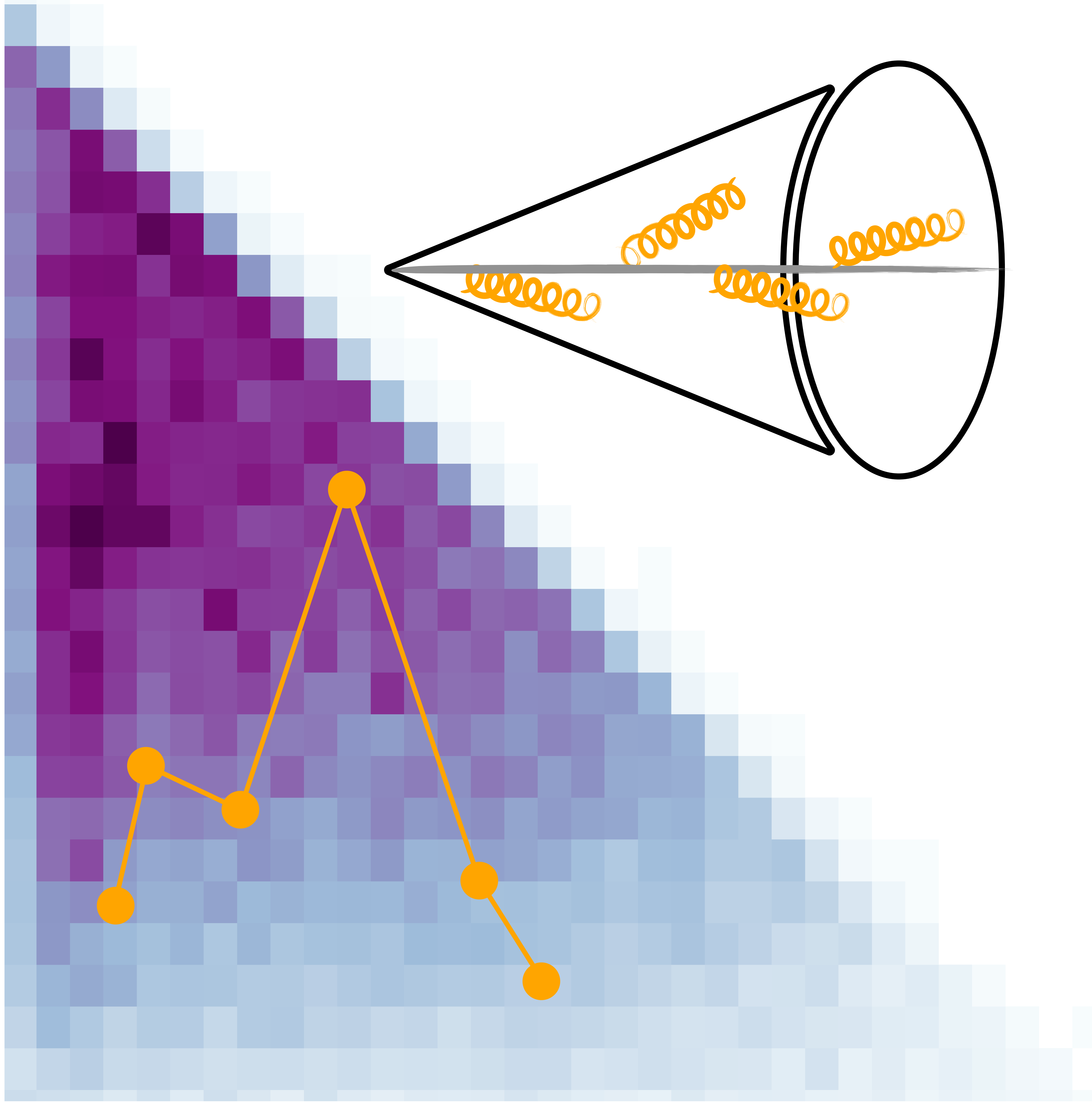
Logarithmic resummation of Lund-plane based observables



Alba Soto-Ontoso

Parton Showers and Resummation

Milano, 6th June, 2023

The Lund plane: core ingredient of PSR

Parton showers

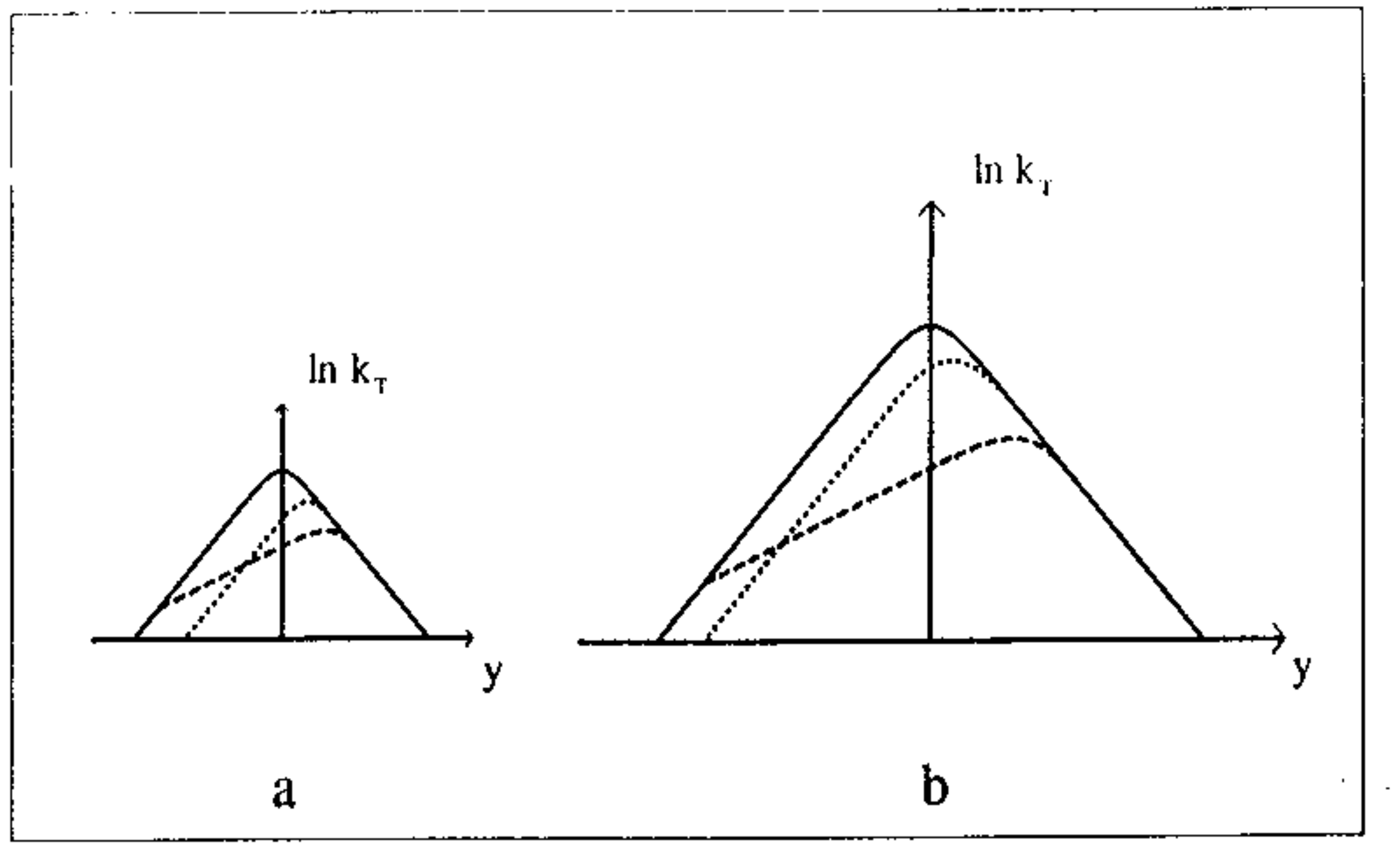
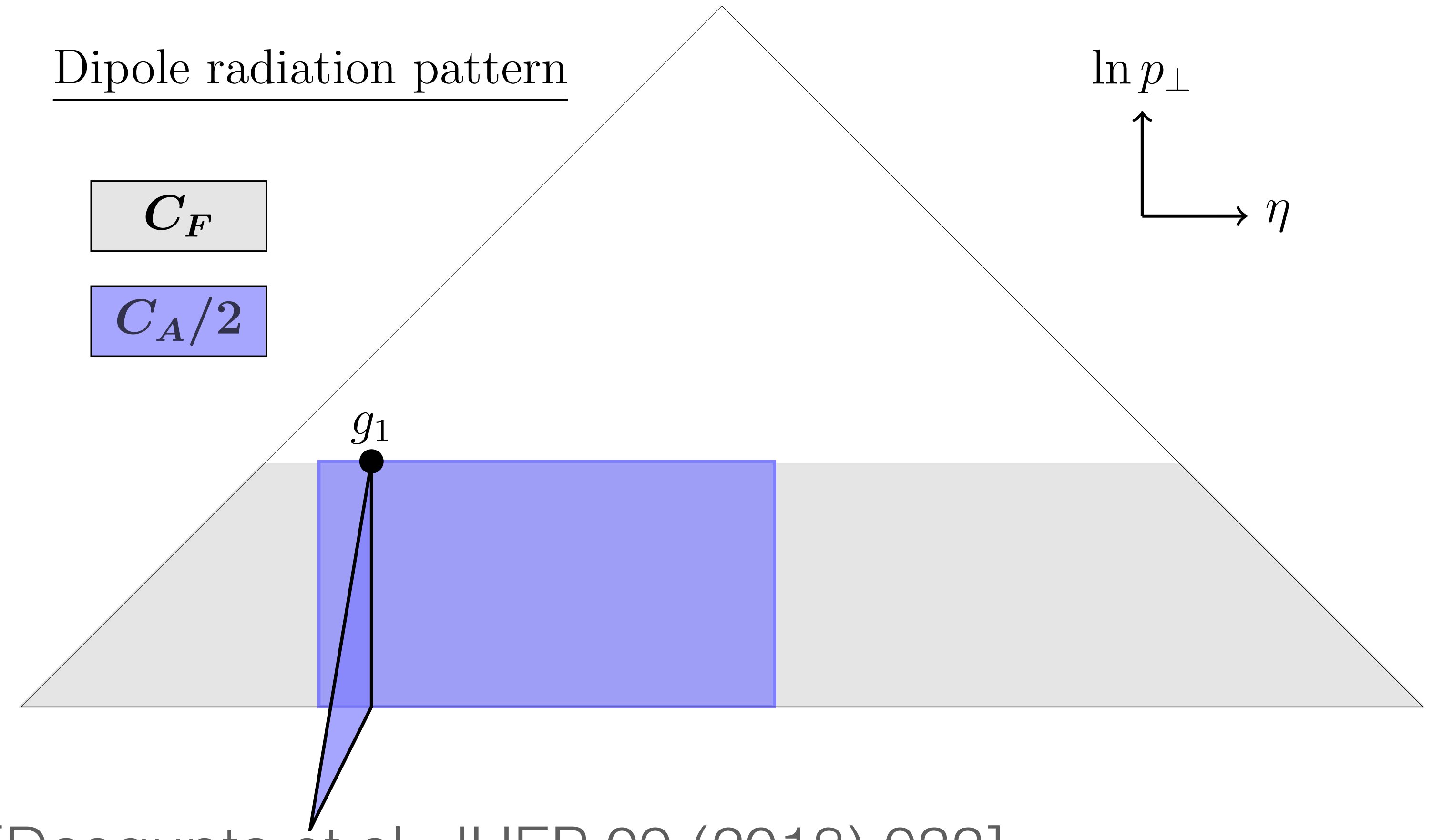


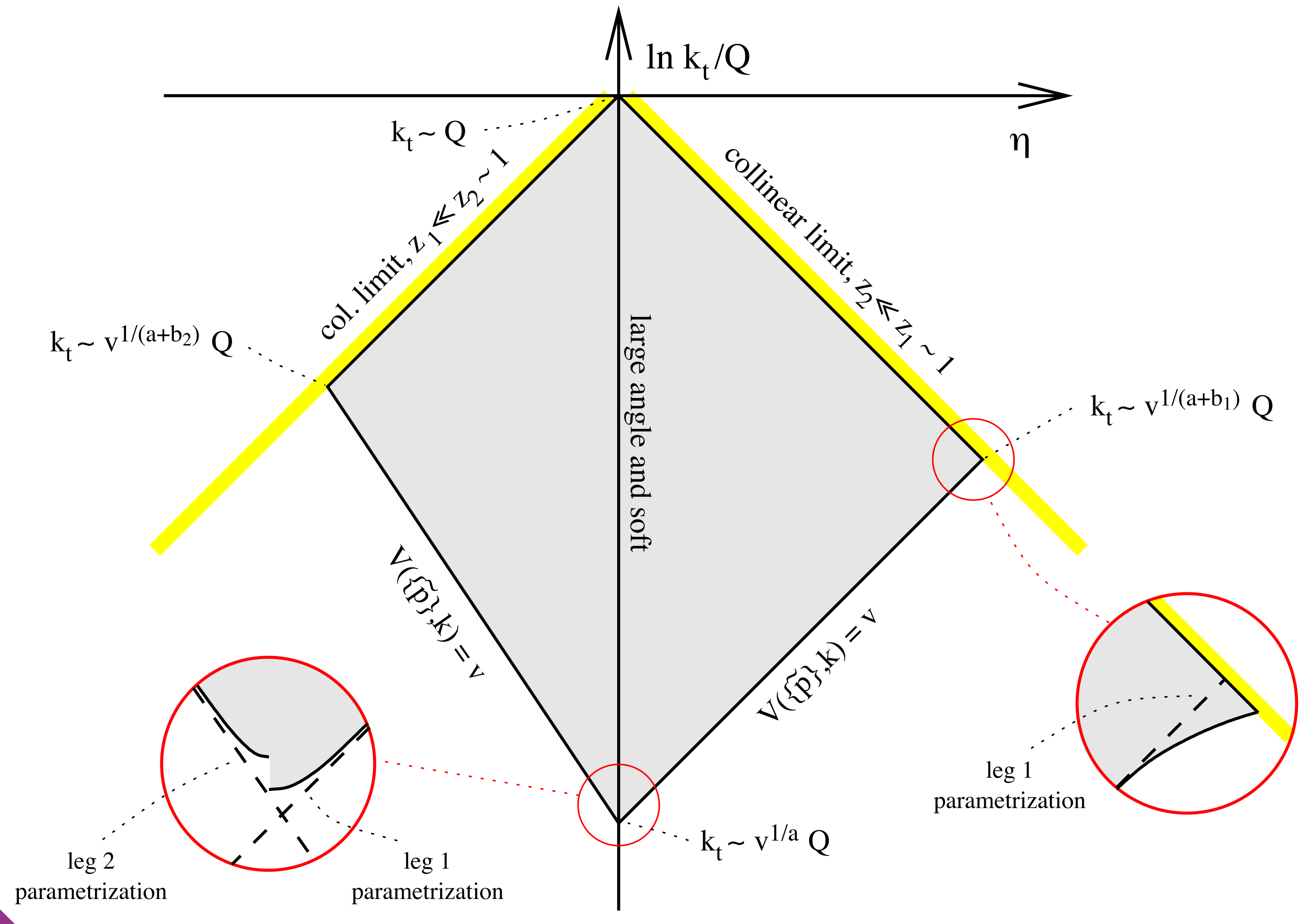
fig. 5

[Andersson et al. Z.Phys.C 43 (1989) 625]

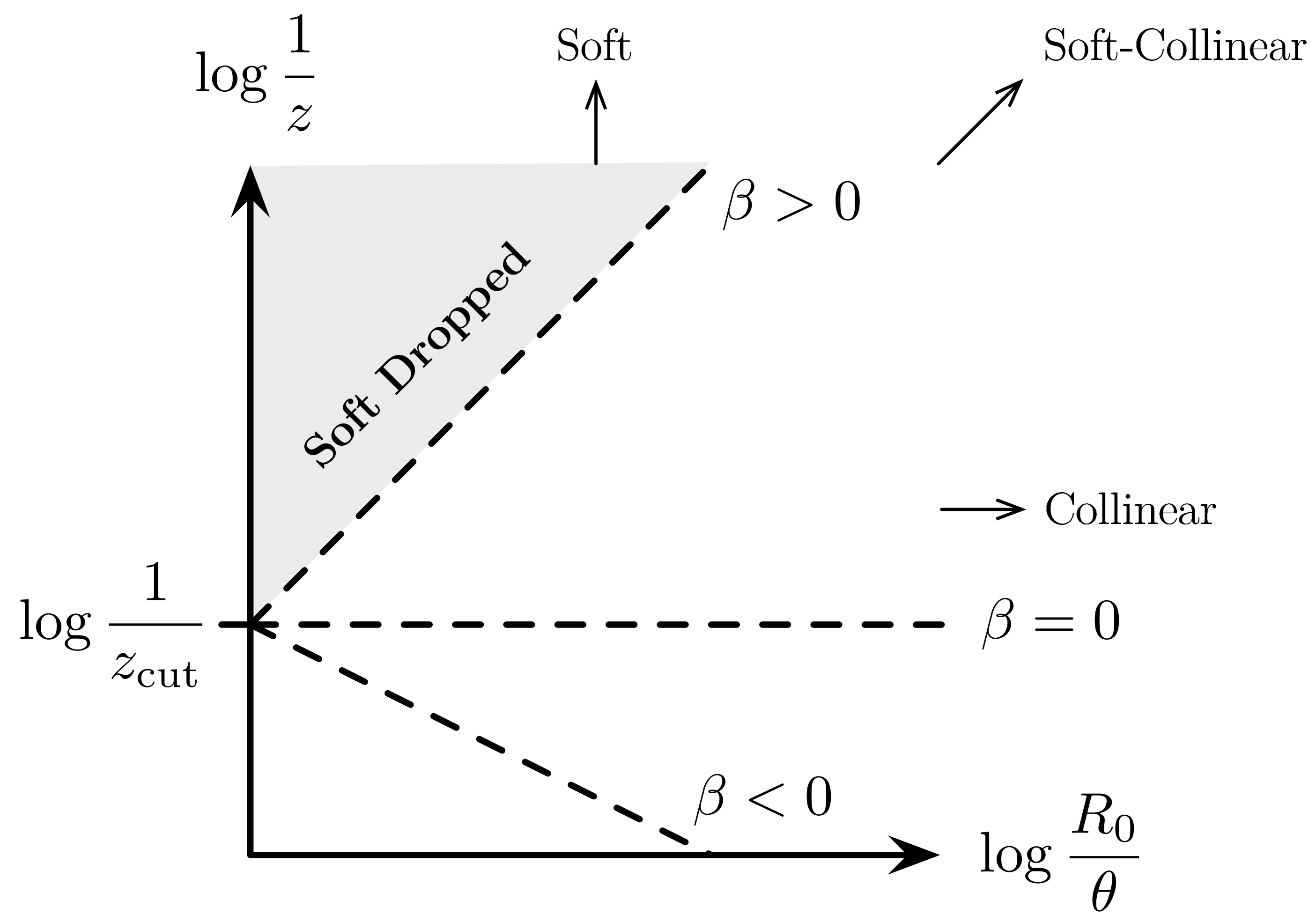


[Dasgupta et al. JHEP 09 (2018) 033]

Resummation

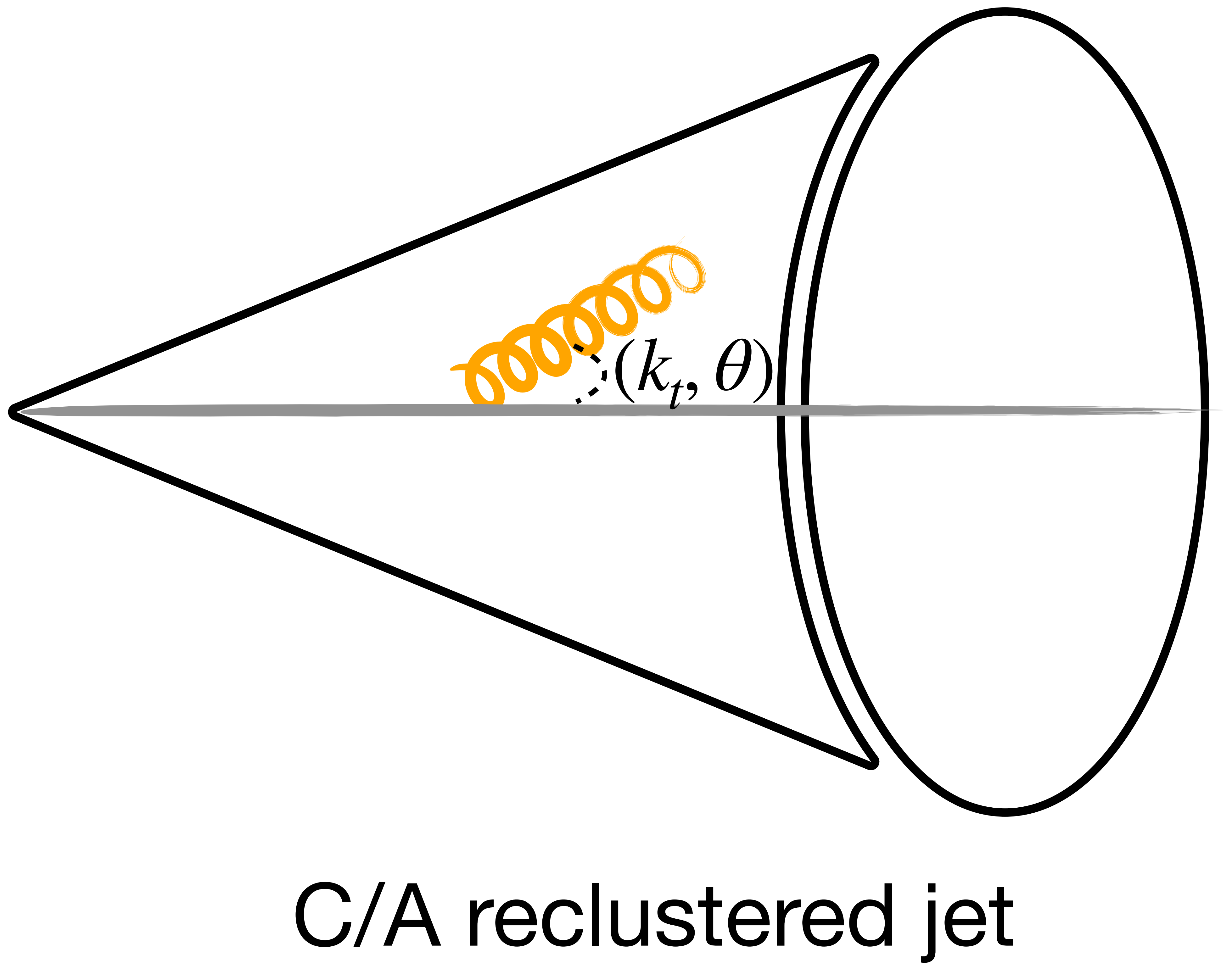


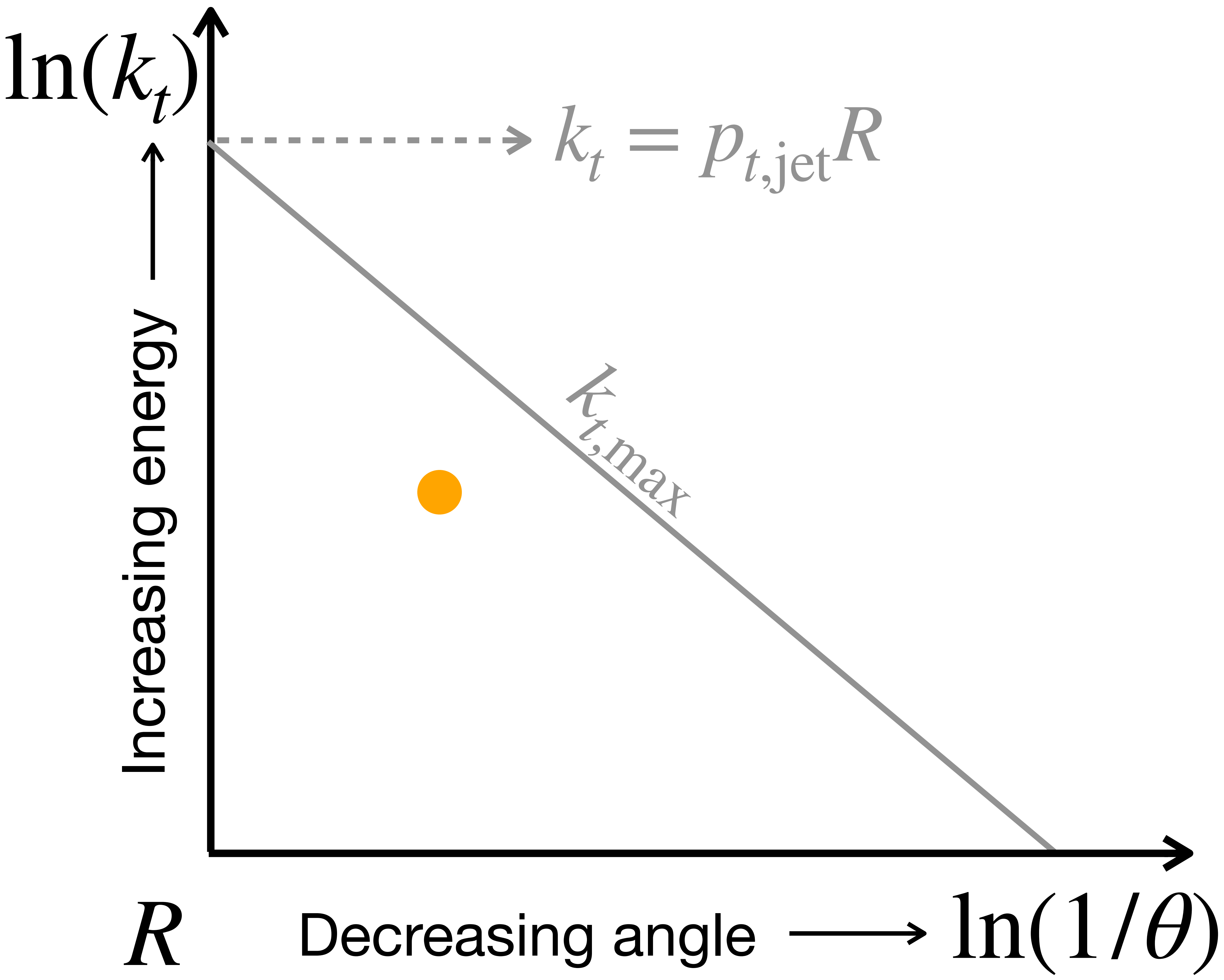
[Banfi, Salam, Zanderighi, JHEP 03 (2005) 073]



