



Studying transverse momentum distributions with jets

Lorenzo Zoppi

Based on work with W. Waalewijn, I. Scimemi, D. Gutierrez-Reyes
PRL 121 162001 and arXiv:1904.[tomorrow]

(ongoing work with D.G.R., I.S., Y. Makris, V. Vaidya)

DIS 2019 - Torino, April 9

Transverse momentum distributions

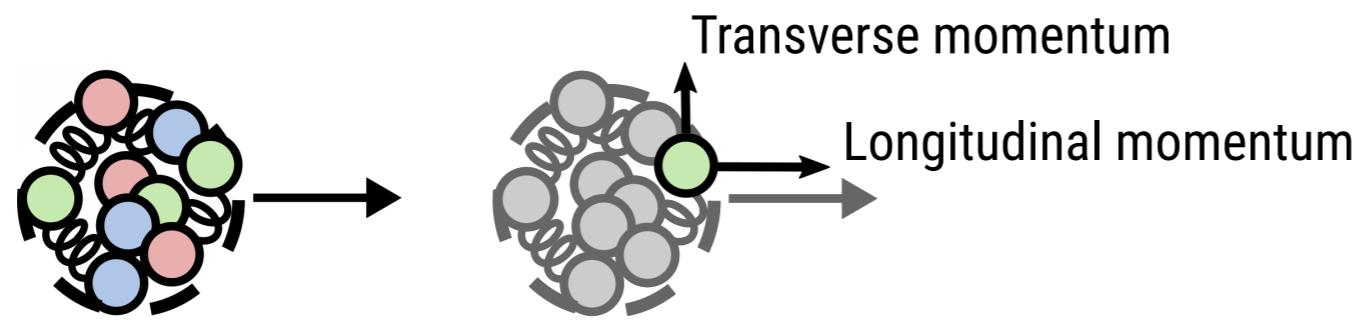
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TMD Parton distribution functions

$$F_{p \rightarrow a}(\mathbf{q}, x, \mu)$$

TMD Fragmentation functions

$$D_{a \rightarrow h}(\mathbf{q}, z, \mu)$$



$$\int d\mathbf{q} F_{p \rightarrow a}(\mathbf{q}, x, \mu) = f_{p \rightarrow a}(x, \mu)$$

$$\int d\mathbf{q} D_{a \rightarrow h}(\mathbf{q}, z, \mu) = d_{a \rightarrow h}(z, \mu)$$

Collinear parton distributions / fragmentation functions

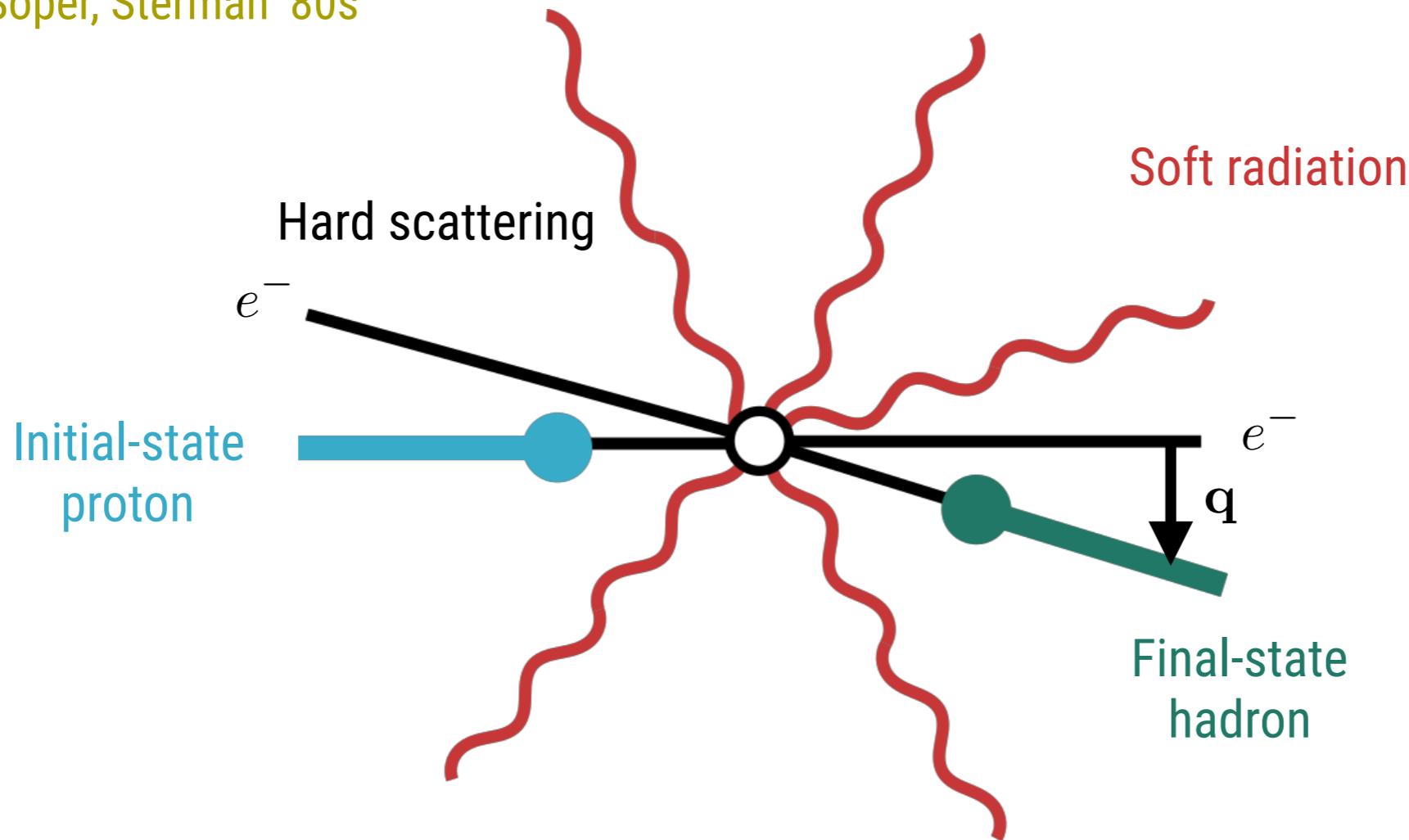
$$F_{p \rightarrow a}(\mathbf{q}, x, \mu) = f_{\text{NP}}(x, \mathbf{q}) \otimes \sum_b \mathcal{C}_{a \leftarrow b}(\mathbf{q}, x, \mu) \otimes f_{p \rightarrow b}(x, \mu) \left[1 + \mathcal{O}\left(\frac{\mathbf{q}^2}{\Lambda_{\text{QCD}}^2}\right) \right]$$

Universal, enter factorisation theorems (extract from a process, apply to different ones)

TMD semi-inclusive DIS

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Collins, Soper, Sterman '80s

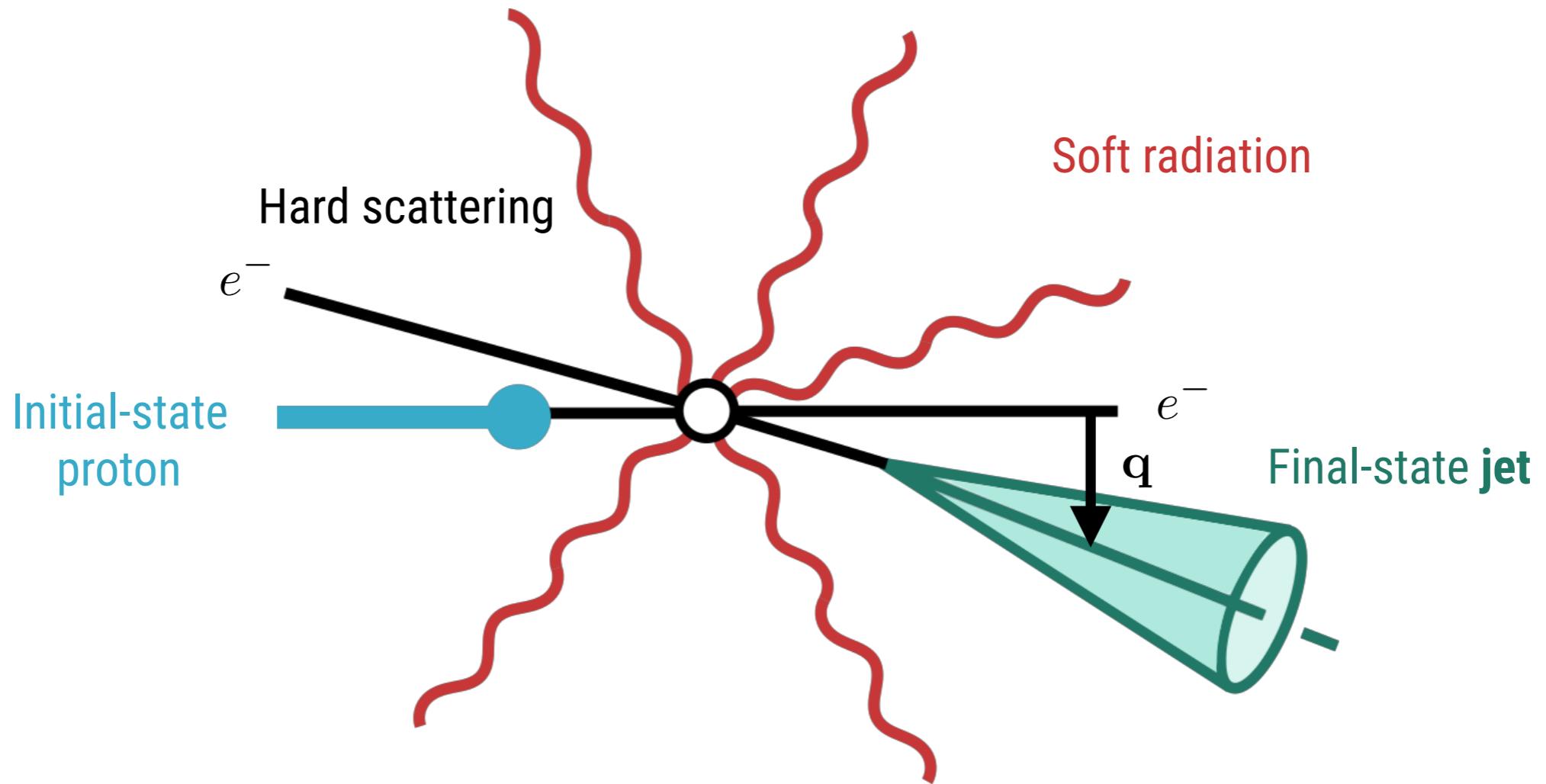


$$\frac{d\sigma_{(ep \rightarrow ehX)}}{dQ^2 dx dz d\mathbf{q}} = H_{eq \rightarrow eq}(Q^2, x) \int d^2 q \delta^{(2)}(\mathbf{q} - \sum_i \mathbf{q}_i) S(\mathbf{q}_s) F_{p \rightarrow q}(\mathbf{q}_1, x) D_{q \rightarrow h}(\mathbf{q}_2, z)$$

