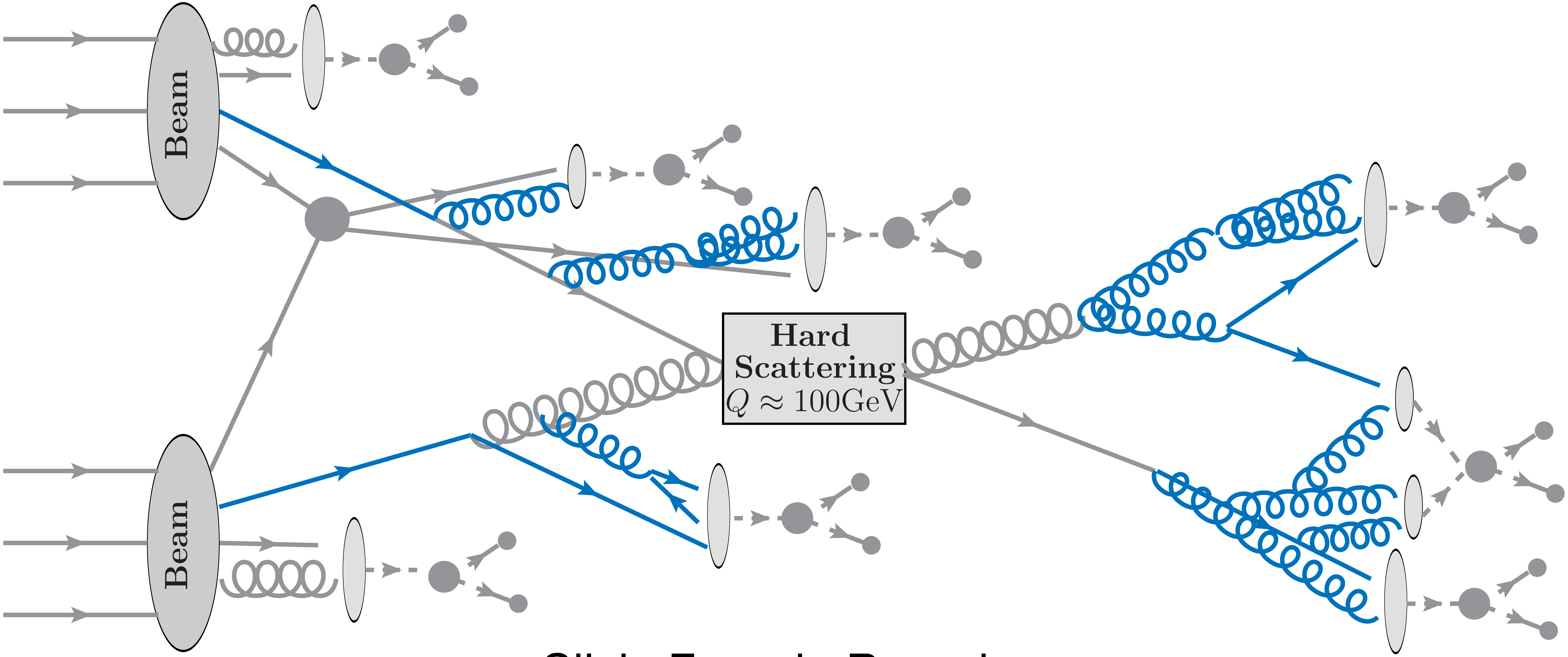
# PanScales Showers

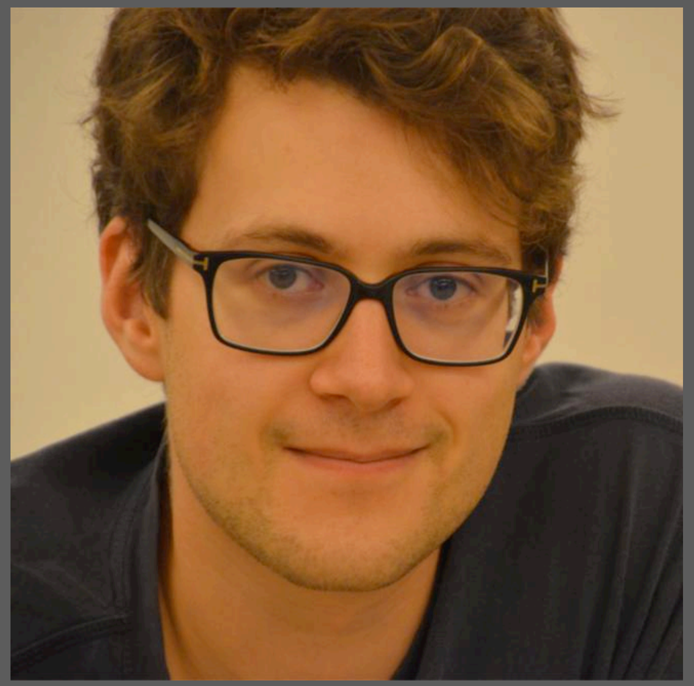



Silvia Ferrario Ravasio

**Parton Showers and Resummation - June 2023**

Università degli Studi di Milano—Bicocca


Mrinal Dasgupta
Manchester/CERN


Frédéric Dreyer
Oxford


Keith Hamilton
Univ. Coll. London


Pier Monni
CERN


Gavin Salam
Oxford


Grégory Soyez
IPhT, Saclay/CERN

since 2017


Emma Slade
Oxford (PhD) → GSK.ai

2018-20


Basem El-Menoufi
Manchester


Alexander Karlberg
CERN


Rok Medves
Oxford (PhD)


Ludovic Scyboz
Oxford


Rob Verheyen
Univ. Coll. London

since 2019

# PanScales

A project to bring logarithmic understanding and accuracy to parton showers


Melissa van Beekveld
Oxford


Silvia Ferrario Ravasio
CERN


Alba Soto-Ontoso
CERN

since 2020

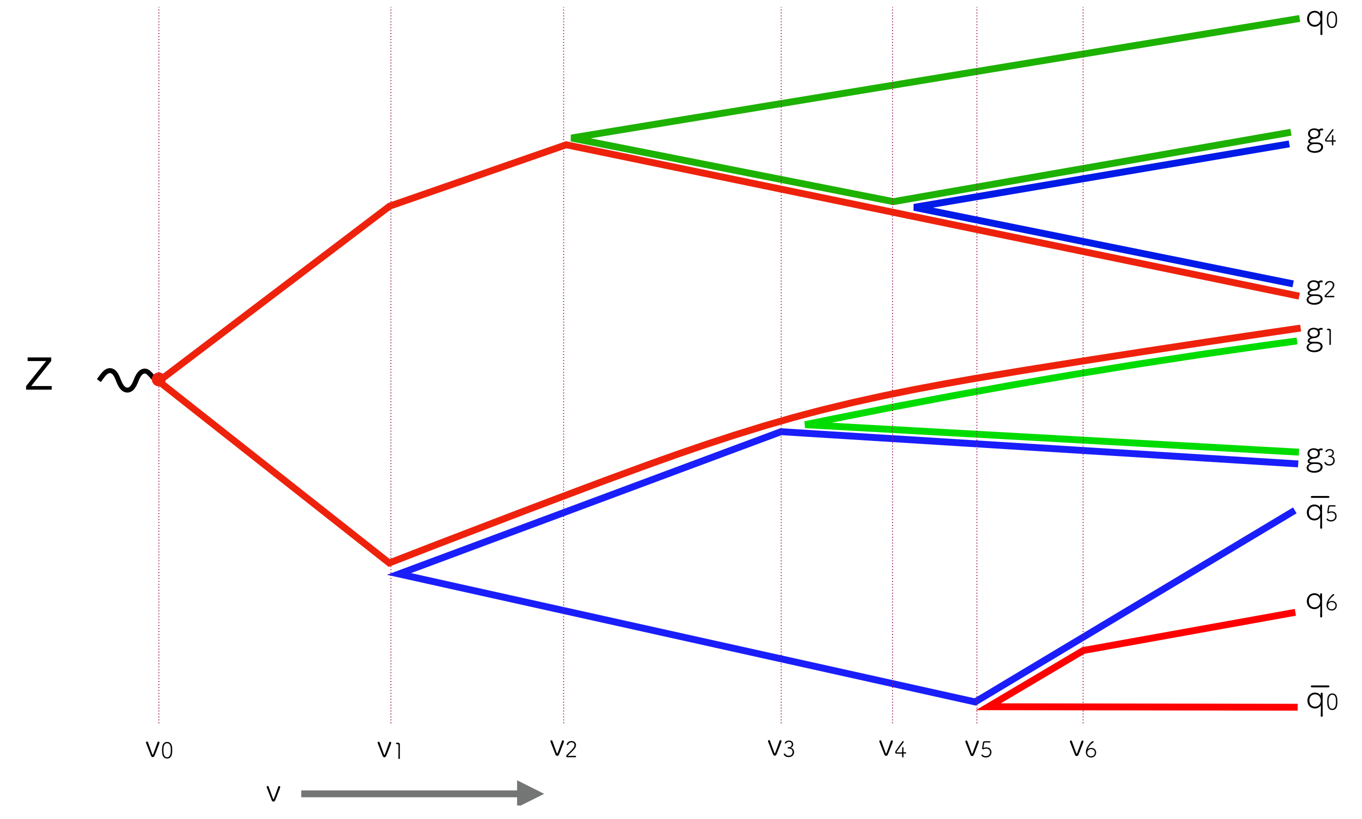

Jack Helliwell
Oxford

since 2022

# Logarithmic accuracy of showers

- Parton showers evolve collider events from a hard scale $Q \approx \mathcal{O}(\mathrm{TeV})$ to soft scales $\Lambda \approx 1\mathrm{GeV}$ through ordered emissions.

- During this evolution, large logarithms $L = \log Q/\Lambda$ will arise.



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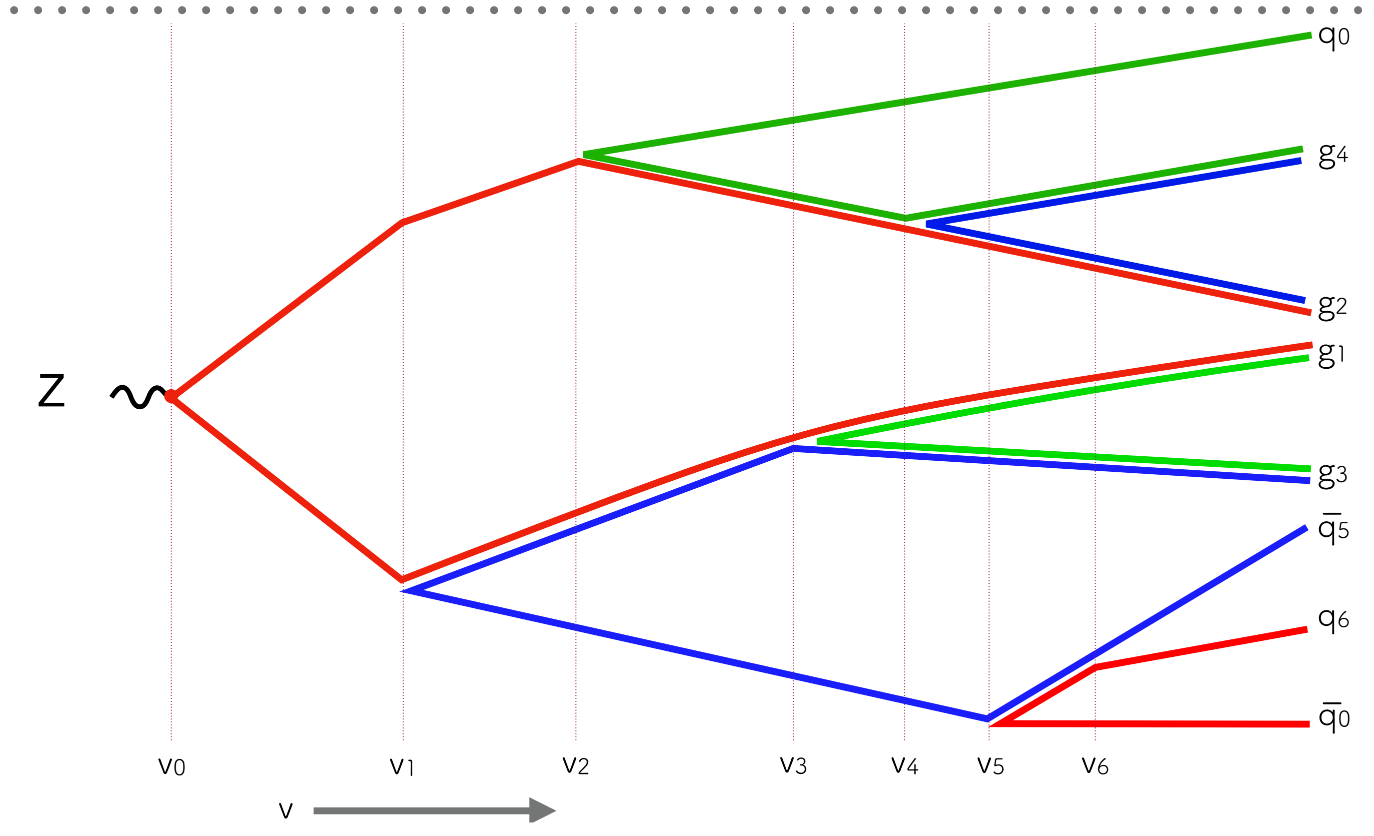



- **Analytic resummation** tells us

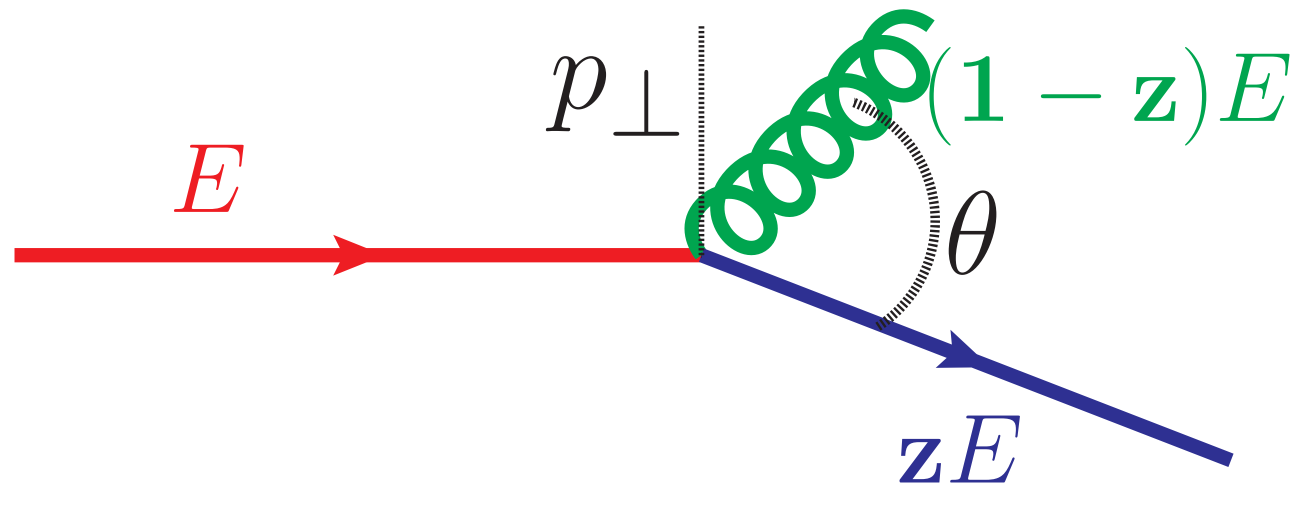
$$\Sigma(\log O < L) = \exp\Big( \underbrace{L g_{\text{LL}}(\alpha_s L)}_{\text{leading logs}} + \underbrace{g_{\text{NLL}}(\alpha_s L)}_{\text{next-to LL}} + \ldots \Big)$$

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 $\mathcal{O}(1)$

**Are the most widely used showers NLL? If not, can we build NLL showers?**

# Starting point: dipole showers

- The Parton Shower generates **ordered** soft and collinear emissions. Each emission is parametrised by $\Phi_{\text{rad}} = \{v, z, \varphi\}$, where $v$ acts as ordering scale, $z$ is "energy fraction" scale, and $\varphi$ is an azimuthal angle.



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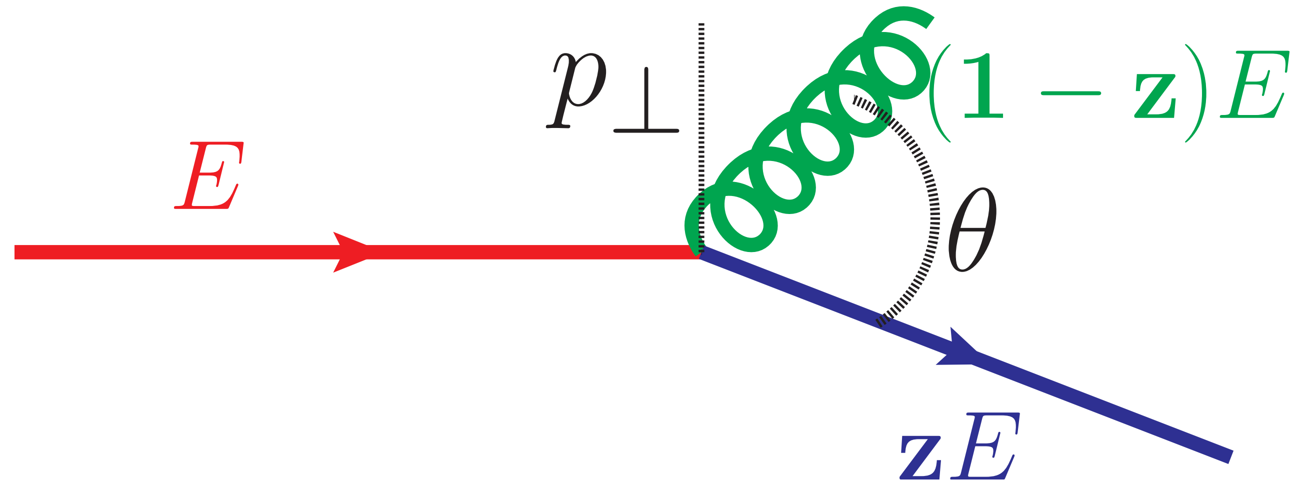


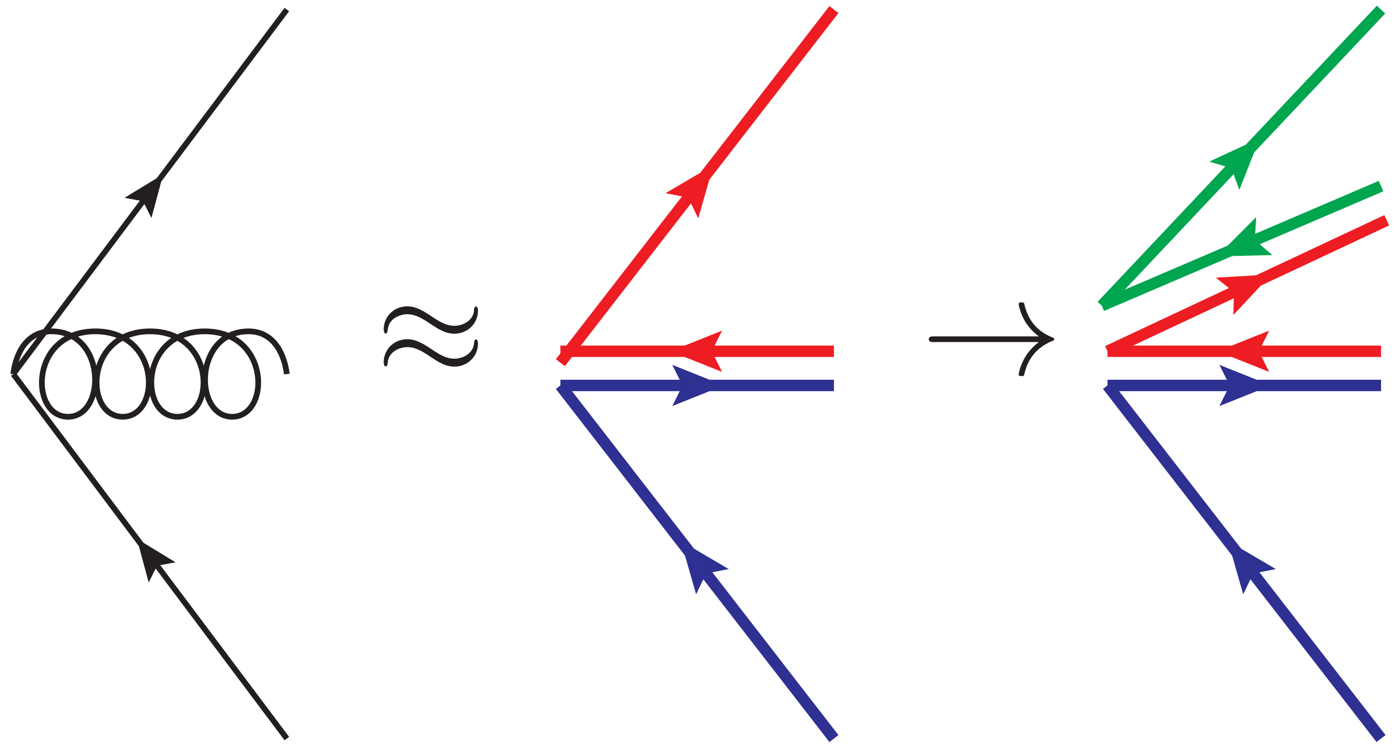

- **Dipole showers** are the most popular shower paradigms [Gustafson, Pettersson, '88]. New partons are emitted from a dipole, which is a pair of colour-connected partons: full angular dependence of soft emissions is retained (necessary to describe non-global observables)

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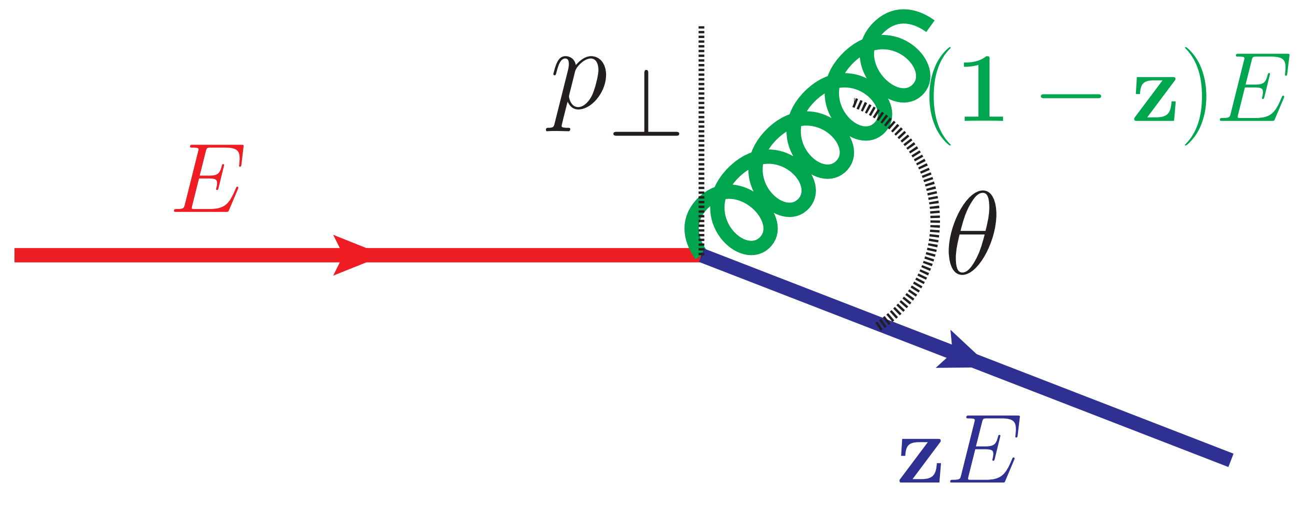


