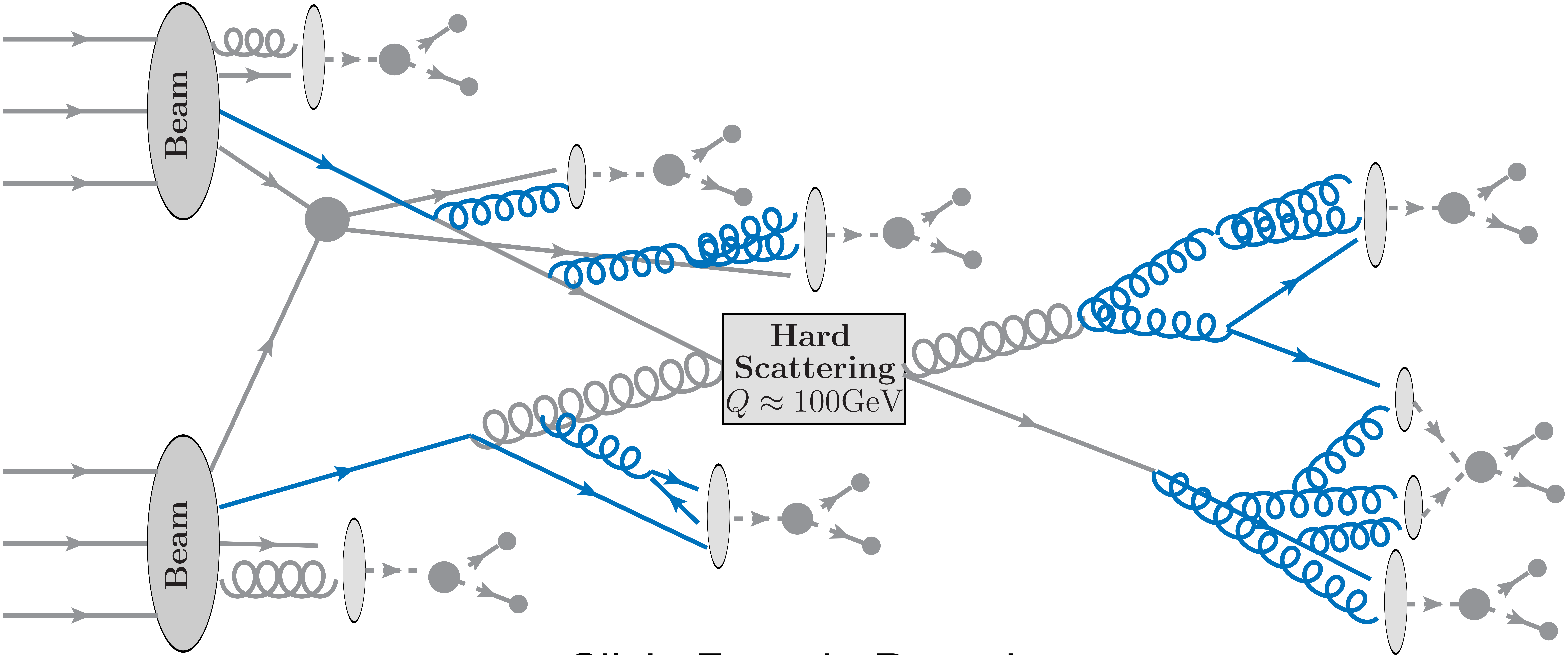
Formally and practically accurate Parton Shower Generators