Interplay between initial-state and final-state non-perturbative physics

Main idea: TMD SIDIS with jets

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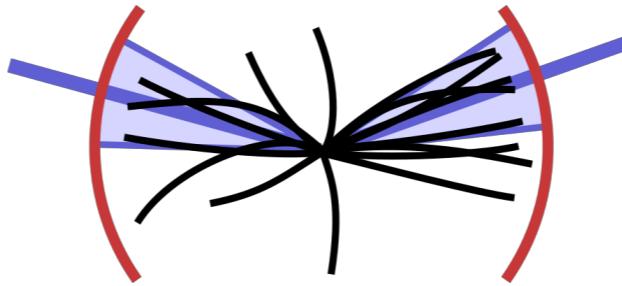


$$\frac{d\sigma_{(ep \rightarrow e\text{Jet}X)}}{dQ^2 dx dz d\mathbf{q}} = H_{eq \rightarrow eq}(Q^2, x) \int d^2 q \delta^{(2)}(\mathbf{q} - \sum_i \mathbf{q}_i) S(\mathbf{q}_s) F_{p \rightarrow q}(\mathbf{q}_1, x) J_q(\mathbf{q}_2, z, R)$$

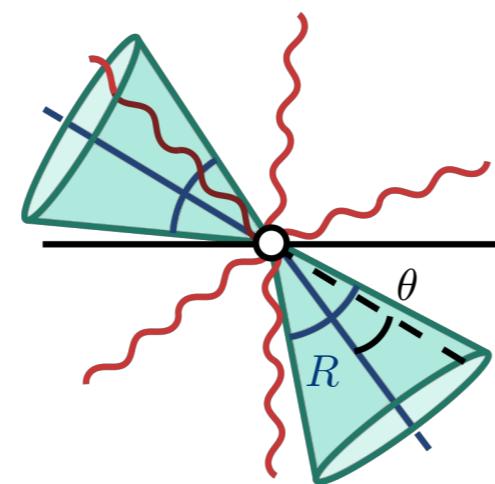
Identical factorisation theorem. Final-state physics is perturbatively calculable

Outline

Recoil-free jets



Clustering algorithms
Winner Take All axis

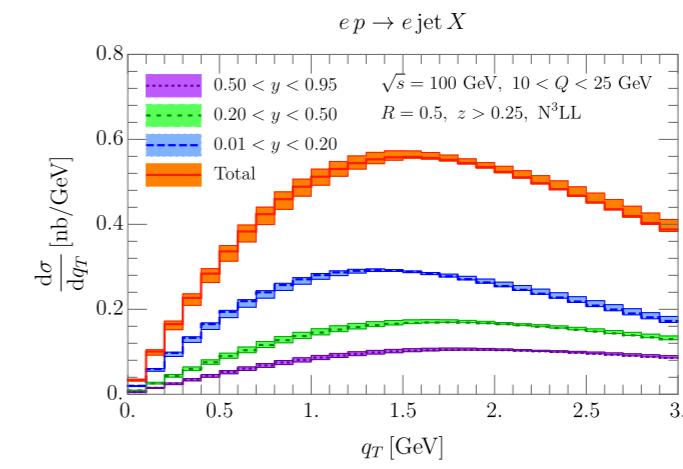
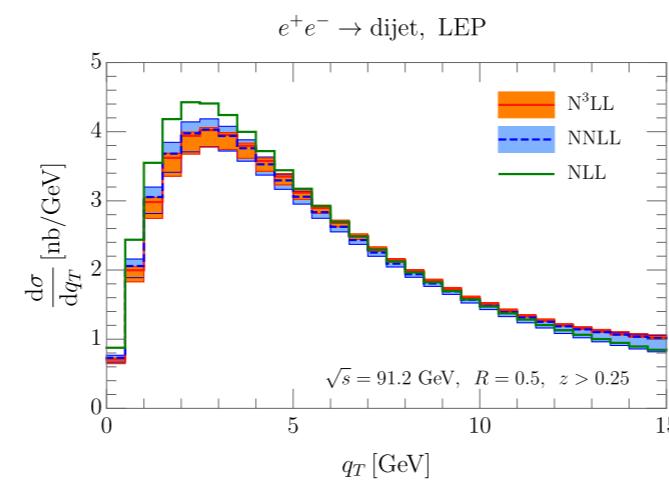


Framework

Factorisation regimes
Evolution and resummation
Extraction of NNLO, large R function

Numerical results

N^3LL predictions for
Belle, LEP, EIC

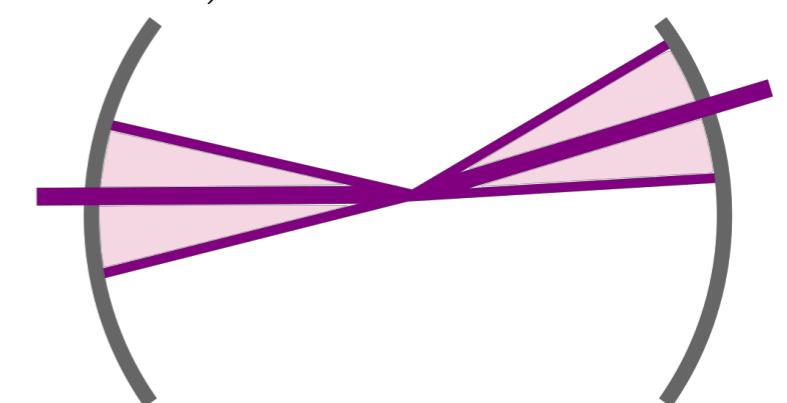
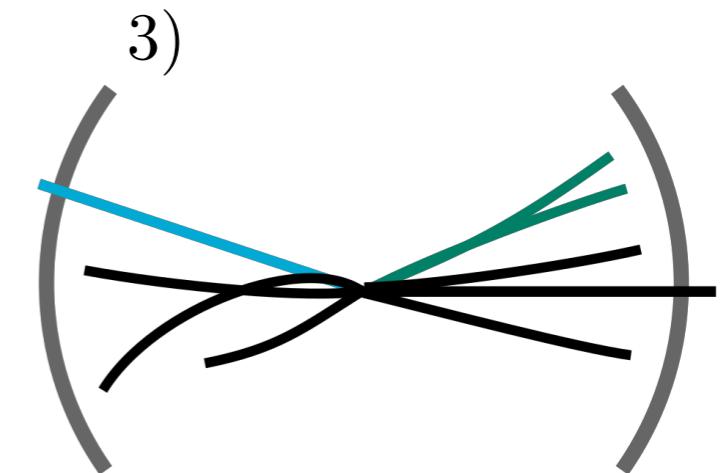
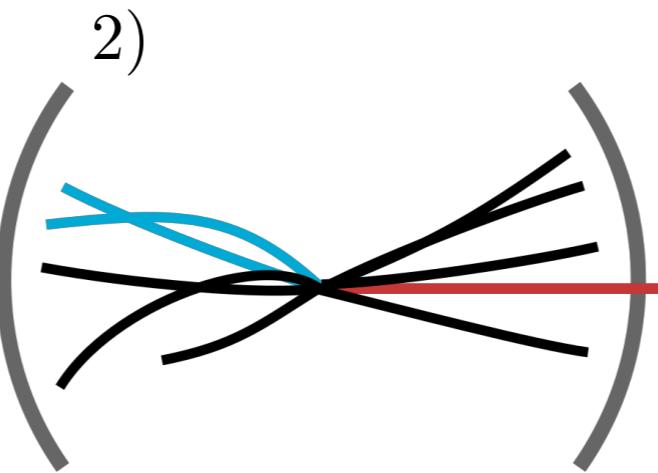
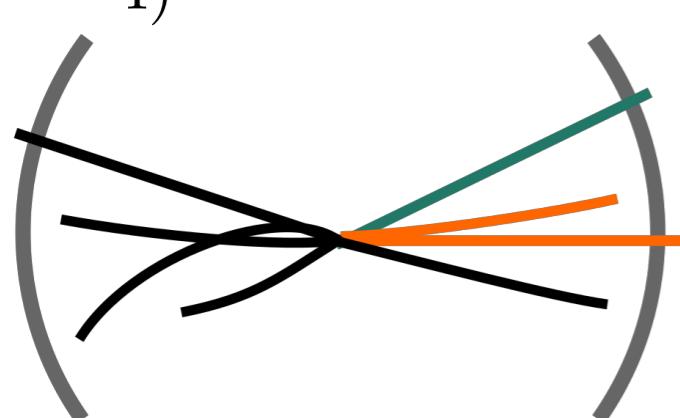
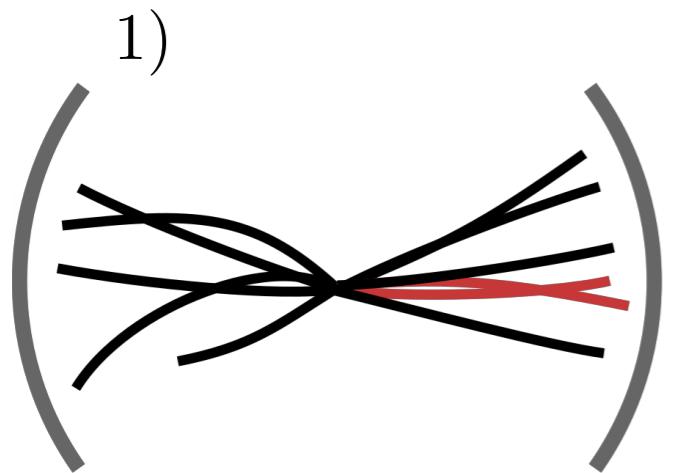


Recoil-free jets

Jet algorithms

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Recombination algorithms



- Repeat
- set a jet radius R
 - locate the **closest** pair
 - if their distance is $< R$
merge them

