Overview of the PanScales showers

Pythia Week
2nd of May 2024

Melissa van Beekveld
Nikhef

The perturbative side of (QCD) showers

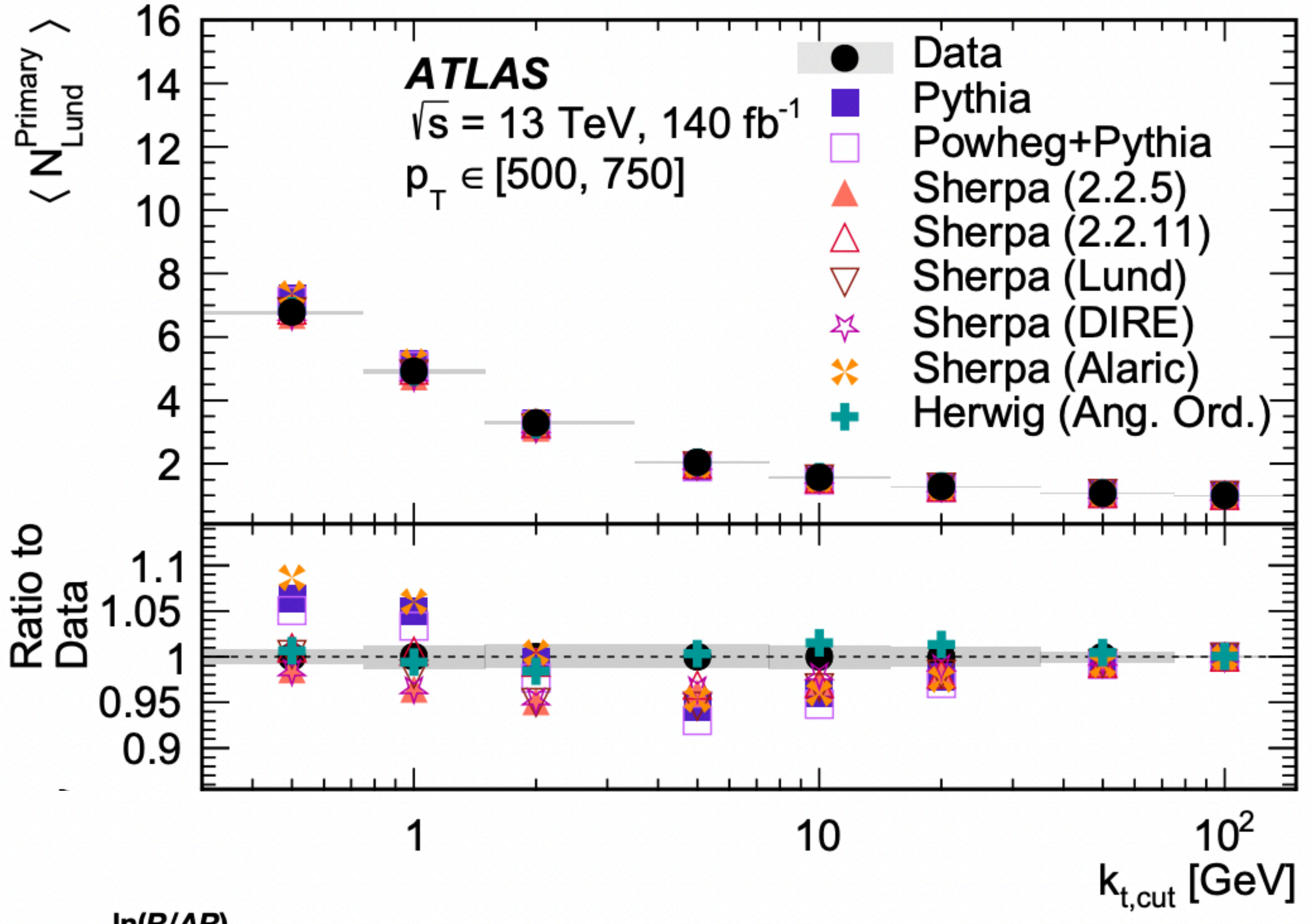
- Designed from first principles: its ingredients are QCD matrix elements (MEs) that describe the unresolved limits, possibly matched to higher-order corrections

- After integration over phase space these MEs give rise to logarithms - roughly:
  - Single unresolved (collinear / soft) → LL and NLL / SL / NDL
  - Double unresolved (triple collinear / double soft) → NNLL / NSL / NNDL

- Perturbative shower accuracy comes in two forms: higher-order matching and logarithmic accuracy

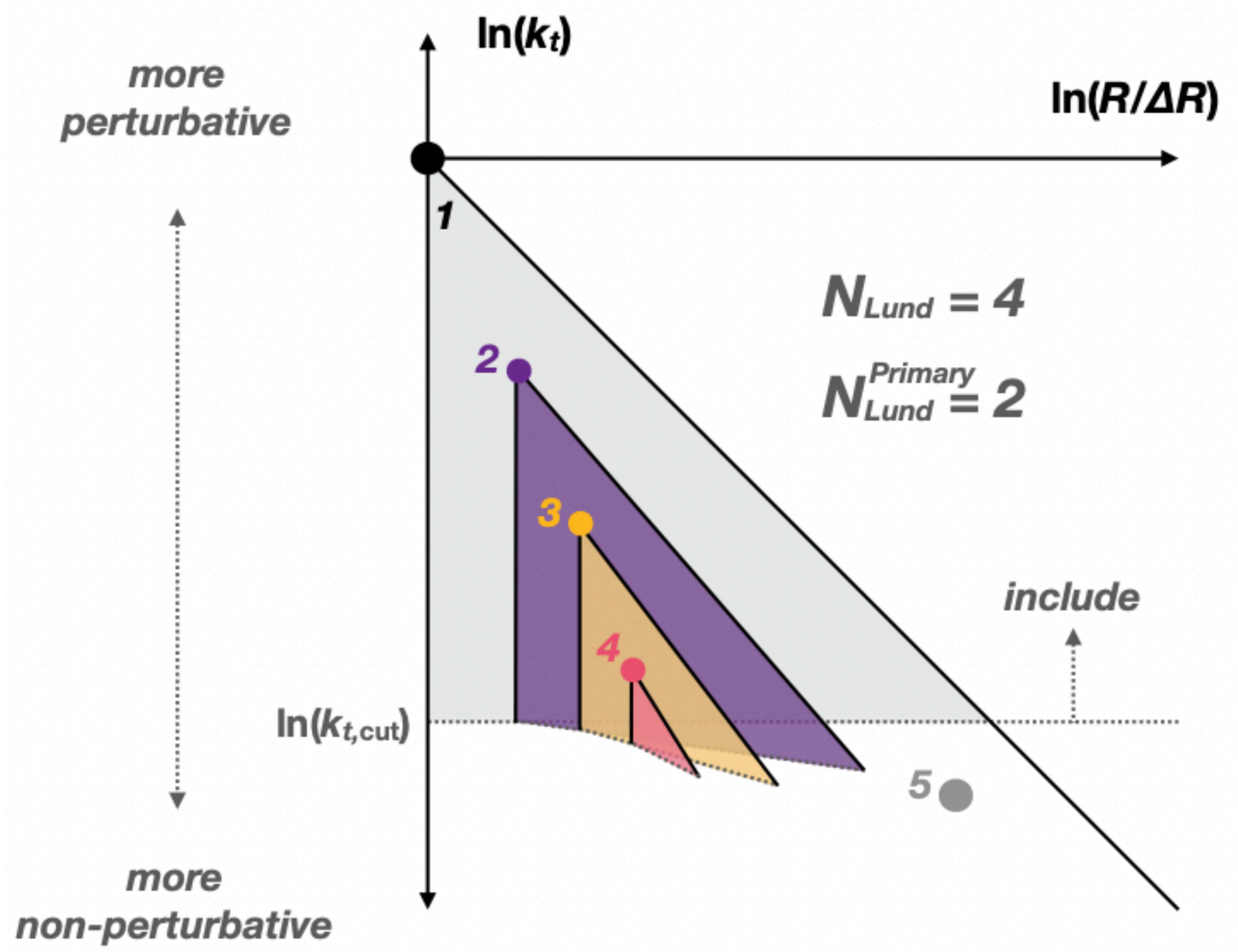
Why do we want a higher accuracy?

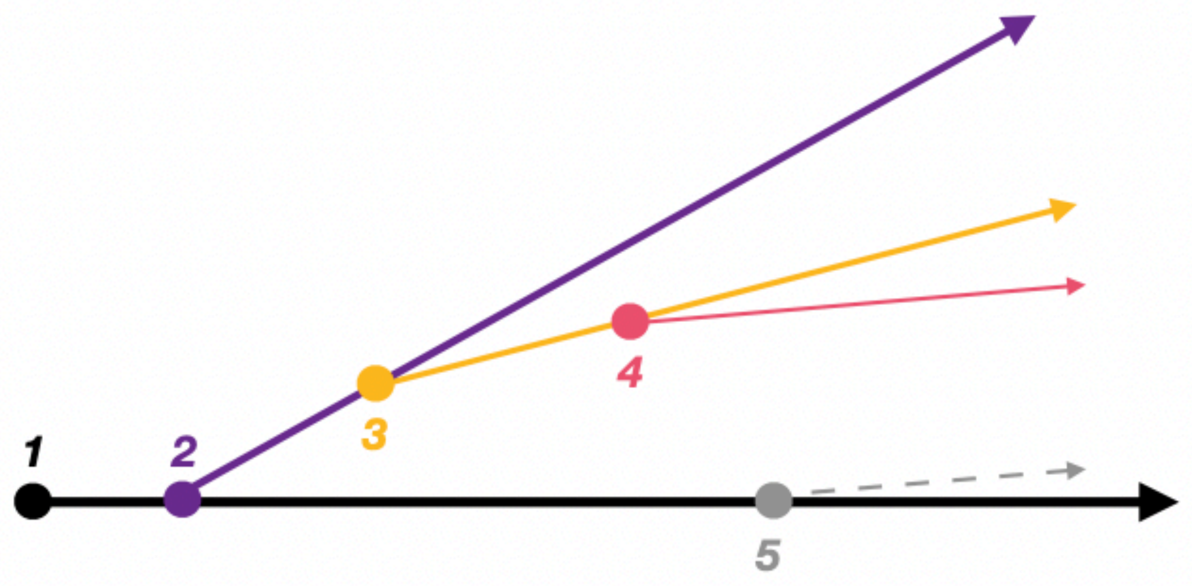
Measurement of Lund subjet multiplicity [2402.13052]



- We see differences between 1. different showers, and 2. showers vs data for several analyses
- As data allows for more and more exclusive analyses, e.g. using the information of jet substructures, we need to improve the theoretical description!

How to achieve a higher logarithmic accuracy?





The PanScales collaboration

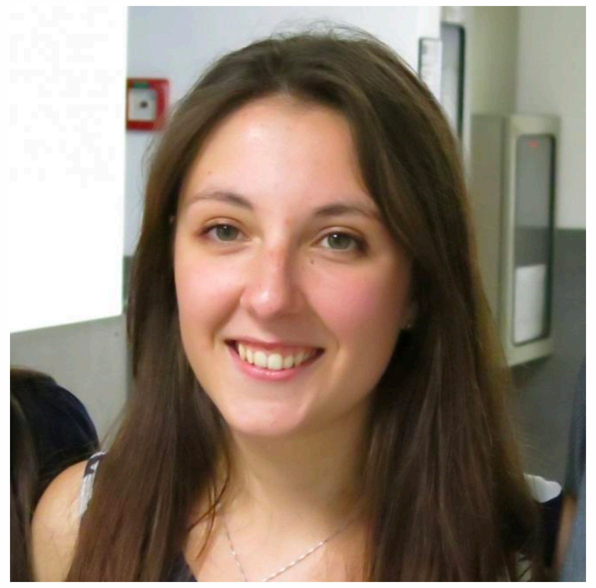

Gavin Salam


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

+ past members
Frederic Dreyer
Emma Slade
Rok Medves
Rob Verheyen

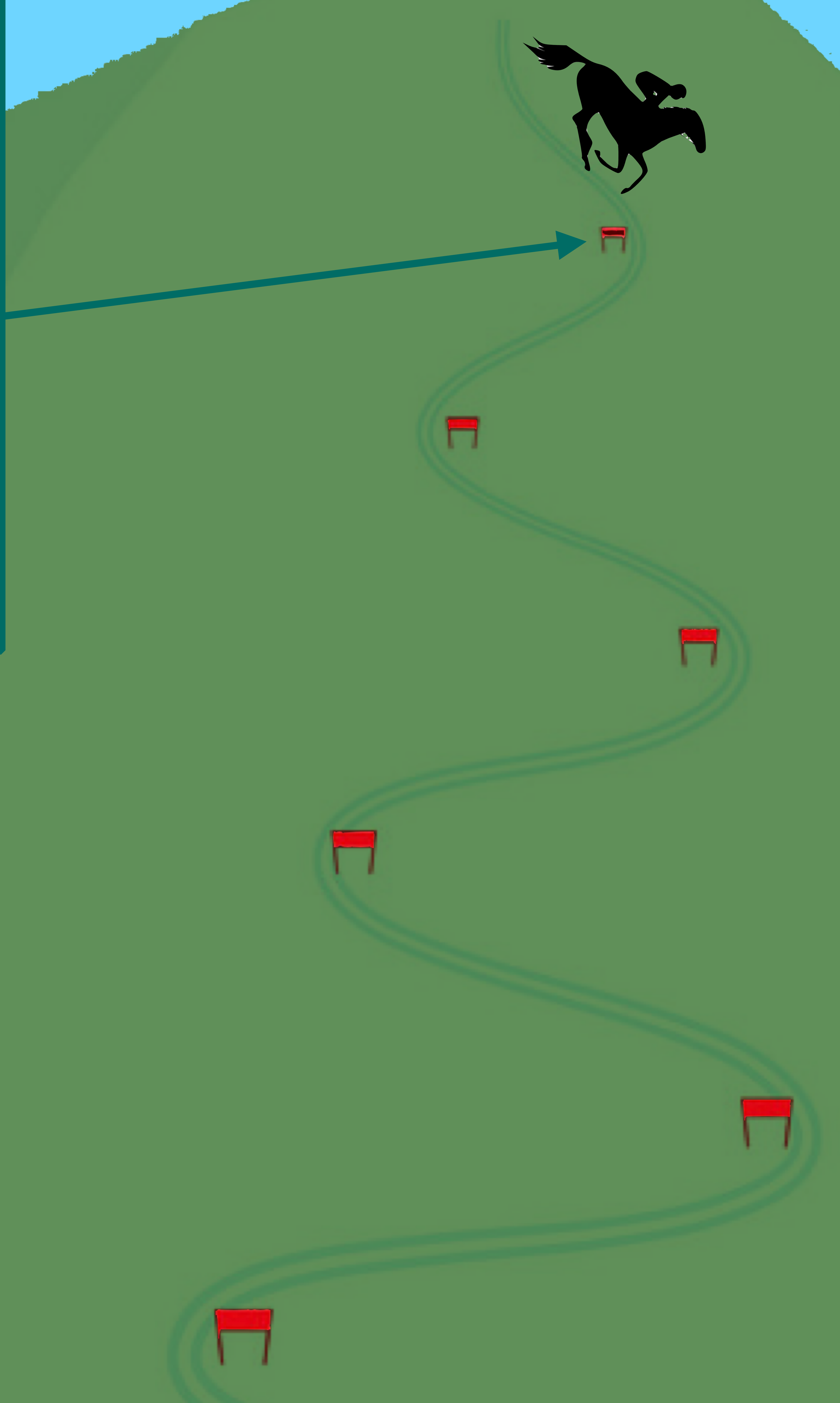
PanScales criteria for logarithmically accurate showers

