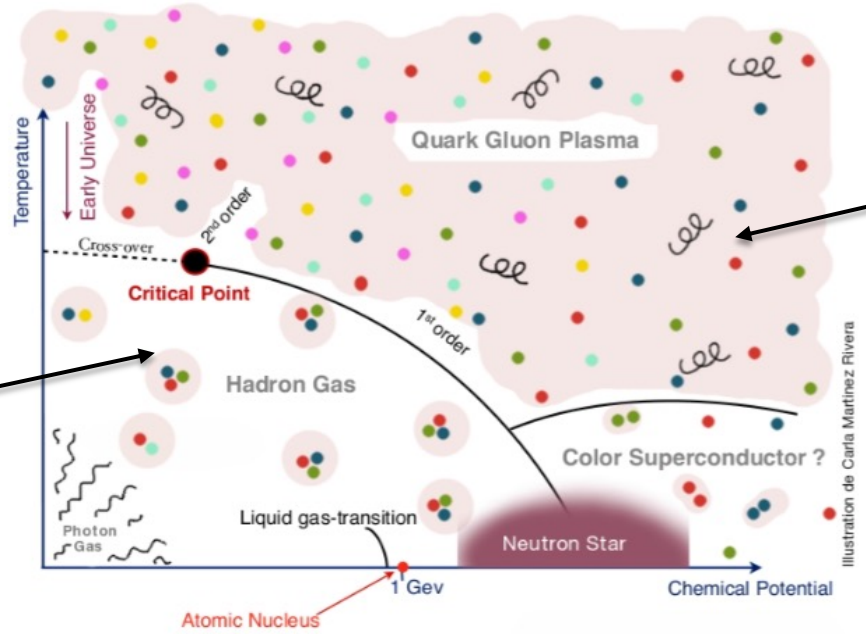
Initial and final state effects on QGP in relativistic heavy-ion collisions

Shingo Sakai

(Tsukuba Univ. of Technology / Univ. of Tsukuba)

QGP

- A goal of the relativistic heavy-ion collisions



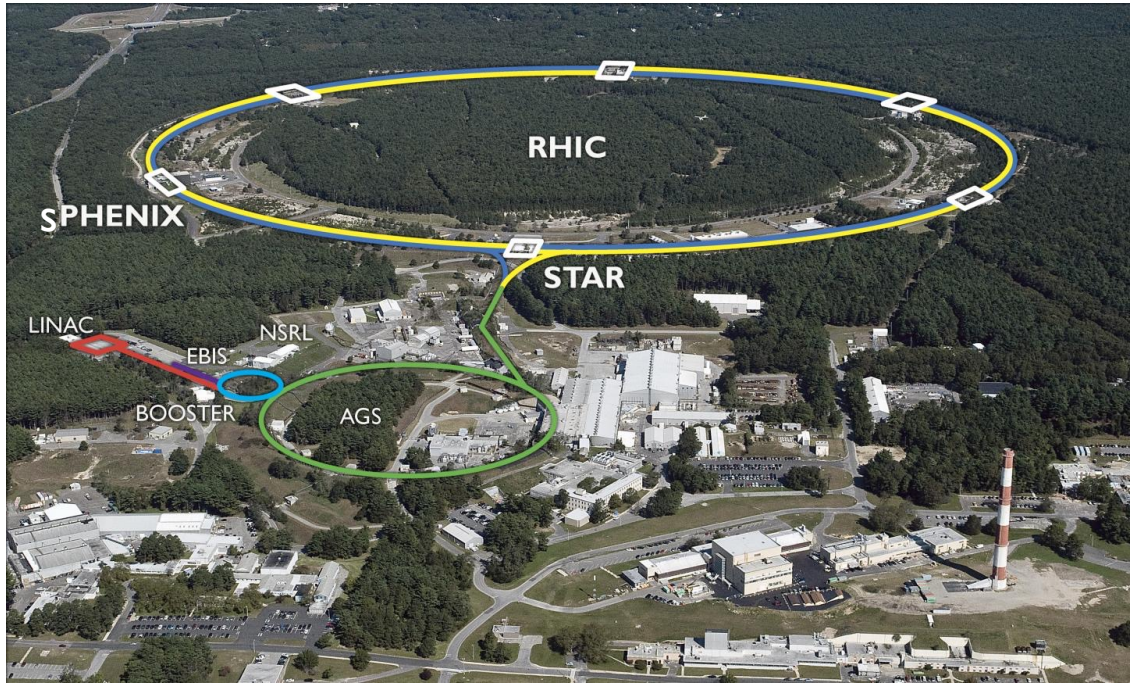
Quarks are confined
in hadron by the strong force
(gluon)

Quark and gluon are deconfined
under high temperature / density
⇒ QGP
⇒ Possibly produce by
heavy-ion collisions

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*"

Relativistic Heavy-ion collisions

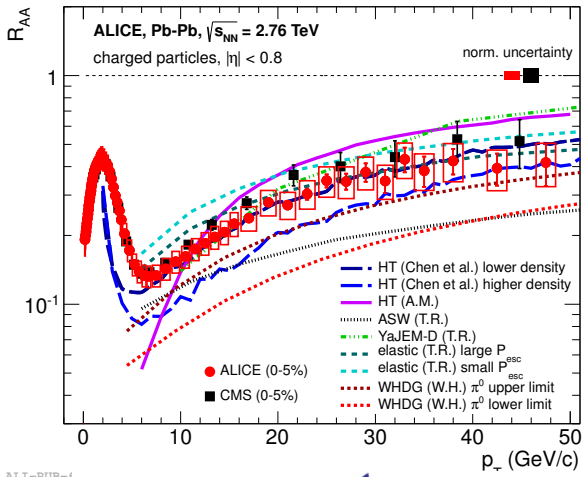


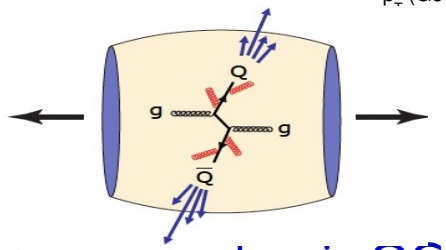
- RHIC (BNL, US)
  - Au+Au : 0.2 TeV
  - STAR, sPHENIX
- LHC (CERN, Switzerland)
  - Pb+Pb : 5.02 TeV
  - ALICE, ATLAS, CMS, LHCb

Discoveries in Heavy-ion collisions (AA)

(1) Suppression of charged particles

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

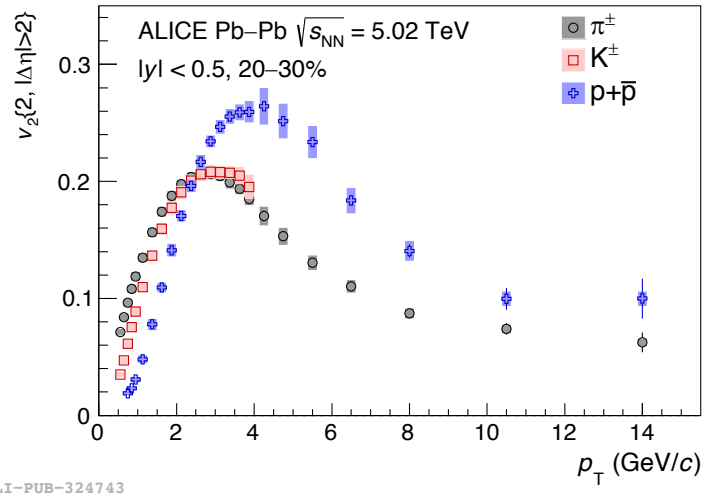


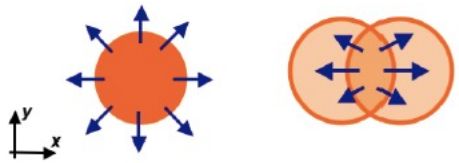


Parton energy loss in QGP

(2) Azimuthal anisotropy v_2

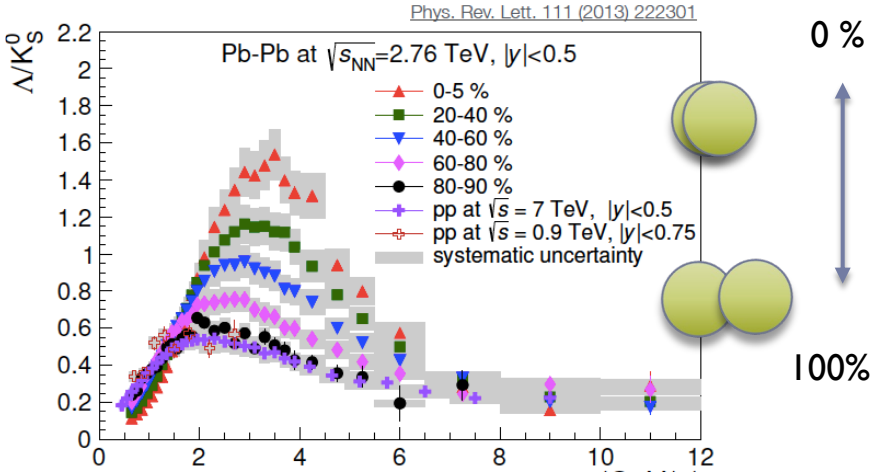
$dN/d(\phi-\psi_{RP}) = \ldots + N_0(1+2v_2\cos(2(\phi-\psi_{RP}))) + \ldots$

