Medium Modifications to Jet Angularities

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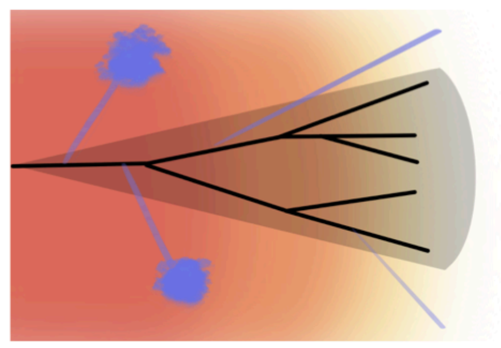
Outline

- Jets and Jet Substructure
- Jet Angularities
- Angularity distributions in pp collisions
- Medium modified jet functions
- Medium modified angularity distributions (Preliminary)
- Summary and outlook

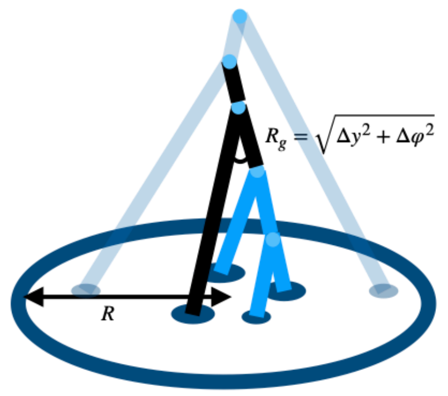
Jets and Jet Substructure

- QGP phase exists for a very small duration ⇒ Look for natural probes that appear in heavy ion collisions→ Jets
- Jets interact with the QGP as they traverse it :

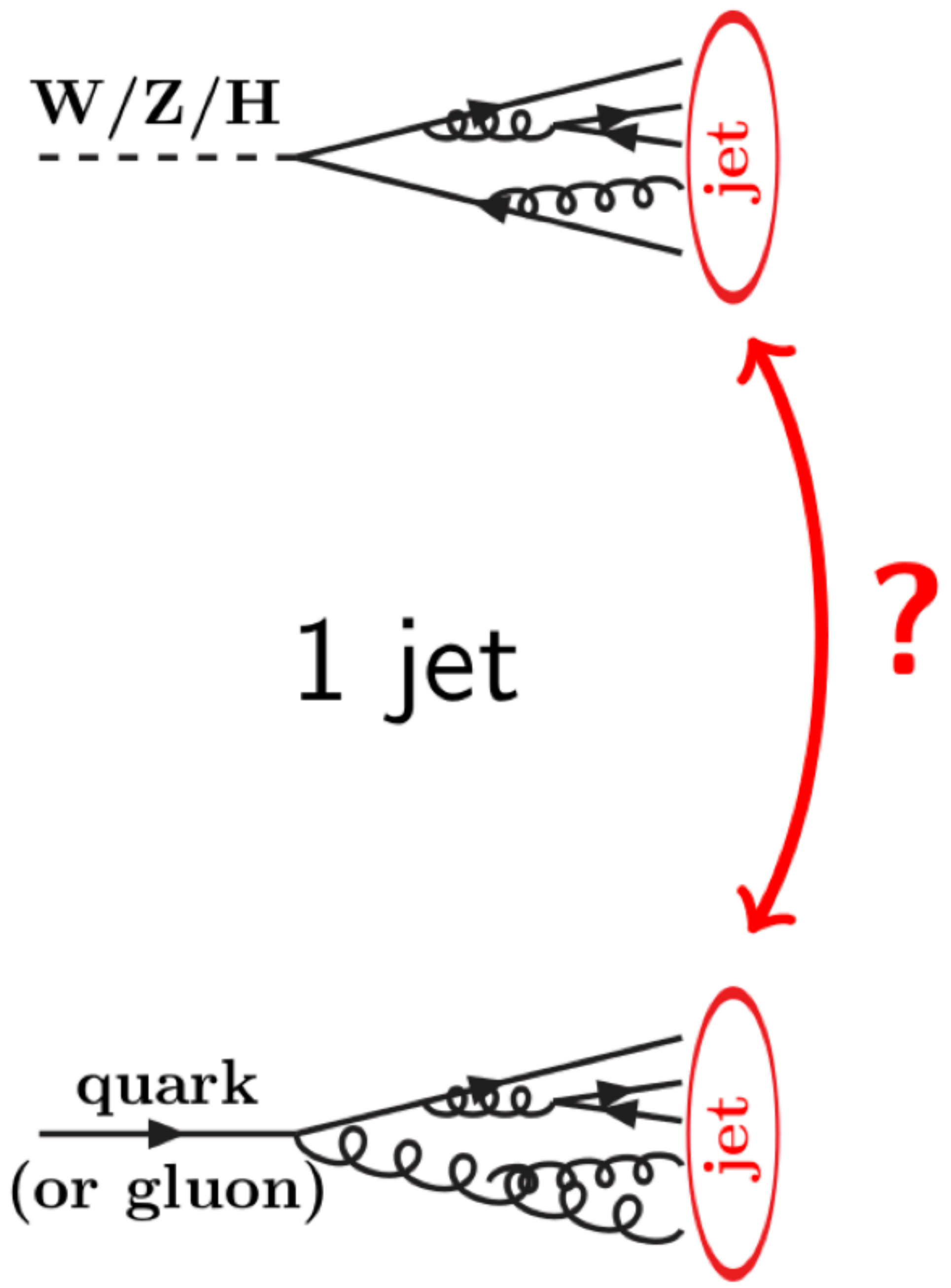
“Energy loss”



