IWHSS, 16-18 NOVEMBER 2020, TRIESTE

JETS AND TMD IN SIDIS AND E+E- EXPERIMENTS

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STRONG 2020

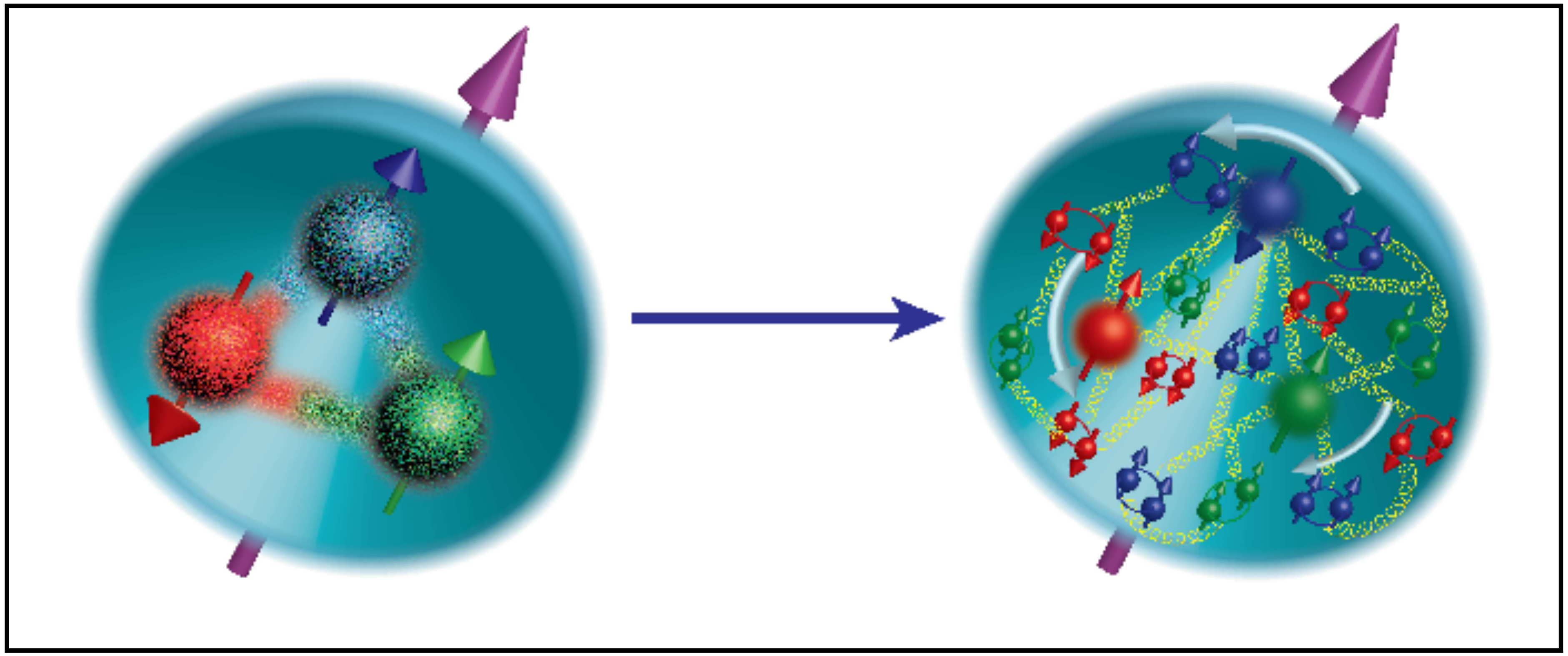
Based on :

D. Gutierrez-Reyes, I.S., W. Waalewijn, L. Zoppi PRL **121,** 162001(2018)

D. Gutierrez-Reyes, I.S., W. Waalewijn, L. Zoppi JHEP 1910 (2019) 031

IPARCOS

UNIVERSITAS COMPLVTENSIS MATRITENSIS



The 3D mapping of hadrons is our challenge…

↓

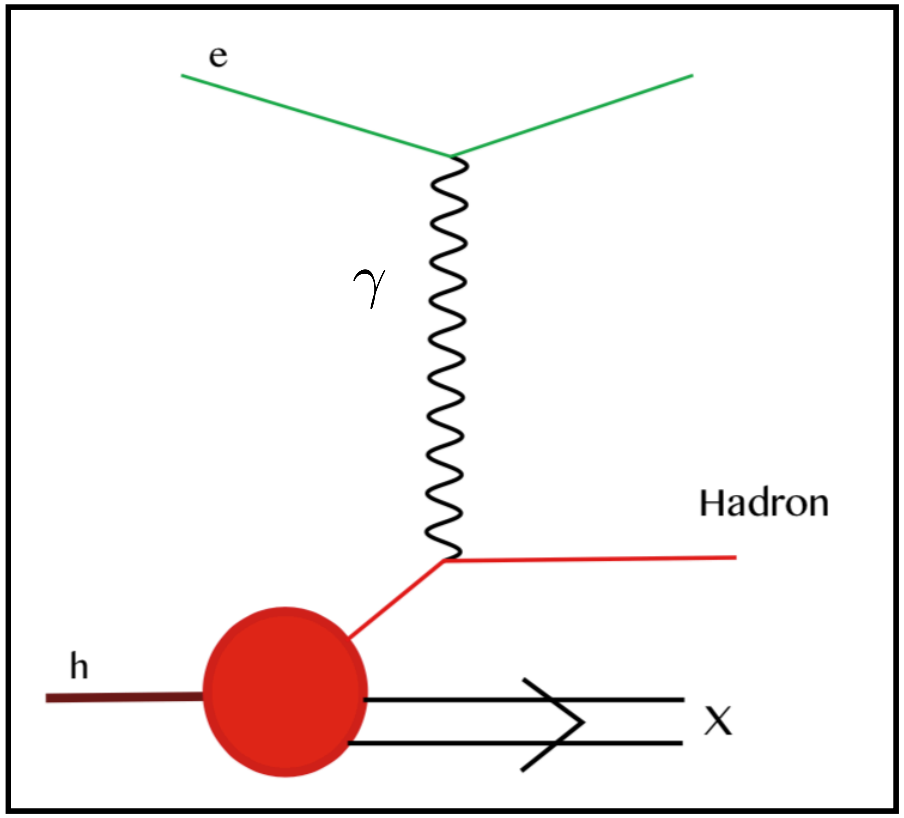
Let us use jets to investigate hadron structure!

Expectations from jet (to be checked!!):

Better control of hadronization effects with respect to fragmentation functions

An alternative study of TMD, using different combinations of jets and TMD

TMDS WITHOUT JETS

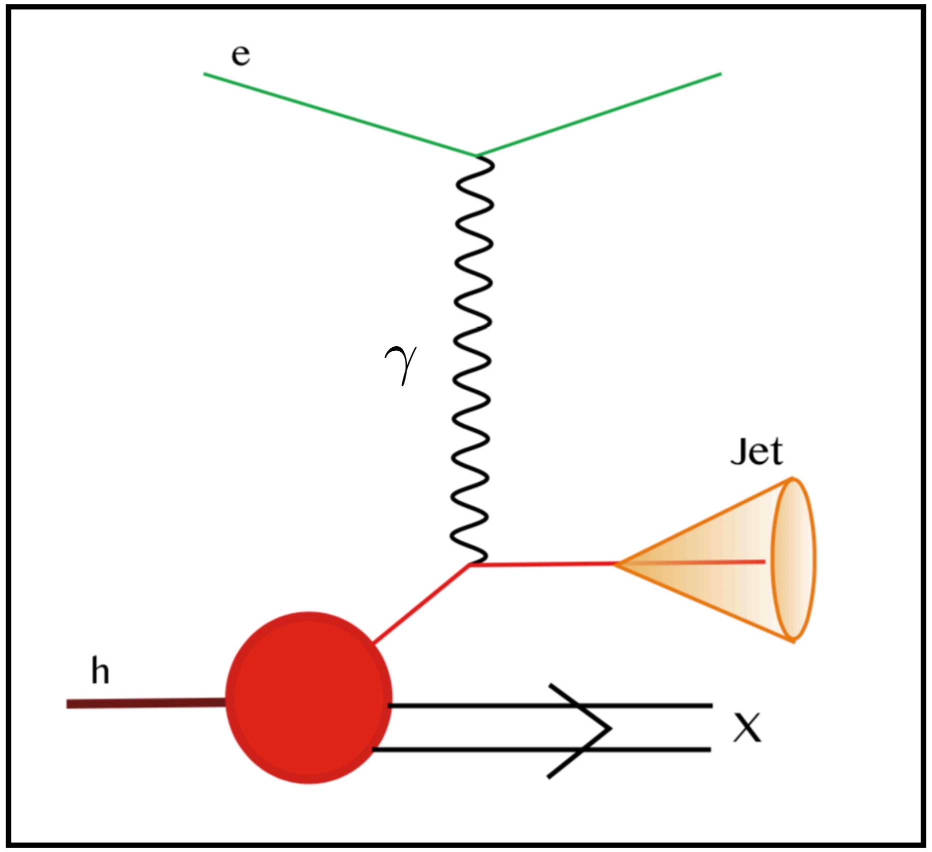


Factorization theorem for SIDIS

$$\frac{d\sigma_{eN\to eN'X}}{dQ^2 dx dz d\boldsymbol{q}} = \sum_a \mathcal{H}_a(Q^2,\mu) \int \frac{d\boldsymbol{b}}{(2\pi)^2} e^{-i\boldsymbol{b}\boldsymbol{q}} f_{a/N}(x,\boldsymbol{b},\mu,\zeta) d_{a/N'}(z,\boldsymbol{b},\mu,\zeta)$$

