Jet energy loss in small systems with finite-size effects and running coupling

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Collaboration with C. Shen, S. Jeon, C. Gale

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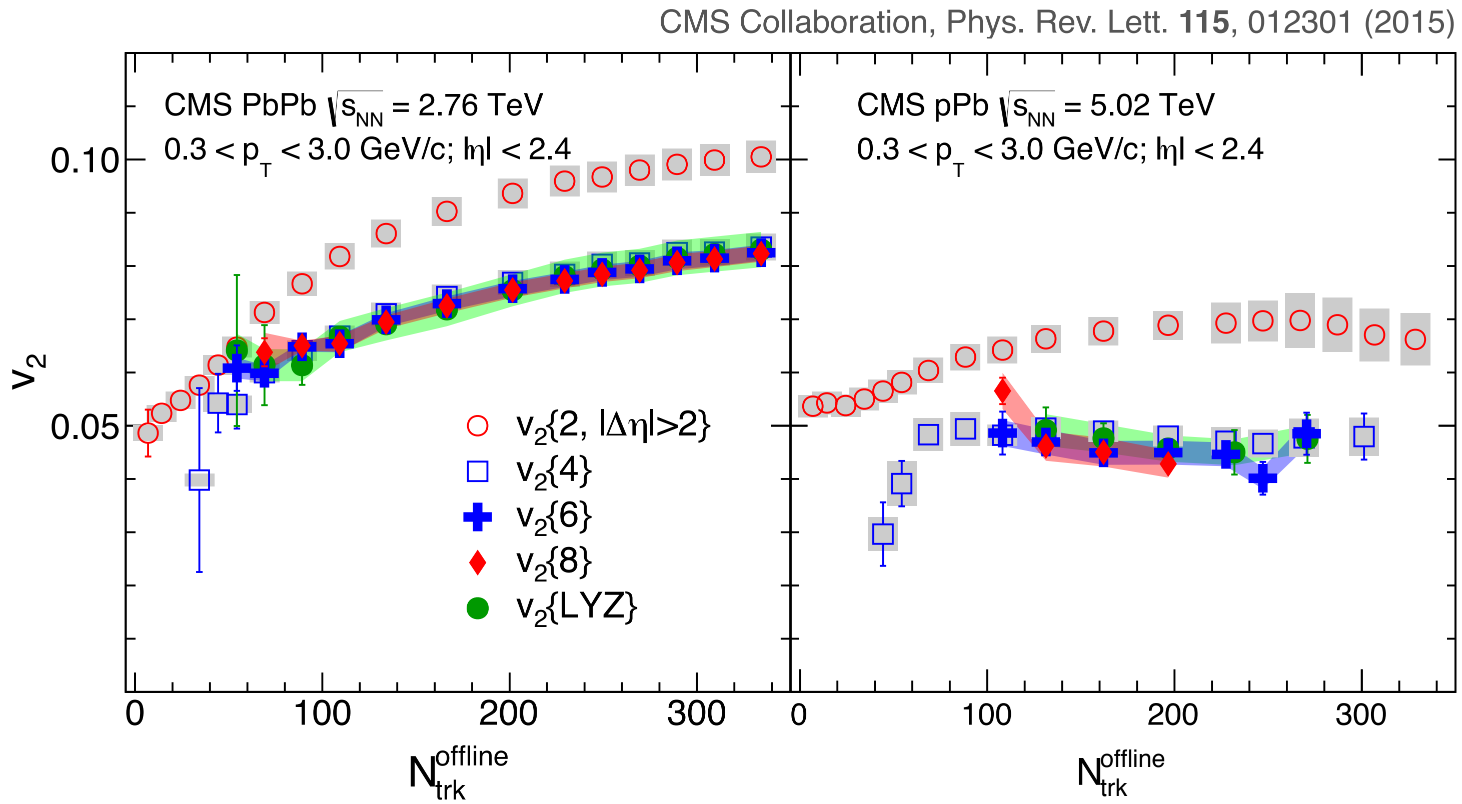
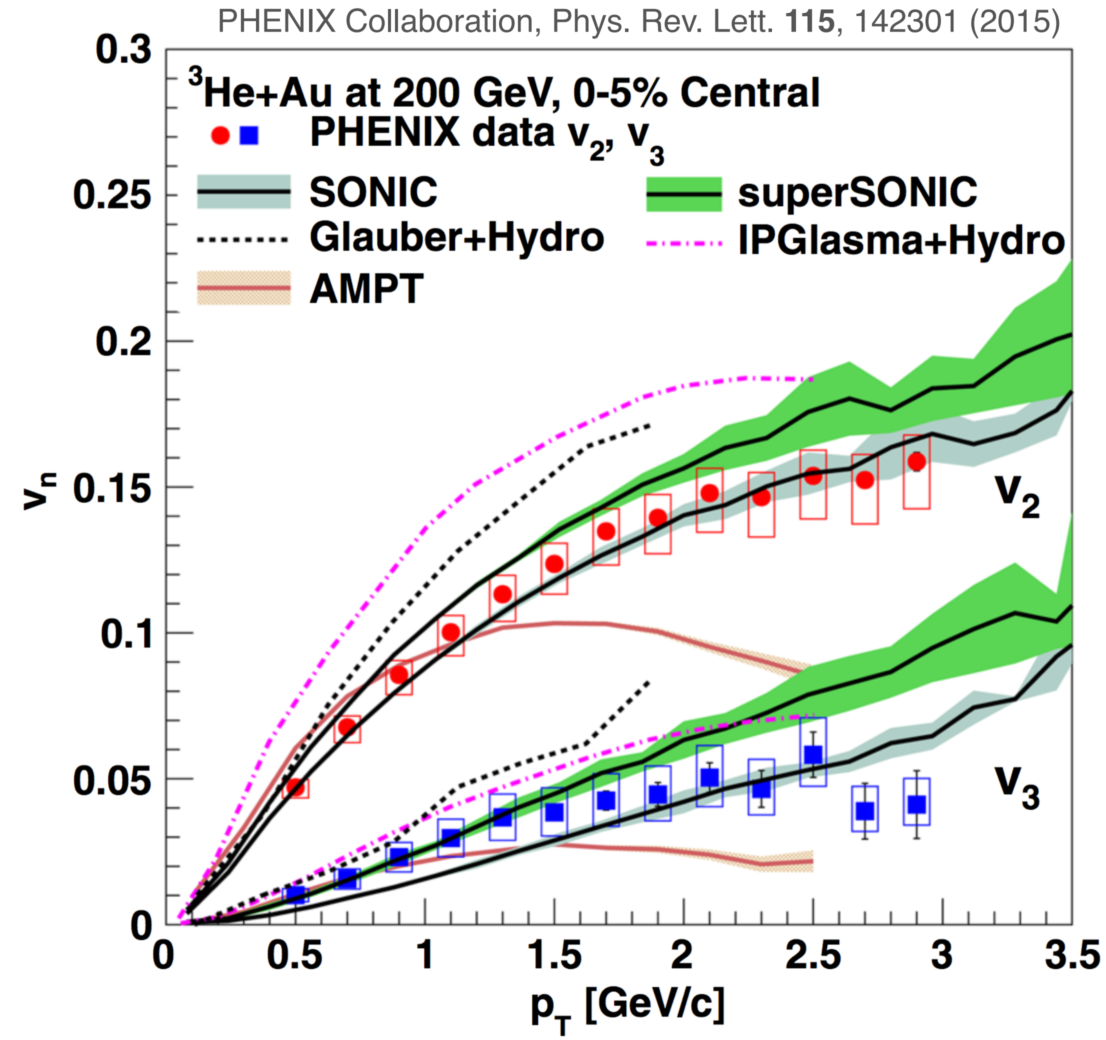
2016 Hard Probe, 24.Sep.2016

Wuhan HP2016

Collectivity in small systems



Pb-Pb/p-Pb CMS



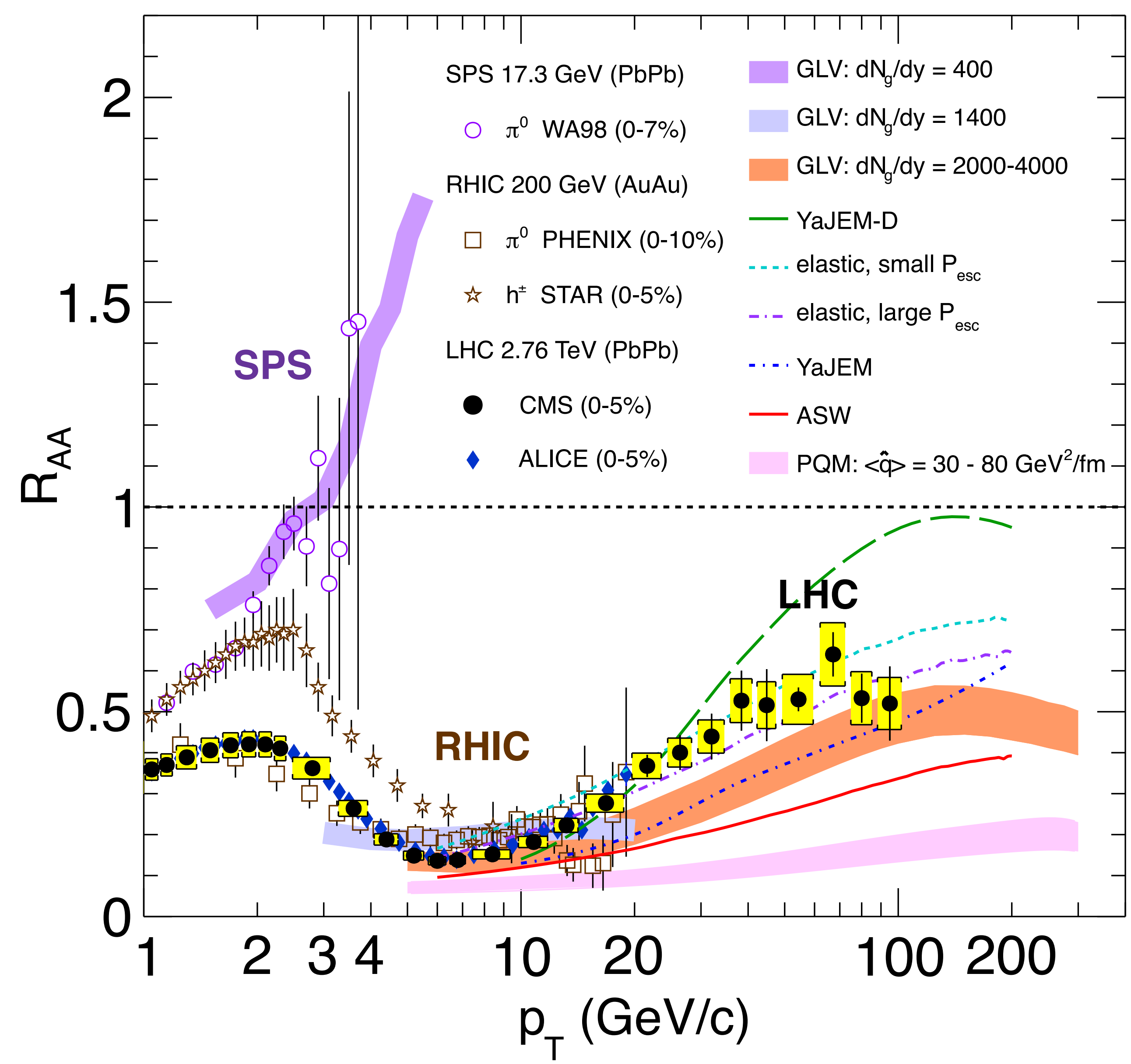
^{3}He-Au at 200GeV PHENIX

- Collective behaviour was measured in central collisions of small systems
- This suggests strongly coupled medium in small systems

A Tool for studying QGP : Jets

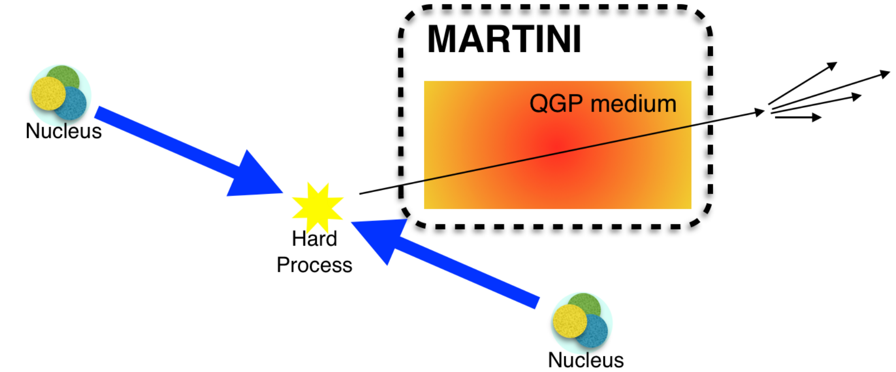
- Jet quenching : due to colour opacity of a strongly coupled medium
- Strong suppression in AA collisions was measured at RHIC and the LHC
- Similar behaviour in small systems?

