Plan for the course

Lecture 1: big picture

- Why jets?
- $\gamma^* \to q\bar{q}g$: singularity structure
- Resummation and parton showers

Lecture 2: jet algorithms

- Core ideas of jet reconstruction
- Sequential recombination algorithms
- Optimising jet parameters

Lecture 3: jet substructure

- The question of flavour
- Calculability: groomed jet mass
- Observables at the LHC

How to define jet flavour? And why is it important?

Light flavour

Is it a quark or a gluon-induced jet?

Possible to address at fixed-order

Relevant for e.g. organising matching to resummation

Heavy flavour

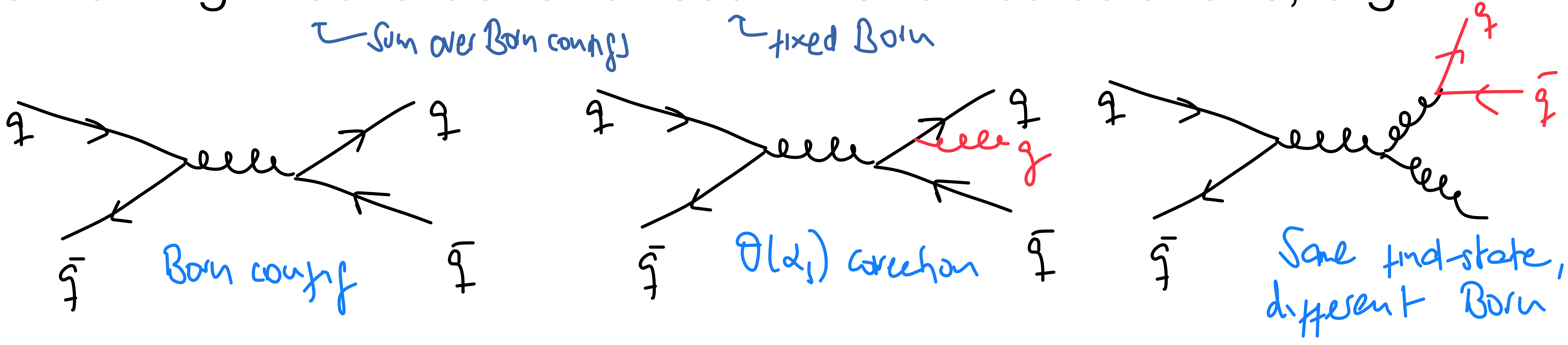
Is it a heavy-quark initiated jet? Exp definition

An (anti-k_t) jet is flavoured if it contains at least one heavy hadron within $\Delta R < R$ with $p_t > p_{t,\mathrm{cut}}$

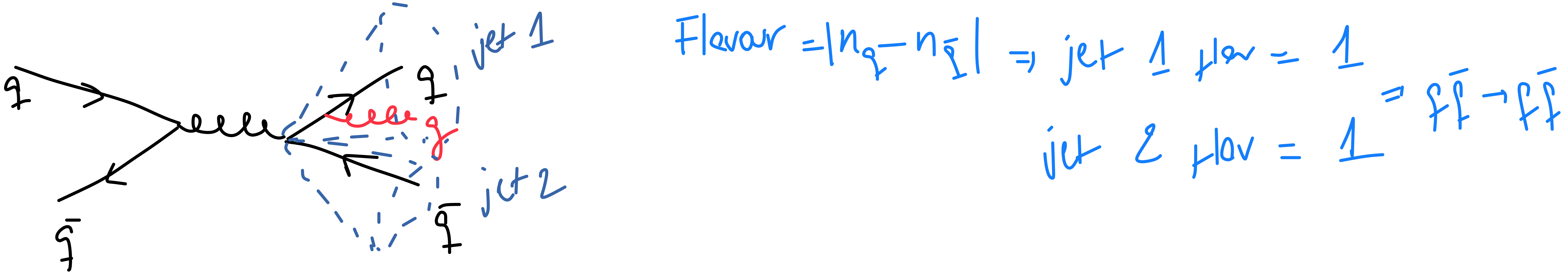
Critical to address calculability for robust theory-to-data comparisons

Importance of jet flavour algo for matching N^kLO and N^kLL

Combining fixed-order and resummation calculations, e.g.



Need procedure to assign $q\bar{q}g$ final-state to $q\bar{q} \to q\bar{q}$ Born, e.g.



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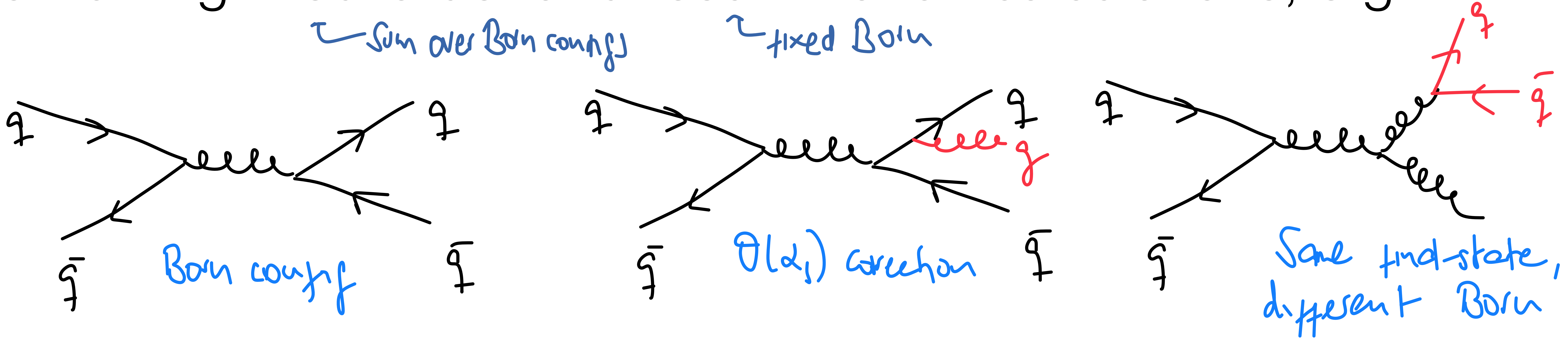

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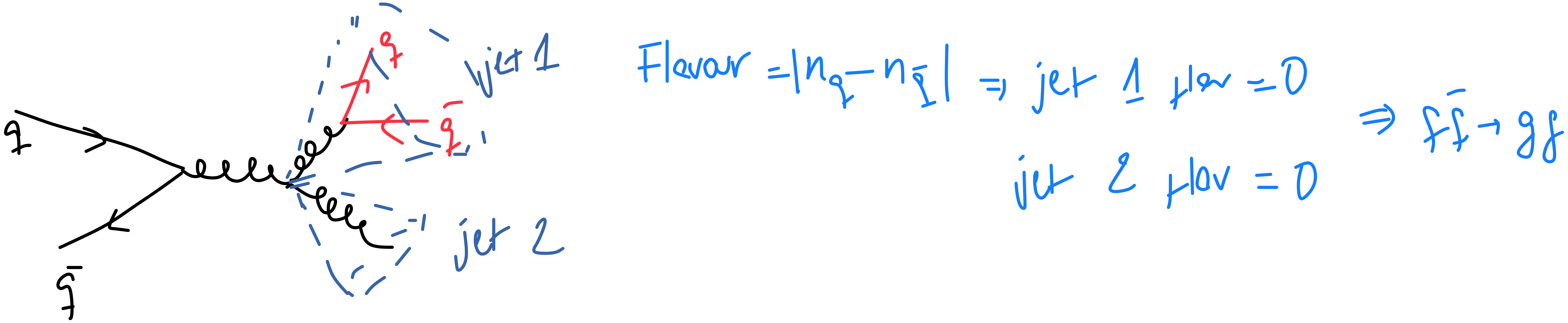

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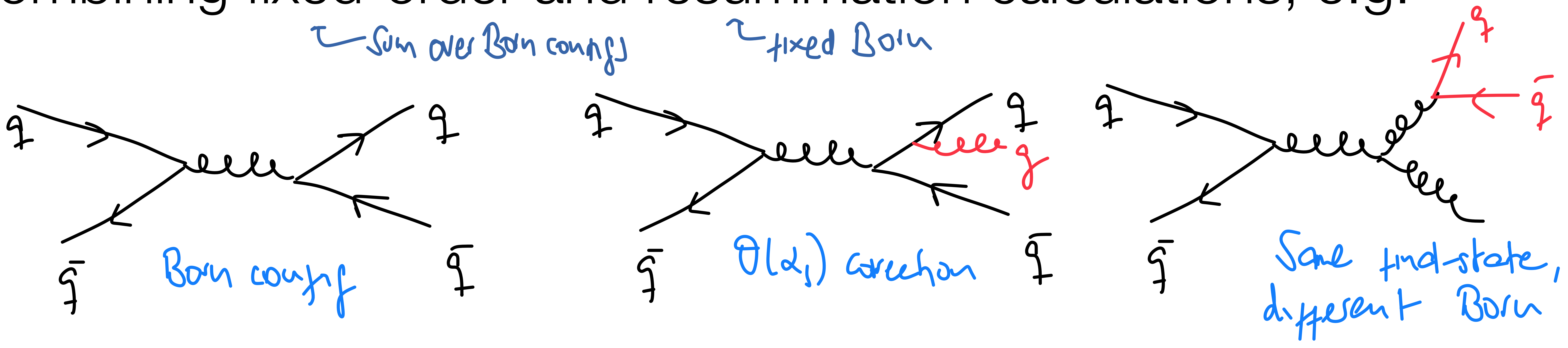
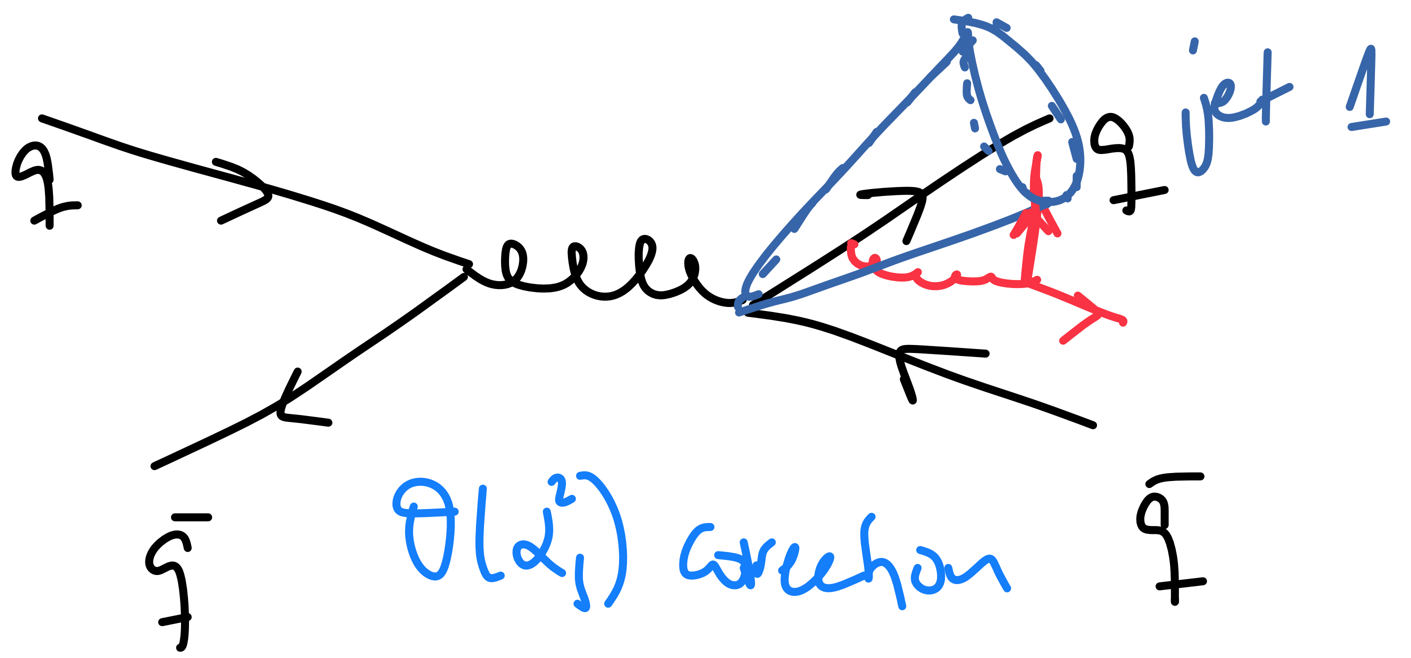


Problem! Again IRC unsafety



Arbitrarily soft $g \rightarrow q\bar{q}$ changes flavour

Importance of jet flavour algo for matching N^{k}LO and N^{k}LL

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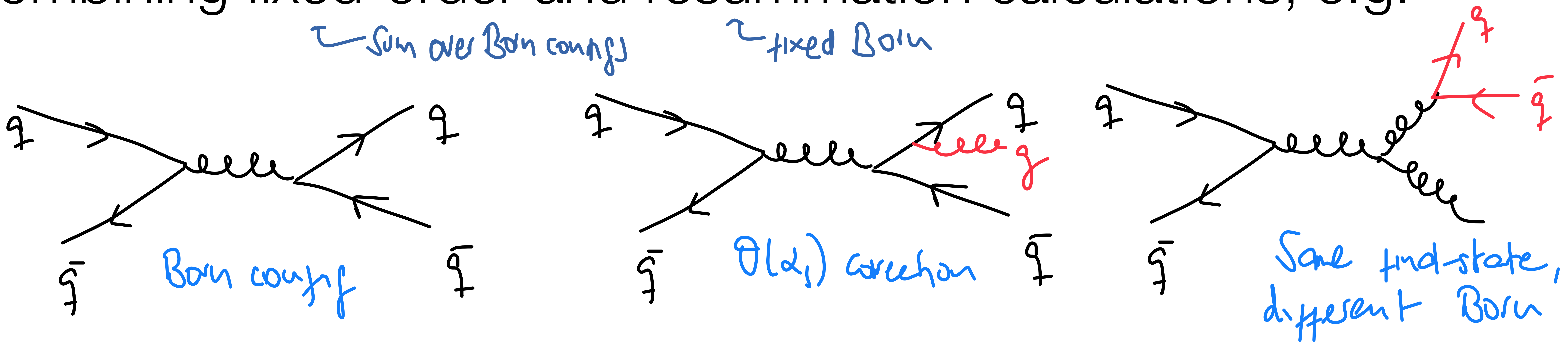
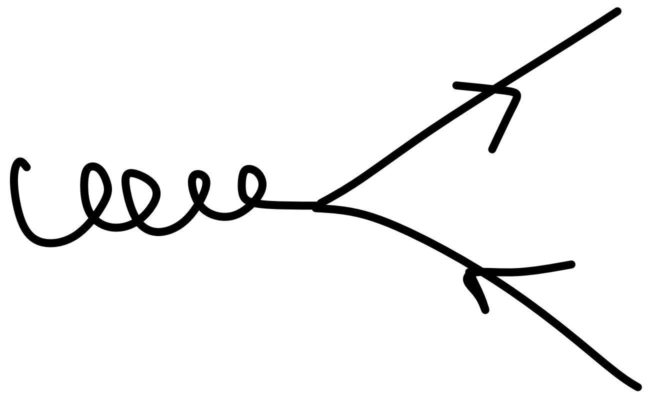


Original solution: flavour k_t algorithm (for ee)

[Banfi et al Eur.Phys.J.C 47 (2006) 113-124]



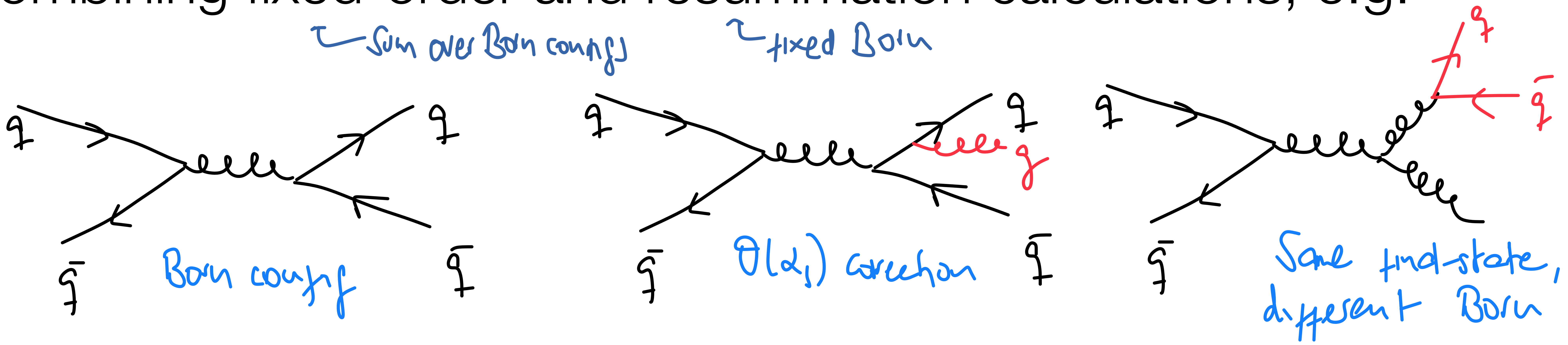
$P \propto \max(z, 1-z)$ (no soft divergence)

$$d_{ij} = \frac{2(1-\cos\theta_{ij})}{Q} \times \begin{cases} \max(E_i^2, E_j^2) & \text{for quark-like} \\ \min(E_i^2, E_j^2) & \text{for gluon-like} \end{cases}$$

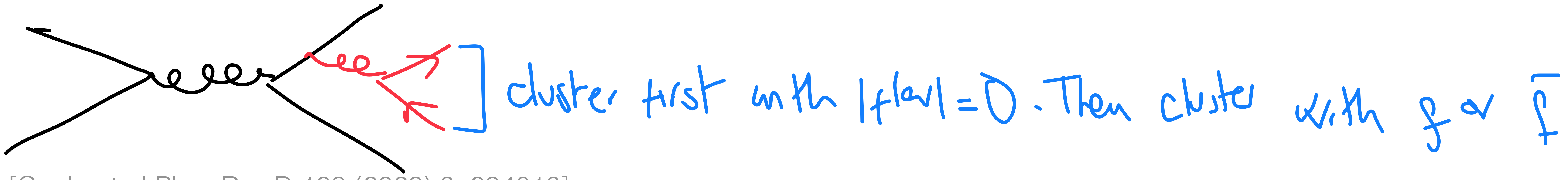
Modify metric to reflect soft quark divergences

Importance of jet flavour algo for matching N^{k}LO and N^{k}LL

Combining fixed-order and resummation calculations, e.g.



Original solution: flavour k_t algorithm in action

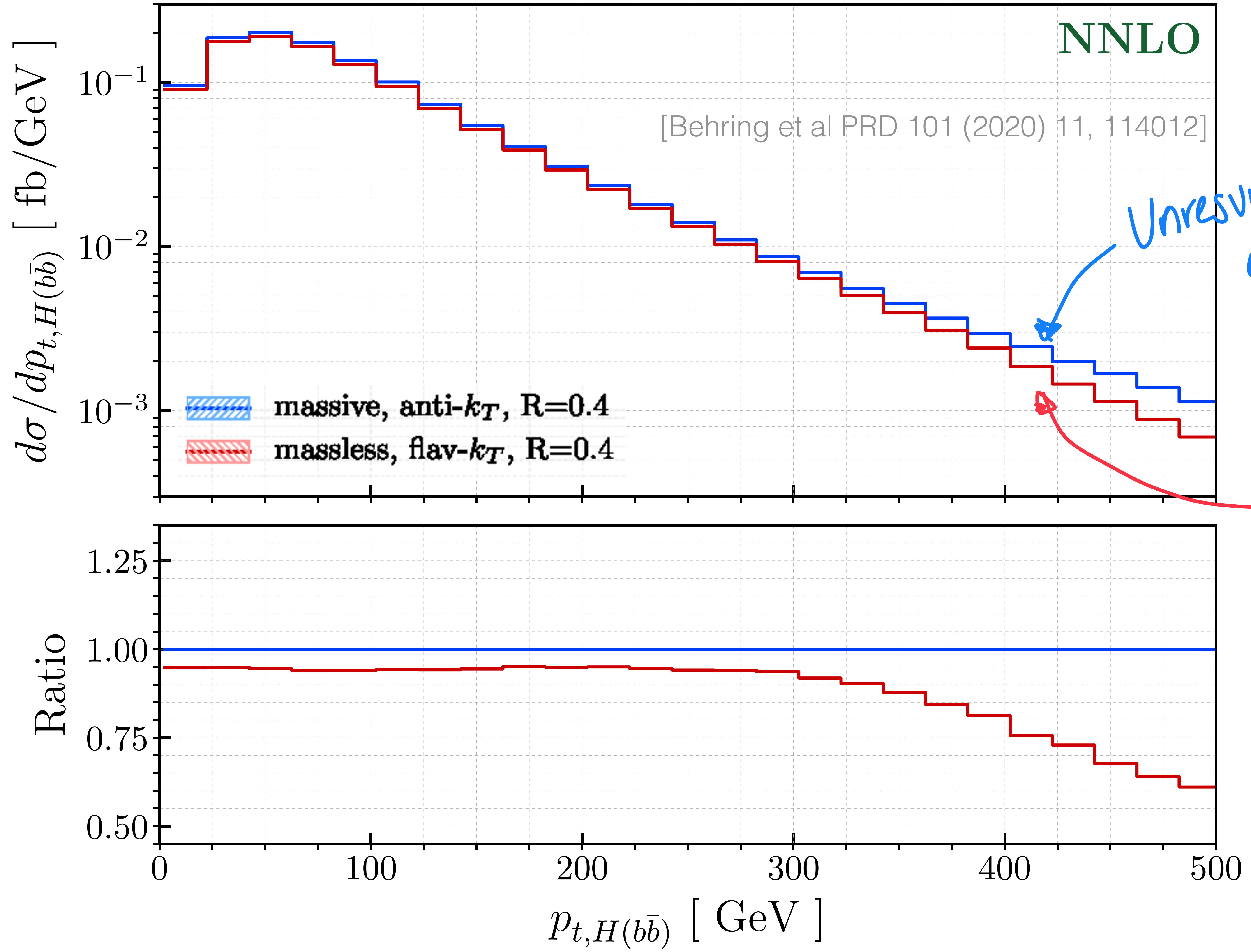


[Caola et al Phys.Rev.D 108 (2023) 9, 094010]

IRC safe in e^+e^- (issues at $\mathcal{O}(\alpha_s^3)$ for pp).
Also, LHC experiments like anti-k_t jets

Issues with heavy-flavour: theory

Theoretically, there are two ways of dealing with heavy-quarks



Unresummed $\ln(p_t/m_b)$. More critical if using IRC unsafe algorithm.

