An Overview of the PanScales Parton Showers

Rob Verheyen

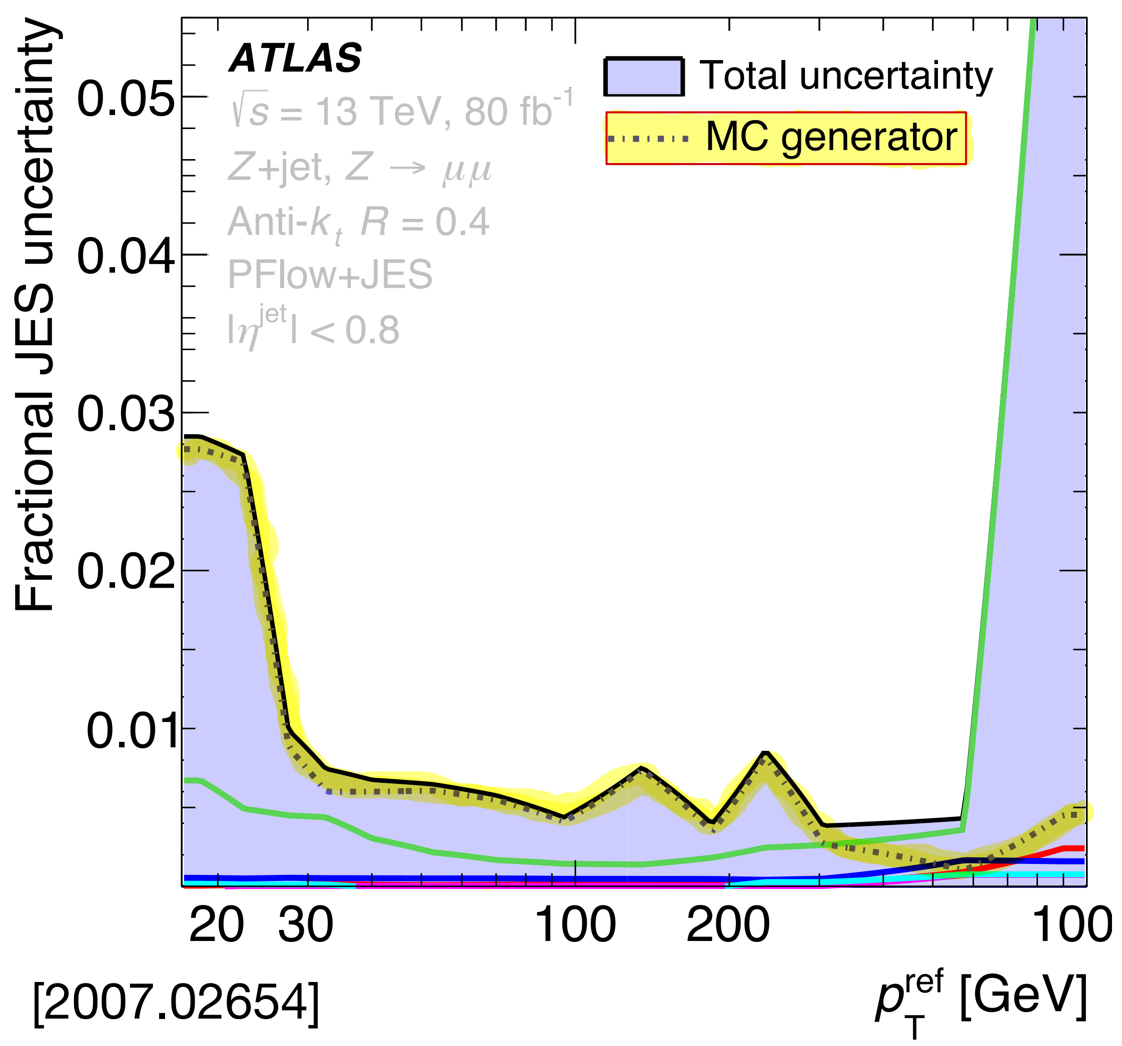
European Research Council
Established by the European Commission

Parton Showers

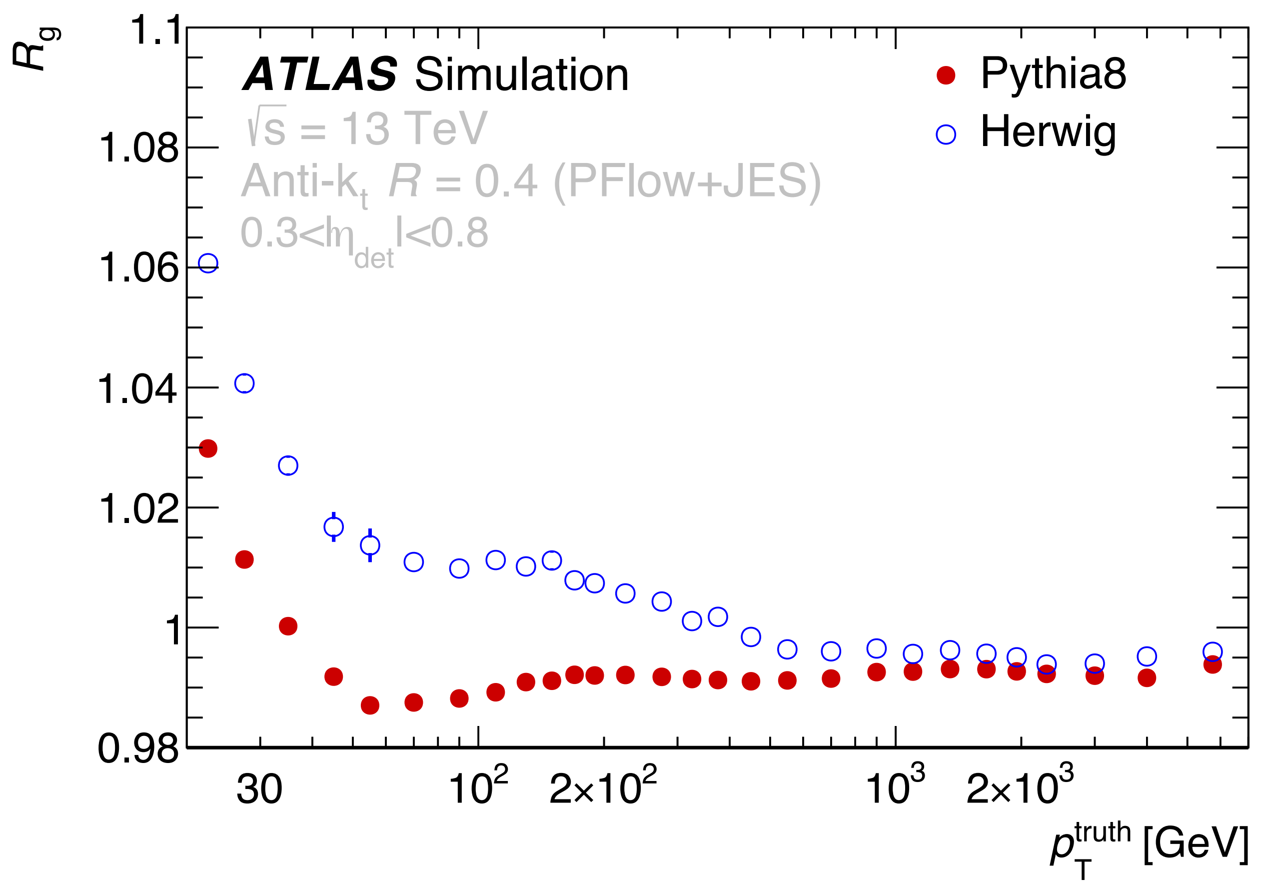
Core component of MC event generators

Need for improvement in theoretical accuracy

Jet Calibration

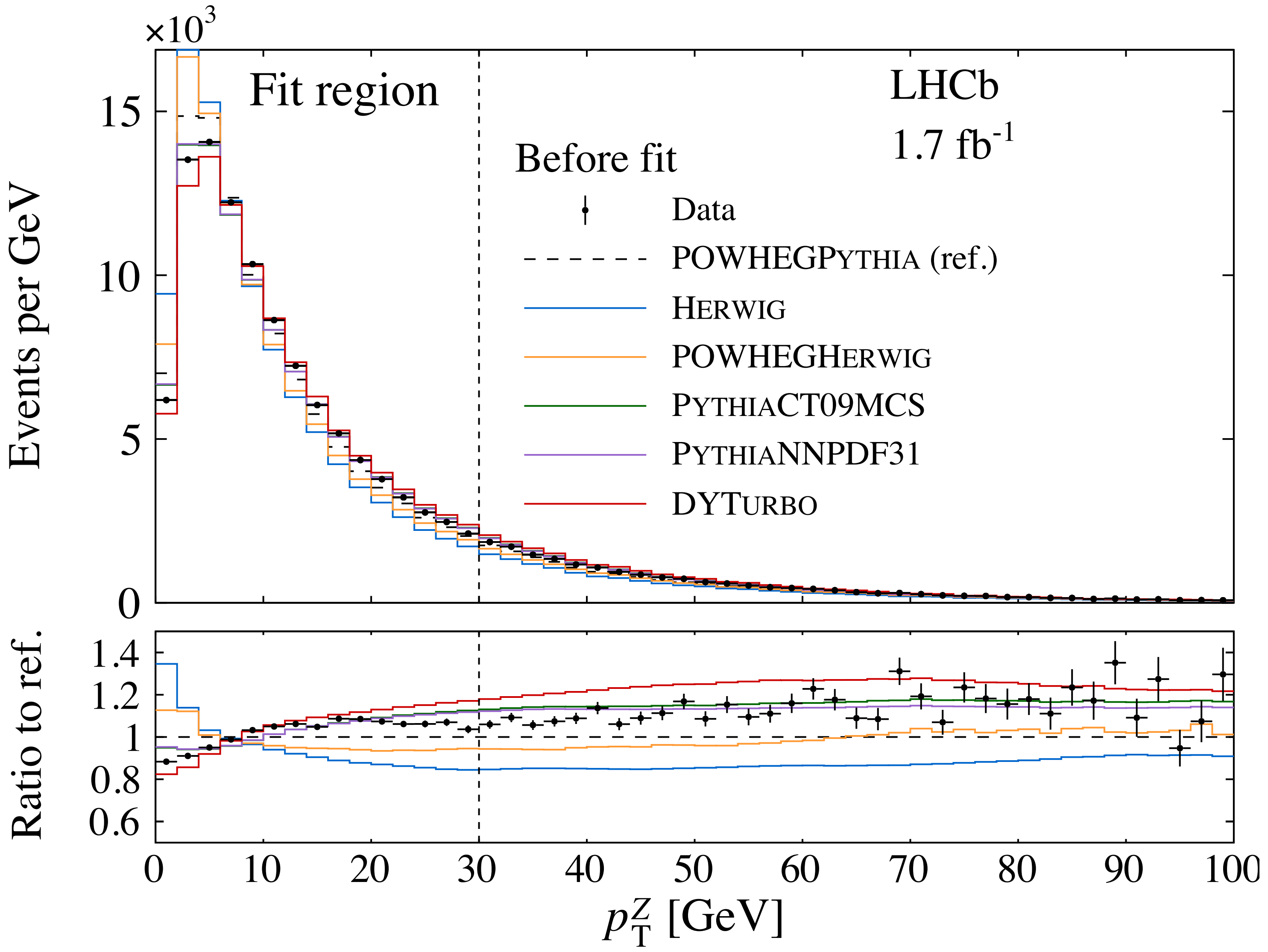


[2007.02654]



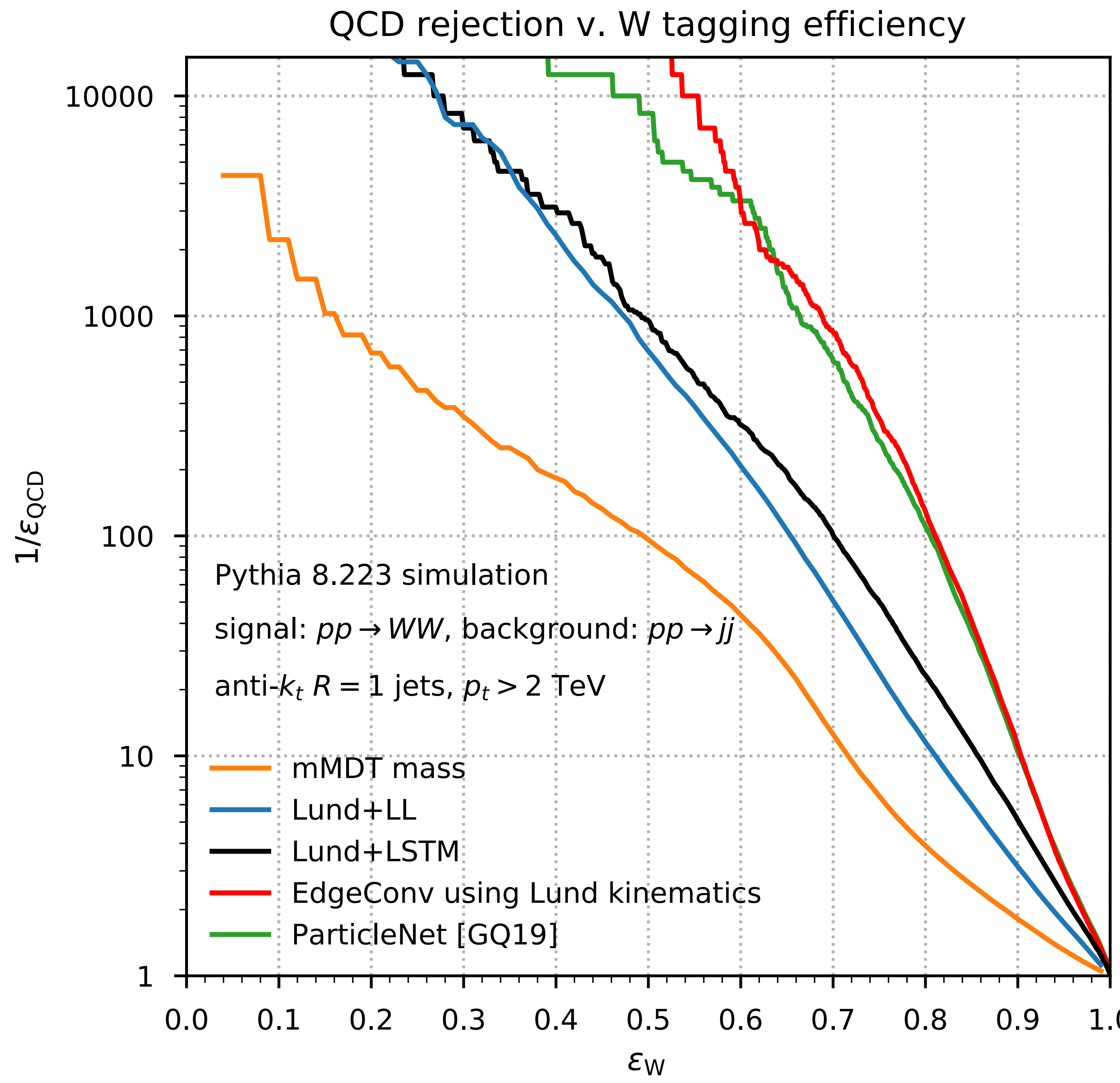
[ATLAS Eur.Phys.J.C 81 (2021) 8, 689]

EW precision measurements



[LHCb JHEP 01 (2022) 036]

