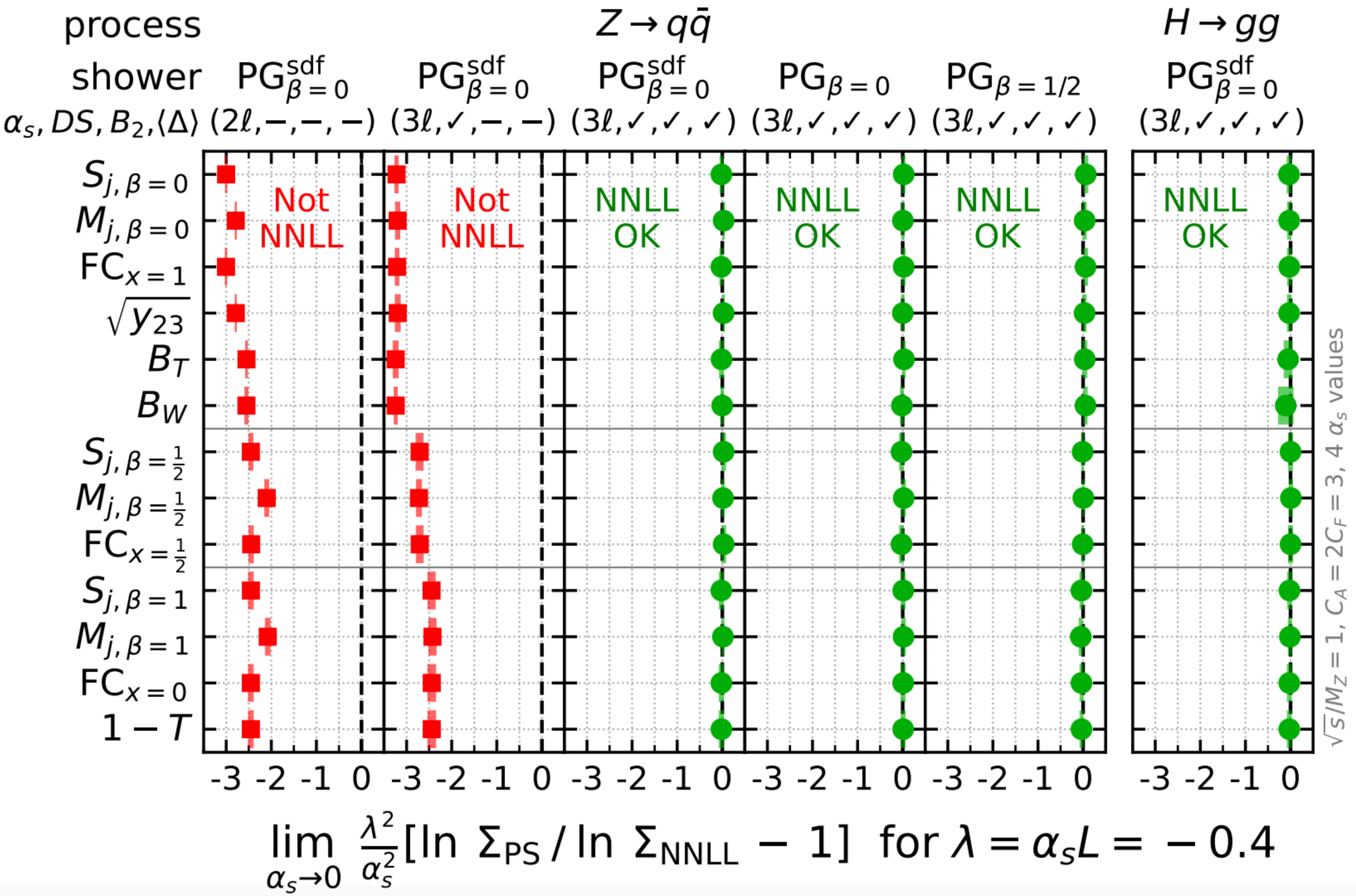
Parton showers with higher logarithmic accuracy



ATLAS meeting - 12/07/2024

Melissa van Beekveld

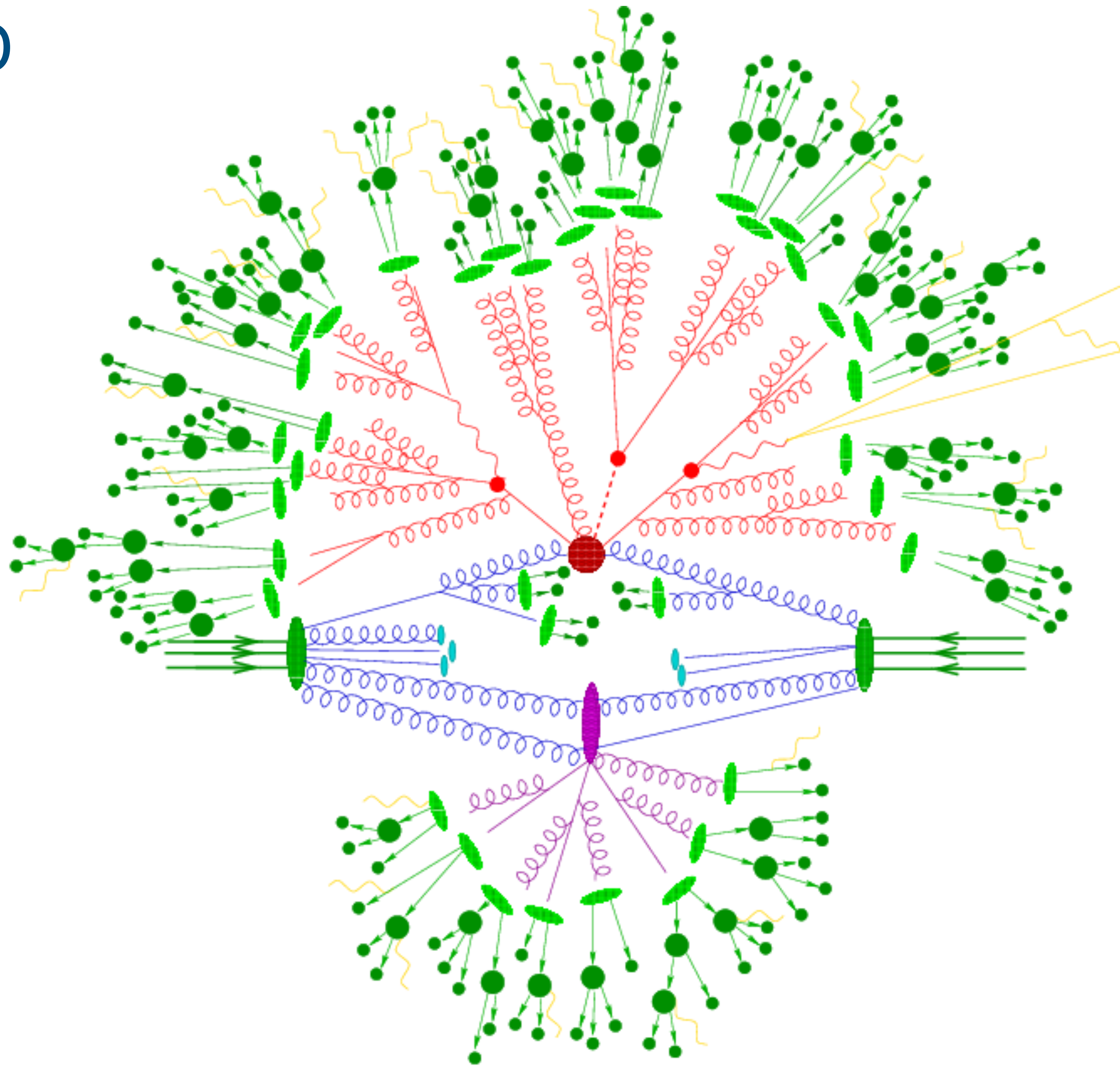
Nikhef

The perturbative side of QCD showers

- Designed from **first principles**: its ingredients are QCD matrix elements (MEs) that describe the unresolved limits

- After integration over phase space these MEs give rise to logarithms - roughly:
  - Single unresolved (collinear / soft) → leading and next-to-leading logarithms
  - Double unresolved (triple collinear / double soft) → next-to-next-to-leading logarithms

- Perturbative shower accuracy comes in two forms:
  1. Higher-order matching (standard game for the past 20 years)
  2. **Logarithmic accuracy** (the new kid on the block)



Parton showers: a crucial ingredient

Pythia 8

An introduction to PYTHIA 8.2 #1

Torbjörn Sjöstrand (Lund U., Dept. Theor. Phys.), Stefan Ask (Cambridge U.), Jesper R. Christiansen (Lund U., Dept. Theor. Phys.), Richard Corke (Lund U., Dept. Theor. Phys.), Nishita Desai (U. Heidelberg, ITP) et al. (Oct 11, 2014)

Published in: *Comput.Phys.Commun.* 191 (2015) 159-177 • e-Print: 1410.3012 [hep-ph]

pdf links DOI cite 6,196 citations

PYTHIA 6.4 Physics and Manual 13,072 citations

A comprehensive guide to the physics and usage of PYTHIA 8.3 509 citations

Herwig 7

Herwig++ Physics and Manual #1

M. Bahr (Karlsruhe U., ITP), S. Gieseke (Karlsruhe U., ITP), M.A. Gigg (Durham U., IPPP), D. Grellscheid (Durham U., IPPP), K. Hamilton (Louvain U.) et al. (Mar, 2008)

Published in: *Eur.Phys.J.C* 58 (2008) 639-707 • e-Print: 0803.0883 [hep-ph]

pdf links DOI cite 3,098 citations

Herwig 7.0/Herwig++ 3.0 release note 1,449 citations

Sherpa

Event generation with SHERPA 1.1 #1

T. Gleisberg (SLAC), Stefan. Hoeche (Zurich U.), F. Krauss (Durham U., IPPP), M. Schonherr (Dresden, Tech. U.), S. Schumann (Edinburgh U.) et al. (Nov, 2008)

Published in: *JHEP* 02 (2009) 007 • e-Print: 0811.4622 [hep-ph]

pdf links DOI cite 3,789 citations

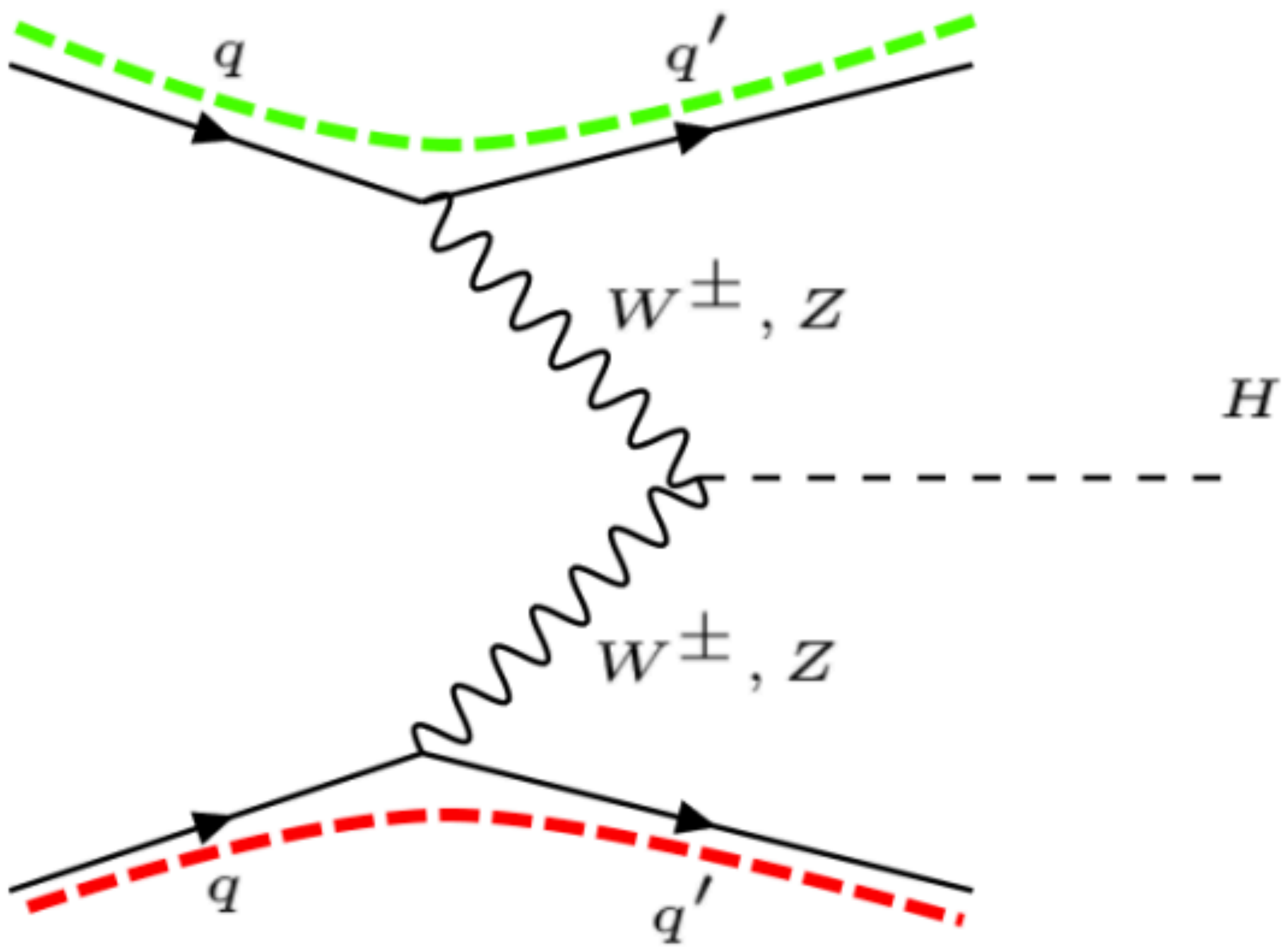
Event Generation with Sherpa 2.2 995 citations

Do an amazing job at describing the phenomenology at colliders
(and sometimes even beyond colliders)

[2003.12435, 2105.11399, 2106.10987]

But differences matter…

VBF production of $h + 2j$

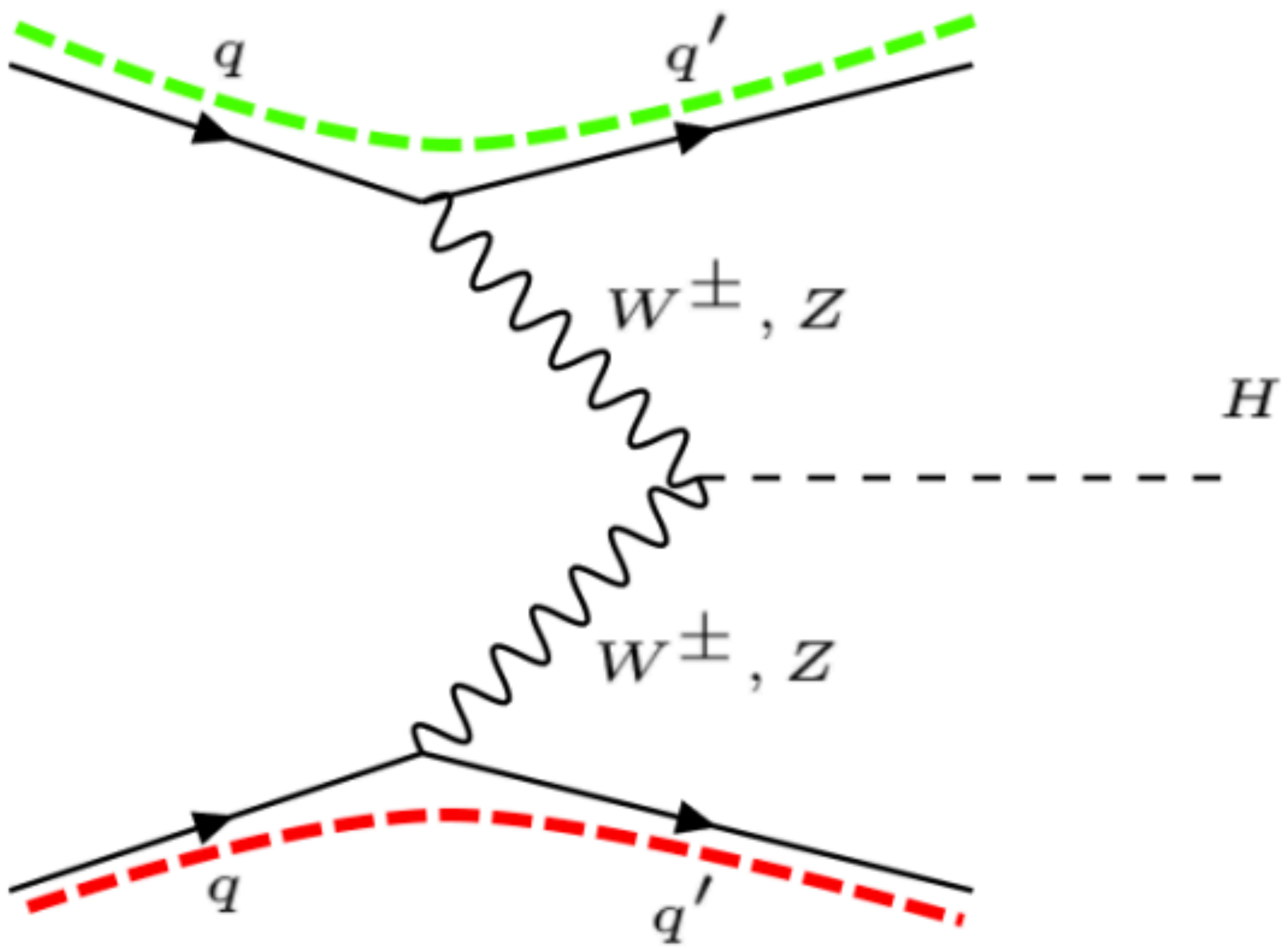


Colour coherence strongly **suppresses** radiation in central rapidity region

[2003.12435, 2105.11399, 2106.10987]

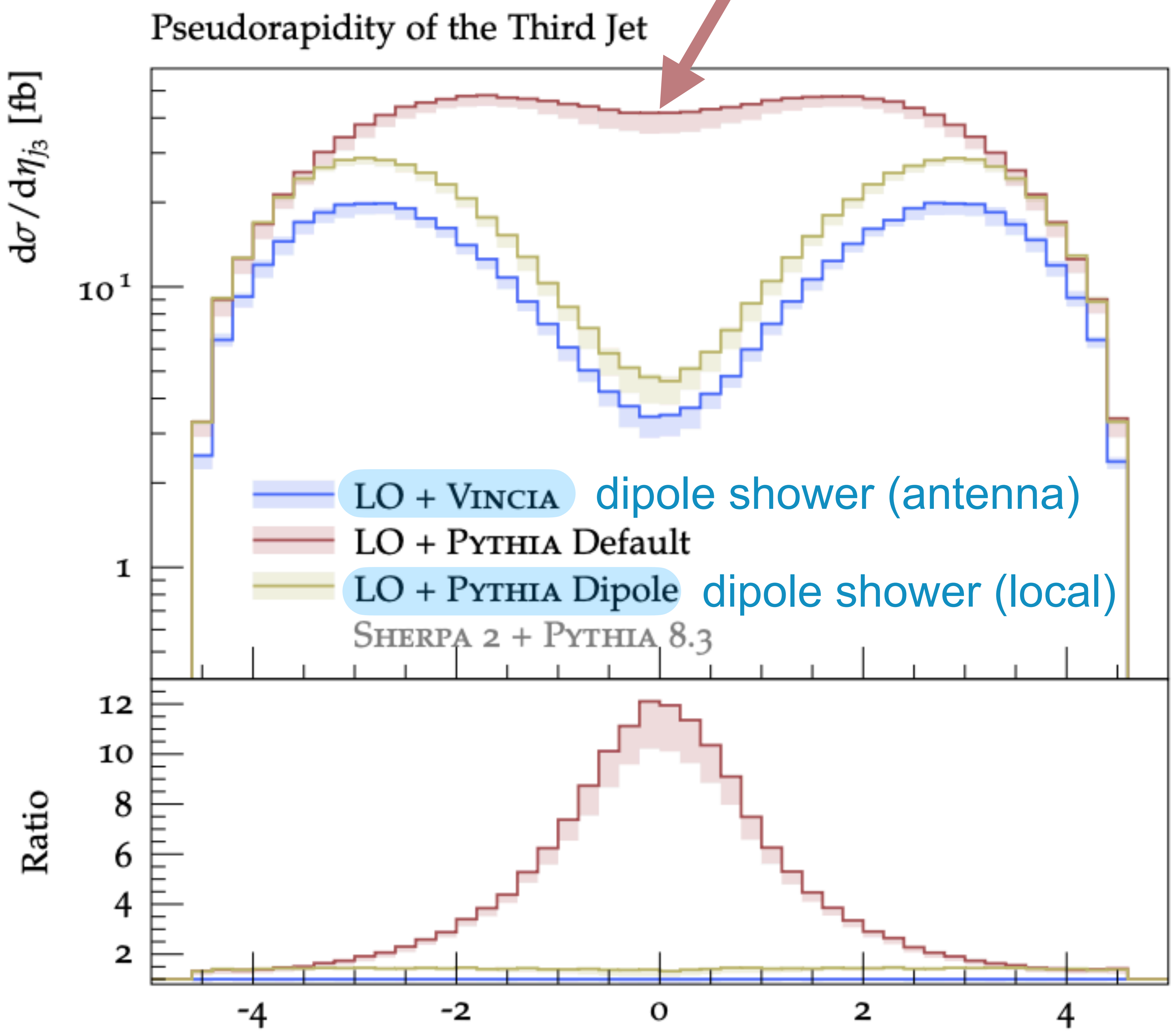
But differences matter…

VBF production of $h + 2j$



Colour coherence strongly **suppresses** radiation in central rapidity region

Pythia's default (global) shower unphysically fills this central region!



Pseudorapidity of the third jet

Sometimes showers are just simply **wrong**

But differences matter…

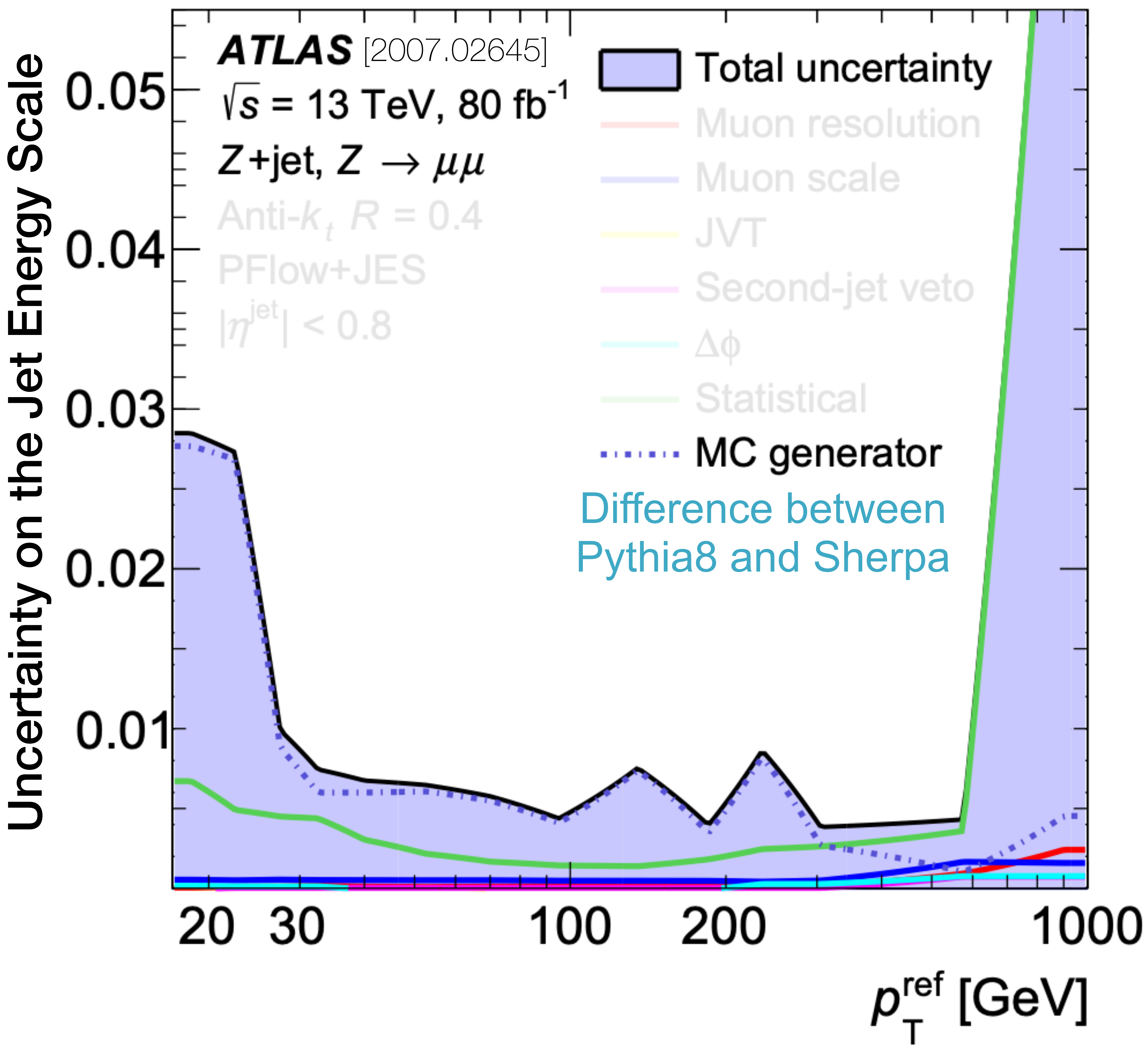
A precise jet-calibration is important for many SM and BSM searches

Corrects directions and energies of measured jets to the objects produced by the MC

Method is robust to effects from pile-up and underlying event…

Leading uncertainty originates from different parton-shower modeling

[see also 2303.17312]

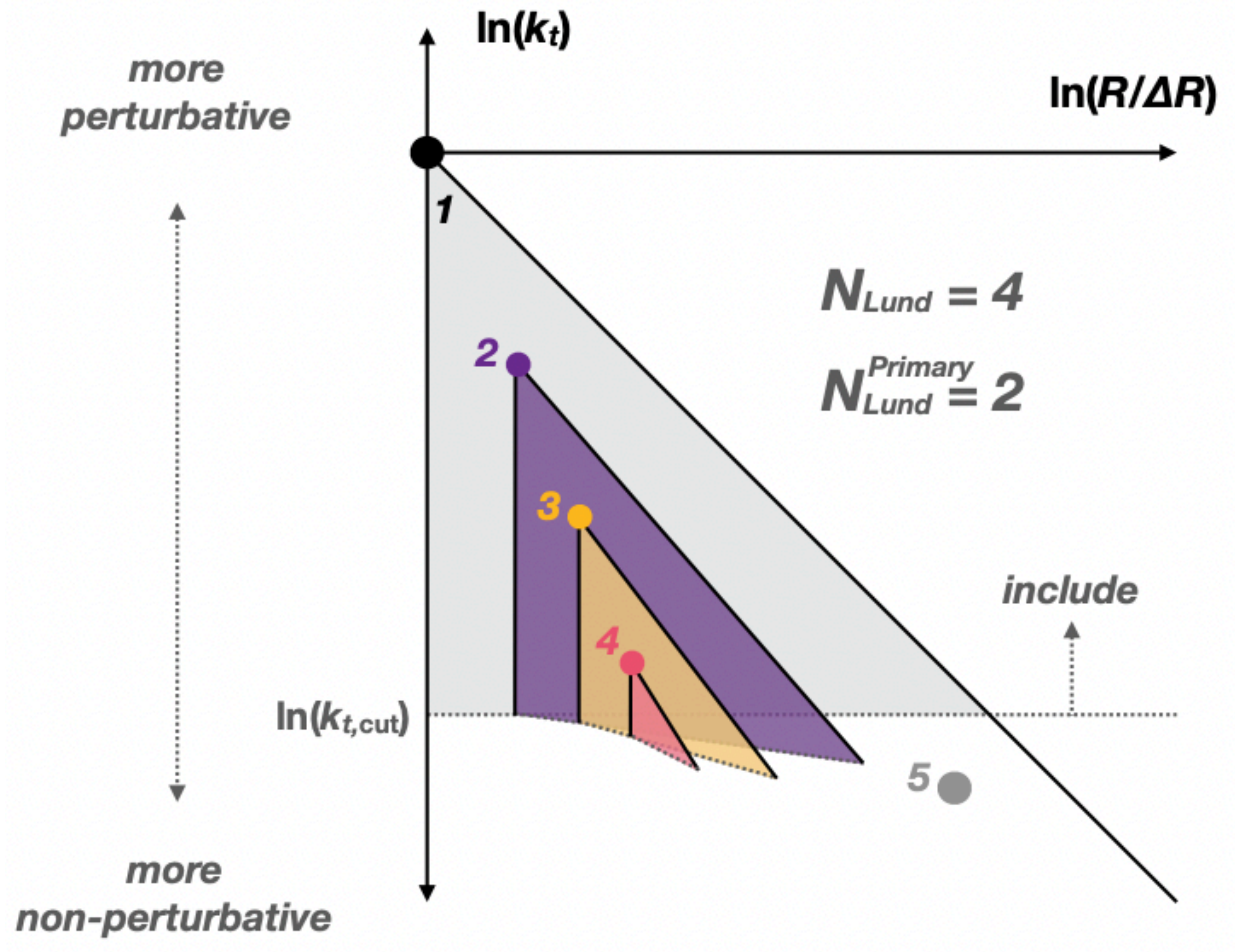


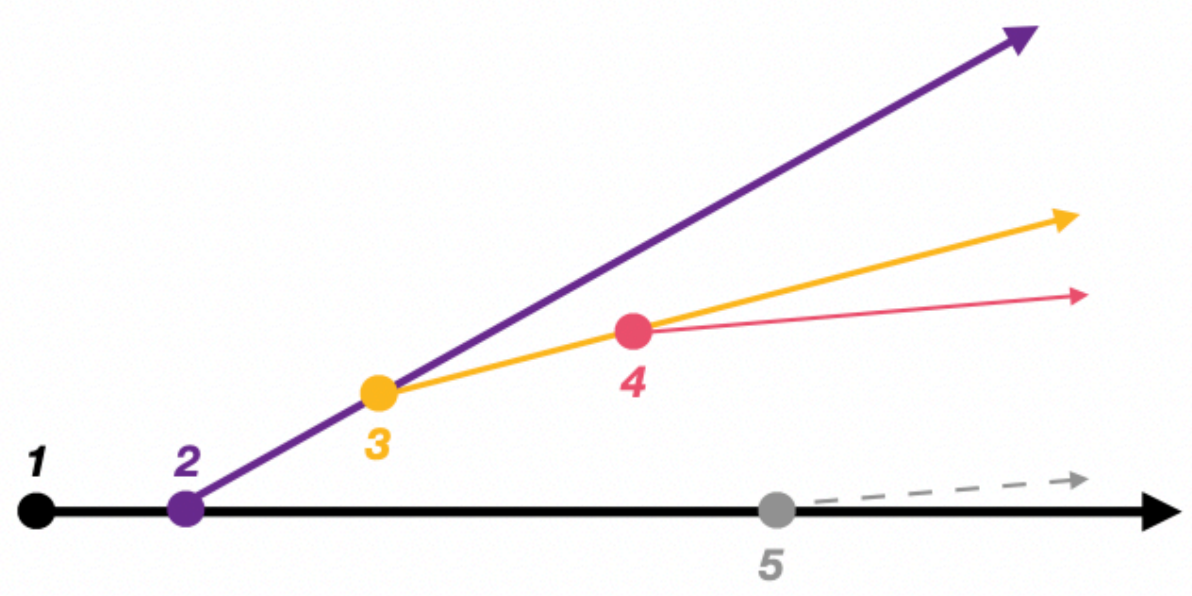
Melissa van Beekveld

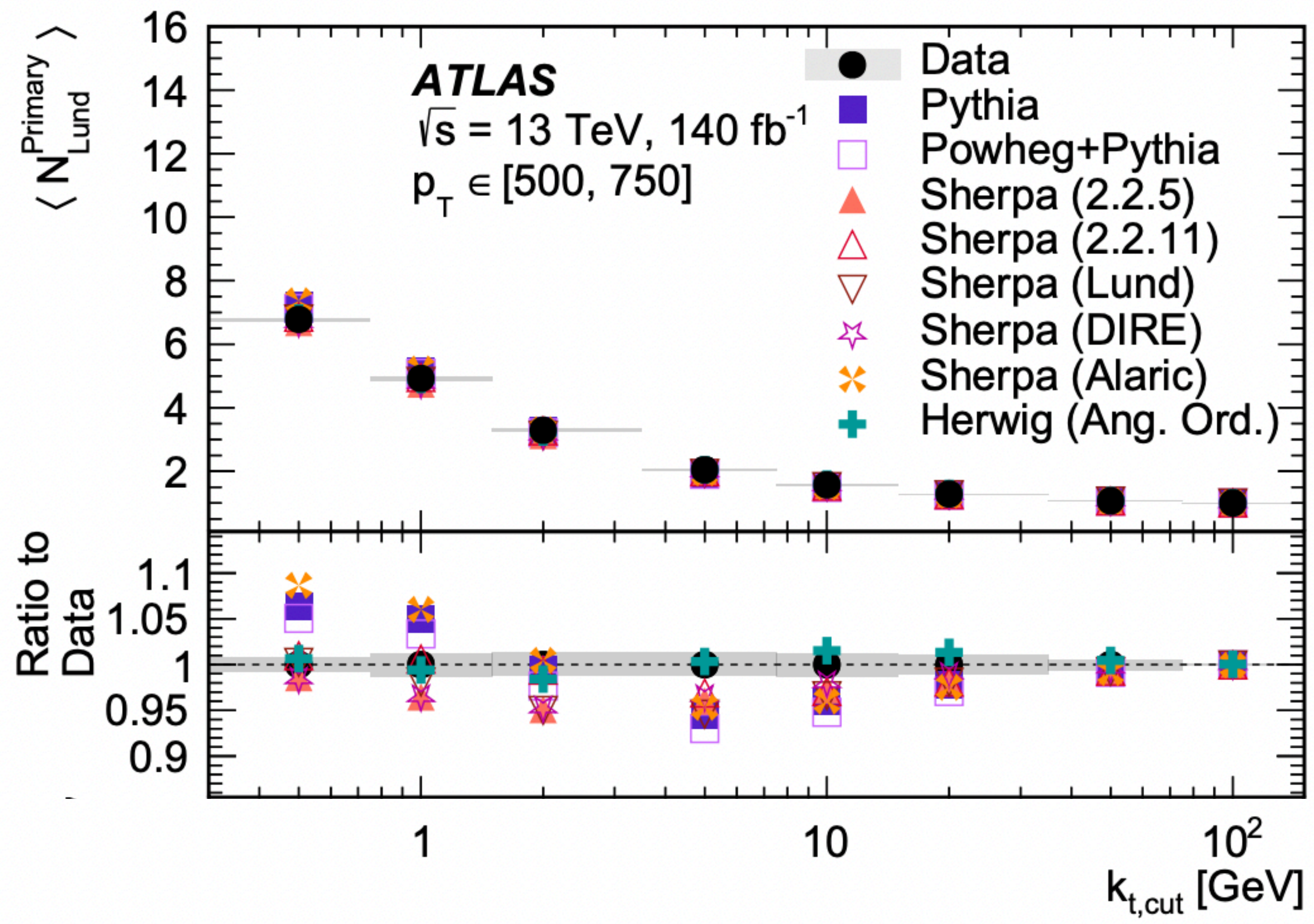
But differences matter…

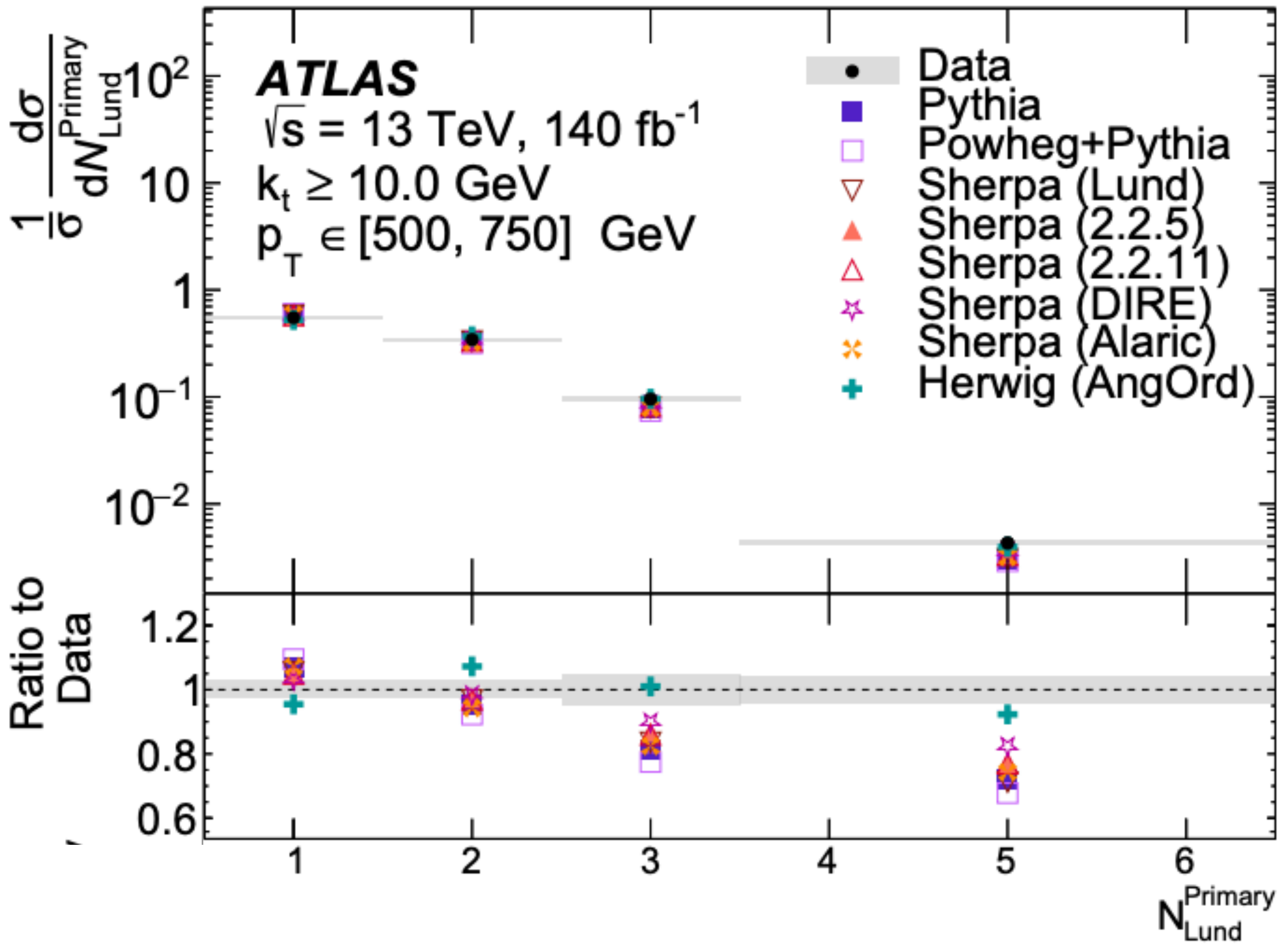
Consider measurement of Lund (sub)jet multiplicity

[2402.13052]









We see differences between
1. different showers
and
2. showers vs data
for several analyses

We need to understand what is going on

- Issues can appear in two regimes:
  1. Hadronic/non-perturbative (no first-principle model → tune shower)
  2. Perturbative (QCD tells us what needs to happen)

- Showers are **always** tuned → faulty shower descriptions may be tuned away
  - Problem: you do not control the more differential observables!

