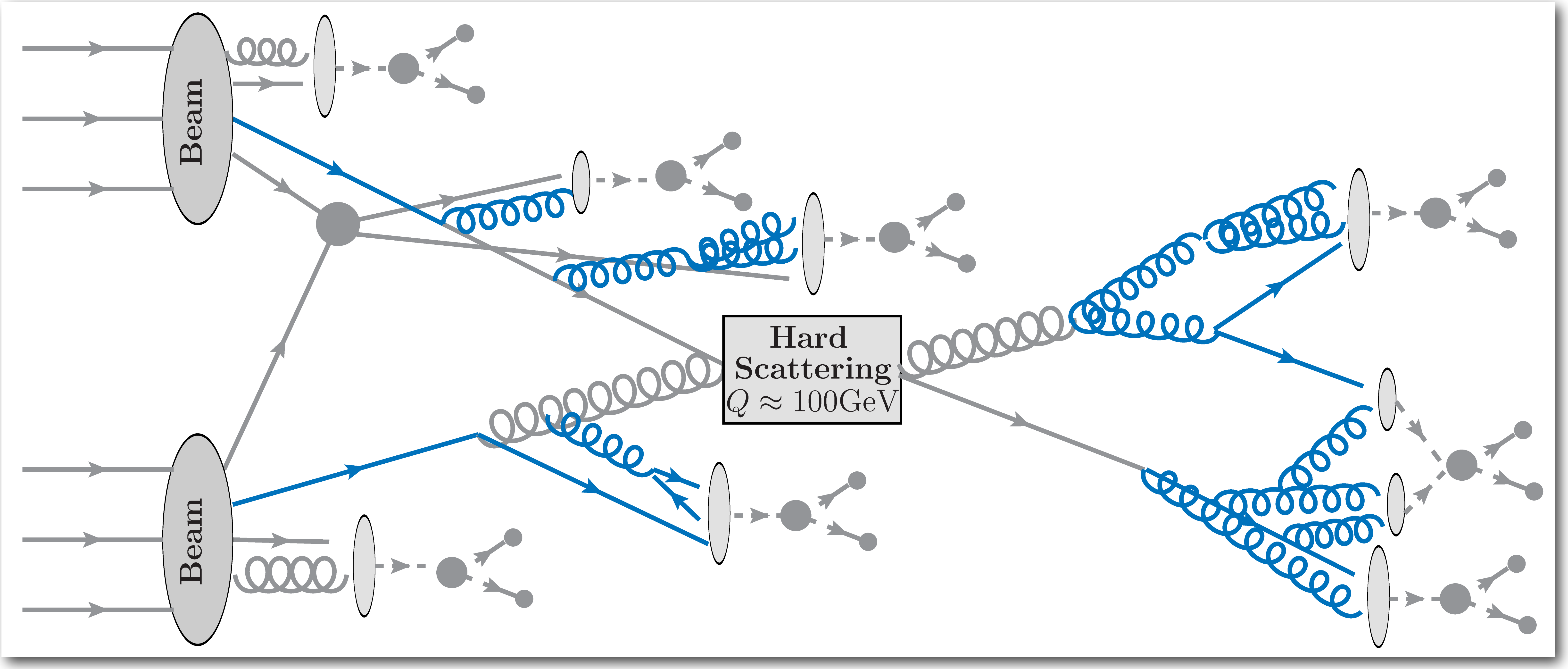
Pushing the accuracy of parton showers for hadron colliders

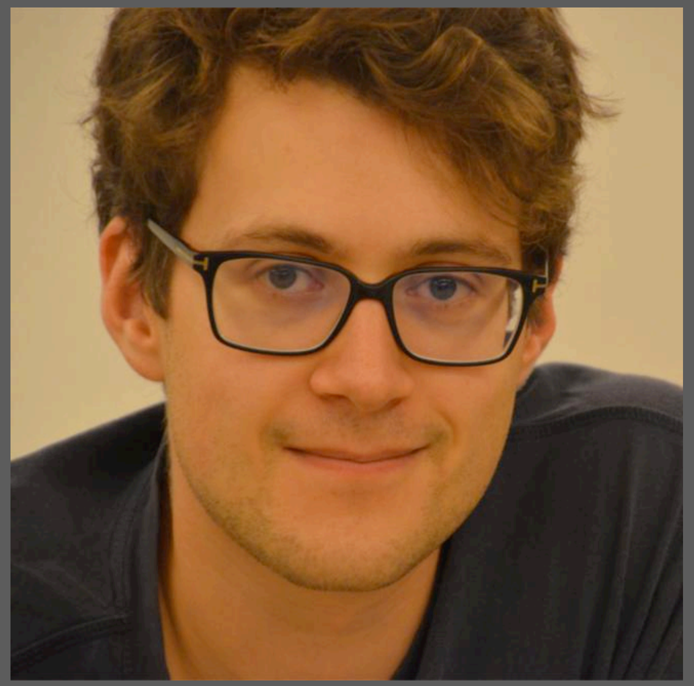
Silvia Ferrario Ravasio



Radcor 2023

2 June 2023

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

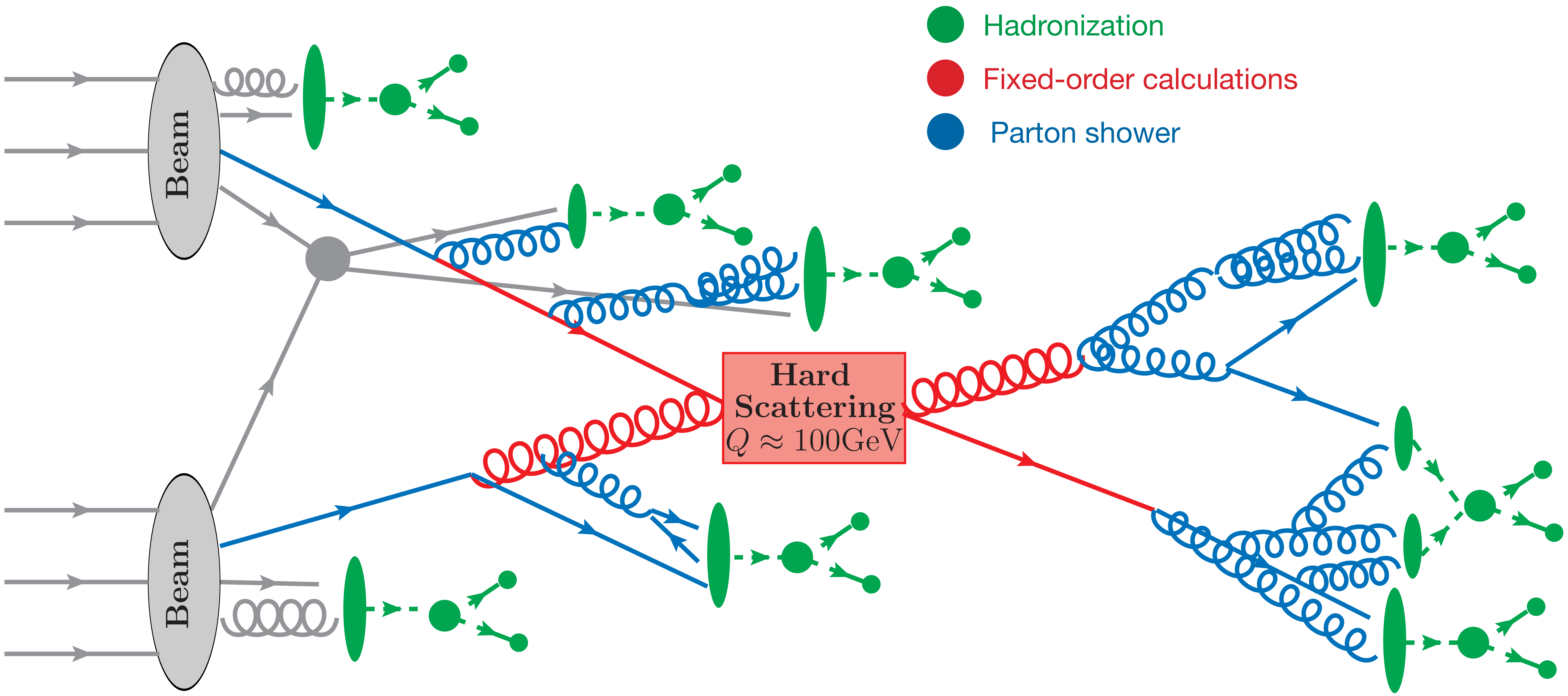
Shower Monte Carlo Event Generators

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

Pythia

Herwig

Sherpa



- Reproduce much of the data from LHC and its predecessors
- Unknown or poor formal accuracy, especially of the Parton Shower component

How do we define how good is a Parton Shower?

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

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

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

E.g. $O = \frac{p_{\perp,Z}}{m_Z}$ and $p_{\perp,Z} \approx 1$ GeV, $|\alpha_s L| = 0.55$: Next-to-Leading Logarithms are $\mathcal{O}(1)$

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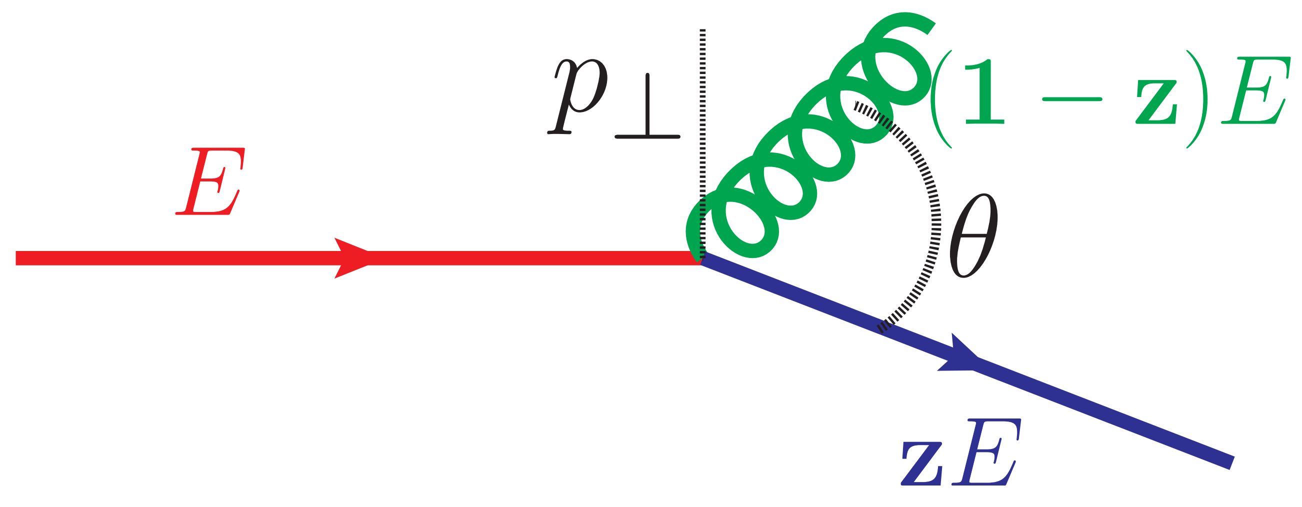
Are the most widely used showers NLL? If no, can we build NLL showers?

- (Abridged) PanScales criteria to assess NLL accuracy:

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

Parton Showers in a nutshell



- Parton showers describe the energy degradation of hard partons via a subsequent chain of 1 → 2 collinear splittings
- $\Phi_{\mathrm{rad}} = \{v, z, \varphi\}$, where $v \in \{p_\perp, E\theta, \dots\}$ acts as ordering scale, z is ``energy fraction" scale, and φ is an azimuthal angle

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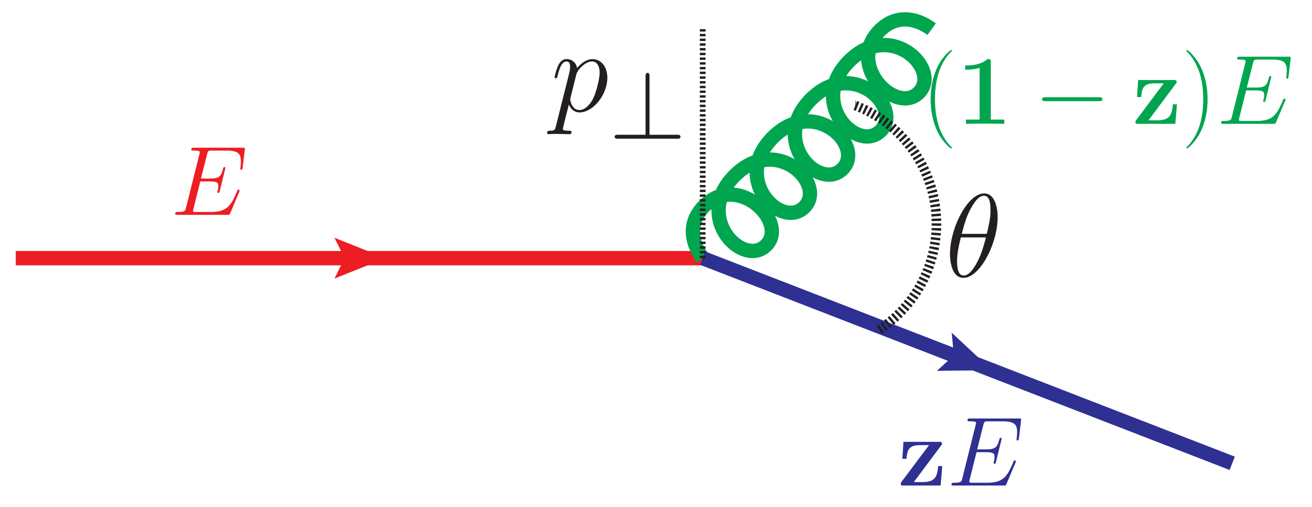

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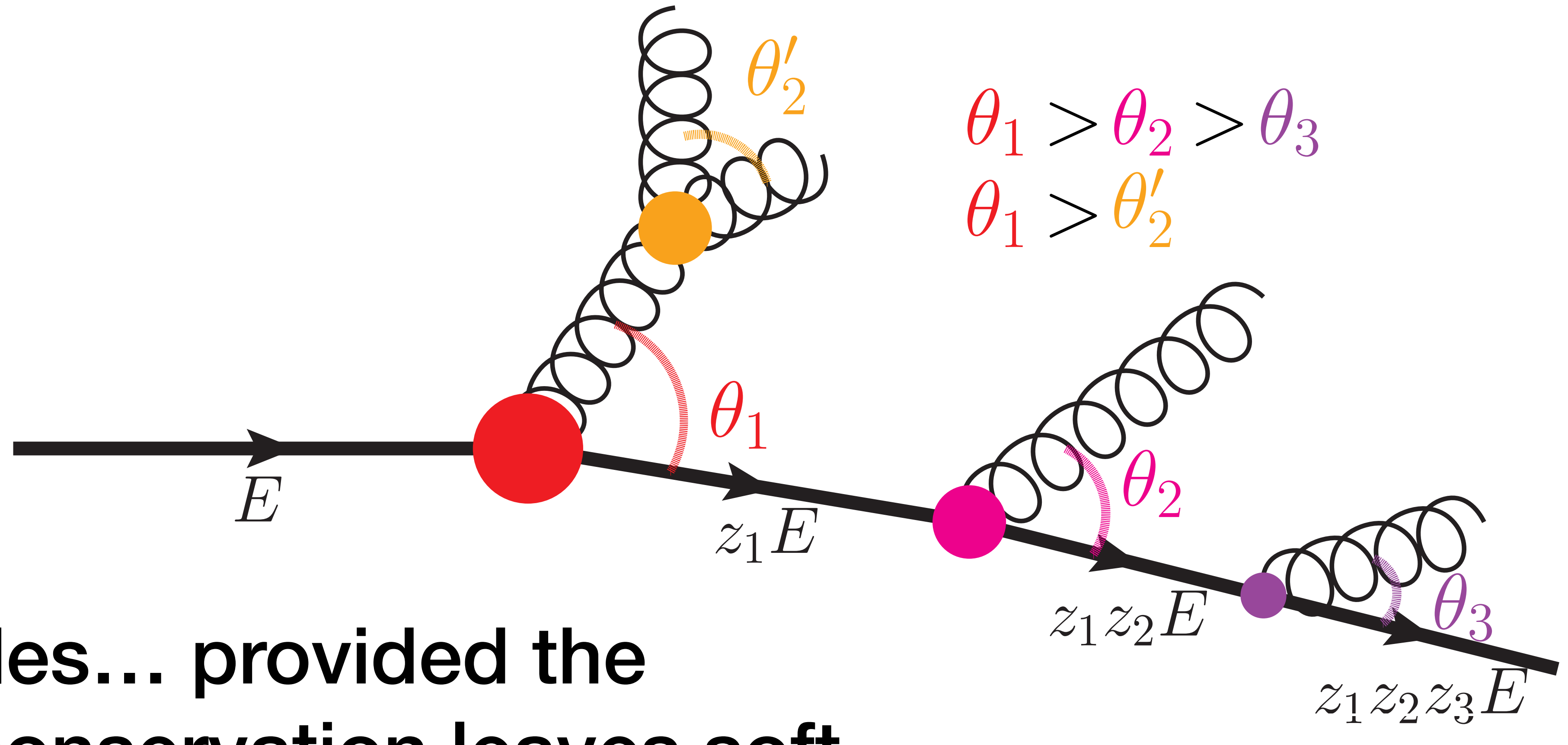
Herwig7 angular-ordered shower

[0803.0883]



- Emissions ordered in angle to describe correctly the soft limit
- The coherent branching formalism [Marchesini, Webber '88], [Gieseke, Stephens, Webber hep-ph/0310083] guarantees "by construction" NLL accuracy across a broad range of observables… provided the actual implementation of the recoil scheme to ensure momentum conservation leaves soft emissions untouched [G. Bewick, SFR, Richardson, Seymour, 1904.11866, 2107.04051]

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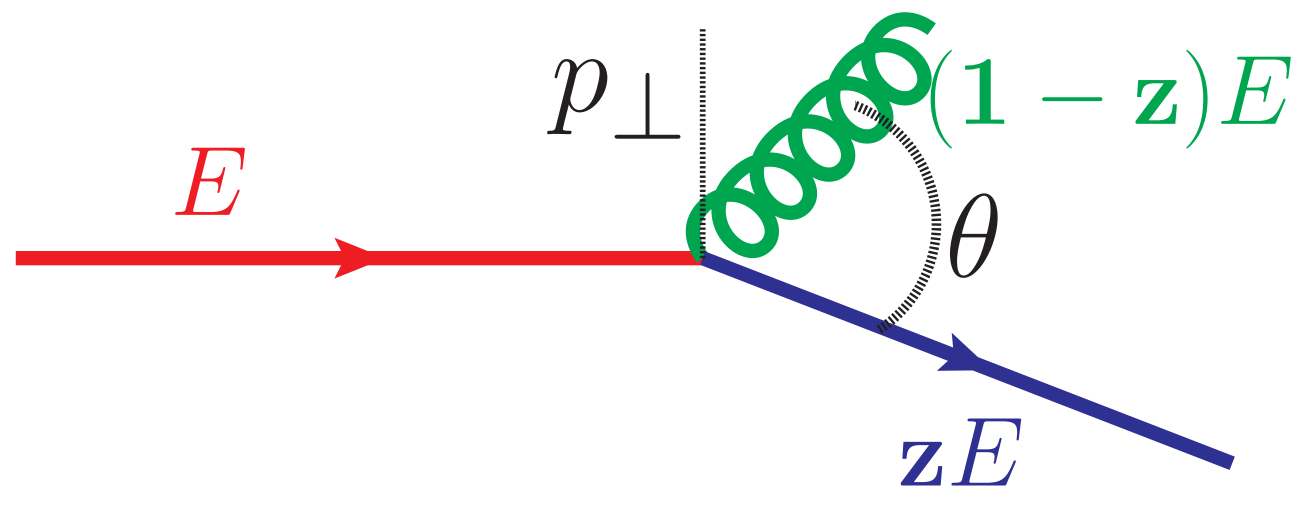

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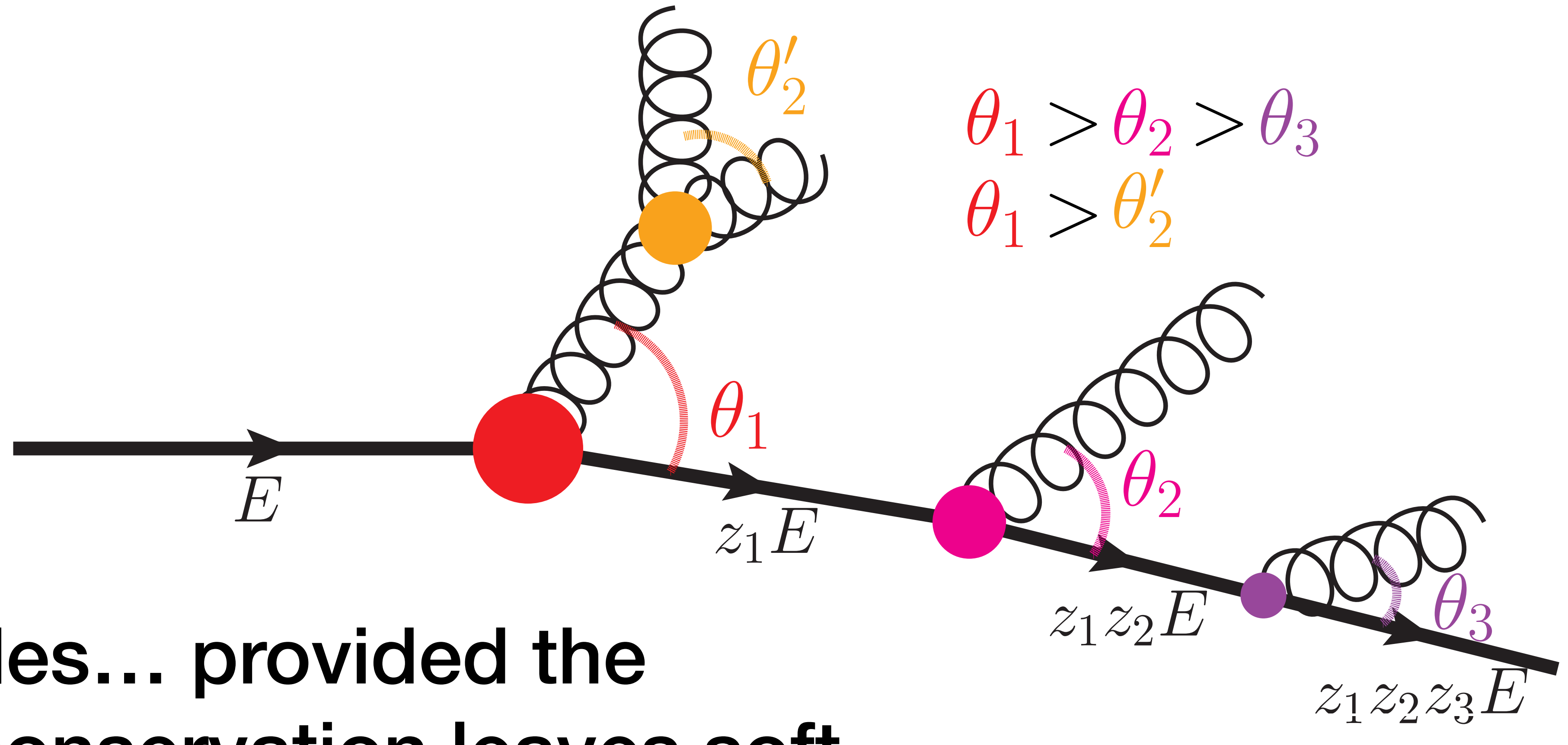

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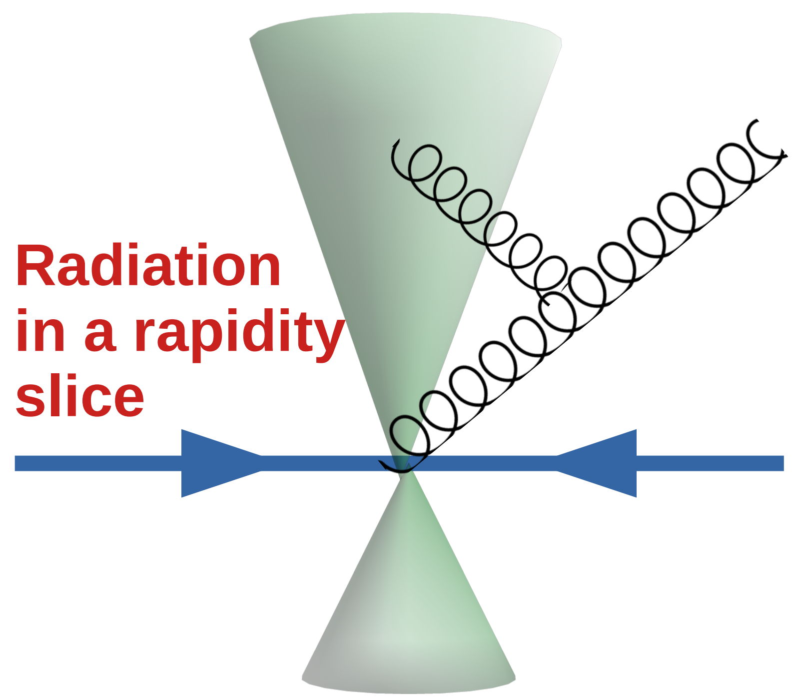
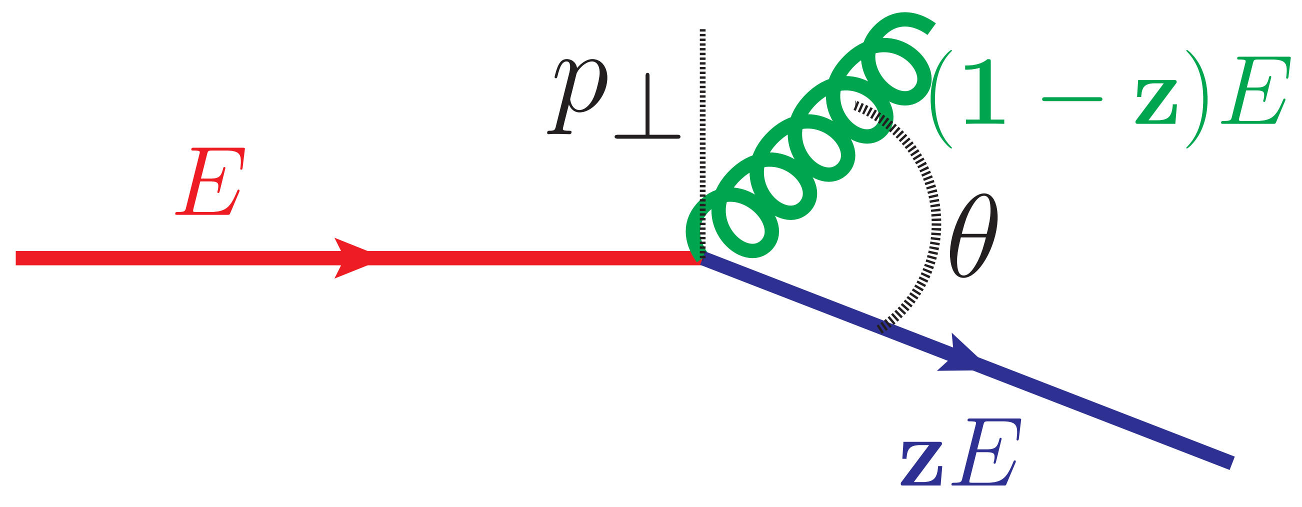


- Angular-ordering arises after azimuthal average: this formalism cannot describe **non-global observables**, which are sensitive to the full angular distribution of soft emsn, at NLL [Banfi, Corcella, Dasgupta, hep-ph/0612282]
- Matching/merging beyond the hardest emission is very difficult (see e.g. 1604.04948), and we are currently limited to NLO!

Parton Showers in a nutshell



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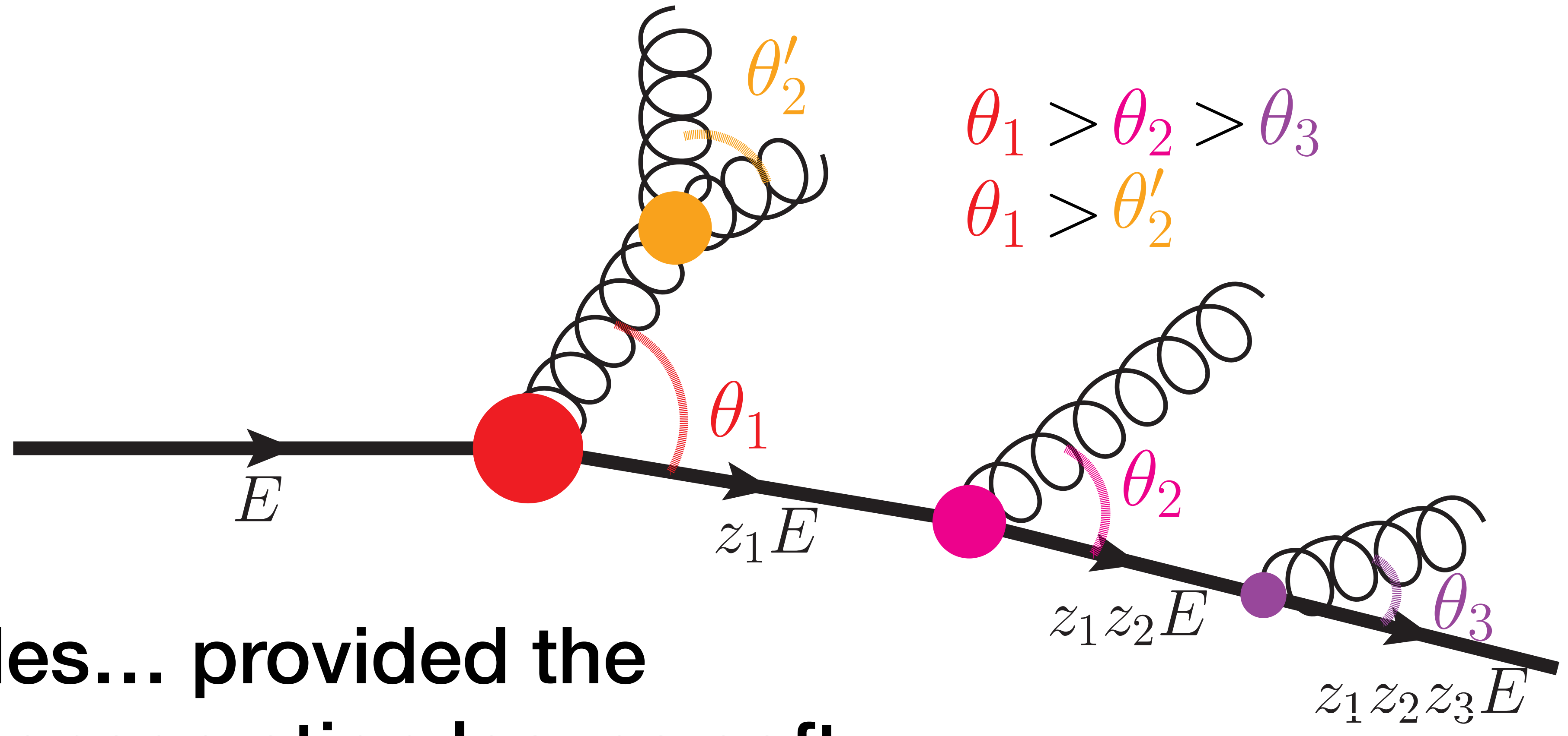

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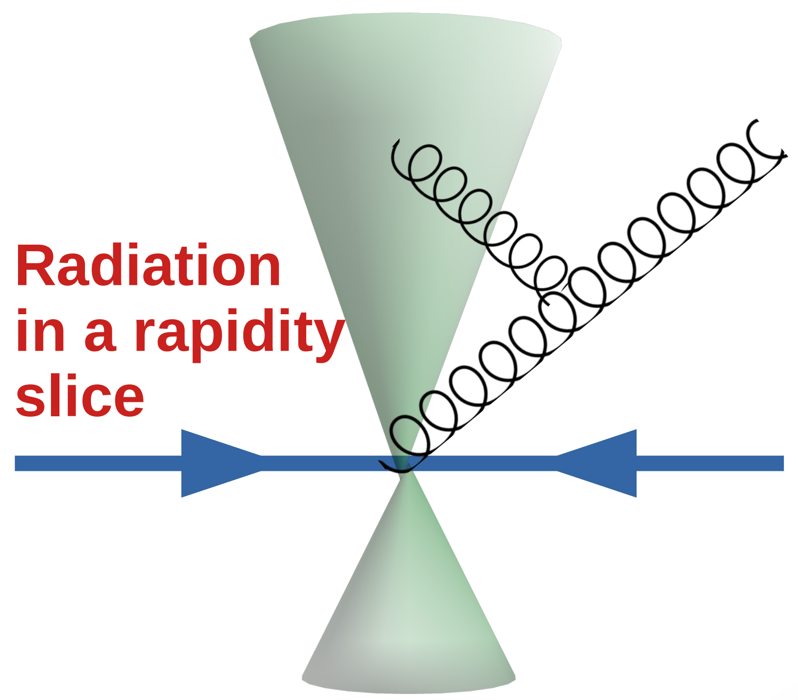

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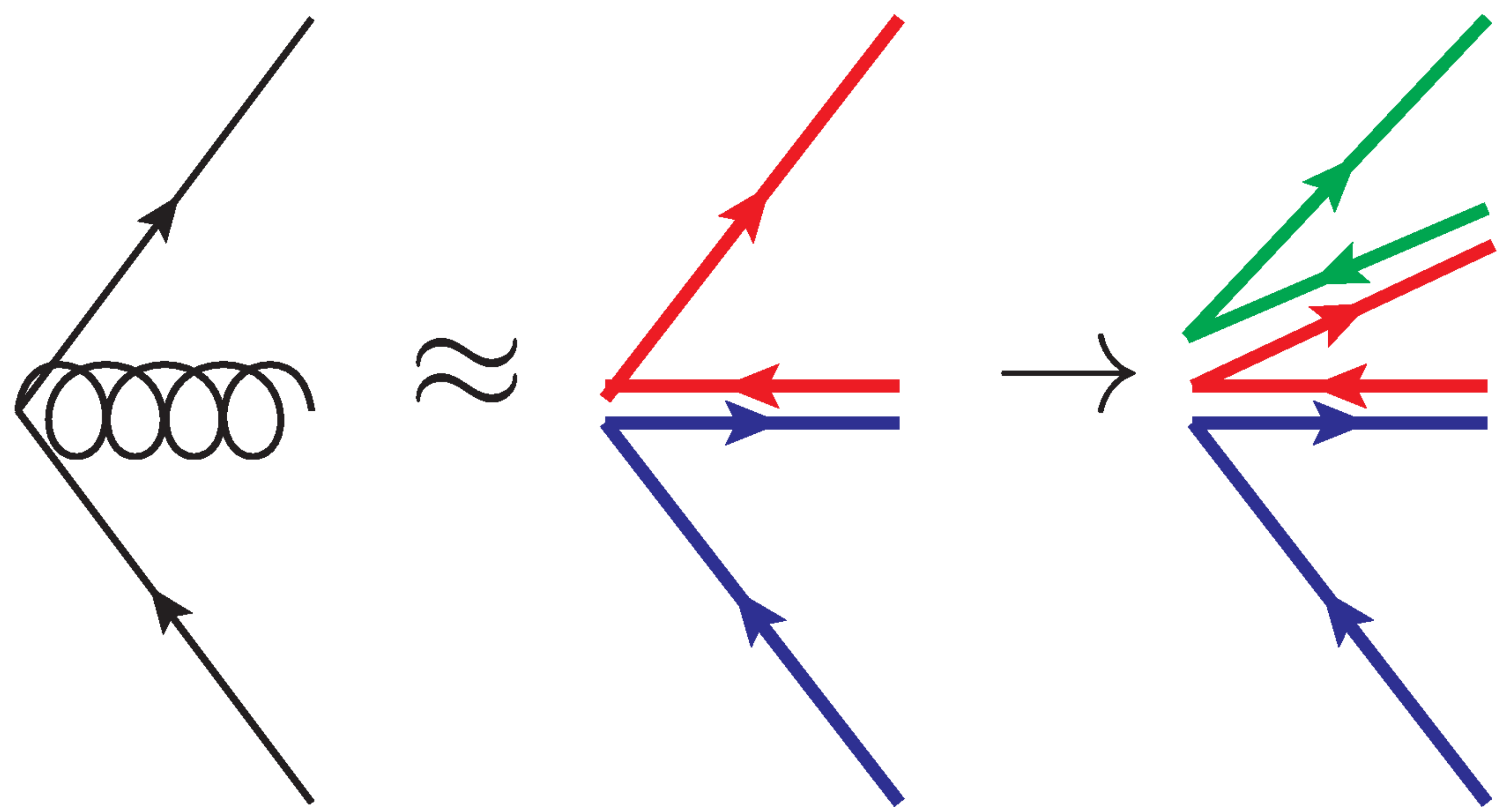
The dipole formalism overcomes both problems! But retaining NLL is more difficult!

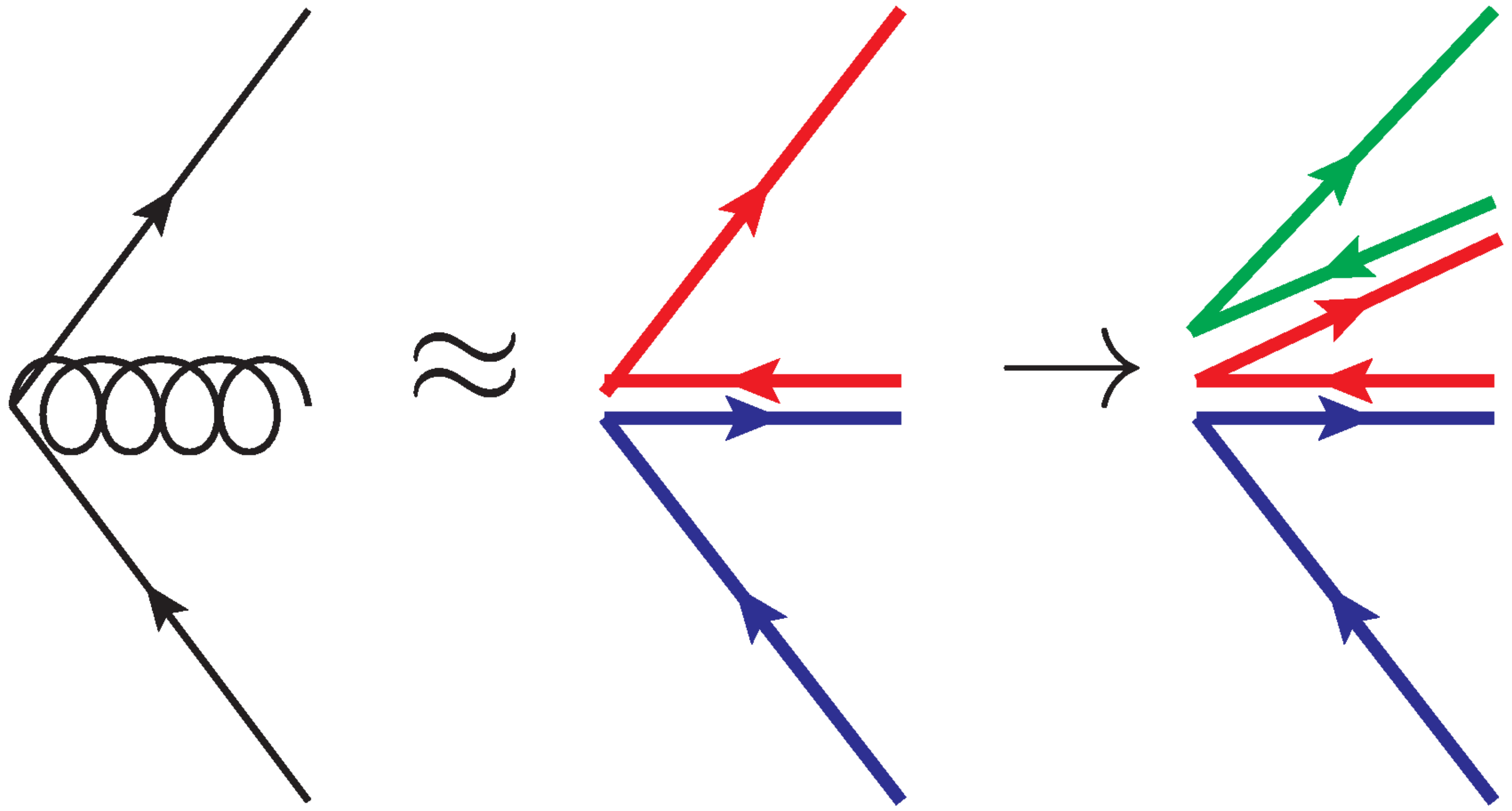
Dipole showers in a nutshell



- The most popular showers are **dipole showers**. [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!