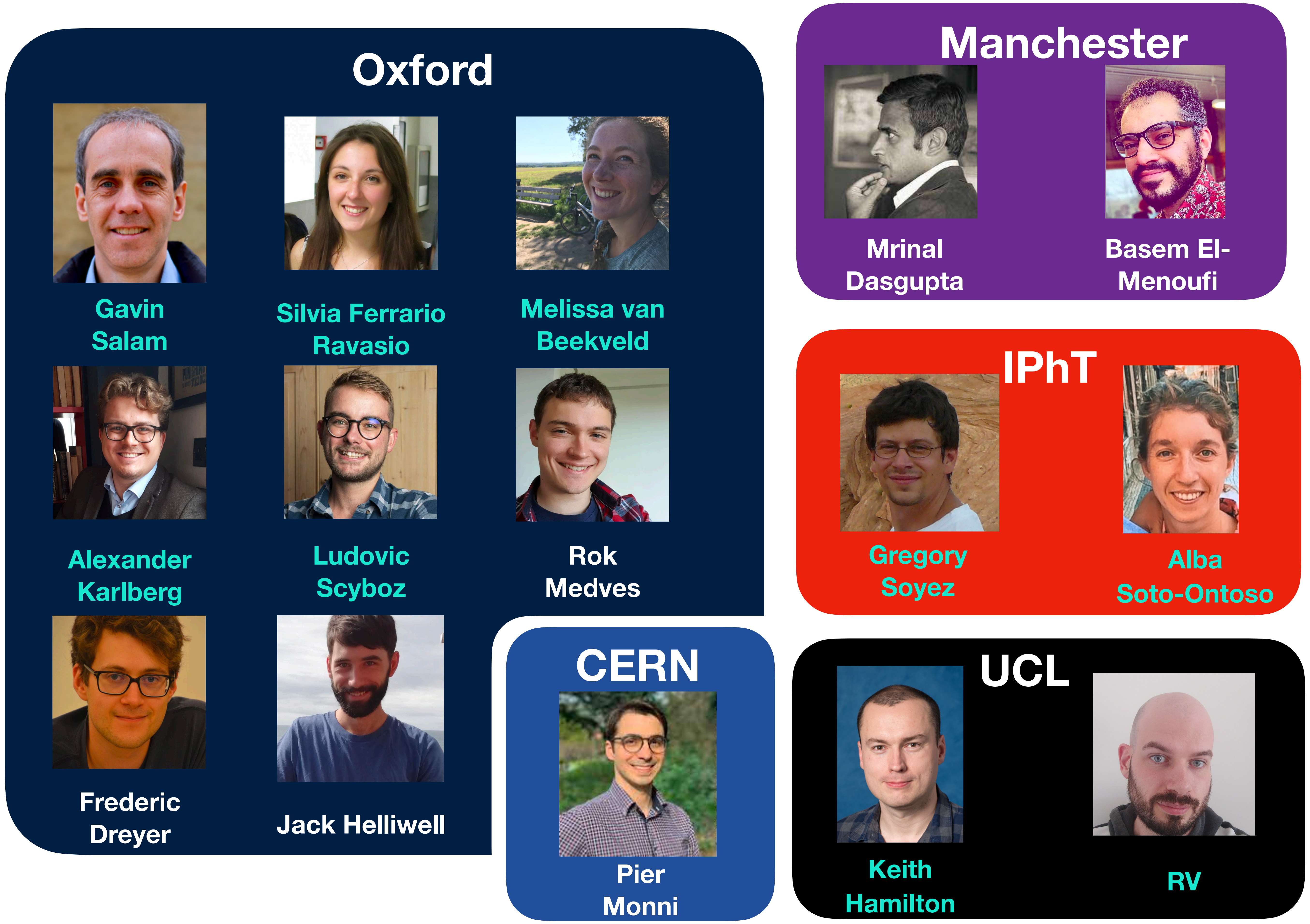
Machine Learning



Adapted from Dreyer, Qu, *JHEP* 03 (2021) 052

PanScales

Goal: Improving theoretical accuracy of parton showers



Work so far

NLL-accurate e^+e^- showers

1805.09327, 2002.11114

Full colour at NLL for global event shapes

2011.10054

Spin correlations at NLL accuracy

2103.16526, 2111.01161

First steps toward NNLL

2007.10355, 2109.07496

NLL-accurate showers in hadronic colour-singlet production

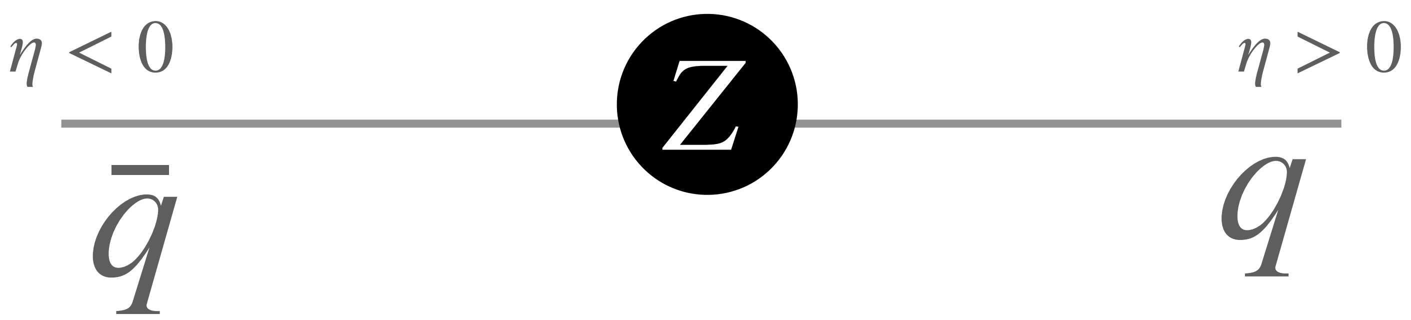
2205.02237, 2207.09467

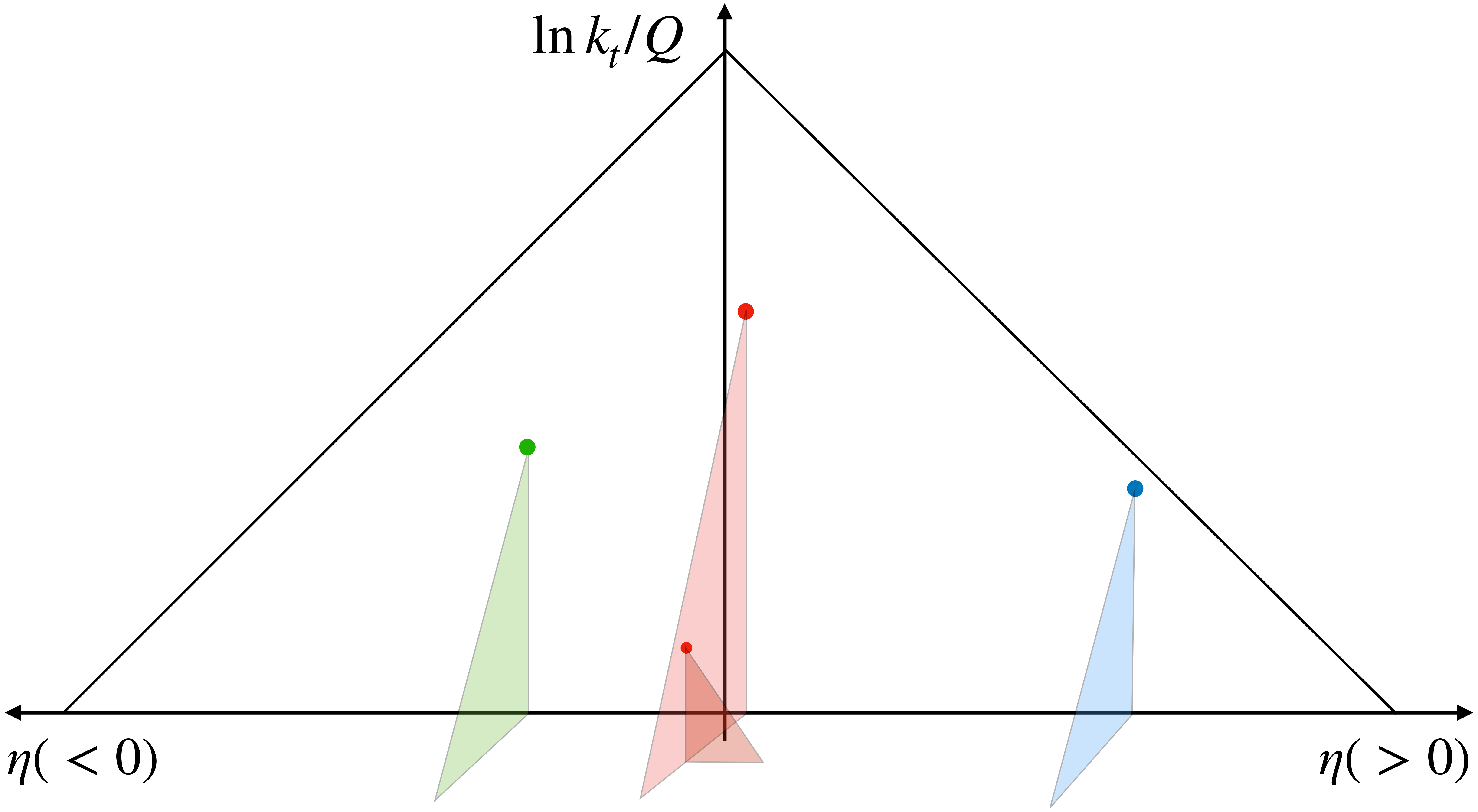
Matching and NNDL accuracy

22xx.xxxxx

The PanScales Parton Showers

The Lund Plane

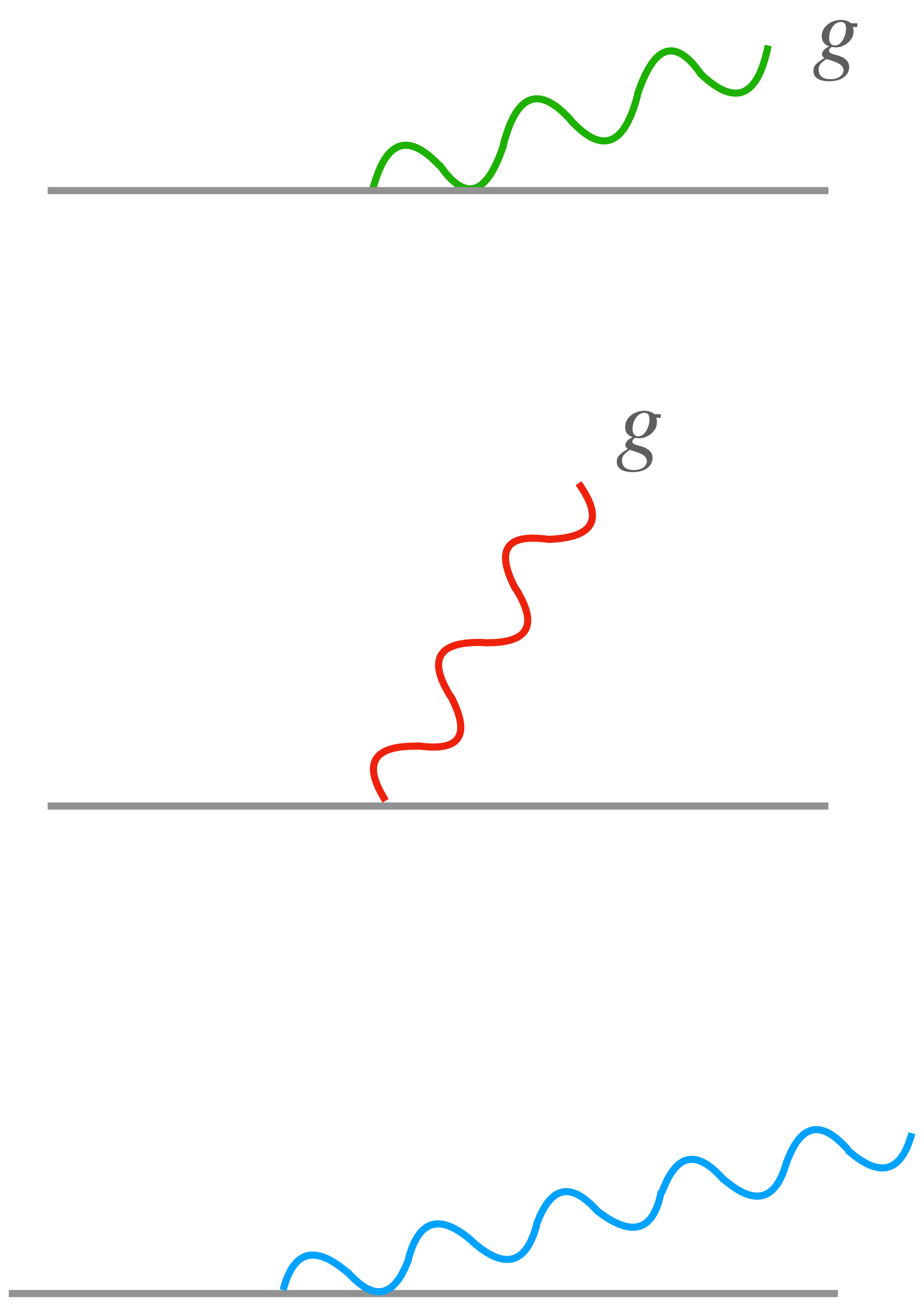




Soft-collinear

Soft wide-angle

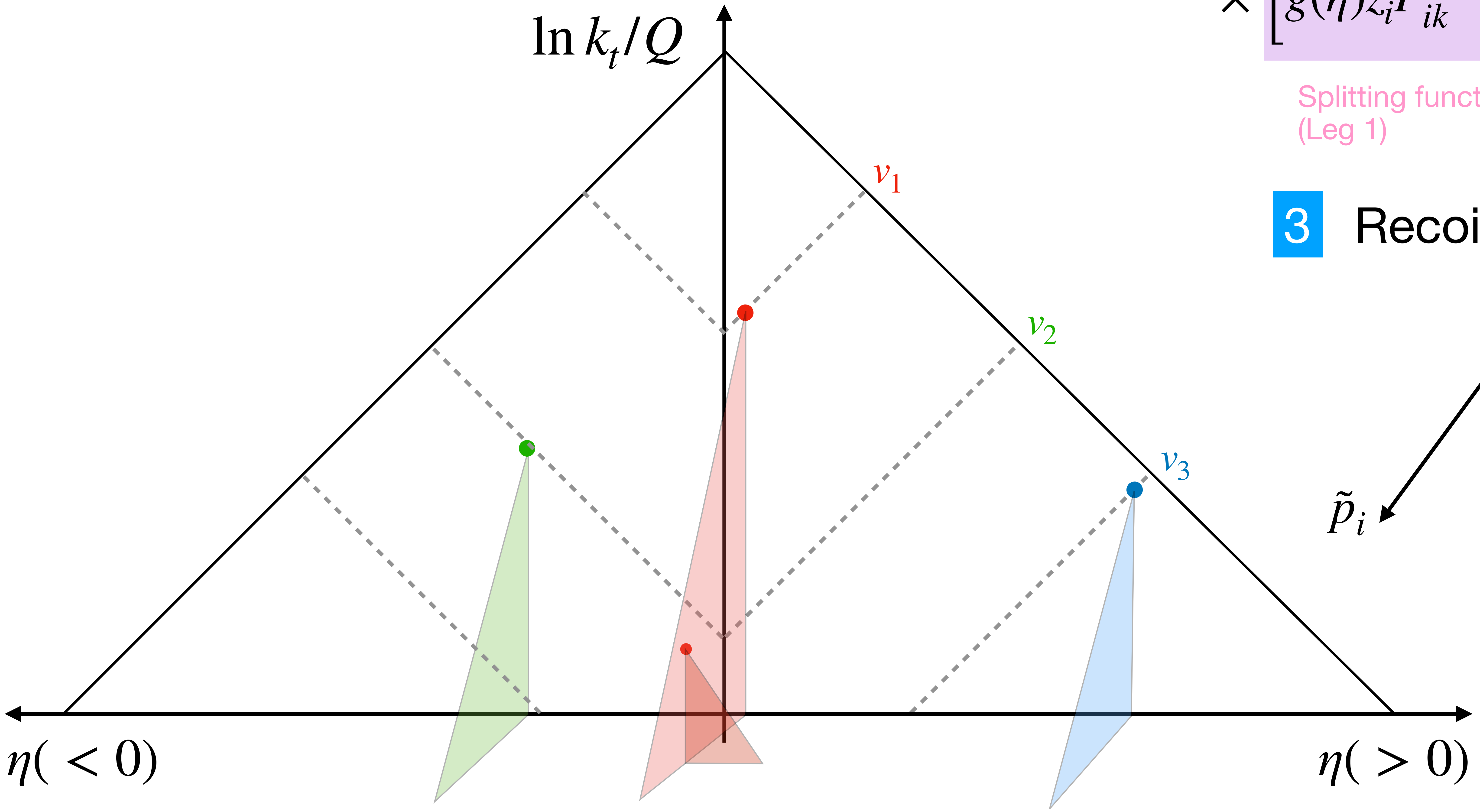
Hard-collinear



Parton Shower

General-purpose resummation framework

1 Ordering scale $v = k_t \exp(-\beta_{\text{ps}} |\eta|)$



2 Differential splitting probability

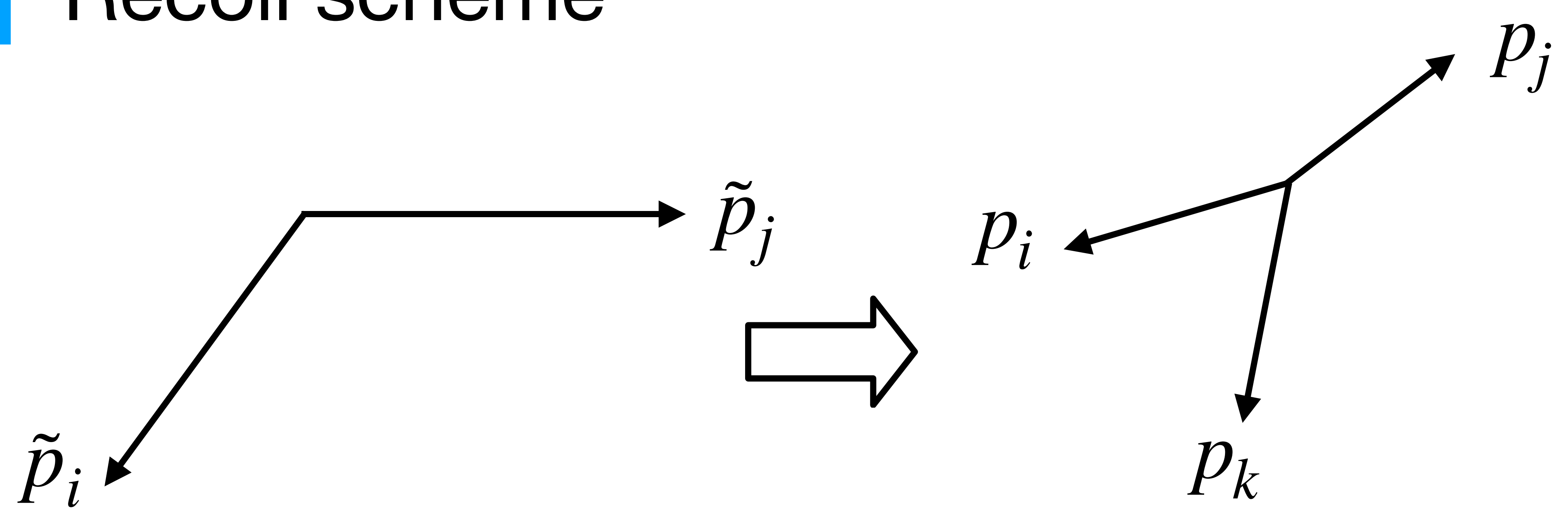
Phase space | PDF factor

$$\mathrm{d}\mathscr{P}_{\tilde{i}\tilde{j}\to ijk} = \frac{\alpha_s(\mu_R^2)}{2\pi}\frac{\mathrm{d}v^2}{v^2}\mathrm{d}\bar{\eta}\frac{\mathrm{d}\varphi}{2\pi}\frac{x_i f_i(x_i,\mu_F^2)}{\tilde{x}_i f_{\tilde{i}}(\tilde{x}_i,\mu_F^2)}\frac{x_j f_j(x_j,\mu_F^2)}{\tilde{x}_j f_{\tilde{j}}(\tilde{x}_j,\mu_F^2)}$$

$$\times \left[g(\eta) z_i P_{ik}^{\text{IS/FS}}(z_i) + g(-\eta) z_j P_{jk}^{\text{IS/FS}}(z_j)\right]$$ ← Dipole partitioning

Splitting function (Leg 1) | Splitting function (Leg 2)

3 Recoil scheme

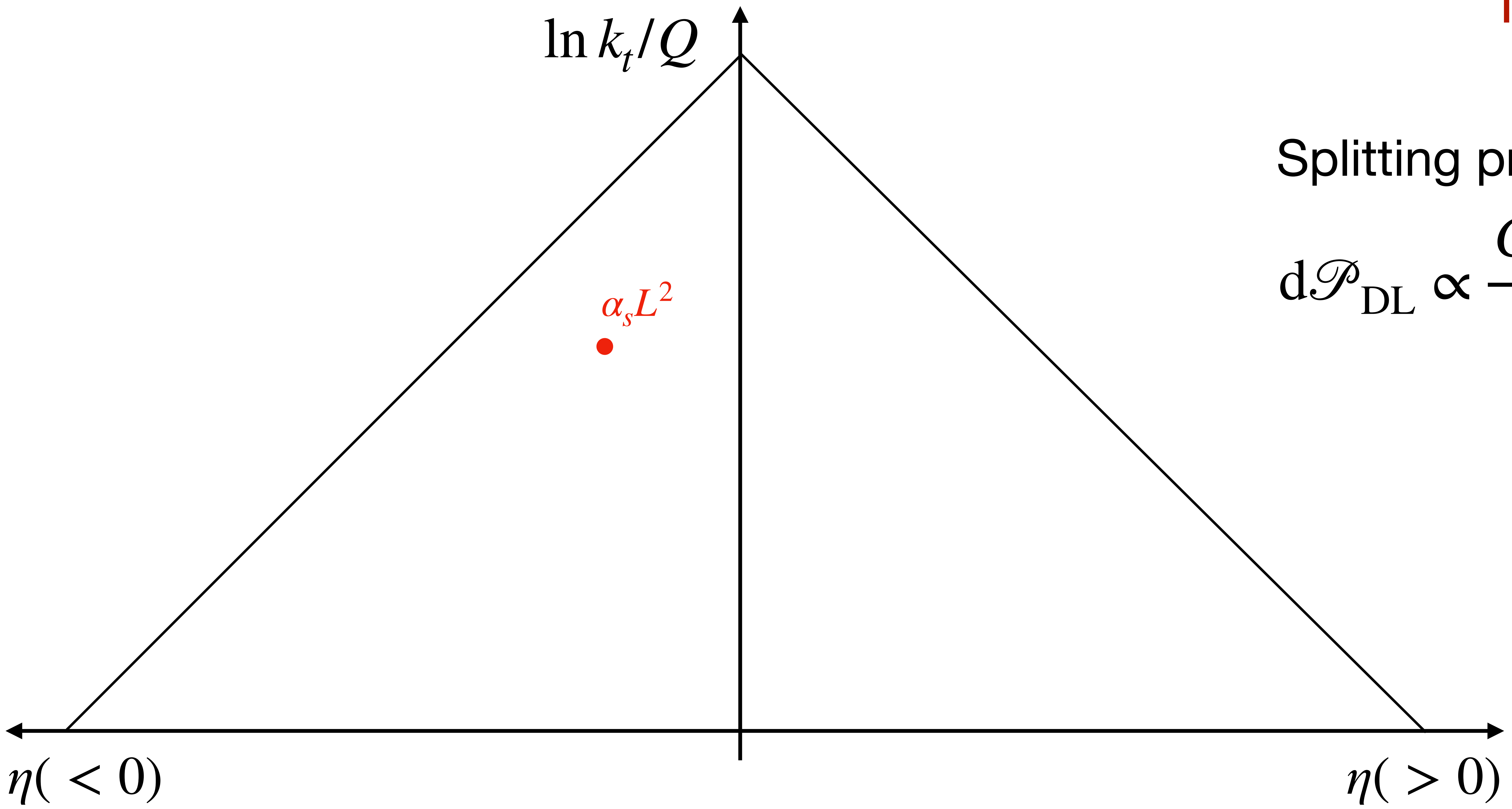


Resummation & the Lund plane

LL$\sim \mathcal{O}(1/\alpha_s)$ NNLL$\sim \mathcal{O}(\alpha_s)$

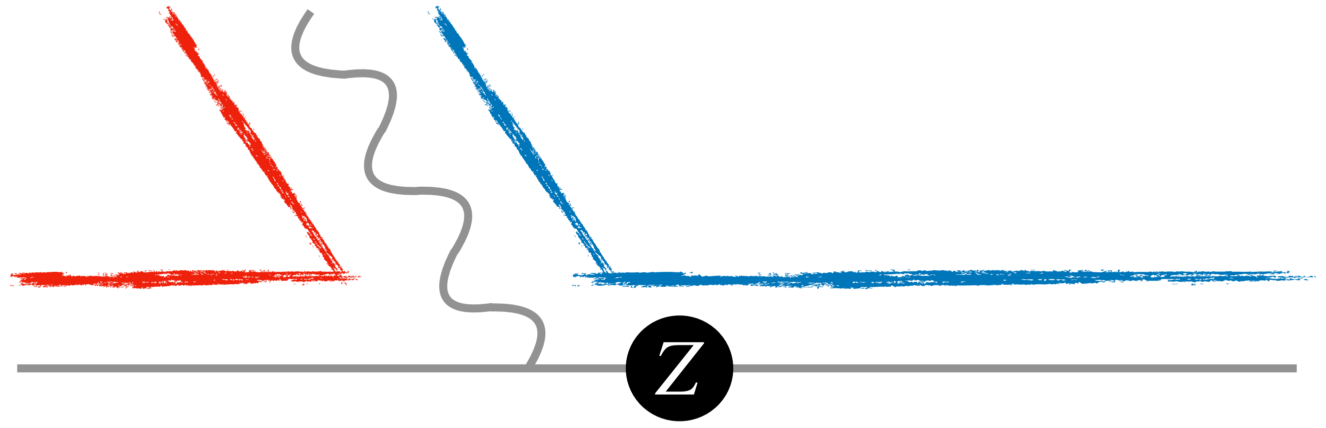
$$\Sigma(\bar{O} < e^{-L}) = \exp\left[Lg_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots\right]$$

NLL$\sim \mathcal{O}(1)$



Splitting probability

$$\mathrm{d}\mathcal{P}_{\mathrm{DL}} \propto \frac{C_F \alpha_s}{2\pi} \mathrm{d}\eta \frac{\mathrm{d}k_t}{k_t}$$



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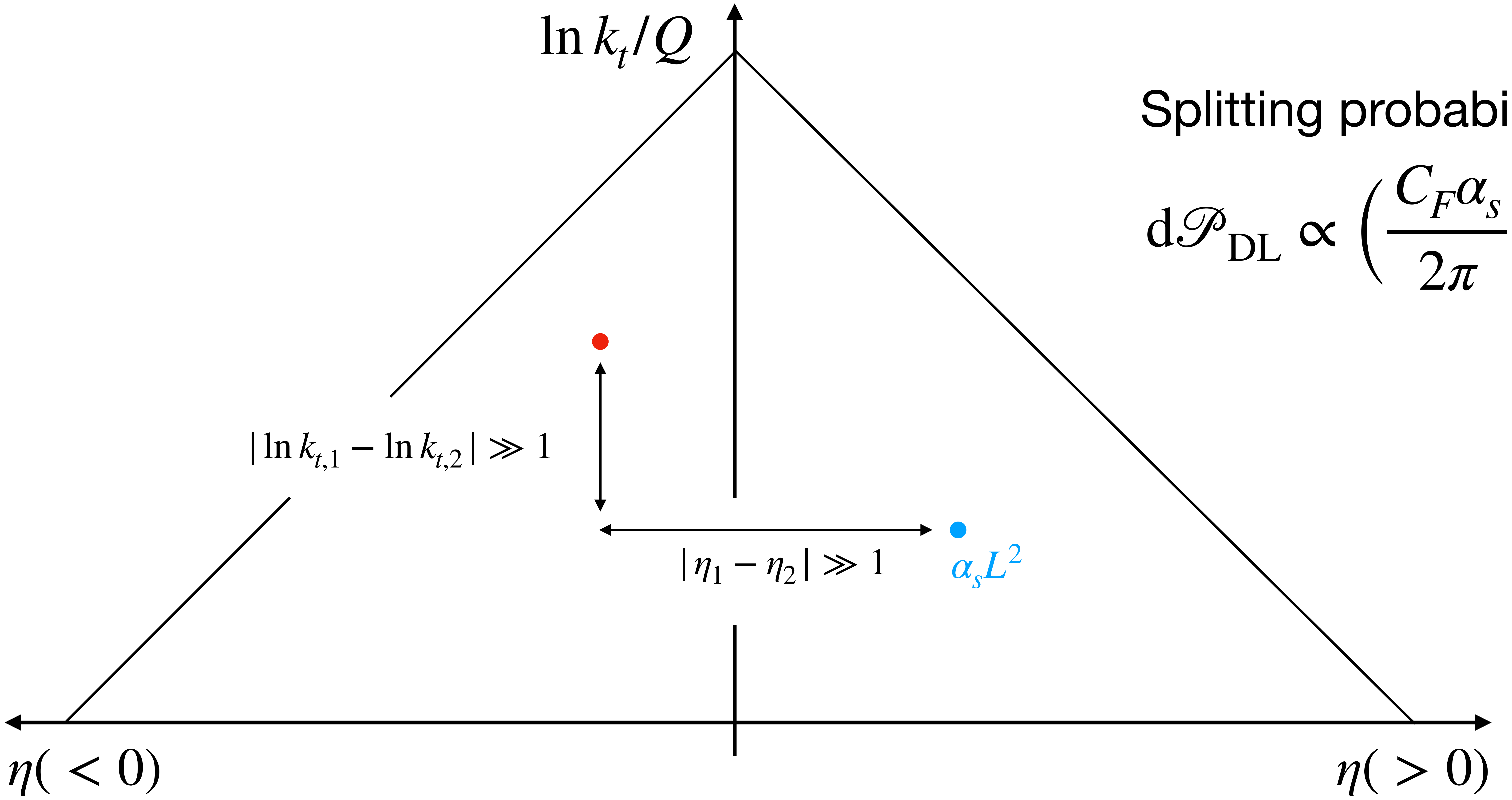
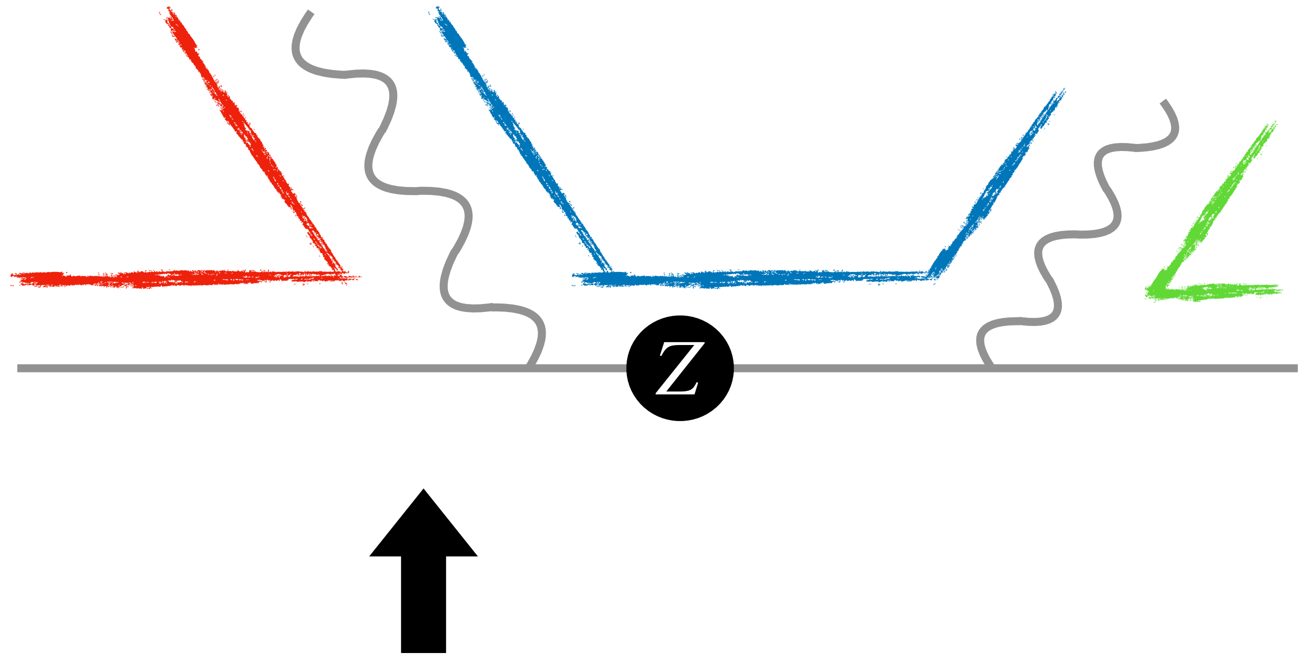


