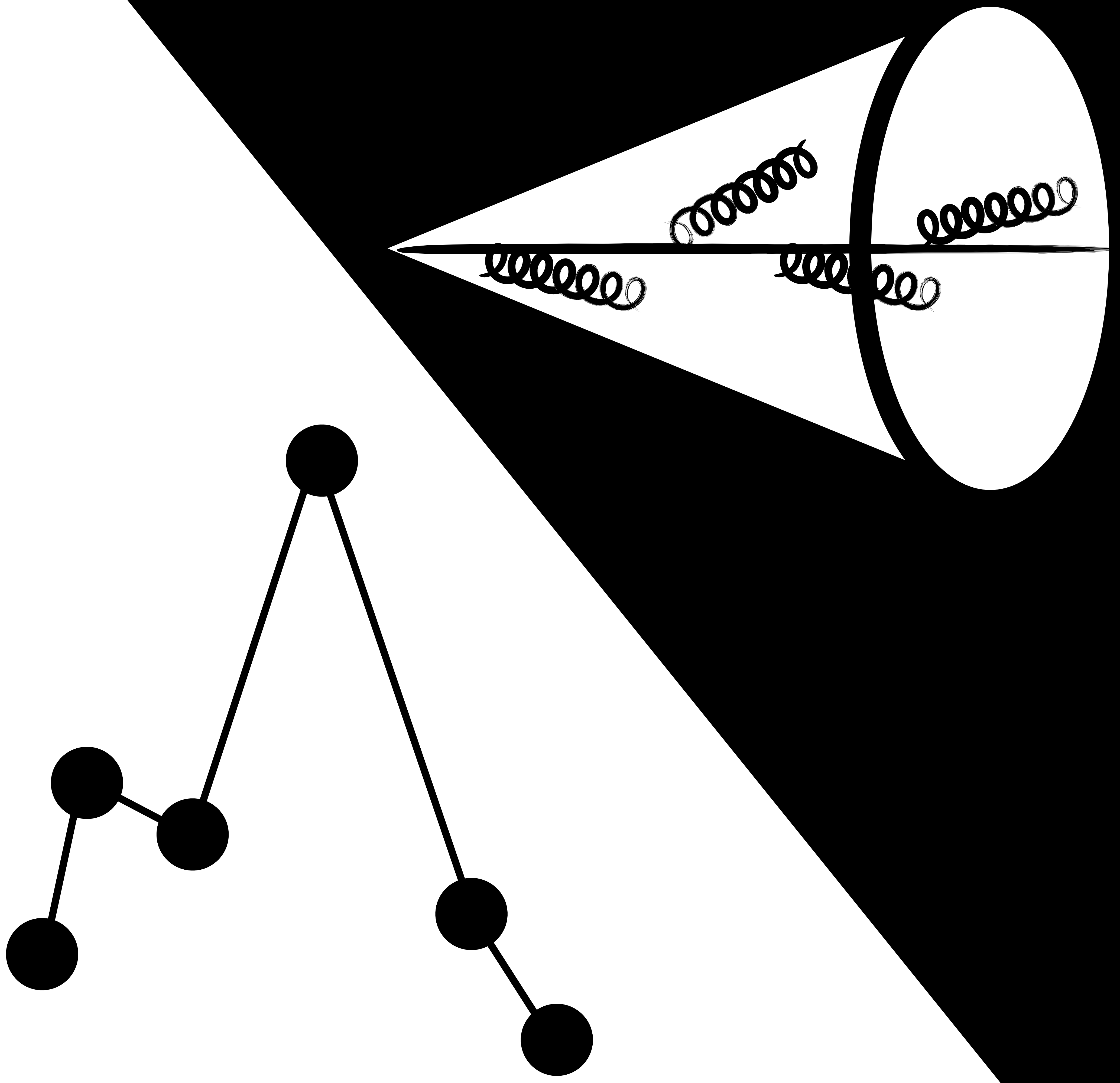
High precision predictions for a new suite of Lund-based observables



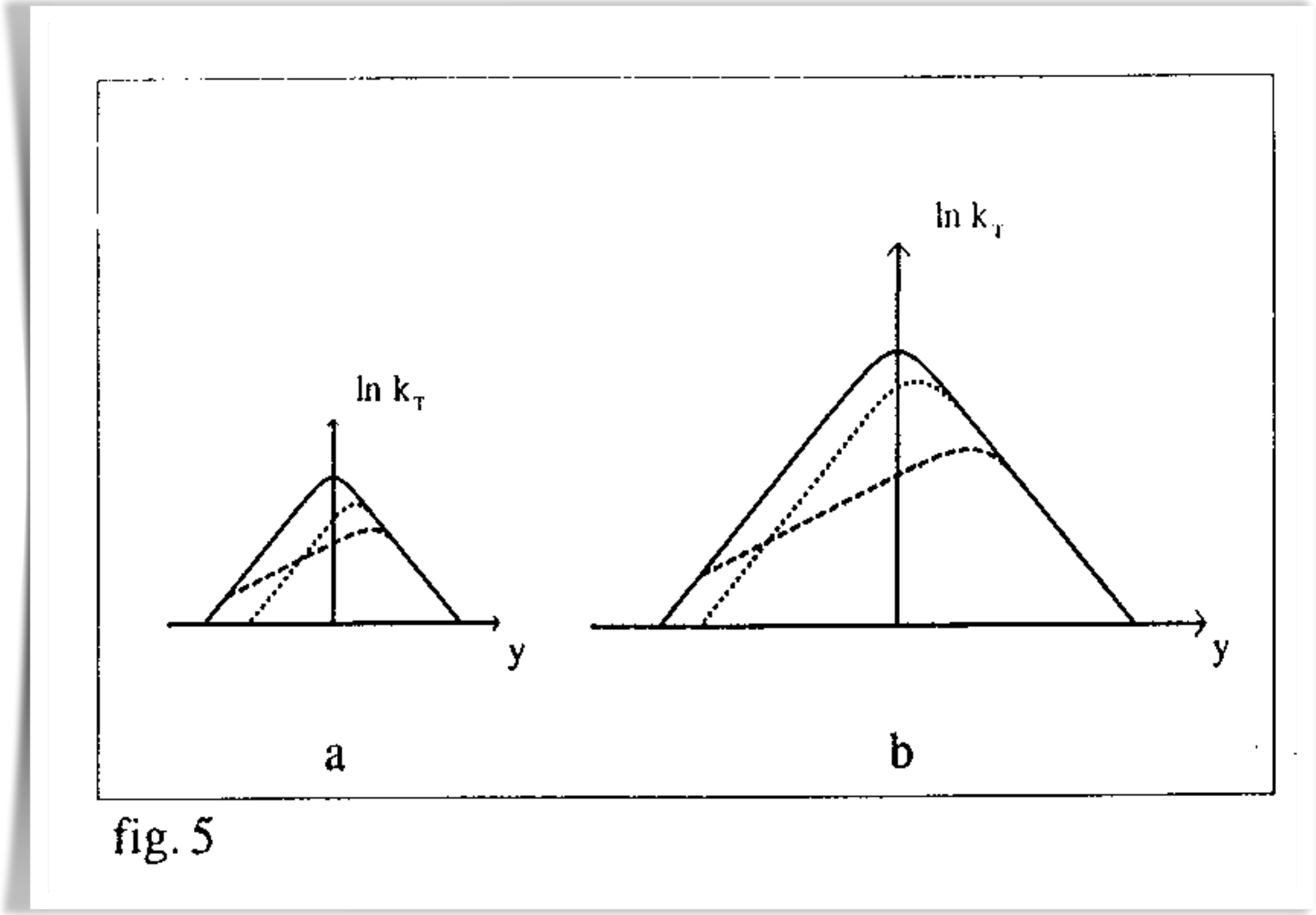
Alba Soto Ontoso

2nd Workshop on Tools for High Precision LHC simulations

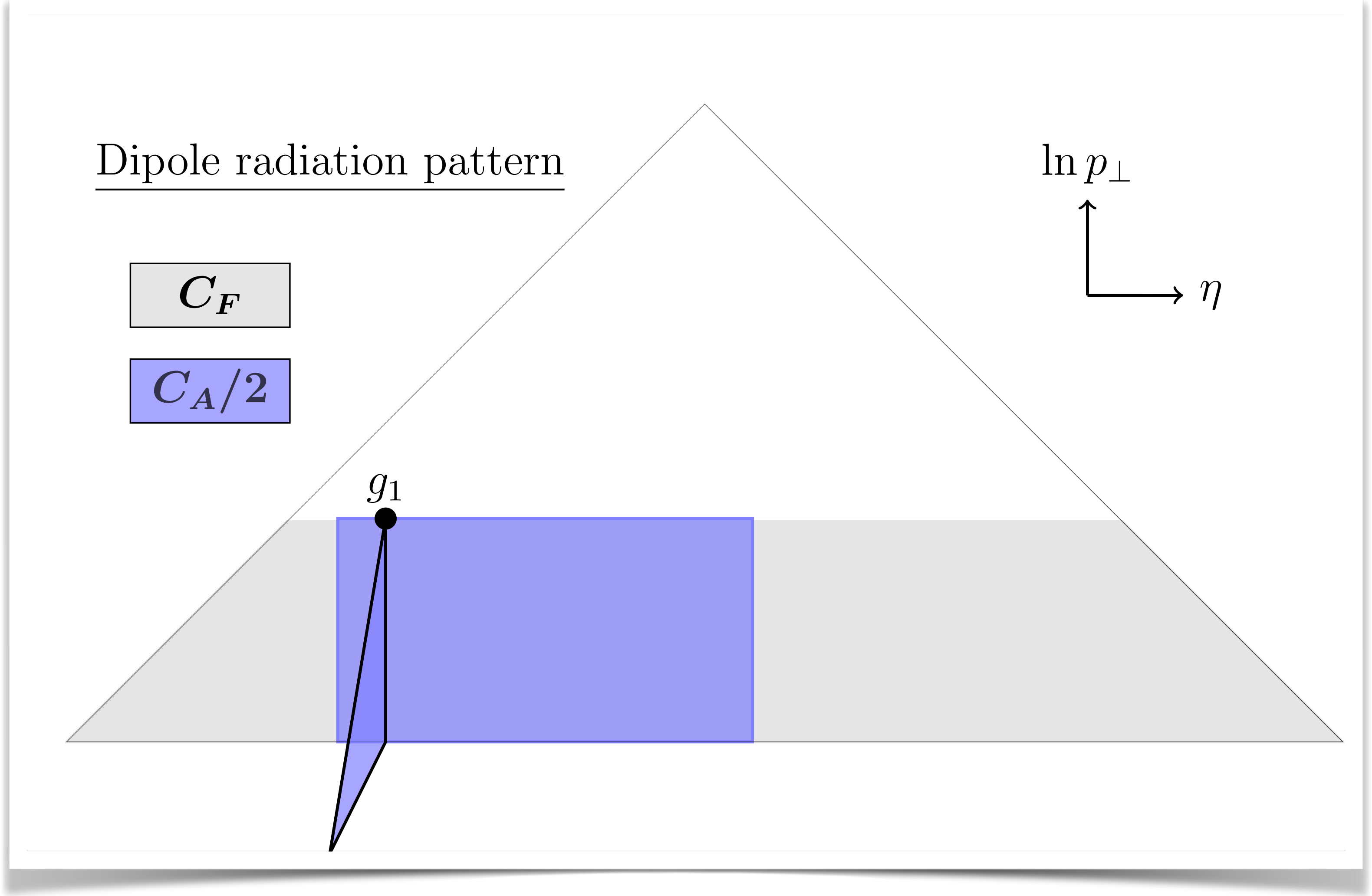
Ringberg, 9th May, 2024

The Lund-plane: central tool for pQCD

Parton showers

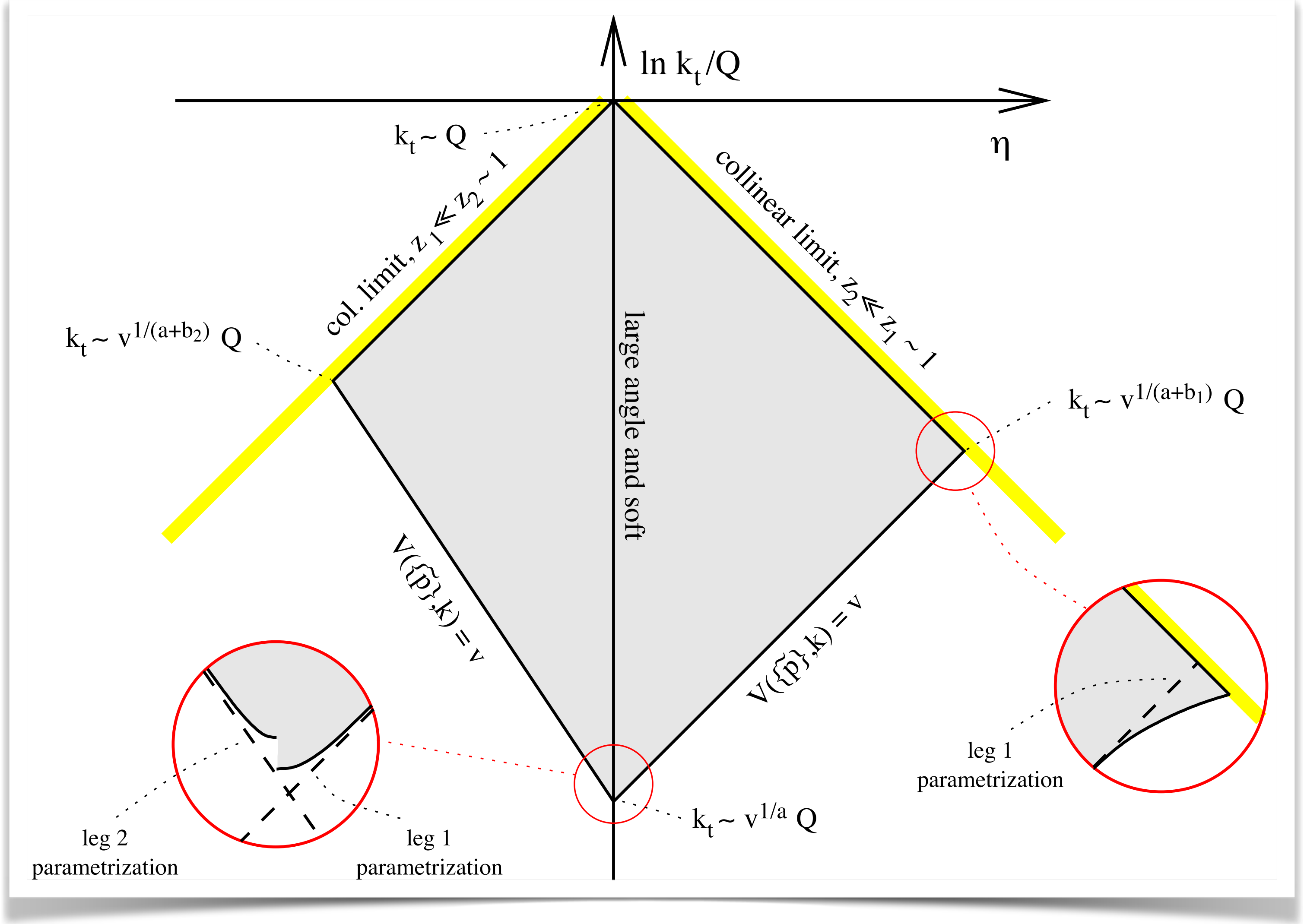


[Andersson et al. Z.Phys.C 43 (1989) 625]