- My fear: we tune away new physics by taking a wrong perturbative shower as baseline!

- Standard answer: we cannot control showers…

The PanScales collaboration

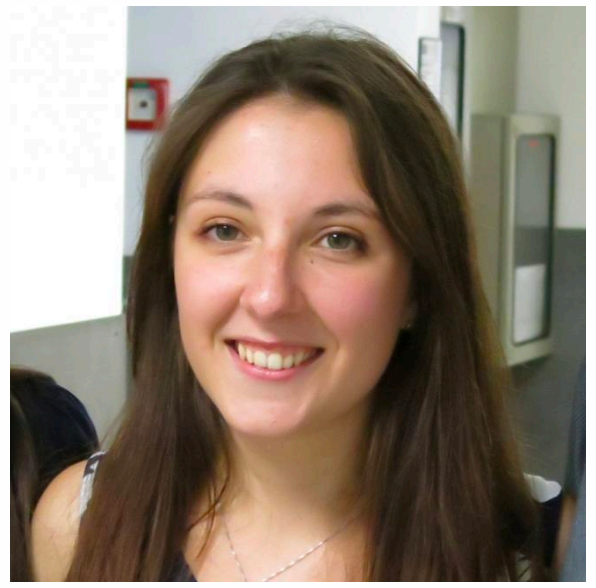

Gavin Salam


Gregory Soyez


Keith Hamilton


Mrinal Dasgupta


Pier Monni


Silvia Ferrario Ravasio


Alba Soto Ontoso


Alexander Karlberg


Basem El-Menoufi


Jack Helliwell


Ludo Scyboz


Silvia Zanoli


Melissa van Beekveld

+ past members
Frederic Dreyer
Emma Slade
Rok Medves
Rob Verheyen

PanScales criteria for logarithmically accurate showers

- Get the correct parton matrix element for kinematic configurations the shower is supposed to control (i.e. soft/collinear for NLL, double-soft/triple-collinear for NNLL)
- Reproduce analytic resummation results at the claimed accuracy
  - Global event shapes
  - Non-global observables
  - Fragmentation/DGLAP evolution
  - Multiplicities

Dasgupta, Dreyer, Hamilton, Monni, Salam [1805.09327], + Soyez [2002.11114]

[2002.11114]

Testing the resummation of showers

Not so easy: showers are numerical, resummation semi-analytic

Testing the resummation of showers

Not so easy: showers are numerical, resummation semi-analytic

Consider e.g. Cambridge y_{23}

Observable with standard resummation at NLL of the form

$$\Sigma_{\mathrm{NLL}}(\lambda, \alpha_s) = \exp\left[-L g_1(\lambda) + g_2(\lambda)\right]$$

with $\lambda = \alpha_s \ln \sqrt{y_{23}}$

Tested by taking $\dfrac{\Sigma^{\mathrm{PS}}(\alpha_s L)}{\Sigma^{\mathrm{NLL/NDL}}(\alpha_s L)}$?

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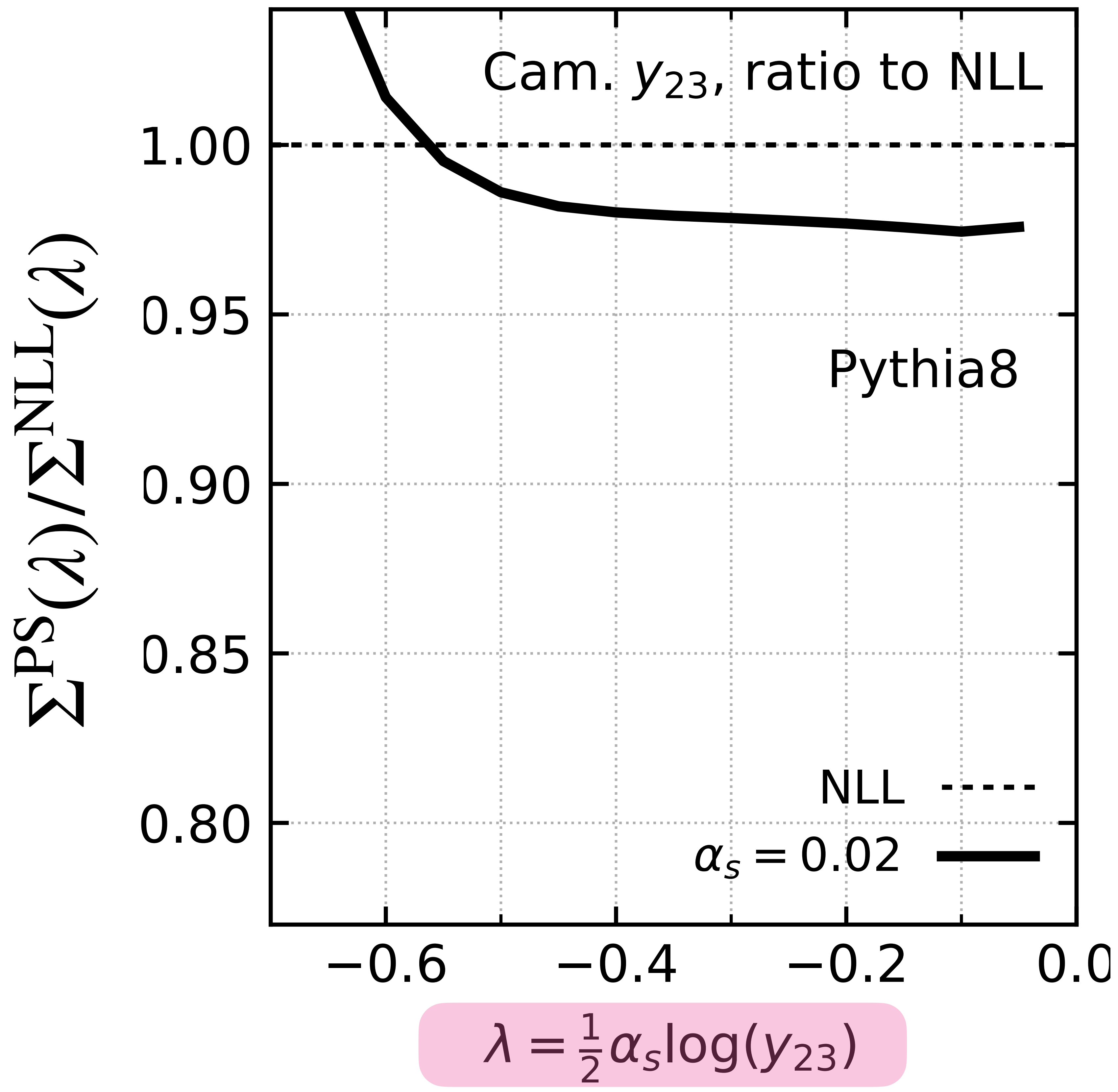

Many plots will be a function of $\lambda \equiv \alpha_s L$

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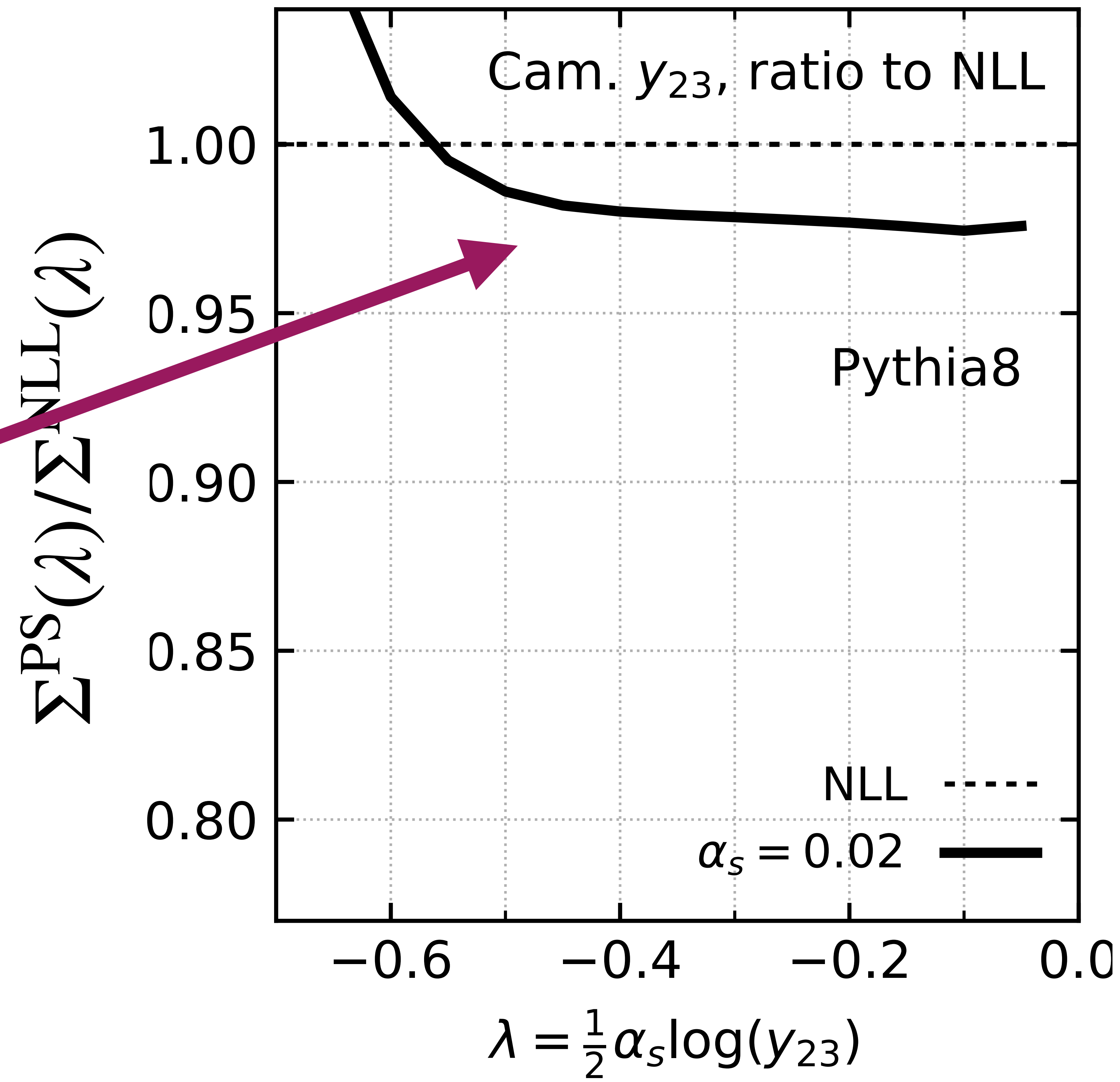
Deviates from 1: NLL mistake?

… or contribution from subleading terms?



Every shower produces uncontrolled junk beyond terms described by the ME → we need to isolate the controlled contributions

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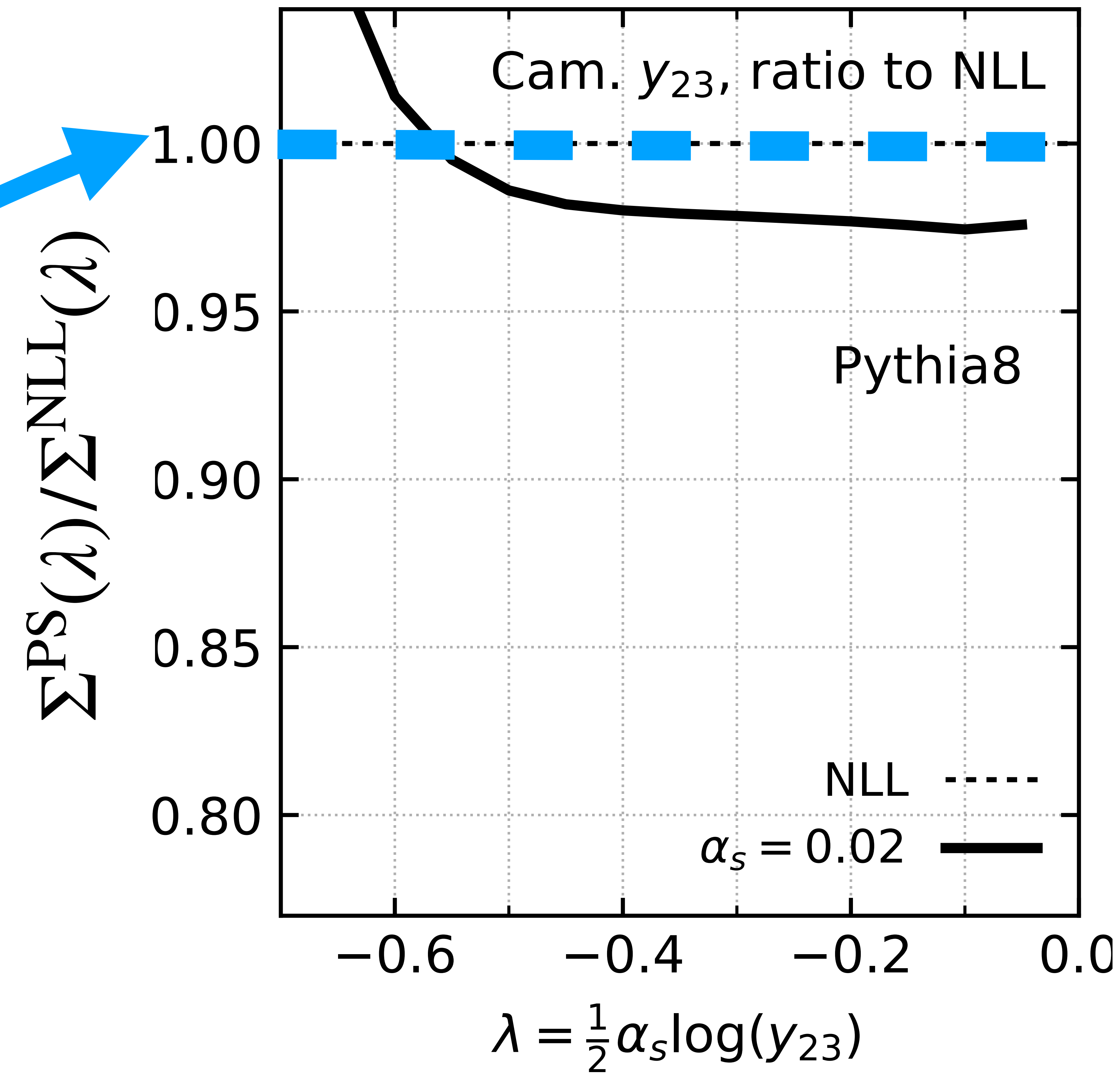
~~**Tested by taking** $\frac{\Sigma^{\text{PS}}(\alpha_s L)}{\Sigma^{\text{NLL/NDL}}(\alpha_s L)}$ **?**~~

Tested by taking $\lim_{\alpha_s \to 0} \frac{\Sigma^{\text{PS}}(\alpha_s L)}{\Sigma^{\text{NLL/NDL}}(\alpha_s L)}$

Should tend to 1 if the shower is NLL



[2002.11114]

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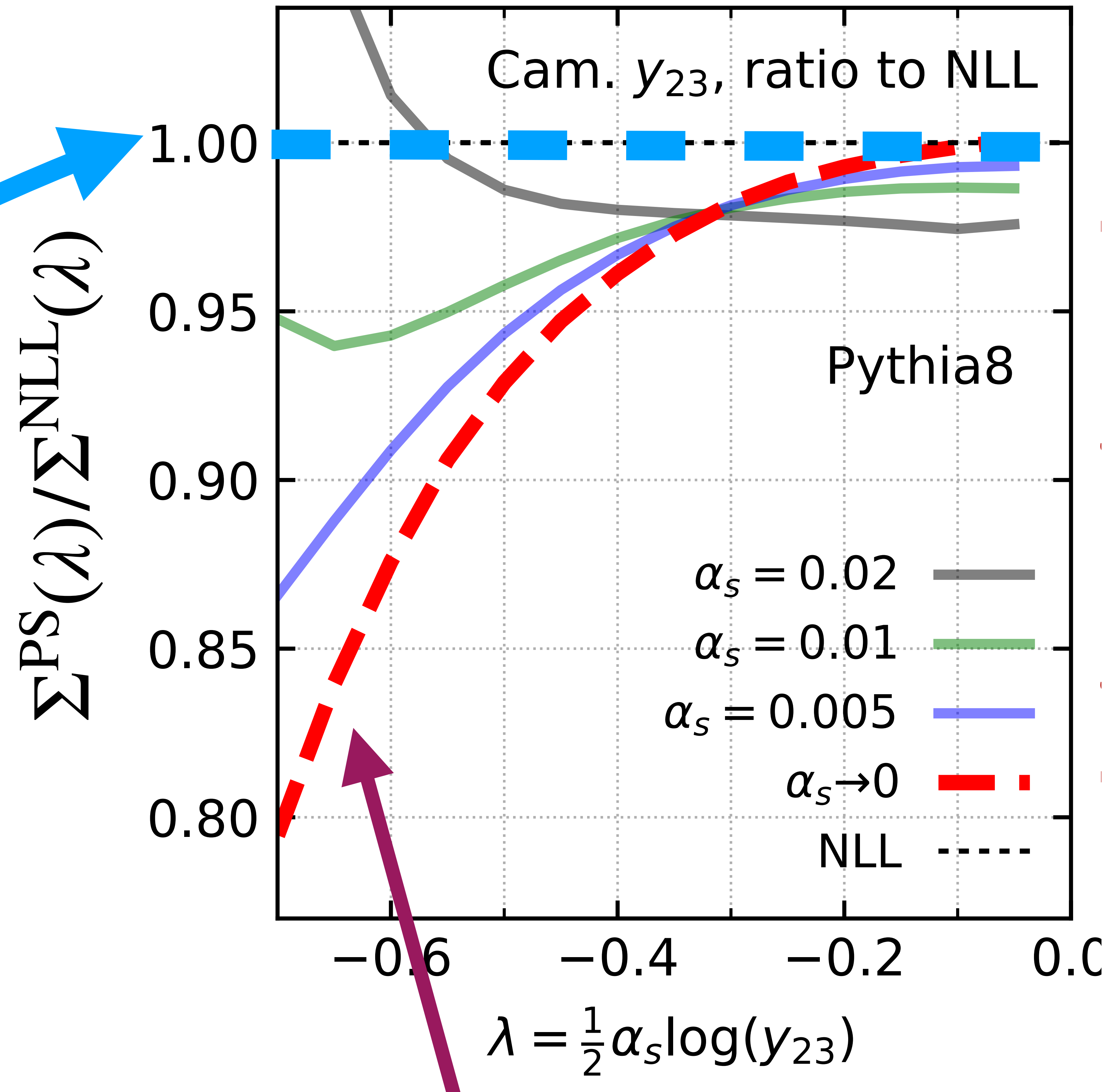


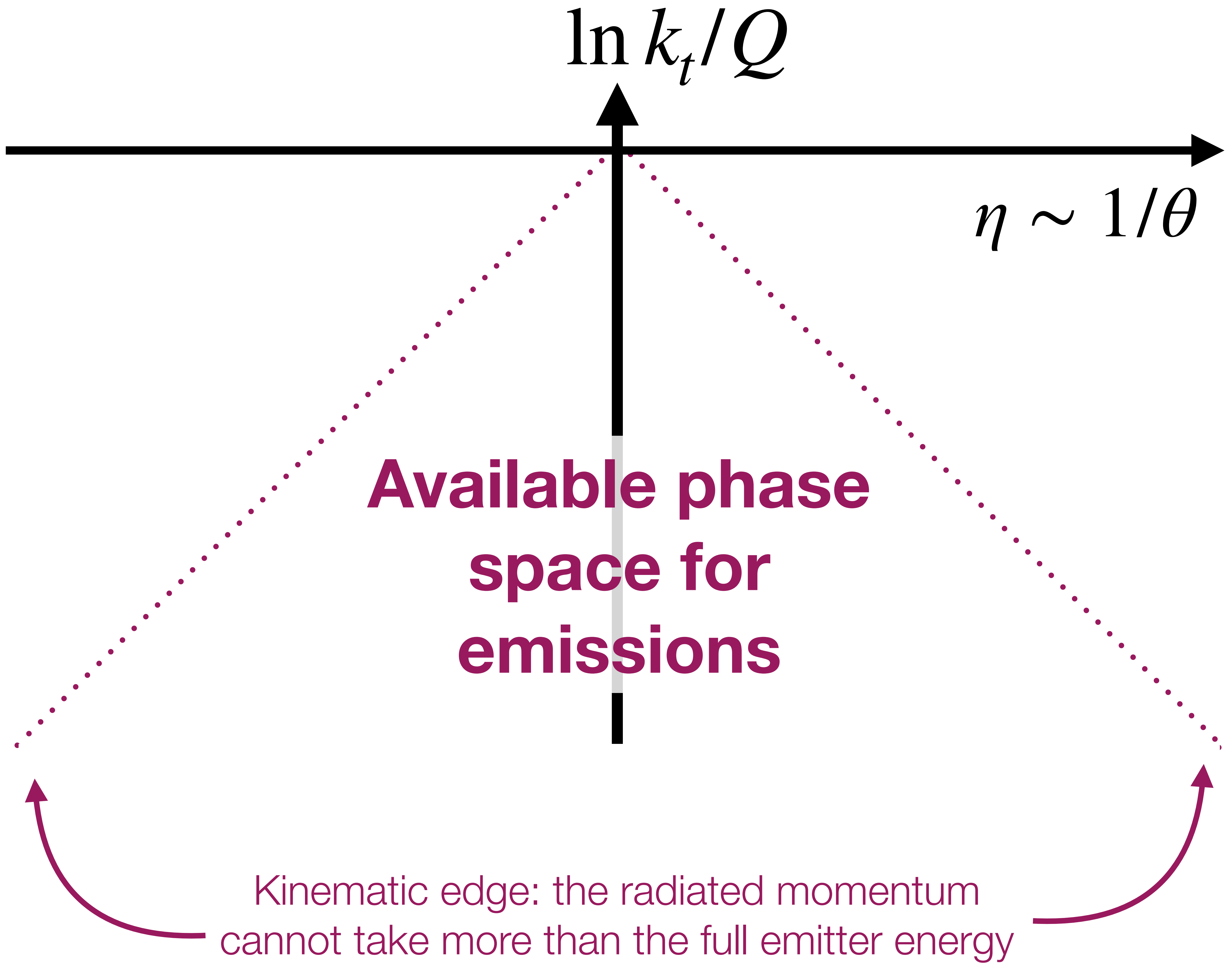
Clear deviation from 1 in the $\alpha_s \to 0$ limit

A shower is not a black box,
but something we can control

Key is to understand parton showers in the context of analytic resummation

Let’s take a theory detour to see this…

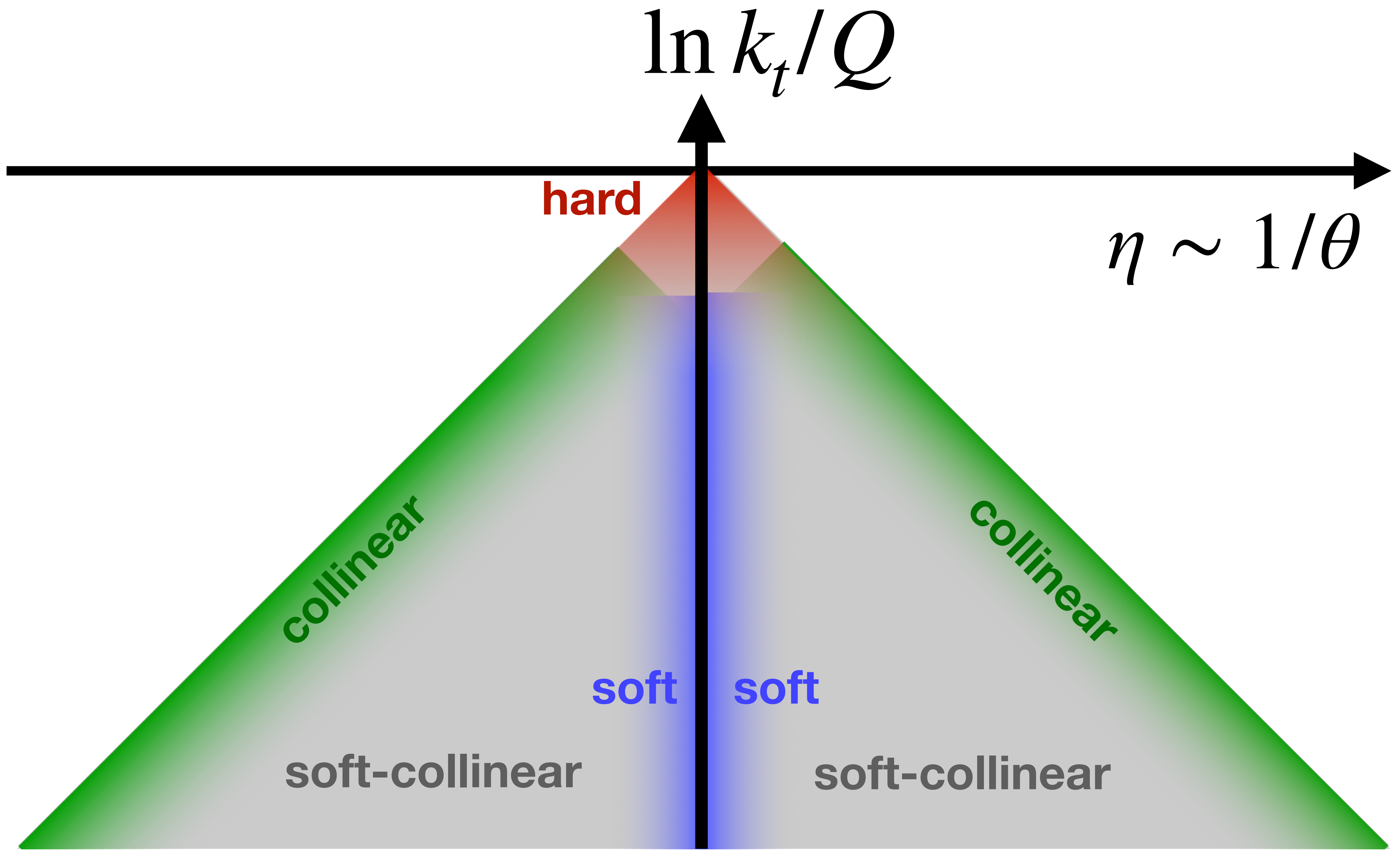
Shower



Lund plane [B. Andersson, G. Gustafson, L. Lonnblad, U. Pettersson, 1989]

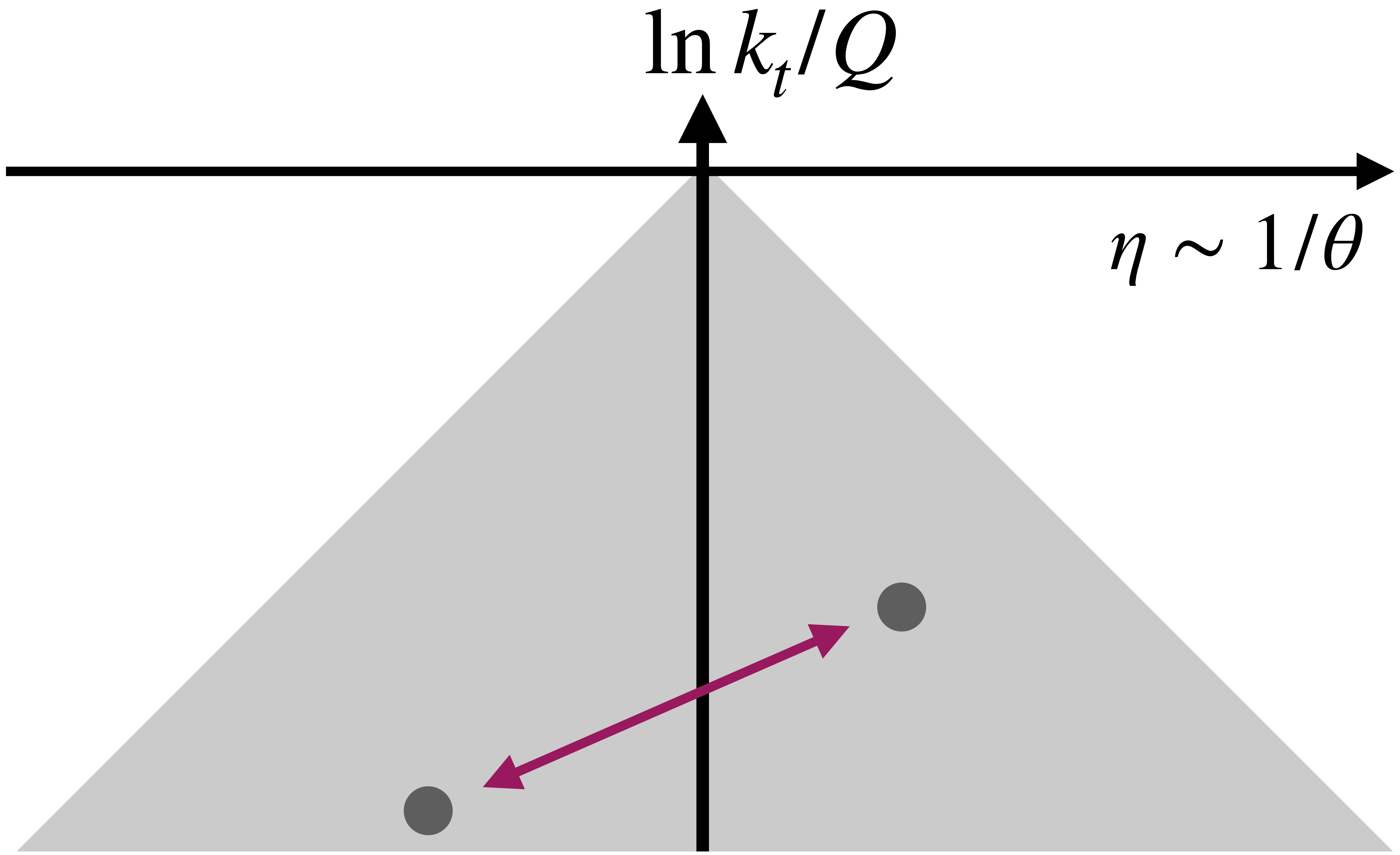
Resummation

Shower



Resummation

Shower @LL
for event shapes



Needs $\mathcal{O}(\alpha_s^n L^{n+1})$ corrections

Resummation

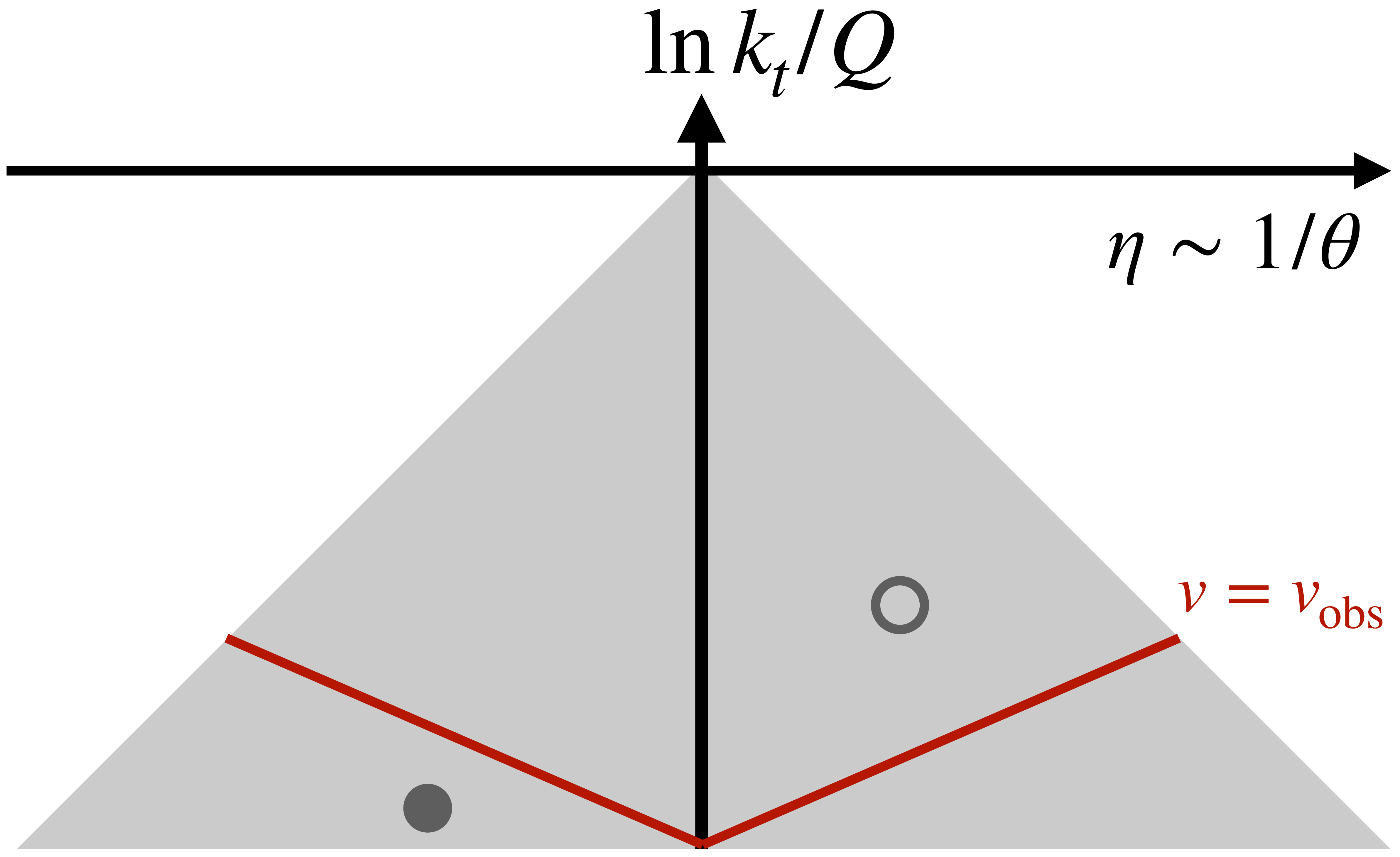
Leading-logarithmic (LL) accuracy

We only care about **soft-collinear** emissions that are **well separated** in $\ln k_t$ and η

$$dP = \frac{2C_l\alpha_s(k_t)}{\pi} d\eta \, d\ln k_t$$

Simple soft-collinear approximation of the splitting function

Shower @LL
for event shapes



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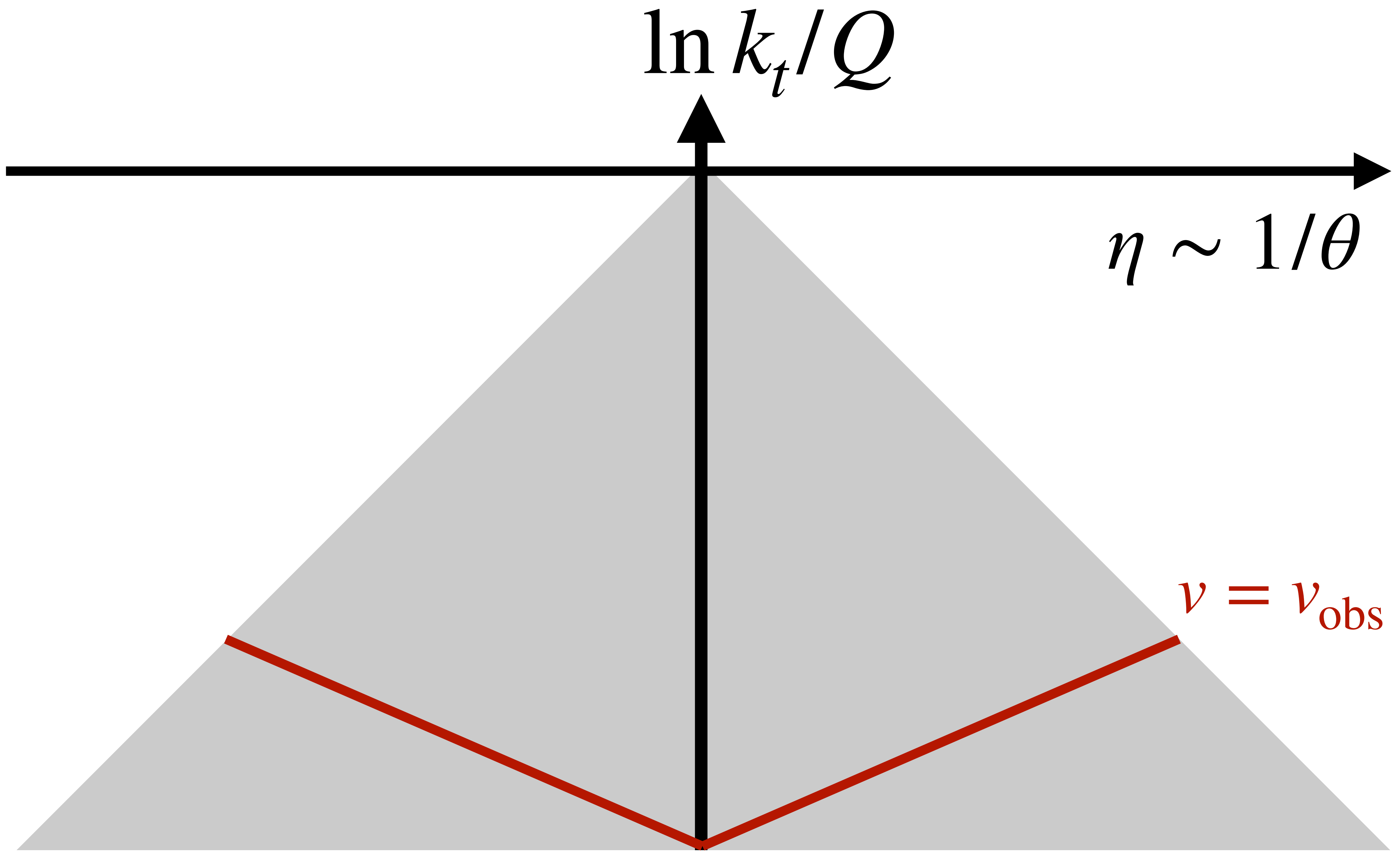
Integrating this 'weight' in a region given by the observable constraint will result in $\alpha_s L^2$ contributions ($L = \ln(v)$)

$$\Sigma_{\rm LL}(v < v_{\rm obs}) = \exp\left[-g_1(\alpha_s L)L\right]$$

Shower @NLL for event shapes



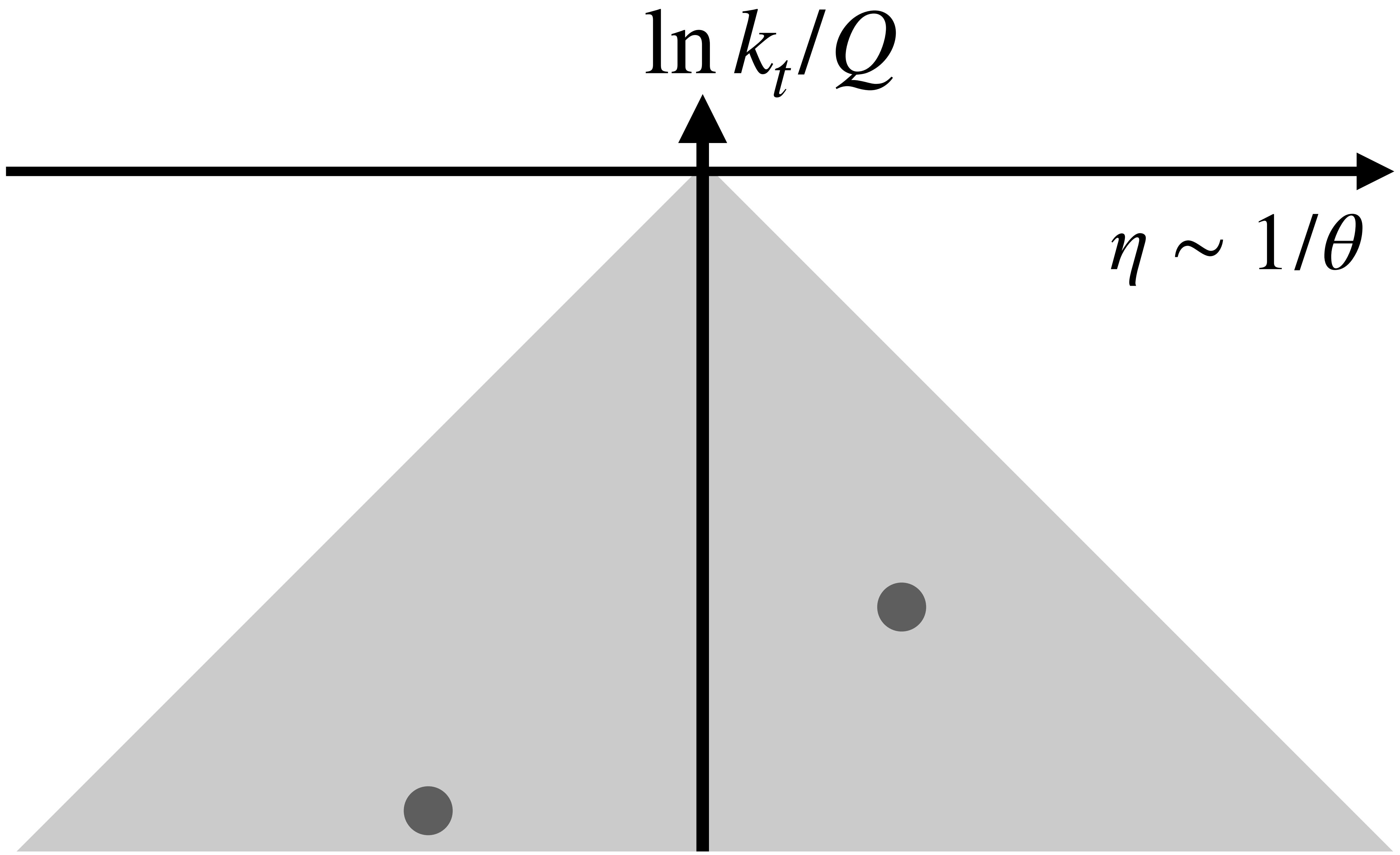
Needs $\mathcal{O}(\alpha_s^n L^n)$ corrections

