Heavy flavour & Jet Summary

Shingo Sakai
(Univ. of Tsukuba)

Heavy flavour & jet topics in QM (from Experimental Summary)

- Heavy flavour (experiment : 2 plenary +13 parallel talks) — Jana (4/12, Sat.)
  - D meson production at $\sqrt{s_{NN}}$ = 16.8 GeV (NA61/SHINE)
  - ALICE first measurement of B mesons in pp collisions
  - Charmonium suppression $\psi(2S)$ / J/ψ
  - First charm baryon v_2 (Λ_c) in ALICE
  - Top quark productions in Pb-Pb collisions in ATLAS
  - Heavy-flavour production in UPC
- Jet (experiment : 2 plenary + 17 parallel talks)
  - Heavy-flavour jet productions in pp collisions (b-tag, D^0-tag, Λ_c-tag)
  - Jet internal structure in Pb-Pb (Energy-Energy Correlators)
  - Medium response with Z – hadron correlations
  - Jet hadrochemistry

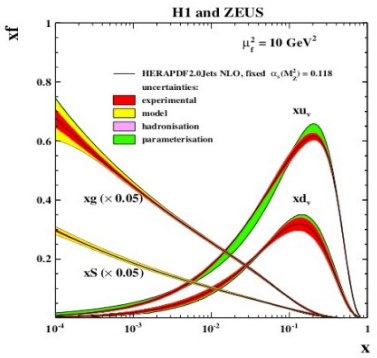
Hard probes production in heavy-ion collisions (pA & AA)

- 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 (parton to hadron)

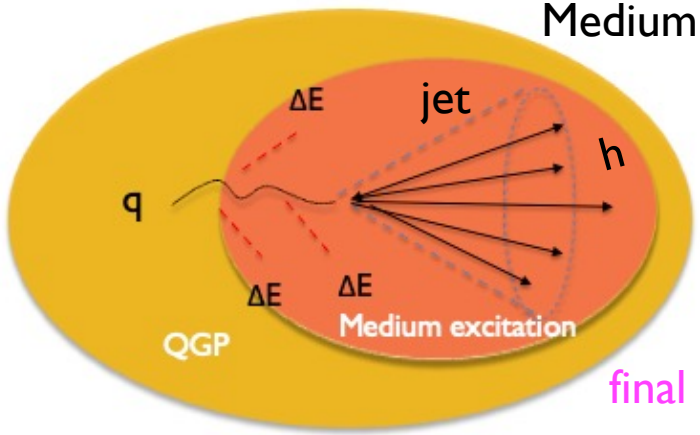
$$d\sigma^{hard}_{AB\to h} = f_{a/A}(x,Q^2) \otimes f_{b/B}(x,Q^2) \otimes d\sigma^{hard}_{ab\to c} \otimes D_{c\to h}(z,Q^2)$$



Gluon distribution in nuclear

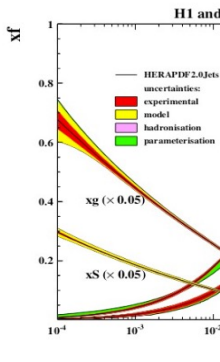
Initial state effect

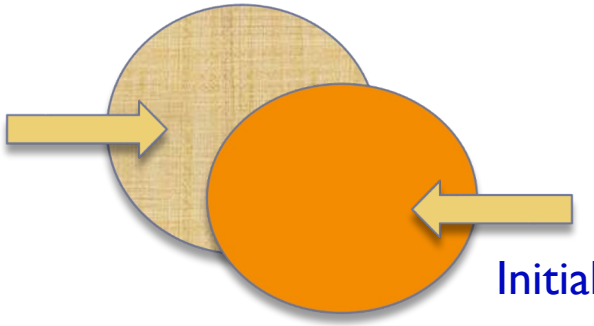
Flow, energy loss
Medium response



final state effect

Initial state

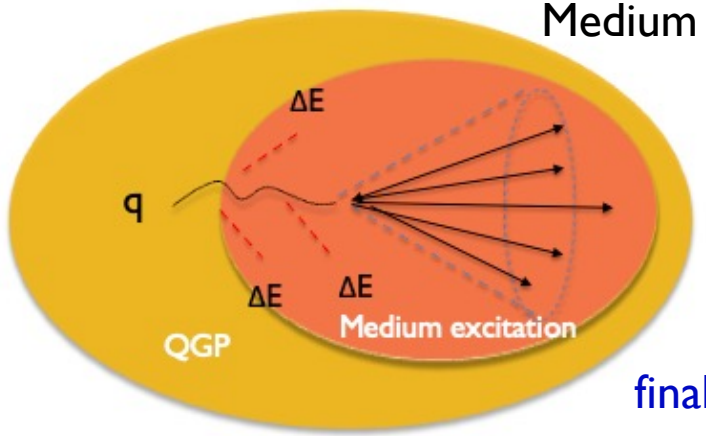




Initial state

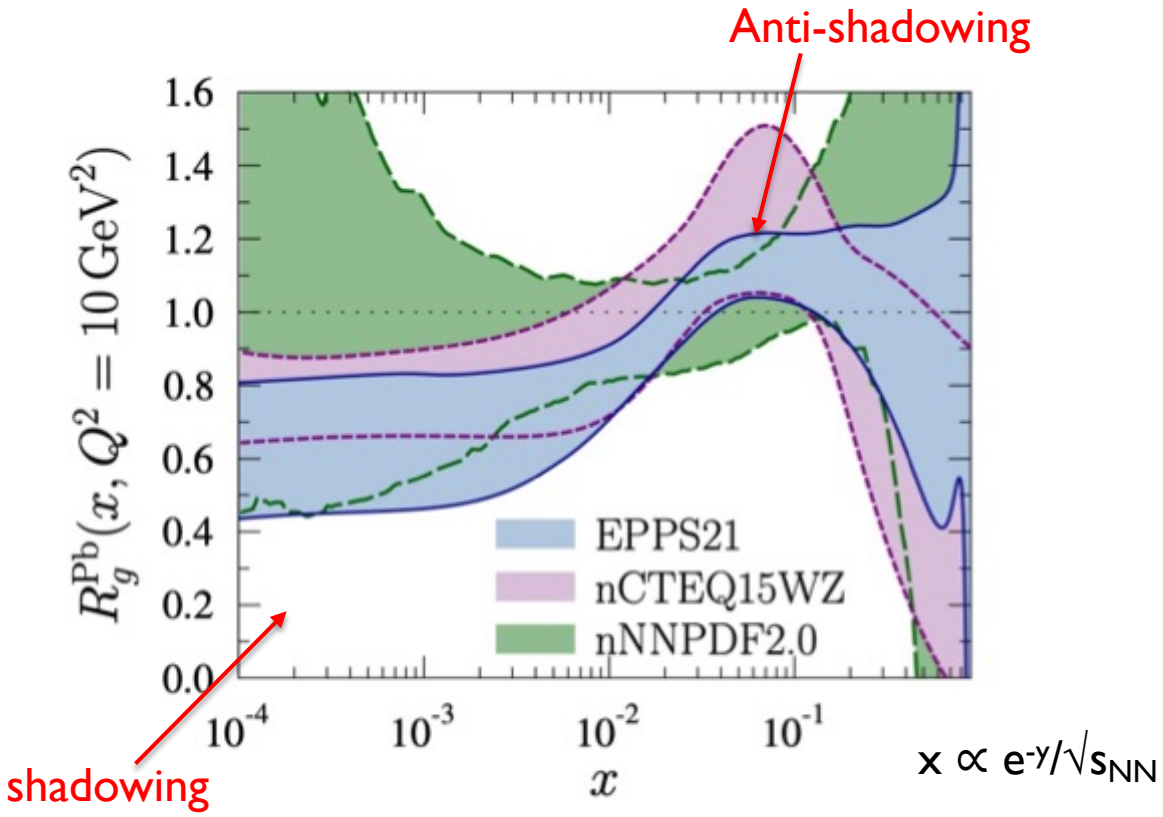
Gluon distribution in A

Flow, energy loss
Medium response



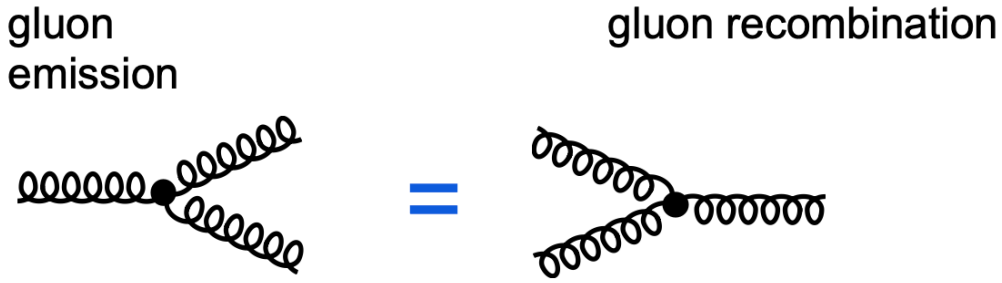
final state

Gluons in nuclear (nPDF)



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

- Parton (gluon) PDF is modified by nuclear medium
  - Suppression at small x (shadowing)
    - Suppression of particle production in small x w.r.t. pp
- Large uncertainty => Important to constrain the nPDF by data



- Gluons in nuclear and nucleon
  - Gluon emission (splitting)
    - Dominant process in small x (large E)
  - Gluon recombination
- Colour Glass condensate
  - Gluon emission = Gluon recombination
  - Key to QGP formation

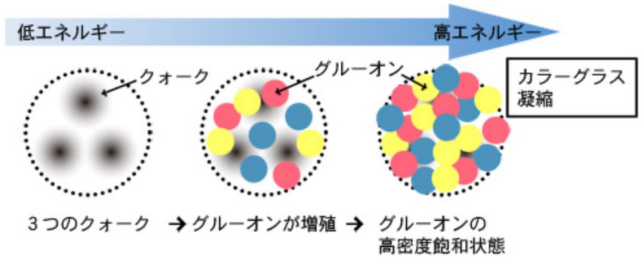


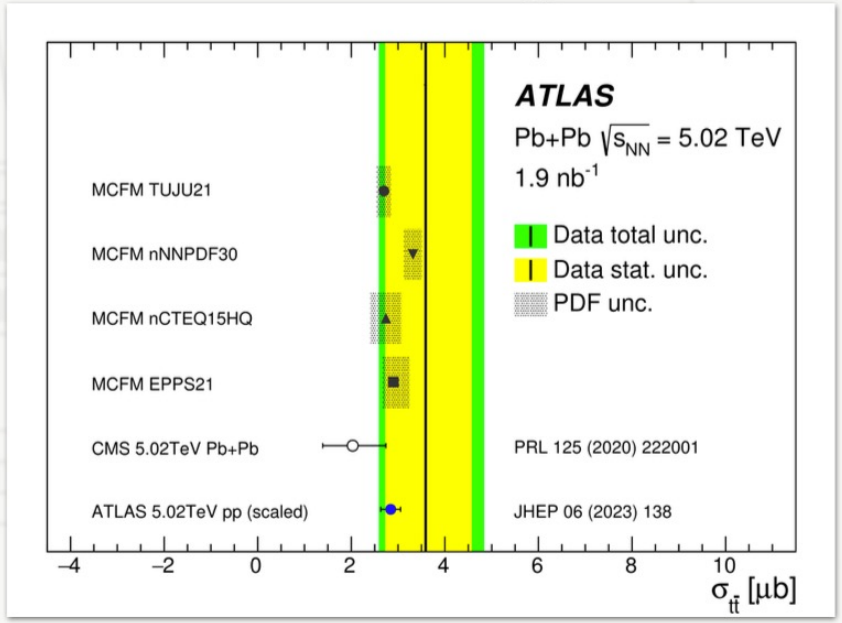
図3
カラーグラス凝縮の出現

t-tbar production in pPb and Pb-Pb

Patrycia Anna Potepa (4/8, Tue)

arXiv:2411.10186 , Acc. PRL

$$\sigma_{t\bar{t}} = 3.6^{+1.0}_{-0.9}\,(\text{stat.})\,^{+0.8}_{-0.5}\,(\text{syst})\,\mu\text{b}$$