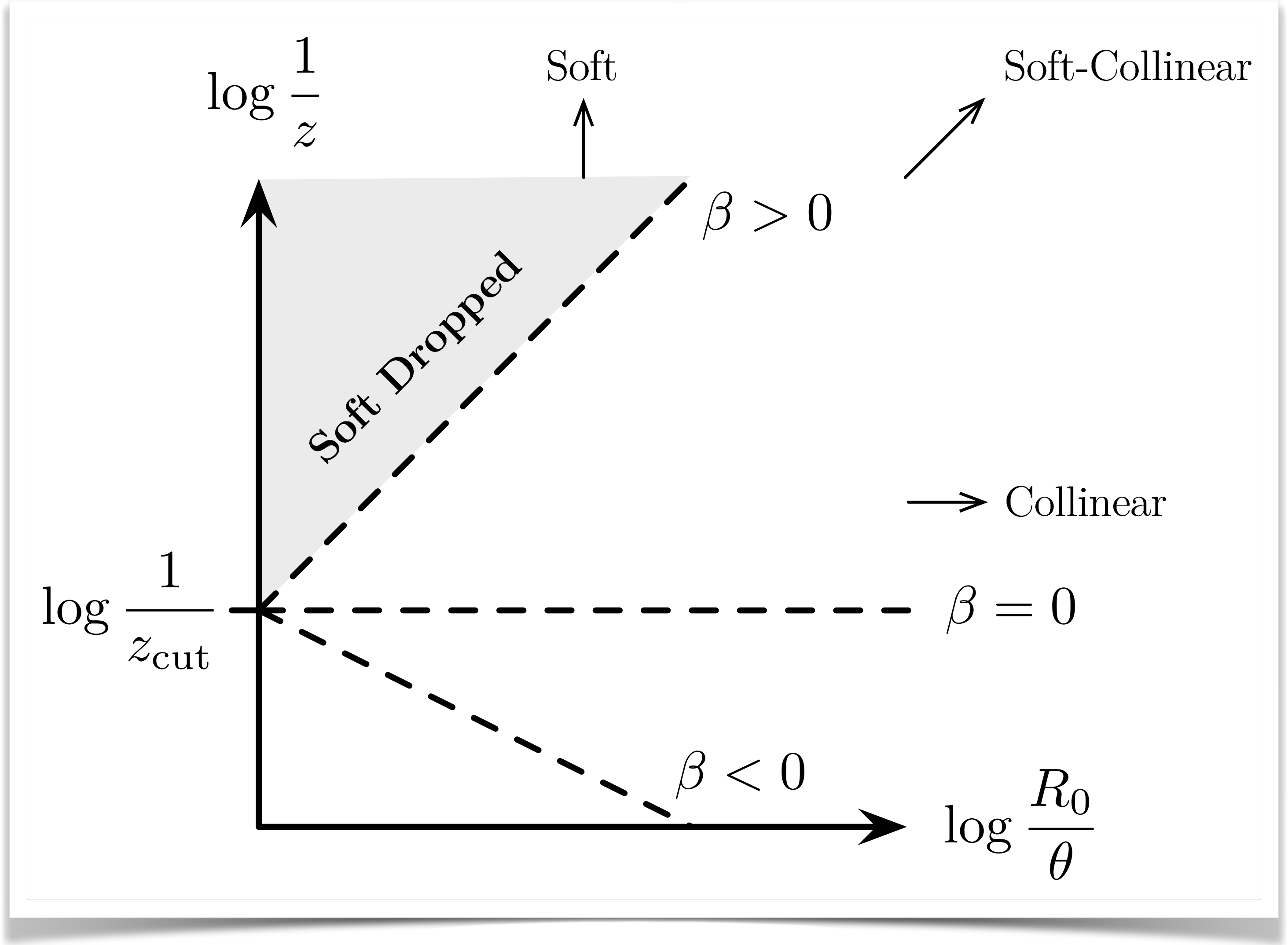


[Dasgupta et al. JHEP 09 (2018) 033]

Resummation



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



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

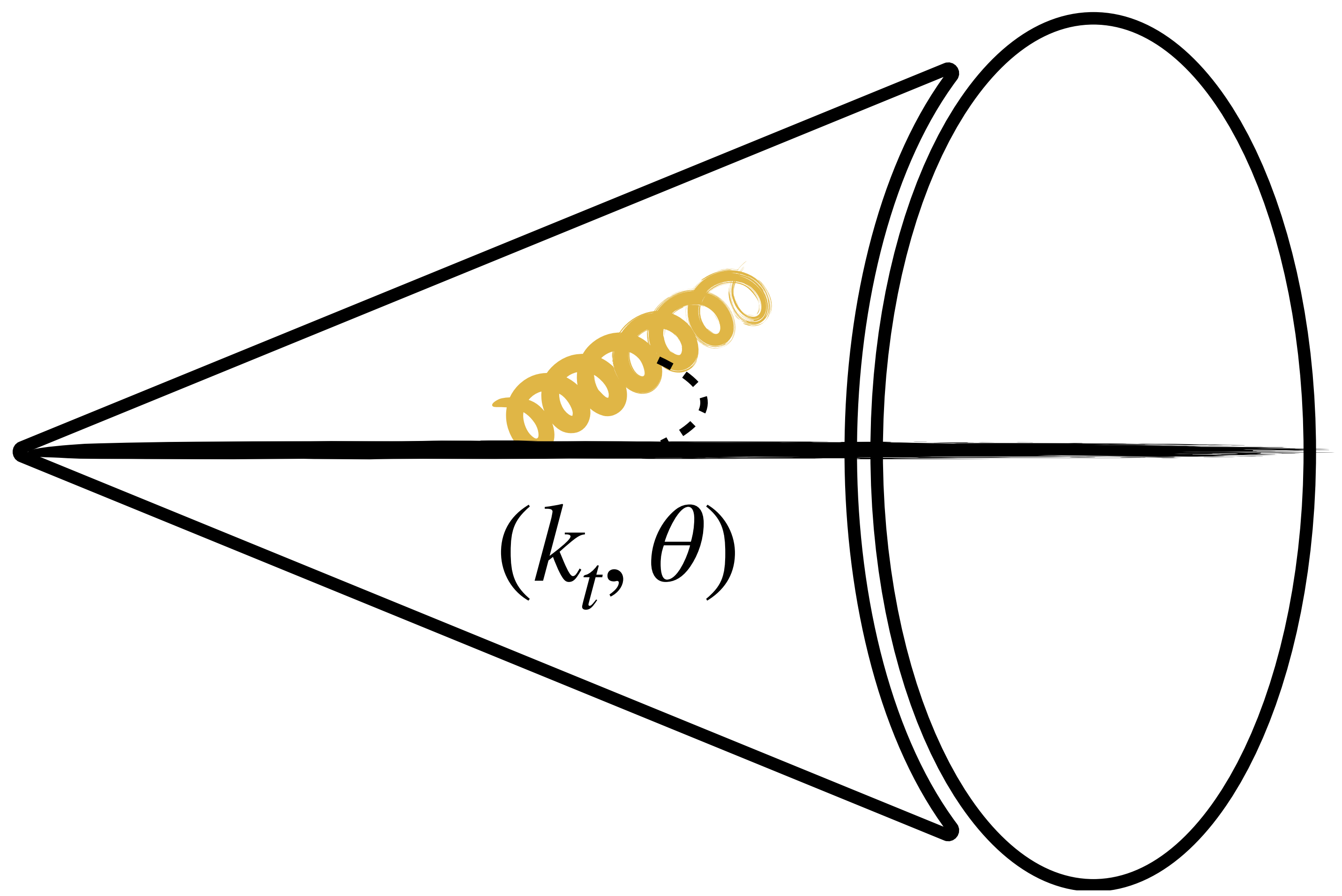
Definition of Lund-based observables

INPUT

Anti-k_t jet

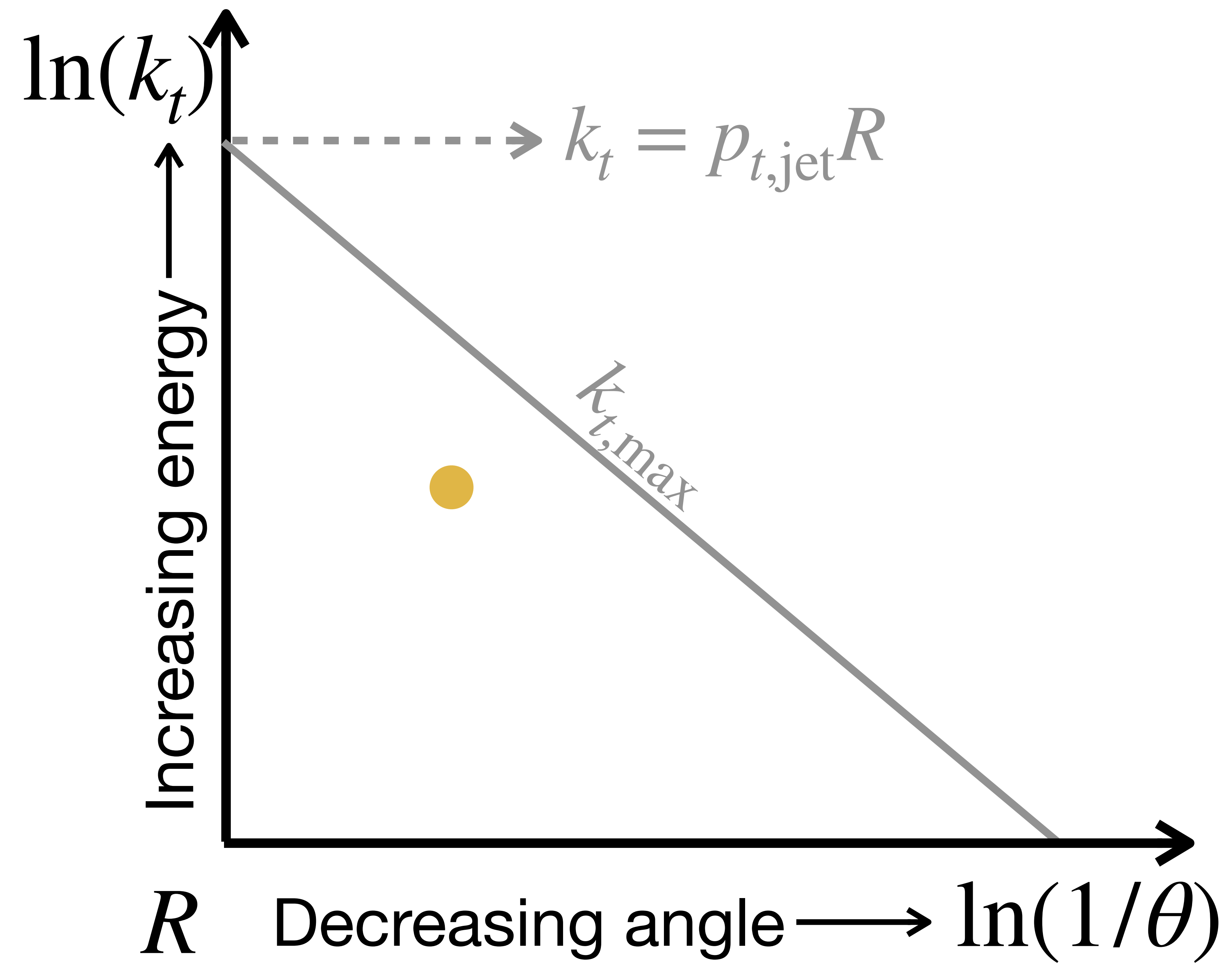
Hemisphere in e^+e^-

...



