Recent improvements in parton shower algorithms (for Higgs production)

Higgs 2022 - 09/11/2022

Melissa van Beekveld

THE ROYAL SOCIETY

Science & Technology Facilities Council

erc

UNIVERSITY OF OXFORD

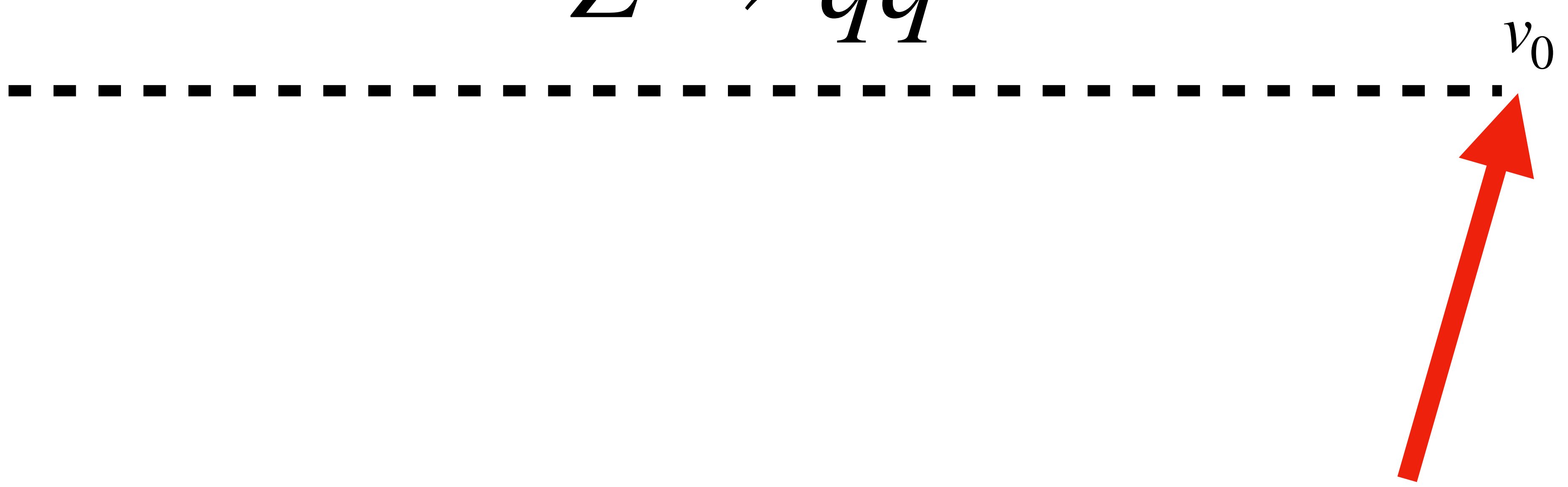
What is a parton shower?

parton shower in pisa

What is a parton shower?

Illustrated with a dipole shower for final-state emissions

$Z \to q\bar{q}$



starting scale
of the shower

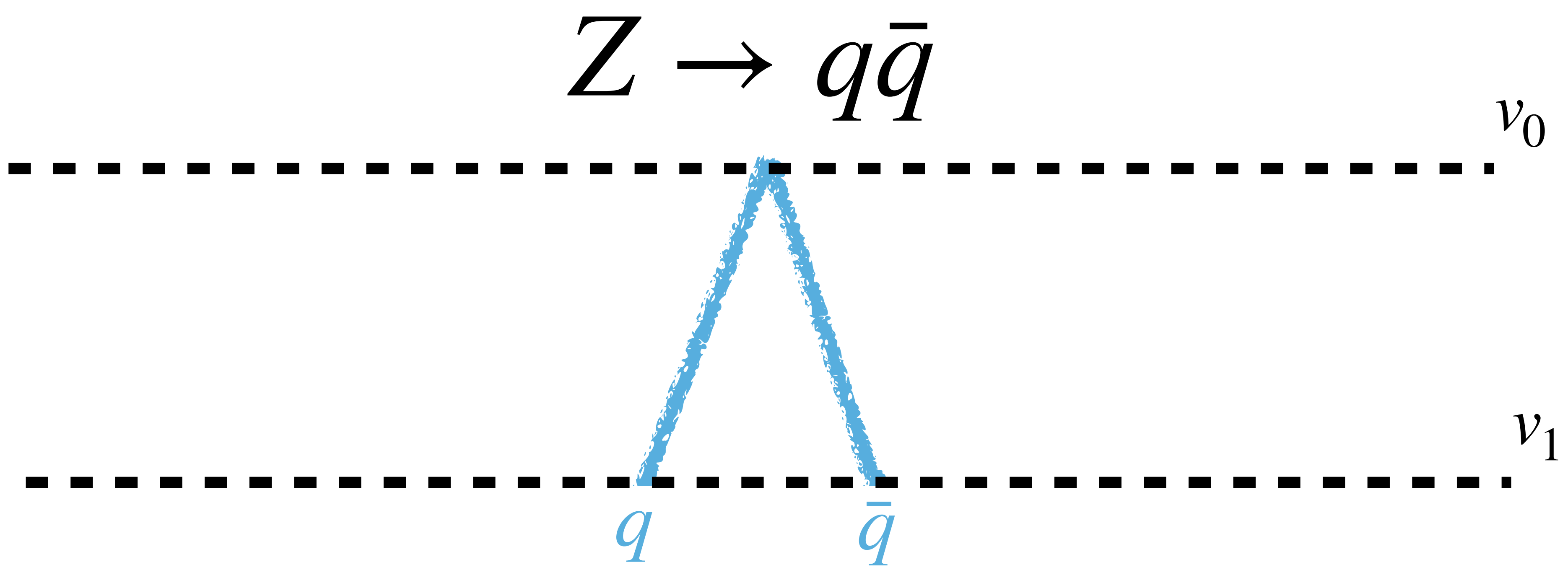
Start with some partonic state
This spans an initial 'colour dipole'

What is a parton shower?

Illustrated with a dipole shower for final-state emissions

Start with some partonic state
This spans an initial 'colour dipole'

Throw a random number to determine the scale v_1 until which 'nothing happens'



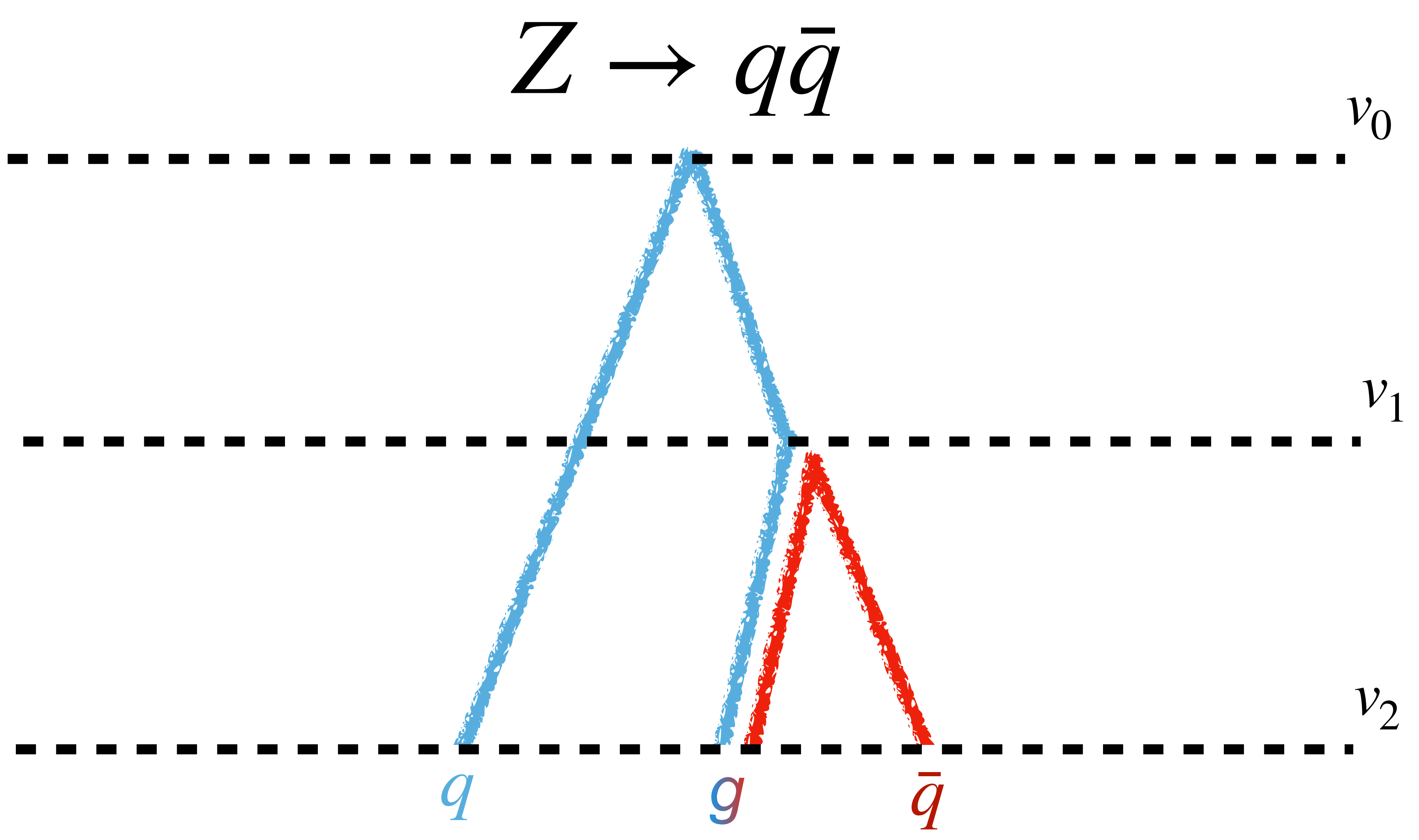
What is a parton shower?

Illustrated with a dipole shower for final-state emissions

Start with some partonic state
This spans an initial ‘colour dipole’

Throw a random number to determine the scale v_1 until which ‘nothing happens’

The state splits…
The new gluon is part of two (independent) dipoles



What is a parton shower?

Illustrated with a dipole shower for final-state emissions

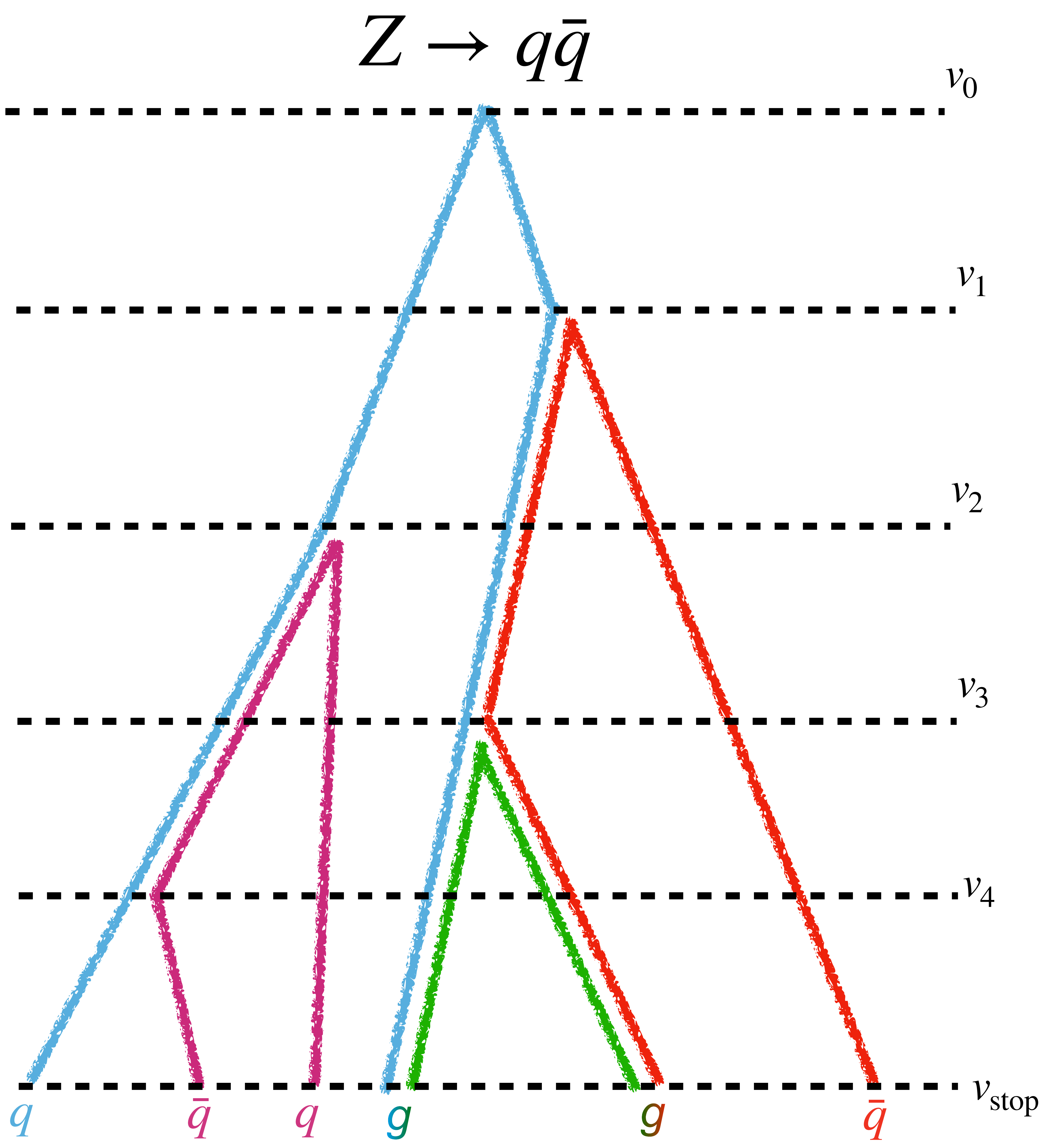
Start with some partonic state
This spans an initial ‘colour dipole’

Throw a random number to determine the scale v_1 until which ‘nothing happens’

The state splits…
The new gluon is part of two (independent) dipoles

Process continues until it reaches a non-perturbative cut-off scale

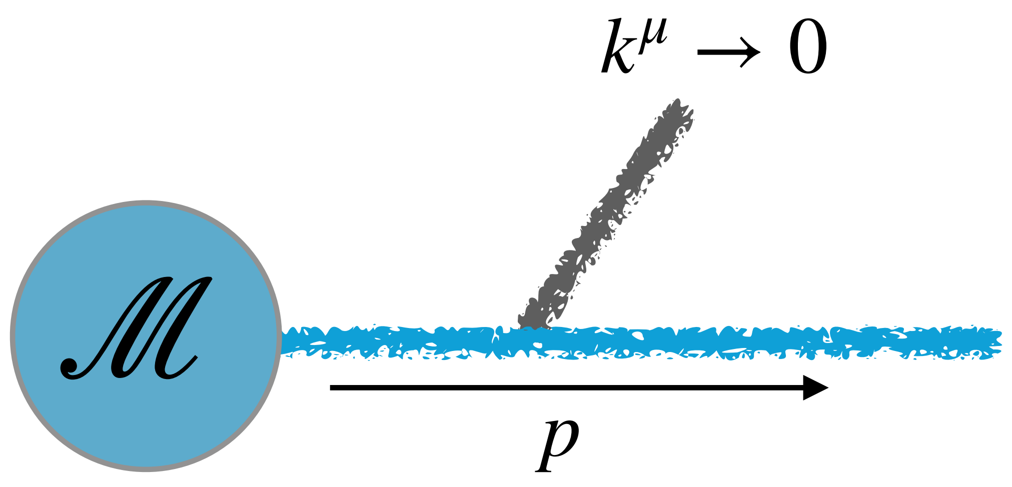
End result: set of particles and their four momenta, from which any (well-defined) observable may be reconstructed



Melissa van Beekveld

The splitting probability

Emission of a soft gluon: the eikonal Feynman rule

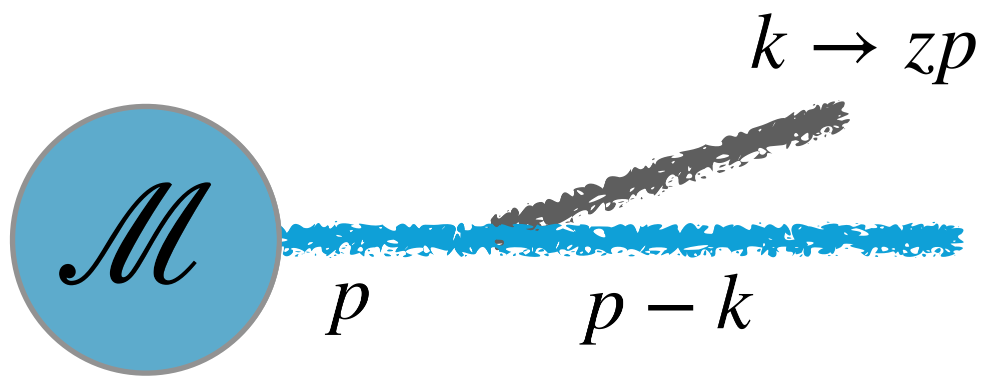


$$\propto g_s \frac{p^\mu}{p \cdot k} \mathbf{T} \otimes \mathcal{M}$$

$\mathbf{T}$ is a colour-generator

- Spin dependence is factorised
- Colour dependence is not

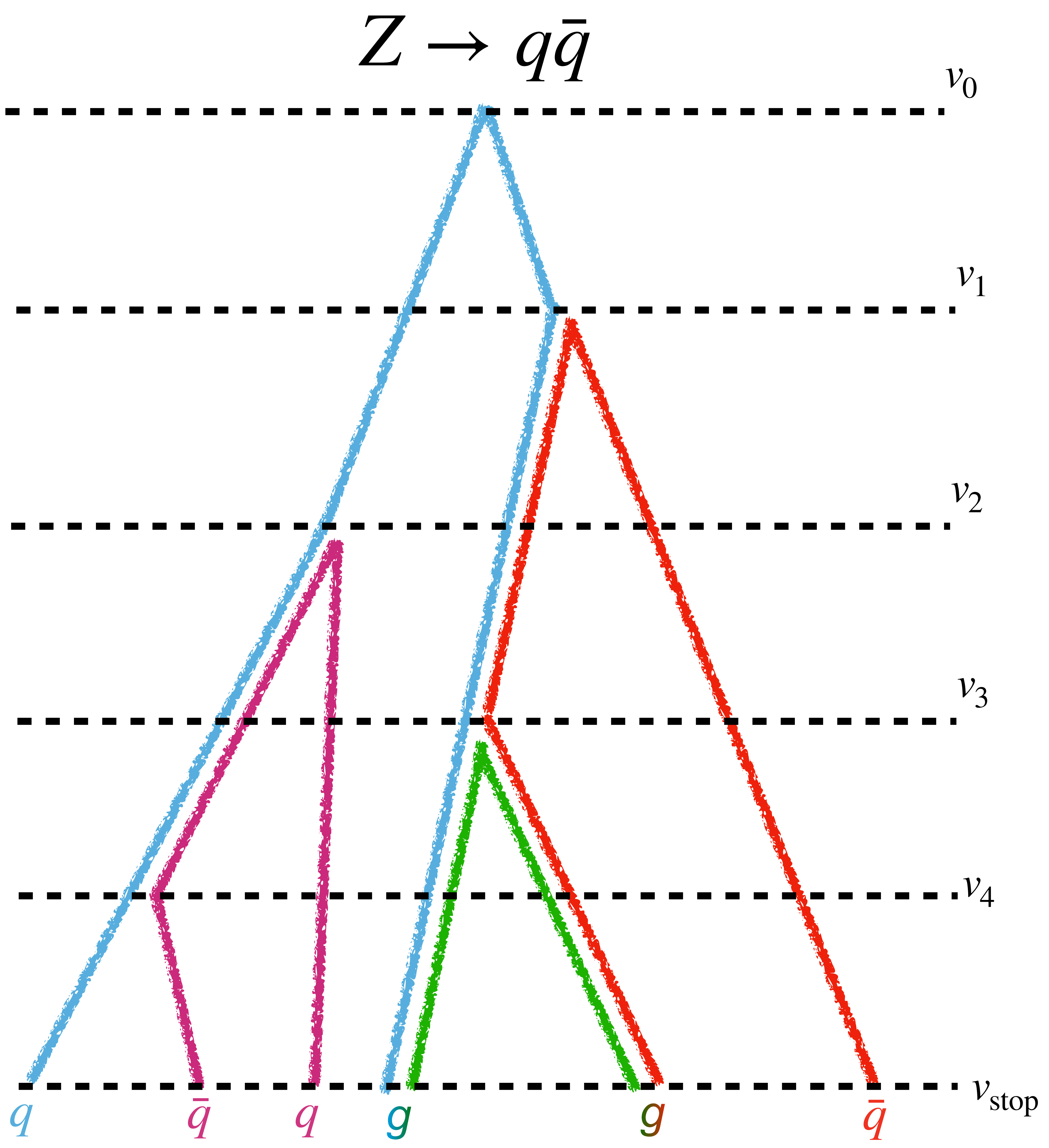
Emission of a collinear particle: Splitting functions $P_{(ij)a}$



$$\propto g_s \frac{1}{p \cdot k} P_{(ij),a}(z) \otimes \mathcal{M}_a$$

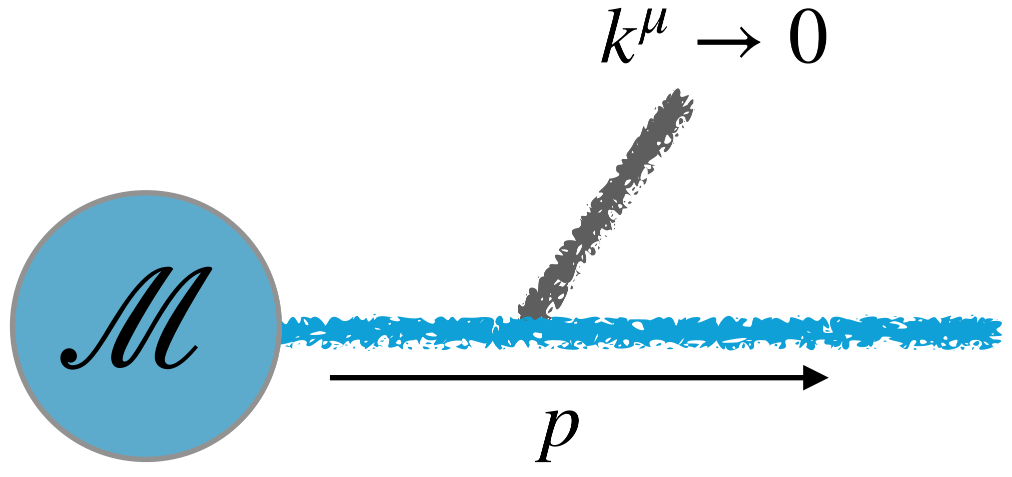
a is a spin index

- Colour dependence is factorised
- Spin dependence is not



The splitting probability

Emission of a soft gluon: the eikonal Feynman rule

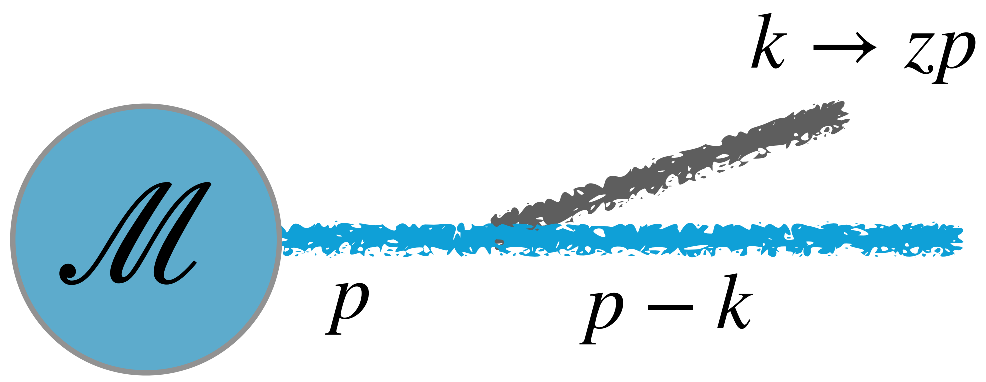


$$\propto g_s \frac{p^\mu}{p \cdot k} \mathbf{T} \otimes \mathscr{M}$$

$\mathbf{T}$ is a colour-generator

- Spin dependence is factorised
- Colour dependence is not

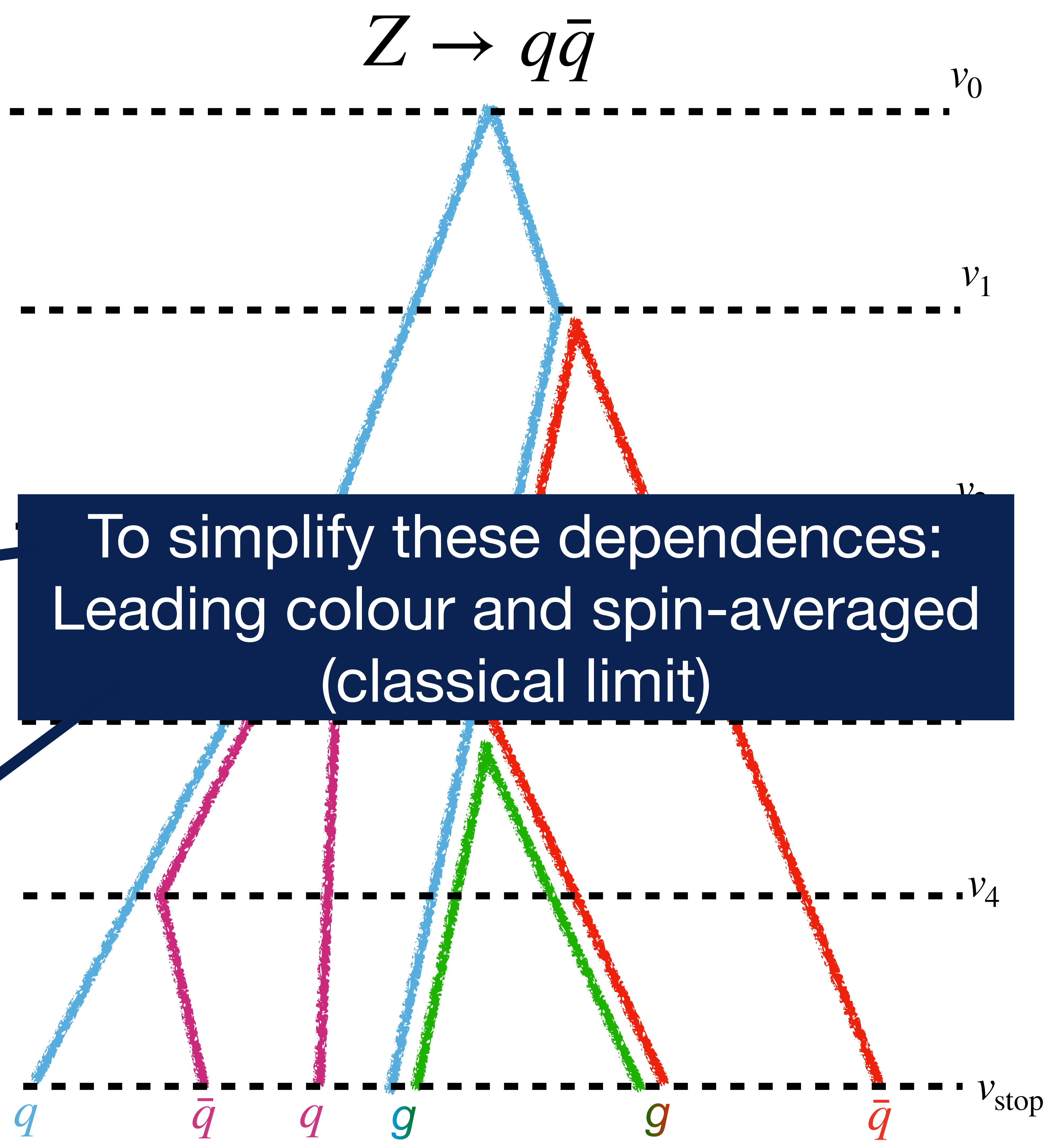
Emission of a collinear particle: Splitting functions $P_{(ij)a}$



$$\propto g_s \frac{1}{p \cdot k} P_{(ij),a}(z) \otimes \mathscr{M}_a$$

a is a spin index

- Colour dependence is factorised
- Spin dependence is not



To simplify these dependences:
Leading colour and spin-averaged
(classical limit)