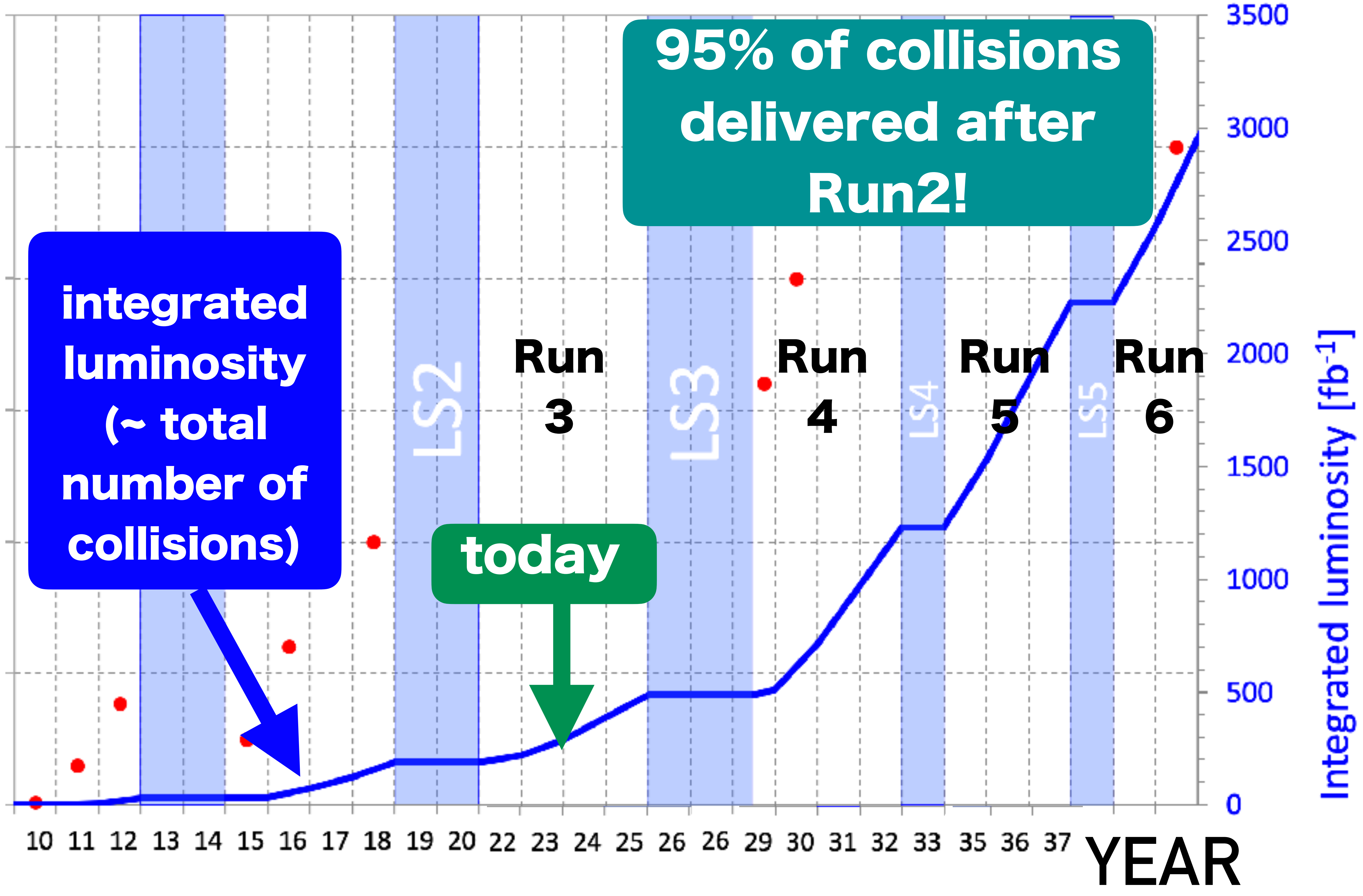
Silvia Ferrario Ravasio

HEP Theory Seminar

19th February 2024, **Universität Bonn**

LHC future prospects

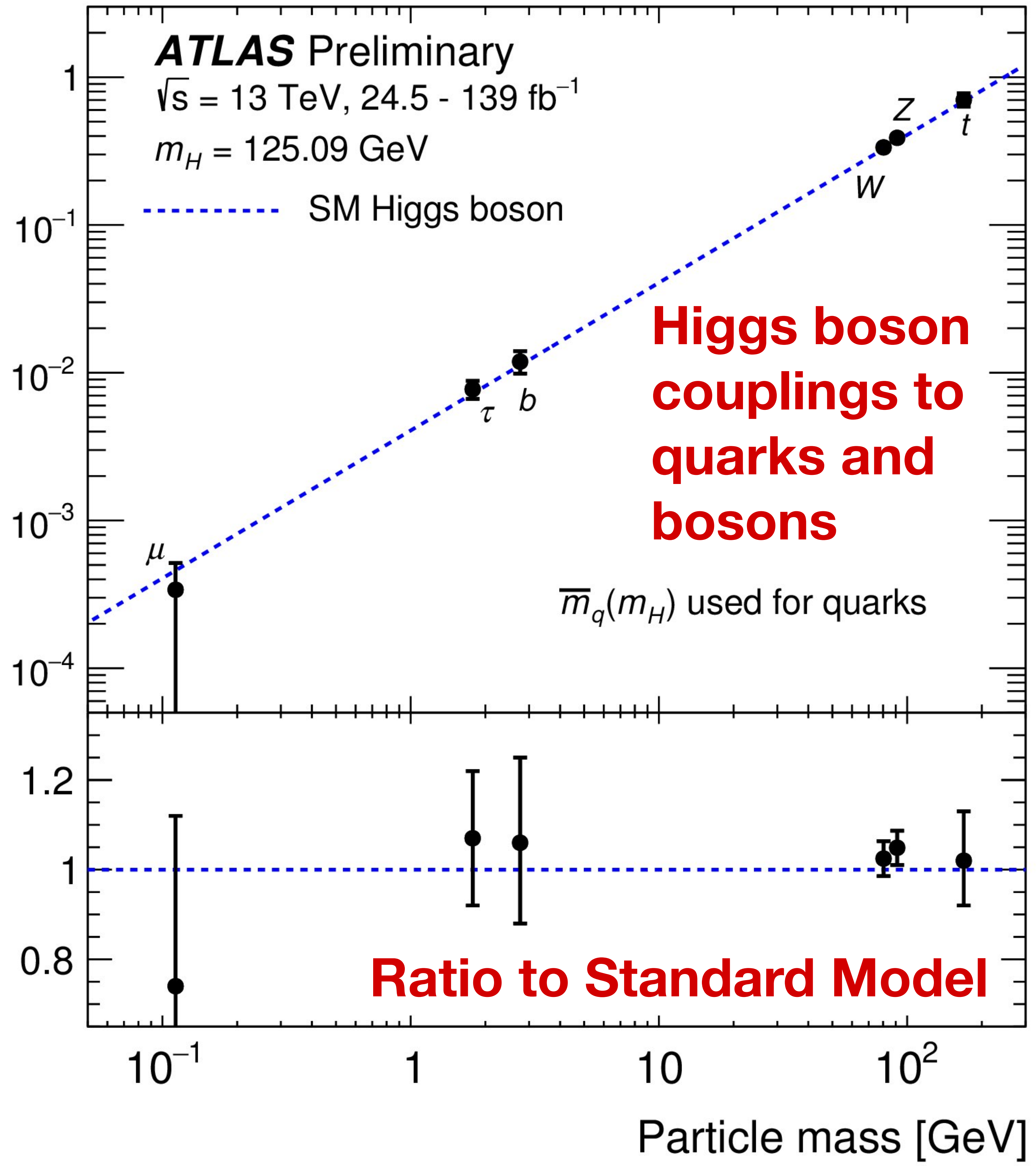
- ➤ LHC represents the future of particle physics for the next 2 decades
- ➤ Precision measurements in the Higgs sector: success of the Standard Model or New Physics



95% of collisions delivered after Run2!

integrated luminosity (~ total number of collisions)

