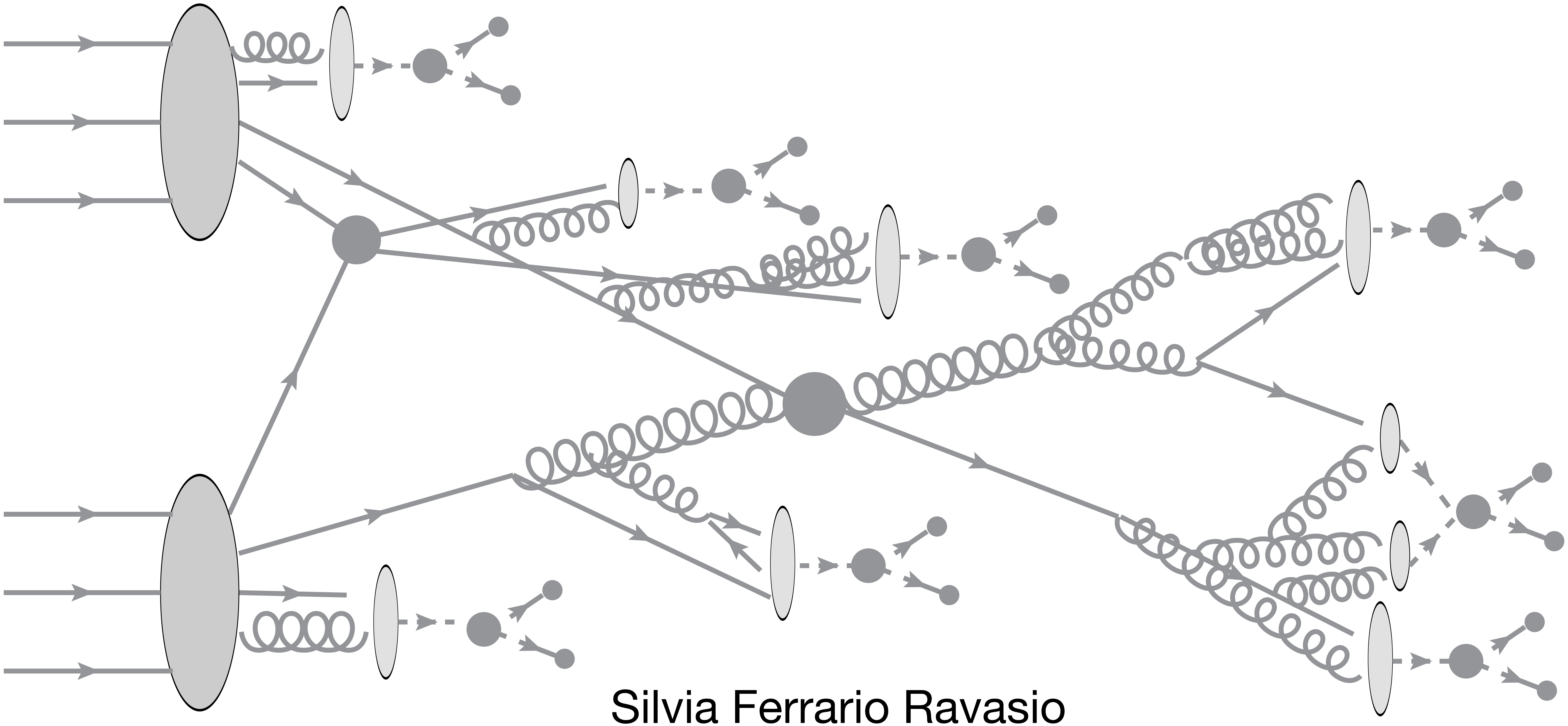
Developments in Monte Carlo Event Generators



Silvia Ferrario Ravasio

Zurich Phenomenology Workshop 2024:

Particle Physics from LHC to Future Colliders

8th January 2024, **University of Zurich (& ETH)**

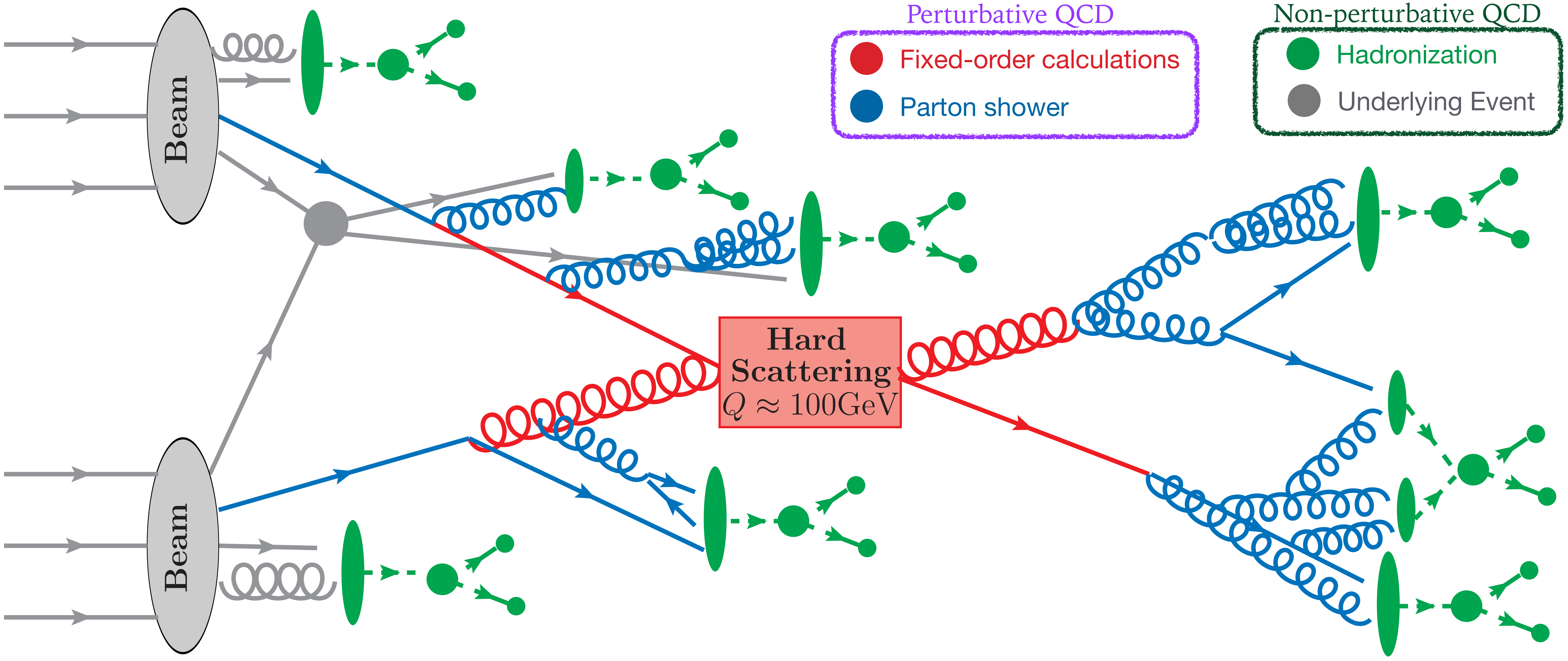
Shower Monte Carlo Generators

- **Shower Monte Carlo** generators have all the ingredients necessary to model complex collider events and are the **default tool** for intepreting collider data and evaluating capabilities of future colliders

Pythia

Herwig

Sherpa



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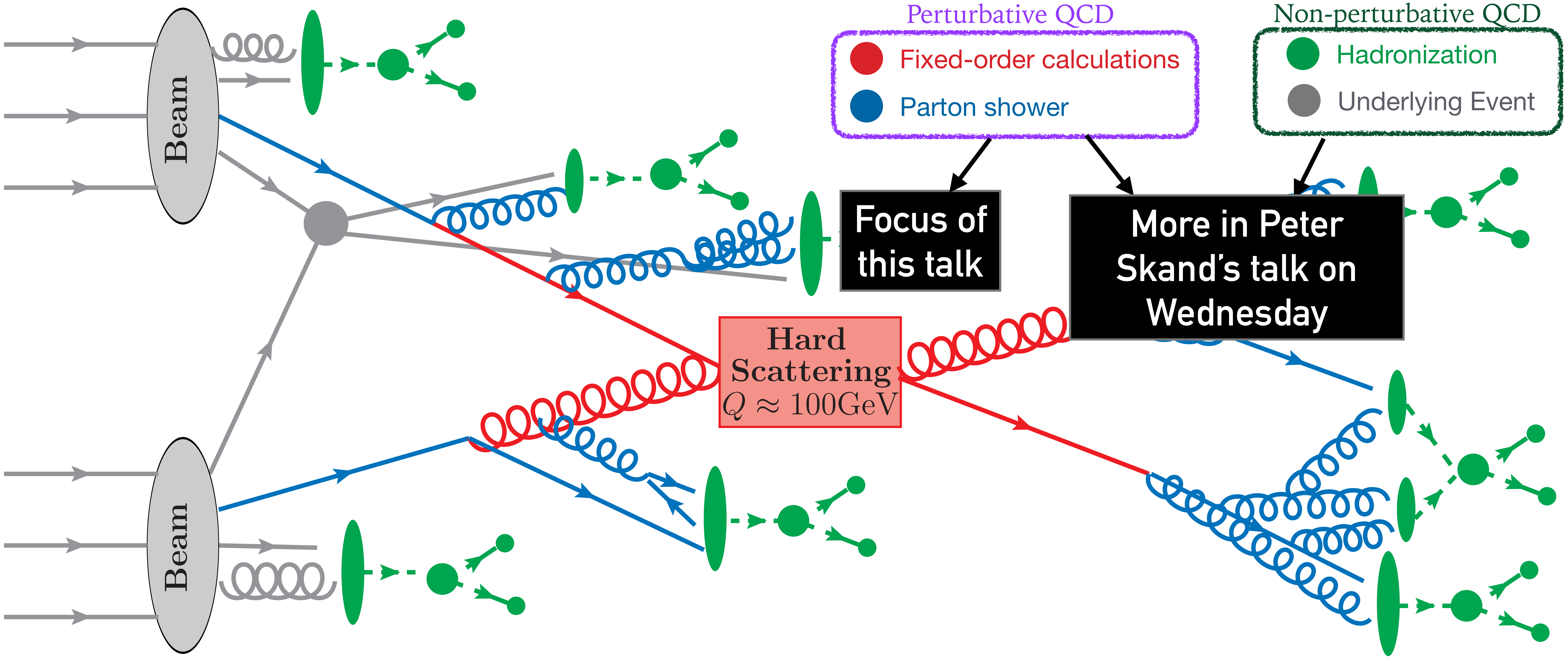
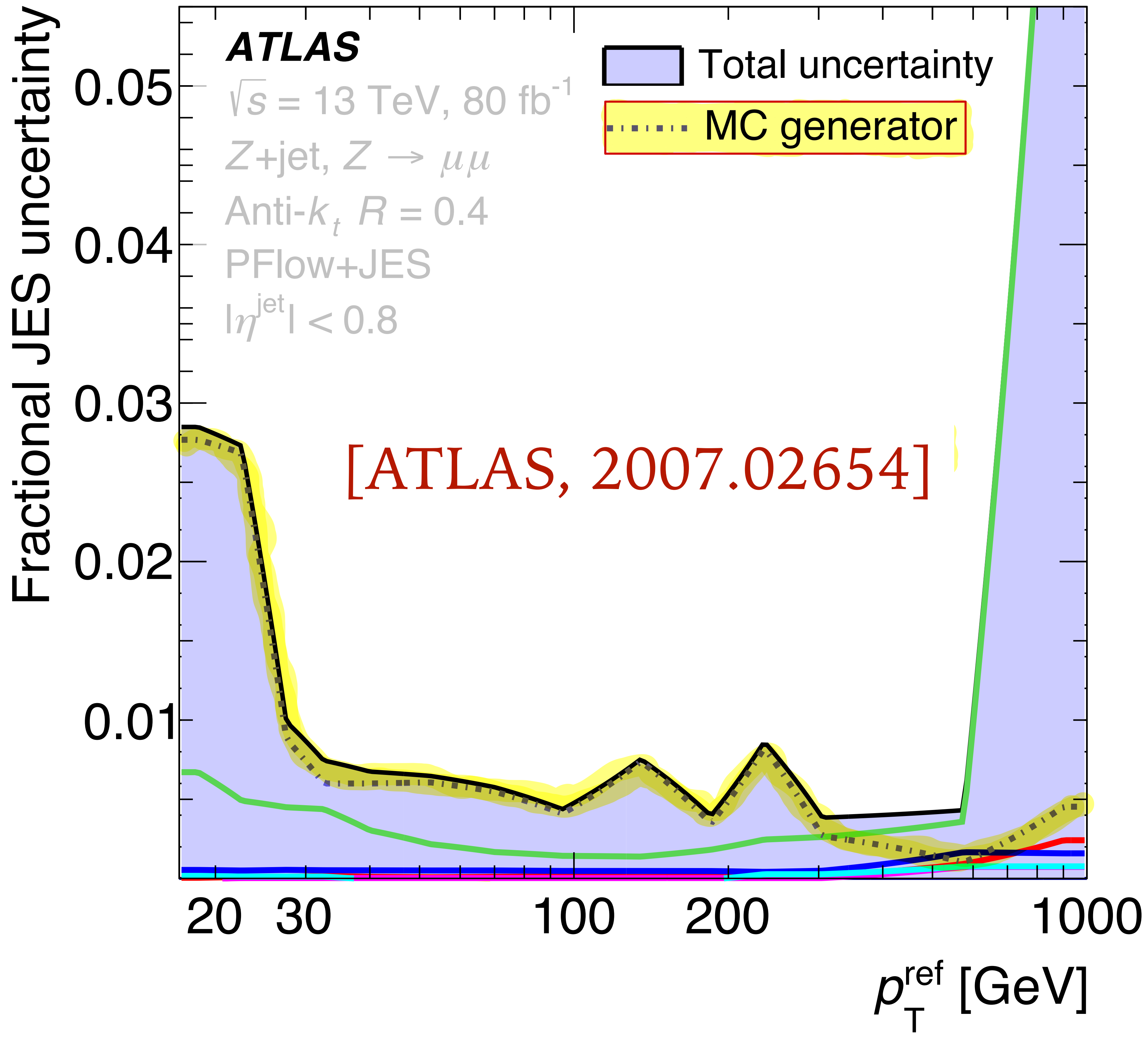


- The flexibility of these tools comes at a cost of a poor formal accuracy that causes systematic uncertainties entering thousands of papers from the LHC

SMC as limiting factor in HEP: Jet Measurements

Any jet physics analysis ($\mathcal{O}(1k)$ **papers!!**) at colliders requires the **jet energy scale** calibration



[ATLAS, 2007.02654]

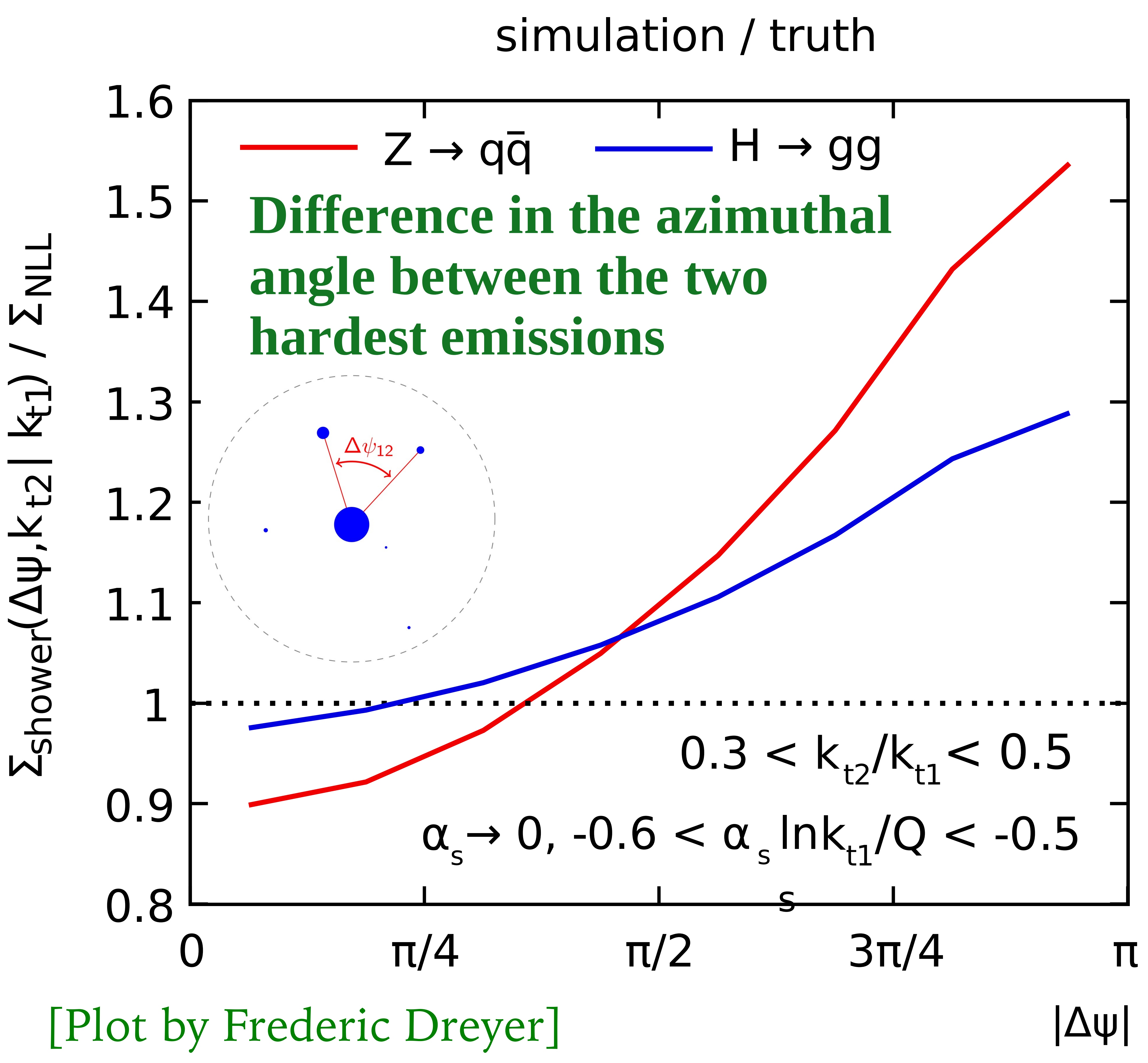
Parton shower (and its interplay with hadronisation) leading source of systematic uncertainty of JES

JES largest uncertainty in **top-mass extractions**

[CMS, 1910.08819]

Source	Uncertainty [GeV]
Trigger	0.02
Lepton ident./isolation	0.02
Muon momentum scale	0.03
Electron momentum scale	0.10
Jet energy scale	0.57
Jet energy resolution	0.09
b tagging	0.12
Pileup	0.09
$t\bar{t}$ ME scale	0.18
tW ME scale	0.02
DY ME scale	0.06
NLO generator	0.14
PDF	0.05
$\sigma_{t\bar{t}}$	0.09
Top quark p_T	0.04
ME/PS matching	0.16
UE tune	0.03
$t\bar{t}$ ISR scale	0.16
tW ISR scale	0.02
$t\bar{t}$ FSR scale	0.07
tW FSR scale	0.02
b quark fragmentation	0.11
b hadron BF	0.07
Colour reconnection	0.17
DY background	0.24
tW background	0.13
Diboson background	0.02
W+jets background	0.04
$t\bar{t}$ background	0.02
Statistical	0.14
MC statistical	0.36
Total m_t^{MC} uncertainty	$^{+0.68}_{-0.73}$

SMC as limiting factor in HEP: BSM searches



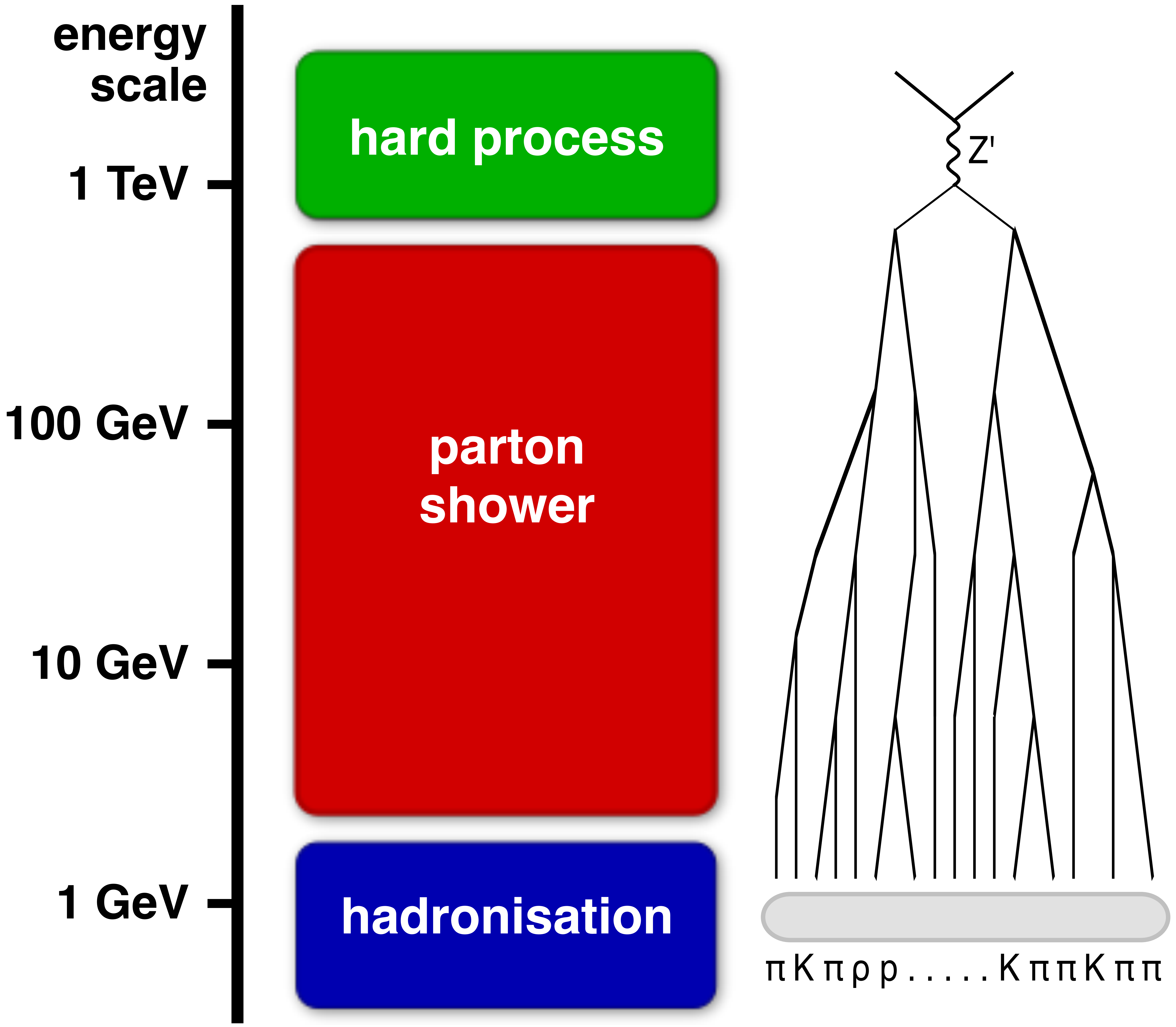
[Plot by Frederic Dreyer]

Unphysical differences in the **radiation pattern** from quark and gluon jets induced by parton showers jeopardizes **Machine Learning** applications for boosted objects tagging, limiting **new physics** searches

Unless you are highly confident in the information you have about the markets, you may be better off ignoring it altogether

Harry Markowitz (1990 Nobel Prize in Economics)

What should a Parton Shower achieve?