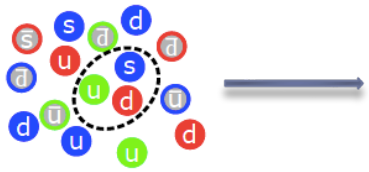




Collective motion in QGP

(3) Baryon-to-meson ratio





Quark recombination in QGP

Not fully understand initial condition and parton dynamics in QGP

Hard probe production in heavy-ion collisions (pA & AA)

- Hard probes (D, B, jet, W, Z …)
  - Large transverse momentum, Large mass (> Λ_{QCD} ~ 200 MeV)
    - Produced initial hard scattering
  - Applicable perturbative QCD

PDF FF

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

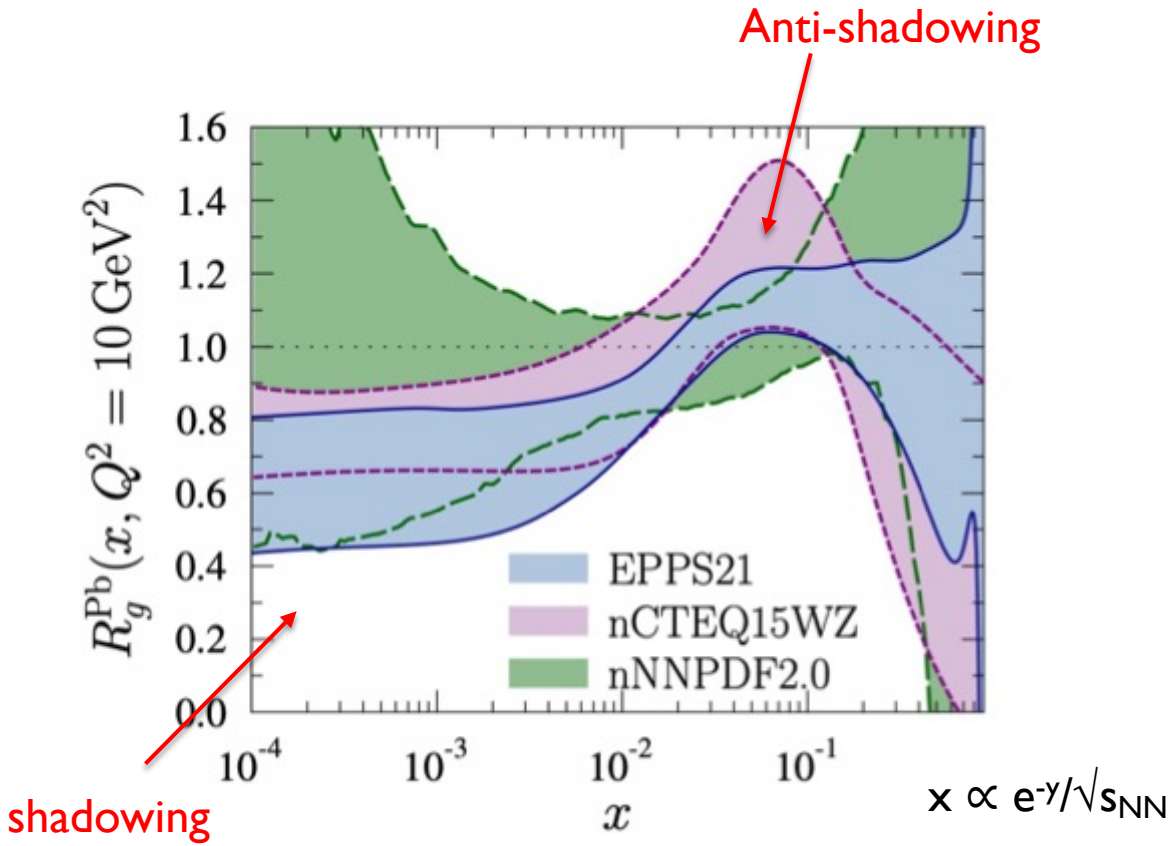
  - Good probe to study QGP

- Production possibly modified in heavy-ion collisions
  - Initial state effect ; Modification of parton distribution function in nuclear matter (nPDF)
    - Important to understand initial condition of QGP
    - Study in pA collisions (reference collisions, w.o. QGP)
  - Final state effect ; Modification of fragmentation by
    - Energy loss of partons (collisional & radiative process)
    - Jet-induced medium response