Algorithms differ for distance and merging prescriptions

Standard jet axis

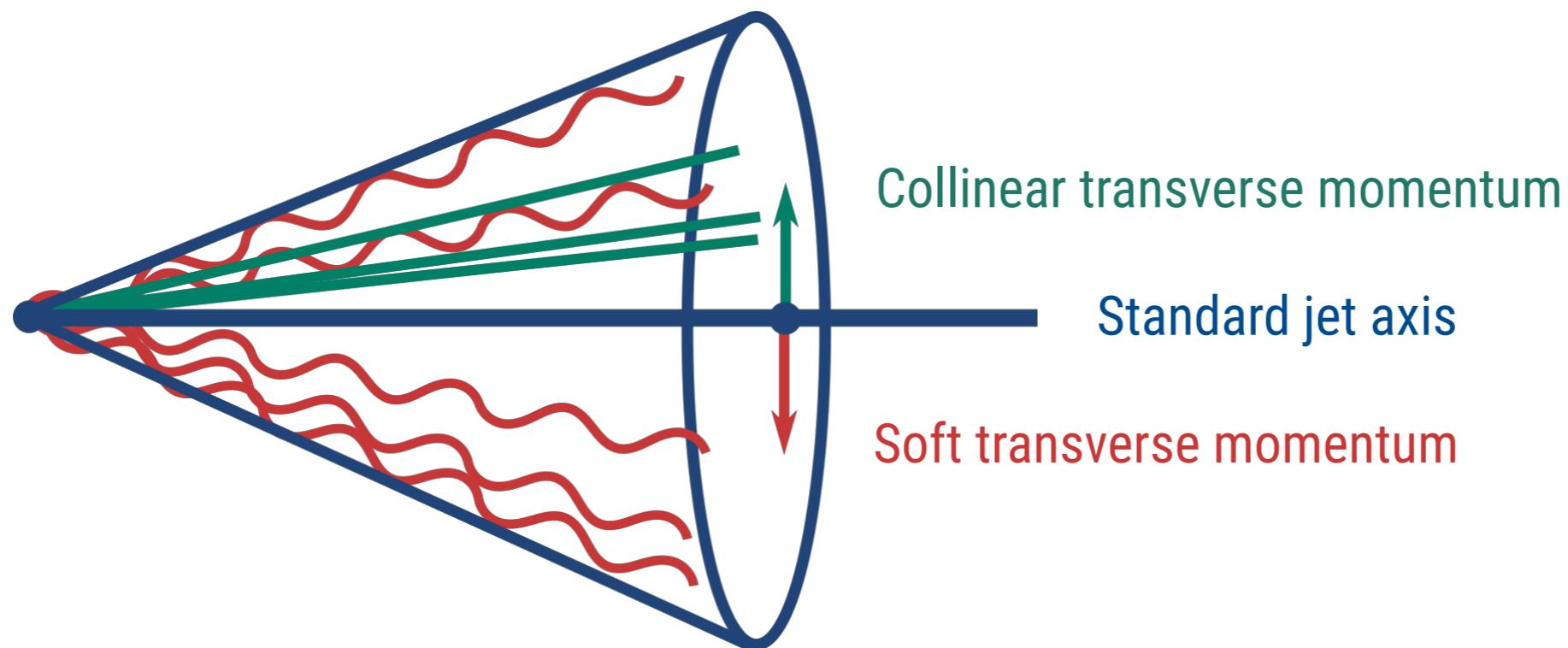
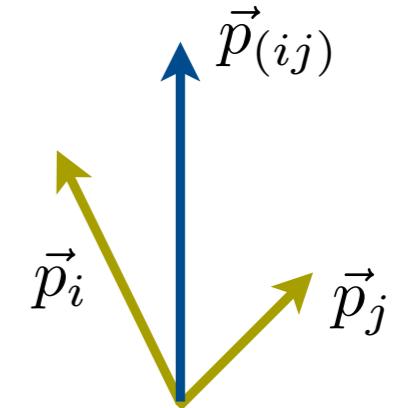
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Distance

$$d_{ij} = \min(k_{T,i}^{2w}, k_{T,j}^{2w}) \frac{\Delta R_{ij}}{R} \quad w \in \{-1, 0, 1\}$$

Merging prescription

$$\begin{aligned} E_{(ij)} &= E_i + E_j \\ \vec{p}_{(ij)} &= \vec{p}_i + \vec{p}_j \end{aligned}$$



Winner Take All axis

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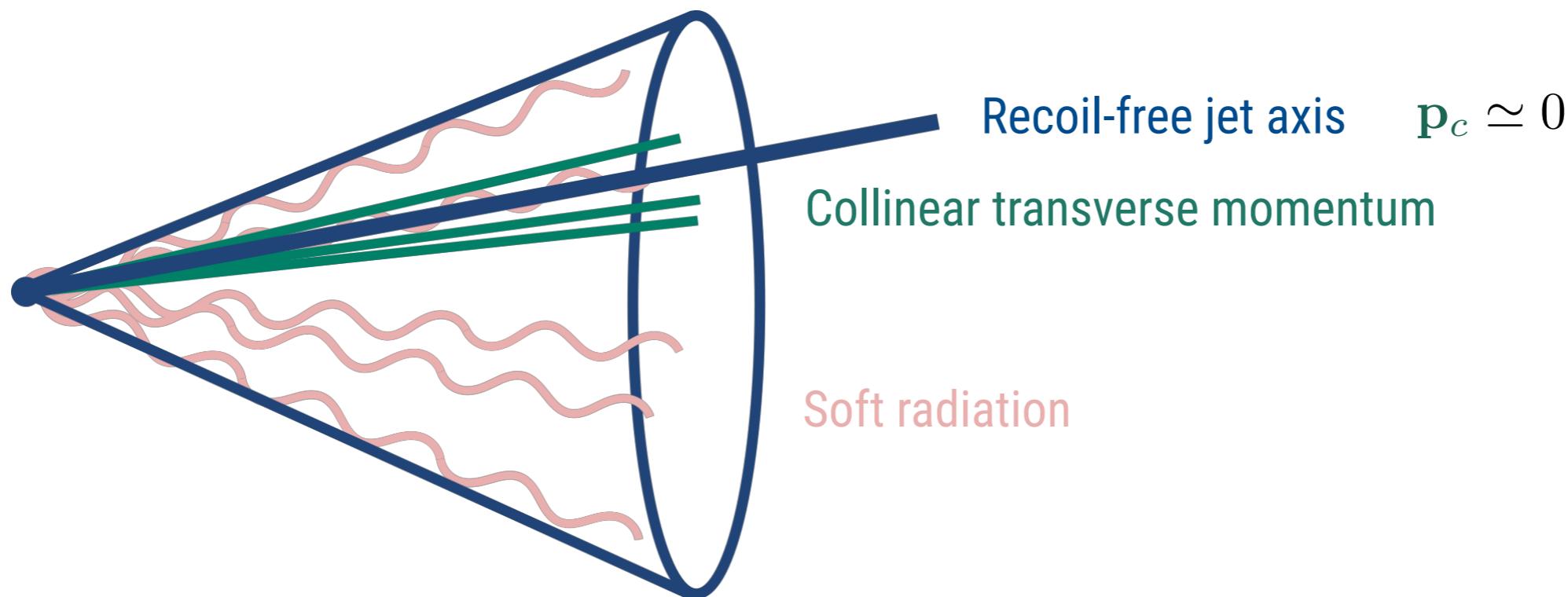
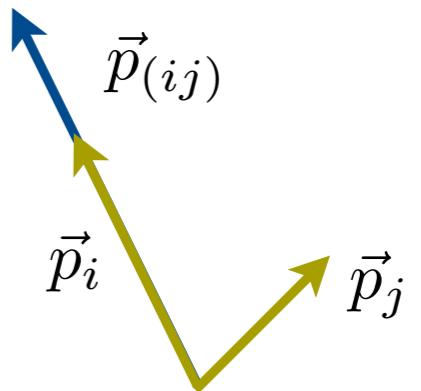
Distance

$$d_{ij} = \min(k_{T,i}^{2w}, k_{T,j}^{2w}) \frac{\Delta R_{ij}}{R} \quad w \in \{-1, 0, 1\}$$

Merging prescription

$$\begin{aligned} E_{(ij)} &= E_i + E_j \\ \hat{n}_{(ij)} &= \hat{n}_i \end{aligned}$$

Salam; Bertolini, Chan, Thaler; Larkoski, Neill, Thaler '14



Transverse-momentum-dependent jets

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Recent focus has been on transverse momentum
of hadrons fragmenting within jets, with standard axis...

Bain, Makris, Mehen'16

Kang, Qiu, Ringer, Xing, Zhang '17

Kang, Procudin, Ringer, Yuan '17

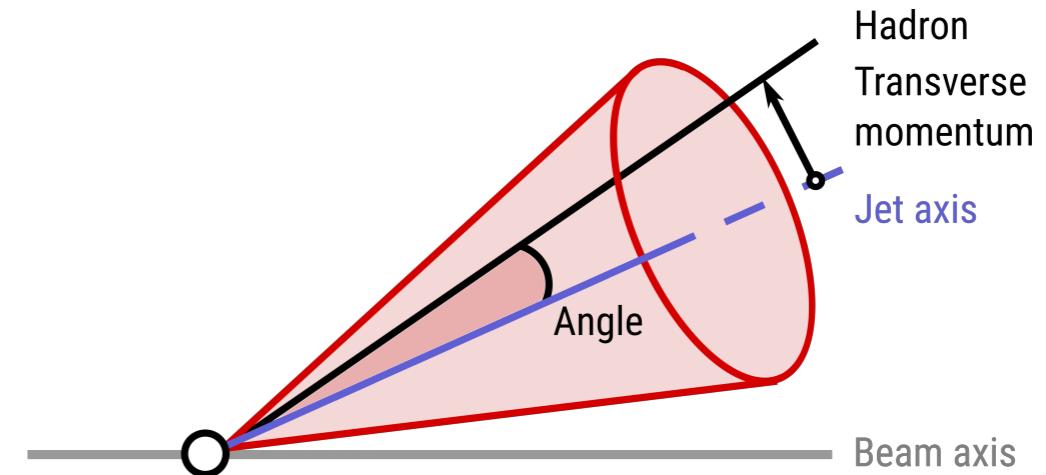
...winner take all axis...

Scimemi, Neill, Waalewijn '16

Neill, Papaefstathiou, Waalewijn, LZ '18

... and jet grooming

Makris, Neill, Vaydia '18



Our focus: transverse momentum of jet themselves

Gutierrez-Reyes, Scimemi, Waalewijn, LZ '18

See also

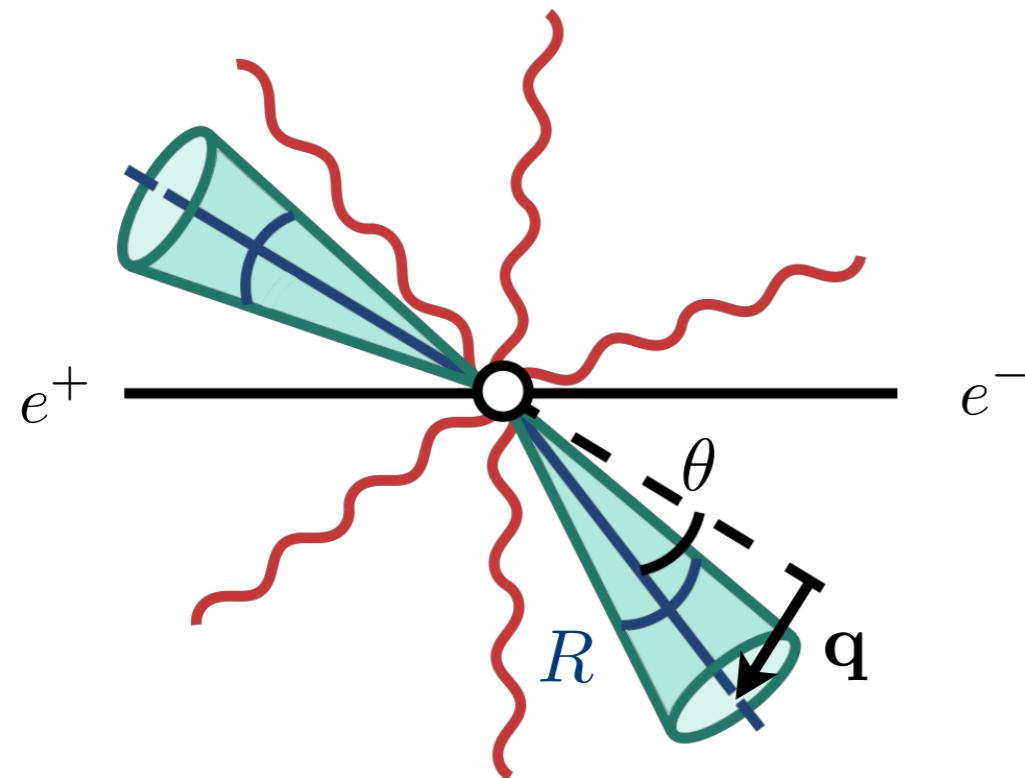
Buffing, Kang, Lee, Liu '18
Liu, Ringer, Vogelsang, Yuan '18