today



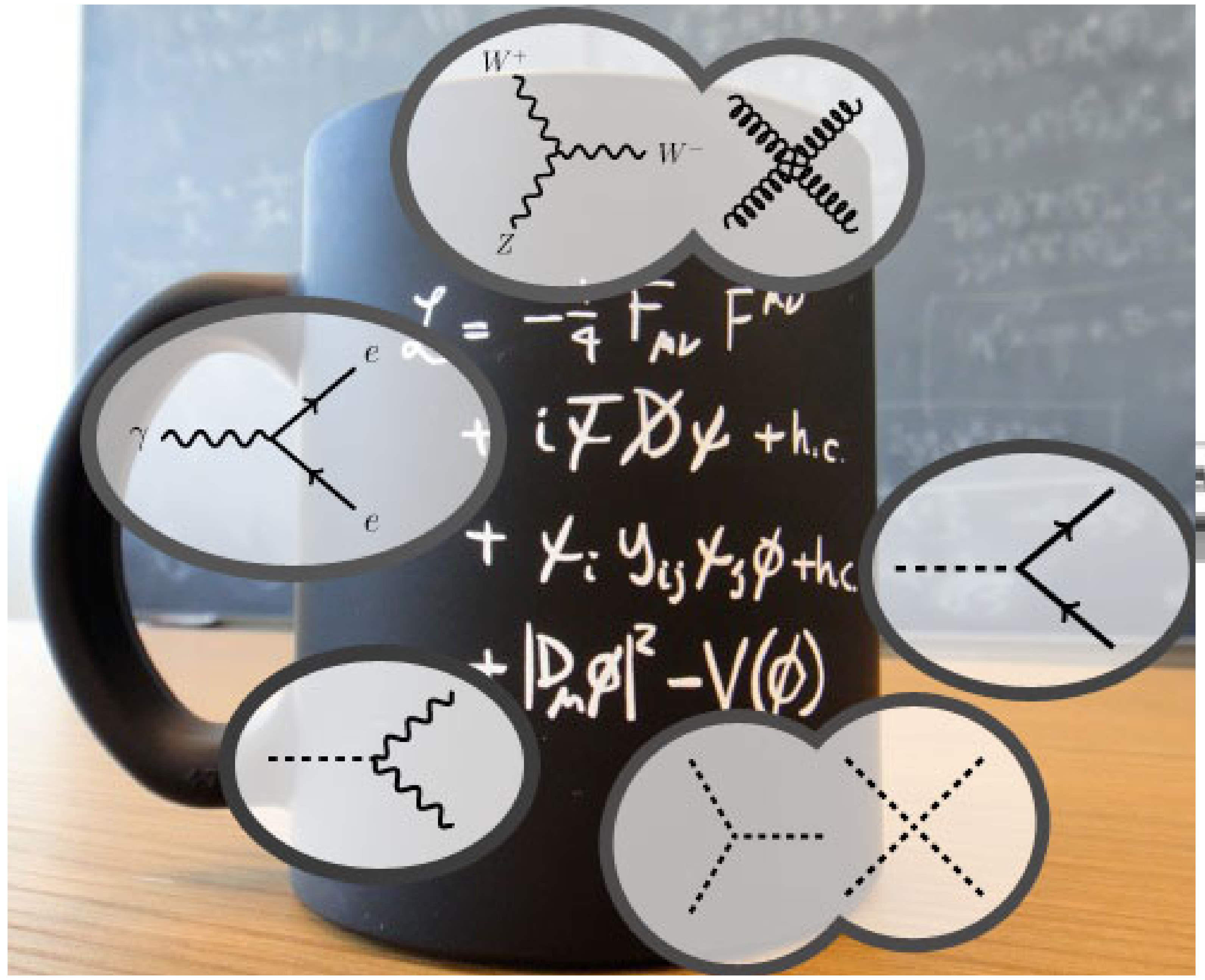
Higgs boson couplings to quarks and bosons