Kinematics are different w.r.t anti-k_t (and even w.r.t k_t)

Issues with heavy-flavour: theory and experiment

[Discussion based on R. Gauld et al Phys.Rev.Lett. 130 (2023) 16, 161901, Eur. Phys. J. C (2023) 83:336]

An (anti-k_t) jet is flavoured if it contains at least one heavy hadron within $\Delta R < R$ with $p_t > p_{t,\mathrm{cut}}$

Issues with heavy-flavour: theory and experiment

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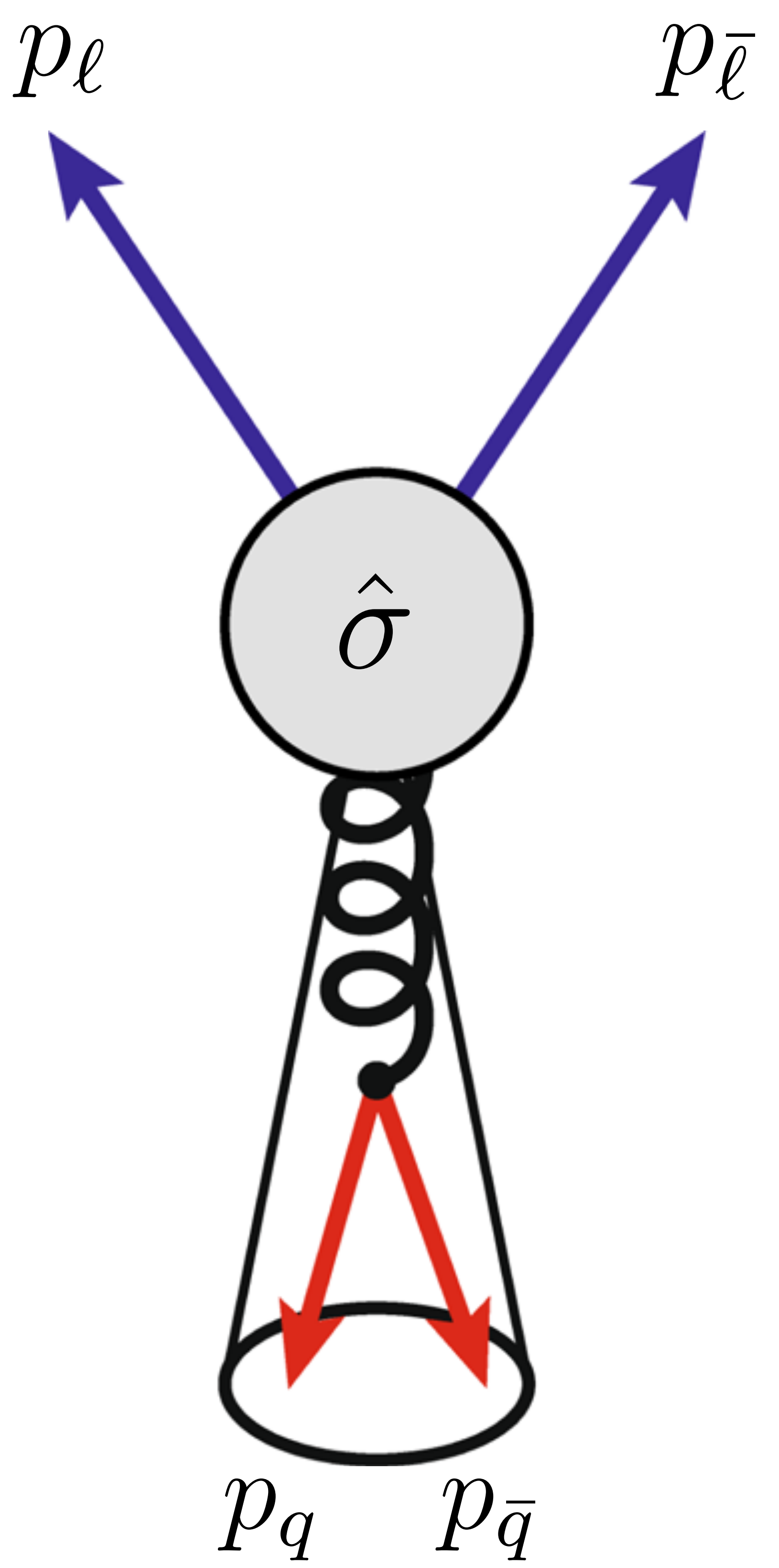
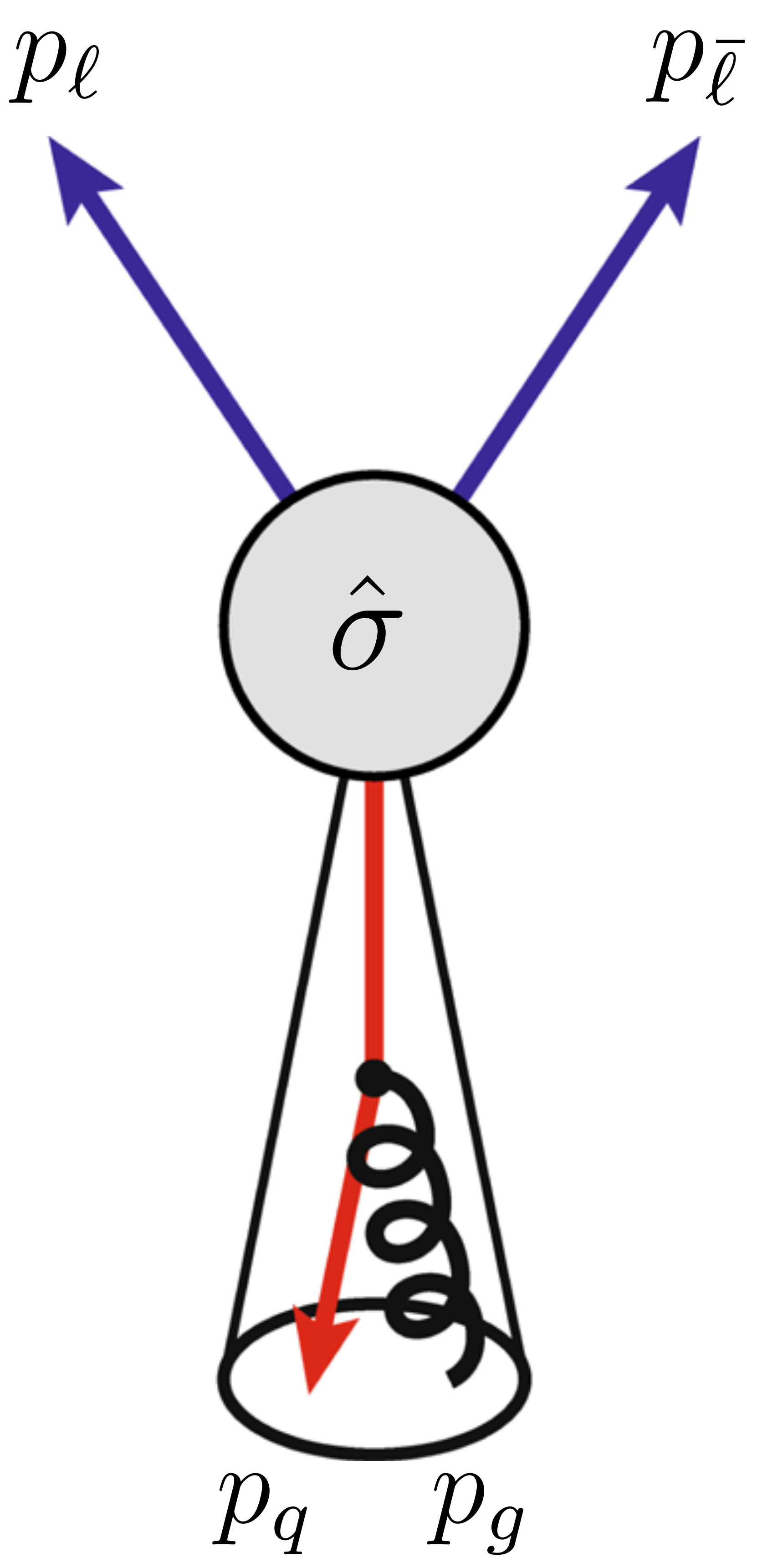


Problem: $g \to q\bar{q}$ is flavoured even in the collinear limit.

Solution: consider flavour jet to have odd number of q and $\bar{q}$

Issues with heavy-flavour: theory and experiment

An (anti-k_t) jet is flavoured if it contains at least one heavy hadron within $\Delta R < R$ with $p_t > p_{t,\text{cut}}$

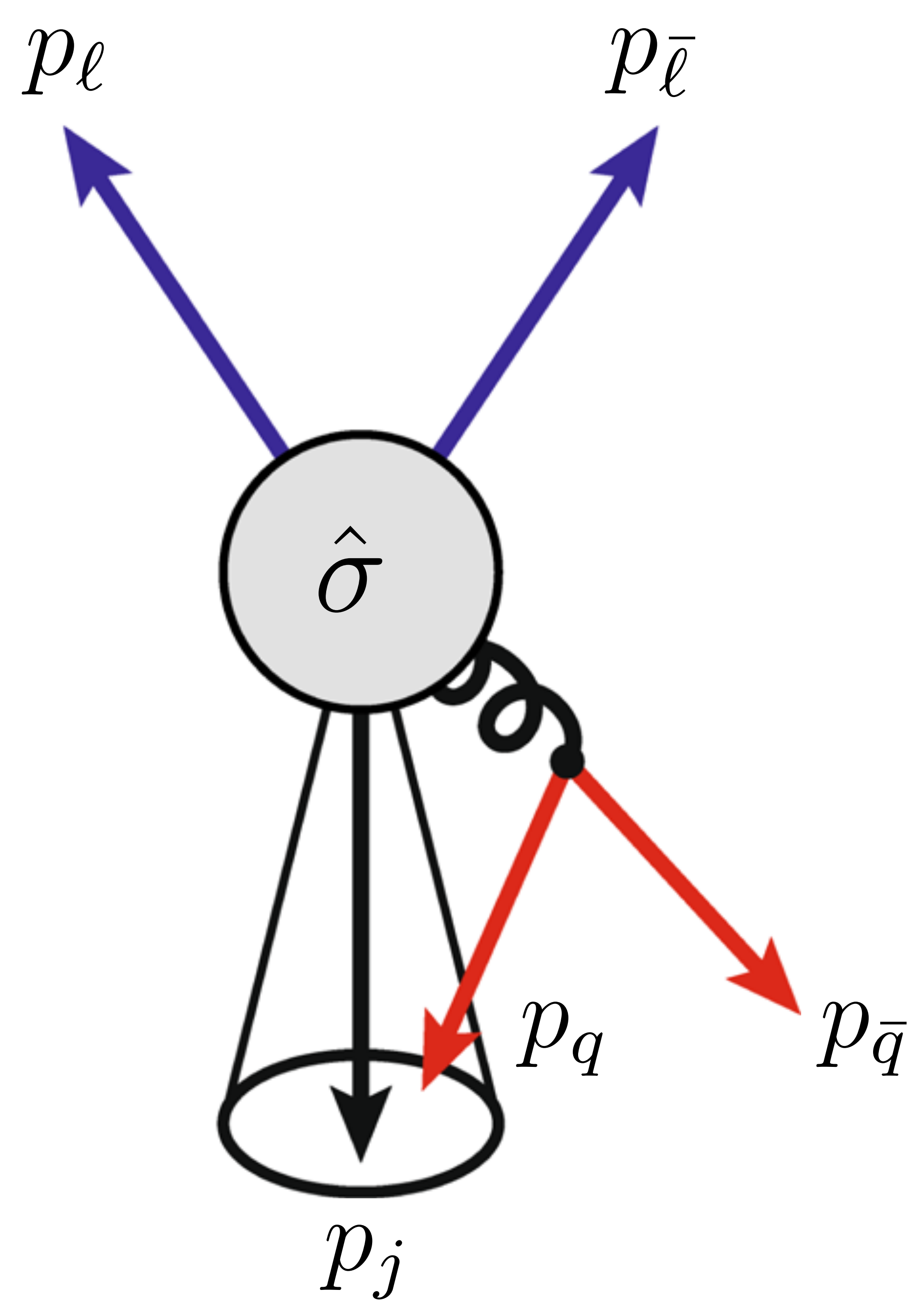


Problem: collinear $q \to qg$ might make the heavy-quark fall below the $p_{t,\text{cut}}$.

Solution: introduce a fragmentation function

Issues with heavy-flavour: theory and experiment

An (anti-k_t) jet is flavoured if it contains at least one heavy hadron within $\Delta R < R$ *with* $p_t > p_{t,\mathrm{cut}}$

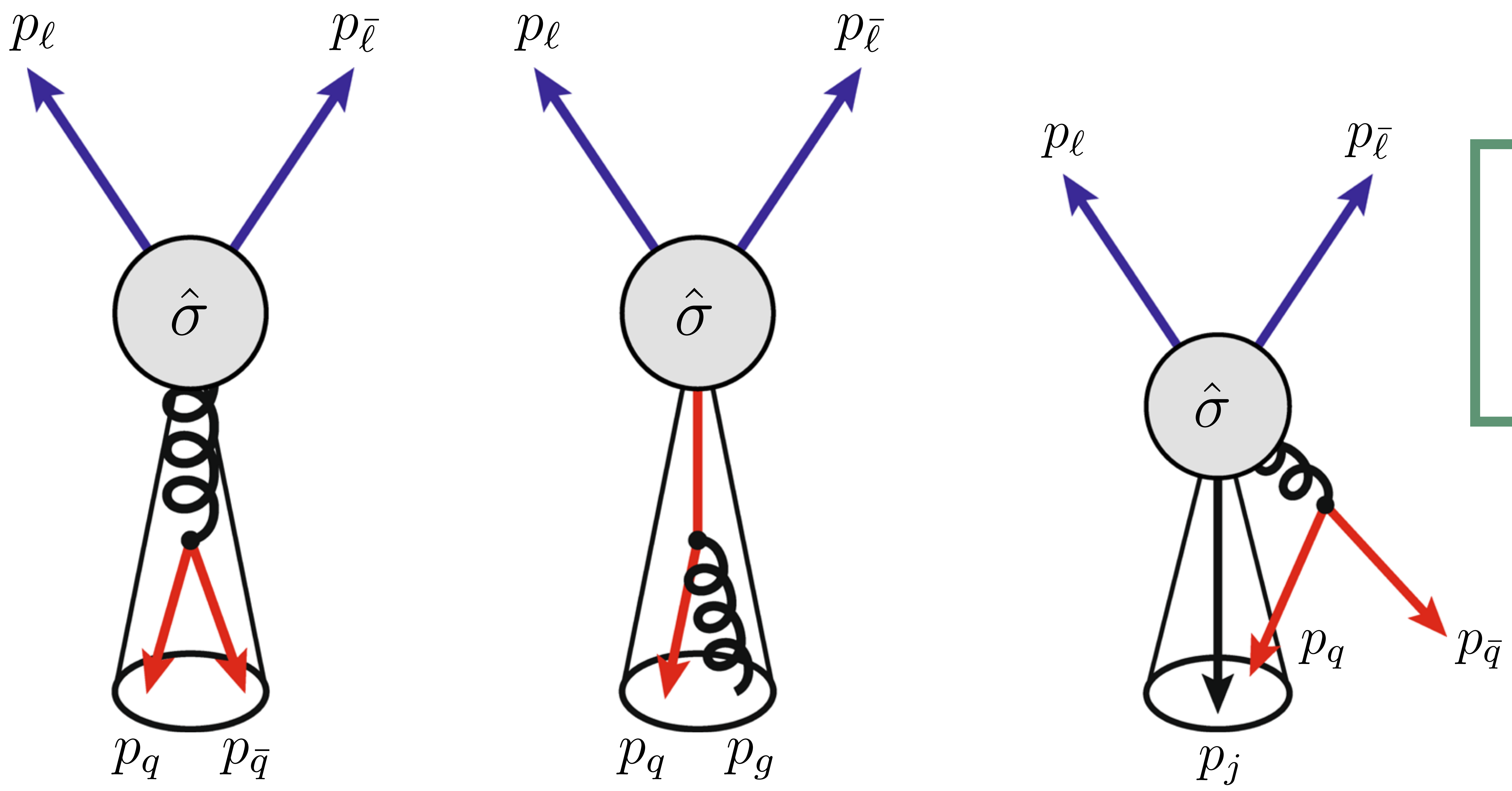


Problem: soft, large-angle $g \to q\bar{q}$ pollutes the flavour of other jets

Solution: none within a flavour agnostic jet algorithm

Issues with heavy-flavour: theory and experiment

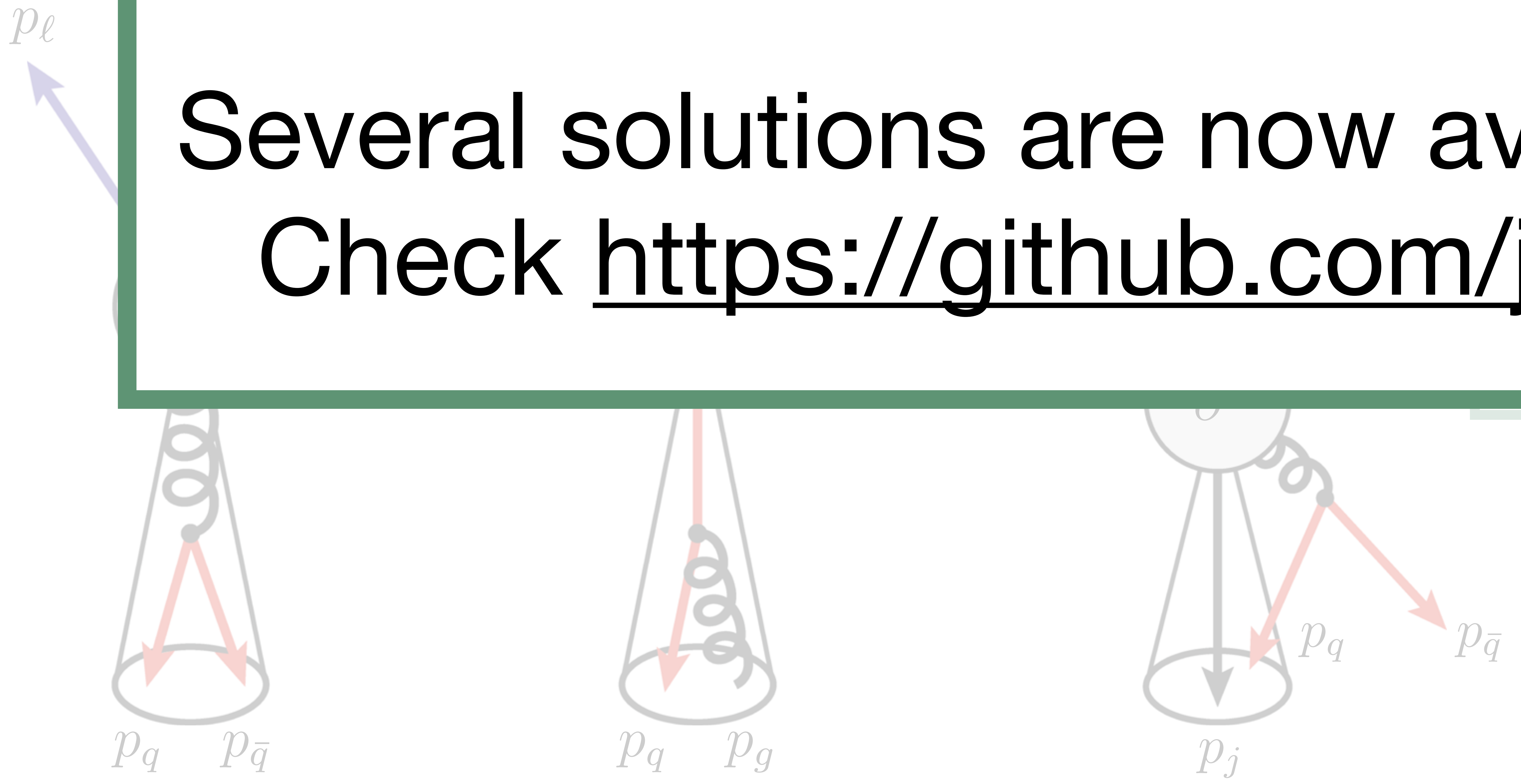
An (anti-k_t) jet is flavoured if it contains at least one heavy hadron within $\Delta R < R$ with $p_t > p_{t,\rm cut}$



