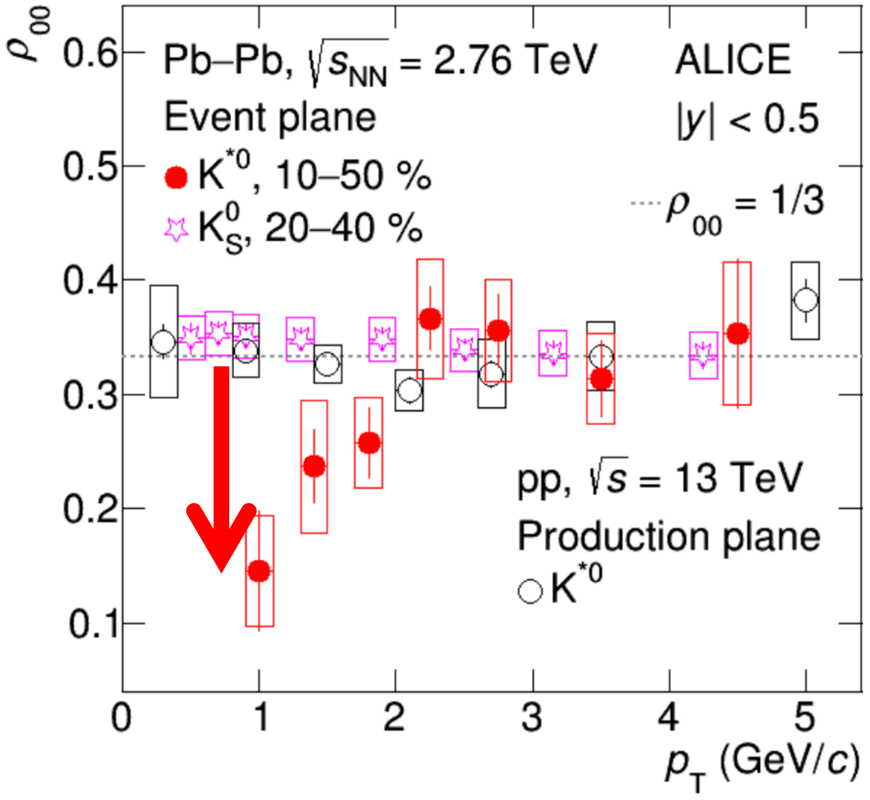


- Large angular momentum **L** in non-central collisions → **rotating QGP** (~ **10^{21}** revolutions per second)
- spin-orbit interactions expected to polarize quarks
- If quarks recombine to produce vector mesons (spin=1), **spin alignment** could appear
- Measurement using **K^{*0} → $K\pi$** decays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

PRL 125 (2020) 012301

EDITORS' SUGGESTION

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



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

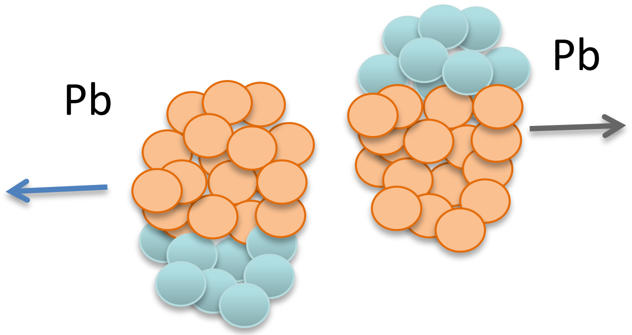
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

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**

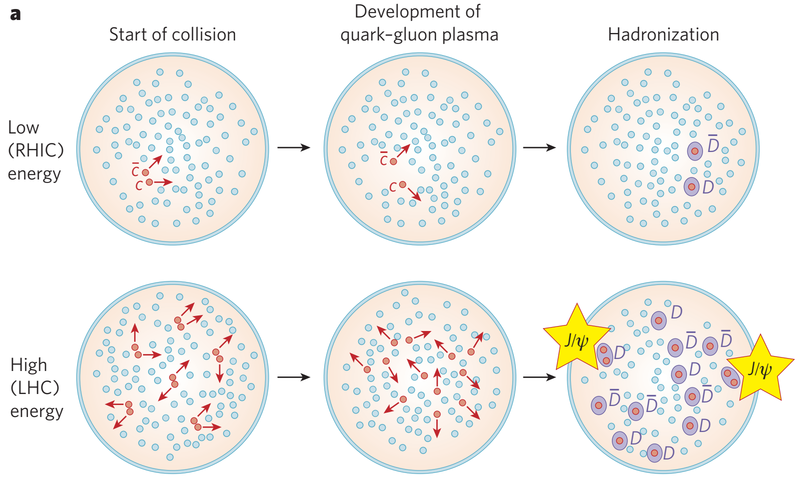
Quarkonia at the LHC

Suppression of quarkonium as QGP signature

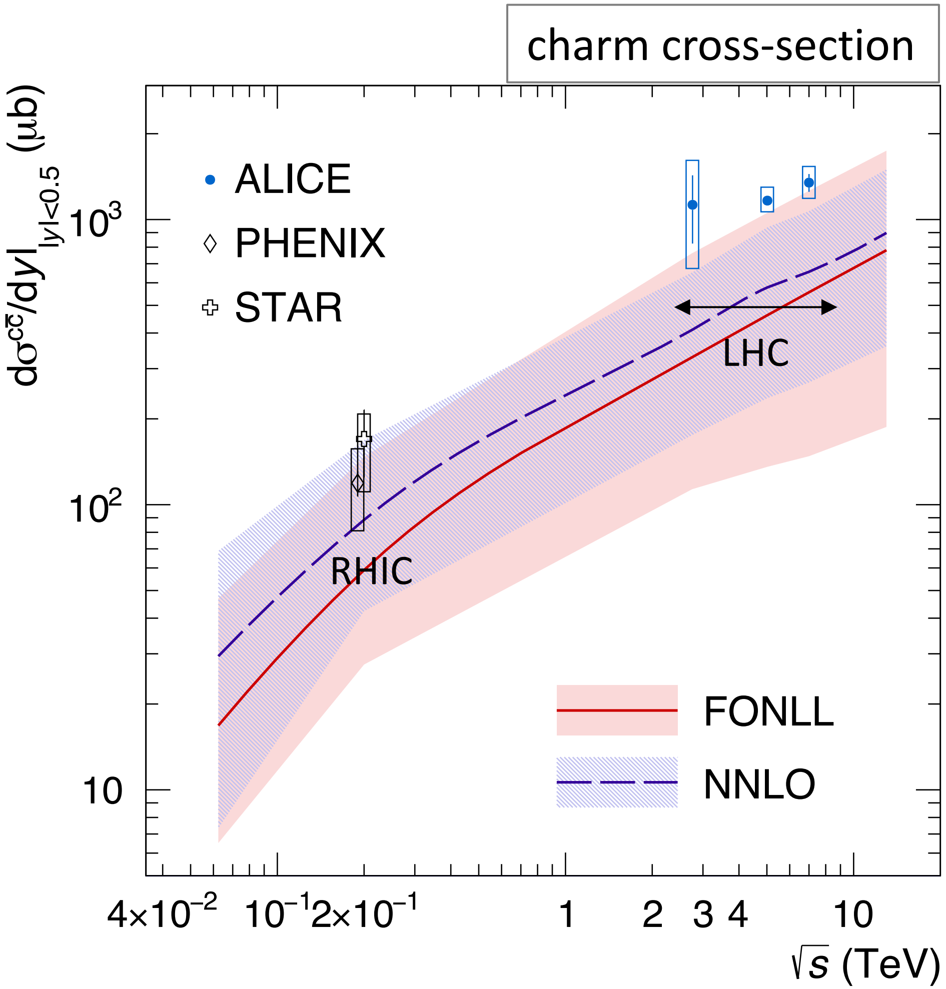
→ $q\bar{q}$ pairs are suppressed due to **color screening in the QGP**

→ 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)]



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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)

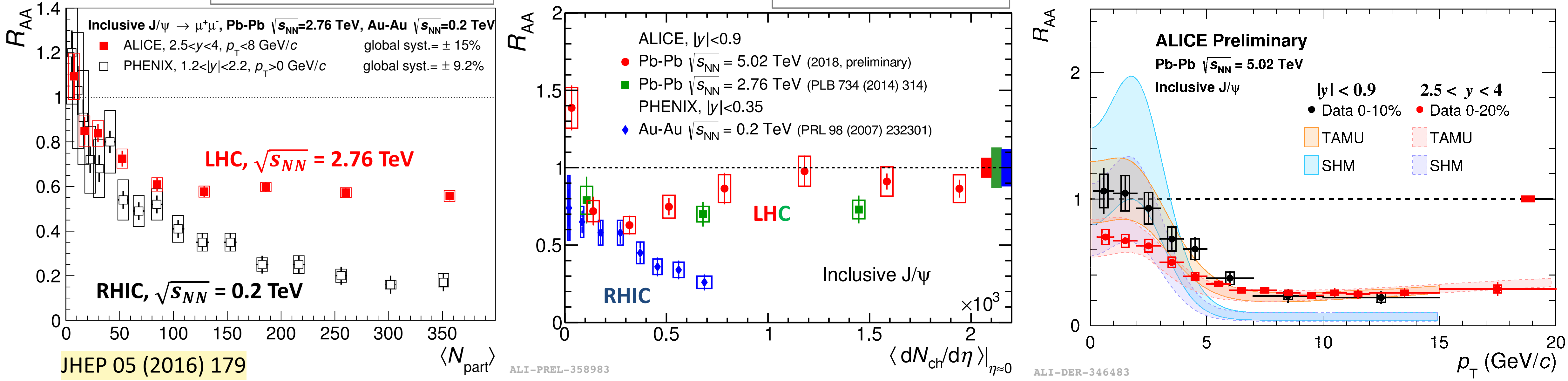
- cc regeneration counterbalances the suppression by screening in the QGP

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

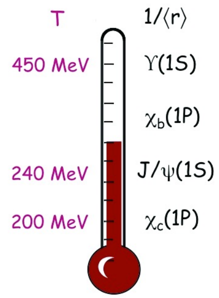


JHEP 05 (2016) 179

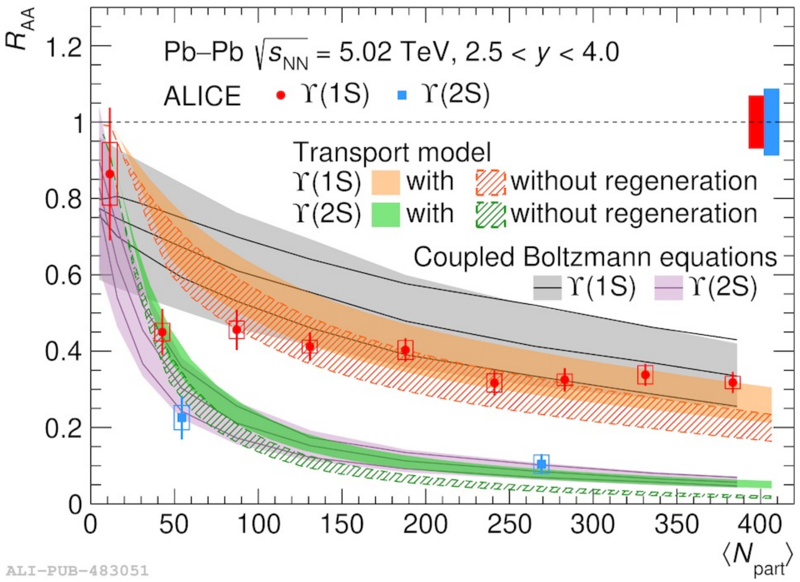
Suppression of bottomonia in Pb-Pb collisions

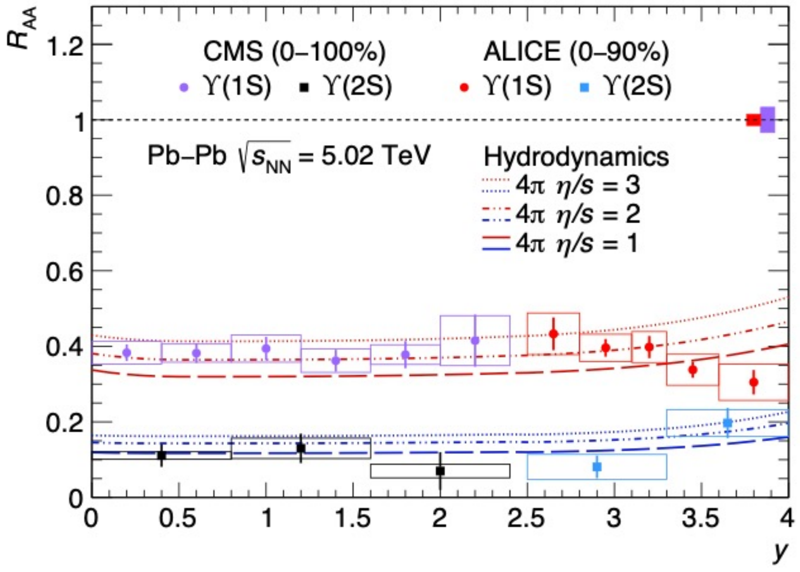
Varying the binding energy: ψ(2S) < Y(2S) < J/ψ < Y(1S)