Ratio to Standard Model

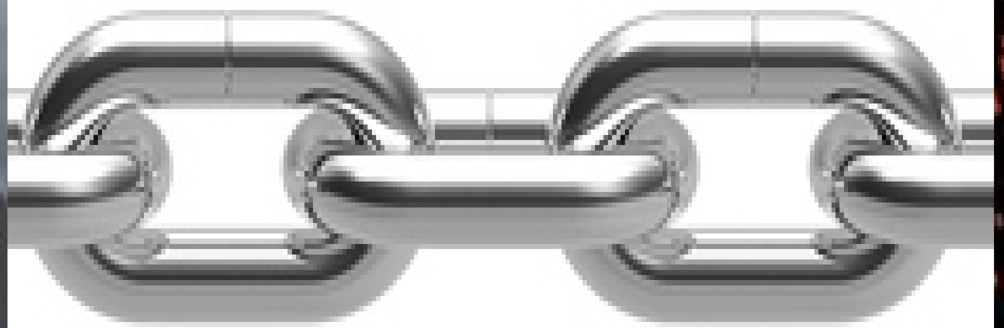
LHC future prospects

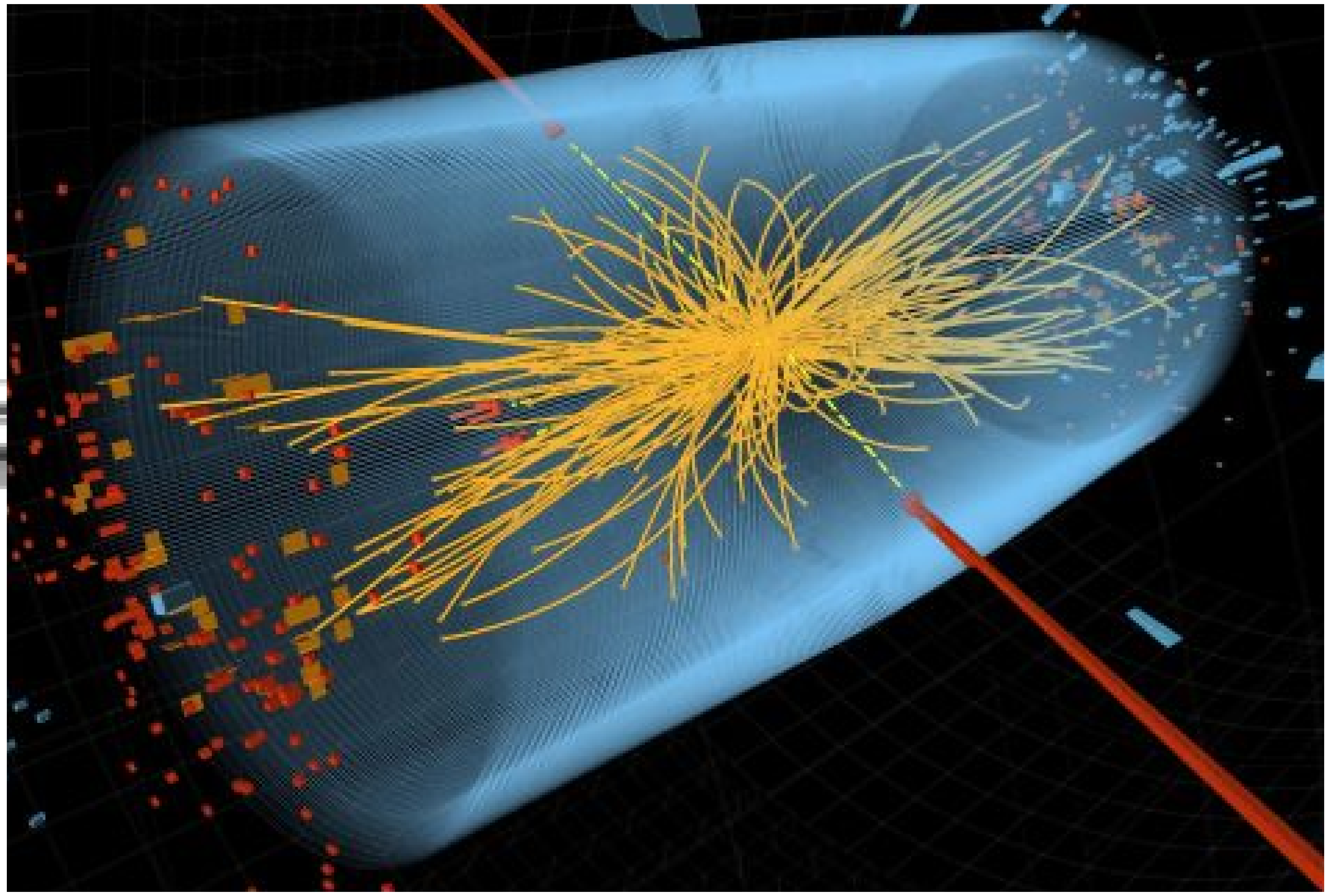
- **LHC** represents the **future of particle physics** for the next **2 decades**
- Precision measurements in the **Higgs sector**: success of the **Standard Model** or **New Physics**
- This requires **accurate theoretical predictions**