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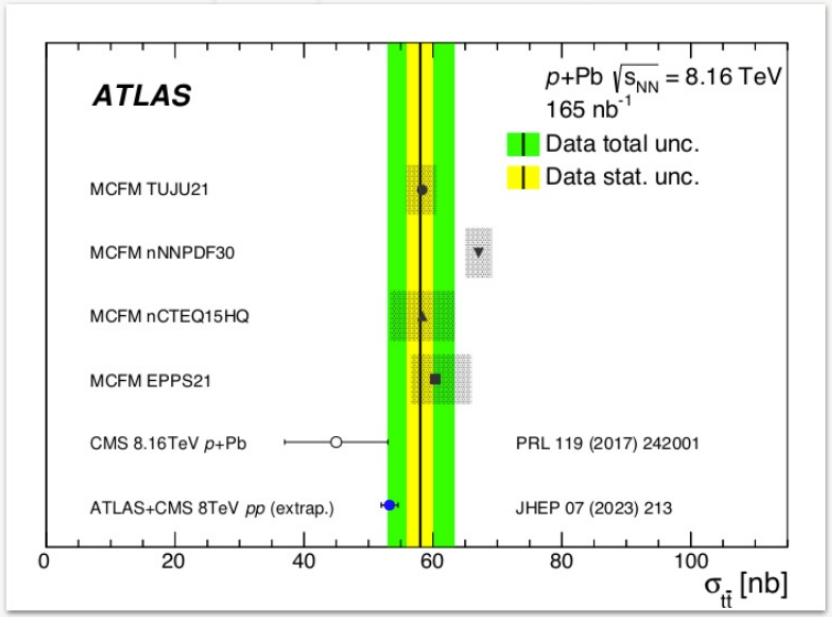
$$\sigma_{t\bar{t}} = 58.1 \pm 2.0\,(\text{stat.})\,^{+4.8}_{-4.4}(\text{syst.})\,\text{nb}$$

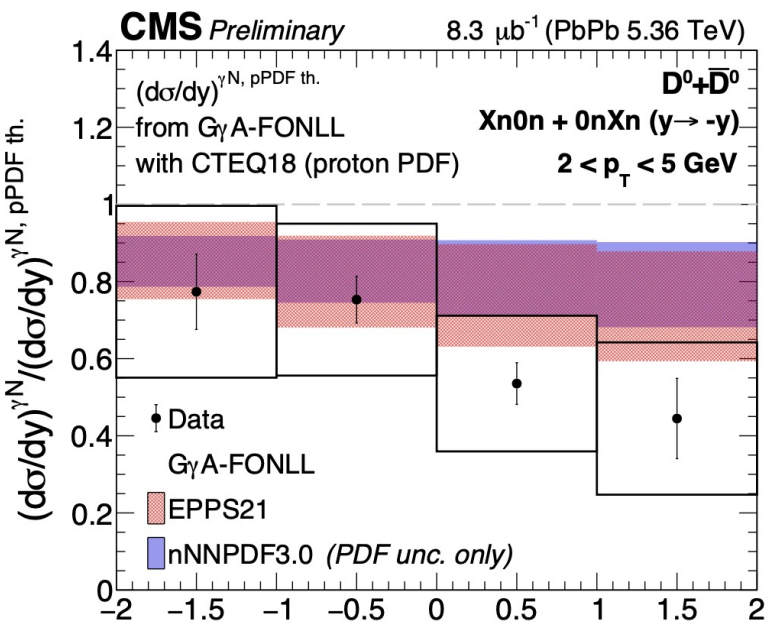


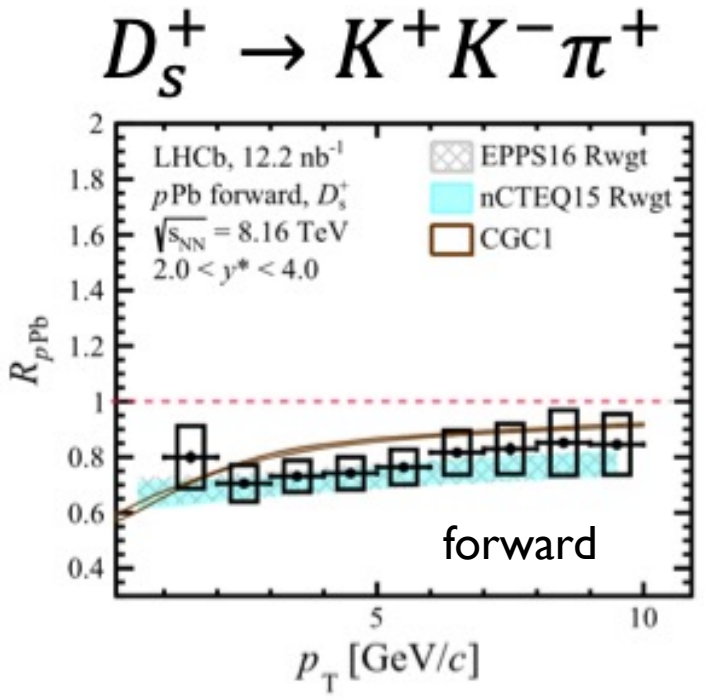
- nNNPDF
  machine learning (NN)
- cTEQ15HQ
  Heavy-flavour
- EPPS21
  LHC data

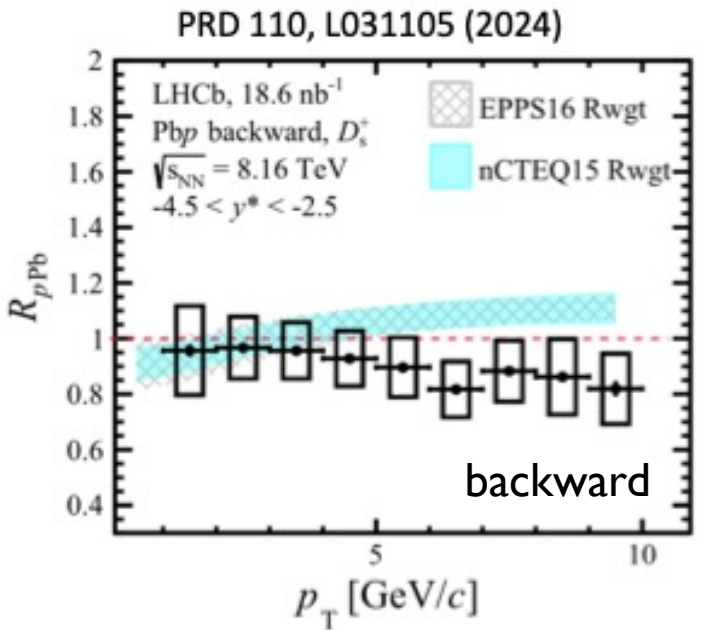
- First observation of t-tbar production cross section in Pb-Pb collisions
- Good agreement with NNLO calculation for three nPDFs (nNNPDF3.0, nCTEQ15HQ, EPPS21)
  - nNNPDF3.0 is rather overestimate the cross section in p-Pb

D meson production and nPDF

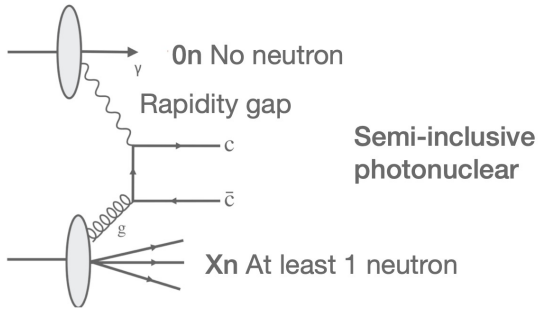
John Matthew Durham (4/9, Wed)
Yu-Chen (4/9, Wed)





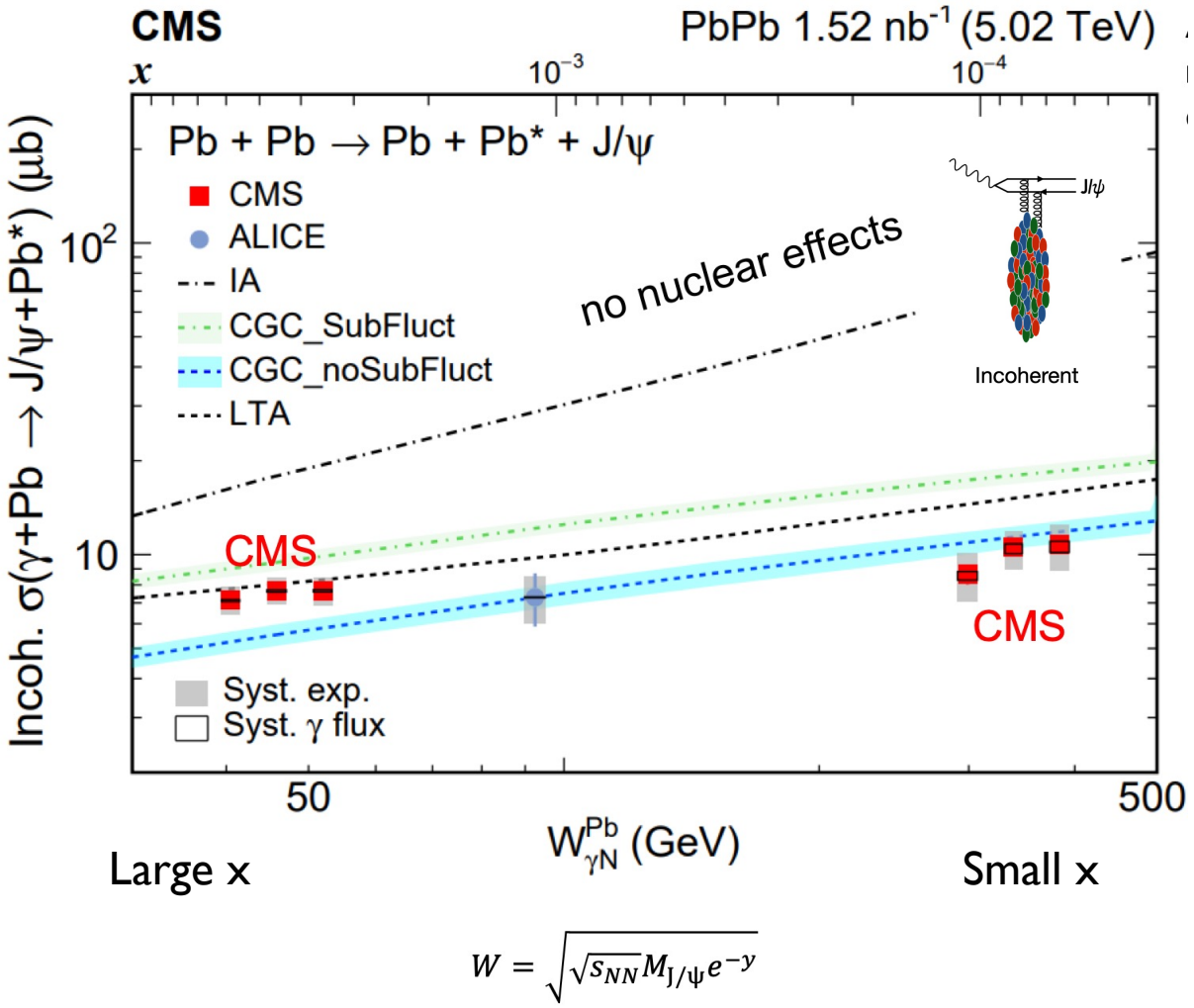


- Photonuclear production of D^0 in UPCs
  - Suppression w.r.t. pQCD without nPDF
  - Models include nPDF (EPS21 & nNNPDF) are consistent with data
- Forward Ds+ data consistent with nPDF (EPP16, nCTEQ15)
  - Tension at backwards rapidity (large x)