- 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]

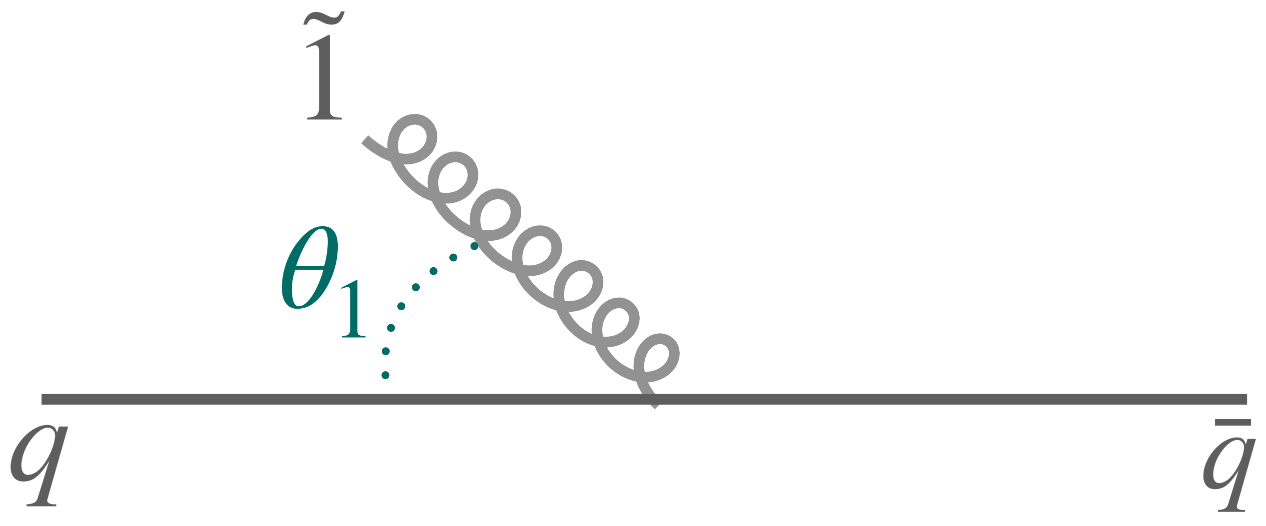
Design and test of NLL showers for $e^+e^- \to$ jets, $pp \to Z/h$, DIS

Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez [2002.11114]; Hamilton, Medves, Salam, Scyboz, Soyez [2011.10054]; Karlberg, Salam, Scyboz, Verheyen [2103.16526]; Karlberg, Hamilton, Salam, Scyboz, Verheyen [2111.01161]; MvB, Ferrario Ravasio, Salam, Soto Ontoso, Soyez, Verheyen [2205.02237]; MvB, Ferrario Ravasio, Hamilton, Salam, Soto Ontoso, Soyez, Verheyen [2207.09467]; MvB, Ferrario Ravasio [2305.08645]



What is the issue with standard dipole showers?

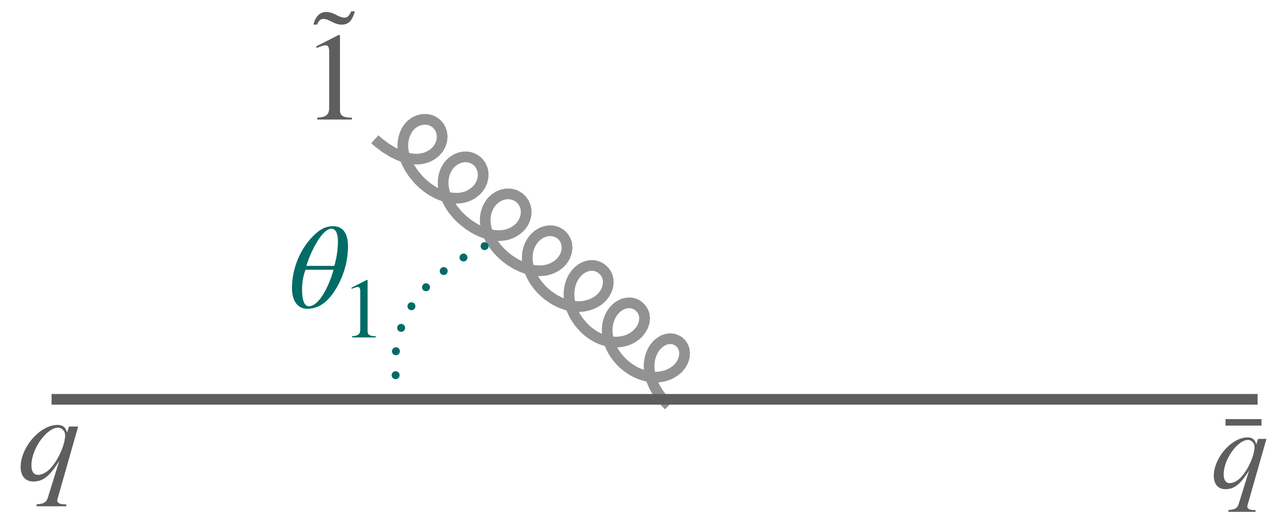
The shower must reproduce QCD: a factorised matrix element



$$dP_{q\to qg} \propto \frac{\alpha_s(k_t)C_F}{2\pi}\frac{\mathrm{d}k_{t1}^2}{k_{t1}^2}\frac{\mathrm{d}\theta_1}{\theta_1}$$

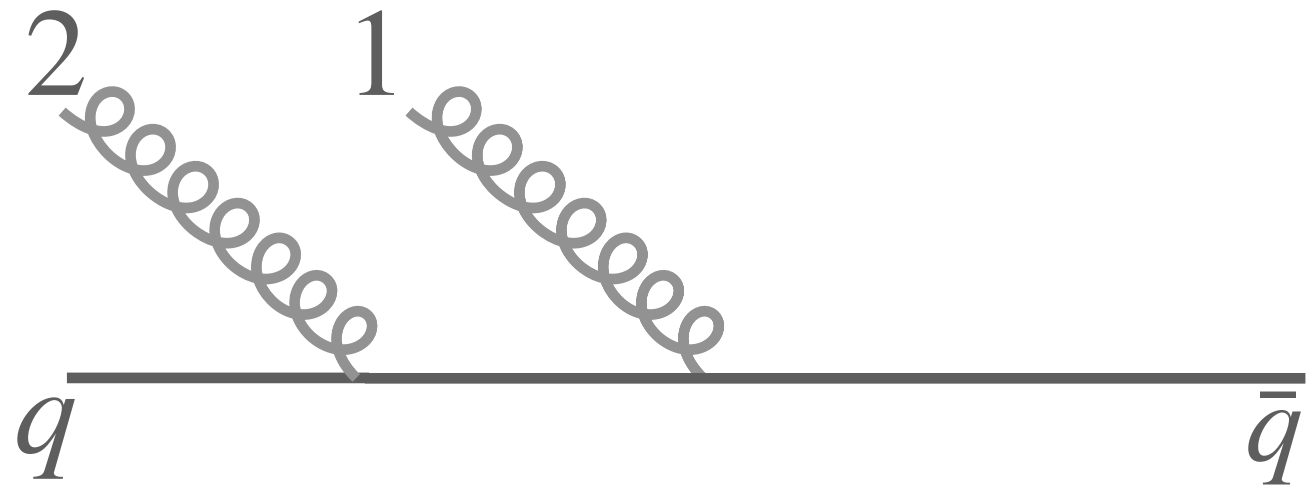
What is the issue with standard dipole showers?

The shower must reproduce QCD: a factorised matrix element



$$dP_{q\to qg} \propto \frac{\alpha_s(k_t)C_F}{2\pi}\frac{\mathrm{d}k_{t1}^2}{k_{t1}^2}\frac{\mathrm{d}\theta_1}{\theta_1}$$

QCD factorisation



$$dP_{q\to qgg} \propto \frac{\alpha_s(k_{t1})C_F}{2\pi}\frac{\mathrm{d}k_{t1}^2}{k_{t1}^2}\frac{\mathrm{d}\theta_1}{\theta_1} \times \frac{\alpha_s(k_{t2})C_F}{2\pi}\frac{\mathrm{d}k_{t2}^2}{k_{t2}^2}\frac{\mathrm{d}\theta_2}{\theta_2}$$

Achieved if 2 takes the recoil from q (only then $k_{t1} = \tilde{k}_{t1}$, $\theta_1 = \theta_{\tilde{1}}$)

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

Recoil in standard dipole showers

Evolution variable v
Which emissions come first?

→ Transverse-momentum ordering

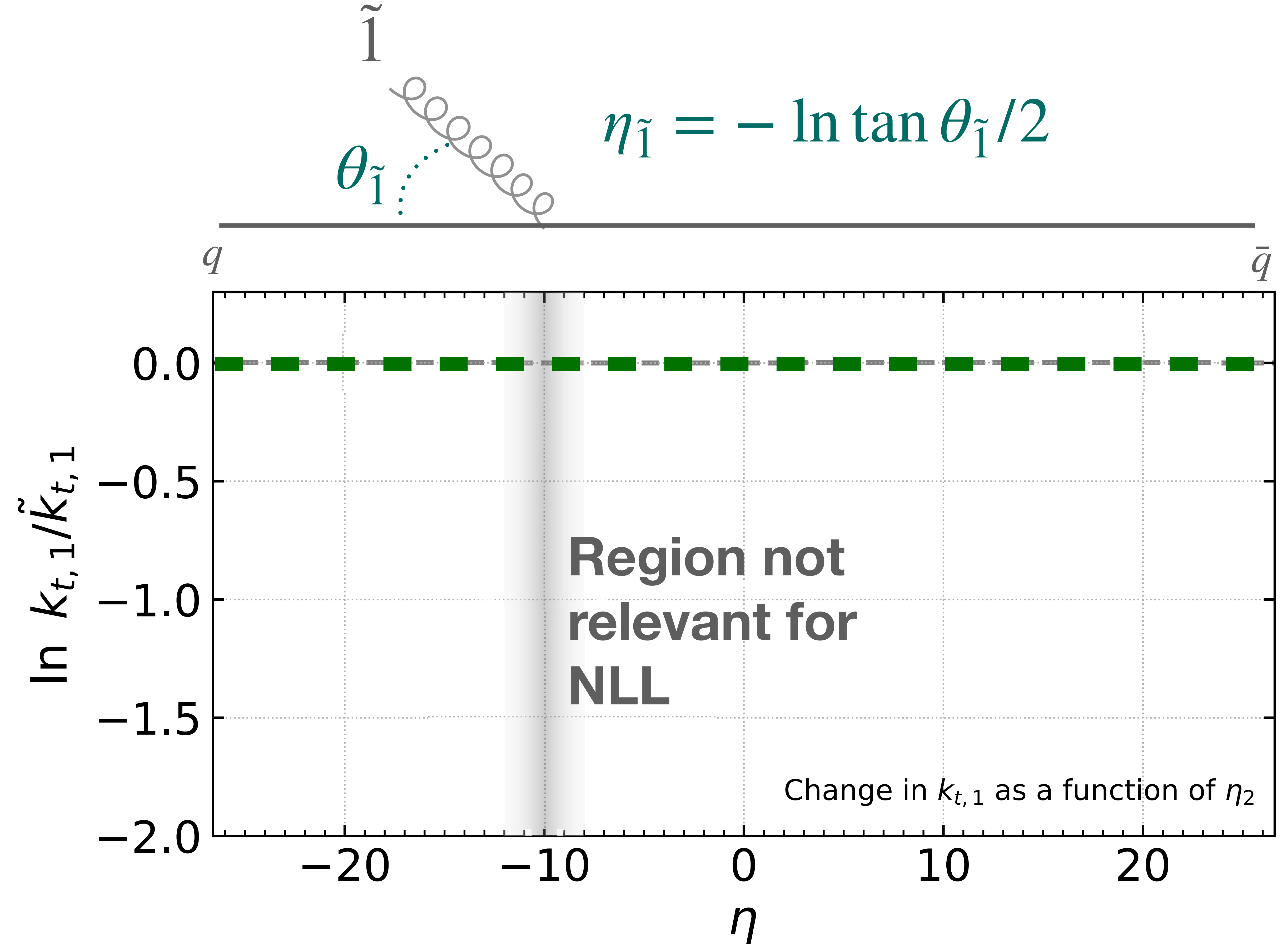
Kinematic map
How to go from n to $n+1$ partonic state?

→ Dipole-local, with one parton absorbing the recoil

Dipole partitioning
How to select an ‘emitter’?