CMS Collaboration, Eur. Phys. J. **C72**, 1945 (2012)

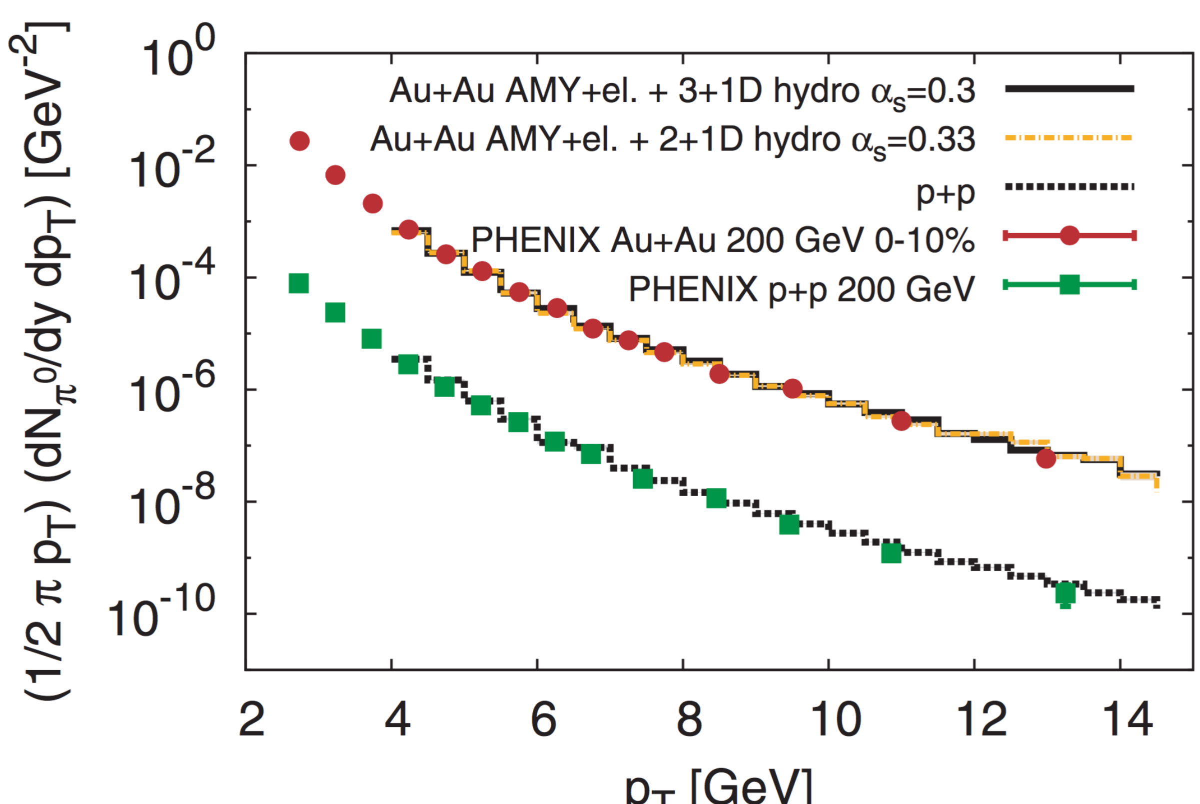


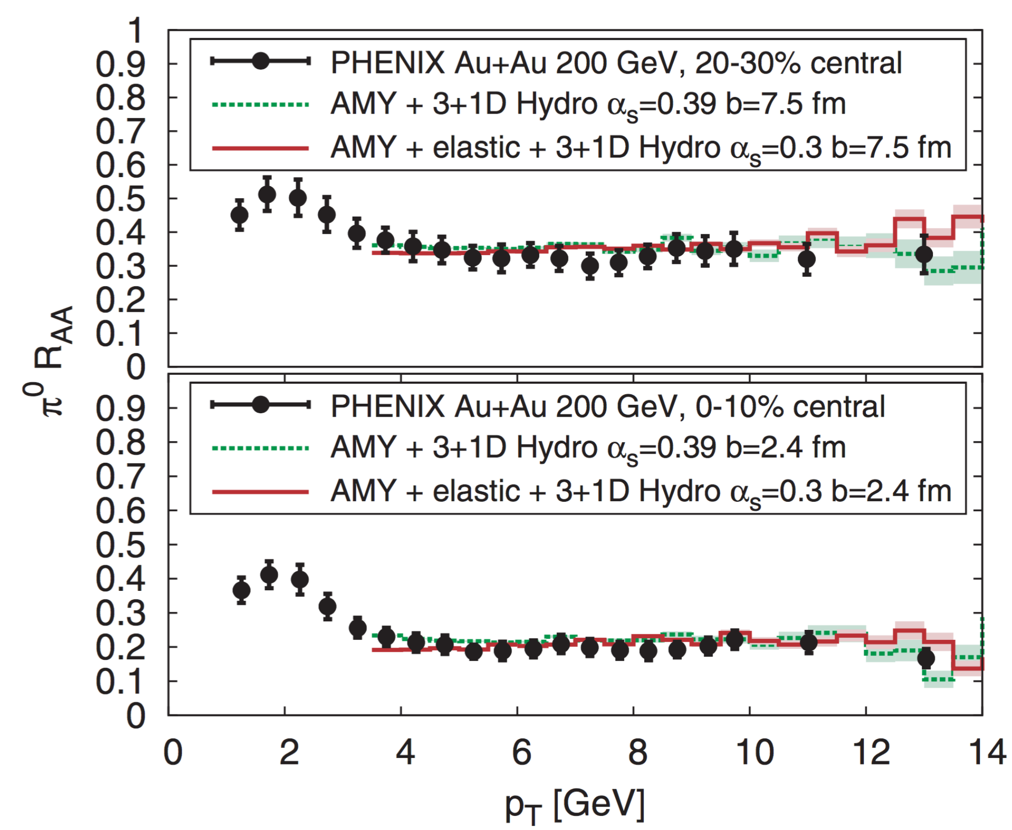
Jet-medium interaction

- **MARTINI** B. Schenke, S. Jeon, C. Gale, Phys. Rev. **C80**, 054913 (2009)



  - Event generator for hard jets in heavy ion collisions
  - Based on PYTHIA 8.2
  - AMY(Arnold-Moore-Yaffe) radiation scheme as well as collisional processes
  - E-by-E hydrodynamics background is available

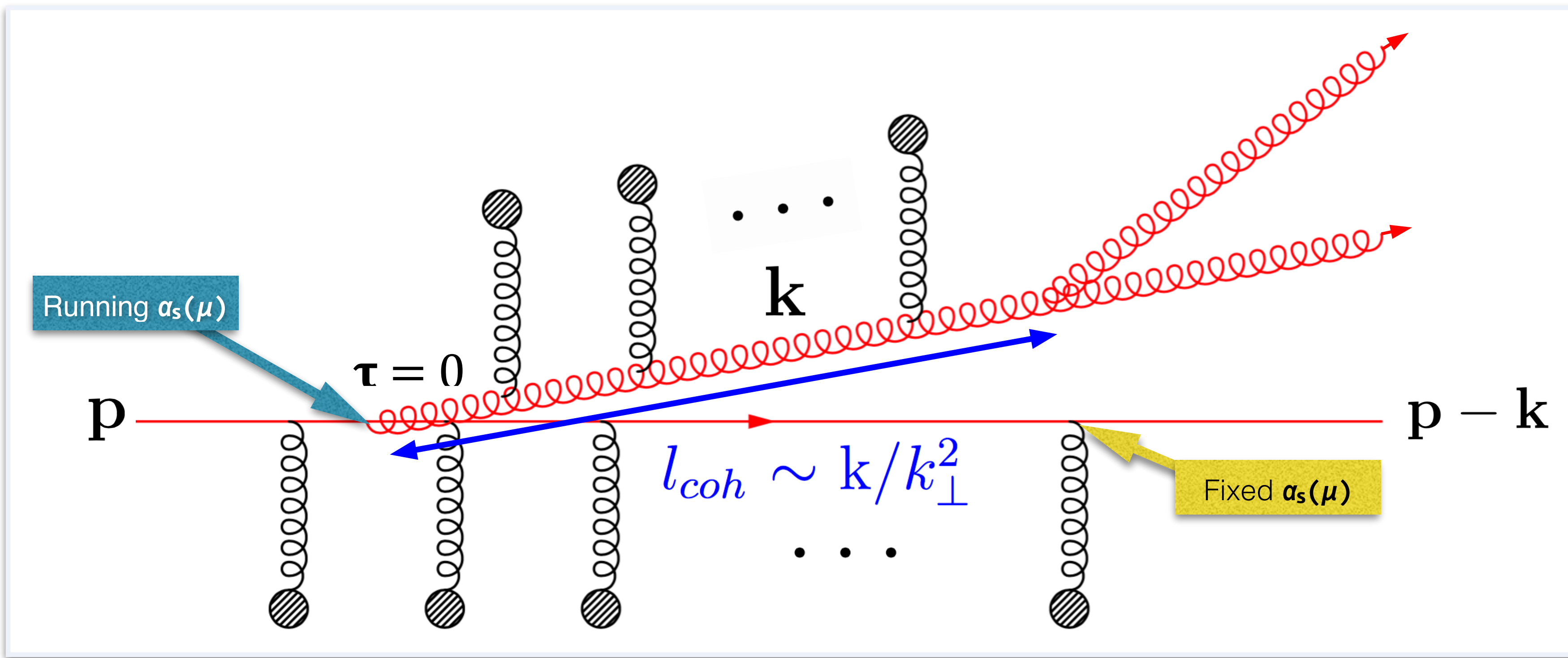




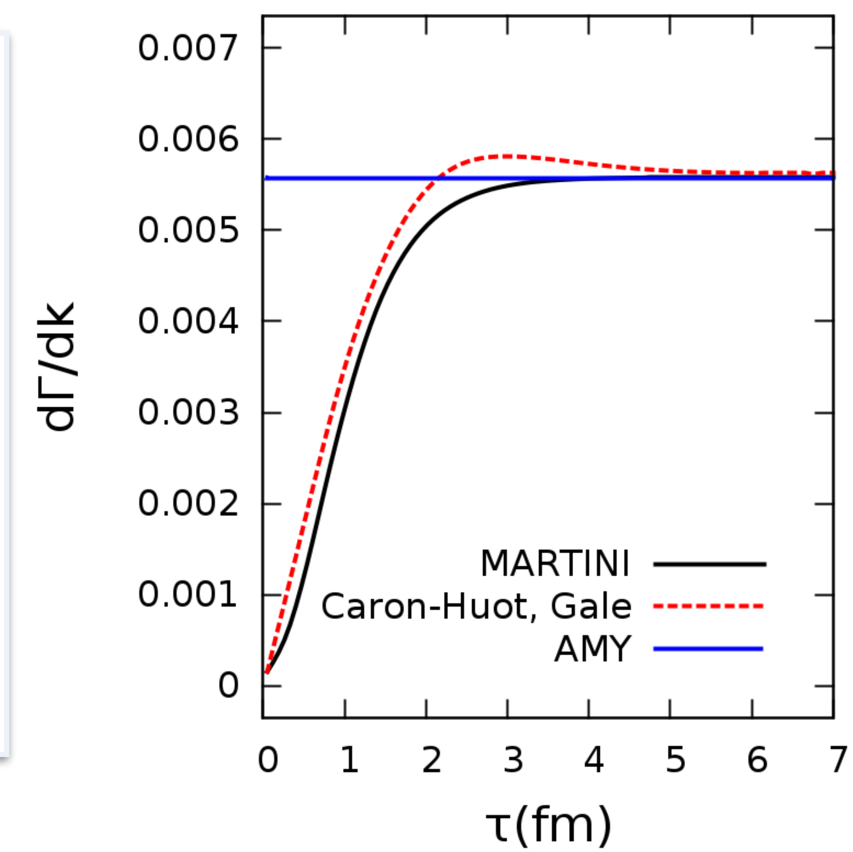
New developments in MARTINI

- Finite-size effects on radiation

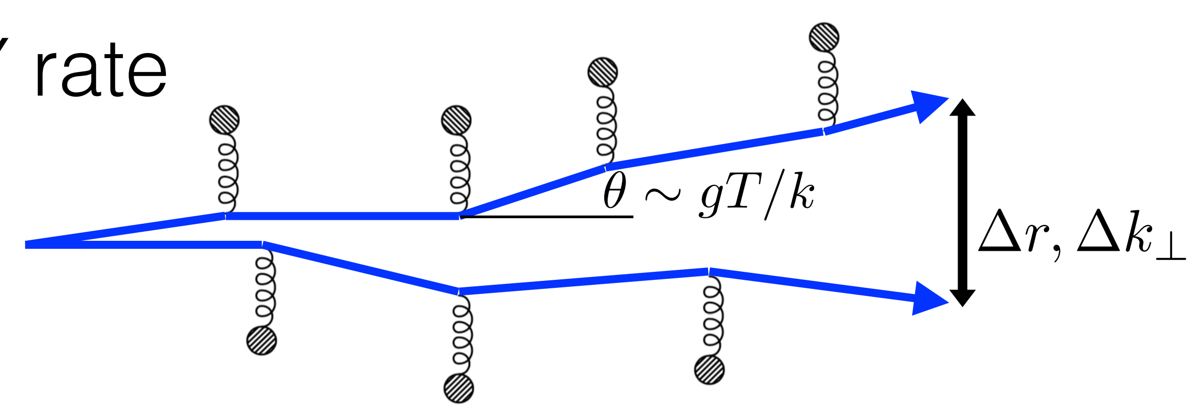
S. Caron-Huot and C. Gale, Phys. Rev. **C82**, 064902 (2010)



