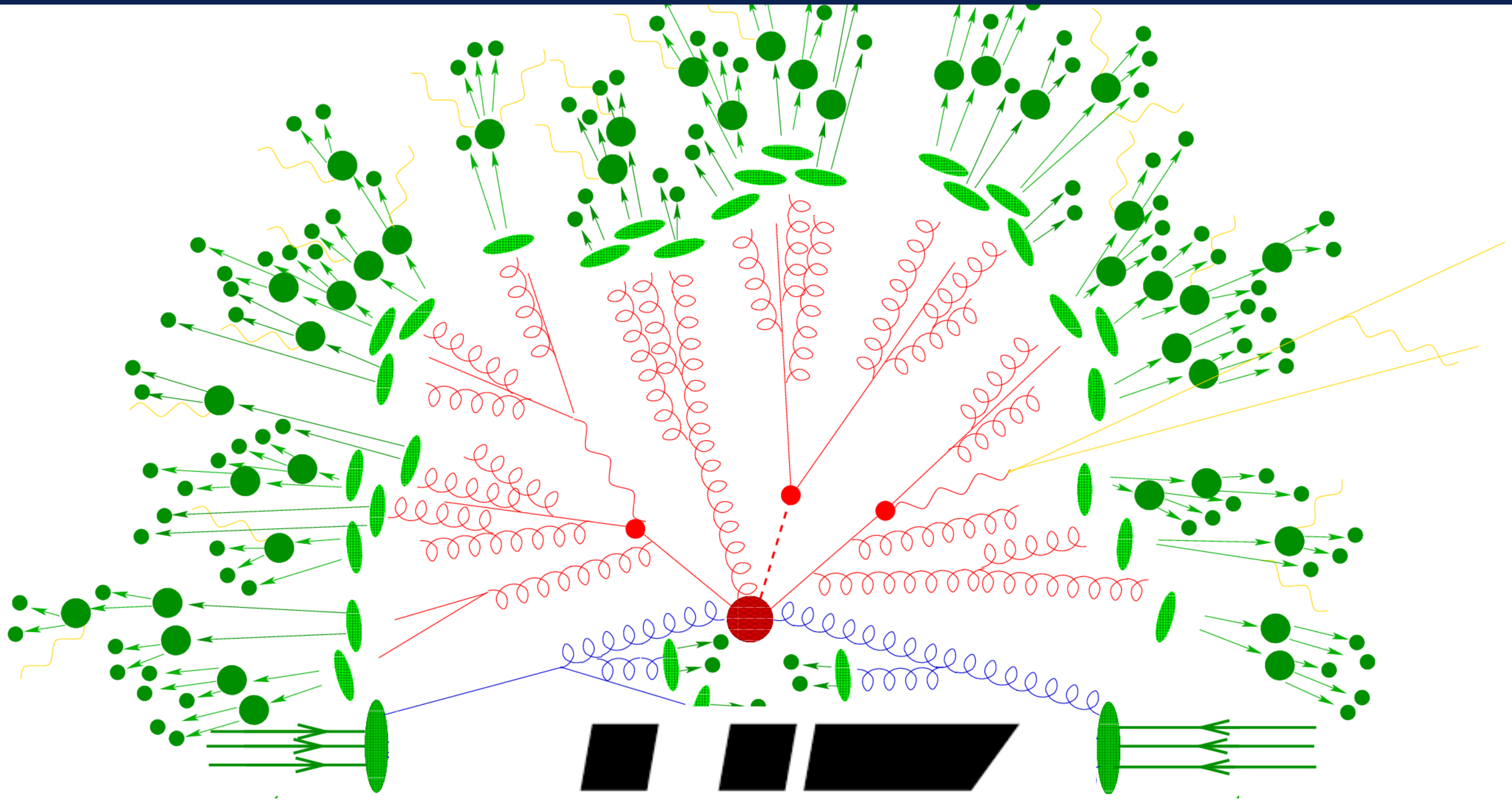
Parton shower development

MBI - 27/09/2024

Melissa van Beekveld

Nikhef

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 6,462 citations

PYTHIA 6.4 Physics and Manual 13,151 citations

A comprehensive guide to the physics and usage of PYTHIA 8.3 607 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 3,165 citations

Herwig 7.0/Herwig++ 3.0 release note 1,517 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 3,834 citations

Event Generation with Sherpa 2.2 1,060 citations

Advances in shower development

I only cover the perturbative side
but note, non-perturbative is as important!

Higher-order matching

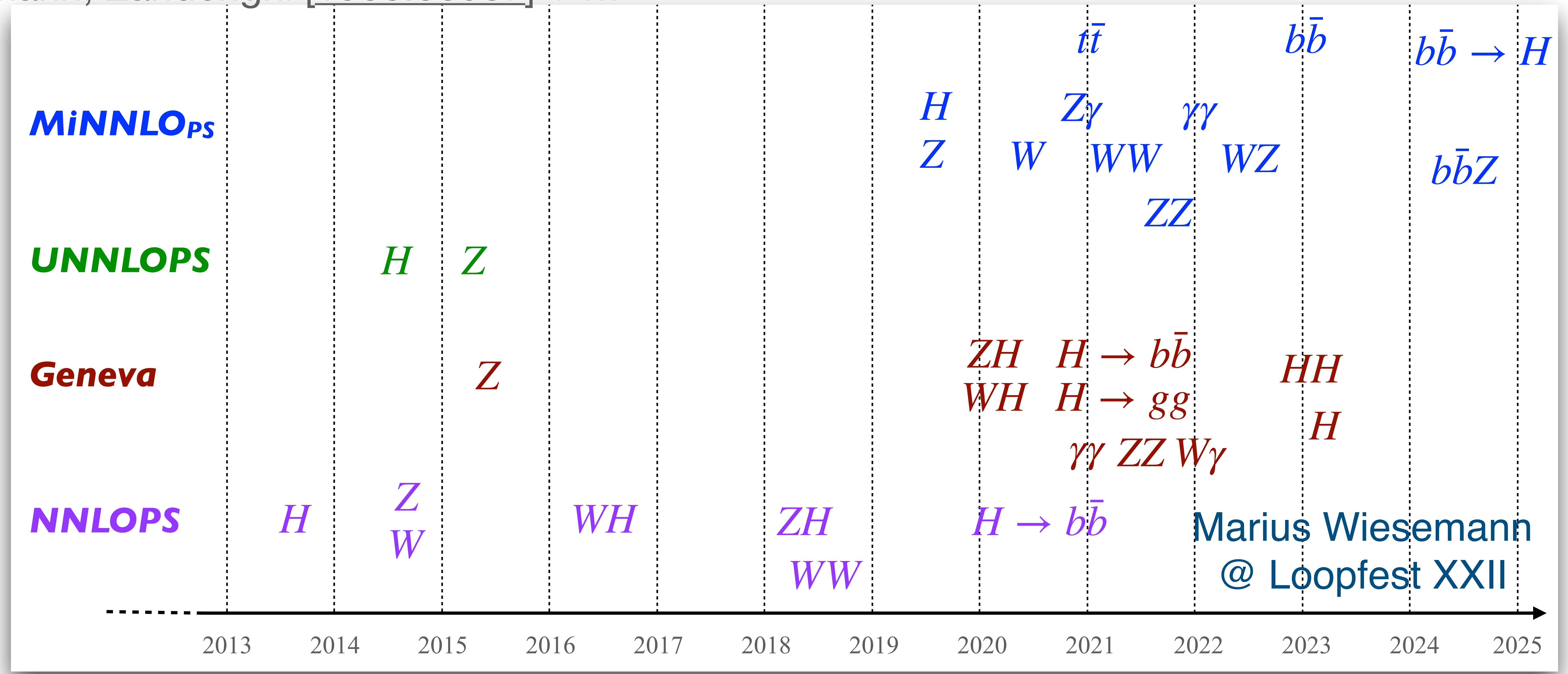
- NLO matching solved: POWHEG Nason [0409146] + …, MC@NLO Frixione & Webber [0204244] + …

Advances in shower development

Higher-order matching

I only cover the perturbative side but note, non-perturbative is as important!

- NLO matching solved: POWHEG Nason [0409146] + …, MC@NLO Frixione & Webber [0204244] + …
- NNLO frontier → selected processes, not automated
  - Geneva Alioli, Bauer, Berggren,Tackmann,Walsh, Zuberi [1311.0286] + …
  - UNNLOPS Höche, Li, Prestel [1405.3607] + …
  - MiNNLOps Monni, Nason, Re, Wiesemann, Zanderighi [1908.06987] + …



Advances in shower development

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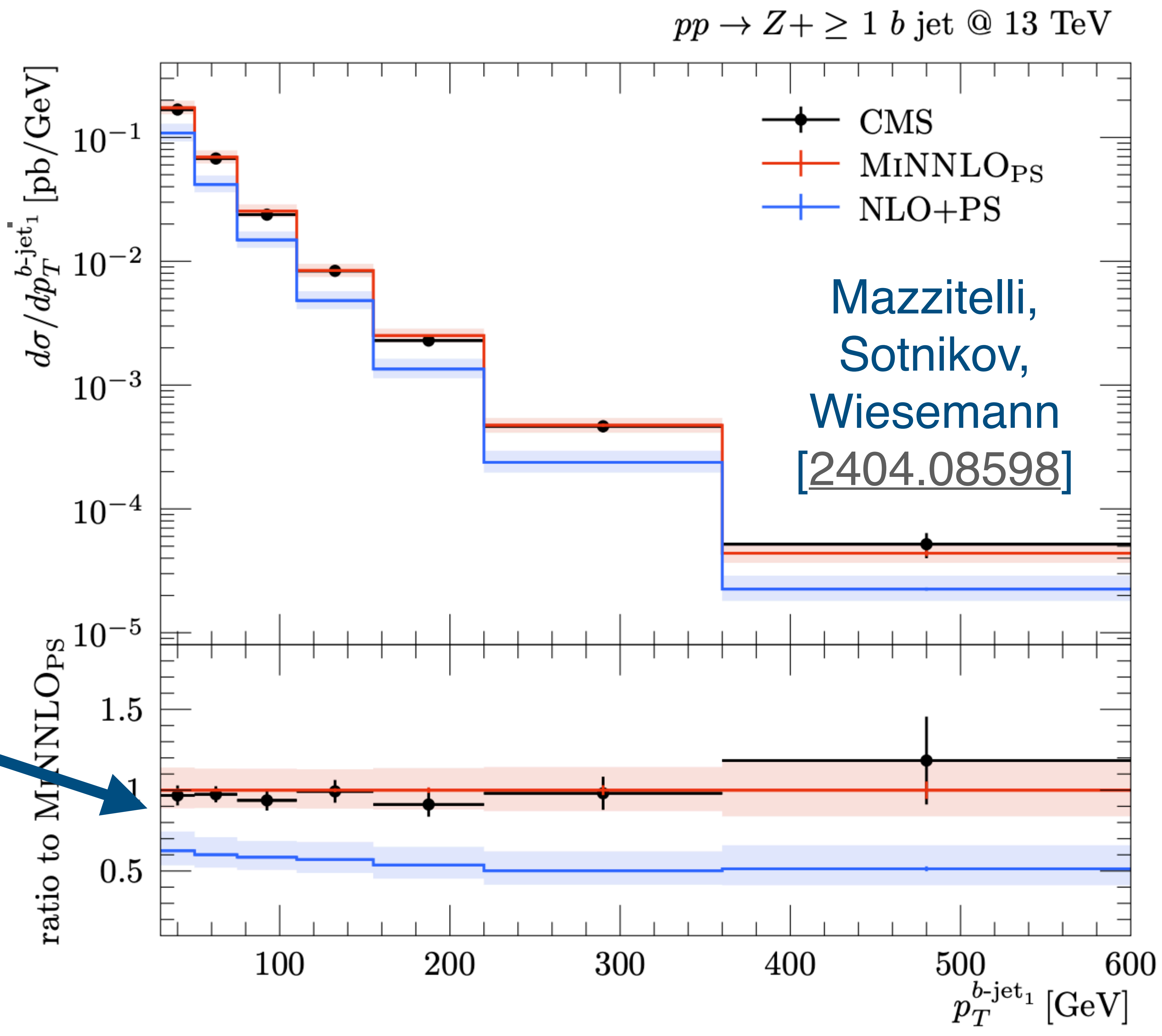
MiNNLOps for $Z\bar{b}b$

Inclusion of (approximate) NNLO effects resolves tension of NLO(+PS) predictions with data in 4FS



Advances in shower development

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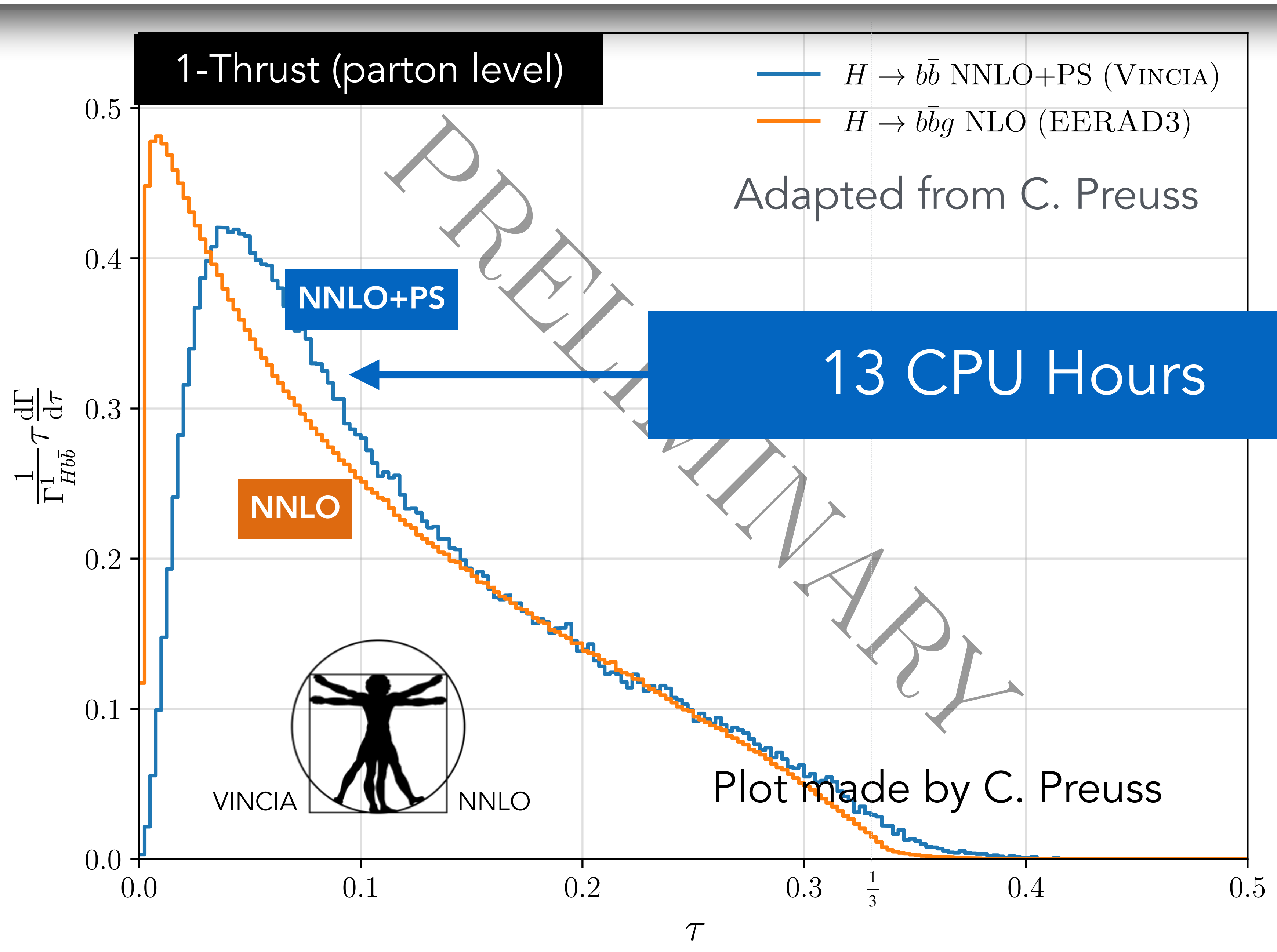
  - Vincia Campbell, Höche, Li, Preuss, Skands [2108.07133] + …

Shower-style phase-space generation ⊗ 2nd-order MECs

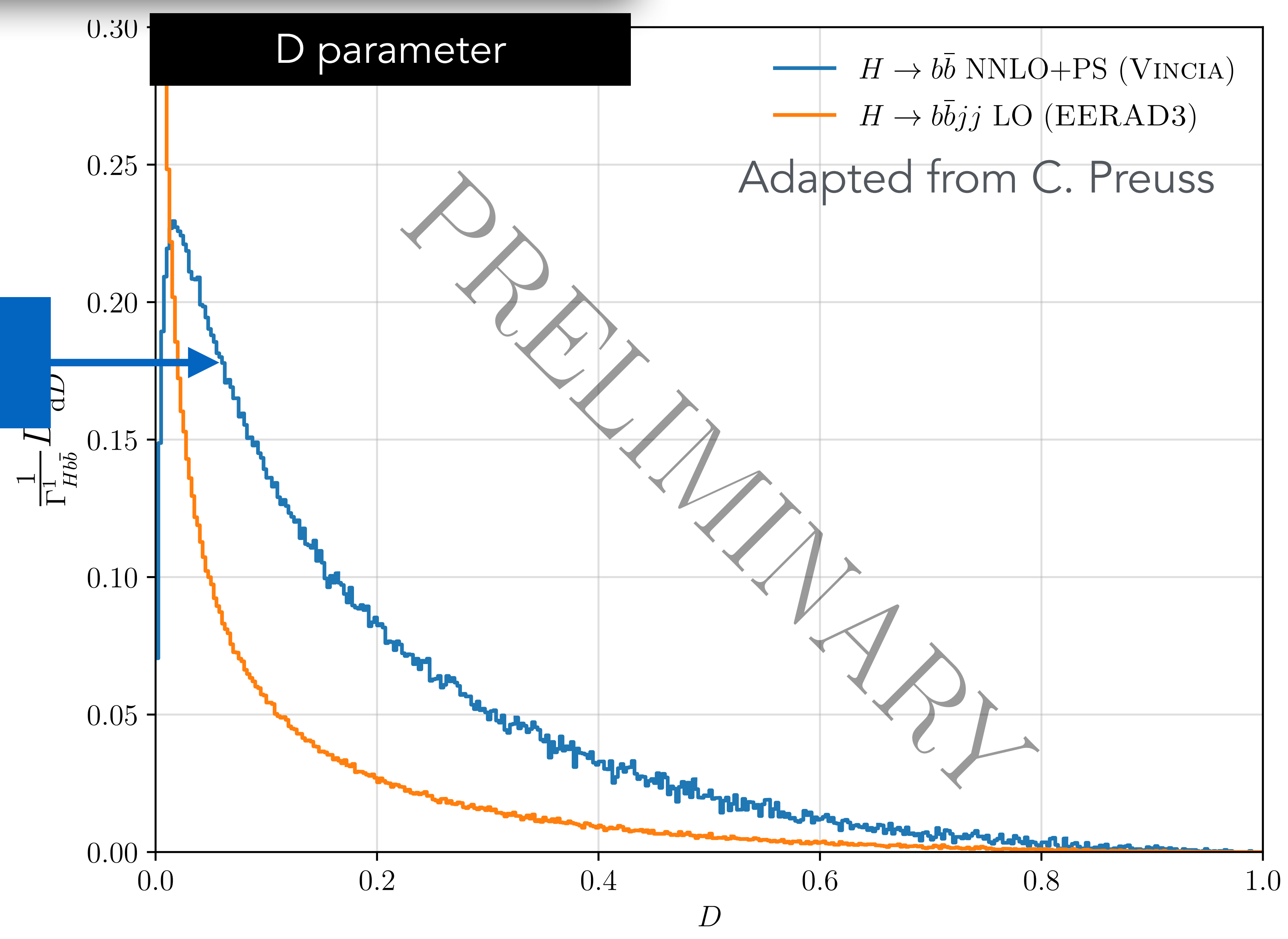
Exploits **sectorization** ➜ defines $d\Phi_{[n]+1}$, unique scales, and allows to use simple ME ratios (instead of sums over partial-fractionings)

See also Preuss, Skands [2310.18671] + refs therein

Peter Skands (CERN theory colloquium)



13 CPU Hours



VINCIA NNLO+PS: shower as phase-space generator: efficient & no negative weights!

➤ Looks ~ 5 x ***faster*** than **EERAD3*** (for equivalent unweighted stats)

+ is **matched to shower** + can be **hadronized**

Proof of concepts now done for $Z/H \to q\bar{q}$; work remains for pp (& for N^{n}LL accuracy)

* Already quite optimised: uses analytical MEs, "folds" phase space to cancel azimuthally antipodal points, and uses antenna subtraction (→ smaller # of NLO subtraction terms than Catani-Seymour or FKS).

Advances in shower development

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  - Vincia Campbell, Höche, Li, Preuss, Skands [2108.07133] + …
- … and even N3LO Prestel + Bertone [2106.03206, 2202.01082]

Advances in shower development

Higher-order matching

Include genuine quantum effects

- 'Classical' ways to include spin/colour corrections
  - See e.g. Herwig [1807.01955] , PanScales [2011.10054, 2103.16526, 2111.01161]

- Amplitude-level shower evolution
  - Deductor Nagy, Soper [0805.0216, 1902.02105, +…]
  - CVolver Plätzer, De Angelis, Forshaw, Holguin [2007.09648, +…] including EW Plätzer, Sjodahl [2204.03258]

Advances in shower development

Higher-order matching

Include genuine quantum effects

Beyond QCD

- Inclusion of EW corrections, e.g.
  - Herwig [2108.10817], Vincia [2002.09248, 2108.10786]
- Sherpa3.0 (July 2024)

Advances in shower development

Higher-order matching

Include genuine quantum effects

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Polarised vector bosons

SHERPA

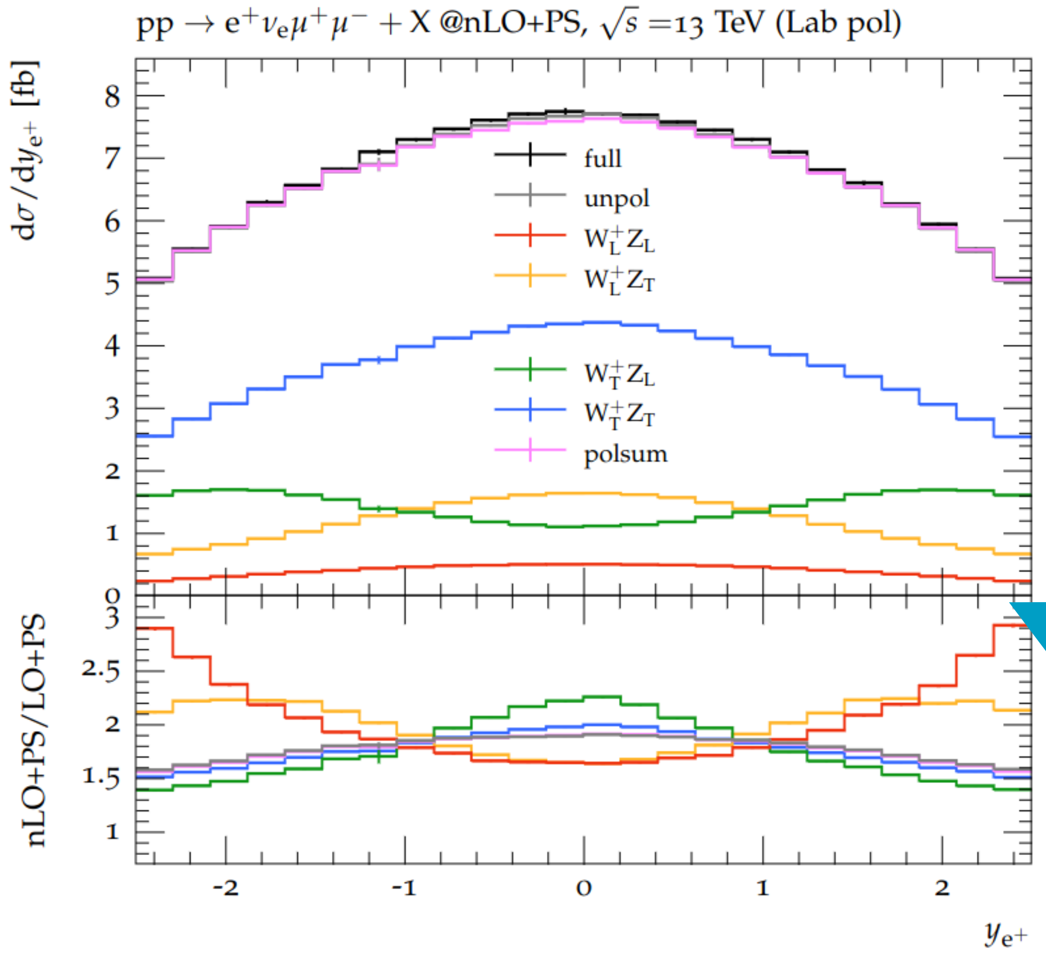
[arxiv:2310.14803] **Note: also see MINLOPS [2311.05220]**