→ Partitioning done at zero rapidity in the dipole rest frame

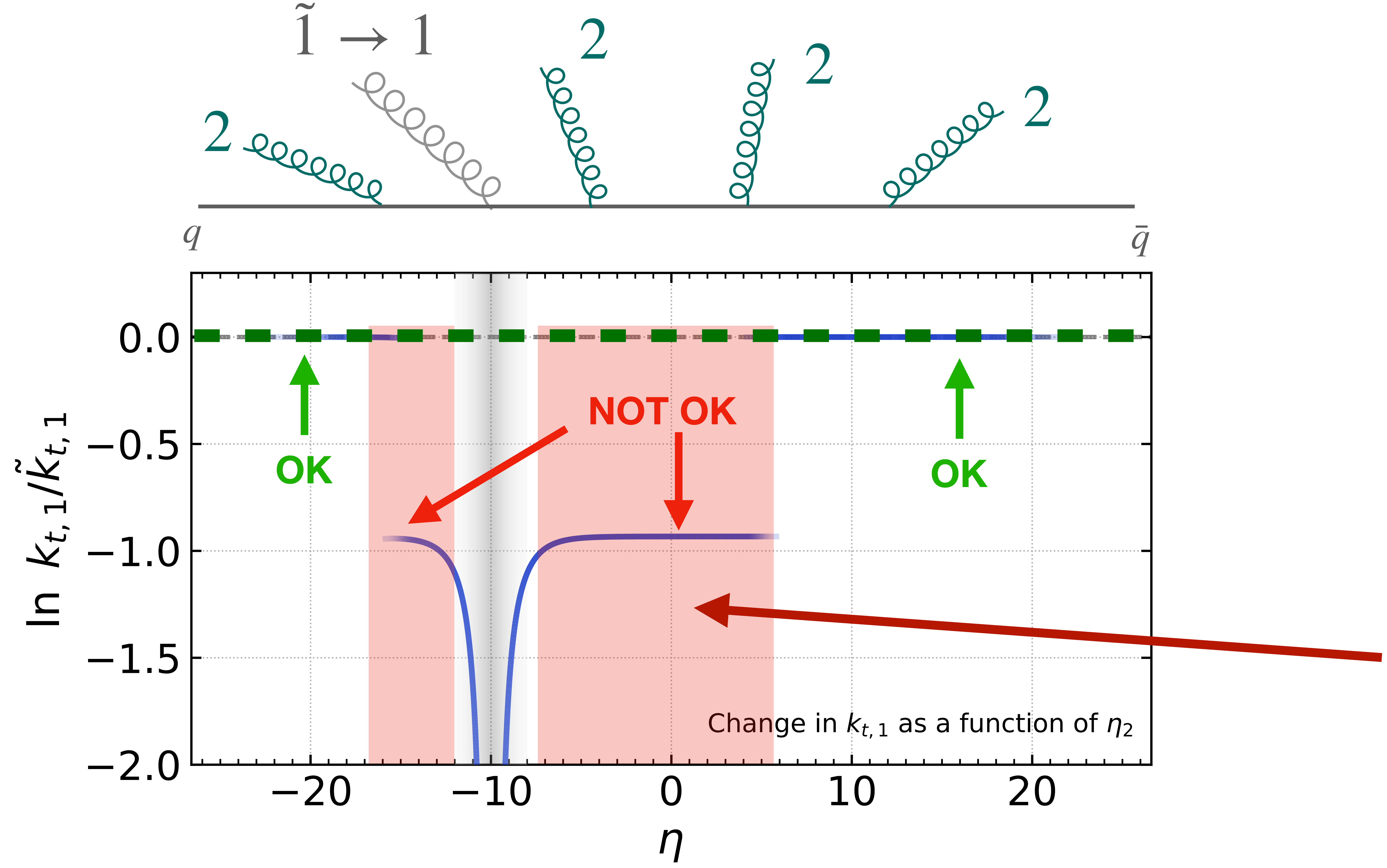
Fixed order criterion



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



Region where the 1st emission recoils:
$\vec{k}_{t,1} \to \vec{k}_{t,1} - \vec{k}_{t,2}$

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

Clear violation of this criterion

[2002.11114, 2207.09467, 2305.08645]

Choices in the PanScales showers

PanGlobal

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

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

3. Attribution of recoil
   Dipole midpoint in *hard-system* CM frame

PanLocal

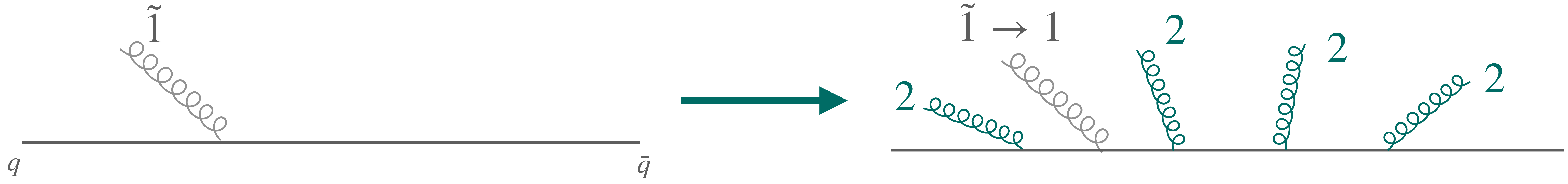
1. Evolution variable
   $v \sim k_t\sqrt{\theta}$ ($\beta_{\rm ps} = 1/2$)

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

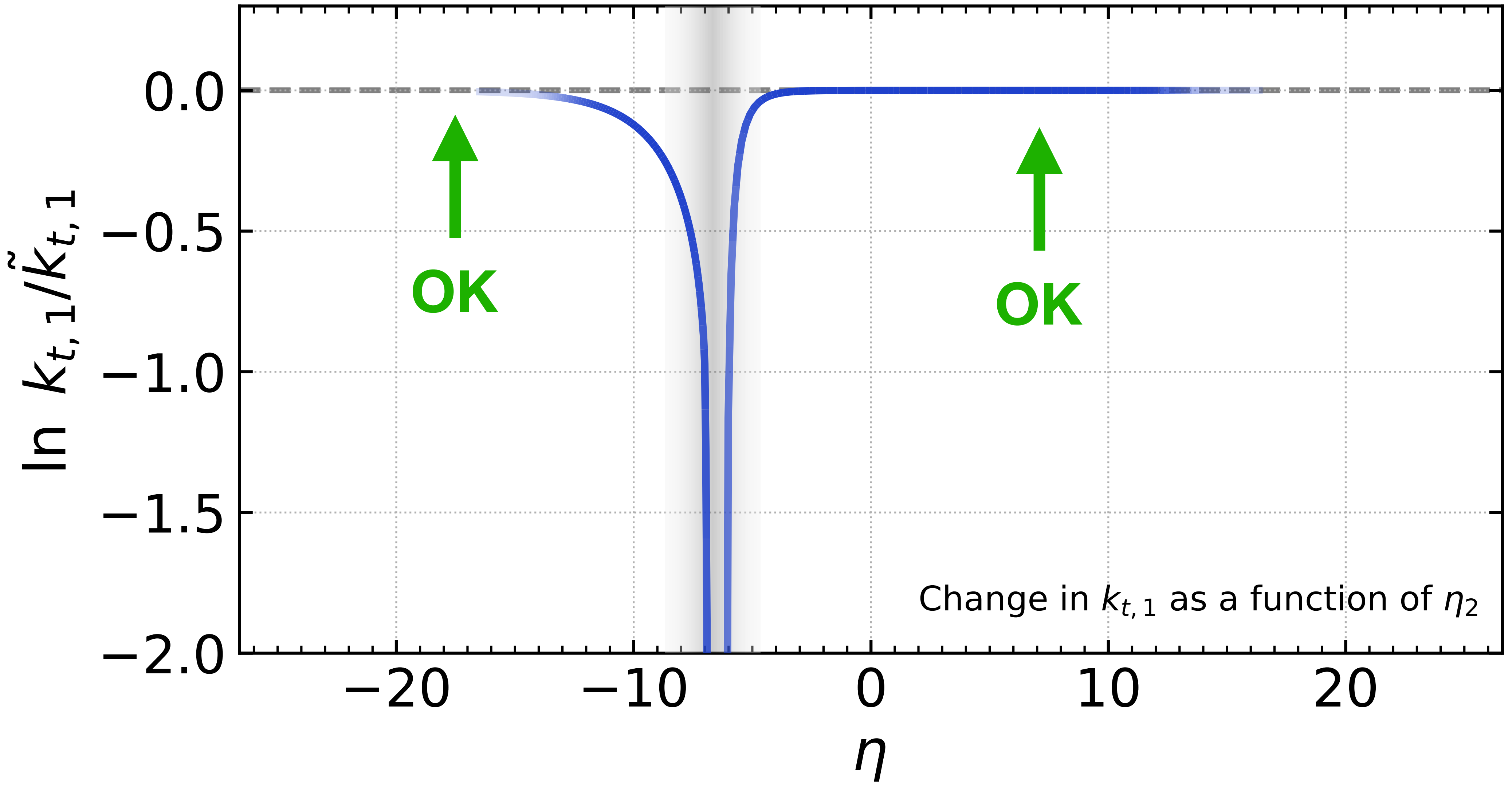
3. Attribution of recoil
   Dipole midpoint in *hard-system* CM frame

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

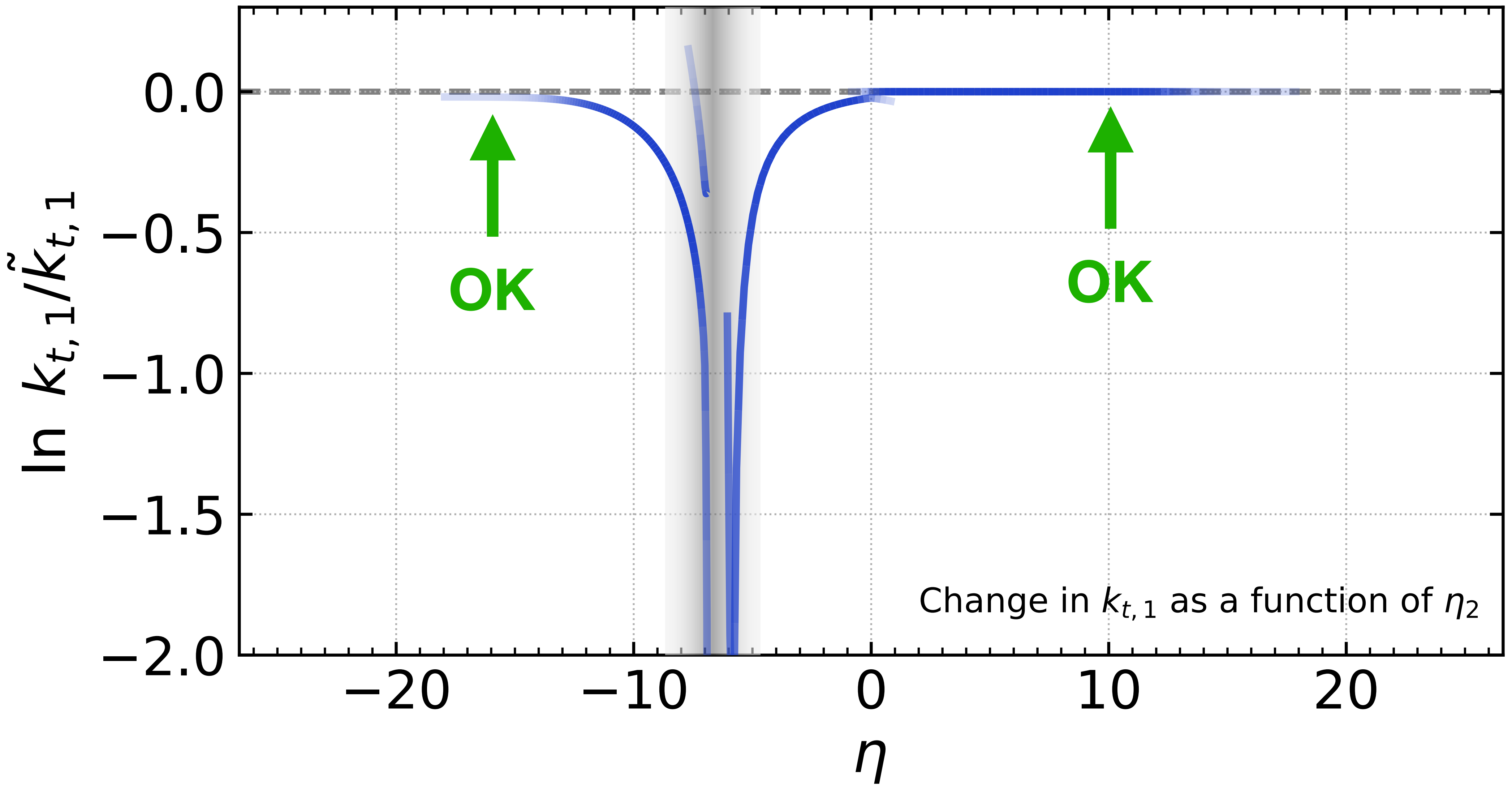
Fixed-order criterion



PanGlobal



PanLocal

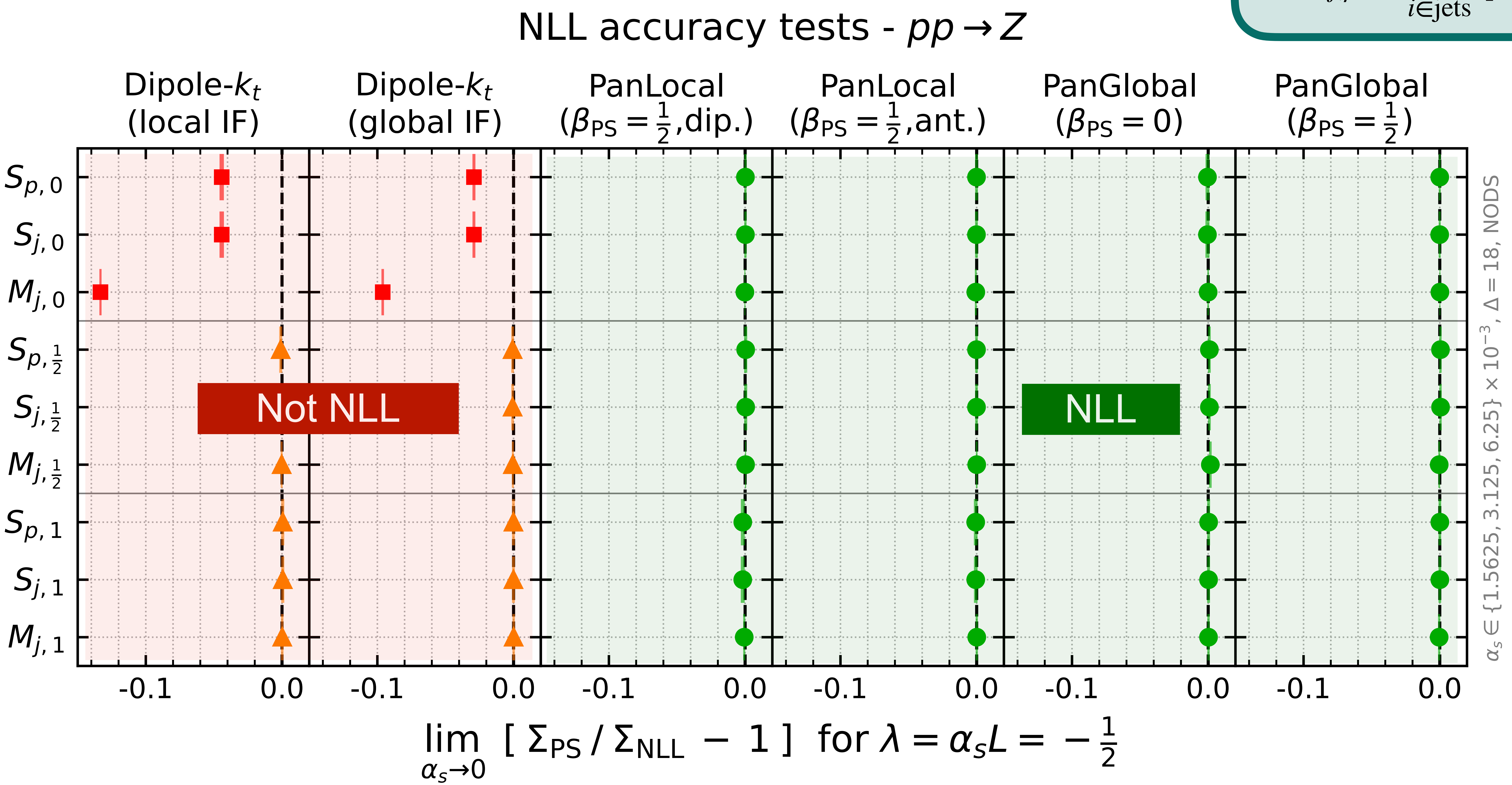


These showers meet the fixed-order criterion

Global observables

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

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



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

NLO matching: NNDL event-shapes for $e^+e^- \to$ jets

Hamilton, Karlberg, Salam, Scyboz, Verheyen [2301.09645]