[Larkorski et al.,JHEP 05 (2014) 146]

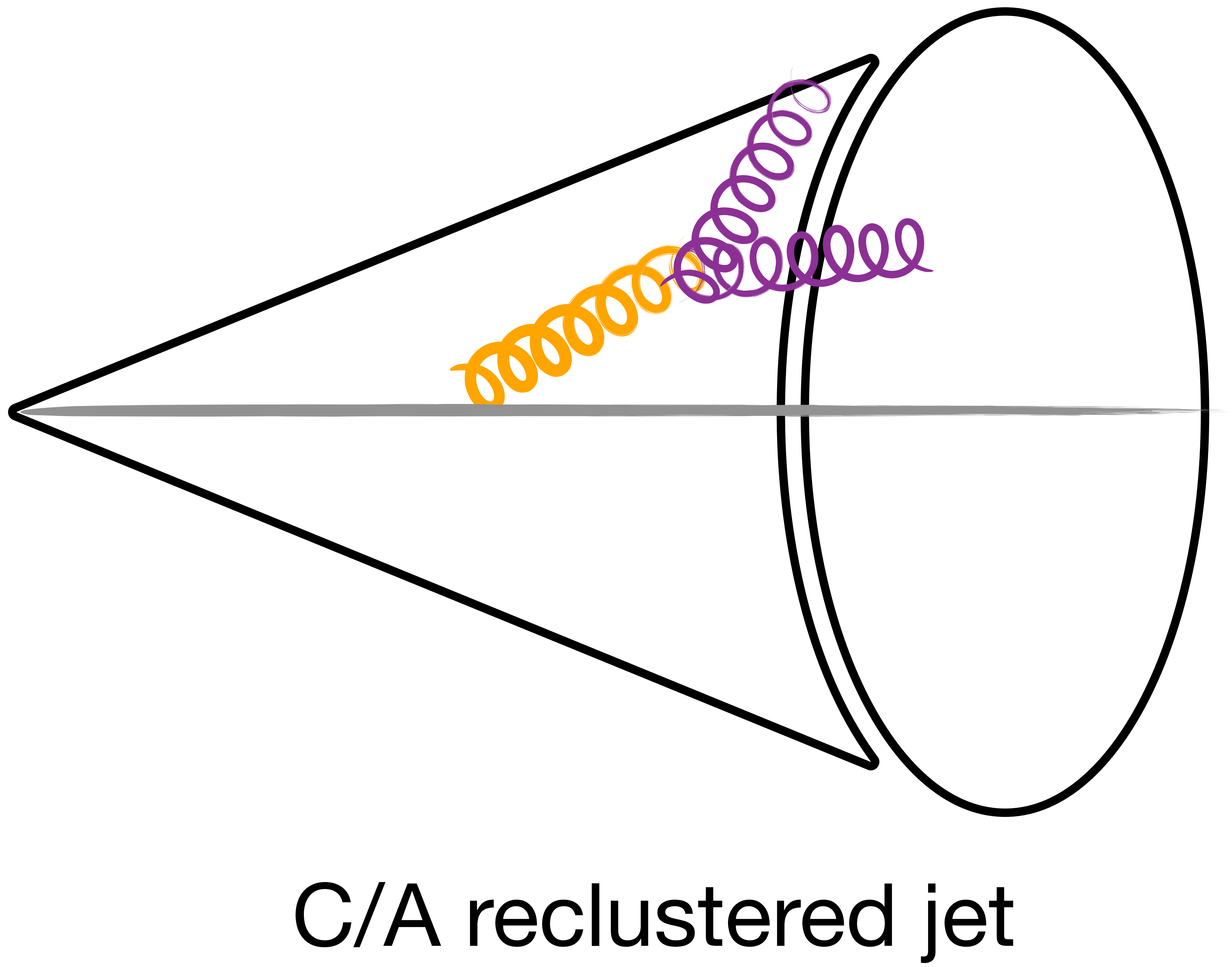
The Lund jet plane [Dreyer, Salam, Soyez JHEP 12 (2018) 064]

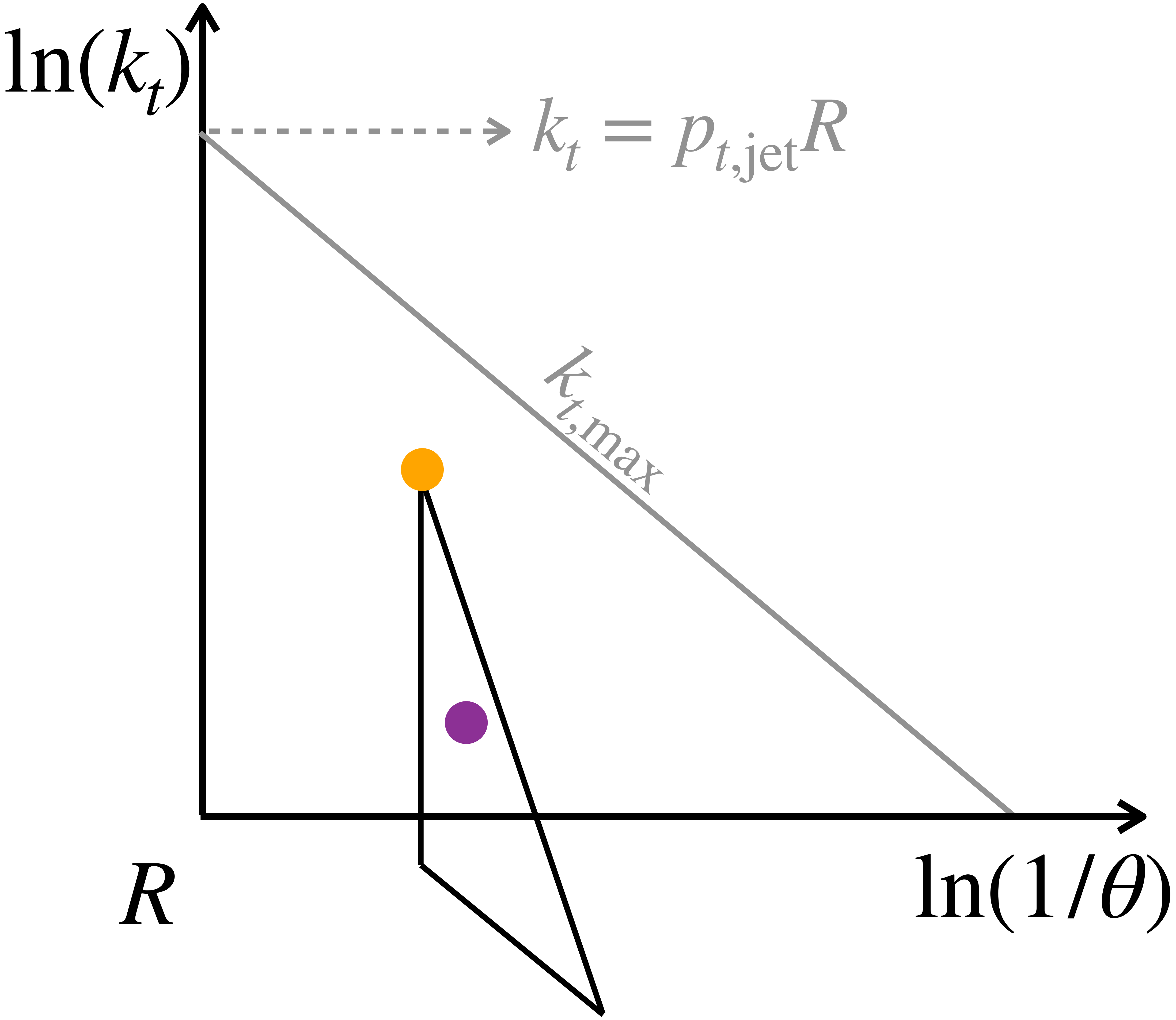




$k_t = z p_{t,\text{jet}} \theta$

The Lund jet plane [Dreyer, Salam, Soyez JHEP 12 (2018) 064]

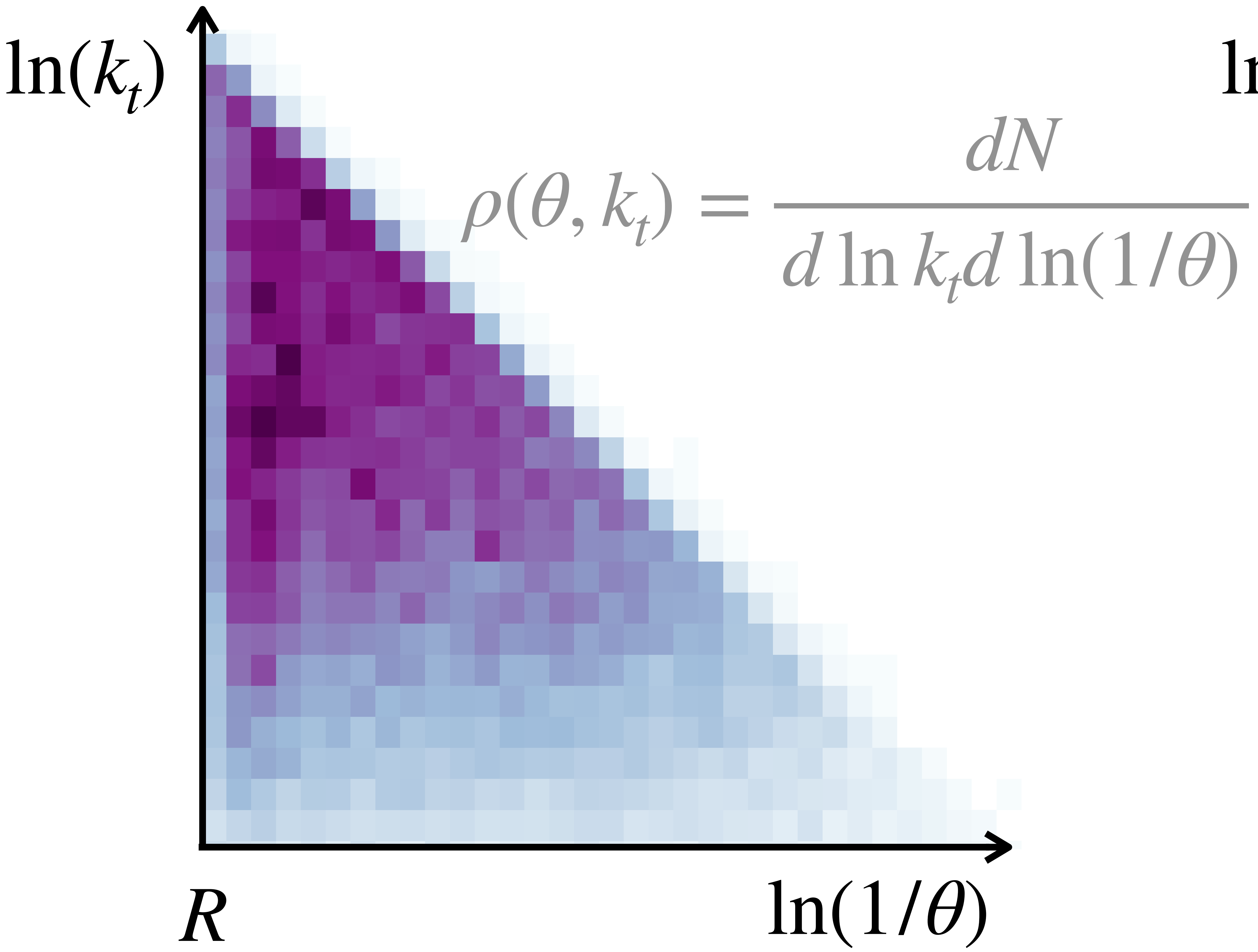




$k_t = z p_{t,\text{jet}} \theta$

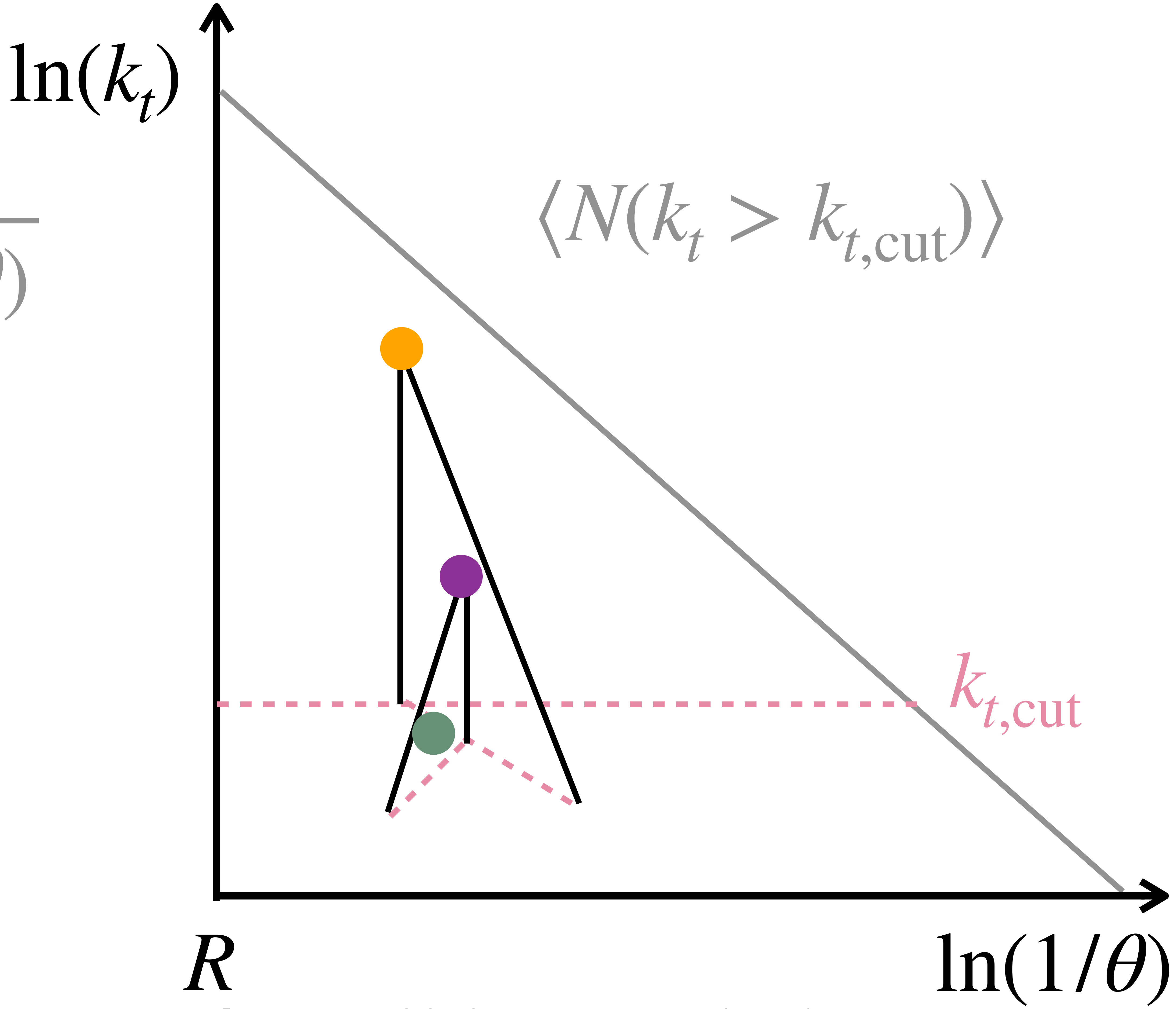
This talk: two spinoffs of the Lund jet plane

Primary Lund-plane density



[Lifson, Salam, Soyez JHEP 10 (2020) 170]

Lund multiplicity



[Medves, ASO, Soyez, JHEP 10 (2022) 156, JHEP 04 (2023) 104]

The primary Lund-plane density: resummation structure

In the soft-and-collinear limit, the Lund plane density is simply given by

$$\rho_{\mathrm{LO}}(\theta, k_t) = \frac{2\alpha_s C_i}{\pi}$$

Beyond LO/LL, two sources of logarithmic enhancements appear

$$\alpha_s^{n+1} \ln^m \theta \ln^{n-m} \frac{p_t}{k_t} \quad \text{with} \quad 0 \le m \le n$$

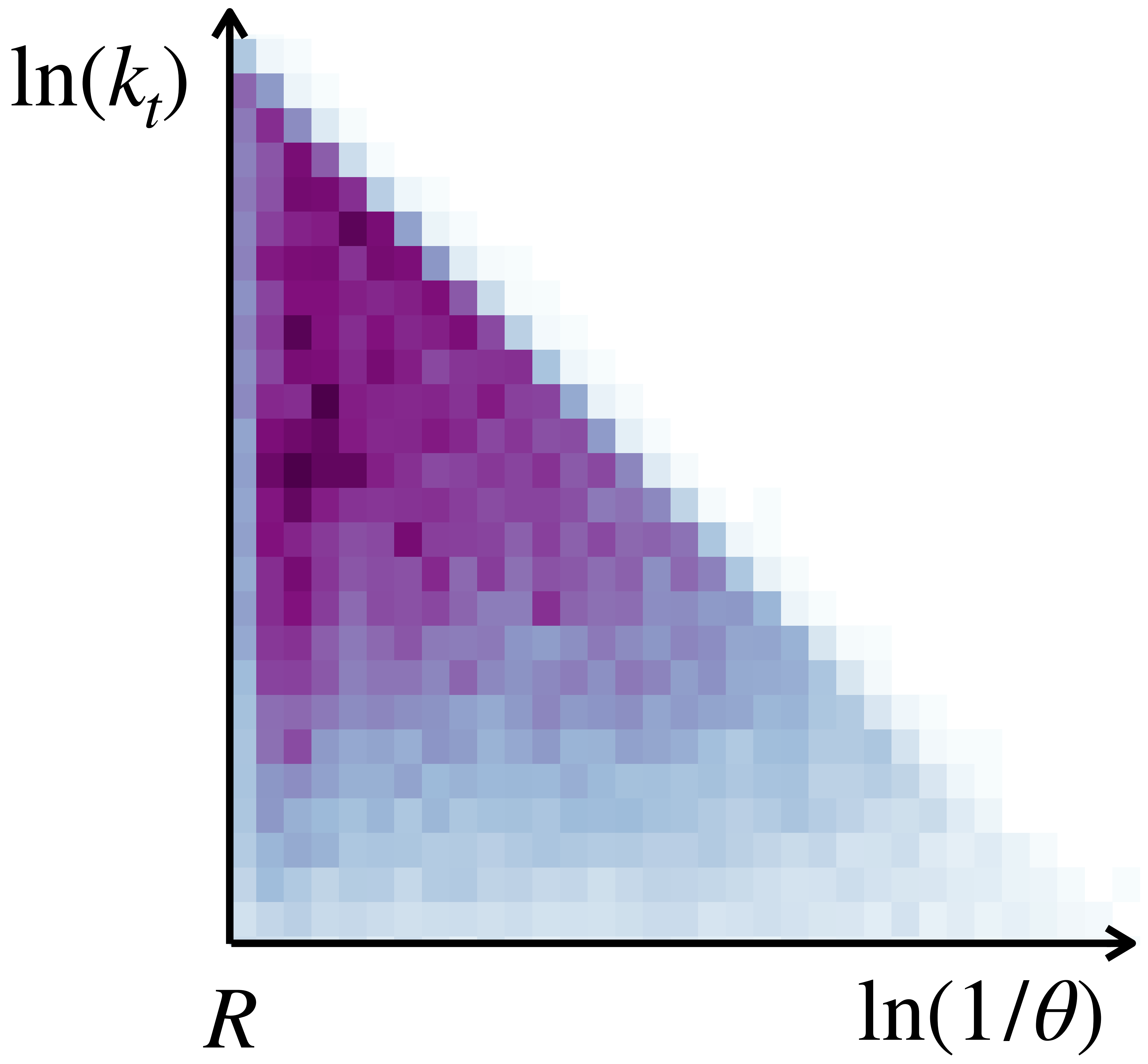
So far, the full set of single-logarithmic corrections has been computed

[Lifson, Salam, Soyez JHEP 10 (2020) 170]