Substructure modification



$$p_t \gg m$$



Jet Substructure

Tagging

- Quark vs Gluon Jets
- Boosted Objects

Fundamental QCD

- Allows for stringent tests of QCD

↓

new physics

- Understanding of non-perturbative physics
- Probes of quark-gluon plasma

→ **This talk**

Jet Angularities

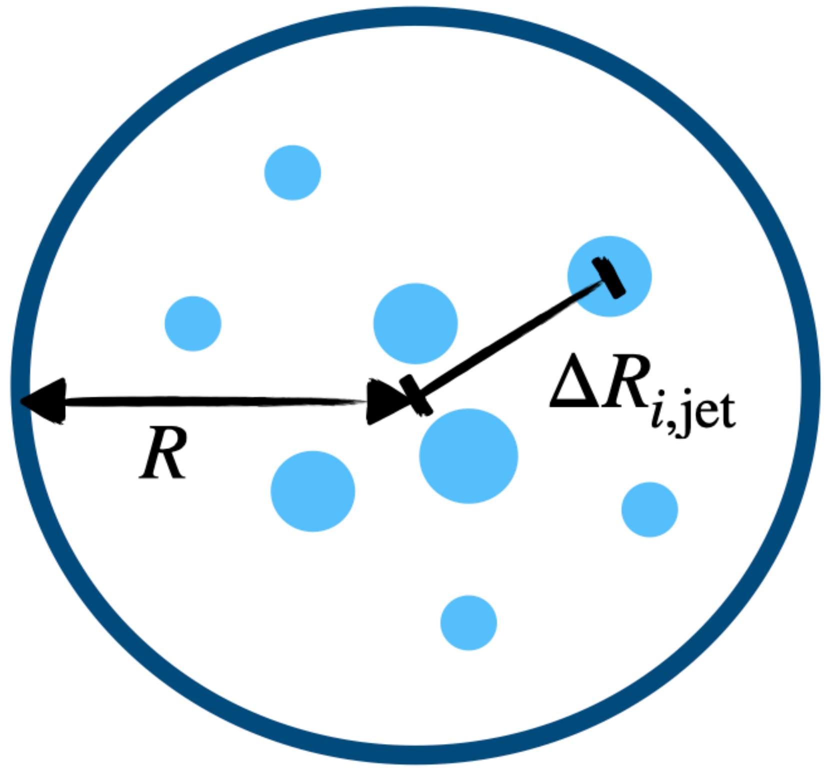
$$\tau_a = \sum_{i \epsilon \text{jet}} z_i \theta_i^{2-a}$$

$$\theta_i \equiv \frac{\Delta R_{i,\text{jet}}}{R}$$

$$z_i \equiv \frac{p_{T,i}}{p_{T,\text{jet}}}$$

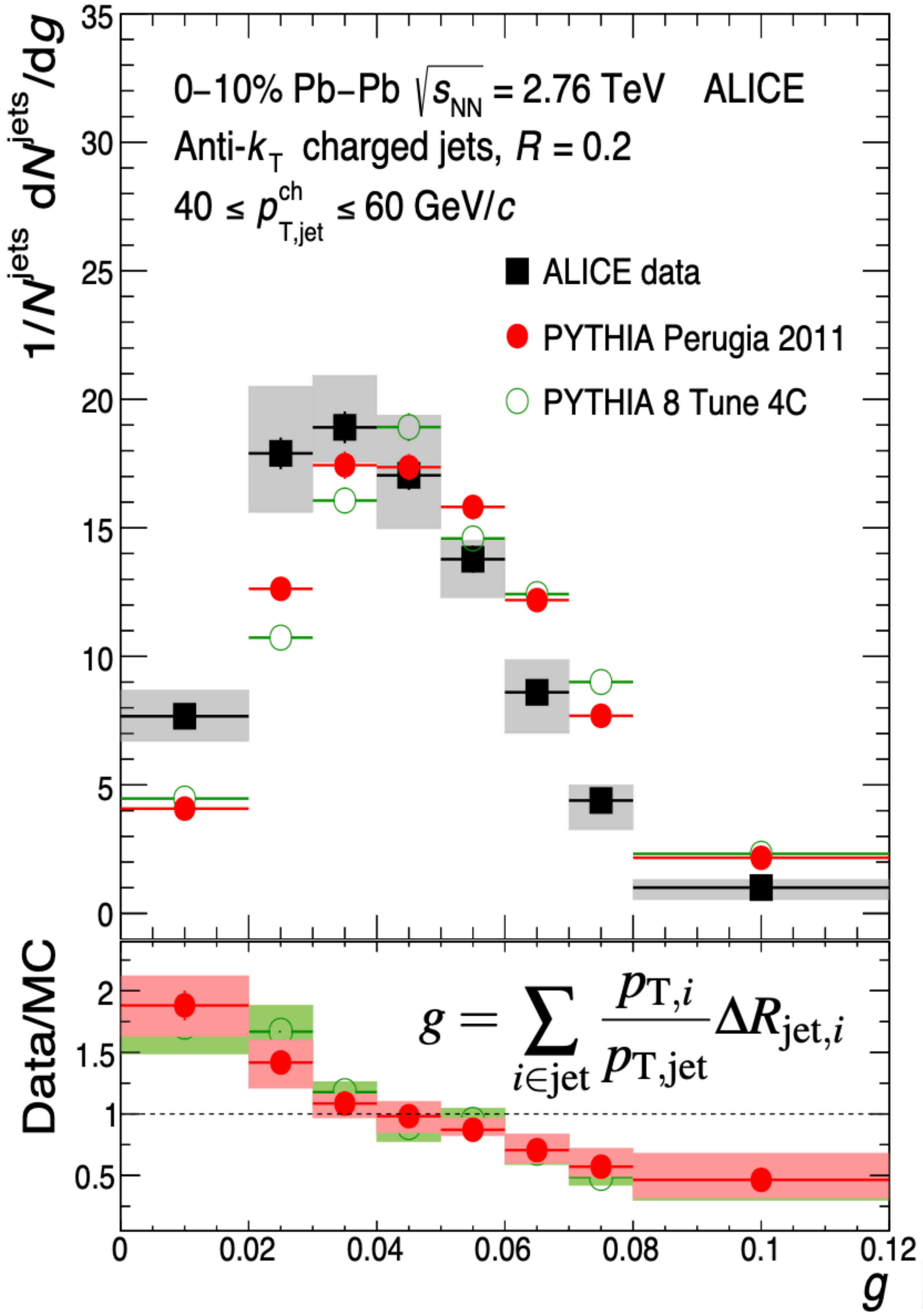
Parameter a varies the weight of collinear radiation

For Infrared and Collinear safety, we require $a < 2$



Jet girth ($a = 1$)