Dipole showers in a nutshell



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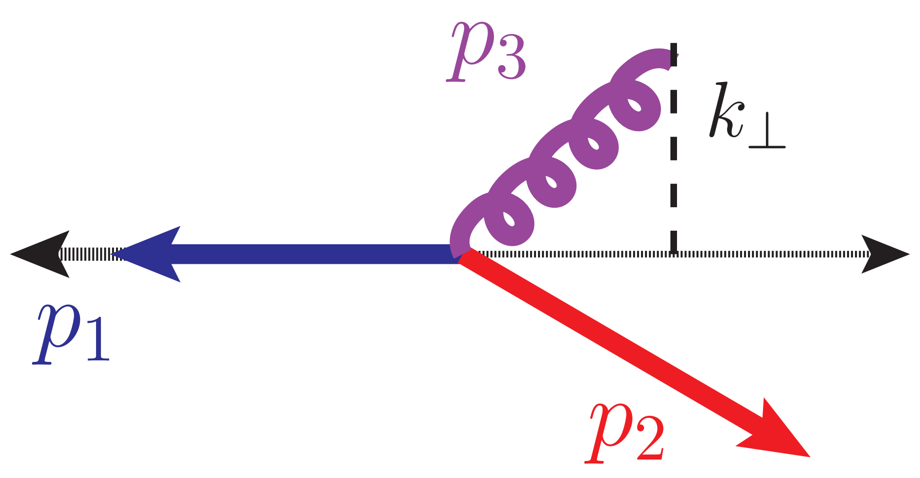
- The original dipole leg closer in angle (in the dipole frame) to the new emission takes the p_T recoil, and is tagged as emitter

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

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



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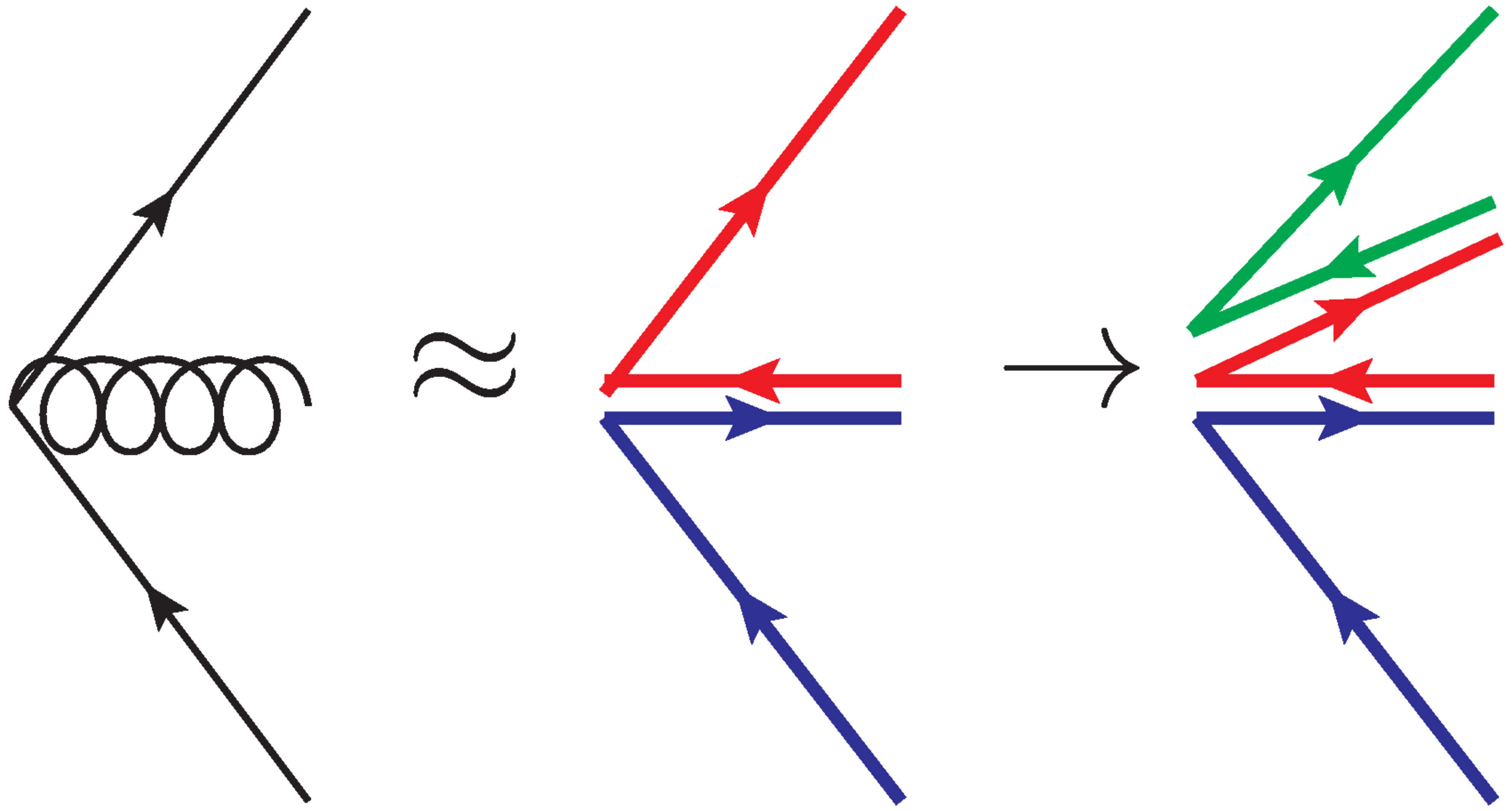

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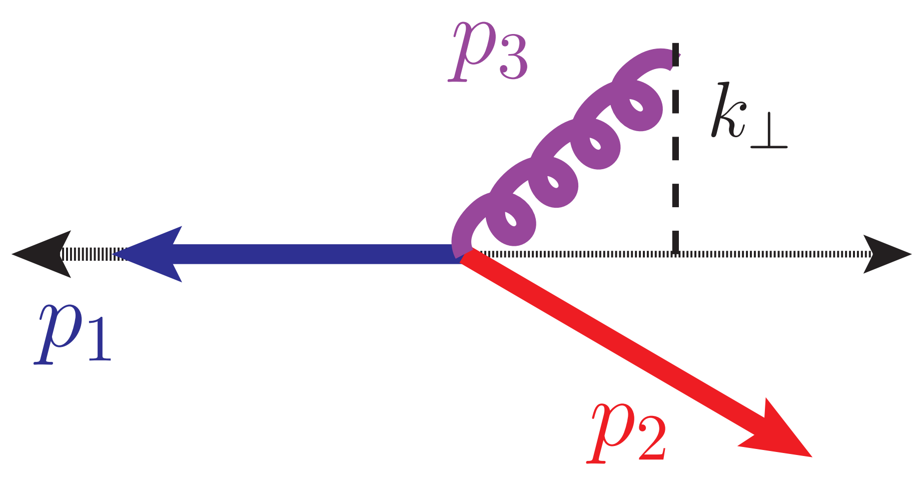
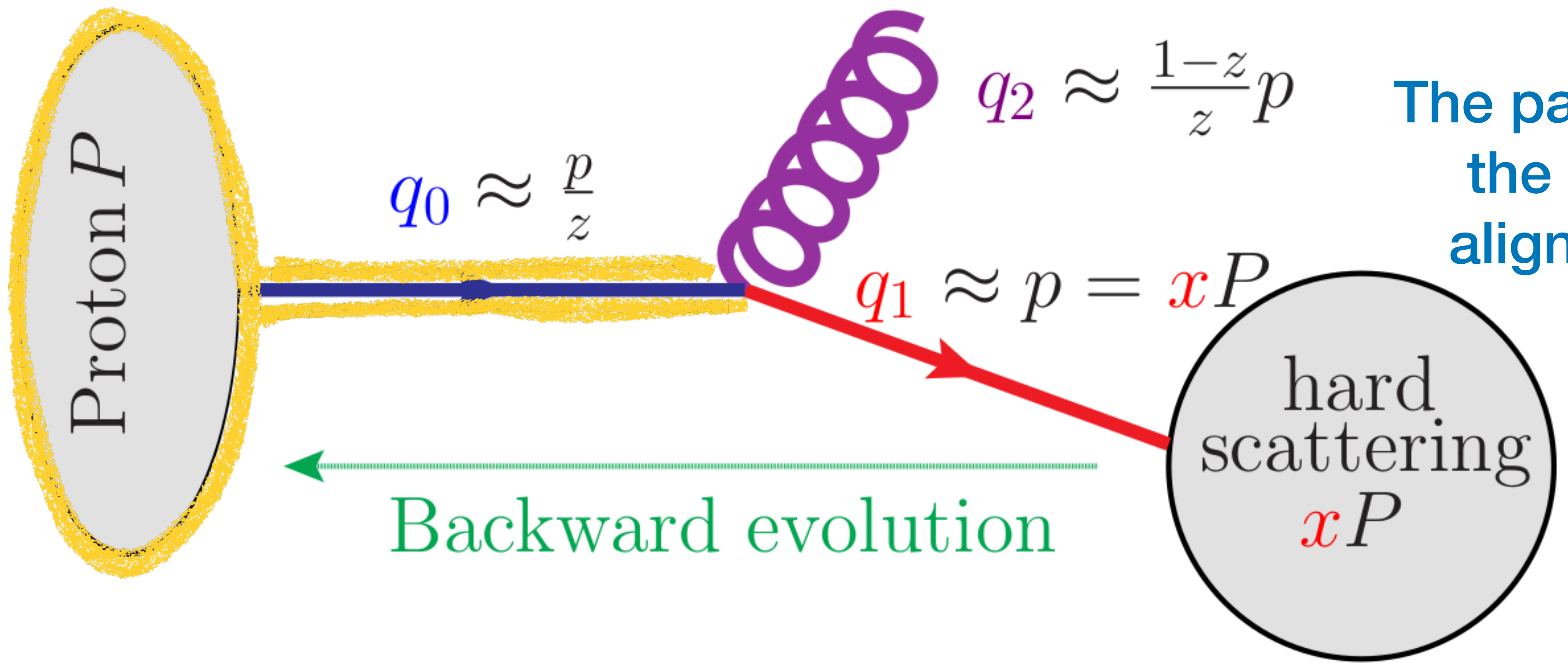
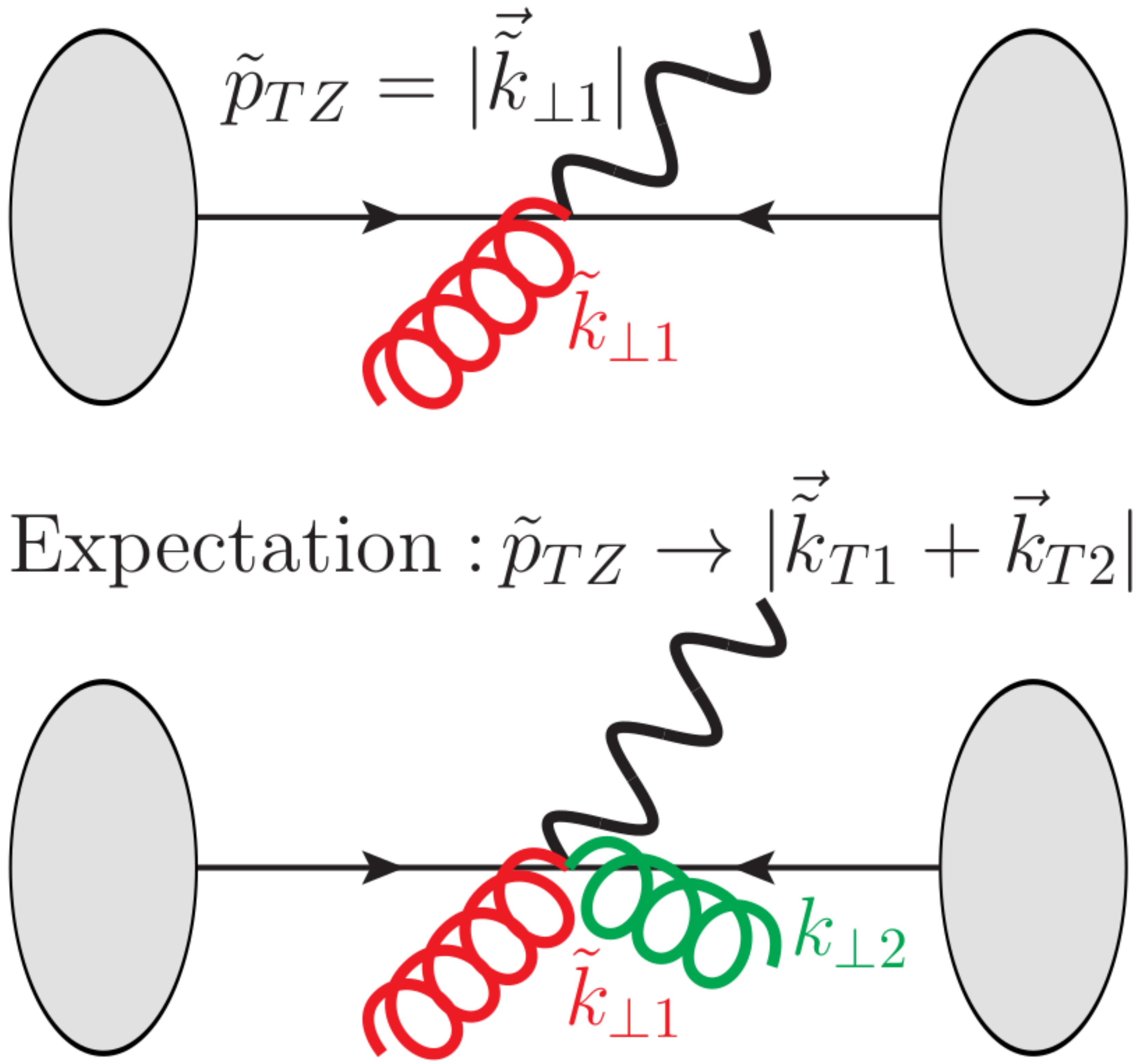


- Emissions are ordered in transverse momentum (or virtuality): this simplifies matching with higher order (NLO or NNLO) calculations, as we can just correct the first (=hardest)

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



The parton extracted from the proton must stay aligned with the beam direction



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

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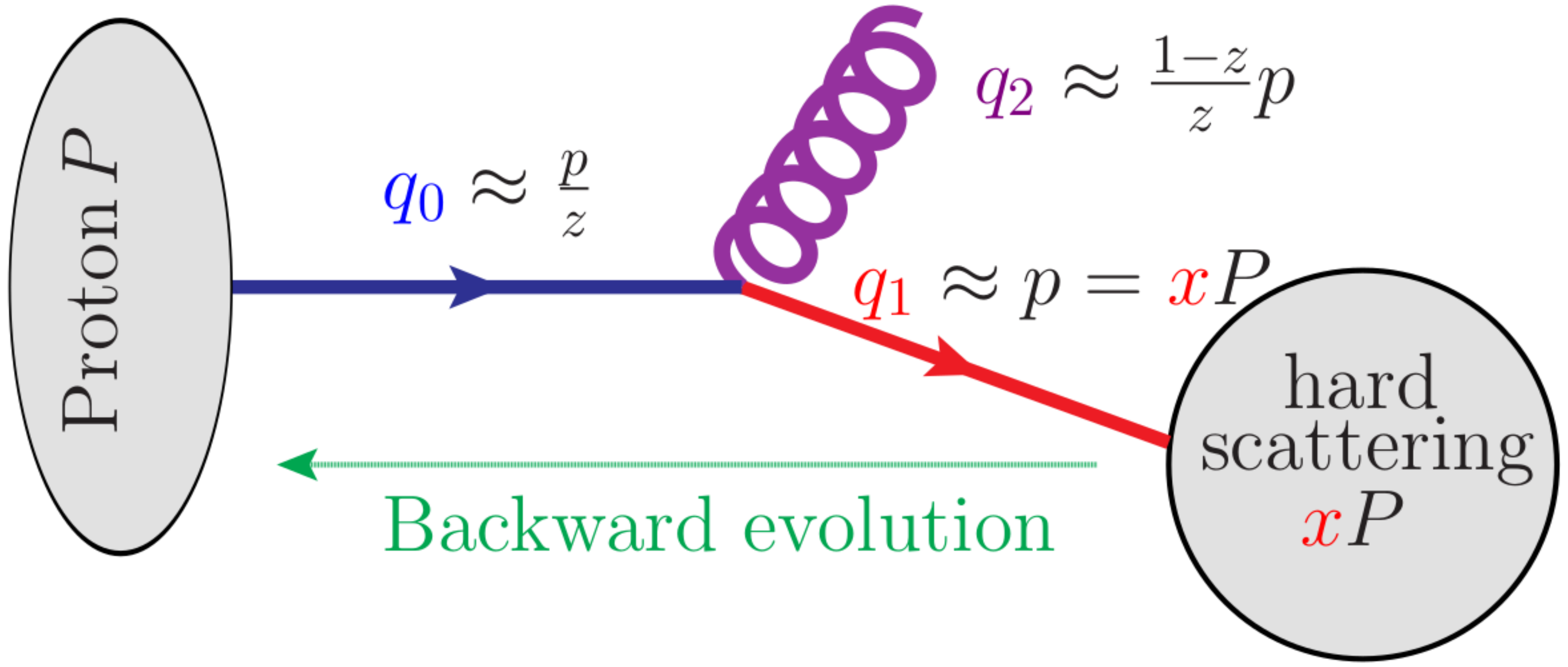

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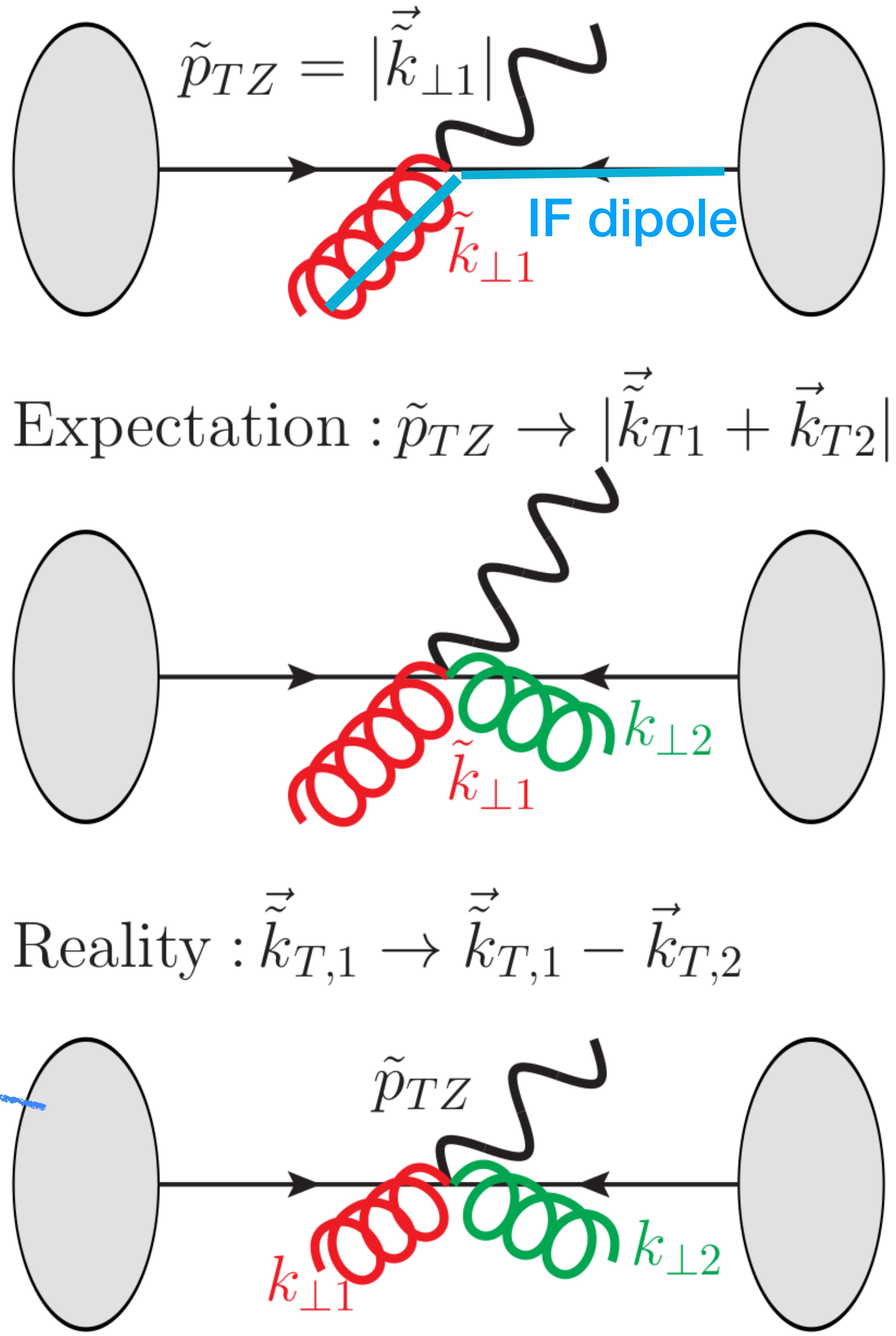
- But in common dipole showers, emissions from Initial-Final dipoles always make the final state leg recoil!
- Known to yield wrong $p_{T,Z}$ at NLL! [Parisi, Petronzio NPB 154 (1979) 427-440, Nagy, Soper 0912.4534]



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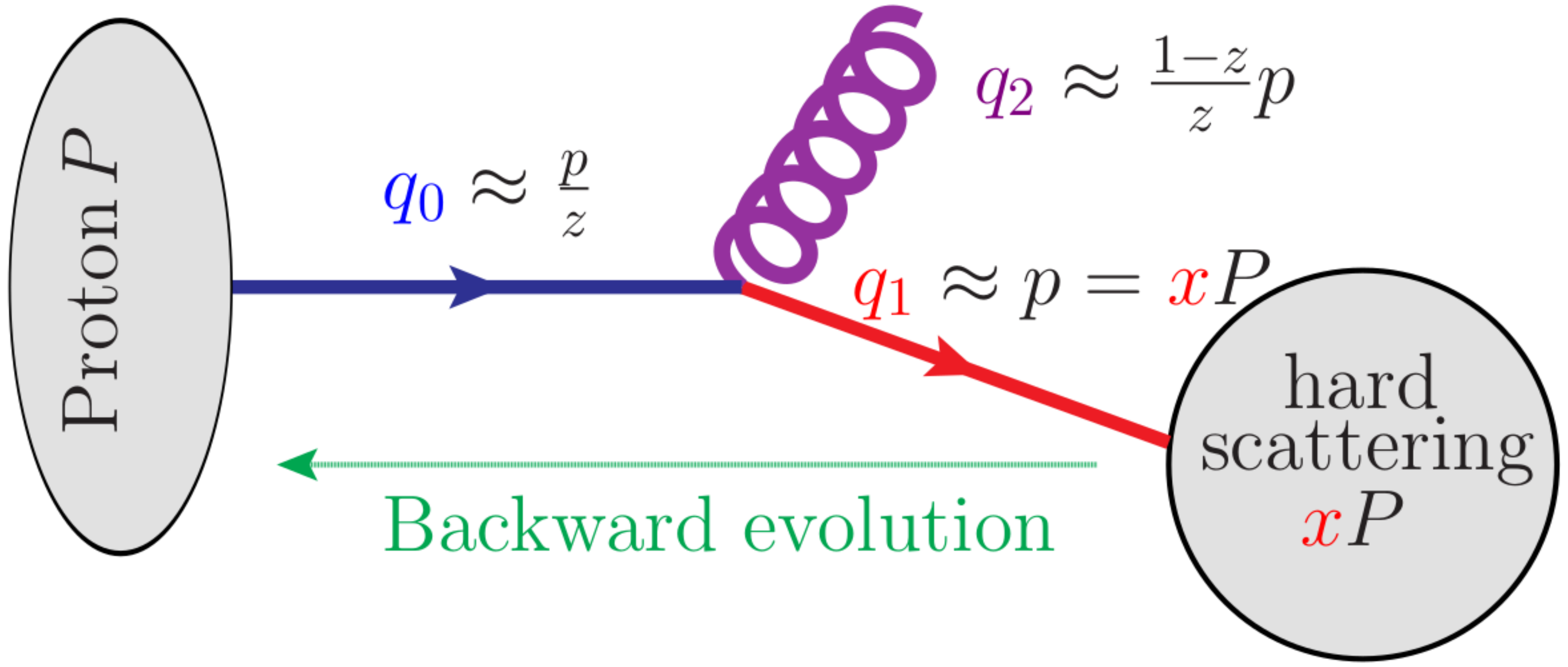
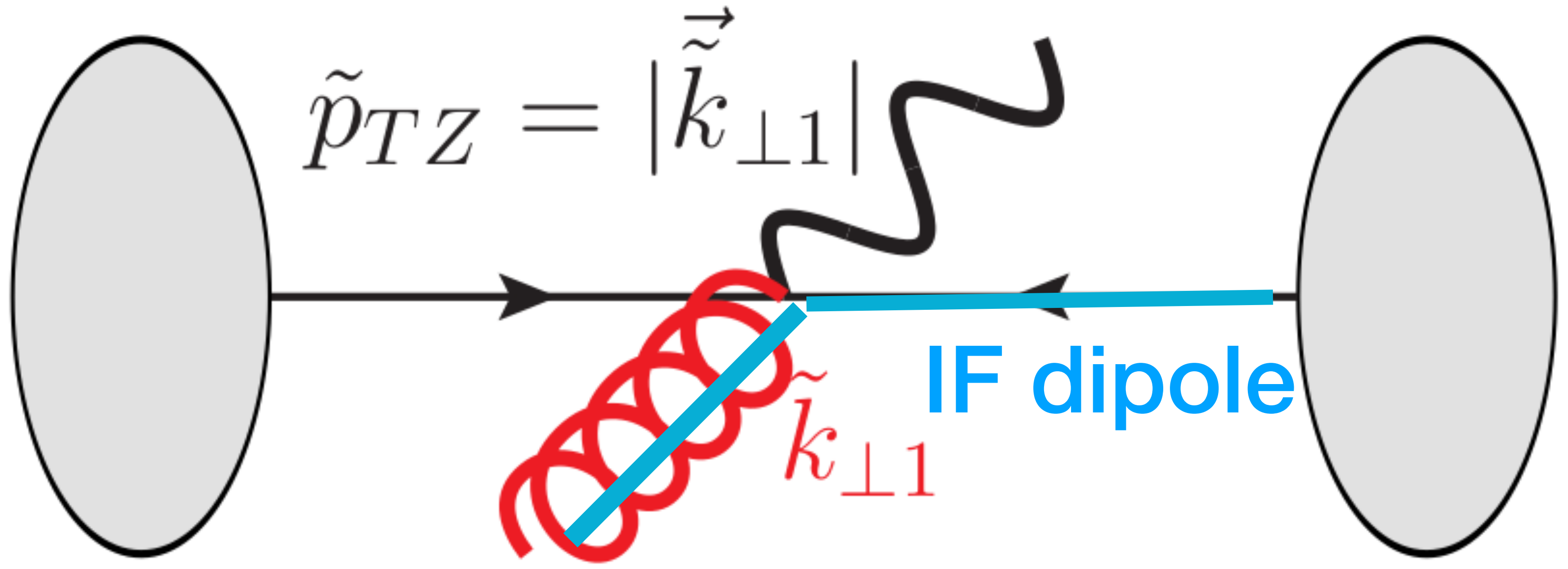
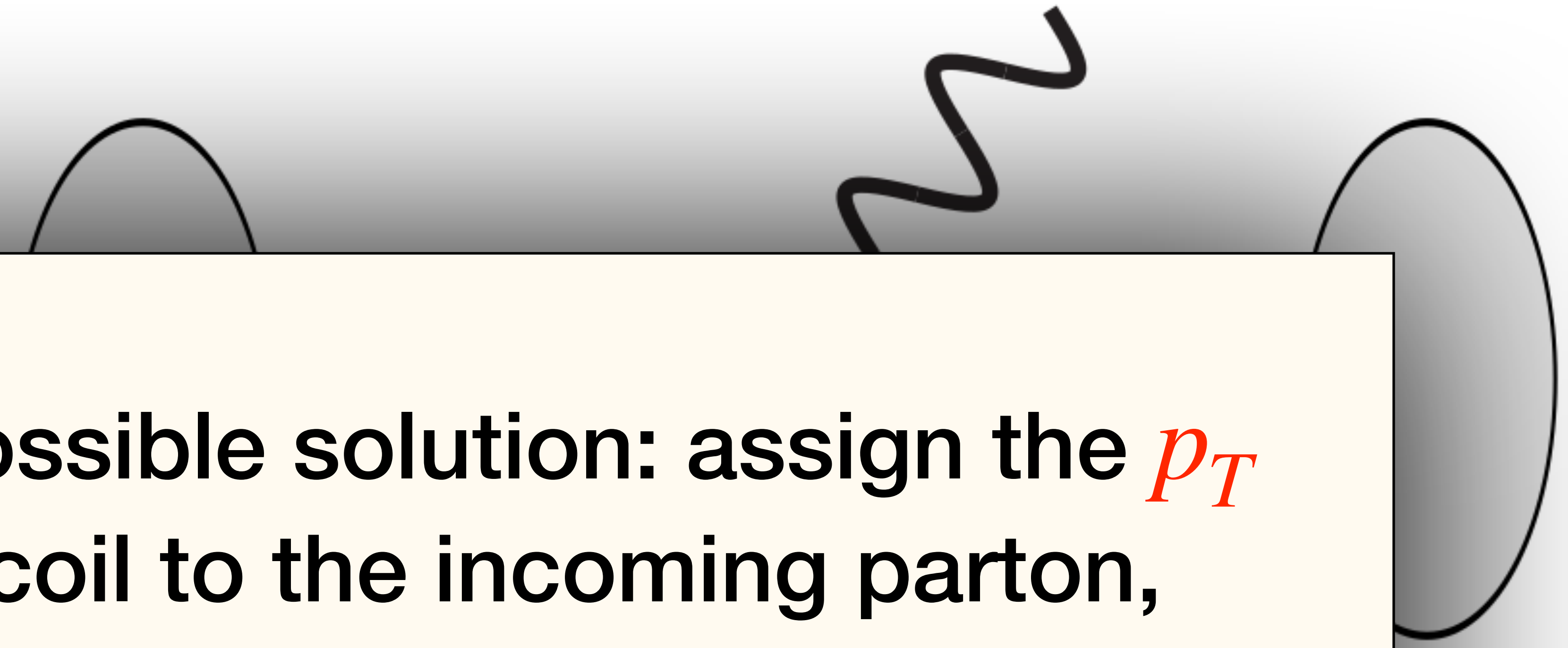
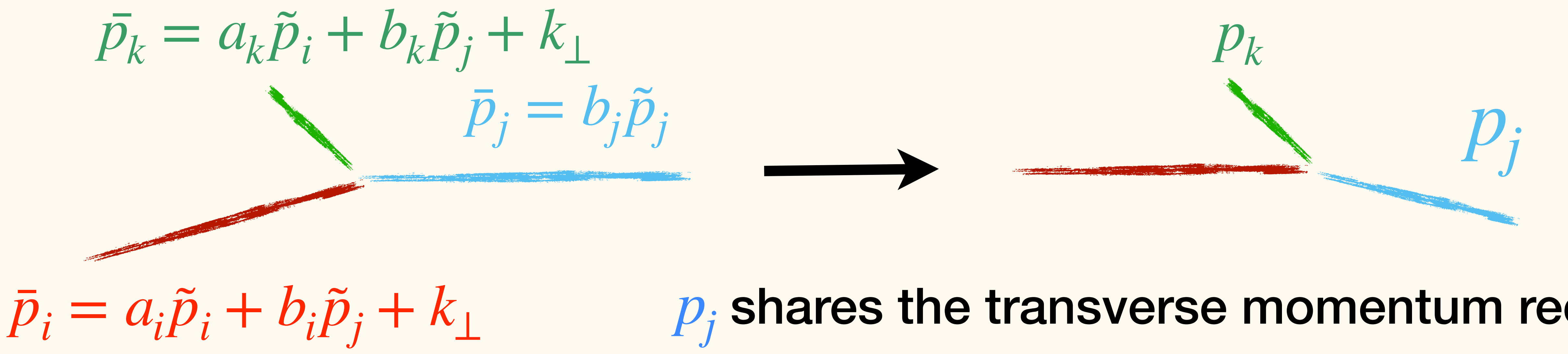




$$\text{Expectation}: \tilde{p}_{TZ} \to |\vec{\tilde{k}}_{T1} + \vec{k}_{T2}|$$



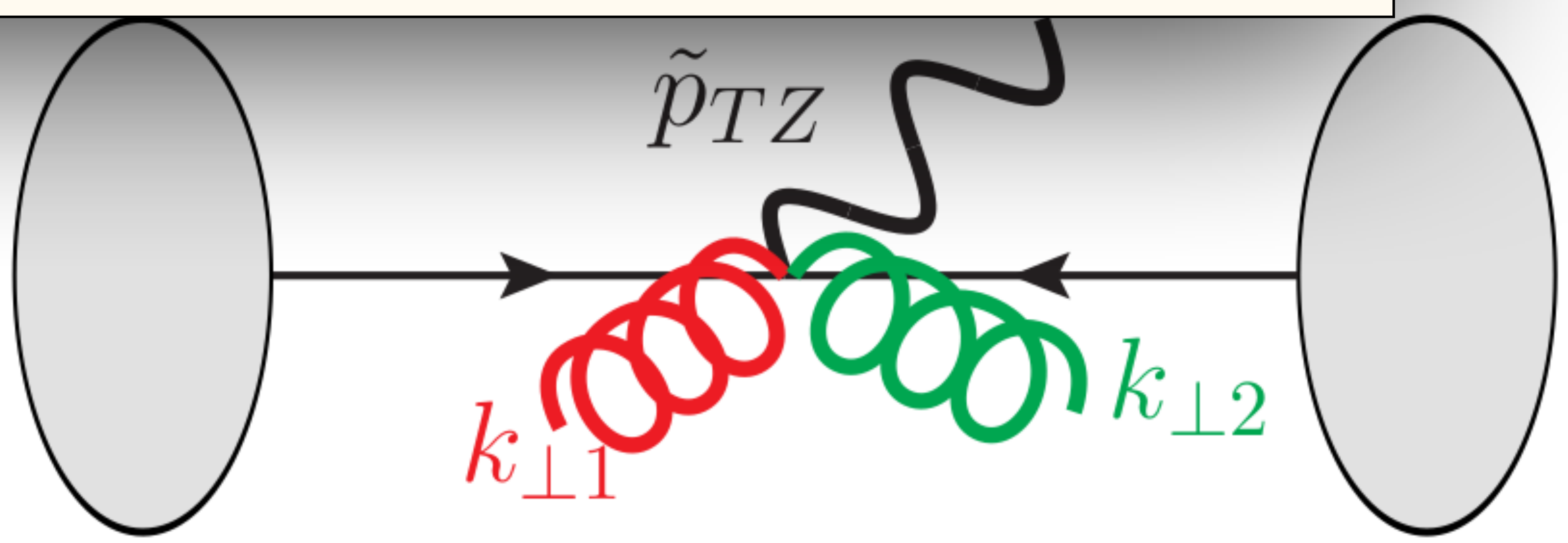
- **Initial-state radiation:** we cannot assign the p_T recoil to the incoming parton



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

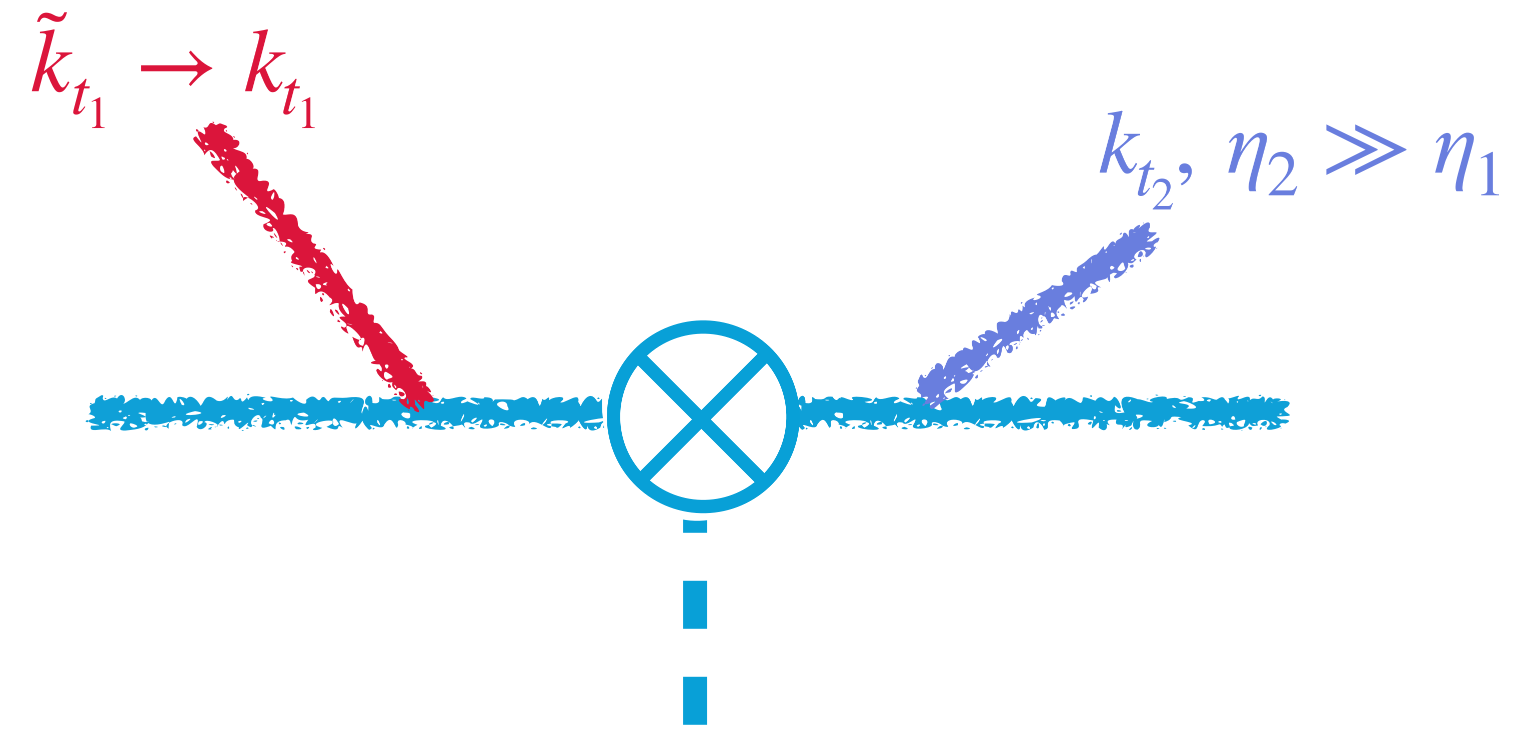
Possible solution: assign the p_T recoil to the incoming parton, and then boost everything to realign it with the beam axis [Platzer, Gieseke 0909.5593]