C/A reclustered jet

OUTPUT



Definition of Lund-based observables

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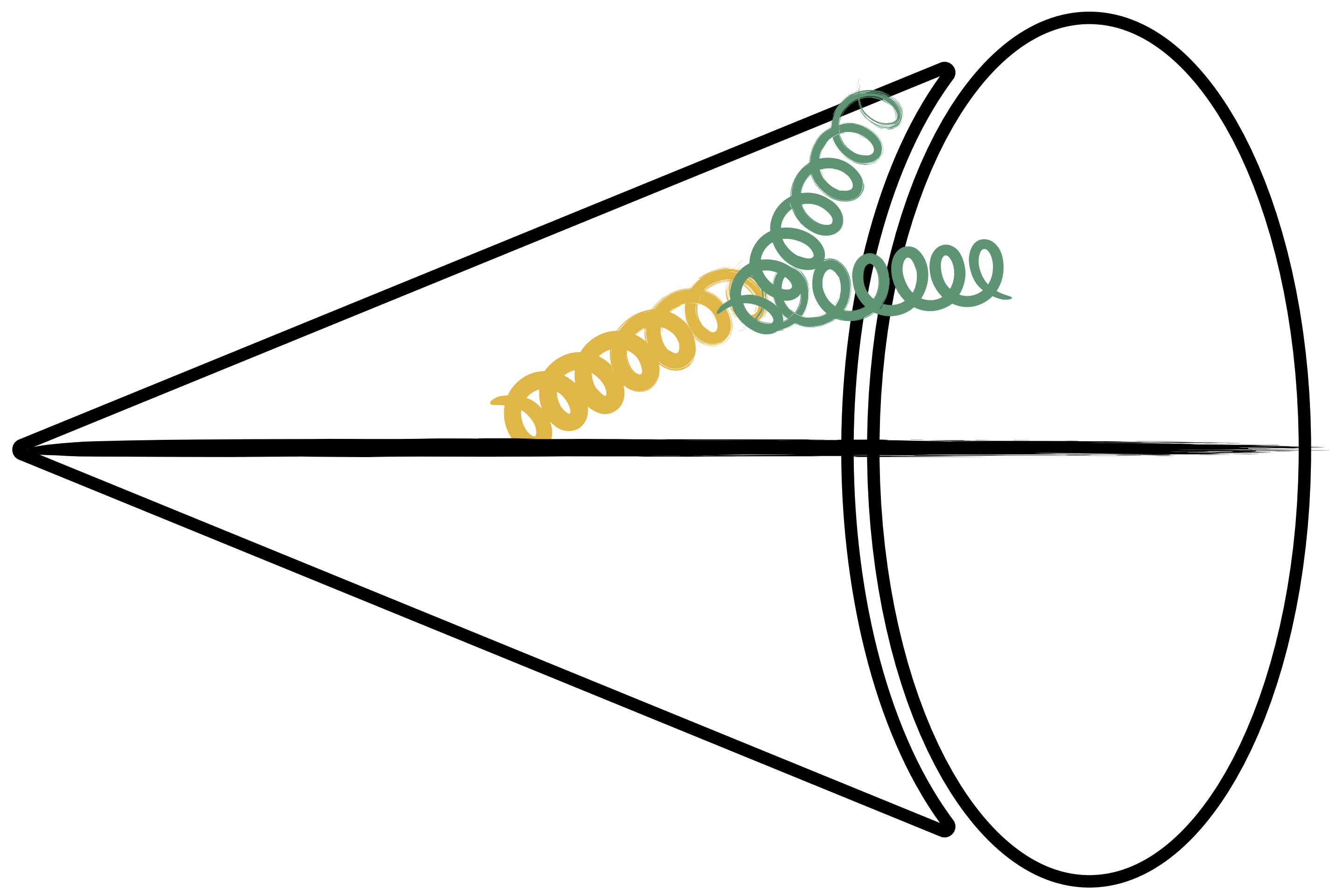
...



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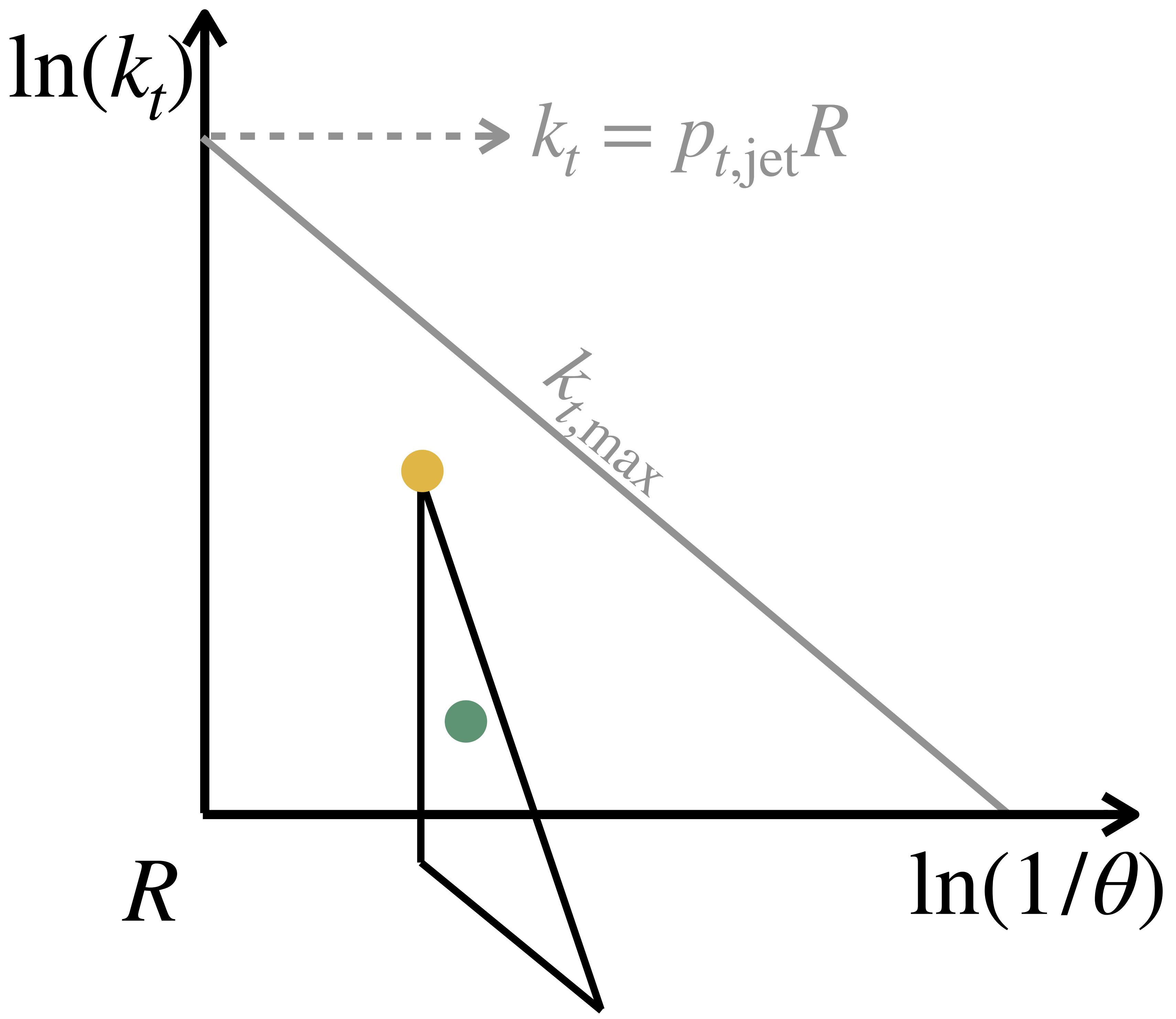
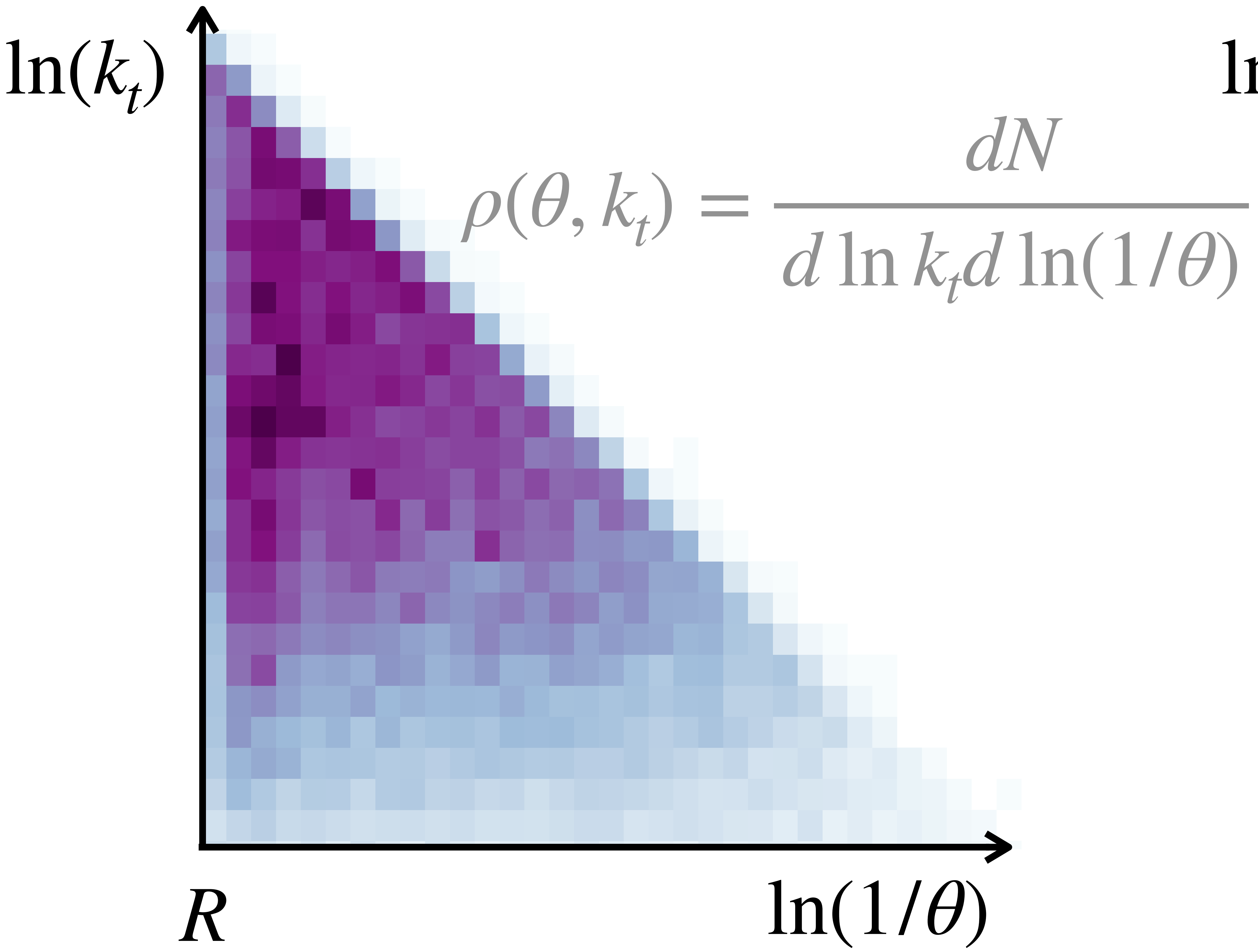


