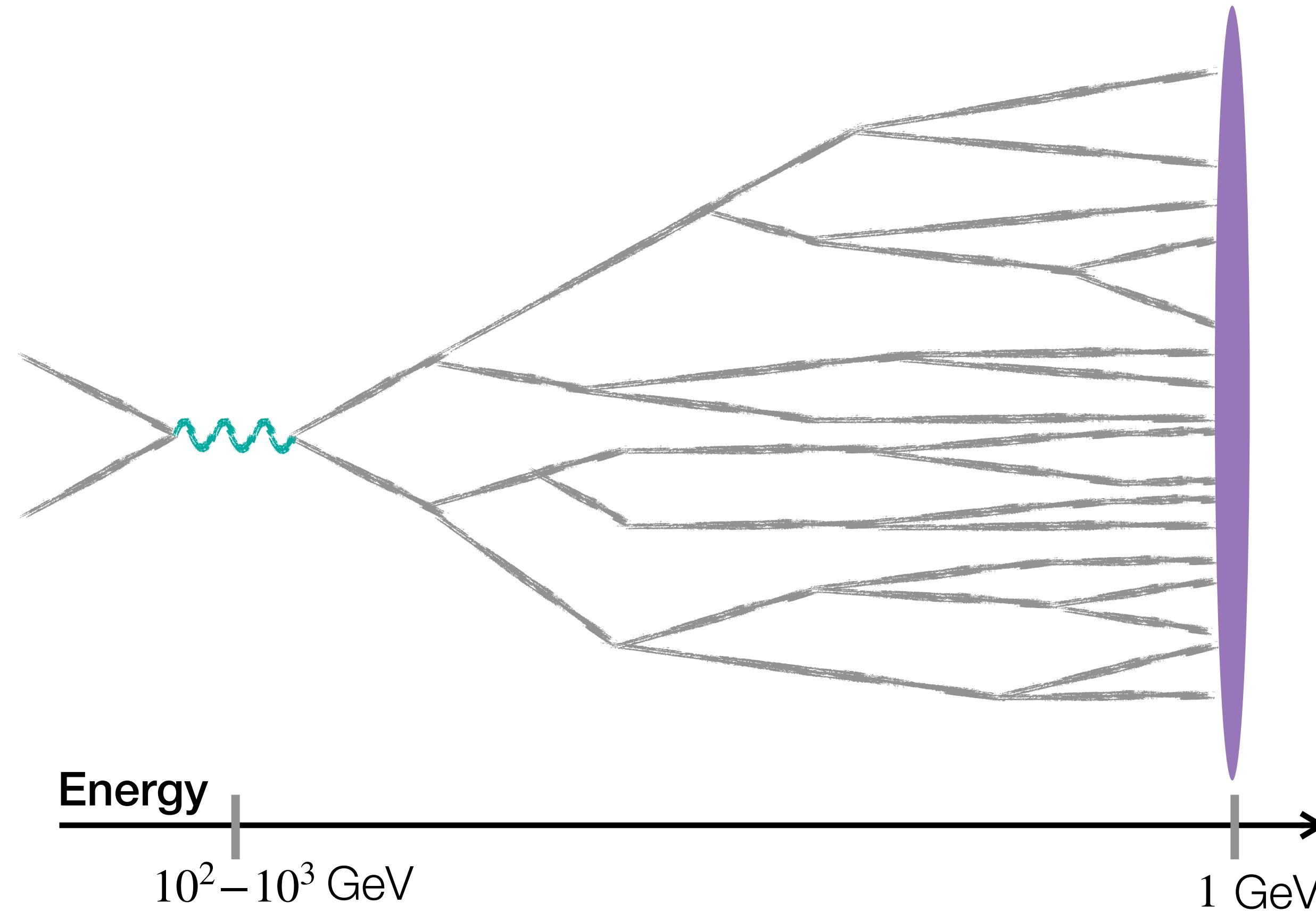


# Better parton showers for hadronic collisions



Alba Soto-Ontoso  
Jet Quenching in the Quark-Gluon Plasma  
ECT\*, 14th June, 2022



# Introduction

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- Homework by the organisers:

“In particular, we would like you to give a theoretical overview of ~~vacuum~~-parton showers and approaches to extend them to in-medium showers”

- Outline:

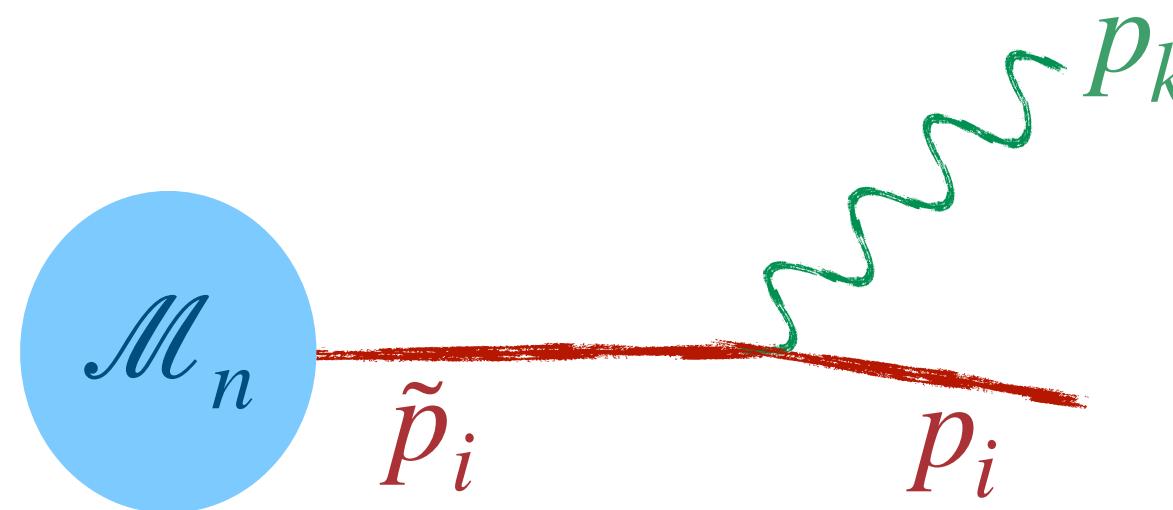
- 1 How to ~~build~~ a parton shower:  $2 \rightarrow 3$  vs  $1 \rightarrow 2$ , evolution variable and recoil scheme
- 2 How to ~~gauge~~ the accuracy of a parton shower: fixed and all-orders tests
- 3 ~~In-medium~~ parton/(dipole?) showers: where do we stand?

- Disclaimer: mostly vacuum showers, but also some **in-medium** physics

# Why does a parton shower work?

- Collinear limit:  $\tilde{p}_i \cdot p_k \rightarrow 0$

$$|\mathcal{M}_{n+1}|^2 \propto \frac{\alpha_s}{(p_i + p_k)^2} P_{\tilde{i} \rightarrow ik}(z) |\mathcal{M}_n|^2$$



[Dominguez talk for in-medium analog]

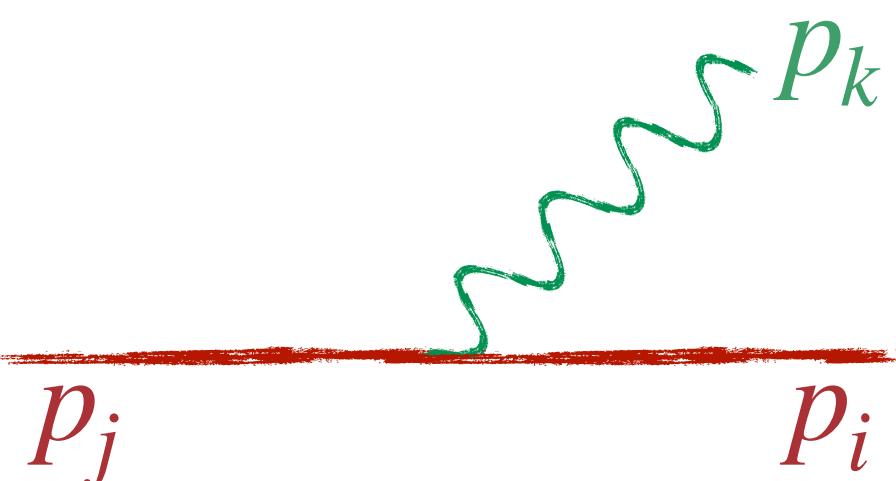
- Soft limit:  $p_k \rightarrow 0$

$$|\mathcal{M}_{n+1}|^2 \propto \alpha_s \frac{p_i \cdot p_j}{(p_i \cdot p_k)(p_j \cdot p_k)} |\mathcal{M}_n|^2$$

Emission kinematics factorises from matrix element in suitable limits

# Interference effects for soft gluon emissions

Emissions are not completely independent from each other. Consider a **soft** gluon

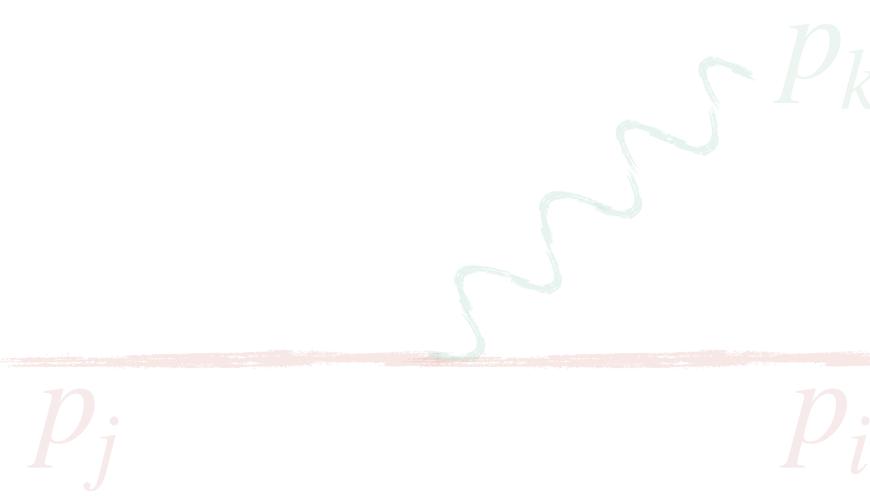

$$(k | ij) = \alpha_s \frac{p_i \cdot p_j}{(p_i \cdot p_k)(p_j \cdot p_k)}$$

$\xrightarrow{\int d\phi_k}$

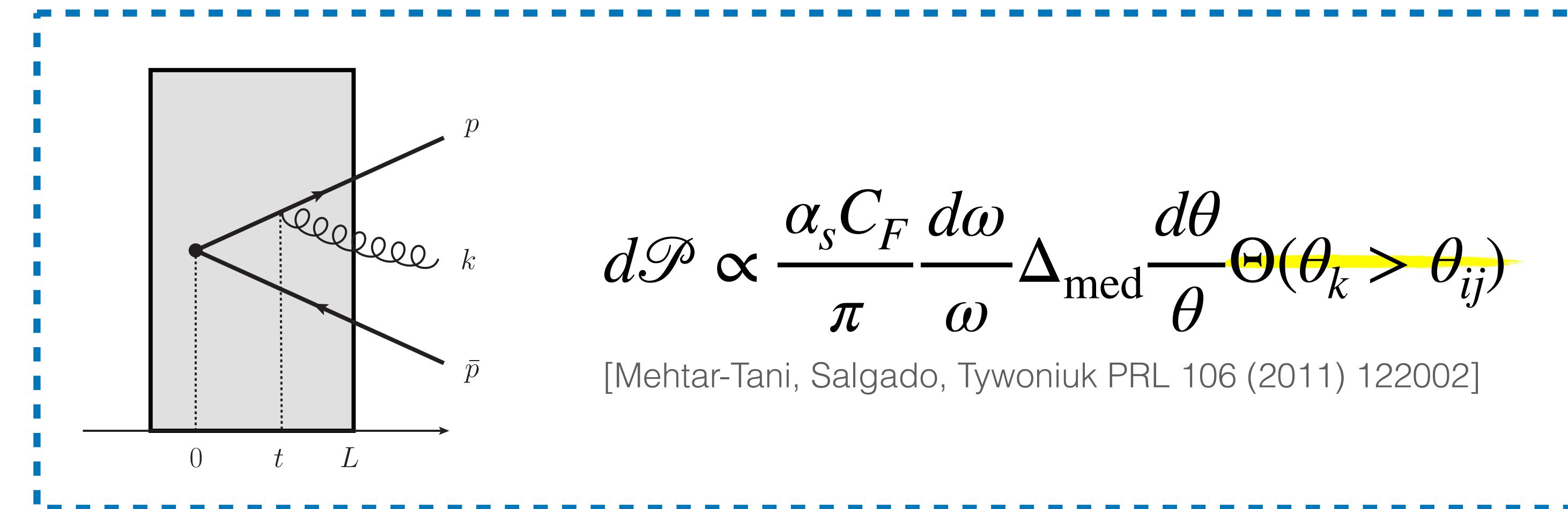
$$d\mathcal{P} \propto \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta}{\theta} \Theta(\theta_k < \theta_{ij})$$

# Interference effects for soft gluon emissions

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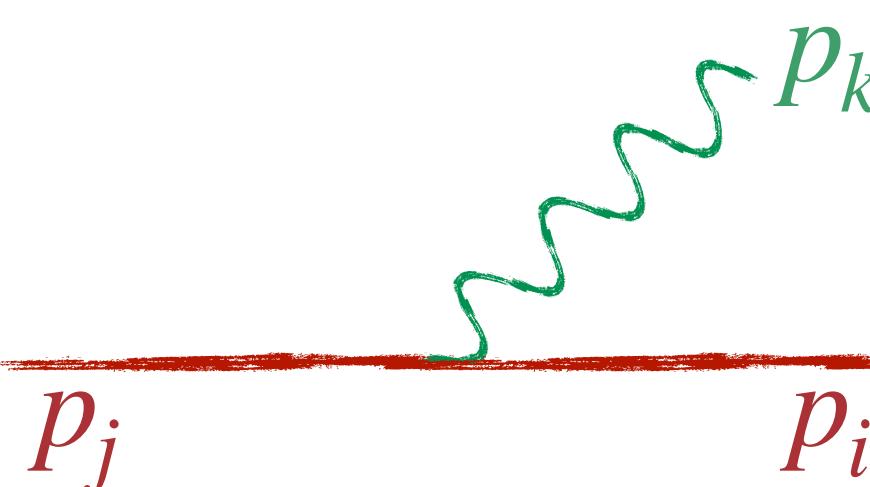

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# Interference effects for soft gluon emissions

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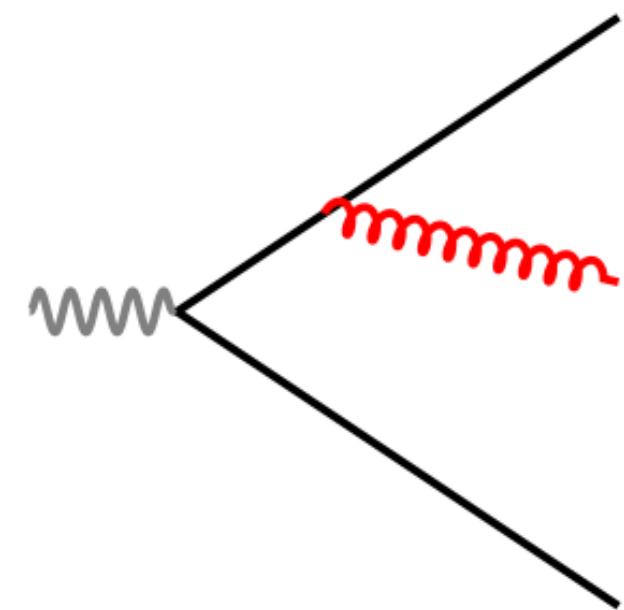

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$$d\mathcal{P} \propto \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta}{\theta} \Theta(\theta_k < \theta_{ij})$$
$$\int d\phi_k$$

Color coherence can be incorporated in at least two ways:

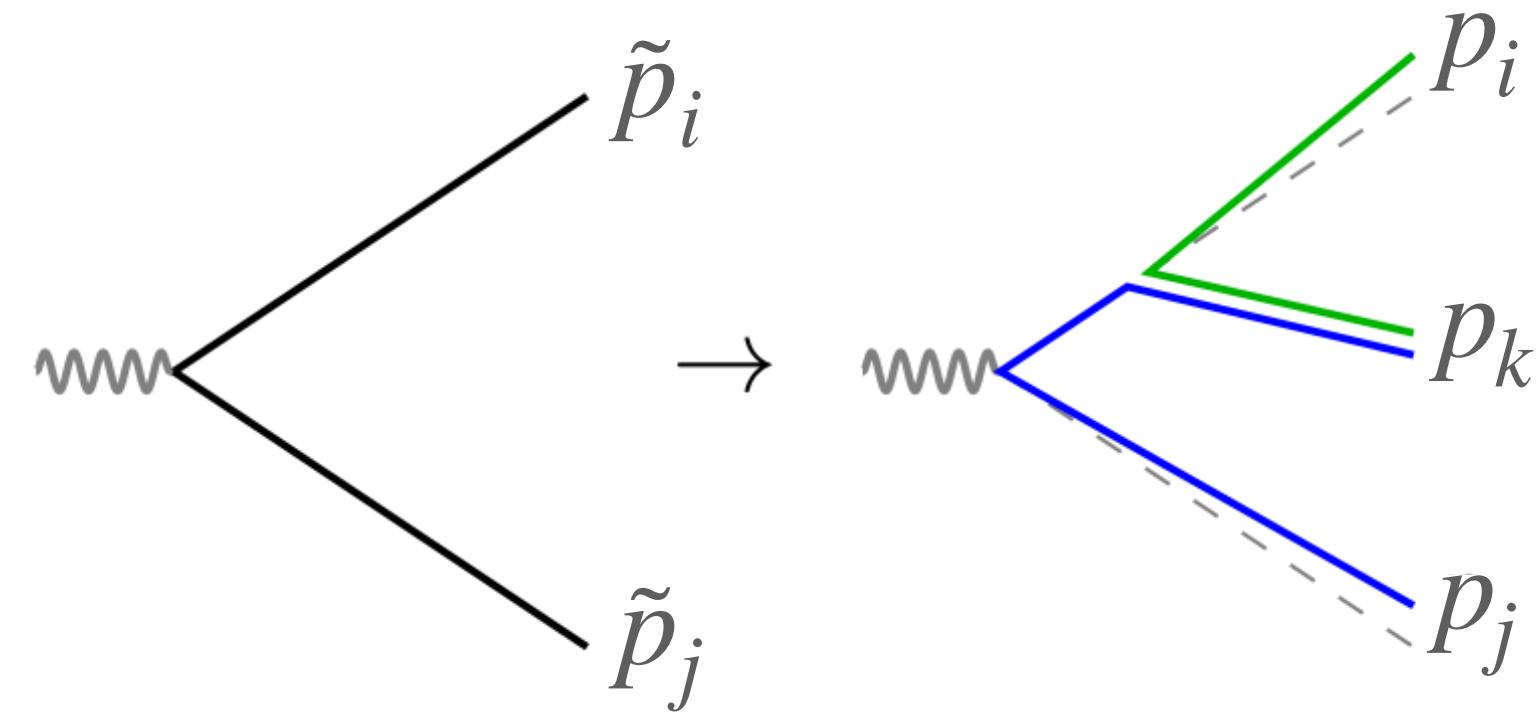
- Angular ordered + global recoil (Herwig)
- Dipole showers (Pythia, Sherpa, PanScales)