The primary Lund-plane density: NLL resummation

1 Running coupling corrections

$$\rho_{\mathrm{rc}}(\theta, k_t) = \frac{2\alpha_s^{1\ell}(k_t) C_i}{\pi}$$



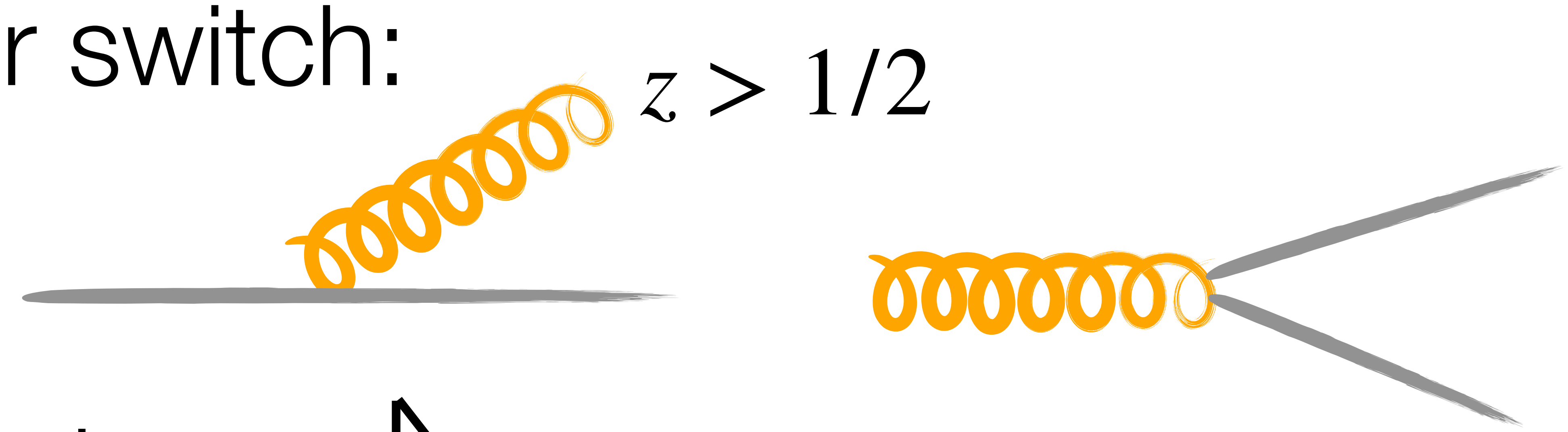
The primary Lund-plane density: NLL resummation

1 Running coupling corrections

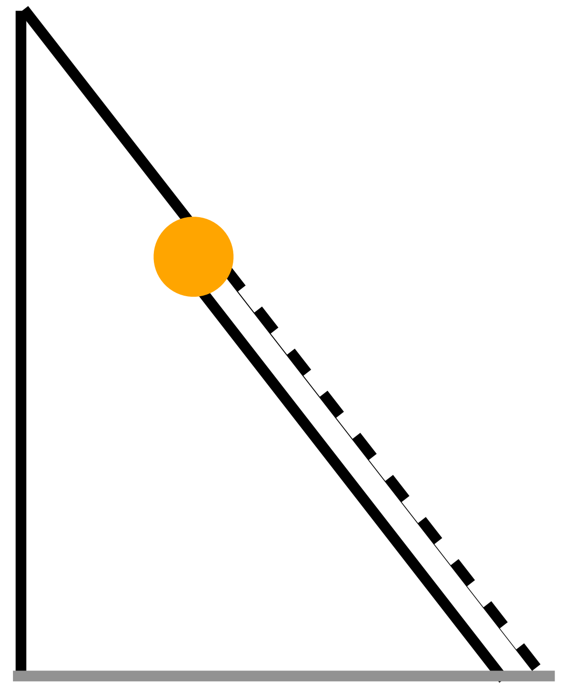
$$\rho_{\rm rc}(\theta, k_t) = \frac{2\alpha_s^{1\ell}(k_t) C_i}{\pi}$$

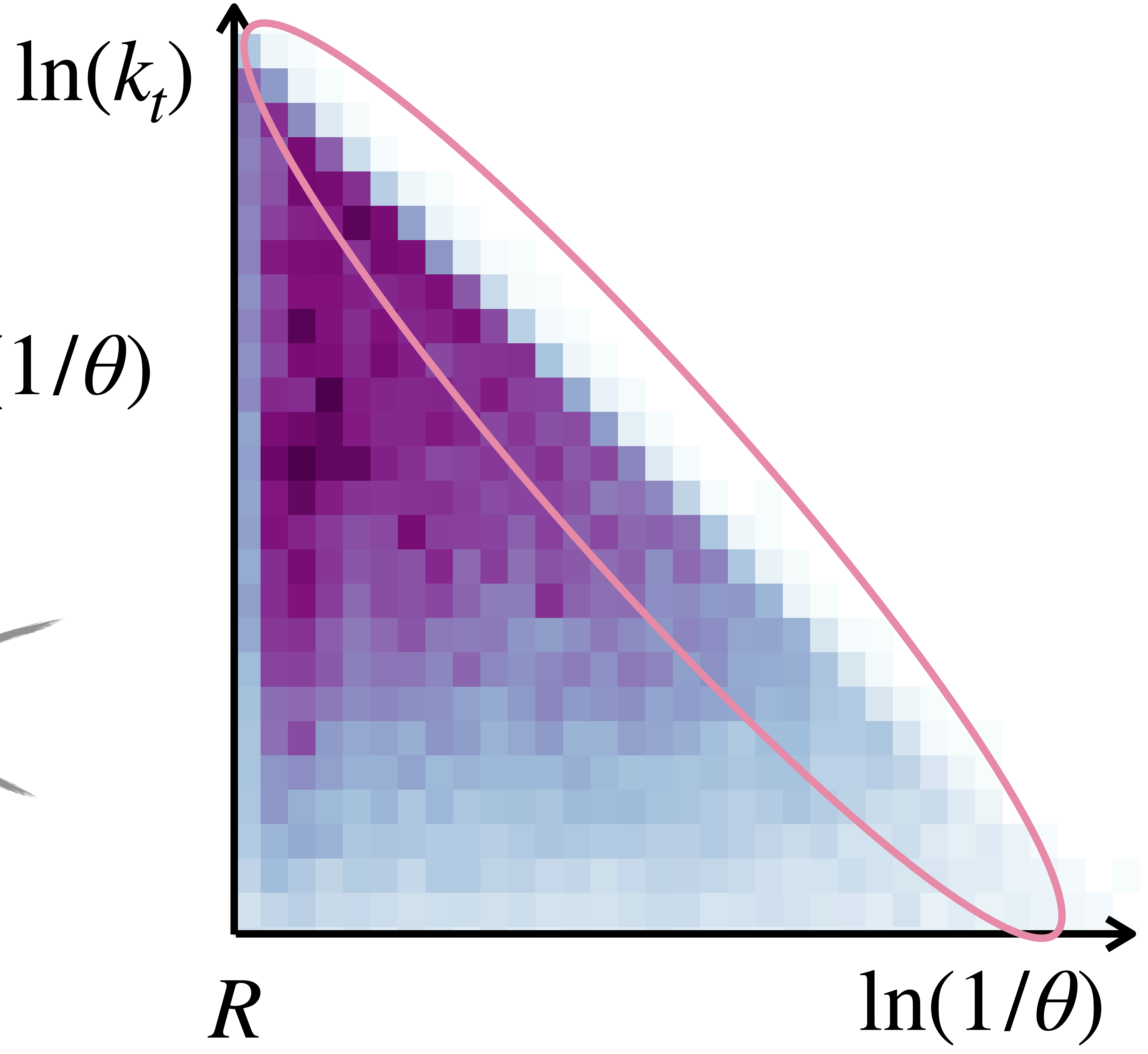
2 Hard-collinear corrections $\alpha_s^{n+1} \ln^n(1/\theta)$

a) Flavour switch:



b) Energy loss:





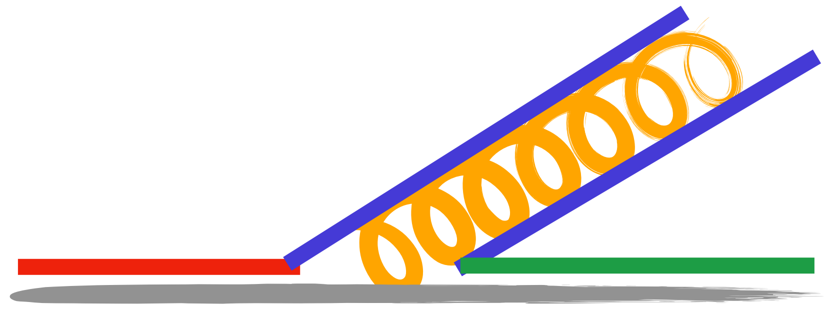
The primary Lund-plane density: NLL resummation

1 Running coupling corrections

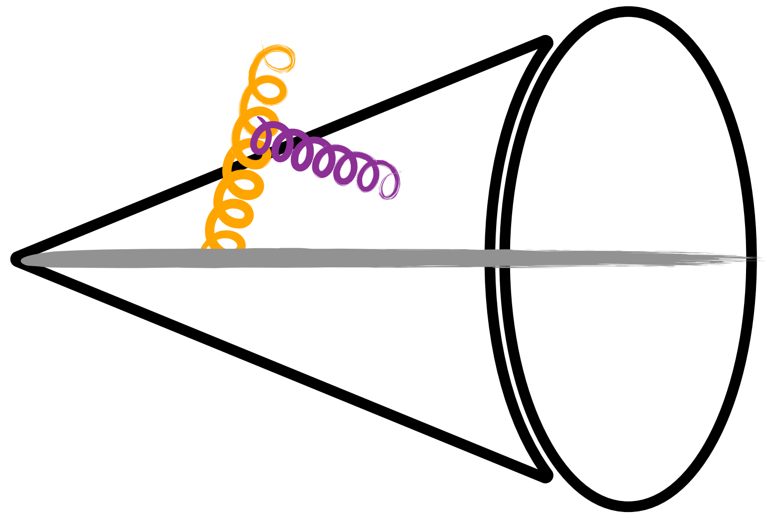
$$\rho_{\rm rc}(\theta, k_t) = \frac{2\alpha_s^{1\ell}(k_t) C_i}{\pi}$$

2 Hard-collinear corrections $\alpha_s^{n+1} \ln^n \theta$

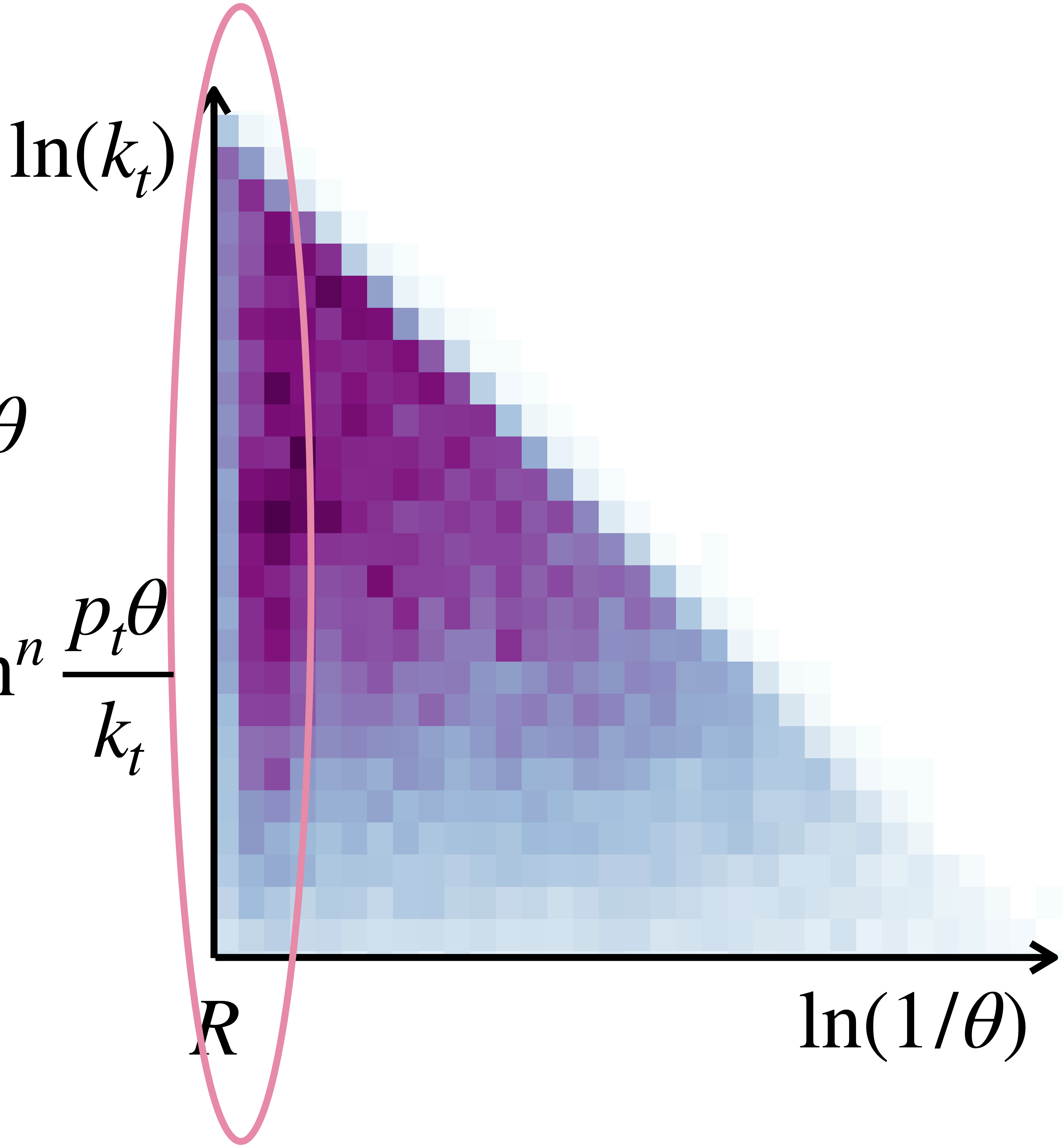
3 Soft, large-angle corrections $\alpha_s^{n+1} \ln^n \frac{p_t \theta}{k_t}$



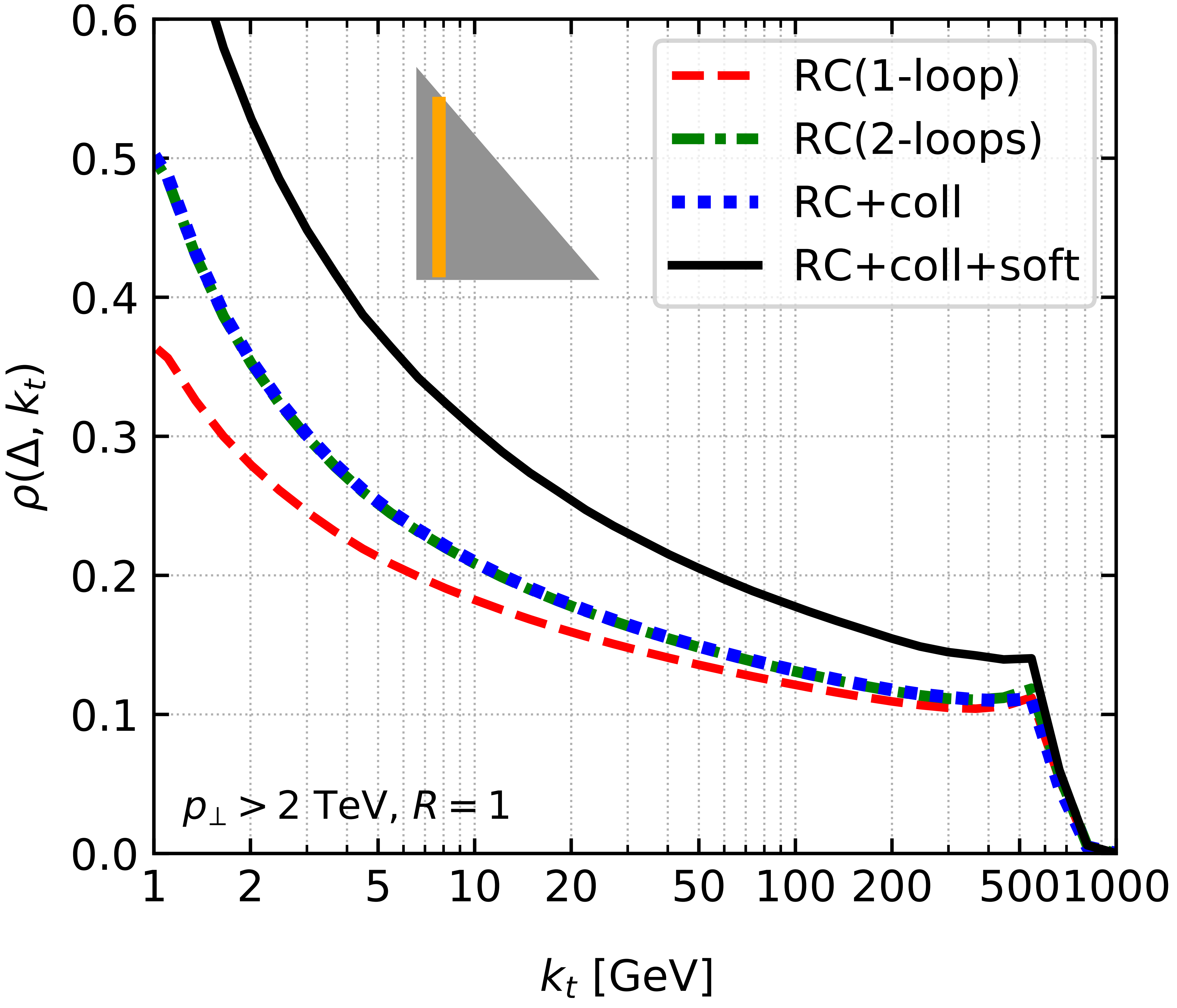
[Ellis, Marchesini, Webber. Nucl.Phys.B 286 (1987) 643]

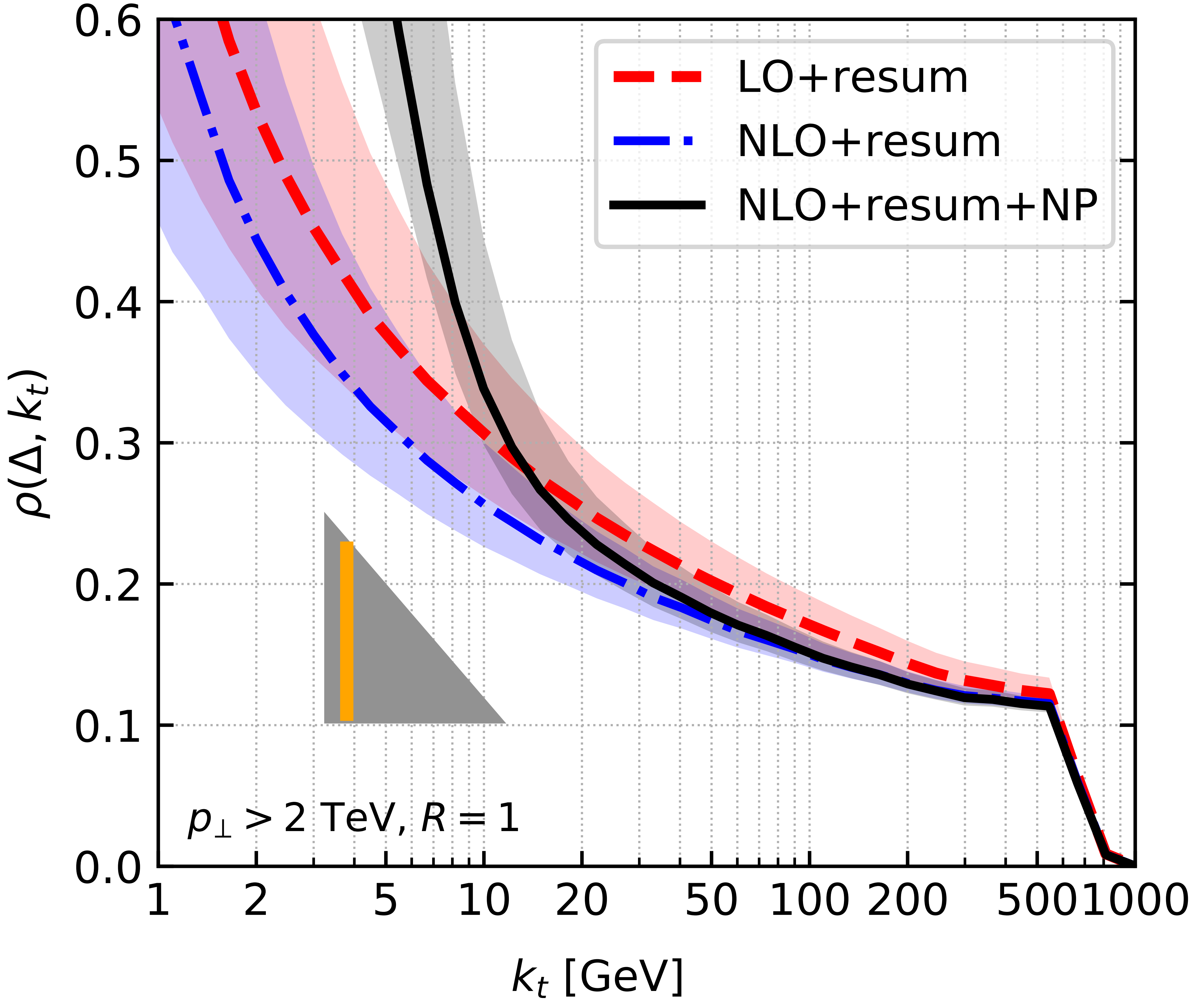


$\ln(R/(R-\theta))$



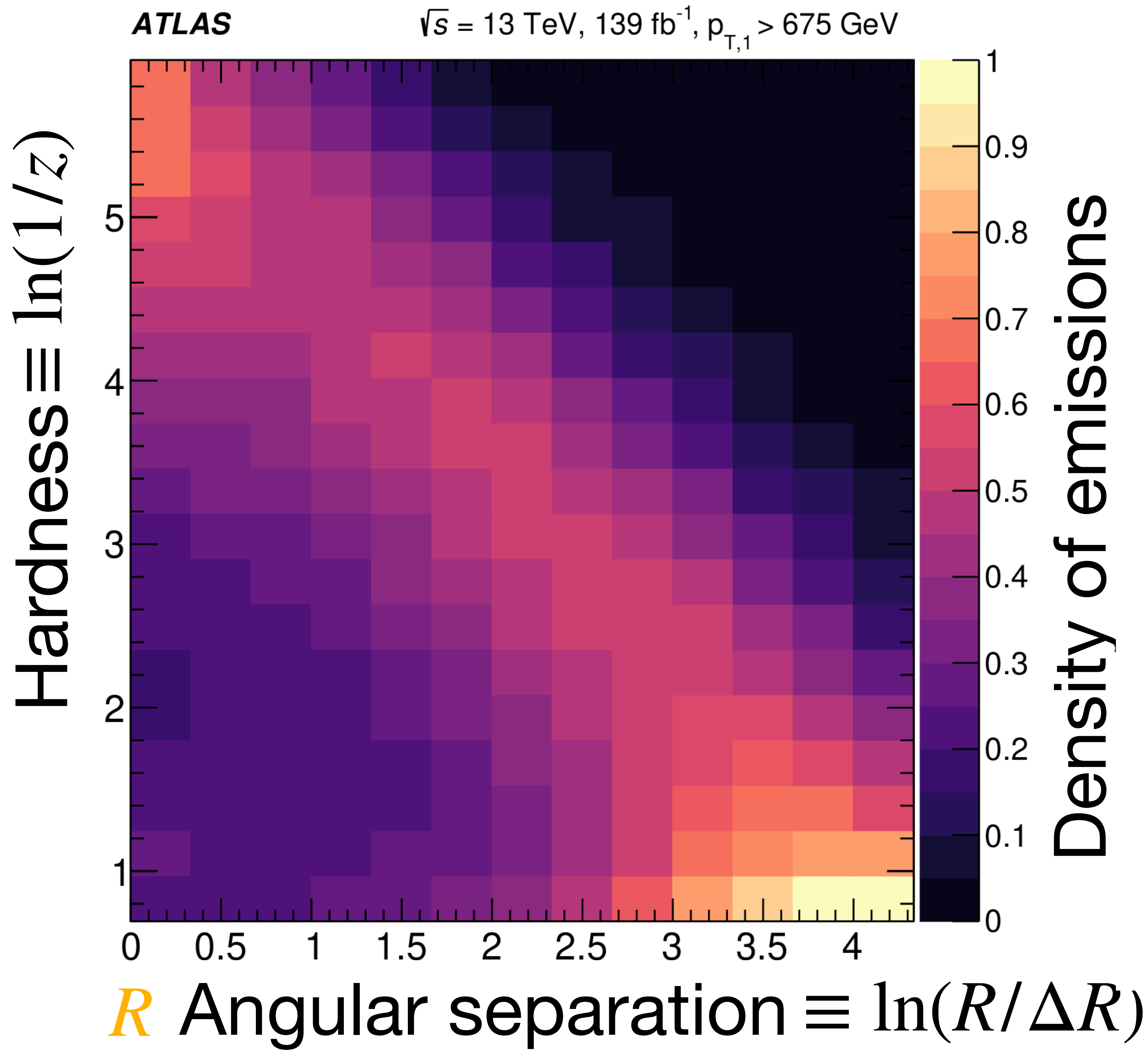
The primary Lund-plane density: NLL+NLO+NP result

