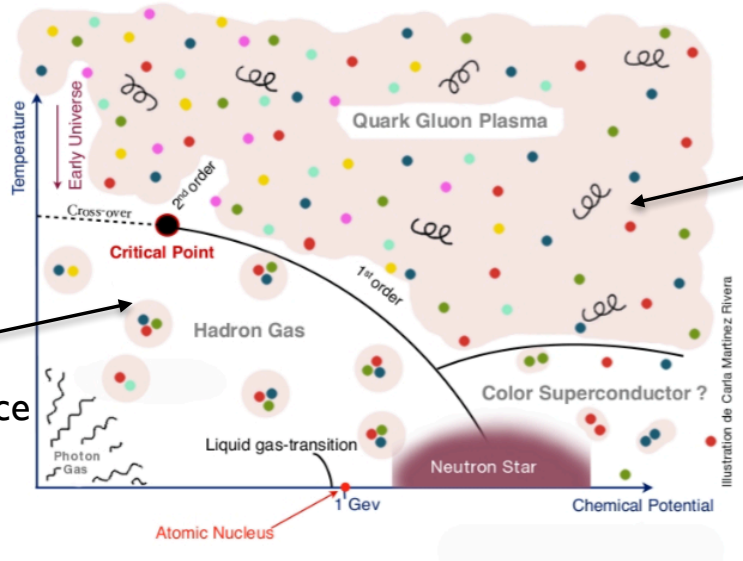
Recent results from LHC-ALICE

Shingo Sakai for High energy nucl. group

ALICE experiment

- ALICE experiment --- dedicate experiment for understanding Quark-Gluon Plasma (QGP) in LHC
- Quark-Gluon plasma



Quarks are confined
in hadron by the strong force
(gluon)

Quark and gluon are deconfined
under high temperature / density
⇒ QGP
⇒ Possibly produce by
⇒ heavy-ion collisions
(LHC PbPb 2.76 & 5.02 TeV)

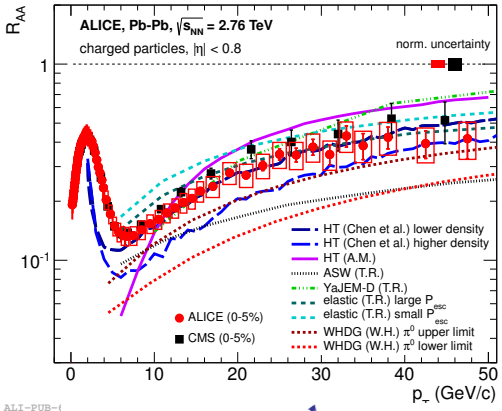
arXiv:1304.1452

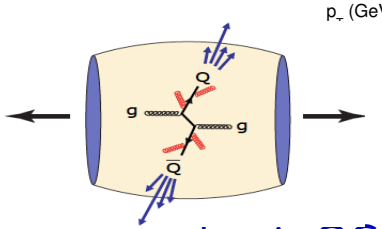
- Predicted by Quantum ChromoDynamics (QCD) under extremely high temperature and density
  - Test for QCD & new QCD phenomena
- State of the matter in the early stage of the universe (~10 μs after Big Bang)
  - Add a new page in "*History of the Universe*"

Results in PbPb collisions

(1) Suppression of charged particles

$$R_{AA}(p_T) = \frac{d\,N_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

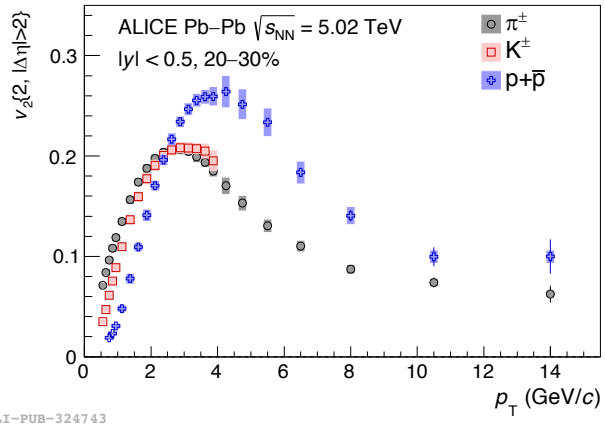


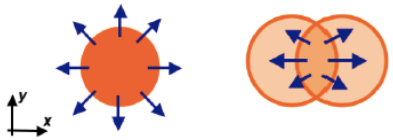


Parton energy loss in QGP

(2) Azimuthal anisotropy v_2

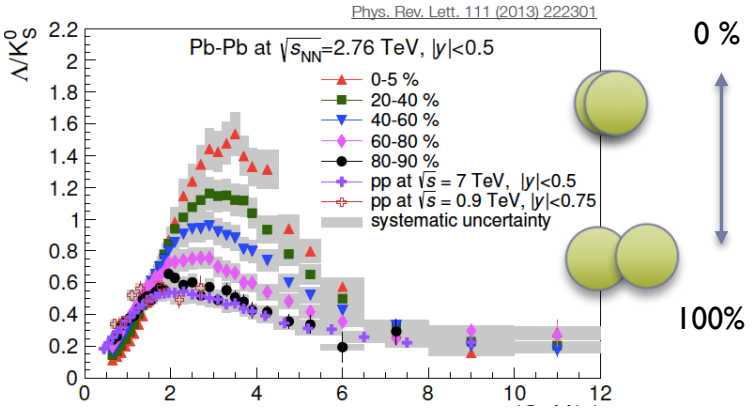
$dN/d(\phi-\psi_{RP}) = \ldots + N_0(1+2v_2\cos(2(\phi-\psi_{RP}))) + \ldots$

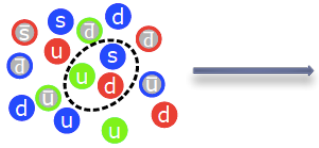




Collective motion in QGP

(3) Baryon-to-meson ratio





Quark recombination in QGP

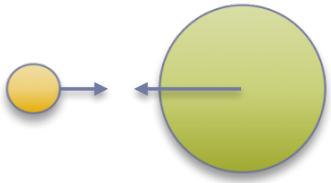
Mechanism ? Origin ? Unique ?

Measurements in ALICE

pp collisions
(reference)

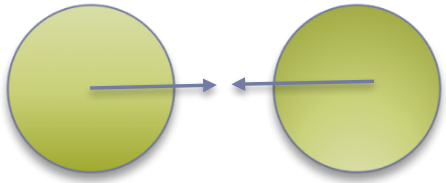
- Hadron production
  - Cross section
  - Fragmentation function

pA collisions
(control)



- Initial state
  - Nuclear PDF
    (parton distribution in A)

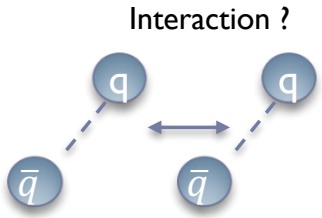
AA collisions
(QGP)