C. Park, M.Sc Thesis, McGill (2015)



- Finite formation time of radiation
  : Time dependence is applied in AMY rate
- Implementation : Random walk
  (separation condition $\Delta r \Delta k_\perp > \dfrac{1}{2}$)



New developments in MARTINI

- Running coupling

C. Young, B. Schenke, S. Jeon, and C. Gale,Nucl. Phys. **A910-911**, 494 (2013)

- Origin of g_s in the AMY rate

$$\frac{d\Gamma(p,k)}{dk} = \frac{C_s g_s^2}{16\pi p^7} \frac{1}{1 \pm e^{-k/T}} \frac{1}{1 \pm e^{-(p-k)/T}} \times \left\{ \begin{array}{ll} \frac{1+(1-x)^2}{x^3(1-x)^2} & q \to qg \\ N_f \frac{x^2+(1-x)^2}{x^2(1-x)^2} & g \to qq \\ \frac{1+x^4+(1-x)^4}{x^3(1-x)^3} & g \to gg \end{array} \right\}$$

$$\times \int \frac{d^2\mathbf{h}}{(2\pi)^2} 2\mathbf{h} \cdot \mathrm{Re}\, \mathbf{F}(\mathbf{h}, p, k),$$

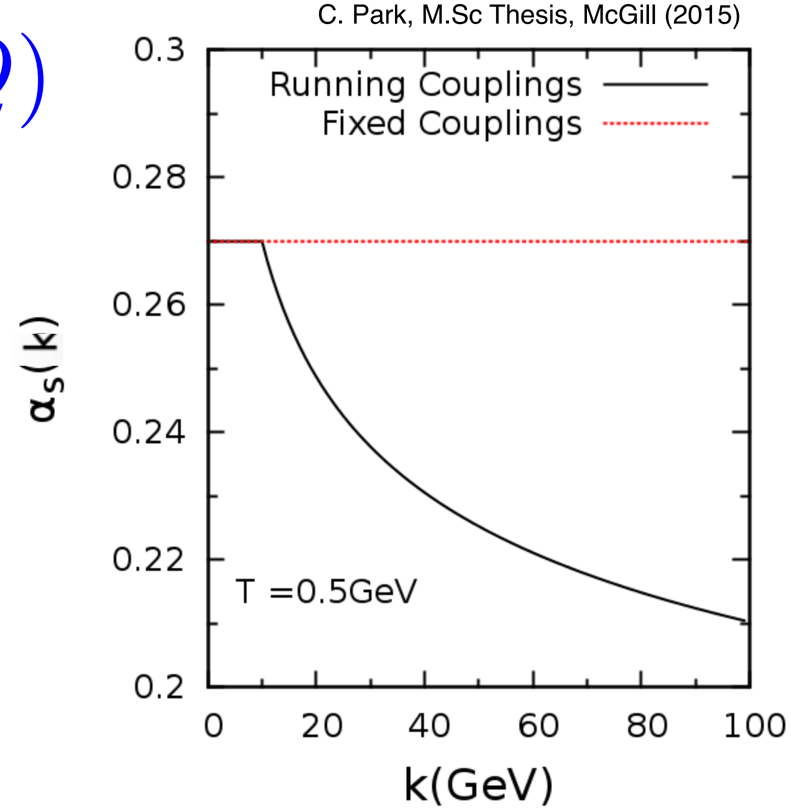
- g_s^2 : Gluon radiation vertex $\rightarrow g_s^2 = 4\pi\alpha_s(Q)$
- In MARTINI, $Q \sim \underline{\langle |k_\perp| \rangle = (\hat{q}k)^{\frac{1}{4}}}$

$$\langle k_\perp^2 \rangle = \hat{q} l_{coh}$$

$$l_{coh} = k / \langle k_\perp^2 \rangle$$

- g_s^2 in the integral equation
  : elastic scattering (soft) $\rightarrow$ fixed

C. Park, M.Sc Thesis, McGill (2015)



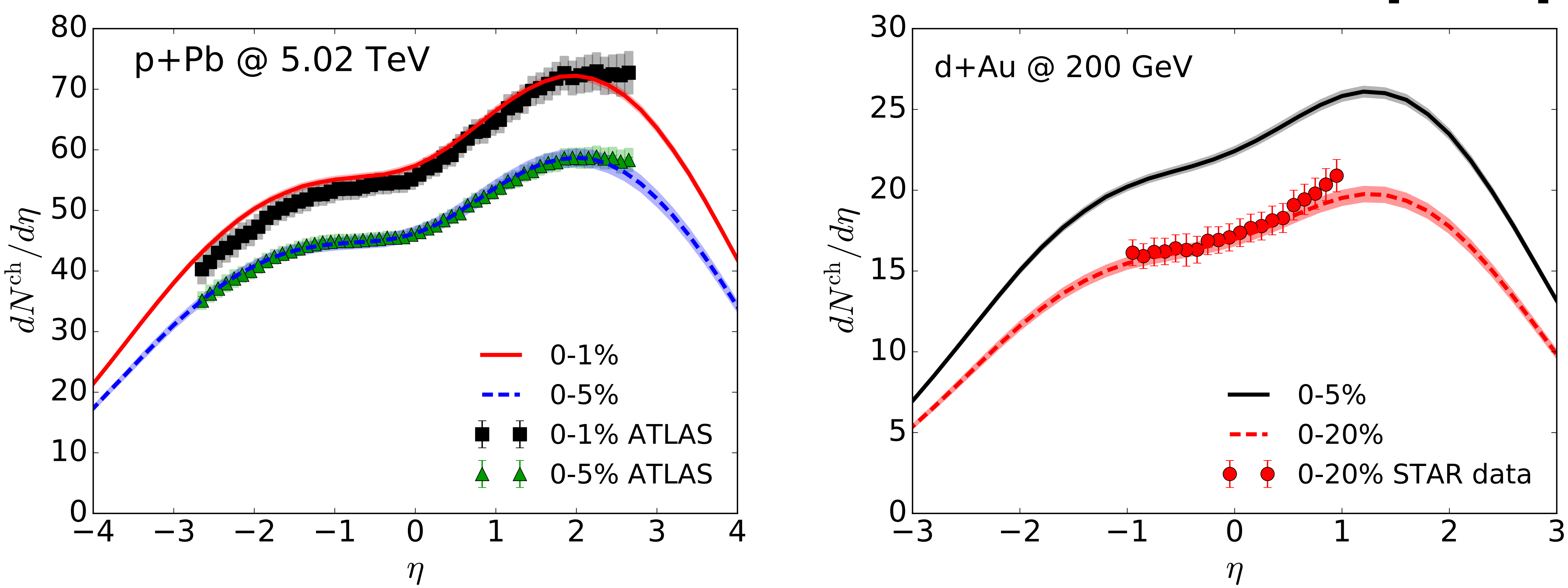
3+1D hydrodynamic simulations

- **MUSIC**

  B. Schenke, S. Jeon, C. Gale, Phys. Rev. **C82**, 014903 (2009)

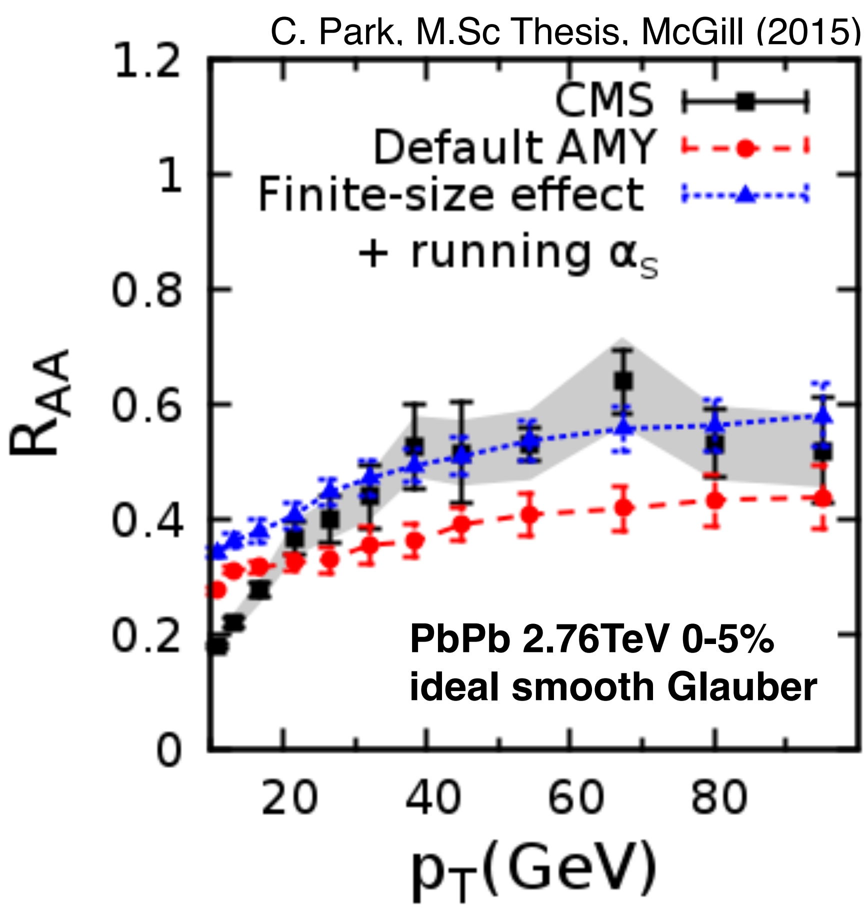
  - 3+1D : Suitable for studying non-trivial longitudinal dynamics and rapidity dependence of jet observables
  - Event-by-event simulation + MC Glauber initial condition