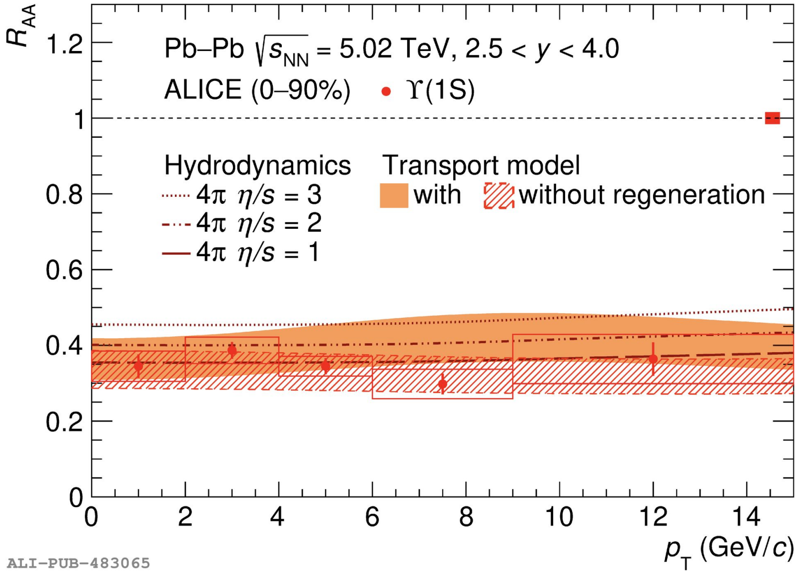
0.05 0.55 0.65 1.1 GeV



arXiv:2011.05758







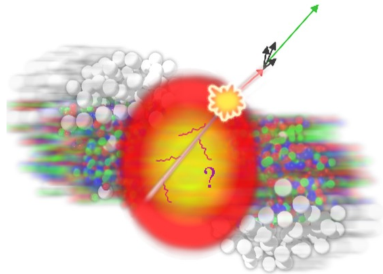
- Centrality dependence consistent with progressive suppression in a hotter medium
- Υ(2S) at forward rapidity - a suppression stronger wrt Υ(1S) consistent with lower binding energy
- Screening induces a strong suppression of Υ production, flat vs p_T ⇨ recombination effects small

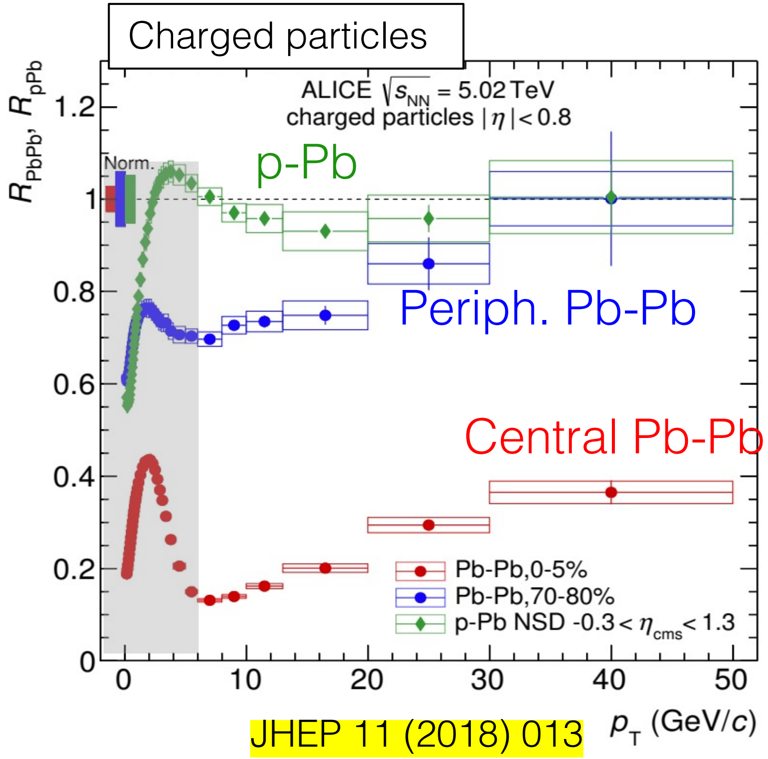
The nuclear modification factor R_{AA}

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

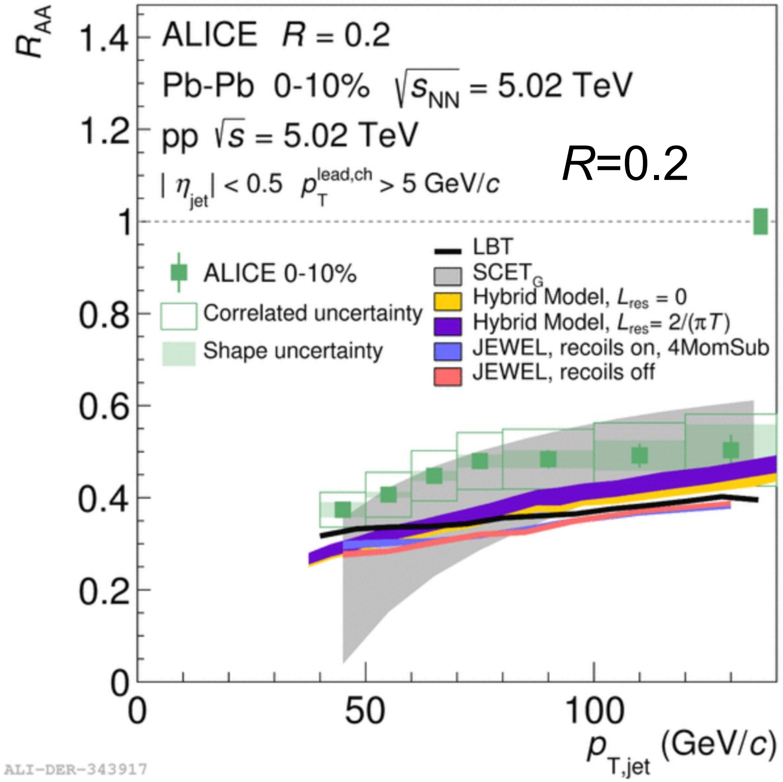


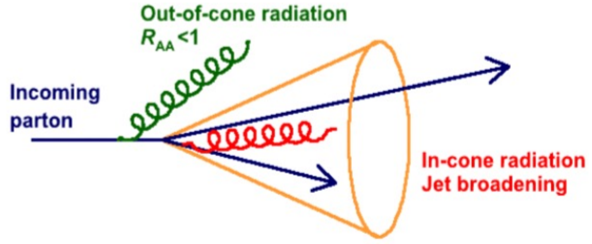


JHEP 11 (2018) 013

PRC 101 (2020) 3, 034911

with area-based background subtraction





Large reduction of jet yields down to 40 GeV/c

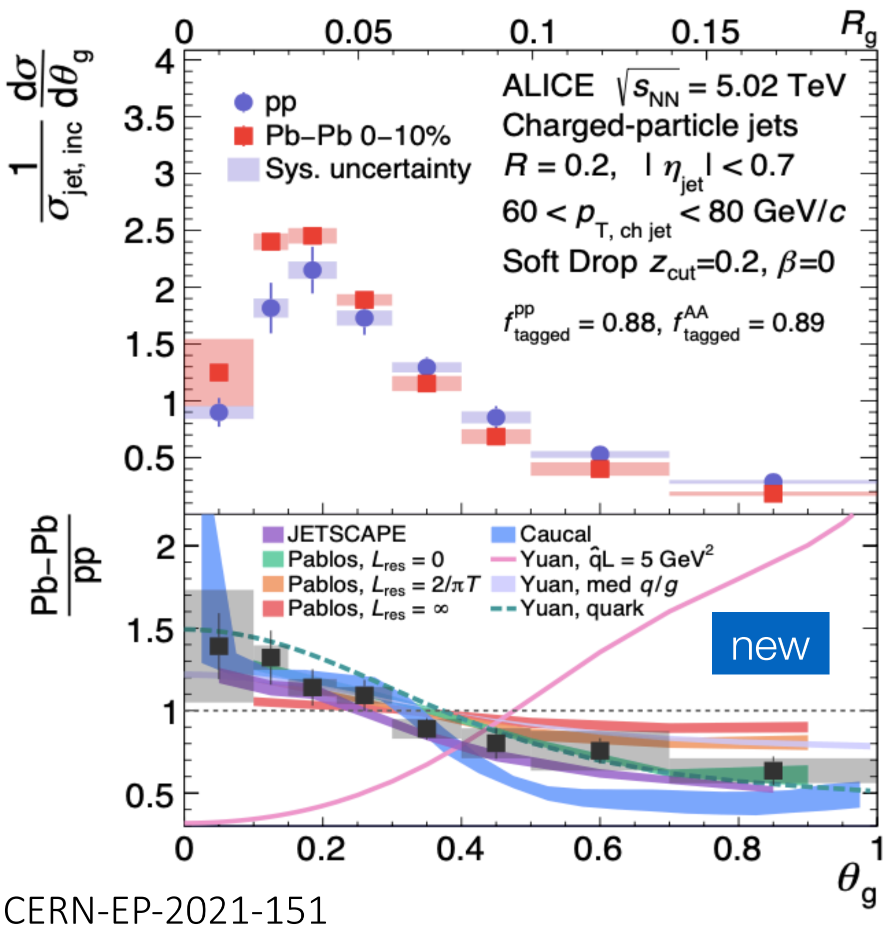
Lost energy not recovered within the jet “cone” (similar suppression for R = 04)

→ large angle QGP-induced gluon emission

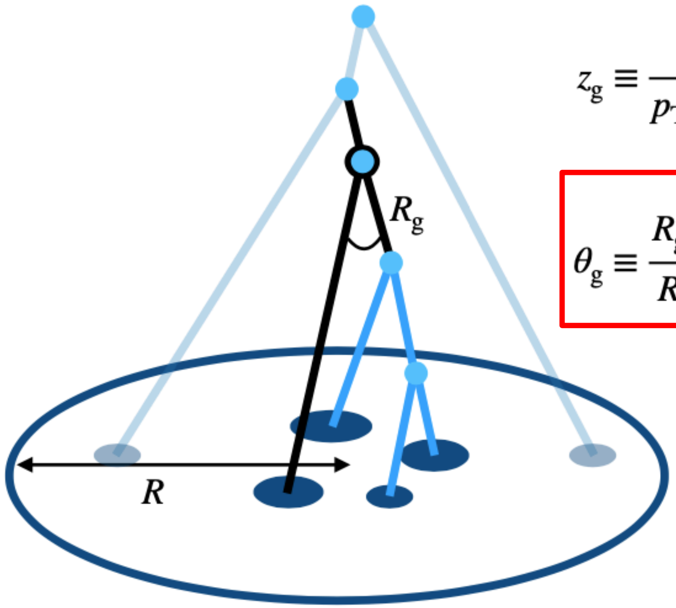
Exploring the QGP with jets

Study medium-modified parton shower

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



CERN-EP-2021-151

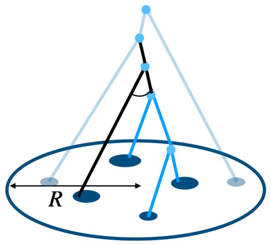


$$z_g \equiv \frac{p_{T,subleading}}{p_{T,leading} + p_{T,subleading}}$$

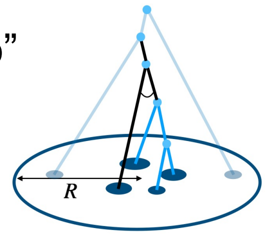
$$\boxed{\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}}$$

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

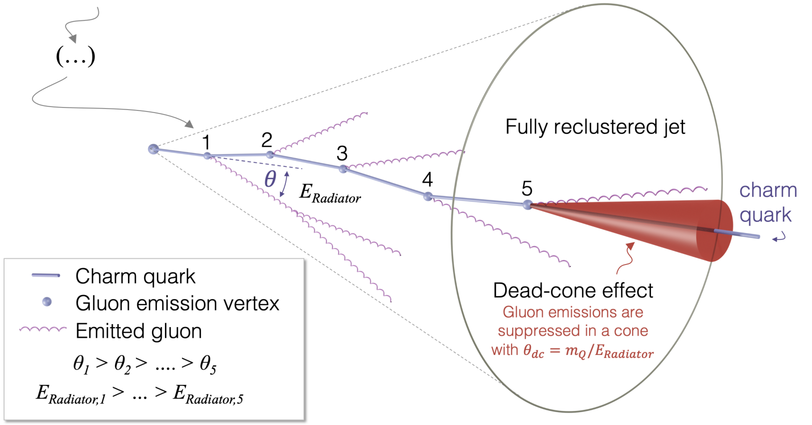
Cartoon: “pp”



“Pb-Pb”