Probe for electroweak gauge sector & electroweak symmetry breaking

Measurement strategy: fully exclusive polarized XS from MC as fitting templates

Methodology in Sherpa:

- Unpolarized simulation run, polarized XS as event weights
- All polarization combinations, interferences, reference frames in one simulation run
- Accuracy up to nLO QCD (via MC@NLO) , multi-leg merging
  - nLO: approximation for calculation of polarization fractions



New version 3.0

SHERPA

Published in July 2024

Peter Meinzinger @ HP2 Turin

New features in Sherpa 3.0:

- NLO EW at Fixed Order [arxiv:1712.07975]
- New MPI/MinBias modelling
- Improved cluster fragmentation incl. Colour Reconnection module [arxiv:2310.14803]
- Photon splittings in YFS resummation [arxiv:2210.07007]
- Dedicated scale setter for VBF and VBS
- Polarized XS for vector bosons [arxiv:2310.14803]
- EW Sudakovs [arxiv:2006.14635], [arxiv:2111.13453]
- Photoproduction and Diffraction at HERA and EIC [arxiv:2310.18674], [arxiv:2311.14571], [arxiv:2407.02133]
- New YAML-based input
- Rivet 4.0 support incl. MPI parallelisation
- UFO 2.0 support

Release paper in preparation

Advances in shower development

- Higher-order matching
- Include genuine quantum effects
- Beyond QCD
- Assessing AND improving their accuracy

Rest of the talk

Disclaimer: I was given 'ample freedom to advertise PanScales'

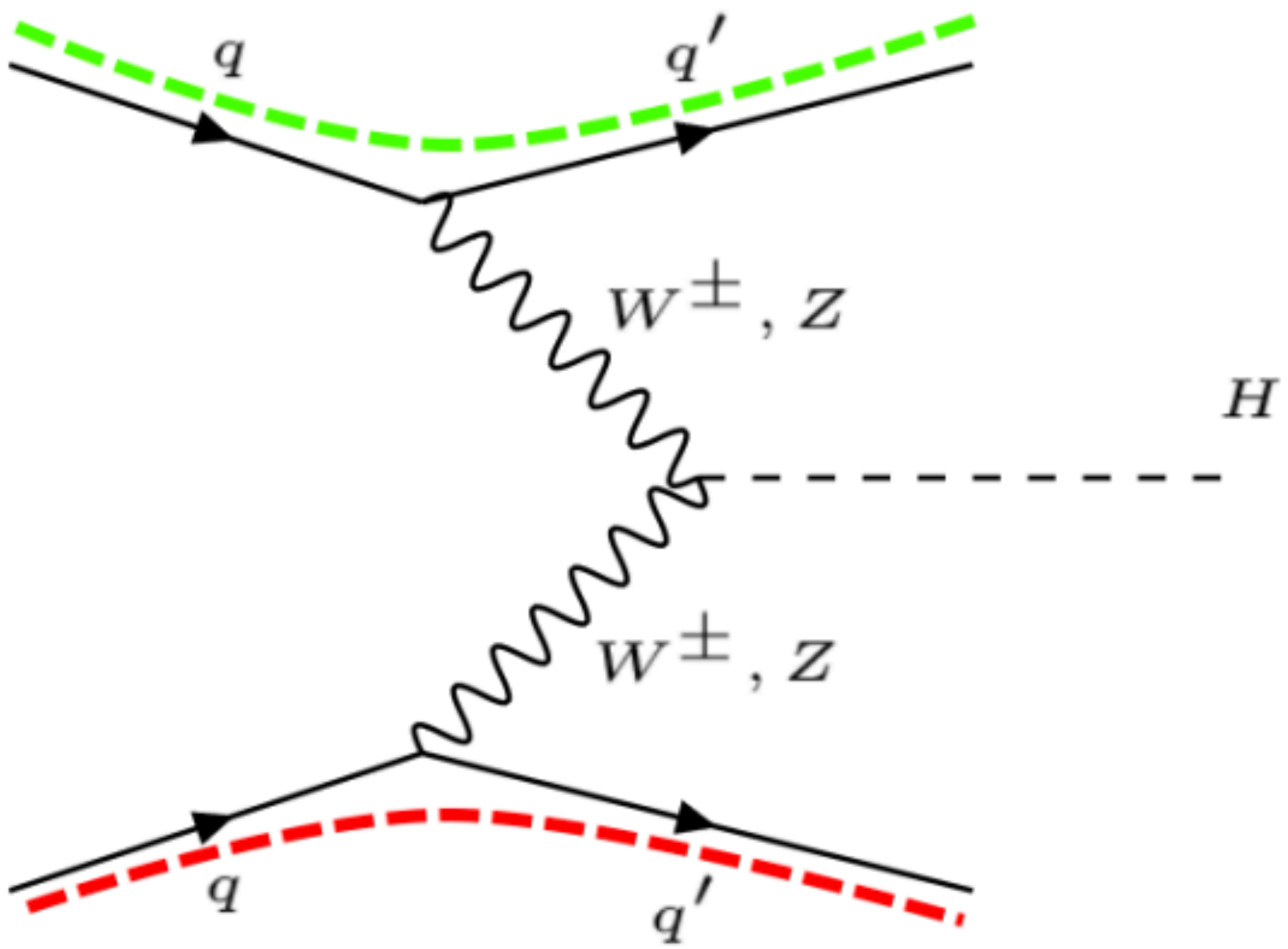
Many choices for the shower's design → differences are expected

But how should these differences be interpreted?

[2003.12435, 2105.11399, 2106.10987]

Differences matter…

VBF production of $h + 2j$



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

[2003.12435, 2105.11399, 2106.10987]

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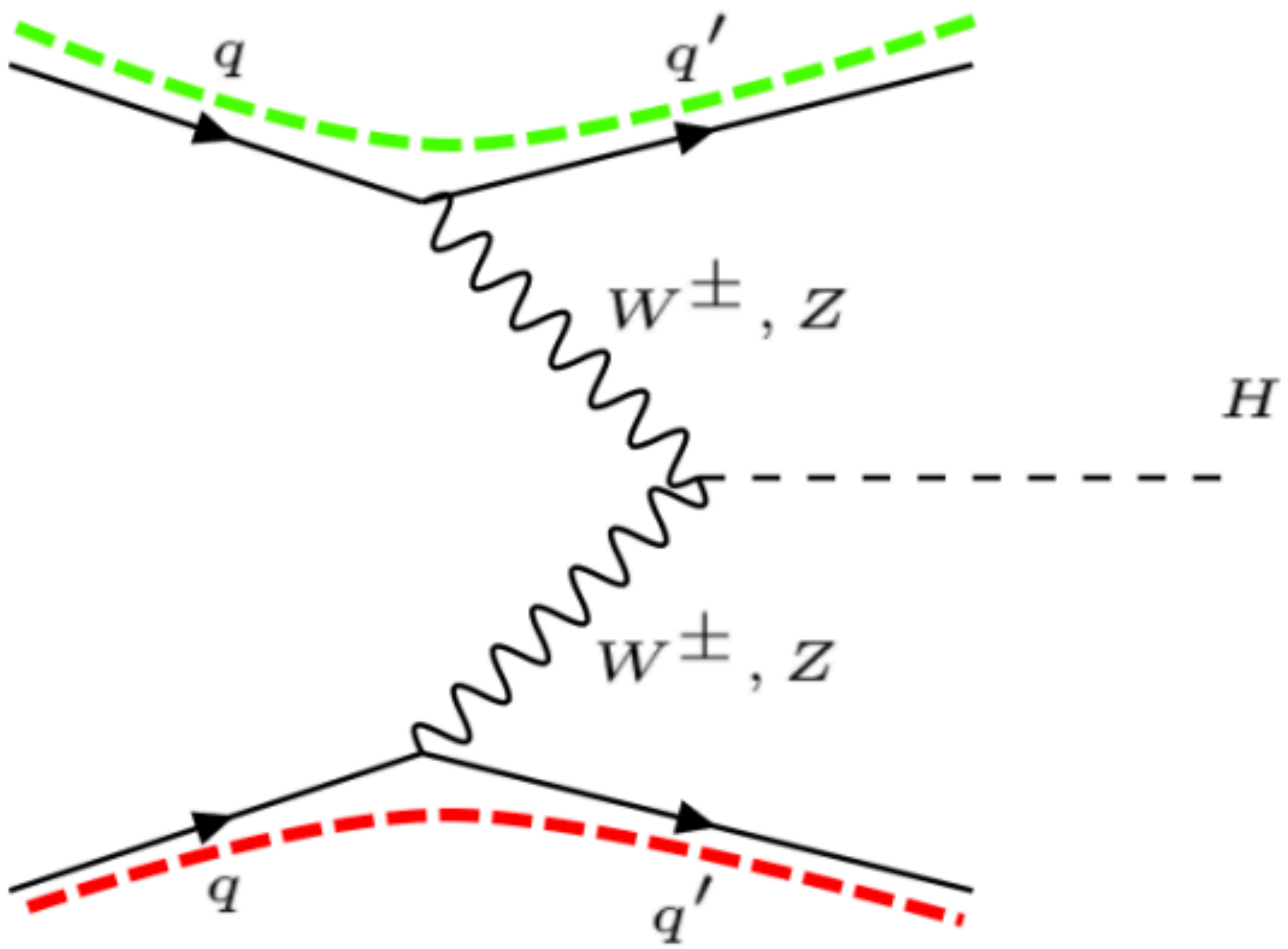
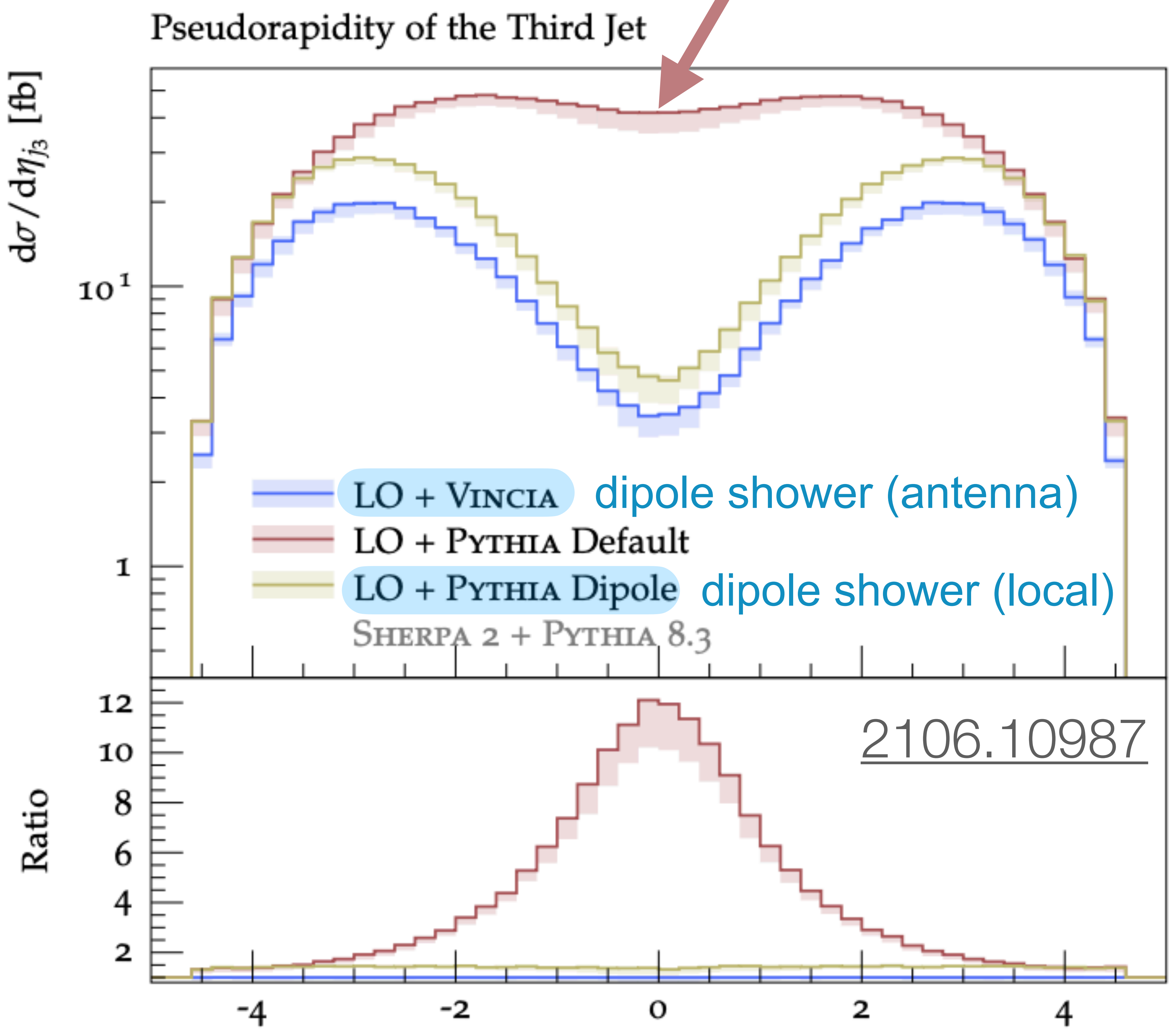


Colour coherence strongly **suppresses** radiation in central rapidity region

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



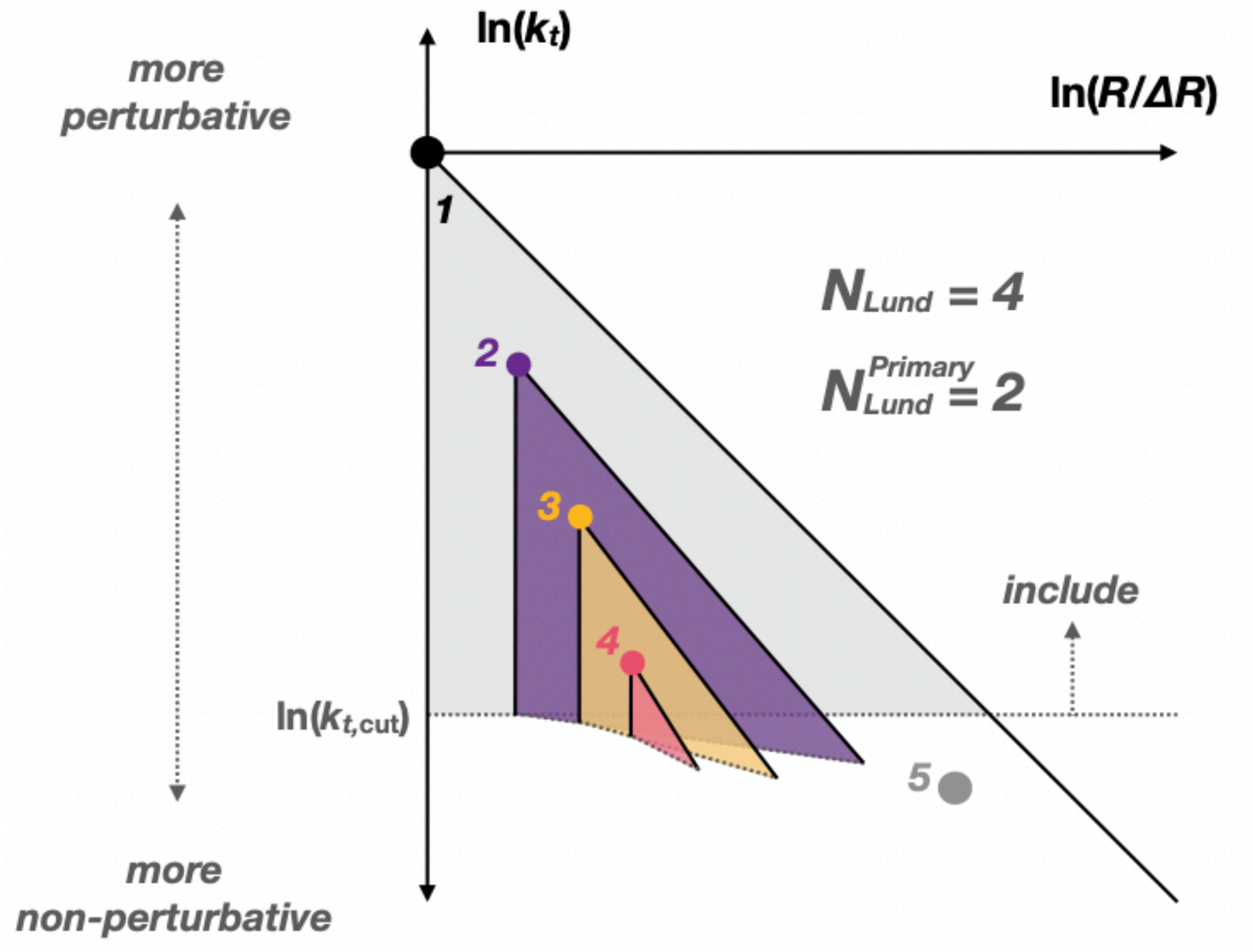
Pseudorapidity of the third jet

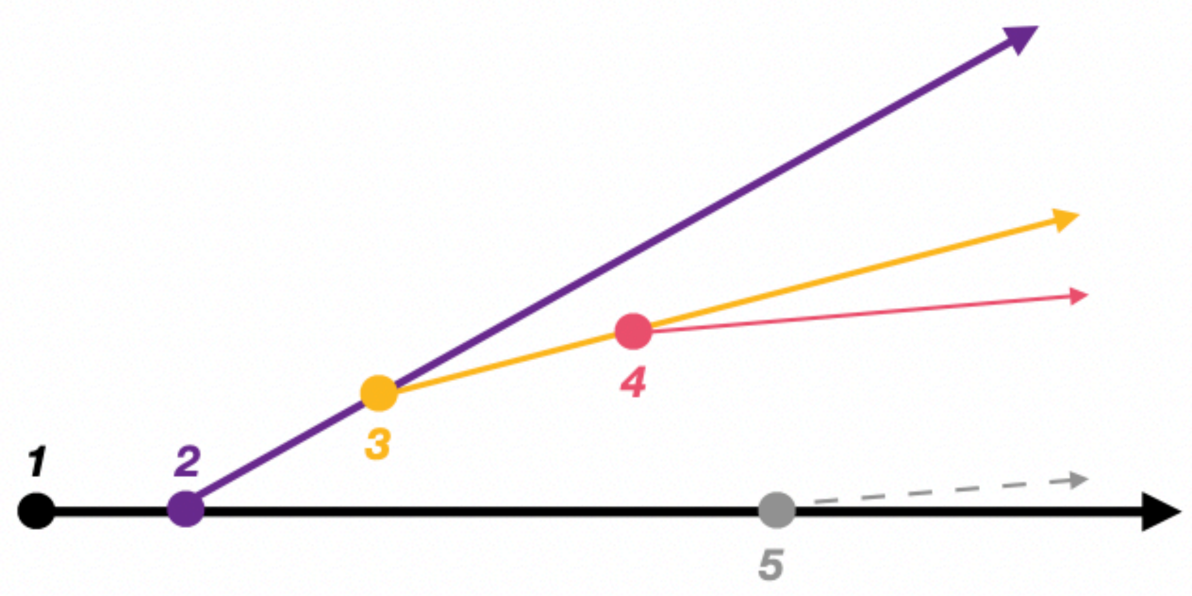
Sometimes showers are just simply **wrong**

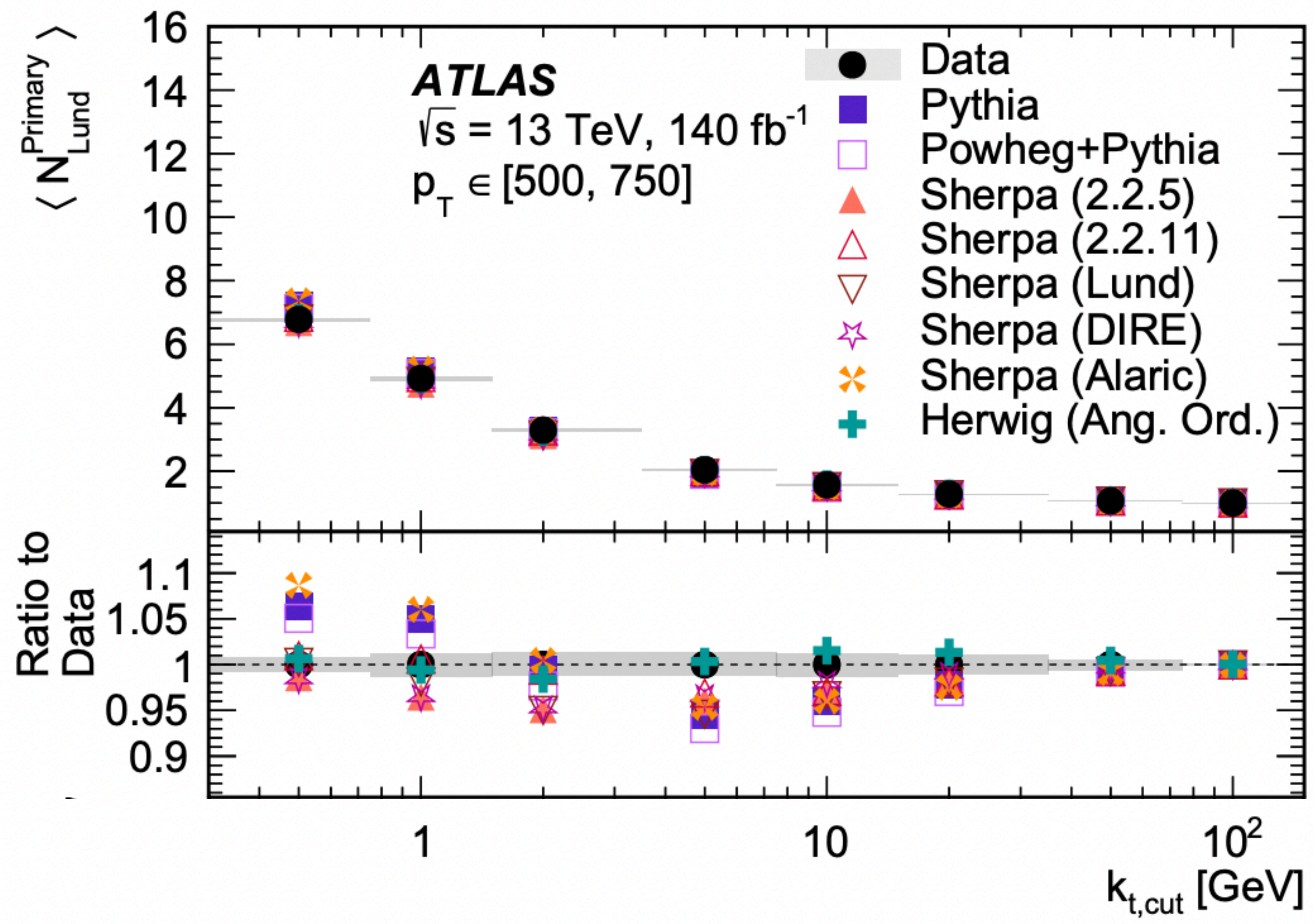
Differences matter…

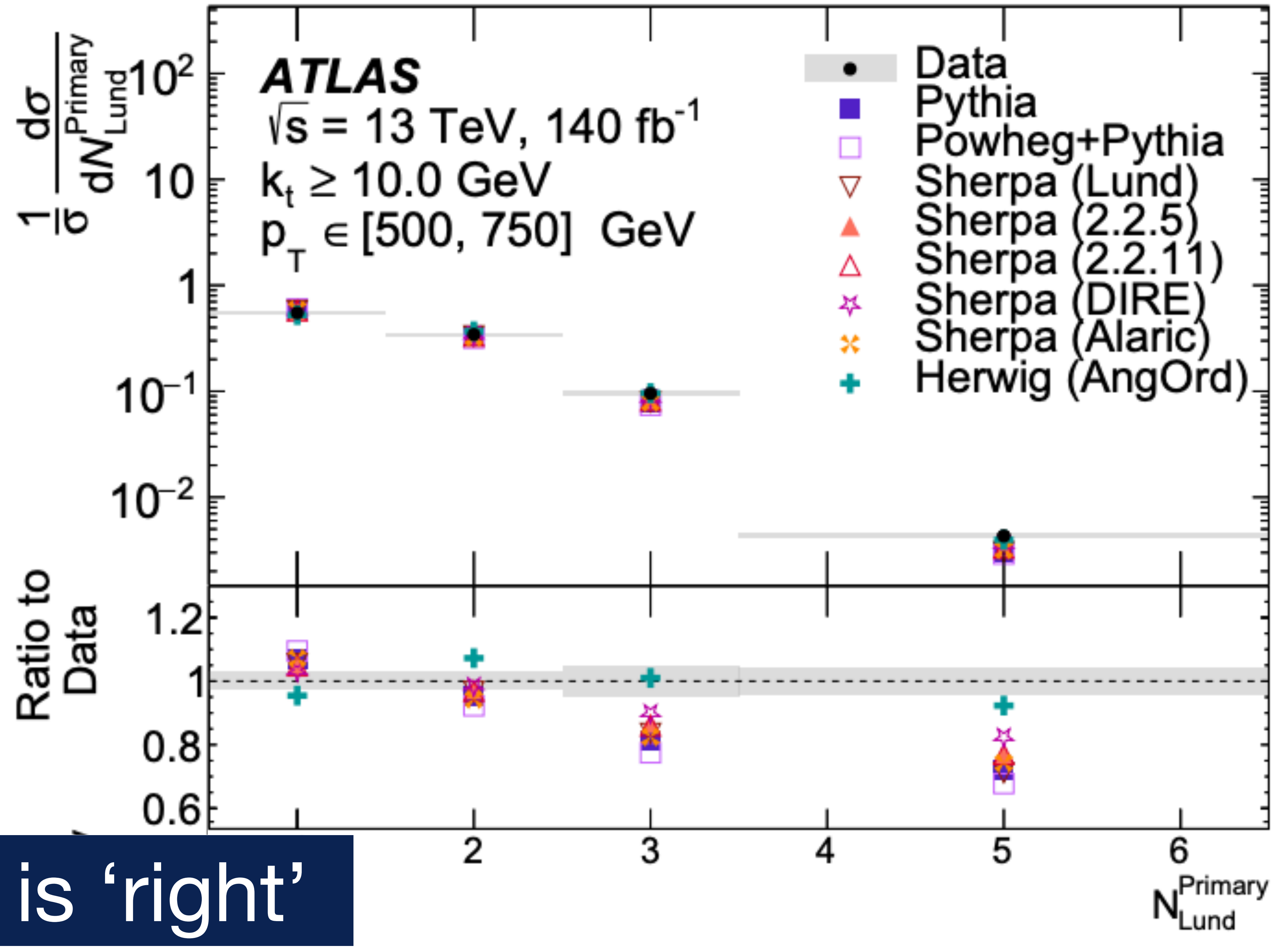
Consider measurement of Lund (sub)jet multiplicity

[2402.13052]









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

Here it is less clear what is 'right'

We need to understand what is going on

- Are these differences a measure of the shower's uncertainty?