# Dipole showers for $e^+e^-$ collisions

Starting from a  $e^+e^- \rightarrow Z^* \rightarrow q\bar{q}$  system, at the evolution scale  $\nu$  a branching occurs



viewed as

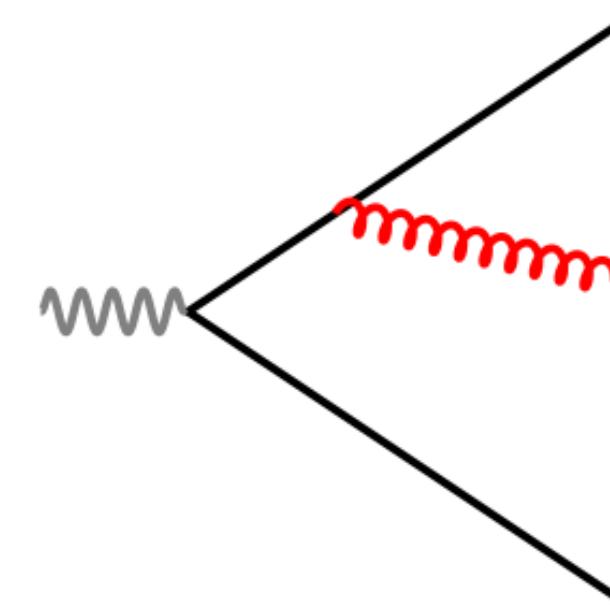


$$d\mathcal{P}_{\tilde{i}\tilde{j} \rightarrow ijk} \sim \frac{\alpha_s}{2\pi} \frac{dv^2}{v^2} d\bar{\eta} \frac{d\varphi}{2\pi}$$

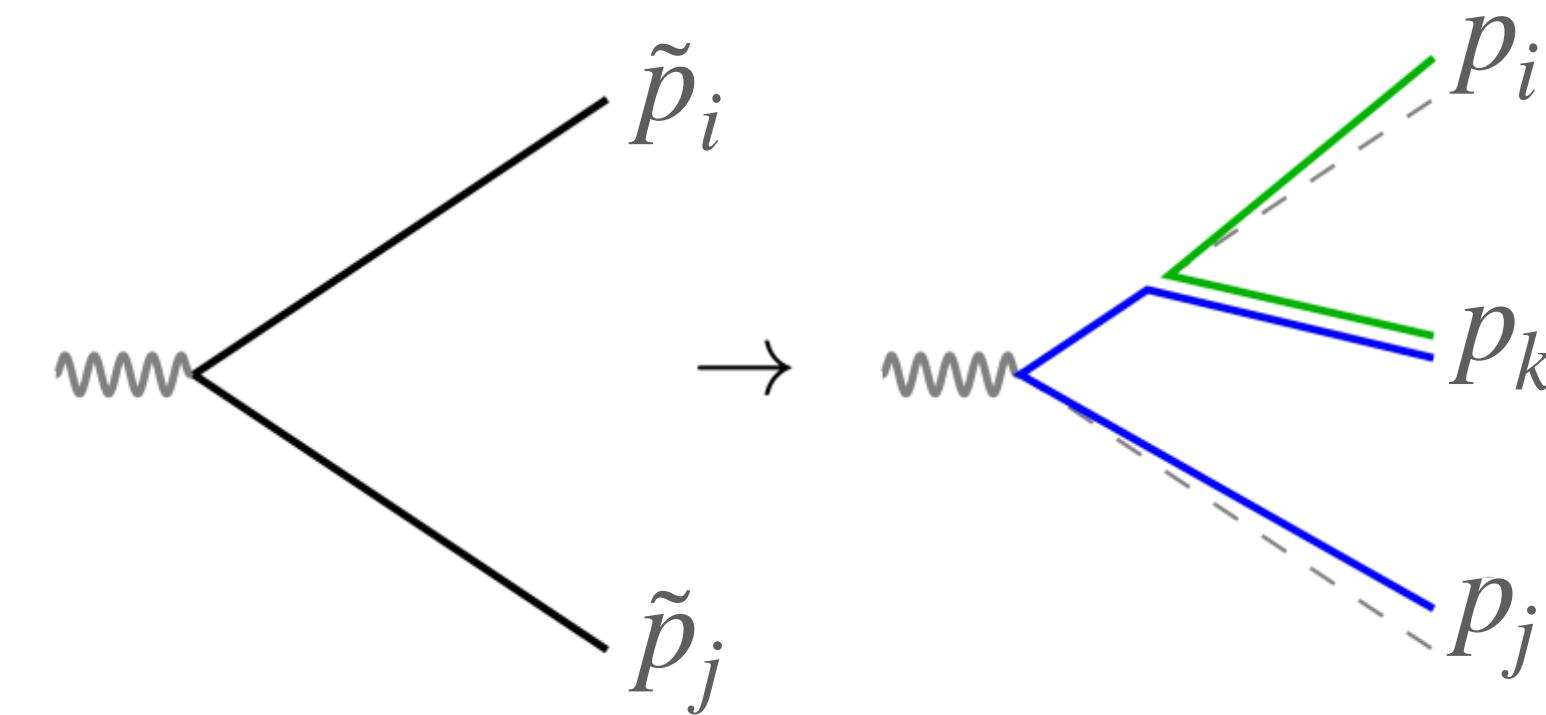
Phase-space

# Dipole showers for $e^+e^-$ collisions

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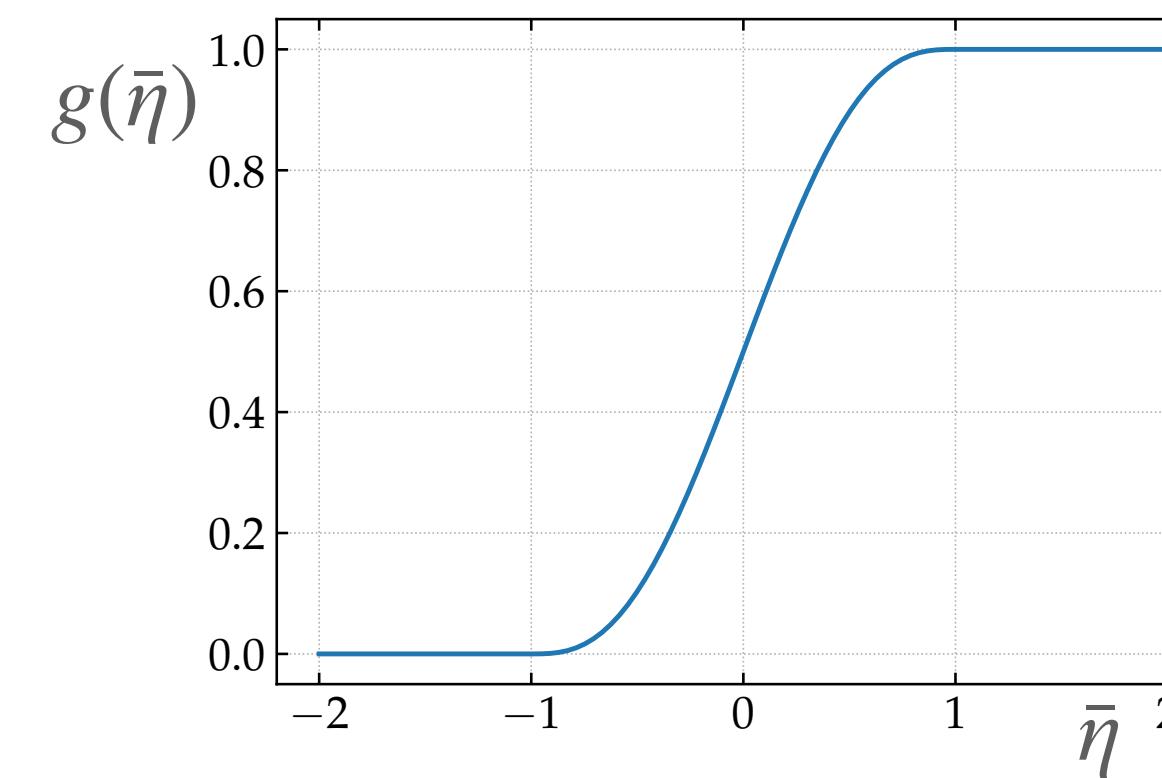
viewed as



$$d\mathcal{P}_{\tilde{i}\tilde{j} \rightarrow ijk} \sim \frac{\alpha_s}{2\pi} \frac{dv^2}{v^2} d\bar{\eta} \frac{d\varphi}{2\pi} \left[ g(\bar{\eta}) z_i P_{ik}(z_i) + g(-\bar{\eta}) z_j P_{jk}(z_j) \right]$$

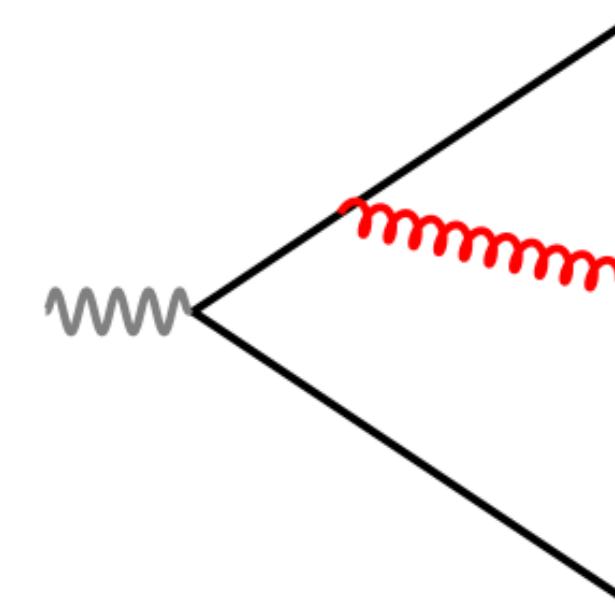
Phase-space

Splitting factor

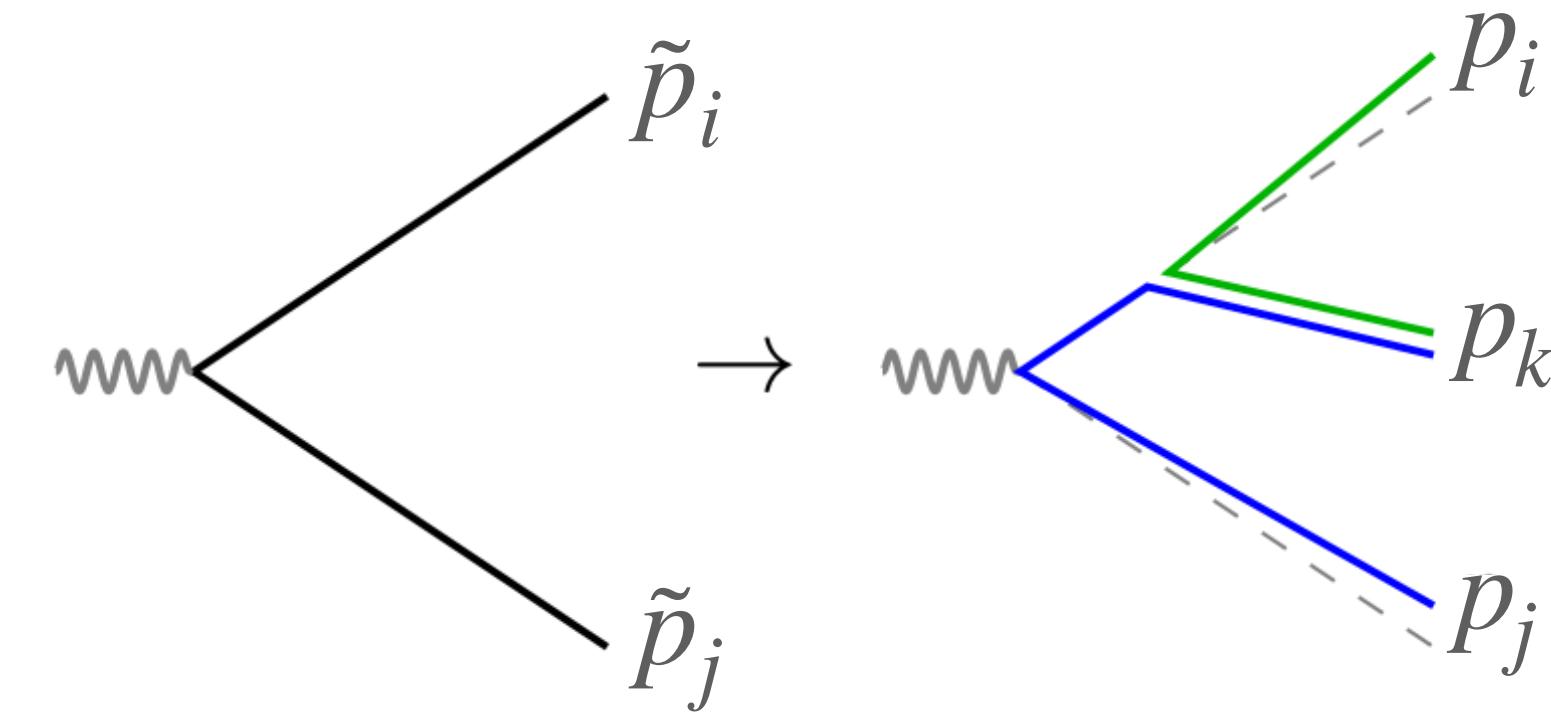


# Dipole showers for $e^+e^-$ collisions

Starting from a  $e^+e^- \rightarrow Z^* \rightarrow q\bar{q}$  system, at the evolution scale  $\nu$  a branching occurs



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$$d\mathcal{P}_{\tilde{i}\tilde{j} \rightarrow ijk} \sim \frac{\alpha_s}{2\pi} \frac{dv^2}{v^2} d\bar{\eta} \frac{d\varphi}{2\pi} \left[ g(\bar{\eta}) z_i P_{ik}(z_i) + g(-\bar{\eta}) z_j P_{jk}(z_j) \right]$$

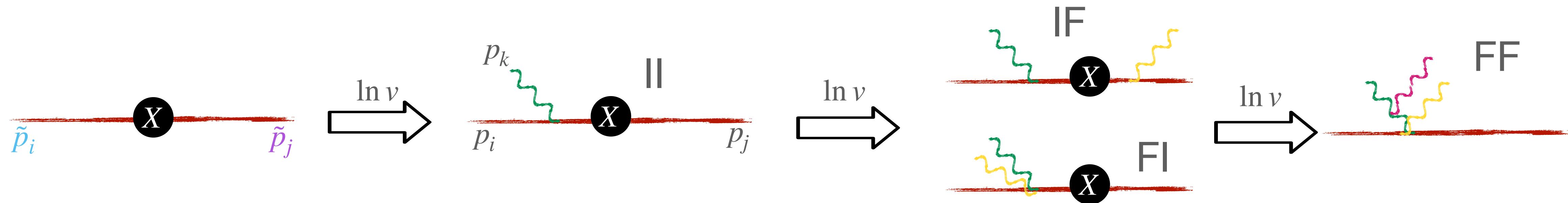
Phase-space      Splitting factor

Singular behavior:  $\lim_{k \rightarrow \text{soft}} d\mathcal{P}_{\tilde{i}\tilde{j} \rightarrow ijk} \propto \frac{1}{z_i z_j}$  and  $\lim_{k \parallel i} d\mathcal{P}_{\tilde{i}\tilde{j} \rightarrow ijk} \propto \frac{1}{z_j} \frac{1 + (1 - z_i)^2}{z_i}$

# Dipole showers with incoming hadrons

The presence of incoming hadrons brings two new ingredients wrt the  $e^+e^-$  case

- 1 Proliferation of dipole types: radiation from initial and final-state legs

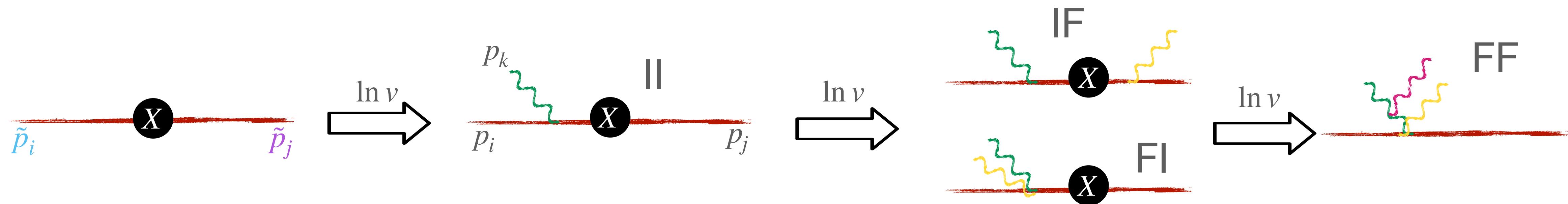


We focus on colour-singlet production, i.e.  $\textcircled{X}$  is a Higgs or a Z boson.  
Dijets and  $\textcircled{X} + \text{jet}$  (more relevant to this audience) are work in progress

# Dipole showers with incoming hadrons

The presence of incoming hadrons brings two new ingredients wrt the  $e^+e^-$  case

- 1** Proliferation of dipole types: radiation from initial and final-state legs



**2** PDFs:  $d\mathcal{P}_{\tilde{i}\tilde{j} \rightarrow ijk} \sim \alpha_s \frac{dv^2}{v^2} d\bar{\eta} \frac{d\varphi}{2\pi} \frac{x_i f_i(x_i, \mu_F^2)}{\tilde{x}_i \tilde{f}_i(\tilde{x}_i, \mu_F^2)} \frac{x_j f_j(x_j, \mu_F^2)}{\tilde{x}_j \tilde{f}_j(\tilde{x}_j, \mu_F^2)} \left[ g(\bar{\eta}) z_i P_{ik}^{\text{IS/FS}}(z_i) + g(-\bar{\eta}) z_j P_{jk}^{\text{IS/FS}}(z_j) \right]$

PDFs

# Dipole showers with incoming hadrons

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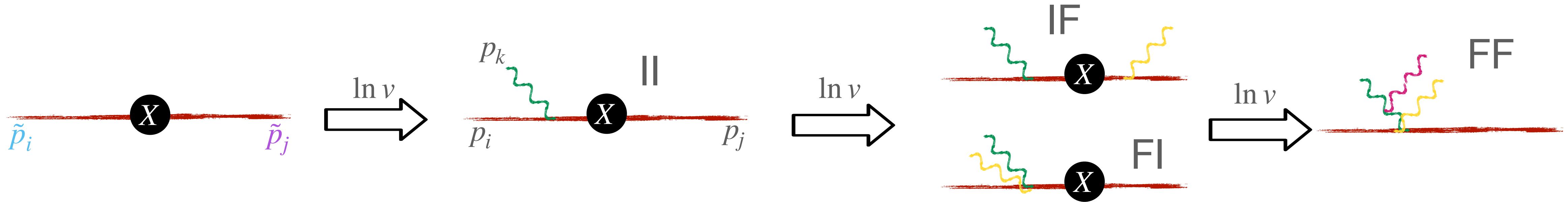
How should we deal with initial-state radiation in heavy-ions?