QCD interlude: dead-cone effect now ‘seen’ in pp

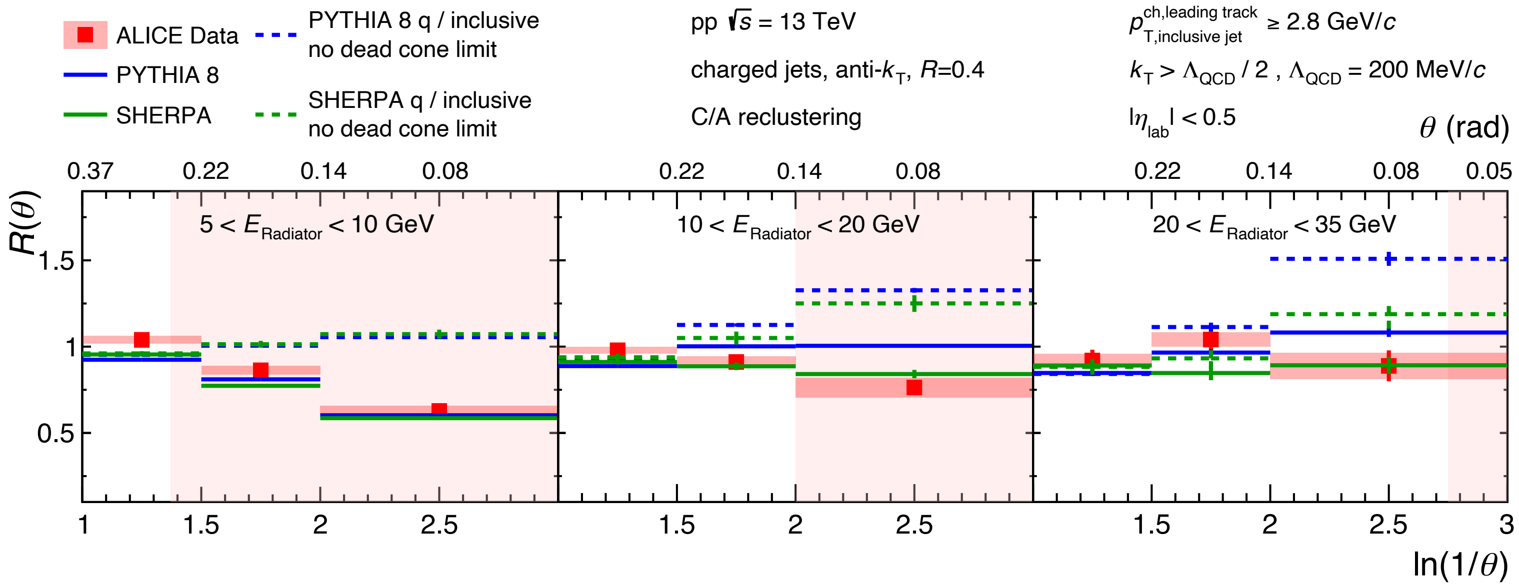


by measuring D^0-meson tagged jets in hadronic collisions (pp 13 TeV)

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 $E_{radiator}$

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



Radiation suppressed in the expected angular region (shaded)

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

arXiv: 2106.05713 [nucl-ex]

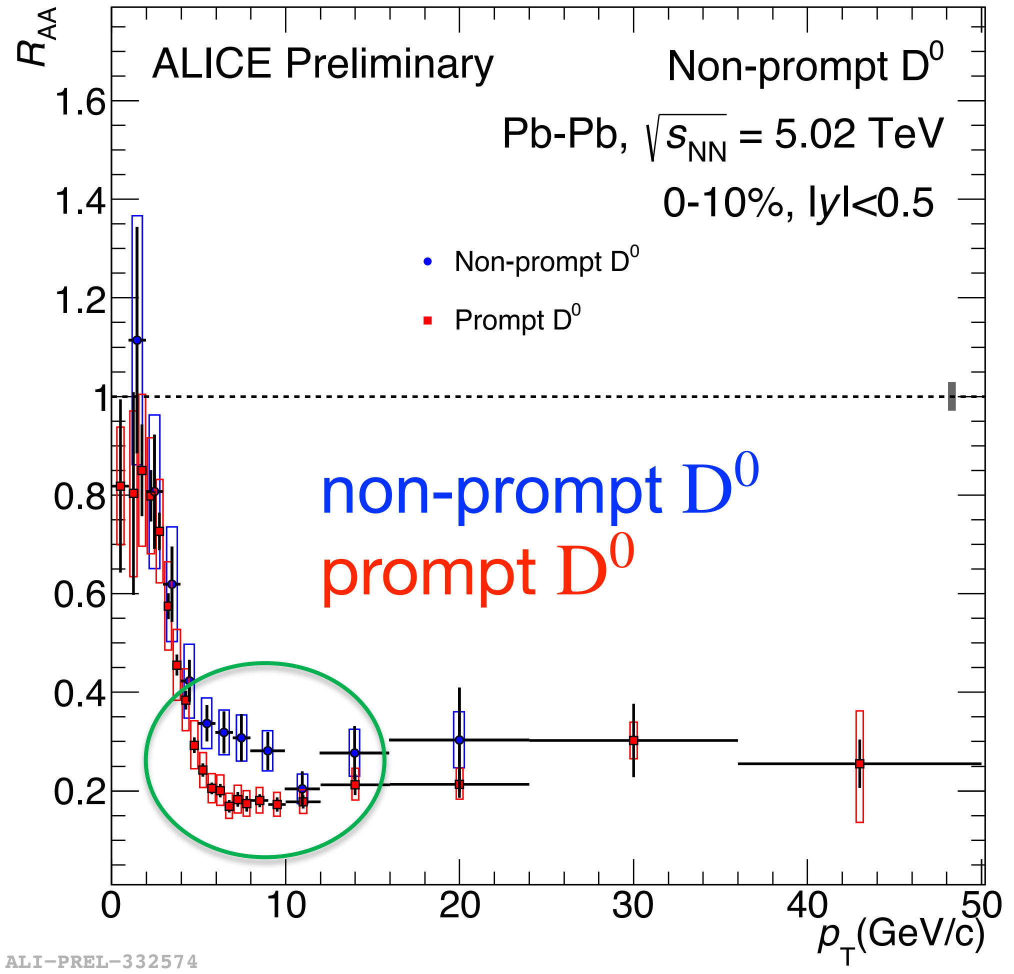
Energy loss of c and b quarks in the QGP

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

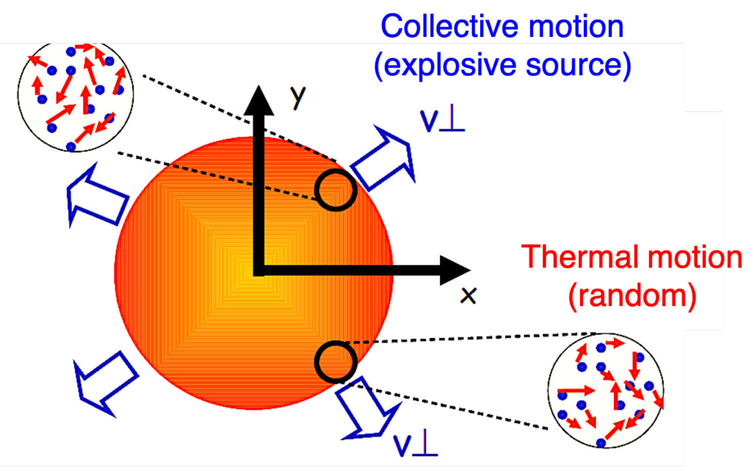
Isotropic Radial flow is a natural consequence of any interacting system expanding into the vacuum under a common velocity field

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

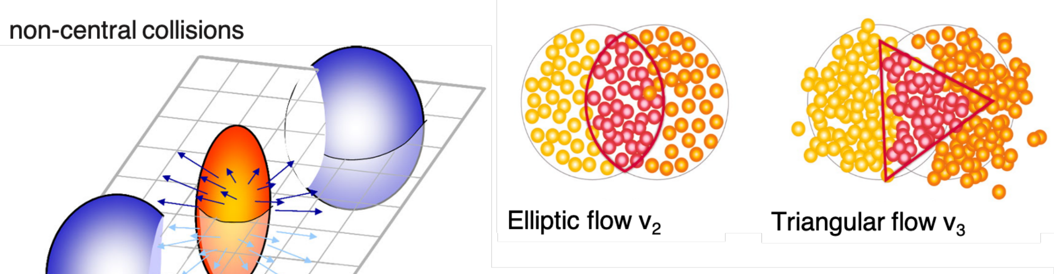
Anisotropic flow:
Pressure gradients convert spatial anisotropy into observable **momentum anisotropies**

- 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

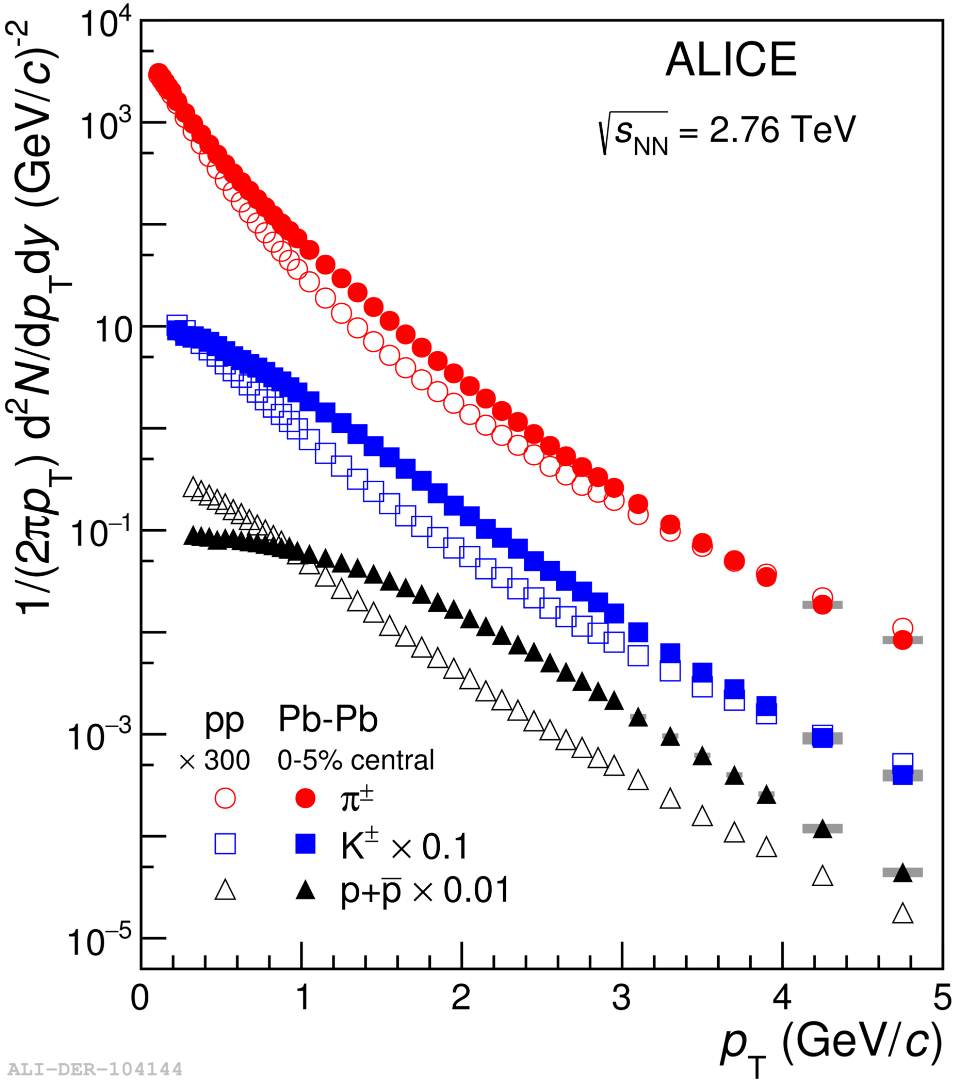


Anisotropic flow



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

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* > *π*) as *velocities* become equalized in the flow field (p = βγ·m)
- Hydrodynamic models show a good agreement with the data.