and a **connection** between theory and experiment



Idel world





Reality

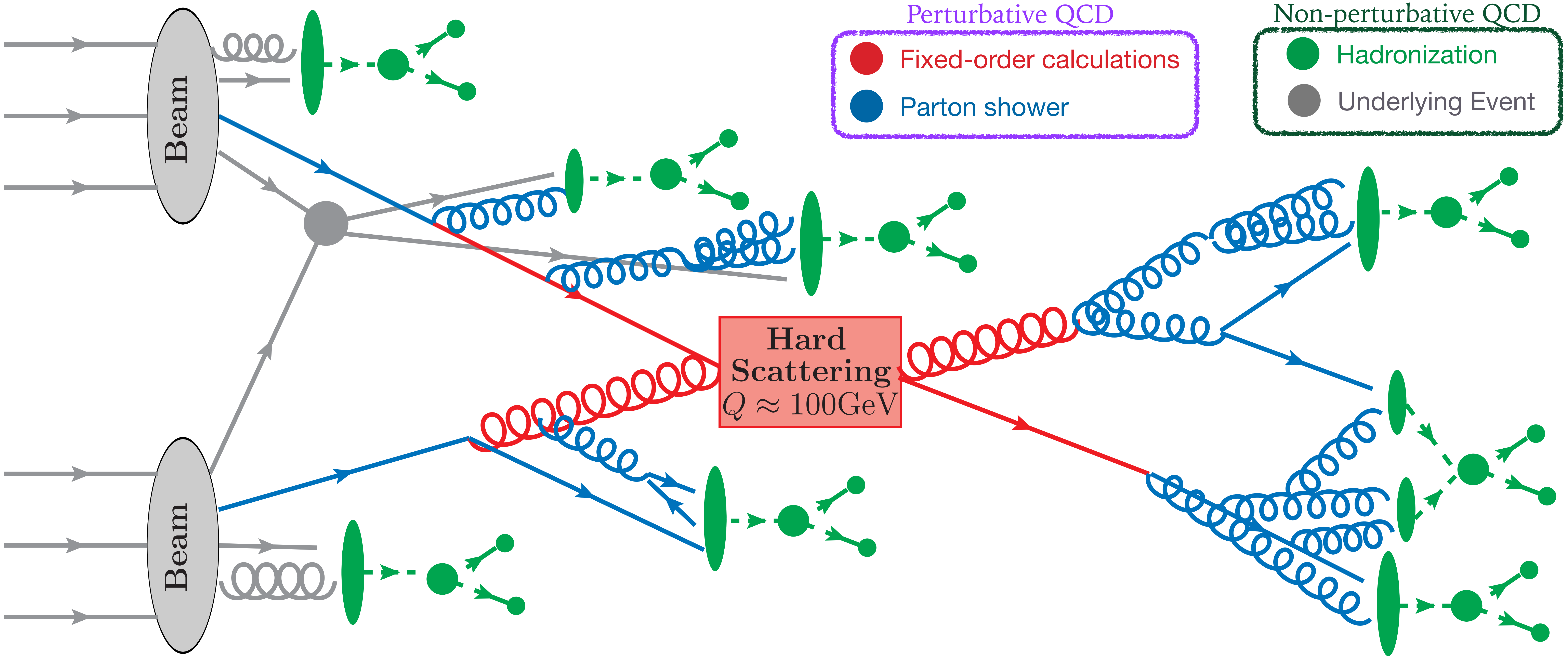
Shower Monte Carlo Generators

- <u>Shower Monte Carlo</u> generators have all the ingredients necessary to model complex collider events and are the **default tool** for intepreting LHC data

Pythia

Herwig

Sherpa



- The flexibility of these tools comes at a cost of a <u>poor formal accuracy</u> that causes systematic <u>uncertainties</u> entering thousands of papers from the LHC