To answer this we need to understand its accuracy!

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- Issues can appear in two regimes:
  1. Hadronic/non-perturbative (no first-principle model for now→ 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 what happens to other observables!

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

Melissa van Beekveld

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- Common answer: we cannot control showers…

  Dangerous viewpoint when differences are of perturbative origin

  We need a framework to pin down the shower accuracy

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

+ Nicolas Schalch (09-2024)

Past members:
Frederic Dreyer
Emma Slade
Rok Medves
Rob Verheyen

Can we address the question of shower differences and uncertainties?

- Can we quantify the accuracy of different showers?
- Can we improve their accuracy?

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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]

Quantifying the accuracy of showers

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

E.g. global event-shape resummation

$$\Sigma(\lambda \equiv \alpha_s L, \alpha_s) \sim \exp\left[-L g_1(\lambda) + g_2(\lambda) + \alpha_s g_3(\lambda) + \ldots\right]$$

LL NLL NNLL

Shower results for a typical e^+e^- event shape (e.g. Cambridge y_{23}) include:

- Terms beyond N^{n}LL accuracy
- Higher-order and power corrections

We cannot test it by taking $\frac{\Sigma^{\mathrm{PS}}(\alpha_s L)}{\Sigma^{\mathrm{NLL}}(\alpha_s L)}$

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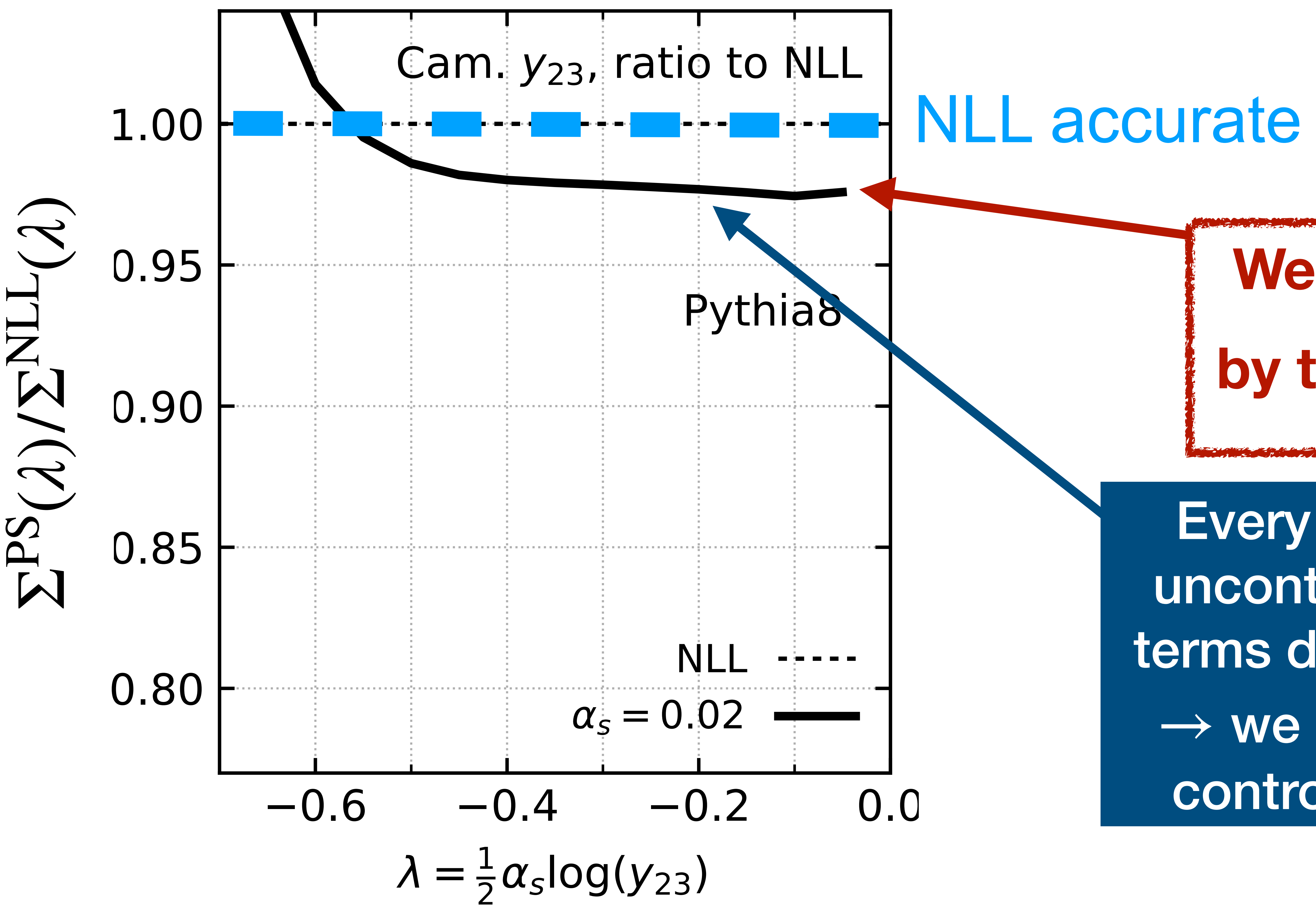

We cannot test it by taking $\dfrac{\Sigma^{\rm PS}(\alpha_s L)}{\Sigma^{\rm NLL}(\alpha_s L)}$

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

Quantifying the accuracy of showers

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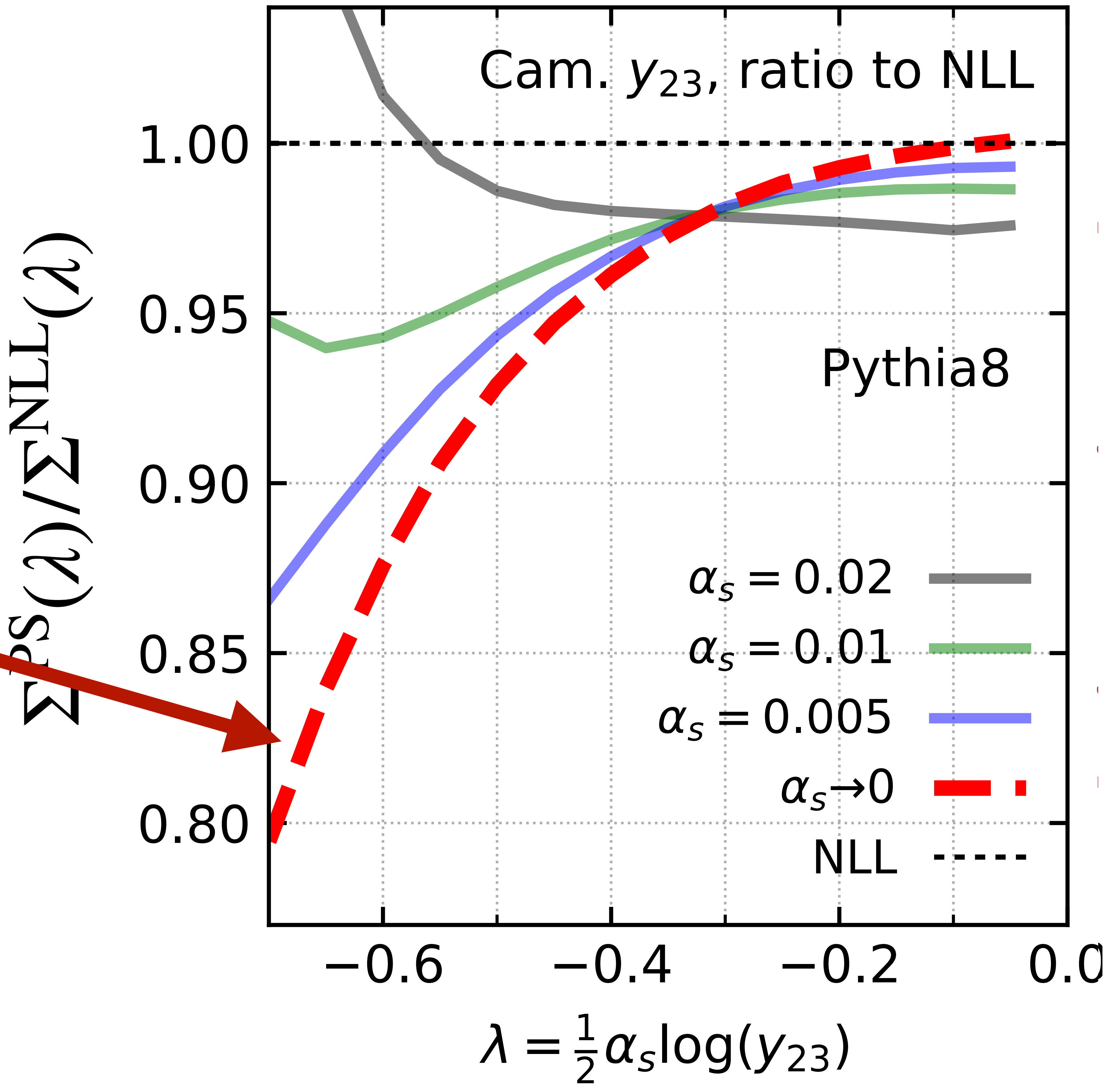

Clear deviation from 1 in the $\alpha_s \to 0$ limit

Now that we know the baseline, can we upgrade it?

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

Should tend to 1 if the shower is NLL

A shower is not a complete black box, but
something we can control (at least) perturbatively

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

Let’s take a theory detour to see this…

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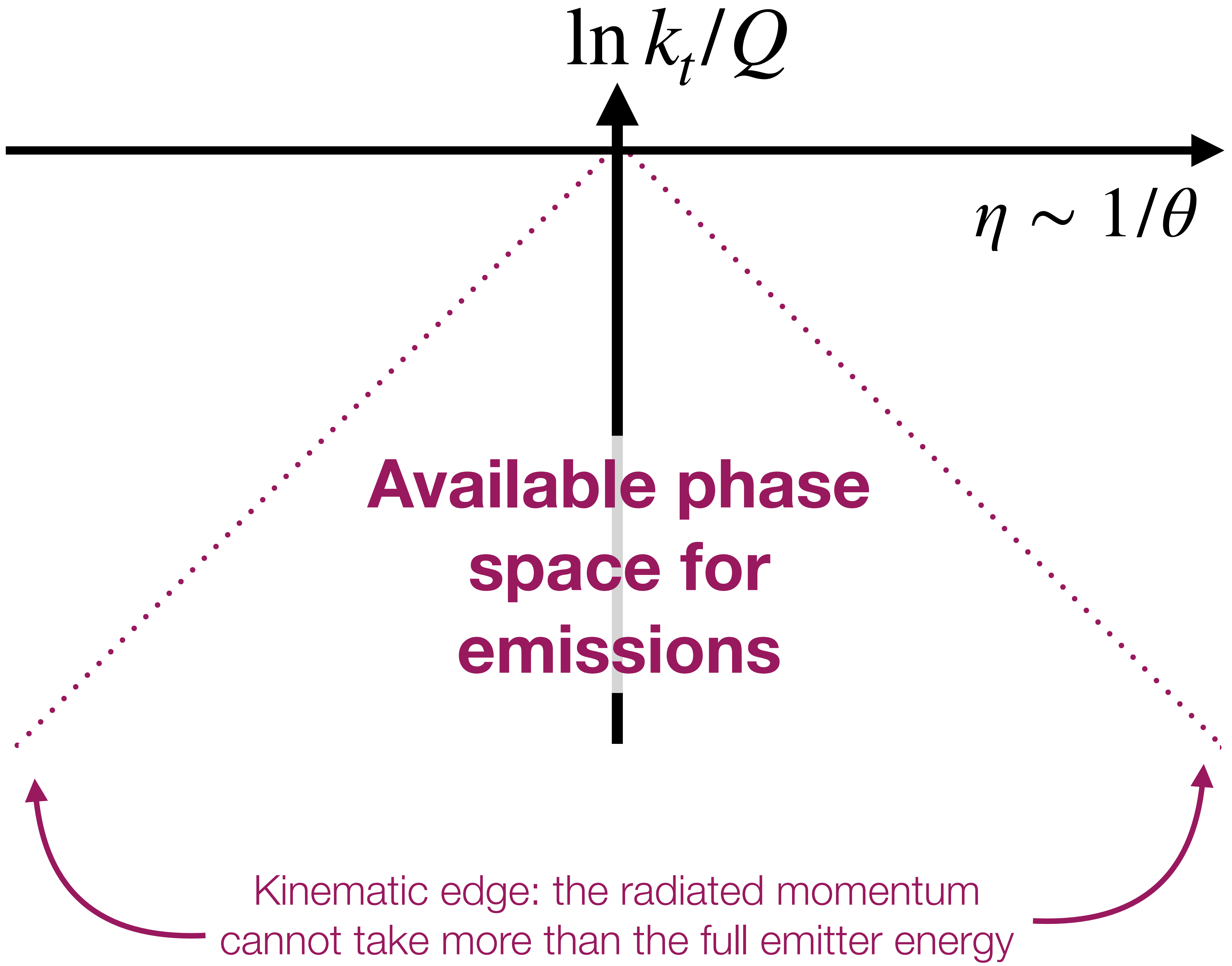
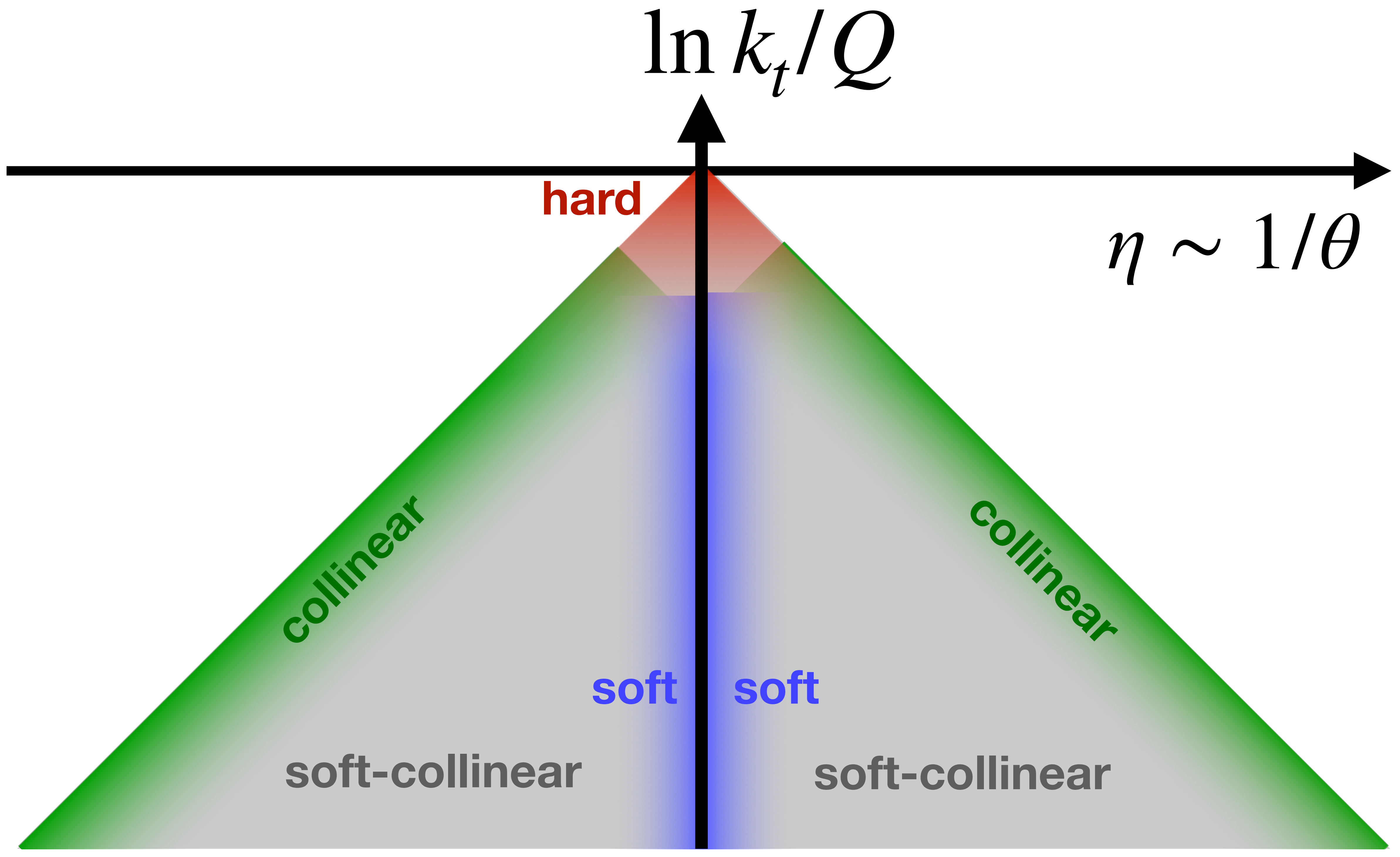
Shower