Resummation

Next-to-leading-logarithmic (NLL) accuracy

$$\Sigma_{\rm NLL}(v < v_{\rm obs}) = \exp\left[-g_1(\alpha_s L)L + g_2(\alpha_s L)\right]$$

Shower @NLL
for event shapes



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Resummation

Next-to-leading-logarithmic (NLL) accuracy

1. Weight for **soft-collinear** emissions receives NLO correction

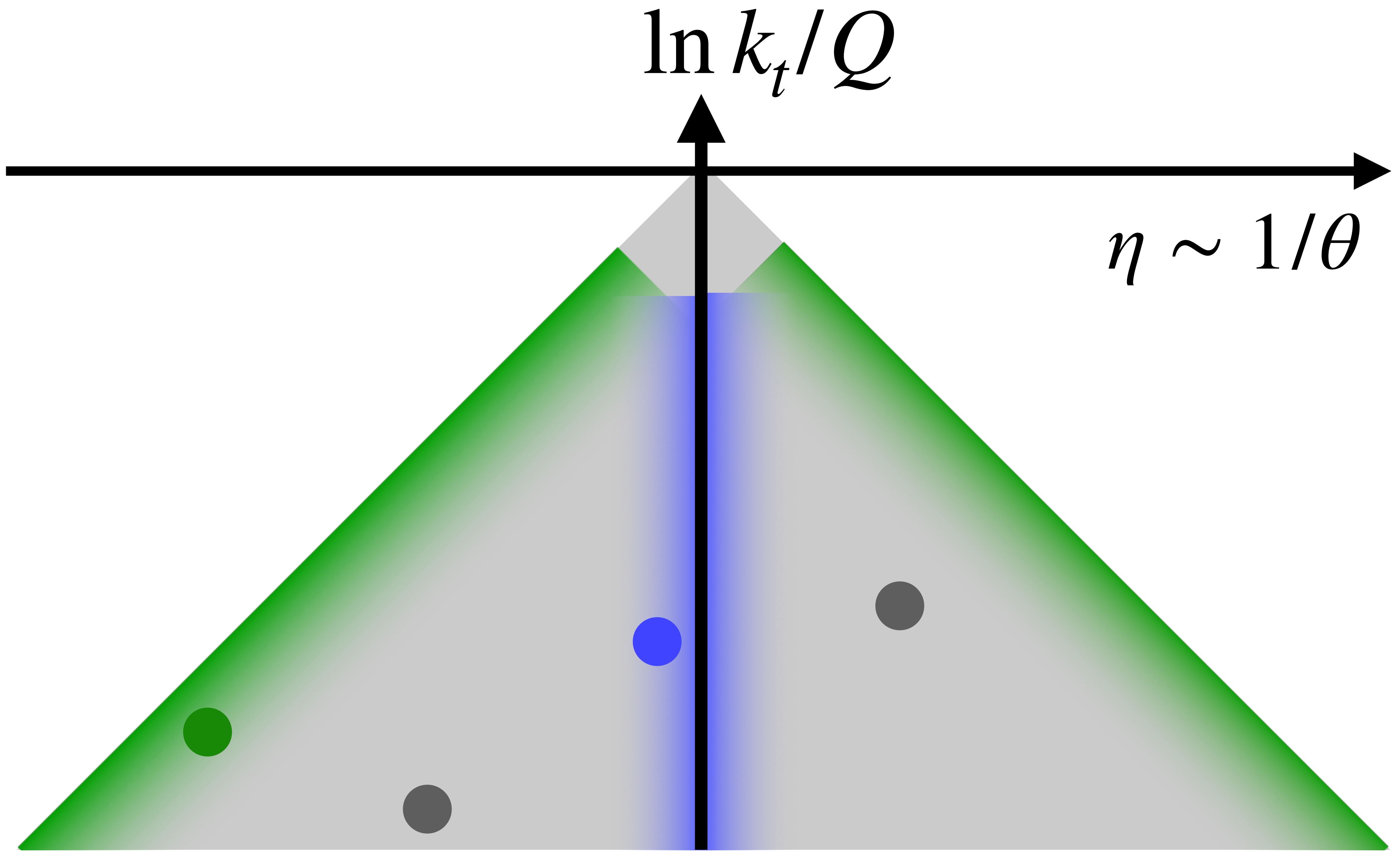
$$\alpha_s(k_t) \to \alpha_s^{\rm CMW} = \alpha_s(k_t)\left(1 + \frac{\alpha_s(k_t)}{2\pi}K_1\right)$$

(at 2 loop)

[Catani, Marchesini, Webber '91]

Shower @NLL

for event shapes



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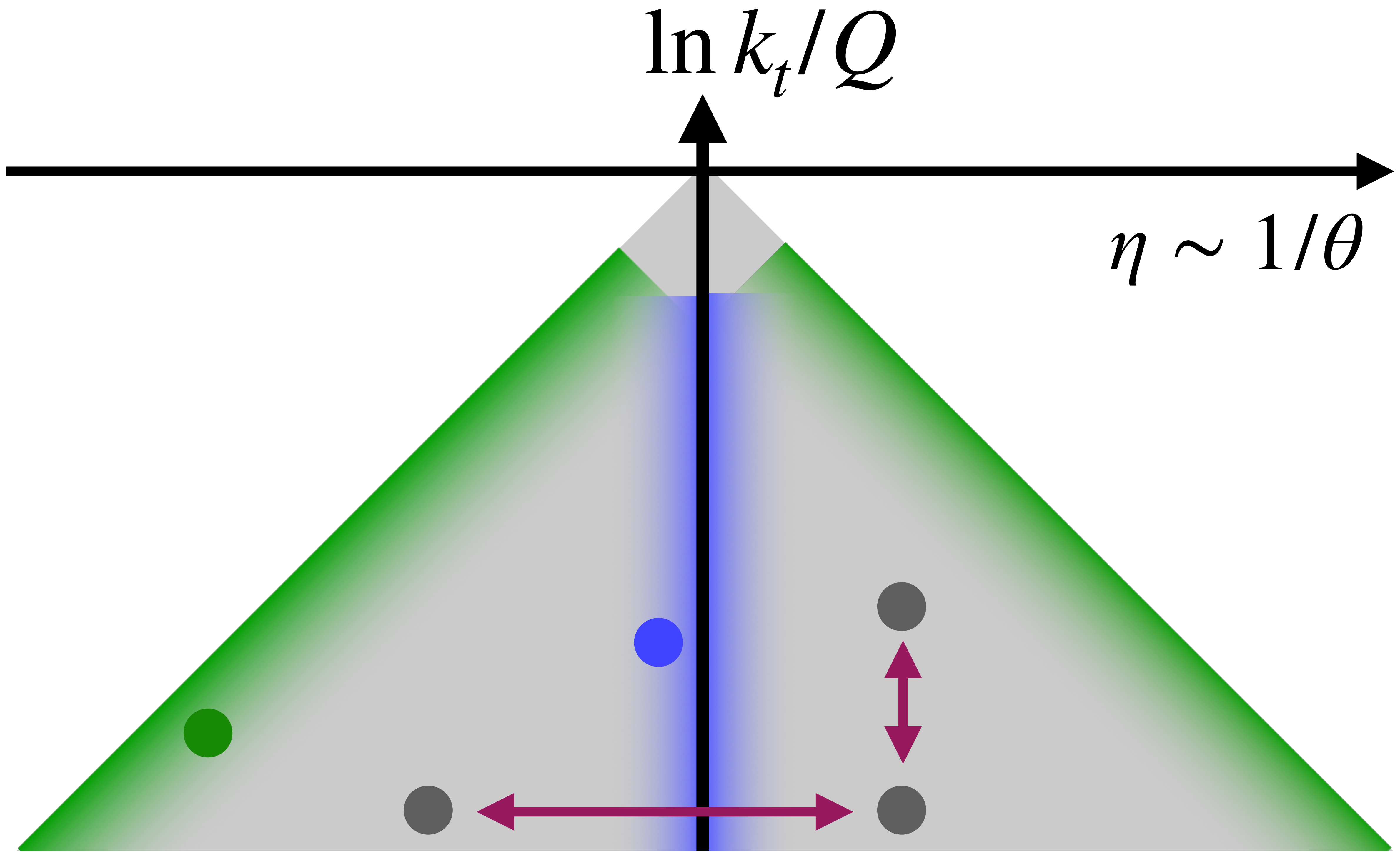
2. Weight for **soft** or **collinear** emissions must be correct

$$dP = \frac{\alpha_s^{\text{CMW}}(k_t)}{\pi} P_{\tilde{i}\to ij}(z)\ \ d\eta\, d\ln k_t$$

Shower @NLL

for event shapes



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Resummation

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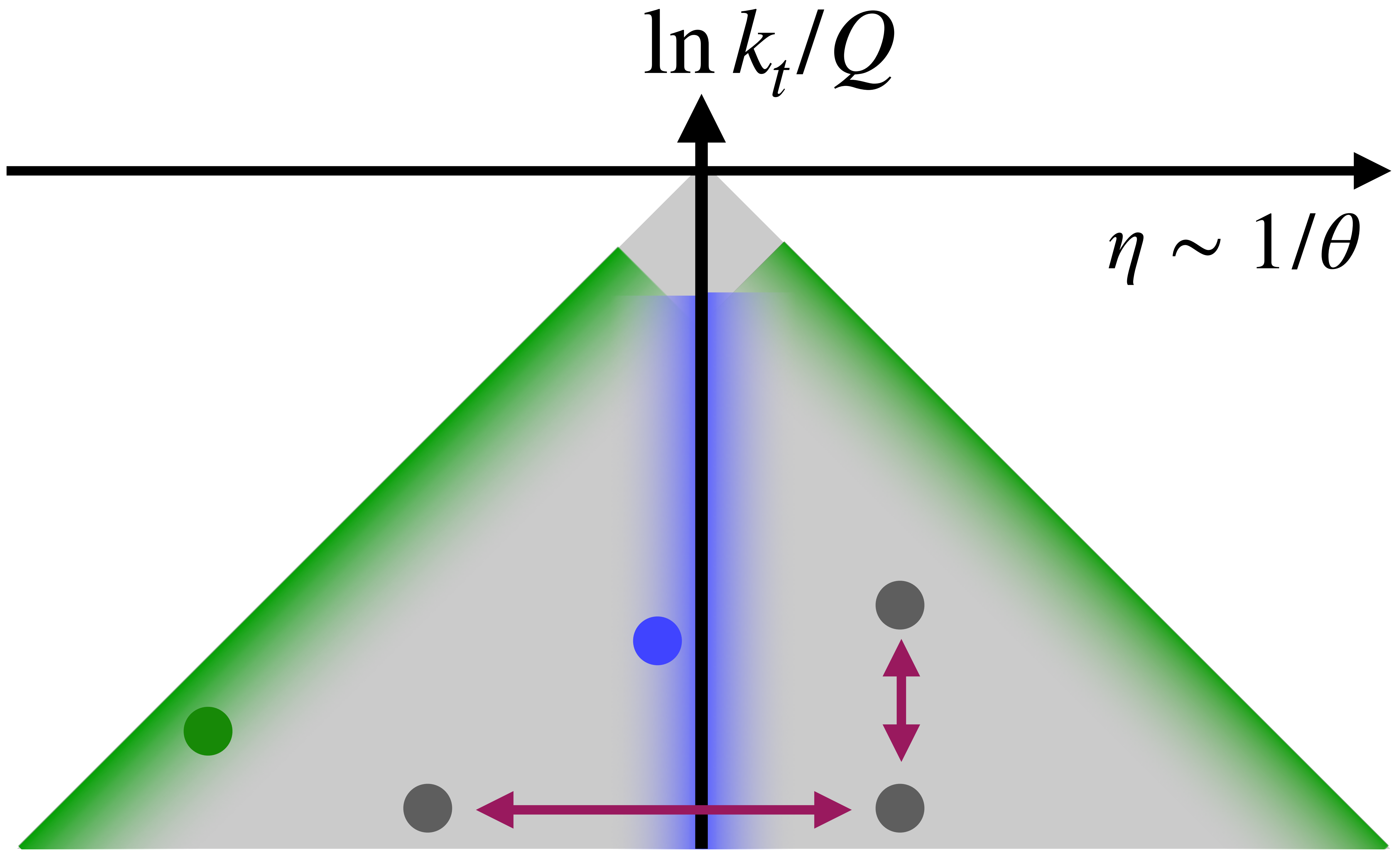
$$dP = \frac{\alpha_s^{\mathrm{CMW}}(k_t)}{\pi} P_{\tilde{i}\to ij}(z)\ \ d\eta\, d\ln k_t$$

3. Correlations between soft-collinear emissions that are **separated in only one direction** must be correct (i.e. reduce to independent emission)

The recoil induced by the kinematic maps of showers may spoil this third correction

[Dasgupta, Dreyer, Hamilton, Monni, Salam, 1805.09327]

Shower @NLL
for event shapes



Needs $\mathcal{O}(\alpha_s^n L^n)$ corrections

Resummation

Next-to-leading-logarithmic (NLL) accuracy

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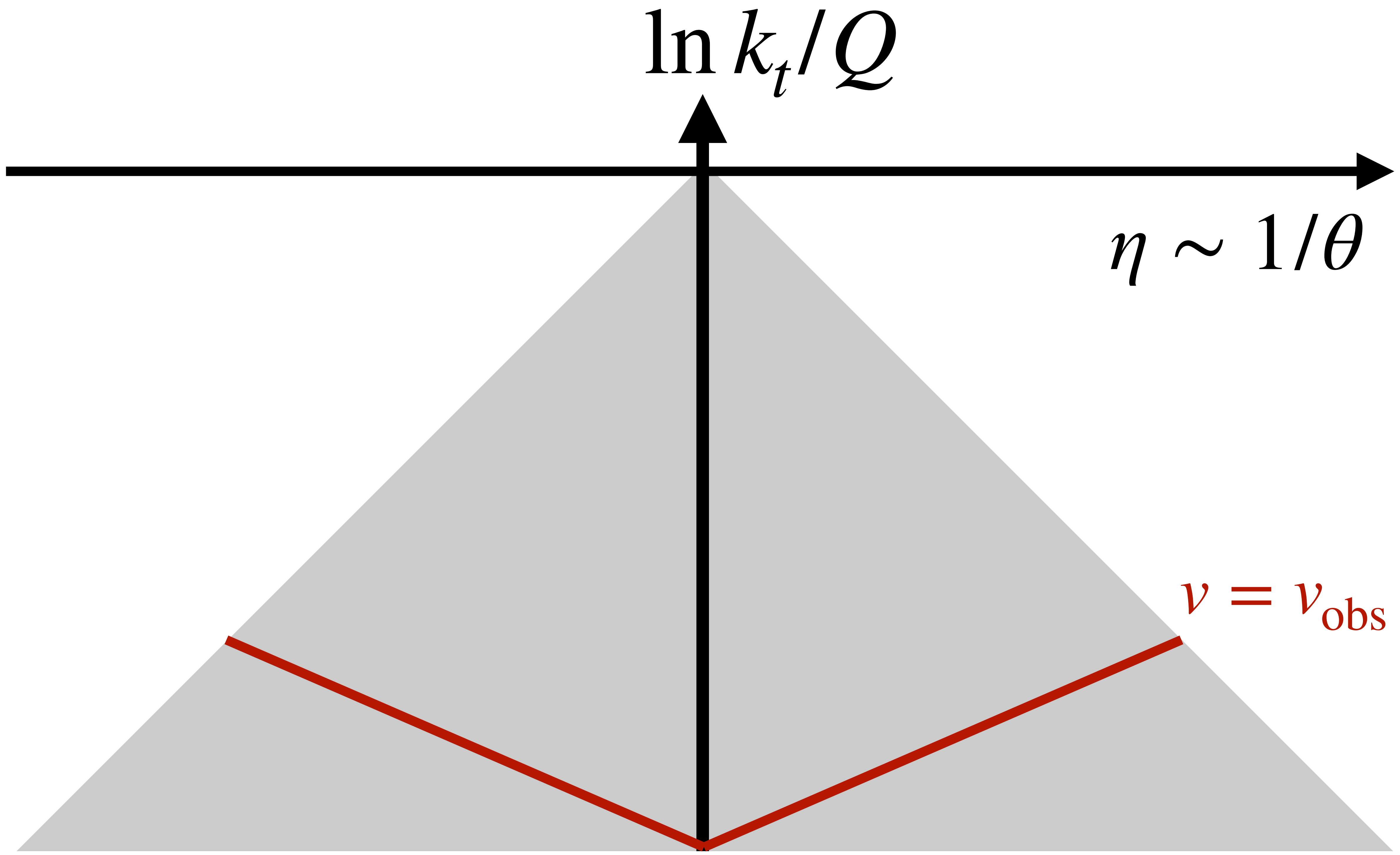
With this principle we designed NLL showers (PanGlobal and PanLocal)

e^+e^-: Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez [2002.11114]
pp: MvB, Ferrario Ravasio, Salam, Soto Ontoso, Soyez, Verheyen [2205.02237]; + Hamilton [2207.09467]
DIS and VBF: MvB, Ferrario Ravasio [2305.08645]

Shower @NNLL
for e+e- event shapes



Needs $\mathcal{O}(\alpha_s^n L^{n-1})$ corrections

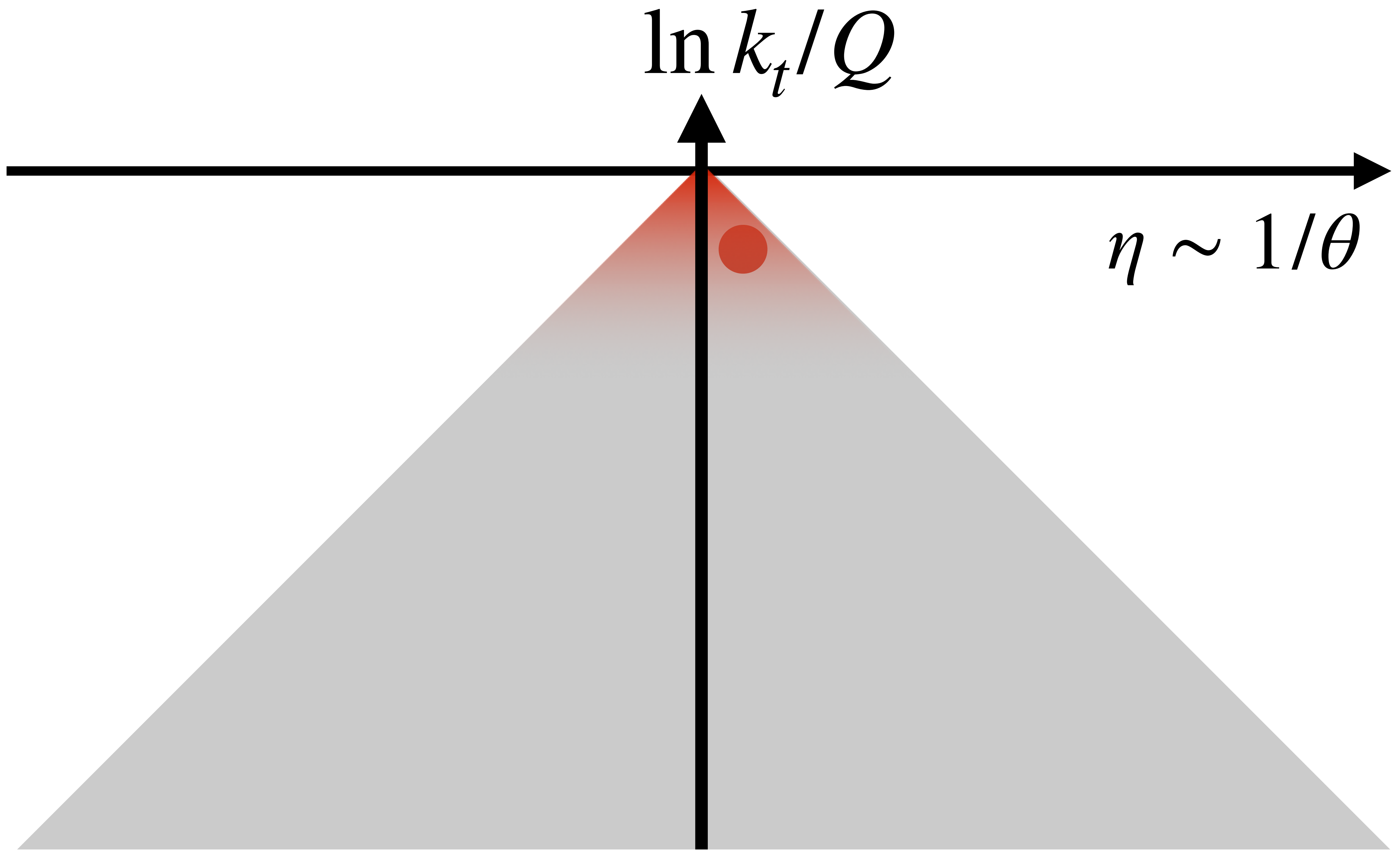
Resummation

Next-to-next-to leading-logarithmic (NNLL) accuracy

$$\Sigma_{\rm NNLL}(v < v_{\rm obs}) = \exp\left[-g_1(\alpha_s L)L + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L)\right]$$

Shower @NNLL

for e+e- event shapes



Needs $\mathcal{O}(\alpha_s^n L^{n-1})$ corrections

Resummation

Next-to-next-to leading-logarithmic (NNLL) accuracy

1. Shower needs to be **matched** to NLO

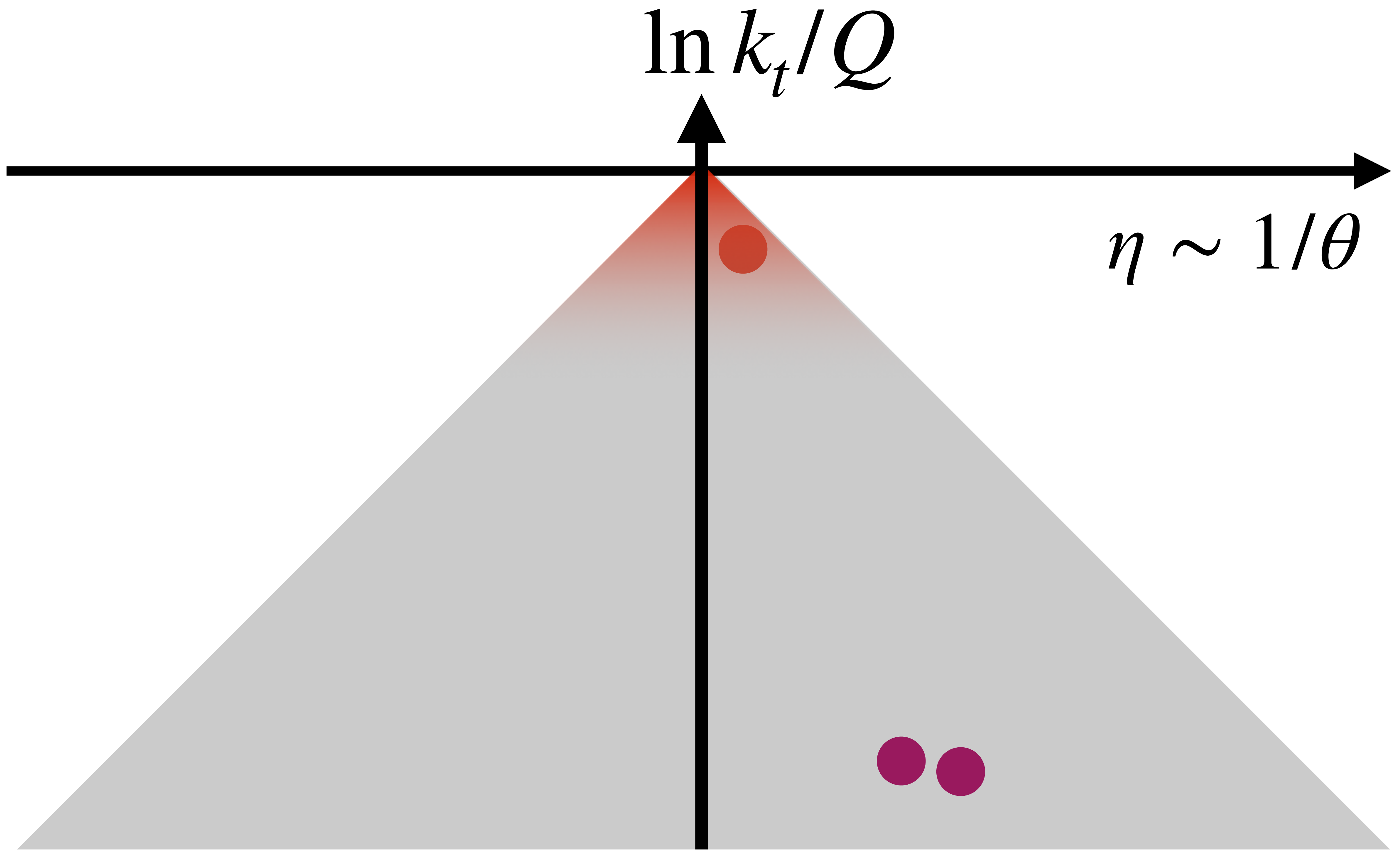
First emission $\mathcal{O}(\alpha_s)$ is fully correct

For e^+e^-:
Hamilton, Karlberg, Salam, Scyboz, Verheyen, [2301.09645]

For pp and DIS: ongoing work

Shower @NNLL

for e+e- event shapes



Needs $\mathcal{O}(\alpha_s^n L^{n-1})$ corrections

Resummation

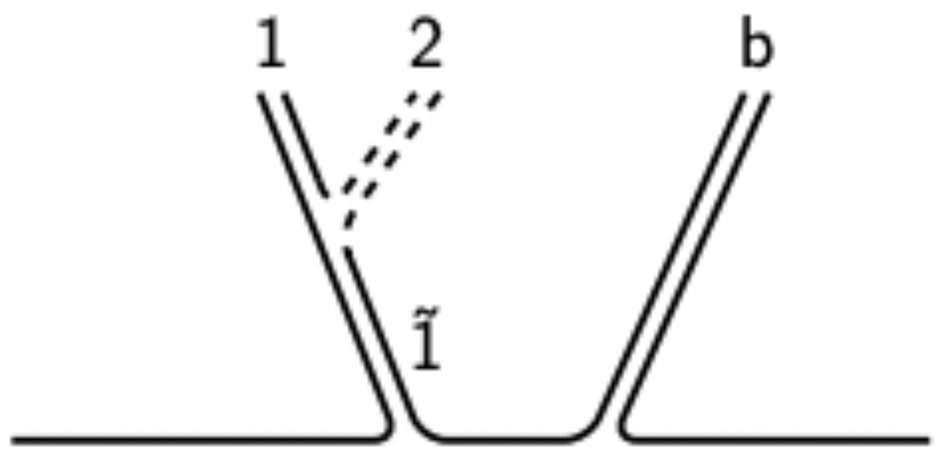
Next-to-next-to leading-logarithmic (NNLL) accuracy

1. Shower needs to be **matched** to NLO

First emission $\mathcal{O}(\alpha_s)$ is fully correct

2. **Commensurate pairs** of soft emissions

Need the double-soft MEs

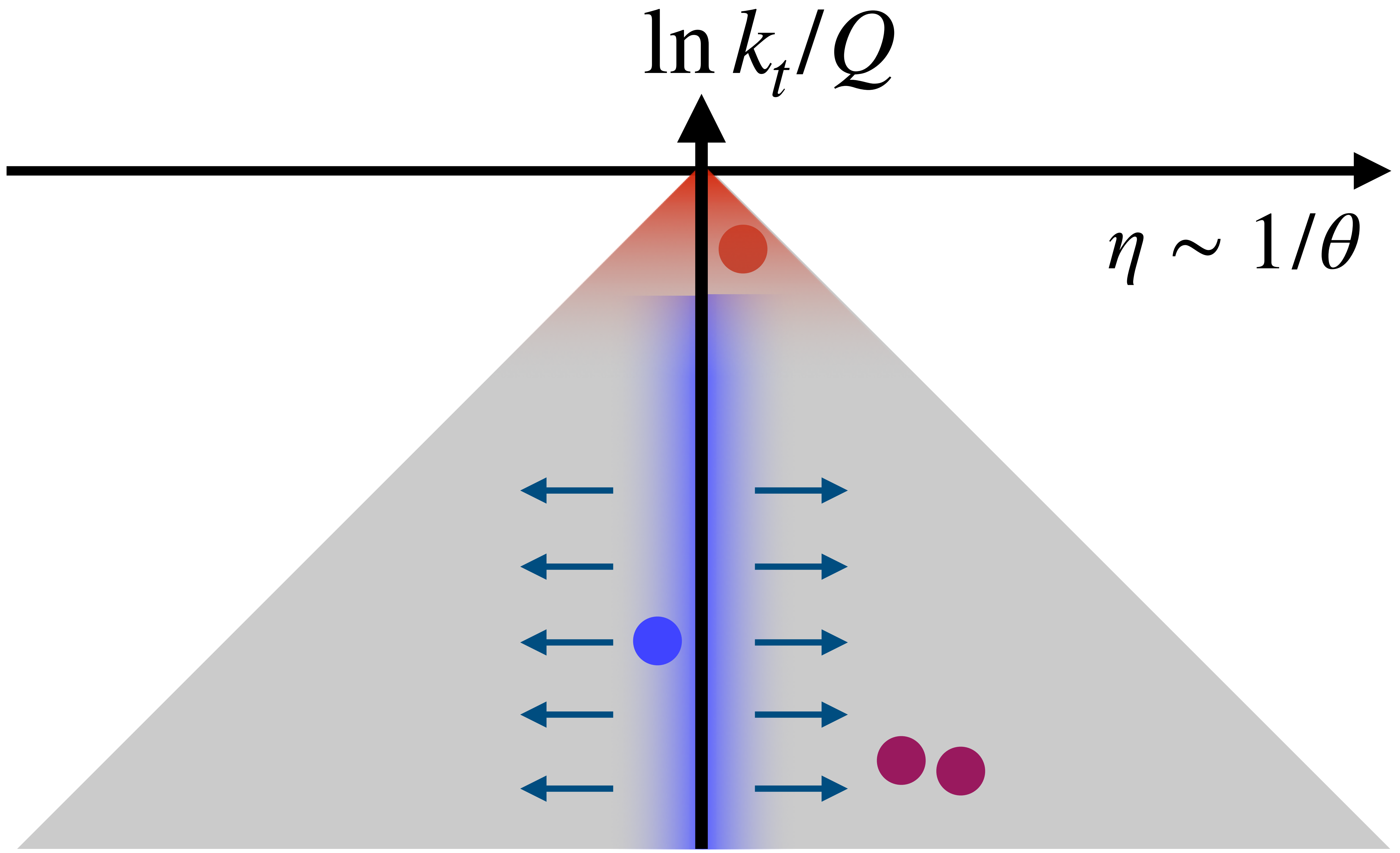


$$|M_{1,2,3,\ldots,n}(p_1,p_2,p_3,\ldots,p_n)|^2 \xrightarrow{12-\text{soft}} \left(4\pi\mu^{2\varepsilon}\alpha_s\right)^2 \sum_{i,j=3}^{n} \mathcal{I}_{ij}(p_1,p_2)\,|M^{(i,j)}_{3,\ldots,n}(p_3,\ldots,p_n)|^2$$

[Campbell, Glover, 9710255
Catani, Grazzini, 9908523]

Shower @NNLL

for e+e- event shapes



Resummation

Next-to-next-to leading-logarithmic (NNLL) accuracy

1. Shower needs to be **matched** to NLO

   First emission $\mathcal{O}(\alpha_s)$ is fully correct

2. **Commensurate pairs** of soft emissions

3. **Soft large-angle** emissions @ NLO

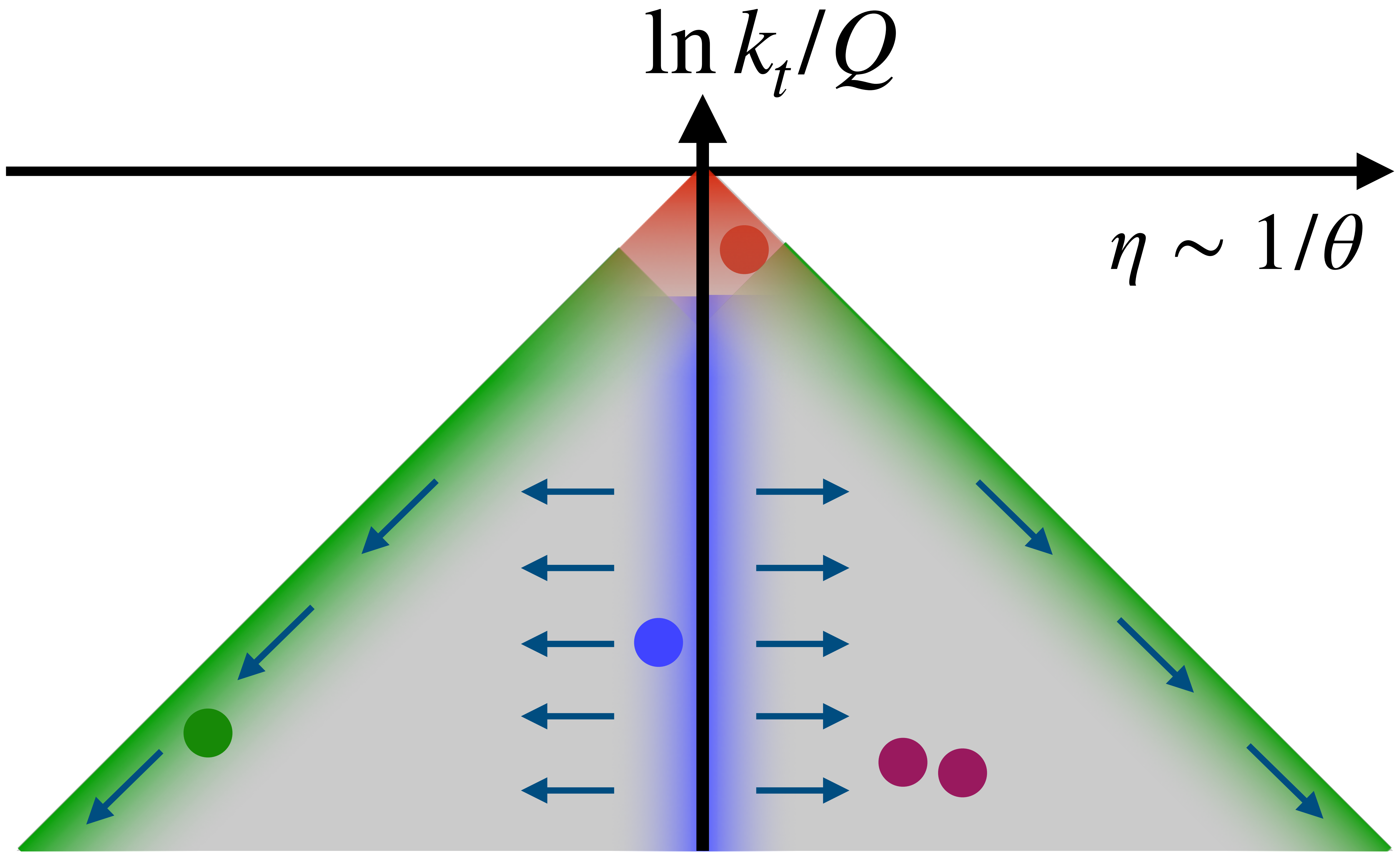
$$\alpha_s^{\text{CMW}} \to \alpha_s^{\text{eff}} = \alpha_s(k_t)\left(1 + \frac{\alpha_s(k_t)}{2\pi}(K_1 + \Delta K_1)\right)$$