[2301.09645]

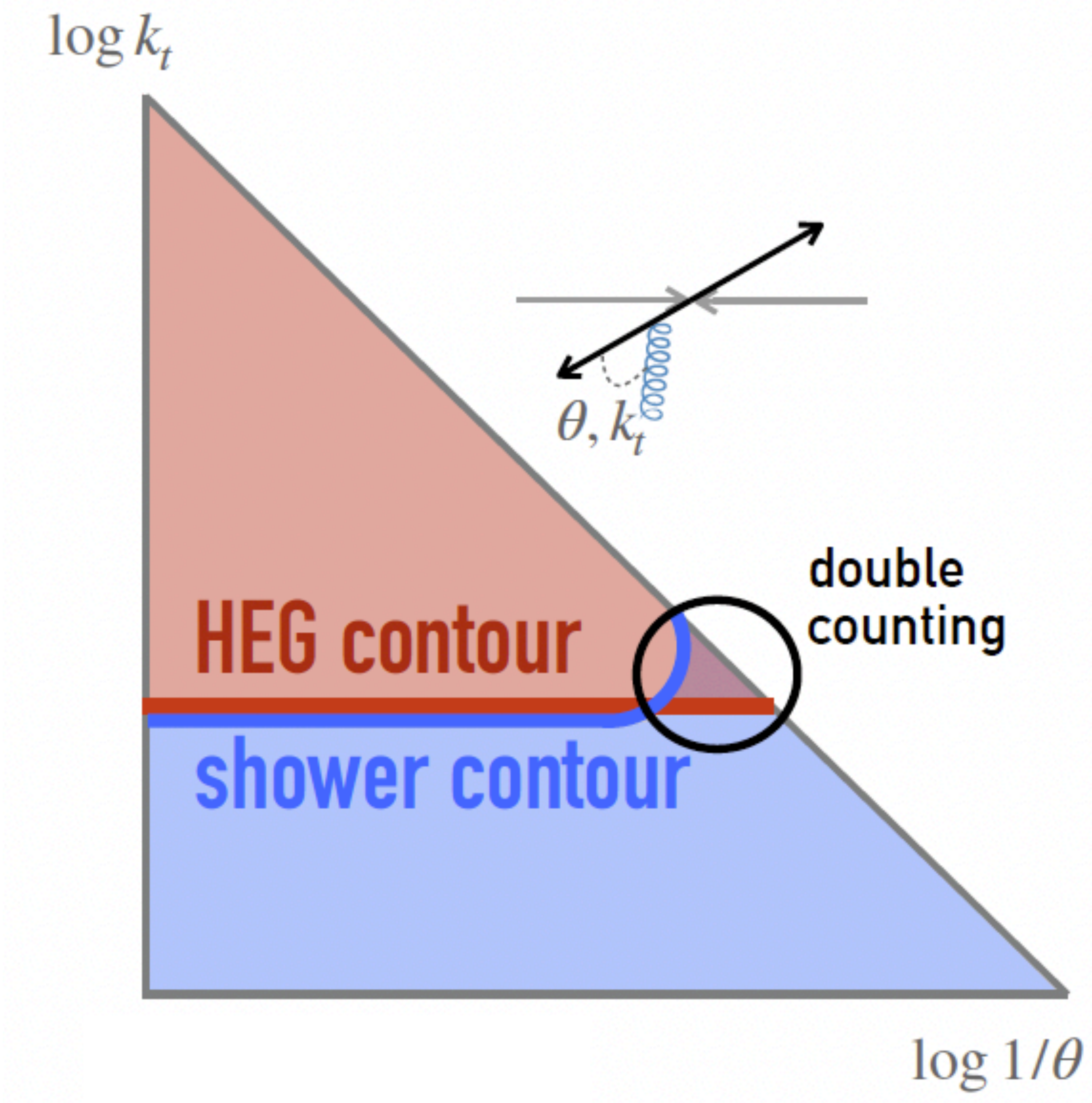
Going beyond NLL: What about matching?

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



‘R&D’ work used to test the showers

Dasgupta, El-Menoufi [2109.07496]; Medves, Soto Ontoso, Soyez [2205.02861, 2212.05076]; Banfi, Dreyer, Monni [2104.06416, 2111.02413], MvB, Dasgupta, El-Menoufi, Helliwell, Monni [2307.15734] same + Karlberg [2402.05170]

NSL/NNDL for soft-dominated observables in $e^+e^- \rightarrow$ jets

- The first major step towards general NNLL accuracy for parton showers
- Requires implementation of the double-soft real ME's and a correct treatment of the virtual correction

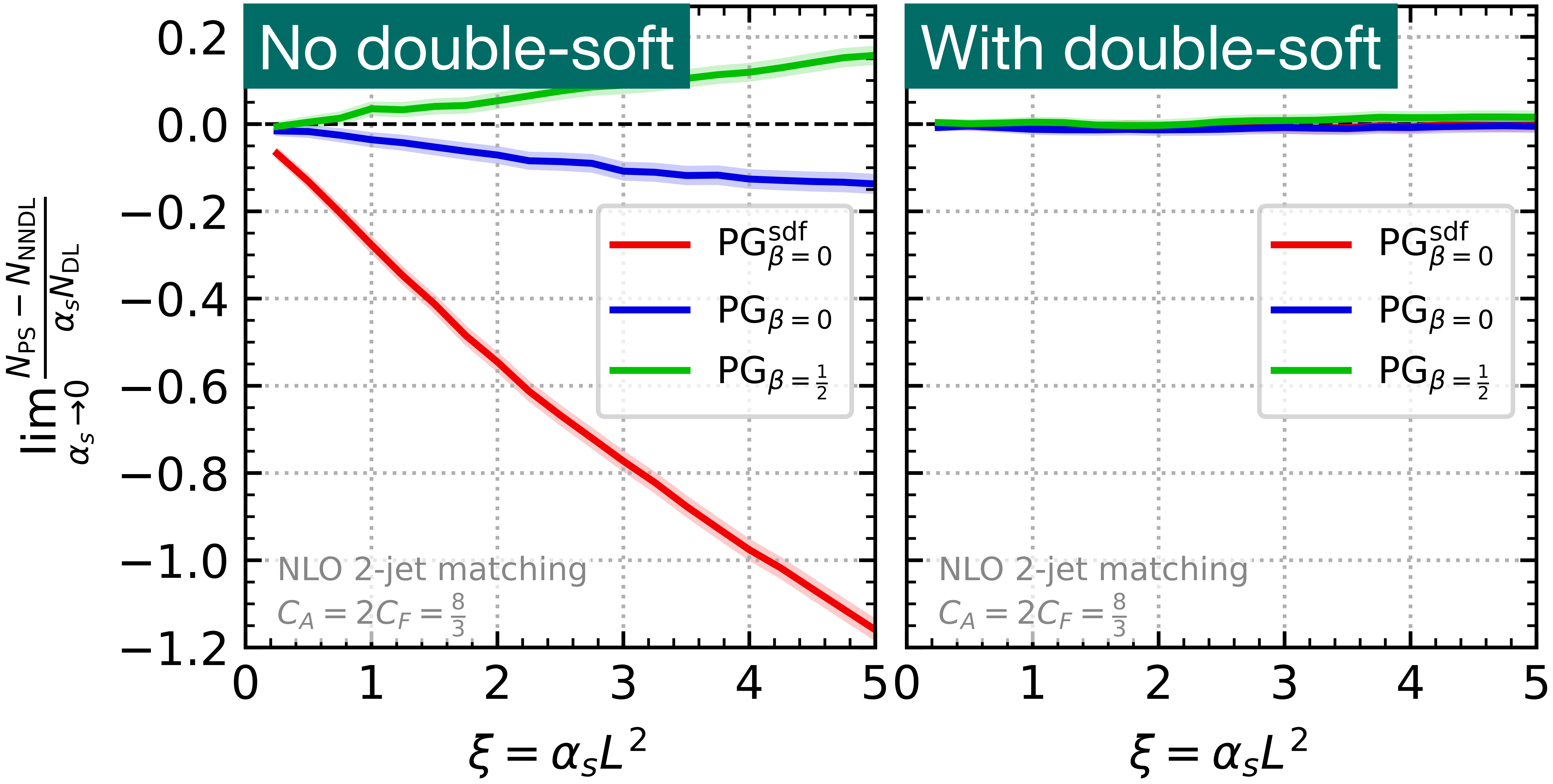
Ferrario Ravasio, Hamilton, Karlberg, Salam, Scyboz, Soyez [2307.11142]

NSL/NNDL for soft-dominated observables in $e^+e^- \to$ jets

- The first major step towards general NNLL accuracy for parton showers
- Requires implementation of the double-soft real ME's and a correct treatment of the virtual correction

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

Log test 1: NNDL Lund subjet multiplicity



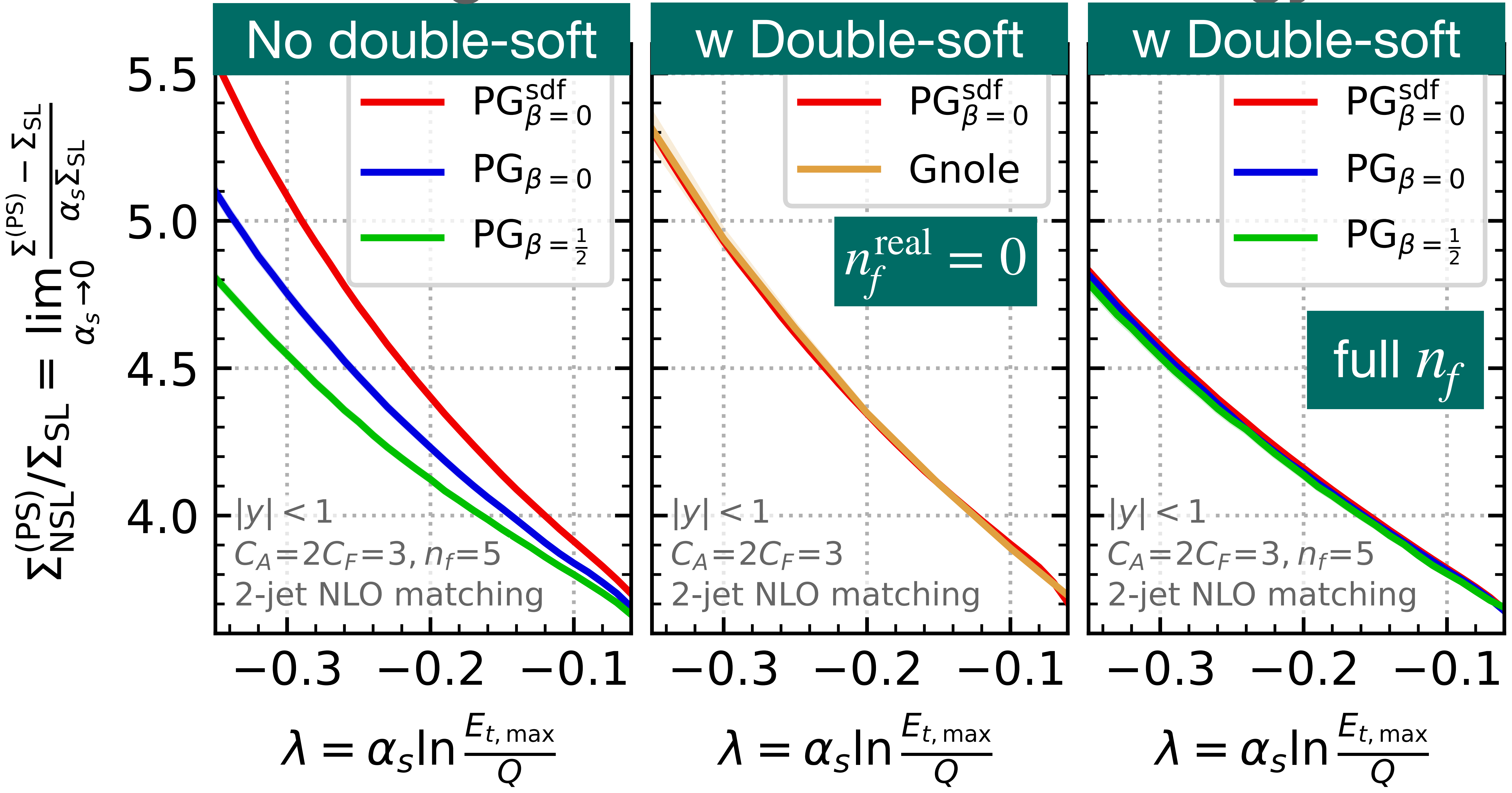
Compared to Medves, Soto Ontoso, Soyez [2212.05076]

NSL/NNDL for soft-dominated observables in $e^+e^- \to$ jets

- The first major step towards general NNLL accuracy for parton showers
- Requires implementation of the double-soft real ME's and a correct treatment of the virtual correction

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

Log test 2: NSL for the energy flow in a slice



Compared to Gnole: Banfi, Dreyer, Monni [2104.06416]

See also Becher, Schalch, Xu [2307.02283]