TMDPDF TMDFF

TMDS WITH JETS



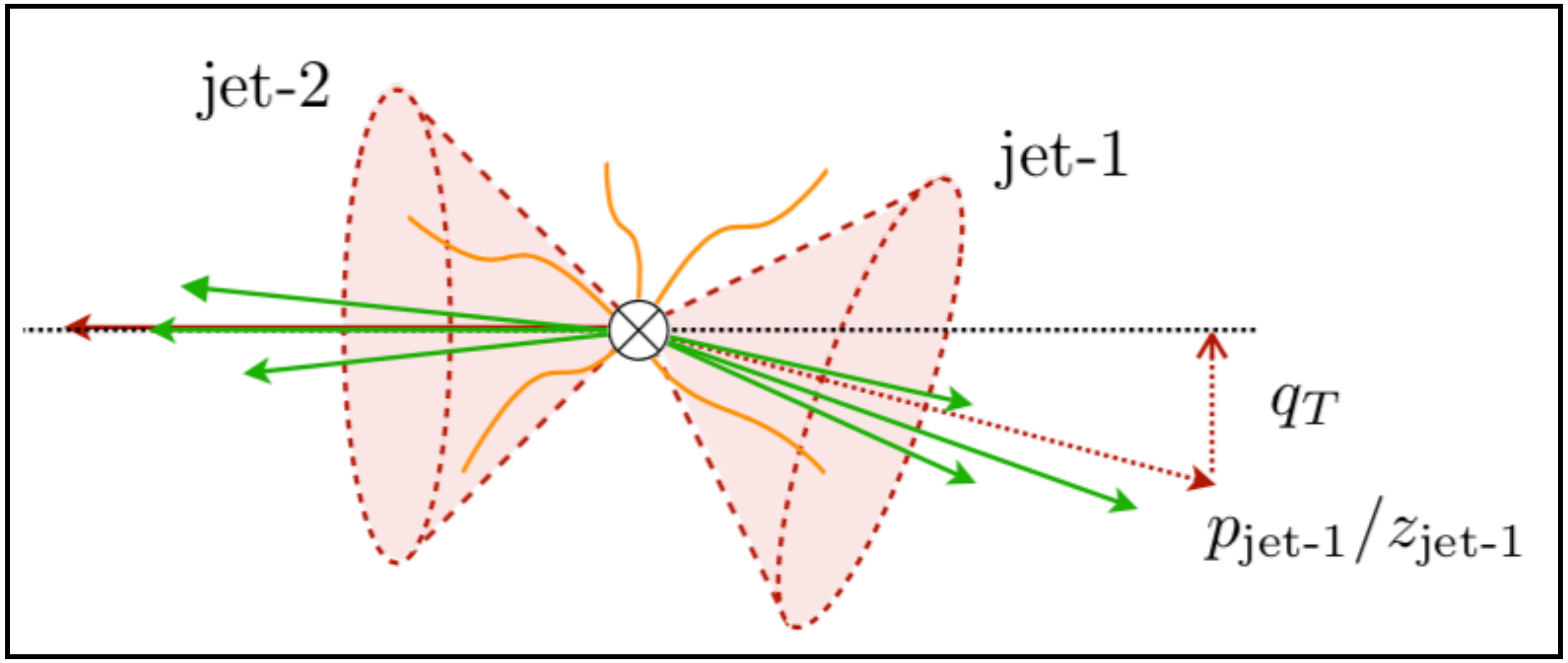
Factorization theorem for SIDIS

$$\frac{d\sigma_{eN\to eJX}}{dQ^2dxdzd\boldsymbol{q}} = \sum_a \mathcal{H}_a(Q^2,\mu)\int\frac{d\boldsymbol{b}}{(2\pi)^2}e^{-i\boldsymbol{b}\boldsymbol{q}} f_{a/N}(x,\boldsymbol{b},\mu,\zeta) J_q^{\text{axis}}(z,\boldsymbol{b},QR,\mu,\zeta)$$

TMDPDF

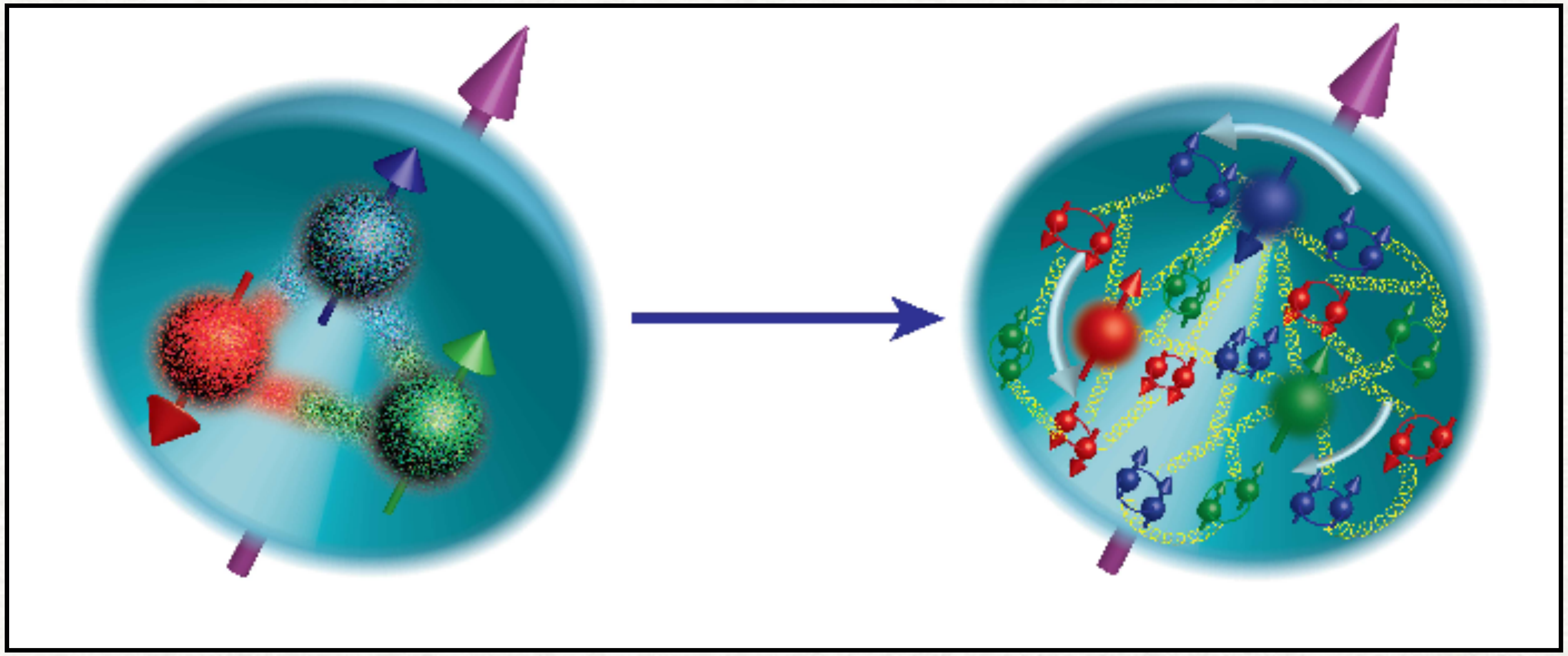
TMD jet function

THE TMD EVOLUTION KERNEL



$$\frac{d\sigma_{e^+e^-\to JJX}}{dz_1\, dz_2\, d\boldsymbol{q}} = \sigma_0^{e^+e^-}(s)\, H_{e^+e^-}(s,\mu) \int \frac{d\boldsymbol{b}}{(2\pi)^2}\, e^{-i\boldsymbol{b}\cdot\boldsymbol{q}} J_q(z_1, \boldsymbol{b}, \tfrac{\sqrt{s}}{2}\mathcal{R}, \mu, \zeta)\, J_{\bar{q}}(z_2, \boldsymbol{b}, \tfrac{\sqrt{s}}{2}\mathcal{R}, \mu, \zeta)$$

When only jets are present in the final state we can study the evolution kernel by itself!



We want to study the non-perturbative part of the evolution kernel:
We consider the possibility to reduce non-perturbative effects in final states using jets.