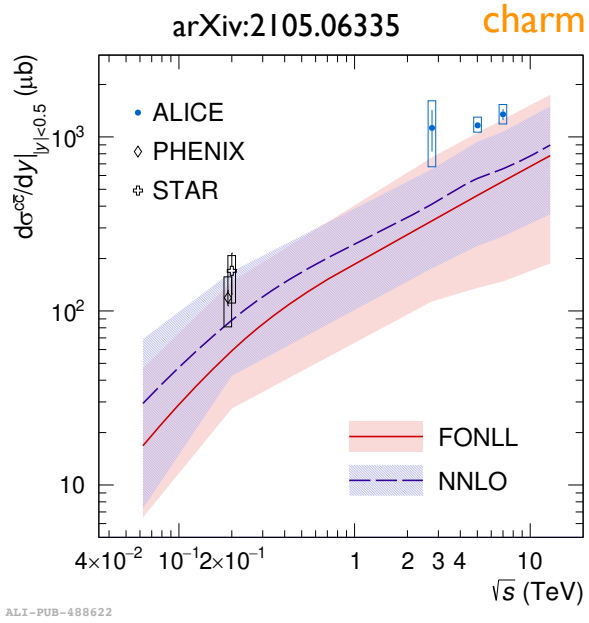
- Property of QGP
- Parton dynamics in
  hot & dense QCD matter
  (strong color filed)

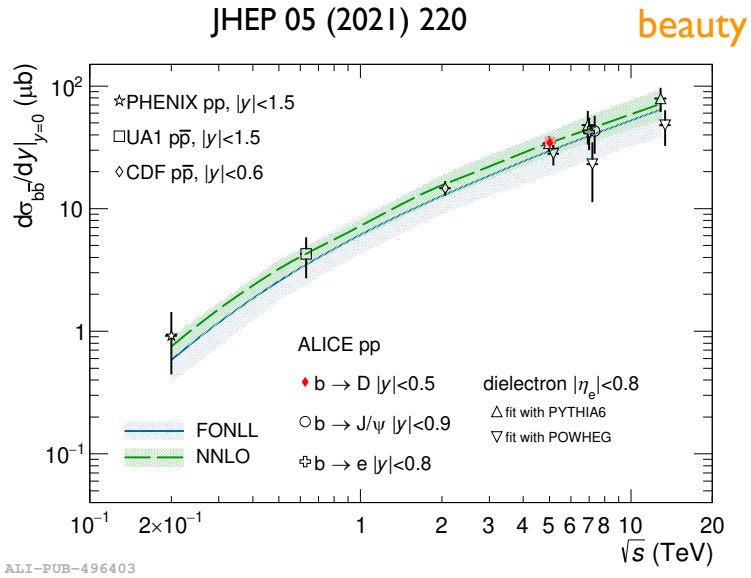
"Small system"
high multiplicity pp & pA events

- Produced several partons in same time
- parton-parton interaction
  - Observed QGP like signals



pp : Hadron production via heavy flavour (1)

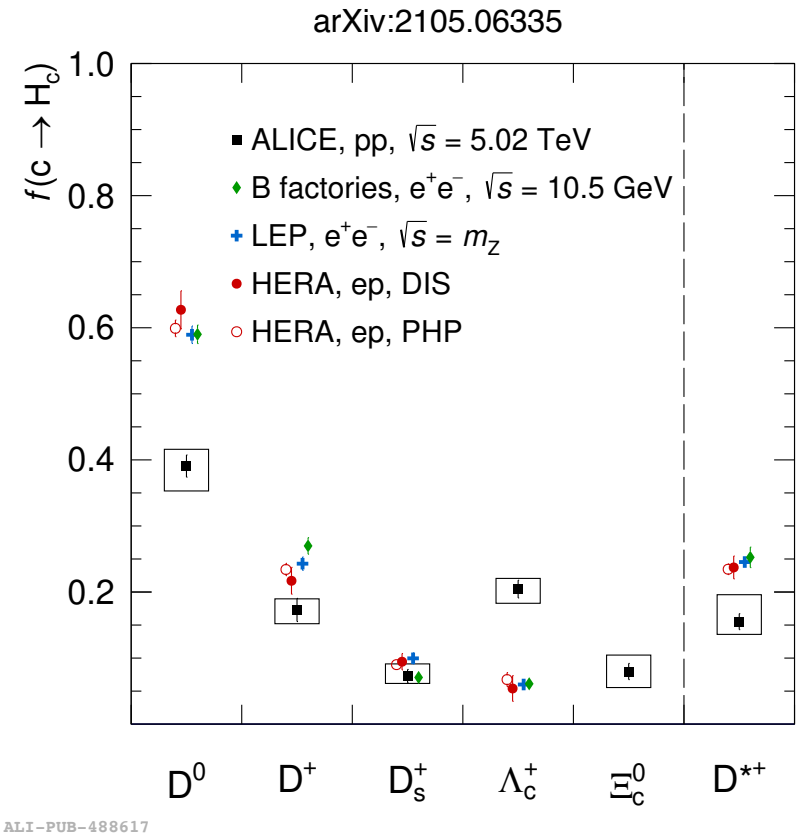




- Heavy flavour --- produced by initial hard scattering
  => good measurements to understand particle production based on QCD
- Total heavy flavour (charm and beauty) productions are in good agreement with pQCD predictions

$$d\sigma^{hard}_{AB\to h} = f_{a/A}(x,Q^2) \otimes f_{b/B}(x,Q^2) \otimes d\sigma^{hard}_{ab\to c} \otimes D_{c\to h}(z,Q^2)$$

pp : Hadron production via heavy flavour (2)



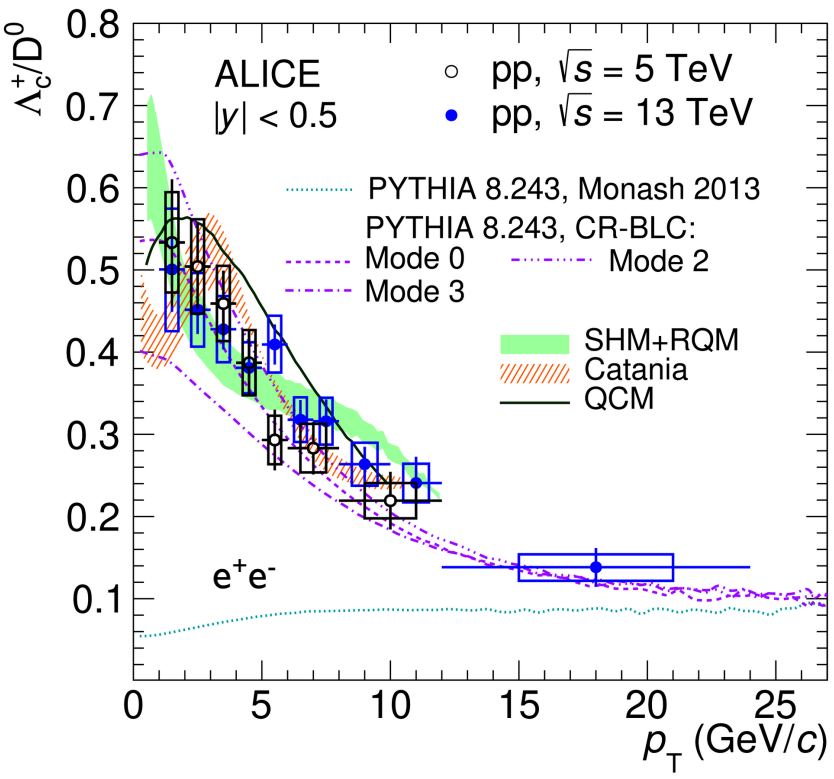
- Charm fragmentation function fractions measured including charm baryons (Λ_c and Ξ_c) for the first time at the LHC

$$d\sigma^{hard}_{AB\to h} = f_{a/A}(x,Q^2) \otimes f_{b/B}(x,Q^2) \otimes d\sigma^{hard}_{ab\to c} \otimes D_{c\to h}(z,Q^2)$$

- Charm fragmentation fractions in pp collisions at the LHC differ significantly from those e+e- and ep collisions
- Indicate additional hadronization process

