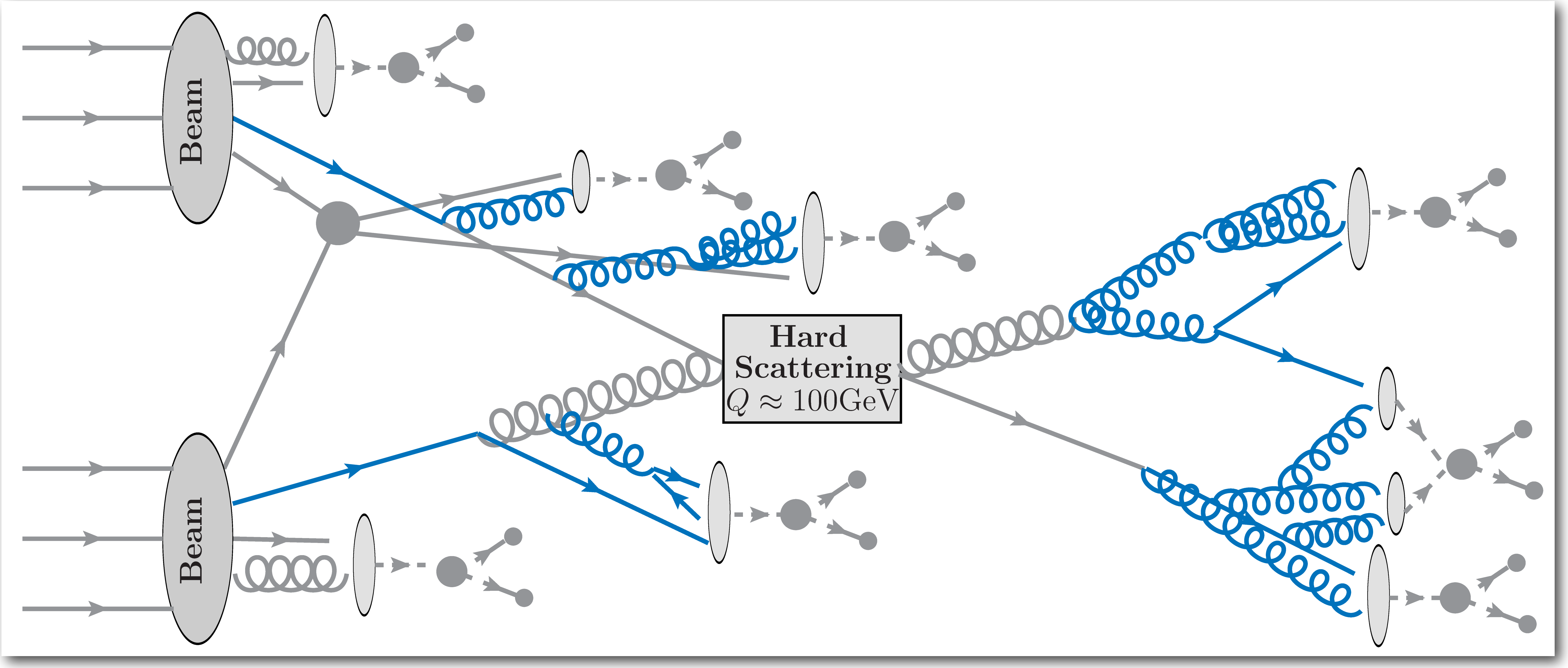
NLL accurate PanScales showers for hadron collisions



Silvia Ferrario Ravasio

Based on:
PanScales showers for hadron collisions: a fixed-order study [arXiv:2205.02237],
PanScales showers for hadron collisions: all-orders validation [in preparation]
with M. van Beekveld, K. Hamilton, G. Salam, A. Soto-Ontoso, G. Soyez, R. Verheyen

International Conference on High Energy Physics (ICHEP 2022)

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European Research Council
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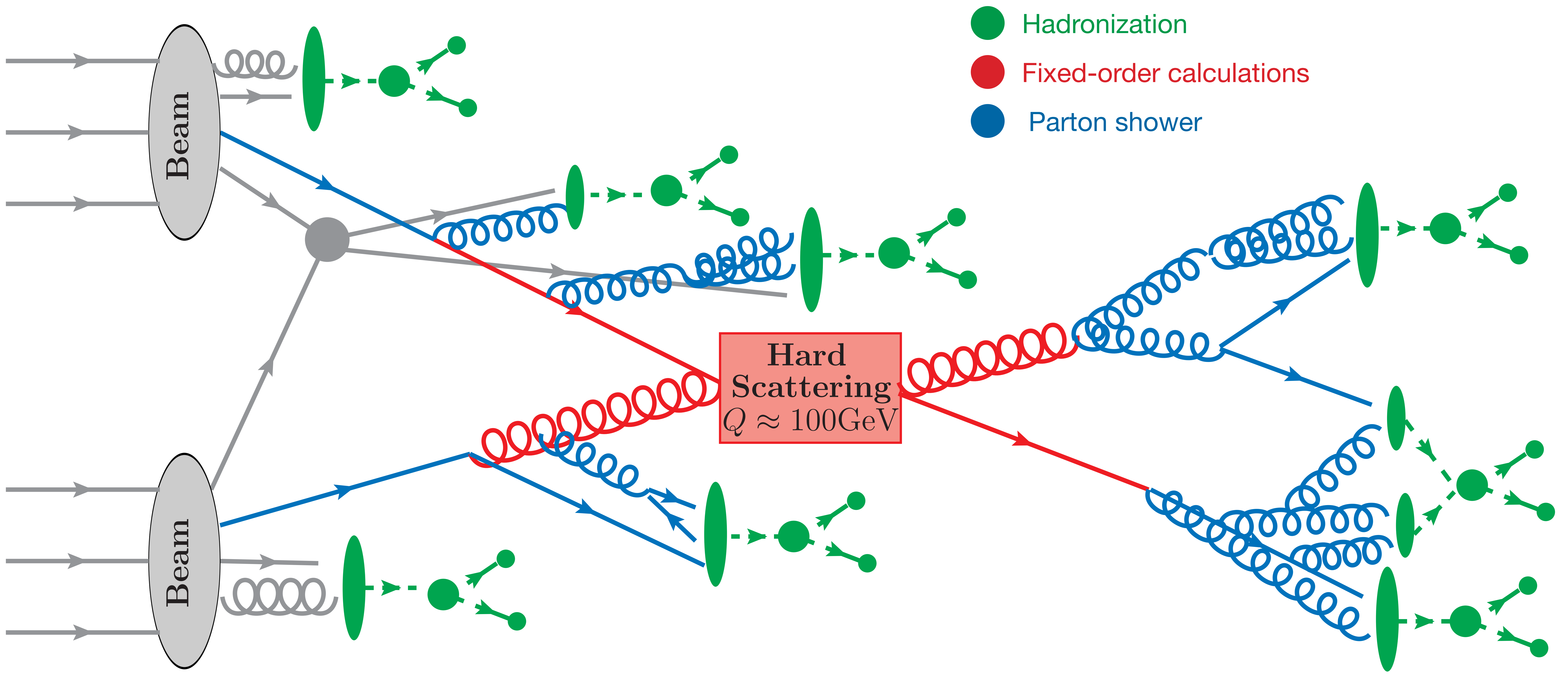
UNIVERSITY OF OXFORD

Shower Monte Carlo Event Generators

- Parton Showers are at the core of Shower Monte Carlo Generators, which contain all the ingredients to realistically describe complex collider events

Herwig

Sherpa

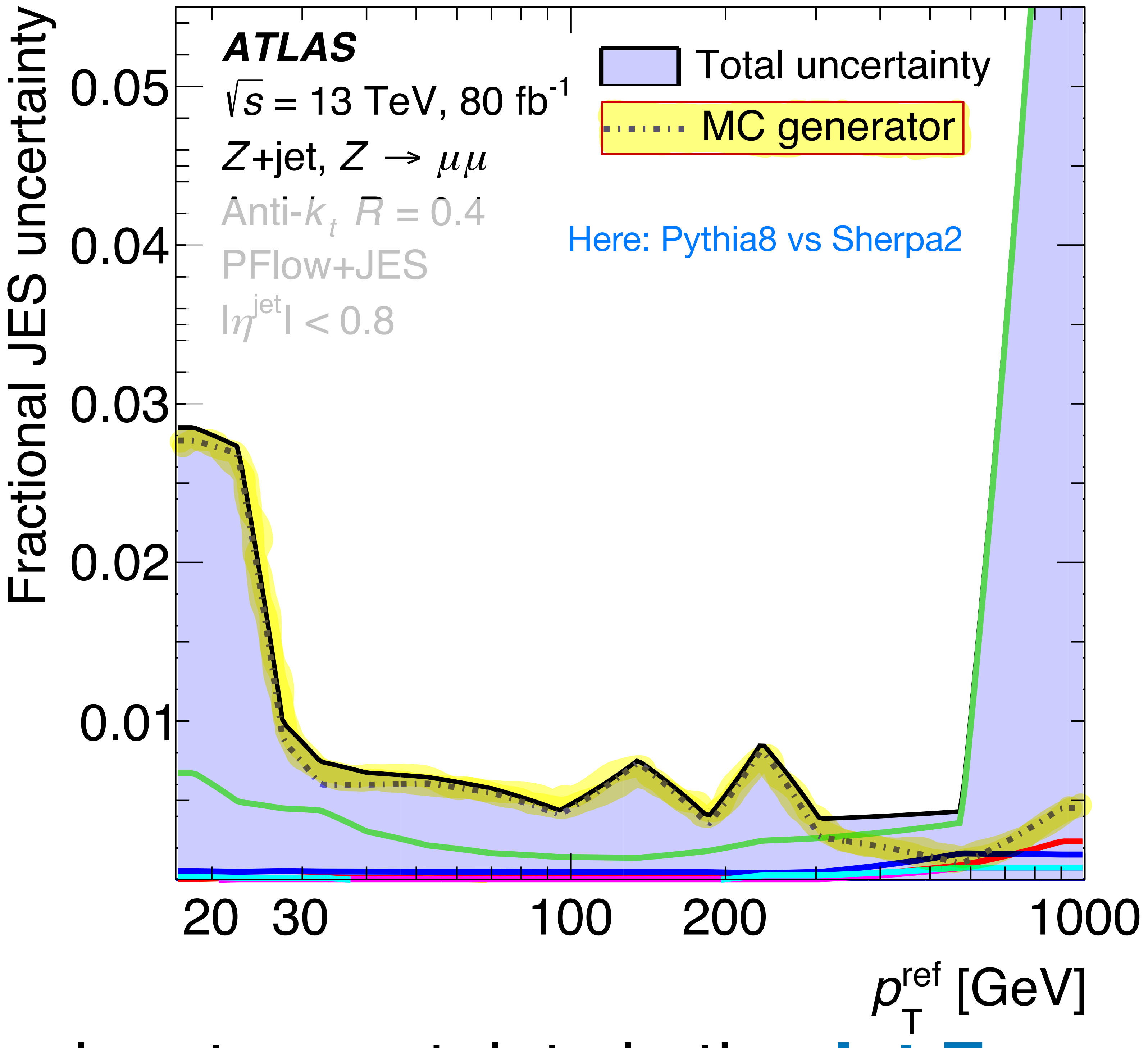


- Their ability to reproduce much of the data from LHC and its predecessors makes them indispensable tools for collider phenomenology
- Their flexibility comes at a cost of an unknown or poor formal accuracy, especially of the Parton Shower component, which translates in large systematic uncertainties $\rightarrow$ let's improve it!

Why do we need to improve Parton Showers?

Jet Calibration

[ATLAS Eur.Phys.J.C 81 (2021) 8, 689]



The dominant uncertainty in the **Jet Energy Scale** determination comes from different **showers' modelling** (and not from the hadronisation!)

→ It enters all the measurements involving jets

→ Contributes to the 70% of uncertainty of precise top mass determinations

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	$^{+0.68}_{-0.73}$

Top quark mass from CMS, 2019 [Eur.Phys.J.C 79 (2019) 5, 368]

$$m_t = 172.33 \pm 0.14(\text{stat}) ^{+0.66}_{-0.72}(\text{syst}) \text{ GeV}$$

How do we define how good is a Parton Shower?