This definition is IRC unsafe in massless pQCD calculations

Issues with heavy-flavour: theory and experiment

An (anti-k_t) jet is flavoured if it contains at least one heavy hadron within $\Delta R < R$ with $p_t > p_{t,\mathrm{cut}}$



n is IRC
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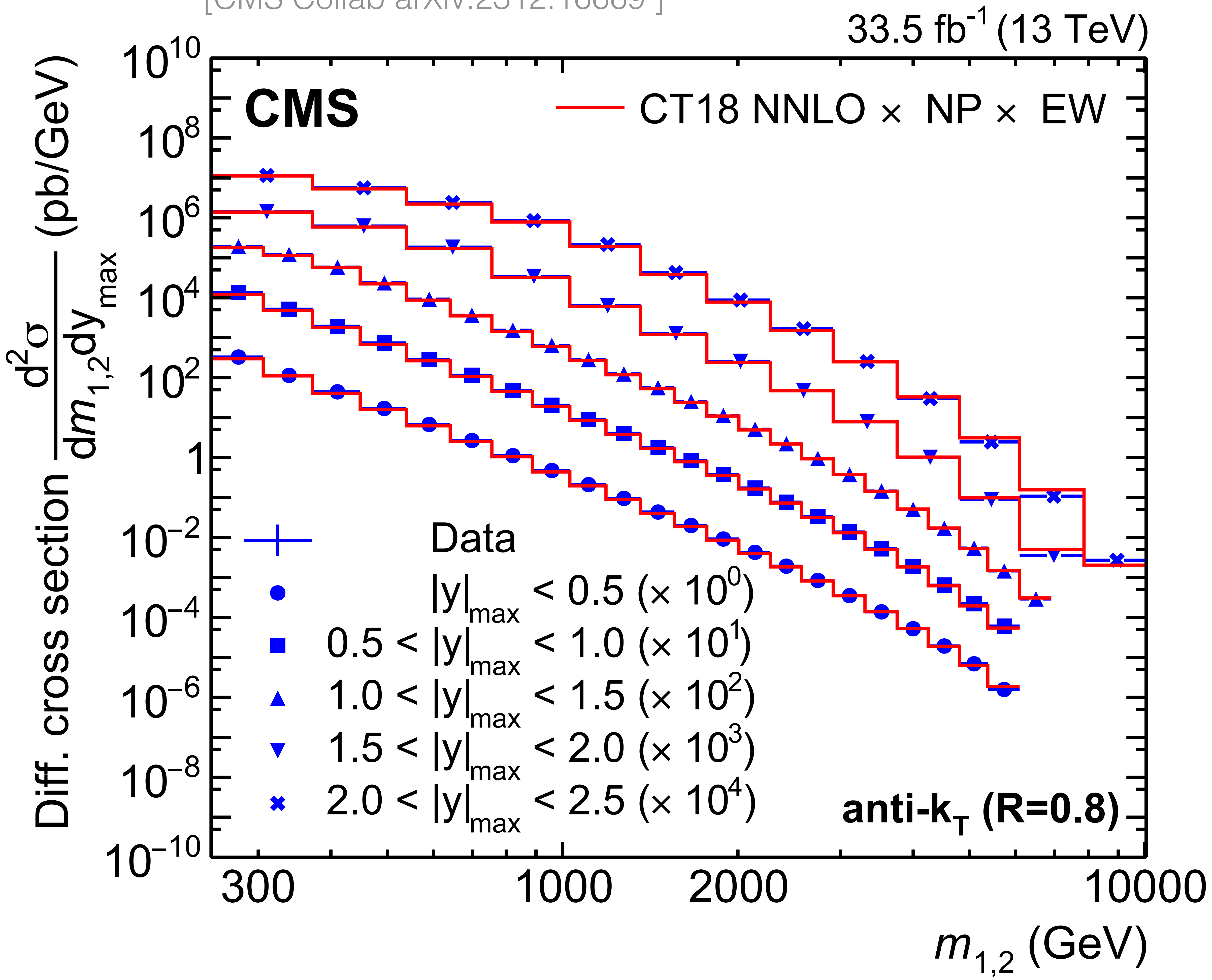
Several solutions are now available.
Check https://github.com/jetflav

What to do with anti-k_t jets?

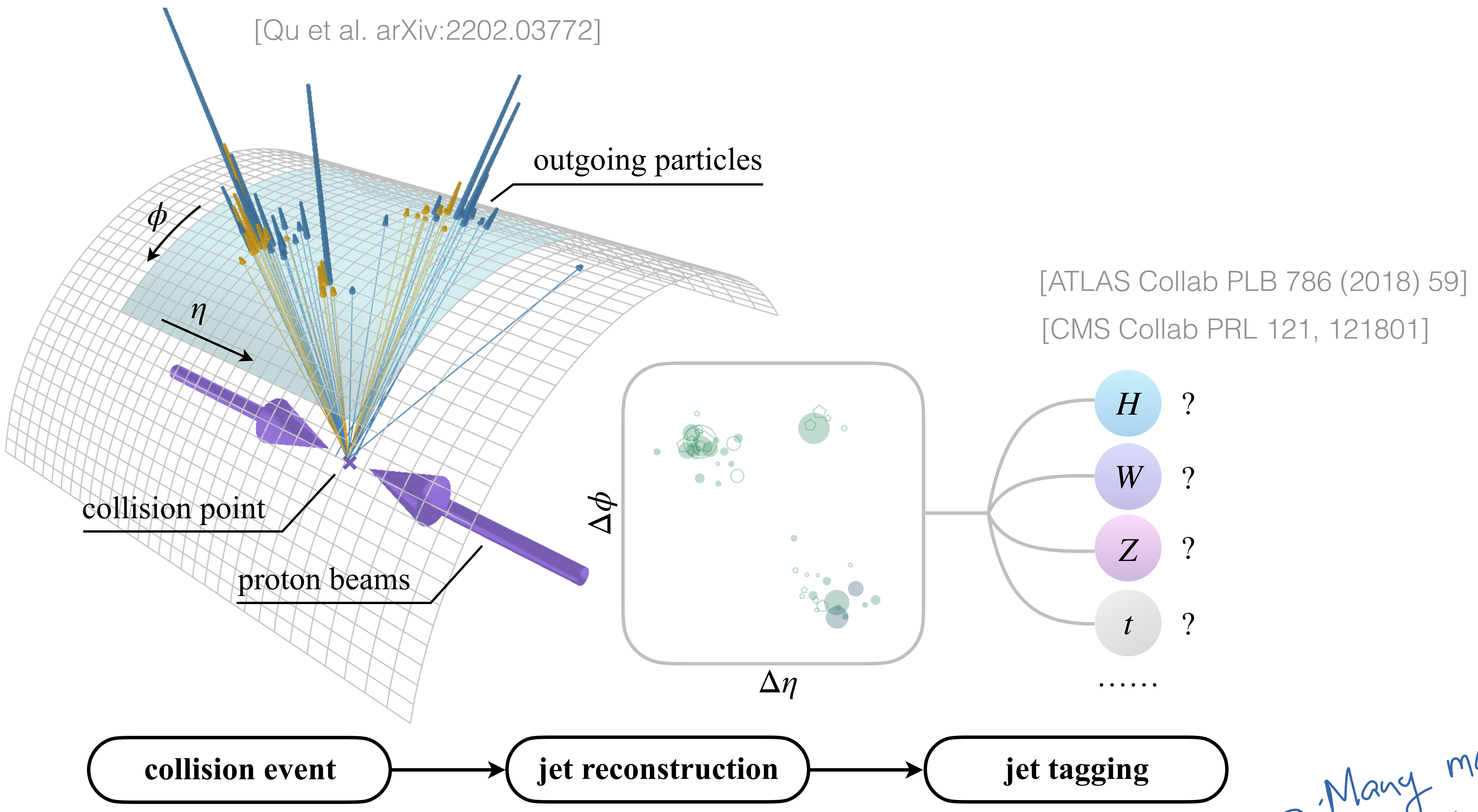
[CMS Collab arXiv:2312.16669]



$$\alpha_s(M_Z) = 0.1179 \pm 0.0019$$

Test QCD (including EW corrections) over 7 orders of magnitude

What to do with anti-k_t jets? Discover resonances

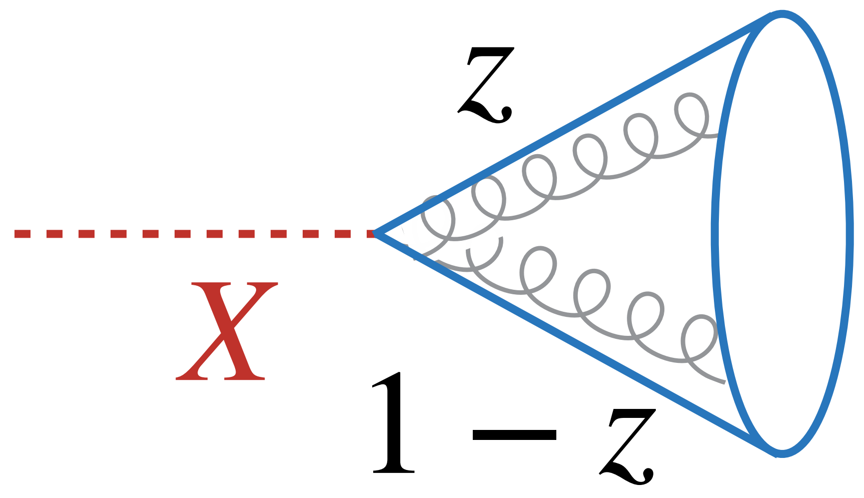


Many machine learning developments

Have to deal with boosted object reconstruction

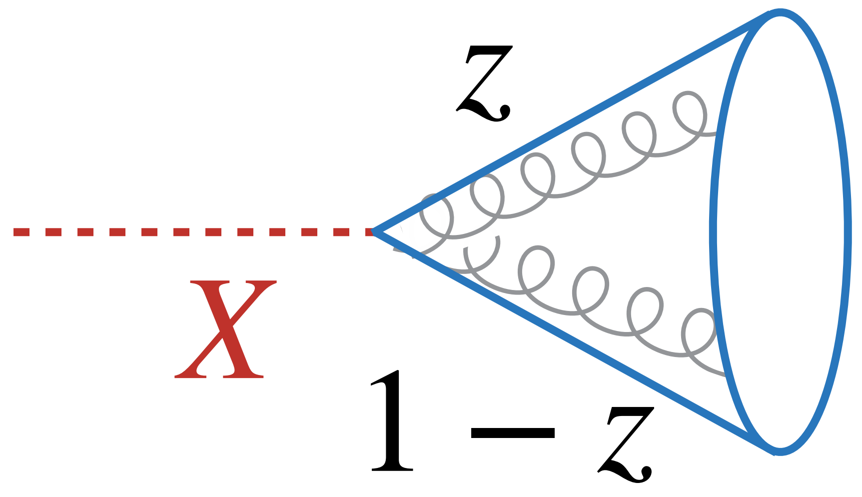
Boosted object reconstruction ($\sqrt{s} \gg E_{\mathrm{EW}}$)

LHC energies (10^4 GeV) >> electroweak scale (10^2 GeV)



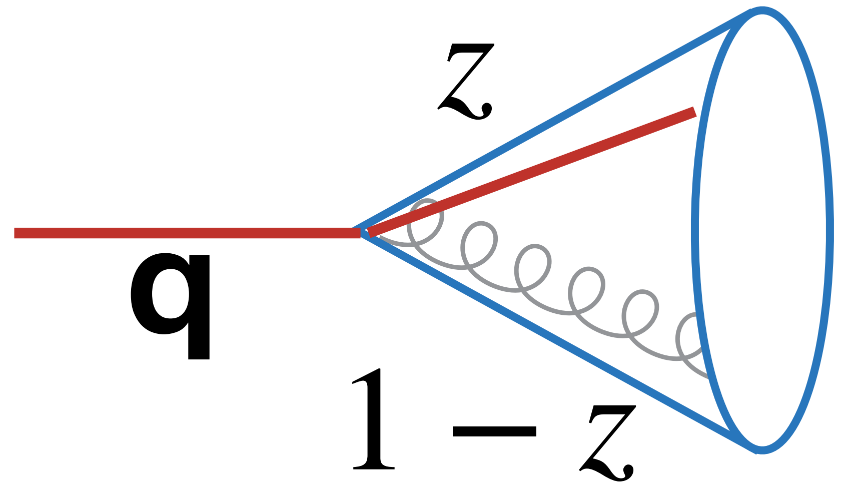
$$\theta \approx \frac{1}{\sqrt{z(1-z)}} \frac{M_X}{p_{T,X}} \quad \text{with} \quad p_{T,X} \gg M_X \quad \text{1 jet}$$

Highly Lorentz-boosted resonances end up reconstructed as a single, large-R jet



Signal

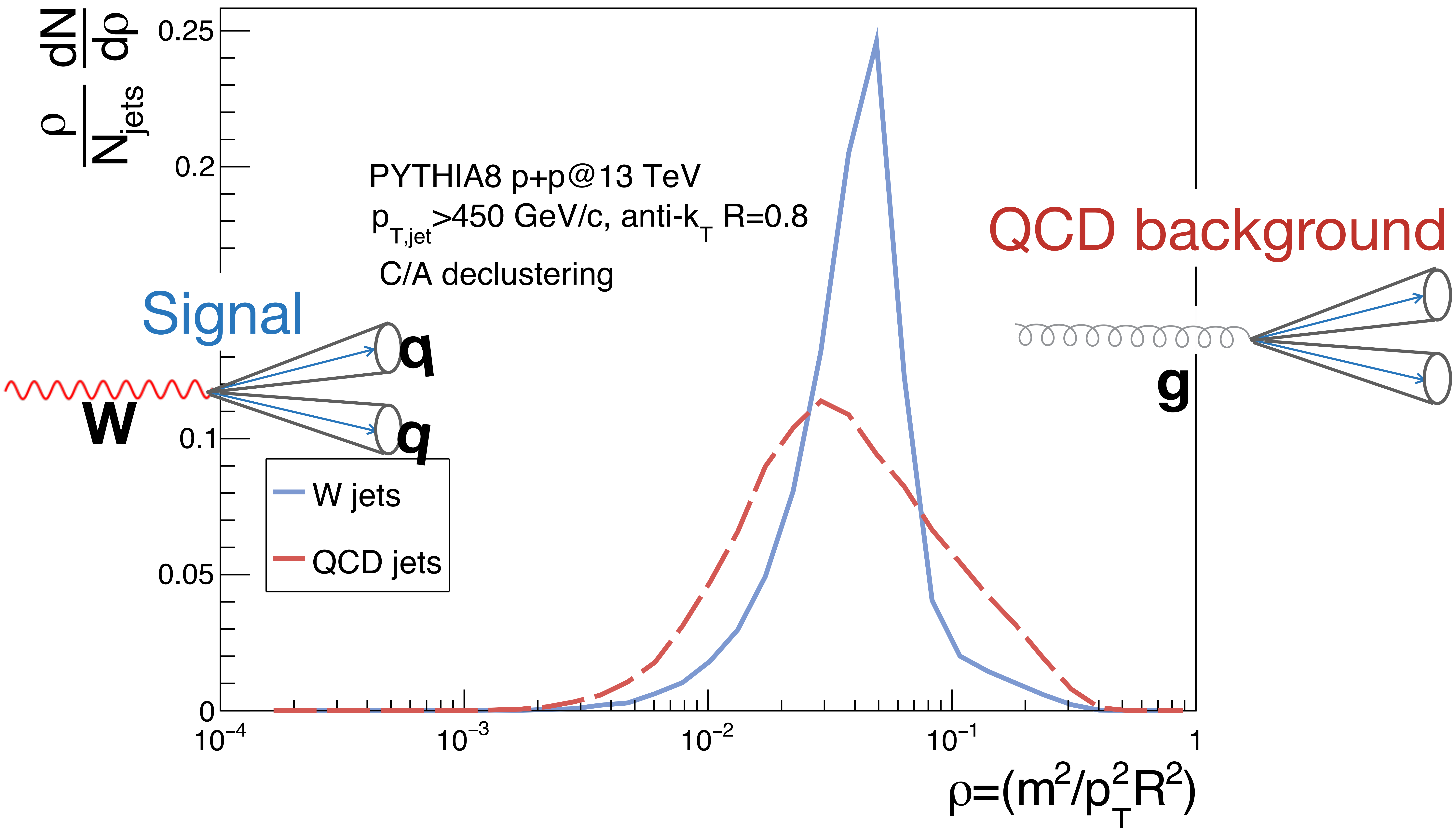
vs



QCD background

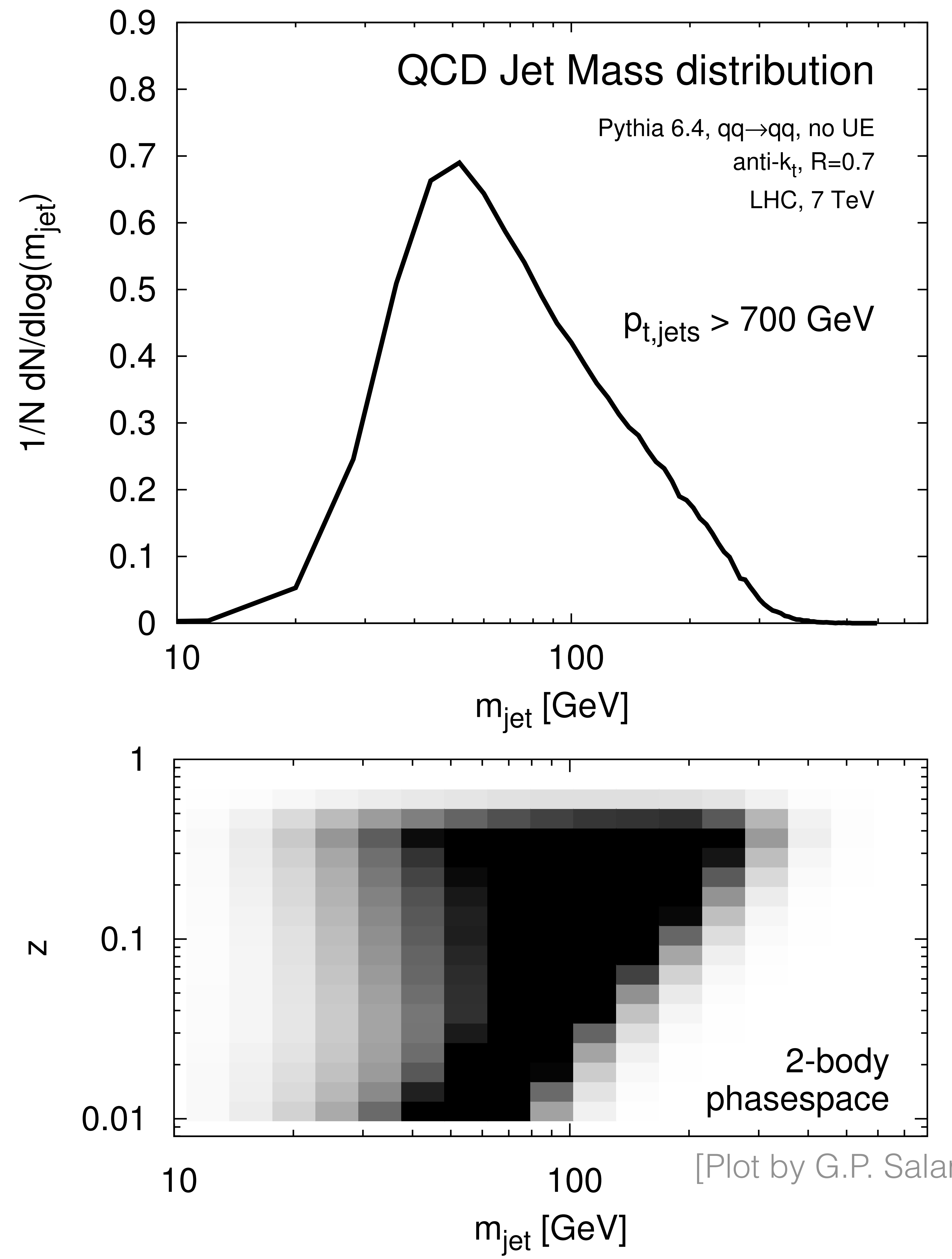
How to distinguish signal jets from QCD background?