- Formation time arguments suggest no quenching of ISR
- Current approach in jet quenching Monte Carlo generators

Generate ISR via Pythia8 with nuclear  
PDFs. FSR off ISR emissions interact with  
the QGP [Hybrid model JHEP 10 (2014) 019, JetScape 1903.07706, Jewel EPJC 60 (2009)  
617-632, Martini PRC 80 (2009) 054913]

- Particularly relevant for acoplanarity-like observables, forward  
rapidities or large jet radii [Zapp talk at QM22]

# Dipole showers with incoming hadrons



$$d\mathcal{P}_{\tilde{i}\tilde{j} \rightarrow ijk} \sim \frac{\alpha_s}{2\pi} \frac{dv^2}{v^2} d\bar{\eta} \frac{d\varphi}{2\pi} \frac{x_i f_i(x_i, \mu_F^2)}{\tilde{x}_i f_{\tilde{i}}(\tilde{x}_i, \mu_F^2)} \frac{x_j f_j(x_j, \mu_F^2)}{\tilde{x}_j f_{\tilde{j}}(\tilde{x}_j, \mu_F^2)} \left[ g(\bar{\eta}) z_i P_{ik}^{\text{IS/FS}}(z_i) + g(-\bar{\eta}) z_j P_{jk}^{\text{IS/FS}}(z_j) \right]$$

Phase-space
PDFs
Splitting factor

~~Degrees of freedom:~~

- 1 Evolution variable:  $v$
- 2 Recoil scheme:  $\tilde{p}_{i,j} \rightarrow p_{i,j,k}$
- 3 Partitioning of dipole:  $\bar{\eta}$

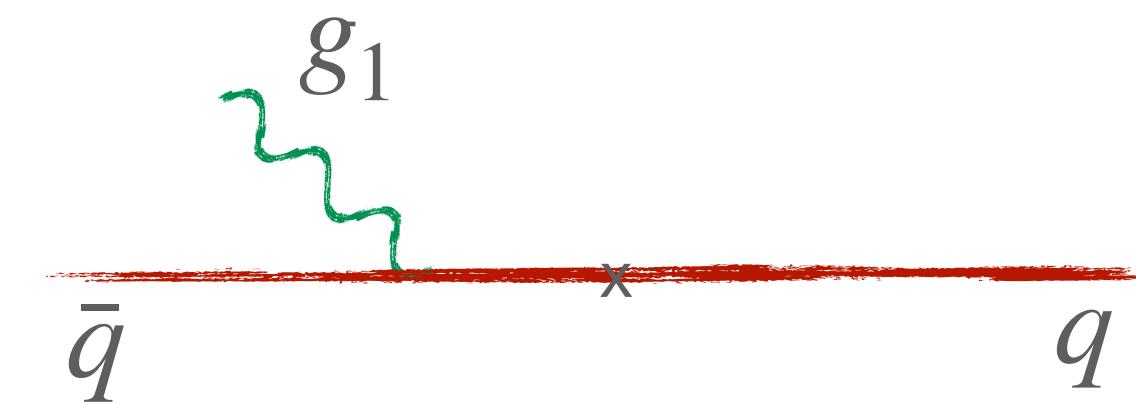
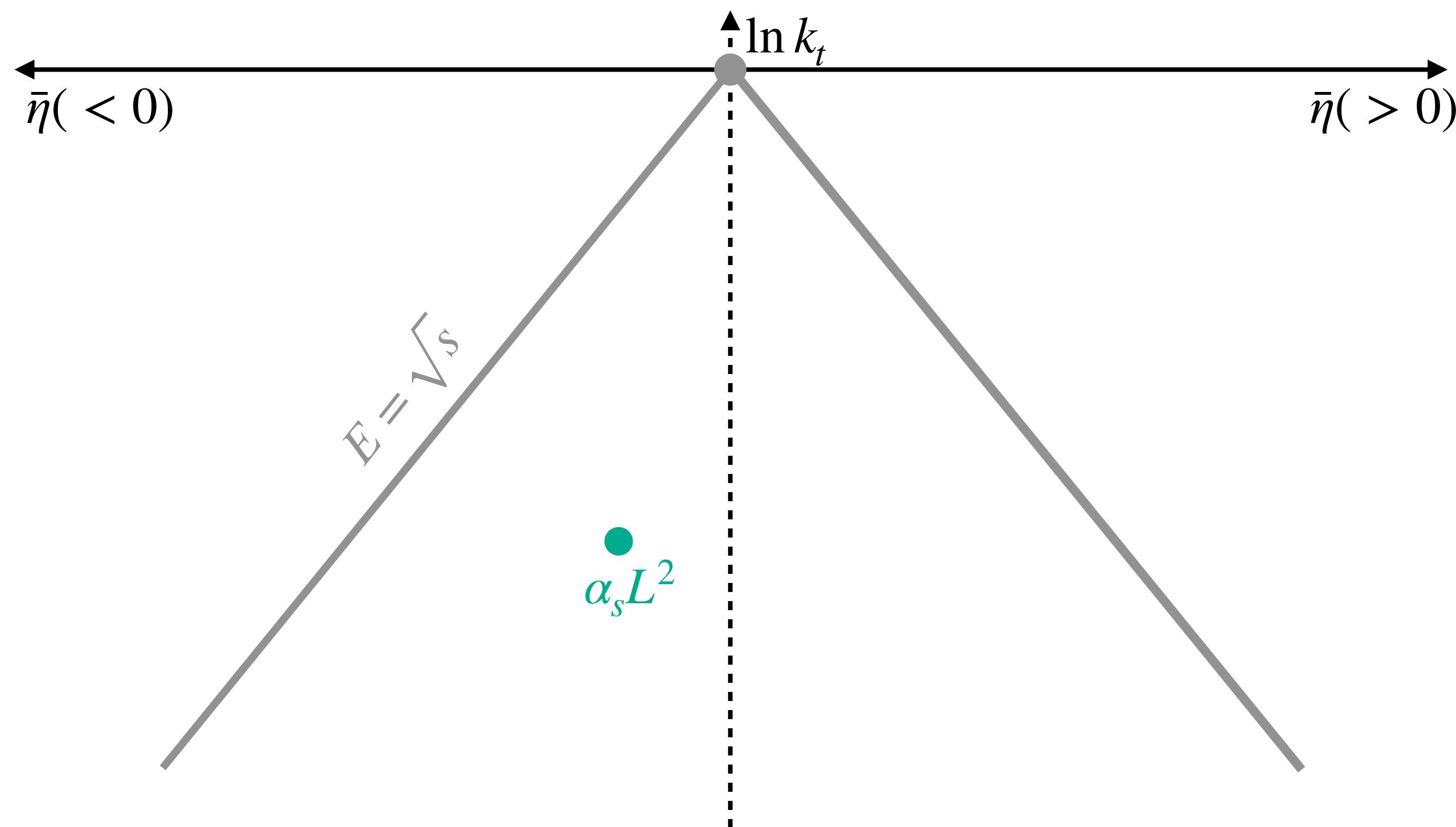
These choices affect the ~~logarithmic accuracy~~ of the shower

# Parton showers and logarithmic accuracy

[Dasgupta et al. PRL 125 (2020) 5, 052002]

1

Fixed-order: the shower must reproduce the exact matrix element in suitable limits  
e.g. double-logarithmic accuracy



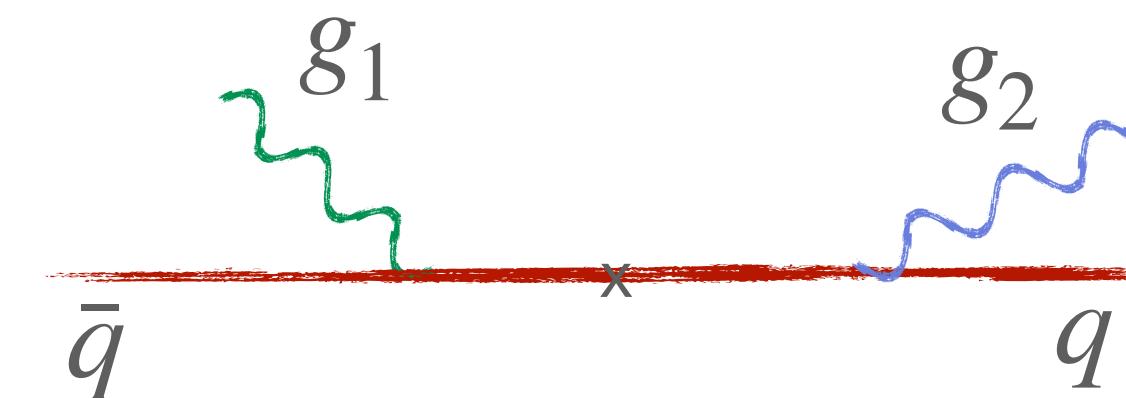
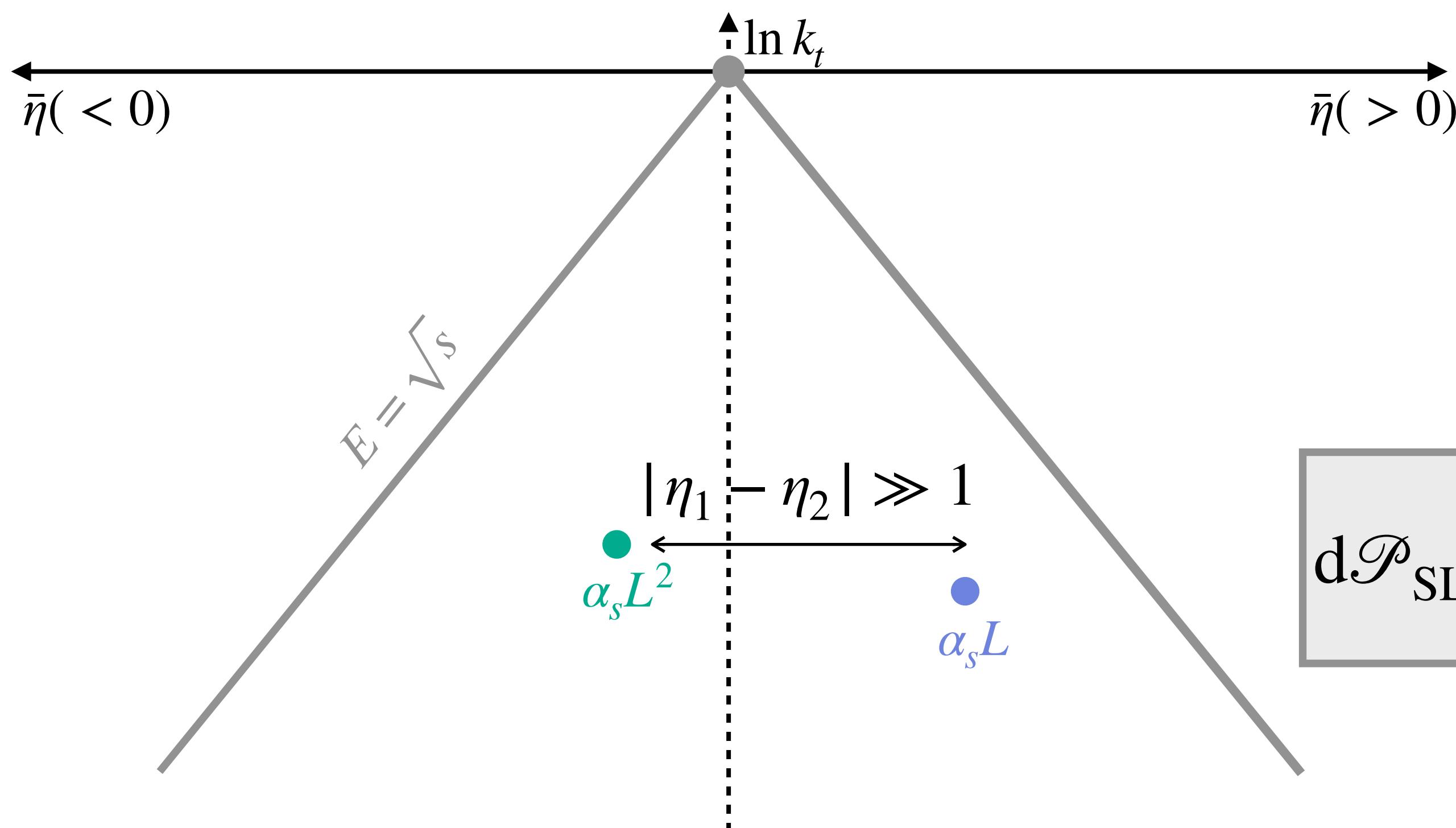
$$d\mathcal{P}_{DL} \propto \frac{C_F \alpha_s}{2\pi} d\eta \frac{dk_t}{k_t}$$

# Parton showers and logarithmic accuracy

[Dasgupta et al. PRL 125 (2020) 5, 052002]

1

Fixed-order: the shower must reproduce the exact matrix element in suitable limits  
e.g. single-logarithmic accuracy



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

# Parton showers and logarithmic accuracy

[Dasgupta et al. PRL 125 (2020) 5, 052002]

- 1 Fixed-order: the shower must reproduce the exact matrix element in suitable limits
- 2 All-orders: the shower must reproduce analytic resummation results for a broad range of observables.

$$\Sigma(\bar{O} < e^{-L}) = \exp \left[ -Lg_1(\alpha_s L) + \textcolor{brown}{g_2(\alpha_s L)} + \textcolor{blue}{\alpha_s g_3(\alpha_s L)} + \mathcal{O}(\alpha_s^n L^{n-1}) \right]$$

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

Resummation regime  
 $\alpha_s \ll 1, \alpha_s L \sim 1$

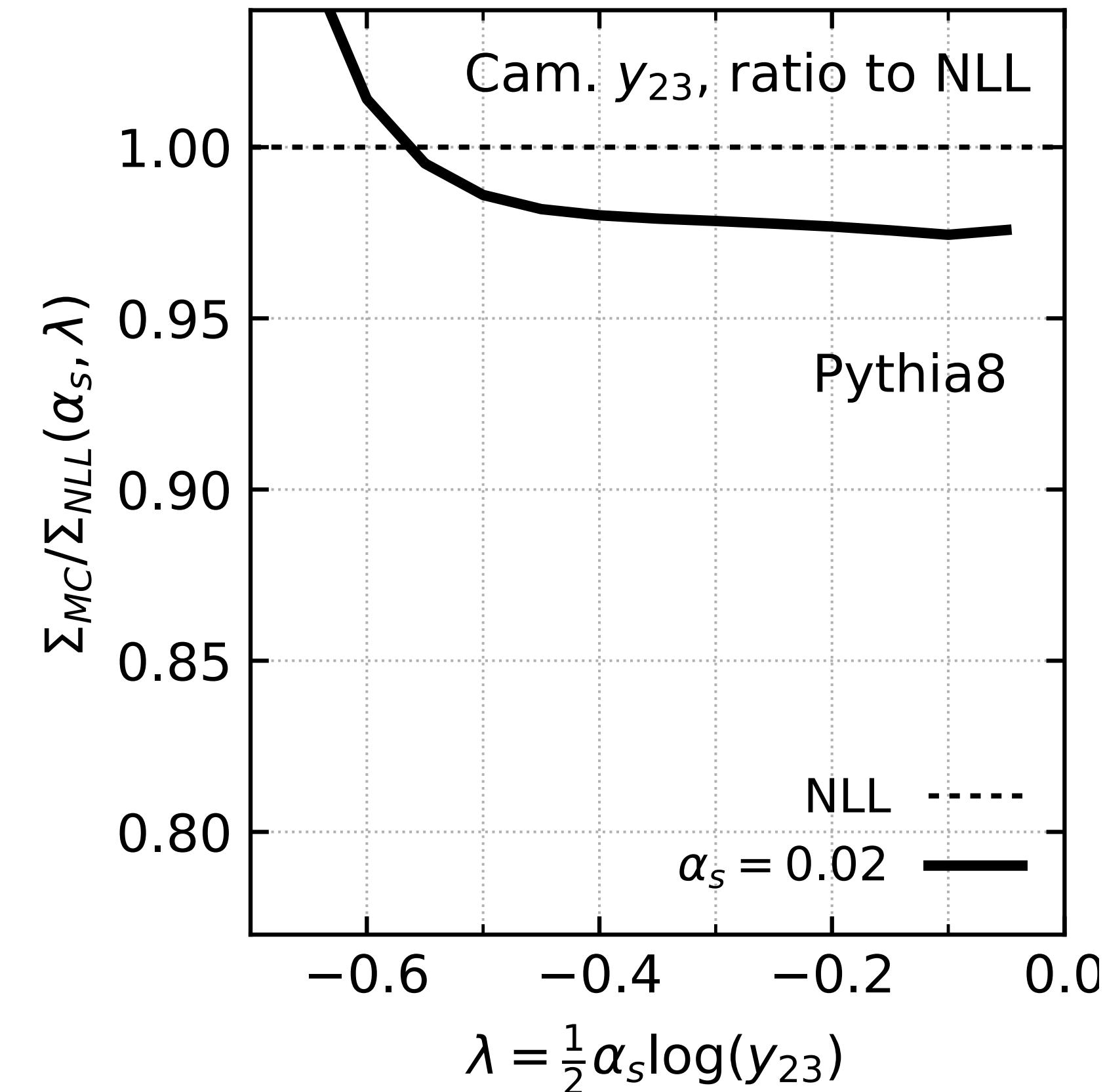
# Parton showers and logarithmic accuracy

[Dasgupta et al. PRL 125 (2020) 5, 052002]

- 1 Fixed-order: the shower must reproduce the exact matrix element in suitable limits
- 2 All-orders: the shower must reproduce analytic resummation results for a broad range of observables.

$$\frac{\Sigma^{\text{MC}}(\alpha_s L)}{\Sigma^{\text{NLL}}(\alpha_s L)} \neq 1$$

NLL deviation or NNLL effect?