- The aim of a Parton Shower is to evolve the system across a large span of scale: large logarithms L of the ratios of the scales involved in the process arise during this evolution

- We can use analytic resummation to classify the logarithmic accuracy of a Shower

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

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 $\mathcal{O}(1)$

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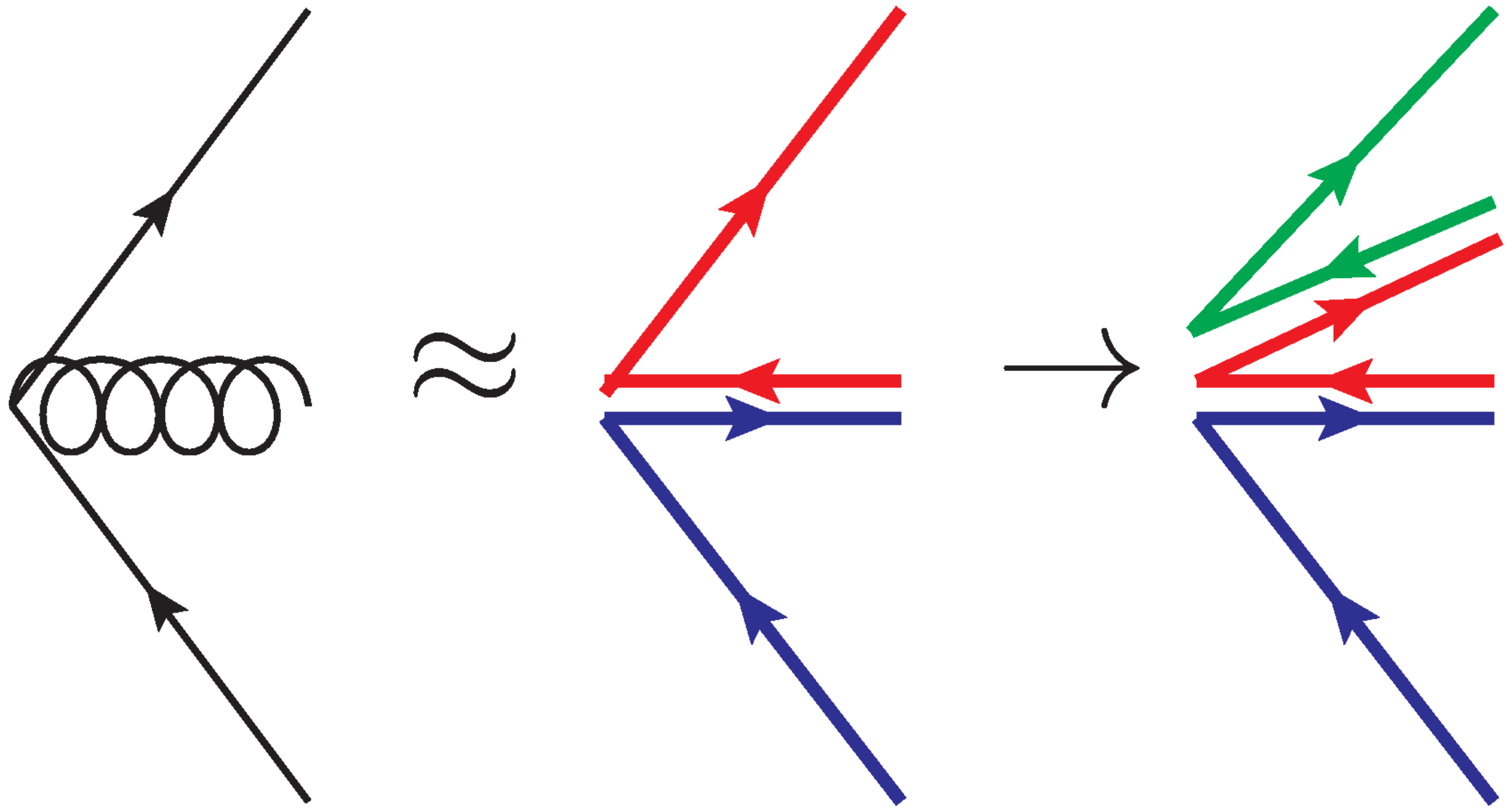
Are the most widely used showers NLL? If no, can we build NLL showers?

- (Abridged) PanScales criteria to assess NLL accuracy:

  A. Fixed-order: emissions **widely separated in angle**, are **independent** from each other
  B. All-orders: the showers reproduces results from **analytic resummation** at NLL

Dipole showers in a nutshell



- Parton showers describe the energy degradation of hard partons via a subsequent chain of soft (small energy) and collinear (small θ) emissions
- The most popular showers are dipole showers.
- New partons are emitted from a dipole, which is a pair of colour-connected partons

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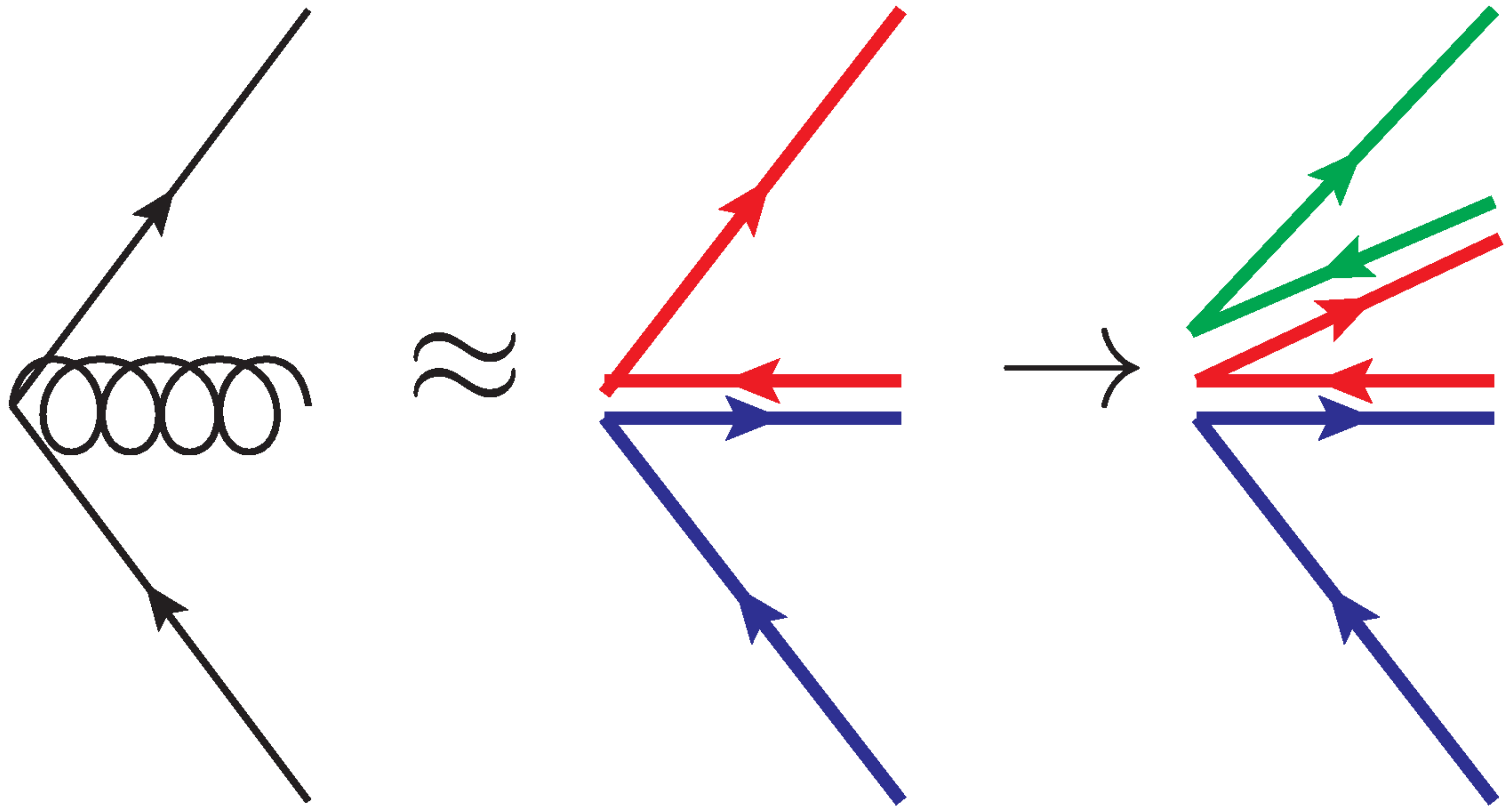

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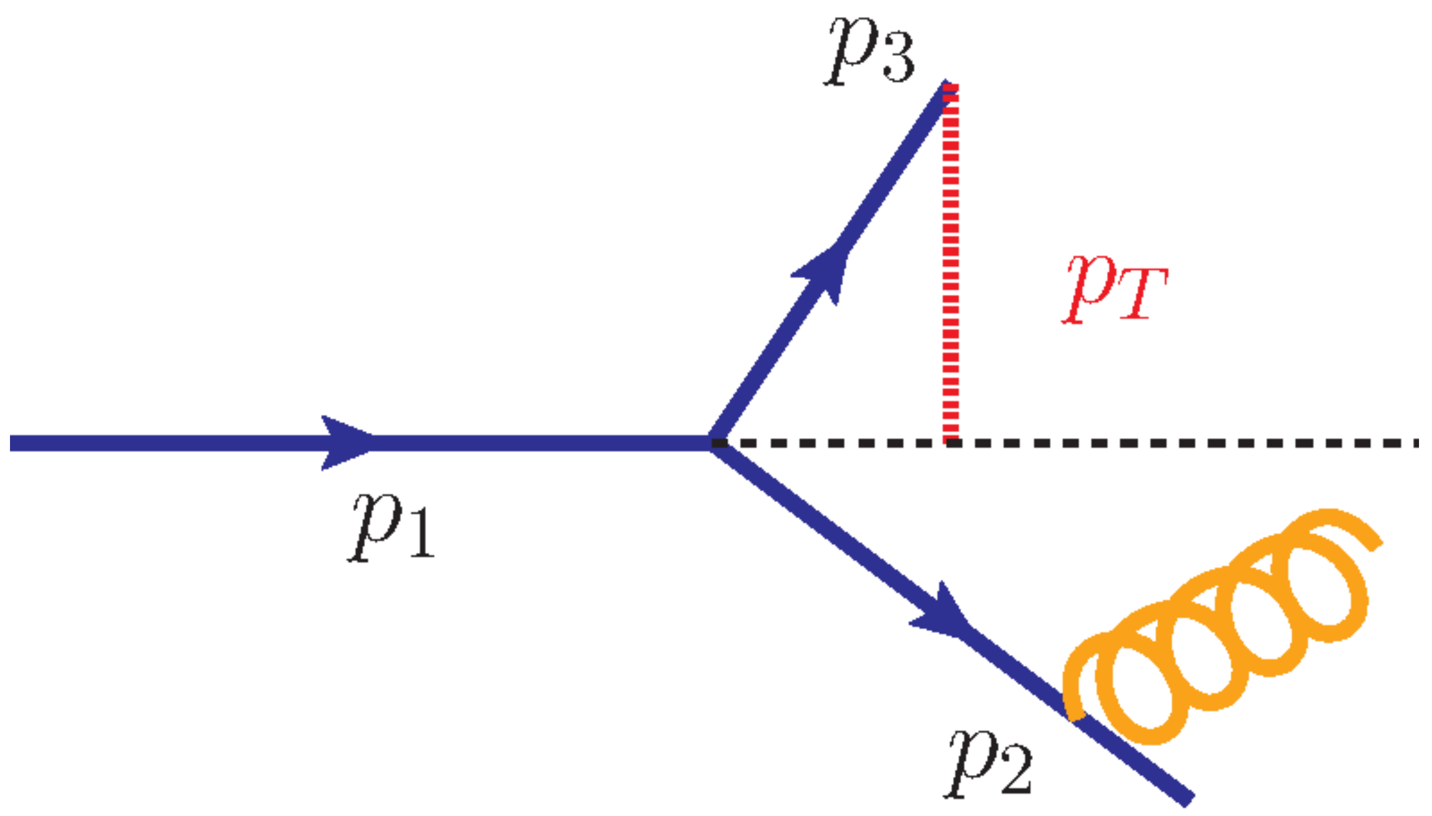
- The original dipole leg closer in angle (in the dipole frame) to the new emission takes the p_T recoil, and is tagged as emitter

$$p_3 = z_1 \tilde{p}_1 + z_2 \tilde{p}_2 + k_\perp$$

$$P_{1,2\to1,2,3} \approx \underbrace{P_{1\to1,3}(z_1)\Theta(\theta_{13}^{\rm dip} > \theta_{23}^{\rm dip})}_{\text{1 is the emitter}} + \underbrace{P_{2\to2,3}(z_2)\Theta(\theta_{23}^{\rm dip} > \theta_{13}^{\rm dip})}_{\text{2 is the emitter}}$$



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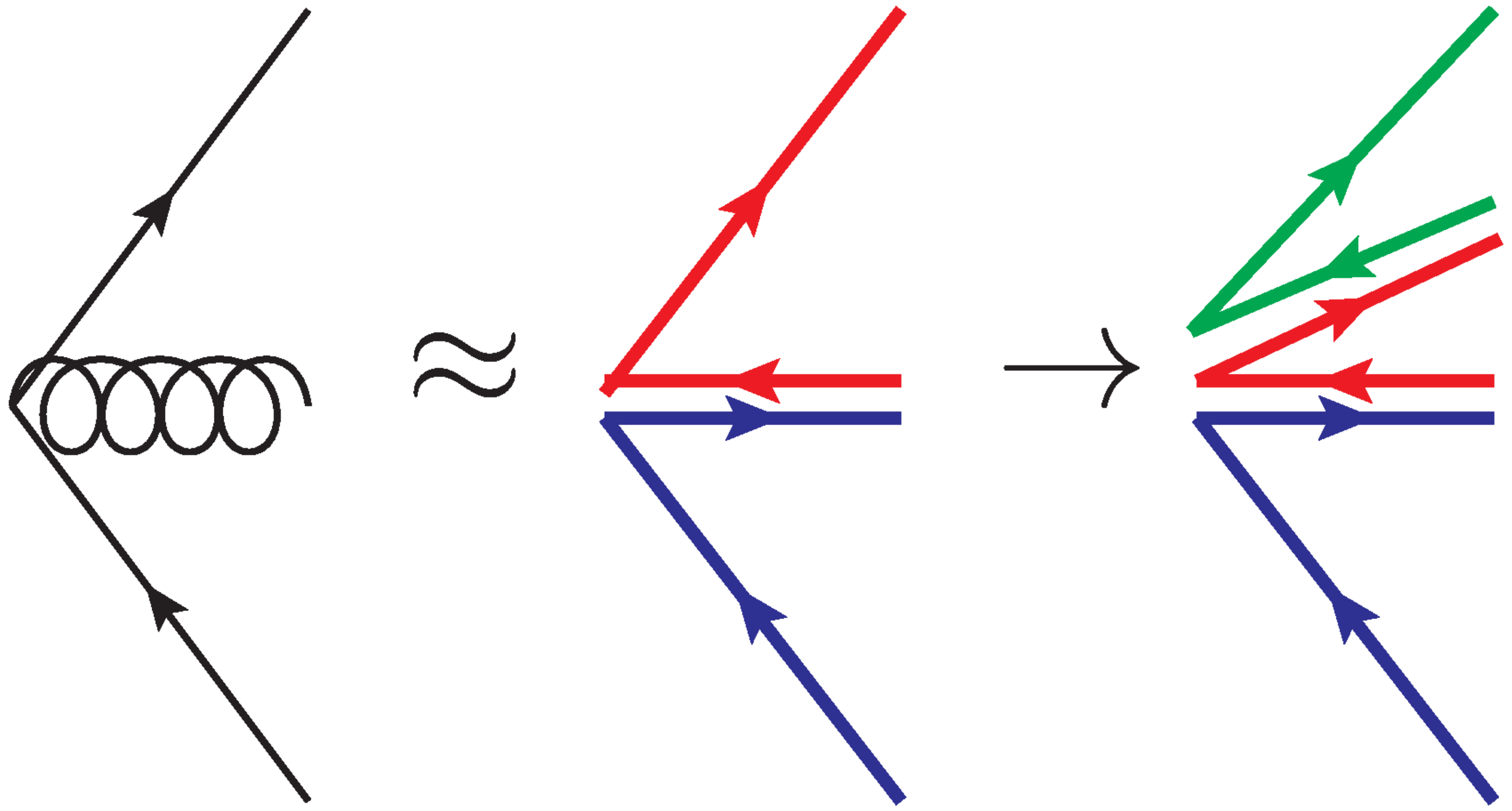