Splitting probability

$$\mathrm{d}\mathcal{P}_{\mathrm{DL}} \propto \left(\frac{C_F\alpha_s}{2\pi}\right)^2 \mathrm{d}\eta_1 \frac{\mathrm{d}k_{t,1}}{k_{t,1}} \times \mathrm{d}\eta_2 \frac{\mathrm{d}k_{t,2}}{k_{t,2}}$$

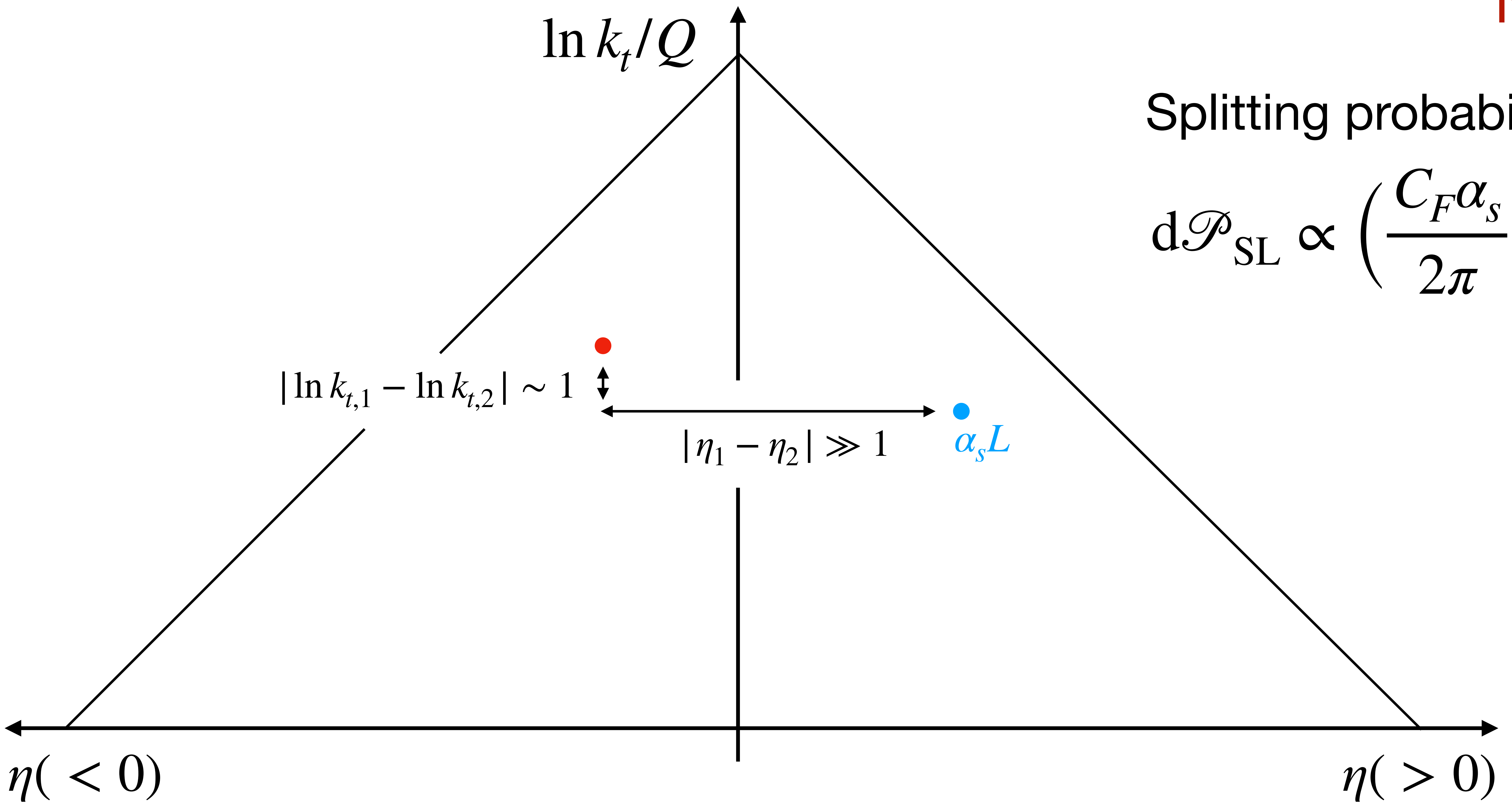


No recoil on the first emission

Resummation & the Lund plane

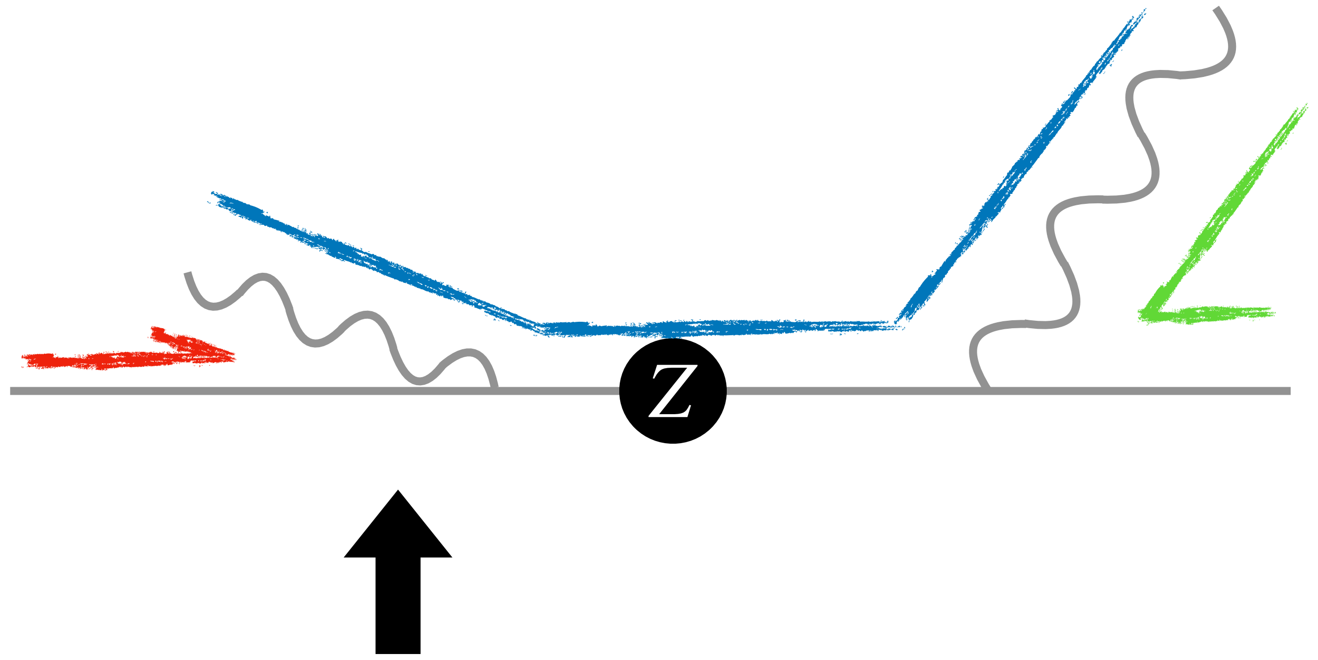
$$\Sigma(\bar{O} < e^{-L}) = \exp\left[Lg_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots\right]$$

NLL $\sim \mathcal{O}(1)$



Splitting probability

$$\mathrm{d}\mathcal{P}_{\mathrm{SL}} \propto \left(\frac{C_F\alpha_s}{2\pi}\right)^2 \mathrm{d}\eta_1 \frac{\mathrm{d}k_{t,1}}{k_{t,1}} \times \mathrm{d}\eta_2 \frac{\mathrm{d}k_{t,2}}{k_{t,2}}$$ ✔

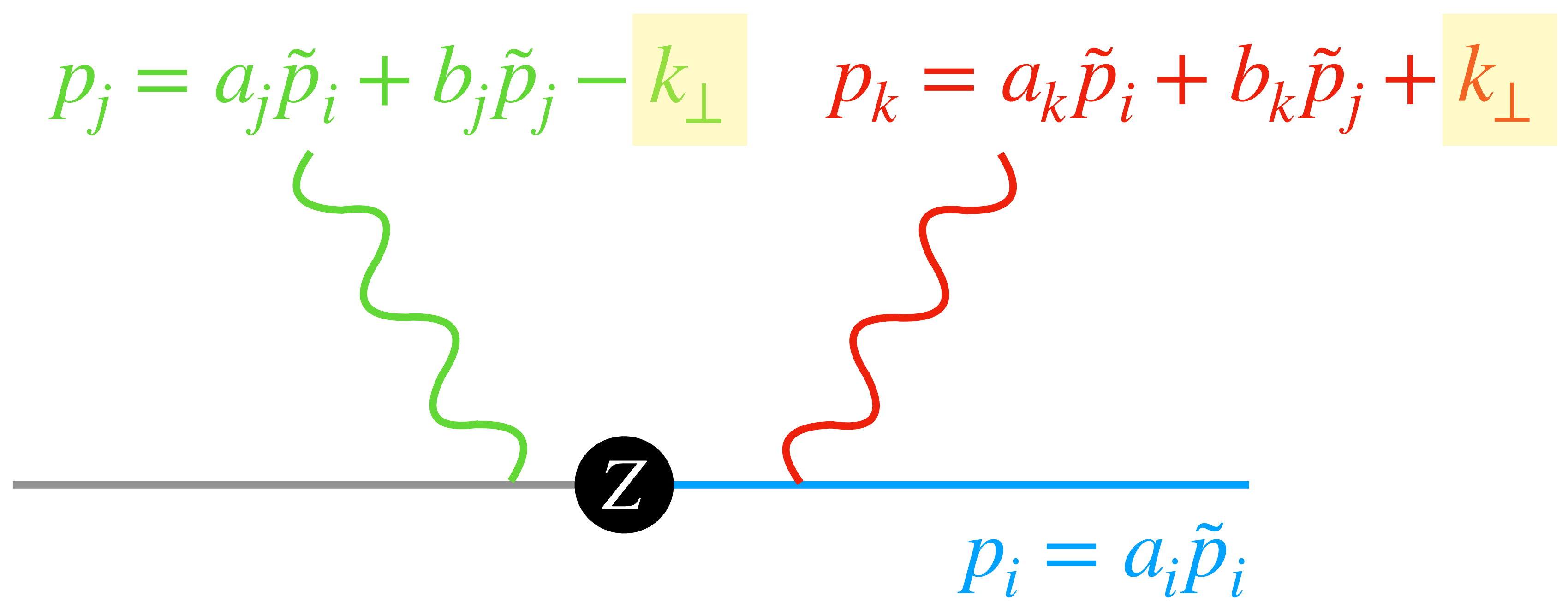


Recoil on the first emission ✘

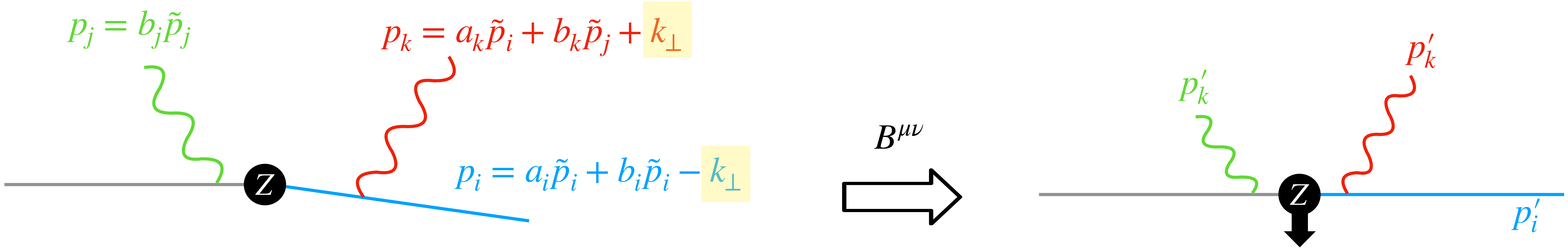
Recoil in standard Parton Showers

Where does the $k_\perp$ go?