PS algorithms - matter of making choices

DGLAP	**v.s.**	**Dipole/Antenna**
Pythia default		Pythia dipole
Herwig default		Herwig dipole
		Sherpa
		Dire
		Vincia

Kinematic map

How to go from n to $n+1$ partonic state?

global / local momentum conservation

Attribution of recoil

How to select an ‘emitter’?

dipole CM frame, event CM frame

Evolution variable v

Which emissions come first?

k_t *ordered, angular ordered, virtuality ordered…*

Parton showers: a crucial ingredient

Pythia 8

An introduction to PYTHIA 8.2 #1

Torbjörn Sjöstrand (Lund U., Dept. Theor. Phys.), Stefan Ask (Cambridge U.), Jesper R. Christiansen (Lund U., Dept. Theor. Phys.), Richard Corke (Lund U., Dept. Theor. Phys.), Nishita Desai (U. Heidelberg, ITP) et al. (Oct 11, 2014)

Published in: *Comput.Phys.Commun.* 191 (2015) 159-177 • e-Print: 1410.3012 [hep-ph]

4,738 citations

PYTHIA 6.4 Physics and Manual 12,519 citations

Herwig 7

Herwig++ Physics and Manual #1

M. Bahr (Karlsruhe U., ITP), S. Gieseke (Karlsruhe U., ITP), M.A. Gigg (Durham U., IPPP), D. Grellscheid (Durham U., IPPP), K. Hamilton (Louvain U.) et al. (Mar, 2008)

Published in: *Eur.Phys.J.C* 58 (2008) 639-707 • e-Print: 0803.0883 [hep-ph]

2,755 citations

Sherpa

Event generation with SHERPA 1.1 #1

T. Gleisberg (SLAC), Stefan. Hoeche (Zurich U.), F. Krauss (Durham U., IPPP), M. Schonherr (Dresden, Tech. U.), S. Schumann (Edinburgh U.) et al. (Nov, 2008)

Published in: *JHEP* 02 (2009) 007 • e-Print: 0811.4622 [hep-ph]

3,518 citations

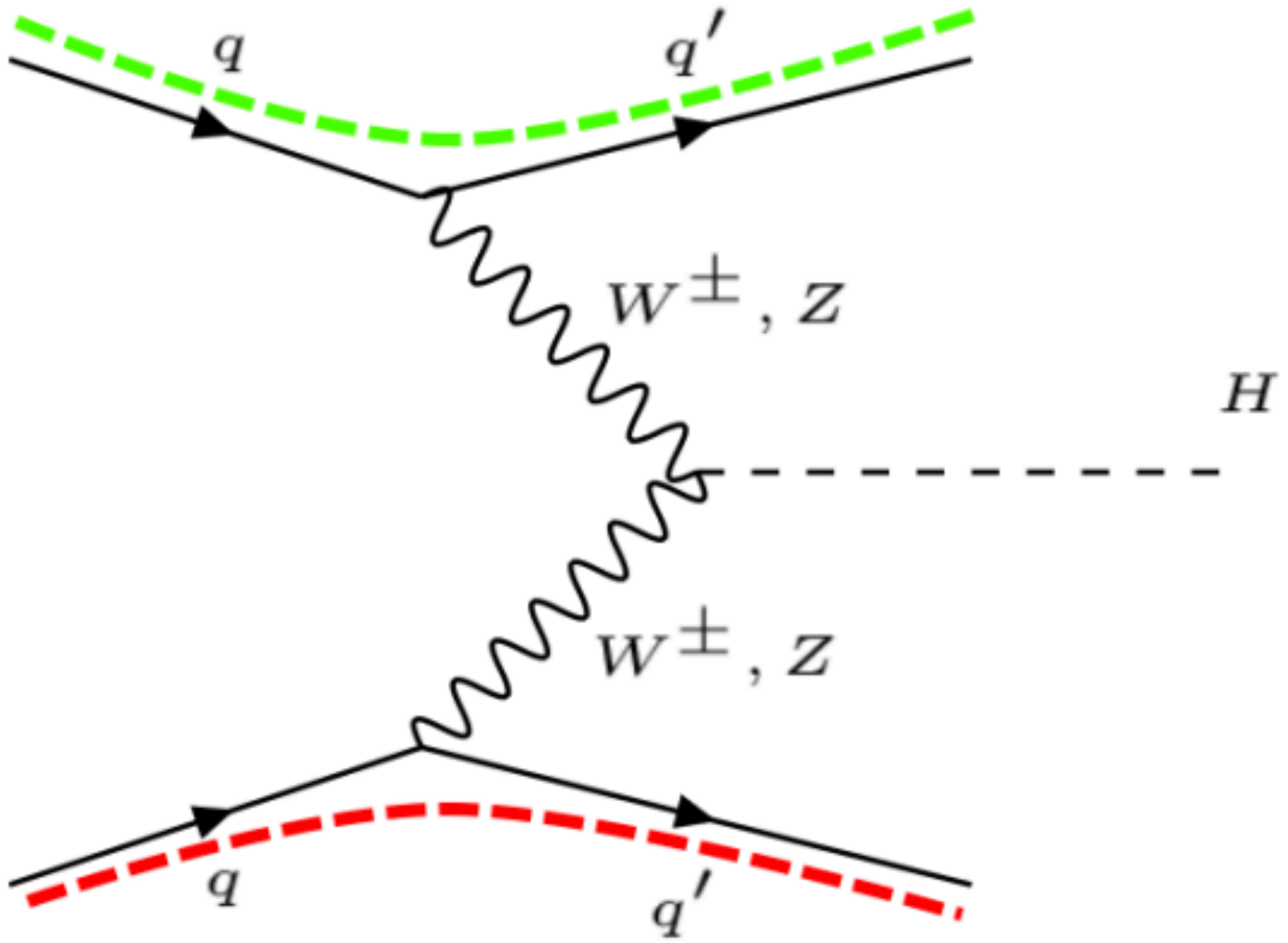
Do an amazing job at describing the phenomenology at colliders
(and sometimes even beyond colliders)

[2003.12435, 2105.11399, 2106.10987]

But differences matter…

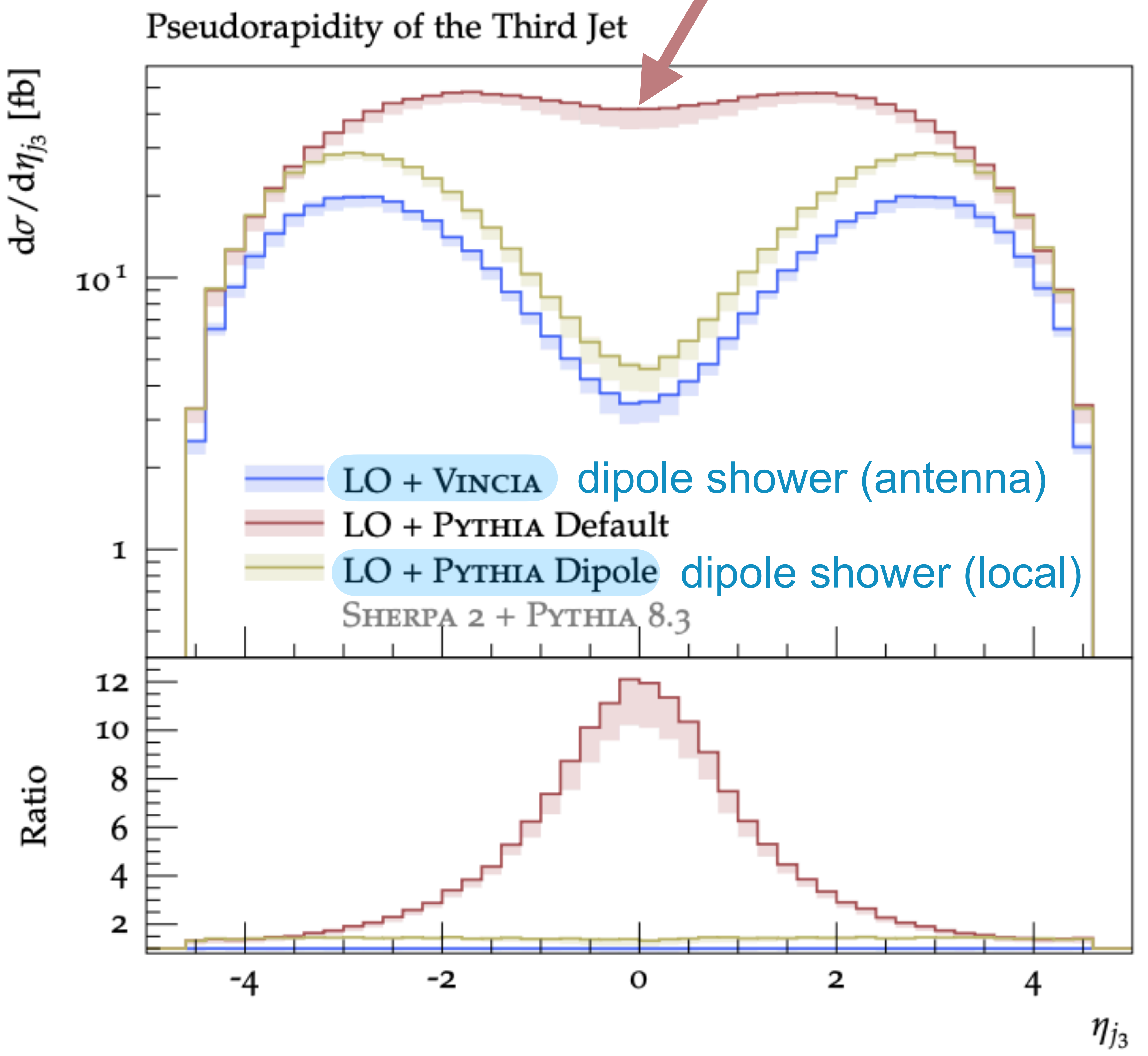
VBF production of $h + 2j$

Focus of the talk will lie mostly on this channel…



Colour coherence strongly **suppresses** radiation in central rapidity region

Pythia’s default (global) shower unphysically fills this central region!



dipole shower (antenna)

dipole shower (local)

Progress in improving the PS accuracy

- Matching to fixed-order

  NLO; i.e. Frixione & Webber [0204244], Nason [0409146], …
  NNLO; i.e. UNNLOPS [1407.3773], MiNNLOps [1908.06987], Geneva [1311.0286], Vincia [2108.07133], …
  NNNLO; Prestel [2106.03206], + Bertone [2202.01082]

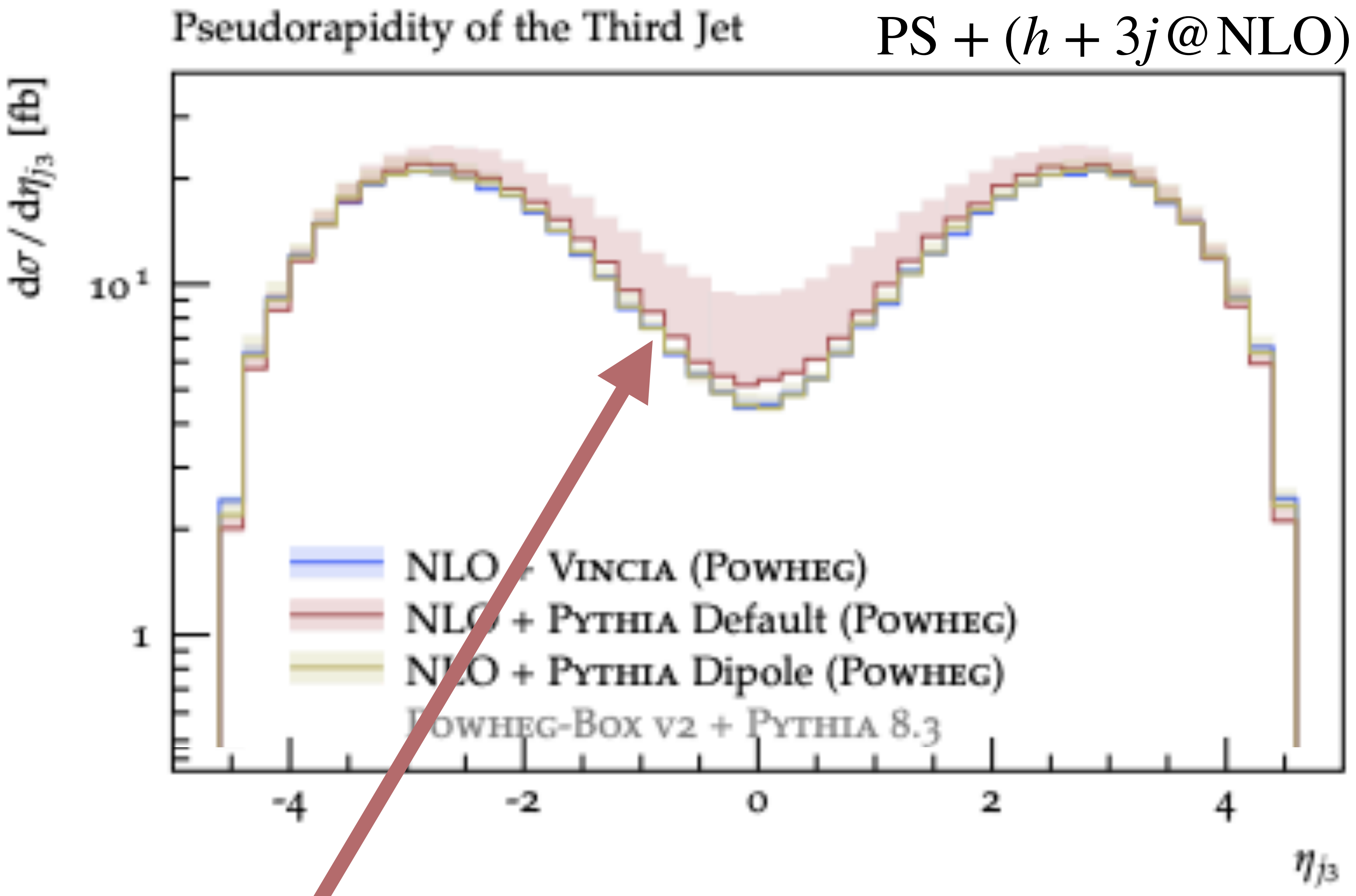
ggF [2006.04133], VH [2112.04168]

colour-singlet (DY) [2102.08390], VH [1909.02026]

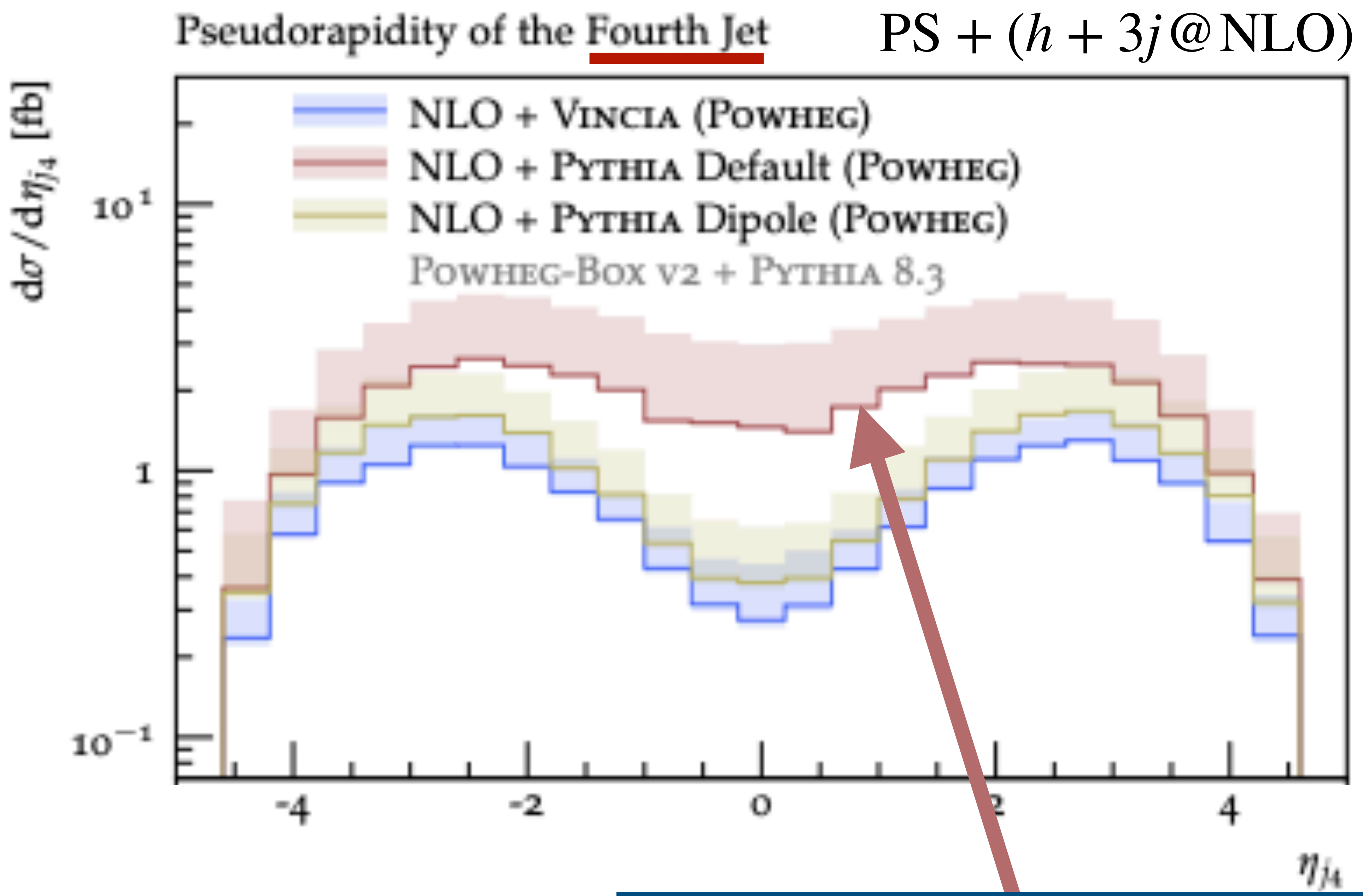
[2106.10987]

Multiplicative matching
[0409146, 0911.5299, 1002.2581]

Matching for VBF (Powheg-box + PS)


Pseudorapidity of the Third Jet $\text{PS} + (h + 3j@\text{NLO})$

Matching fixes the rapidity distribution of the 3rd jet…


Pseudorapidity of the Fourth Jet $\text{PS} + (h + 3j@\text{NLO})$

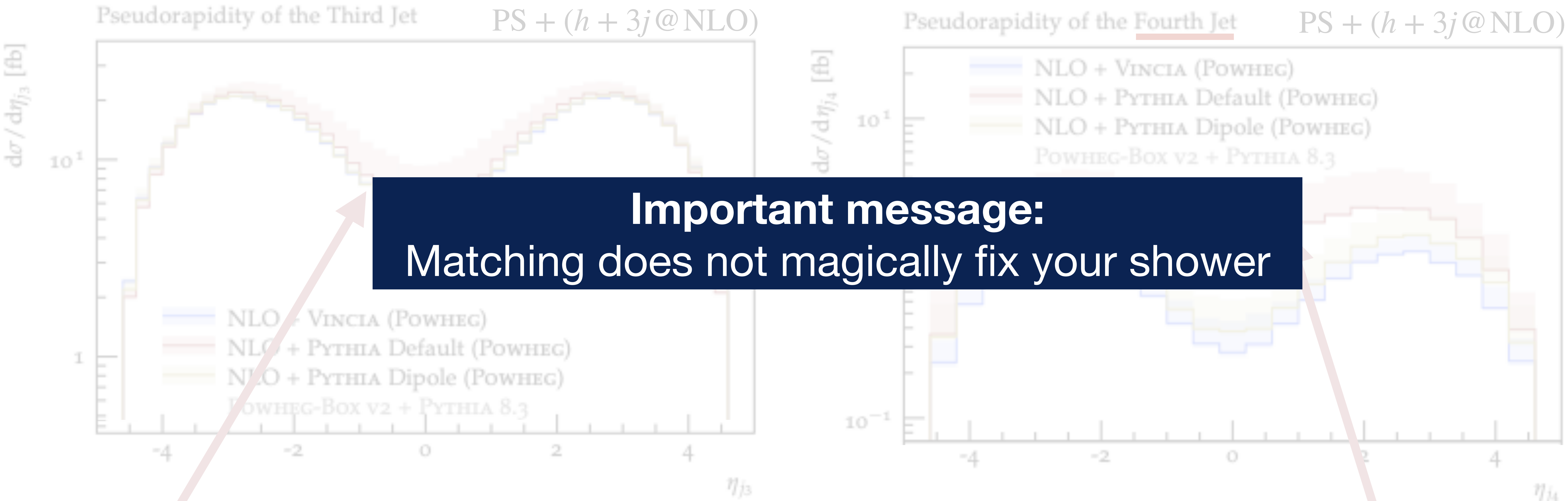
But we again see a **huge** discrepancy for four-jet observables!

MC@NLO + Pythia/Herwig in [2003.12435]

[2106.10987]

Multiplicative matching
[0409146, 0911.5299, 1002.2581]

Matching for VBF (Powheg-box + PS)



Important message:
Matching does not magically fix your shower

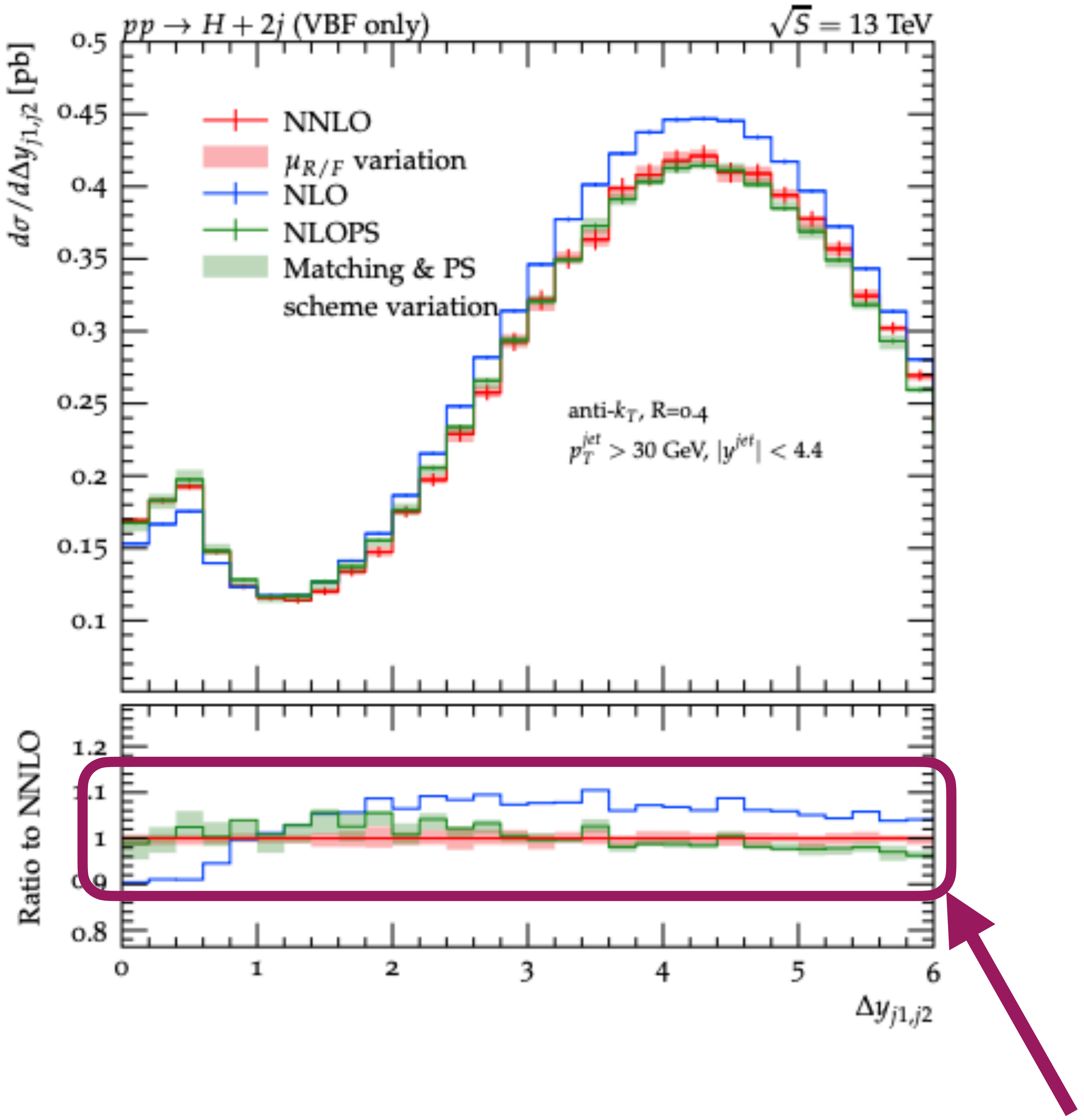
Matching fixes the rapidity distribution of the 3rd jet…

But we again see a huge discrepancy for four-jet observables!