First large-N_c full n_f results for non-global logs at NSL

Release of PanScales 0.1

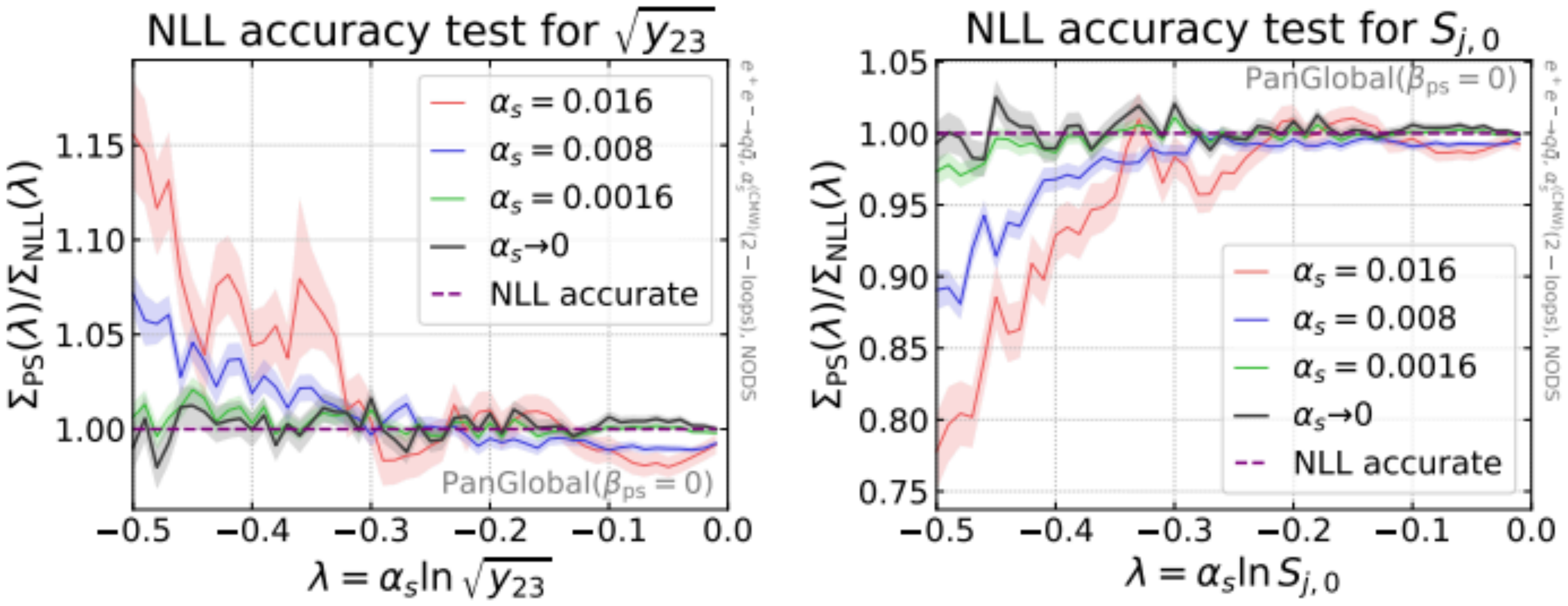
Code available on git

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

Panscales [2312.13275]

1. Log tests in under 2 minutes using 8 cores of my M1*

We provide scripts that automate tests of NLL accuracy of (non)global event-shapes and multiplicity with full colour and spin-correlations



*O(1-2%) accurate for $\beta_{obs} = \beta_{ps}$

Release of PanScales 0.1

Code available on git

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

Panscales [2312.13275]

2. Interface to Pythia 8

Use the functionality of Pythia (e.g. LO process generation, hadronisation) with our showers

n.b. our showers are not tuned and miss higher-order matching, so we do not encourage usage for pheno just yet…

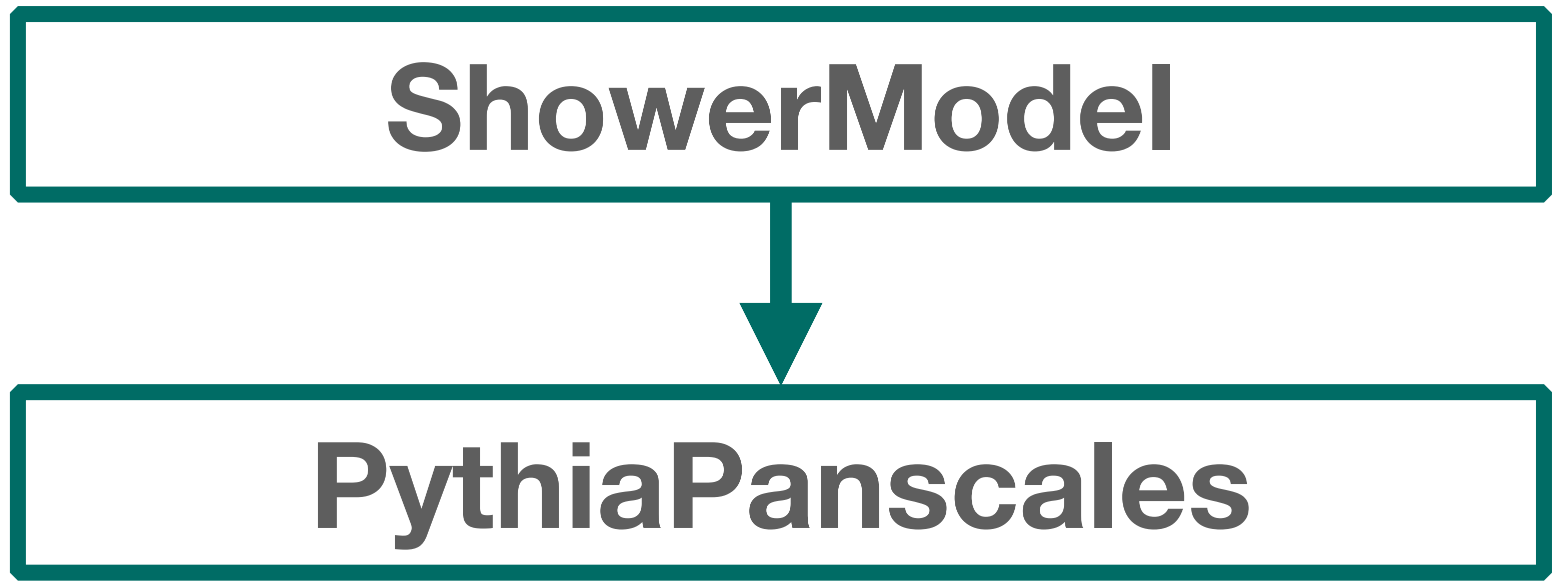
Release of PanScales 0.1

Code available on git

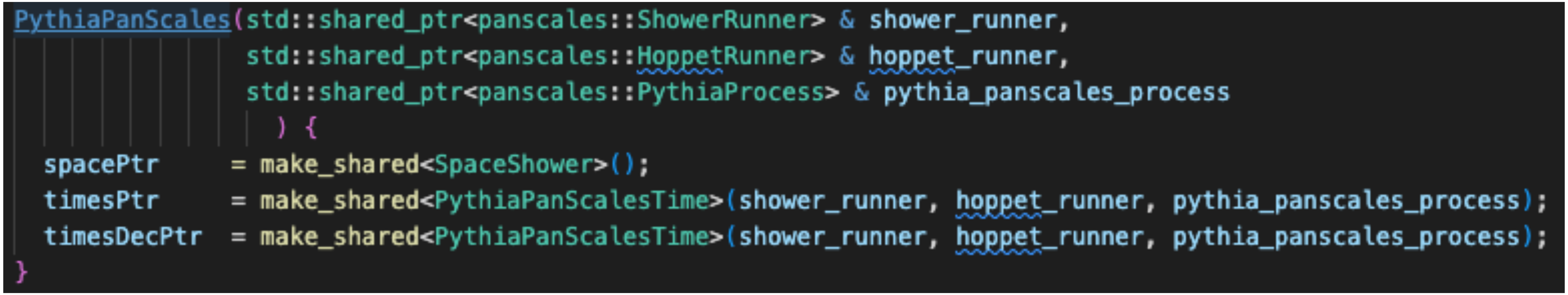
```
git clone https://gitlab.com/panscales/panscales-0.X
```

Panscales [2312.13275]

Pythia interface


ShowerModel

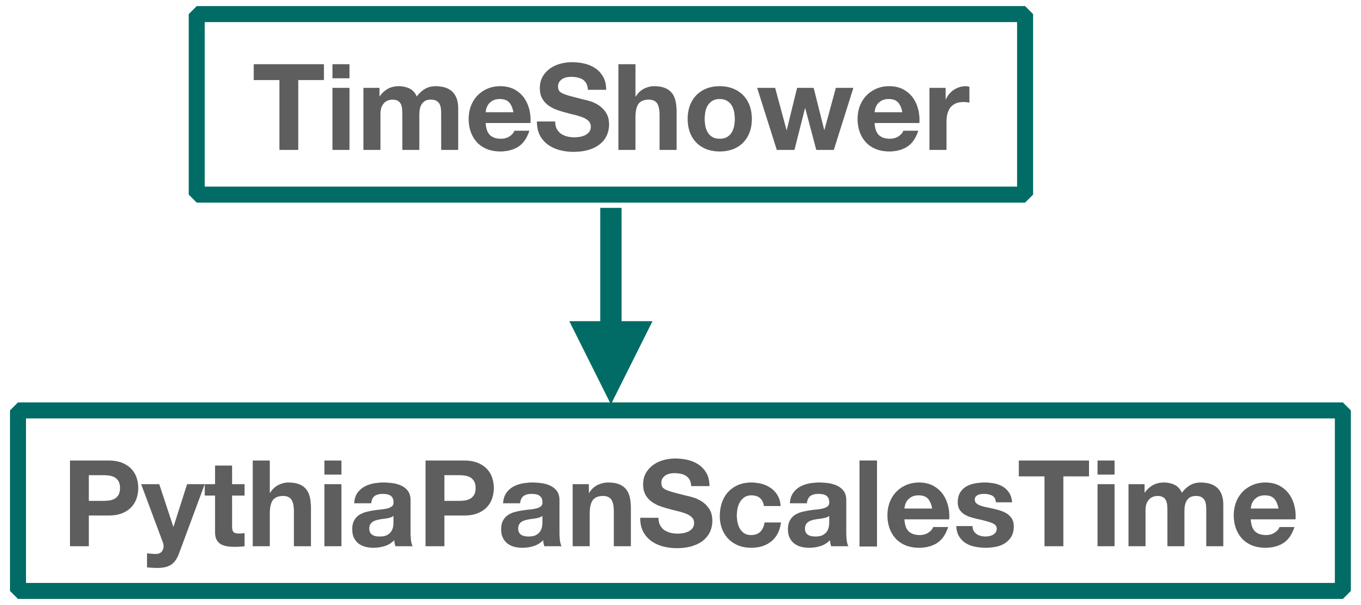
PythiaPanscales


```
PythiaPanScales(std::shared_ptr<panscales::ShowerRunner> & shower_runner,
                std::shared_ptr<panscales::HoppetRunner> & hoppet_runner,
                std::shared_ptr<panscales::PythiaProcess> & pythia_panscales_process
                  ) {
  spacePtr     = make_shared<SpaceShower>();
  timesPtr     = make_shared<PythiaPanScalesTime>(shower_runner, hoppet_runner, pythia_panscales_process);
  timesDecPtr  = make_shared<PythiaPanScalesTime>(shower_runner, hoppet_runner, pythia_panscales_process);
}
```

Note: we use the same shower for the ‘times’ and ‘decay’ shower pointer, and do not use a space shower (initial-state radiation is handled internally in the time shower)

Question: will this cause any issues on the pythia side?

Pythia interface



TimeShower

PythiaPanScalesTime

init(…)

- Sets parton masses to 0
- Initialises core shower class (ShowerRunner), the shower, helpers

prepare(…)

- Copies over the hard event to a PanScales event
- Resets ShowerRunner

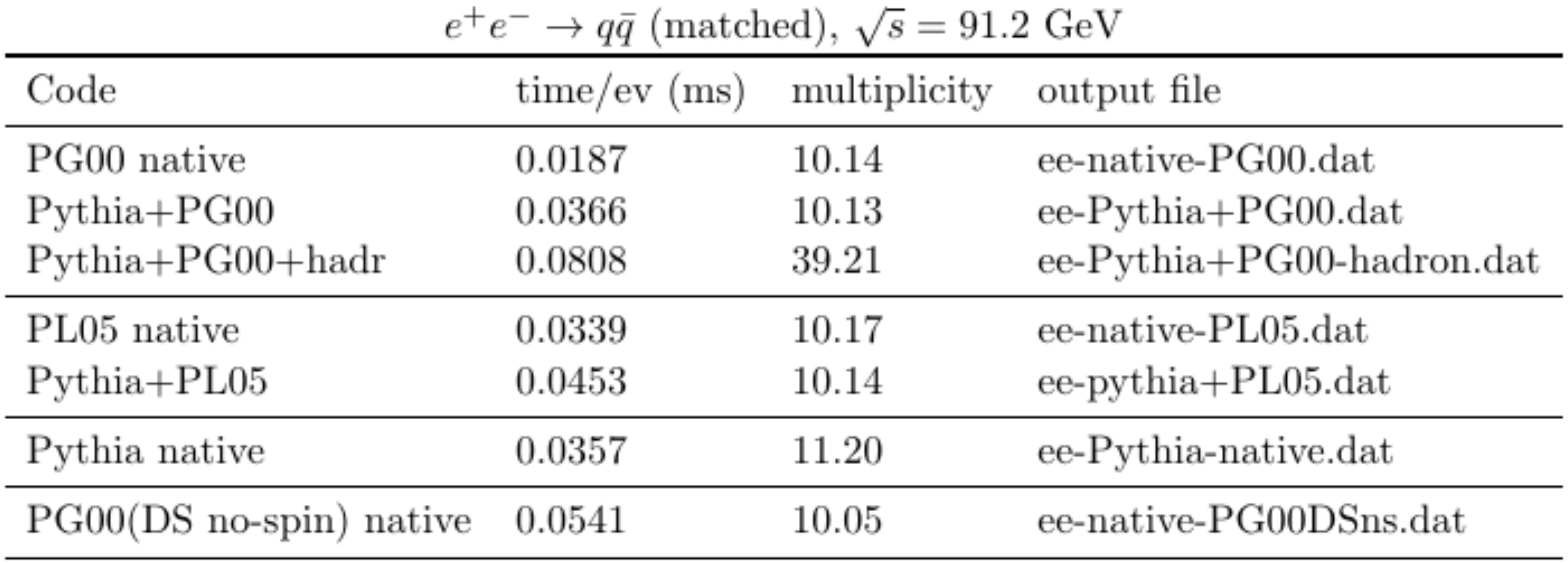
pTnext(…)

- Calls ShowerRunner to give a ‘pt’ (plus selects a dipole + emitter)

branch(…)

- Computes acceptance and if allowed, adds new particle
- Updates pythia event from panscales event update
    - Sets colour indices
    - Sets mother-daughter relations
    - Updates the momenta that were touched by making copies
    - Updates beams & parton system

Pythia interface



$e^+e^- \to q\bar{q}$ (matched), $\sqrt{s} = 91.2$ GeV

Code	time/ev (ms)	multiplicity	output file
PG00 native	0.0187	10.14	ee-native-PG00.dat
Pythia+PG00	0.0366	10.13	ee-Pythia+PG00.dat
Pythia+PG00+hadr	0.0808	39.21	ee-Pythia+PG00-hadron.dat
PL05 native	0.0339	10.17	ee-native-PL05.dat
Pythia+PL05	0.0453	10.14	ee-pythia+PL05.dat
Pythia native	0.0357	11.20	ee-Pythia-native.dat
PG00(DS no-spin) native	0.0541	10.05	ee-native-PG00DSns.dat

branch(…)

- Computes acceptance and if allowed, adds new particle
- Updates pythia event from panscales event update
    - Sets colour indices
    - Sets mother-daughter relations
    - Updates the momenta that were touched by making copies
    - Updates beams & parton system

This means we store two sets of events: one inside pythia and one inside panscales, which is not ideal

MPI

- Currently we do not support MPI
- The technology on our side is more-or-less there (except that for storing seperate event systems)
- Unclear to us: what does Pythia need in terms of initialisation & updates for the MPI systems
- Currently, turning on MPI gives infinite dijet cross sections when using LHAPDF

Can you point us to a place where initialisation is done properly?