Elliptic flow of hadrons … and also light nuclei

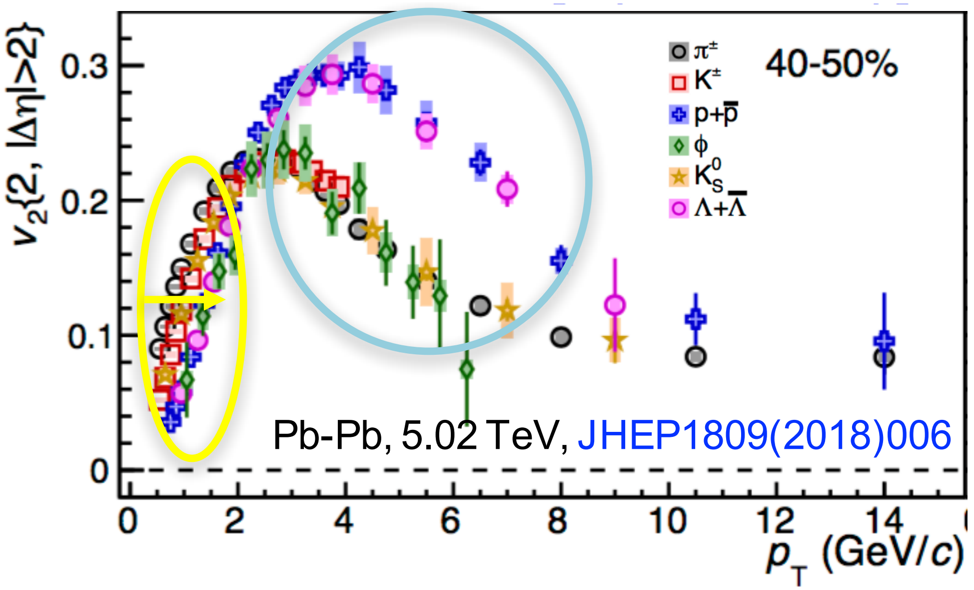
Nearly all particles species partcipate in collective flow, even A=2 and A-3 light nuclei

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

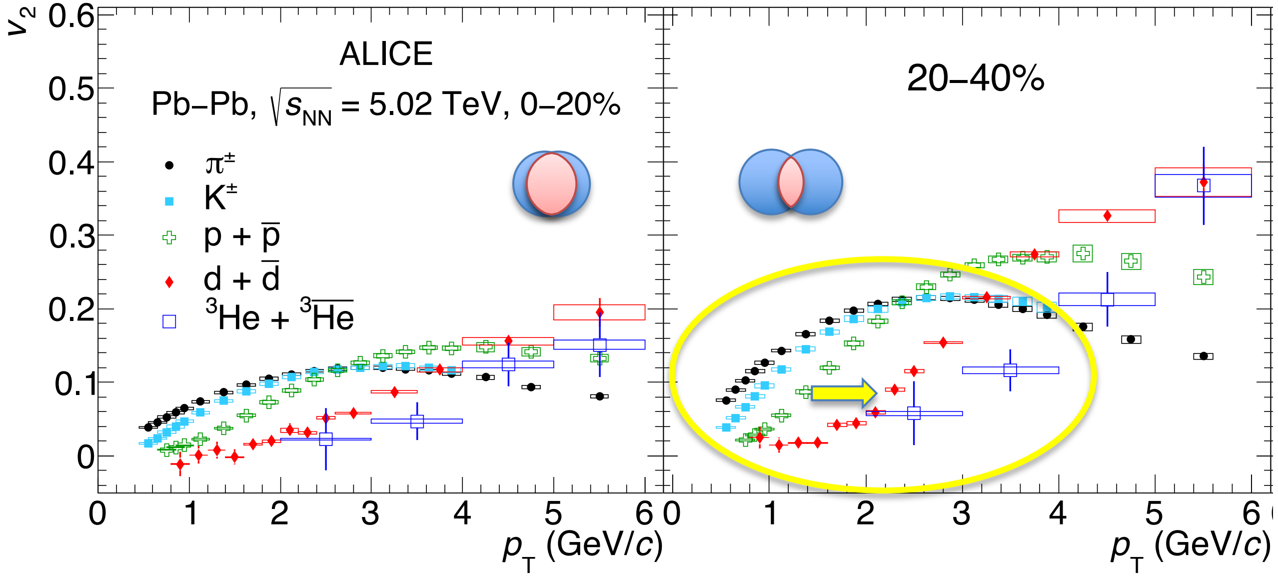
p_T < 2-3 GeV/c - from collective dynamics during hydro expansion (heavier hadrons shifted to higher p_T by radial flow

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

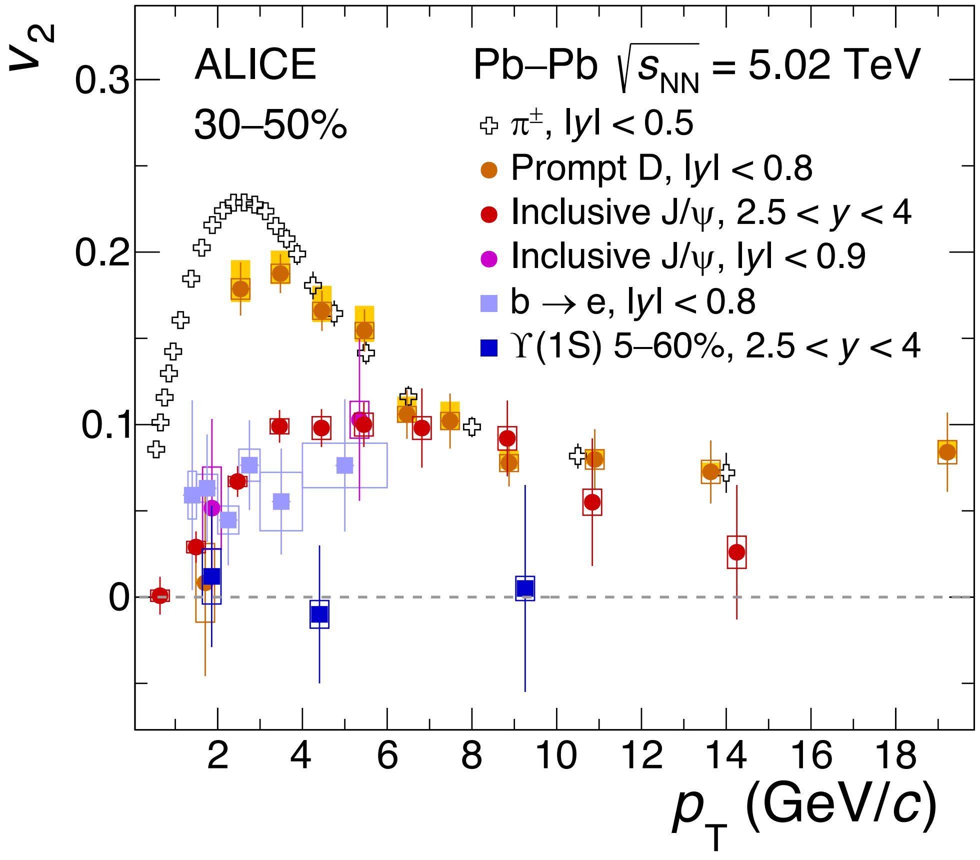
Model description indicates c quark thermalisation time ~3-8 fm/c < QGP lifetime

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

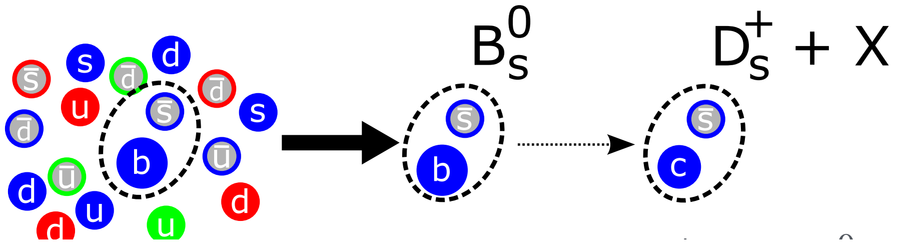
b → e: arXiv: 2005.11130 Y(1S): PRL 123(2019)192301

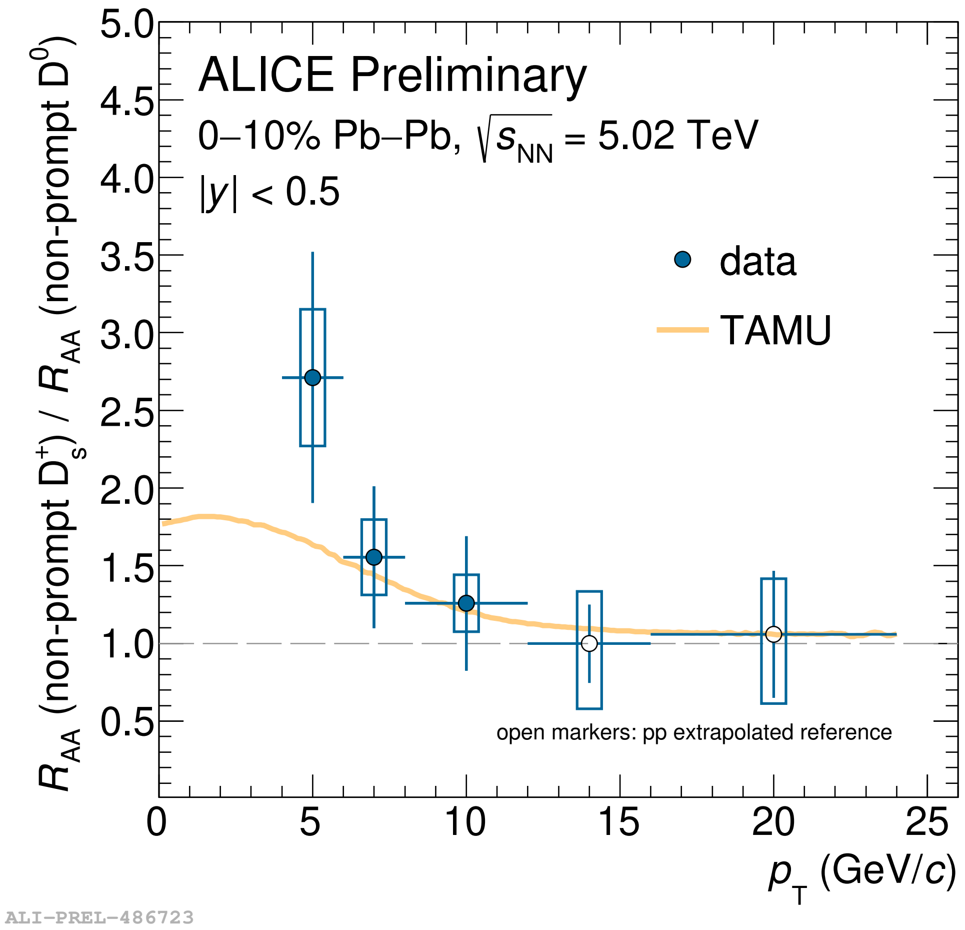
Energy loss and hadronization of c and b quarks in the QGP

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)



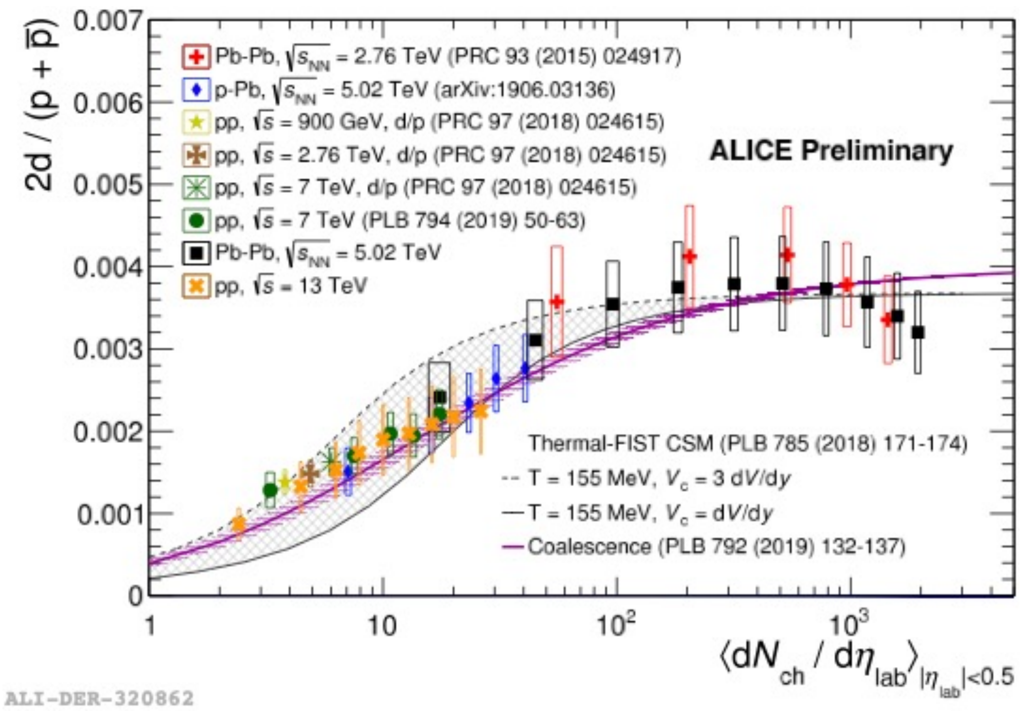


From hadrons to light nuclei

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

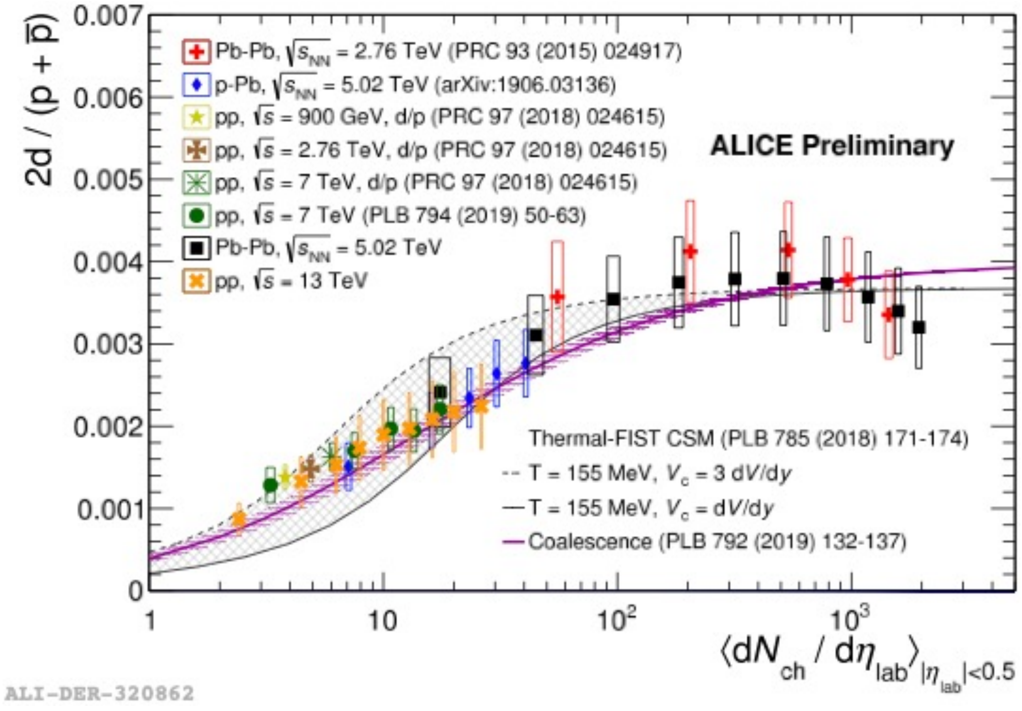
- cluster forms when nucleons are close in phase space
- dependence on the source size
- dependence on the nucleus internal structure