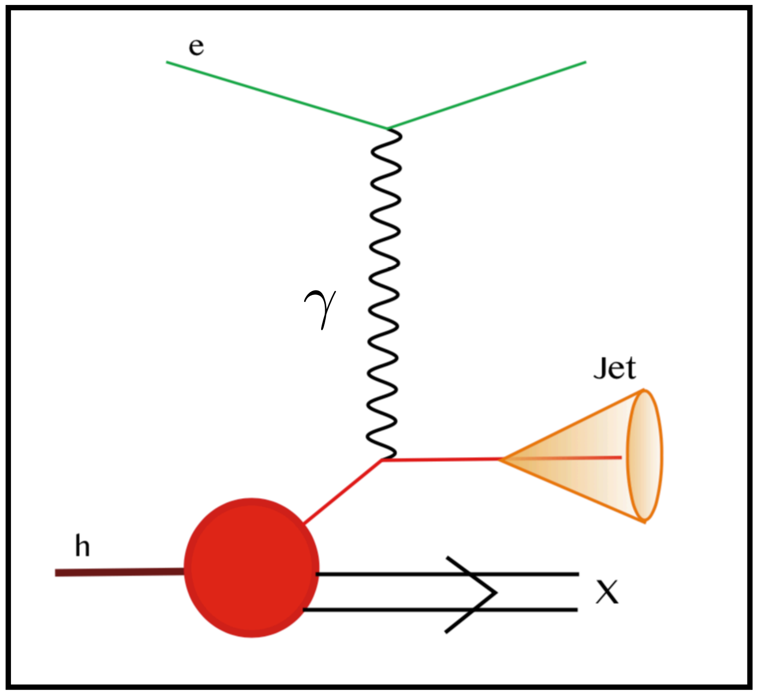
In SIDIS
With a jet:

$$\frac{d\sigma}{dQ^2 dx dz dq_T^2} = \sigma_0 \sum_{f_1, f_2} \int \frac{d^2\mathbf{b}}{4\pi} e^{i\mathbf{b}\mathbf{q_T}} \{R[\mathbf{b}; (Q, Q^2)]\}^2 F_{f_1 \leftarrow h}(x, \mathbf{b}) J_{f_2 \to J}(z, \mathbf{b})$$

In e+e-:

$$\frac{d\sigma}{dz_1 dz_2 dq_T^2} = \sigma_0 \sum_{f_1, f_2} \int \frac{d^2\mathbf{b}}{4\pi} e^{i\mathbf{b}\mathbf{q_T}} \{R[\mathbf{b}; (Q, Q^2)]\}^2 J_{f_1 \to J_1}(x, \mathbf{b}) J_{f_2 \to J_2}(z, \mathbf{b})$$

TMDS WITH JETS



Questions:
Can we write TMD factorization theorems for processes with jets?

Can we write factorization theorems for jets regardless of the size of the jet?

(With the same evolution kernel as in the standard TMD case)

Experimental set-ups are not always ideal, so compatibility with factorization theorem should be checked

Hadronization effects can be considered (ungroomed/groomed jets)

Dijet decorrelation

In all cases
$\theta \ll 1$

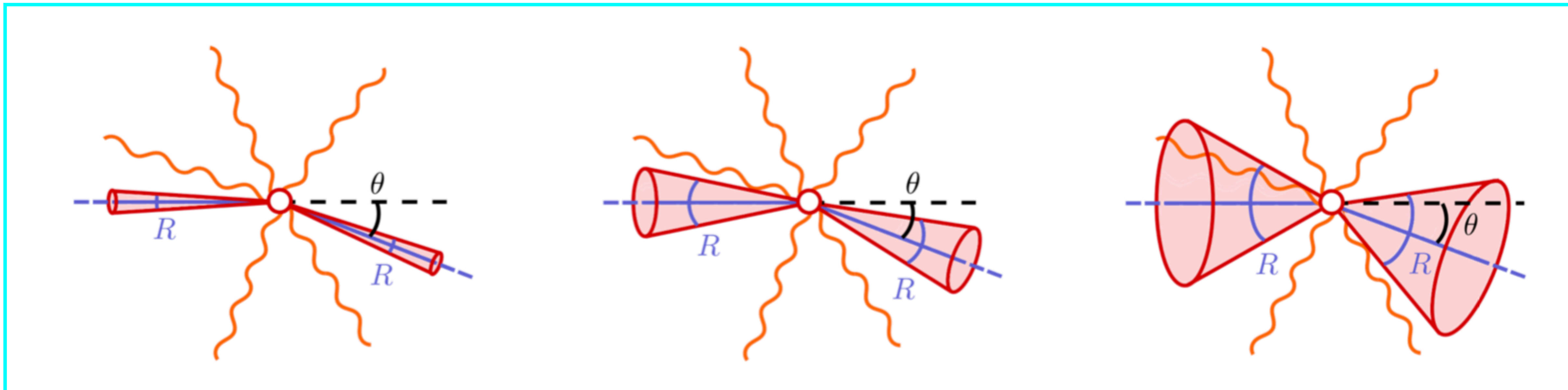
$e^+e^- \to \text{dijet} + X$

$$\boldsymbol{q} = \frac{\boldsymbol{p}_1}{z_1} + \frac{\boldsymbol{p}_2}{z_2}$$
$$\tan\theta = 2q_T/\sqrt{s} \qquad z_i = 2E_i/\sqrt{s}$$

$e^- + H \to e^- + \text{jet} + X$

$$\boldsymbol{q} = \frac{\boldsymbol{P}_J}{z} + q_{in}$$
$$\tan\theta = 2q_T/Q \qquad z_i = 2E_J/Q$$

θ competes with R



$\theta \gg R$ $\qquad$ $\theta \sim R$ $\qquad$ $\theta \ll R$

For $R \to 0$ one recovers the (hadronic) TMD limit

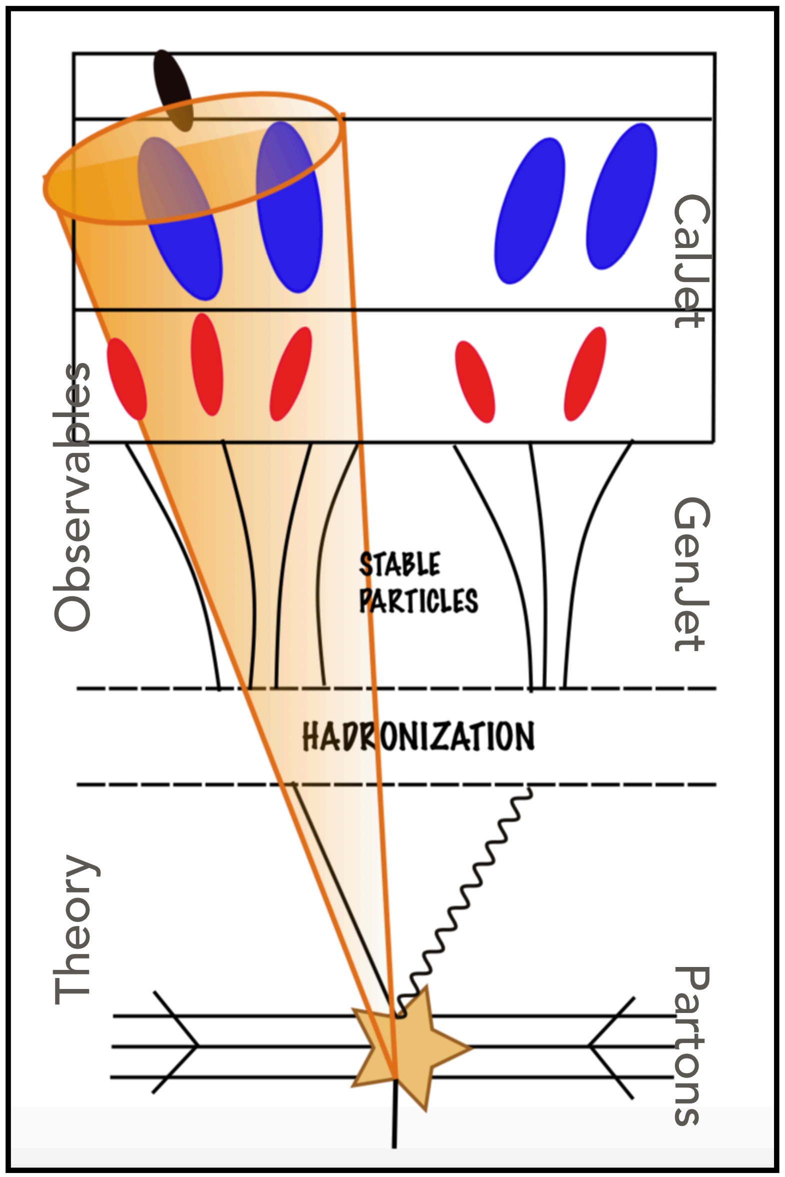
Most interesting case for Belle and EIC!

RADIUS AND JET ALGORITHMS

Standard kt-type algorithms

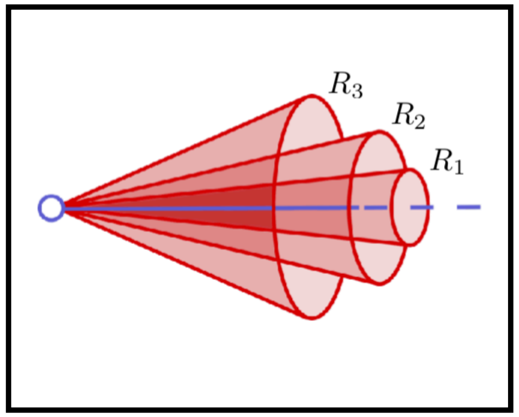
$$d_{ij} = \min\left(k_{T,1}^{2w}, k_{T,2}^{2w}\right) \frac{\Delta R_{ij}}{R}$$

