Recent heavy-ion results from ALICE

Nicole Apadula for the ALICE Collaboration

14th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2022)

August 29 – September 4

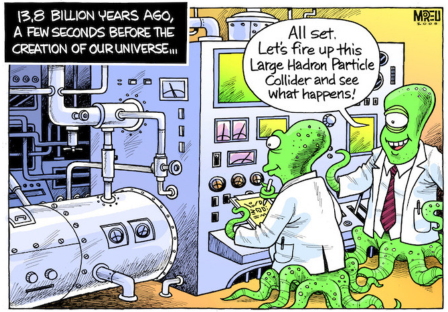
The ALICE Collaboration

40 countries, 173 institutions, >2000 members

10+ years of ALICE data

System	Year(s)	$\sqrt{s_{NN}}$(TeV)	L_{int}
Pb+Pb	2010, 2011 2015, 2018	2.76 5.02	~75 mb^{-1} ~800 mb^{-1}
Xe+Xe	2017	5.44	~0.3 mb^{-1}
p+Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}
p+p	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**



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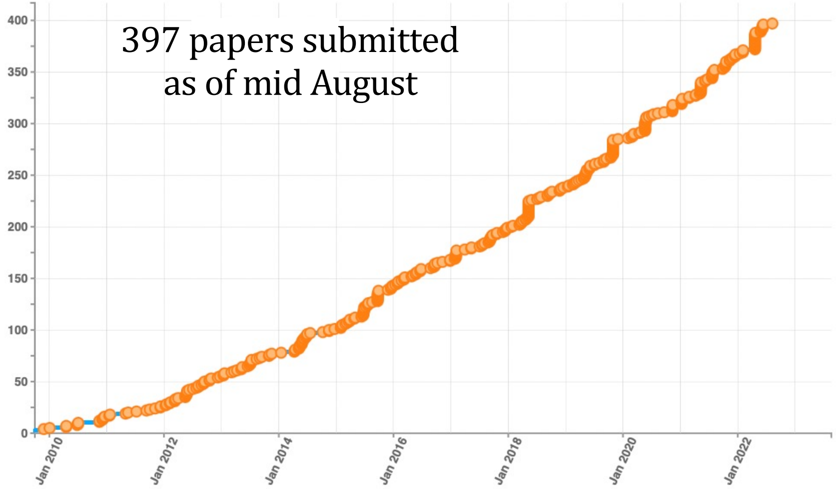
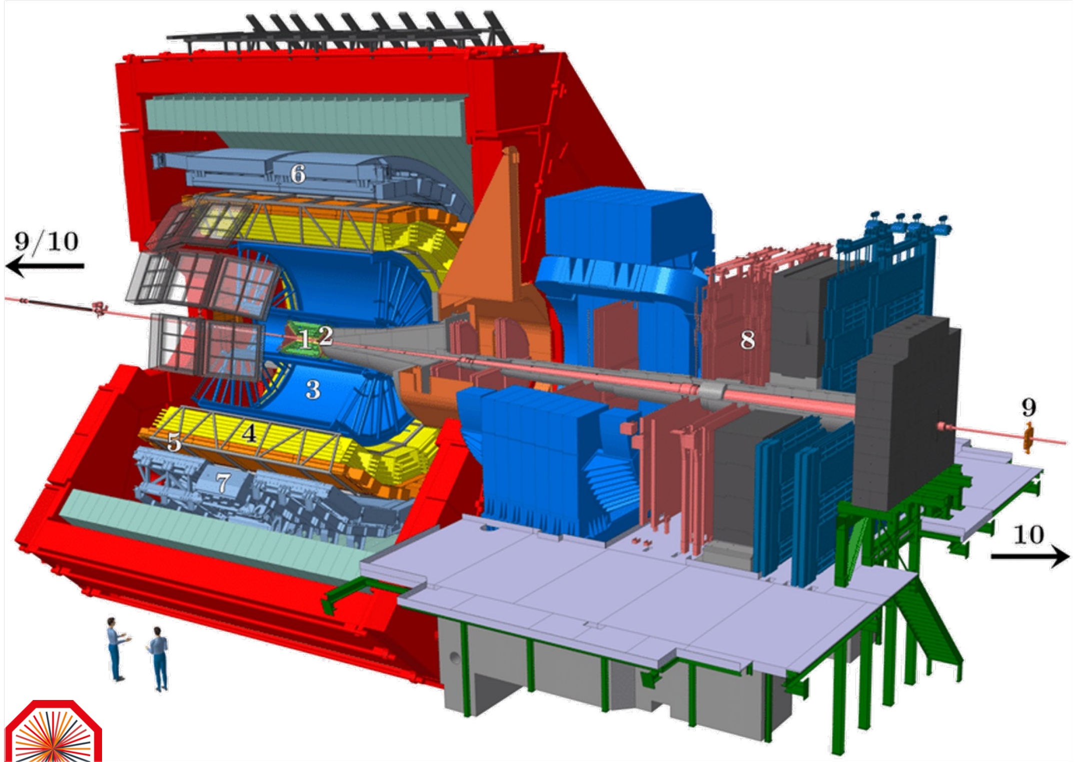


ALICE

The ALICE detector (Runs 1 + 2)



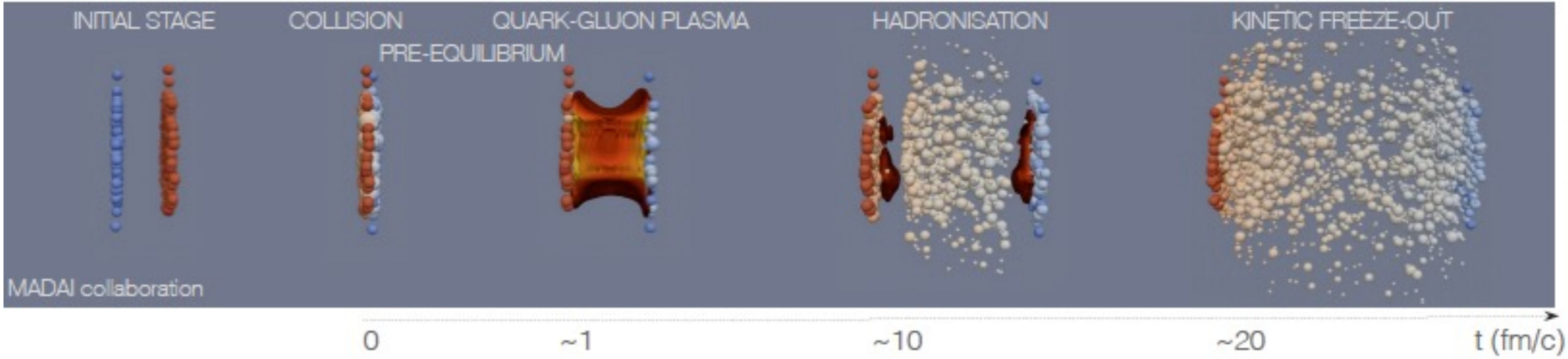
1. **ITS** – Inner Tracking System
2. **V0 & T0** – Centrality & vertex
3. **TPC** – Time Projection Chamber
4. **TRD** – Transition Radiation Detector
5. **TOF** – Time of Flight
6. **EMCal** – Electromagnetic Calorimeter
7. **PHOS** – Photon Spectrometer
8. **Muon Spectrometer**
9. **AD** – ALICE Diffractive Detector
10. **ZDC** – Zero Degree Calorimeter

ALICE optimized for Heavy-Ions

- Excellent tracking at low momentum
  - Efficient particle identification

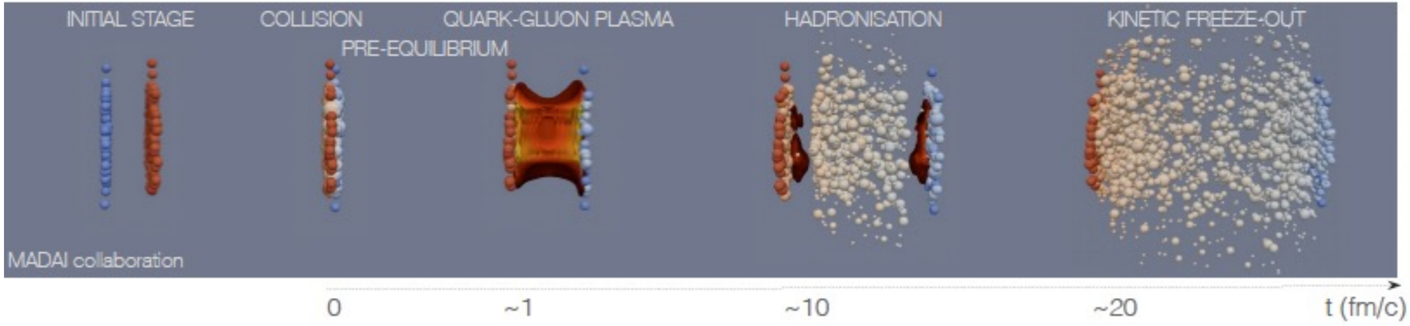
ALICE

ALICE physics: the quark-gluon plasma



- Quark-gluon plasma (QGP) → **strongly-interacting** QCD matter
- Aim to characterize the **medium**
  - Different probes: **hard** or *soft* ("direct" or "indirect")
  - Different stages: early scattering, late stage hadronization, etc.

QGP: in broad, simplified strokes



Hot

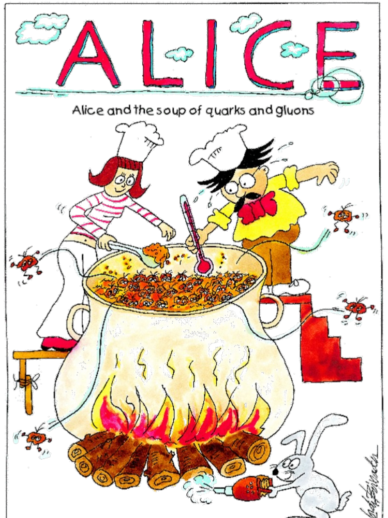
- Thermal photon radiation

Dense

- Parton energy loss
- Jet modification

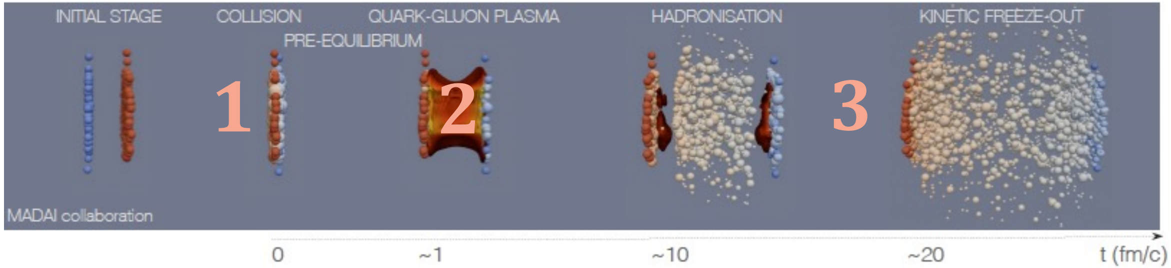
Liquid

- Momentum & angular distribution modification



ALICE-Brochure-2004-001-Eng

(Hot) Thermalized: photons



Direct photons produced in all stages of collision

1. Prompt photons
2. Thermal photons from **QGP phase**
3. Thermal photons from **hadron gas**

$$\frac{d^2N}{p_T dp_T dy} \sim e^{-p_T/T_{eff}}$$

- Thermal photons probe **QGP temperature**
  - T_{eff} from slope of photon spectrum

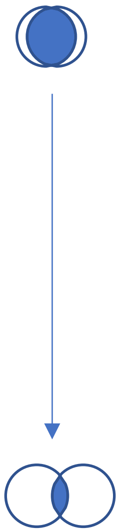
Photon production → investigation of medium evolution