- **Parton showers** evolve collider events from $Q \approx \mathcal{O}(\text{TeV})$ to $\Lambda \approx 1\text{GeV}$
- During this evolution, large logarithms $L = \log Q/\Lambda$ will arise.
- Logarithmic accuracy to assess showers

$$\Sigma(\log O < L) = \exp\Big(\underbrace{L g_{\text{LL}}(\alpha_s L)}_{\text{leading logs}} + \underbrace{g_{\text{NLL}}(\alpha_s L)}_{\text{next-to LL}} + \ldots \Big)$$

E.g. $O = \frac{p_{\perp,Z}}{m_Z}$ and $p_{\perp,Z} \approx 1$ GeV,

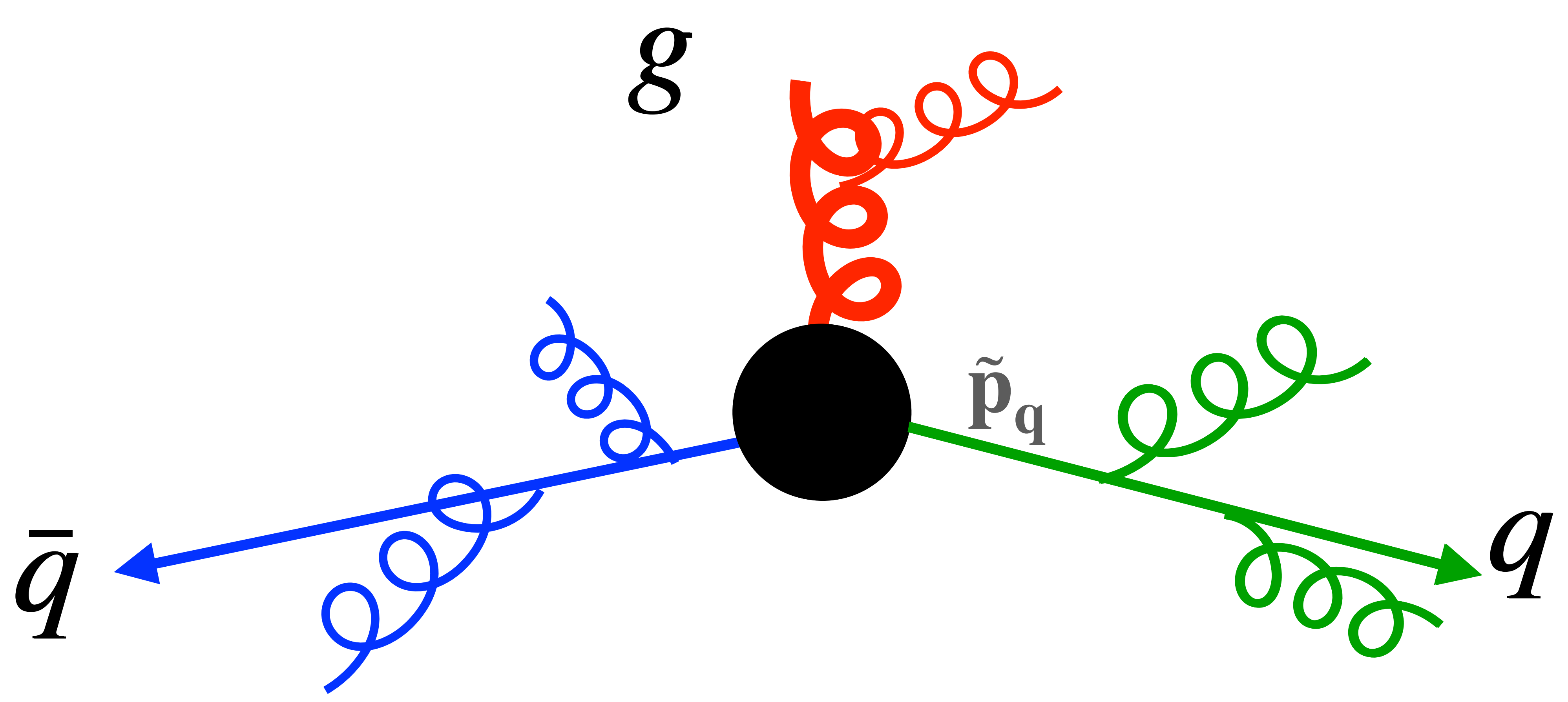
$|\alpha_s L| = 0.55$:

Next-to-Leading Logarithms are $\mathcal{O}(1)$

Herwig7 Angular-Orderd parton shower

[Marchesini, Webber ’88; Gieseke, Stephens, Webber hep-ph/0310083]

- ➤ Each **parton** produced in the hard scattering showers independently



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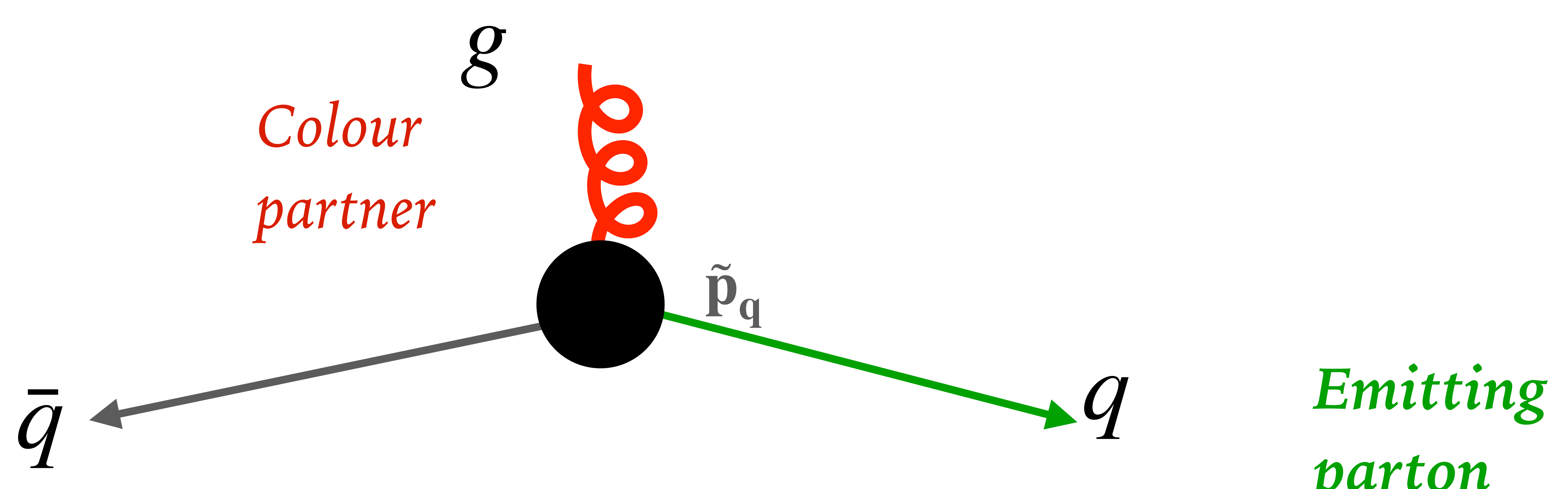

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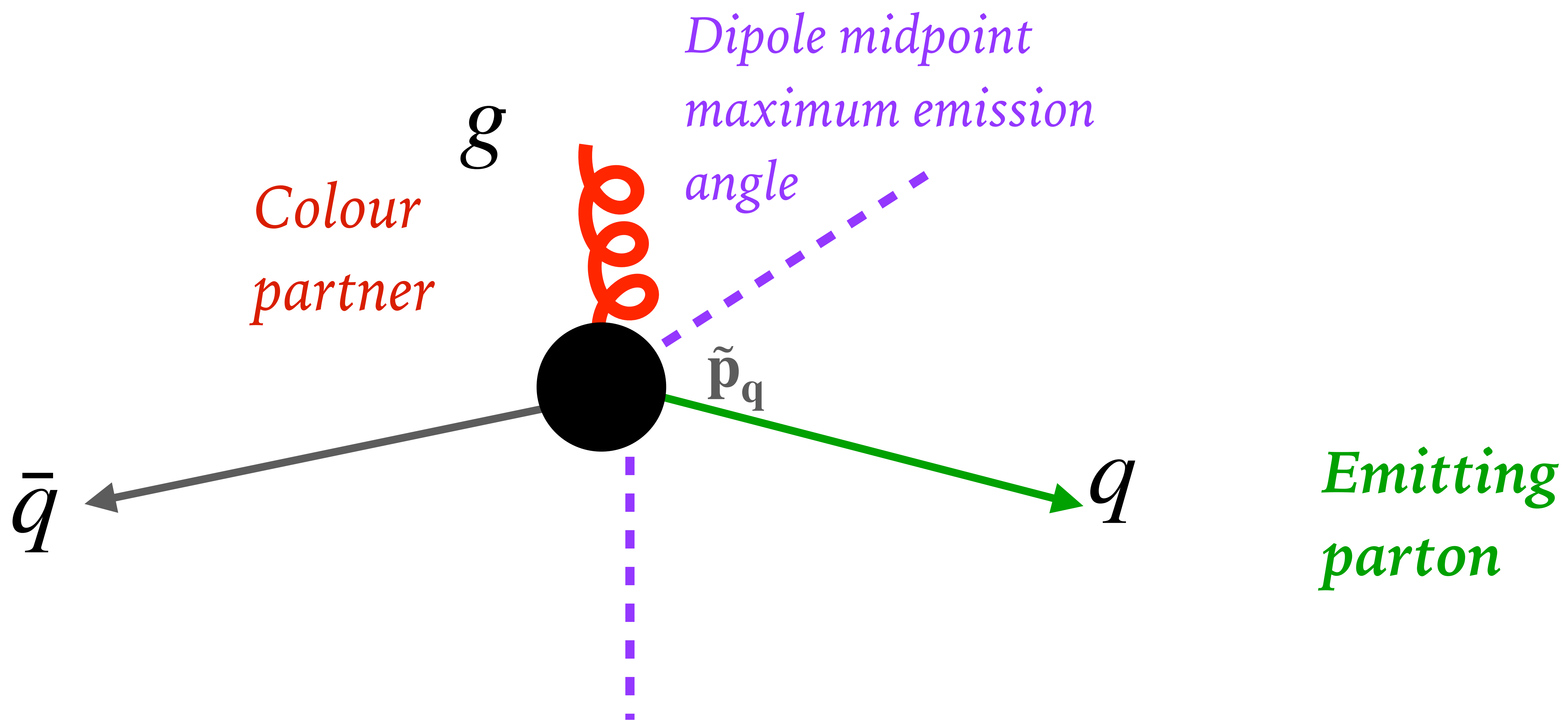

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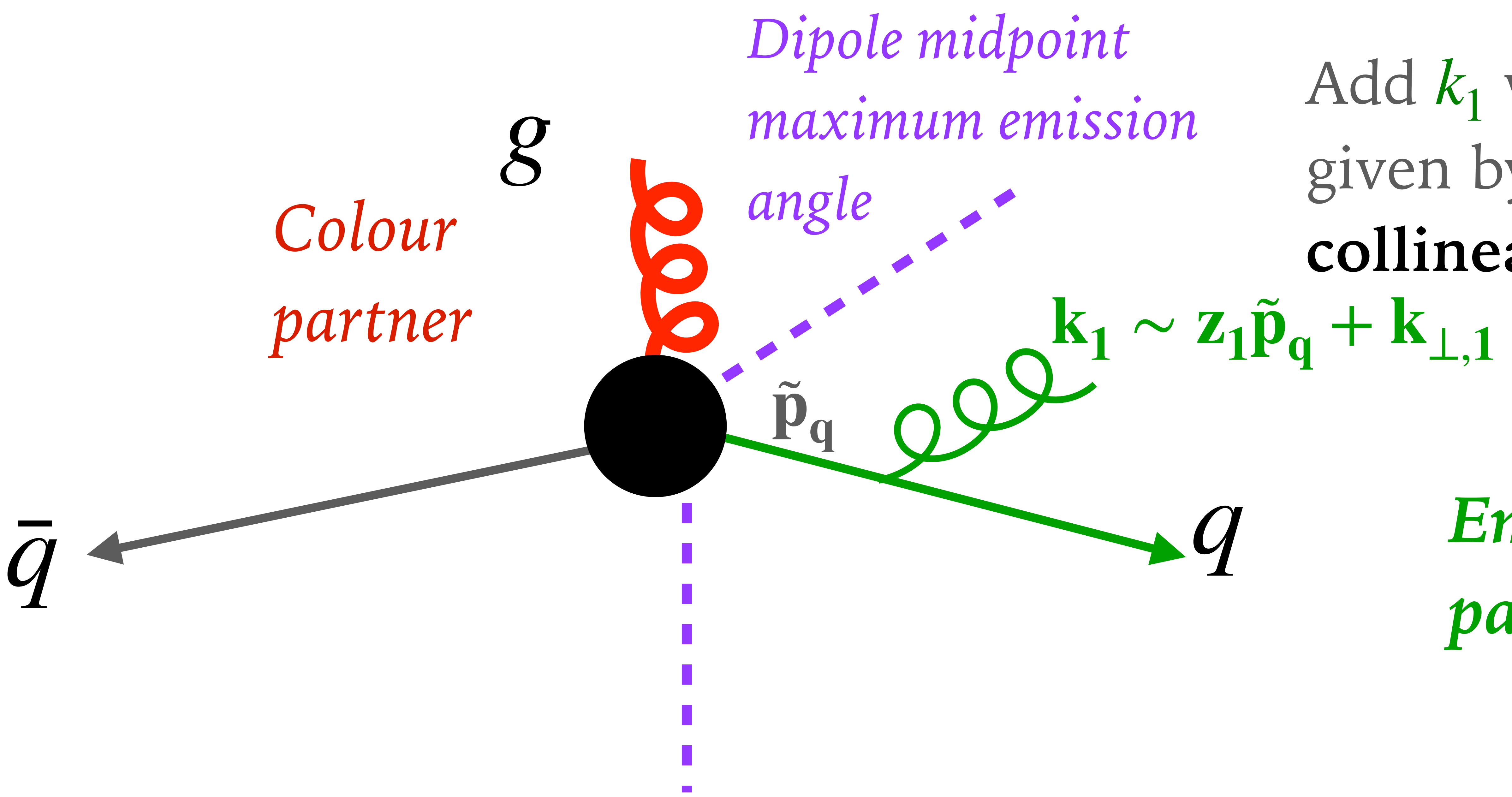

Add k_1 with a probability given by the Altarelli-Parisi **collinear splitting function**

Emitting parton

Herwig7 Angular-Orderd parton shower

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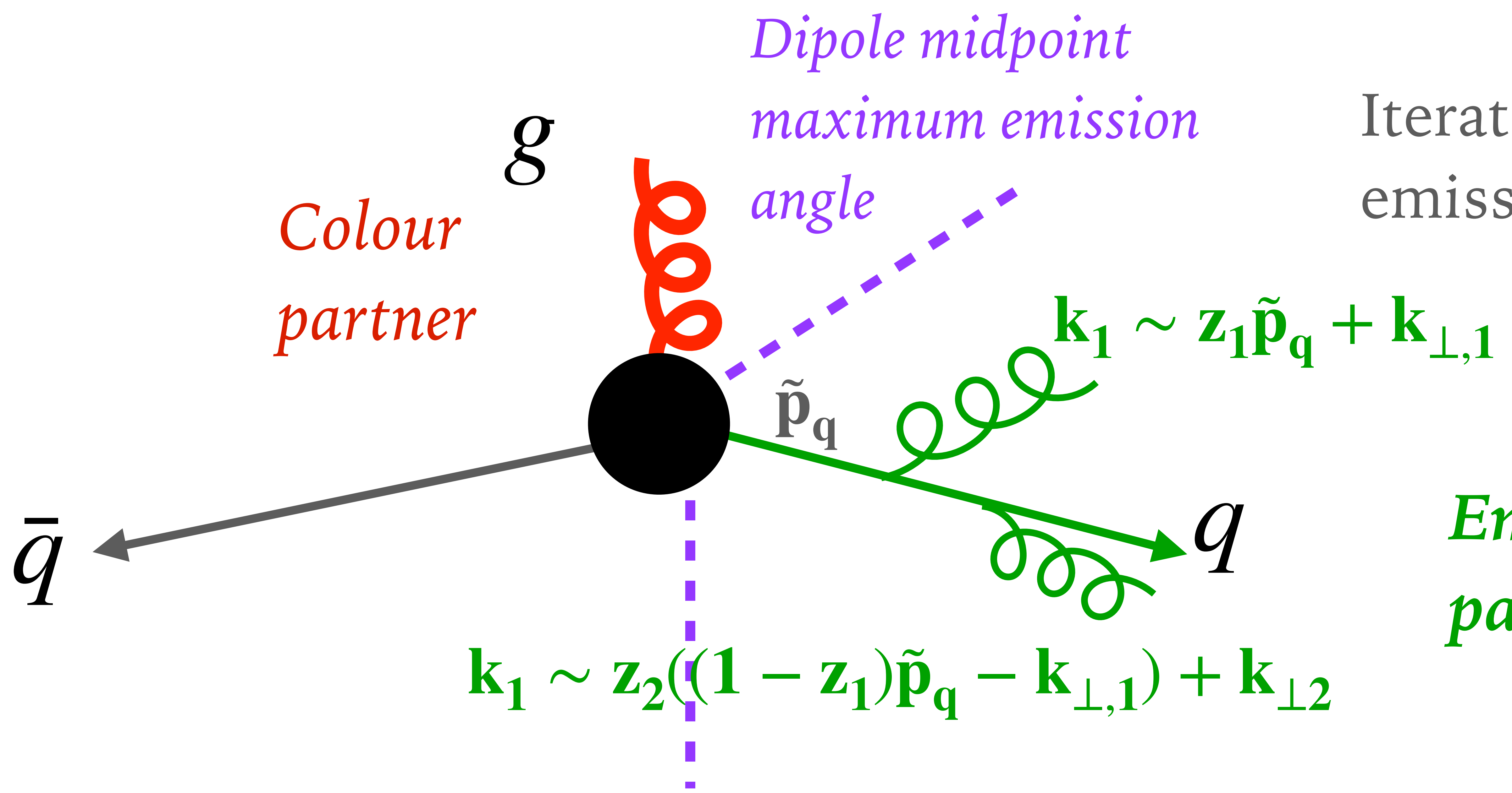

Iterate considering **smaller** emissions **angles**

Herwig7 Angular-Orderd generalised shower

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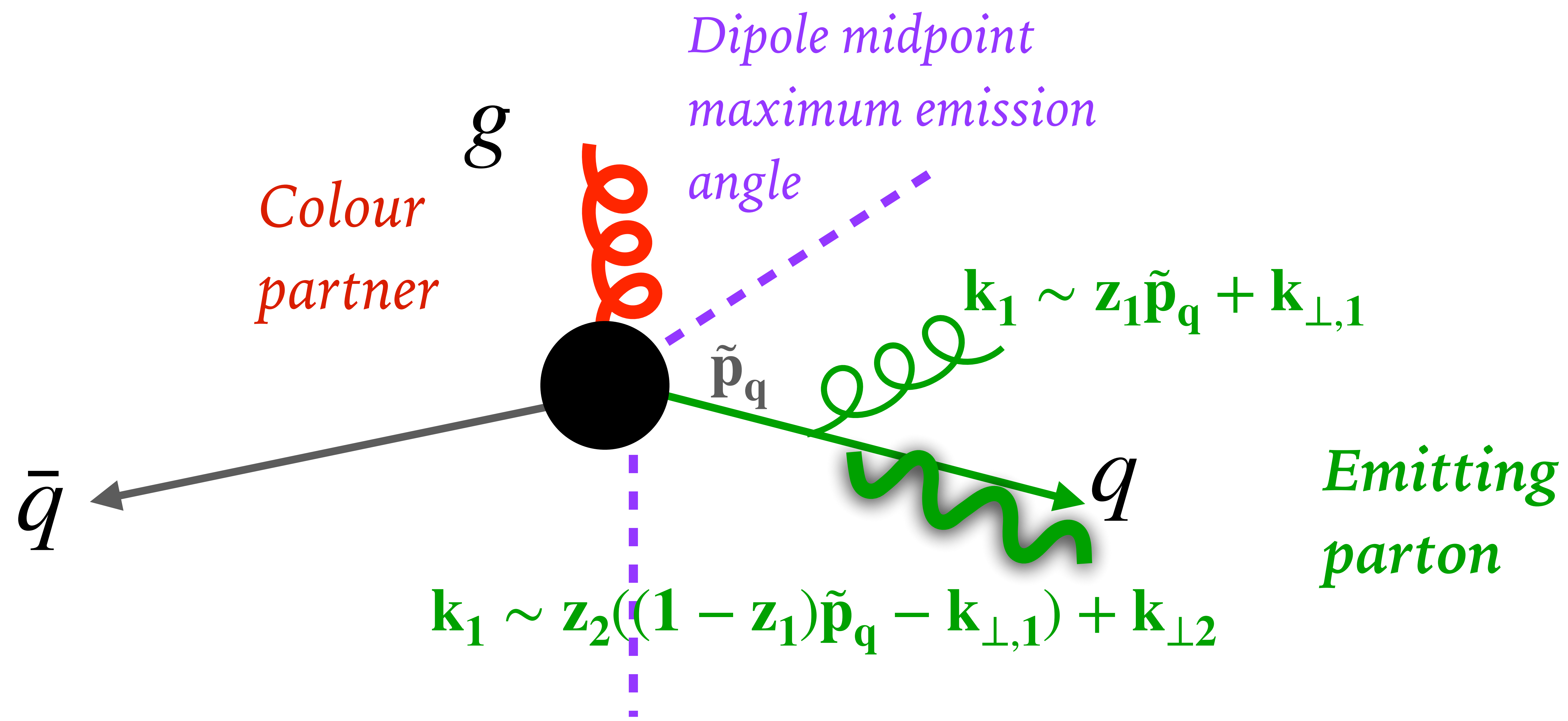