Framework

Observables

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e+e- to dijet



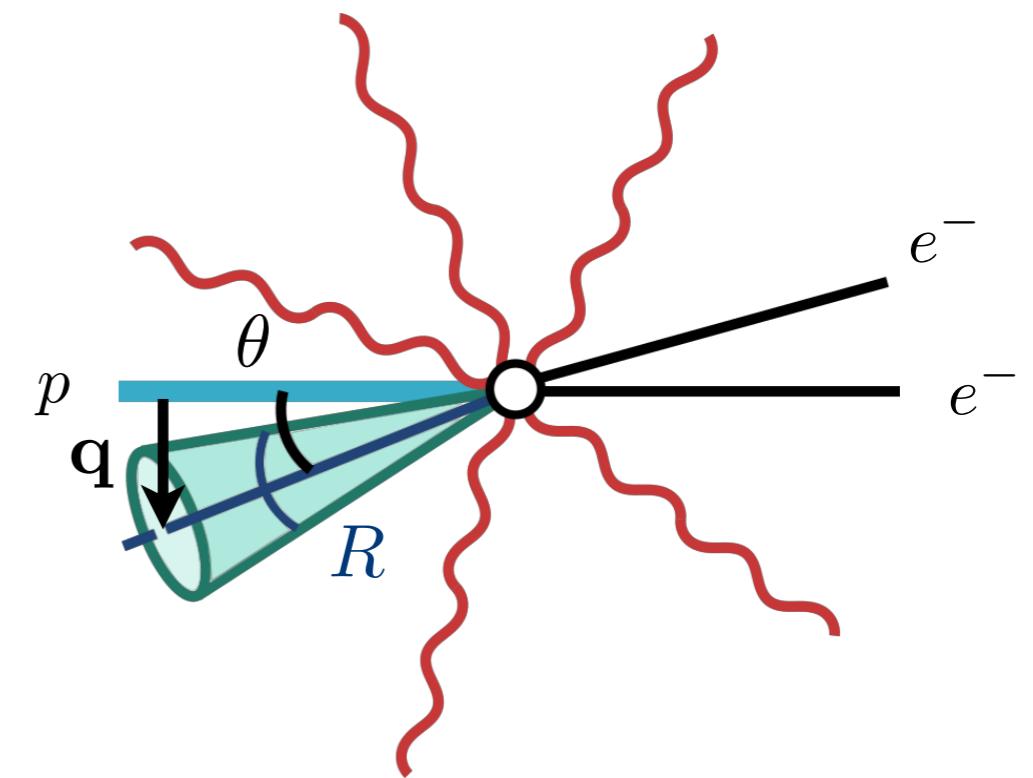
$$\mathbf{q} = \frac{\mathbf{p}_1}{z_1} + \frac{\mathbf{p}_2}{z_2}$$

$$\theta \simeq \frac{2|\mathbf{q}|}{\sqrt{s}}$$

\mathbf{q} Transverse momentum
 z_i Jet energy fractions

\mathbf{p}_i Jet transverse momenta

SIDIS (Breit frame)



$$\mathbf{q} = \frac{\mathbf{p}}{z}$$

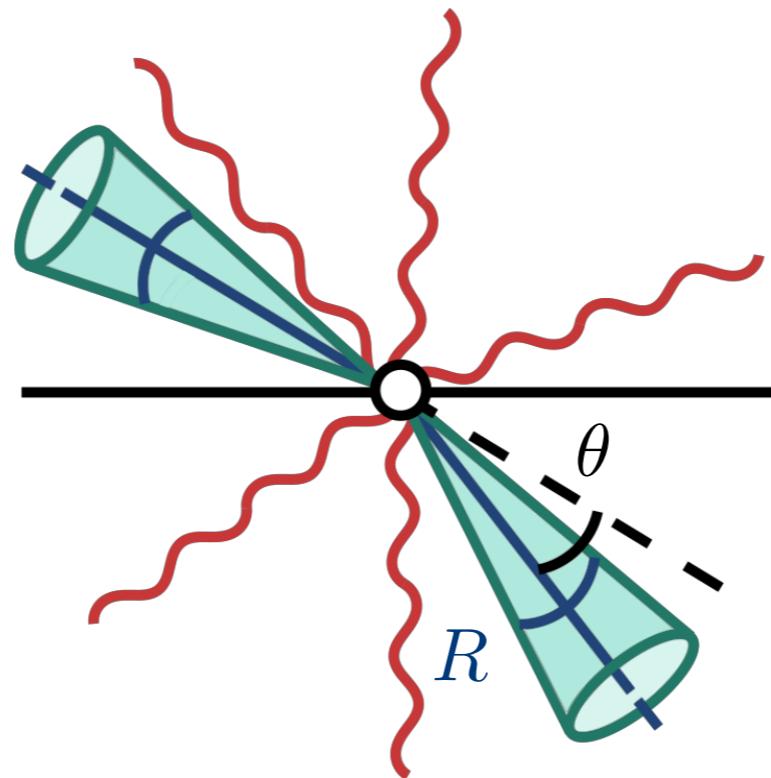
$$\theta \simeq \frac{2|\mathbf{q}|}{Q}$$

Factorization requires $\theta \ll 1$, but different hierarchies with the jet radius are possible!

Regime $R \sim \theta$

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Same factorisation formula than for hadrons (same modes!)



Jet functions depend on the choice of axis

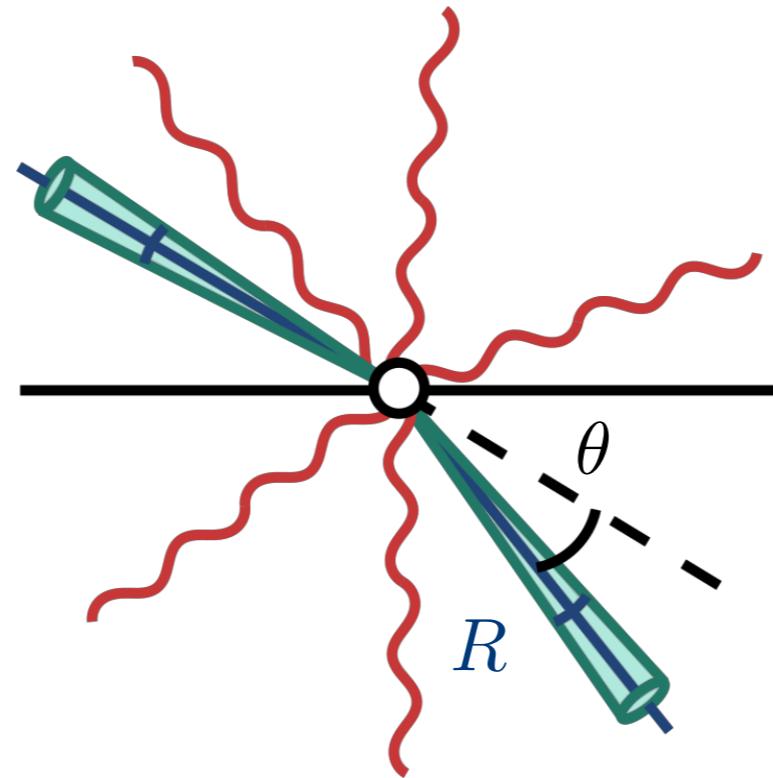
$$\frac{d\sigma_{(ee \rightarrow JJX)}}{dz_1 dz_2 d\mathbf{q}} = H_{ee \rightarrow q\bar{q}}(\sqrt{s}) \int \{ d\mathbf{q}_i \} J_q^{\text{axis}}(\mathbf{q}_1, z_1, \sqrt{s}R) J_{\bar{q}}^{\text{axis}}(\mathbf{q}_2, z_2, \sqrt{s}R)$$

Soft function absorbed in the jet functions

Regime $R \ll \theta$

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Limited phenomenological interest / useful theoretical check



Choice of axis becomes irrelevant

$$J_i^{\text{axis}}(\mathbf{q}, z, QR) = \sum_j \int \frac{dz'}{z'} \mathbb{C}_{ij}\left(\frac{z}{z'}, \mathbf{q}\right) \mathcal{J}_j(z, QR)$$

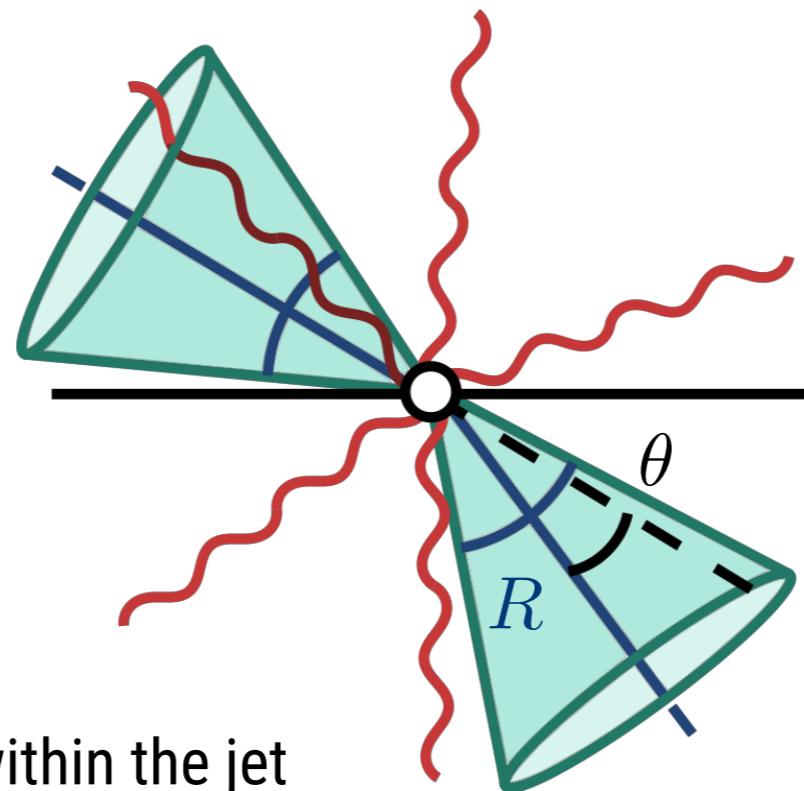
TMD matching coefficients

Gutierrez-Reyes, Echevarria, Scimemi, Vladimirov '15 - '18
Li, Neill, Zhu '16

Semi-inclusive jet functions

Kang, Ringer, Vitev '16

Radiation sees the jet boundary! End of factorisation?



