High Precision for Hard Processes 2024 - 10.09.24

MATCHING NLO CALCULATIONS WITH NLL PANSCALES SHOWERS WITH INITIAL-STATE PARTONS

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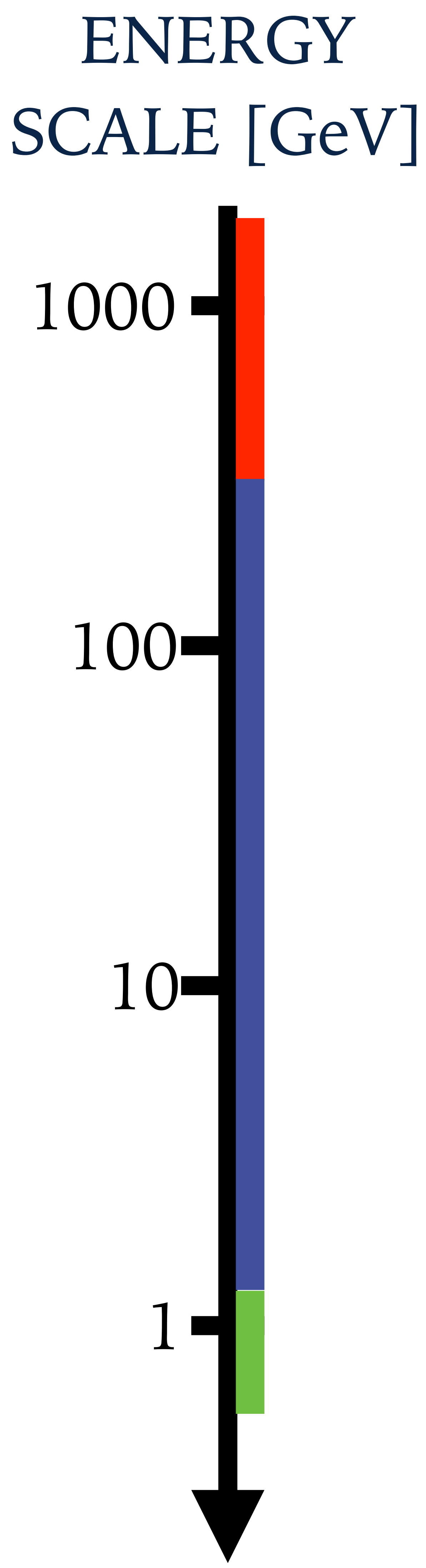
UNIVERSITY OF OXFORD

with M. van Beekveld, S. Ferrario Ravasio, J. Helliwell, A. Karlberg, G.P. Salam, L. Scyboz, A. Soto-Ontoso, G. Soyez

A LHC EVENT

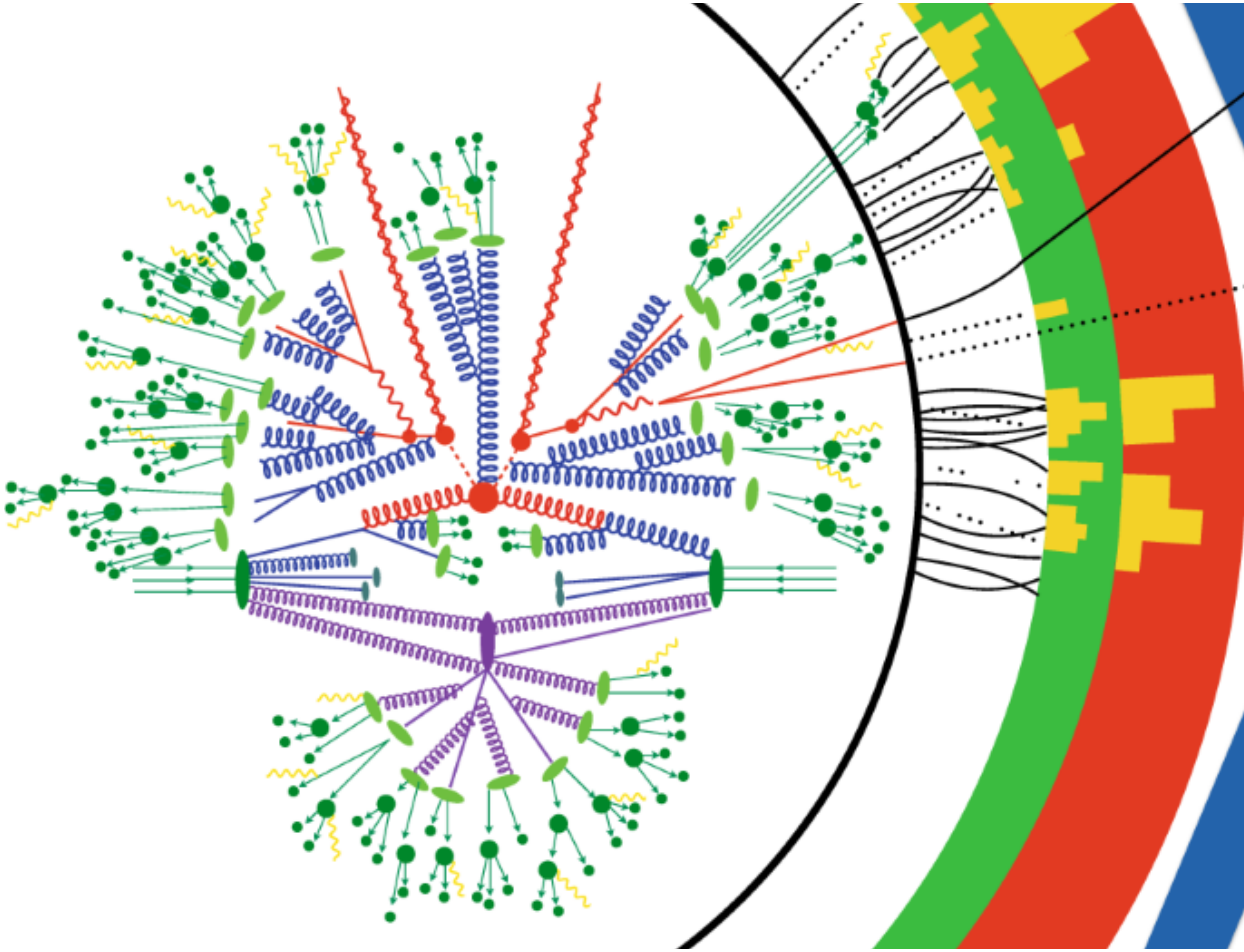


HARD SCATTERING

PARTON SHOWER

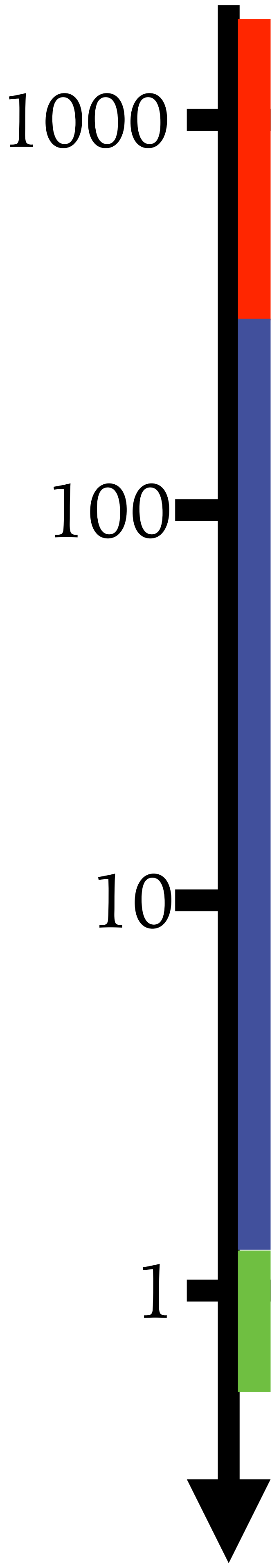
HADRONIZATION

UNDERLYING EVENT



A LHC EVENT

ENERGY SCALE [GeV]



MATCHING

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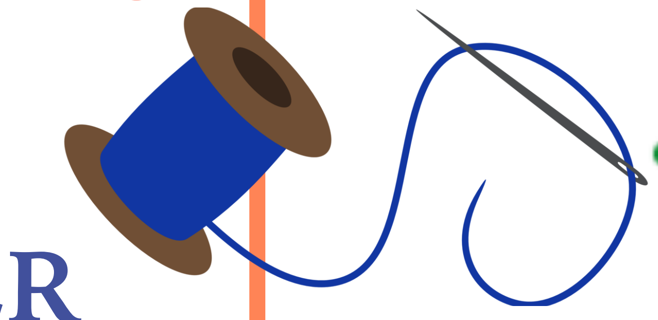

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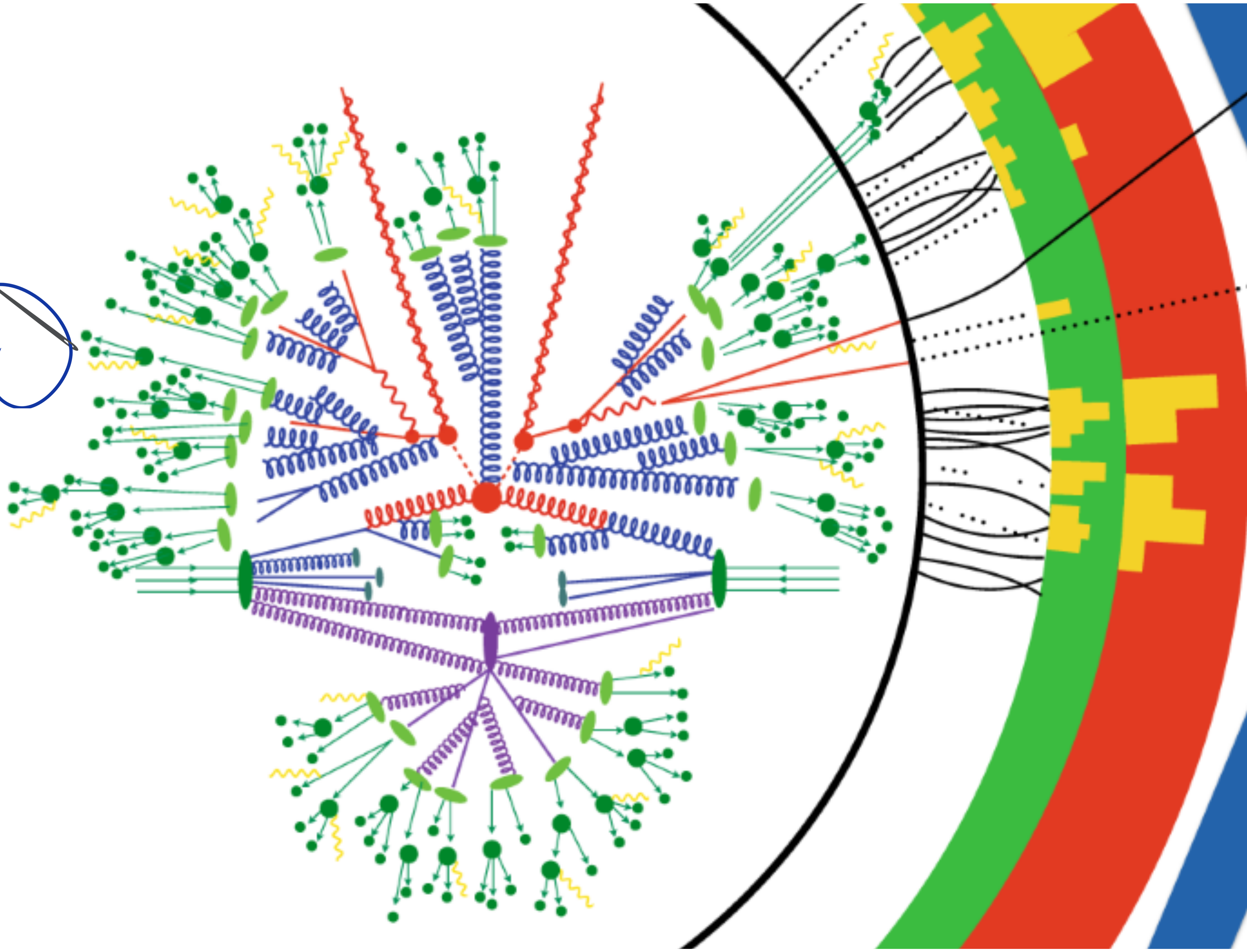
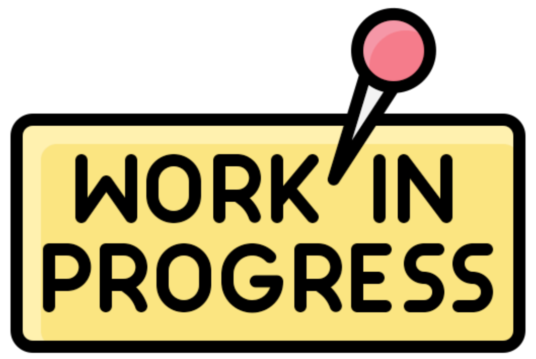


MATCHING

NLO+LL$_{\text{PS}}$

- A **solved problem** for long time.
- Completely understood and **fully automatized**.
- Two main approaches available: POWHEG [Nason '04; Frixione, Nason, Oleari '07; Alioli, Nason, Oleari, Re '10] and MC@NLO [Frixione, Webber '02].



