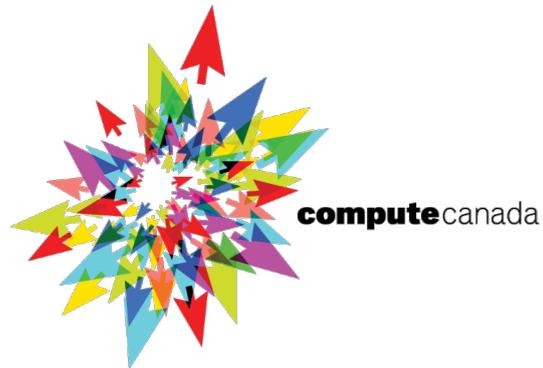


Jet modification with medium recoil in quark-gluon plasma

Chanwook Park

Collaboration with S. Jeon, C. Gale

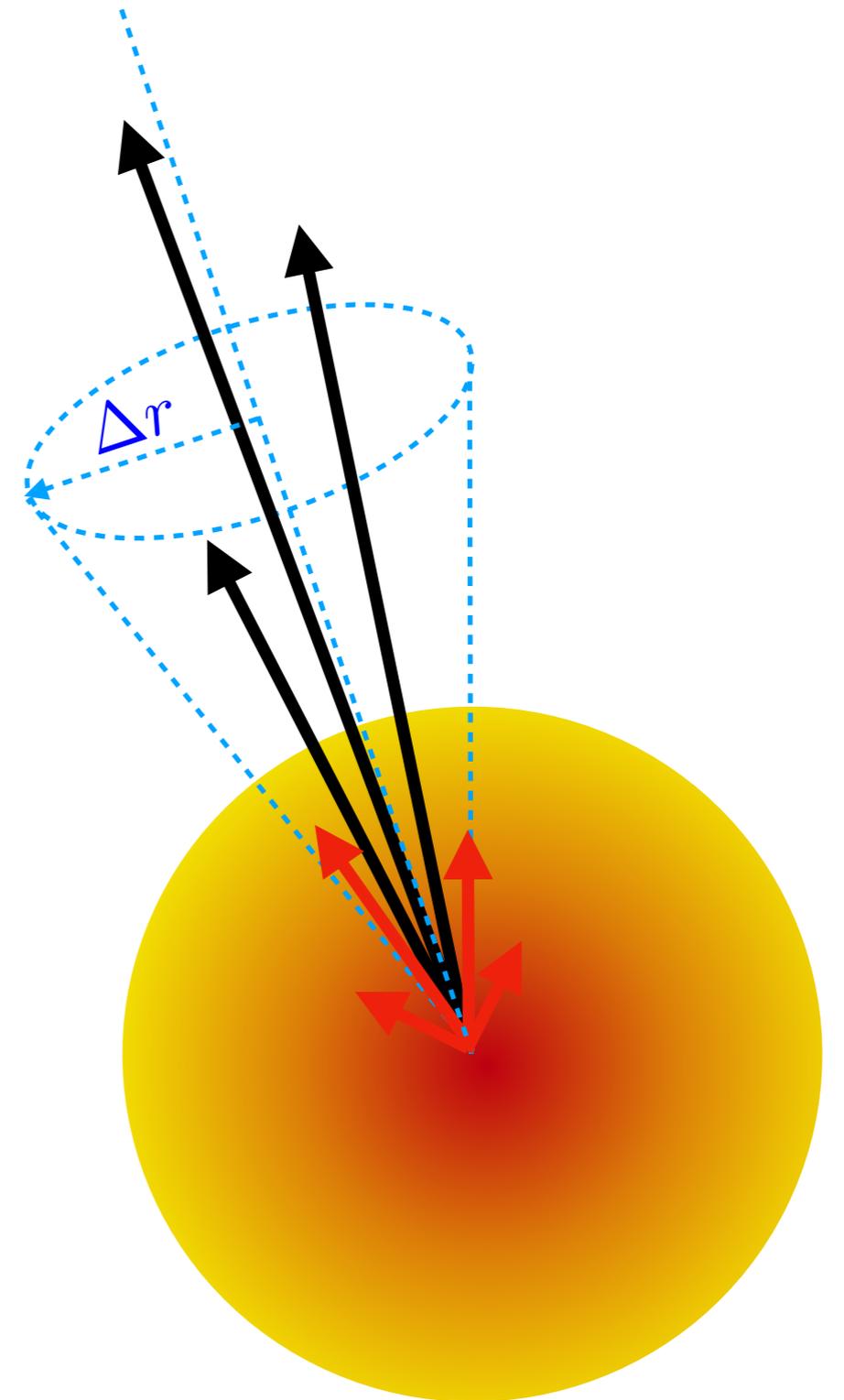


16 May 2018



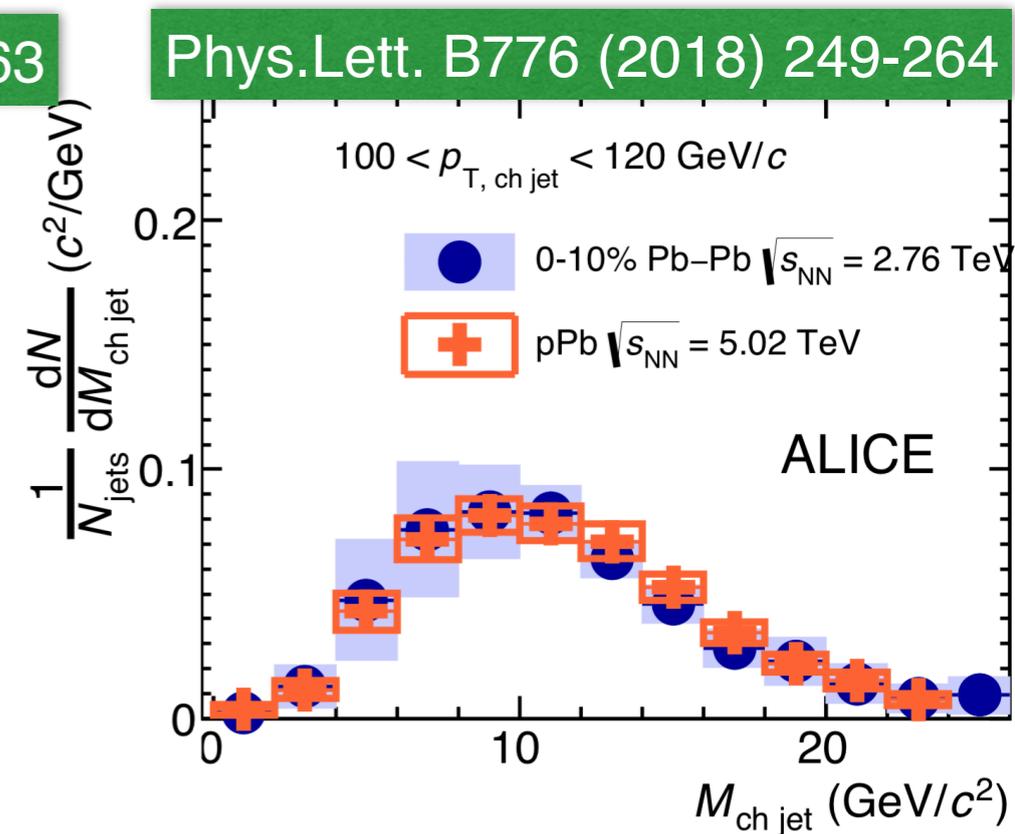
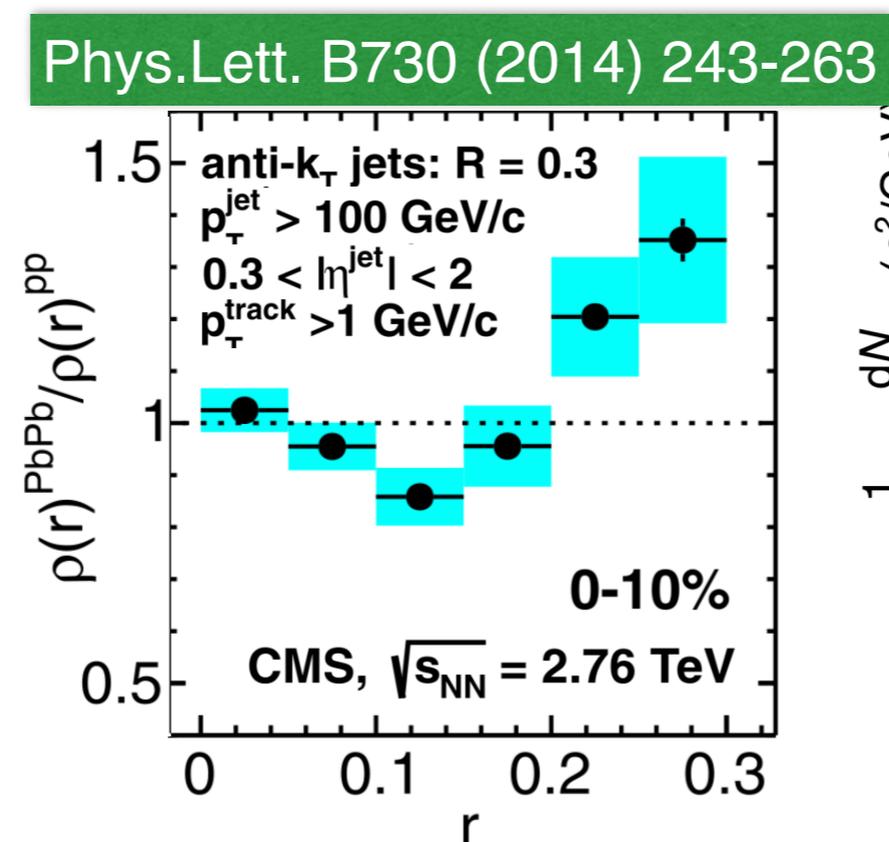
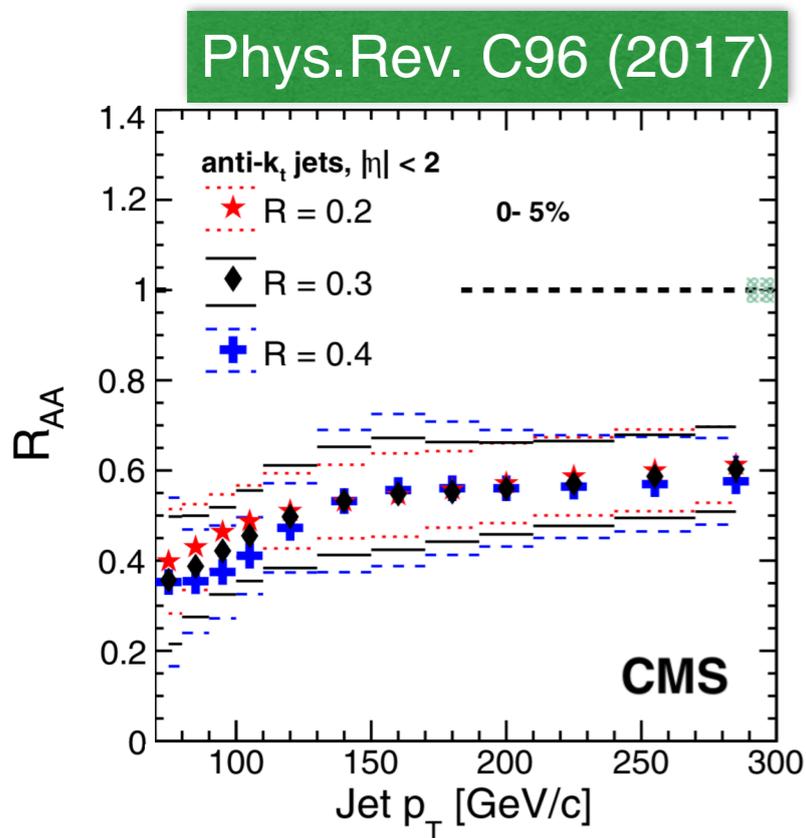
Why we need medium recoil

- Jet and medium exchanges energy-momentum.
- Energy lost by energetic partons may still be within jet cone.
- Redistributed energy changes jet shape.
- Energy-momentum of the whole system should be conserved.