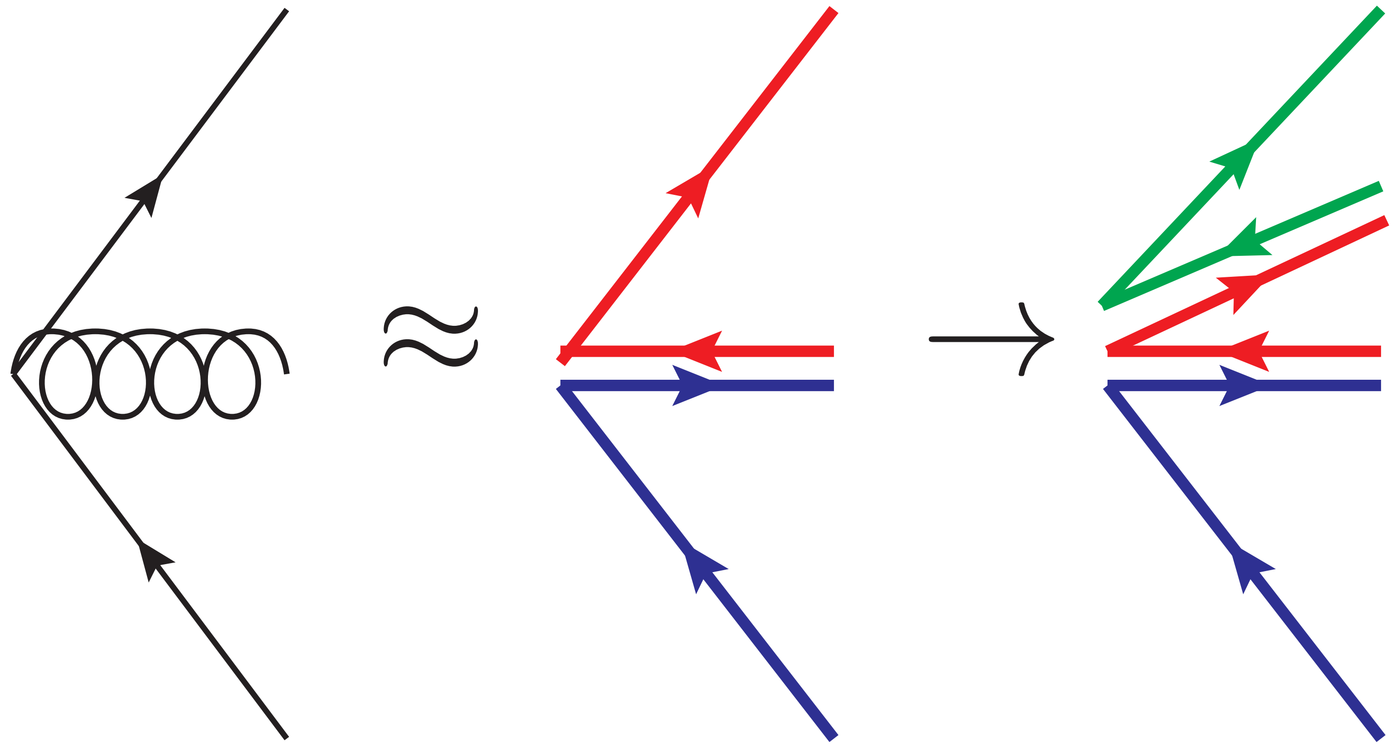

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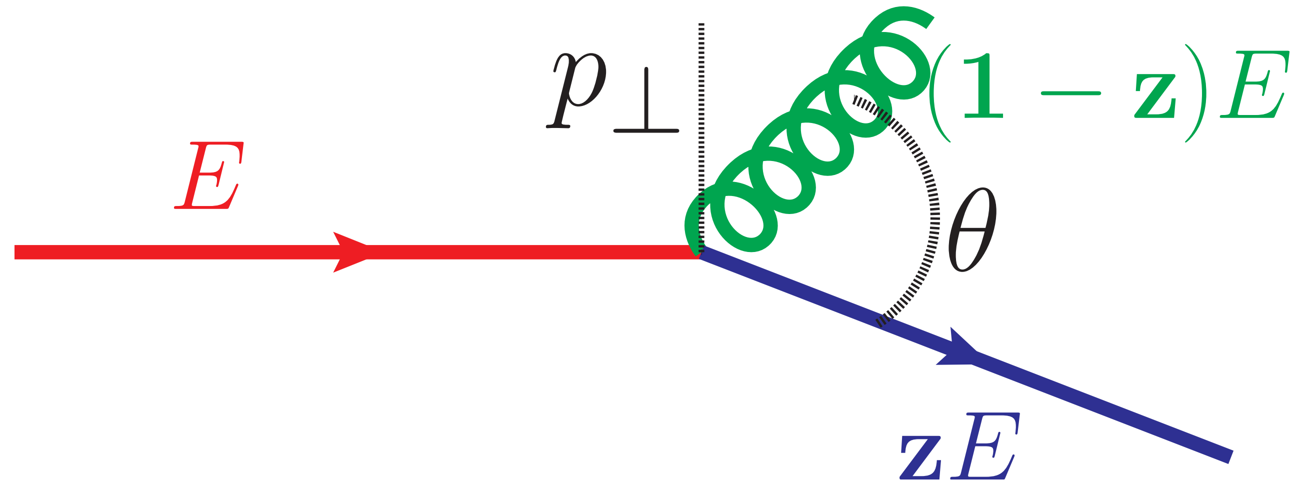
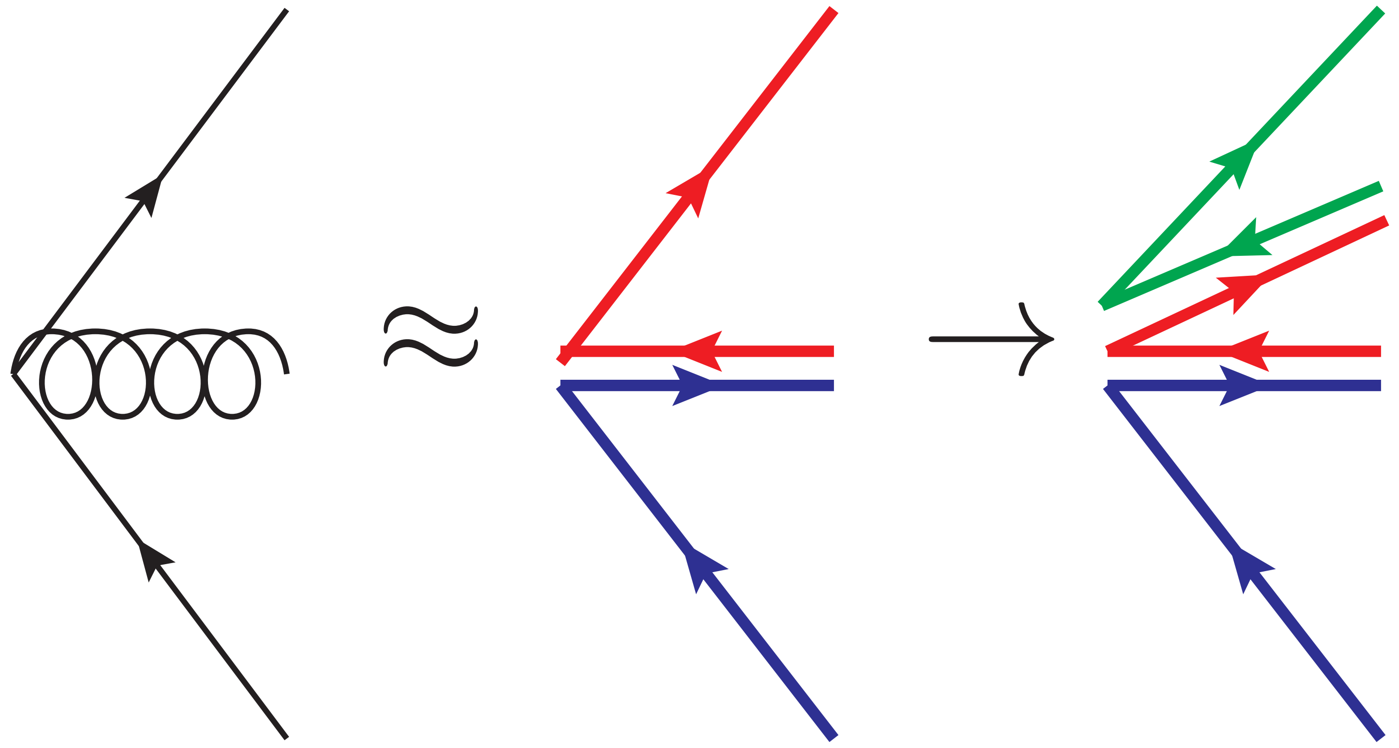


Dipoles are defined in the large number of colour. The inclusion of subleading colour corrections in PanScales was discussed by Ludo in PSR21

**Subleading colour effects in the PanScales parton showers and beyond**
*Ludovic Scyboz*

Alternative proposal, based on the use of a colour-density matrix, where also presented by Simon Plätzer and Dave Soper at PSR21

**Improved dipole showers**
*Simon Platzer*

**Subleading effect in parton showers**
*Davison Soper*

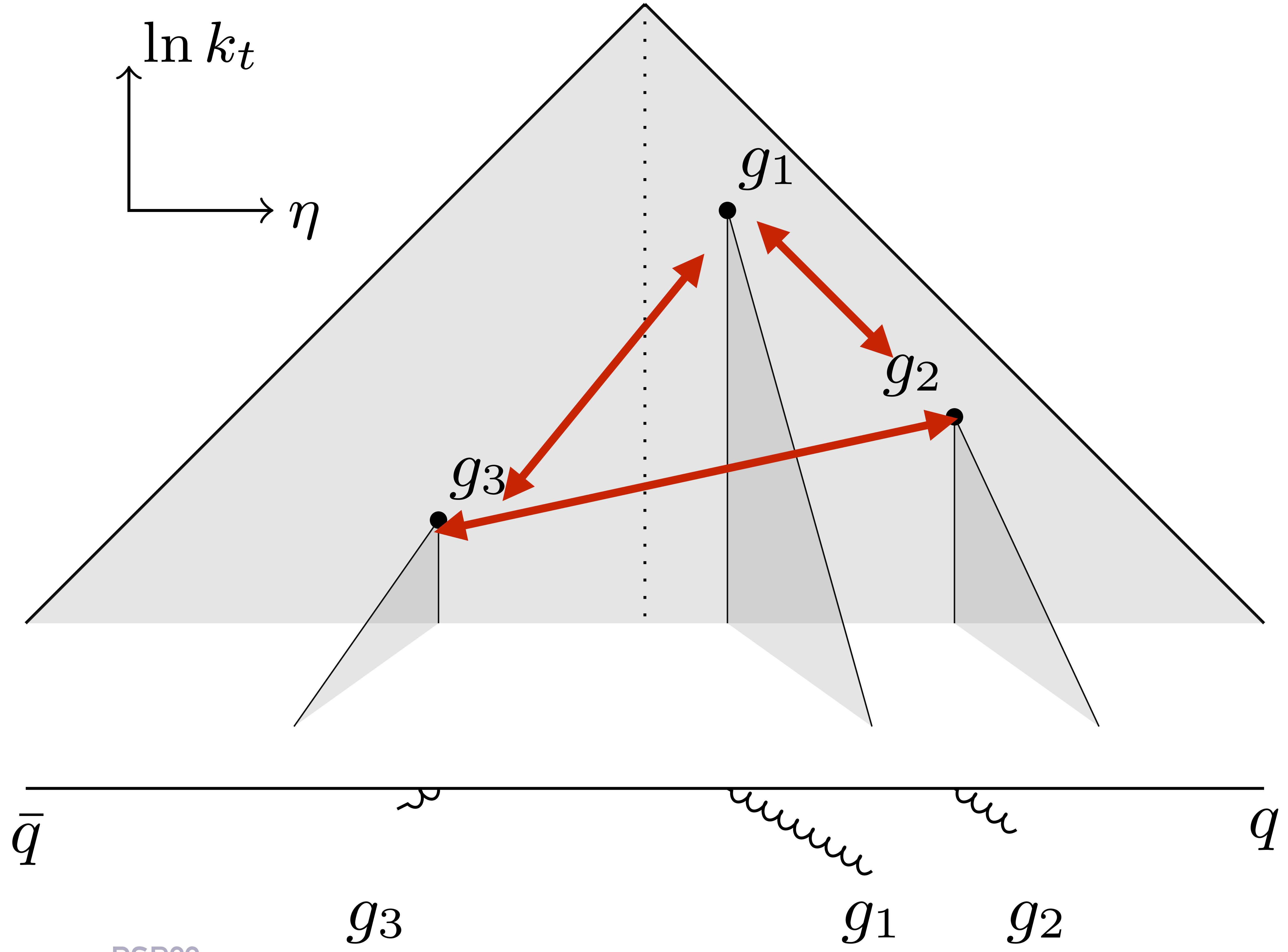
- Emissions are typically ordered in hardness (**transverse momentum** or **virtuality**): this largely simply **matching** with fixed order corrections and renders dipole shower so popular (and "improvable").

# Dissecting the structure of NLL showers

To be NLL, a Parton Shower must reproduce the matrix element for the emission of soft partons well-separated in at least one direction of the **Lund plane**

**Lund plane resummation**
*Alba Soto Ontoso*

**Jet substructure and non global logs**
*Gregory Soyez*



# Dissecting the structure of NLL showers

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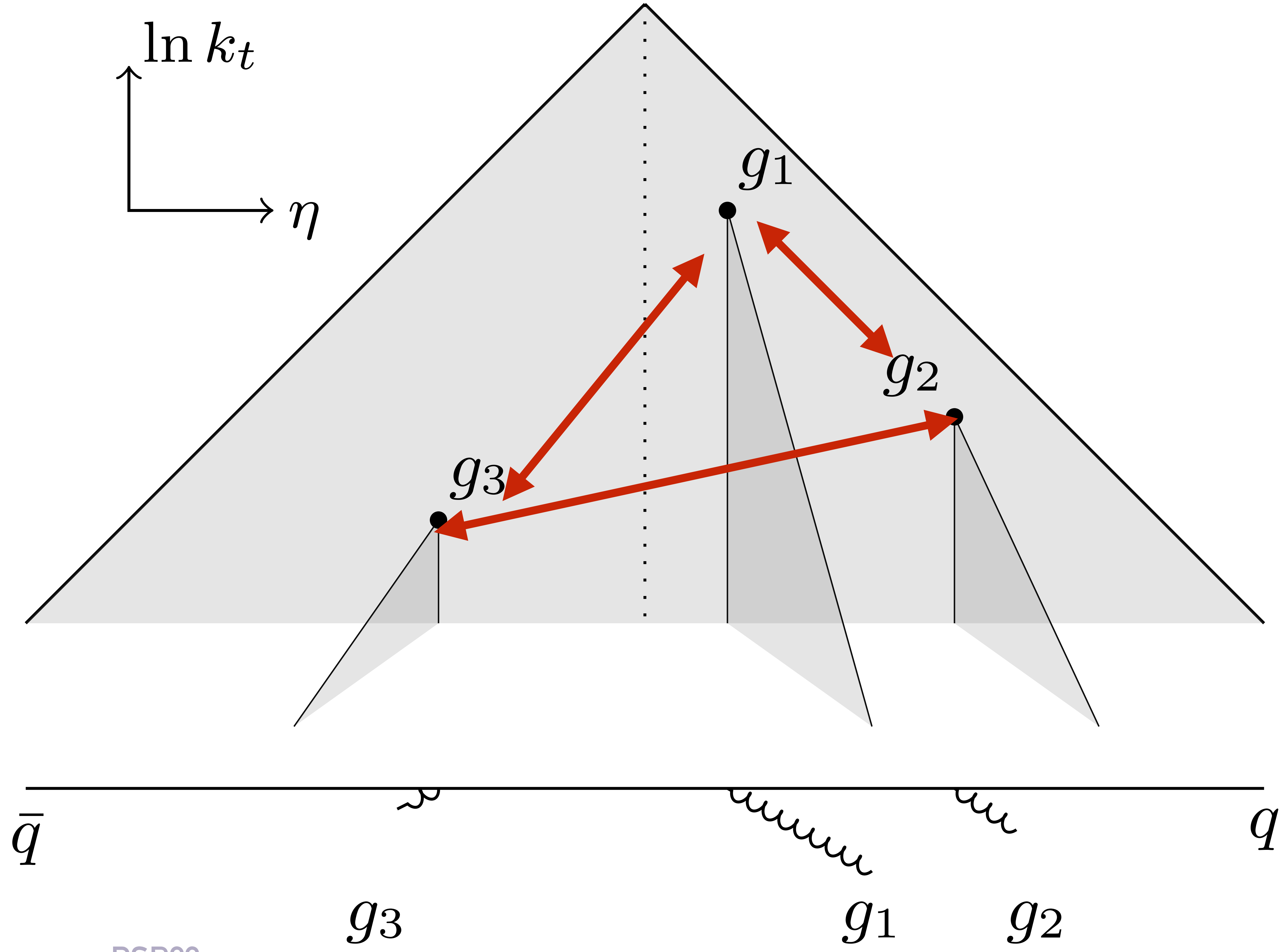
**PanScales criterium**: a new emission cannot affect previous ones if they are well-separated in at least one direction of the Lund plane

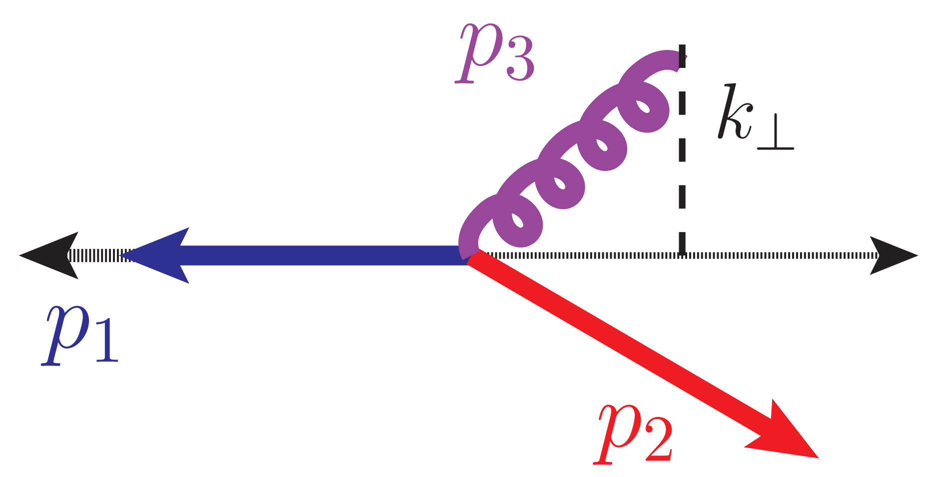


# Dissecting the structure of NLL showers

Dipole showers use **fully local** recoil: 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**

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

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



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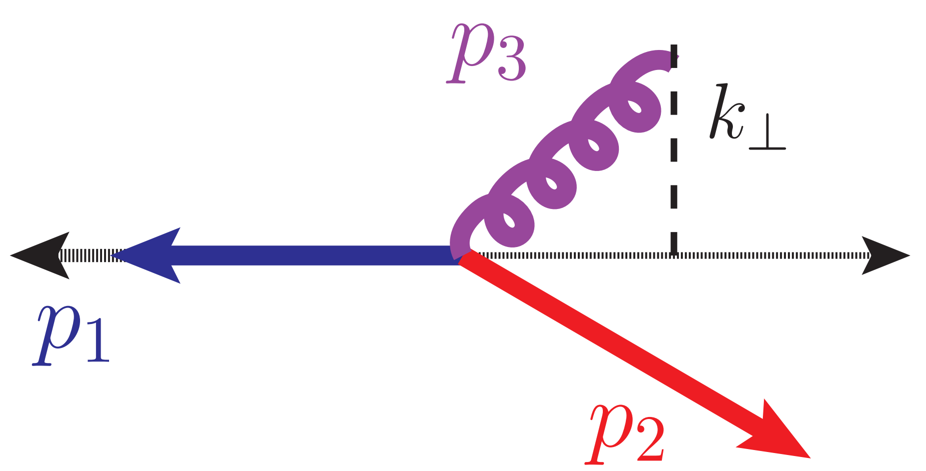
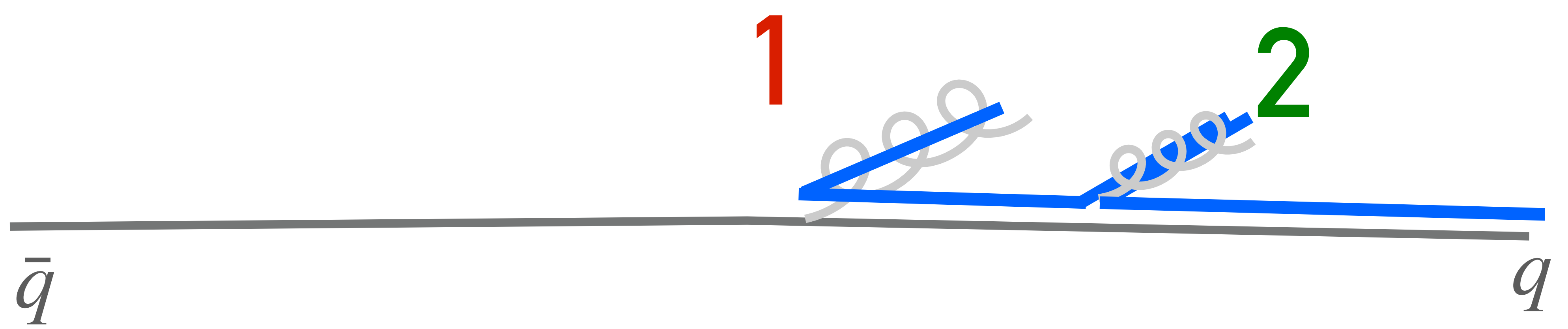
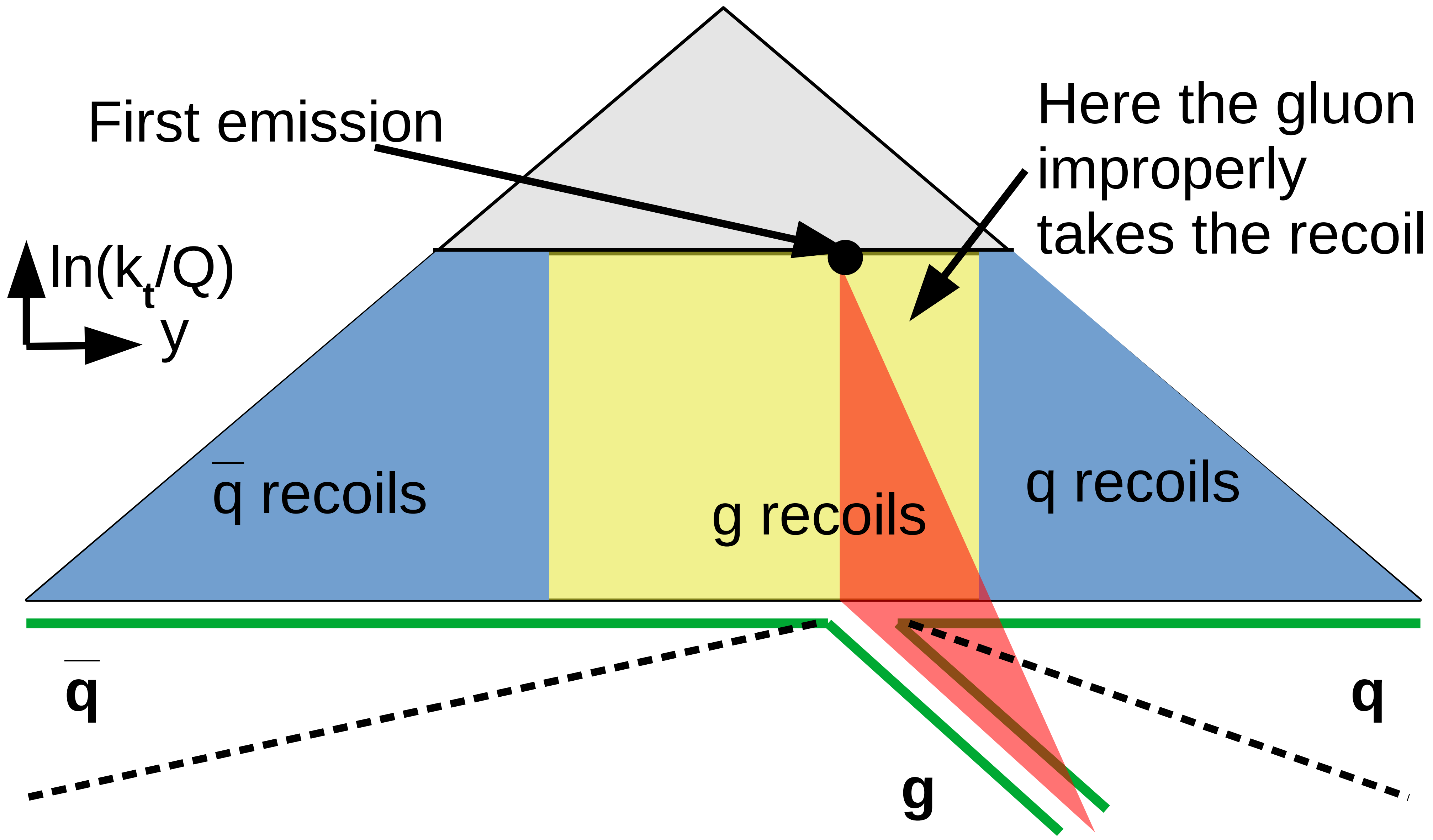



*Double gluon emission in $e^+e^- \to q\bar{q}$: the first emission kinematics changes too after after adding the second gluon!*

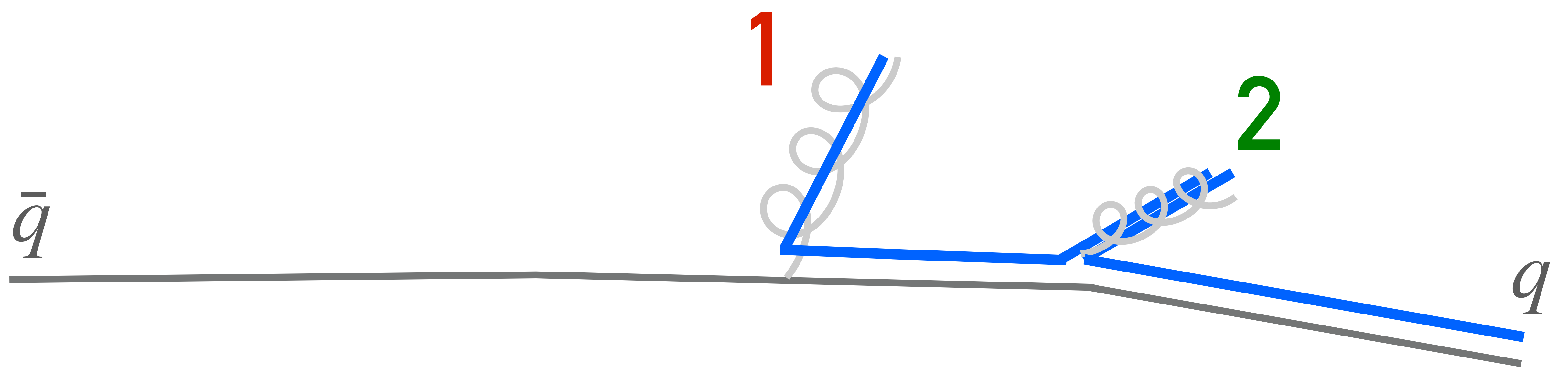



1805.09327 Dasgupta, Dreyer, Hamilton, Monni, Salam



# Correct recoil rule: no side effects on other distant emissions

We instead want 1 to be unaffected by subsequent emissions very distant in angle, even when they are commensurate in hardness

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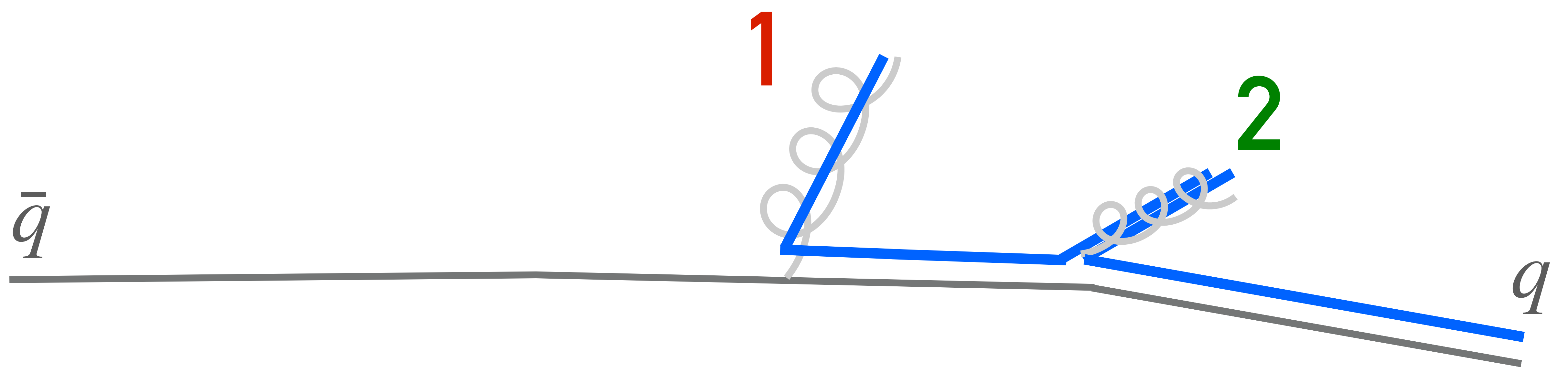


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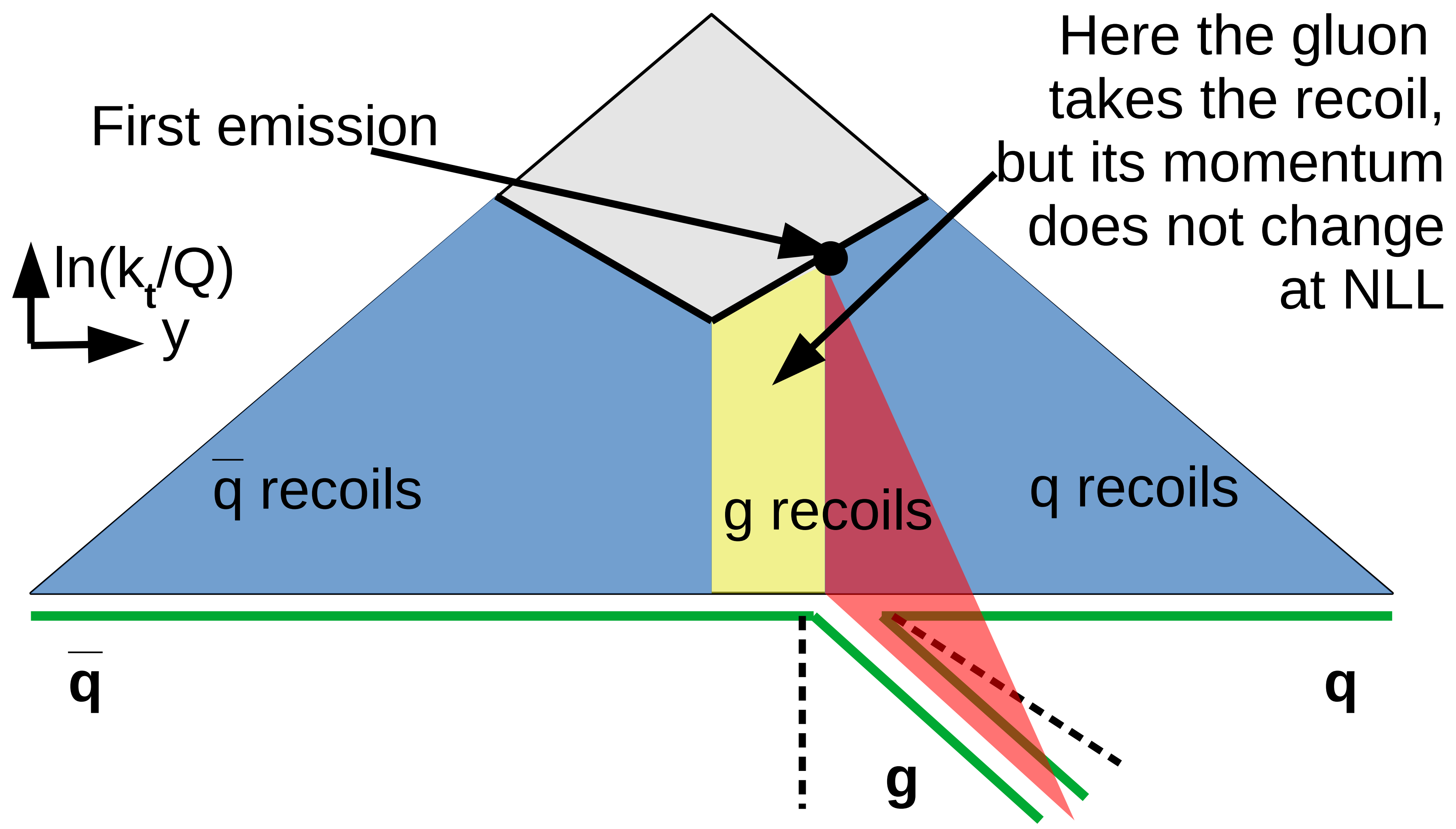
Can be achieved in multiple ways:

➤ local transverse recoil, with non-standard shower ordering ($v \sim k_t e^{-\beta|\eta|}$) & dipole partition (dipole midpoint defined in the event frame) [Dasgupta et al 2002.11114, "PanLocal"; Nagy & Soper 0912.4534, "Deductor"]



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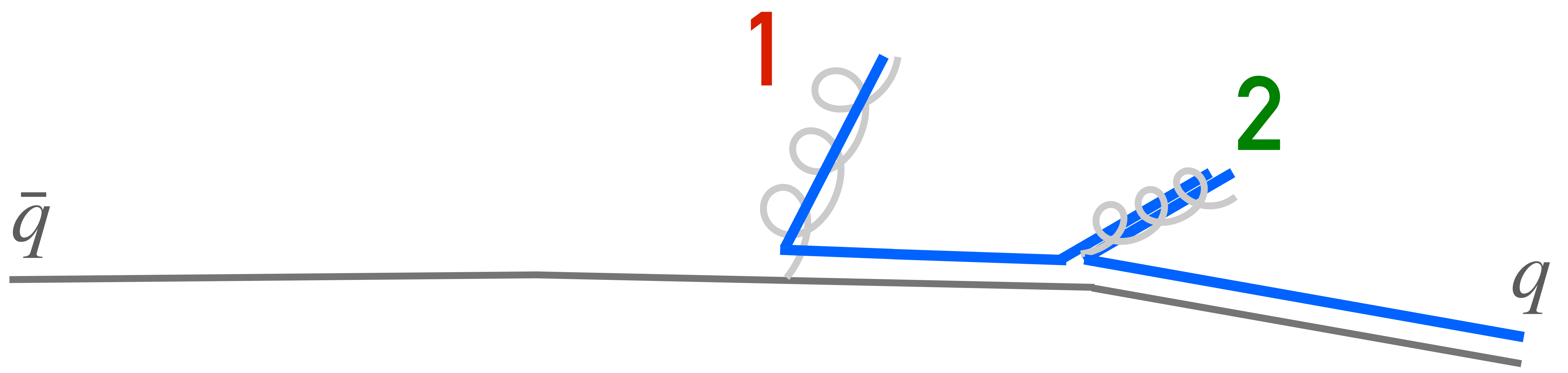


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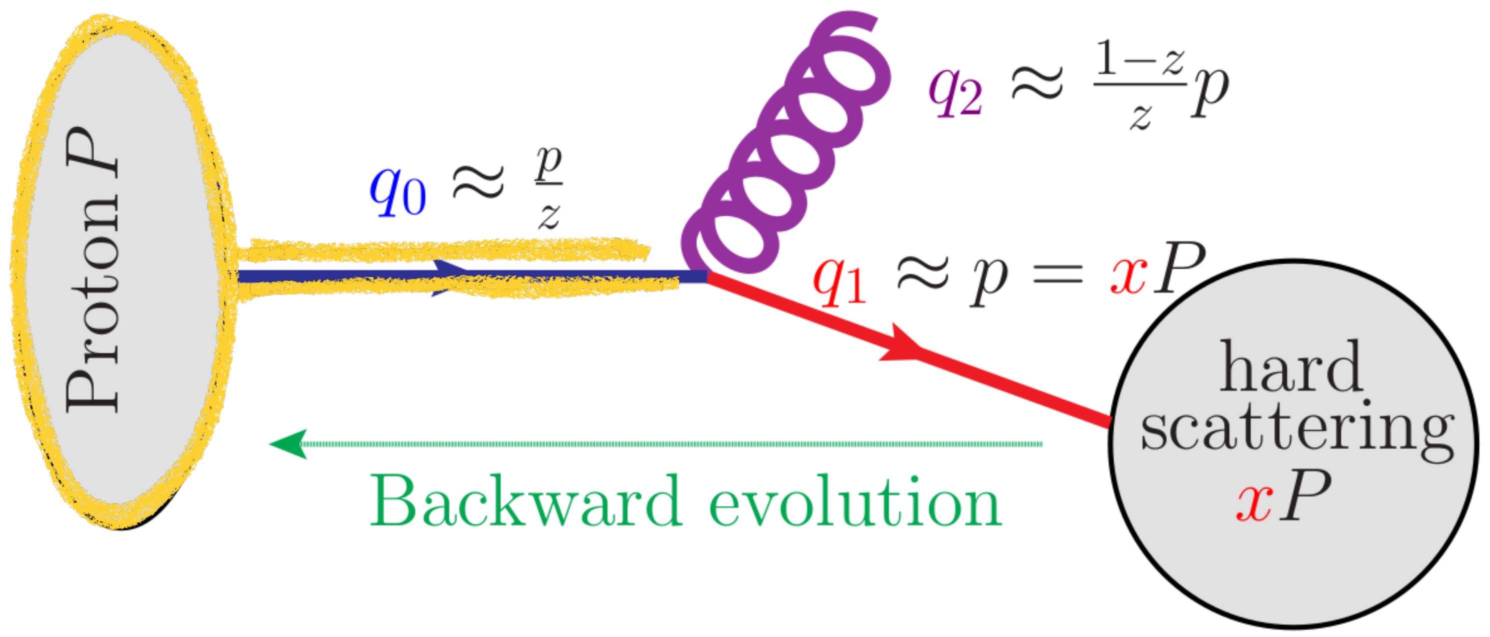
- global transverse recoil (Dasgupta et al 2002.11114, "**PanGlobal**"; Holguin, Forshaw and Plätzer 2003.06400, Herren et al. 2208.06057 "Alaric" ). This is the only recoil option that enables $k_t$-ordering.

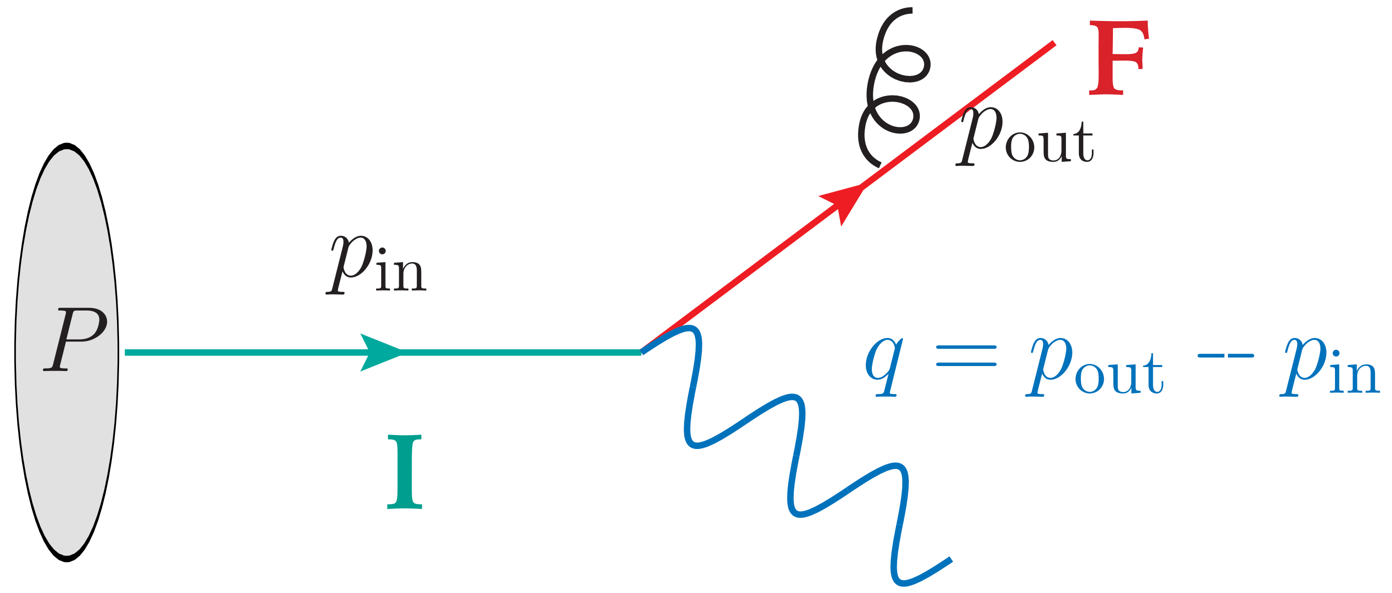
**Alaric** *Daniel Reichelt*

*U4-08, Milan-Bicocca University*

# Initial-state radiation in common dipole showers




- Initial-state radiation: we cannot assign the $p_T$ recoil to the incoming parton ($q_0$), as it must stay aligned with the incoming beam




- The $k_t$-recoil due to ISR in initial-final dipoles is always taken by the final-state leg.

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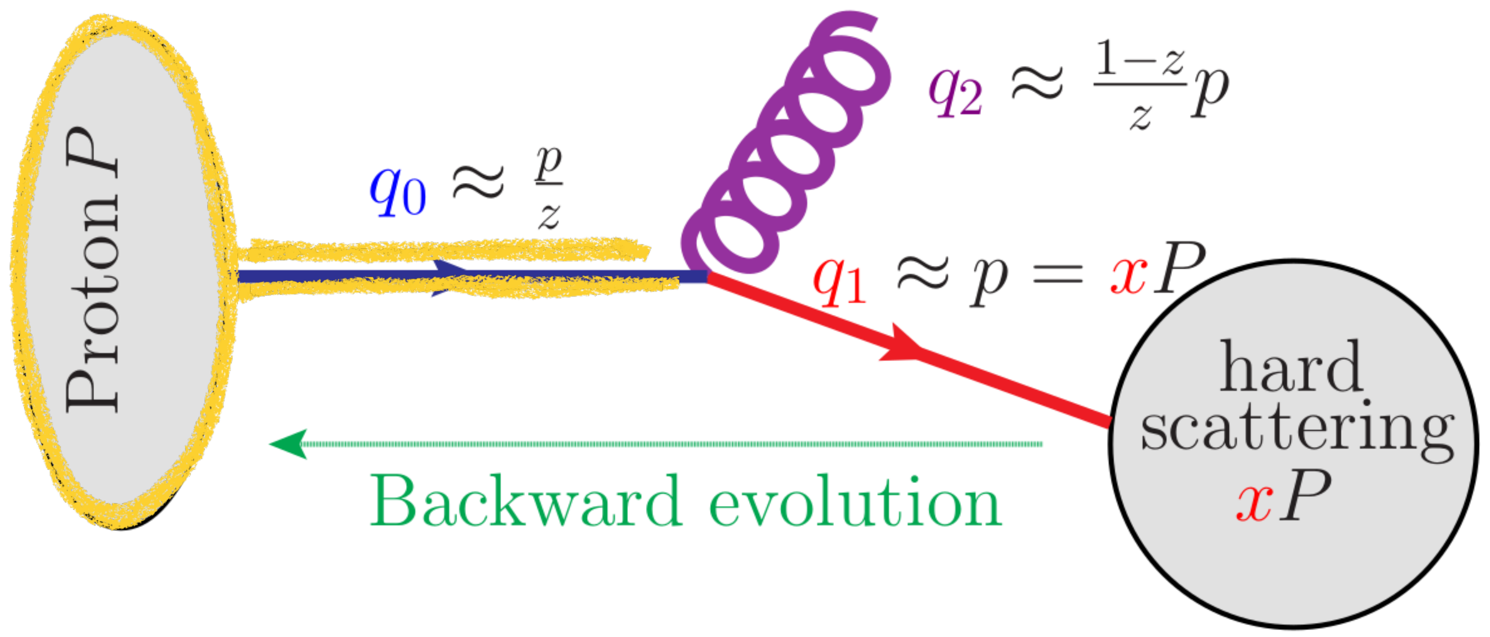


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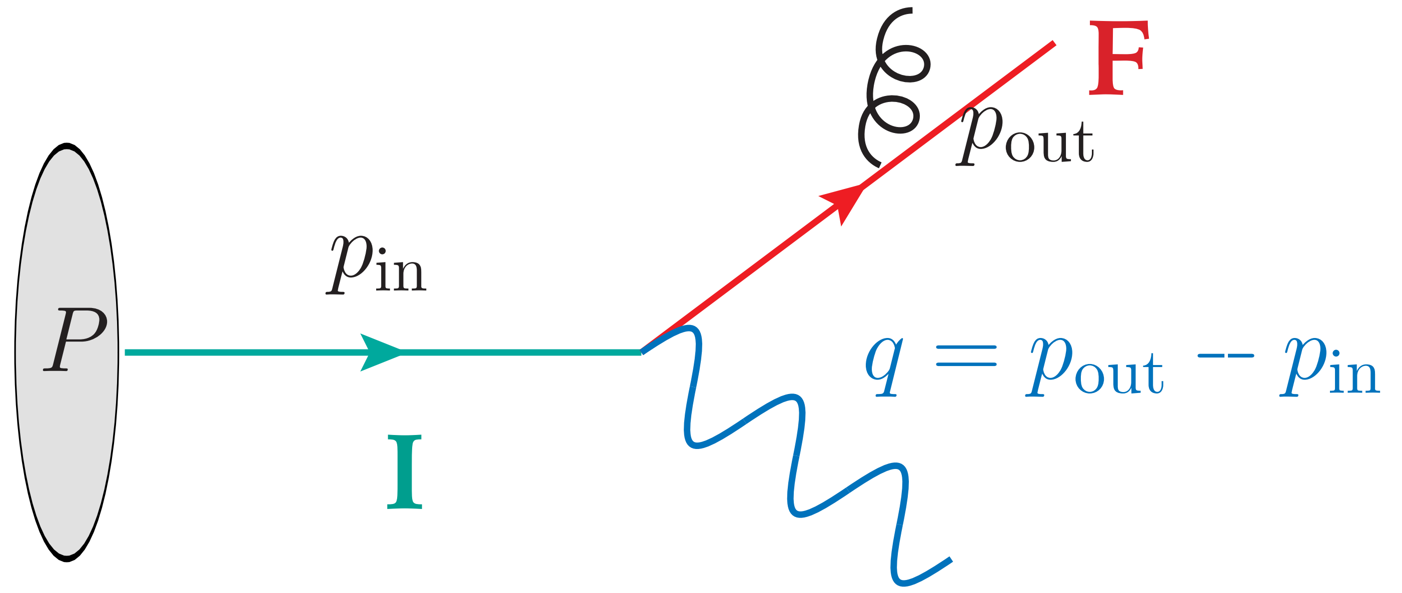


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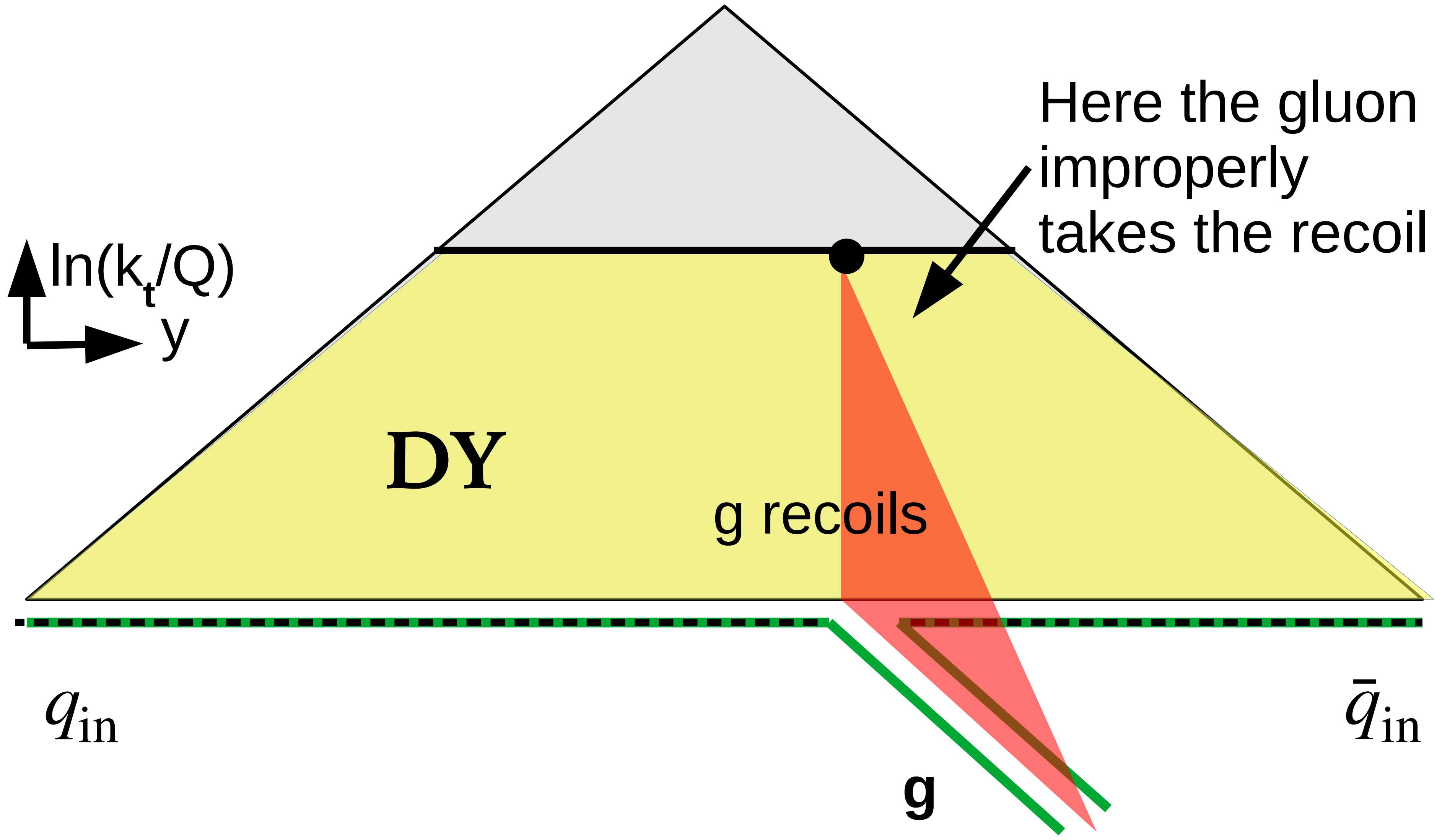
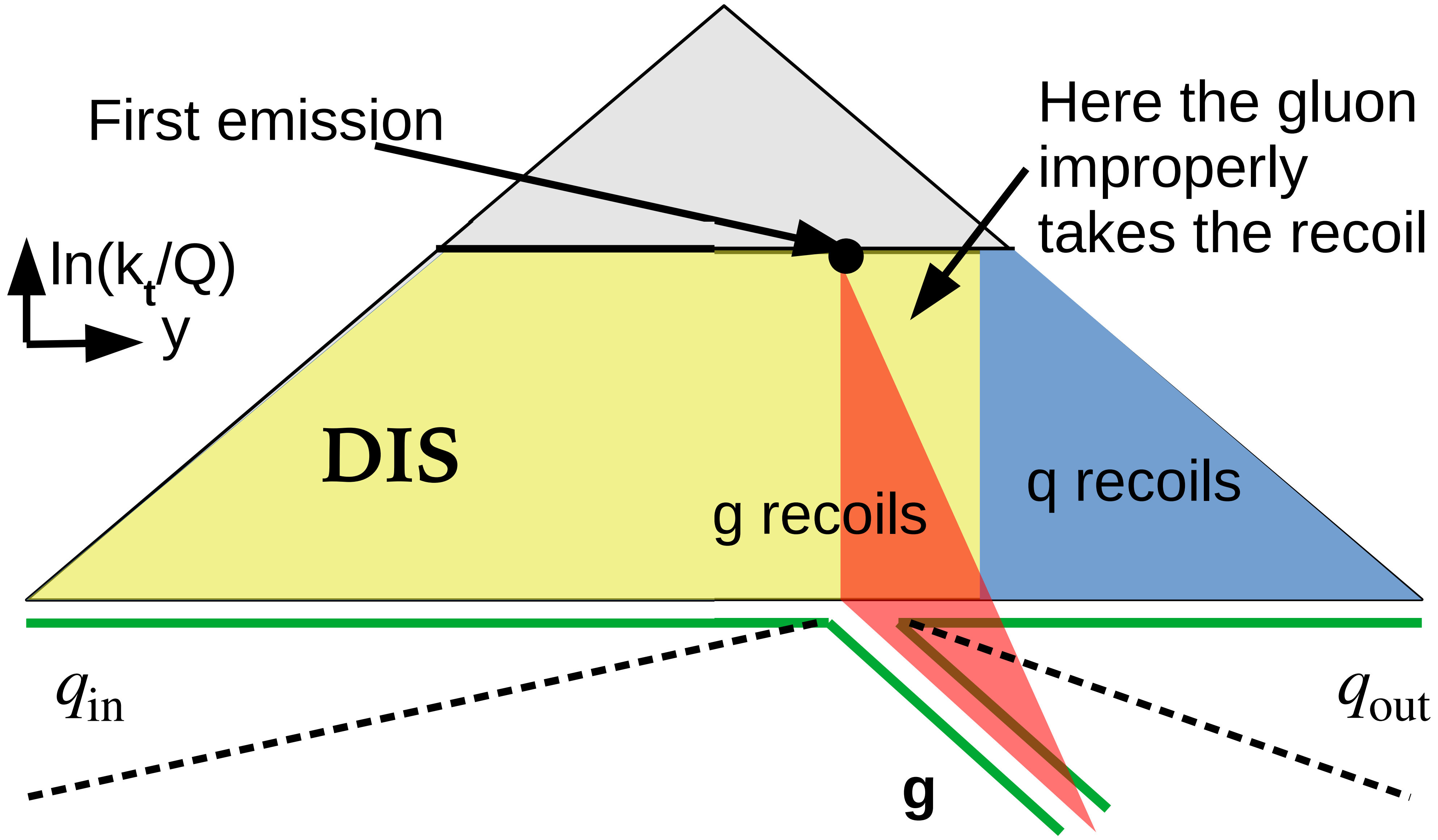
This renders even more sizeable the impact of the wrong recoil terms!



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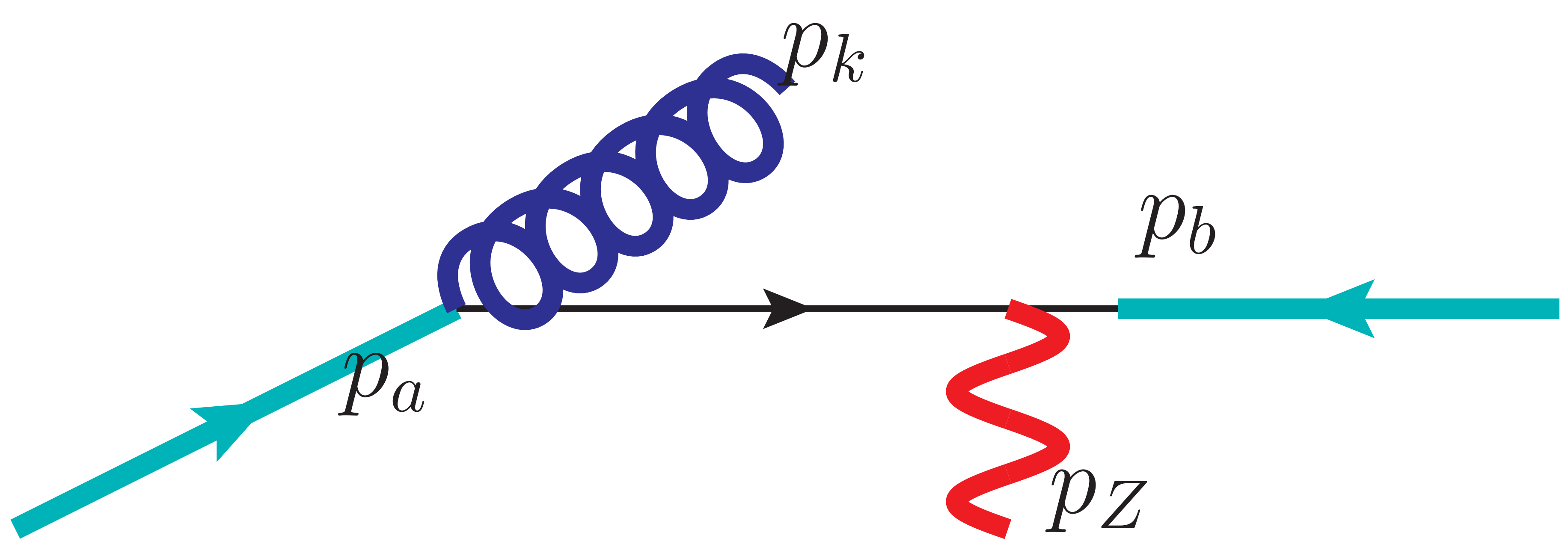


To remedy the ISR issue, for **hadron-hadron** colliders, it is possible to give a transverse kick to the incoming parton when it emits, and then perform global boost and rotations to realign it with the z axis

[Plätzer and Gieseke 0909.5593 ]