C. Shen et al. arXiv:1609.02590v1 [nucl-th]

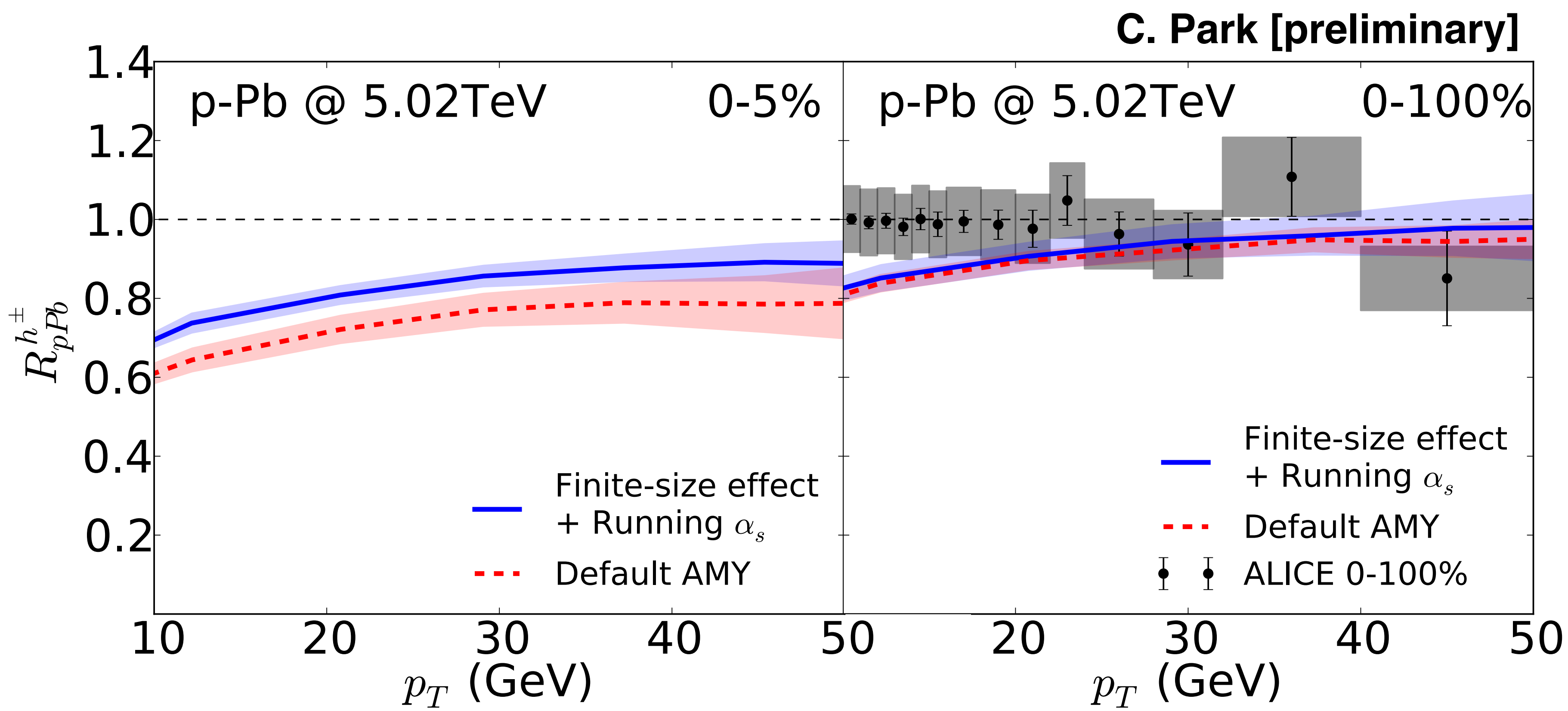


p-going side **Pb-going side** **d-going side** **Au-going side**

Finite-size effects & running coupling



Pb-Pb @ 2.76TeV

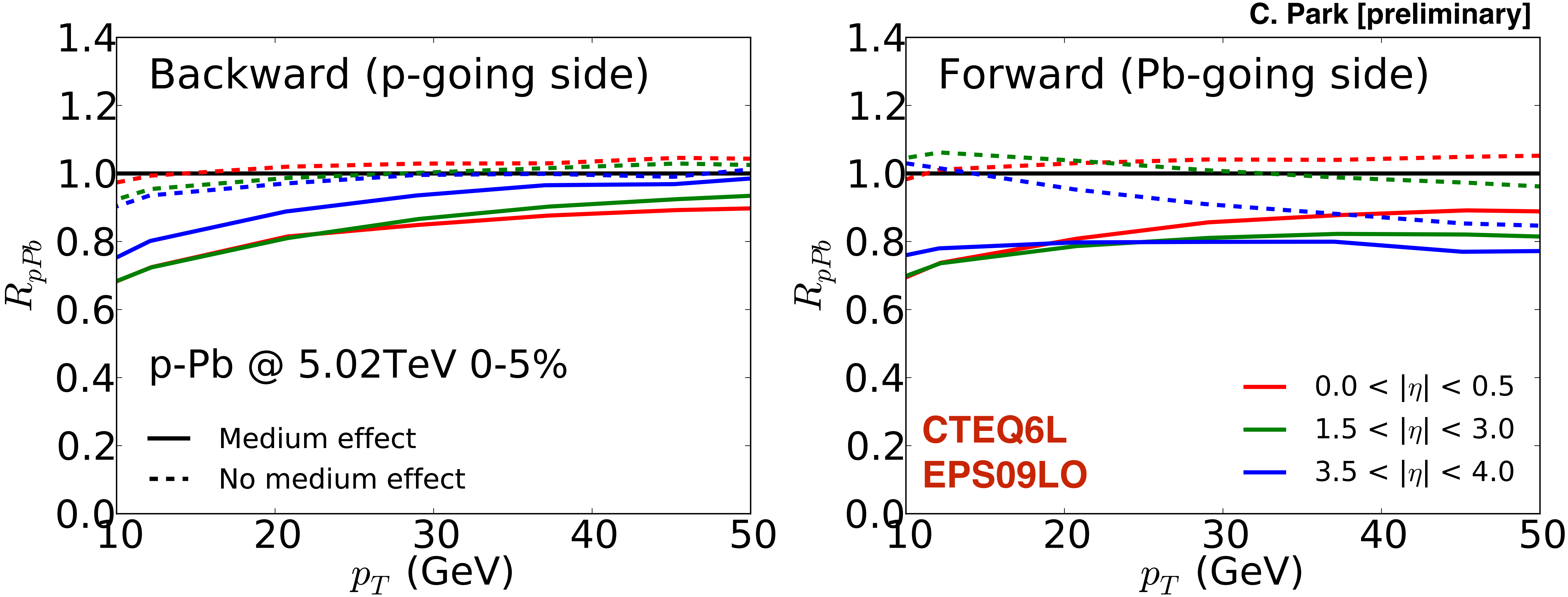


p-Pb@ 5.02TeV

- Two effects give constant shifts in R_{AA} & R_{pA}
- For large systems, the new prescriptions were favoured, but underestimated ALICE data @ 10-20GeV in small systems.

Rapidity dependent energy loss

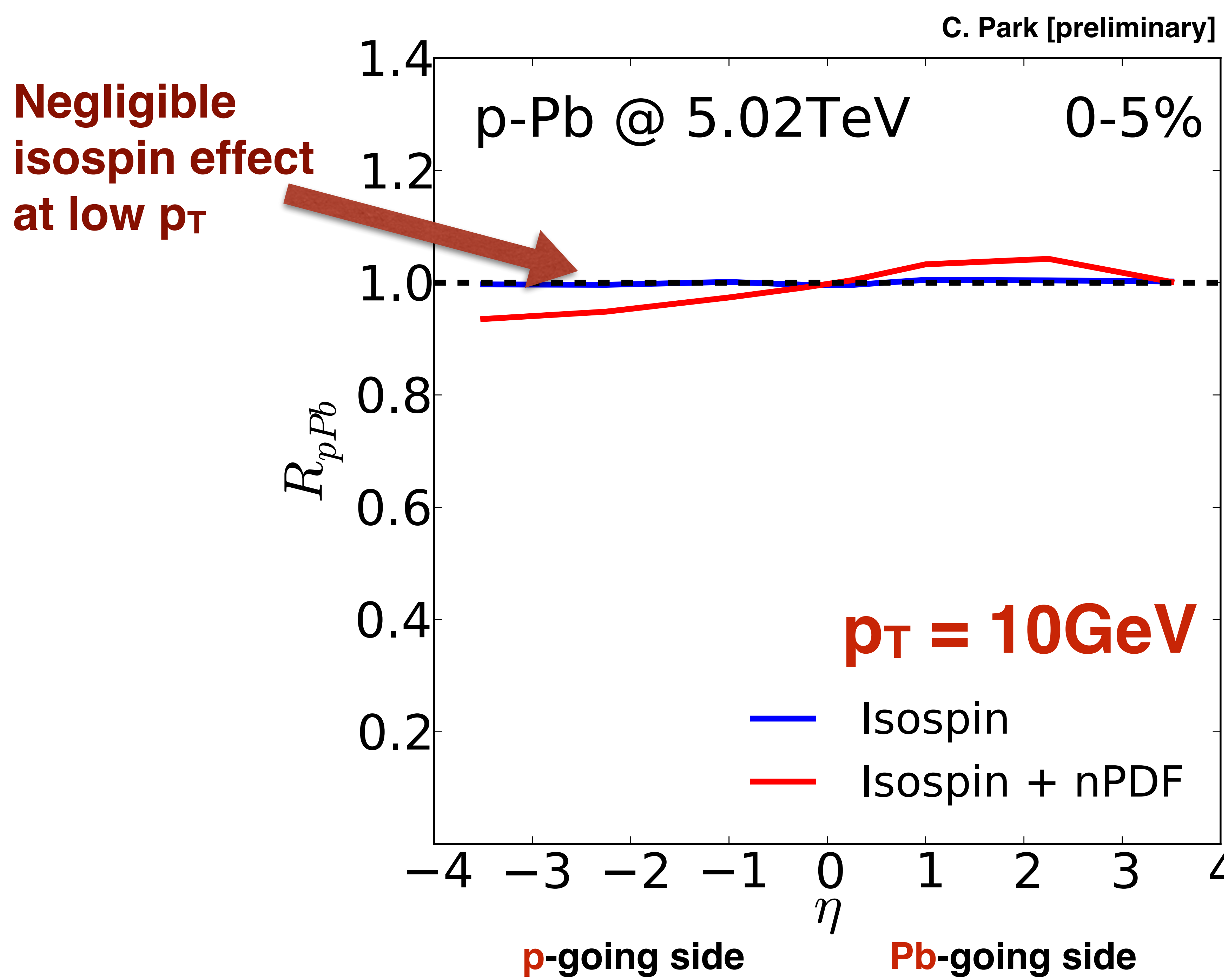
C. Park [preliminary]

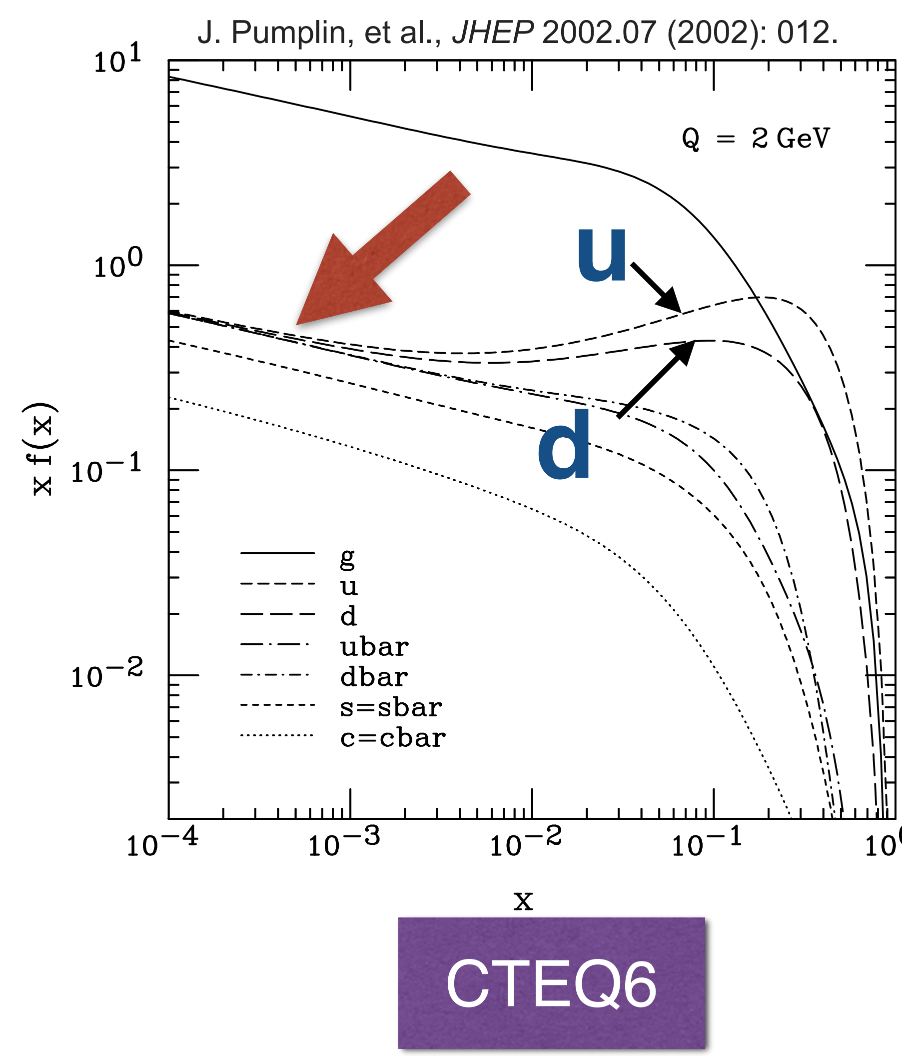


- Net effect : Convolution of medium effect + nuclear PDF + isospin
- Better understanding of their effects in rapidity directions is required.