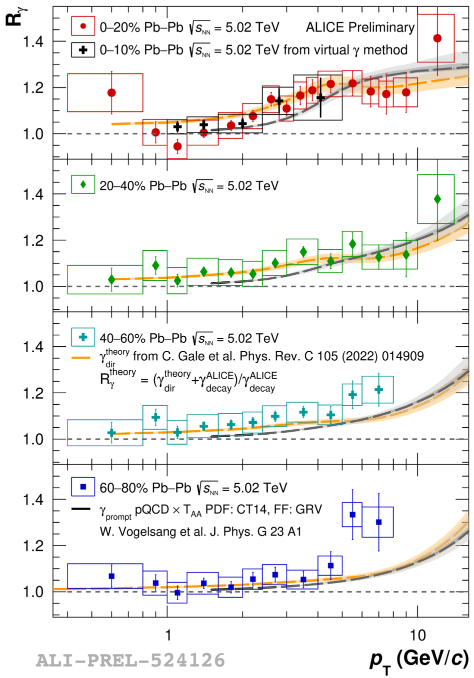
Direct photons

$$R_\gamma = \frac{\gamma_{inc}}{\gamma_{decay}}$$

$R_\gamma > 1 \rightarrow$ direct photon signal

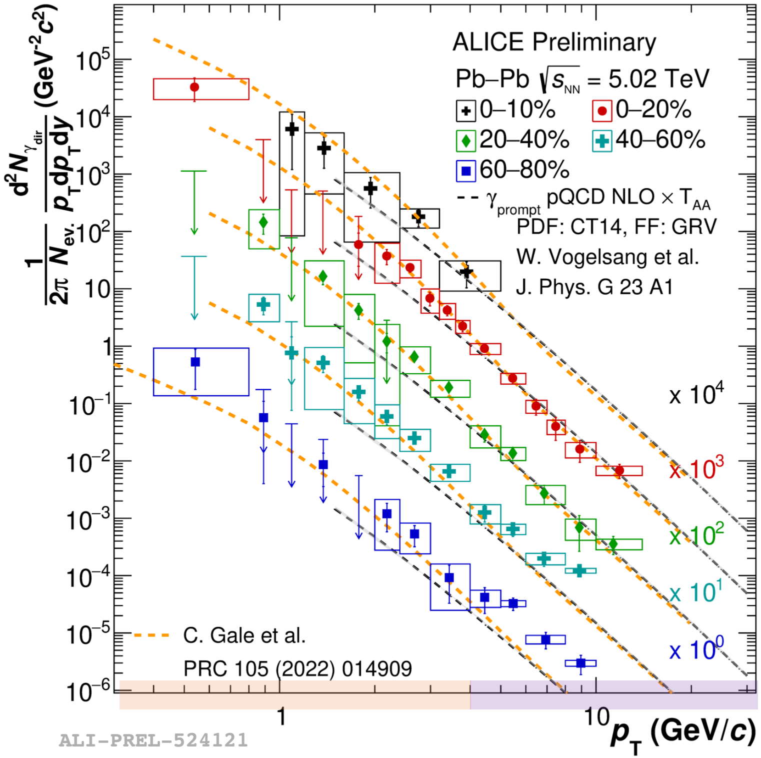
- **Thermal:** $p_T < 4$ GeV/c
  - Consistent with pre-equilibrium & thermal photons
- **Prompt:** $p_T > 4$ GeV/c
  - Consistent with pQCD





Direct γ spectrum in Pb-Pb

- 0-10 % : virtual γ (ee pairs) method
- All others: real γ (conversions) method



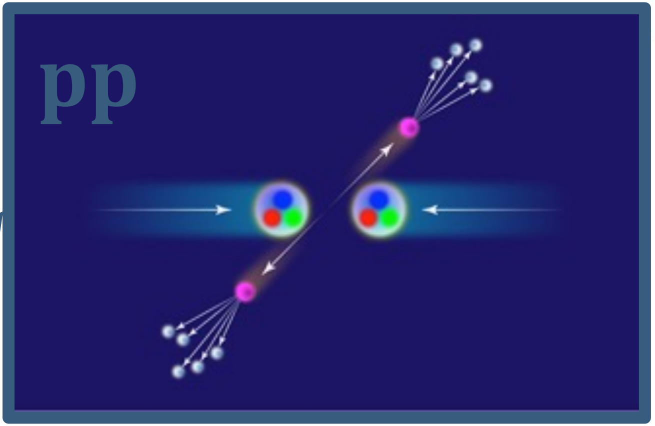
Dense: "energy loss"

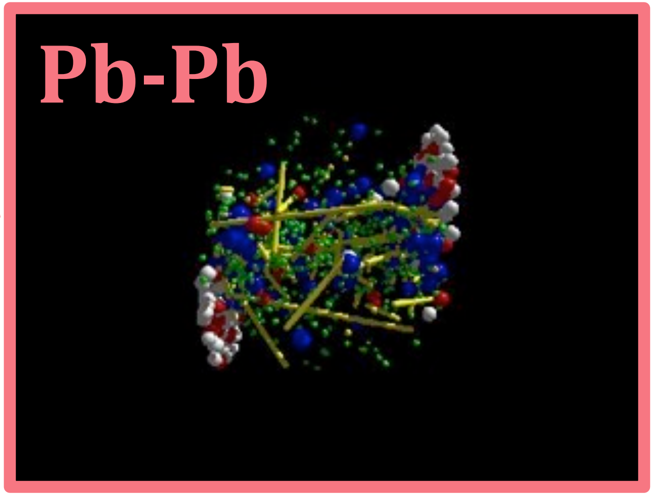
A way to quantify energy loss:

Nuclear Modification Factor → R_{AA}

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

- $R_{AA} > 1$: **Enhancement**
- $R_{AA} = 1$: **no medium effect**
- $R_{AA} < 1$ at high p_T: **suppression/energy loss**

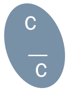




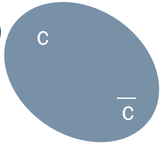
ALICE

Quarkonia suppression

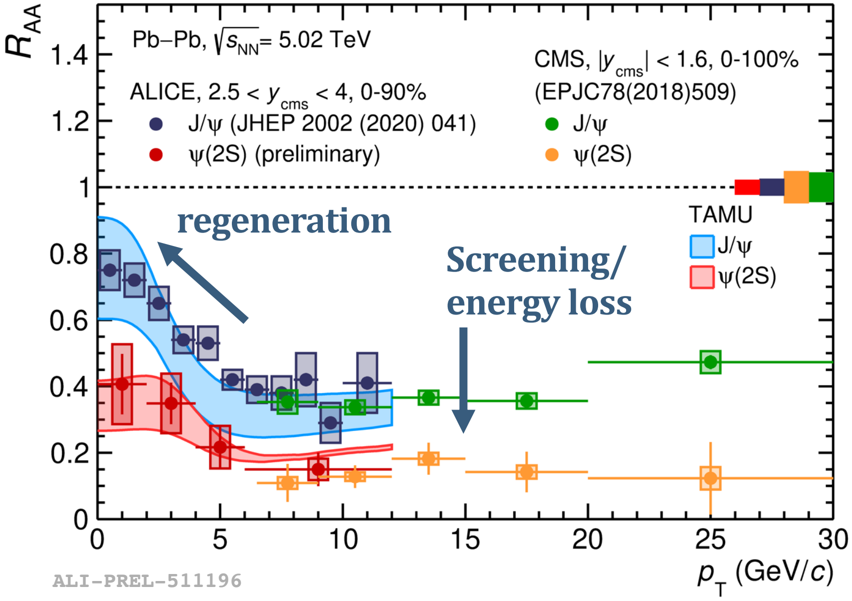
J/ψ

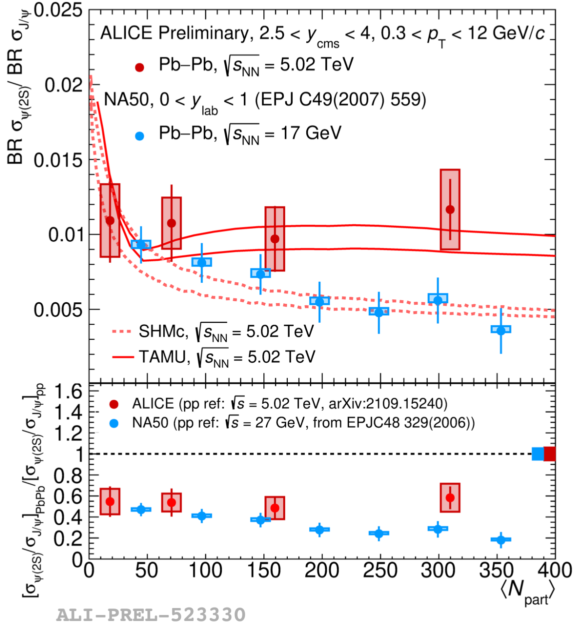


ψ(2S)



TAMU: X. Du and R. Rapp, NPA 943 (2015) 147
SHMc: A. Andronic et. al., Nature 561 no. 7723 (2018) 321



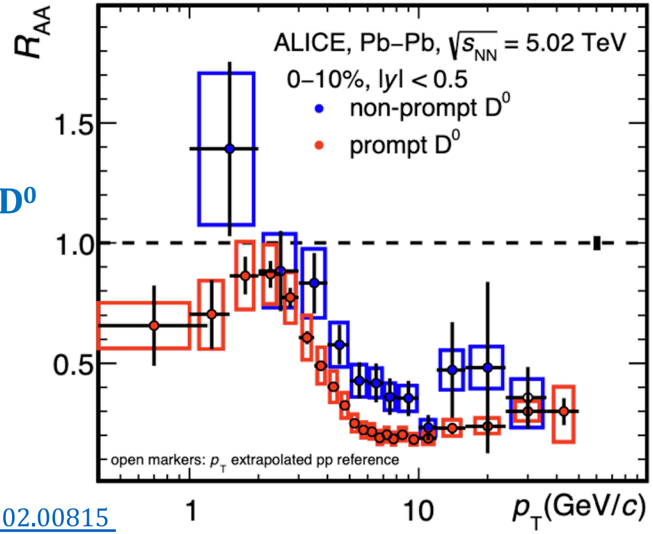


- High p_T → **stronger suppression**, low p_T → **increasing trend**
  - **Explained by regeneration**
- **ψ(2S) more suppressed than J/ψ**

- ψ(2S)-to-J/ψ ratio → **no centrality dependence at LHC**
- Larger ratio at LHC than SPS

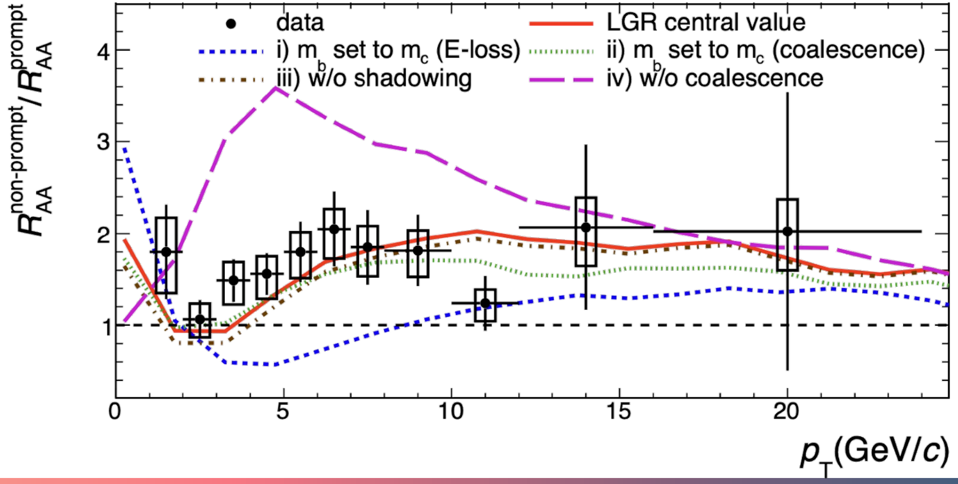
Mass dependence

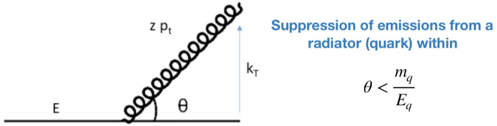
Bottom
- Non-prompt D⁰
Charm
- Prompt D⁰