Jet mass discriminating power



Not enough to put a cut on the plain jet mass

Idea: exploit substructure



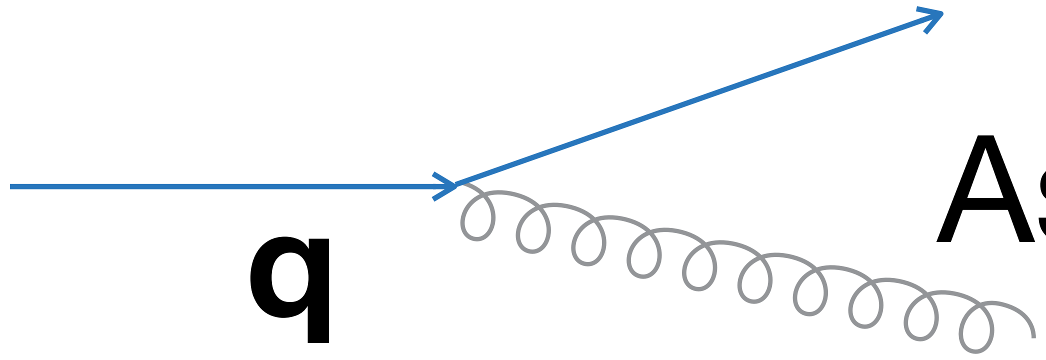
[Plot by G.P. Salam]

$$\rho = \frac{4m^2}{Q^2R^2}$$

$$\int_0^1 dz\left[\frac{P_q(z)}{2C_F} - \frac{1}{z}\right] = -\frac{3}{4}$$

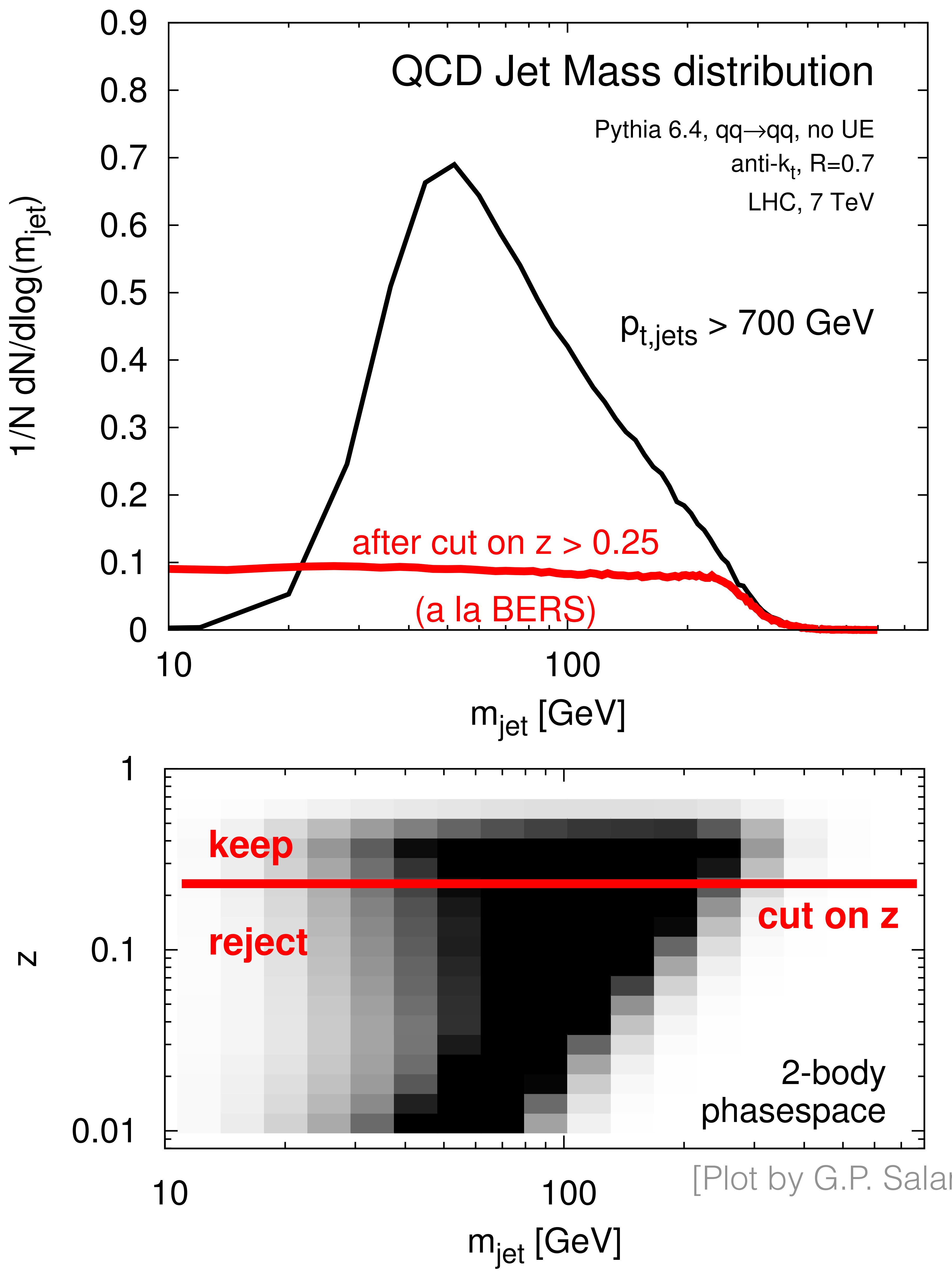
$$\alpha_s \Sigma^{(1)}(\rho) = -\frac{\alpha_s C_F}{\pi}\left[\frac{1}{2}\ln^2\frac{1}{\rho} + B_q \ln\frac{1}{\rho}\right]$$

The logarithmic structure can be traced back to the soft divergence



Asymmetric $P_{q\to qg}(z)$

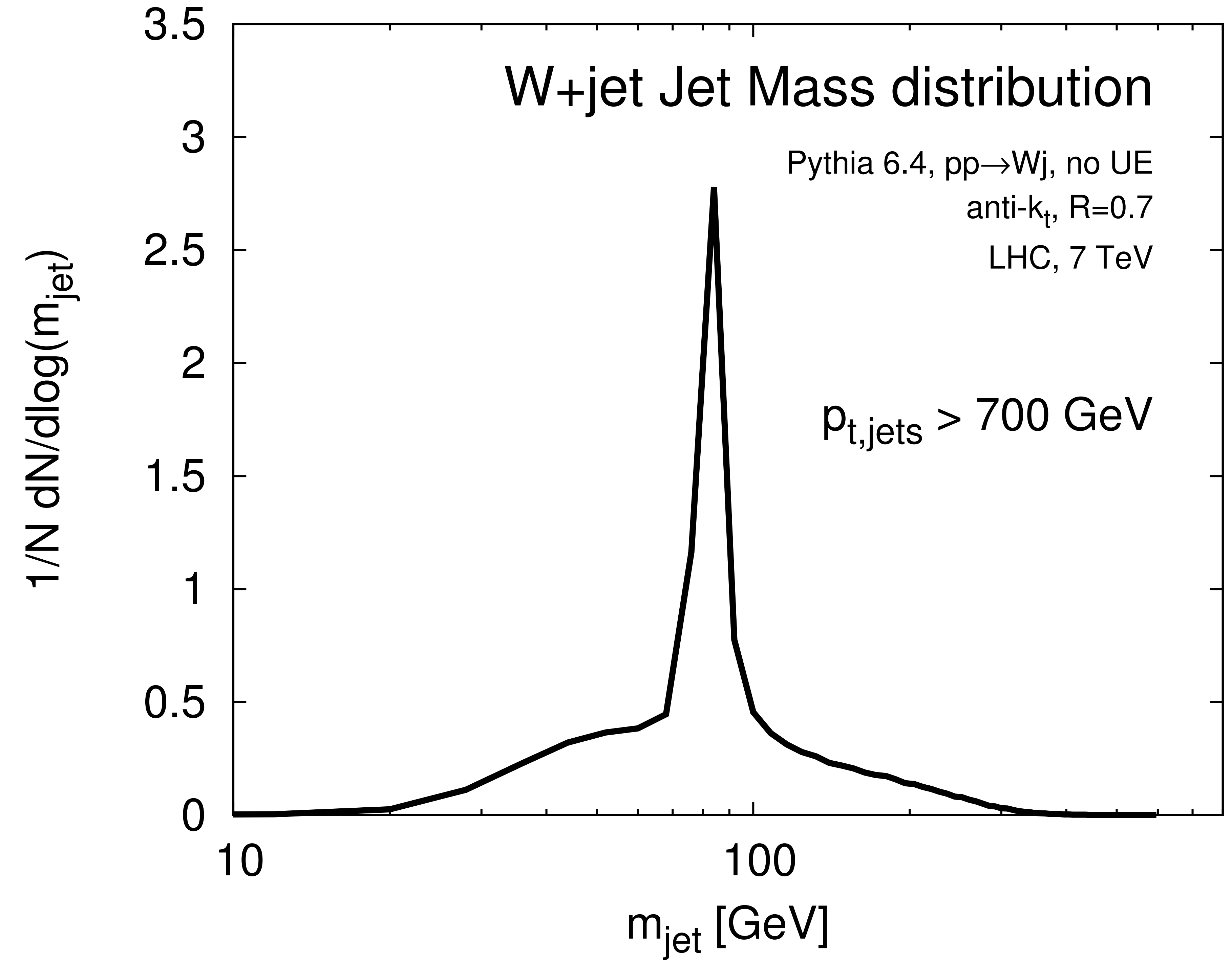
Idea: exploit substructure

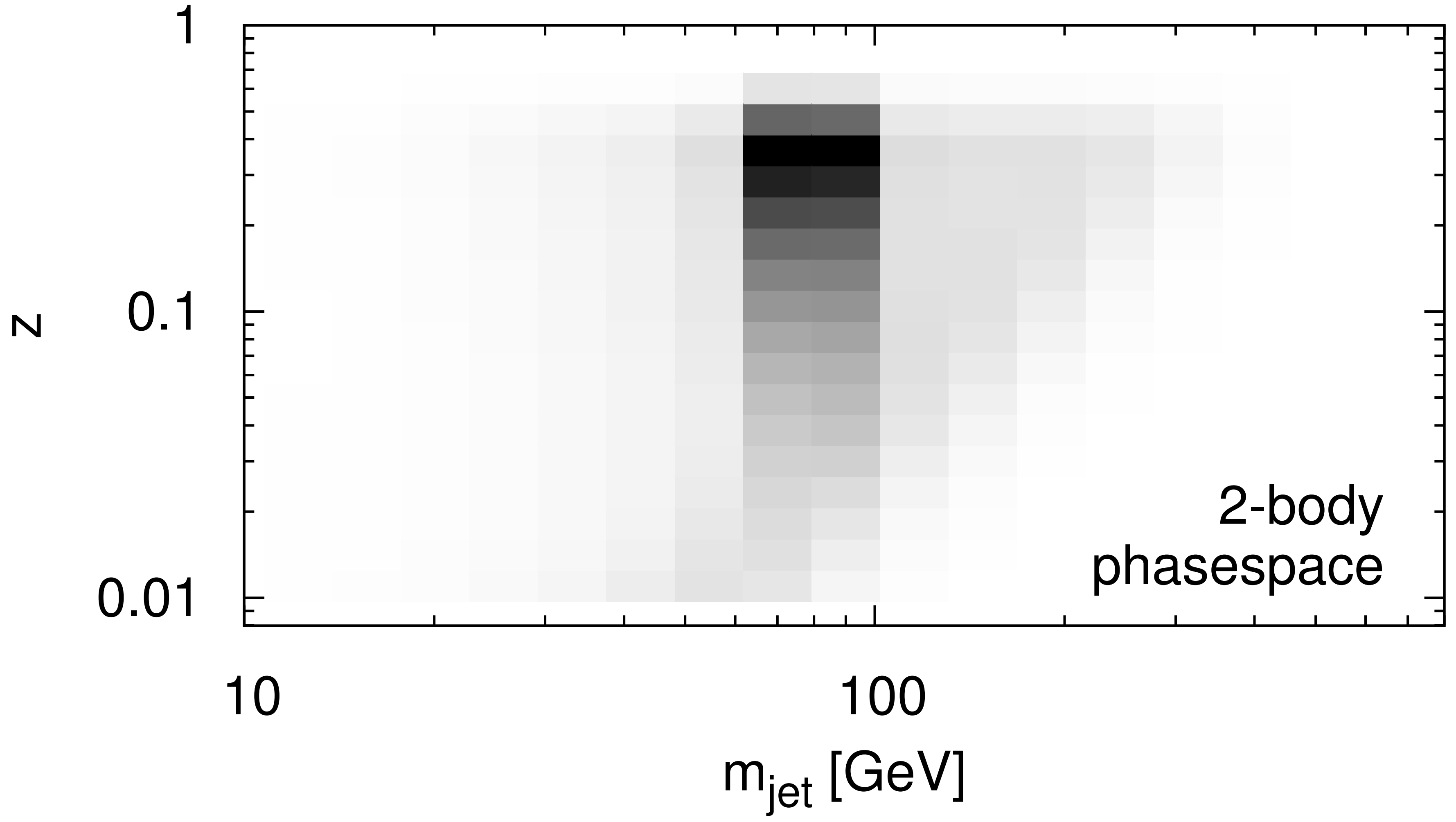


[Plot by G.P. Salam]

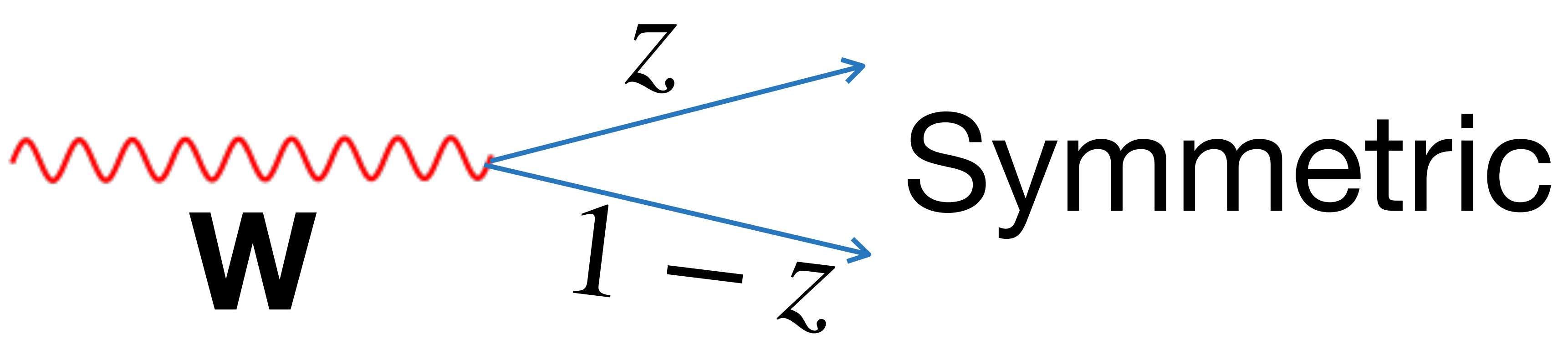
A hard cut on z reduces QCD background and simplifies it shape

Idea: exploit substructure





$$\rho_X = \frac{m_X^2}{p_t^2 R^2} = z(1-z)\,\theta_1^2$$



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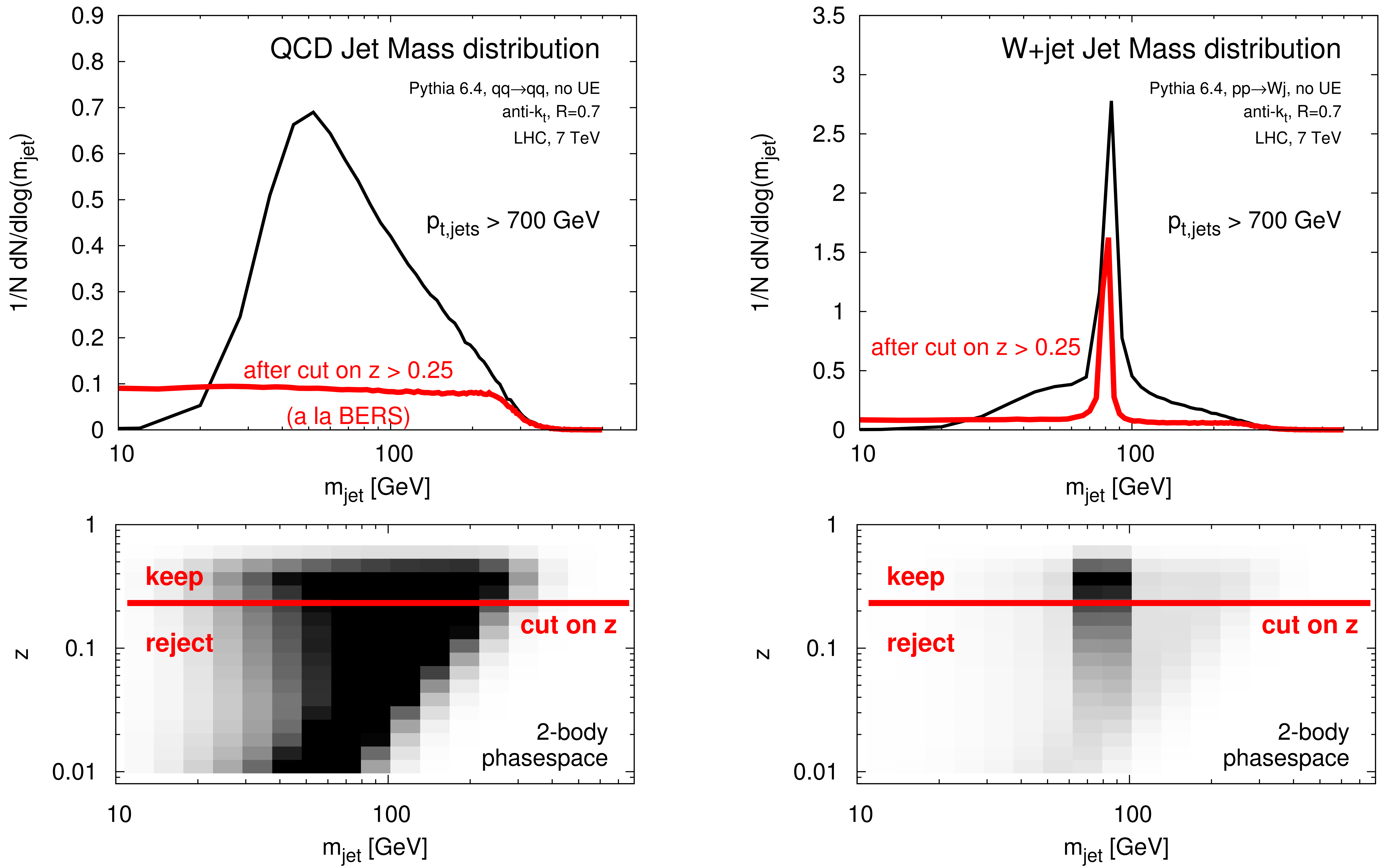