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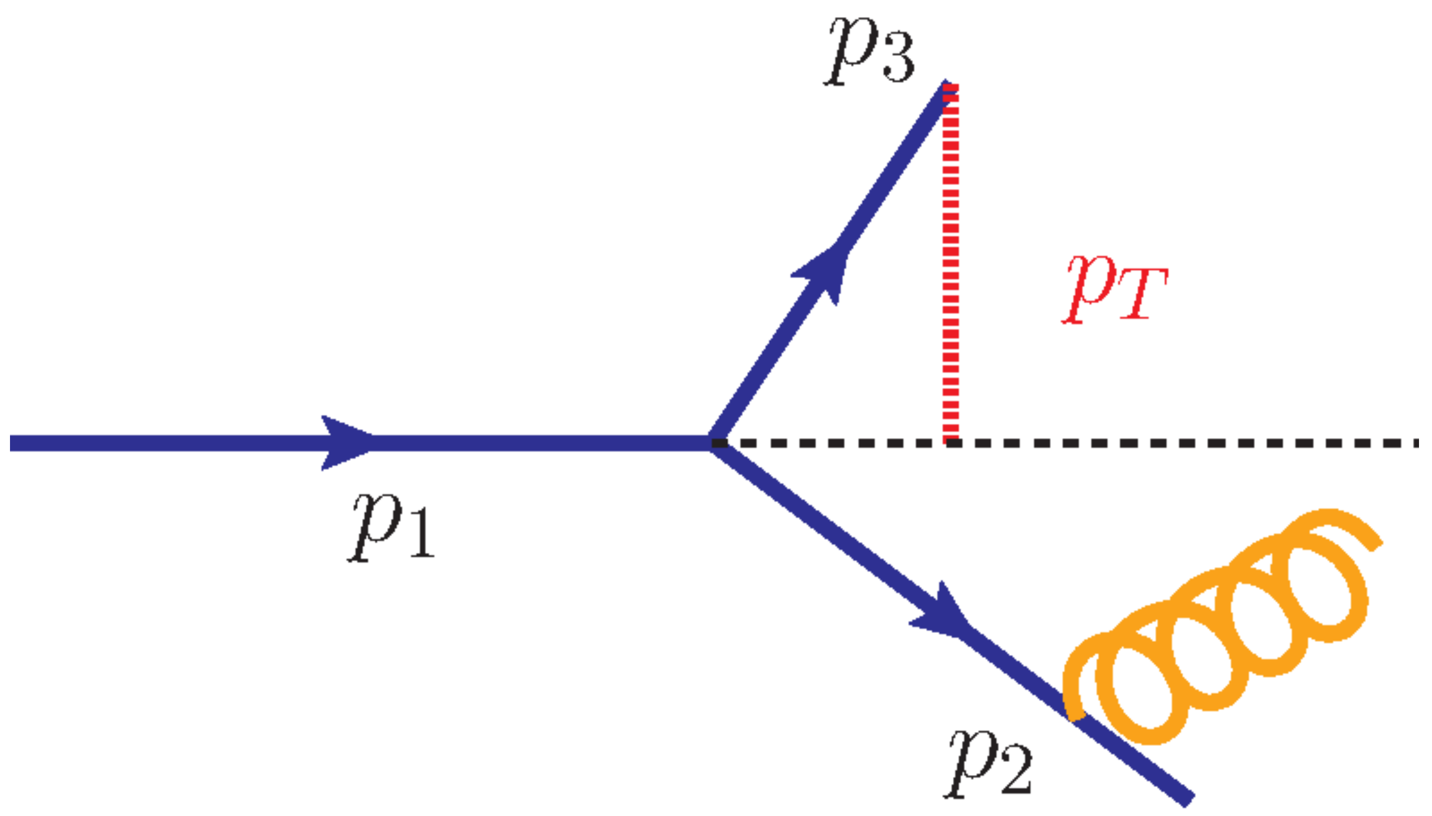
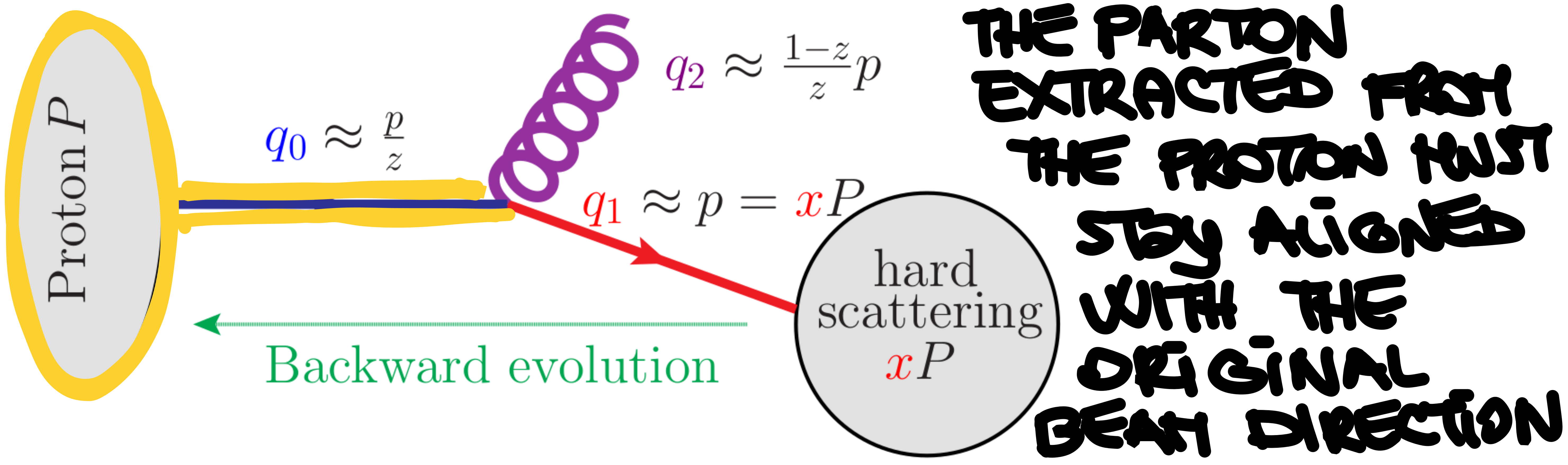
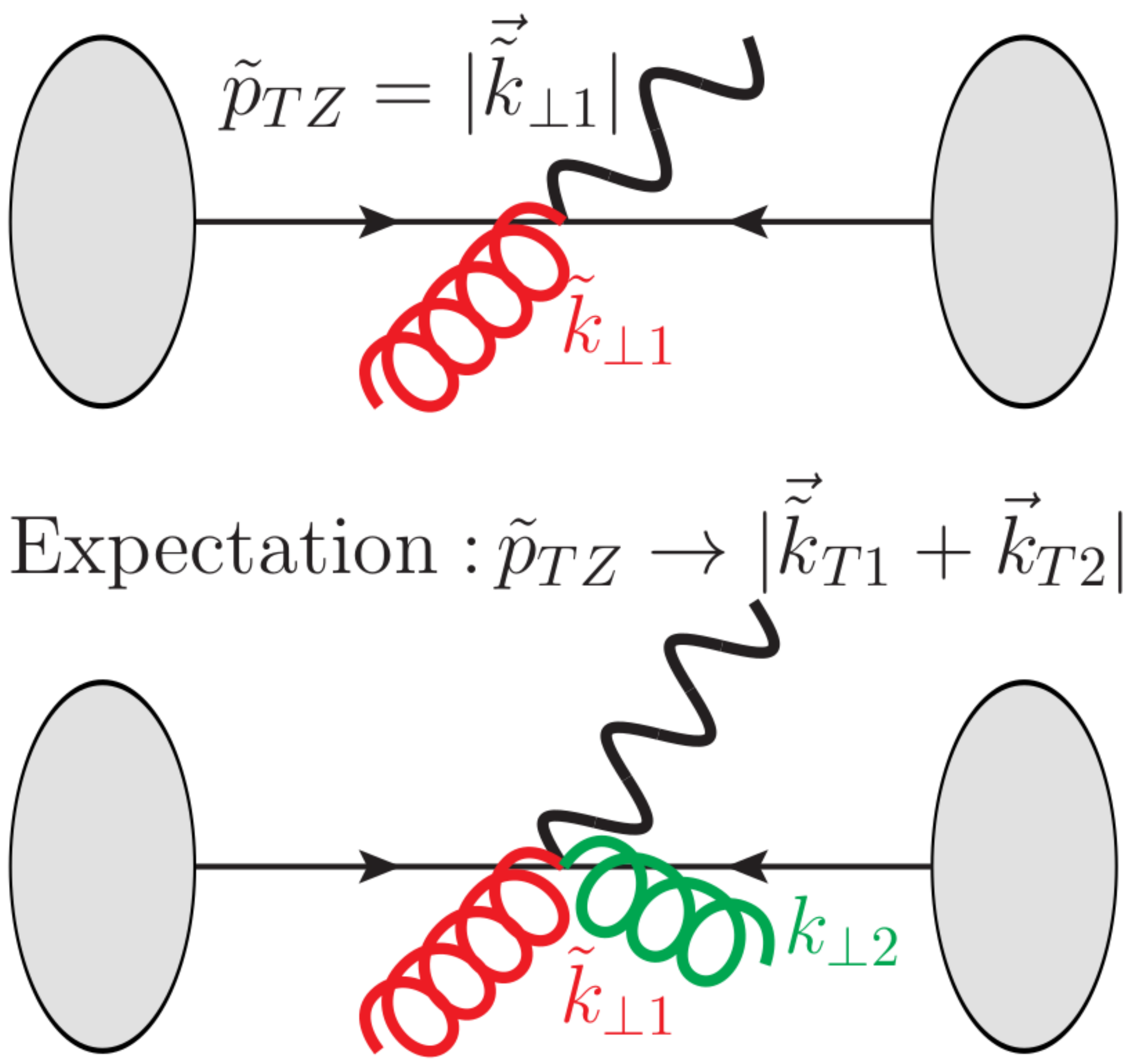


- Emissions are ordered in transverse momentum (or virtuality): this simplifies matching with higher order (NLO or NNLO) calculations, as we can just correct the first (=hardest)

State-of-the-art dipole showers for hadron collision





- **Initial-state radiation:** we cannot assign the p_T recoil to the **incoming parton** (q_0)
- In $pp \to Z$ the Z **boson** must absorb the p_T recoil for each initial-state emission