[arXiv:2202.00815](https://arxiv.org/abs/2202.00815)

- Data described well by models that include:
  - Collisional, radiative energy loss
  - Recombination
- R_{AA} less suppressed for **bottom** than **charm**
  - "Dead cone" effect → reduces small angle gluon radiation ∝ to mass

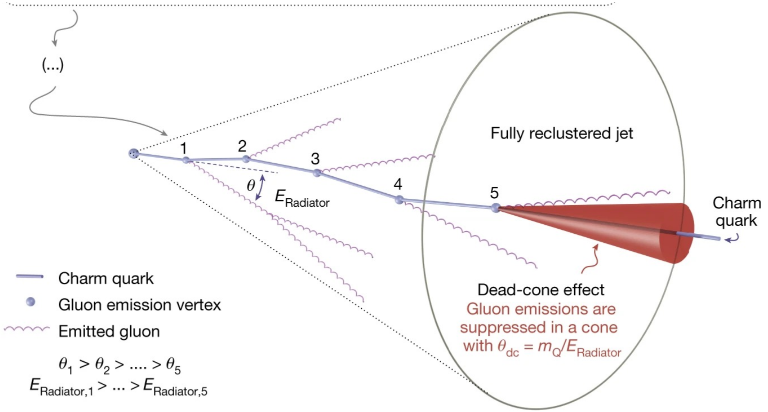


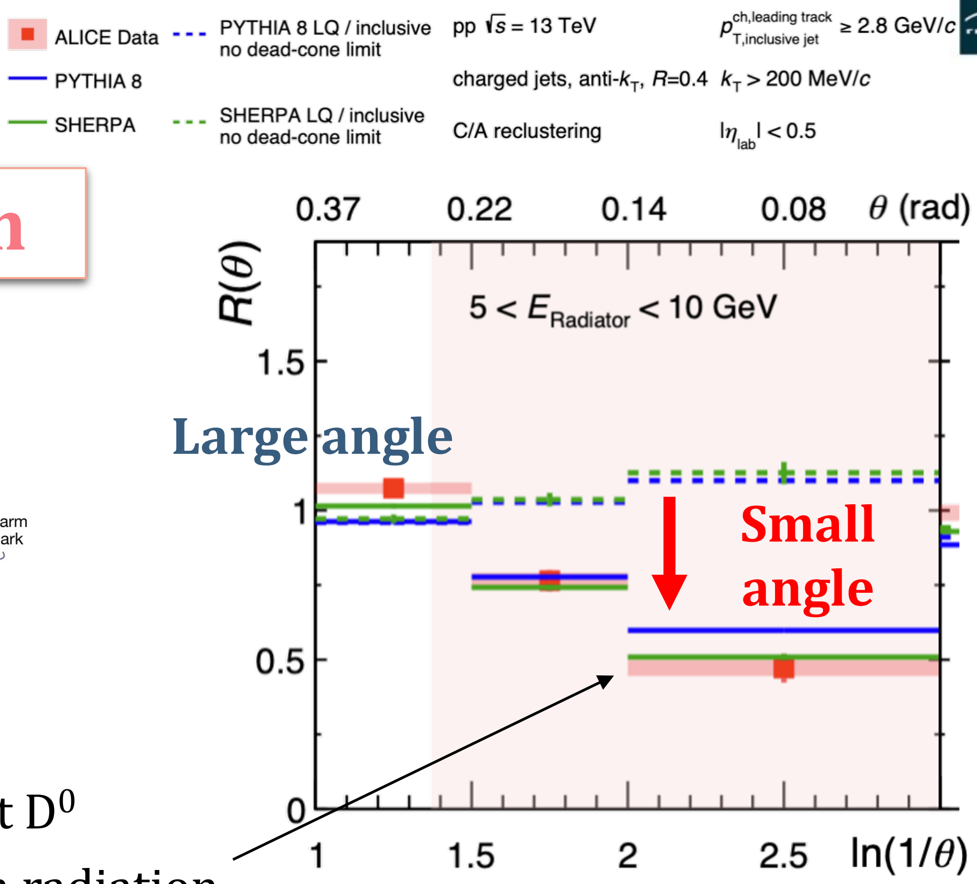


ALICE

Dead-cone effect (pp)

First direct observation





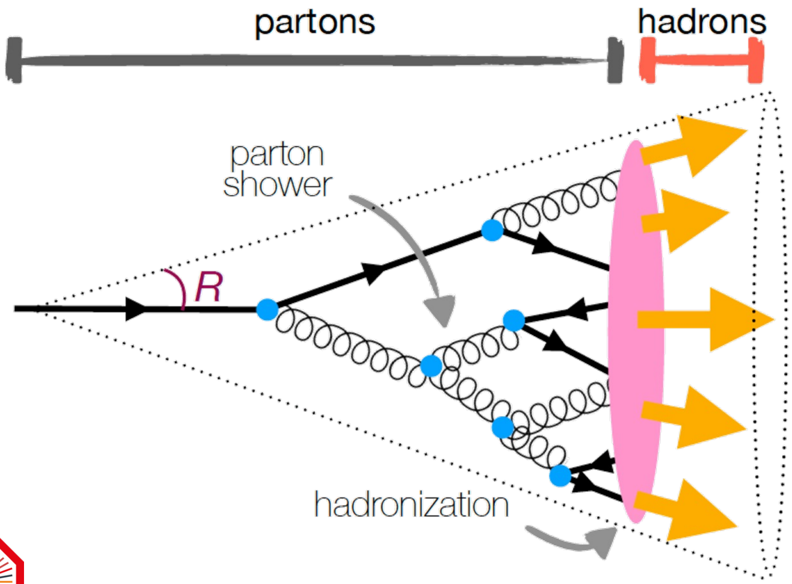
- Analysis of jets that contain soft D^0
- Reduction of **small angle** gluon radiation

[Nature 605 (2022) 7910, 440](https://doi.org/)

Dense: jet modification

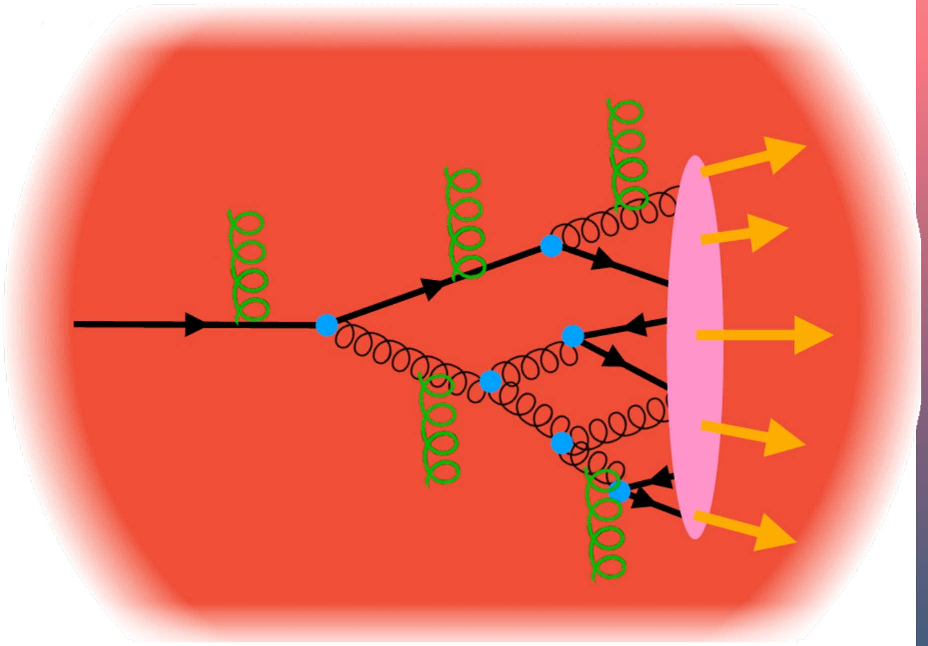
Vacuum fragmentation (pp)

Sprays of hadrons from "high-energy" quarks & gluons



In-medium fragmentation (Pb-Pb)

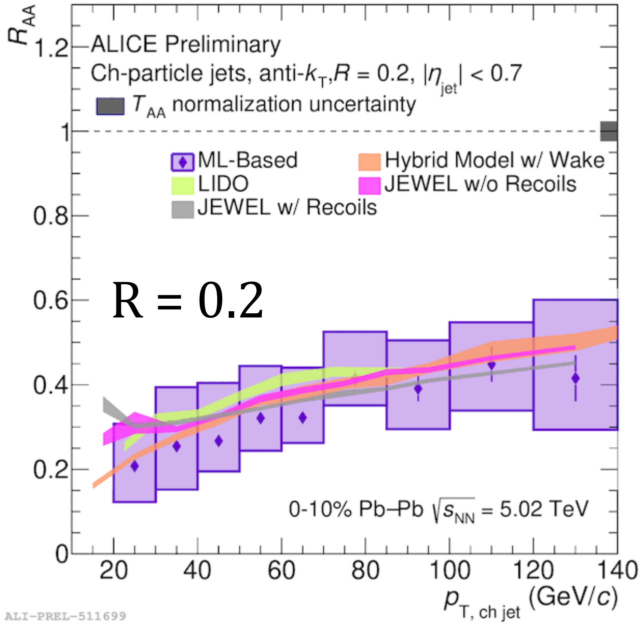
Quenching → medium-induced parton energy loss

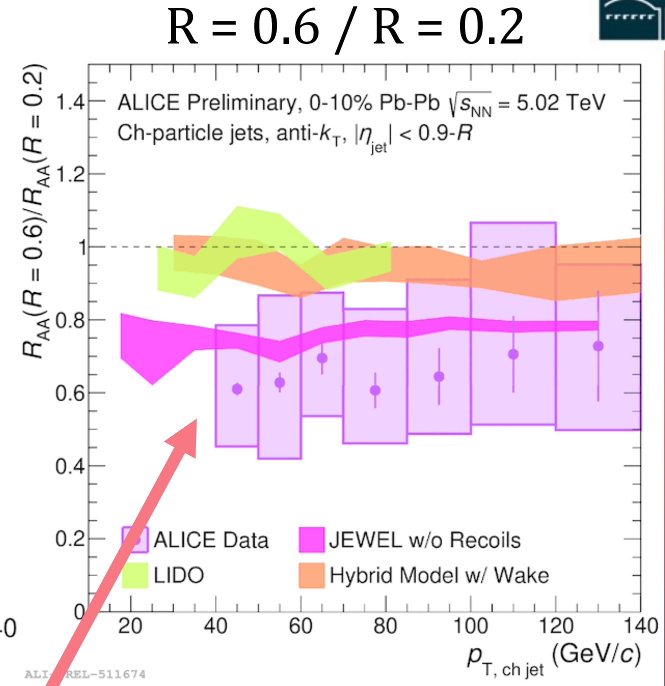


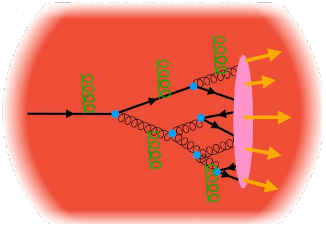
Cartoon from R. Cruz-Torres

Jet quenching

- New method to subtract underlying event
    - Jet yields down to low jet p_T







- Possibly more suppression in **larger** jet radius **(R = 0.6)**
    - "Lost" energy not recovered