MC@NLO + Pythia/Herwig in [2003.12435]

[2105.11399]

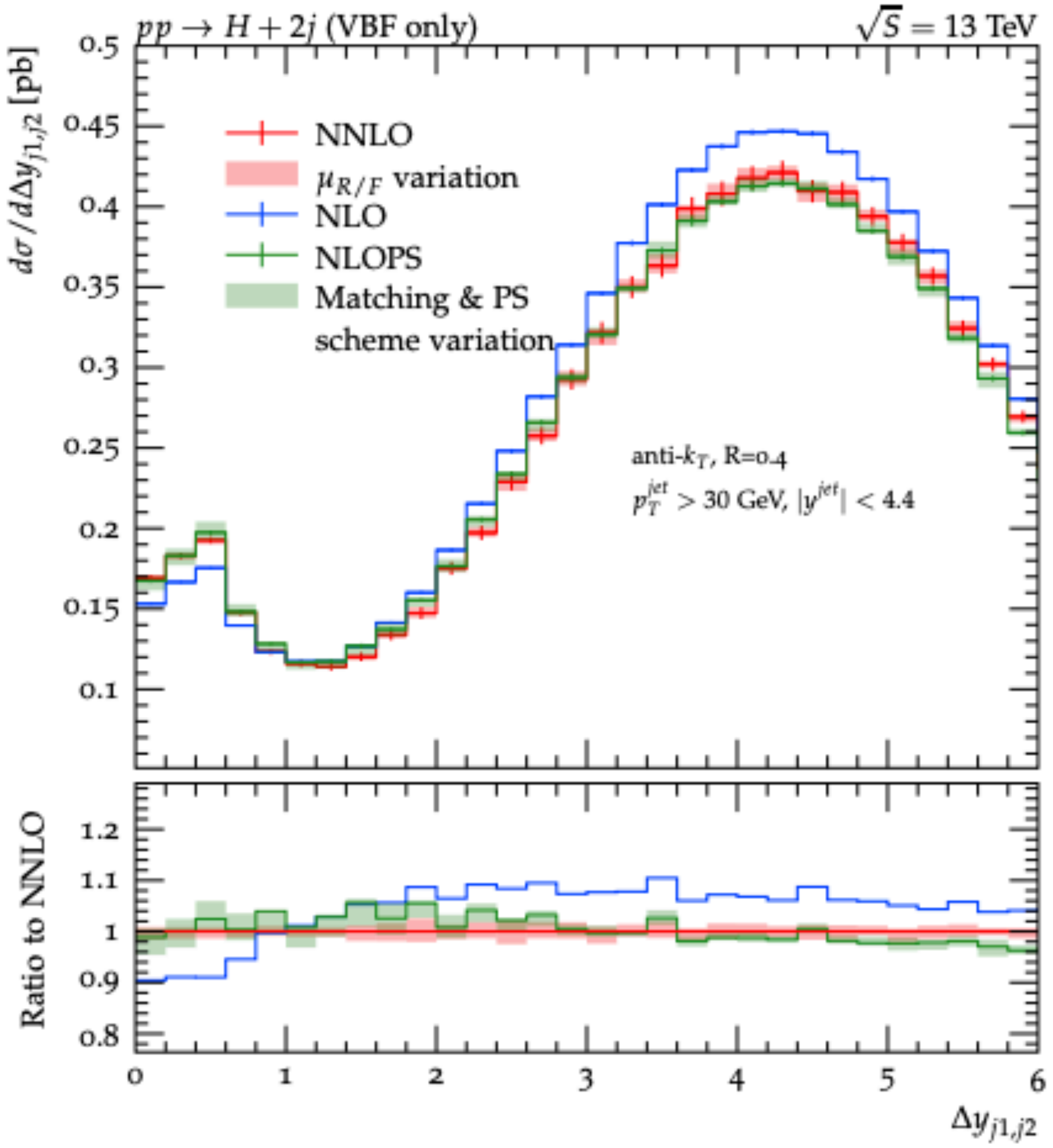
NLOPS vs NNLO



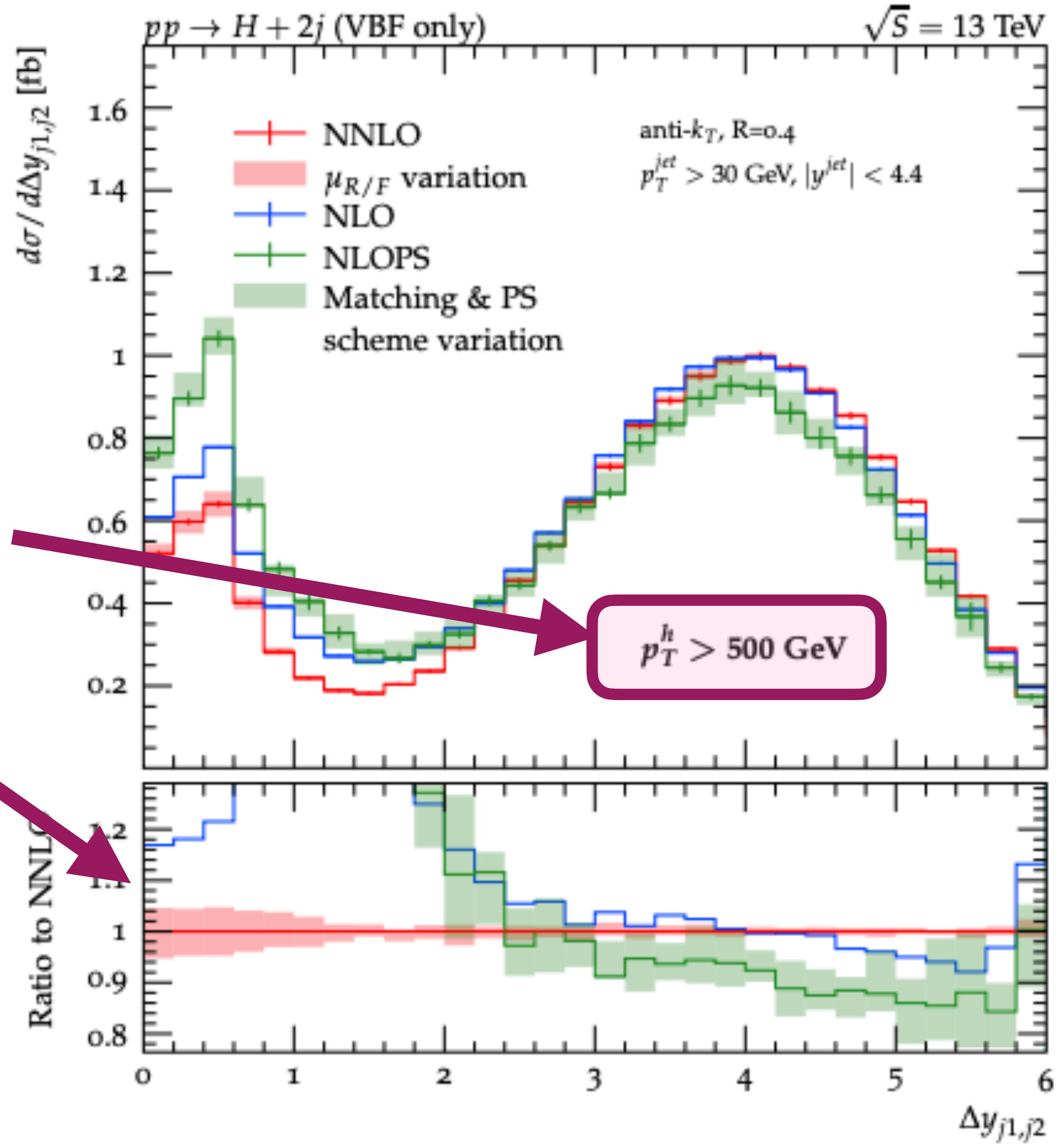
Good agreement between NLOPS (Herwig dipole [0909.5593] +MC@NLO)
and NNLOjet [1802.02445]

[2105.11399]

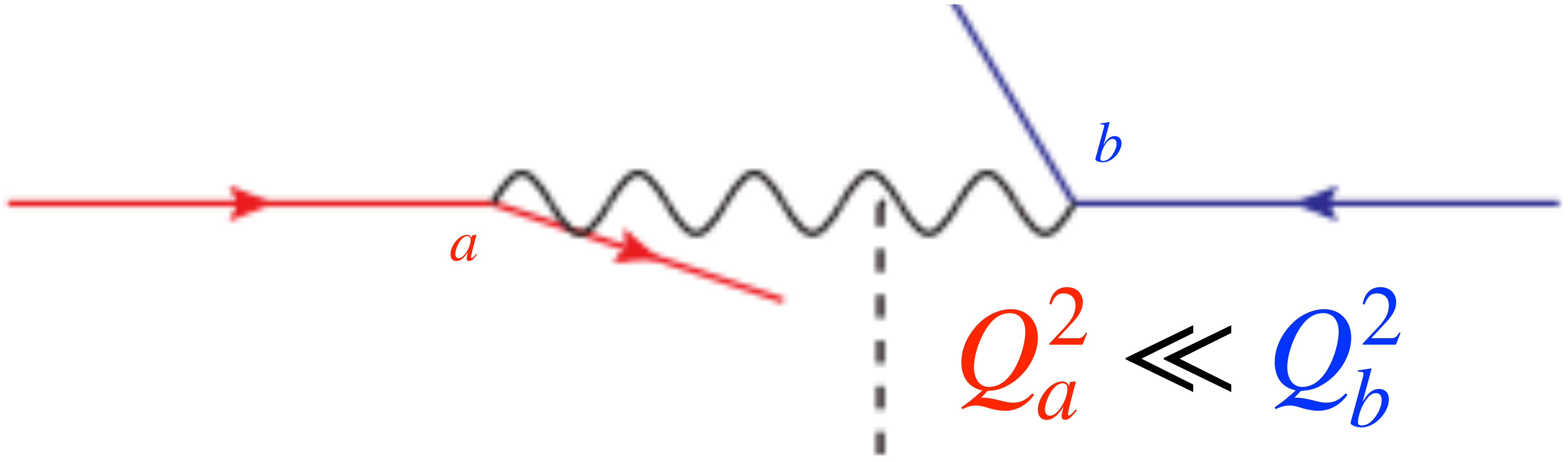
NLOPS vs NNLO



Agreement **completely** lost with higher Higgs p_T cut



Consequence of large **scale** difference between the two LO dipoles



$Q_a^2 \ll Q_b^2$

Progress in improving the PS accuracy

- Matching to fixed-order

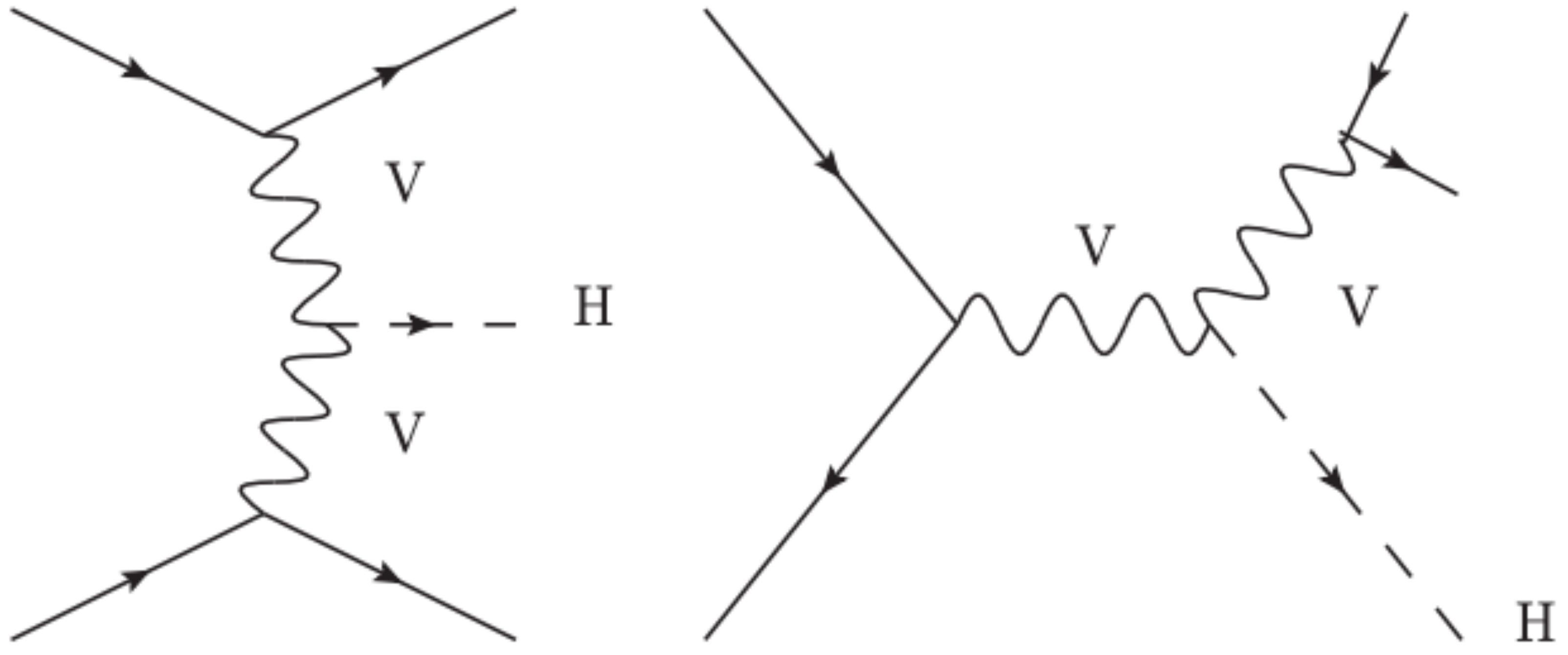
  NLO; i.e. Frixione & Webber [0204244], Nason [0409146], …
  NNLO; i.e. UNNLOPS [1407.3773], MiNNLOps [1908.06987], Geneva [1311.0286], Vincia [2108.07133], …
  NNNLO; Prestel [2106.03206], + Bertone [2202.01082]

- Electroweak corrections

  Vincia [2002.09248, 2108.10786], Pythia [1401.5238], Herwig [2108.10817], …

[2208.00013]

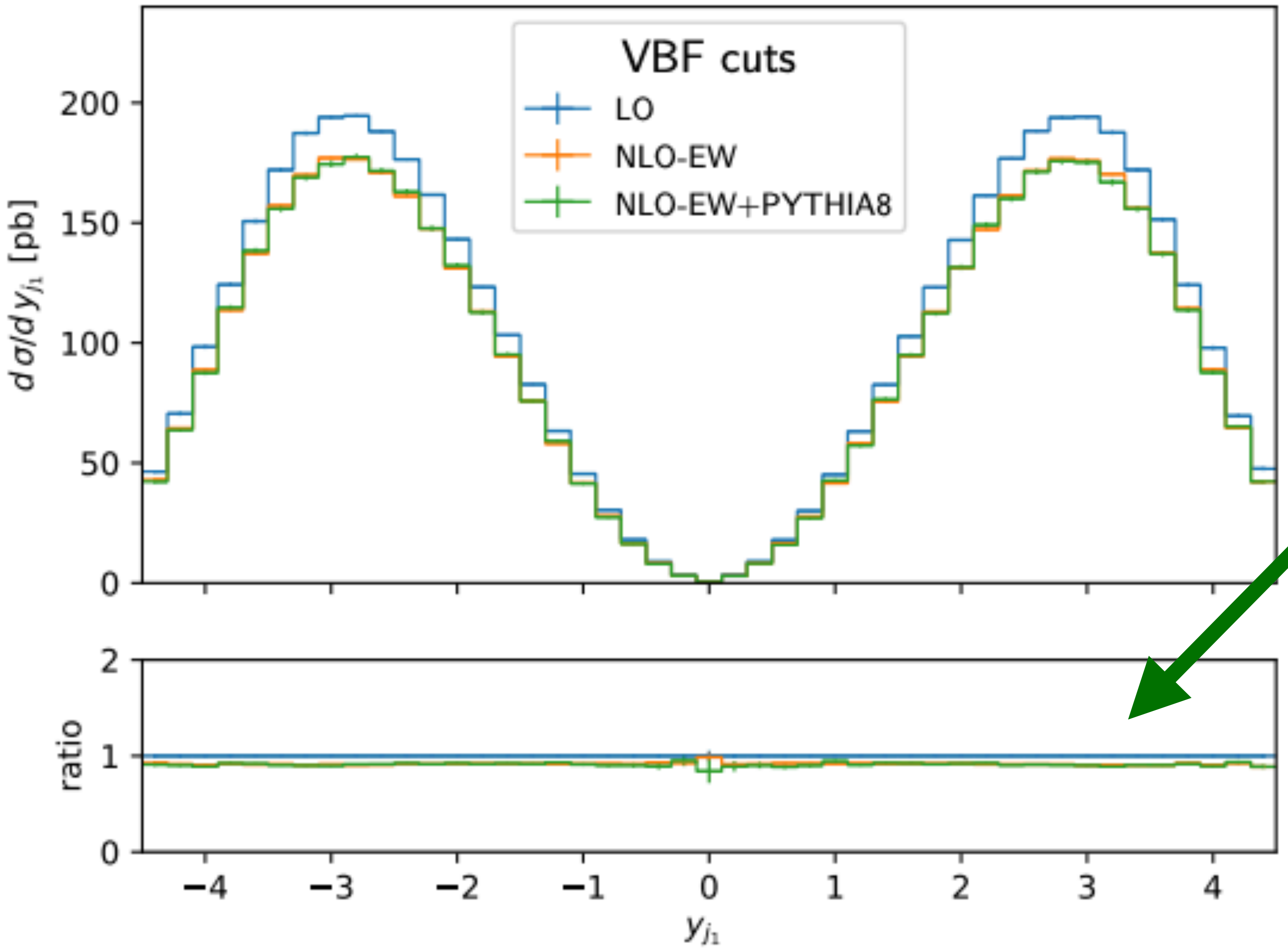
Electroweak effects in $h + 2j$



VBF cuts

$$p_{T,\text{jet}} > 25\text{GeV}, \quad |y_{\text{jet}}| < 4.5$$
$$m_{jj} > 600\text{GeV}, \quad \Delta y_{jj} > 4.5$$
$$y_{j_1} \cdot y_{j_2} < 0$$

Designed to decouple the two topologies, but with EW corrections they are interfered



QED shower has little impact

Progress in improving the PS accuracy

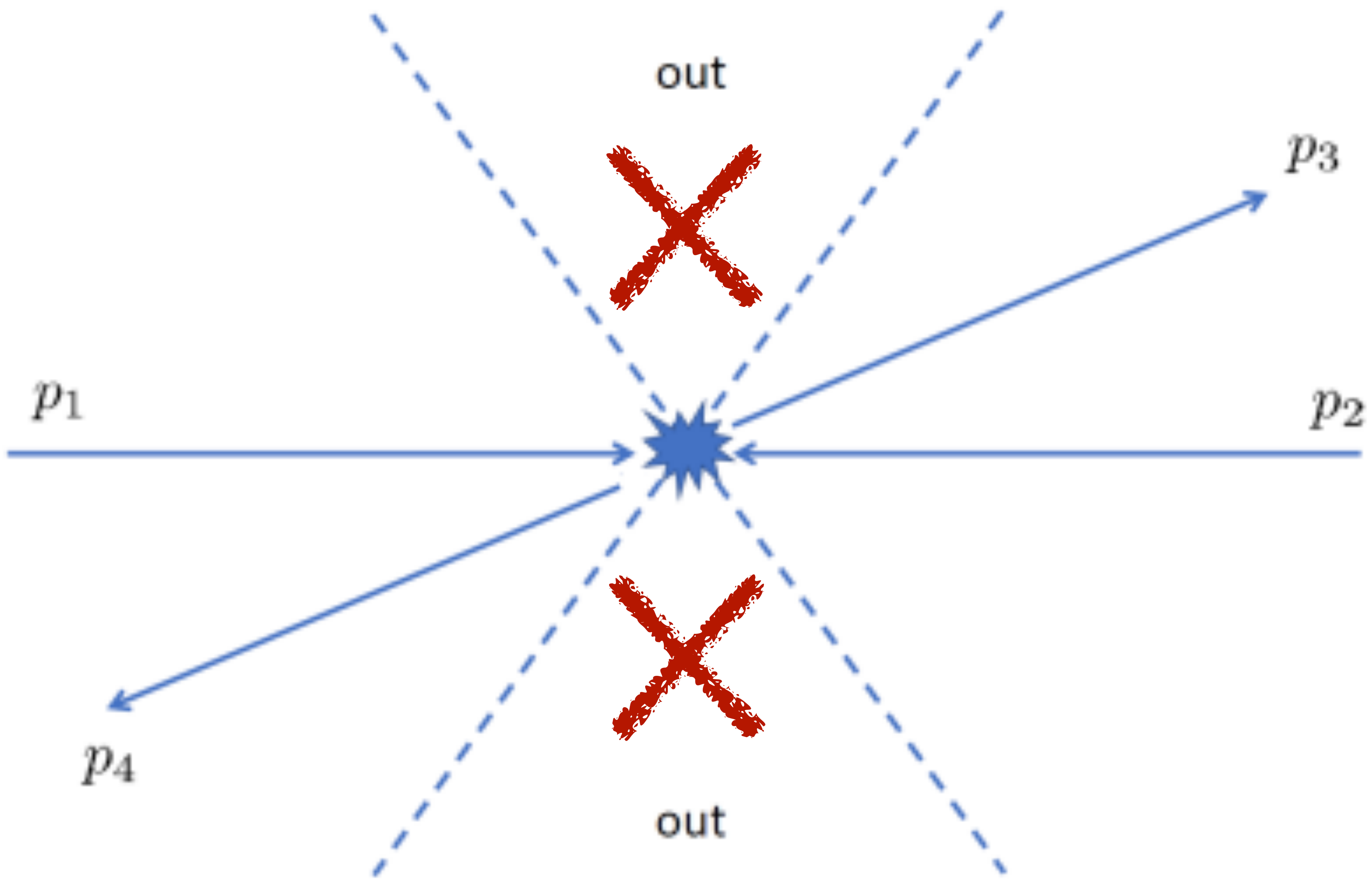
- Matching to fixed-order
  NLO; i.e. Frixione & Webber [0204244], Nason [0409146], …
  NNLO; i.e. UNNLOPS [1407.3773], MiNNLOps [1908.06987], Geneva [1311.0286], Vincia [2108.07133], …
  NNNLO; Prestel [2106.03206], + Bertone [2202.01082]

- Electroweak corrections
  Vincia [2002.09248, 2108.10786], Pythia [1401.5238], Herwig [2108.10817], …

- Spin and colour correlations
  Forshaw, Holguin, Plätzer, Sjödahl [1201.0260, 1808.00332, 1905.08686, 2007.09648, 2011.15087]
  Deductor [0706.0017, 1401.6364, 1501.00778, 1902.02105], Herwig [1807.01955]
  PanScales [2011.10054, 2103.16526, 2111.01161], …

[2011.04154]

Subleading colour corrections - jet veto in $h + 2j$



Non-global observable: sensitive to wide-angle soft gluon emissions in restricted regions of phase space

Soft gluons are sensitive to **colour flow** of underlying process

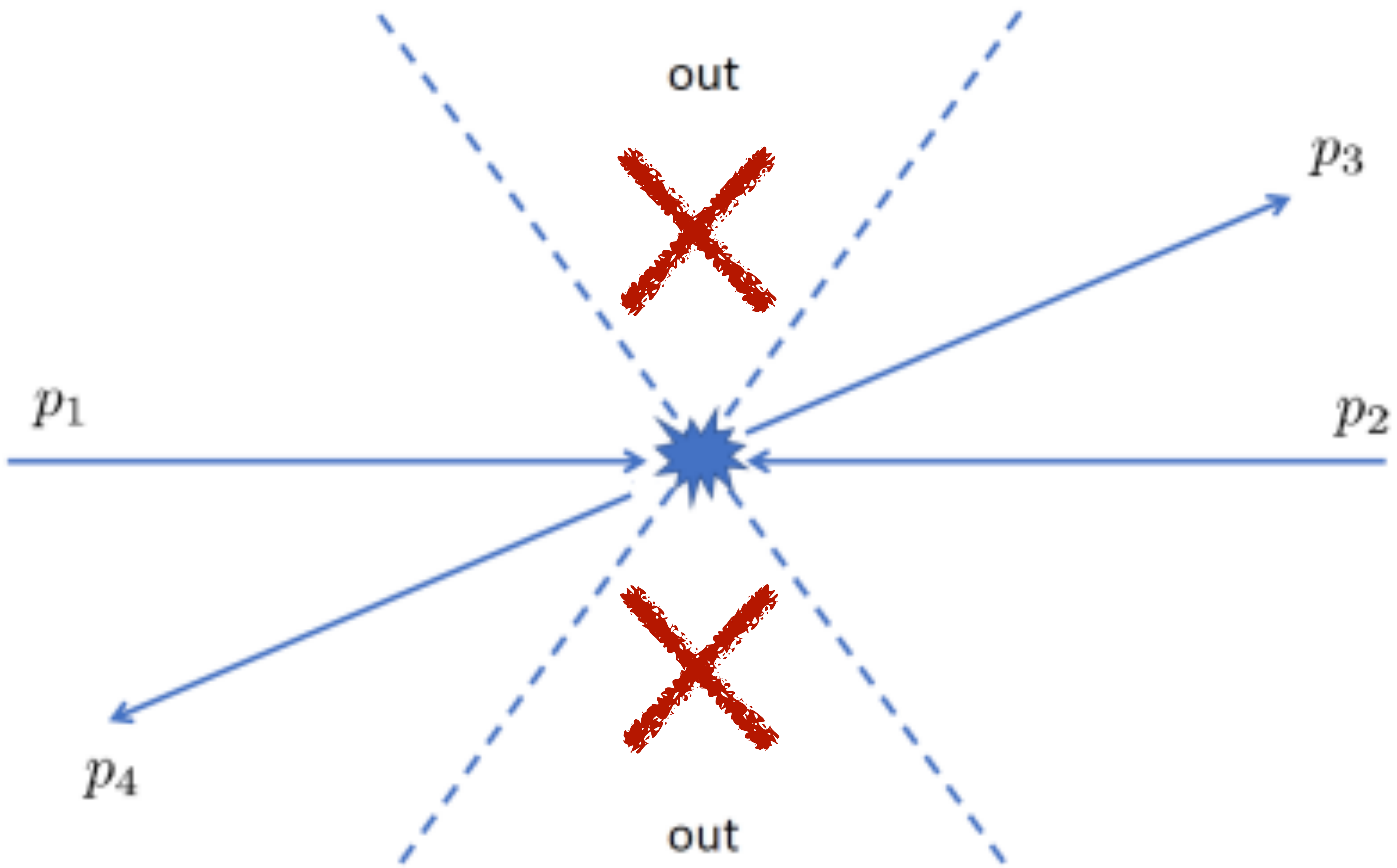
i.e.

$qq \rightarrow qqH$

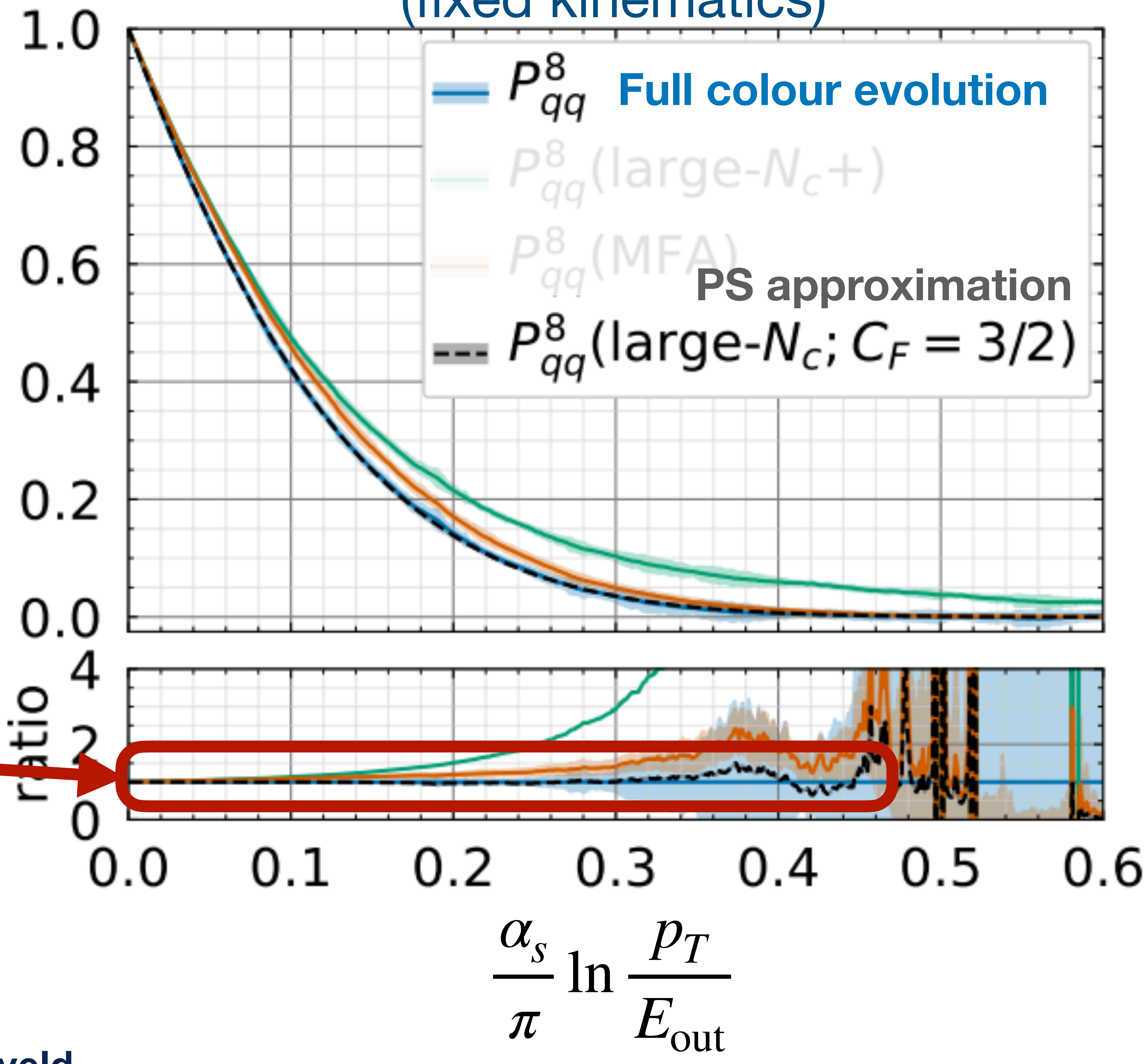
has an **octet** and a **singlet** channel

[2011.04154]

Subleading colour corrections - jet veto in $h + 2j$



Gap survival probability for octet channel
(fixed kinematics)



Puzzling agreement between large-N_c and full colour, observed in **all** channels!