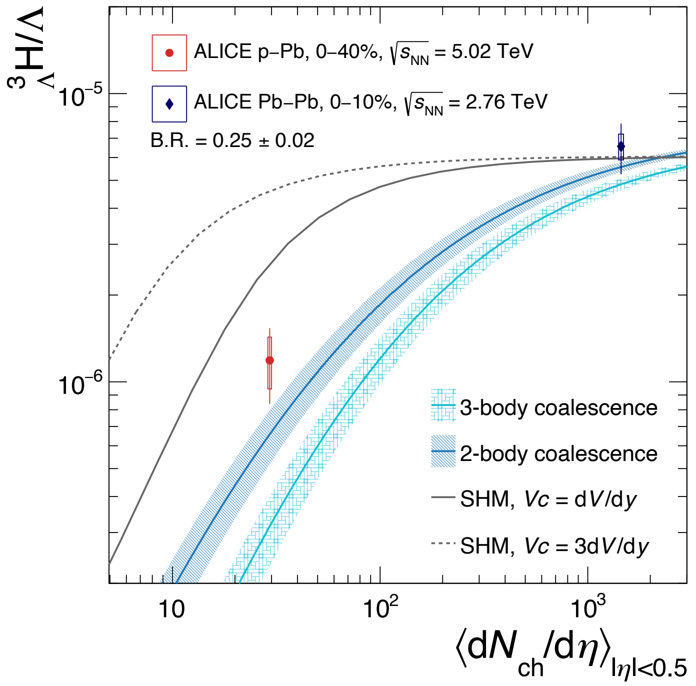
➪ test with **hypertriton** (Λpn):
loosely bound ($B_\Lambda \sim$ 130 keV) and large (r ~ 10-14 fm)

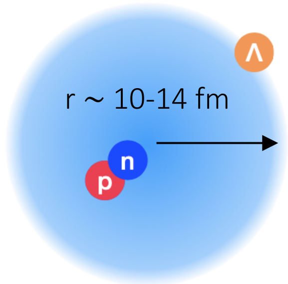
From hadrons to light nuclei

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 ~ 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

ALICE

Beyond QGP physics

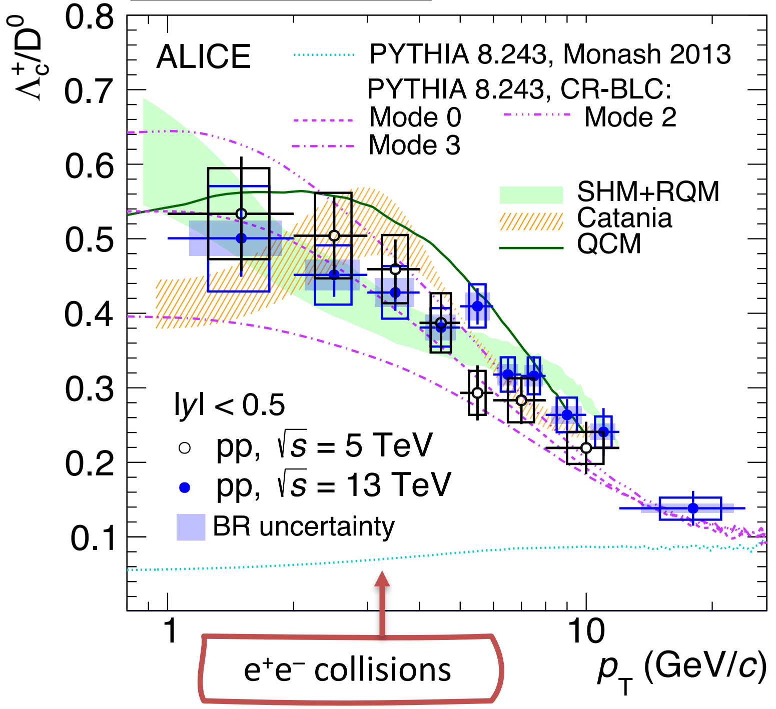
… a few examples

ALICE

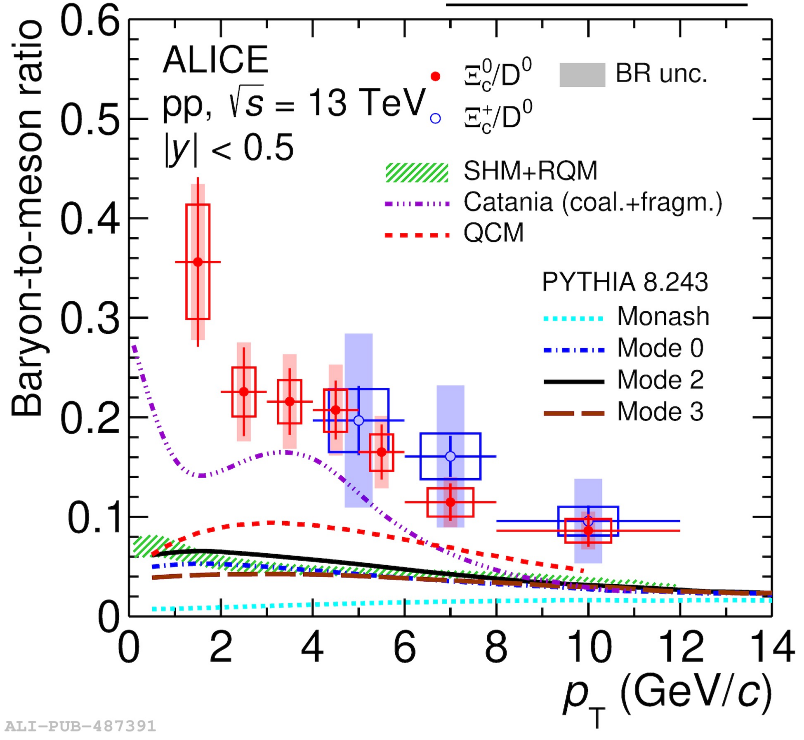
Charm baryon/meson measurements in pp collisions

Charm hadronization differs at the LHC

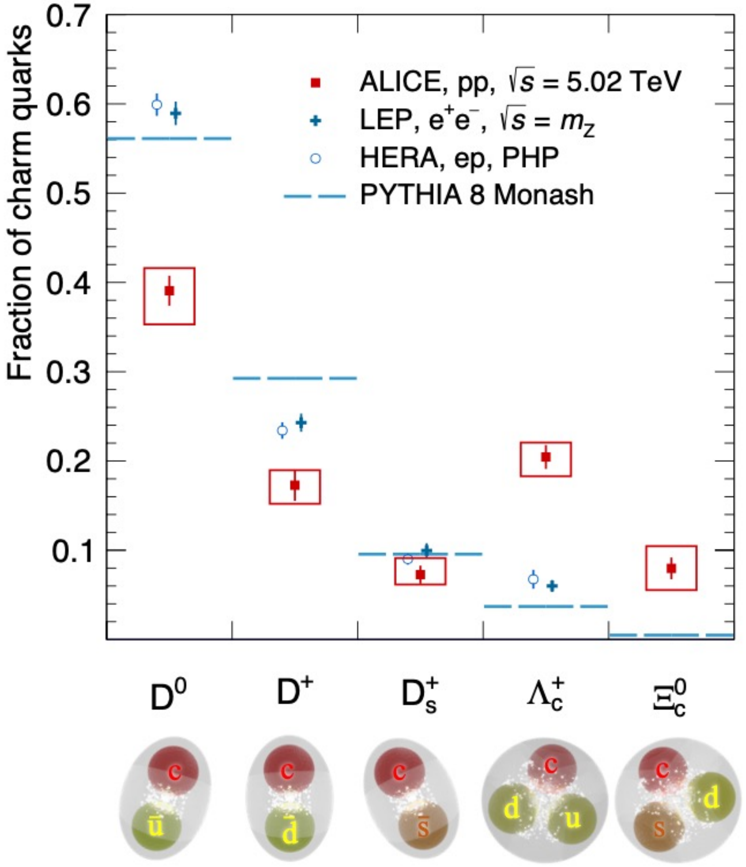
arXiv:2011.06078 arXiv:2106.08278



arXiv:2105.05187



arXiv:2105.06335

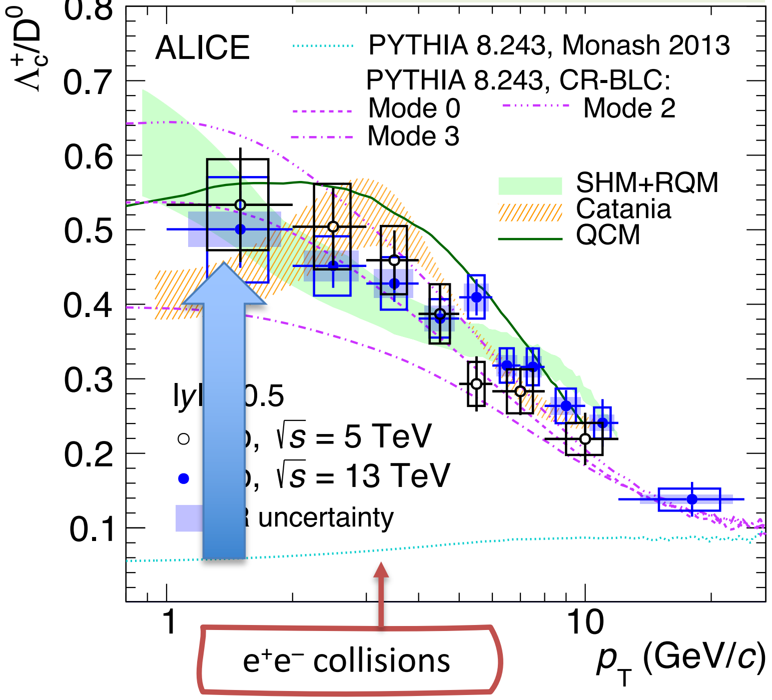


- unique measurements (at low-momenta) of Λ_c (also Ξ_c and Ω_c)
- cross section (fragmentation fraction) larger than expected (ee and ep)

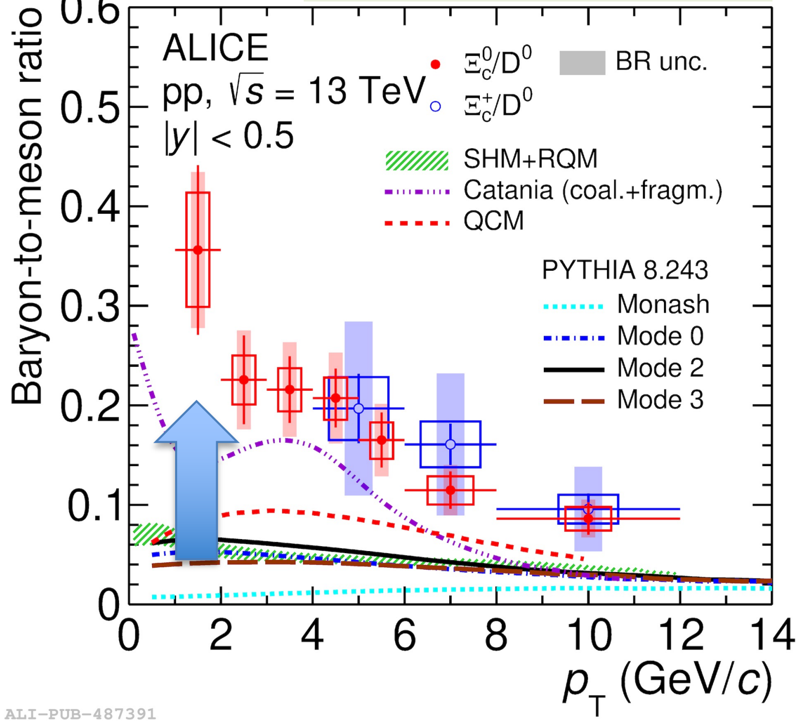
Charm baryon/meson measurements in pp collisions