Standard jet axis: almost

$$\mathbf{p}_s + \mathbf{p}_c = 0$$

- Each energetic emission within the jet is a source of soft radiation

Larkoski, Moult, Neill '15
Becher, Neubert, Rothen, Shao '16
Caron-Huot '18

- Large sensitivity to non-global logarithms

Dasgupta, Salam '01

WTA axis: not at all

$$\mathbf{p}_c \approx 0$$

- Same factorisation formula!

- Jet function largely simplifies

$$J_i^{\text{WTA}}(\mathbf{q}, z, QR) = \delta(1 - z) \mathcal{J}_i(\mathbf{q})$$

Towards resummed predictions

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Same factorisation formula: build on results valid for hadrons!

$$\frac{d\sigma_{(ee \rightarrow J J X)}}{dz_1 dz_2 d\mathbf{q}} = H_{ee \rightarrow q\bar{q}}(\sqrt{s}, \mu) \int \frac{d\mathbf{b}}{(2\pi)^2} J_q(\mathbf{b}, z_1, \sqrt{s}R, \mu, \zeta) J_{\bar{q}}(\mathbf{b}, z_2, \sqrt{s}R, \mu, \zeta)$$

- Subtraction of rapidity divergences; double-scale evolution

See talk by A. Vladimirov, WG3

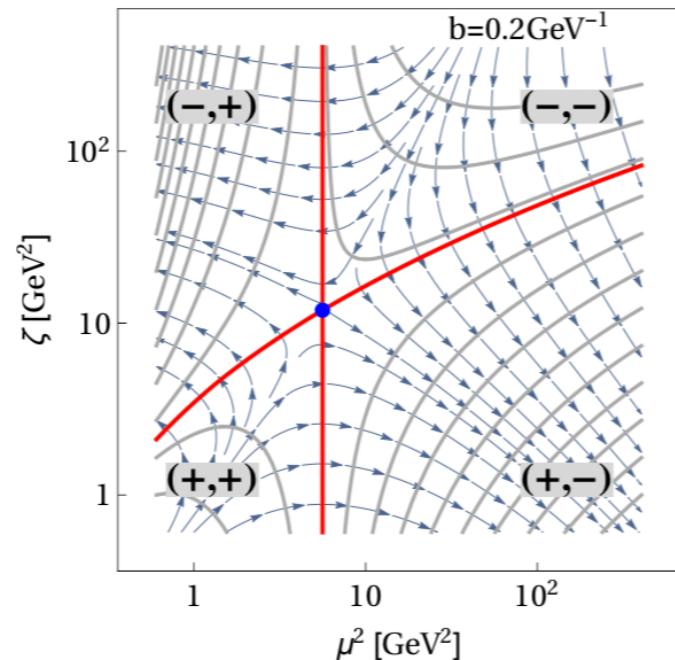
Collins, Soper '85, Becher, Neubert '10

Chiu, Jain, Neill, Rothstein '11

Echevarria, Idilbi, Scimemi, Vladimirov '11 - '18

- Existing software Artemide

Scimemi, Vladimirov '17



$$\mu \frac{d}{d\mu} J_i(\mathbf{b}, z, QR, \mu, \zeta) = +\gamma_i(\mu, \zeta) J_i(\mathbf{b}, z, QR, \mu, \zeta)$$

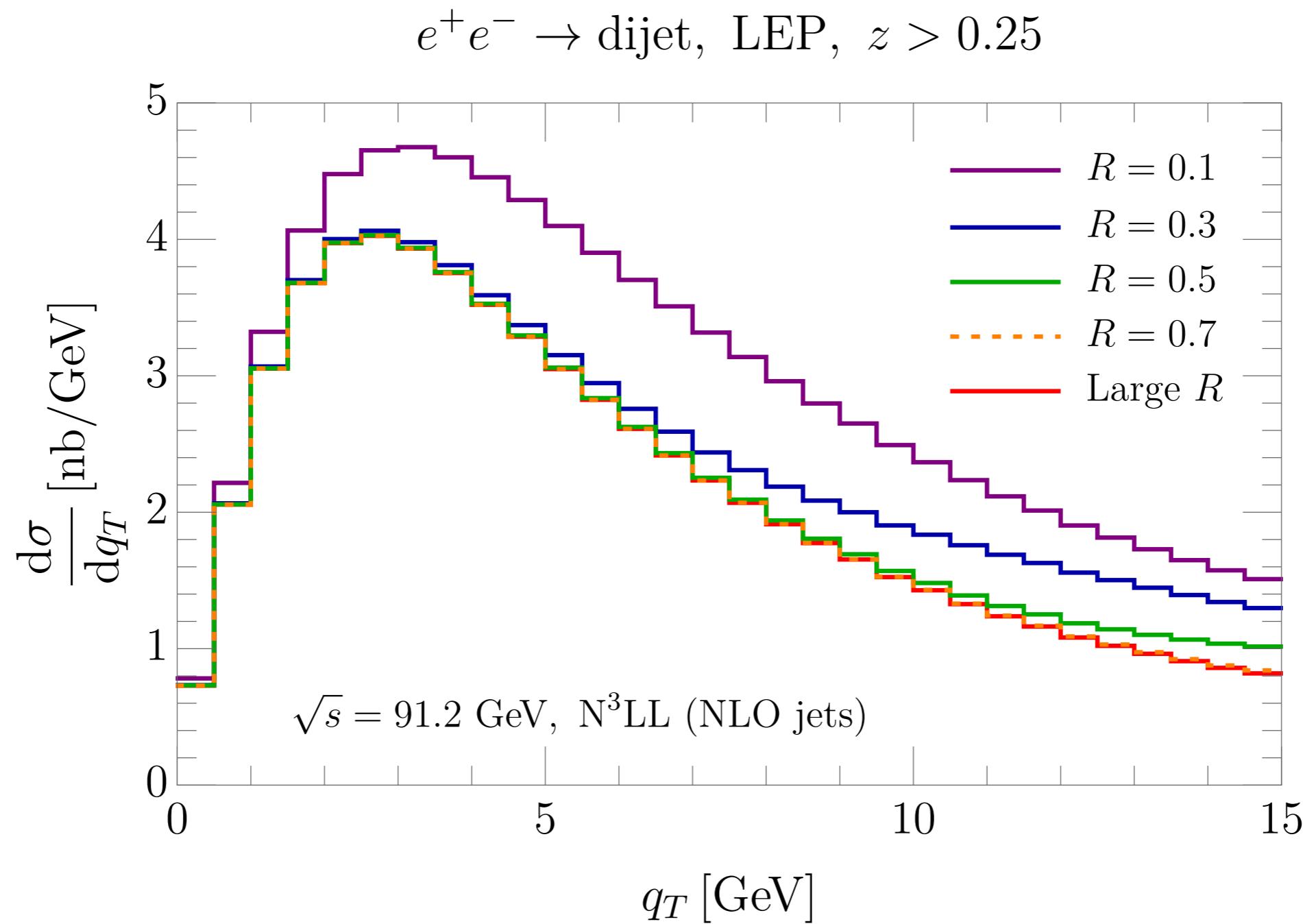
$$\zeta \frac{d}{d\zeta} J_i(\mathbf{b}, z, QR, \mu, \zeta) = -\mathcal{D}_i(\mu, \mathbf{b}) J_i(\mathbf{b}, z, QR, \mu, \zeta)$$

$$(\mu_J^2, \zeta_J) \sim (\mathbf{b}^{-2}, \mathbf{b}^{-2}) \quad \rightarrow \quad (\mu_H^2, \zeta_H) \simeq (s, s)$$

Numerical results

e+e- to dijets: varying jet radius

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Even for medium radii the large-radius limit is an extremely good approximation

Back to framework
(just for a minute)

Two-loop, large-R jet function

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$$J_q^{\text{WTA}}(\mathbf{b}, z, QR, \mu, \zeta) = \delta(1 - z) \mathcal{J}_q^{\text{WTA}}(\mathbf{b}, \mu, \zeta)$$

$$\mathcal{J}_q^{\text{WTA}[1]}(\mathbf{b}) = C_F \left(-L_\mu^2 + 2L_\mu L_\zeta - 3L_\mu + 7 - 6\ln 2 - \frac{5}{6}\pi^2 \right)$$

Logarithms predicted by
renormalisation group evolution A number

$$L_\mu = 2 \ln \left(\frac{\mu b}{2e^{-\gamma_E}} \right) \quad L_\zeta = \ln \left(\frac{\mu^2}{\zeta} \right)$$