Incoherent J/psi in UPC

Xiao Huang (4/9,Wed)

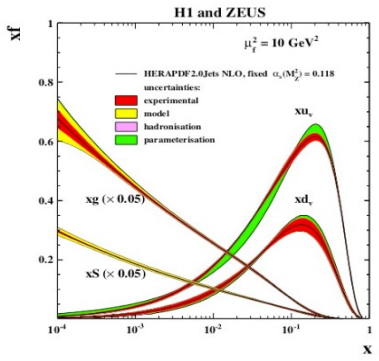


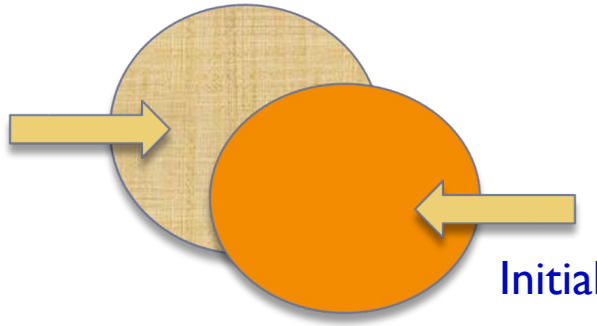
$$W = \sqrt{\sqrt{s_{NN}} M_{J/\psi} e^{-y}}$$

- Incoherent J/ψ production from photo interaction
  - Sensitive gluon nPDF
- Strong suppression from prediction of no nuclear effect
- Nuclear shadowing model (LTA)
  - Good agreement with CMS result at $10^{-3} < x < 10^{-2}$
- CGC + w.o. sub-nucleonic fluctuations *
  - Good agreement with ALICE and CMS at $x < 10^{-4}$

* Event by event fluctuation of parton distribution in space

Final state

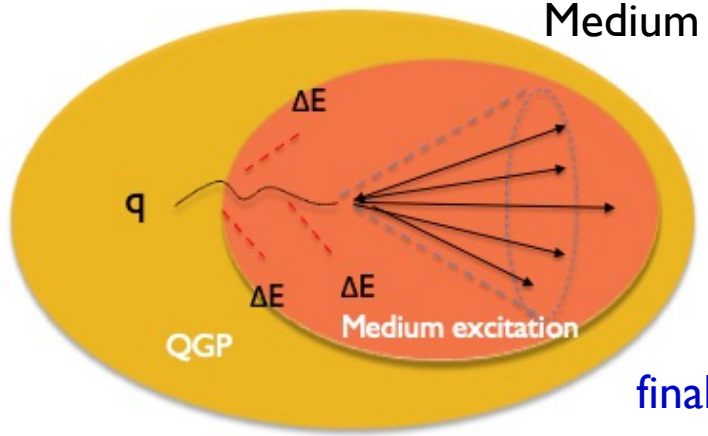




Initial state

Gluon distribution in A

Flow, energy loss
Medium response

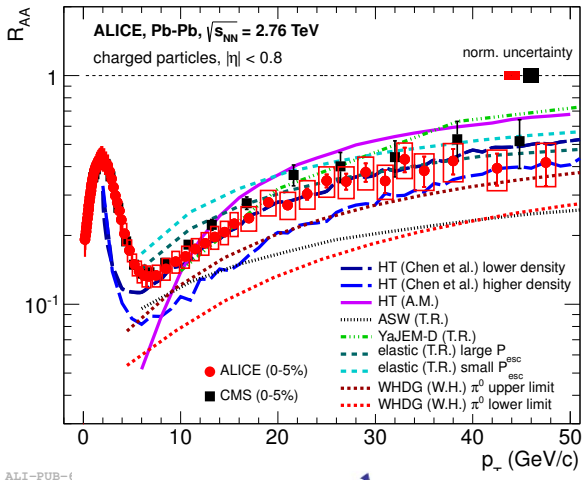


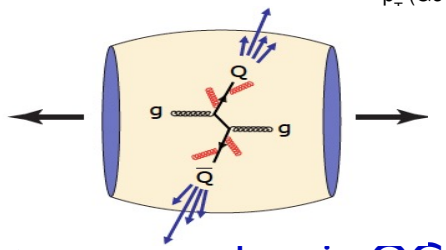
final state

Feature of particle productions in QGP

(1) Suppression of charged particles

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

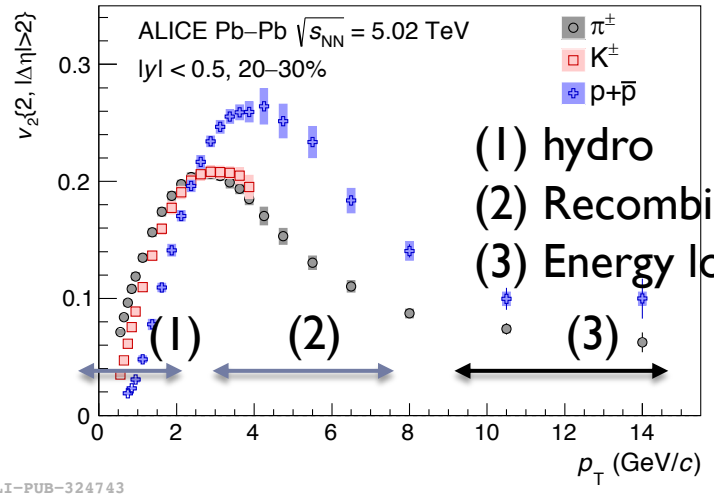




Parton energy loss in QGP

(2) Azimuthal anisotropy v_2

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



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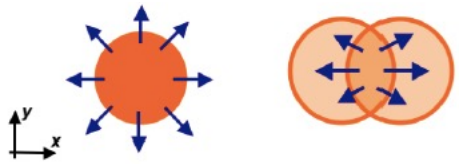
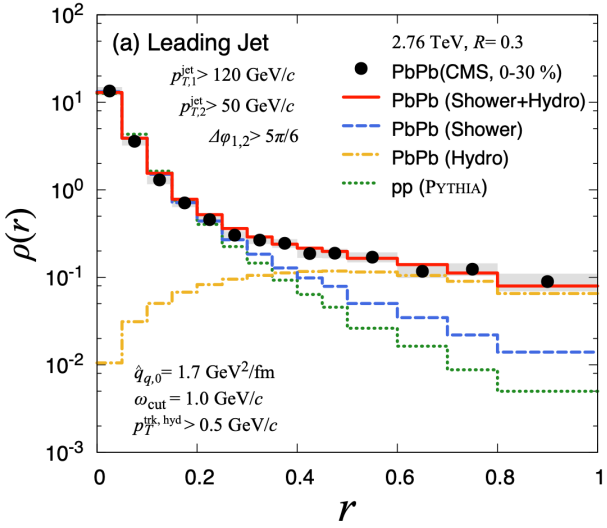
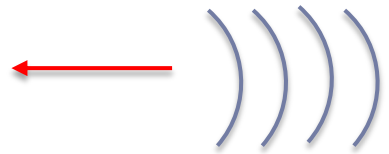


Collective motion in QGP

(3) Medium response

Hot topic !





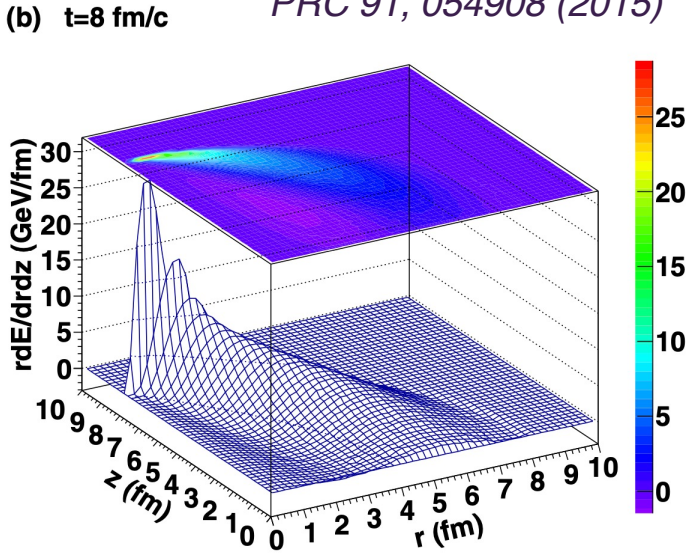
Jet (parton) & QGP interaction

* v_2 signal also observed in small system (high multiplicity pp collision events, pPb, dAu) => small system in QGP ?

Medium response (model predictions)

■ Recoil model LBT, JEWEL, MARTINI

PRC 91, 054908 (2015)

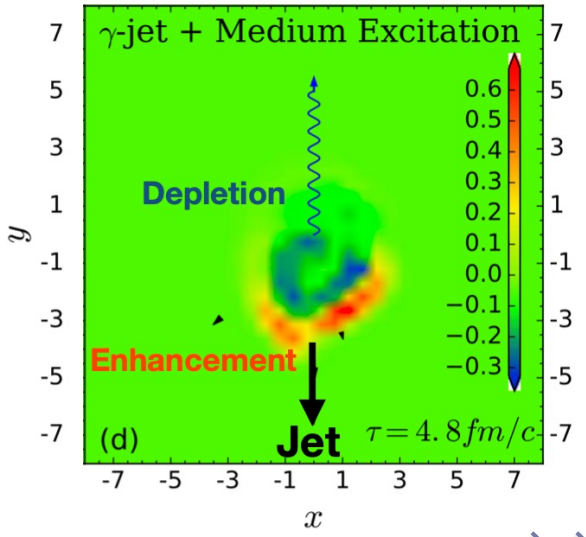


Partons of QGP constituent are scattered by hard parton

■ Recoil + Hydro model

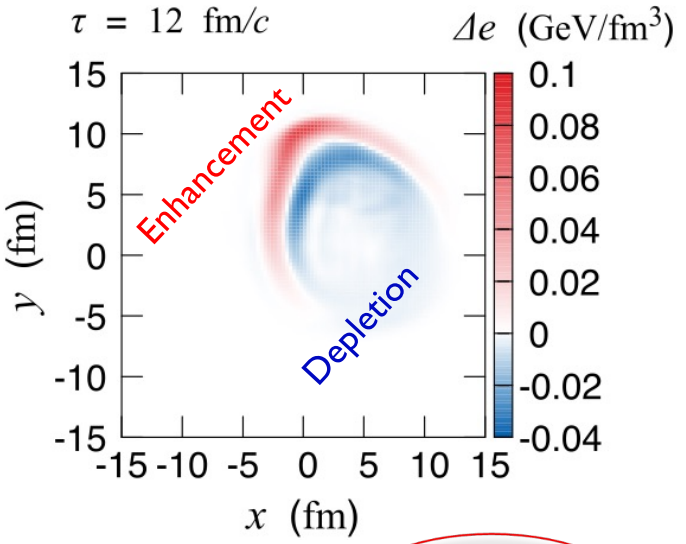
(CO)LBT-hydro, JETSCAPE

PLB 777 (2018) 86



■ Hydro model Coupled Jet-Fluid

PRC 95, 044909 (2017)