Corrects for difference in shower kinematics and those of theory calculation for K_1

These corrections bring us NNDL multiplicity and NSL non-global logarithmic accuracy

[Ferrario Ravasio, Hamilton, Karlberg, Salam, Scyboz, Soyez, 2307.11142]

Shower @NNLL
for e+e- event shapes



Resummation

Next-to-next-to leading-logarithmic (NNLL) accuracy

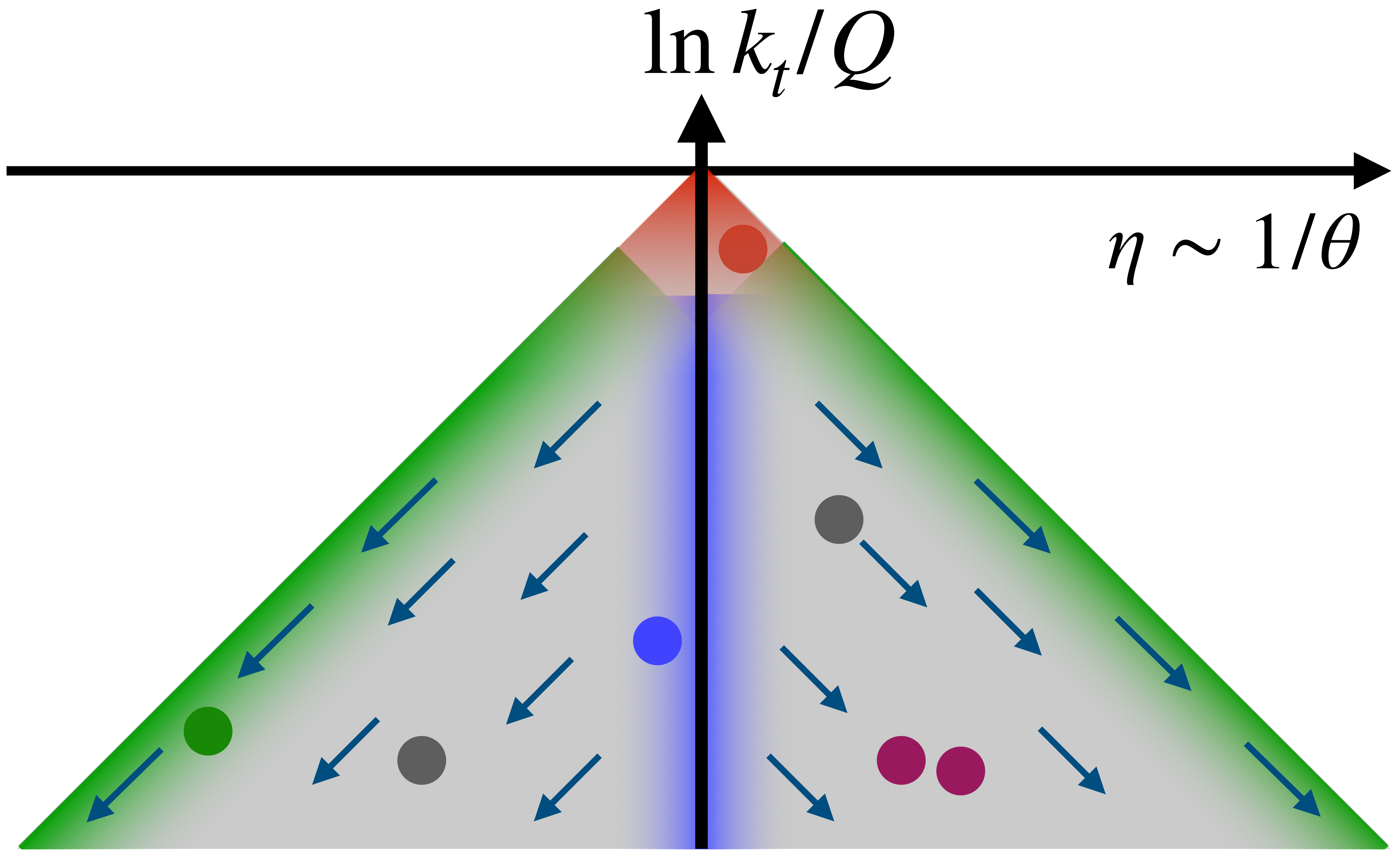
1. Shower needs to be **matched** to NLO
   First emission $\mathcal{O}(\alpha_s)$ is fully correct
2. **Commensurate pairs** of soft emissions
3. **Soft large-angle** emissions @ NLO
4. **Collinear** emissions @ NLO

$$\alpha_s^{\text{eff}} = \alpha_s(k_t)\left(1 + \frac{\alpha_s(k_t)}{2\pi}(K_1 + \Delta K_1 + B_2 + \Delta B_2)\right)$$

B_2 calculation and tests: Dasgupta, El-Menoufi [2109.07496]; MvB, Dasgupta, El-Menoufi, Helliwell, Monni [2307.15734]; MvB, Dasgupta, El-Menoufi, Helliwell, Karlberg, Monni [2402.05170]

Shower @NNLL

for e+e- event shapes



Resummation

Next-to-next-to leading-logarithmic (NNLL) accuracy

1. Shower needs to be **matched** to NLO

   First emission $\mathcal{O}(\alpha_s)$ is fully correct

2. **Commensurate pairs** of soft emissions

3. **Soft large-angle** emissions @ NLO

4. **Collinear** emissions @ NLO

5. **Soft-collinear** emissions @ NNLO

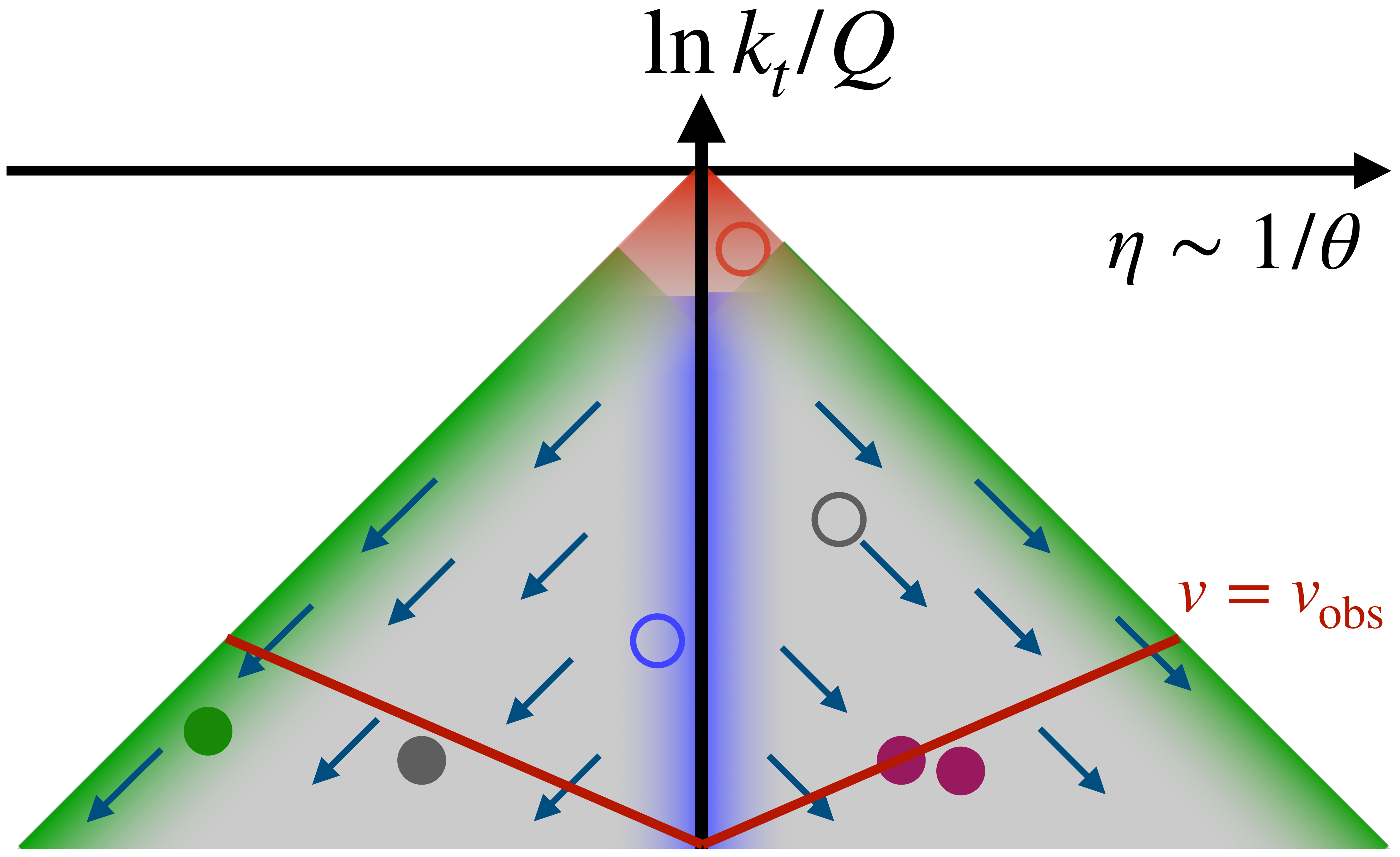
$\alpha_s^{\text{eff}} = \alpha_s(k_t)$ (at 3 loop)

$$+\frac{\alpha_s^2(k_t)}{2\pi}(K_1 + \Delta K_1 + B_2 + \Delta B_2)$$

$$+\frac{\alpha_s^3(k_t)}{2\pi}(K_2 + \Delta K_2)$$

K_2 calculation: Banfi, El-Menoufi, Monni,[1807.11487]; Catani, De Florian, Grazzini,[1904.10365]

Shower **@NNLL**
for e+e- event shapes



Resummation

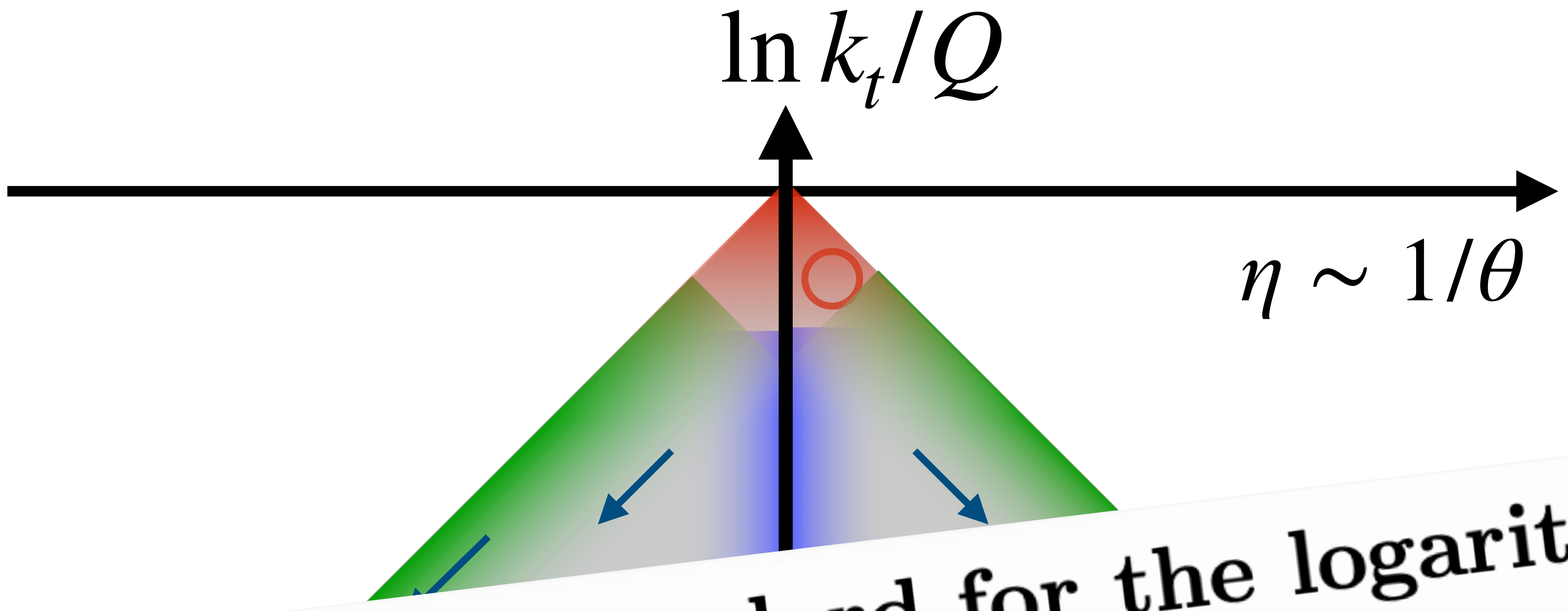
Next-to-next-to leading-logarithmic (NNLL) accuracy

1. Shower needs to be **matched** to NLO
   First emission $\mathcal{O}(\alpha_s)$ is fully correct
2. **Commensurate pairs** of soft emissions
3. **Soft large-angle** emissions @ NLO
4. **Collinear** emissions @ NLO
5. **Soft-collinear** emissions @ NNLO

Analytically, we expect that this will give us event shapes at NNLL

$$\Sigma_{\rm NNLL}(v < v_{\rm obs}) = \exp\left[-g_1(\alpha_s L)L + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L)\right]$$

Shower @NNLL
for e+e- event shapes



Resummation

Next-to-next-to leading-logarithmic (NNLL) accuracy

1. Shower needs to be **matched** to NLO

First emission $\mathcal{O}(\alpha_s)$ is fully correct [...]

... @ NNLO

A new standard for the logarithmic accuracy of parton showers [2406.02661]

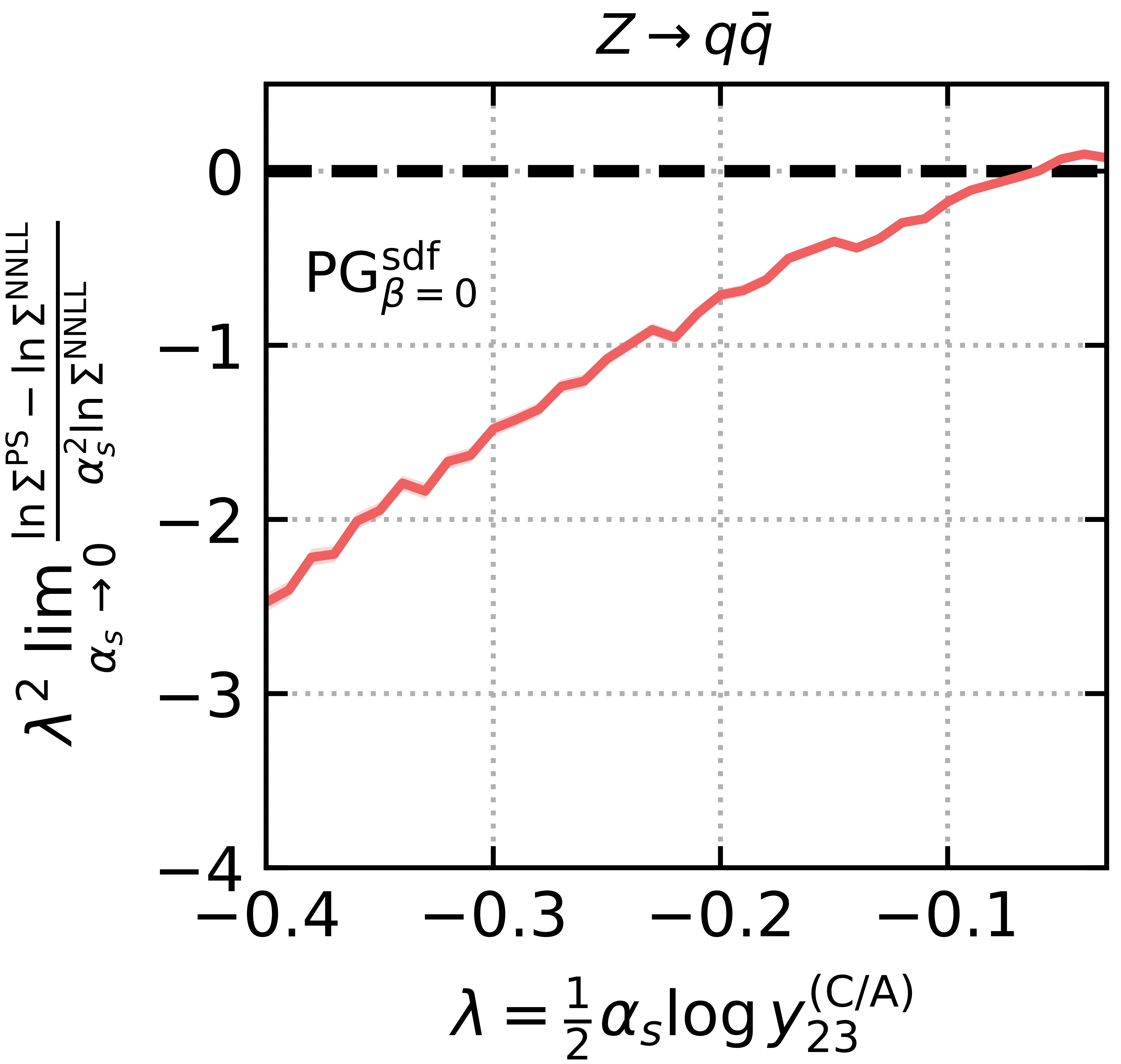
Melissa van Beekveld,[1] Mrinal Dasgupta,[2] Basem Kamal El-Menoufi,[3] Silvia Ferrario Ravasio,[4] Keith Hamilton,[5] Jack Helliwell,[6] Alexander Karlberg,[4] Pier Francesco Monni,[4] Gavin P. Salam,[6,7] Ludovic Scyboz,[3] Alba Soto-Ontoso,[4] and Gregory Soyez[8]

Analytically, we expect that this will give us event shapes at NNLL

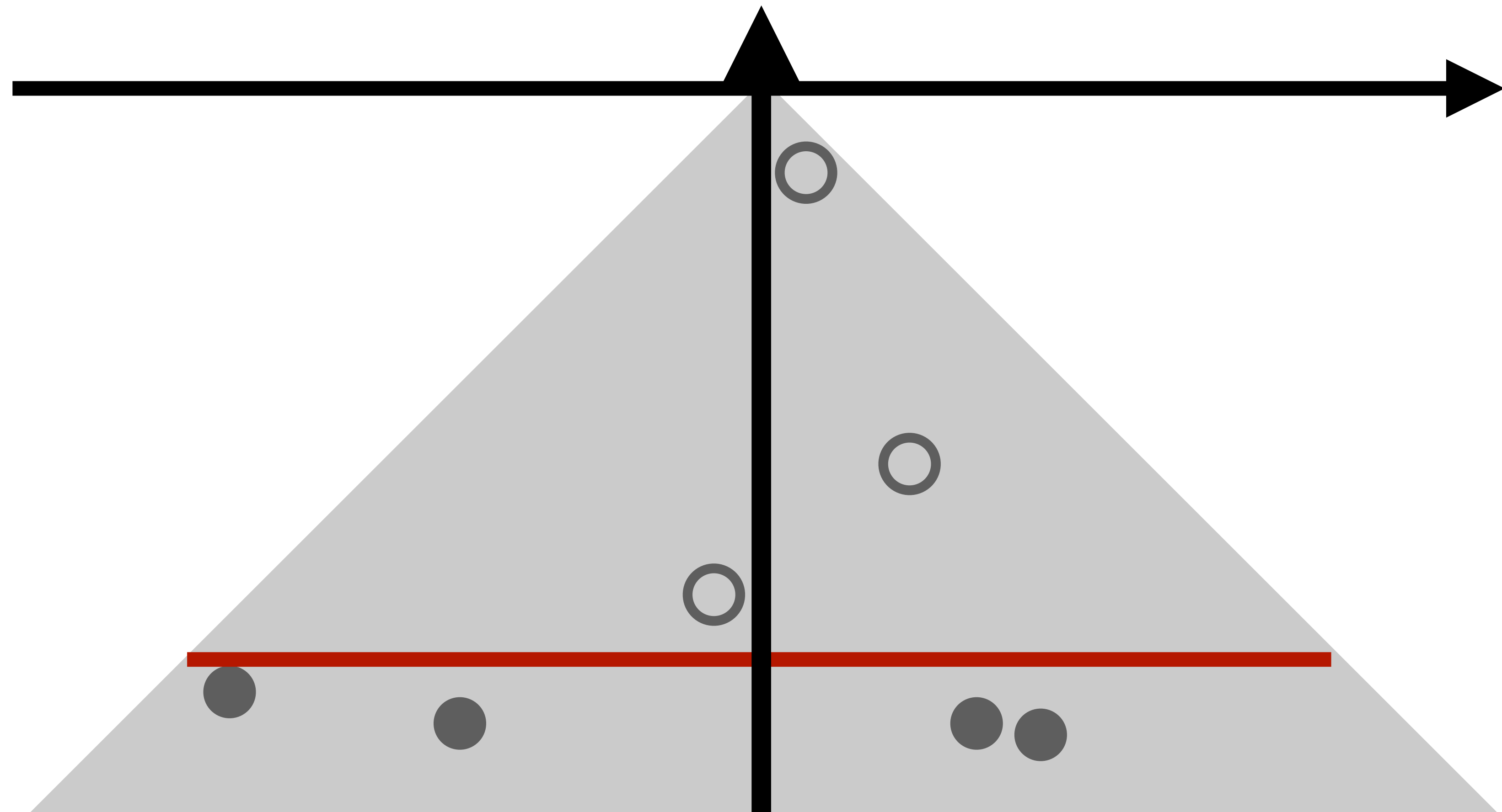
$$\Sigma_{\rm NNLL}(v < v_{\rm obs}) = \exp\left[-g_1(\alpha_s L)L + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L)\right]$$

But we also test this numerically

Consider again Cambridge y_{23}



NLL baseline NNLL discrepancy is O(1)!



[2406.02661]

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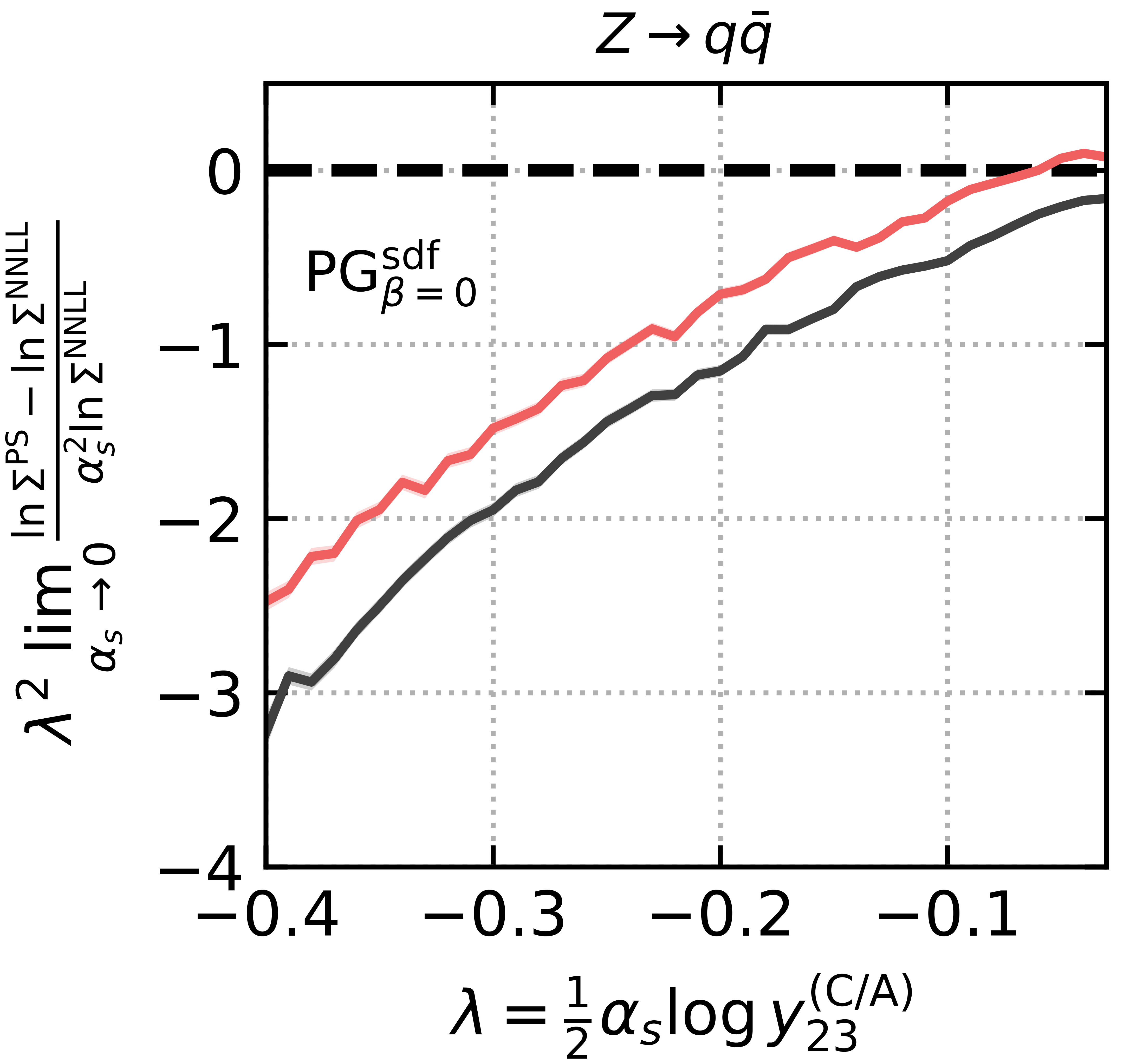
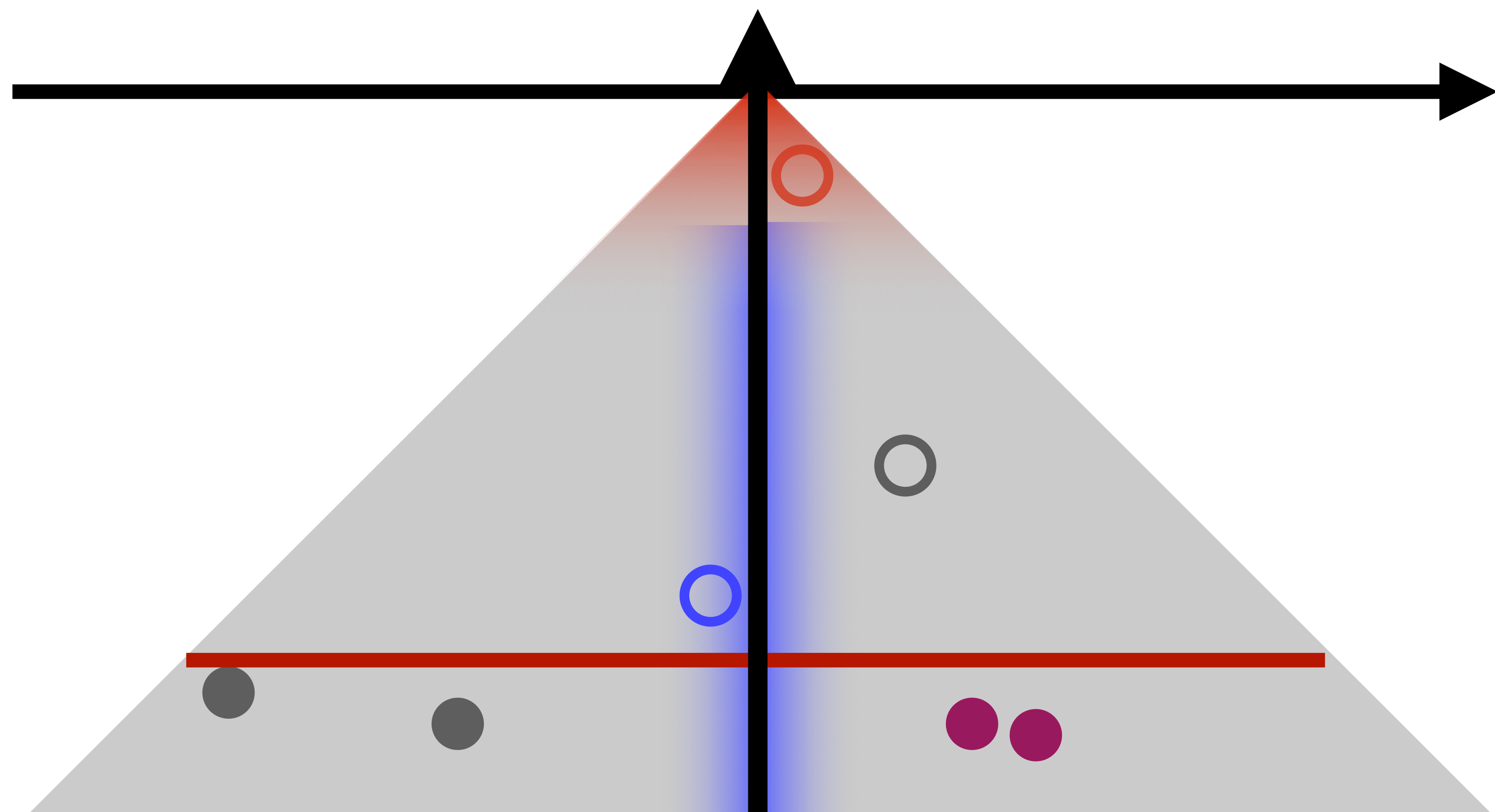


NLL baseline NNLL discrepancy is O(1)!

+ matching and double-soft real emission corrections



[2406.02661]

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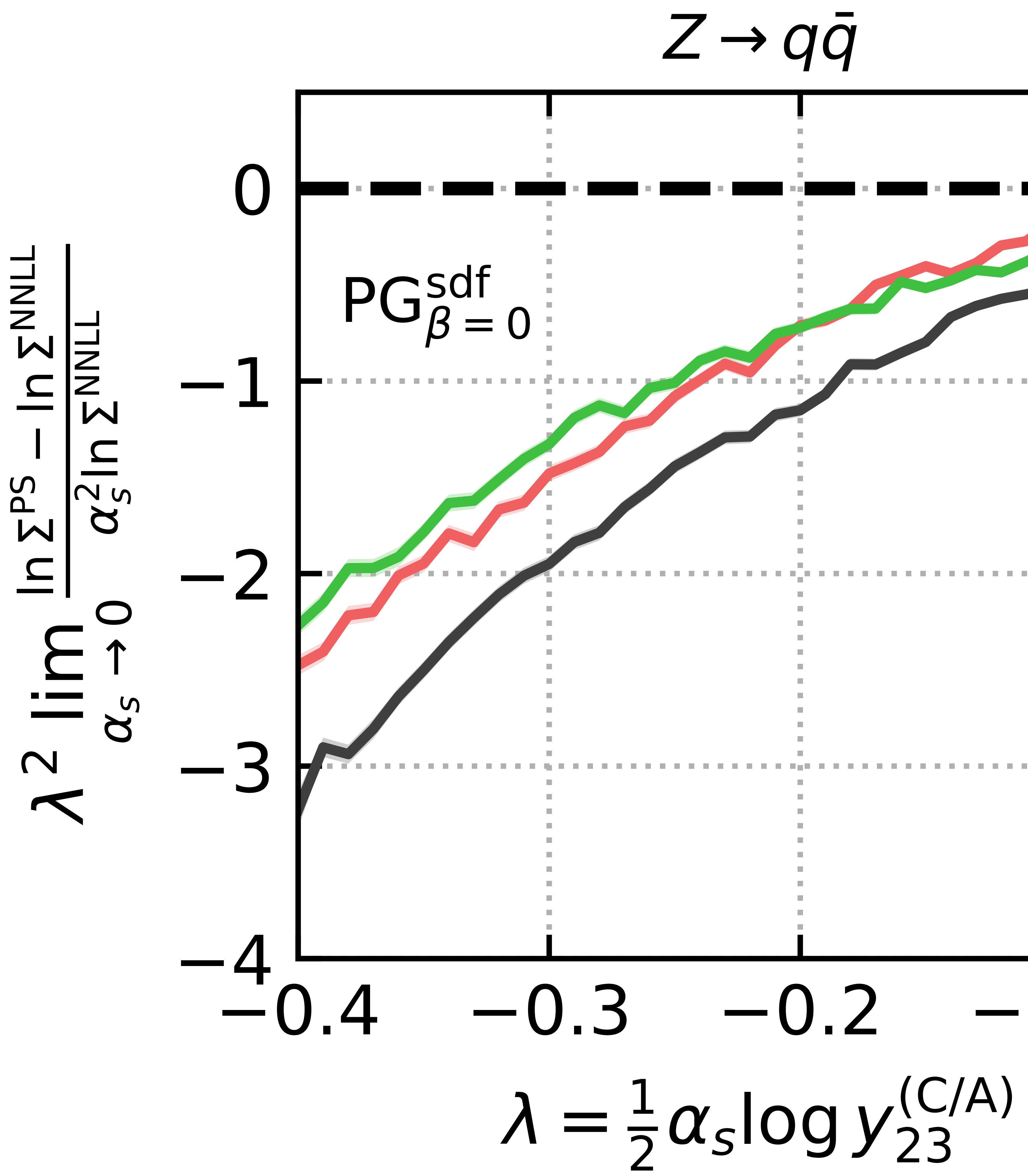

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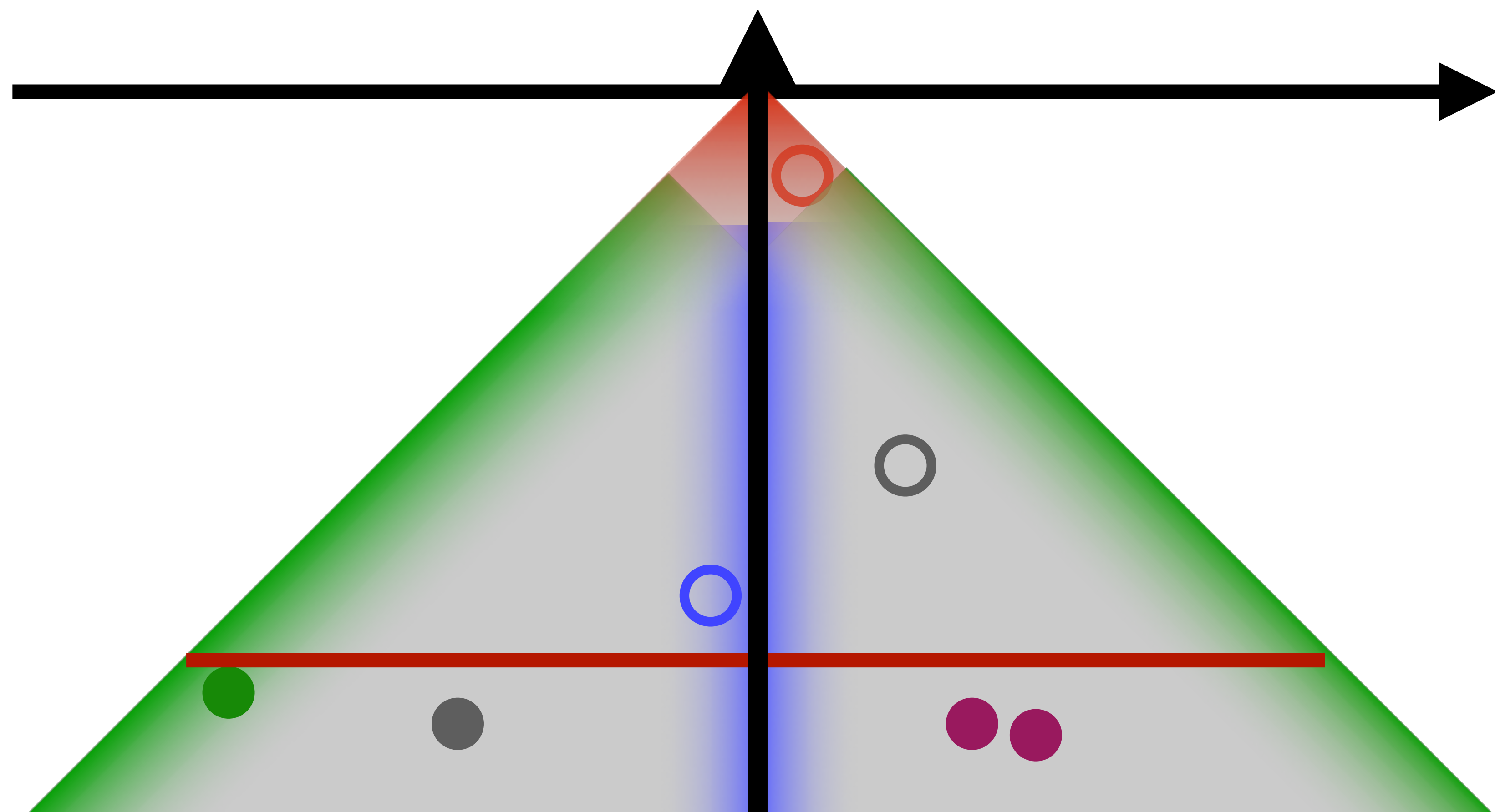
+ 3-loop α_s running, NNLO soft-collinear (K_2) and NLO collinear normalisation (B_2)



[2406.02661]