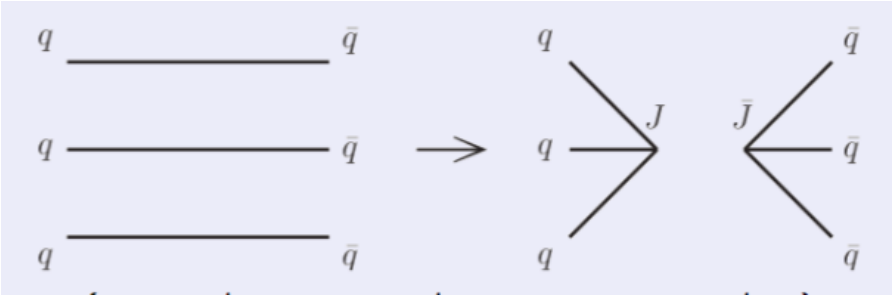
pp : Hadron production via heavy flavour (3)

arXiv:2011.06079



ALI-DER-493847

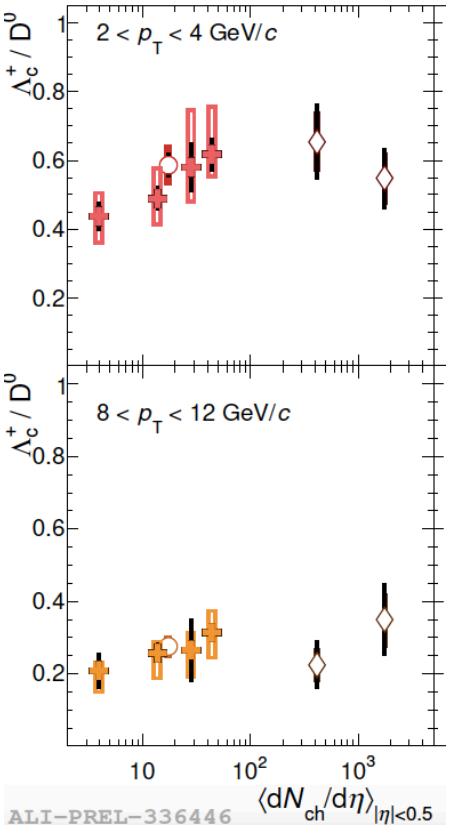
- Λ_c / D^0 ratio as a function of p_T
- Clear enhancement in lower p_T w.r.t. Λ_c / D^0 in e+e- (~0.1)
- PYTHIA8 + Color reconnection (CR)
  - CR --- allow reshuffle the colors before hadronization

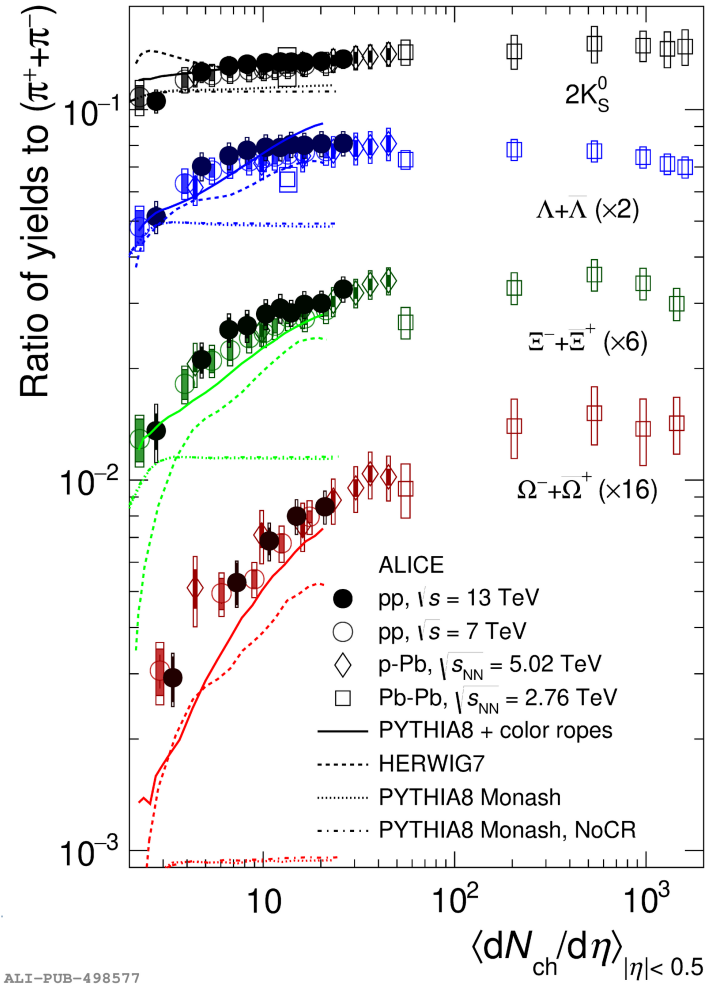


- Catania --- quark coalescence
  - Assume free quarks form hadrons (in QGP) & thermalizaion
- SHM + RQM --- statistical hadronization

pp : Charm & strangeness hadron production vs. multiplicity

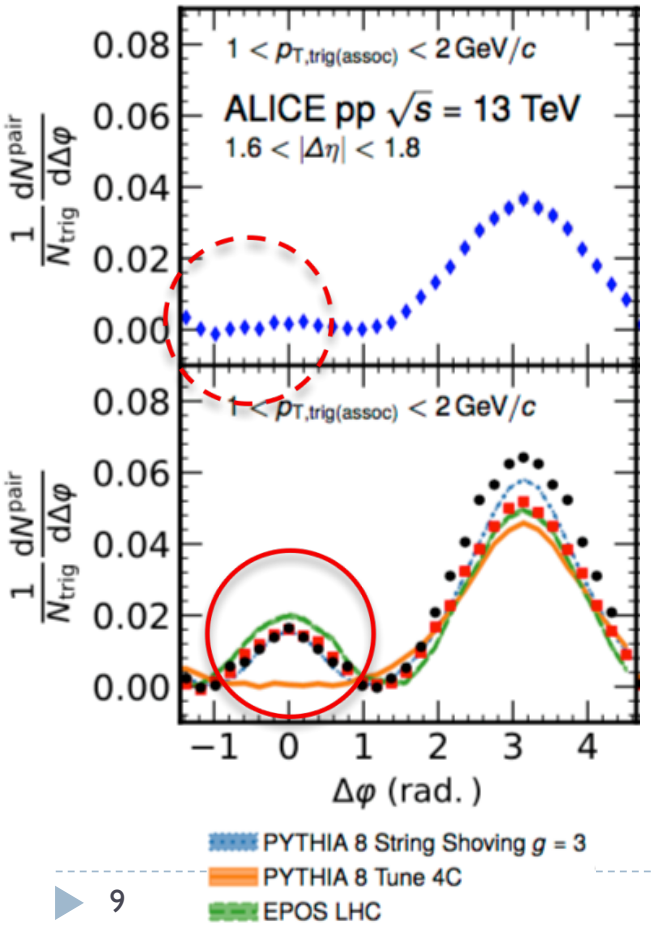
- Λ_c / D^0 ratio
  - increase with charged multiplicity up to d*N*/dη ~50
- K^0_s, Λ, Ξ, Ω production w.r.t π
  - Contain strange quark
  - Also increase with multiplicity up to d*N*/dη ~50
  - The trend catch up with PYTHIA + color reconnection
- Indicate same hadronimzation mechanism between light (s) and heavy (c) quarks
  - color reconnection play a role