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- Two main methods available: MiNNLO$_{\text{PS}}$ [Monni, Nason, Re, Wiesemann, Zanderighi '19] and Geneva [Alioli, Bauer, Berggren,Tackmann,Walsh, Zuberi '13, + subsequent papers].

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… what's the next step?

NLL SHOWERS

NLL showers are now available

Parton showers beyond leading logarithmic accuracy #1

Mrinal Dasgupta (U. Manchester (main)), Frédéric A. Dreyer (Oxford U., Theor. Phys.), Keith Hamilton (U. Coll. London), Pier Francesco Monni (CERN), Gavin P. Salam (Oxford U., Theor. Phys.) et al. (Feb 25, 2020)

Published in: *Phys.Rev.Lett.* 125 (2020) 5, 052002 • e-Print: 2002.11114 [hep-ph]

PanScales

A new approach to color-coherent parton evolution #1

Florian Herren (Fermilab), Stefan Höche (Fermilab), Frank Krauss (Durham U., IPPP), Daniel Reichelt (Durham U., IPPP), Marek Schoenherr (Durham U., IPPP) (Aug 11, 2022)

Published in: *JHEP* 10 (2023) 091 • e-Print: 2208.06057 [hep-ph]

Alaric

A partitioned dipole-antenna shower with improved transverse recoil #1

Christian T. Preuss (Wuppertal U.) (Mar 28, 2024)

Published in: *JHEP* 07 (2024) 161 • e-Print: 2403.19452 [hep-ph]

Apollo

Building a consistent parton shower #1

Jeffrey R. Forshaw (Manchester U. and Schrodinger Inst., Vienna), Jack Holguin (Manchester U. and Schrodinger Inst., Vienna), Simon Plätzer (Schrodinger Inst., Vienna and Vienna U.) (Mar 13, 2020)

Published in: *JHEP* 09 (2020) 014 • e-Print: 2003.06400 [hep-ph]

Forshaw-Holguin-Plätzer

Summations of large logarithms by parton showers #1

Zoltán Nagy (DESY), Davison E. Soper (Oregon U.) (Nov 9, 2020)

Published in: *Phys.Rev.D* 104 (2021) 5, 054049 • e-Print: 2011.04773 [hep-ph]

Deductor

NLL SHOWERS

For e^+e^- matching, see [2301.09645]

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#1

APOLLO

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THIS TALK:

NLO+NLL$_{\text{PS}}$ matching with PanScales showers with initial-state partons

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DEDUCTOR

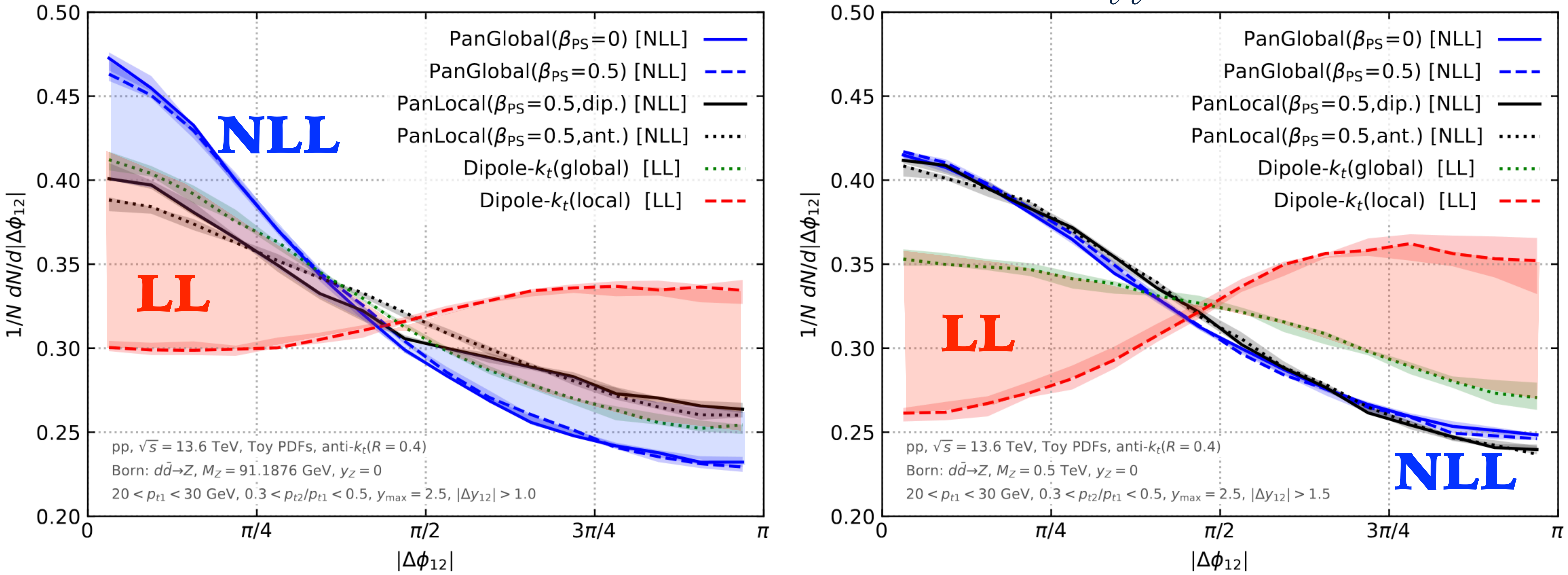
[van Beekveld, Ferrario Ravasio, Hamilton, Salam, Soto-Ontoso, Soyez, Verheyen ‘22]

MOTIVATION

1. NLL showers are likely to become a fundamental ingredient of the precision physics program at the LHC.

DY - azimuthal angle between leading jets

$m_{\ell\ell} = m_Z$ $\qquad$ $m_{\ell\ell} = 500$ GeV



Different shape between LL and NLL showers, especially at high energies

MOTIVATION

1. NLL showers are likely to become a fundamental ingredient of the precision physics program at the LHC.
2. NLO matching can augment the shower accuracy.

$$\Sigma(\alpha_s, L) = \exp\left(\underbrace{\frac{1}{\alpha_s} g_1(\alpha_s L)}_{\text{LL},\ \mathcal{O}(1/\alpha_s)} + \underbrace{g_2(\alpha_s L)}_{\text{NLL},\ \mathcal{O}(1)} + \underbrace{\alpha_s\, g_3(\alpha_s L)}_{\text{NNLL},\ \mathcal{O}(\alpha_s)}\right)$$

NLO MATCHING

$$\Sigma(\alpha_s, L) = (1 + \underbrace{\alpha_s C_1}_{\text{NLO},\ \mathcal{O}(\alpha_s)}) \exp\left(\frac{1}{\alpha_s} g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s\, g_3(\alpha_s L)\right)$$

Using a double log expansion:

$$\Sigma(\alpha_s, L) = \underbrace{h_1(\alpha_s L^2)}_{\text{DL}} + \underbrace{\sqrt{\alpha_s}\, h_2(\alpha_s L^2)}_{\text{NDL}} + \underbrace{\alpha_s\, h_3(\alpha_s L^2)}_{\text{NNDL}}$$

For event-shapes:
C_1 + NLL → NNDL

MOTIVATION

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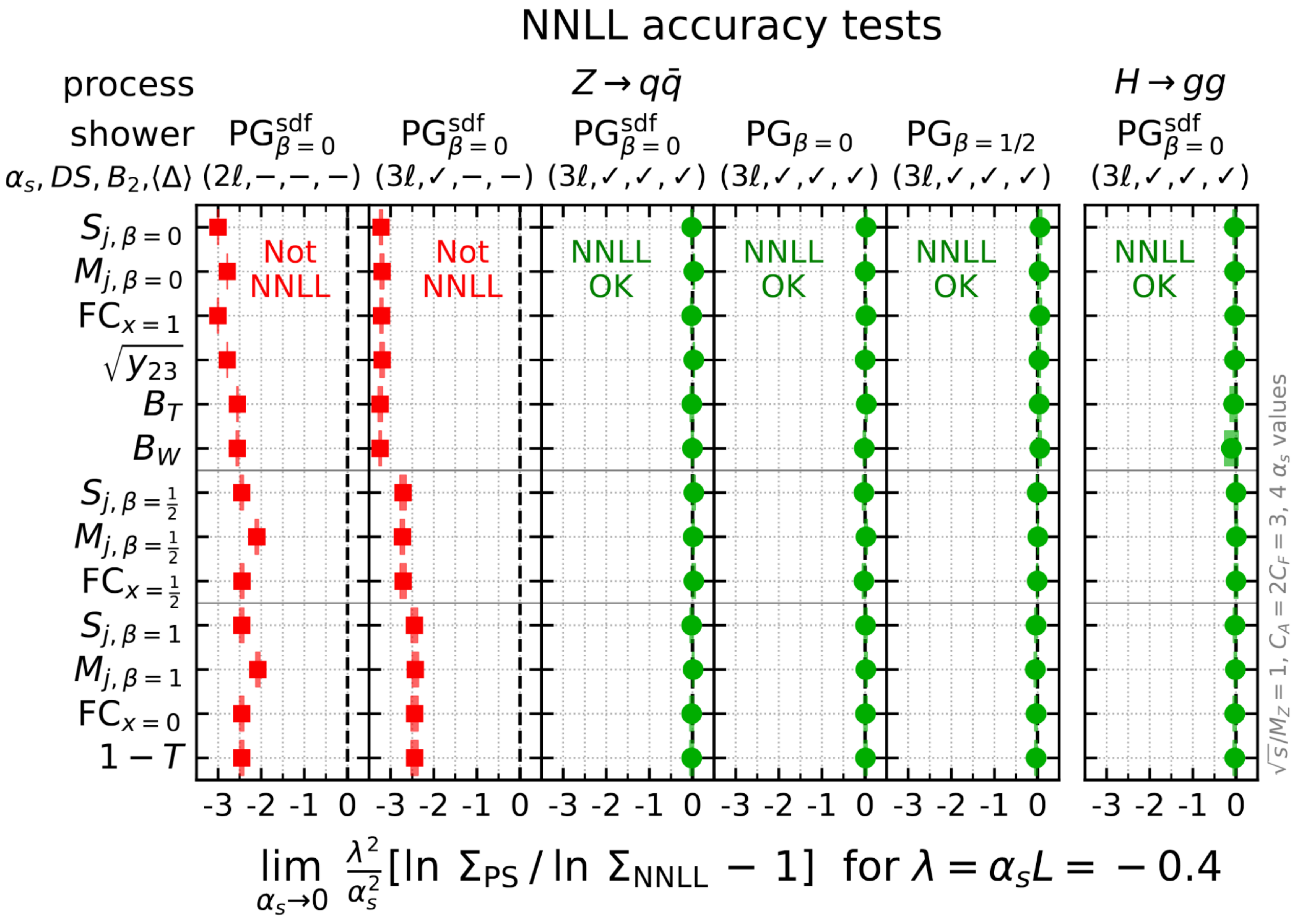
3. NLO matching is needed for obtaining NNLL accurate showers.