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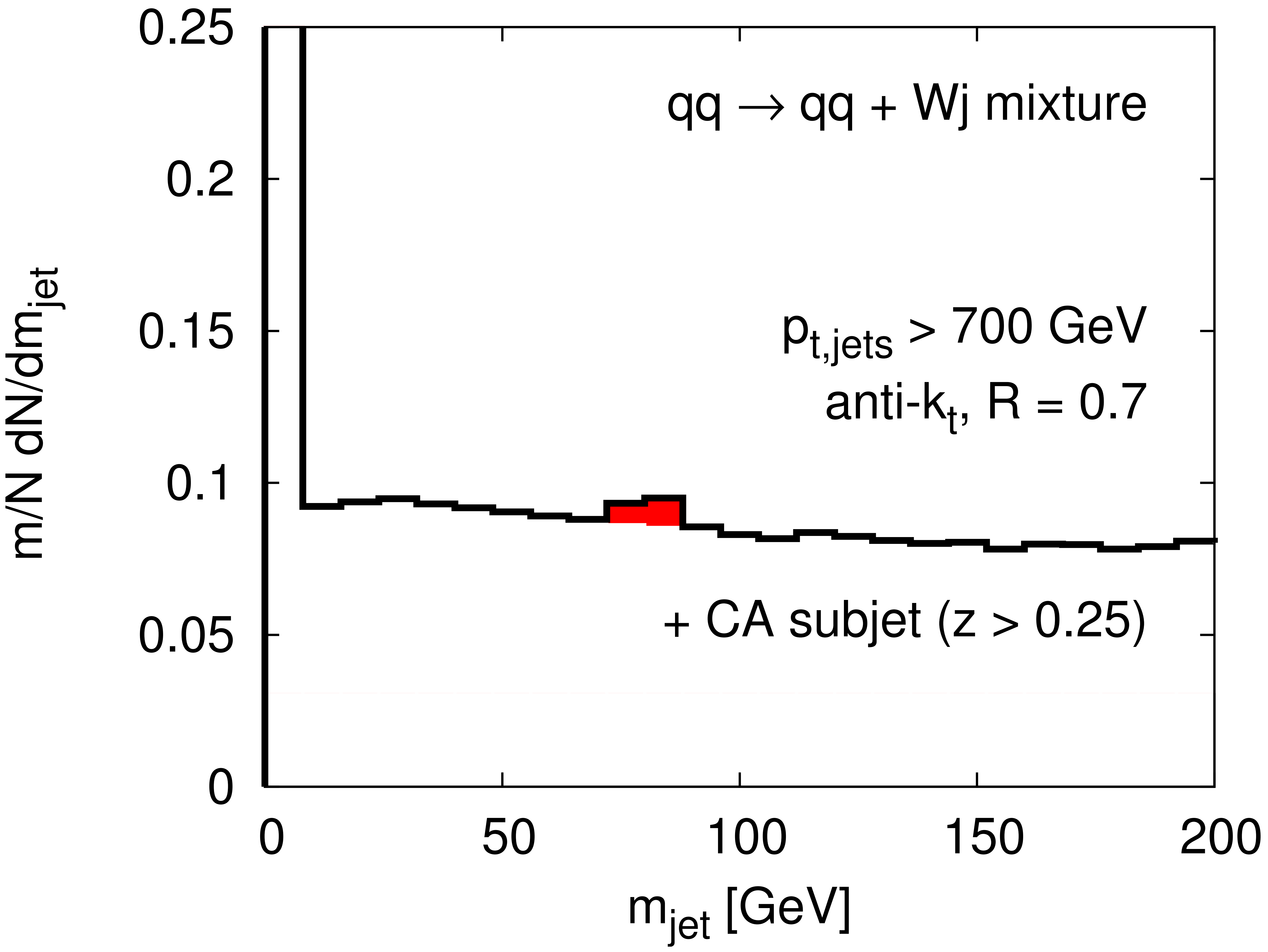
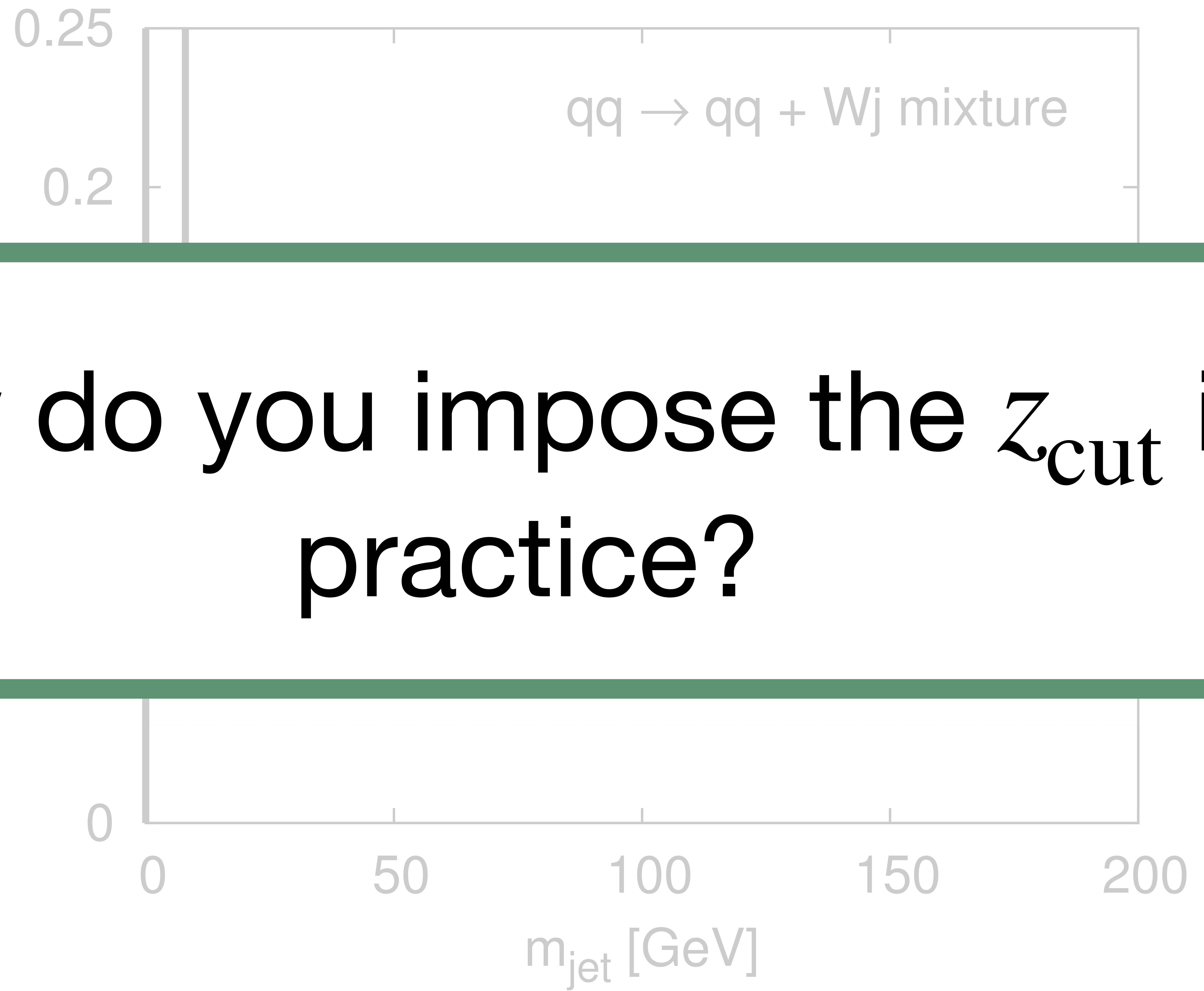


Cut on jet substructure enables bump hunting

Idea: exploit substructure



How do you impose the $z_{\rm cut}$ in practice?

Cut on jet substructure enables bump hunting

Grooming (using SoftDrop as an example) experimentally

[Larkoski et al JHEP 05 (2014) 146]

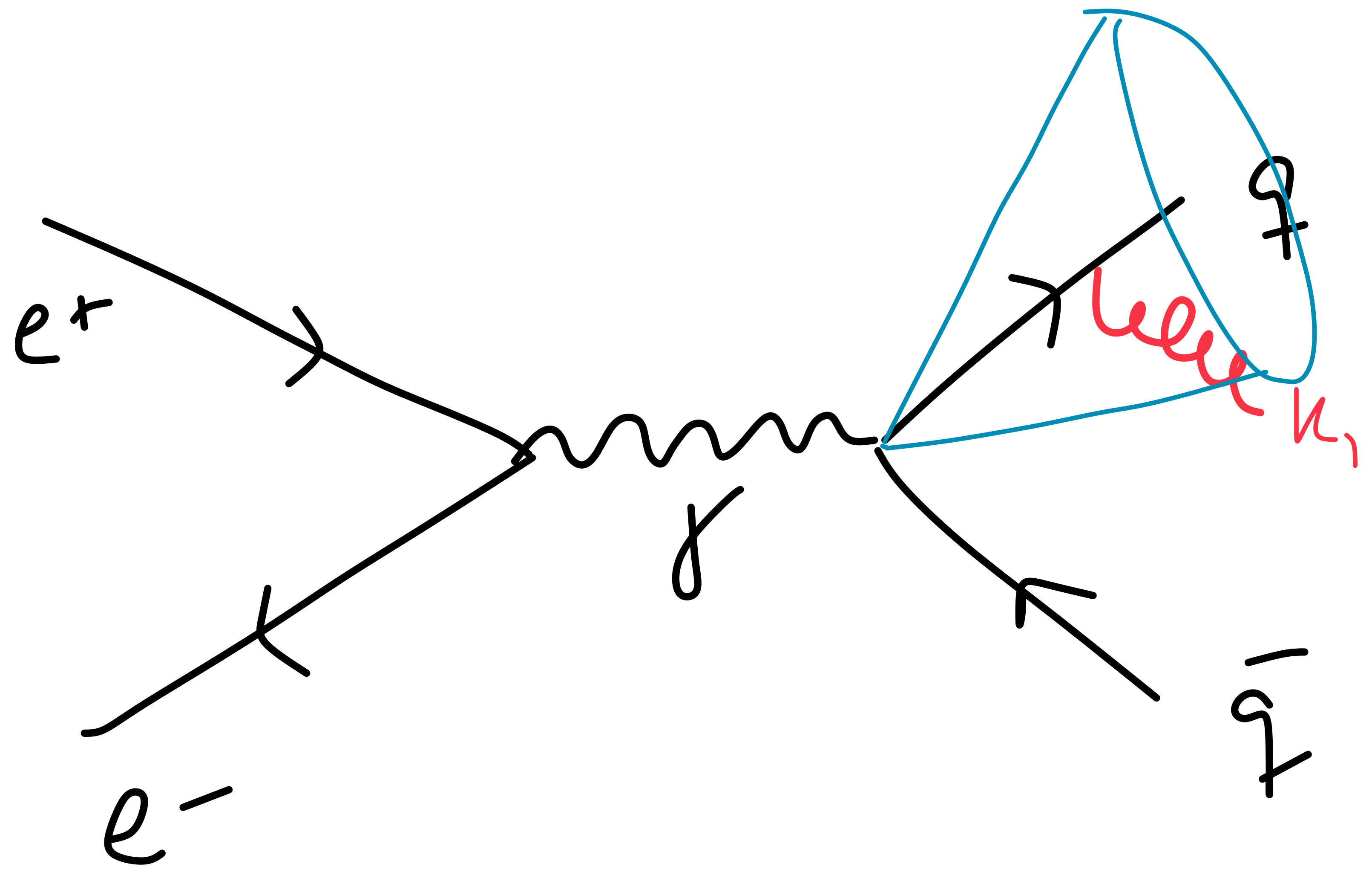
- Recluster anti-k_t jet with C/A algorithm: angular ordered sequence
- Undo last clustering step, i.e. pair of subjets with largest angle

$z = \min(p_{t1}, p_{t2})$

- Check SoftDrop condition: $z > z_{cut}\,\theta^{\beta}$, (z_{cut}, β) ~ free parameters
  - If branch point satisfies the condition, stop
  - Else, remove the softer branch and continue down the hard branch

Net effect for $\beta = 0$ is to remove soft radiation from the jet

Grooming (using SoftDrop as an example) theoretically



Definitions: $m^2 = \left(\sum_{i \in jet} k_i\right)^2$; $\Sigma(m^2) = \frac{1}{\sigma}\int_0^{m^2} dm'^2 \frac{d\sigma}{dm'^2} = 1 + \alpha_s \Sigma^{(1)} + \mathcal{O}(\alpha_s^2)$

Soft limit: $|M_R|^2 = \frac{\alpha_s}{2\pi}(2C_F)\frac{k_1\cdot k_2}{(k_1\cdot k_3)(k_2\cdot k_3)}$

$k_1 = \frac{Q}{2}(1,0,0,1)$

$k_2 = \frac{Q}{2}(1,0,0,-1)$

$k_3 = \omega(1, \sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$

Phase-space: $\int d\Phi = \int_0^\infty \omega\, d\omega \int_{-1}^{1} d\cos\theta \int_0^{2\pi} \frac{d\phi}{2\pi}$

$$\alpha_s \Sigma^{(1)}(m^2) = \int_{-1}^{1} d\cos\theta \int_0^{2\pi}\frac{d\phi}{2\pi}\int_0^{Q/2}\omega\, d\omega\, \frac{2C_F\alpha_s}{\pi}\frac{1}{\omega^2(1-\cos\theta)(1+\cos\theta)}$$

$$\times\left[\Theta_{in\text{-}jet}\,\Theta\left(\frac{2Q\omega}{2}(1-\cos\theta) < m^2\right)\Theta\left(z > z_{cut}\left(\frac{\theta}{R}\right)^\beta\right) + \Theta_{out\text{-}jet} - 1\right]$$

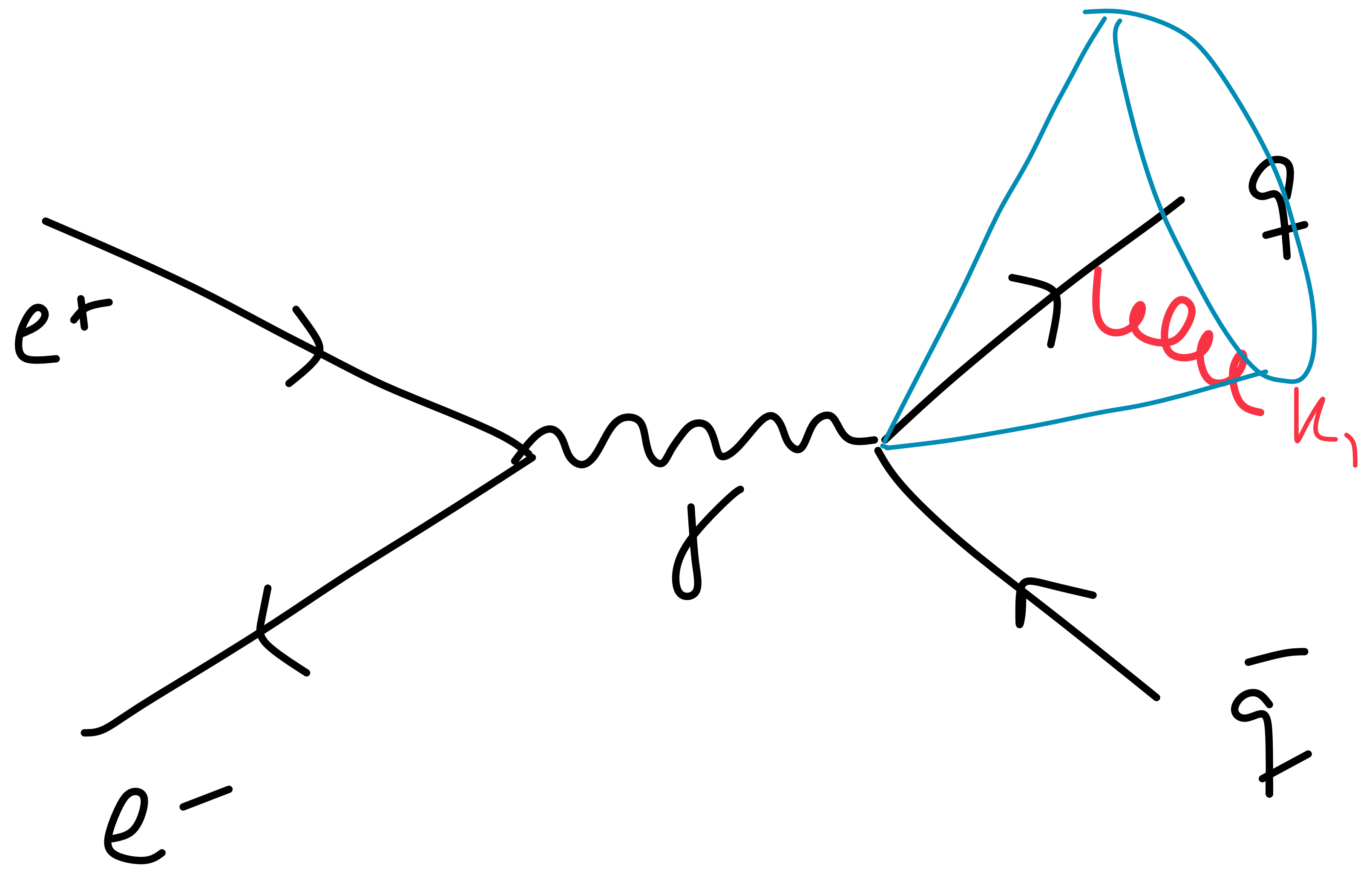
$\Theta_{in\text{-}jet}$: $\Theta(1-\cos\theta < 1-\cos R)$

$z = \frac{\omega}{p_t}$

$\Theta_{out\text{-}jet}$: $1 - \Theta_{in\text{-}jet}$

-1: virtual

Grooming (using SoftDrop as an example) theoretically



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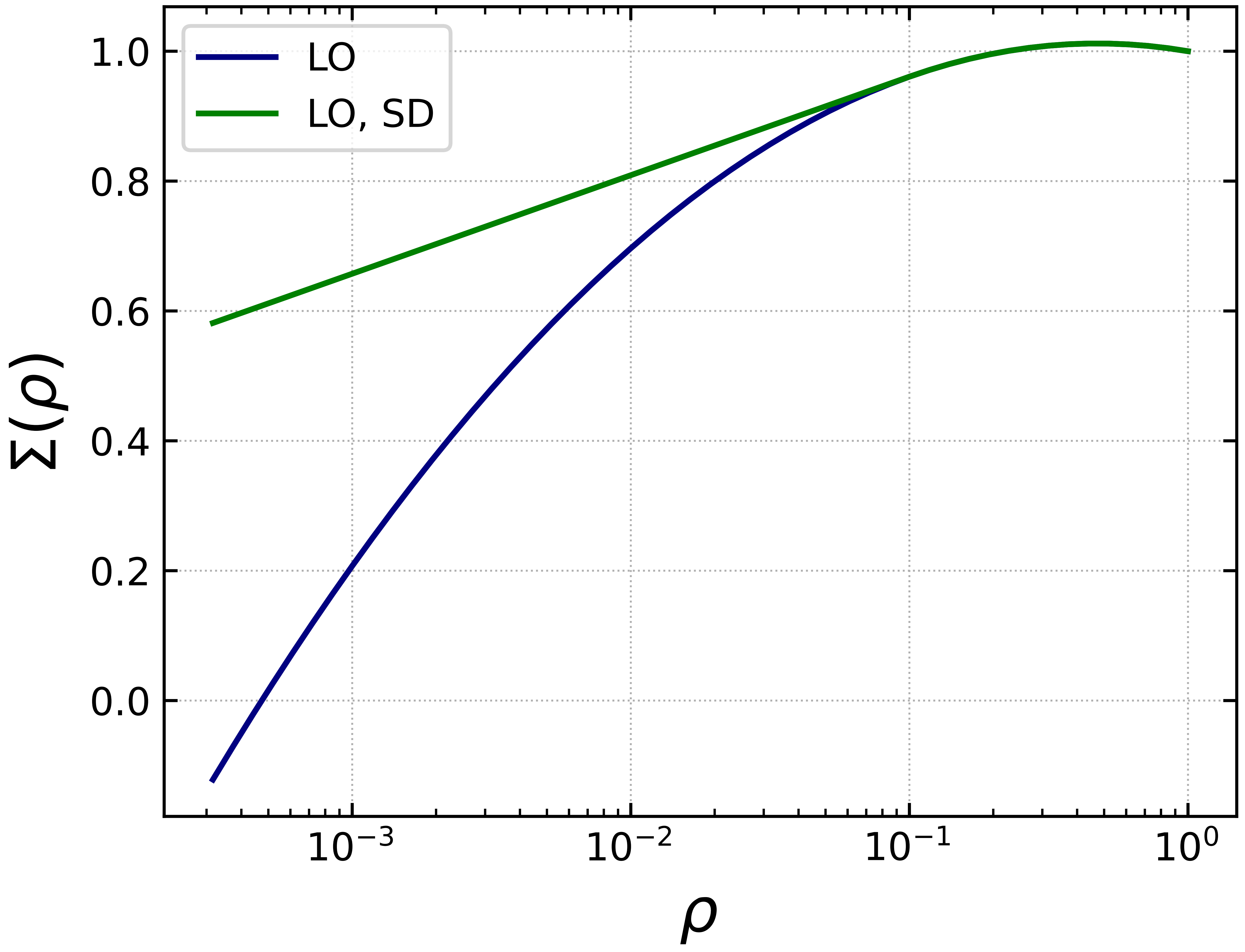
$$\Sigma_{SD}^{(LO)}(\rho) = \begin{cases} 1 - \frac{\alpha_s C_F}{\pi}\left[\frac{1}{2}\ln^2\left(\frac{1}{\rho}\right) - \frac{3}{4}\ln\left(\frac{1}{\rho}\right)\right], & \text{if } \rho > z_{cut} \\ 1 - \frac{\alpha_s C_F}{\pi}\left[\frac{1}{2}\ln^2\left(\frac{1}{\rho}\right) - \underbrace{\frac{1}{2+\beta}\ln^2\left(\frac{z_{cut}}{\rho}\right)}_{\text{for } \beta=0\text{, no doble-log divergence}} - \frac{3}{4}\ln\left(\frac{1}{\rho}\right)\right], & \text{if } \rho < z_{cut} \end{cases}$$