$$w \in \{-1, 0, 1\}$$

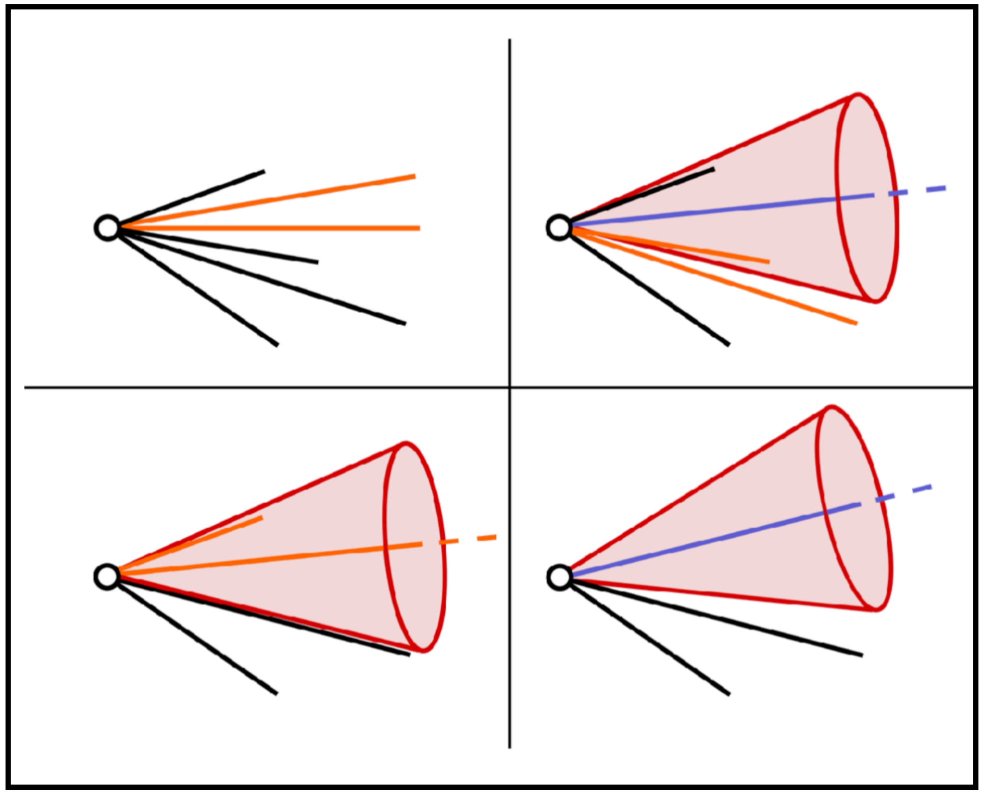


Building a jet…

Step 1:
Set a size
(Radius)



Step 2:
Run a jet
algorithm



JET FUNCTIONS AND MODES

$$J_q(z, \boldsymbol{b}, E\mathcal{R}) = \frac{z}{2N_c}\mathrm{Tr}\Big[\frac{\not{\bar{n}}}{2}\langle 0|\big[\delta\big(2E/z - \bar{n}\cdot P\big)e^{\mathrm{i}\boldsymbol{b}\cdot\boldsymbol{P}}\chi_n(0)\big]\sum_X |J_{\mathrm{alg},R}X\rangle\langle J_{\mathrm{alg},R}X|\bar{\chi}_n|0\rangle$$

$$\mathcal{R} \equiv 2\tan\frac{R}{2}$$

Mode	$R \ll \theta \ll 1$	$\theta \sim R \ll 1$	$\theta \ll R$ (WTA)	$\theta \ll R \ll 1$ (SJA)	$\theta \ll R \sim 1$ (SJA)
hard	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
n-coll.	$(1, \sqrt{\theta}, \theta)$	$(1, \sqrt{\theta}, \theta)$	$(1, \sqrt{\theta}, \theta)$		
$\bar{n}$-coll.	$(\sqrt{\theta}, 1, \theta)$	$(\sqrt{\theta}, 1, \theta)$	$(\sqrt{\theta}, 1, \theta)$		
n-coll$_2$	$(1, \sqrt{R}, R)$			$(1, \sqrt{R}, R)$	
$\bar{n}$-coll$_2$	$(\sqrt{R}, 1, R)$			$(\sqrt{R}, 1, R)$	
n-csoft				$\theta/R(1, \sqrt{R}, R)$	
$\bar{n}$-csoft				$\theta/R(\sqrt{R}, 1, R)$	
soft	(θ, θ, θ)	(θ, θ, θ)	(θ, θ, θ)	(θ, θ, θ)	(θ, θ, θ)

JET AXES

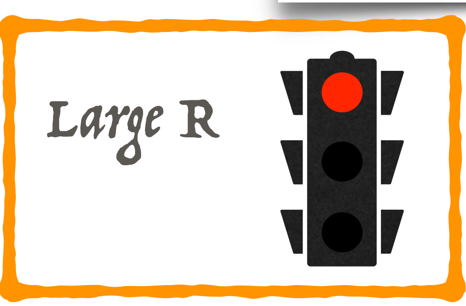
Larkoski, Neill, Thaler `14
arXiv: 1401.2158

Standard jet axis (SJA)

The sum of the momentum of collinear and soft particles is zero

Introduces soft-sensitivity to the axis definition. Important with unintegrated transverse momentum

$$E_{(12)} = E_1 + E_2, \quad \vec{p}_{(12)} = \vec{p}_1 + \vec{p}_2 \,,$$

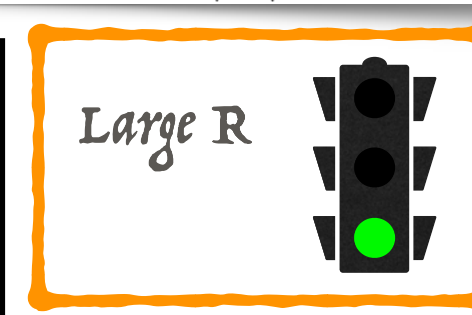


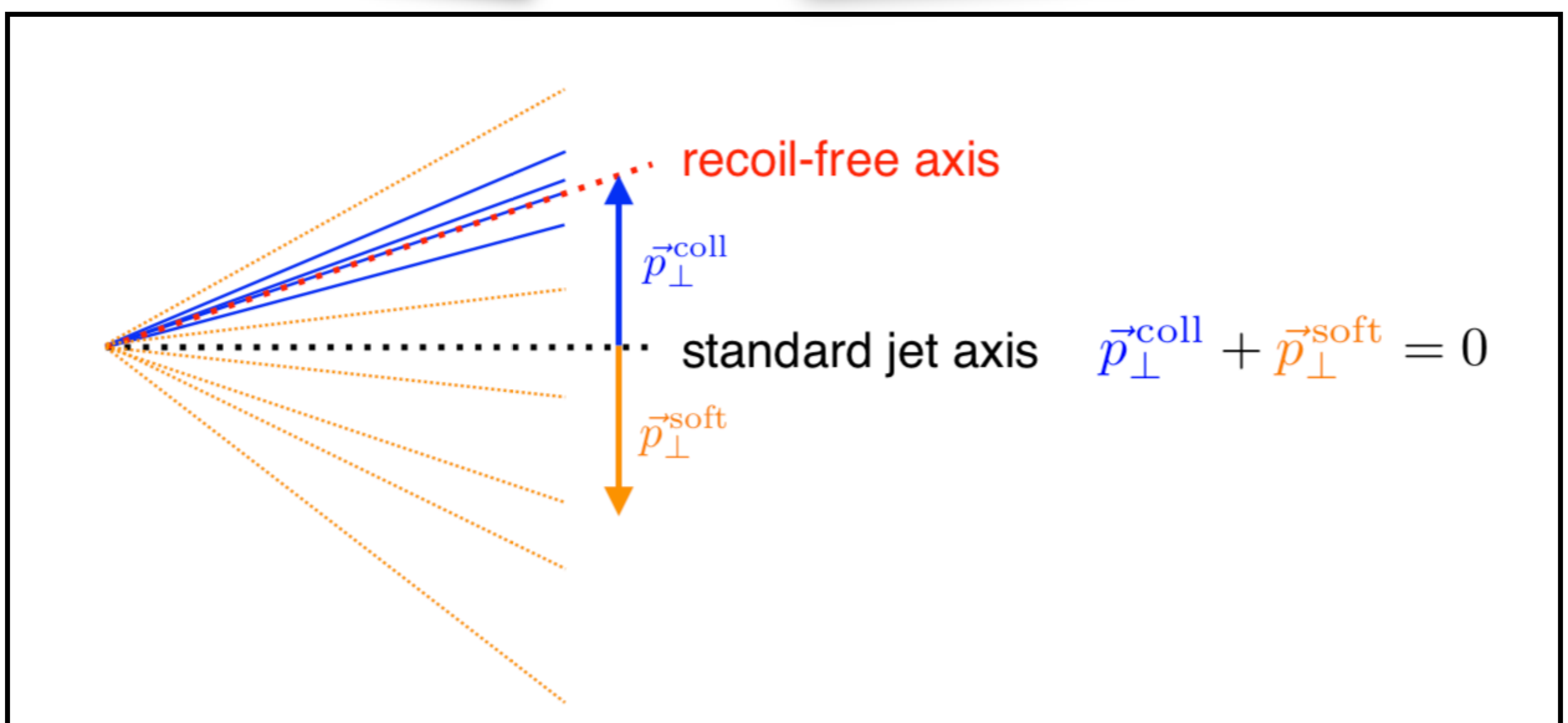
Winner-take-all (WTA)