It is straighforward to include **QED** [since v 7.0 1512.01178], **Electro-Weak** [Masoumnia, Richardson, 2108.10817; available since v 7.3 2312.05175], **Dark sectors** [Lee, Masouminia, Seymour, Yang, 2312.13125; will be available in v 7.4]

Log Accuracy of the Angular-Orderd parton shower

- **Angular-ordering** = algorithmic implementation of the QCD **coherent branching formalism**, used for **NLL** calcultions for **global observables** (event shapes, many kinematic distributions e.g. $p_{\perp,Z}$) [Marchesini, Webber '88; Gieseke, Stephens, Webber hep-ph/0310083]

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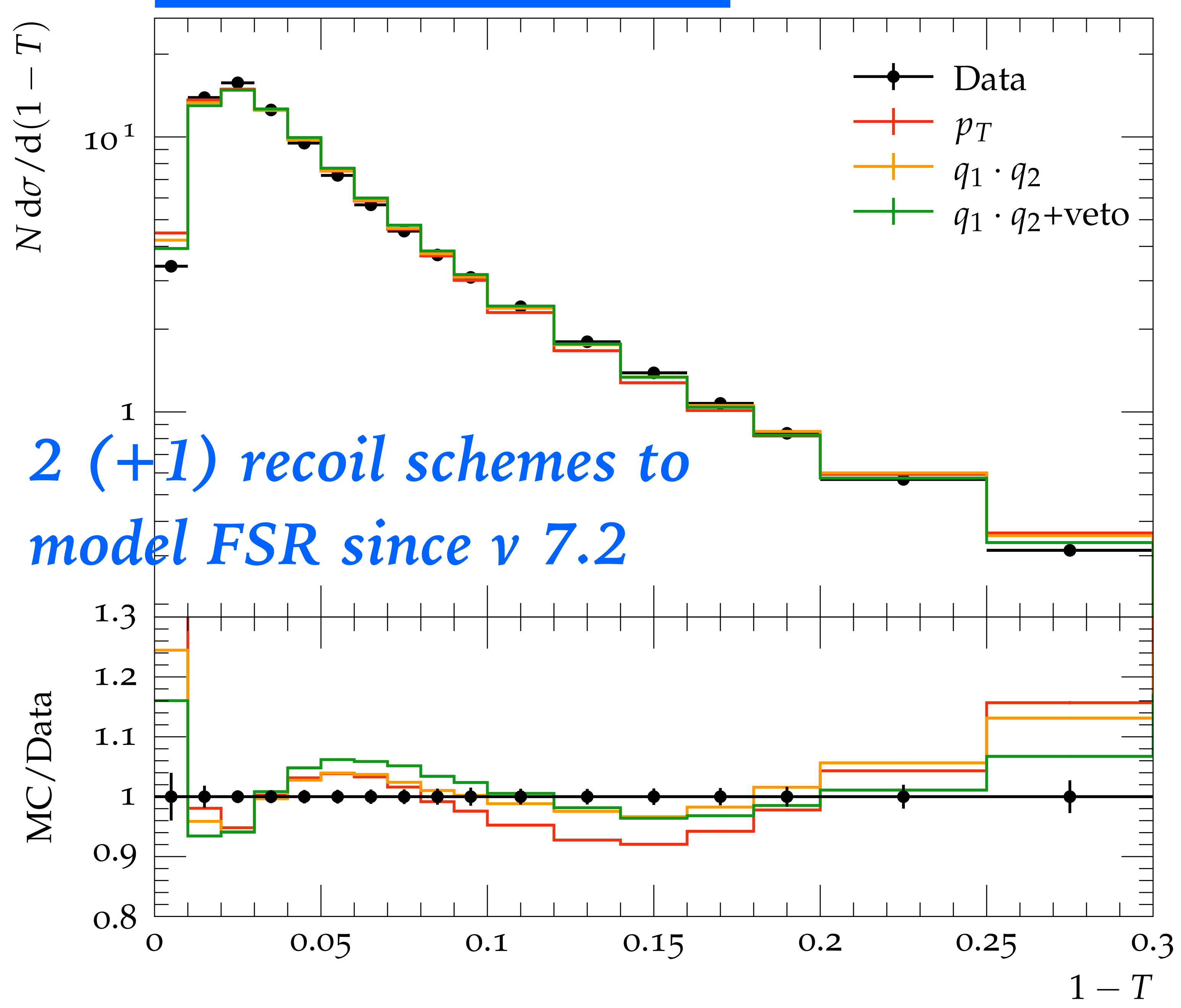
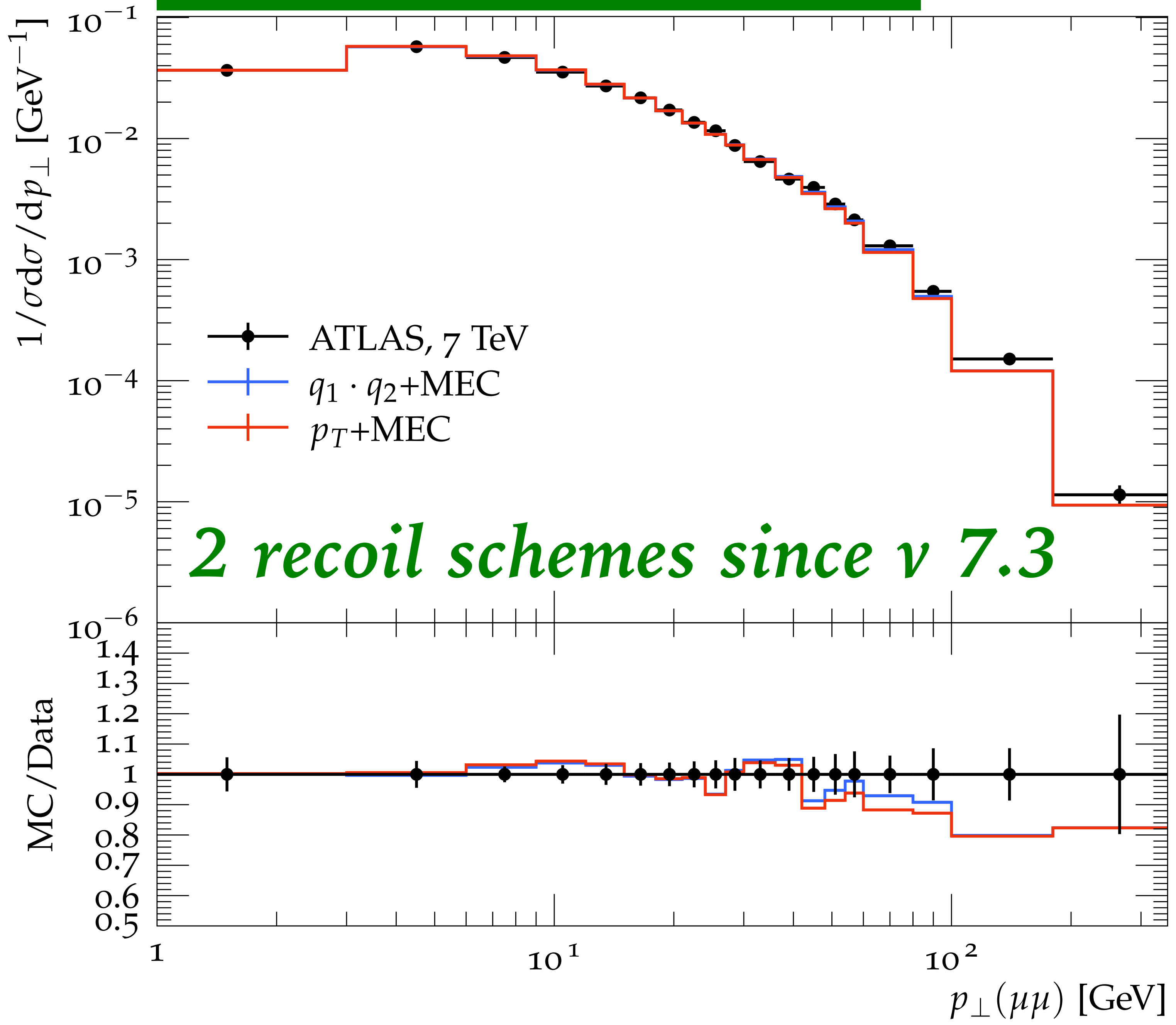
- **Some freedom in the actual implementation** (in the soft limit we need to reproduce the original kinematic map by Marchesini and Webber to preserve the NLL accuracy) [Bewick, SFR, Richardson, Seymour; 1904.11866, 2107.04051]

Thrust at LEP



2 (+1) recoil schemes to model FSR since v 7.2

$p_\perp$ of the Z at LHC



2 recoil schemes since v 7.3

2 recoil schemes that achieve NLL accuracy for global event shapes *(difference can be used to estimate shower uncertainties)*

Logarithmic accuracy beyond QCD

- The **angular-ordering of QCD emissions** ensures that also the **soft** limit is correct, and hence NLL accuracy is achieved
- For **QED** and **EW**, the parton branching formalism ensures **only collinear** (and soft-collinear) logs are resummed: only **LL accuracy** is expected

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- **QCD**: $\alpha_s \sim 0.1, \quad \alpha_s L = \mathcal{O}(1) \quad \Sigma = \exp(L g_{\rm LL}(\alpha_s L) + g_{\rm NLL}(\alpha_s L) + \ldots)$
- **QED**: $\alpha_{em} \sim 0.01, \quad \alpha_{\rm em} L^2 = \mathcal{O}(1) \quad \Sigma = f_{\rm DL}(\alpha_{\rm em} L^2) + \boxed{\sqrt{\alpha_{\rm em}} f_{\rm NDL}(\alpha_{\rm em} L^2)} + \ldots$ (DL = double logs)

Only colliner ones are included, not soft ones: few % mistake for processes without QCD; necessary (but not sufficient) for the FCC-ee

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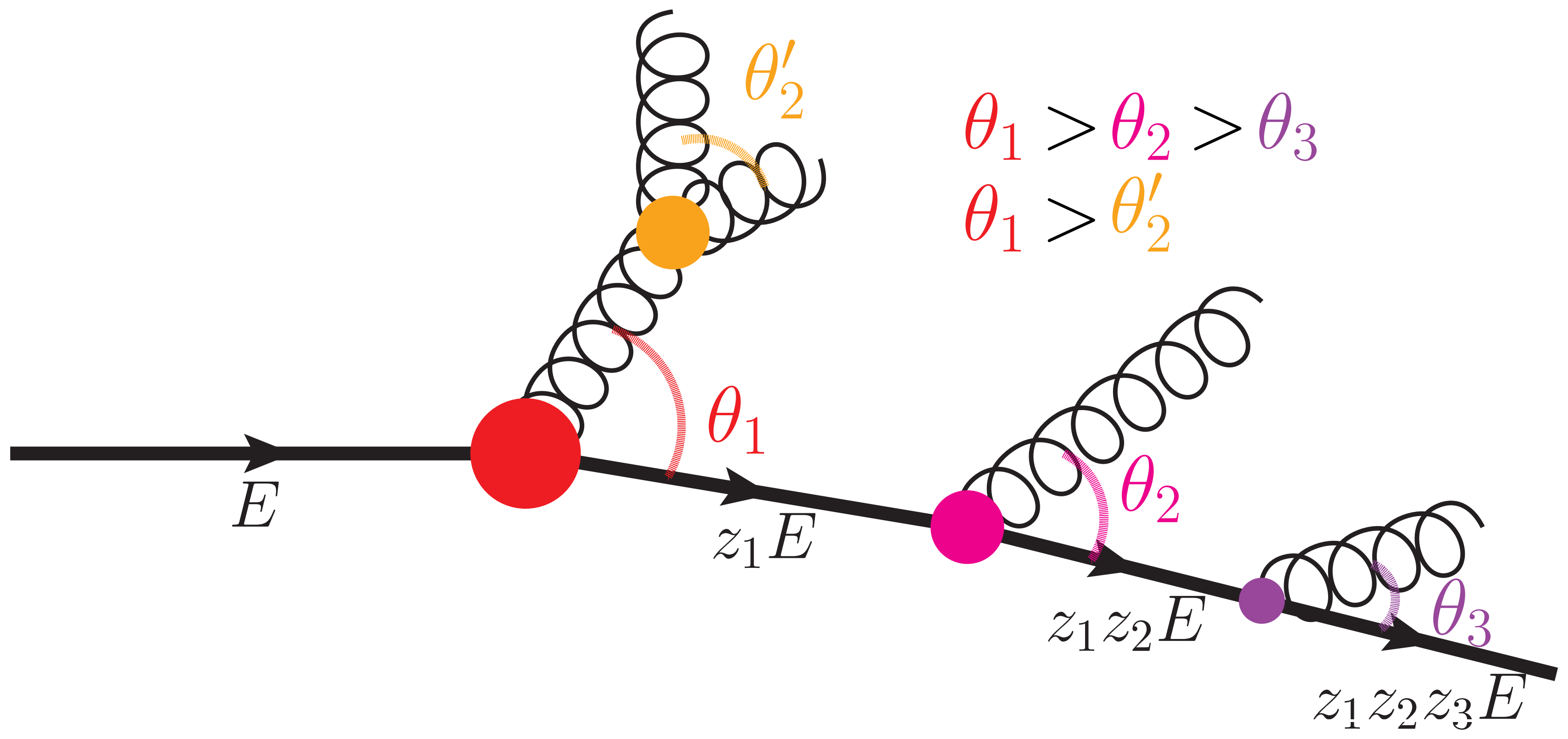
QED and EW logs in other SMC tools

- SHERPA: soft QED logs implemented with the **YFS formalism** [Krauss, Price, Schönherr, 2203.10948]; one-loop virtual **EW Sudakov Logs** [Bothmann, Napoletano 2006.14635]
- PYTHIA (and VINCIA): see P. Skand's talk!

Parton Showers in a nutshell

Angular-ordered shower (Herwig)



- Achieve **NLL** for many observables
  [Marchesini, Webber '88]

BUT

- **Matching** with fixed-order calculations **beyond NLO** is painful (and not available)
- **Non-global logarithms** are not correctly described [Banfi, Corcella, Dagupta hep-ph/0612282]

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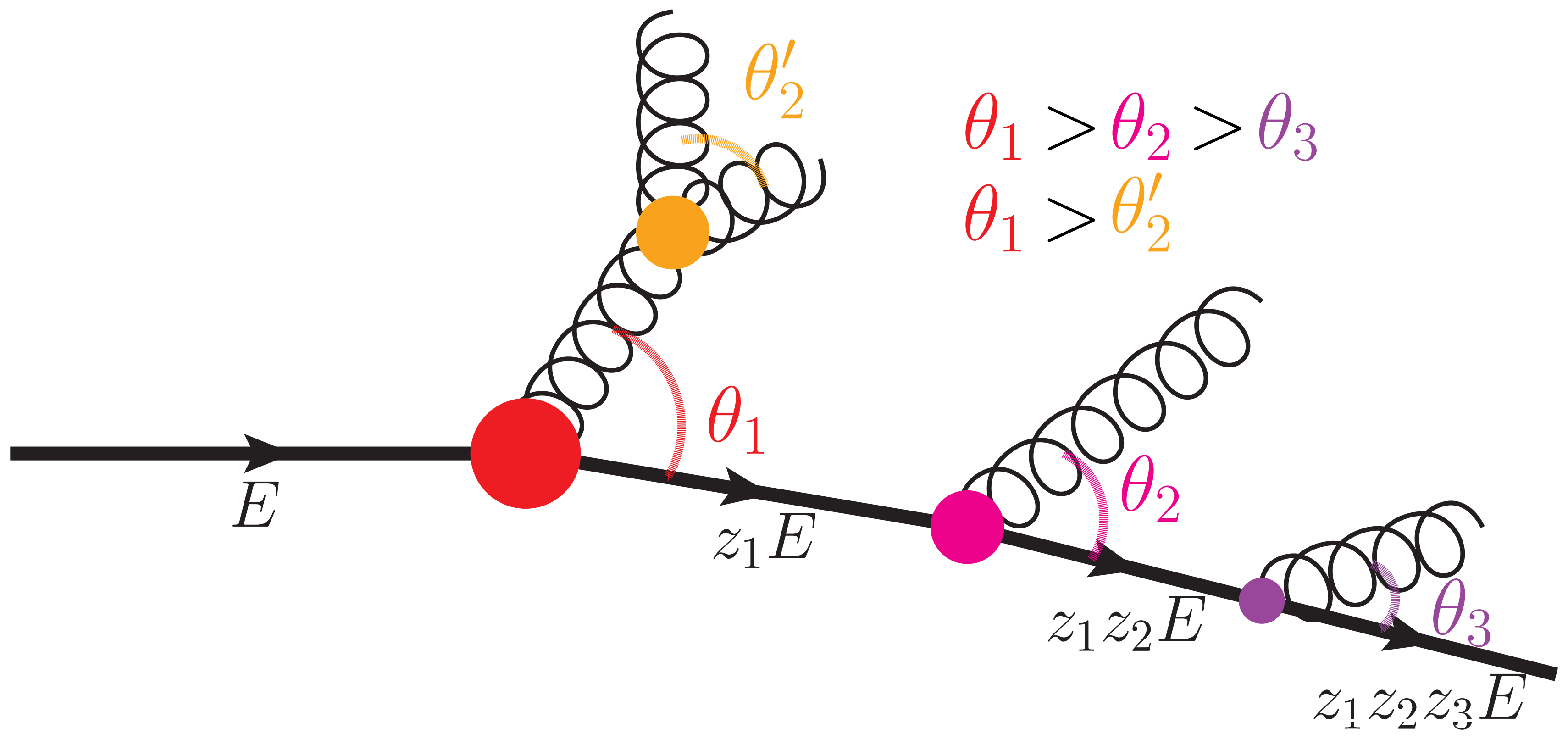

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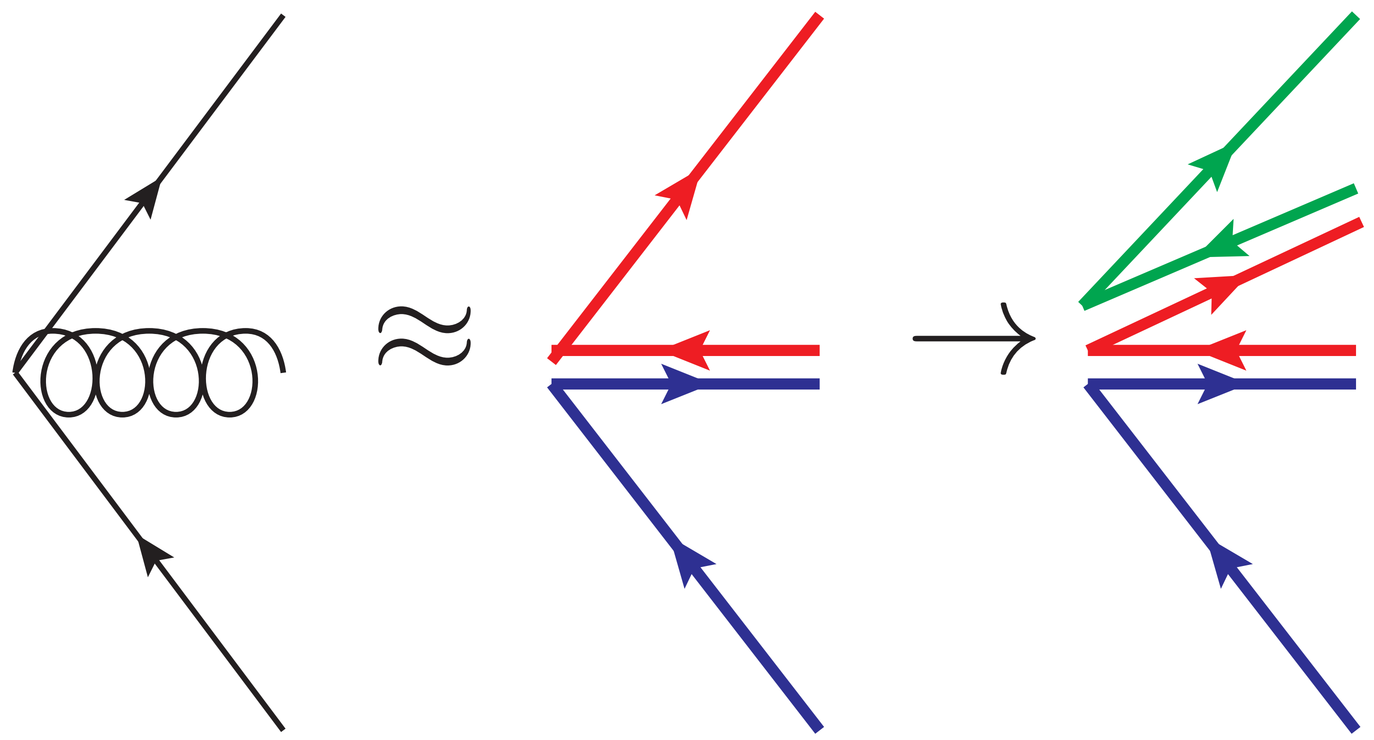
Dipole shower (Pythia, Sherpa, Herwig)