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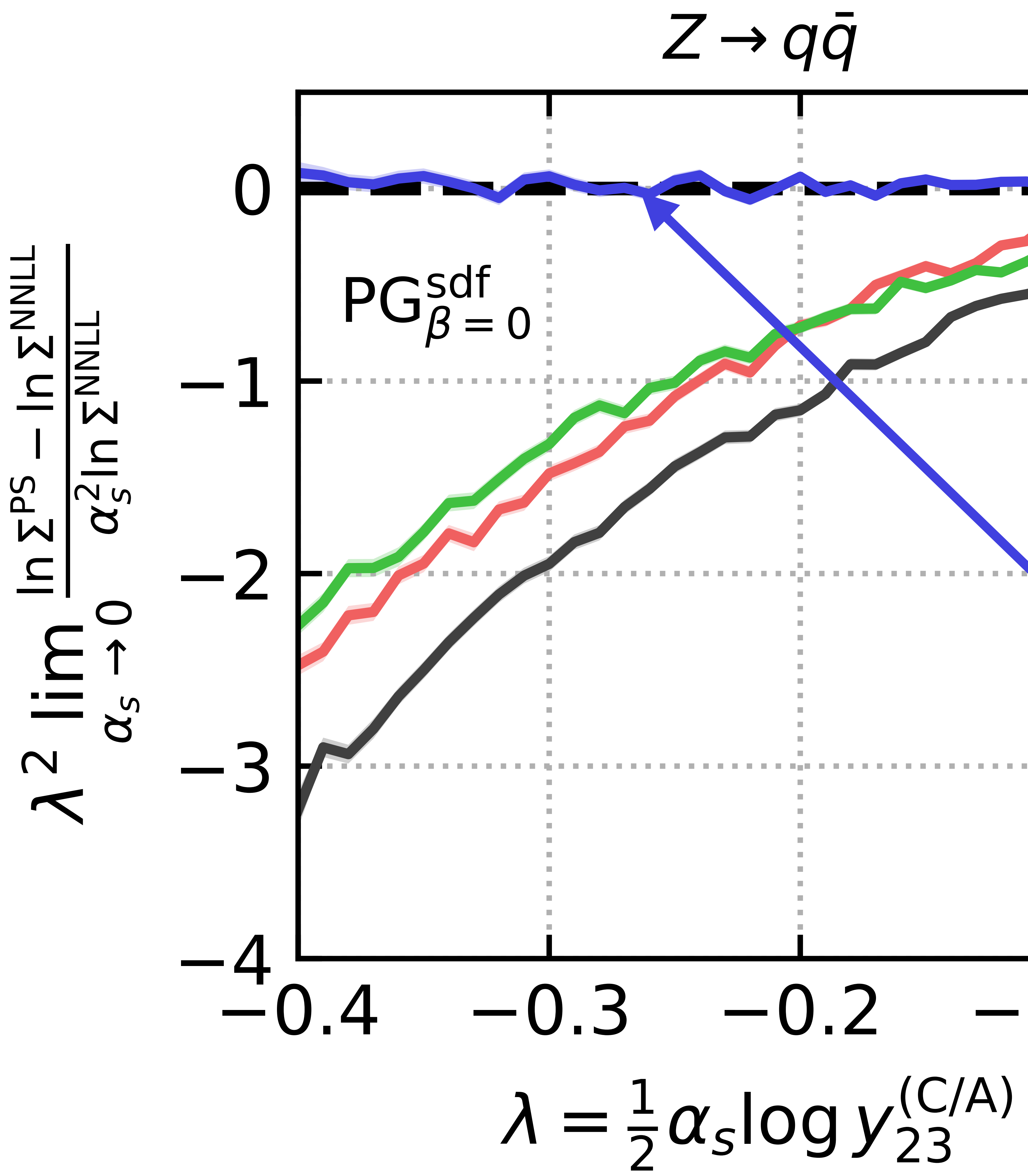
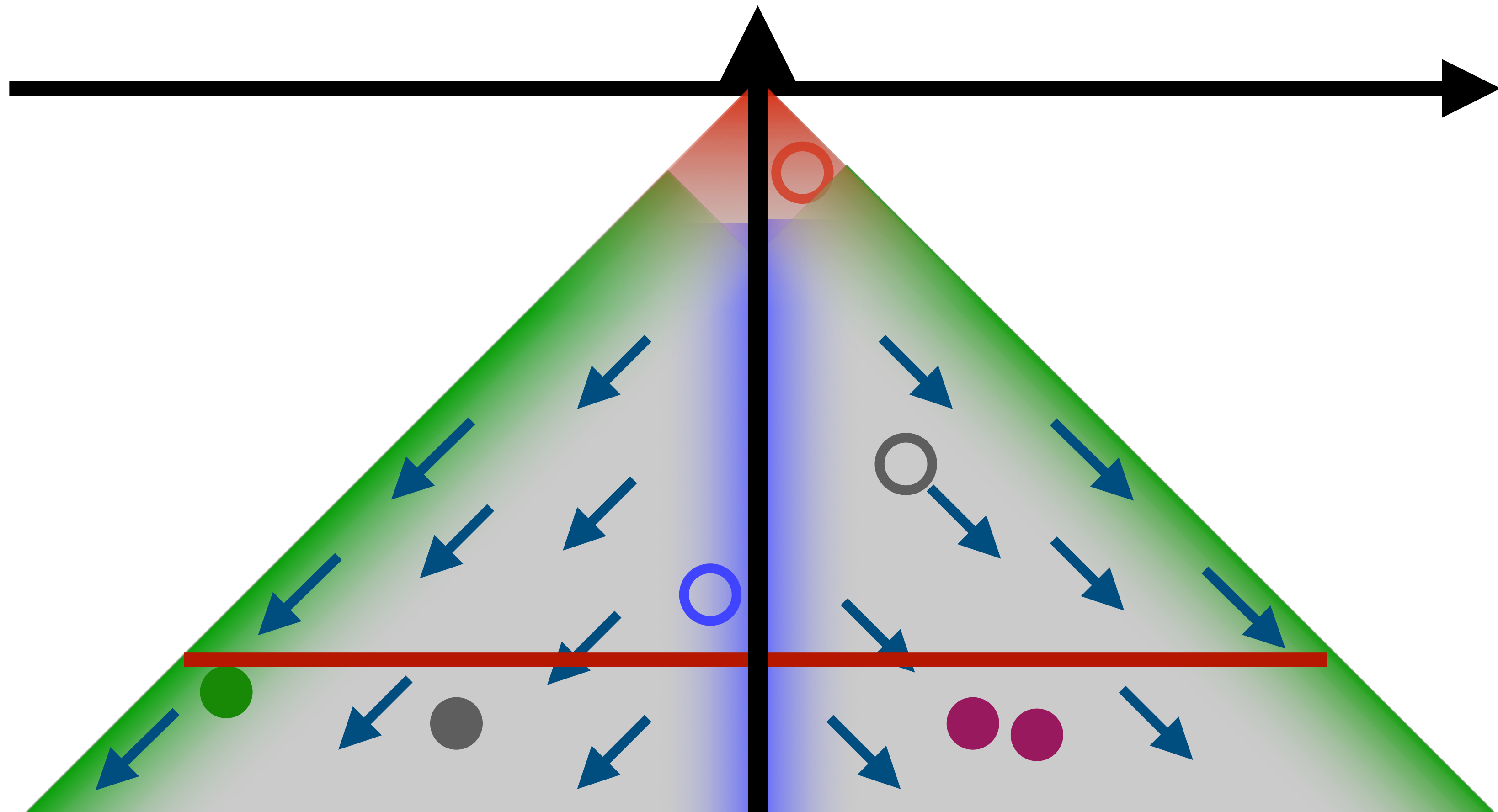


NLL baseline NNLL discrepancy is O(1)!

+ matching and double-soft real emission corrections

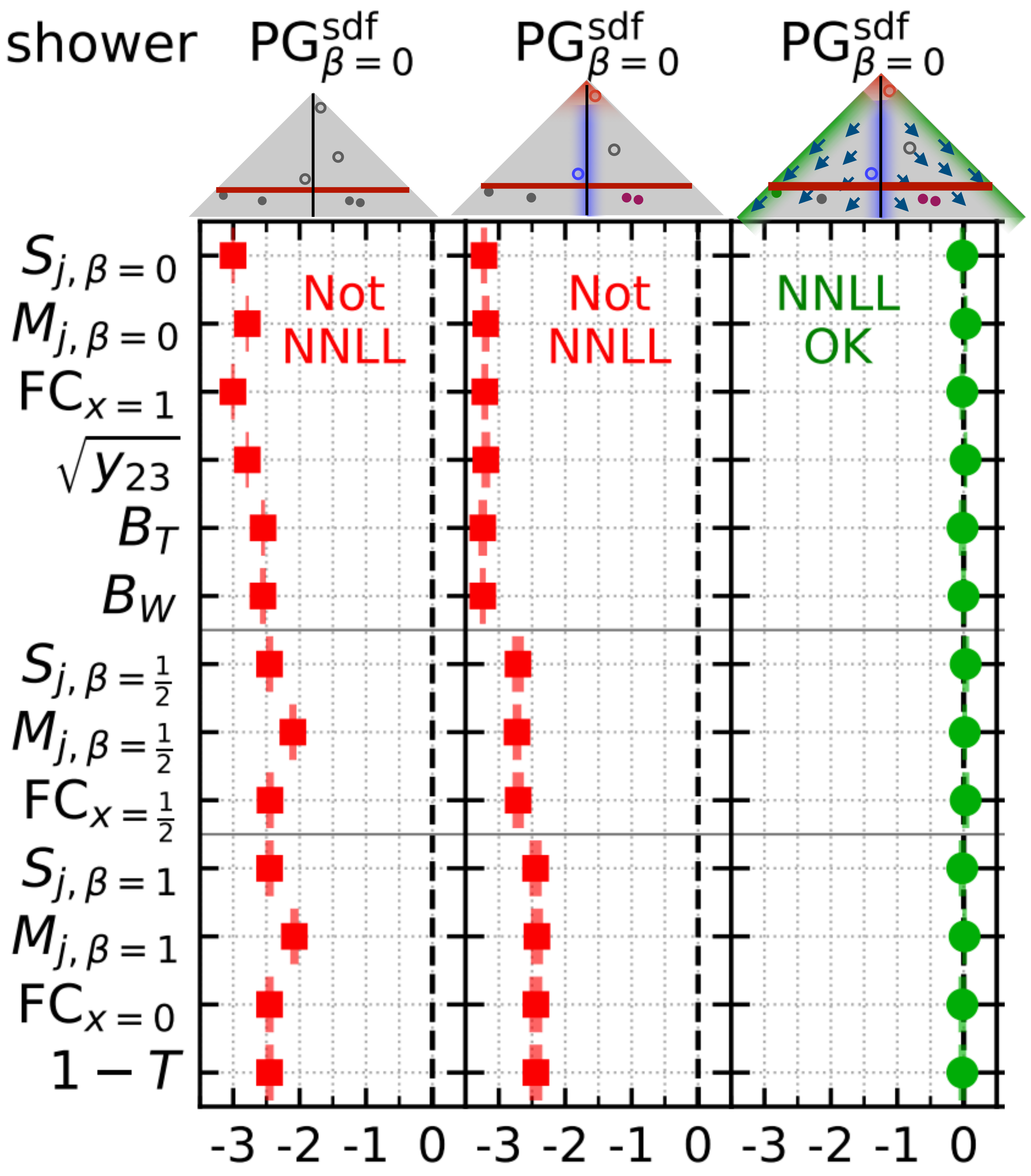
+ 3-loop α_s running, NNLO soft-collinear (K_2) and NLO collinear normalisation (B_2)

+ Δ correction



And not just for one observable…

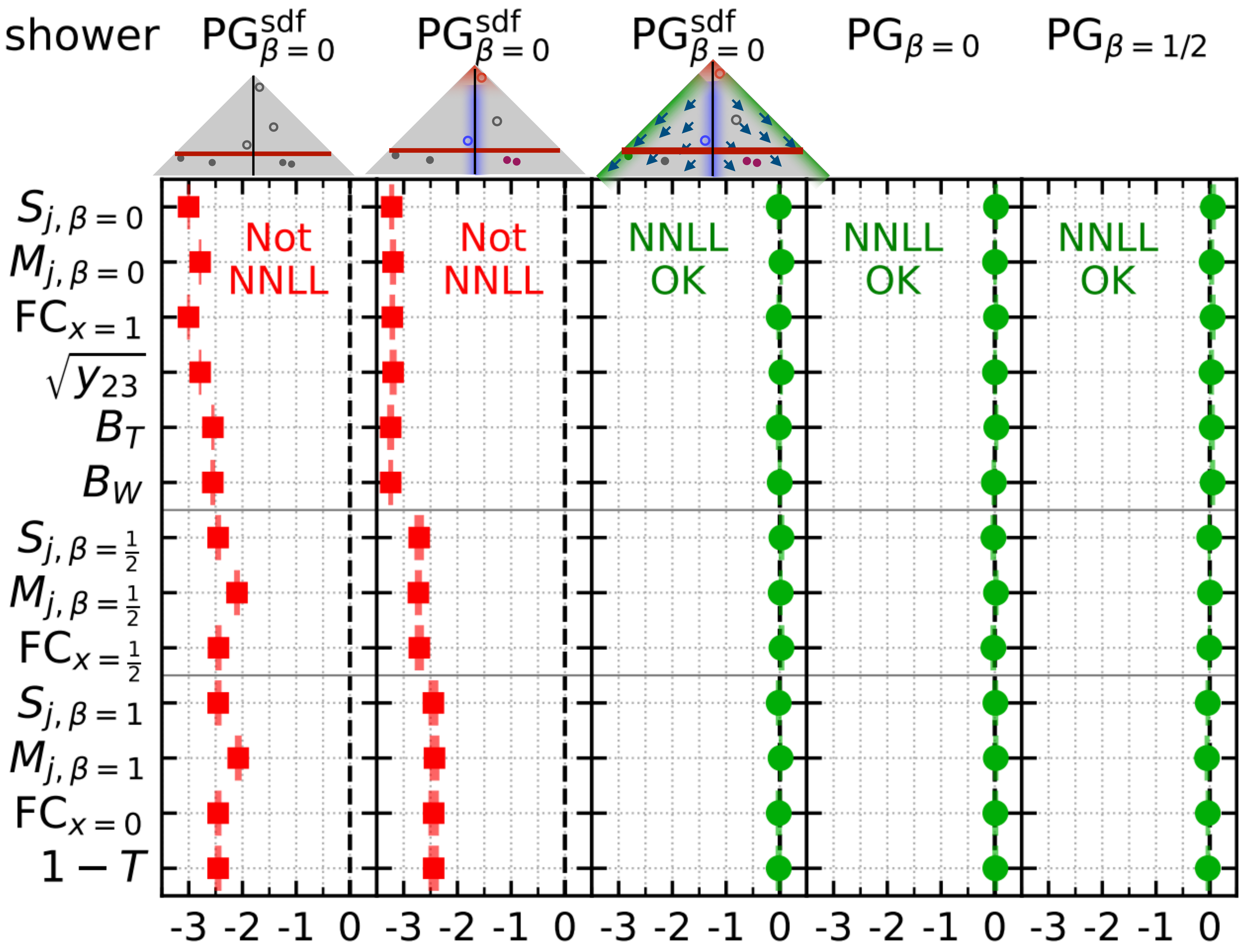
[2406.02661]



NNLL discrepancy for $\lambda = \alpha_s \ln(v) = -0.4$

And not just for one observable/shower…

[2406.02661]



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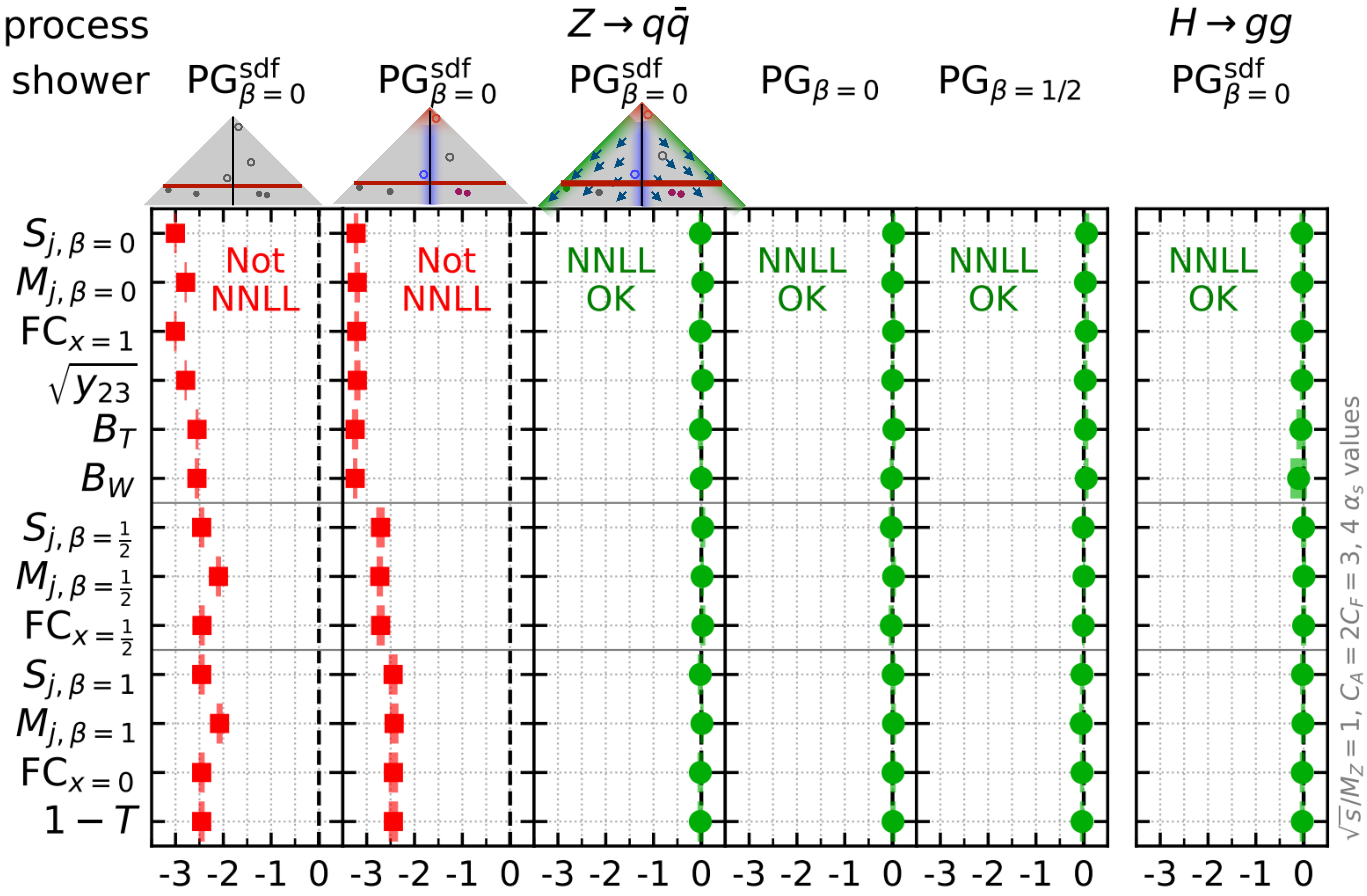
And not just for one observable/shower/process

[2406.02661]



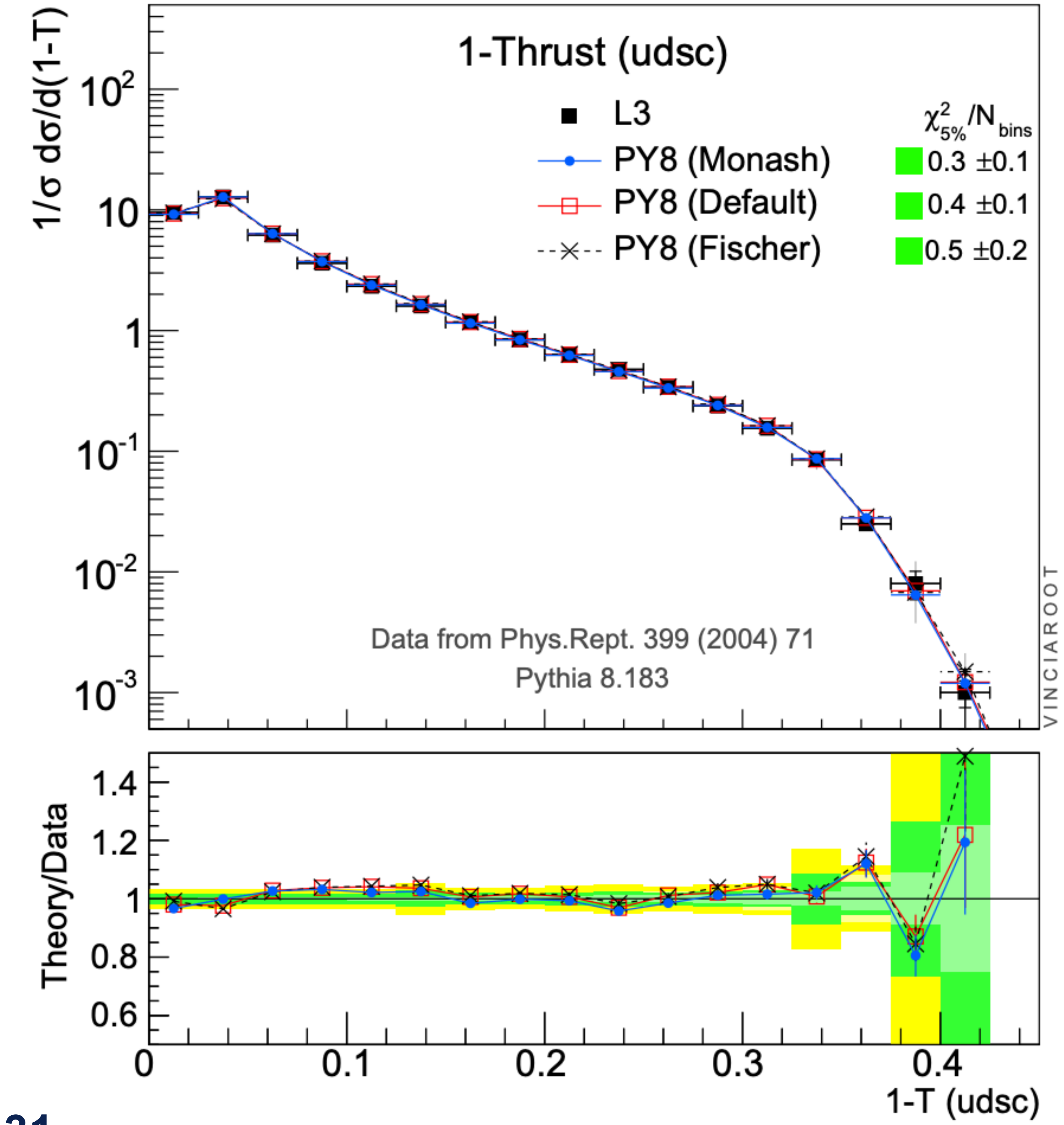
NNLL discrepancy for $\lambda = \alpha_s \ln(v) = -0.4$

Relevance for phenomenology?

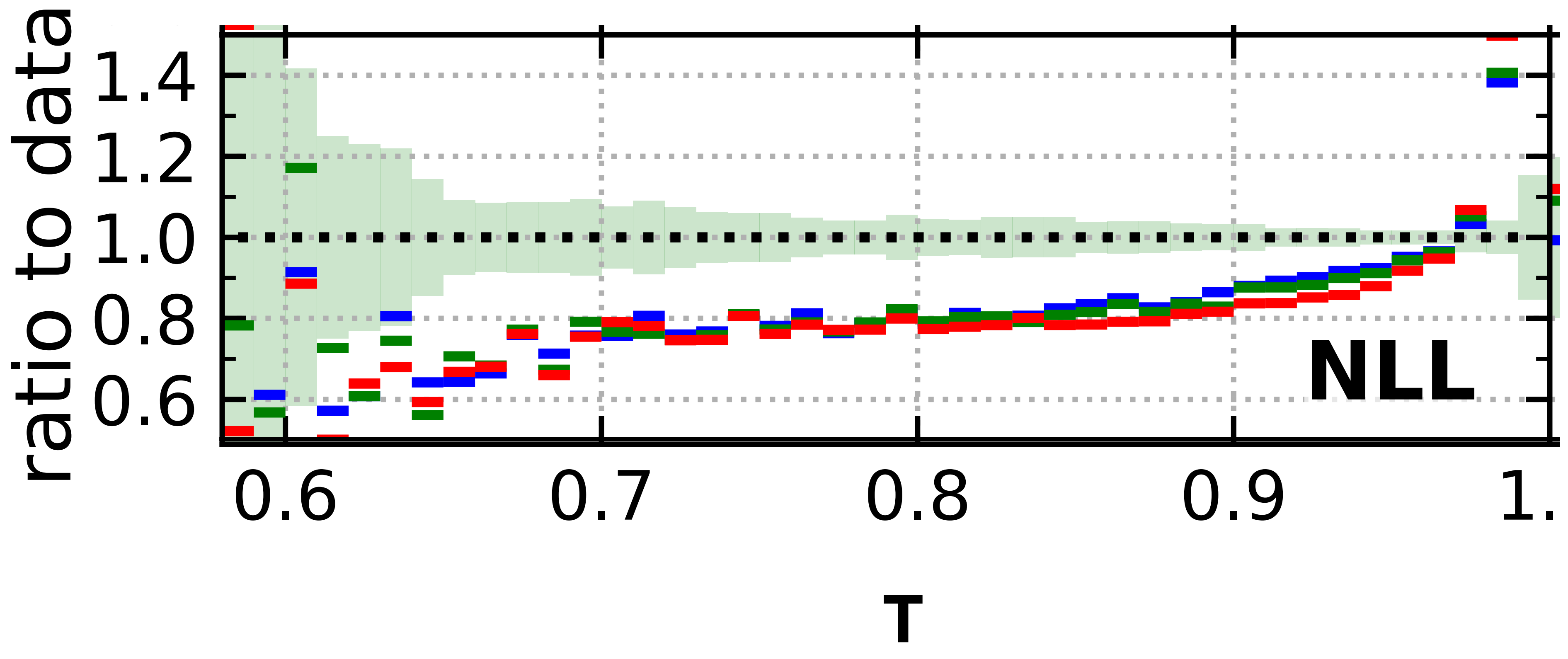
[2406.02661]

Longstanding discrepancy between true value of $\alpha_s(M_z) = 0.118$ and that needed to describe LEP data: $\alpha_s(M_z) = 0.1365$

[Skands, Carrazza, Rojo, 1404.5630]



Also observed for our showers, i.e. with $\alpha_s(M_z) = 0.118$:



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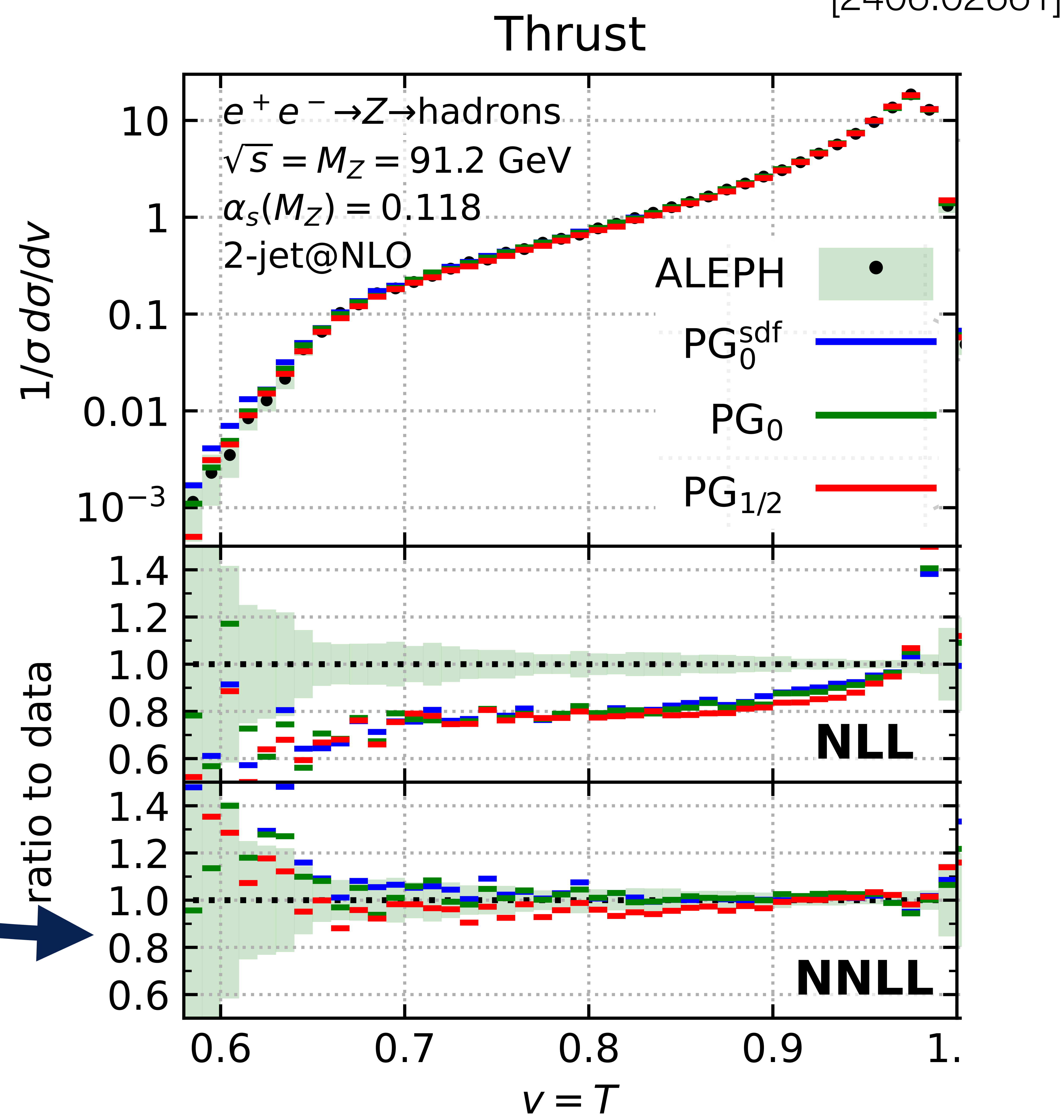
With our NNLL showers this picture changes: we no longer need an anomalously large α_s value!

We observe large NNLL corrections for all showers under consideration



Pythia8.311 used for hadronisation, Rivet for comparison with LEP data

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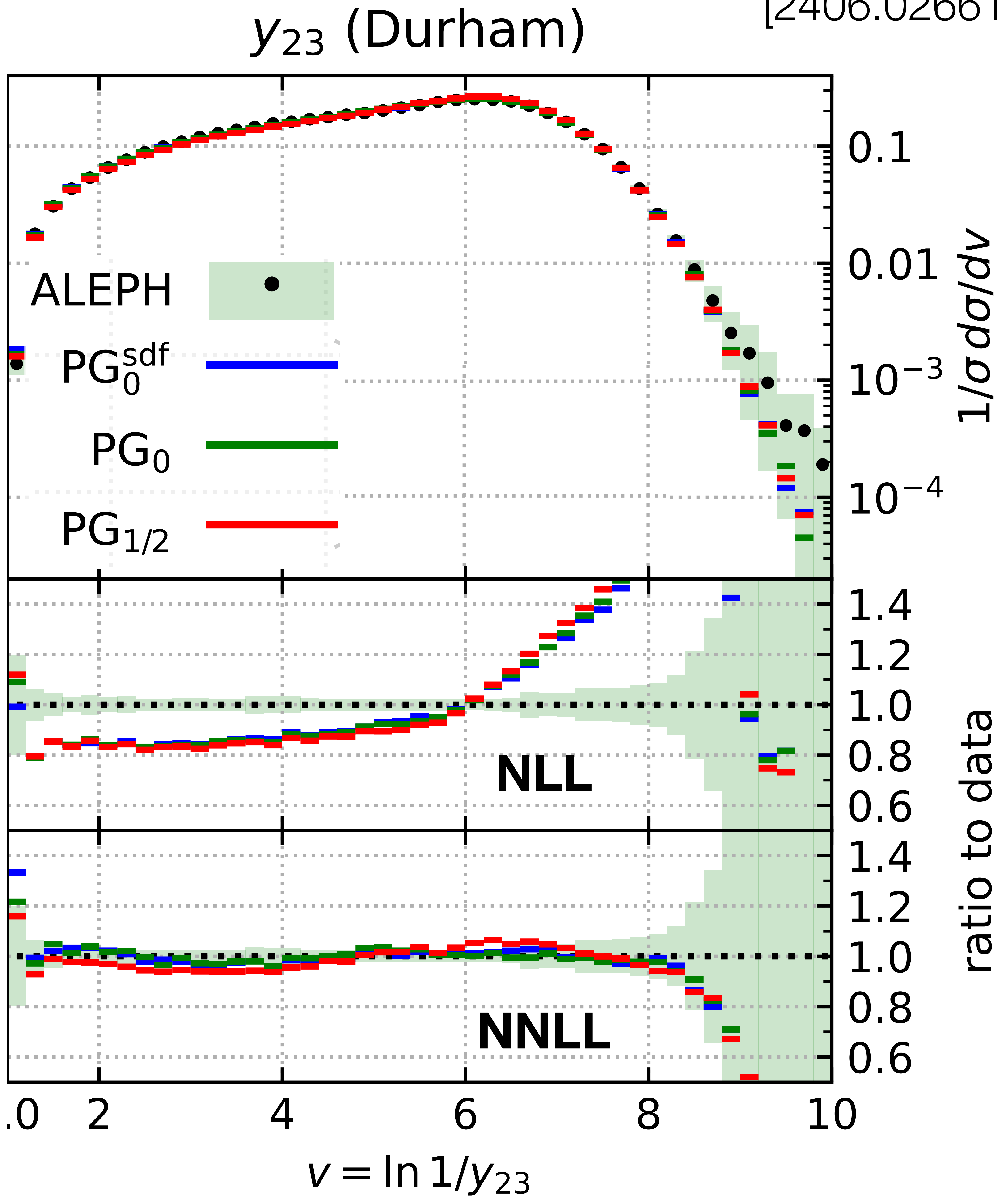
Same holds true for other LEP observables



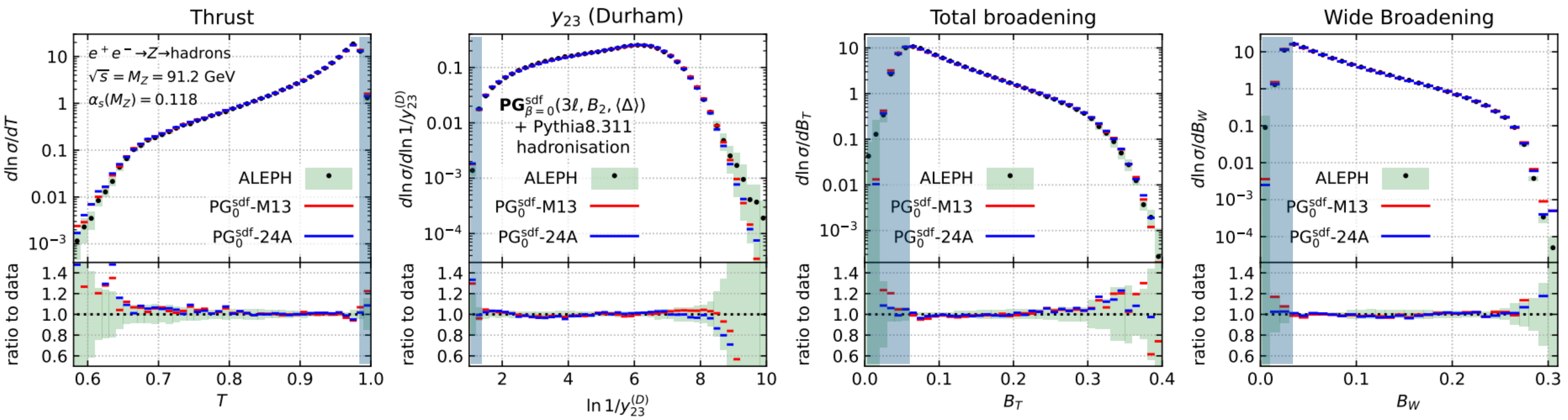
Pythia8.311 used for hadronisation, Rivet for comparison with LEP data

Do we still need to tune?

Yes - but it does not affect observables that should not be affected!

[2406.02661]

M13: (almost) tune of [Skands, Carrazza, Rojo, 1404.5630]
24A: own tune



= hadronisation region

We see that the perturbative region is not much affected by the tune

Do we still need to tune?

Yes - but it does not affect observables that should not be affected!

[2406.02661]

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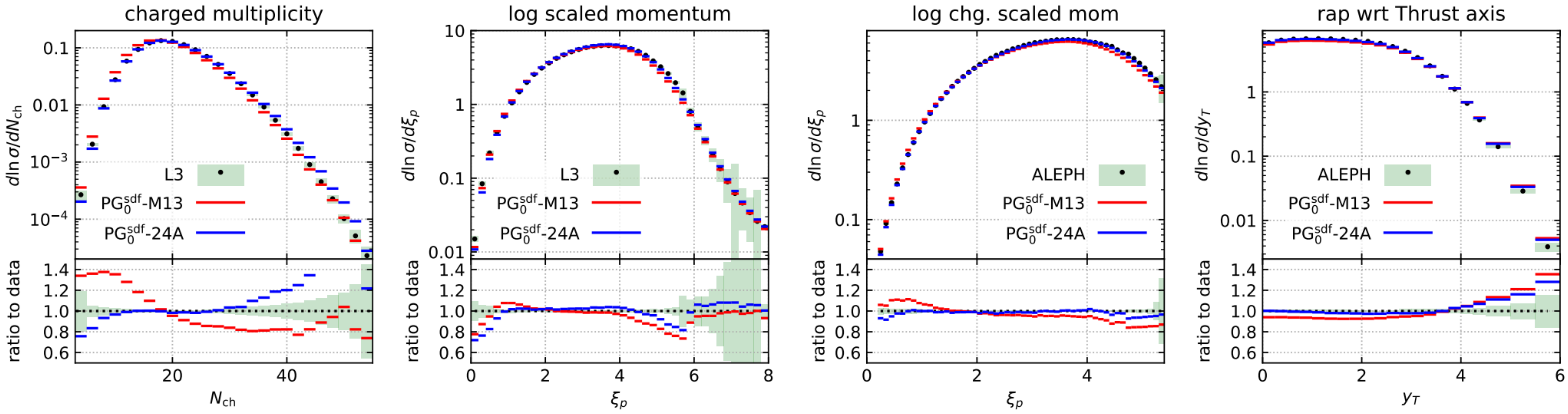
24A: own tune



Infrared unsafe observables are effected (as expected)

Conclusions

- Parton showers will continue to play an indispensable role in any (future) particle physics experiment

- PanScales NLL showers for massless partons in e^+e^-, pp and DIS collisions are now available
  - Next steps include: fast NLO matching, including massive partons, processes with a complicated colour structure

- Actively working towards NNLL showers
  - Achieved a big milestone: NNLL showers for e^+e^- collisions
    - But so far only for PanGlobal, and spin corrections are not compatible with double-soft (work in progress)
  - Working to get also triple-collinear corrections for e^+e^- (relevant for jet-shape observables)
  - NNLL for pp and DIS is on the horizon!