- *This talk => nPDF & energy loss in LHC*

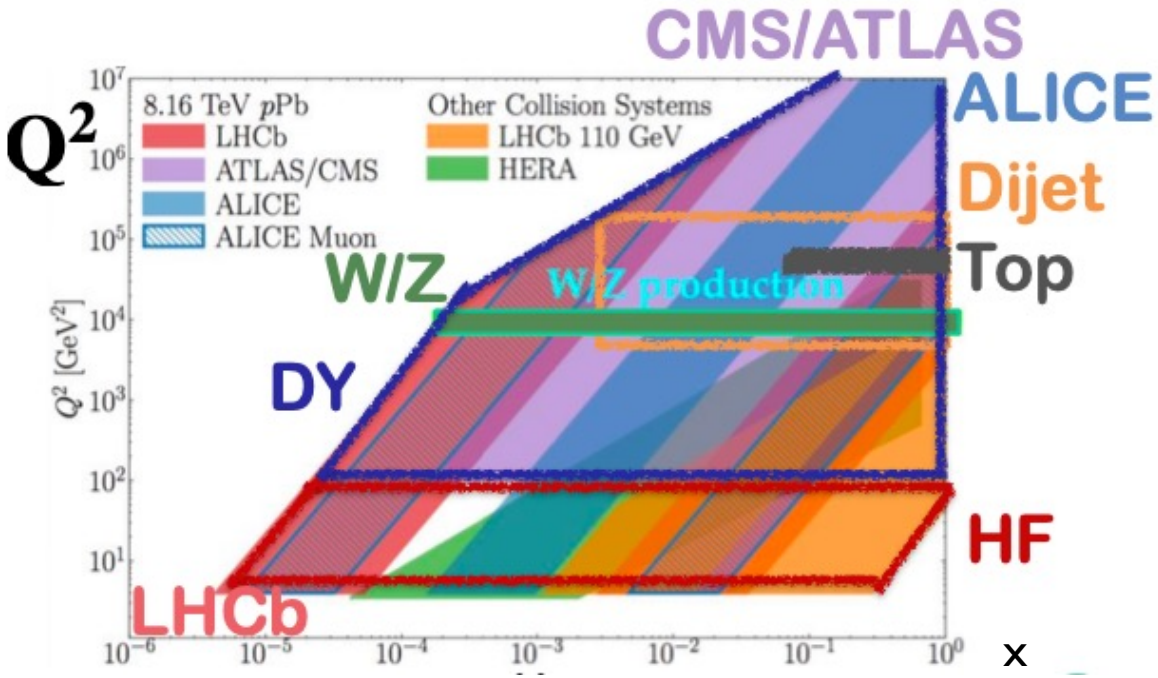
- Initial state effect
  - nPDF

nPDF



$x \propto e^{-y}/\sqrt{s_{NN}}$

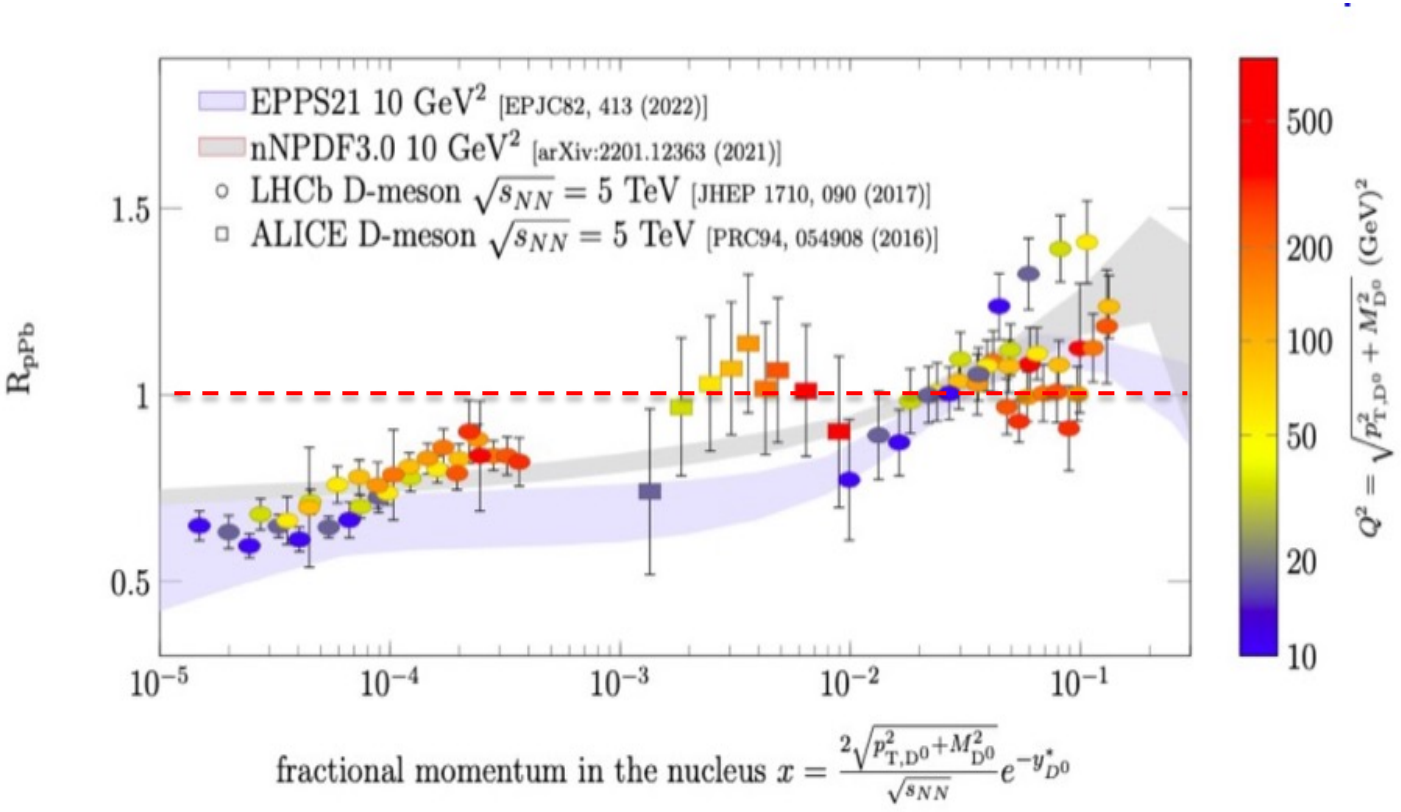
- Parton PDFs modified by nuclear medium
  - Suppression at small x (shadowing)



Andre Stahl Snowmass meeting, EF07

- W/Z bosons – PDF for u, d
- HF (charm & bottom) – PDF for gluons

Heavy-flavour (D meson) production in pPb



Cesar Luiz da Silva, QCD Challenges 2023 workshop

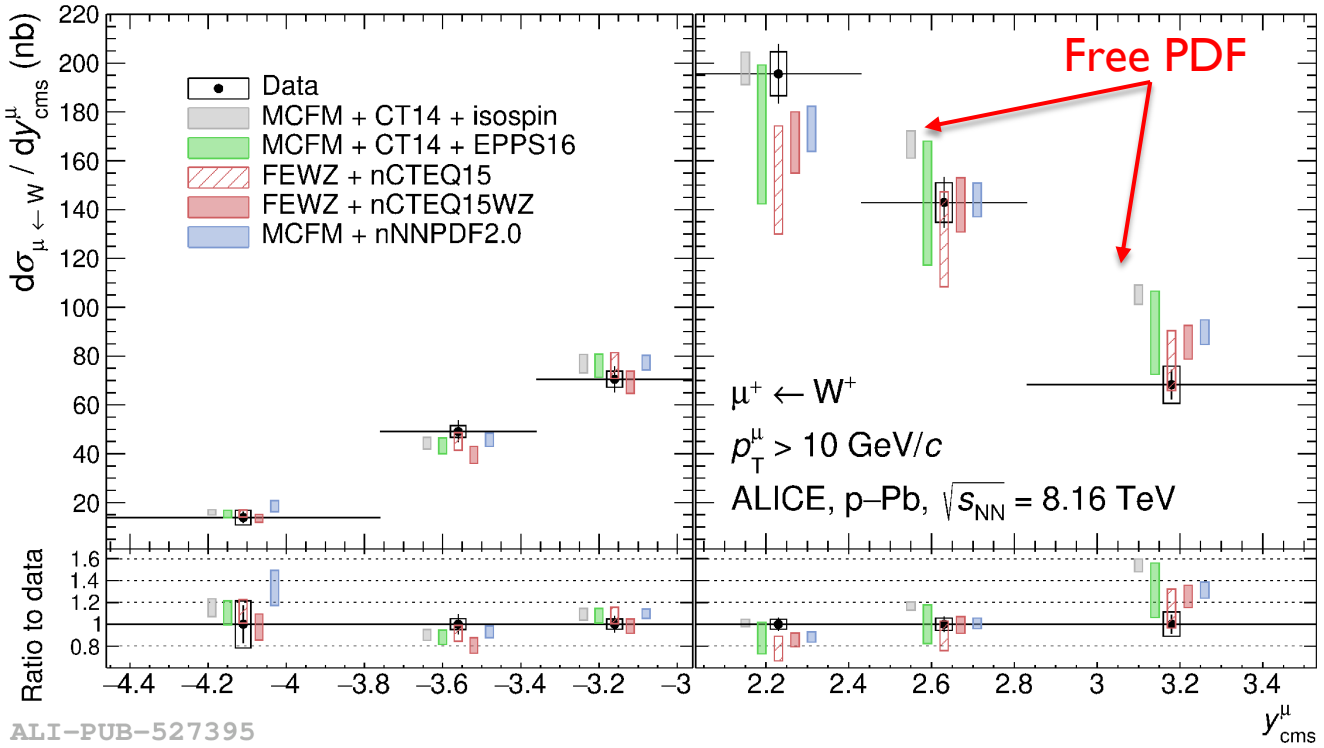
- D meson production as a function of x
  - Down to x ~ 10^{-5}
- Reduction at small x (forward y)
- Possibly enhancement at large x (backward y)
- nPDFs with shadowing describe D meson production in pPb

$$R_{\mathrm{pPb}} = \frac{1}{A} \frac{\mathrm{d}\sigma_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}},$$

$W^{\pm}$ production in pPb (1)

$\mu^+ \leftarrow W^+$

arXiv:2204.10640[nucl-ex]