- Dipole showers are the more popular alternative to angular-ordered showers

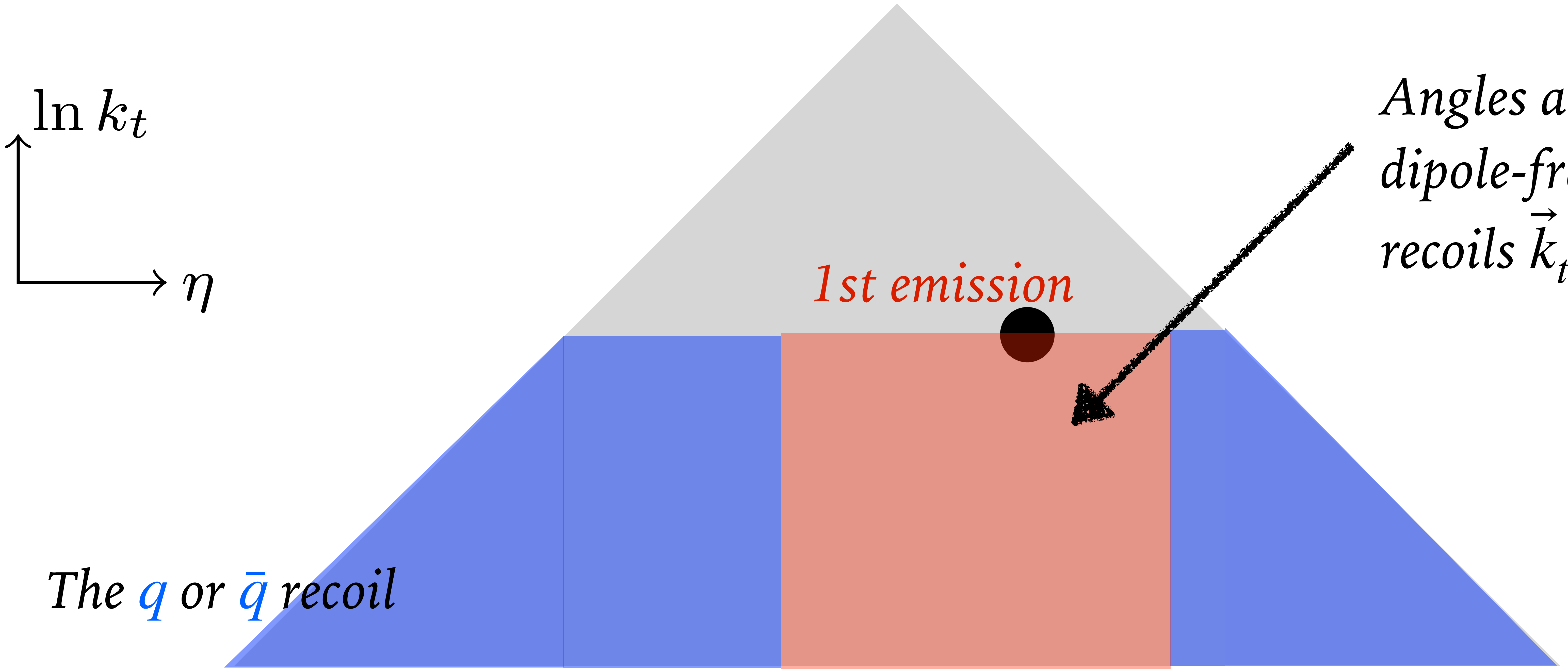
  [Gustafson, Pettersson '88]

- **Matching beyond NLO and multi-jet merging** much simpler as hardest emissions come first
- Azimuthal dependendece of soft emission necessary for **non-global logs**

BUT THEY ARE <u>NOT YET</u> (N)NLL!

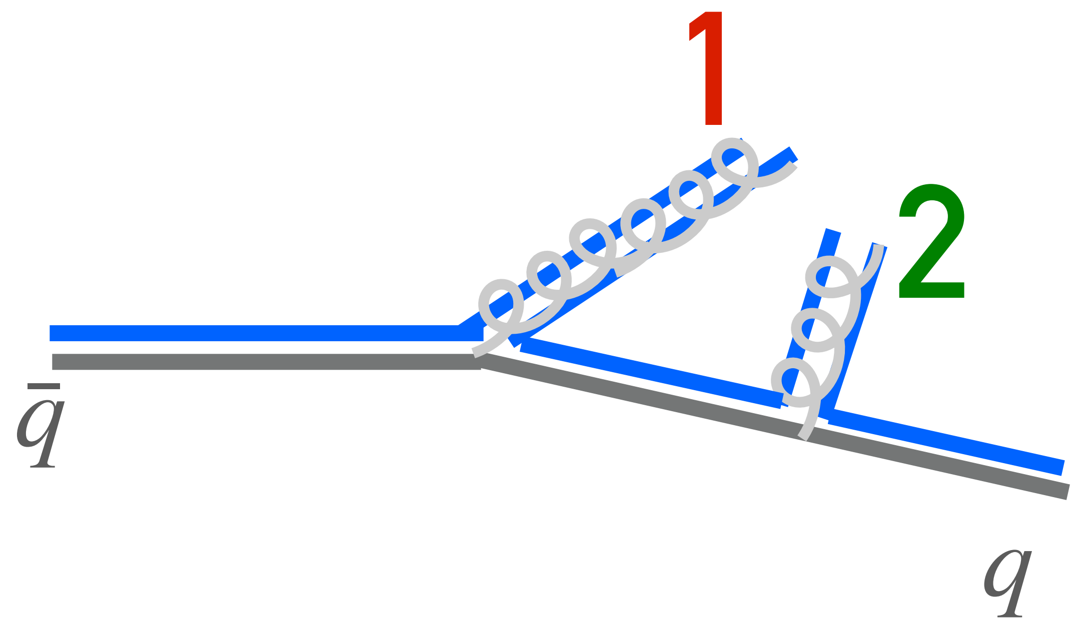
What is the the logarithmic accuracy of “standard” dipole showers

Emission of a **soft-collinear gluon** g_2, from a $q\bar{q}g_1$ final-state, where g_1 is soft-collinear as well



Angles are measured in the dipole-frame: ***1st emission*** *recoils* $\vec{k}_{t1} \to \vec{k}_{t1} - \vec{k}_{t2}$

Who takes the $k_\perp$ recoil of the new emission?



1805.09327 Dasgupta, Dreyer, Hamilton, Monni, Salam

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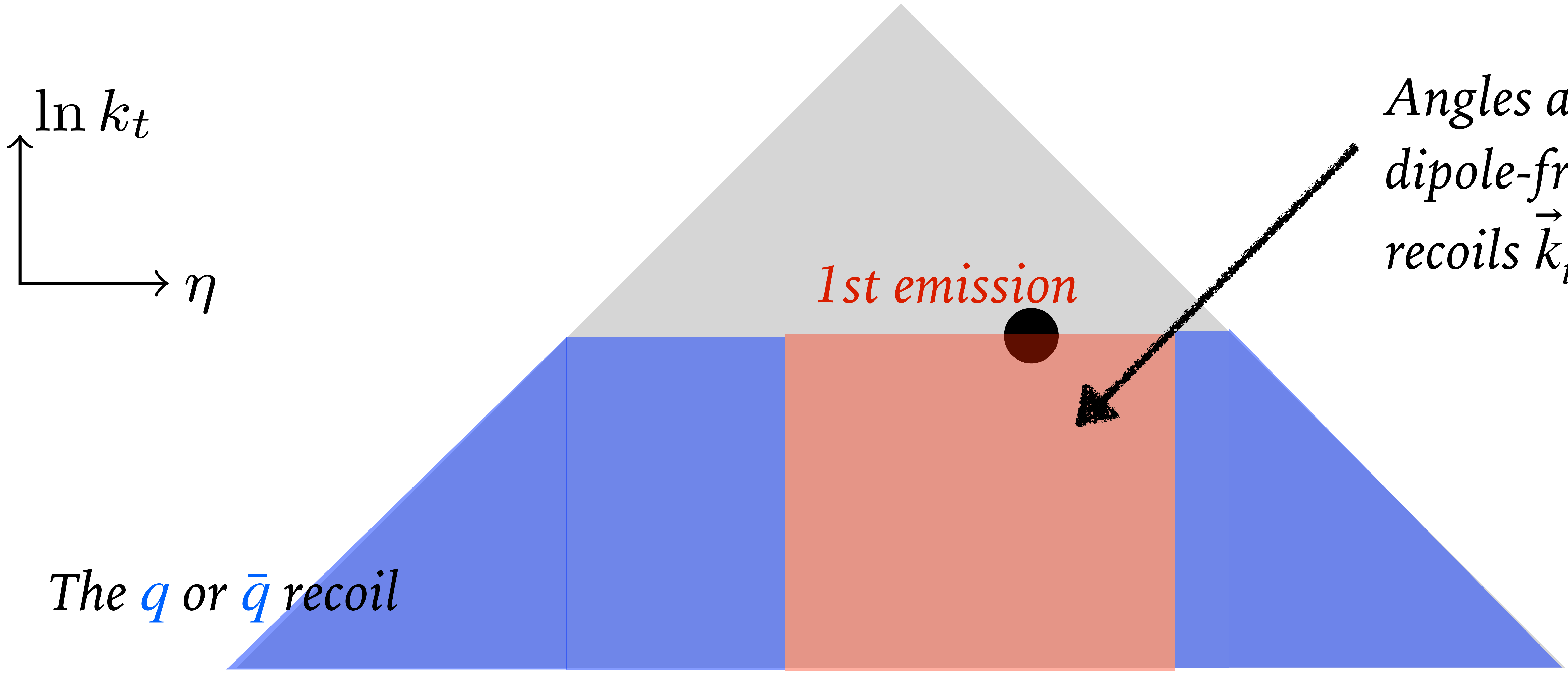

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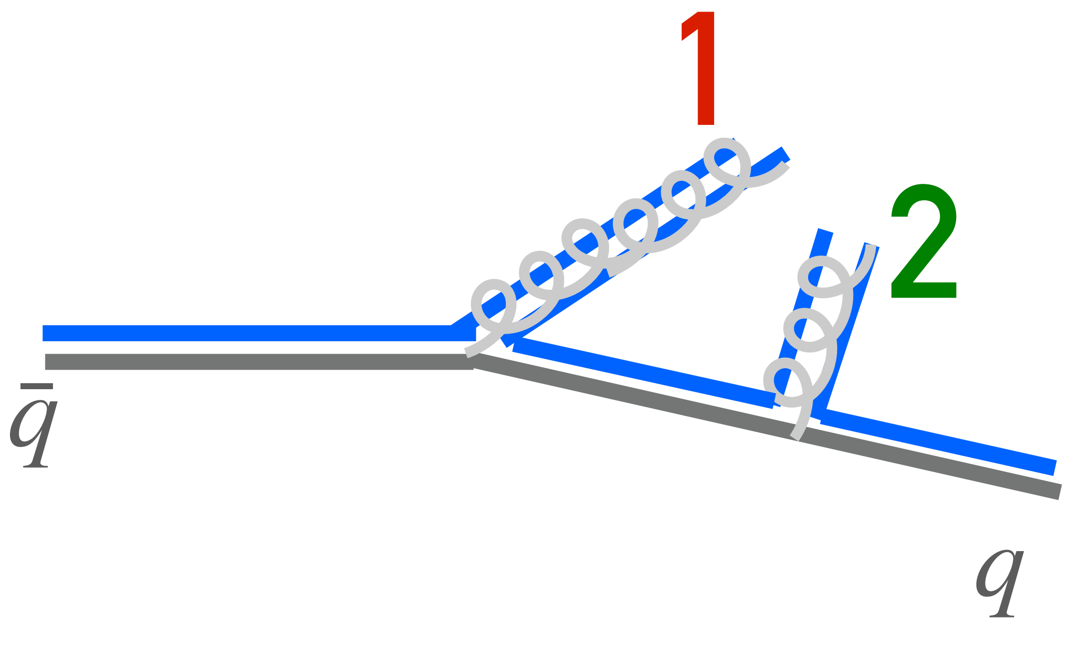

Double strong ordering: $|\eta_1 - \eta_2| \gg 1,\ \ln k_{t,1}/k_{t,2} \gg 1,$ *the recoil is not an issue in this limit and the 1st emission is independent from the 2nd:* ***LL is OK***!

1805.09327 Dasgupta, Dreyer, Hamilton, Monni, Salam

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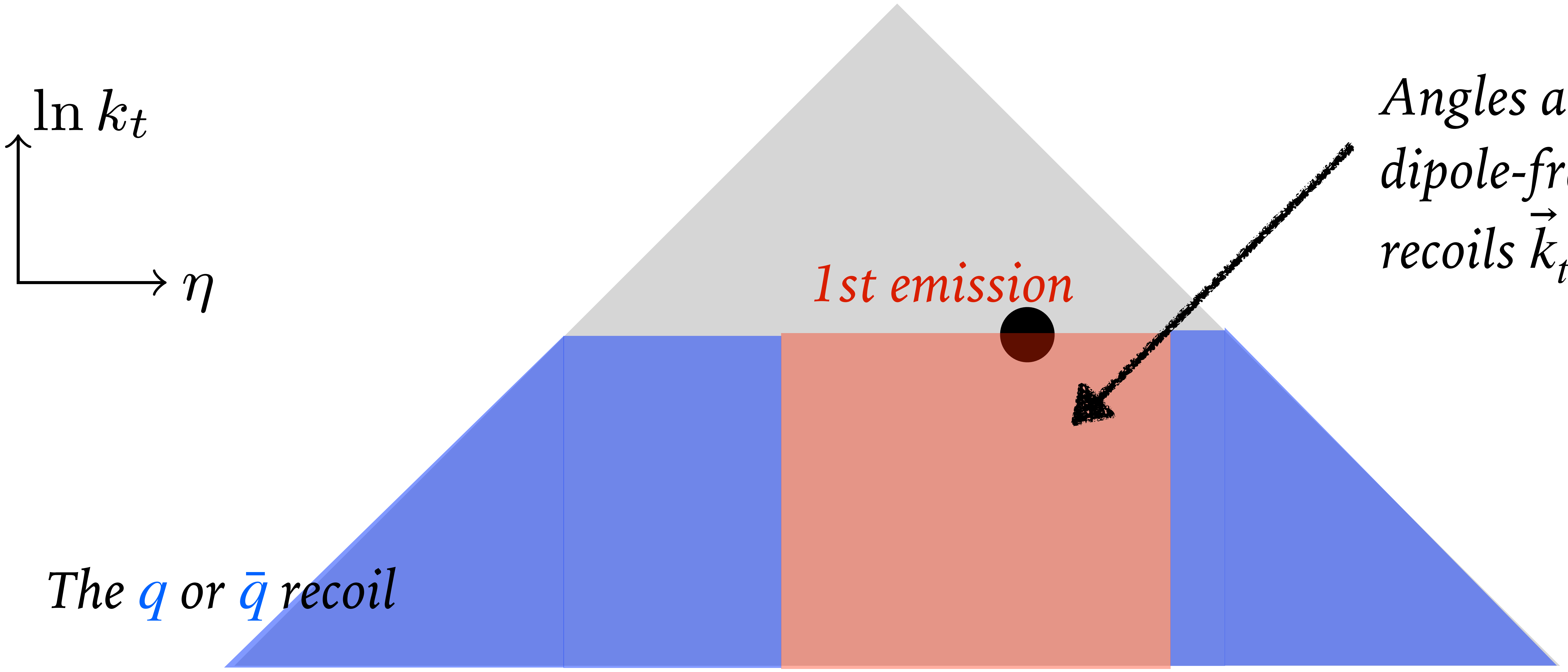
Emission of a **soft-collinear gluon** g_2, from a $q\bar{q}g_1$ final-state, where g_1 is soft-collinear as well



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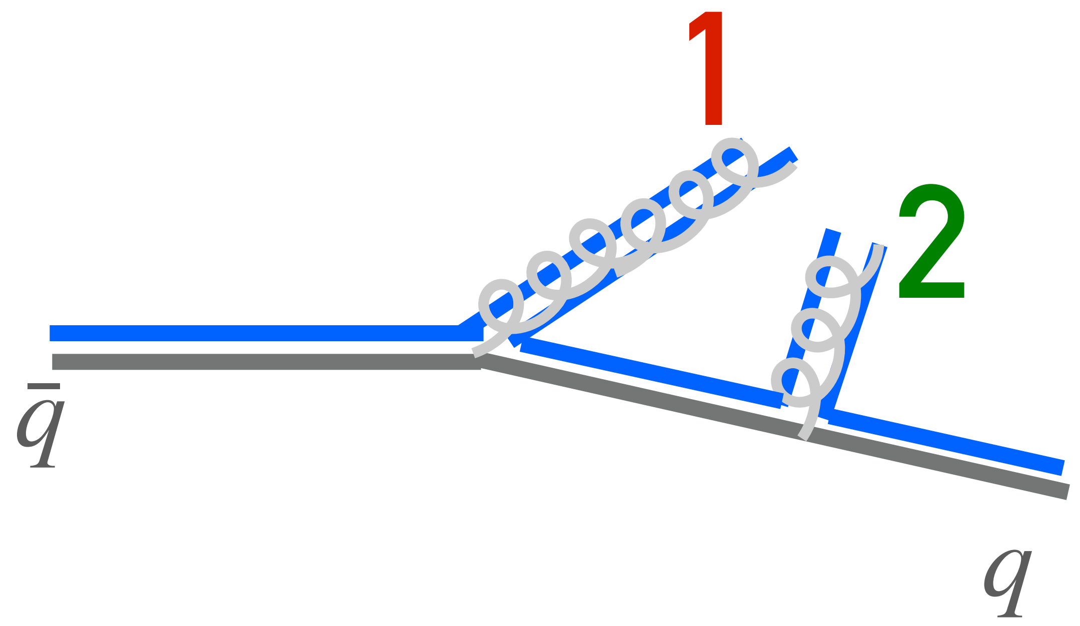


*Single strong ordering: $|\eta_1 - \eta_2| \gg 1$ but $k_{t,1} \sim k_{t,2}$, the 1st emission is affected by the 2nd: **NLL is not OK!***

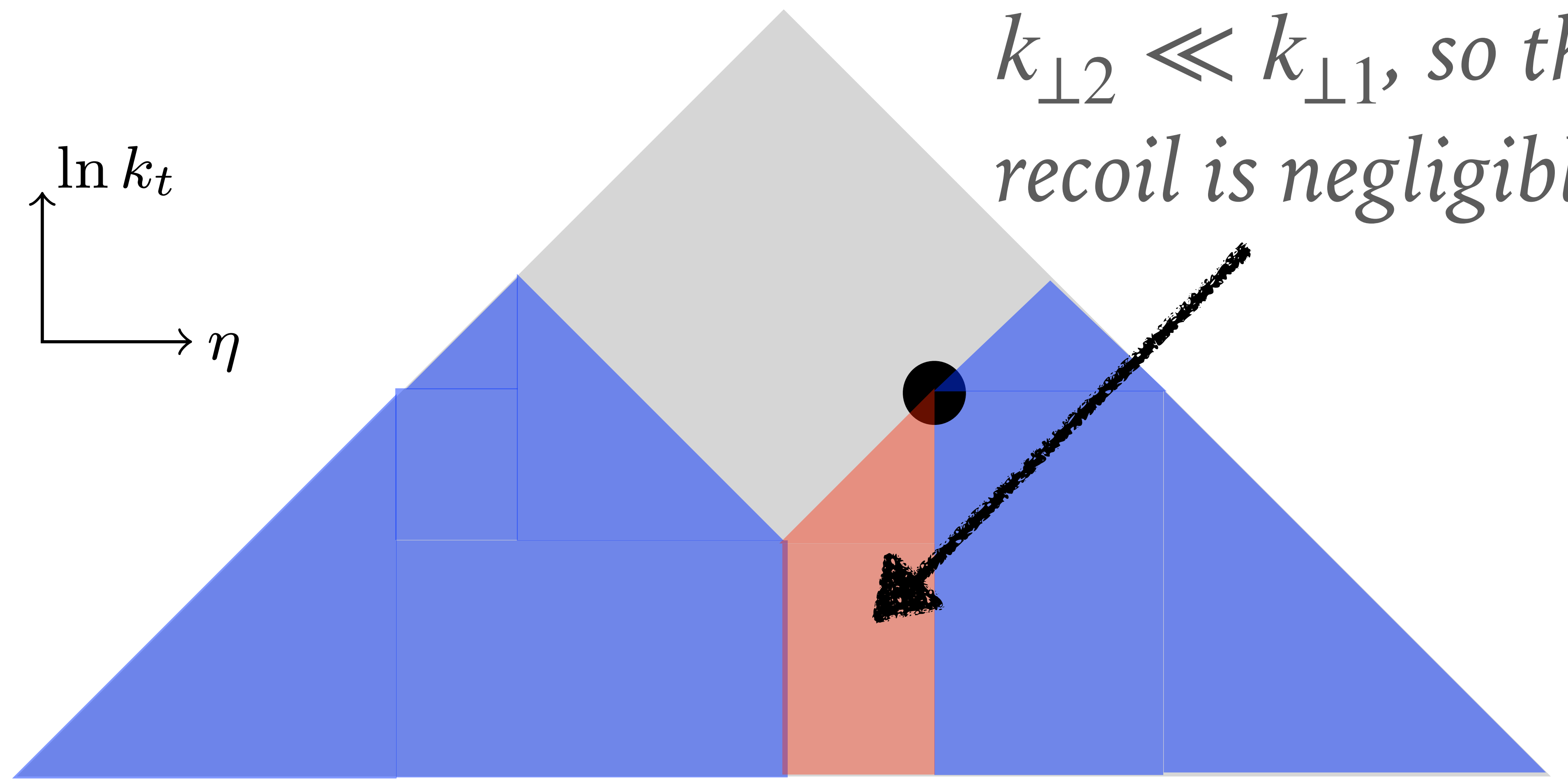
1805.09327 Dasgupta, Dreyer, Hamilton, Monni, Salam

Building a NLL shower

2002.11114 Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez

Angles are measured in the event frame

PanLocal$(0 < \beta < 1)$



$k_{\perp 2} \ll k_{\perp 1}$, *so the recoil is negligible*

Evolution variable: $v \sim k_\perp e^{-\beta|y|}$

Deductor by Nagy & Soper 0912.4534 follows a similar approach (with $\beta = 1$)