Rapidity dependent energy loss

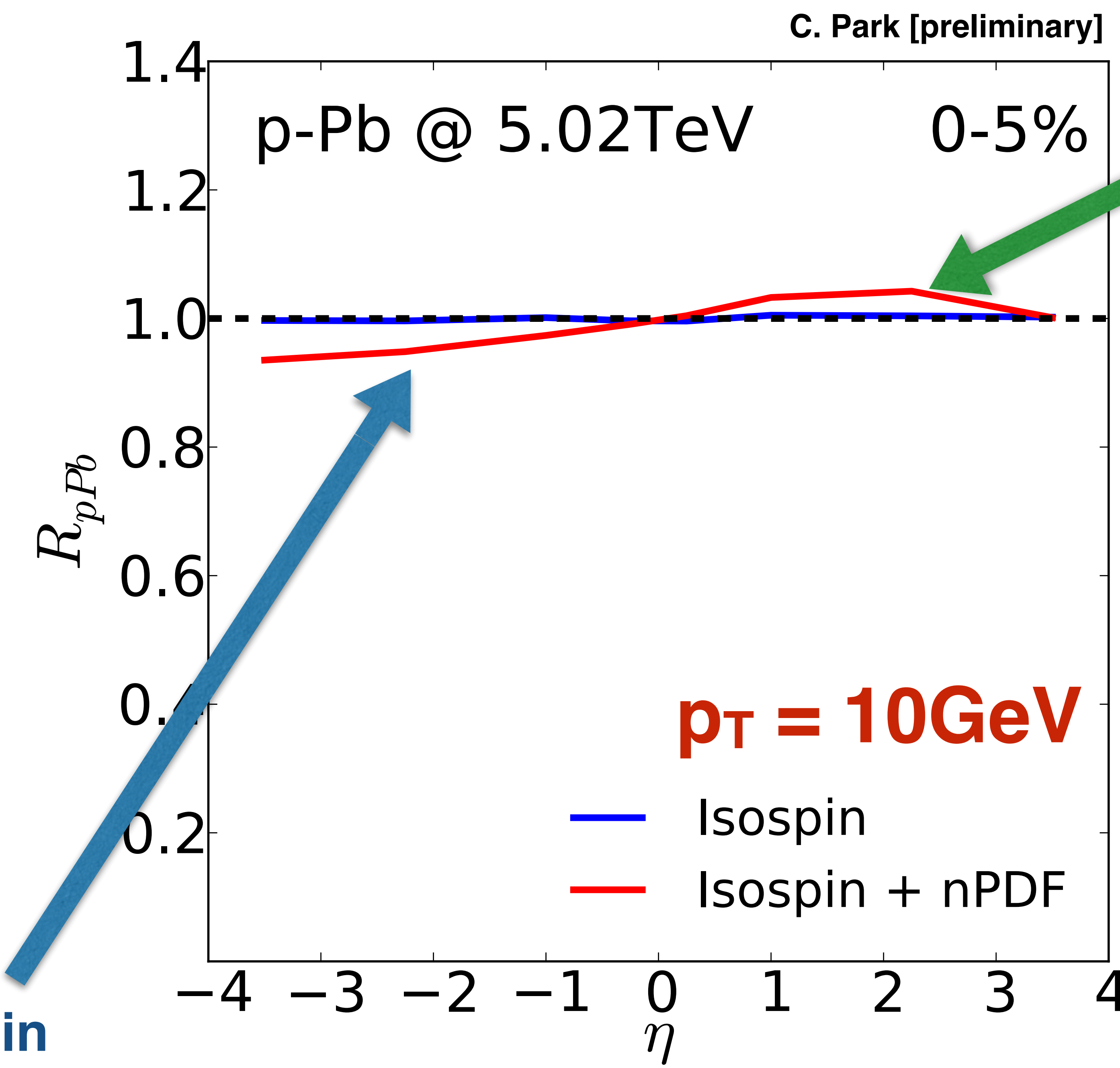
- Dominant nuclear PDF effect in low p_T R_{pPb}



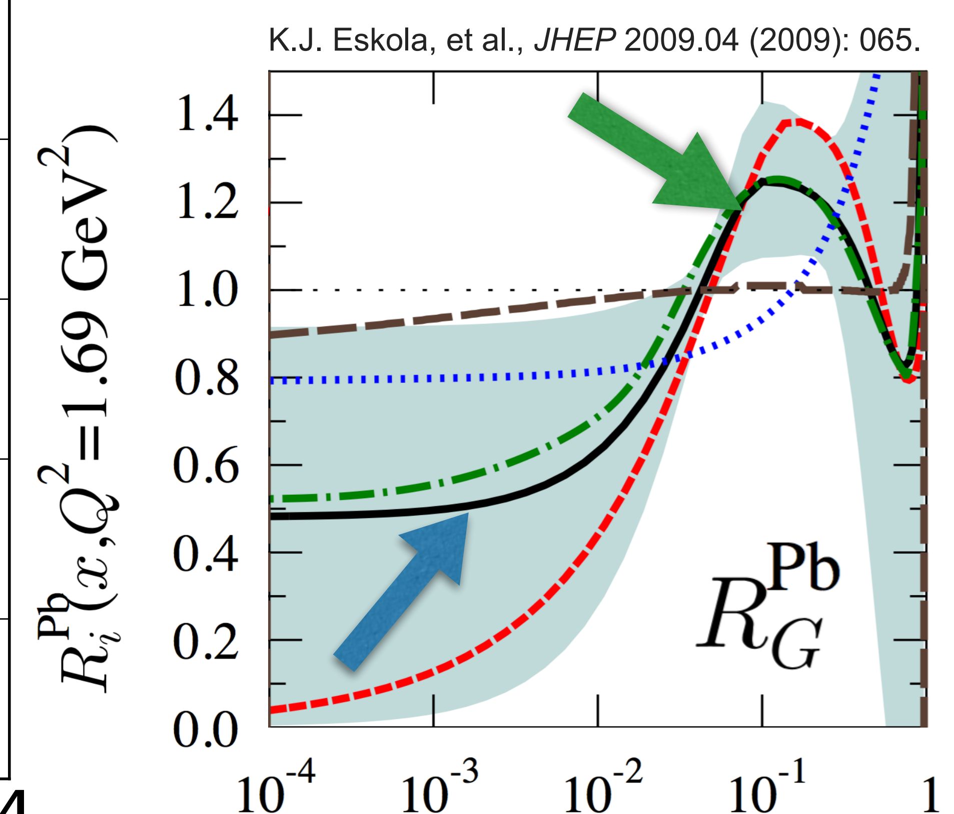


Rapidity dependent energy loss

- Dominant nuclear PDF effect in low p_T R_{pPb}



Anti-shadowing
x ~ 0.1 from Pb



EPS09LO

Shadowing in backward rapidity due to small x from Pb

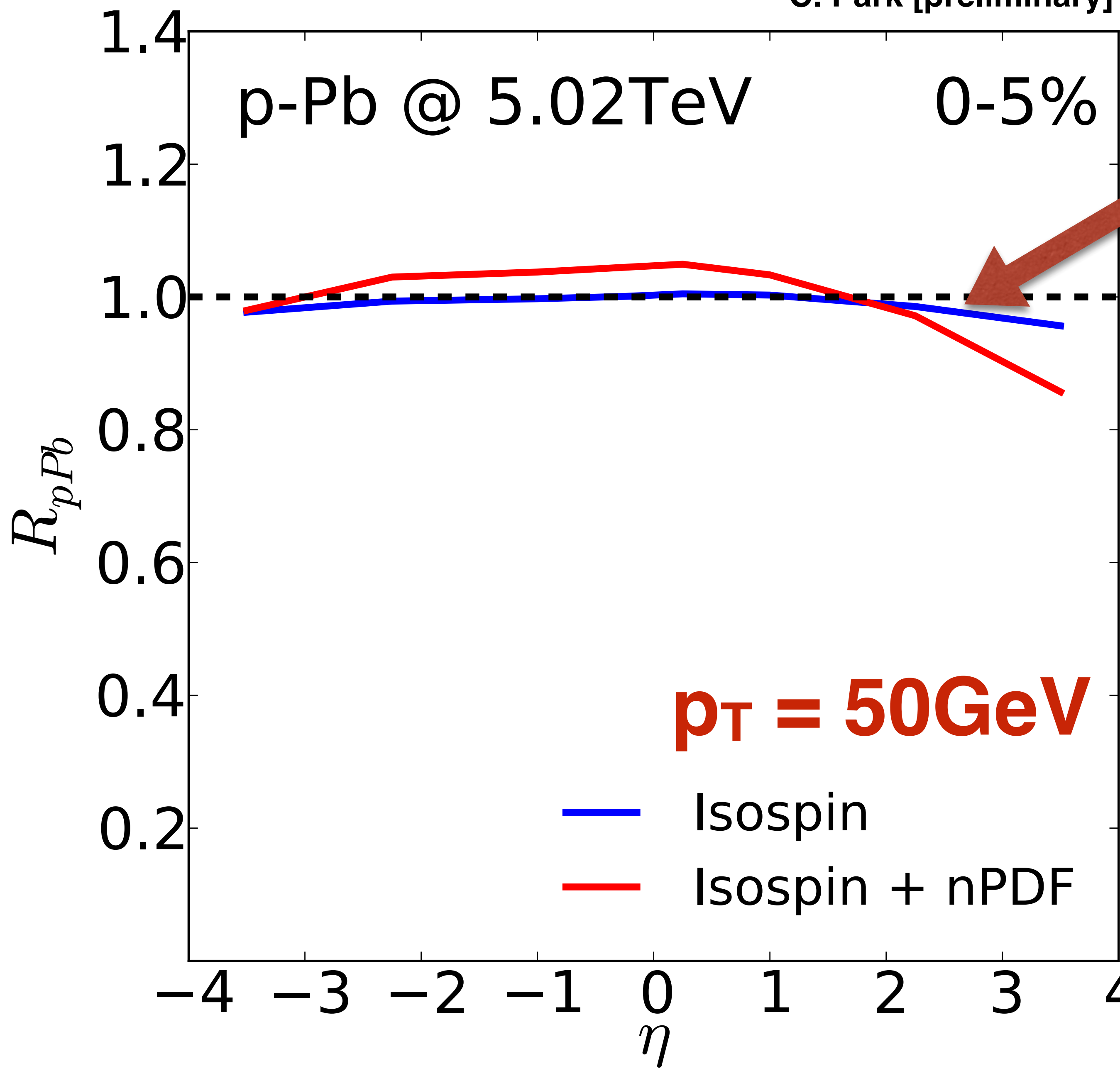
p-going side **Pb-going side**

Rapidity dependent energy loss

high p_T = larger x

- Isospin effect and anti-shadowing in high p_T R_{pPb}

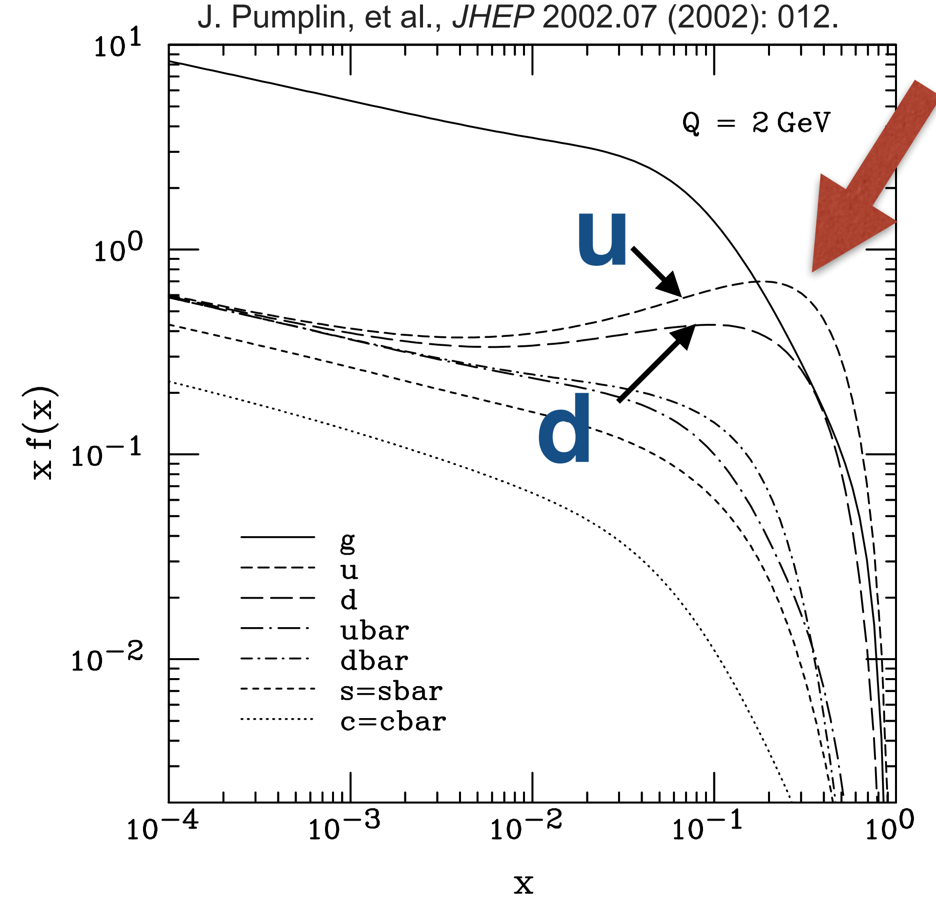
C. Park [preliminary]