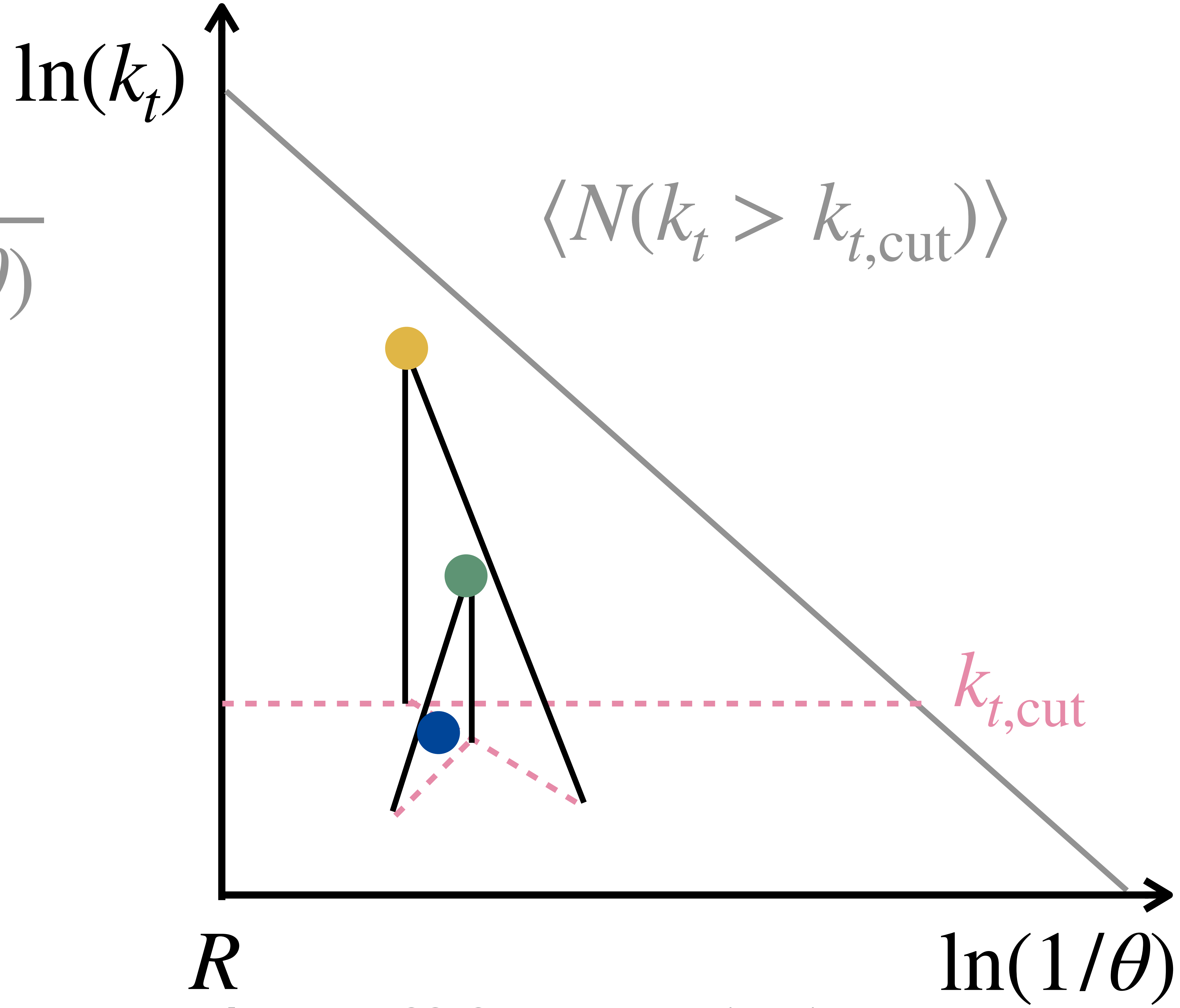
Two examples

Primary Lund-plane density



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

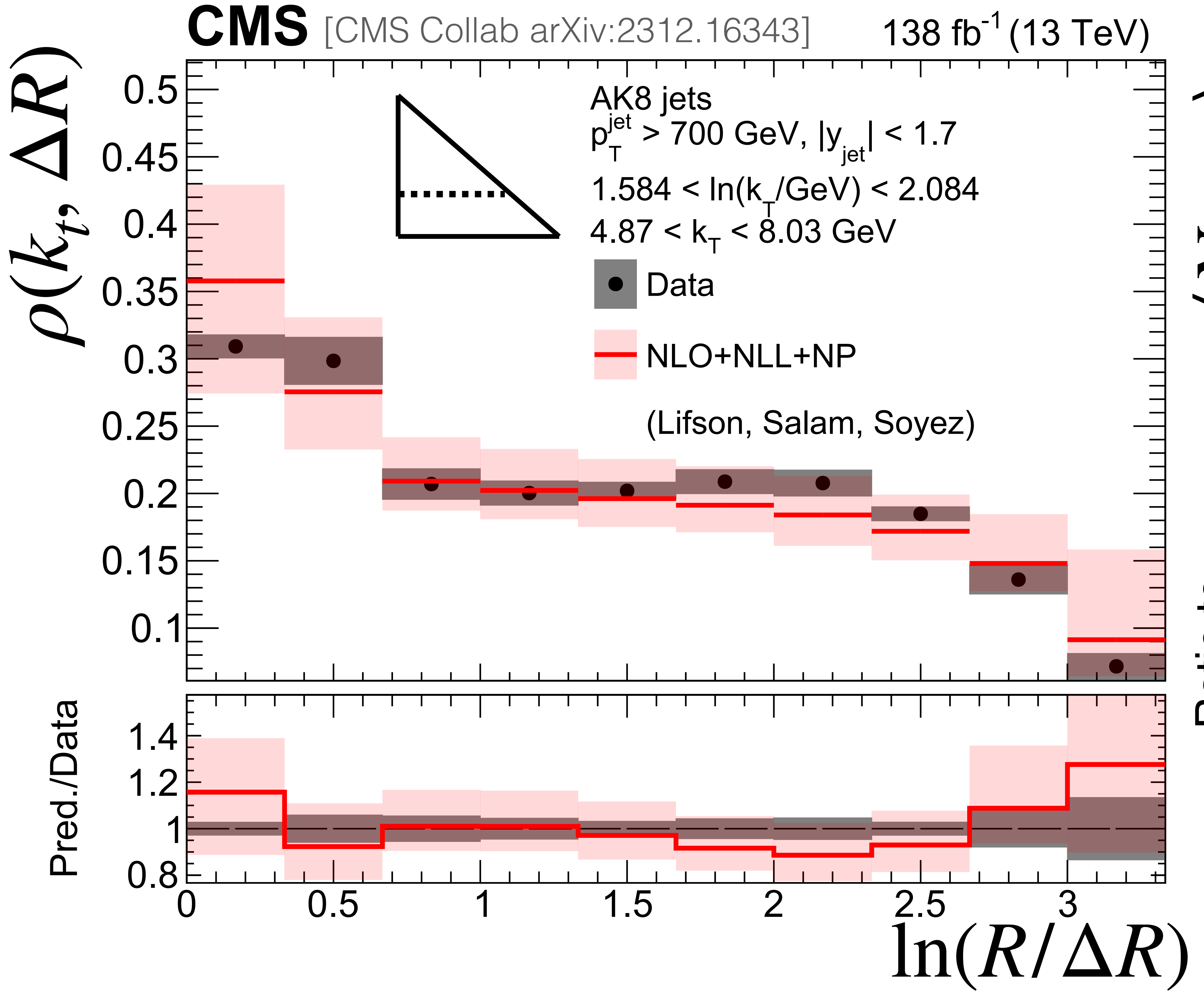
Lund multiplicity



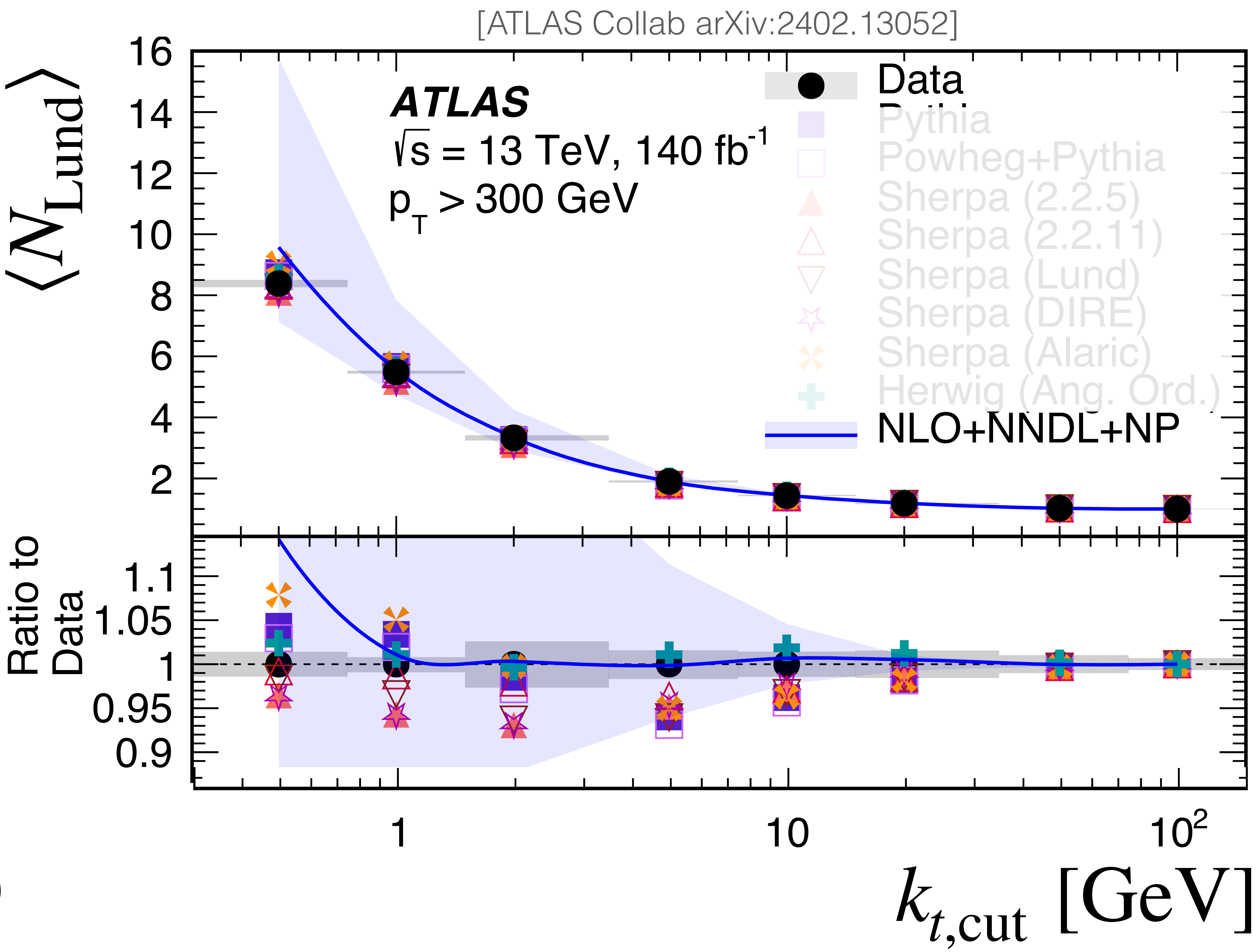
[Medves, ASO, Soyez, JHEP 10 (2022) 156, JHEP 04 (2023) 104]

Lund-based observables: resummation vs data

Primary Lund-plane density



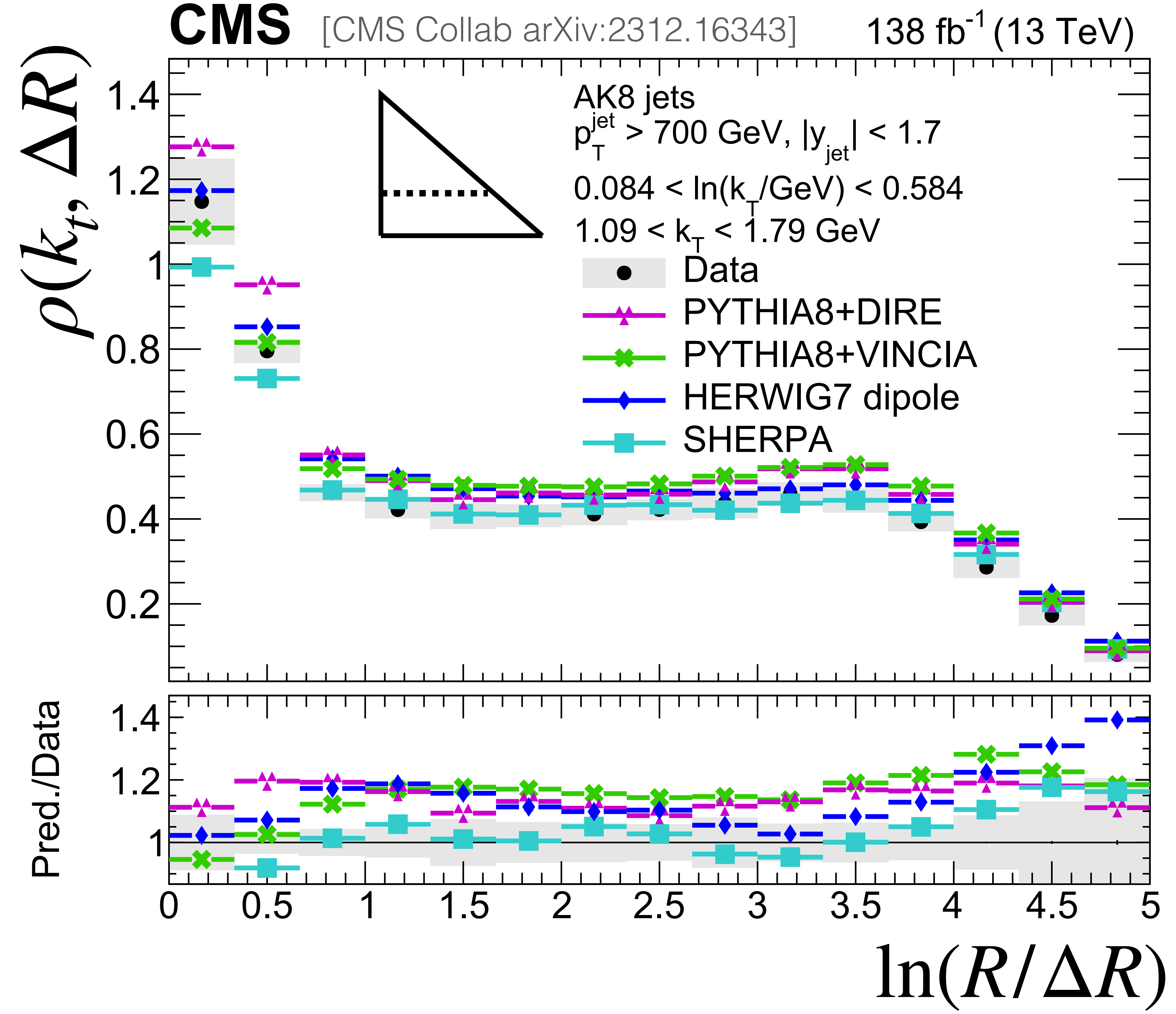
Lund multiplicity



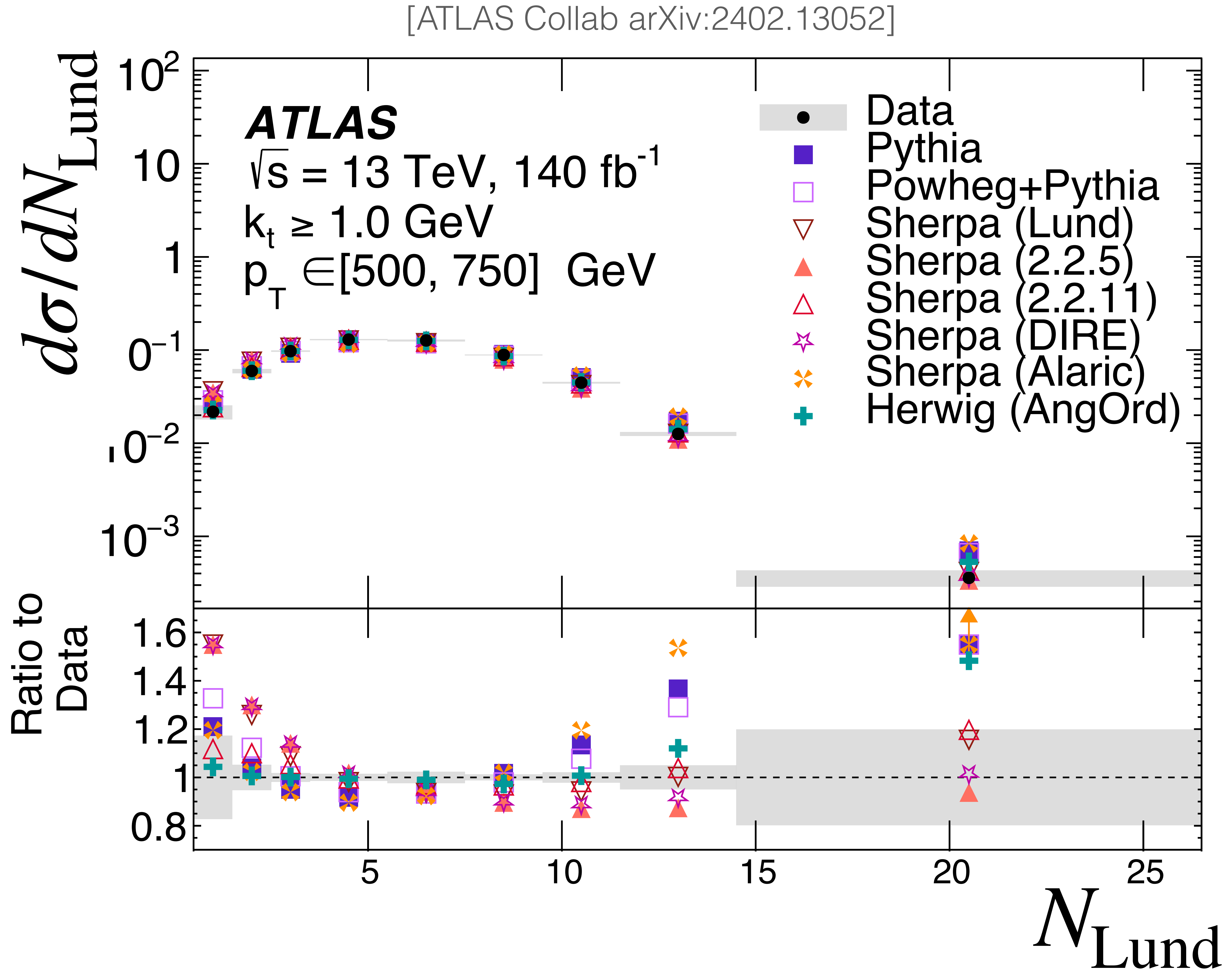
State-of-the-art calculations describe data within 10-20% precision