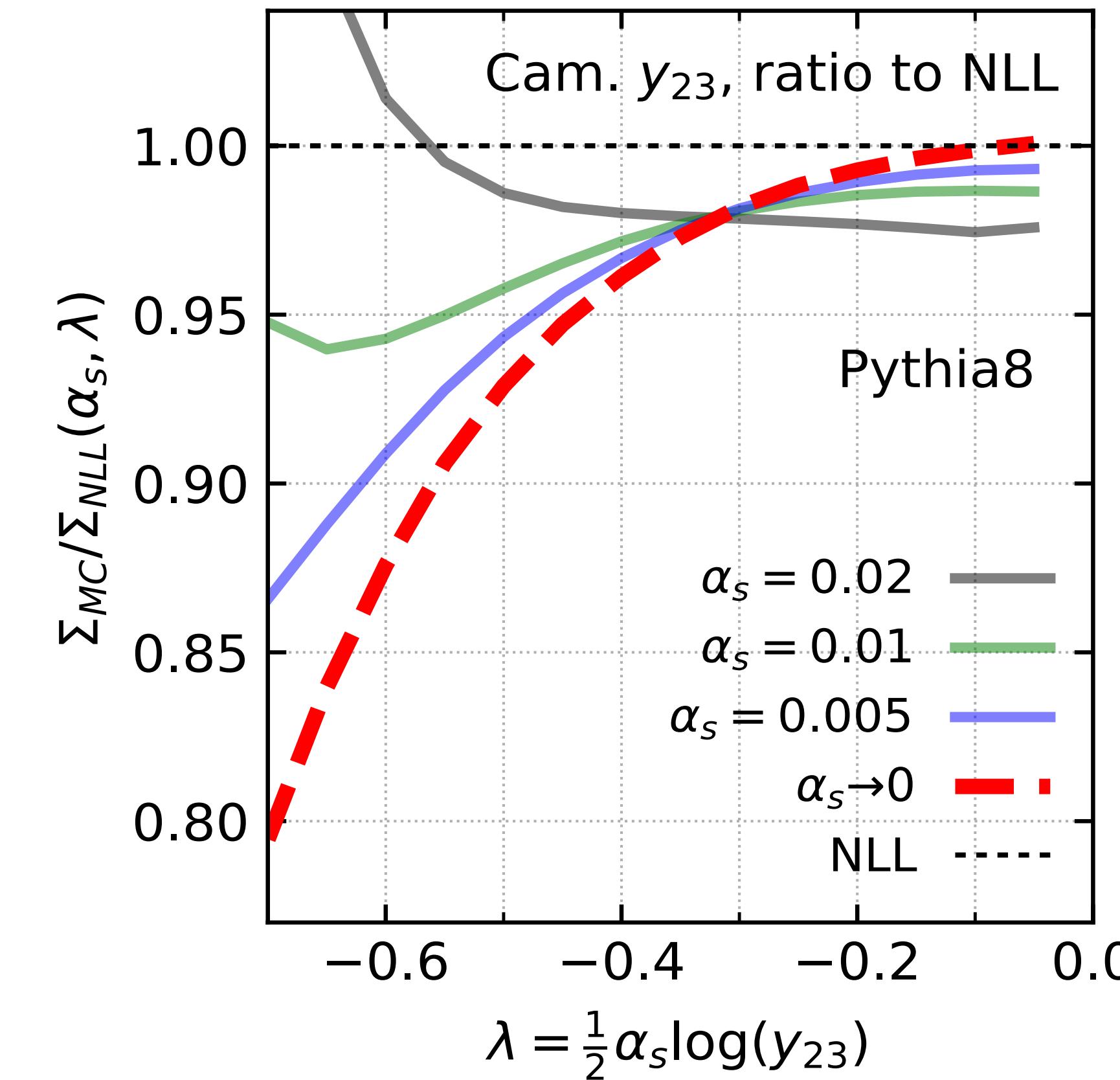
# Parton showers and logarithmic accuracy

[Dasgupta et al. PRL 125 (2020) 5, 052002]

- 1 Fixed-order: the shower must reproduce the exact matrix element in suitable limits
- 2 All-orders: the shower must reproduce analytic resummation results for a broad range of observables.

$$\lim_{\alpha_s \rightarrow 0} \frac{\Sigma^{\text{MC}}(\alpha_s L)}{\Sigma^{\text{NLL}}(\alpha_s L)} \rightarrow 1$$

NLL deviation or ~~NNLL effect?~~



# Parton showers and logarithmic accuracy

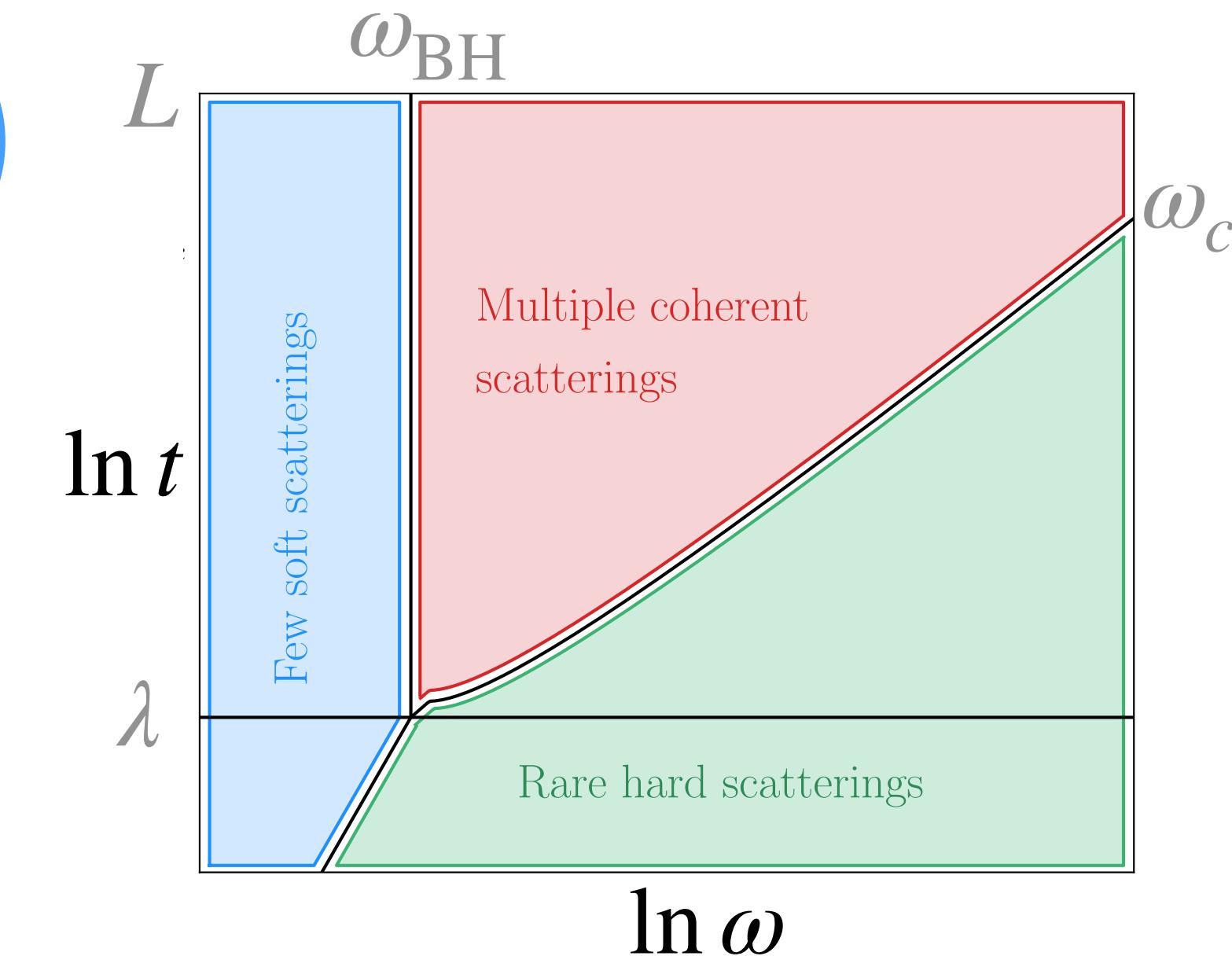
How to define the accuracy of a medium induced shower?

- Multiple, soft scattering approximation resummation parameter:  $\alpha_s \frac{L}{t_f}$
- Sudakov form factor including a few hard scatterings:

$$\begin{aligned}\ln \Delta(t) = & \alpha_s \frac{t}{\lambda} \left( f_1 \ln^2 \frac{\omega_{\text{BH}}}{\omega_{\text{IR}}} + f_2 \ln \frac{\omega_{\text{BH}}}{\omega_{\text{IR}}} + f_3 \right) \\ & + \alpha_s \left( g_1 \sqrt{\frac{\omega_c}{\omega_{\text{BH}}}} + g_2 \ln \frac{t}{\lambda} + g_3 \right) \\ & + \alpha_s \left( h_1 \ln \frac{t}{\lambda} + h_2 \right)\end{aligned}$$

[Takacs poster at QM22]

- Interplay with vacuum emissions?



[Isaksen, Takacs and Tywoniuk arXiv:2206.02811]

# PanScales criteria for NLL parton showers

[Dasgupta et al. PRL 125 (2020) 5, 052002]

- 1** Fixed-order: the shower must reproduce the exact matrix element in the limit where every pair of emissions is well separated in at least  $k_t$  or  $\eta$
- 2** All-orders: the shower must reproduce analytic resummation results for a broad range of observables including event shapes, non-global observables etc

The rest of this talk: the first NLL shower for colour singlet production

## PanScales showers for hadron collisions: formulation and fixed-order studies

2205.02237

Melissa van Beekveld,<sup>a</sup> Silvia Ferrario Ravasio,<sup>a</sup> Gavin P. Salam,<sup>a,b</sup>  
Alba Soto-Ontoso,<sup>c</sup> Gregory Soyez,<sup>c</sup> Rob Verheyen<sup>d</sup>

<sup>a</sup>Rudolf Peierls Centre for Theoretical Physics, Clarendon Laboratory, Parks Road, University of Oxford, Oxford OX1 3PU, UK

<sup>b</sup>All Souls College, Oxford OX1 4AL, UK

<sup>c</sup>Université Paris-Saclay, CNRS, CEA, Institut de physique théorique, 91191, Gif-sur-Yvette, France

<sup>d</sup>Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK

## PanScales showers for hadron collisions: all-orders validation

soon on the arXiv!

Melissa van Beekveld,<sup>a</sup> Silvia Ferrario Ravasio,<sup>a</sup> Keith Hamilton,<sup>b</sup> Gavin P. Salam,<sup>a,c</sup>  
Alba Soto-Ontoso,<sup>d</sup> Gregory Soyez,<sup>d</sup> Rob Verheyen<sup>b</sup>

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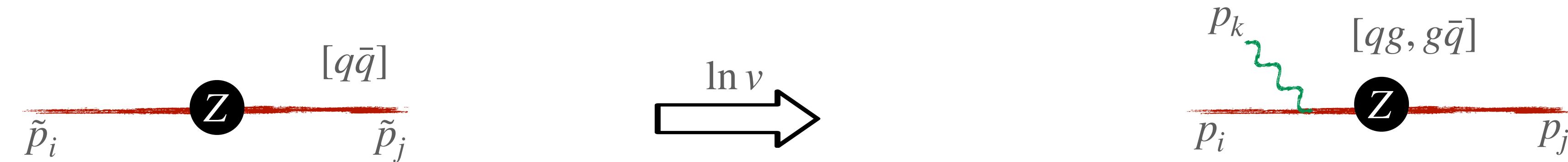
<sup>b</sup>Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK

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<sup>d</sup>Université Paris-Saclay, CNRS, CEA, Institut de physique théorique, 91191, Gif-sur-Yvette, France

# Dipole- $k_t$ : a standard dipole shower

- 1 Evolution variable: transverse momentum  $v \sim k_t$
- 2 Recoil scheme: depends on whether the dipole legs are initial (I) or final (F) state

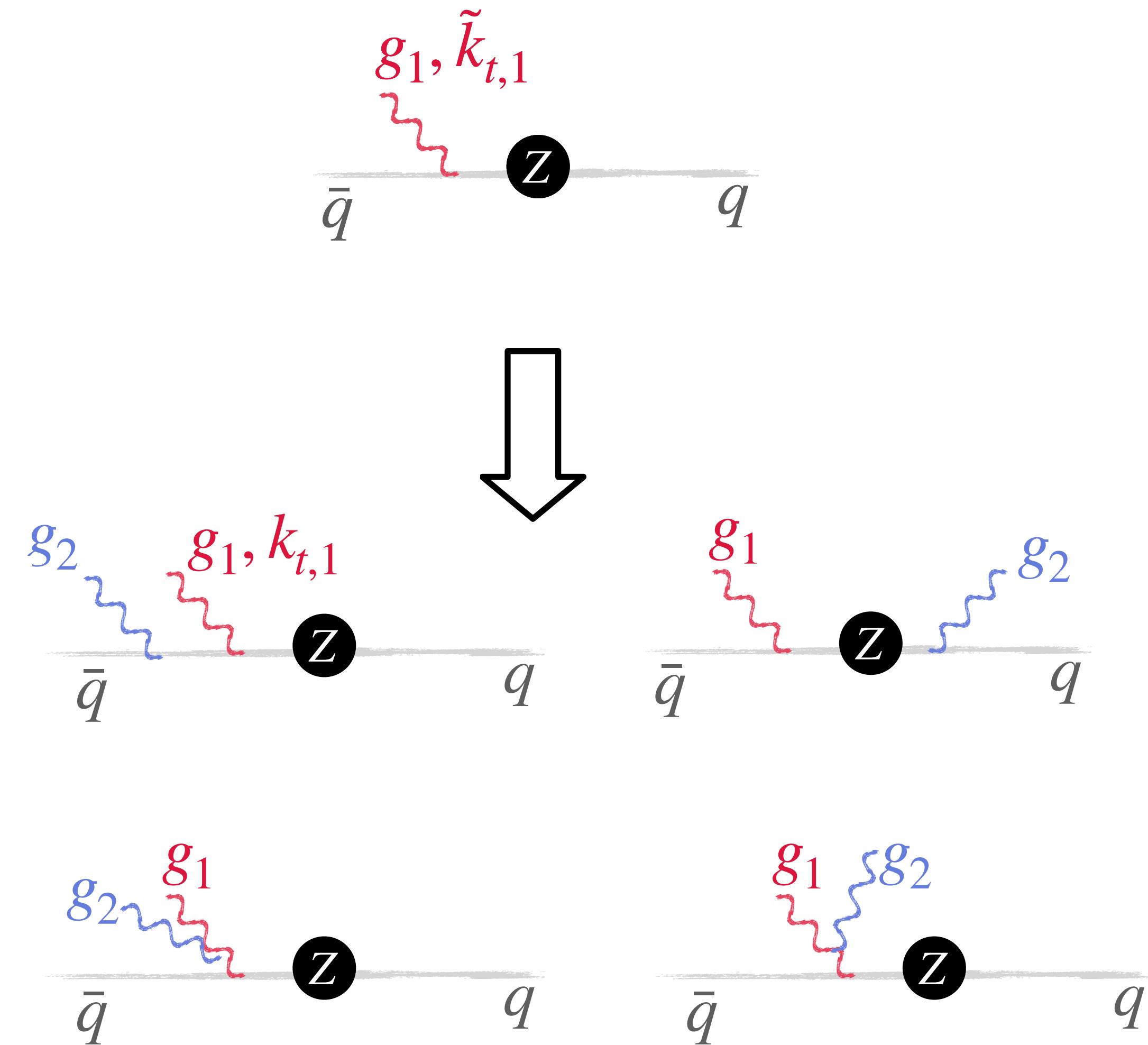
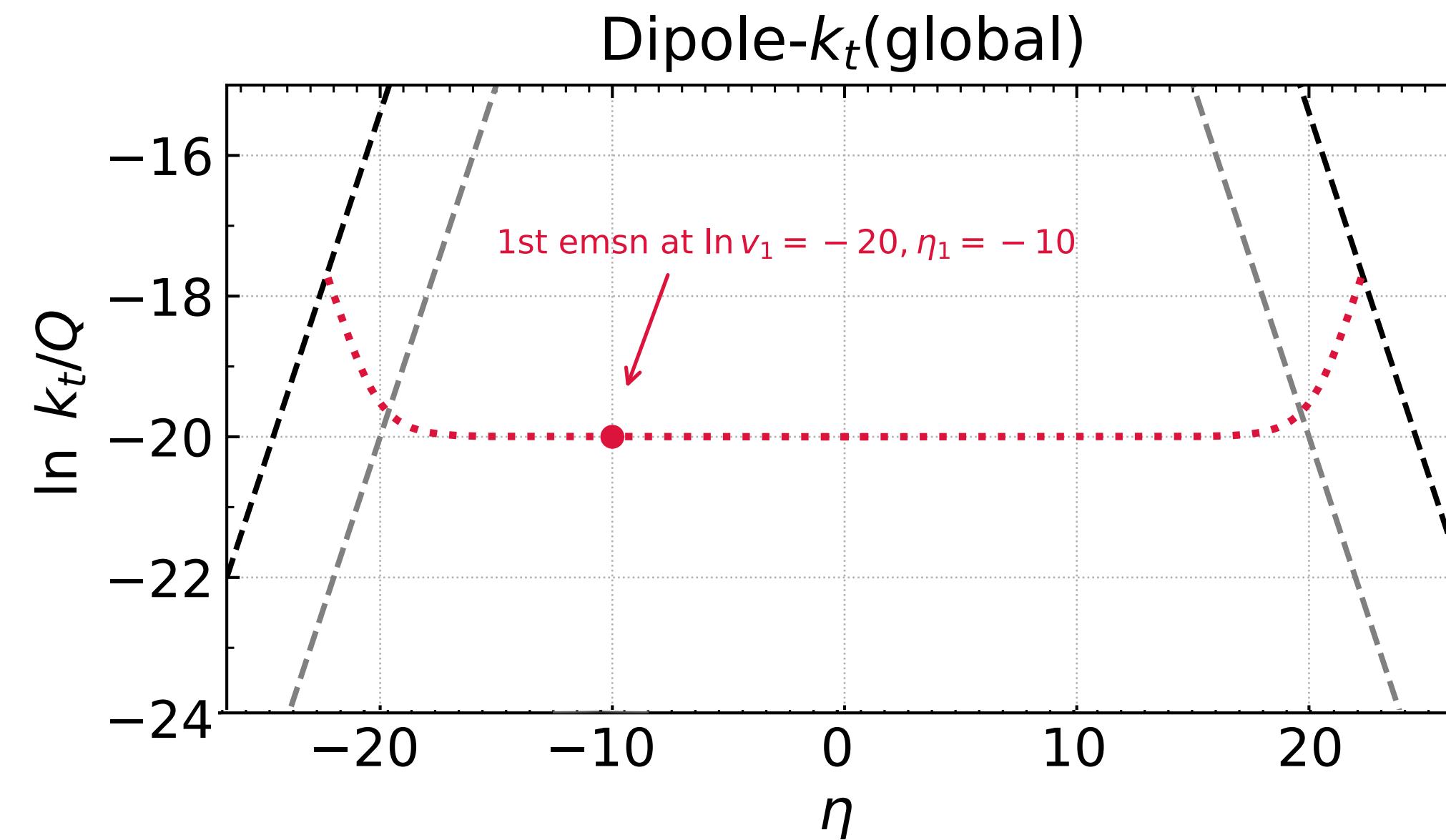


- a) FF, FI dipoles: local recoil
- b) II dipole: global recoil
- c) IF dipoles: local or global recoil

