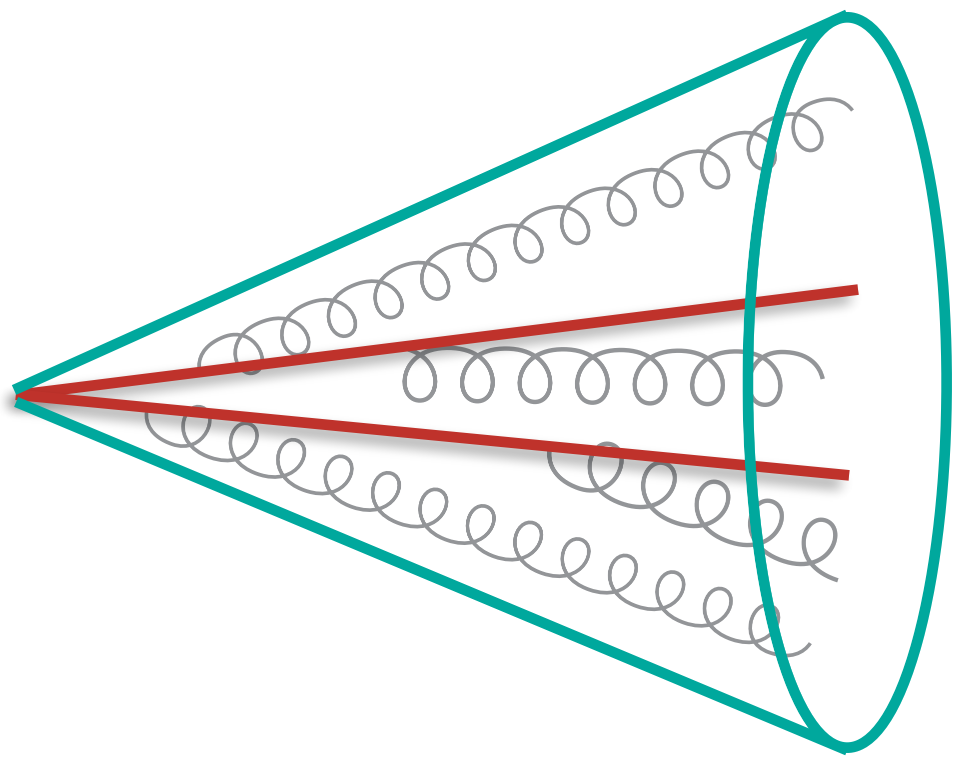
PINNING DOWN THE SPACE-TIME EVOLUTION OF JETS WITH SUBSTRUCTURE



Alba Soto-Ontoso

9th APS Hadronic physics Workshop

Remote, 15th April, 2021

Outline and disclaimer

1 Jet substructure in proton-proton collisions at LHC energies

- Theoretical calculations with pQCD: logarithmic accuracy and resummation
- Observables: Lund plane density, z_g-distribution, **dynamical grooming**

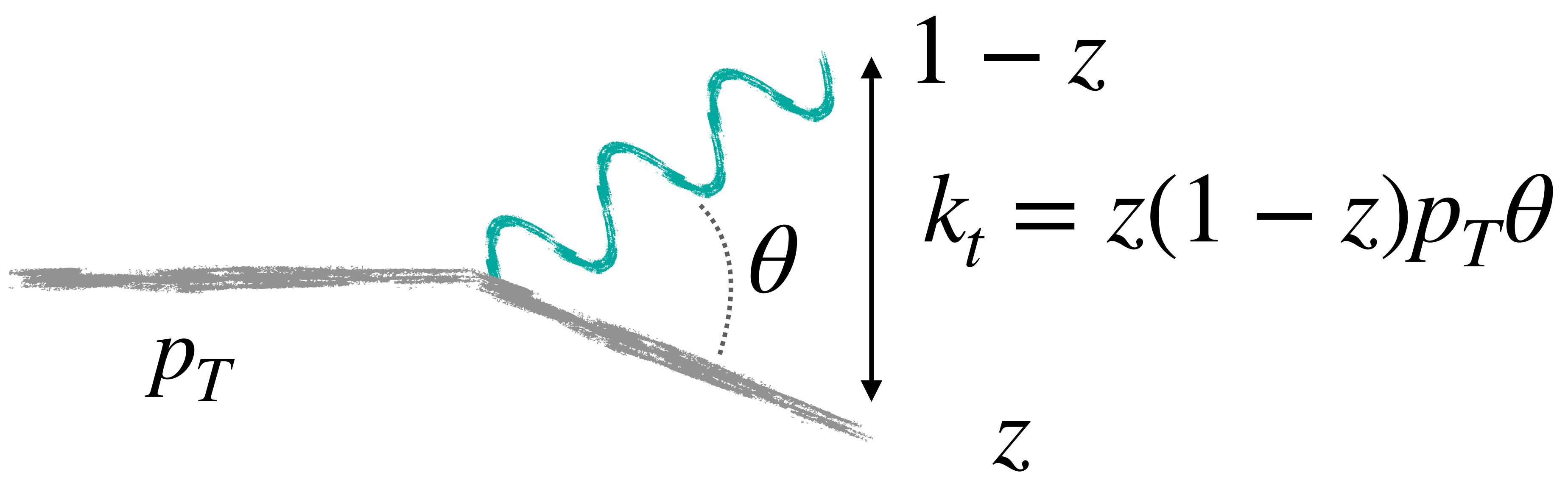
2 Jet substructure in Pb+Pb collisions at LHC energies

- Analytic approach to in-medium jet evolution: BDMPS-Z, GLV and **IOE**
- Observables: z_g-distribution, θ_g with dynamical grooming

Topics not covered (but very relevant)

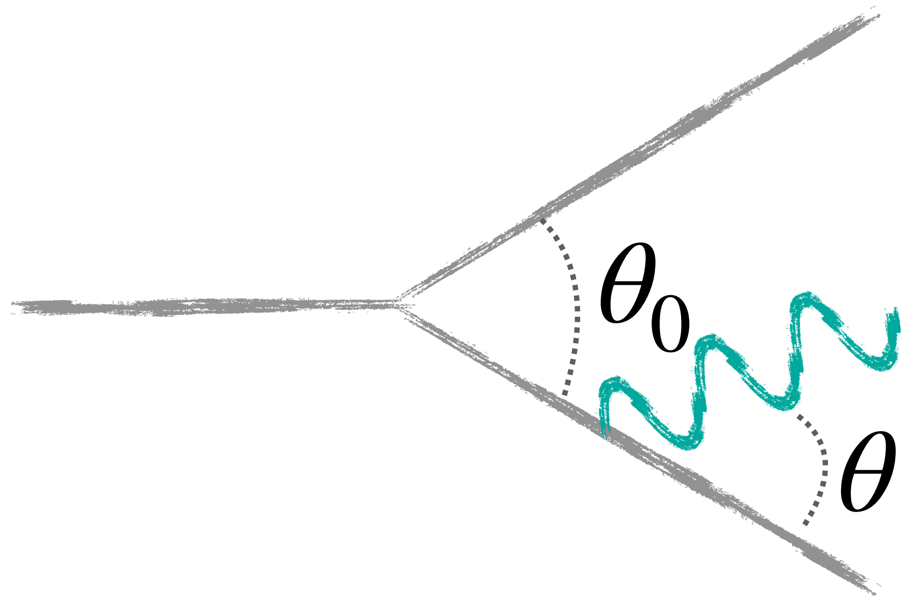
- Machine learning: [Dreyer et al. JHEP 03 (2021) 052, Du et al JHEP 03 (2021) 206, Lai et al 2012.06582]
- Jet physics at the EIC and RHIC: [EIC Yellow Report 2103.05419, STAR Phys.Lett.B 811 (2020), STAR NPA 967 (2017)]
- New clustering algorithms: [Arratia et al 2006.10751, Apolinario et al 2012.02199, Wei et al PRD 101 (2020) 9, 094015]

Parton branching in vacuum



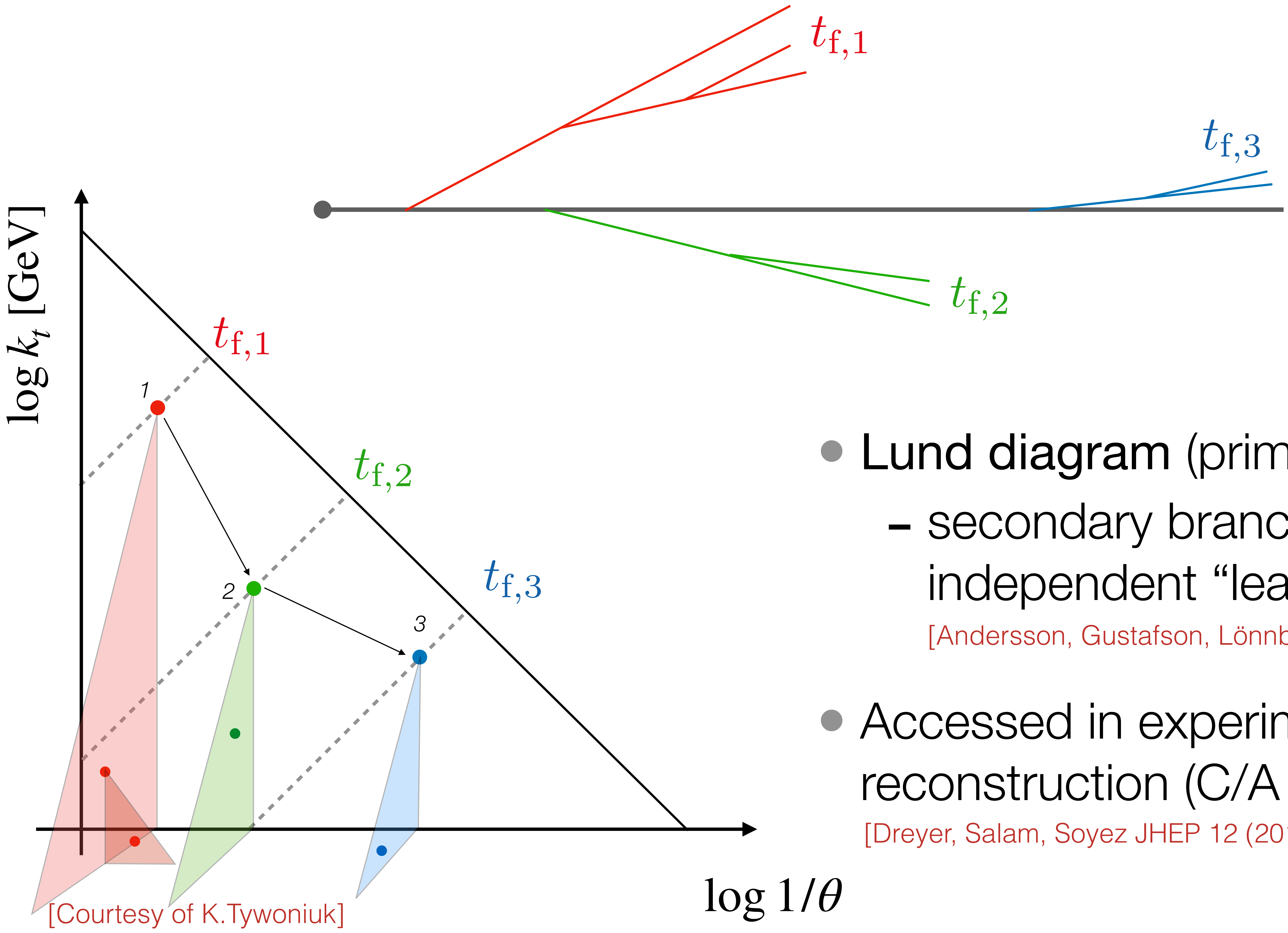
$$\mathrm{d}\Pi_{a\to bc} = \frac{C_R\alpha_s(k_t)}{\pi}\frac{\mathrm{d}\theta}{\theta}P_{a\to bc}(z)\mathrm{d}z$$

- Soft and collinear divergences: $z \ll 1, \theta \ll 1 \Longrightarrow \mathrm{d}\Pi_{\mathrm{LL}} = \frac{2C_R\alpha_s(k_t)}{\pi}\frac{\mathrm{d}\theta}{\theta}\frac{\mathrm{d}z}{z}$
- Angular ordering:



$$\mathrm{d}N^{z\ll 1} \propto C_R\alpha_s\frac{\mathrm{d}z}{z}\frac{\sin\theta\mathrm{d}\theta}{1-\cos\theta}[\Theta(\cos\theta_0 - \cos\theta)]$$

Space-time picture of a jet: Lund plane representation



$$t_f = \frac{2z(1-z)p_T}{k_t^2}$$

- Lund diagram (primary emission plane)
  - secondary branchings located on independent “leaves”
    [Andersson, Gustafson, Lönnblad, Pettersson ’89]
- Accessed in experimental data using jet reconstruction (C/A algorithm)
  [Dreyer, Salam, Soyez JHEP 12 (2018) 064]

Engineering jet substructure observables

Minimal checklist to keep in mind for potential jet substructure observables

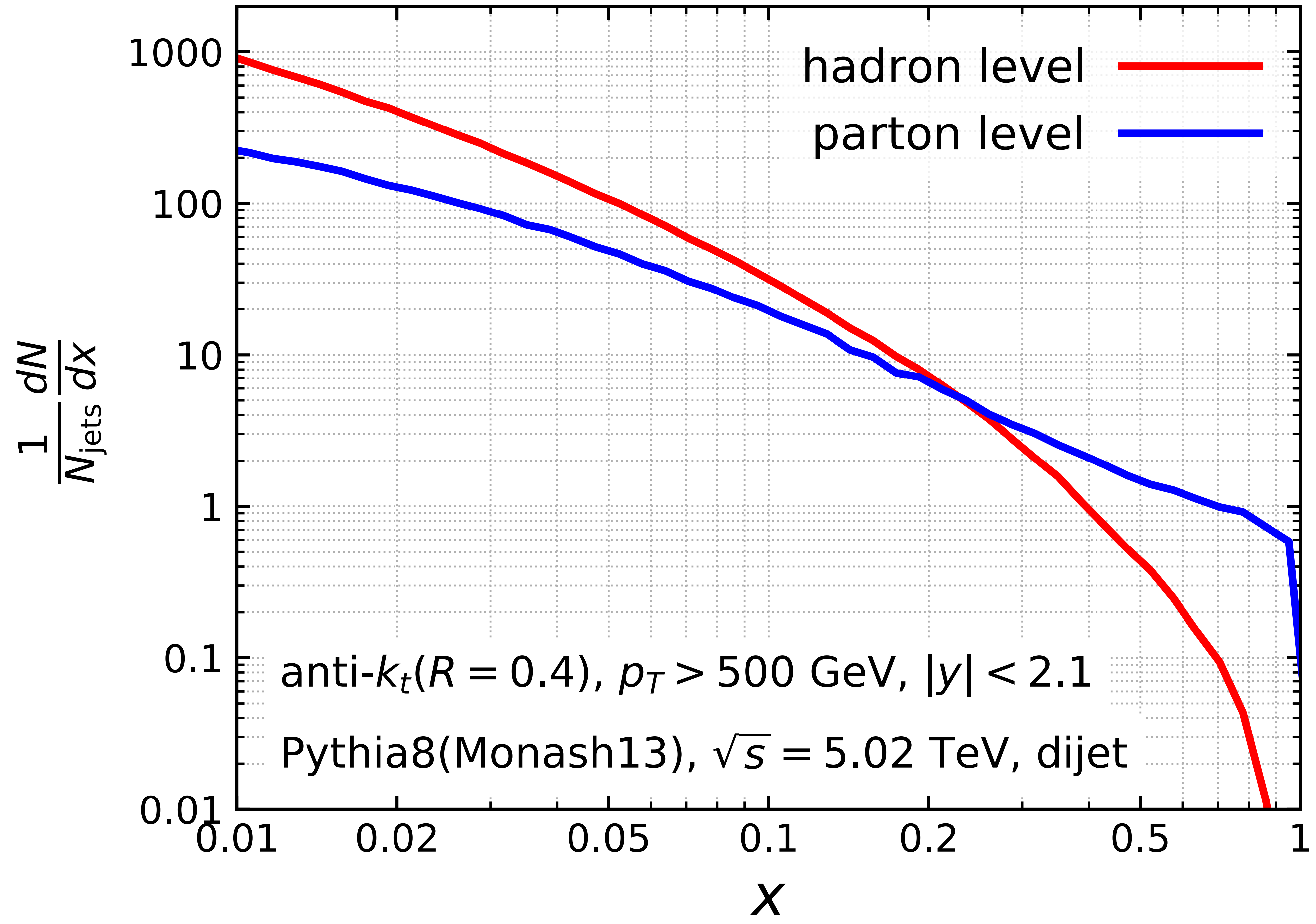
- Theoretically calculable: IRC (or at least Sudakov) safety

e.g. fragmentation function $D(x) = \frac{1}{N_{\text{jets}}} \frac{\mathrm{d}N}{\mathrm{d}x}$ with $x = \frac{p_t \cos\theta}{p_{t,\text{jet}}}$

$$xD_{\text{LL}}(x) = 2\frac{\alpha_s C_R}{\pi} \int_0^R \frac{\mathrm{d}\theta}{\theta} f(1/x, 1/\theta)$$

$$\Downarrow$$

$$xD_{\text{LL}}(x) = 2\frac{\alpha_s C_R}{\pi} \int_{k_{\perp,\min}/(xp_t)}^R \frac{\mathrm{d}\theta}{\theta} f(1/x, 1/\theta)$$