Lund-based observables: MCs vs data

Primary Lund-plane density



Lund multiplicity



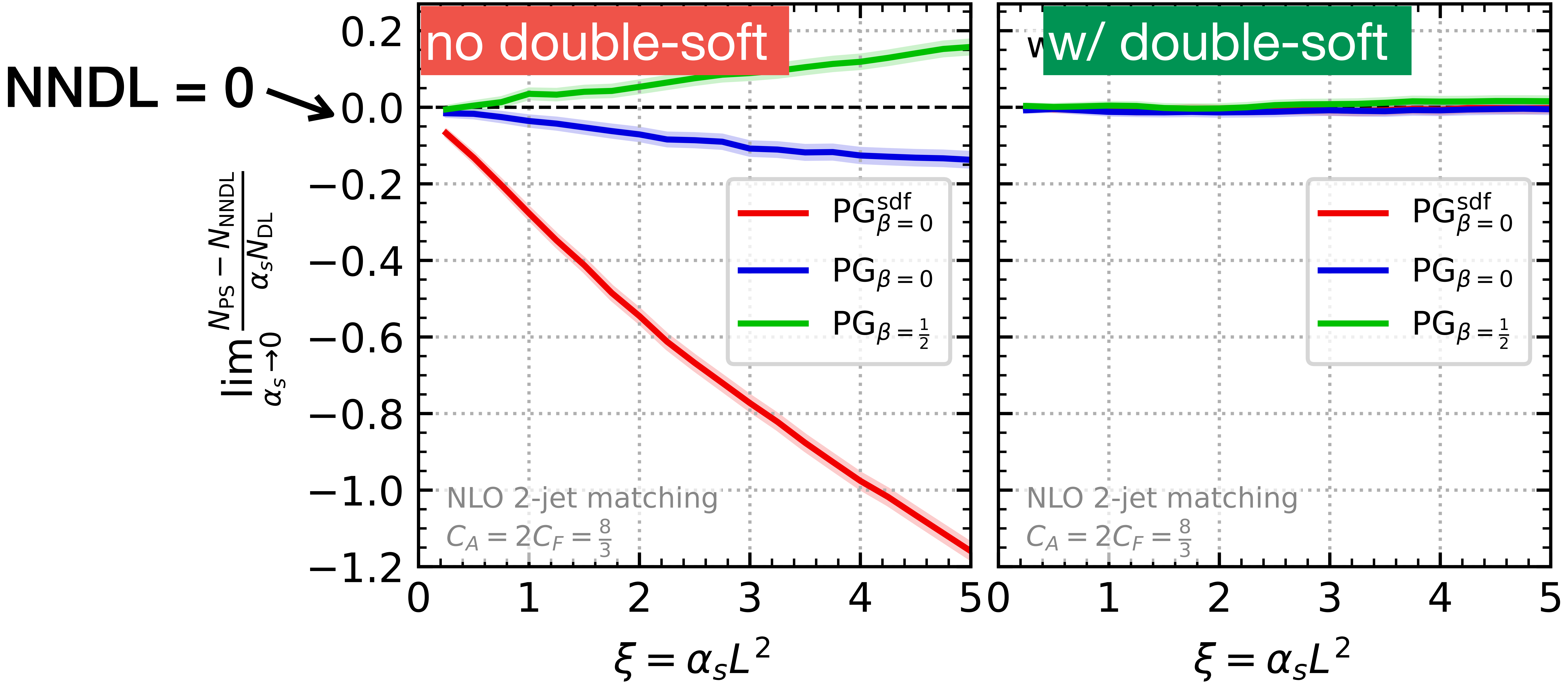
Data able to distinguish parton shower vs hadronization effects

Lund-based observables: resummations vs parton showers

See Alexander's talk next

[Ferrario Ravasio et al. PRL 131 (2023) 16, 161906]

PanGlobal's NNDL accuracy test



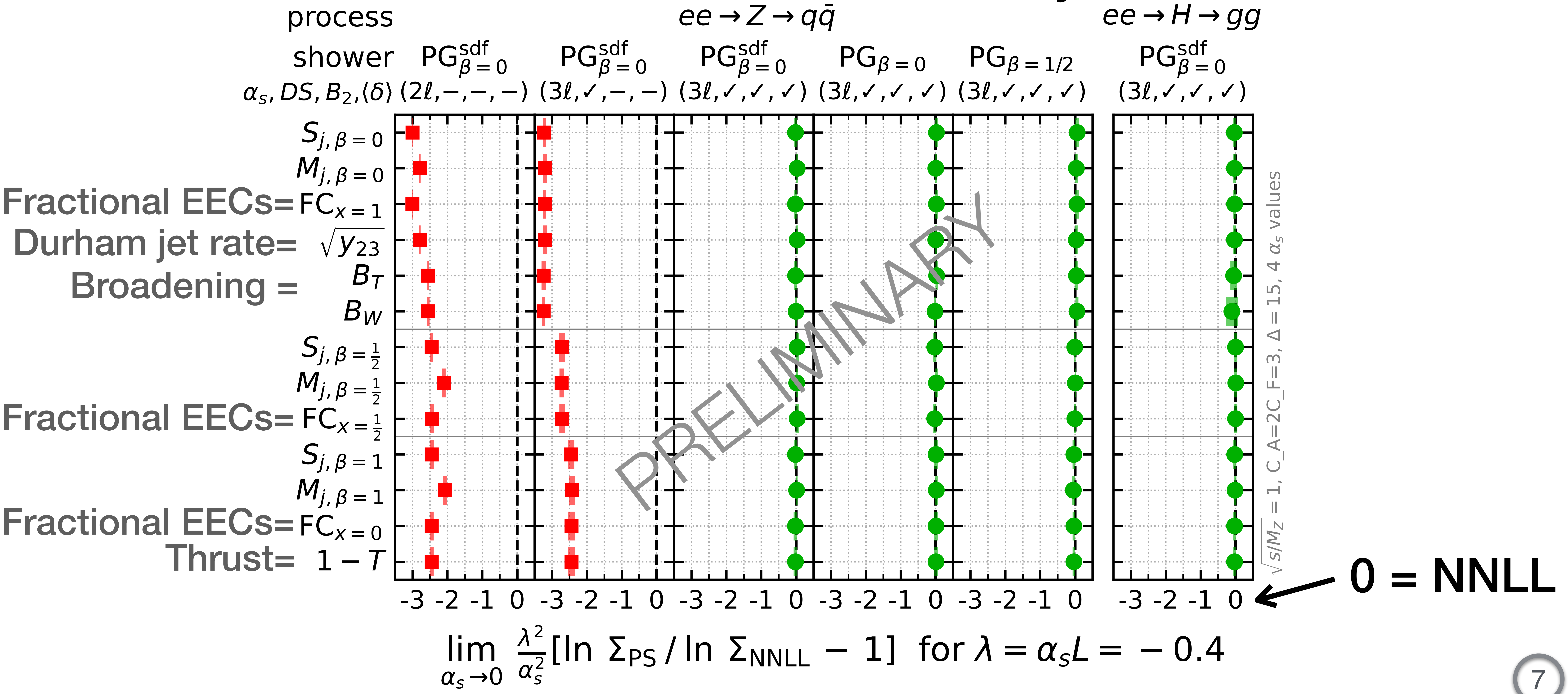
New application of resummation calculations: test of parton showers

Lund-based observables: resummations vs parton showers

See Alexander's talk next

[PanScales Collaboration, in preparation]

PanGlobal's NNLL accuracy tests



Lund-based observables: resummations vs parton showers

See Alexander's talk next

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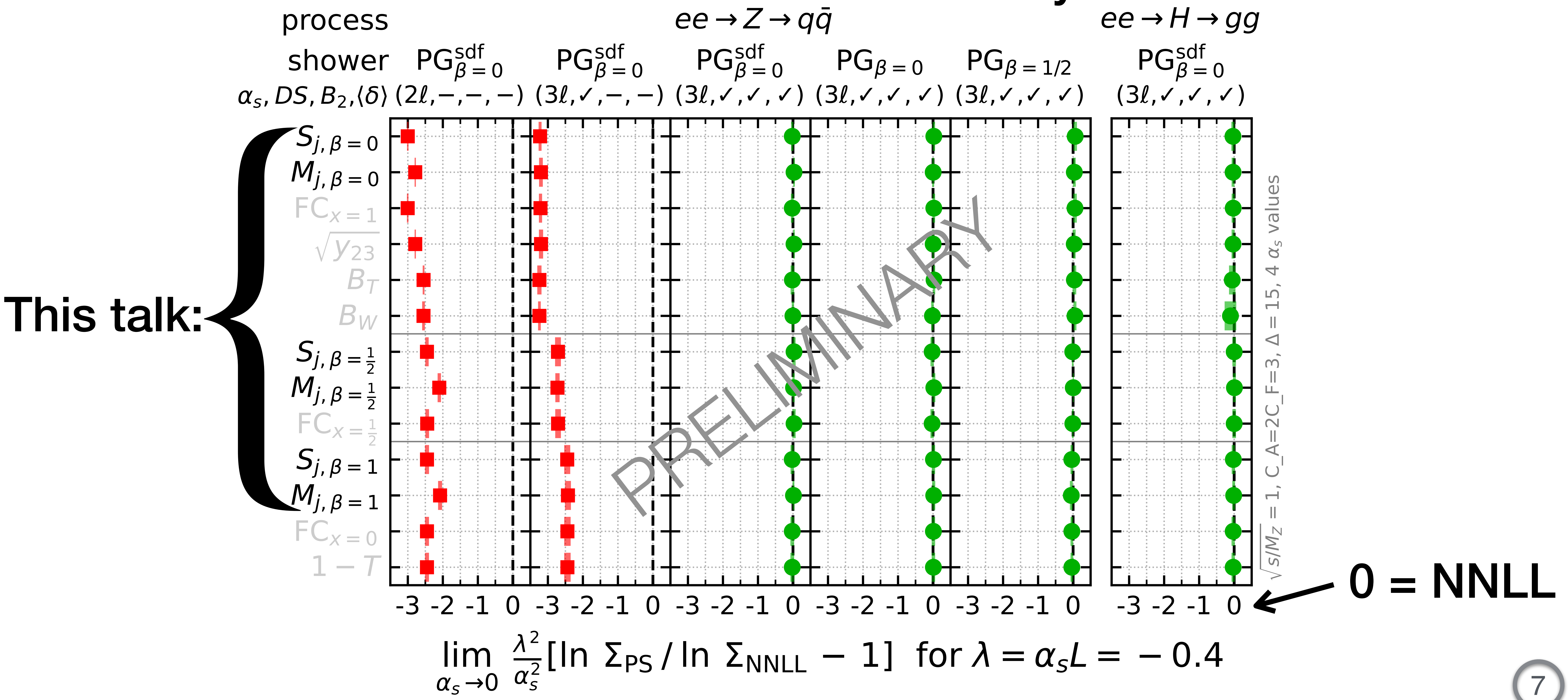
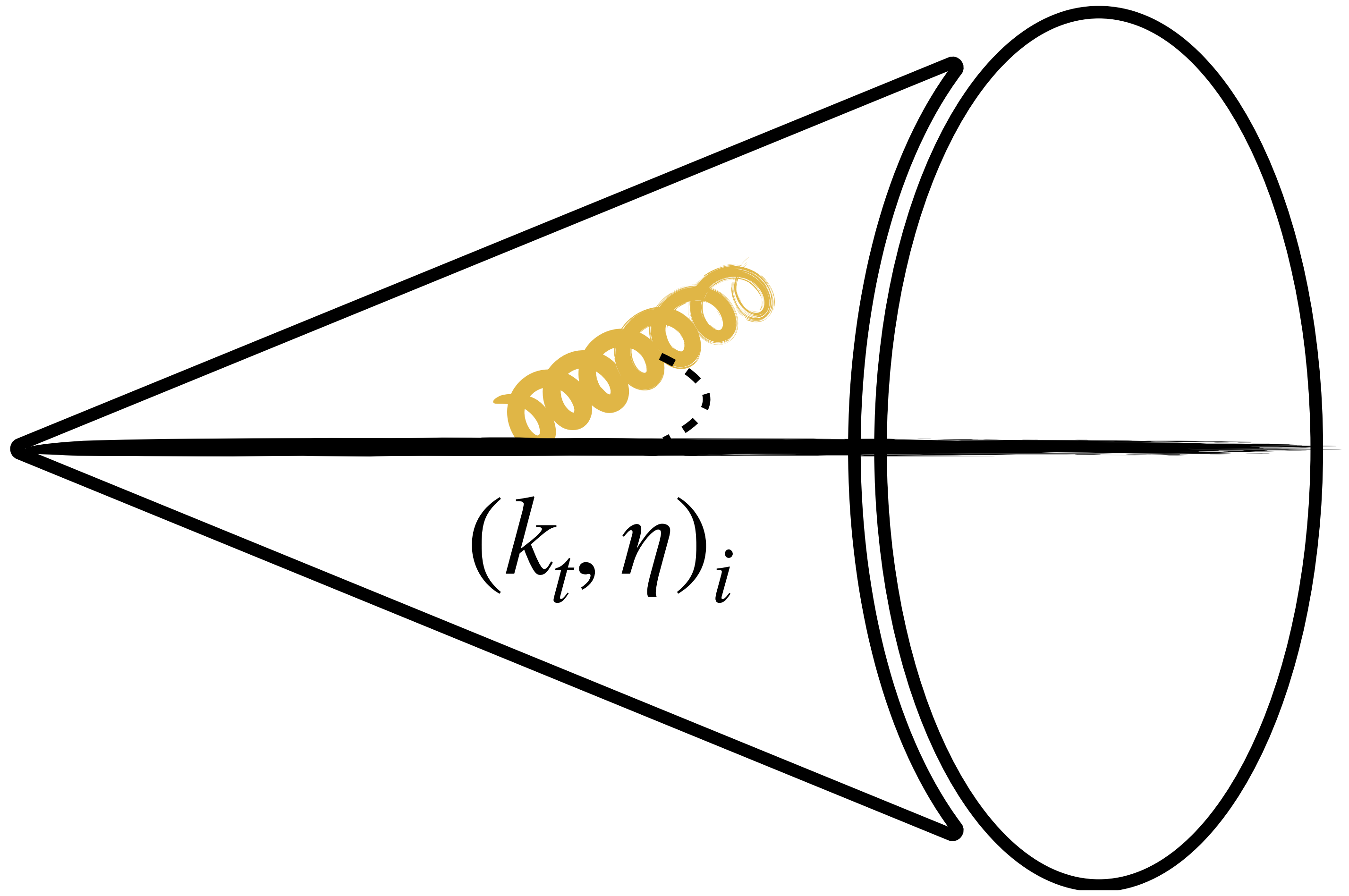