Local recoil



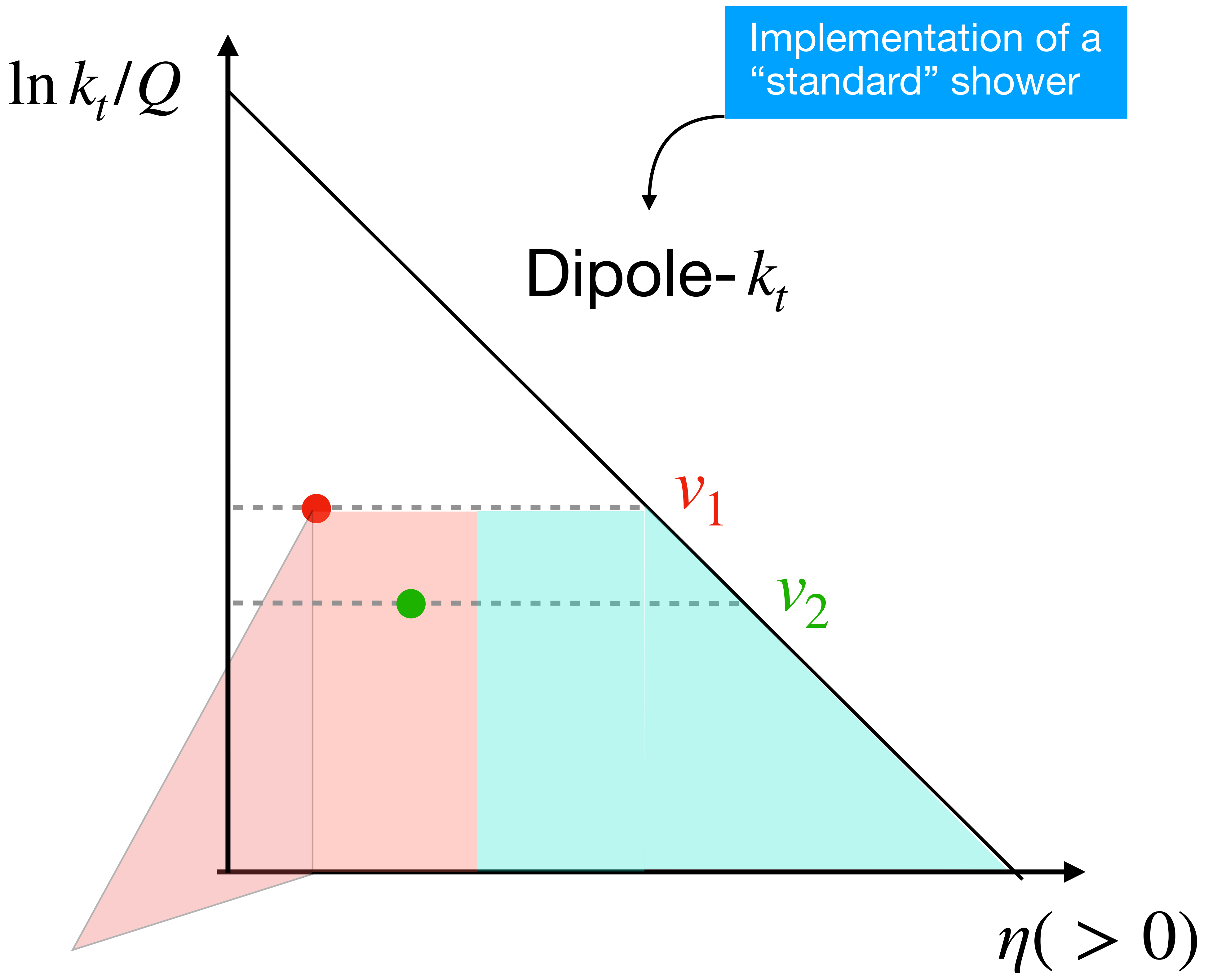
Global recoil

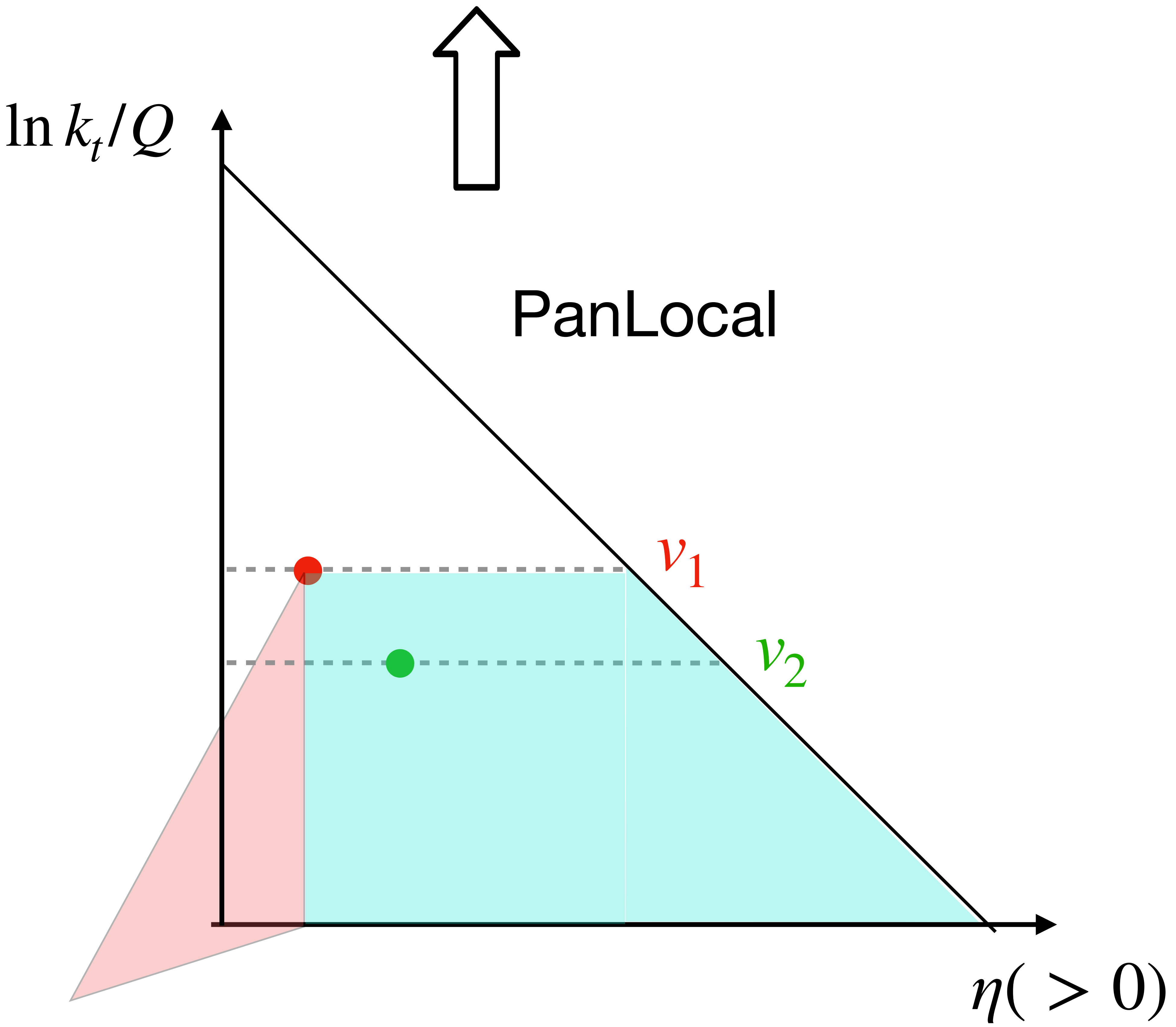


The PanLocal Shower

1 Partition dipole in *event* CoM frame

Previous emissions at smaller $|\eta|$ are unaffected



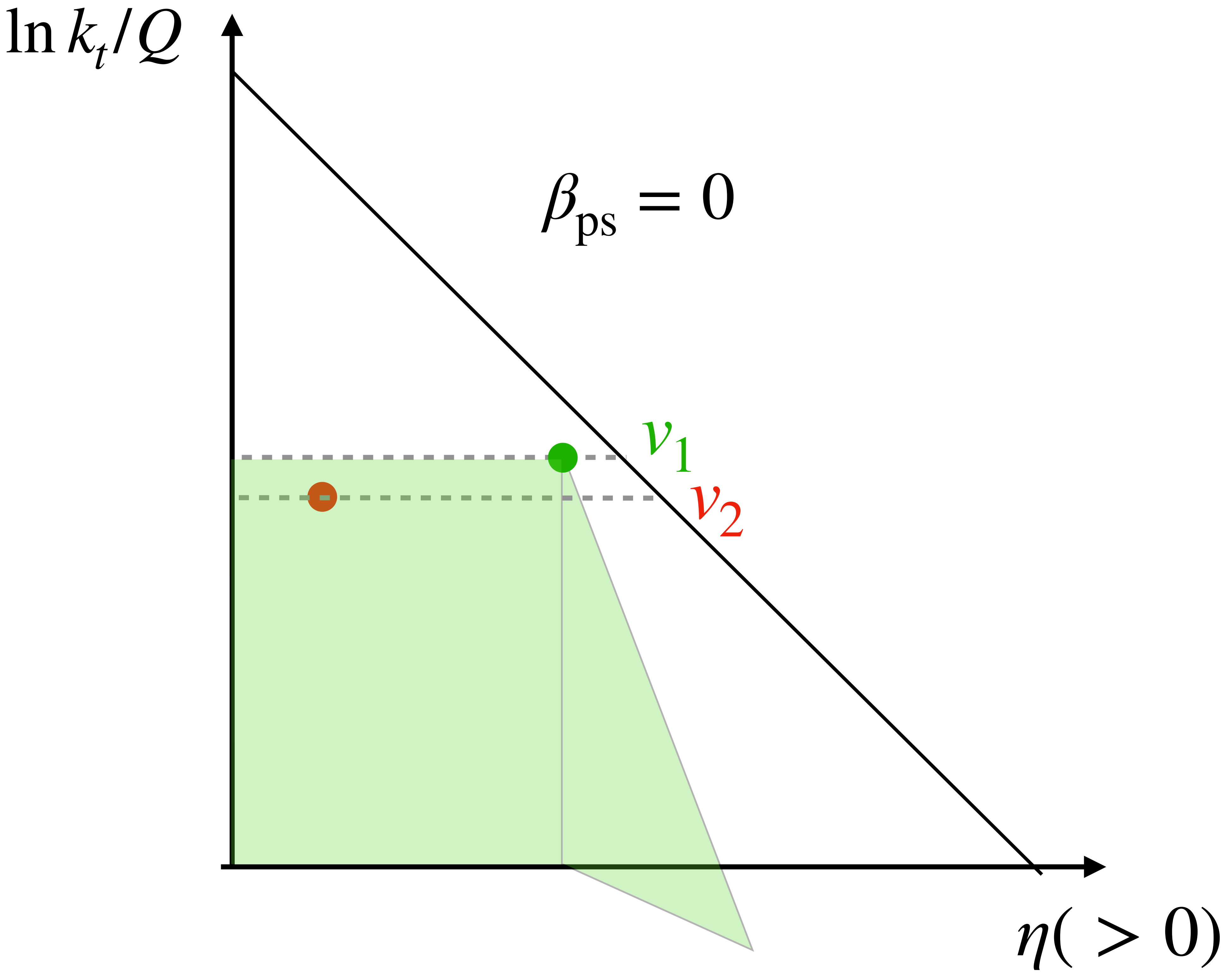


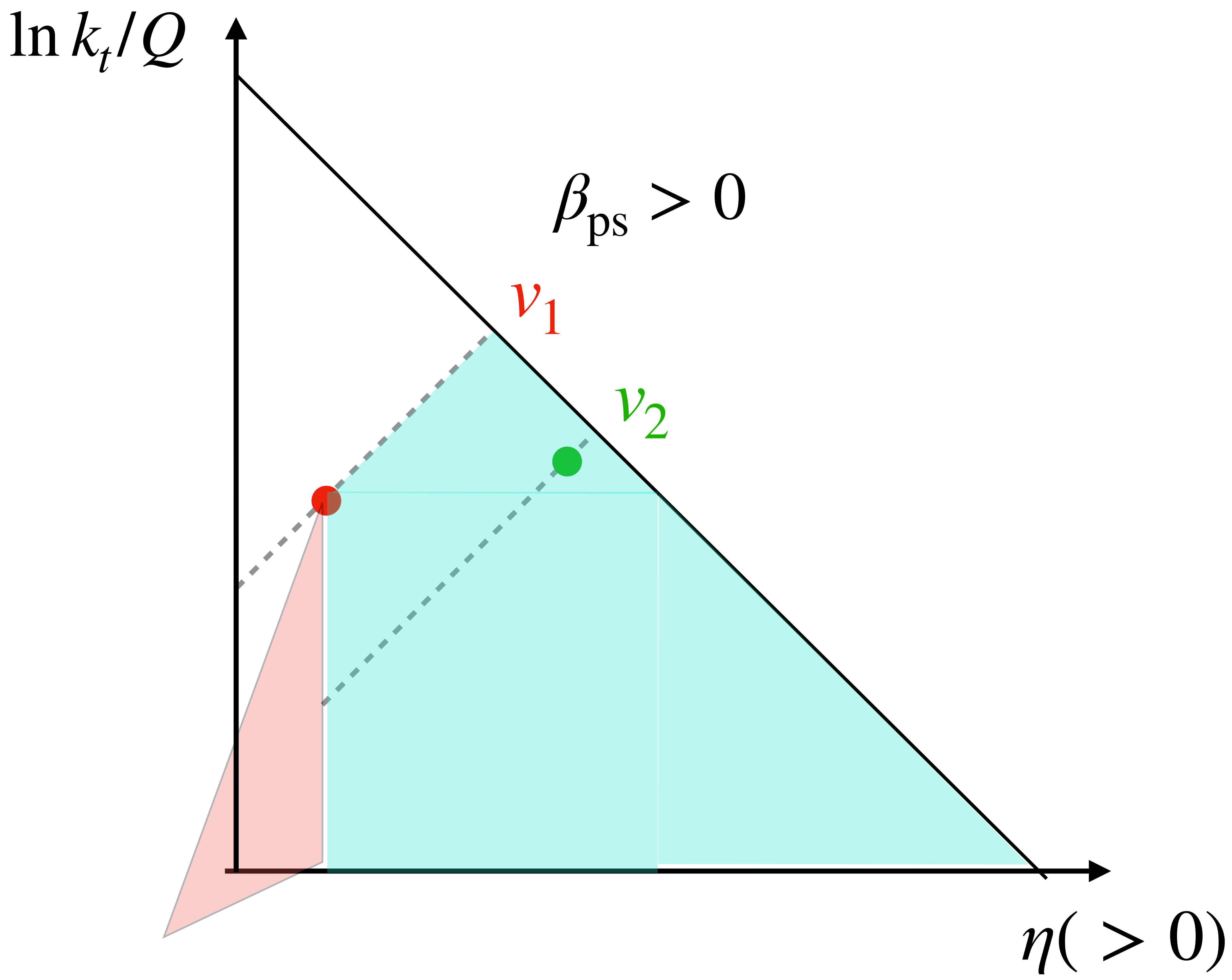
The PanLocal Shower

$v = k_t \exp(-\beta_{ps} |\eta|)$

Emissions at large $|\eta|$ occur later
⟶ Recoil always taken from the hard leg

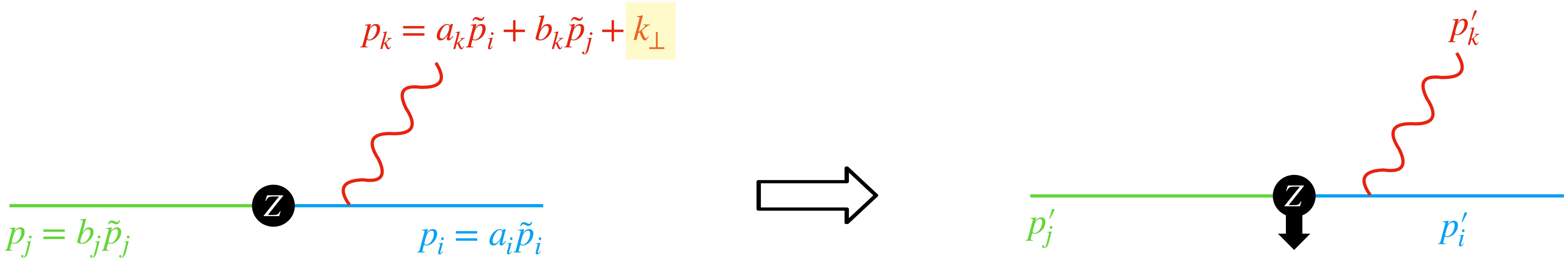
1. Partition dipole in *event* CoM frame
2. Require $\beta_{ps} > 0$