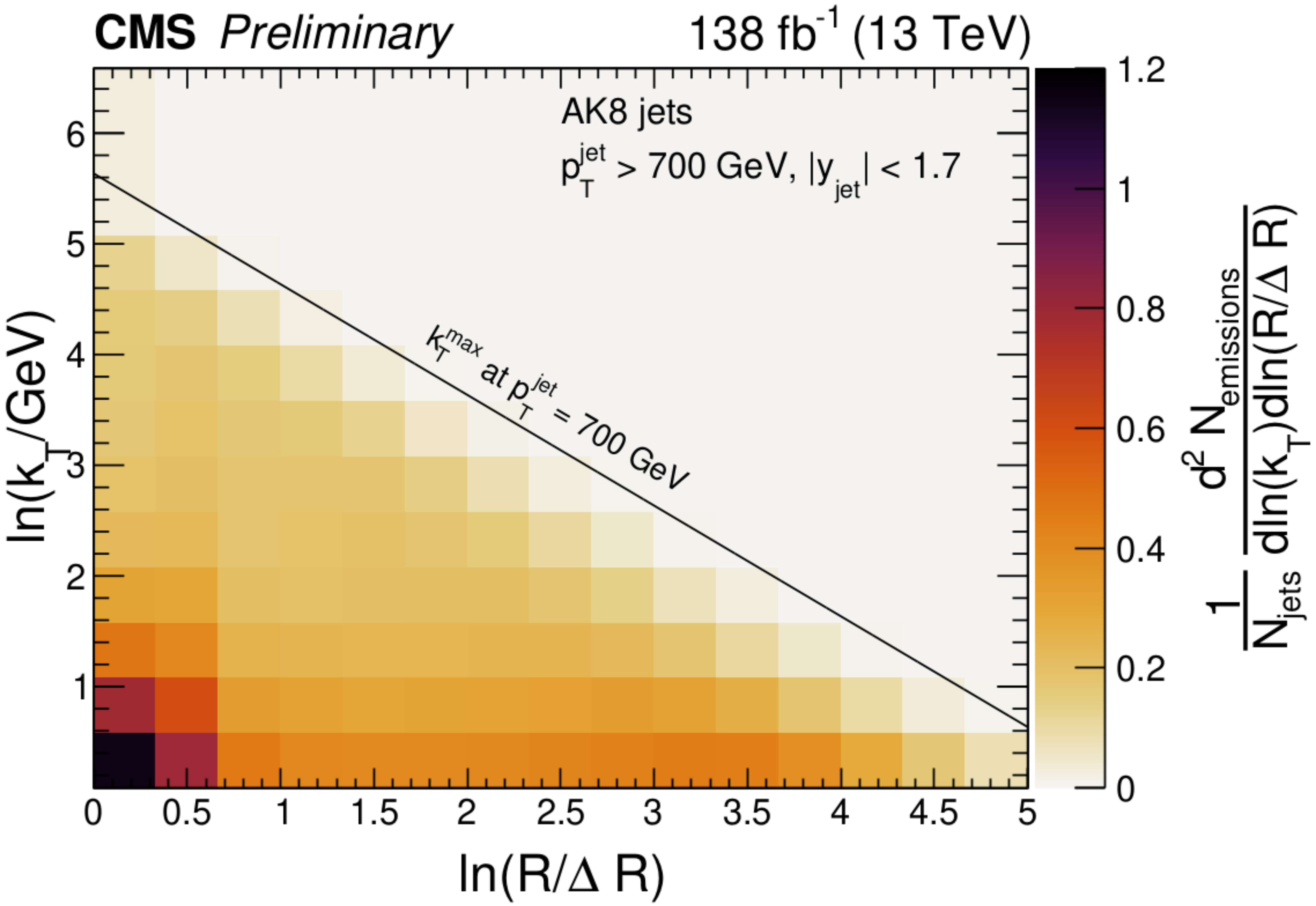




The primary Lund-plane density: measurements

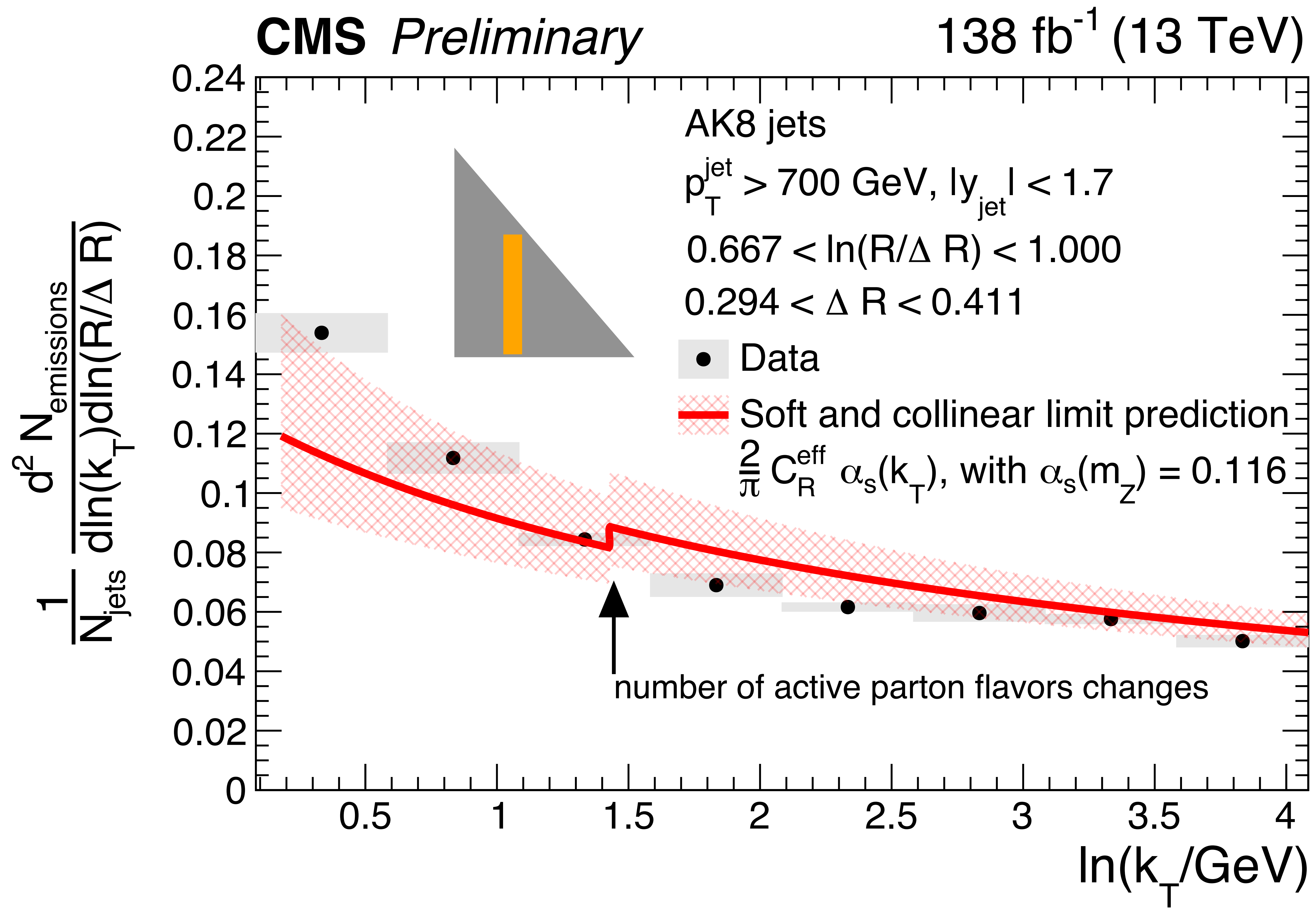
[ATLAS PRL 124 (2020) 22, 222002]

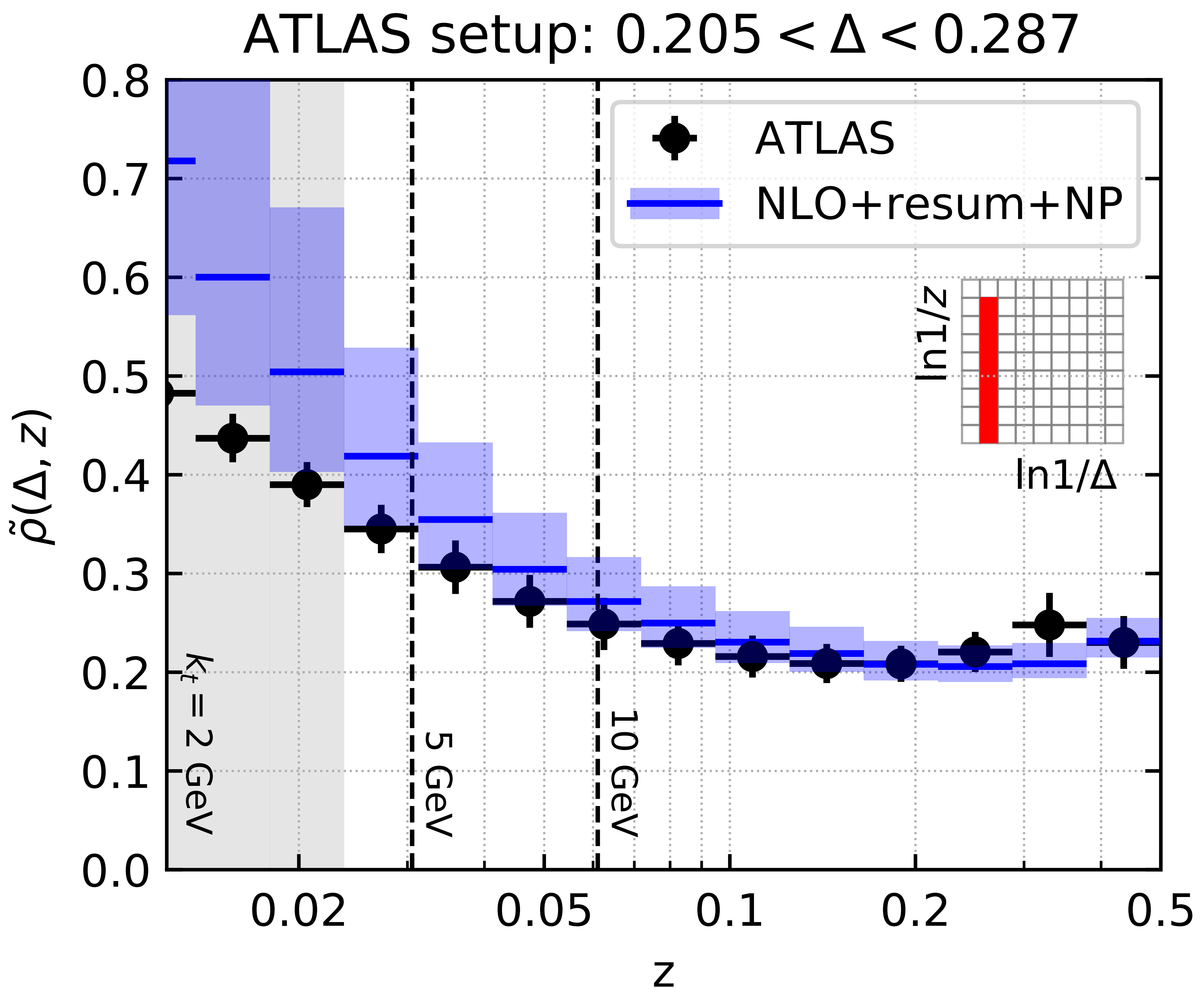




[CMS-PAS-SMP-22-007]

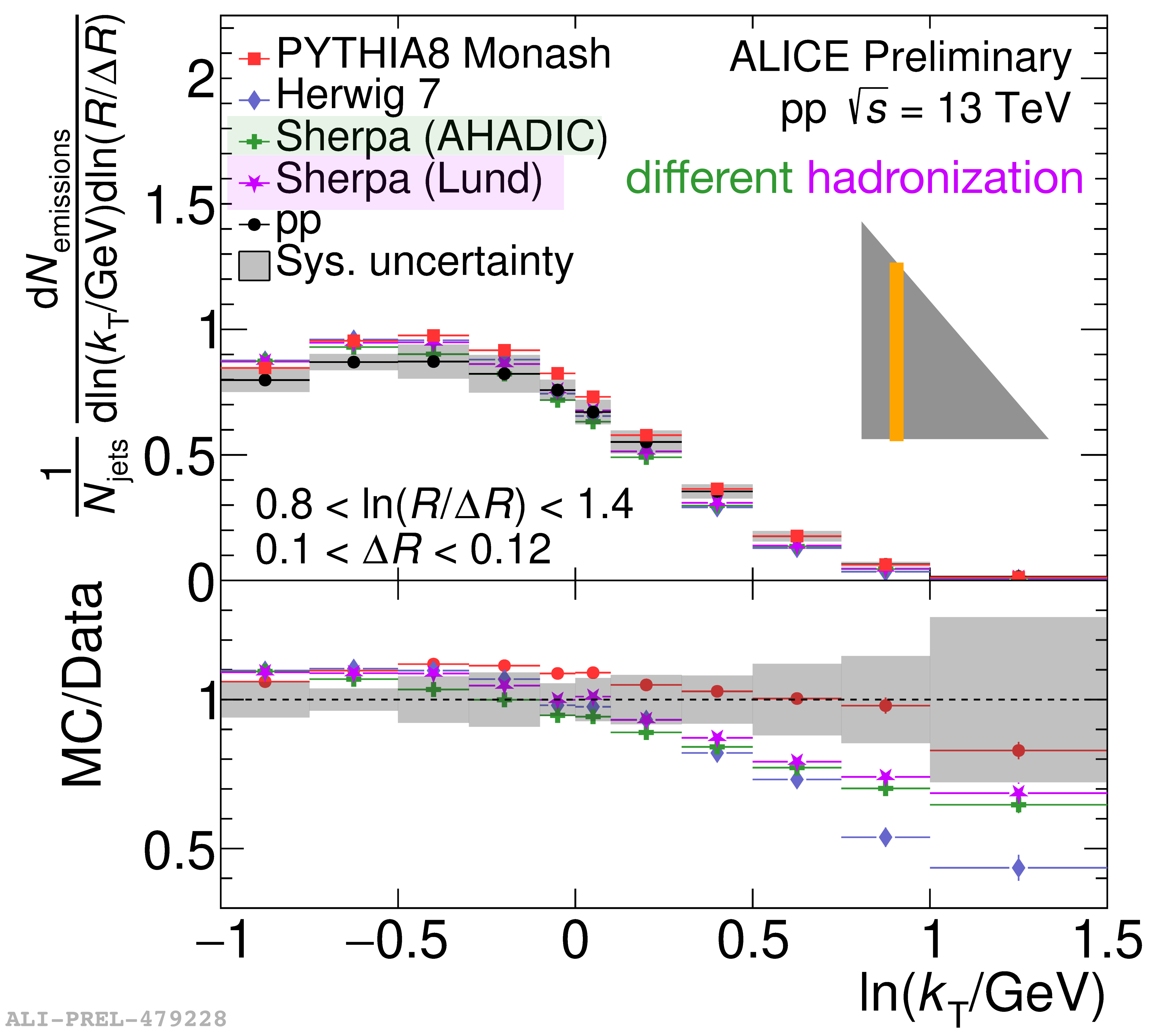
The primary Lund-plane density: theory-to-data

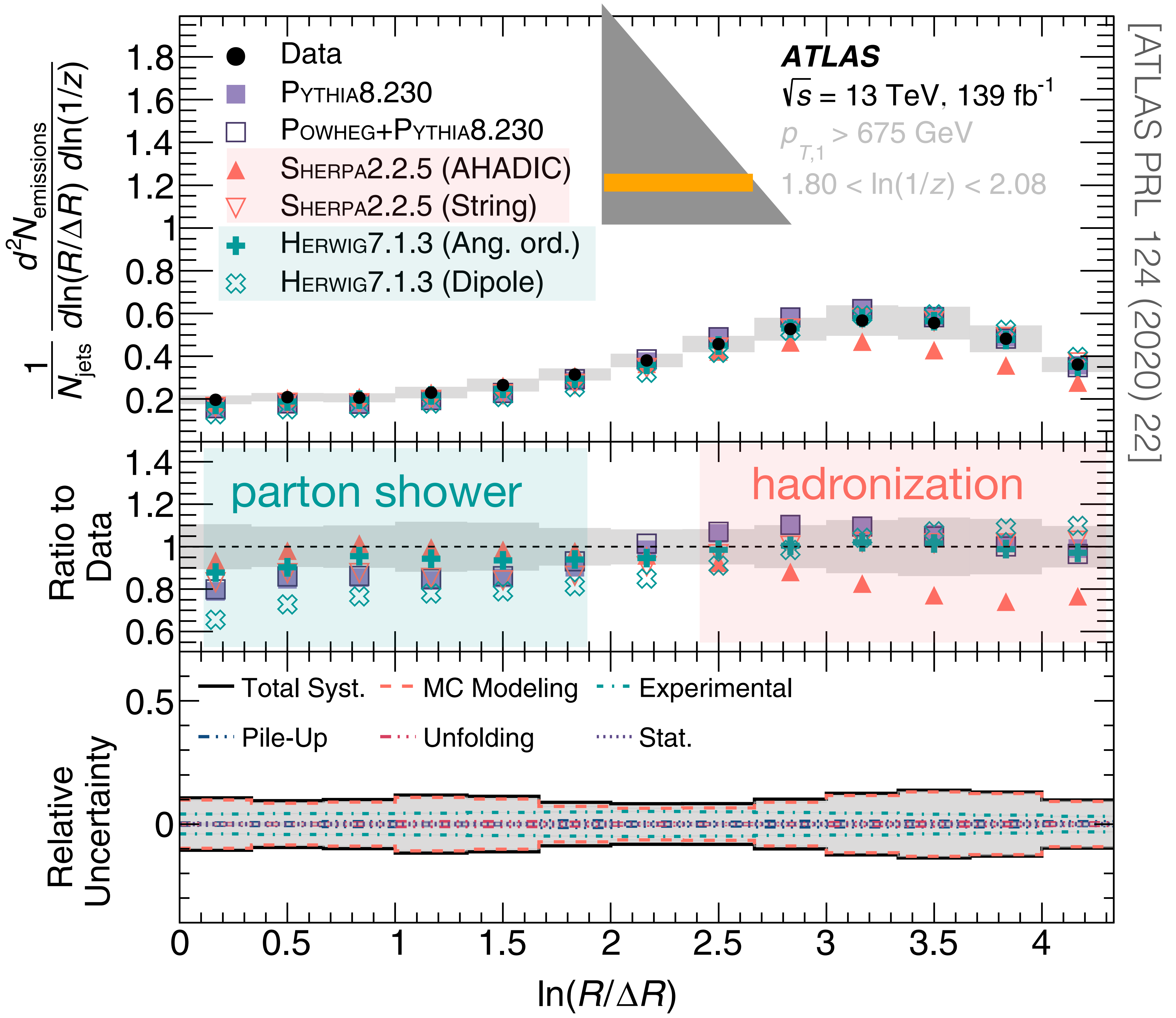




$\rho_{\rm LO}(\theta, k_t)$ agrees with data in bulk of LP. N^{k}LL terms required elsewhere