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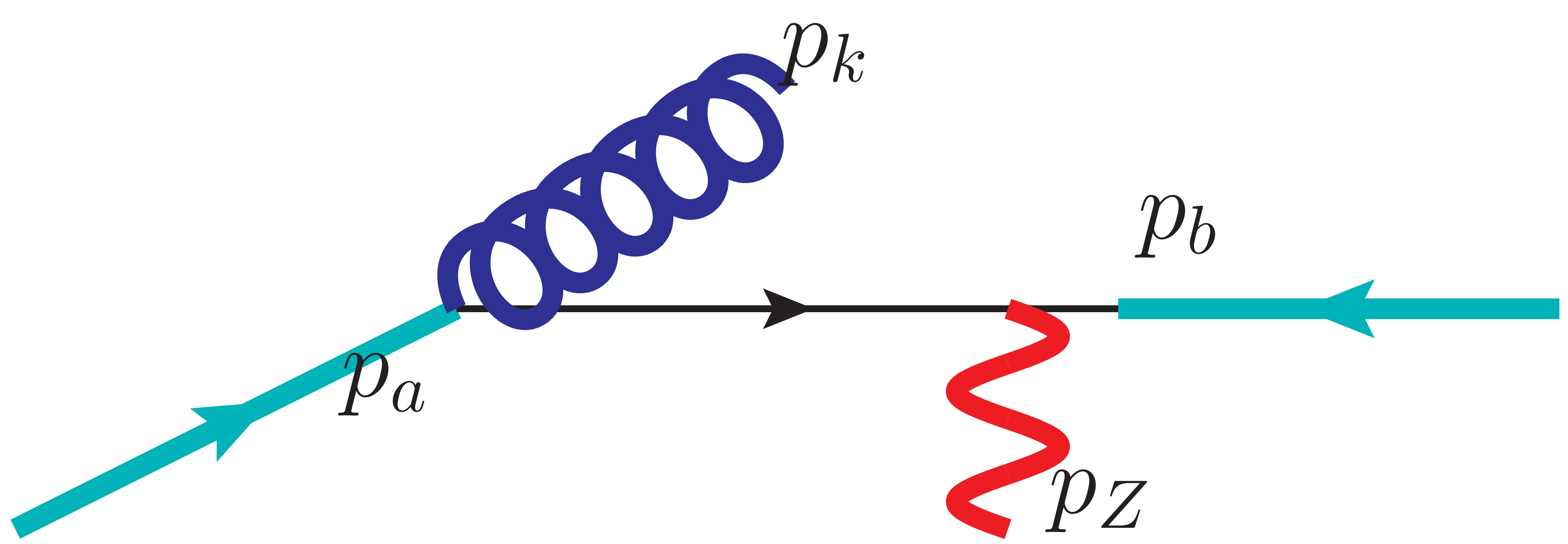


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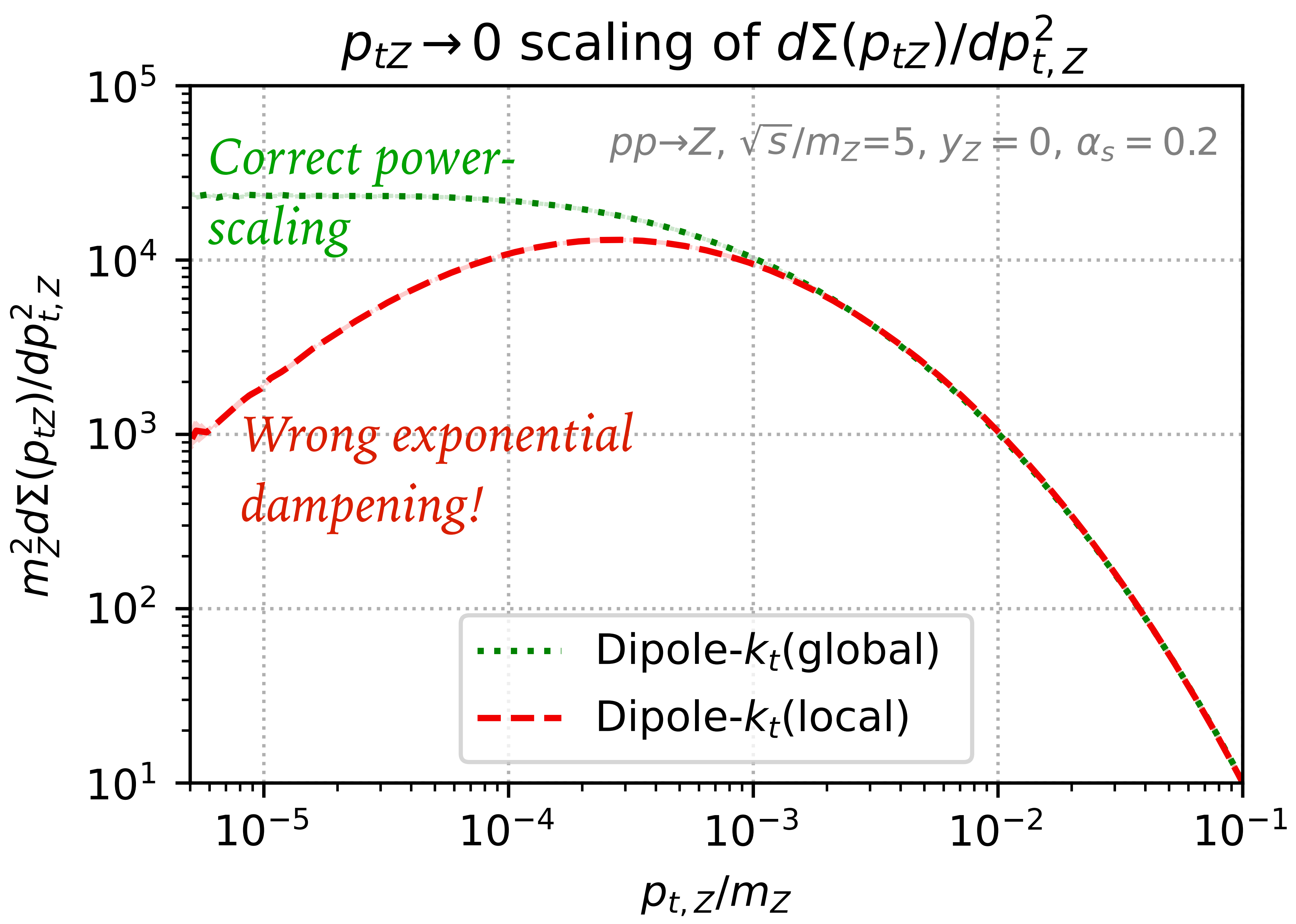
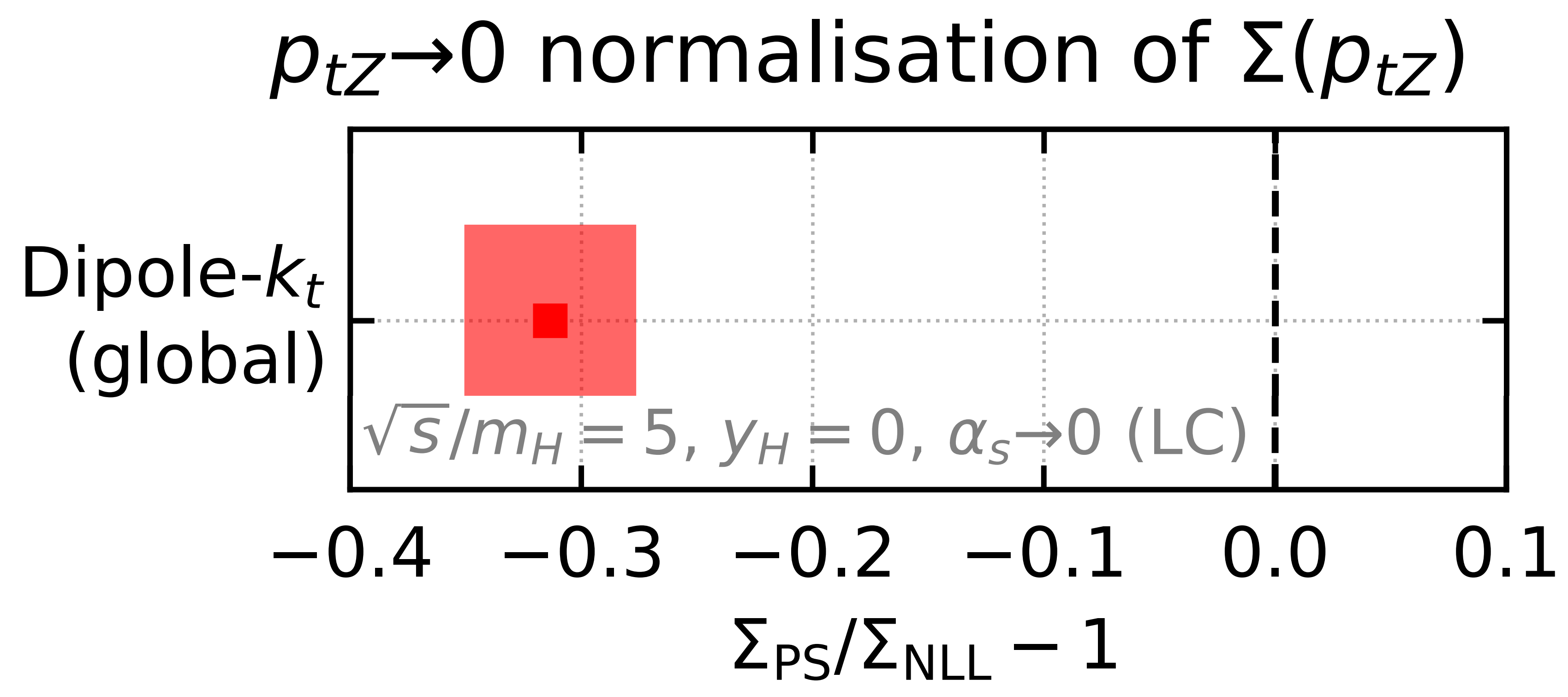


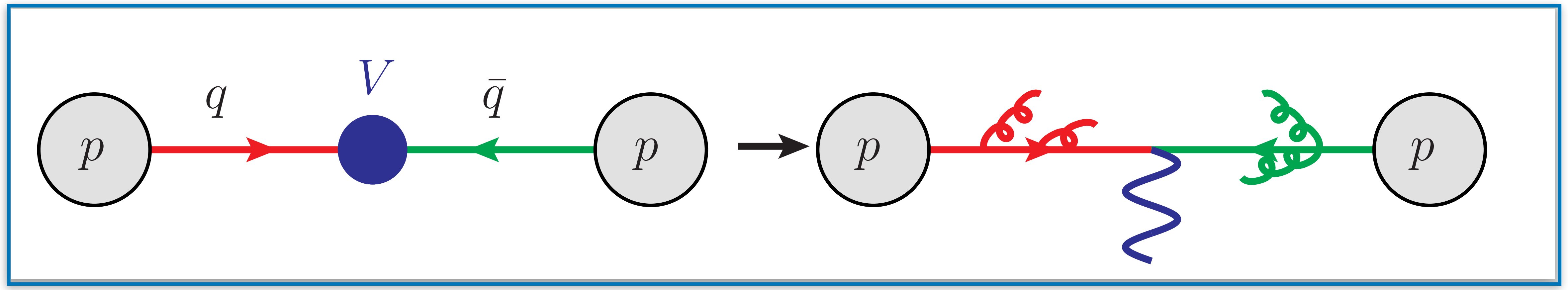

This solution yields to correct power-scaling behavour of the colour singlet in Drell Yan [Parisi, Petronzio NPB 154 (1979) 427-440], but not the correct normalisation! (It simply makes ISR "as bad as" FSR)




van Beekveld, S.F.R., Hamilton, Salam, Soto-Ontoso, Soyez, Verheyen, 2207.09467

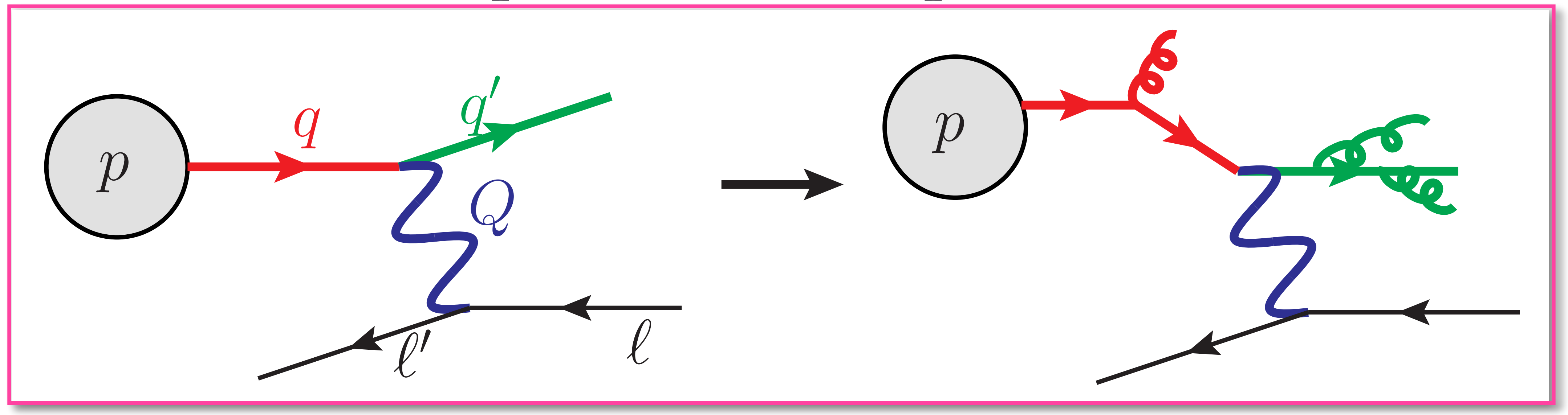
# Initial-state radiation in the PanScales showers

➤ The $p_T$ recoil due to ISR is taken by a "hard system", whose definition depends on the process




In colour-singlet production, the colour singlet absorbs the $k_\perp$ recoil for all the ISR emissions

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




In DIS, the final-state quark (and its children) absorbs the $k_\perp$ recoil for all the ISR emissions.

van Beekveld, S.F.R., 2305.08645

Similar in spirit to the Herwig7 angular-ordered shower [Plätzer, Richardson]!

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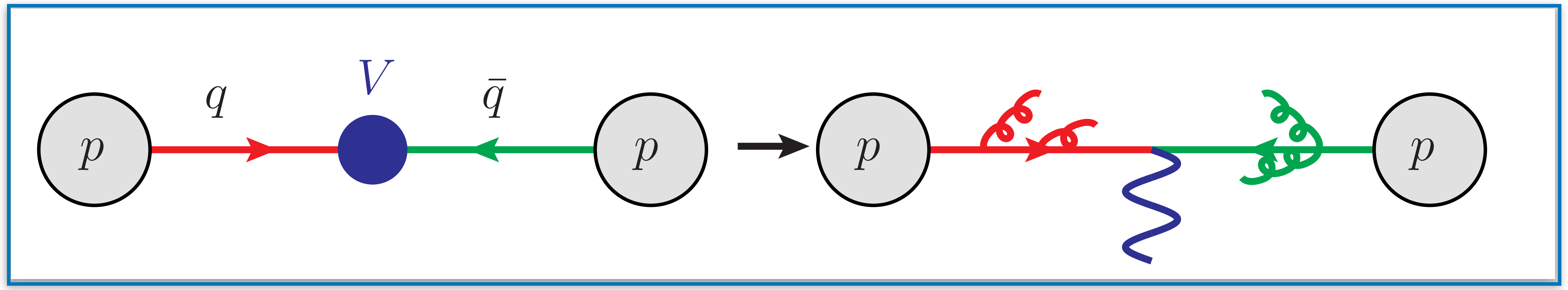


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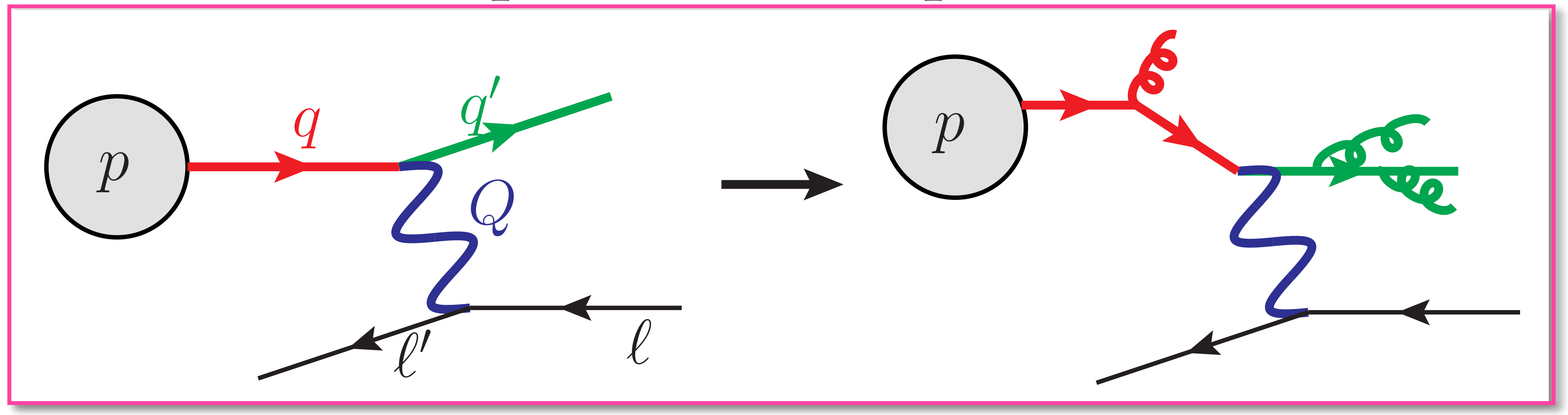
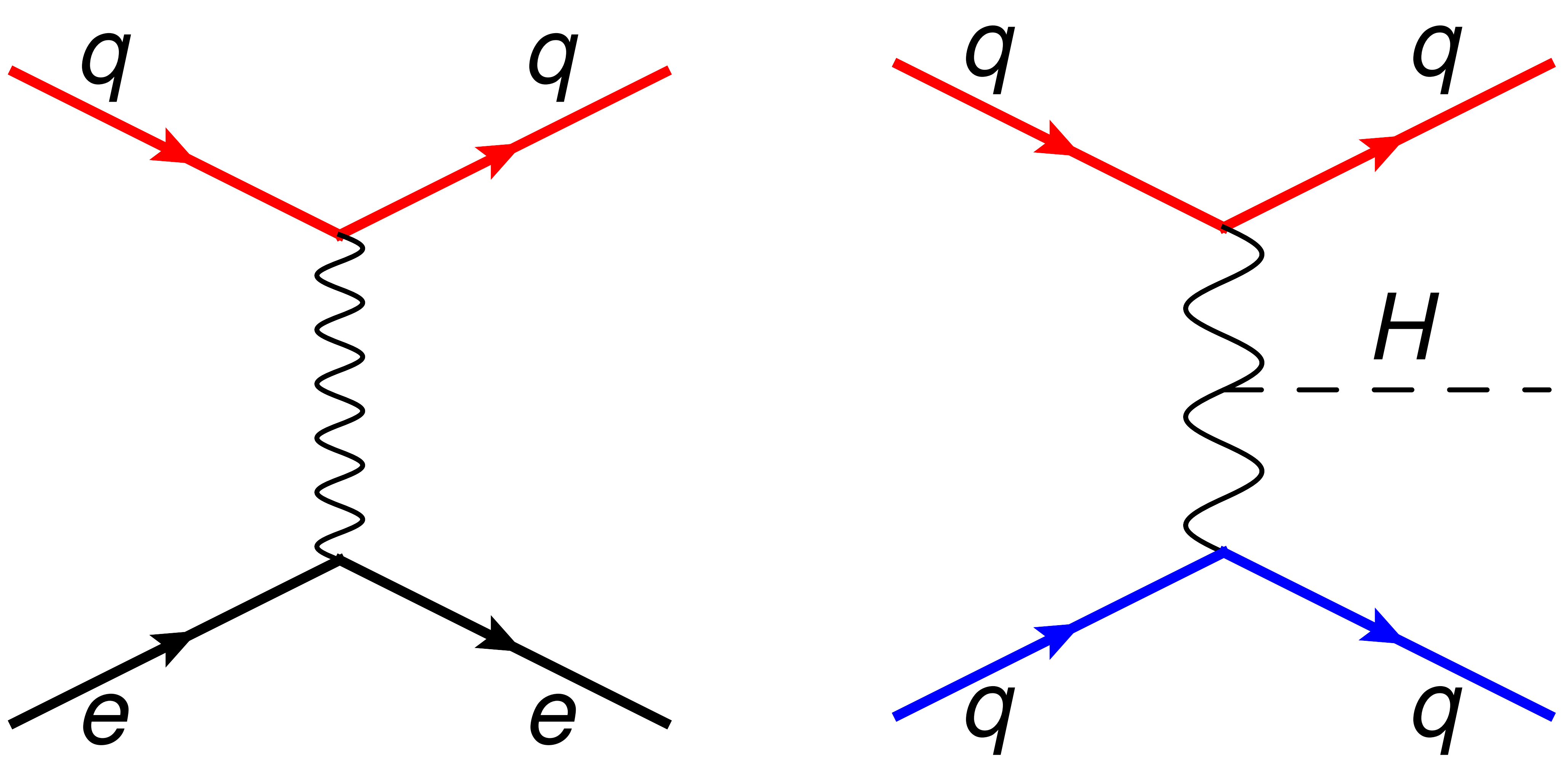



In **DIS**, the final-state quark (and its children) absorbs the $k_\perp$ recoil for all the ISR emissions. **VBF=DIS$^2$**

van Beekveld, S.F.R., 2305.08645

Our PanScales showers for VBF represent the first tool to achieve NLL accuracy* for this process, for both global and non-global observables!




*NLL at LC, as we miss (unknown!) non-factorisable corrections, LL at FC

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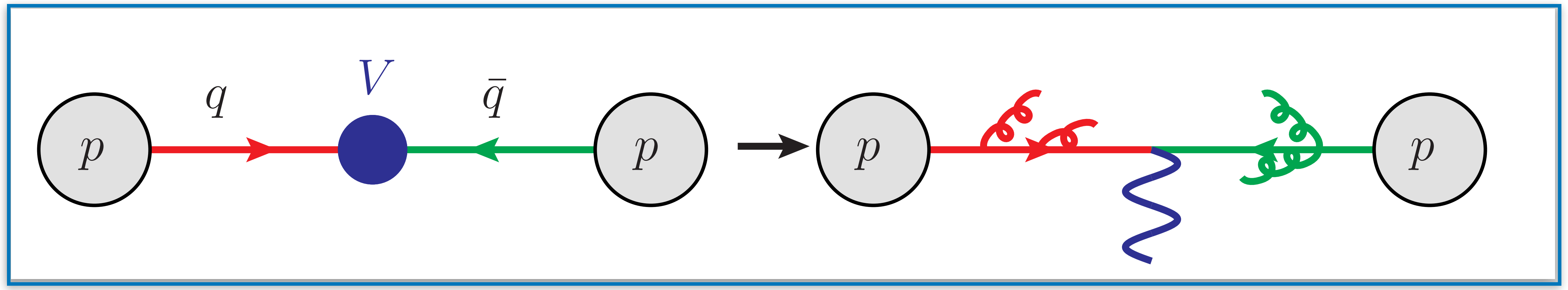


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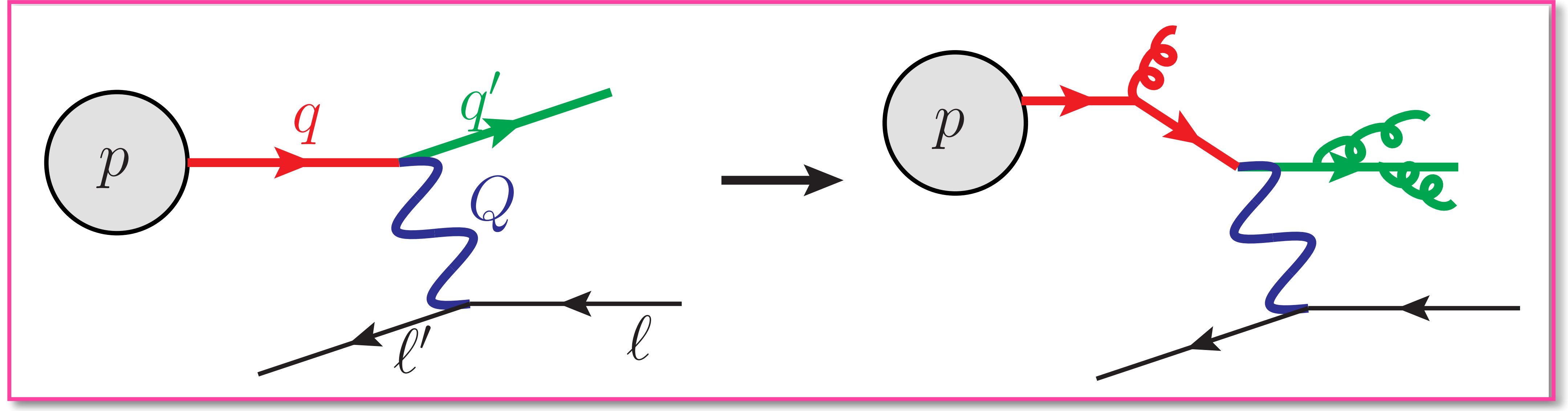


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PanGlobal → The $k_t$ recoil of an emission is never conserved locally within the dipole

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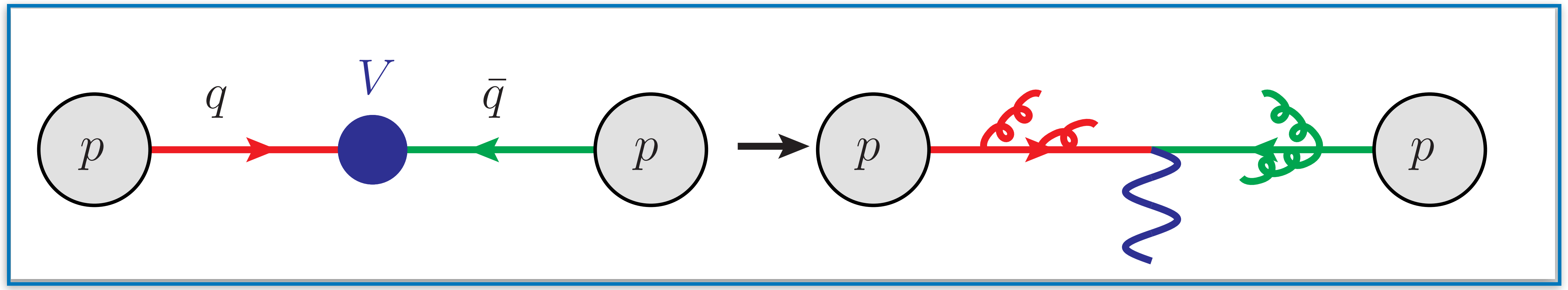


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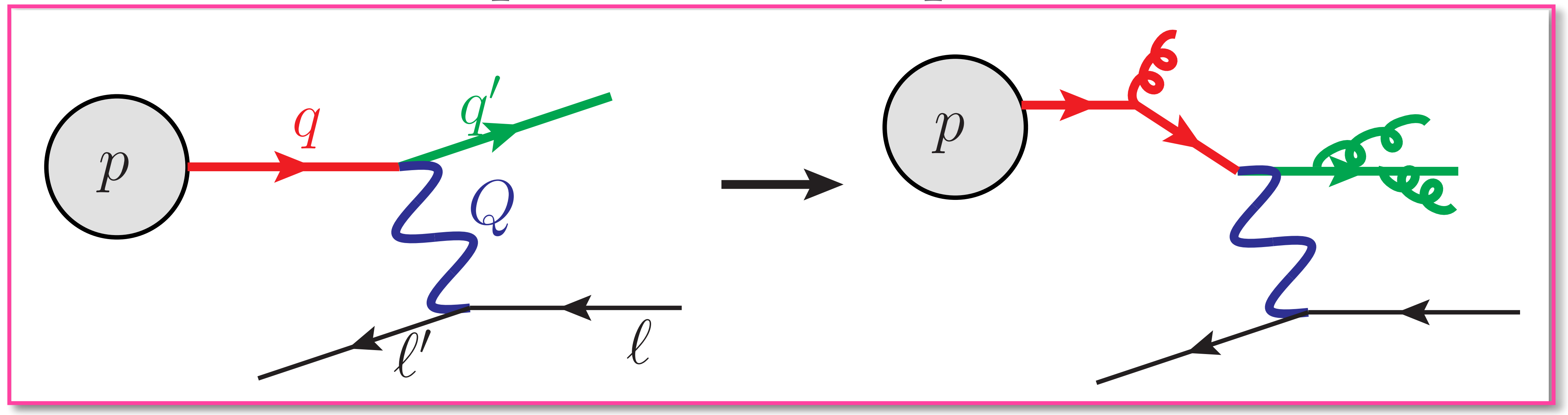


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van Beekveld, S.F.R., 2305.08645

PanGlobal → The $k_t$ recoil of an emission is never conserved locally within the dipole

In **colour-singlet** production, the $k_t$ recoil of all the emissions is taken by the colour-singlet, whose mass and rapidity is preserved at each stage.