- Beta-version of public code is now available, we'd love to help and receive feedback

```
git clone --recursive https://gitlab.com/panscales/panscales-0.X
```

Back up

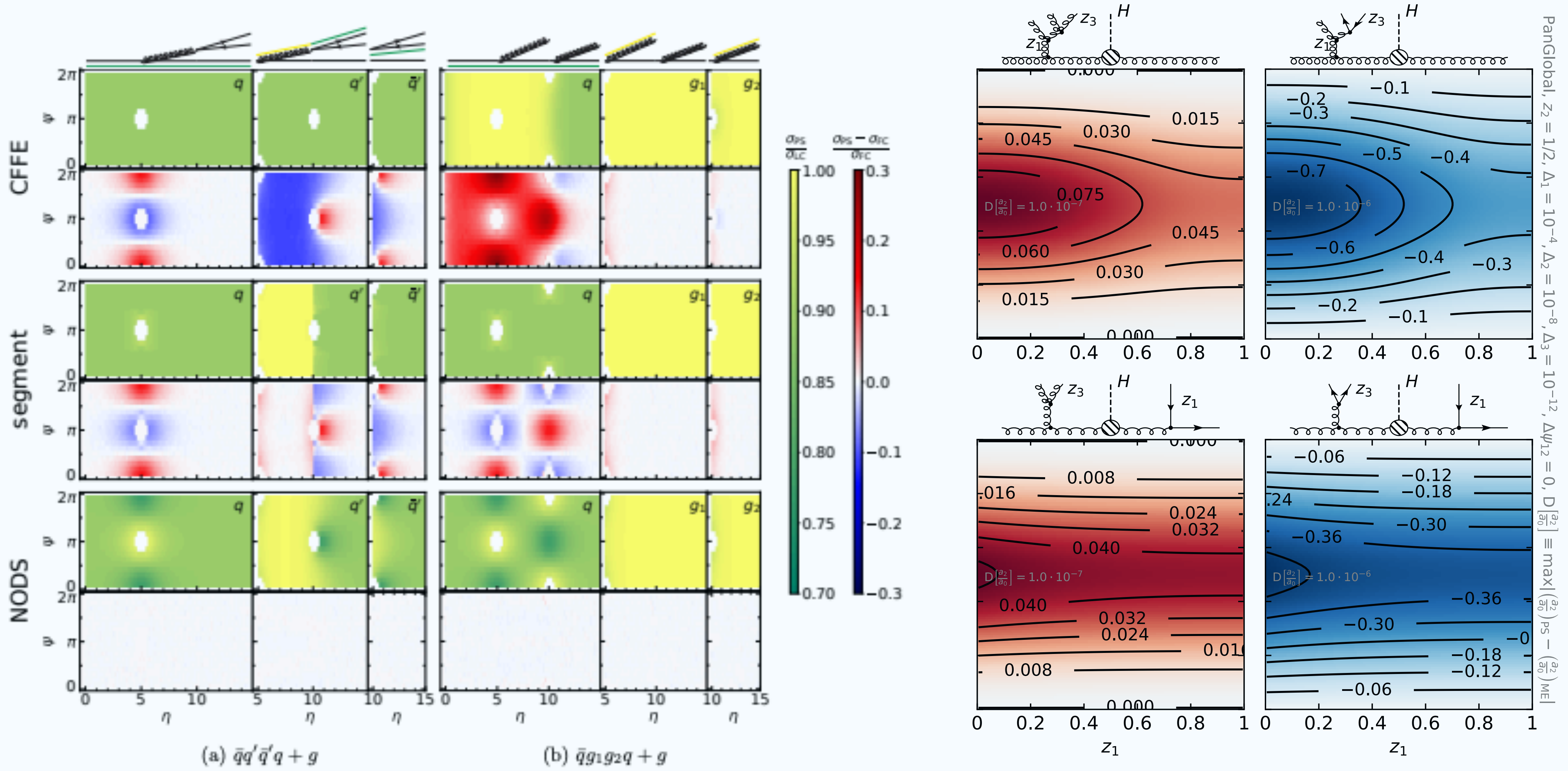
Tune parameters

parameter	$\mathrm{PG}_0^{\mathrm{sdf}}$-24A	PG_0-24A	$\mathrm{PG}_{1/2}$-24A	$\mathrm{PG}_0^{\mathrm{sdf}}$-M13	Monash13
$\alpha_s(M_Z)$	0.118	0.118	0.118	0.118	0.1365
use CMW for α_s	true	true	true	true	false
n loops for α_s	3	3	3	3	1
$k_{t,\min}$ shower cutoff	0.5 GeV	0.5 GeV	0.5 GeV	0.5 GeV	0.5 GeV
`StringPT:sigma`	0.3026	0.294	0.29	0.335	0.335
`StringPT:enhancedFraction`	0.0084	0.0107	0.0196	0.01	0.01
`StringPT:enhancedWidth`	1.6317	1.5583	2.0	2.0	2.0
`StringZ:aLund`	0.6553	0.7586	0.6331	0.68	0.68
`StringZ:bLund`	0.7324	0.7421	0.5611	0.98	0.98
`StringZ:aExtraDiquark`	0.9713	0.7267	0.8707	0.97	0.97

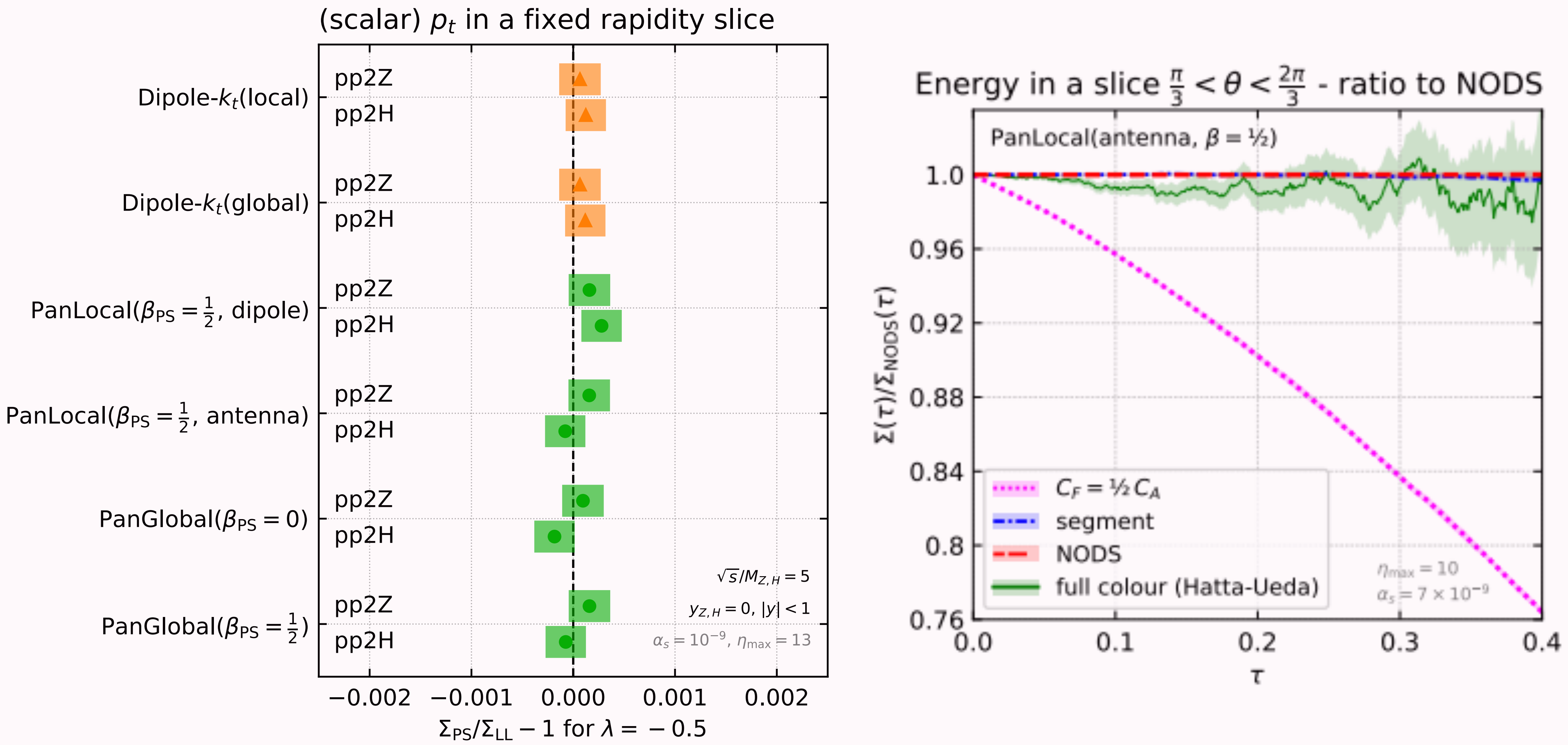
Other tests

[2002.11114, 2103.16526, 2011.10054, 2111.01161, 2205.02237, 2207.09467]

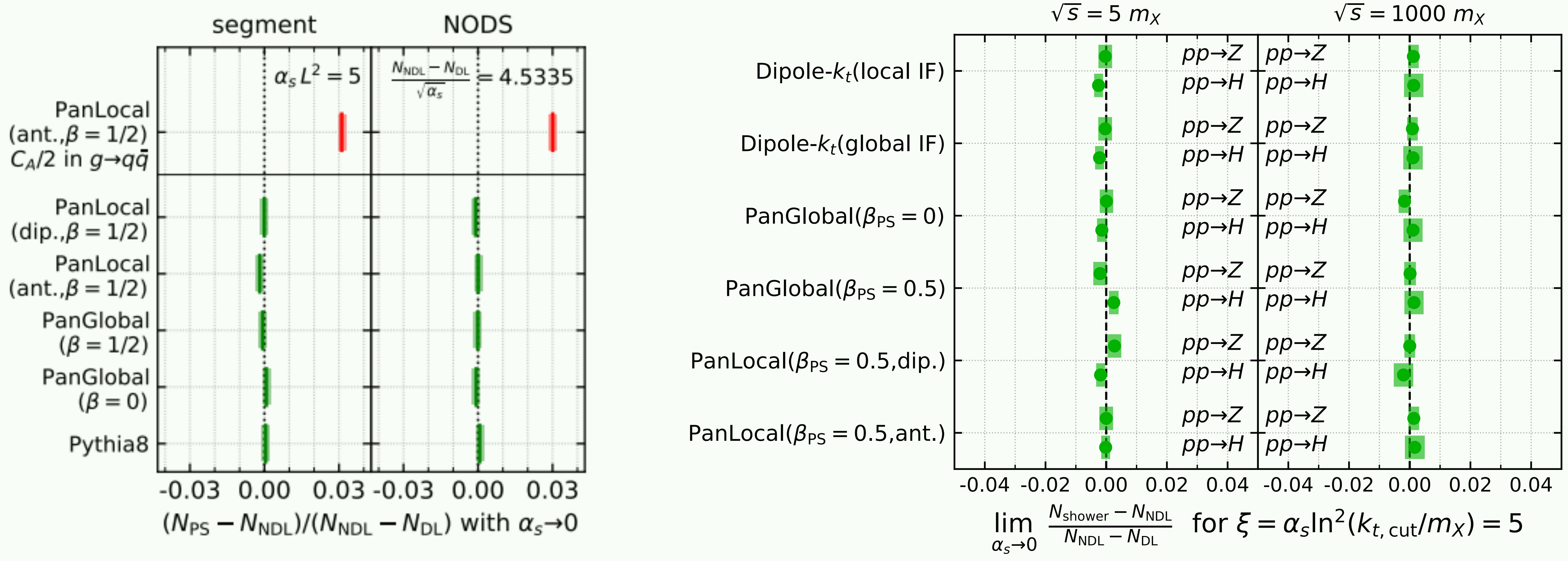
Fixed-order checks



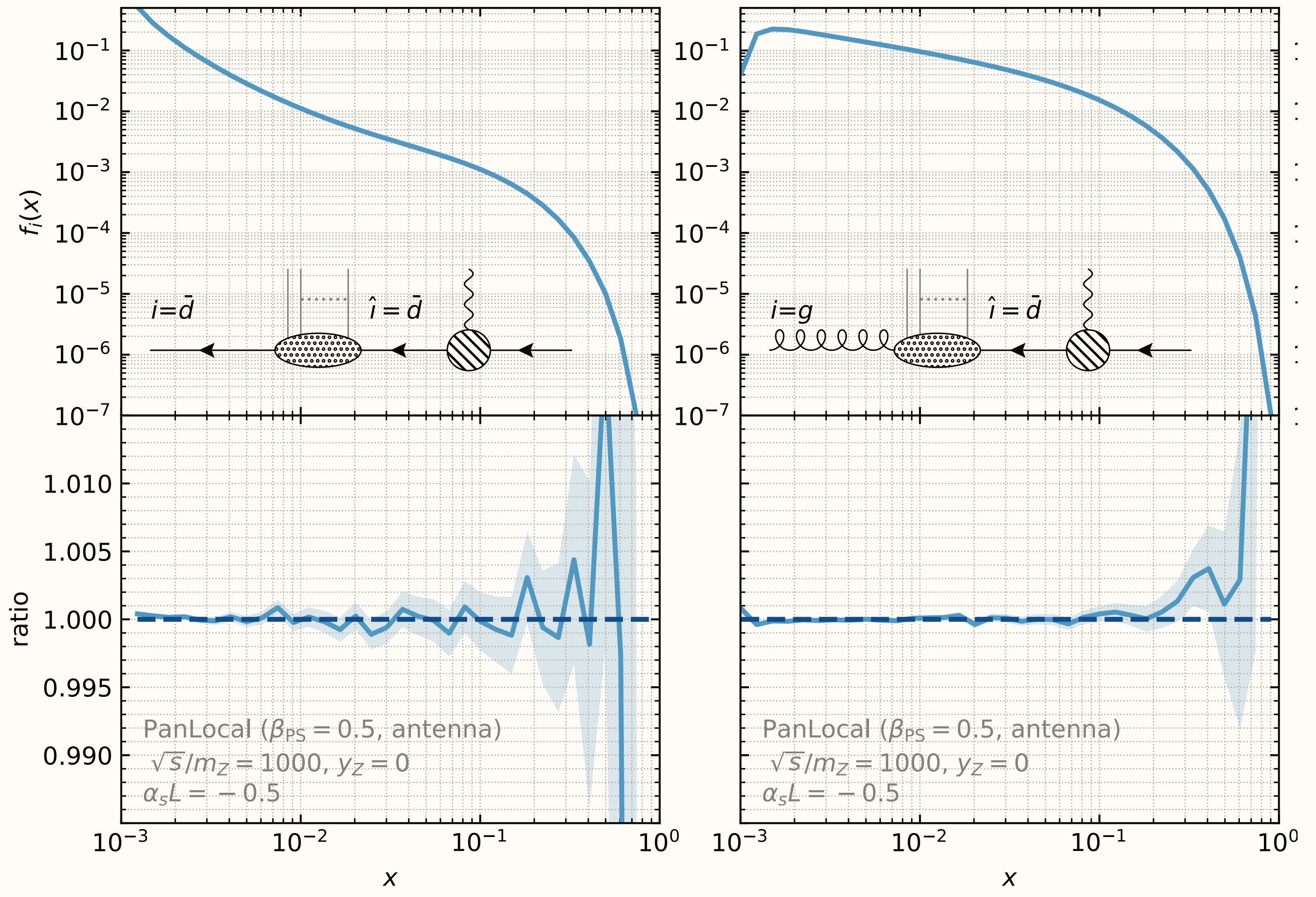
Non-global observables



Multiplicity



DGLAP evolution



[2301.09645]

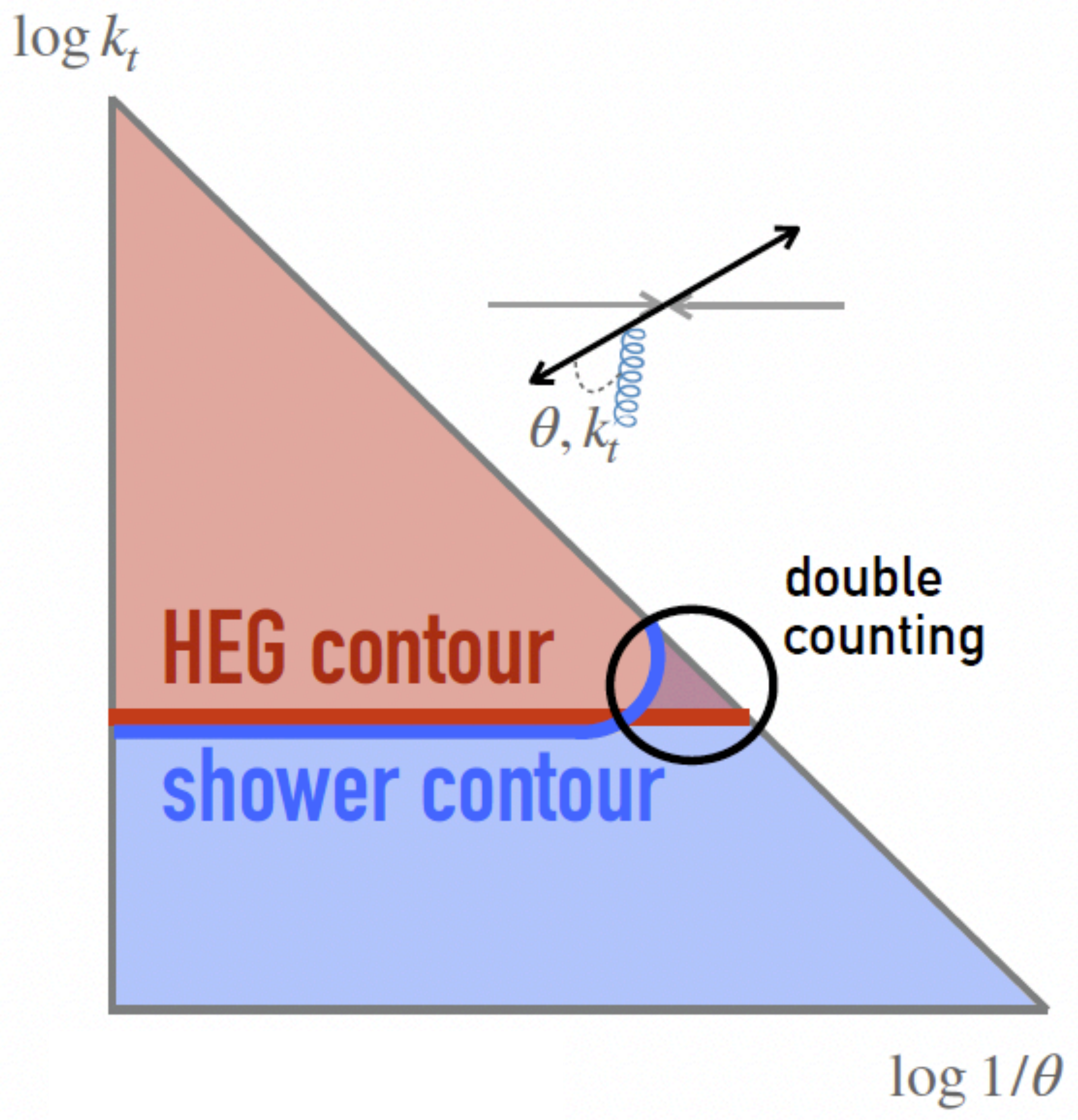
Matching and log accuracy in parton showers

Long known: do not double-count (i.e. [1003.2384])
Less known: how does that affect the logarithmic accuracy?

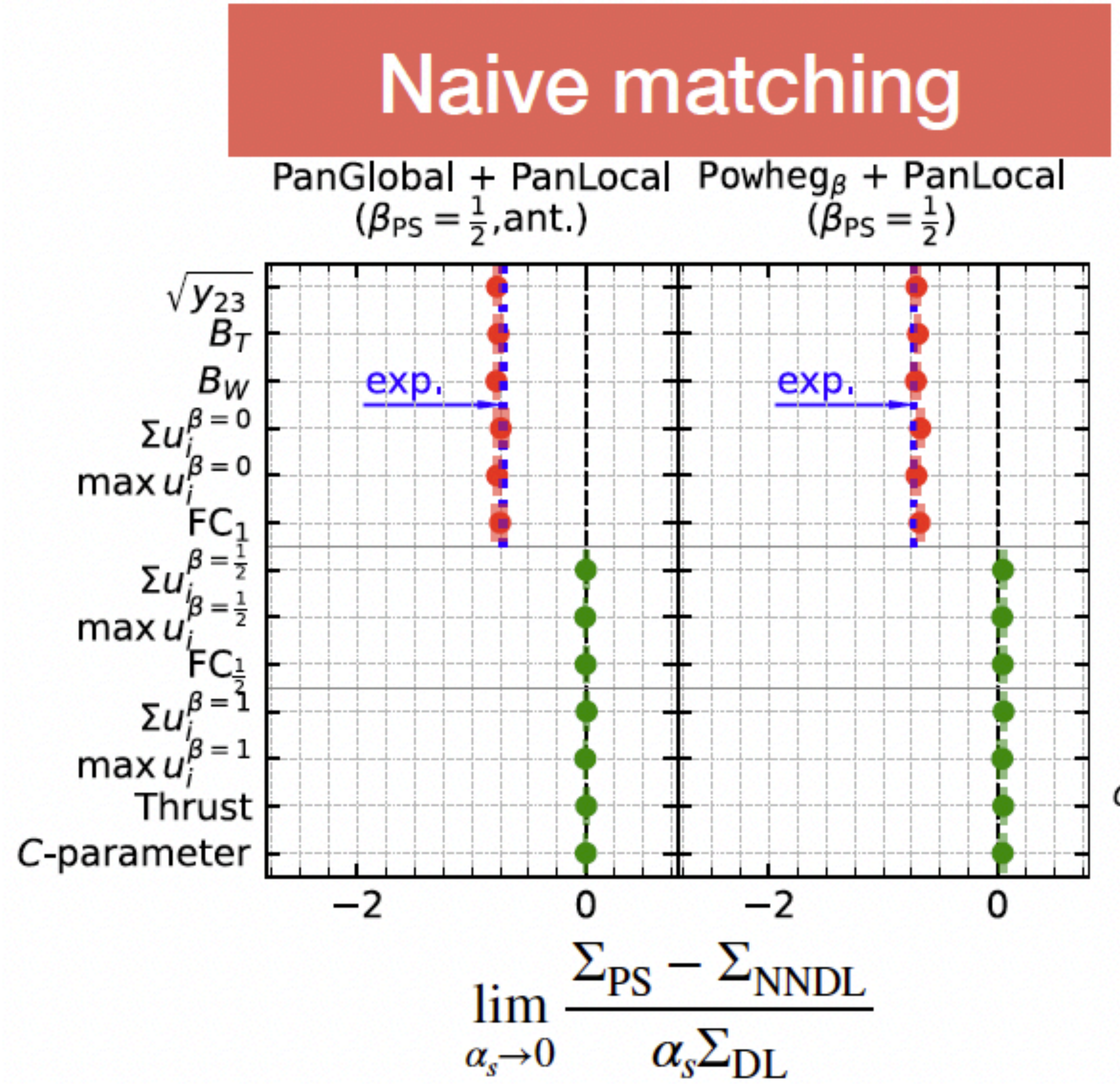
- Matching schemes using the shower phase-space to generate the first emission (i.e. MC@NLO, multiplicative matching) don't suffer from this

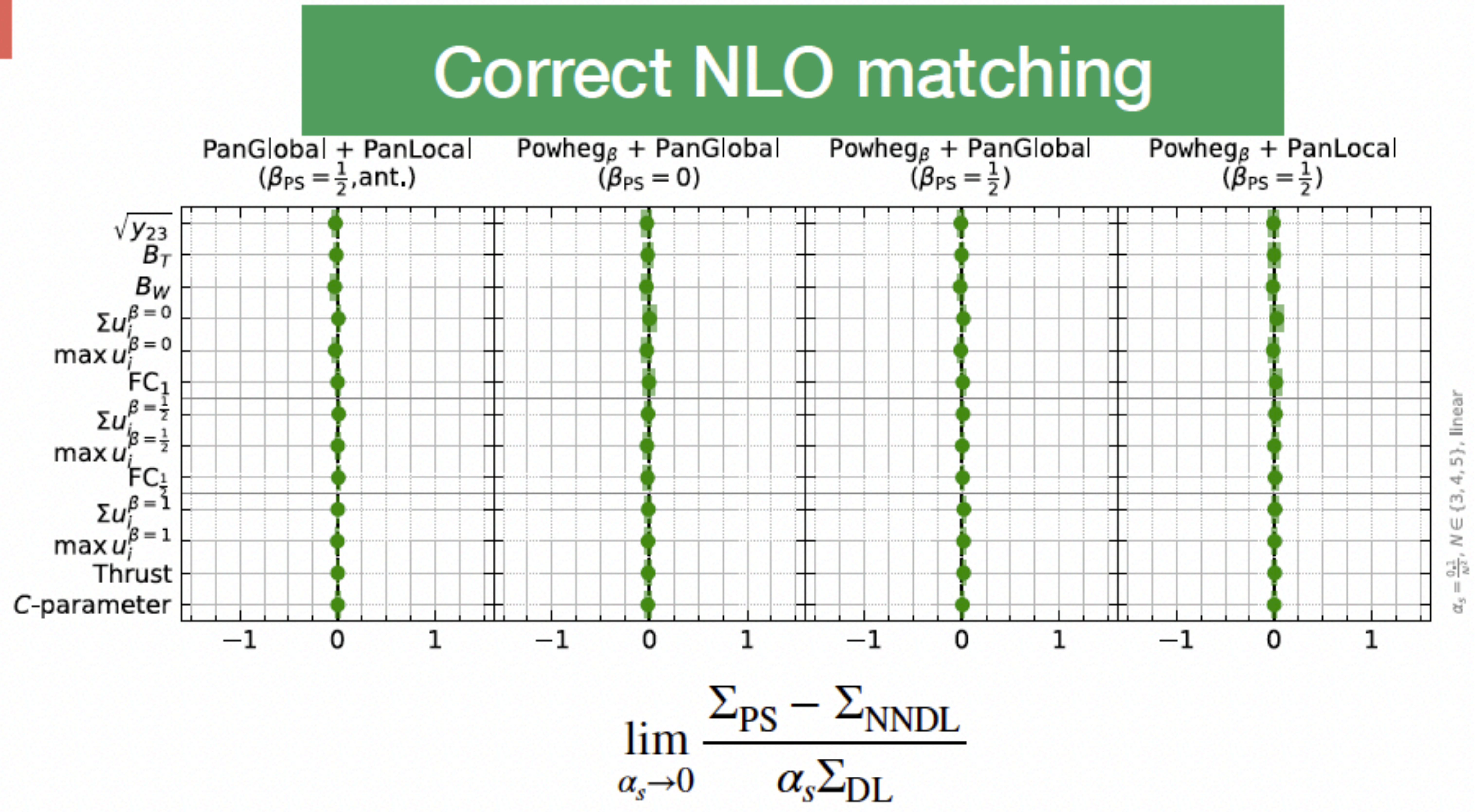
- With PowHeg-style matching be careful with:
  - Differences in kinematic maps
  - Differences in $g \to gg(q\bar{q})$ partitioning

- These lead to $\mathcal{O}(\alpha_s)$ = NNDL discrepancies



Matching and log accuracy in parton showers





This brings us NNDL (=NLL') accuracy!

Recoil in standard dipole showers

Evolution variable v
Which emissions come first?

→ Transverse-momentum ordering

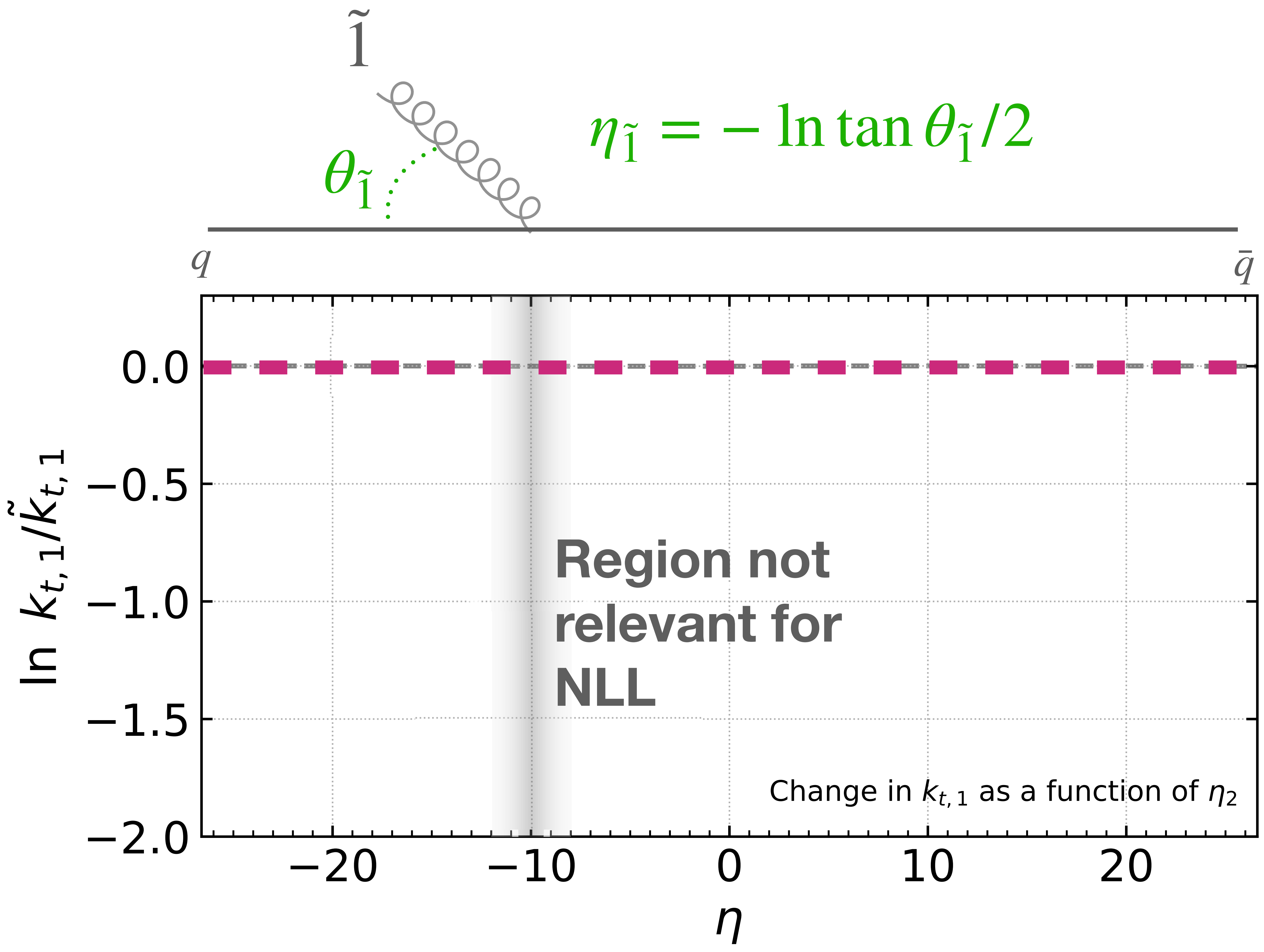
Kinematic map
How to go from n to $n+1$ partonic state?

→ Dipole-local, with one parton absorbing the recoil

Matrix element treatment
How to select an 'emitter'?

→ Partioning done at zero rapidity in the dipole rest frame

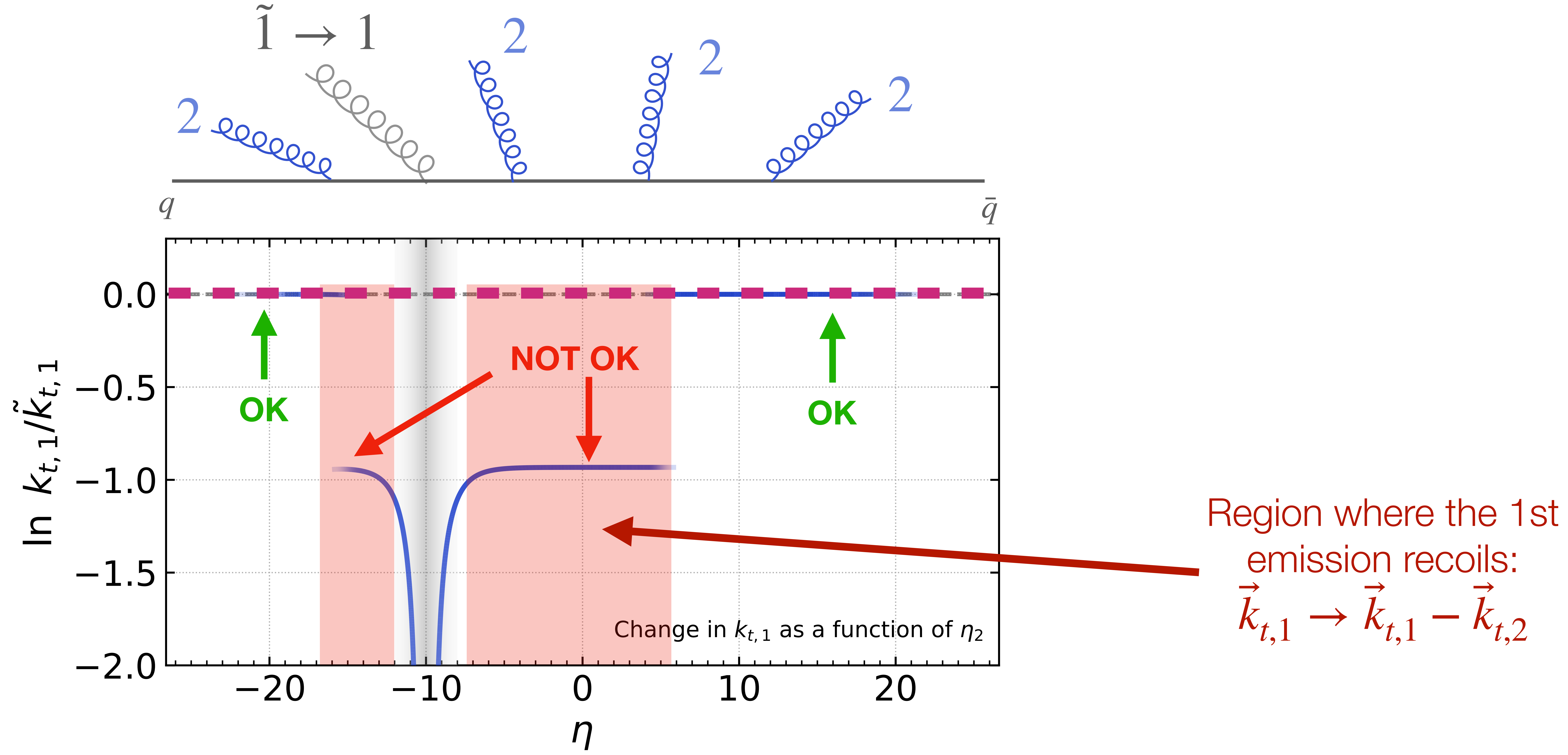
Fixed-order criterion



NLL expectation: $k_{t,1}$ should not change as an effect of the $k_{t,2}$ recoil

We need $k_{t1} = \tilde{k}_{t1}$ for phase-space points where QCD factorisation holds

Fixed-order criterion



We need $k_{t1} = \tilde{k}_{t1}$ for phase-space points where QCD factorisation holds

Clear violation of this criterion
happens in **all** publicly available dipole showers

Fixing the recoil brings NLL accuracy!