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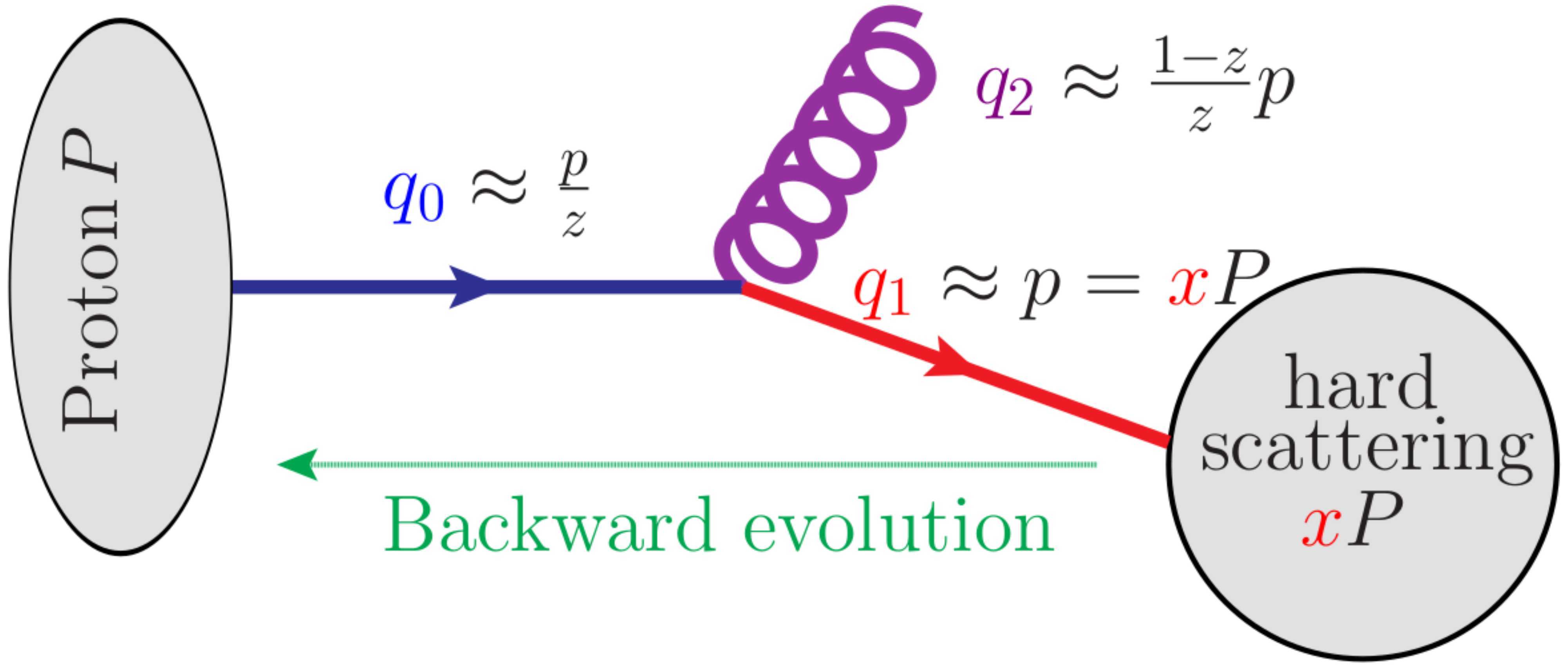
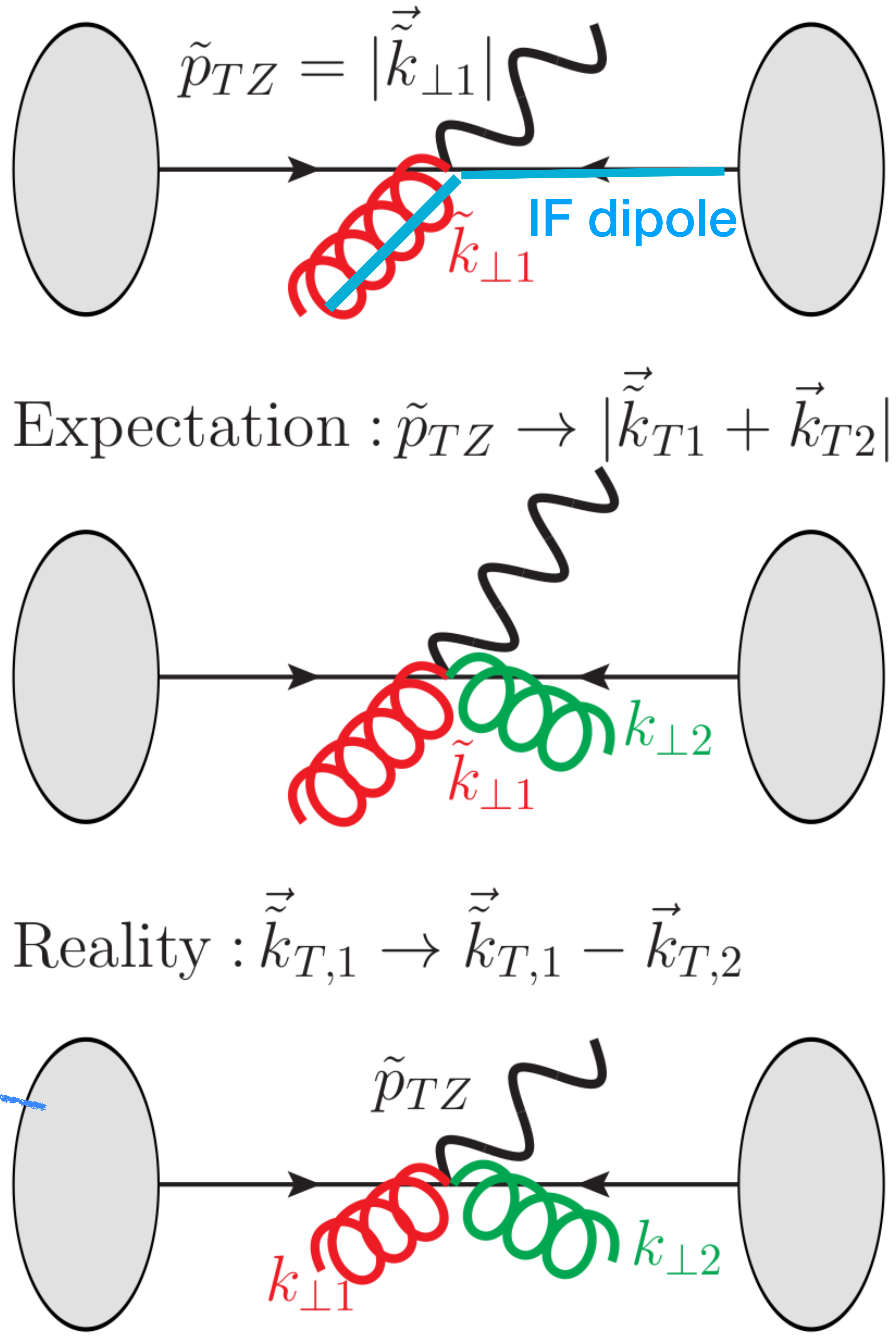


- **Initial-state radiation:** we cannot assign the p_T recoil to the **incoming parton**
- In $pp \to Z$ the Z **boson** must absorb the p_T recoil for each initial-state emission

- But in common dipole showers, emissions from Initial-Final dipoles always make the final state leg recoil!
- Known to yield wrong $p_{T,Z}$ at NLL! [Parisi, Petronzio NPB 154 (1979) 427-440, Nagy, Soper JHEP 03 (2010) 097]



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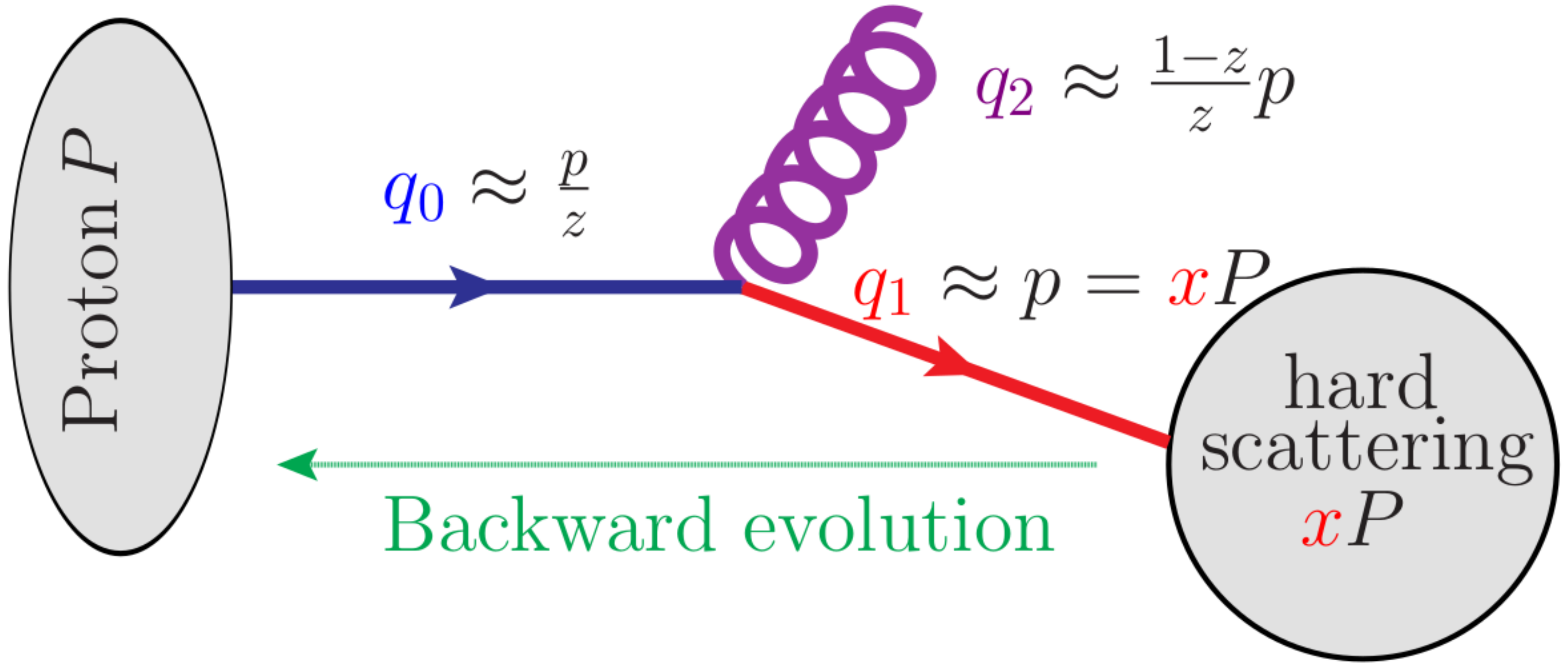

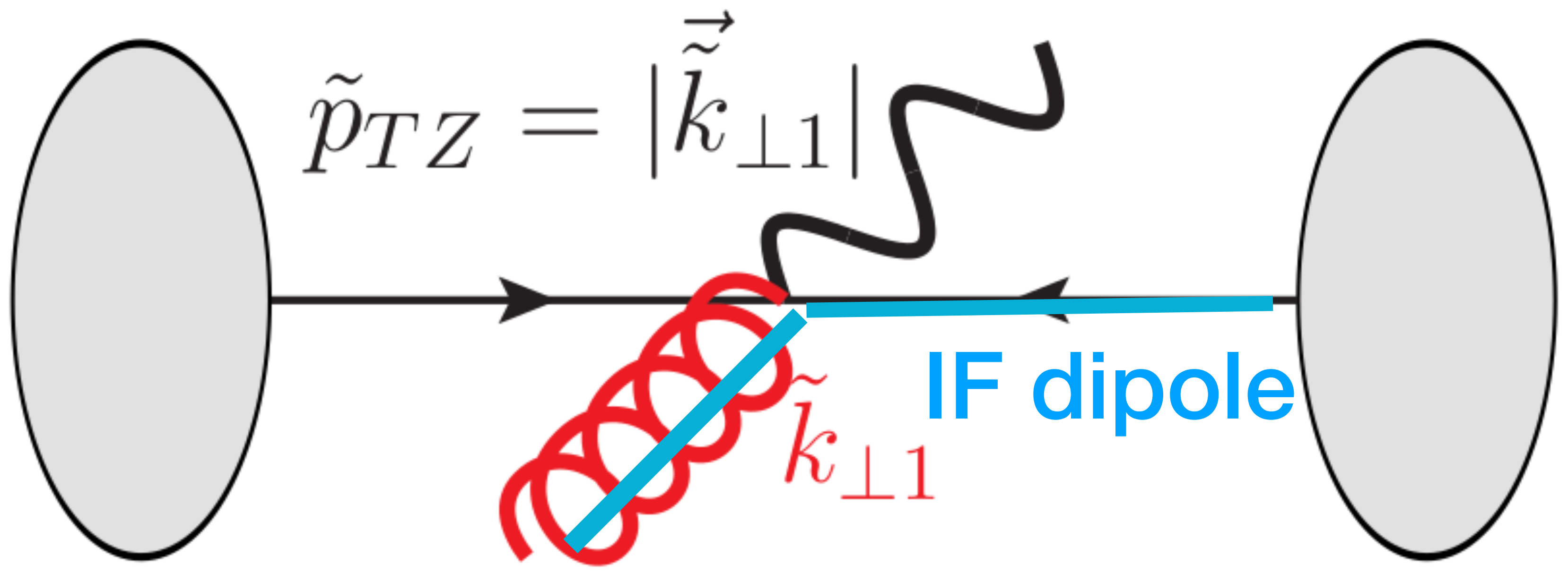

Expectation : $\tilde{p}_{TZ} \to |\vec{\tilde{k}}_{T1} + \vec{k}_{T2}|$

- **Initial-state radiation:** we cannot assign the p_T recoil to the **incoming parton**
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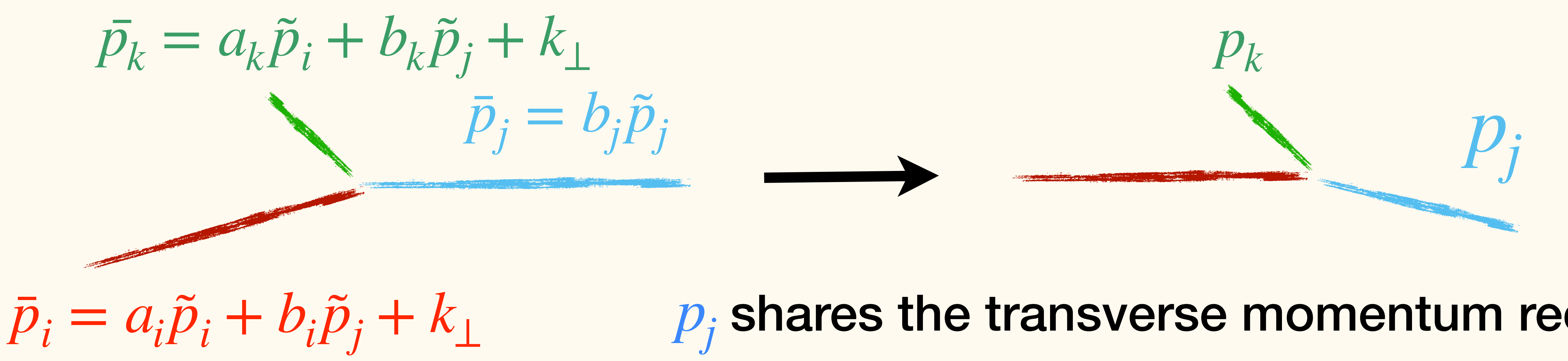
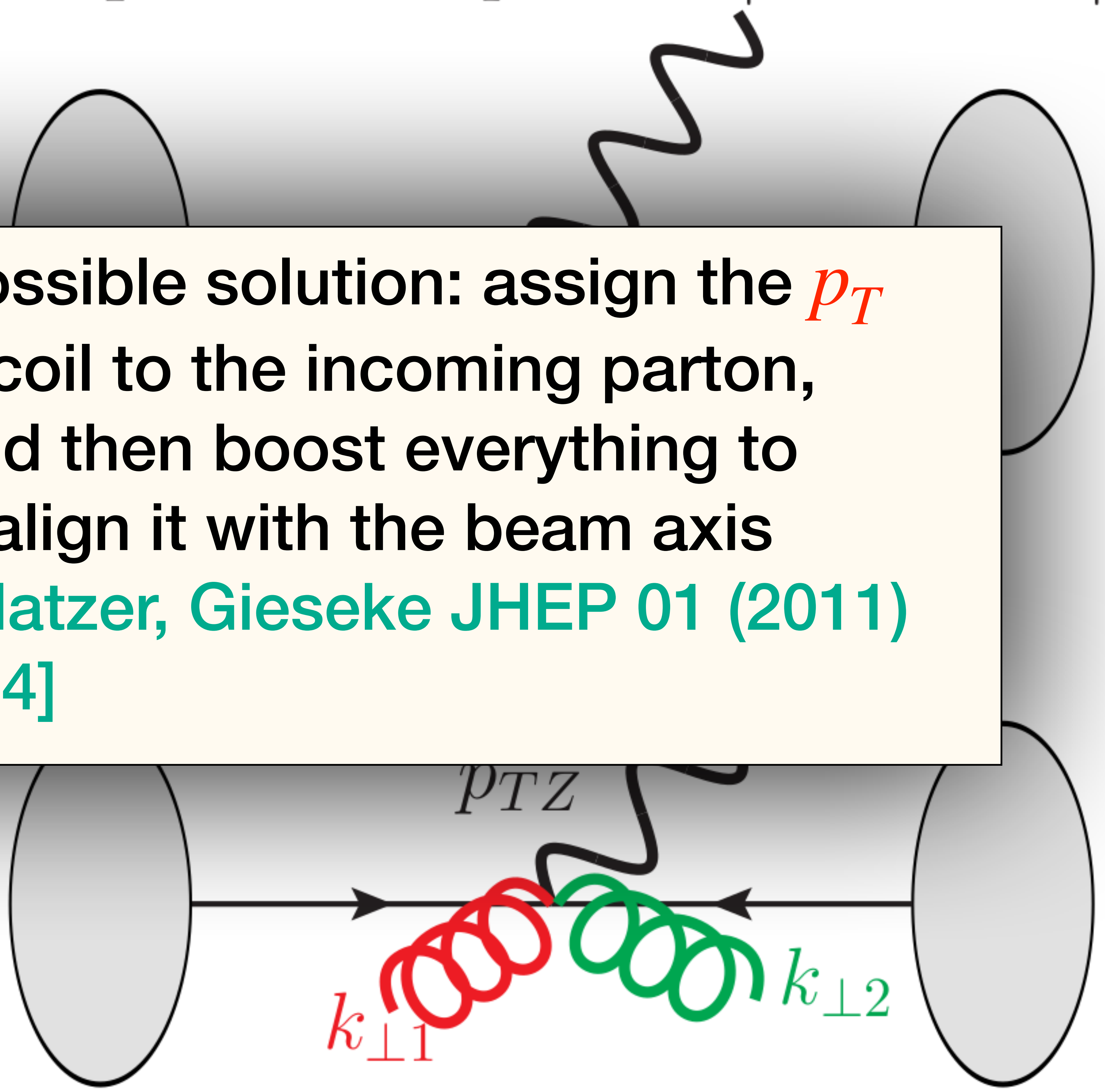