p-going side **Pb-going side**

Little isospin effect at high p_T

J. Pumplin, et al., *JHEP* 2002.07 (2002): 012.



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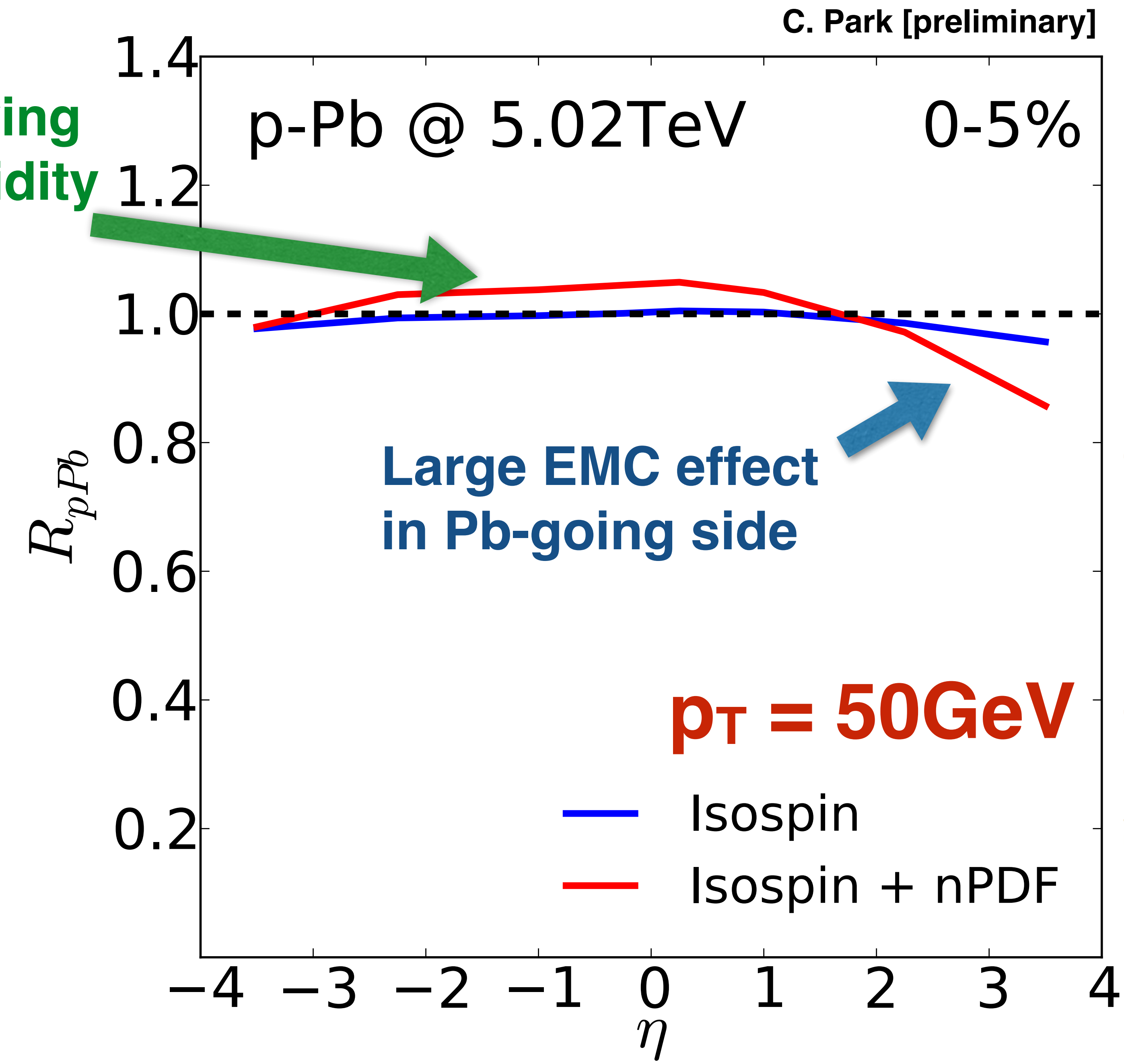
Rapidity dependent energy loss