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

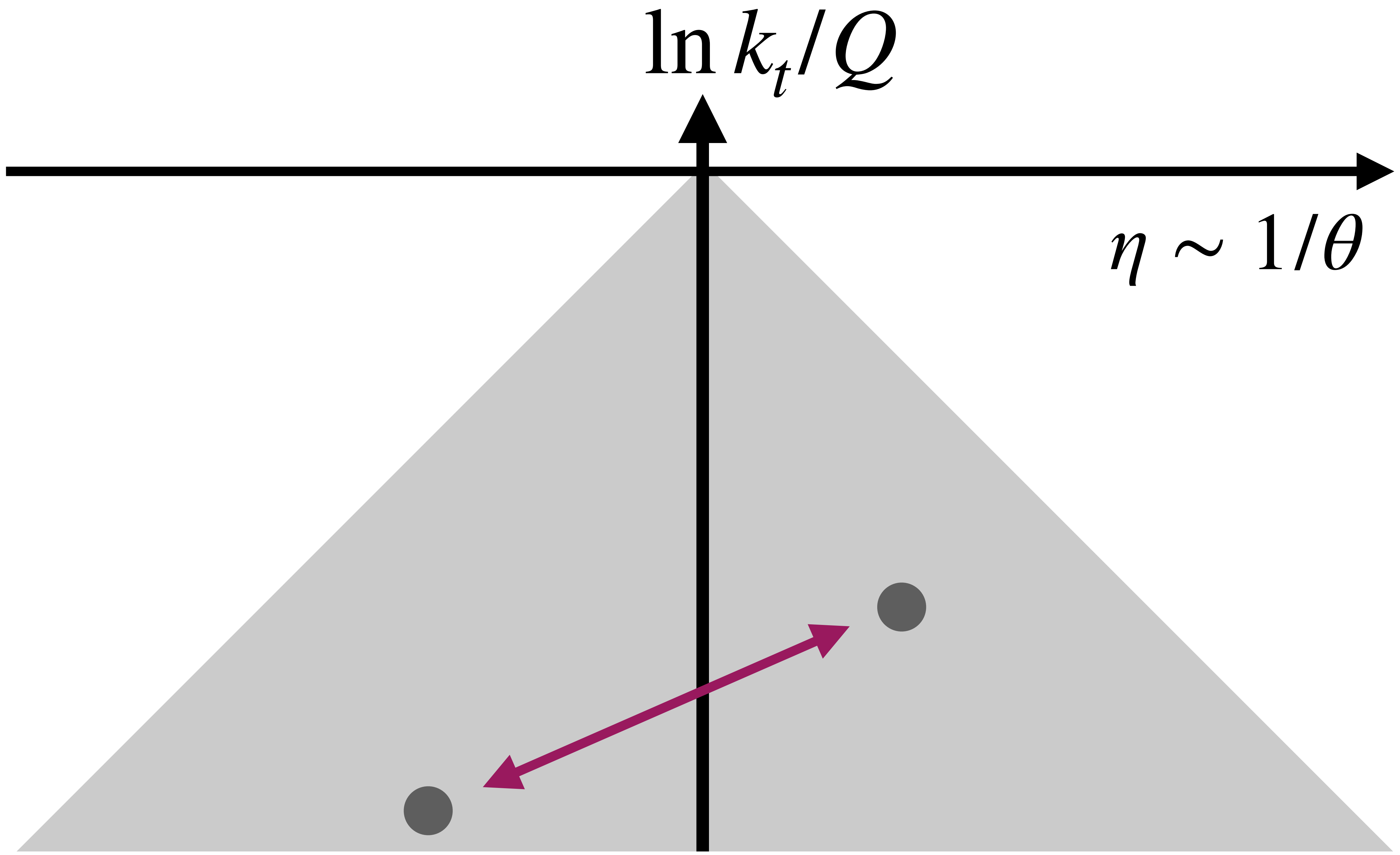
Resummation

Shower



Resummation

Shower @LL
for event shapes



Resumption

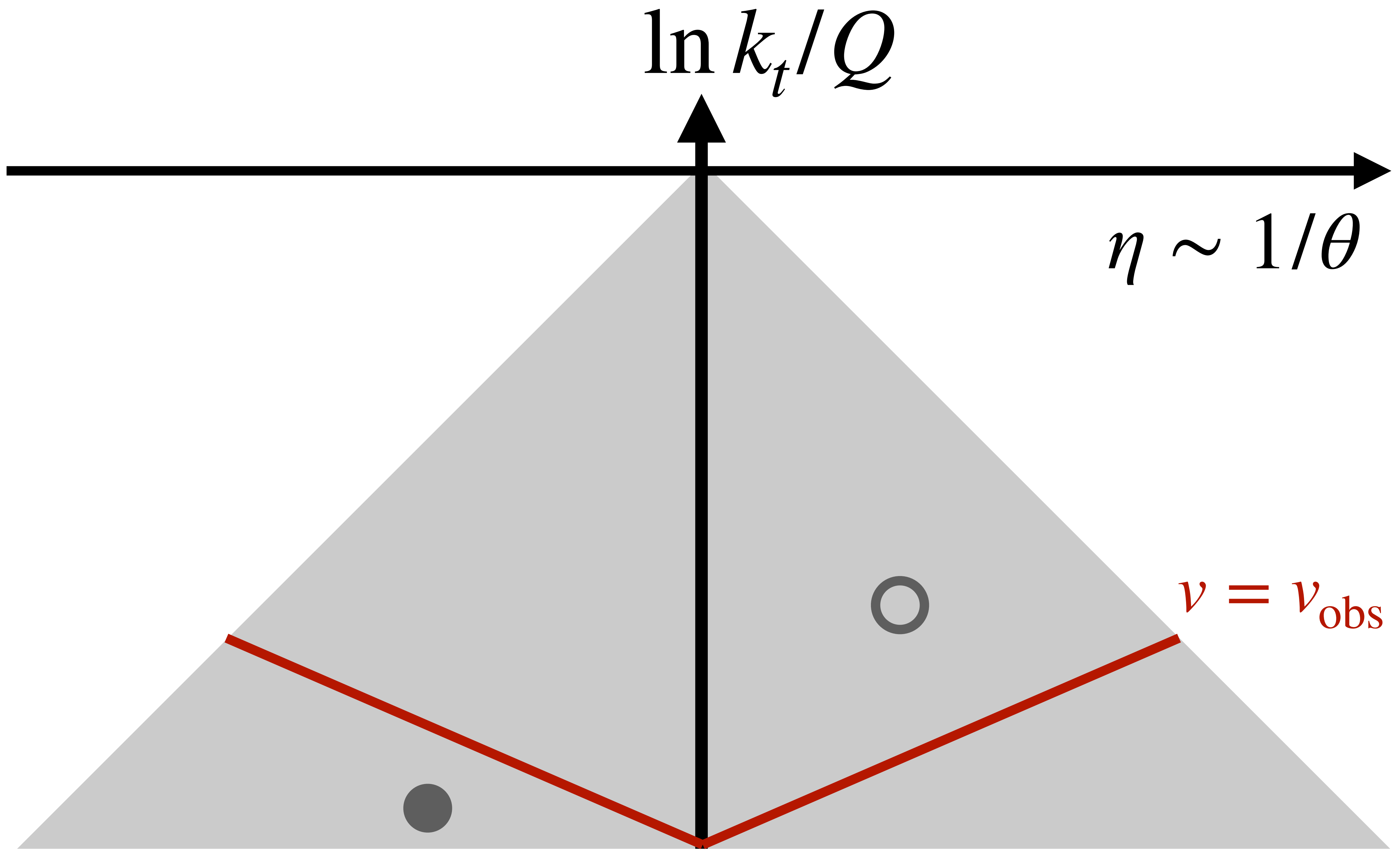
Leading-logarithmic (LL) accuracy

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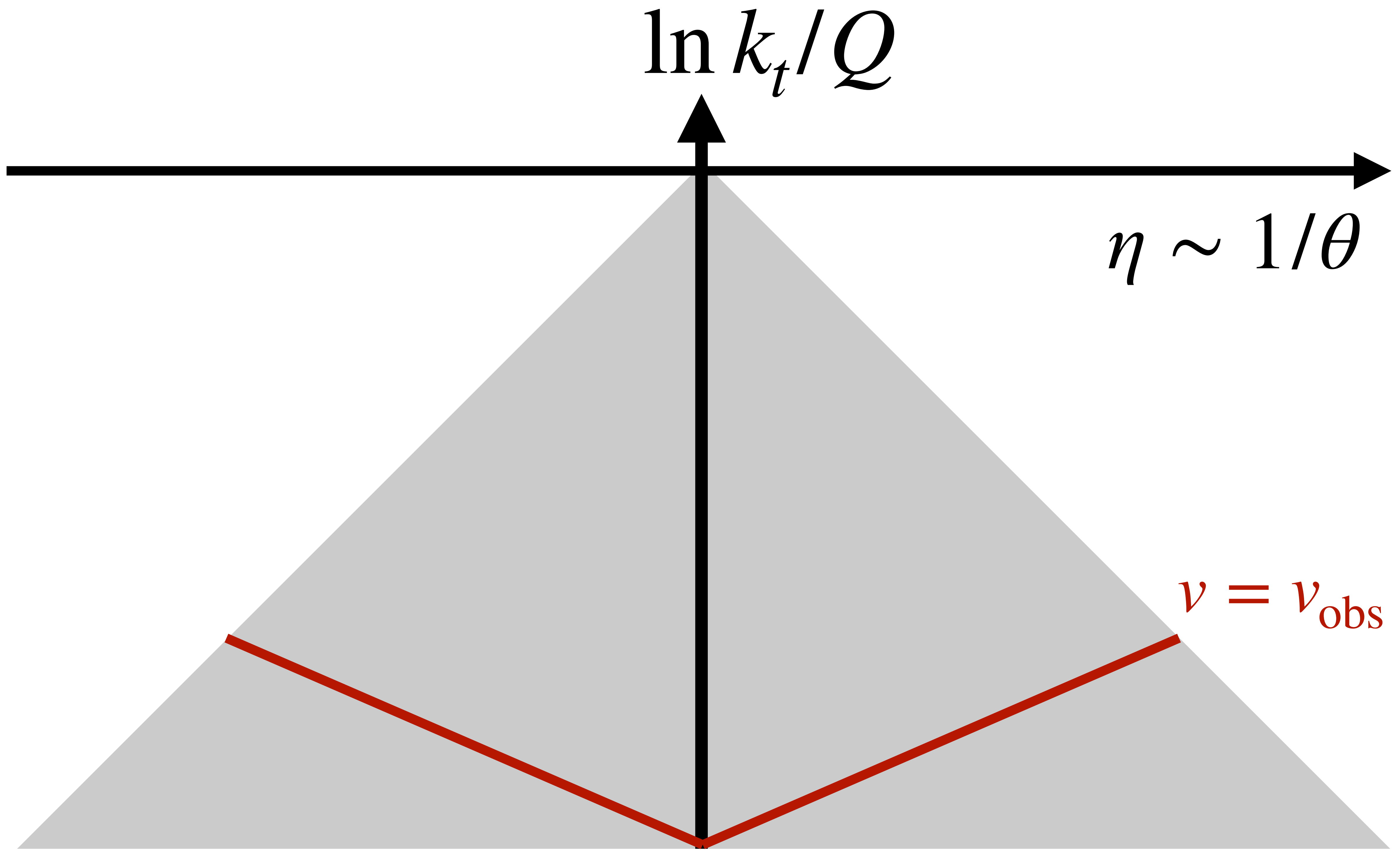
$$dP = \frac{2C_l \alpha_s(k_t)}{\pi} d\eta \, d\ln k_t$$

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

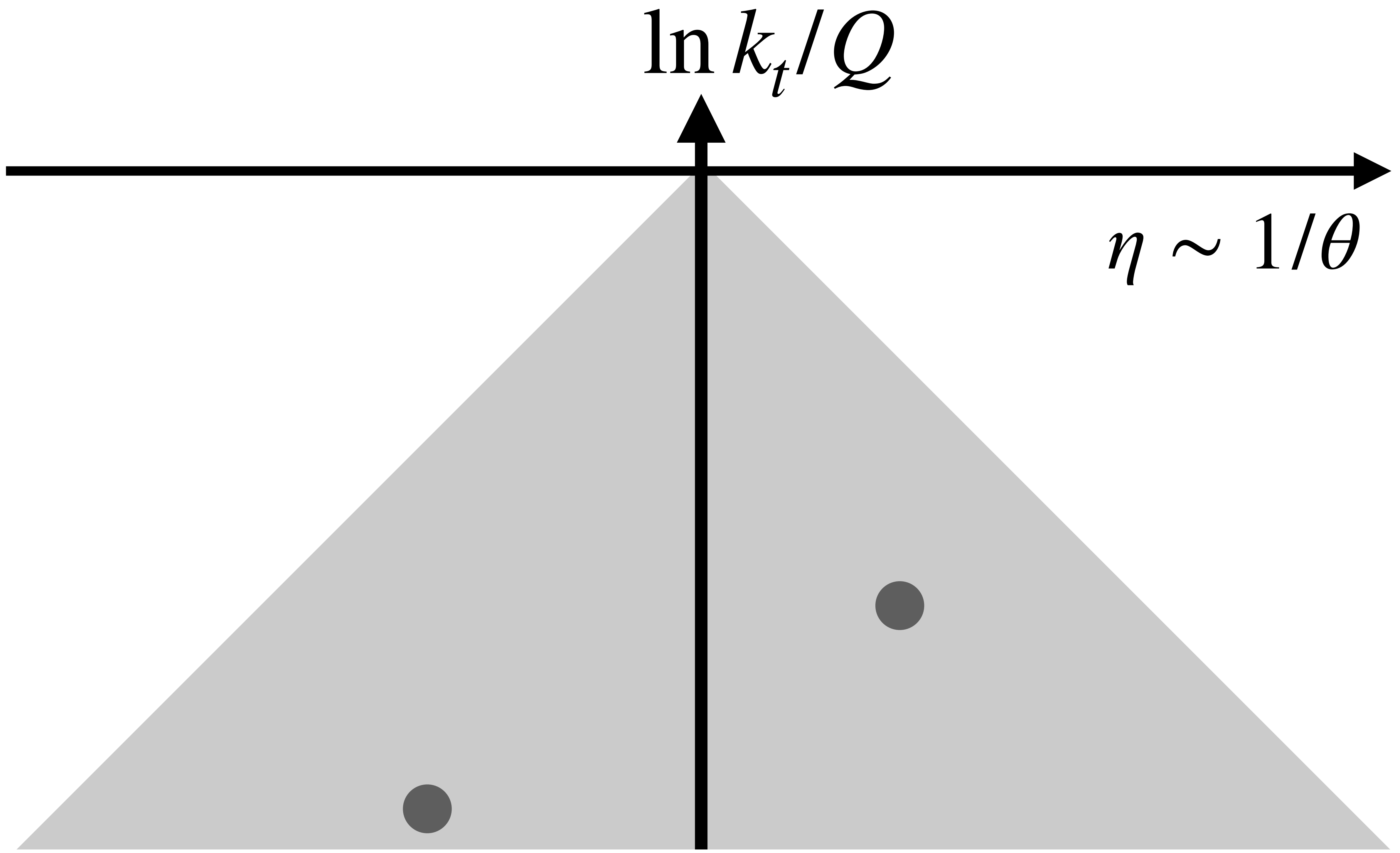


Resummation

Next-to-leading-logarithmic (NLL) accuracy

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

Shower @NLL
for event shapes



Resumption

Next-to-leading-logarithmic (NLL) accuracy

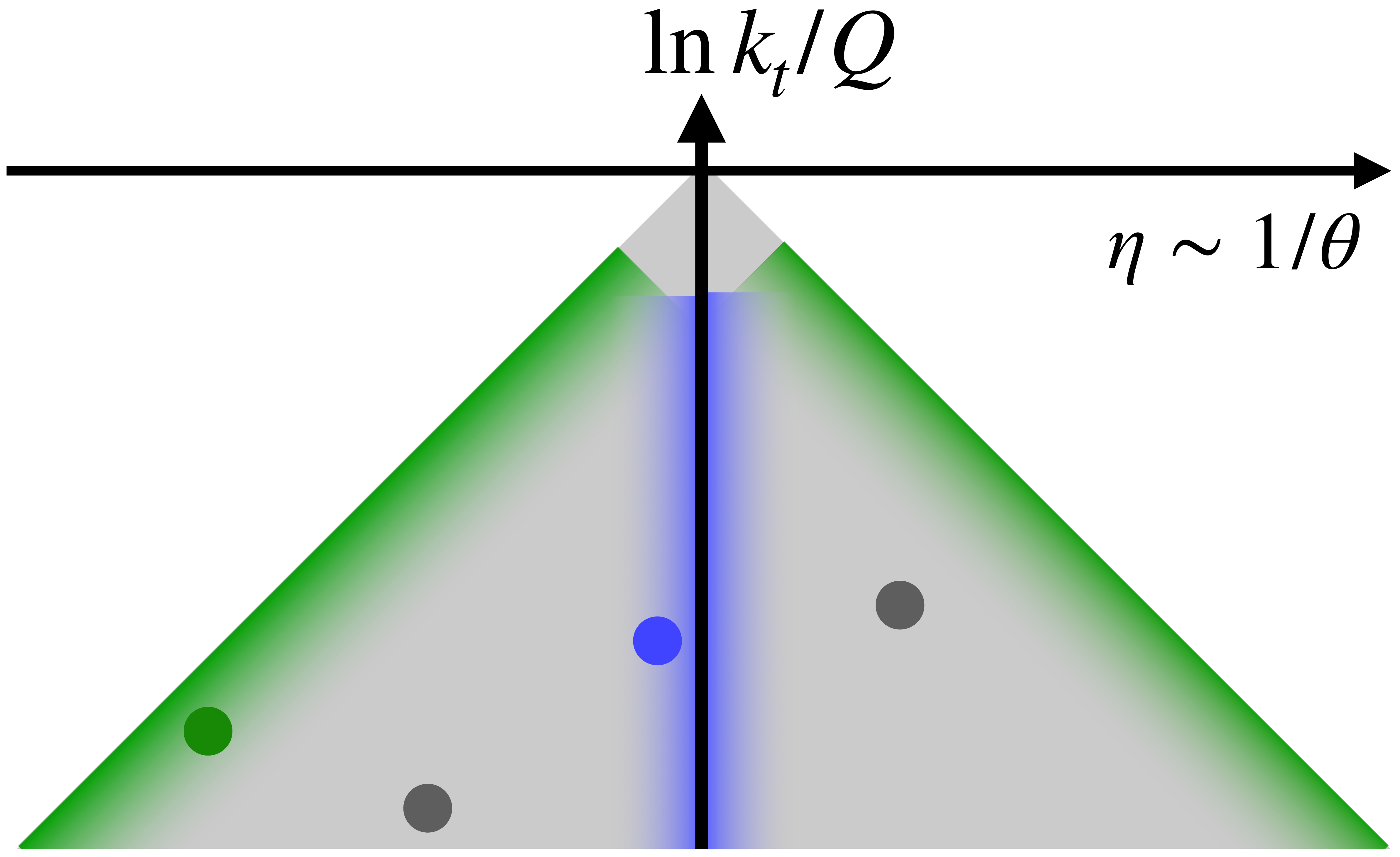
1. Weight for **soft-collinear** emissions receives NLO correction

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

(at 2 loop)

[Catani, Marchesini, Webber '91]

Shower @NLL
for event shapes



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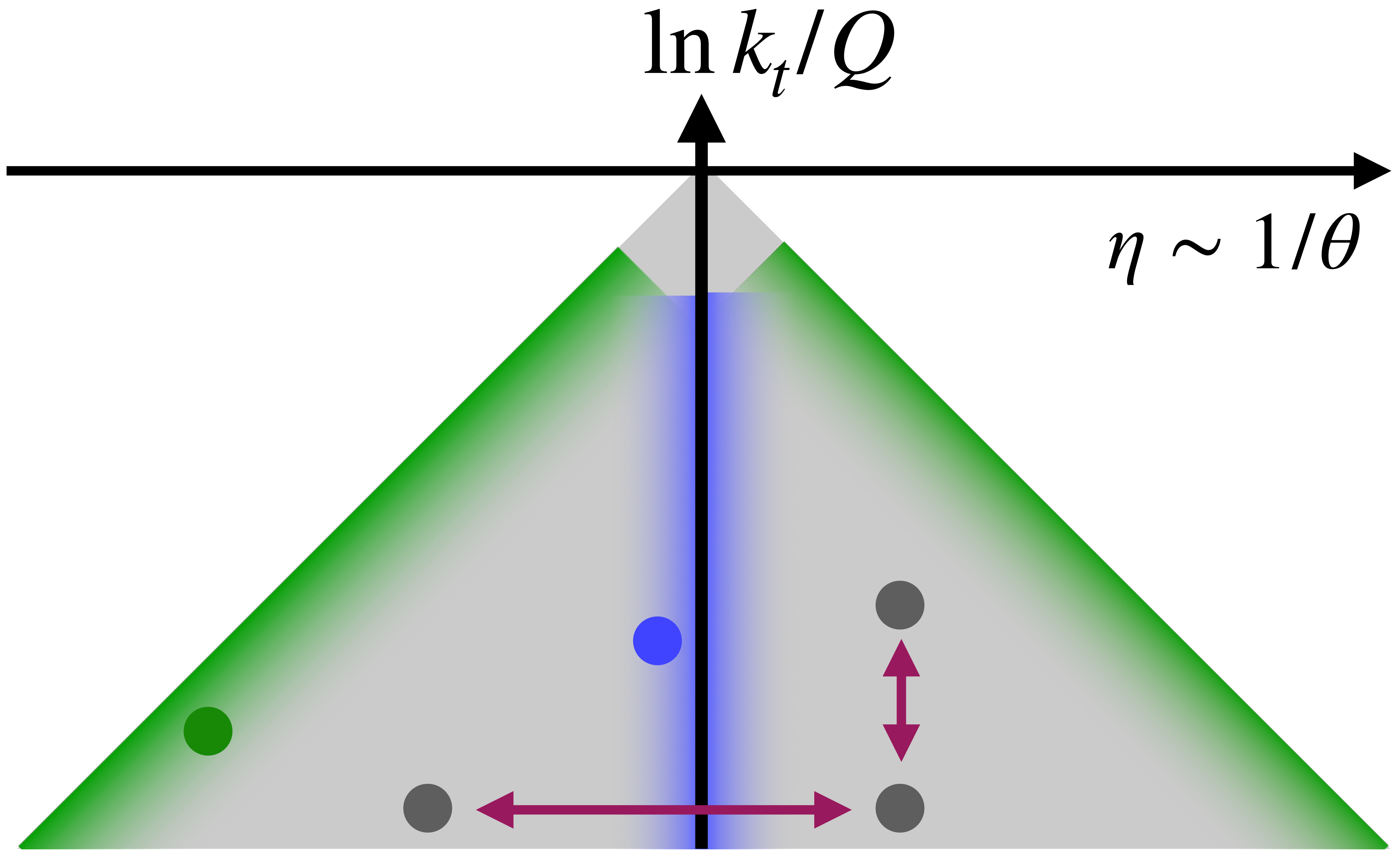
$$dP = \frac{\alpha_s^{\mathrm{CMW}}(k_t)}{\pi} P_{\tilde{i}\to ij}(z)\;\; d\eta\, d\ln k_t$$

Shower @NLL

for event shapes



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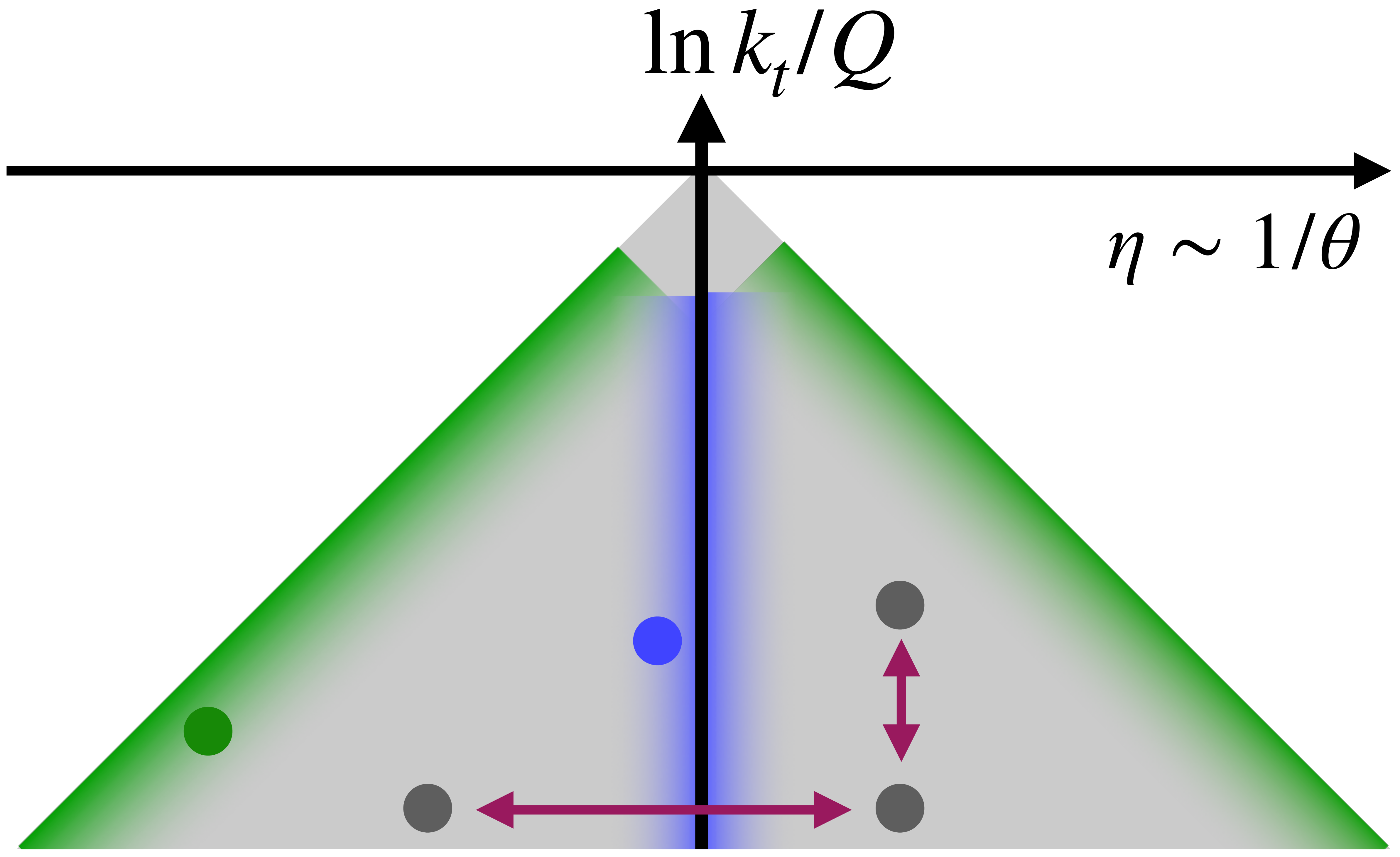
$$dP = \frac{\alpha_s^{\text{CMW}}(k_t)}{\pi}P_{\tilde{i}\to ij}(z)\;\; d\eta\, d\ln k_t$$

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



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

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]

And we are not the only ones

Building a consistent parton shower

Jeffrey R. Forshaw (Manchester U. and Schrodinger Inst., Vienna), Jack Holguin (Manchester U. and Schrodinger Inst., Vienna), Simon Plätzer (Schrodinger Inst., Vienna and Vienna U.) (Mar 13, 2020)

Published in: *JHEP* 09 (2020) 014 • e-Print: 2003.06400 [hep-ph]

Summations of large logarithms by parton showers

Zoltán Nagy (DESY), Davison E. Soper (Oregon U.) (Nov 9, 2020)

Published in: *Phys.Rev.D* 104 (2021) 5, 054049 • e-Print: 2011.04773 [hep-ph]

Initial state radiation in the Herwig 7 angular-ordered parton shower

Gavin Bewick (Durham U., IPPP), Silvia Ferrario Ravasio (Durham U., IPPP and Oxford U., Theor. Phys.), Peter Richardson (Durham U., IPPP and CERN), Michael H. Seymour (Manchester U.) (Jul 8, 2021)

Published in: *JHEP* 01 (2022) 026 • e-Print: 2107.04051 [hep-ph] **Note: not accurate for non-global observables**

A new approach to color-coherent parton evolution

Florian Herren (Fermilab), Stefan Höche (Fermilab), Frank Krauss (Durham U., IPPP), Daniel Reichelt (Durham U., IPPP), Marek Schoenherr (Durham U., IPPP) (Aug 11, 2022)

Published in: *JHEP* 10 (2023) 091 • e-Print: 2208.06057 [hep-ph]

The Alaric parton shower for hadron colliders

Stefan Höche (Fermilab), Frank Krauss (Durham U., IPPP), Daniel Reichelt (Durham U., IPPP) (Apr 22, 2024)

e-Print: 2404.14360 [hep-ph]

New approach to QCD final-state evolution in processes with massive partons

Benoit Assi (Fermilab), Stefan Höche (Fermilab) (Jul 2, 2023)

Published in: *Phys.Rev.D* 109 (2024) 11, 114008 • e-Print: 2307.00728 [hep-ph]

A partitioned dipole-antenna shower with improved transverse recoil

Christian T. Preuss (Wuppertal U.) (Mar 28, 2024)

Published in: *JHEP* 07 (2024) 161 • e-Print: 2403.19452 [hep-ph]