The primary Lund-plane density: MC-to-data

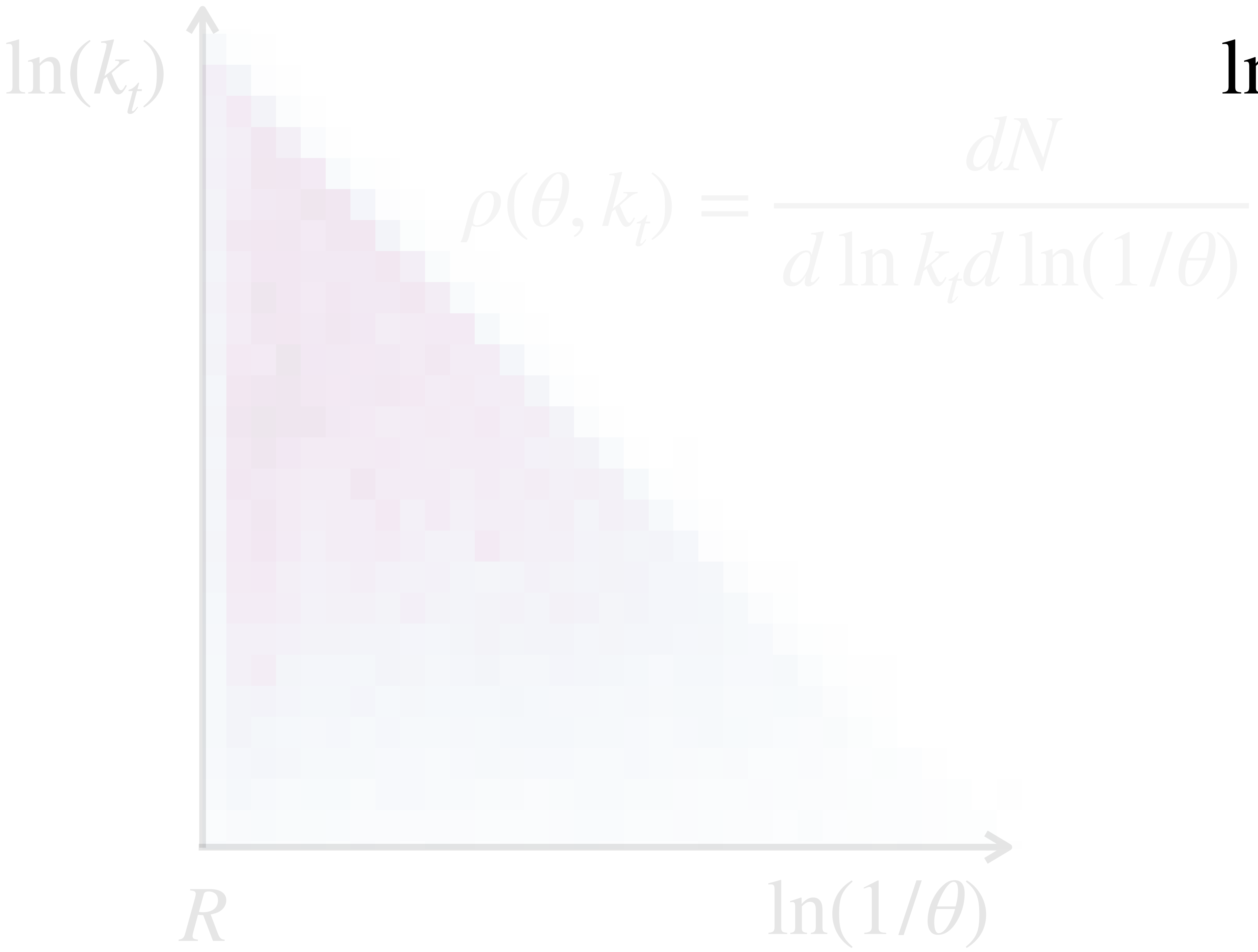




Powerful tool to disentangle between different MC ingredients

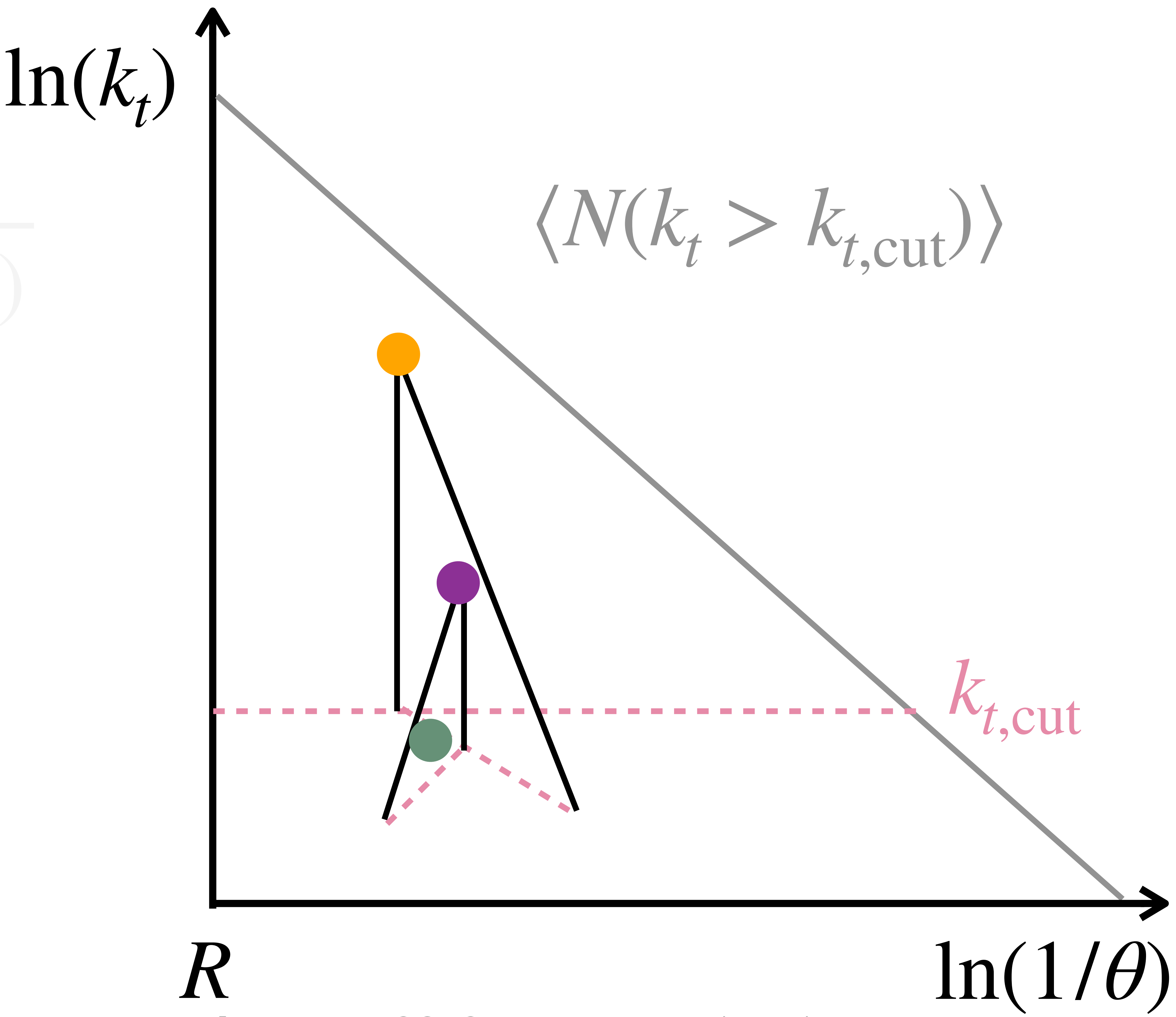
This talk: two spinoffs of the Lund jet plane

Primary Lund-plane density



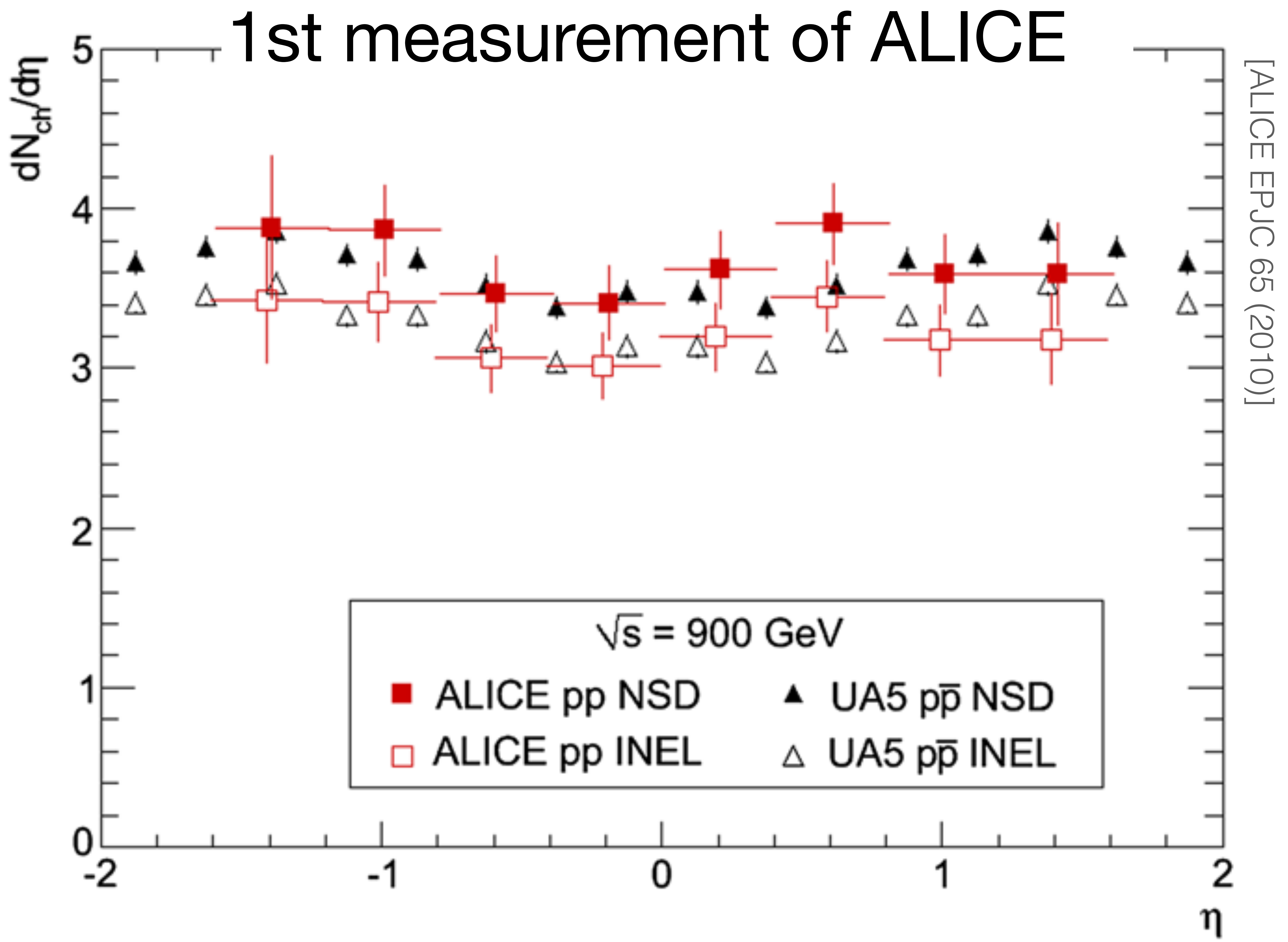
[Lifson, Salam, Soyez JHEP 10 (2020) 170]

Lund multiplicity



[Medves, ASO, Soyez, JHEP 10 (2022) 156, JHEP 04 (2023) 104]

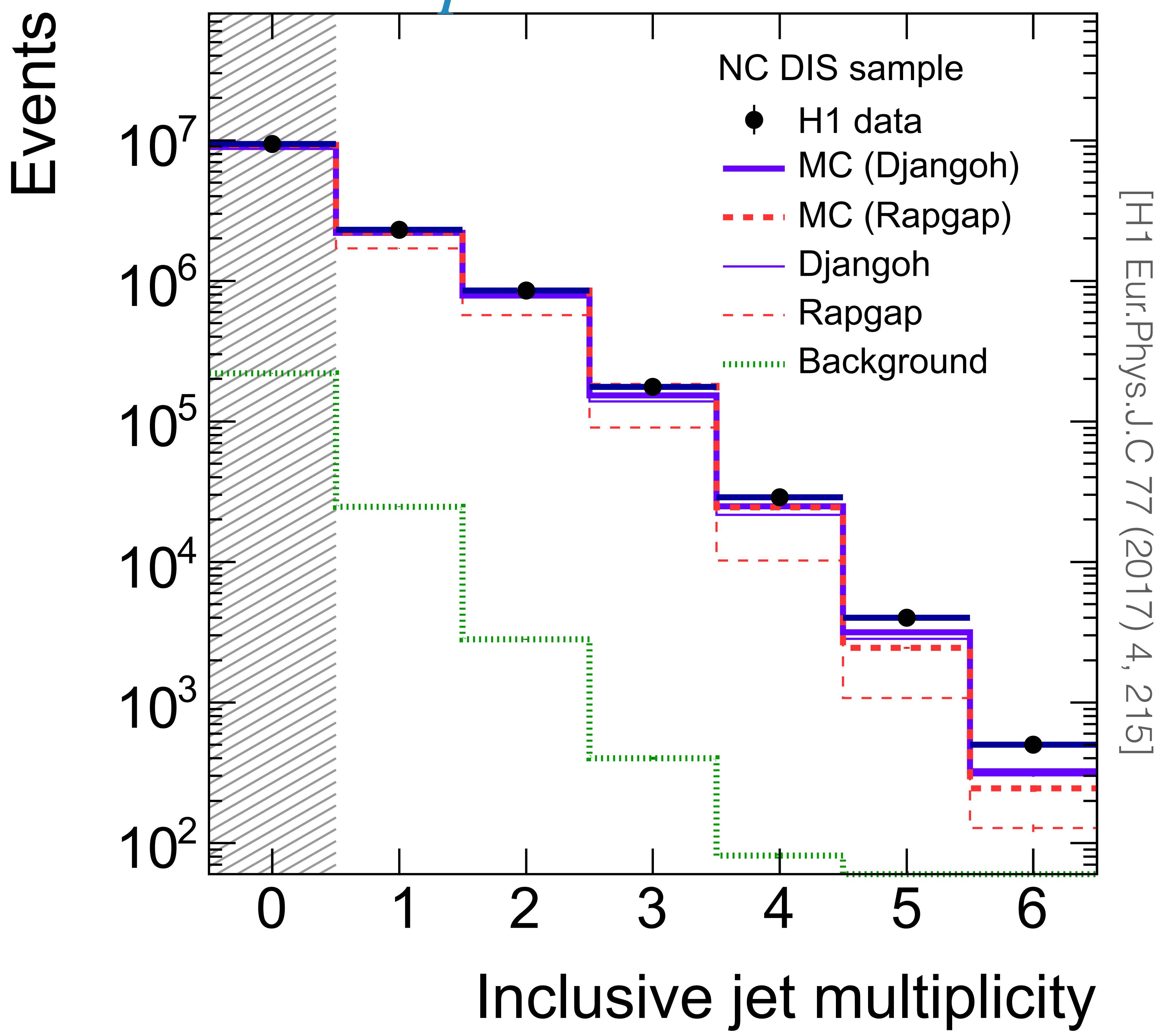
Why? One of the most studied observables in colliders



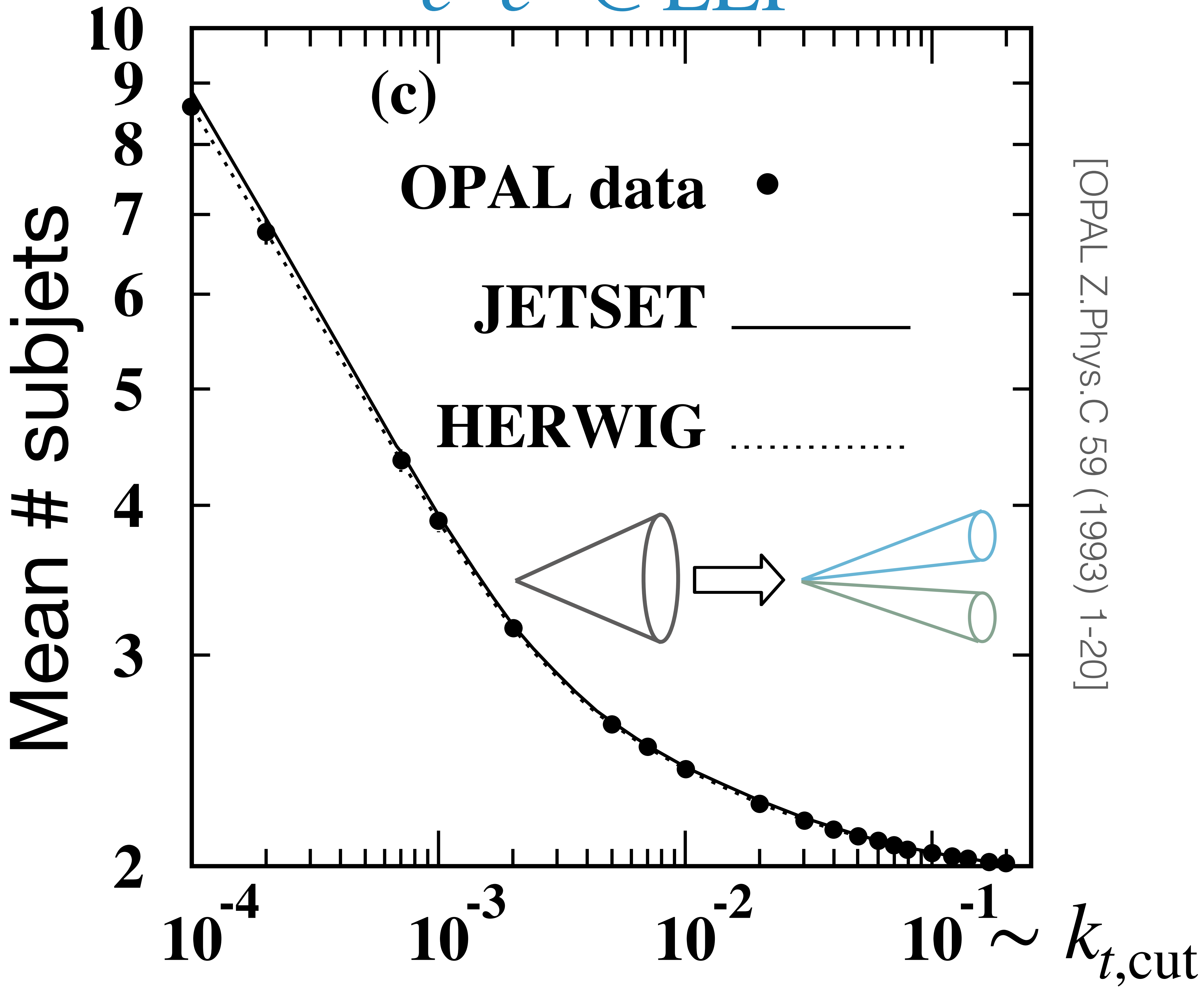
Particle multiplicities are non-perturbative objects

Why? One of the most studied observables in colliders

ep @ HERA



e^+e^- @ LEP



(Sub)jet multiplicities are calculable in pQCD $N(\alpha_s, L \equiv \ln(Q/k_{t,\text{cut}}))$

Analytic structure of the average subjet multiplicity

The perturbative expansion of the average subjet multiplicity reads

$$\langle N(\alpha_s; L)\rangle \underset{\substack{\alpha_s \ll 1 \\ \alpha_s L^2 \sim 1}}{=} \Big[\underbrace{h_1(\alpha_s L^2)}_{\text{DL}} + \underbrace{\sqrt{\alpha_s} h_2(\alpha_s L^2)}_{\text{NDL}} + \underbrace{\alpha_s h_3(\alpha_s L^2)}_{\text{NNDL}\sim 10\%} + \ldots\Big]$$

where $\mathrm{N}^k\mathrm{DL}$ accuracy implies control over $\alpha_s^n L^{2n-k}$ terms with $0 < n < \infty$

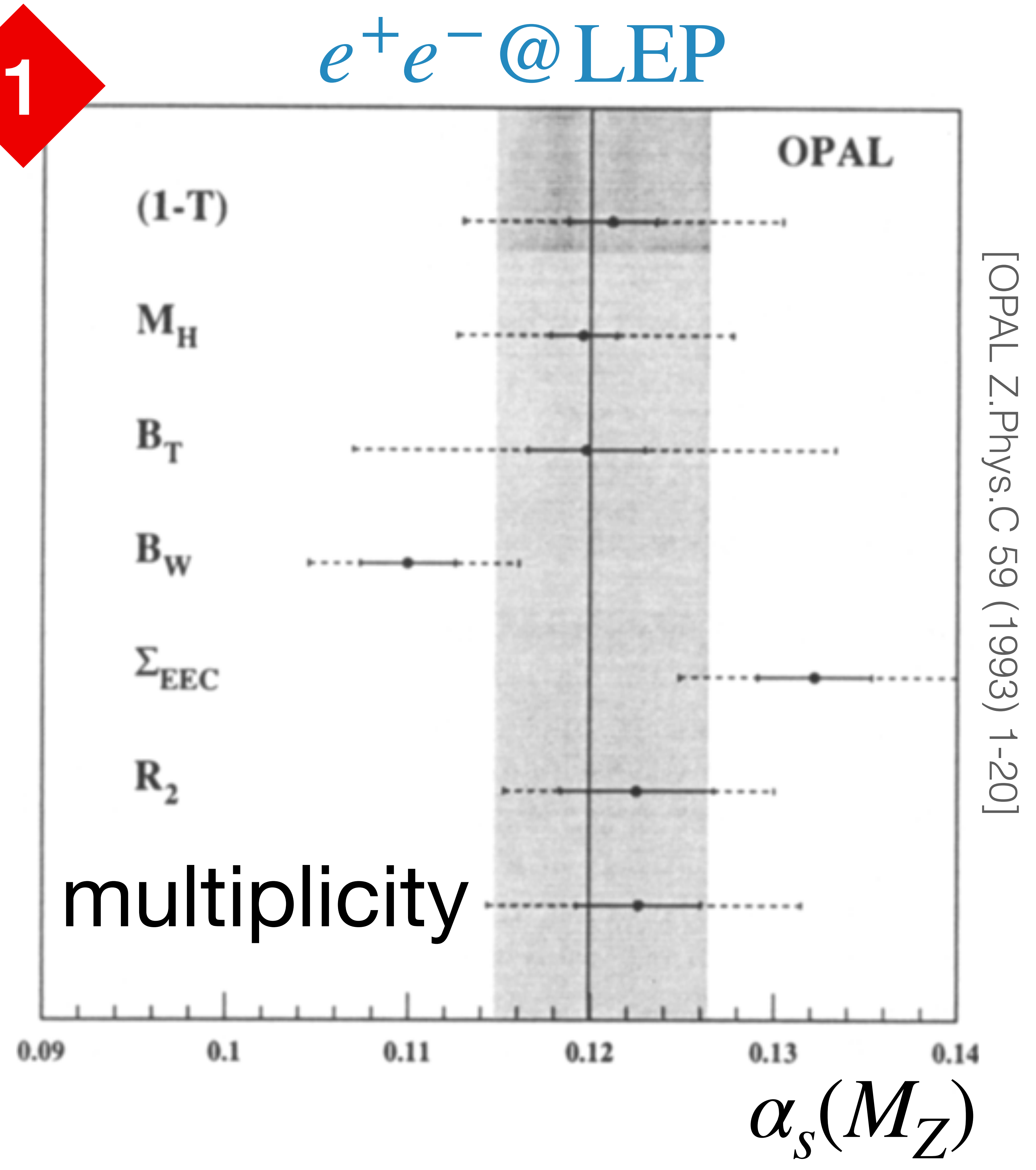
Goal: NNDL calculation of average subjet multiplicity

[Medves, ASO, Soyez, JHEP 10 (2022) 156, JHEP 04 (2023) 104]

[NDL: Catani, Dokshitzer, Fiorani, Webber NPB 377 (1992) 445-460]

Motivations to push for higher accuracy

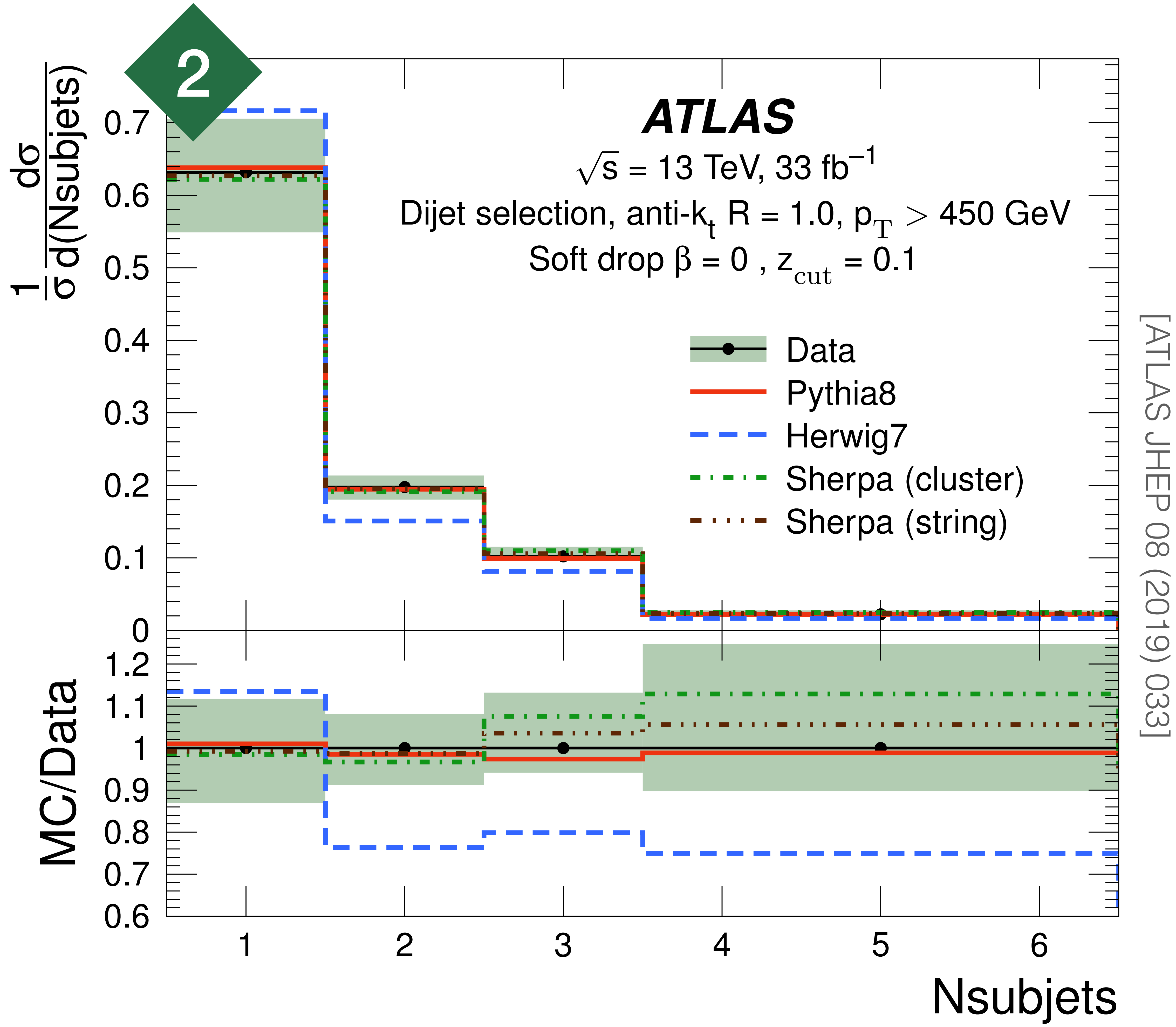
1



[Catani, Dokshitzer, Fiorani, Webber NPB 377 (1992) 445-460]