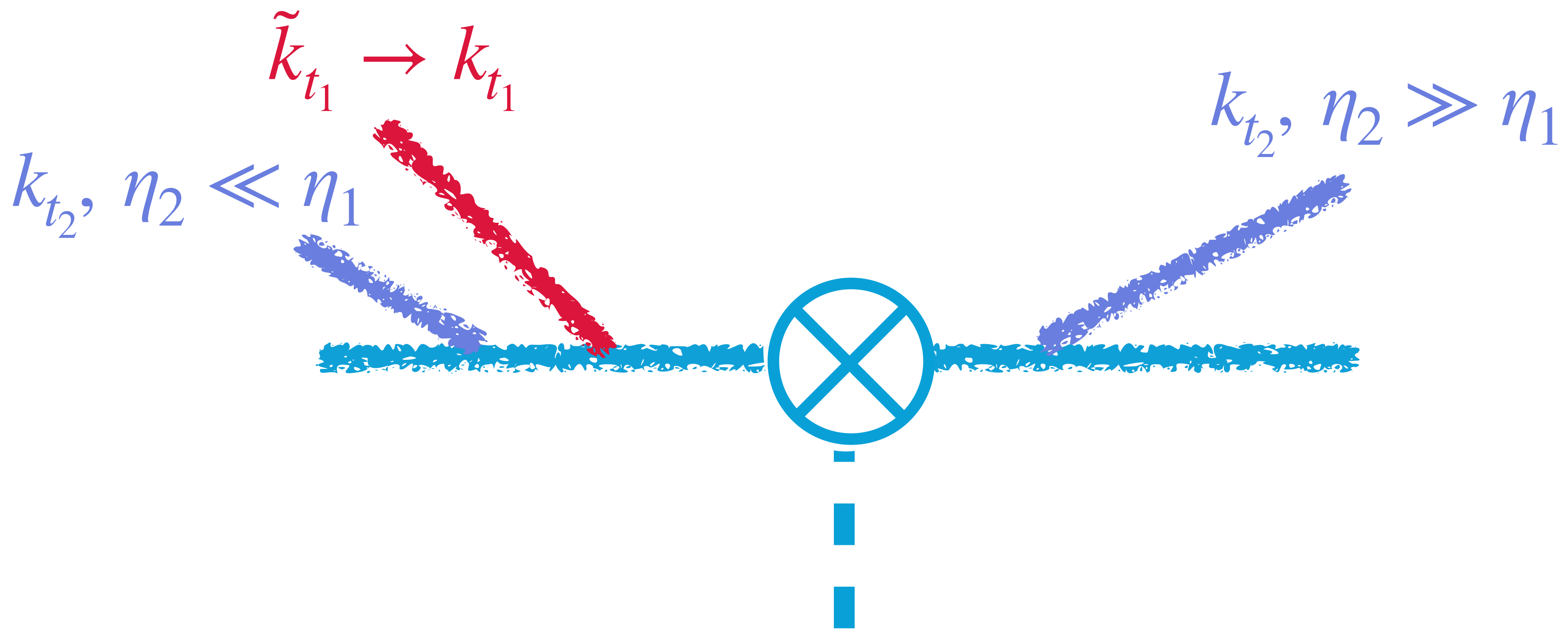
p_j shares the transverse momentum recoil with all the other particles, in proportion to its **energy**

Possible solution: assign the p_T recoil to the incoming parton, and then boost everything to realign it with the beam axis [Platzer, Gieseke JHEP 01 (2011) 024]

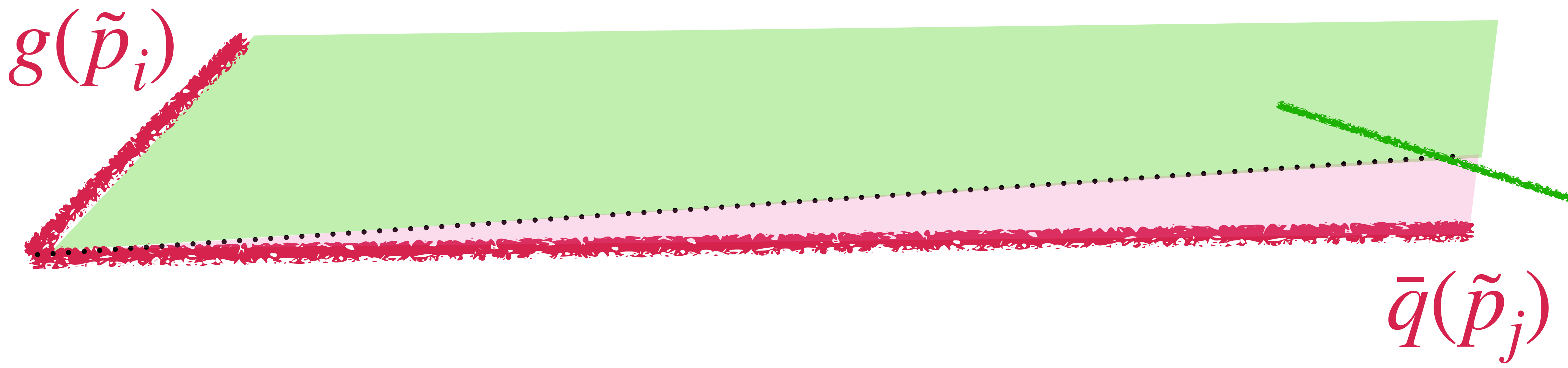


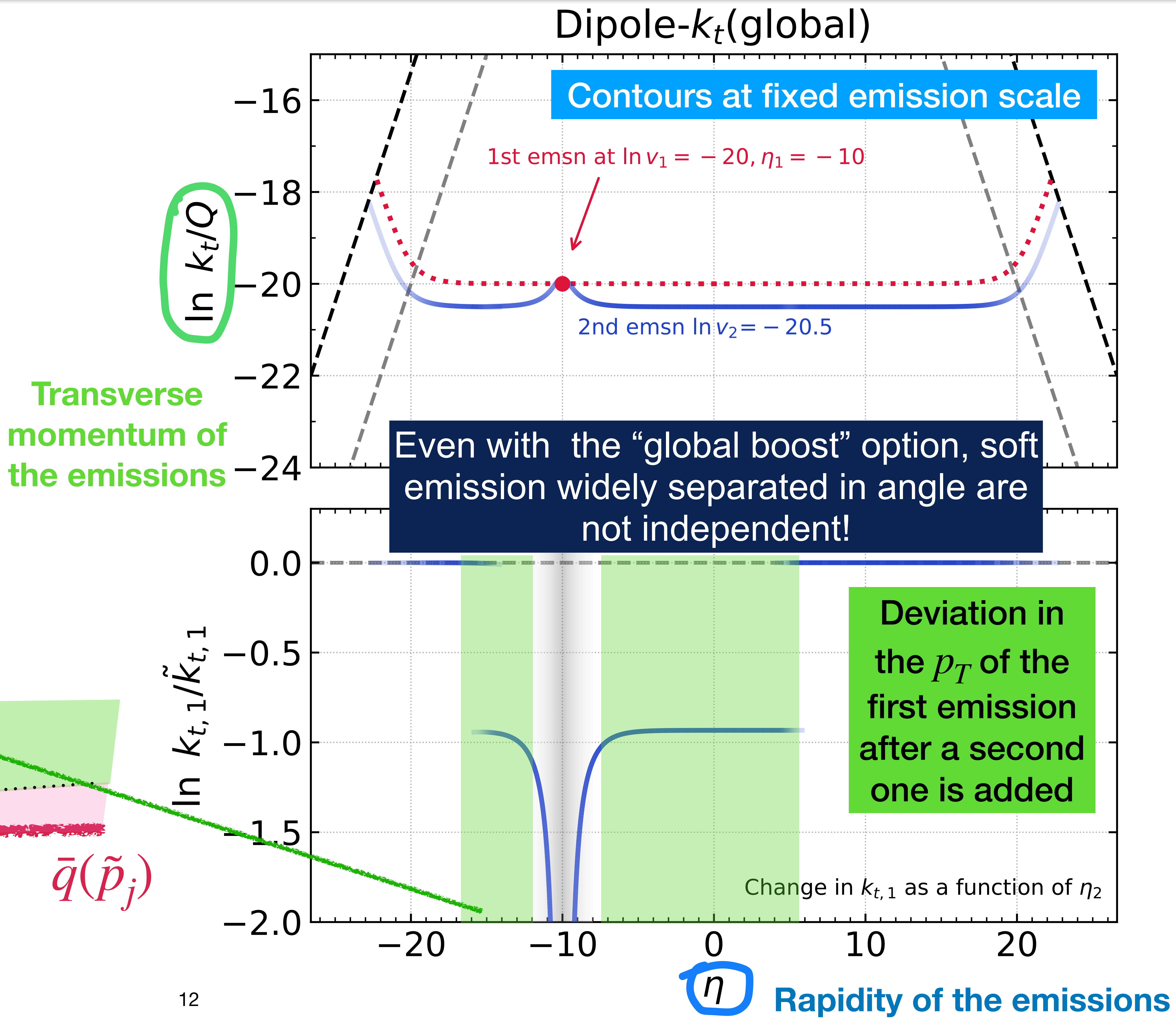
State-of-the-art dipole showers for hadron collision

How does a **second** emission affect the **first** emission's momentum?