It always follows the direction of the most energetic particle

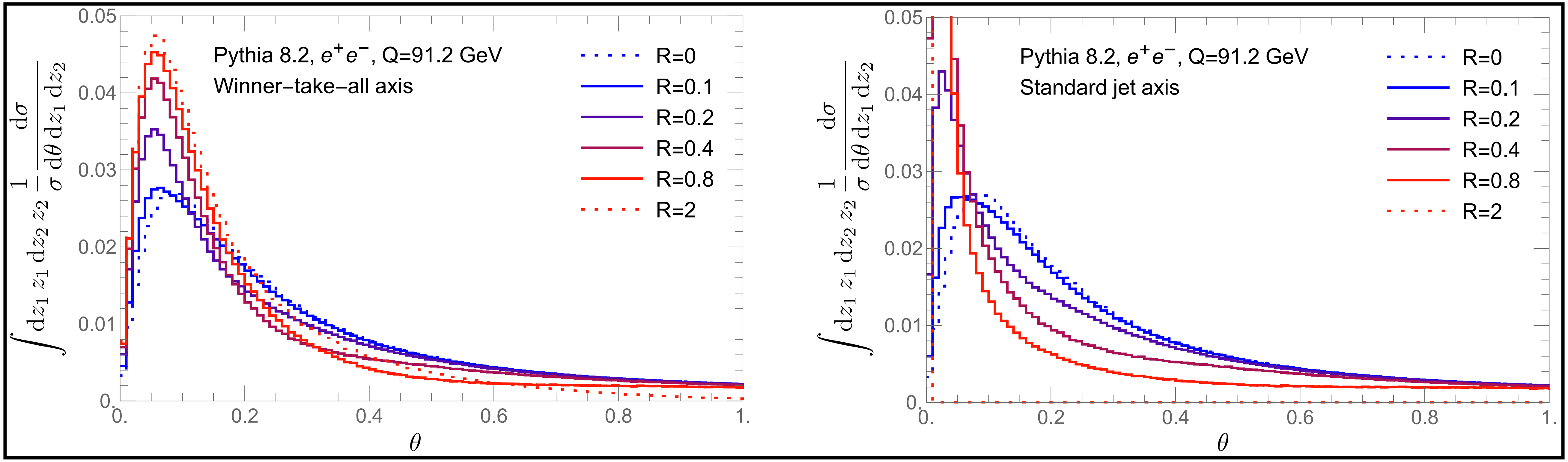
Recoil invariant. It is not sensitive to soft radiation

$$E_{(12)} = E_1 + E_2, \quad \vec{p}_{(12)} = E_{(12)} \left[\frac{\vec{p}_1}{|\vec{p}_1|} \theta(E_1 - E_2) + \frac{\vec{p}_2}{|\vec{p}_2|} \theta(E_2 - E_1) \right]$$





CHECKING WITH PYTHIA 8.2.



Cross-section of angular decorrelation for different values of the radii of the jets

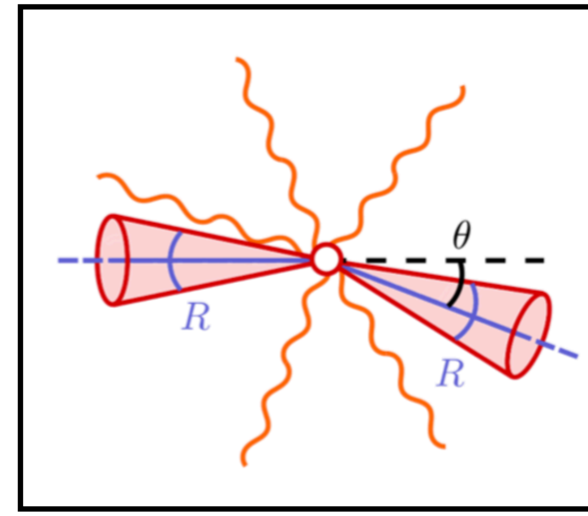
For small values of R the cross-section for both axis elections agrees!

For big values of R the cross section in SJA is inconsistent!

Factorization is broken

WTA axis solves the problems!

FACTORIZATION



$$\theta \sim R \ll 1$$

The wide angle soft radiation does not resolve individual collinear emissions in the jet

$$\frac{d\sigma_{ee\to JJX}}{dz_1 dz_2 d\boldsymbol{q}} = H(s,\mu) \int \frac{d\boldsymbol{b}}{(2\pi)^2} e^{-i\boldsymbol{b}\boldsymbol{q}} J_q^{\text{axis}}\left(z_1, \boldsymbol{b}, \frac{\sqrt{s}}{2}R, \mu, \zeta_1\right) J_q^{\text{axis}}\left(z_2, \boldsymbol{b}, \frac{\sqrt{s}}{2}R, \mu, \zeta_2\right)\left[1 + \mathcal{O}\left(\frac{\boldsymbol{q}^2}{s}\right)\right]$$

The soft function is the same as in (hadronic) TMD fragmentation

$$R \ll \theta \ll 1$$

Refactorization as in standard TMD case

$$J_i^{\text{axis}} = \sum_j \int \frac{dz'}{z'} \left[(z')^2 \mathbb{C}(z', \boldsymbol{b}, \mu, \zeta)\right] \mathcal{J}_i\left(\frac{z}{z'}, \frac{\sqrt{s}}{2}R, \mu\right)\left[1 + \mathcal{O}\left(b^2 s^2 R^2/4\right)\right]$$

NNLO TMDFFs Coefficients $\otimes$ Coll. jet Function

Echevarría, S., Vladimirov arXiv: 1604.07869

Kang, Ringer, Vitev, arXiv:1606.06732
Dal, Kim, Leibovich, arXiv:1606.07411

TMD SEMI-INCLUSIVE JET FUNCTION AT NLO

$$\theta \ll 1$$
$$\theta \ll R$$

Collinear radiation of typical angle θ sees the jet boundary infinitely far away

↓

Independence of the radius of the jet!

The collinear radiation is mostly inside the jet

↓

The dependence on z is power suppressed!

$$J_i^{\rm WTA}(z, \boldsymbol{b}, ER, \mu, \zeta) = \delta(1-z)\, \mathscr{J}_i^{\rm WTA}(\boldsymbol{b}, \mu, \zeta) \left[1 + \mathcal{O}\left(\frac{1}{\boldsymbol{b}^2 E^2 R^2}\right)\right]$$

where

$$\mathscr{J}_i^{\rm WTA}(\boldsymbol{b}, \mu, \zeta) = \frac{1}{2N_c(\bar{n}\cdot p_J)} \mathrm{Tr}\left\{ \frac{\not{\bar{n}}}{2} \langle 0| e^{-i\boldsymbol{b}\boldsymbol{P}_\perp} \chi_n(0) | J_{\rm alg}^{\rm WTA}\rangle \langle J_{\rm alg}^{\rm WTA} | \bar{\chi}_n(0)|0\rangle \right\}$$

$$\mathscr{J}_i^{[0]\rm WTA}(\boldsymbol{b}, \mu, \zeta) = 1$$

$$\mathscr{J}_i^{[1]\rm WTA}(\boldsymbol{b}, \mu, \zeta) = 2\left\{ N_i + L_\mu \left[\mathcal{C}_i' + \mathcal{C}_i \left(\mathbf{l}_\zeta - \frac{1}{2} L_\mu \right)\right]\right\}$$

$$N_q = C_F\left(\frac{7}{2} - \frac{5\pi^2}{12} - 3\ln 2\right)$$

$$N_g = C_A\left(\frac{131}{36} - \frac{5\pi^2}{12}\right) - \frac{17}{18} n_f T_R - \beta_0 \ln 2$$

TMD SEMI-INCLUSIVE JET FUNCTION AT NNLO

We know the evolution of the TMD jet function and in this limit it does not depend on radius or z

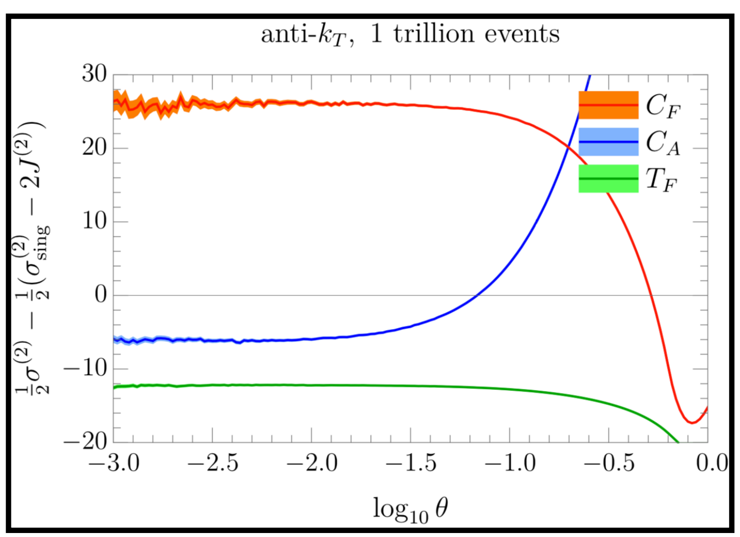
↓

We can predict the log behavior of the two-loop jet function solving renormalization group equations and the constant can be numerically calculated (EVENT2)

$$\theta \ll 1$$
$$\theta \ll R$$

Predicted by RG equations ↑ C_{kl} — Predicted by EVENT2 ↑ C_0

$$\mathscr{J}^{[2]\mathrm{WTA}}(\boldsymbol{b}, \mu, \zeta) = \sum_{k=1}^{4} \sum_{l=0}^{k} C_{kl} L_\mu^k \mathbf{l}_\zeta^l + C_0$$



$$C_0 = j_{C_F} + j_{C_A} + n_f j_{T_F}$$

SUMMING UP ON WTA AXIS

Measuring jet decorrelation using WTA axes we have that
factorization theorem holds for all jet radii.