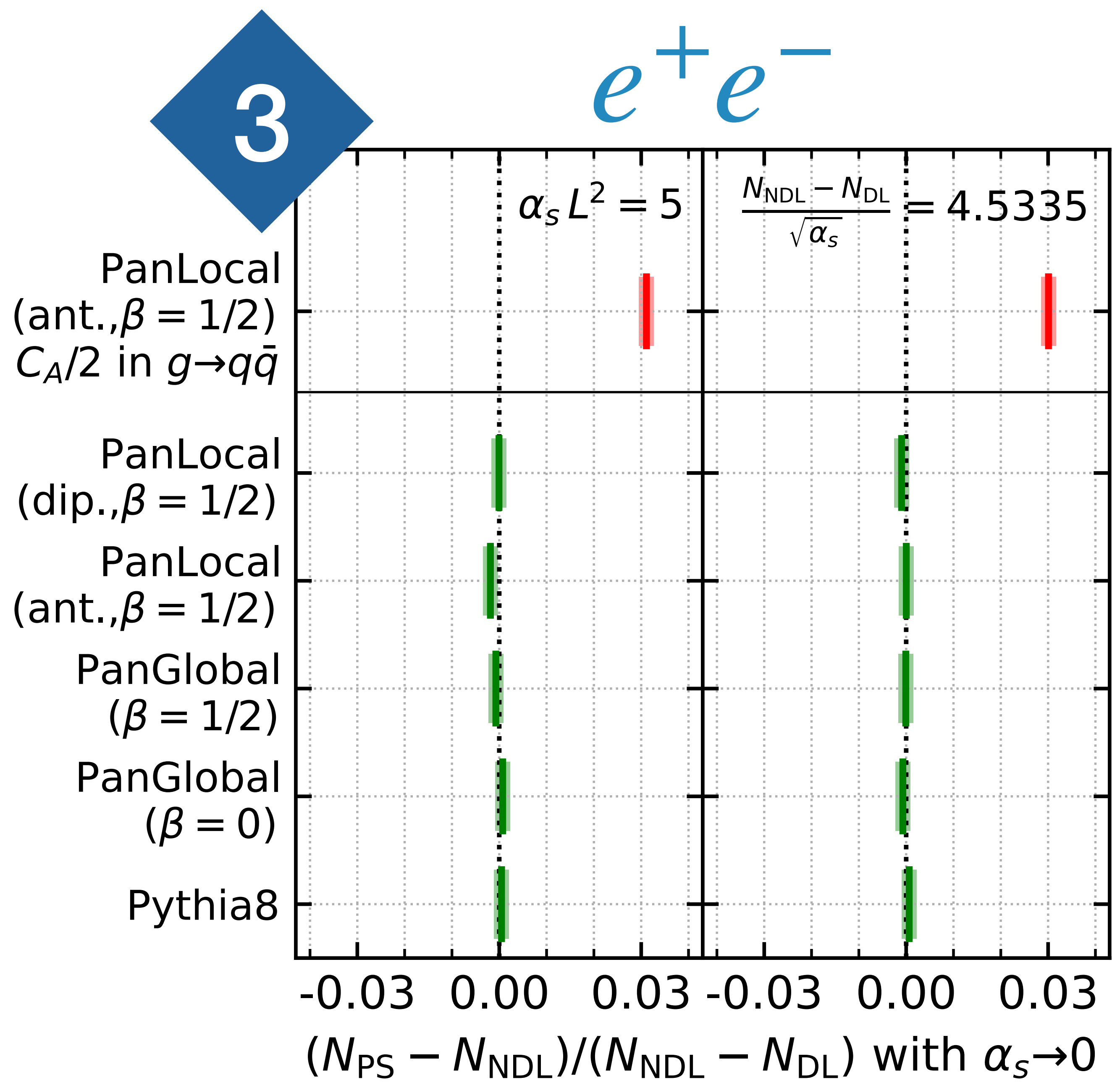
$\alpha_s(M_Z)$ extractions at e+e- colliders

2

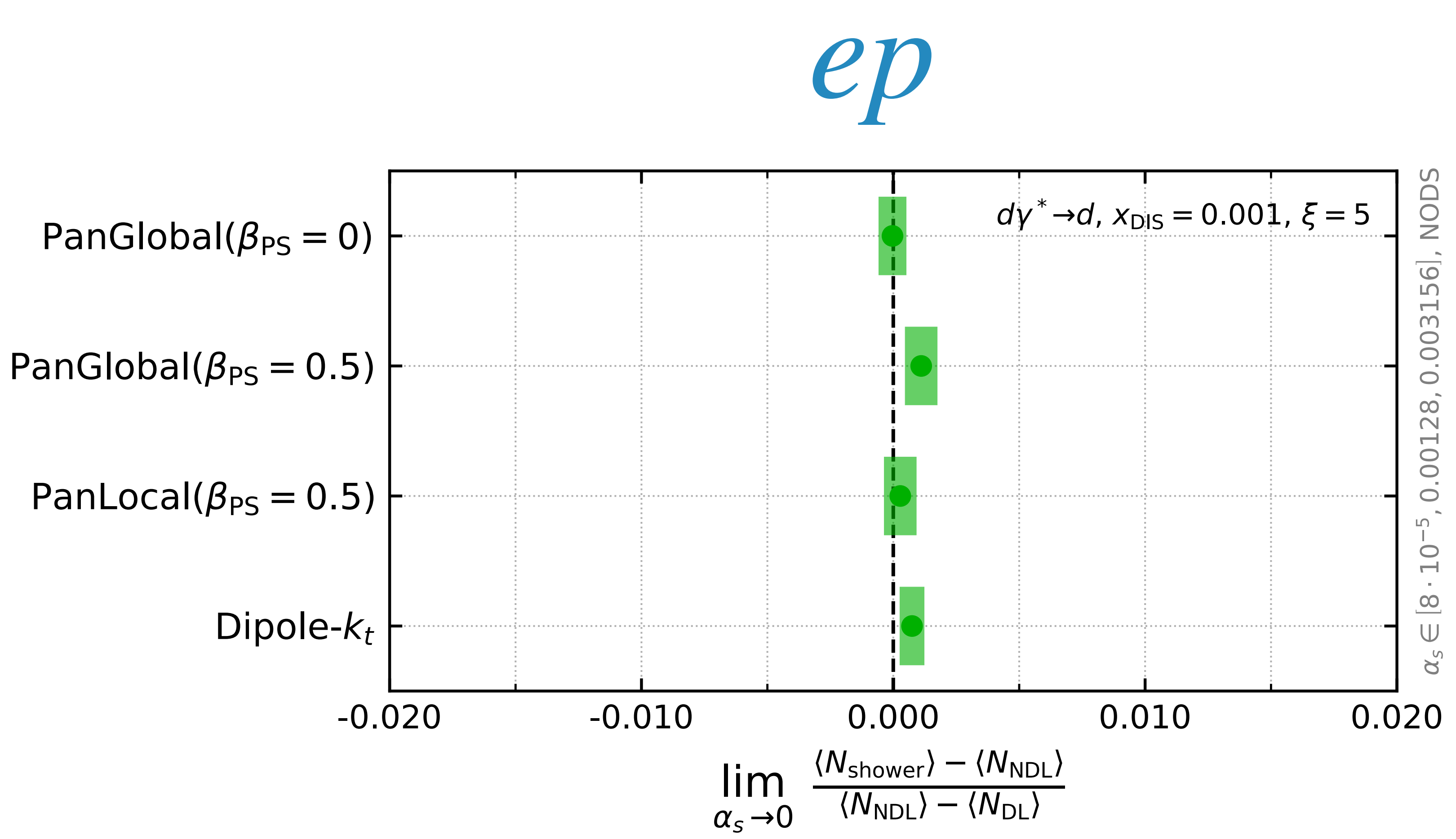


Calibrate MC generators

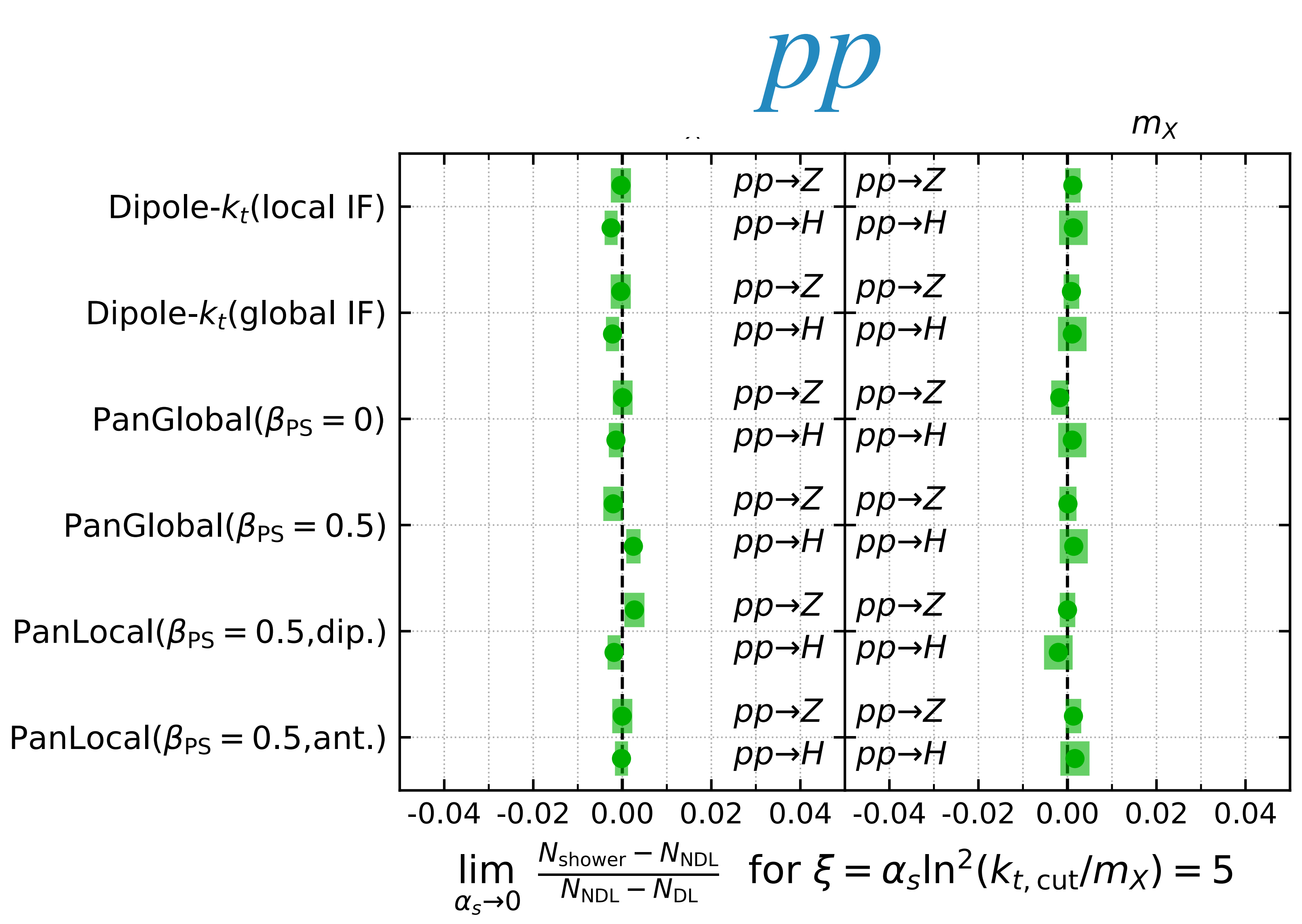
Motivations to push for higher accuracy



[Hamilton et al. JHEP 03 (2021) 041]



[van Beekveld, Ferrario Ravasio arXiv: 2305.08645]



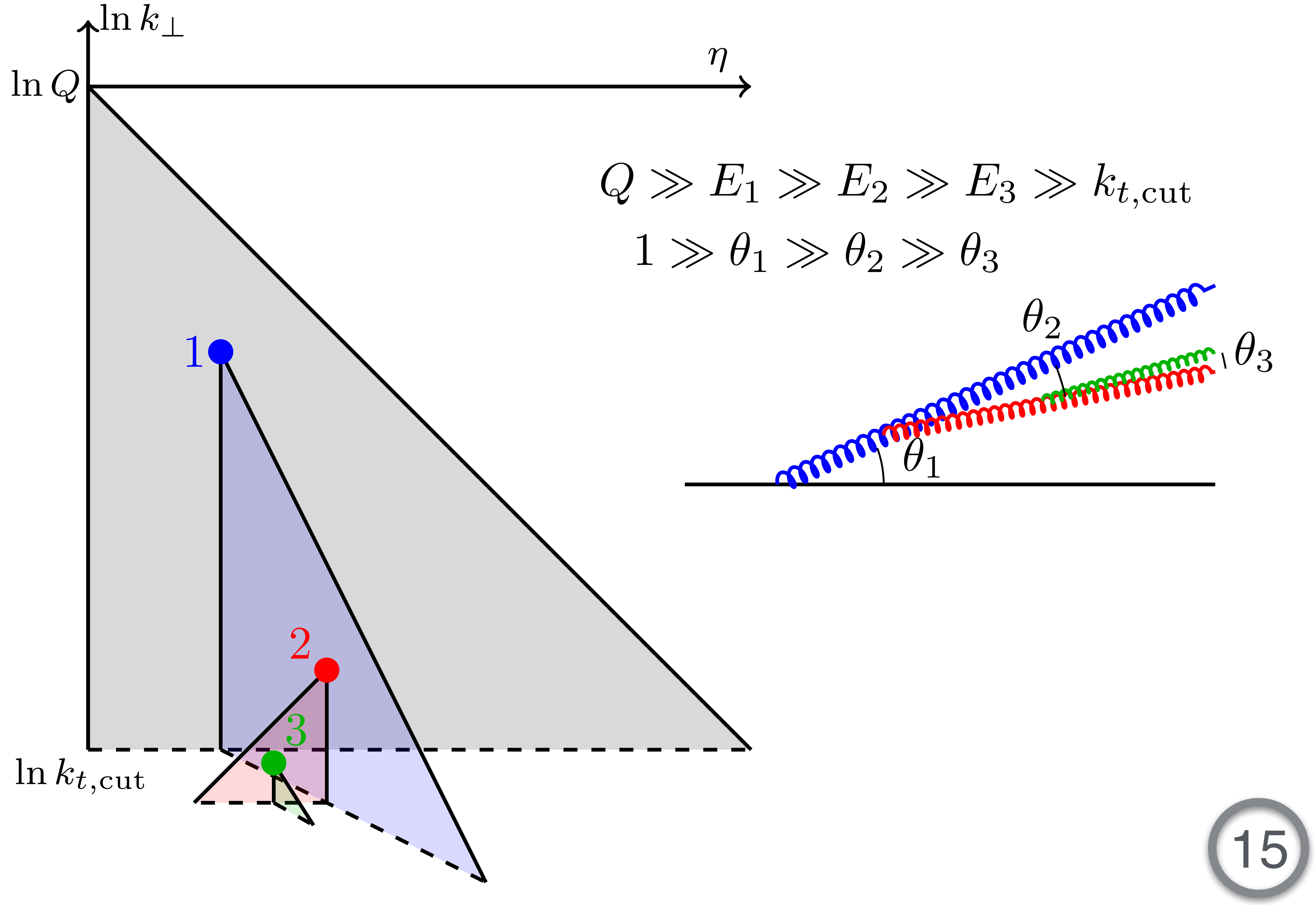
[van Beekveld, ASO et al. JHEP 11 (2022) 020]

Test parton showers with improved logarithmic accuracy

Lund multiplicity: DL resummation $(\alpha_s L^2)^n$

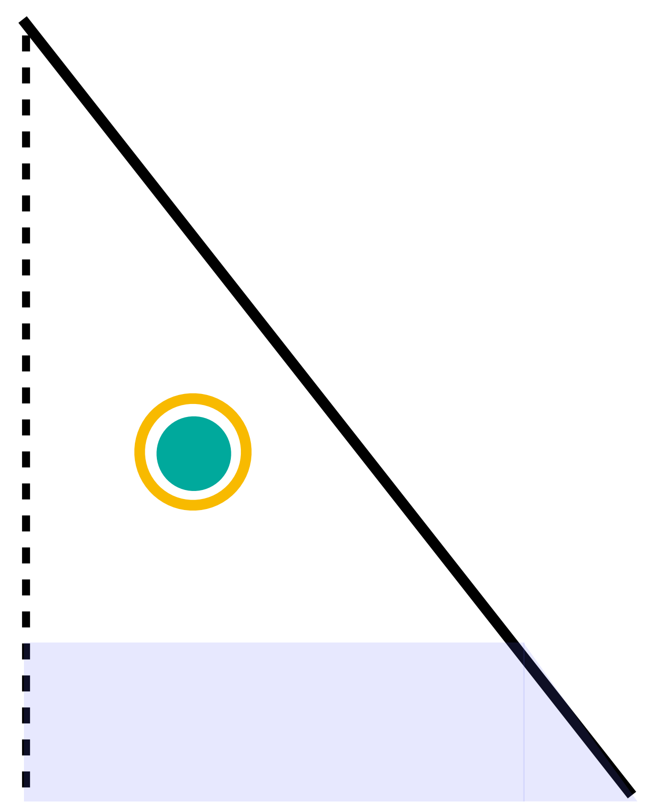
$$\langle N \rangle_{\mathrm{DL}} = 1 + \frac{C_i}{C_A} \sum_{n=1}^{\infty} \bar{\alpha}^n \underbrace{\int_0^\infty \mathrm{d}\eta_1 \int_{\eta_1}^\infty \mathrm{d}\eta_2 \ldots \int_{\eta_{n-1}}^\infty \mathrm{d}\eta_n}_{\text{angular-ordering}} \underbrace{\int_0^1 \frac{\mathrm{d}x_1}{x_1} \int_0^{x_1} \frac{\mathrm{d}x_2}{x_2} \ldots \int_0^{x_{n-1}} \frac{\mathrm{d}x_n}{x_n}}_{\text{energy-ordering}} \underbrace{\Theta(x_n e^{-\eta_n} > e^{-L})}_{k_t > k_{t,\mathrm{cut}}}$$

$$\langle N \rangle_{\mathrm{DL}} = 1 + \frac{C_i}{C_A}\left[\cosh \nu - 1\right]$$



$$\nu = \sqrt{2\alpha_s C_A L^2/\pi}$$

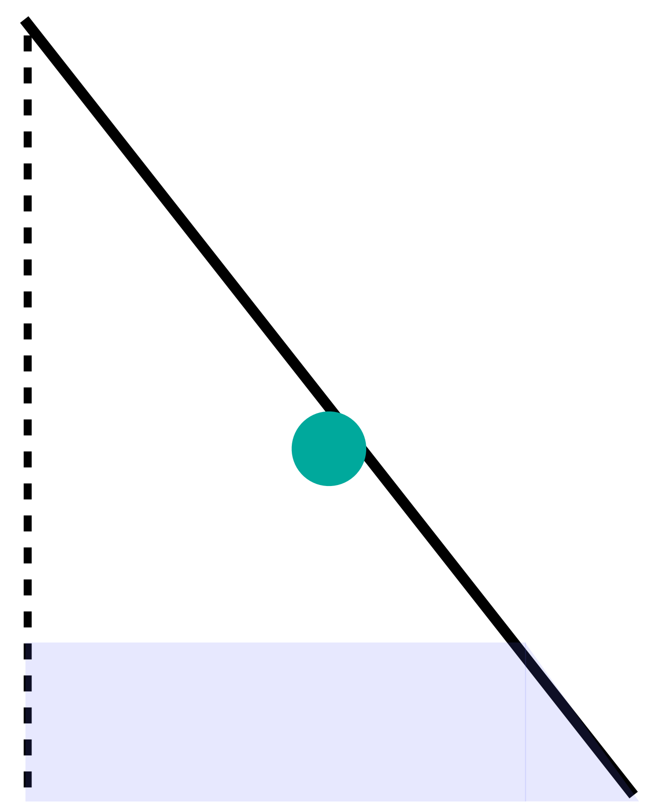
Lund multiplicity: NDL resummation $\alpha_s L(\alpha_s L^2)^n$



Running coupling

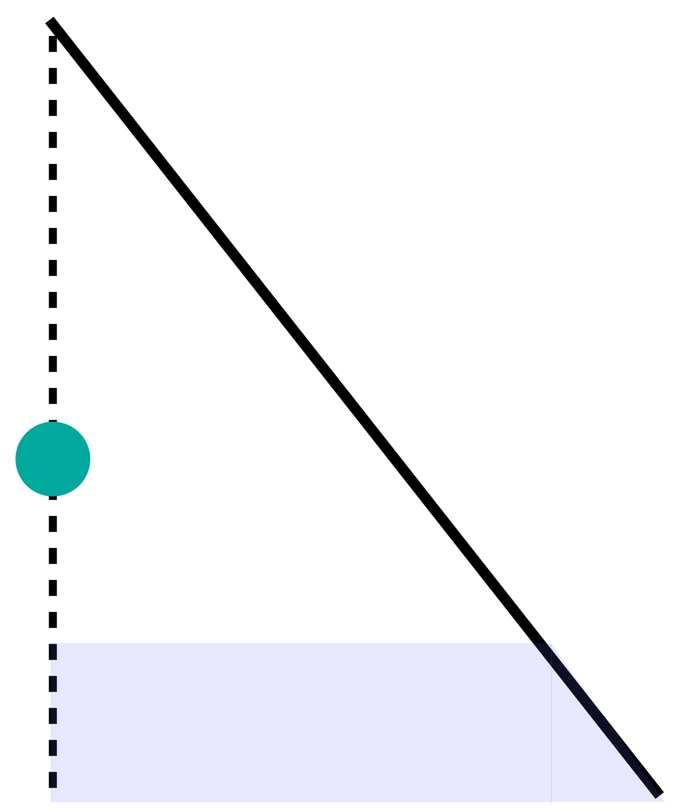
$$\alpha_s \to \alpha_s - 2\alpha_s^2 \beta_0 \ell + \mathcal{O}(\alpha_s^3)$$

with $\ell \equiv \ln(k_t/Q)$



Hard-collinear

$$\frac{1}{z} \to C_F \left(\frac{1-z}{z} + \frac{z}{2} \right)$$

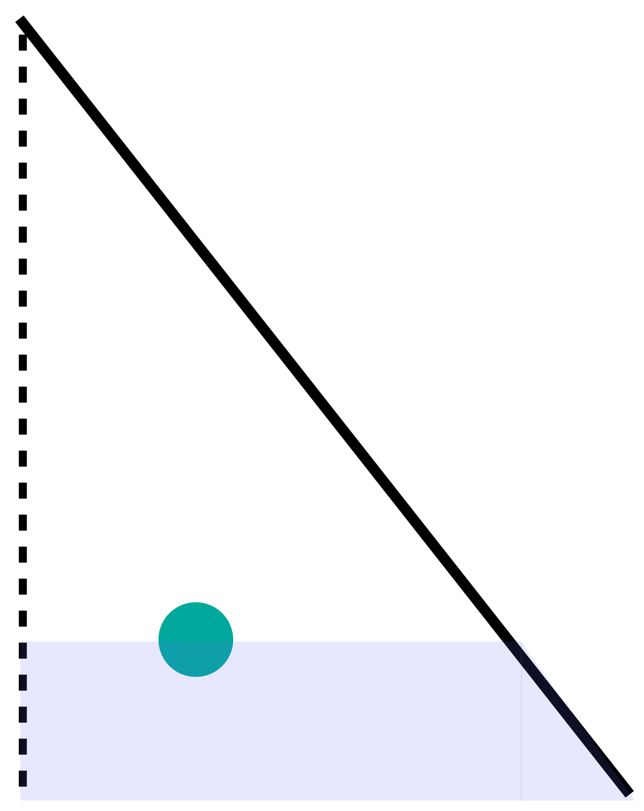


Large-angle

$$\frac{\mathrm{d}z}{z}\mathrm{d}\eta$$

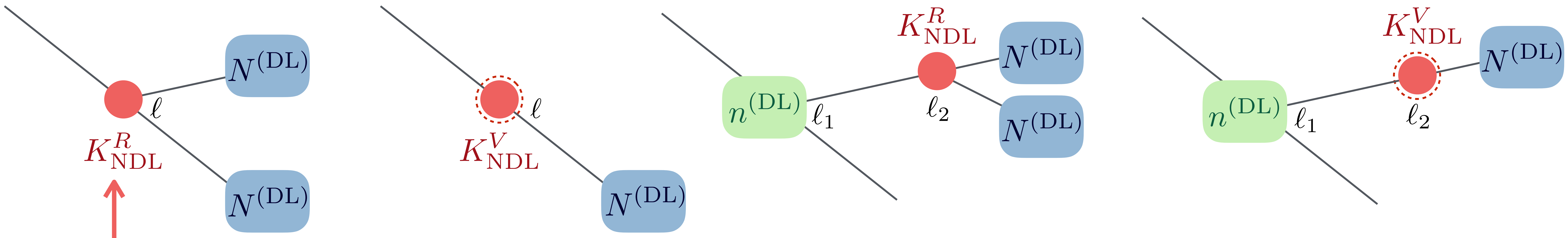
$$\downarrow$$

$$\frac{p_i \cdot p_j}{p_i \cdot p_k p_j \cdot p_k} \frac{\mathrm{d}\phi}{2\pi} \mathrm{d}\cos\theta$$