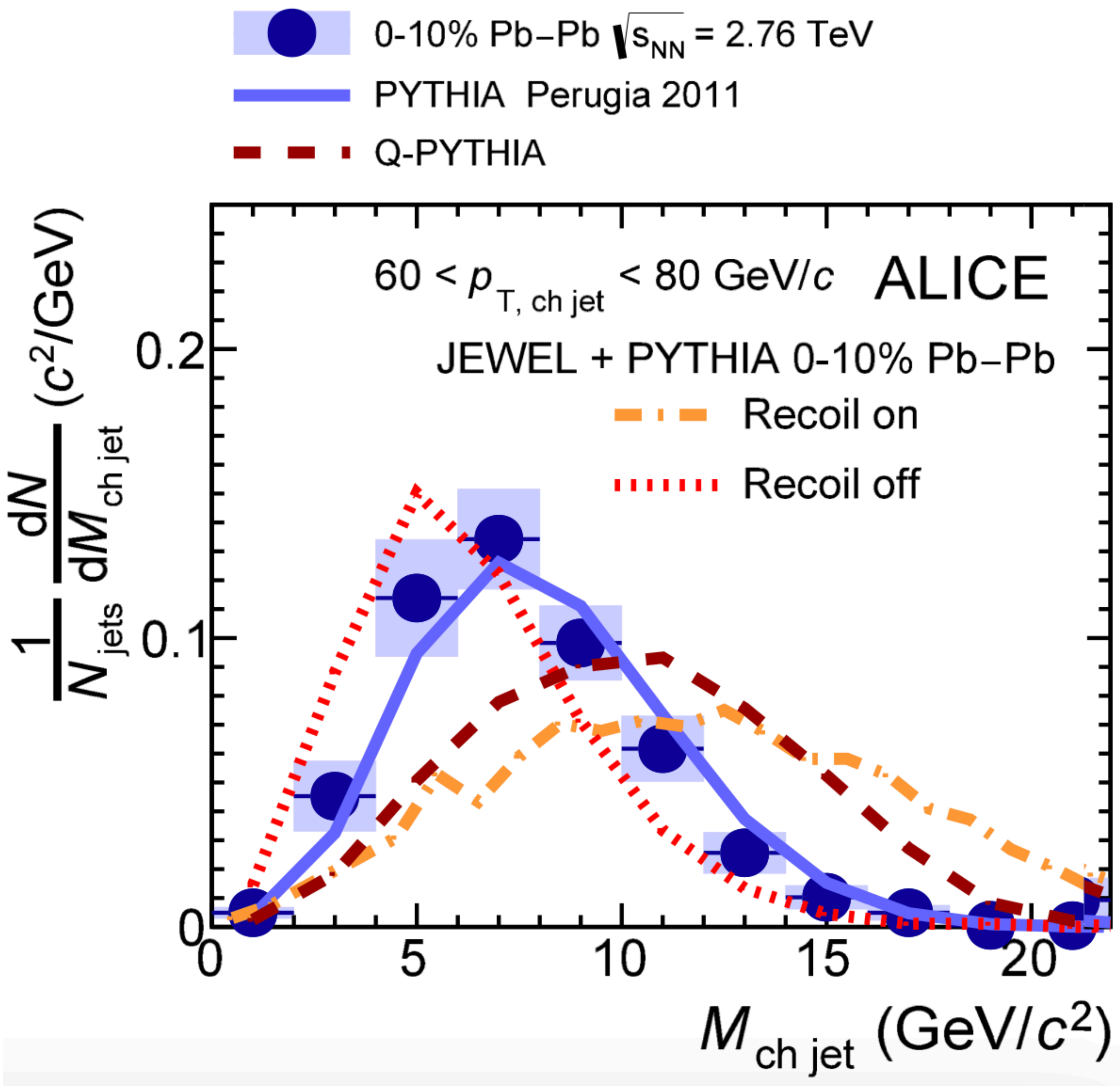
ALICE JHEP 10 (2018) 139



Jet mass ($a \sim 0$)

$$\tau_0 = \left(\frac{m}{p_T}\right)^2 + \mathcal{O}(\tau_0^2)$$

ALICE PLB 776 (2018) 249
CMS JHEP 10 (2018) 161

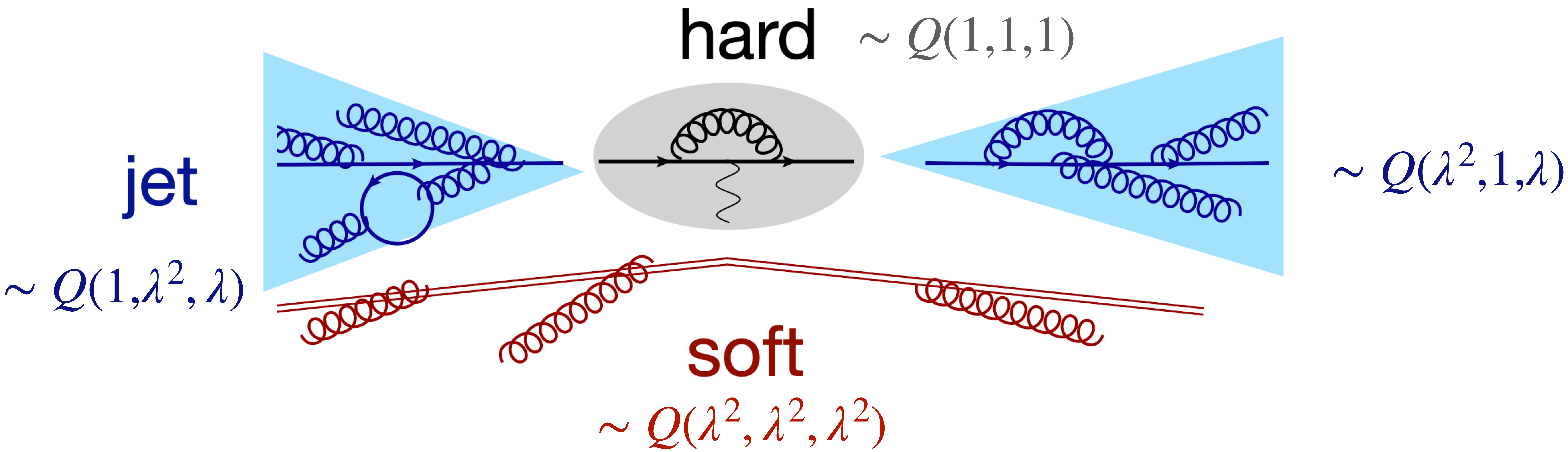


Soft Collinear Effective Theory

Bauer, Pirjol, Stewart, et al. 2001, 2002; Beneke, Diehl et al. 2002; ….

- Jets are multi-scale objects ⇒ EFT description → SCET.

- SCET describes the dynamics of soft and collinear modes. Short distance physics with $p^2 \sim Q^2$ is integrated out.