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

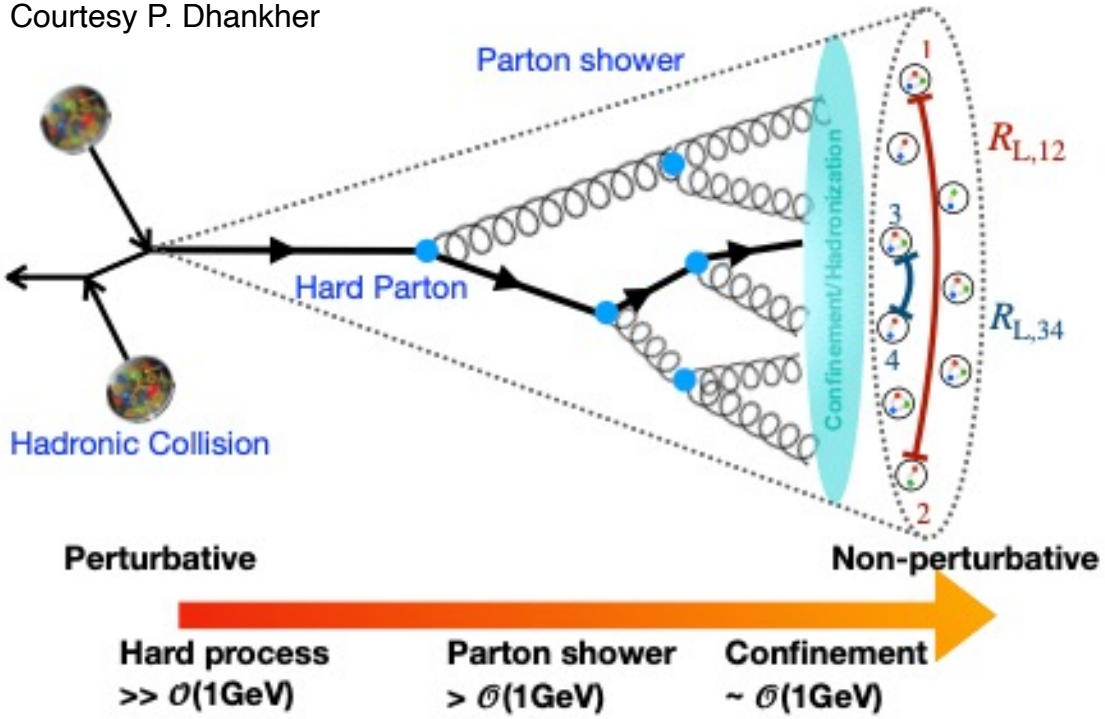
- Assume lost energy reaches thermalization
- further evolution of medium

■ Mach cone like structure in jet direction => enhancement

■ Diffusion wake in opposite direction of jet => suppression

Energy-energy Correlator

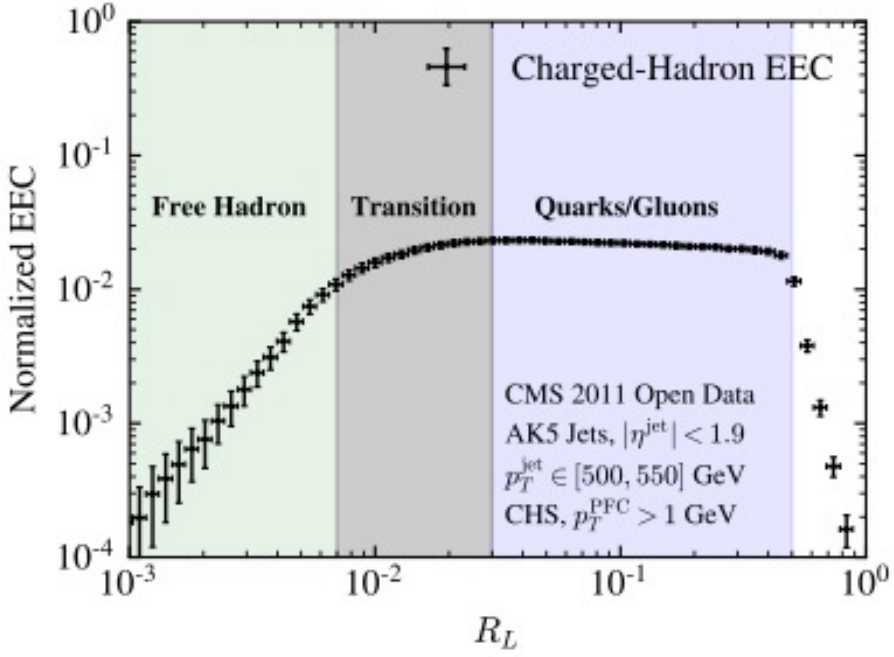
Courtesy P. Dhankher



$$\frac{d\sigma_{EEC}}{dR_L} = \sum_{ij} \int d\sigma(R'_L) \frac{p_{T,i} p_{T,j}}{p^2_{T,jet}} \delta(R'_L - R_{L,ij})$$

arXiv:2201.07800

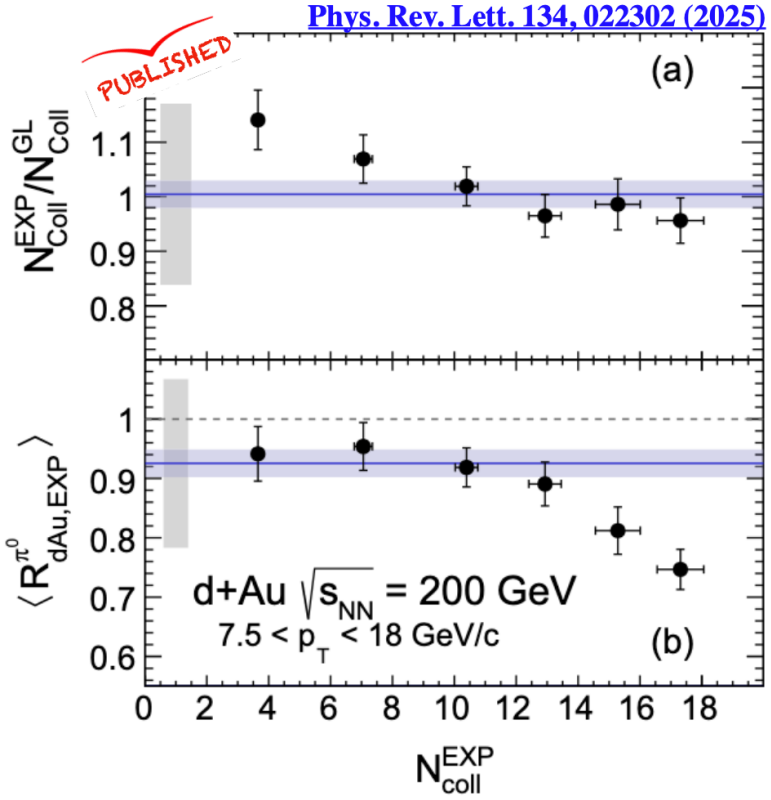
Hot topic !

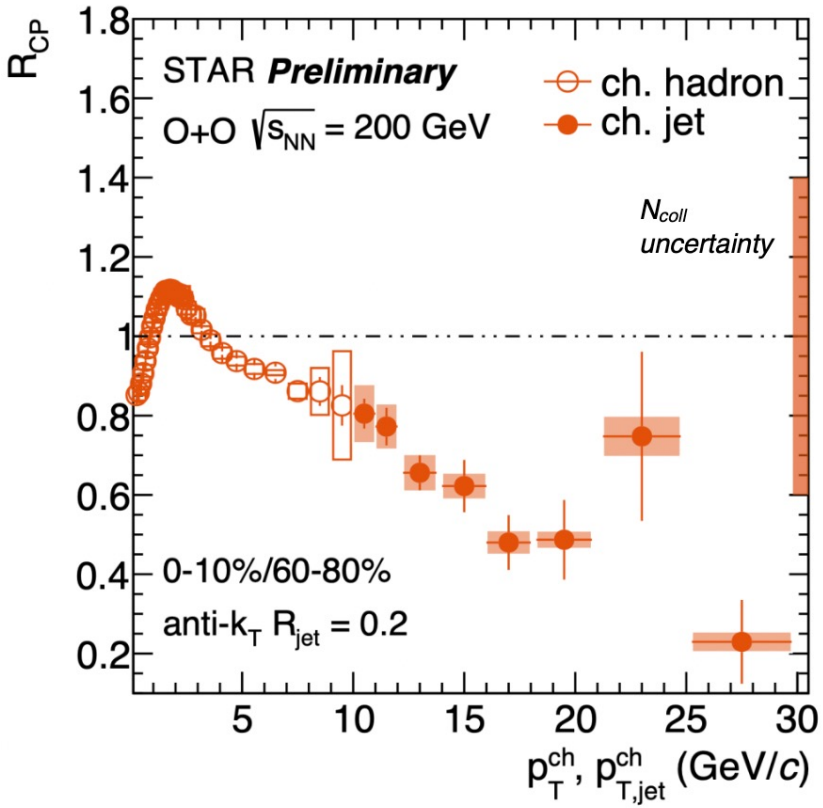


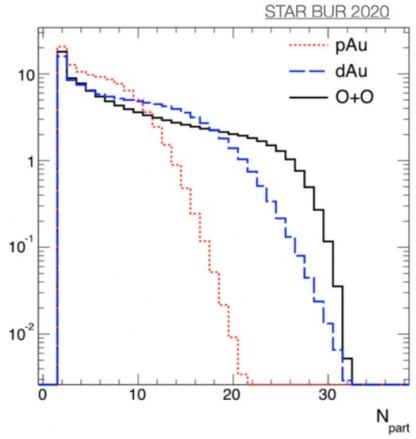
- Mapping time evolution of jet formation
  - Large R_L : partonic, perturbative
  - Middle R_L : confinement phae
  - Small R_L : hadronic phase

Results from small systems

High p_T particle production in small systems at RHIC

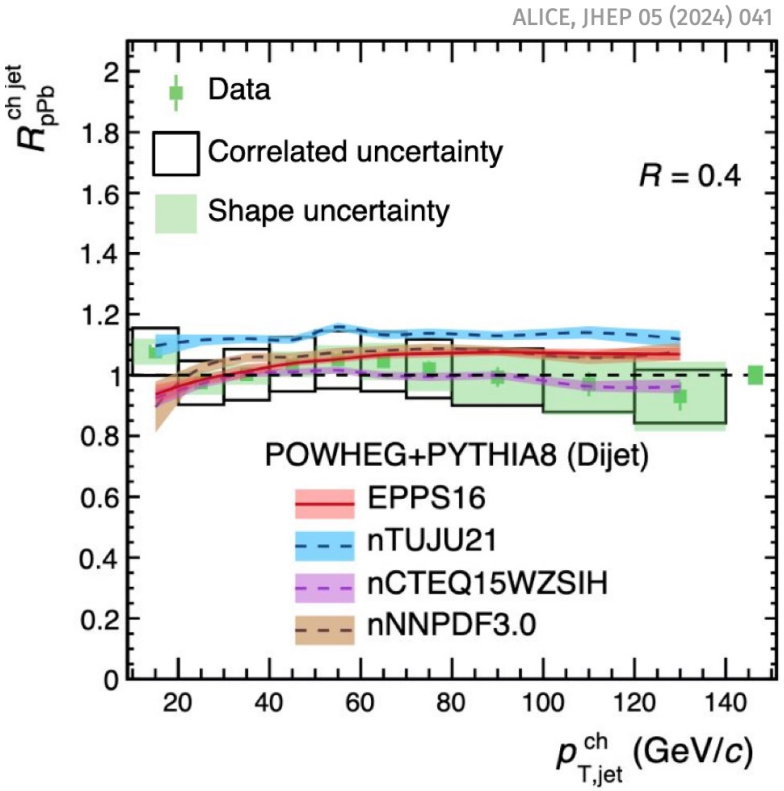


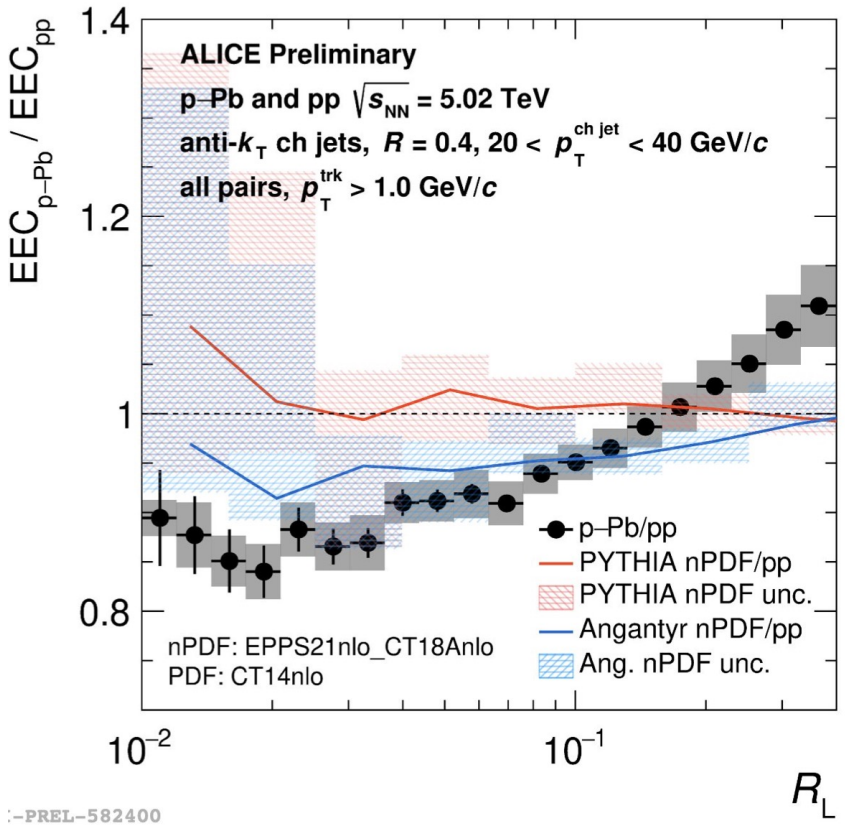




- QGP in small system ?
  - Observed positive v_2 in small systems (presentation by Y. Sekiguchi)
- PHENIX & STAR results shows a suppression at high p_T
  - Centrality bias in the STAR result ? (not the case in the PHENIX result)