Where we can see medium recoil

- **Jet observables that are sensitive to medium recoil**
 - ✓ Jet R_{AA}
 - ✓ Jet shape
 - ✓ Jet mass
- ➔ Need to consider all energy-momentum in a jet cone.



Jet evolution in MARTINI

MARTINI¹

- ▶ Event generator for jet simulation in heavy ion collisions
- ▶ Compatible with event-by-event 3D hydrodynamic medium

- **Radiation** : AMY formalism² (collinear)

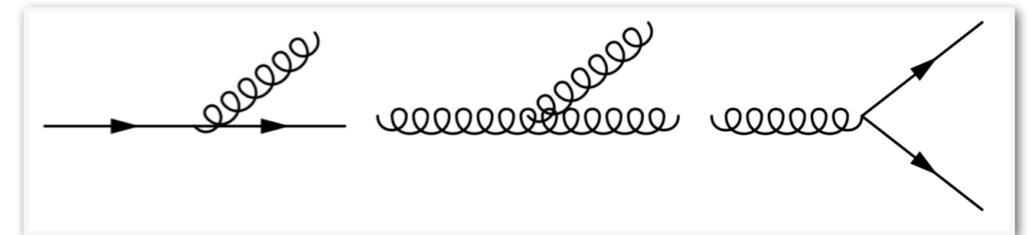
- ➔ Formation time of radiation³, $t_f \sim k/k_{\perp}^2$
- ➔ Running coupling in splitting vertex⁴, $\alpha_s(Q)$

- **Elastic Scattering**⁵

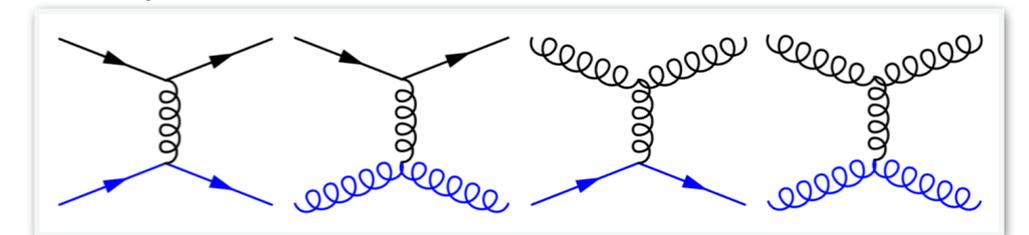
- ➔ 2-2 scattering causing space-like momentum transfer, q
- ➔ Momentum broadening

- **Conversion**¹

- ➔ quark-gluon, jet-photon, photon conversion



Hard particles



Soft particles

¹ B. Schenke, C. Gale, and S. Jeon, Phys. Rev. C **80**, 054913 (2009)

² P. Arnold, G. D. Moore, and L. G. Yaffe, JHEP **0206** (2002) 030

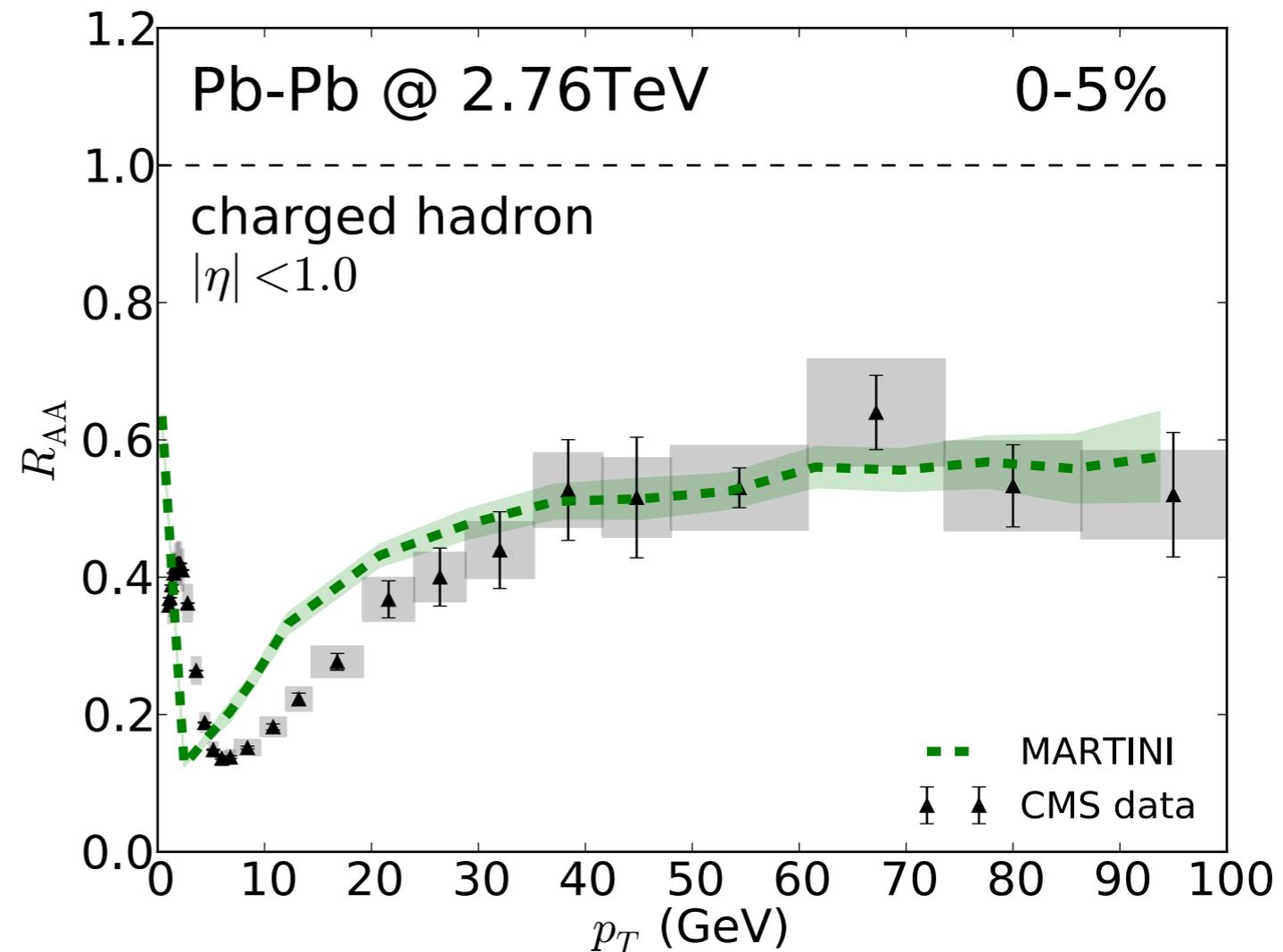
³ S. Caron-Huot and C. Gale, Phys. Rev. C **82**, 064902 (2010)

⁴ C. Young, B. Schenke, S. Jeon, and C. Gale, Nucl. Phys. A **910-911**, 494 (2013)

⁵ B. Schenke, C. Gale, and G-Y. Qin, Phys. Rev. C **79**, 054908 (2009)

Leading hadron dynamics

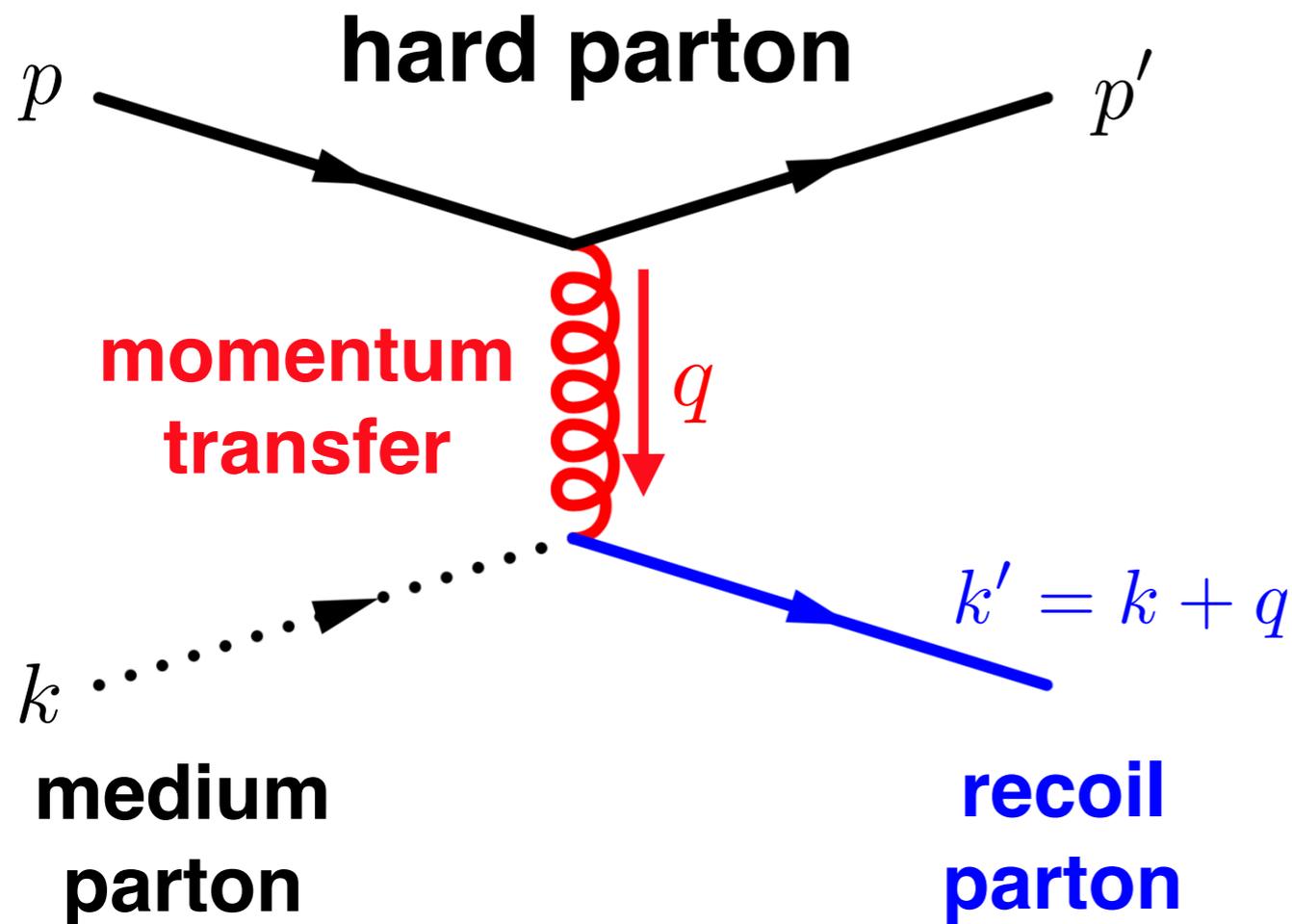
- IP-Glasma I.C.¹
+ e-by-e 3D hydrodynamics²
+ MARTINI jet energy loss
- ➔ Compute charged hadron R_{AA}
- ➔ Validated event generator to study medium recoil.