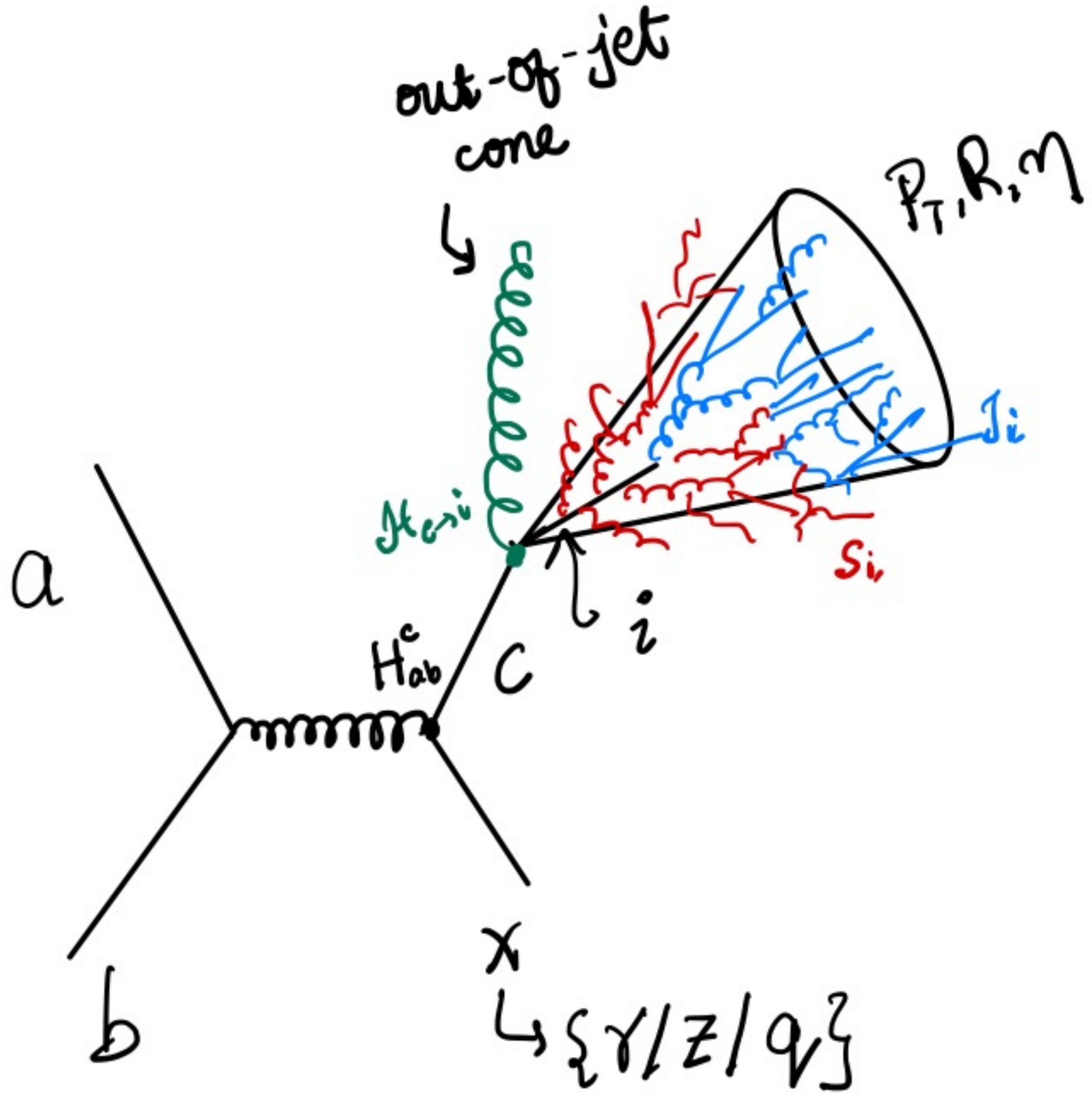
- SCET allows to analyse the factorization of the cross-section into a hard, jet and soft function each sensitive to physics at a single scale and the scale of factorization.

- Resummation of the large perturbative logarithms obtained through the renormalisation group evolution.

Factorization Theorem for Angularities

- For $a < 1$ angularities and $\tau_a^{\frac{1}{2-a}} \ll R$, the factorized differential distribution is

$$\frac{d\sigma^{AA\to(jet\,\tau_a)X}}{d\tau_a\,dp_T\,d\eta} = \sum_{abc}\sum_i f_a(x_a,\mu)\otimes f_b(x_b,\mu)\otimes H^c_{ab}(x_a,x_b,\eta,p_T/z,\mu)\otimes \mathscr{H}_{c\to i}(z,p_T R,\mu)\times J(\tau_a^c,p_T,R,\mu)\otimes S(\tau_a^s,p_T,R,\mu)$$



for $c = q$:

H^c_{ab} : $qq \to qX$
$q\bar{q} \to q/\bar{q}\,X$
$qg \to q/\bar{q}\,X$
$gg \to q\,X$

for $c = g$:

H^c_{ab} : $gg \to gX$
$qg \to gX$
$q\bar{q} \to gX$
$qq \to gX$

Angularity Hard, Jet and Soft functions

- For H_{ab}^{c} : we compute all processes up-to next-to-leading-order.

- $\mathscr{H}_{c\to i}$ satisfies a DGLAP-type evolution equation

$$\mu\frac{d}{d\mu}\mathscr{H}_{c\to i}(z,p_TR,\mu)=\sum_k\int_z^1\frac{dz'}{z'}\gamma_{ck}\left(\frac{z}{z'},p_TR,\mu\right)\mathscr{H}_{k\to i}(z',p_TR,\mu)$$

- Jet function is related to spin averaged QCD splitting function with appropriate phase factors   Ritzmann, Waalewijn 2014

$$J_i(\ldots)=\sum_j\int\prod_{n=1}^{m}\frac{d^4k_n}{(2\pi)^3}P_{ij}\,\delta(\ldots)\delta(k_n^2)$$

- Soft function $S_g(\ldots)=\frac{1}{N^2-1}\langle 0|\bar{Y}_n\delta(\ldots)Y_{\bar{n}}|X\rangle\langle X|\bar{Y}_{\bar{n}}Y_n|0\rangle$

H_{ab}^{c} — $\mu_H\sim p_T$

$\mathscr{H}_{c\to i}$ — $\mu_{\mathscr{H}}\sim p_TR$

J_i — $\mu_J\sim p_T(\tau_a)^{\frac{1}{(2-a)}}$

S_i — $\mu_S\sim\frac{p_T\tau_a}{R^{1-a}}$

Non-perturbative effects via Shape function

- As $\mu_S \sim \Lambda_{\rm QCD}$, non-perturbative effects become relevant → incorporate through a shape function