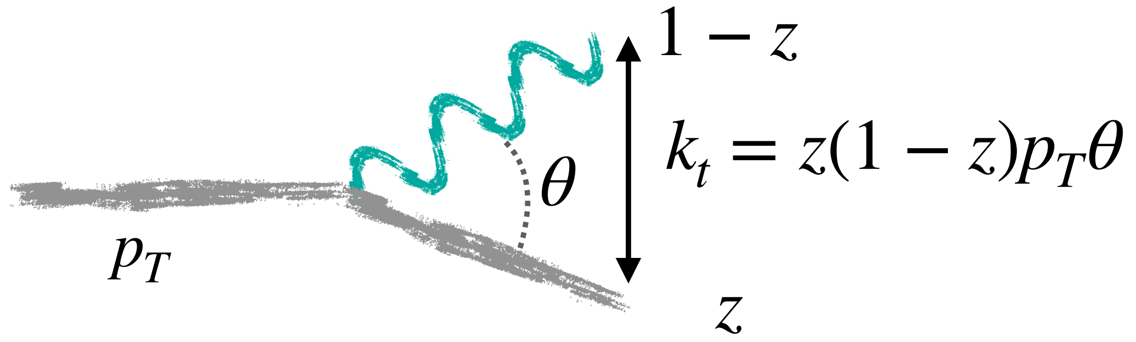


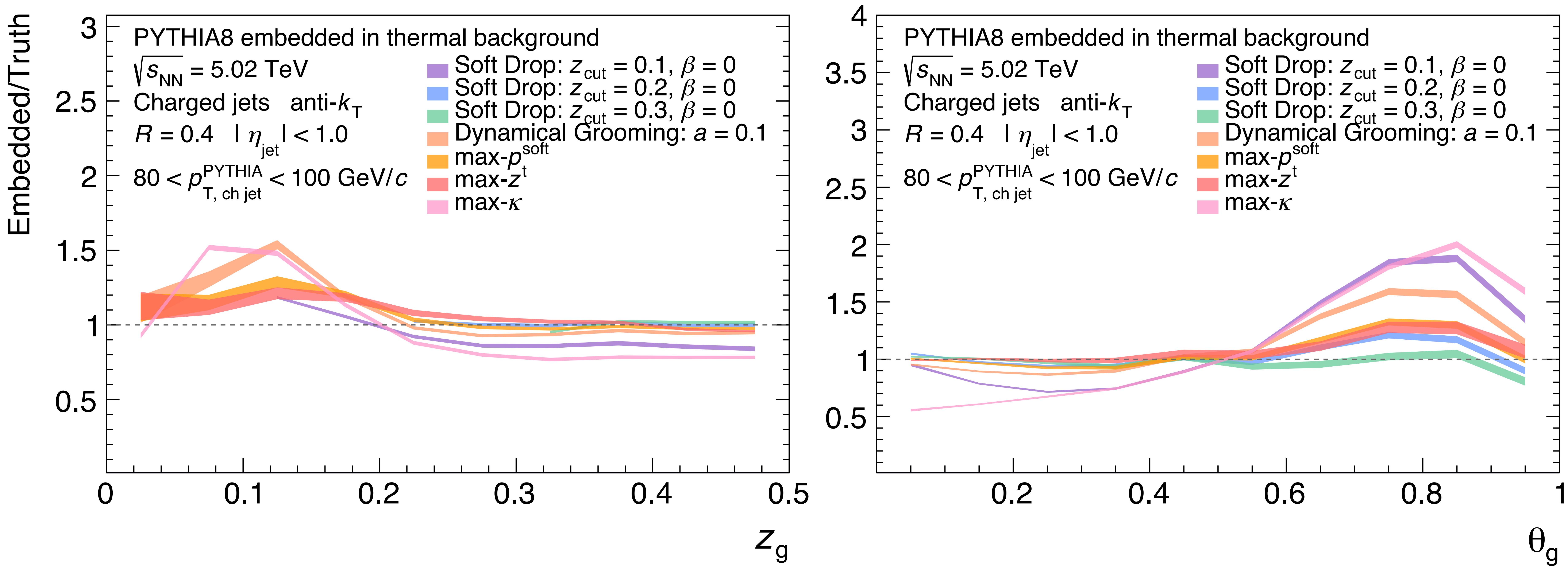
[Caucal et al JHEP10(2020)204]

Engineering jet substructure observables

Minimal checklist to keep in mind for potential jet substructure observables

- Theoretically calculable: IRC (or at least Sudakov) safety
- Experimentally measurable, e.g. thermal background impact on



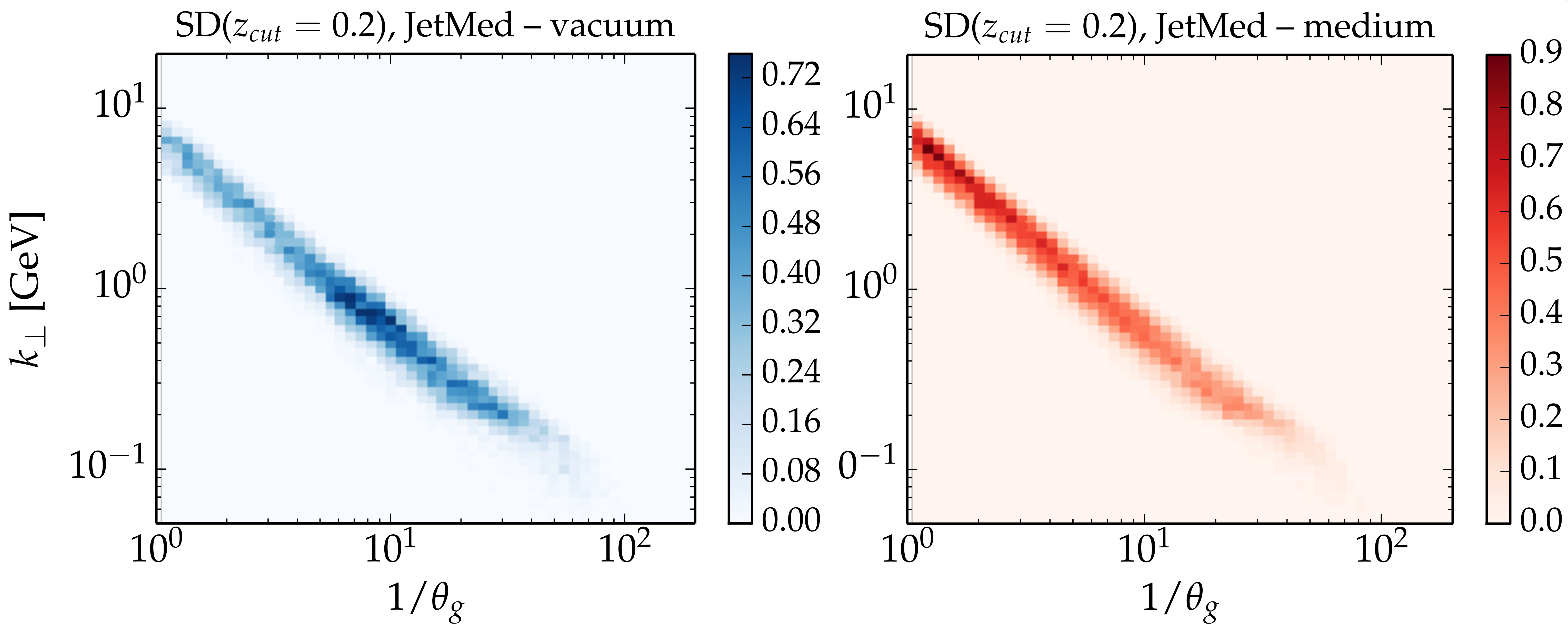


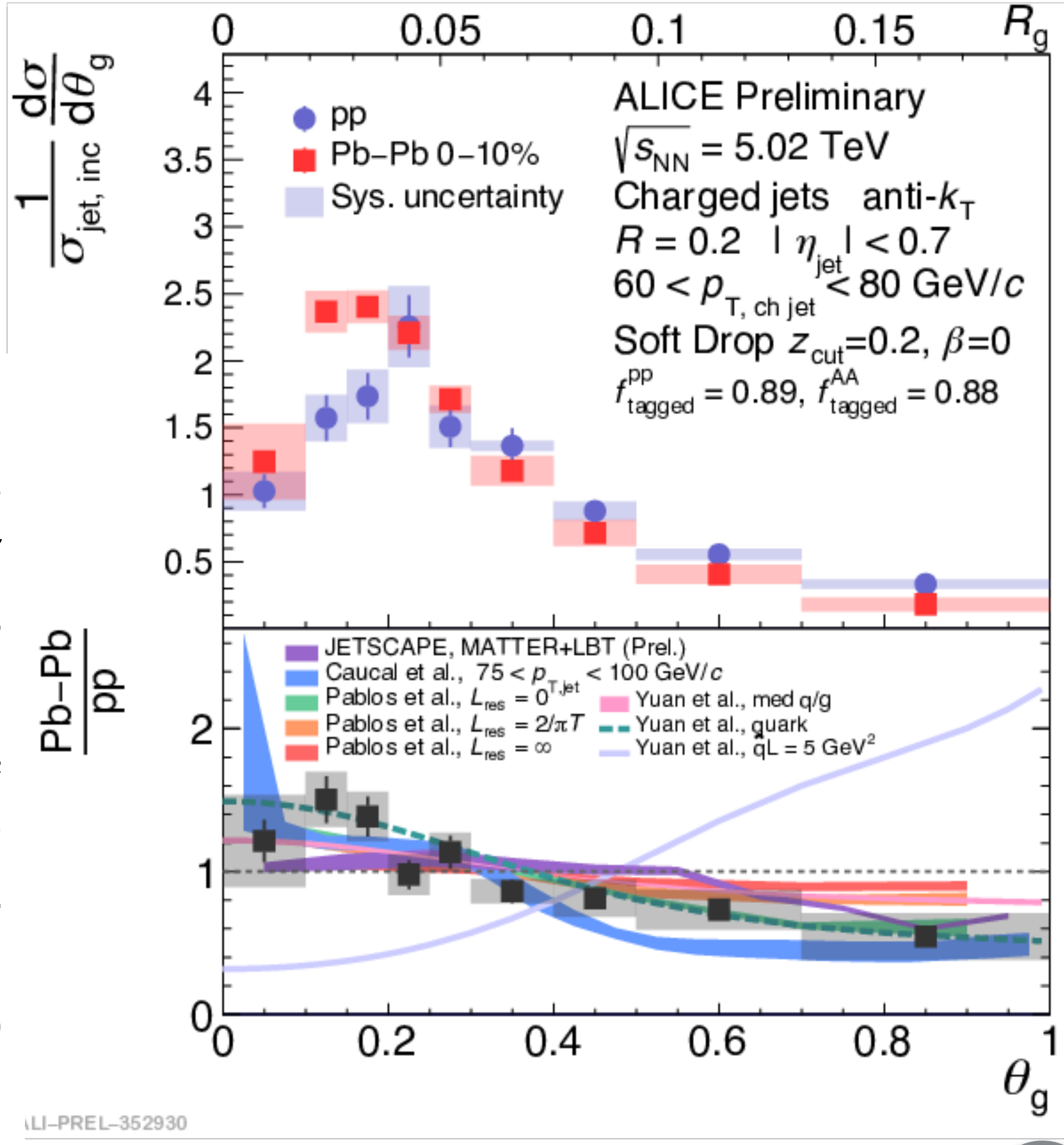
[Mulligan, Ploskon PRC 102(2020) 4]

Engineering jet substructure observables

Minimal checklist to keep in mind for potential jet substructure observables

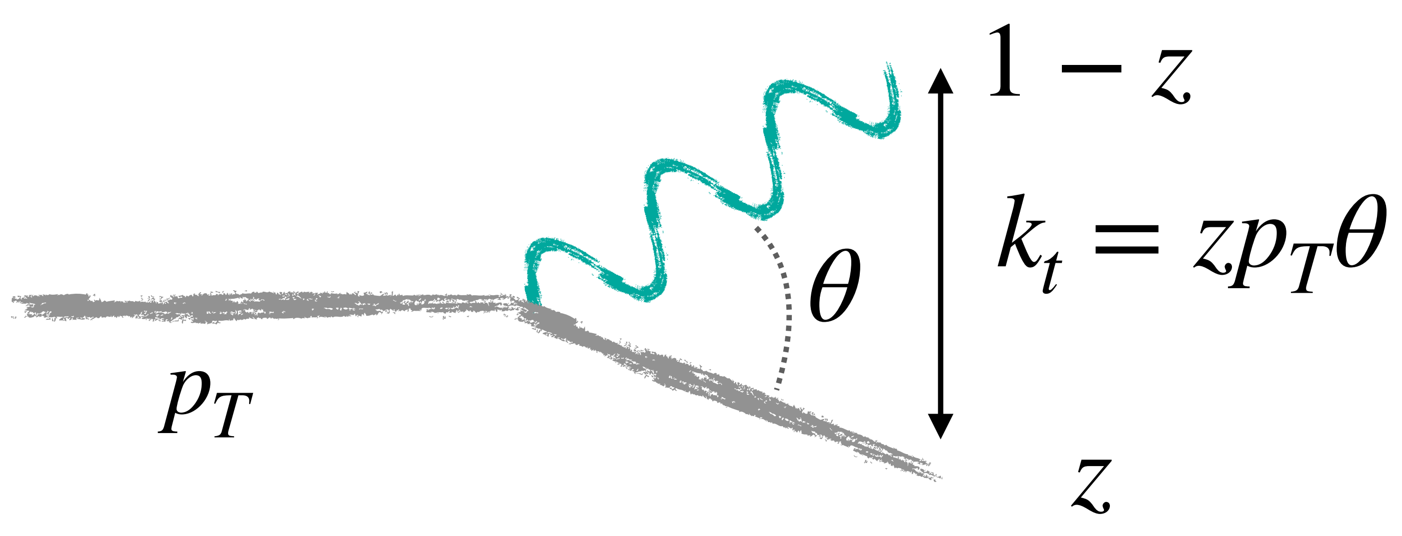
- Theoretically calculable: IRC (or at least Sudakov) safety
- Experimentally measurable
- Designed to probe a particular physics mechanism
  e.g. opening angle of the splitting with $z > z_{\mathrm{cut}}\theta^{\beta}$