In **DIS**, we boost all the *final-state partons*, leaving $Q = p_{\text{out}} - p_{\text{in}}$ unchanged. The boost affects mainly partons close in angle to the original final-state quark.

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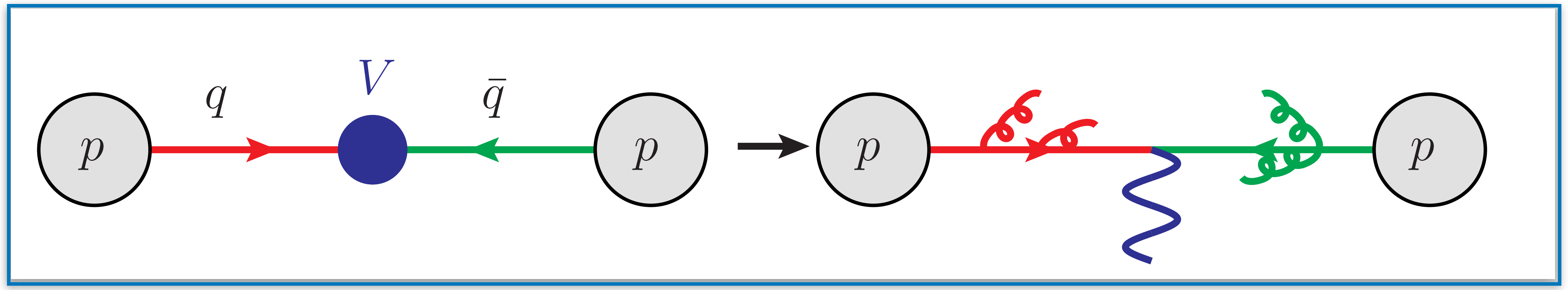


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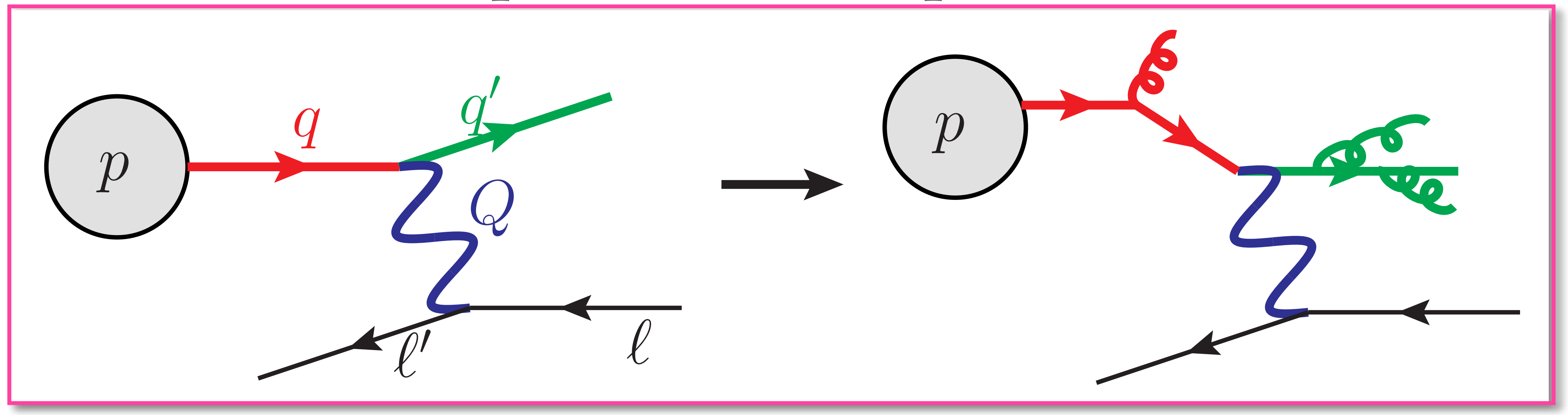


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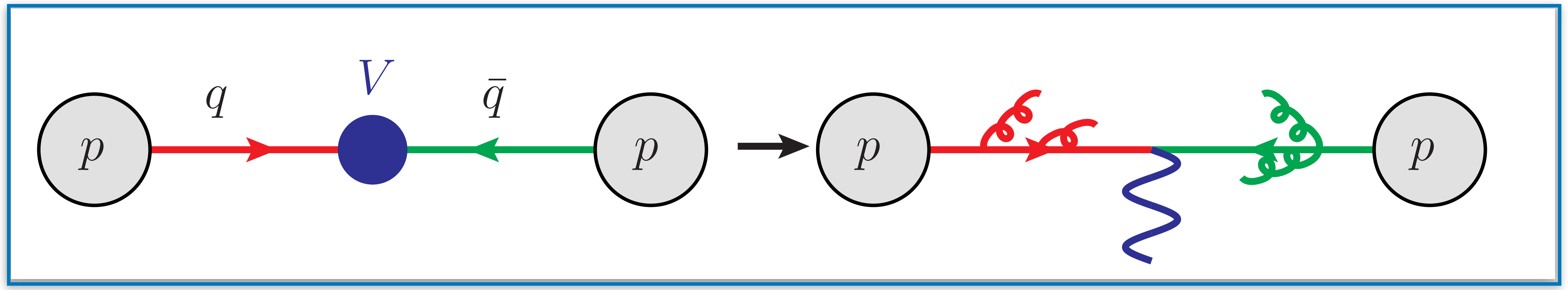
van Beekveld, S.F.R., 2305.08645

PanLocal → The $k_t$ recoil is always taken by the emitter. In case of ISR, this misalignes the incoming partons with respect to the beams

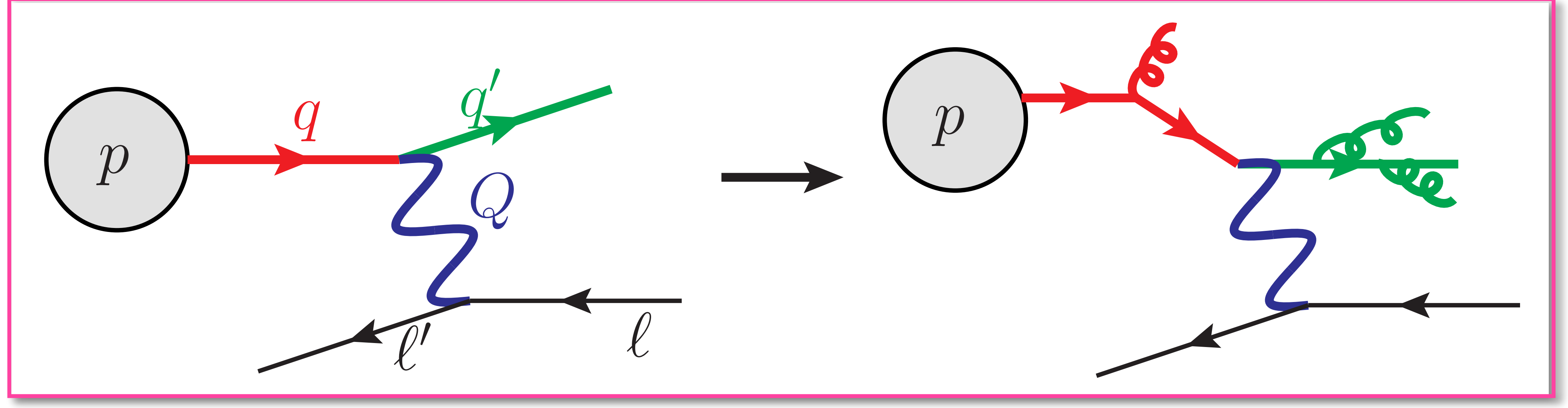
# Initial-state radiation in the PanScales showers

➤ The $p_T$ recoil due to ISR is taken by a “hard system”, whose definition depends on the process




In **colour-singlet** production, the colour singlet absorbs the $k_\perp$ recoil for all the ISR emissions

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




In **DIS**, the final-state quark (and its children) absorbs the $k_\perp$ recoil for all the ISR emissions. **VBF=DIS$^2$**

van Beekveld, S.F.R., 2305.08645

**PanLocal** → The $k_t$ recoil is always taken by the emitter. In case of ISR, this misalignes the incoming partons with respect to the beams

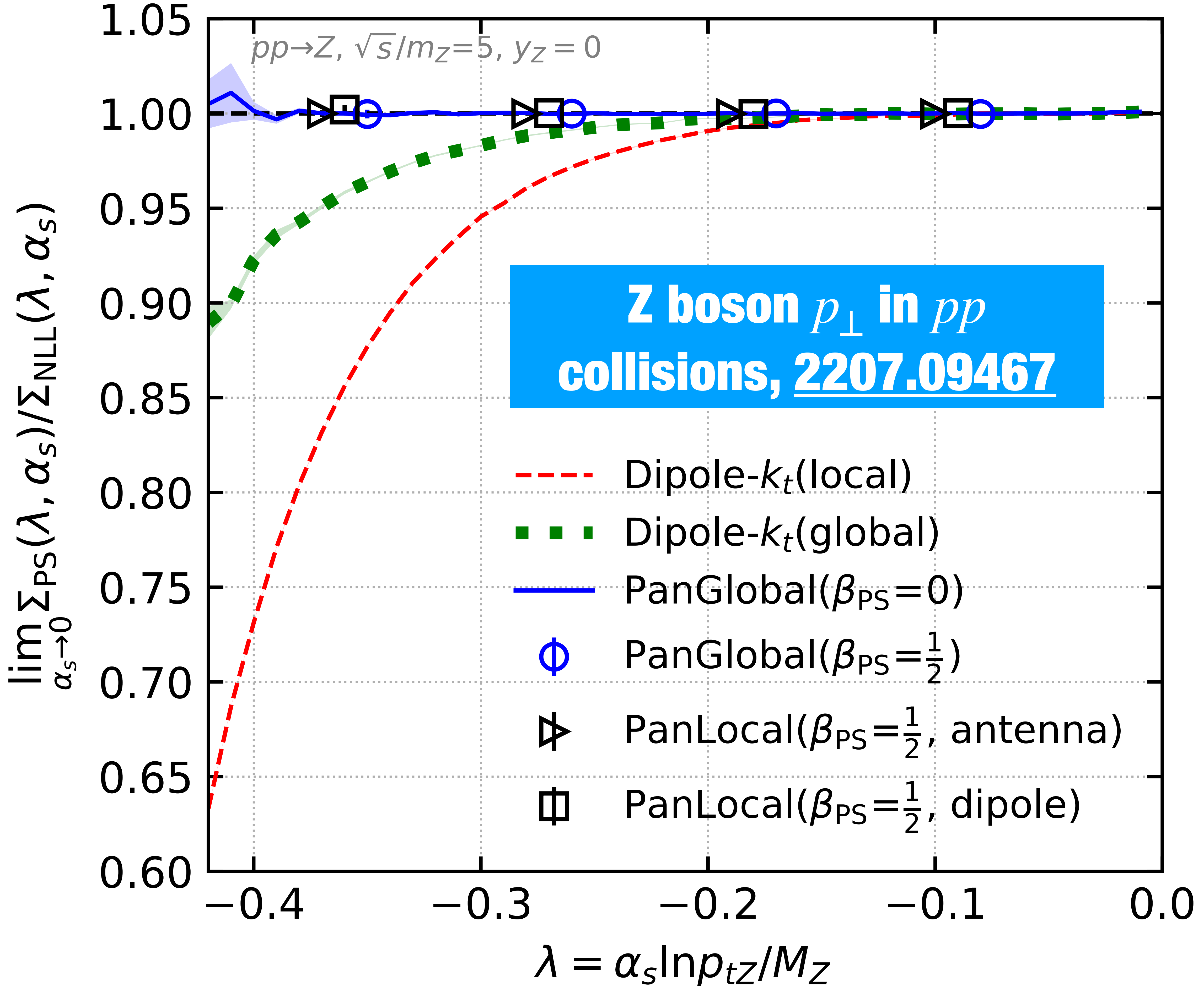
In **colour-singlet** production, we apply a Lorentz transformation to the whole event to realign the incoming partons with the beams. The rapidity of the colour-singlet is preserved.

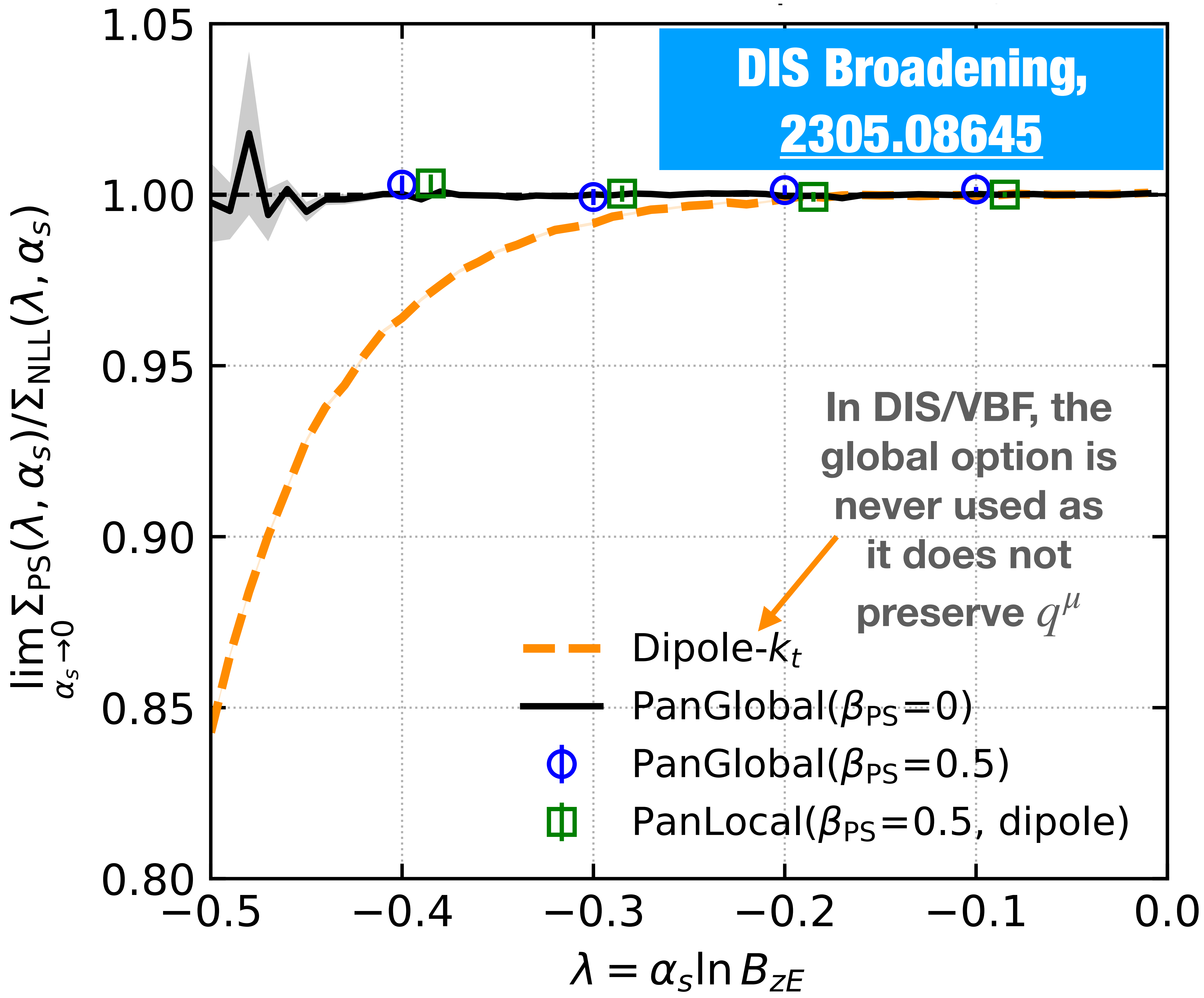
In **DIS**, we apply a Lorentz transformation to all the *partons*, leaving $Q = p_{\text{out}} - p_{\text{in}}$ unchanged. The transform affects mainly partons close in angle to the original final-state quark.

# All-orders validation of the PanScales showers

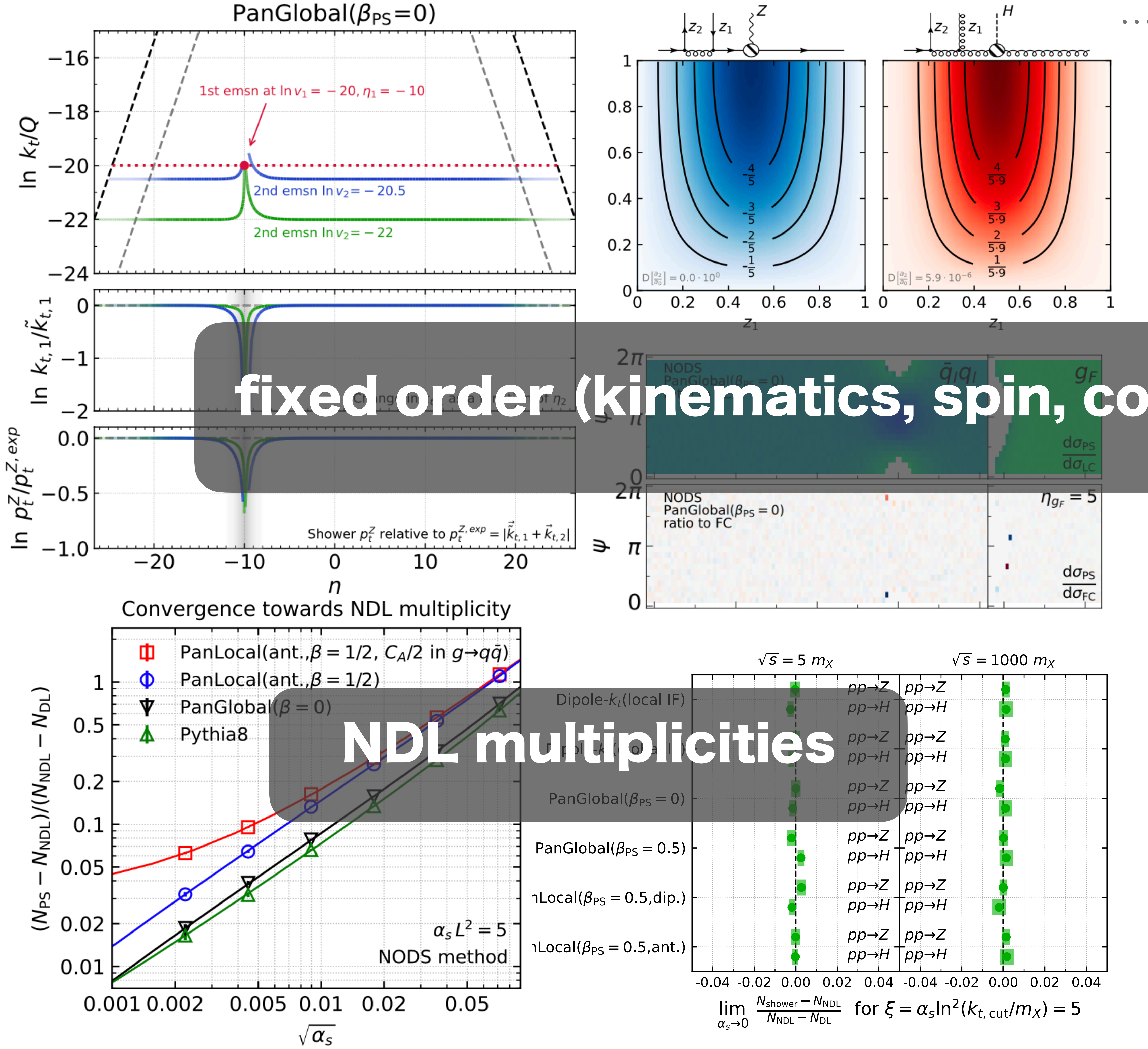
$$\Sigma(O < e^L) = \exp\left(Lg_{\mathrm{LL}}(\alpha_s L) + g_{\mathrm{NLL}}(\alpha_s L) + \alpha_s g_{\mathrm{NNLL}}(\alpha_s L) + \dots\right)$$

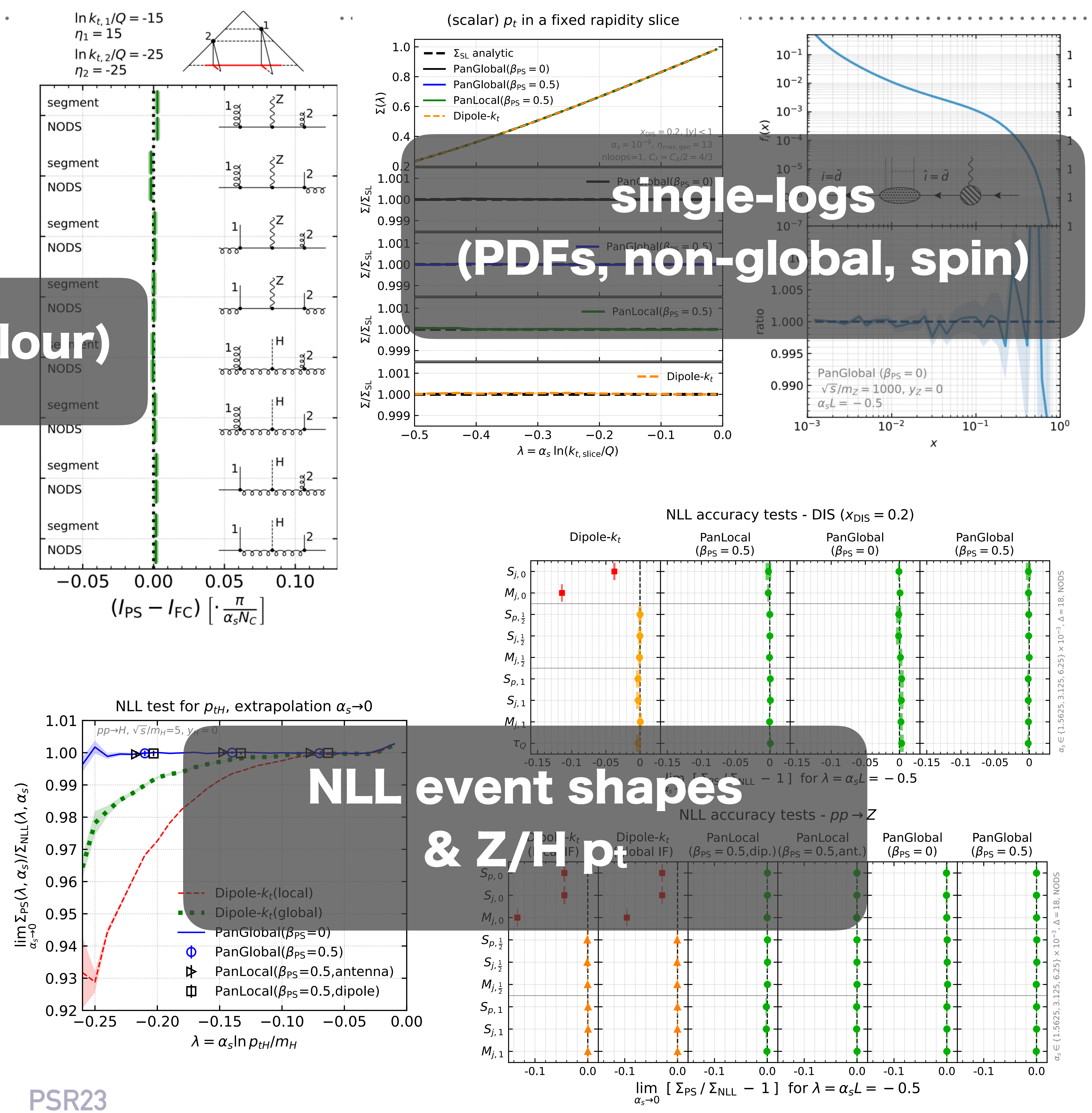
$$\lim_{\alpha_s \to 0} \frac{\Sigma_{\mathrm{PS}}(\alpha_s, \log V < L)}{\Sigma_{\mathrm{NLL}}(\alpha_s, \log V < L)} = 1 \quad \text{at fixed } \lambda = \alpha_s L$$



# All-orders validation of the PanScales showers




$e^+e^-$ NLL showers at LC: 2002.11114

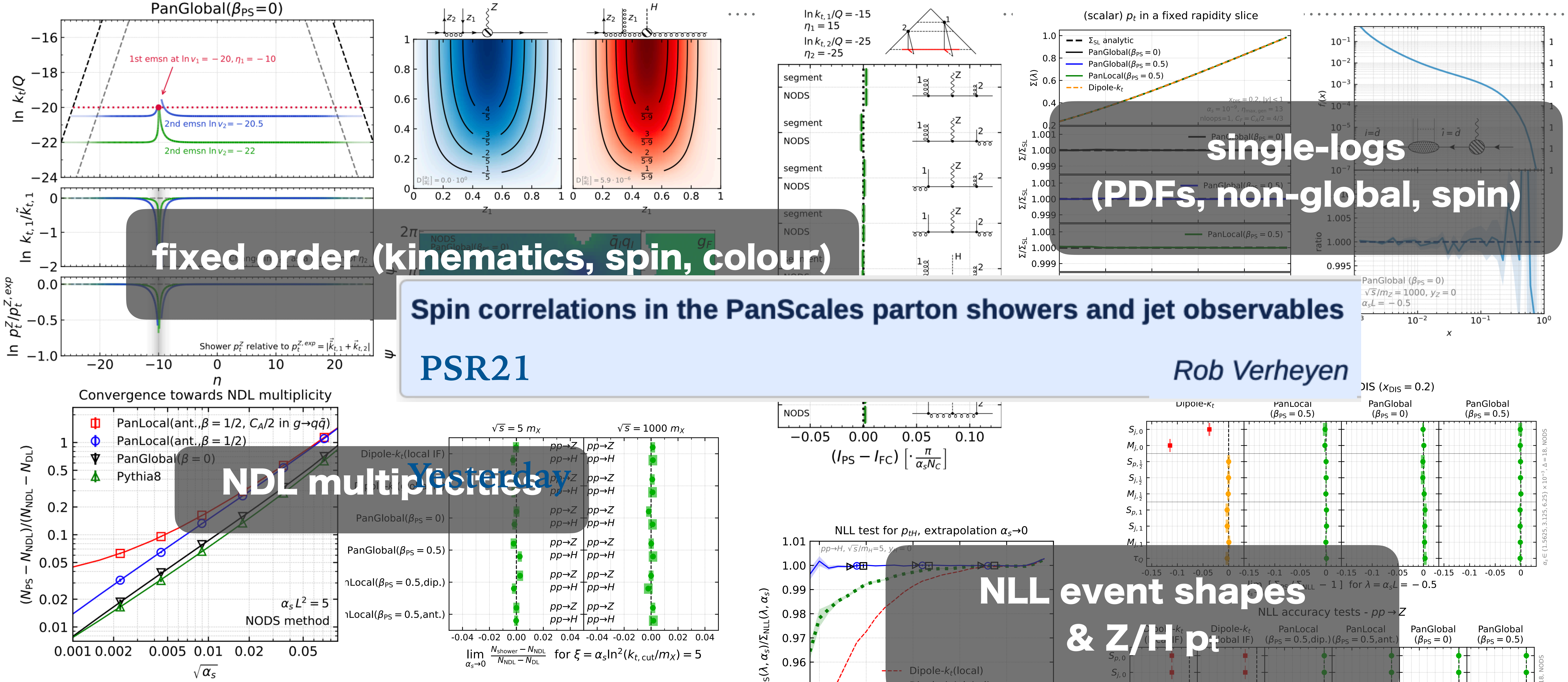
Colour in $e^+e^-$ 2011.10054 and in $pp$ 2205.02237