$R \ll \theta \ll 1$

$\theta \sim R \ll 1$

$$\frac{d\sigma_{ee\to JJX}}{d\boldsymbol{q}} = H(Q^2,\mu)\int \frac{d\boldsymbol{b}}{(2\pi)^2} e^{-i\boldsymbol{b}\boldsymbol{q}} J_f^{\rm WTA}\left(\mathbf{b}, z, \frac{\sqrt{s}}{2}R;\mu_i,\zeta_i\right) J_f^{\rm WTA}\left(\mathbf{b}, z\frac{\sqrt{s}}{2}R;\mu_i,\zeta_i\right) R^2[\mathbf{b};(\mu_i,\zeta_i)\to(\mu,\zeta)]$$

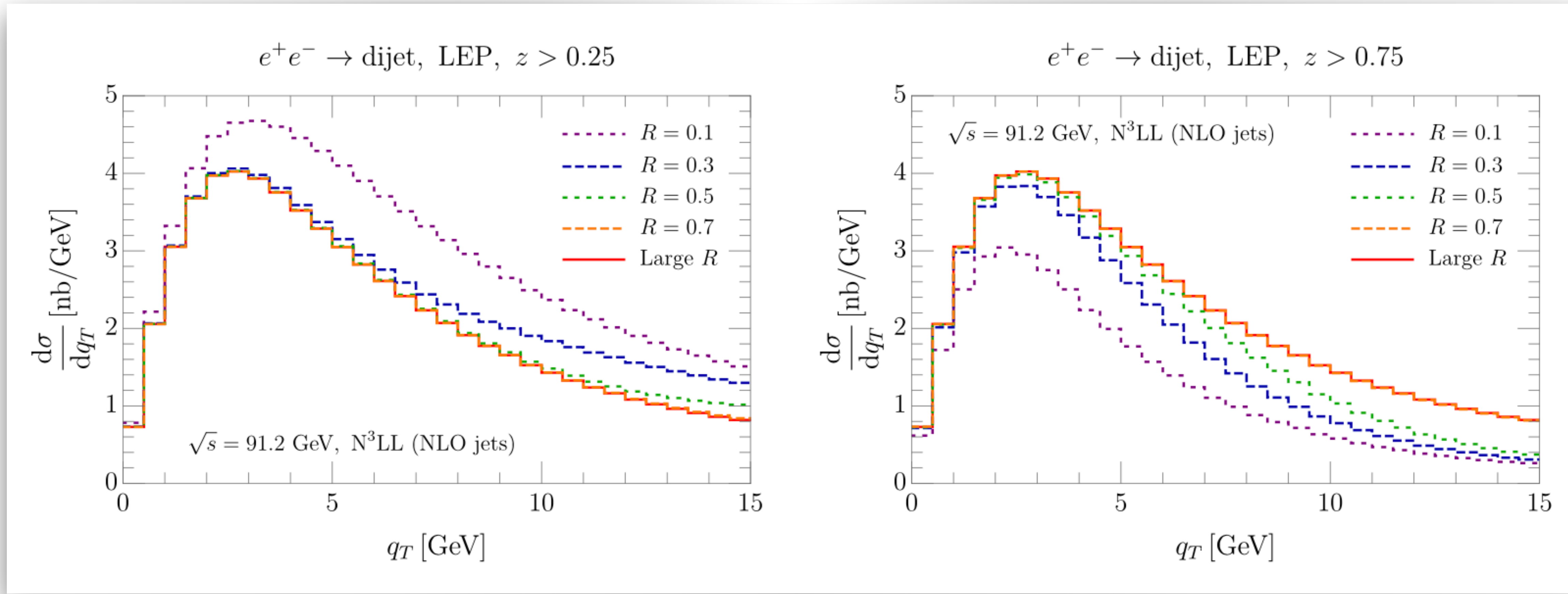
$\theta \ll 1$

$\theta \ll R$

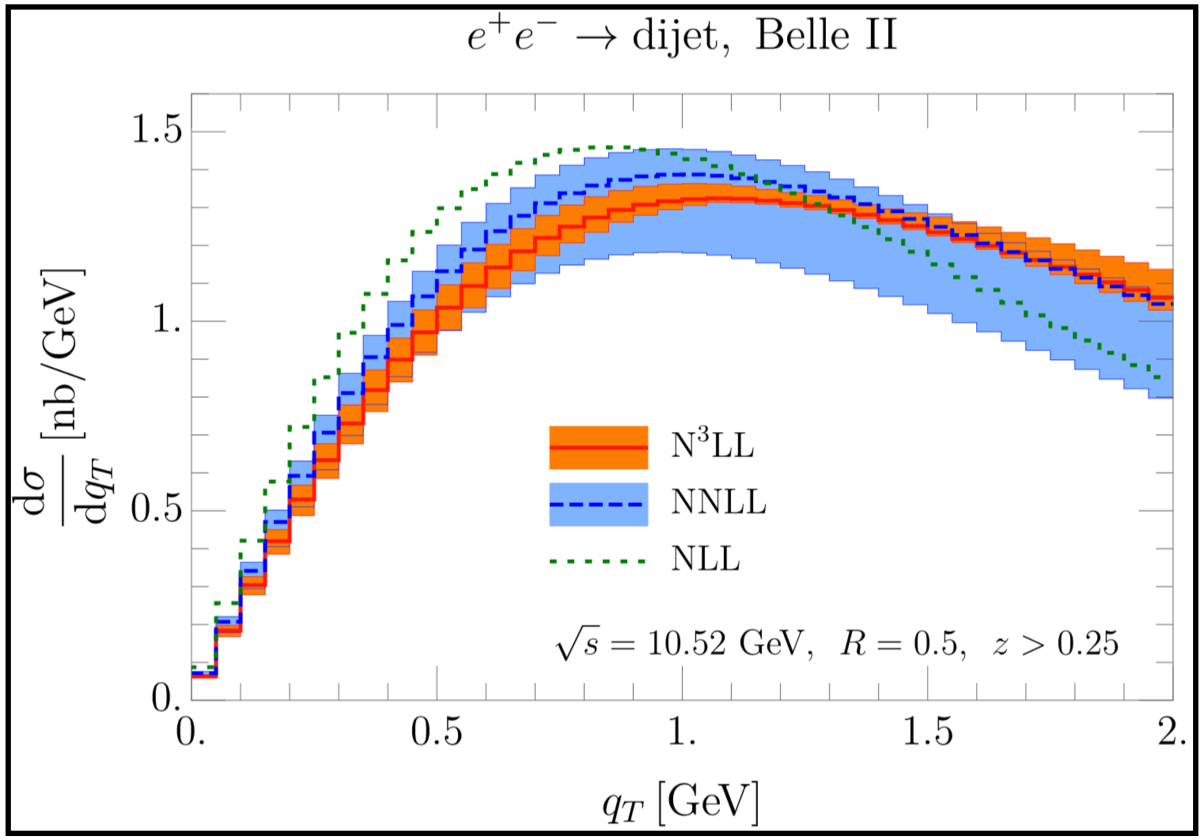
TMD evolution kernel

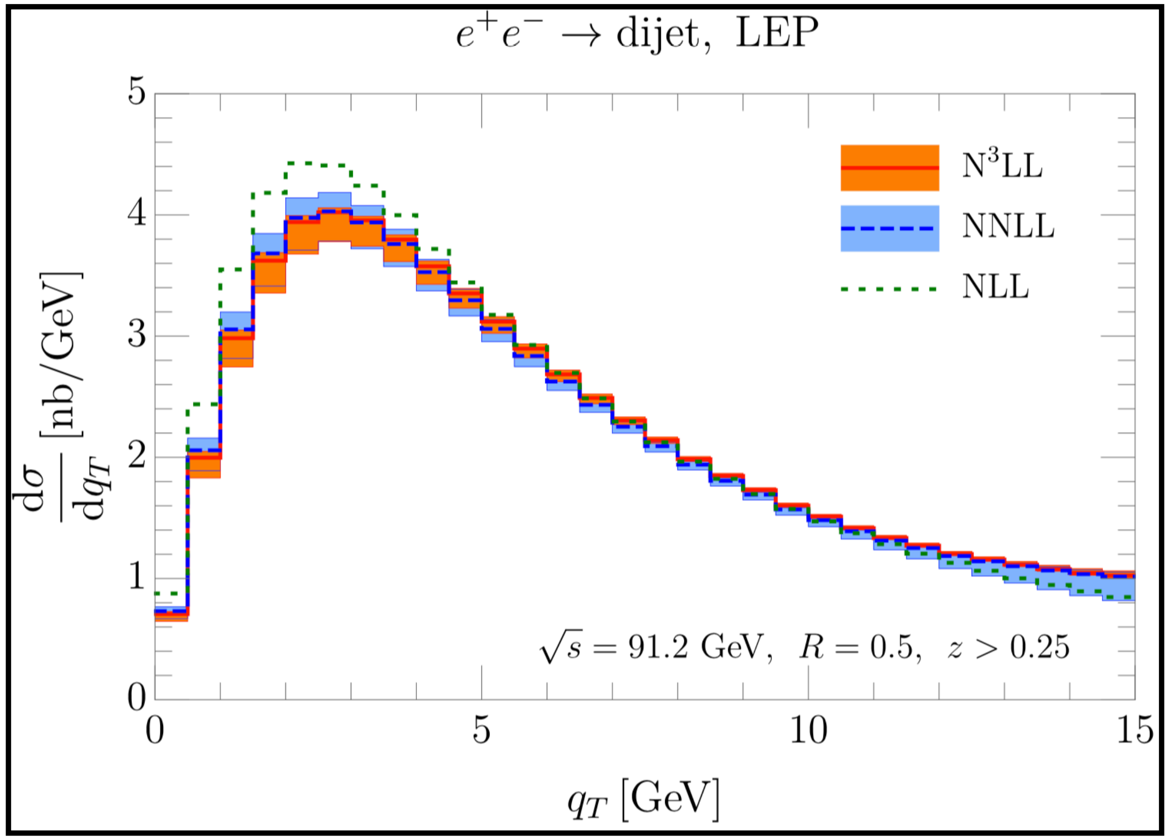
$$\frac{d\sigma_{ee\to JJX}}{dq} = H(Q^2,\mu)\int \frac{db}{(2\pi)^2} e^{-ibq} \mathscr{J}_f^{\rm WTA}(\mathbf{b};\mu_i,\zeta_i)\, \mathscr{J}_f^{\rm WTA}(\mathbf{b};\mu_i,\zeta_i) R^2[\mathbf{b};(\mu_i,\zeta_i)\to(\mu,\zeta)]$$