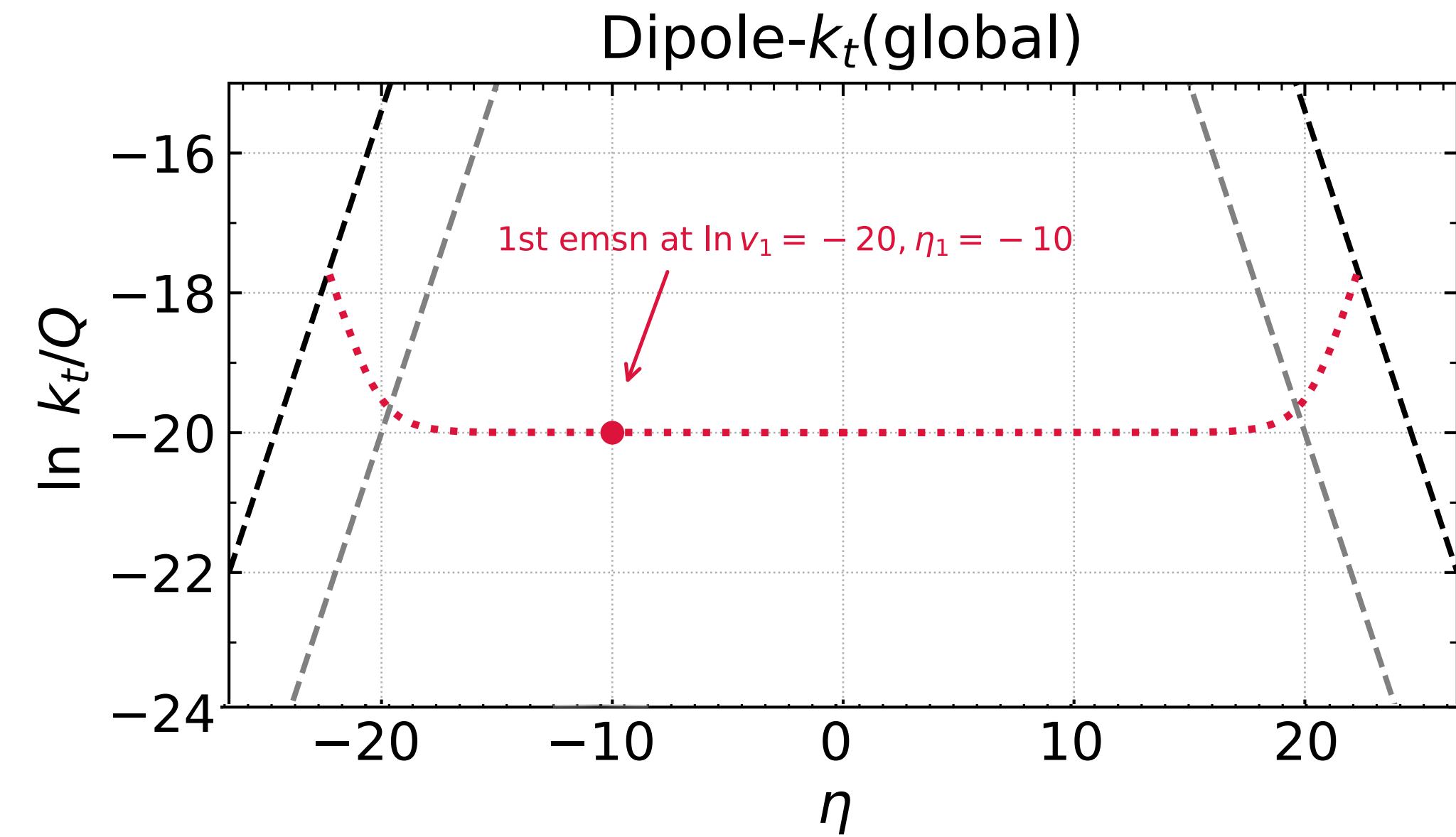
- 3 Dipole partitioning:  $\bar{\eta} = 0$  corresponds to zero rapidity in the dipole rest frame

What is the logarithmic accuracy of state-of-the-art dipole showers?

# What is the accuracy of Dipole- $k_t$ ? Fixed-order test



# What is the accuracy of Dipole- $k_t$ ? Fixed-order test



NLL expectation:

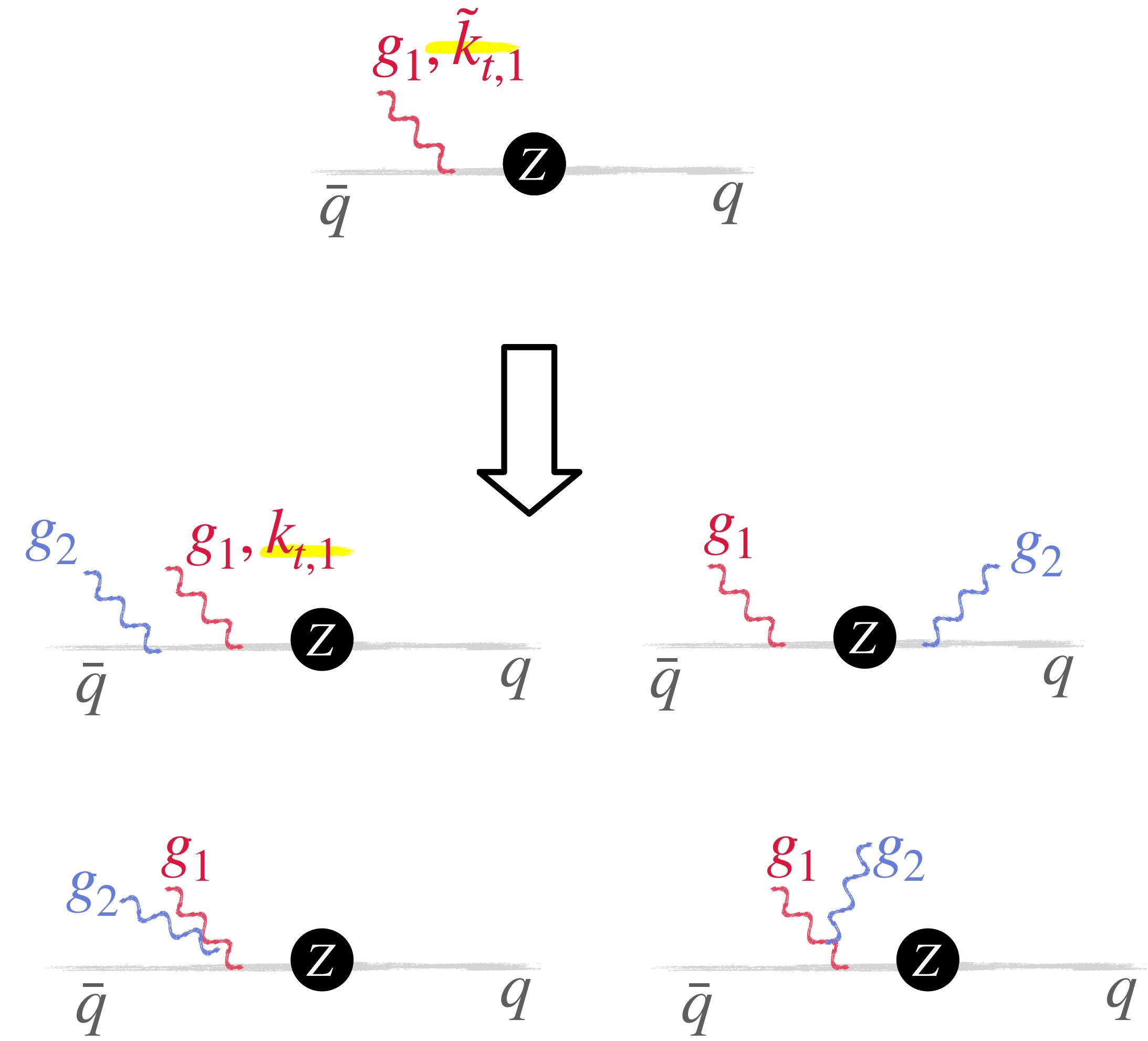
If  $|\eta_1 - \eta_2| \gg 1$ , emissions are independent

$$k_{t,1} = \tilde{k}_{t,1}$$

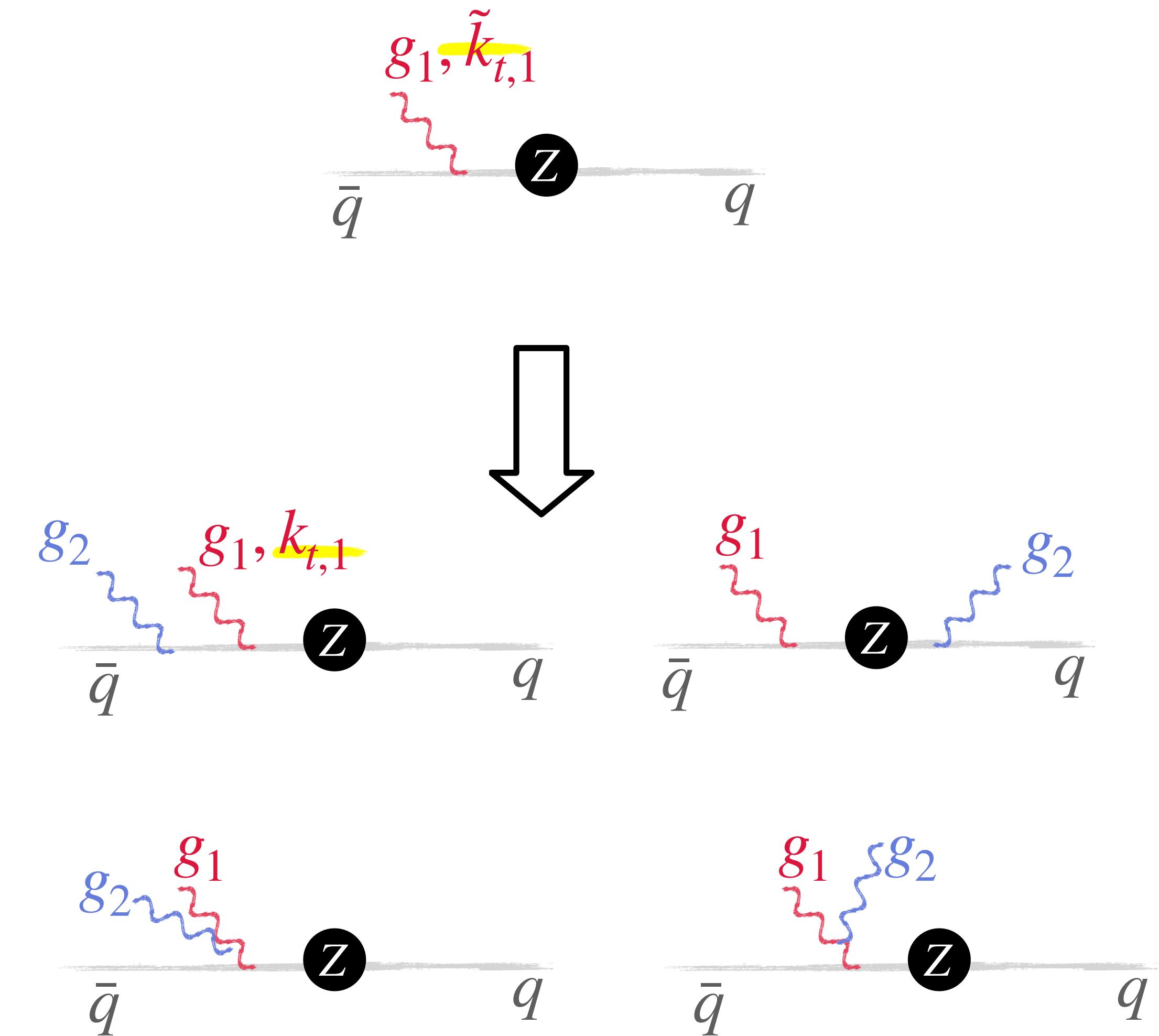
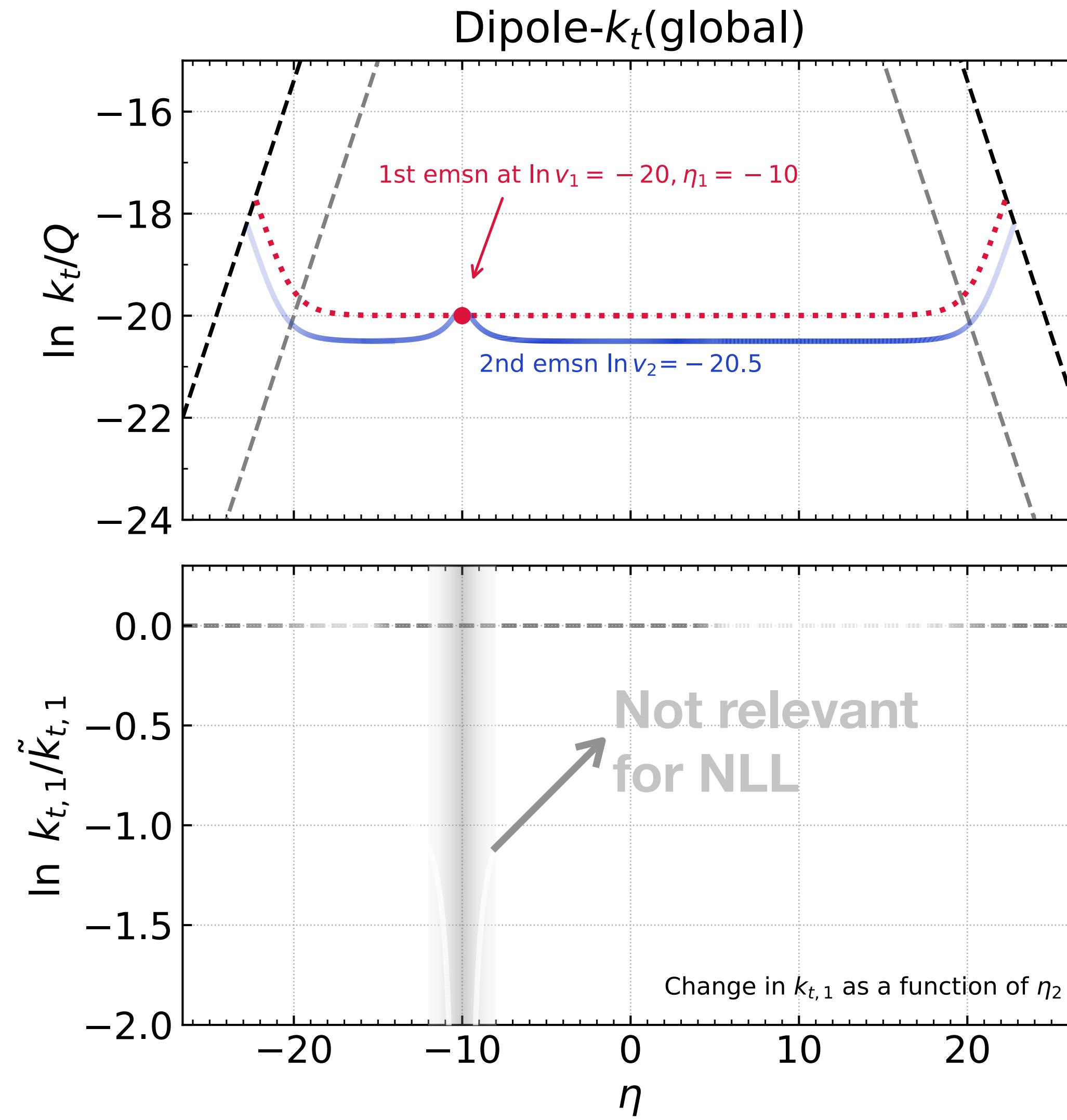
That is,