This talk: two *new* Lund-based observables [Dasgupta et al. PRL 125 (2020) 5, 052002]

INPUT

Hemisphere in e+e-



C/A reclustered jet

OUTPUT

$$M_\beta = \max_{i \in \text{declust}} \frac{k_{t,i}}{Q} e^{-\beta|\eta_i|}$$

$$S_\beta = \sum_{i \in \text{declust}} \frac{k_{t,i}}{Q} e^{-\beta|\eta_i|}$$

Note: definition for colour singlet events in pp given in [van Beekveld, ASO et al. JHEP 11 (2022) 020]

This talk: two *new* Lund-based observables [Dasgupta et al. PRL 125 (2020) 5, 052002]

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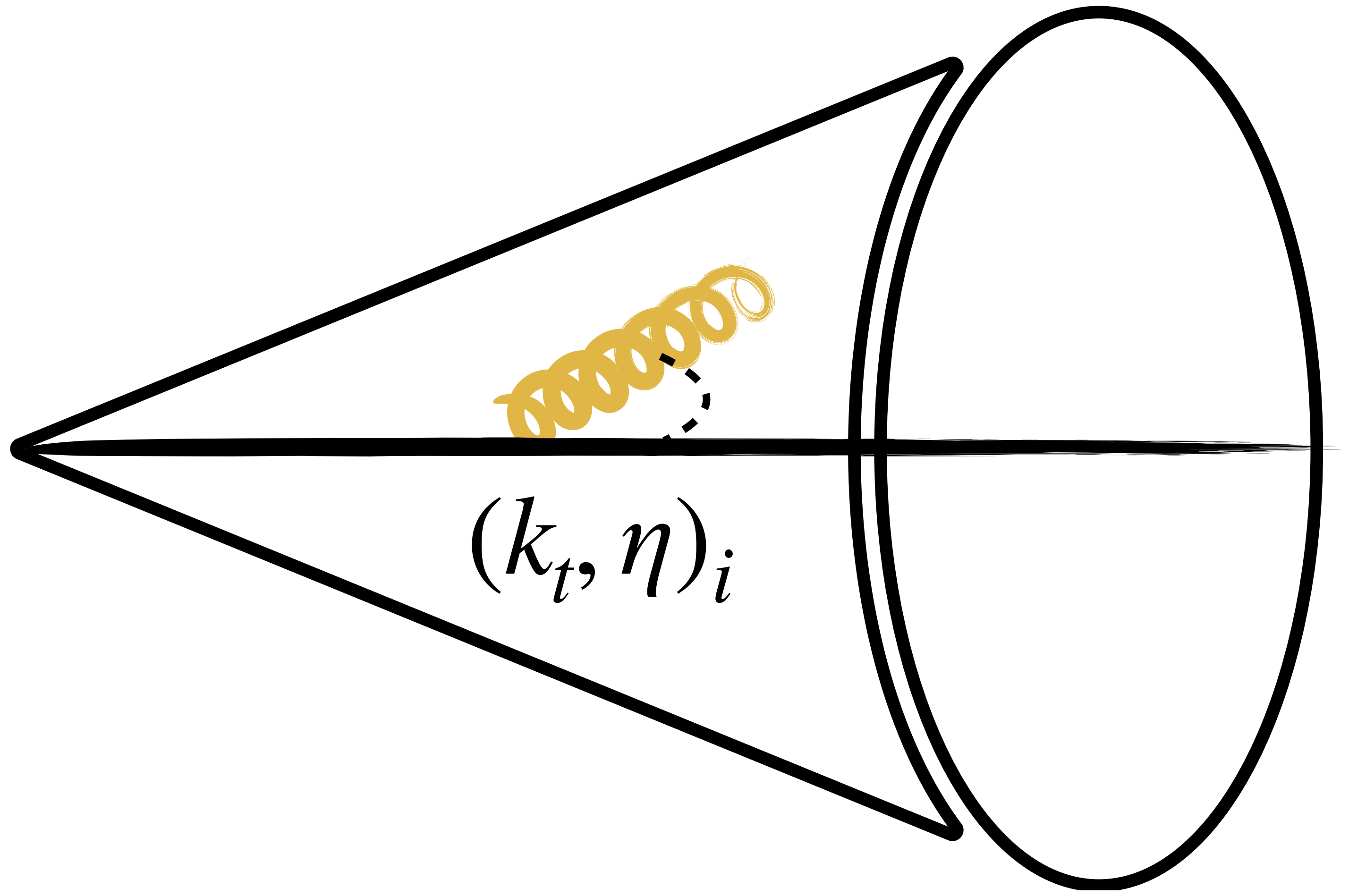
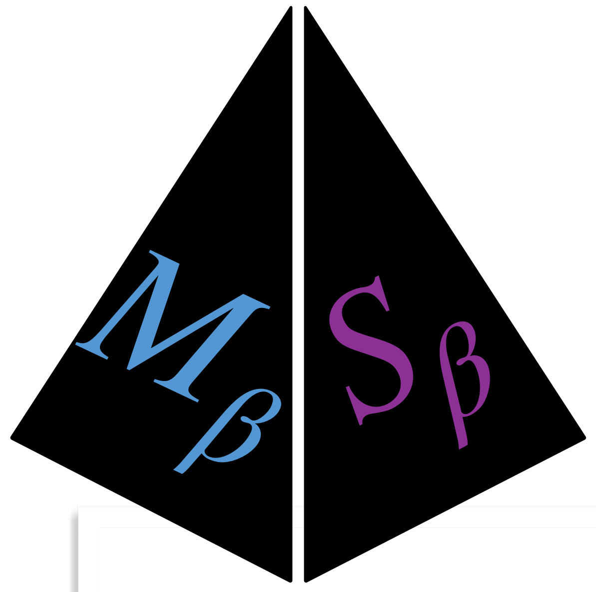


C/A reclustered jet

OUTPUT



$$V(\{\tilde{p}\}, k) = d_\ell \left(\frac{k_t^{(\ell)}}{Q}\right)^{a_\ell} e^{-b_\ell \eta^{(\ell)}} g_\ell(\phi^{(\ell)})$$

Reminiscent of soft-and-collinear behaviour of event shapes

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

[See also Berger et al. PRD 68 (2003) 014012]

Note: definition for colour singlet events in pp given in [van Beekveld, ASO et al. JHEP 11 (2022) 020]

This talk: two *new* Lund-based observables [Dasgupta et al. PRL 125 (2020) 5, 052002]

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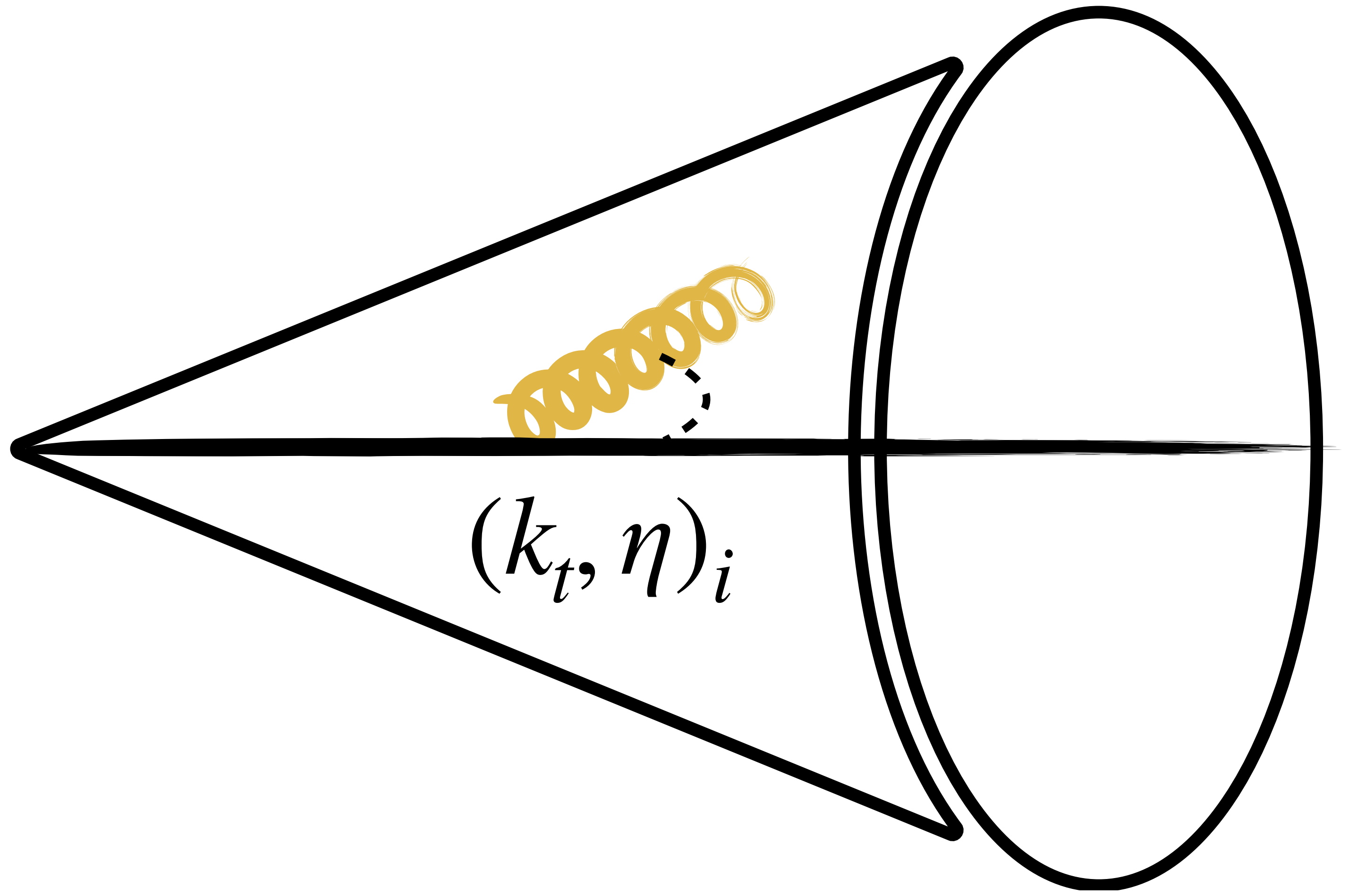


C/A reclustered jet

OUTPUT

$$M_{\beta=0} \stackrel{\text{NLL}}{=} \sqrt{y_{23}}$$

$$S_{\beta=1} \stackrel{\text{NLL}}{=} T$$

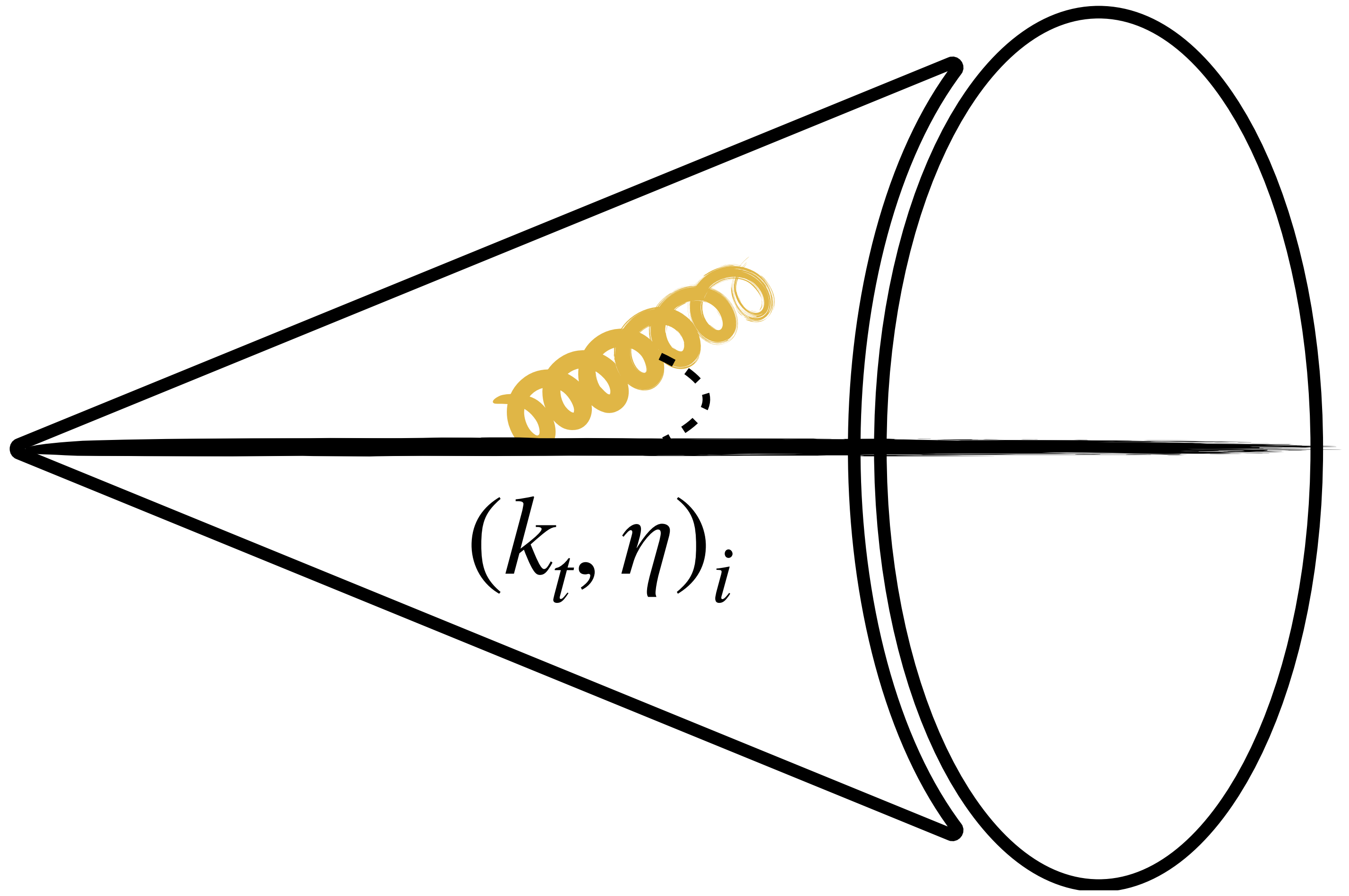
Note: definition for colour singlet events in pp given in [van Beekveld, ASO et al. JHEP 11 (2022) 020]