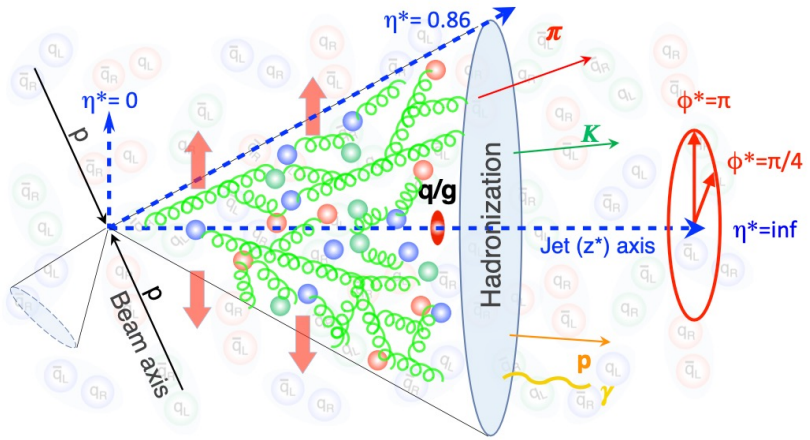
Modification of jet internal structure in p-Pb (1)



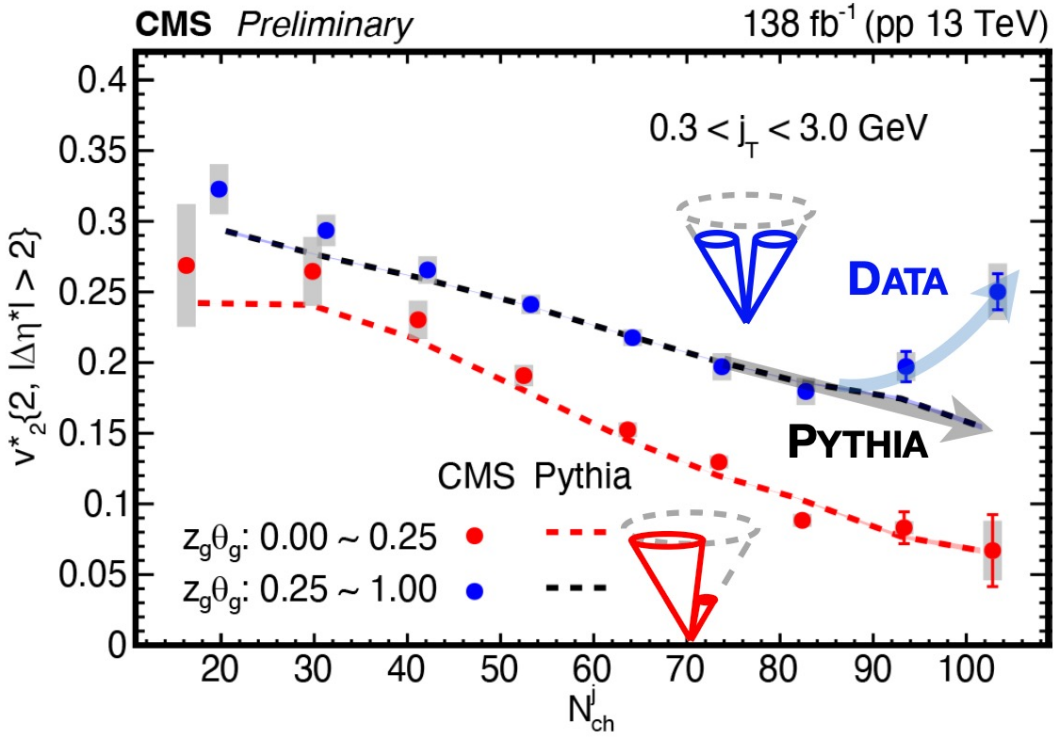


- p_T spectrum for jet in p-Pb is not modified in p-Pb collisions (R_{pPb} = 1)
- However, jet internal structure (EEC) is modified in p-Pb collisions
  - Tension at large R_L w.r.t. model with nPDF

Modification of jet internal structure in p-Pb (2)



v_2^*: long range elliptic anisotropy in jet axis frame



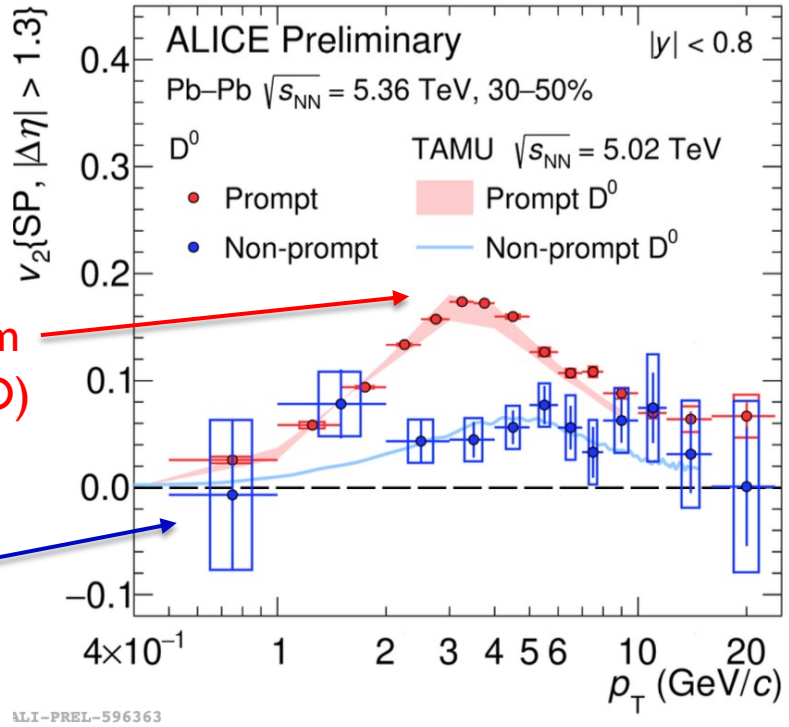
- Long range correlation w.r.t. jet axis in p-Pb (jet frame)
- v_2^* for smaller $Z_g\theta_g$ is consistent with PYTHIA calculation
- Observed v_2^* enhancement w.r.t. PYTHIA for hard splitting (larger $Z_g\theta_g$)

Multiplicity in jet

- Zg : transverse momentum balance
- Θg : angular separation

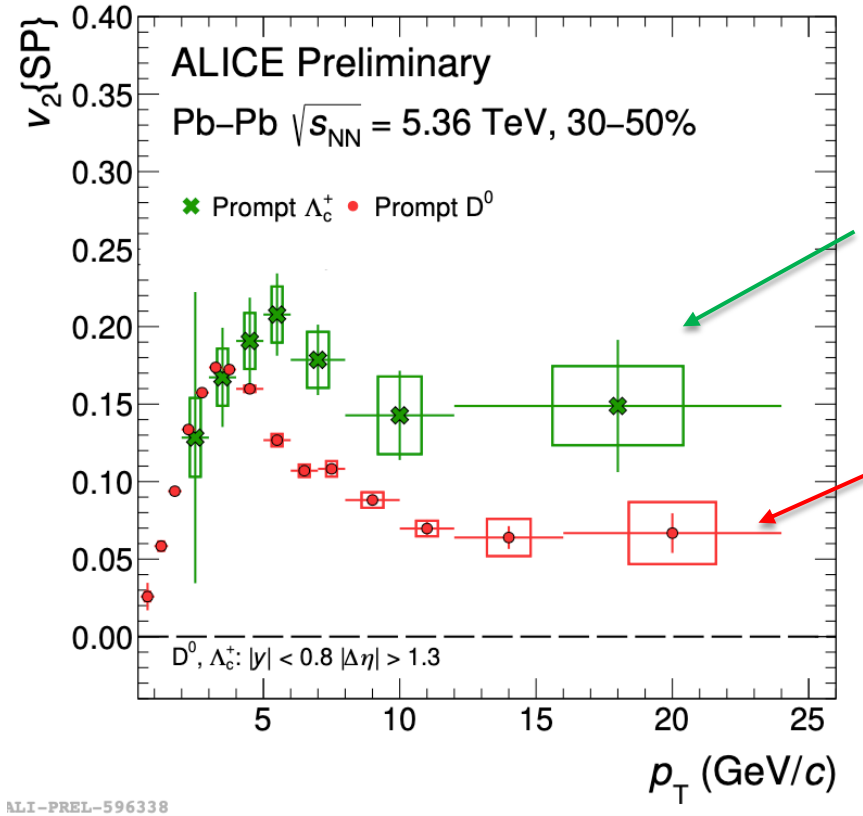
Results from Heavy-ion collisions

Heavy-flavour v_2 (1)



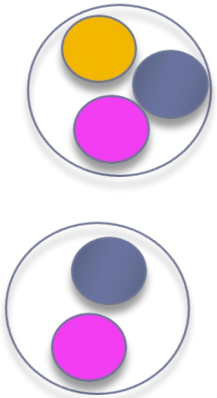
charm (c->D)

Beauty (b->c->D)



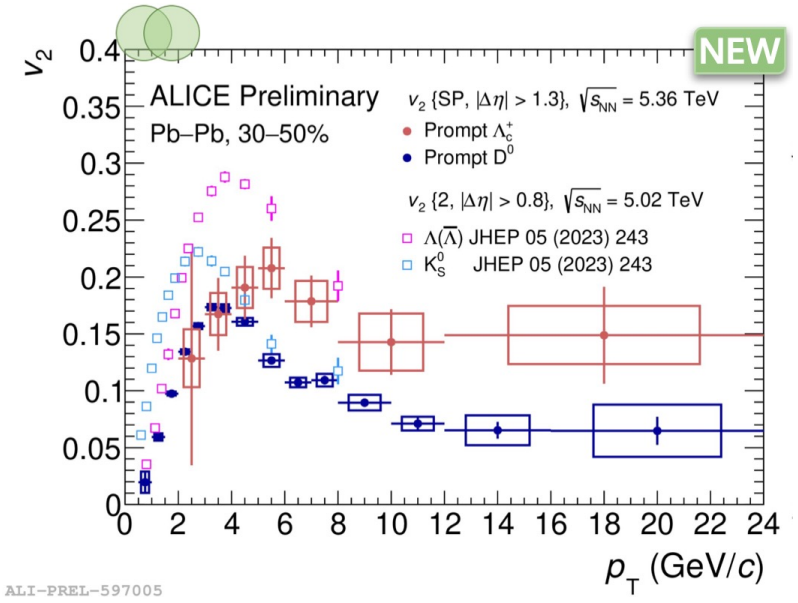
Λc

D



- v_2 (c) > v_2 (b)
  - Clear mass dependence of v_2 in charm and beauty
- v_2 (Λ_c) > v_2 (D)
  - Baryon / meson splitting in v_2 also in heavy flavour