¹ IP-Glasma provided by Scott McDonald

² Hydro provided by Mayank Singh

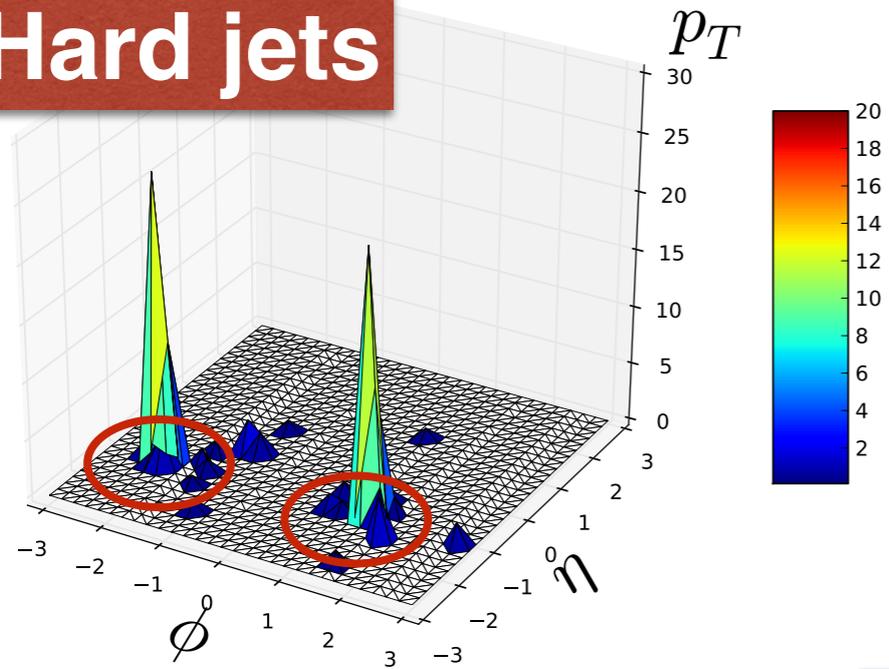
Recoil in MARTINI



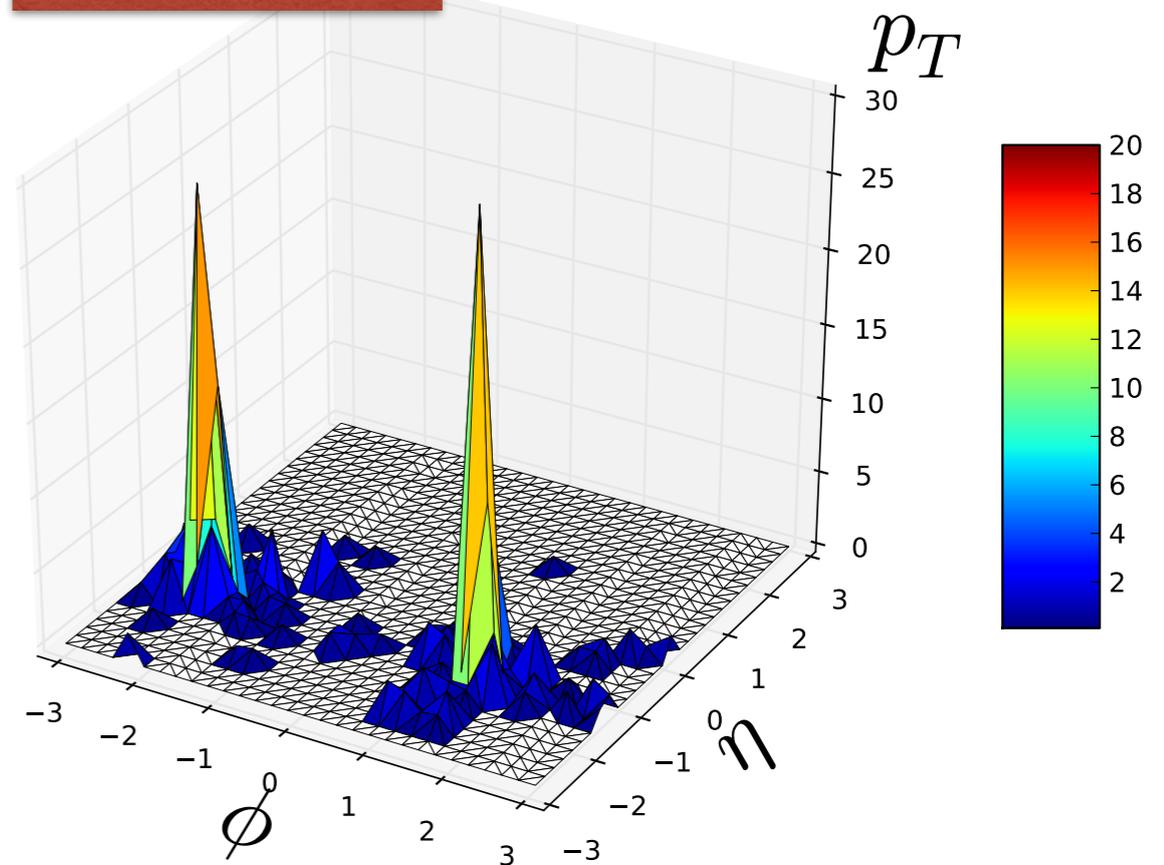
- Once q is sampled, k is sampled in a way that k' satisfies on-shell condition.
- If $k' > p_{cut}$:
 $k' \Rightarrow$ promoted to a recoil parton.
- Recoil partons can **fully participate in jet-medium interactions**.

Recoil in MARTINI

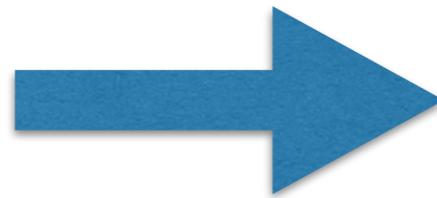
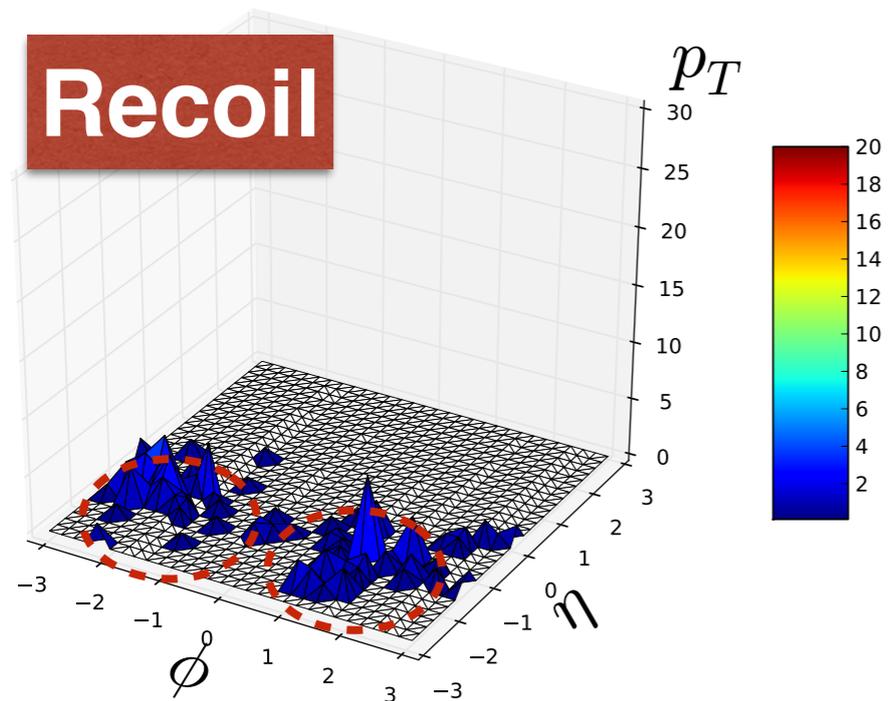
Hard jets



Full jets



Recoil

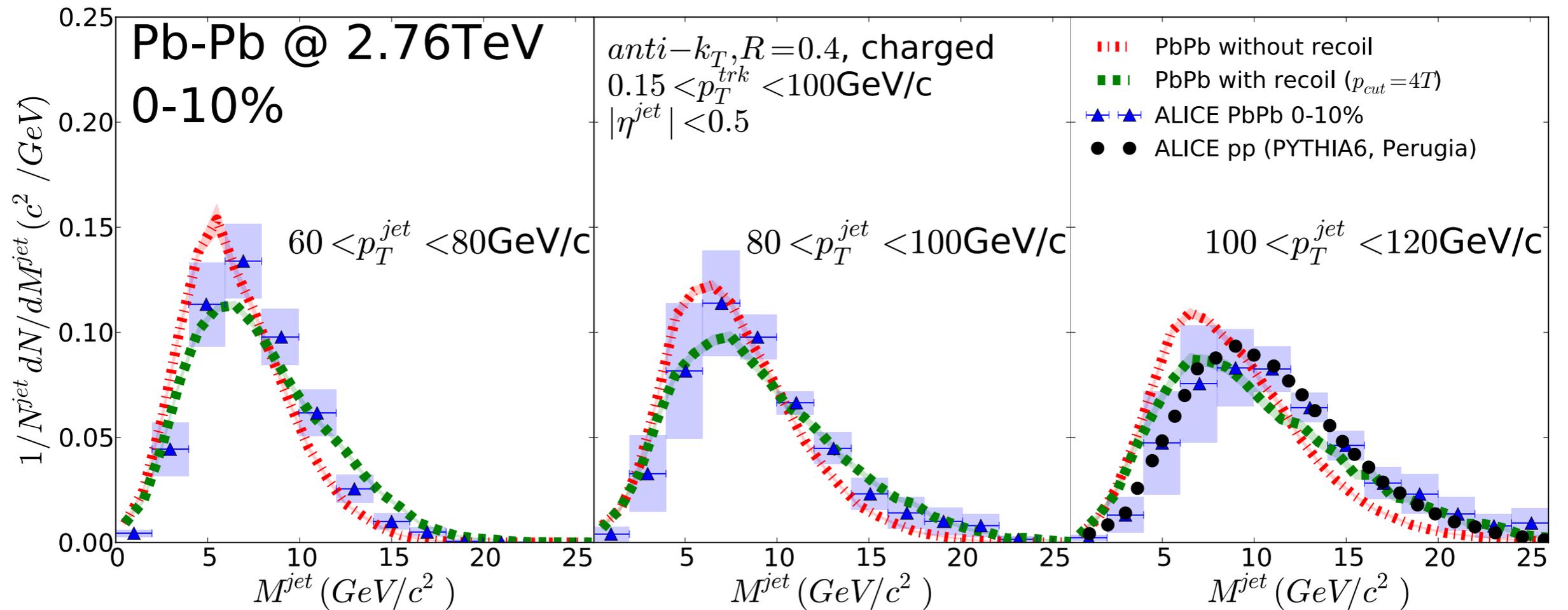


Recoil in MARTINI

- **Typical kinematic cut**, $p_{cut} \simeq 4T$
 - ➔ Lower bound for the AMY framework.
- **Missing contributions :**
 1. Recoil $k' < 4T$?
 2. Missing medium energy k ?
 - ➔ Should be treated as sources of medium response.