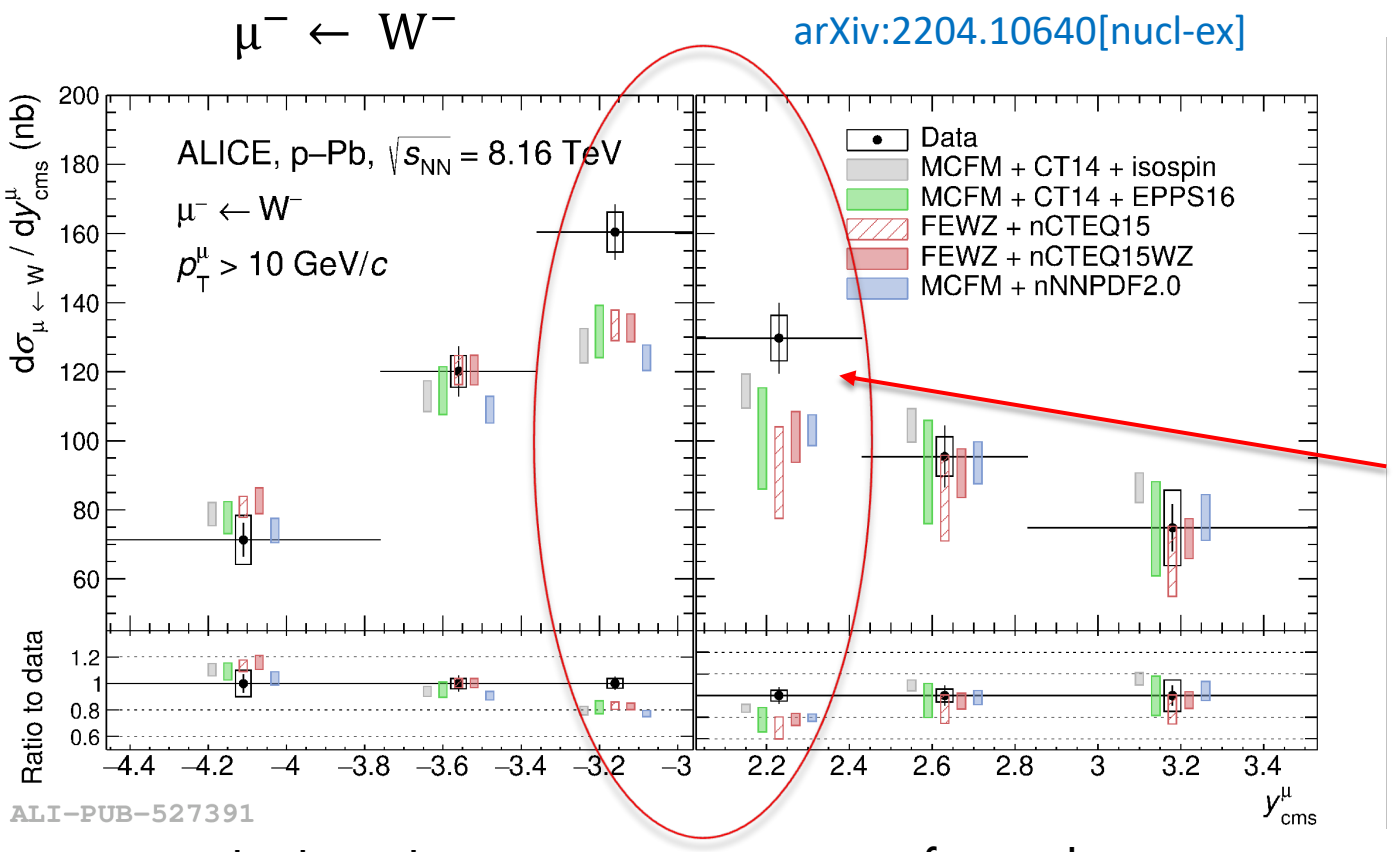
backward
$x \sim 10^{-1}$
Anti-shadowing

forward
$x \sim 10^{-4}$
Shadowing

- W^+ production cross section measured as a function of rapidity
- Model calculations
  - Based on pQCD predictions
  - including isospin effect with/without nPDF
- Significant deviation from free-PDF calculation (MCFM + CT14 + isospin) for W^+ at forward rapidity for the bin at largest rapidity

MCFM : T. Campbell and T. Neumann, JHEP 12 (2019) 034
FEWZ : R. Gavin, Y. Li. F. Petriello and S. Quackenbush, CPC 182 (2011) 2388-2403
CT14 : S. Dular et. al., PRD 93 (2016) 033006
CT14 + EPPS16 : K. J. Eskola et. al., EPJ C77 (2017) 163
nCTEQ15 : K. Kovarik et. al., PRD 93 (2016) 085037
nCTEQ15WZ: A. Kusina et. al., EPJC 80 (2020) 968
nNNPDF2.0 : JHEP 09 (2020) 183

$W^{\pm}$ production in pPb (2)



backward
$x \sim 10^{-1}$
Anti-shadowing

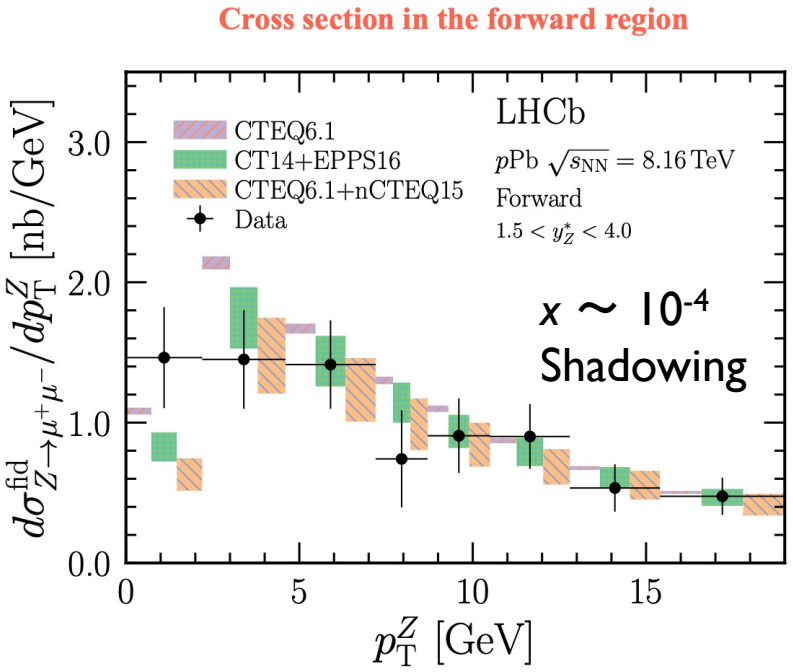
forward
$x \sim 10^{-4}$
Shadowing

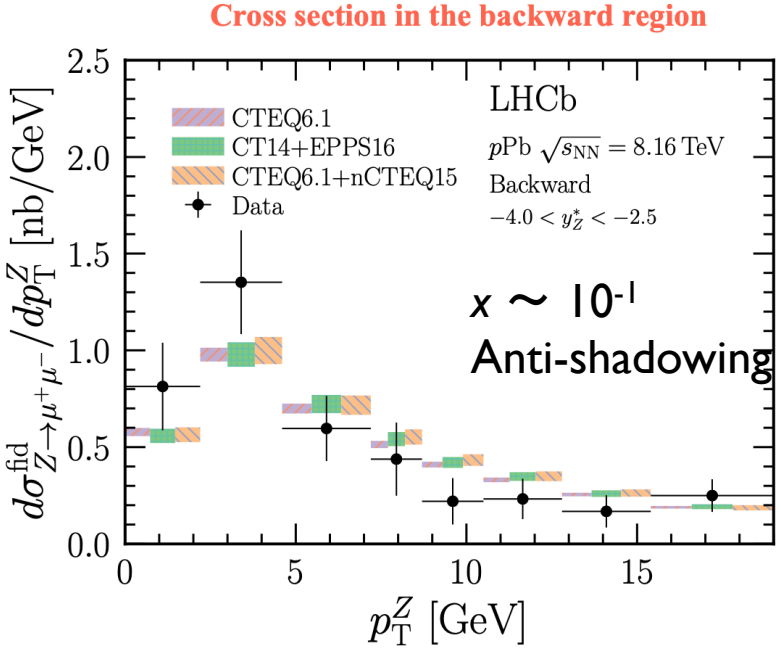
- W^- production cross section measured as a function of rapidity
- Model calculations
  - Based on pQCD predictions
  - including isospin effect with/without nPDF
- Calculations underestimate data for bins closest to midrapidity, both at forward and backward (1.4 and 2 σ from EPPS16 predictions)