- Known to yield wrong $p_{T,Z}$ at NLL! [Parisi, Petronzio NPB 154 (1979) 427-440, Nagy, Soper JHEP 03 (2010) 097]



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

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



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

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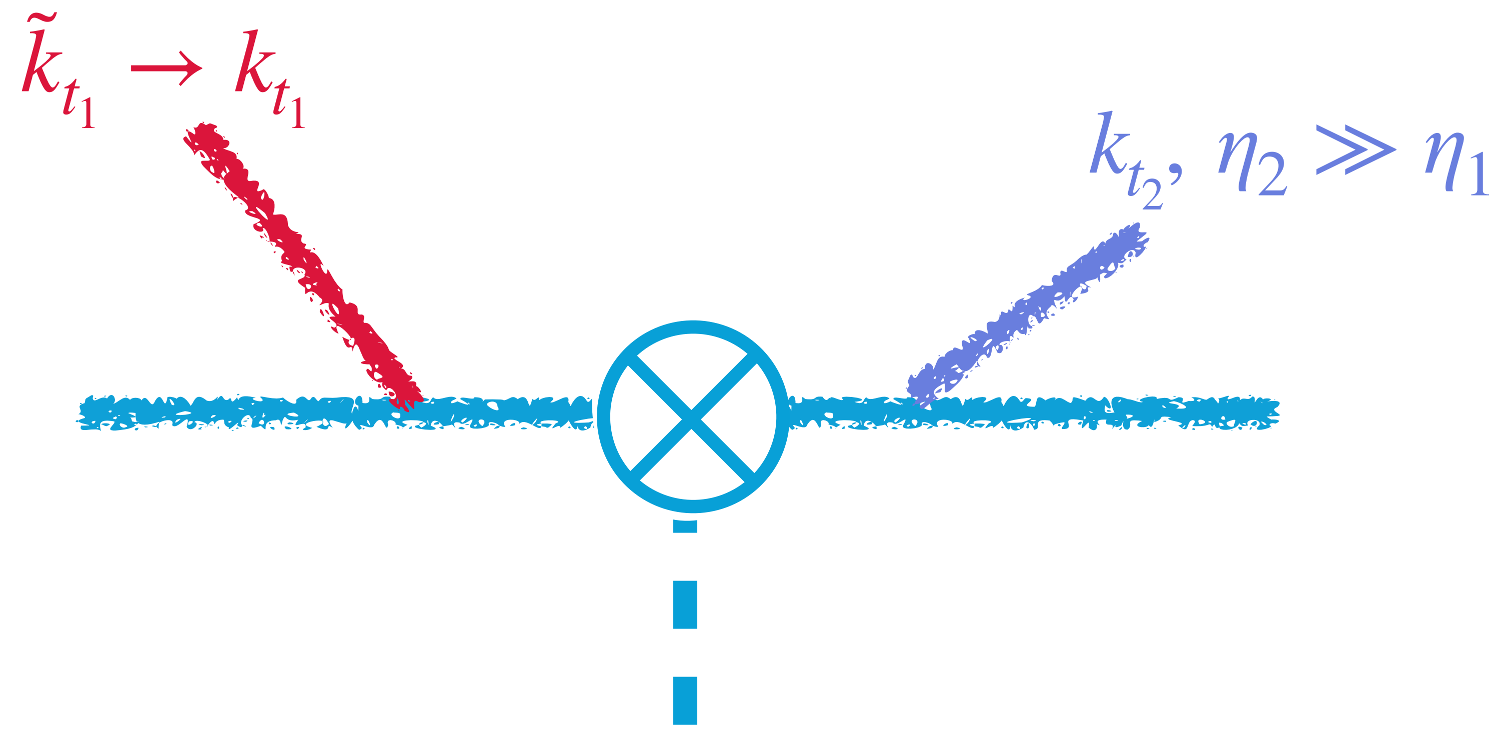

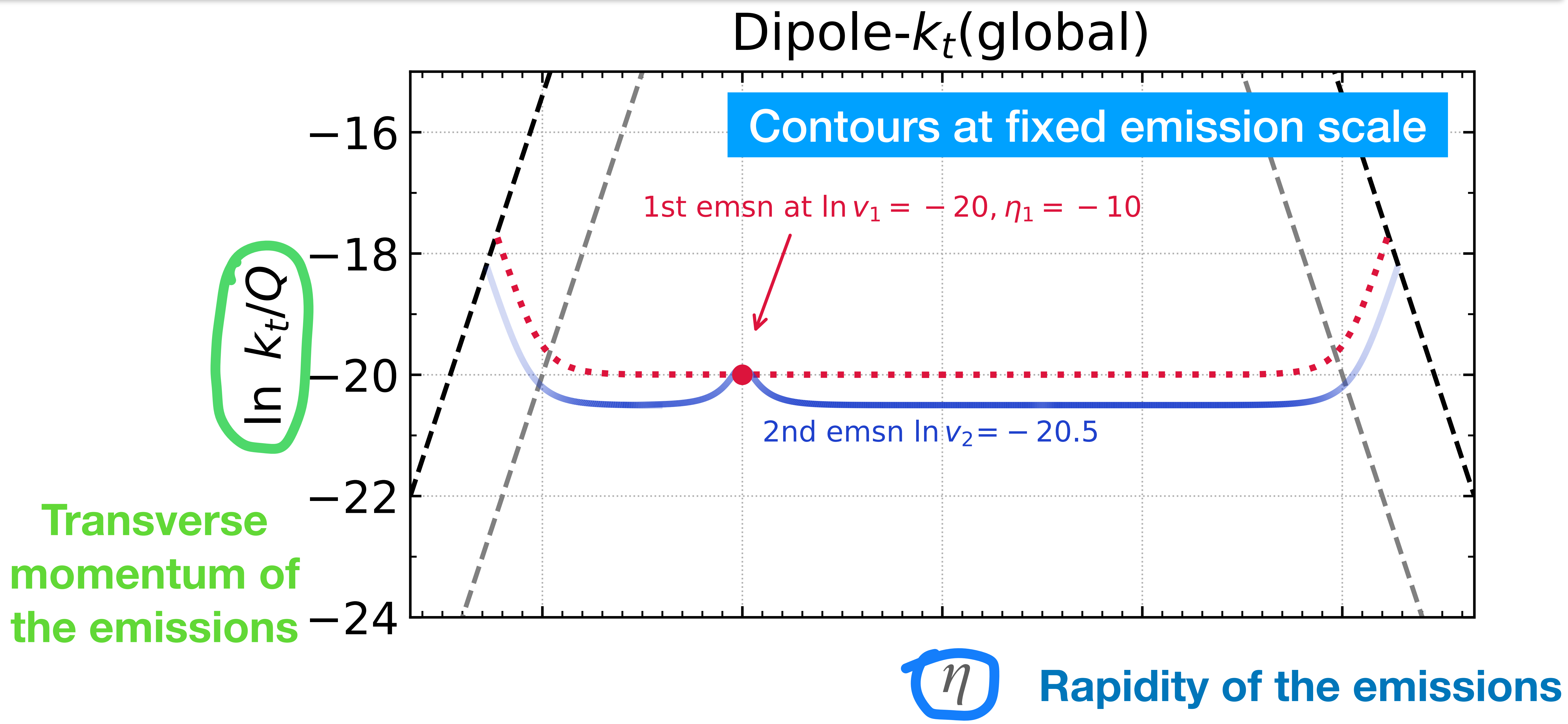

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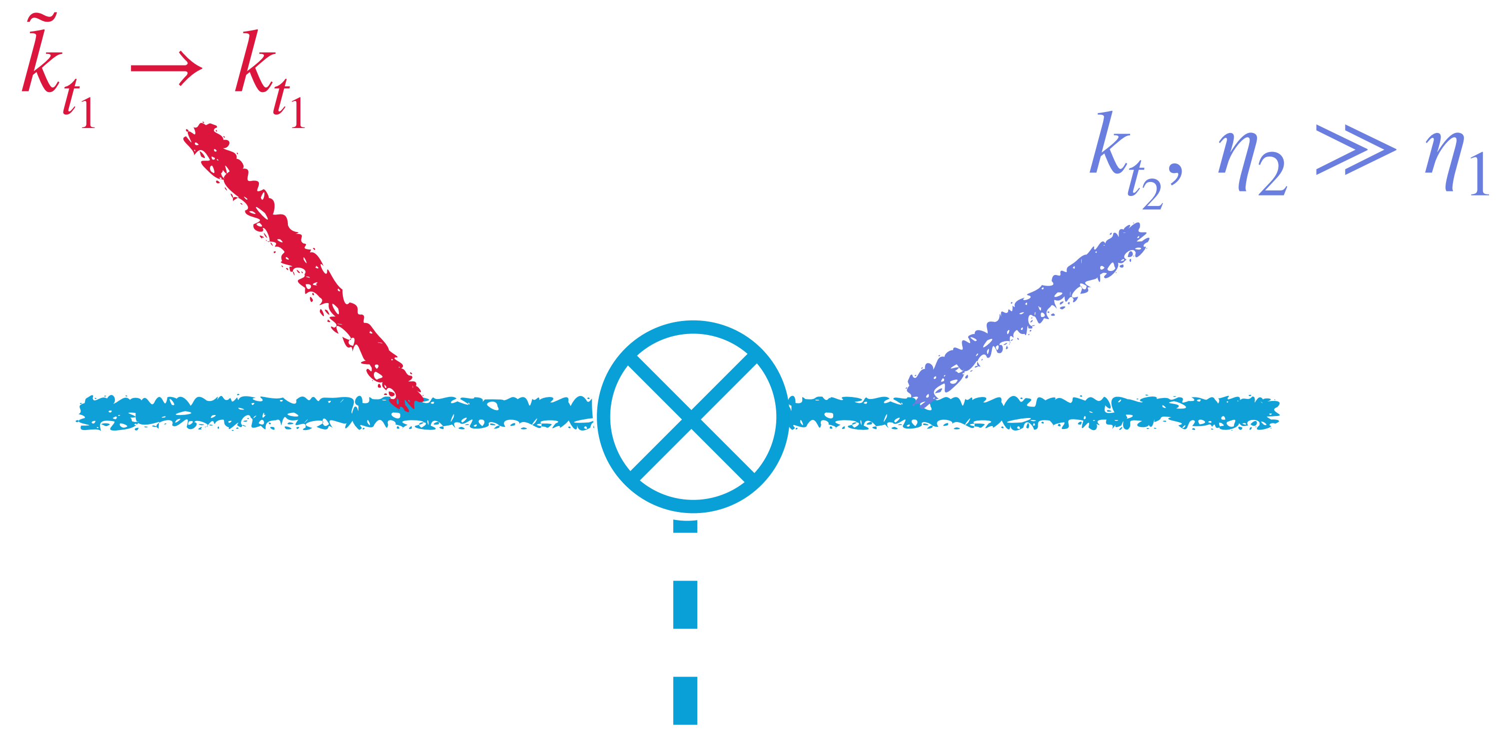

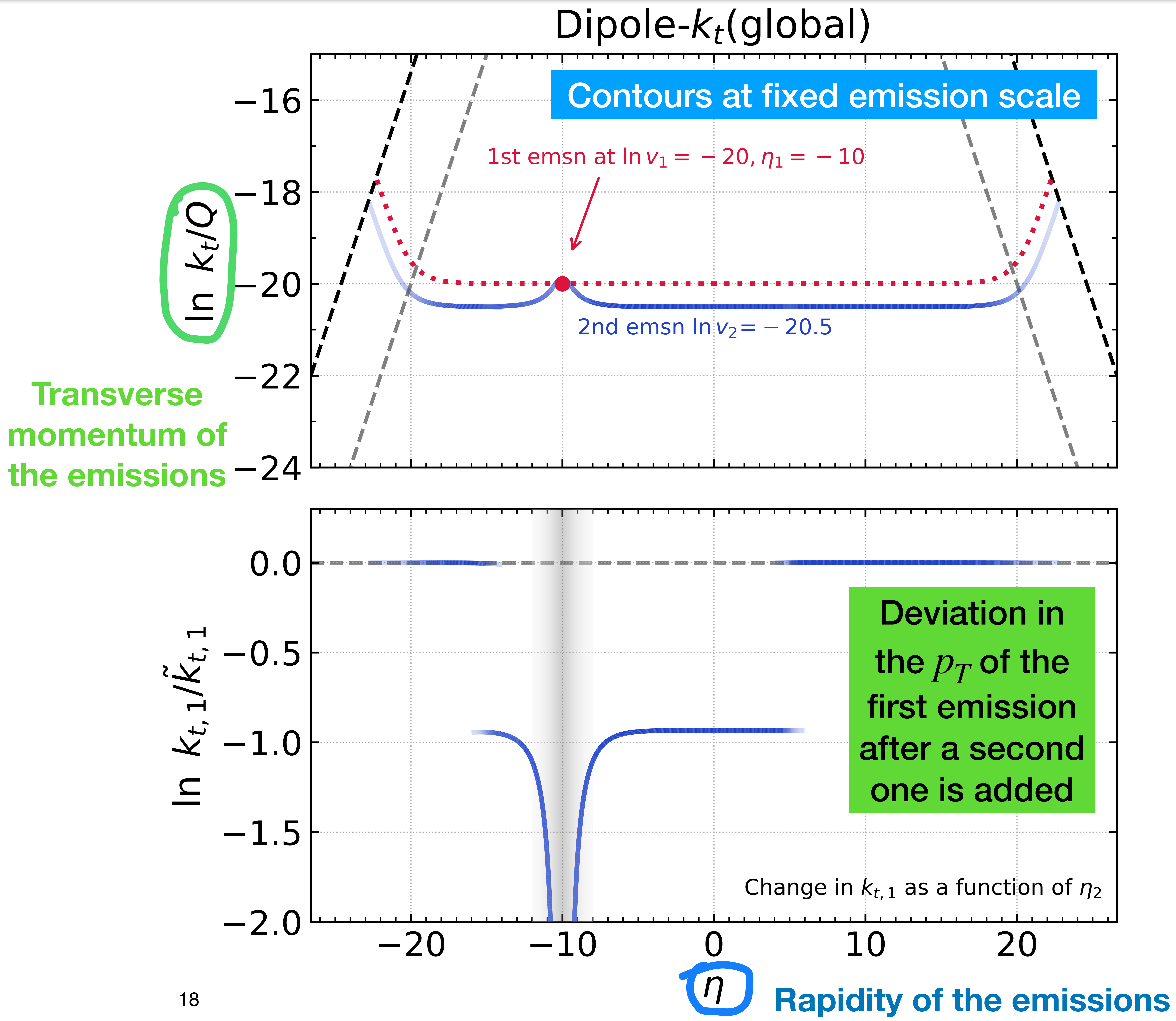

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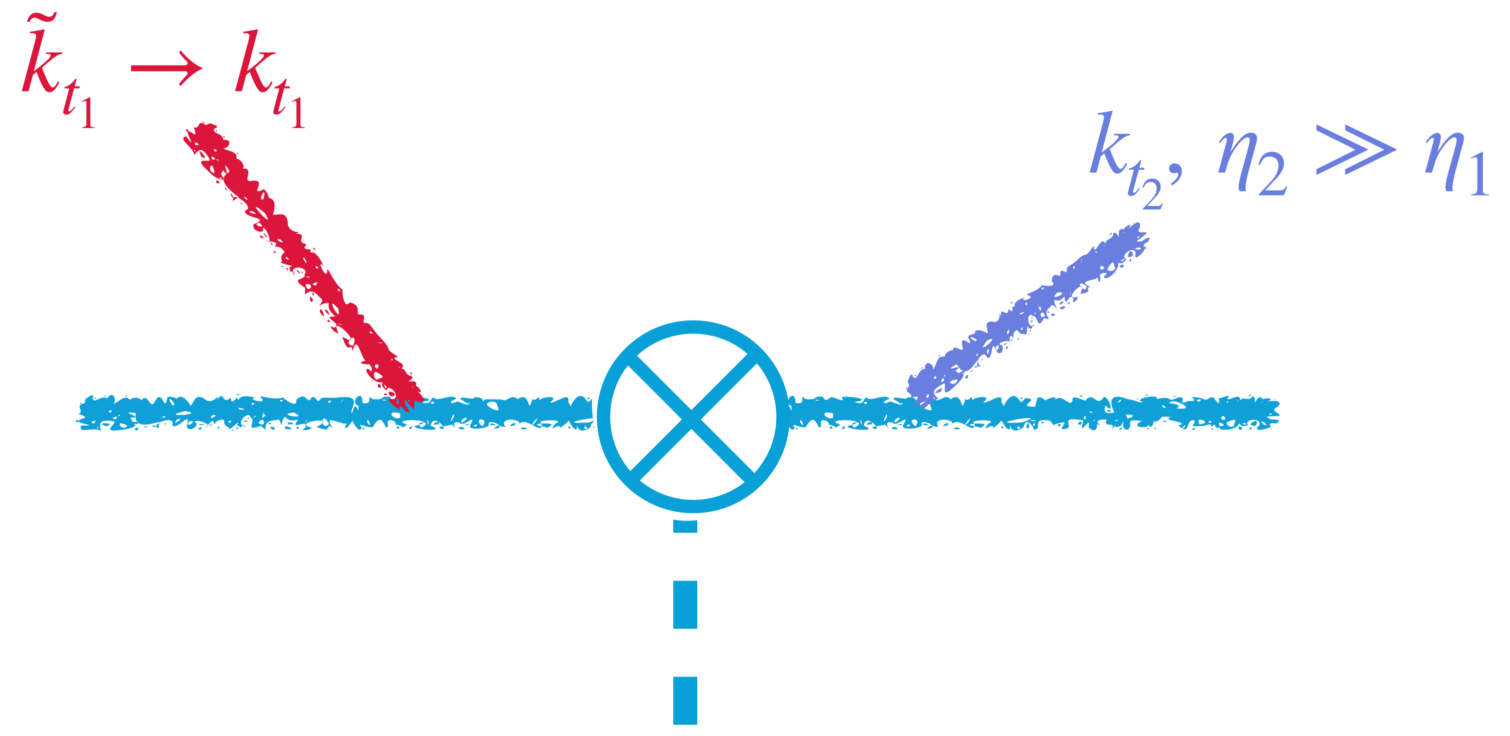
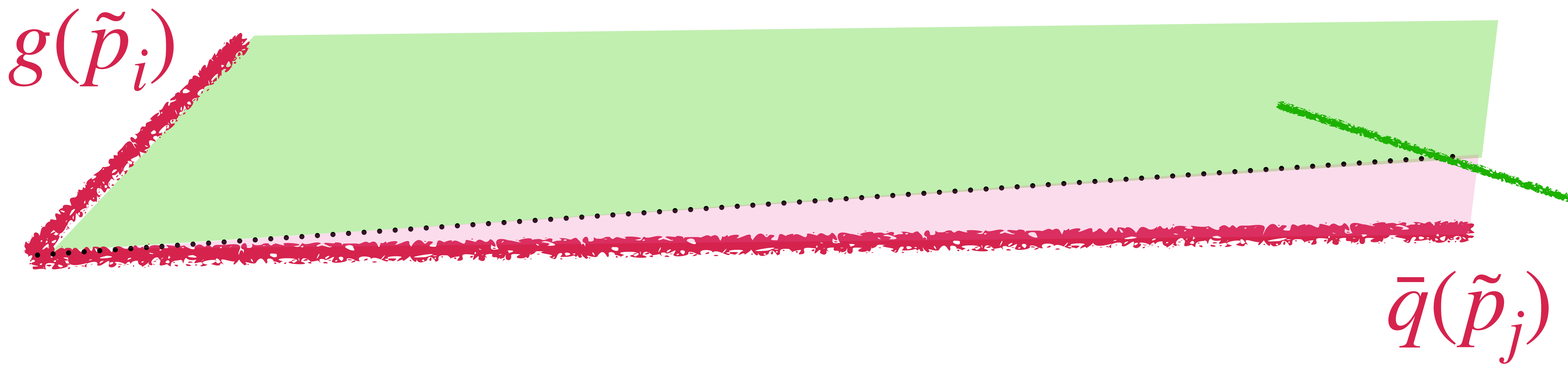
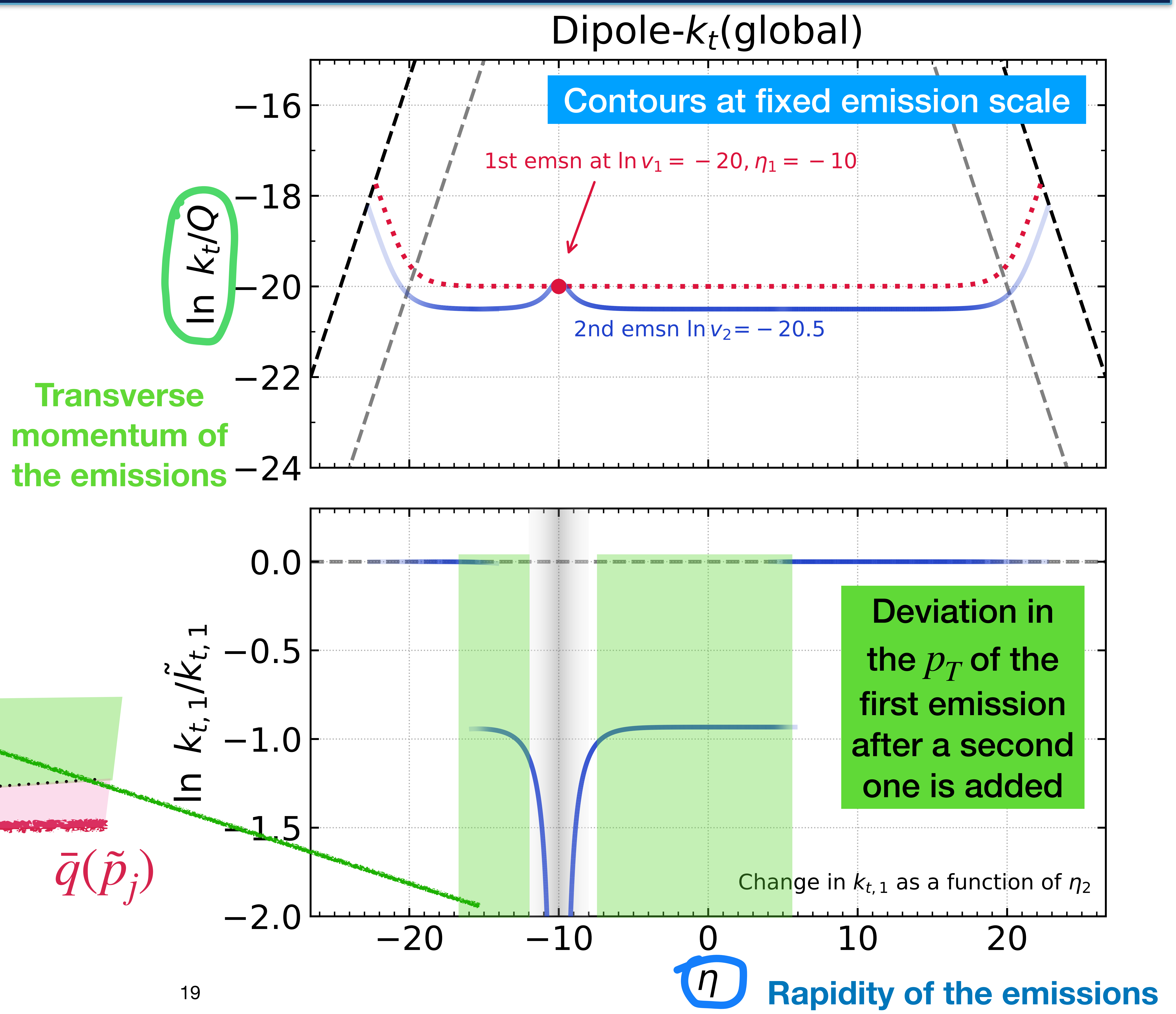


Direct consequence of CM dipole separation

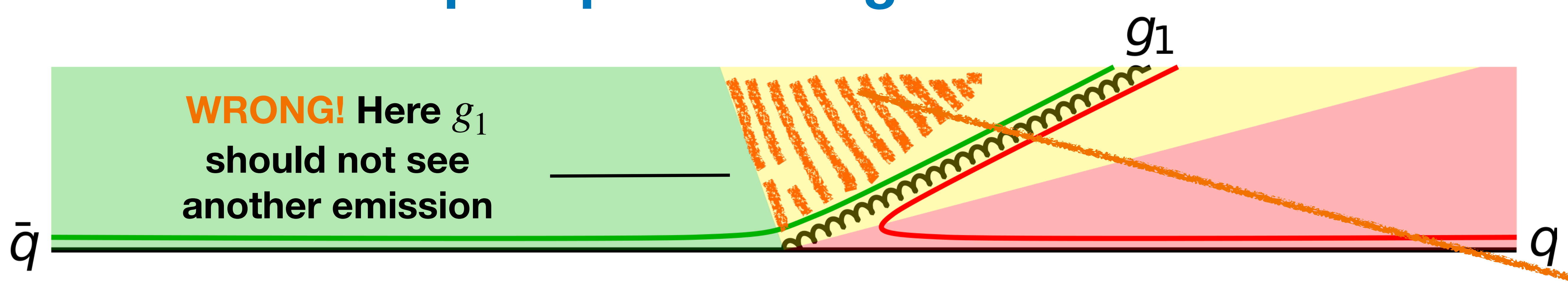


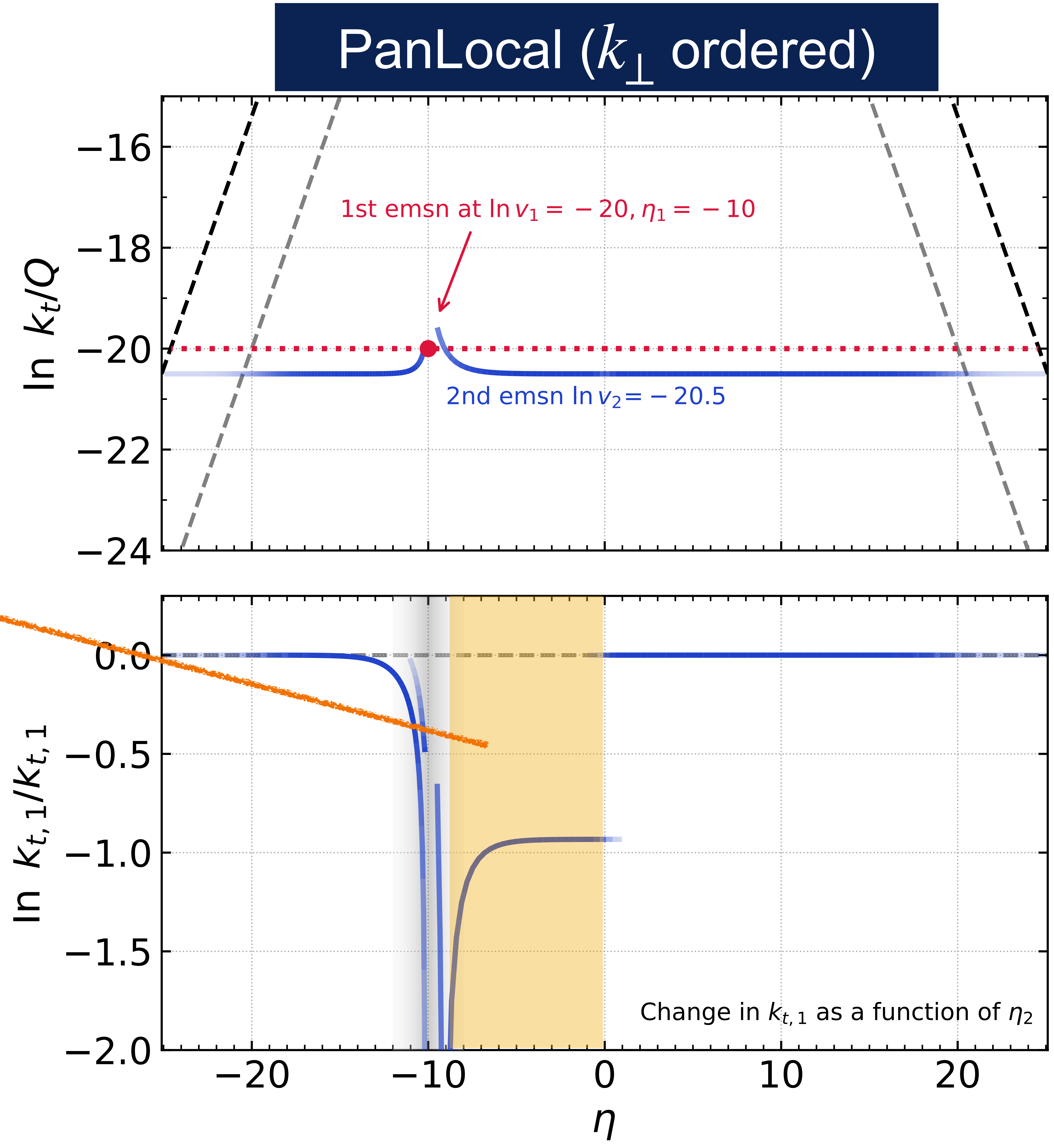


van Beekveld, S.F.R., Salam, Soto-Ontoso, Soyez, Verheyen, 2205.02237

NLL PanScales showers for hadron collision: PanLocal

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





PanLocal for FSR: Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez, 2002.11114

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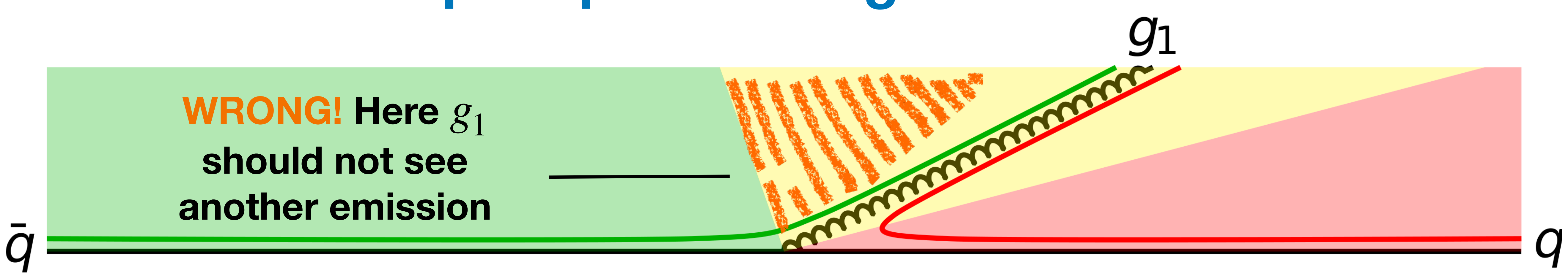
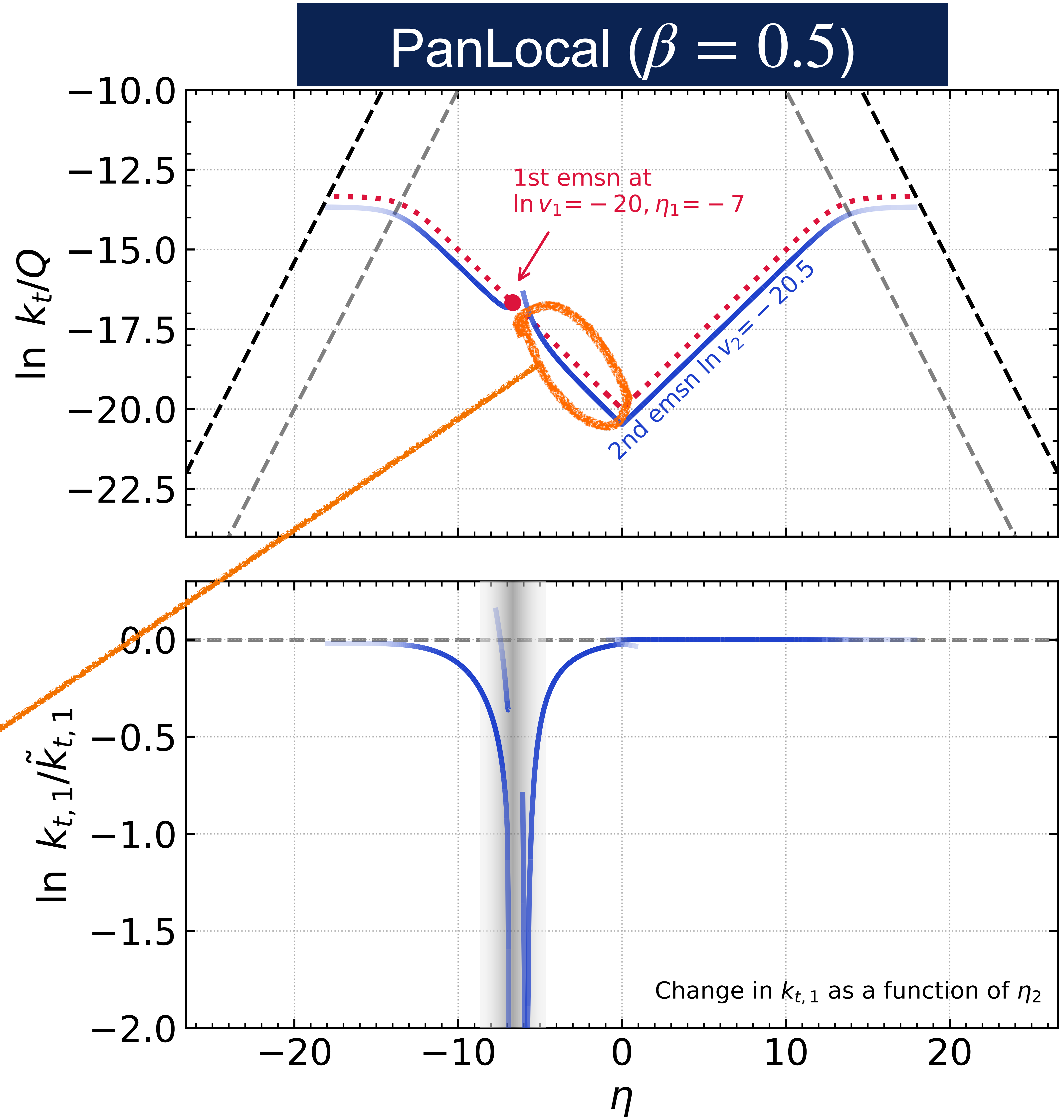


- **Ordering scale** $v = p_T e^{-\beta|\eta|} \approx p_T \theta^{-\beta}$ with $0 < \beta < 1$, so $p_{T2} \ll p_{T1}$ since $\theta_1 > \theta_2$ in the "wrong" region: recoil is negligible ...