Direct consequence of CM dipole separation

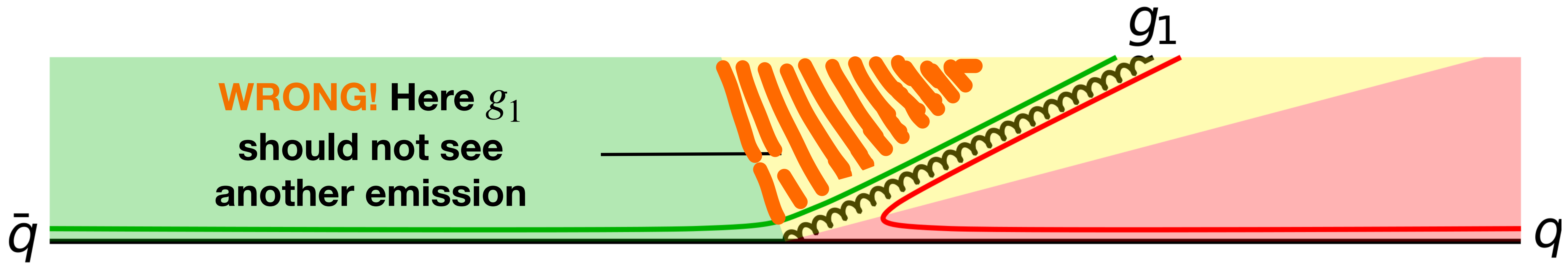


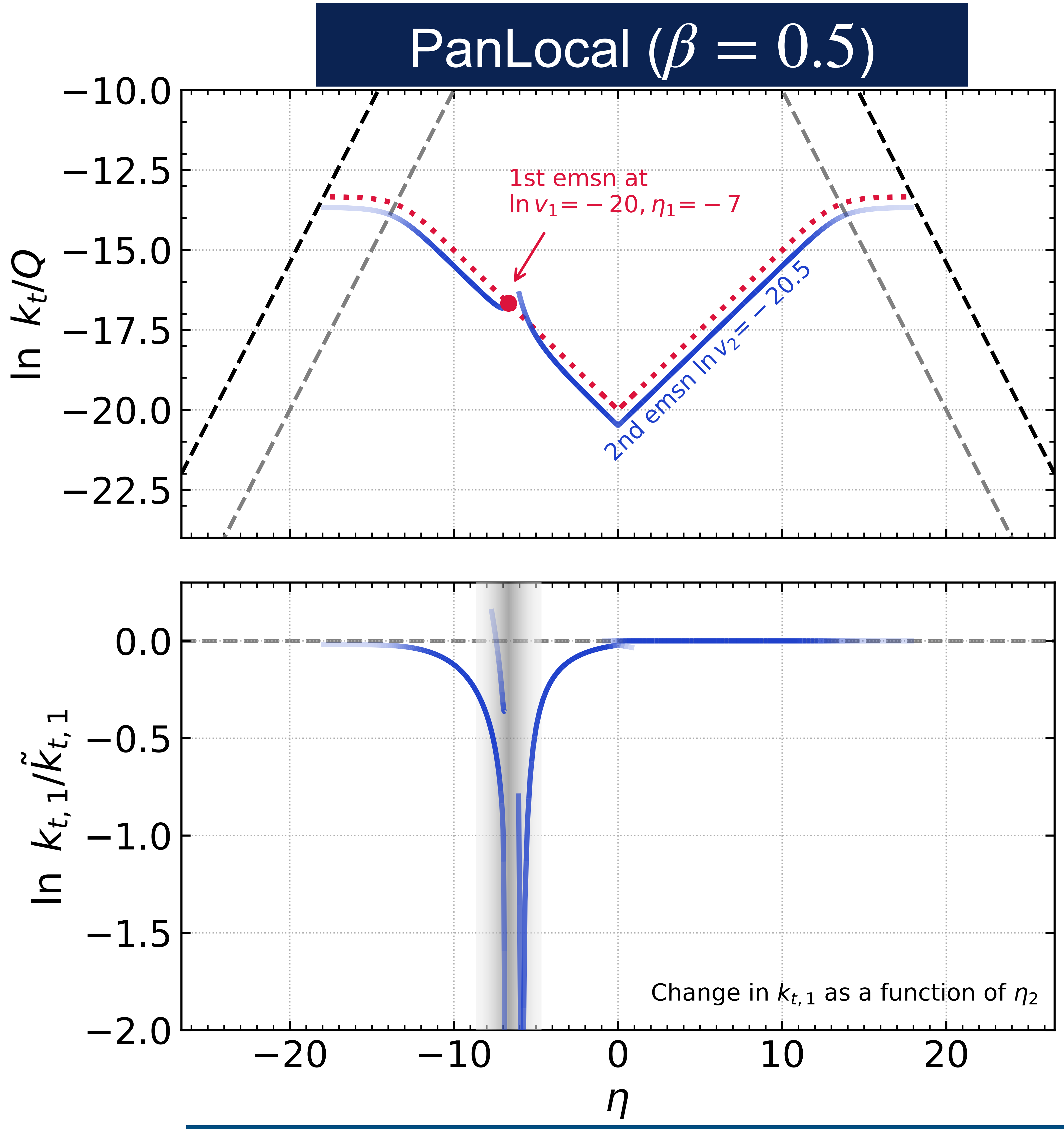


van Beekveld, S.F.R., Salam, Soto-Ontoso, Soyez, Verheyen, arXiv:2205.02237

NLL PanScales showers for hadron collision: PanLocal

- Kinematic map with the **global boost for ISR**
- We define the **dipole partitioning** in the **event frame**





PanLocal for FSR: Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez, Phys.Rev.Lett. 125 (2020) 5, 052002

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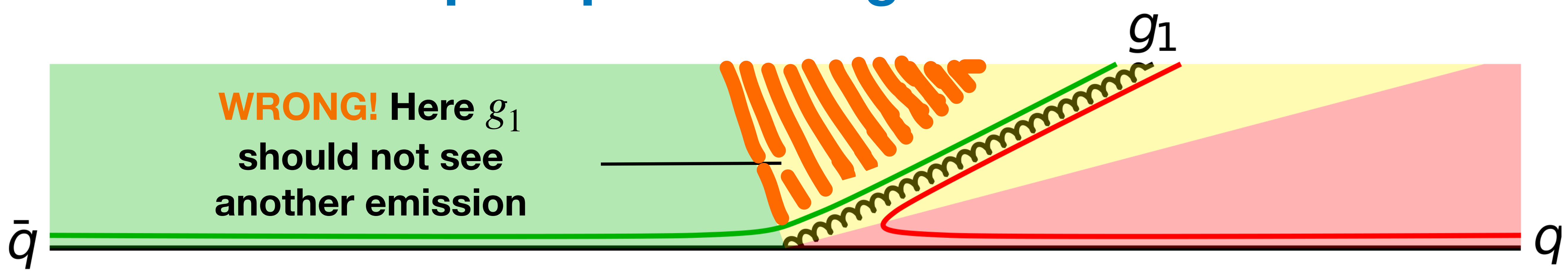
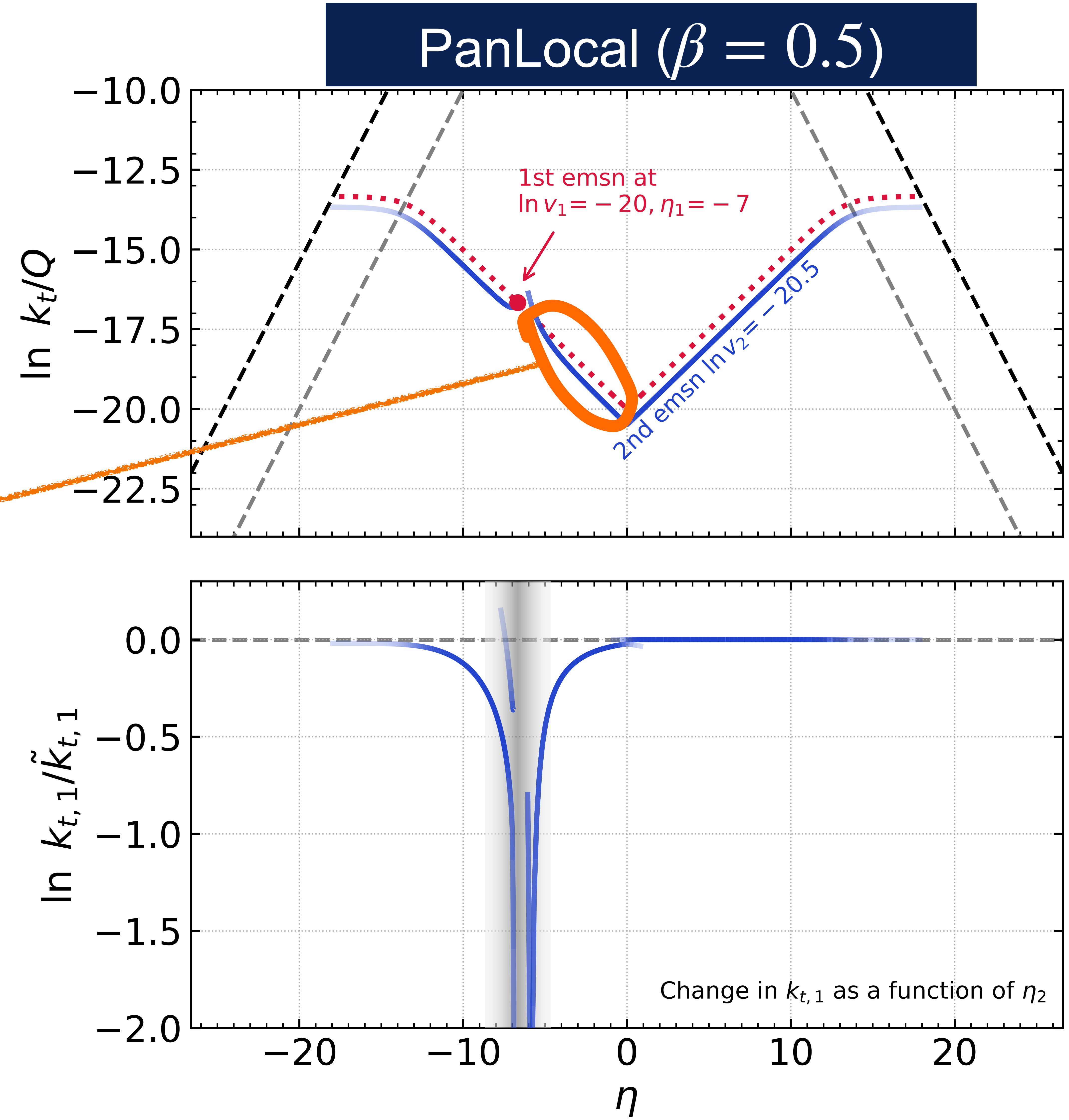


- **Ordering scale** $v = p_T e^{-\beta|\eta|} \approx p_T \theta^{-\beta}$ with $0 < \beta < 1$, so $p_{T2} \ll p_{T1}$ since $\theta_1 > \theta_2$ in the "wrong" region: recoil is negligible …



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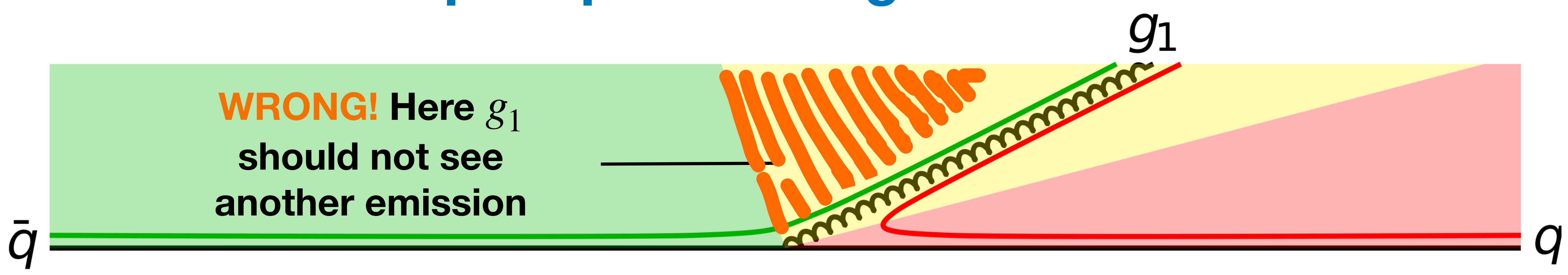

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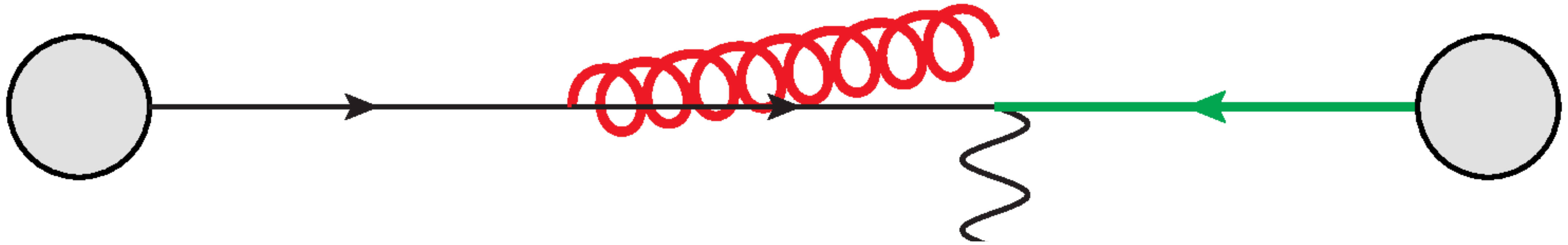
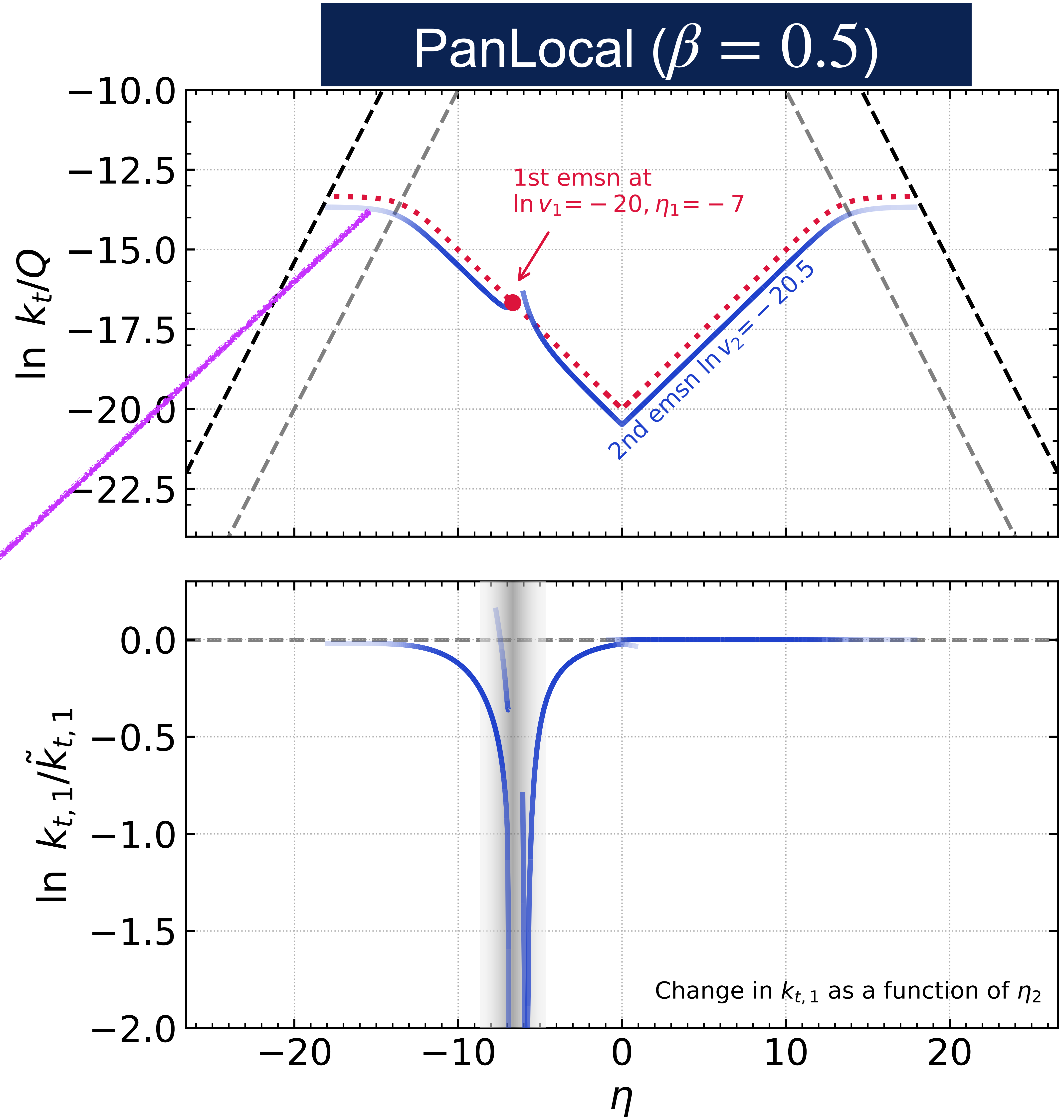
- ... but we restore to p_T ordering for very collinear emissions to prevent very energetic collinear parton from taking unphysical recoil