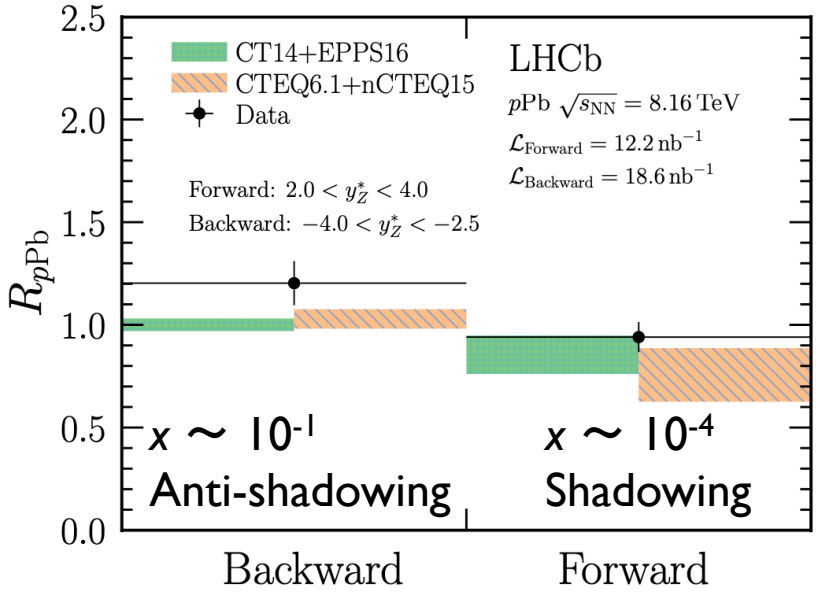
MCFM : T. Campbell and T. Neumann, JHEP 12 (2019) 034
FEWZ : R. Gavin, Y. Li. F. Petriello and S. Quackenbush, CPC 182 (2011) 2388-2403
CT14 : S. Dular et. al., PRD 93 (2016) 033006
CT14 + EPPS16 : K. J. Eskola et. al., EPJ C77 (2017) 163
nCTEQ15 : K. Kovarik et. al., PRD 93 (2016) 085037
nCTEQ15WZ: A. Kusina et. al., EPJC 80 (2020) 968
nNNPDF2.0 : JHEP 09 (2020) 183

Z boson production in pPb

Arxiv:2205.10213



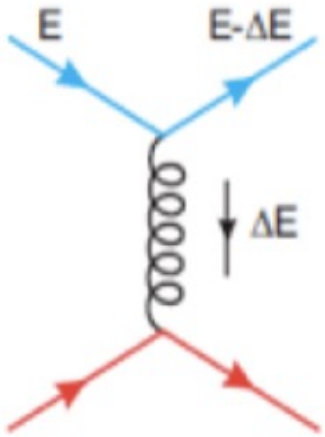


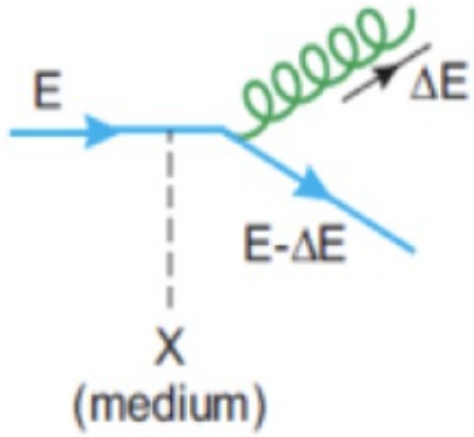


- Z boson production in forward (1.5 < y < 4.0) and backword (-4.0 < y < -2.5)
- The nuclear modification factor in the forward region is well described theoretical predictions
- The backward region is slightly higher but consistent with data within errors

- Final state effect
  - Energy loss

Parton energy loss in QGP (AA collisions)



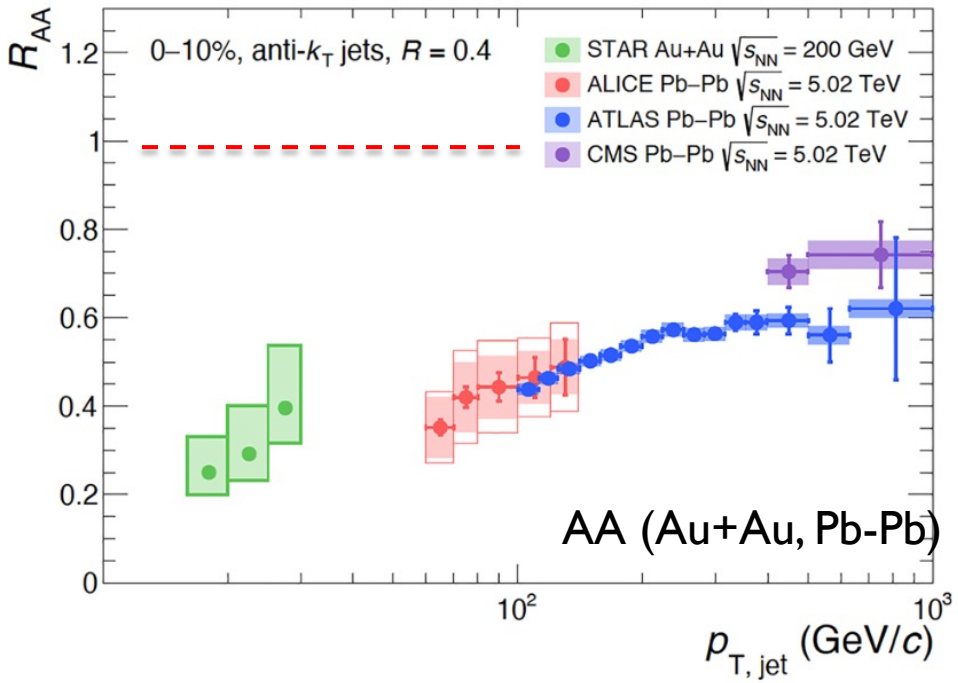


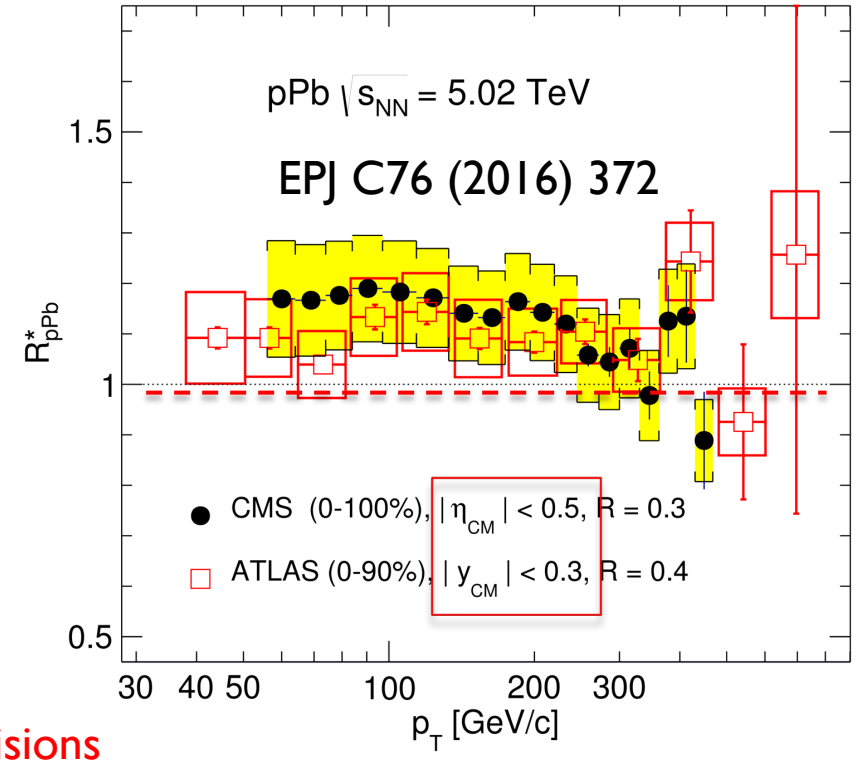
$$R_{AA}(p_T) = \frac{d\,N_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

- Interaction between partons (qaurk and gluon) 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 $\propto 1/(\theta^2 + (m/E)^2)^2$
  - $E_{loss}(g) > E_{loss}(u,d,s) > E_{loss}(c) > E_{loss}(b)$