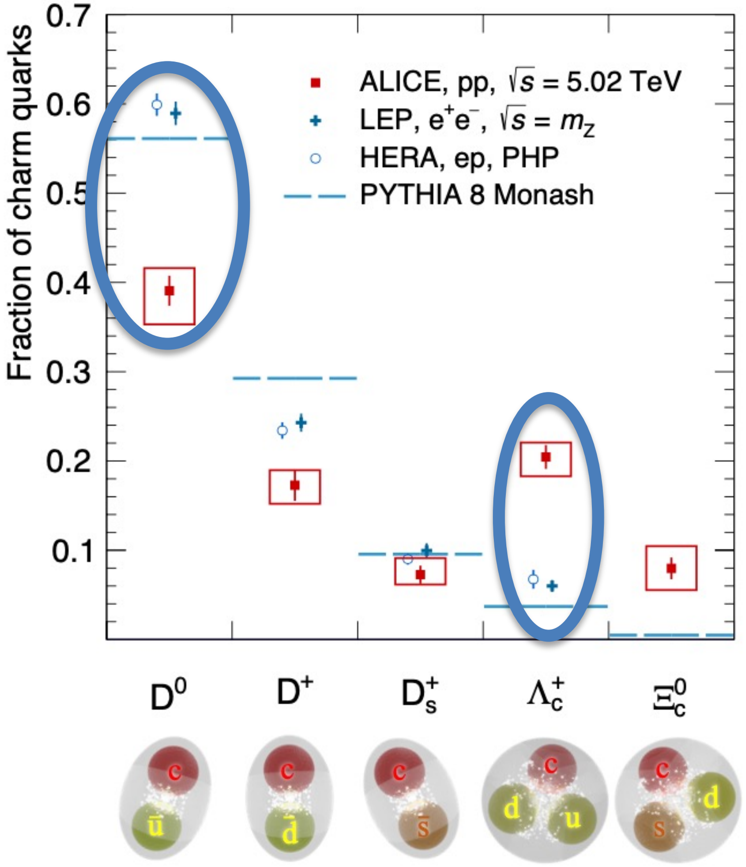
Charm hadronization differs at the LHC

arXiv:2011.06078 [nucl-ex]



arXiv:2105.05187 [nucl-ex]

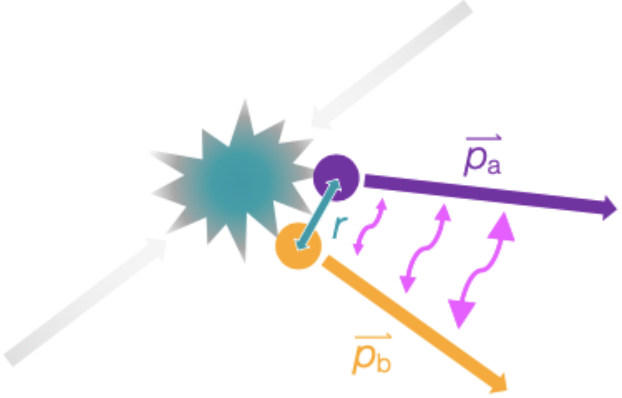




- unique measurements (at low-momenta) of Λ_c (also Ξ_c and Ω_c)
- cross section (fragmentation fraction) larger than expected (ee and ep)

Strong interaction between hadrons

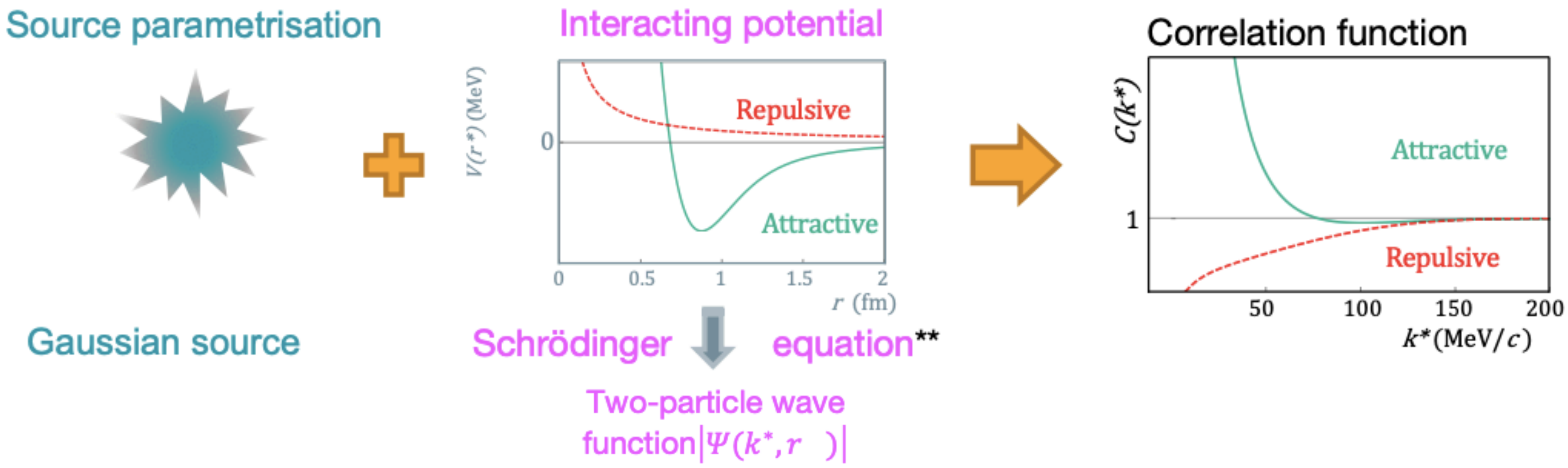
Correlation function sensitive to interaction potential



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

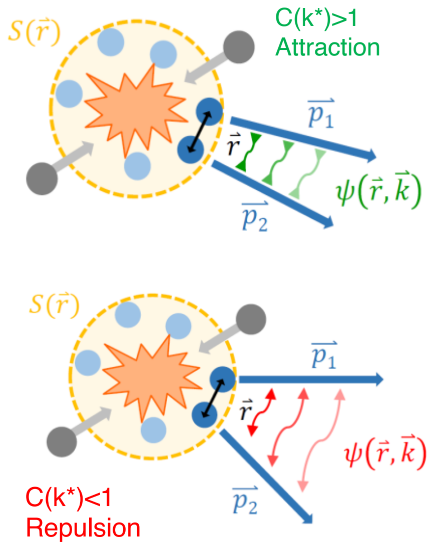


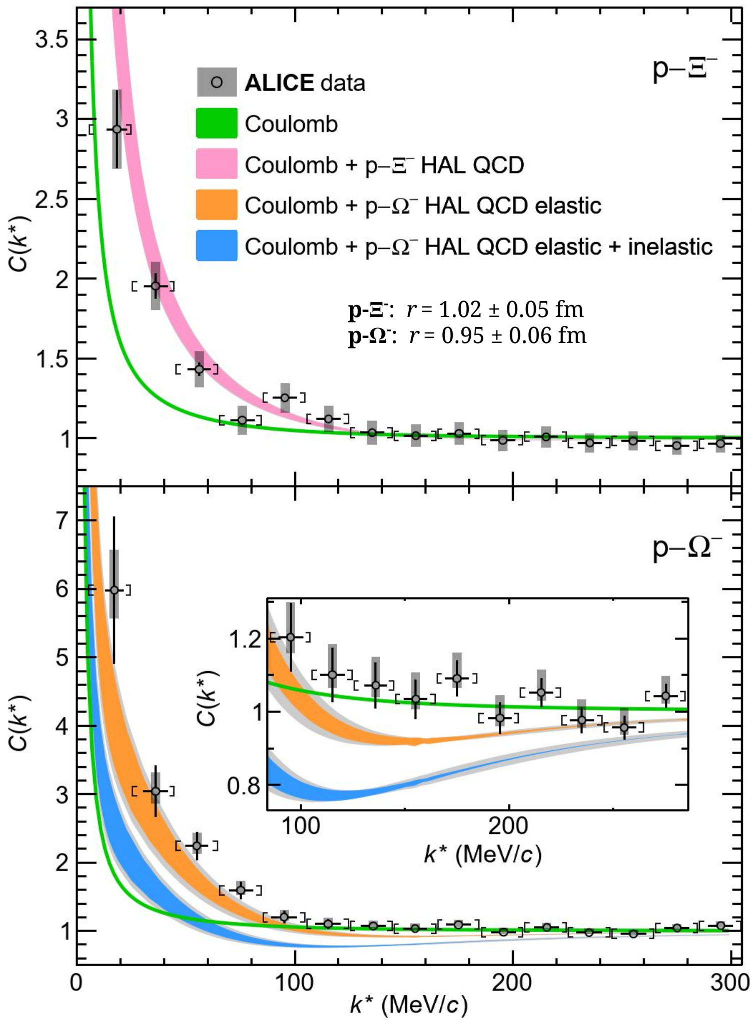
Strong interaction between hadrons

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





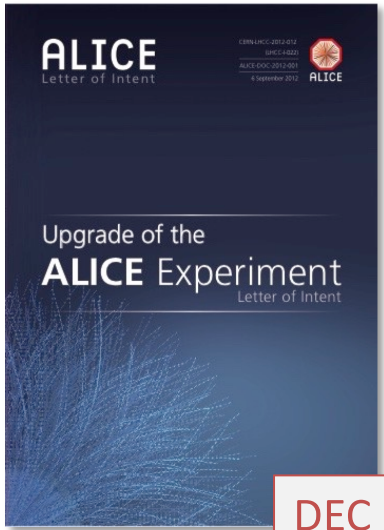
Proton-hyperon (p-Y) strong interaction poorly known

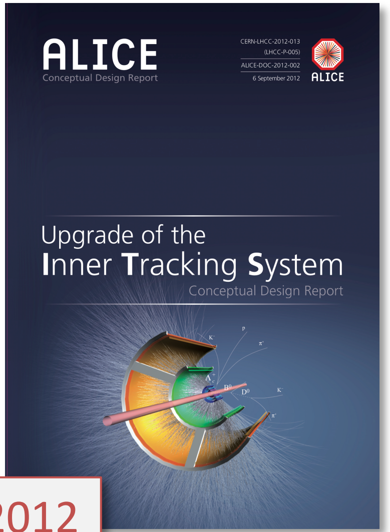
precise measurement of strong interaction for p-Ξ^- and p-Ω^-

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

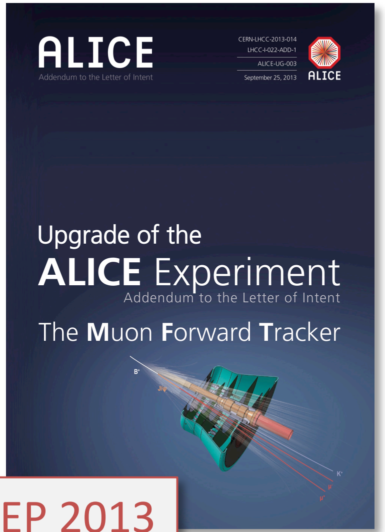
ALICE Upgrades
ongoing activties and future plans

ALICE Detector Version 2.0 (Upgrades for Run 3+)



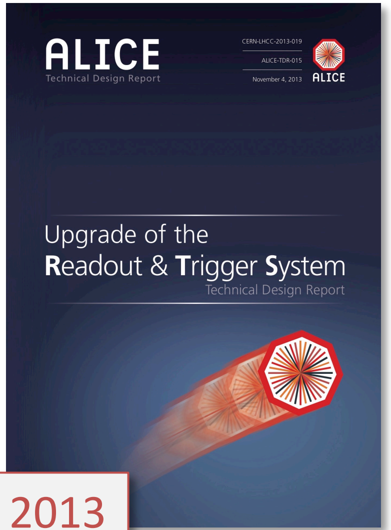


DEC 2012

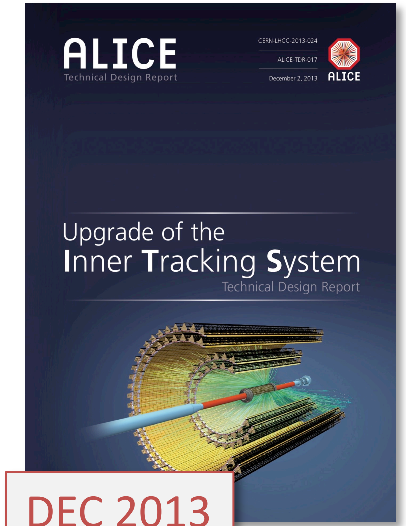


SEP 2013

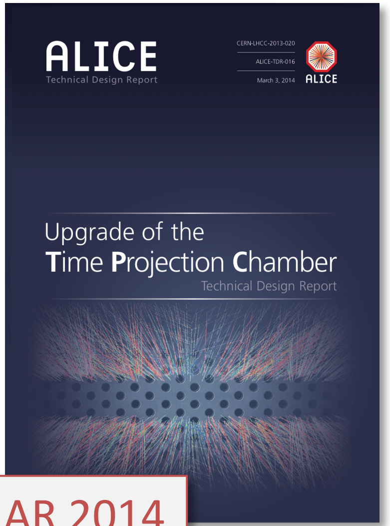
- From LoI to last TDR: 2013 – 2015 ✓
- Construction: 2016 – 2019 ✓
- Installation: 2020 – 2021 ✓
- Global commissioning: ongoing



NOV 2013

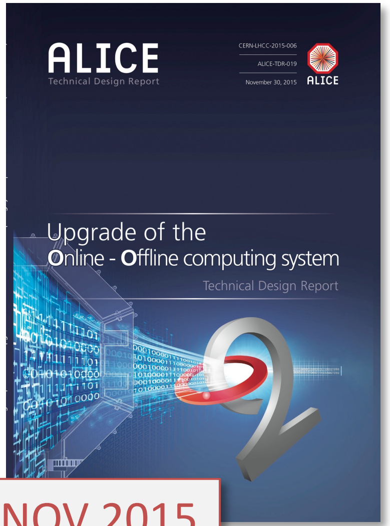


DEC 2013



MAR 2014

MAY 2015



NOV 2015

ALICE Detector Version 2.0 (Upgrades for Run 3+)