[van Beekveld, et al. ’24]

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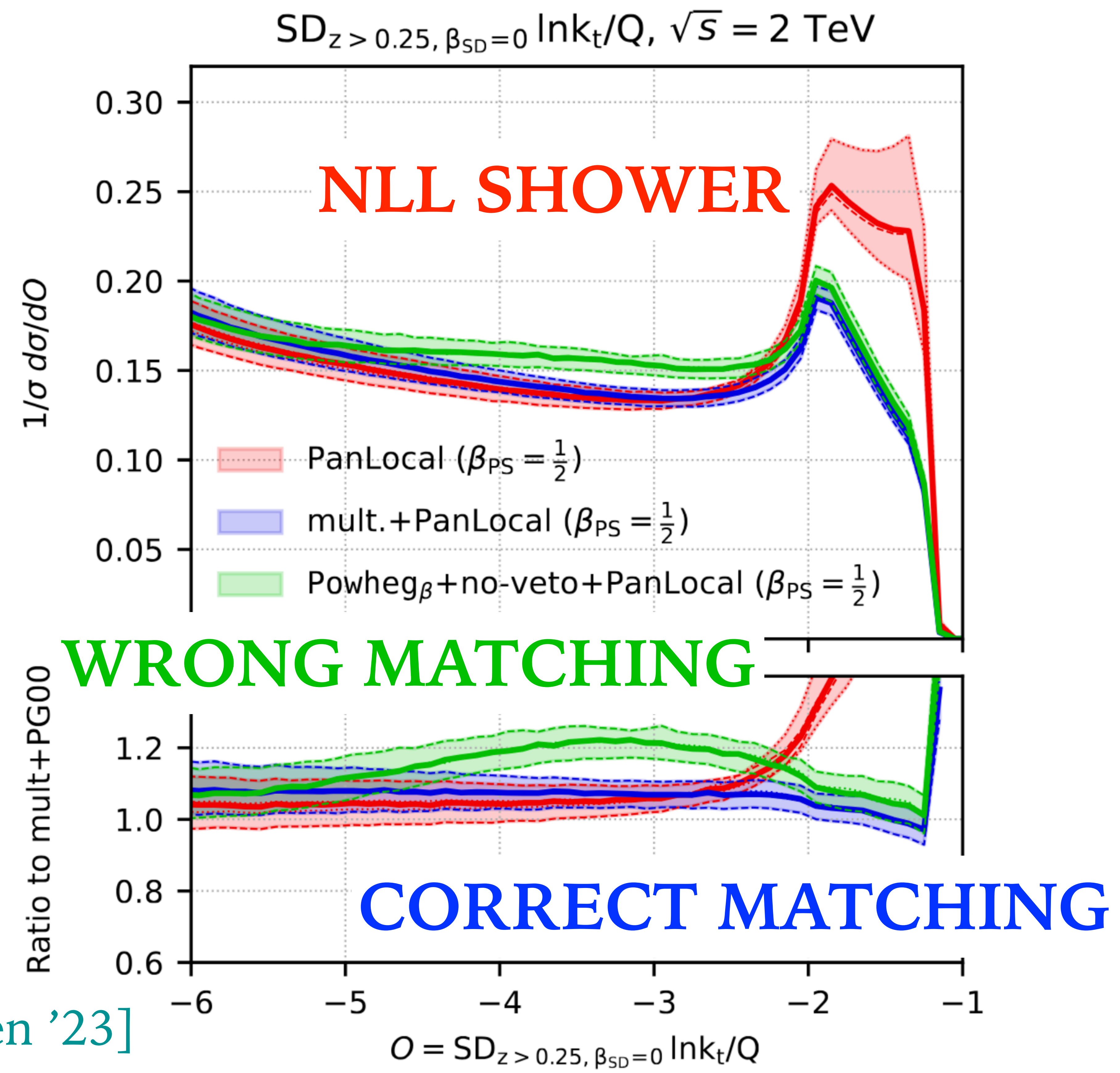
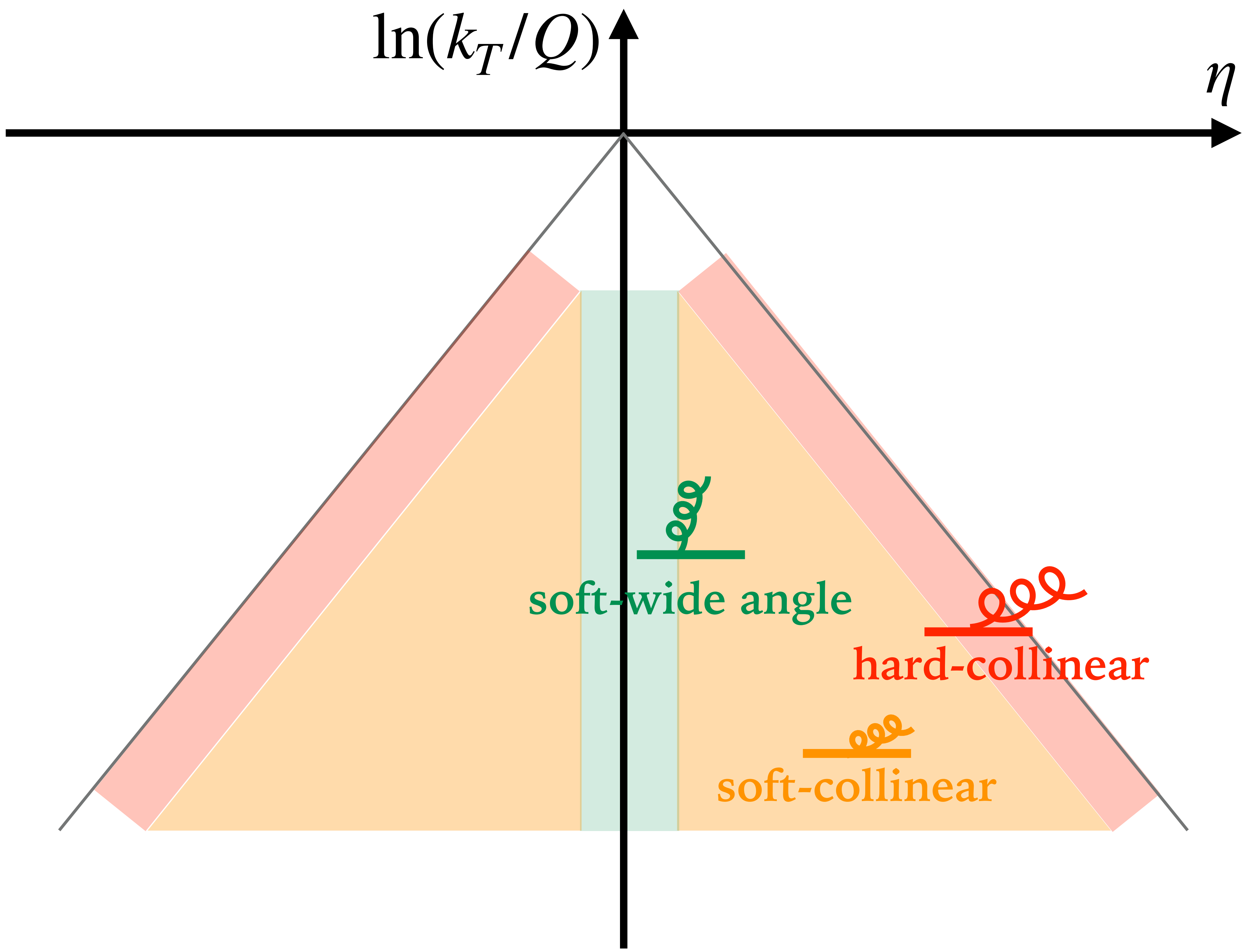
IF MATCHING IS DONE WRONGLY, THE STRUCTURE OF THE SHOWER CAN BREAK.



[Hamilton, Karlberg, Salam, Scyboz, Verheyen ’23]

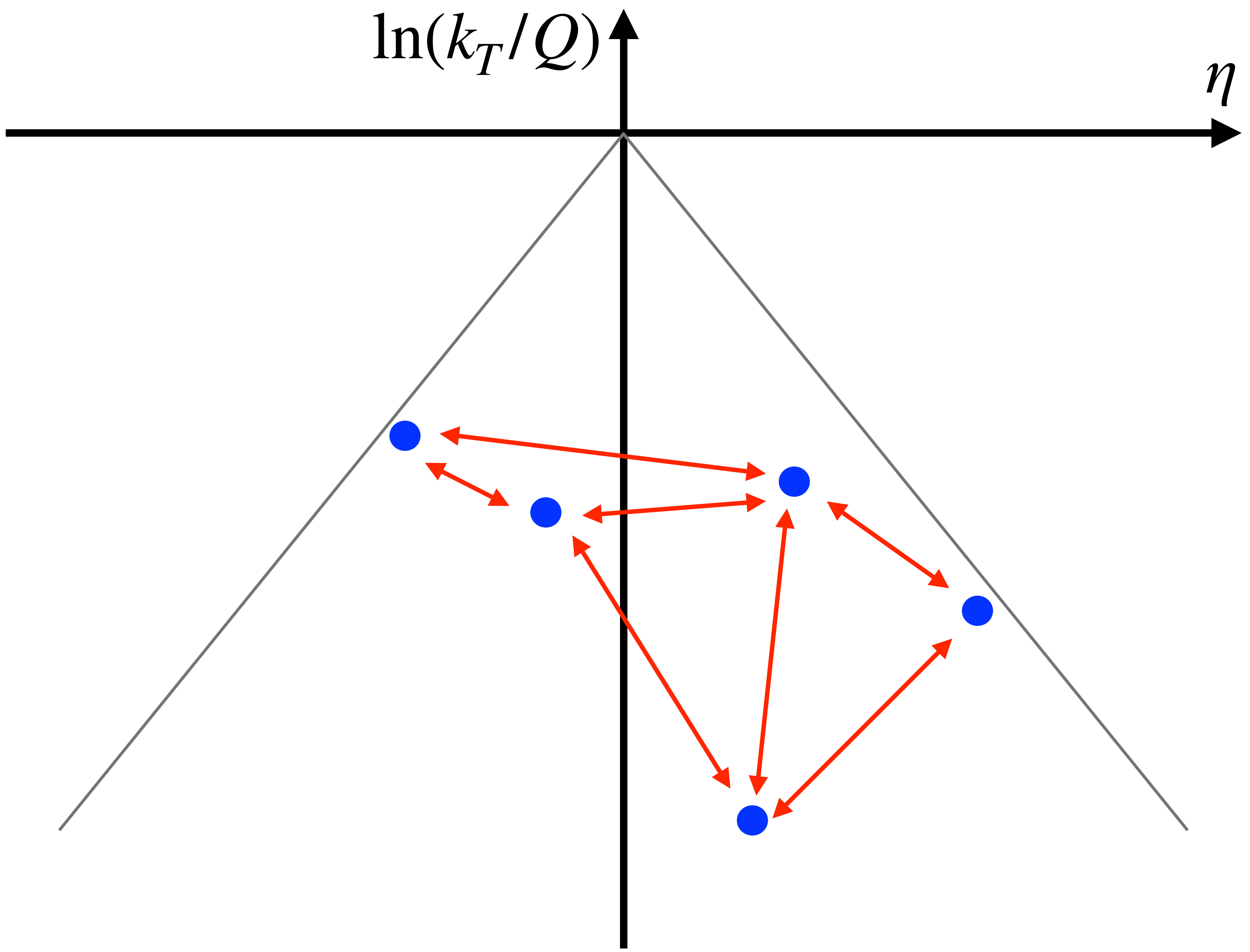
NLL PanScales SHOWERS IN A NUTSHELL



NLL PanScales SHOWERS IN A NUTSHELL

1. The shower must reproduce the exact matrix element when all emissions are well separated in at least k_T or η.

2. The shower must reproduce NLL analytic results for a broad class of observables (e.g. event shapes, subjet multiplicities).