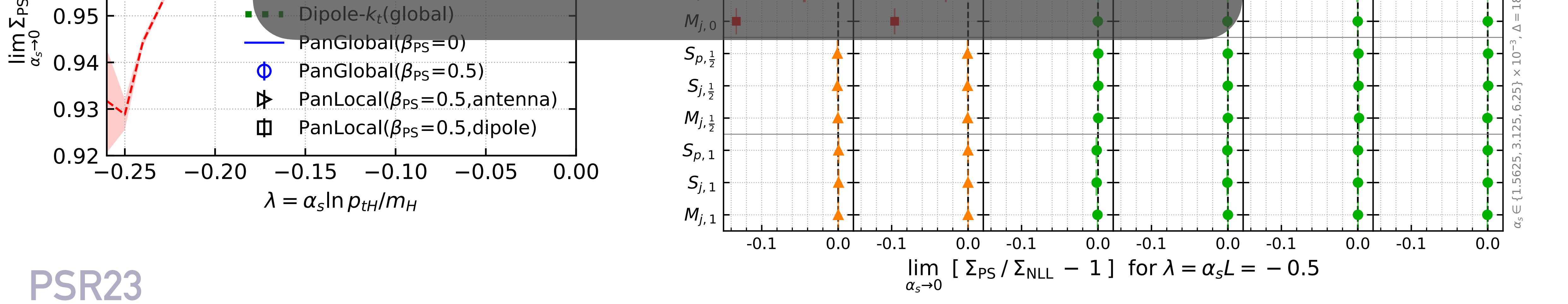
Spin in $e^+e^-$ 2103.16526, 2111.01161 and in $pp$ 2205.02237

All-orders tests for $pp$ 2207.09467

DIS NLL tests 2305.08645

# All-orders validation of the PanScales showers

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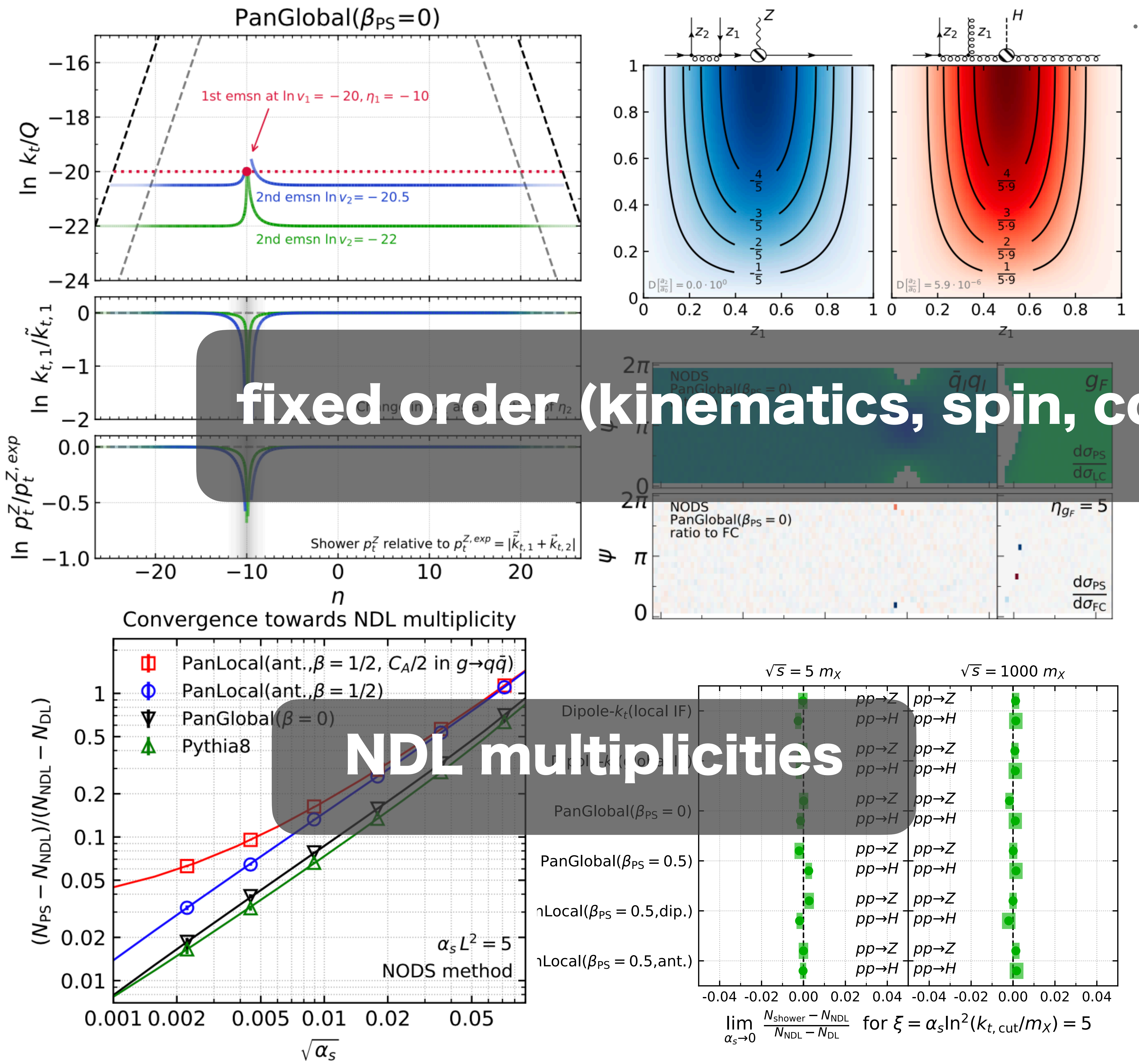


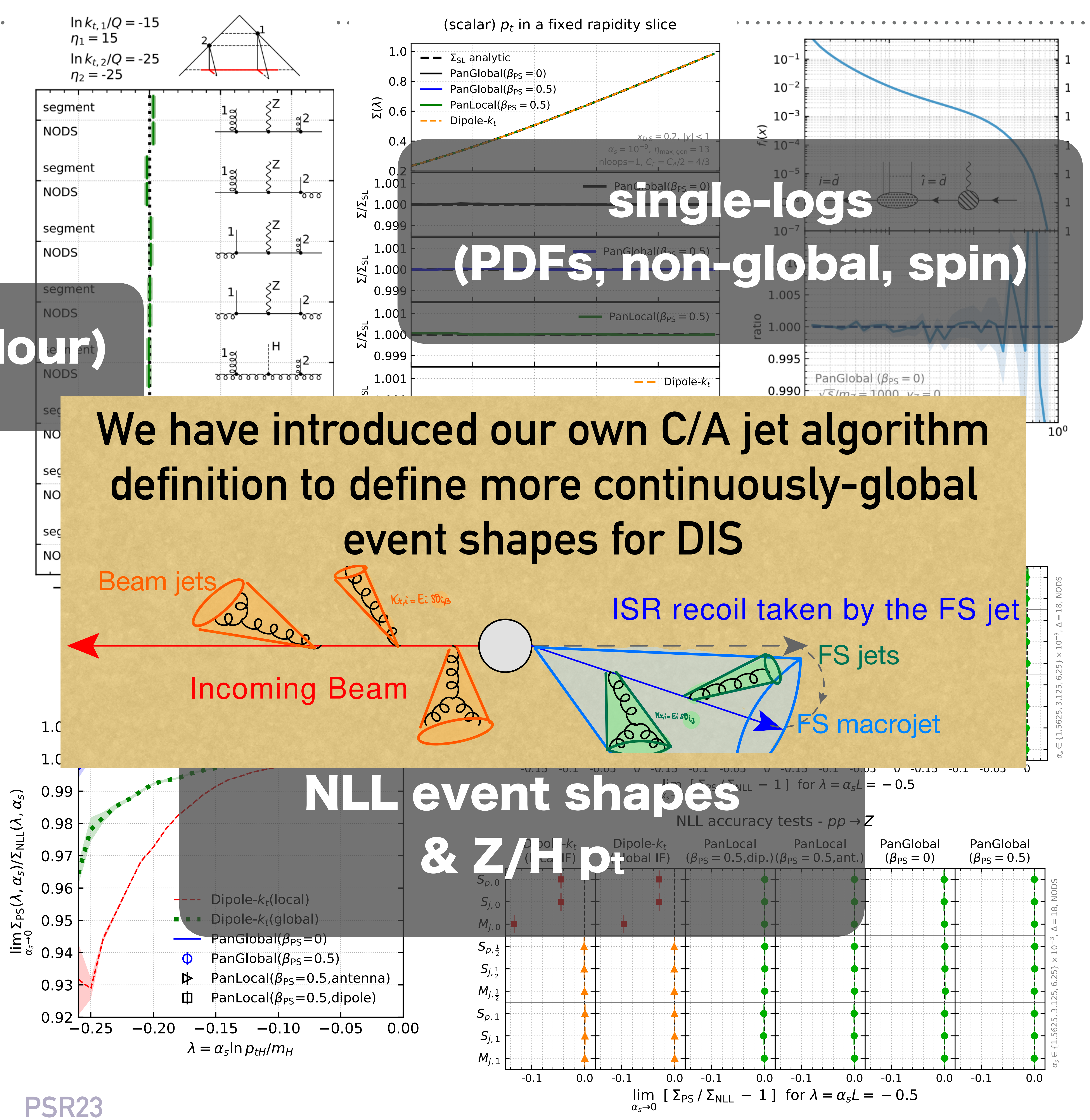


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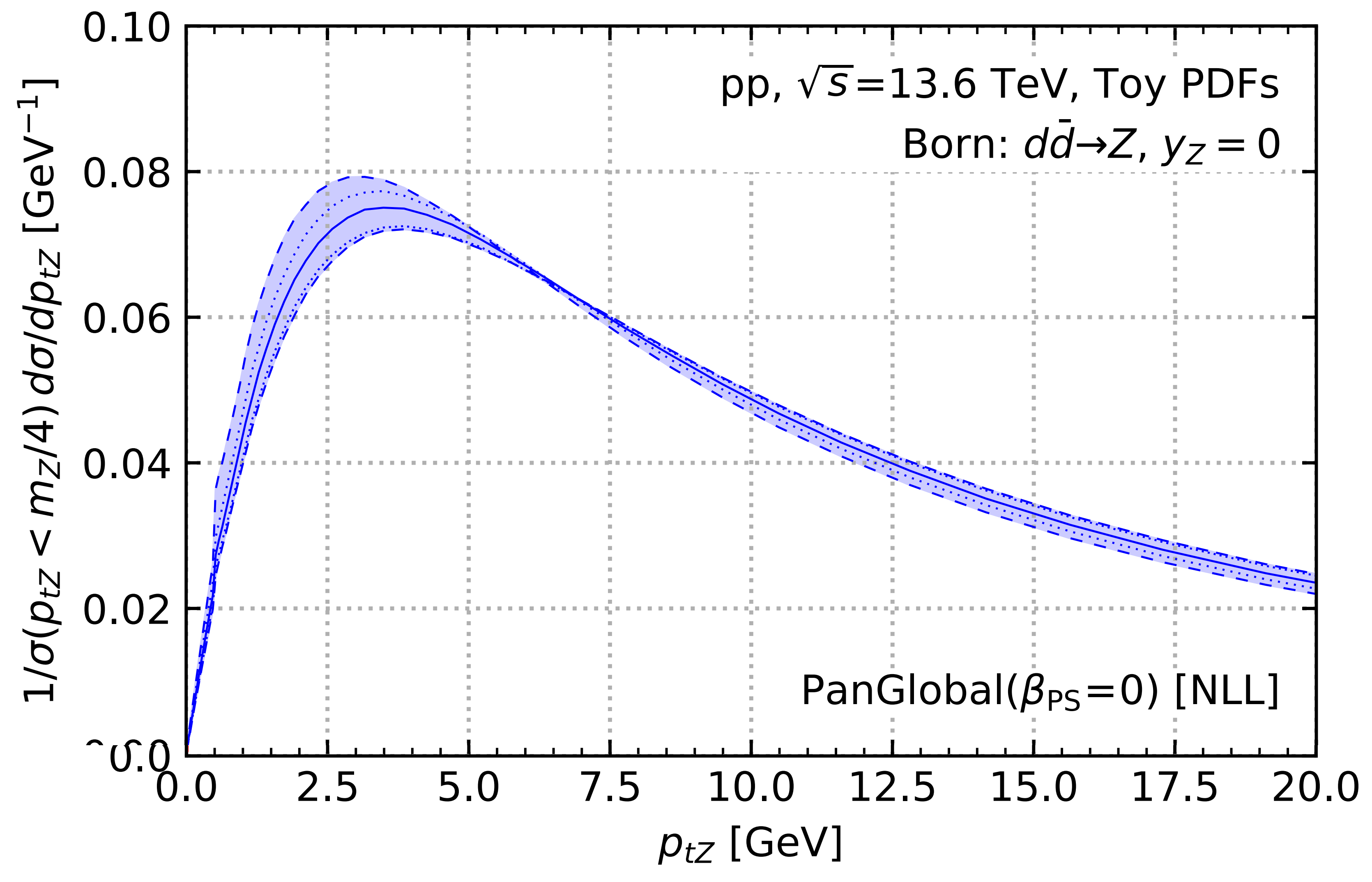
All-orders tests for $pp$ 2207.09467

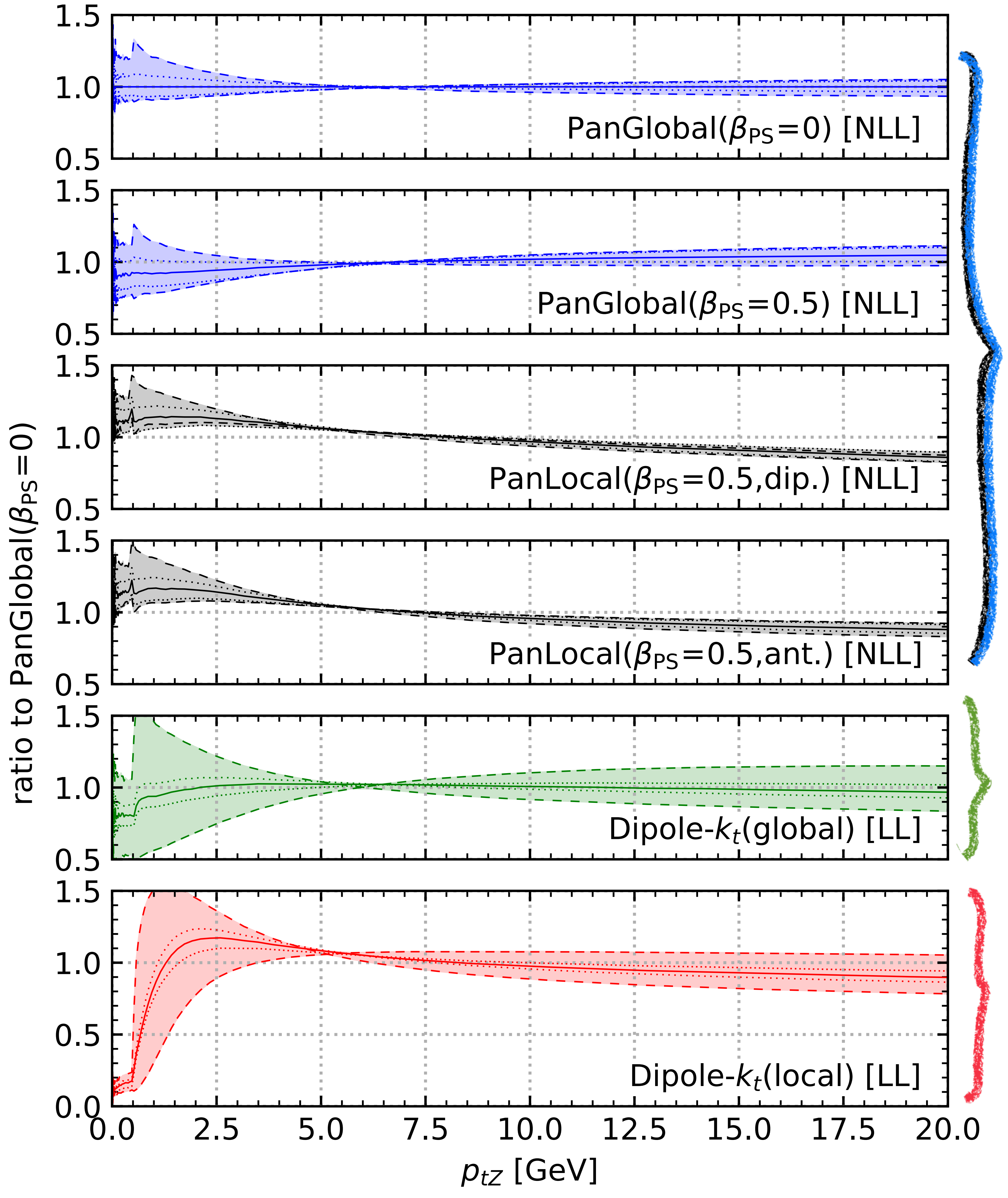
DIS NLL tests 2305.08645

# Exploratory LHC phenomenology

# Transverse-momentum of the Z boson




$$\sqrt{s} = 13.6\text{TeV}, m_Z = 91\text{GeV}, y_Z = 0$$



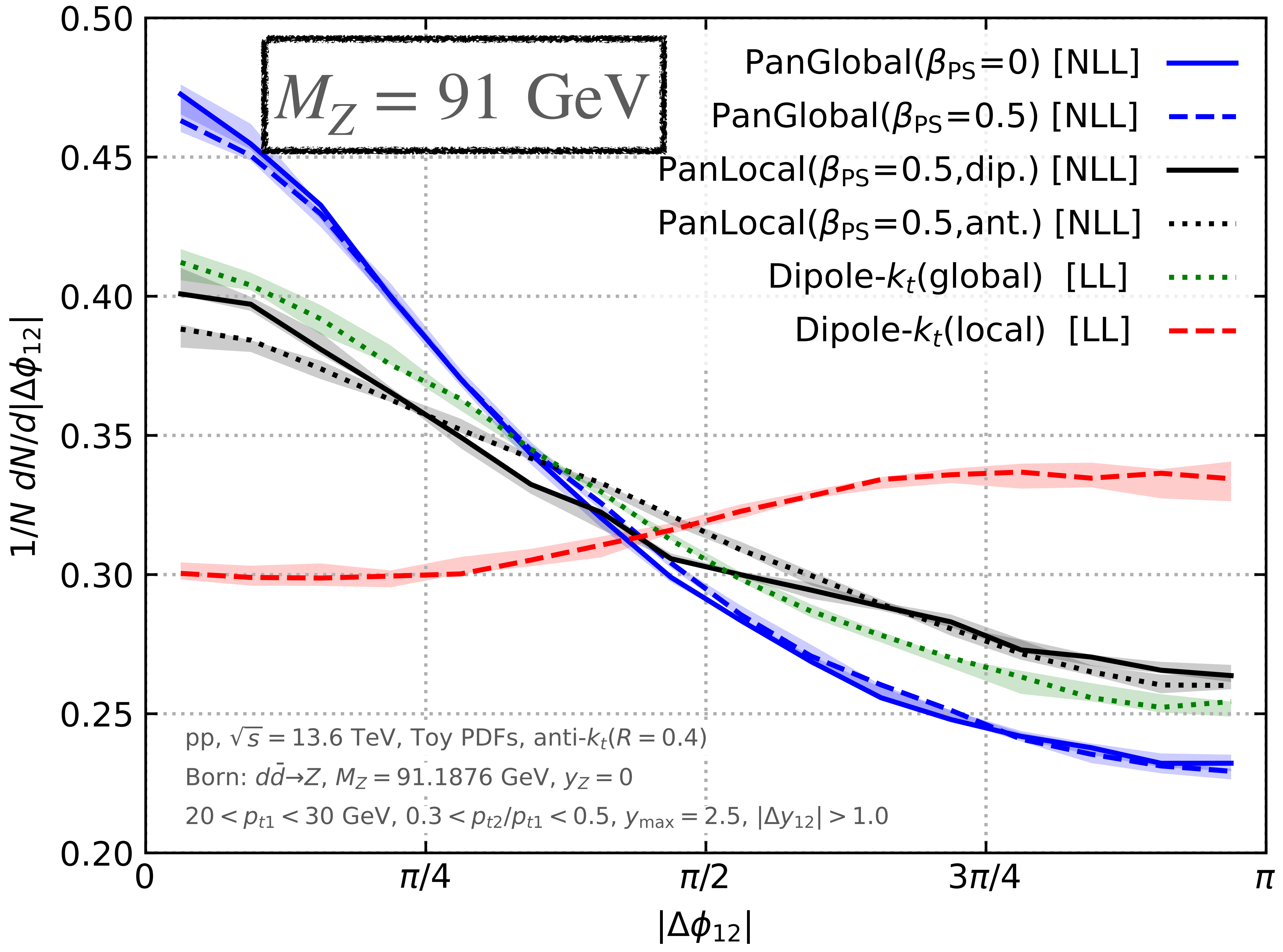

PanScales NLL showers with global [blue] or local [black] recoil. At small pTZ, the spectrum is power-suppressed with the correct normalisation.

LL shower. At small pTZ, the spectrum is power-suppressed, but with the WRONG normalisation

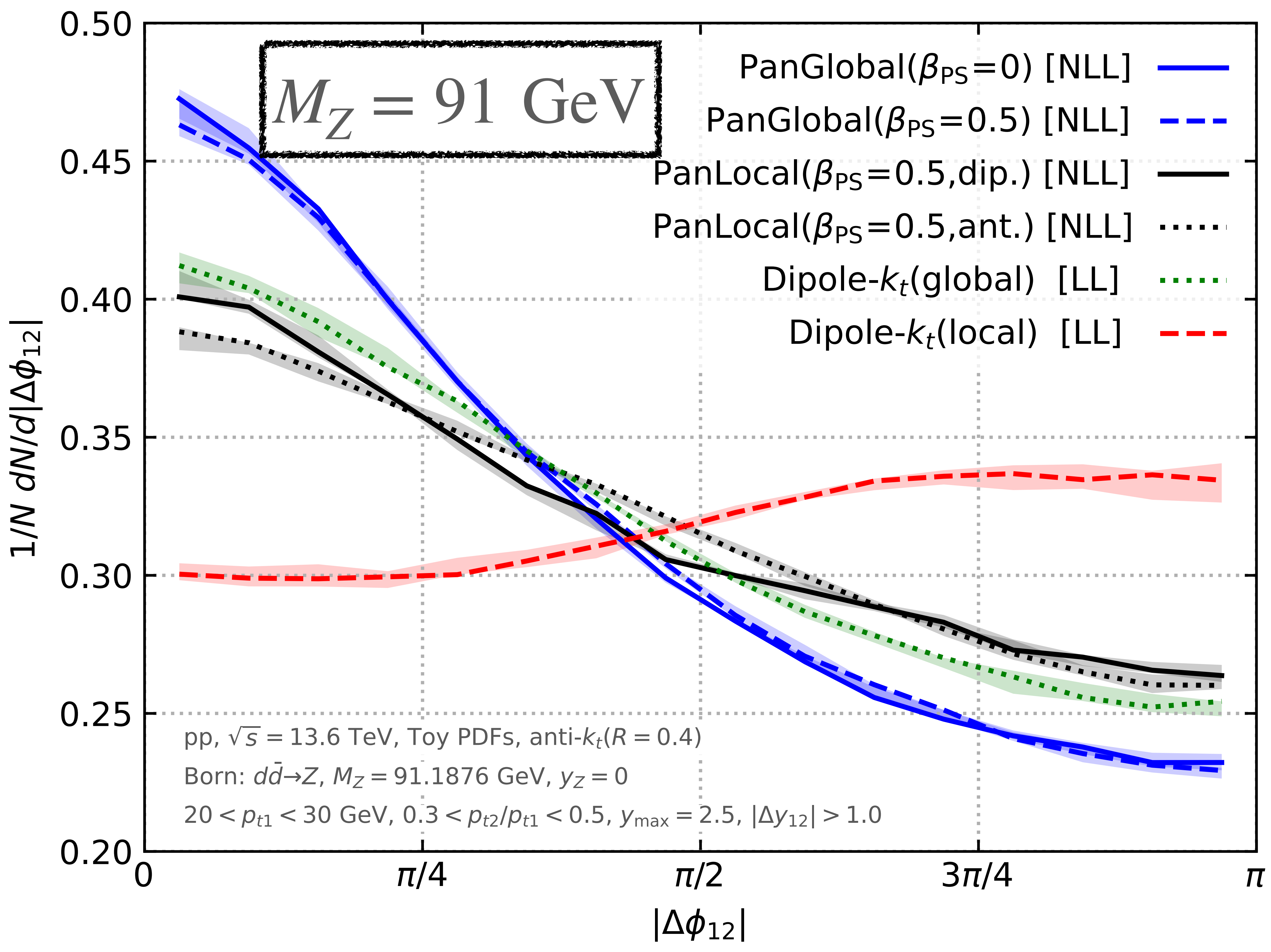
LL shower. At small pTZ, the spectrum is EXPONENTIALLY suppressed!

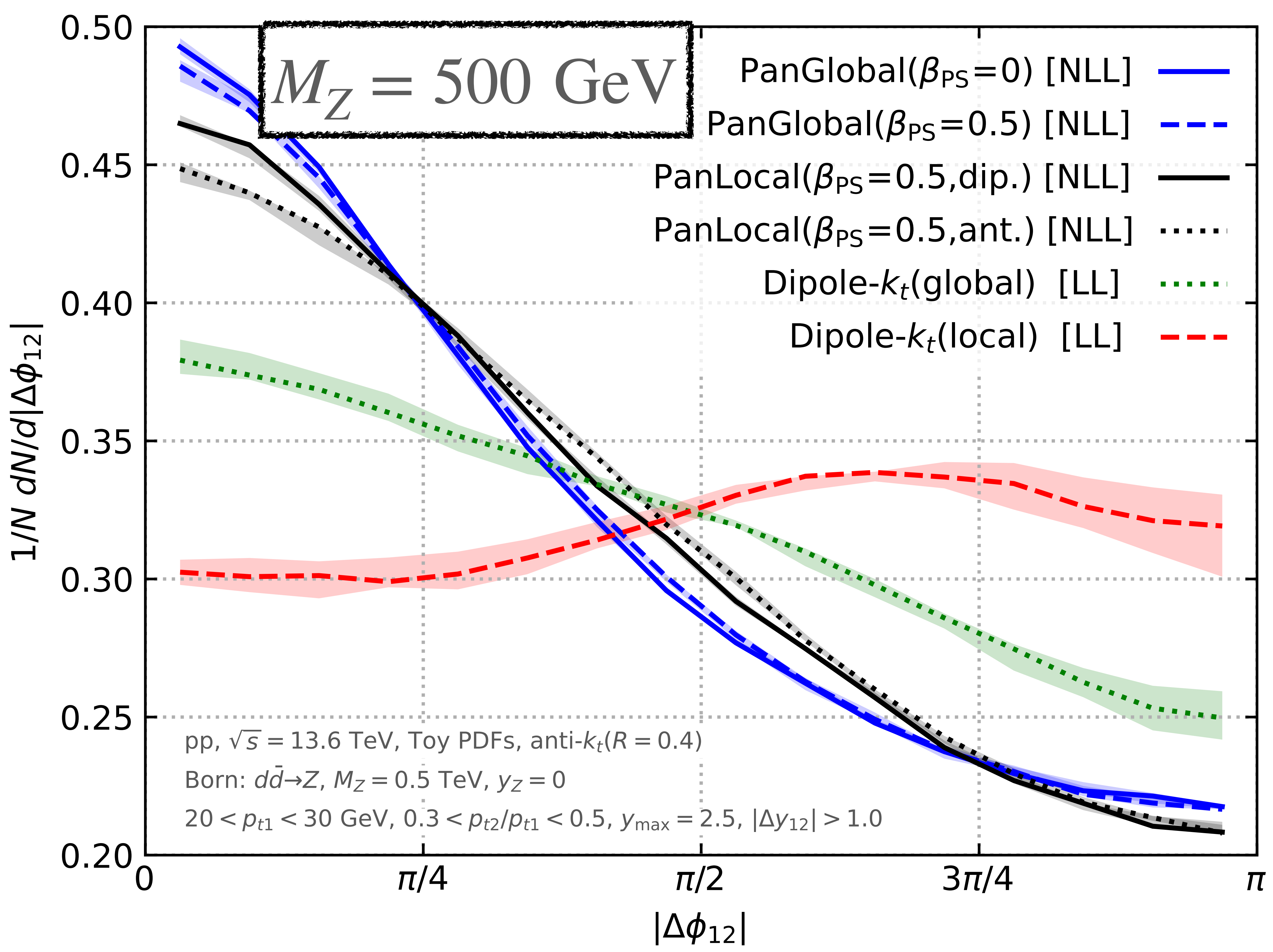
- The "better" LL shower is remarkably similar from the other NLL showers.
  - Is NLL important? Can we live with LL tuned showers?
- Scale variations smaller than PanLocal vs PanGlobal differences.
  - How to estimate PS uncertainties? PanLocal vs PanGlobal? Is this enough?