Analytic insight: k_t-distribution of the hardest splitting

Fixed order

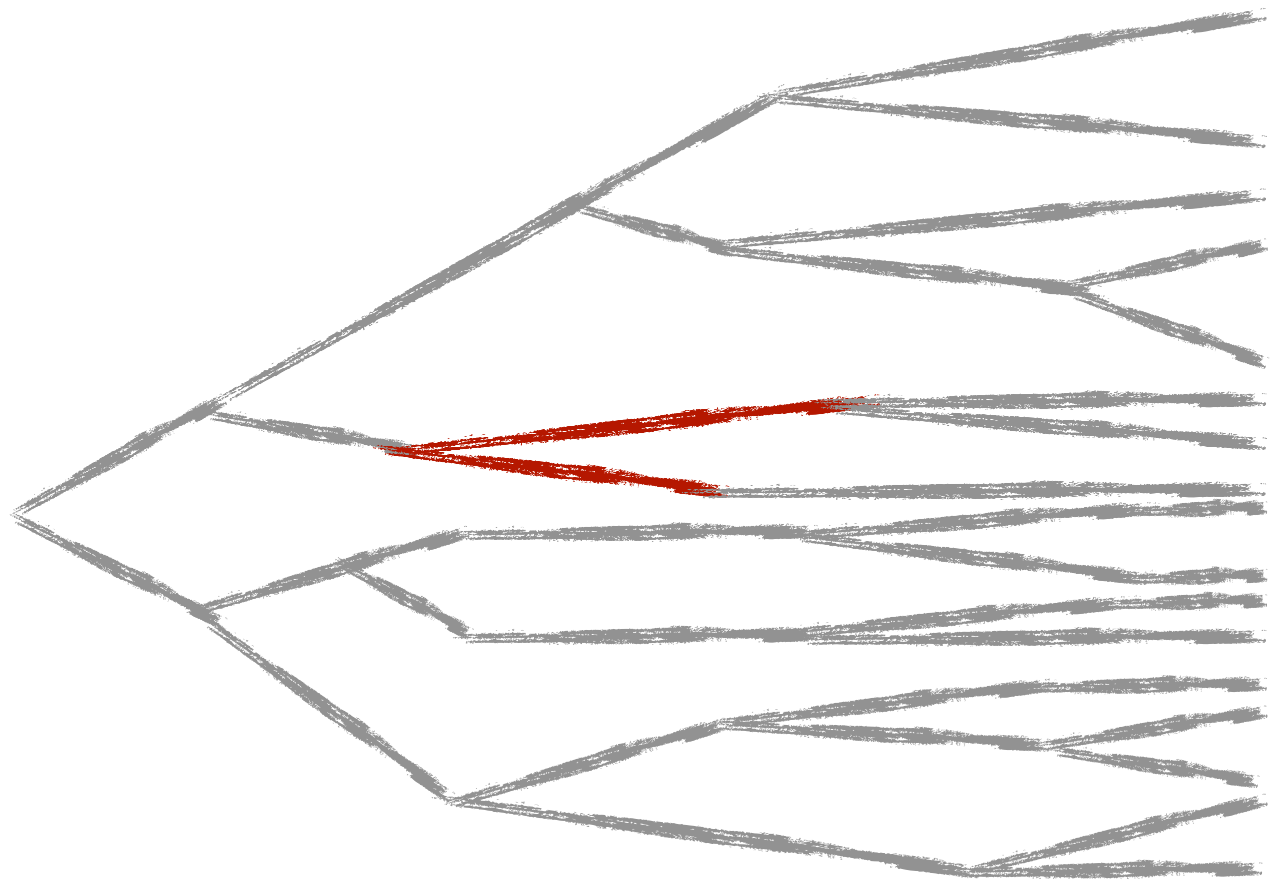


In the $\alpha_s \ll 1, k_{t,g} \ll 1$ regime,

$$\mathcal{O}(\alpha_s): \quad \frac{1}{\sigma}\frac{d\sigma}{dk_{t,g}} \sim \alpha_s \frac{\ln(k_{t,g})}{k_{t,g}} \Longrightarrow \mathcal{O}(\alpha_s \ln(k_{t,g})) = 1$$

Large logarithms enter order-by-order and must be resumed

Resummation



2D probability for a splitting to the hardest

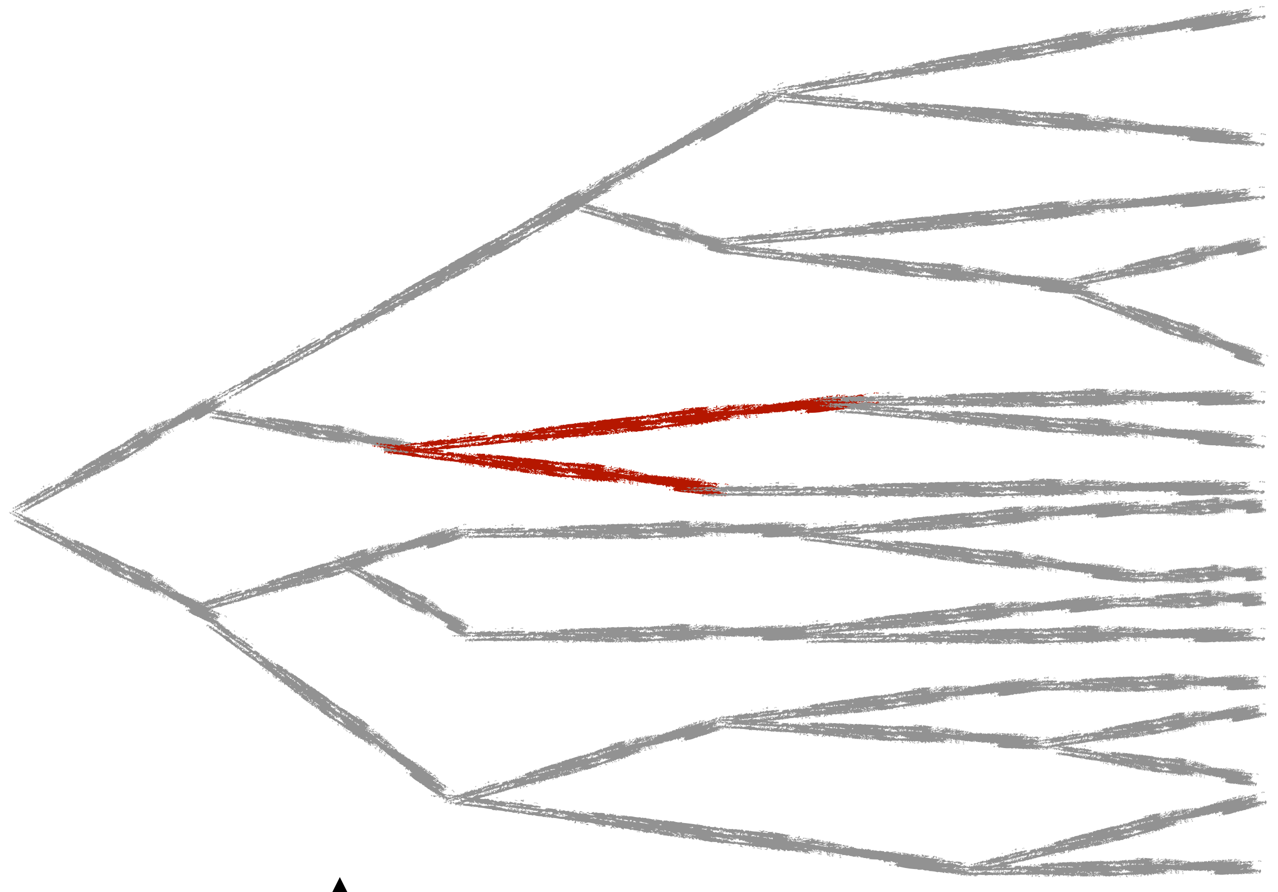
$$\frac{\mathrm{d}^2\mathcal{P}_i(z,\theta)}{\mathrm{d}\theta \mathrm{d}z} = \widetilde{P}_i(z,\theta)\Delta_i(k_t)$$

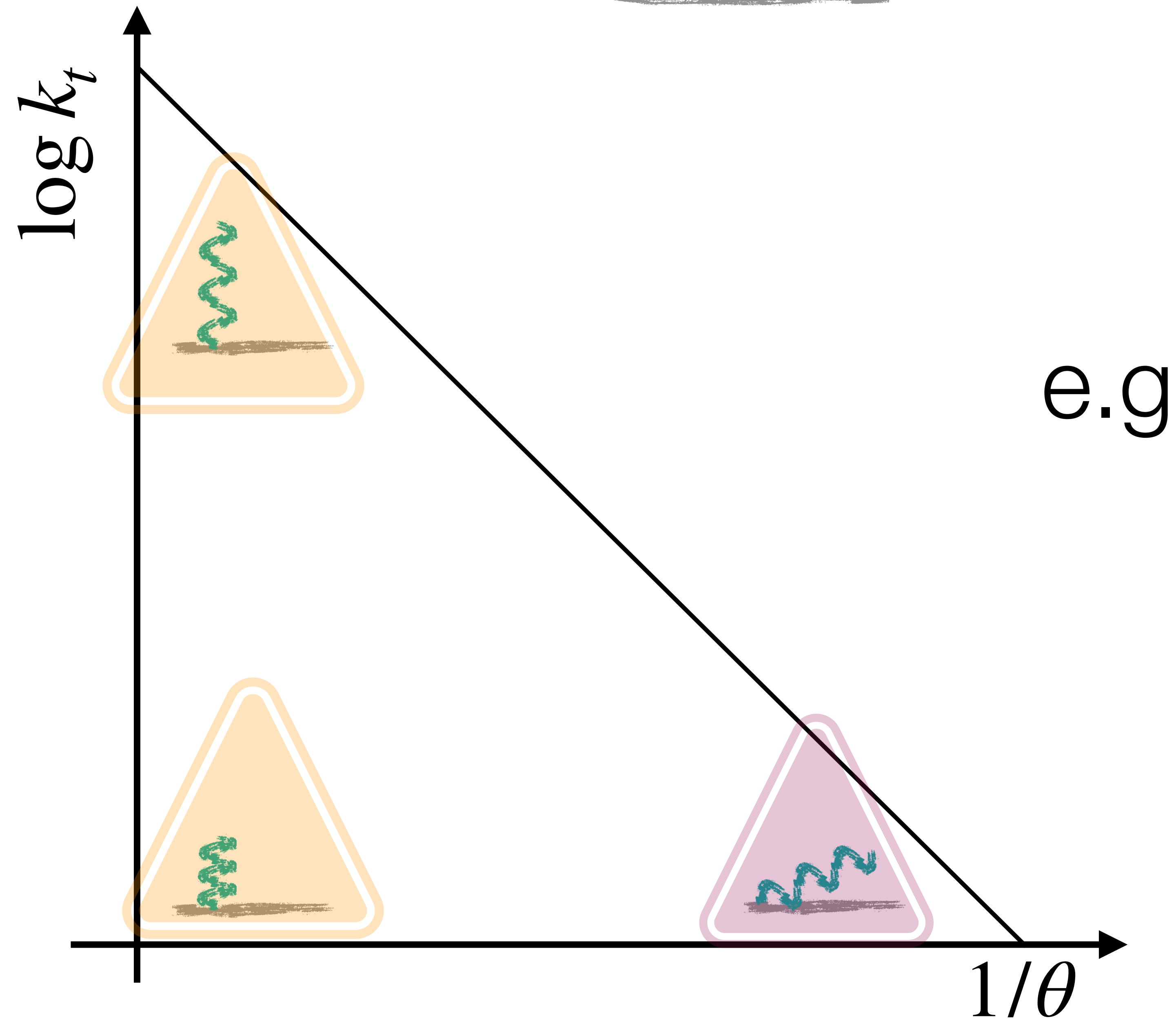
== branching kernel x Sudakov form factor

$$\ln \Delta_i(k_{t,g}) = -\int_0^1 \mathrm{d}z' \int_0^1 \mathrm{d}\theta' \widetilde{P}_i(z',\theta')\Theta(z'\theta' - k_{t,g})$$

Analytic insight: k_t-distribution of the hardest splitting

Resummation





k_t distribution of the hardest splitting

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}k_{t,g}} = \int_0^1 \mathrm{d}\theta \int_0^1 \mathrm{d}z \mathscr{P}_i(z,\theta)\delta(z\theta - k_{t,g})$$

This expression admits a perturbative expansion

$$\frac{1}{\sigma}\frac{d\sigma}{dk_{t,g}} \propto e^{\ln(k_{t,g})g_1(x) + g_2(x) + \alpha_s g_3(x) + \mathcal{O}(\alpha_s^{n+2}\ln^n k_{t,g})}$$

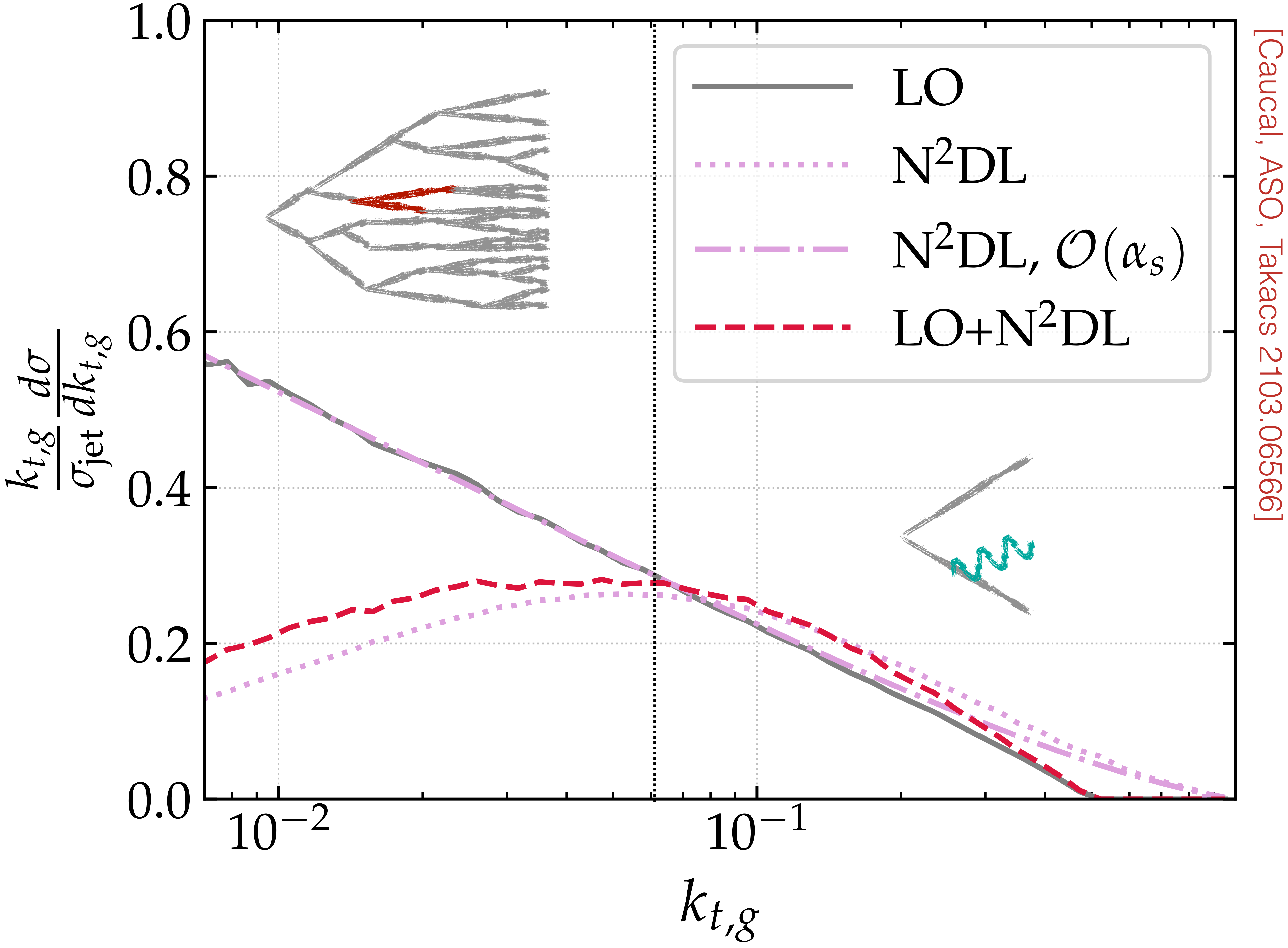
LL	NLL	NNLL
$\ln(k_{t,g})g_1(x)$	$g_2(x)$	$\alpha_s g_3(x)$
$\mathcal{O}(1/\alpha_s)$	$\mathcal{O}(1)$	$\mathcal{O}(\alpha_s)$