RADIUS DEPENDENCE AT LEP



PERTURBATIVE CONVERGENCE: LARGE RADIUS



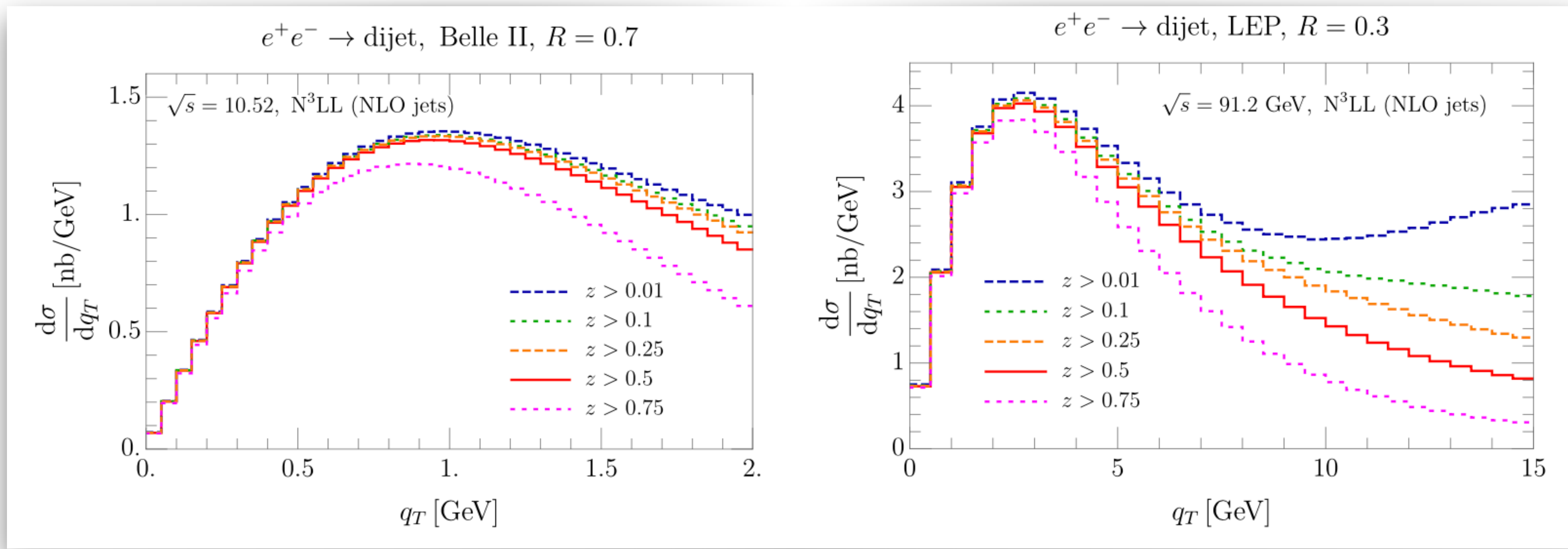


As the large-R jet function does not depend on radius or z, we can predict the two loop jet function by RG + Numerical constant (Event2)

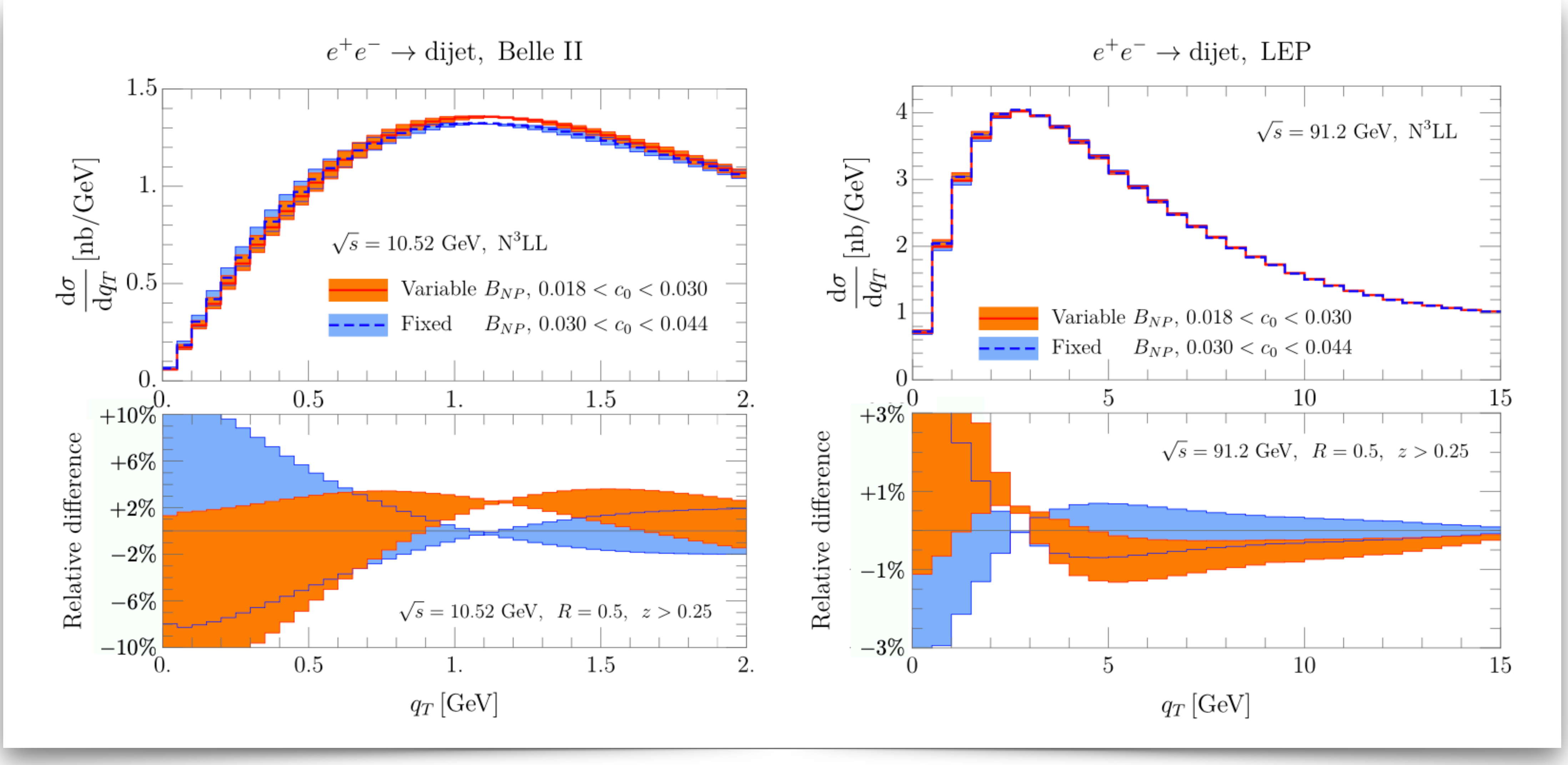
We use an improved NLO + NNLO large-R jet functions
Resummation up to N3LL!

Theoretical errors are reduced when the perturbative order is increased!

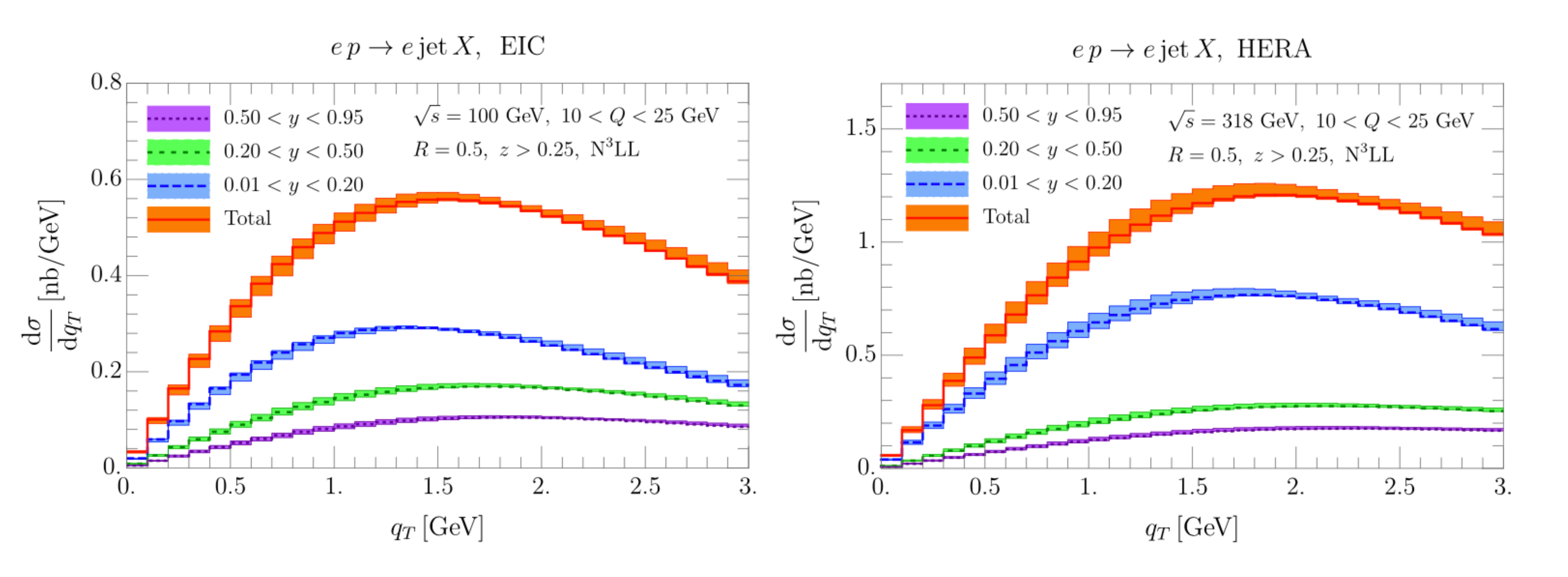
Z-DEPENDENCE (BELLE, LEP)