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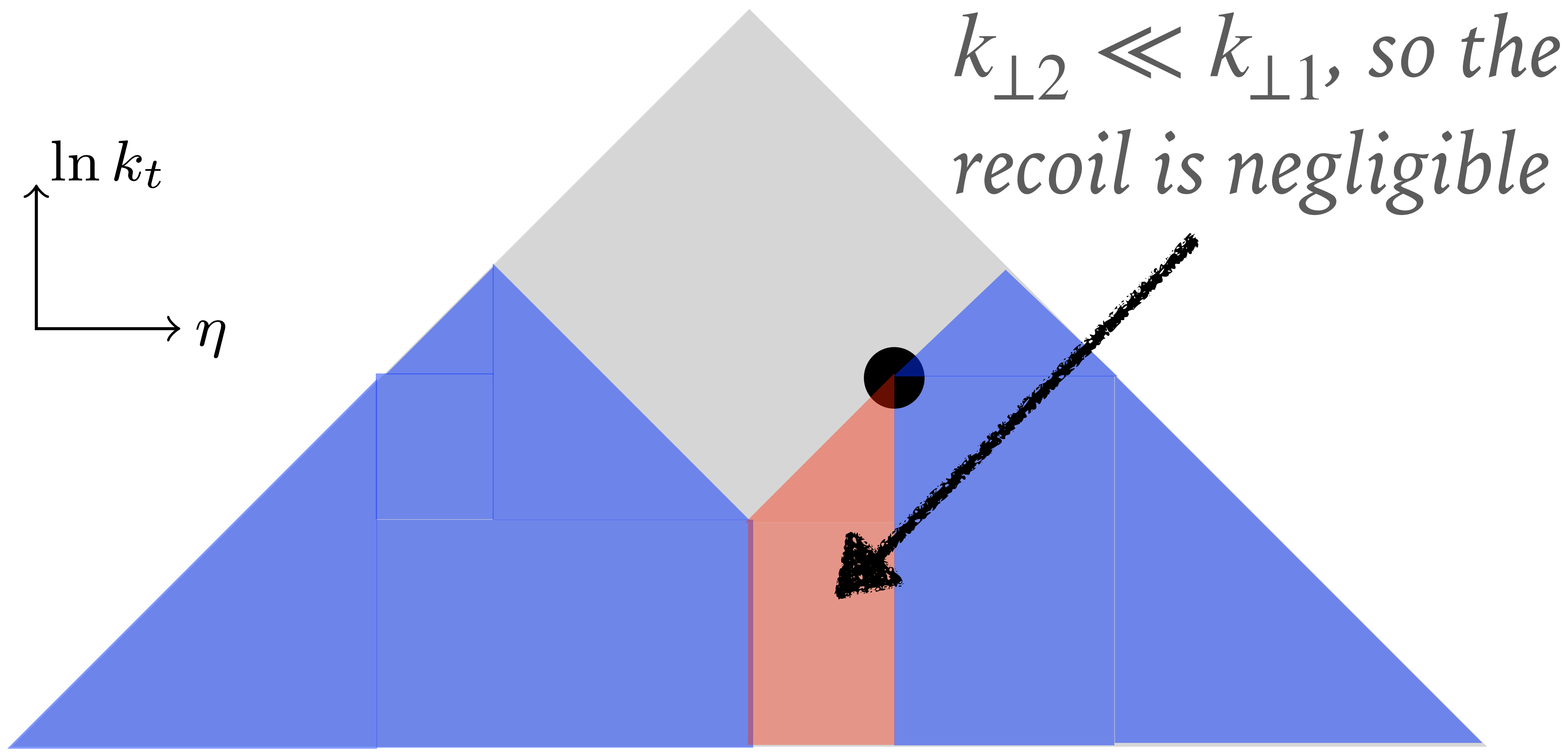

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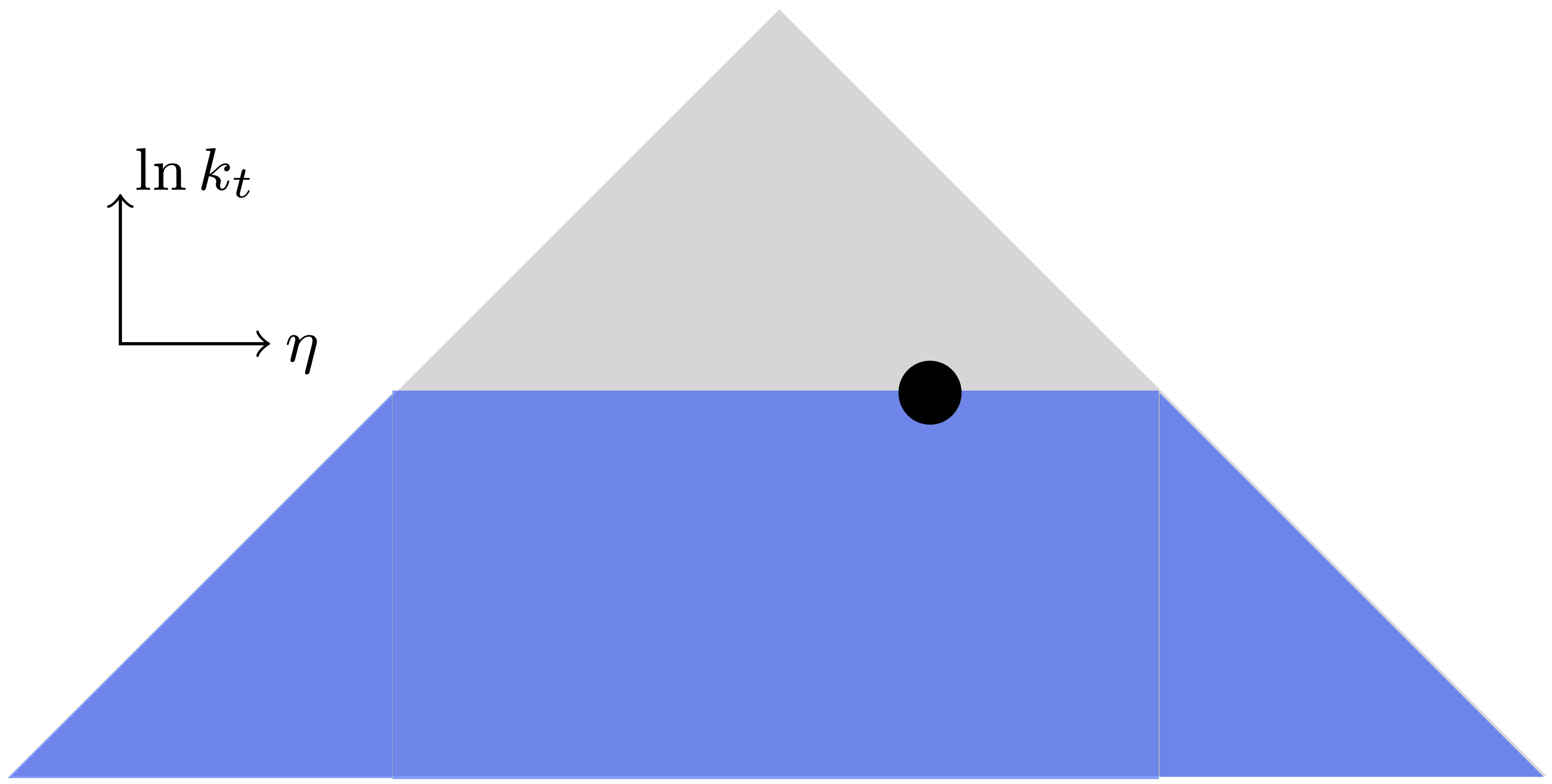

Recoil: $k_\perp$ is redistributed among all the partons in the event (mainly the hardest)

Deductor by Nagy & Soper 0912.4534 follows a similar approach (with $\beta = 1$)

Forshaw, **H**olguin, and **P**lätzer 2003.06400, and **Alaric** by Herren et al. 2208.06057 follow a similar approach

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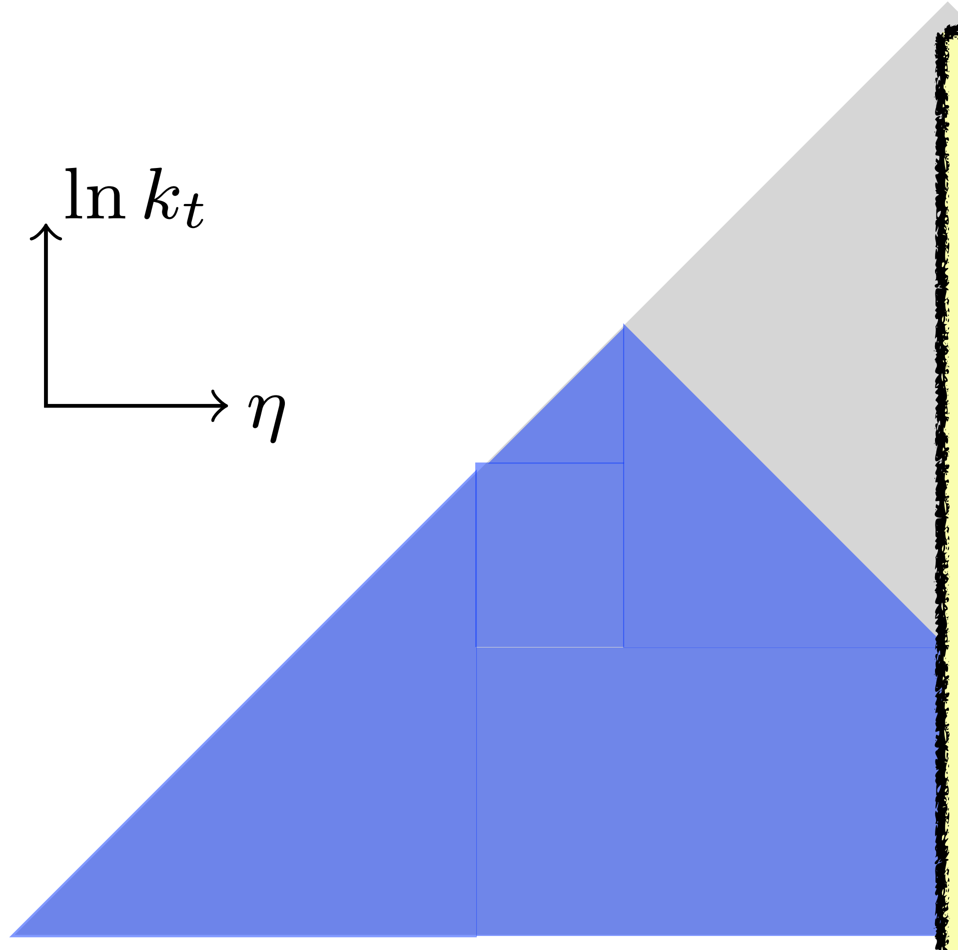

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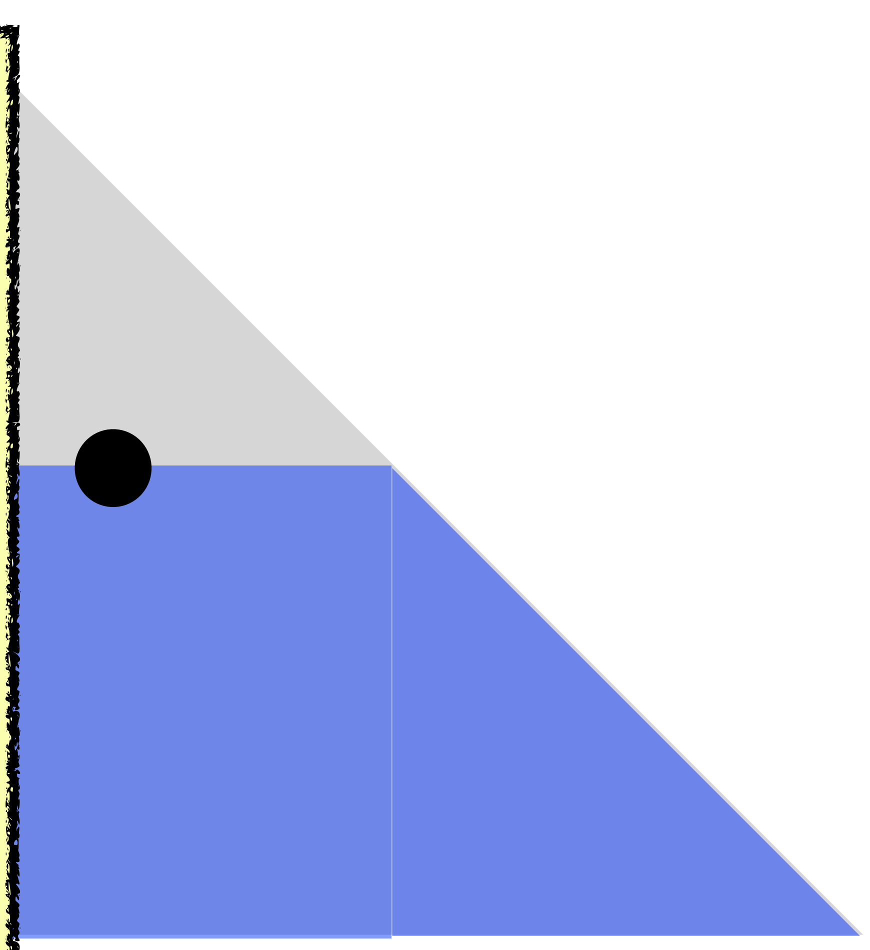
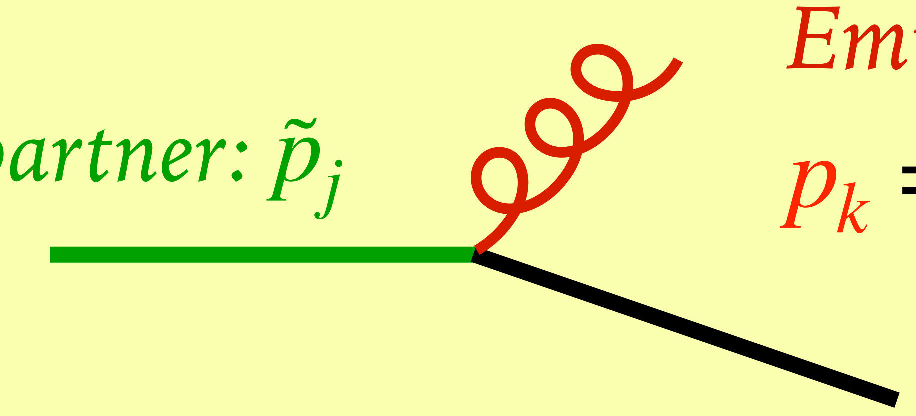


Recoil: $k_\perp$ is redistributed among all the partons in the event (mainly the hardest)

Conversely by the ***PanScales*** *showers,* ***Deductor****,* ***Alaric*** *and* ***FHP****,* **colour parter $\neq$ recoiler**



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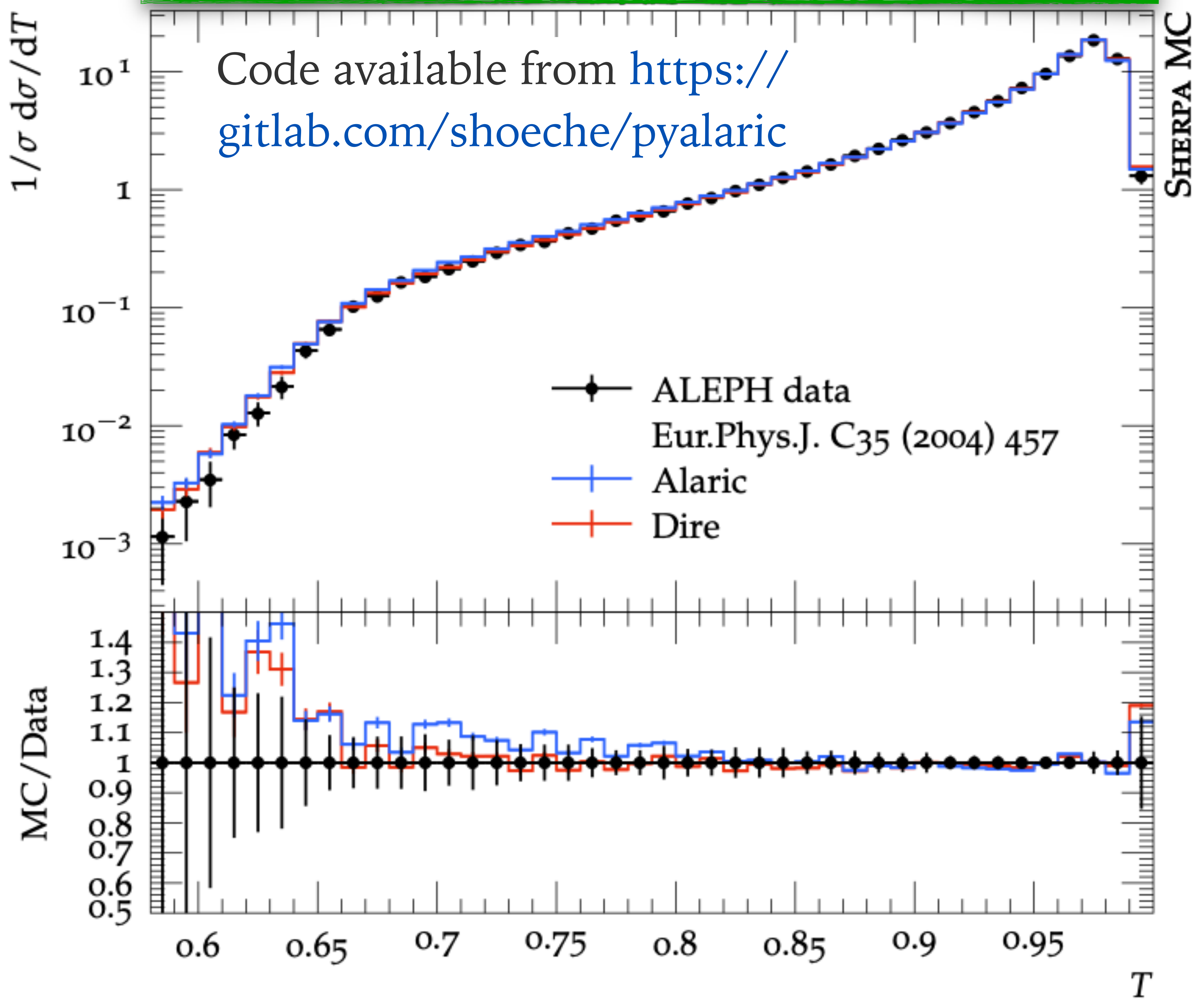
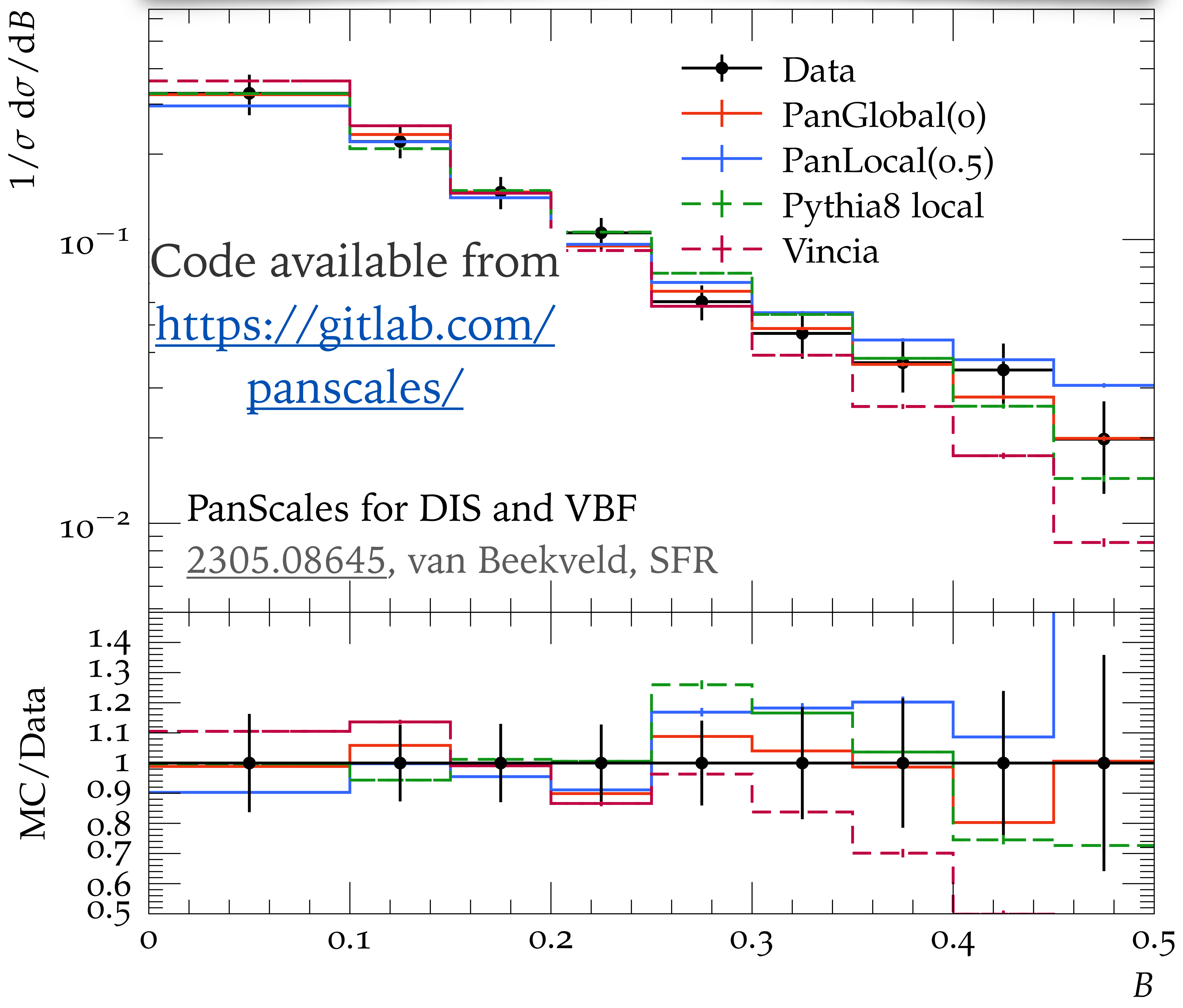
Comparison with data