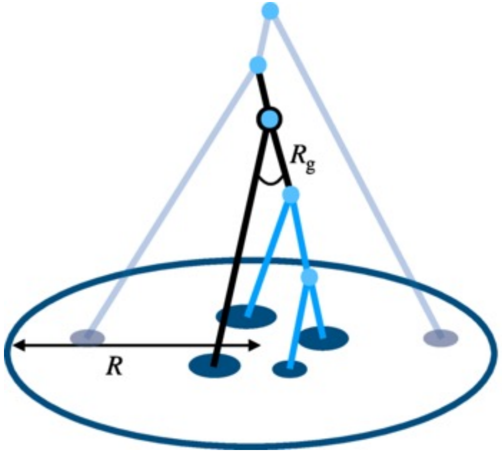
Jet substructure

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

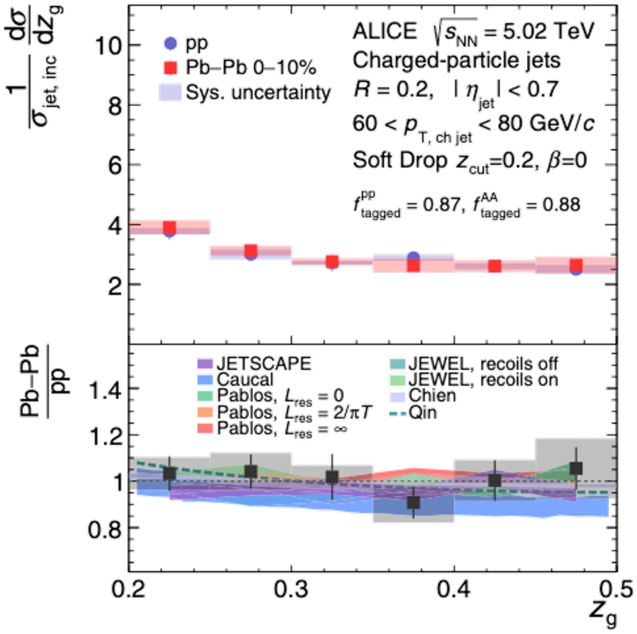
$$\theta_g = \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

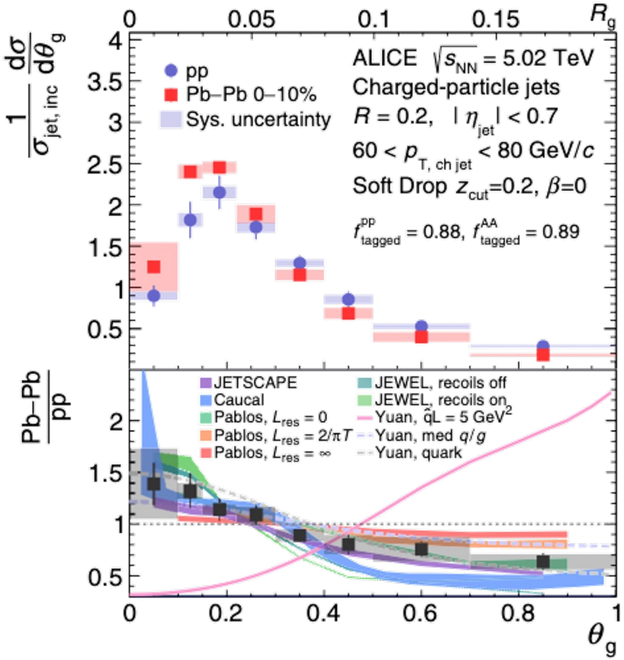
Z_g → momentum

θ_g → angle



Wide jets suppressed in the medium



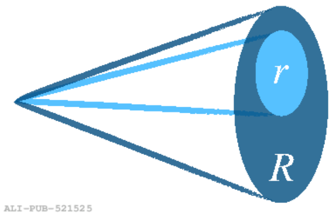


No significant modification in momentum sharing

The cores of jets are narrower in Pb-Pb compared to pp collisions

PRL 128 (2022) 10, 102001

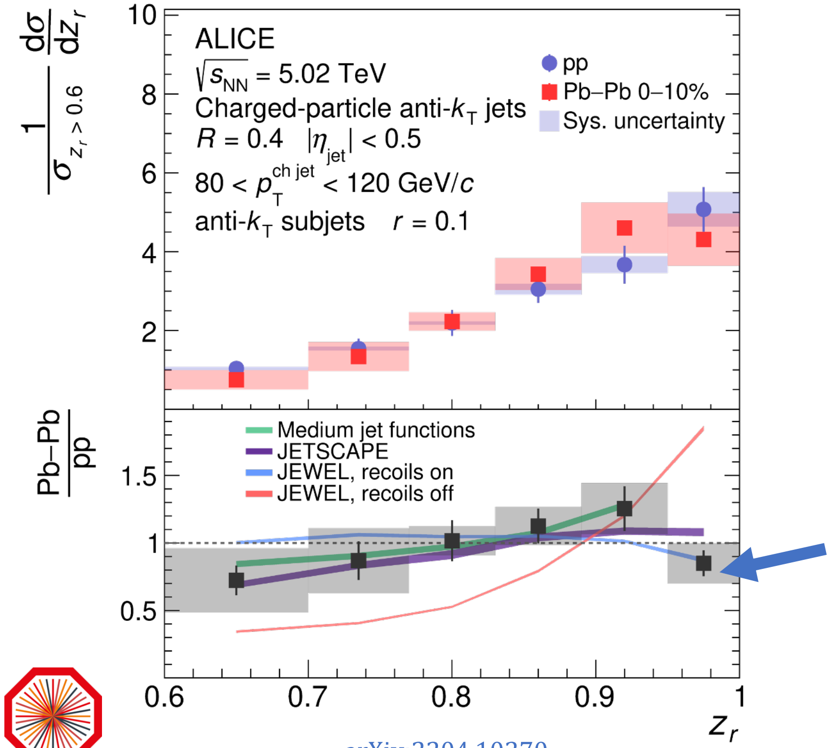
Subjet fragmentation



Neill, Ringer, Sato JHEP 07 (2021) 041
Kang, Ringer, Waalewijn JHEP 07 (2017) 064

$$z_r = \frac{p_T^{\text{ch subjet}}}{p_T^{\text{ch jet}}}$$

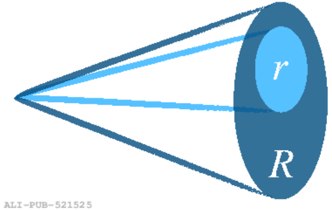
Leading subjets



arXiv:2204.10270

- Jets clustered with radius ***R***, then re-clustered with radius ***r***
- Hint of hardening at mid z_r, competing effects
  - Gluon suppression → **large z_r**
  - Soft radiation → **smaller z_r**
- Turnover as z_r goes to 1

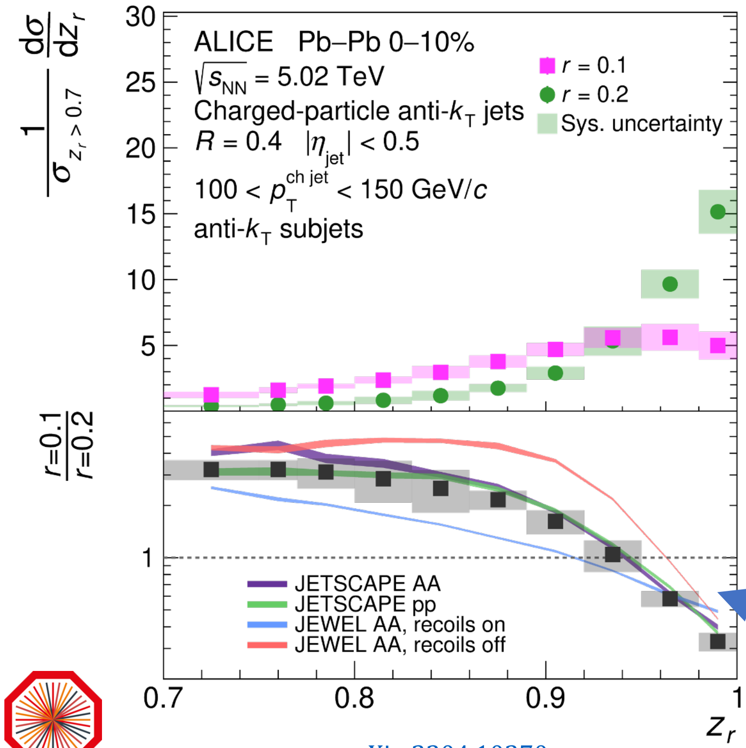
Subjet fragmentation



Neill, Ringer, Sato JHEP 07 (2021) 041
Kang, Ringer, Waalewijn JHEP 07 (2017) 064

$$z_r = \frac{p_T^{\text{ch subjet}}}{p_T^{\text{ch jet}}}$$

r = 0.1, r = 0.2



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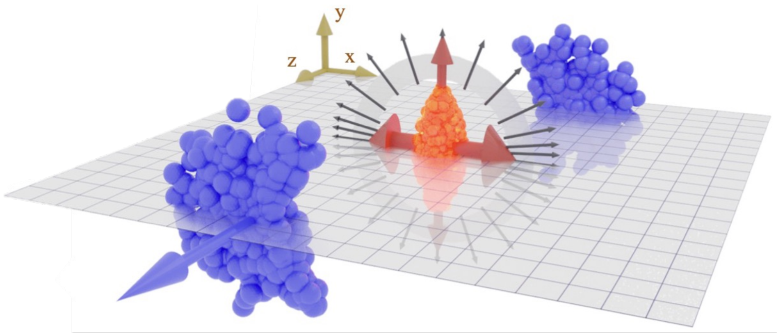
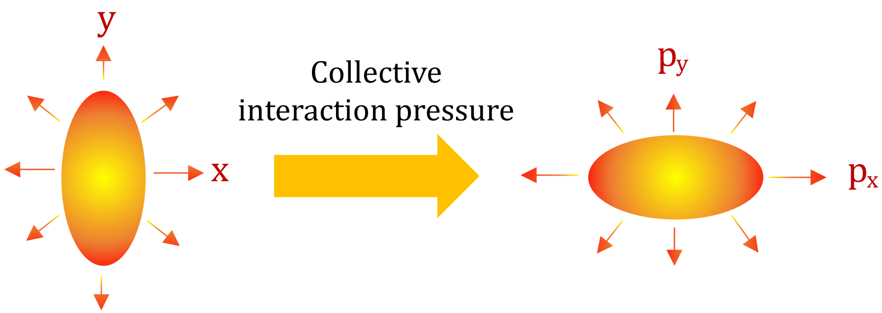
- Jets clustered with radius ***R***, then re-clustered with radius ***r***
- Hint of hardening at mid z_r, competing effects
  - Gluon suppression → **large z_r**
  - Soft radiation → **smaller z_r**
- Turnover as z_r goes to 1
- Broader jets at larger z_r

Liquid: flow

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



- **Radial flow**
  - Outward boost with common velocity
  - Particle p_T spectra hardening
- **Elliptic flow (v_2)**
  - Sensitive to initial geometry & event-by-event fluctuations