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

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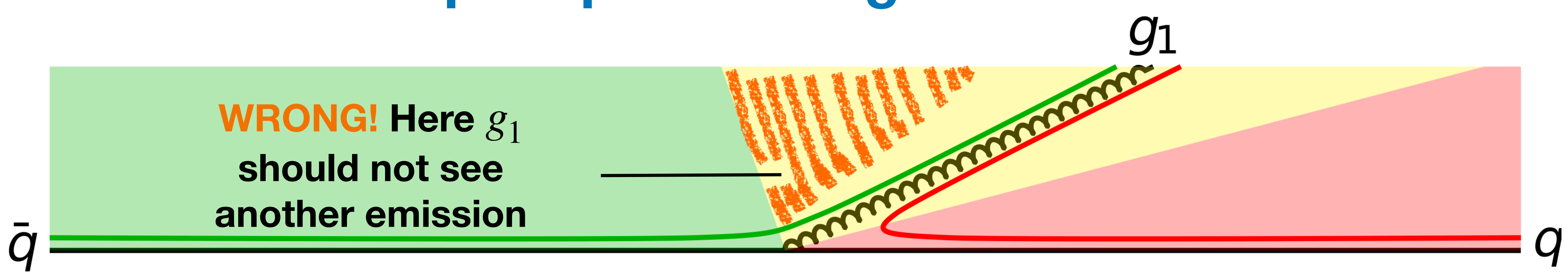
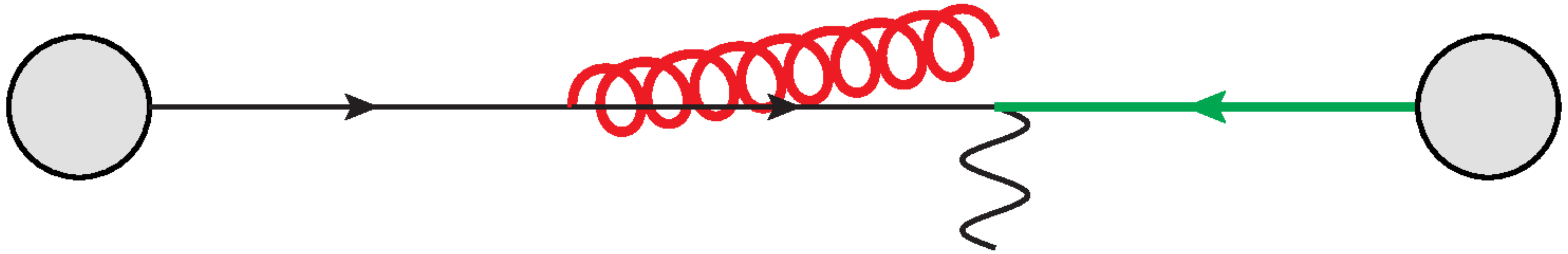
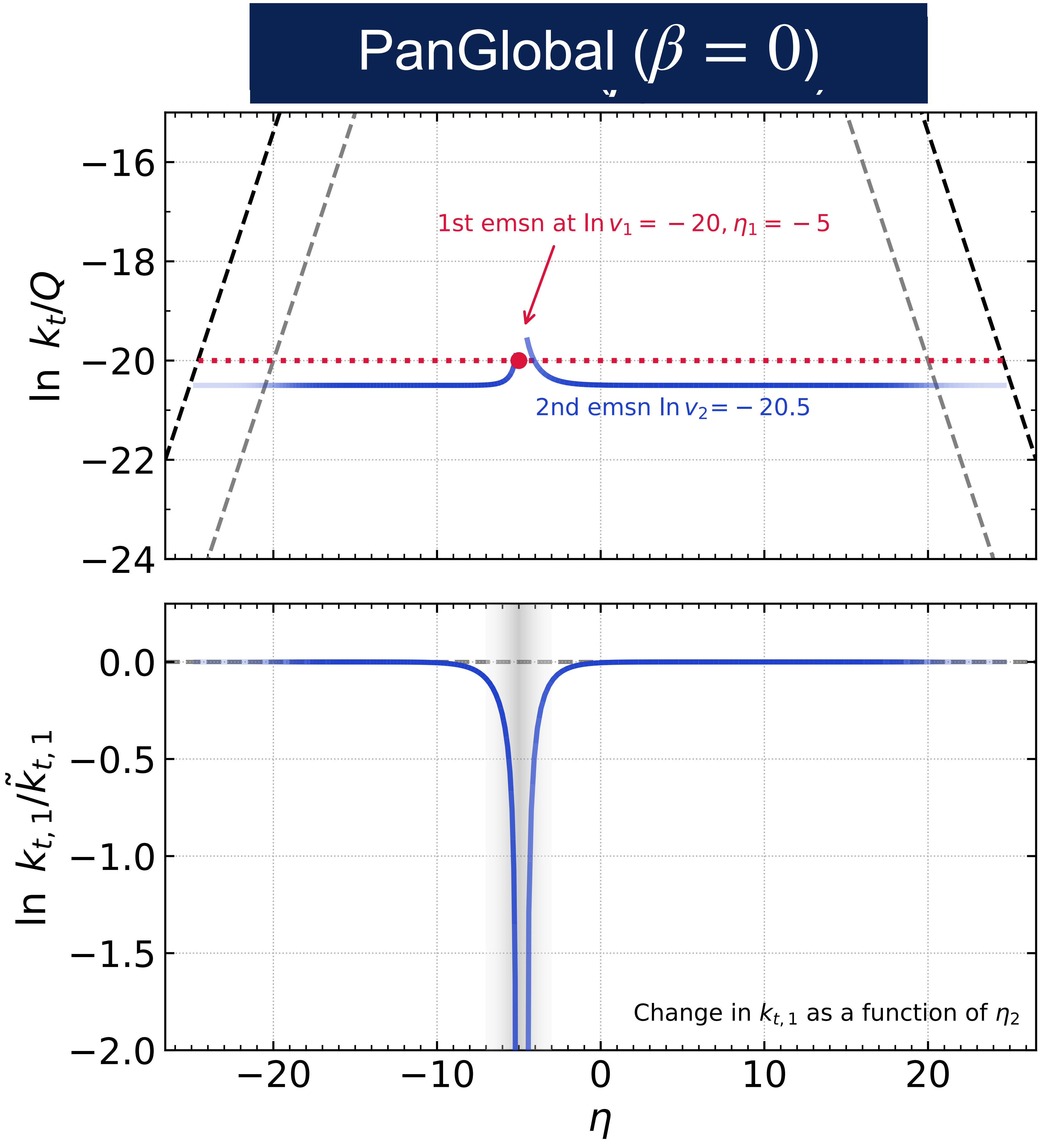


- **Ordering scale** $v = p_T e^{-\beta|\eta|} \approx p_T \theta^{-\beta}$ with $0 \leq \beta < 1$

- The p_T recoil is always taken by the **Z** boson





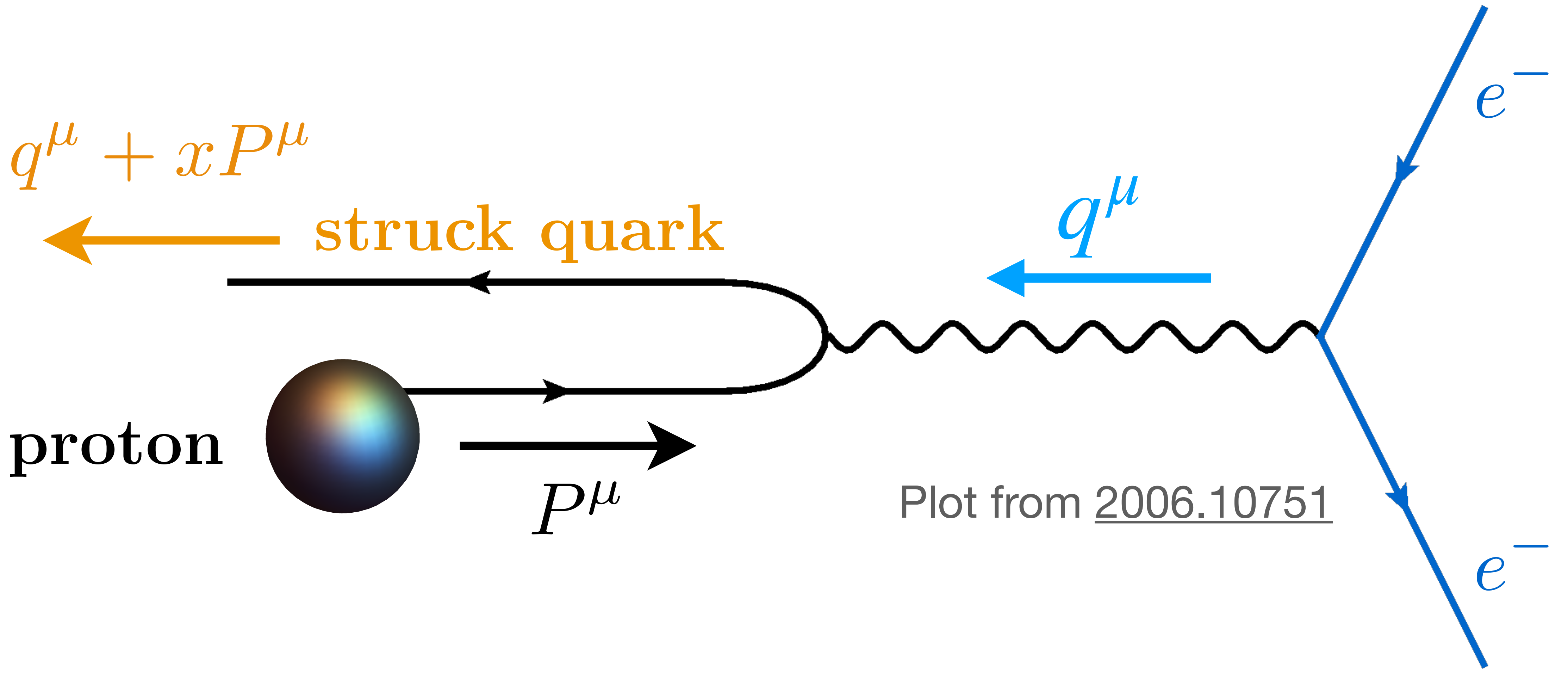
PanGlobal for FSR: Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez, 2002.11114

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

NLL PanScales showers for DIS

The PanScales showers for DIS differ from the one for pp in their treatment of ISR, and in the choices of the invariants to preserve.

- Global boost that assignes the $k_\perp$ recoil due to ISR mainly to partons that carry a large fraction of the original struck quark momentum
- We preserve the t-channel momentum transferred q^μ



Plot from 2006.10751

van Beekveld, S.F.R., 2305.08645

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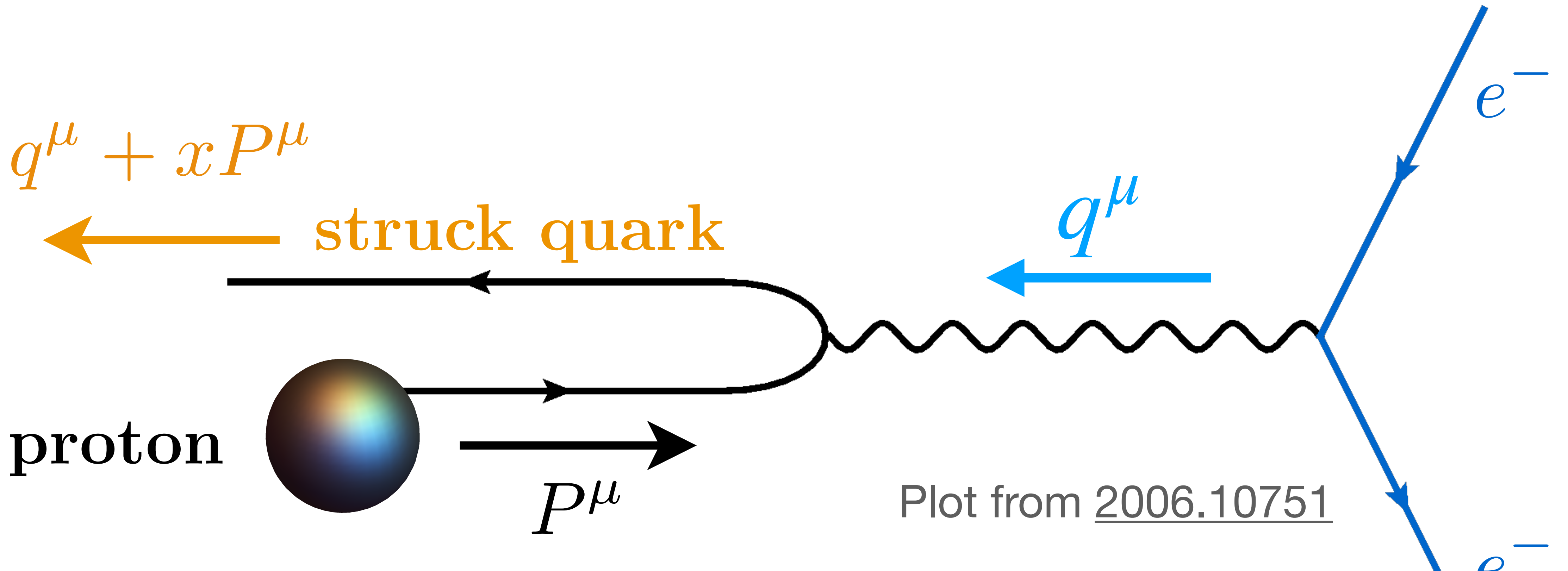
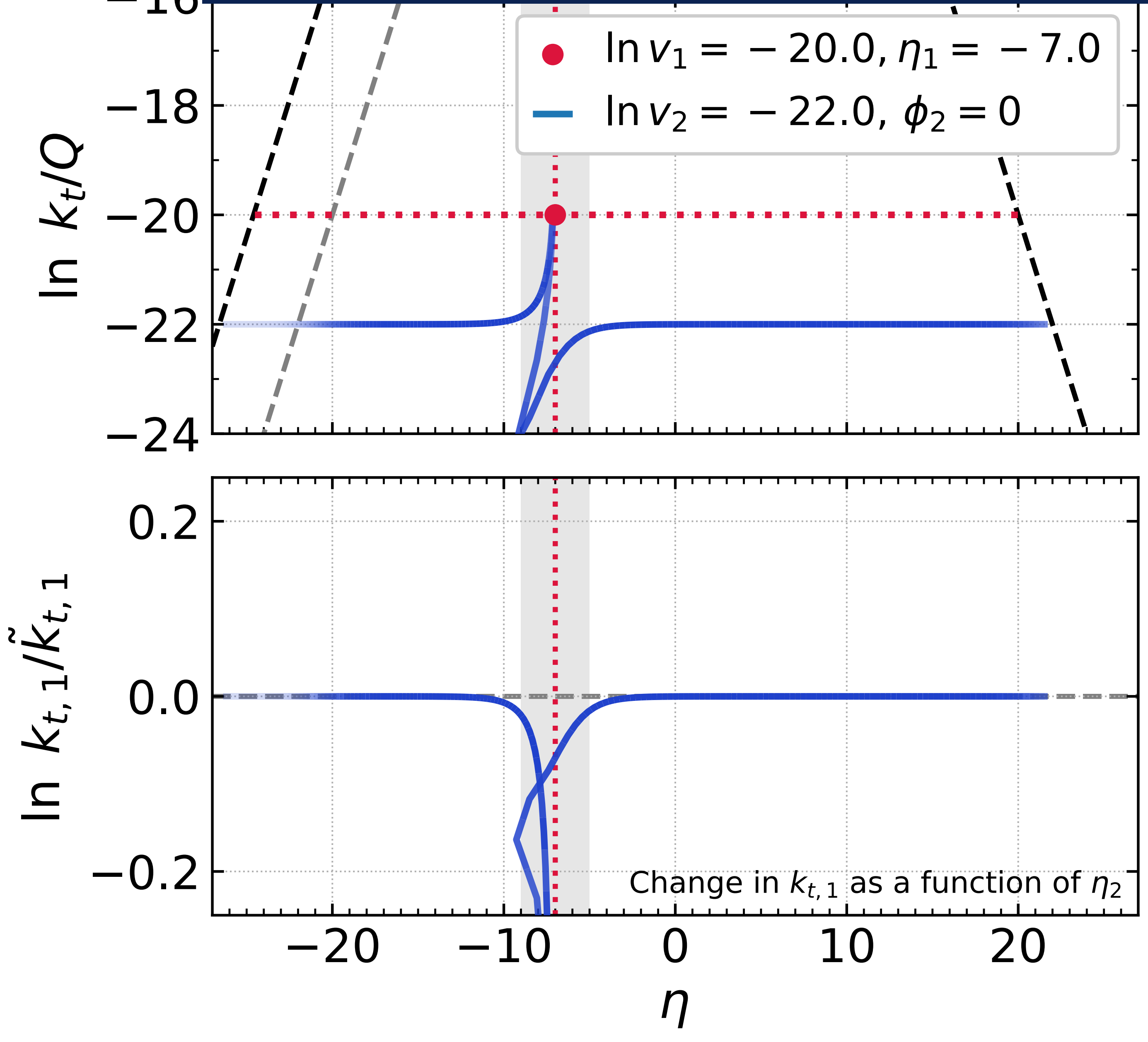
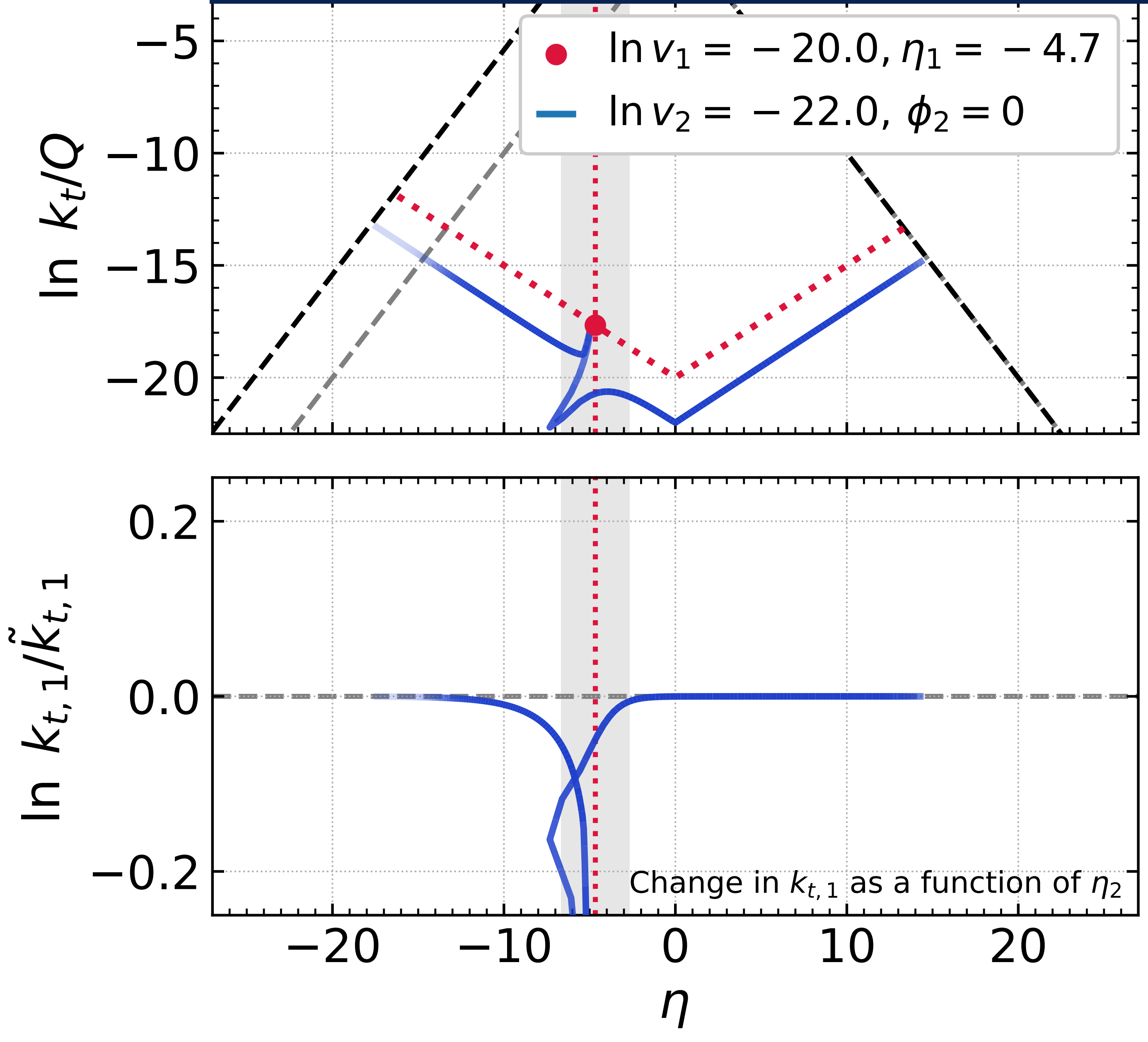


Plot from 2006.10751

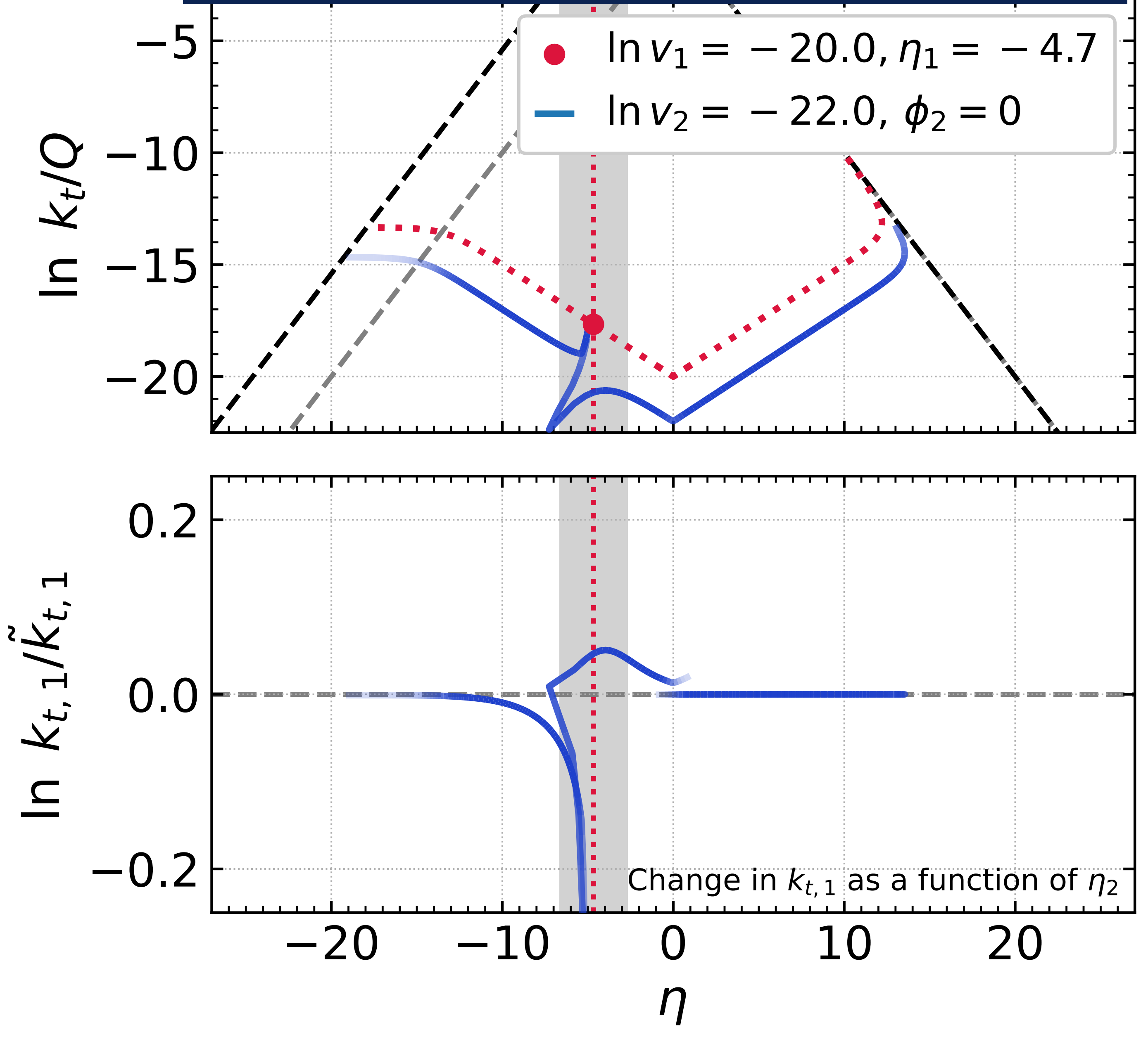
PanGlobalDIS ($\beta = 0$)



PanGlobalDIS ($\beta = 0.5$)



PanLocalDIS ($\beta = 0.5$)

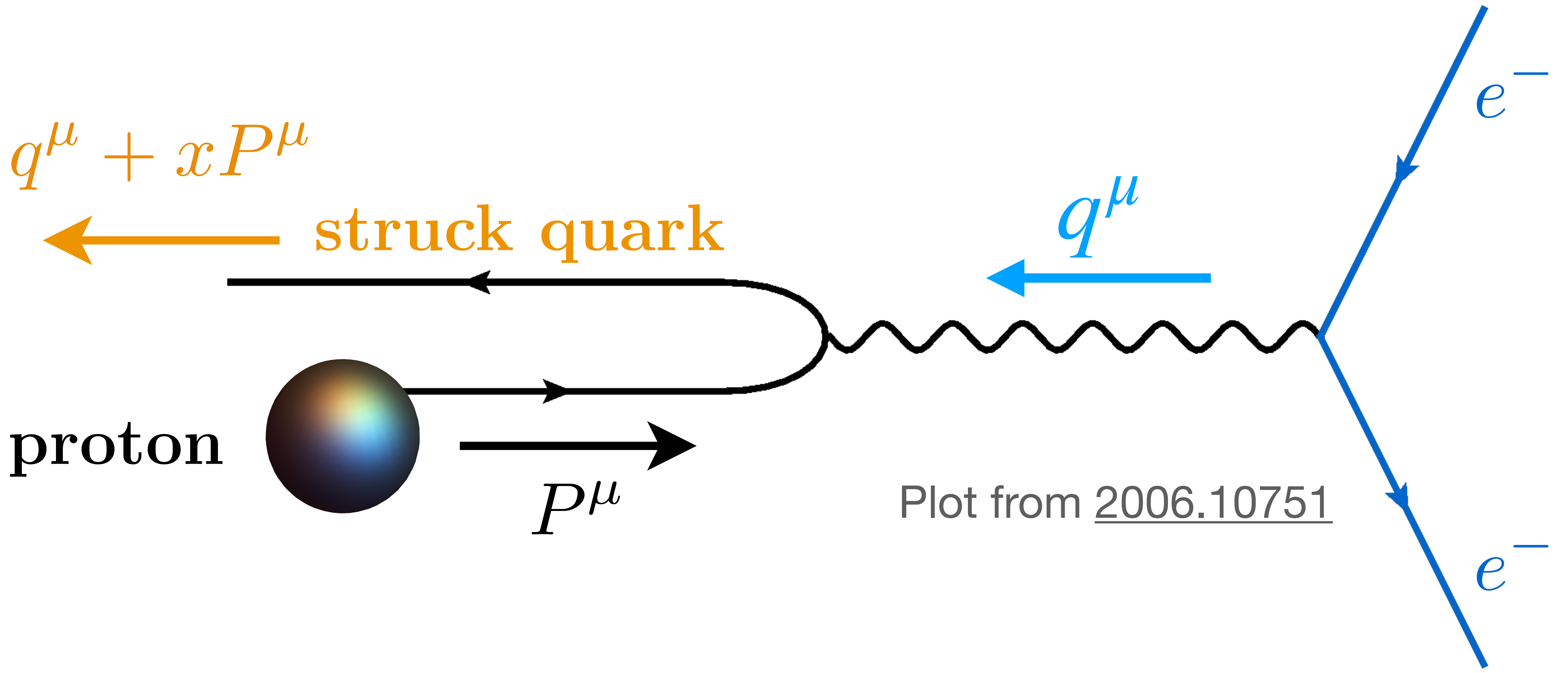


van Beekveld, S.F.R., 2305.08645

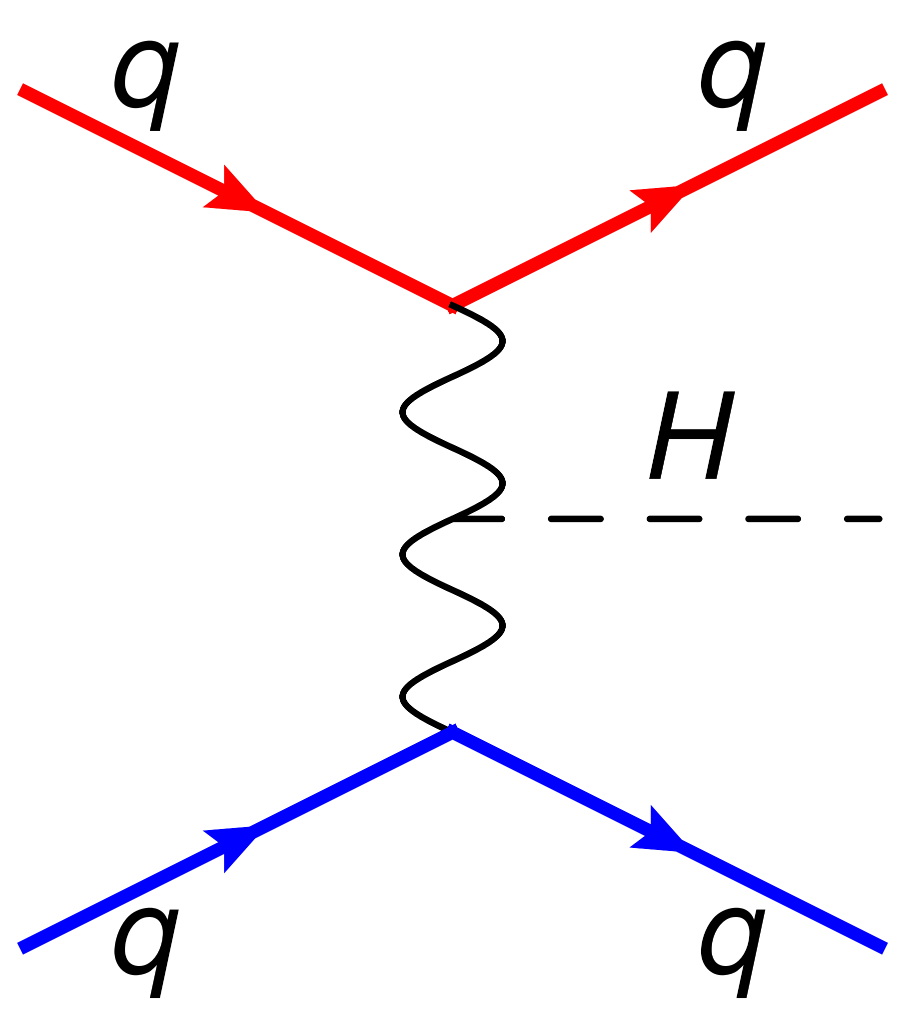
NLL PanScales showers for DIS and VBF

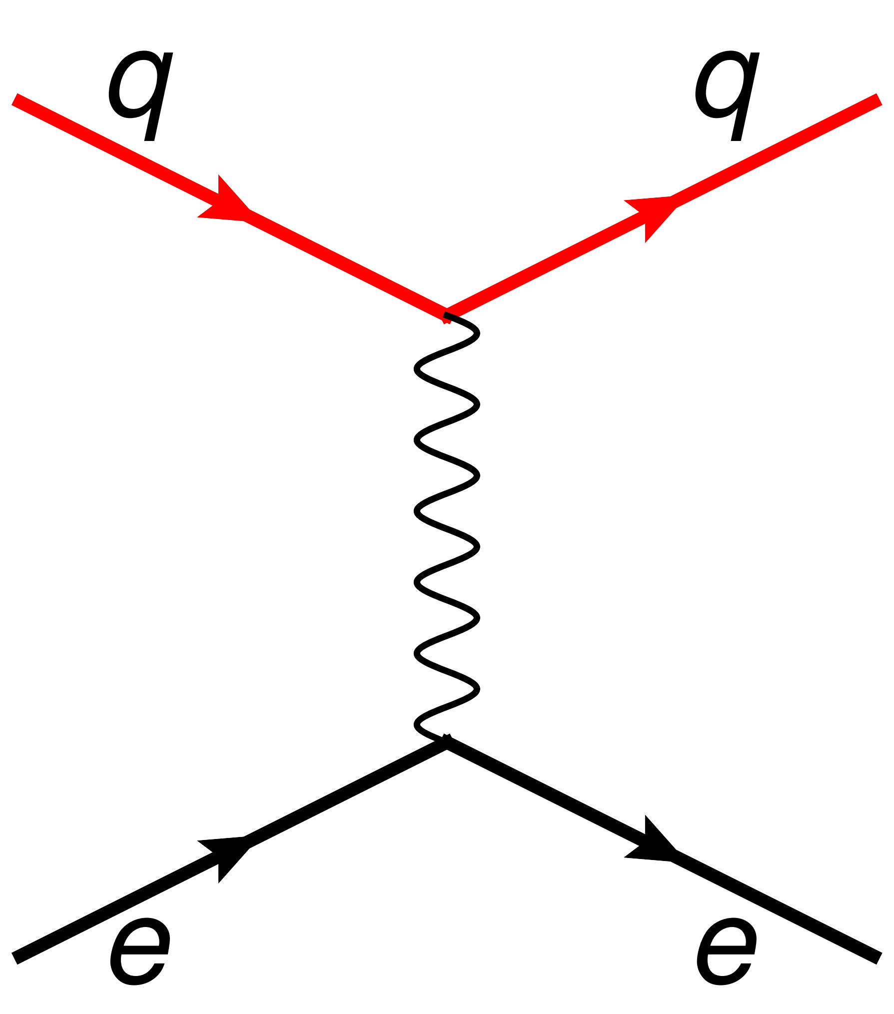
The PanScales showers for DIS differ from the one for pp in their treatment of ISR, and in the choices of the invariants to preserve.

- Global boost that assignes the $k_\perp$ recoil due to ISR mainly to partons that carry a large fraction of the original struck quark momentum
- We preserve the t-channel momentum transferred q^μ



Plot from 2006.10751





We treat Higgs production in **Vector Boson Fusion** as a double copy of **DIS**: the two hadronic sectors are showered independently. We miss **non-factorisable corrections**, which are subleading-colour NLL contributions that appear at NNLO, and are typically very small after VBF cuts (see Christian Brønnum-Hansen's talk)

van Beekveld, S.F.R., 2305.08645

NLL checks for popular global observables in DY and DIS

$$\Sigma(O < e^L) = \exp\Big(L g_{\mathrm{LL}}(\alpha_s L) + g_{\mathrm{NLL}}(\alpha_s L) + \alpha_s g_{\mathrm{NNLL}}(\alpha_s L) + \ldots \Big)$$