# Azimuthal correlations between the two leading jets in DY



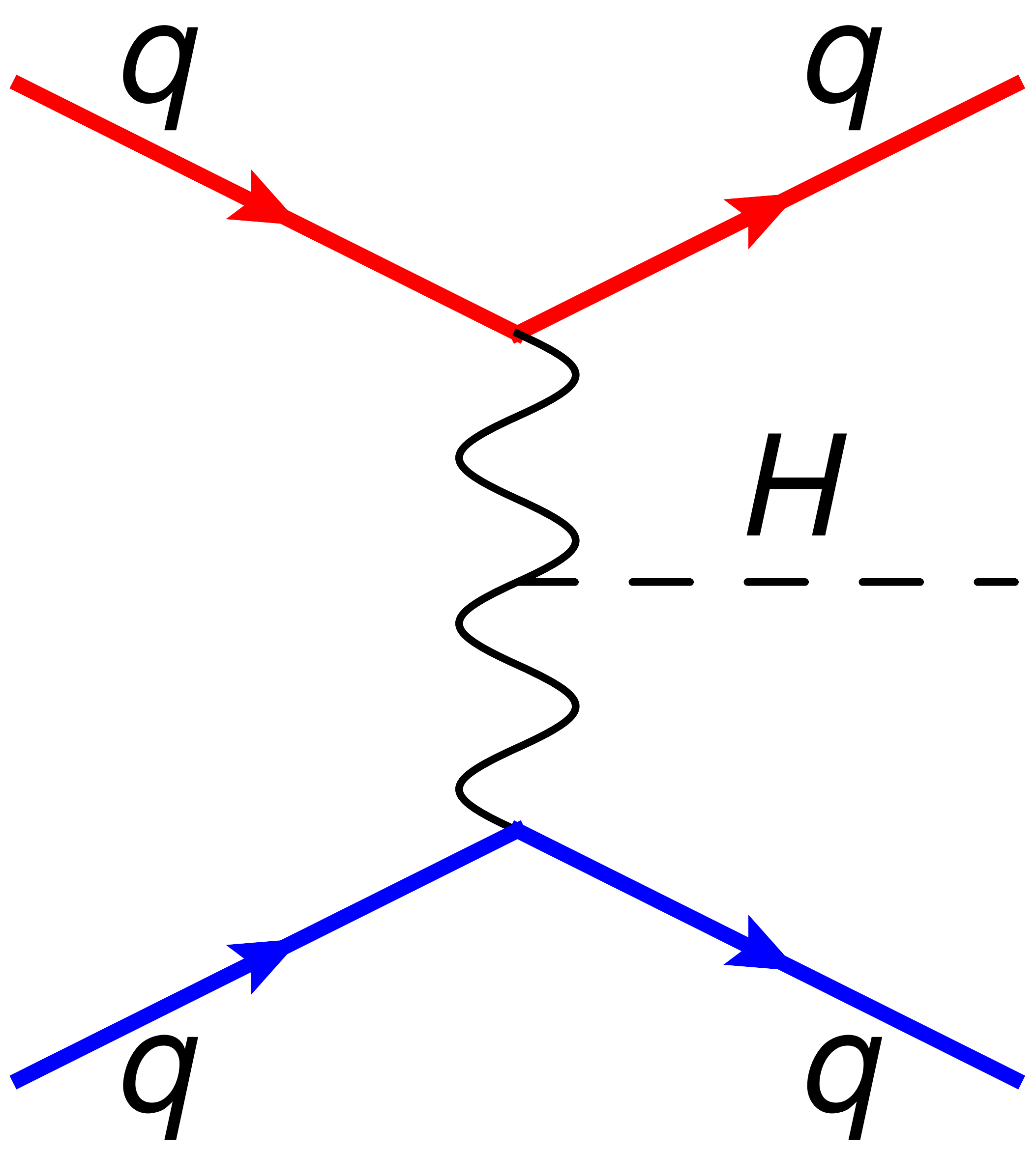
# Azimuthal correlations between the two leading jets in DY



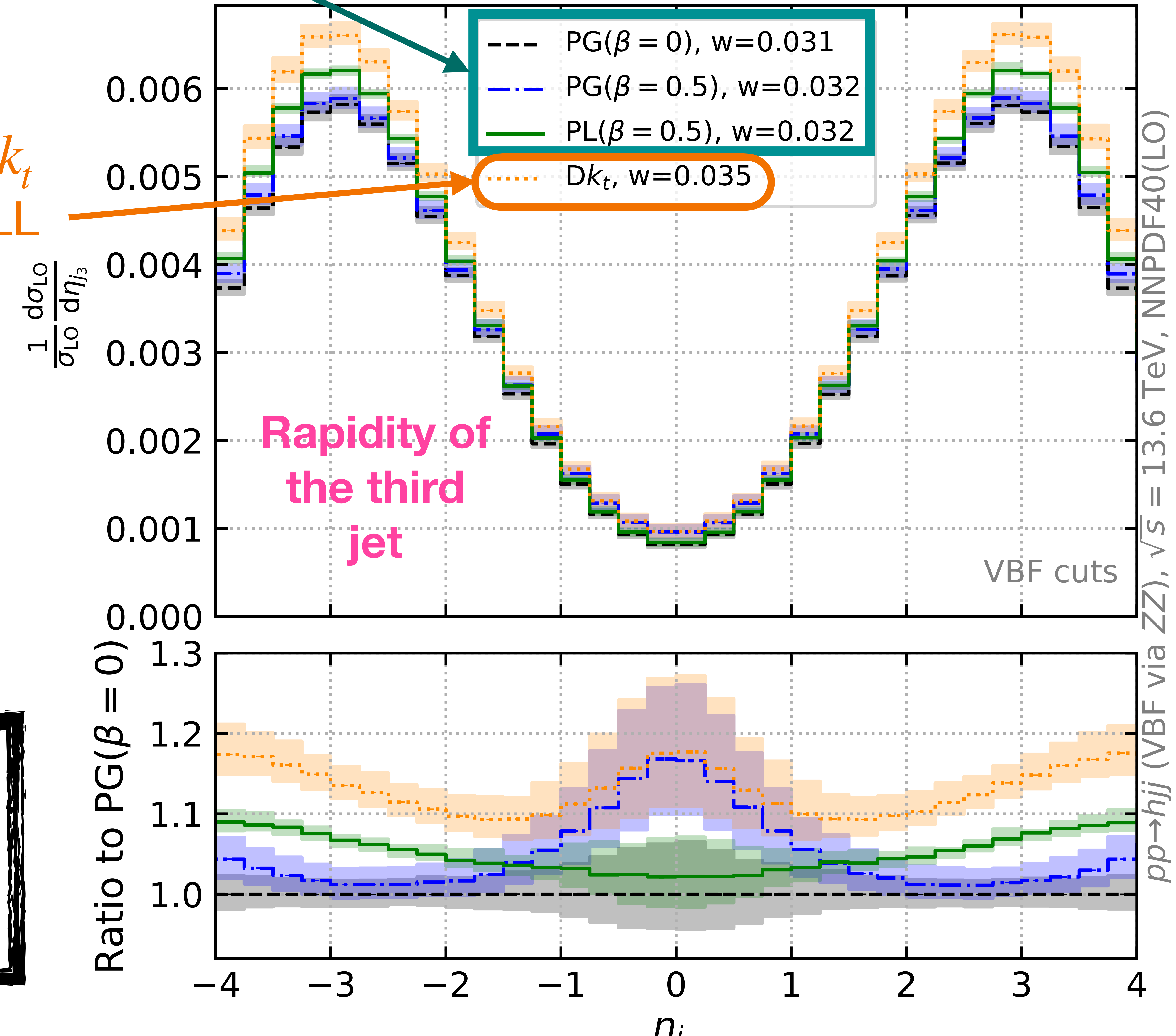

- Impossible to tune a **LL shower** to reproduce a NLL across several energy scales (at 91 GeV subleading effects are more sizeable and the shower is more tunable than at 500 GeV!)
- Difference among PS larger than scale uncertainty, and hence should be used to estimate **PS uncertainties**, until we gain more analytic understanding is required (i.e. PS differences might not be enough)

# Exploratory phenomenology for VBF




LO events obtained thanks to our **Pythia8.3** [2203.11601] interface!

➤ For exclusive observables, the LL shower lies outside the band spanned by the NLL showers



# Next steps

**Towards a complete public NLL shower**

**Going beyond NLL**

# Next steps

**Towards a complete public NLL shower**

**hadron collisions**:
more complex processes & associated tests

**Heavy quarks & resonances**
Essential for phenomenology

**Matching to hard matrix elements**
Essential for phenomenology, must be done in way that retains NLL accuracy, and possibly augments it. Already achieved for $e^+e^-$ [Karlberg, Hamilton, Salam, Scyboz, Verheyen, 2301.09645], work in progress for $e^+e^-$ with massive quarks, DY, ggH, DIS, VBF

**Interface to Pythia**
work in progress

**uncertainty estimates**

# Next steps

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more complex processes & associated tests

**Heavy quarks & resonances**
Essential for phenomenology

**Matching to Panscales NLL parton showers** — *Dr Alexander Karlberg*
*U4-08, Milan-Bicocca University* — 17:30 - 18:00

that retains NLL accuracy, and possibly augments it. Already achieved for $e^+e^-$ [Karlberg, Hamilton, Salam, Scyboz, Verheyen, 2301.09645], work in progress for $e^+e^-$ with massive quarks, DY, ggH, DIS, VBF

**Interface to Pythia**
work in progress

**uncertainty estimates**

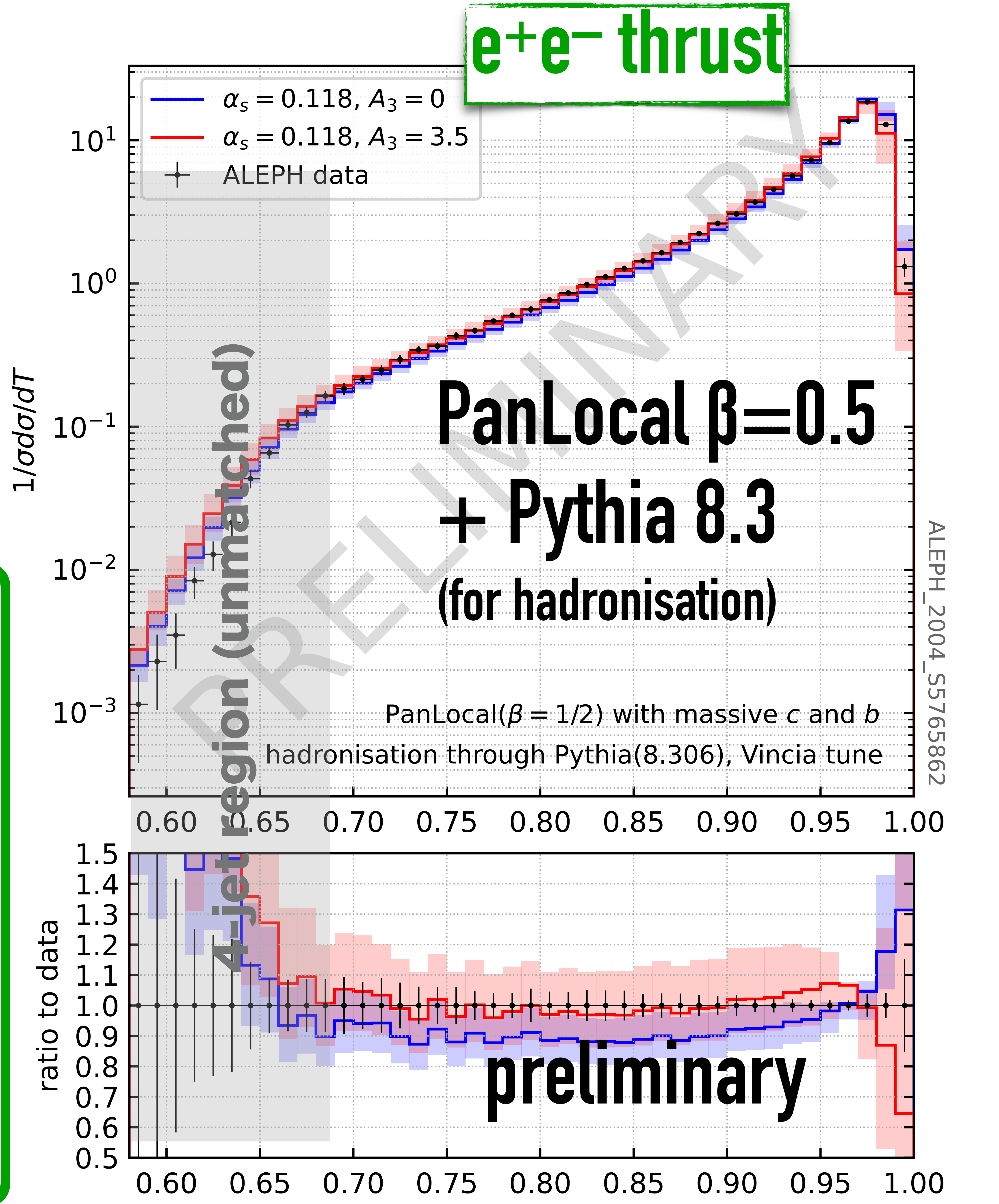
# Next steps

**Towards a complete public NLL shower**

## Comparison with data

- we're starting with $e^+e^-$ data
- understand nature of perturbative shower uncertainties
- and interplay with non-perturbative tuning
- preliminary treatment of heavy-quark masses

Medium term: making proper use of LEP data for tuning almost certainly requires NLO 3-jet accuracy.



# Next steps

**Underlying Calculations**

We need (a) reference results and (b) understanding of NNLL logs in soft & collinear limits

...

**Going beyond NLL**

...

Other groups' work (prior to our NLL understanding): Jadach et al 1103.5015 & 1503.06849, Li & Skands 1611.00013, Höche & Prestel 1705.00742, +Krauss 1705.00982, +Dulat 1805.03757,

# Next steps

**Underlying Calculations**
We need (a) reference results and (b) understanding of NNLL logs in **soft** & **collinear** limits

**Next-to-leading non-global logarithms in QCD**
Banfi, Dreyer and Monni, 2104.06416, 2111.02413

**Lund and Cambridge multiplicities**
Medves, Soto-Ontoso, Soyez, 2205.02861, 2212.05076

**Groomed jet mass studies**
Anderle, Dasgupta, El-Menoufi, Guzzi, Helliwell, 2007.10355; Dasgupta, El-Menoufi, Helliwell 2211.03820
[see also SCET work, Frye, Larkoski, Schwartz & Yan, 1603.09338 + …]

**Dissecting the collinear structure of quark splitting at NNLL**
Dasgupta, El-Menoufi, 2109.07496

# Next steps

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| | |
|---|---|
| **Lund plane resummation** | *Alba Soto Ontoso* |
| *U4-08, Milan-Bicocca University* | 16:30 - 17:00 |

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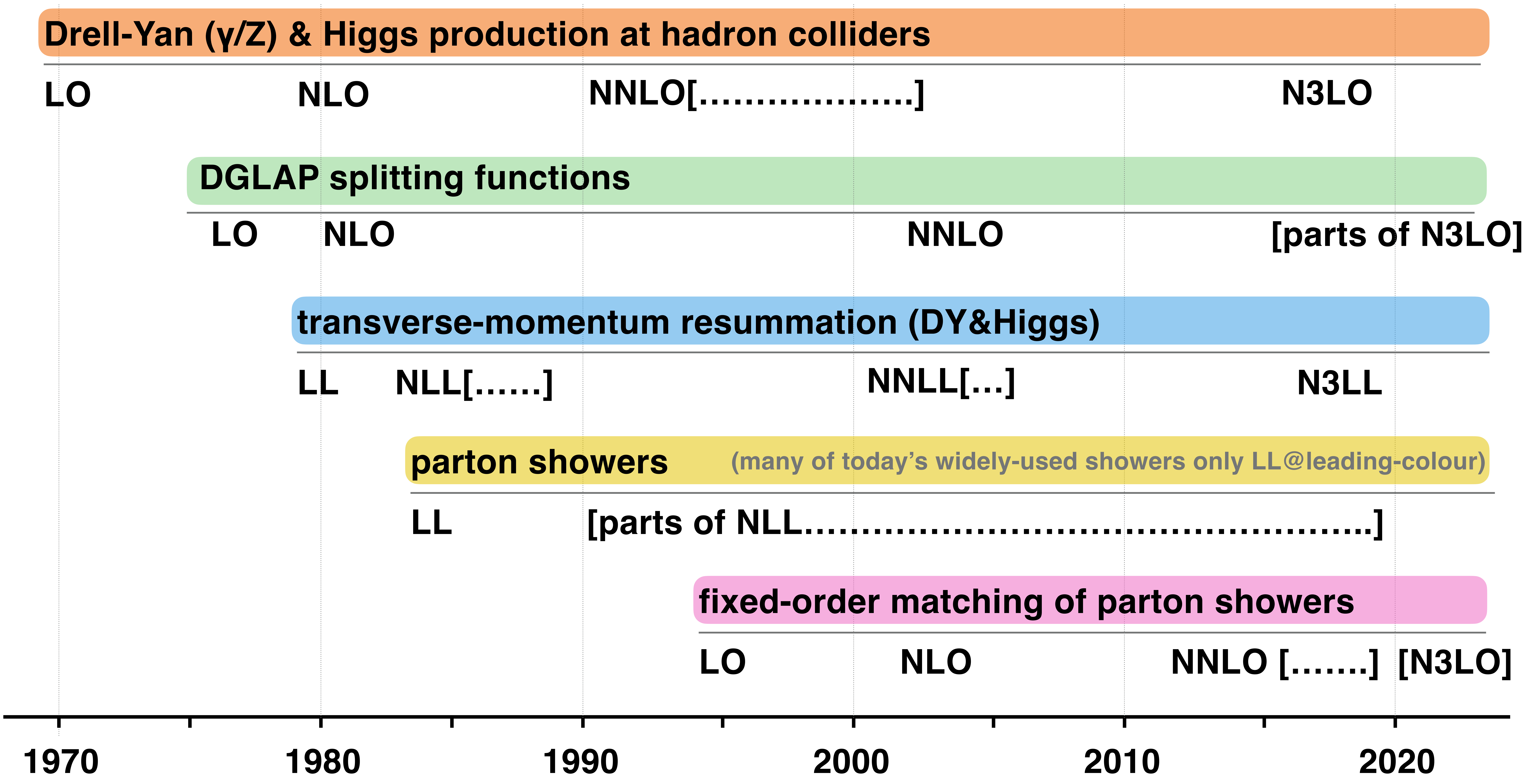
| | |
|---|---|
| **Collinear fragmentation of gluon jets at NNLL** | *Basem El-Menoufi* |
| *U4-08, Milan-Bicocca University* | 17:00 - 17:30 |

# BACKUP

# It's time for better Parton Showers!

*Slide from G. Salam*



# PanScales status: $e^+e^- \to$ jets, $pp \to Z/W/H$, DIS, VBF (structure function) (w. massless quarks)

| phase space region | critical ingredients | observables | accuracy | colour |
|---|---|---|---|---|
| **soft collinear** | no long-distance recoil | global event shapes | NLL | full |
| **hard collinear** | DGLAP split-fns + amplitude spin-correlations | fragmentation functions & special azimuthal observables | NLL | full |
| **soft commensurate angle** | large-$N_c$ dipoles | energy flow in slice | NLL | full up to 2 emsns, then LC |
| **soft, then hard collinear** | soft spin correlations | special azimuthal observables | NLL | full up to 2 emsns, then LC |
| **all nested** | – | subjet and/or particle multiplicity | NDL | full |

*Slide from G. Salam*

# how large are the logarithms?

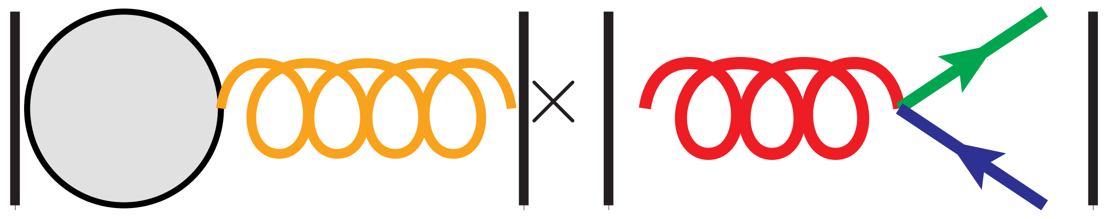
| $Q$ [GeV] | $\alpha_s(Q)$ | $p_{t,\min}$ [GeV] | $\xi = \alpha_s L^2$ | $\lambda = \alpha_s L$ | $\tau$ |
|---|---|---|---|---|---|
| 91.2 | 0.1181 | 1.0 | 2.4 | −0.53 | 0.27 |
| 91.2 | 0.1181 | 3.0 | 1.4 | −0.40 | 0.18 |
| 91.2 | 0.1181 | 5.0 | 1.0 | −0.34 | 0.14 |
| 1000 | 0.0886 | 1.0 | 4.2 | −0.61 | 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 |

**Table 1**: Values of $\xi = \alpha_s L^2$, $\lambda = \alpha_s L$ and $\tau$ (defined in Eq. (7.10)) for various upper ($Q$) and lower ($p_{t,\min}$) momentum scales. The coupling itself is in a 5-loop variable flavour number scheme [45–48], while $\tau$ is evaluated for 1-loop evolution with $n_f = 5$.

# Collinear spin-correlations in showers

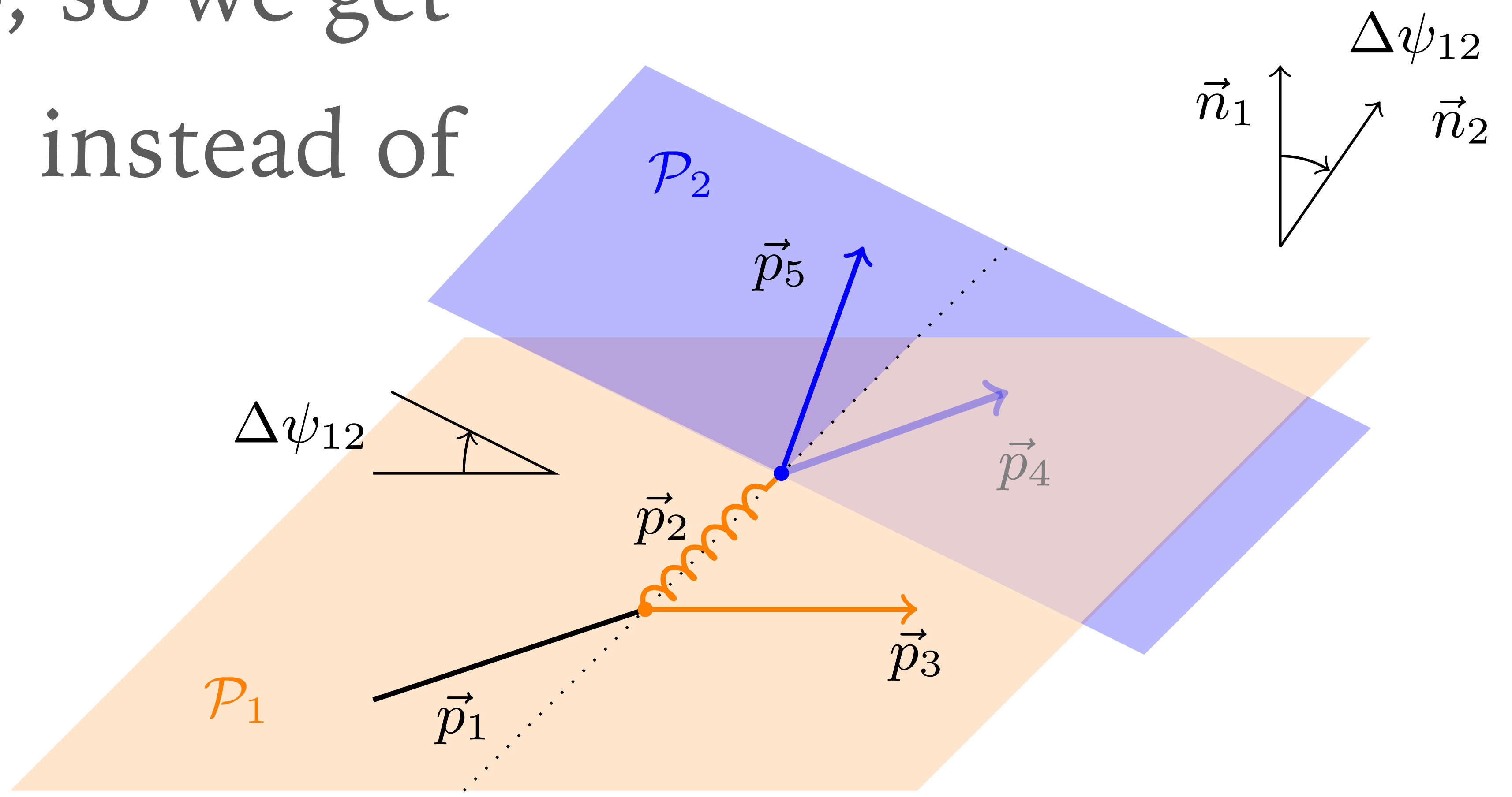
Shower emission probability are polarisations-averaged at every step, so we get

$$|\mathcal{M}|^2_{\mathrm{PS}} = \sum_{\lambda'_{\widetilde{ik}}} |\mathcal{M}_g^{\lambda'_{\widetilde{ik}}}|^2 \times \sum_{\lambda_{\widetilde{ik}}} \sum_{\lambda_i,\lambda_j} |\mathcal{M}_{g\to i,j}^{\lambda_{\widetilde{ik}}\lambda_i\lambda_k}|^2 =$$

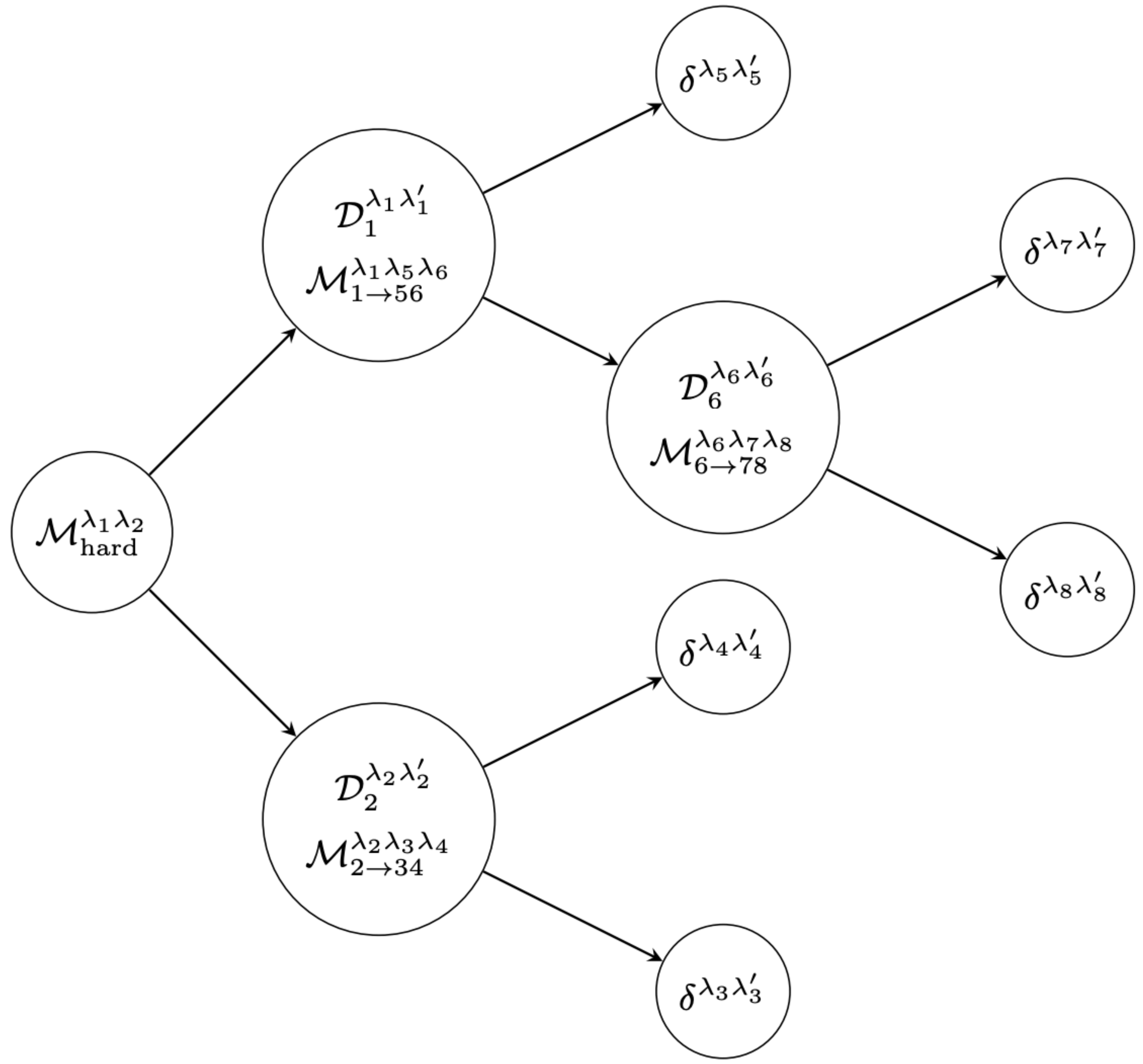


instead of

$$|\mathcal{M}|^2 = \sum_{\lambda_i,\lambda_j} |\sum_{\lambda_{\widetilde{ik}}} \mathcal{M}_g^{\lambda_{\widetilde{ik}}} \mathcal{M}_{g\to i,j}^{\lambda_{\tilde{ik}}\lambda_i\lambda_k}|^2 = |\mathcal{M}|^2_{\mathrm{PS}}(1+a\cos\Delta\psi)$$




**Spin-correlations capture the azimuthal modulations**




Collin ('88, FSR) Knowles ('88, ISR) algorithm.