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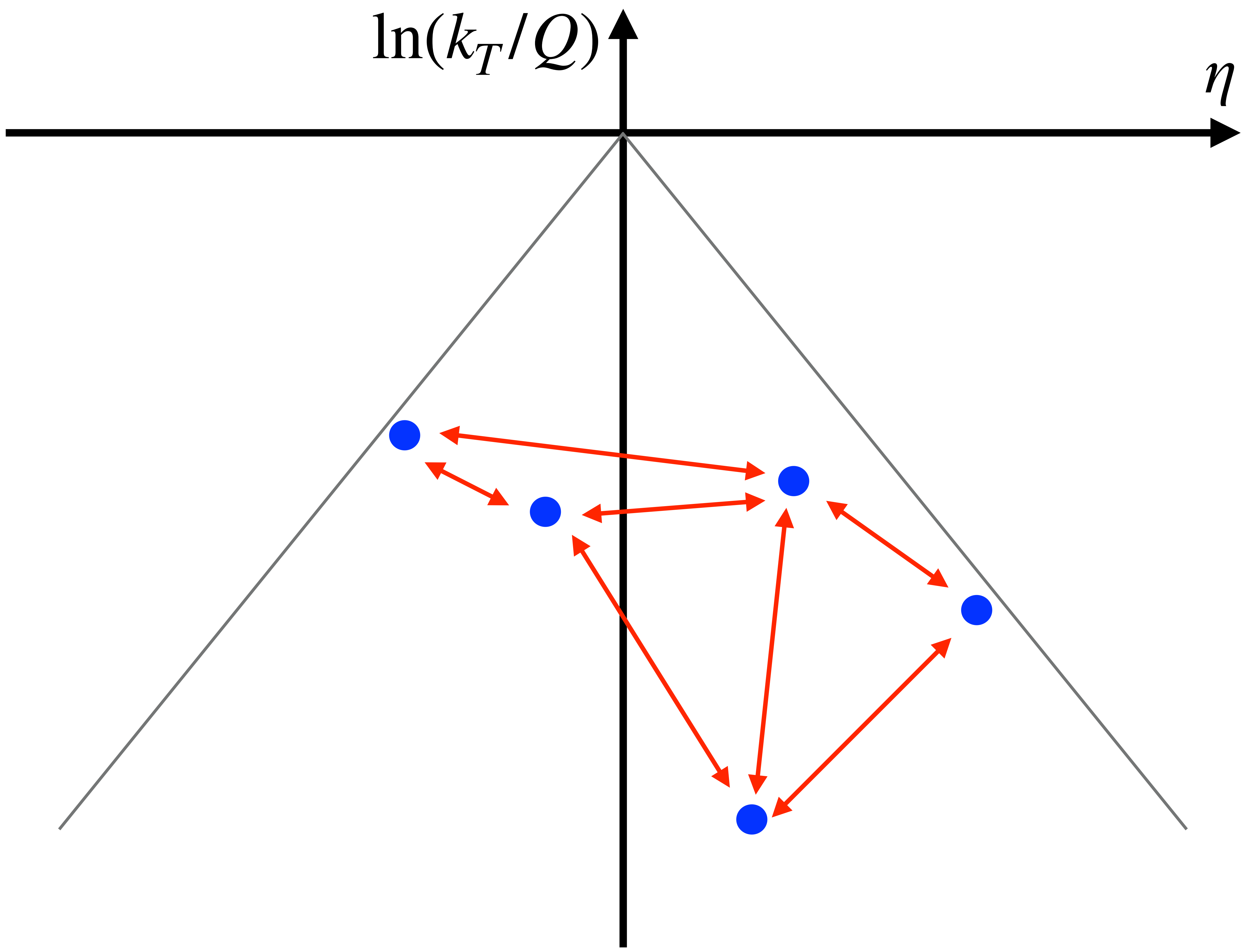
The PanScales Recipe

- **Ordering variable:** $v = k_t e^{-\beta|\eta|}$
- **Recoil scheme:**

  PanLocal: $\{\perp, +, -\}$ local

  PanGlobal: $\perp$ global, $\{+, -\}$ local
- **Partitioning of the dipole in event com frame**



THE METHOD

MULTIPLICATIVE MATCHING

$$d\sigma(\Phi_B) = \bar{B}(\Phi_B) \left[S(\Phi_B) \times \frac{R(\Phi_B, \Phi_{\mathrm{rad}})}{B(\Phi_B)} d\Phi \right] I_{\mathrm{PS}}$$

THE METHOD

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a) Reach NLO accuracy in the normalization $\bar{B}$. Analytically when possible, otherwise numerically.

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a) Reach NLO accuracy in the normalization $\bar{B}$. Analytically when possible, otherwise numerically.

b) Generate the first emission with the exact real matrix element.

c) Generate all the subsequent emissions through a NLL shower.

a) Normalization

The Born kinematics is generated according to the NLO cross section as:

$$d\sigma = \bar{B}(\Phi_B)\, d\Phi_B \qquad \text{with} \qquad \bar{B}(\Phi_B) = B + V + \int R\, d\Phi_{\text{rad}}$$

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Use analytic $\bar{B}$ when available:

DIS (photon only): $$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}y} = \frac{4\pi\alpha^2}{xyQ^2}\left(\left(1-y\right)F_2 + y^2 x F_1\right)$$

with:

- x and y usual DIS variables
- F_1 and F_2 NLO structure functions

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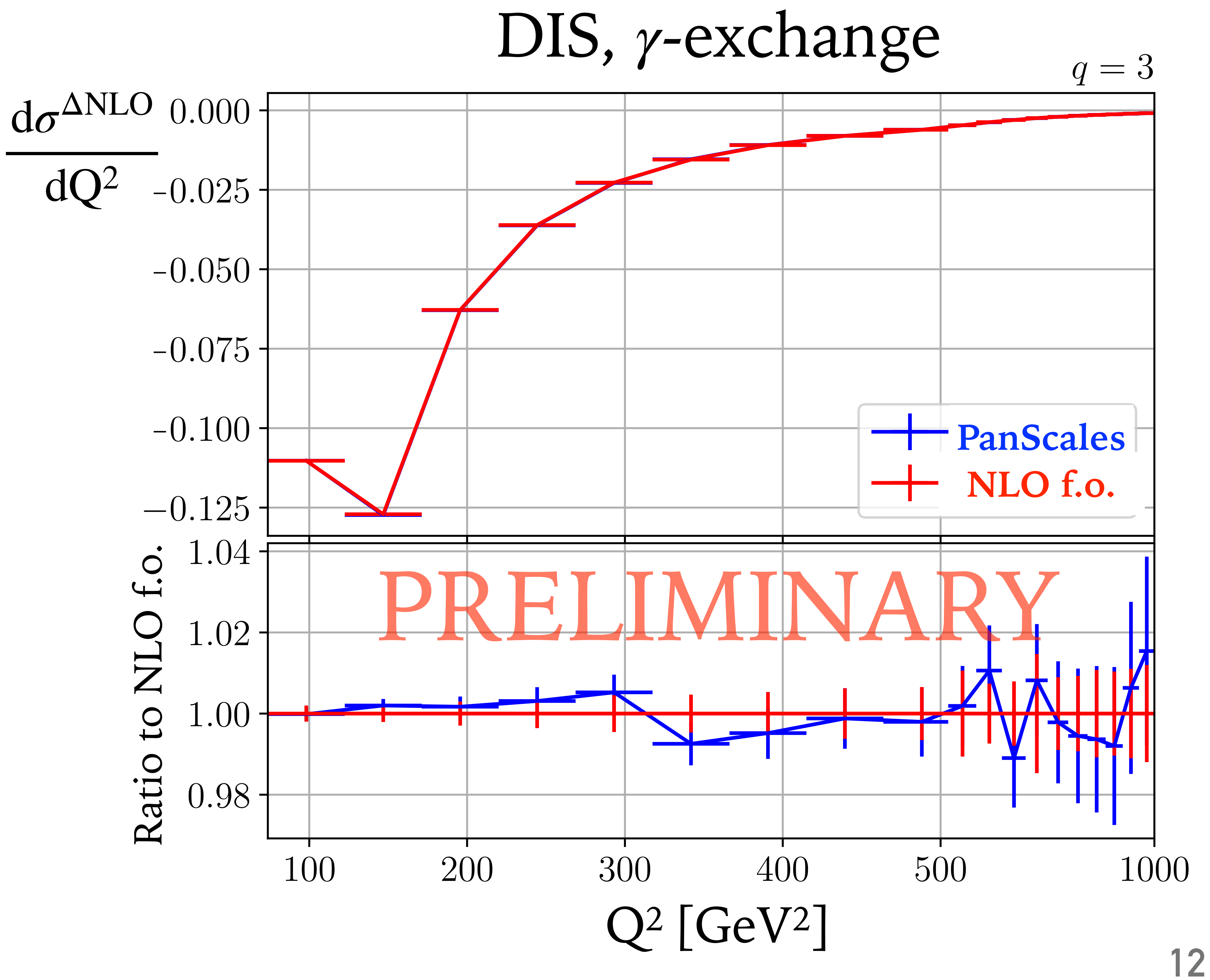
At NLO this requires a careful flavour decomposition
(more on this later)



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Obtain $\bar{B}$ numerically:

POWHEG: $$\bar{B}(\Phi_B) = \int dX_1 dX_2 dX_3\, \tilde{B}(\Phi_B, X_1, X_2, X_3)$$

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$$\tilde{B}(\Phi_B, X_1, X_2, X_3) \rightarrow \tilde{B}(\Phi_B, X_1, X_2, X_3) + \Delta\tilde{B}(\Phi_B, X_1, X_2, X_3)$$

$$\Delta\tilde{B} = \mathrm{Jac} \cdot \mathrm{R}(\Phi^{\rm PS}_{\rm rad}) - \mathrm{R}(\Phi^{\rm FKS}_{\rm rad})$$

Correct FKS/PanScales mappings

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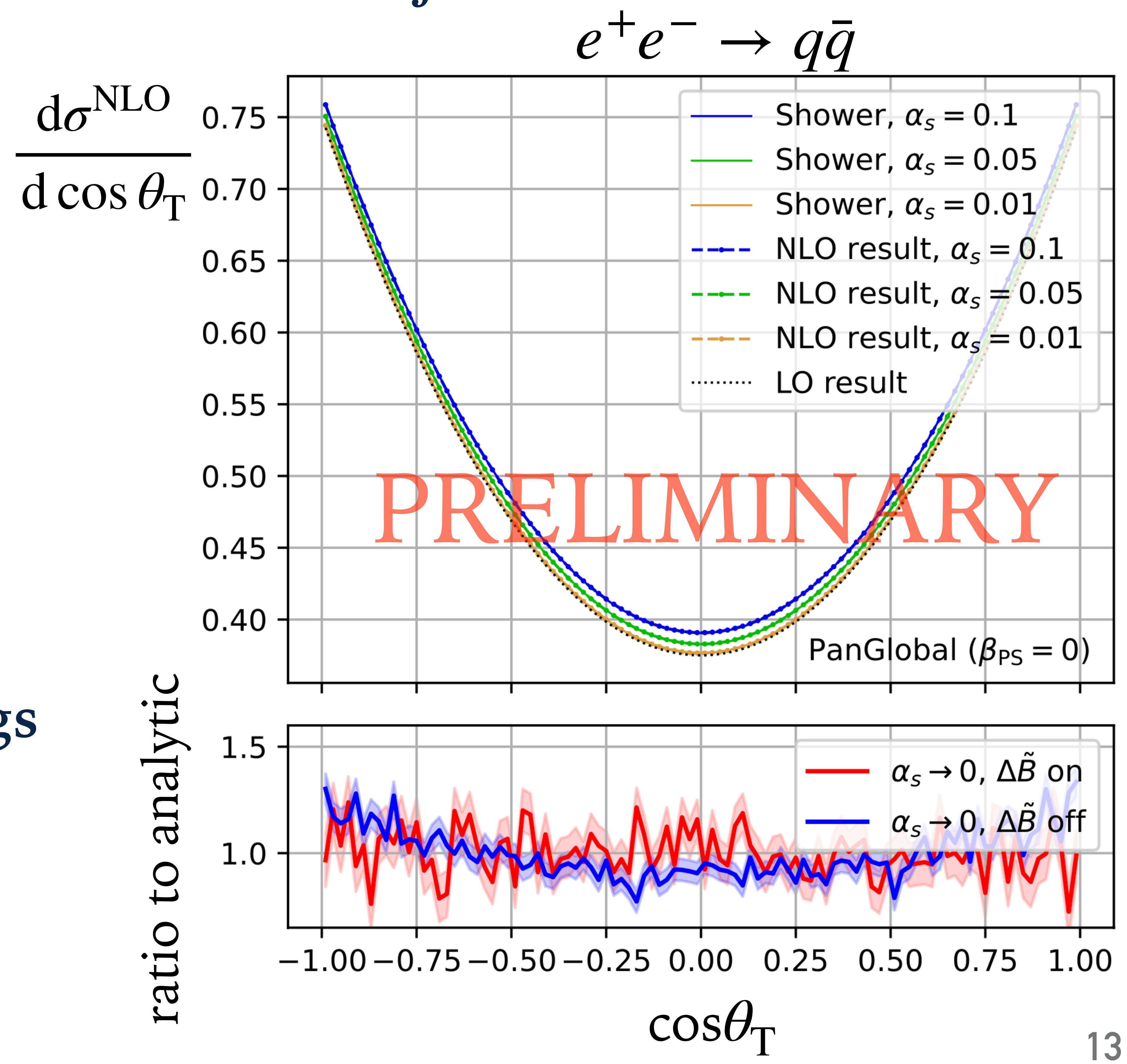