PanGlobal

1. Evolution variable
   $v \sim k_t,\ k_t\sqrt{\theta}$ (indicated by $\beta_{\mathrm{ps}} = 0,\ 1/2$)

2. Kinematic map
   Global $\perp$
   Local $+/-$

3. Matrix element treatment
   Dipole midpoint in *hard-system* CM frame

PanLocal

1. Evolution variable
   $v \sim k_t\sqrt{\theta}$ ($\beta_{\mathrm{ps}} = 1/2$)

2. Kinematic map
   Local $\perp$
   Local $+/-$

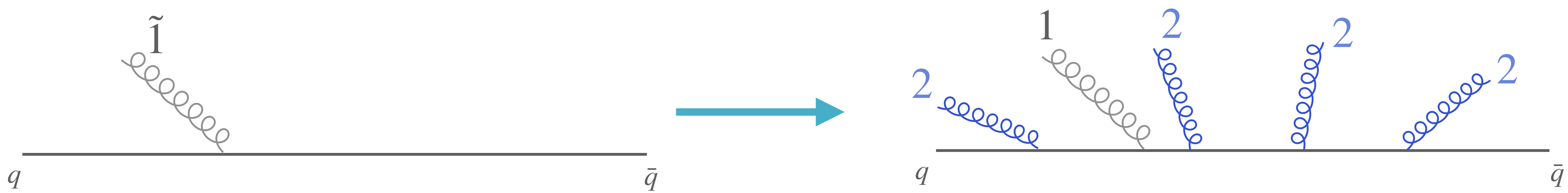
3. Matrix element treatment
   Dipole midpoint in *hard-system* CM frame

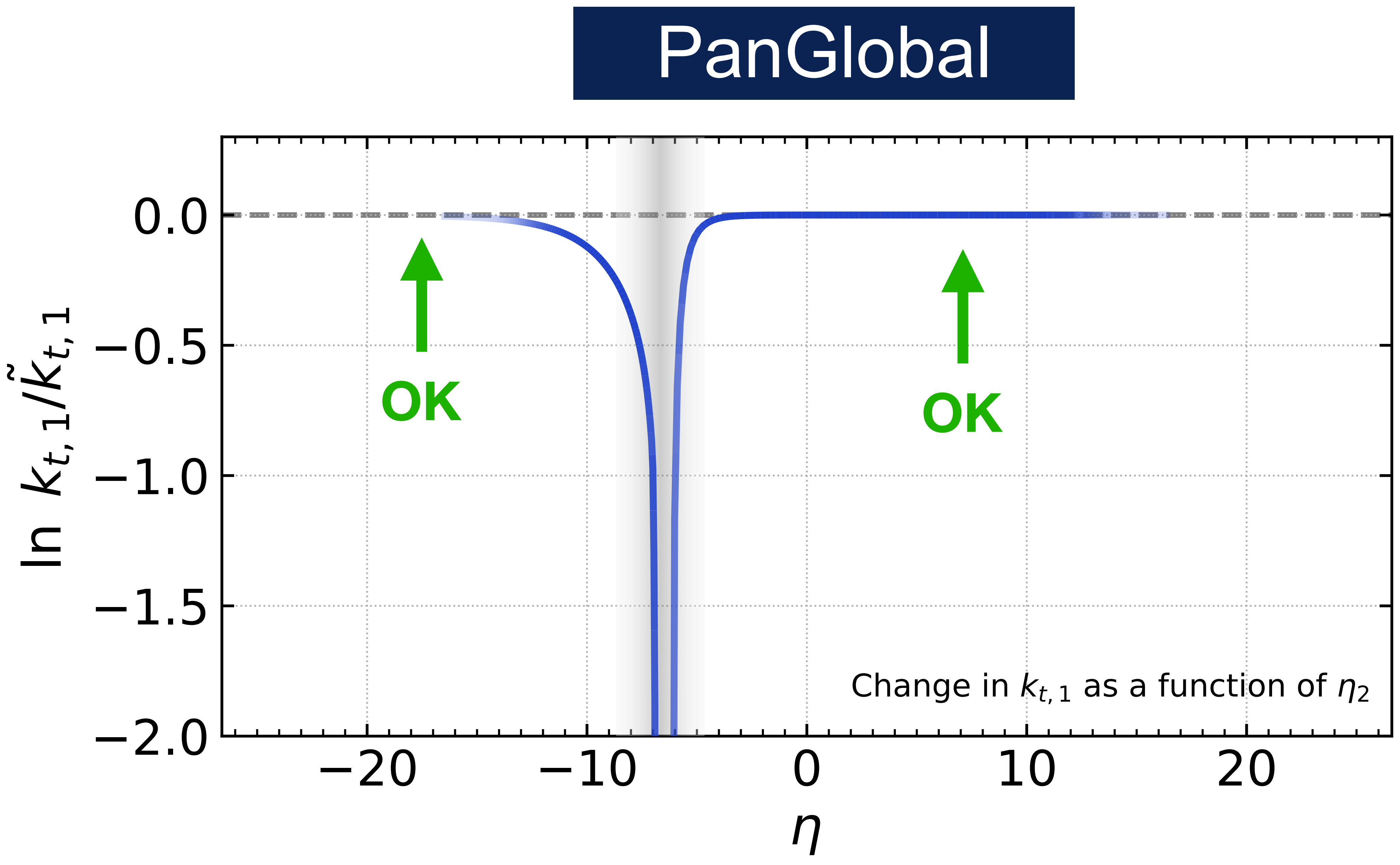
+ spin correlations [2103.16526, 2111.01161, 2205.02237]
+ subleading colour corrections $(1/N_c^2 \sim 0.1 \sim \mathrm{NLL})$ [2011.10054, 2205.02237]

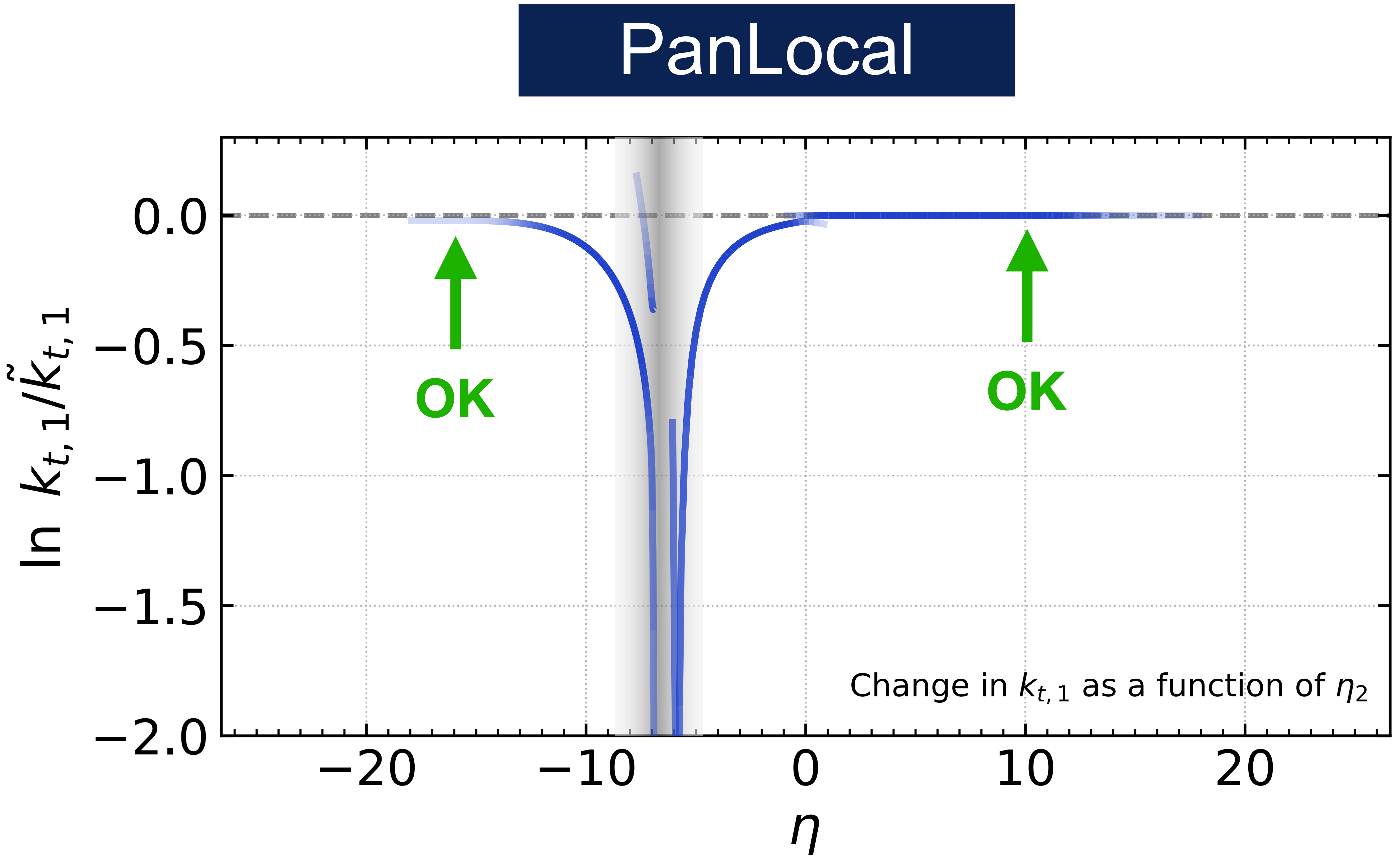
With this we have NLL showers for e^+e^-, pp and DIS

e^+e^-: Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez [2002.11114]
pp: MvB, Ferrario Ravasio, Salam, Soto Ontoso, Soyez, Verheyen [2205.02237]; + Hamilton [2207.09467]
DIS: MvB, Ferrario Ravasio [2305.08645]

Fixed-order criterion





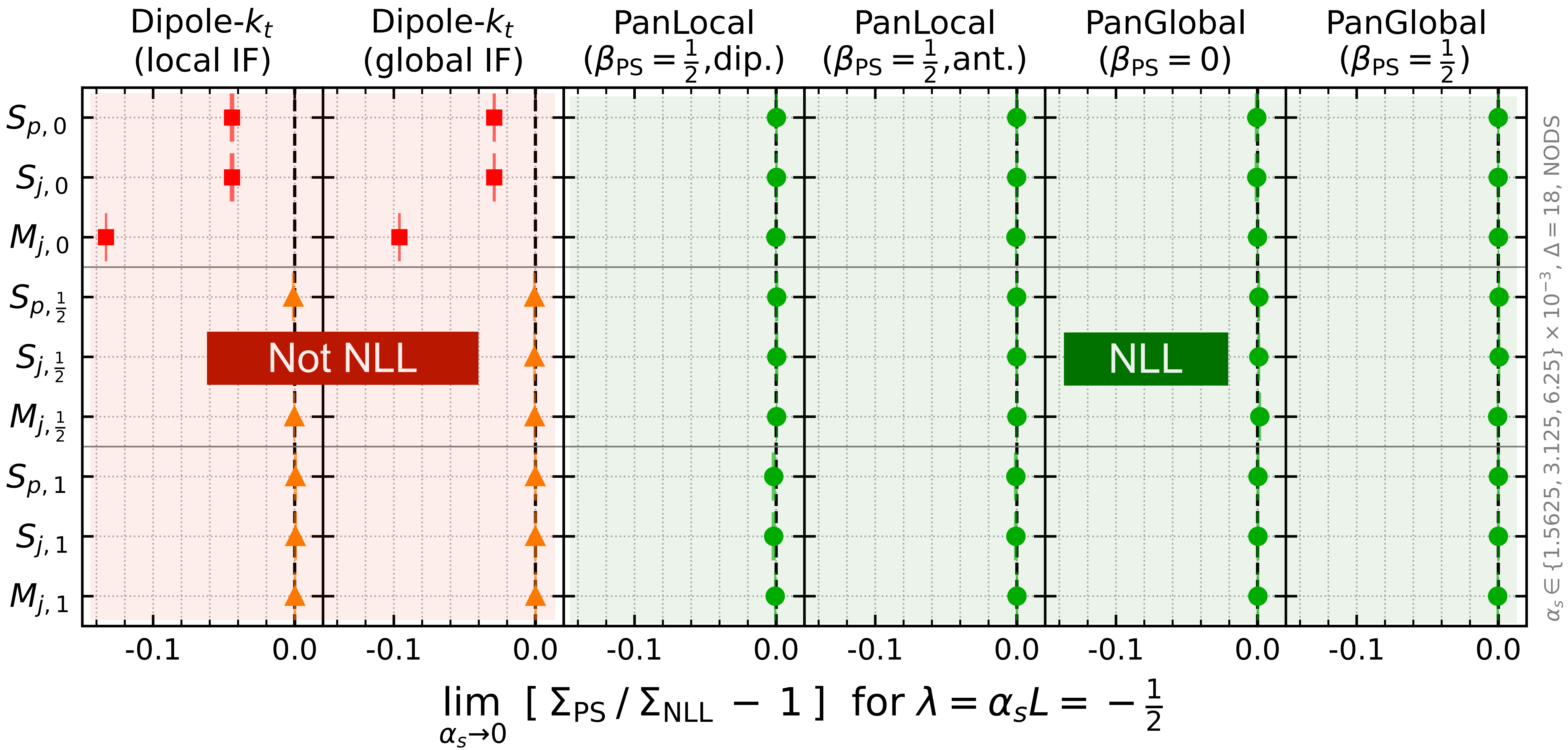


These showers meet the fixed-order criterion

Global observables NLL tests for $pp \to Z$

$$S_{p/j,\beta} = \sum_{i \in f/\text{jets}} p_{\perp,i}\, e^{-\beta|\eta_i|}$$

$$M_{j,\beta} = \max_{i \in \text{jets}} \left[p_{\perp,i}\, e^{-\beta|\eta_i|}\right]$$



Note: this is just a small selection of the tests we did

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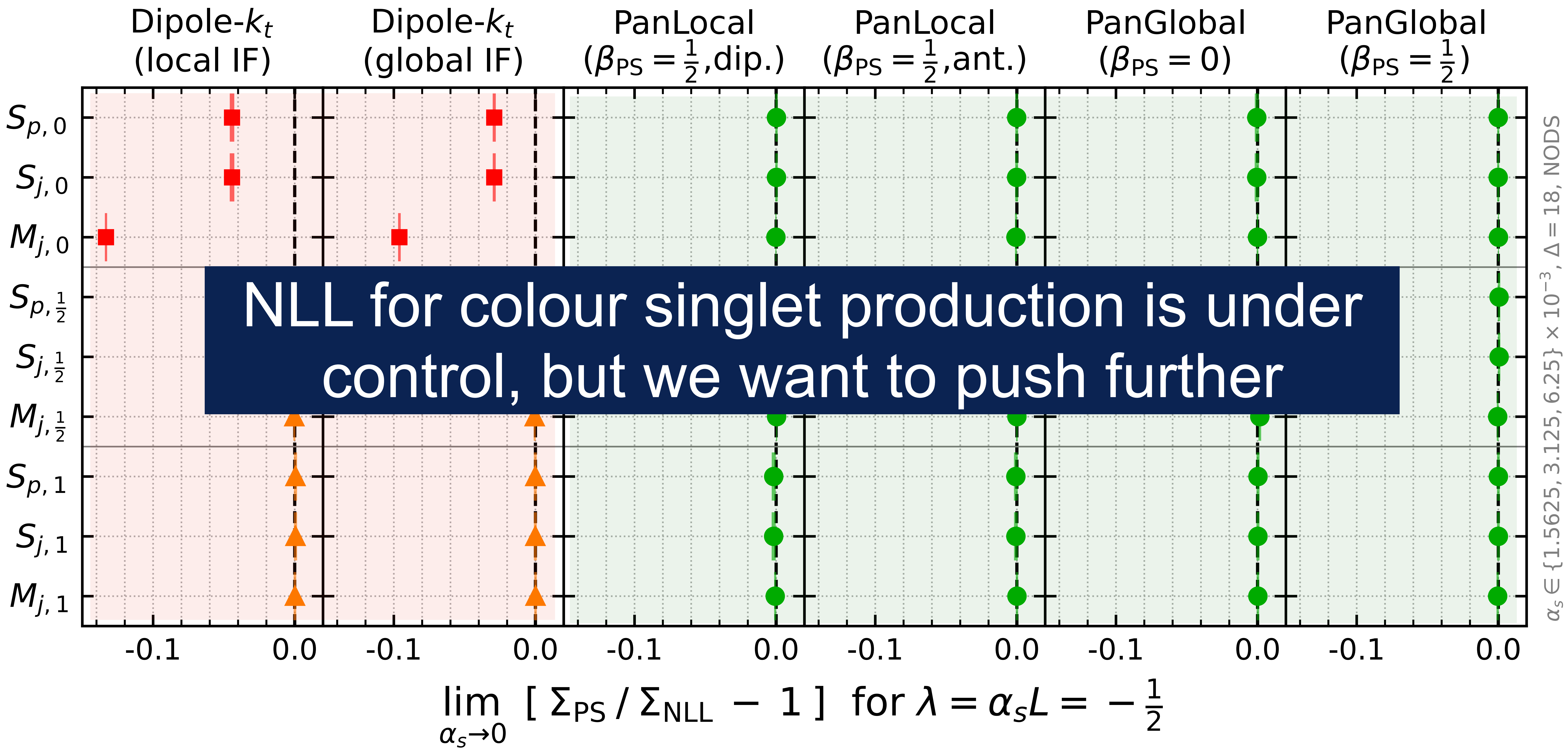
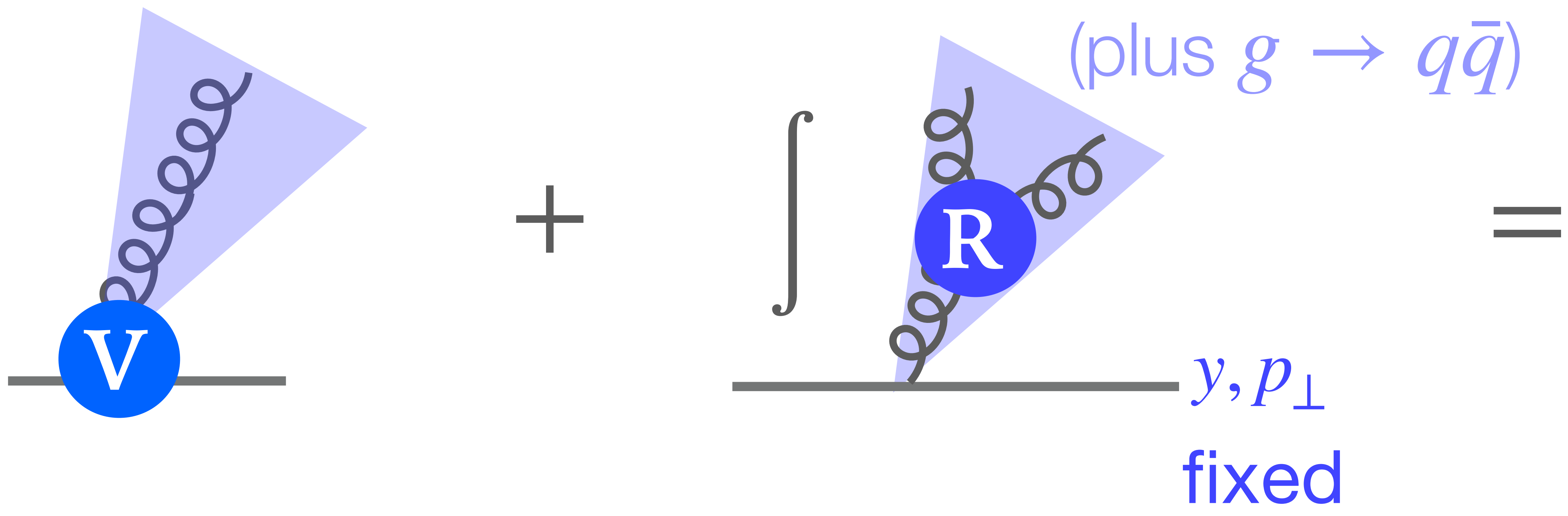


NLL for colour singlet production is under control, but we want to push further

Note: this is just a small selection of the tests we did

Definition of the cusp anomalous dimension:

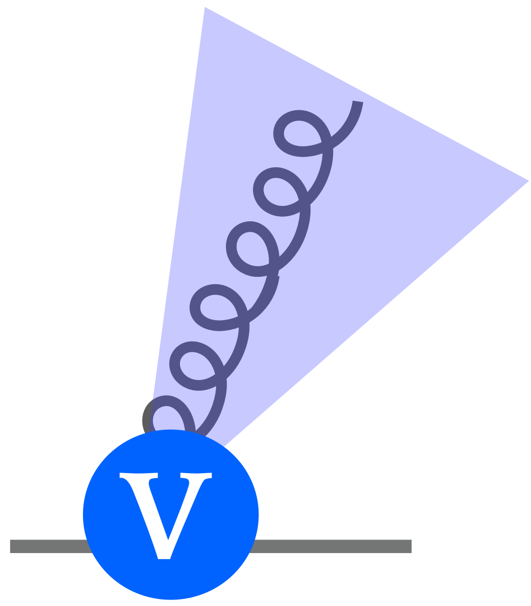


$$= \frac{\alpha_s}{2\pi} K_1$$

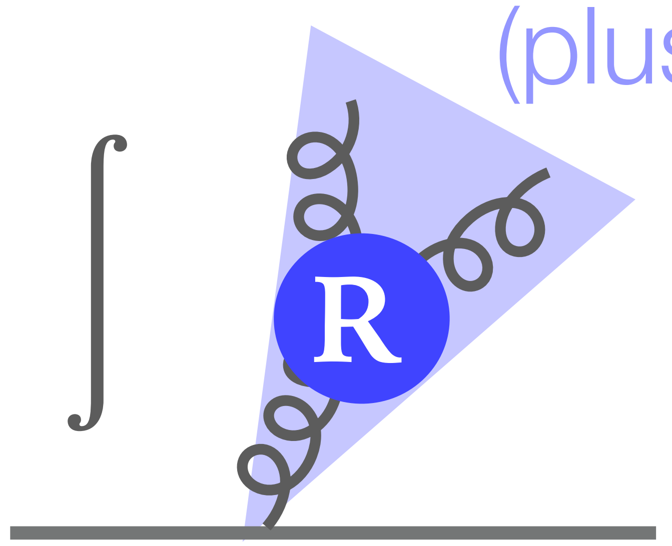
This is the NLO weight for a soft emission

[2307.11142]

Definition of the cusp anomalous dimension:



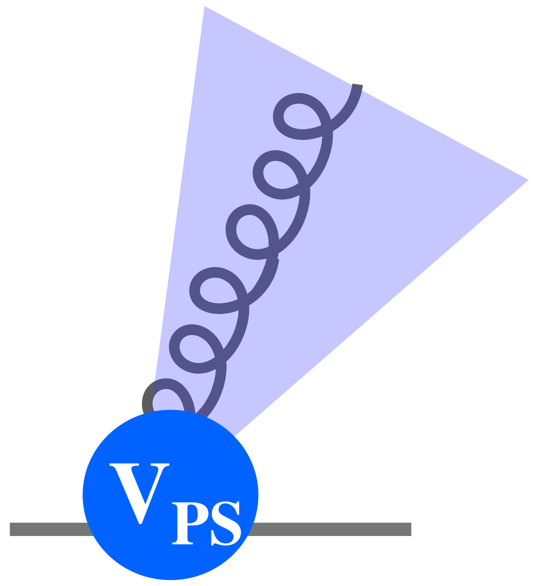
$+ \int$



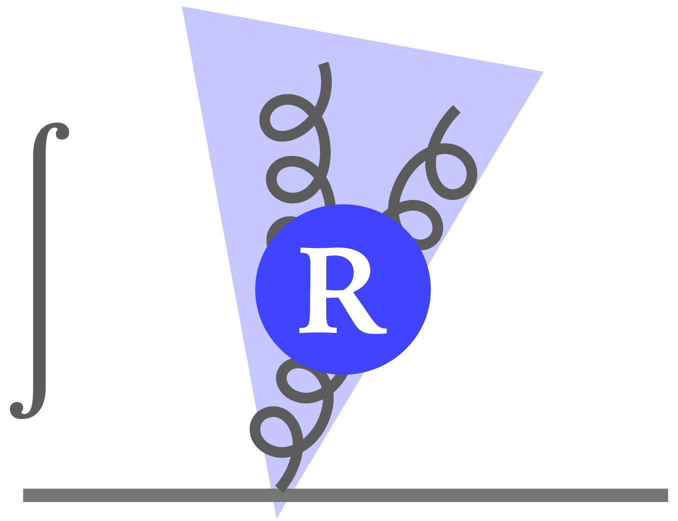
$= \frac{\alpha_s}{2\pi} K_1$

This is the NLO weight for a soft emission

The shower generates virtual corrections through unitarity



$\equiv \; - \int$



Introduce $\alpha_s^{\mathrm{CMW}} = \alpha_s \left(1 + \frac{\alpha_s}{2\pi} K_1\right)$ such that $\mathbf{V_{PS}} + \int \mathbf{R_{PS}} = \frac{\alpha_s}{2\pi} K_1$

[2307.11142]

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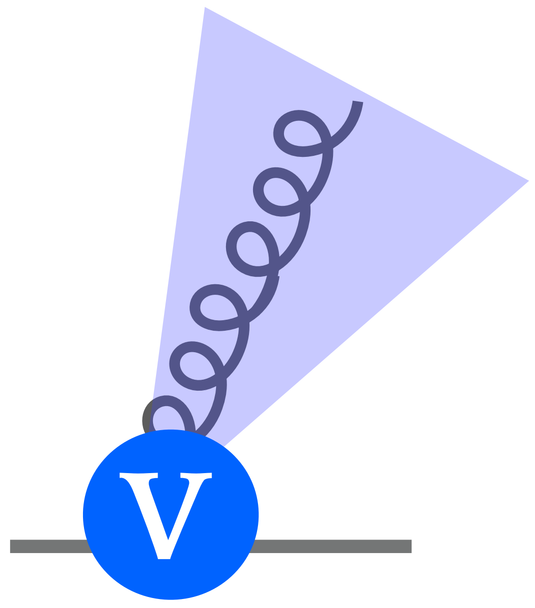
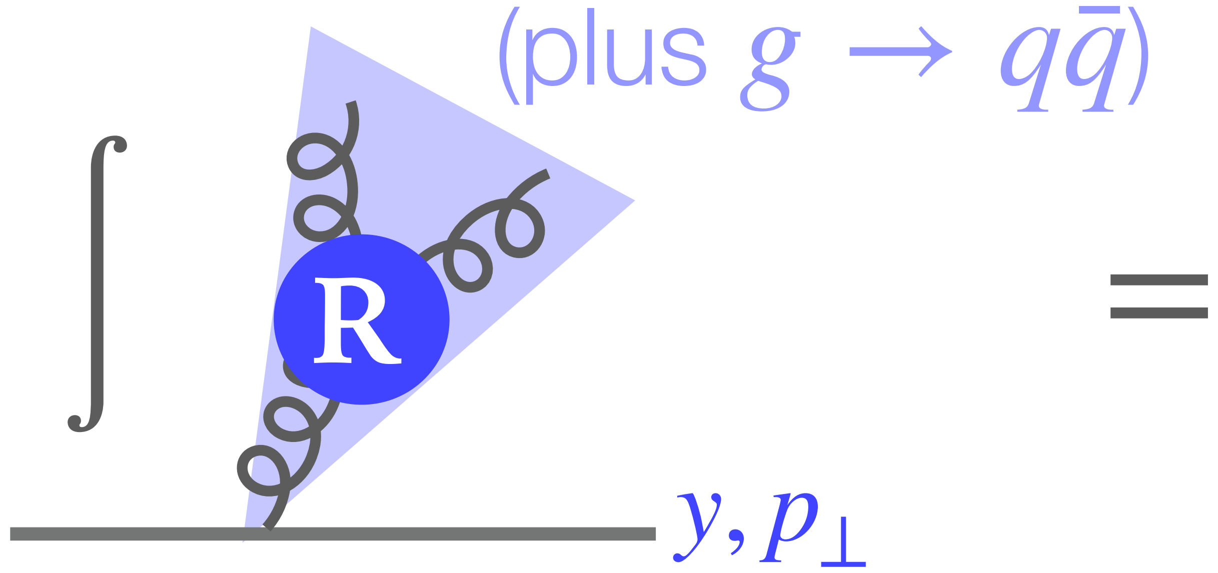


$+ \int$

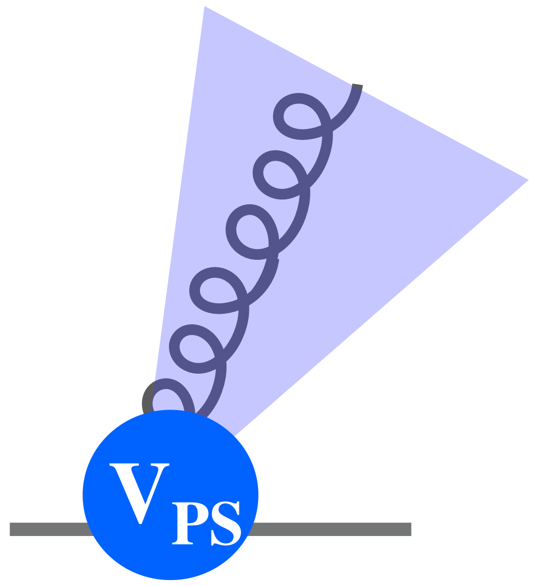


fixed

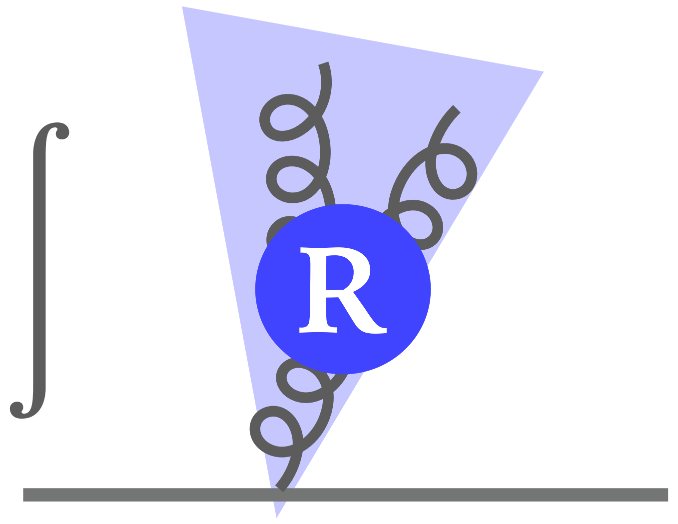
$= \frac{\alpha_s}{2\pi} K_1$

This is the NLO weight for a soft emission

The shower generates virtual corrections through unitarity



$\equiv - \int$



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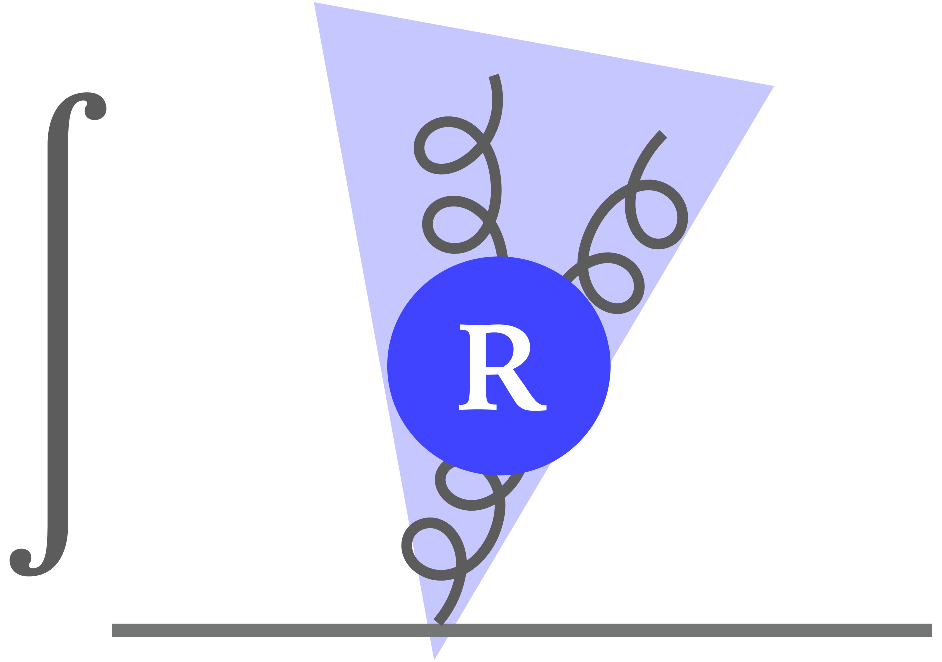
Shower violates this for soft wide-angle emissions

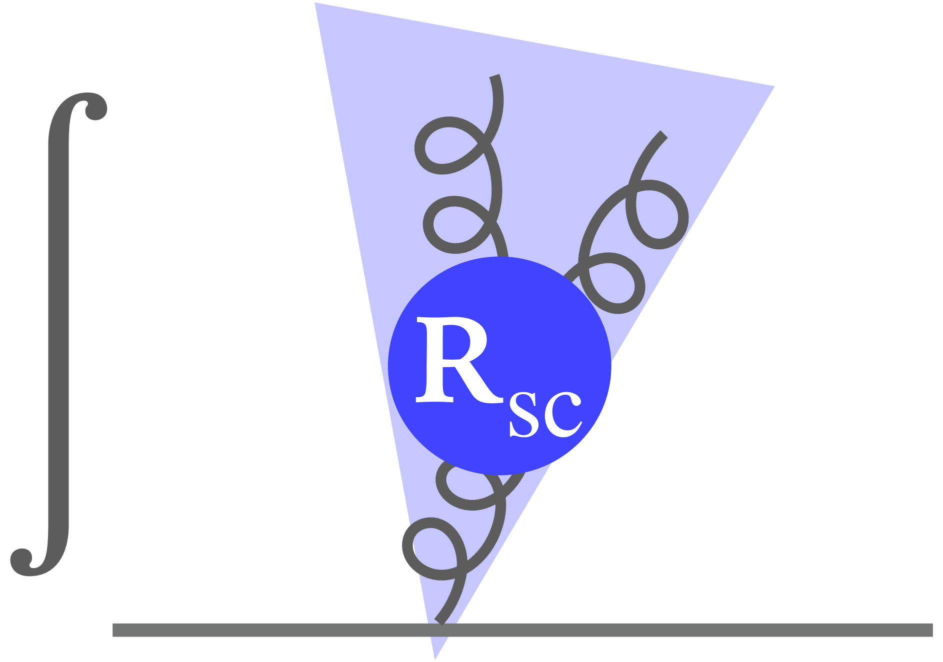
[2307.11142]

Introduce $\Delta K_1(\tilde{1}) =$



in shower phase-space holding $\tilde{1}$ fixed

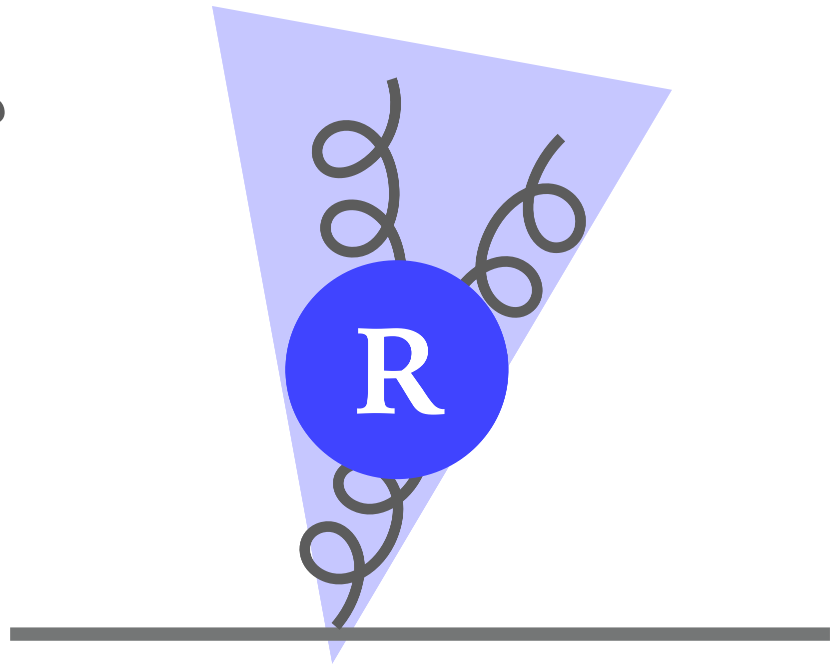
$-$



in shower phase-space holding $\tilde{1}_{sc}$ fixed

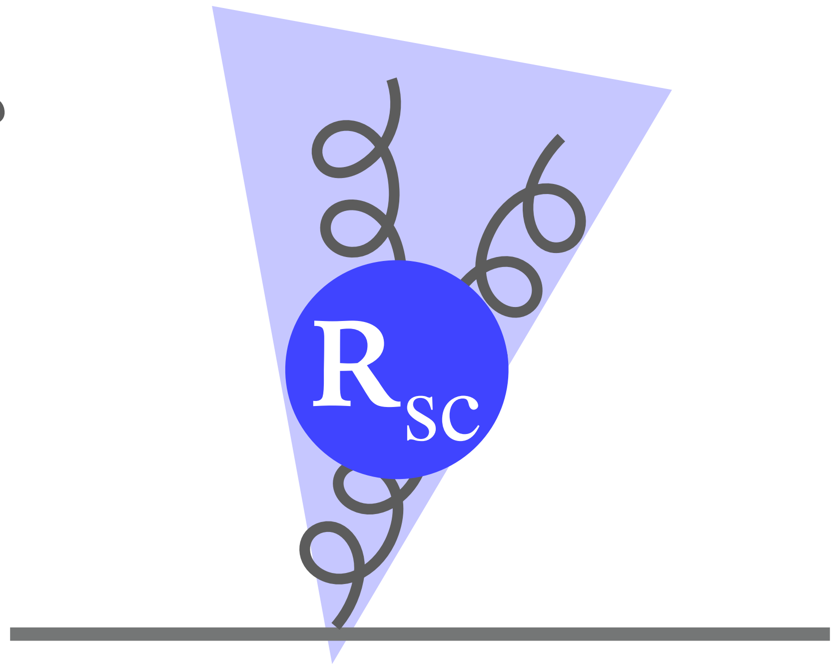
[2307.11142]

Introduce $\Delta K_1(\tilde{1}) = \int$

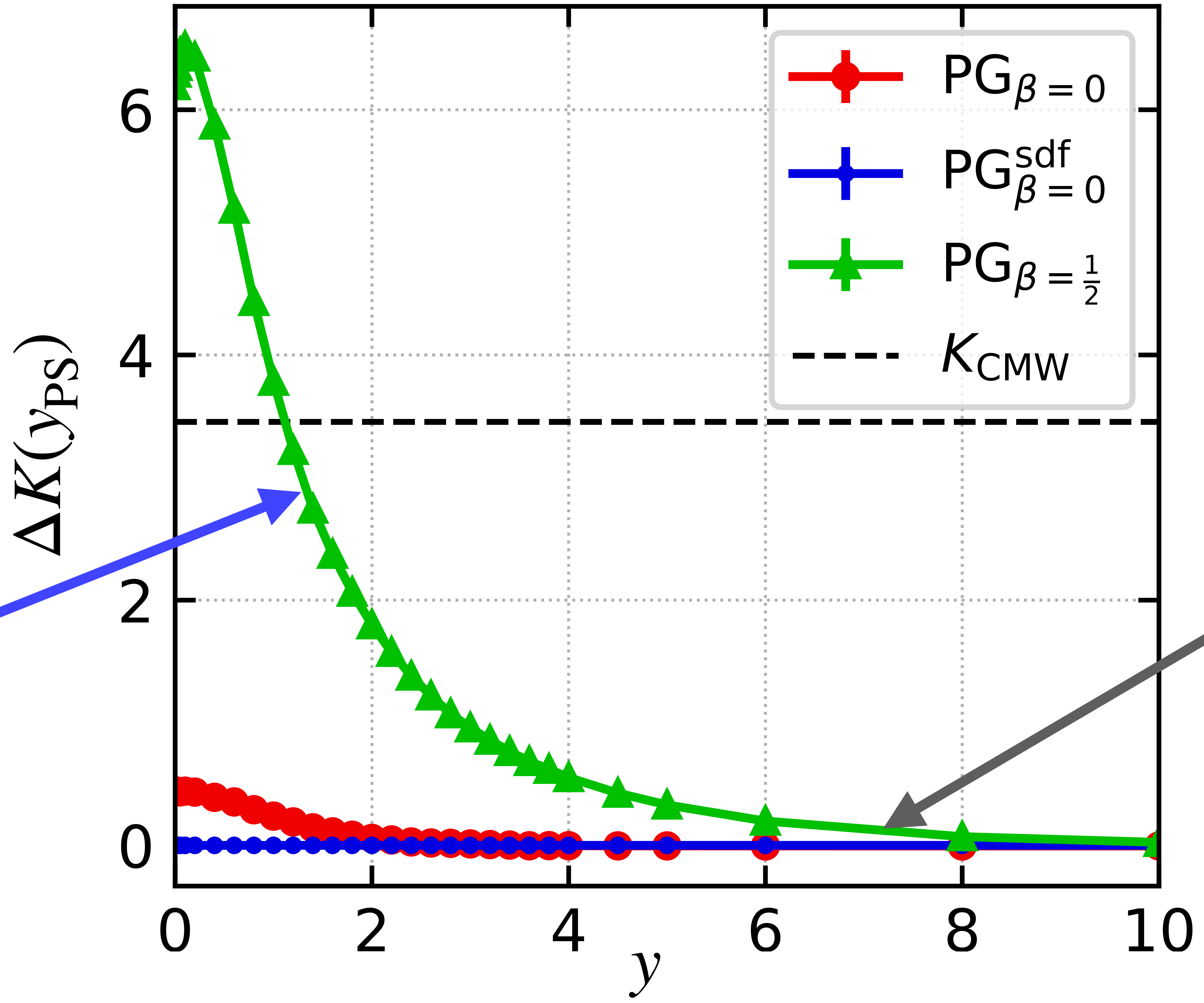


in shower phase-space holding $\tilde{1}$ fixed

$- \int$



in shower phase-space holding $\tilde{1}_{sc}$ fixed

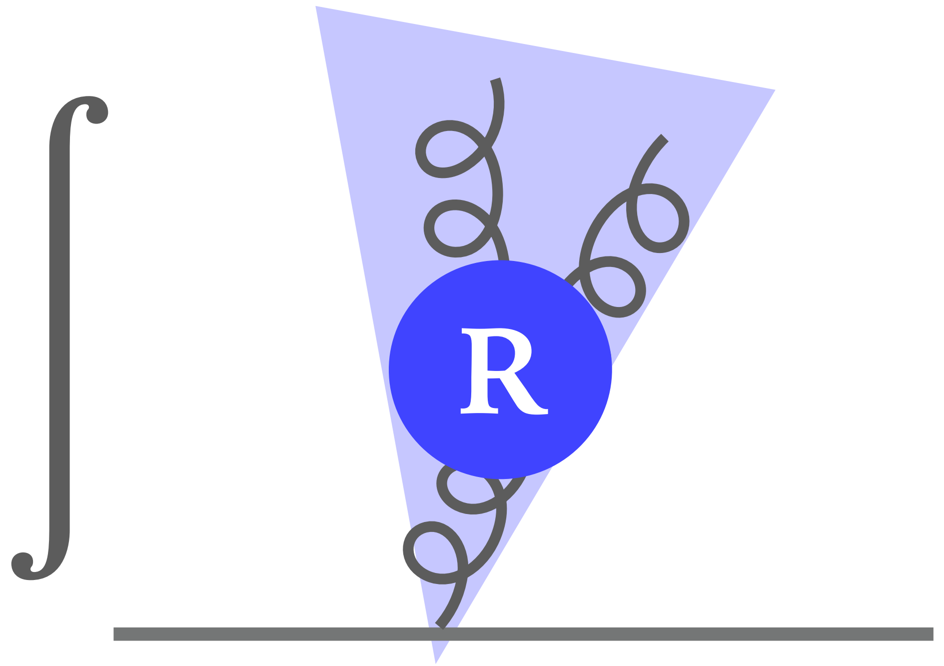


Soft **large-angle** emissions can have a large ΔK_1

Soft-collinear emissions are already OK (because the shower is NLL)