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

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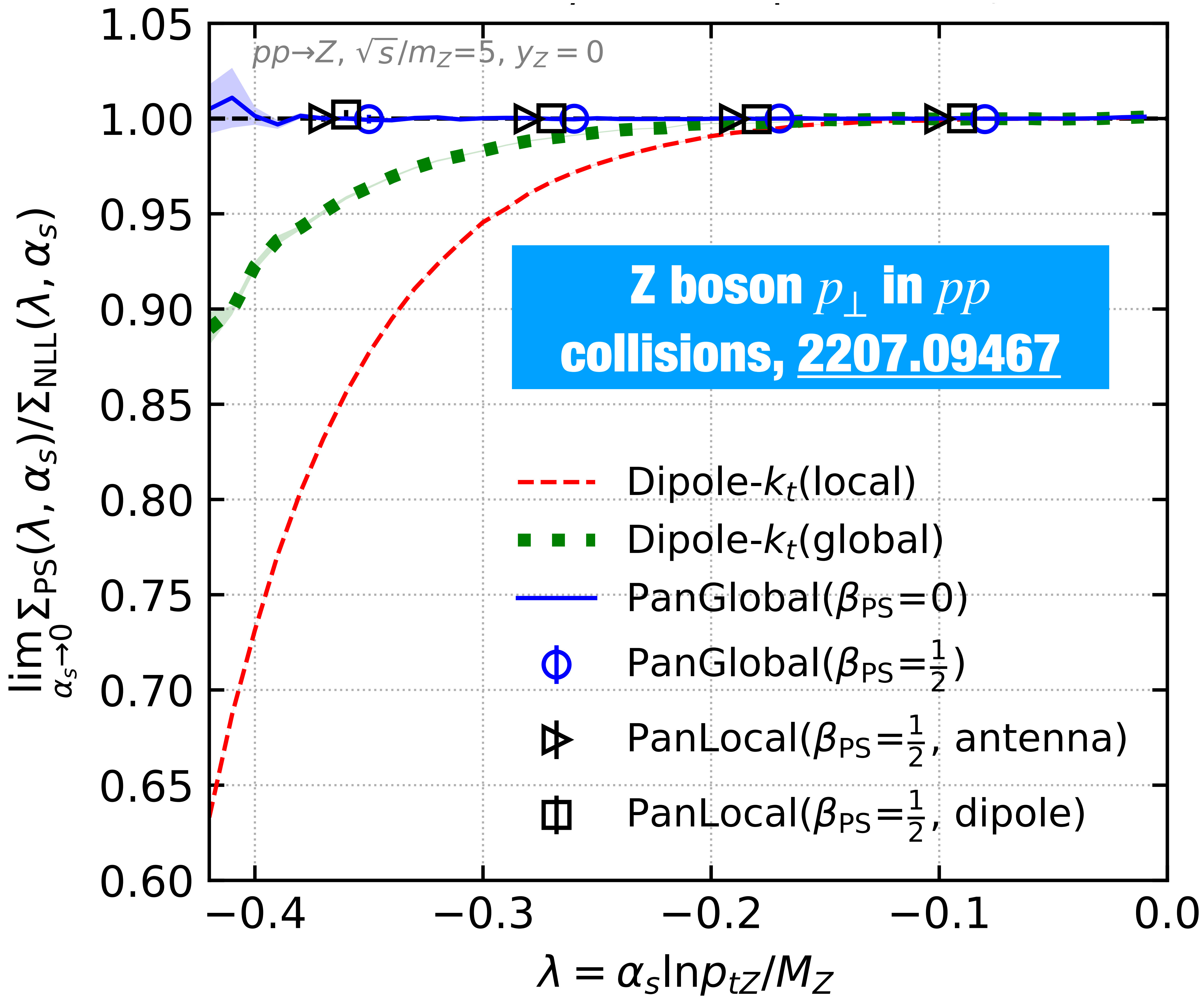
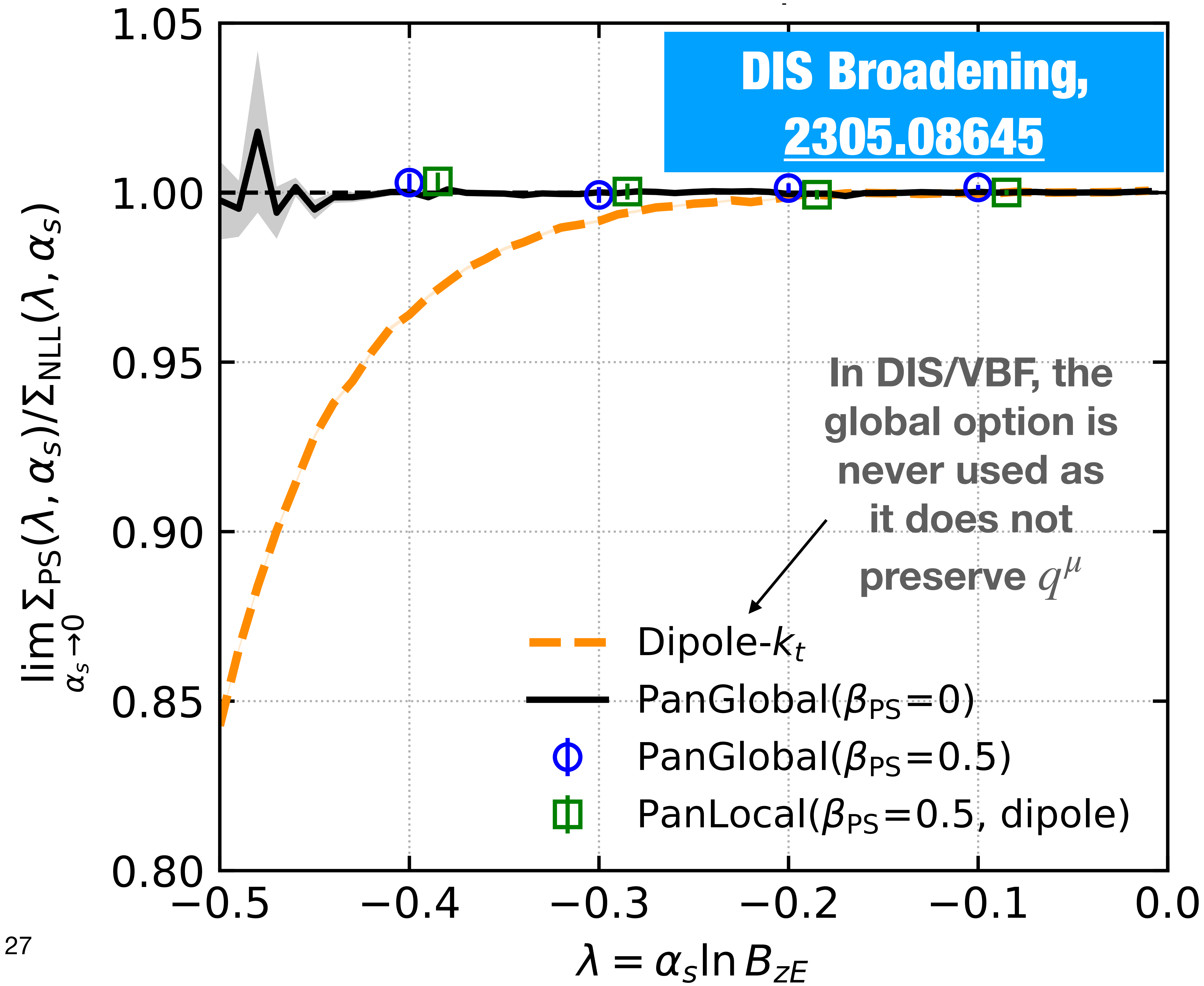
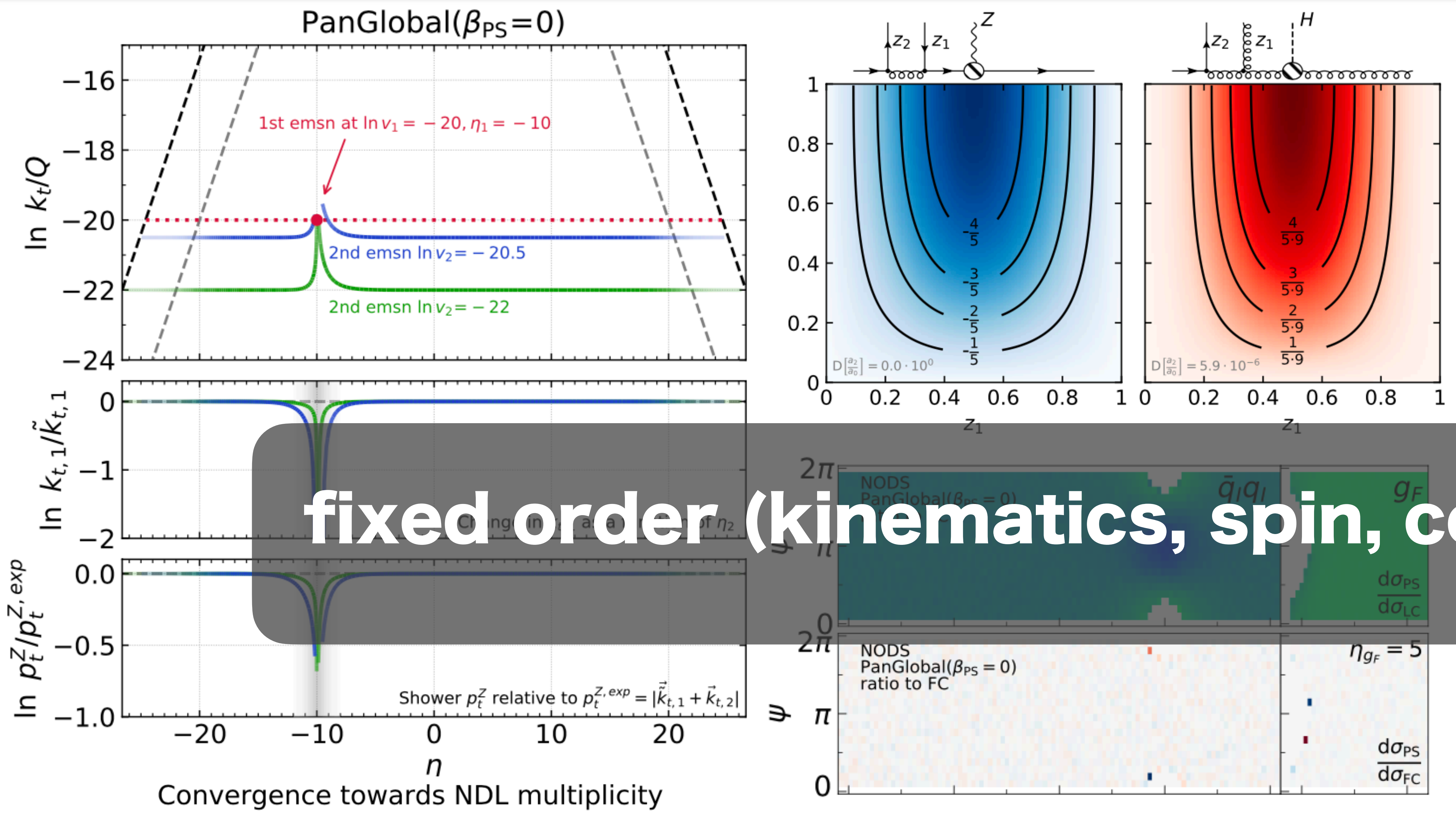
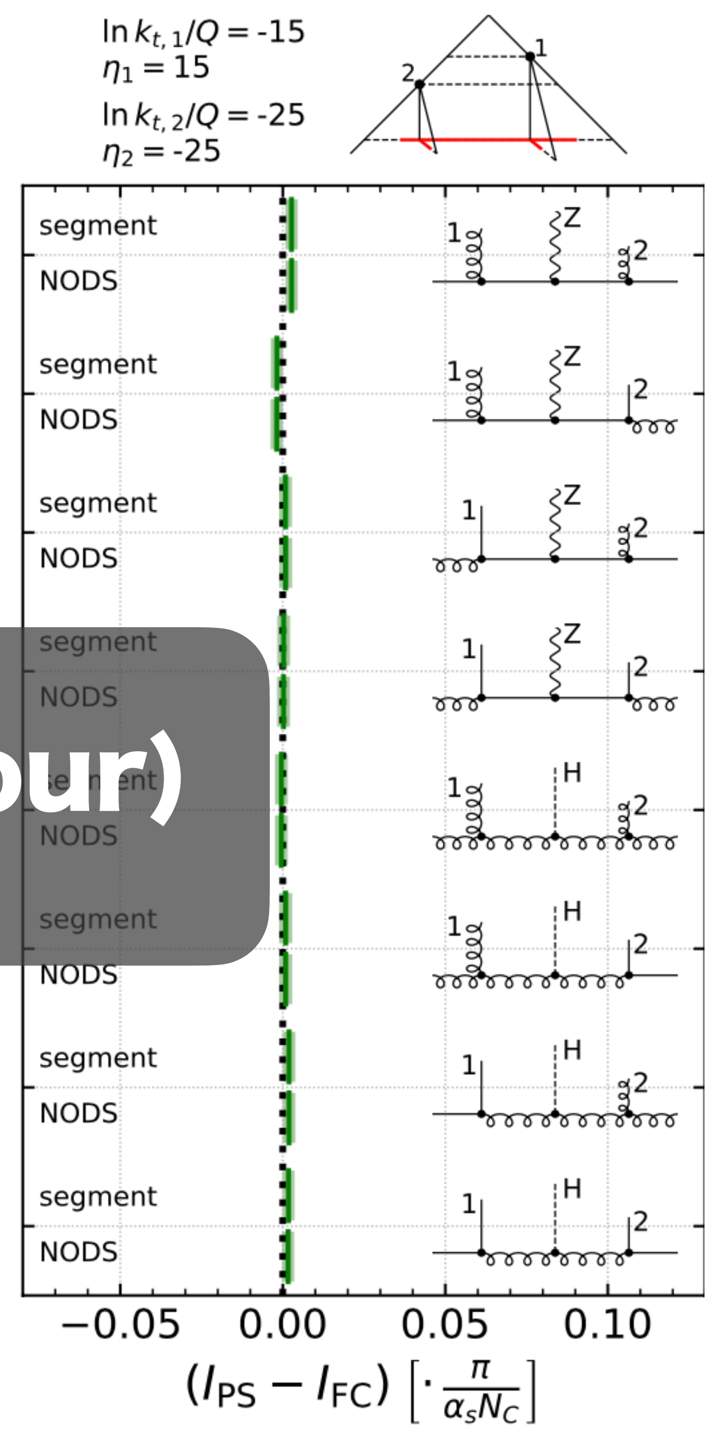
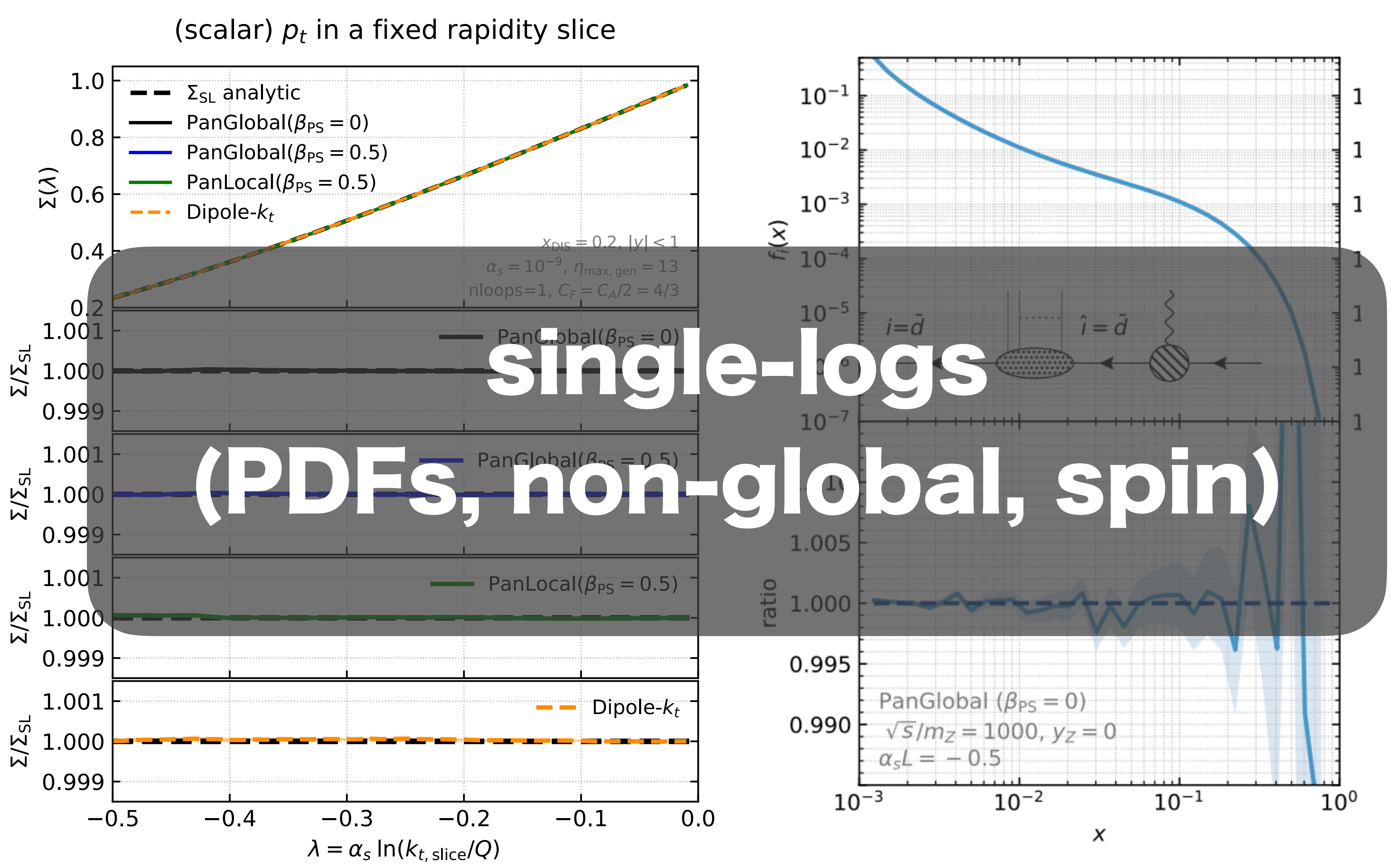


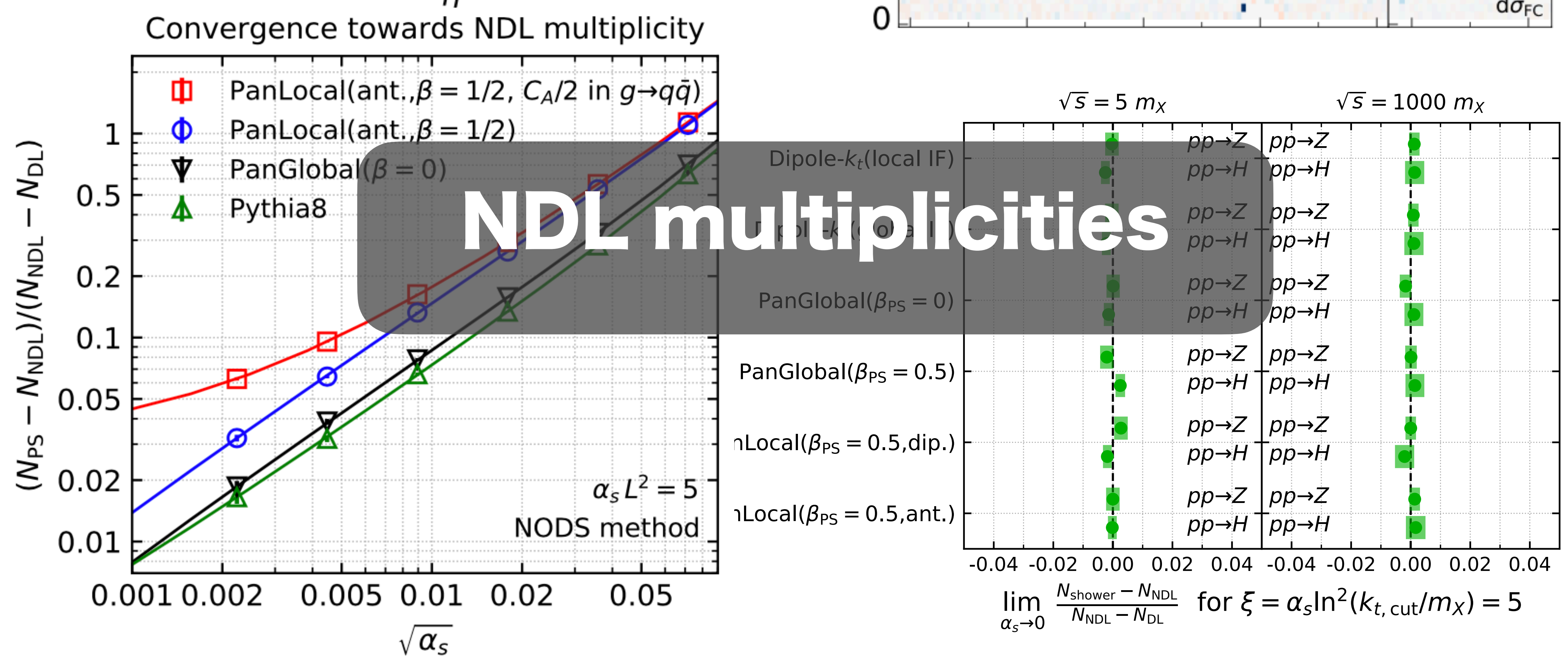


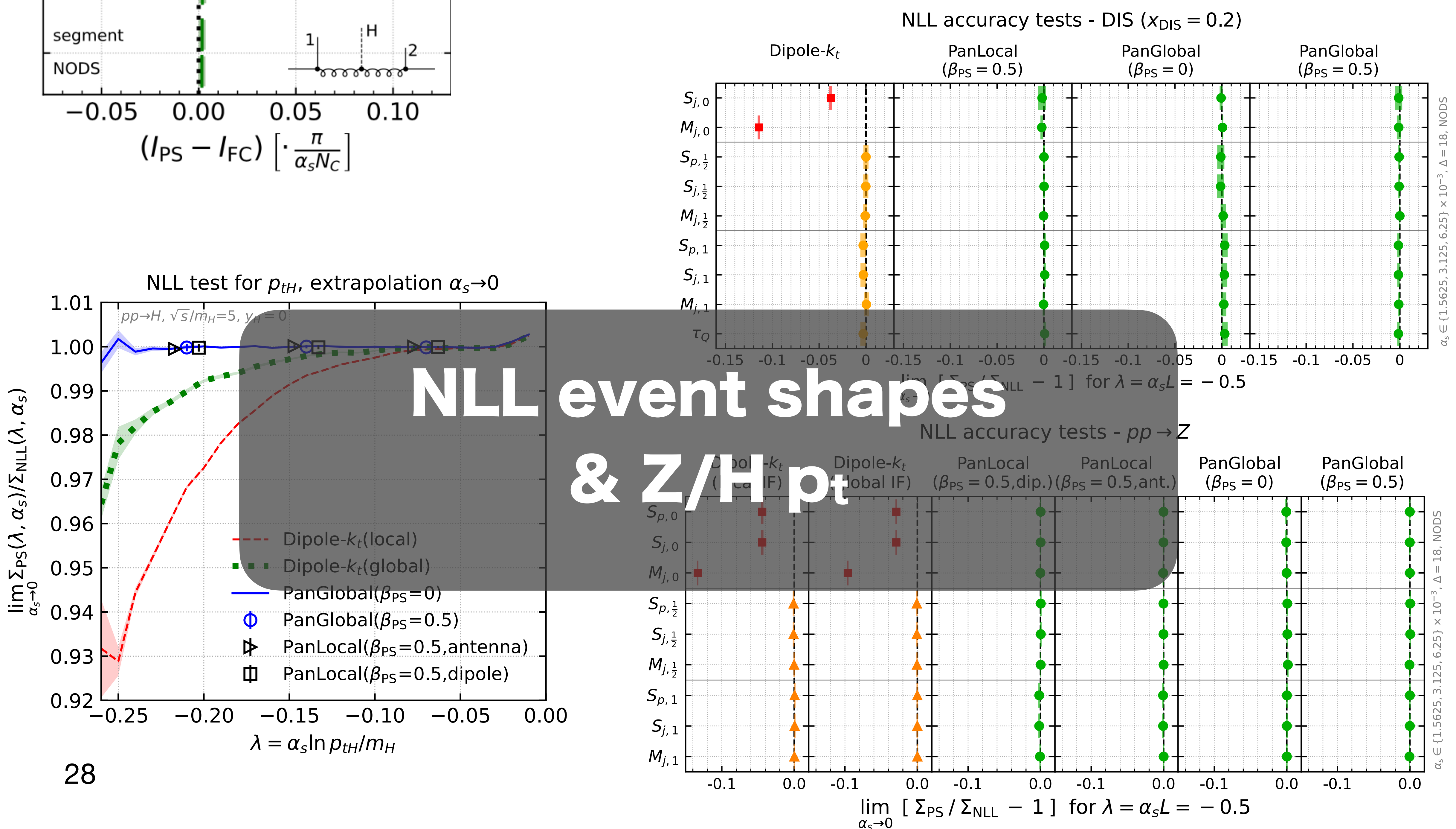
Selection of NLL accuracy tests for e^+e^-, DY, ggH and DIS











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

NLL dipole showers in the literature

Several NLL showers for e^+e^- have been developed also by other groups. NLL accuracy is achieved thanks to a careful choice of the ordering scale and of the recoil: $p_k = z_+ n_+ + z_- n_- + k_\perp$

PanLocal	PanGlobal	Deductor	FHP	Alaric
$k_t\sqrt{\theta}$ ordered	k_t or $k_t\sqrt{\theta}$ ordered	$k_t\theta$ (“Λ”) ordered	k_t ordered	k_t ordered
Recoil $\perp$: local +: local –: local	**Recoil** $\perp$: global +: local –: local	**Recoil** $\perp$: local +: local –: global	**Recoil** $\perp$: global +: local –: global	**Recoil** $\perp$: global +: local –: global
Tests analytical + explicit numerical for many global and non global observables, for e^+e^-, ggH, DY, DIS	**Tests** analytical + explicit numerical for many global and non global observables, for e^+e^-, ggH, DY, DIS	**Tests** analytical /numerical for thrust in e^+e^-	**Tests** analytical for thrust & multiplicity in e^+e^-	**Tests** analytical + explicit numerical for some event shapes in e^+e^-

e^+e^- :Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez 2002.11114
pp : van Beekveld, SFR, Hamilton, Soto-Ontoso, Salam, Soyez, Verheyen, 2205.02237; DIS/VBF: van Beekveld, SFR 2305.08645

Nagy & Soper 2011.04777 (+past decade)

Forshaw, Holguin, Plätzer: 2003.06400

Herren, Hoche, Krauss, Reichelt, Shoenner: 2208.06057

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PanLocal

$k_t\sqrt{\theta}$ ordered

Recoil

$\perp$: local
+: local
−: local

Tests

analytical + explicit

PanGlobal

k_t or $k_t\sqrt{\theta}$ ordered

Recoil

$\perp$: global
+: local
−: local

Tests

analytical + explicit

Only showers that can do Deep Inelastic Scattering, colour-singlet production in pp collisions (e.g. Drell Yan, gluon fusion) and Vector Boson Fusion at NLL

Deductor

$k_t\theta$ (“Λ”) ordered

Recoil

$\perp$: local
+: local
−: global

Tests

Can handle hadron-hadron collisions, but not DIS. Formal accuracy only investigated for e^+e^-

FHP

k_t ordered

Recoil

$\perp$: global
+: local
−: global

Tests

analytical for thrust & multiplicity in e^+e^-

Alaric

k_t ordered

Recoil

$\perp$: global
+: local
−: global

Tests

analytical + explicit numerical for some event

Limited to final state radiation

e^+e^- :Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez 2002.11114
pp : van Beekveld, SFR, Hamilton, Soto-Ontoso, Salam, Soyez, Verheyen, 2205.02237; **DIS/VBF**: van Beekveld, SFR 2305.08645

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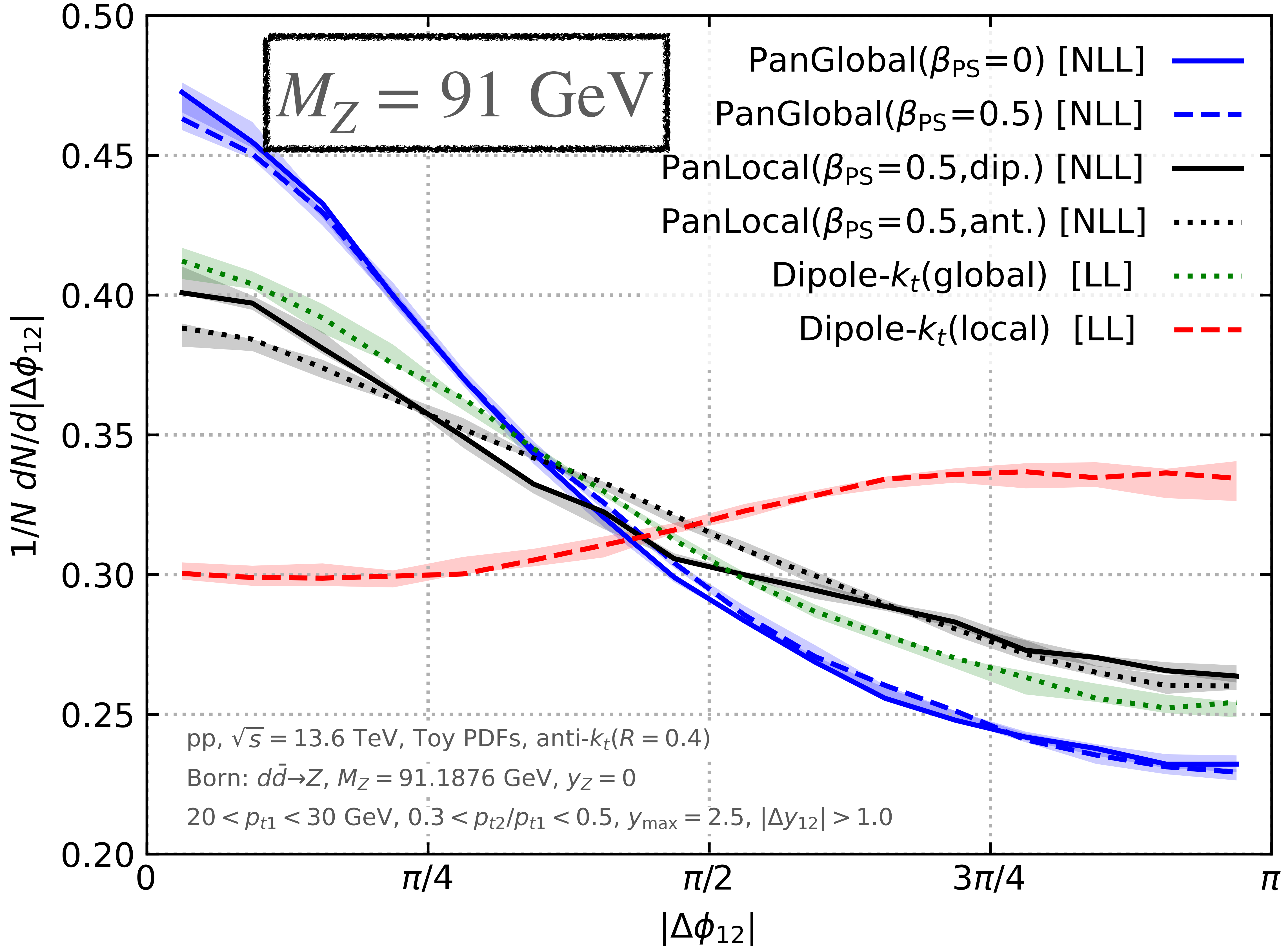
Exploratory phenomenology: azimuthal correlations in DY



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

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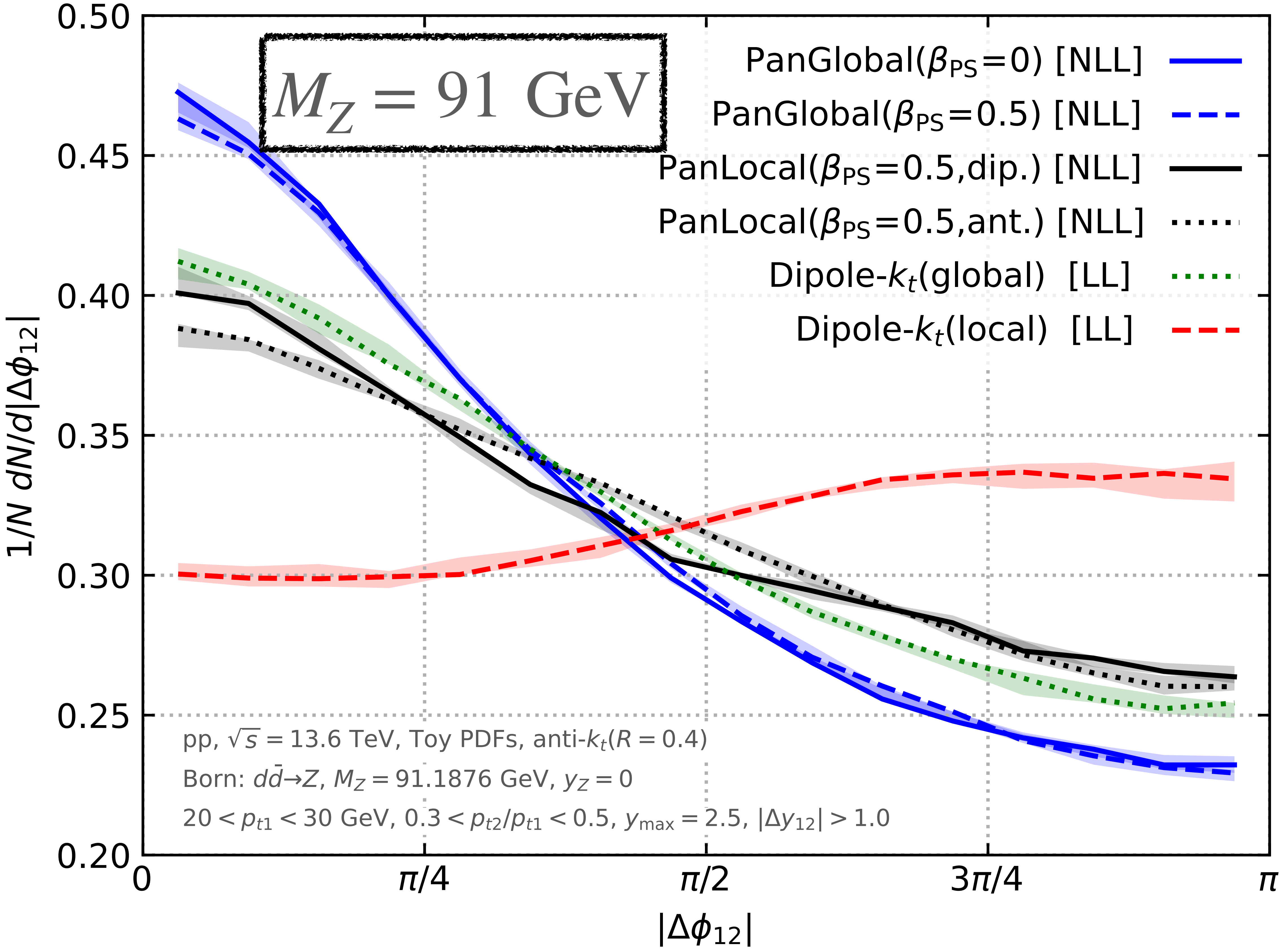
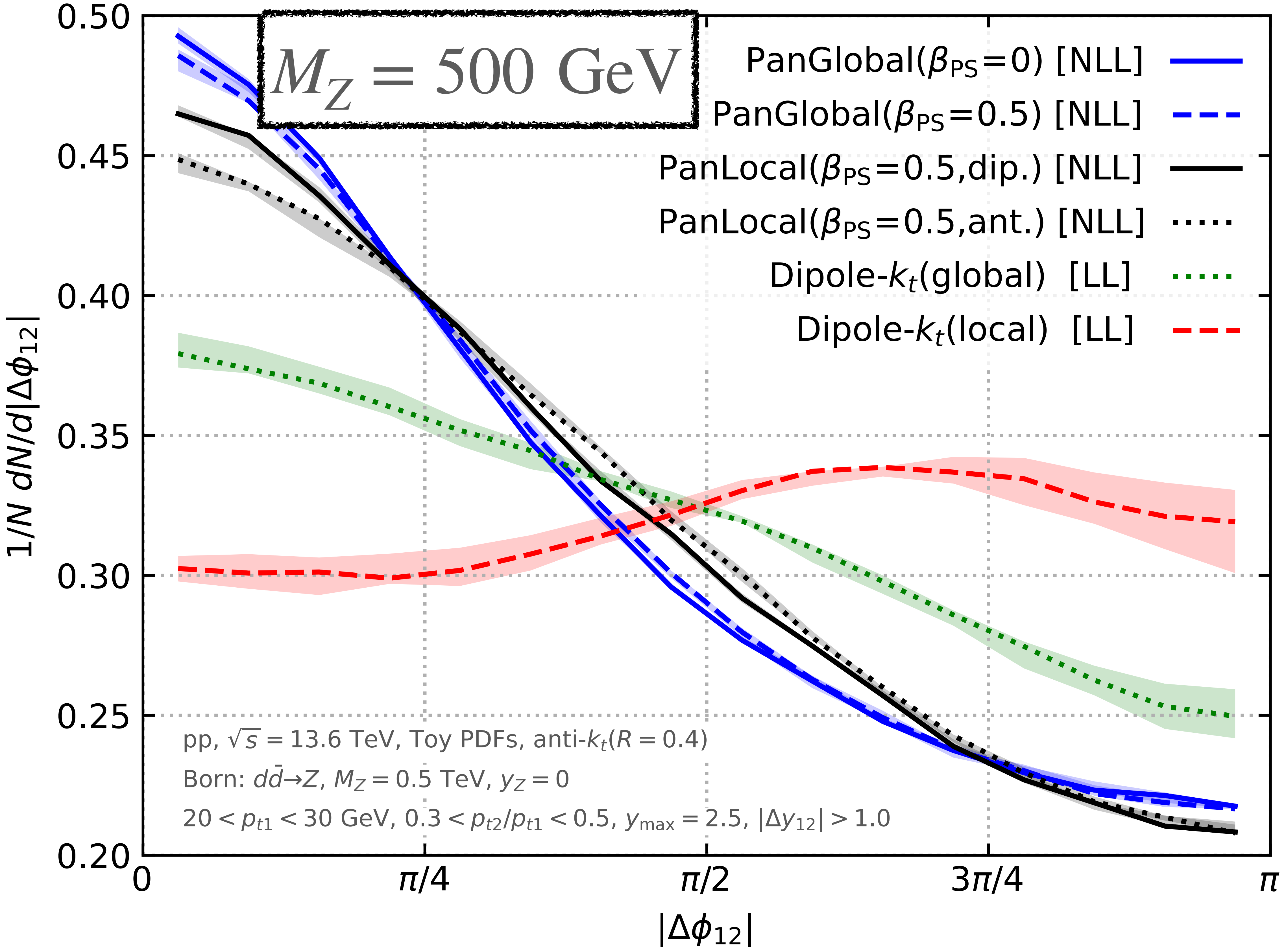
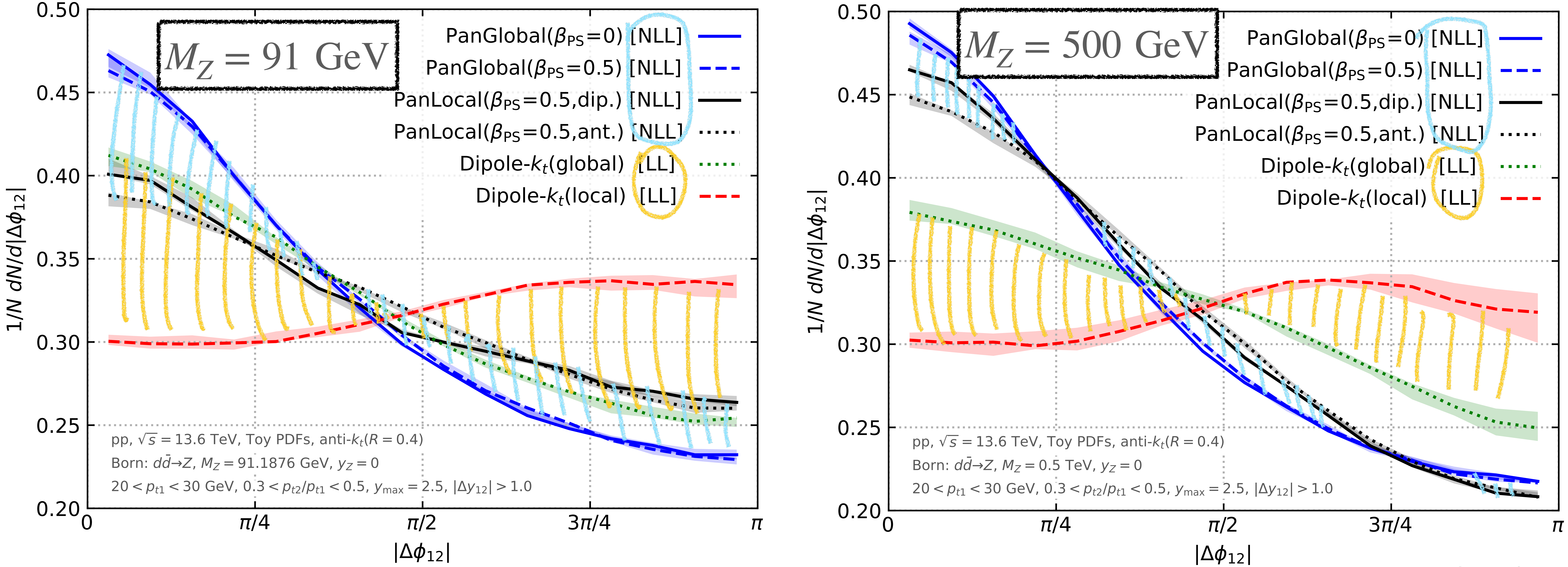




- Impossible to tune a LL shower to reproduce a NLL across several energy scales (at 91 GeV subleading effects are more sizeable and the shower is more tunable than at 500 GeV!)

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

Exploratory phenomenology: azimuthal correlations 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 should be done to estimate PS uncertainties, but more analytic understanding is required (i.e. PS differences might not be enough)

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

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
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

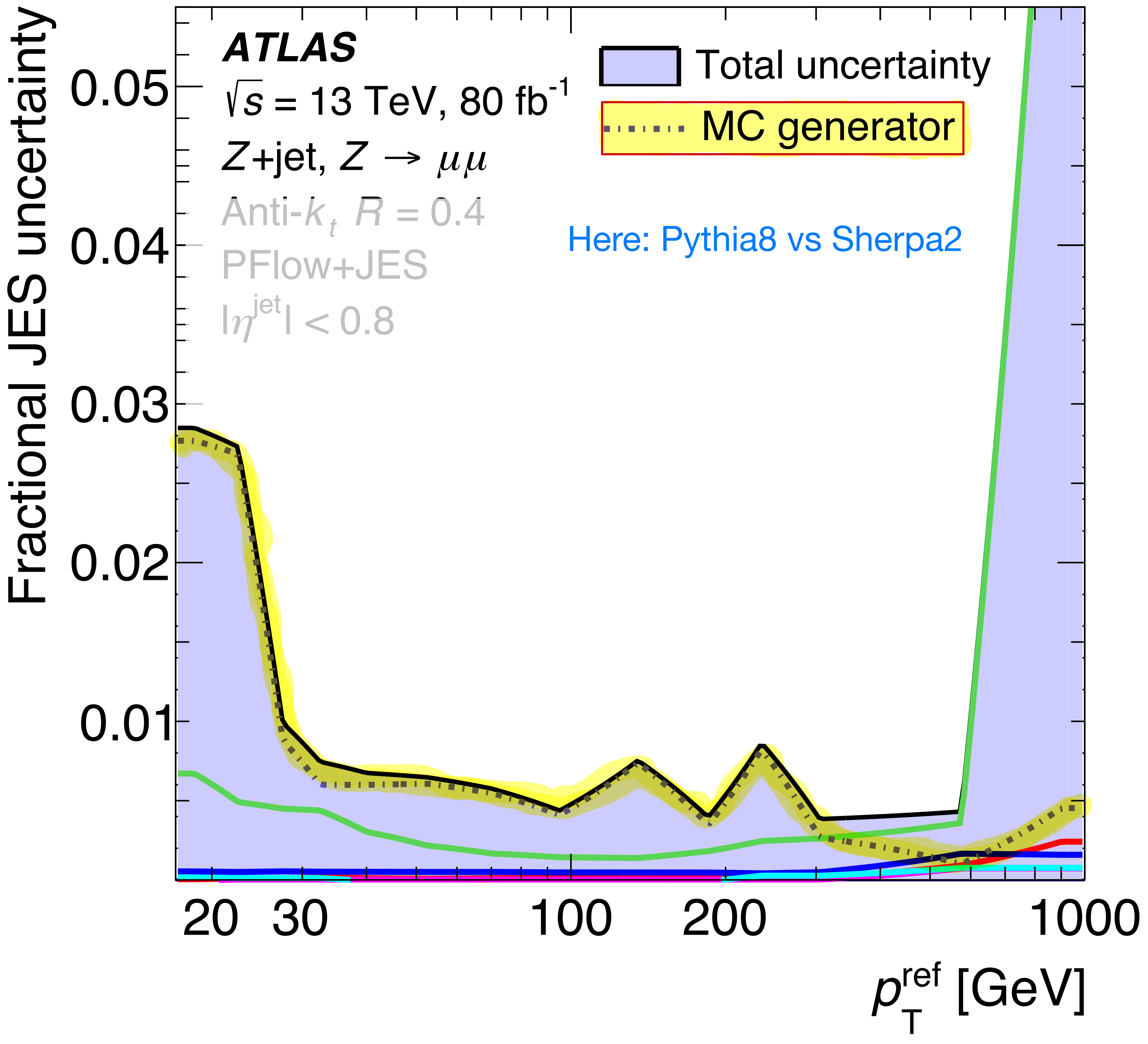
Interface to Pythia
work in progress

uncertainty estimates

BACKUP

Why do we need to improve Parton Showers?