Maybe good news for the large-N_c parton showers, but need to understand what is happening here…

Progress in improving the PS accuracy

- Matching to fixed-order

  NLO; i.e. Frixione & Webber [0204244], Nason [0409146], …
  NNLO; i.e. UNNLOPS [1407.3773], MiNNLOps [1908.06987], Geneva [1311.0286], Vincia [2108.07133], …
  NNNLO; Prestel [2106.03206], + Bertone [2202.01082]

- Electroweak corrections

  Vincia [2002.09248, 2108.10786], Pythia [1401.5238], Herwig [2108.10817], …

- Spin and colour correlations

  Forshaw, Holguin, Plätzer, Sjödahl [1201.0260, 1808.00332, 1905.08686, 2007.09648, 2011.15087]
  Deductor [0706.0017, 1401.6364, 1501.00778, 1902.02105], Herwig [1807.01955]
  PanScales [2011.10054, 2103.16526, 2111.01161], …

- Assessing the logarithmic accuracy of a shower

  Herwig [1904.11866, 2107.04051], Deductor [2011.04777], Forshaw, Holguin, Plätzer [2003.06400]
  Alaric [2208.06057], PanScales [1805.09327, 2002.11114, 2205.02237, 2207.09467], …

This is all about understanding the impact of different choices made in PS algorithms!

Addressing the accuracy of a parton shower

For a given observable, one may address the question of accuracy systematically

At fixed order

$$\sigma = \sum_n c_n \alpha_s^n = c_0 + c_1 \alpha_s + \ldots$$

At all orders using analytic resummation

$$\Sigma^{\mathrm{NLL}}(\lambda \equiv \alpha_s L) = \exp(\frac{1}{\alpha_s} g_1(\lambda) + g_2(\lambda) + \ldots) \qquad \Sigma^{\mathrm{NDL}}(\xi \equiv \alpha_s \ln^2 L) = h_1(\xi) + \sqrt{\alpha_s} h_2(\xi) + \ldots$$

A parton shower produces an *arbitrary set* of final-state particles, which may be recombined into *arbitrary* observables!

How to address this question of accuracy?

[1805.09327]

PanScales NLL correctness requirements

Resummation

Require single-logarithmic accuracy for suitably defined observables

- global event shapes ($\alpha_s^n L^n$)
- parton distribution / fragmentation functions ($\alpha_s^n L^n$)
- non-global observables ($\alpha_s^n L^n$)
- particle multiplicity ($\alpha_s^n L^{2n-1}$)

Matrix element tests

Require correctness of effective matrix elements generated by the shower for well-separated emissions

[1805.09327]

PanScales NLL correctness requirements

Resummation

Require single-logarithmic accuracy for suitably defined observables

- global event shapes ($\alpha_s^n L^n$)
- parton distribution / fragmentation functions ($\alpha_s^n L^n$)
- non-global observables ($\alpha_s^n L^n$)
- particle multiplicity ($\alpha_s^n L^{2n-1}$)

Tested by taking $\dfrac{\Sigma^{\mathrm{PS}}(\alpha_s L)}{\Sigma^{\mathrm{NLL/NDL}}(\alpha_s L)}$ **?**

[1805.09327]

PanScales NLL correctness requirements

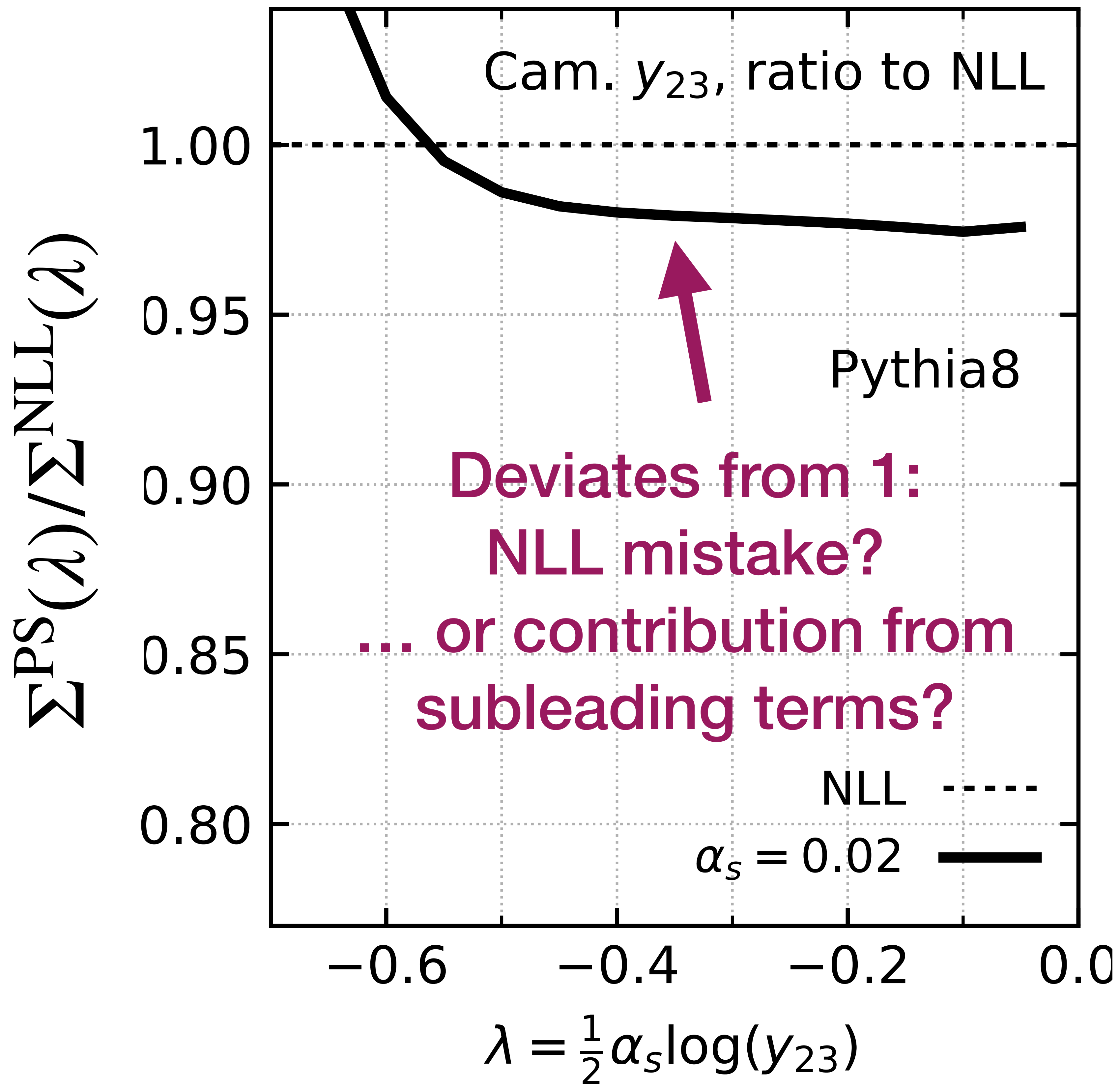
Resummation

Require single-logarithmic accuracy for suitably defined observables

- global event shapes ($\alpha_s^n L^n$)
- parton distribution / fragmentation functions ($\alpha_s^n L^n$)
- non-global observables ($\alpha_s^n L^n$)
- particle multiplicity ($\alpha_s^n L^{2n-1}$)

Tested by taking $\dfrac{\Sigma^{\mathrm{PS}}(\alpha_s L)}{\Sigma^{\mathrm{NLL/NDL}}(\alpha_s L)}$ **?**

Let us try this for an arbitrary observable



Deviates from 1:
NLL mistake?
… or contribution from subleading terms?

[1805.09327]

PanScales NLL correctness requirements

Resummation

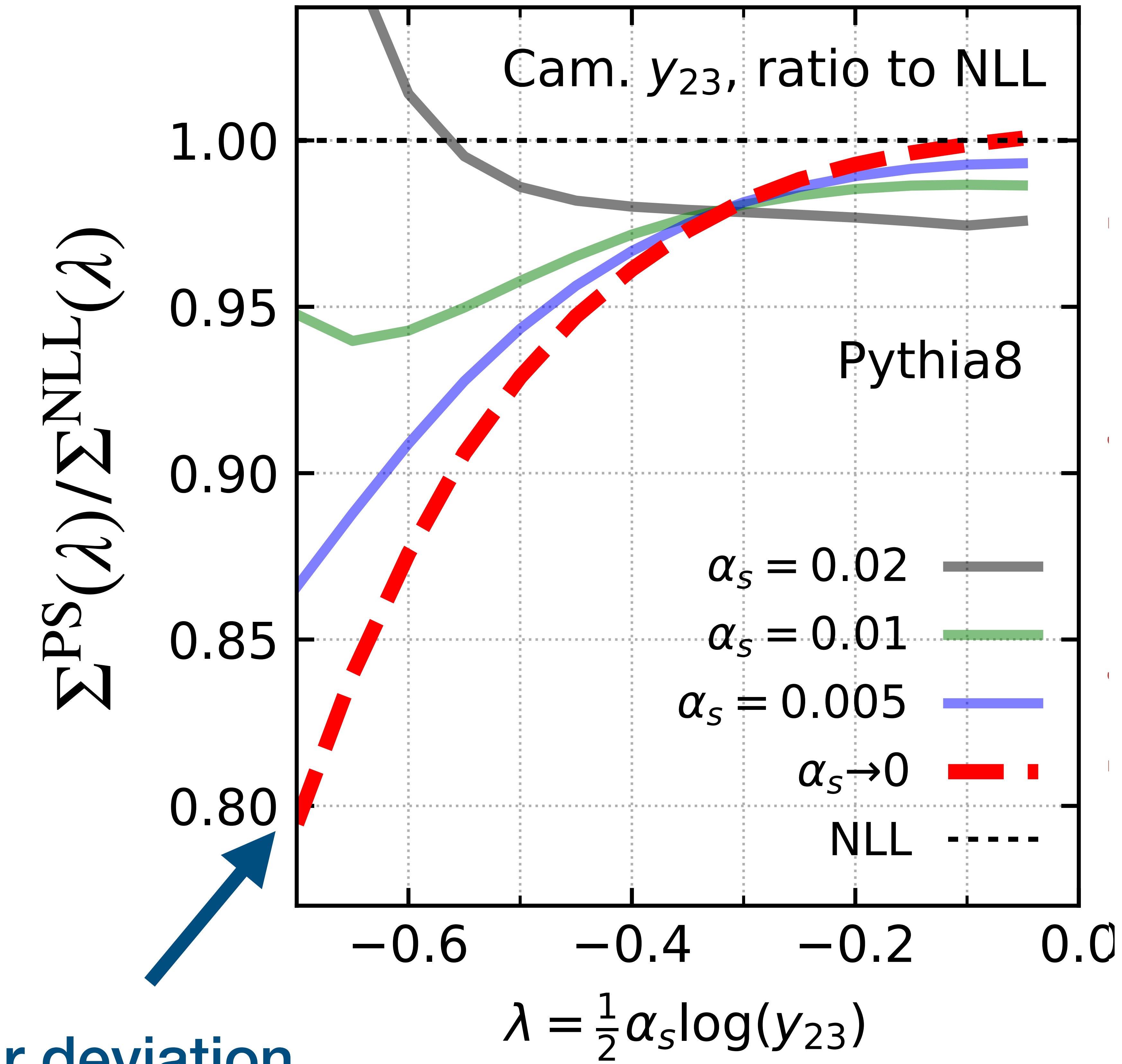
Require single-logarithmic accuracy for suitably defined observables

- global event shapes ($\alpha_s^n L^n$)
- parton distribution / fragmentation functions ($\alpha_s^n L^n$)
- non-global observables ($\alpha_s^n L^n$)
- particle multiplicity ($\alpha_s^n L^{2n-1}$)

~~**Tested by taking** $\frac{\Sigma^{\mathrm{PS}}(\alpha_s L)}{\Sigma^{\mathrm{NLL/NDL}}(\alpha_s L)}$ **?**~~

Tested by taking $\lim_{\alpha_s \to 0} \frac{\Sigma^{\mathrm{PS}}(\alpha_s L)}{\Sigma^{\mathrm{NLL/NDL}}(\alpha_s L)}$

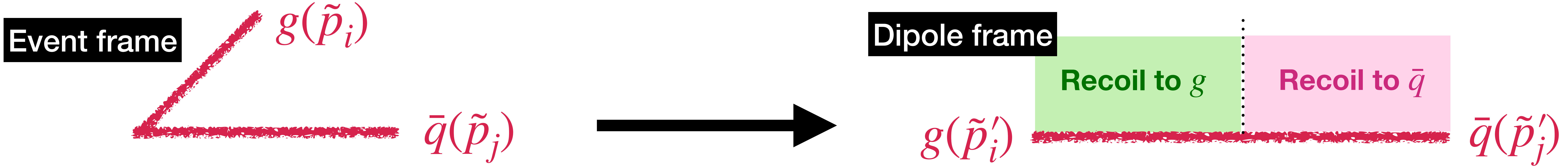
(While keeping the size of $\lambda = \alpha_s L$ fixed)



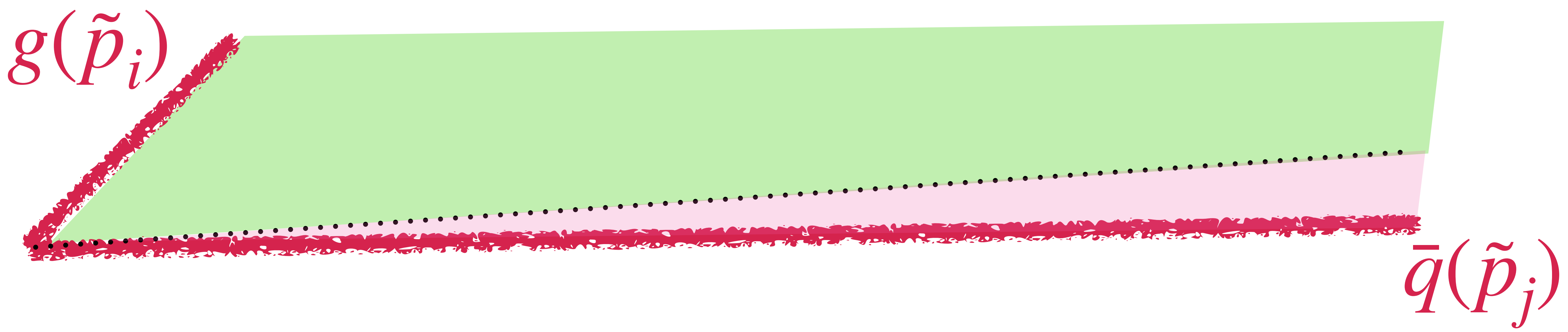
Clear deviation from 1 in the $\alpha_s \to 0$ limit!

Important issue in dipole showers: attribution of recoil

Standard dipole showers distinguish the emitter from the spectator at $\eta = 0$ in the CM dipole frame



Boosting back to the event frame…



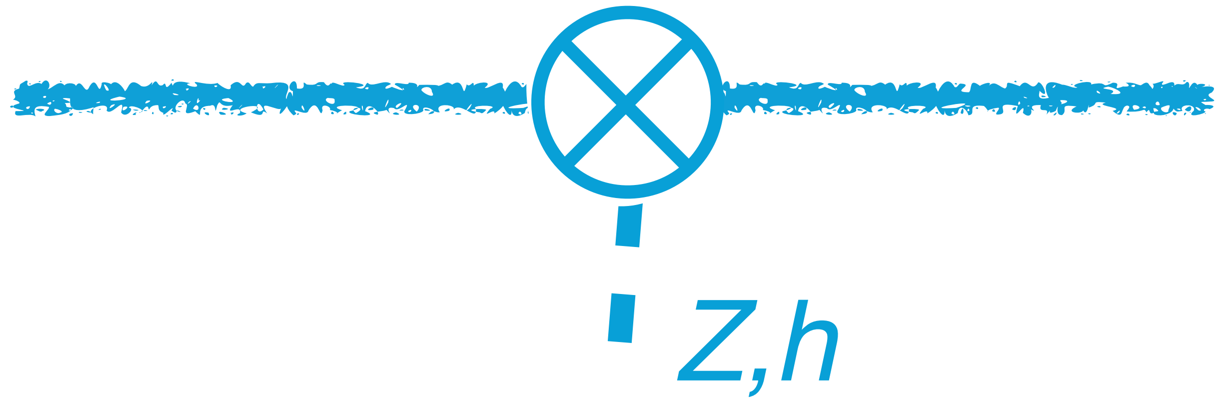
Leads to an incorrect (and quite unphysical) recoil picture!

Physical attribution of recoil

[2205.02237], [2207.09467]

What is the impact of this?

Examine this question for **colour-singlet production** at the LHC



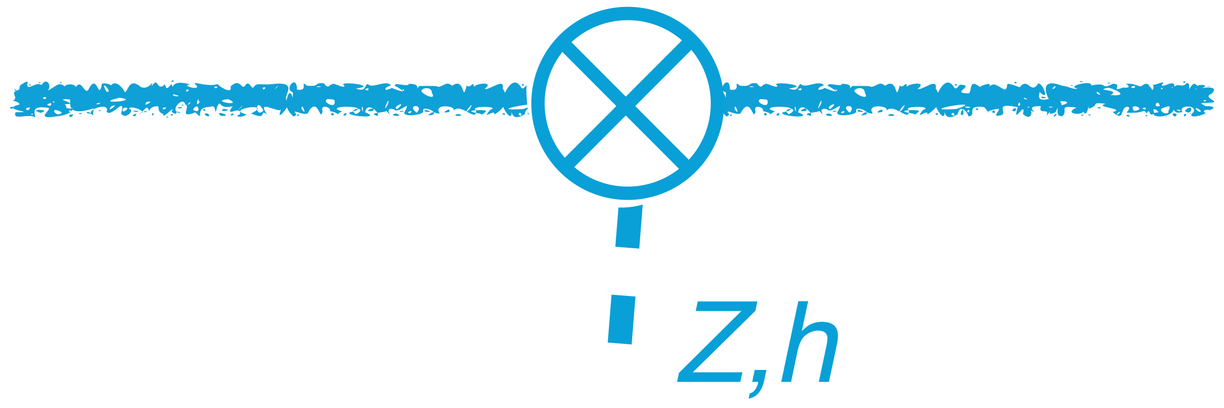
	Kinematic map	Evolution variable v	Attribution of recoil
Dipole-kt local	local	k_t	Dipole CM
Dipole-kt global	global ⊥, local +/-	k_t	Dipole CM
PanLocal Antenna	local	$k_t \times \exp[\lvert\eta\rvert/2]$	Event CM
PanLocal Dipole	local	$k_t \times \exp[\lvert\eta\rvert/2]$	Event CM
PanGlobal $\beta = 0$	global ⊥, local +/-	k_t	Event CM
PanGlobal $\beta = 1/2$	global ⊥, local +/-	$k_t \times \exp[\lvert\eta\rvert/2]$	Event CM

For the impact in e^+e^- collisions, see [2002.11114]

[2205.02237], [2207.09467]

What is the impact of this?

Examine this question for **colour-singlet production** at the LHC



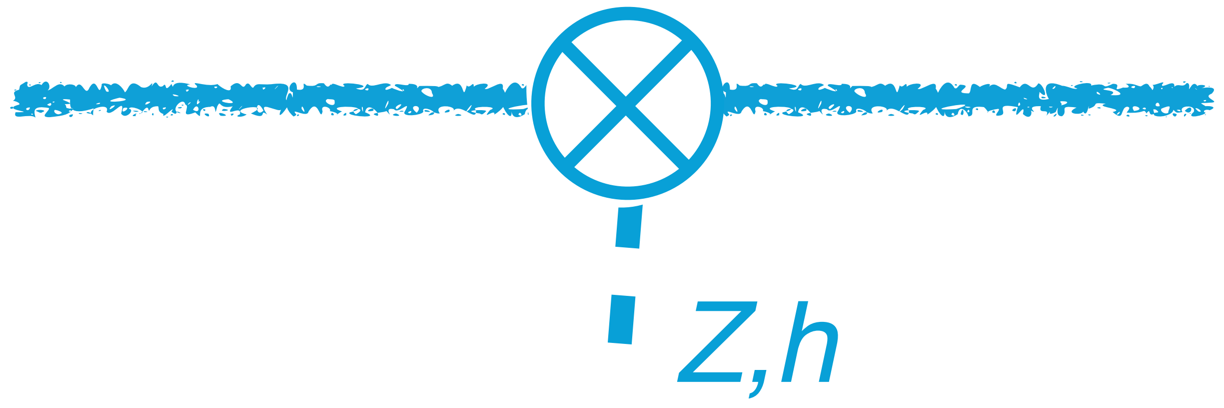
Much like Dire, Vincia, Sherpa and Pythia dipole

	Kinematic map	**Evolution variable v**	**Attribution of recoil**
Dipole-kt local	local	k_t	Dipole CM
Dipole-kt global	global ⊥, local +/-	k_t	Dipole CM
PanLocal Antenna	local	$k_t \times \exp[\lvert\eta\rvert/2]$	Event CM
PanLocal Dipole	local	$k_t \times \exp[\lvert\eta\rvert/2]$	Event CM
PanGlobal $\beta = 0$	global ⊥, local +/-	k_t	Event CM
PanGlobal $\beta = 1/2$	global ⊥, local +/-	$k_t \times \exp[\lvert\eta\rvert/2]$	Event CM

[2205.02237], [2207.09467]

What is the impact of this?

Examine this question for **colour-singlet production** at the LHC



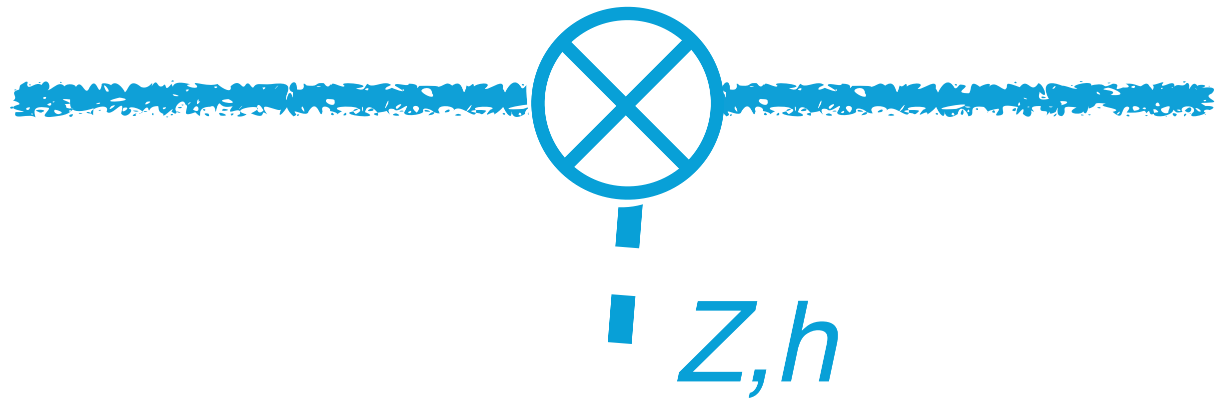
	Kinematic map	Evolution variable v	Attribution of recoil
Dipole-kt local	local	k_t	Dipole CM
Dipole-kt global	global ⊥, local +/-	k_t	Dipole CM
PanLocal Antenna	local	$k_t \times \exp[\|\eta\|/2]$	Event CM
PanLocal Dipole	local	$k_t \times \exp[\|\eta\|/2]$	Event CM
PanGlobal $\beta = 0$	global ⊥, local +/-	k_t	Event CM
PanGlobal $\beta = 1/2$	global ⊥, local +/-	$k_t \times \exp[\|\eta\|/2]$	Event CM

New showers

[2205.02237], [2207.09467]

What is the impact of this?

Examine this question for **colour-singlet production** at the LHC



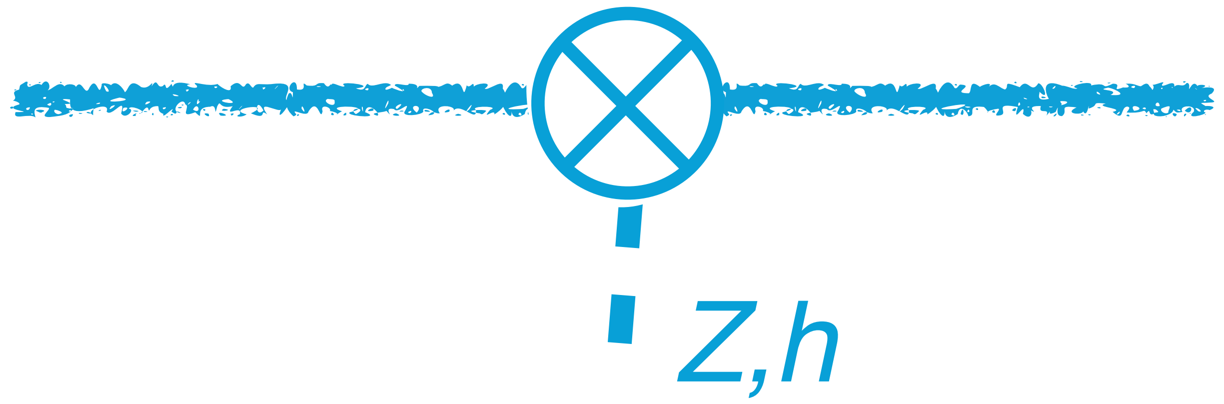
	Kinematic map	**Evolution variable v**	**Attribution of recoil**
Dipole-kt local	local	k_t	Dipole CM
Dipole-kt global	global ⊥, local +/-	k_t	Dipole CM
PanLocal Antenna	local	$k_t \times \exp[\|\eta\|/2]$	Event CM
PanLocal Dipole	local	$k_t \times \exp[\|\eta\|/2]$	Event CM
PanGlobal $\beta = 0$	global ⊥, local +/-	k_t	Event CM
PanGlobal $\beta = 1/2$	global ⊥, local +/-	$k_t \times \exp[\|\eta\|/2]$	Event CM

Test different choices
for the kinematic map

[2205.02237], [2207.09467]

What is the impact of this?