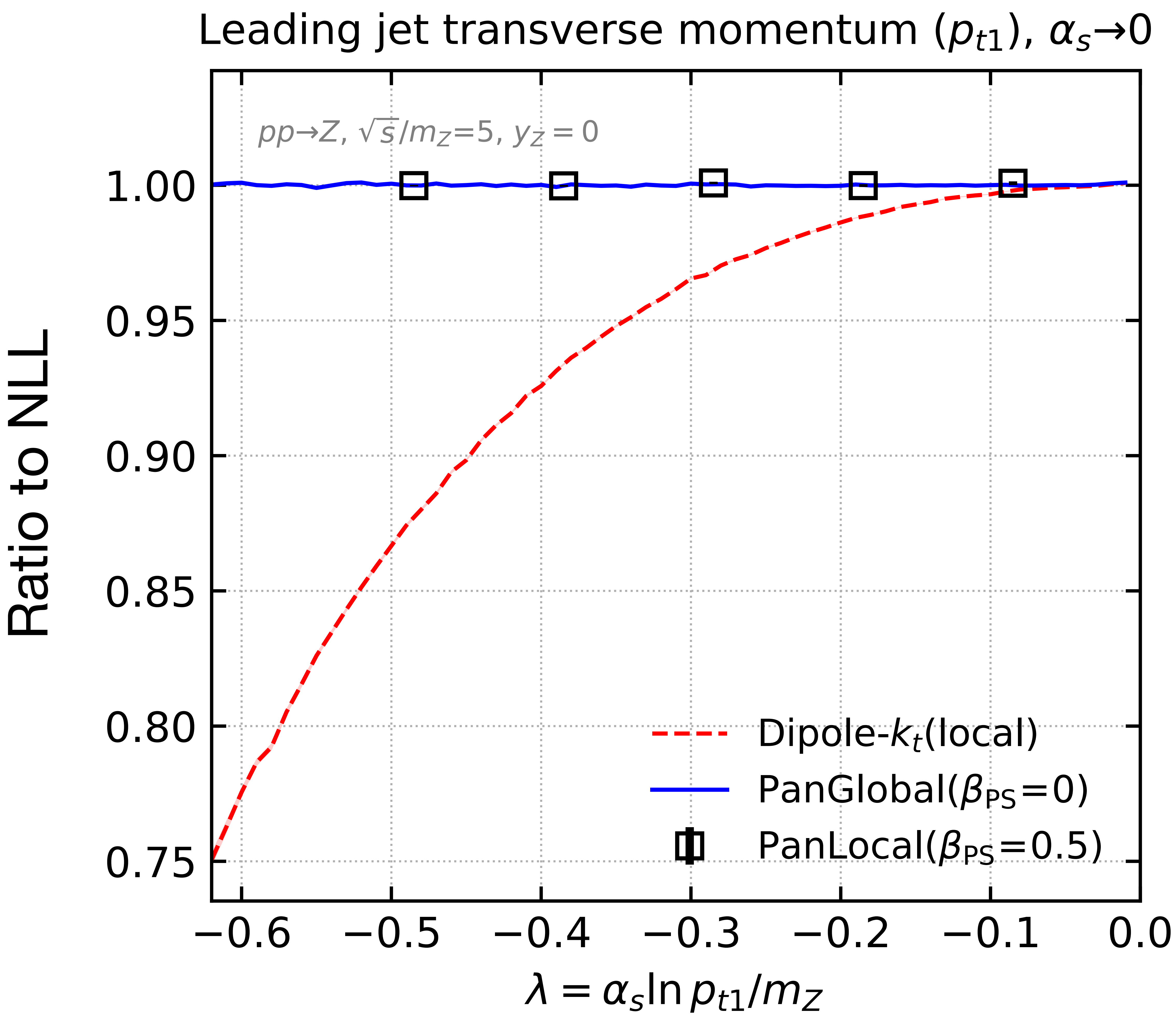


The PanGlobal Shower

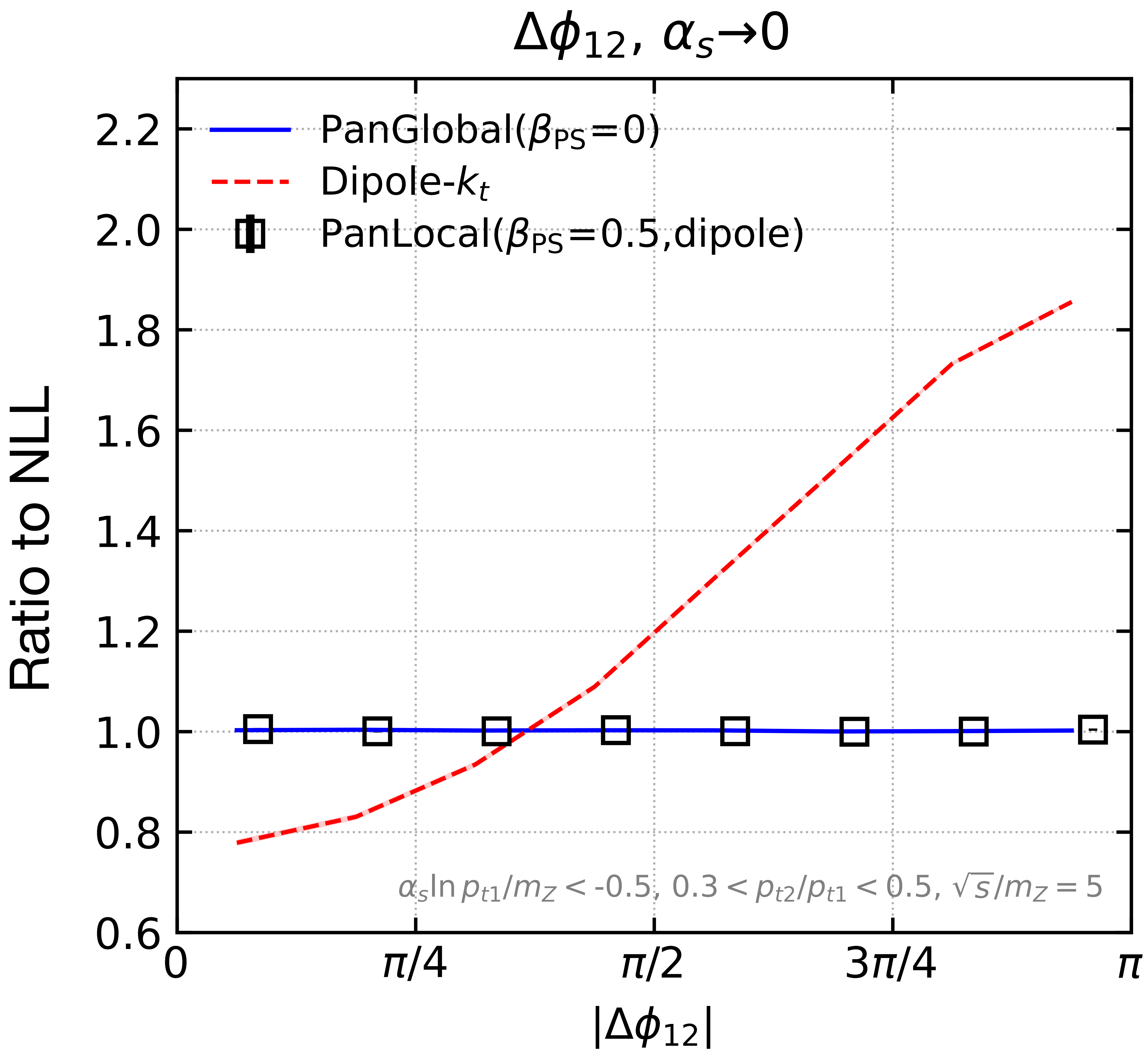
Always distribute recoil globally



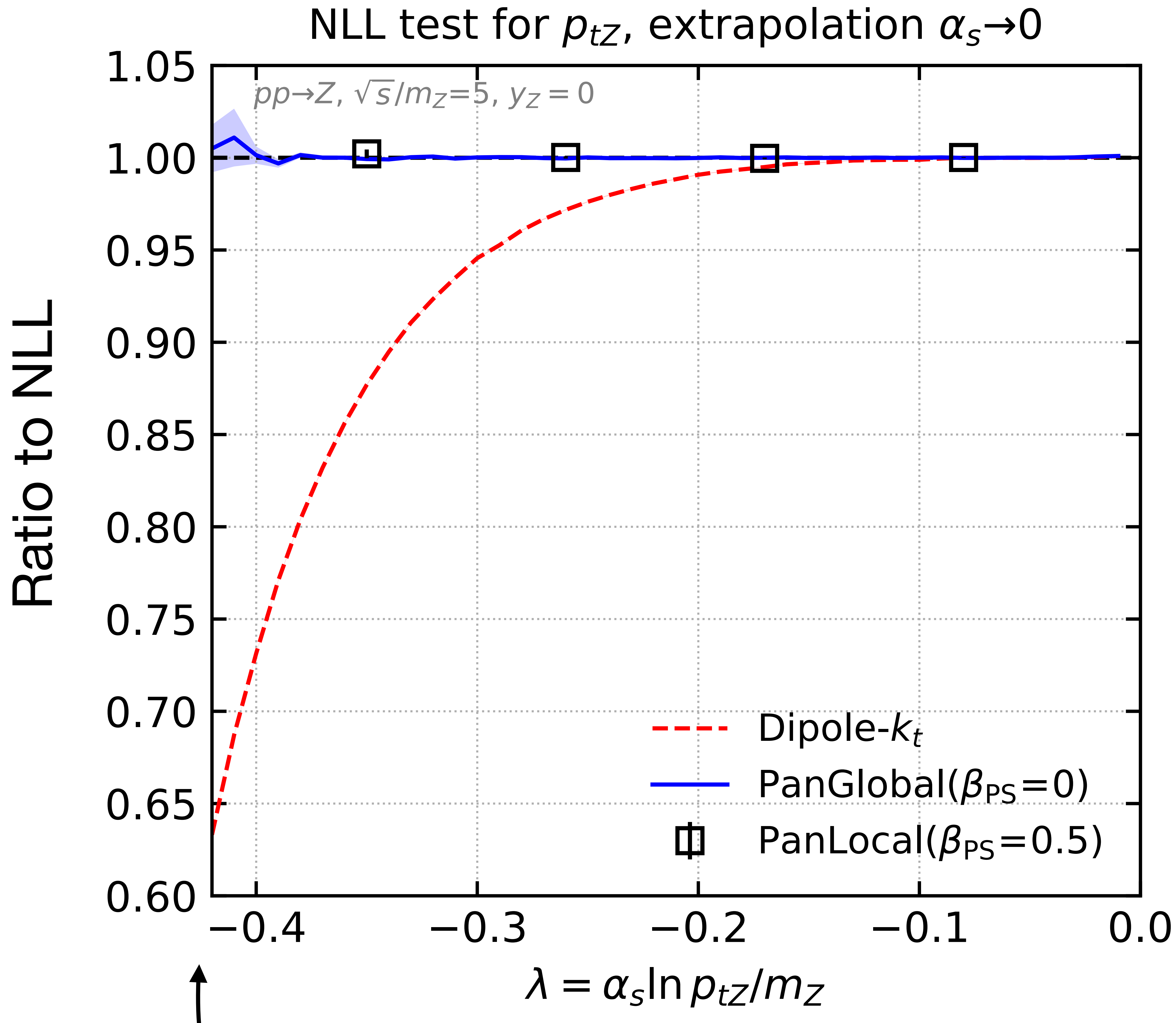
All-order Tests



Azimuthal angle between the leading jets

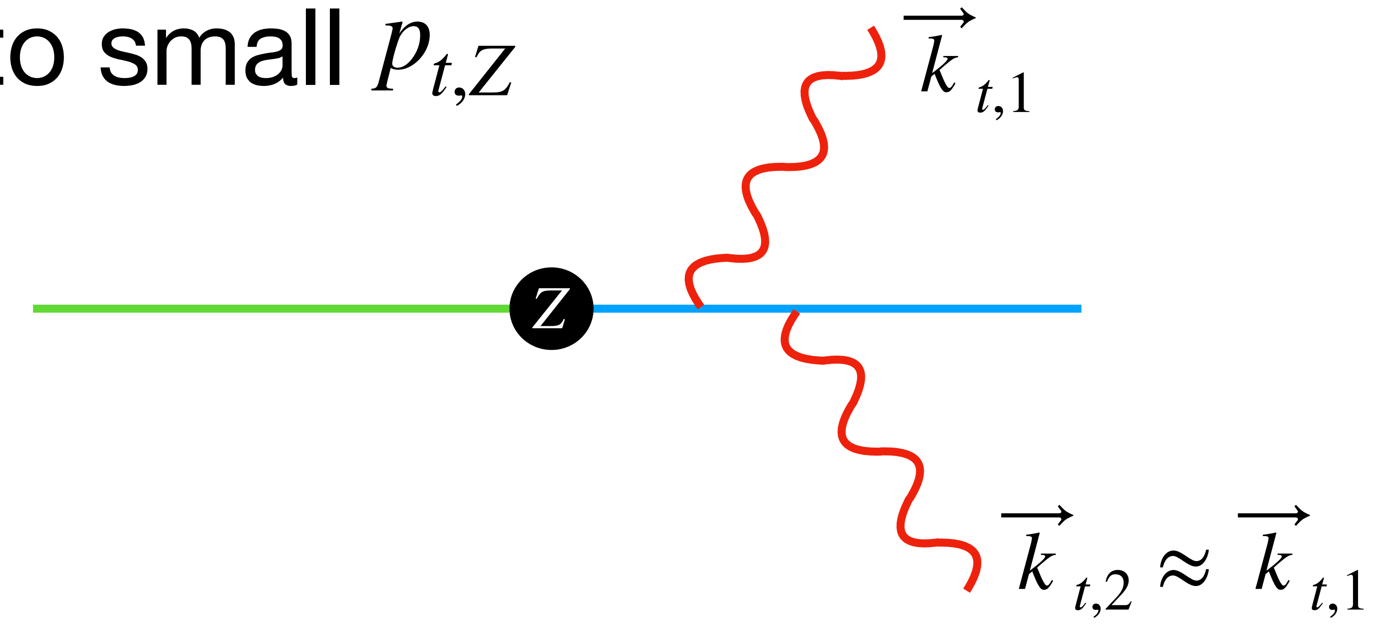


Colour Singlet $p_{t,Z}$



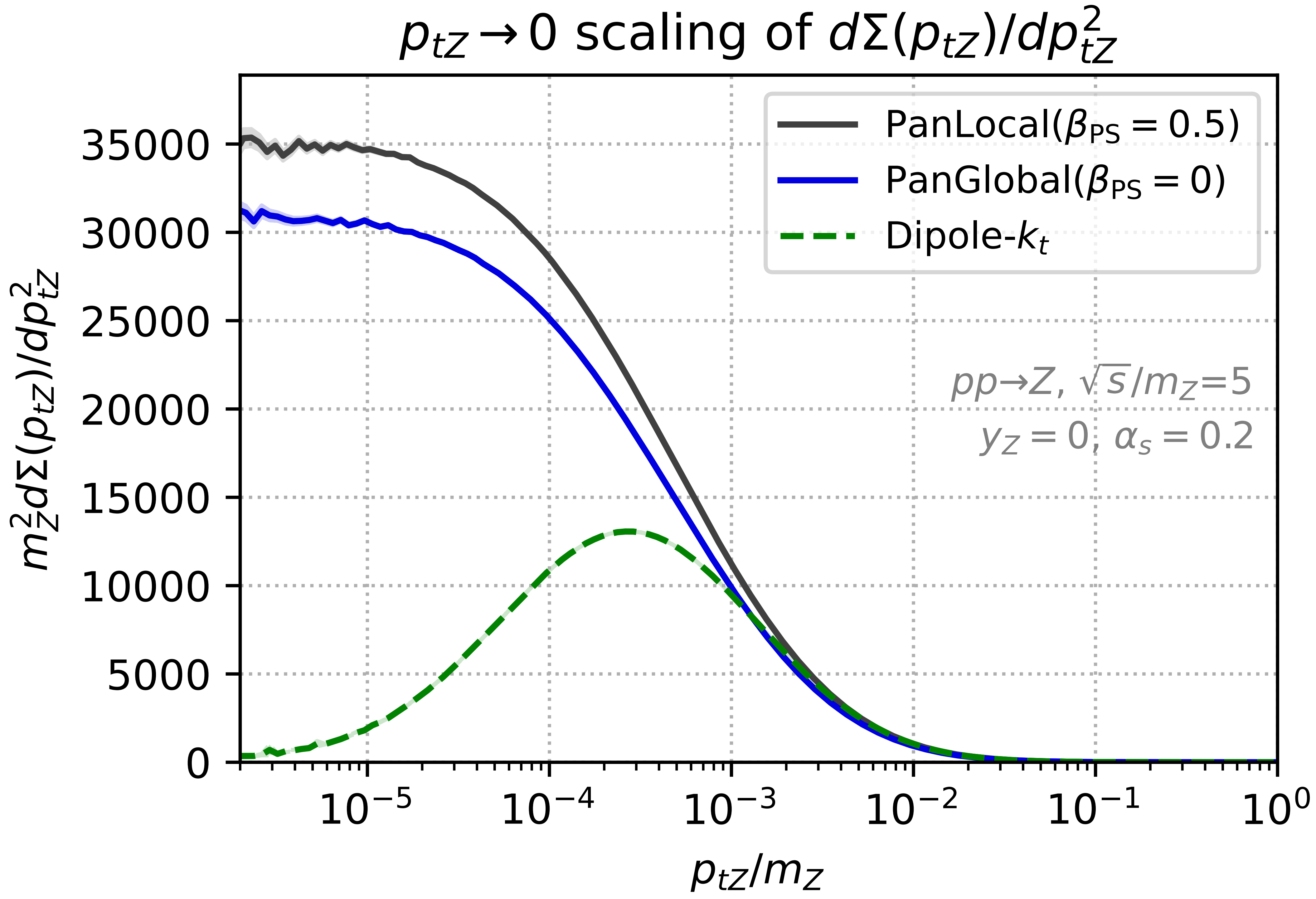
Breakdown of normal resummation

Another way to get to small $p_{t,Z}$

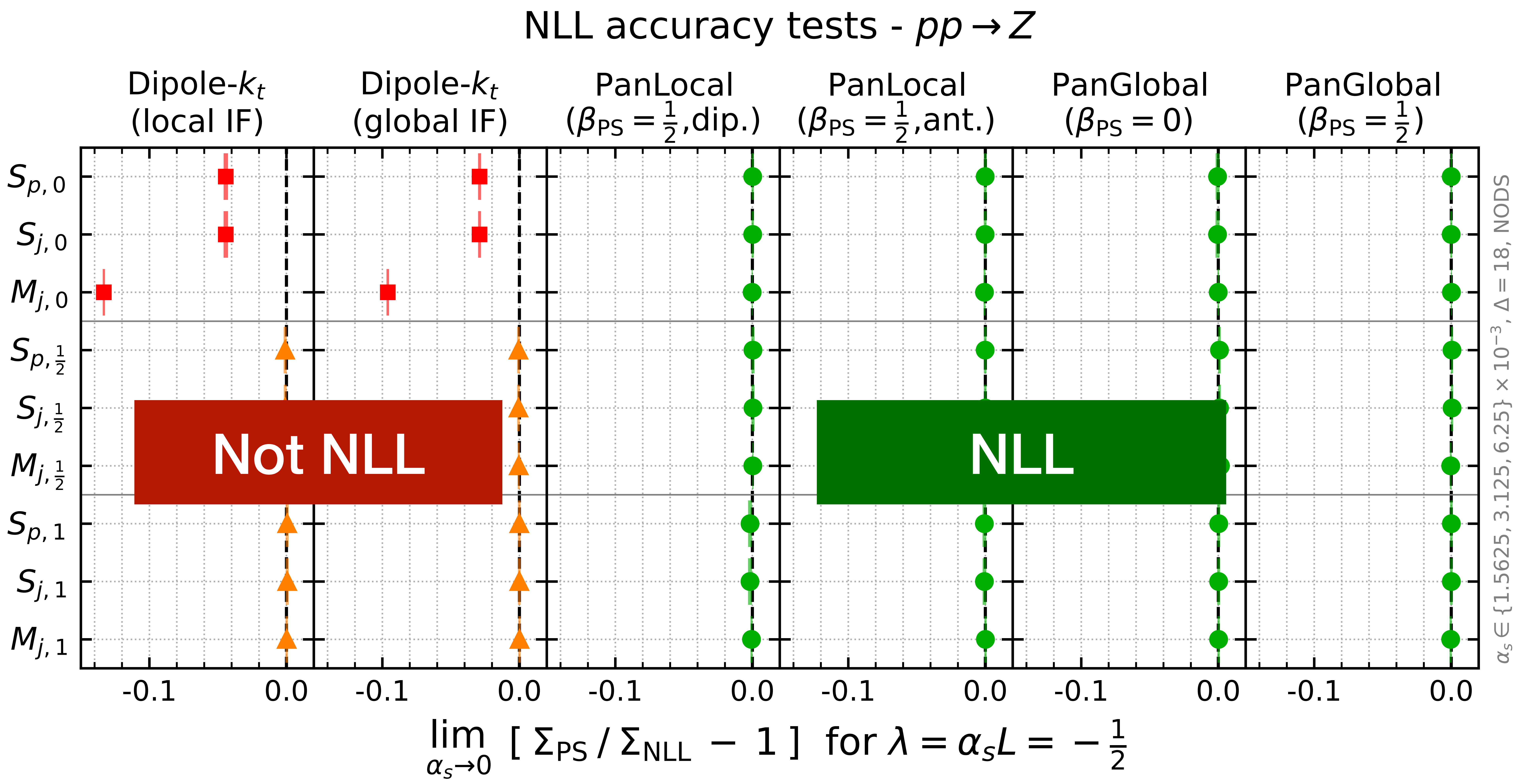


Should converge to a constant as $p_{t,Z} \to 0$

Parisi, Petronzio, Nucl. Phys. B 154 (1979)



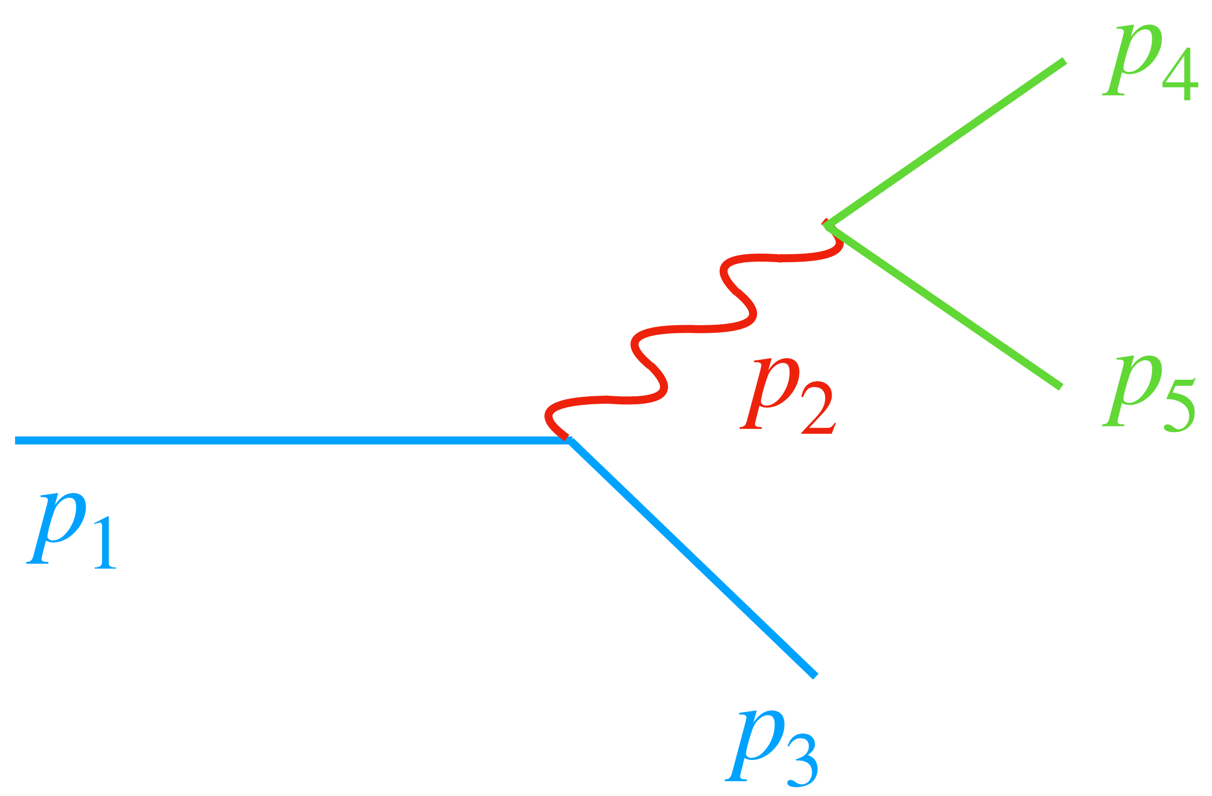
NLL tests for global event shapes



$$S_{p,\beta_{obs}} = \sum_{i \in \text{particles}} \frac{k_{t,i}}{Q} e^{-\beta_{obs}|\eta_i|} \qquad S_{j,\beta_{obs}} = \sum_{i \in \text{jets}} \frac{k_{t,i}}{Q} e^{-\beta_{obs}|\eta_i|} \qquad M_{j,\beta_{obs}} = \max_{i \in \text{jets}} \frac{k_{t,i}}{Q} e^{-\beta_{obs}|\eta_i|}$$

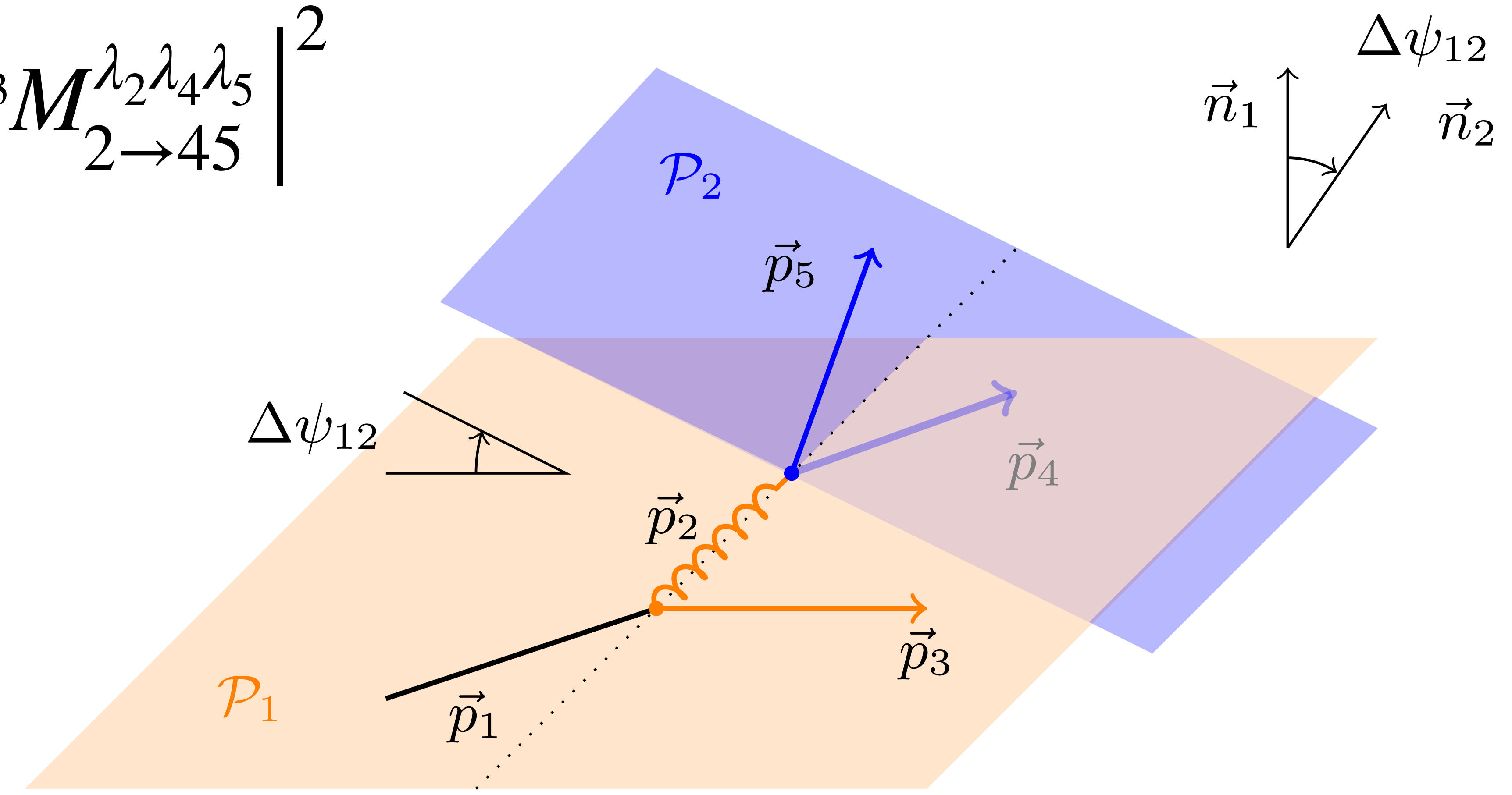
Spin Correlations

Spin Correlations



Collinear

$$|M|^2 \propto \left| \sum_{\lambda_2} M^{\lambda_1\lambda_2\lambda_3}_{1\to 23} M^{\lambda_2\lambda_4\lambda_5}_{2\to 45} \right|^2$$



Spin correlations lead to azimuthal modulation

$$\frac{d\sigma}{d\Delta\psi_{12}} \propto a_0 + a_2 \cos(2\Delta\psi_{12})$$

Enters logarithmic structure at NLL

Implementation in shower

- Modulate azimuthal distribution of branchings
- Leave all else the same

Implementing Spin Correlations

- Store amplitude during shower evolution? ⟹ $\mathcal{O}\left(2^N\right)$ in memory

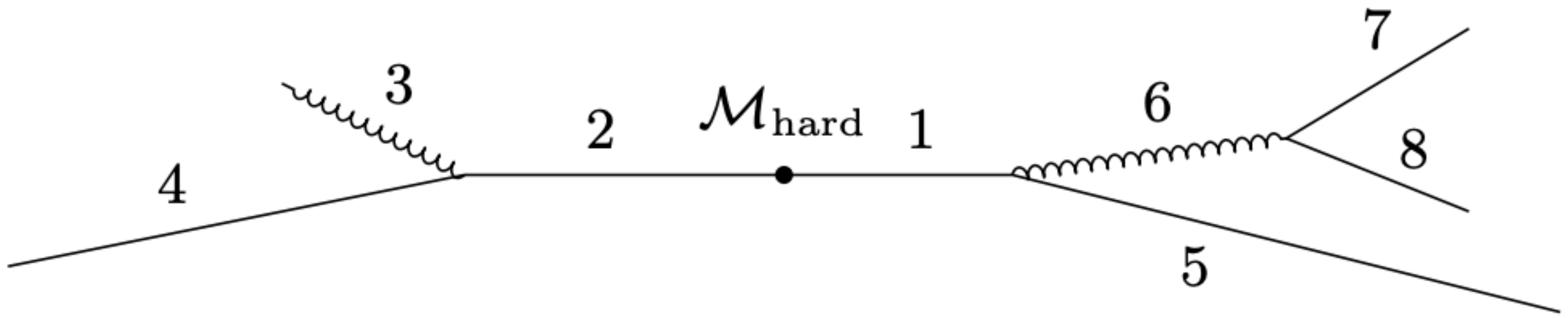
- Redo contractions at every step? ⟹ $\mathcal{O}\left(N^2\right)$ in compute

- Collins-Knowles algorithm ⟹ $\mathcal{O}\left(N\right)$ in memory, $\mathcal{O}\left(N \log N\right)$ in compute

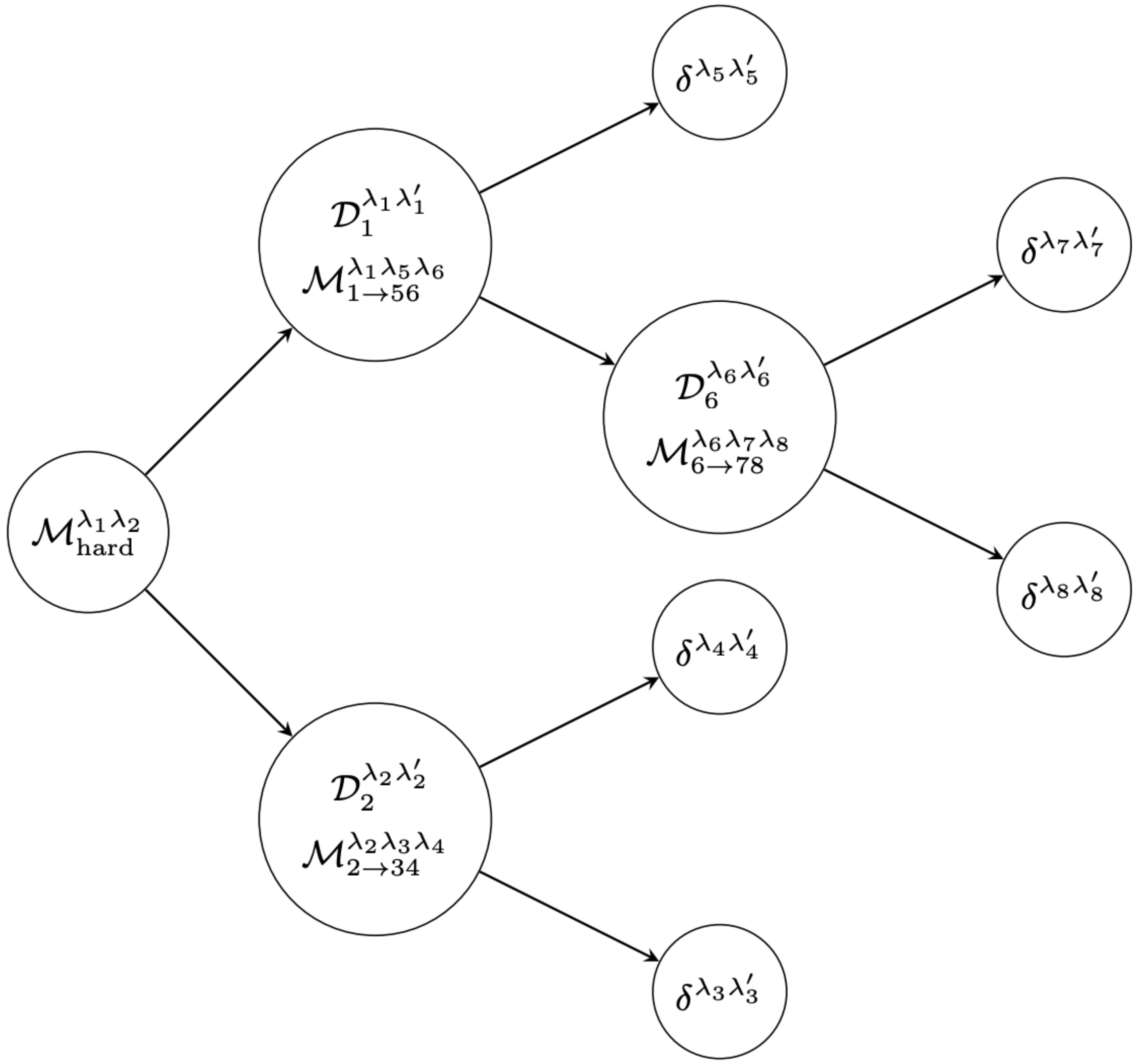
  Collins Nucl.Phys.B 304 (1988)

  Knowles Nucl.Phys.B 304 (1988)

  Richardson, Webster Eur.Phys.J.C 80 (2020)