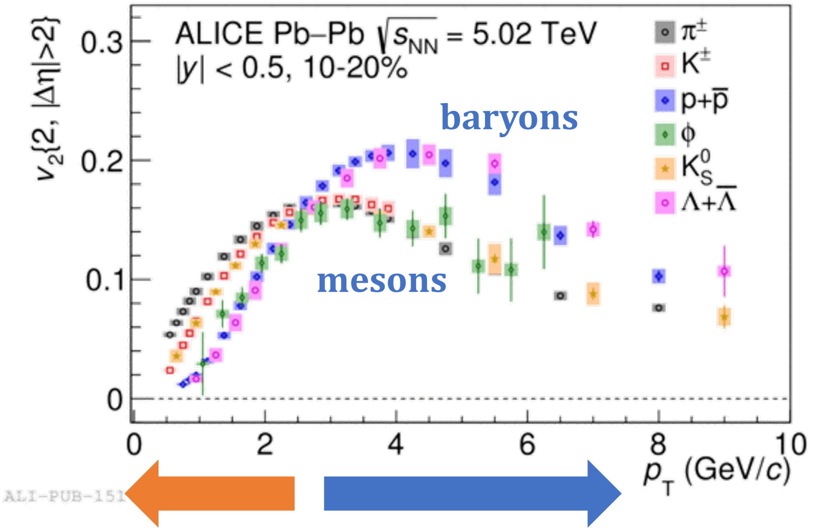


Coordinate space: Initial asymmetry

Momentum space: Final asymmetry

Collective motion in Pb-Pb

JHEP09 (2018) 006

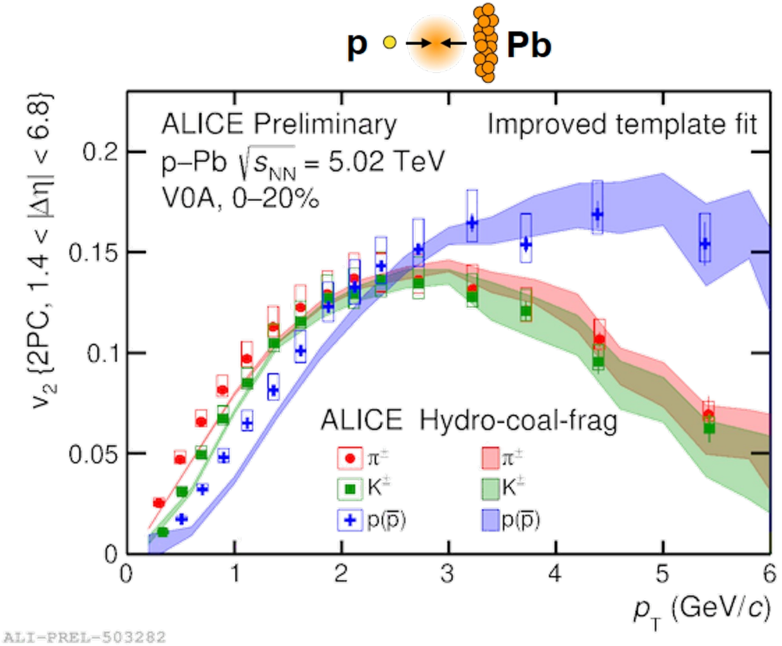


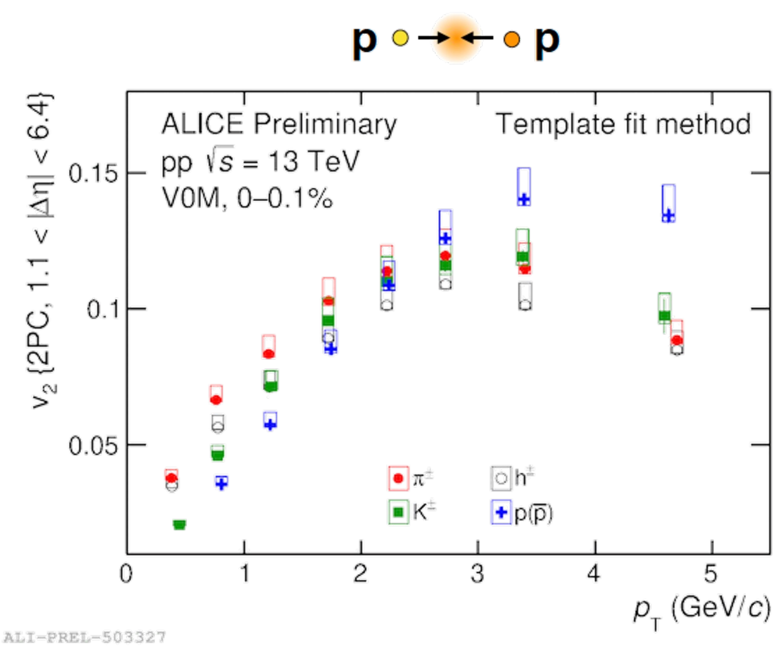
Low p_T:
Mass ordering

Intermediate p_T:
Particle type grouping

- **Heavier** objects push to higher momentum
  - Low p_T mass ordering
- Near-by partons recombine to hadrons
  - Particle type grouping
- Flow coefficients depend on viscosity of medium
  - Low viscosity → Large anisotropy

Collective motion in smaller systems



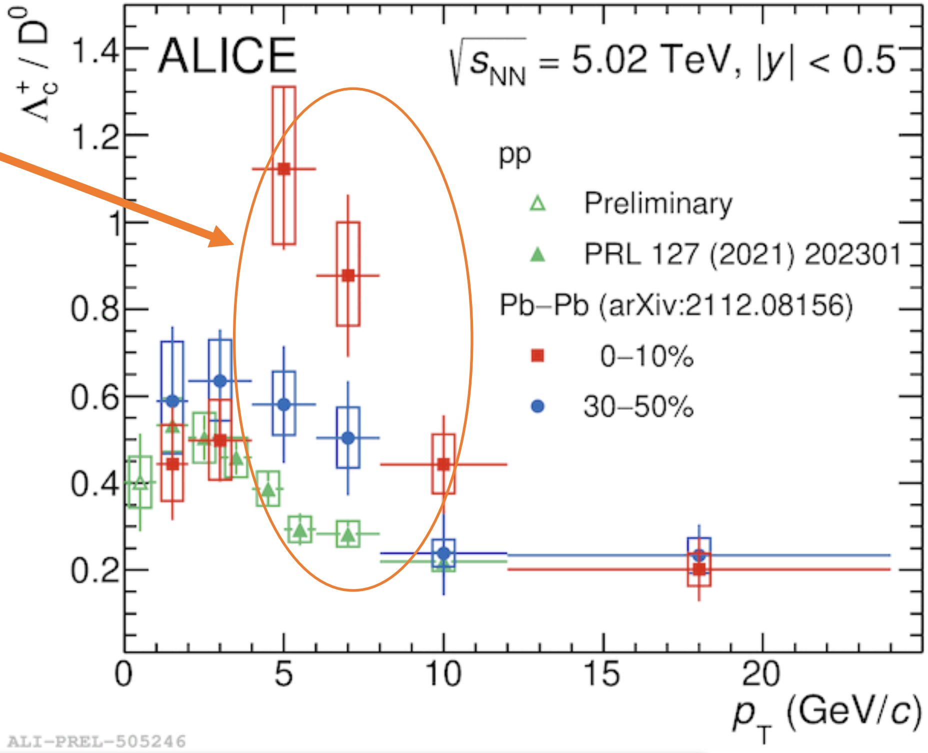


- **Mass ordering** & **particle type grouping** observed in p-Pb & pp
- Described quantitatively by model (**partonic flow + coalescence**)

Hadronization: baryon or meson?

arXiv:2112.08156

- Λ_c/D^0 **enhancement** in Pb-Pb collisions compared to pp
- Hadronization from **recombination**
- **Mass-dependent shift** from collective expansion
- **Opposite** trend of hadronization via fragmentation



Priority measurement for run 3 with enhanced ALICE capabilities

What’s coming next?

ALICE

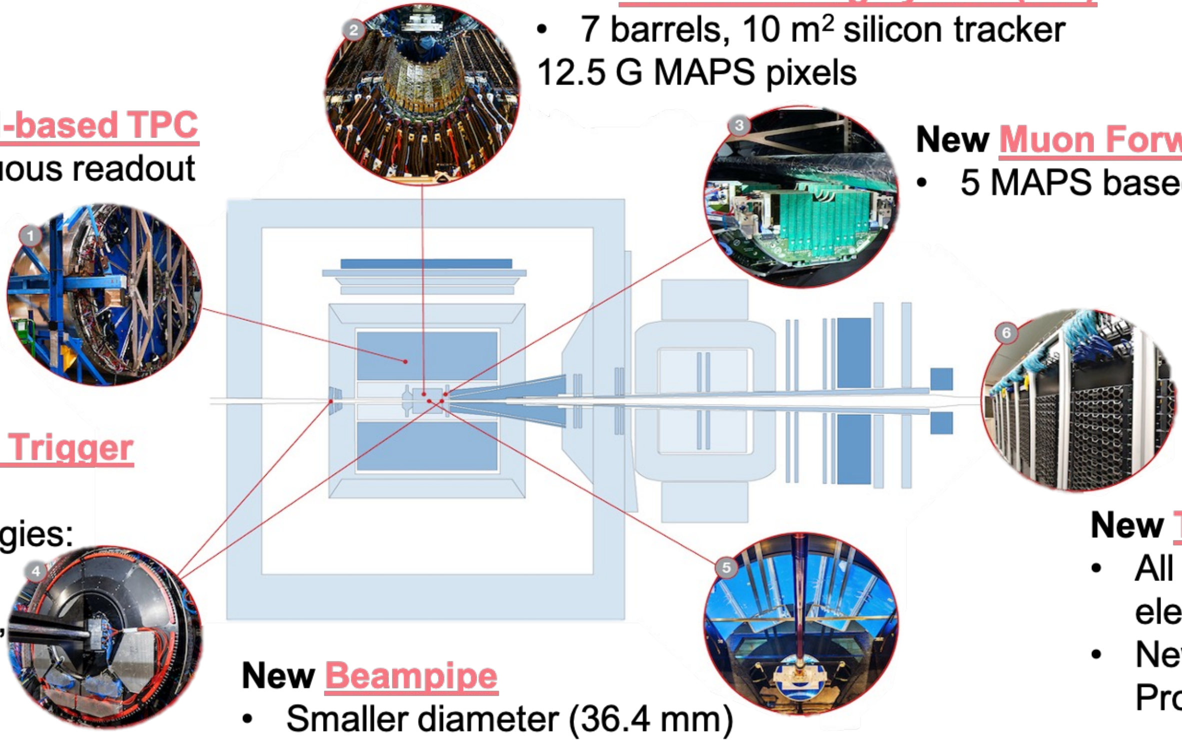
ALICE → ALICE 2 (now running!)

New **Inner Tracking System (ITS)**
- 7 barrels, 10 m^2 silicon tracker

12.5 G MAPS pixels

New **GEM-based TPC**
- Continuous readout

New **Muon Forward Tracker (MFT)**
- 5 MAPS based discs



New **Fast Interaction Trigger (FIT)**
- 3 detector technologies: Interaction trigger, online luminometer, forward multiplicity

New **Trigger & Readout**
- All detector readout electronics upgraded
- New Central Trigger Processor

New **Beampipe**
- Smaller diameter (36.4 mm)
- First detection layer at 20 mm

ALICE → ALICE 2

New Inner Tracking System (ITS)
- 7 barrels, 10 m² silicon tracker
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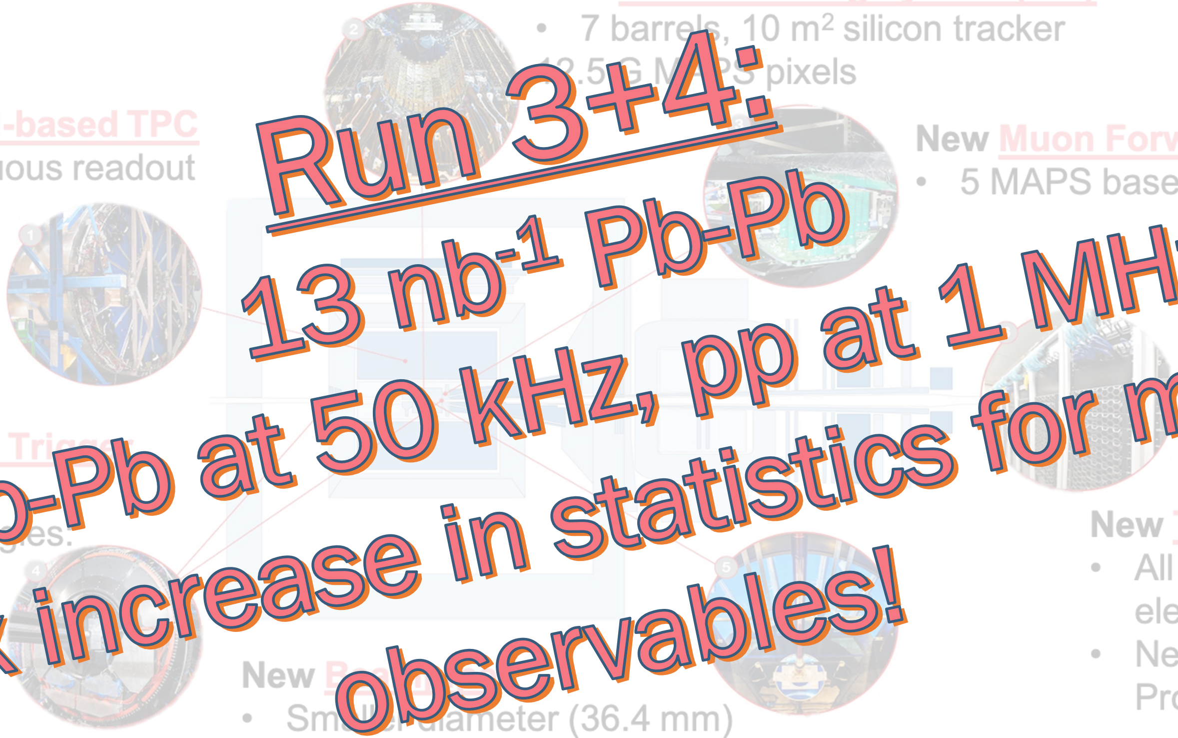