Stewart, Tackmann, Waalewijn 2015

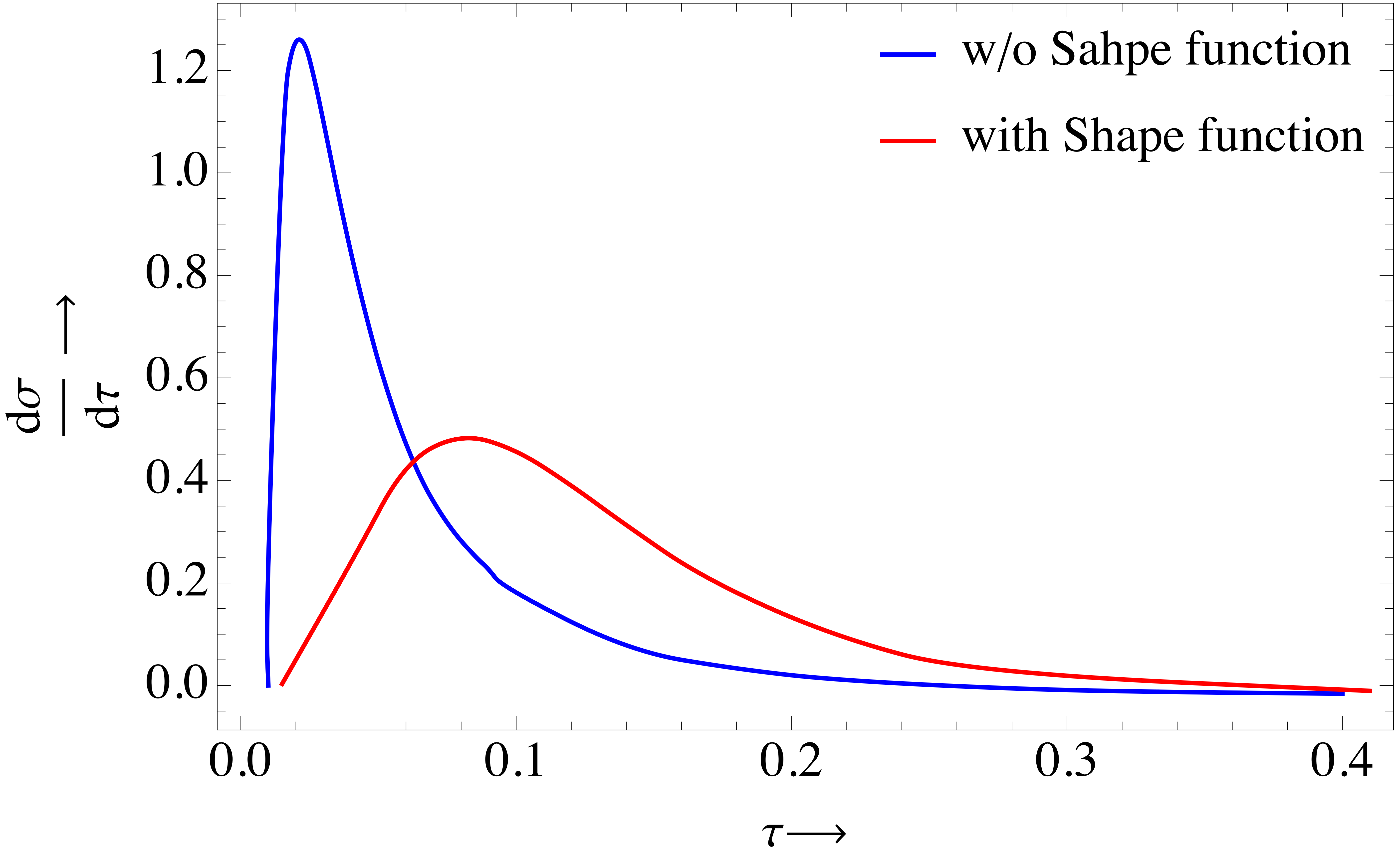
$$S_{NP}(k) = \frac{4k}{\Omega_a^2} exp(-2k/\Omega_a) \qquad \text{with} \qquad \Omega_a = \frac{\Omega_0}{1-a} \qquad \Omega_0 \sim 1\,\text{GeV}$$

- The final angularity cross-section is then

$$\frac{d\sigma}{dp_T d\tau} = \int \frac{d\sigma^{\rm pert}}{dp_T d\tau}(\tau - \tau_{\rm shift}(k)) S_{NP}(k) dk$$