Examine this question for **colour-singlet production** at the LHC



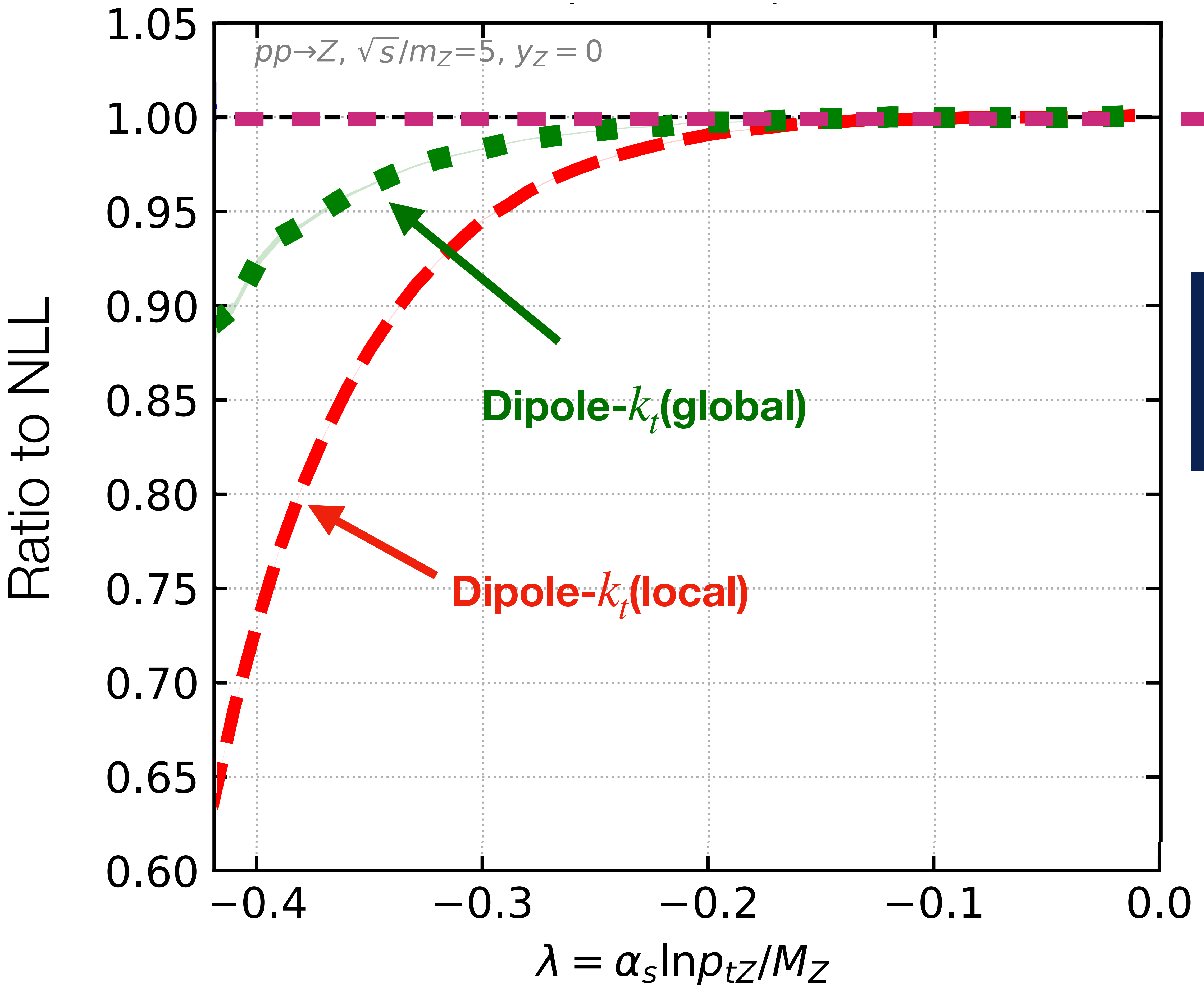
	Kinematic map	**Evolution variable v**	**Attribution of recoil**
Dipole-kt local	local	k_t	Dipole CM
Dipole-kt global	global ⊥, local +/-	k_t	Dipole CM
PanLocal Antenna	local	$k_t \times \exp[\|\eta\|/2]$	Event CM
PanLocal Dipole	local	$k_t \times \exp[\|\eta\|/2]$	Event CM
PanGlobal $\beta = 0$	global ⊥, local +/-	k_t	Event CM
PanGlobal $\beta = 1/2$	global ⊥, local +/-	$k_t \times \exp[\|\eta\|/2]$	Event CM

Notice difference
in attribution of recoil

[2207.09467]

Transverse momentum of the Z boson

Cumulative distribution
(ratio to analytic prediction)

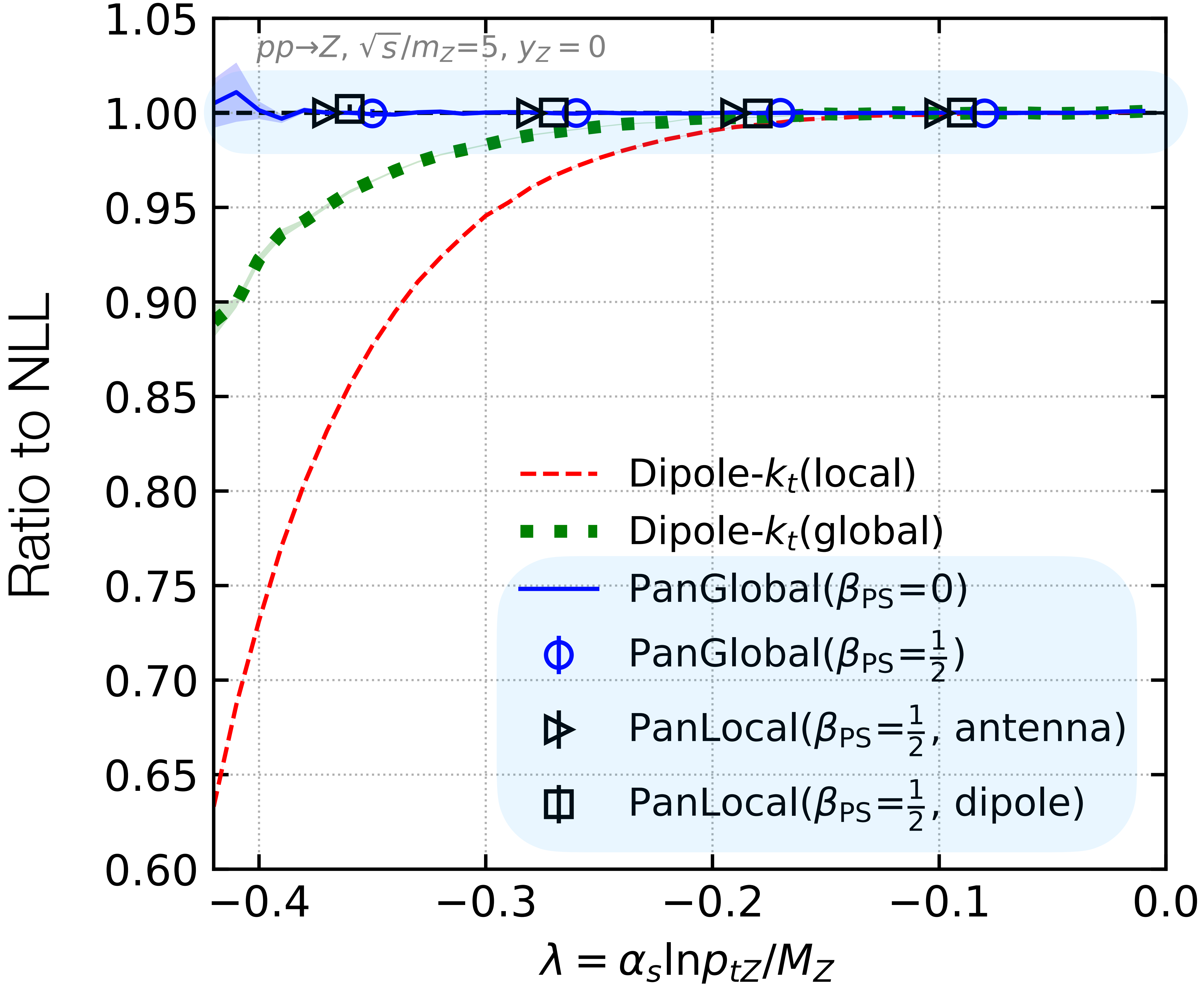


NLL expectation

Both fail the NLL criterion
for the transverse
momentum of the Z boson!

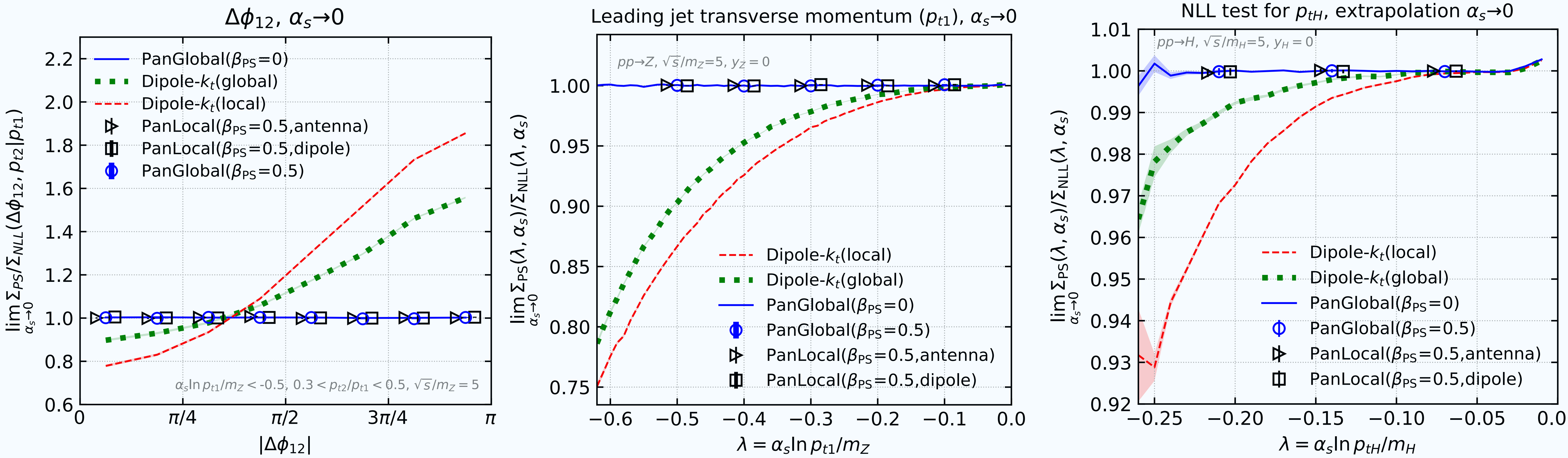
Transverse momentum of the Z boson

Cumulative distribution
(ratio to analytic prediction)

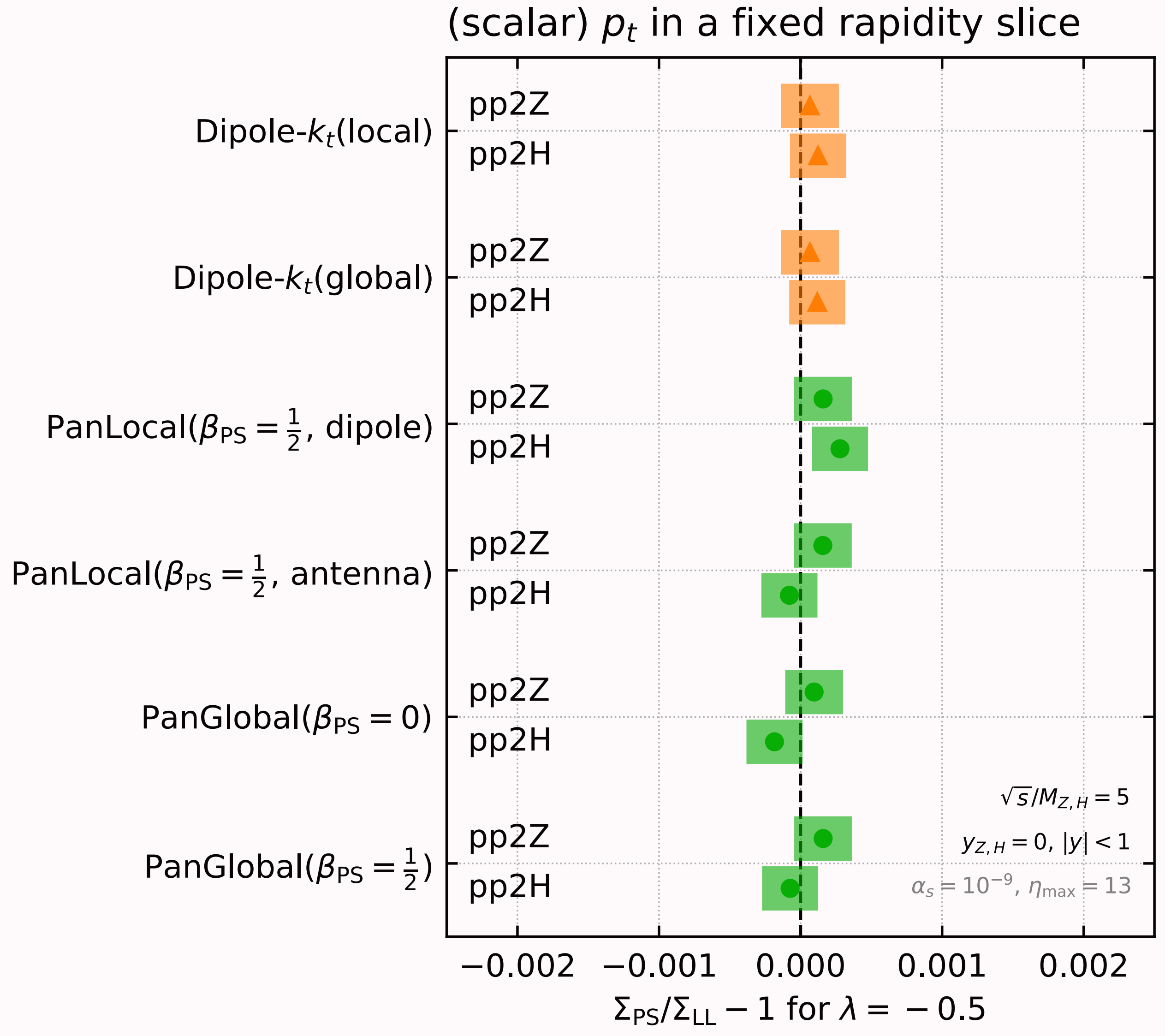


In line with NLL prediction

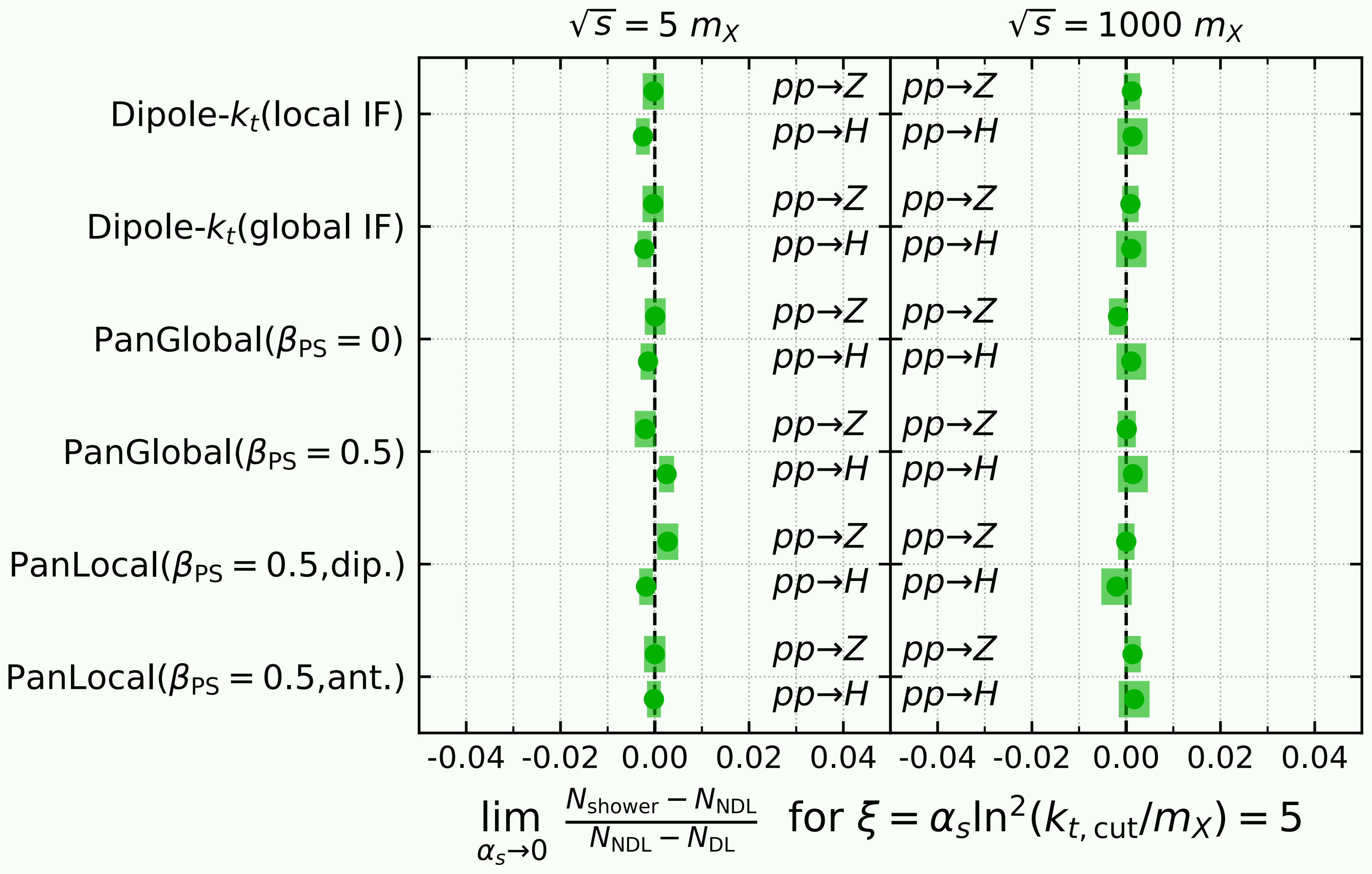
Global observables



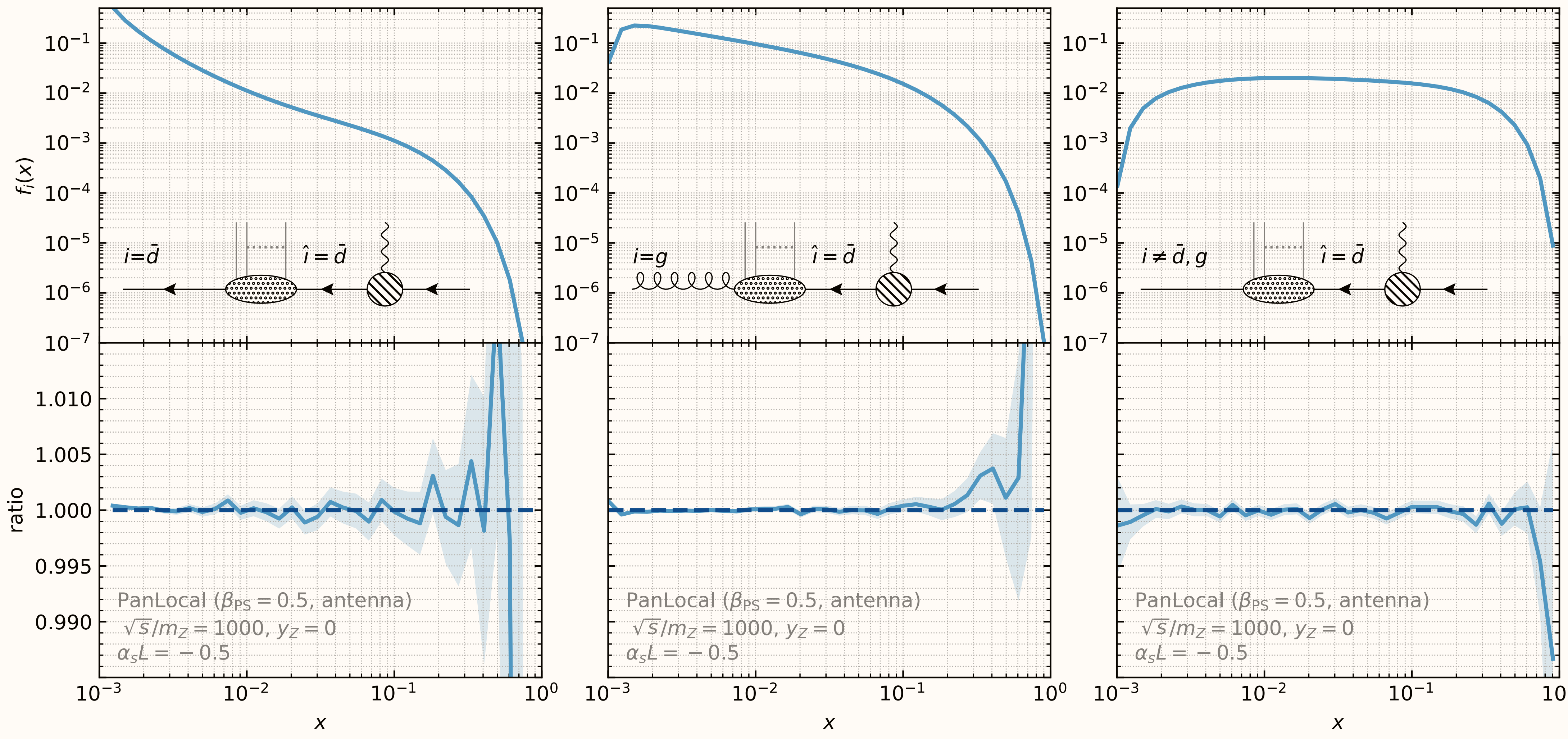
Non-global observables



Multiplicity



DGLAP evolution



Note spin correlations and subleading-colour corrections are **included**

Conclusions

- Different shower algorithms show **substantial** differences in their predictions

- Difference between showers often a **dominant** uncertainty in analysis

- Pythia's default shower does not describe VBF physics, and **should not be used**

Recommended settings for showers, matching and merging in VBF with Pythia:
https://gitlab.com/Pythia8/releases/-/issues/141

- Control over logarithmic accuracy in colour-singlet production (ggF)

Standard dipole showers (like Dire, Vincia, Sherpa and Pythia's dipole shower) are **not NLL** accurate!

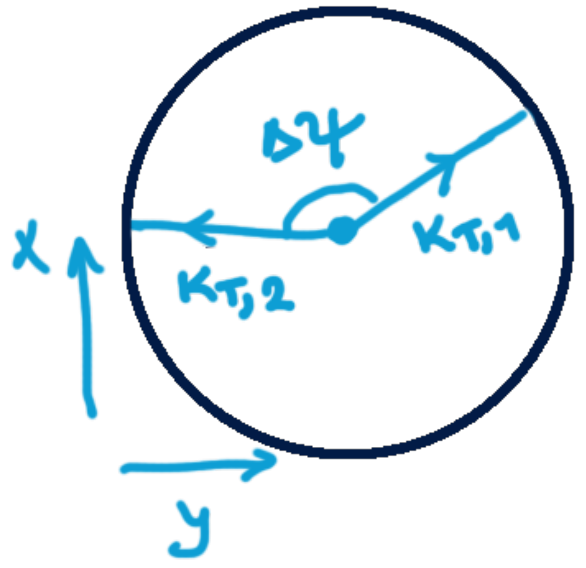
- Stay tuned for a log-study of VBF

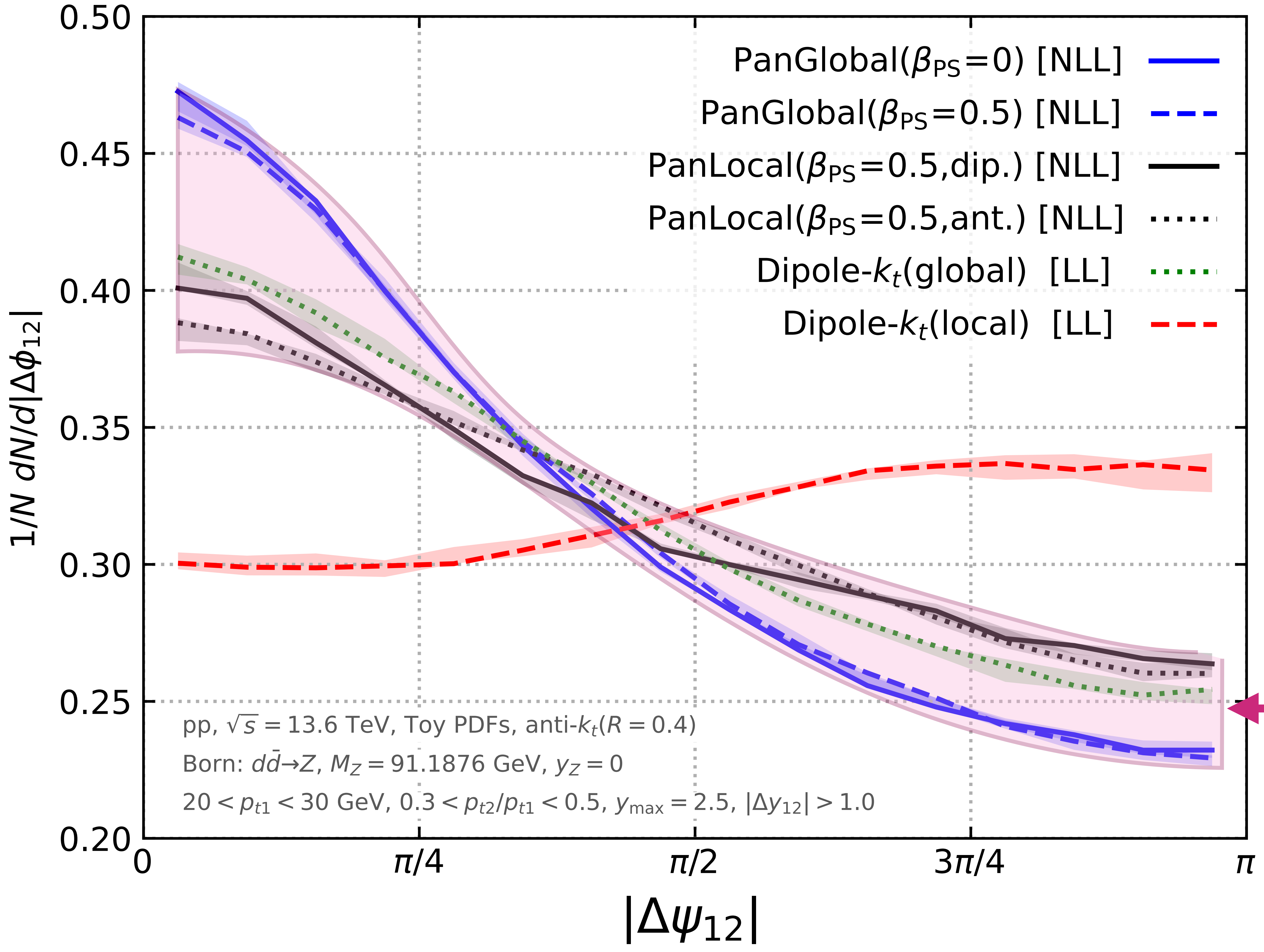
Back up

Mapping between λ and physical quantities

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

Towards phenomenology - $\Delta\Psi_{12}$

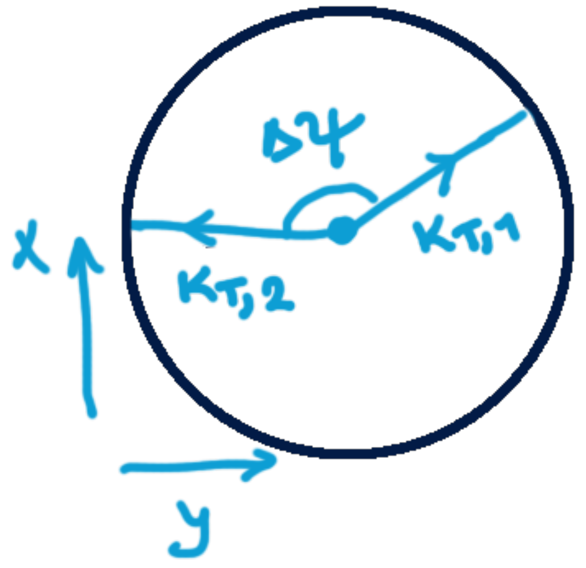


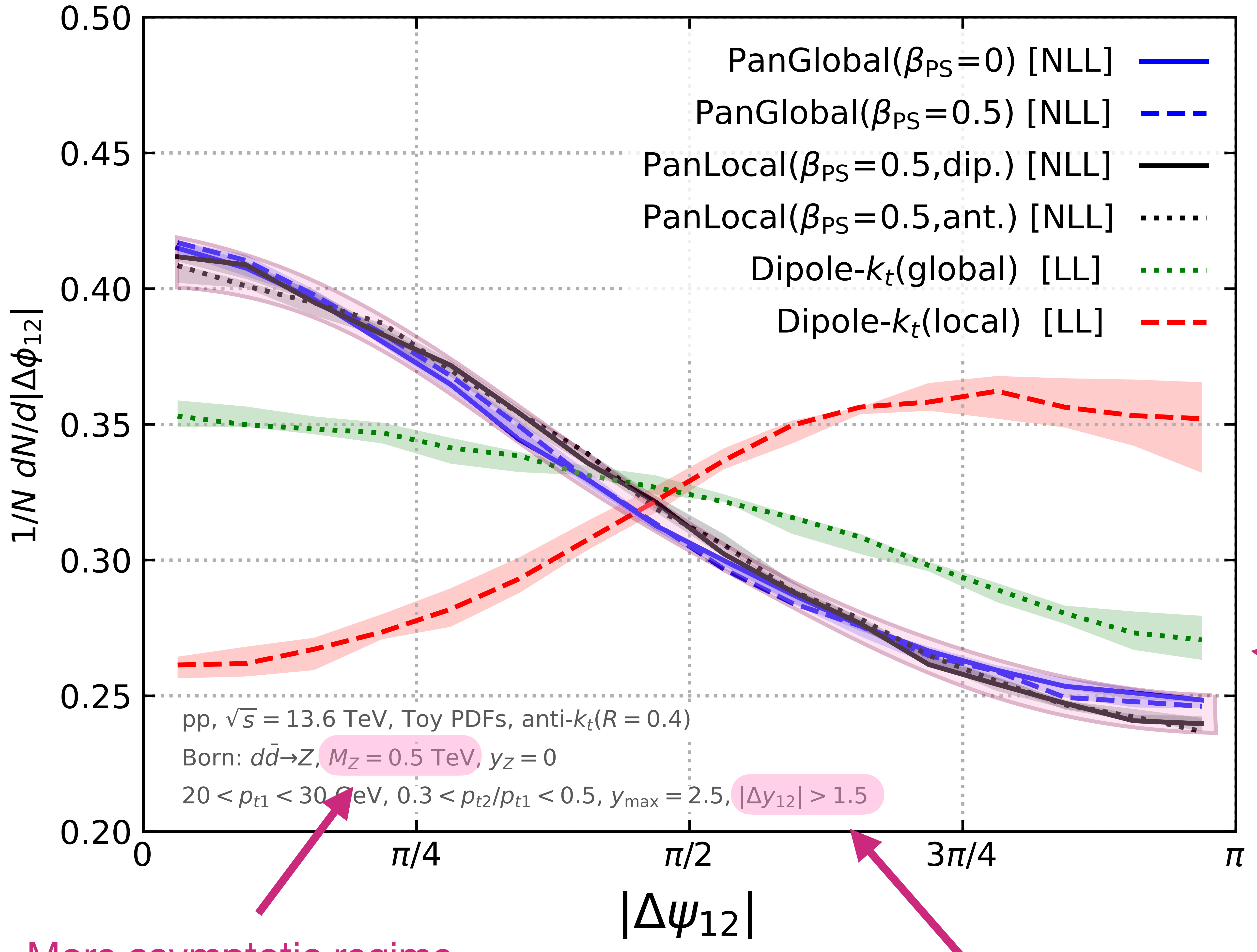


Spread of NLL showers
(Dipole-kt global is contained)

$$\alpha_s(x_r\mu_{r,0})\left(1+\frac{K\alpha_s(x_r\mu_{r,0})}{2\pi}+2\alpha_s(x_r\mu_{r,0})b_0(1-z)\ln x_r\right)$$