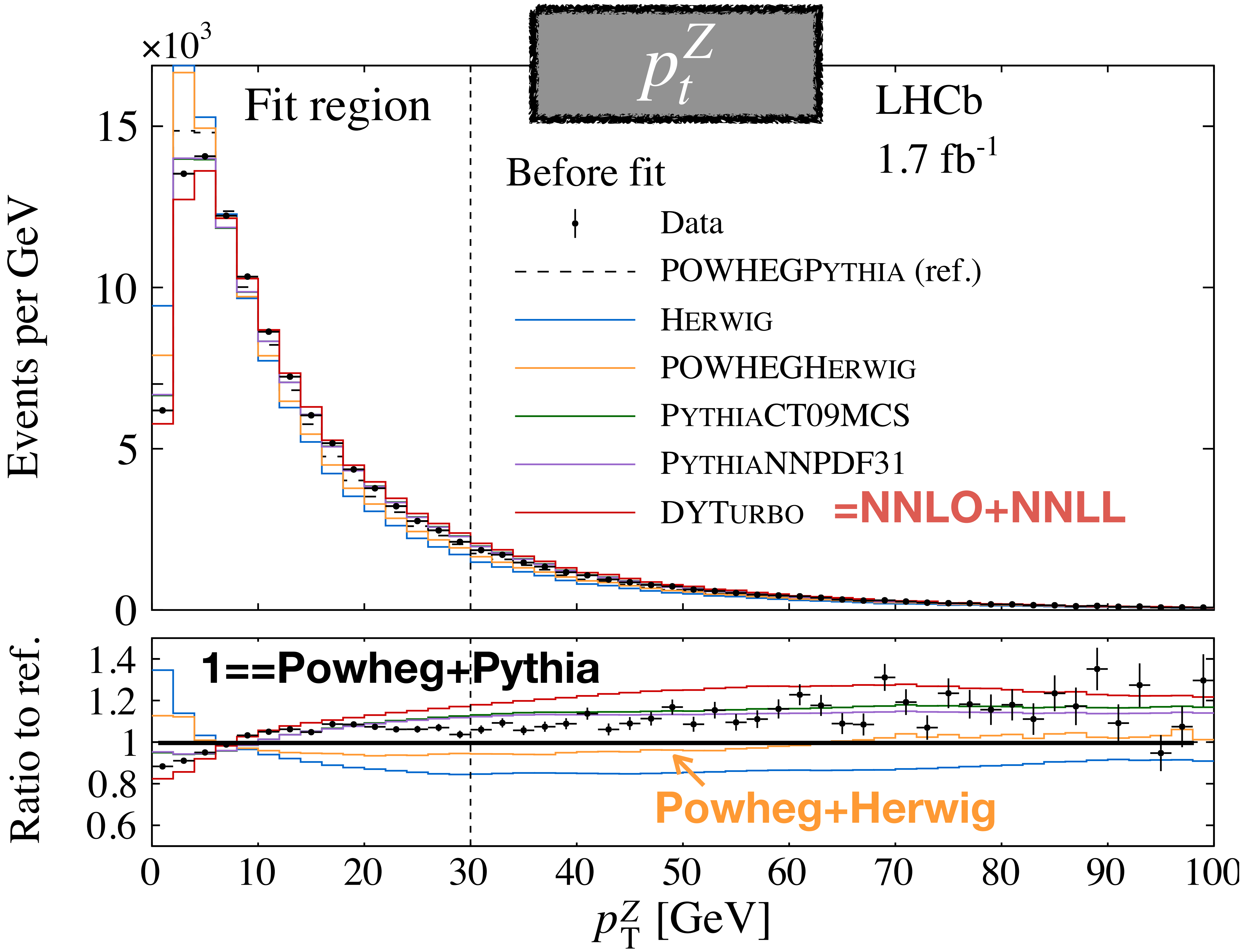
SMC as limiting factor in HEP: Standard Candles

Electroweak precision measurements in Drell-Yan processes at the LHC such as

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

[LHCb JHEP 01 (2022) 036]