Jet Calibration



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

The dominant uncertainty in the **Jet Energy Scale** is from the **showers' modelling**

→ It enters all the measurements involving jets

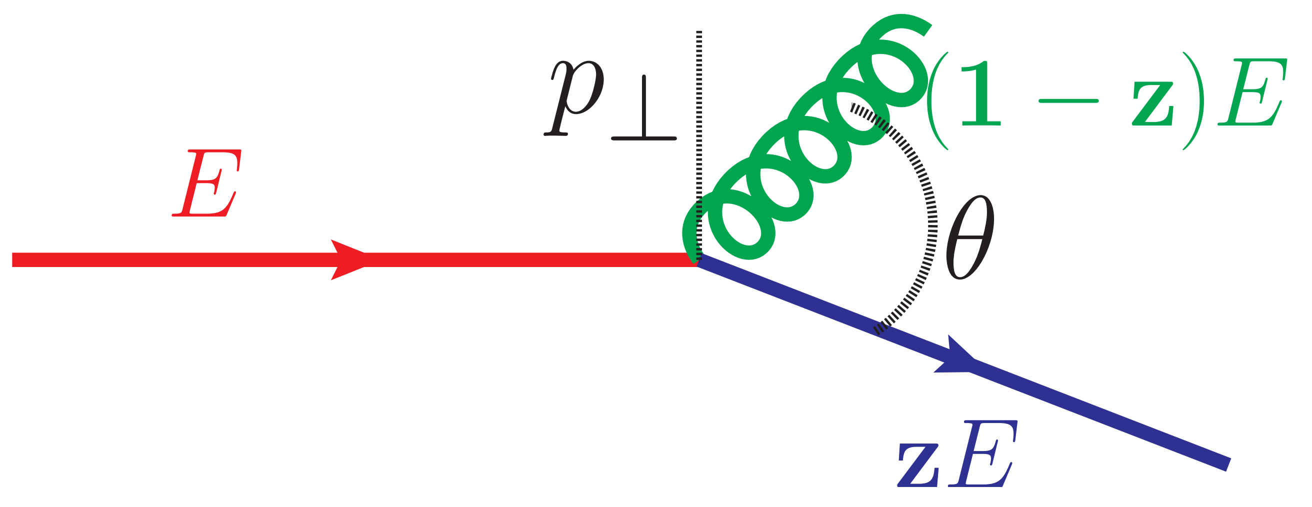
→ Contributes to the 70% of uncertainty of precise top mass determinations

Source	Uncertainty [GeV]
Trigger	0.02
Lepton ident./isolation	0.02
Muon momentum scale	0.03
Electron momentum scale	0.10
Jet energy scale	0.57
Jet energy resolution	0.09
b tagging	0.12
Pileup	0.09
$t\bar{t}$ ME scale	0.18
tW ME scale	0.02
DY ME scale	0.06
NLO generator	0.14
PDF	0.05
$\sigma_{t\bar{t}}$	0.09
Top quark p_T	0.04
ME/PS matching	0.16
UE tune	0.03
$t\bar{t}$ ISR scale	0.16
tW ISR scale	0.02
$t\bar{t}$ FSR scale	0.07
tW FSR scale	0.02
b quark fragmentation	0.11
b hadron BF	0.07
Colour reconnection	0.17
DY background	0.24
tW background	0.13
Diboson background	0.02
W+jets background	0.04
$t\bar{t}$ background	0.02
Statistical	0.14
MC statistical	0.36
Total m_t^{MC} uncertainty	$^{+0.68}_{-0.73}$

Top quark mass from CMS, 2019 [1812.10505]

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

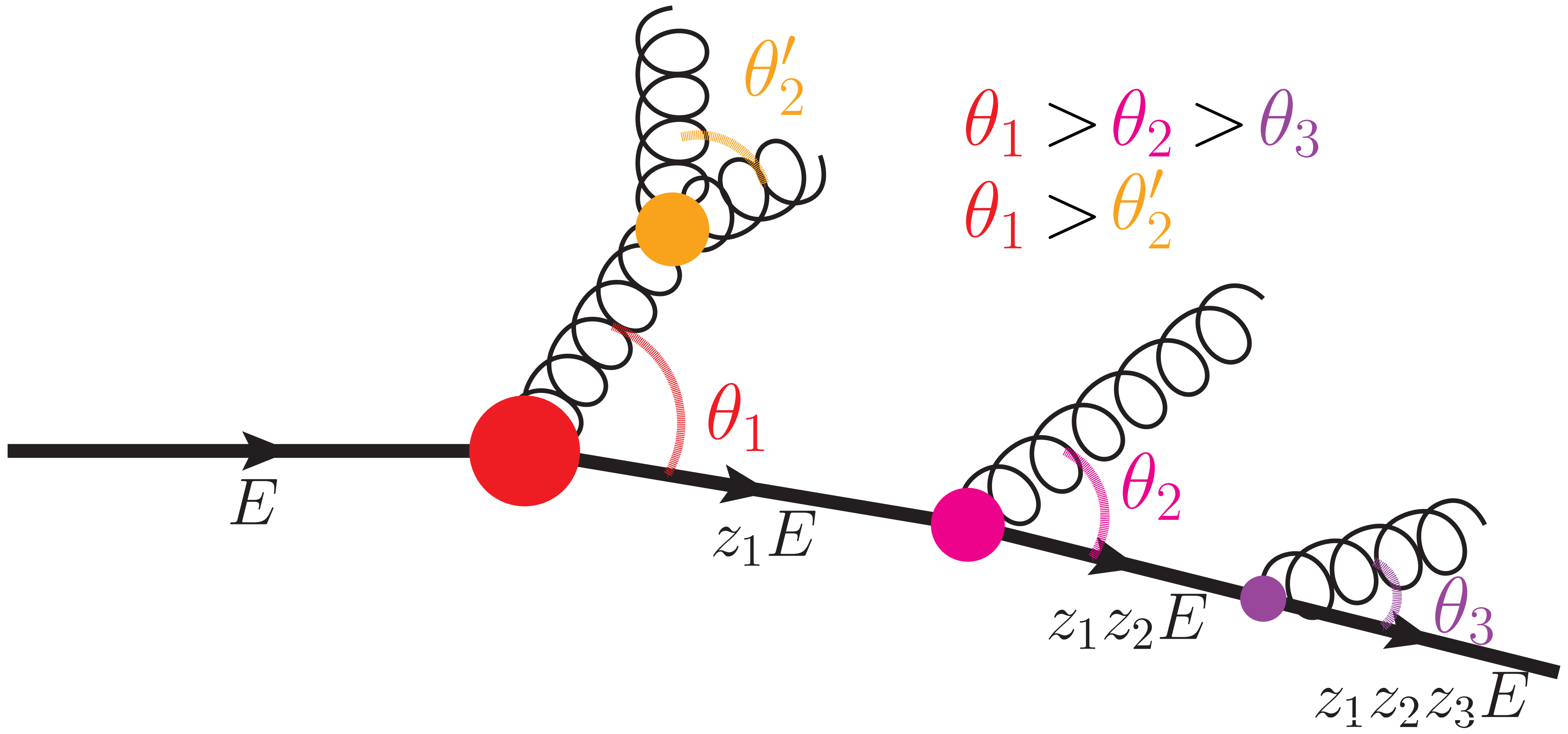
Angular-ordered Parton Showers



- Parton showers describe the energy degradation of hard partons via a subsequent chain of soft (small energy) and collinear (small θ) emissions
- $\Phi_{\text{rad}} = \{v, z, \varphi\}$, where $v \in \{p_\perp, E\theta, \dots\}$ acts as ordering scale, z is ``energy fraction" scale, and φ is an azimuthal angle

Herwig7 angular-ordered shower

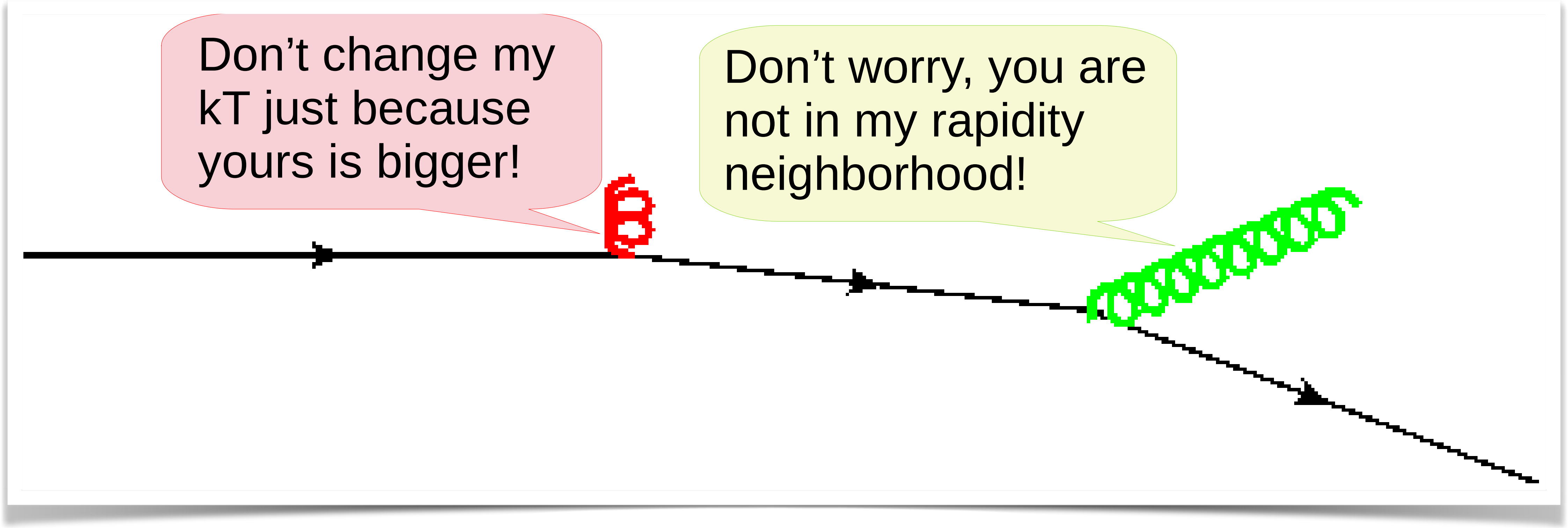
- Derived in the collinear limit (1 → 2 splittings)
- Emissions ordered in angle . . .
- . . . to describe correctly the soft limit



Logarithmic Accuracy of Angular-ordered Showers

- Ordering a **parton shower** in angle easily enable to have colour coherence, formalism used to make several NLL calculations [Marchesini, Webber '88], [Gieseke, Stephens, Webber hep-ph/0310083]

- Such calculations implicitely assume emissions widely separated in angle are independent from each others: practical implementation of the shower recoil scheme must also satisfy this requirement [G. Bewick, SFR, Richardson, Seymour, 1904.11866]



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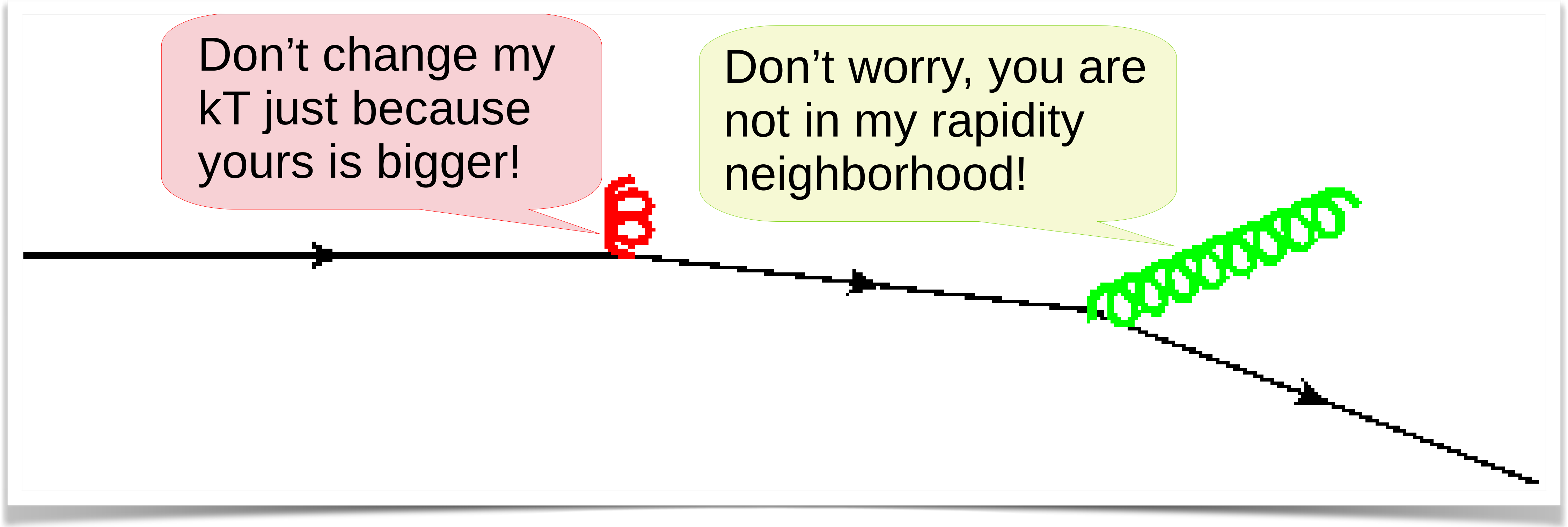
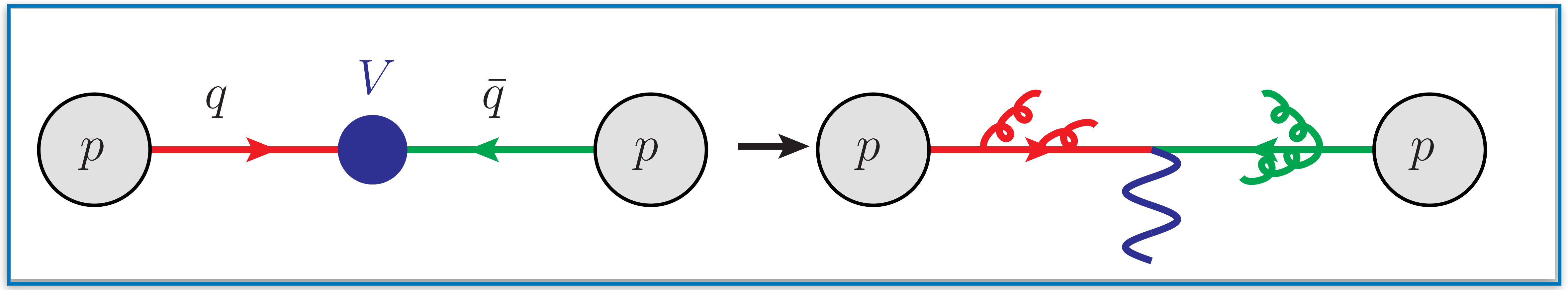
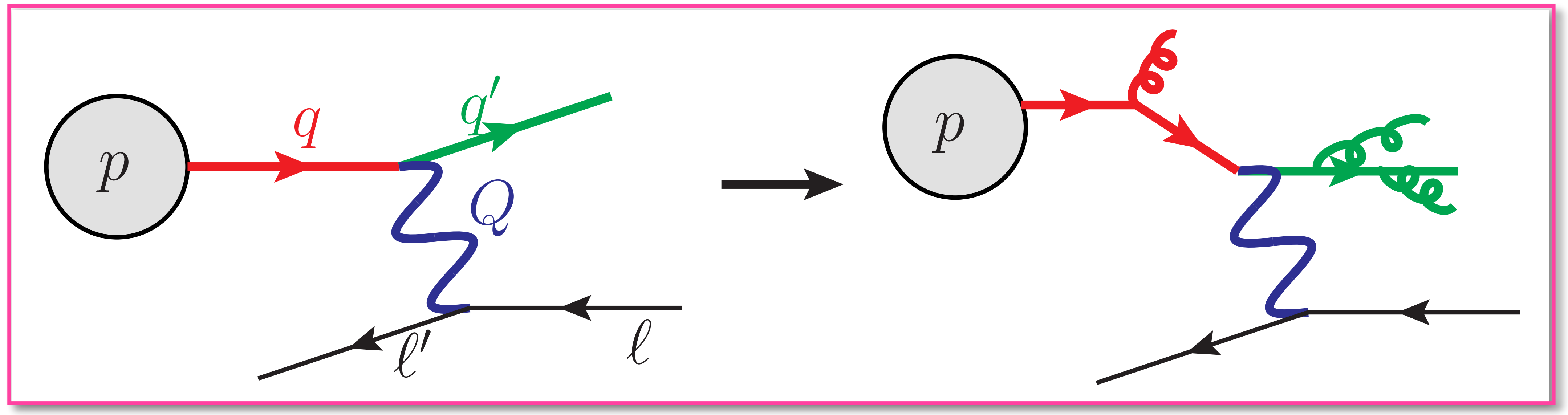


- Assinging the $k_\perp$ recoil is non-trivial when incoming partons are present [Platzer, Richardson]



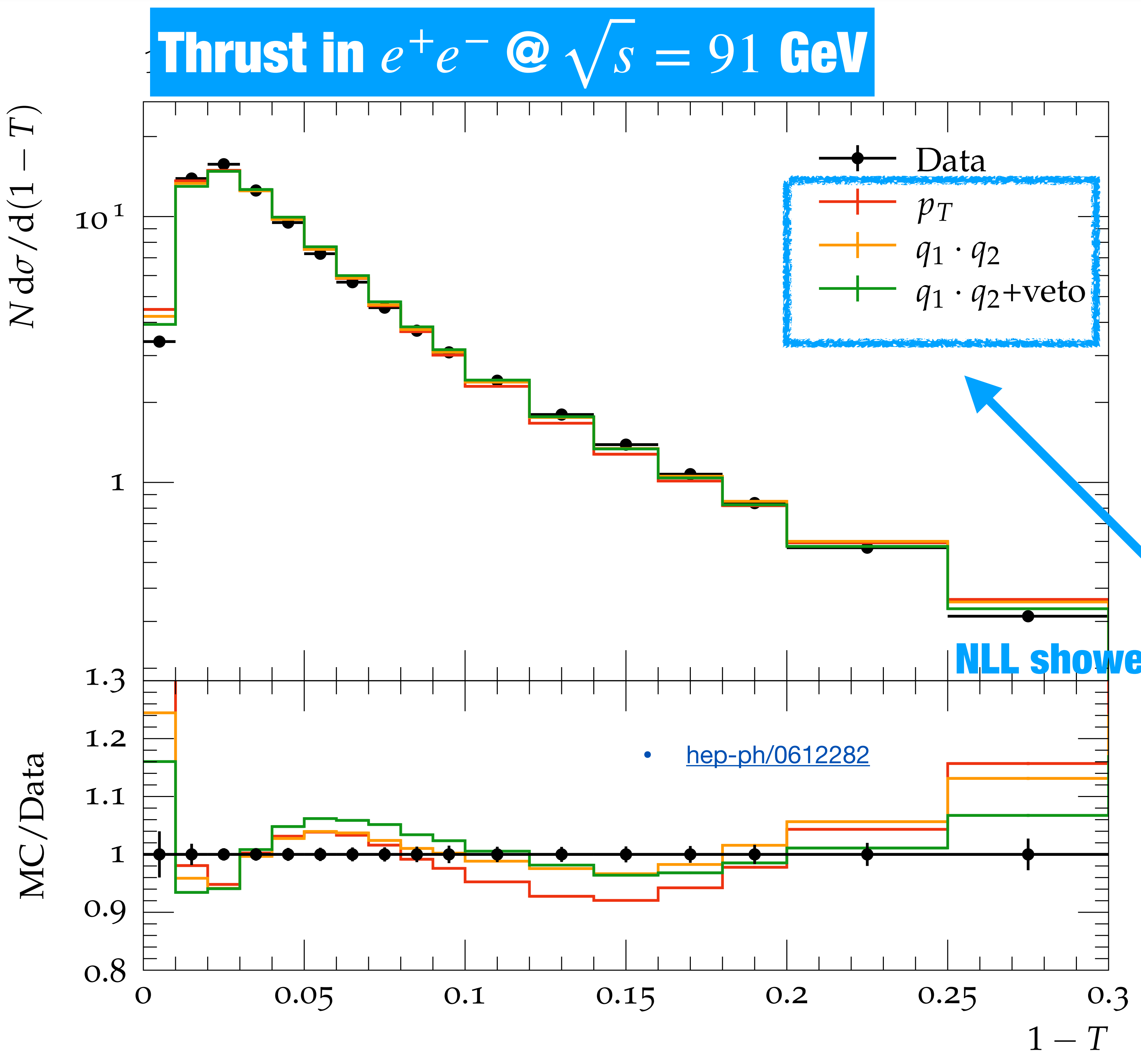
In colour-singlet production, the colour singlet absorbs the $k_\perp$ recoil for all the ISR emissions

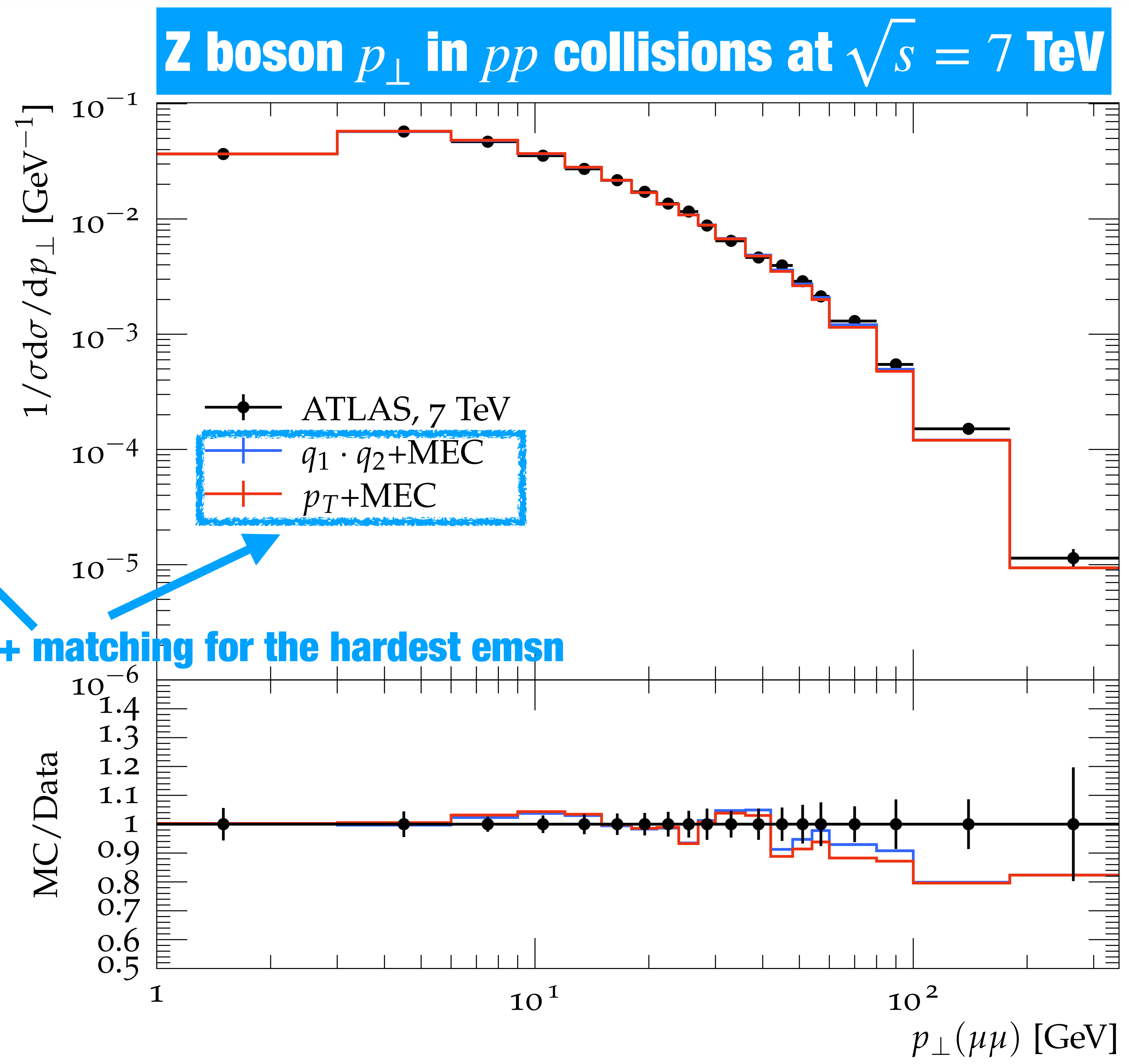


In DIS, the final-state quark (and its children) absorbs the $k_\perp$ recoil for all the ISR emissions

Limitations of Angular-Ordered Showers

- Life is not just made by logarithms: fixed-order corrections are crucial to model **hard jets**!
- Going beyond **NLO** is very challenging, but it seems necessary!





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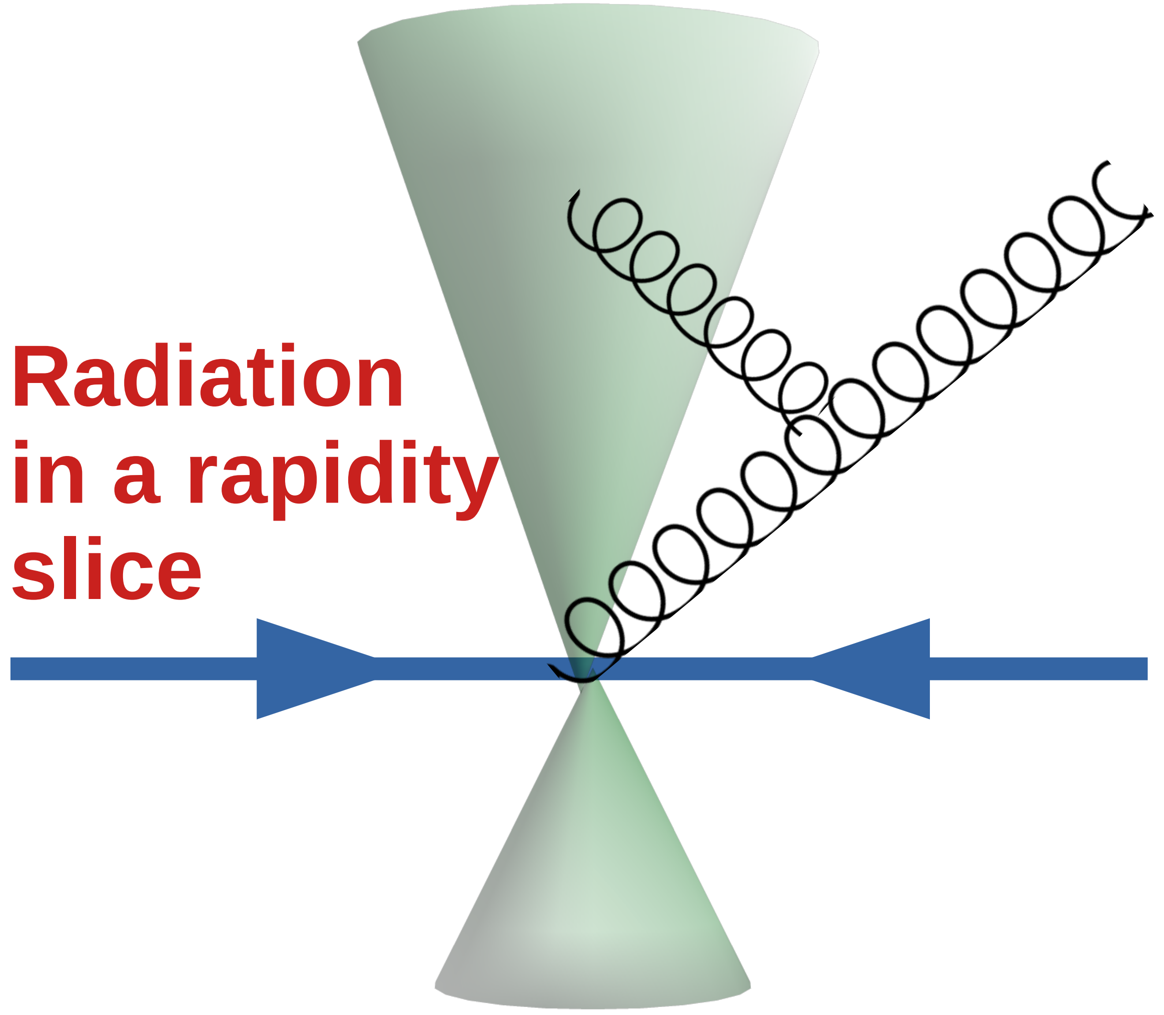
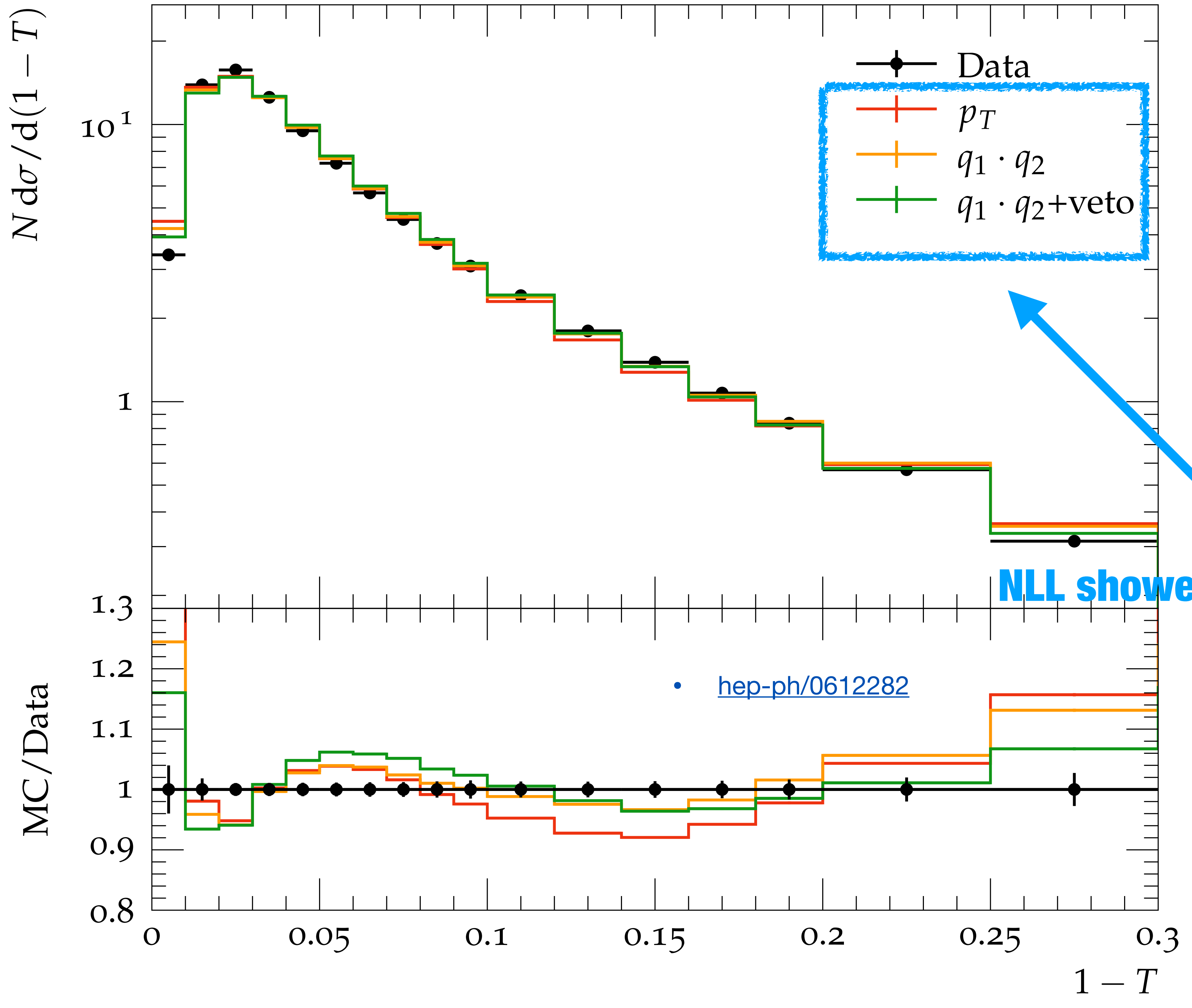
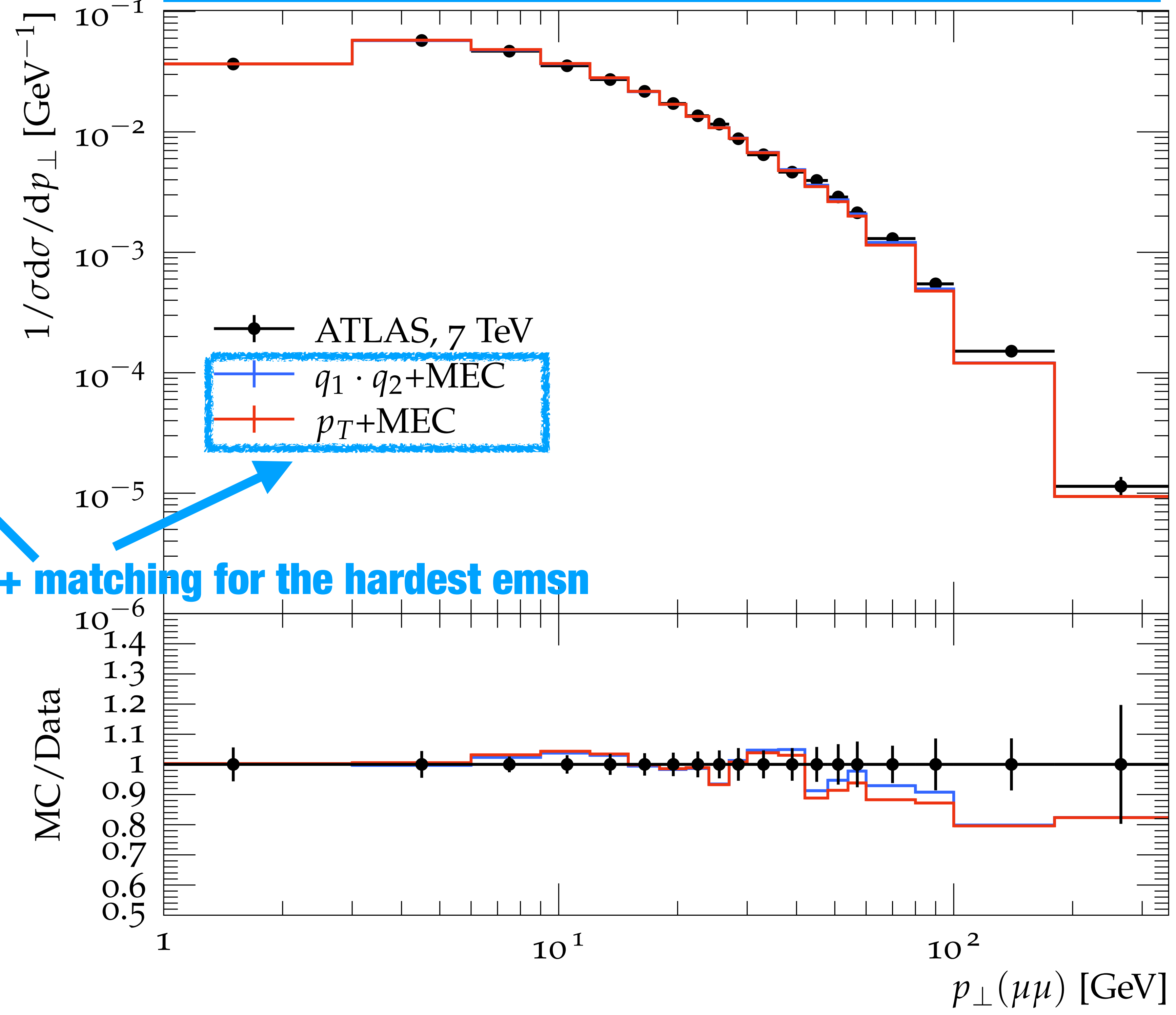


Thrust in e^+e^- @ $\sqrt{s} = 91$ GeV



Z boson $p_\perp$ in pp collisions at $\sqrt{s} = 7$ TeV



NLL showers + matching for the hardest emsn

- Angular-ordering arises after azimuthal average: this formalism cannot describe **non-global observables**, which are sensitive to the full angular distribution of soft emsn, at NLL [Banfi, Corcella, Dasgupta, hep-ph/0612282]

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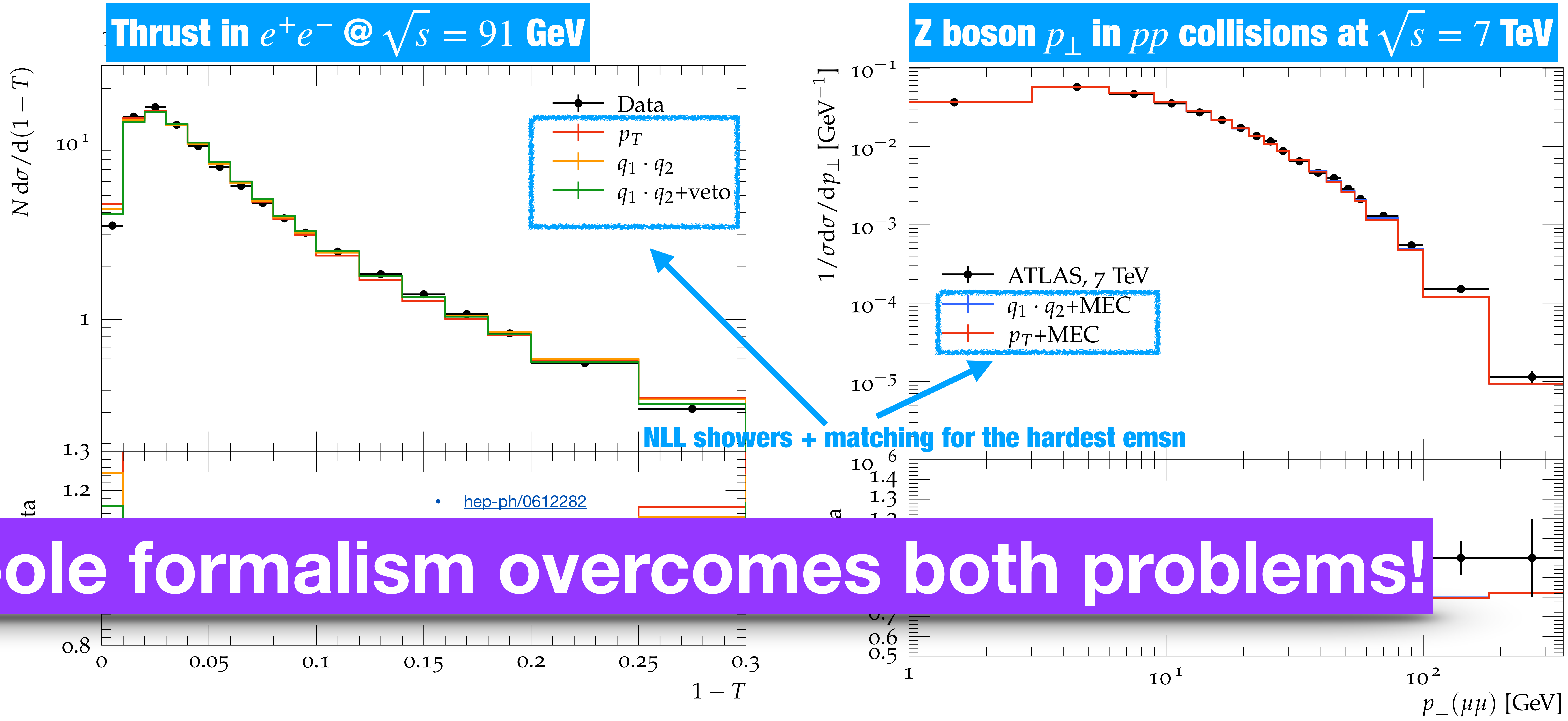
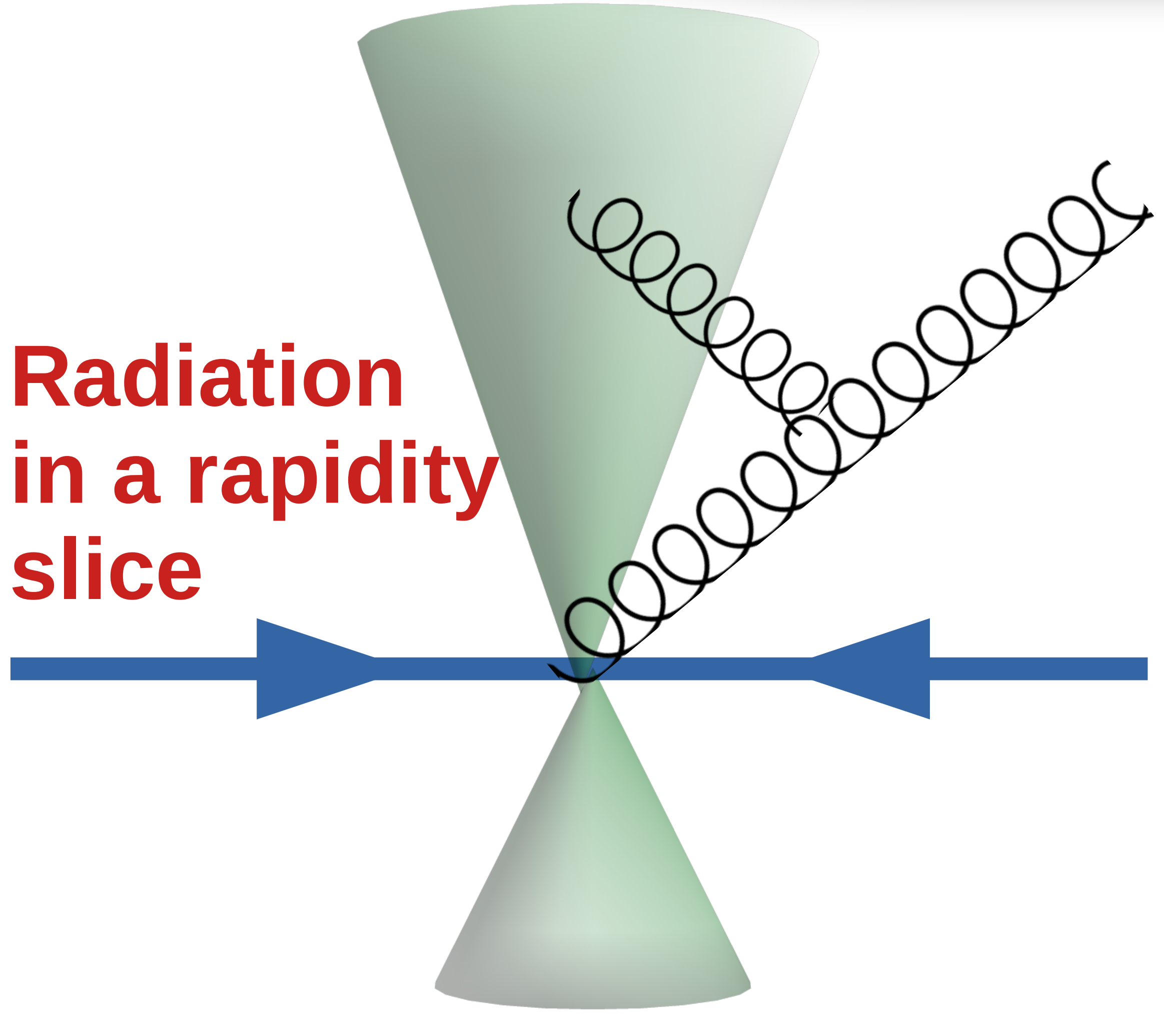


The dipole formalism overcomes both problems!