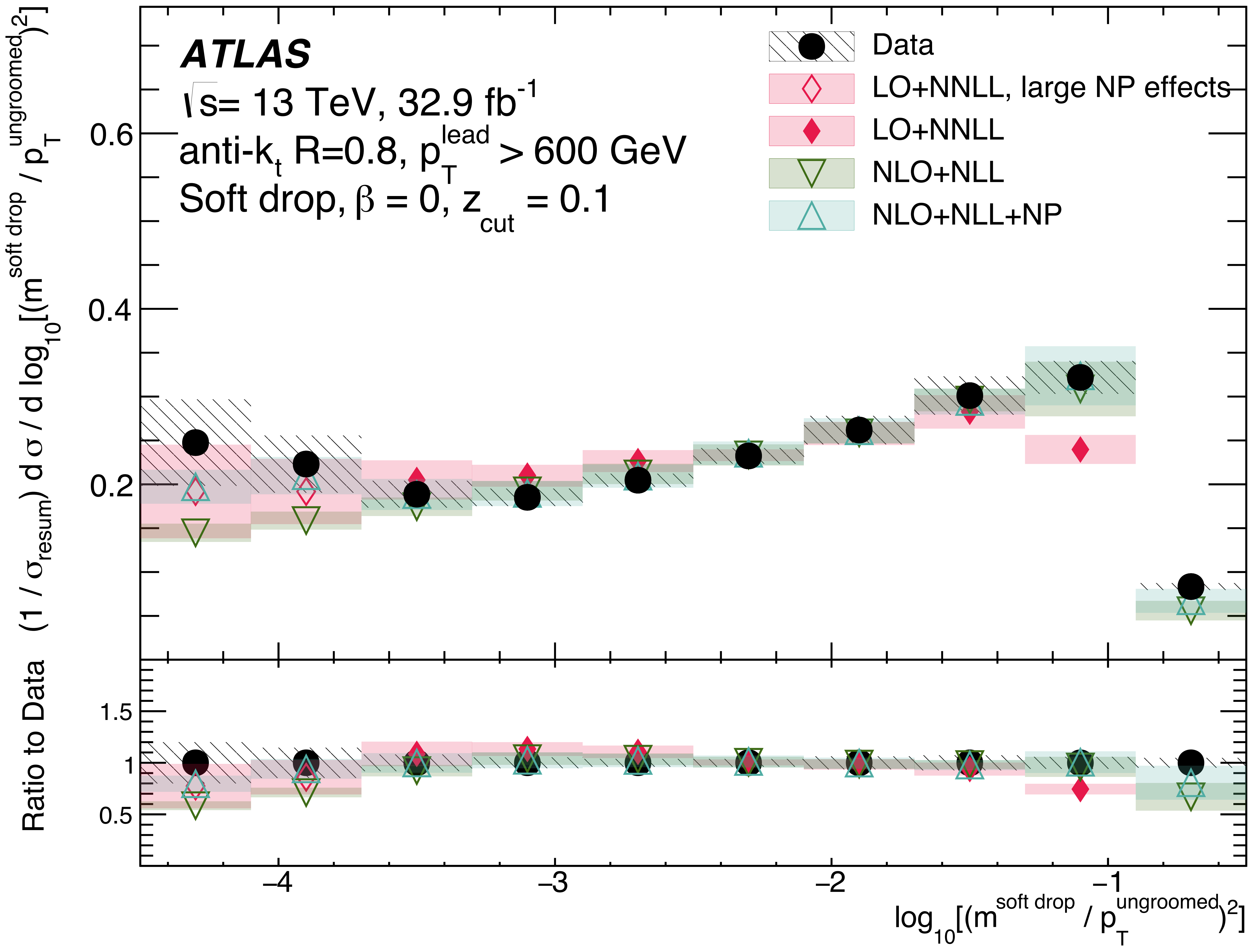
Grooming (using SoftDrop as an example) theoretically



SoftDrop becomes active when $\rho < z_{\text{cut}}$

Grooming: theory meets experiment

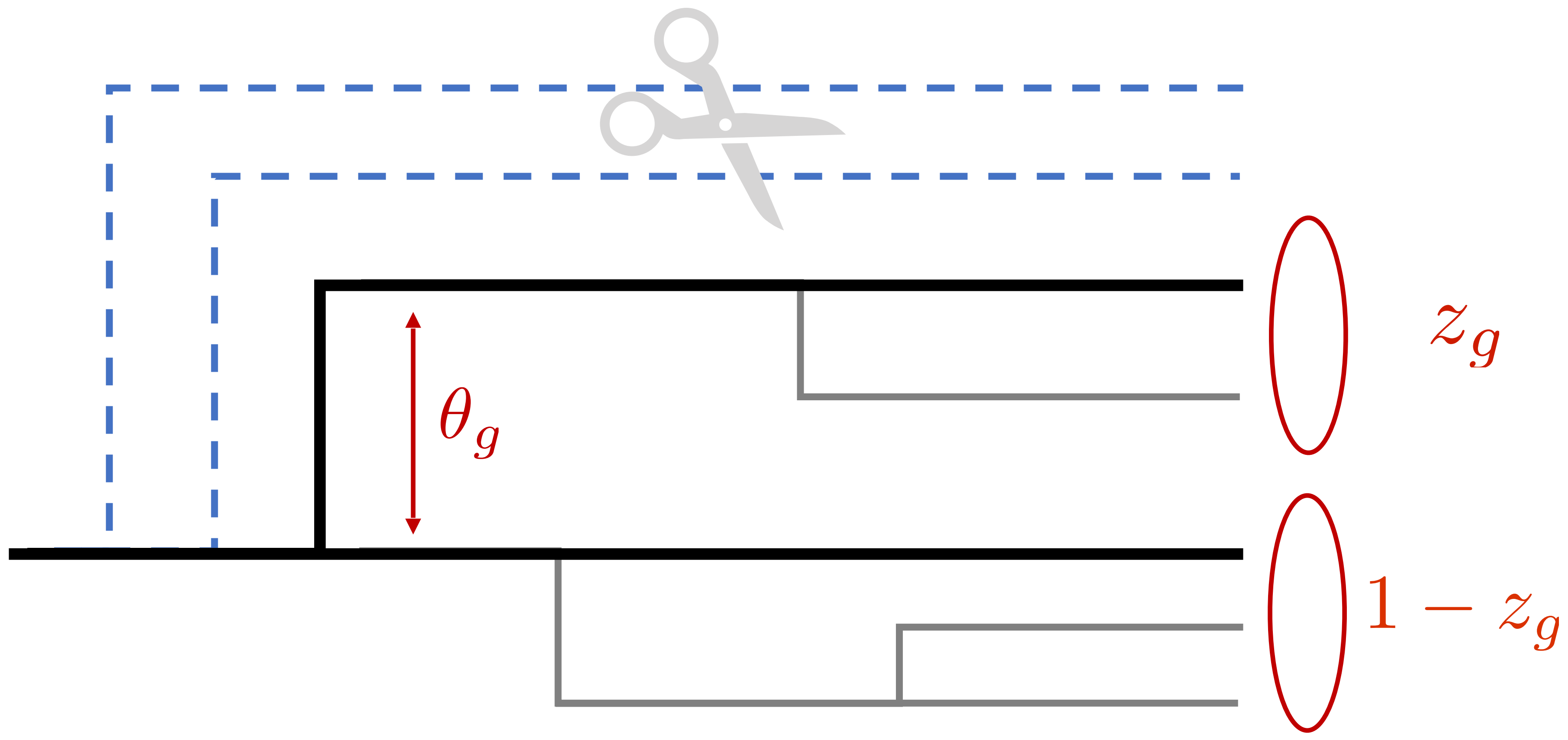
[Calculation: Frye et al JHEP 07 (2016) 064] [Data: ATLAS Collab PRL 121 (2018) 092001]

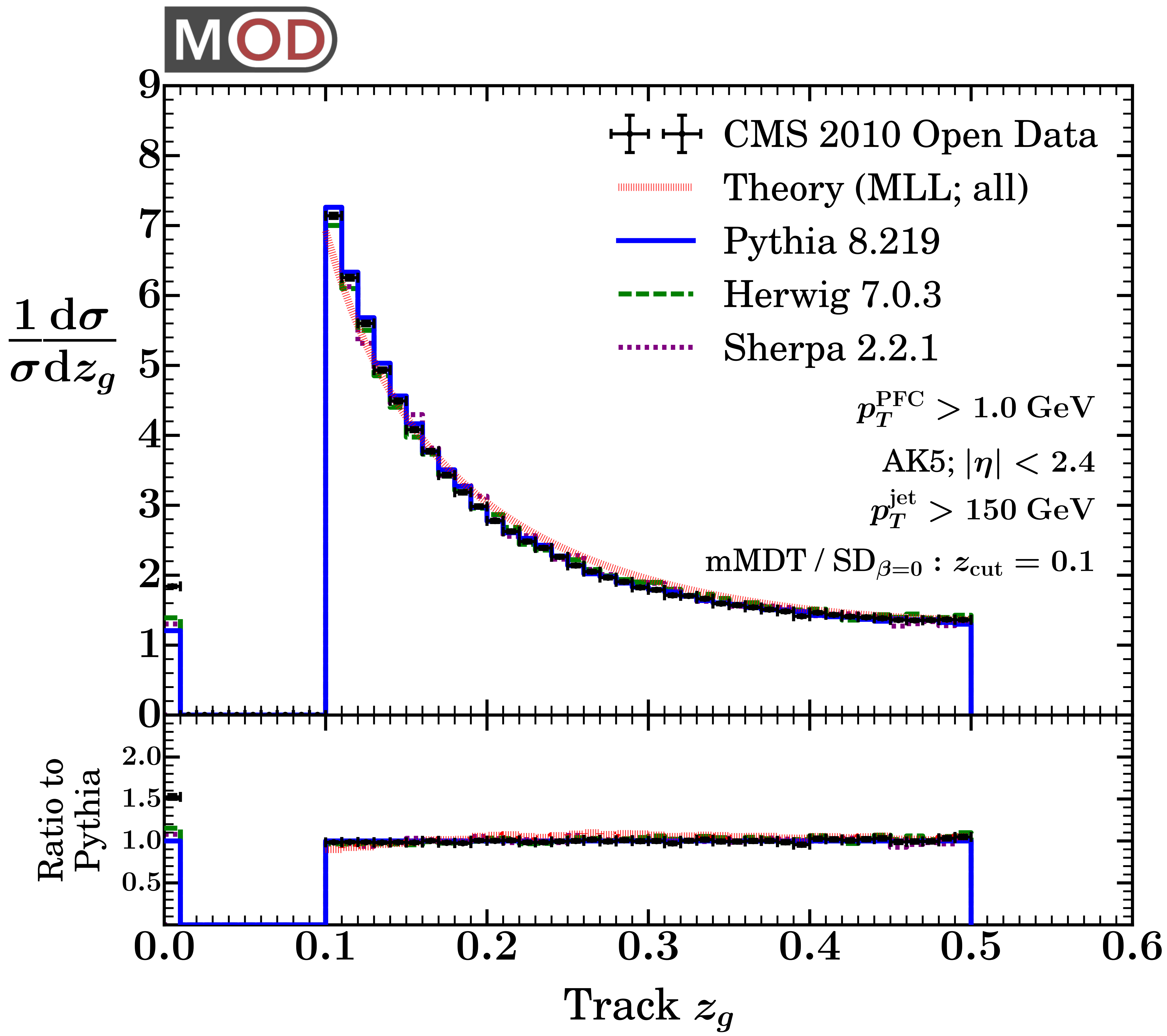


Amazing agreement (% level) between pQCD and data

Another interesting SoftDrop observable: z_g

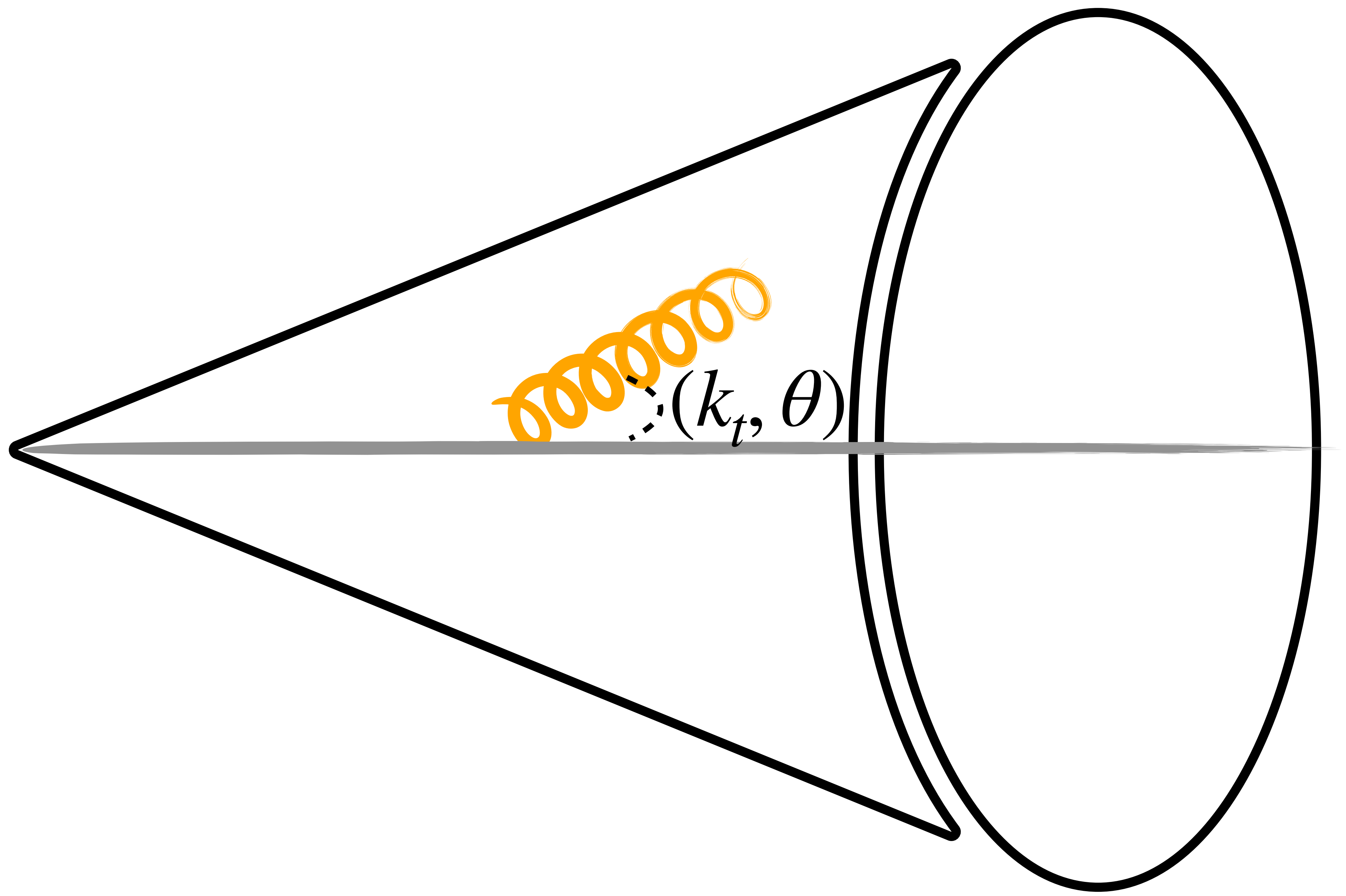
[Larkoski et al PRL 119 (2017) 13, 132003]