$k_t \sim k_{t,\mathrm{cut}}$

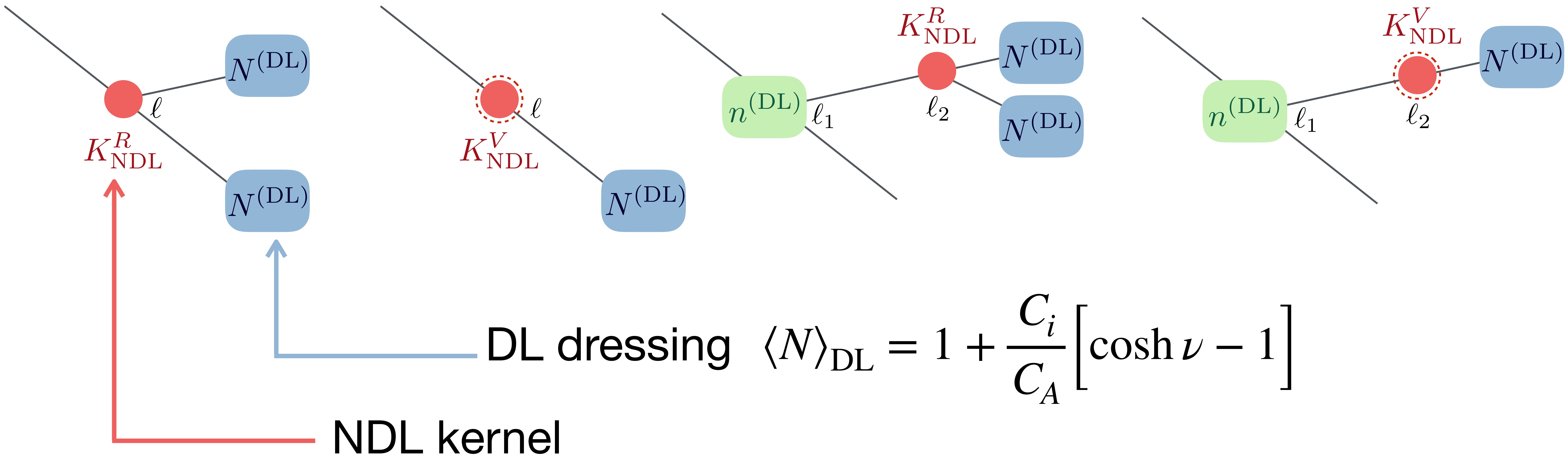
Lund multiplicity: NDL resummation strategy



NDL kernel, e.g. $K_{\mathrm{hc}} = \dfrac{2\alpha_s C_i}{\pi} \times B$

$$B = \int_0^1 \left(P(z) - \frac{1}{z}\right) dz$$

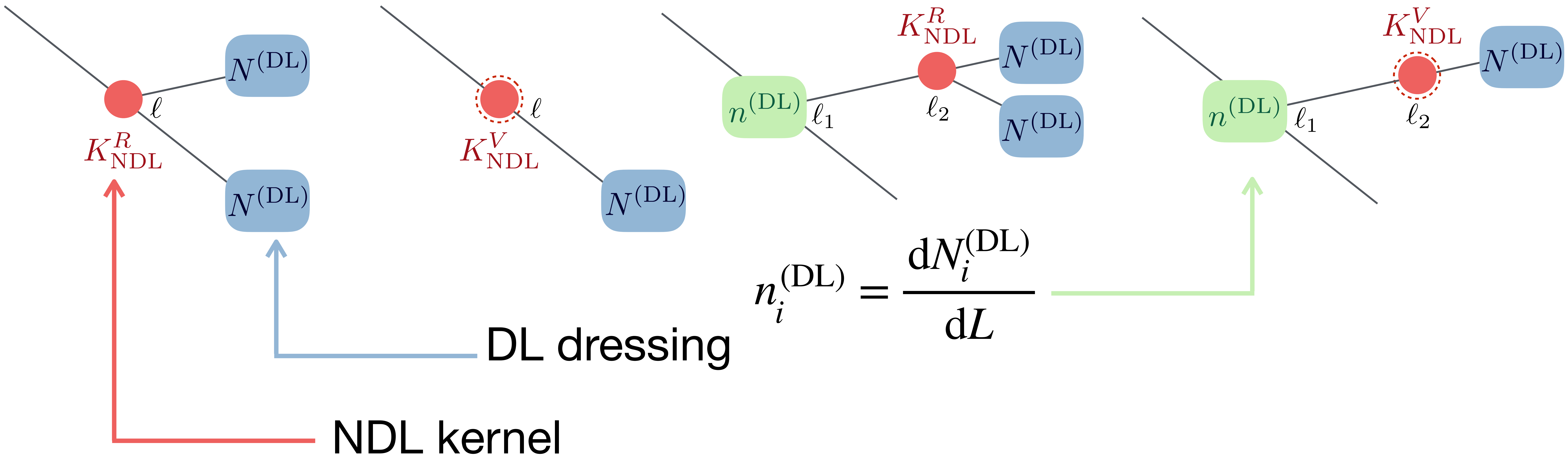
Lund multiplicity: NDL resummation strategy



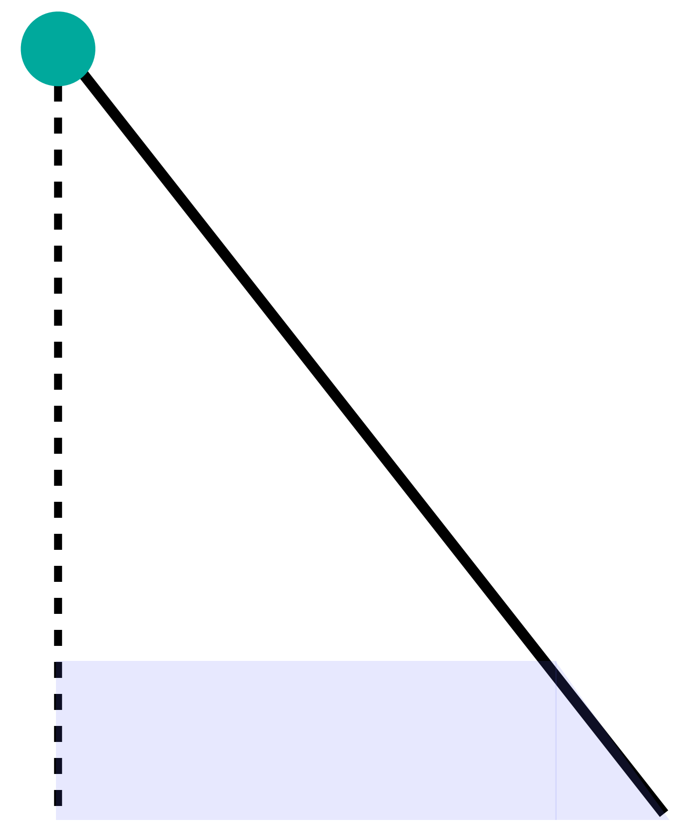
DL dressing $\langle N \rangle_{\mathrm{DL}} = 1 + \frac{C_i}{C_A}\left[\cosh \nu - 1\right]$

NDL kernel

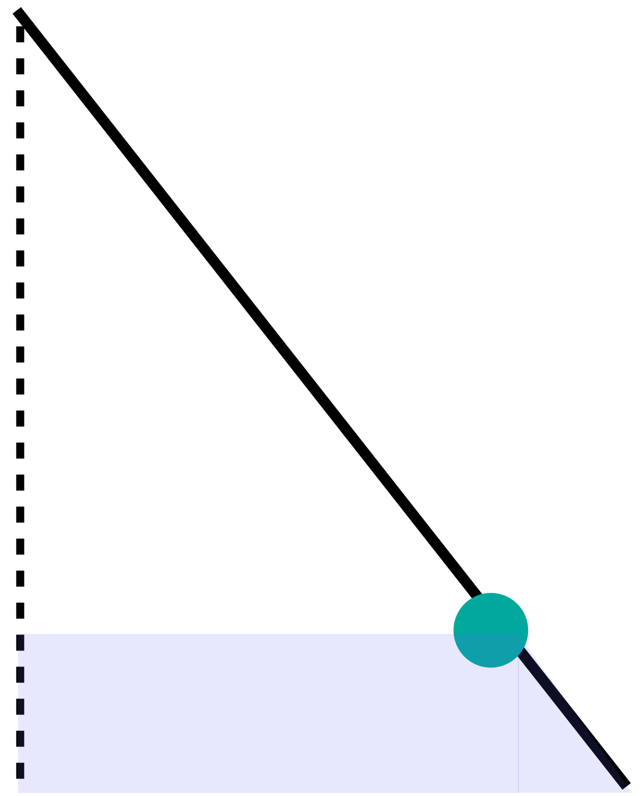
Lund multiplicity: NDL resummation strategy



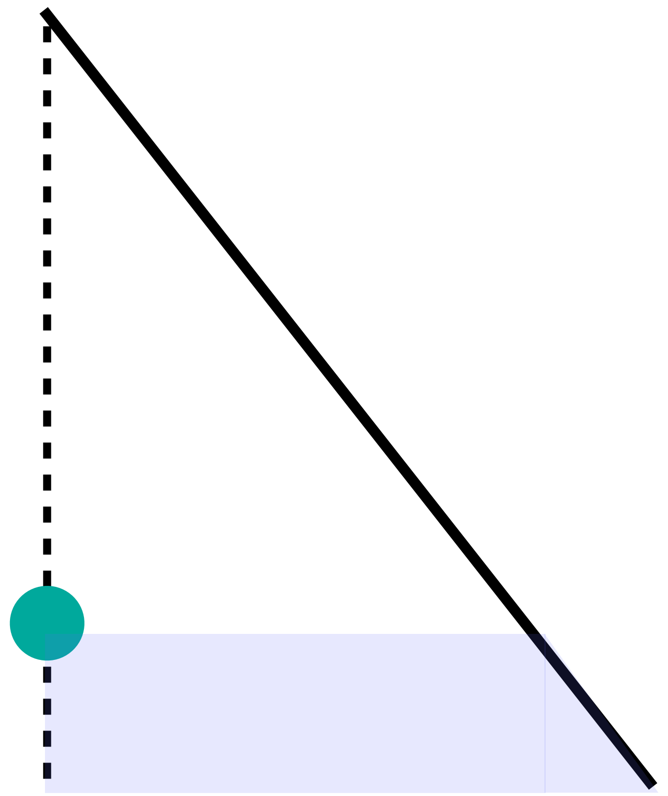
Lund multiplicity: NNDL resummation $\alpha_s(\alpha_s L^2)^n$



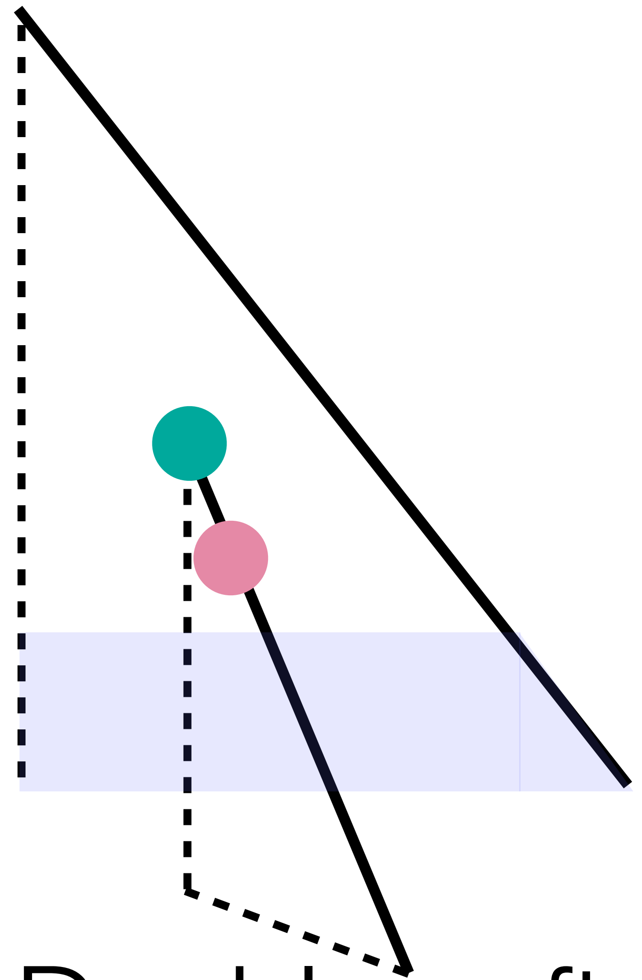
Hard ME



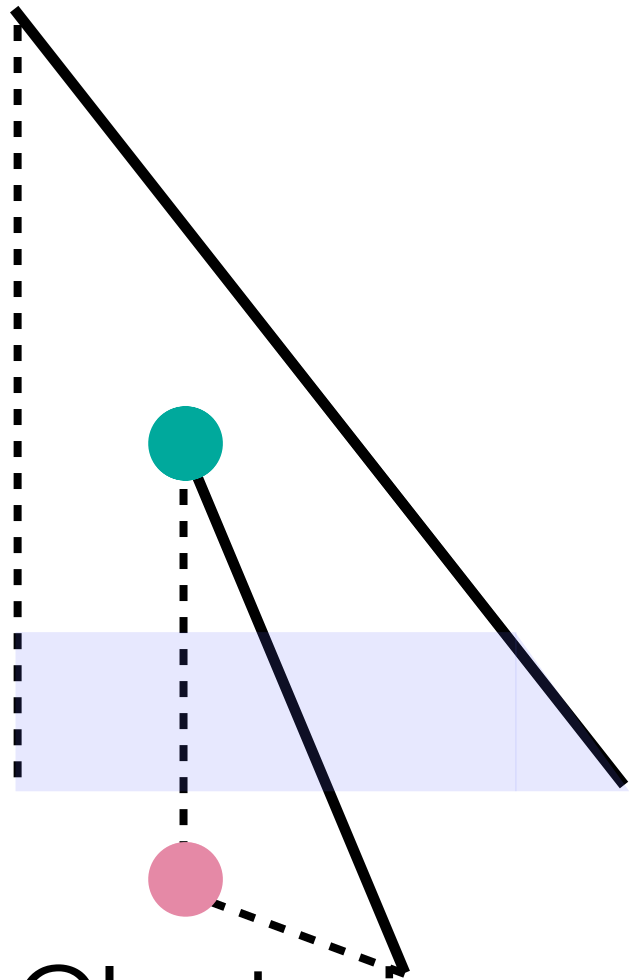
Collinear
end-point



Large angle
$+ k_t \sim k_{t,\text{cut}}$

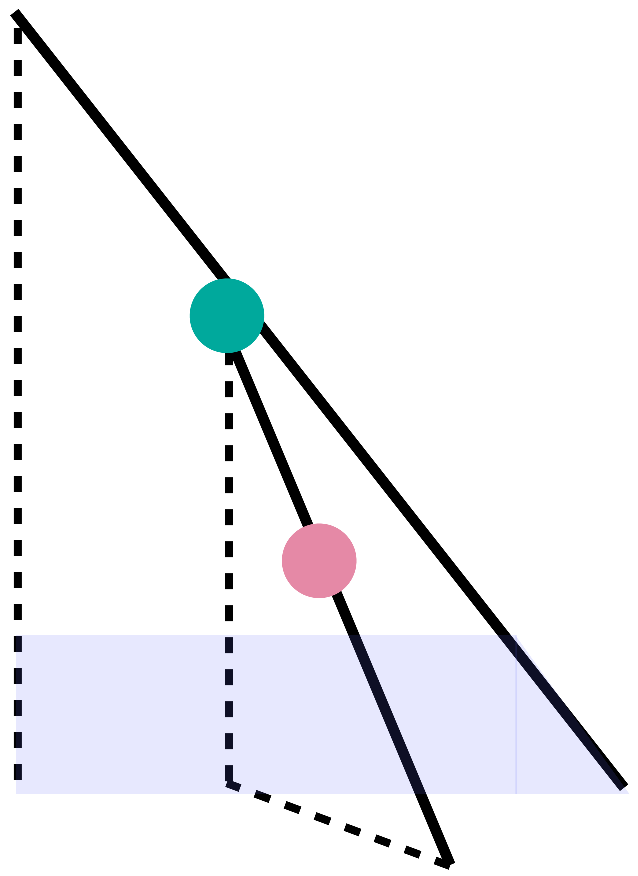


Double soft

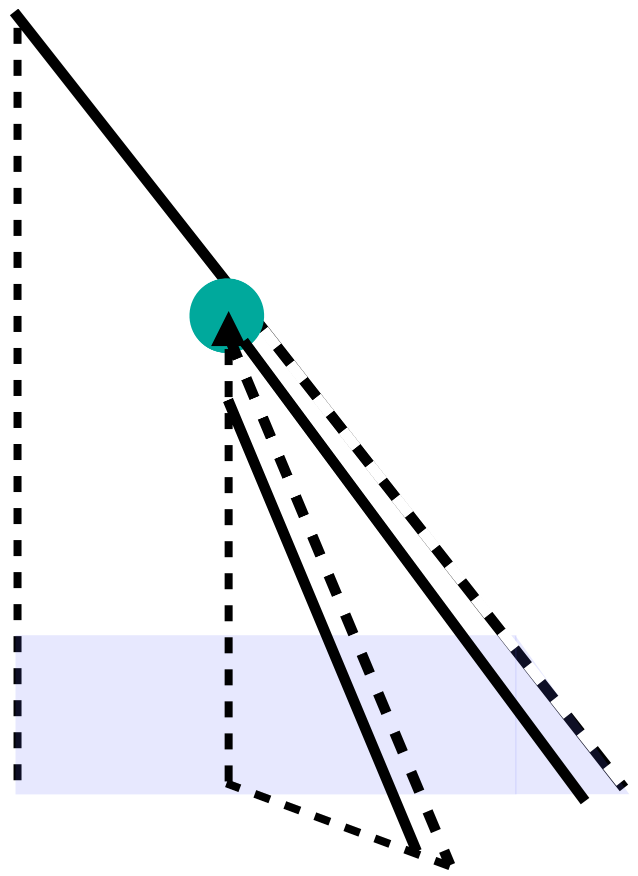


Clustering

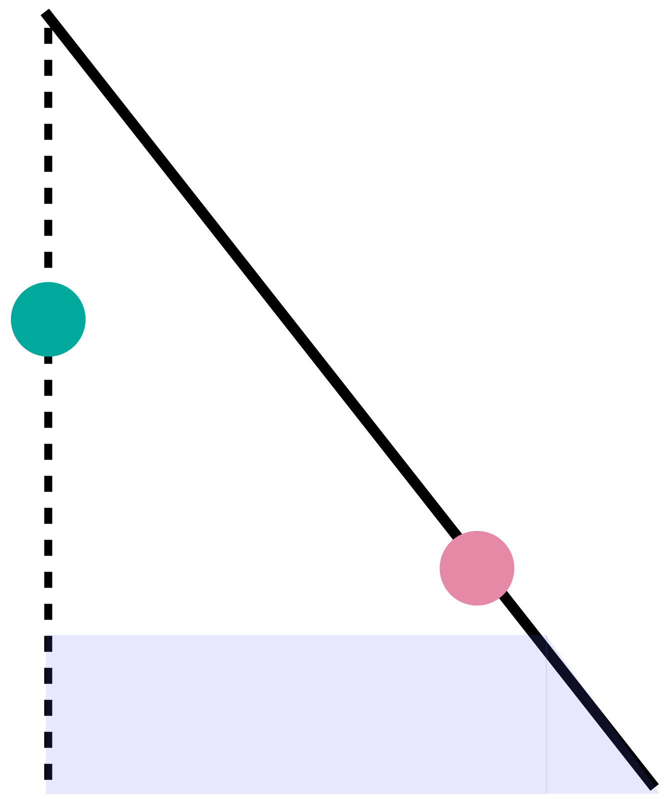
Lund multiplicity: NNDL resummation $(\alpha_s L)(\alpha_s L)(\alpha_s L^2)^n$