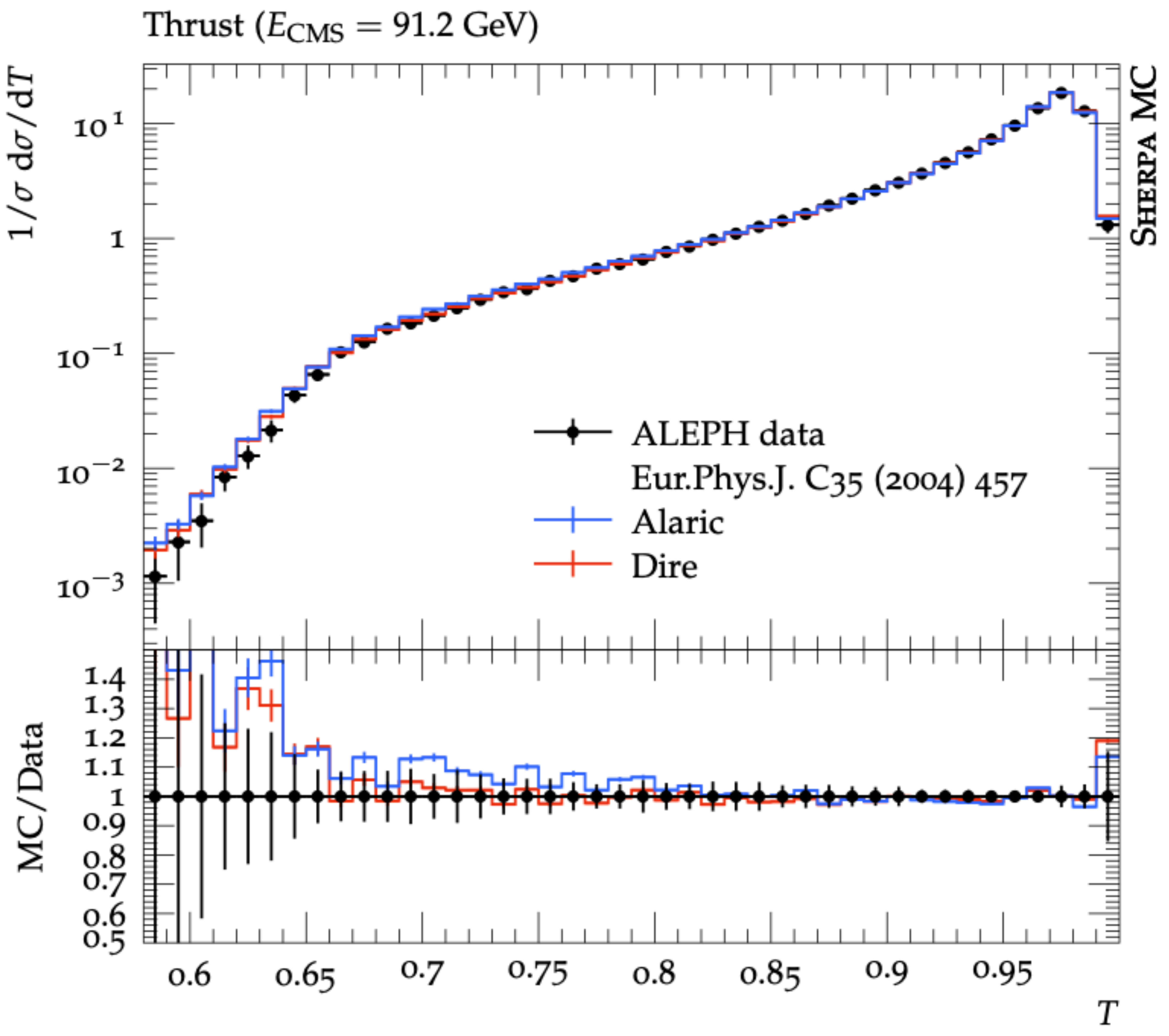
Alaric (to become part of Sherpa)

NLL shower for e^+e^- collisions

Herren, Höche, Krauss, Reichelt, Schönherr [2208.06057]

Numerical & Analytical proof

NLL shower behaves very similar as its LL counterpart (observed also for the PanScales showers)



Melissa van Beekveld

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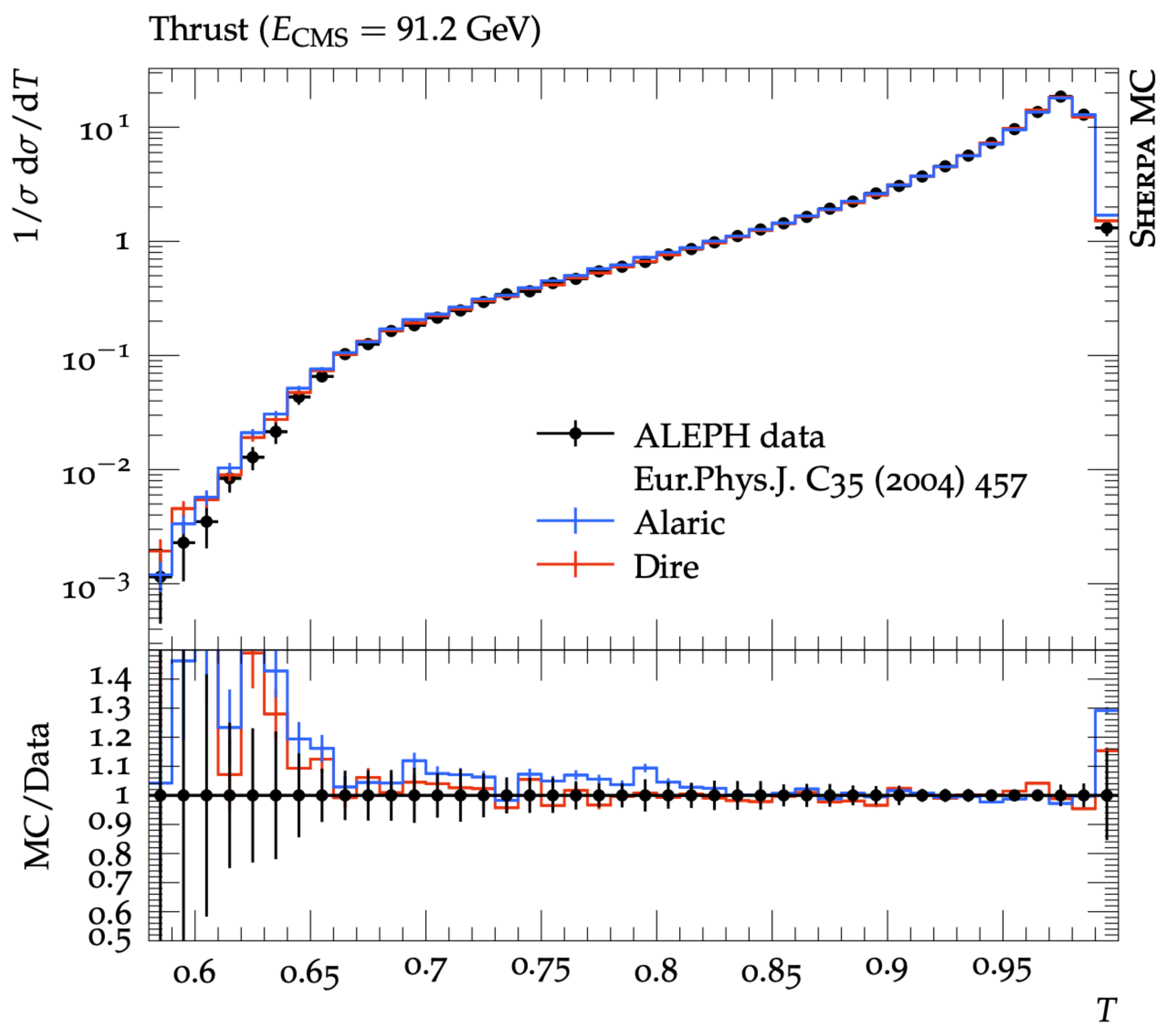
Including mass effects in e^+e^- collisions

Assi, Höche [2307.00728]

Analytical proof

Similar to the massless shower (where mass thresholds in α_s running where included)



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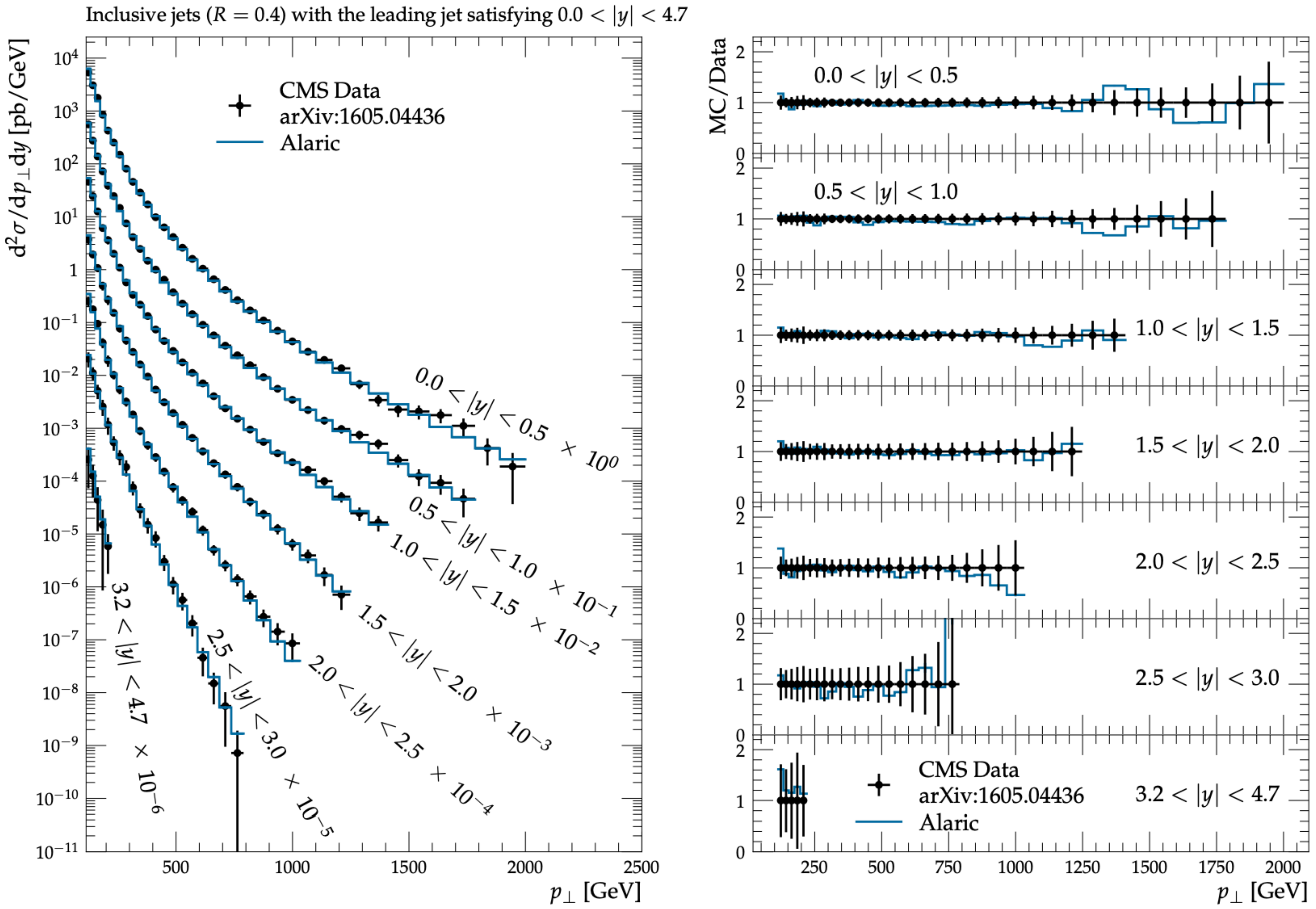
Analytical proof

Similar to the massless shower (where mass thresholds in α_s running where included)

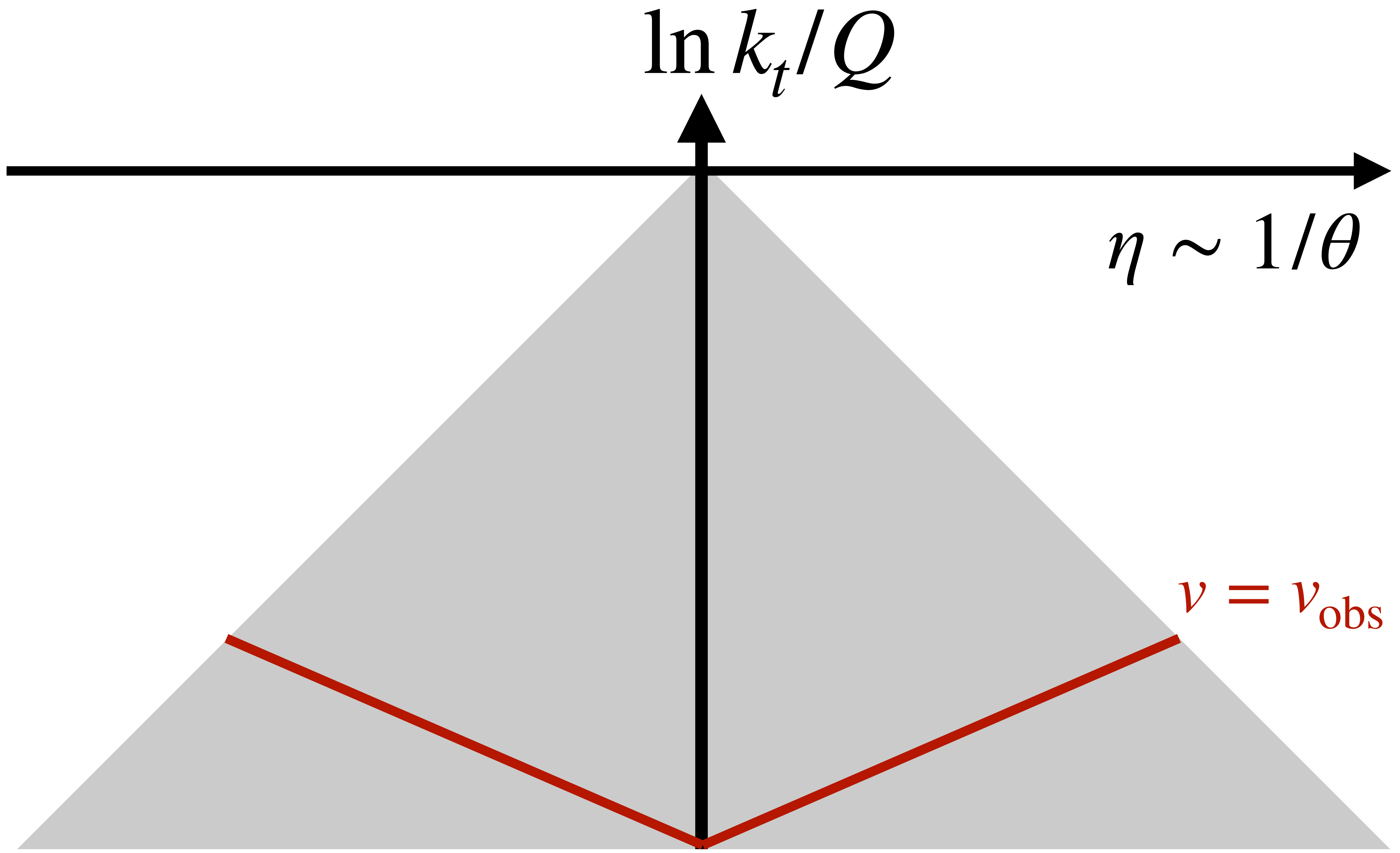
Formulation for pp colliders including multi-jet merging

Höche, Krauss, Reichelt [2404.14360]

Analytical proof for the collinear parts



Shower @NNLL
for e+e- event shapes



Resummation

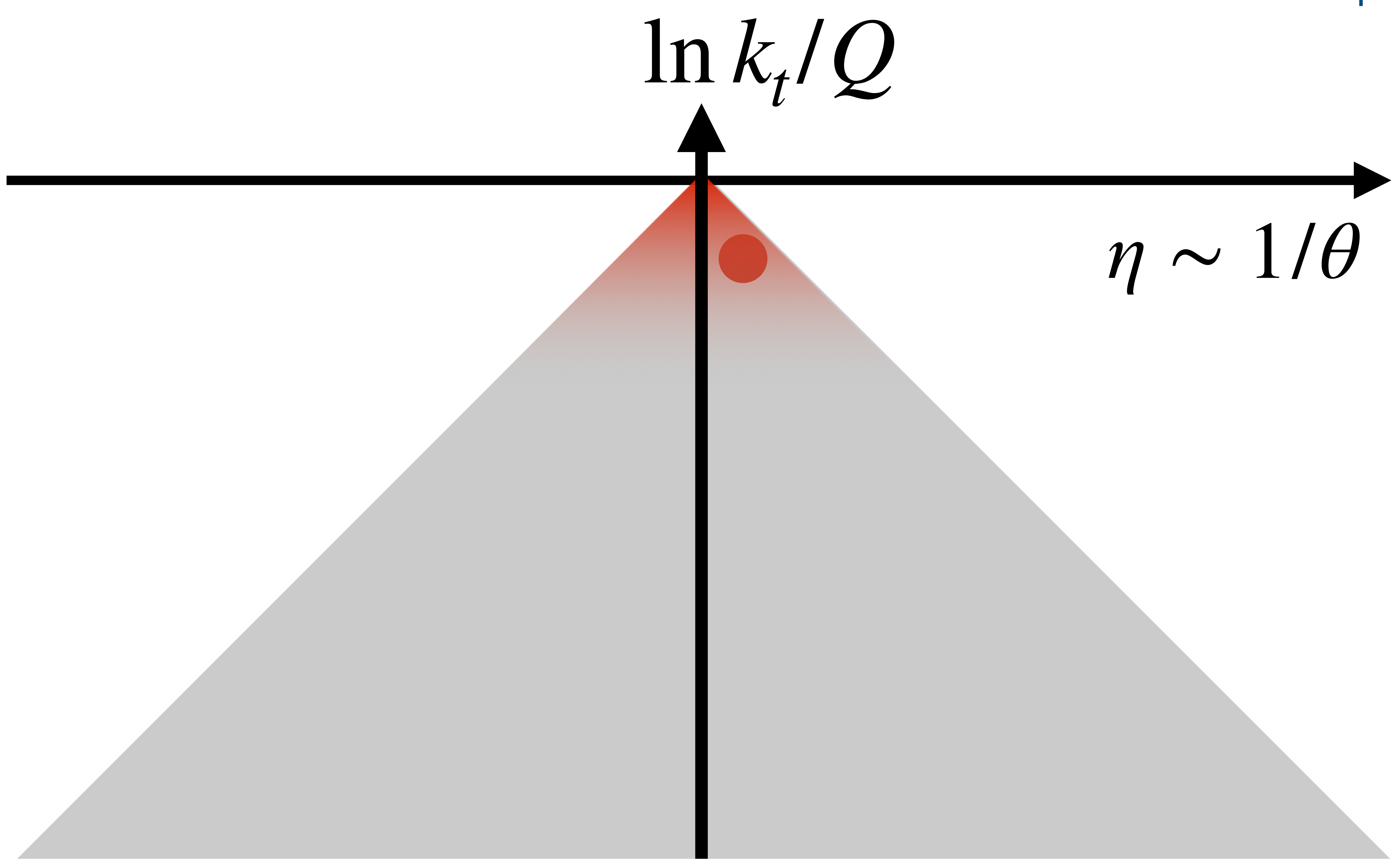
Next-to-next-to leading-logarithmic (NNLL) accuracy

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

Requires many non-trivial ingredients on the shower side…

Shower @NNLL

for e+e- event shapes



Resumption

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

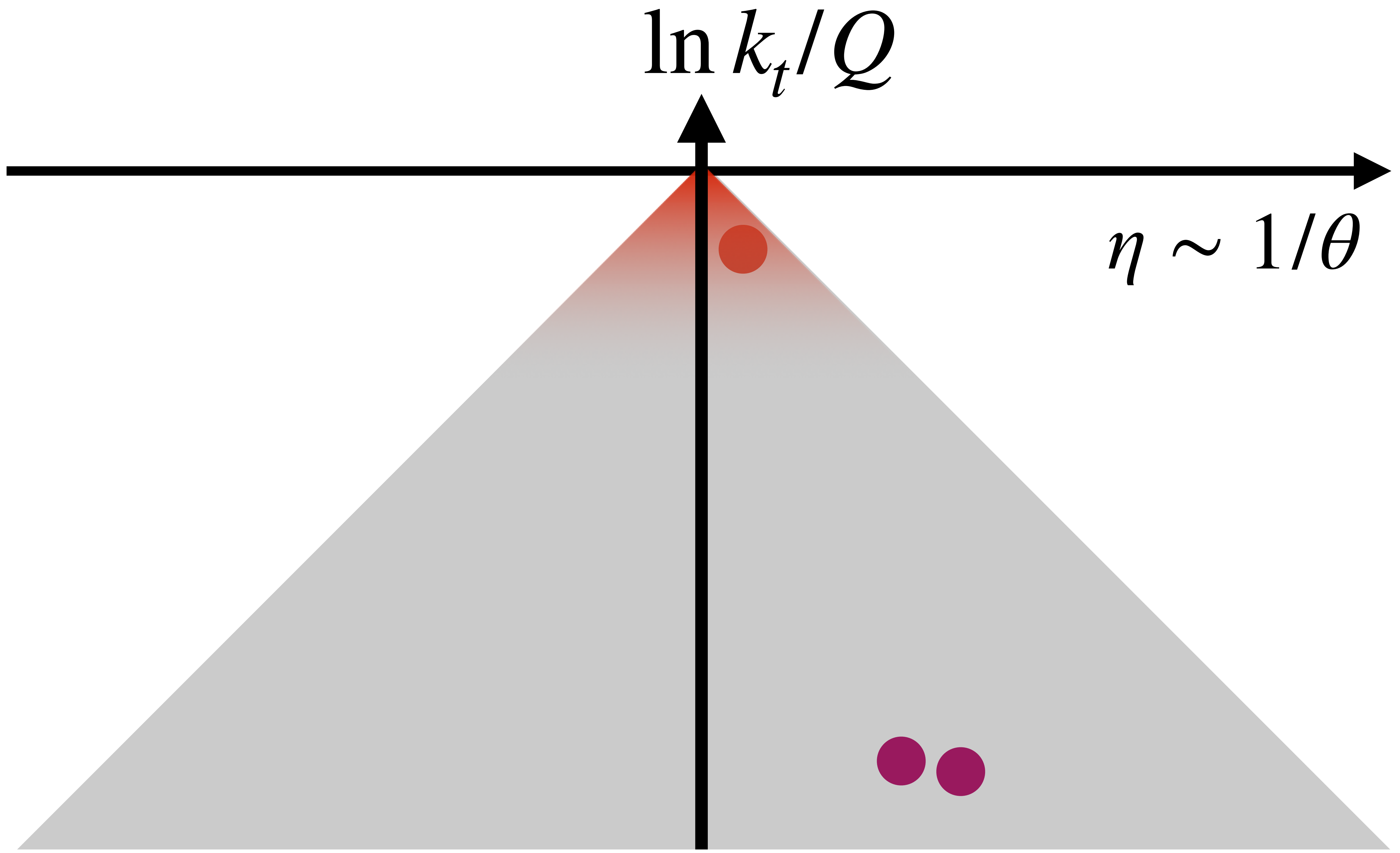
1. Shower needs to be **matched** to NLO

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



Resummation

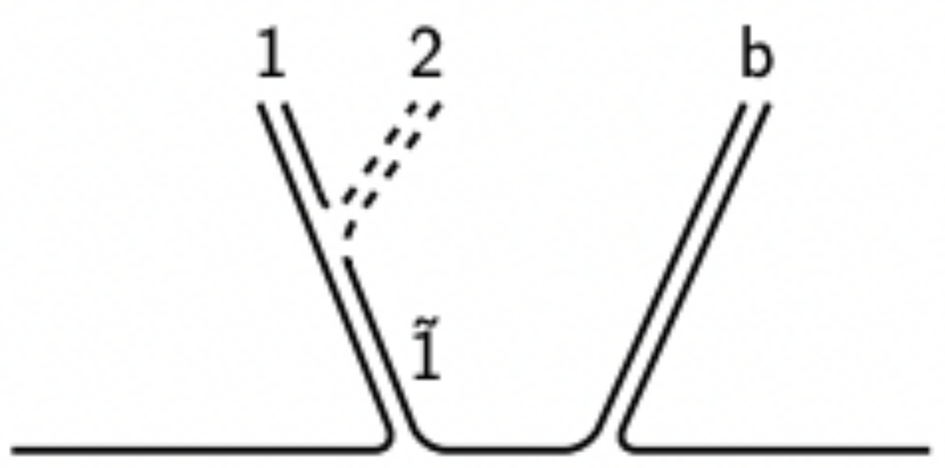
Next-to-next-to leading-logarithmic (NNLL) accuracy