Ongoing work!

Jet mass with recoil



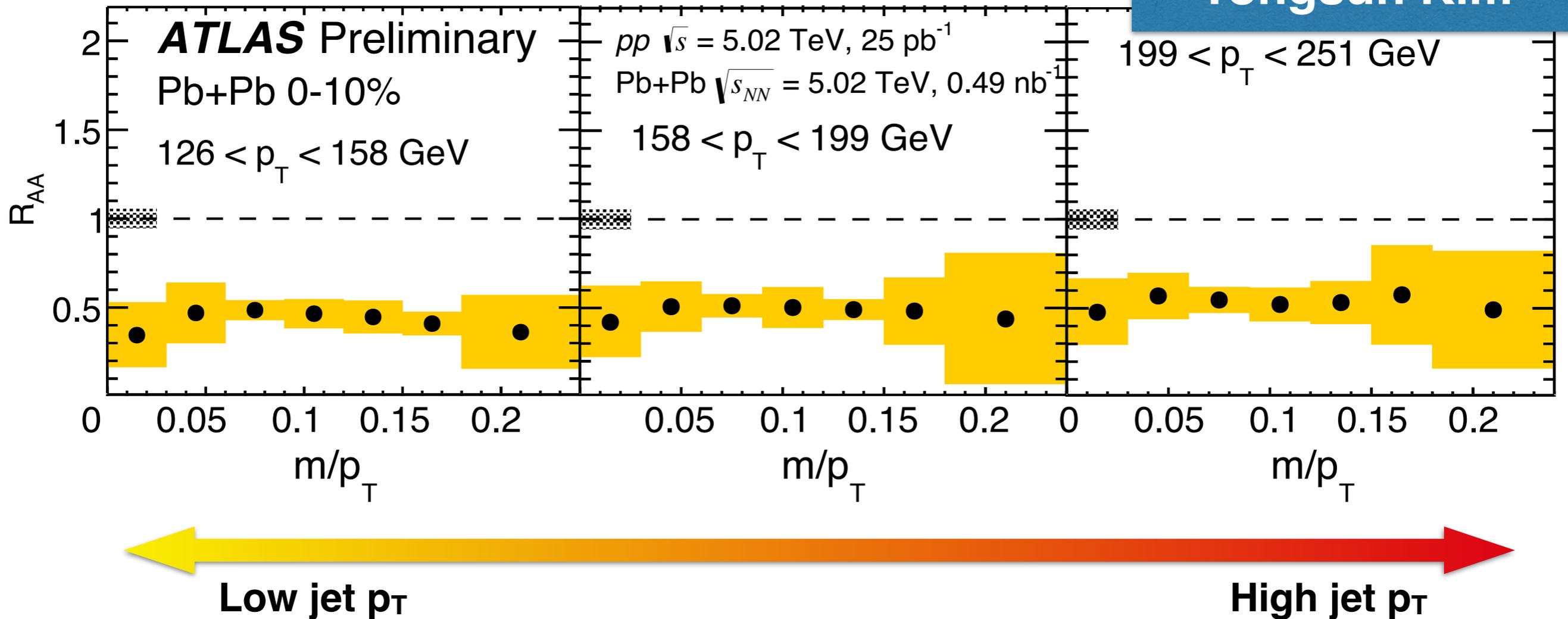
Low jet p_T

High jet p_T

- Two competing effects : Decrease by jet quenching
+ Increase by including recoil
- Competing effects result in small deviation on the jet mass distribution

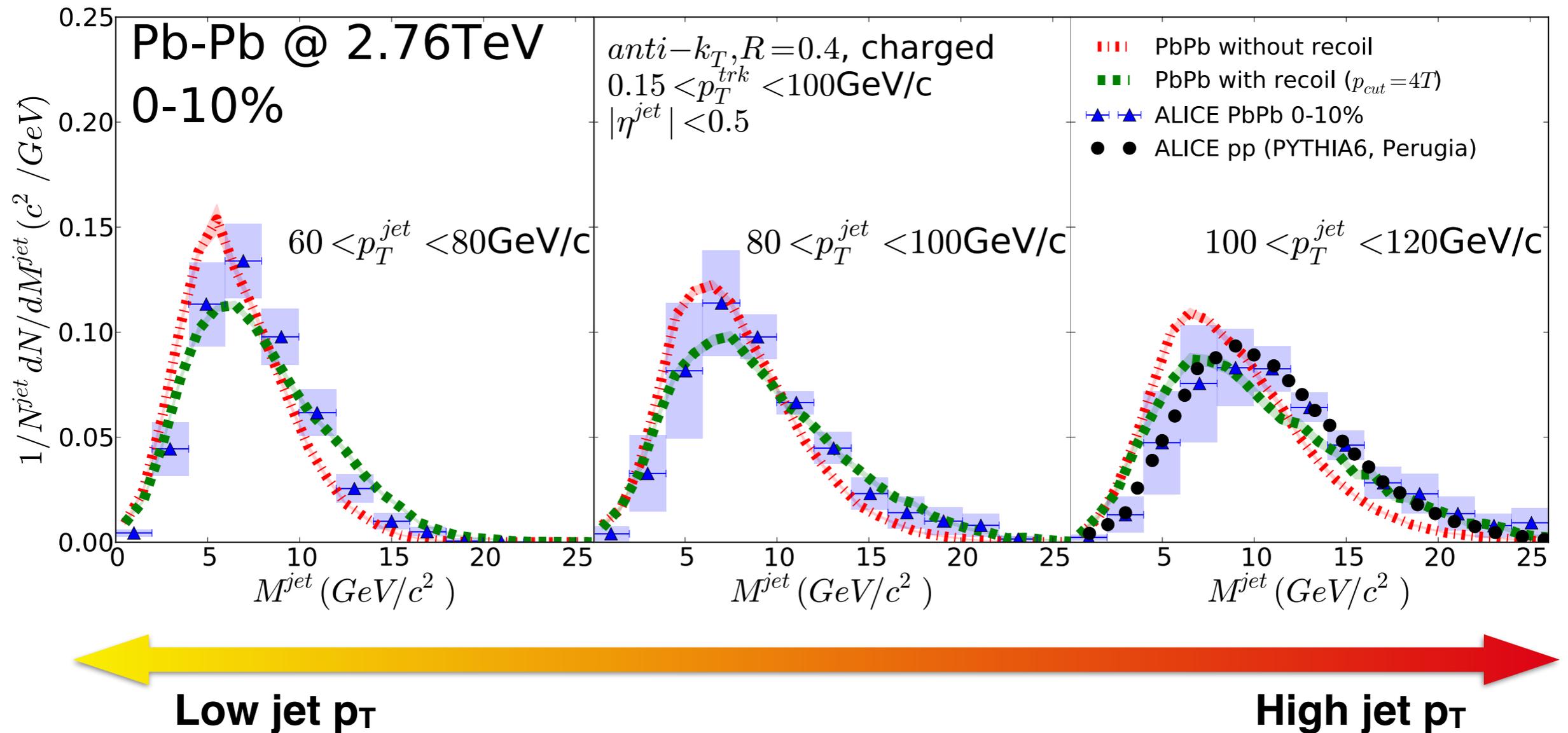
Jet mass with recoil

Poster JET-16 by
Yongsun Kim



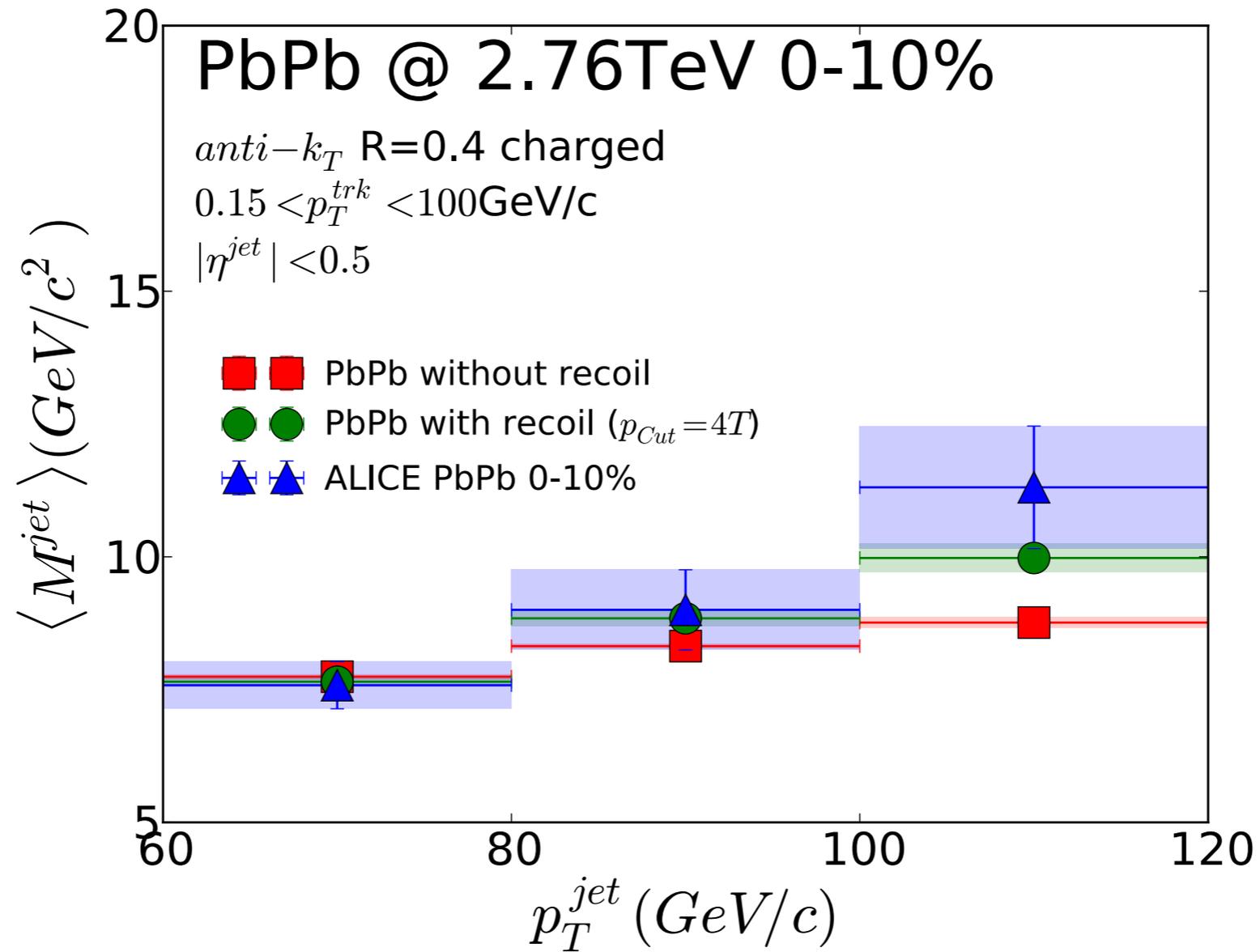
- Two competing effects : Decrease by jet quenching
+ Increase by including recoil
- Net effect yields jet R_{AA} weakly depending on invariant jet mass.