e.g leading-log is achieved by taking soft and collinear limit

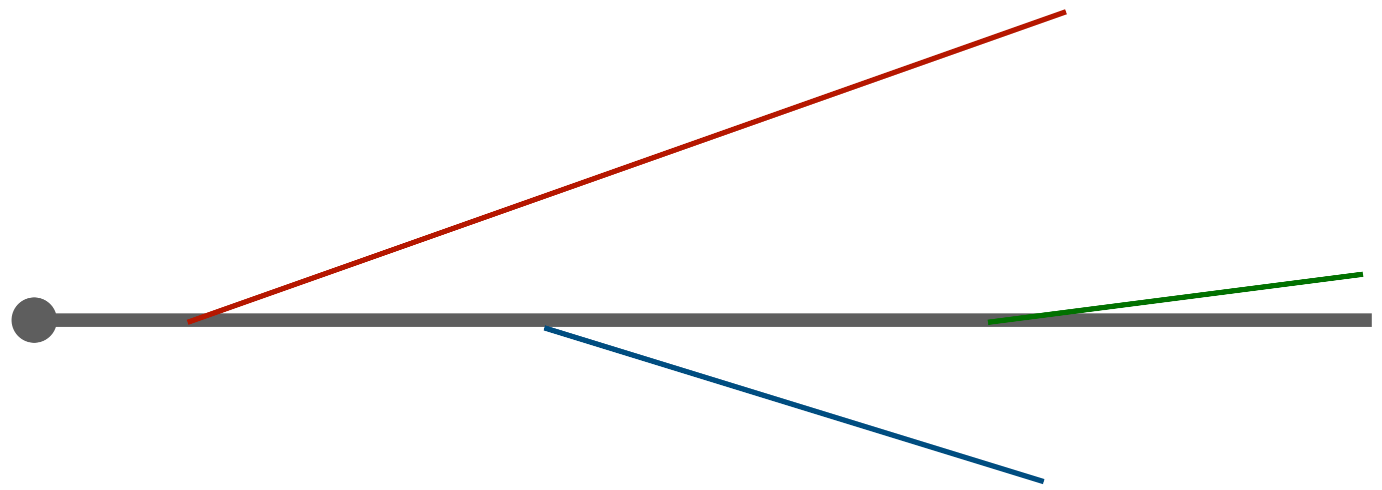
$$\widetilde{P}_i(z,\theta) = \frac{\alpha_s^{1l}(k_t)}{\theta\pi}P_i(z) \quad \text{with} \quad P_i(z) = \frac{2C_R}{z}$$

Analytic insight: k_t-distribution of the hardest splitting

Analytical full coverage of $k_{t,g}$ is obtained by matching $d^2\sigma_i^{LO+N^2DL} = \frac{d^2\sigma_i^{LO} \times d^2\sigma_i^{N^2DL}}{d^2\sigma_{i,1}^{N^2DL}}$



Observable #1: Primary Lund jet plane density at NLL



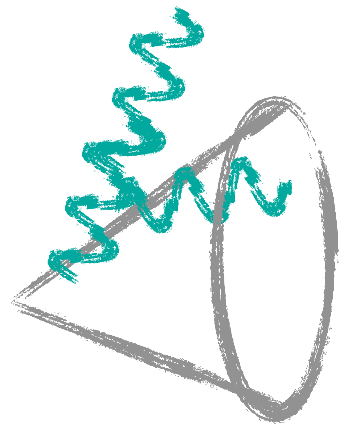
$$\rho(\Delta \equiv \theta, k_t) = \frac{1}{N_{\text{jets}}} \frac{\mathrm{d}N}{\mathrm{d}\ln 1/\Delta \,\mathrm{d}\ln k_t} \xrightarrow[\text{LO}]{} \frac{2\alpha_s C_R}{\pi}$$

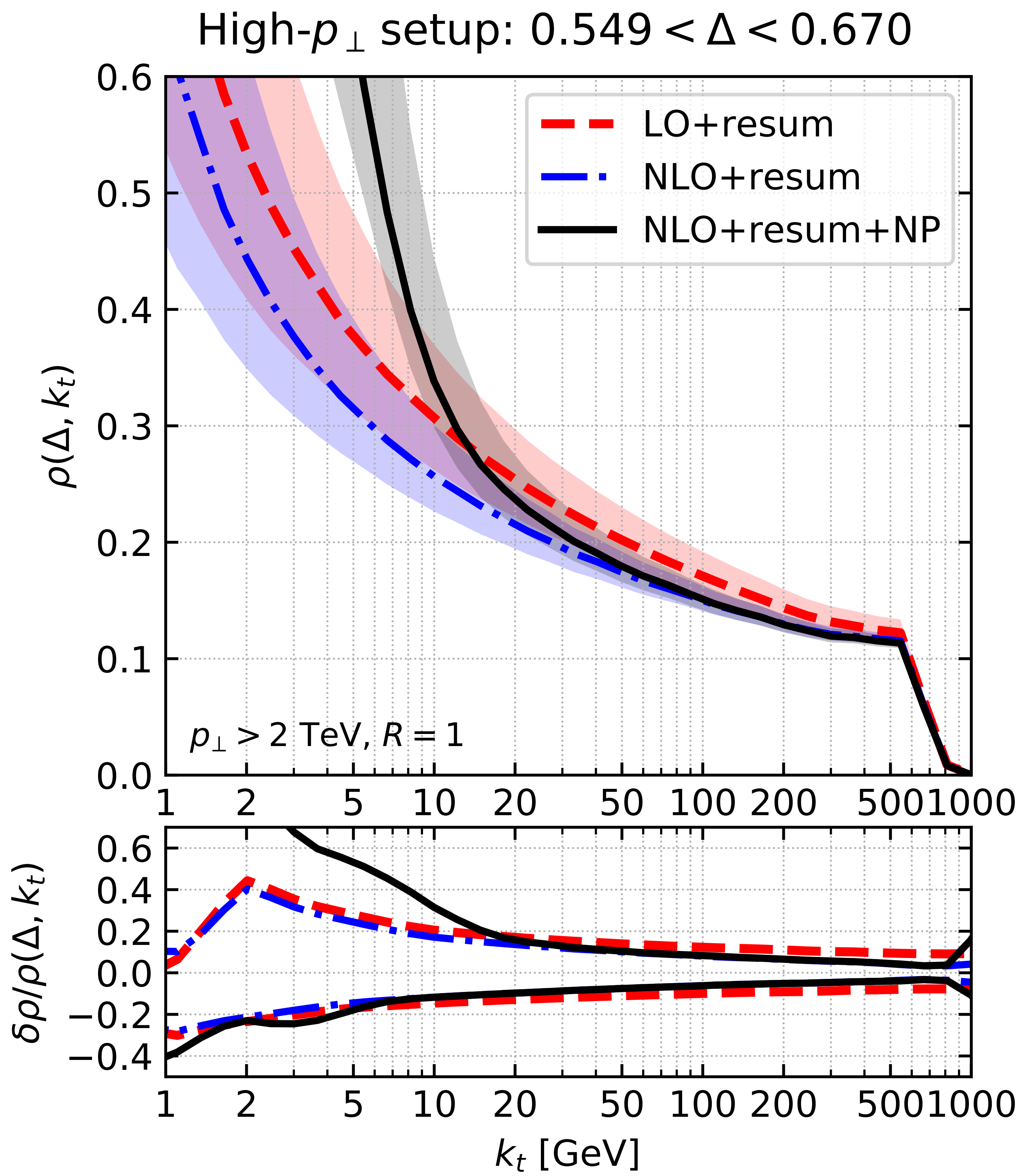
Collinear ingredients:

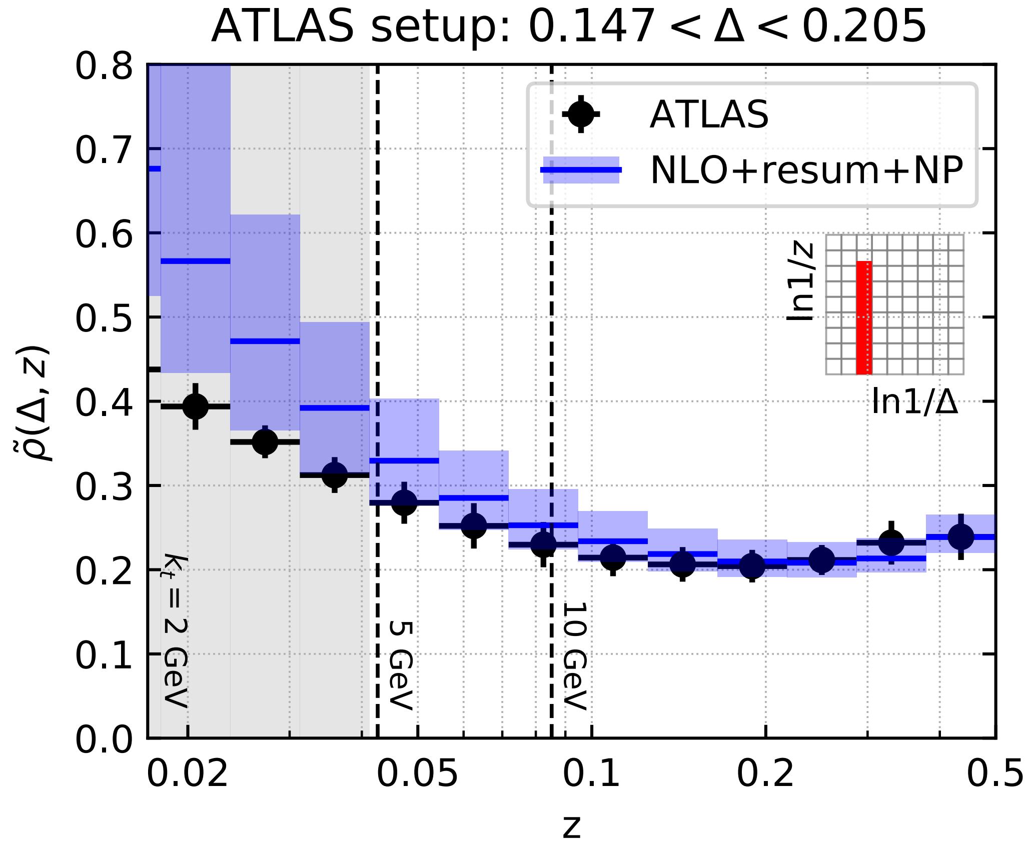
- Running coupling $\alpha_s^{2l}(k_t)$
- pt-degradation $k_t = x p_t \theta z$
- Flavor changing $p(x, i\,|\,j)$

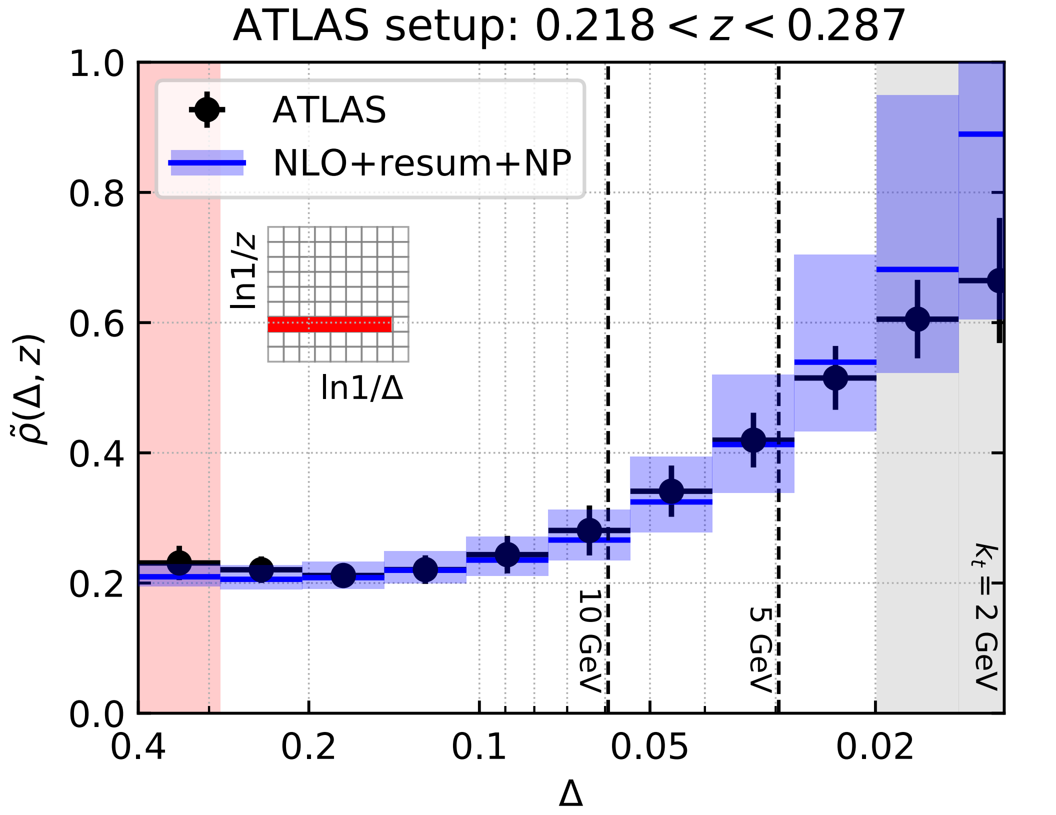
Soft, wide angle contributions:

- Boundary effects: anti-kt+C/A
- Non-global logarithms





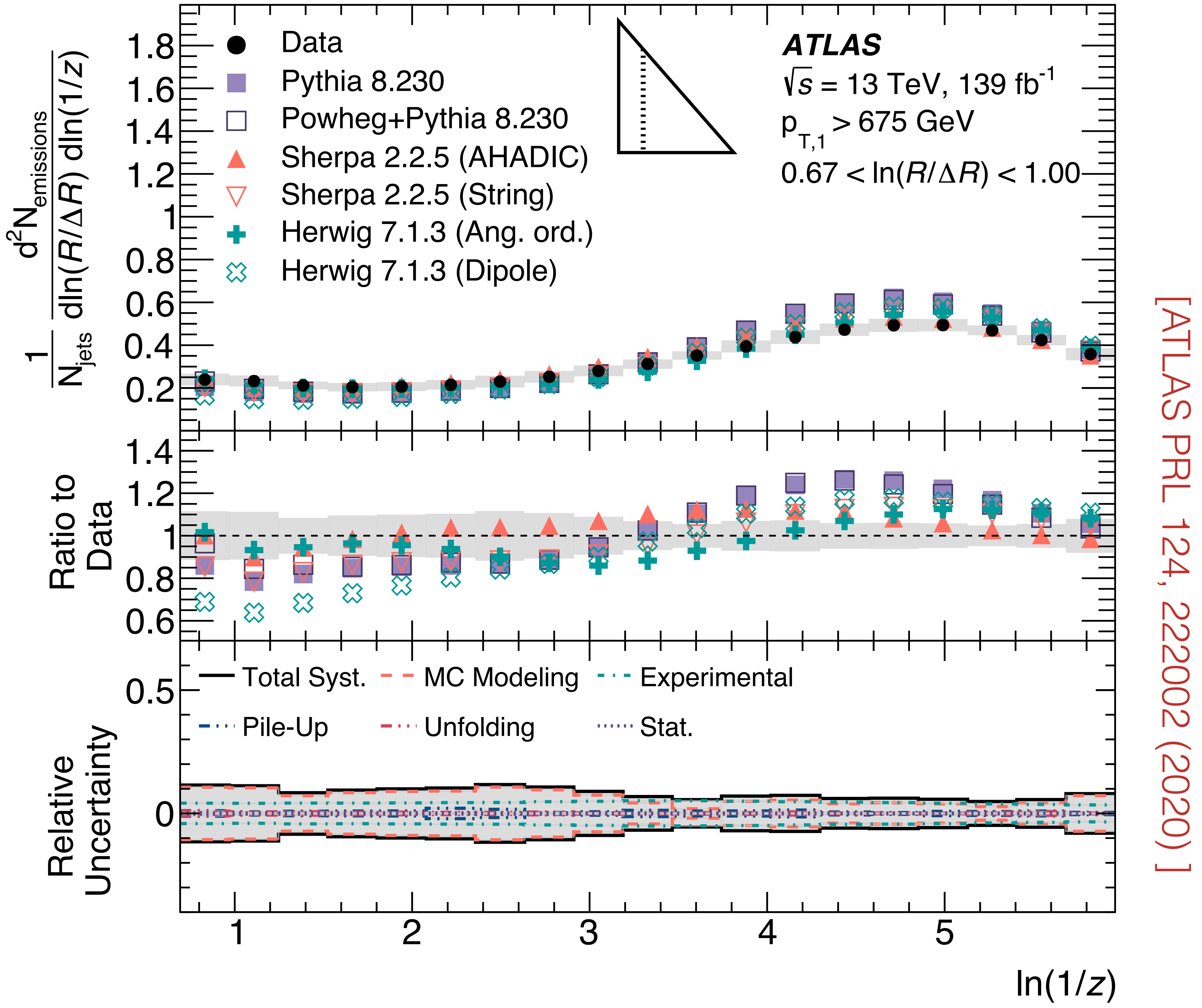




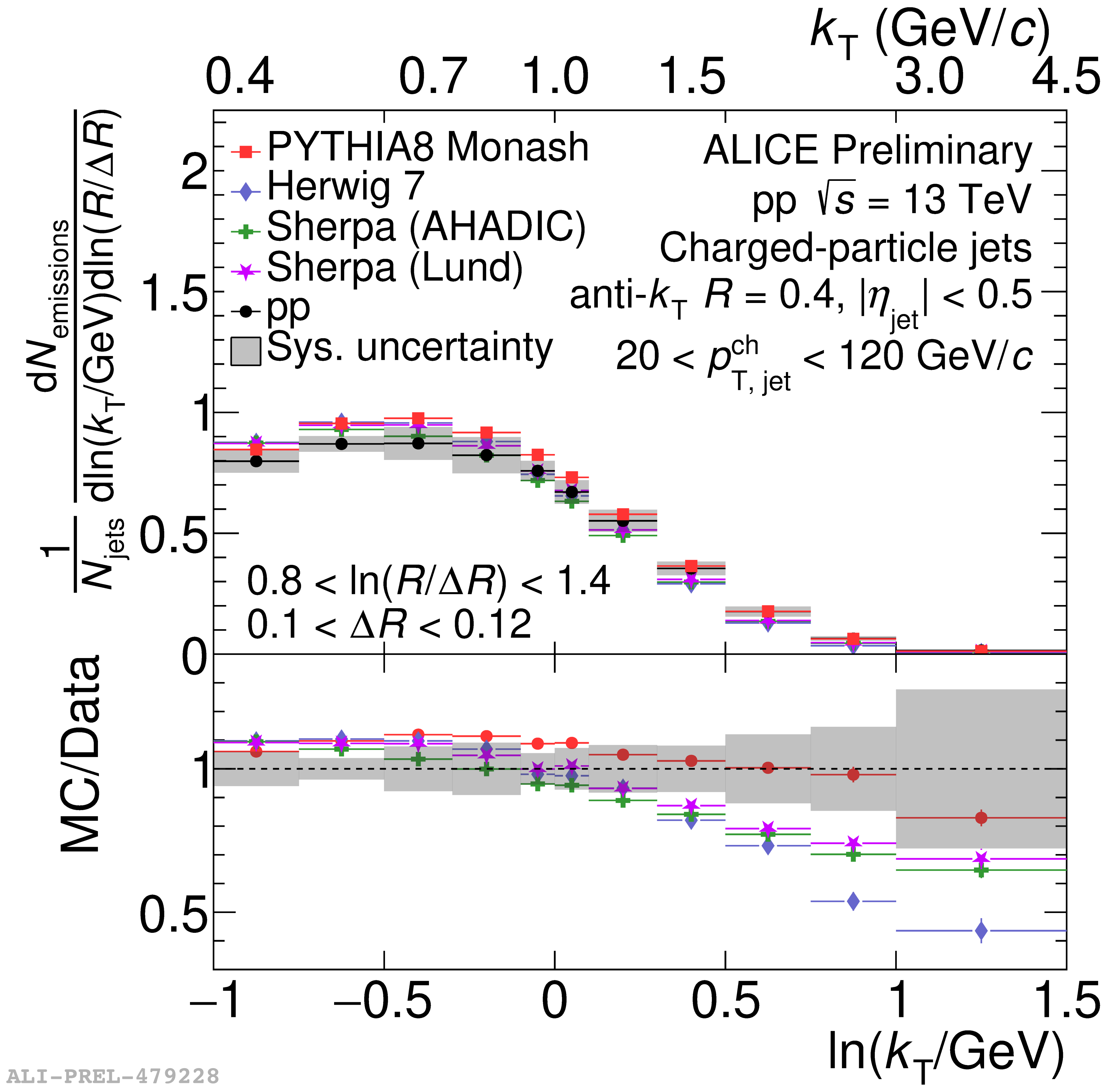
[Lifson, Soyez, Salam JHEP 10 (2020) 170]

Observable #1: Primary Lund jet plane density

$p_{t,\mathrm{jet}} > 675$ GeV



$20 < p_{t,\mathrm{jet}} < 120$ GeV

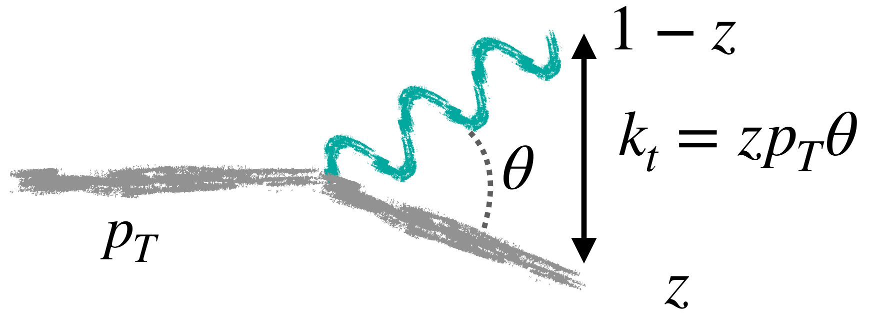


Complementary measurements. Challenge for pQCD calculations.

Observable #2: z_g-distribution

[Larkorski et al. JHEP'14]
[Butterworth et al.PRL'08]

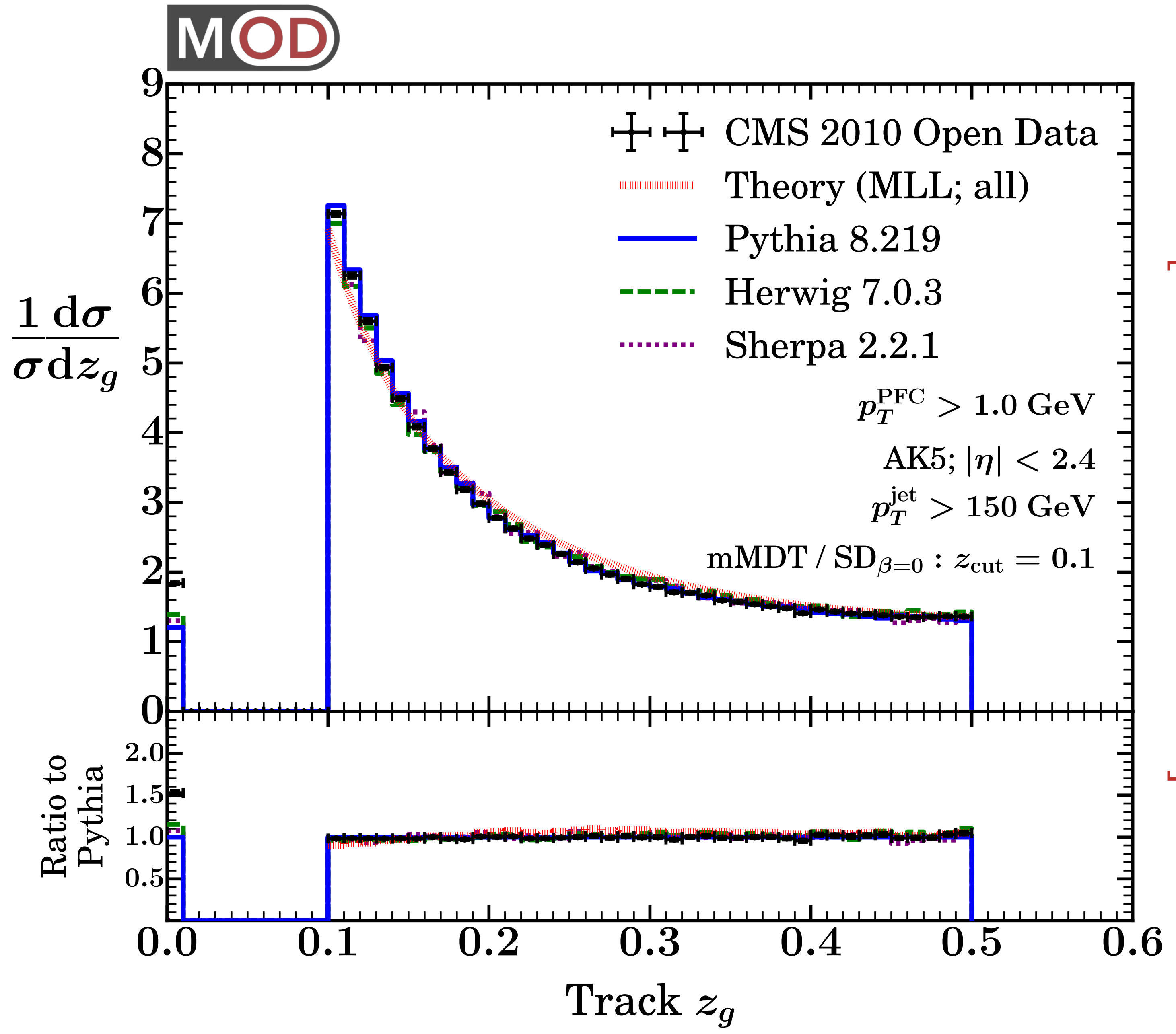
SoftDrop selects the first splitting that satisfies $z > z_{\rm cut}\theta^\beta$



Resummation: $$\frac{1}{\sigma}\frac{d\sigma}{dz_g} = \int_0^R \mathscr{P}(z,\theta)\Theta(z - z_{\rm cut}\theta^\beta)d\theta$$ with $$\frac{d^2\mathscr{P}_i(z,\theta)}{d\theta dz} = \widetilde{P}_i(z,\theta)\Delta_i(z > z_{\rm cut}\theta^\beta)$$

$$\mathcal{O}(\alpha_s): \frac{1}{\sigma}\frac{d\sigma}{dz_g} = \sqrt{\frac{\alpha_s C_R}{\beta}} P_{\rm AP}(z_g)$$ Non-analytic Taylor series in α_s when $\beta > 0$ [Marzani et al PRD'15]

Sudakov safety hampers achieving higher precision, matching…
Not ideal baseline for heavy-ion collisions



[Komiske et al PRD'20]

Observable #3: dynamical grooming

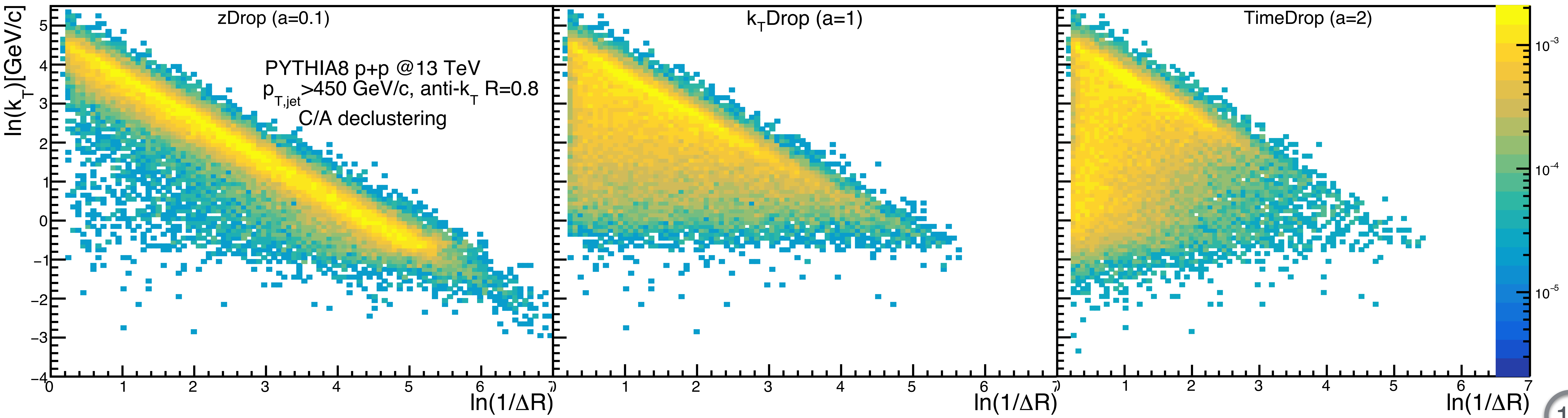
[Mehtar-Tani, ASO, Tywoniuk PRD 101 (2020) 3, 034004]

Find **hardest** branch in the C/A sequence, i.e.

$$\kappa^{(a)} = \frac{1}{p_T} \max_{i \in \mathrm{C/A}} z_i(1 - z_i) p_{T,i} (\theta_i / R)^a$$

Physical interpretation:
- a=2: TimeDrop
- a=1: k_TDrop
- a~0: zDrop

zDrop | k_TDrop | TimeDrop



Observables #3: $k_{t,g}$ with dynamical grooming [Caucal, ASO, Takacs 2103.06566]

Resummation: the cumulative distribution $\Sigma(\nu) = \int_0^\nu \mathrm{d}\nu' \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\nu'}$ reads

$$\Sigma(k_{t,g}\,|\,a) = \int_0^1 \mathrm{d}z \int_0^1 \mathrm{d}\theta\, \widetilde{P}(z,\theta)\Delta(\kappa\,|\,a)\Theta(k_{t,g} - z\theta) \Longrightarrow \Sigma(k_{t,g}) = \sum_{n=0}^{\infty} \alpha_s^n \sum_{m=0}^{2n} c_{nm} \ln^m(k_{t,g})$$

Non-exponentiation leads to N^{p}DL type of counting. We reach N^{2}DL in the narrow jet limit:

Collinear ingredients:

- Running coupling $\alpha_s^{2l}(k_t)$
- Hard-collinear correction to splitting function

Soft, wide angle contributions:

- Non-global logarithms $\propto \ln(z_g)$

Flavor switching leads to a power correction, p_t-degradation of the primary branch is N^{3}DL

Multiple emissions do not enter by definition and free of clustering logarithms

Observables #3: $k_{t,g}$ with dynamical grooming [Caucal, ASO, Takacs 2103.06566]

Resummation: we reach N^{2}DL in the narrow jet limit by including

Collinear ingredients:

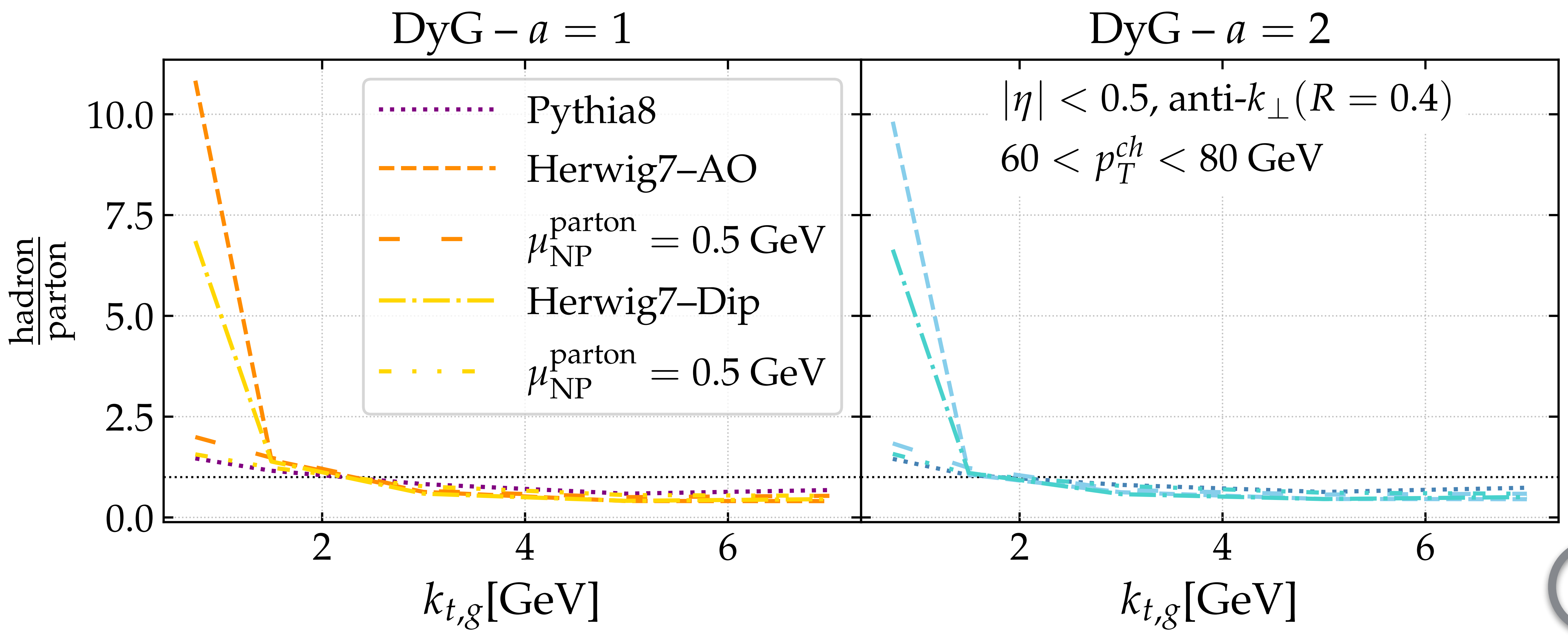
- Running coupling
- Hard-collinear correction to splitting function

Soft, wide angle contributions:

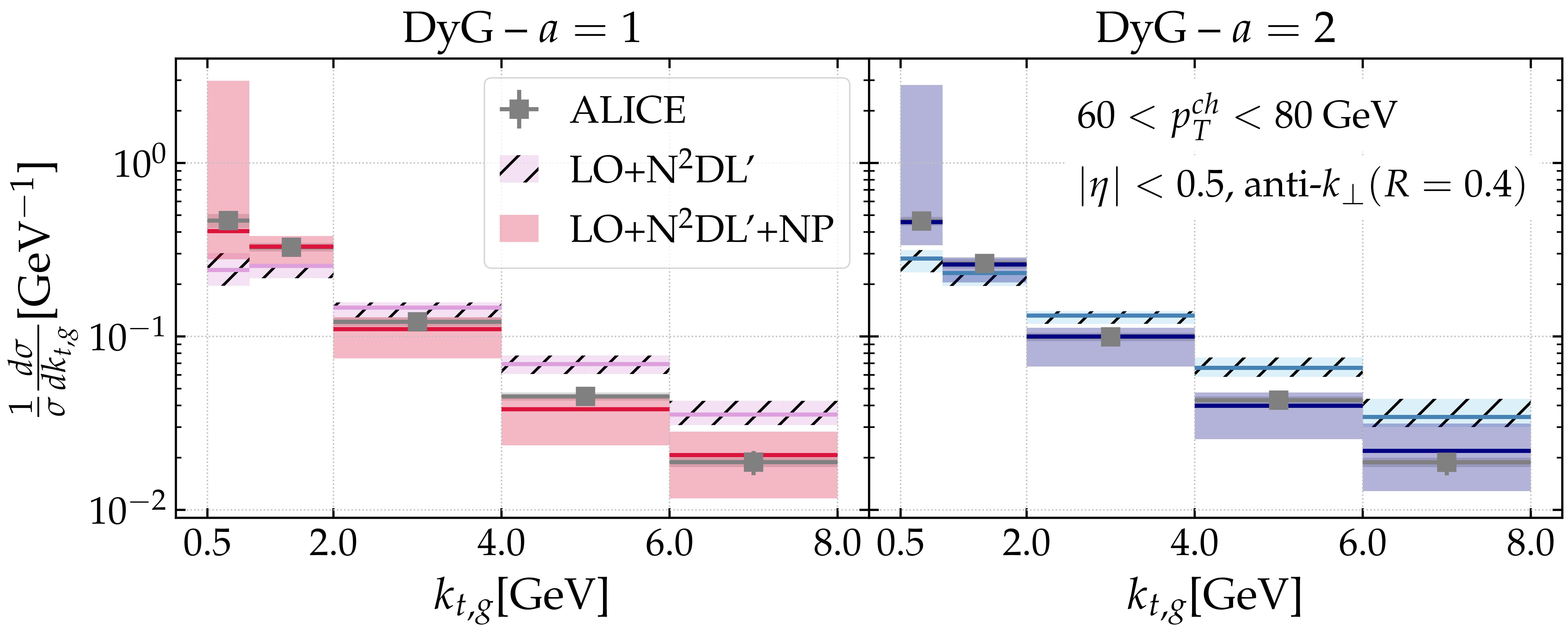
- Non-global logarithms

Fixed order: exact matrix element at $\mathcal{O}(\alpha_s)$ with MadGraph. C_1 term through matching

Non-perturbative corrections:
strong sensitivity to the infra-red cutoff, i.e. $\alpha_s(\mu_{\rm NP})=0$, of the parton shower



Observables #3: $k_{t,g}$ with dynamical grooming [Caucal, ASO, Takacs 2103.06566]

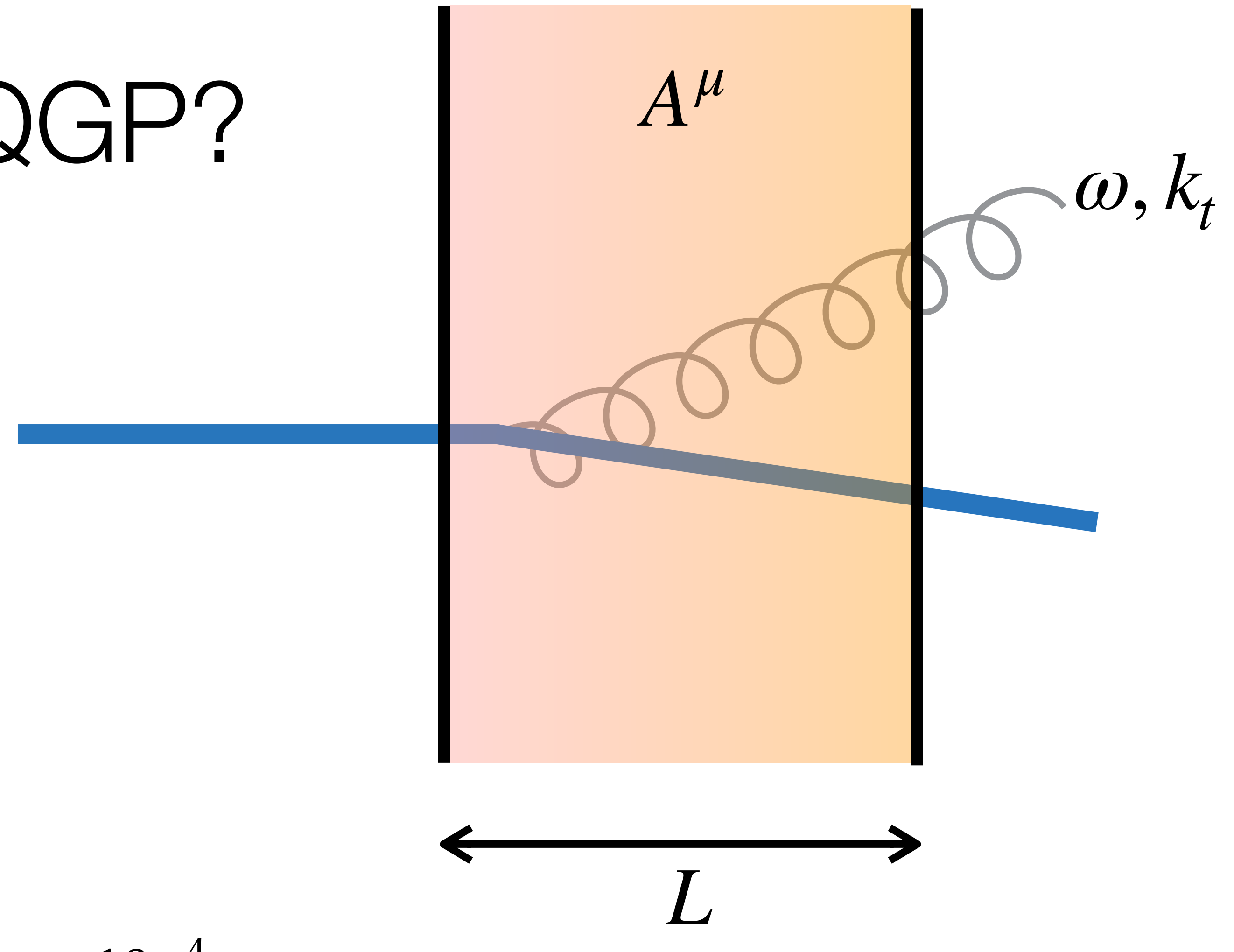


Very good description of ALICE data (also for z_g, θ_g) after including NP

Space-time picture of an in-medium jet

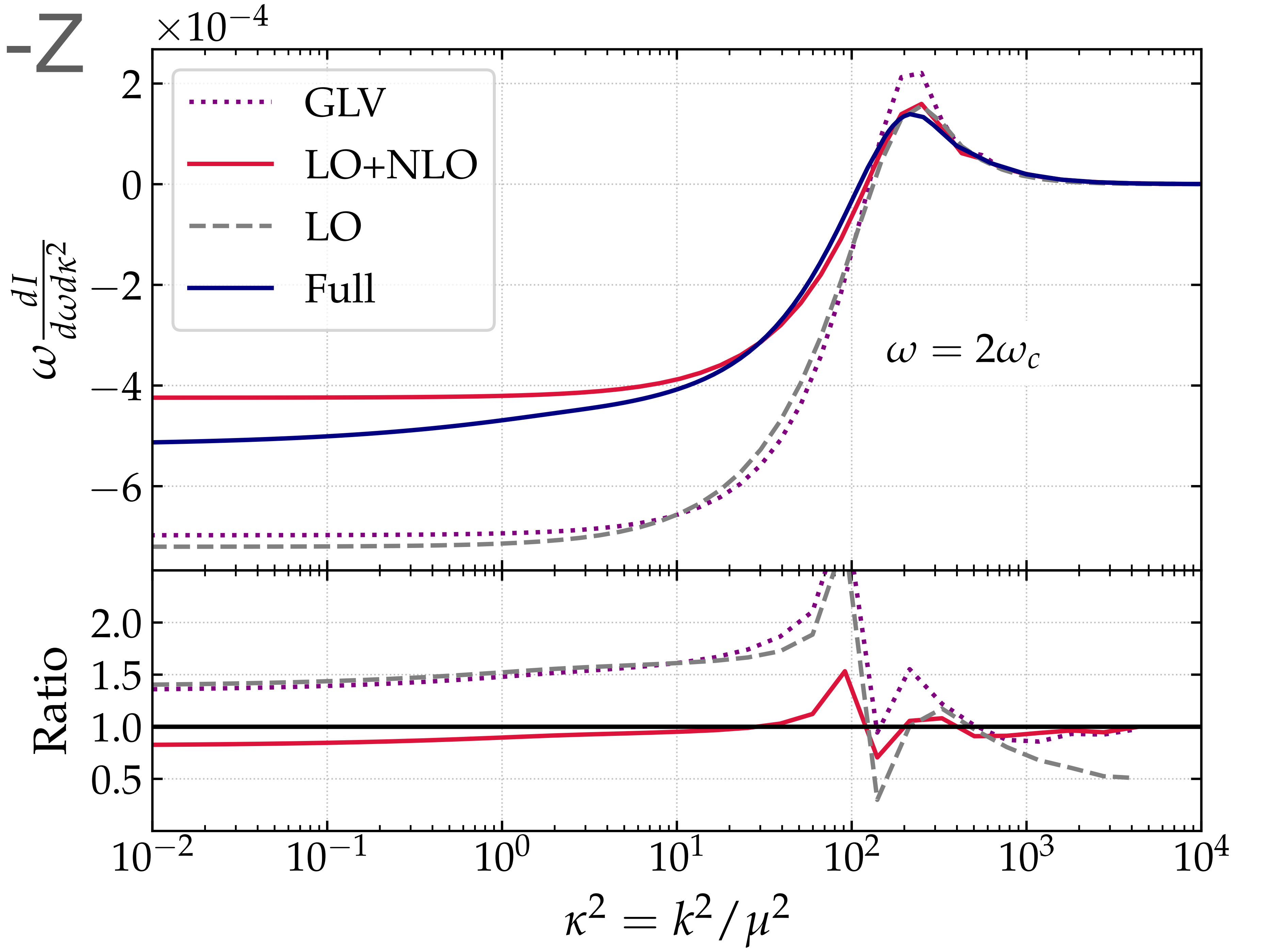
How is the branching kernel, $\widetilde{P}_i(z,\theta)$, modified by the QGP?

$$\widetilde{P}^{\,\mathrm{vac}}(z,\theta) \propto \frac{\mathrm{d}\theta}{\theta} P_{\mathrm{AP}}(z) \quad \Longrightarrow \quad \frac{dI}{\mathrm{d}\omega \mathrm{d}^2 k_t}$$



Analytic approaches to compute the branching kernel

- Multiple soft scattering approximation/BDMPS-Z
  [Baier, Dokshitzer, Mueller, Peigné, Schiff'96]
  [Zakharov'96]
- Opacity expansion/GLV LO (N=0): vacuum radiation. NLO (N=1): single, hard scattering
  [Gyulassy, Levai, Vitev'01] [Sievert, Vitev'19]
  [Wiedemann'00]
- Improved Opacity expansion LO:BDMPS-Z, NLO includes N=1 GLV [Mehtar-Tani, Barata, Tywoniuk, ASO'19-21]



[Barata, Mehtar-Tani, ASO, Tywoniuk to appear]

All-orders numerical solution [Andres, Apolinario, Dominguez'20]