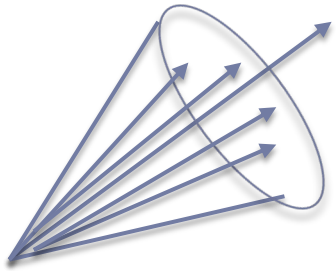
Jet production in PbPb





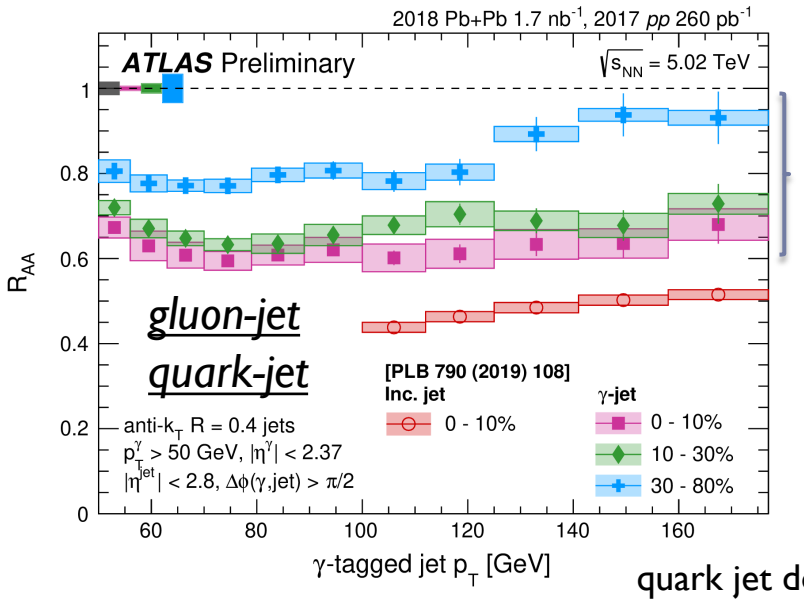
- Strong suppression of jet production in AA (Au+Au, Pb-Pb) collisions
  - Inclusive jets (gluon dominant @ LHC energy)
  - $R_{AA} < 1$
  - Mid-rapidity
  - No suppression in pPb

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



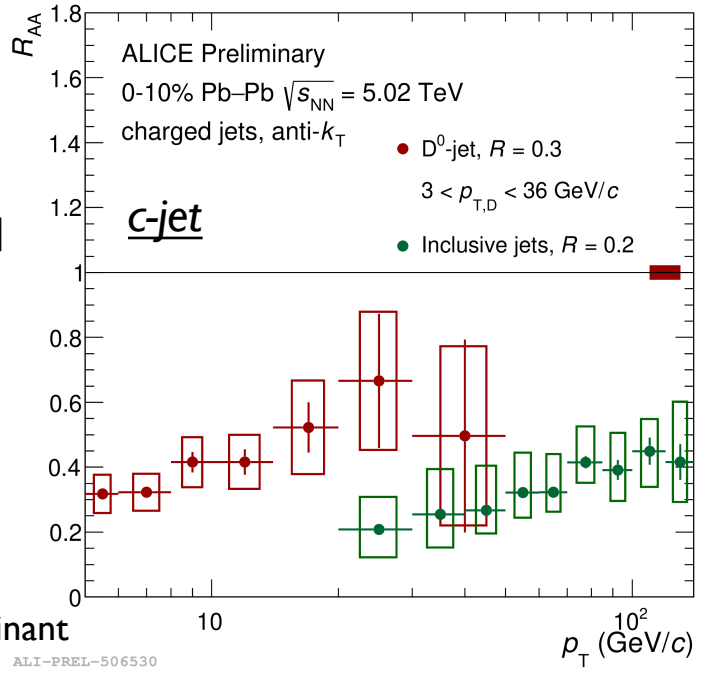
Quark, gluon and HF jet production in PbPb

ATLAS-CONF-2022-019



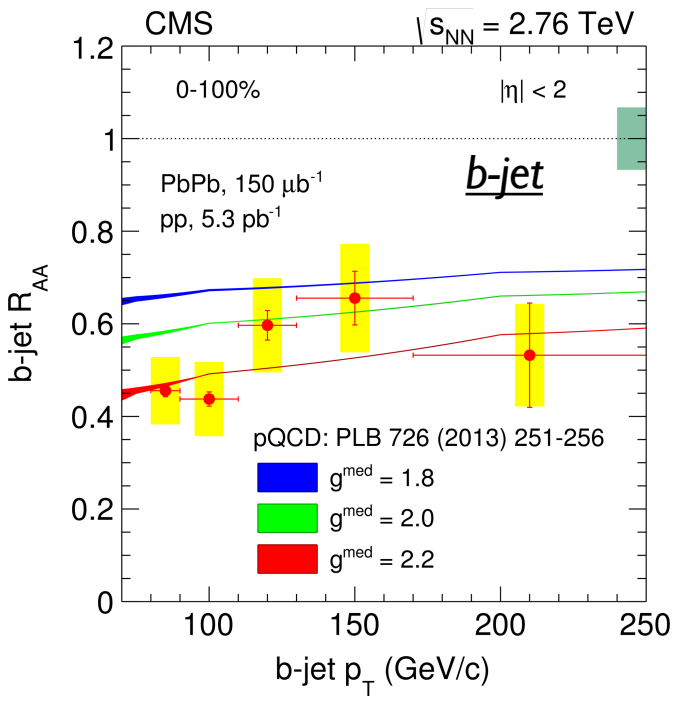
q

g



quark jet dominant

PRL113 (2014) 132301



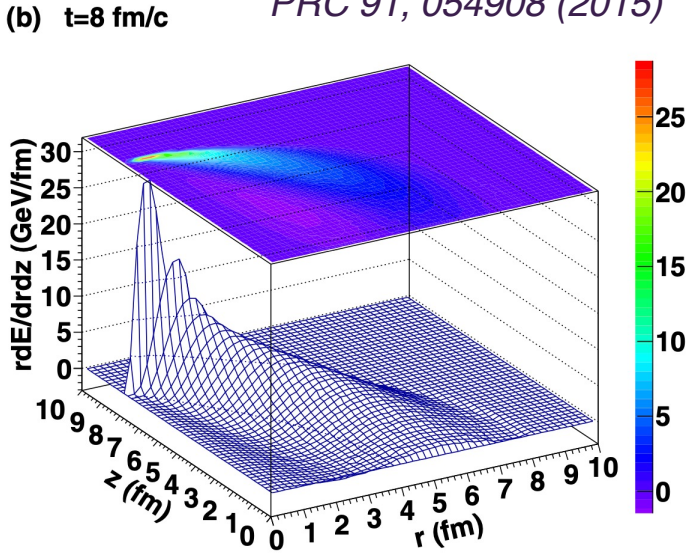
- Strong suppression of jet production in PbPb collisions
  - Originally from gluon & quark (left), charm (middle), beauty (right)
- Indicate energy loss of partons (up to beauty) in PbPb collisions
  - Jet kinematics ~ parton kinematics

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

Medium response (model predictions)

■ Recoil model LBT, JEWEL, MARTINI

PRC 91, 054908 (2015)

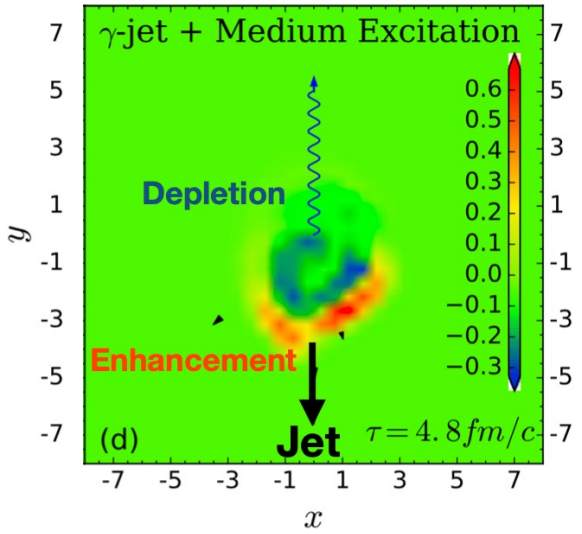


Partons of QGP constituent are scattered by hard parton

■ Recoil + Hydro model

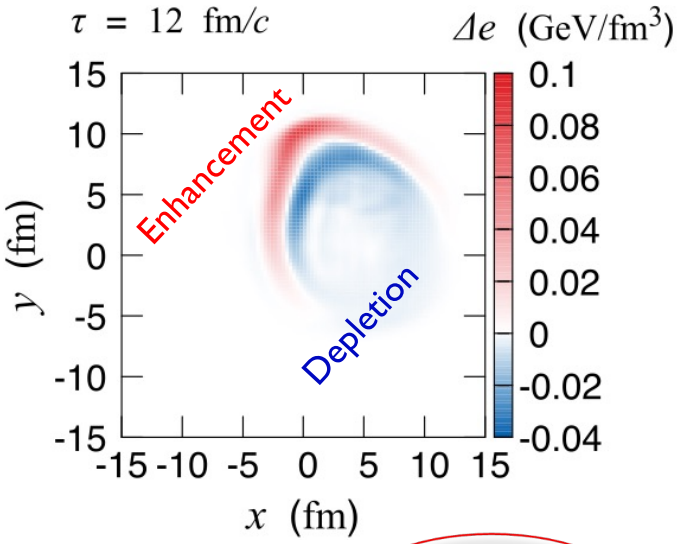
(CO)LBT-hydro, JETSCAPE

PLB 777 (2018) 86



■ Hydro model Coupled Jet-Fluid

PRC 95, 044909 (2017)