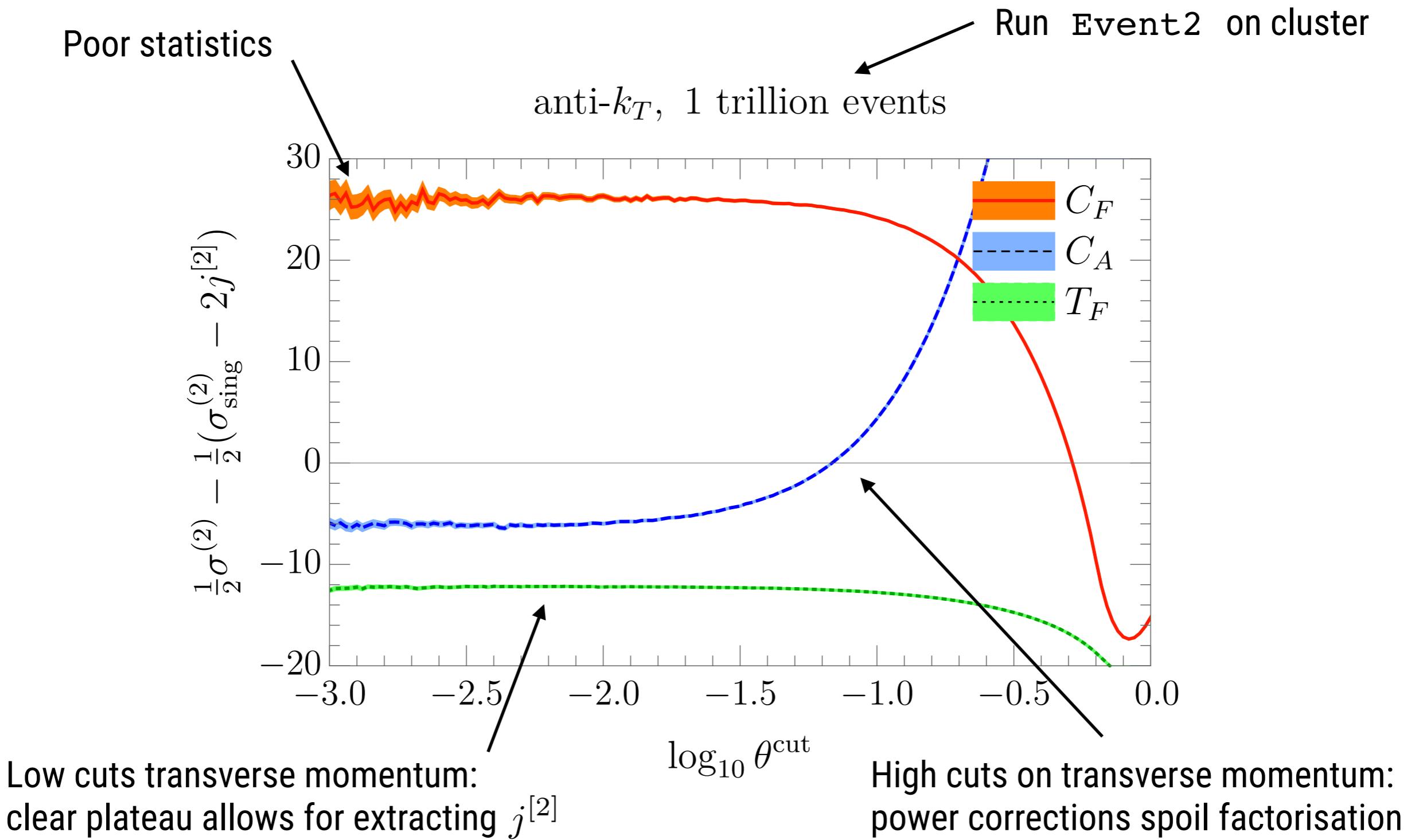
$$\mathcal{J}_q^{\text{WTA}[2]}(\mathbf{b}) = \left(a_{4,0} L_\mu^4 + a_{3,1} L_\mu^3 L_\zeta + a_{3,0} L_\mu^3 + \dots + j^{[2]} \right)$$

More logarithms, still predicted by
renormalisation group evolution A number

$$\left(\frac{d\sigma}{dq_T} \right)^{\text{N}^3\text{LL}} = \left(\frac{d\sigma}{dq_T} \right)^{\text{NLO}} + \left(\frac{d\sigma}{dq_T} \right)_{\mathcal{R} \rightarrow \infty}^{\text{NNLO}} - \left(\frac{d\sigma}{dq_T} \right)_{\mathcal{R} \rightarrow \infty}^{\text{NLO}}$$

Extracting the two-loop constant

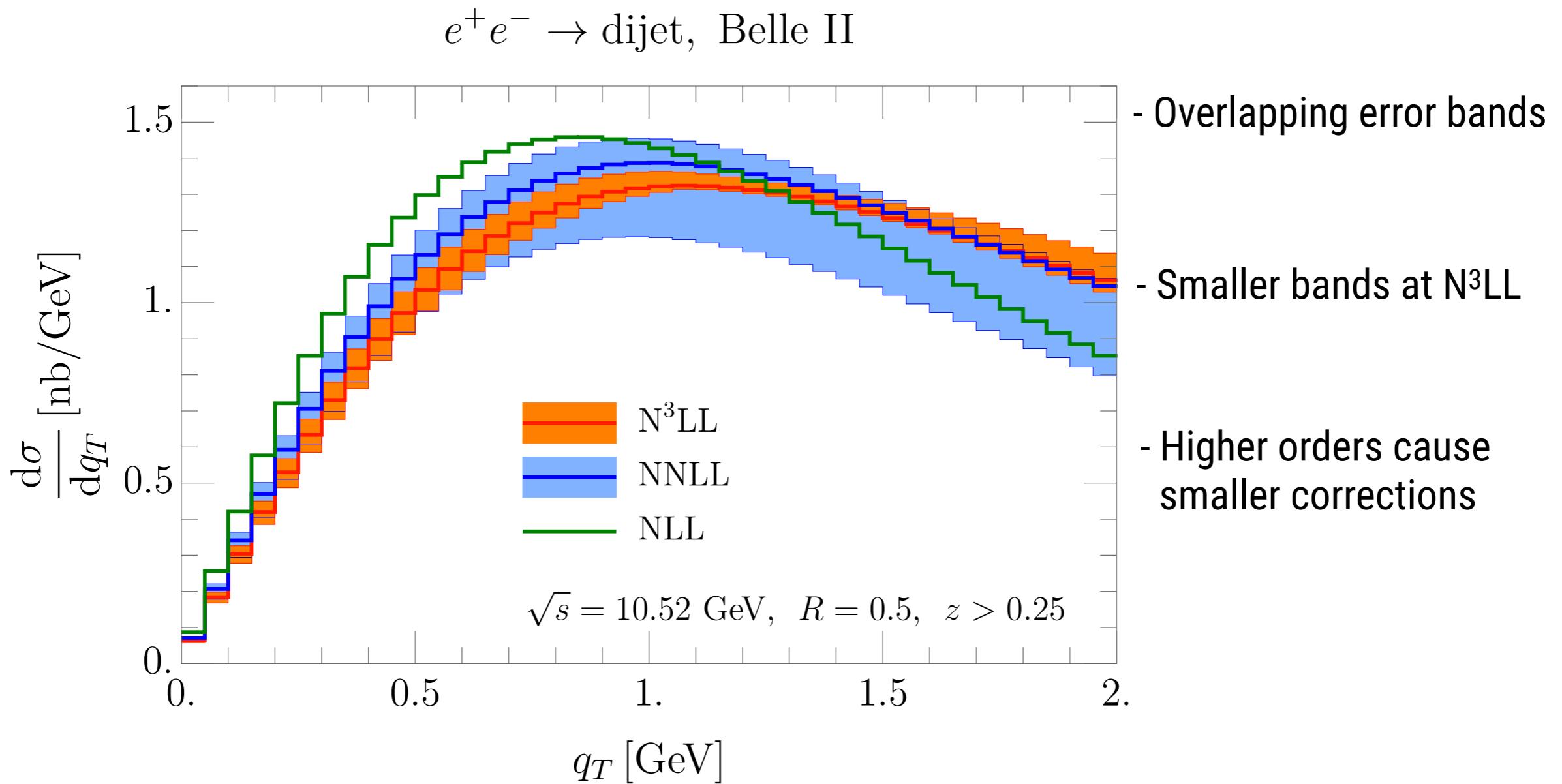
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Numerical results (this time for real)

Predictions for Belle II

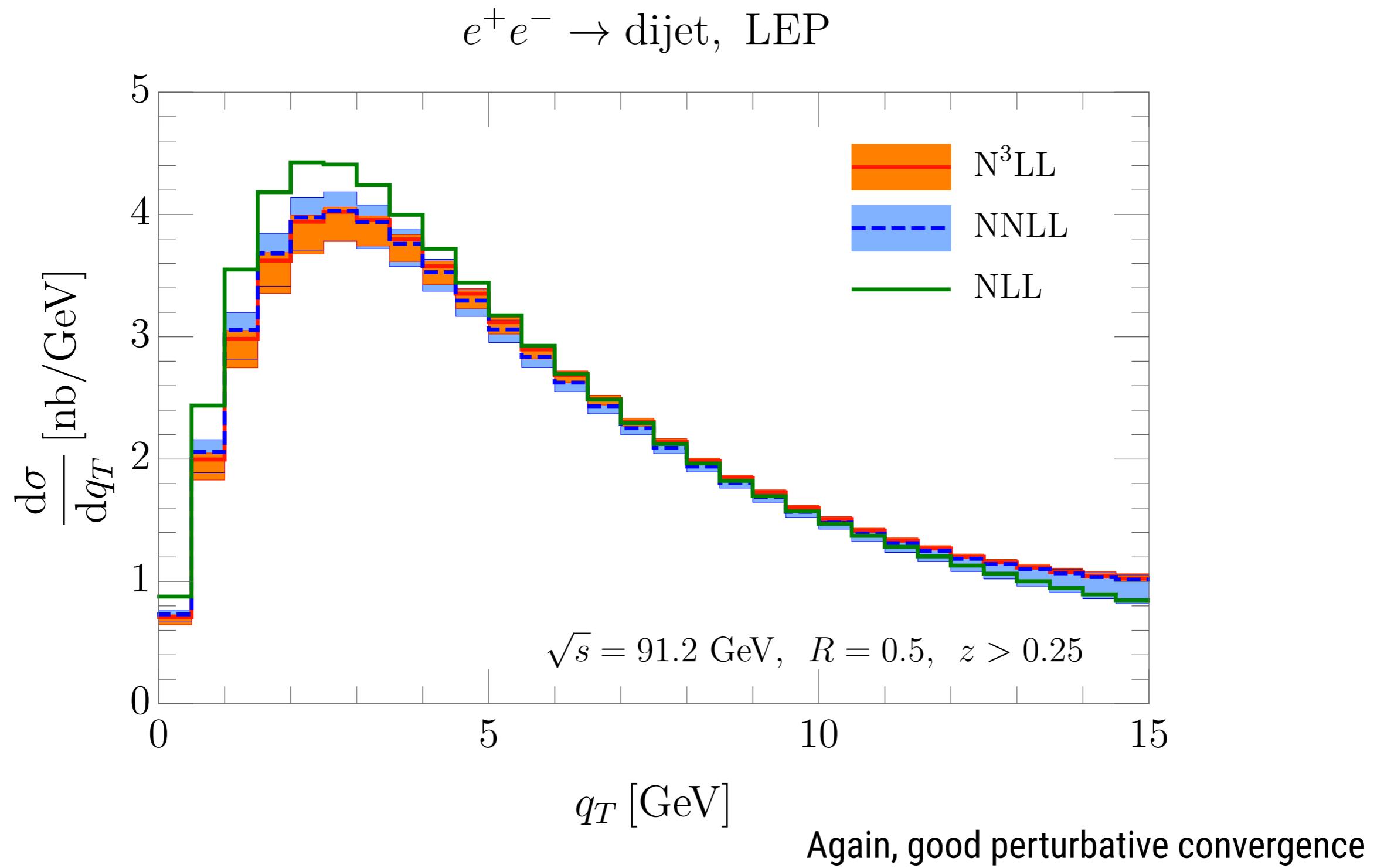
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The perturbative convergence is rather good