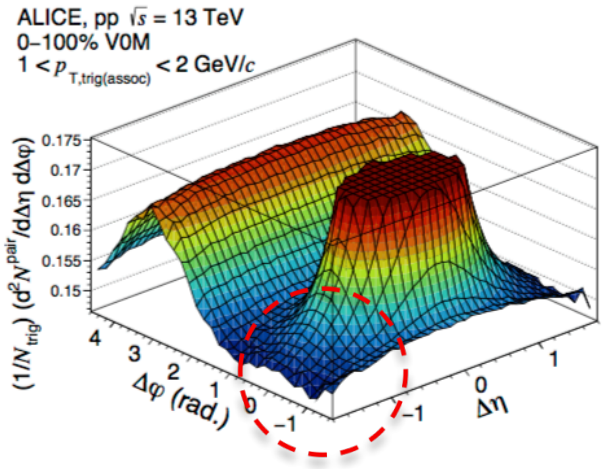


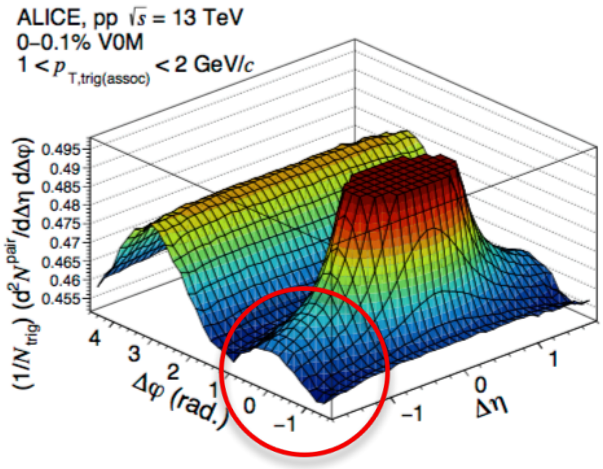


pp : Long range correlation in high multiplicity pp events

arXiv:2101.03110





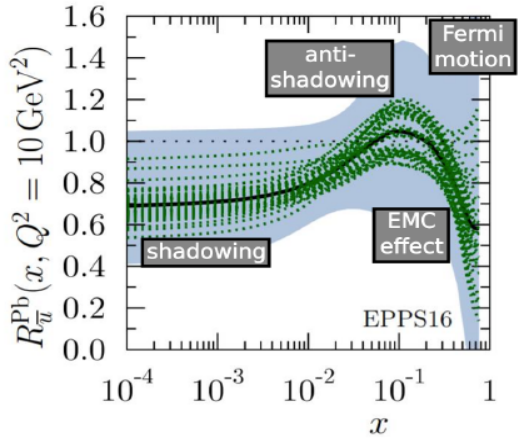


- Long range (large rapidity correlation) in near-side ($\Delta\phi \sim 0$) in high multiplicity pp collisions (0-0.1% V0M)
  - Such the correlation also observed in Pb-Pb collisions
- Near-side correlation in high multiplicity events are reproduced by
  - PYTHIA + color reconnection
  - EPOS (include 3D+1 ideal hydro)

pPb : Initial state- Gluon distribution at low x

- Parton (gluon and quark) distribution in nucleus (nPDF)
  - effect total particle production in heavy-ion collisions

$$d\sigma^{hard}_{AB\to h} = f_{a/A}(x,Q^2) \otimes f_{b/B}(x,Q^2) \otimes d\sigma^{hard}_{ab\to c} \otimes D_{c\to h}(z,Q^2)$$



- photo production of J/Ψ give access to the shadowing of gluon at low Bjorken-x

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

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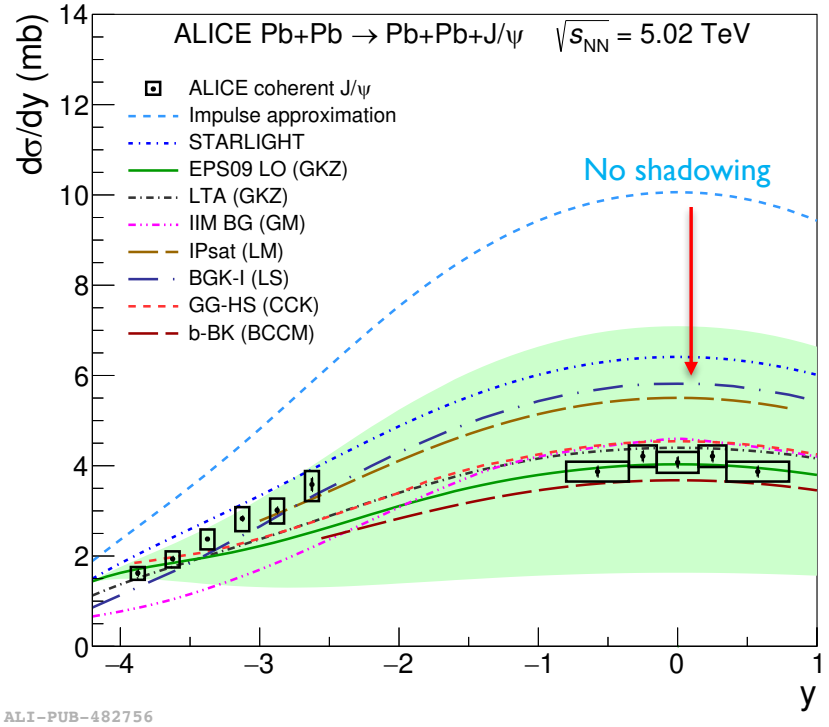
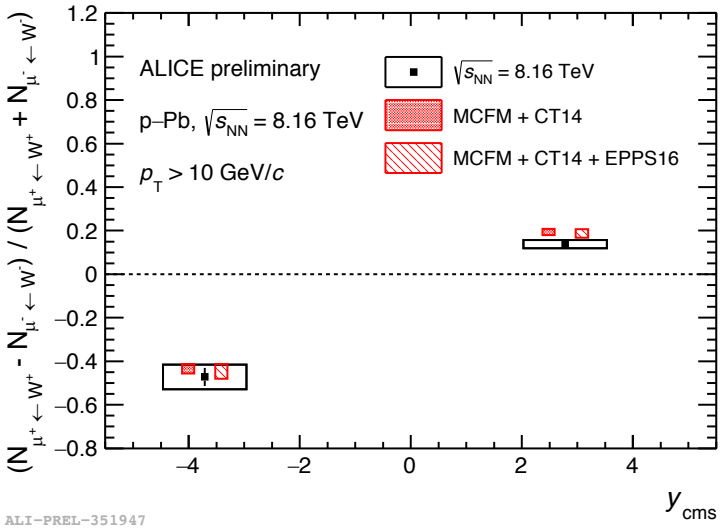