$$\partial_\mu T^{\mu\nu}_{\text{fluid}} = J^\nu_{\text{jet}}(x)$$

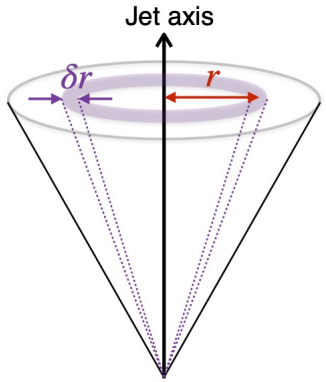
- Assume lost energy reaches thermalization
- further evolution of medium

■ Mach cone like structure in jet direction => enhancement

■ Diffusion wake in opposite direction of jet => suppression

Jet shape in PbPb

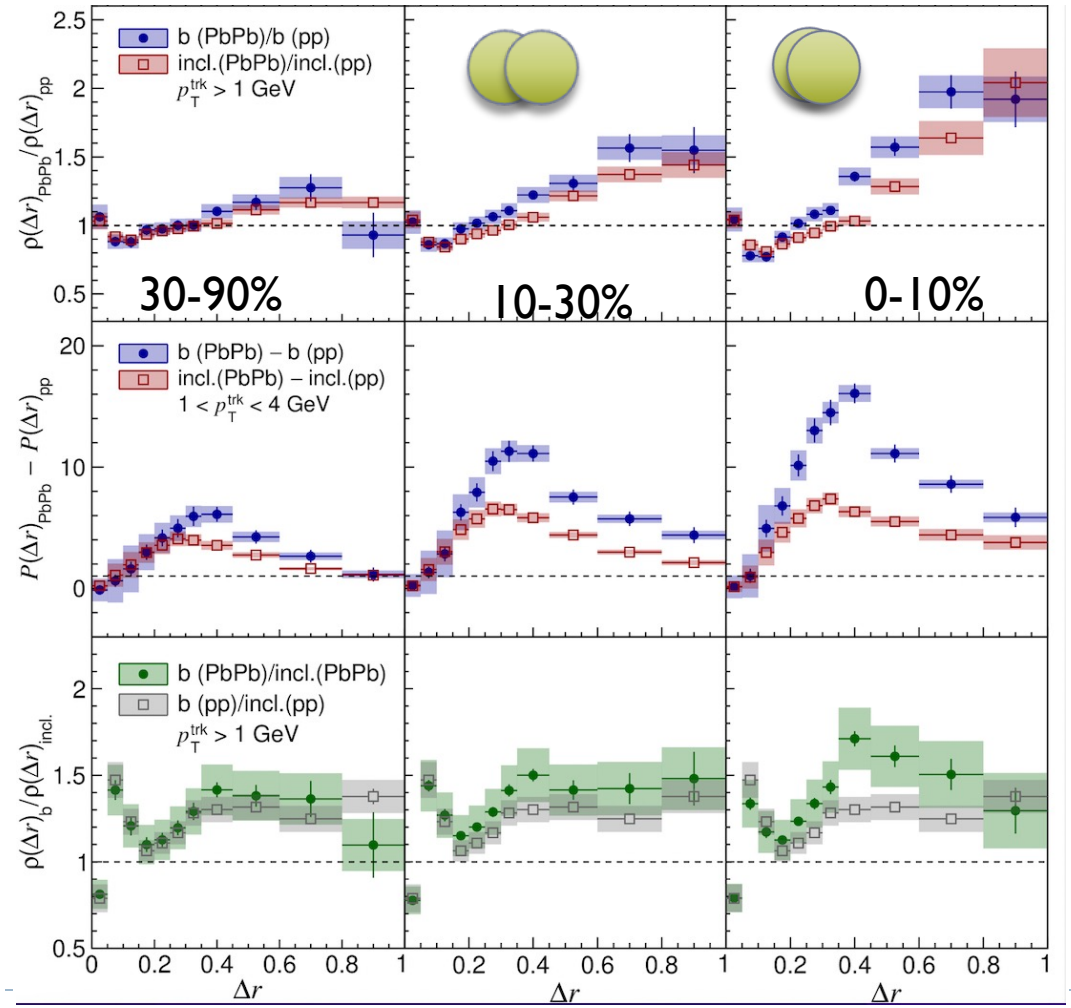
- Radial distribution of charged hadrons in inclusive and b-jets
  - PLB 844 (2023) 137849



- Both inclusive and b jets show the enhancement of soft particle around $\Delta r \sim 0.4$
  - Could be medium response
  - More enhancement in b-jet
    - b-jet can cause a larger medium response ?

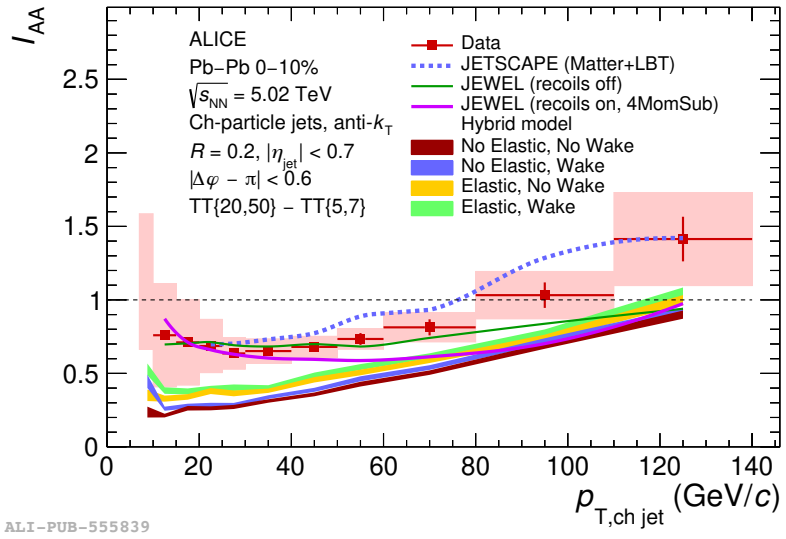
- Medium-induced redistribution of energy is larger for b-jet than inclusive jets

$\sqrt{s_{NN}}$ = 5.02 TeV, PbPb 1.69 nb^{-1}, pp 27.4 pb^{-1}, anti-k_T jet (R = 0.4): $p_T^{jet} > 120$ GeV, $|\eta_{jet}| < 1.6$