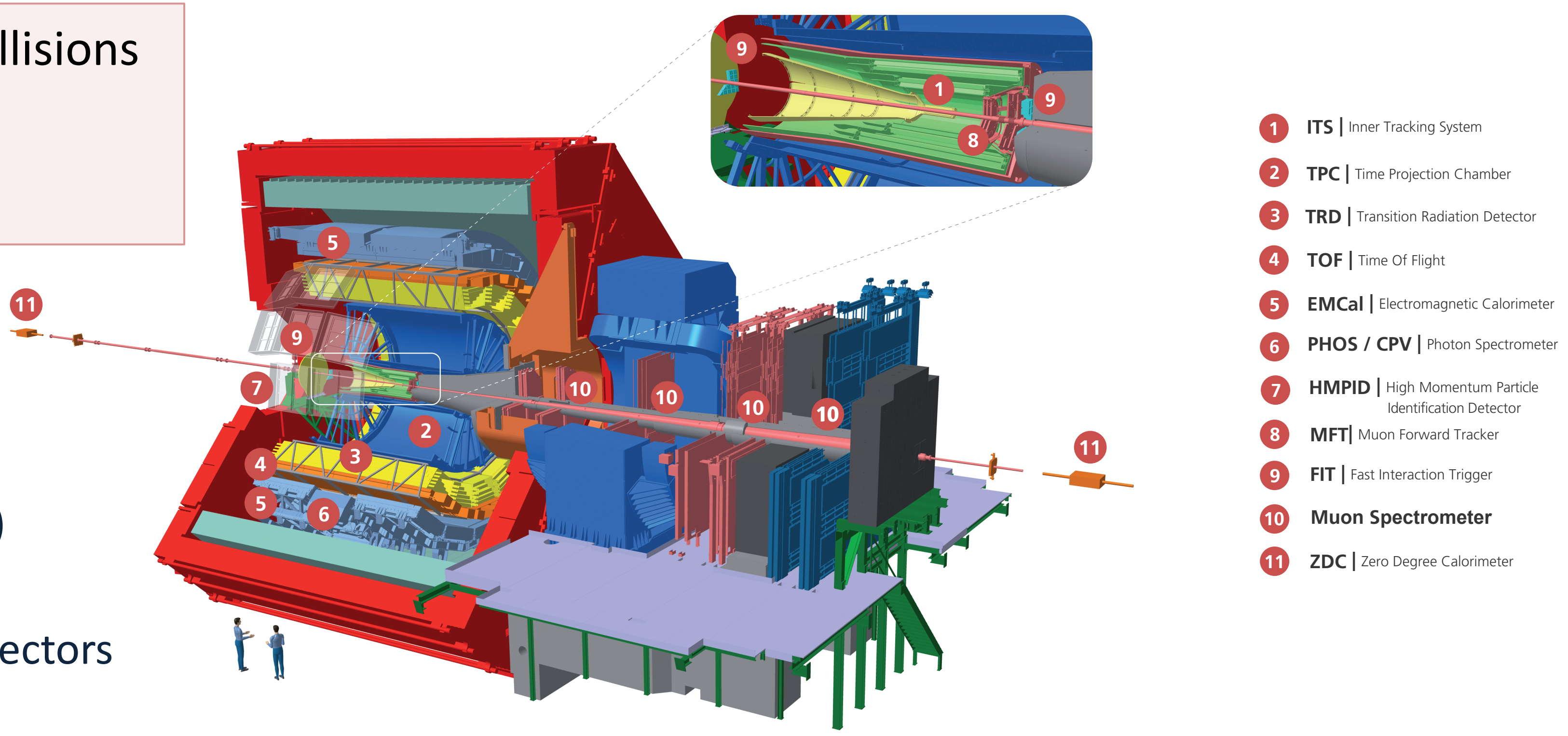
Runs 1 and 2: 1 nb^{-1} of Pb-Pb collisions

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

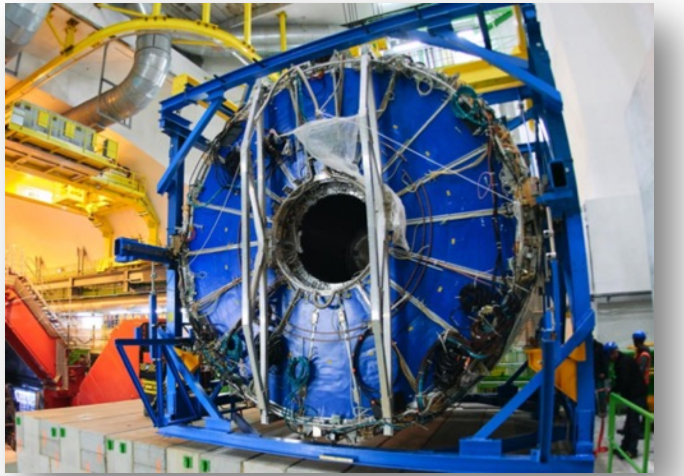
Run 3+Run 4: **13 nb^{-1} of Pb-Pb collisions**

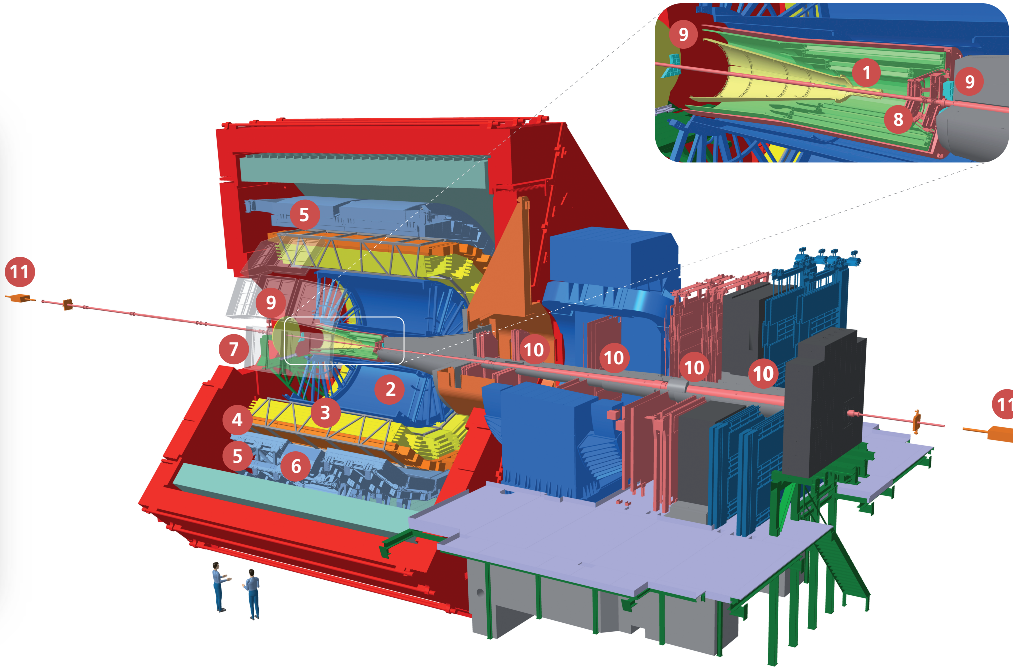
readout rate ≈ 50 kHz (Pb-Pb), ≈ 1 MHz (pp)

online reconstruction : all events to storage!

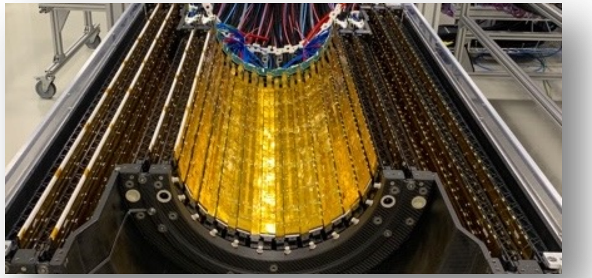
ALICE Detector Version 2.0 (Upgrades for Run 3+)

GEM-based TPC readout

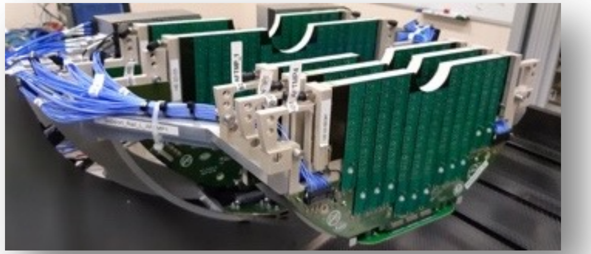




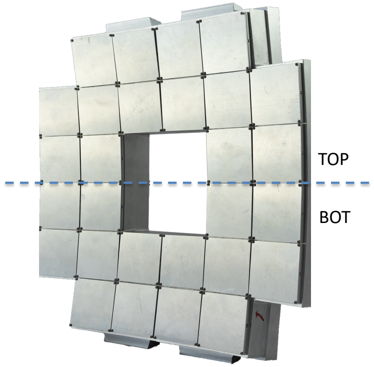
Monolithic-pixel - ITS2



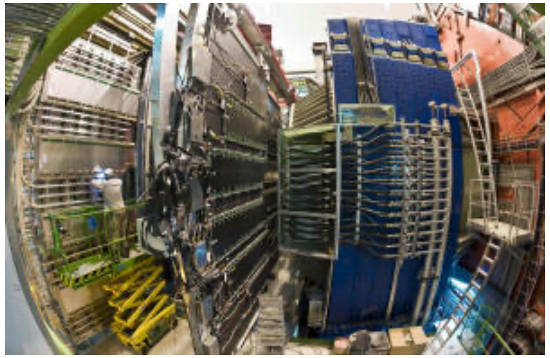
Pixel Muon Forward Tracker (MFT)



Fast Interaction Trigger FIT

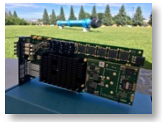


Muon Spectrometer



New Central Trigger Processor (CTP)

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

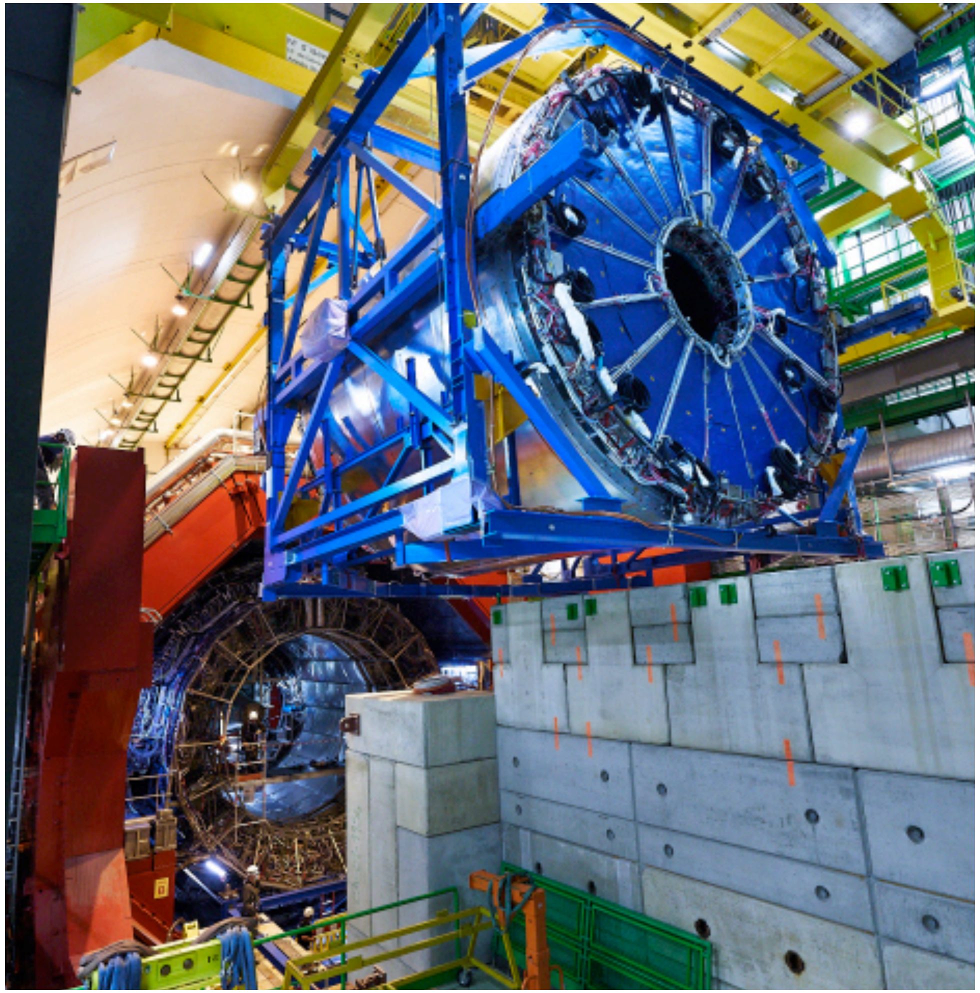


New Online/Offline (O2)