How do you communicate the change in available proton momentum? (beam system?)

What does the ‘global’ flag mean for time showers in the MPI context?

3. Implement your own shower

Want to test your own shower-algorithm on NLL accuracy?
The class `ShowerUserDefined` should get you started!

Release of PanScales 0.1

Code available on git

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

Panscales [2312.13275]

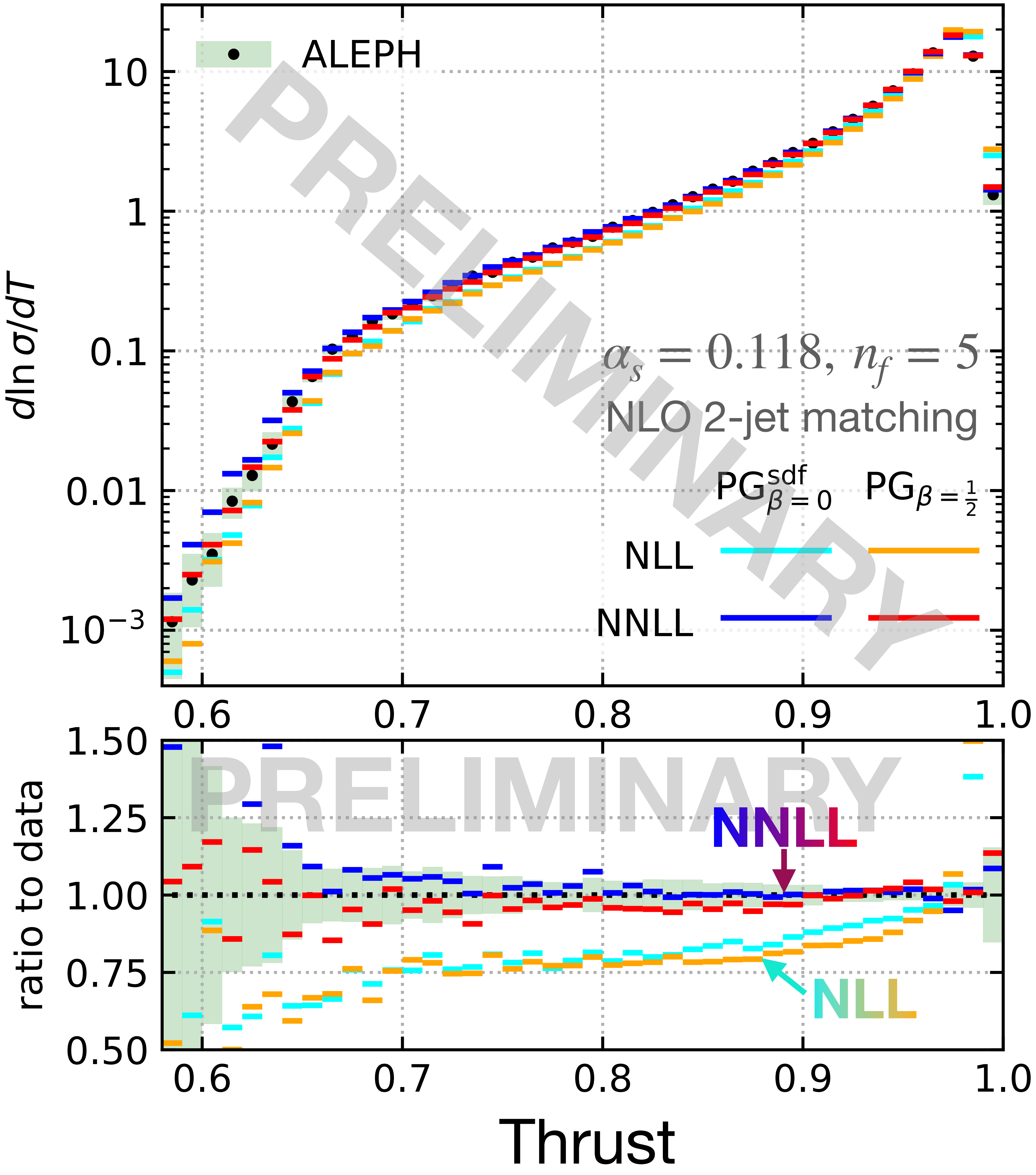
NNLL for global event shapes

- Second major step towards getting NNLL: NNLL for global event shapes in $e^+e^- \to$ jets

- Phenomenological studies show that **NNLL** brings a large correction with respect to the **NLL** baseline

- To be careful with:
  1. We have not mapped out the full set of uncertainties: plots may look different for different showers
  2. Absent 3-jet NLO corrections are relevant as $T \to 0.5$

Panscales [240X.XXXXX]



NLL for $e^+e^- \rightarrow$ jets, $pp \rightarrow Z/h$, DIS

NNDL event-shapes for $e^+e^- \rightarrow$ jets

R&D for the NNLL goal

NSL/NNDL for soft-dominated observables in $e^+e^- \rightarrow$ jets

Release of PanScales 0.1

NNLL for global event shapes

Outlook

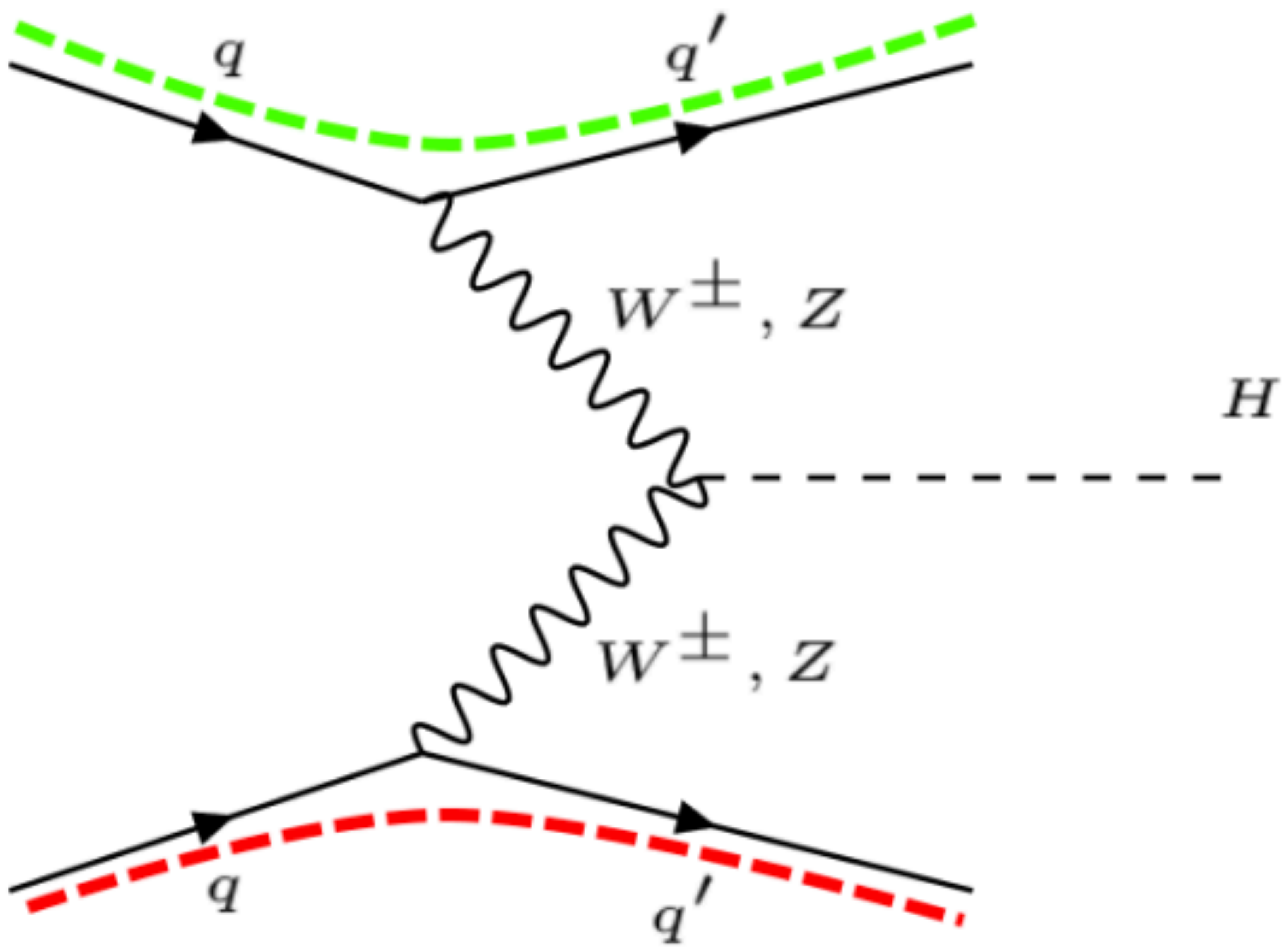
- Full NNLL for e^+e^-, pp and DIS
- Applicability for phenomenology, including consistent NLO matching, correct MPI handling…

Backup

[2003.12435, 2105.11399, 2106.10987]