Jet mass with recoil



- Two competing effects : Decrease by jet quenching
+ Increase by including recoil
- Recoil affects on the jet mass.

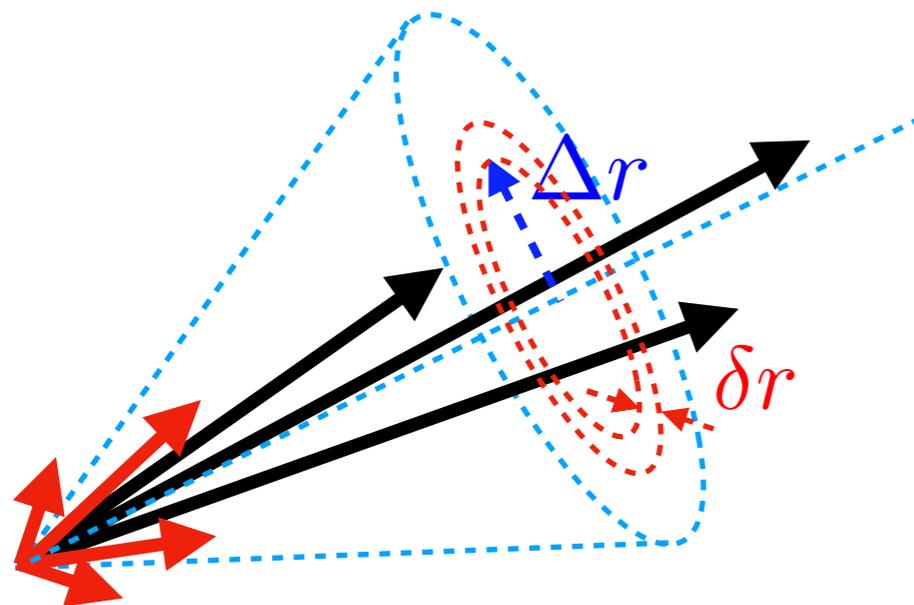
Jet mass with recoil



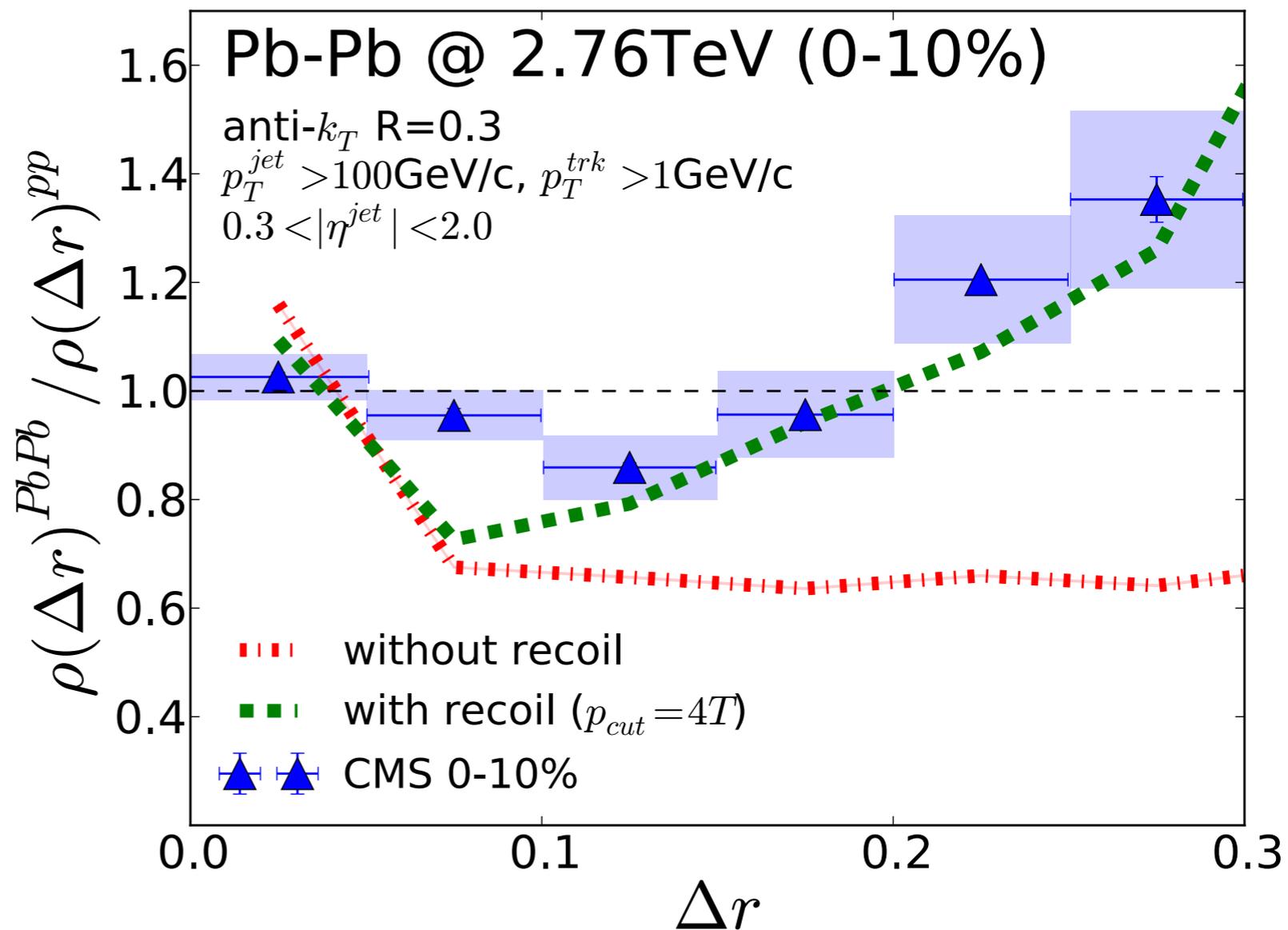
- Recoil on/off are almost same at low p_T ; they become well separated at higher p_T .
- Recoil helps the jet mass get enough enhancement at higher p_T .

Jet shape with recoil

$$\rho(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{jet}} \sum_{jet} \frac{\sum_{track \in [\Delta r - \delta r/2, \Delta r + \delta r/2)} p_T^{track}}{p_T^{jet}}$$

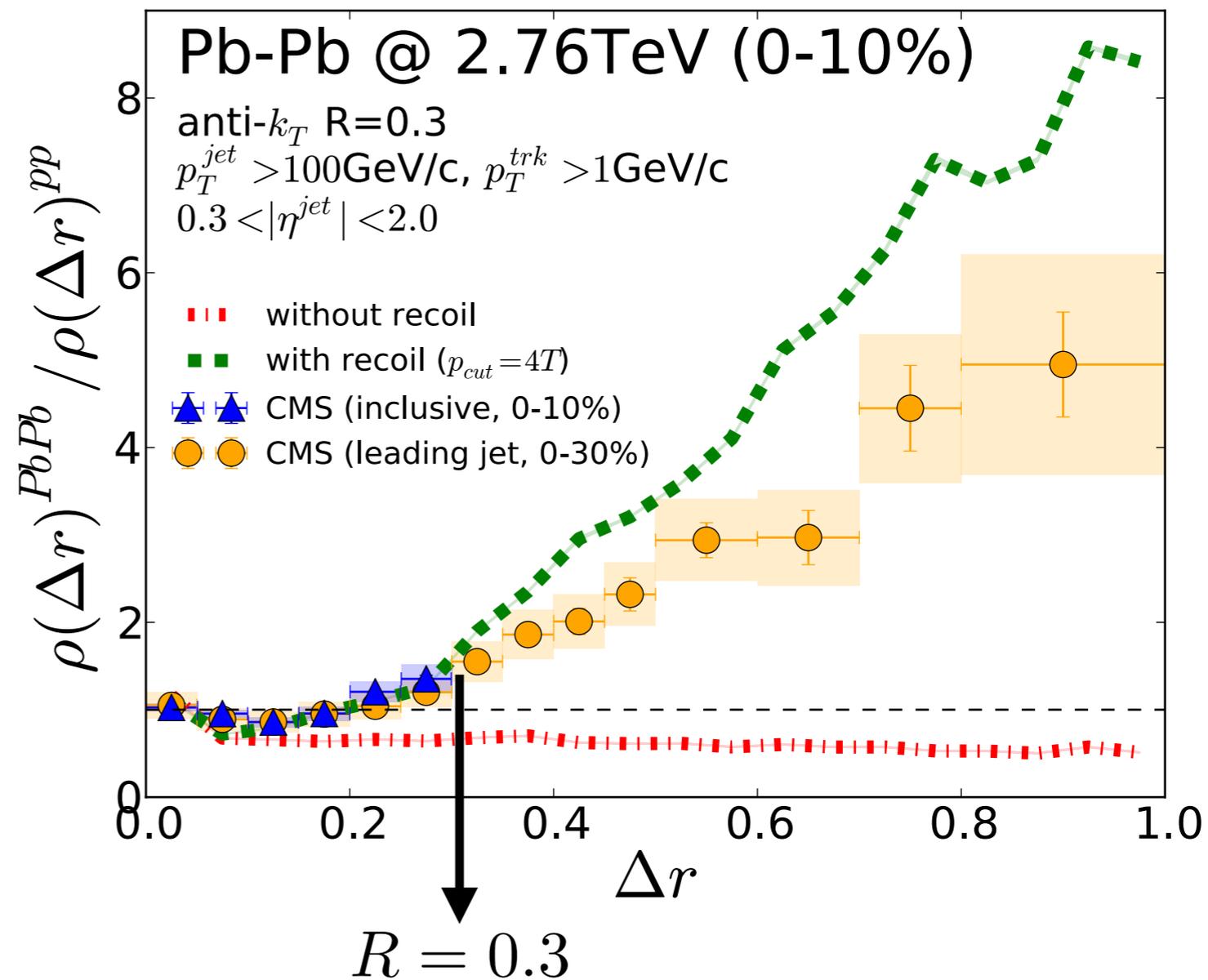


- The ratio shows flat shape without recoil.
- Recoil yields a significant contribution to the jet shape at large angles.