Towards phenomenology - $\Delta\Psi_{12}$





More asymptotic regime

Less double-soft contamination

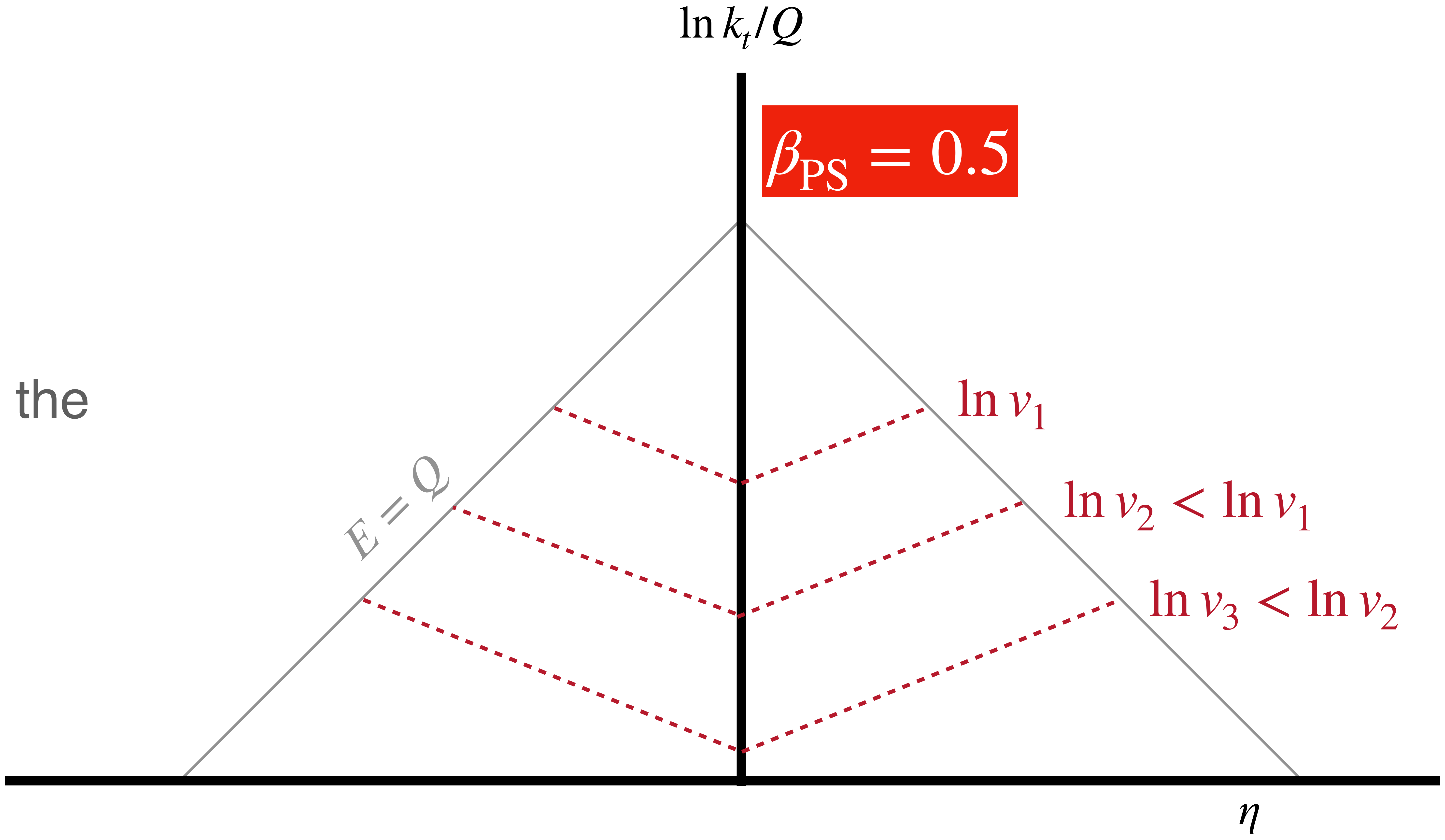
Dipole-kt global now falls outside the spread

Evolution variable

A parton shower orders emissions

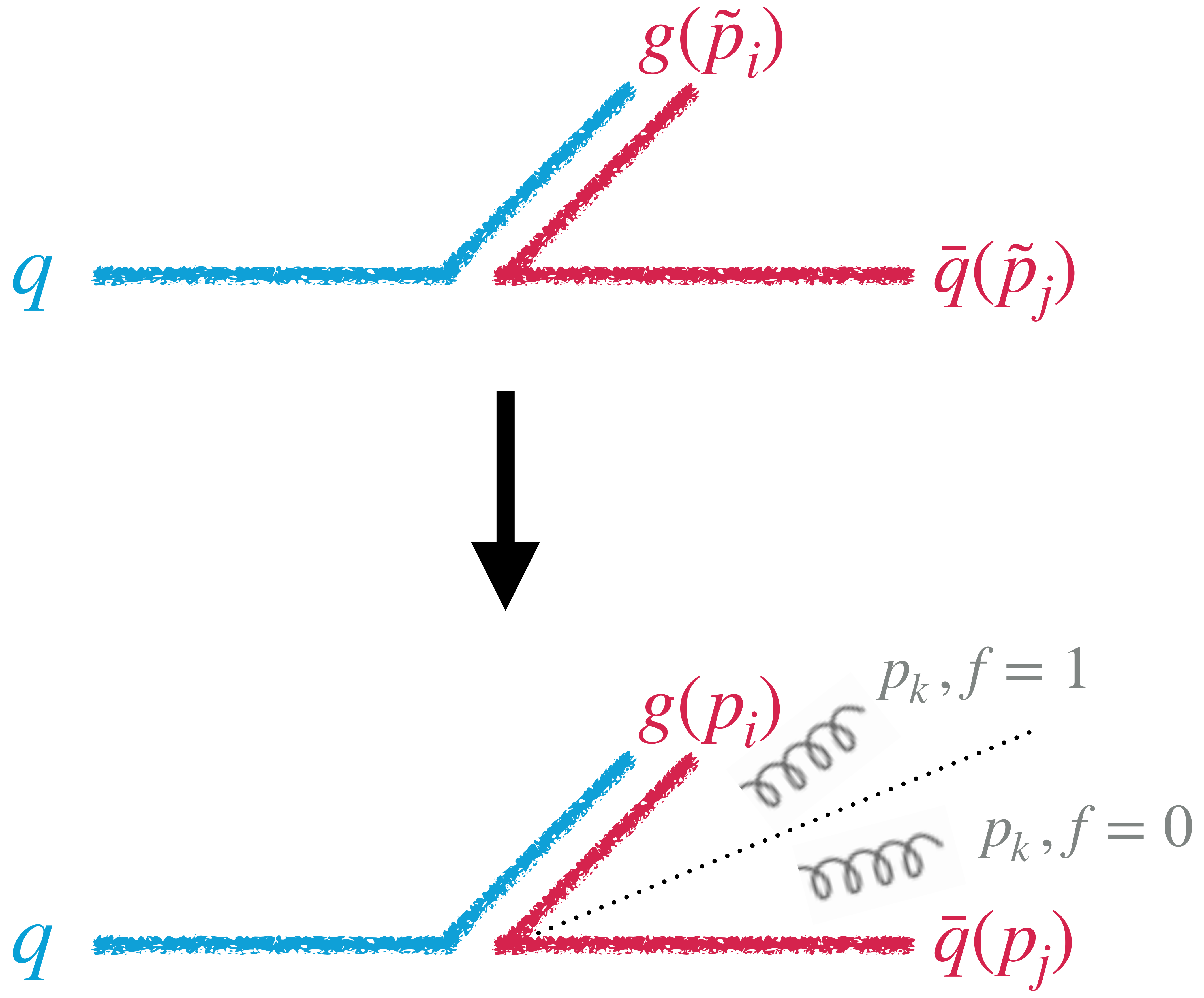
The evolution variable v tells us which emissions come first, and which later in the showering process

We use the definition $v \simeq k_t e^{-\beta_{\mathrm{PS}}|\eta|}$



Introduce some angular dependence with $\beta_{\mathrm{PS}} > 0$

Kinematic map



Local kinematic map

$$p_i = a_i\tilde{p}_i + b_i\tilde{p}_j + fk_\perp$$

$$p_j = a_j\tilde{p}_i + b_j\tilde{p}_j + (1-f)k_\perp$$

$$p_k = a_k\tilde{p}_i + b_k\tilde{p}_j + k_\perp$$

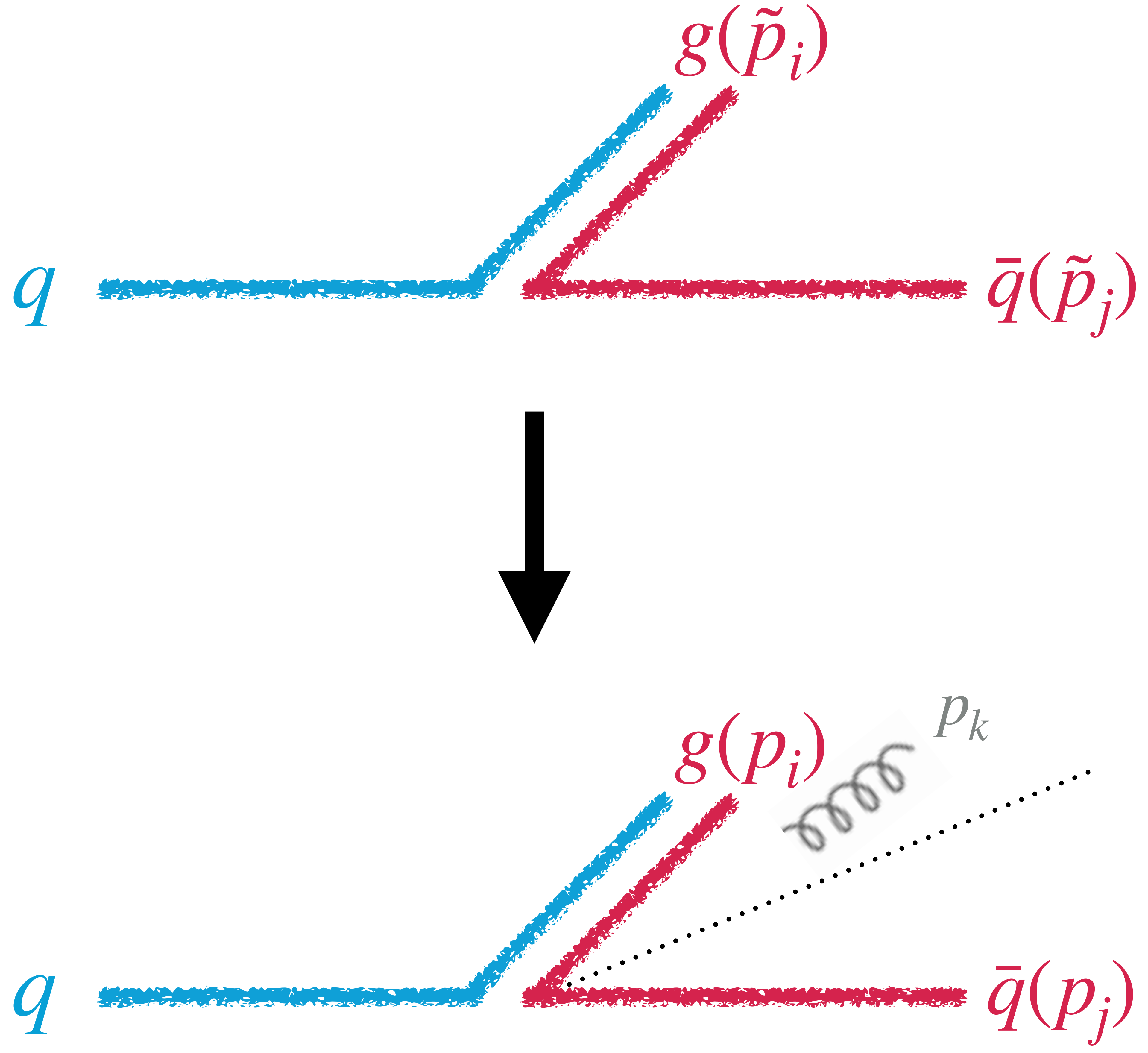
Mapping coefficients depend on

- Evolution variable $\ln v$
- Rapidity η

Dipole: step function for f

Antenna: smooth transition for f

Kinematic map



Global kinematic map

$$p_i = a_i \tilde{p}_i$$

$$p_j = b_j \tilde{p}_j$$

$$p_k = a_k \tilde{p}_i + b_k \tilde{p}_j + k_\perp$$

Boost (part of) event after each emission to restore momentum conservation

Choice: global in some/all $+/-$ and $\perp$ components

A standard dipole shower: **dipole-k_t**

1. Evolution variable: transverse momentum (k_t)

2. Kinematic map:

   a) Local Dates back to Gustafson, Petterson [Nucl. Phys. B 306 (1988)], Catani, Seymour [hep-ph/9605323], many variations available

   For every emission the momentum is locally conserved
   This means that the e.g. the Z-boson p_t almost never gets rescaled
   → not in line with the NLL prediction Plätzer, Gieseke [0909.5593], Nagy, Soper [0912.4534]

   b) Global Plätzer, Gieseke [0909.5593], Höche, Prestel [1506.05057] [Pythia8 (global ISR), Deductor and Alaric have different solutions]

   The Z-boson absorbs the k_t imbalance induced by the global map through a boost
   Claimed to fix the Z-p_t distribution

3. Attribution of recoil: dipole CM frame

Introducing NLL-accurate showers for pp

PanGlobal

1. Evolution variable

   $v \simeq k_t e^{-\beta_{\rm PS}|\eta|}$ with $0 \leq \beta_{\rm PS} < 1$

   ($\beta_{\rm PS} = 0$ is standard k_t-ordering)

2. Kinematic map

   Global $\perp$

   Local $+/-$

   Transverse-momentum imbalance is absorbed by the hard system (Z/h)

3. Attribution of recoil

   hard-system CM frame

PanLocal

1. Evolution variable

   $v \simeq k_t e^{-\beta_{\rm PS}|\eta|}$ with $0 < \beta_{\rm PS} < 1$

2. Kinematic map

   Local $\perp$

   Local $+/-$

   Initial-state particles that gain a k_t component are realigned with the beam axis with a boost

3. Attribution of recoil

   hard-system CM frame

PanGlobal details

- Kinematic map $$\begin{aligned} p_k &= a_k \tilde{p}_i + b_k \tilde{p}_j + k_\perp, \\ p_i &= a_i \tilde{p}_i \\ p_j &= b_j \tilde{p}_j, \end{aligned}$$ (emitted particle)
- Constraining the coefficients:
  - **1** $p_k^2 = p_i^2 = p_j^2 = 0$
  - **2** Relate a_k and b_k to the shower variables
- The transverse-momentum imbalance is absorbed into the FS partons in a two-step process:
  - **1** Rescale IS partons such that $r^2 Q_{\text{in}}^2 = Q_{\text{out}}^2$, $r^2 = r_a r_b$
  - **2** Boost (part of the) FS such that $\Lambda(Q_{\text{out}}) = r Q_{\text{in}}$

PanGlobal boost

Never boost partons created by the shower, only give recoil to the 'hard system' H

- Just boost the Z/h

$$\Lambda(\tilde{p}_H) = r_a \tilde{p}_a + r_b \tilde{p}_b - p_k - \sum_{f \notin H} \tilde{p}_f$$

- We furthermore require

$\boxed{1}$ The mass of the hard system is preserved

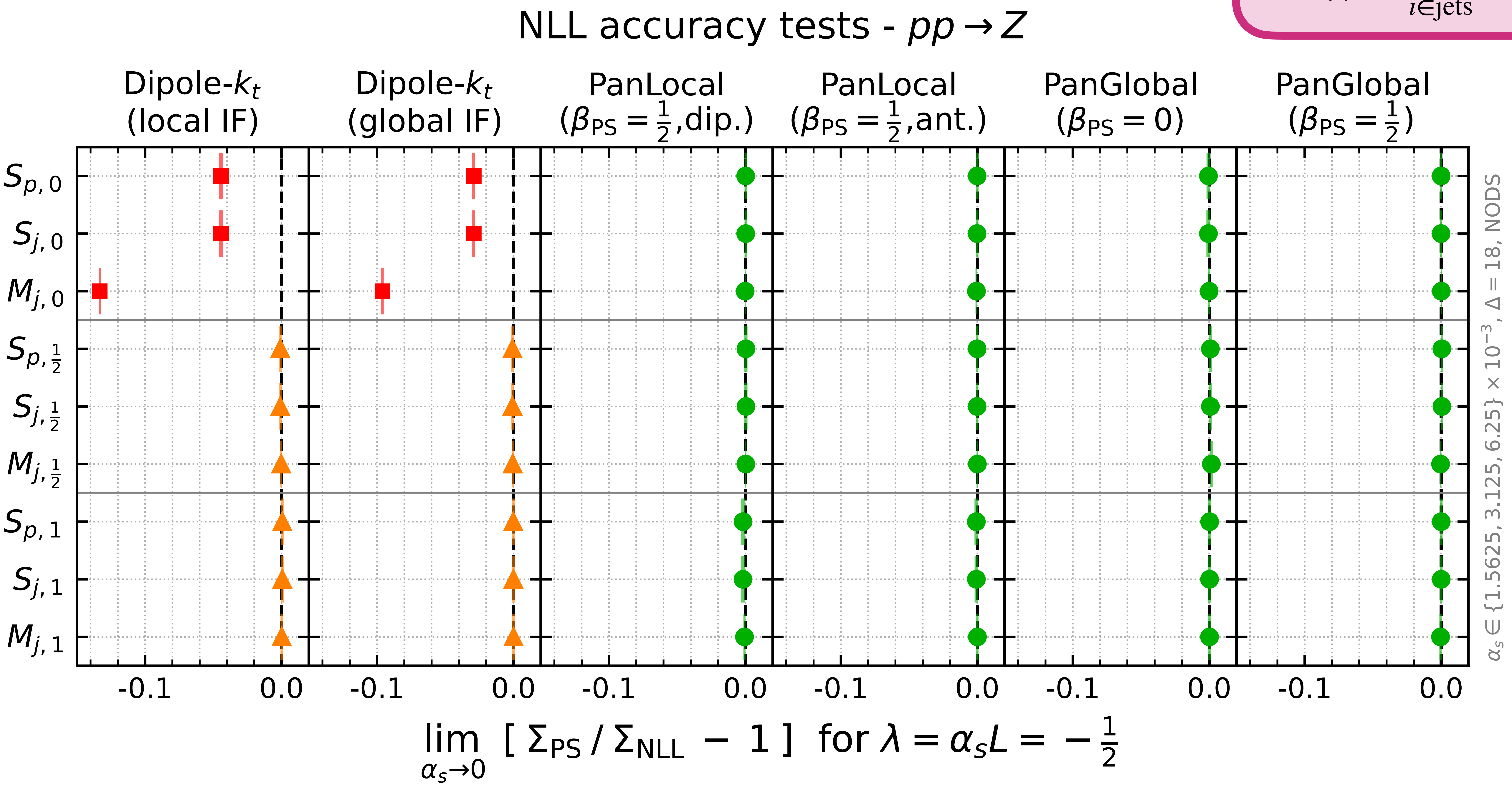
$\boxed{2}$ The rapidity of the hard system is preserved

This fixes r_a and r_b

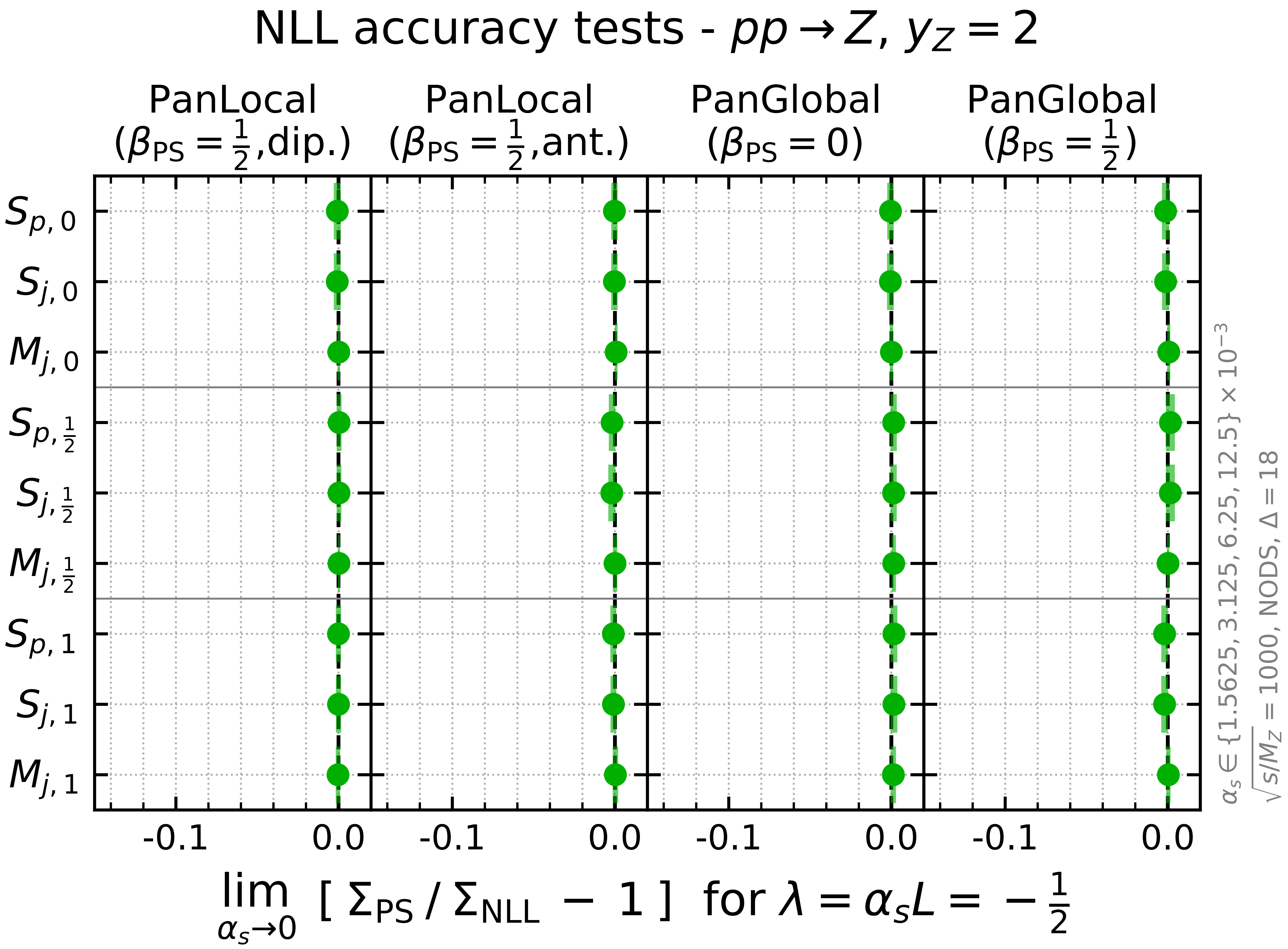
General global observables

$$S_{p/j,\beta} = \sum_{i\in f/\text{jets}} p_{\perp,i}\, \mathrm{e}^{-\beta|\eta_i|}$$

$$M_{j,\beta} = \max_{i\in\text{jets}} \left[p_{\perp,i}\, \mathrm{e}^{-\beta|\eta_i|}\right]$$