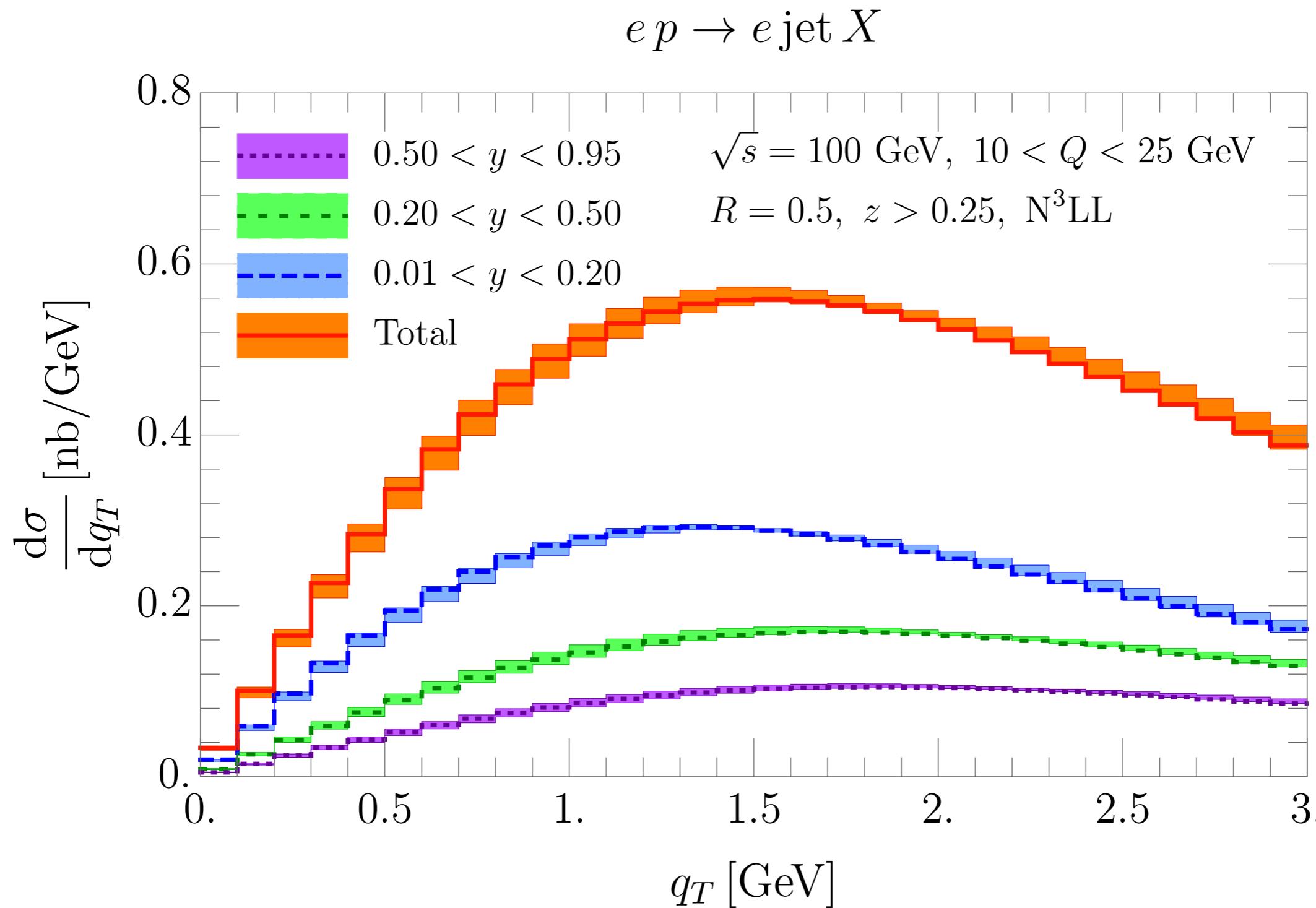
Predictions for LEP

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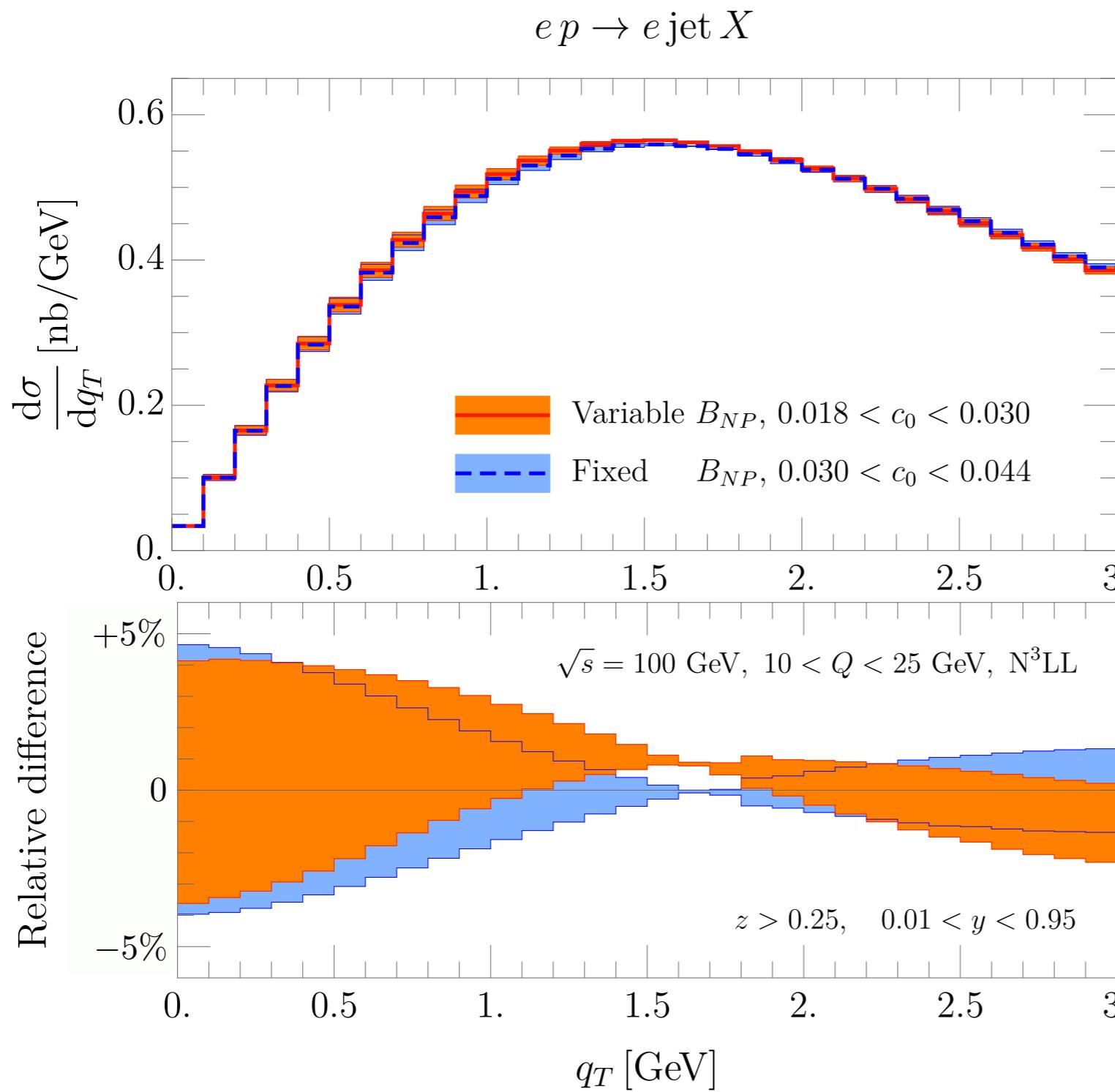
Predictions for the EIC

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Sensitivity to NP physics

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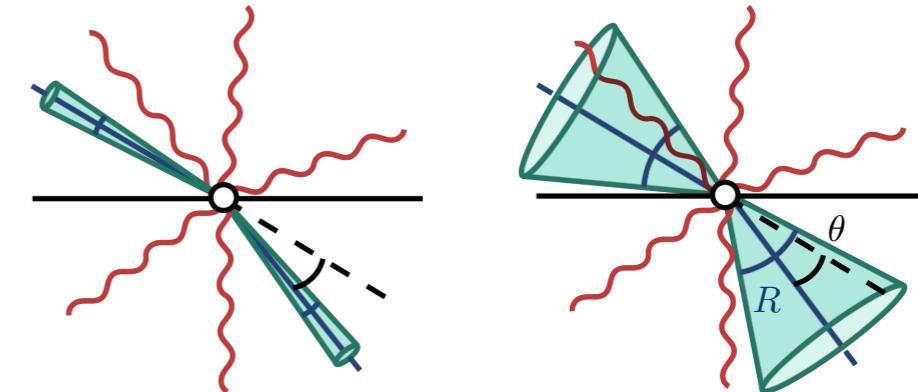
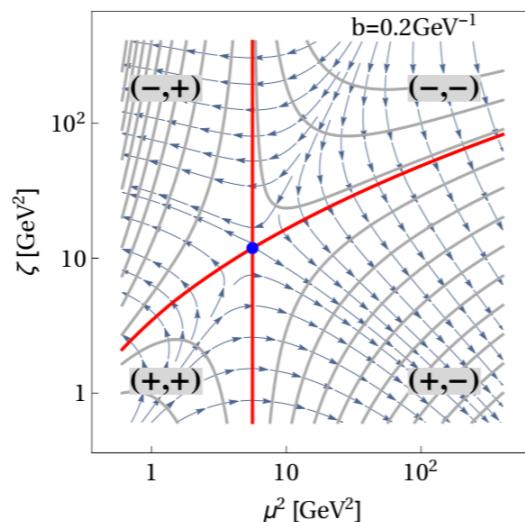
NP model from
Bertone, Scimemi, Vladimirov '19

- Small but non-negligible dependence on NP input

- Results within different schemes are compatible

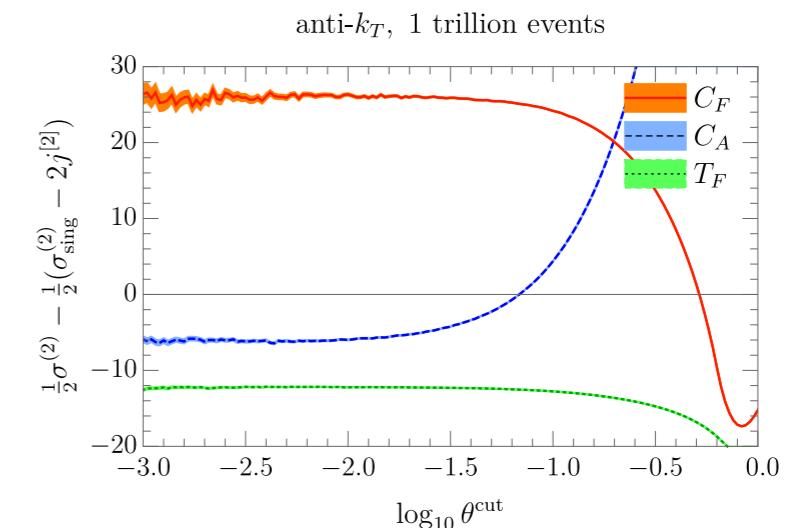
Outlook

The Winner-Take-All axis provides a framework that works for jets of arbitrary size