Moderate shadowing of 0.65 at x ~ 6×10^{-4}

pPb : Initial state- Quark distribution at low & high x



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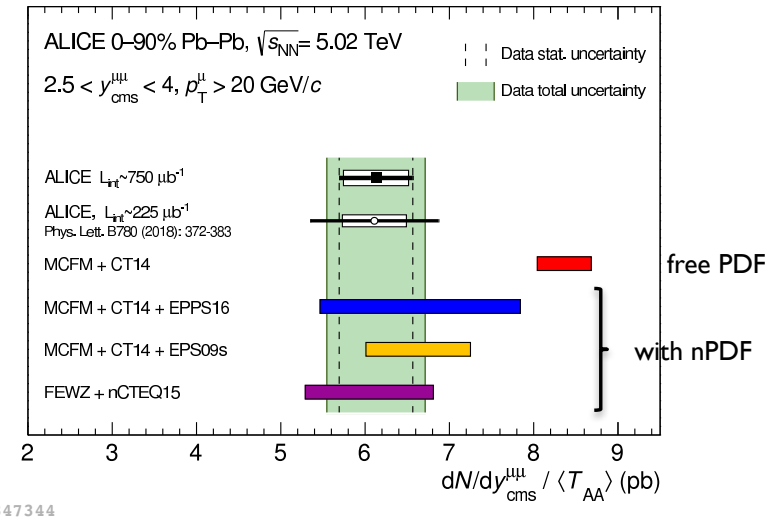
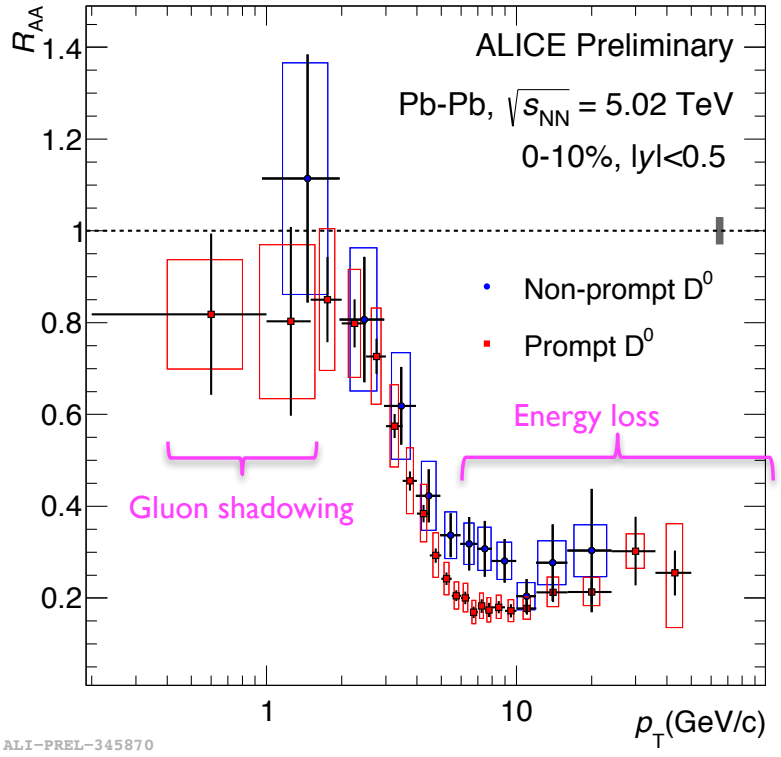


- W/Z boson productions
  - Predominatly via a quark – antiquark pair annihilation (Drell-Yan)
    - $u\bar{d} \rightarrow W^+, d\bar{u} \rightarrow W^-$, and $q\bar{q} \rightarrow Z$
  - Sensitive to quark and antiquark content in nucleon / nucleus
    - Difference in pp & p-Pb (Pb-Pb) --- nuclear Parton Distribution Function (nPDF)
    - W charge asymmetry --- sensitive to the down / up ratio (isospin)

PbPb : Parton – medium interaction ; Parton energy loss (1)



Prompt; c->D
Non-prompt; b->c->D

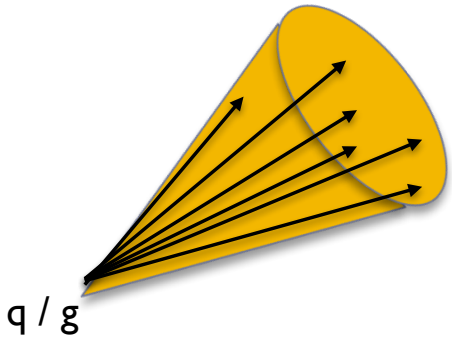
- Interaction between partons and QGP
  - Low p_T : Elastic scattering (collisional energy loss)
  - High p_T : Gluon bremsstrahlung in color field (radiative energy loss)
- Radiative energy loss (QCD base prediction)
  - Smaller energy loss for heavy quark than for light quark due to "dead cone" effect
  - Bremsstrahlung probability $\propto 1/(\theta^2 + (m/E)^2)^2$
  - $E_{loss}(g) > E_{loss}(u,d,s) > E_{loss}(c) > E_{loss}(b)$

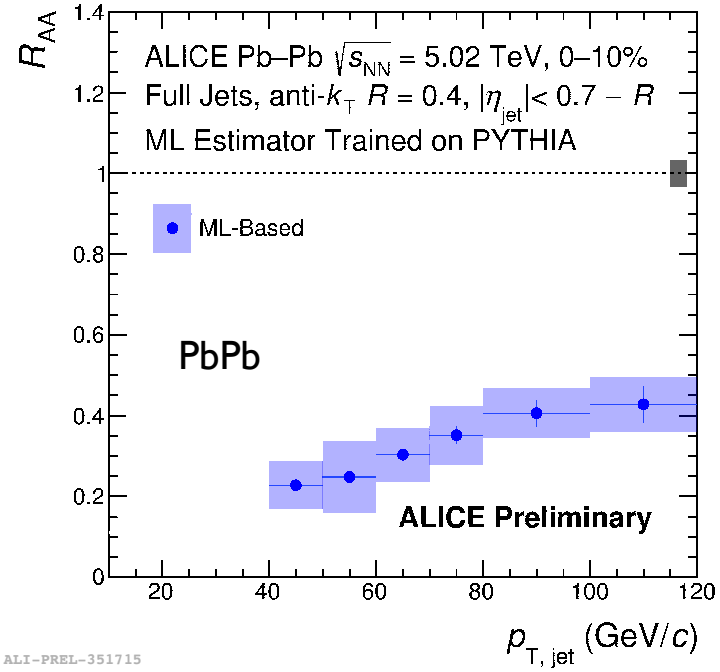
$$R_{AA}(p_T) = \frac{d\,N_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

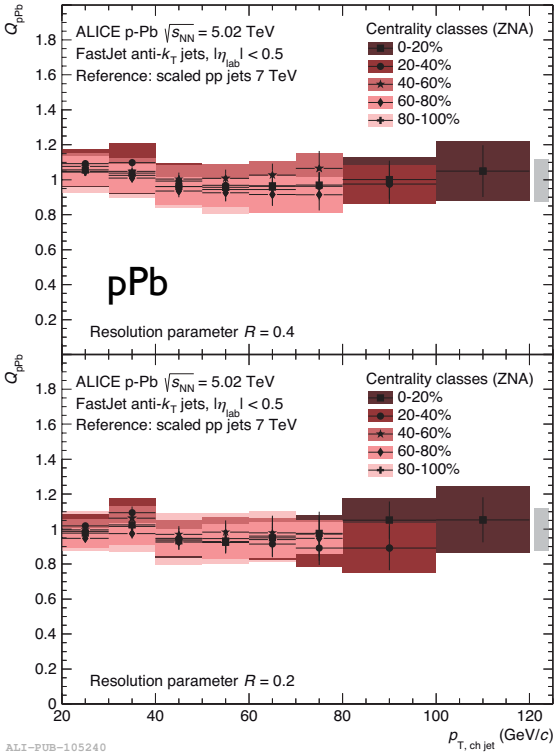
- Both charm and beauty lose energy in QGP
- Smaller R_{AA} of non-prompt (from B decay) than D mesons
  - Indicate smaller energy loss of beauty than charm

PbPb : Parton – medium interaction ; Parton energy loss (2)

- R_{AA} for full jets
  - cluster of hadron made by parton
  - Address parton kinematic