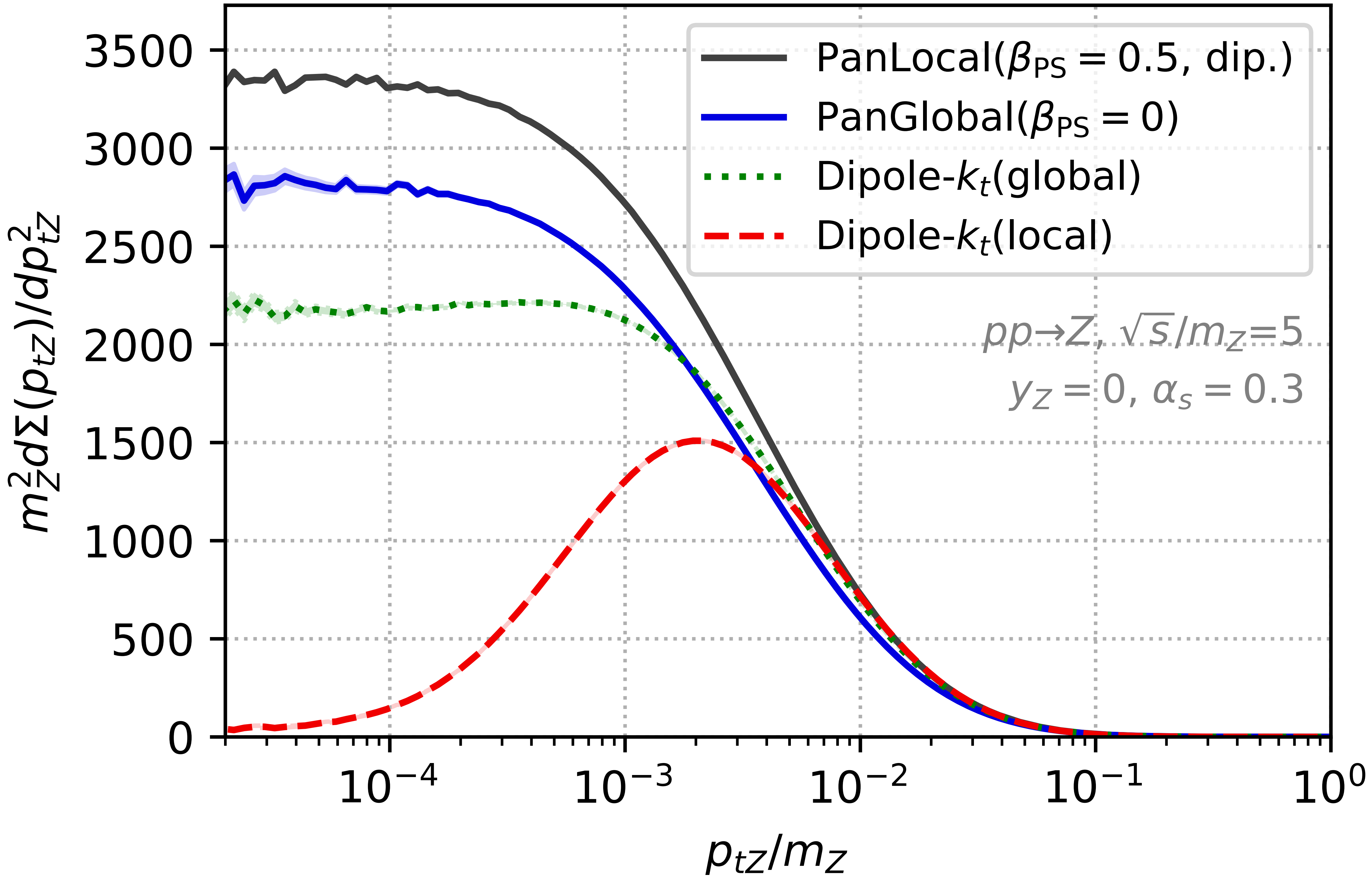
Global event shapes for $y_Z \neq 0$



Transverse momentum of the Z boson

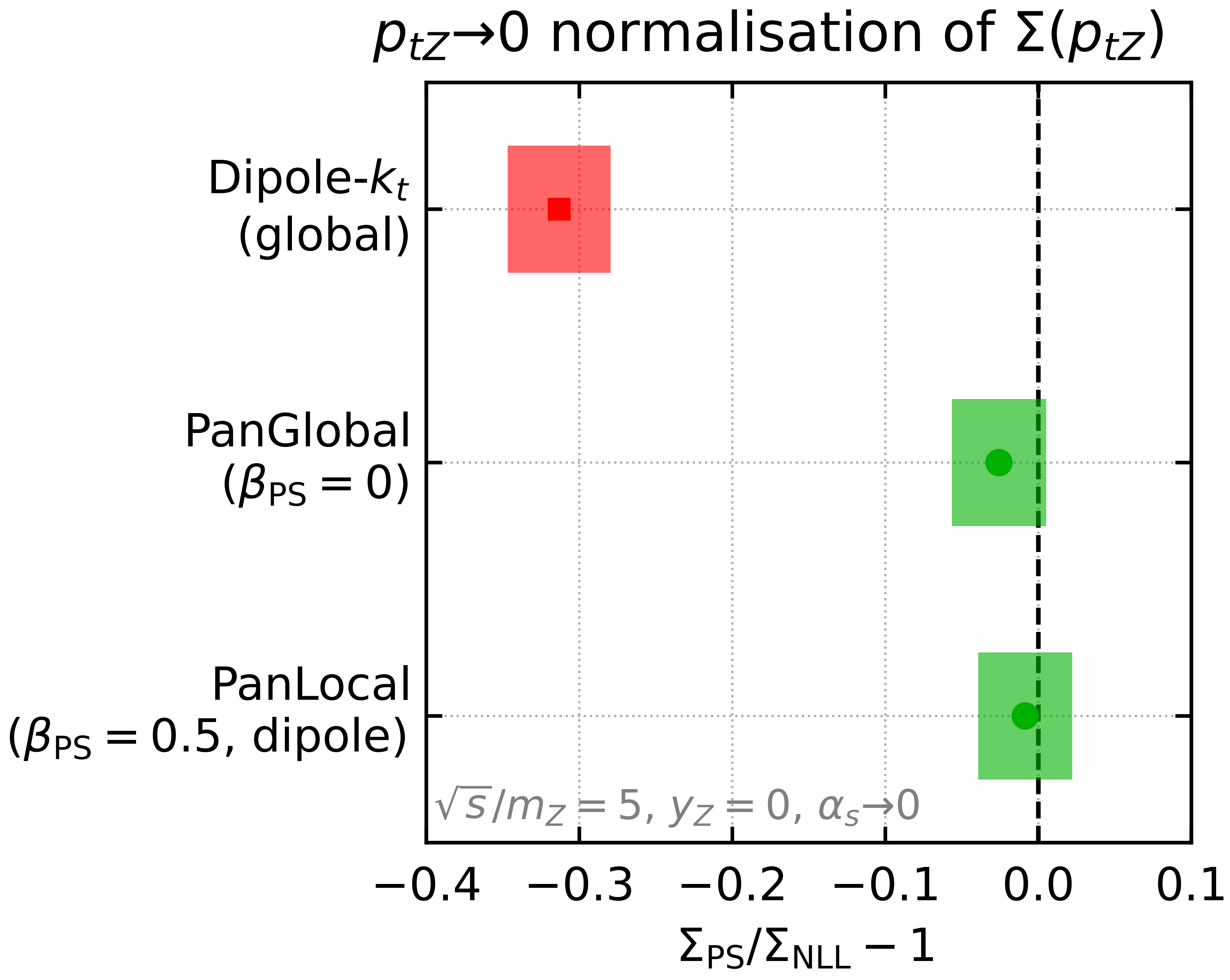
Scaling at small p_t

The Sudakov suppression is compensated by
azimuthal cancellations at small p_t
Leads to a power-law fall-off



Parisi, Petronzio [NPB 154 (1979) 427-440]

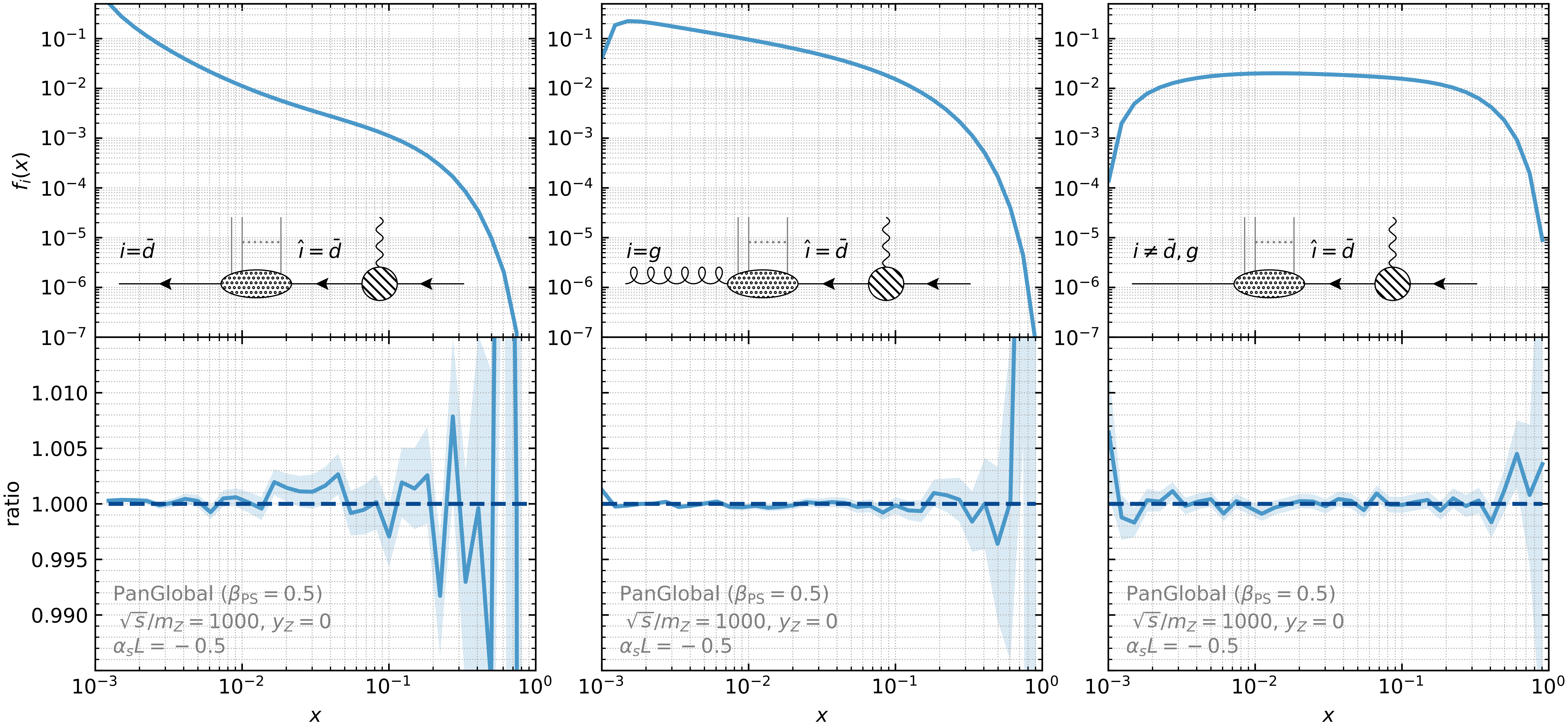
$$\frac{d\Sigma}{dp_{tZ}^2} = \int_0^\infty \frac{db}{2} b\, J_0(bp_{tZ})\, \Sigma_V(b_0/b)$$



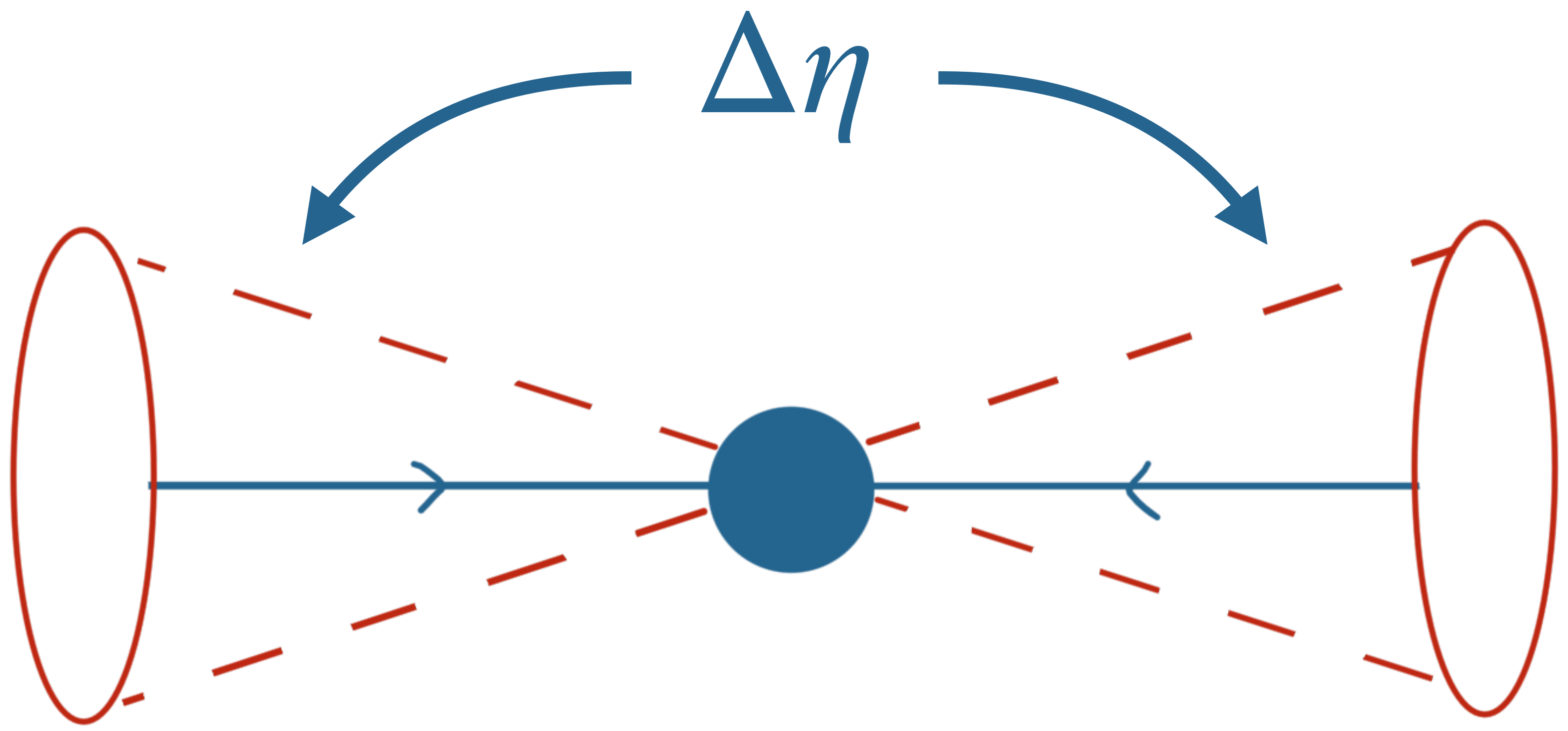
Parton distribution functions

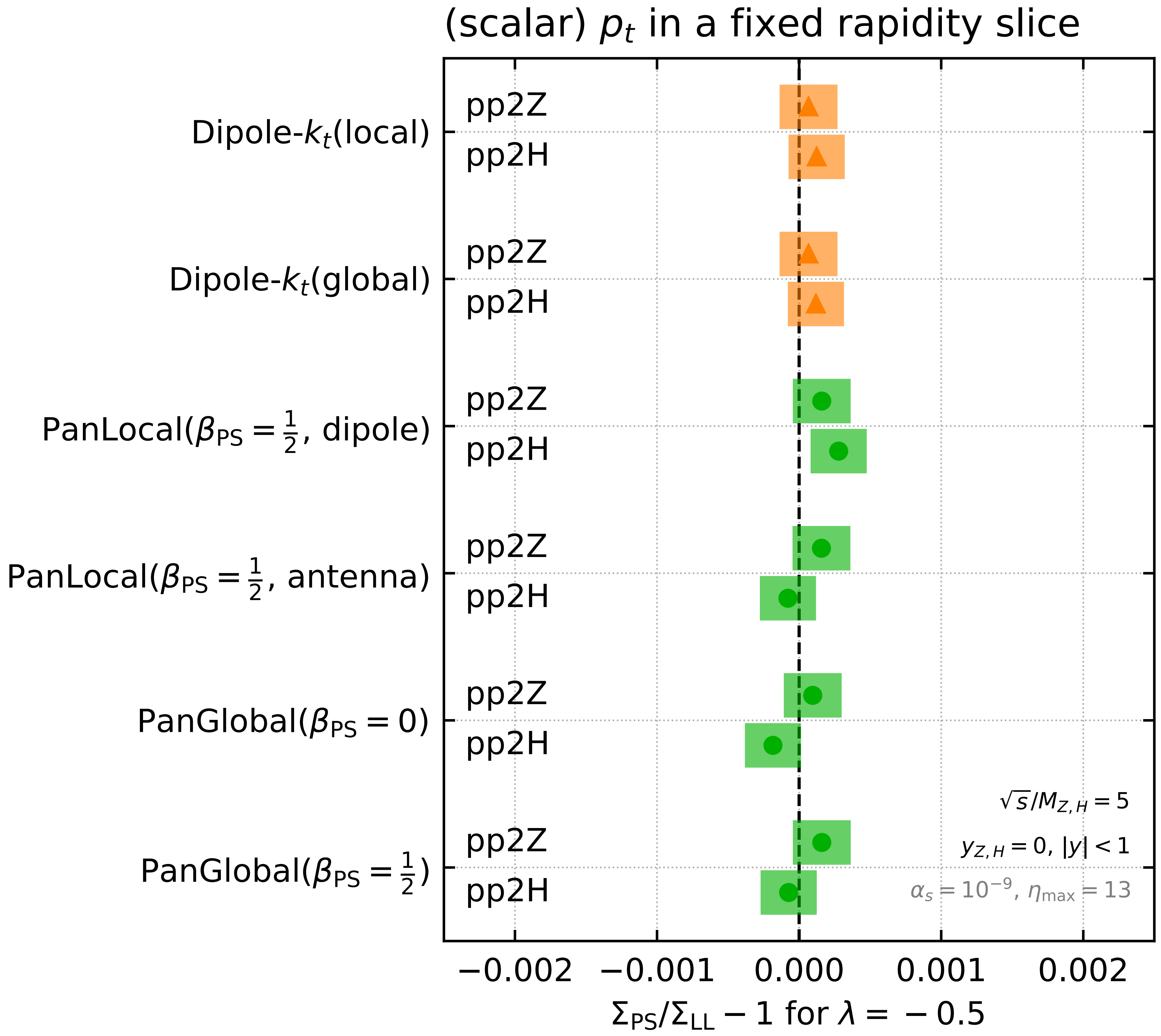
DGLAP expectation

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma_i}{\mathrm{d}x} = \frac{1}{f_{\hat{i}}(\hat{x}, m_Z^2)}\int_{\hat{x}}^{1}\frac{\mathrm{d}z}{z}D_{\hat{i}i}(z,\alpha_s L) f_i\left(\frac{\hat{x}}{z}, p_{t,\mathrm{cut}}^2\right)\delta\left(\frac{\hat{x}}{z}-x\right)$$



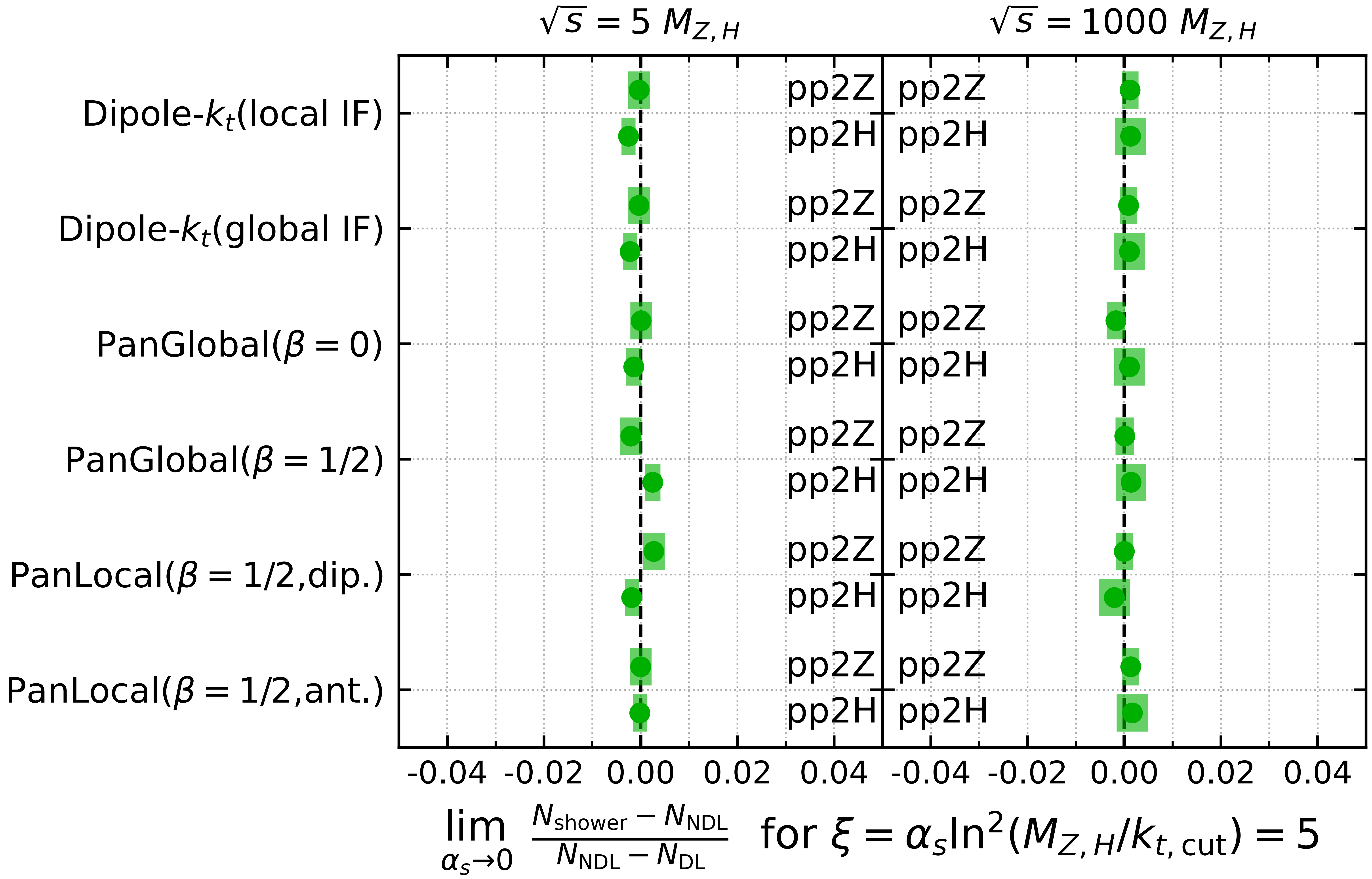
Non-global observable: rapidity gap



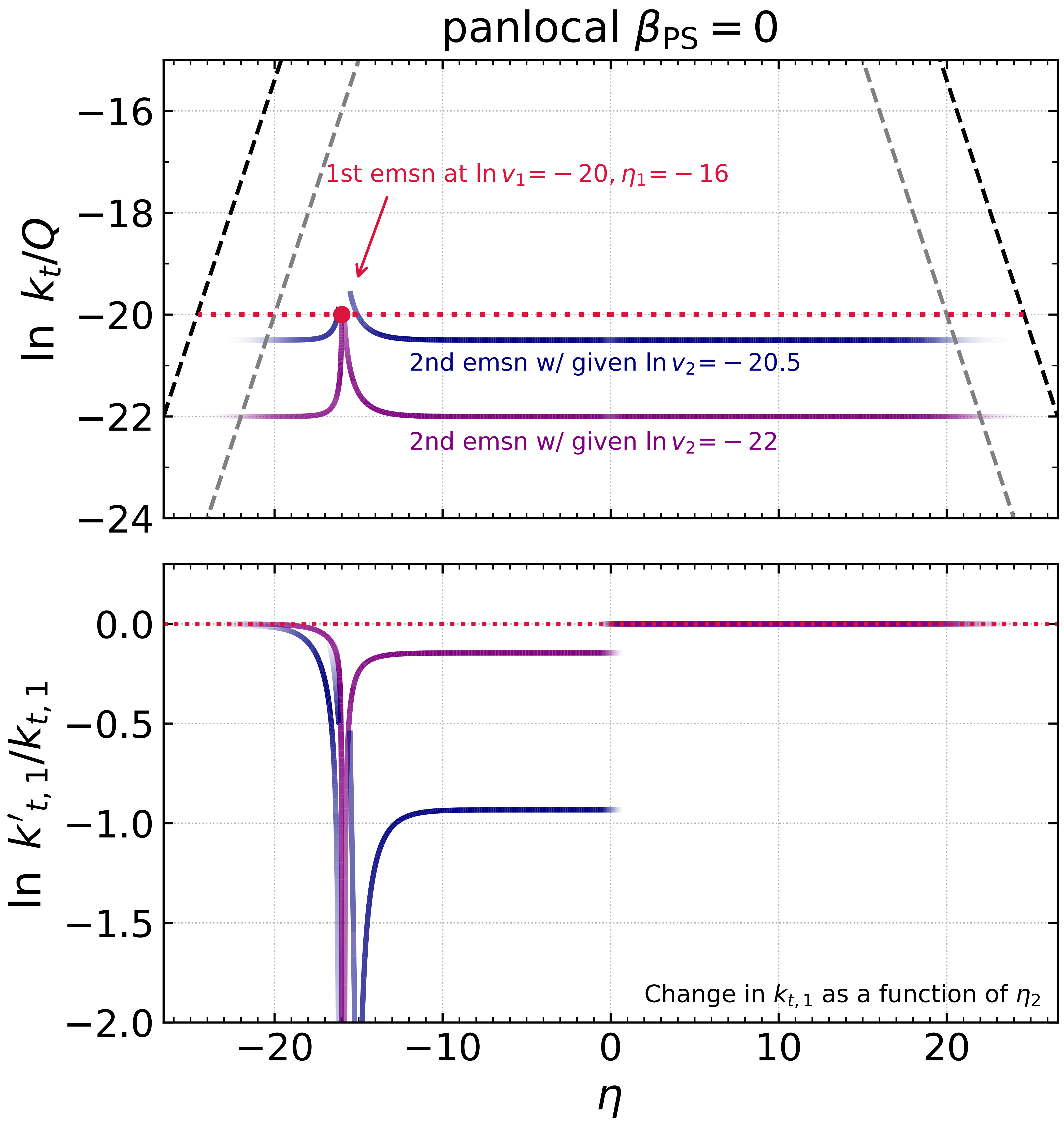


Melissa van Beekveld

Particle multiplicity

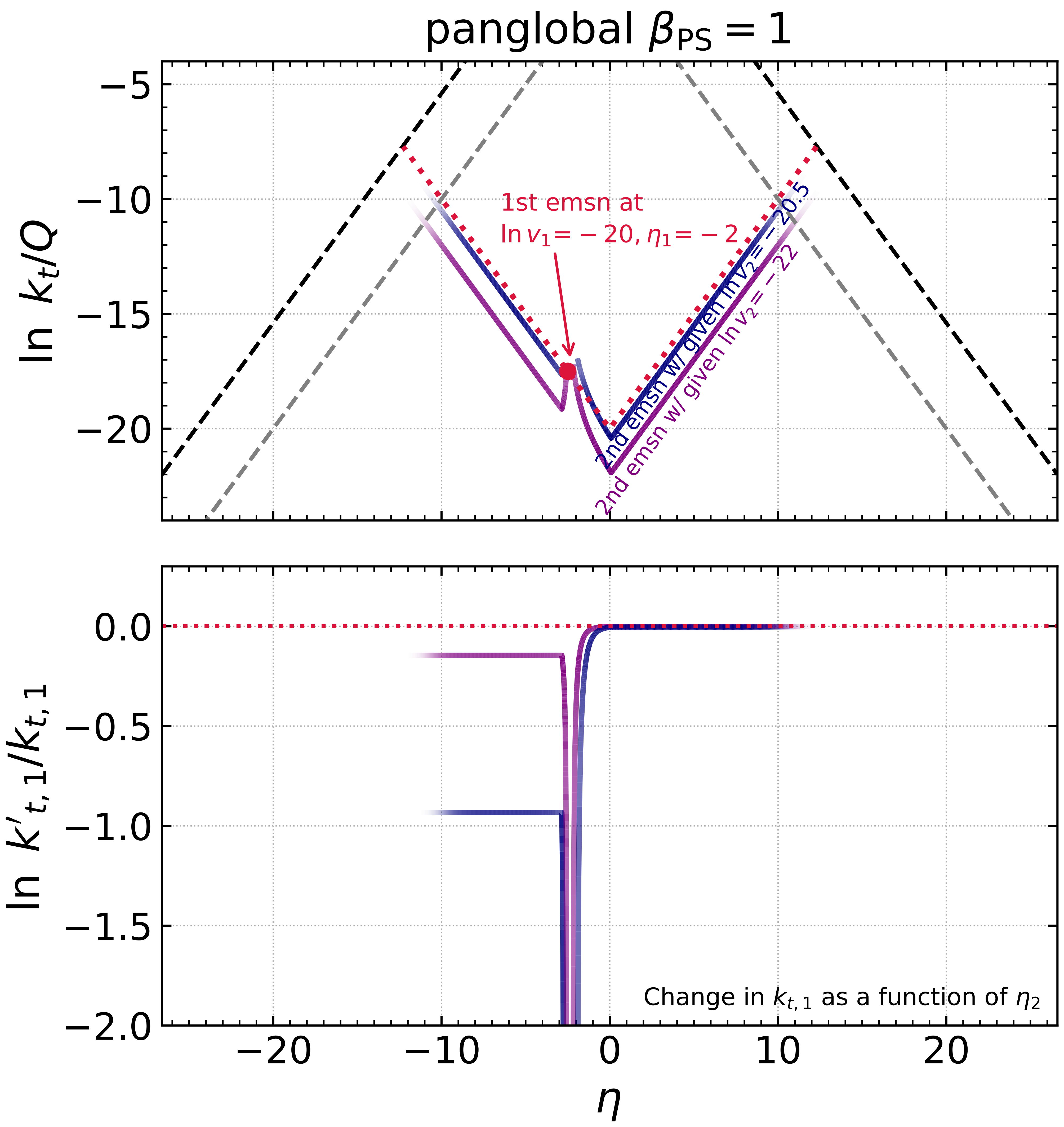


PanLocal issue for $\beta_{\mathrm{PS}} = 0$



- Recoil is taken from the first gluon even when emissions are separated in rapidity
- Separation of dipole in event CM frame is not enough to cure dipole-showers with local maps from locality issue, the transverse momentum ordering is problematic here
- Only when emissions are ordered in angle ($\beta_{\mathrm{PS}} > 0$) we solve this
- Then commensurate k_t emissions are ordered in angle, so they take their recoil from the hard system (after boost)