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New Beam pipe
- Smaller diameter (36.4 mm)
- First detection layer at 20 mm

Run 3+4:

13 nb^{-1} Pb-Pb

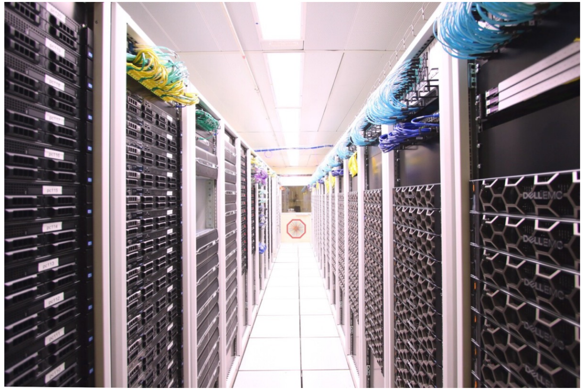
Pb-Pb at 50 kHz, pp at 1 MHz

50x increase in statistics for most observables!

ALICE 2: Computing

New Readout & Online-Offline (O^2) system

First Level Processors (FLP)



Event Processing Nodes (EPN)

Permanent Storage

0.6 TB/s → 0.1 TB/s

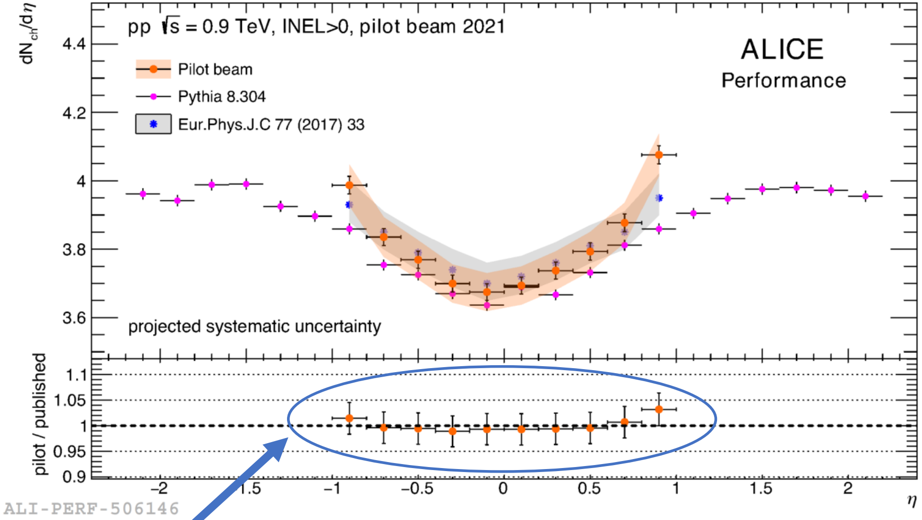
- Readout of detectors & raw data processing
  - 3.5 TB/s → 0.6 TB/s
- Synchronous processing & asynchronous reprocessing
  - Final calibration & full reconstruction

ALICE

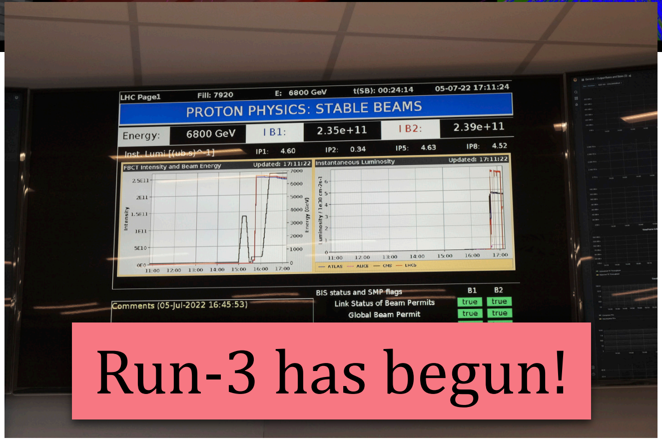
Commissioning & pilot beam

Pilot beam October '21

- Benchmark physics analysis
  - Charged particle density vs η



Good agreement with previous results

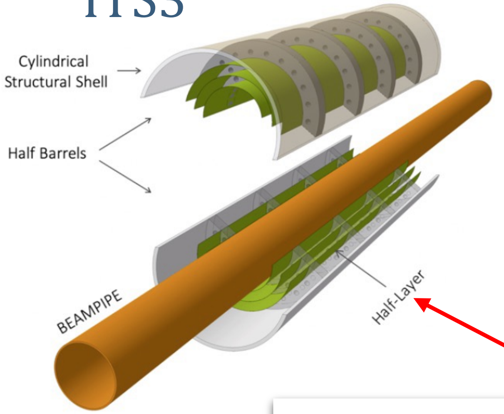


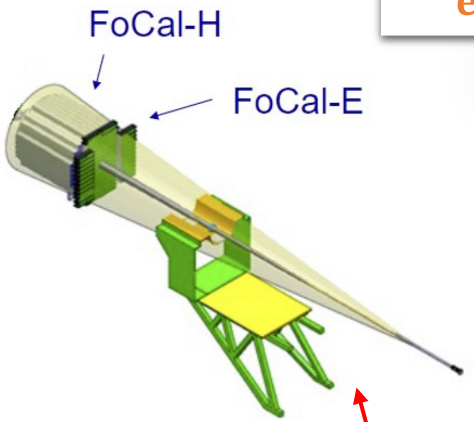
Run-3 has begun!

The next generation

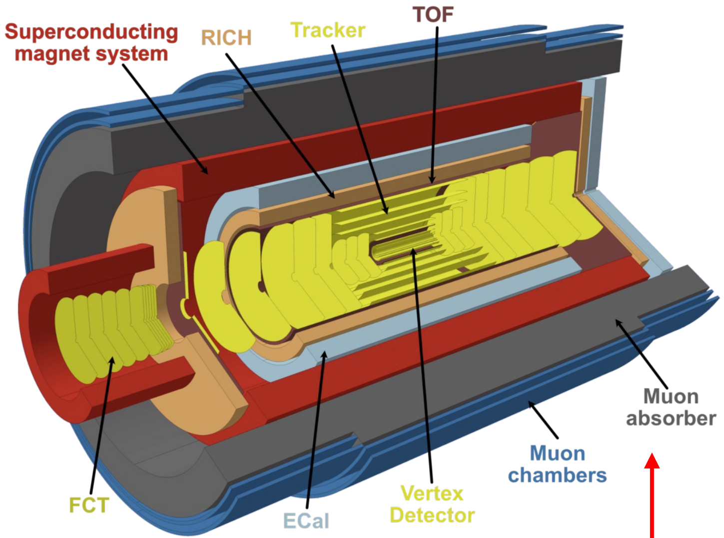
ALICE3: LOI submitted in early 2022

ITS3





ALICE3



ITS3 & FoCal: Extensive R&D ongoing Working towards TDR

Where we've been…

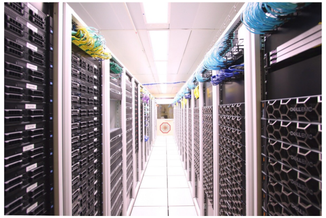
- **Run 1 + 2** physics with ALICE: a detailed study of **QGP** properties
  - Heavy flavor, flow, jet modification, photons, etc.
  - Still more to learn!
- **So much more** that couldn't be covered
  - Check out the other ALICE talks here at CIPANP

"Recent results on ultra-peripheral heavy ion collisions with ALICE at the LHC"
Valerii Pozdniakov - Fri @ 12:10 pm

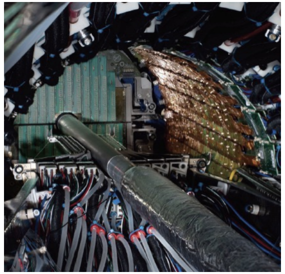
"Recent ALICE results on charmonium photoproduction"
Simone Ragoni – Tues @ 1:40 pm

"Measuring Jet Constituent Yields in 5.02 TeV Pb--Pb Collisions Using Jet-Hadron Correlations with ALICE"
Charles Hughes - Sat @ 2 pm

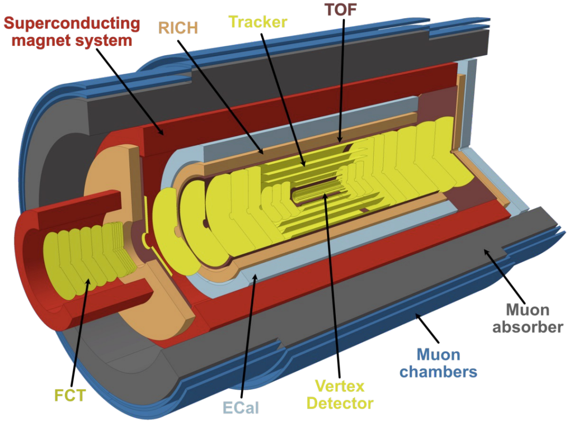
...where we're going



- ALICE → **ALICE 2**
  - New subsystems, significant new capabilities
  - **Now** taking data for LHC Run 3

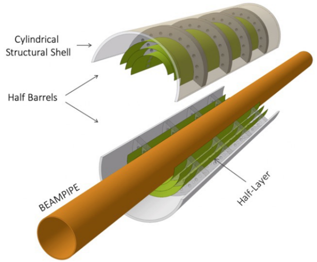


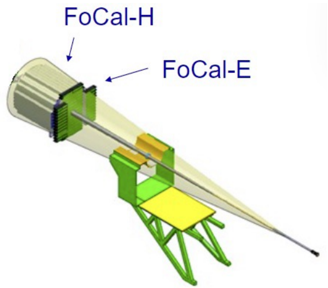
ALICE3



- New plans for upgrades in the works!