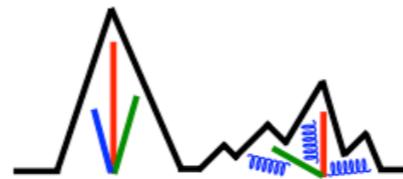
Jet shape with recoil

- Jet shape with $\Delta r \leq 1$:
(*caveat*) naive comparison to data.
- Theory shows a rising trend for the ratio.
- Medium response ($< 4T$) would affect at out-of-cone region more.



Conclusion

- Medium recoil plays an important role in describing jet structure observables.
- Recoil significantly contributes to the jet shape at larger angles.
- **MARTINI** with recoil can reproduce the measured jet shape and jet mass.
- Future work : Incorporating medium response for contribution below p_{cut} .



- **MARTINI** is included in the **JETSCAPE** framework.

Backup

AMY integral equation

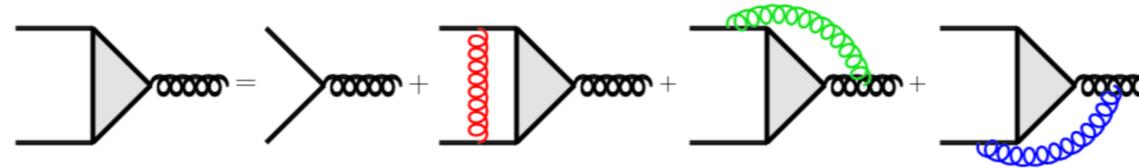


Image by G. Qin

Integral equation

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

Differential rate to exchange \mathbf{q}_\perp

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

Energy difference δE

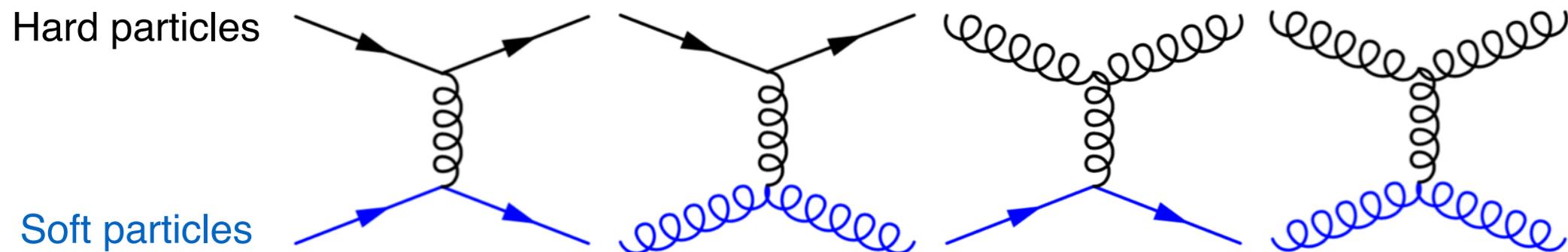
$$\delta E(\mathbf{h}, p, k) = \frac{\mathbf{h}^2}{2pk(p - k)} + \frac{m_k^2}{2k} + \frac{m_{p-k}^2}{2(p - k)} - \frac{m_p^2}{2p}$$

AMY radiative rate

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

Collisional process

All the possible 2-2 scattering diagrams



Matrix elements

$$|\mathcal{M}|_{qq}^2 = \frac{4}{9}g^4 \frac{s^2 + u^2}{t^2},$$

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

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

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

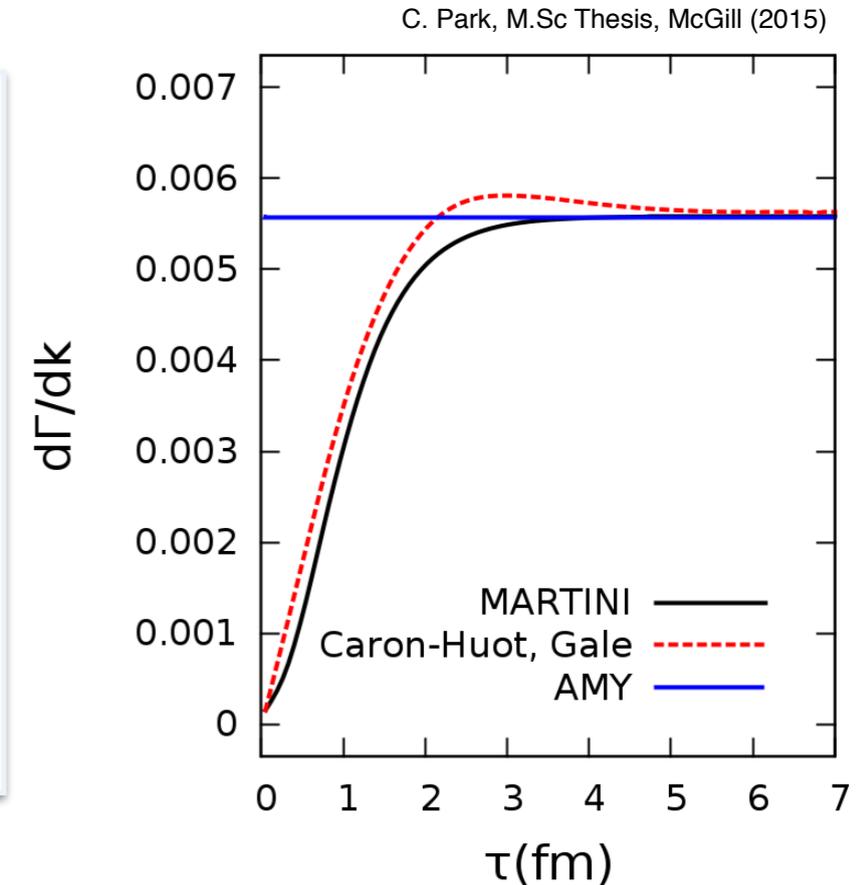
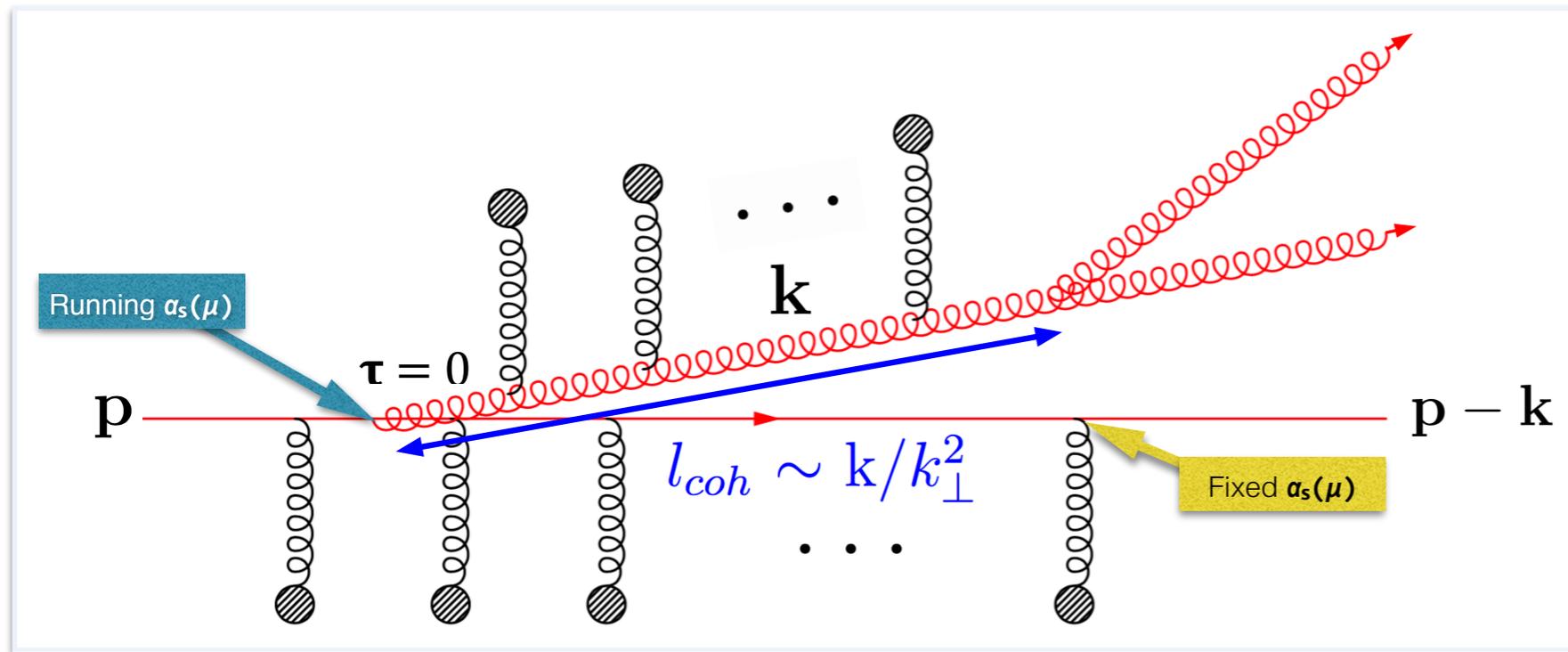
2-2 scattering rate