Issue for $\beta_{\text{PS}} = 1$



- For IF dipoles, momentum of first emission is rescaled by $b_j = 1 - \beta_k$ in map
- For $\beta = 1$ this equates to $1 - \frac{\tilde{s}_i}{\tilde{s}_{ij}} \frac{v}{Q}$ and becomes independent of $\bar{\eta}$
- Consider change in first emitted parton:

$$p_{k,1} = \tilde{p}_j \rightarrow b_j p_{k,1} = \left(1 - \frac{\tilde{s}_i}{\tilde{s}_{ij}} \frac{v_2}{Q}\right) p_{k,1}$$

- With $\frac{\tilde{s}_i}{\tilde{s}_{ij}} = \frac{2\tilde{p}_i \cdot Q}{2\tilde{p}_i \cdot \tilde{p}_j} = \frac{1}{b_{k,1}}$ and $b_{k,1} = \beta_{k,1} = \frac{v_1}{Q}$

$$\boxed{\frac{k_{\perp,1}}{k_{\perp,1 \text{ after } 2}} = \left(1 - \frac{v_2}{v_1}\right)}$$

Colour tests

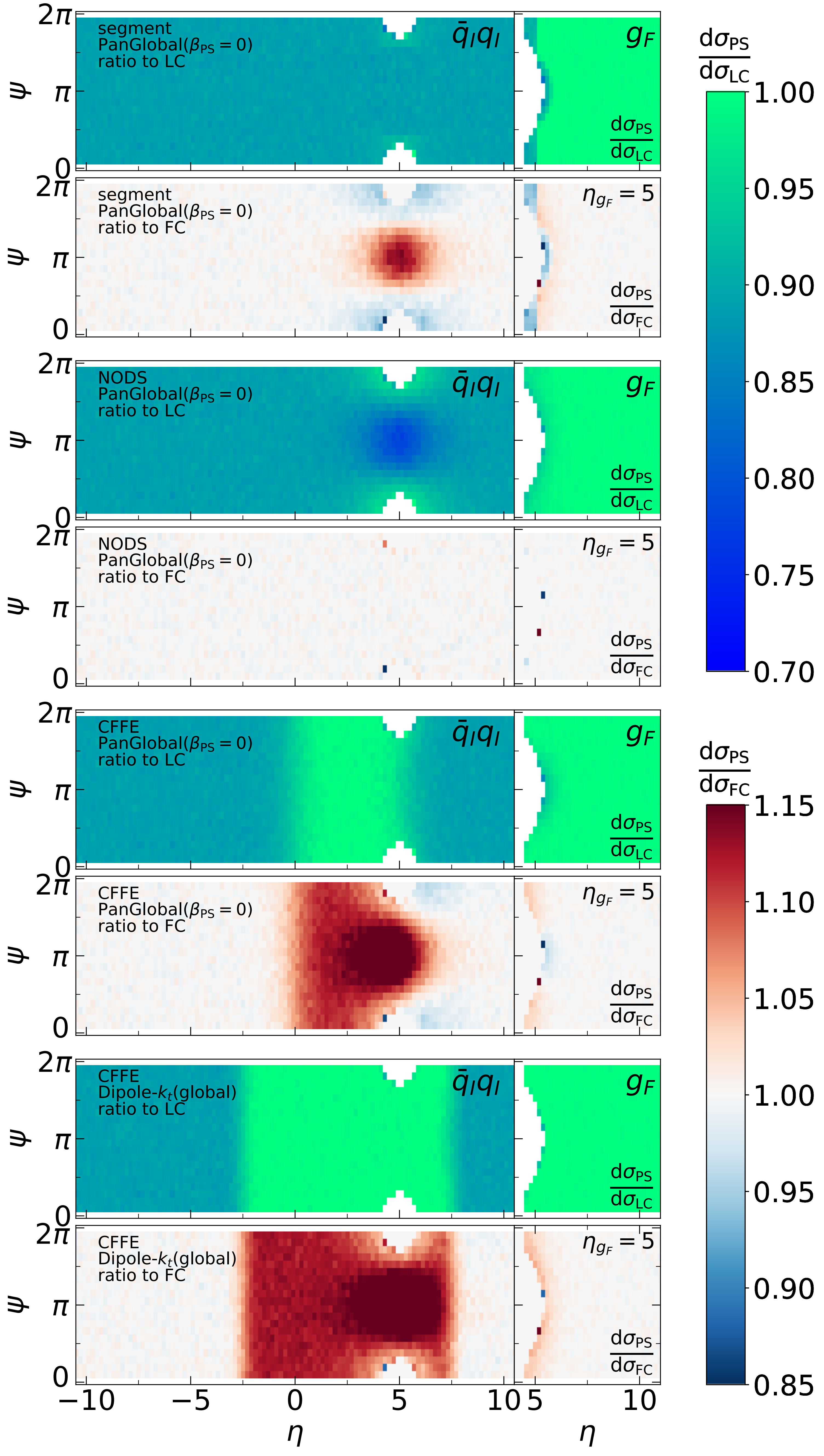
Test of the differential matrix element

Here primary $\bar{q}q$ Lund plane and the new g Lund leaf

LC = leading colour (standard)
FC = full colour

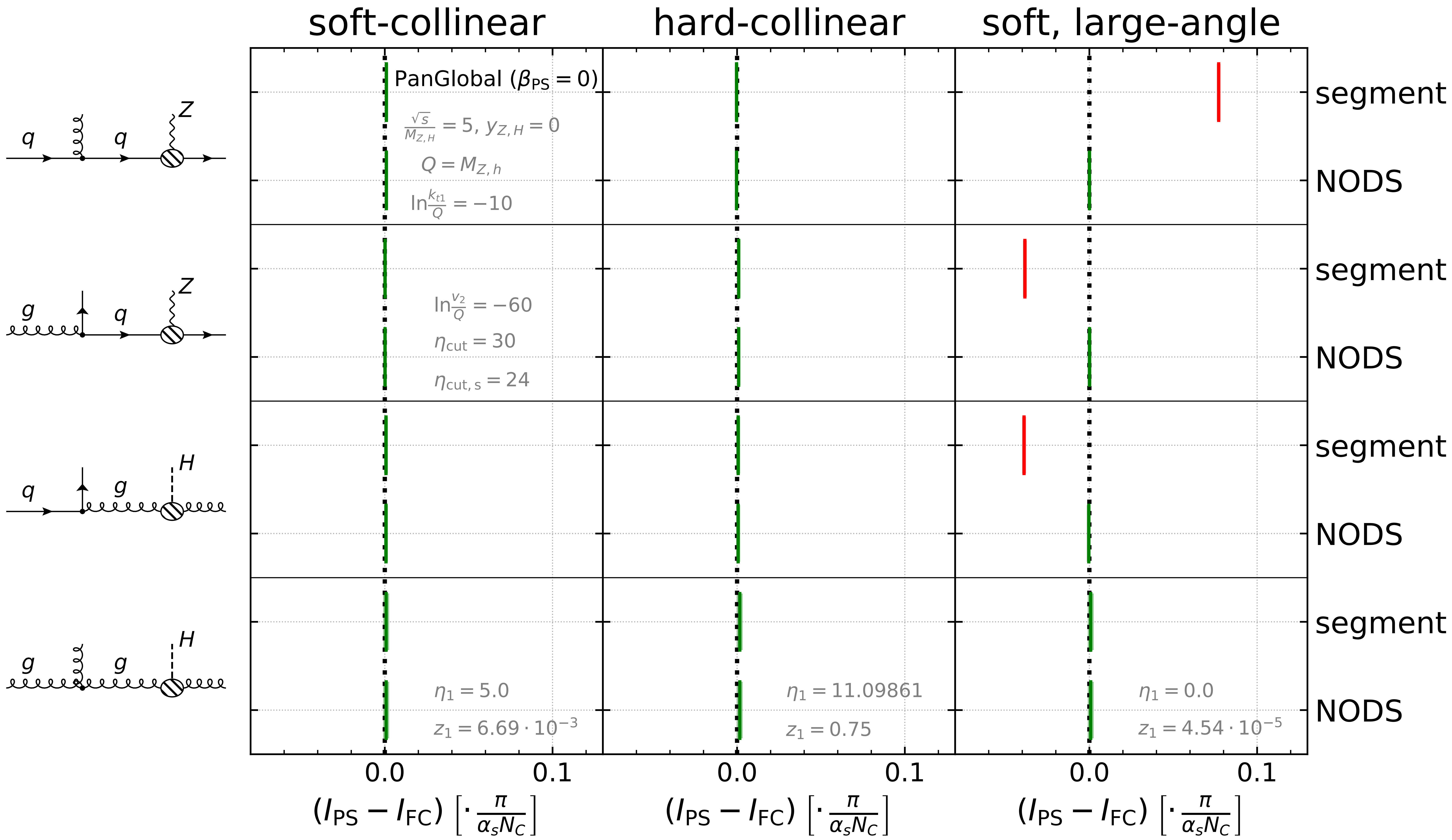
CFFE = standard colour treatment

Segment and NODS two ways to improve the colour handling in the PanScales showers



Colour tests

$$I_{\mathrm{FC}}^{Zg_1} \equiv \int \frac{\mathrm{d}\Omega}{2\pi} \frac{\left|\mathcal{M}_{q\bar{q}g_1g_2}\right|^2}{\left|\mathcal{M}_{q\bar{q}g_1}\right|^2}$$

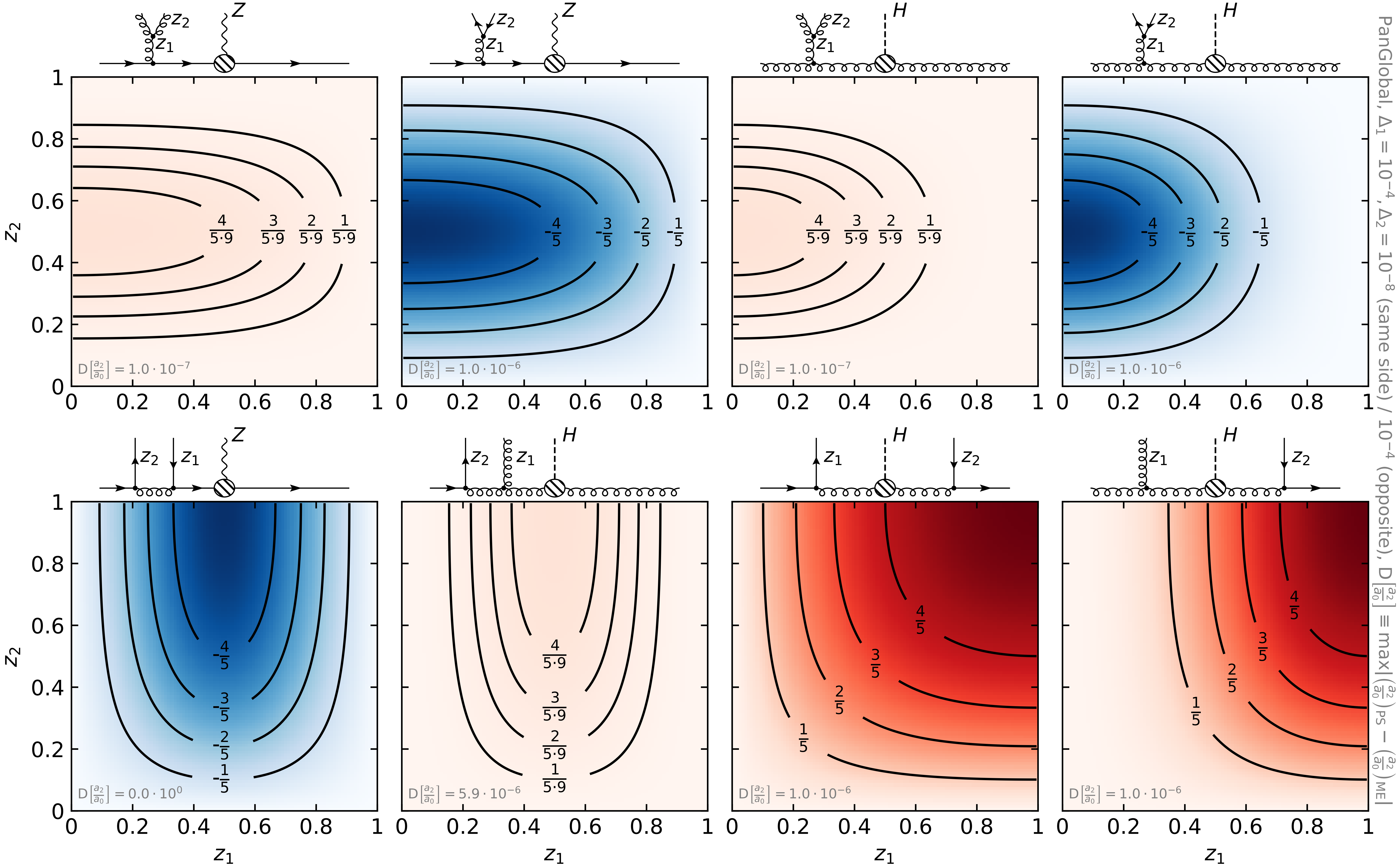


Test of the integrated rate of emissions

Spin tests

$$\frac{d\sigma}{d\Delta\psi_{ij}} \propto a_0 \left(1 + \frac{a_2}{a_0}\cos(2\Delta\psi_{ij})\right)$$

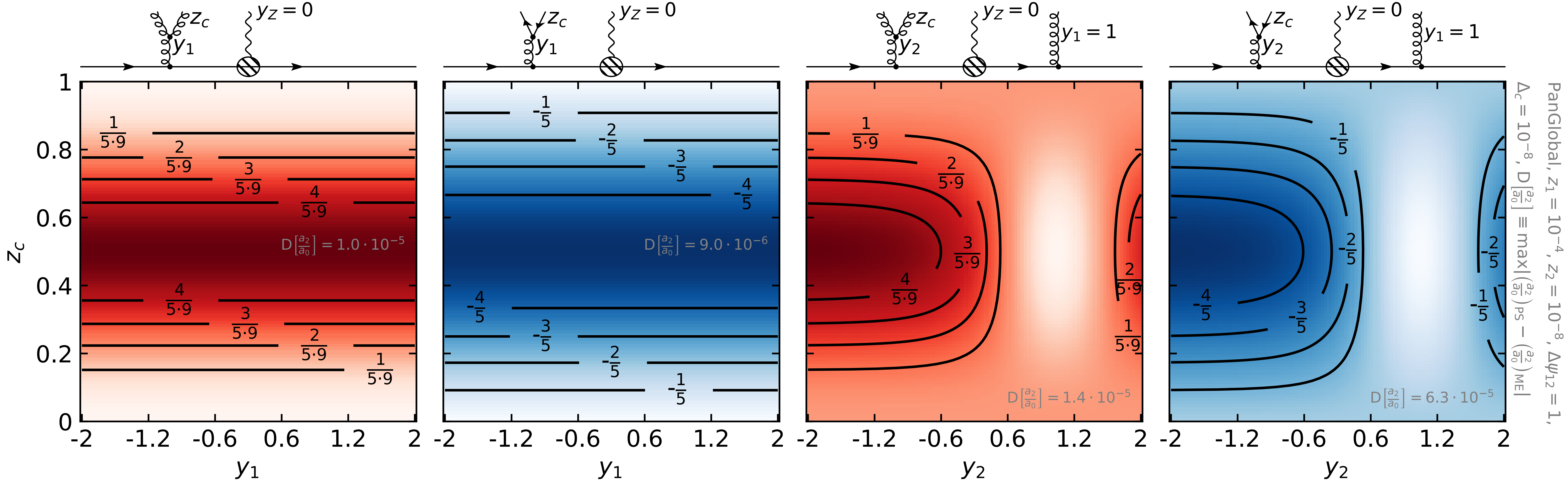
Two collinear emissions



Spin tests

$$\frac{d\sigma}{d\Delta\psi_{ij}} \propto a_0 \left(1 + \frac{a_2}{a_0}\cos(2\Delta\psi_{ij})\right)$$

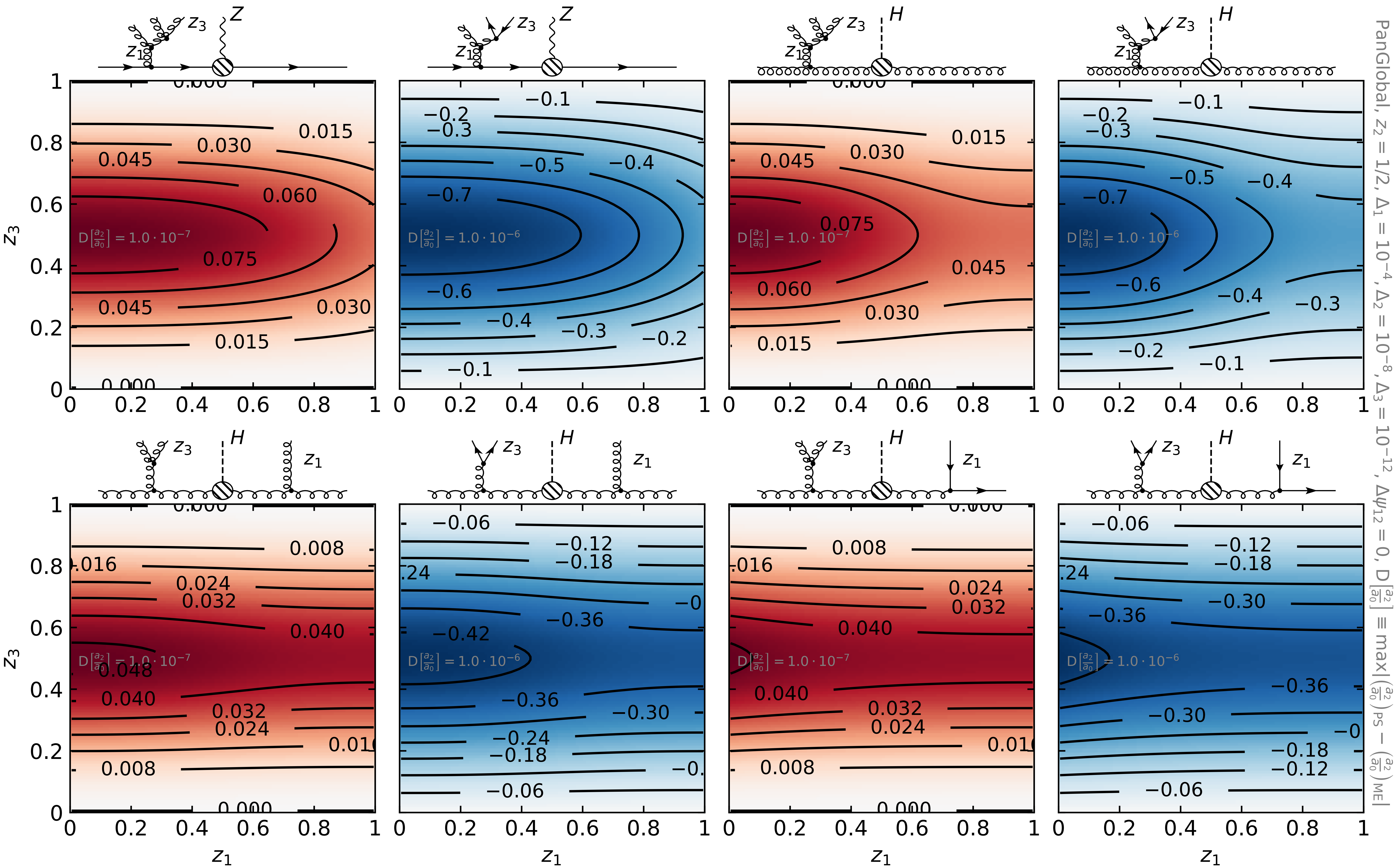
One collinear, one soft emission



Spin tests

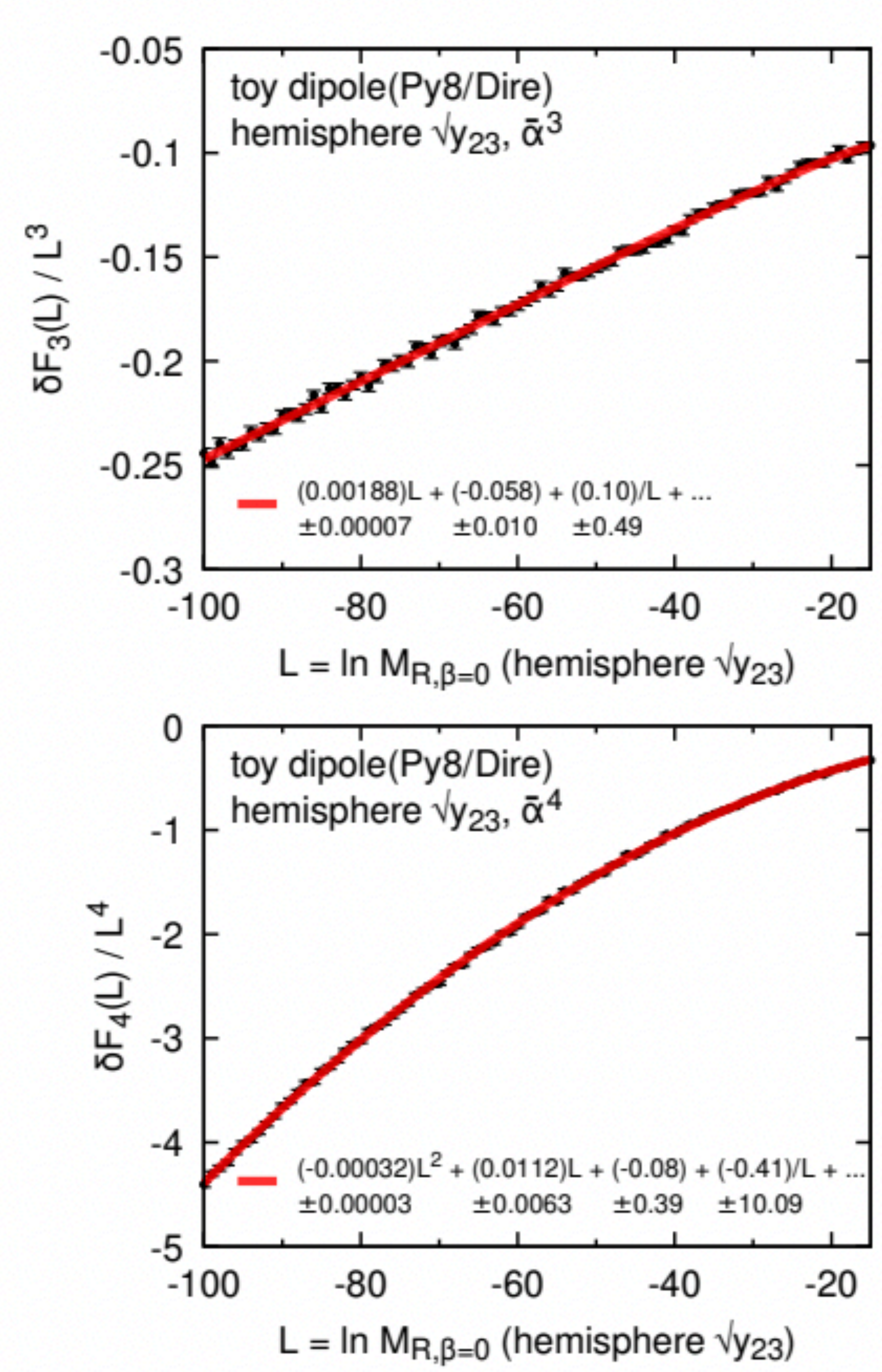
$$\frac{d\sigma}{d\Delta\psi_{13}} \propto a_0 \left(1 + \frac{a_2}{a_0}\cos(2\Delta\psi_{13}) + \frac{b_2}{a_0}\sin(2\Delta\psi_{13})\right)$$

Three collinear emissions



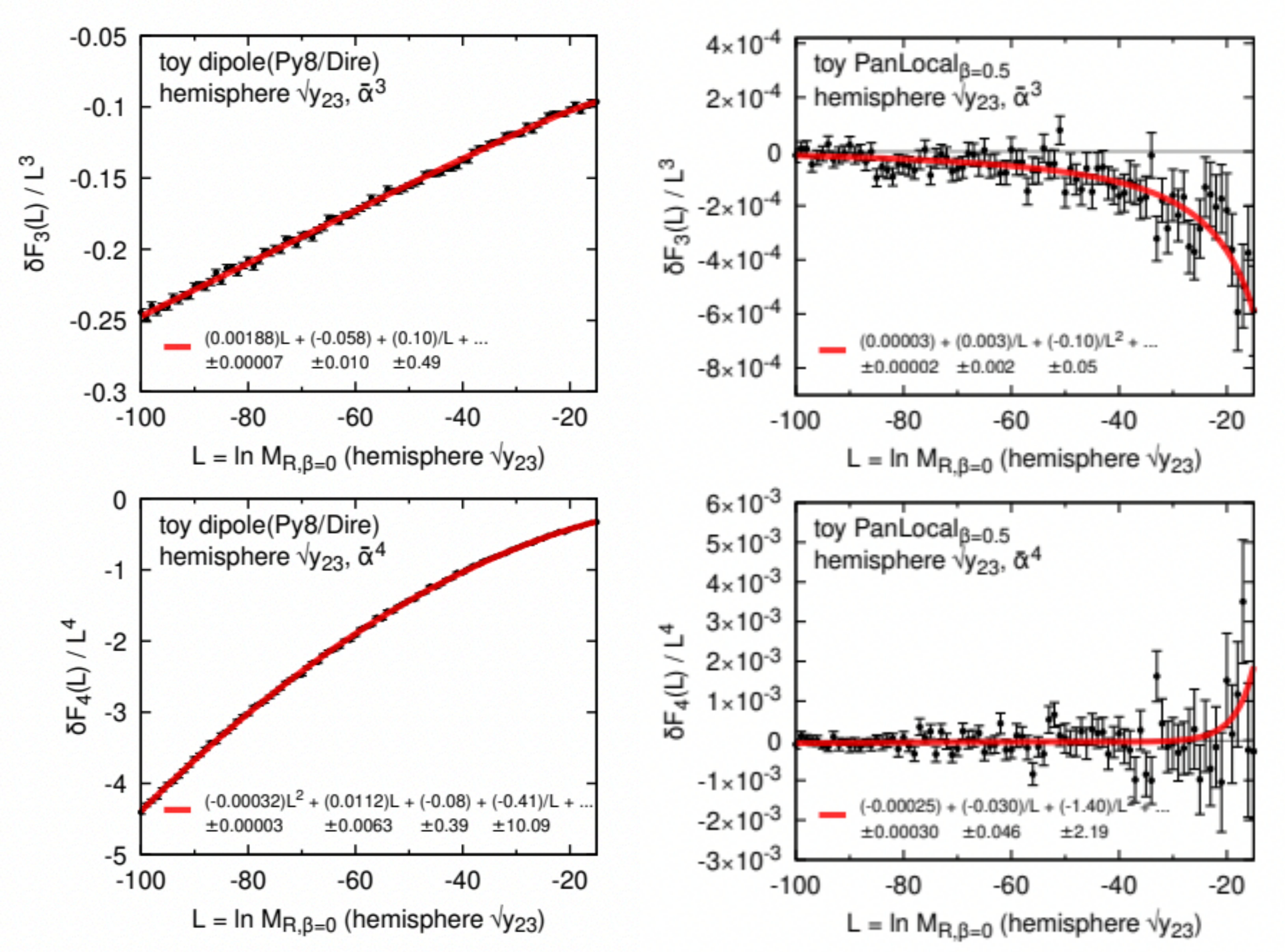
2002.11114

Super-leading logarithms



- Consider $M_{R,0}$, max $p_\perp$ of emissions in the right hemisphere (sensitive to super-leading logs at $\mathcal{O}(\alpha_s^3)$)
- Take toy-model approach with only soft primary emissions and fixed coupling
- Take difference between CEASAR result and toy shower $\delta F_n(L)$, n = order in α_s, where $F = \sum \alpha_s^n F_n$ has terms of $\alpha_s^n L^m$ with $m \leq n$
- Clearly a discrepancy at fixed-order for standard dipole showers
- Vanishes at all orders because it is numerically comparable to the NNLL terms -> orange points

Super-leading logarithms



- Discrepancy not there for PanScales family of showers