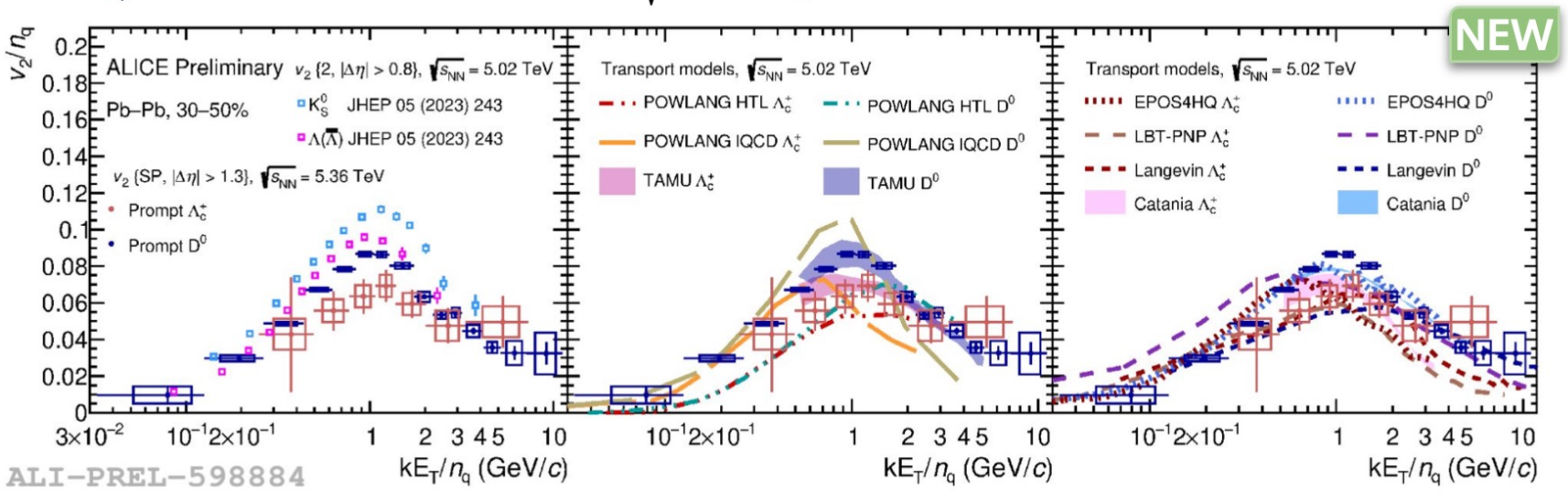
Heavy-flavour v_2 (2)



NCQ scaling

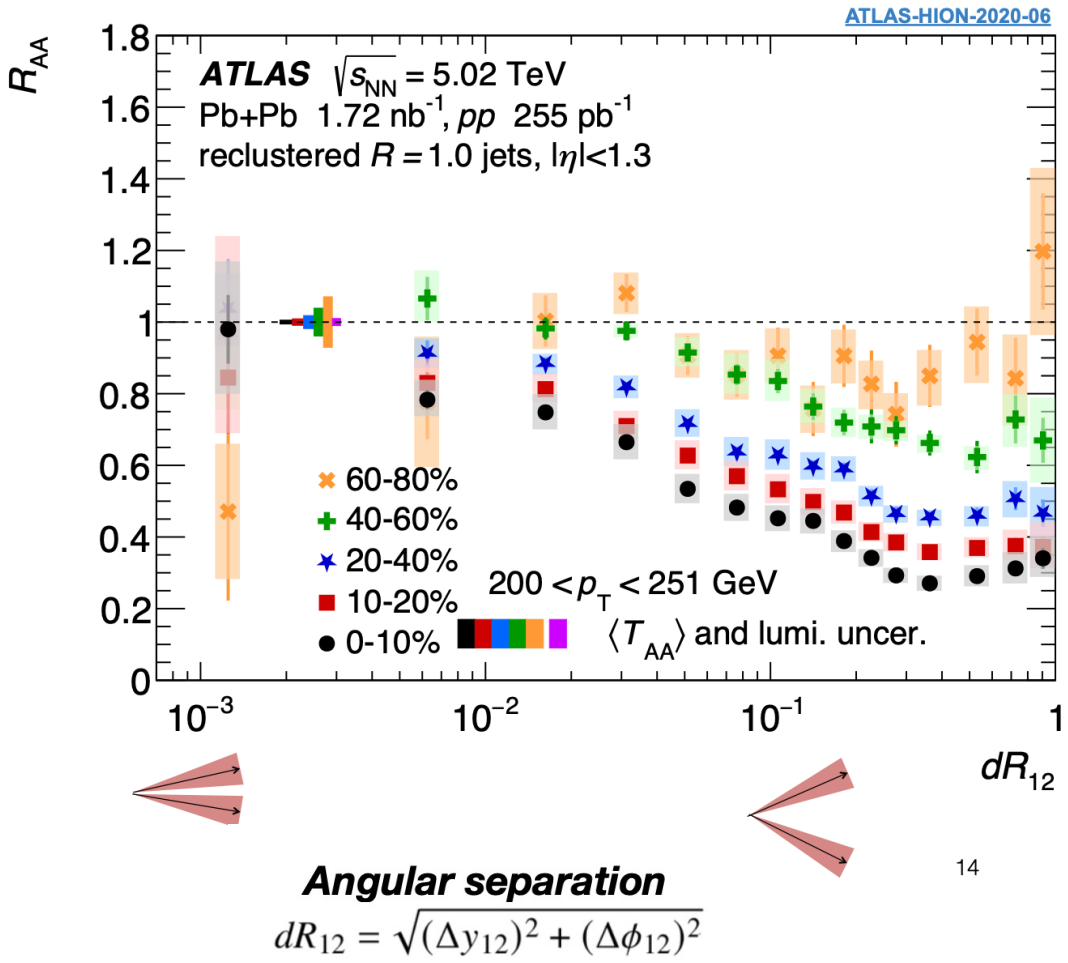
n_q: Number of constituent quarks

$$kE_T = \sqrt{m^2 + p_T^2} - m$$

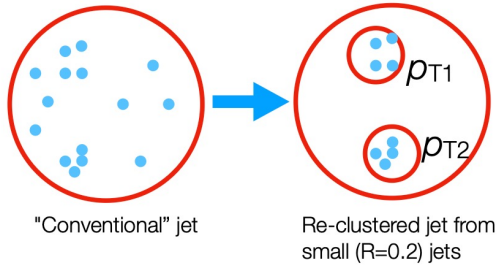


- NCQ scaling is violated for both light and heavy flavours at LHC energies
  - similar trends in data and models

Energy loss vs. Jet internal structure



- Jets suppression in heavy ion collisions depends on the internal structure of the jet
  - Jets with wider angular separations between subject stronger suppression

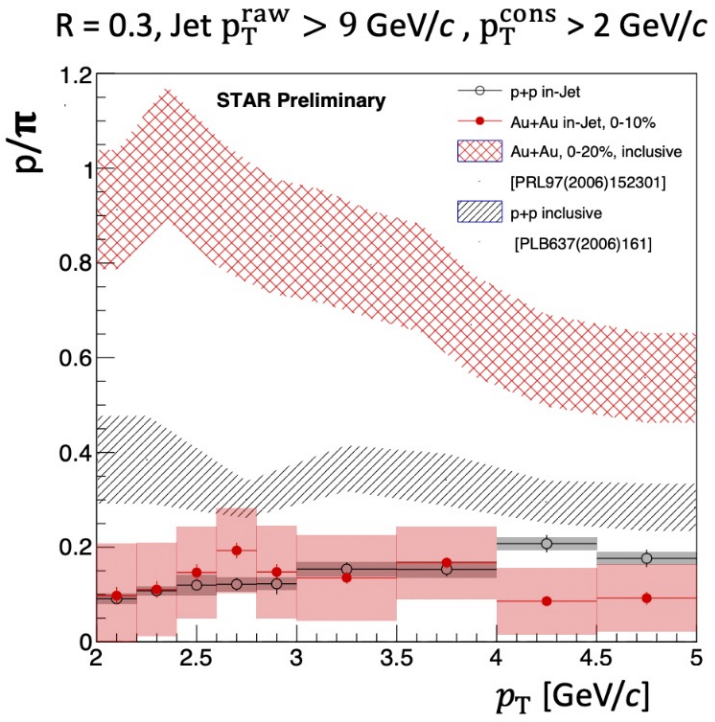


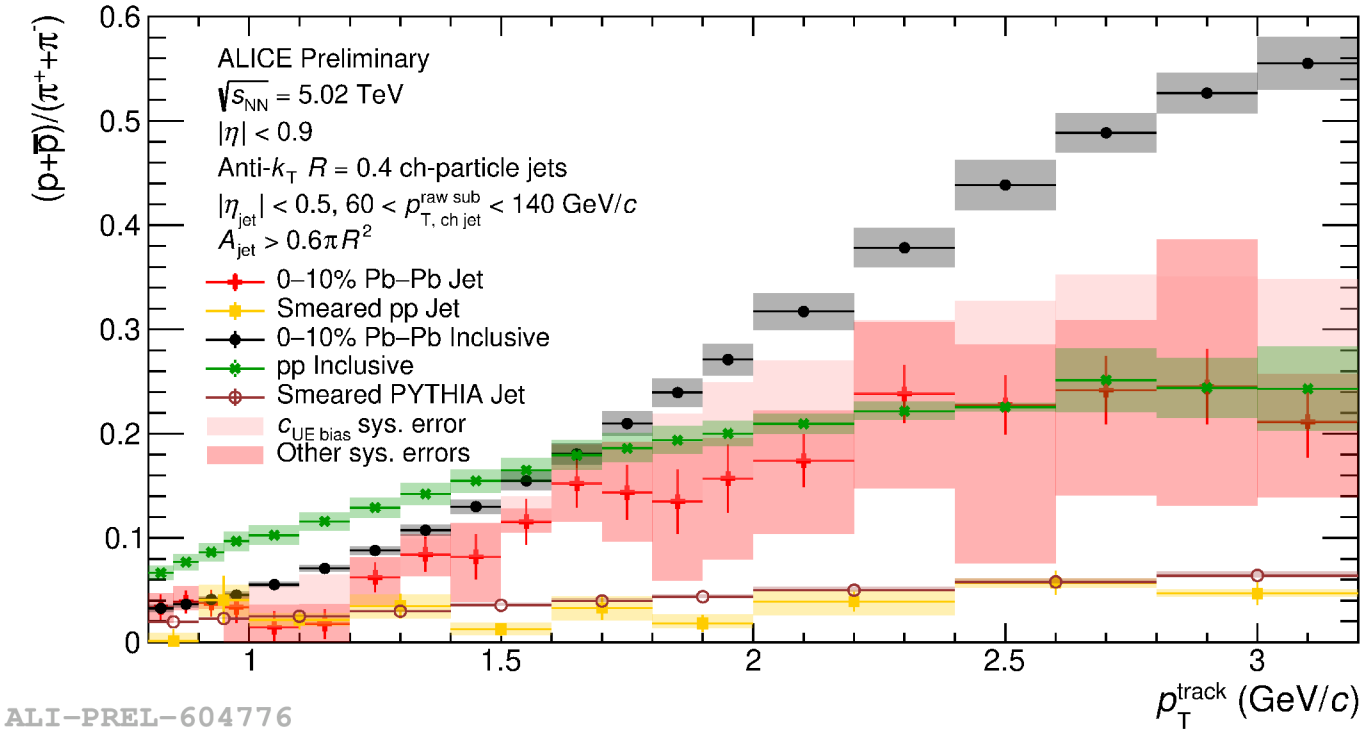
- Reconstructed R=1 jet
  - Re-clustering R= 0.2 jet in side the jet