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

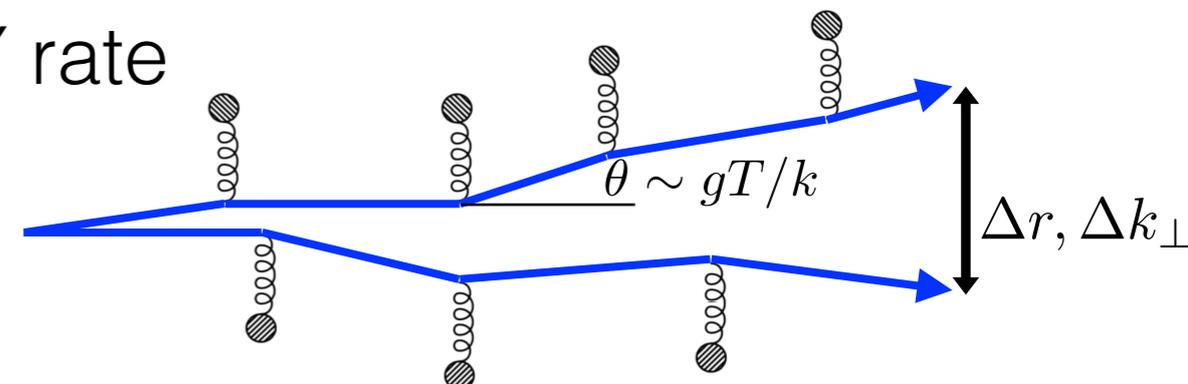
New developments in MARTINI

- Finite-size effects on radiation

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



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



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

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

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

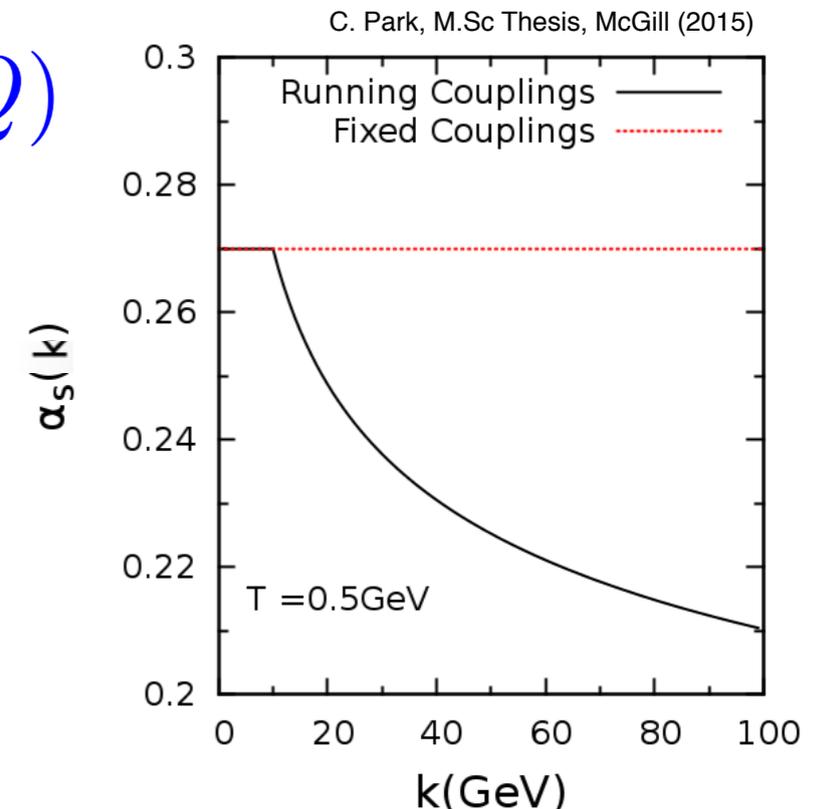
- g_s^2 : Gluon radiation vertex $\rightarrow g_s^2 = 4\pi\alpha_s(Q)$

- In MARTINI, $Q \sim \langle |k_\perp| \rangle = (\hat{q}k)^{\frac{1}{4}}$

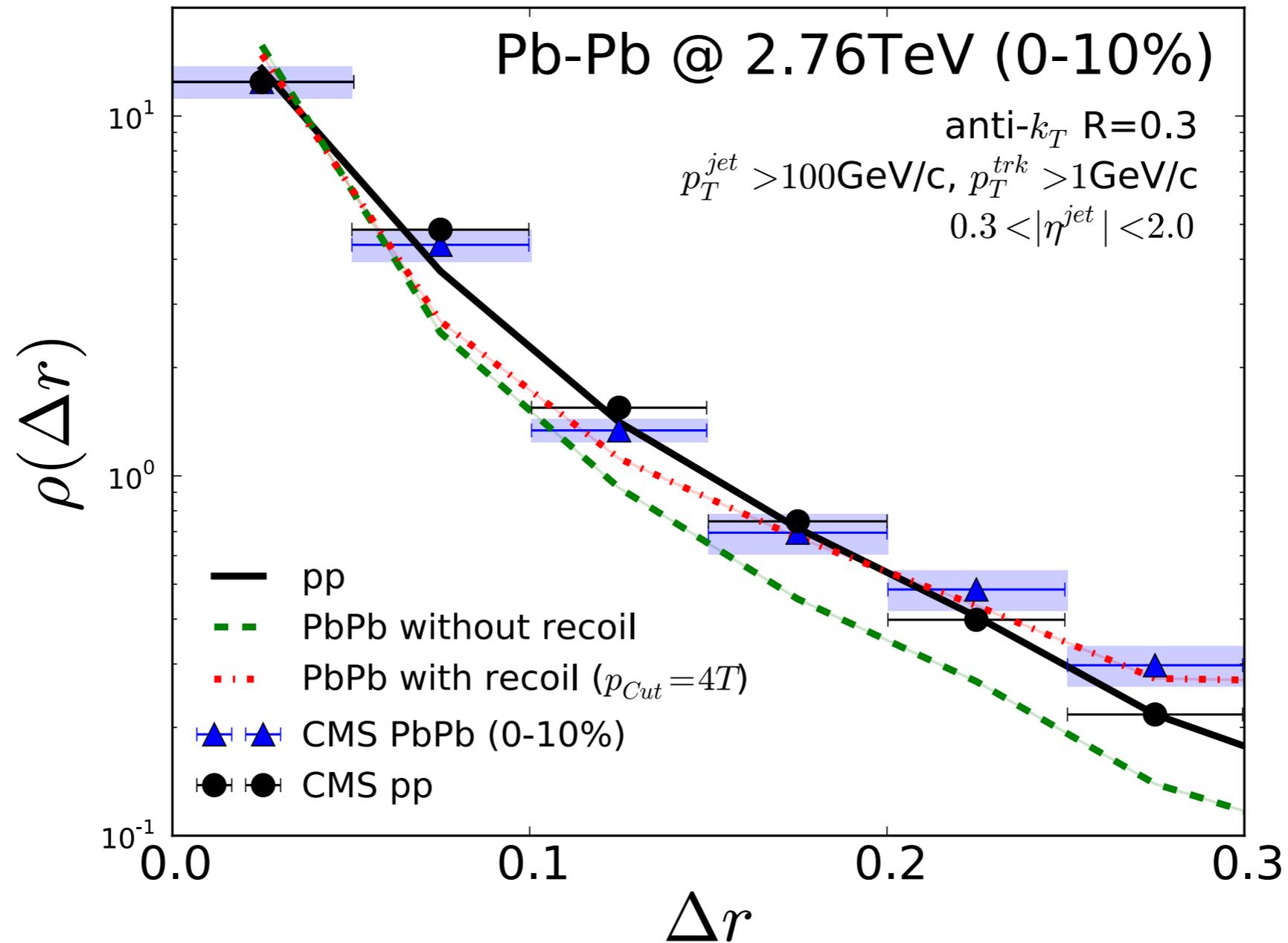
$$\langle k_\perp^2 \rangle = \hat{q}l_{coh}$$