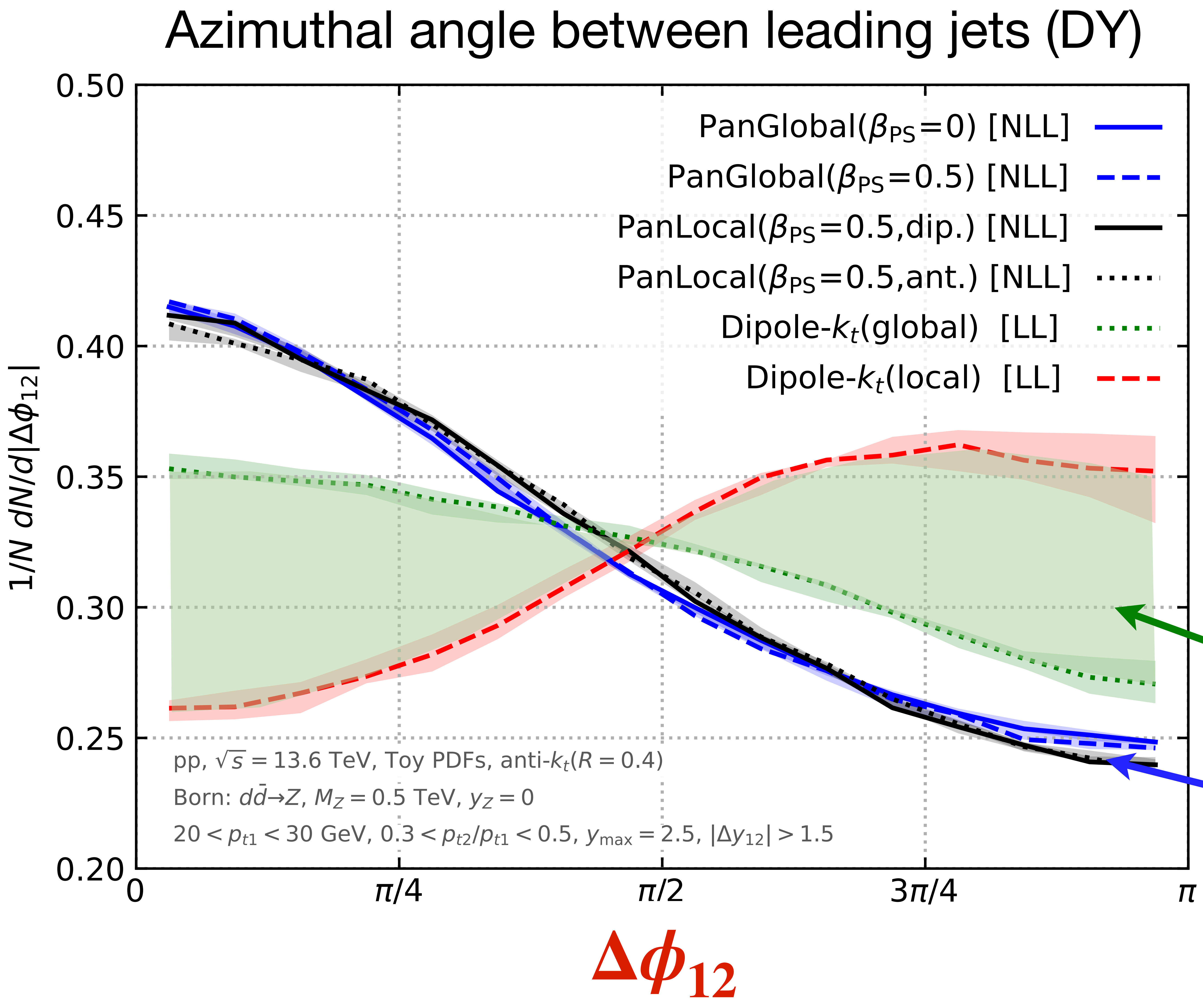
e+e− thrust at $\sqrt{s}$=91 GeV

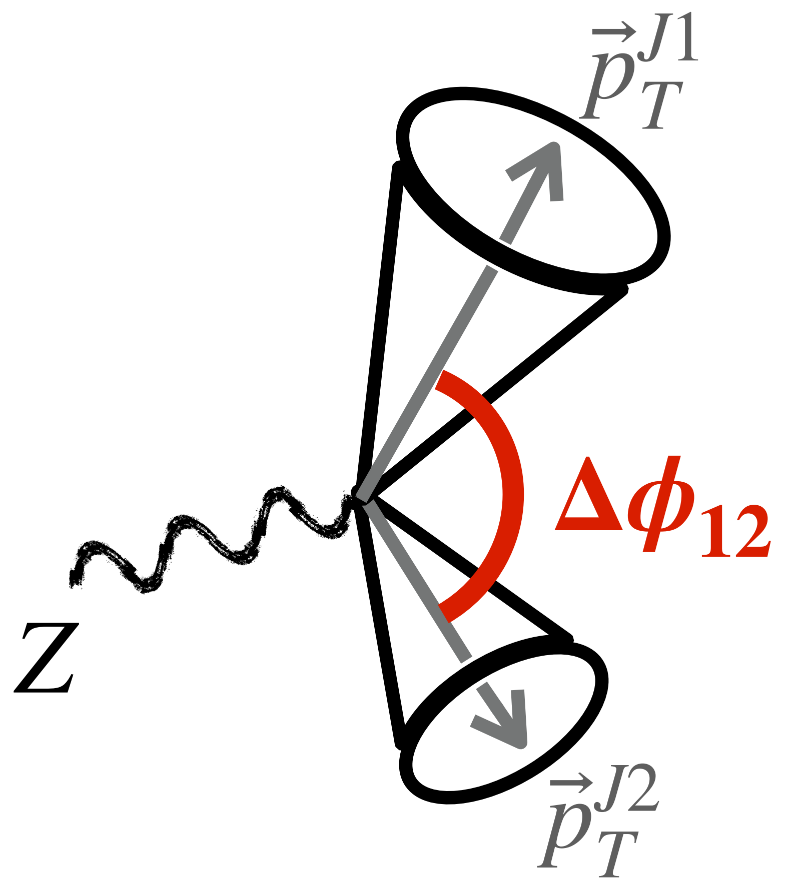


DIS broadeing at Q=58 GeV



$m_{\ell\ell} = 500\,\text{GeV}$





PanScales for $pp \to$ colour singlet: 2207.09467, van Beekveld, SFR, Hamilton, Salam Soto Ontoso, Soyez, Verheyen:

NLL/LL discrepancies at larger scales

LL showers

NLL showers

NNLO matching

NLO matching ~ $\mathcal{O}(20\%)$ control on inclusive observables
%-level precision requires at least NNLO matching

MiNNLO [Monni, Nason, Re, Wiesemann, Zanderighi, 1908.06987]

- Start with a **POWHEG NLO** generator for the process with an extra jet
- Use **NNLL' resummation** for a transverse observable to regulate the unresolved limit and achieve NNLO accuracy for the inclusive distributions

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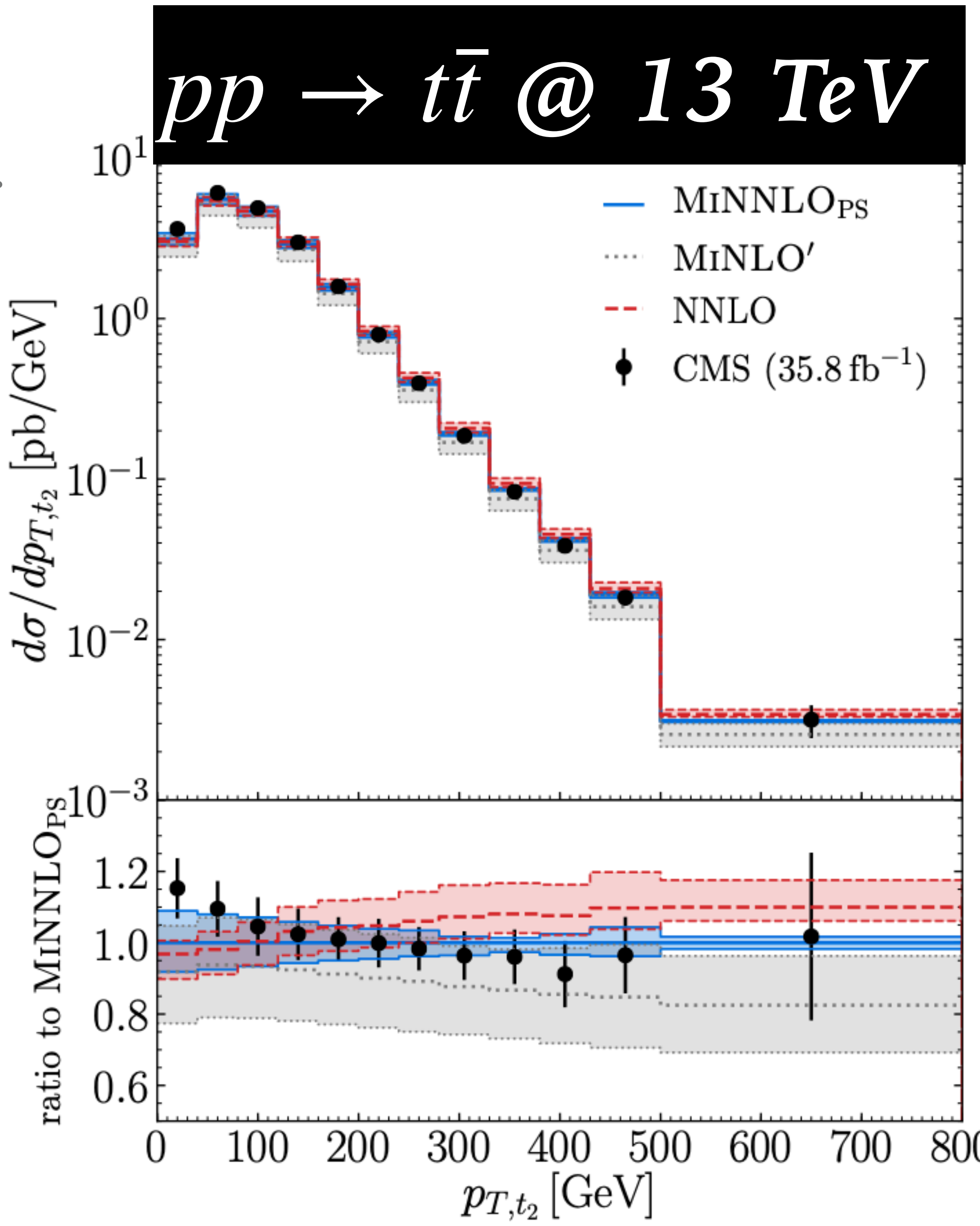
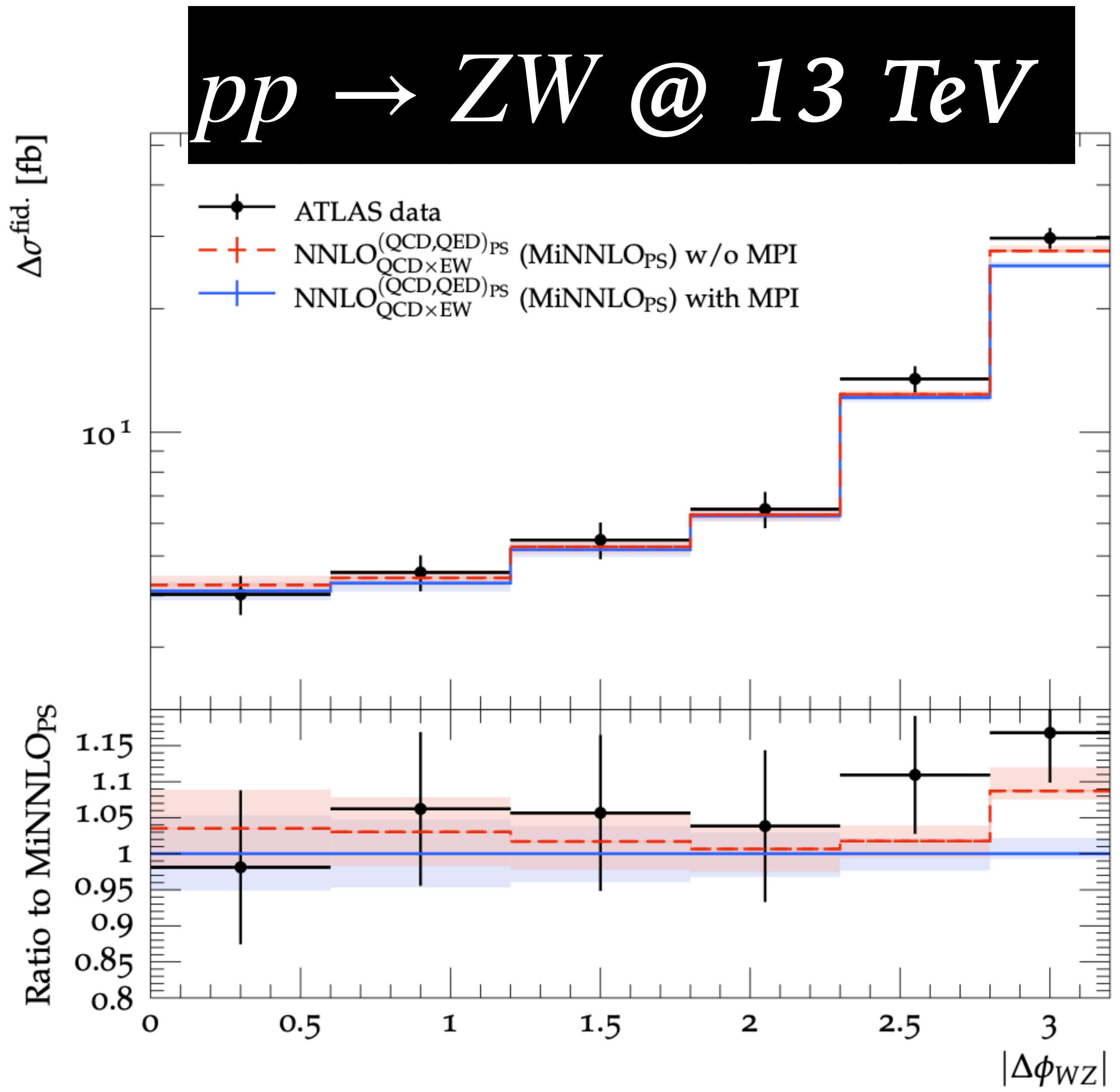
- Use **NNLL' resummation** for a transverse observable to regulate the unresolved limit and achieve NNLO accuracy for the inclusive distributions
- It can handle $pp \to$ colour-singlet and $pp \to Q\bar{Q}$
  $t\bar{t}$: Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi, *2012.14267*
  $b\bar{b}$: Mazzitelli, Ratti, Wiesemann, Zanderighi, *2302.01645*
- Exploration on how to include **EW corrections** just begun
  NNLO QCD and **NLO EW** for $pp \to WZ$, Lindert, Lombardi, Wiesemann, Zanderighi, Zanoli *2208.12660*

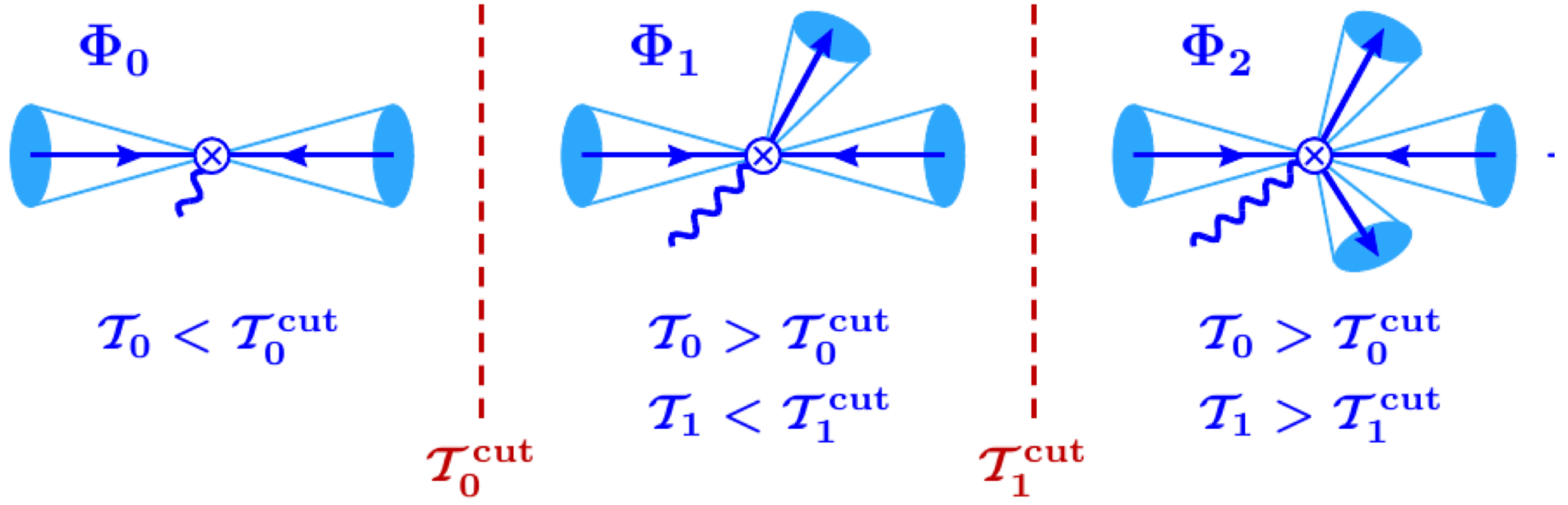




NNLO matching

GENEVA [Alioli, Bauer, Berggren, Tackmann, Walsh 1311.0286]

- Fully differential **NNLO calculation** using **N-jettiness**
- Slice the phase space, the separation between 0(1) and 1(2) jets is determined by the **NNLL'** (**NLL'**) resummation of $\tau_0^{\text{cut}}(\tau_1^{\text{cut}})$

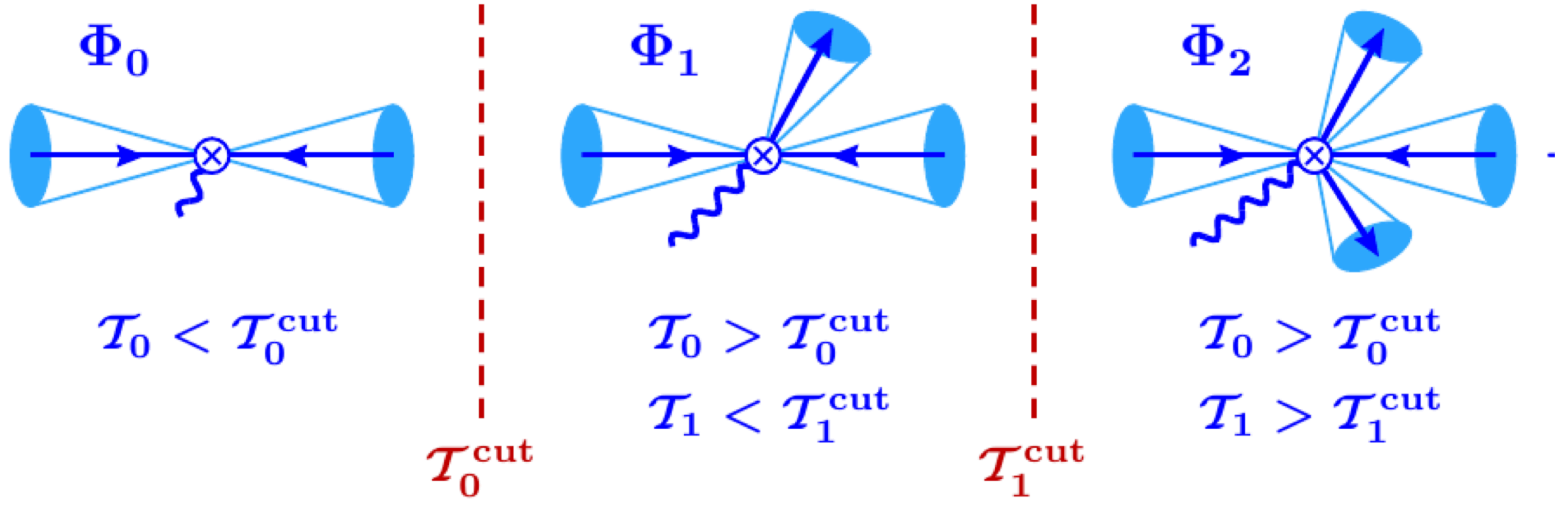


- Variant (2): **transverse-momentum of the colour singlet** plus 1-jettiness [Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, Nagar, Napolitano, Rottoli, 2102.08390]