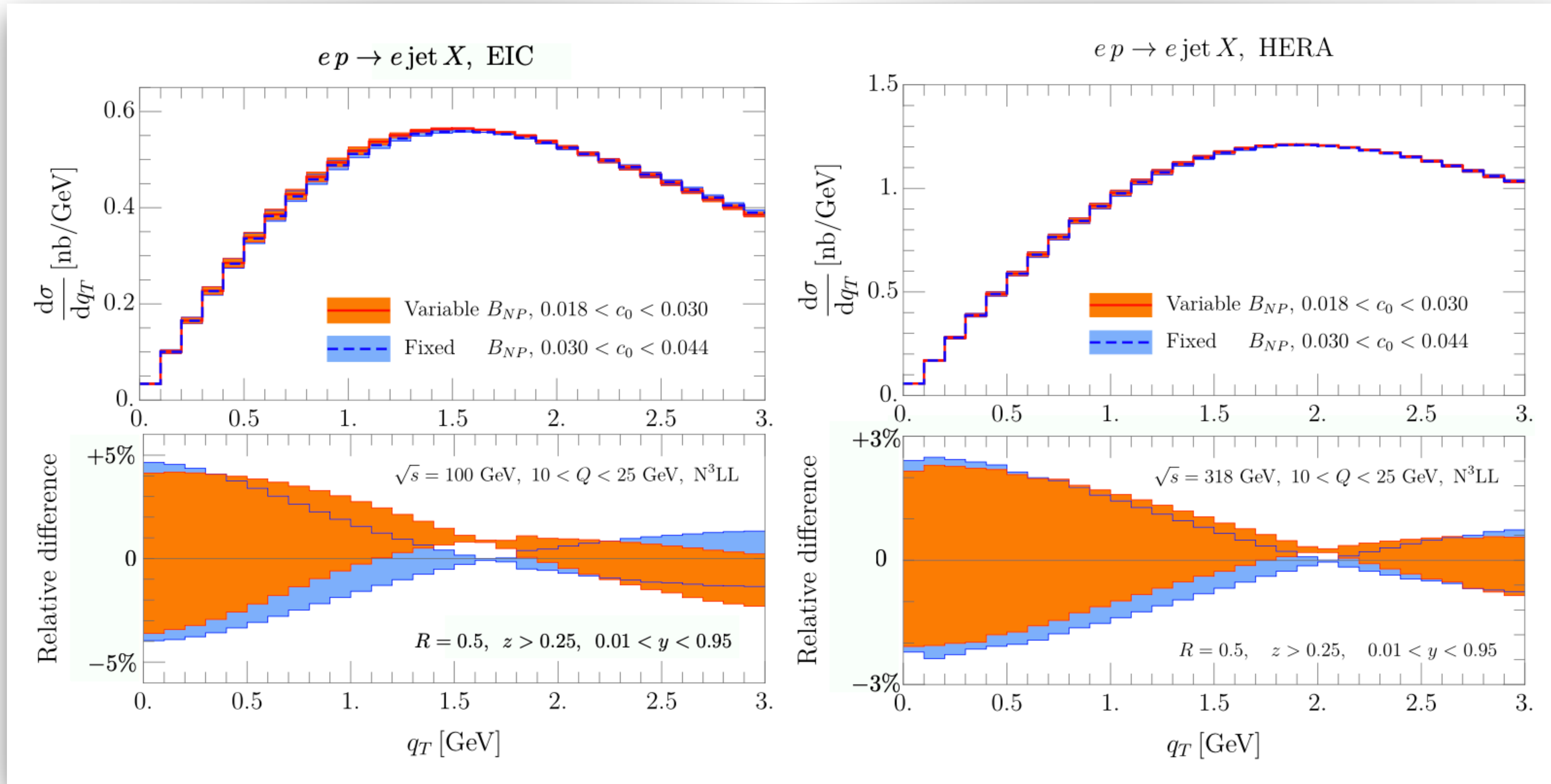
TMD KERNEL (BELLE, LEP)



SIDIS (EIC, HERA)



SIDIS (EIC, HERA)



TODO: there can be a stronger dependence on the PDF sets

CONCLUSIONS

- ✓ **Jets offer an opportunity to study TMD and hadronization**
- ✓ *There exist observables for which the factorization theorems have the same soft function for TMD and are independent of jet details like radius, algorithms*
- ✓ We expect that perturbation theory is more controllable with jets than with hadrons
- ✓ **For the e+e- case we can achieve an incredible precision for the TMD evolution kernel**

BACKUP SLIDES

DOUBLE-SCALE RENORMALIZATION GROUP EVOLUTION

Same RG evolution for hadronic TMDs and for TMD jet functions!

TMDs

$$\mu^2 \frac{d}{d\mu^2} D_i(z, \boldsymbol{b}, \mu, \zeta) = \frac{1}{2}\gamma_F^i(\mu, \zeta) D_i(z, \boldsymbol{b}, \mu, \zeta)$$

$$\zeta \frac{d}{d\zeta} D_i(z, \boldsymbol{b}, \mu, \zeta) = -\mathcal{D}^i(\mu, \boldsymbol{b}) D_i(z, \boldsymbol{b}, \mu, \zeta)$$

Jets

$$\mu^2 \frac{d}{d\mu^2} J_i^{\text{axis}}(z, \boldsymbol{b}, QR, \mu, \zeta) = \frac{1}{2}\gamma_F^i(\mu, \zeta) J_i^{\text{axis}}(z, \boldsymbol{b}, QR, \mu, \zeta)$$

$$\zeta \frac{d}{d\zeta} J_i^{\text{axis}}(z, \boldsymbol{b}, QR, \mu, \zeta) = -\mathcal{D}^i(\mu, \boldsymbol{b}) J_i^{\text{axis}}(z, \boldsymbol{b}, QR, \mu, \zeta)$$

DOUBLE-SCALE RENORMALIZATION GROUP EVOLUTION

They have a common evolution factor

TMDs

$$D_i(z,\boldsymbol{b},\mu_f,\zeta_f) = \exp\left[\int_{(\mu_i,\zeta_i)}^{(\mu_f,\zeta_f)} \left(\gamma_F^i(\mu,\zeta)\frac{d\mu}{\mu} - \mathcal{D}^i(\mu,\boldsymbol{b})\frac{d\zeta}{\zeta}\right)\right] D_i(z,\boldsymbol{b},\mu_i,\zeta_i)$$

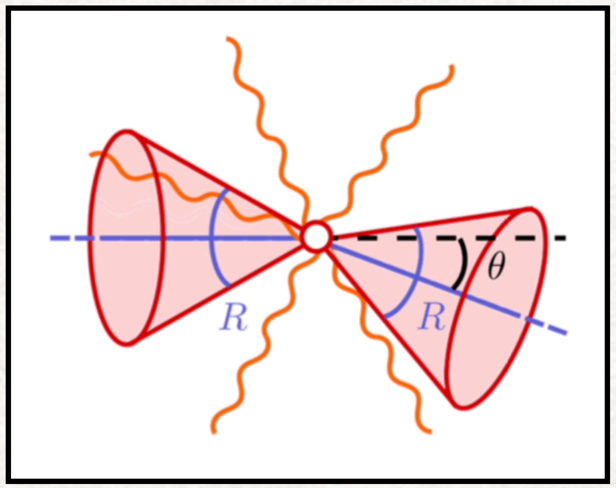
Jets

$$J_i^{\text{axis}}(z,\boldsymbol{b},QR,\mu_f,\zeta_f) = \exp\left[\int_{(\mu_i,\zeta_i)}^{(\mu_f,\zeta_f)} \left(\gamma_F^i(\mu,\zeta)\frac{d\mu}{\mu} - \mathcal{D}^i(\mu,\boldsymbol{b})\frac{d\zeta}{\zeta}\right)\right] J_i^{\text{axis}}(z,\boldsymbol{b},QR,\mu_i,\zeta_i)$$

This fact makes phenomenological analysis simpler!

FACTORIZATION: UNGROOMED JETS

$\theta \ll 1 \quad \theta \ll R$



Standard Jet Axis

The SJA is aligned with the total momentum of the jet

↓

Hard splittings with typical angle R are allowed inside the jet, generating additional soft radiation

↓

Factorization broken!

$$\frac{d\sigma^{\mathrm{SJA}}_{(ee\to JJX)}}{d\boldsymbol{q}} = \sum_{m=2}^{\infty} \mathrm{Tr}_c \left[\mathcal{H}_m(\{n_i\}) \otimes \mathcal{S}_m(\boldsymbol{q}, \{n_i\})\right]$$