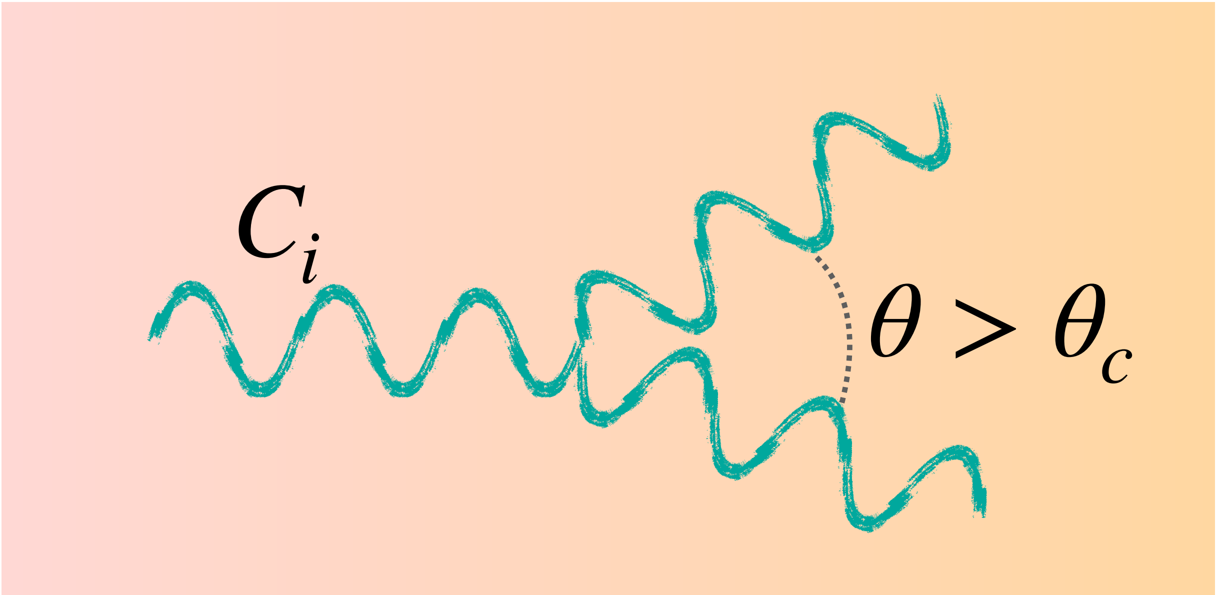
Space-time picture of an in-medium jet

Not only the branching kernel gets modified but also the prongs lose energy

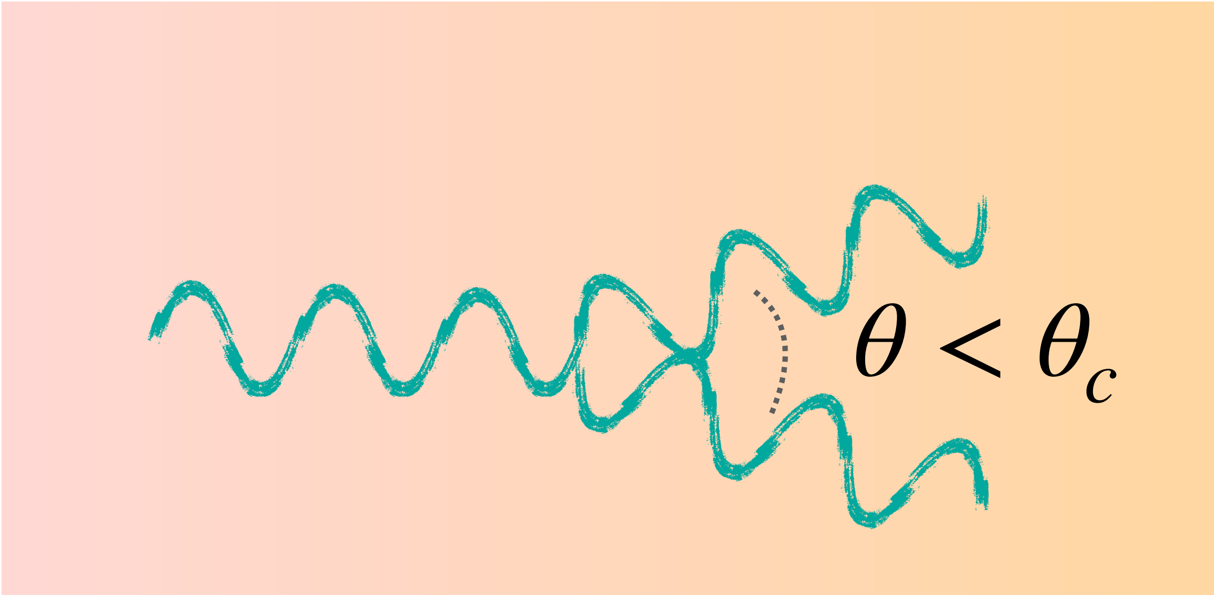
e.g. opening angle of the hardest splitting as tagged by DyG

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\theta_g}_{|p_T} = \mathcal{N}_{\mathrm{med}}^{-1}\sum_{i\in\{q,g\}}\int \mathrm{d}\varepsilon \frac{\mathrm{d}\sigma_i^h}{\mathrm{d}p_{T0}}(p_T+\varepsilon)\mathscr{E}_{i,p_T,R}(\varepsilon\,|\,\theta_g)\times\int \mathrm{d}z_g'\mathscr{P}_i(z_g',\theta_g)$$

with $\mathscr{E}_{i,p_T,R}(\varepsilon\,|\,\theta_g)$ the energy loss probability distribution that depends on θ_g: color coherence



$\langle\varepsilon\rangle \propto C_A + C_i$



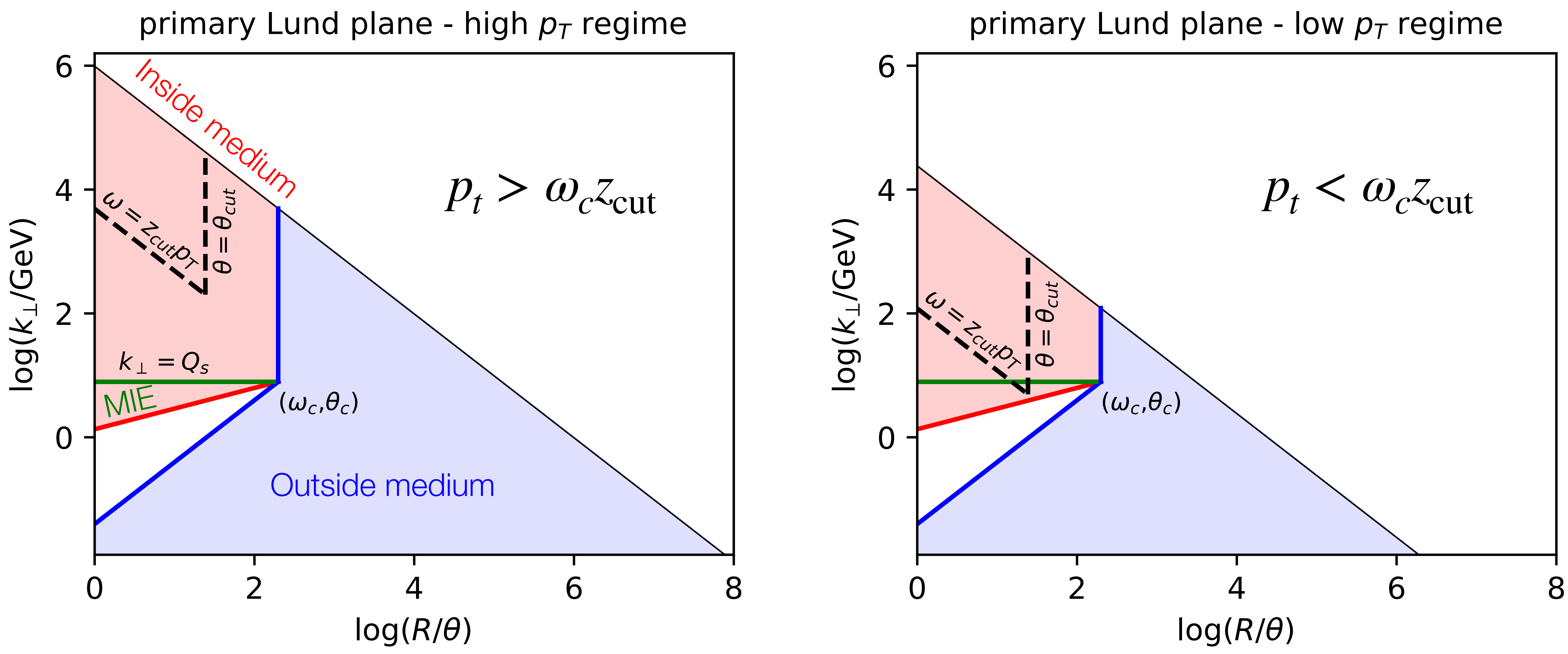
$\langle\varepsilon\rangle \propto C_i$

$$\theta_c = (\hat{q}L^3)^{-1/2}$$

Observable #1: z_g-distribution

[Caucal, Iancu, Soyez JHEP10 (2019) 273]

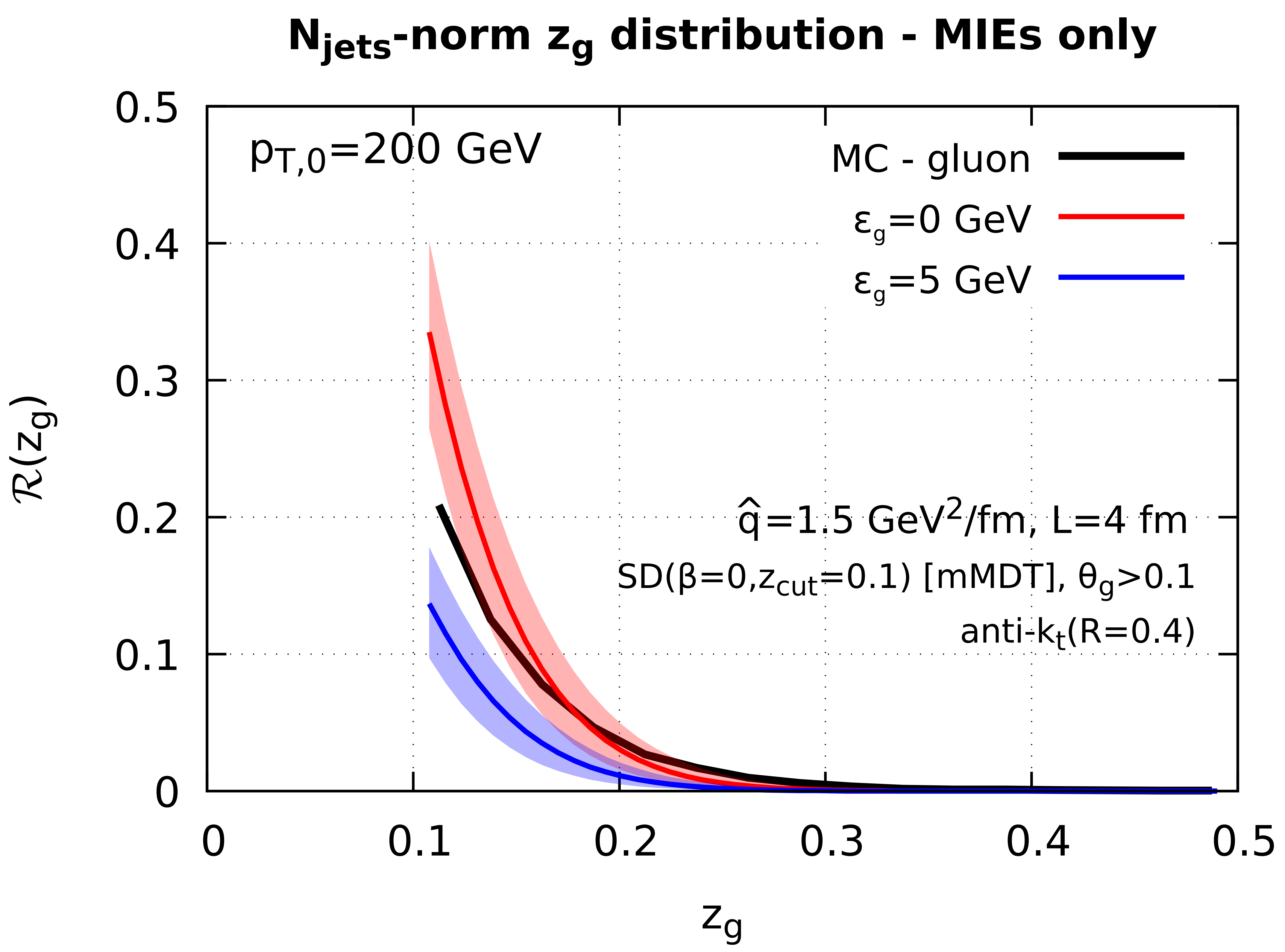
$$z > z_{\rm cut} + \theta > \theta_{\rm cut}$$

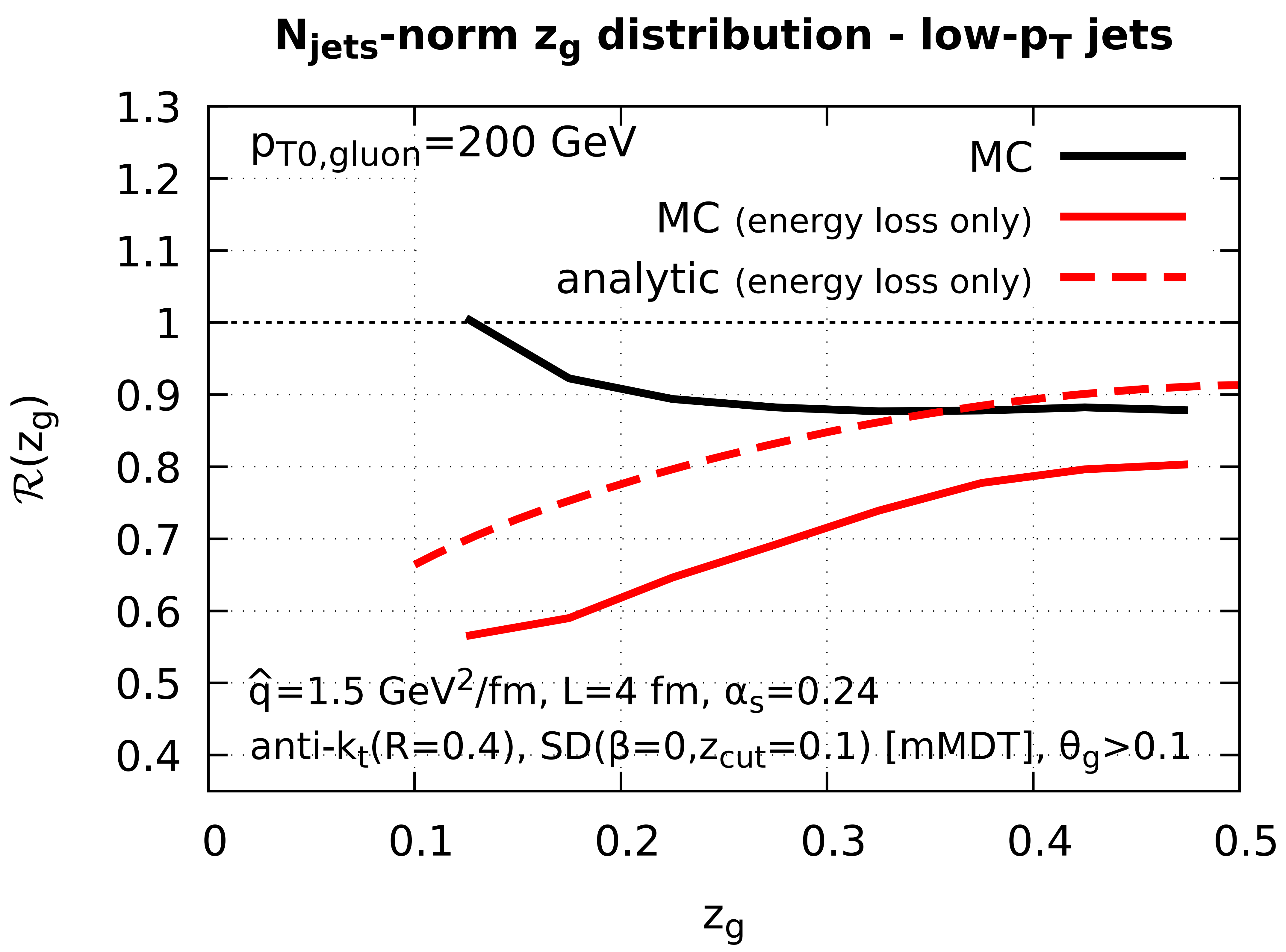


Tune the grooming condition to explore different in-medium physics

Observable #1: z_g-distribution

[Caucal, Iancu, Soyez JHEP10 (2019) 273]