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

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

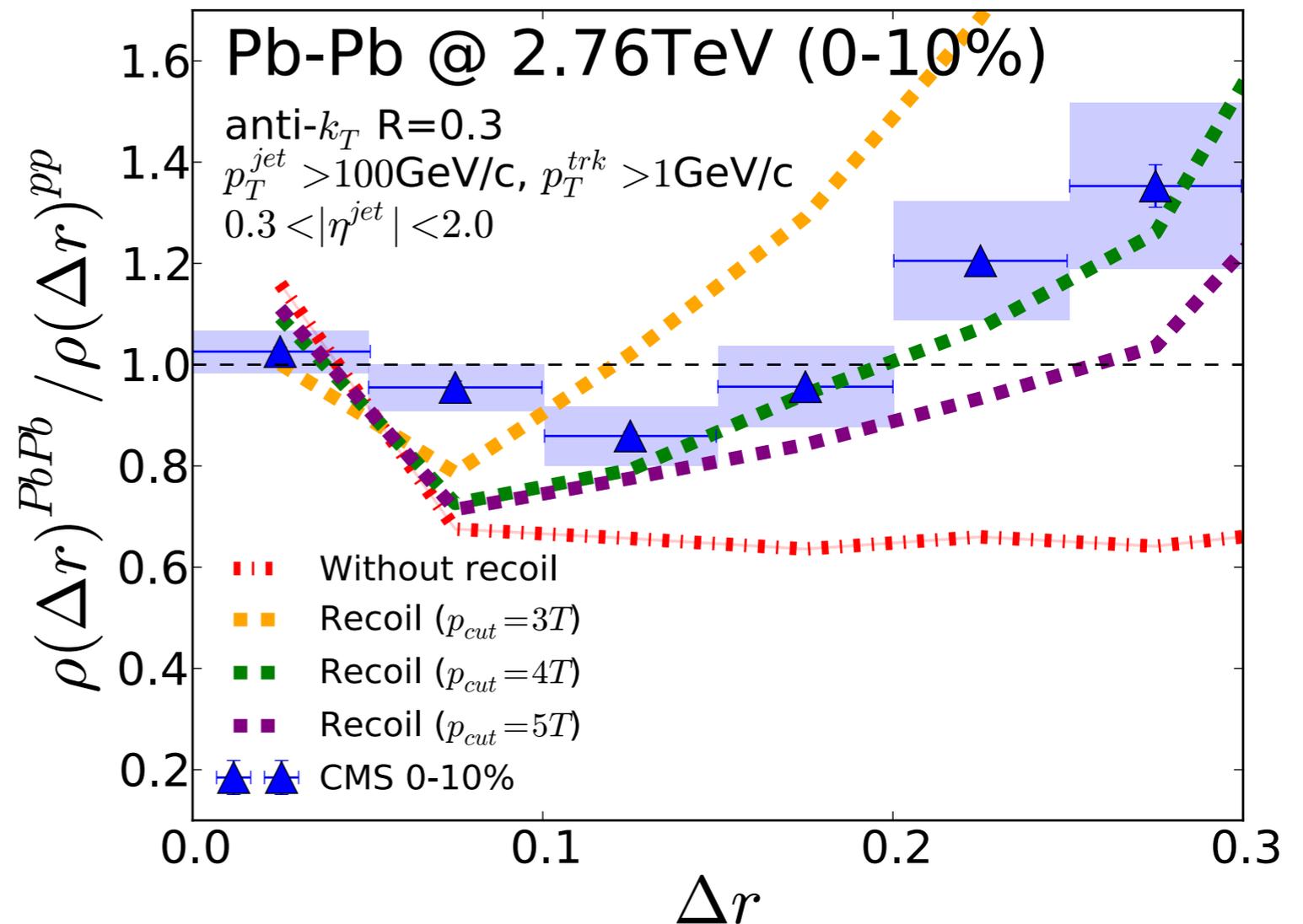


Jet shape spectrum with recoil



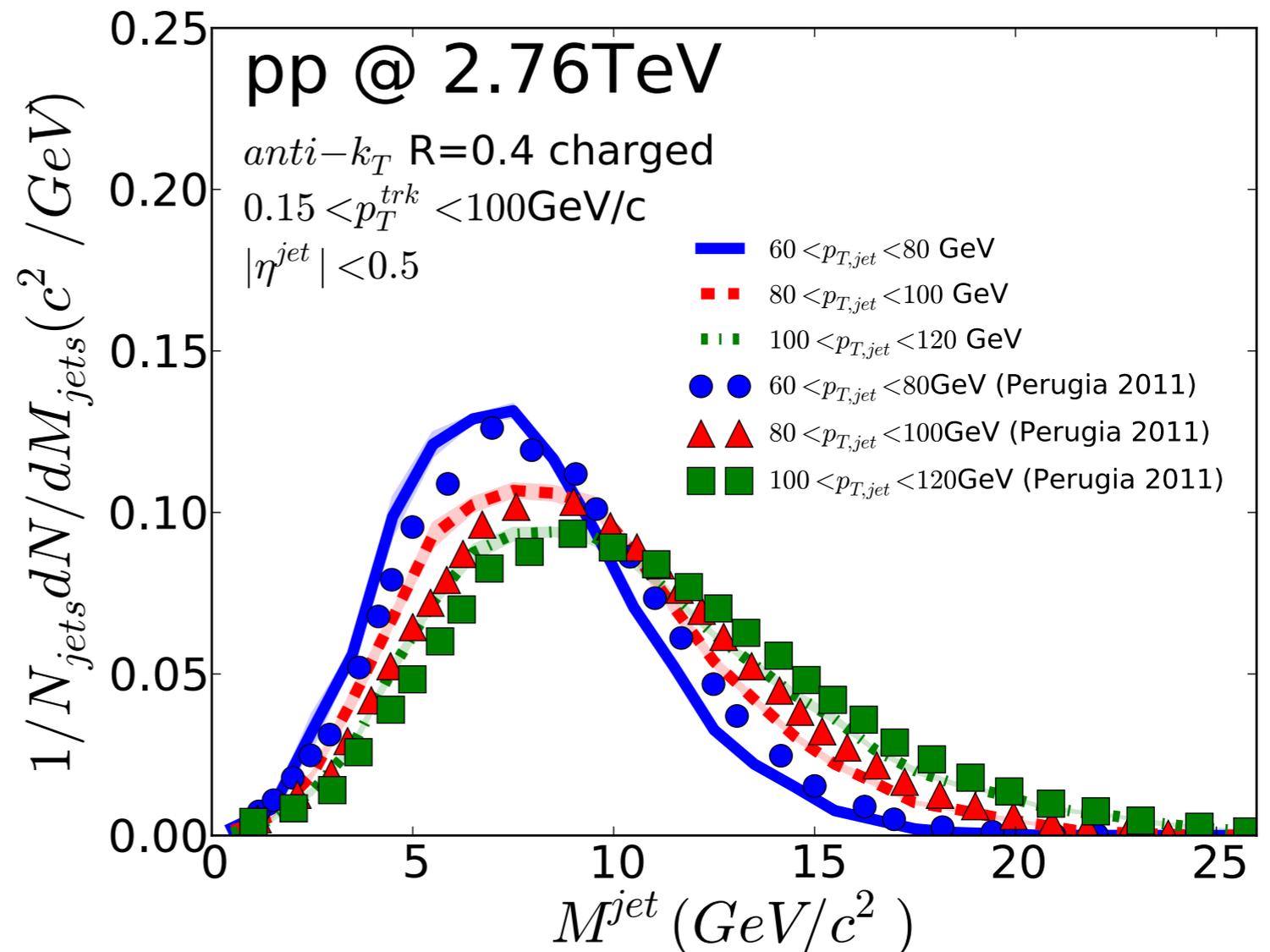
Jet shape spectrum with recoil

- Looks sensitive to p_{cut} .
- Compensated by medium response part.
- 3T: Smaller contribution from medium response.
- 5T: Larger contribution from medium response.

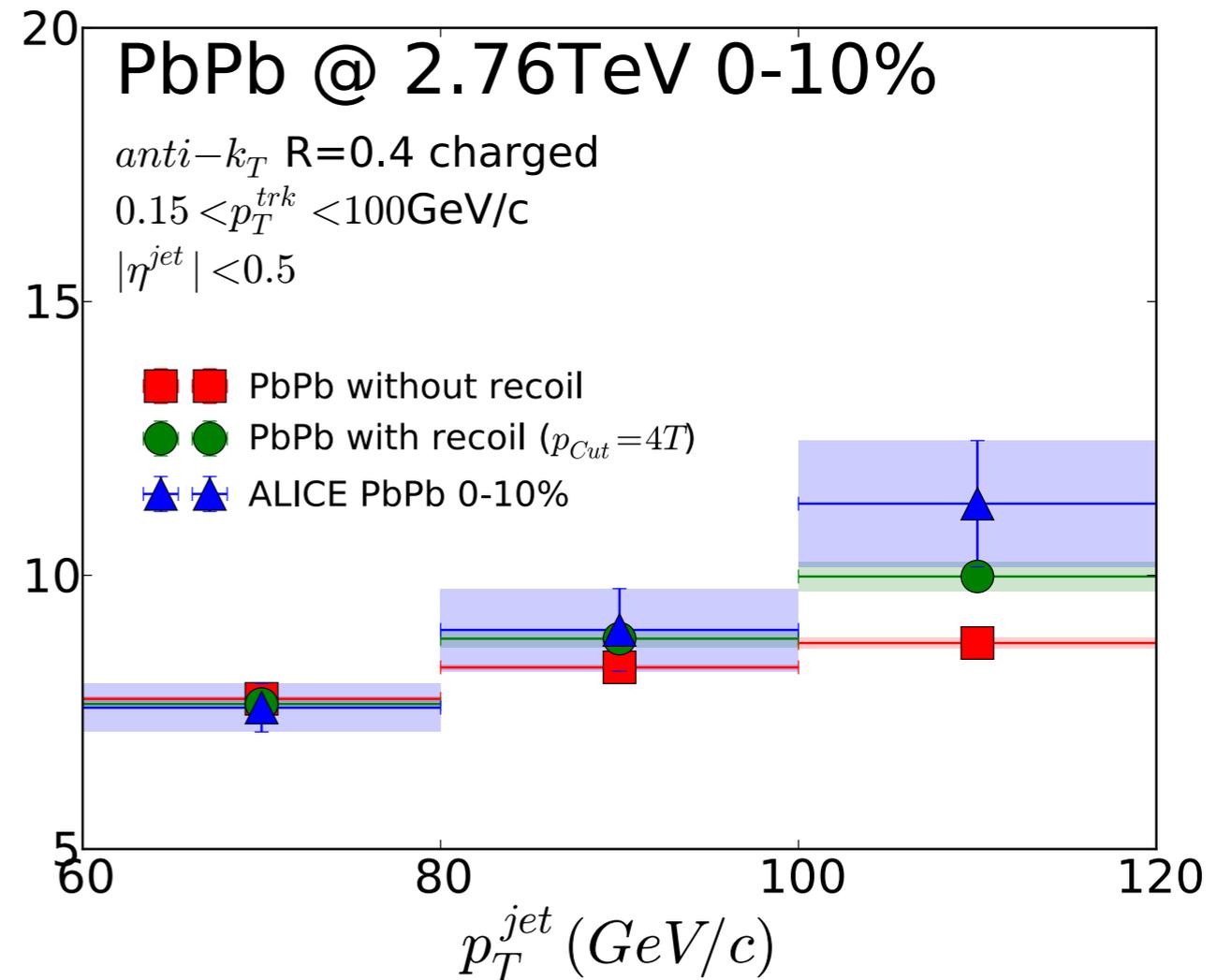
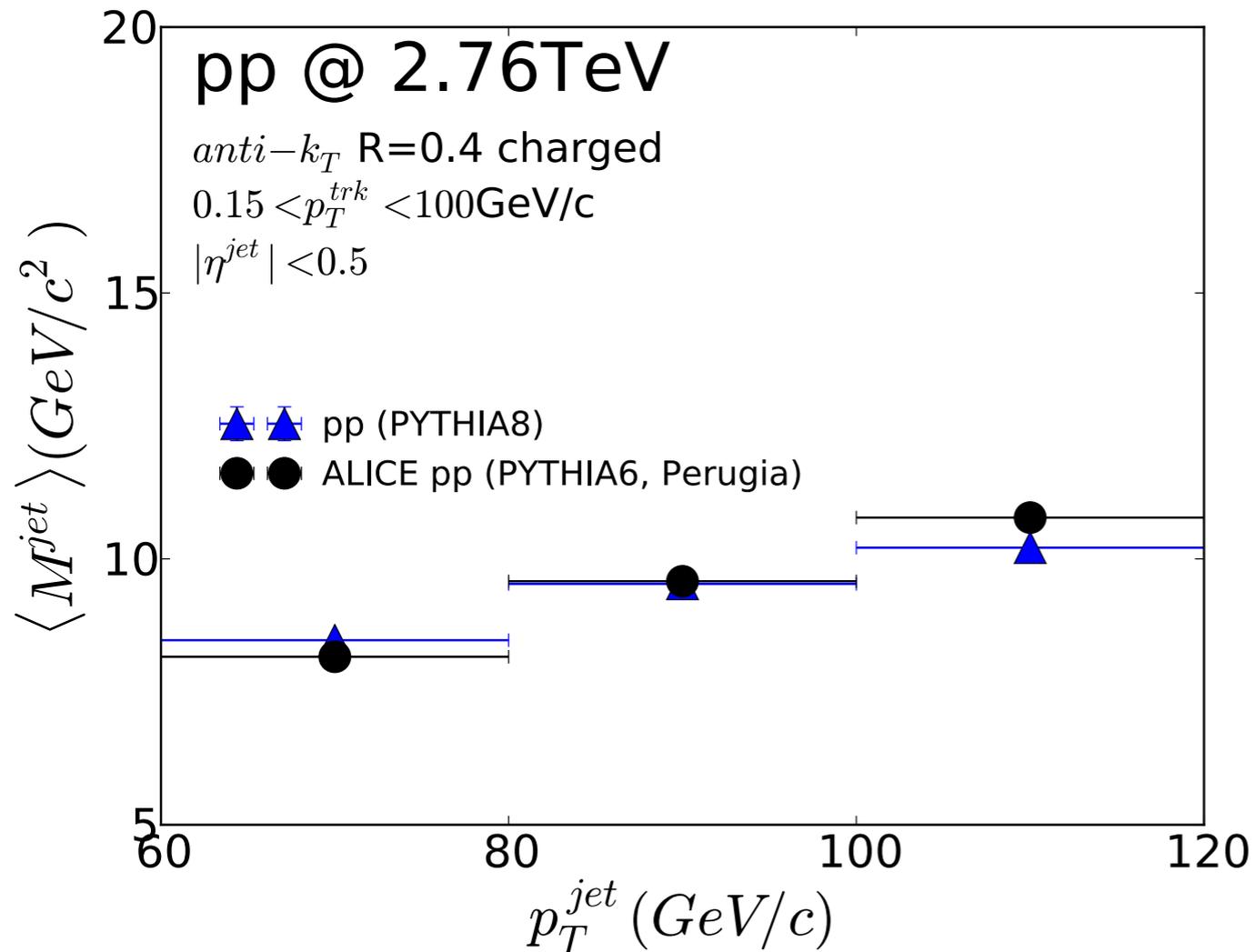


Jet mass with recoil

- pp baseline is slightly shifted left.
 - Need to be tuned more.
 - Possibility to get better PbPb results.



Jet mass with recoil



- Tuning pp baseline could result in a better agreement for PbPb.

Jet R_{AA} with recoil + hole subtraction

- Without recoil, theory shows too much quenching.
- Recoil + hole subtraction gives a qualitative description.
- Treating holes as medium response could improve the result.