Gabe Dale-Gau (4/8, Tue)

Sierra Weyhmiller (4/8, Tue)

Jet hadrochemistry (1)

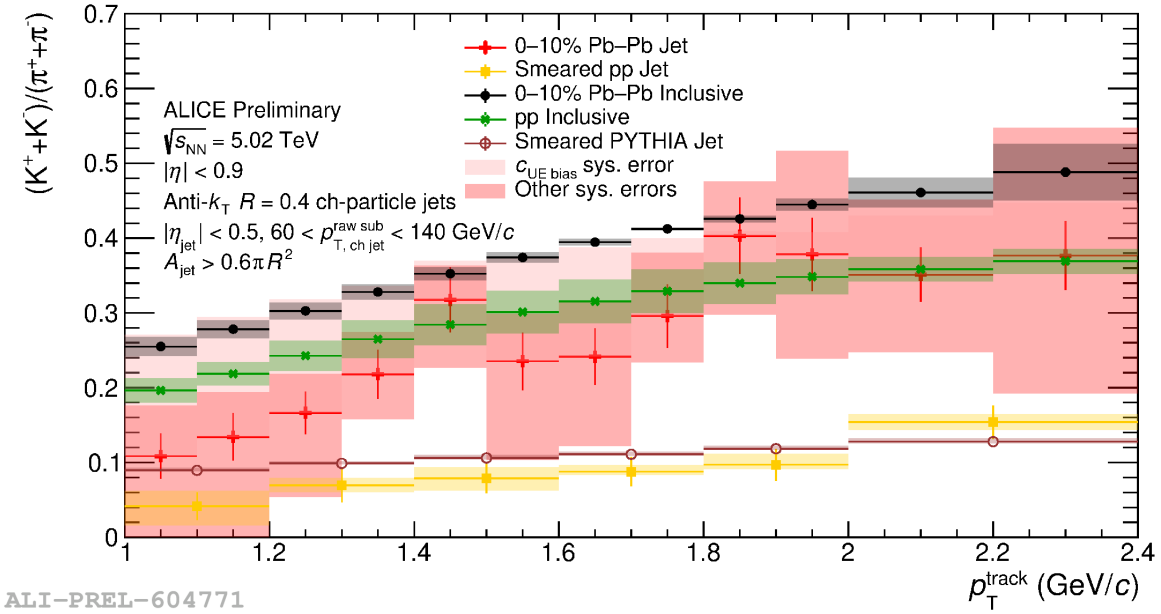


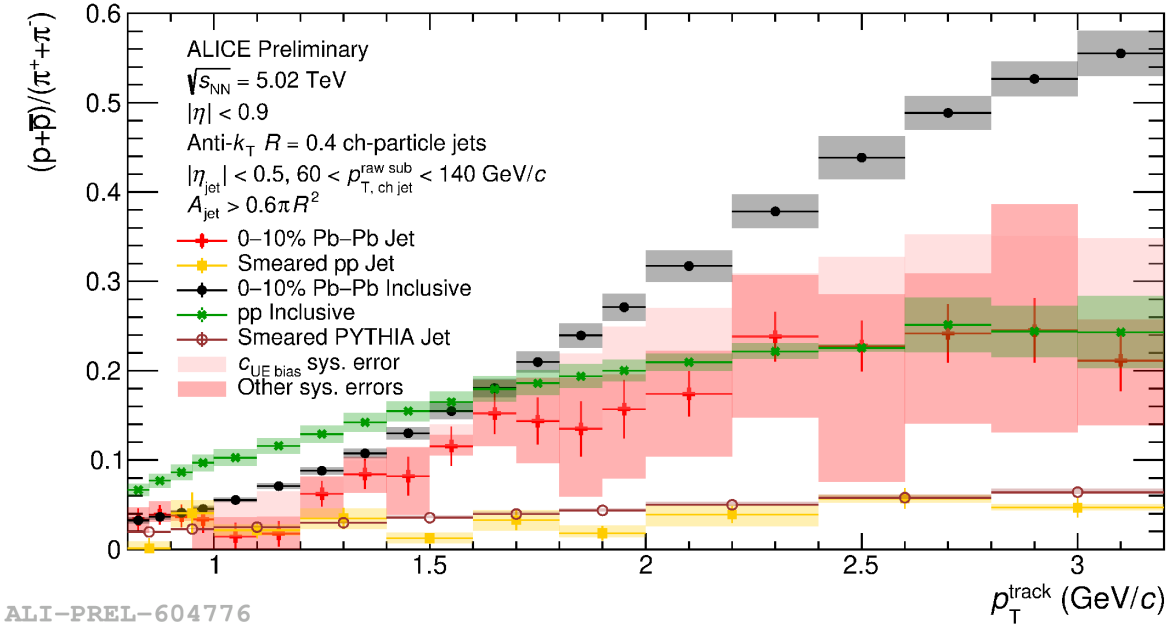


- Baryon enhancement (proton) w.r.t. pp collisions observed in Au+Au collisions at RHIC
- p/π ratio in jets are smaller than the ratio of inclusive in AA collisions
  - LHC : p/π ratio in jets in Pb-Pb is larger than the ratio in jets in pp collisions
  - RHIC : p/π ratio in jets in AuAu is same as ratio in jets in pp collisions

Jet hadrochemistry (2)

Sierra Weyhmiller (4/8, Tue)

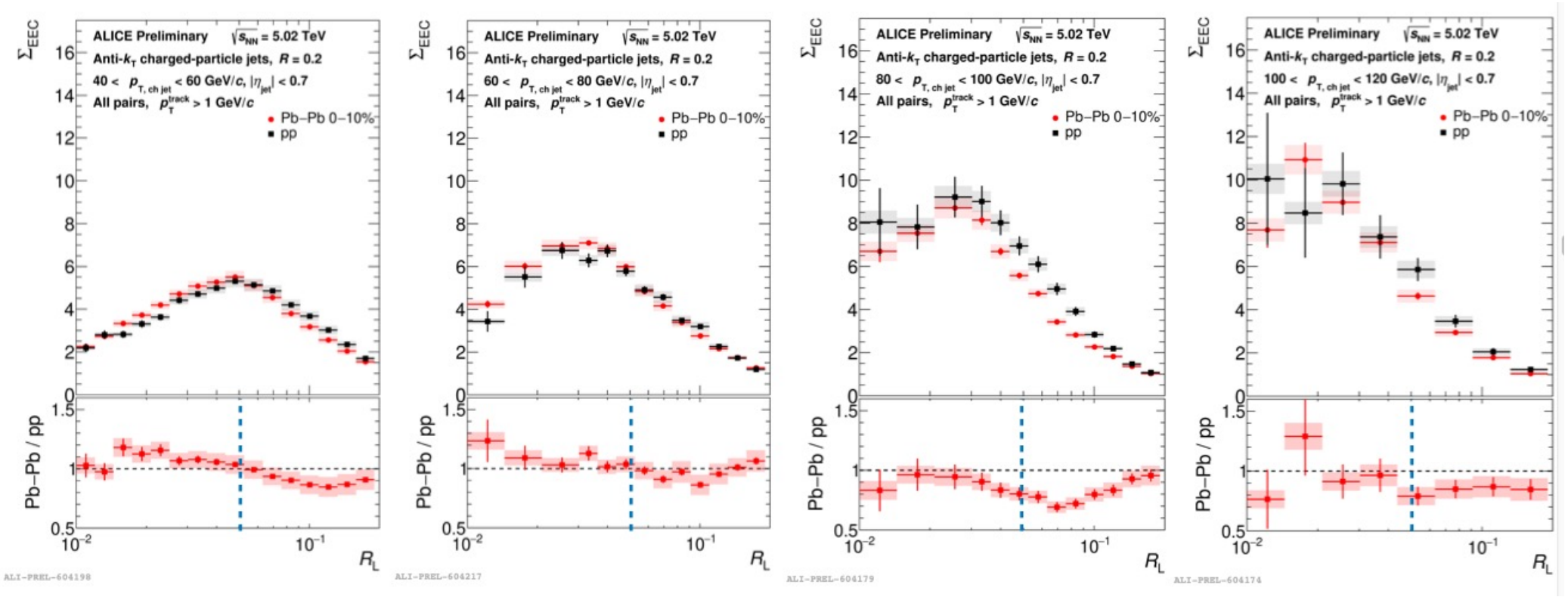




- k/π ratio in Pb-Pb collisions is larger than the ratio in pp collisions
  - Strangeness enhancement in Pb-Pb collisions
- k/π ratio in jets in Pb-Pb collisions is larger than the ratio in jets in pp collisions
  - Same trend as p/π ratio

EEC in Pb-Pb collisions (1)

A. Ray (4/7, Mon)



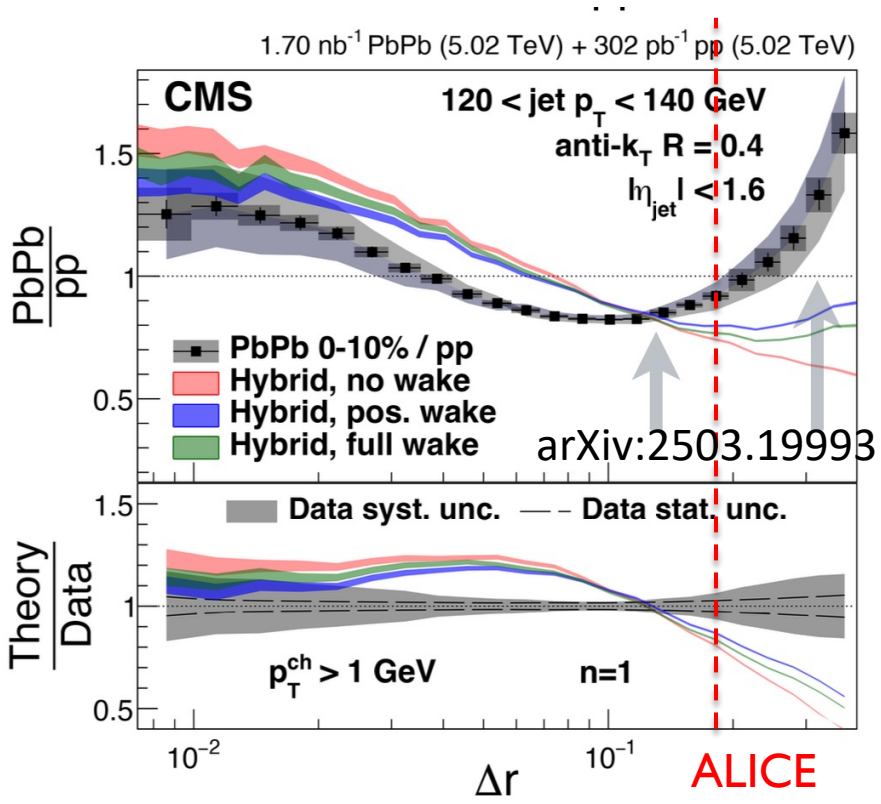
- Internal structure of jets (EEC) is modified in Pb-Pb collisions
  - Suppression at large R_L (partonic phase)
    - Suppression shift smaller R_L w.r.t jet p_T ?
  - Enhancement at small R_L (hadroic phase)