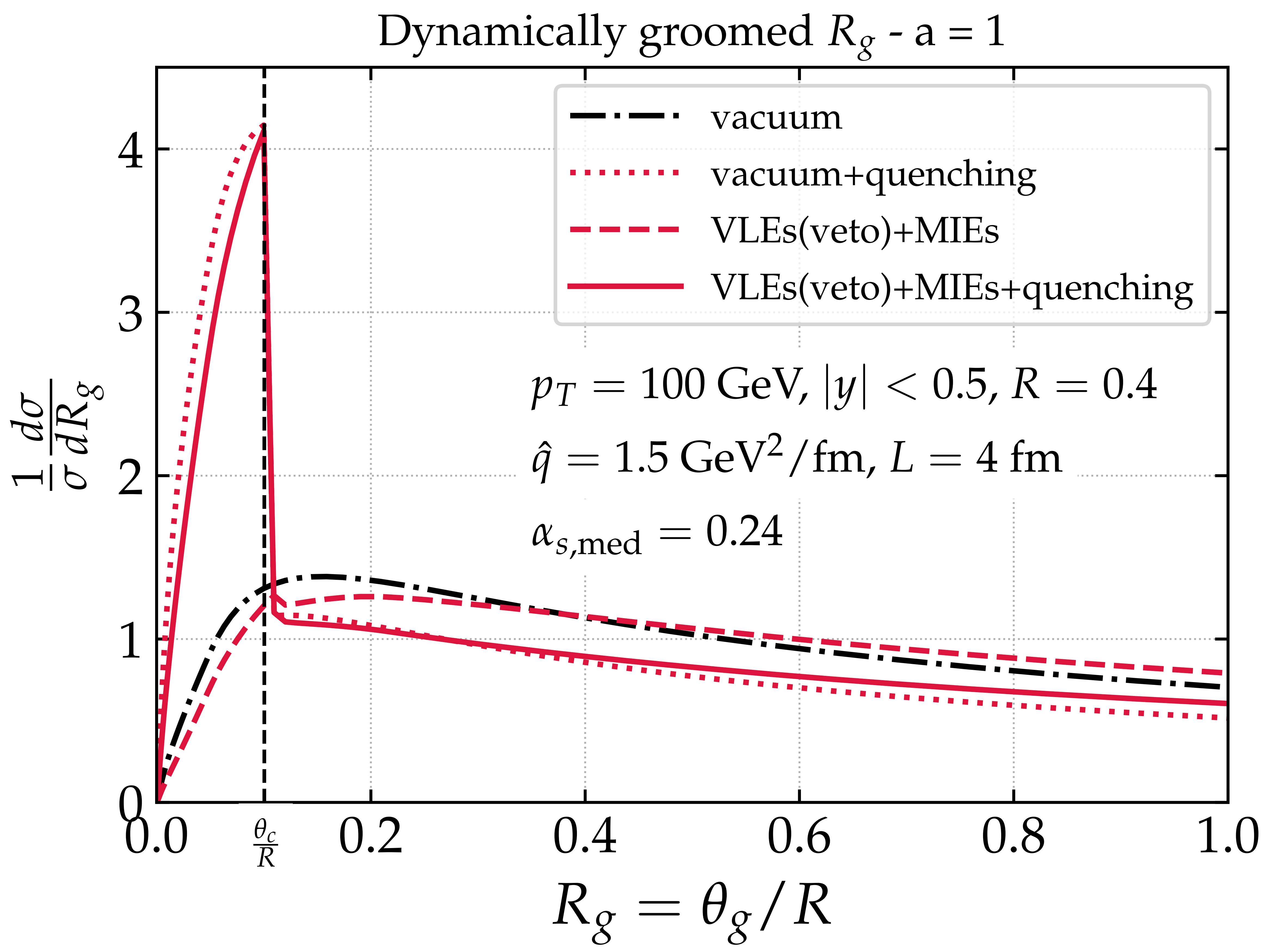


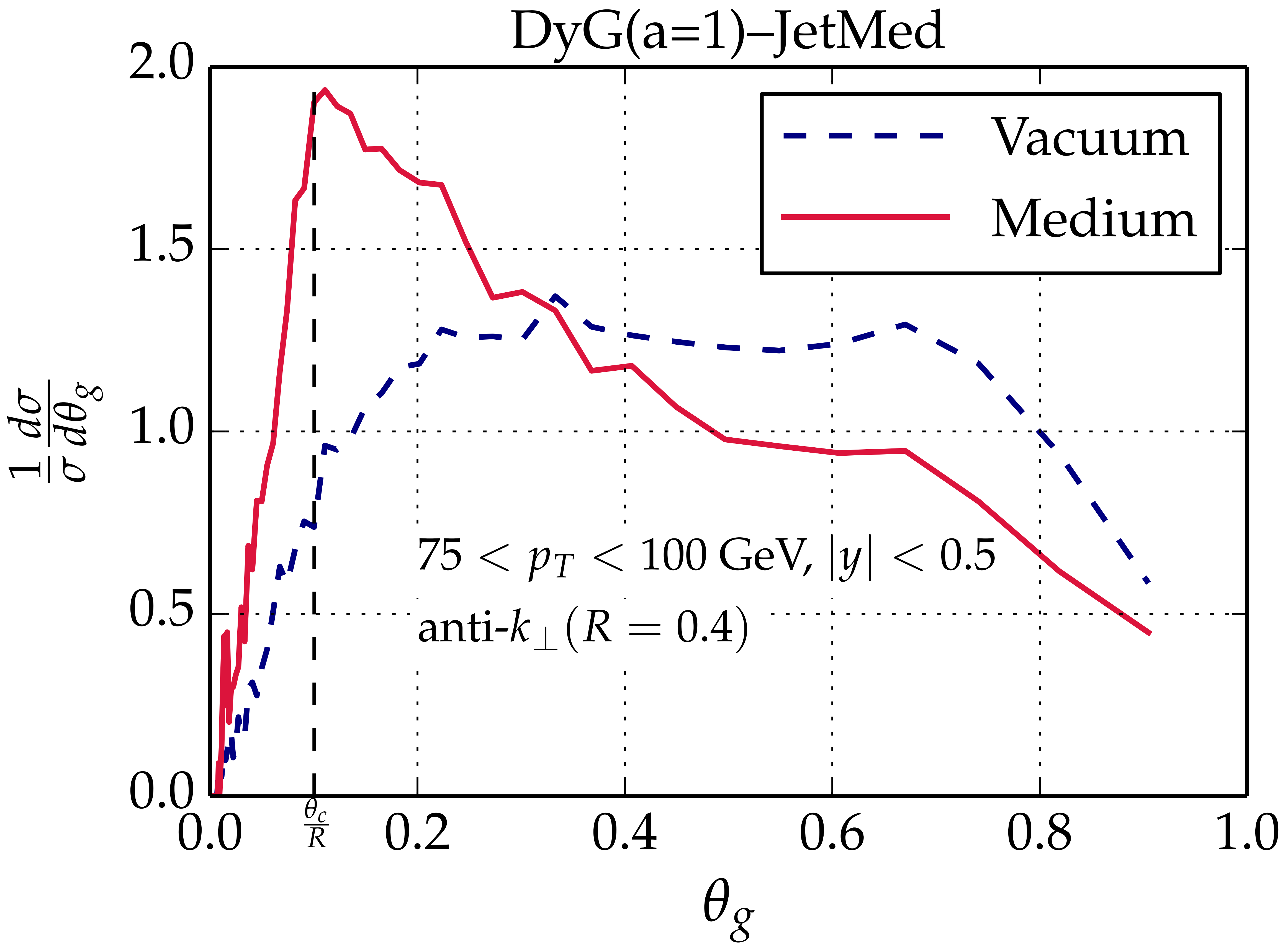


Small z_g: hard medium-induced emissions $P^{\rm BDMPS}(z)/P_{\rm AP}(z) \sim z^{-1/2}$

Large z_g: incoherent energy loss

Observable #2: θ_g-distribution [Caucal, ASO, Takacs in preparation]



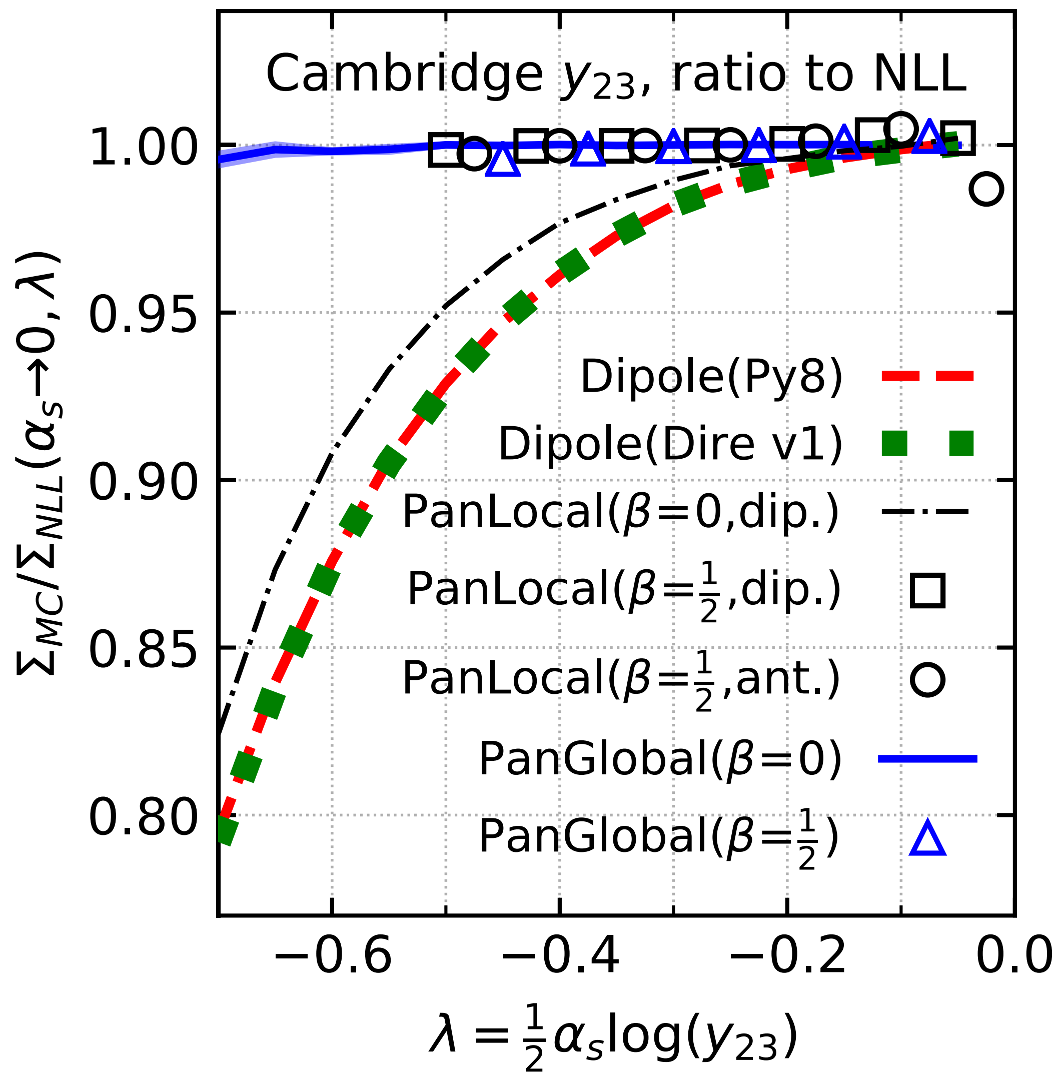


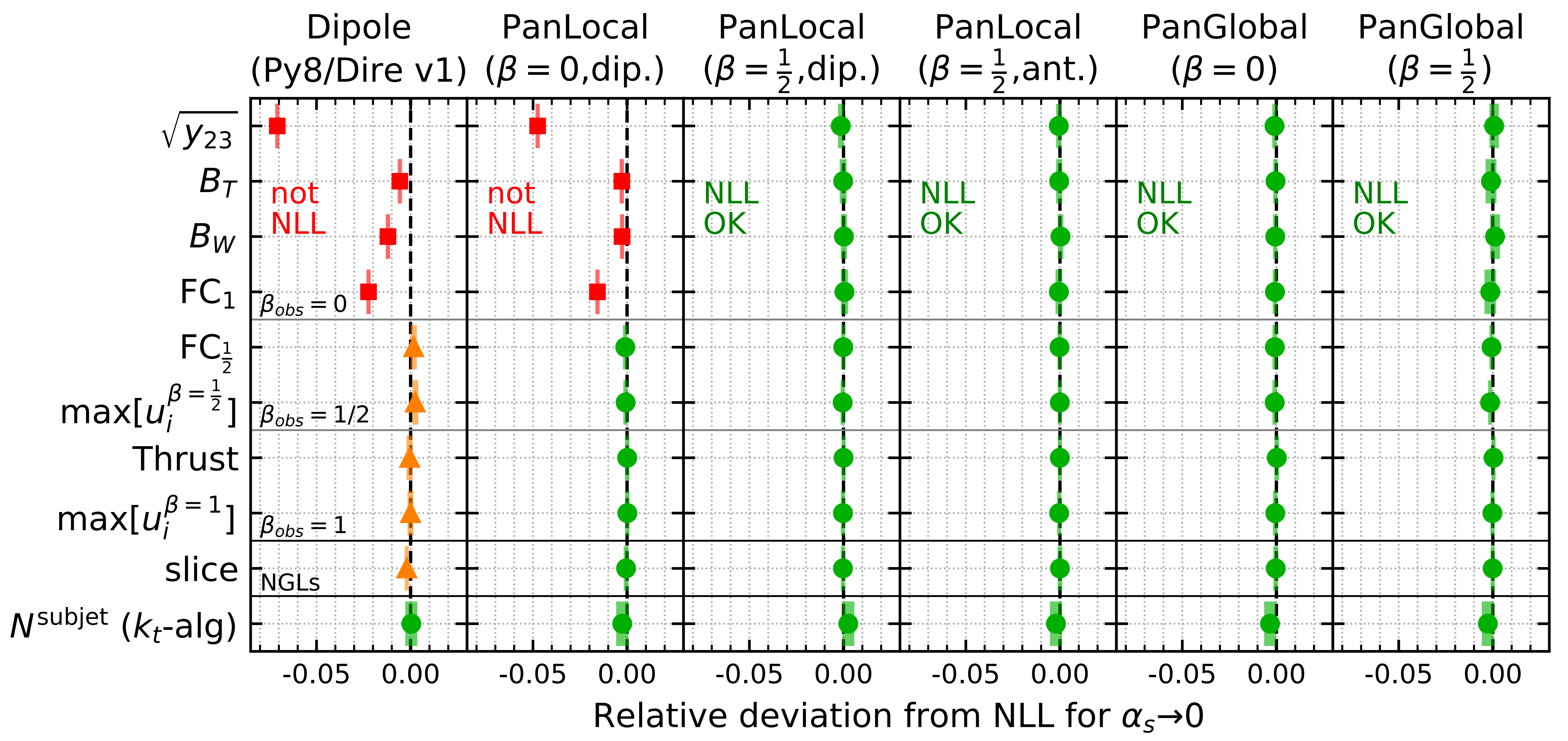
New opportunity to measure the QGP resolution angle θ_c

Wrap-up

- Analytic understanding of jet substructure observables to probe the different regimes of radiation phase space both in vacuum and in the medium

- In vacuum, jet substructure as tool to gauge the accuracy of parton showers





[Dasgupta et al. PRL 125 (2020)]

- Recent developments in jet quenching theory are paving the way to quantitative theory-to-data comparisons