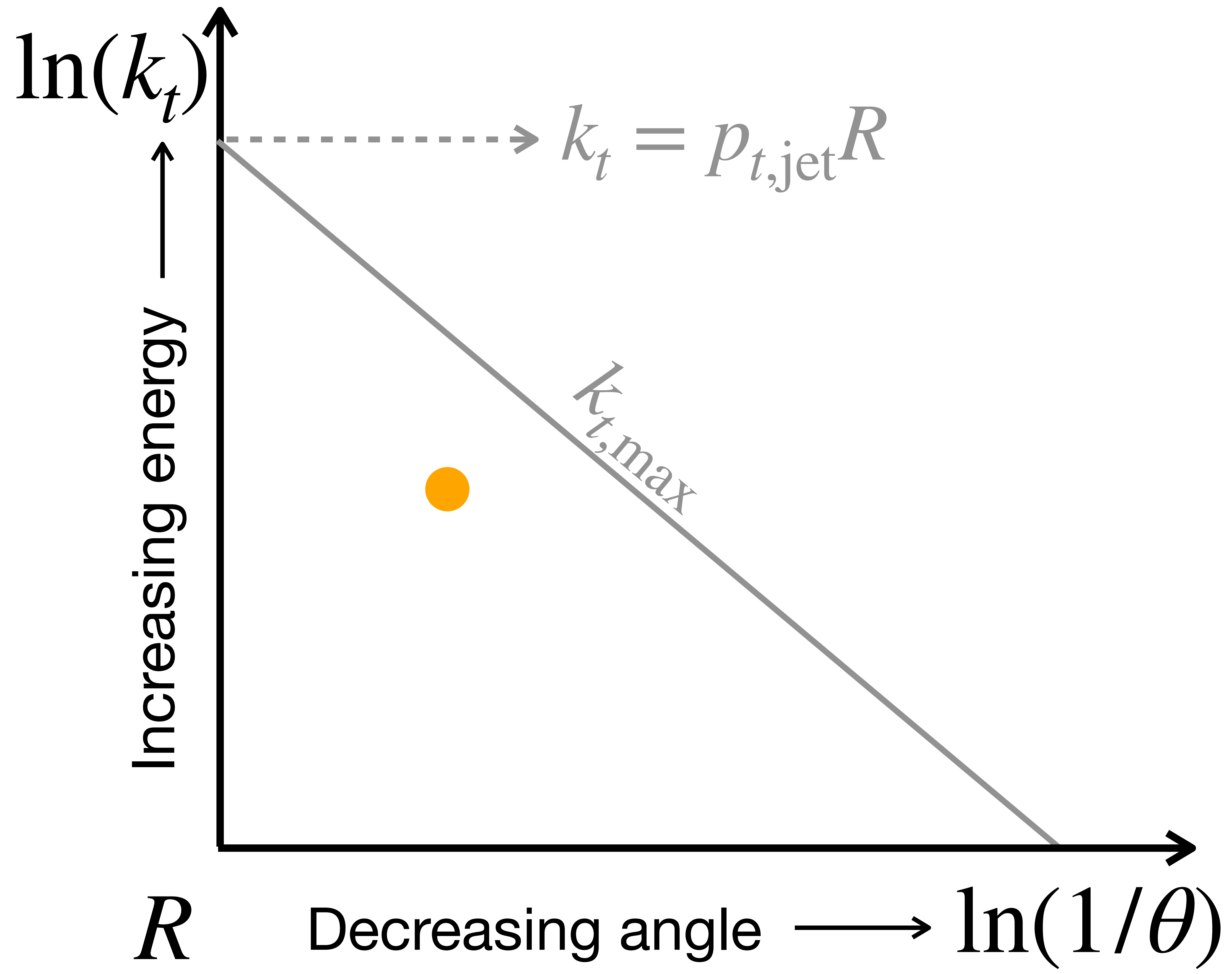


Exposing the QCD splitting function with jet substructure

THE substructure observable: the Lund jet plane

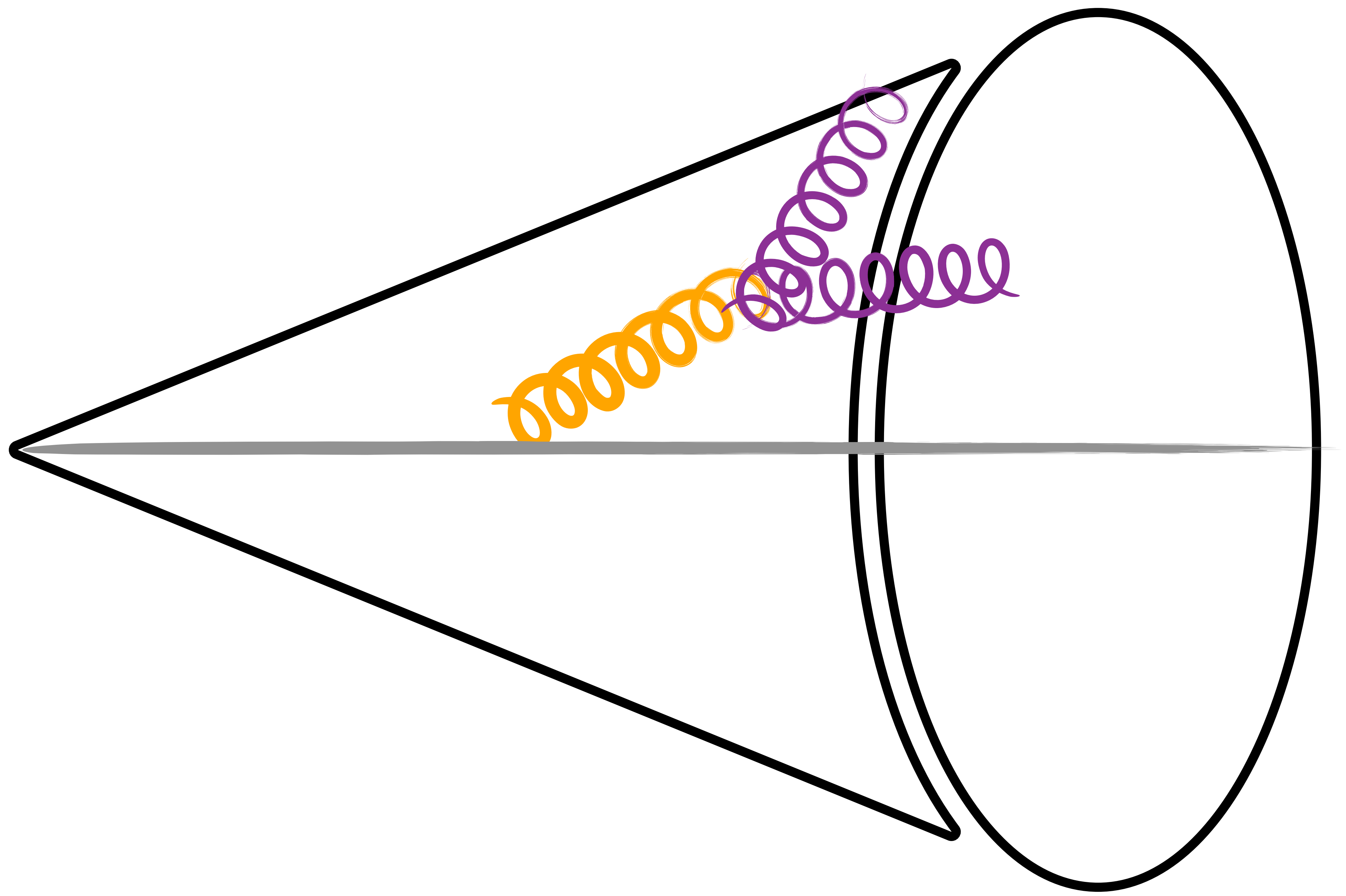


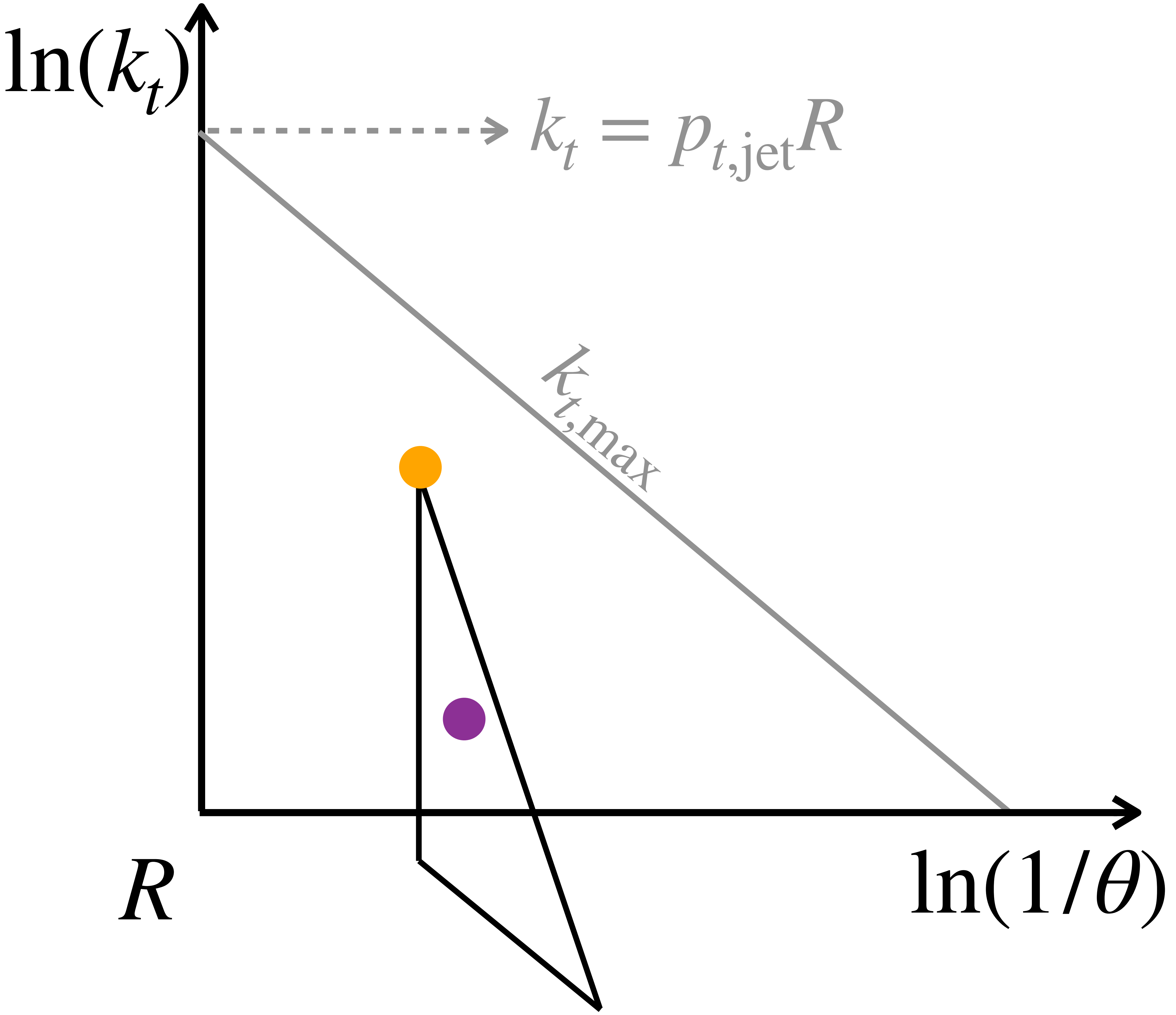
C/A reclustered jet



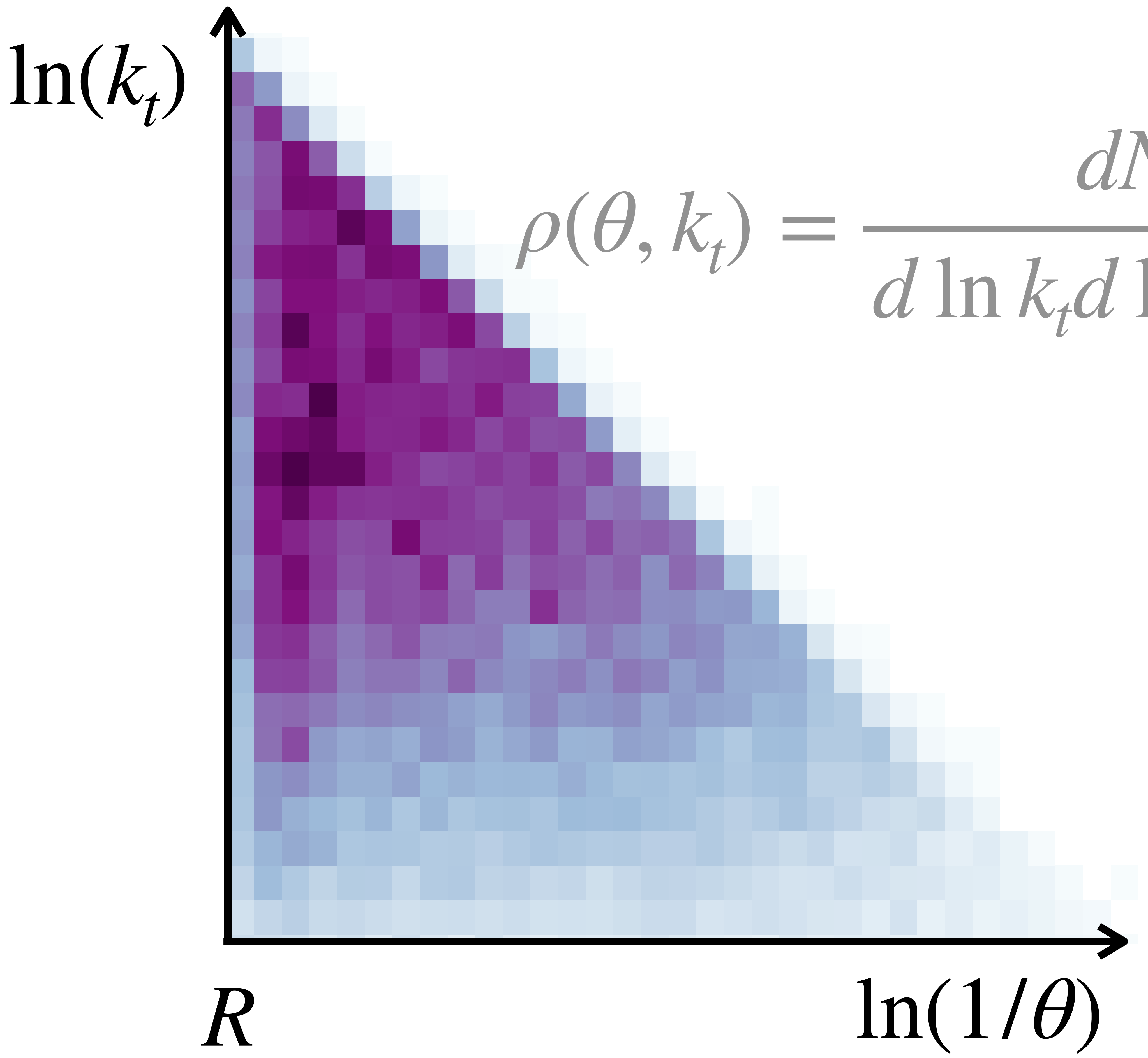
$k_t = z p_{t,\text{jet}} \theta$

THE substructure observable: the Lund jet plane





The primary Lund-plane density



$$\rho(\theta, k_t) = \frac{dN}{d\ln k_t d\ln(1/\theta)}$$

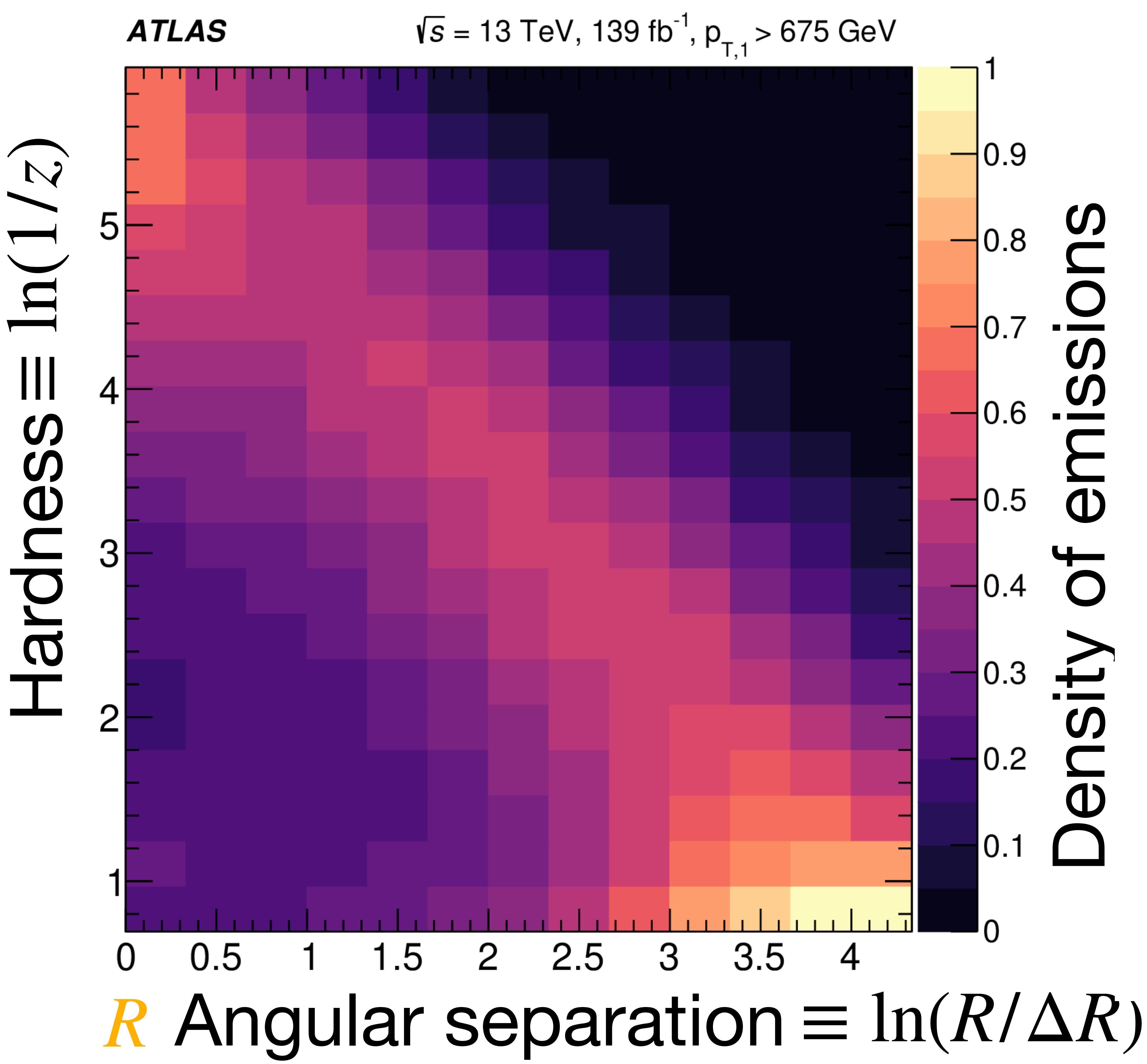
[Lifson, Salam, Soyez JHEP 10 (2020) 170]

In the soft-and-collinear limit

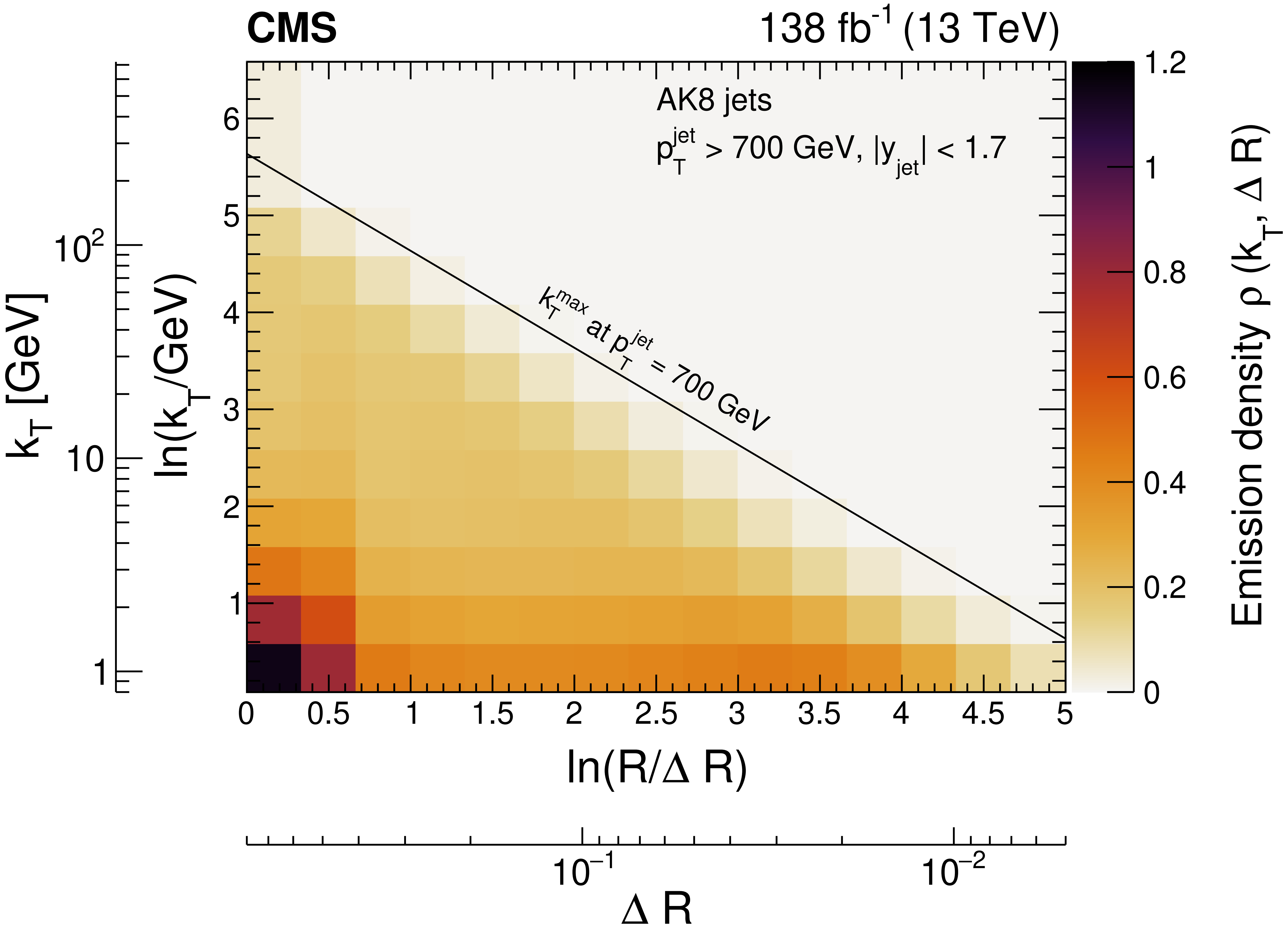
$$\rho_{\mathrm{LO}}(\theta, k_t) = \frac{2\alpha_s C_i}{\pi}$$

The primary Lund-plane density: measurements

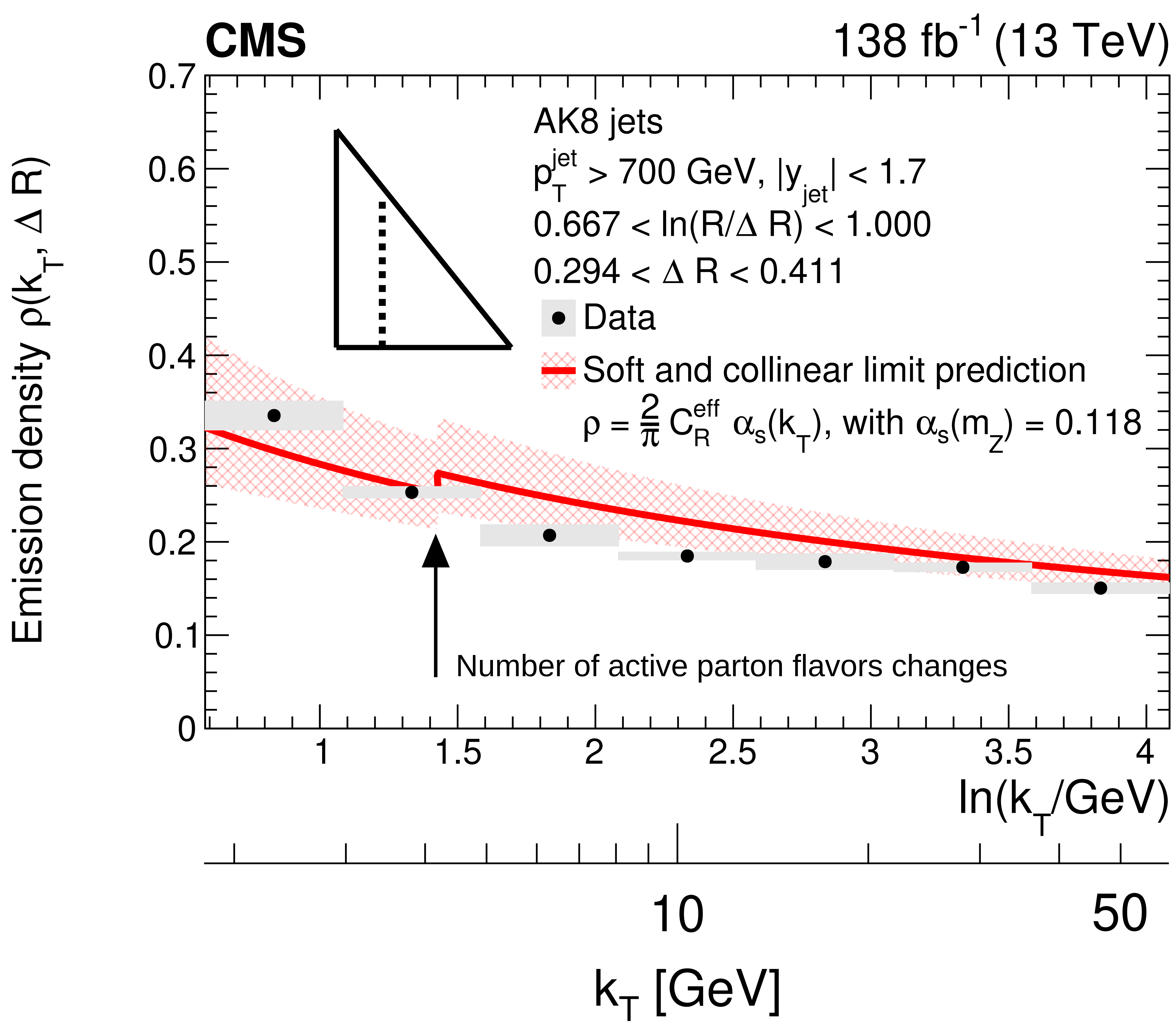
[ATLAS PRL 124 (2020) 22, 222002]