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

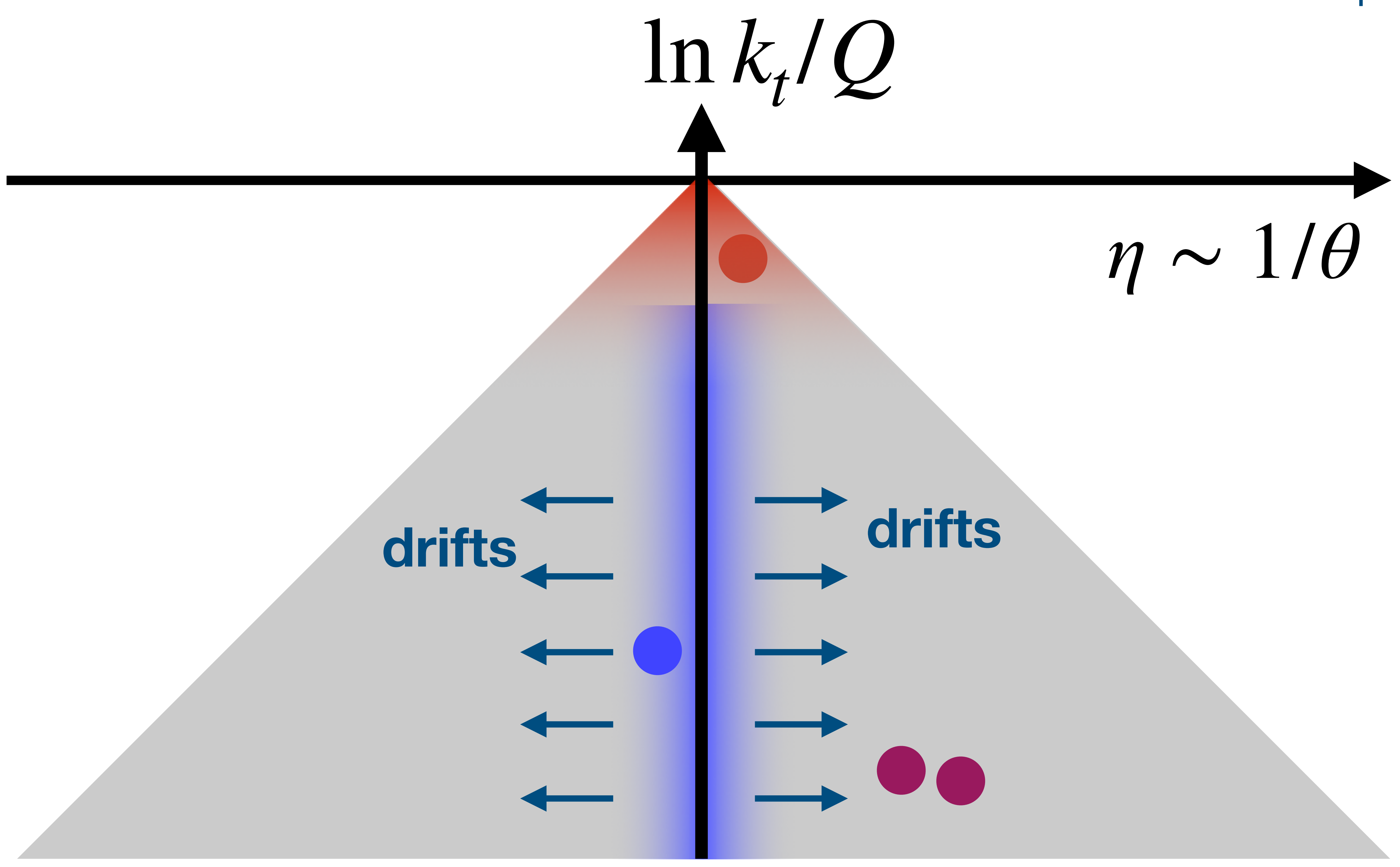


$$|M_{1,2,3,\ldots,n}(p_1,p_2,p_3,\ldots,p_n)|^2 \xrightarrow{12-\text{soft}} (4\pi\mu^{2\varepsilon}\alpha_s)^2 \sum_{i,j=3}^{n} \mathcal{I}_{ij}(p_1,p_2)\,|M^{(i,j)}_{3,\ldots,n}(p_3,\ldots,p_n)|^2$$

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

Shower @NNLL

for e+e- event shapes



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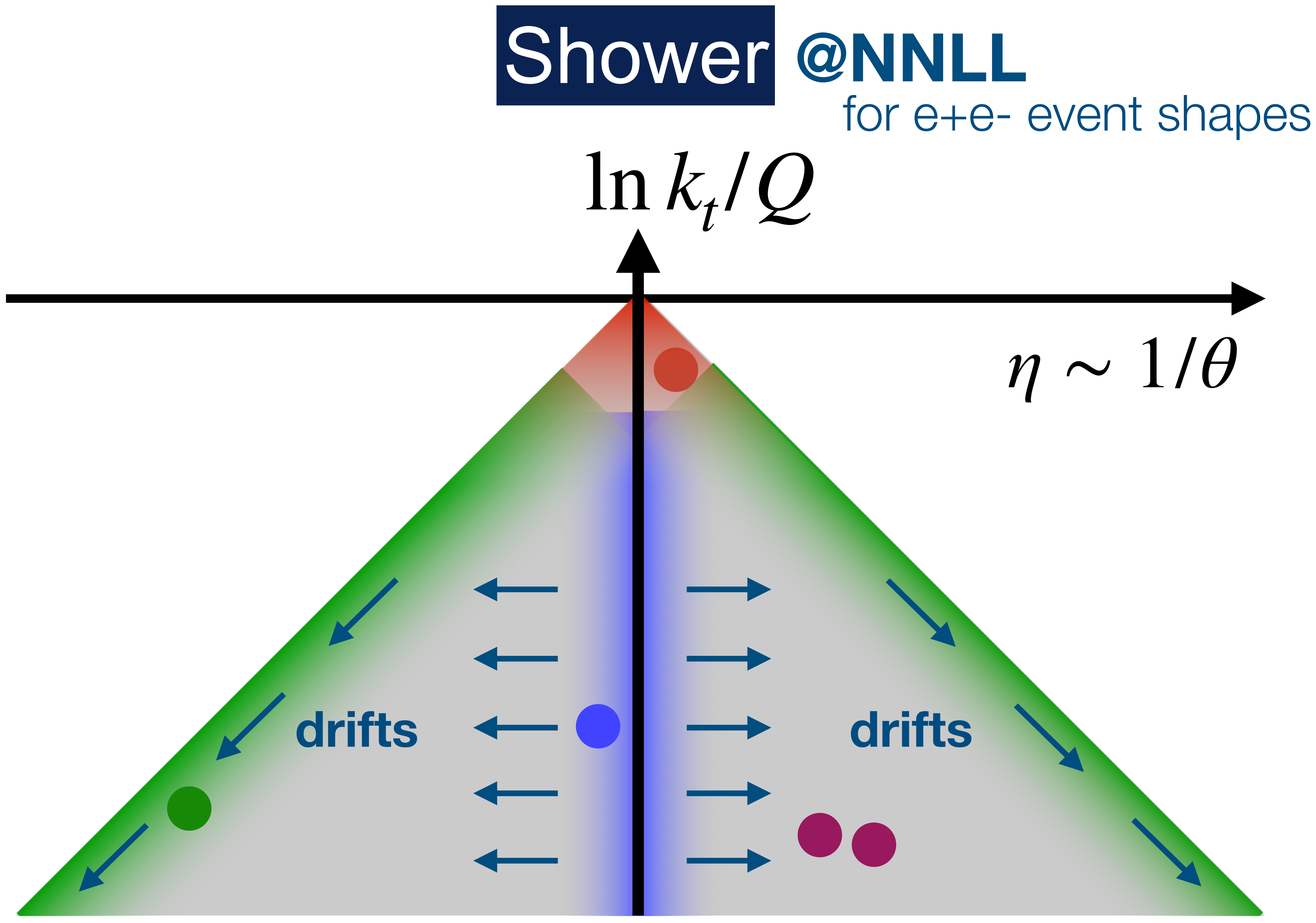
3. **Soft large-angle** emissions @ NLO

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

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

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



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1. Shower needs to be **matched** to NLO
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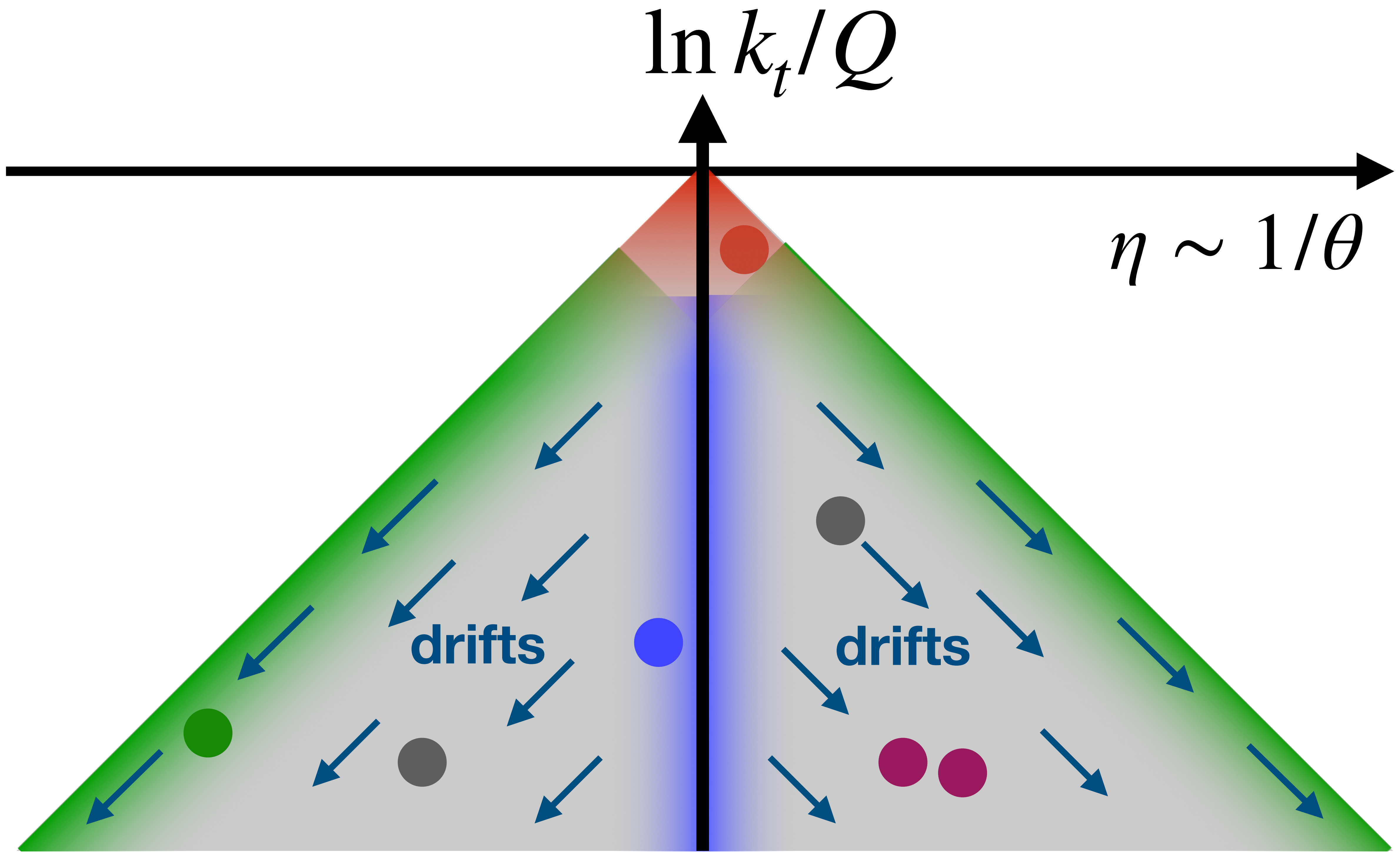
2. **Commensurate pairs** of soft emissions
3. **Soft large-angle** emissions @ NLO
4. **Collinear** emissions @ NLO

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

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



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4. **Collinear** emissions @ NLO
5. **Soft-collinear** emissions @ NNLO

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

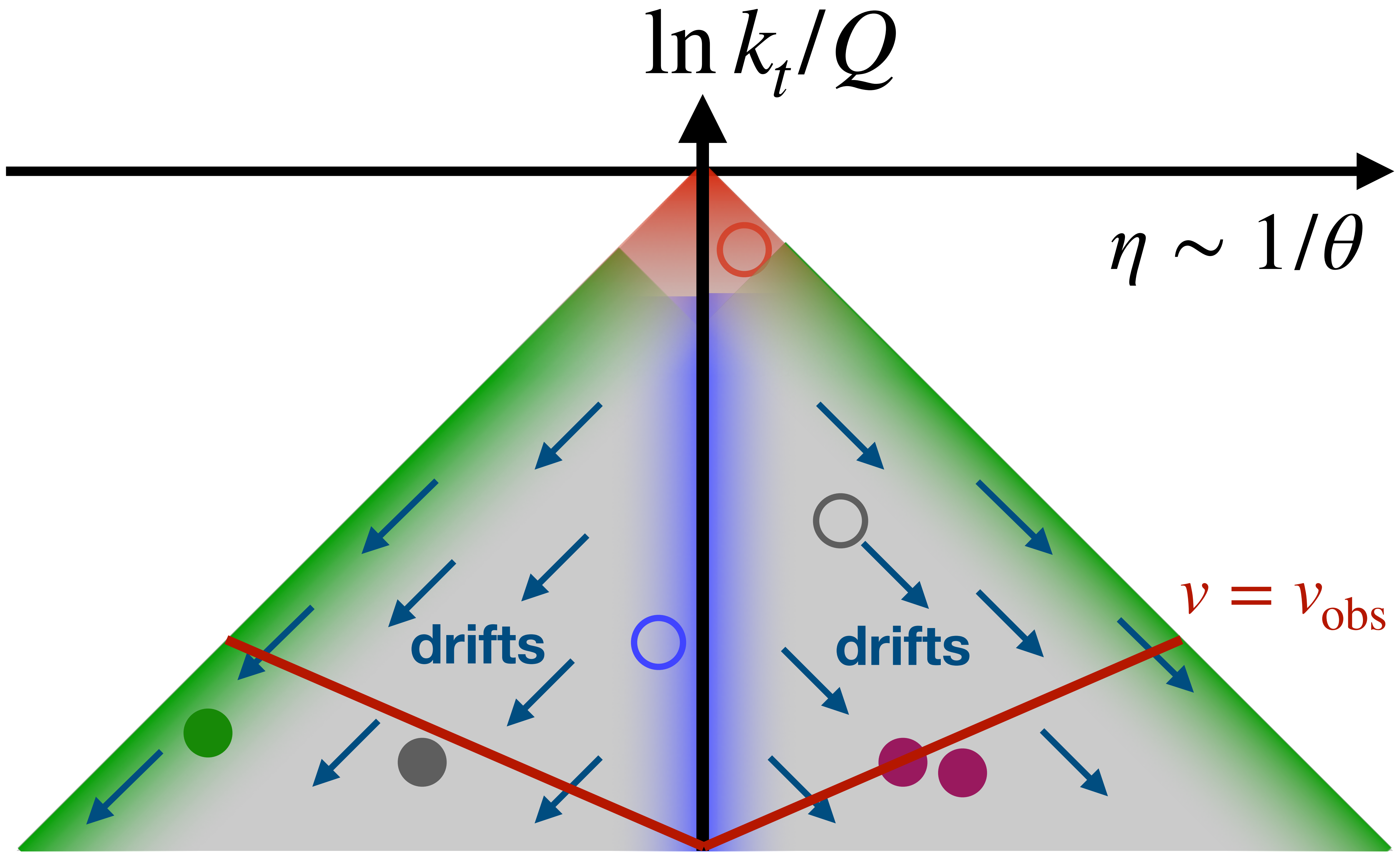
$$+\frac{\alpha_s^2(k_t)}{2\pi}(K_1 + \Delta K_1 + B_2 + \Delta B_2)$$

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

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

Shower @NNLL

for e+e- event shapes



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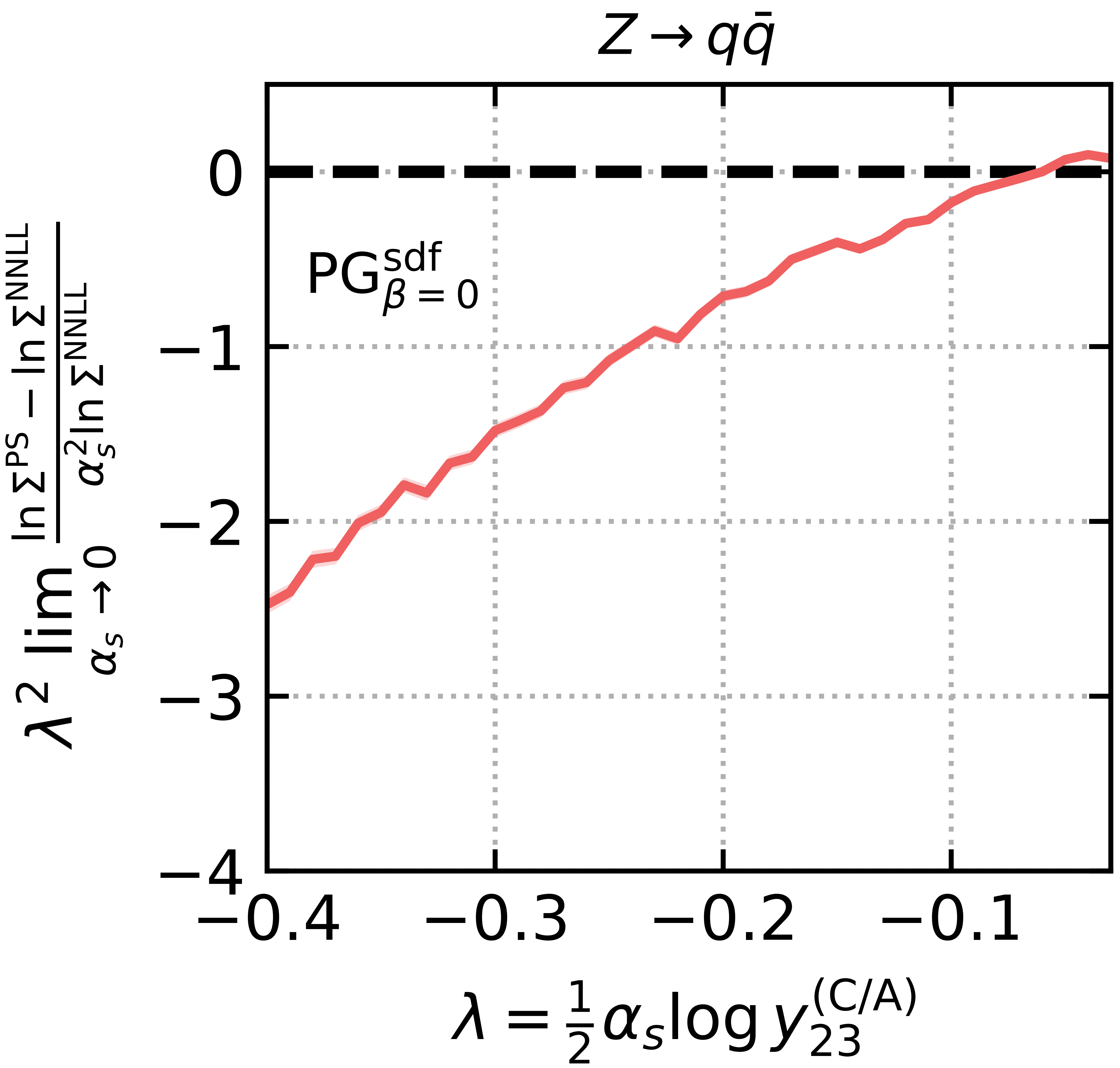
4. **Collinear** emissions @ NLO
5. **Soft-collinear** emissions @ NNLO

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

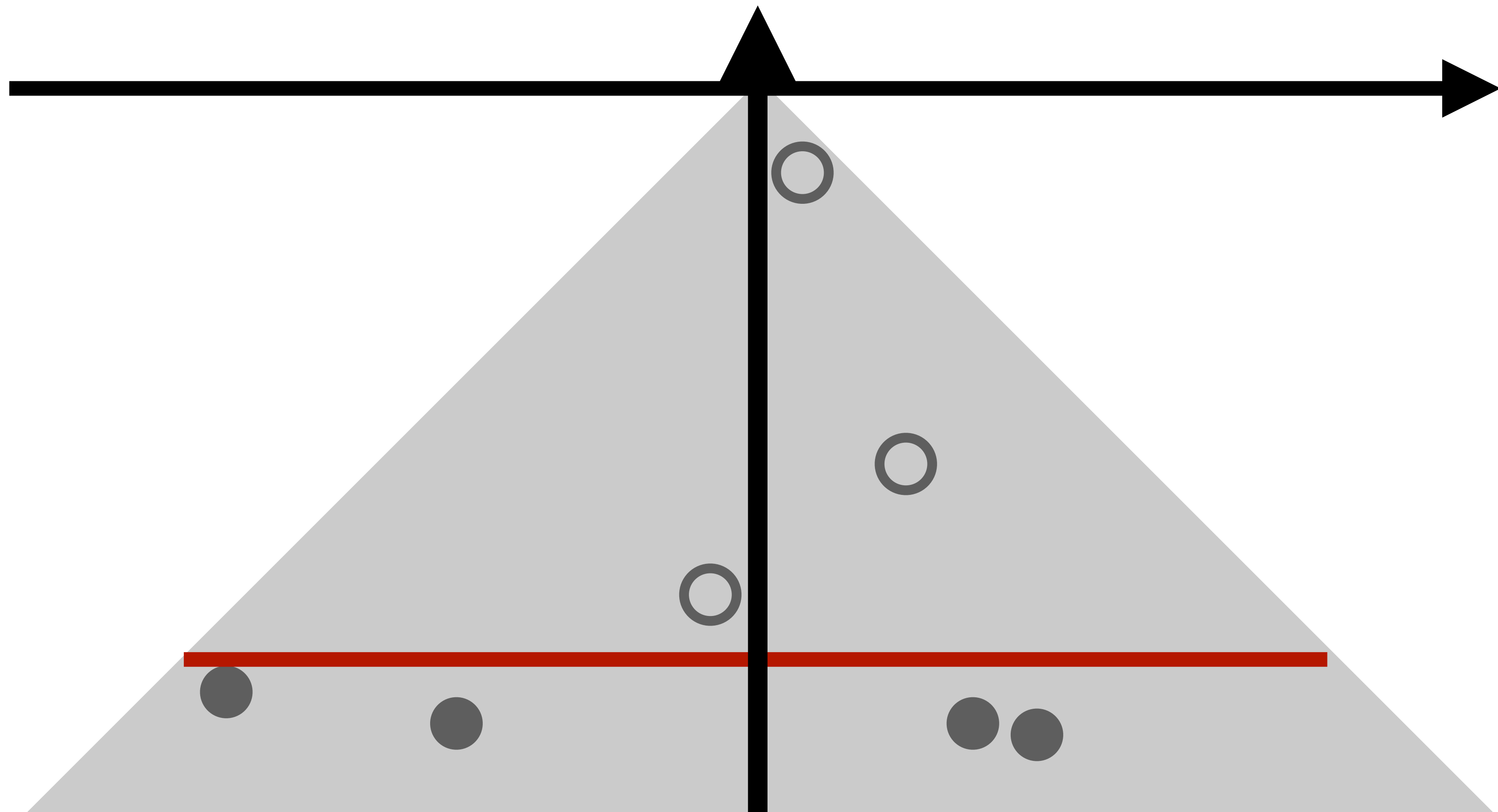
$$\Sigma_{\mathrm{NNLL}}(v < v_{\mathrm{obs}}) = \exp\left[-g_1(\alpha_s L)L + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L)\right]$$

But we also test this numerically

Consider again Cambridge y_{23}

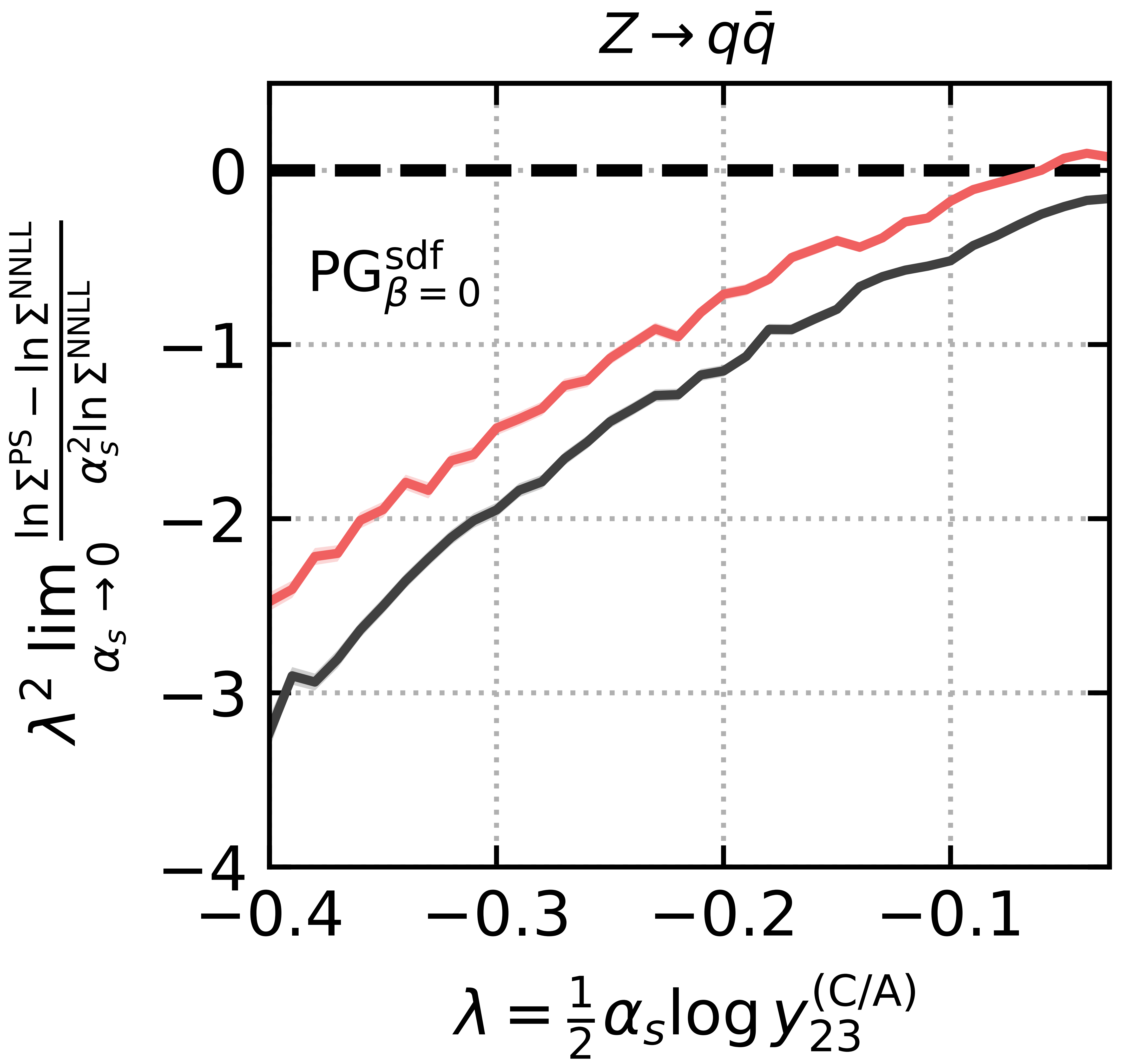


NLL baseline NNLL discrepancy is O(1)!