ITS3



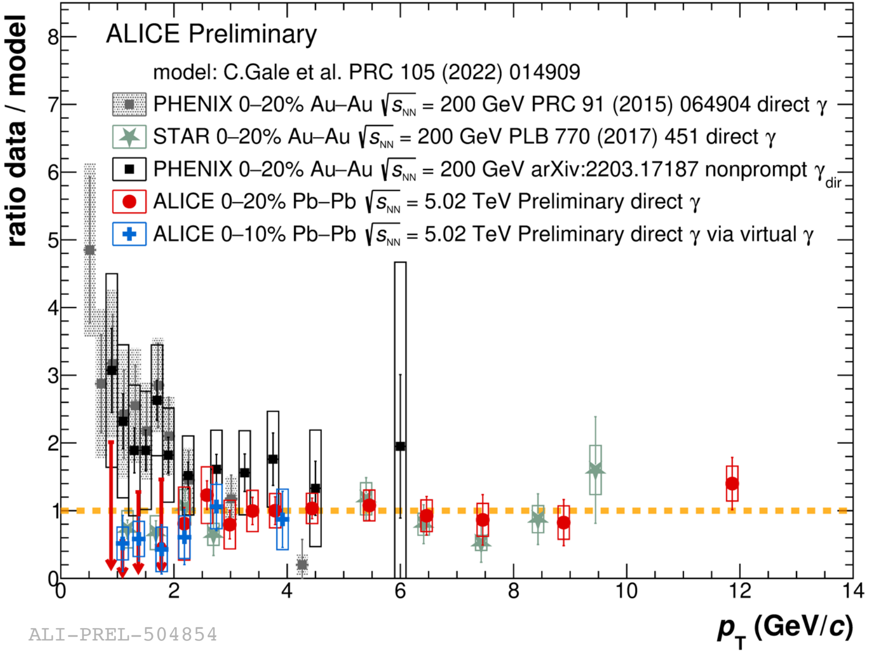


ALICE

Look out for more from ALICE in the near future!

Backups

Photon puzzle



- Comparing measured direct photon spectra with model calculations for the respective collision energies $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ and $5.02\,\mathrm{TeV}$
- Just looking at the spectra, there is **no puzzling discrepancy** between state-of-the art models and **new ALICE measurement**
- Similar finding by measurement via virtual photons, Talk by Jerome Jung, T13, **Thursday 15:20**

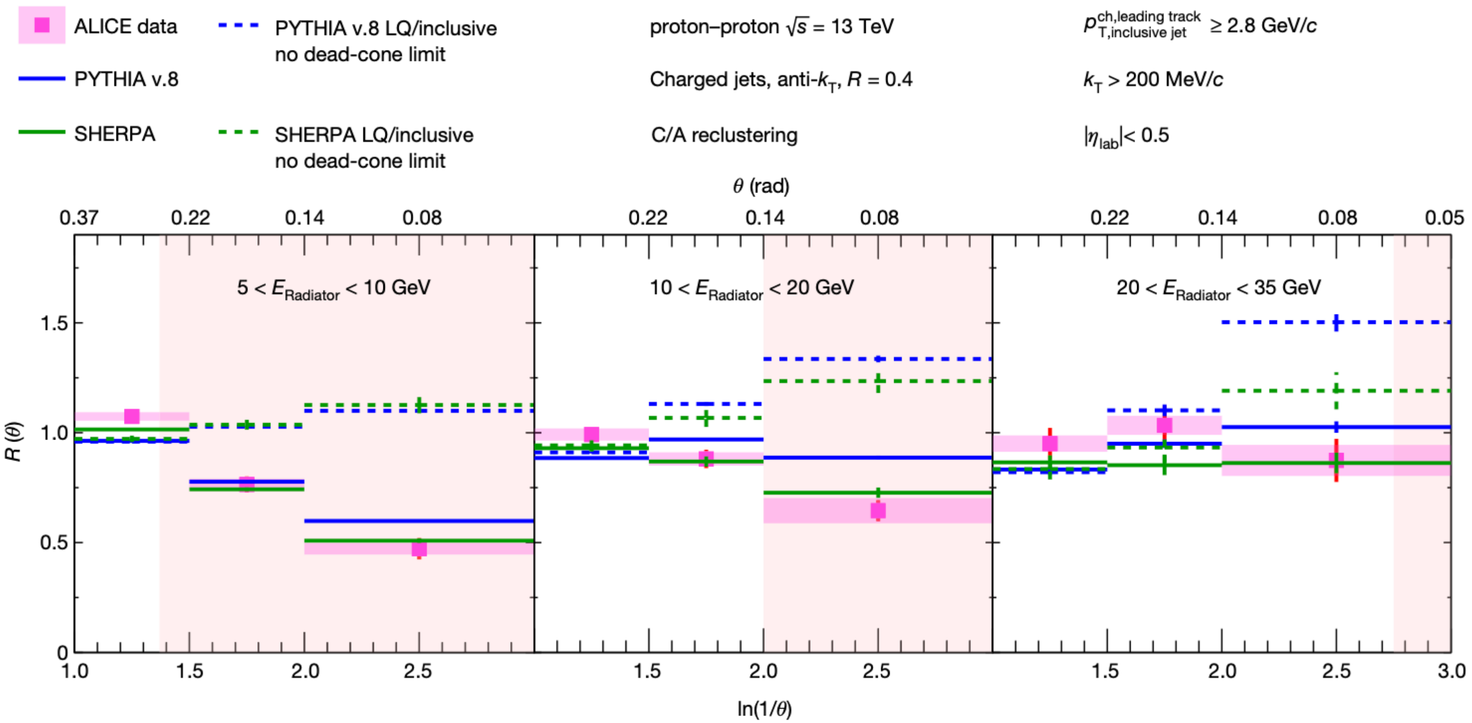


Fig. 2 | Ratios of splitting angle probability distributions. The ratios of the splitting-angle probability distributions for D^0-meson tagged jets to inclusive jets, $R(\theta)$, measured in proton–proton collisions at $\sqrt{s}$ = 13 TeV, are shown for $5 < E_{Radiator} < 10$ GeV (left panel), $10 < E_{Radiator} < 20$ GeV (middle panel) and $20 < E_{Radiator} < 35$ GeV (right panel). The data are compared with PYTHIA v.8 and SHERPA simulations, including the no dead-cone limit given by the ratio of the angular distributions for light-quark jets (LQ) to inclusive jets. The pink shaded areas correspond to the angles within which emissions are suppressed by the dead-cone effect, assuming a charm-quark mass of 1.275 GeV/c^2.

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

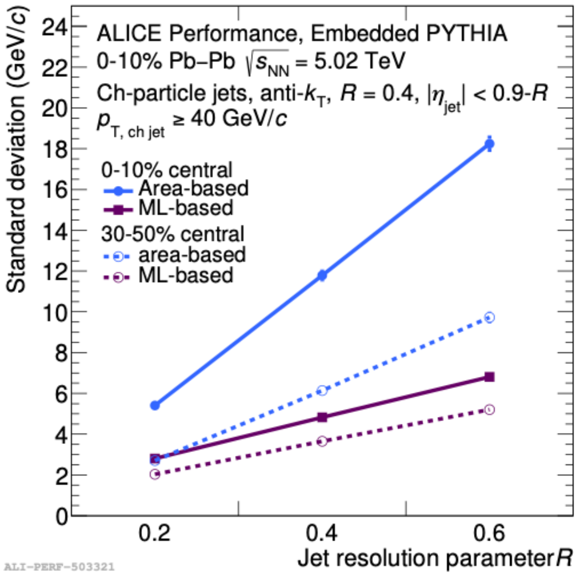
ALICE

ML background estimator

- **ML approach:** Use ML to construct the mapping between measured and corrected jet. Use as input jet properties (and properties of jet constituents).
- Keep the models simple from an ML-perspective (shallow NNs, minimal set of variables), for transparency and to reduce biases on the training sample.

Goal is to use ML to reduce the residual fluctuations remaining after background subtraction, making measurements at large R and low p_{T} possible.

- Fragmentation bias introduced when learning on constituents, handled in a systematic of the analysis.



R.Haake, C. Loizides Phys. Rev. C 99, 064904 (2019)

Nuclear modification factors (0-10%)

LIDO: JHEP 05 (2021) 041
Linearized transport for jet-medium interactions, includes jet-induced hydrodynamic medium response.

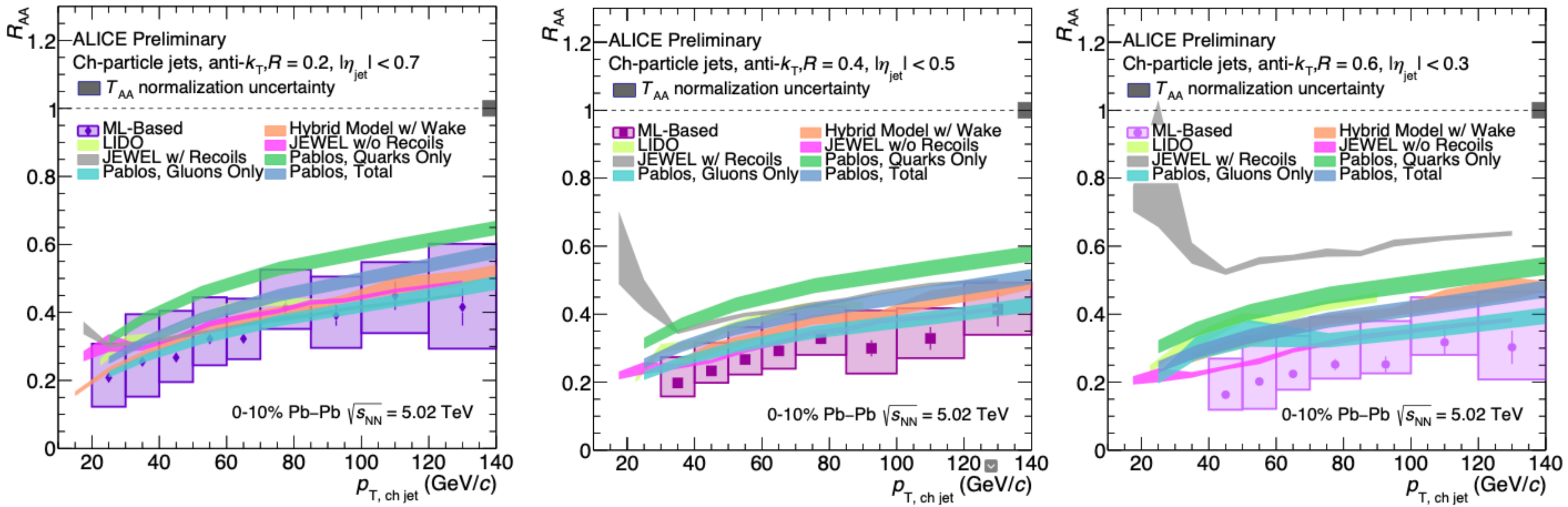
JEWEL: JHEP 1707 (2017) 141
Scattering and radiative energy loss with and without recoiling medium.

Hybrid Model: Phys. Rev. Lett. 124, 052301 (2020)
Medium response via wake. AdS/CFT non-pert. regime.

New for QM

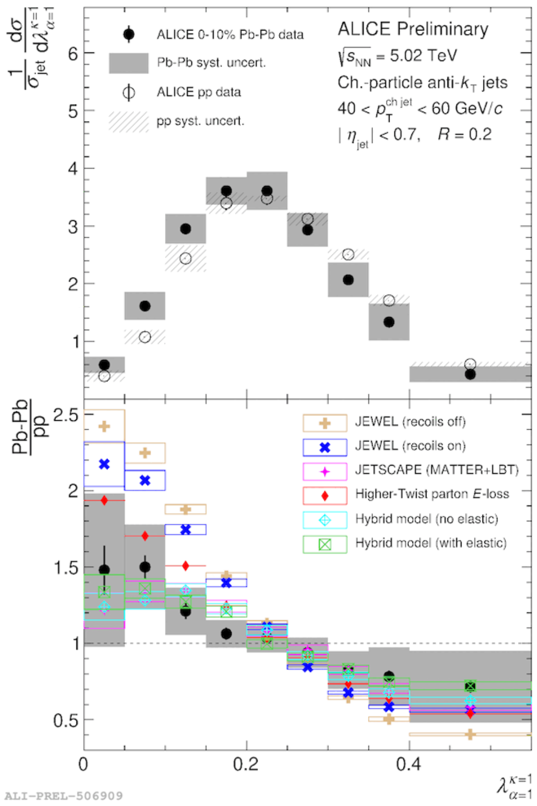
Pablos et. al: Phys. Rev. Lett. 127, 252301 (2021) **Analytical calculation with resummation of energy loss from vacuum-like emissions includes soft energy flow and recovery.**

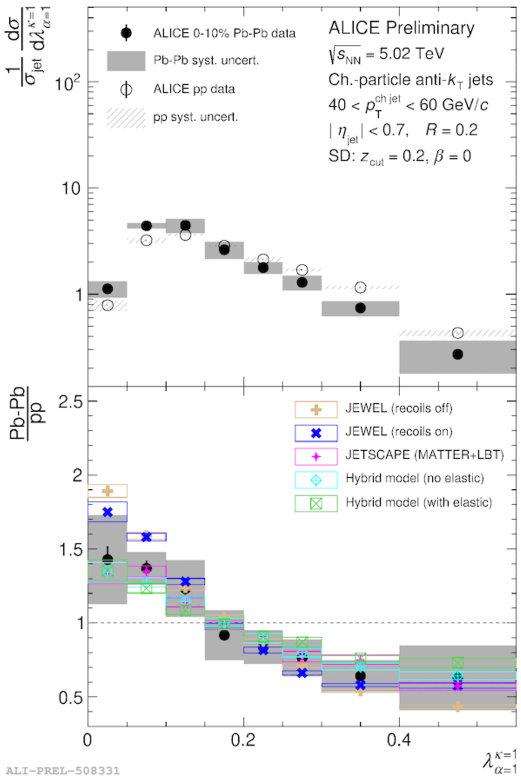
$R = 0.2$ $\qquad$ $R = 0.4$ $\qquad$ $R = 0.6$



→ Measuring down to lower p_T and larger R than ever before in heavy-ions at the LHC!