Applied to $e^+e^- \to Z$ and $pp \to Z$ but easily extendable to more complicated processes taking $\tilde{B}$ directly from POWHEG.

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The **hardest emission** is generated with the **correct real matrix element.**

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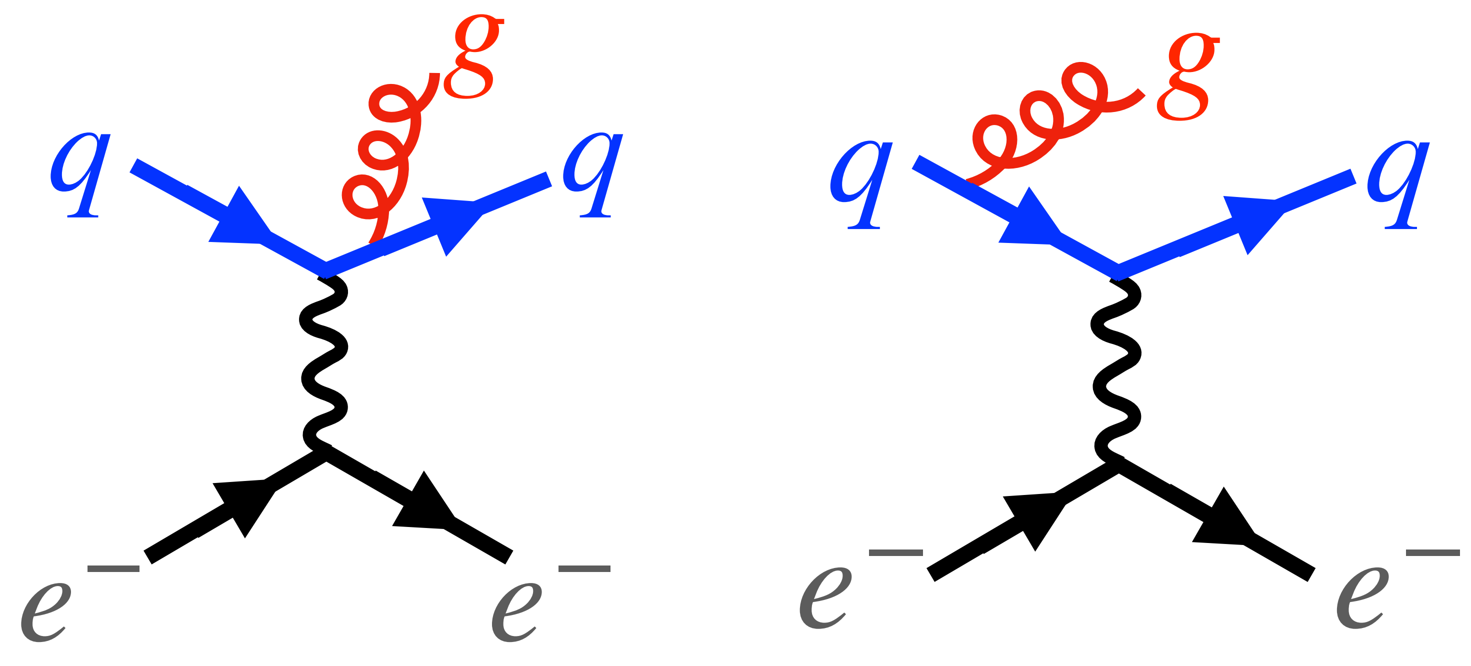
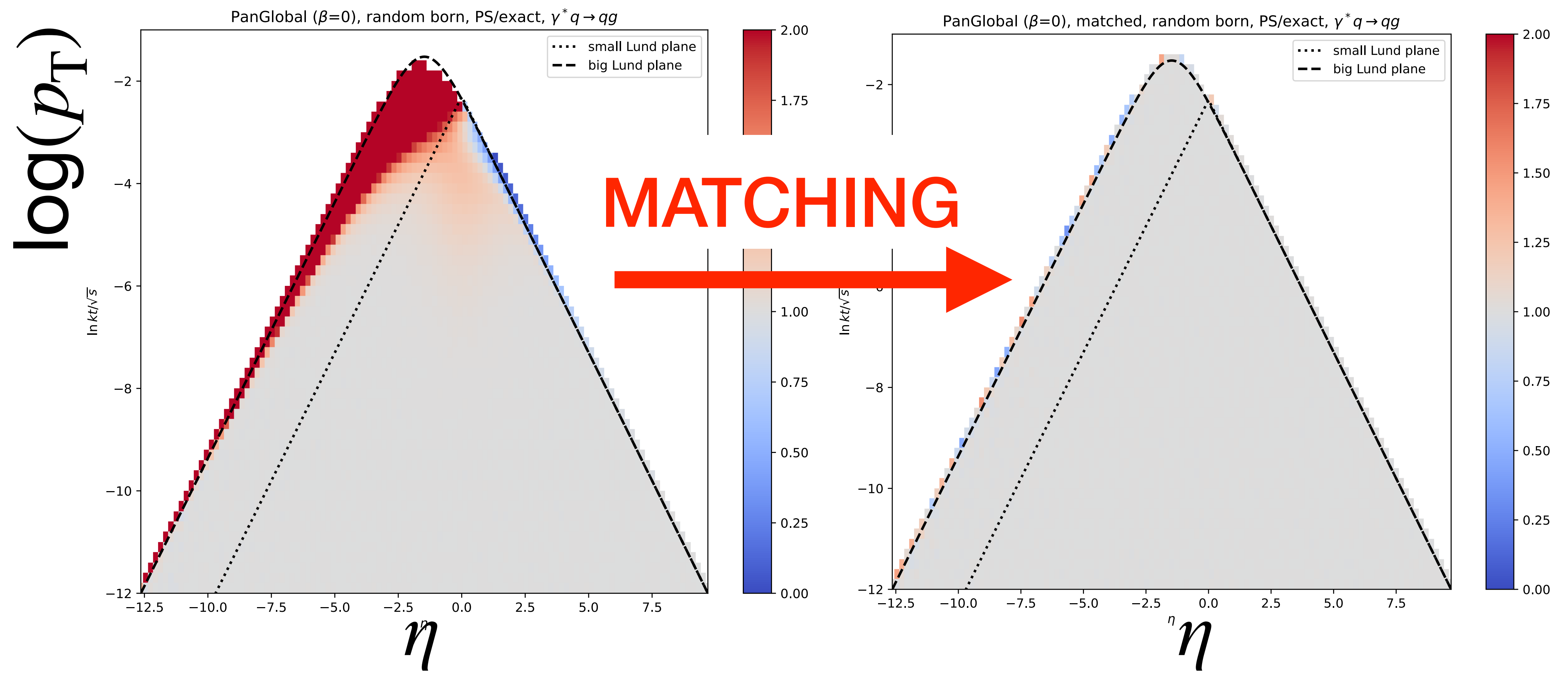
Simple example: DIS, only $\gamma^* q \to qg$ channel



(+ $\bar{q}$-contributions)

RATIO PS/exact ME



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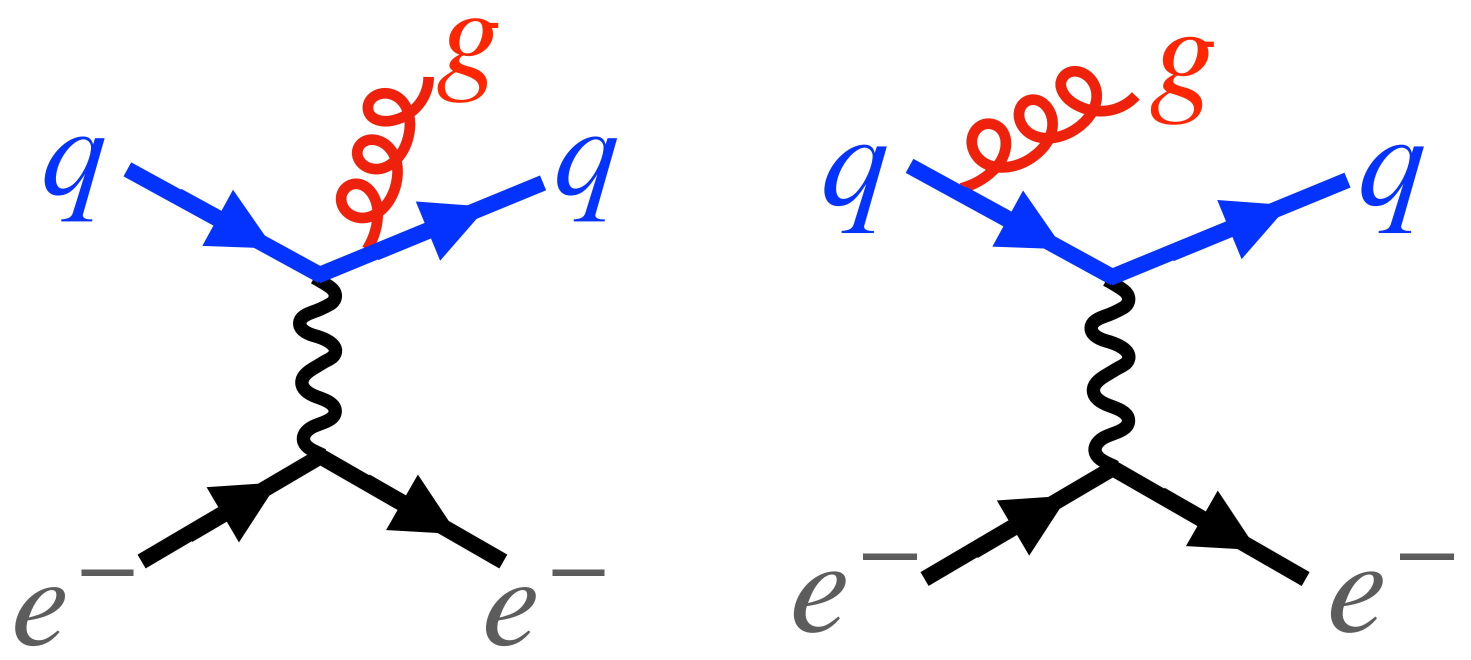