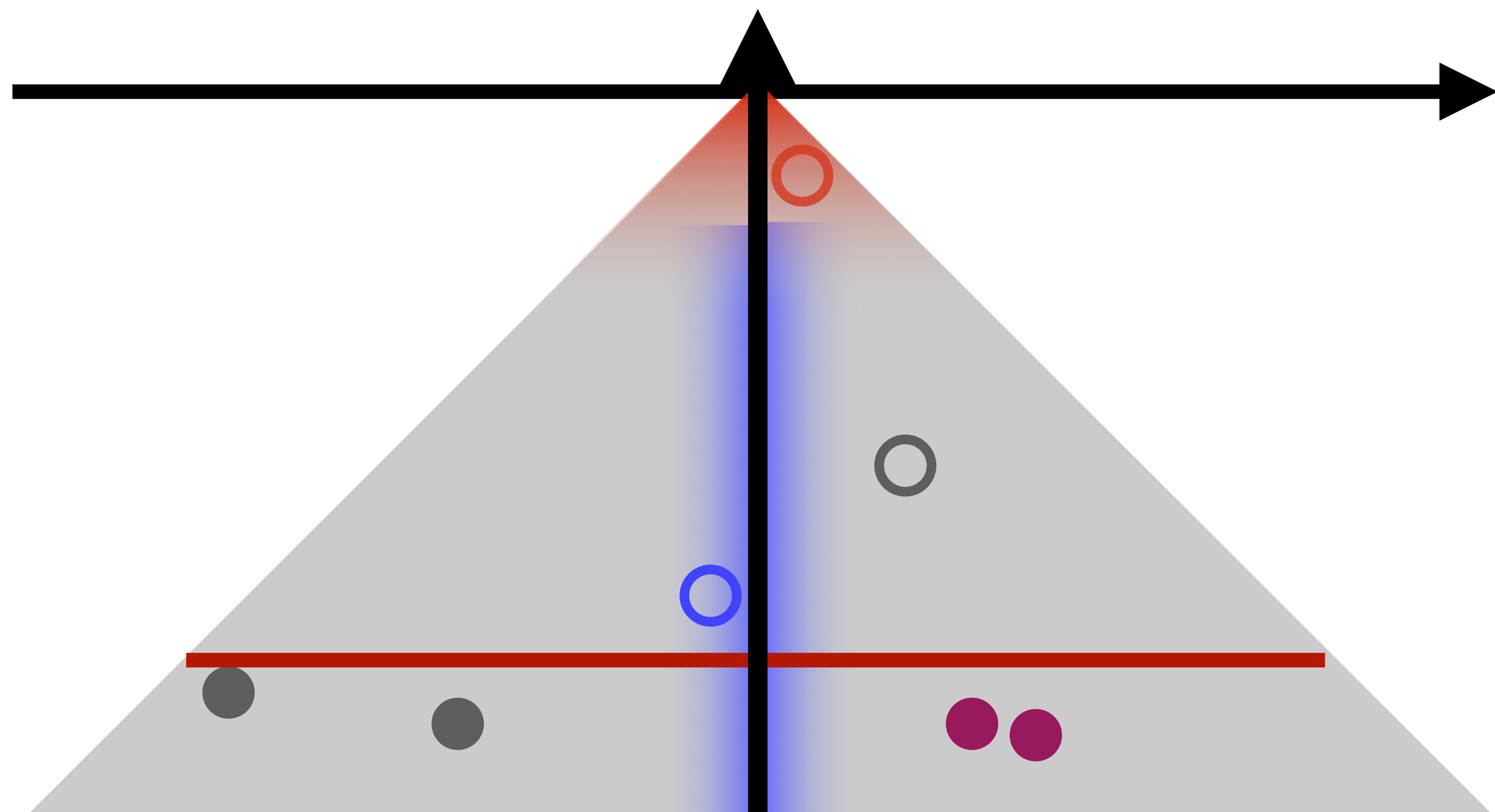
[2406.02661]

But we also test this numerically



NLL baseline NNLL discrepancy is O(1)!

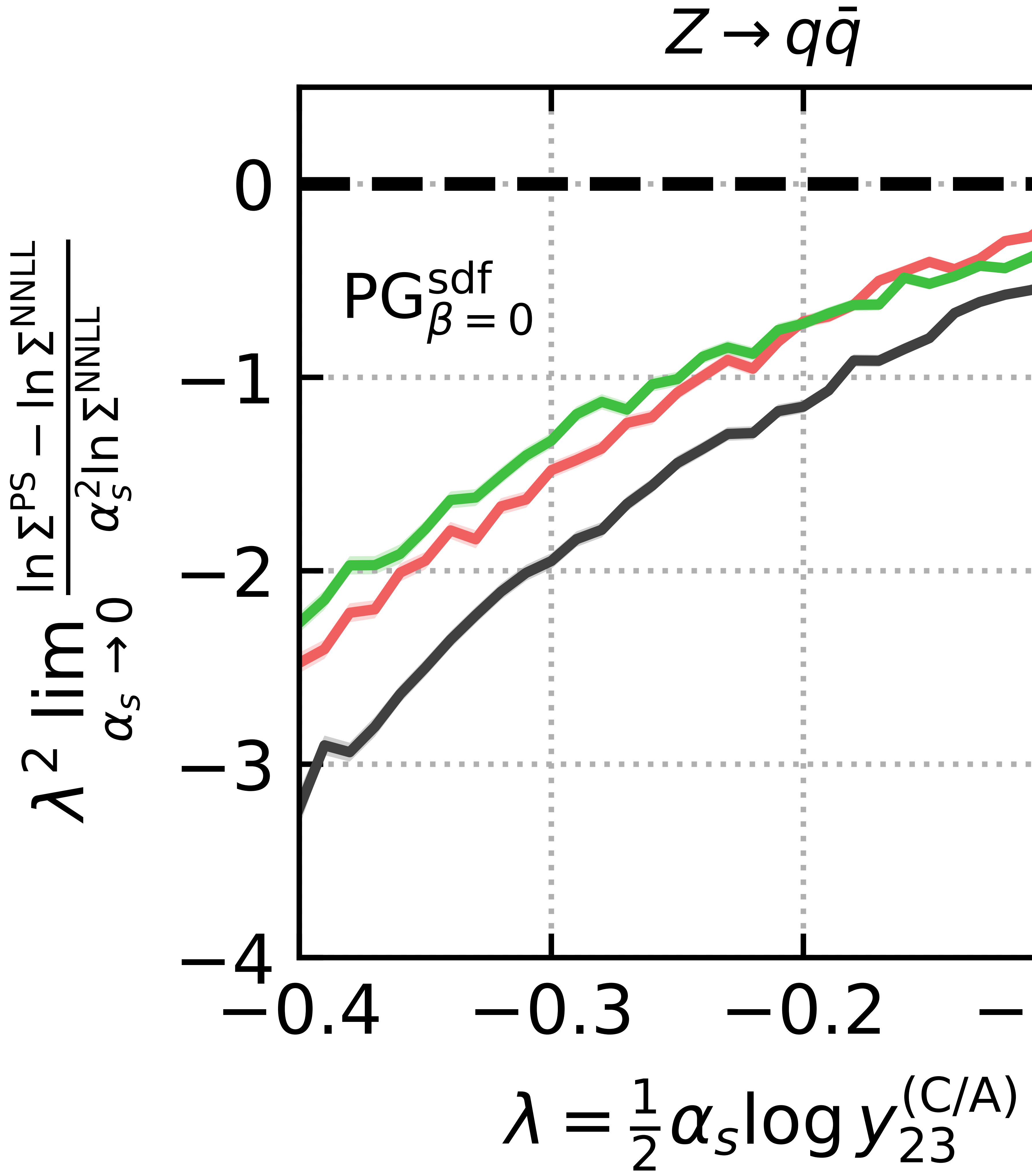
+ matching and double-soft real emission corrections



Melissa van Beekveld

[2406.02661]

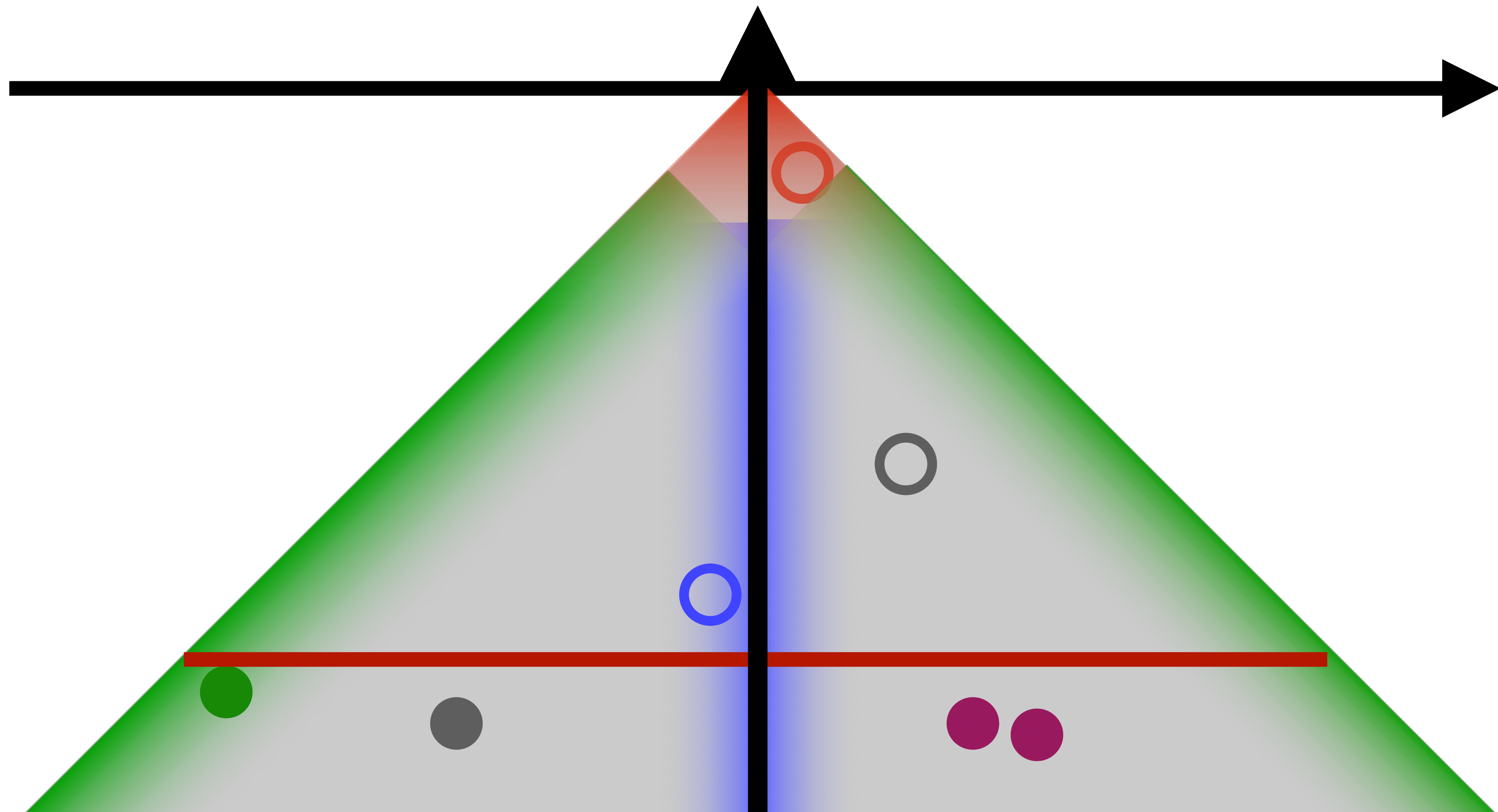
But we also test this numerically



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)



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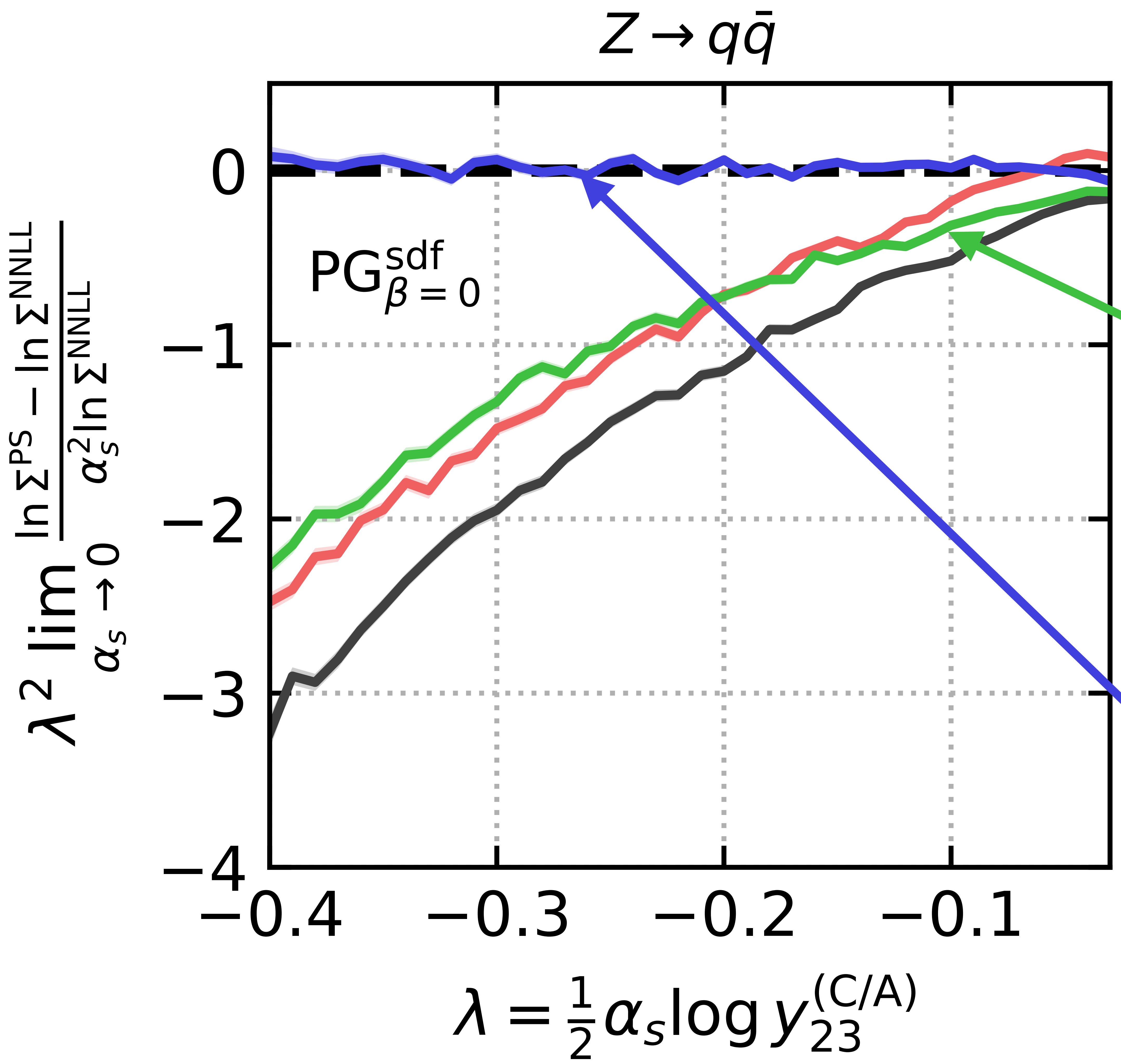
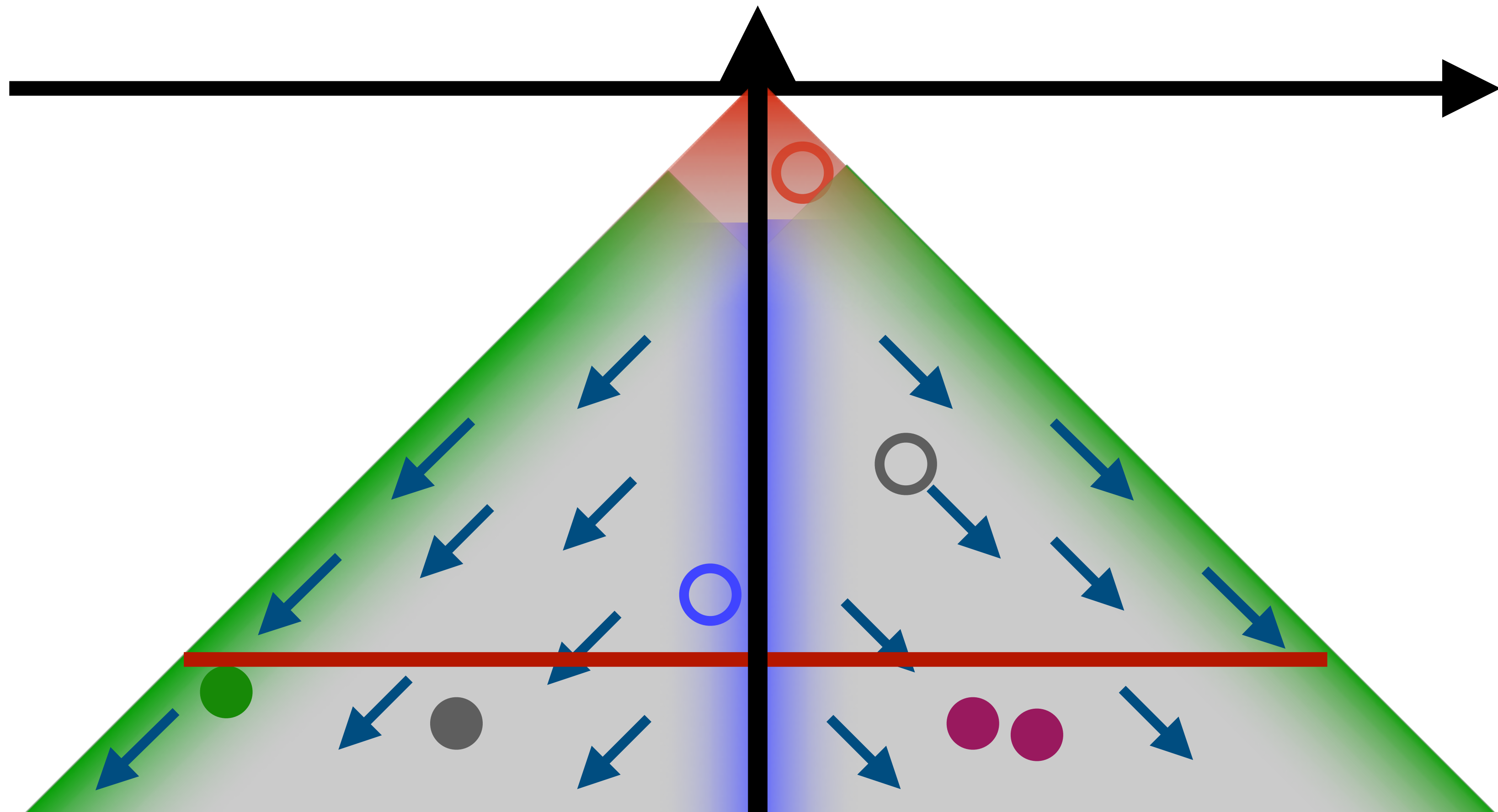


NLL baseline NNLL discrepancy is O(1)!

+ matching and double-soft real emission corrections

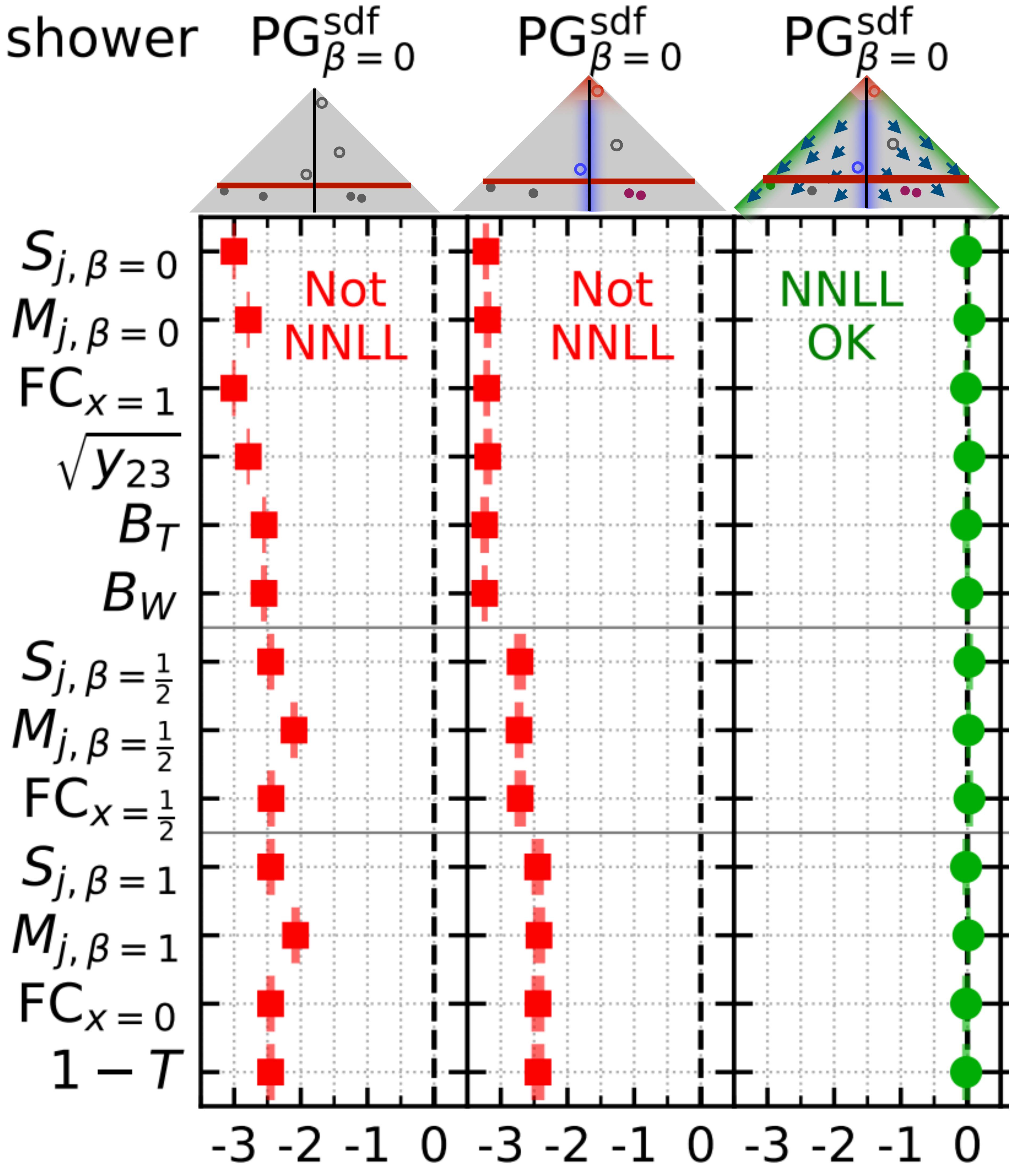
+ 3-loop α_s running, NNLO soft-collinear (K_2) and NLO collinear normalisation (B_2)