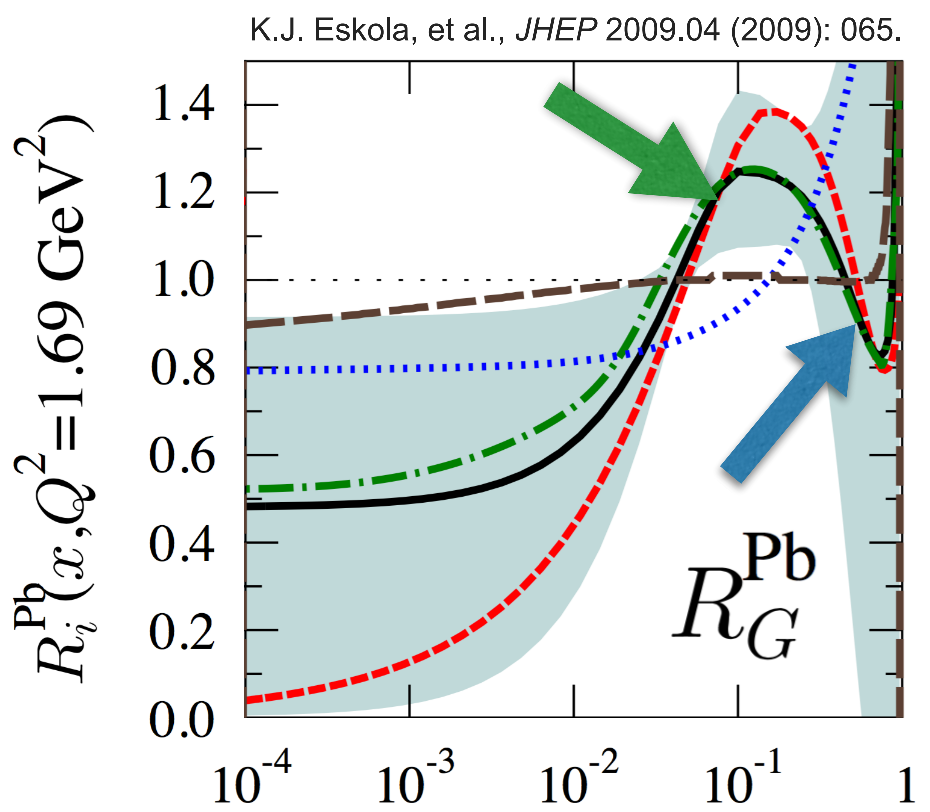
high p_T = larger x

- Isospin effect and anti-shadowing/EMC in high p_T R_{pPb}

Anti-shadowing at broad rapidity range



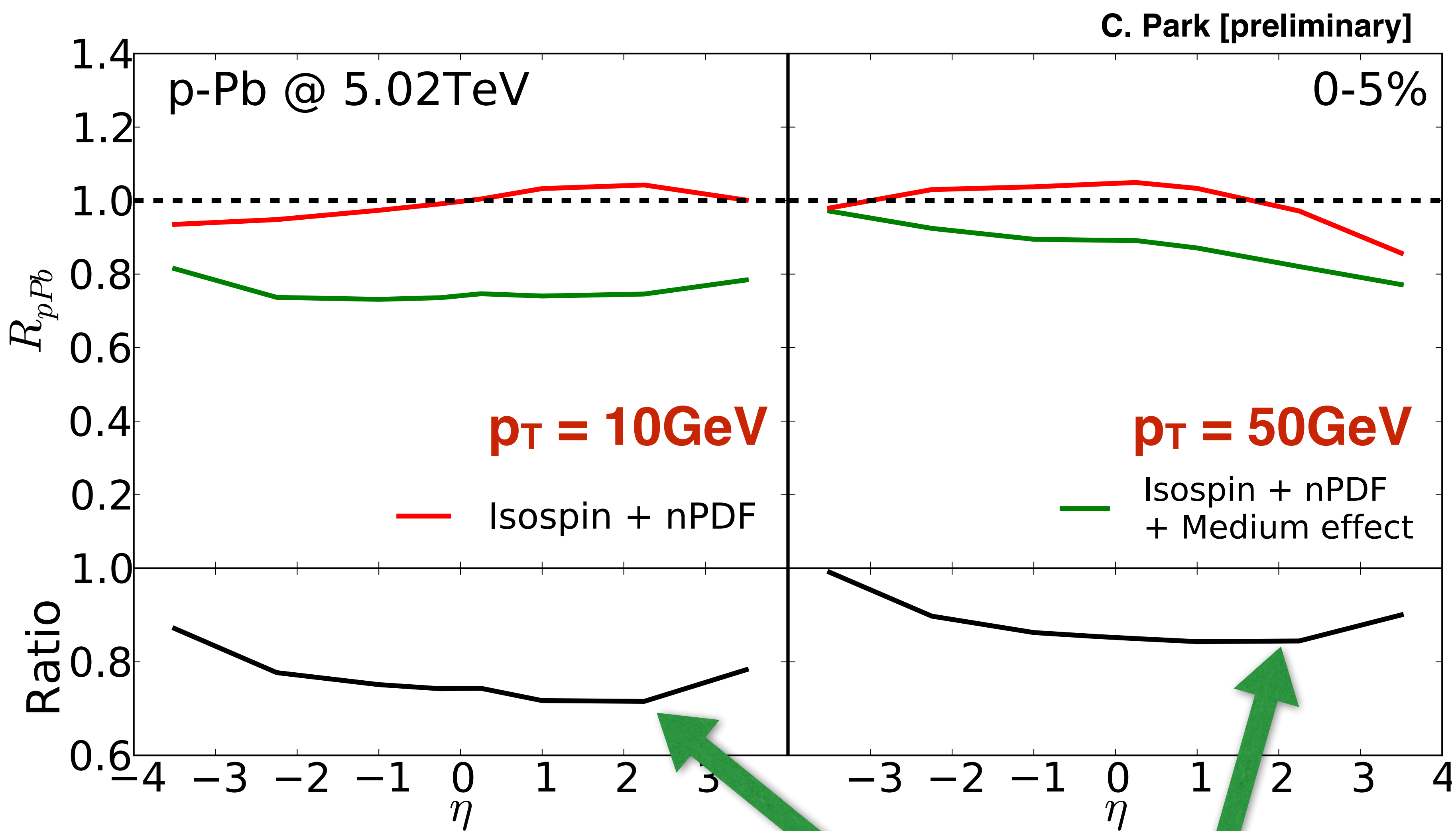
p-going side **Pb-going side**

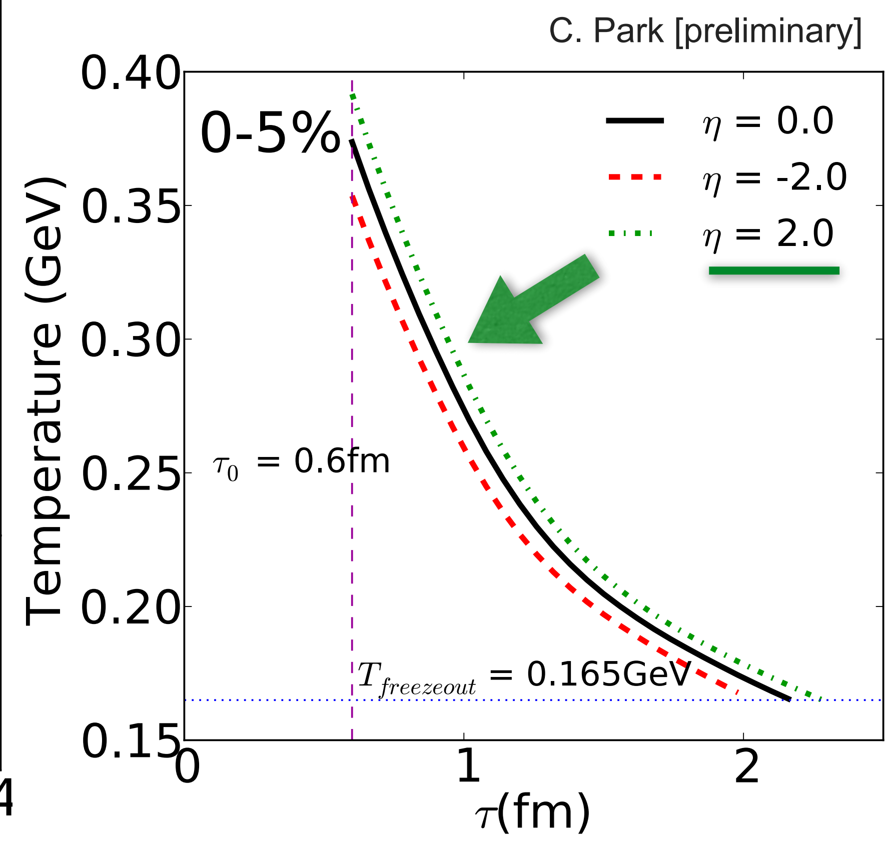


EPS09LO

Rapidity dependent energy loss

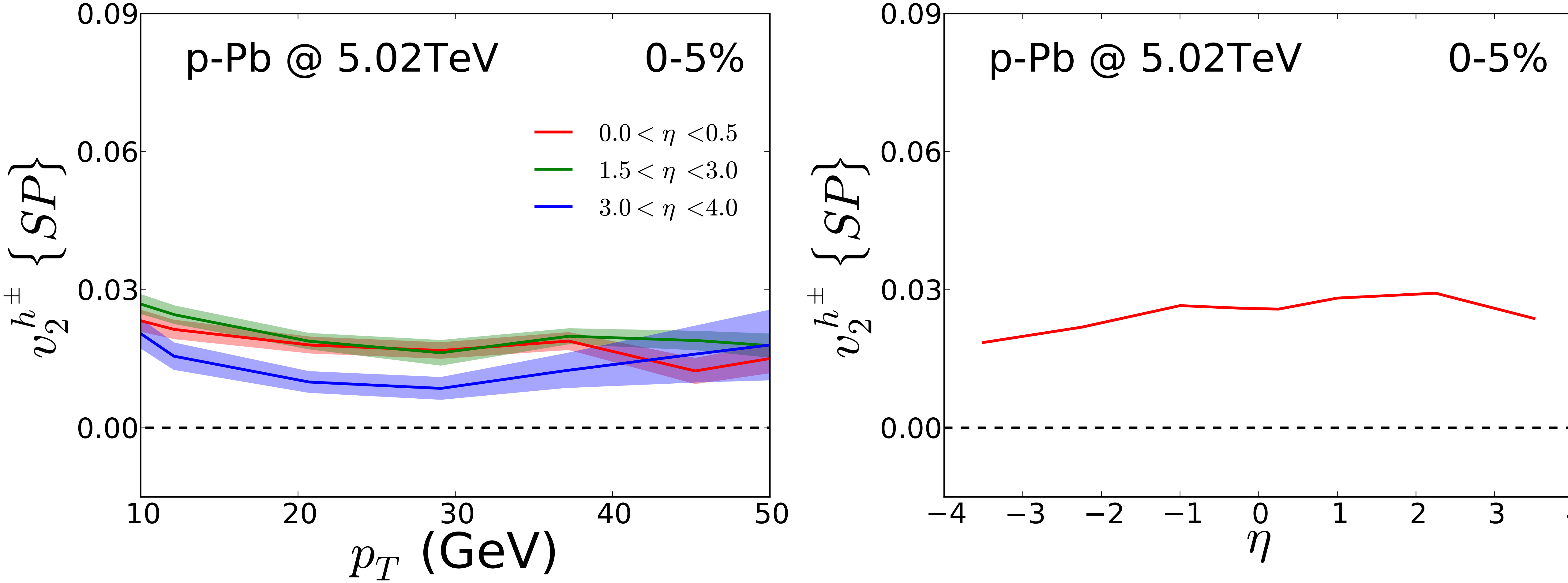
- Net QGP medium energy loss related to temperature and energy
  - a clear signature of QGP droplet in central collisions is predicted





Sizable medium induced energy loss due to high T

Charged hadron v_2 at high p_T



- Scalar product method; reference flow integrated from 0.3 - 3GeV
- 1~3% v_2 in central p-Pb collisions
- Medium induced energy loss dependency on integrated v_2

Conclusion

- Finite-size effect and running coupling for the radiation are essential to describe R_{AA} in large systems.
- A 3+1D medium in the small system offers the opportunity to study the key physics that governs different rapidity regimes. e.g. nPDF, isospin, and medium induced energy loss
- We predict sizable energy loss in central collisions of small systems due to the formation of the QGP droplet.
- We predict non-zero v_2 in central collisions of small systems having energy loss dependency.
    - Next work : jet reconstruction to find missing energy in small systems

Backup

AMY integral equation

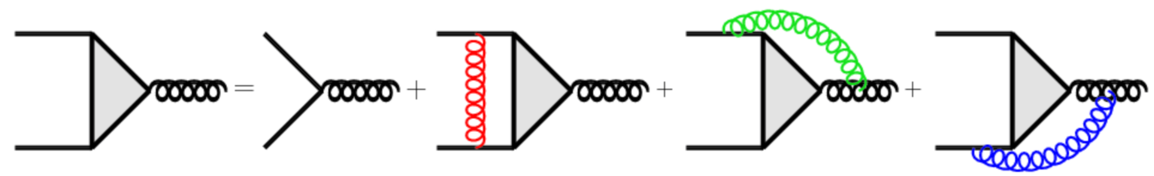


Image by G. Qin

Integral equation

$$2\mathbf{h} = i\delta E(\mathbf{h},p,k)\mathbf{F}(\mathbf{h}) + g_s^2 \int \frac{d^2\mathbf{q}_\perp}{(2\pi)^2} C(\mathbf{q}_\perp)\Big\{(C_s - C_A/2)[\mathbf{F}(\mathbf{h}) - \mathbf{F}(\mathbf{h} - k\mathbf{q}_\perp)] + (C_A/2)[\mathbf{F}(\mathbf{h}) - \mathbf{F}(\mathbf{h} + P\mathbf{q}_\perp) + (C_s - C_A/2)[\mathbf{F}(\mathbf{h}) - \mathbf{F}(\mathbf{h} - (p-k)\mathbf{q}_\perp)]\Big\}$$

Differential rate to exchange q⊥

$$C(\mathbf{q}_\perp) = \frac{m_D^2}{\mathbf{q}_\perp^2(\mathbf{q}_\perp^2 + m_D^2)}, \quad m_D^2 = \frac{g_s^2 T^2}{6}(2N_c + N_f).$$

Energy difference **δ**E

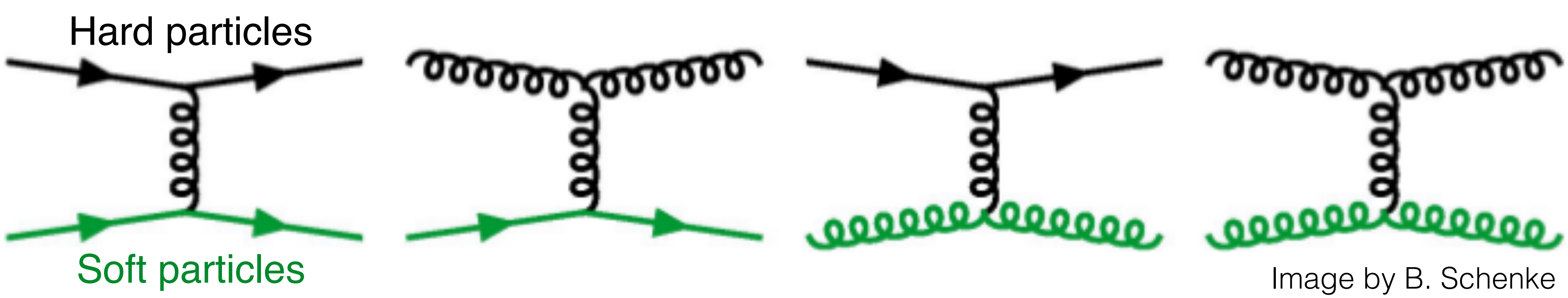
$$\delta E(\mathbf{h},p,k) = \frac{\mathbf{h}^2}{2pk(p-k)} + \frac{m_k^2}{2k} + \frac{m_{p-k}^2}{2(p-k)} - \frac{m_p^2}{2p}$$

AMY radiative rate

$$\frac{d\Gamma(p,k)}{dk} = \frac{C_s g_s^2}{16\pi p^7} \frac{1}{1 \pm e^{-k/T}} \frac{1}{1 \pm e^{-(p-k)/T}} \times \begin{Bmatrix} \frac{1+(1-x)^2}{x^3(1-x)^2} & q \to qg \\ N_f \frac{x^2+(1-x)^2}{x^2(1-x)^2} & g \to qq \\ \frac{1+x^4+(1-x)^4}{x^3(1-x)^3} & g \to gg \end{Bmatrix} \times \int \frac{d^2\mathbf{h}}{(2\pi)^2} 2\mathbf{h} \cdot \mathrm{Re}\, \mathbf{F}(\mathbf{h},p,k),$$

Collisional process

All the possible 2-2 scattering diagrams



Matrix elements

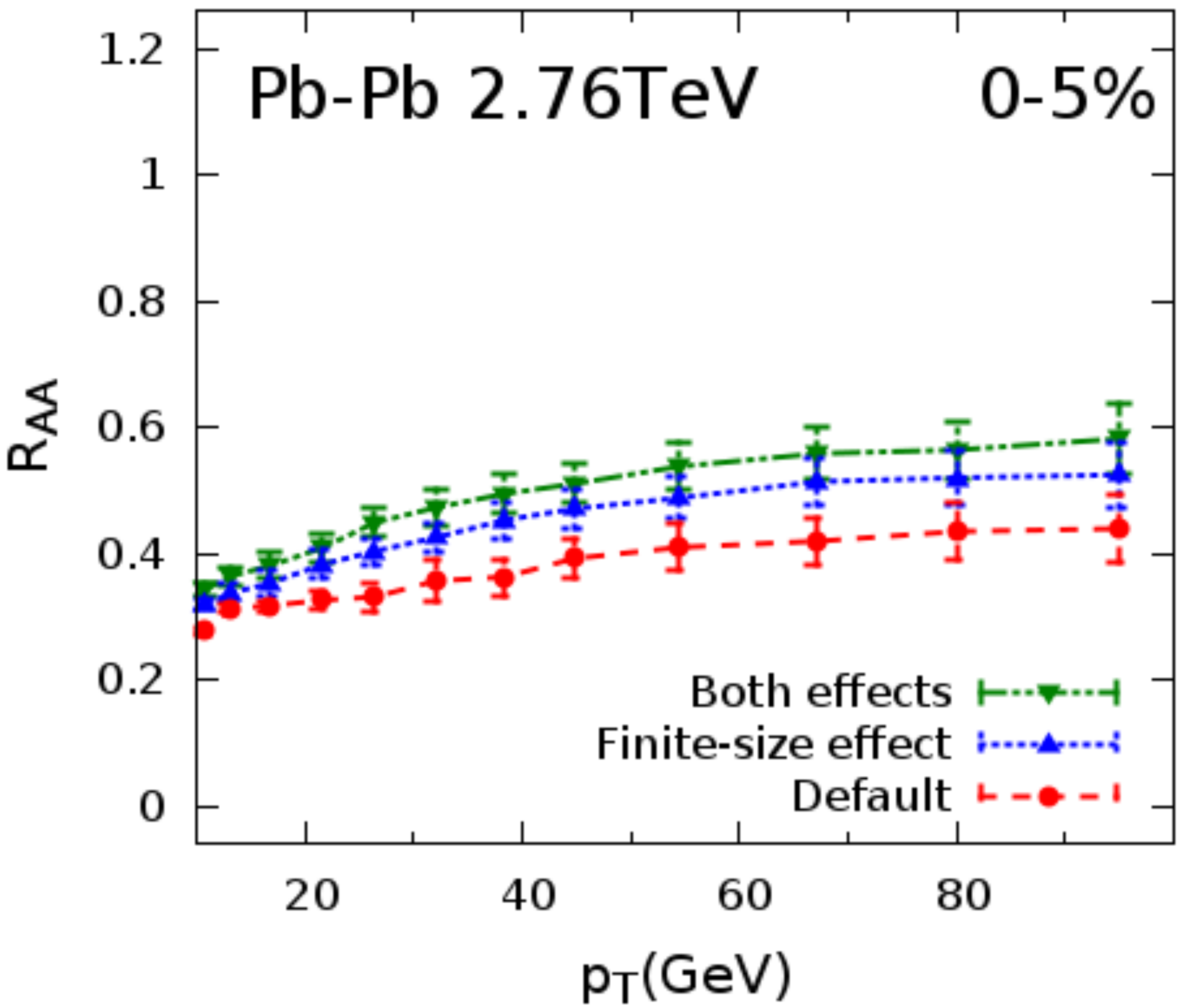
$$|\mathcal{M}|^2_{qq} = \frac{4}{9}g^4\frac{s^2+u^2}{t^2}, \qquad |\mathcal{M}|^2_{qg} = 2g^4\left(1-\frac{su}{t^2}\right),$$