⟹

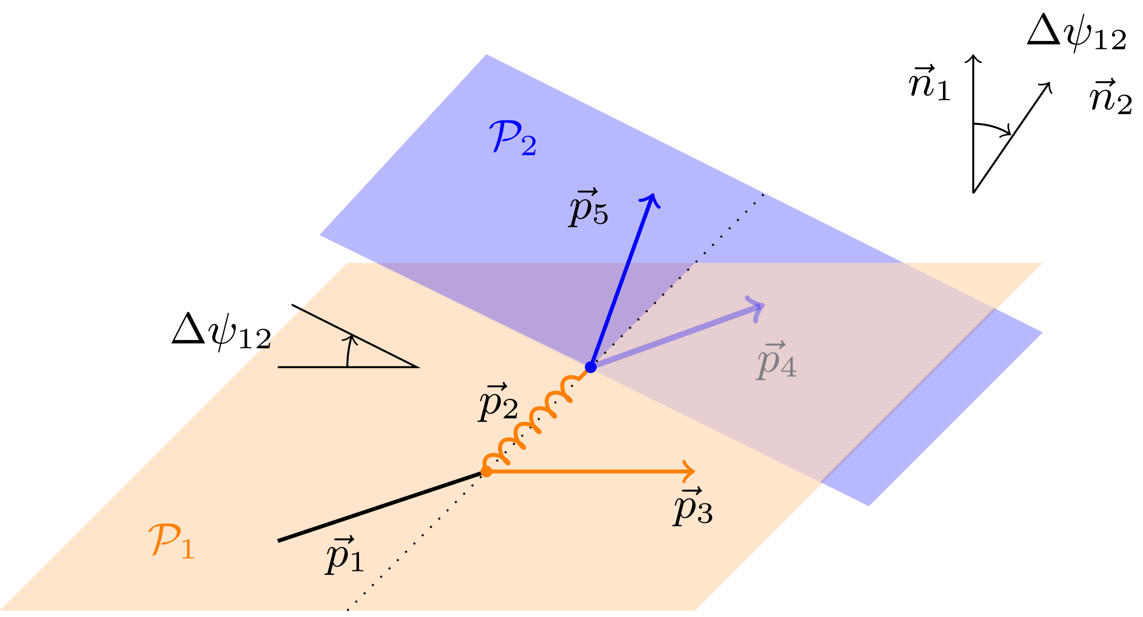


Spin Correlations

Comparison with NLL resummations
(toy shower)

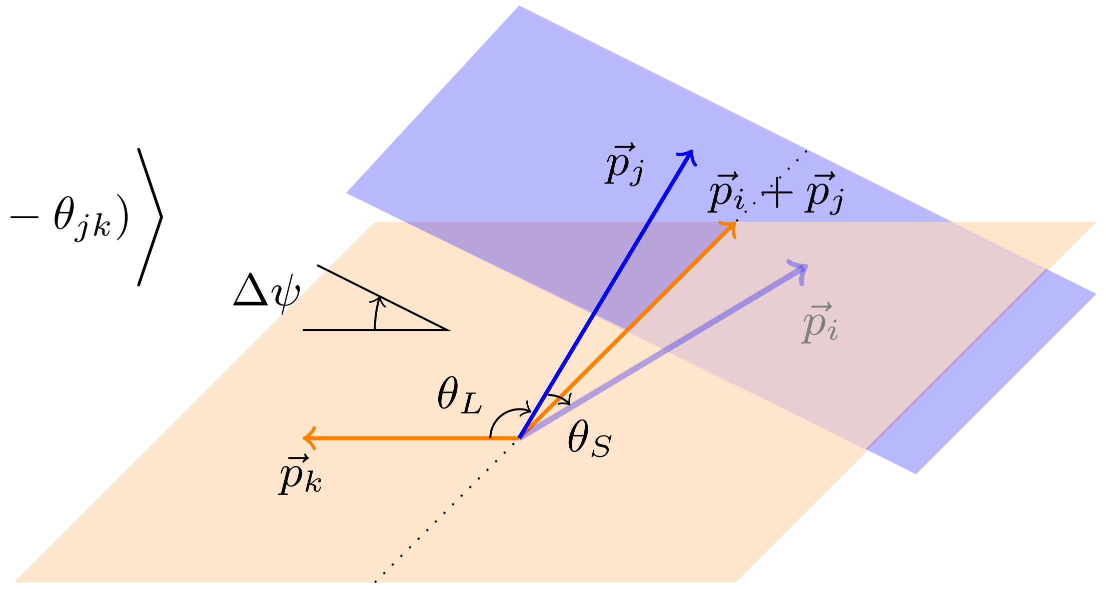
$\Delta\psi_{12}$ - All-order observable using Lund plane declustering

Dreyer, Salam, Soyez JHEP 12 (2018) 064



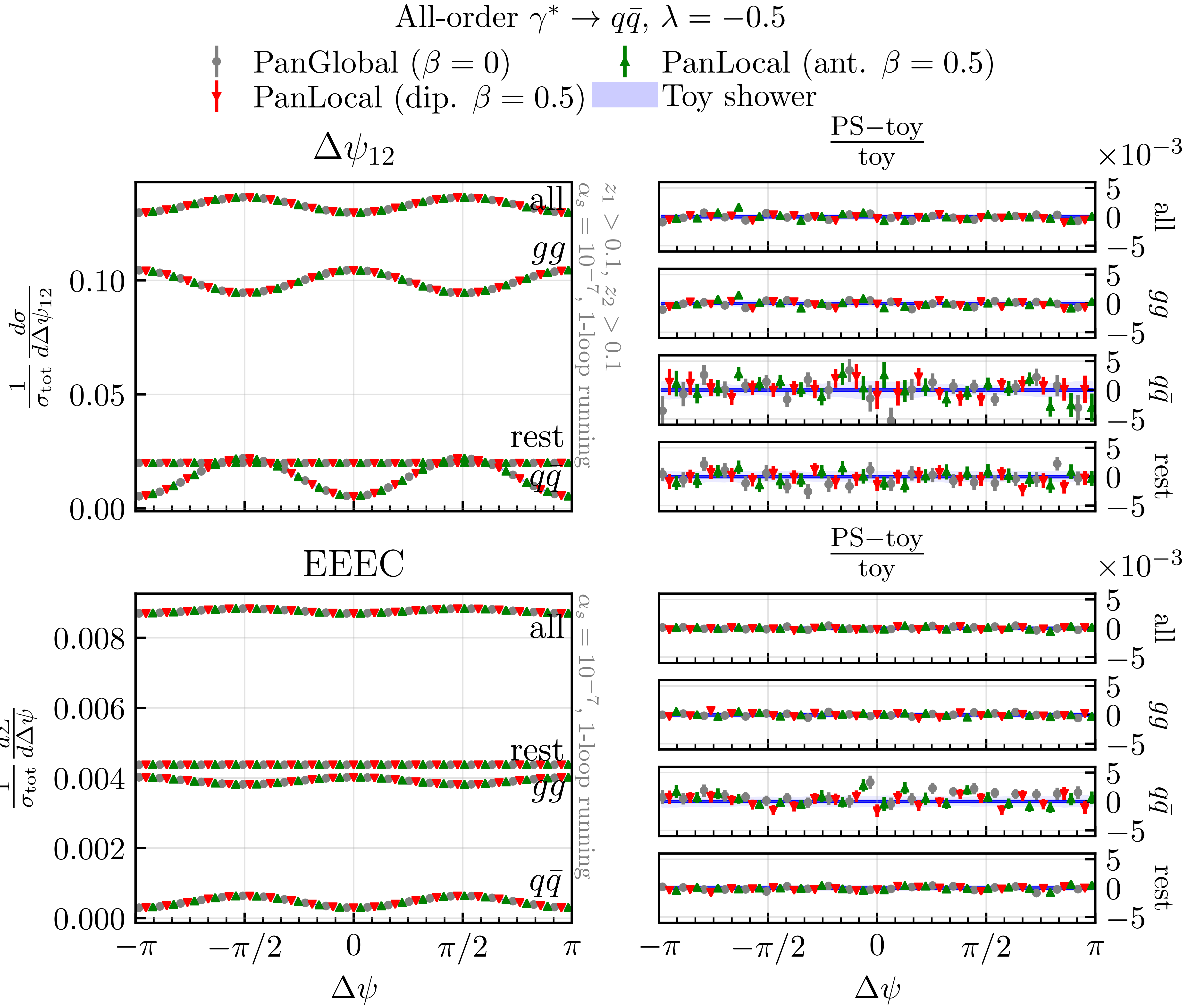
EEEC - Triple-energy correlator

$$\frac{1}{\sigma_{\rm tot}}\frac{d^3\Sigma}{d\Delta\psi\, d\theta_S\, d\theta_L} = \left\langle \sum_{i,j,k=1}^{N} \frac{8E_iE_jE_k}{Q^3}\,\delta\left(\Delta\psi - \phi_{(ij)k}\right)\delta\left(\theta_S-\theta_{ij}\right)\delta\left(\theta_L-\theta_{jk}\right)\right\rangle$$



Analytic resummation

Chen, Moult, Zhu Phys. Rev. Lett. 126 (2021)



Matching and Logarithmic Accuracy

(in e^+e^-)

NNDL Accuracy

Contributes at NNNL

Hard function

$\sim 1 + C_1\alpha_s + \dots$

NLL $\sim \mathcal{O}(1)$

$$\Sigma(\bar{O} < e^{-L}) = H(\alpha_s) \exp\left[Lg_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \dots\right]$$

LL $\sim \mathcal{O}(1/\alpha_s)$

NNLL $\sim \mathcal{O}(\alpha_s)$

$\Downarrow$

DL $\sim \alpha_s^n L^{2n}$

NNDL $\sim \alpha_s^n L^{2n-2}$

Contribution from C_1 and g_2

$$\Sigma(\bar{O} < e^{-L}) = h_1(\alpha_s L^2) + h_2(\alpha_s L^2)\, L^{-1} + h_3(\alpha_s L^2)\, L^{-2} + \dots$$

NDL $\sim \alpha_s^n L^{2n-1}$

NLL shower with NLO matching should be accurate up to NNDL

NLO Matching in Parton Showers

MC@NLO

Regular shower

$$d\sigma_{\text{NLO}} = \bar{B}_s(\Phi_B)\left(\Delta(v_{\text{cut}})\, d\Phi_B + \Delta(v_\Phi) \frac{R_{\text{PS}}(\Phi)}{B_0(\Phi_B)} d\Phi \right) + \left(R(\Phi) - R_{\text{PS}}(\Phi) \right) d\Phi$$

Add the mistake

- Shower-dependent
- Negative weights
- Preserves log accuracy

Powheg

Separate "shower"

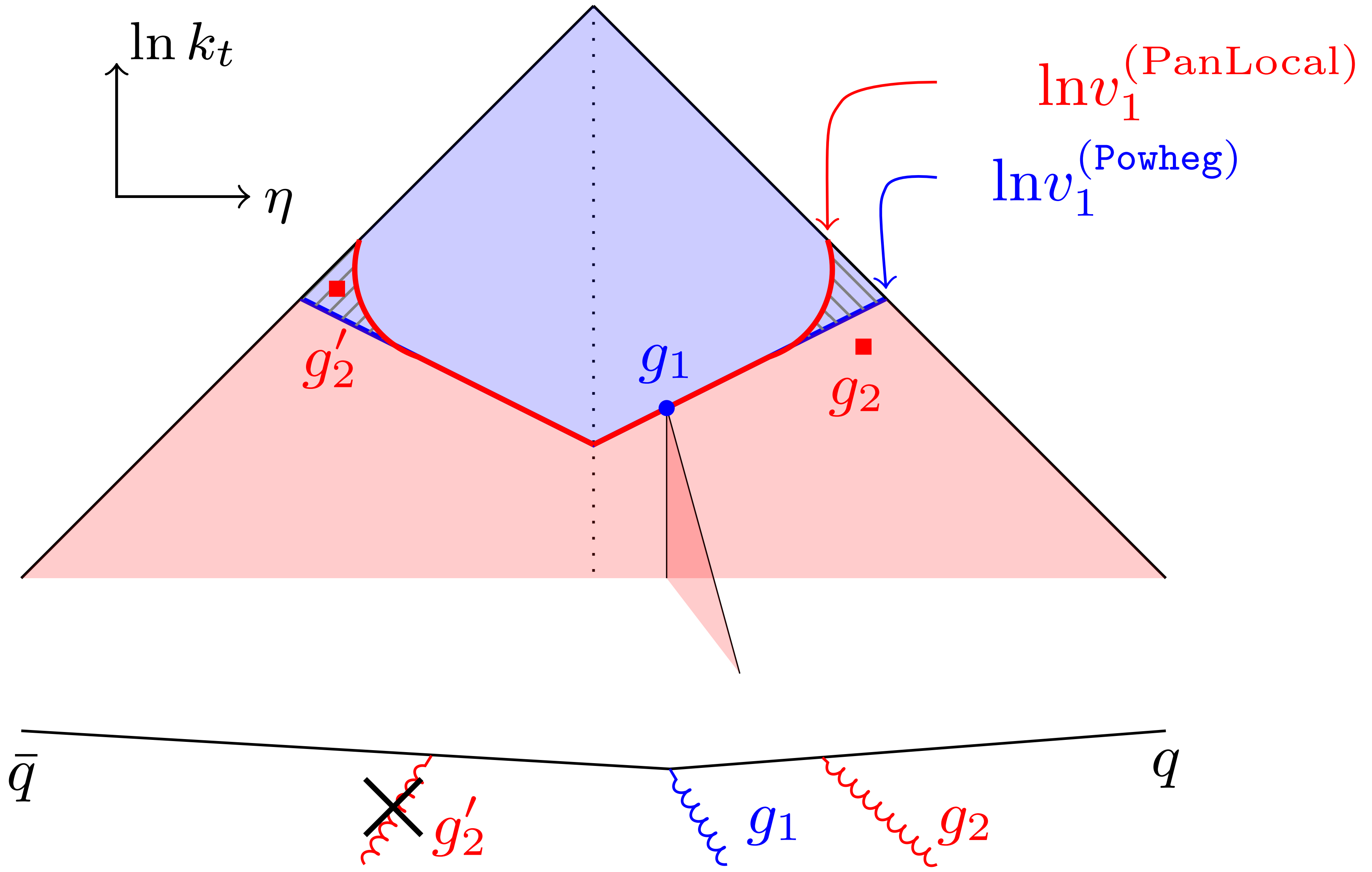
$$d\sigma_{\text{NLO}} = \bar{B}_s(\Phi_B)\left(\Delta(v_{\text{cut}})\, d\Phi_B + \Delta(v_\Phi) \frac{\boxed{R(\Phi)}}{B_0(\Phi_B)} d\Phi \right)$$

ME as the branching kernel

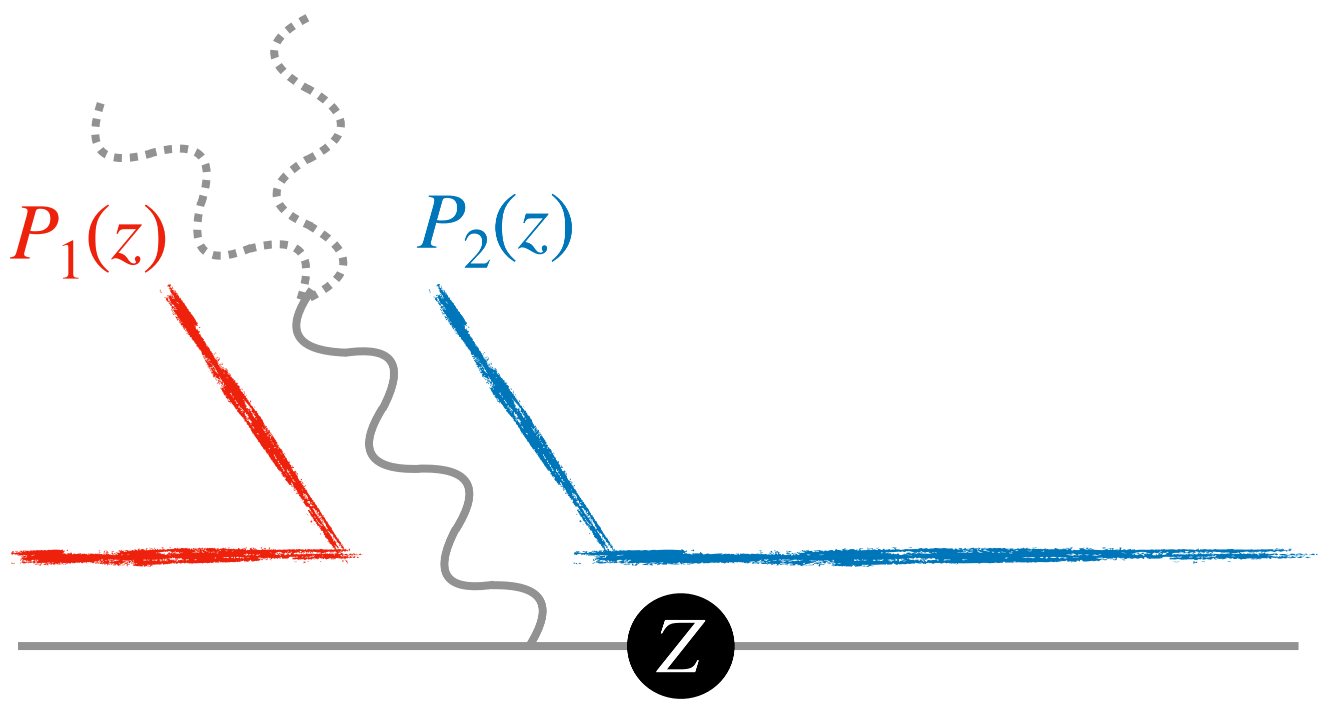
- Shower-independent
- Careful with log accuracy!

Preserving Logarithmic Accuracy (Powheg)

Avoid double-counting



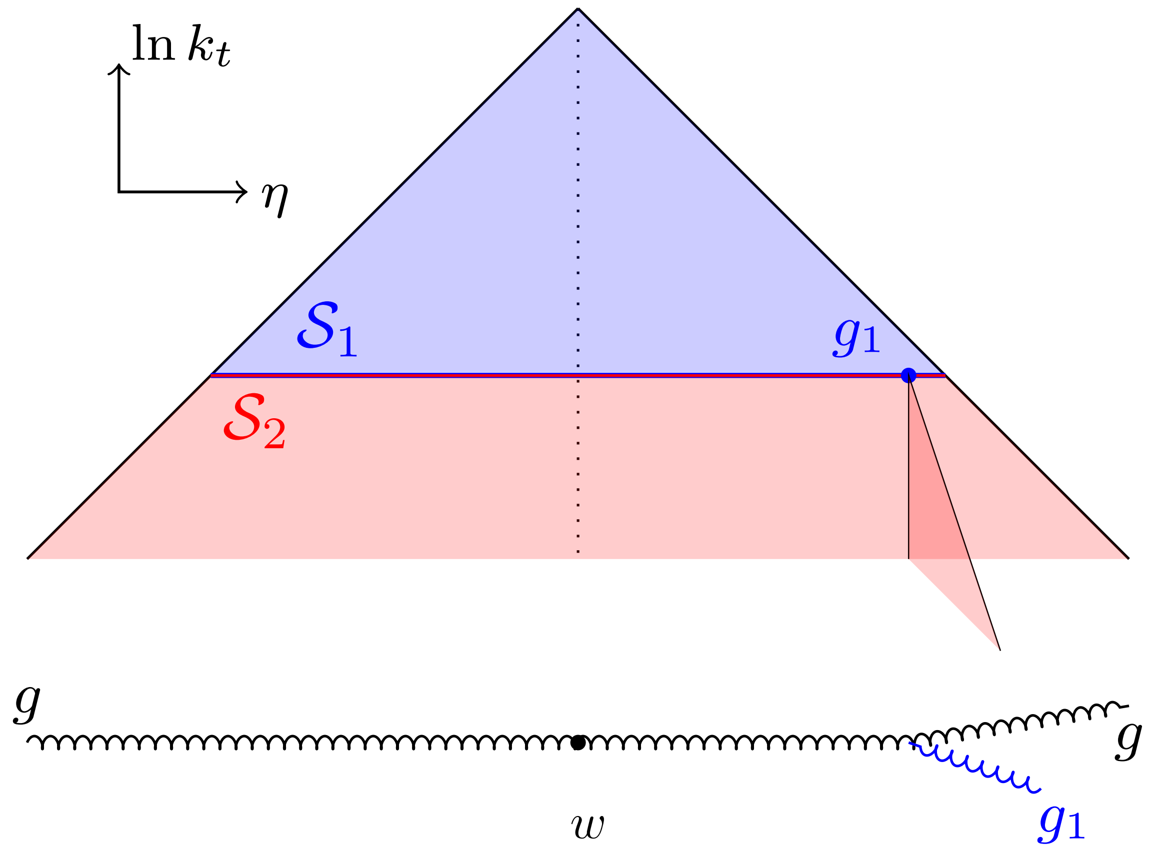
Partitioning of collinear gluon splitting