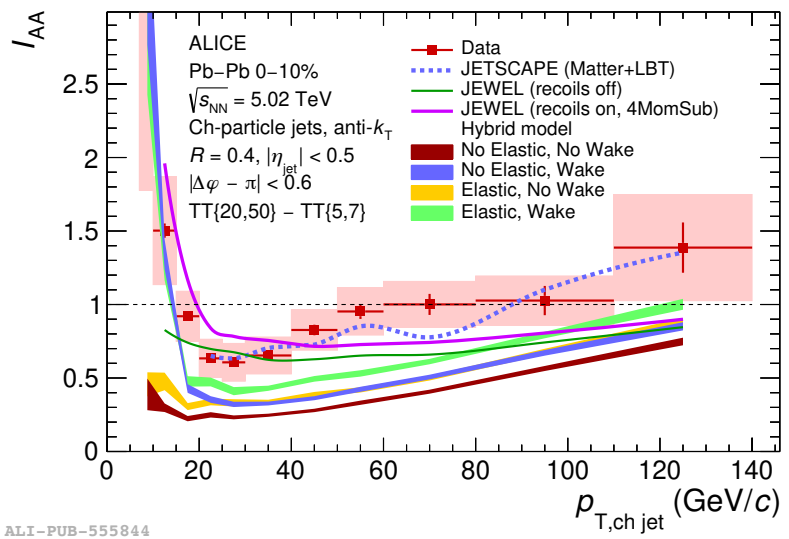


Hadron + jet production in PbPb

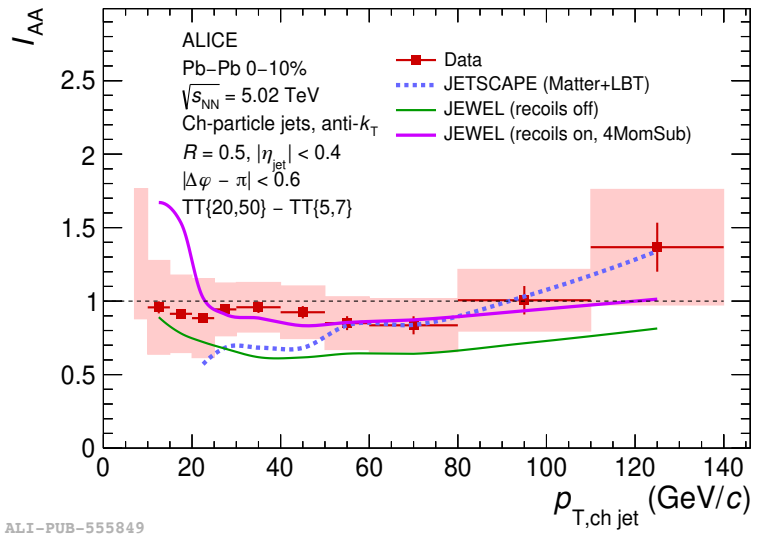
R=0.2



R=0.4

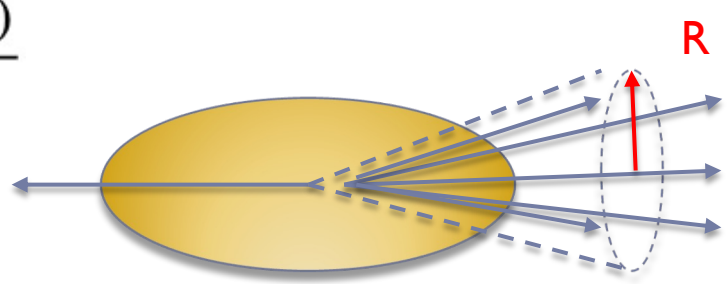


R=0.5



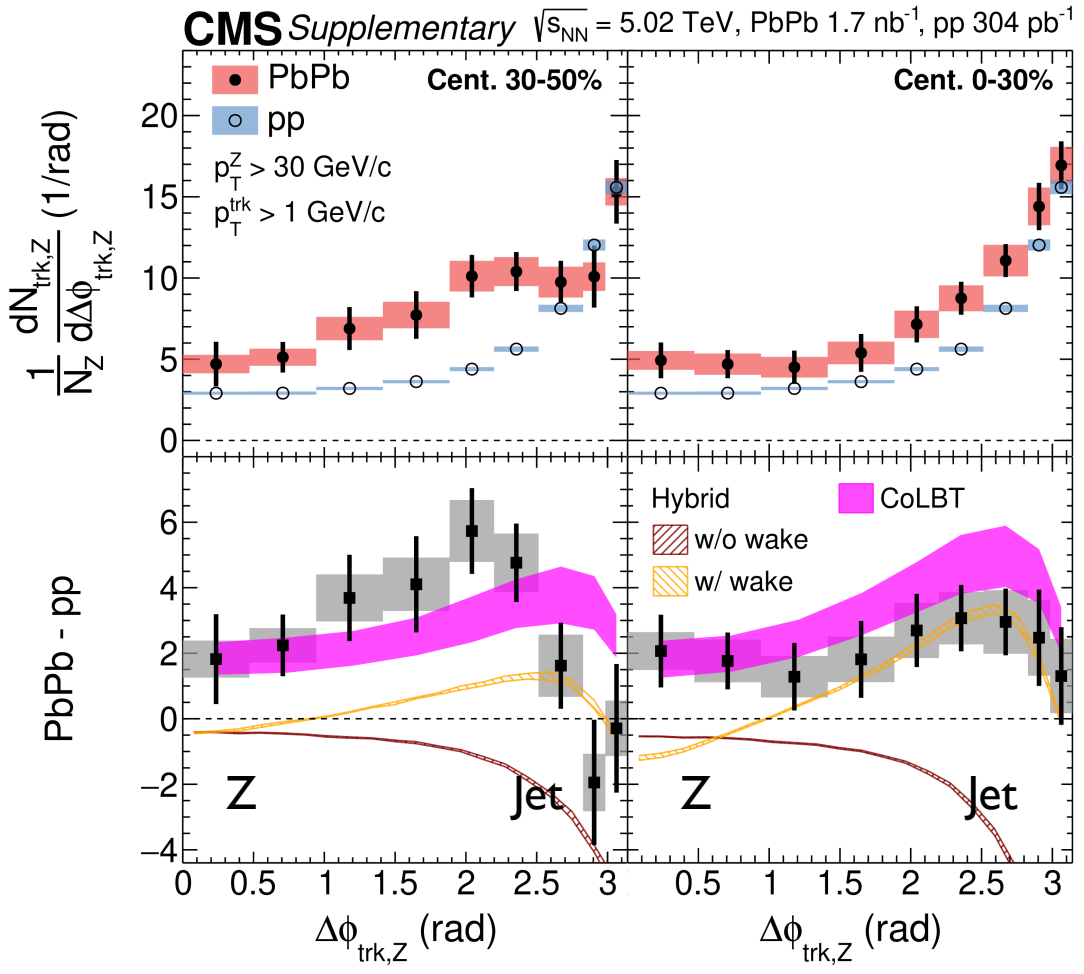
- Recoil jet yield modification in Pb-Pb collisions
  - arXiv:2308.16131, arXiv:2308.16128

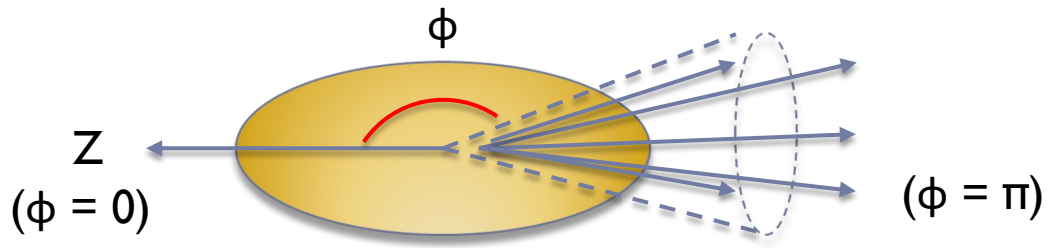
$$I_{AA} = \frac{\Delta_{recoil}(Pb-Pb)}{\Delta_{recoil}(pp)}$$



- R = 0.2 & 0.4
  - Suppression at 20 < p_T < 80 GeV/c -> parton energy loss
  - Not observed R = 0.5 ; consistent with unity
- R = 0.4 ; Enhancement at low p_T ; model with wake (medium response) reproduce the trend

Z-jet correlation in PbPb





- Azimuthal correlation between Z boson and particles
  - PRL 128 (2022) 122301
- Enhancement of hadrons in recoil jet direction (Δϕ = π)
  - Mach-cone-like excitation
  - Models with medium response well reproduce the enhancement in the jet direction
- Also enhancement in Z direction (Δϕ = 0)
  - Contrary to the expectation of a depletion due to jet-induced diffusion wake ?
  - Possibly medium modification of partons from MPI
    - PRL 127 (082301) 2021

Summary

- Initial state effect (nPDF)
  - Charm production in pPb suppresses at small x (10^{-4})
    - Models including shadowing reproduces the data
  - W/Z boson production in pPb generally reproduces pQCD with nPDF
    - Some tension between data and model predictions
- Final state effect (energy loss)
  - Flavour dependence of energy loss
  - Enhancement of soft particle production at large R
  - model including medium response catch up the data