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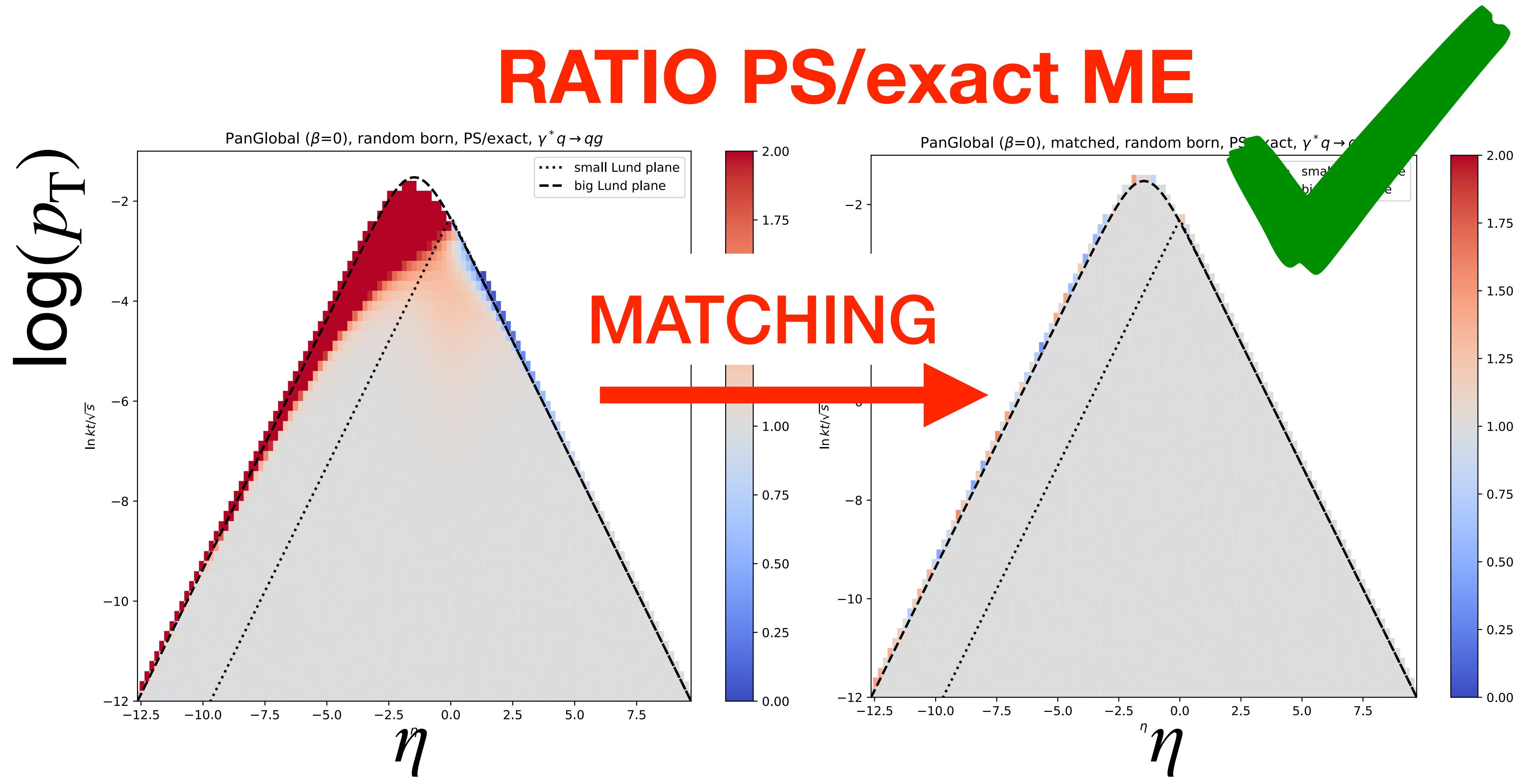

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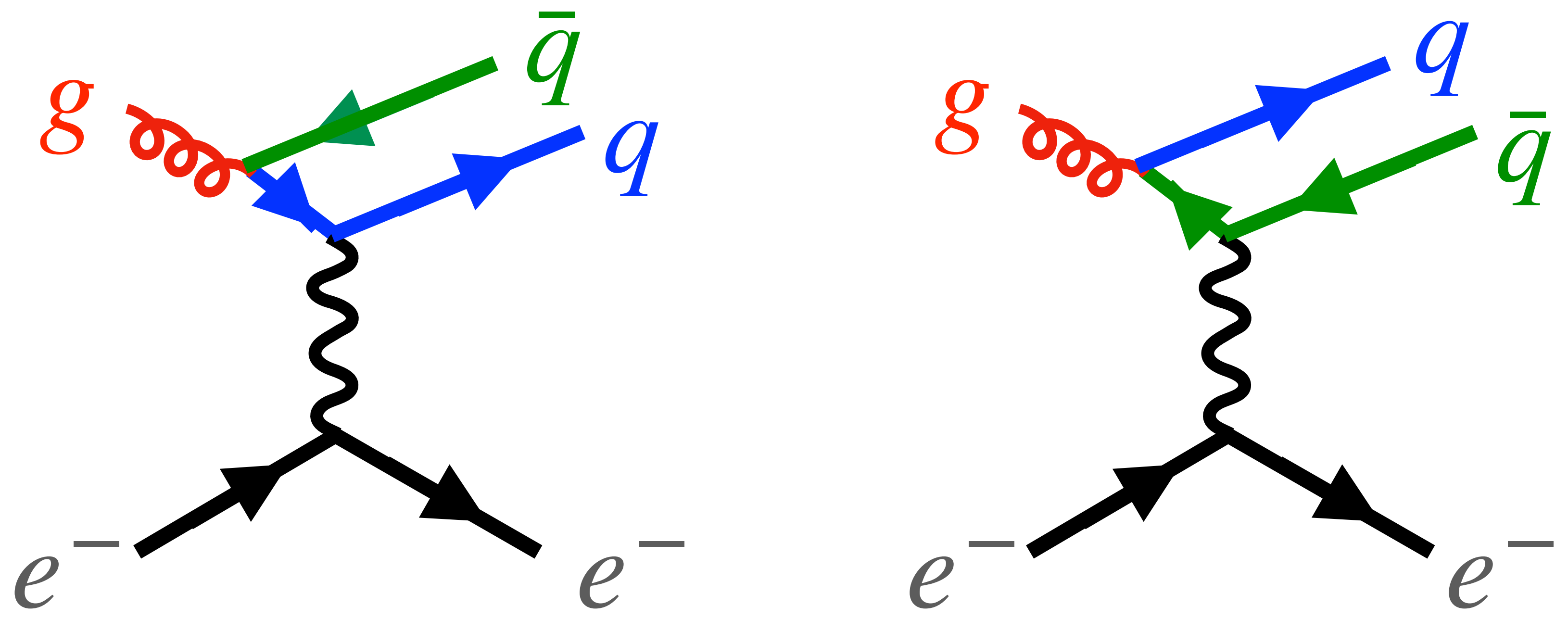

Two possible underlying Borns for the same real configuration!

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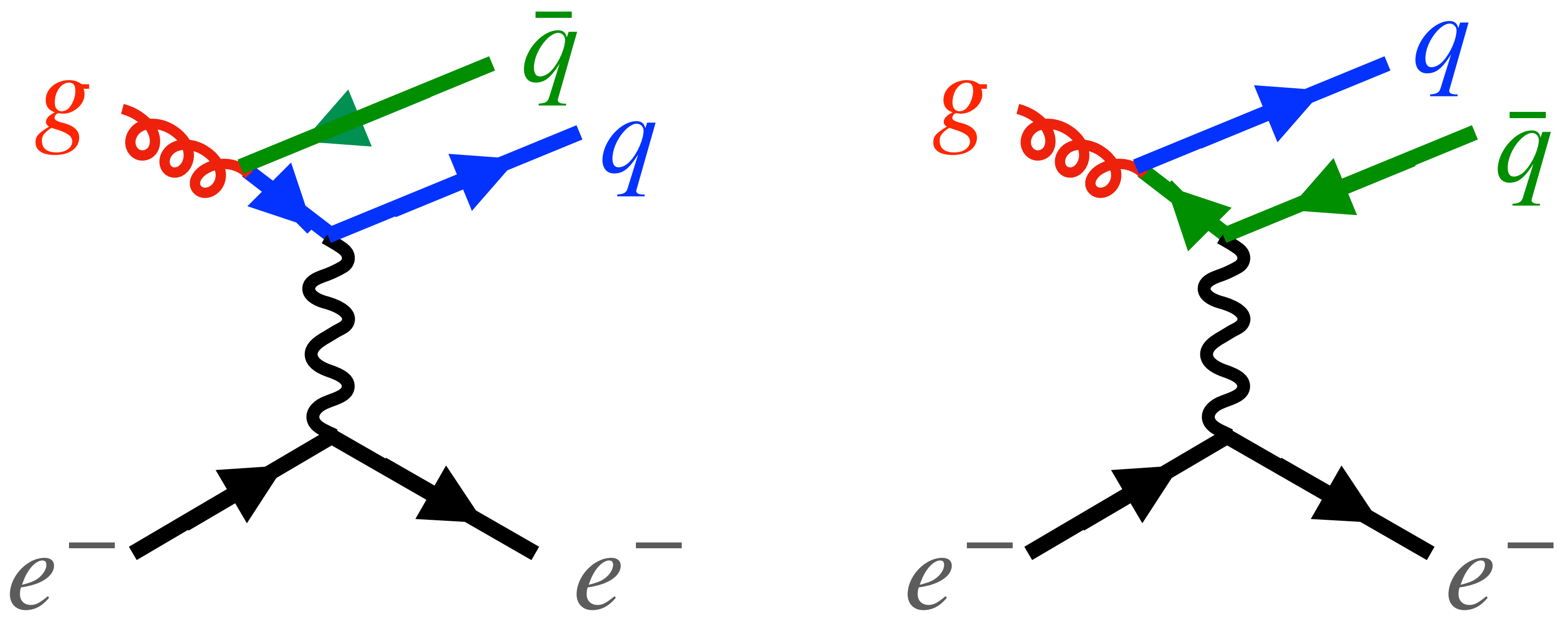

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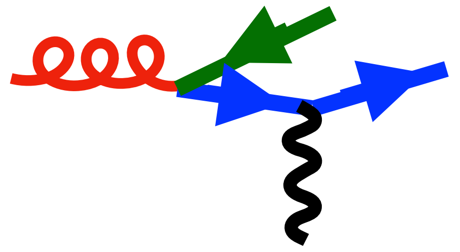
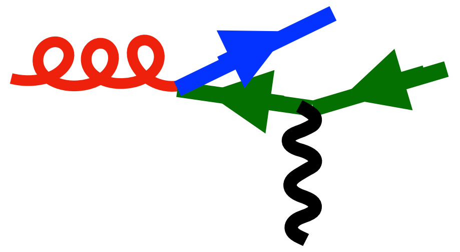
The fraction of real associated to a given Born is taken as:

$\gamma^* q \to q$  $\longrightarrow$ $\theta(p_q \cdot p_g < p_{\bar{q}} \cdot p_g)$

$\gamma^* \bar{q} \to \bar{q}$  $\longrightarrow$ $\theta(p_{\bar{q}} \cdot p_g < p_q \cdot p_g)$