+ Δ (drift) correction



And not just for one observable…

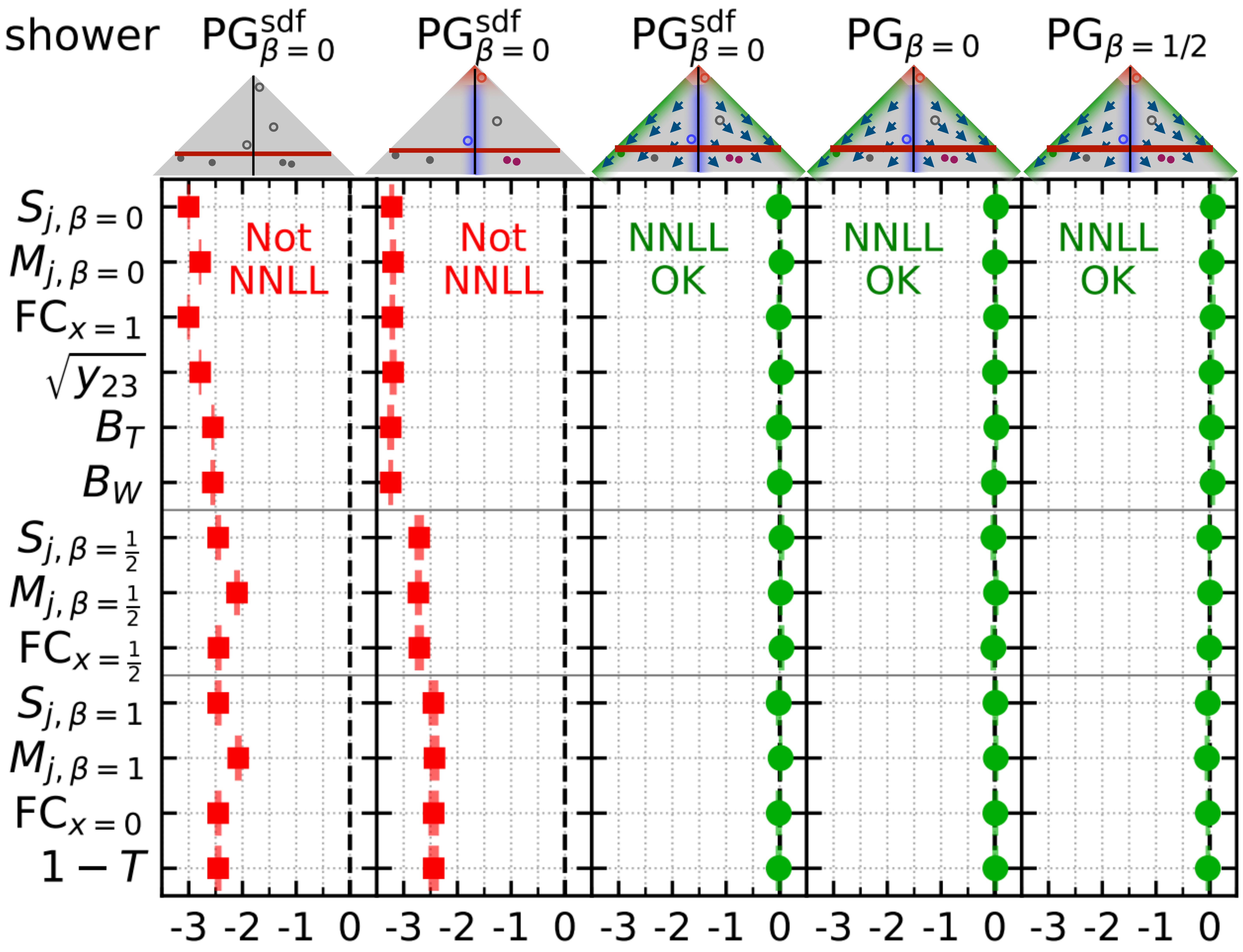
[2406.02661]



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

And not just for one observable/shower…

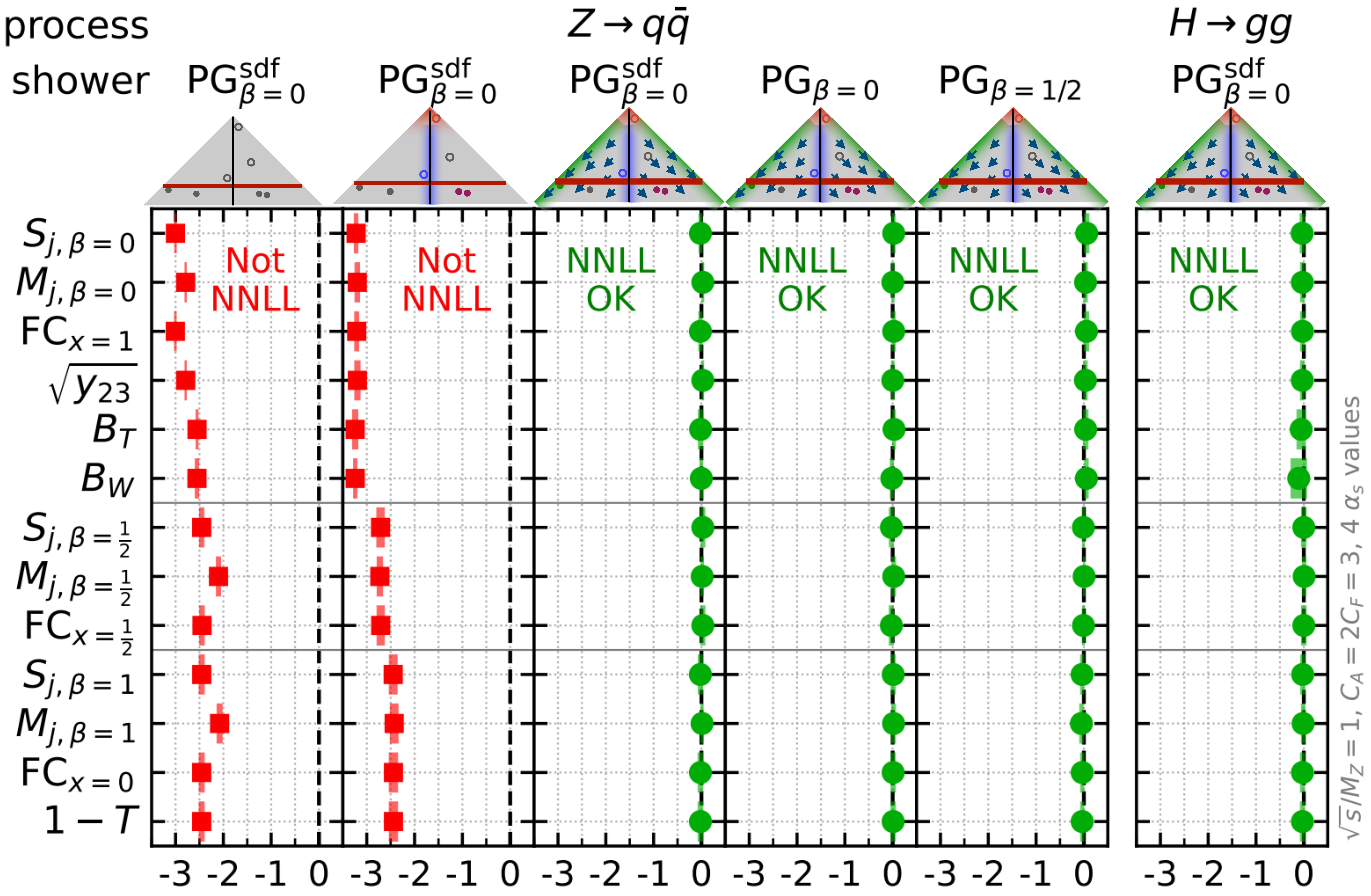
[2406.02661]



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

And not just for one observable/shower/process

[2406.02661]



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

Theory detour over

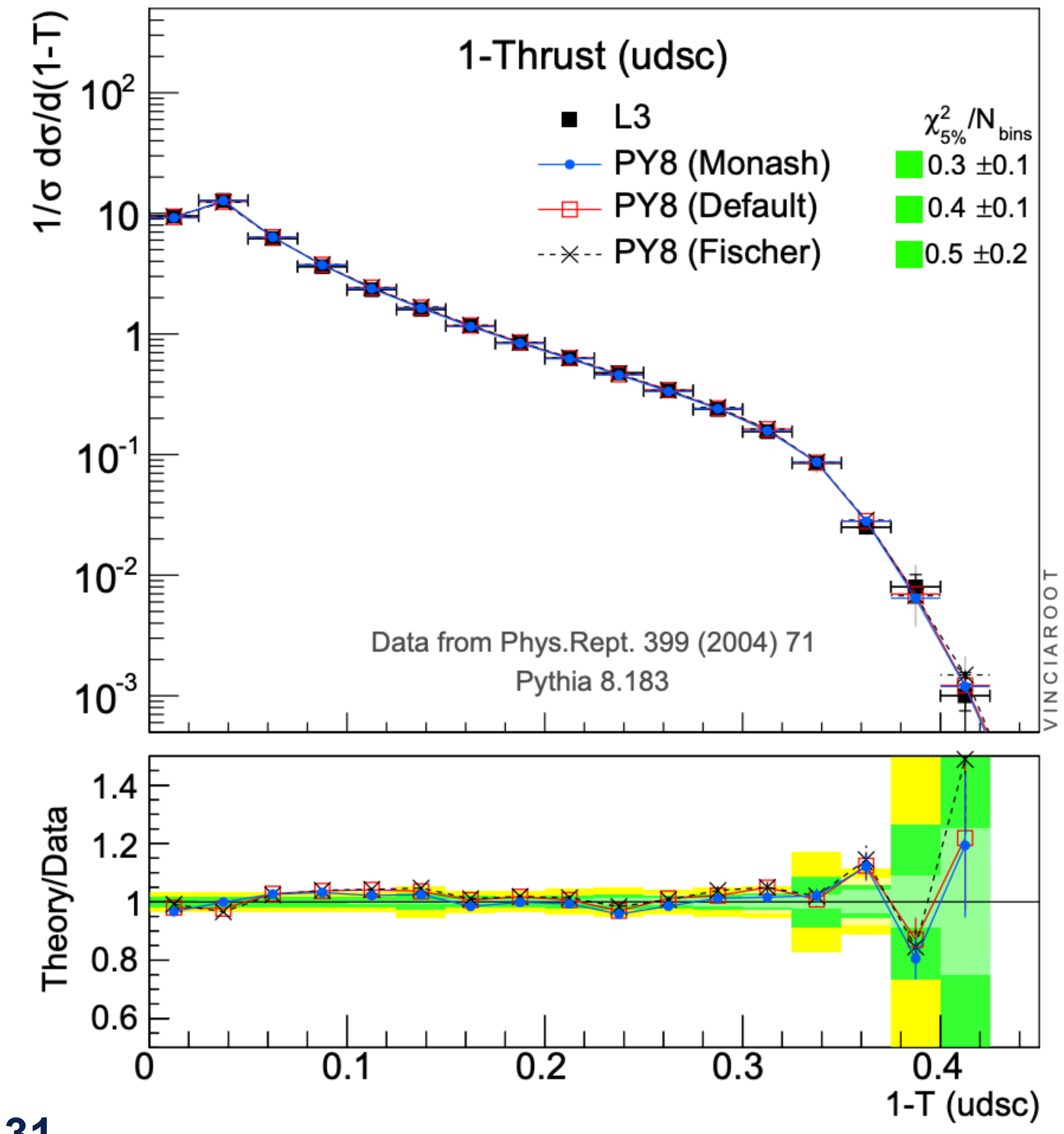
What is the impact on pheno?

Relevance for phenomenology?

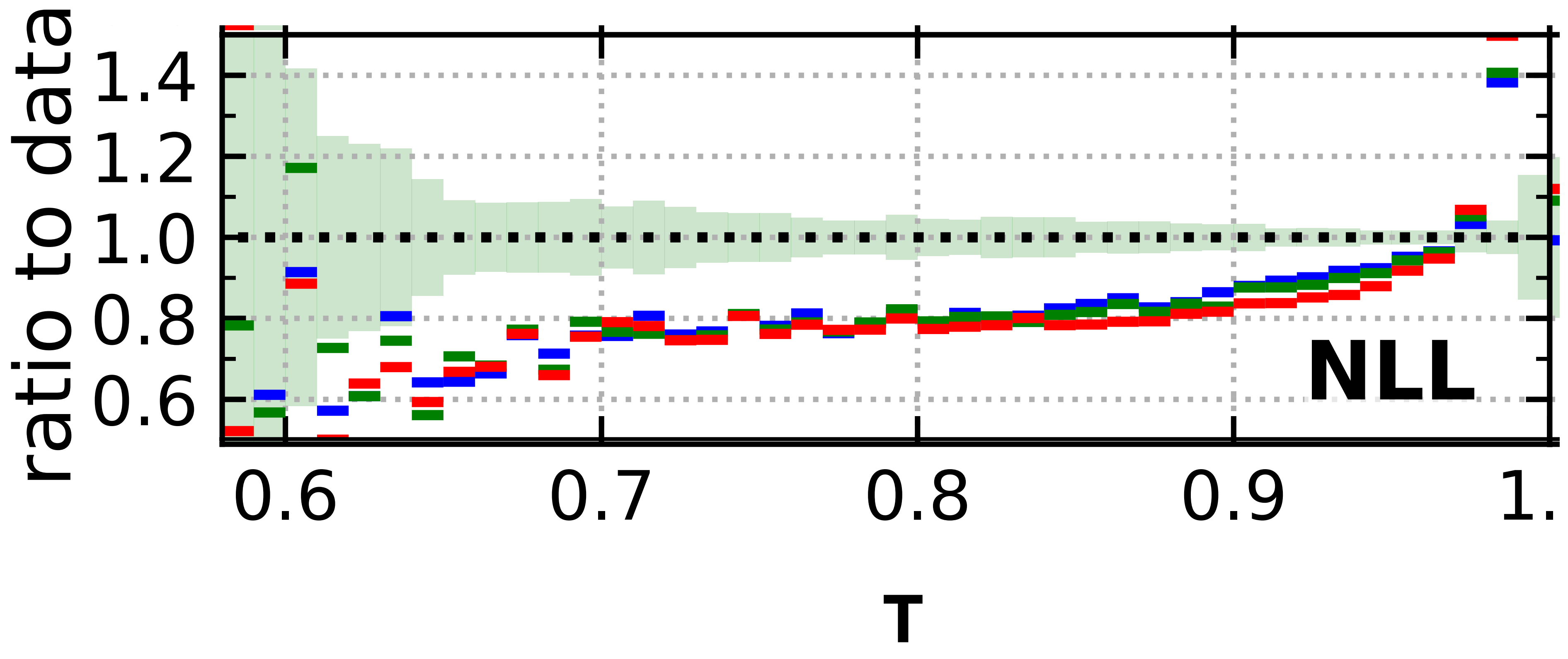
[2406.02661]

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 NLL showers, i.e. with $\alpha_s(M_z) = 0.118$:



Relevance for phenomenology?

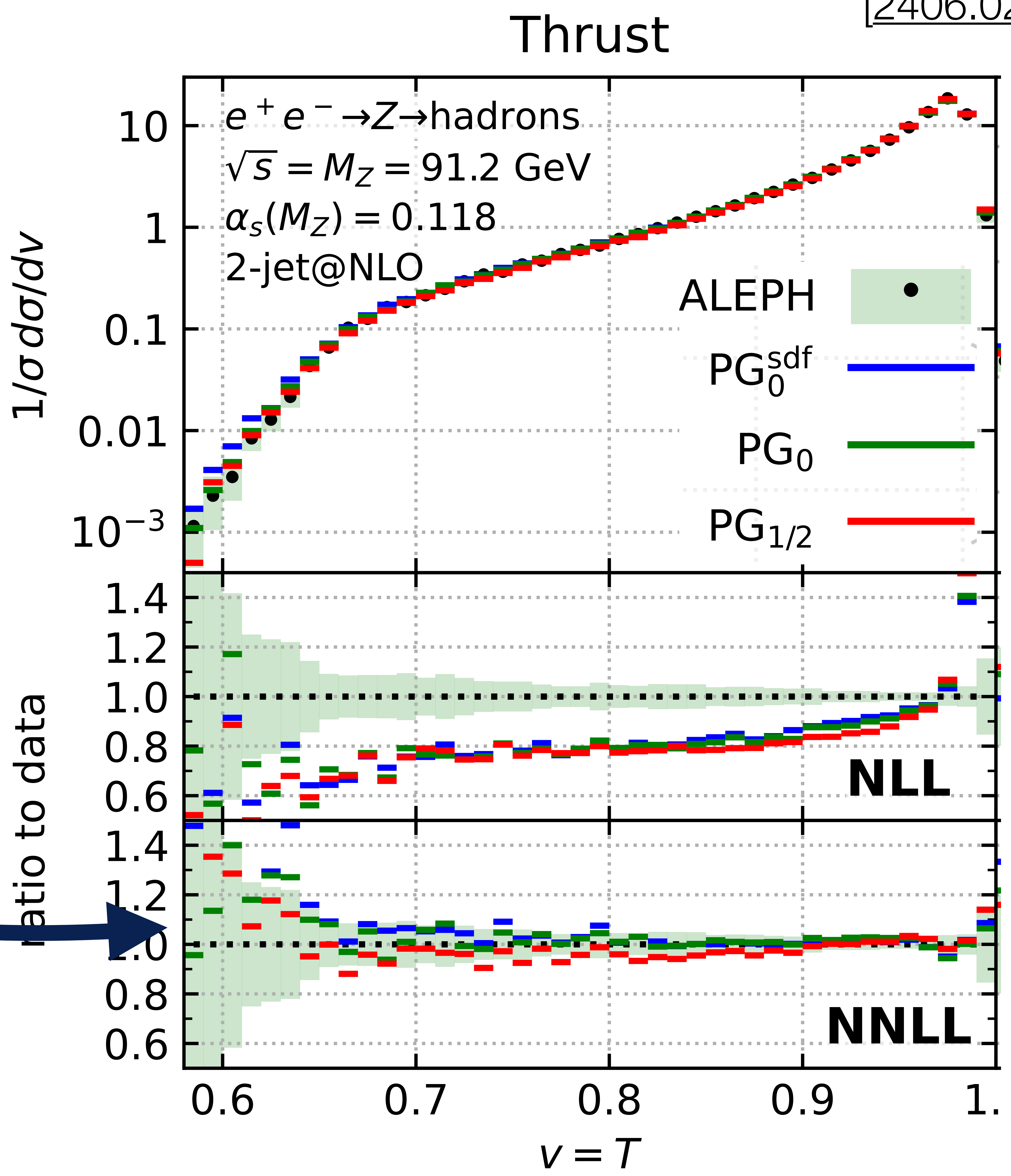
Longstanding discrepancy between true value of $\alpha_s(M_z) = 0.118$ and that needed to describe LEP data: $\alpha_s(M_z) = 0.1365$

Skands, Carrazza, Rojo [1404.5630]

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
- Same holds true for other LEP observables
- Caveat: NNLO corrections are missing, agreement in the 3-jet region may be 'lucky'

[2406.02661]

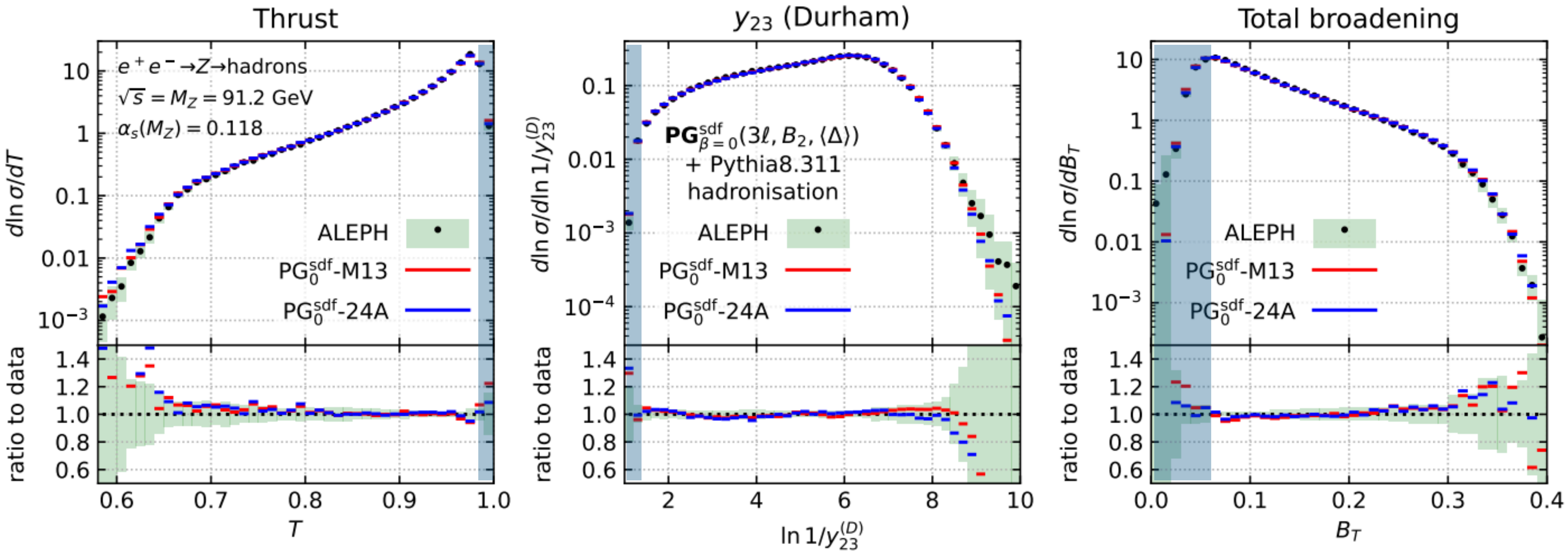


Pythia8.311 used for hadronisation
Rivet for comparison with LEP data

Do we still need to tune?

[2406.02661]

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



~ hadronisation region

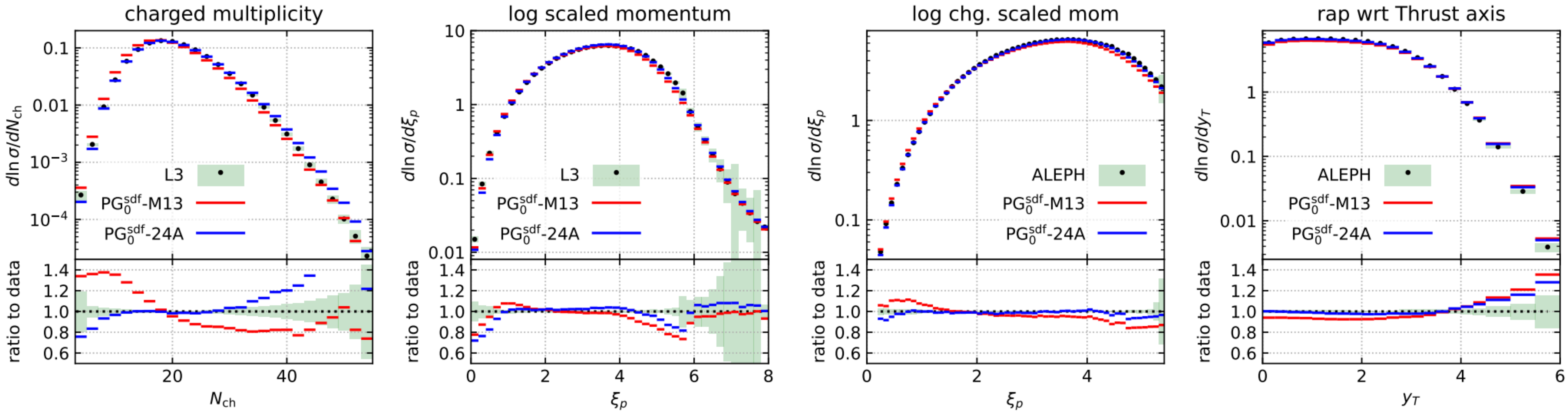
We see that the perturbative region is not much affected by the tune

M13: (almost) tune of [1404.5630]
24A: own tune

Do we still need to tune?

[2406.02661]

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



Infrared unsafe observables are affected (as expected)

Beta-version of public PanScales code is available (with Pythia8 interface)

we'd love to understand what you need (but we are not pheno ready)

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

Conclusions and open questions

- Parton showers will continue to play an indispensable role

- New NLL showers are popping up everywhere
  - Opens novel doors: matching N(N)LO to NLL showers

- Next big perturbative obstacle: NNLL showers
  - Achieved a big milestone: NNLL showers for e^+e^- collisions
    - So far only PanGlobal; spin corrections are not double-soft compatible (work in progress)
  - Still needed: triple-collinear corrections for e^+e^- (needed for jet-shape observables) and NNLL for pp and DIS (colour-singlet)

- Question of uncertainty is incredibly difficult without a handle on the accuracy → this now becomes a completely new game

- The other elephant in the room: how to get better control over non-perturbative corrections?