This talk: two *new* Lund-based observables [Dasgupta et al. PRL 125 (2020) 5, 052002]

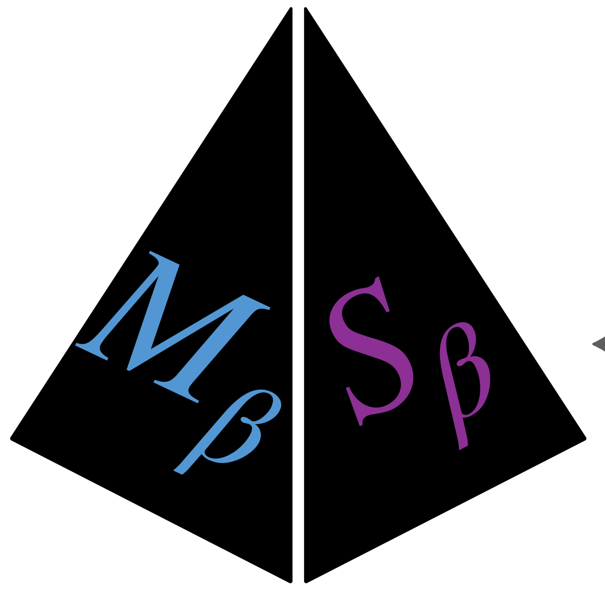
INPUT

OUTPUT

Hemisphere in e^+e^-



C/A reclustered jet



$$\leftrightarrow v = \frac{k_t}{Q} e^{-\beta|\eta|}$$

PanScales showers evolution variable

Note: definition for colour singlet events in pp given in [van Beekveld, ASO et al. JHEP 11 (2022) 020]

Plan for this talk

- NNLL resummation in e^+e^- collisions
- Sneak peek at pheno with PanScales-Pythia interface
  [PanScales Collab. arXiv:2312.13275]

Work in progress with:

Melissa van Beekveld (NIKHEF), Luca Buonocore (CERN), Basem El-Menoufi (Monash U.), Silvia Ferrario Ravasio, Pier Francesco Monni (CERN) and Gregory Soyez (IPhT)

Revisiting NLL resummation (CAESAR approach)

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

The cumulative cross section for an (rIRC safe) observable v reads

$$\Sigma(v) = \exp\left(- \int [dk]\, |M(k)|^2 \right) \times \sum_{m=1}^{\infty} \frac{1}{m!} \prod_{i=1}^{m} \int [dk_i]\, |M(k_i)|^2 \, \Theta(v - v(k_1, \ldots, k_m))$$

virtual corrections

real emissions

Revisiting NLL resummation (CAESAR approach)

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

The cumulative cross section for an (rIRC safe) observable v reads

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virtual corrections   real emissions

Introduce a slicing parameter satisfying $\epsilon \ll 1, \ln 1/\epsilon \ll \ln 1/v$

$$\sum_{m=1}^{\infty} \frac{1}{m!} \prod_{i=1}^{m} \int [\mathrm{d}k_i]\,|M(k_i)|^2 = \sum_{n=1}^{\infty} \frac{1}{n!} \prod_{i=1}^{n} \int_{\epsilon v} [\mathrm{d}k_i]\,|M(k_i)|^2 \quad \text{resolved}$$

$$\times \sum_{k=0}^{\infty} \frac{1}{k!} \prod_{i=n+1}^{n+k} \int^{\epsilon v} [\mathrm{d}k_i]\,|M(k_i)|^2 \quad \text{unresolved}$$

Revisiting NLL resummation (CAESAR approach)

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

rIRC safety implies that unresolved emissions don't contribute to v

$$\Sigma(v) = \exp\left(- \int [dk] \, |M(k)|^2 (1 - \Theta(\epsilon v - v(k))\right) \quad \text{virtual \& unresolved}$$

$$\times \sum_{m=1}^{\infty} \frac{1}{m!} \prod_{i=1}^{m} \int_{\epsilon v} [dk_i] \, |M(k_i)|^2 \Theta(v - v(k_1, \ldots, k_m)) \quad \text{real emissions}$$

At NLL, we can further expand the no-emission probability

$$\exp\left(- \int [dk] \, |M(k)|^2 (1 - \Theta(\epsilon v - v(k))\right) = \exp\left(- R(v) - R' \ln 1/\epsilon \right)$$

Revisiting NLL resummation (CAESAR approach)

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

So that the cumulative cross-section can be written as

$$\Sigma(v) = \exp\left(- \int [dk] |M(k)|^2 [(1 - \Theta(v - v(k))]\right) \times$$ Sudakov radiator

$$\times e^{-R \ln 1/\epsilon} \sum_{m=1}^{\infty} \frac{1}{m!} \prod_{i=1}^{m} \int_{\epsilon v} [dk_i] |M(k_i)|^2 \Theta(v - v(k_i))$$ Transfer function

Different log counting for Sudakov and Transfer function ($\epsilon v < v(k_i) < v$)

$$\int [dk] |M(k)|^2 \sim \int \frac{dk_t}{k_t} \alpha_s^{\text{CMW}}(k_t) dz P(z)$$ CMW + hard-coll. splitting

$$[dk_i] |M(k_i)|^2 \sim \alpha_s(k_t) \frac{dk_t}{k_t} d\eta$$ Ensemble of independent soft-collinear gluons

NLL results for Lund observables

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

So that the cumulative cross-section can be written as

$$\Sigma(v) = e^{-R_{sc}(v)-R_{hc}(v)} \times \mathcal{F}_{\mathrm{NLL}}$$

Analytic

Numerical (in general)

The NLL results for the Lund observables are: [Dasgupta et al. PRL 125 (2020) 5, 052002]

$$\Sigma(M_\beta) = e^{-R^{\mathrm{NLL}}(M_\beta)}$$

$$\Sigma(S_\beta) = e^{-R^{\mathrm{NLL}}} \times \frac{e^{-\gamma_E R'}}{\Gamma(1+R')}$$

NNLL resummation (ARES approach) in a nutshell

[Banfi, McAslan, Monni, Zanderighi JHEP 05 (2015) 102]   [Banfi, El-Menoufi and Monni JHEP 01 (2019) 083]

The interplay between real and virtual emissions notably more delicate

$$\Sigma_{\rm NNLL}(v) = e^{-R_{sc}(v)-R_{hc}(v)}$$
$$\times \left[\mathscr{F}_{\rm NLL}\left(1+\frac{\alpha_s(Q)}{2\pi}H^1+\frac{\alpha_s(Q_{hc})}{\pi}C^1\right)+\frac{\alpha_s(Q)}{\pi}\delta\mathscr{F}_{\rm NNLL}\right]$$

where, **schematically**, the physical origin of each NNLL correction is

- $e^{-R_{sc}(v)}$: $\alpha_s^{\rm phys} = \alpha_s(1+\sum_{n=1}^{2}\left(\frac{\alpha_s}{2\pi}\right)^n K^n)$ with $K^1 = K^{\rm CMW}$
- $e^{-R_{hc}(v)}, C_1$: end-point of DGLAP splitting function
- H_1 : finite part of one-loop virtual corrections

NNLL resummation (ARES approach) in a nutshell

[Banfi, McAslan, Monni, Zanderighi JHEP 05 (2015) 102] [Banfi, El-Menoufi and Monni JHEP 01 (2019) 083]

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$$\Sigma_{\rm NNLL}(v) = e^{-R_{sc}(v)-R_{hc}(v)} \times \left[\mathcal{F}_{\rm NLL}\left(1+\frac{\alpha_s(Q)}{2\pi}H^1+\frac{\alpha_s(Q_{hc})}{\pi}C^1\right)+\frac{\alpha_s(Q)}{\pi}\delta\mathcal{F}_{\rm NNLL}\right]$$

where, **schematically**, the physical origin of each NNLL correction is

- $\delta\mathcal{F}_{\rm NNLL}$: one single emission with NLL-like kinematics

hard-collinear $\delta\mathcal{F}_{\rm rec}$ $\delta\mathcal{F}_{\rm hc}$

soft-coll, wide-angle $\delta\mathcal{F}_{\rm wa}$ $\delta\mathcal{F}_{\rm sc}$

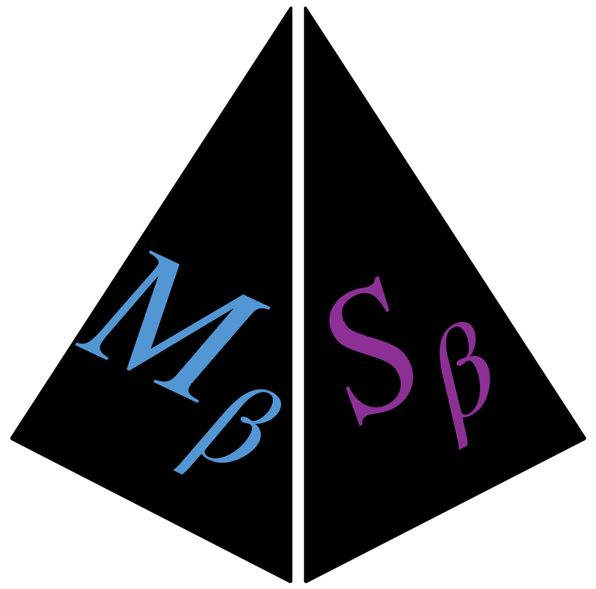
soft, commensurate angle to other emission $\delta\mathcal{F}_{\rm correl}$, $\delta\mathcal{F}_{\rm clust}$

Some remarks for Lund observables at NNLL

We recycled a few ingredients from previous works

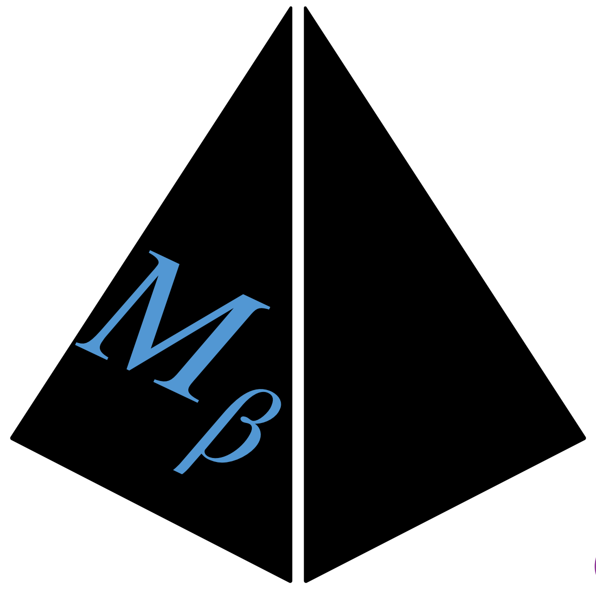
- $e^{-R_{sc}(v)-R_{hc}(v)}$ $\left(1+\frac{\alpha_s(Q)}{2\pi}H^1+\frac{\alpha_s(Q_{hc})}{\pi}C^1\right)$ analytic and computed in [Banfi, El-Menoufi and Monni JHEP 01 (2019) 083]
- $\mathscr{F}_{\mathrm{NLL}}$ analytic and computed in [Dasgupta et al. PRL 125 (2020) 5, 052002]

and computed the remaining NNLL corrections



$\delta\mathscr{F}_{\mathrm{wa}}=0$

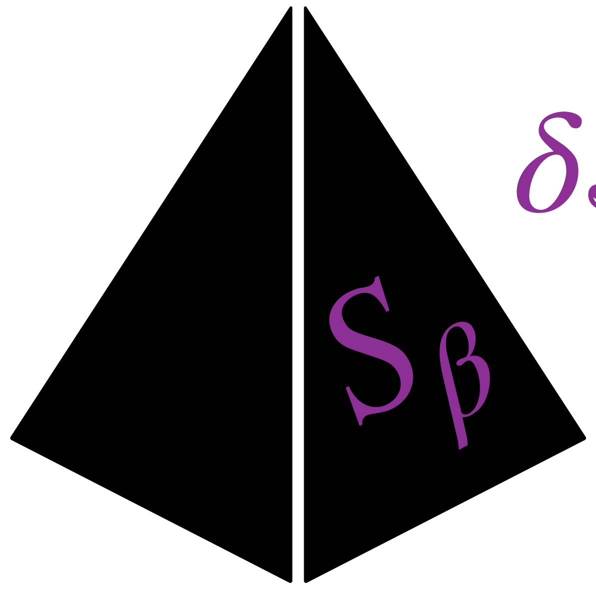
$\delta\mathscr{F}_{\mathrm{clust}}, \delta\mathscr{F}_{\mathrm{correl}}$ semi-analytic, same for both