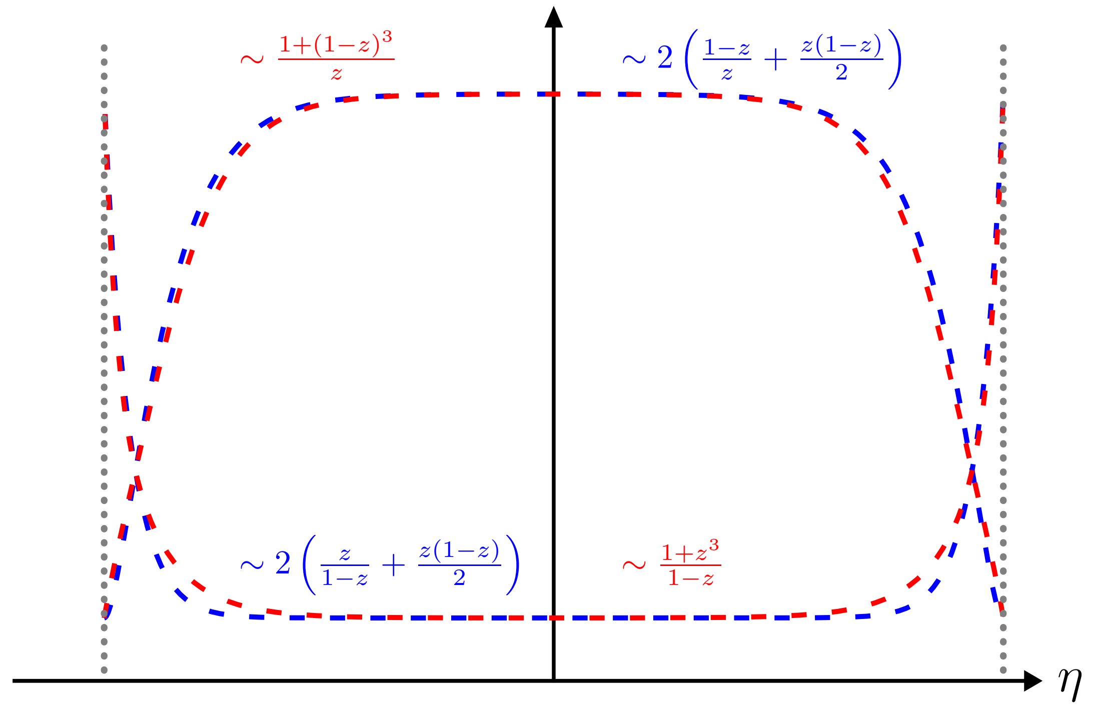


$$P_1(z) + P_2(z) = P_{g\to gg}(z)$$

$$\Downarrow$$

$$P_1^{S_1}(z) = P_1^{S_2}(z)$$
$$P_2^{S_1}(z) = P_2^{S_2}(z)$$

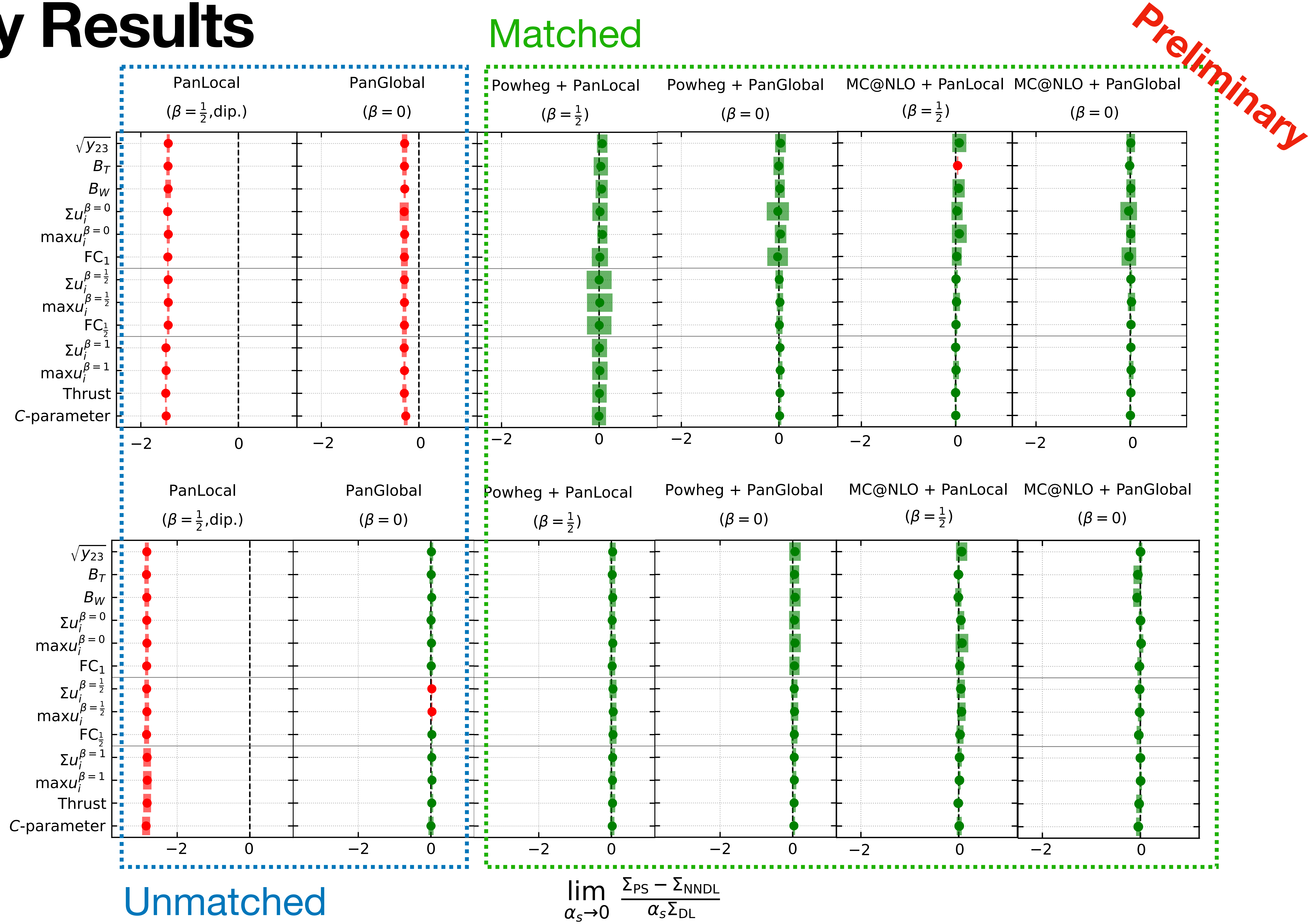




NNDL Accuracy Results

$\gamma^* \to q\bar{q}$ NNDL accuracy tests, $\alpha_s L^2 = 2.025$

$H \to gg$ NNDL accuracy tests, $\alpha_s L^2 = 0.50625$



Conclusions

- PanScales: a project to bring logarithmic understanding & accuracy to parton showers
- NLL accuracy ⟹ e^+e^- and colour singlet production in pp
- Spin correlations ⟹ NLL accuracy for sensitive observables
- Matching + NLL shower ⟹ NNDL accuracy, first step to NNLL
- Next steps include (not in order of priority):
  - **Extension of pp showers** to more complex processes, i.e. Z+jet and dijets
  - **NLL showers for deep-inelastic scattering**
  - **Interface to Pythia:** retuning of hadronisation model
  - **Heavy quarks:** needed for pheno + interesting resummation
  - **Towards NNLL showers:** higher-order kernels, i.e. double soft, triple collinear

Backup

Dipole showers in hadron collisions

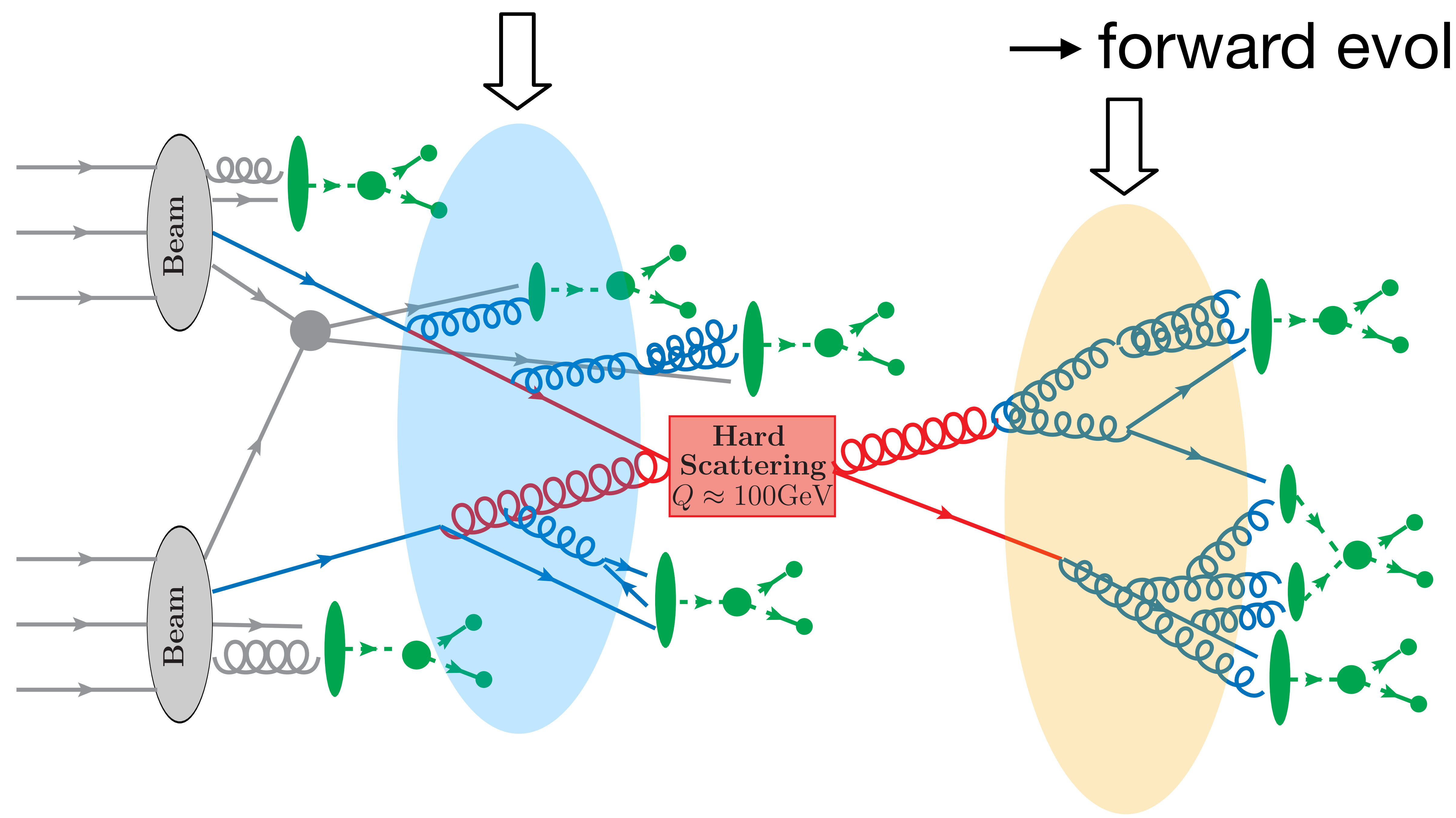
QCD in large-N_c limit ⟶ several dipole types

- Initial-Initial (II)
- Initial-Final (IF)
- Final-Final (FF)

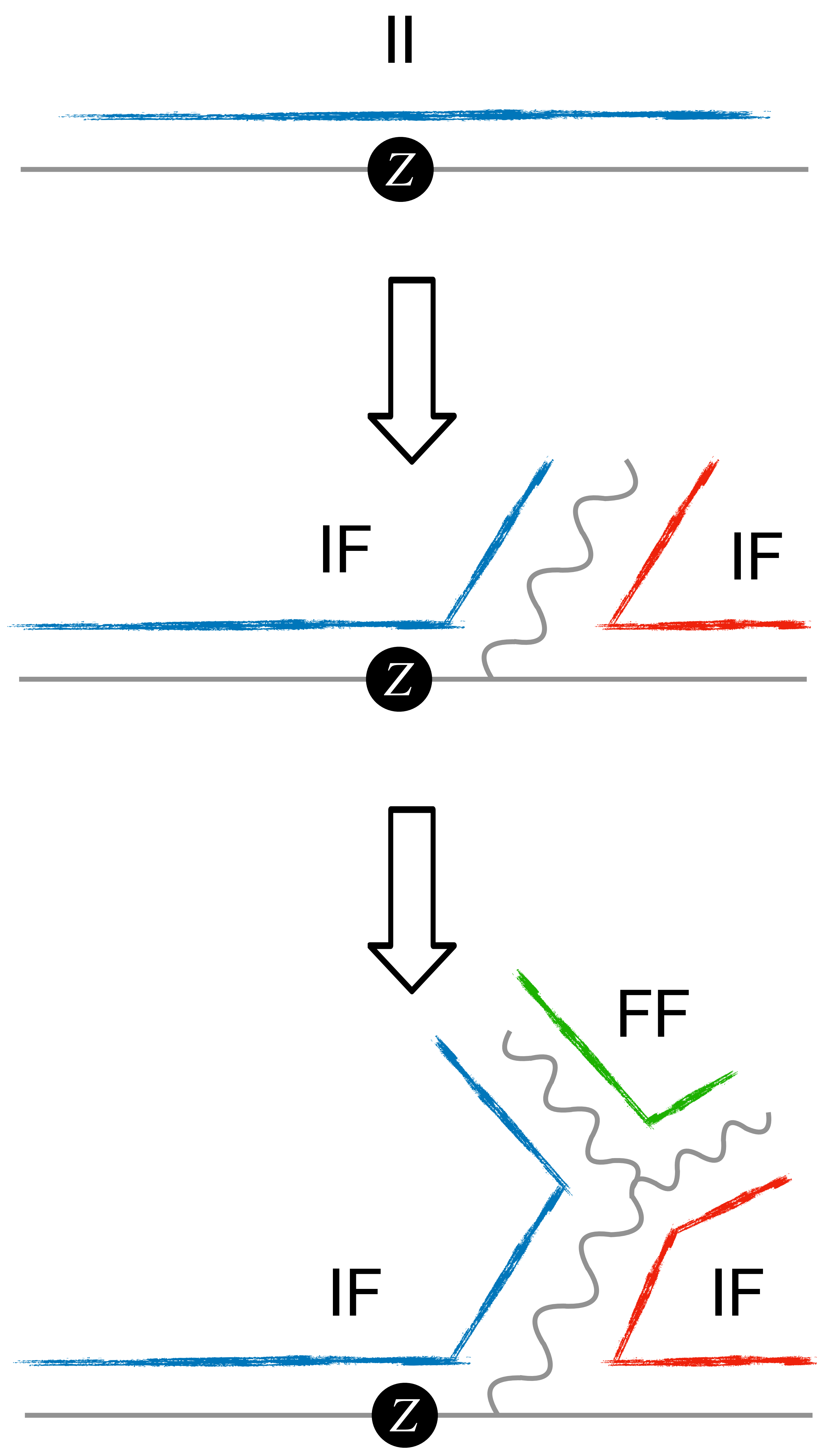
Initial-state radiation
⟶ backward evolution

T. Sjöstrand, Phys. Lett. 157B (1985) 321–325.

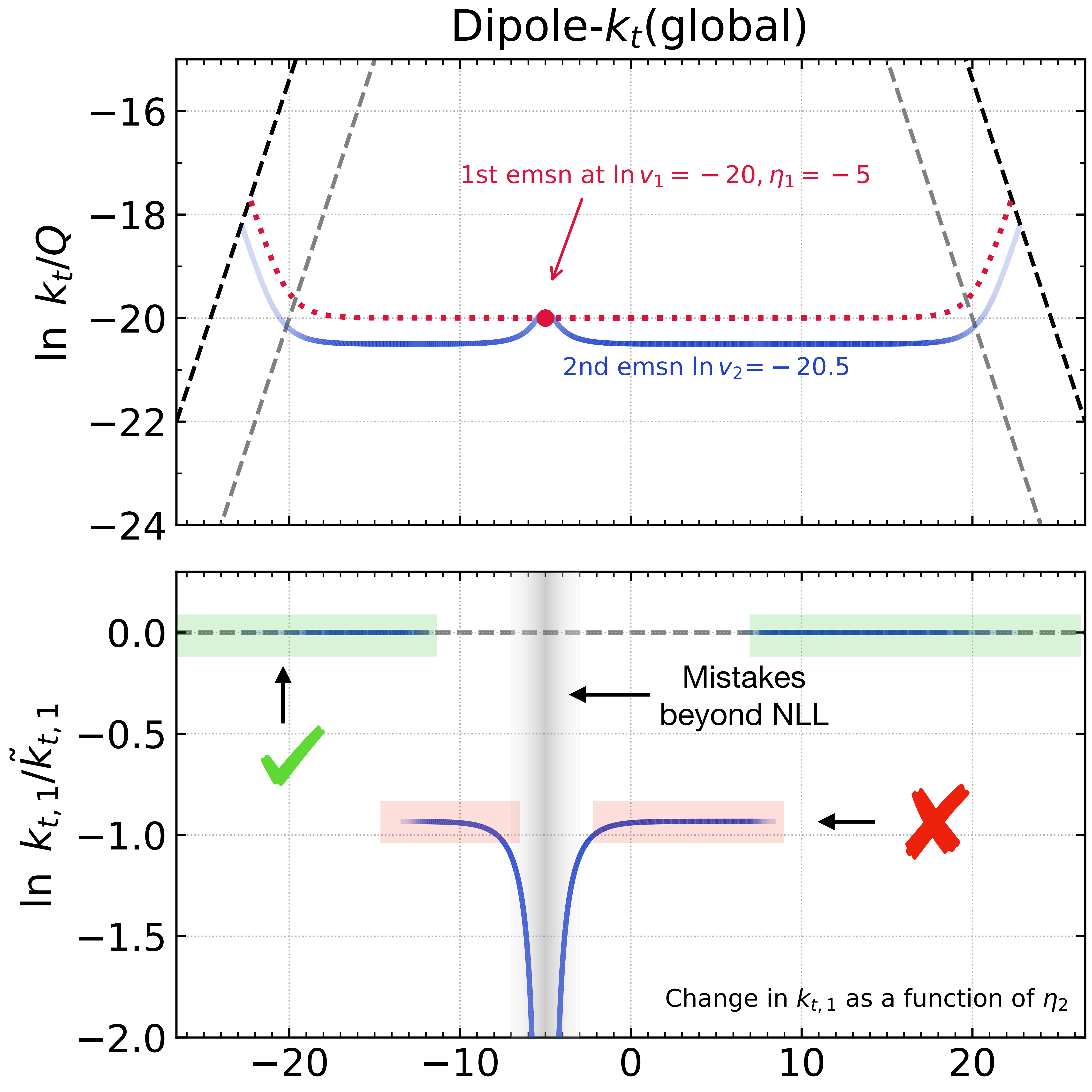
Final-state radiation
⟶ forward evolution

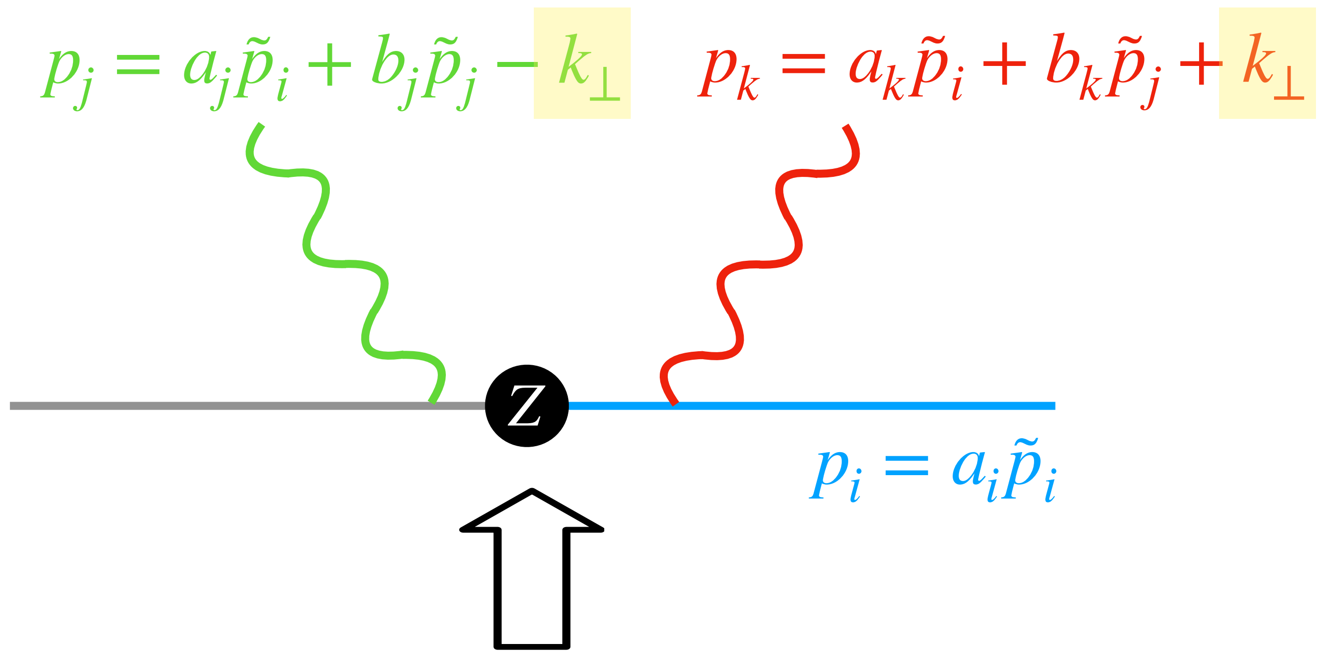


[Courtesy of Silvia Ferrario Ravasio]

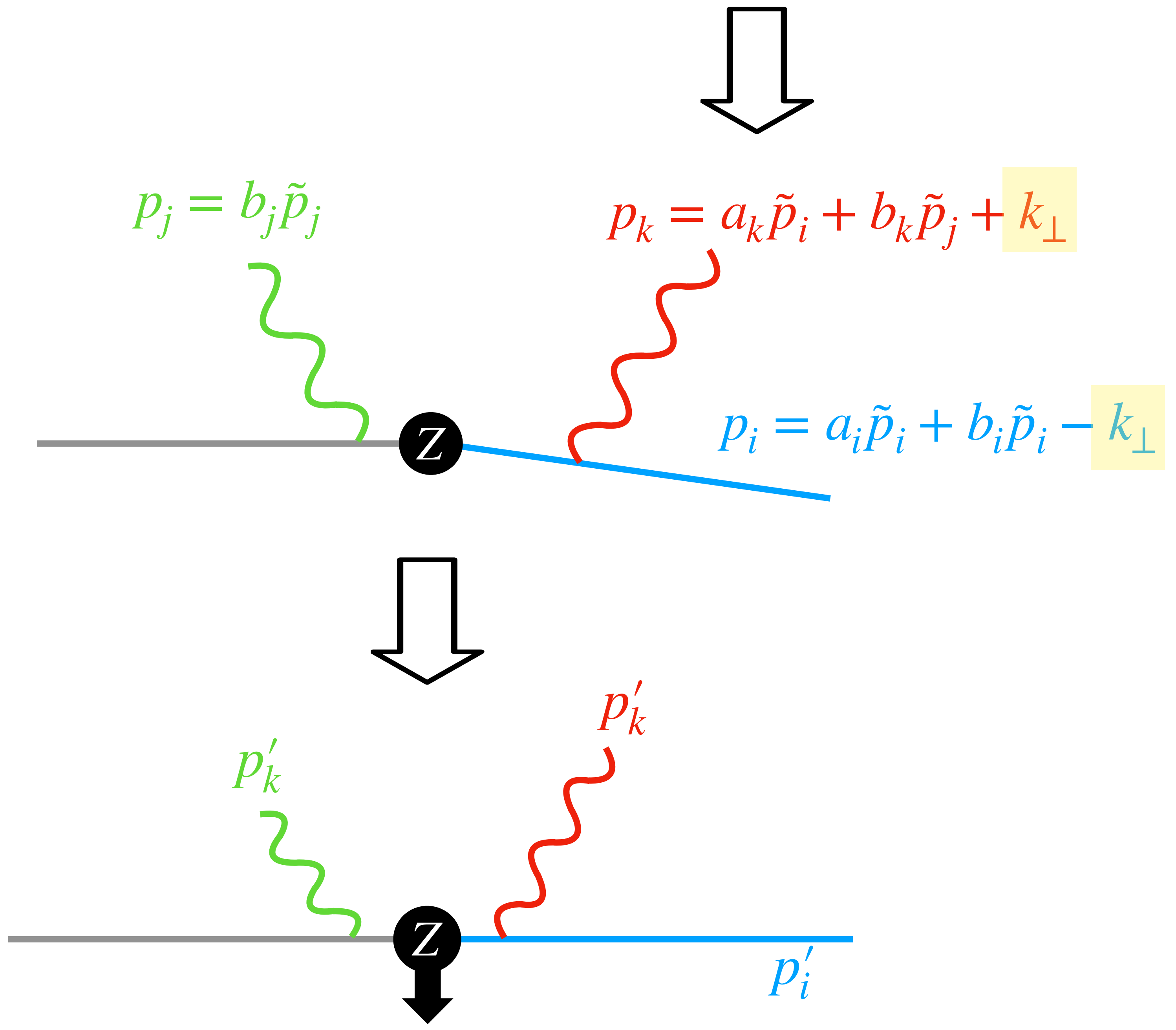


Dipole-k_t: Fixed-order tests





$$\mathrm{d}\mathscr{P}_{\tilde{i}\tilde{j}\to ijk} \propto \left[g(\eta) z_i P_{ik}^{\mathrm{IS}}(z_i) + g(-\eta) z_j P_{jk}^{\mathrm{FS}}(z_j) \right]$$