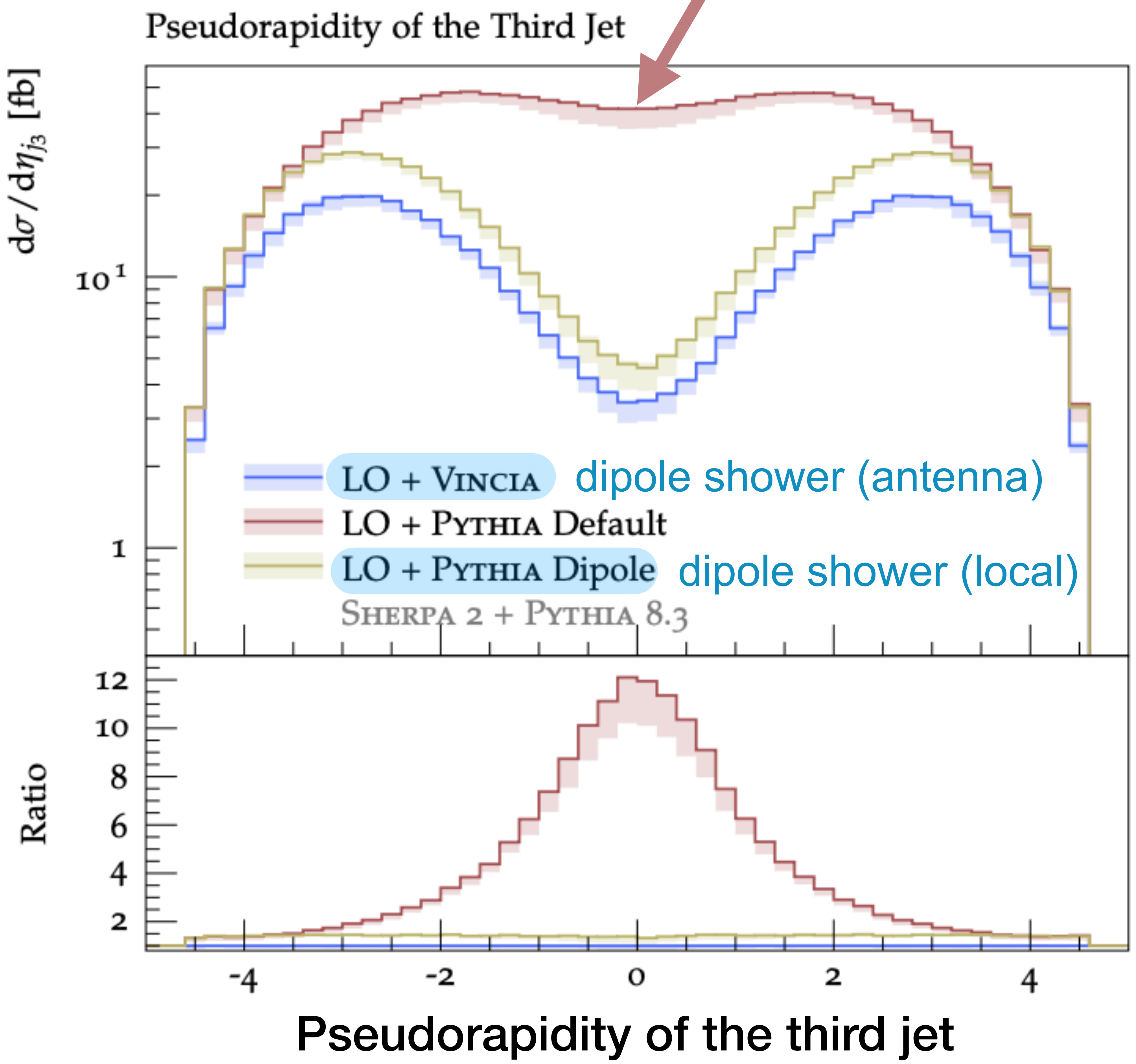
VBF recoil issue

VBF production of $h + 2j$



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

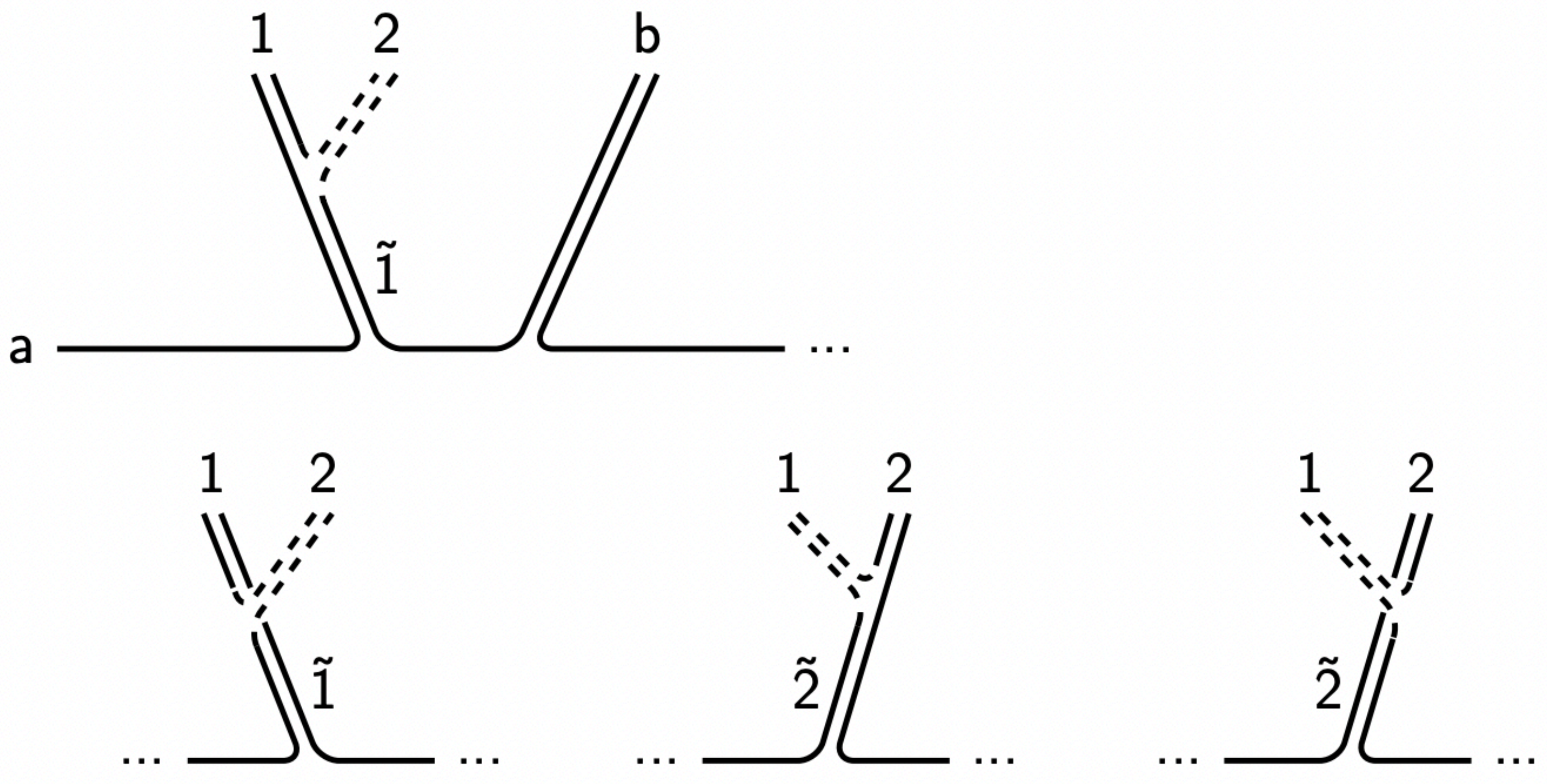
Pythia's default (global) shower unphysically fills this central region!



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

Double-soft corrections - real corrections

A given set of momenta [a,1,2,b] could have originated from several underlying shower histories



Get the correct kinematics: accept the last emission (2) with probability

$$P_{\text{accept}} = \frac{|M_{\text{DS}}|^2}{\sum_h |M_{\text{shower},h}|^2}$$

→ Double-soft ME

→ Sum over shower histories

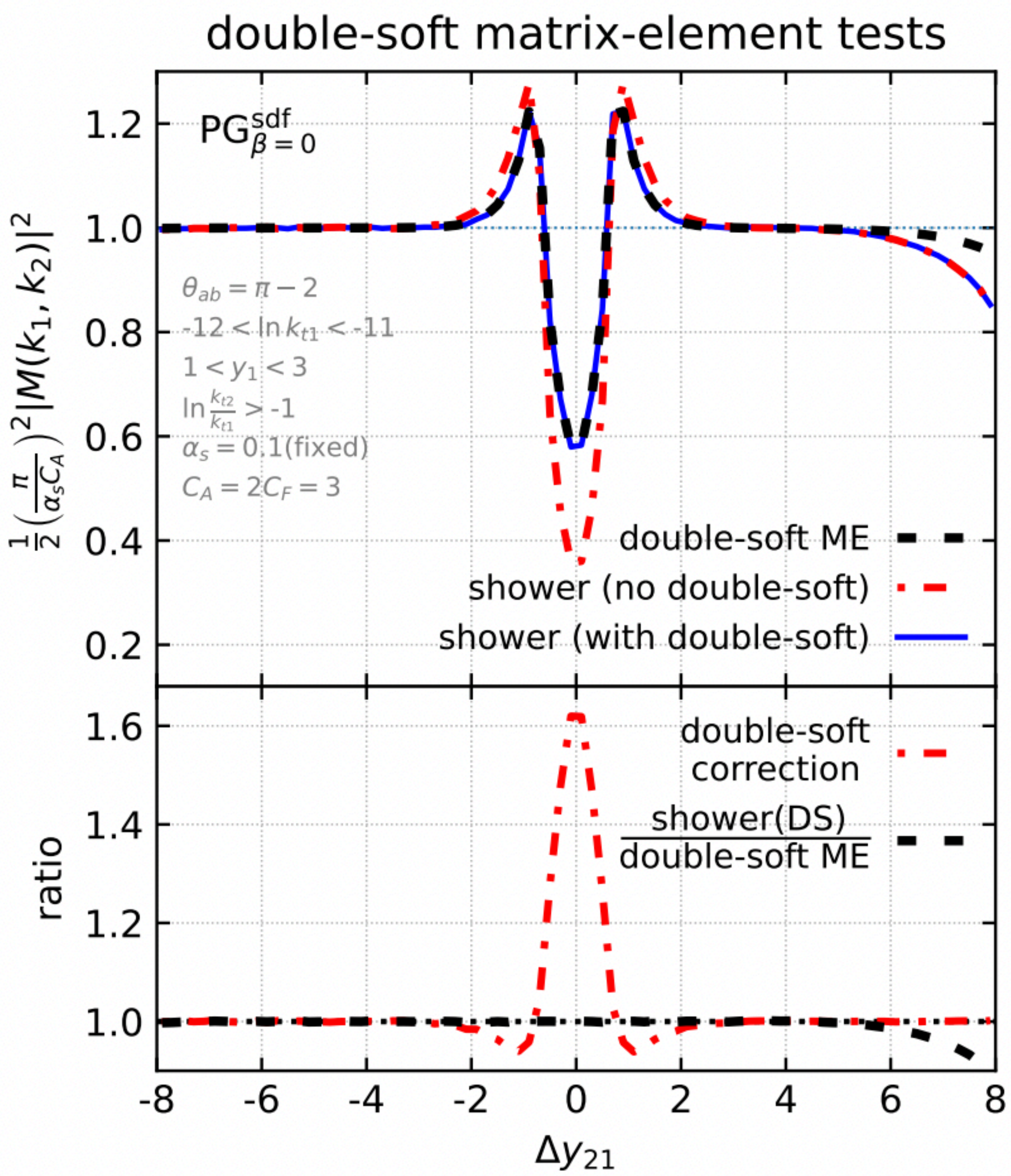
Get the correct colour connections (a12b vs a21b) and gg vs qqbar splittings swap the colour / identities according to the probability

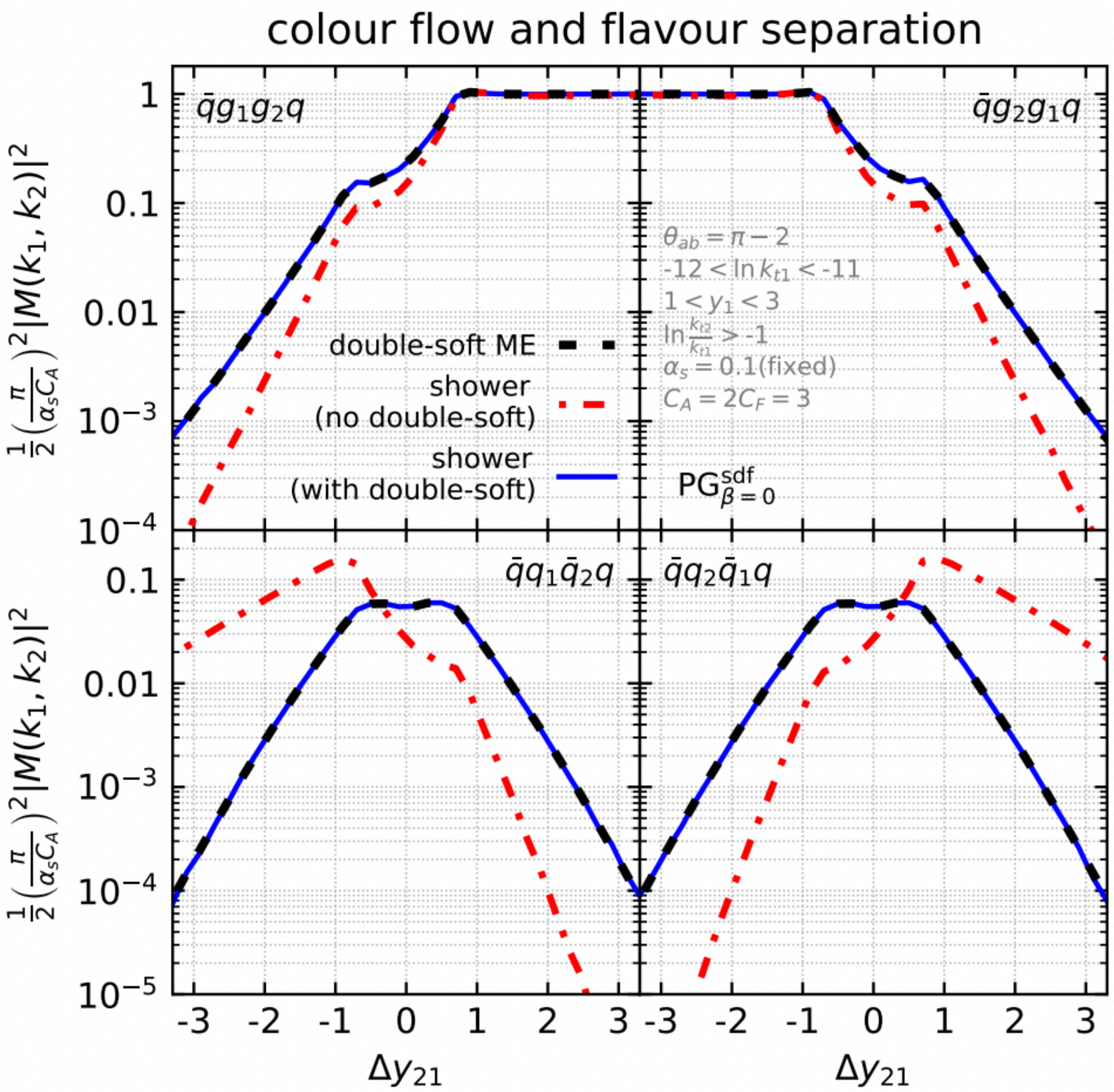
$$P_{\text{swap}} = \frac{F^{(12)}_{\text{shower}} - F^{(12)}_{\text{DS}}}{F^{(12)}_{\text{shower}}}$$

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

Double-soft corrections - real corrections

Matrix element tests for the real emissions


double-soft matrix-element tests

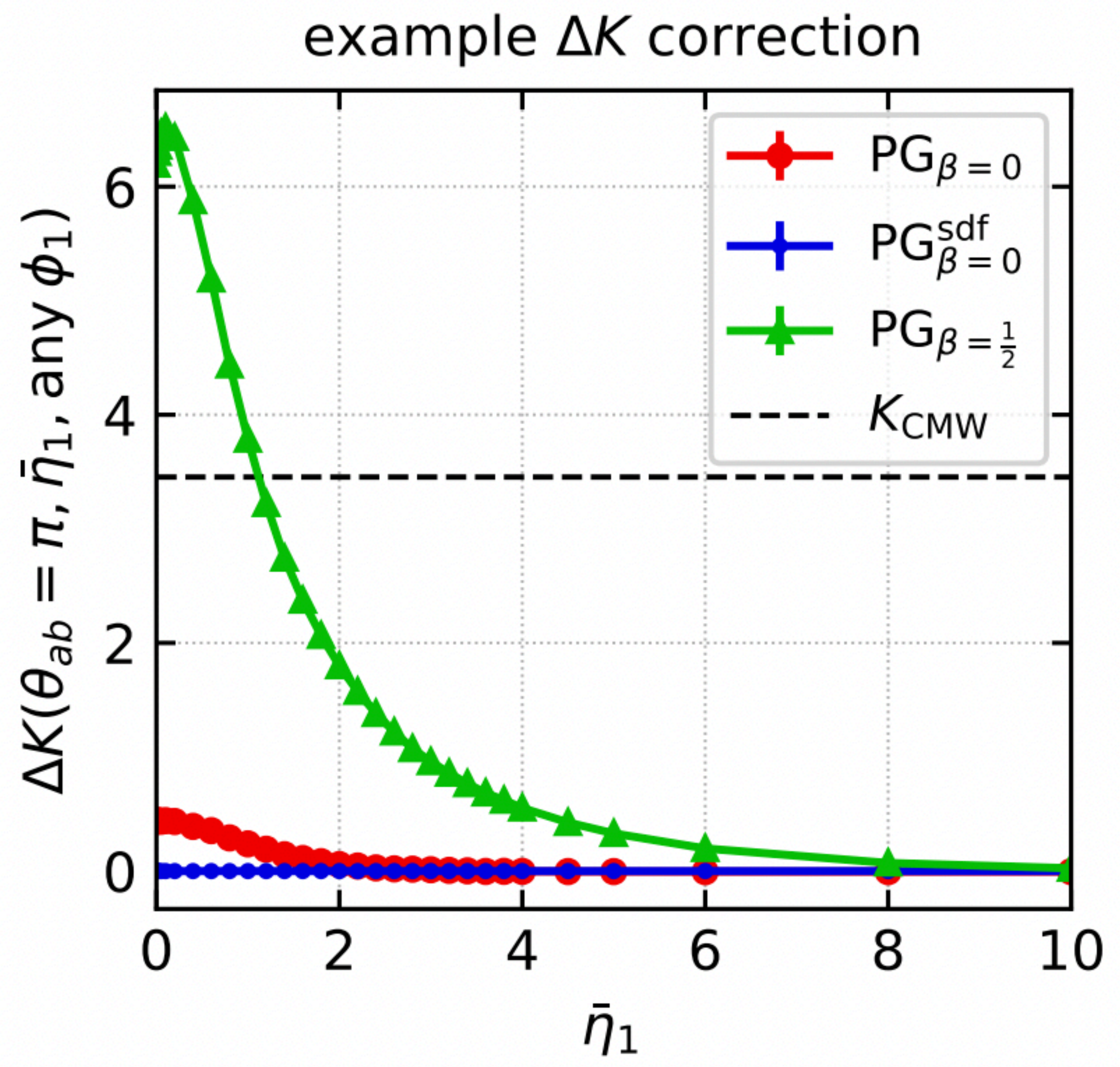

colour flow and flavour separation

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

Double-soft corrections - virtual corrections

- To reach NLL we have $\alpha_s^{eff} = \alpha_s(1 + \frac{\alpha_s}{2\pi}K_{CMW})$
- K_{CMW} is calculated by integrating over gluon splittings keeping the rapidity and transverse momentum of the gluon fixed
- The shower emission probability is generally not boost-invariant (the PG sdf version is), this requires a correction: $K_{CMW} \to K_{CMW} + \Delta K(\Phi_{\tilde{i}})$

$$\Delta K = \int_r d\Phi^{(\text{PS})}_{12/\tilde{1}}\,|M^{(\text{PS})}_{12/\tilde{1}}|^2 - \int_{r_{\text{sc}}} d\Phi^{(\text{PS})}_{12/\tilde{1}_{\text{sc}}}|M^{(\text{PS})}_{12/\tilde{1}_{\text{sc}}}|^2$$