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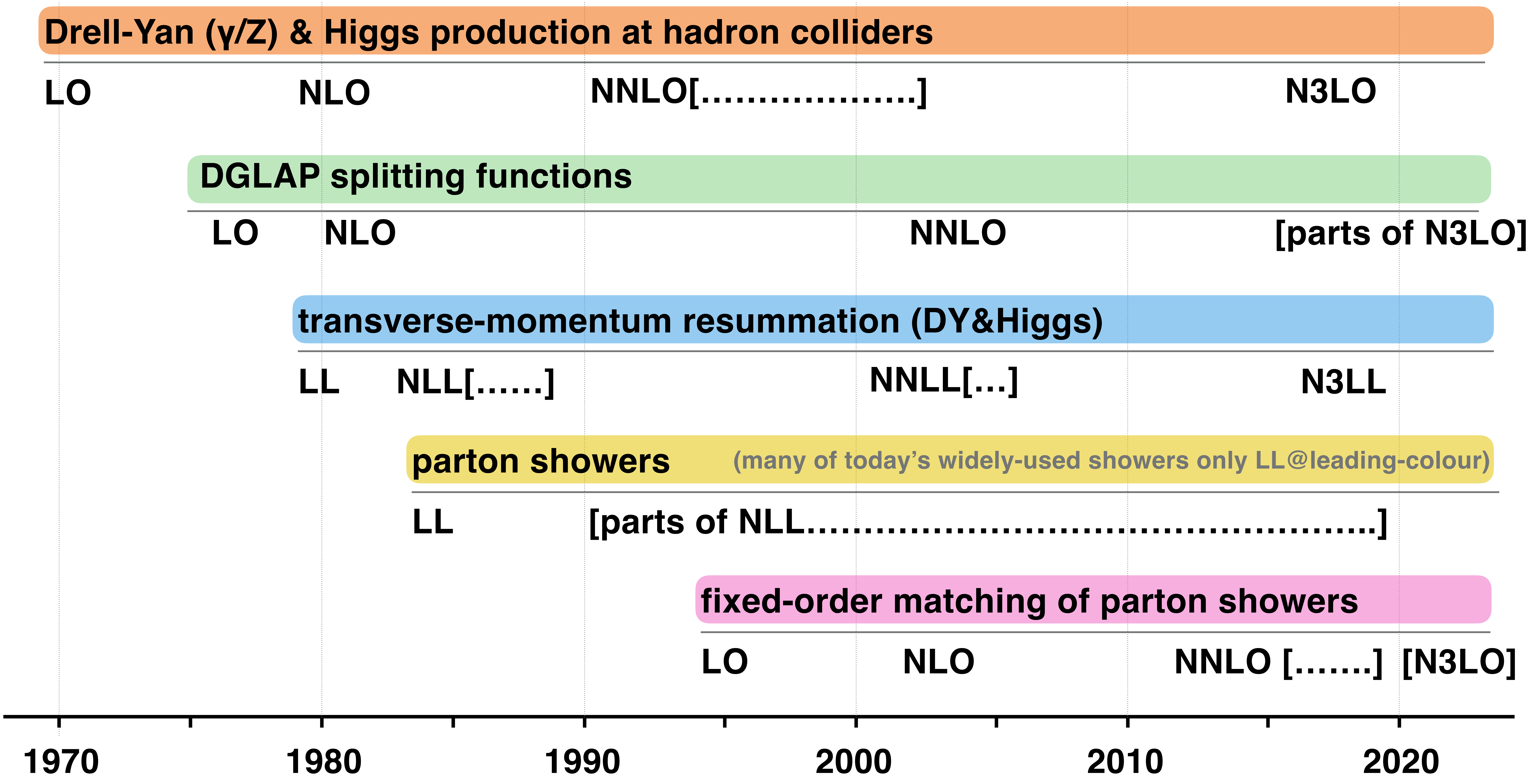
It's time for better Parton Showers!

Slide from G. Salam



PanScales status: e^+e^- → jets, pp → Z/W/H, DIS, VBF (structure function approx) (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

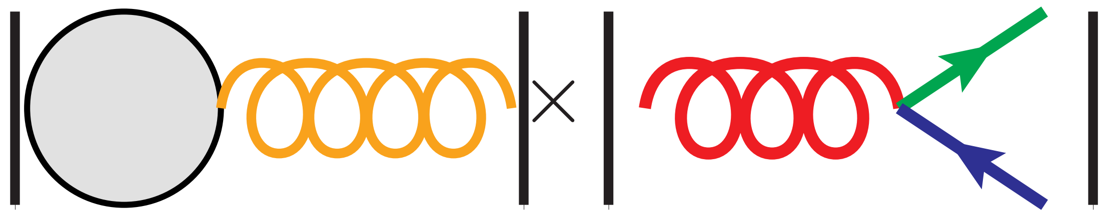
how large are the logarithms?

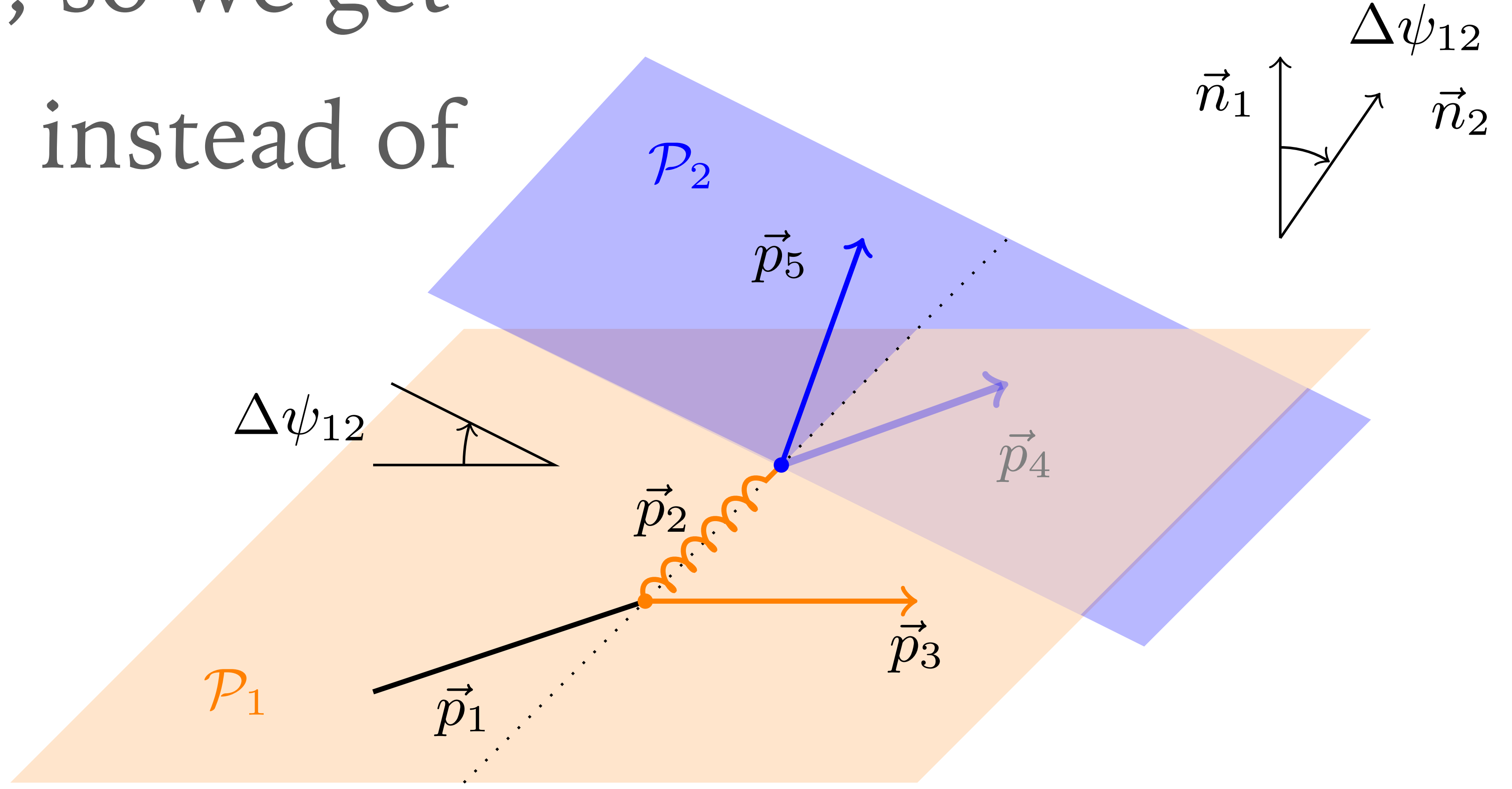
Q [GeV]	$\alpha_s(Q)$	$p_{t,\min}$ [GeV]	$\xi = \alpha_s L^2$	$\lambda = \alpha_s L$	τ
91.2	0.1181	1.0	2.4	−0.53	0.27
91.2	0.1181	3.0	1.4	−0.40	0.18
91.2	0.1181	5.0	1.0	−0.34	0.14
1000	0.0886	1.0	4.2	−0.61	0.36
1000	0.0886	3.0	3.0	−0.51	0.26
1000	0.0886	5.0	2.5	−0.47	0.22
4000	0.0777	1.0	5.3	−0.64	0.40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

Table 1: Values of $\xi = \alpha_s L^2$, $\lambda = \alpha_s L$ and τ (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 τ is evaluated for 1-loop evolution with $n_f = 5$.

Collinear spin-correlations in showers

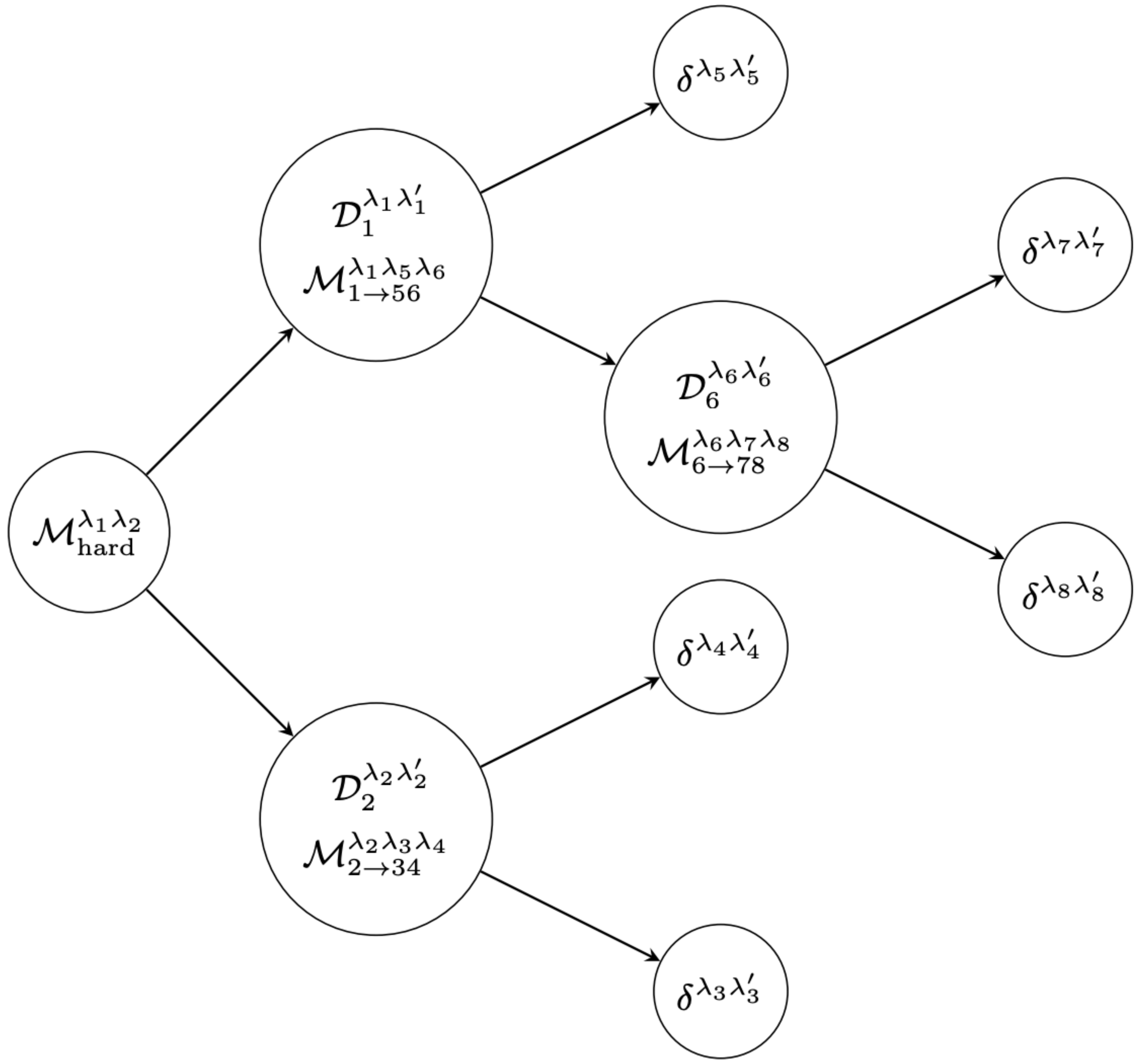
Shower emission probability are polarisations-averaged at every step, so we get

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



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

Spin-correlations capture the azimuthal modulations



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

For every emission, ϕ 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.

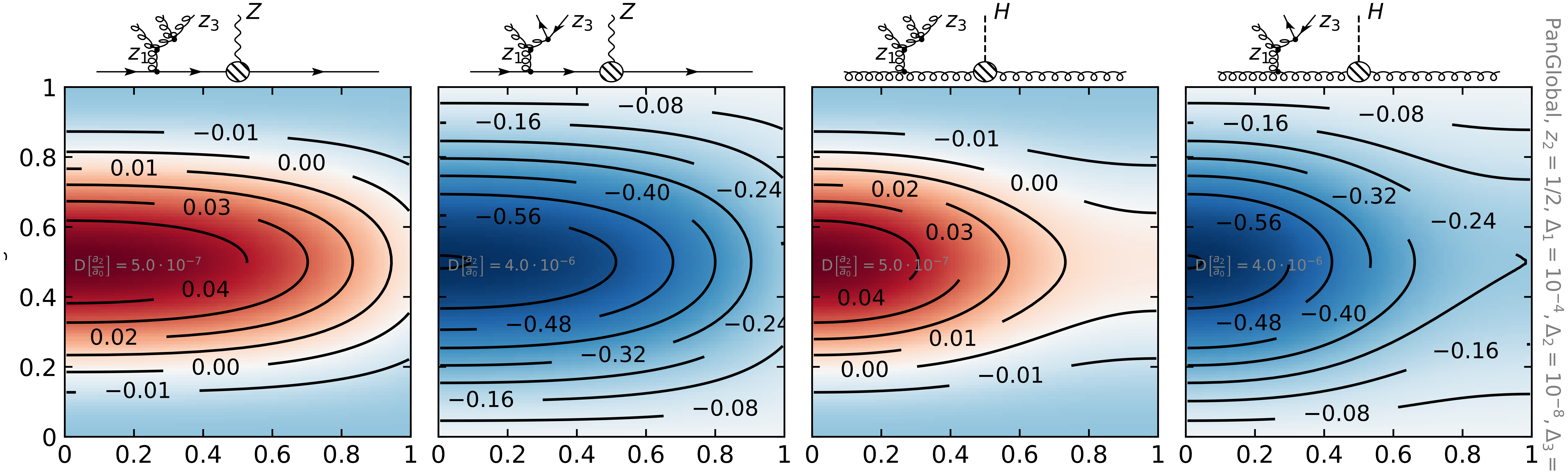
Soft and collinear spin in PanScales

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]**

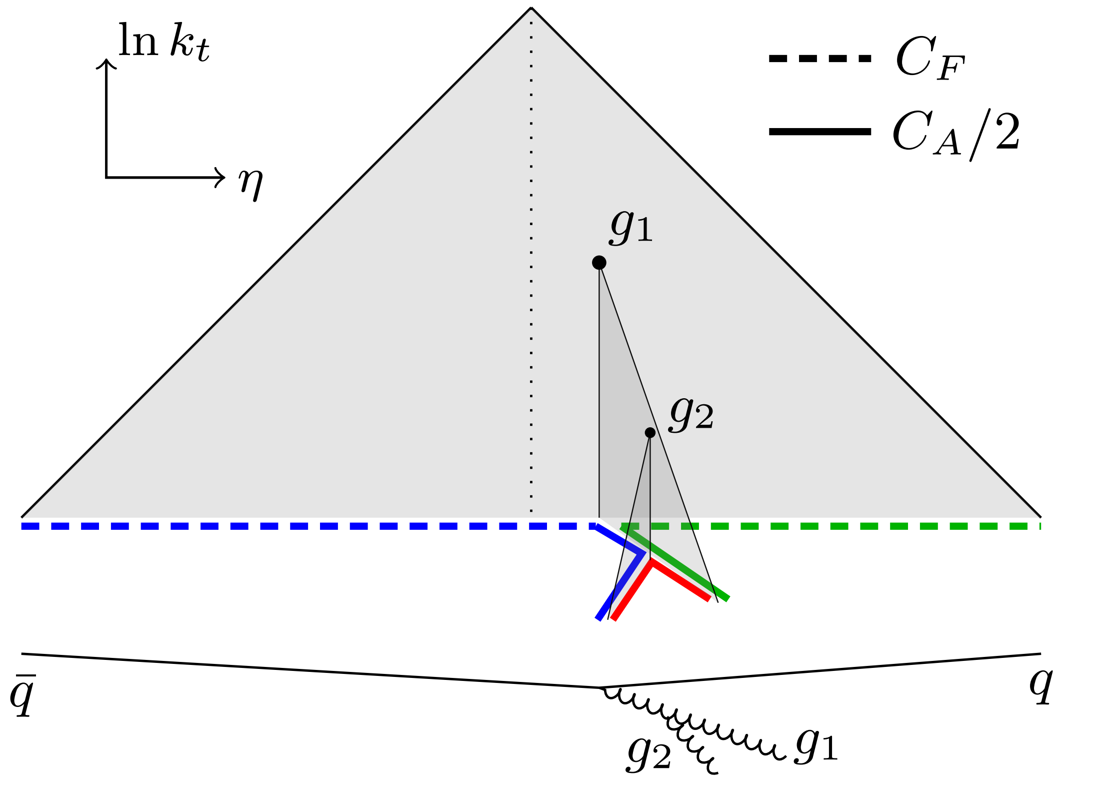
Also for hadron collisions **[van Beekveld, SFR, Salam, Soto-Ontoso, Soyez, Verheyen '22]**



Colour in the PanScales showers

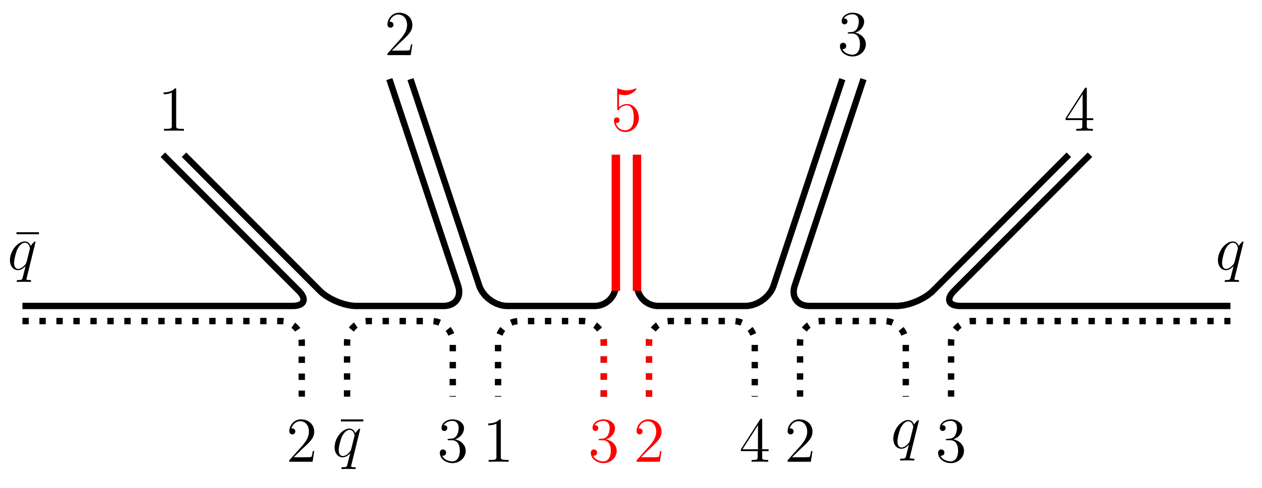
Hamilton, Medves, Salam, Scyboz, Soyez, 2011.10054 [FSR]
van Beekveld, SFR, Salam, Soto-Ontoso, Soyez, Verheyen [generalisation to ISR]

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

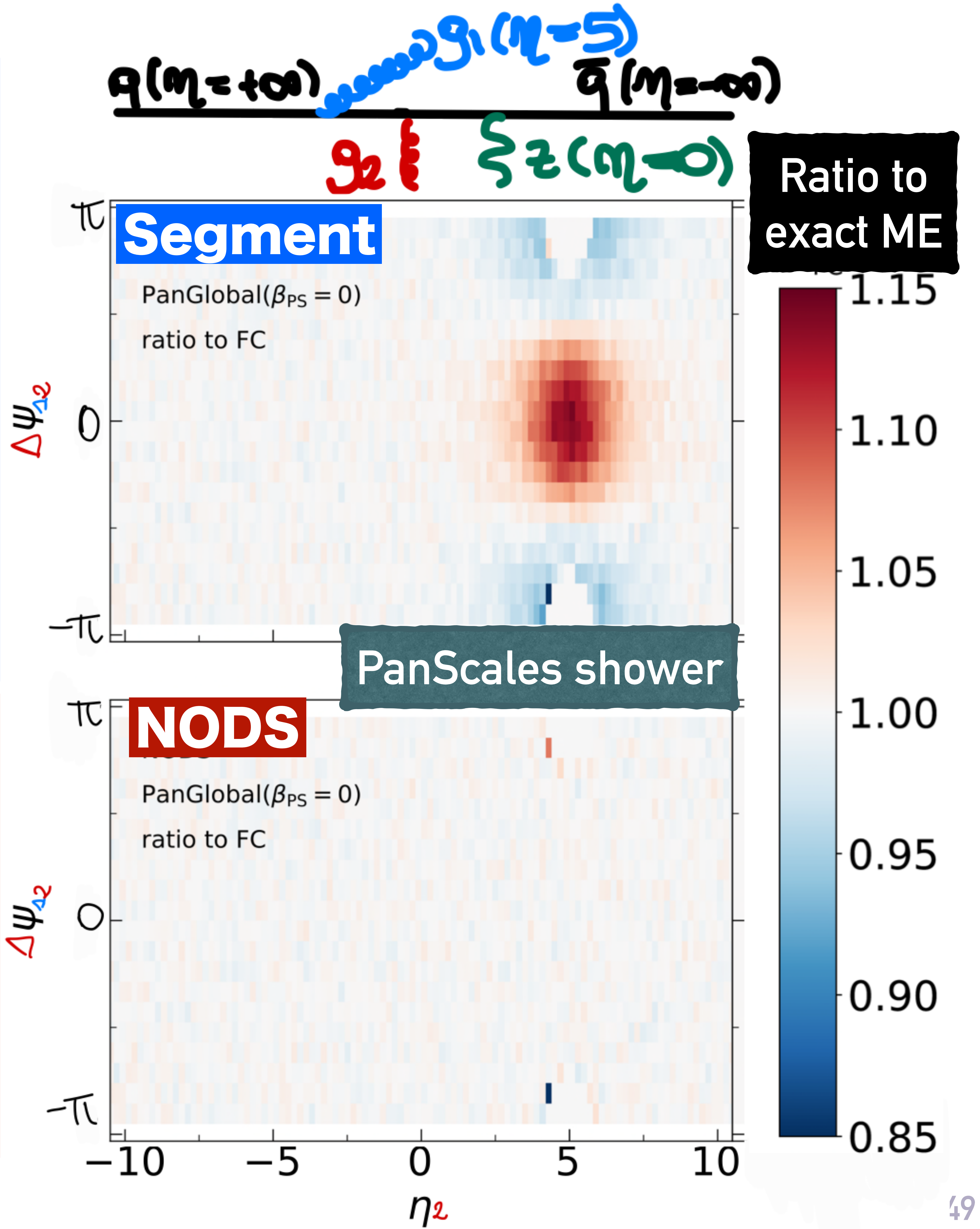


$$\bar{q}[-\infty, C_F, \eta_1^L, C_A, \eta_2^L, +\infty]_{g_2}$$
$$g_2[-\infty, C_A, \eta_2^R, C_A, +\infty]_{g_1}$$
$$g_1[-\infty, C_A, \eta_1^R, C_F, +\infty]_q$$
$$\eta_L = \max(0,\eta), \quad \eta_R = \min(0,\eta)$$

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



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



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

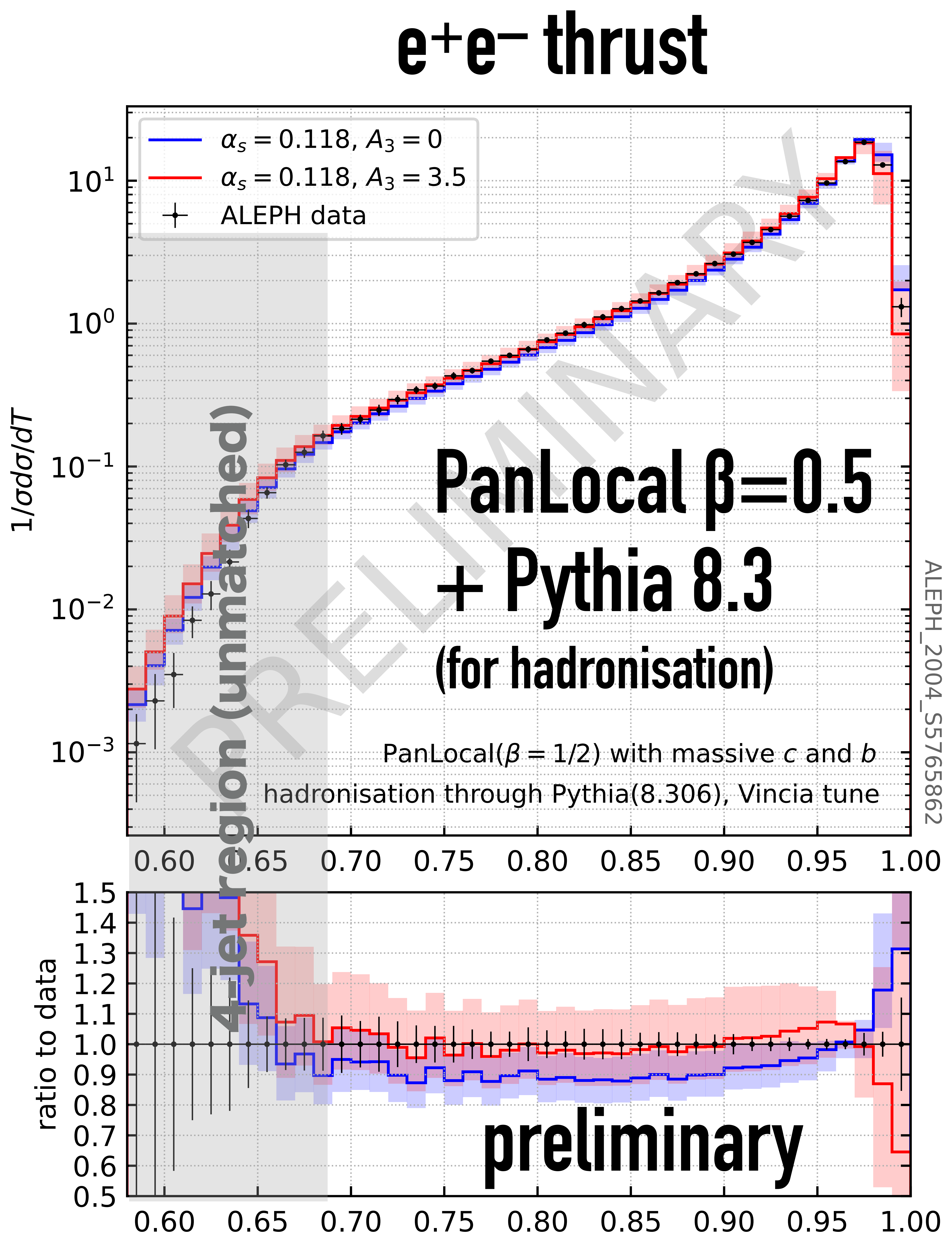
Underlying Calculations
We need (a) reference results and (b) understanding of NNLL logs in **soft** & **collinear** limits

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

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

Groomed jet mass as a direct probe of collinear parton dynamics
Anderle, Dasgupta, El-Menoufi, Guzzi, Helliwell, 2007.10355
[see also SCET work, Frye, Larkoski, Schwartz & Yan, 1603.09338 + …]

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



First comparisons to data

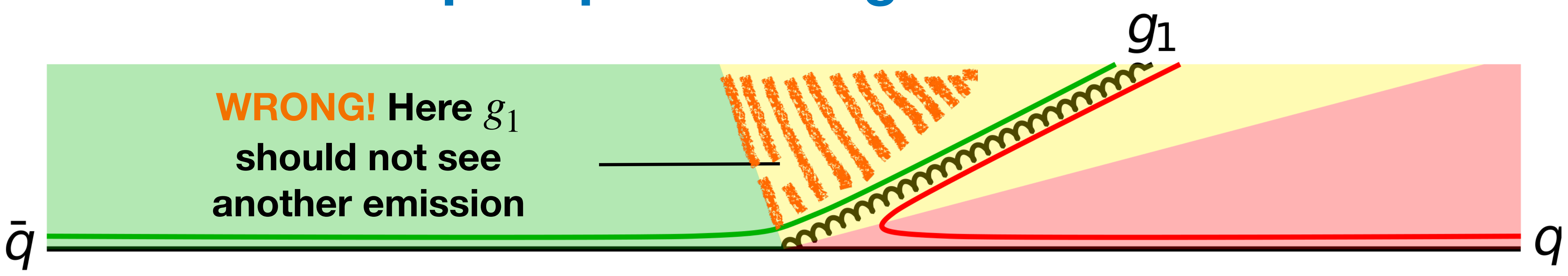
- we're starting with e^+e^- data
- aiming to understand nature of residual perturbative shower uncertainties
- and interplay with non-perturbative tuning
- plot includes preliminary treatment of heavy-quark masses

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

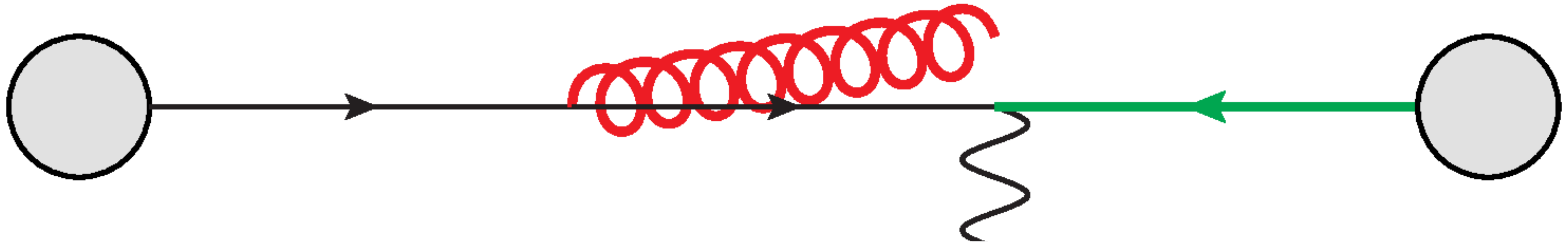
Slide from G. Salam

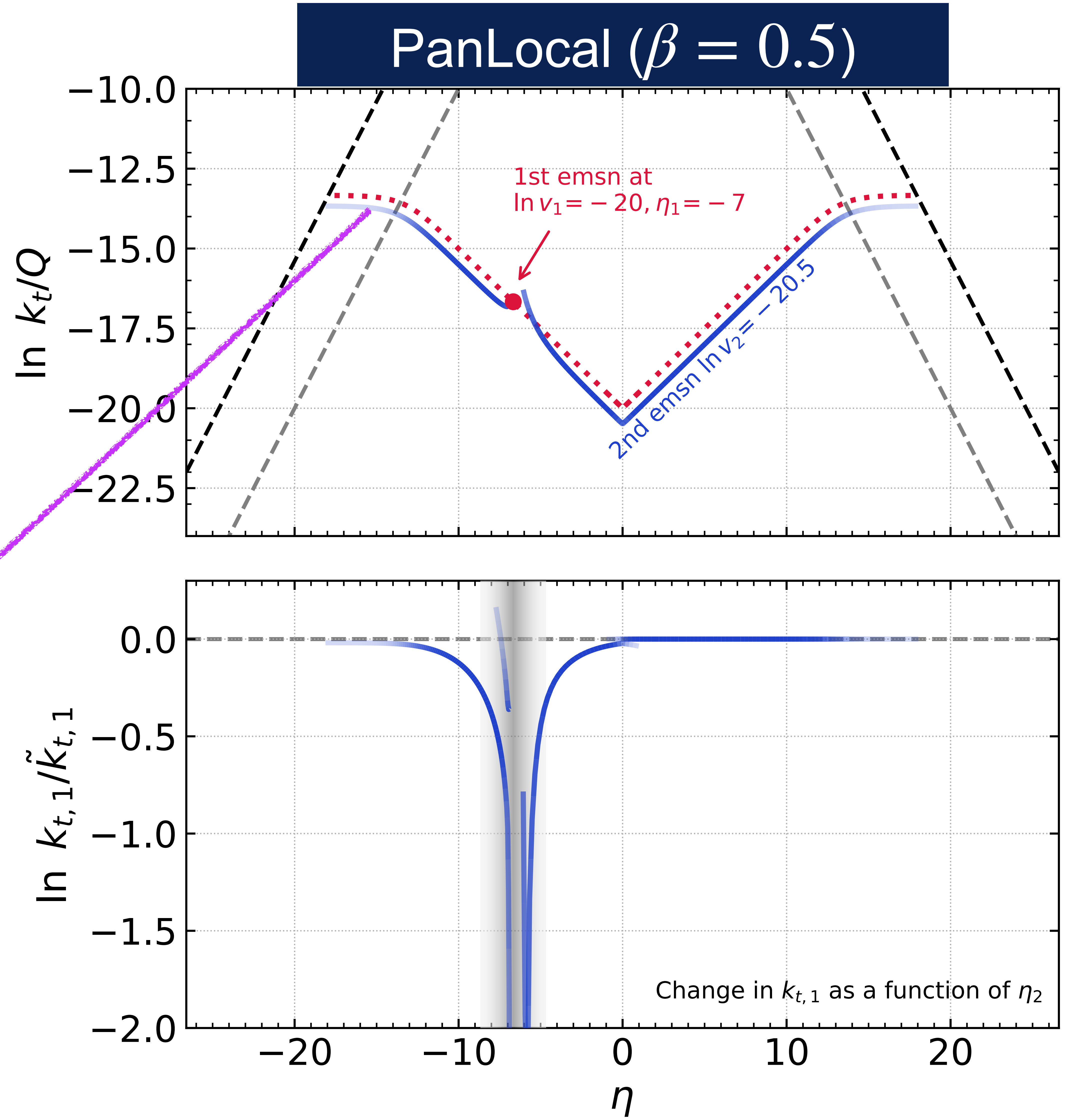
NLL PanScales showers for hadron collision: PanLocal