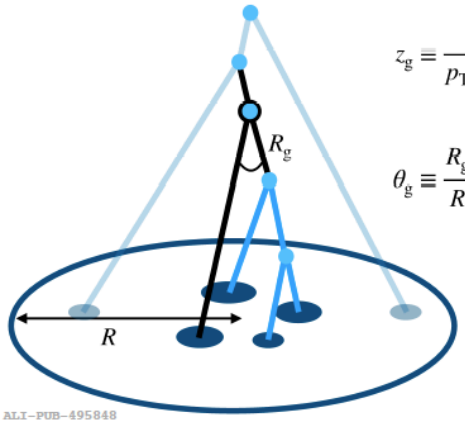






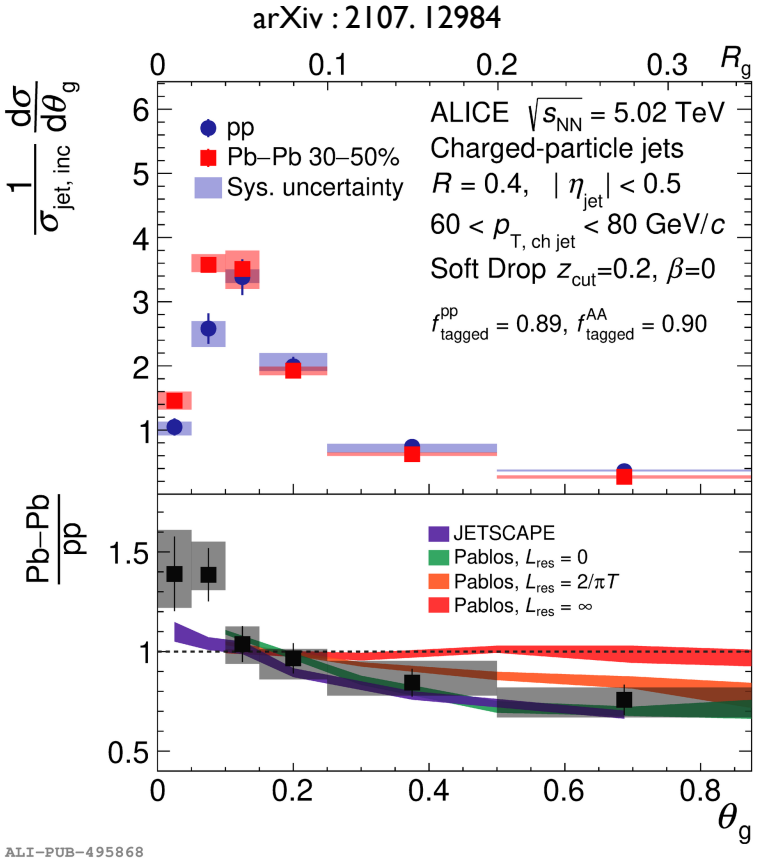
- Difficulty jet measurement in low pT in PbPb
  - Large contribution from Underlying events used Machine learning techniqe
- Strong suppression of full jets in PbPb => indicate parton level energy loss
  - Not observed the suppression in small system (pPb)

PbPb : Parton – medium interaction ; modification jet shape



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

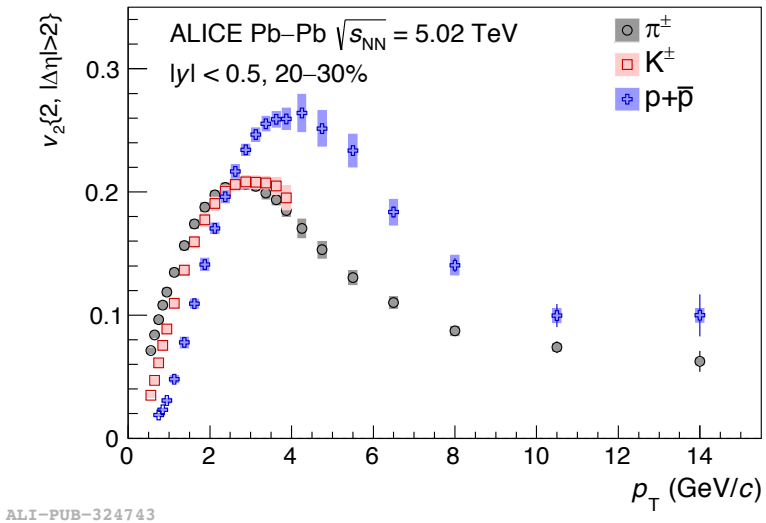
$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$



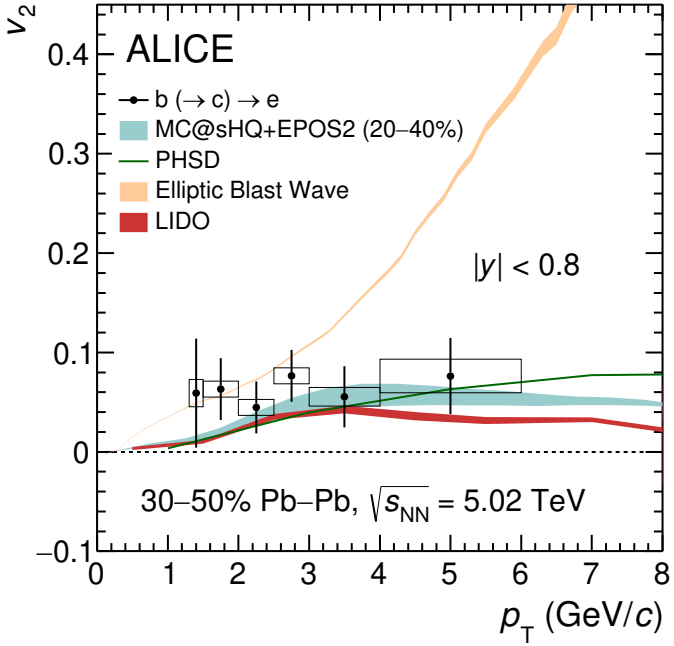
- The core of jets (leading & sub-leading particles) are narrower in Pb-Pb compared to pp
  - Find first hard splitting by soft drop grooming
- First direct experimental evidence for the modification of angular scale of jets in heavy-ion collisions

PbPb : Azimuthal anisotropy (v_2)