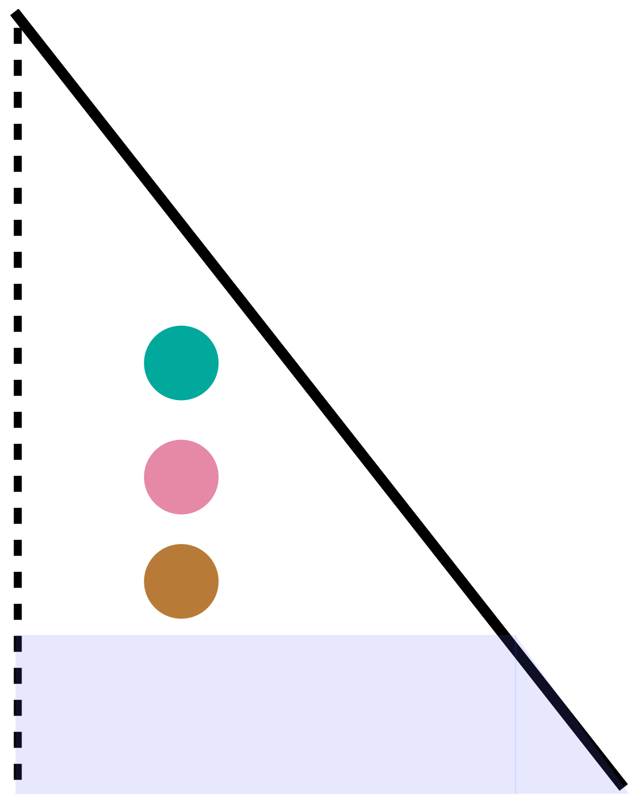
2 hard collinear



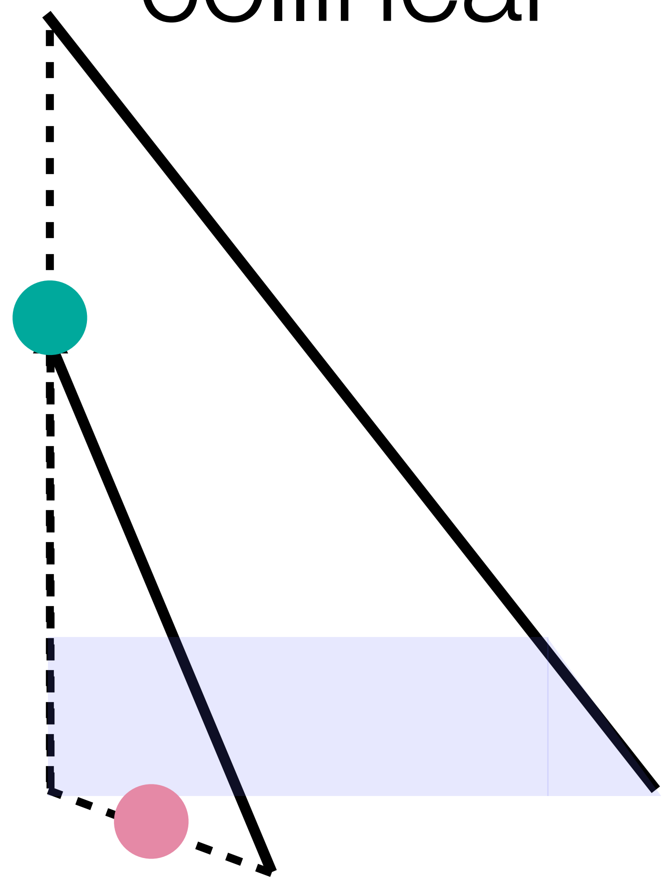
Energy loss



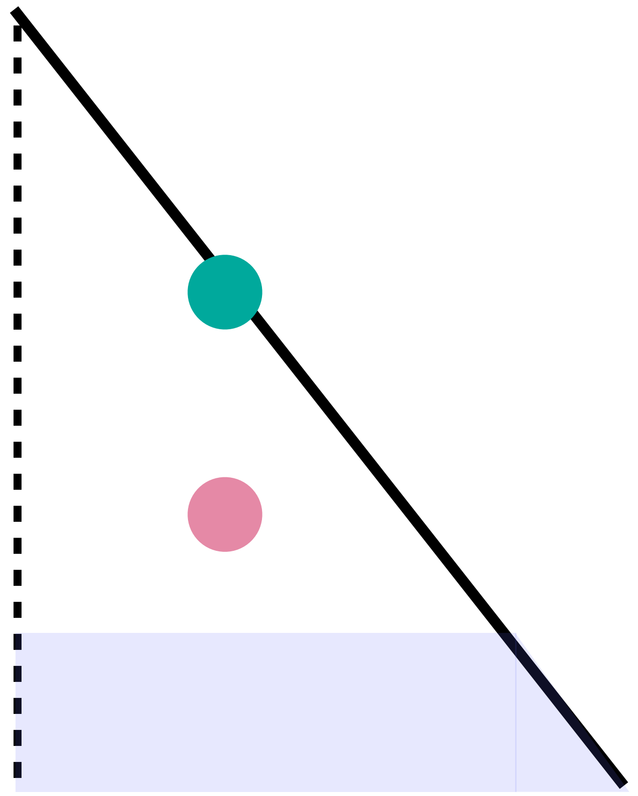
Large angle + hard-collinear



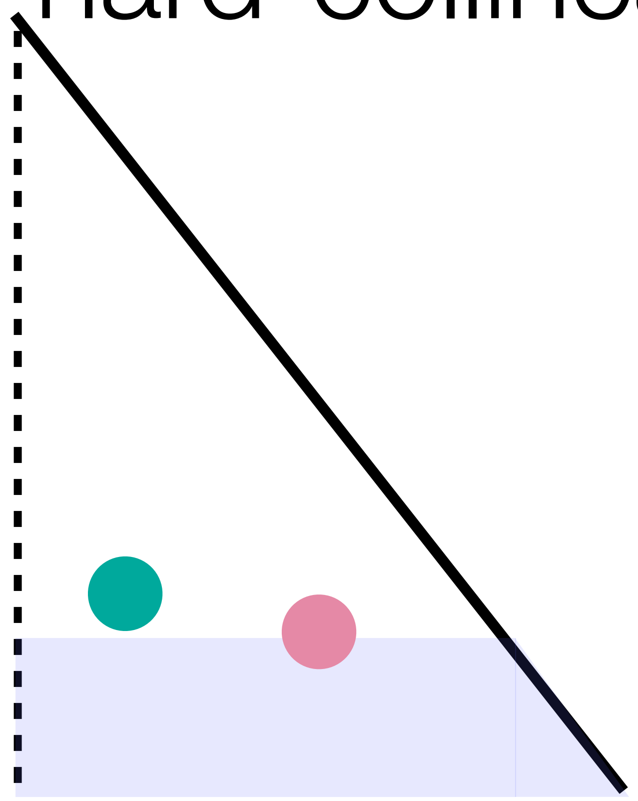
3 commensurate angles



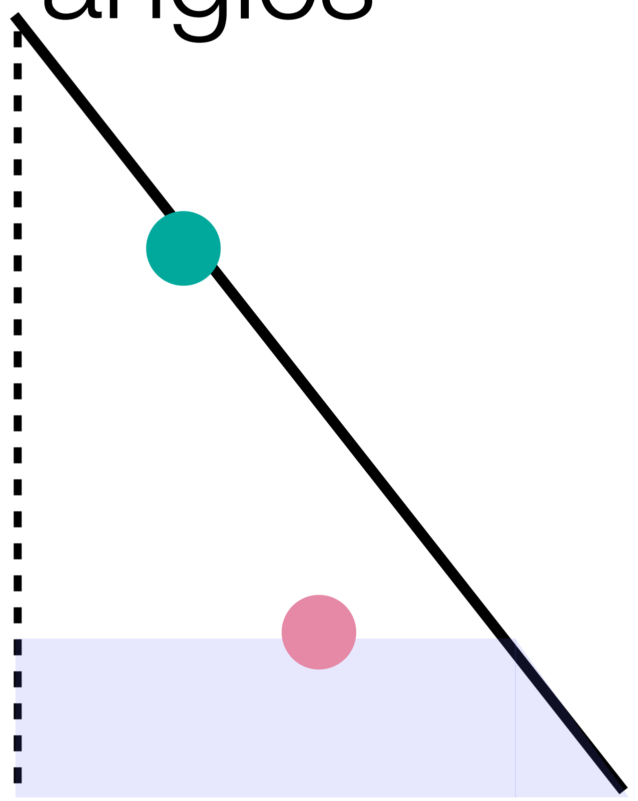
Large angle + $k_t \sim k_{t,\text{cut}}$



Hard coll. + commensurate η

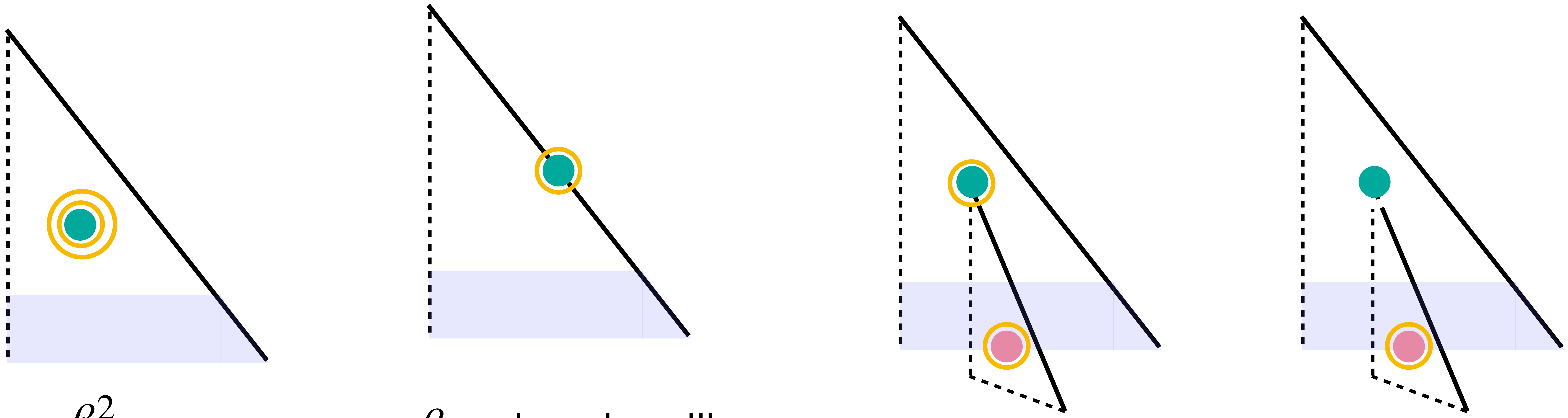


2 $k_t \sim k_{t,\text{cut}}$



Hard coll. + $k_t \sim k_{t,\text{cut}}$

Lund multiplicity: NNDL resummation (running coupling)

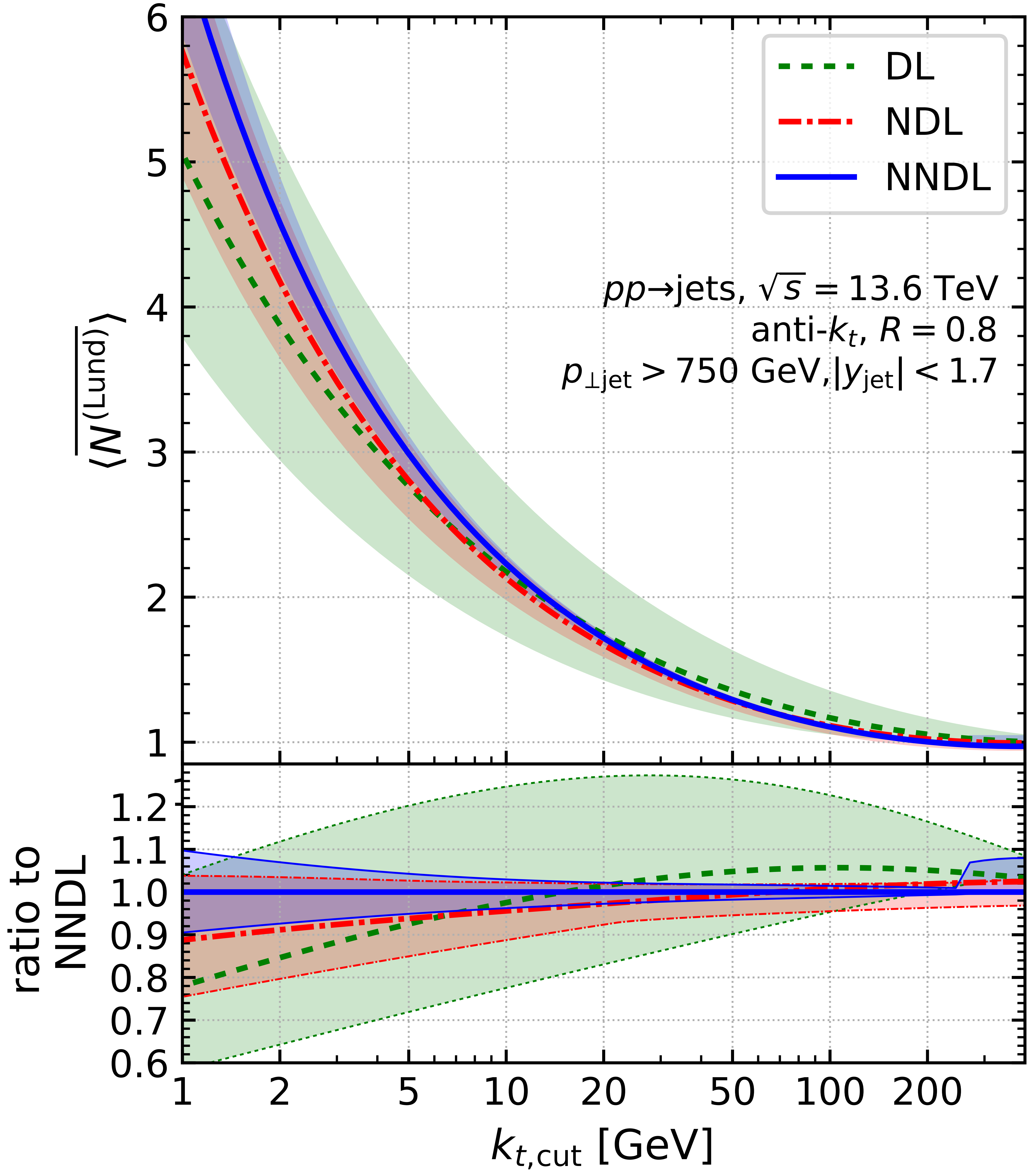


β_0^2 $\quad$ β_0 + hard-collinear $\quad$ $\beta_0 \times \beta_0$ $\quad$ $\beta_0 \times$hard-collinear

Lund multiplicity: NNDL result

NNDL: $$2\pi h_3^{(q)} = D_{\text{end}}^{q\to qg} + \left(D_{\text{end}}^{g\to gg} + D_{\text{end}}^{g\to q\bar{q}}\right)\frac{C_F}{C_A}(\cosh\nu - 1) + D_{\text{hme}}^{qqg}\cosh\nu$$
$$+ \frac{C_F}{C_A}\left[(1-c_\delta)D_{\text{pair}}^{q\bar{q}}(\cosh\nu - 1) + \left(K + D_{\text{pair}}^{gg} + c_\delta D_{\text{pair}}^{q\bar{q}}\right)\frac{\nu}{2}\sinh\nu\right]$$
$$+ C_F\left[\left(\cosh\nu - 1 - \frac{1-c_\delta}{4}\nu^2\right)D_{\text{clust}}^{(\text{prim})} + (\cosh\nu - 1)D_{\text{clust}}^{(\text{sec})}\right]$$
$$+ \frac{C_F}{C_A}\left[D_{\text{e-loss}}^{g}\frac{\nu}{2}\sinh\nu + \left(D_{\text{e-loss}}^{q} - D_{\text{e-loss}}^{g}\right)(\cosh\nu - 1)\right]$$
$$+ \frac{C_F}{2}\Big\{(B_{gg} + c_\delta B_{gq})^2\nu^2\cosh\nu + 8\left[2c_\delta B_{gg} - 2c_\delta B_q - (1-3c_\delta^2)B_{gq}\right]B_{gq}\cosh\nu$$
$$+ \left[4B_q(B_{gg} + (2c_\delta + 1)B_{gq}) - (B_{gg} + c_\delta B_{gq})(B_{gg} + 9c_\delta B_{gq})\right]\nu\sinh\nu$$
$$+4(1-c_\delta^2)B_{gq}^2\nu^2 + 8\left[2c_\delta B_q - 2c_\delta B_{gg} + (1-3c_\delta^2)B_{gq}\right]B_{gq}\Big\}$$
$$+ \frac{C_F}{C_A}\frac{\pi\beta_0}{2}\Big\{(B_{gg} + c_\delta B_{gq})\nu^3\sinh\nu + \left[2B_q - 2B_{gg} + (6-8c_\delta)B_{gq}\right]\nu\sinh\nu$$
$$+2(B_q + B_{gg} + B_{gq})\nu^2\cosh\nu - 4(1-c_\delta)B_{gq}(2\cosh\nu - 2 + \nu^2)\Big\}$$
$$+ \frac{C_F}{C_A}\frac{\pi^2\beta_0^2}{8C_A}\left[3\nu(2\nu^2 - 1)\sinh\nu + (\nu^4 + 3\nu^2)\cosh\nu\right]$$

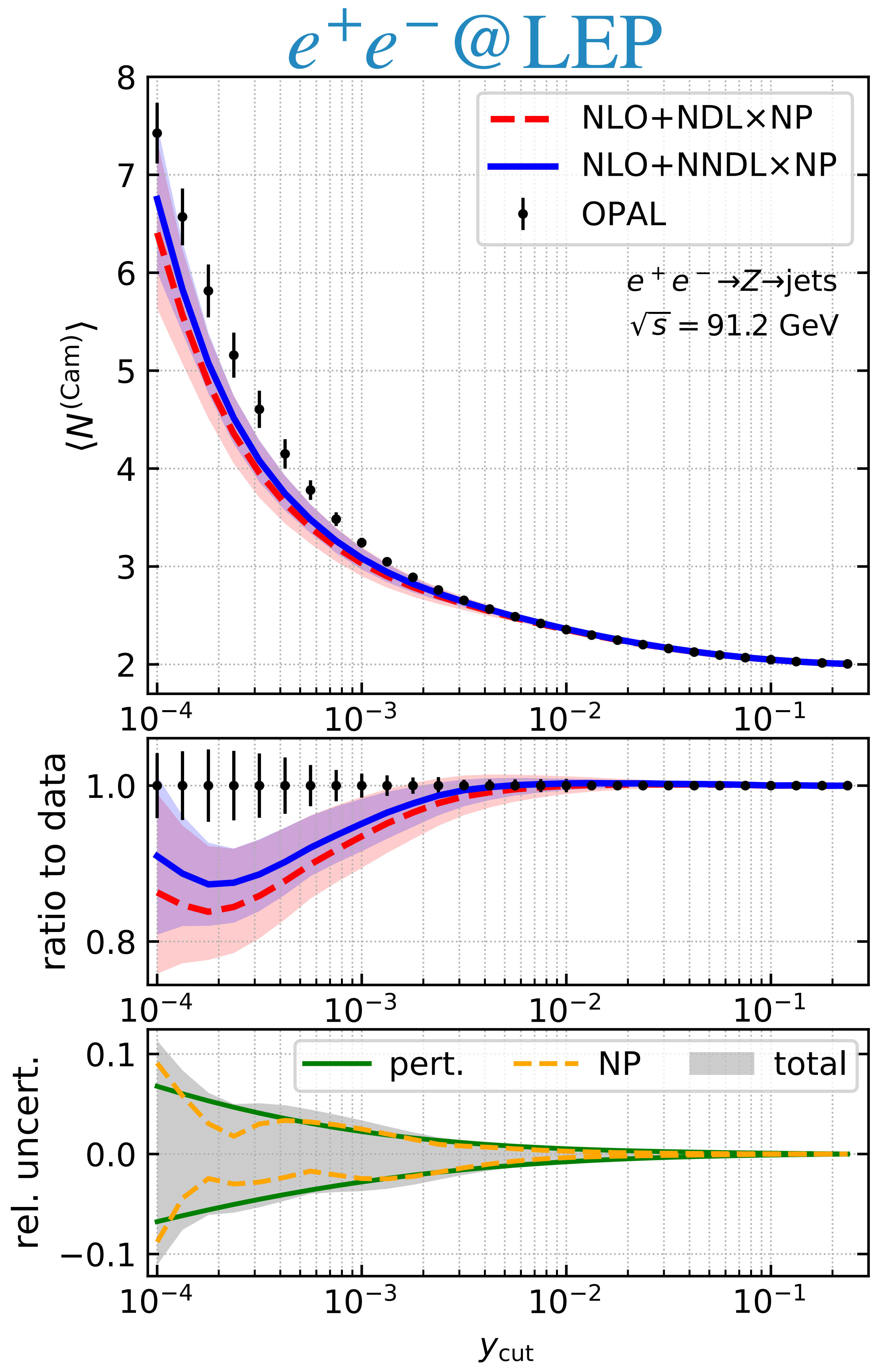
The importance of higher logarithmic accuracy

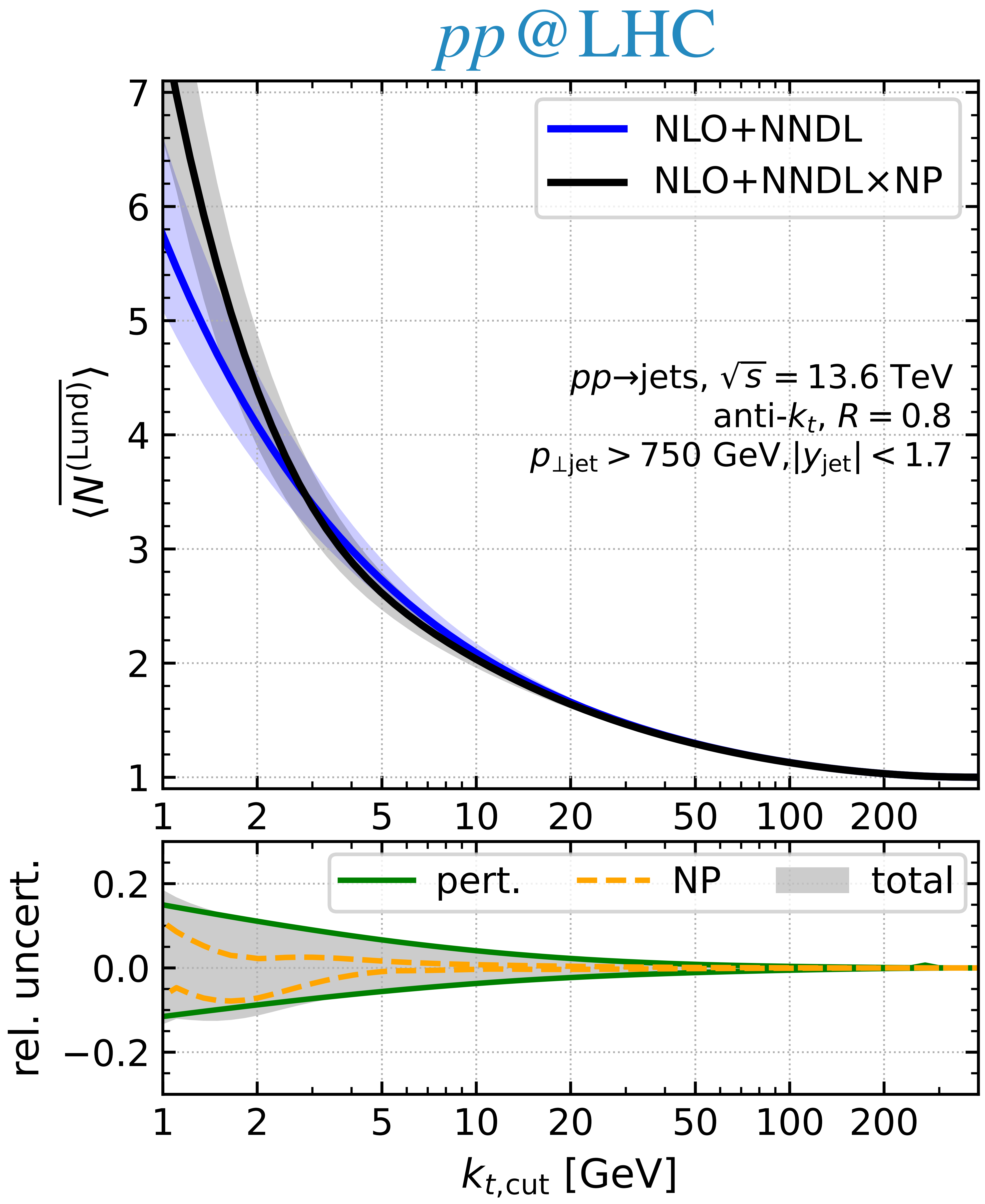


The uncertainty of the theoretical prediction at $k_{t,\mathrm{cut}} = 5$ GeV is

DL: $28\,\%$, NDL: $10\,\%$, NNDL: $5\,\%$

Phenomenological studies





Wrap up

- The Lund plane plays a key role in parton showers and resummation R&D
- The Lund jet plane bridges the gap between theory and experiment
- The resummation toolkit for Lund plane observables is rapidly developing
- Predictions status: <10% uncertainty in a wide region of phase-space

Wrap up

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First Lund Jet Plane Institute

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