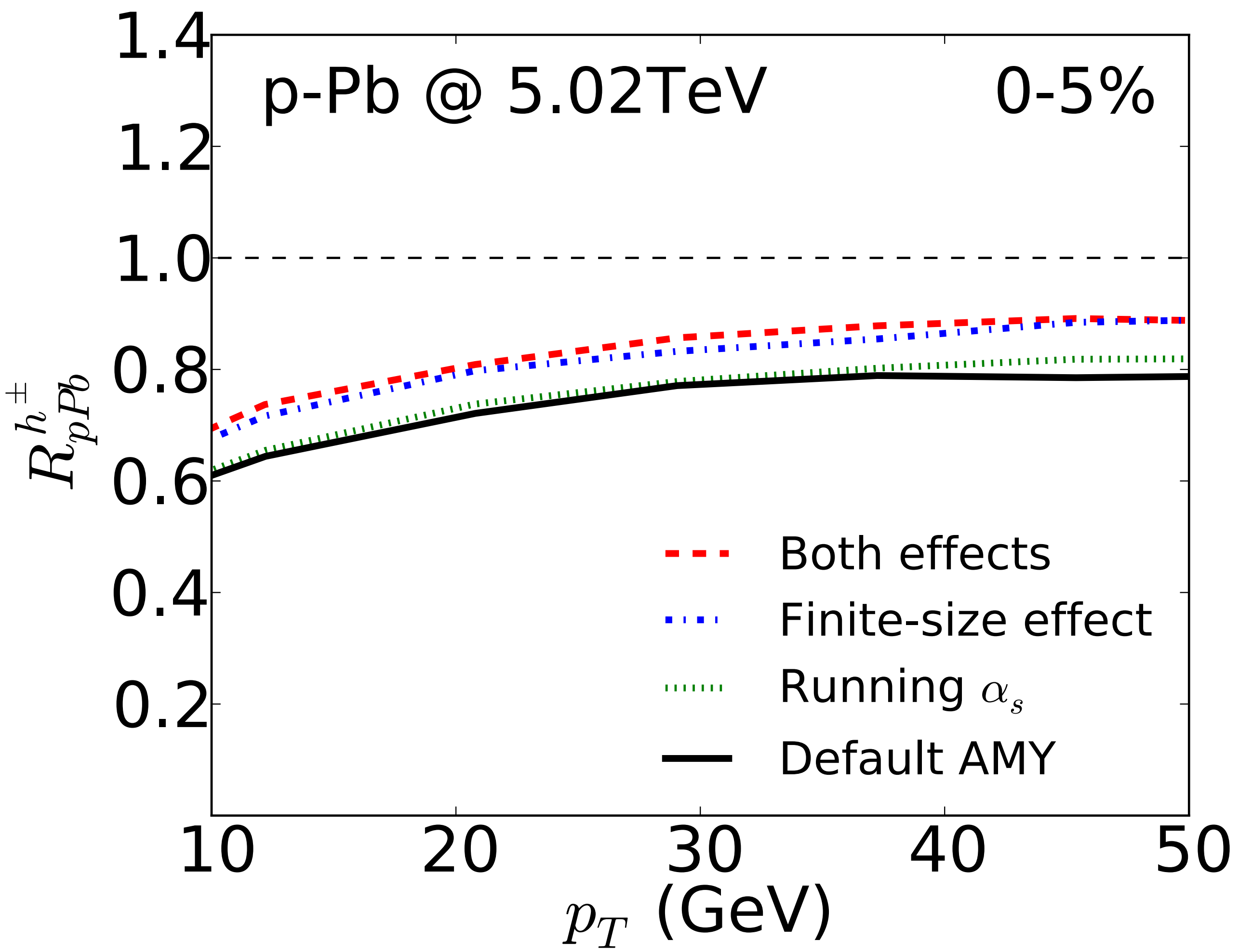
$$|\mathcal{M}|^2_{gq} = 2g^4\left(1-\frac{su}{t^2}\right), \qquad |\mathcal{M}|^2_{gg} = \frac{9}{2}g^4\left(\frac{17}{8}-\frac{su}{t^2}\right)$$

2-2 scattering rate

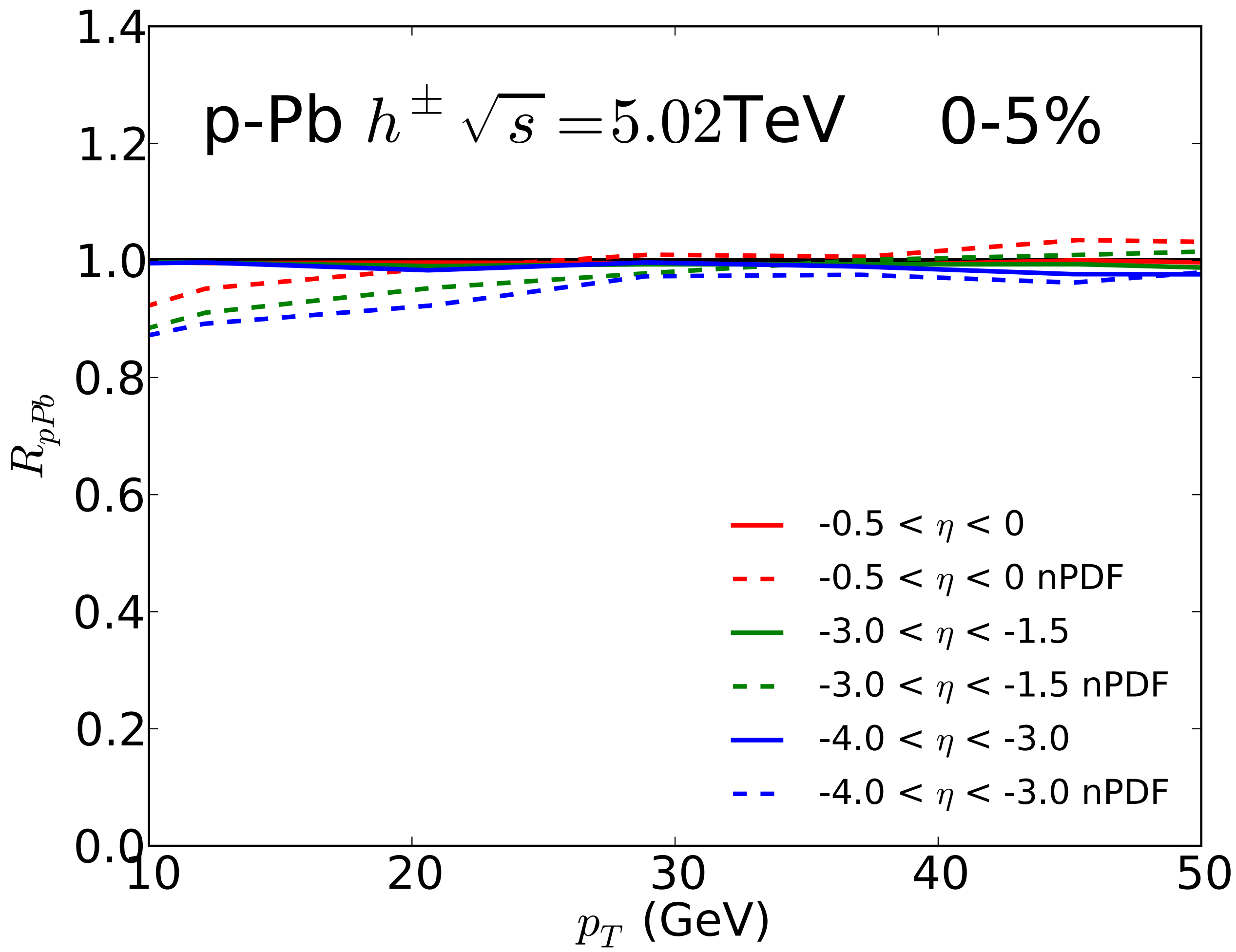
$$\frac{d\Gamma_{\rm el}}{d\omega}(E,\omega,T) = d_k\int_{kk'}\frac{2\pi}{4pp'}\delta(p-p'-\omega)\delta(k'-k-\omega) \times |\mathcal{M}|^2 f(k,T)(1\pm f(k',T)),$$

Finite-size effects & running coupling

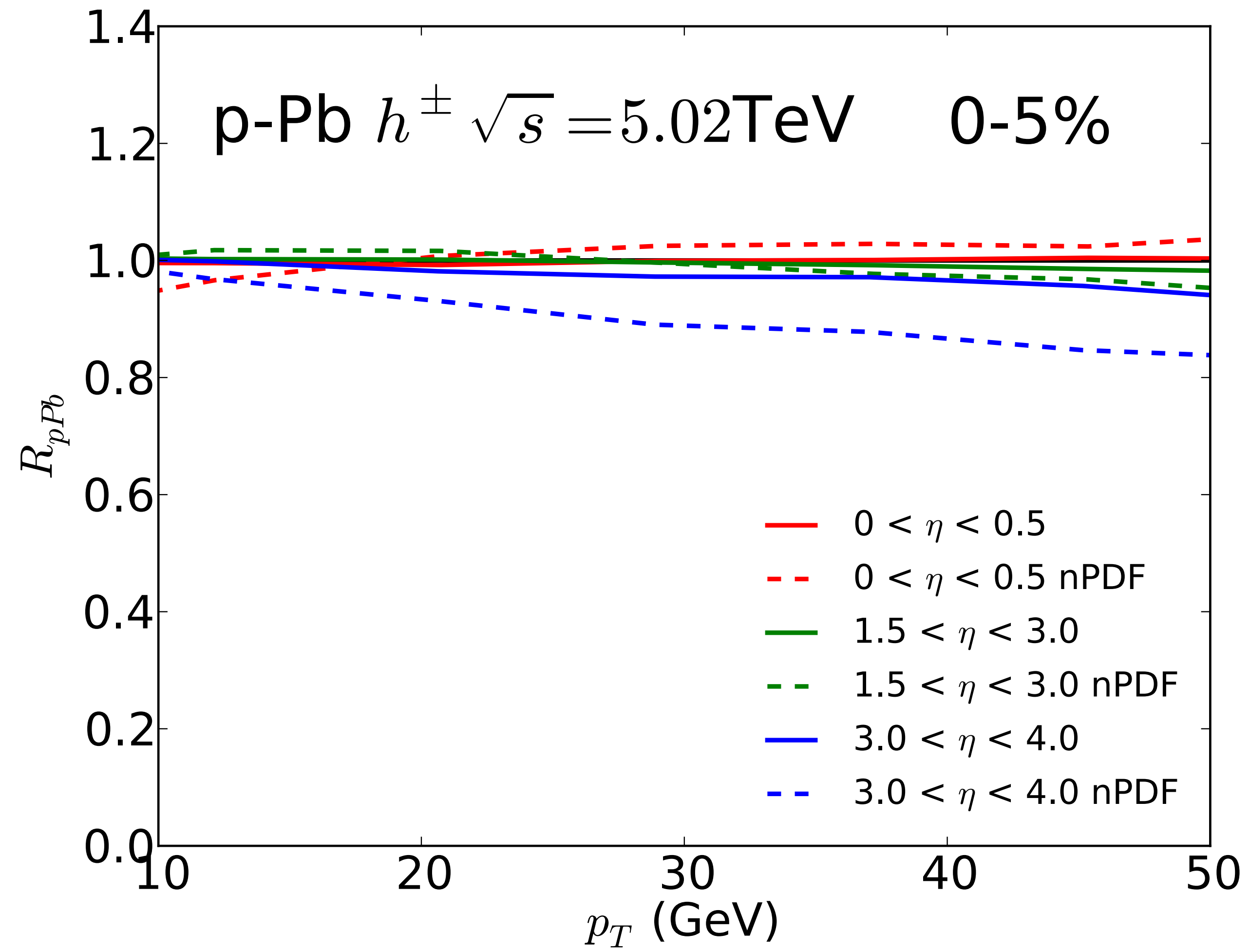




Isospin & nuclear PDF



p-going side



Pb-going side