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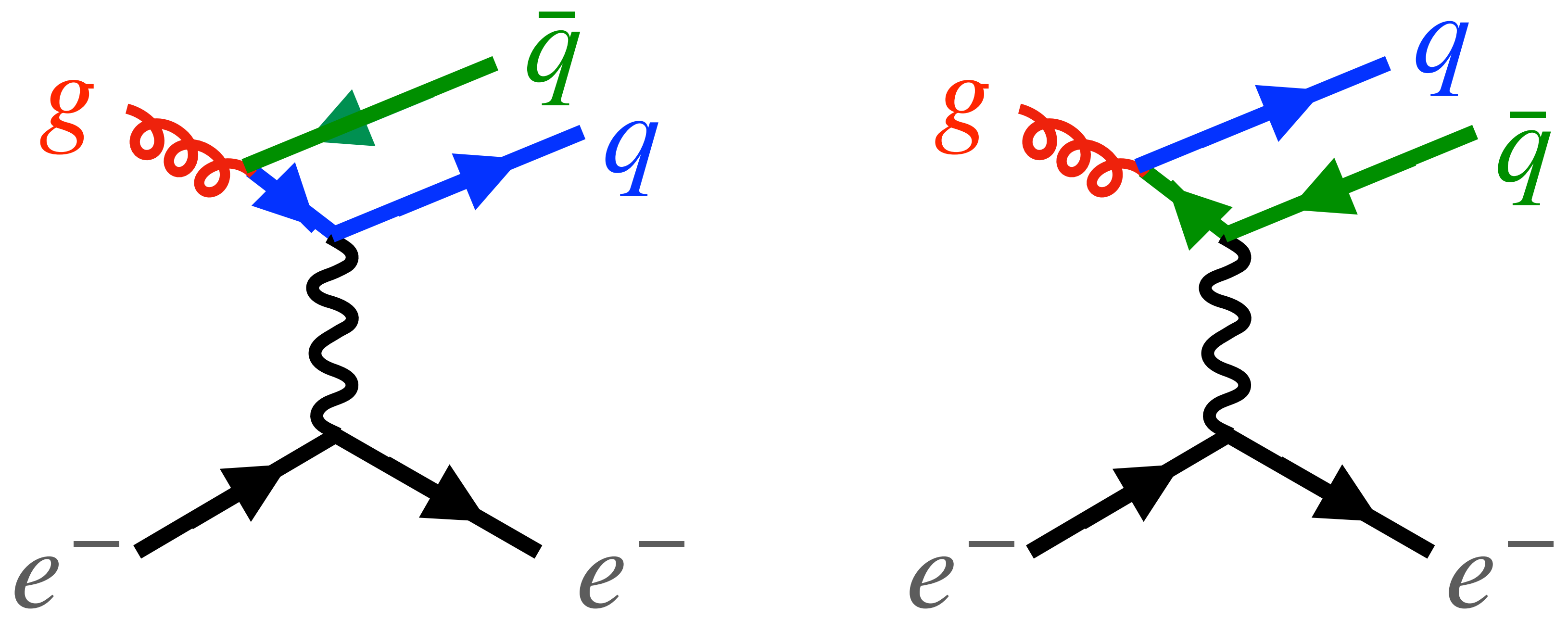

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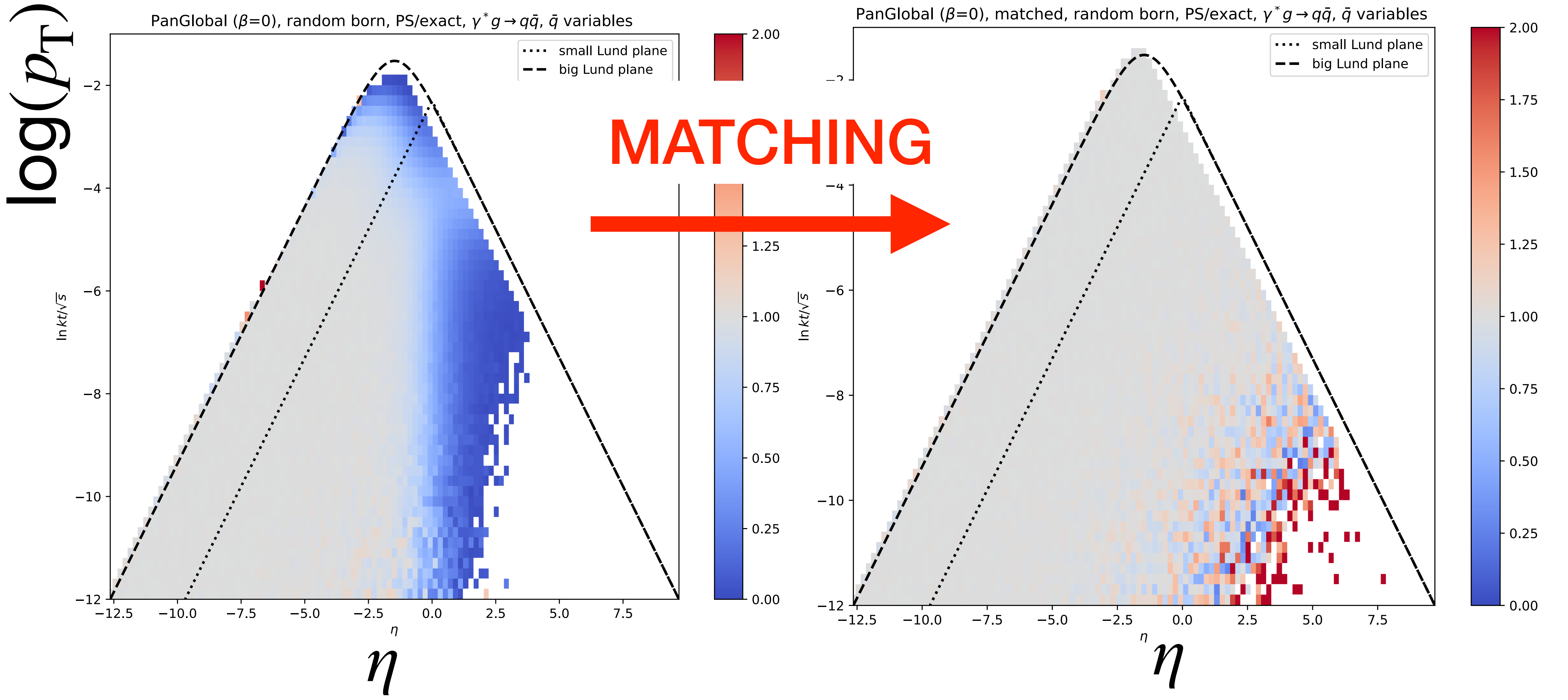

Separation of singular regions between the two underlying Borns.

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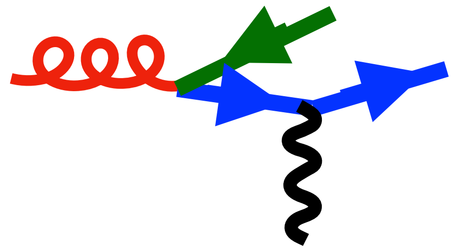
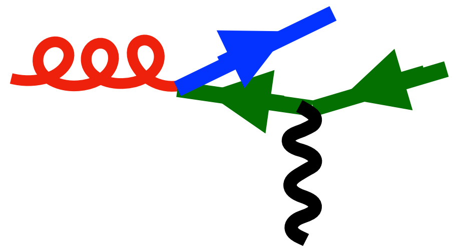
- $\gamma^* q \to q$  $\longrightarrow \theta(p_q \cdot p_g < p_{\bar{q}} \cdot p_g)$
- $\gamma^* \bar{q} \to \bar{q}$  $\longrightarrow \theta(p_{\bar{q}} \cdot p_g < p_q \cdot p_g)$

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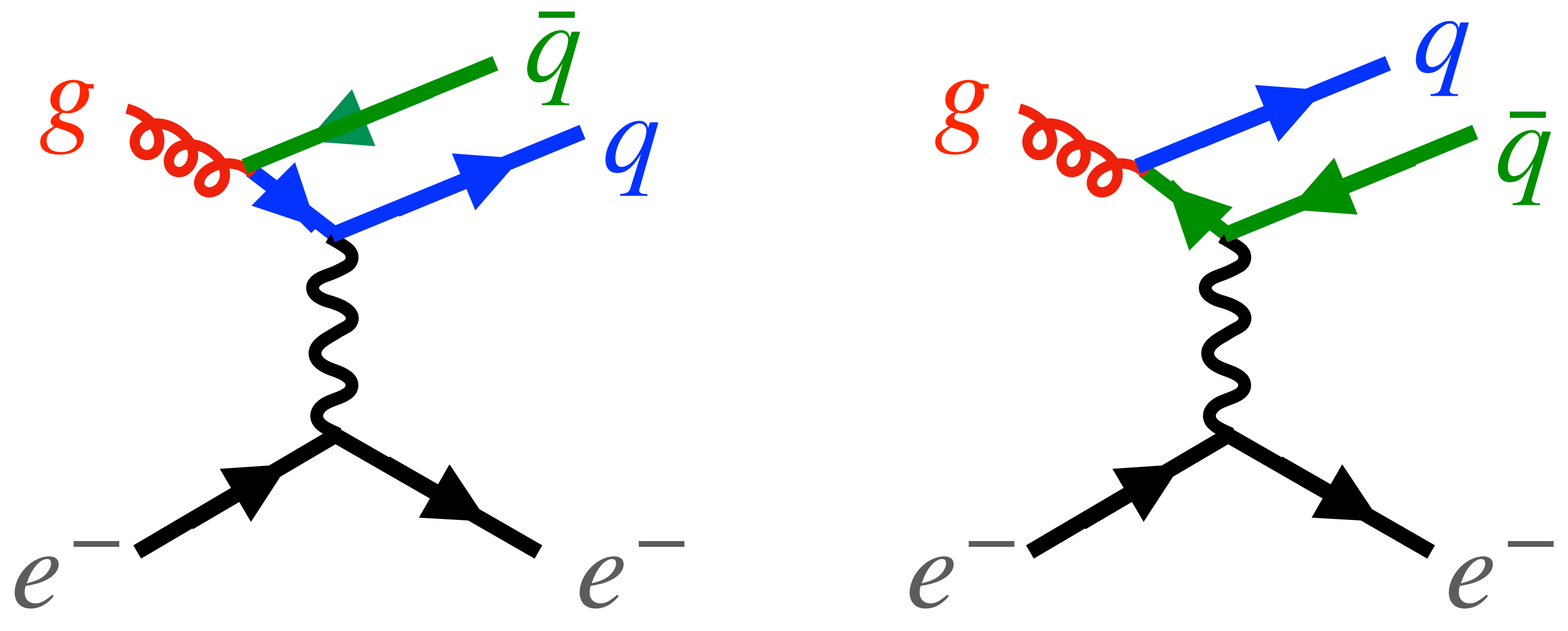

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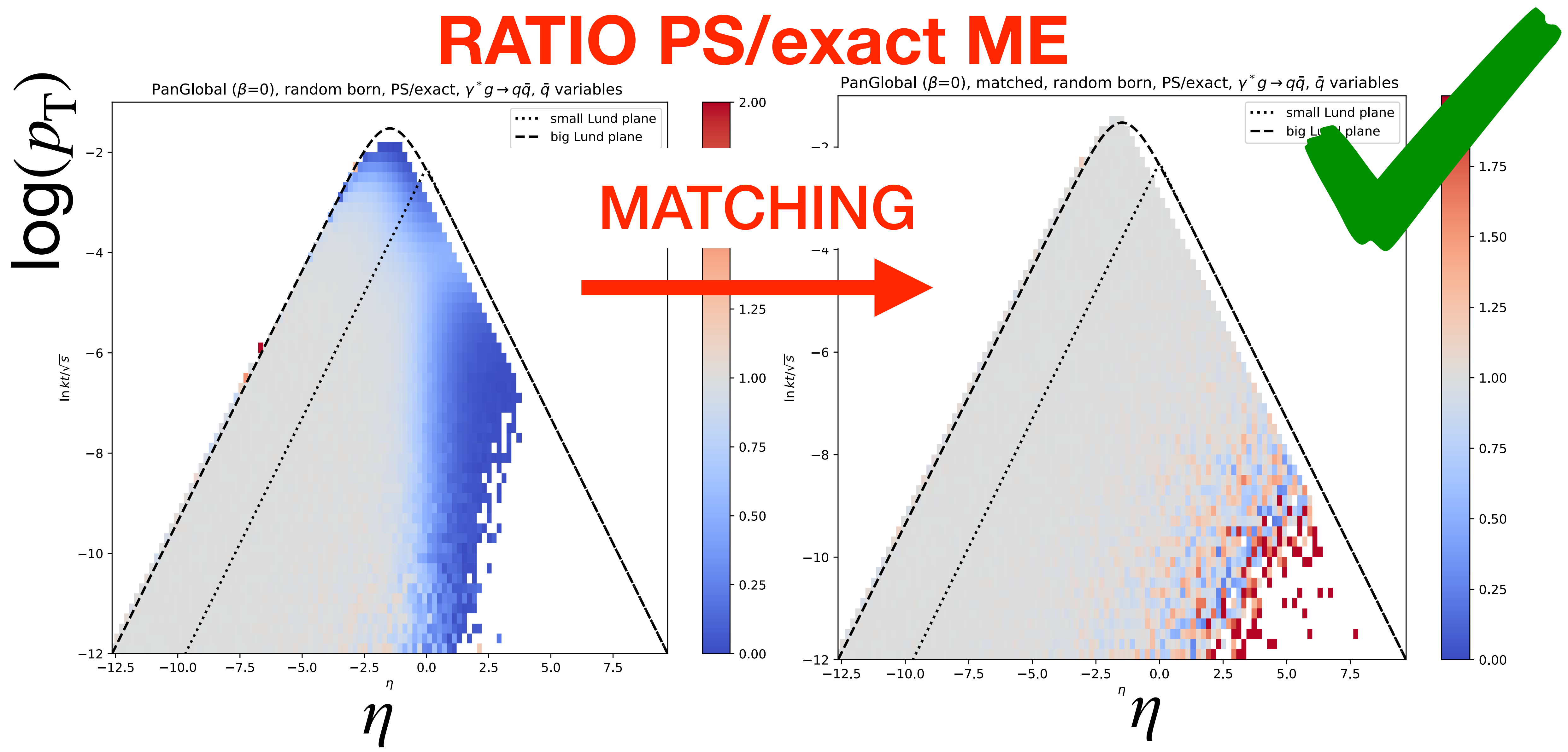