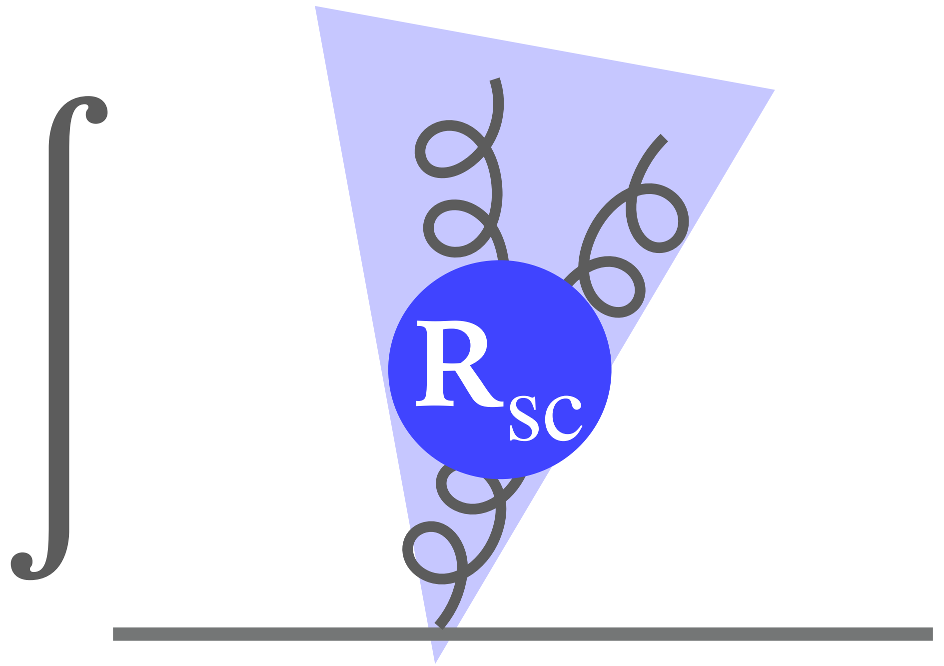
[2307.11142]

Introduce $\Delta K_1(\tilde{1}) = \int$



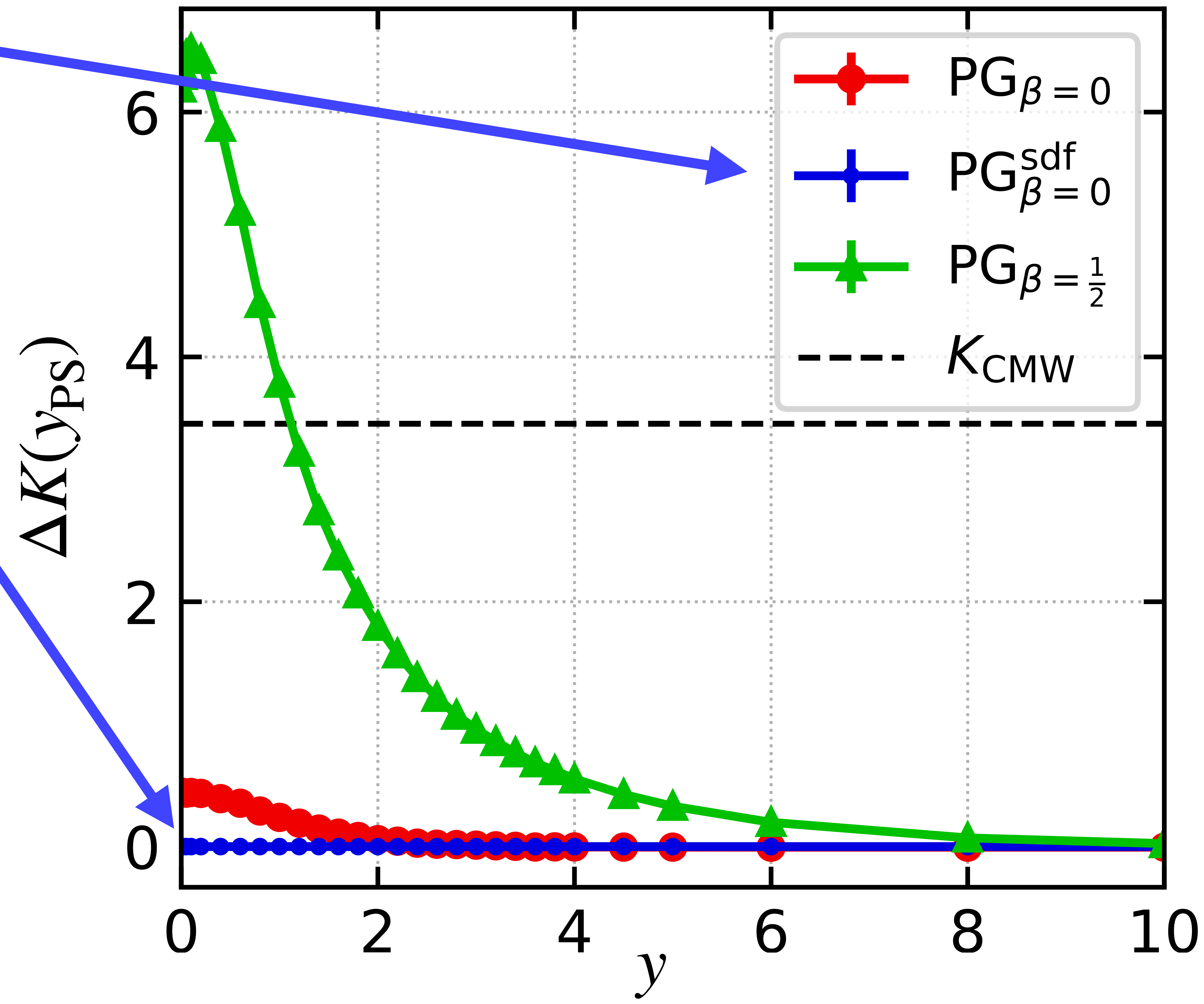
in shower phase-space holding $\tilde{1}$ fixed

$-\int$



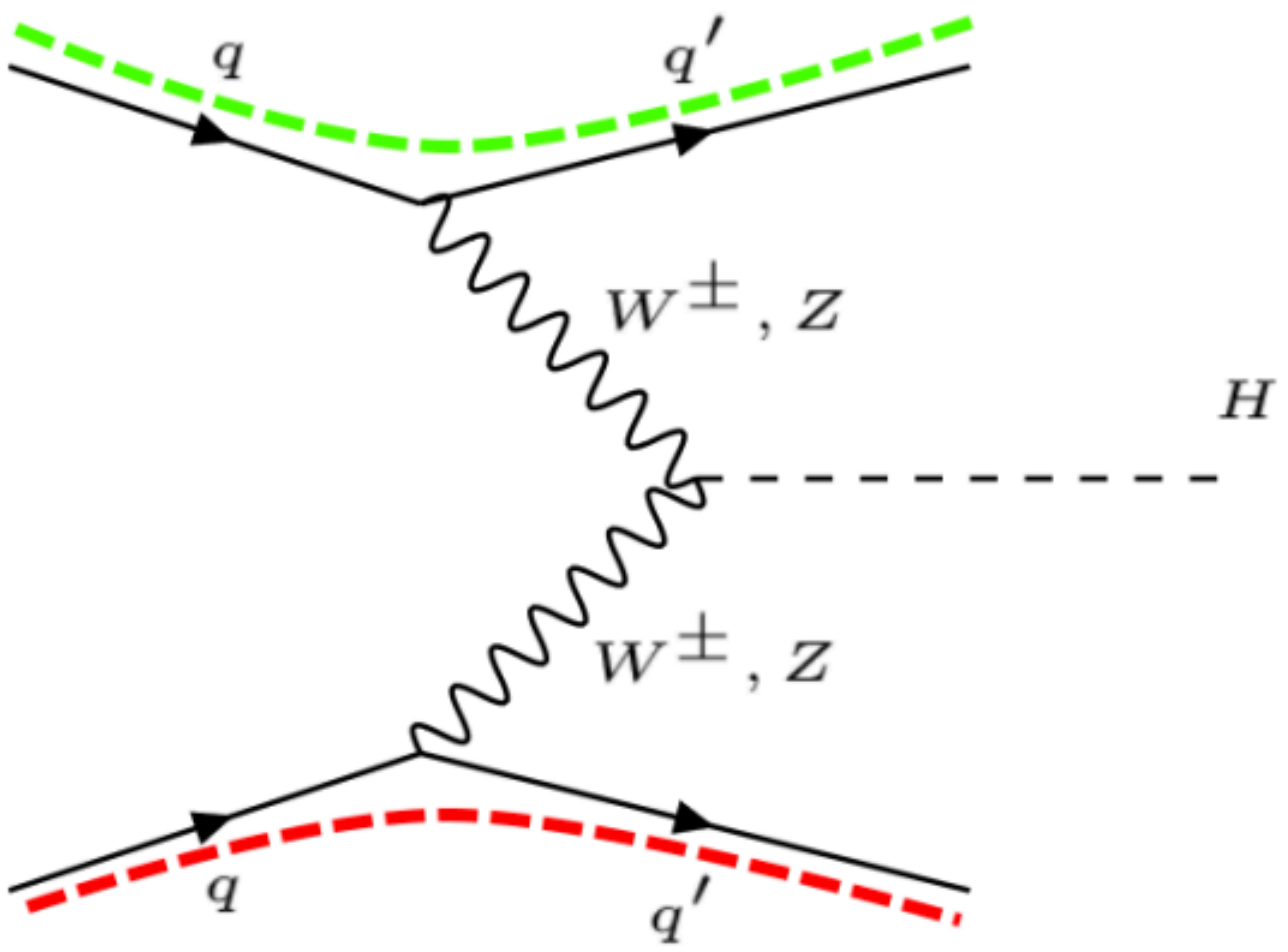
in shower phase-space holding $\tilde{1}_{sc}$ fixed

Split-dipole-frame (SDF): shower with $\Delta K_1 = 0$



[2307.11142]

Towards LHC phenomenology - VBF



Error budget dominated by the shower

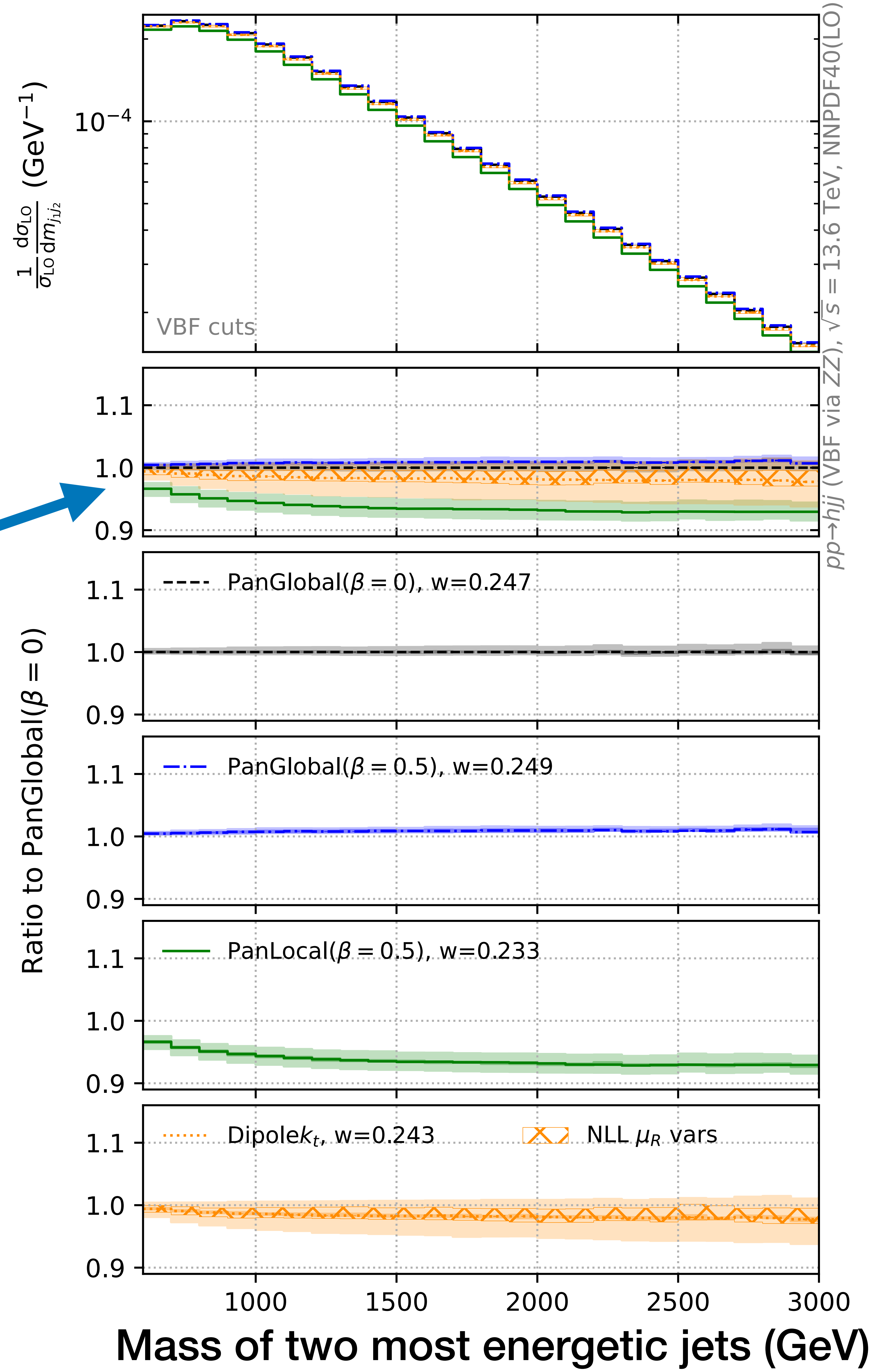
Table by M. Pellen, 2023 Higgs WG meeting	VBF H	ggH (in VBF-enriched region)
PDF	<1%	<3%
QCD scale	<1%	2-20%
UE	<1.5%	<2-3%
Parton shower	5-15%	4-10%

Towards LHC phenomenology - VBF

[2305.08645]

- Hard process generated with Pythia at LO accuracy (no beam remnants, hadronisation or multi-parton interaction)
- NNPDF 4.0 LO PDF set
- Shower starting scale is set separately for the two DIS chains
- VBF cuts: at least two jets with $p_{T,j} > 25$ GeV, $|\eta_j| < 4.5$, $\Delta\eta_{j_1j_2} > 4.5$, $\eta_{j_1}\eta_{j_2} < 0$, $m_{j_1j_2} > 600$ GeV

For observables that are non-vanishing at LO, the LL shower lies in-between the spread of NLL showers



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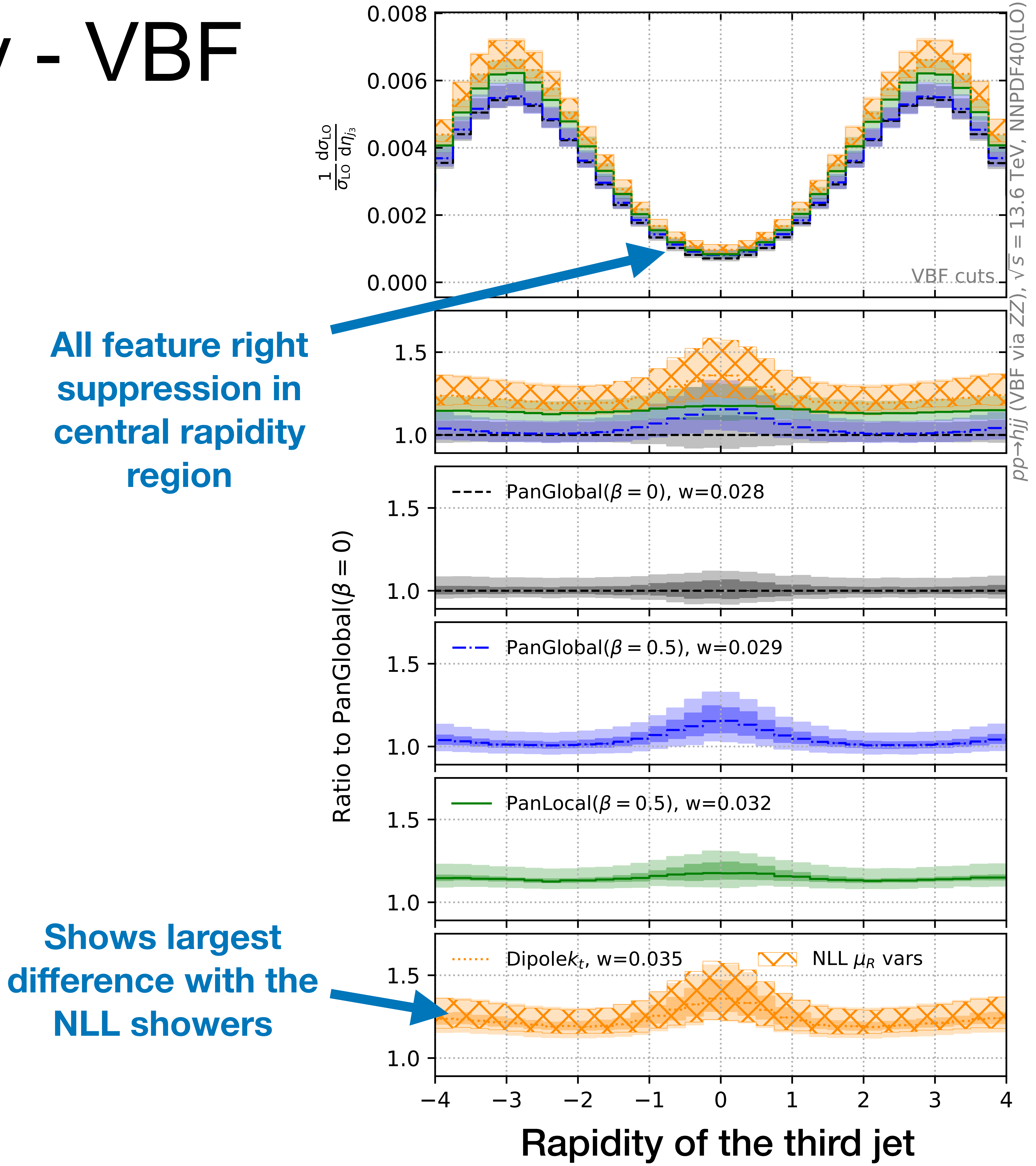

DIS phenomenology at HERA

Rivet analysis for hep-ex/0512014

- HERA at $\sqrt{s} = 319$ GeV
- $Q \in [14{,}200]$ GeV, $y \in [0.1{,}0.7]$

Divided up in bins of Q

# of Q bin	1	2	3	4	5	6	7
Q Interval/GeV	[14,16]	[16,20]	[20,30]	[30,50]	[50,70]	[70,100]	[100,200]
$\langle Q \rangle$/GeV	14.9	17.7	23.8	36.9	57.6	80.6	115.6
$\langle x \rangle$	0.00841	0.0118	0.0209	0.0491	0.116	0.199	0.323

$$x = \frac{Q^2}{sy}$$

Select bins with a not too low Q (dominated by hadronisation and thus the tune) and not too high Q (more sensitive to PDF and less data available)

DIS phenomenology at HERA

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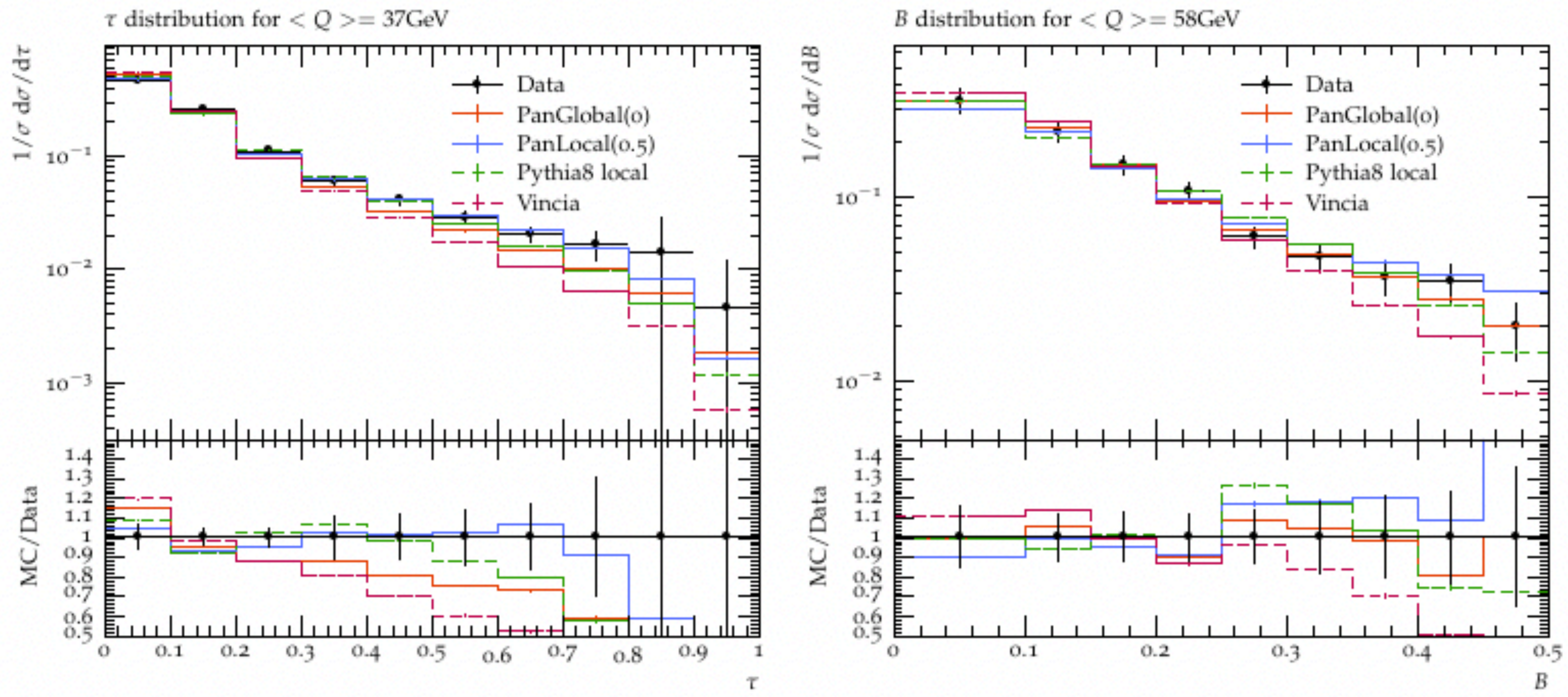
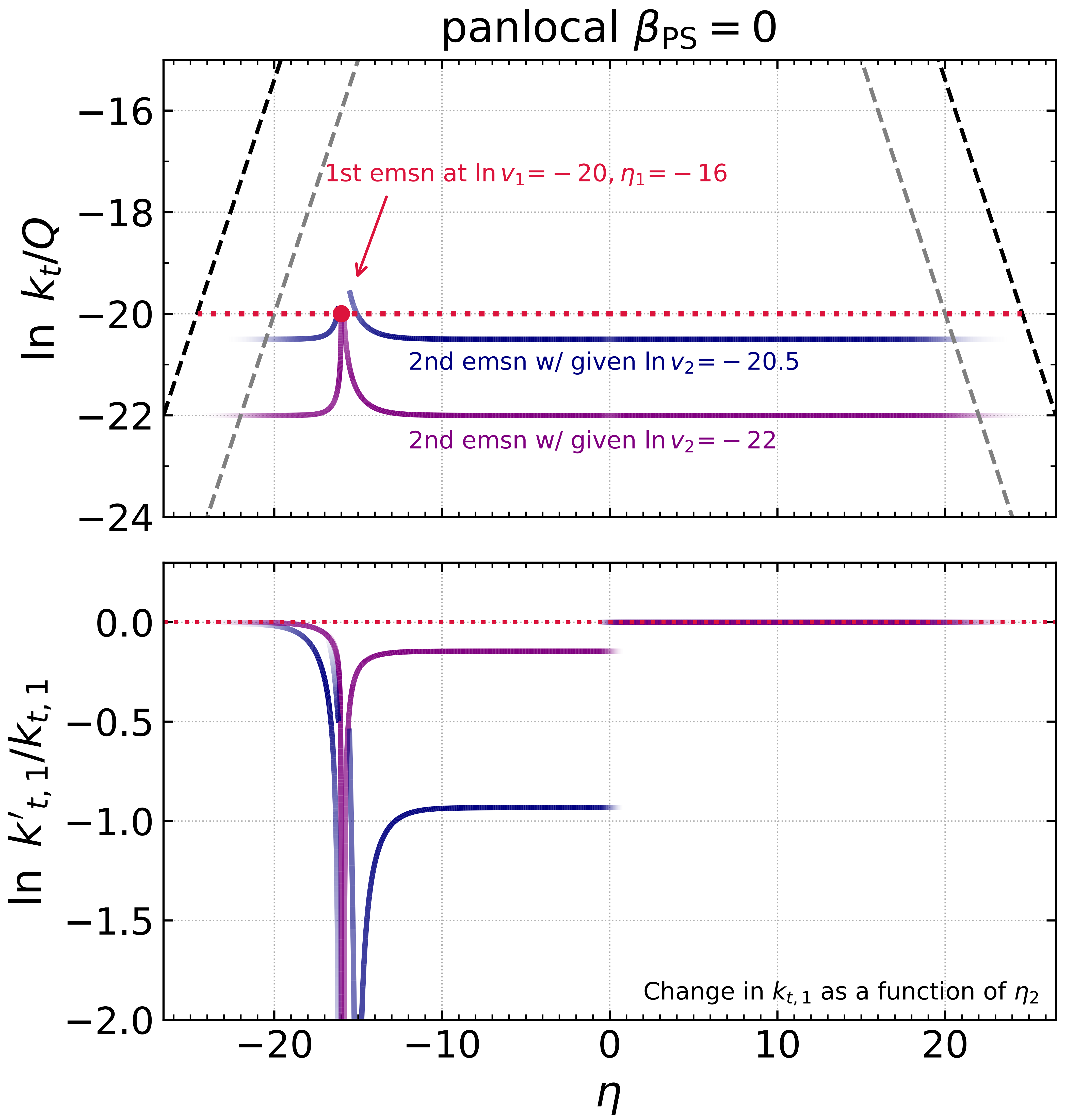


Overal we observe good agreement

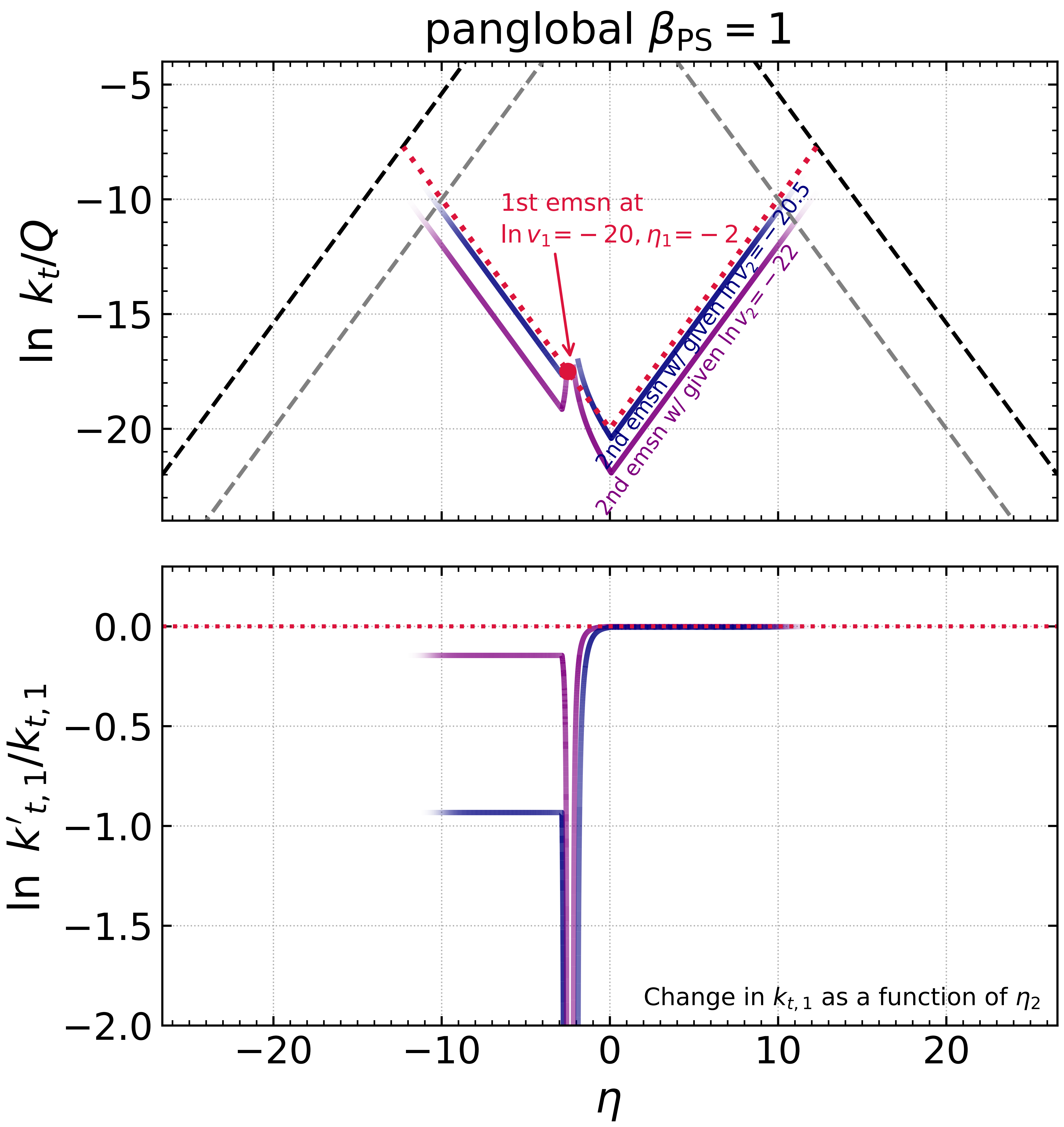
Note $\tau \to 1$ and $B \to 0.5$ regions are dominated by (absent) matching corrections

PanLocal issue for $\beta_{\text{PS}} = 0$



- Recoil is taken from the first gluon even when emissions are separated in rapidity
- Separation of dipole in event CM frame is not enough to cure dipole-showers with local maps from locality issue, the transverse momentum ordering is problematic here
- Only when emissions are ordered in angle ($\beta_{\text{PS}} > 0$) we solve this
- Then commensurate k_t emissions are ordered in angle, so they take their recoil from the hard system (after boost)

Issue for $\beta_{\mathrm{PS}} = 1$



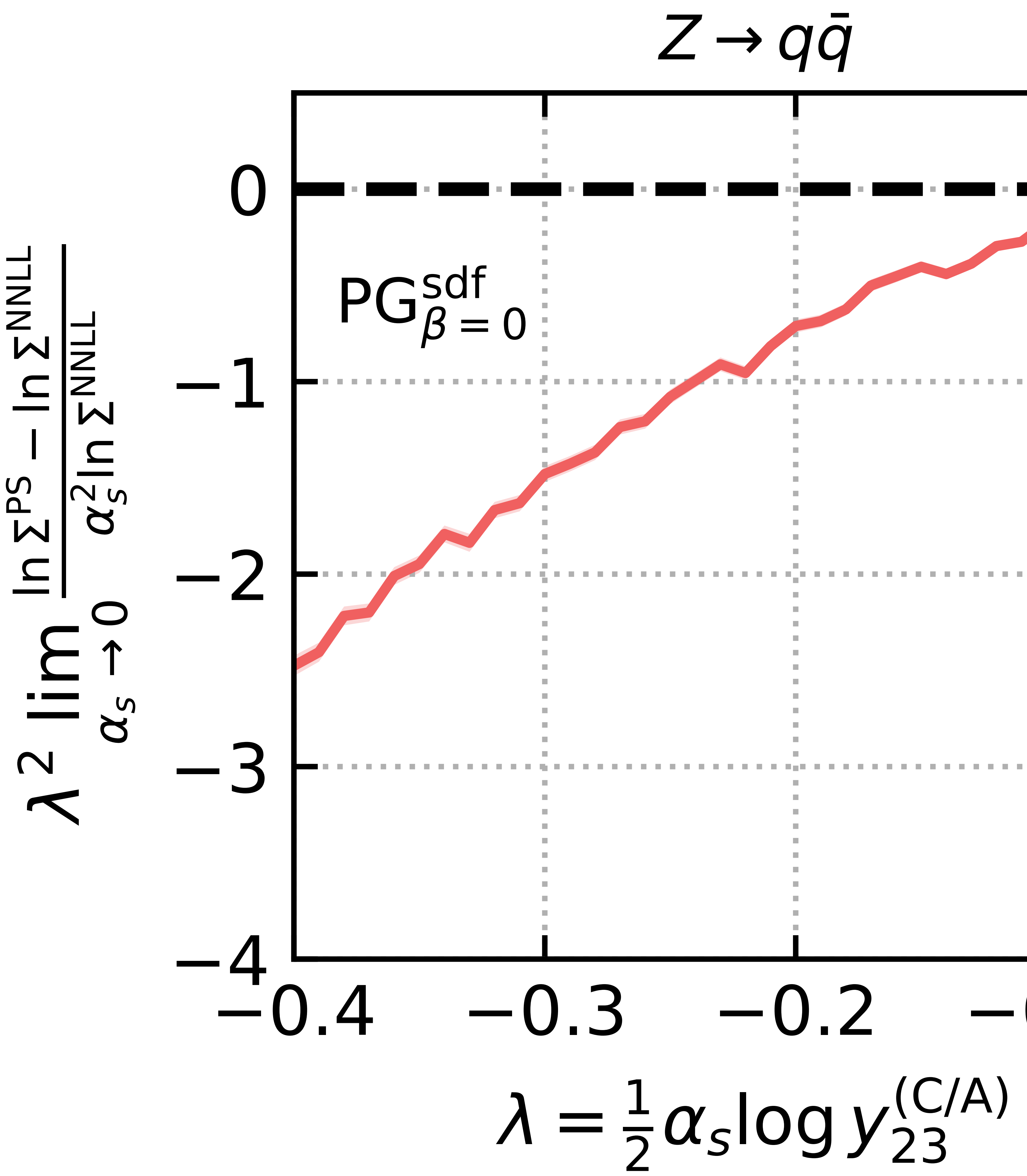
- For IF dipoles, momentum of first emission is rescaled by $b_j = 1 - \beta_k$ in map
- For $\beta = 1$ this equates to $1 - \frac{\tilde{s}_i}{\tilde{s}_{ij}} \frac{v}{Q}$ and becomes independent of $\bar{\eta}$
- Consider change in first emitted parton:

$$p_{k,1} = \tilde{p}_j \rightarrow b_j p_{k,1} = \left(1 - \frac{\tilde{s}_i}{\tilde{s}_{ij}} \frac{v_2}{Q}\right) p_{k,1}$$

- With $\frac{\tilde{s}_i}{\tilde{s}_{ij}} = \frac{2\tilde{p}_i \cdot Q}{2\tilde{p}_i \cdot \tilde{p}_j} = \frac{1}{b_{k,1}}$ and $b_{k,1} = \beta_{k,1} = \frac{v_1}{Q}$

$$\frac{k_{\perp,1}}{k_{\perp,1 \text{ after } 2}} = \left(1 - \frac{v_2}{v_1}\right)$$

But we also test this numerically



Consider again Cambridge y_{23}

Test NNLL by taking $\lim_{\alpha_s \to 0} \frac{\ln \Sigma^{\mathrm{PS}} - \ln \Sigma^{\mathrm{NNLL}}}{\alpha_s^2 \ln \Sigma^{\mathrm{NNLL}}}$

Why?

$$\ln \Sigma^{\mathrm{PS}} = g_1^{\mathrm{PS}}(\lambda)L + g_2^{\mathrm{PS}}(\lambda) + \alpha_s g_3^{\mathrm{PS}}(\lambda)$$

$$\ln \Sigma^{\mathrm{NNLL}} = g_1^{\mathrm{NNLL}}(\lambda)L + g_2^{\mathrm{NNLL}}(\lambda) + \alpha_s g_3^{\mathrm{NNLL}}(\lambda)$$

We know $g_1^{\mathrm{PS}}(\lambda) = g_1^{\mathrm{NNLL}}(\lambda)$ $\quad g_2^{\mathrm{PS}}(\lambda) = g_2^{\mathrm{NNLL}}(\lambda)$

$$\lim_{\alpha_s \to 0} \frac{\ln \Sigma^{\mathrm{PS}} - \ln \Sigma^{\mathrm{NNLL}}}{\alpha_s^2 \ln \Sigma^{\mathrm{NNLL}}} = \frac{g_3^{\mathrm{PS}}(\lambda) - g_3^{\mathrm{NNLL}}(\lambda)}{g_1(\lambda)}$$