JHEP 09 (2018) 006



PRL 126 (2021) 162001

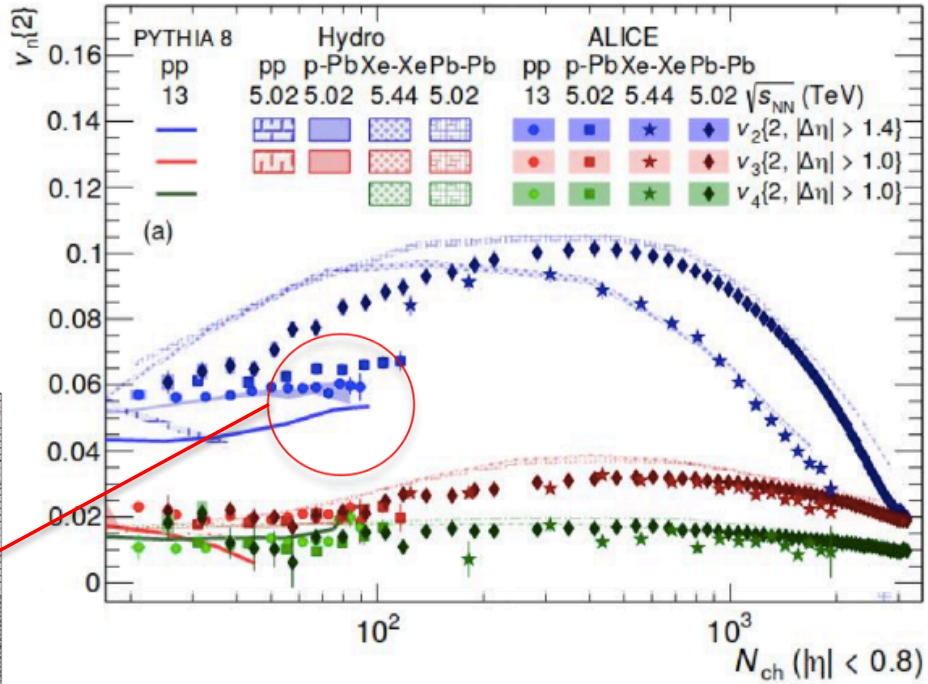


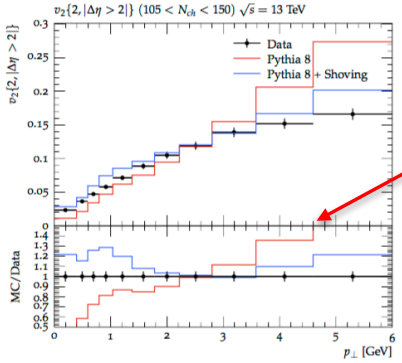
- Azimuthal anisotropy
  - $dN/d(\phi-\psi_{RP}) = \ldots + N_0(1+2v_2\cos(2(\phi-\psi_{RP}))) + \ldots$
  - Low p_T; collectivity, driven by pressure gradient in the system
  - High p_T; path-length dependence of enery loss
- Non-zero v_2 from light to heavy quarks
  - Clear mass dependence; v_2 (light) > v_2 (heavy)

PbPb : Azimuthal anisotropy (v_2) from pp to PbPb

- v_n measurements from pp to PbPb (mult. dependence)
- Similar values of v_n in pp, pPb and PbPb at low multiplicity
  - Both hydro & PYTHIA are not well reproduced the v_2 in pp at 13 TeV
  - PYTHIA + Shoving (CR base) at high multiplicity
    - Reproduced the p_T dependence

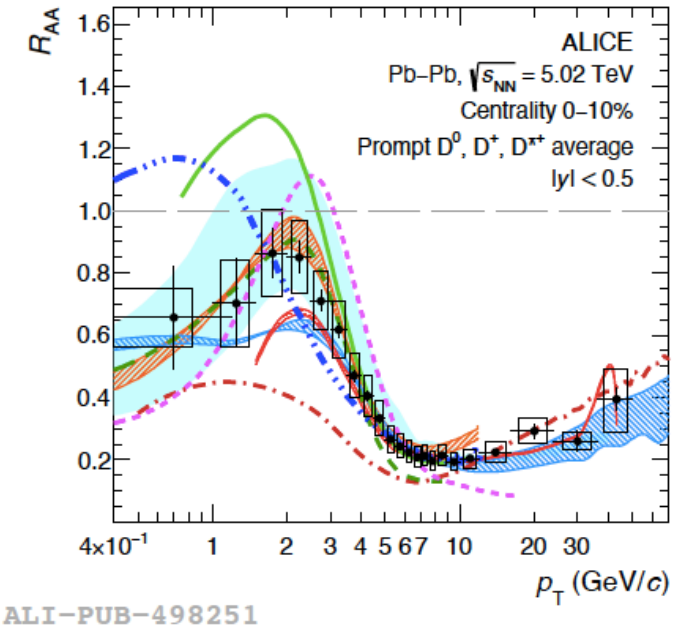
PRL 123 142301 (2019)





arXiv:2010.07595

PbPb : transport property



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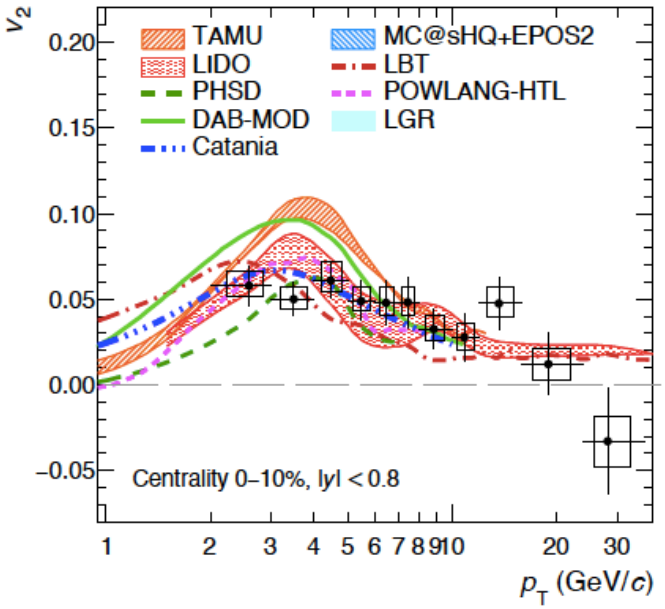
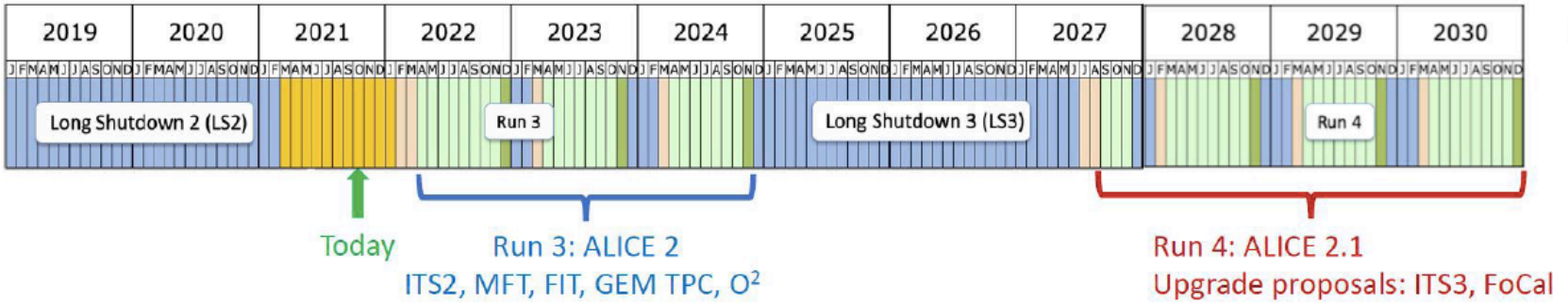


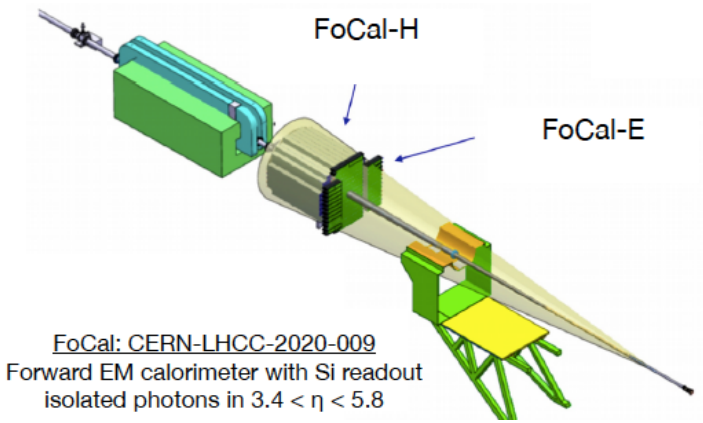
arXiv: 2110.09420

- Large suppression and v_2 for D mesons
  - Sensitive to medium transport property
- Several models reproduce the measurement
- Models use heavy-quark diffusion coefficient ; $1.5 < 2\pi DT < 4.5$