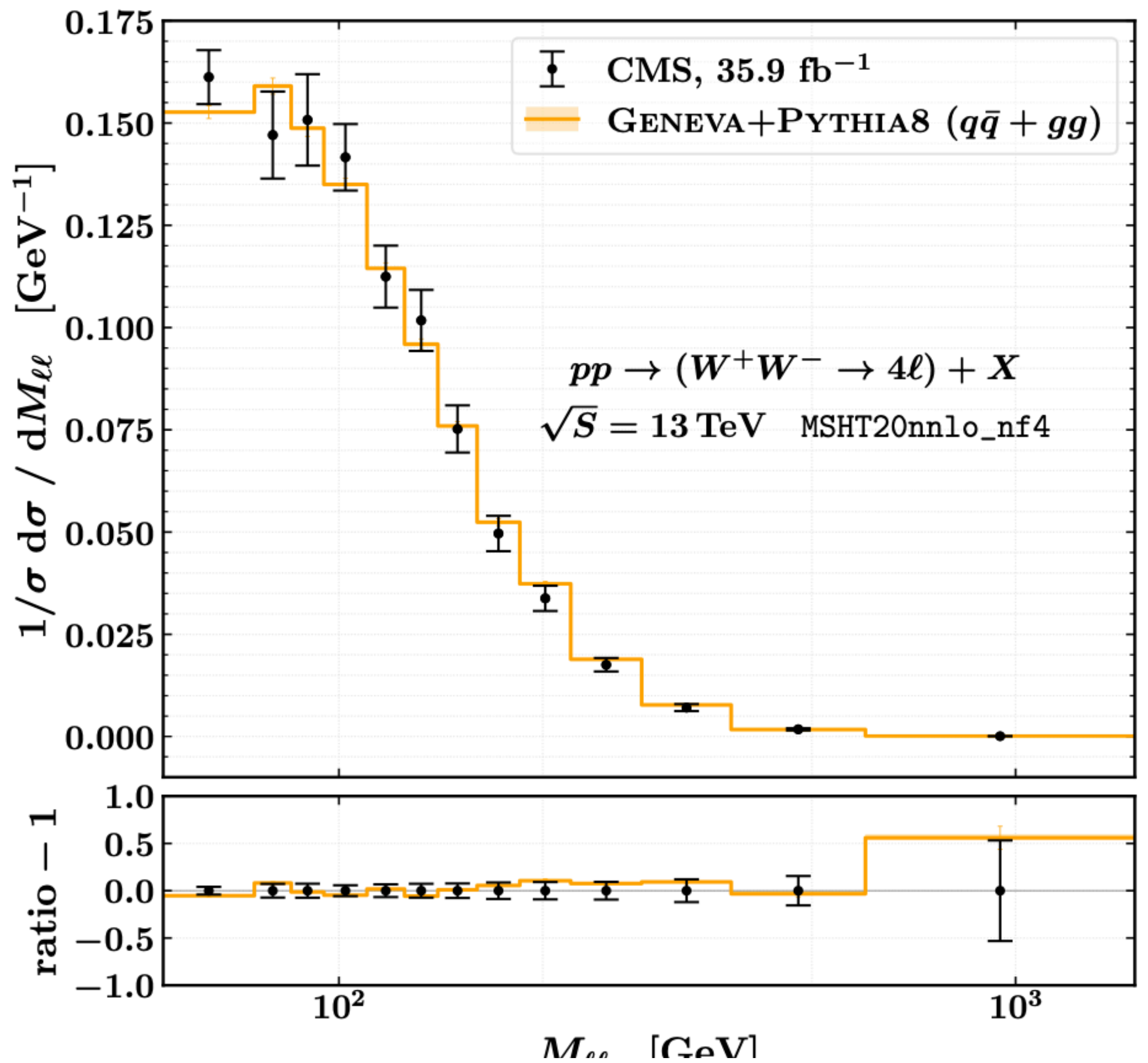
NNLO matching

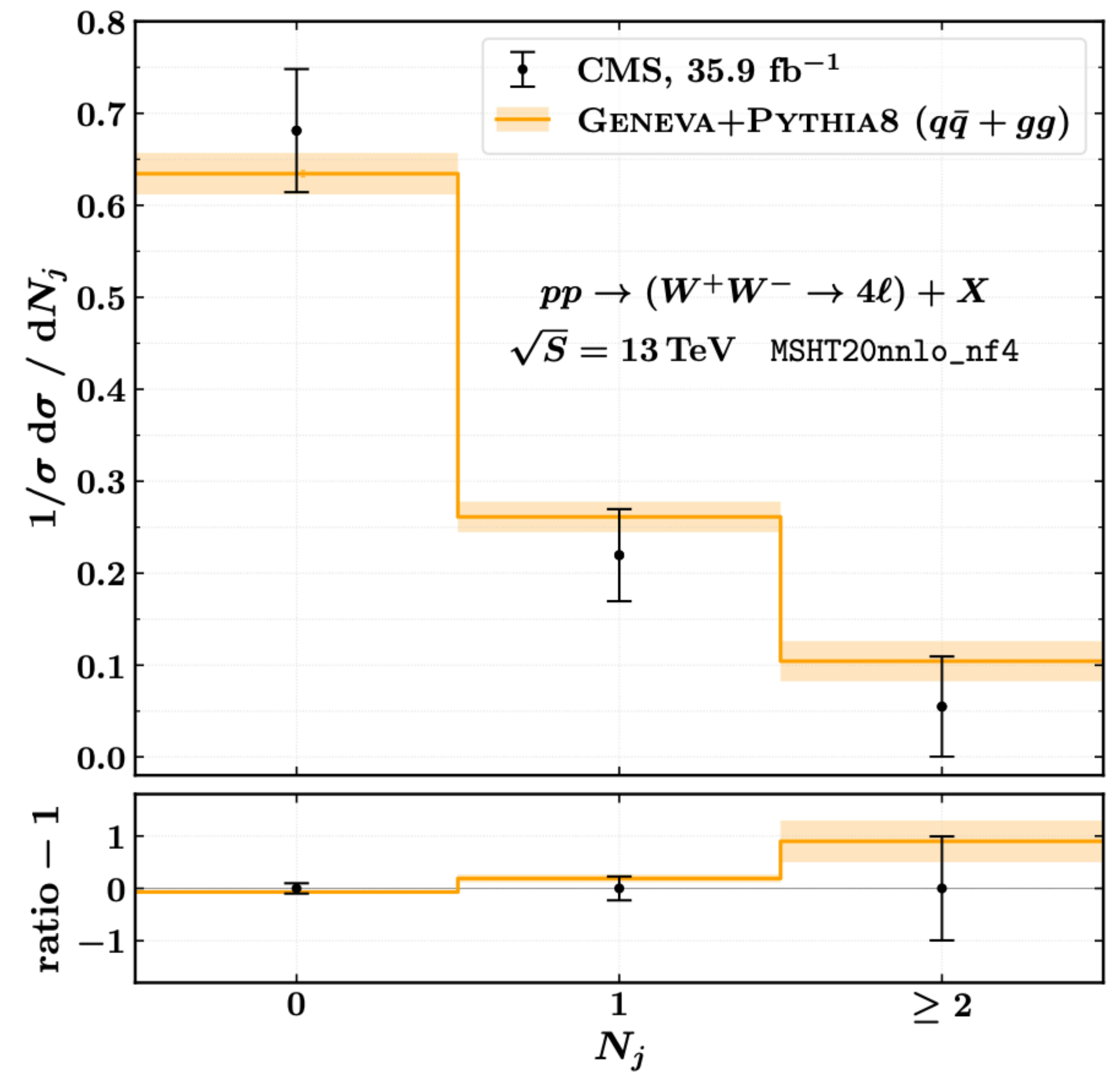
GENEVA [Alioli, Bauer, Berggren, Tackmann, Walsh 1311.0286]

- ➡ Fully differential **NNLO calculation** using **N-jettiness**
- ➡ Slice the phase space, the separation between 0(1) and 1(2) jets is determined by the **NNLL'** (**NLL'**) resummation of $\tau_0^{cut}(\tau_1^{cut})$



- ➡ Variant (2): **transverse-momentum of the colour singlet** plus 1-jettiness [Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, Nagar, Napolitano, Rottoli, 2102.08390]
- ➡ Variant (3): **jet veto** (for both the 0 and 1 jet case) [Gavardi, Lim, Alioli, Tackmann, 2308.11577]

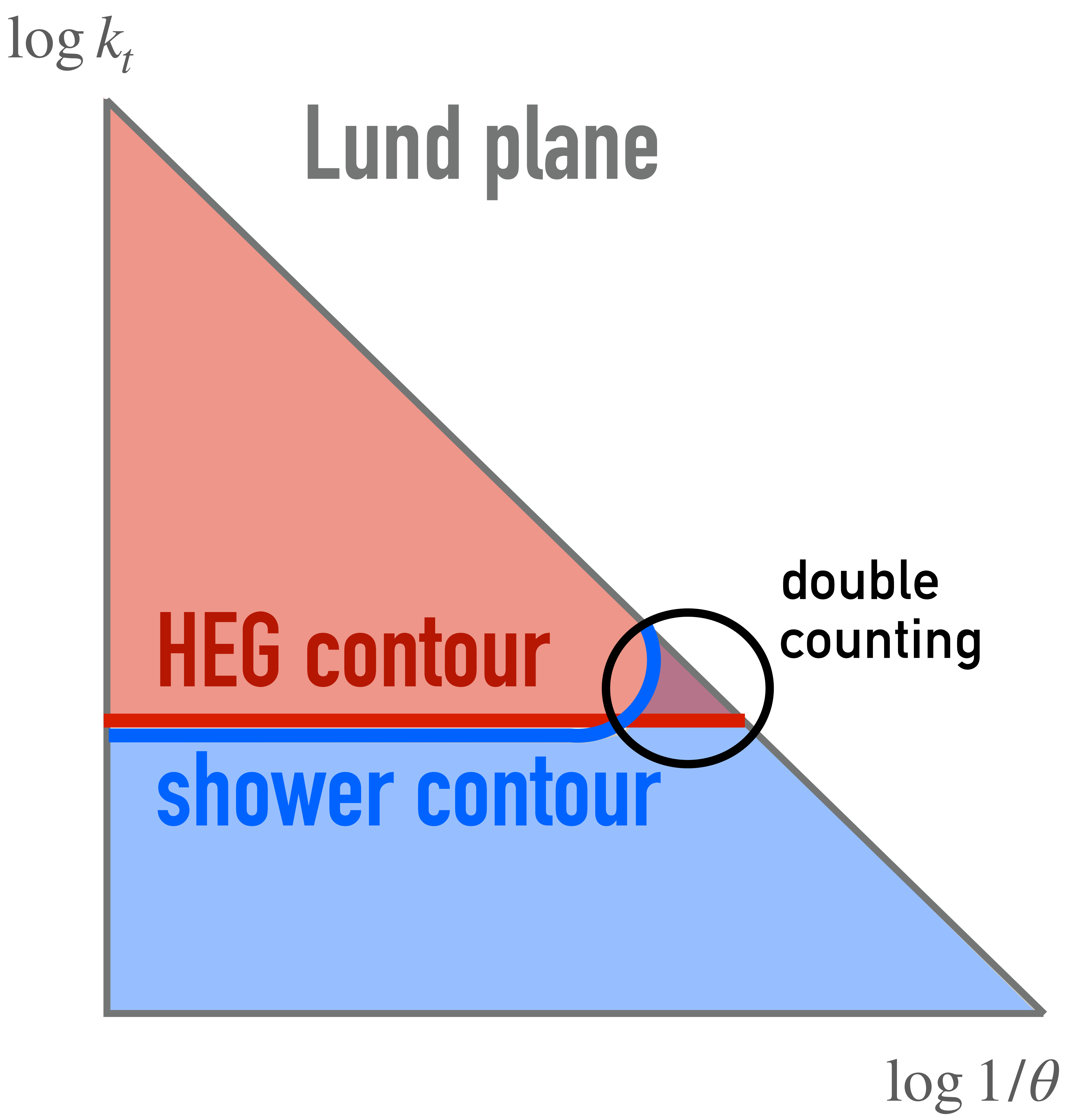


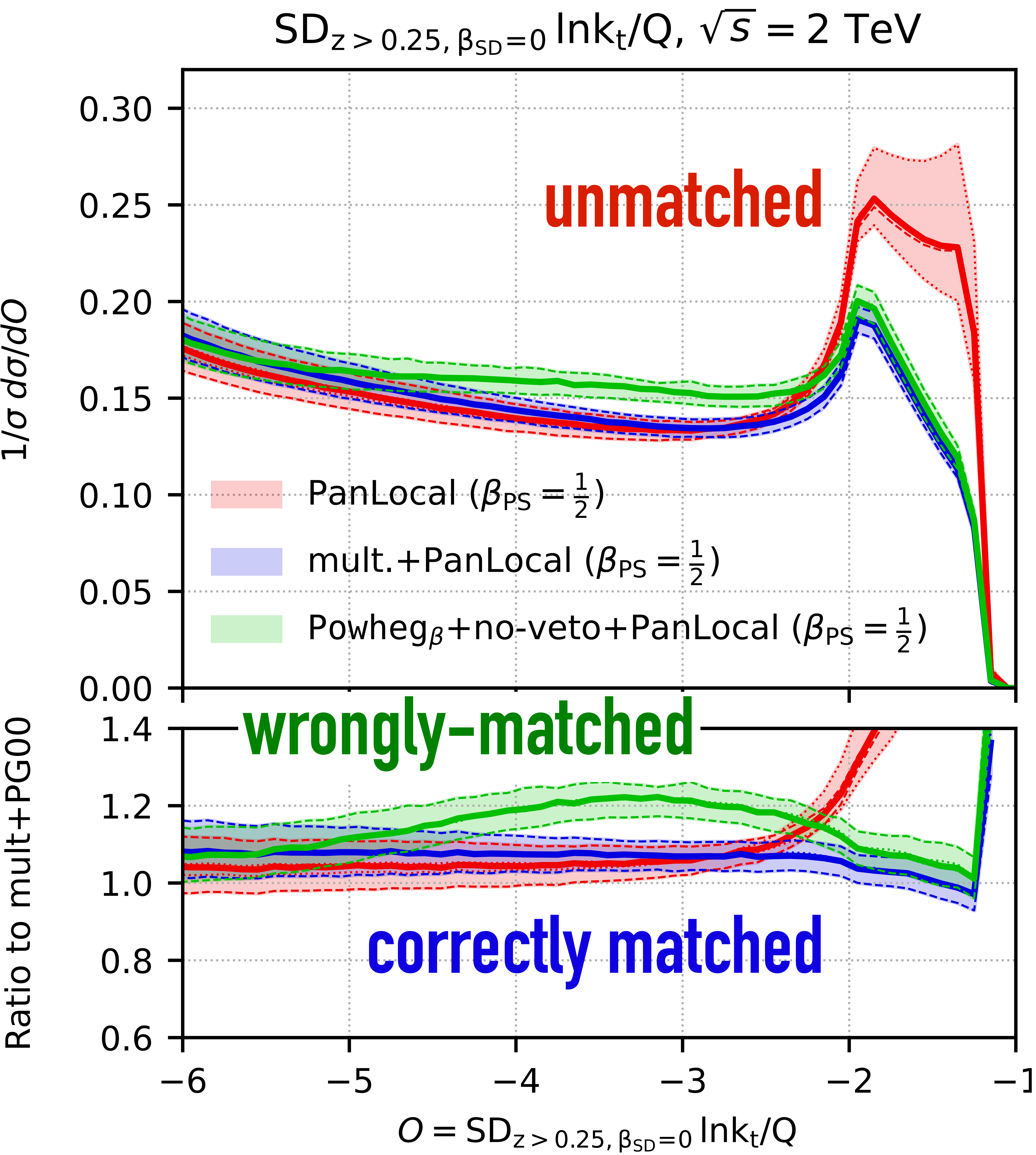


Matching and Logarithmic Accuracy

Hamilton, Karlberg, Salam, Scyboz, Verheyen, 2301.09645

- Proof of concept explored for $e^+e^- \to 2\,\text{jets}$ @ NLO
- some matching schemes supplement shower with pure $\mathcal{O}(\alpha_s)$, e.g. MC@NLO:
  Shower log accuracy easy to maintain
  (**not necessarily easy to implement**, ongoing efforts in Alaric, see e.g. 2307.00728)
- in other schemes, first emission is generated by an external program (**POWHEG BOX, MiNNLO, Geneva**, etc.):
  Shower log accuracy subtle to maintain
- NB: concern is not just kinematic mismatch, but also any mismatch in partitioning functions





NLO matching & log-accuracy

Hamilton, Karlberg, Salam, Scyboz, Verheyen, 2301.09645

- Done correctly, **NLO matching augments accuracy** of shower from NLL to NLL + NNDL (for event shapes), and it is a **prerequisite for NNLL accuracy**
- Done wrongly, it breaks exponentiation structure of shower (impact depends on observable)
- example with significant impact is **SoftDrop transverse momentum** (i.e. jet substructure)

$$\partial_L \Sigma_{\mathrm{SD}}(L) = \bar{\alpha} c\, e^{\bar{\alpha} c L - \bar{\alpha}\Delta} - 2\bar{\alpha} L e^{-\bar{\alpha} L^2}(1 - e^{-\bar{\alpha}\Delta})$$

spurious term from wrong matching

Towards NNLL accuracy

SFR, Hamilton, Karlberg, Salam, Scyboz, Soyez, 2307.11142

(Few) % precision in exclusive observables requires at least NNLL accuracy

Soft emission — i.e. inclusion of **double-soft current** + associated **virtual corrections**

- NB: Vincia and Sherpa groups have also explored inclusion of the double-soft current; part of novelty here is doing so to get the log-accuracy benefit.

This maintains NLL accuracy and further achieve

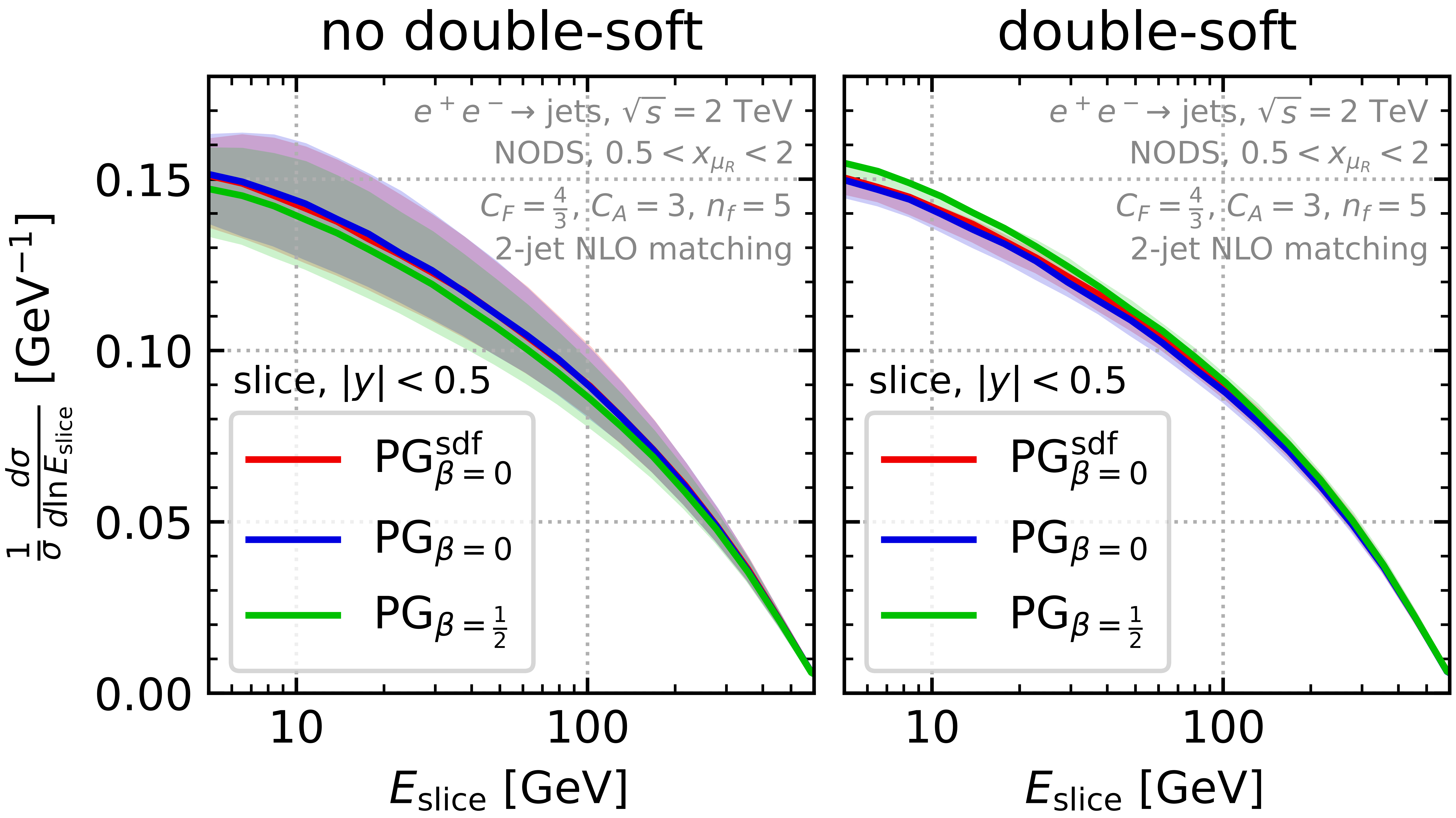
- **NNDL accuracy** for [subjet] multiplicities, i.e. terms $\alpha_s^n L^{2n}$, $\alpha_s^n L^{2n-1}$, $\boldsymbol{\alpha_s^n L^{2n-2}}$
- **Next-to-Single-Log (NSL) accuracy** for non-global logarithms, e.g. energy in a slice, all terms $\alpha_s^n L^n$ and $\boldsymbol{\alpha_s^n L^{n-1}}$ (at leading-N_c)

NB: done using PanGlobal, so far just in $e^+e^- \to q\bar{q}$

NSL Pheno outlook

S.F.R., Hamilton, Karlberg, Salam, Scyboz, Soyez
2307.11142

- Energy flow in slice between two 1 TeV jets
- First time non-global obs is known at **NSL** (at leading N_c) including the **full n_f dependence**
- **Double-soft reduces uncertainty band**



Uncertainty here is estimated varying the renormalisation scale

$$\alpha_s^{\mathrm{CMW}}(k_t; x_R) = \alpha_s(x_R k_t)\left(1 + \frac{\alpha_s(x_R k_t)}{2\pi}(K_{\mathrm{CMW}} + \Delta K(\Phi)) + 2\alpha_s(x_R k_t) b_0 (1-z)\ln x_R\right)$$

Summary and Conclusions

- **NLL shower are about to become the new standard**
  - benefits of LL → NLL include reduced uncertainties (**reliable estimate uncertainties**)
  - for realistic applications we also need **massive quarks** (Deductor and Alaric already include them), at least NLO matching, and tuning
- **Higher log accuracy is one of the next frontiers**
  - double-soft (+ virtual) corrections: NNDL multiplicity and NSL non-global logarithms
- **Percent precision requires at least NNLO matching**
  - NLO+NLL matching is in place only for simple processes, ongoing work for generic processes
  - The way is long, but not too long, for NNLO+(N)NLL matching