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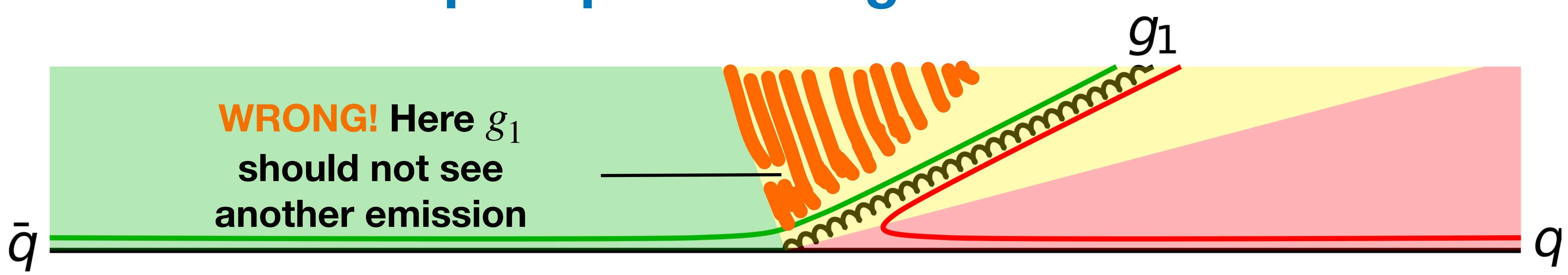
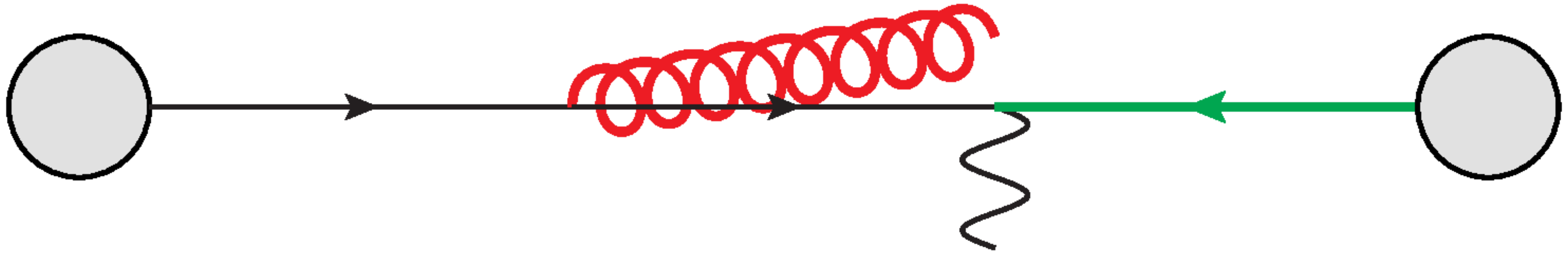
NLL PanScales showers for hadron collision: PanGlobal

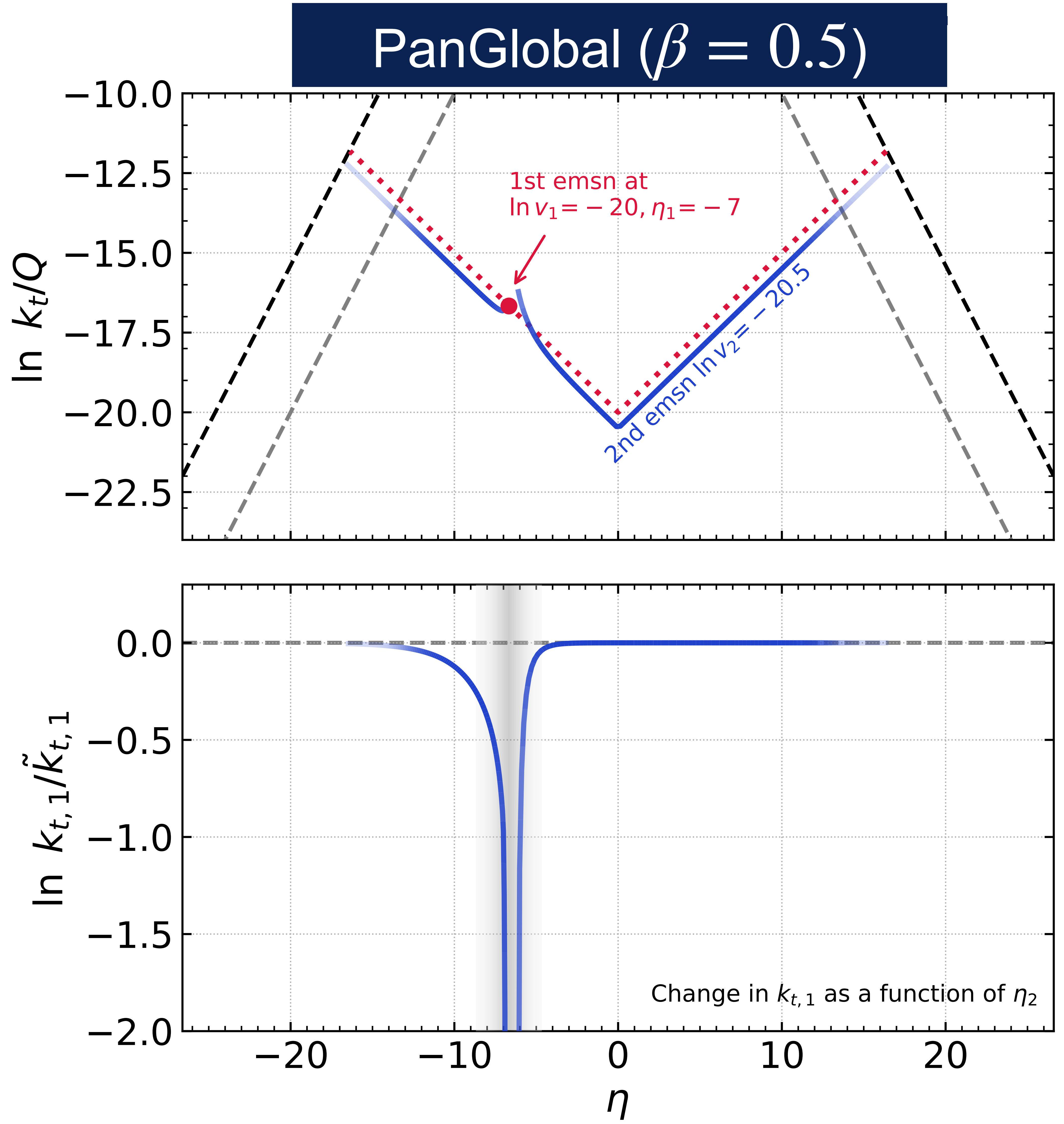
- We define the **dipole partitioning** in the **event frame**



- **Ordering scale** $v = p_T e^{-\beta|\eta|} \approx p_T \theta^{-\beta}$ with $0 \leq \beta < 1$

- The p_T recoil is always taken by the Z boson: no special treatment for the "wrong" partitioning region, and very energetic collinear parton do not take unphysical recoil





PanGlobal for FSR: Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez, Phys.Rev.Lett. 125 (2020) 5, 052002

van Beekveld, S.F.R., Salam, Soto-Ontoso, Soyez, Verheyen, arXiv:2205.02237

Are we sure PanScales showers are NLL for $p_{T,Z}$?

$$\Sigma = \exp\Big(Lg_{\text{LL}}(\alpha_s L) + g_{\text{NLL}}(\alpha_s L) + \alpha_s g_{\text{NNLL}}(\alpha_s L) + \dots\Big)$$

WE NEED TO EXTRACT ONLY THE NLL PART! HOW?.

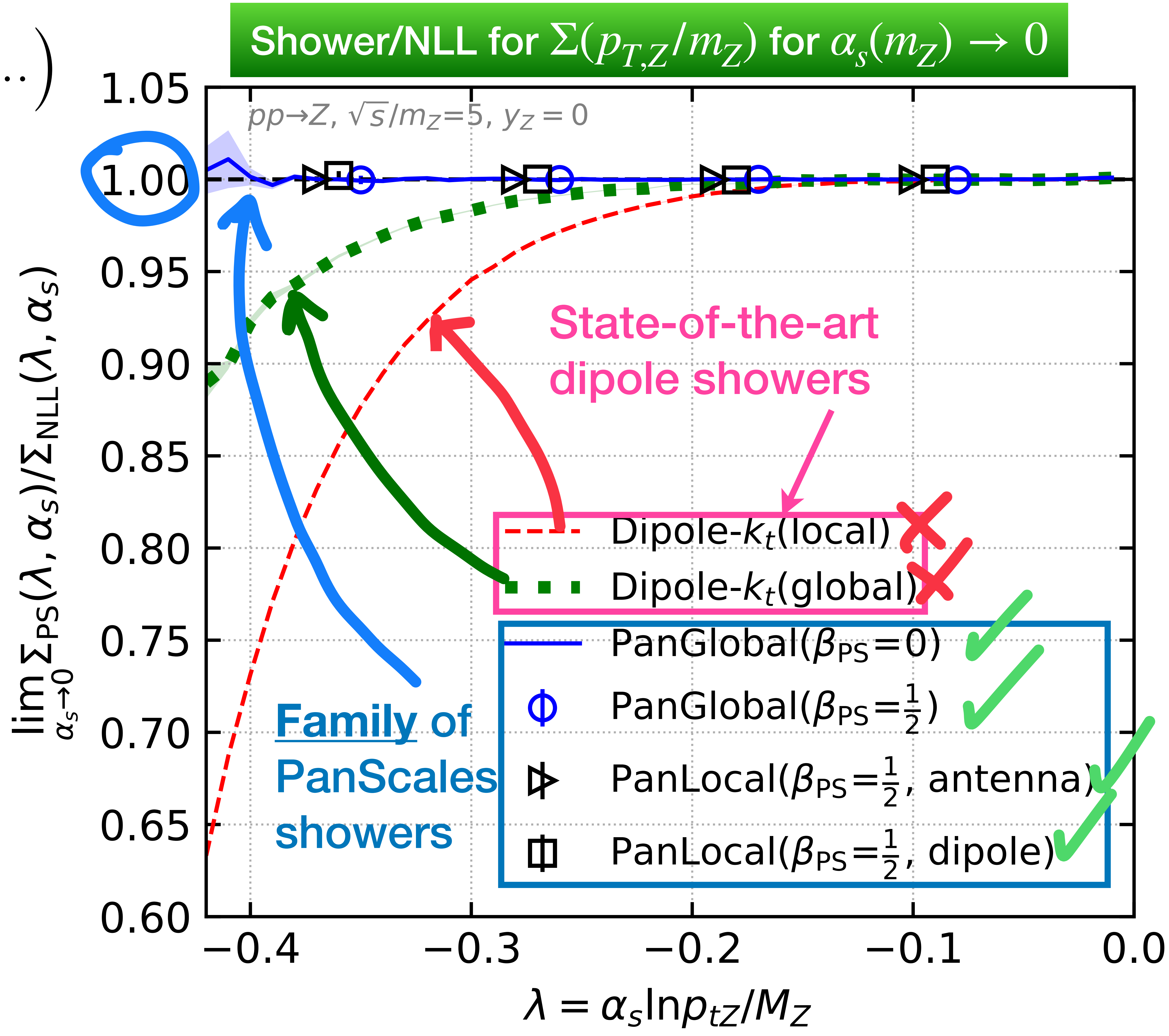
⟹

All-orders tests: check if

$$\lim_{\alpha_s \to 0} \frac{\Sigma_{\text{PS}}(\alpha_s, \log V < L)}{\Sigma_{\text{NLL}}(\alpha_s, \log V < L)} = 1$$