MvB, Dasgupta, El-Menoufi, Helliwell, Monni, Karlberg [2402.05170]

Anomalous dimension small-R jets

- Cross section is

$$\frac{1}{\sigma_0}\frac{d\sigma^{\text{jet}}}{dz} \equiv \sum_{i=q,\bar{q},g} \int_z^1 \frac{d\xi}{\xi} C_i^{\text{jet}}\left(\xi, \mu, Q\right) D_i^{\text{jet}}\left(\frac{z}{\xi}, \mu, E\,R\right)$$

- Frag function D is governed by

$$\frac{dD_k^{\text{jet}}\left(z, \mu, E\,R\right)}{d\ln\mu^2} = \sum_i \int_z^1 \frac{d\xi}{\xi} \hat{P}_{ik}\left(\frac{z}{\xi}, \mu\right) D_i^{\text{jet}}\left(\xi, \mu, E\,R\right)$$

- We find that $\hat{P}_{ik}^{(1)} = \hat{P}_{ik}^{(1),\,\text{AP}} - \delta\hat{P}_{ik}^{(1)}$

- Deviation from DGLAP anomalous dimension start at 2loop with

$$\delta\hat{P}_{EA}^{(1)}(z) \equiv \left(2\,\ln z\,\hat{P}_{BA}^{(0)}\right) \otimes \hat{P}_{EB}^{(0)}\,; \quad \delta\hat{P}_{DA}^{(1)}(z) \equiv \left(2\,\ln z\,\hat{P}_{BA}^{(0)}\right) \otimes \hat{P}_{DB}^{(0)}$$

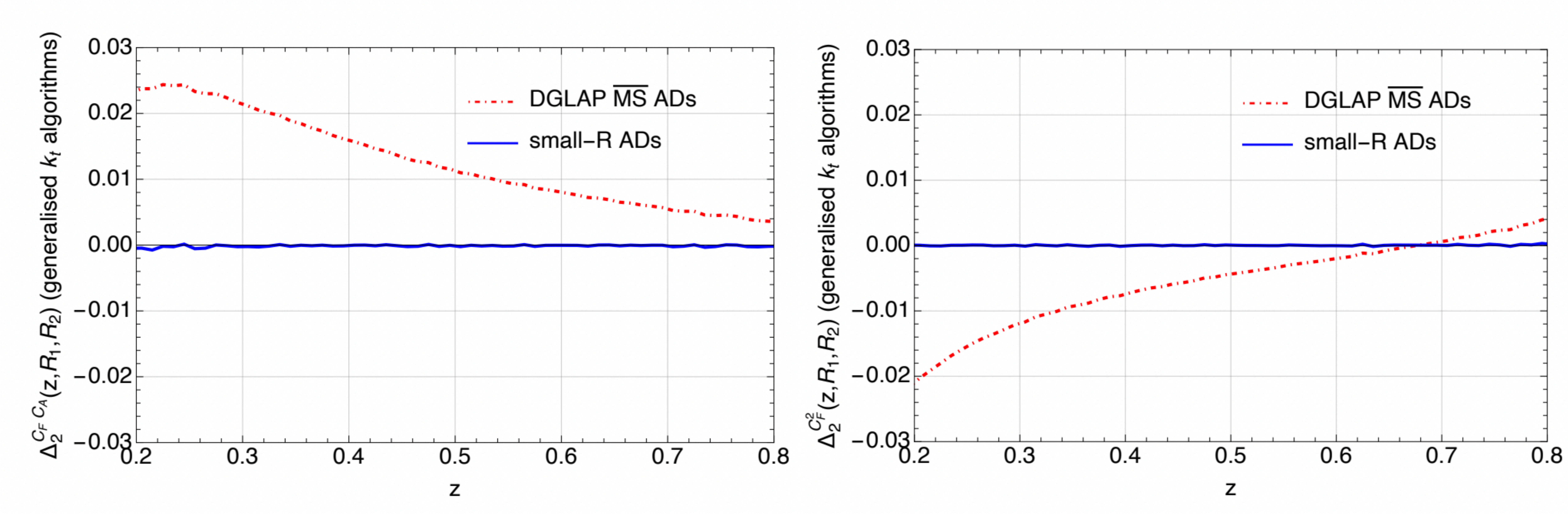
$$\delta\hat{P}_{GA}^{(1)}(z) \equiv \left(2\,\ln z\,\hat{P}_{CA}^{(0)}\right) \otimes \hat{P}_{GC}^{(0)}\,; \quad \delta\hat{P}_{FA}^{(1)}(z) \equiv \left(2\,\ln z\,\hat{P}_{CA}^{(0)}\right) \otimes \hat{P}_{FC}^{(0)}$$

MvB, Dasgupta, El-Menoufi, Helliwell, Monni, Karlberg [2402.05170]

Anomalous dimension small-R jets

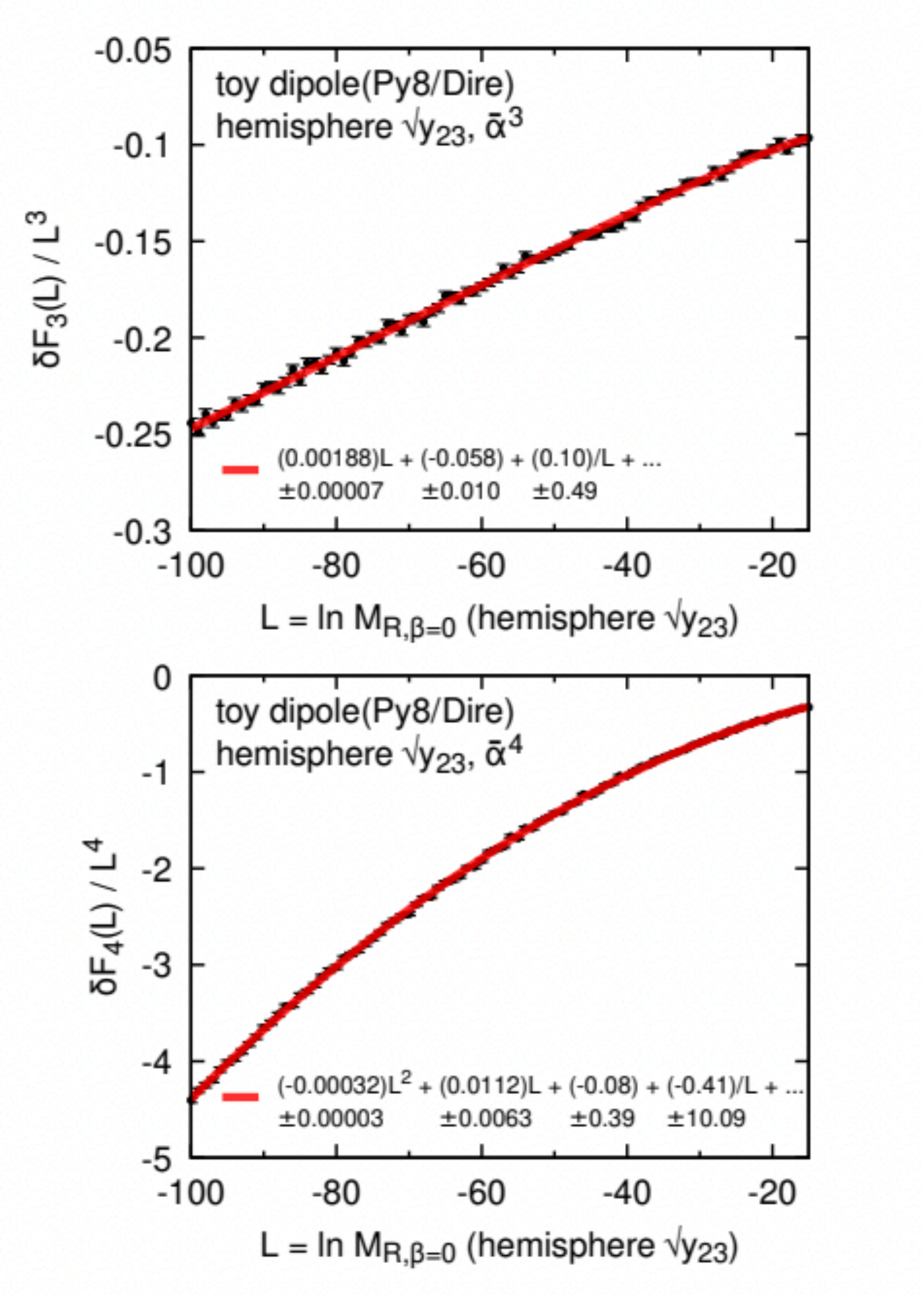
- Verification with Event2

$$\Delta_i(z,R) \equiv \frac{1}{\sigma_0}\left(\left.\frac{d\sigma^{\rm jet}}{dz}\right|^{(i)}_{\rm EVENT2} - \left.\frac{d\sigma^{\rm jet}}{dz}\right|^{(i)}\right)$$



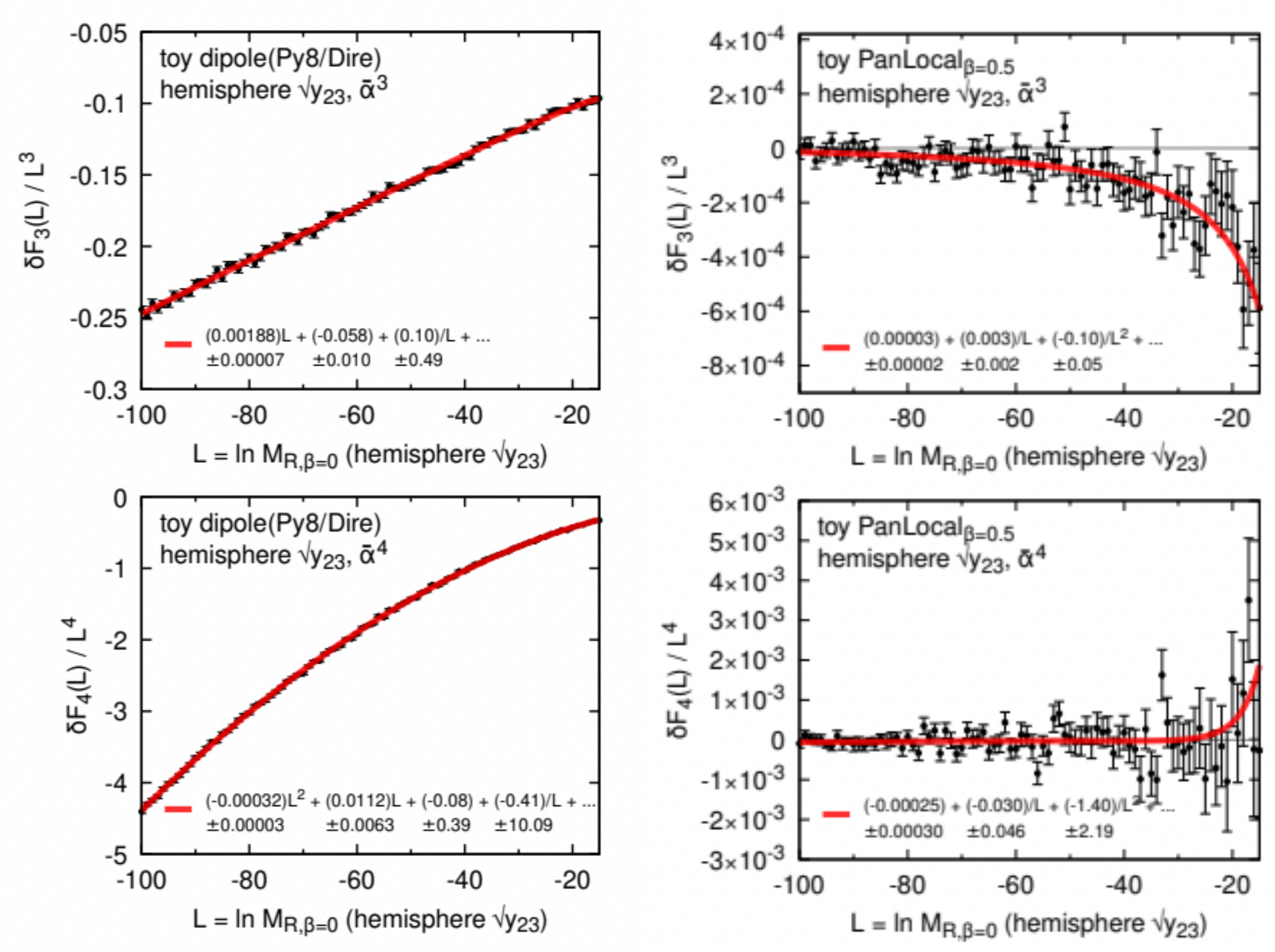
2002.11114

Super-leading logarithms



- Consider $M_{R,0}$, max $p_\perp$ of emissions in the right hemisphere (sensitive to super-leading logs at $\mathcal{O}(\alpha_s^3)$)
- Take toy-model approach with only soft primary emissions and fixed coupling
- Take difference between CEASAR result and toy shower $\delta F_n(L)$, n = order in α_s, where $F = \sum \alpha_s^n F_n$ has terms of $\alpha_s^n L^m$ with $m \leq n$
- Clearly a discrepancy at fixed-order for standard dipole showers
- Vanishes at all orders because it is numerically comparable to the NNLL terms -> orange points

Super-leading logarithms



- Discrepancy not there for PanScales family of showers