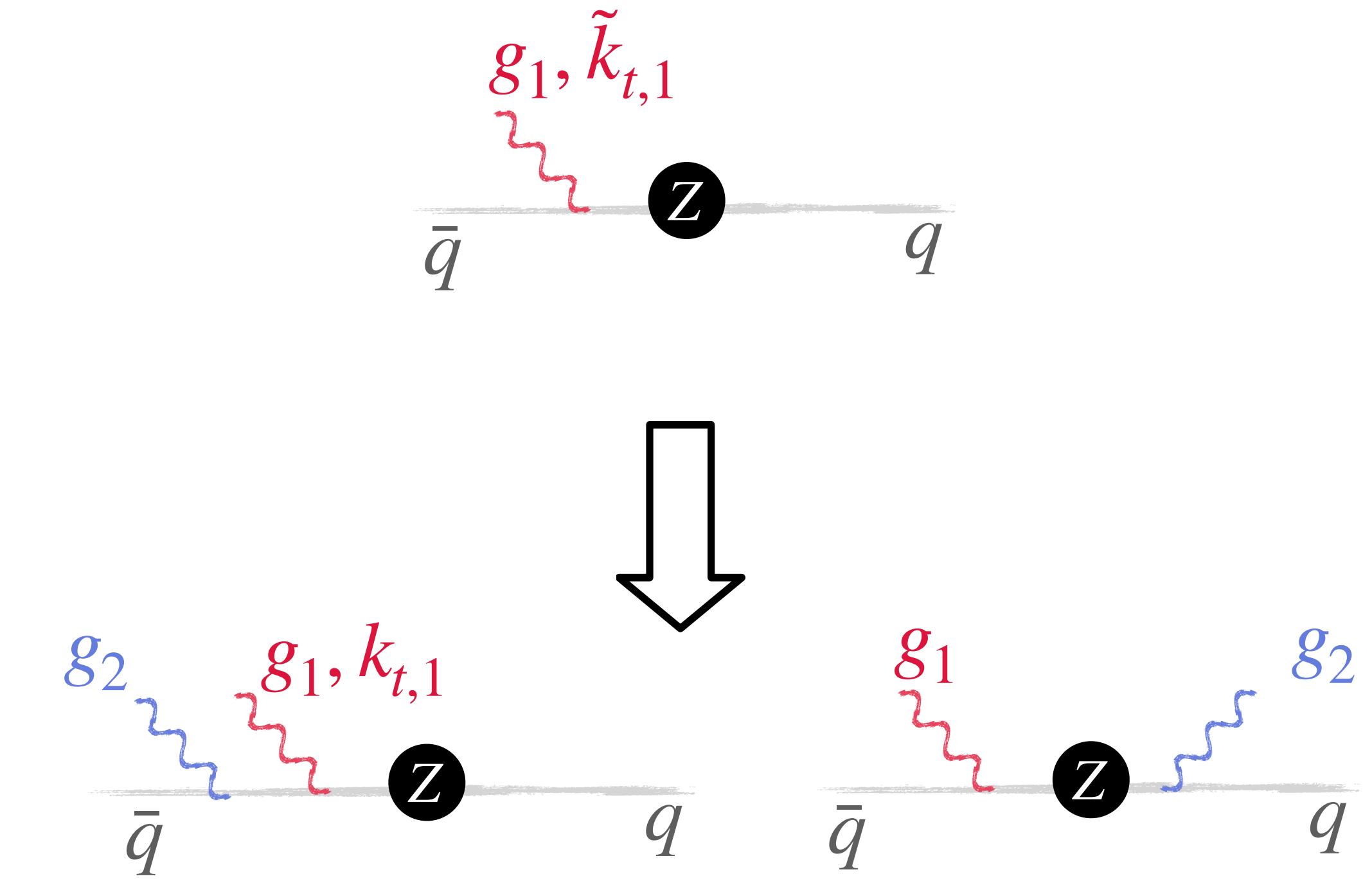
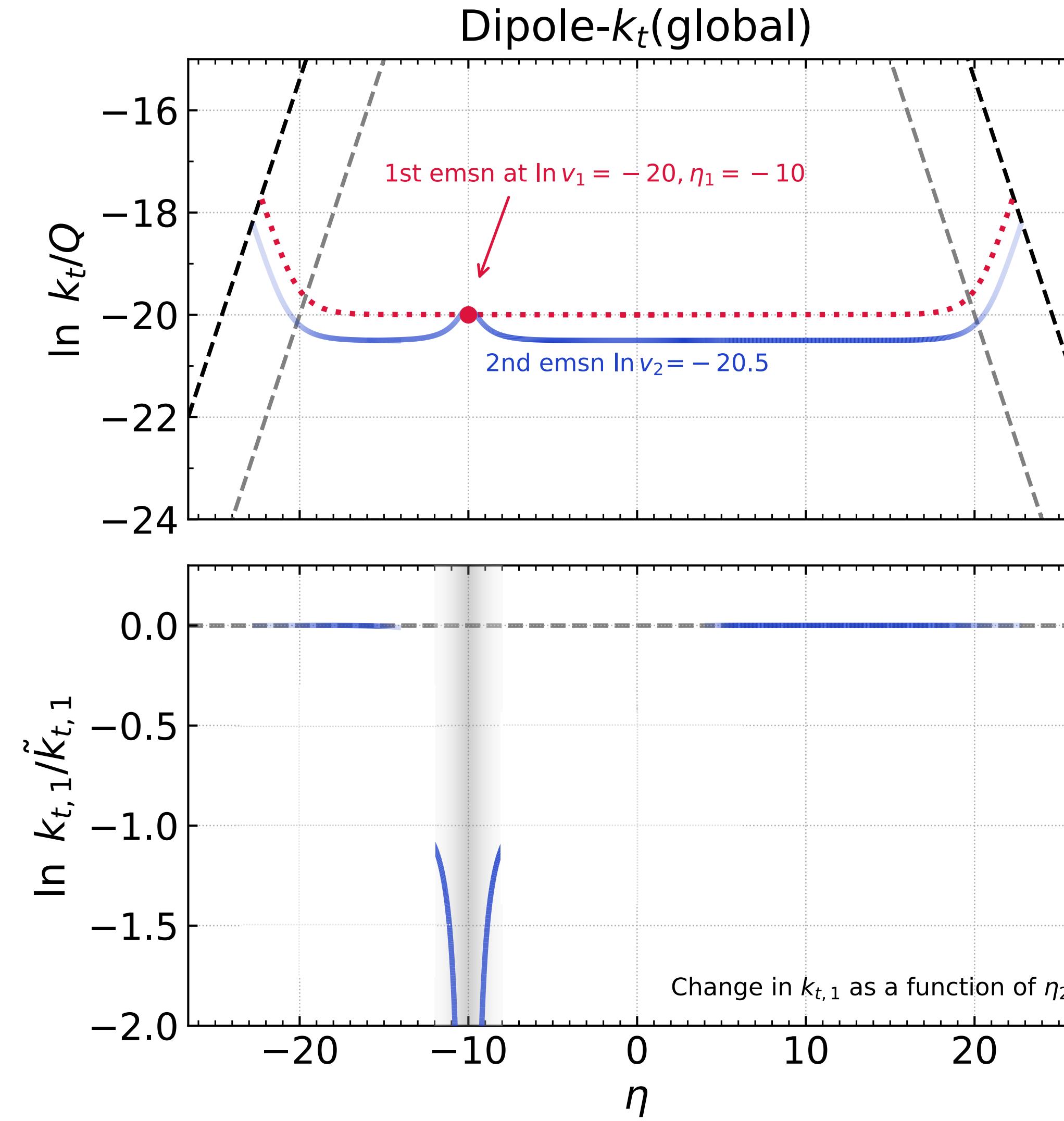
$C_F, q(\bar{q})$  recoils  
 $C_A, g$  recoils



# What is the accuracy of Dipole- $k_t$ ? Fixed-order test

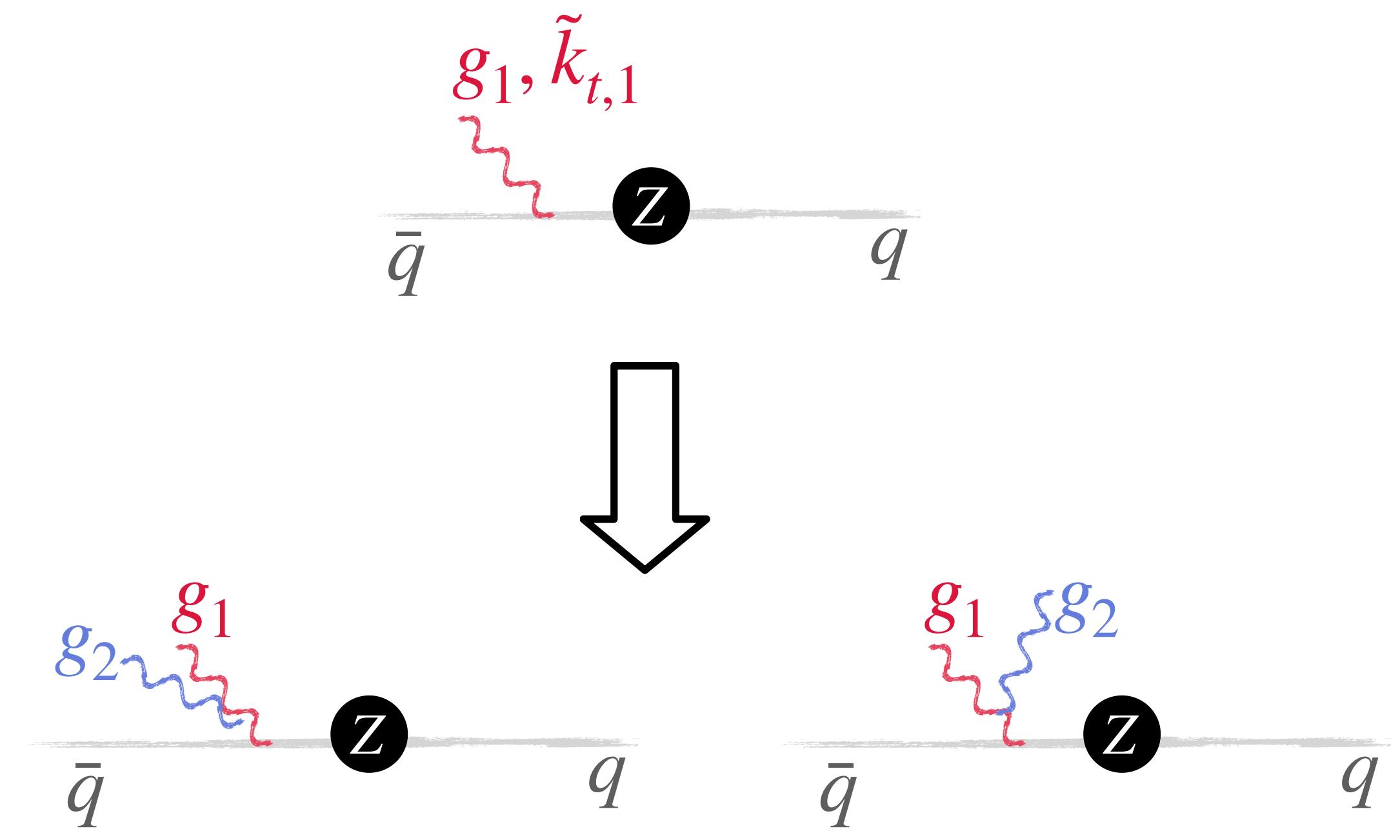
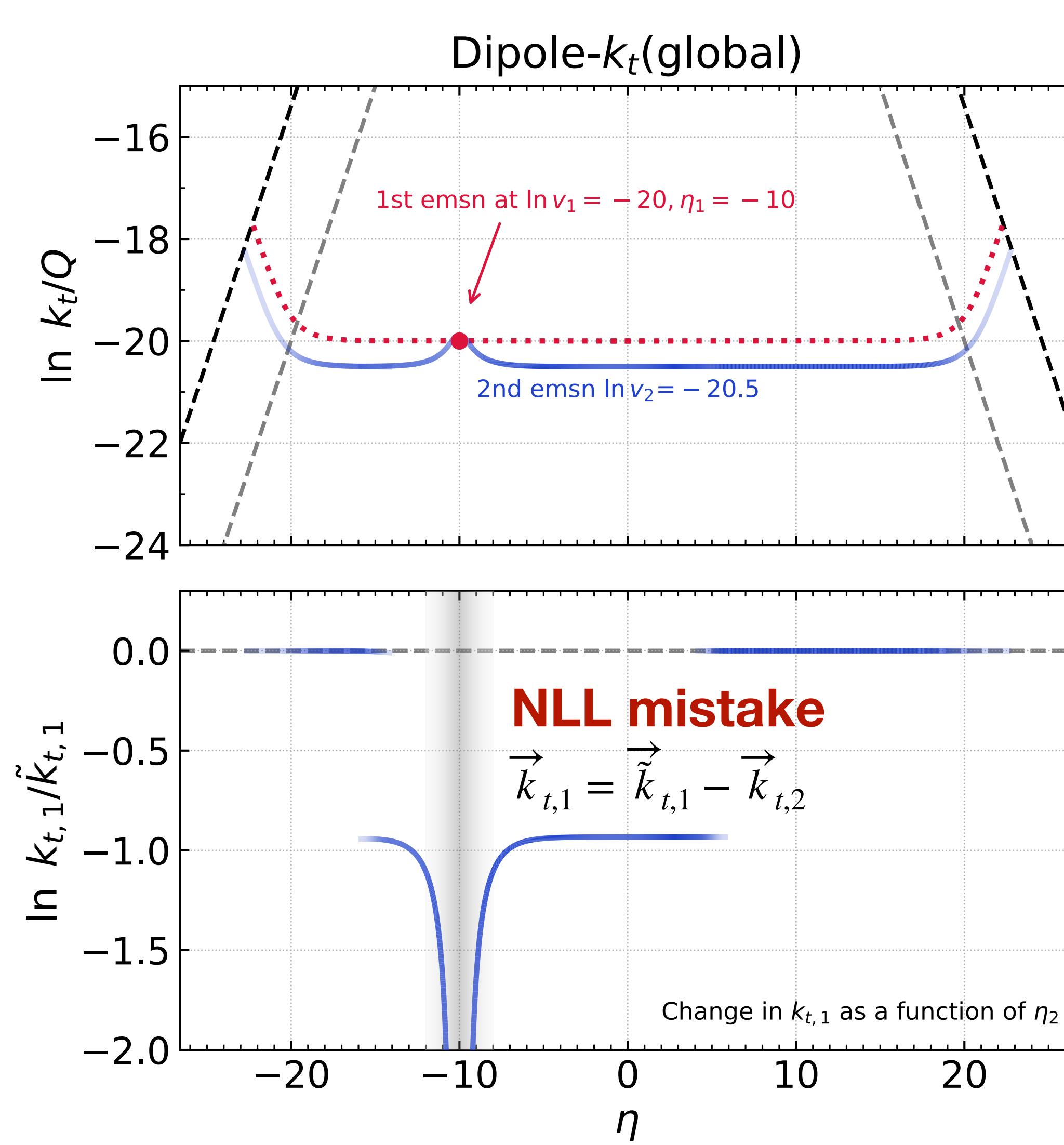


# What is the accuracy of Dipole- $k_t$ ? Fixed-order test



Correct behavior for IF splittings  
with the global recoil scheme

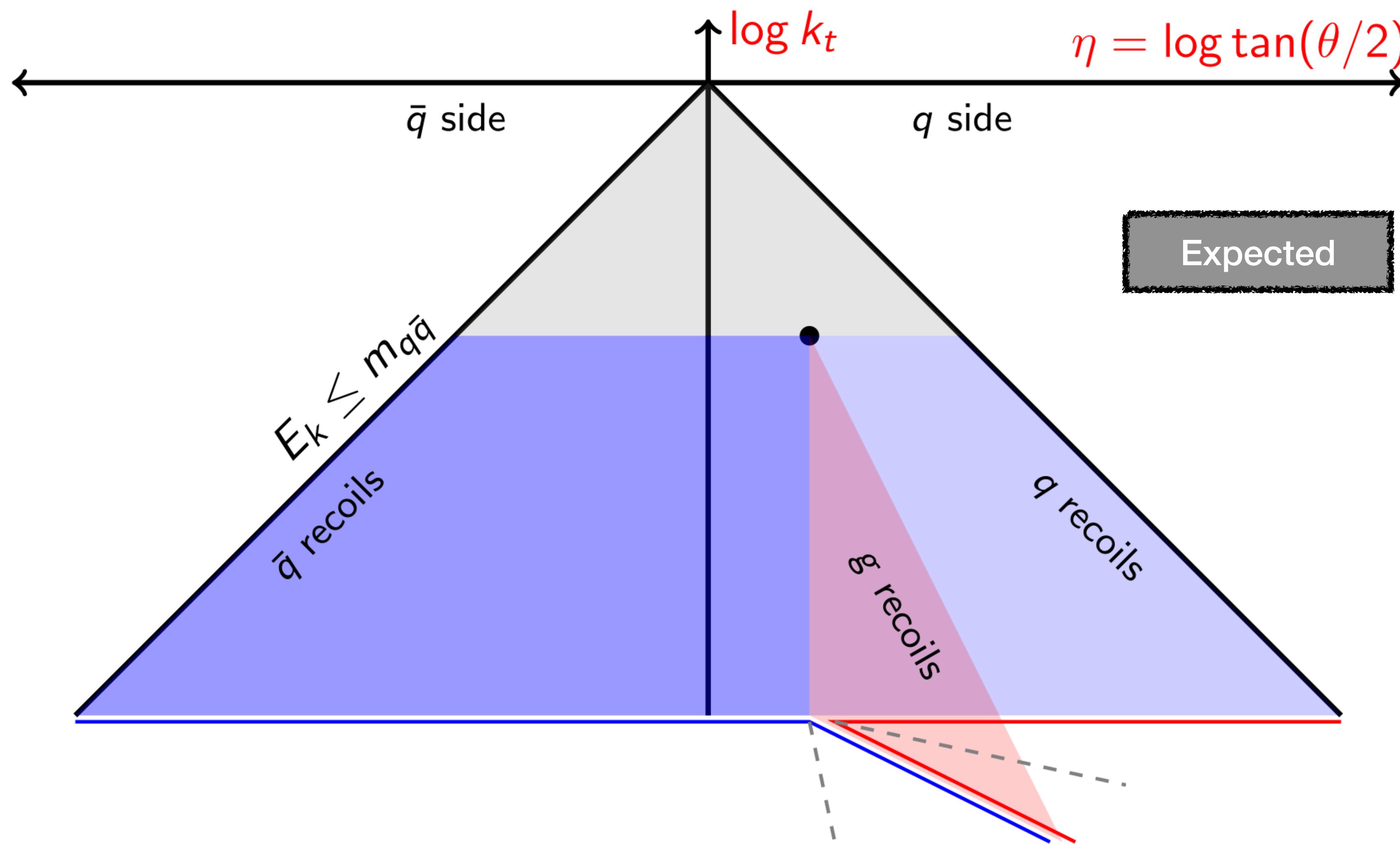
# What is the accuracy of Dipole- $k_t$ ? Fixed-order test



Breakdown of the independent  
emissions picture

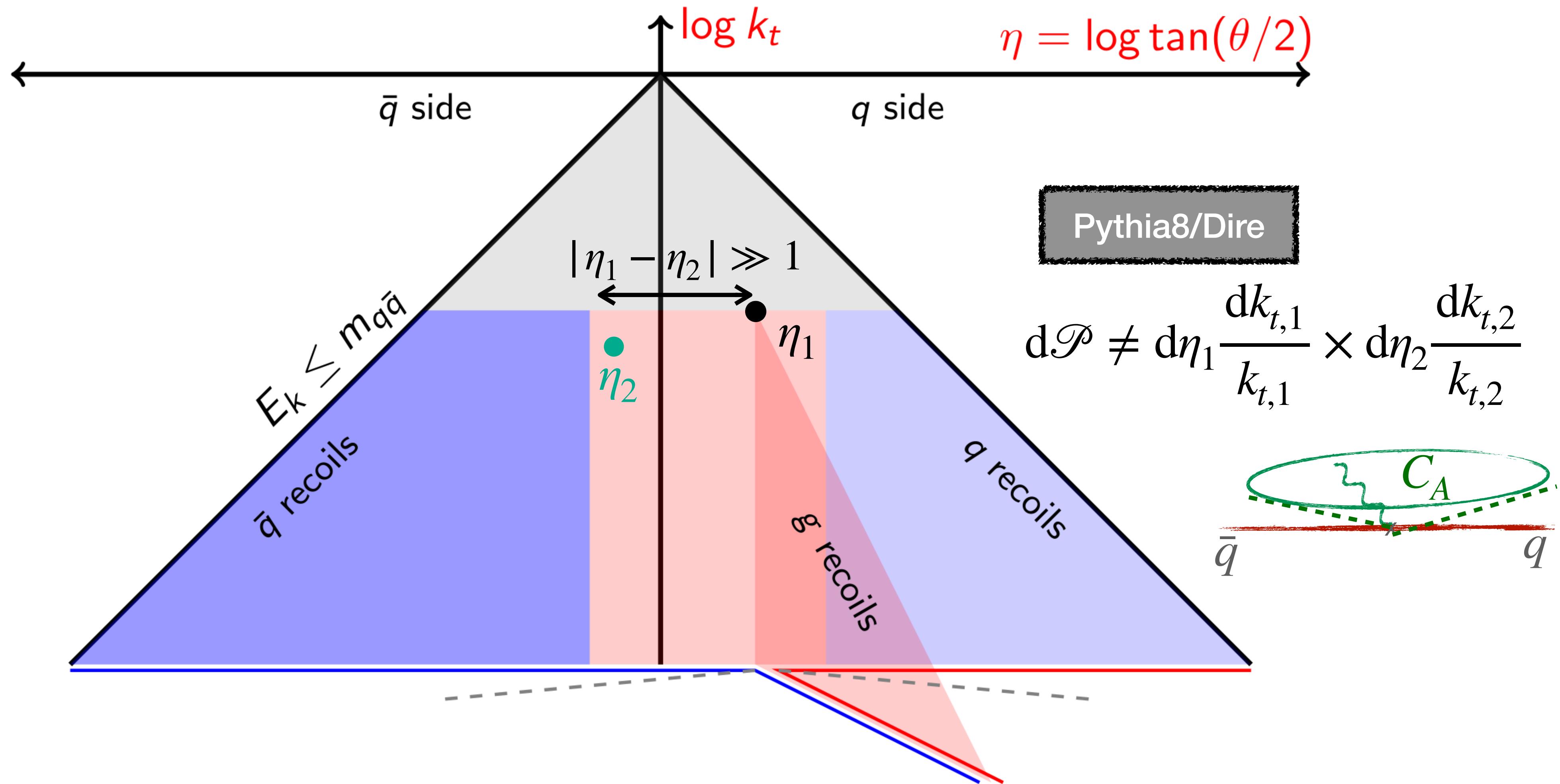
# Why does Dipole- $k_t$ fail?