For every emission, $\phi$ is decided on the basis of a **spin-density matrix**, which is then updated after the branching.

Implemented in the **Herwig7 angular-ordered**, **Herwig7 dipole [Richardson, Webster '18]**, and **PanScales [Karlberg, Salam, Scyboz, Verheyen '21]** showers.

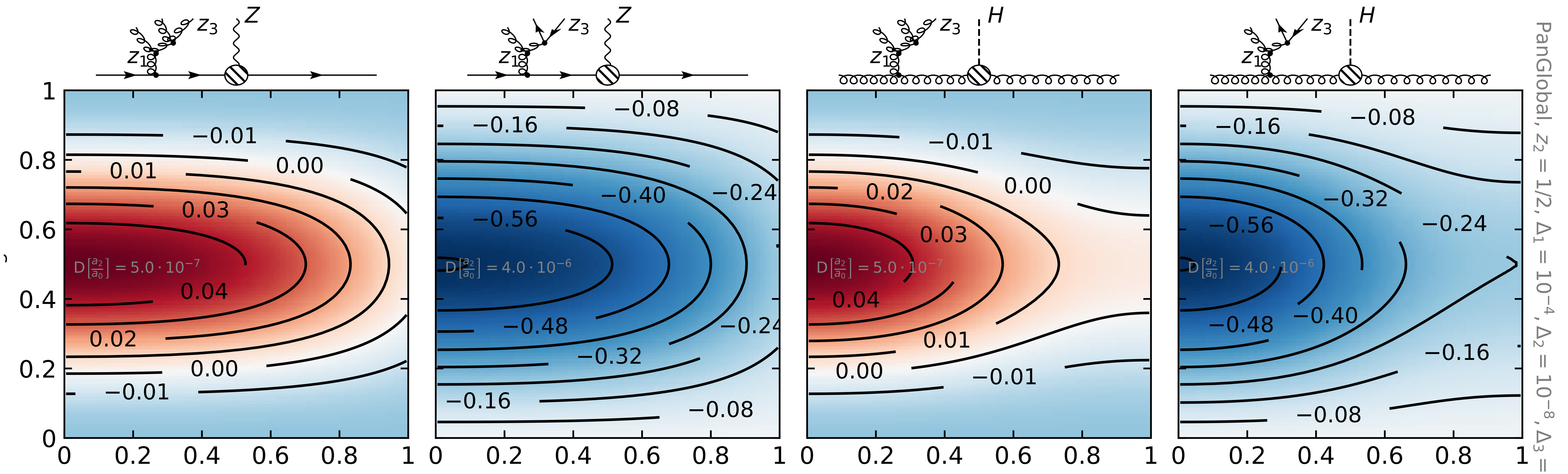
# Soft and collinear spin in PanScales

Karlberg, Salam, Scyboz, Verheyen, 2011.10054 [collinar spin in FSR]
Karlberg, Hamilton, Salam, Scyboz, Verheyen, 2111.01161 [soft spin in FSR]
van Beekveld, SFR, Salam, Soto-Ontoso, Soyez, Verheyen [generalisation to ISR]

We can have also azimuthal modulations due to the emission of a **soft gluon** $\mathscr{M} \approx \left( \frac{p_i}{p_i \cdot k} - \frac{p_j}{p_j \cdot k} \right) \epsilon_k$

Since it does not modify the spin of $i$ and $j$, it is possible to **interleave soft spin-correlations** (at leading colour) with **collinear ones** (at full colour), using the eikonal matrix element to update the spin-density tree for soft gluon emissions. **[Karlberg, Hamilton, Salam, Scyboz, Verheyen, '21]**

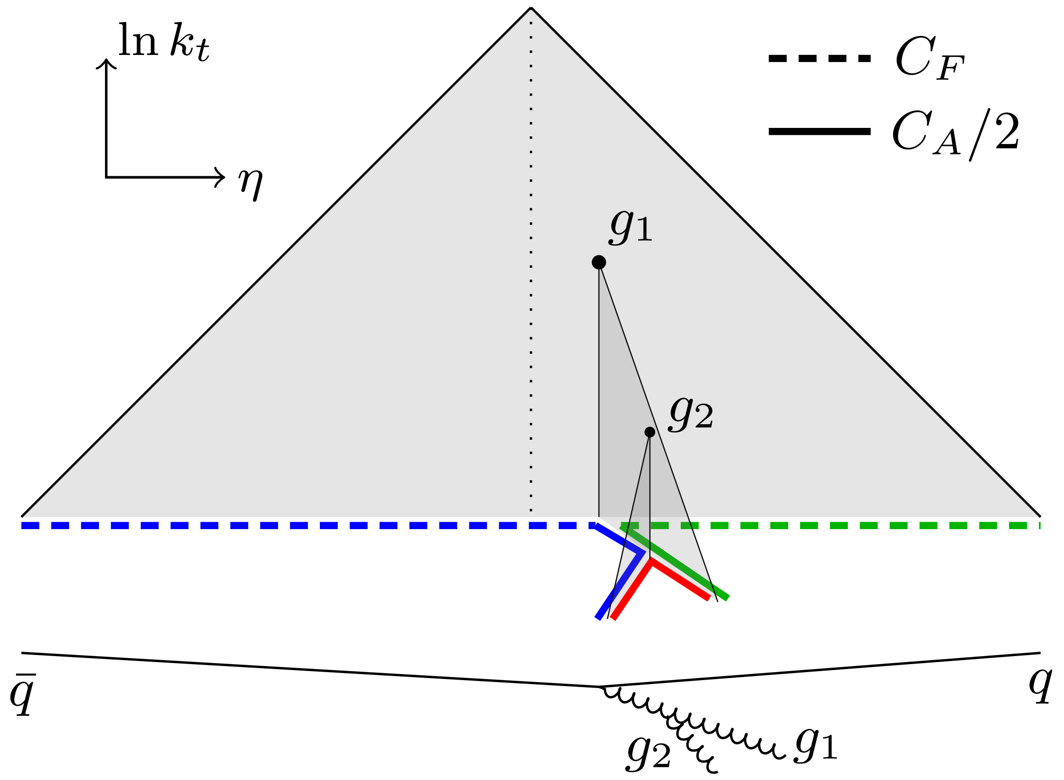
Also for hadron-collisions **[van Beekveld, SFR, Salam, Soto-Ontoso, Soyez, Verheyen '22]**



# Colour in the PanScales showers

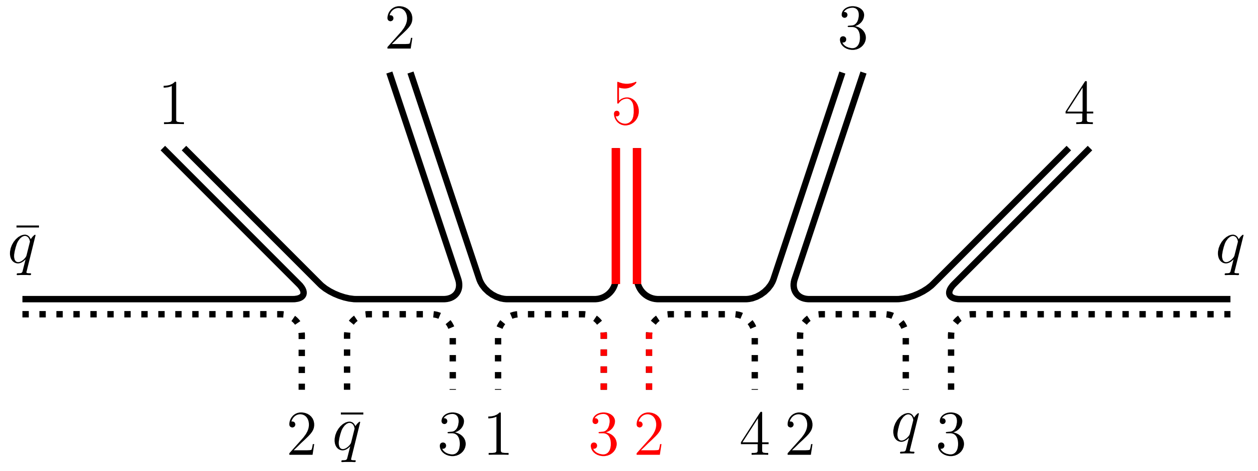
Hamilton, Medves, Salam, Scyboz, Soyez, 2011.10054 [FSR]
van Beekveld, SFR, Salam, Soto-Ontoso, Soyez, Verheyen [generalisation to ISR]

**Segment:** colour decided looking to which Lund plane the emission belongs: as good as an angular-ordered shower

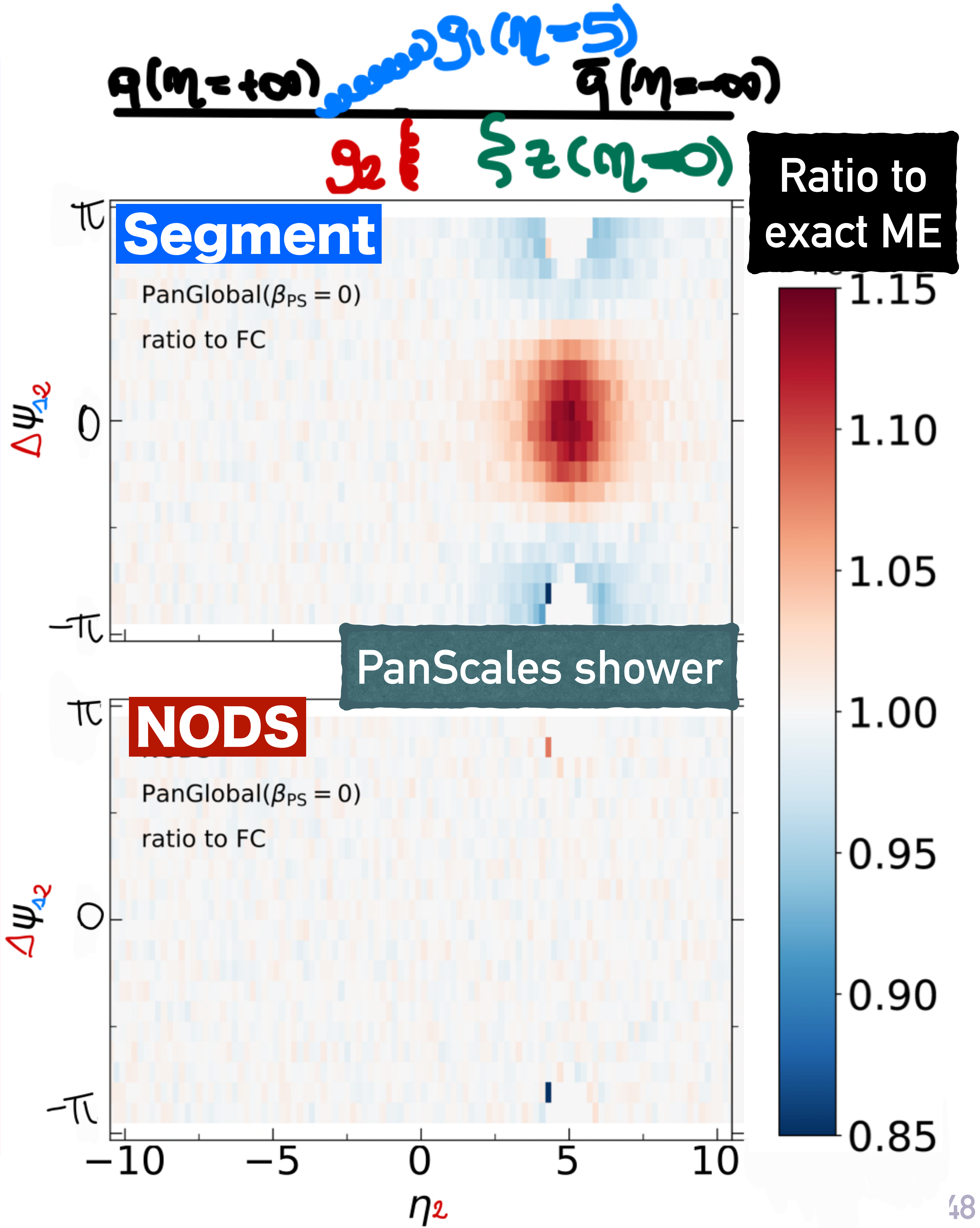



$$\bar{q}[-\infty, C_F, \eta_1^L, C_A, \eta_2^L, +\infty]_{g_2}$$
$$g_2[-\infty, C_A, \eta_2^R, C_A, +\infty]_{g_1}$$
$$g_1[-\infty, C_A, \eta_1^R, C_F, +\infty]_q$$
$$\eta_L = \max(0,\eta), \quad \eta_R = \min(0,\eta)$$

**NODS:** nested (double soft) matrix element corrections assuming last emission is the softest




$$p(g_5 | g_2, g_3) \approx 1 - \left(\frac{C_A - 2C_F}{C_A}\right) \frac{(1,4)}{(1,2) + (2,3) + (3,4)}$$



# The Past

## PSR21 - Parton Showers and Resummation

**The PanScale shower approach** *Pier Francesco Monni*
14:20 - 14:40

**Spin correlations in the PanScales parton showers and jet observables** *Rob Verheyen*
15:10 - 15:25

**Subleading colour effects in the PanScales parton showers and beyond** *Ludovic Scyboz*
16:00 - 16:15

**Groomed jet mass as a direct probe of collinear parton dynamics** *Basem El-Menoufi*
16:15 - 16:30

# The Past

PSR21 - Parton Showers and Resummation

**The PanScale shower approach** *Pier Francesco Monni*

Next-To-Leading-Logarithmic, leading colour, dipole showers for lepton colliders

**Spin correlations in the PanScales parton showers and jet observables** *Rob Verheyen*

Soft and collinear spin correlations to reach NLL in dipole showers (final-state radiation only)

**Subleading colour effects in the PanScales parton showers and beyond** *Ludovic Scyboz*

Next-To-Leading-Logarithmic dipole showers for lepton colliders at full colour

**Groomed jet mass as a direct probe of collinear parton dynamics** *Basem El-Menoufi*

Gaining analytic insights to build NNLL showers

# The Present

**Lund plane resummation** *Alba Soto Ontoso*

*U4-08, Milan-Bicocca University* 16:30 - 17:00

Gaining more analytic insights to build NNDL/NNLL showers

**Collinear fragmentation of gluon jets at NNLL** *Basem El-Menoufi*

*U4-08, Milan-Bicocca University* 17:00 - 17:30


**Panscales** *Silvia Ferrario Ravasio*

*U4-08, Milan-Bicocca University* 16:30 - 17:00

NLL showers for hadron colliders

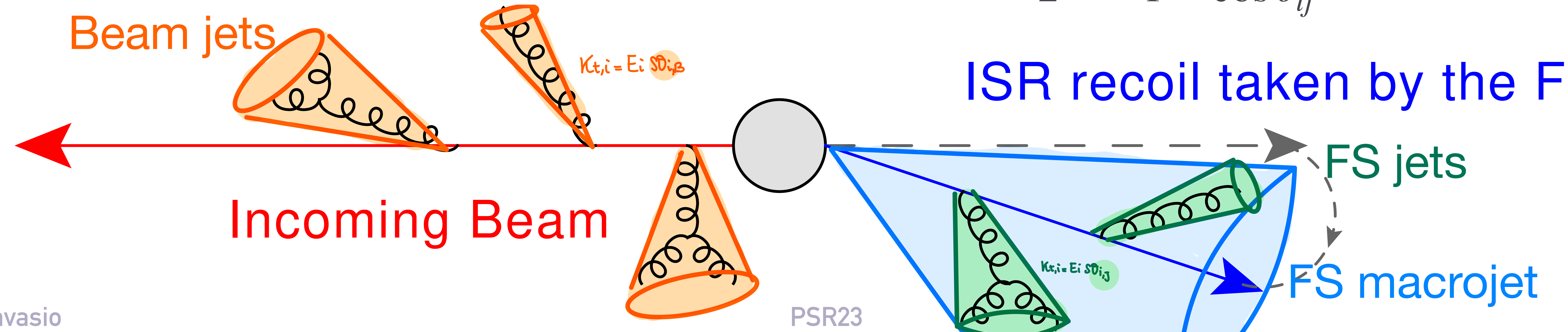
**Matching to Panscales NLL parton showers** *Dr Alexander Karlberg*

*U4-08, Milan-Bicocca University*

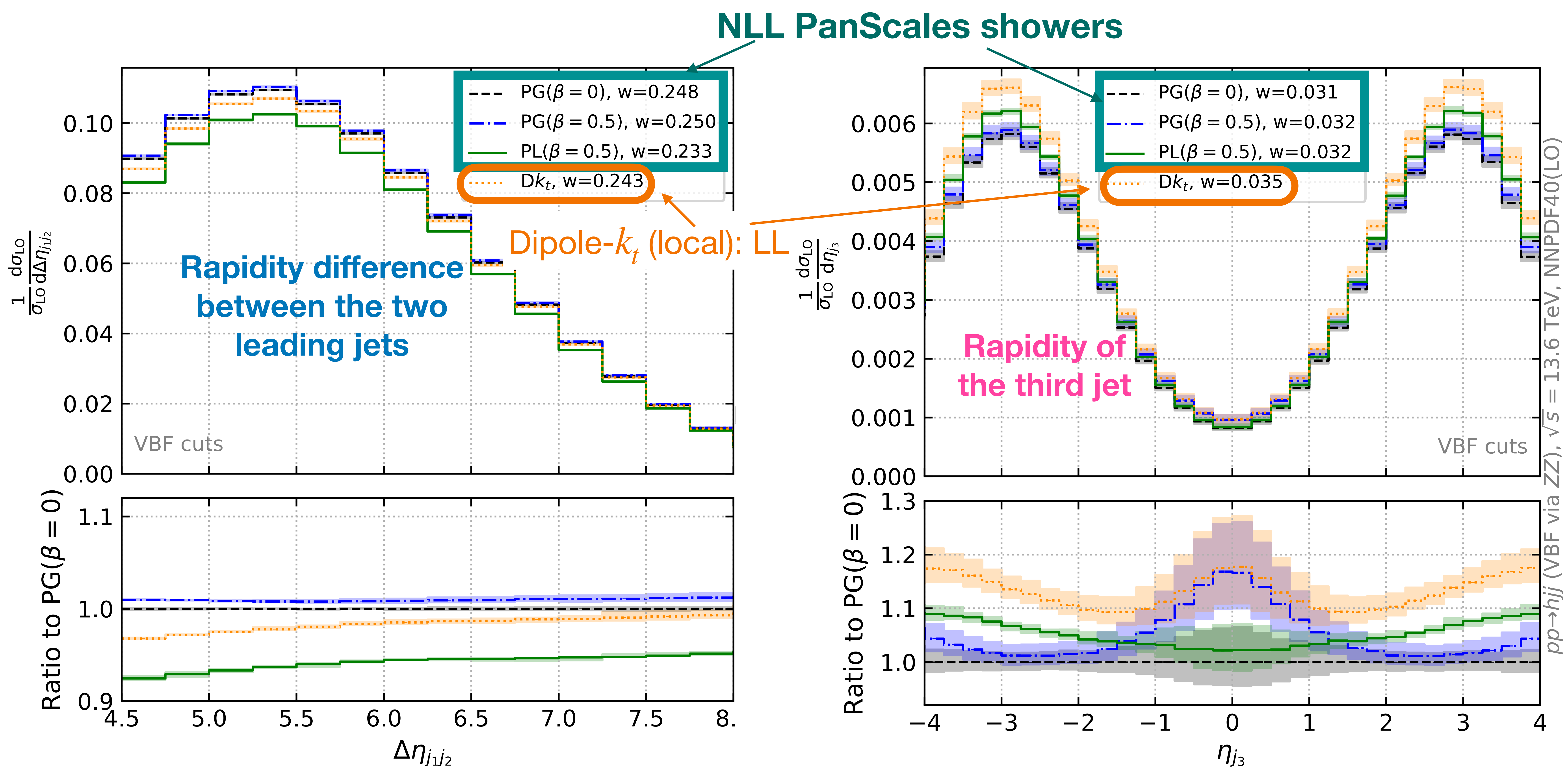
Matching to reach NNDL in $e^+e^-$ event shapes

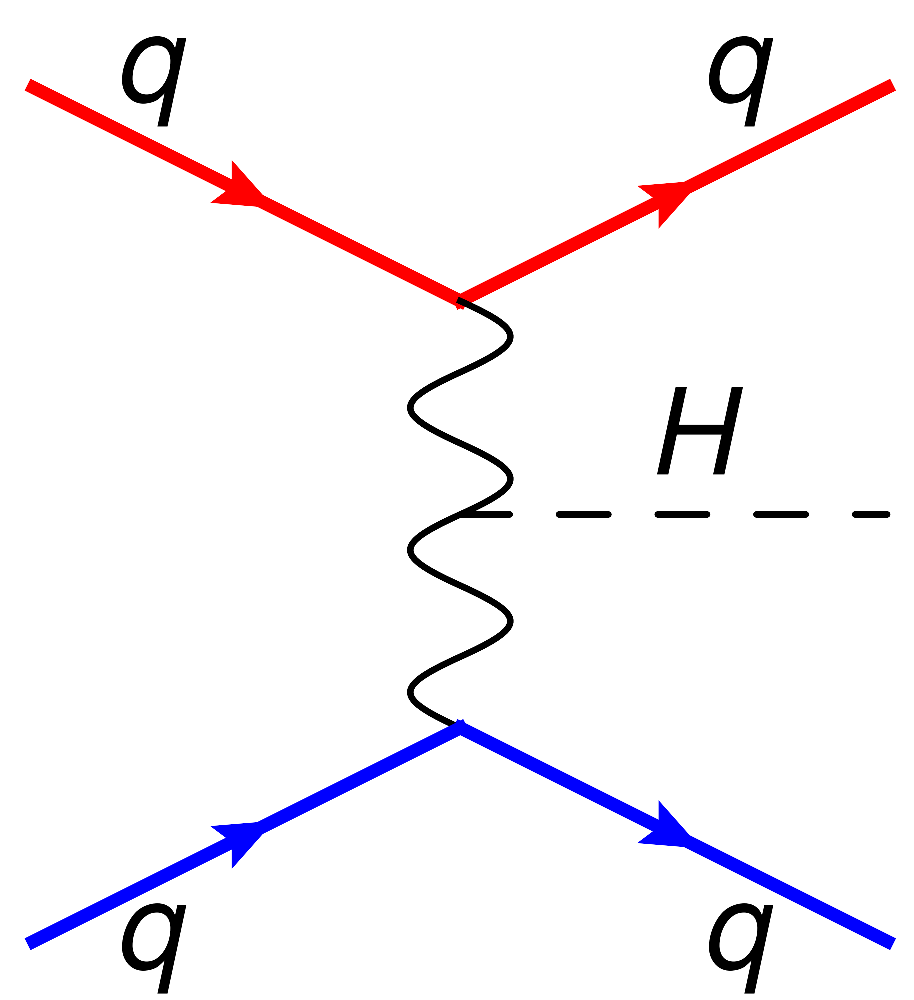
# Jet algorithm and Lund variables for DIS

- Use **C/A**-type distance to beam (B) and to each pair of partons: $d_{iB} = 1 - \cos\theta_i, \qquad d_{ij} = 1 - \cos\theta_{ij}$
- If $d_{ij}$ is smallest → cluster, if $d_{iB}$ is smallest → call it a "proto-jet". Stop when all the final-state partons have been clustered in proto-jets.
- The protojets comprise several **beam jets**, and one fat **'final-state' macro-jet:** latter is tagged by **largest** $\beta_j$ where $p_j^\mu = \alpha_j n_1^\mu + \beta_j n_2^\mu + p_{j,\perp}^\mu$, with $n_1^\mu = x_{\rm dis} P^\mu, \;\; n_2^\mu = q_{\rm dis}^\mu + n_1^\mu$.
- Inspect the cluster history of the **final-state macro-jet**: for every branching, the softest pseudo-jet becomes now a **final-state jet.**
- The Lund coordinates associated with each **beam jet** correspond to its physical rapidity and $k_t$, for a **final-state jet** $j$, originated from a $\widetilde{ij} \to i, j$ splitting, we have $k_{t,j}^2 = E_j^2 \sin^2\theta_{ij}, y_j = \frac{1}{2}\log\frac{1+\cos\theta_{ij}}{1-\cos\theta_{ij}}$



# Exploratory phenomenology for VBF




**LO events** obtained thanks to our **Pythia8.3** [2203.11601] interface!

- For inclusive observables, differences have the same size of NLO corrections. LL shower lies between the NLL predictions.
- For exclusive observables, the LL shower lies outside the band spanned by the NLL showers