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



- **Ordering scale** $v = p_T e^{-\beta|\eta|} \approx p_T \theta^{-\beta}$ with $0 < \beta < 1$, so $p_{T2} \ll p_{T1}$ since $\theta_1 > \theta_2$ in the "wrong" region: recoil is negligible...
- ... but we restore to p_T ordering for very collinear emissions to prevent very energetic collinear parton from taking unphysical recoil





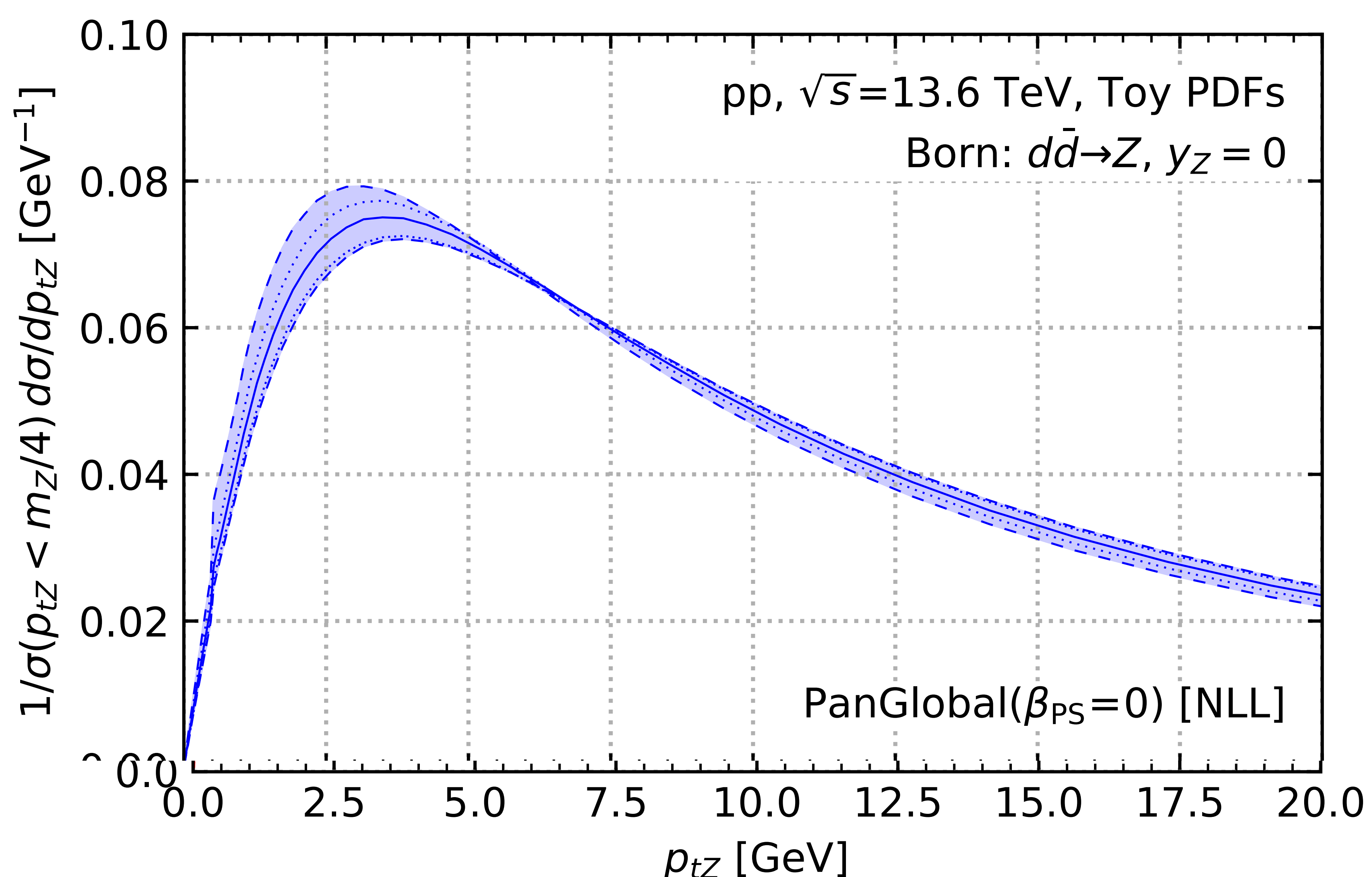
PanLocal for FSR: Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez, 2002.11114

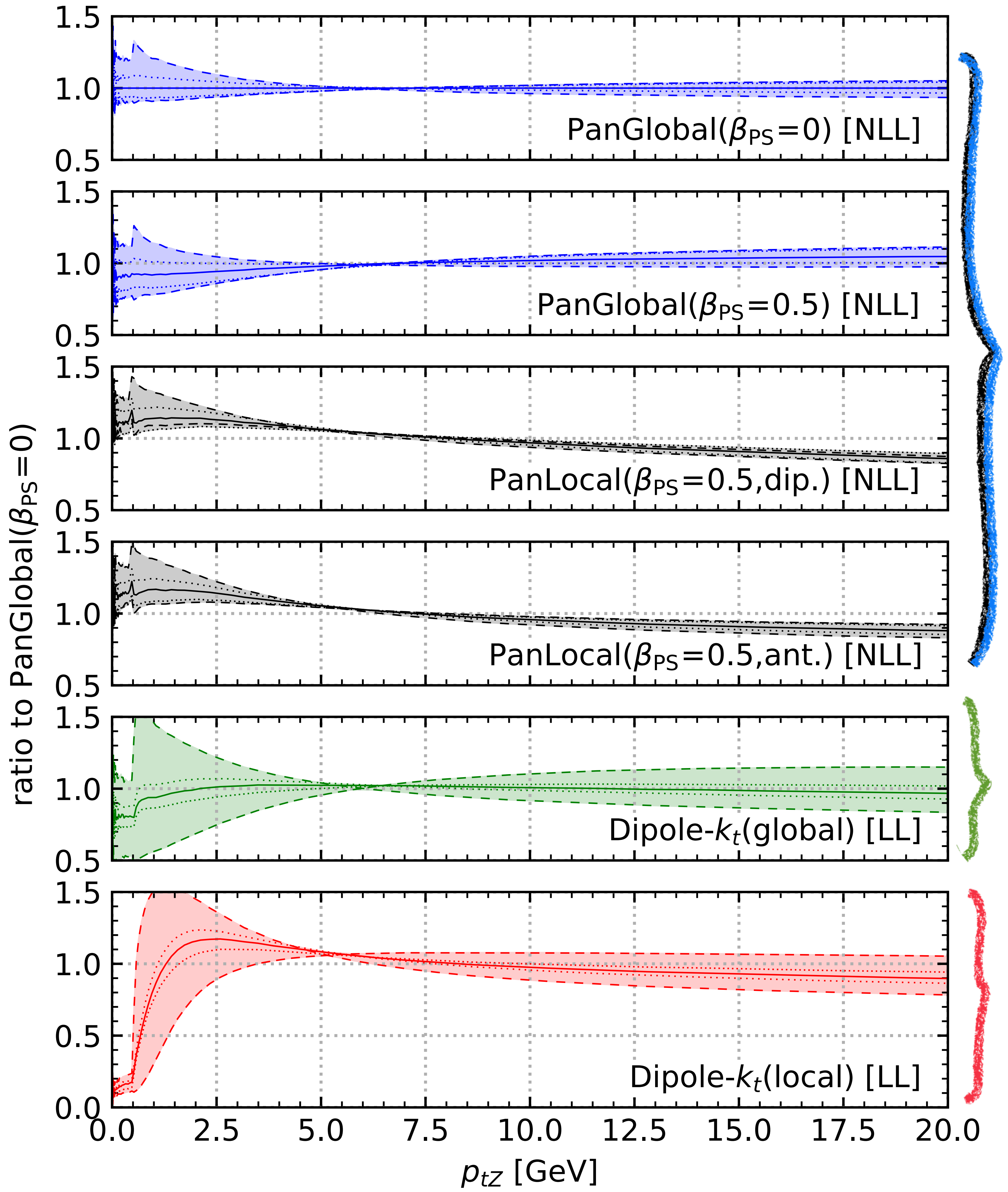
van Beekveld, S.F.R., Salam, Soto-Ontoso, Soyez, Verheyen, arXiv:2205.02237

Exploratory phenomenology for $p_\perp$ of the Z boson

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

- The "less wrong" LL shower cannot be distinguished from the other NLL showers.
  - Is NLL important? Can we live with LL tuned showers?
- Scale variations [Mrenna, Skands, 1605.08352] much smaller than PanLocal vs PanGlobal differences.
  - How do estimate PS uncertainties? PanLocal vs PanGlobal? Is this enough?





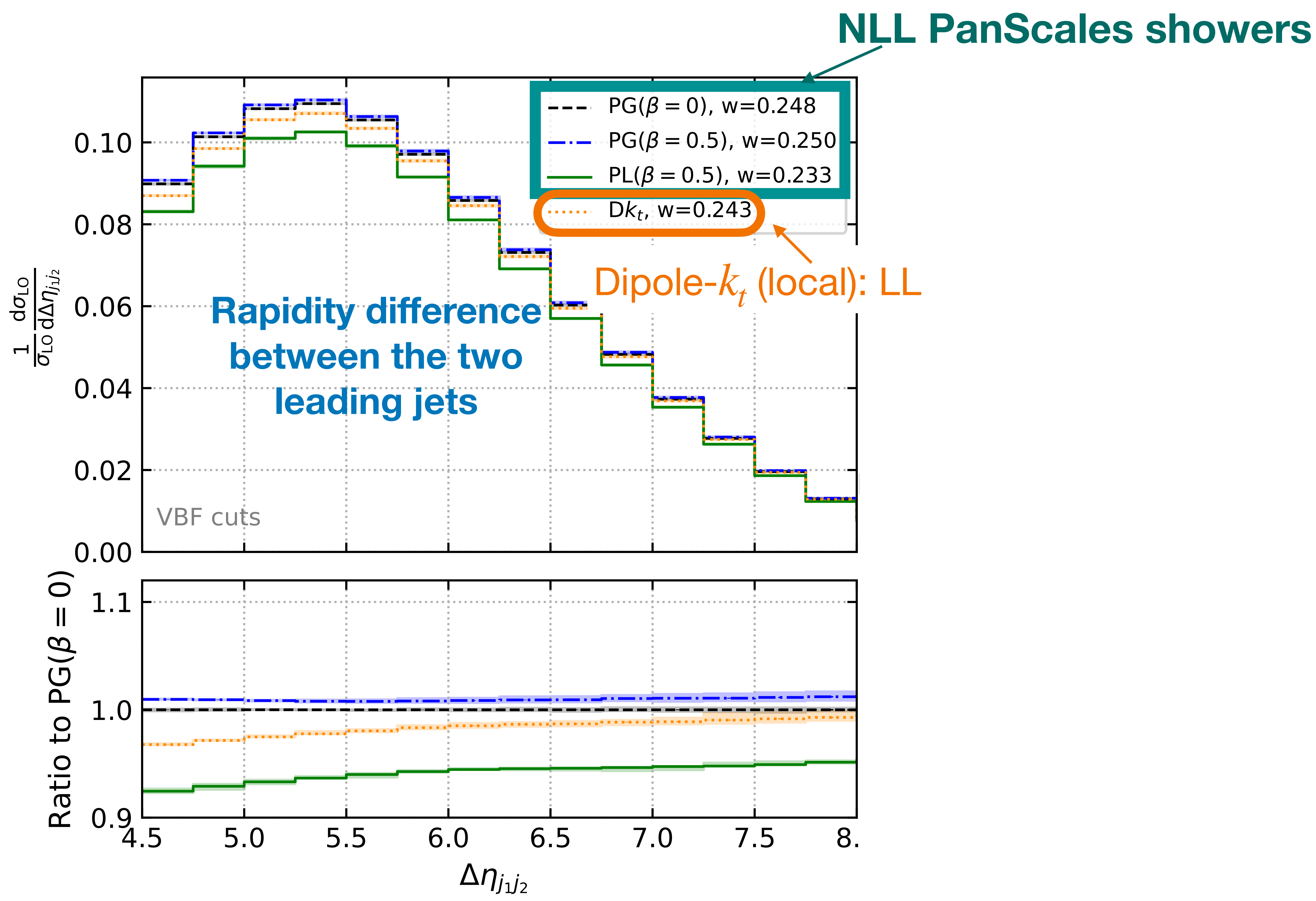
PanScales NLL showers with global [blue] or local [black] recoil. At small pTZ, the spectrum is power-suppressed with the correct normalisation.

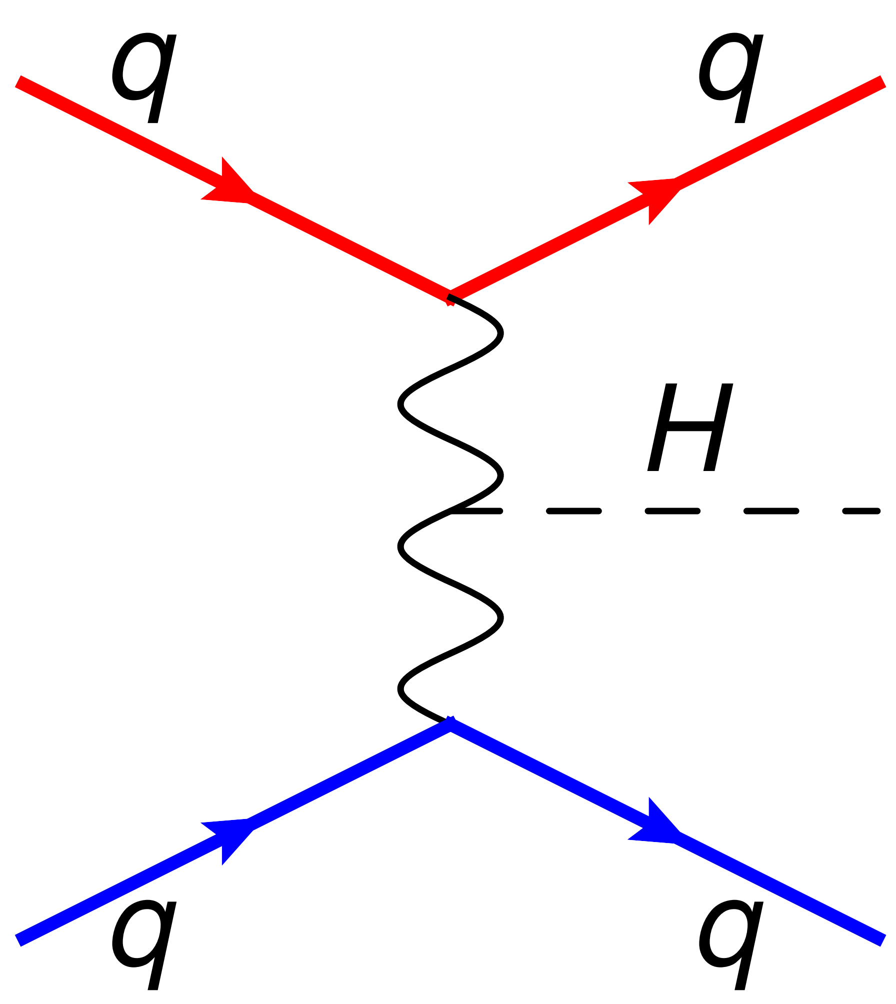
LL shower. At small pTZ, the spectrum is power-suppressed, but with the WRONG normalisation

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

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

Exploratory phenomenology for VBF at 13.6 TeV





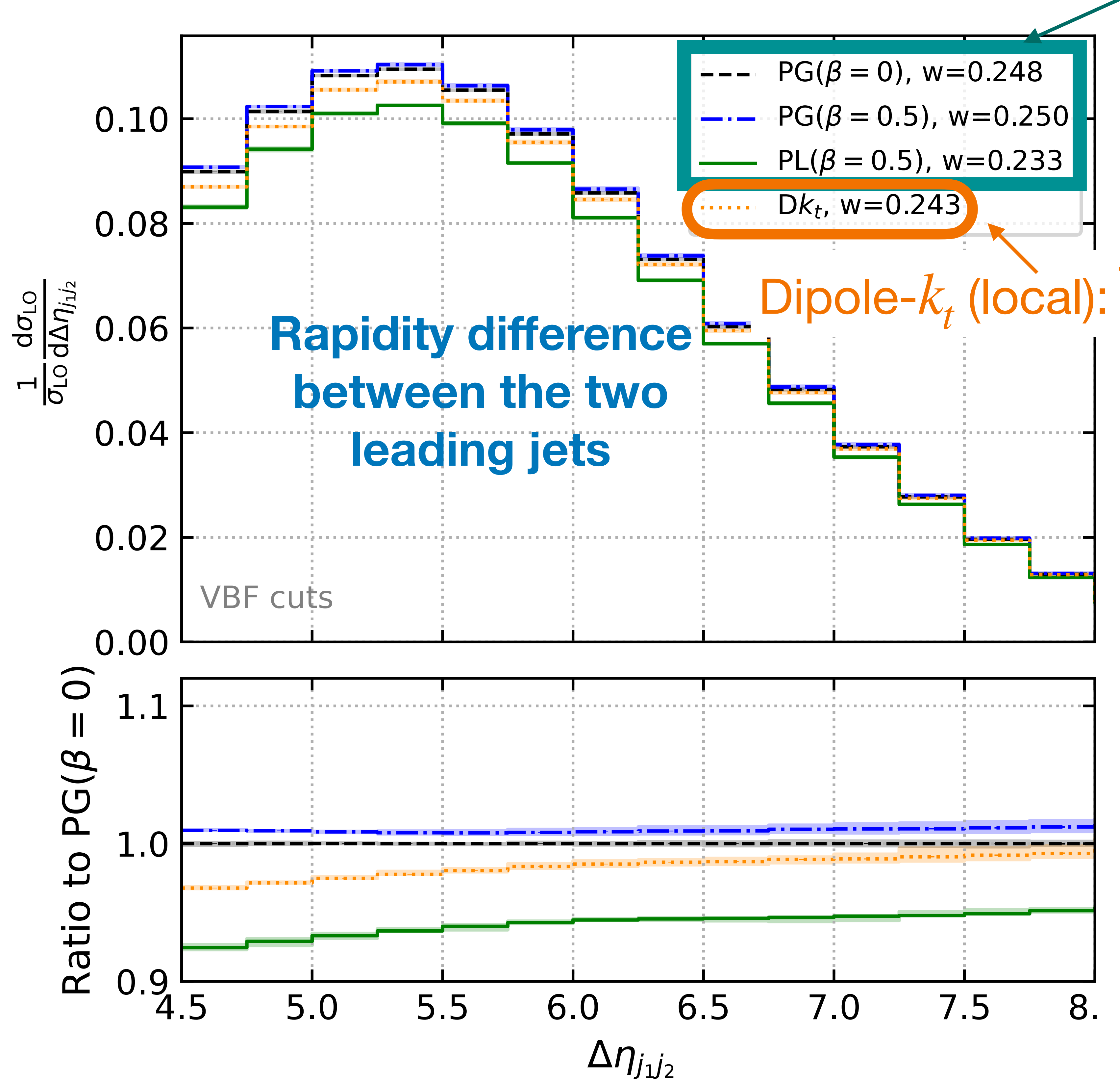
LO events obtained thanks to our **Pythia8.3** [2203.11601] interface!

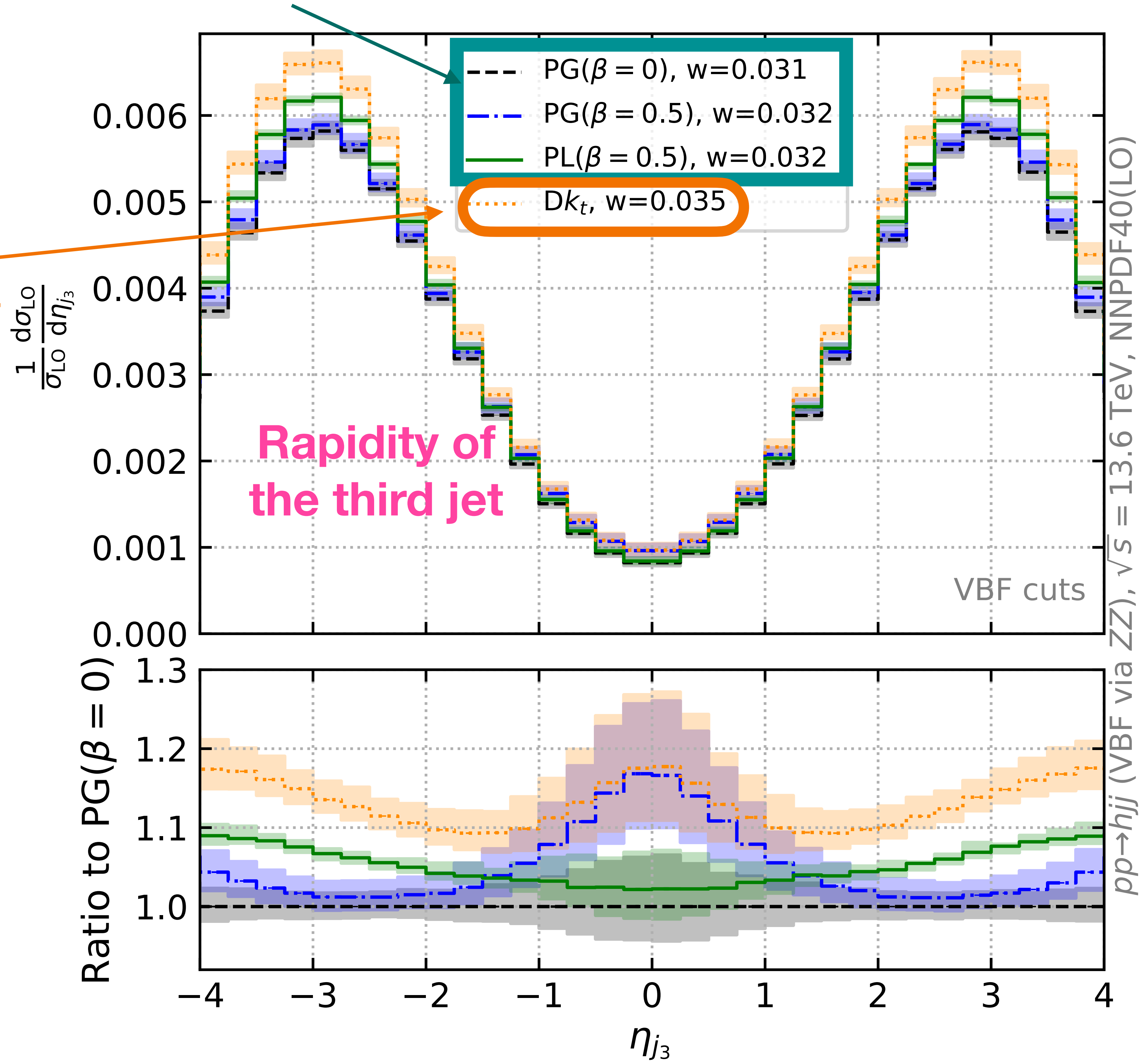
➤ For inclusive observables, differences have the same size of NLO corrections. LL shower lies between the NLL predictions.

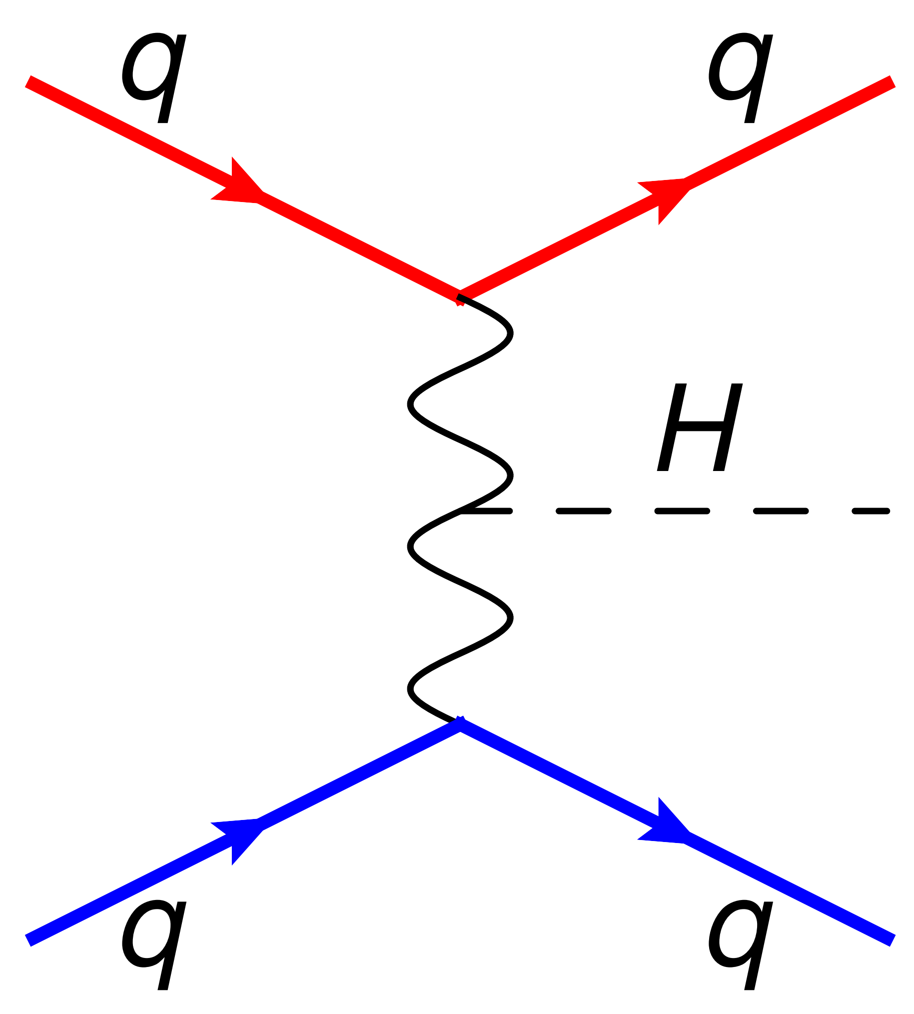
van Beekveld, S.F.R., 2305.08645

Exploratory phenomenology for VBF at 13.6 TeV

NLL PanScales showers







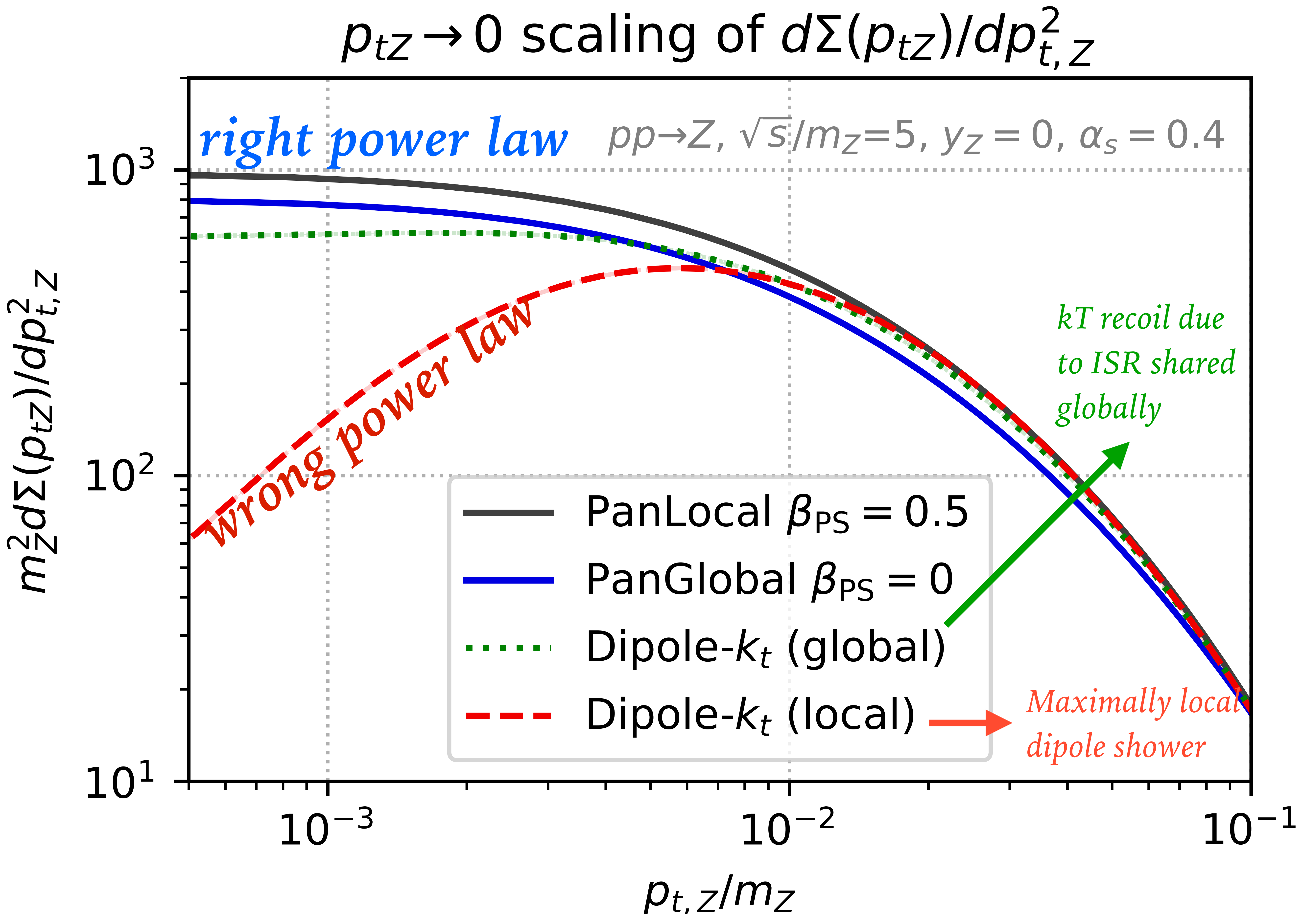
LO events obtained thanks to our **Pythia8.3** [2203.11601] interface!

- 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

van Beekveld, S.F.R., 2305.08645

Transverse momentum of the colour-singlet in the power-suppressed regime

Parisi-Petronzio '79, predicted power-law scaling of Z p_t spectrum at low p_t: which showers do reproduce it?



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

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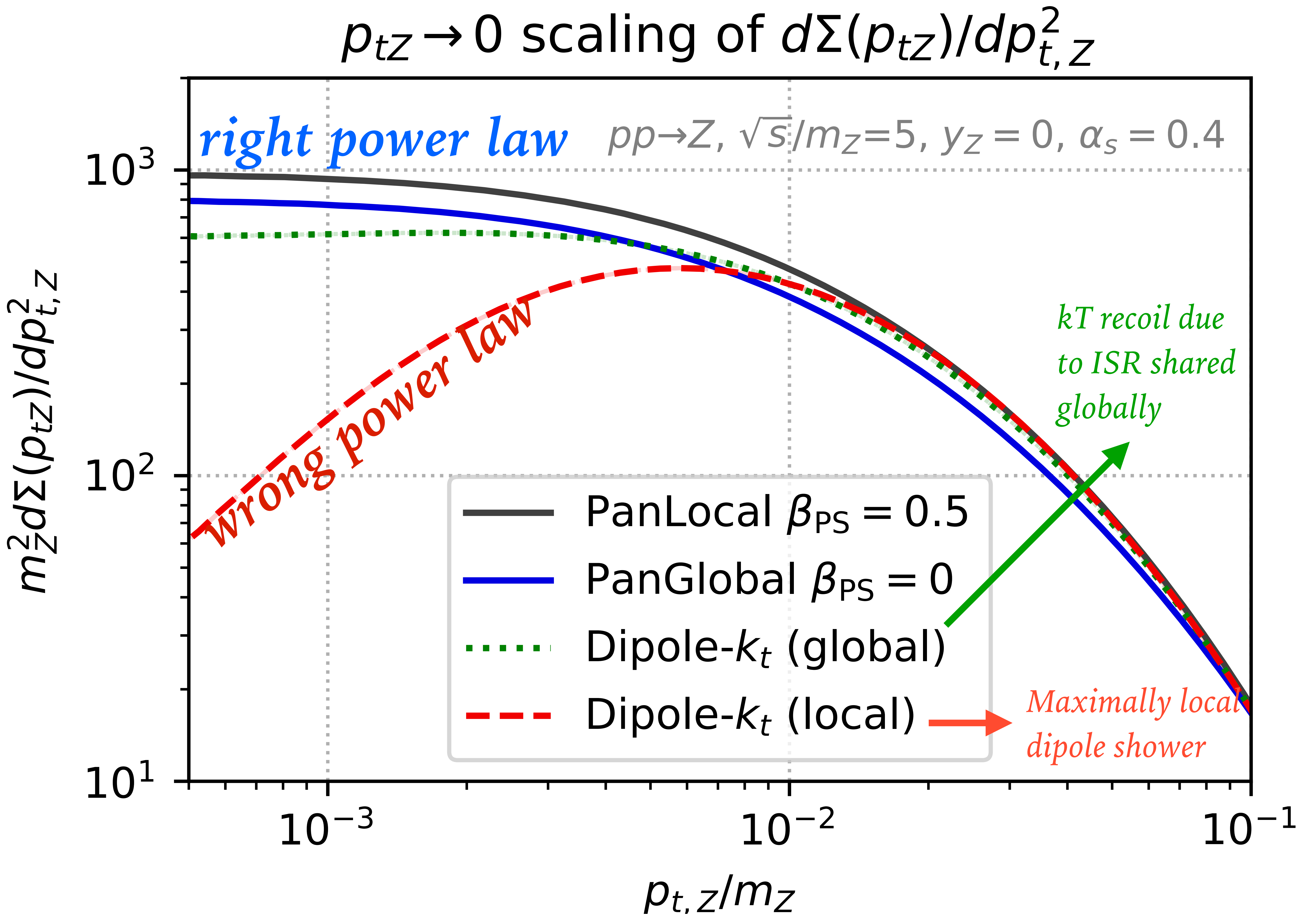

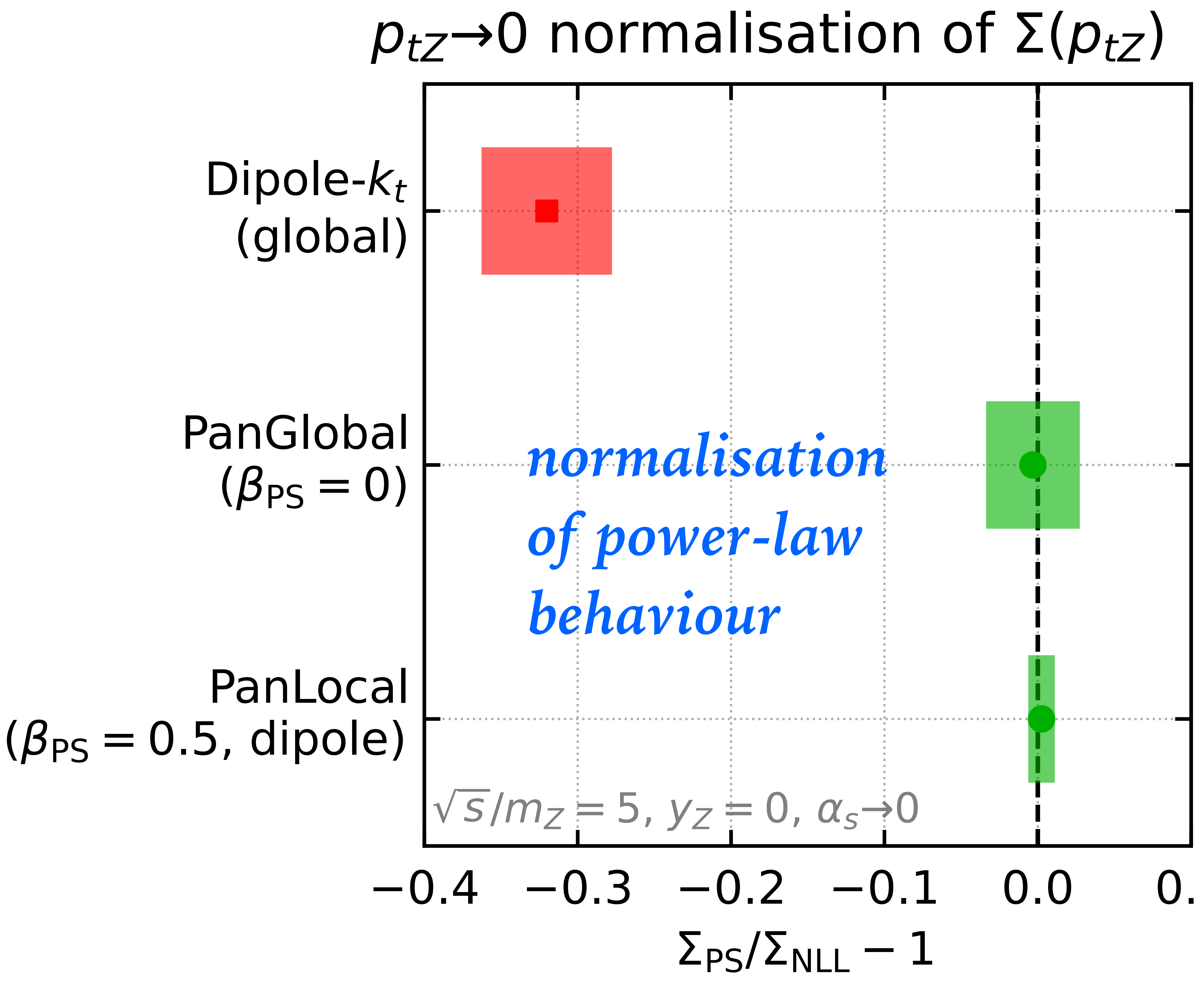

van Beekveld, S.F.R., Hamilton, Salam, Soto-Ontoso, Soyez, Verheyen, 2207.09467