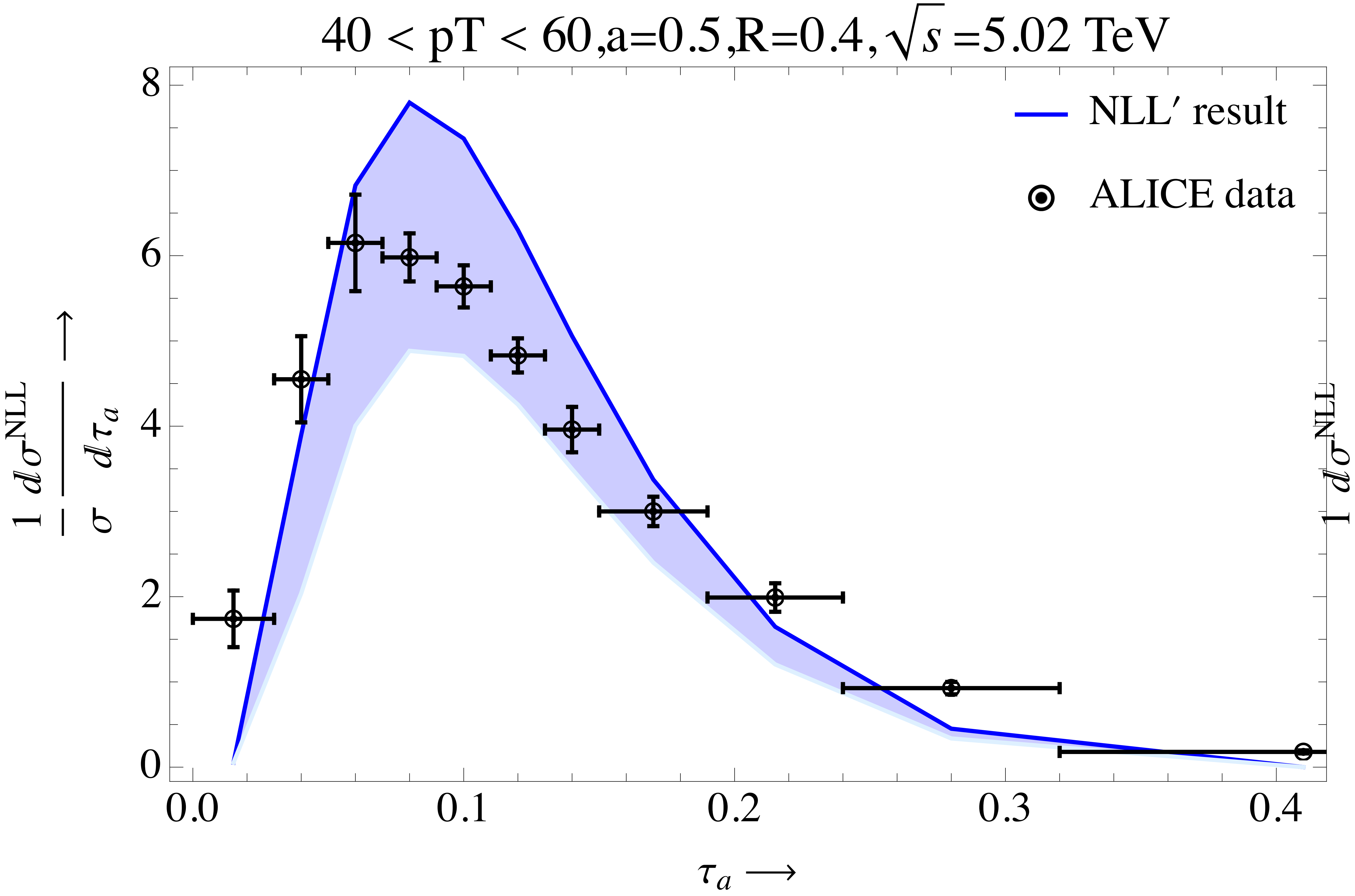
with

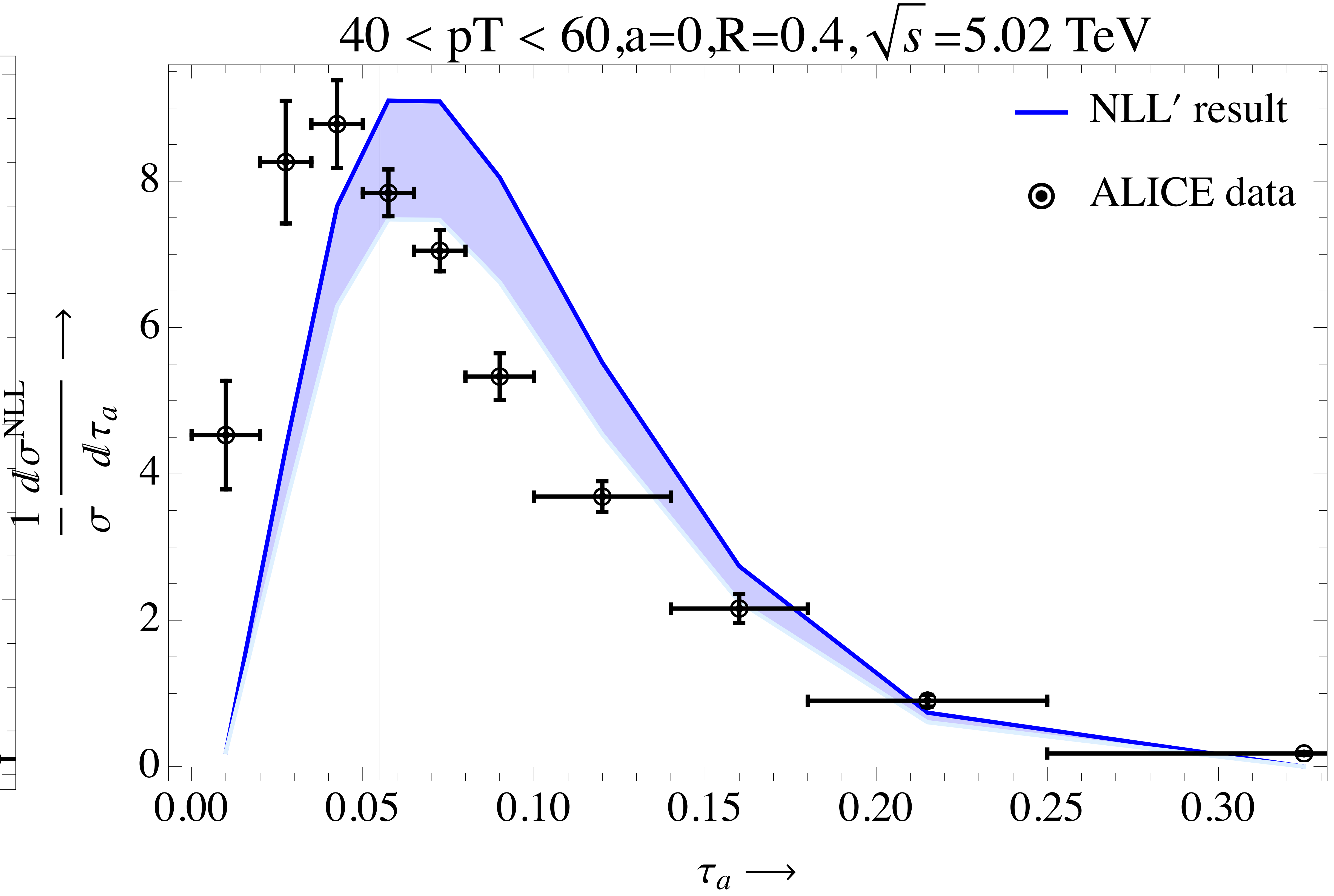
$$\tau_{\rm shift}(k) = \frac{k}{p_T R}$$



Resummed Distributions for pp-collisions

ALICE 2021





Soft Collinear Effective Theory with Glaubers

Majumdar et al. 2009, Rajagopal et al. 2009, Vitev et al. 2011

- SCET has no quenching effects so we need extra degrees of freedom; Glaubers

- t-channel dominance ⇒ transverse momentum transfer to describe jet-medium interactions
  $p_G \sim Q(\lambda^2, \lambda^2, \lambda)$

- Treat Glaubers as background fields generated from colour charges in the QGP

- Glauber gluons interact with both collinear $p_C \sim Q(\lambda^2, 1, \lambda)$ and soft $p_S \sim Q(\lambda^{2-a}, \lambda^{2-a}, \lambda^{2-a})$ modes of the theory

$\lambda \sim \tau_a^{\frac{1}{2-a}}$

- The Lagrangian in terms of collinear and Glauber field is

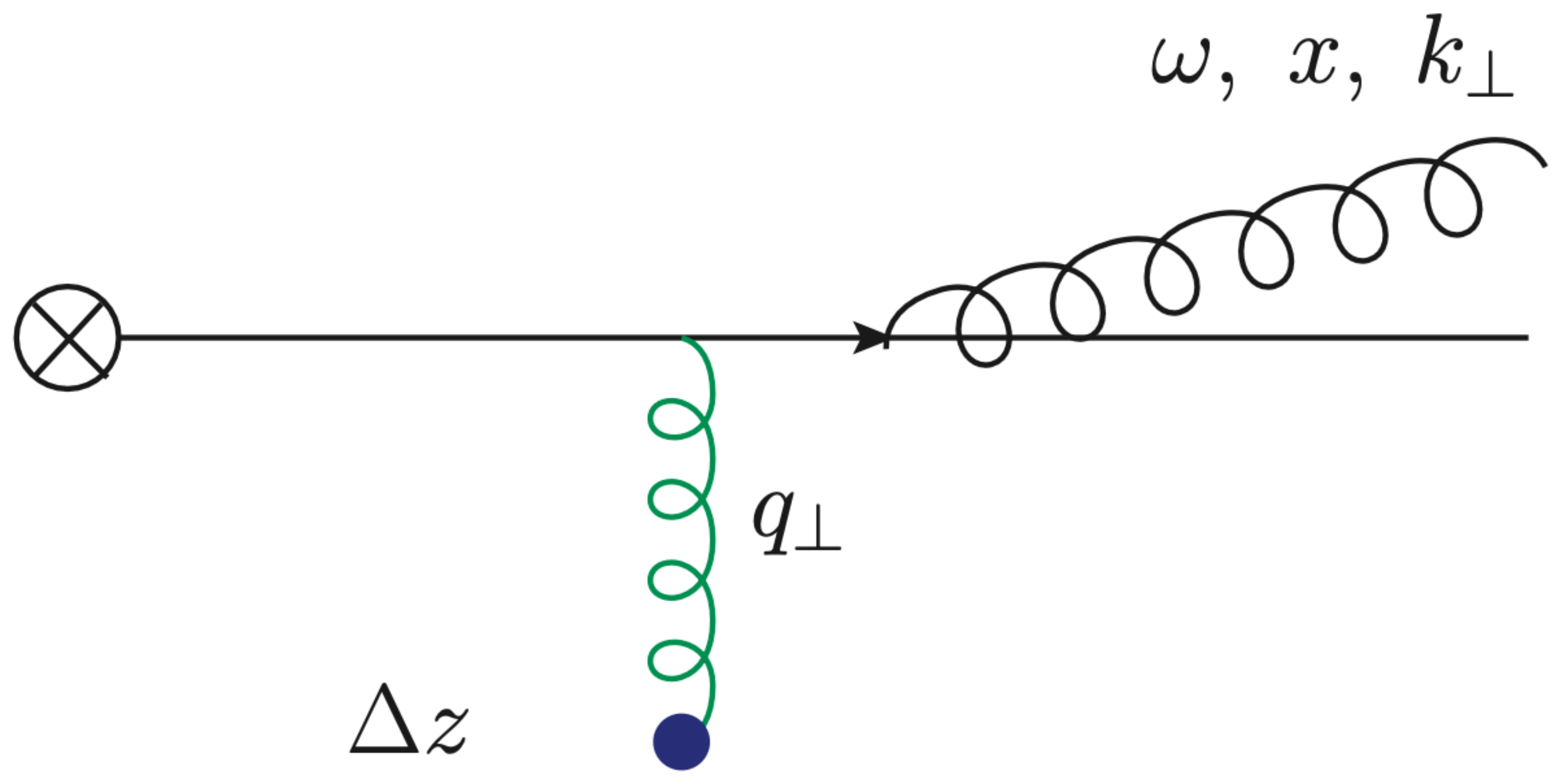
$$\mathscr{L}_G(\xi_n, A_n, A_G) = g \sum_{p,p'} e^{-i(\vec{p}-\vec{p}')\cdot\vec{x}} \left(\bar{\xi}_{n,p'} t^a \frac{\gamma \cdot \bar{n}}{2} \xi_{n,p} - i f^{abc} A^{\lambda,c}_{n,p'} A^{\nu,b}_{n,p} g^{\perp}_{\nu\lambda} \bar{n} \cdot p \right) n \cdot A^a_G$$