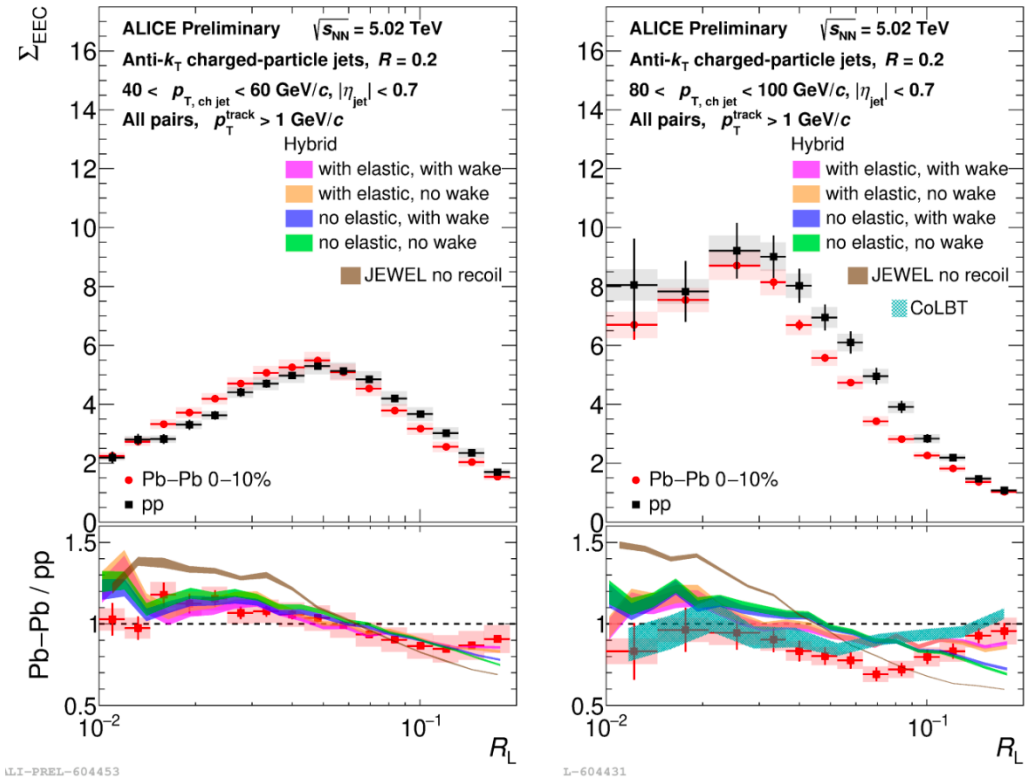
$$\frac{d\sigma_{EEC}}{dR_L} = \sum_{ij} \int d\sigma(R'_L) \frac{p_{T,i} p_{T,j}}{p^2_{T,jet}} \delta(R'_L - R_{L,ij})$$

EEC in Pb-Pb collisions (2)

A. Ray (4/7, Mon)

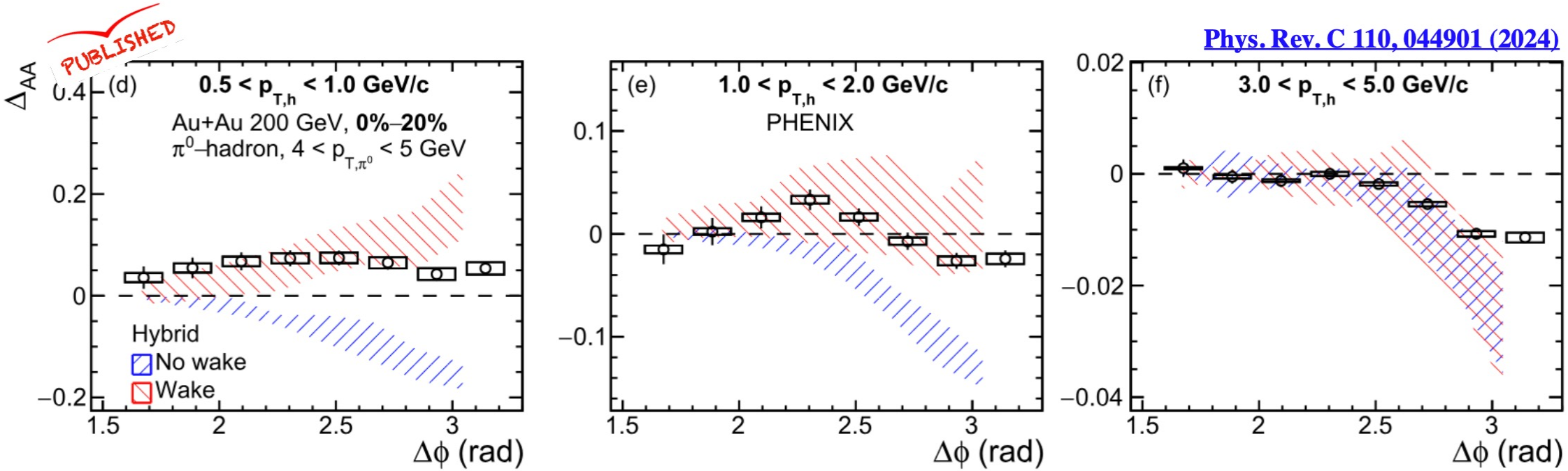
J.Viinikainen (4/10, Thu.)



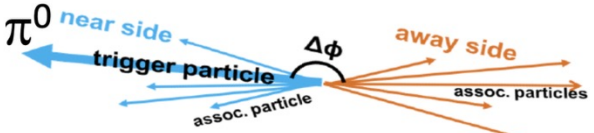


- EEC measured by CMS (R=0.4, p_T > 120 GeV/c)
  - EEC suppression around R_L = 0.1 and enhancement around R_L > 0.2
- Comparison model of medium response (Hybrid model)
  - Challenge to explain the EEC for high p_T jet (p_T > 80 GeV/c)

Medium response in AuAu collisions



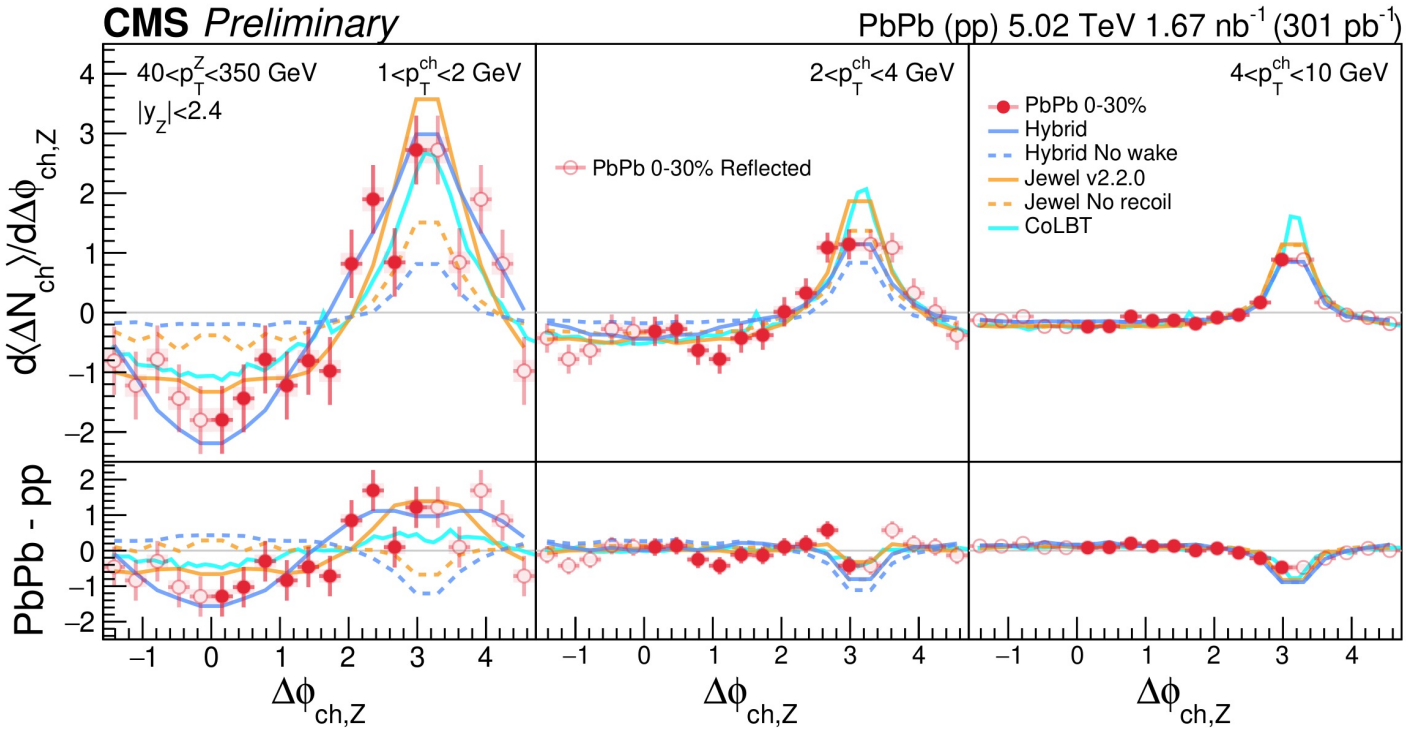
- Modification of away-side jet production in AuAu collisions
  - Enhancement of low p_T particle productions
- Experimental results in different p_T range for the associated hadron prefer the model with medium response (wake)
  - Same picture as LHC results

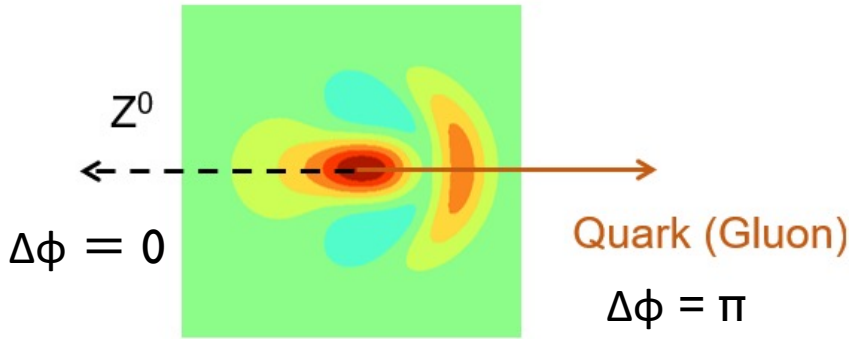


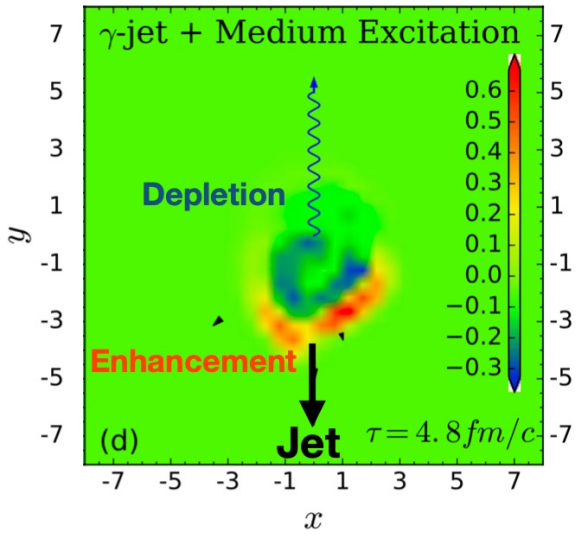
$$\Delta_{AA} = Y_{AA} - Y_{pp}$$

Yen-Jie Lee (4/9, Wed.)

Medium response by Z-hadron correlation







- Clear depletion of low p_T associate particles ($1 < p_T < 2$ GeV/c) around the Z ($\Delta\phi = 0$)
  - Diffusion wake ?
- Models include wake (positive and negative) reproduces the data

Summary

- nPDF study in LHC
  - New approach by top quark, photonuclear production of heavy flavours
    - Good agreement with model with nPDF, but observed some tension
- Hard probes in small system
  - Suppression is observed in RHIC, but not in LHC
  - Modification of jet internal structure in pPb ?
    - Modified EEC & enhancement v_2* at high multiplicity w.r.t QCD prediction
- Hard probes in AA collisions
  - Clear mass & baryon / meson splitting in heavy-flavour v_2
  - Modification of EEC
    - Model with medium response doesn't reproduce the trend for high p_T jet and large R_L
  - Signal of diffusion wake in Z-hadron correlation