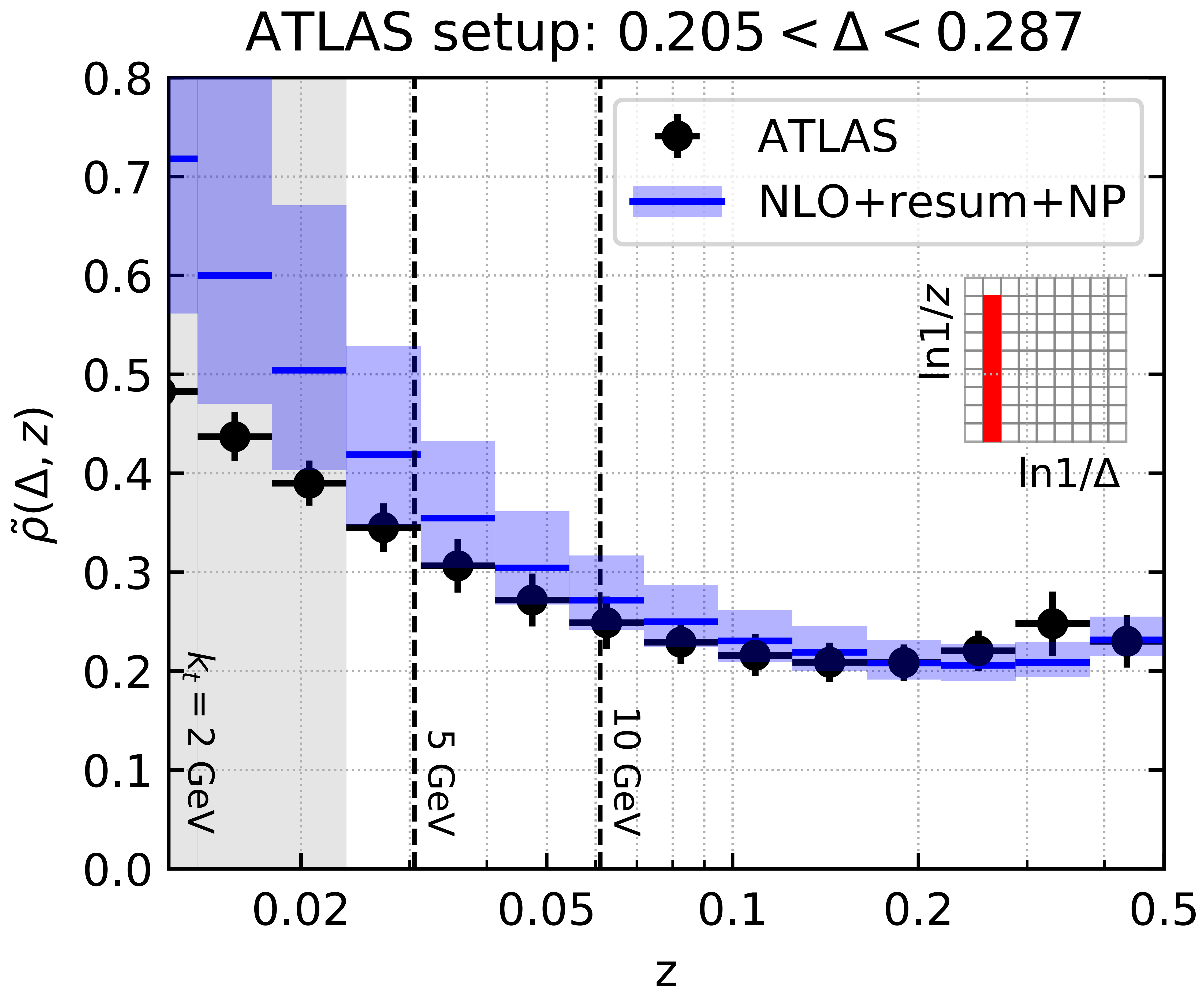


[CMS JHEP 05 (2024) 116]



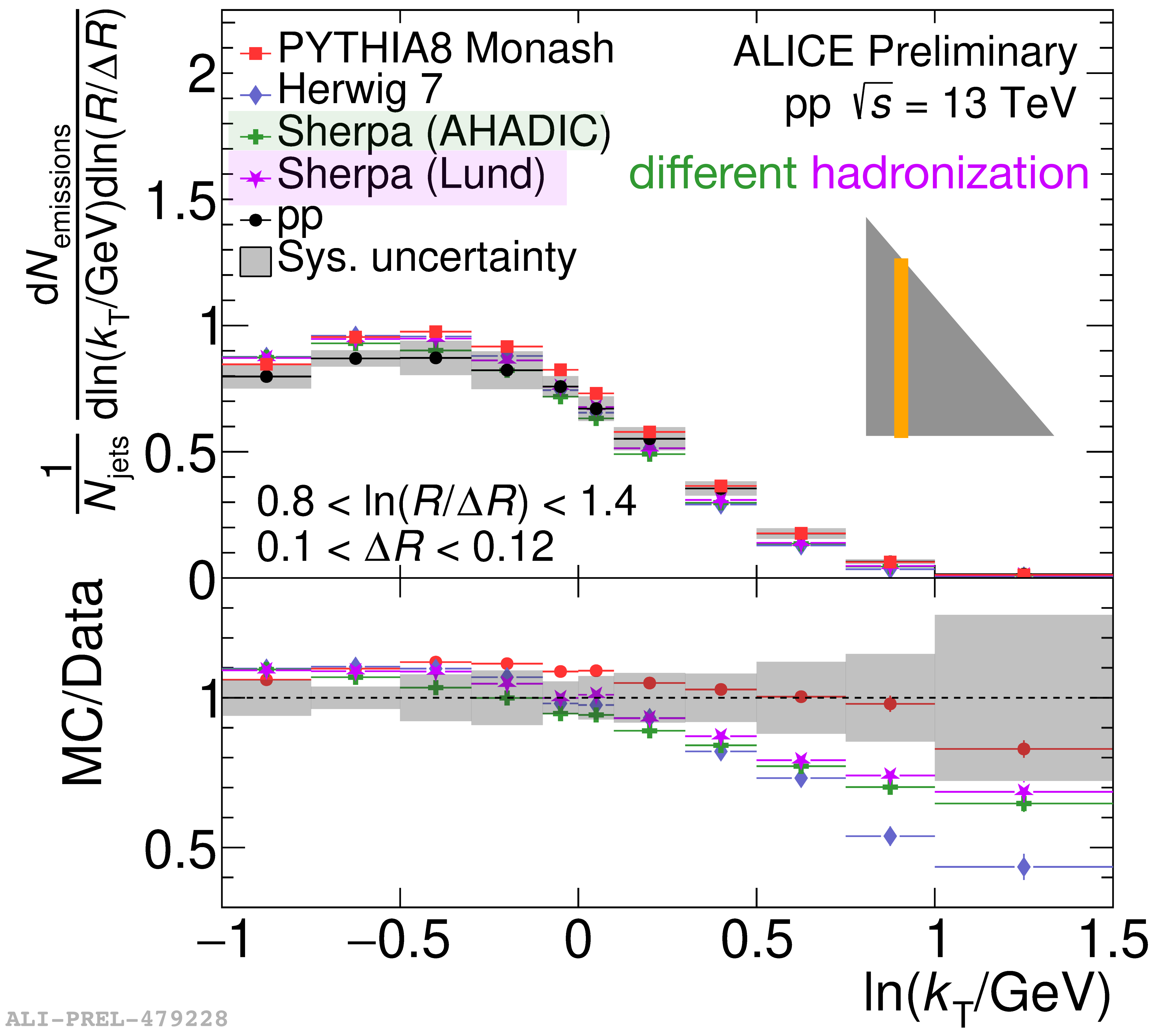
The primary Lund-plane density: theory-to-data

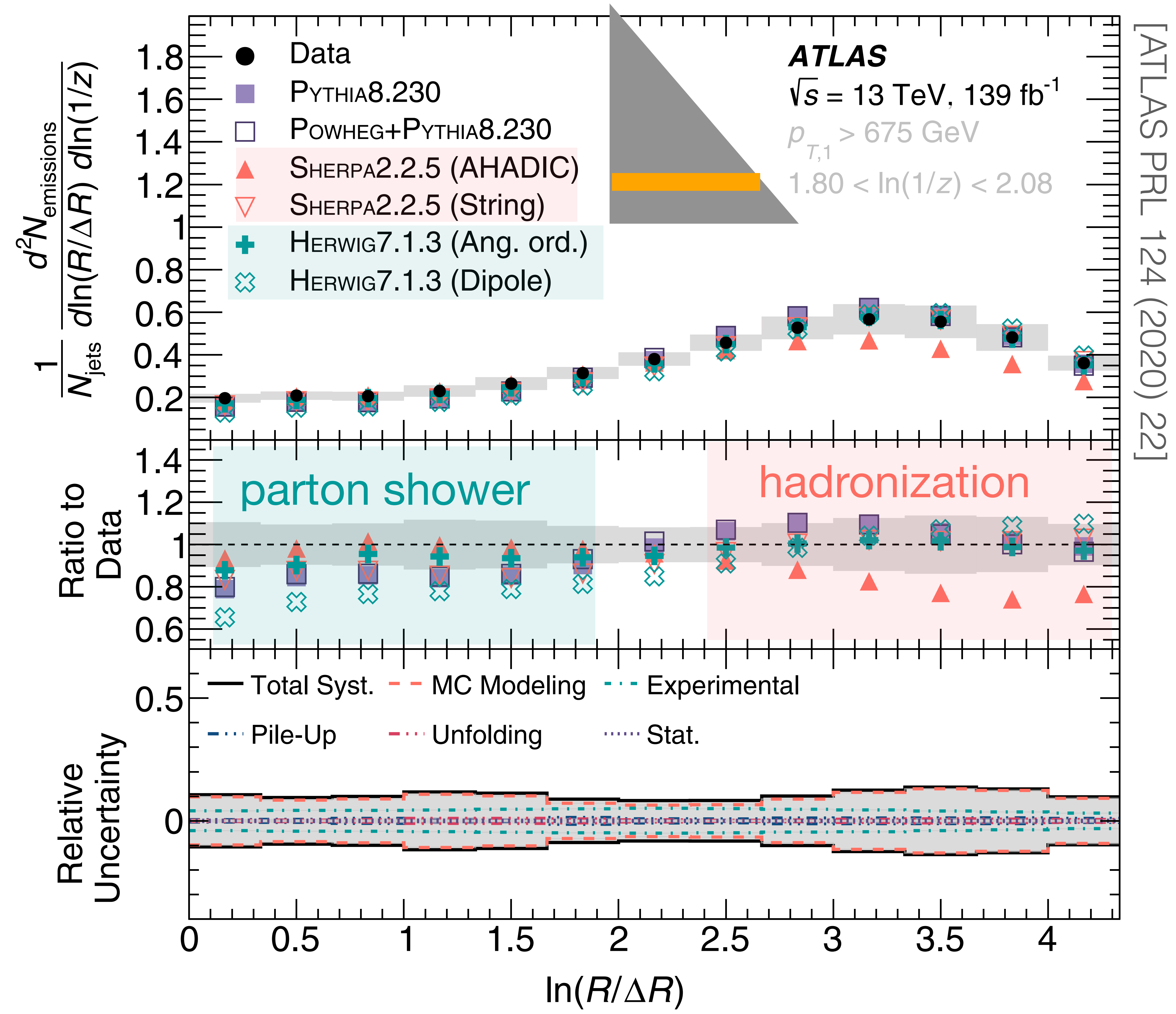




$\rho_{\rm LO}(\theta, k_t)$ agrees with data in bulk of LP. N^{k}LL terms required elsewhere

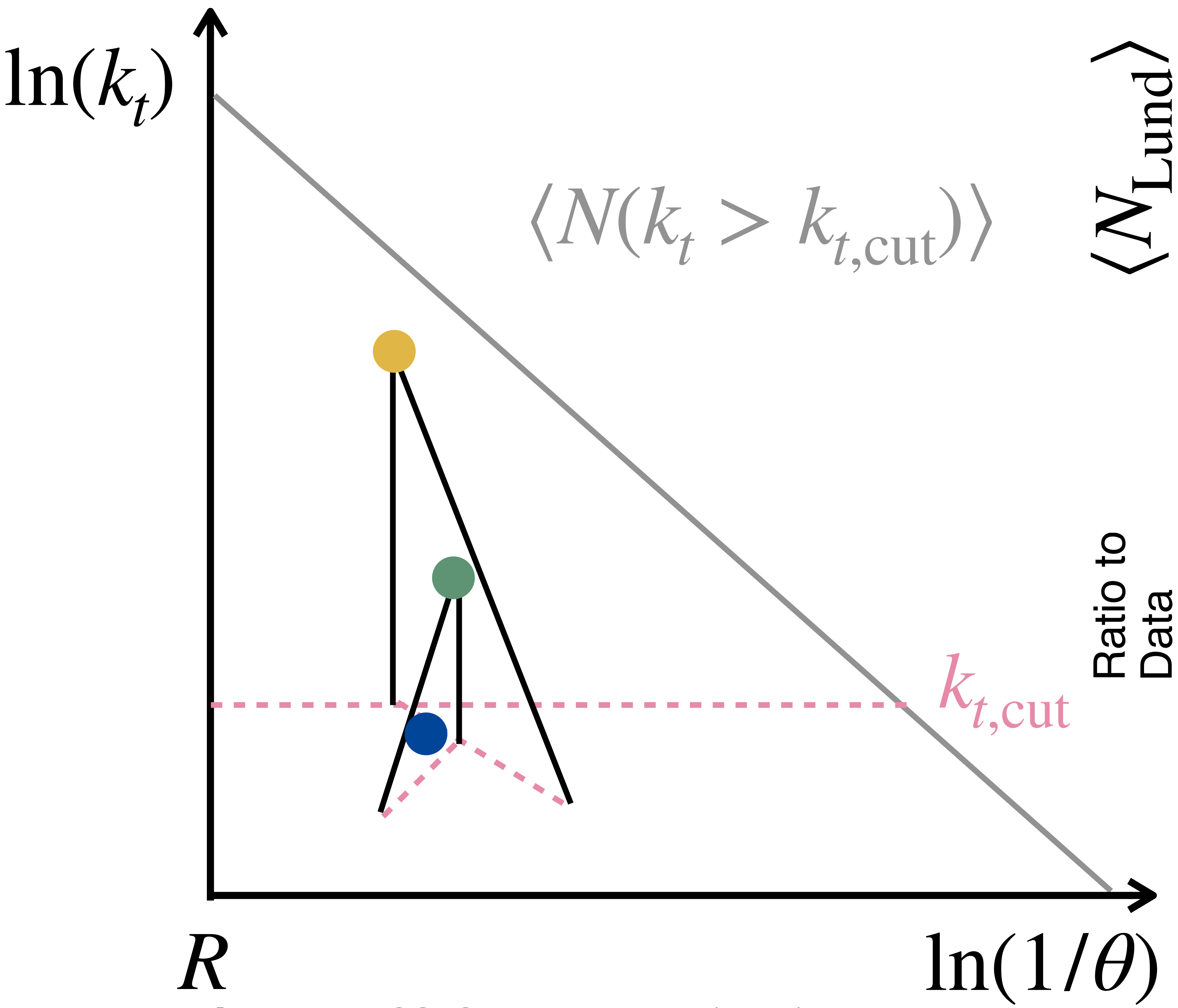
The primary Lund-plane density: MC-to-data





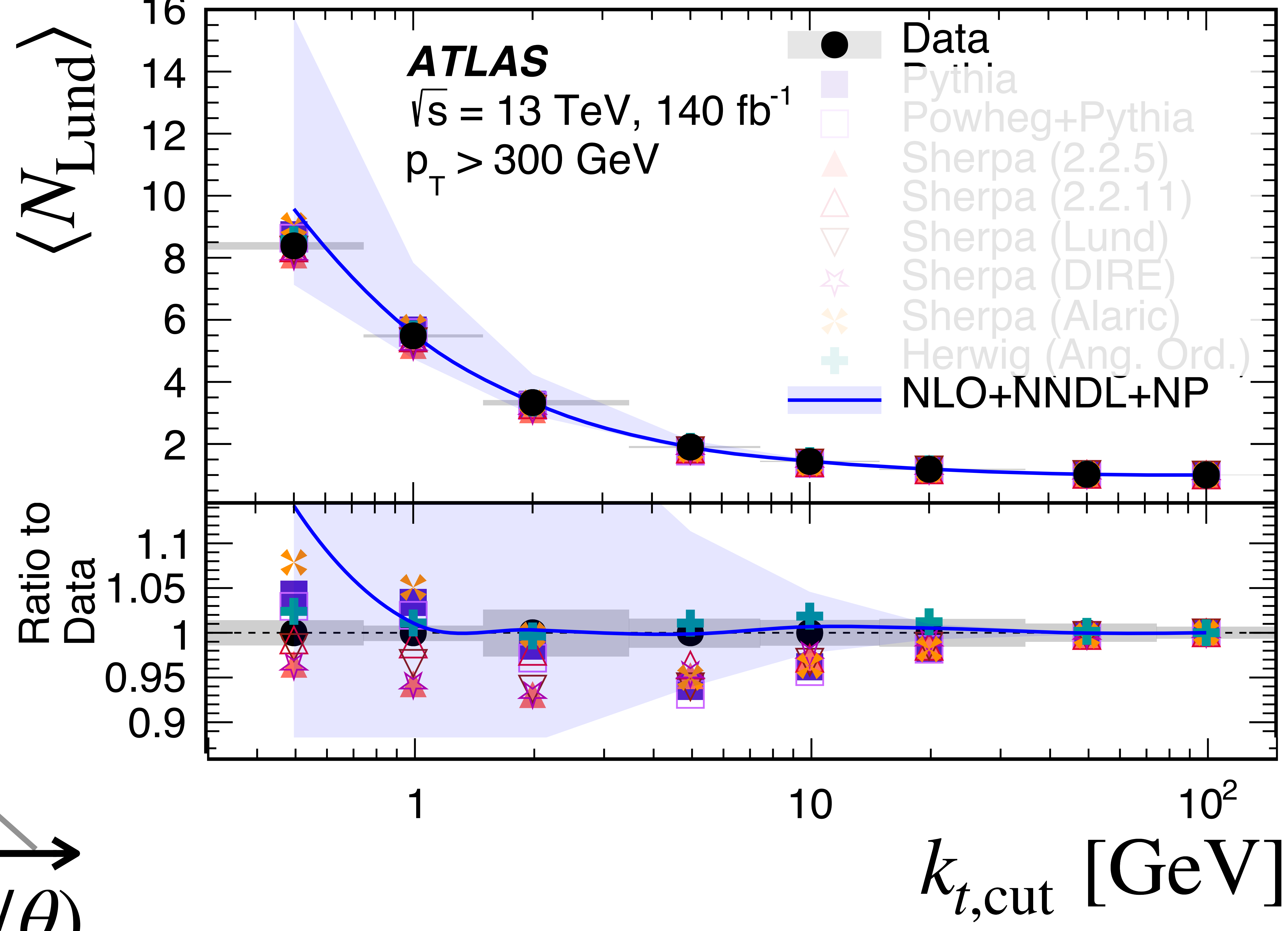
Powerful tool to disentangle between different MC ingredients

The Lund multiplicity: most recent substructure measurement



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

[ATLAS Collab arXiv:2402.13052]



State-of-the-art calculation describes data within 10-20% precision

Mission (hopefully) accomplished !