Medium Induced Splittings

- The interaction between jet and medium is approximated by a screened potential
- Parton shower is modified due to coherent multiple scatterings
- Interplay between different scales m_D, λ and τ_f

Vitev et al. 2011, 2015

$$\tau_f = \frac{x\,\omega}{(q_\perp - k_\perp)^2}$$



- In the small x limit

$$x\frac{dN_{q\to q\,g}}{dxd^2k_\perp} = \tilde{\alpha}\int_0^{\bar{L}} \frac{d\Delta z}{\lambda} d^2q_\perp \frac{1}{\sigma}\frac{d\sigma}{d^2q_\perp}\frac{2k_\perp \cdot q_\perp}{k_\perp^2(q_\perp - k_\perp)^2}\left[1 - \cos\left(\frac{(q_\perp - k_\perp)^2\Delta z}{x\,\omega}\right)\right]$$

$$\frac{1}{\sigma}\frac{d\sigma}{d^2q_\perp} = \frac{m_D^2}{\pi(q_\perp^2 + m_D^2)^2}$$

- We use general expression (without any assumptions on x) for splitting functions

Medium Modified Jet function

- Medium modified splitting functions give jet function

$$J_i^{\rm med}(\tau_a, p_T, R, \mu) = \frac{\alpha_s(\mu)}{2\pi^2}\frac{e^{\epsilon\gamma_E}\mu^{2\epsilon}}{\Gamma(1-\epsilon)}\int_0^{2\pi} d\phi \sum_j \int dx \frac{dk_\perp}{k_\perp^{2\epsilon-1}} P_{ij}(x, k_\perp)\delta(\tau_a - \hat{\tau}_a)$$

$$J_i^{\rm med}(\tau_a, p_T, R, \mu)_{i*\to j,k} = \frac{1}{2-a}\frac{\alpha_s}{\pi}\frac{e^{\epsilon\gamma_E}\mu^{2\epsilon}}{\Gamma(1-\epsilon)}\frac{p_T^{2-2\epsilon}}{\tau_a^{\frac{2\epsilon-a}{2-a}}}\sum_j \int_0^1 dx \left(x^{\frac{1-a}{2-a}}\right)^{2-2\epsilon} P_{ij}\left(x, (p_T^{2-a}\tau_a x^{1-a})^{\frac{1}{2-a}}\right)$$

- Two things can be observed:
  1. No extra divergences are induced by the medium
  2. Jet function is not defined for $a \geq 2$

- RGs are same as vacuum

- Total jet function in AA collision $J_i(\ldots) = J_i^{\rm vac}(\ldots) + J_i^{\rm med}(\ldots)$

Data vs Theory (Preliminary)

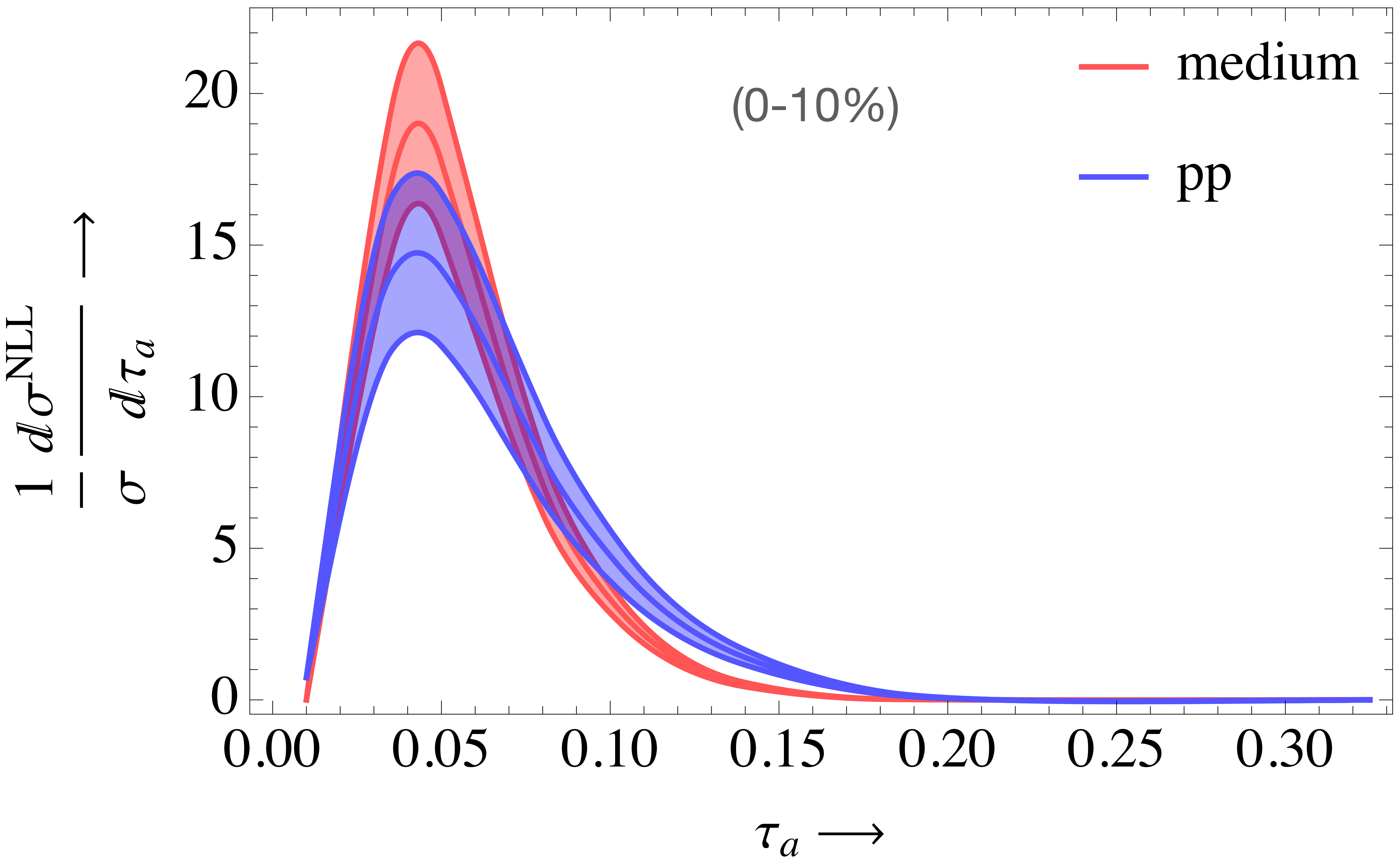
- Average system size: From initial state glauber model
- Assuming 1-dimensional Bjorken flow $T = T_0\left(\frac{\tau_0}{\tau}\right)^{\frac{1}{3}}$
- Average temperature and Debye mass $m_D \sim gT$ with $g = 2$