at fixed $\lambda = \alpha_s L$

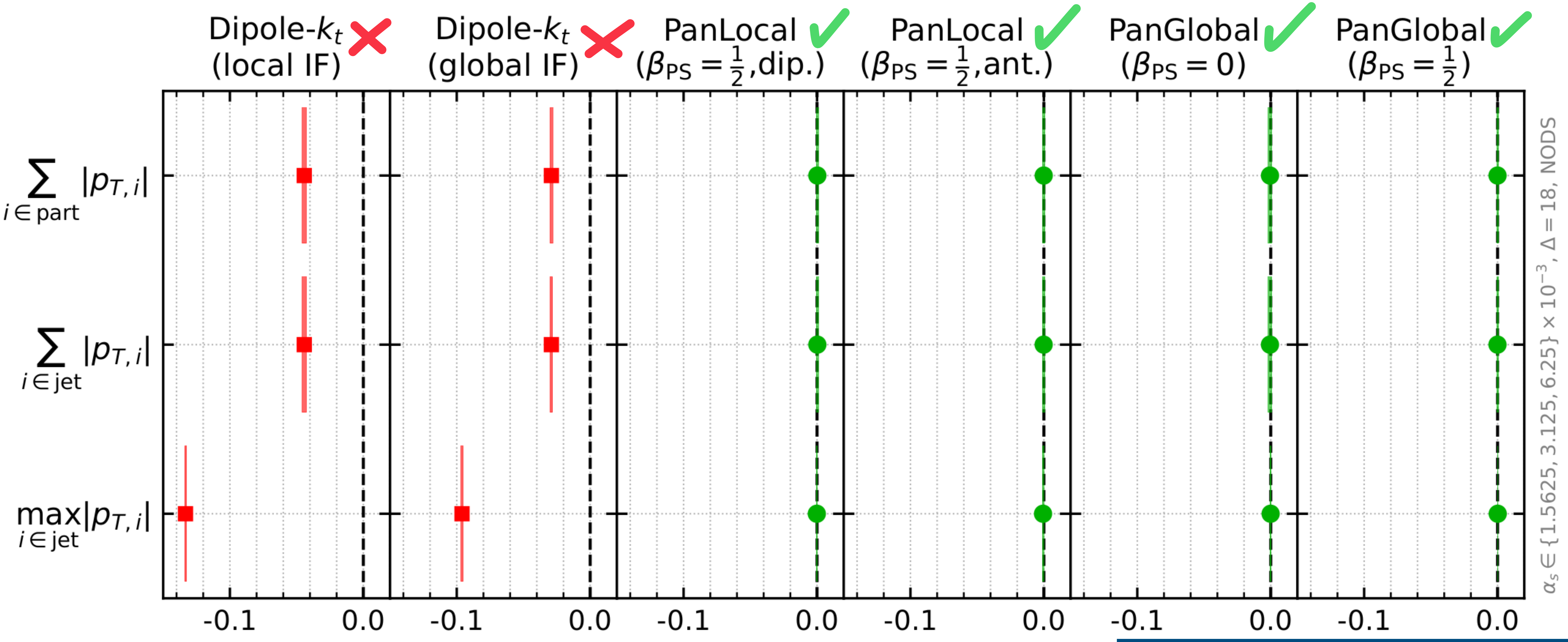
van Beekveld, S.F.R., Hamilton, Salam, Soto-Ontoso, Soyez, Verheyen, in preparation



Are we sure PanScales showers are NLL for event shapes?

All-orders tests: check if $\lim_{\alpha_s \to 0} \frac{\Sigma_{\text{PS}}(\alpha_s, \log V < L)}{\Sigma_{\text{NLL}}(\alpha_s, \log V < L)} = 1$ at fixed $\lambda = \alpha_s L$

(Shower/NLL -1) for $\Sigma(O < m_Z e^{-|L|})$ for $\alpha_s(m_Z) \to 0$ and $\alpha_s L = 0.5$



We also tested particle multiplicities, central jet vetos, and other 6 event shapes

van Beekveld, S.F.R., Hamilton, Salam, Soto-Ontoso, Soyez, Verheyen, in preparation

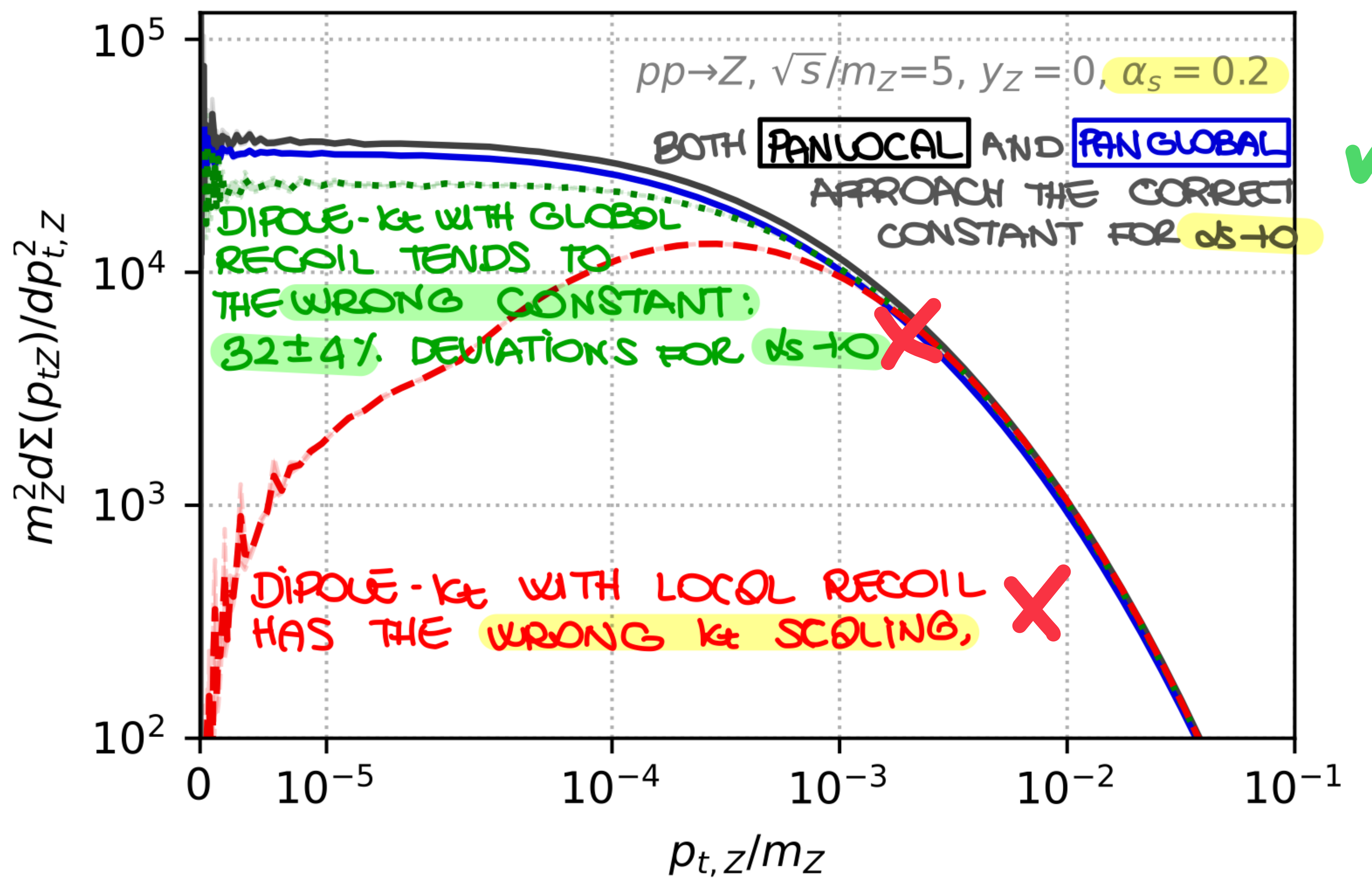
Conclusions and outlook

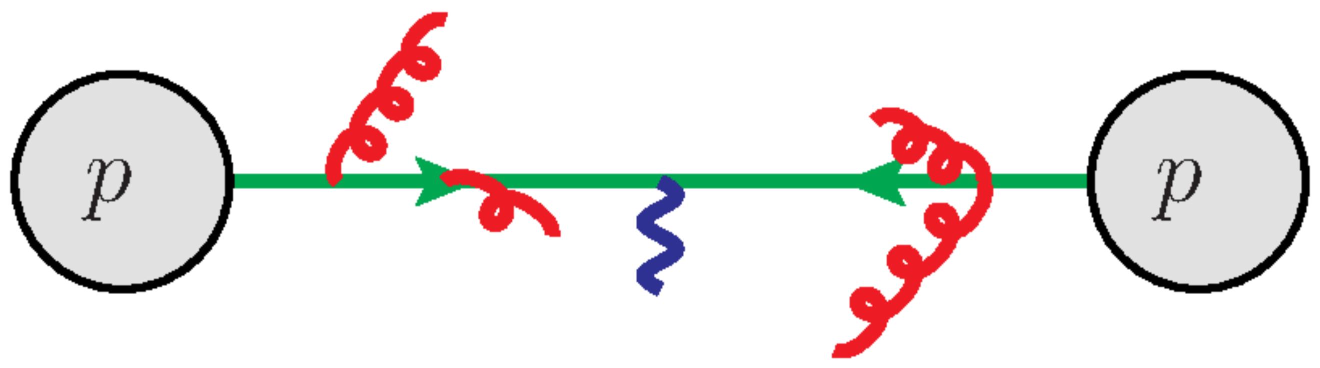
- PanScales: a project to bring **understanding & log accuracy** to parton showers
- NLL accuracy has been achieved for **e^+e^-** and **colour singlet production in hadron collisions** via revisiting:
  1. Interplay between **kinematic mapping** and **ordering scale**
  2. Assignment of **colour** (not discussed here, [JHEP 03 (2021) 041, 041 for FSR, arXiv:2205.02237 for ISR])
  3. **Spin correlations** (not discussed here, [Eur.Phys.J.C 81 (2021) 8, 681 and JHEP 03 (2022) 193 for FSR, arXiv:2205.02237 for ISR])
- We devised a **family of NLL showers**: differences can be used to assess uncertainties
- Next steps include (not in order of priority):
  - Extension of showers to more complex processes, i.e. Z+jet and dijets
  - Matching to hard matrix elements
  - Interface to Pythia to include soft physics effects (e.g. hadronisation)
  - Heavy quarks
  - …
  - … NNLL

Are we sure PanScales showers are NLL for $p_{T,Z}$?

All-orders tests: check if $\lim_{\alpha_s \to 0} \frac{\Sigma_{\text{PS}}(\alpha_s, \log V < L)}{\Sigma_{\text{NLL}}(\alpha_s, \log V < L)} = 1$ at fixed $\lambda = \alpha_s L$

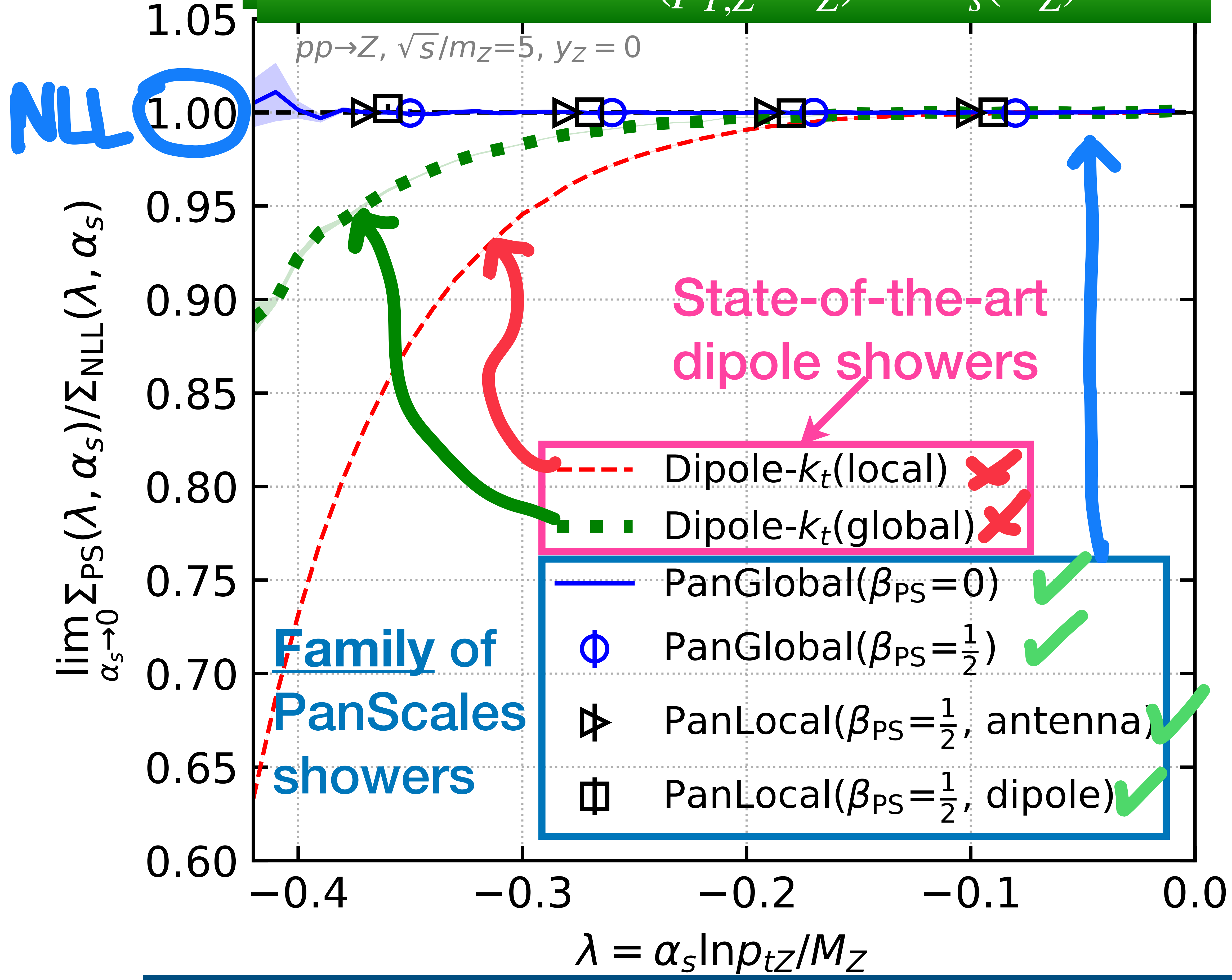
Correct power scaling at low $p_{T,Z}$





Enhanced by emissions at opposite but not so small p_T

Shower/NLL for $\Sigma(p_{T,Z}/m_Z)$ for $\alpha_s(m_Z) \to 0$



van Beekveld, S.F.R., Hamilton, Salam, Soto-Ontoso, Soyez, Verheyen, in preparation