Future plan in ALICE : ALICE Run3 & Run4

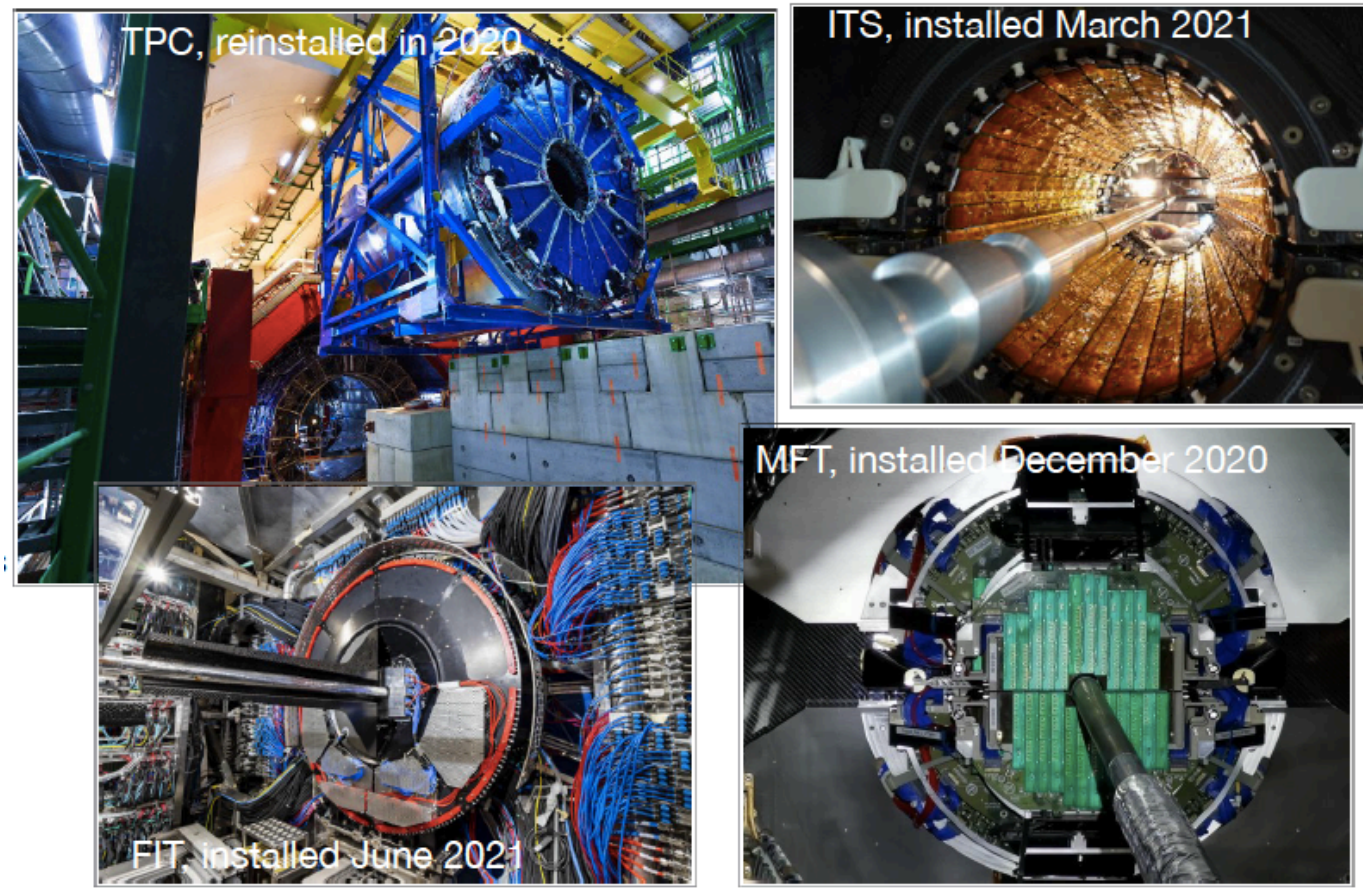


- 50 kHz Pb-Pb event readout rate
  - Previously ~ 1 kHz in the central barrel
- Physics goal
  - Heavy-flavour mesons and baryons
  - Charmonium
  - Dileptons from QGP radiation
  - High-precision measurement of light and hyper nuclei
- FoCal --- Tsukuba-group contribution (lead by T. Chujo)



FoCal: CERN-LHCC-2020-009
Forward EM calorimeter with Si readout
isolated photons in $3.4 < \eta < 5.8$

Future plan in ALICE : ALICE Run3 (& Run4)

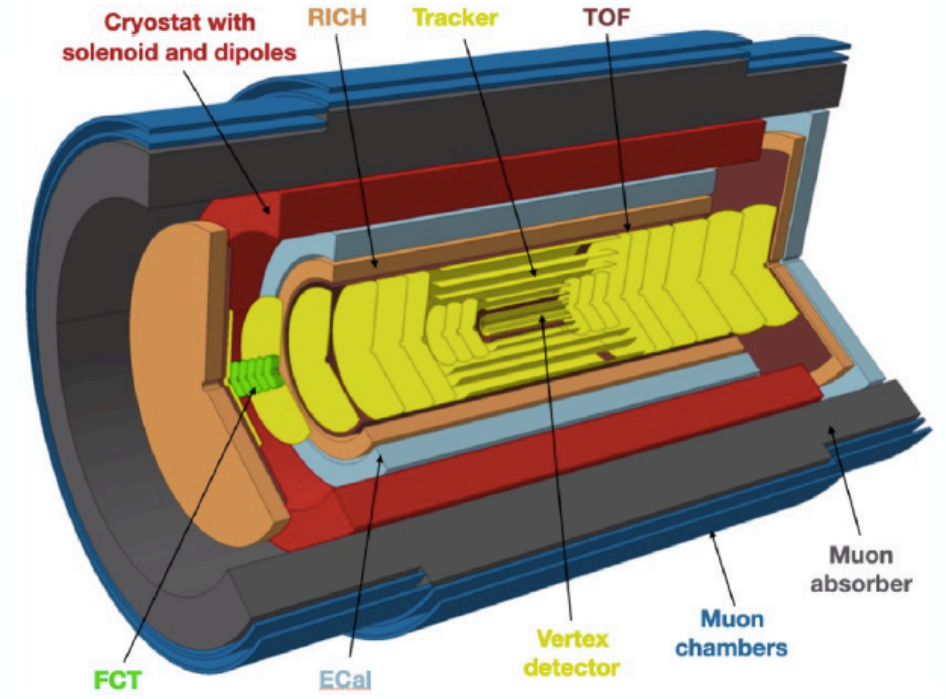


Future plan in ALICE : ALICE beyond Run4 (ALICE 3)

- ALICE 3
  - A new silicon-based heavy-ion dedicated detector for Run5+ (2030~)

- Physics goal
  - Hadron formation in QGP
  - QGP transport property
  - QGP radiation
  - Pre-hydrodynamization phase
  - Chirals symmetry restoration

ALICE 3 workshop @ Oct. 18-19 2021
https://indico.cern.ch/event/1063724/



Summary

- Goal of the ALICE experiment
  - Understand Quark-Gluon plasma
- Recent results
  - Important to understand multi-parton interaction for the results in PbPb
    - v_2 & baryon enhancement also observed in small system
    - QCD base calculation (PYTHIA + Color reconnection) reproduced both results
  - Improved knowledge of the energy loss
    - Flavour dependent energy loss predicted by QCD
  - Experimental observation for parton medium interaction
    - modification of jet shape in PbPb