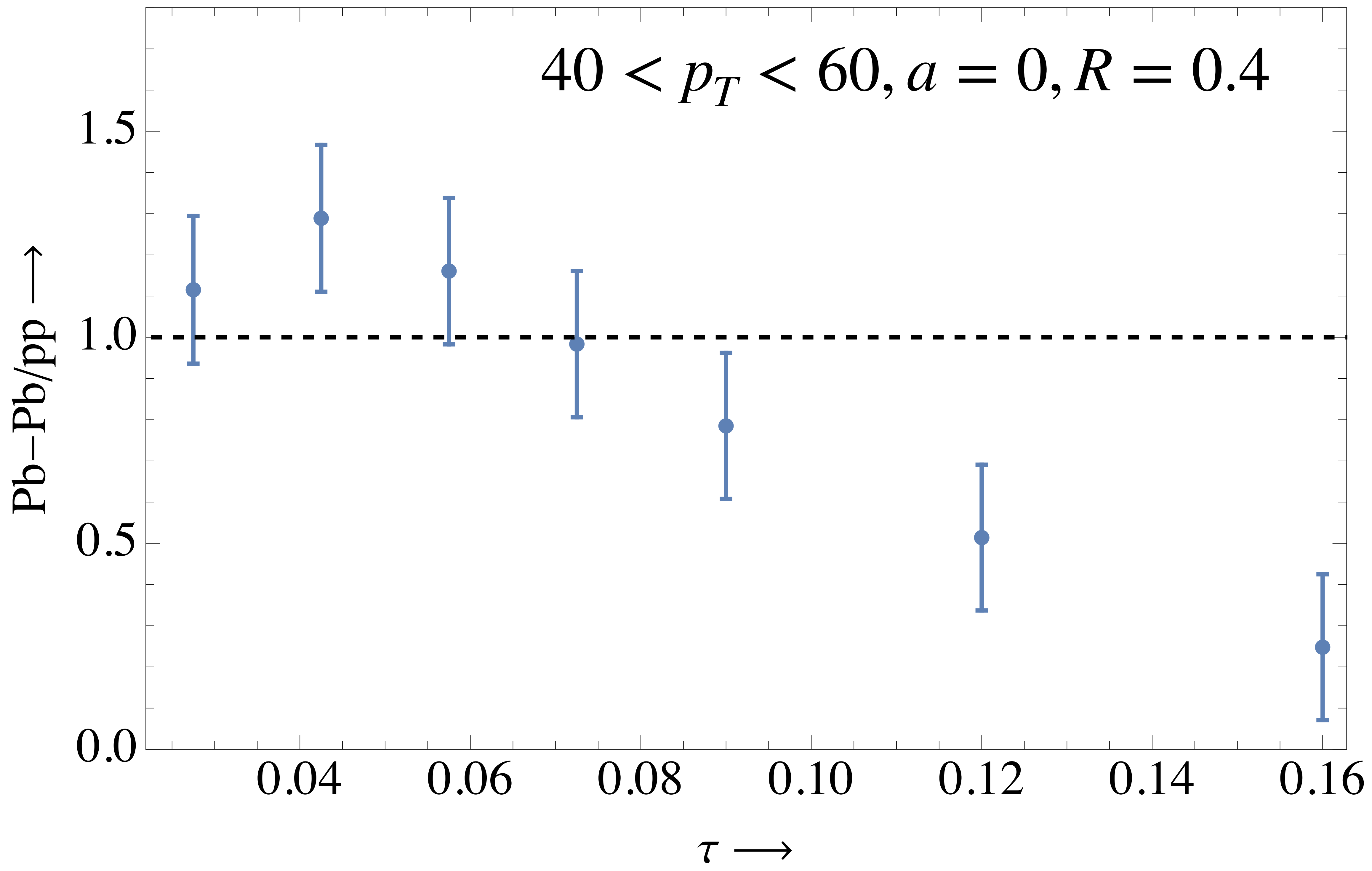
- Average energy loss to reduce jet selection bias

$$\epsilon = 4\pi \int_0^{1/2} dx\, x \int_{\omega x(1-x)tan\frac{R}{2}}^{\omega x(1-x)tan\frac{R_0}{2}} dk_\perp\, k_\perp \left[P_{qg}^{\text{med}} + P_{gq}^{\text{med}}\right](x, k_\perp)$$

Vitev et al. 2016

- Shift p_T as $p_T^{\text{med}} \approx p_T^{\text{vac}} e^{-\epsilon}$





Summary and Outlook

- Jet Angularities serve as novel observables that allow to study a class of substructure observables.
- Model jet-medium interaction through Glauber gluons.
- Medium modified splitting functions give jet function.
- Jet selection bias reduced by accounting for an average energy loss separately for both quark and gluon jets.
- Small τ jets are enhanced indicating narrowing of the jet core while large τ jets are suppressed indicating broadening of jets in the medium.
- For a cleaner understanding of medium effects on the jet core, one needs to look at groomed angularities $\rightarrow$ less sensitive to hadronization and selection bias effects (ongoing work)