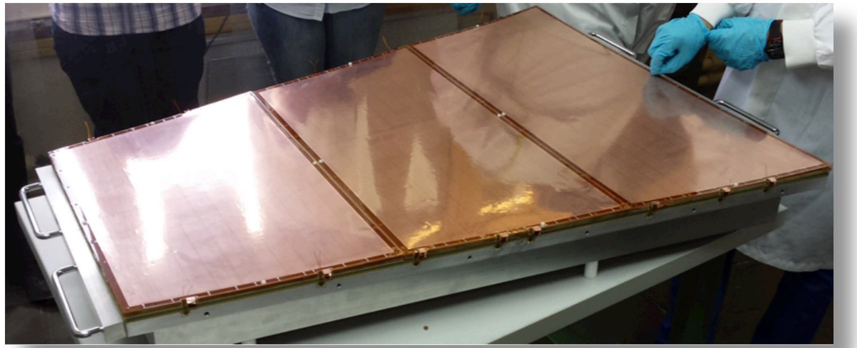
TPC Upgrade for continuous readout

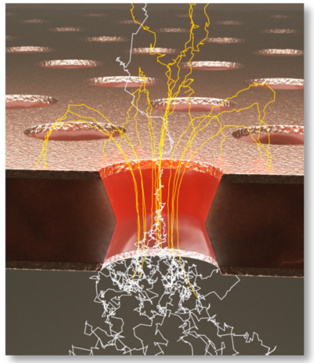
Goal: TPC continuous readout (➪ no gating grid)

Solution: Replace MWPC with 4-GEMs



100 m^2 single-mask foils GEM production



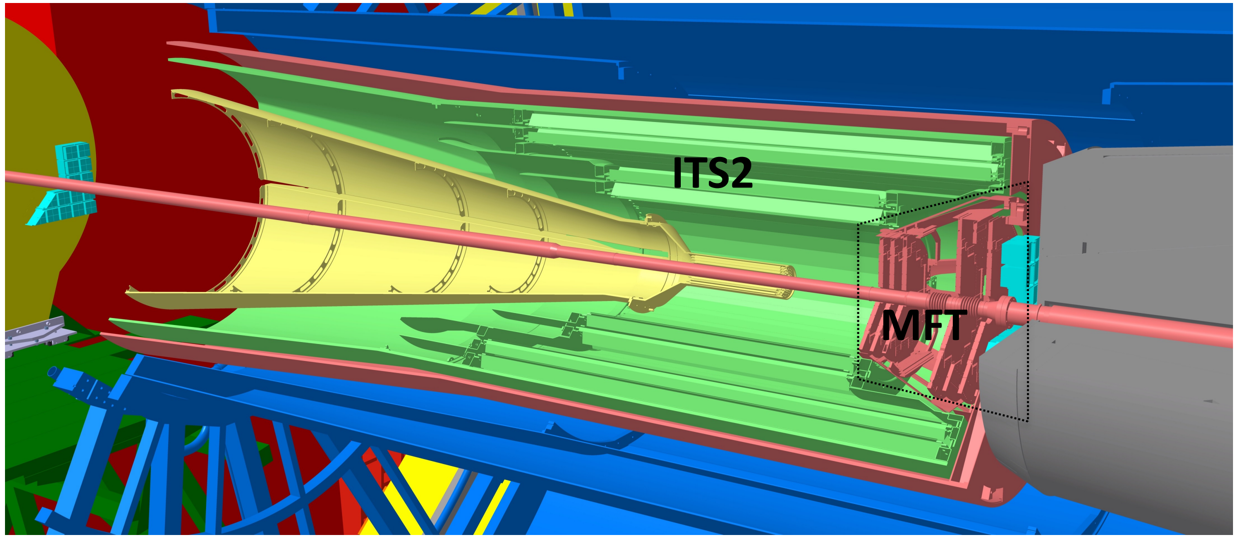


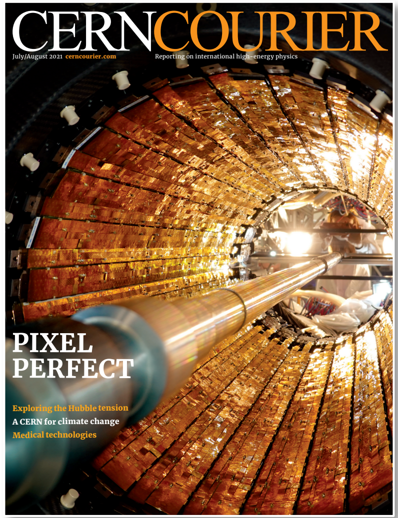
Read Out Chamber

➪ 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 m^2** active silicon area
- **12.5 G-pixels**
- **50 μm** thin sensor
- Spatial resolution **~5µm**
- Max particle rate ~ **100 MHz /cm^2**

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**)

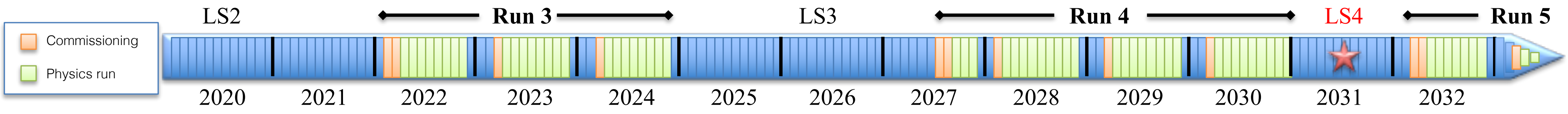
⇨ Improved tracking efficieny at low p_T

New Muon Forward Tracker (MFT)

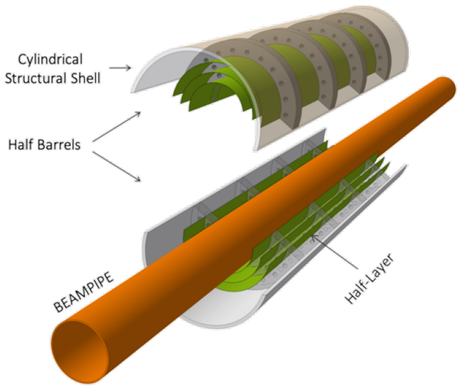
- New forward vertex detector upstream muon absorber

⇨ improved muon pointing resolution

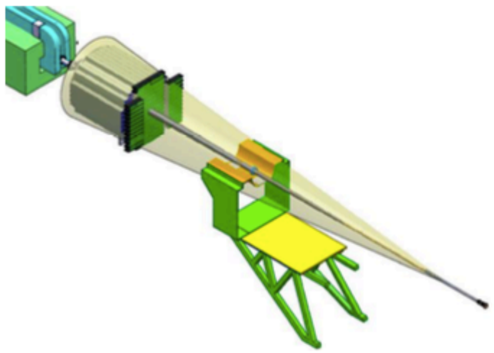
Perspectives: upgrades for Run 4, ALICE 3 for Run 5



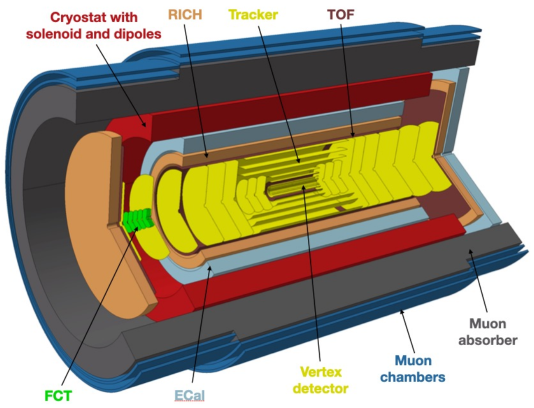
ITS3



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

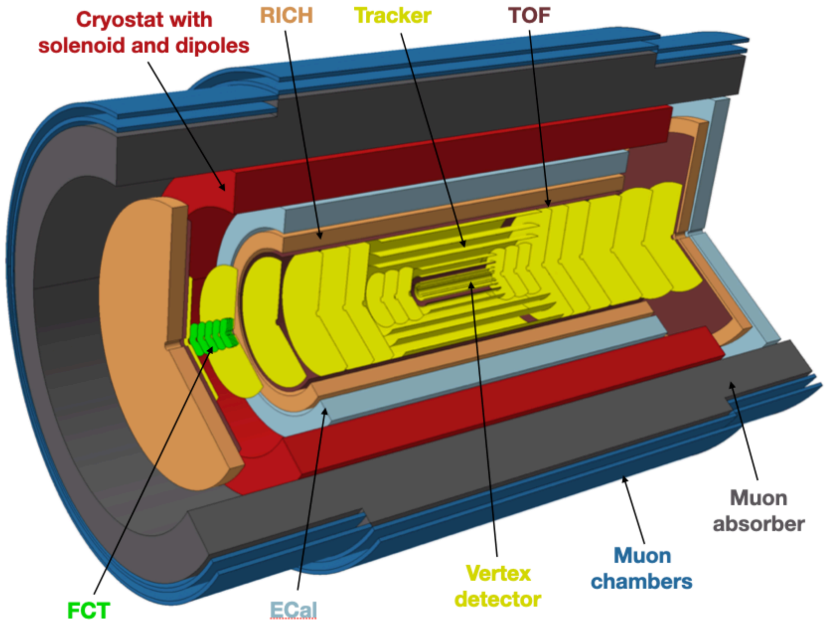
FoCal: forward EM calo with Si readout
for isolated γ measurement in $3.4 < \eta < 5.8$ in p-Pb

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, …

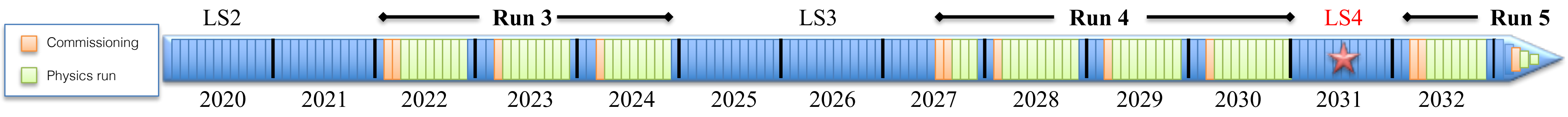


Expression of Interest arXiv:1902.01211

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:

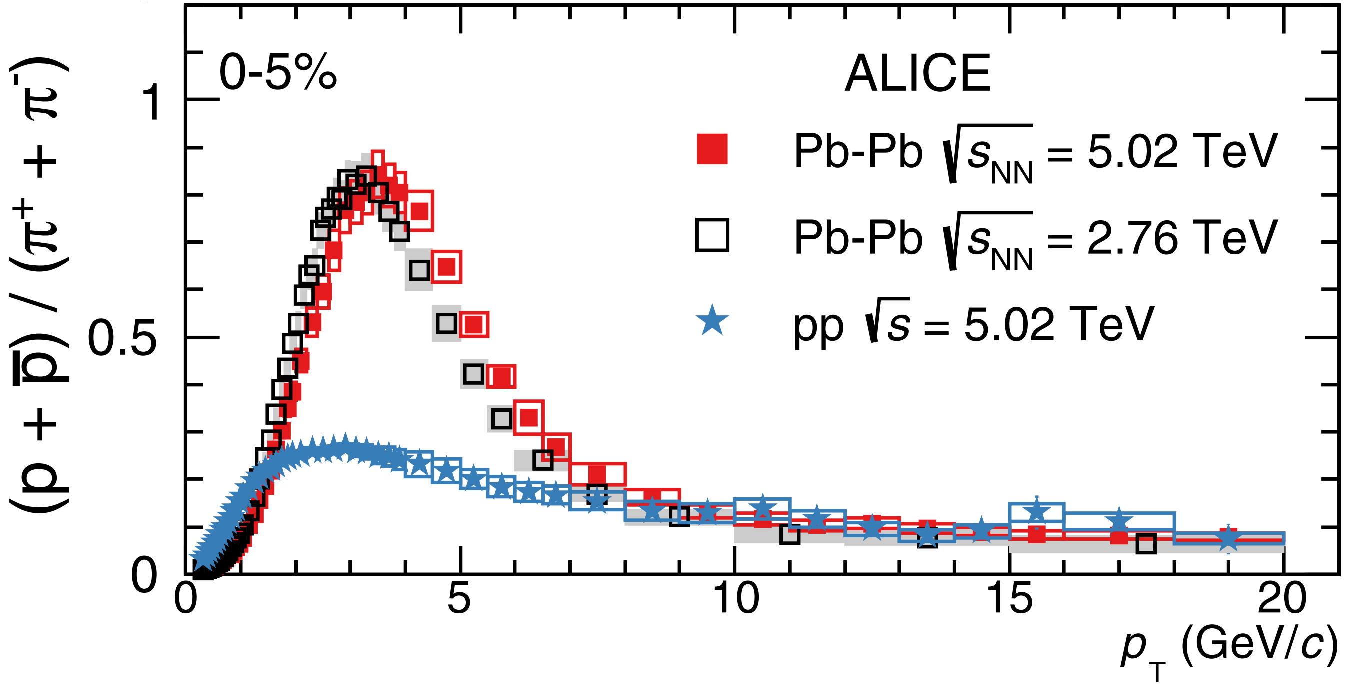
- Major upgrade for Run 3 on track (ALICE v. 2.0)
- In preparation: ITS3, FoCal for Run 4 (ALICE v. 2.1)
- Plans for next generation dedicated HI experiment for Run 5+ (ALICE v. 3.0)

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)

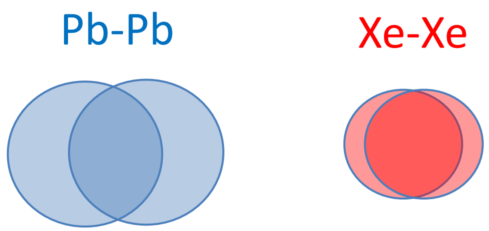


Radial and elliptic flow in AA collisions

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**)



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