Same factorisation/evolution as for hadrons allows us to build on existing code

Large-radius limit works very well so we can push accuracy to NNLO (+N³LL)



We established jets as a promising probe of TMD distributions
N³LL predictions for Belle, LEP, EIC

Next: TMDs with groomed jets

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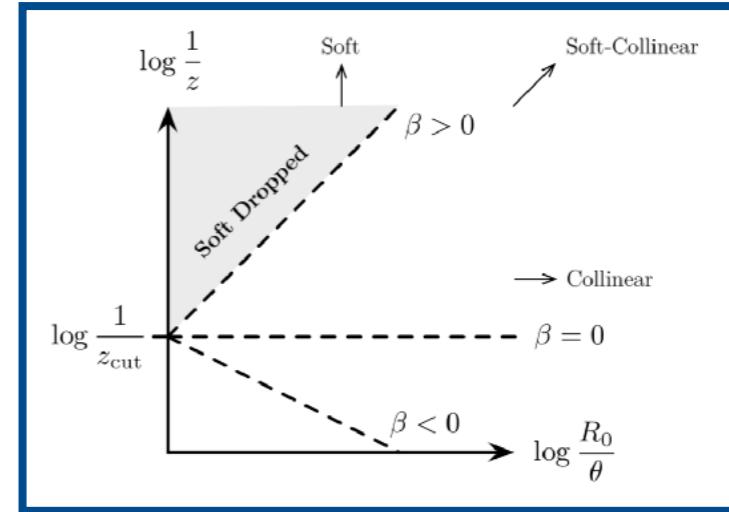
Soft drop

Larkoski, Marzani, Soyez, Thaler '14

- cluster jets using Cambridge/Aachen algorithm
- set an energy-fraction threshold z_{cut}
- de-cluster jets, remove radiation below threshold

$$\text{Measure groomed jet thrust } e = \frac{Q^2}{m_J^2}$$

Small thrust \rightarrow highly-collimated jets



$$\mathcal{J}_i(\mathbf{q}, e, Q, z_{\text{cut}}, \mu, \zeta) = S_{\text{sc}}(\mathbf{q}, Qz_{\text{cut}}, \mu, \zeta) \int de' S_{\text{cs},i}(e - e', \mu) J_i(e', Q, \mu)$$



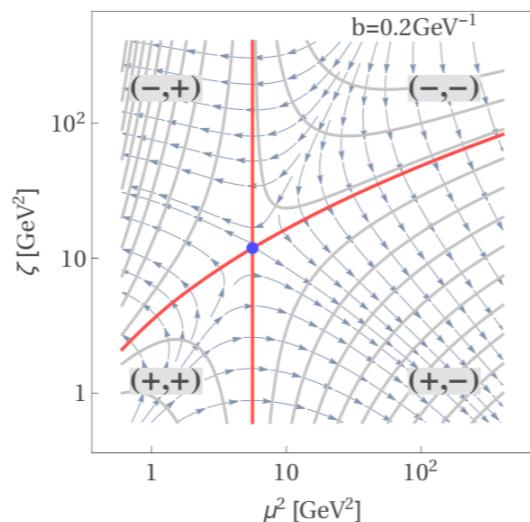
Different factorisation structure:
soft-drop parameter induces new modes

$$Q \gg Qz_{\text{cut}} \gg |\mathbf{q}| \sim Q\sqrt{e_{\text{cut}}}$$

Numerical predictions available soon!

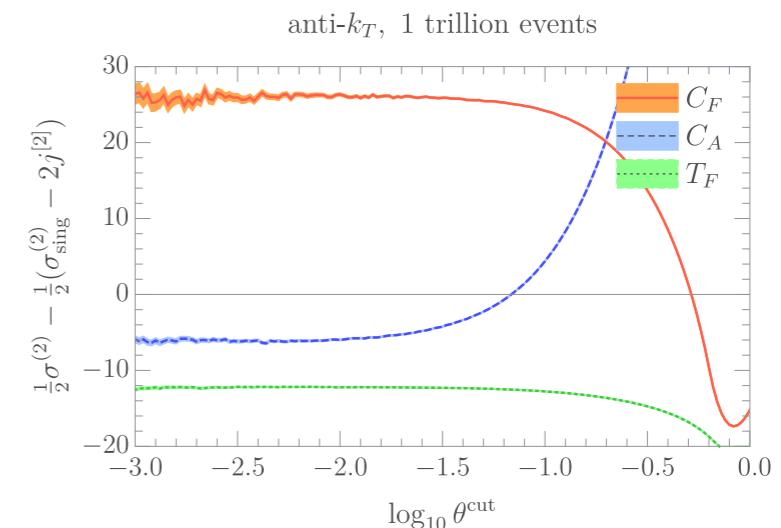
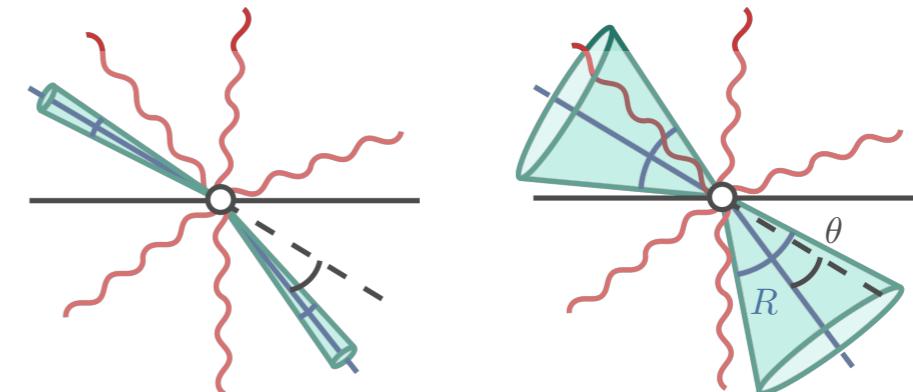
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Backup

Non-perturbative model

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We use the NP model from Bertone, Scimemi, Vladimirov '19

$$\mathcal{D}_{q,\text{NP}} = \mathcal{D}_{q,\text{resum}} + c_0 b b^* \quad b^* = \frac{b}{\sqrt{1 + \left(\frac{b}{B_{\text{NP}}}\right)^2}}$$

$$\mu \frac{d}{d\mu} J_i(\mathbf{b}, z, QR, \mu, \zeta) = +\gamma_i(\mu, \zeta) J_i(\mathbf{b}, z, QR, \mu, \zeta)$$

$$\zeta \frac{d}{d\zeta} J_i(\mathbf{b}, z, QR, \mu, \zeta) = -\mathcal{D}_i(\mu, \mathbf{b}) J_i(\mathbf{b}, z, QR, \mu, \zeta)$$

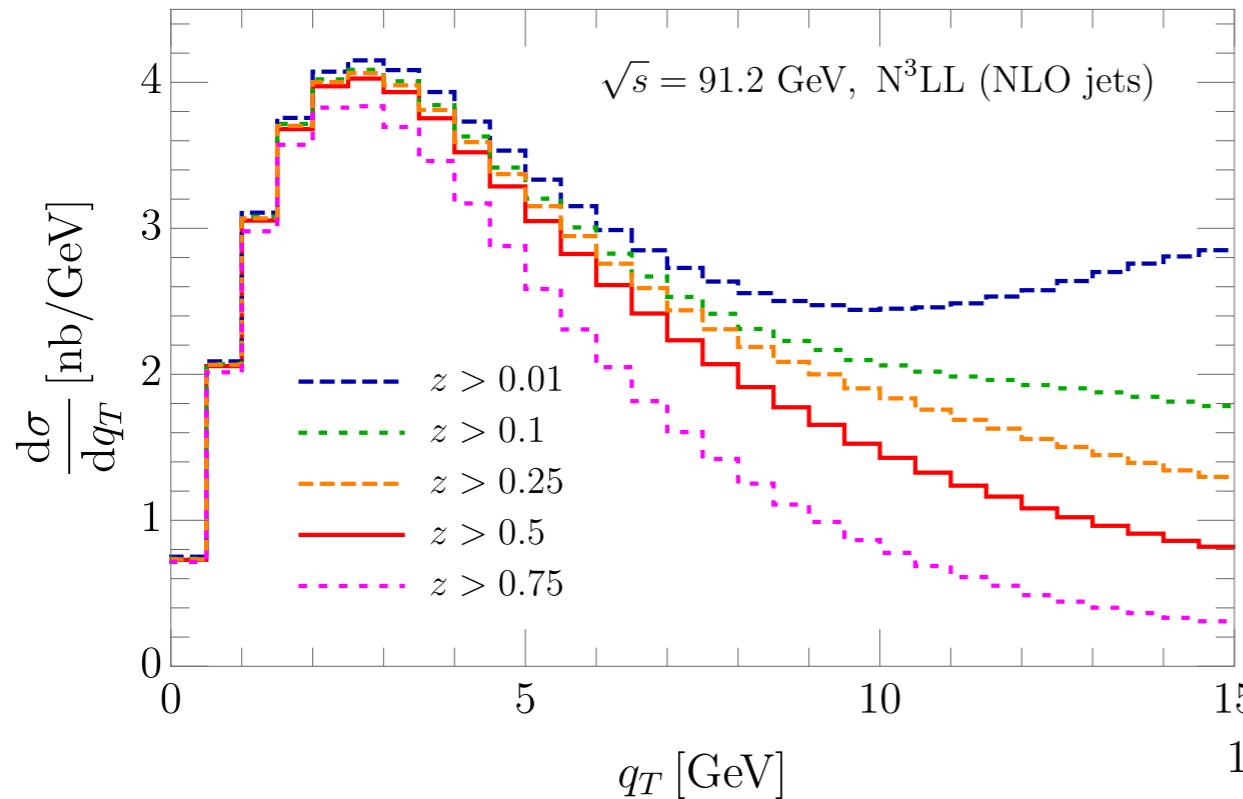
$$D_{a \rightarrow h}(\mathbf{q}, x, \mu) = f_{\text{NP}}(x, \mathbf{b}) \sum_b \mathbb{C}_{a \rightarrow b}(\mathbf{b}, x, \mu) f_{b \rightarrow h}(x, \mu)$$

$$f_{\text{NP}}(x, \mathbf{b}) = \exp \left\{ -\frac{\lambda_1(1-x) + \lambda_2 x + \lambda_3 x(1-x)}{\sqrt{1 + \lambda_4 x_5^\lambda \mathbf{b}^2}} \mathbf{b}^2 \right\}$$

Cuts on jet energy fraction

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$e^+e^- \rightarrow \text{dijet, LEP, } R = 0.3$



Cut at $z=0.5$: predictions are independent of the jet radius
(one-loop WTA accident)

Mild dependence at high R
as expected from large- R limit