[Dasgupta et al. JHEP 09 (2018) 033]



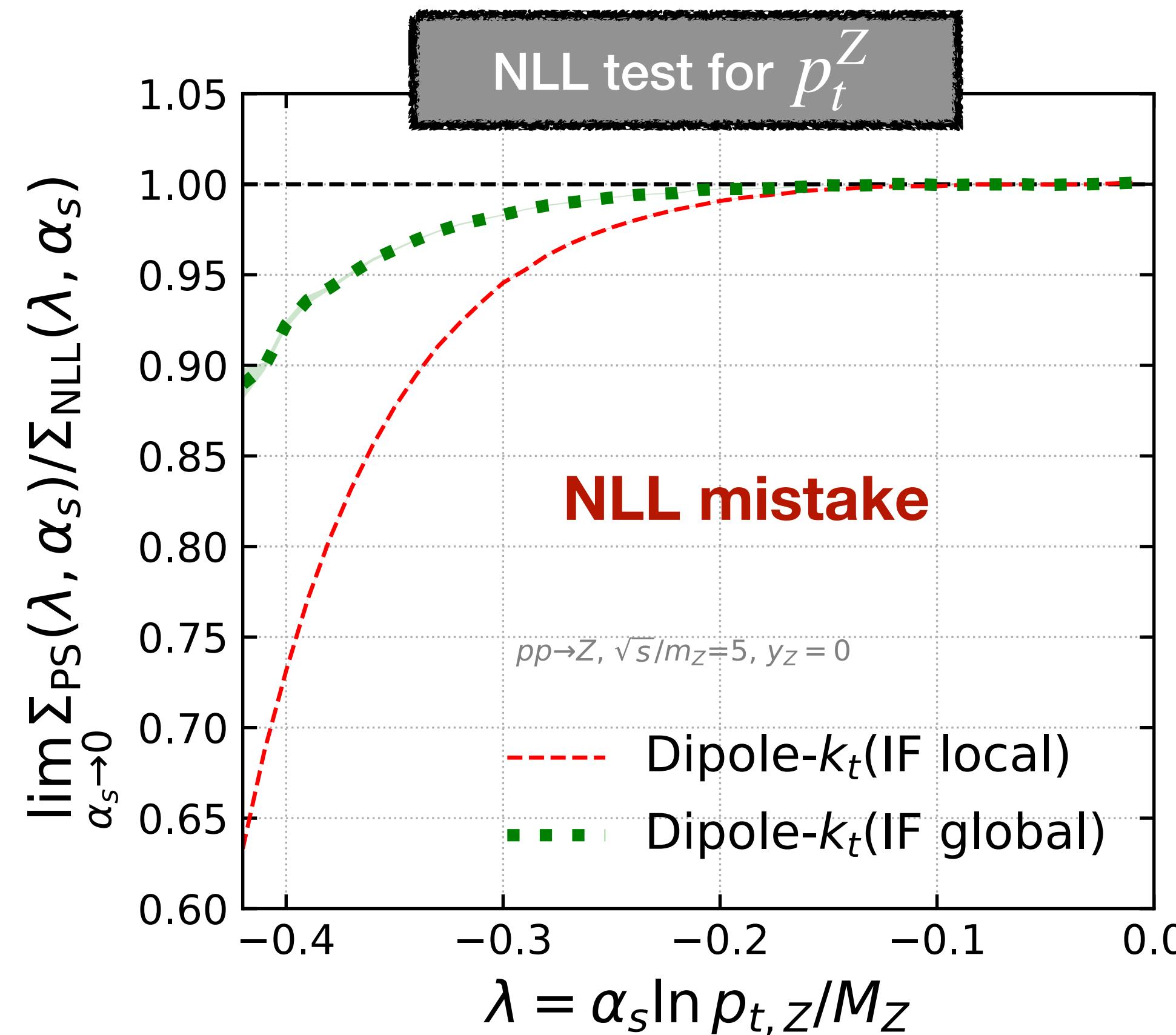
# Why does Dipole- $k_t$ fail?

[Dasgupta et al. JHEP 09 (2018) 033]



$\bar{\eta} = 0$  in the dipole frame leads to wrong transverse recoil assignment

# Dipole- $k_t$ : some all-orders tests



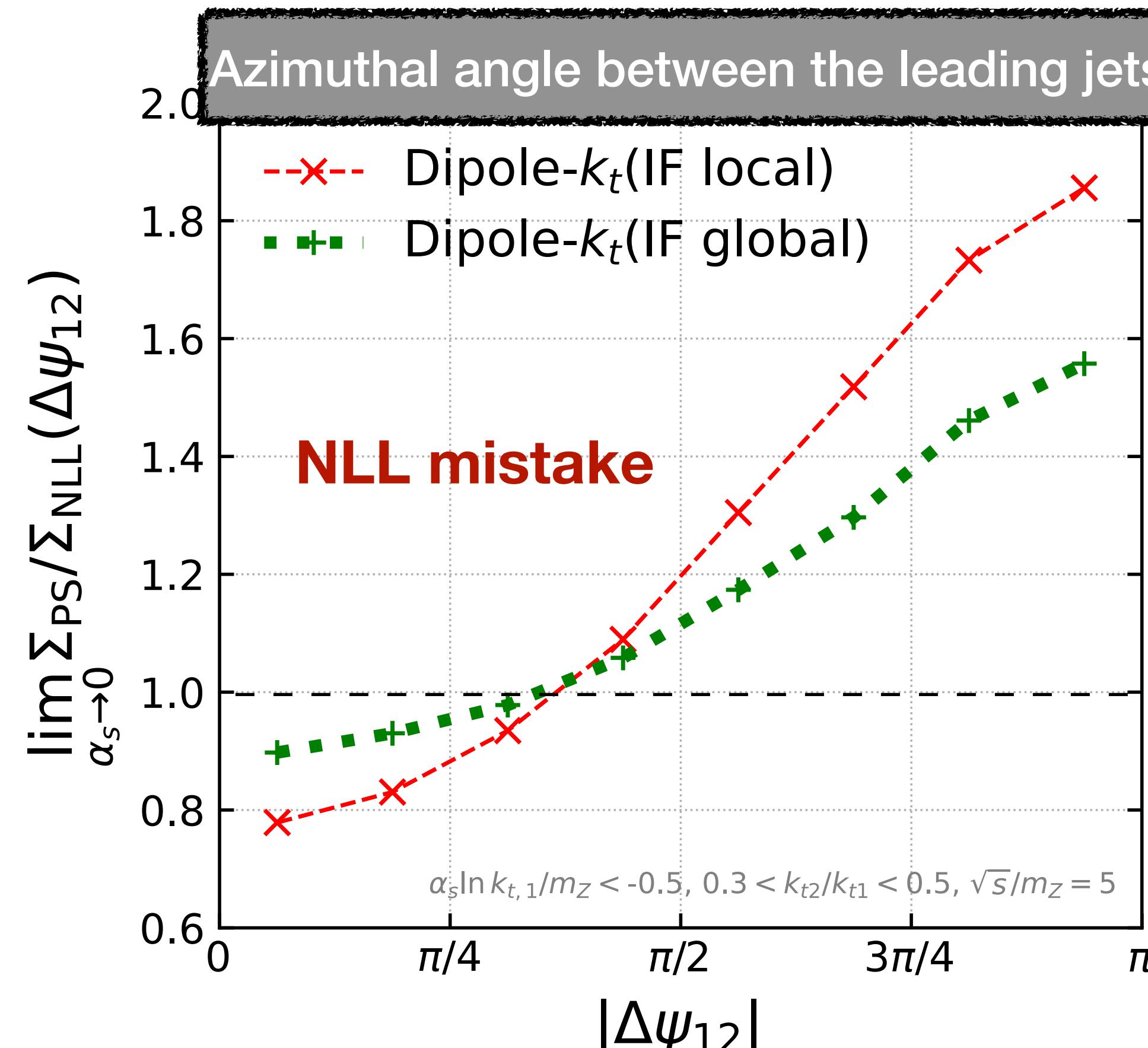
Electroweak precision measurements such as

$$m_W = 80363 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$

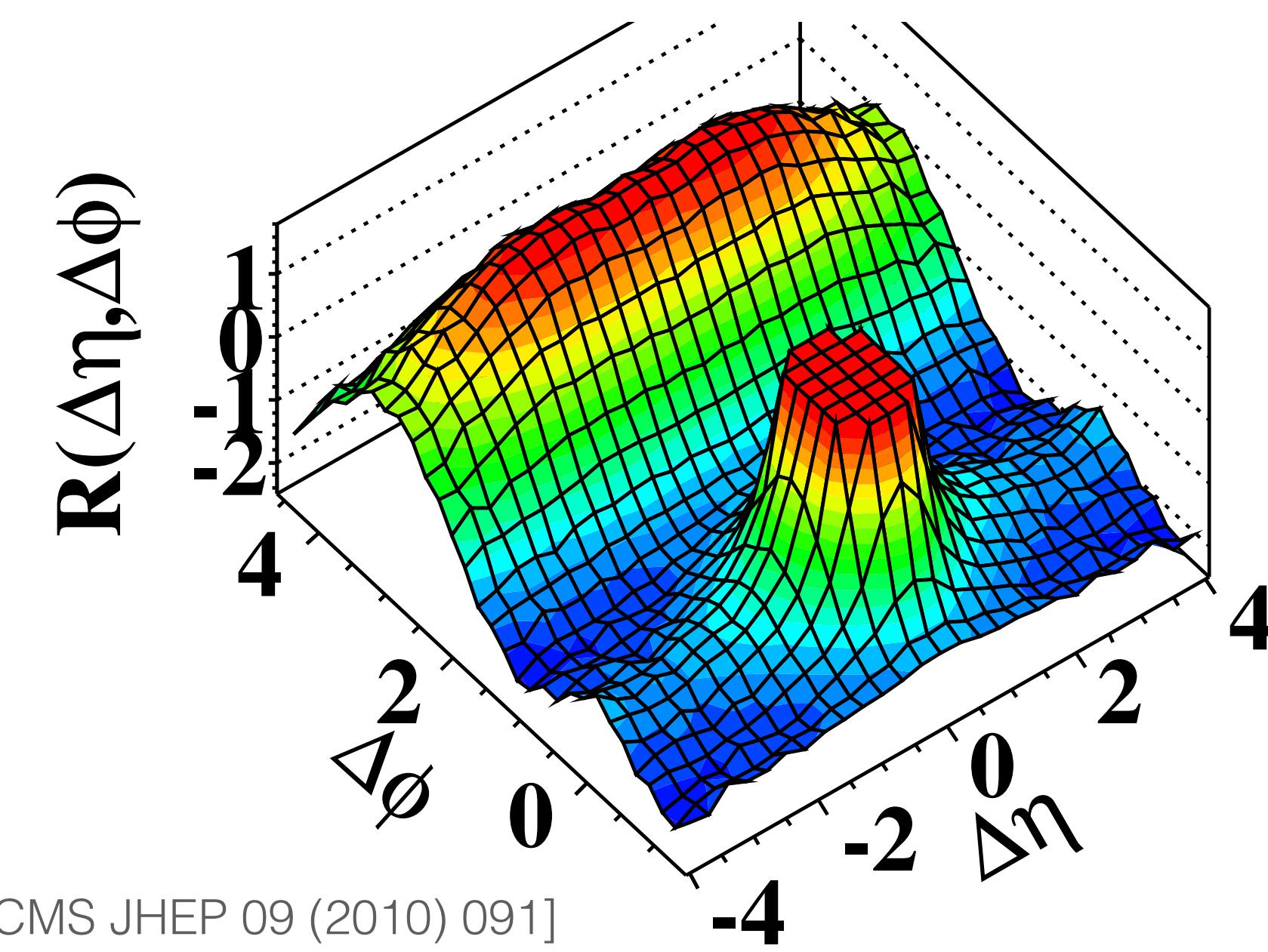
[LHCb JHEP 01 (2022) 036]

require the theory description of the boson pt

# Dipole- $k_t$ : some all-orders tests



Azimuthal correlations are important for the identification of ridge-like structures



[CMS JHEP 09 (2010) 091]

Dipole- $k_t$  (the default option in most MCs) is not an NLL shower

# The PanScales solutions: PanLocal

**A** PanLocal: local recoil scheme. If initial-state particles participate in the splitting

$$\bar{p}_k = a_k \tilde{p}_i + b_k \tilde{p}_j + k_{\perp}$$
$$\bar{p}_i = a_i \tilde{p}_i + b_i \tilde{p}_j + k_{\perp}$$
$$\bar{p}_j = a_j \tilde{p}_i + b_j \tilde{p}_j$$

Realign

$$p_i$$
$$p_X = \lambda^{\mu\nu} \tilde{p}_X$$
$$p_j$$

- Dipole partitioning:  $\bar{\eta} = 0$  corresponds to zero rapidity in the event rest frame

$$\bar{\eta} = \ln \sin \theta_{\tilde{i}k} - \ln \sin \theta_{\tilde{j}k}$$

# The PanScales solutions: PanLocal

A

PanLocal: local recoil scheme. If initial-state particles participate in the splitting

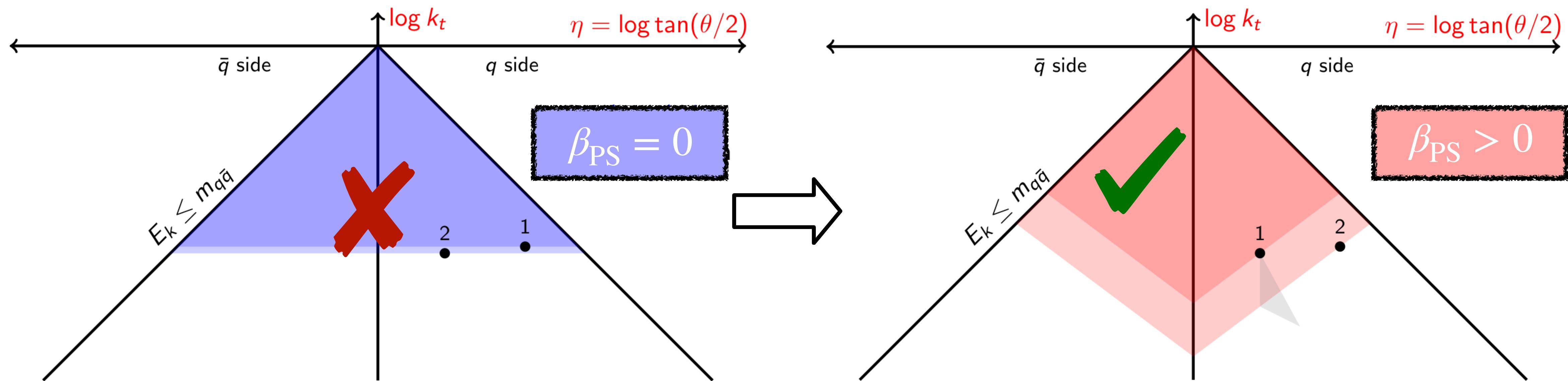
$$\bar{p}_k = a_k \tilde{p}_i + b_k \tilde{p}_j + k_\perp$$
$$\bar{p}_i = a_i \tilde{p}_i + b_i \tilde{p}_j + k_\perp$$
$$\bar{p}_j = a_j \tilde{p}_i + b_j \tilde{p}_j$$

Realign

$$p_i$$
$$p_X = \lambda^{\mu\nu} \tilde{p}_X$$
$$p_j$$

- Dipole partitioning:  $\bar{\eta} = 0$  corresponds to zero rapidity in the event rest frame
- Evolution variable:  $v \sim k_t e^{|\bar{\eta}| \beta_{\text{PS}}}$  with  $0 < \beta_{\text{PS}} < 1$

# The PanScales solutions: PanLocal



Emissions with commensurate  $k_t$  are radiated ordered in angle

# The PanScales solutions: PanGlobal

B

PanGlobal: global recoil scheme for all dipole types

$$\bar{p}_k = a_k \tilde{p}_i + b_k \tilde{p}_j + k_\perp$$
$$\bar{p}_i = a_i \tilde{p}_i$$
$$\bar{p}_j = b_j \tilde{p}_j$$

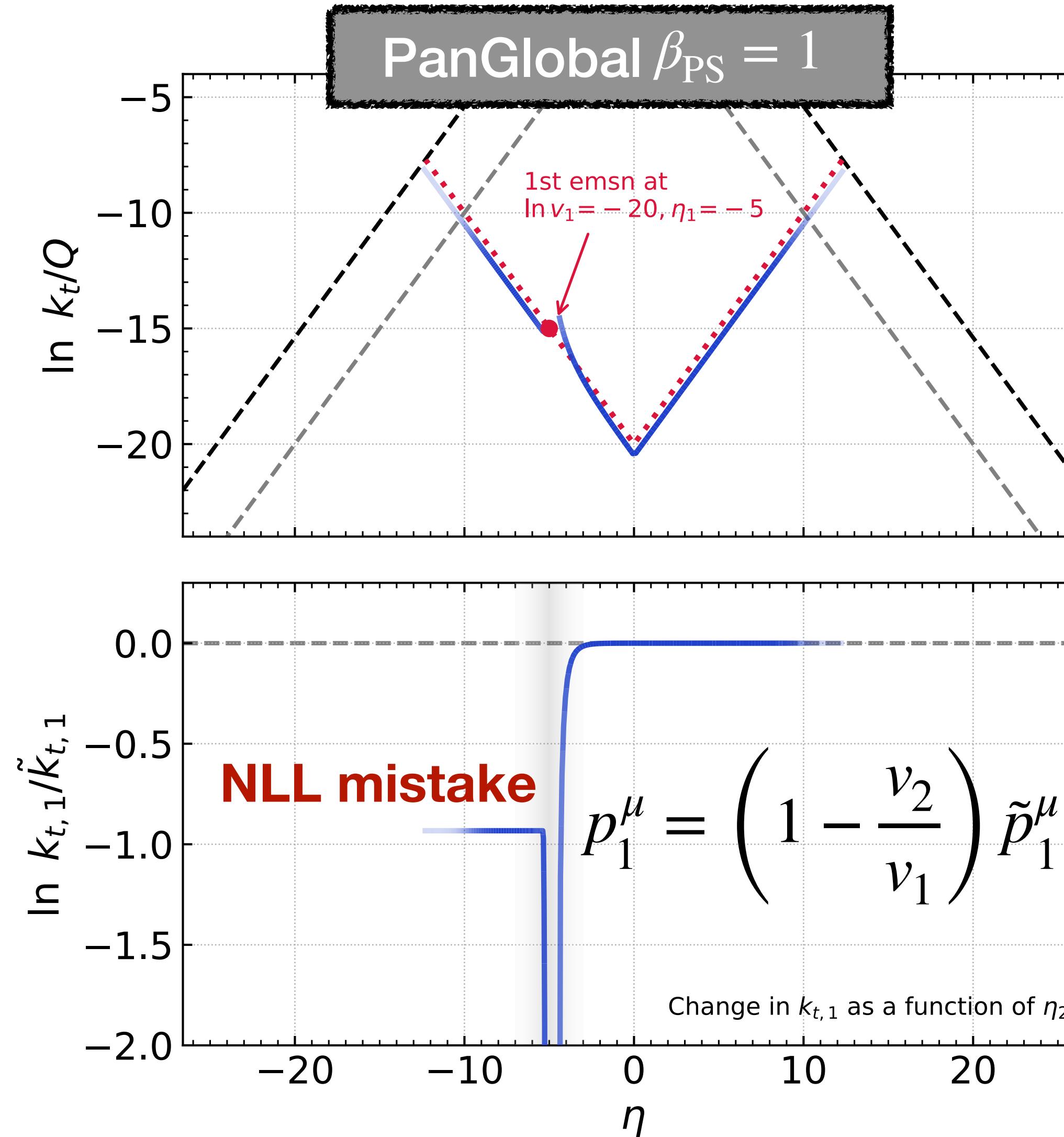
In order to restore ~~momentum conservation~~:

- 1  $P_\perp$  restored by boosting the hard system (keeping  $y_X$  fixed)
- 2 Longitudinal momentum restored by  $p_a = P_+/2$   
 $p_b = P_-/2$

- Dipole partitioning:  $\bar{\eta} = 0$  corresponds to zero rapidity in the event rest frame
- Evolution variable:  $v \sim k_t e^{|\bar{\eta}| \beta_{PS}}$  with  $0 \leq \beta_{PS} < 1$

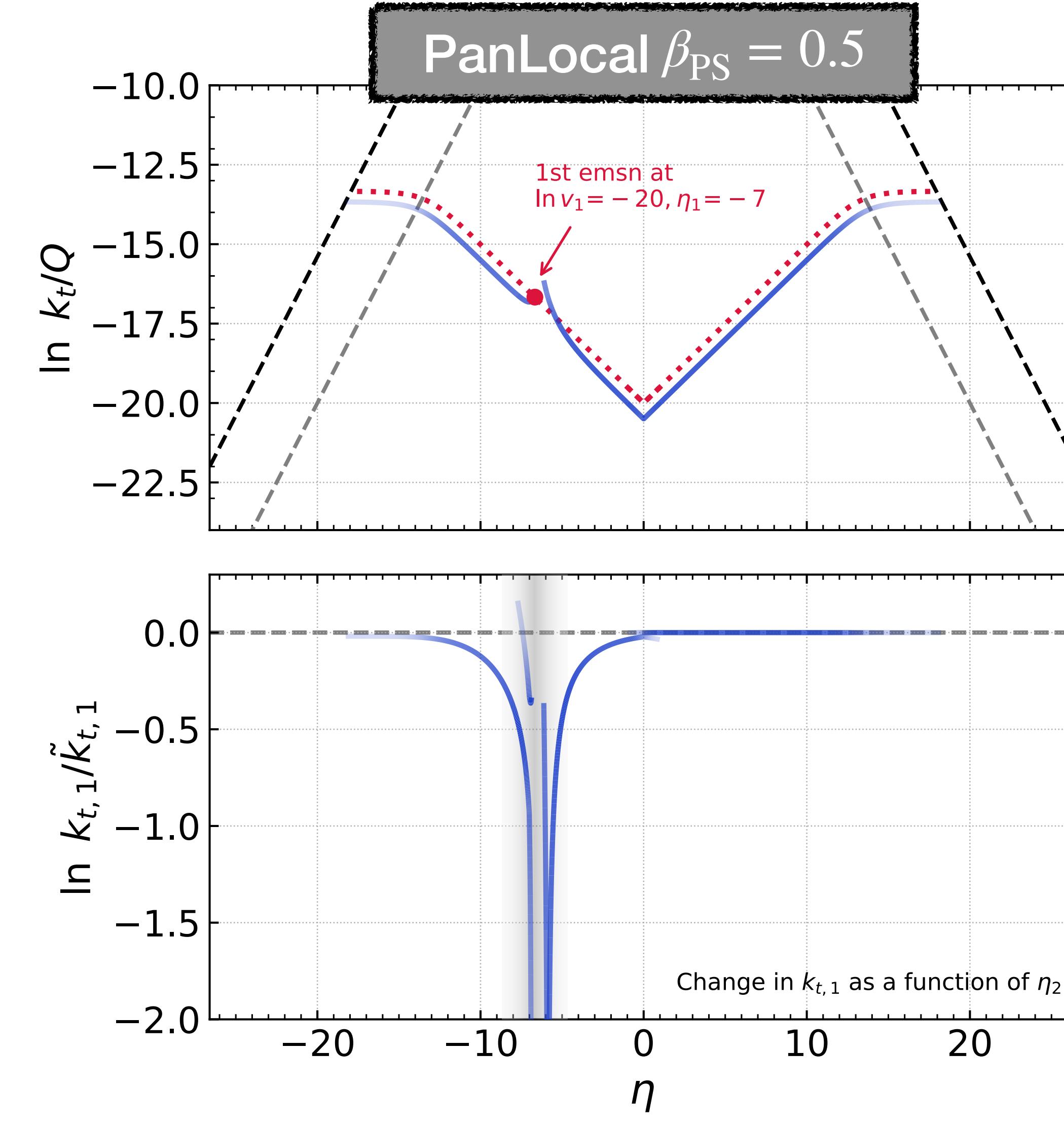
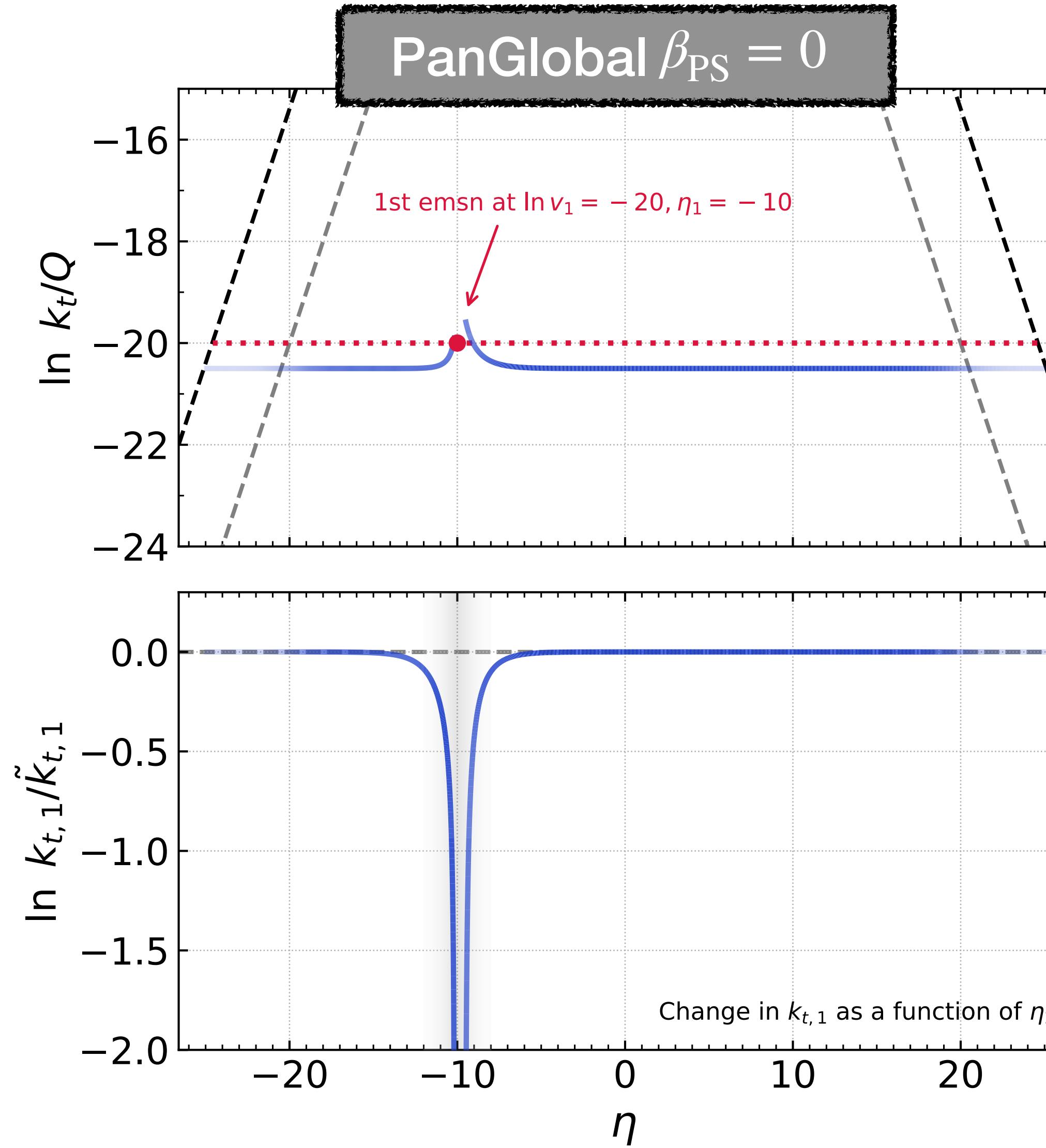
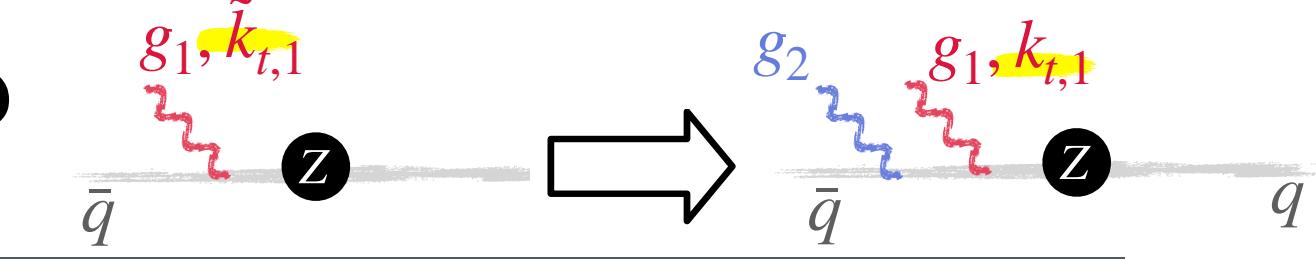
# Time-ordered shower: $\beta_{\text{PS}} = 1$

An NLL time-ordered shower is particularly relevant for a jet quenching MC. However,

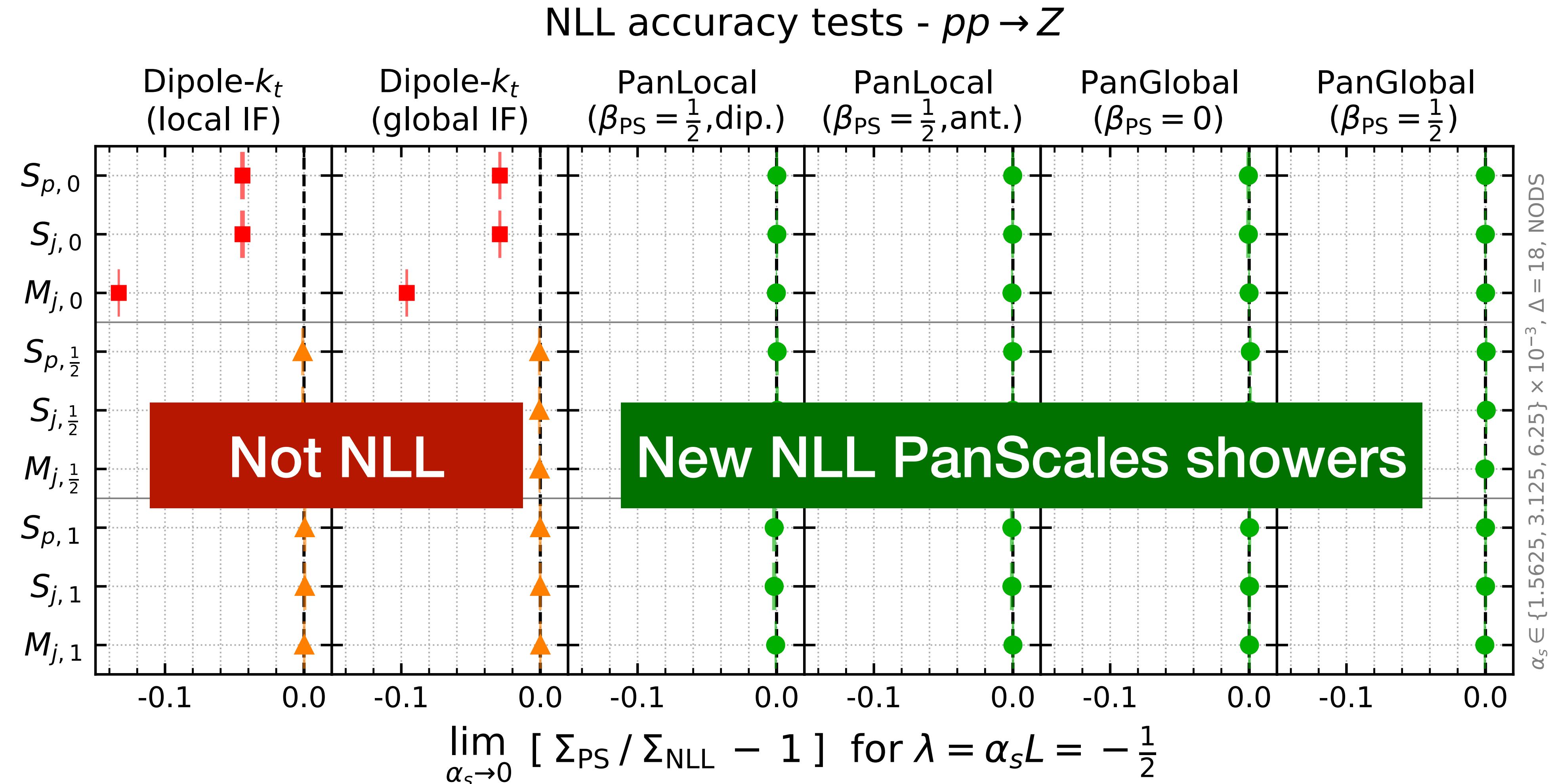


Longitudinal rescaling of the first emitted parton after emitting a second one breaks NLL. An alternative recoil scheme is currently under development

# What is the accuracy of the PanScales showers?



# What is the accuracy of the PanScales showers?



$$S_{p,\beta_{obs}} = \sum_{i \in p} \frac{k_{t,i}}{Q} e^{-\beta_{obs} |\eta_i|}$$

$$S_{j,\beta_{obs}} = \sum_{i \in j} \frac{k_{t,i}}{Q} e^{-\beta_{obs} |\eta_i|}$$

$$M_{j,\beta_{obs}} = \max_{i \in j} \frac{k_{t,i}}{Q} e^{-\beta_{obs} |\eta_i|}$$

# An idea to combine PanScales with JetMed

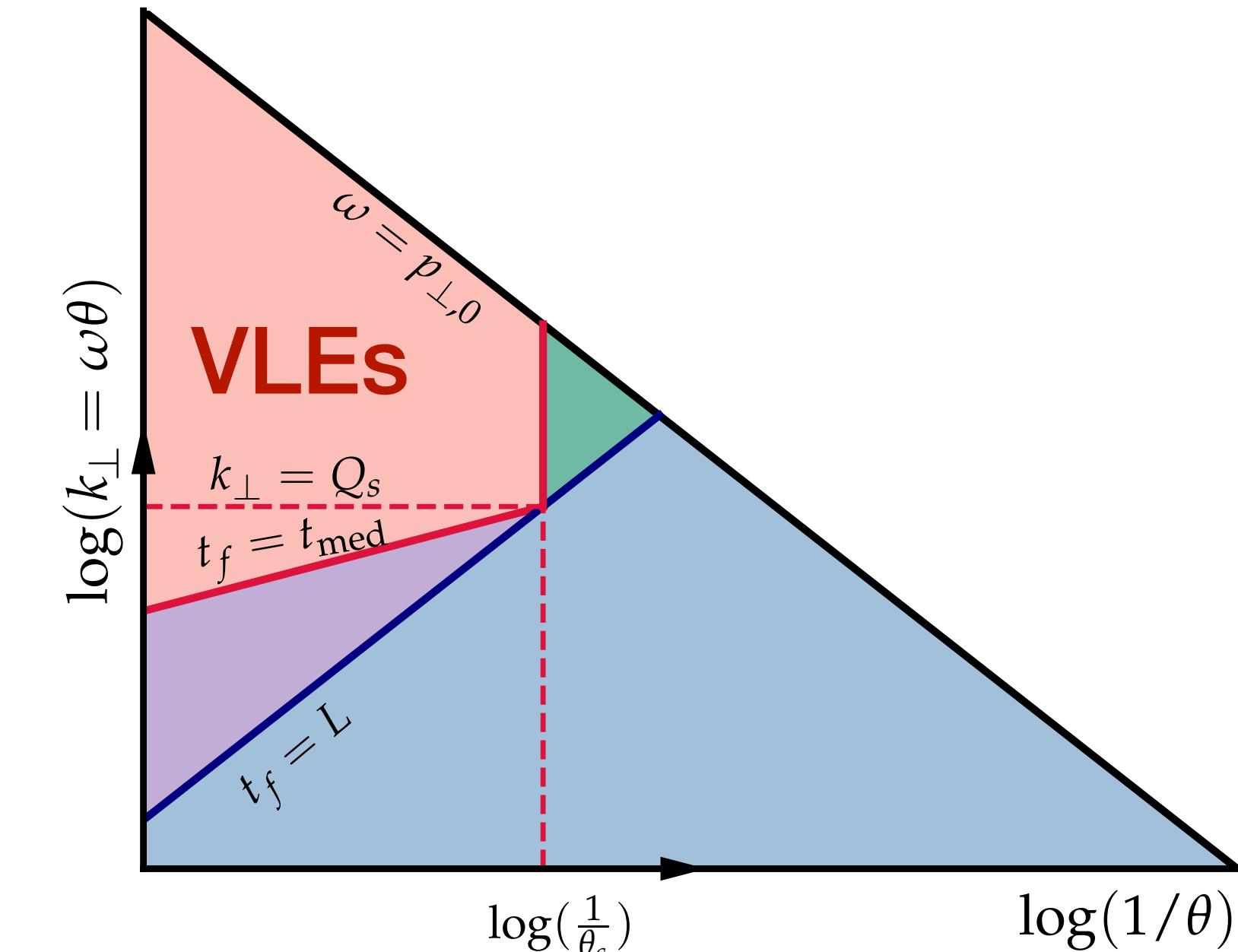
[Caucal talk]

- 1 Run the PanScales shower for a given hard system with a constrained phase-space for FSR

- 2 Generate medium-induced emissions either via

$$\frac{dI}{d\omega dt} + P^{\text{broad}}(\theta)$$

or via a medium-induced dipole shower (?)



- 3 Pass back the list of partons/dipoles to PanScales for the out-of-medium cascade  
What happens with color correlations?
- 4 Find suitable limits to compare the shower with analytic resummations  
and establish the accuracy