$\delta\mathscr{F}_{\mathrm{sc}}=0$

$\delta\mathscr{F}_{\mathrm{hc}}=0$

$\delta\mathscr{F}_{\mathrm{rec}}$ analytic

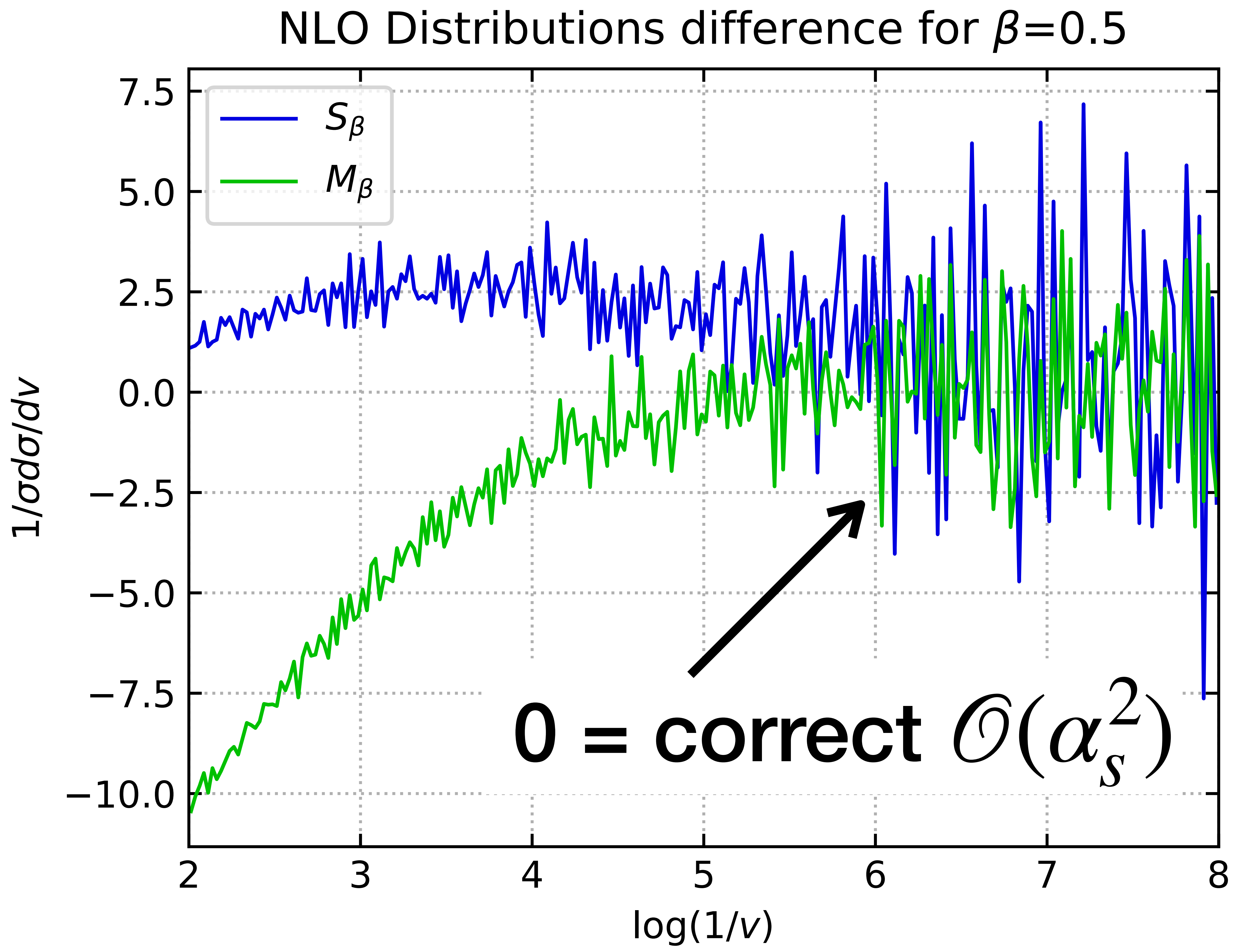


$\delta\mathscr{F}_{\mathrm{sc}}, \delta\mathscr{F}_{\mathrm{hc}}$

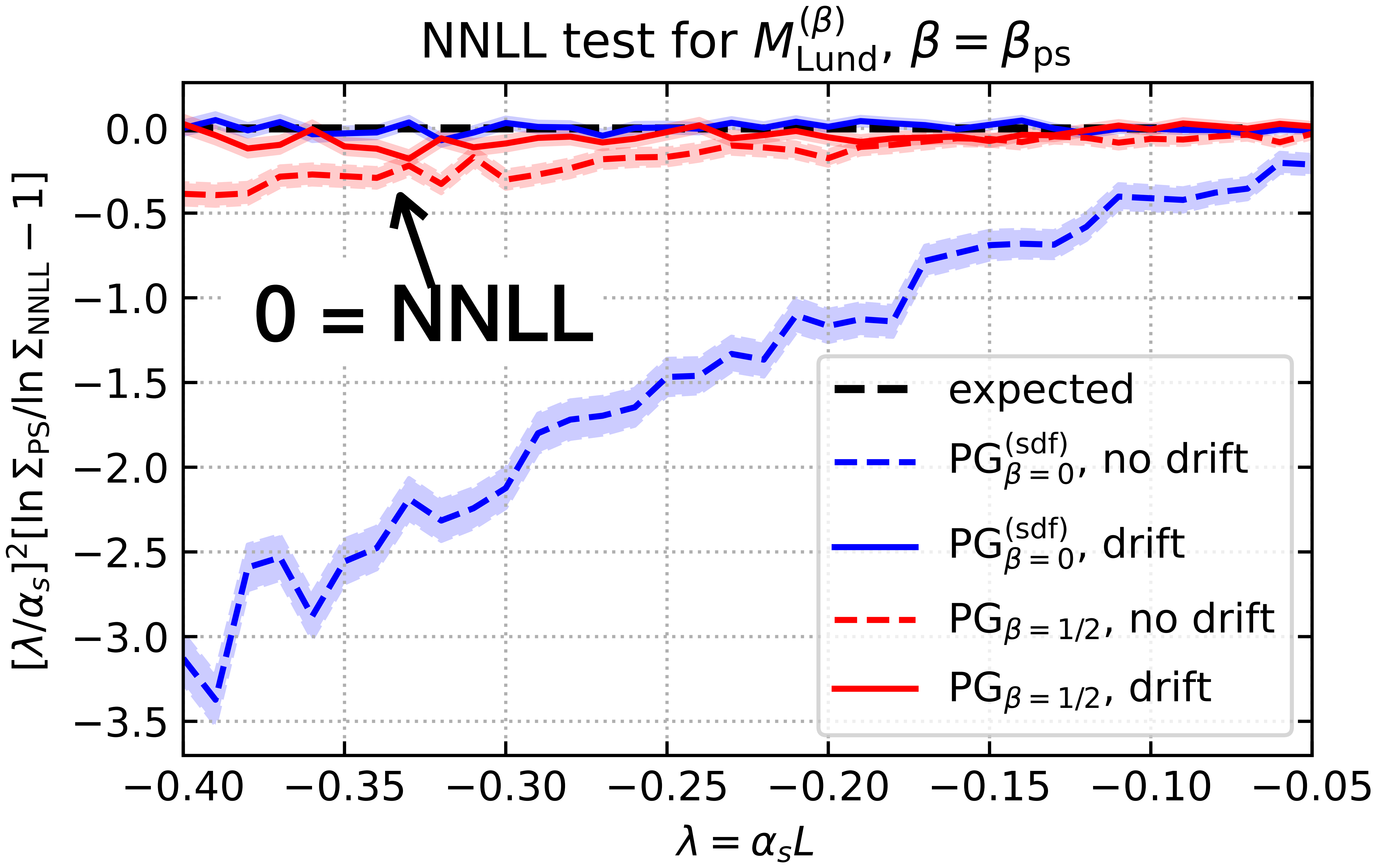
$\delta\mathscr{F}_{\mathrm{rec}}$ analytic

Cross-checks against Event2 and PanScales showers

Fixed-order check



All-orders check



Full agreement between analytic calculation and numerics

Plan for this talk

NNLL resummation in e^+e^- collisions

Sneak peek at pheno with PanScales-Pythia interface

[PanScales Collab. arXiv:2312.13275]

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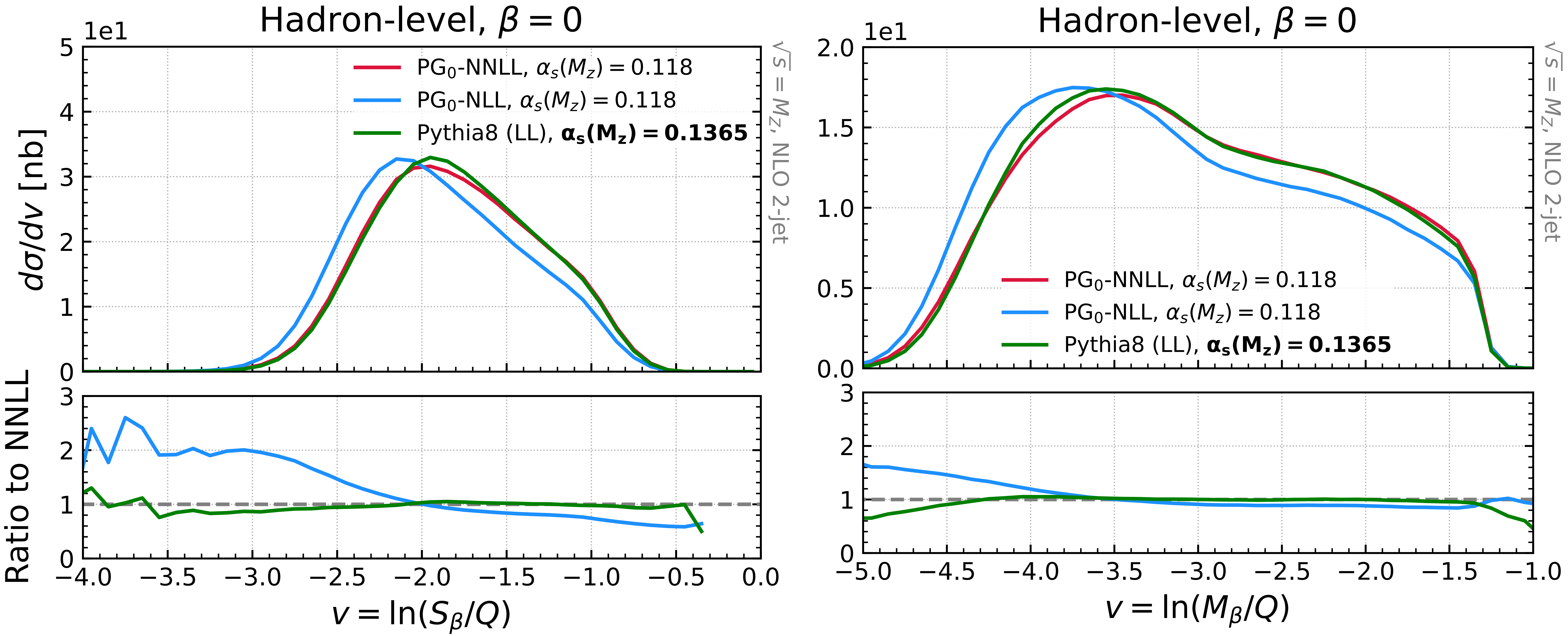
Sensitivity to non-perturbative corrections @LEP energies

Significantly smaller hadronisation corrections for M_β

Sensitivity to non-perturbative corrections @FCs energies

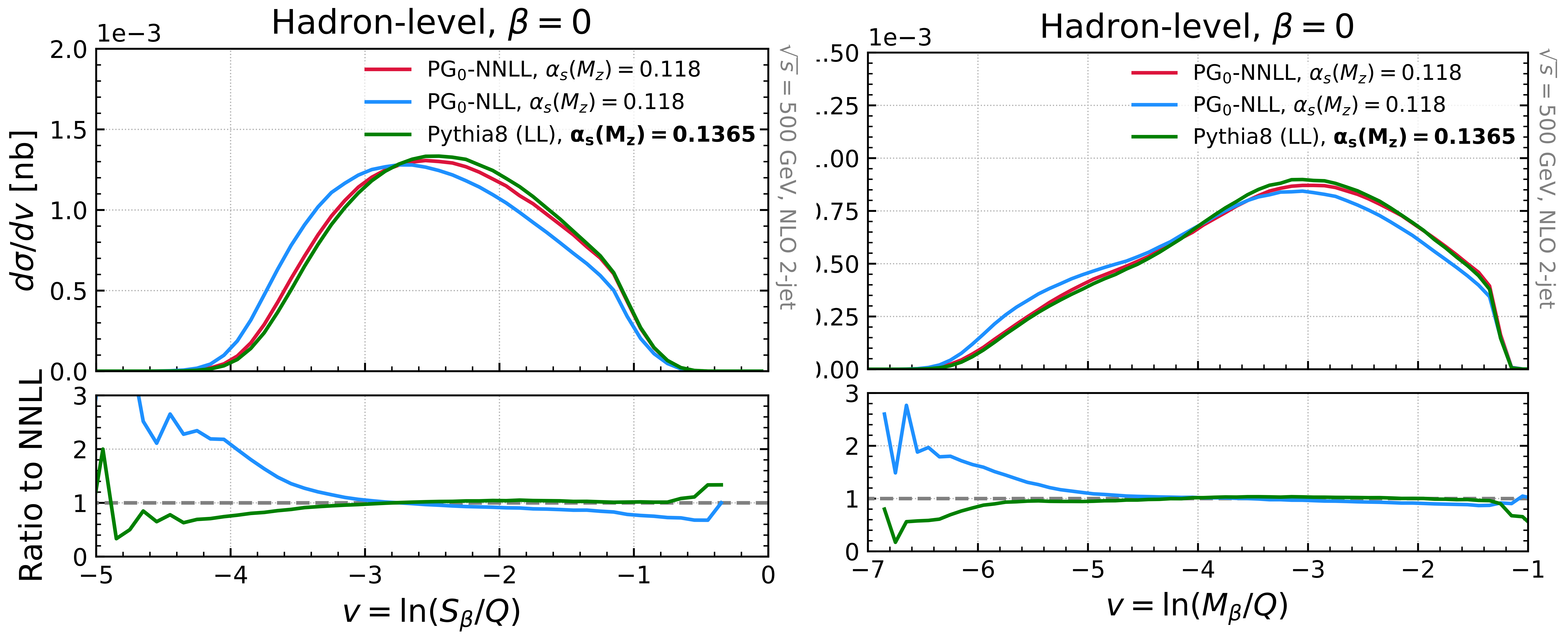
Perturbative regime clearly extended when going to higher energies

Comparison between showers @LEP energies



Physical value of $\alpha_s(M_Z)$ for PG$_0$. Missing shower uncertainties

Comparison between showers @FCs energies



Similar results for other β values. Plots with uncertainties coming soon

Summary and outlook

- Presented NNLL resummation for two new Lund observables

$$S_\beta = \sum_{i\in\text{declust}} \frac{k_{t,i}}{Q} e^{-\beta|\eta_i|} \qquad M_\beta = \max_{i\in\text{declust}} \frac{k_{t,i}}{Q} e^{-\beta|\eta_i|}$$

- M_β has a particularly simple resummation structure and small sensitivity to non-perturbative corrections

- Future directions: extension to hadron collisions (both globally and inside a jet), matching of the resummed predictions, systematic pheno study @LHC