Jet angularities



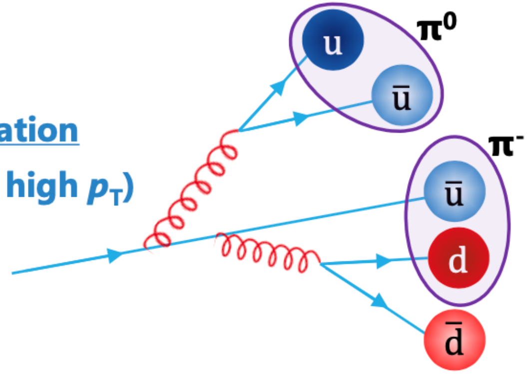


HADRON PRODUCTION MECHANISMS

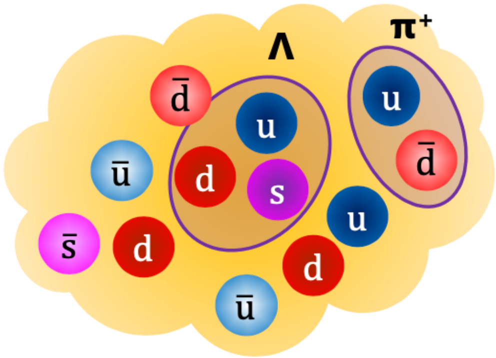
- **Large quark-density** environment at QGP→hadron gas phase transition can **alter the hadron formation mechanism**, compared to in-vacuum hadronisation via fragmentation

- **Coalescence (recombination) mechanism** for hadron formation, opposed to fragmentation
  - Quark close in space and momentum merge into higher p_T hadrons

Fragmentation
(dominant at high p_T)



Coalescence
(dominant at low/intermediate p_T)



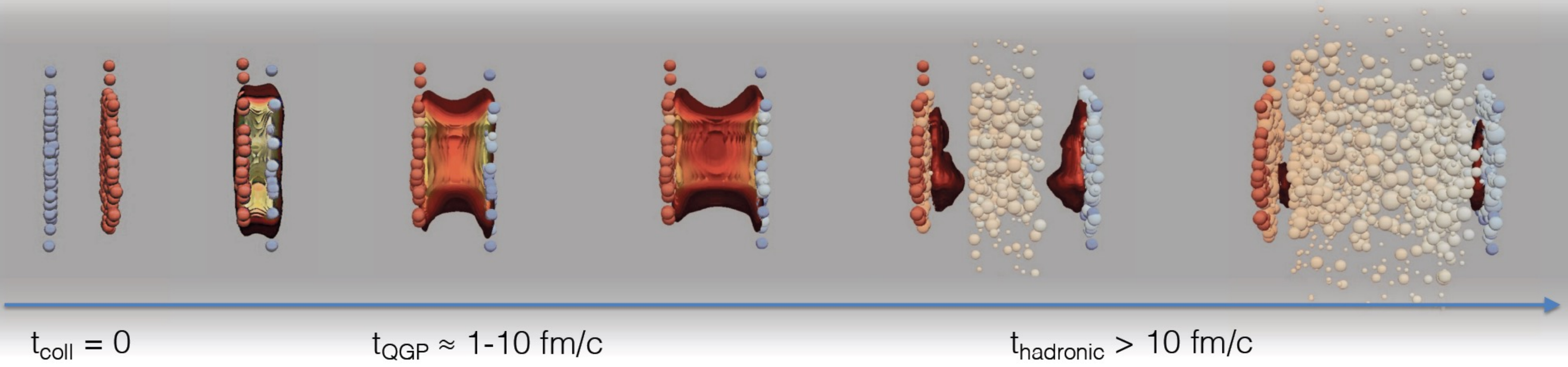
- Coalescence nicely explains the observed **baryon/meson hierarchy of v_2** at intermediate p_T, and **baryon/meson enhancement** in Pb-Pb (next slides)

F. Prino, 16/5
HI & QCD

ALICE Physics Program: Current and Future Challenges

- **Two main physics items driving the ALICE experimental approach:**
  - **Transport and hadronization of heavy flavors in the medium:** differential measurements of HF hadron production (suppression, enhancement, flow…) down to vanishing p_T
  - **Electromagnetic radiation from the medium:** dilepton measurements below J/ψ mass, down to zero p_T, to map the evolution of the collision

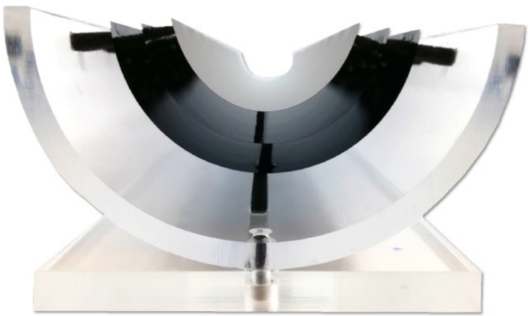
Light and high-granularity detector + continuous readout to access untriggerable probes with high S/B



ITS3 R&D: excellent progress towards TDR

LoI: CERN-LHCC-2019-018

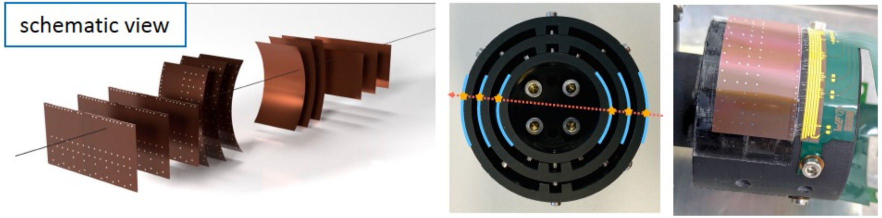
Replace beam pipe and three inner layers of ITS2 (1st layer @ 18 mm)



wafer-scale MAPS sensors curled around beam pipe

- **~6x** less material budget
- **2x** tracking precision and efficiency at low p_T

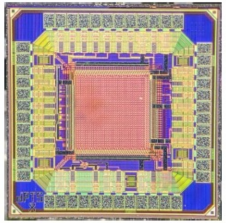
Curved pixel sensors (ALPIDE) extensively validated at in-beam tests (https://doi.org/10.1016/j.nima.2021.166280)



Full-size prototype of half-layers (unprocessed silicon)

Good progress on mechanical, electrical and thermal studies using ITS2 or dummy silicon wafers

First prototype sensors using 65 nm process showed excellent performance!



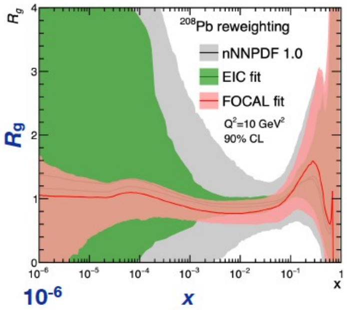
First wafer-scale pixels sensor ready for fabrication (26 cm x 1.4 cm)

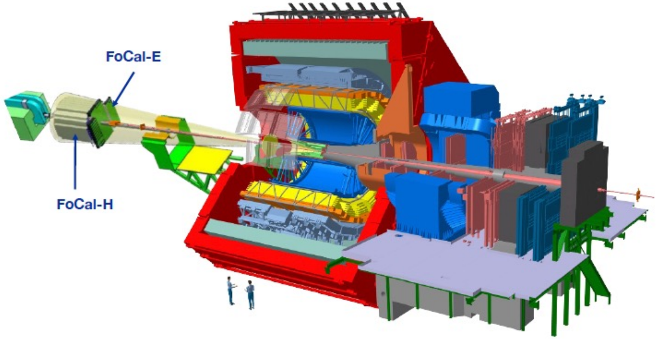
FoCal: new detector in preparation for Run 4

LoI ALICE-PUBLIC-2019-005

FoCal: forward electromagnetic + hadronic calorimeter

- **FoCal-E**: high-granularity Si-W sampling calorimeter for **direct γ** and π_0
- **FoCal-H**: metal-scintillator sampling hcal for **photon isolation** and **jets**





Main goal: study saturation/shadowing at low-x with direct photons in pp and p-Pb

Impact on gluon nuclear PDFs: present nNNPDF, w/FoCal pseudodata, w/EIC pseudodata

Test beam in 2021

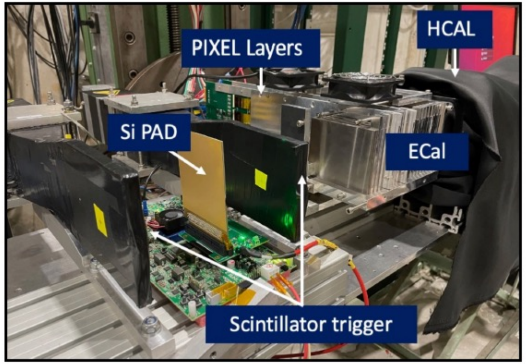
- **FoCal-E**: 2 pixel (ALPIDE) layers, 1 pad layer
- **FoCal-H**: complete prototype, commercial readout system
- Full-pixel prototype: **EPICAL-2**

Main activity in 2022

- Preparation of full demonstrator for test beam in Sep/Oct

HCAL prototype

SPS Test beam Sep/Oct



A. Uras, 20/05, 14h:15

ALICE 3 - a next-generation heavy-ion detector for LHC Run 5 & 6

Key physics questions and drivers

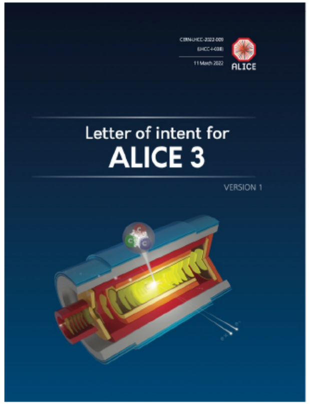
- Nature of **interactions with the QGP** of highly energetic quarks and gluons
- To what extent do quarks of different mass reach **thermal equilibrium** ?
- What are the **mechanisms of hadron formation** in QCD?

⇨ Systematic measurement of (multi-)charm hadrons

- QGP **temperature** throughout its temporal evolution
- What are the mechanisms of **chiral symmetry restoration** in the QGP?

⇨ Precision measurements of dileptons

- QCD chiral phase structure (⇨ fluctuations of conserved charges)
- Hadron interaction potential (⇨ hadron-hadron correlations)
- ....



Letter of Intent: CERN-LHCC-2022-009

planned for installation in LS4

LHCC review completed in March

"a roadmap for exciting heavy-ion physics in 2035"

"ALICE 3 detector concept [...] is well matched to the proposed, ambitious physics program"

L. Fabbietti, 16/05, 17h:00