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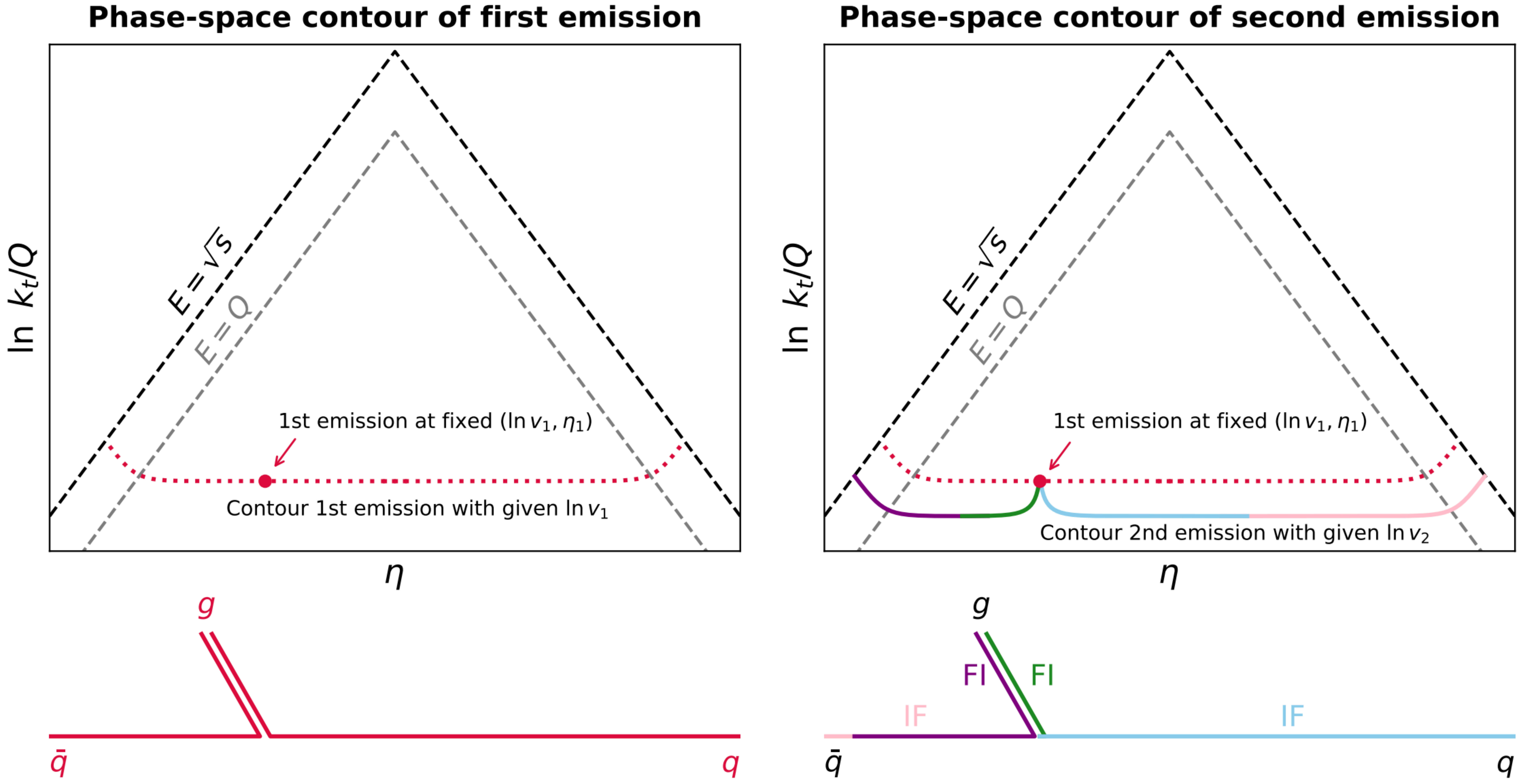
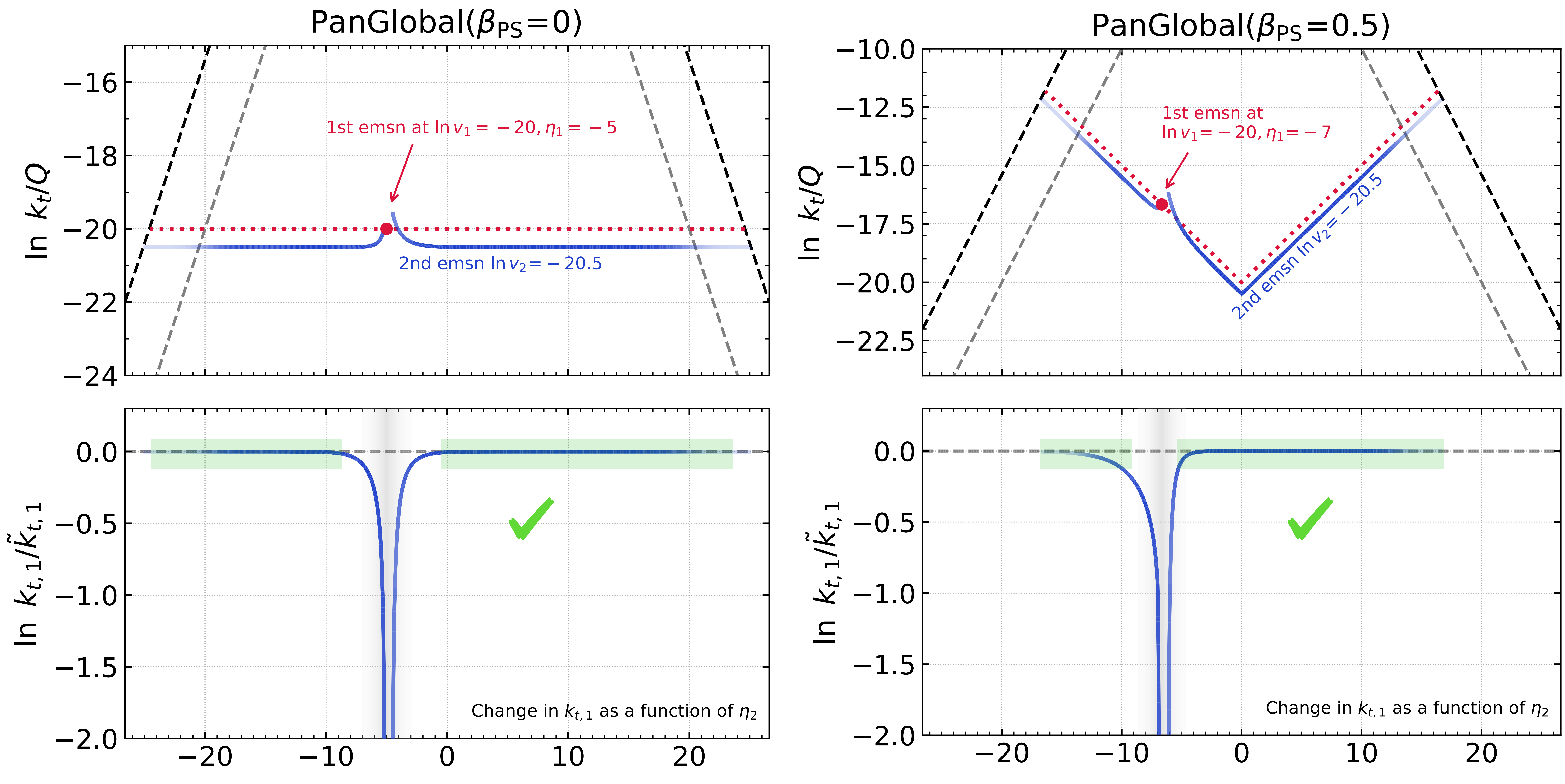
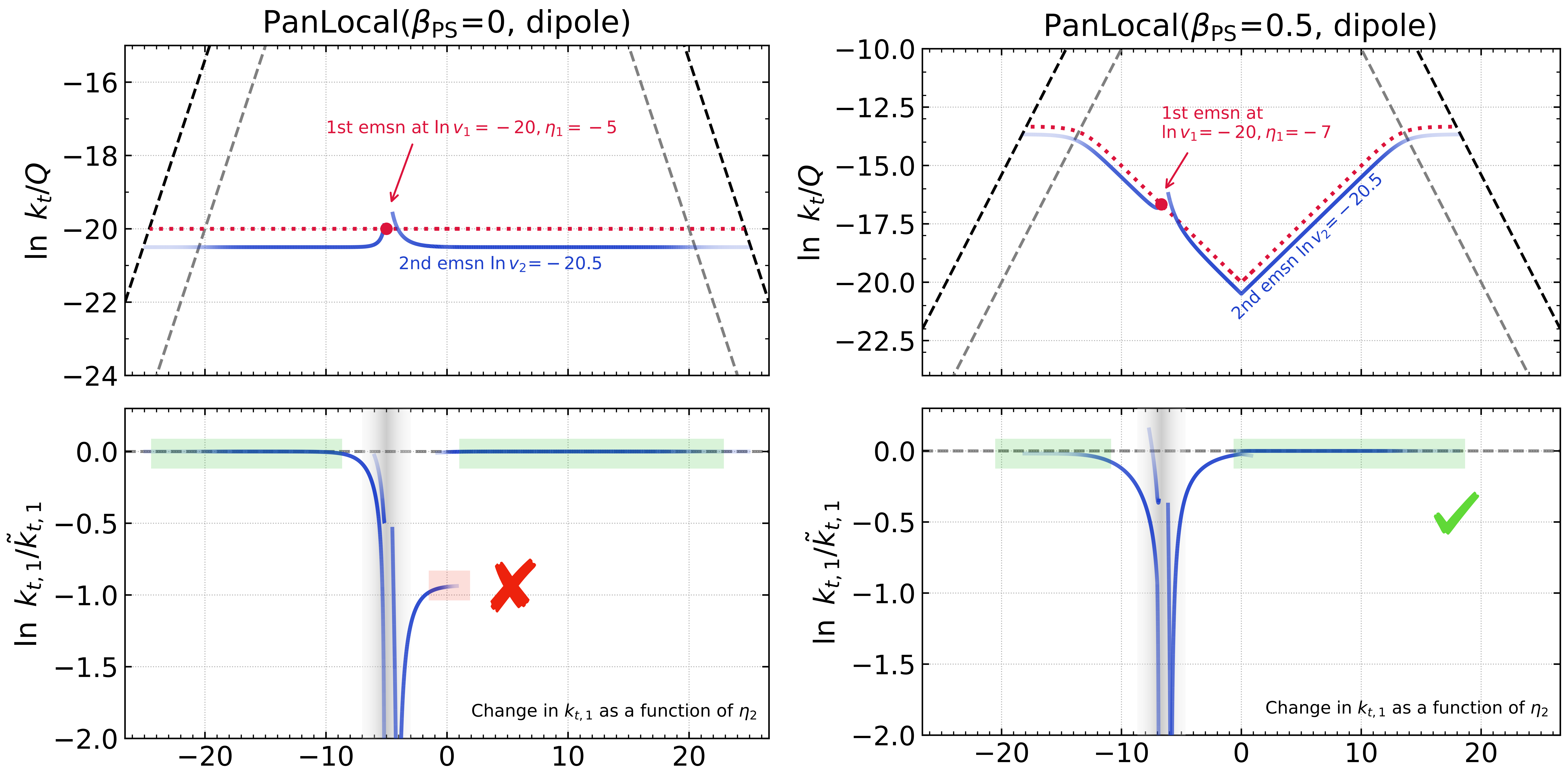


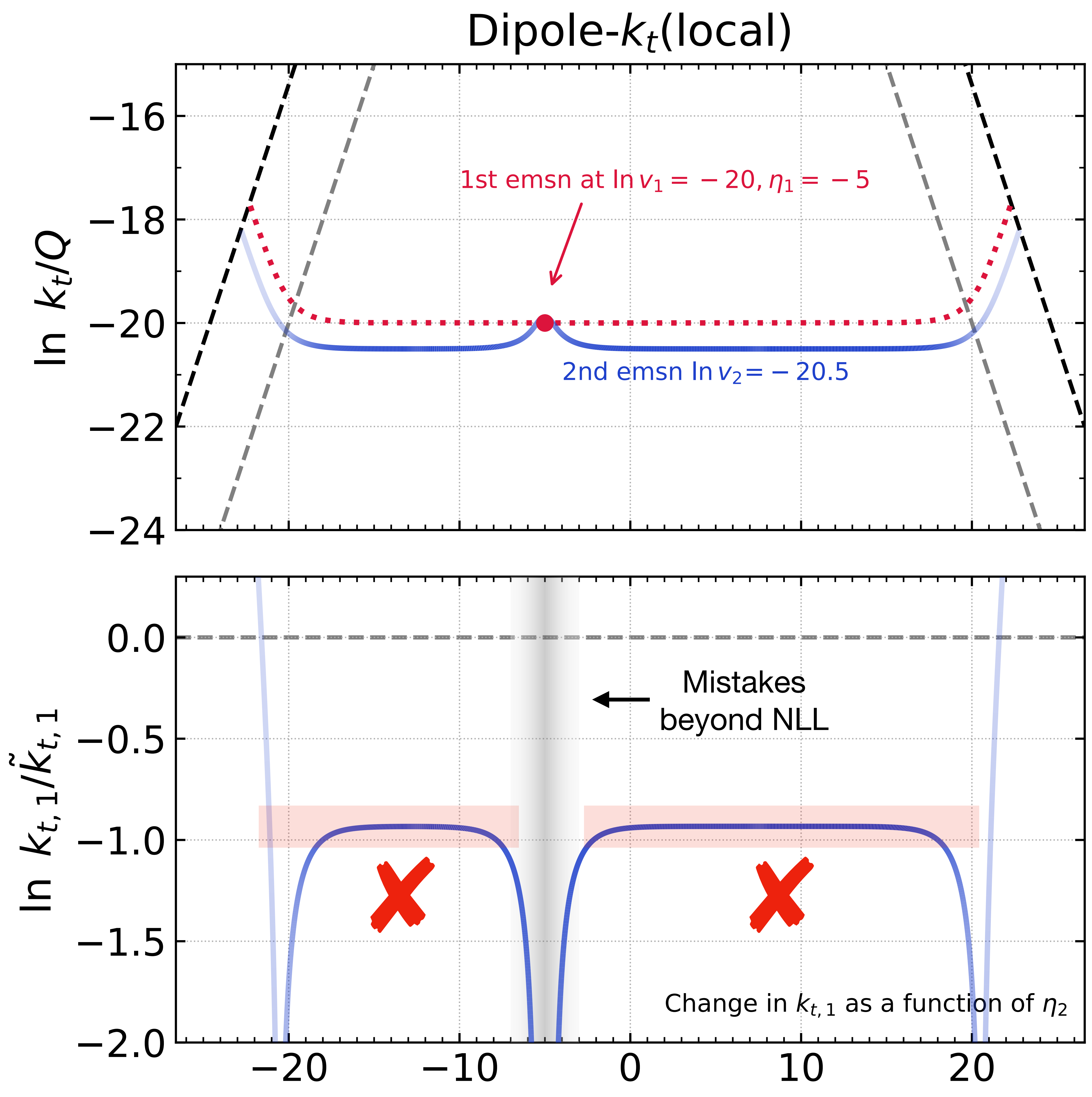
PanGlobal: Fixed-order tests

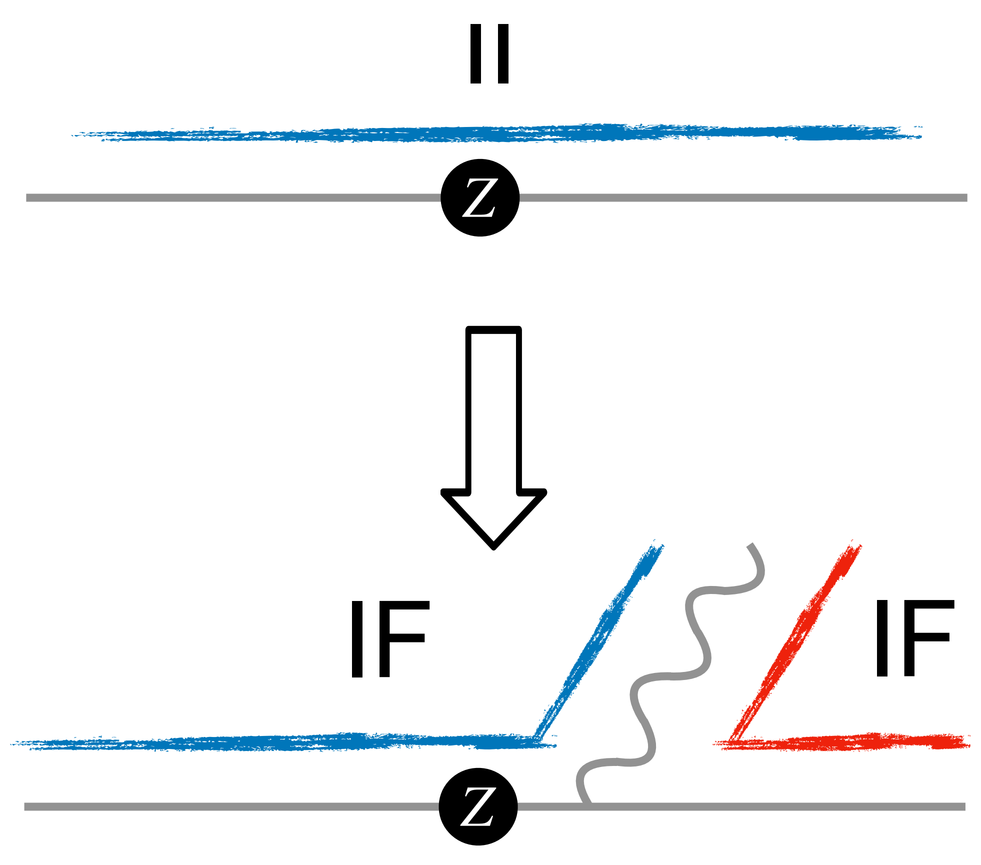


PanLocal: Fixed-order tests

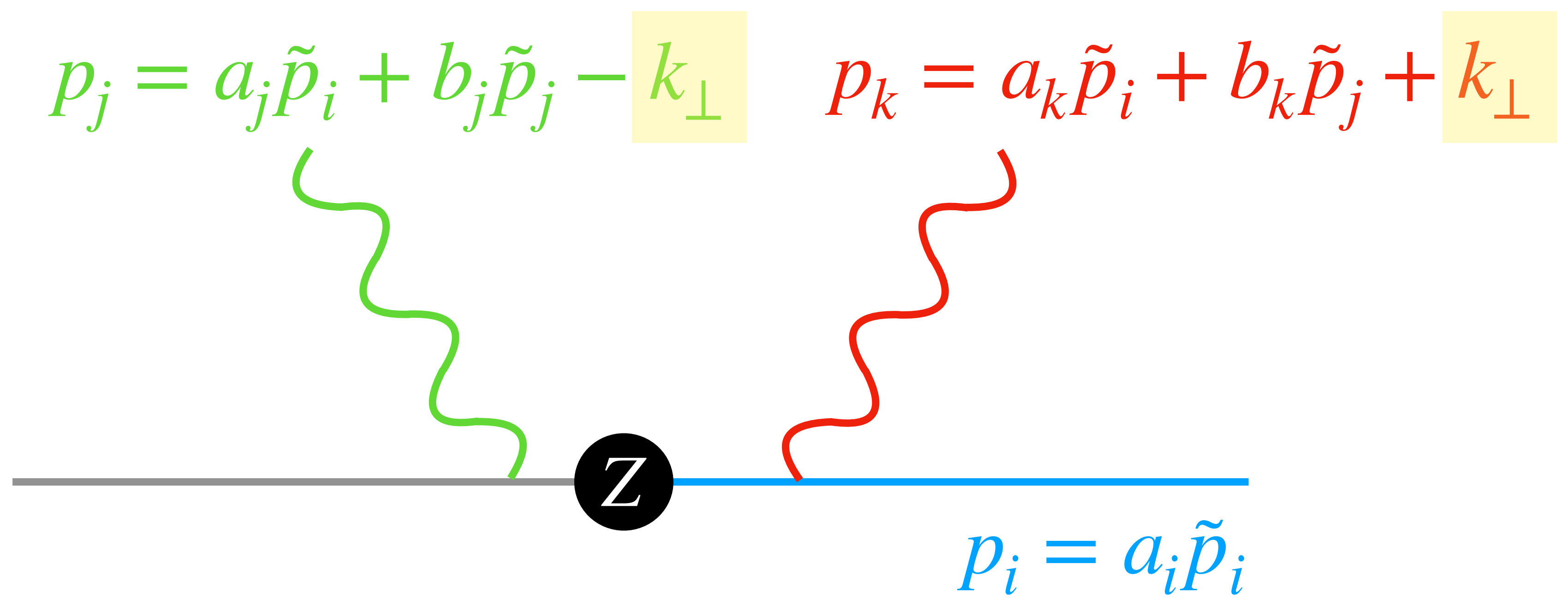


Dipole-k_t: Fixed-order tests





Always use local map in IF dipoles



Already known:
Wrong p_t^Z at NLL

[Parisi, Petronzio, NPB 154 (1979) 427-440]
[Nagy, Soper JHEP 03 (2010) 097]
[Platzer, Gieseke JHEP 01 (2011) 024]

Mapping from logarithmic to physical

Q [GeV]	$\alpha_s(Q)$	$p_{t,\min}$ [GeV]	$\xi = \alpha_s L^2$	$\lambda = \alpha_s L$	τ
91.2	0.1181	1.0	2.4	−0.53	0.27
91.2	0.1181	3.0	1.4	−0.40	0.18
91.2	0.1181	5.0	1.0	−0.34	0.14
1000	0.0886	1.0	4.2	−0.61	0.36
1000	0.0886	3.0	3.0	−0.51	0.26
1000	0.0886	5.0	2.5	−0.47	0.22
4000	0.0777	1.0	5.3	−0.64	0.40
4000	0.0777	3.0	4.0	−0.56	0.30
4000	0.0777	5.0	3.5	−0.52	0.26
20000	0.0680	1.0	6.7	−0.67	0.45
20000	0.0680	3.0	5.3	−0.60	0.34
20000	0.0680	5.0	4.7	−0.56	0.30

Extrapolation