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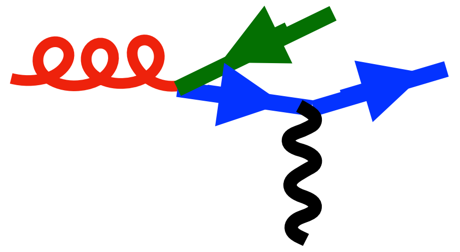
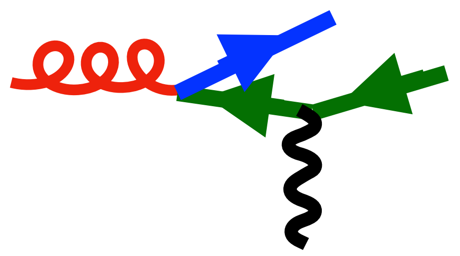
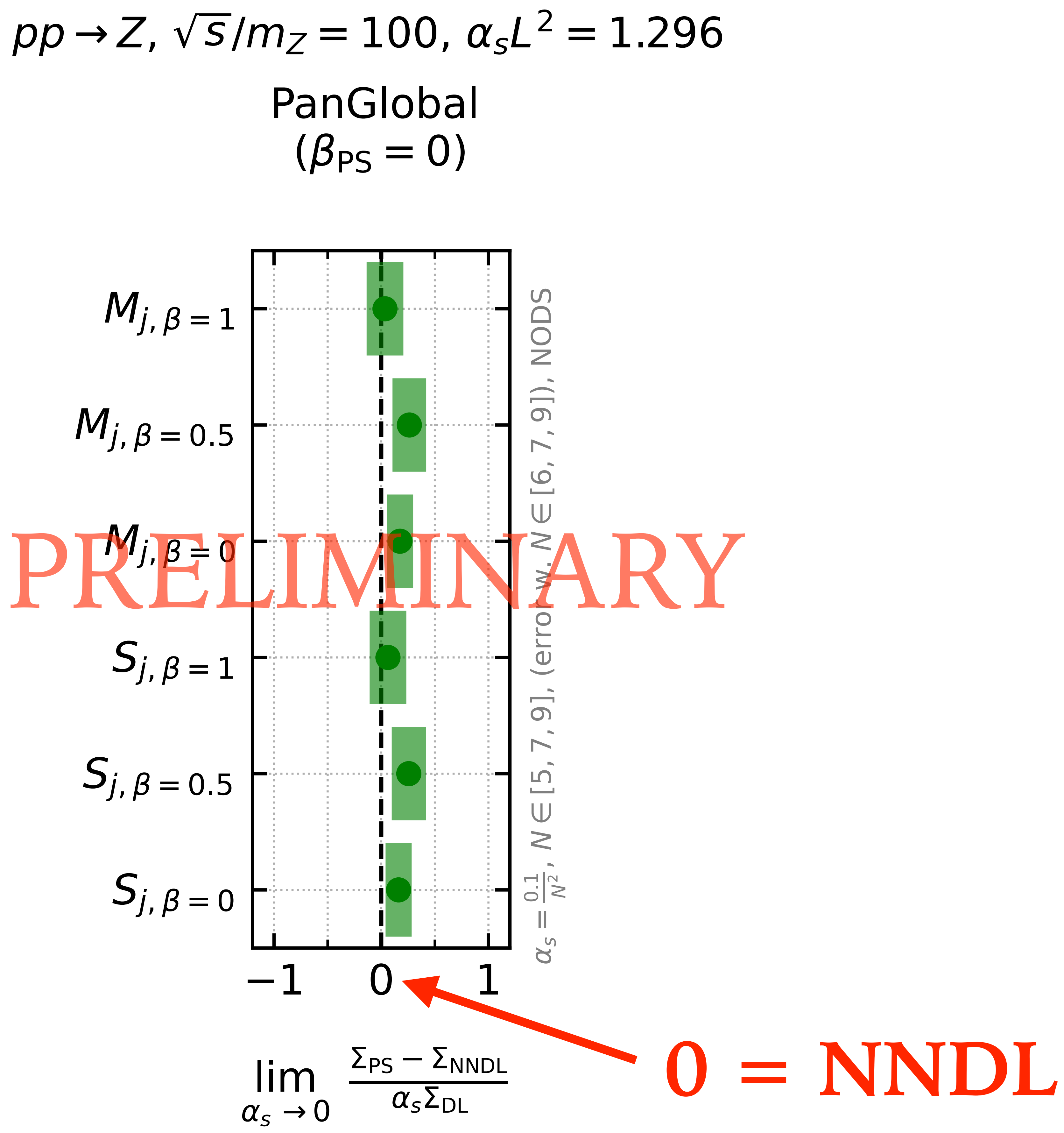
The fraction of real associated to a given Born is taken as:

$\gamma^* q \to q$  $\longrightarrow \theta(p_q \cdot p_g < p_{\bar{q}} \cdot p_g)$

$\gamma^* \bar{q} \to \bar{q}$  $\longrightarrow \theta(p_{\bar{q}} \cdot p_g < p_q \cdot p_g)$

NNDL TEST



- NNDL $= \mathcal{O}(\alpha_s^n L^{2n-2})$
- Compare the parton shower result with analytic calculations.
- Eliminate spurious contributions generated by the shower with:

$$\lim_{\alpha_s \to 0} \frac{\Sigma_{PS} - \Sigma_{NNDL}}{\alpha_s \Sigma_{DL}} \Bigg|_{\alpha_s L^2 \text{ fixed}}$$

$$M_{j,\beta} = \max_{i \in \text{jets}} \frac{k_{T_i}}{Q} e^{-\beta|\eta_i - \eta_Z|} \qquad S_{j,\beta} = \sum_{i \in \text{jets}} \frac{k_{T_i}}{Q} e^{-\beta|\eta_i - \eta_Z|}$$

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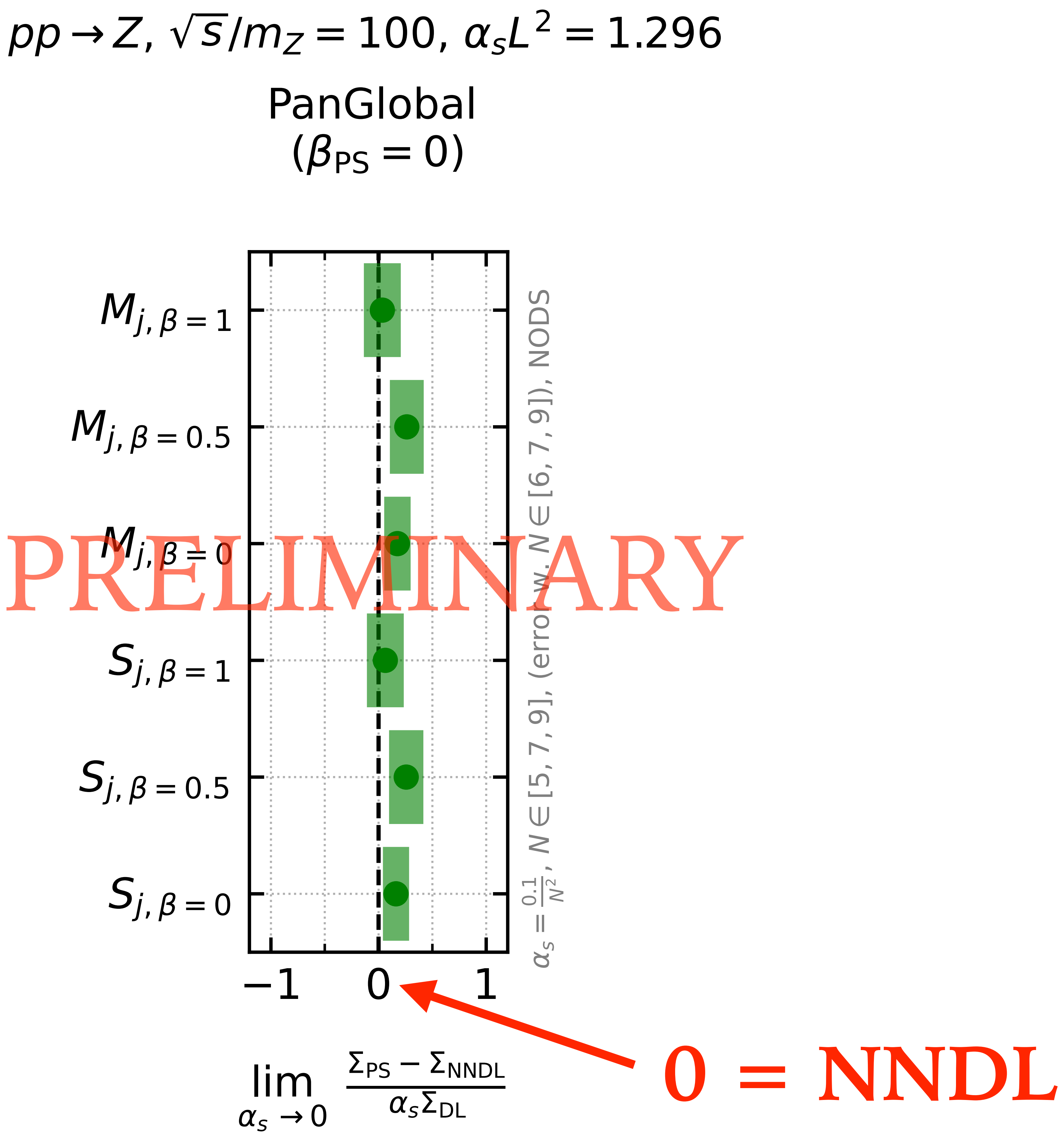

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First time a shower demonstrably generates NNDL accurate results across many observables for pp collisions.

CONCLUSIONS and OUTLOOK

- NLO matching with NLL showers is needed for precision physics.
- **Results for DIS, DY and oriented e^+e^- have been obtained at NLO+NLL accuracy** through a multiplicative matching with PanScales showers.
- **Extension to more complicated processes is possible** through an on-the-fly conversion of $\tilde{B}^{\mathrm{FKS}}$ to $\tilde{B}^{\mathrm{PS}}$.
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The PanScales collaboration is currently working on a new NLO matching scheme with the nice feature of **generating only positive weights.**

IDEA: use a simple (=analytic) $\bar{B}$ function and correct it à la MacNLOPS.

…more on this soon!