Backup

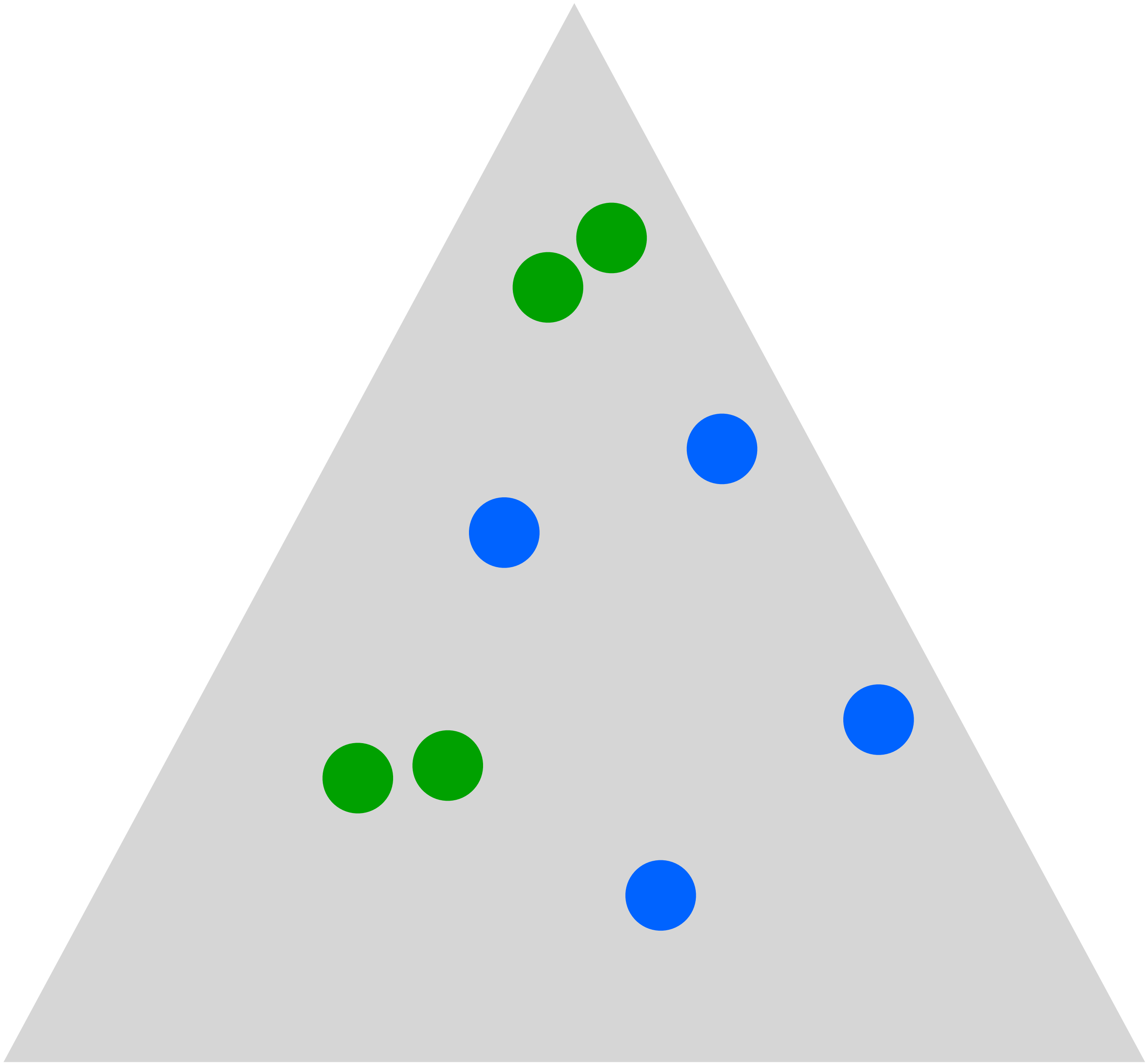
Towards NNLL accuracy

SFR, Hamilton, Karlberg, Salam, Scyboz, Soyez, 2307.11142

(Few) % precision in exclusive observables requires at least NNLL accuracy

Soft emission — i.e. inclusion of **double-soft current** + associated **virtual corrections**

- any pair of soft emissions with commensurate energy and angles should be produced with the correct [double-soft] matrix element
- probability for any single soft emission should be NLO accurate
- NB: Vincia and Sherpa groups have also explored inclusion of the double-soft current; part of novelty here is doing so to get the log-accuracy benefit.

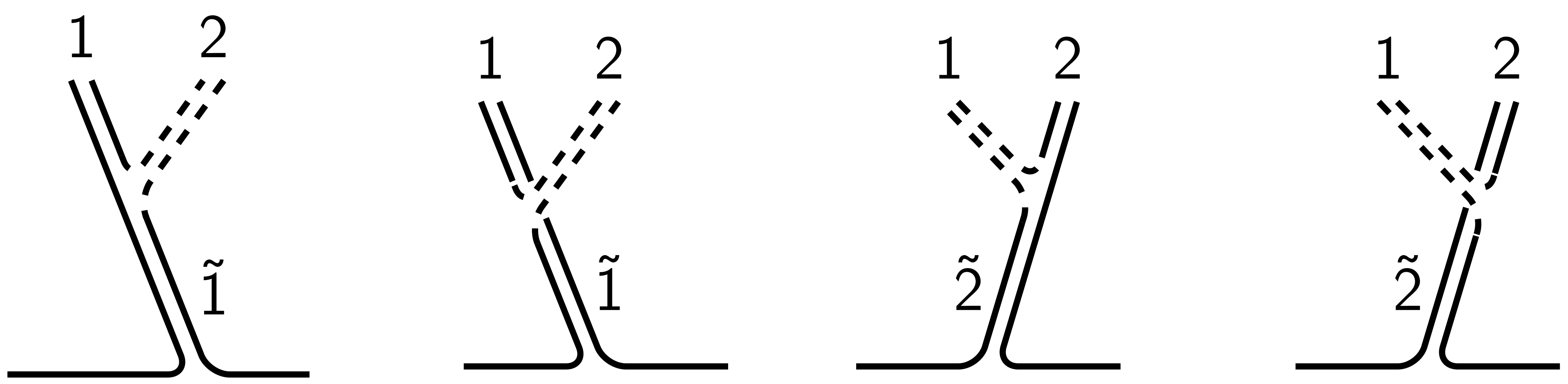


This should maintain NLL accuracy and further achieve

- **NNDL accuracy** for [subjet] multiplicities, i.e. terms $\alpha_s^n L^{2n}$, $\alpha_s^n L^{2n-1}$, $\boldsymbol{\alpha_s^n L^{2n-2}}$
- **Next-to-Single-Log (NSL) accuracy** for non-global logarithms, e.g. energy in a slice, all terms $\alpha_s^n L^n$ and $\boldsymbol{\alpha_s^n L^{n-1}}$ (at leading-N_c)

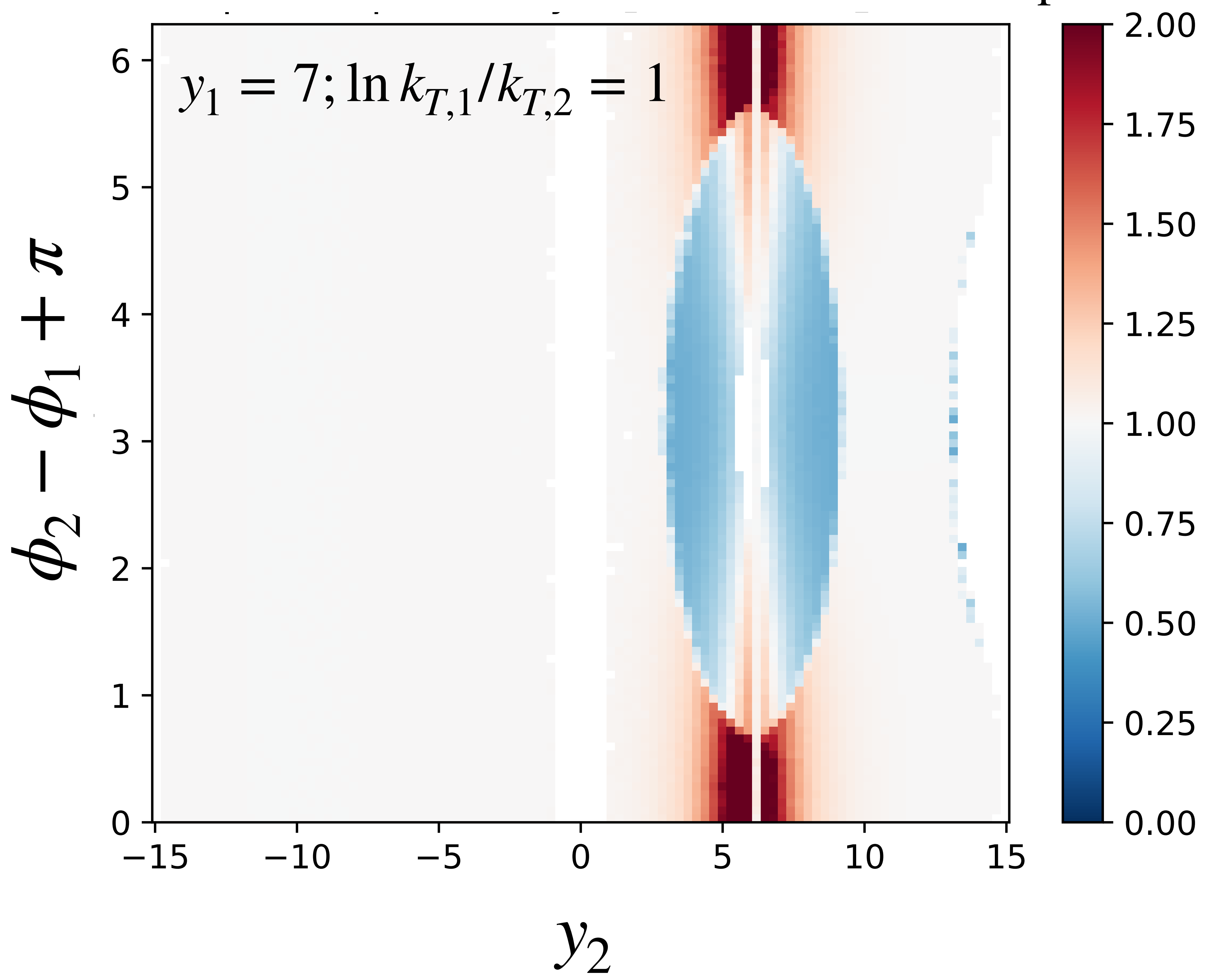
NB: done using PanGlobal, so far just in $e^+e^- \to q\bar{q}$

1. Real corrections: pair of soft emissions



- a given two-emission configuration can come from several shower histories
- **accept a given emission with exact double-soft $M^{(\mathrm{DS})}_{\mathrm{exact}}$ divided by shower's effective double-soft matrix element** summed over the histories h that could have produced that configuration

Double-soft acceptance P_{accept}

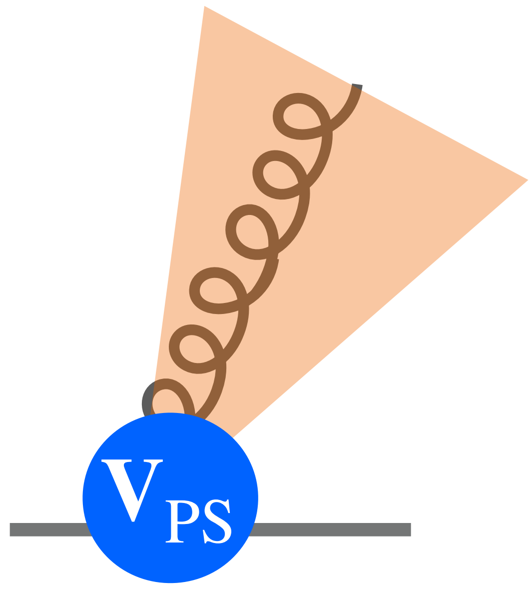


$$P_{\mathrm{accept}} = \frac{M^{(\mathrm{DS})}_{\mathrm{exact}}}{\sum_h M^{(\mathrm{DS})}_{h,\mathrm{PS}}}$$

2. Virtual corrections for soft emissions

With our double soft acceptance we have $\mathbf{R}_{\mathbf{PS}} = \mathbf{R}$.

To ensure



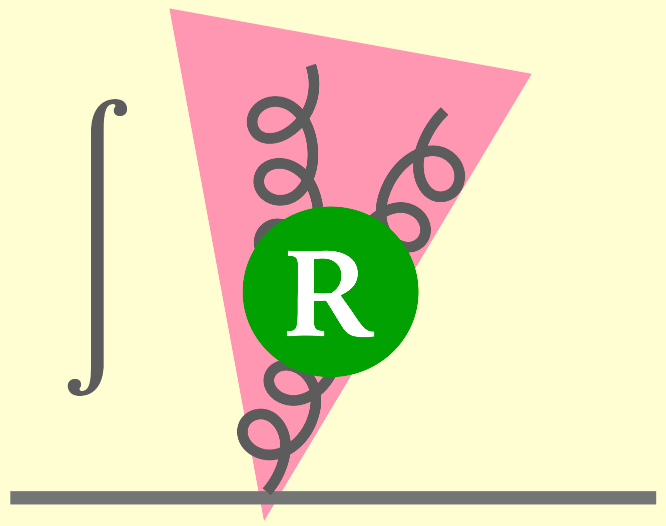
$$= \frac{\alpha_s}{2\pi} K_{\rm CMW} - \int$$

We modify the CMW scheme

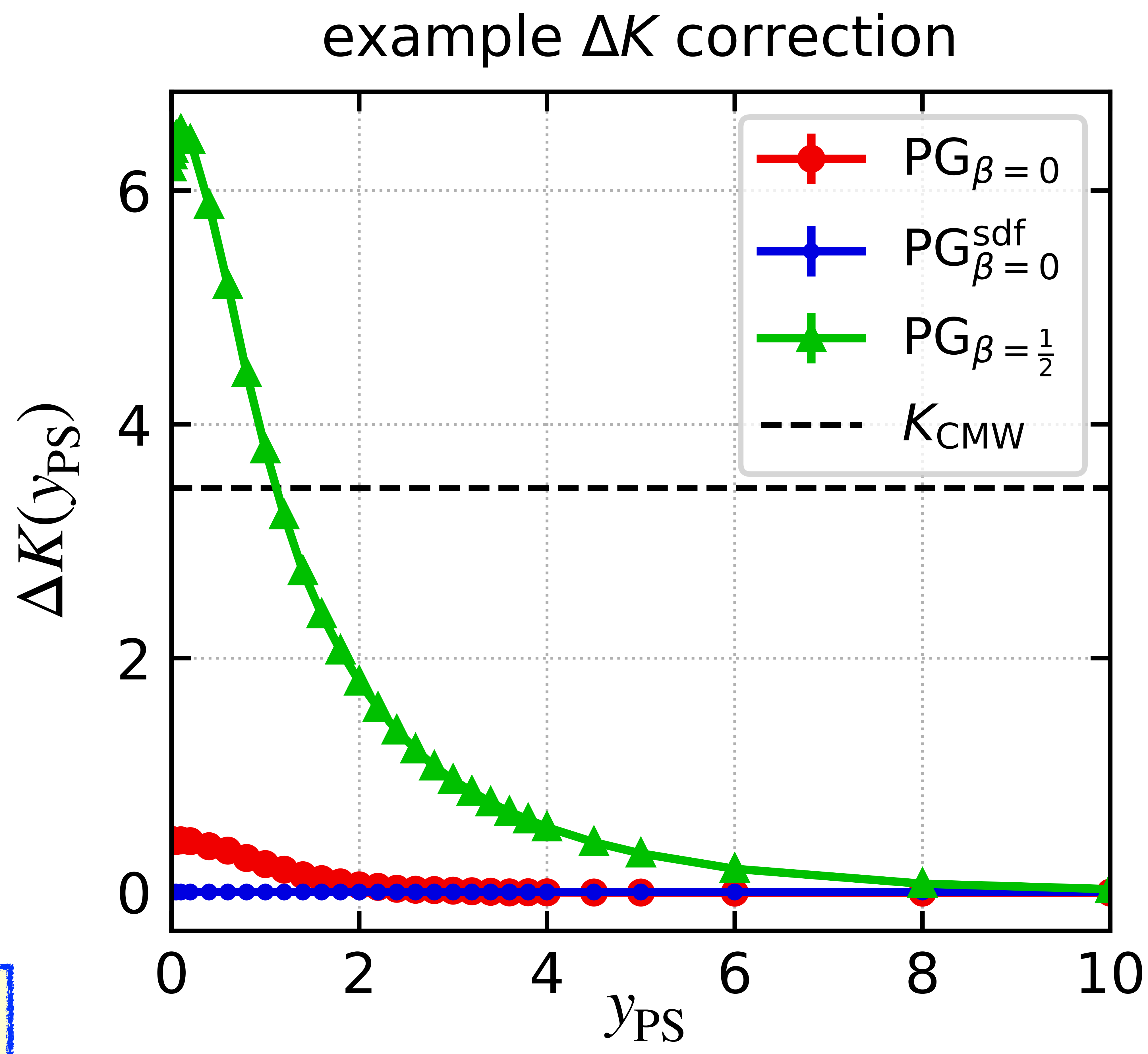
$$K_{\rm CMW} \to K_{\rm CMW} + \Delta K(\Phi^{(1)}_{\rm PS})$$

fixed "shower variables"

$$\frac{\alpha_s}{2\pi} \Delta K(\Phi^{(1)}_{\rm PS}) = \int$$

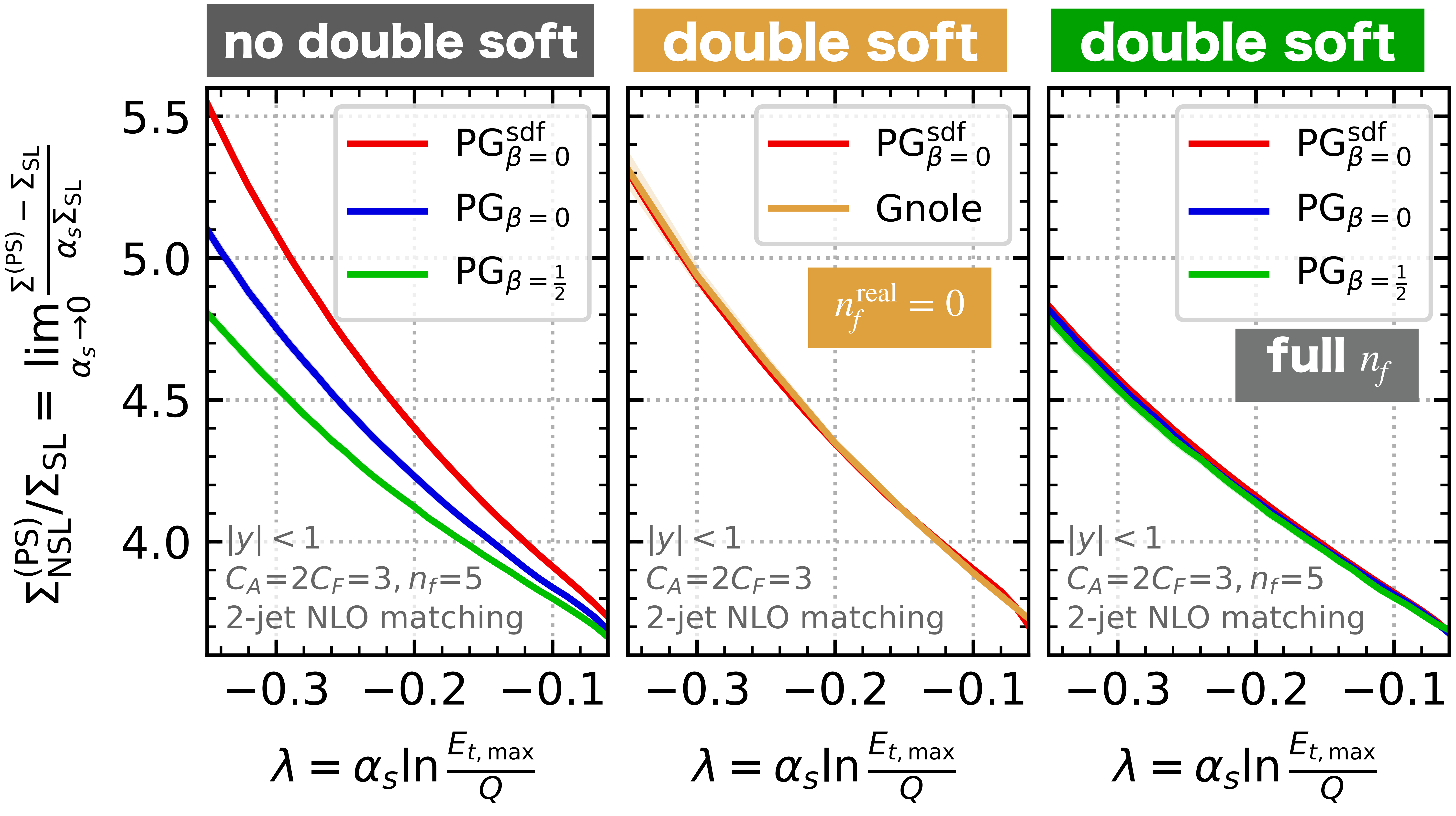


$$- \int$$



ΔK vanishes for large rapidities since virtual corrections to soft-collinear emissions are OK for NLL showers

NSL for the energy flow in a rapidity slice



$$\Sigma^{(PS)}_{NSL} = \lim_{\alpha_s \to 0} \left. \frac{\Sigma^{(PS)} - \Sigma_{SL}}{\alpha_s} \right|_{\text{fixed } \alpha_s L}, \qquad L \equiv \ln \frac{E_{t,\max}}{Q}$$

- **NSL ($\alpha_s^n L^{n-1}$)** = Banfi, Dreyer, Monni, 2104.06416, 2111.02413 (“Gnole”) [NB: see also Becher, Schalch, Xu, 2307.02283]
- **NSL agreement with Gnole for $n_f^{real} = 0$**
- First large-N_c **full-n_f** results for NSL non-global logs

S.F.R., Hamilton, Karlberg, Salam, Scyboz, Soyez 2307.11142

All-orders validation

$$\lim_{\alpha_s \to 0} \frac{\Sigma_{\text{PS}}}{\Sigma_{\text{NLL}}} \quad \text{at fixed } \lambda = \alpha_s L$$

PanScales *= only validated NLL shower for DIS/VBF and pp → colour-singlet*

$$\Sigma(O < e^L) = \exp\Big(L g_{\text{LL}}(\alpha_s L) + g_{\text{NLL}}(\alpha_s L) + \alpha_s g_{\text{NNLL}}(\alpha_s L) + \dots \Big)$$