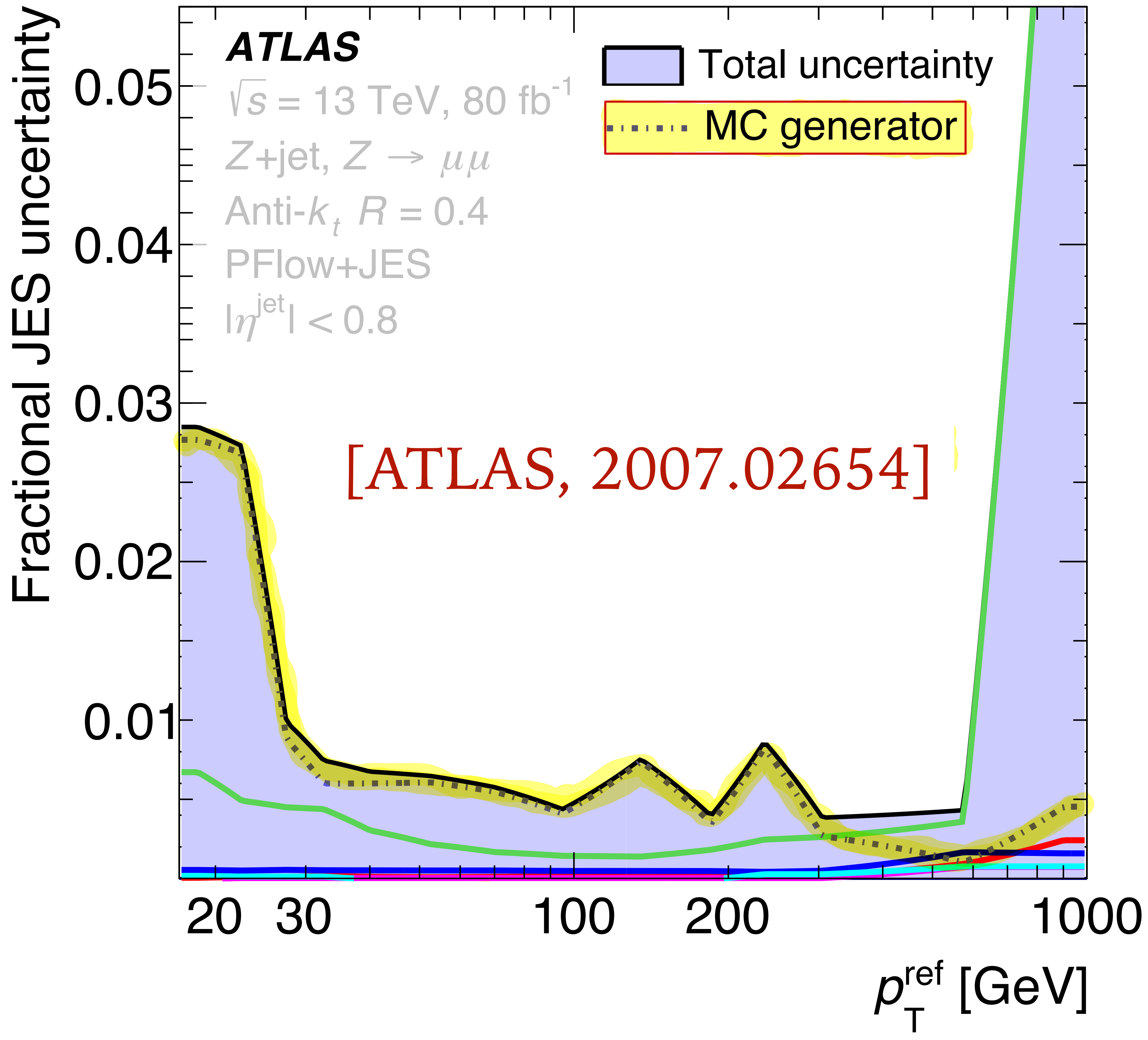
require a theory description of the boson transverse momentum distribution



Even if very accurate pQCD calculations are available, **SMC** are invariably used for the modelling of **realistic experimental acceptance and isolation cuts**

SMC as limiting factor in HEP: Jet Measurements

Any jet physics analysis (**$\mathcal{O}(1k)$ papers!!**) at colliders requires the **jet energy scale** calibration



[ATLAS, 2007.02654]

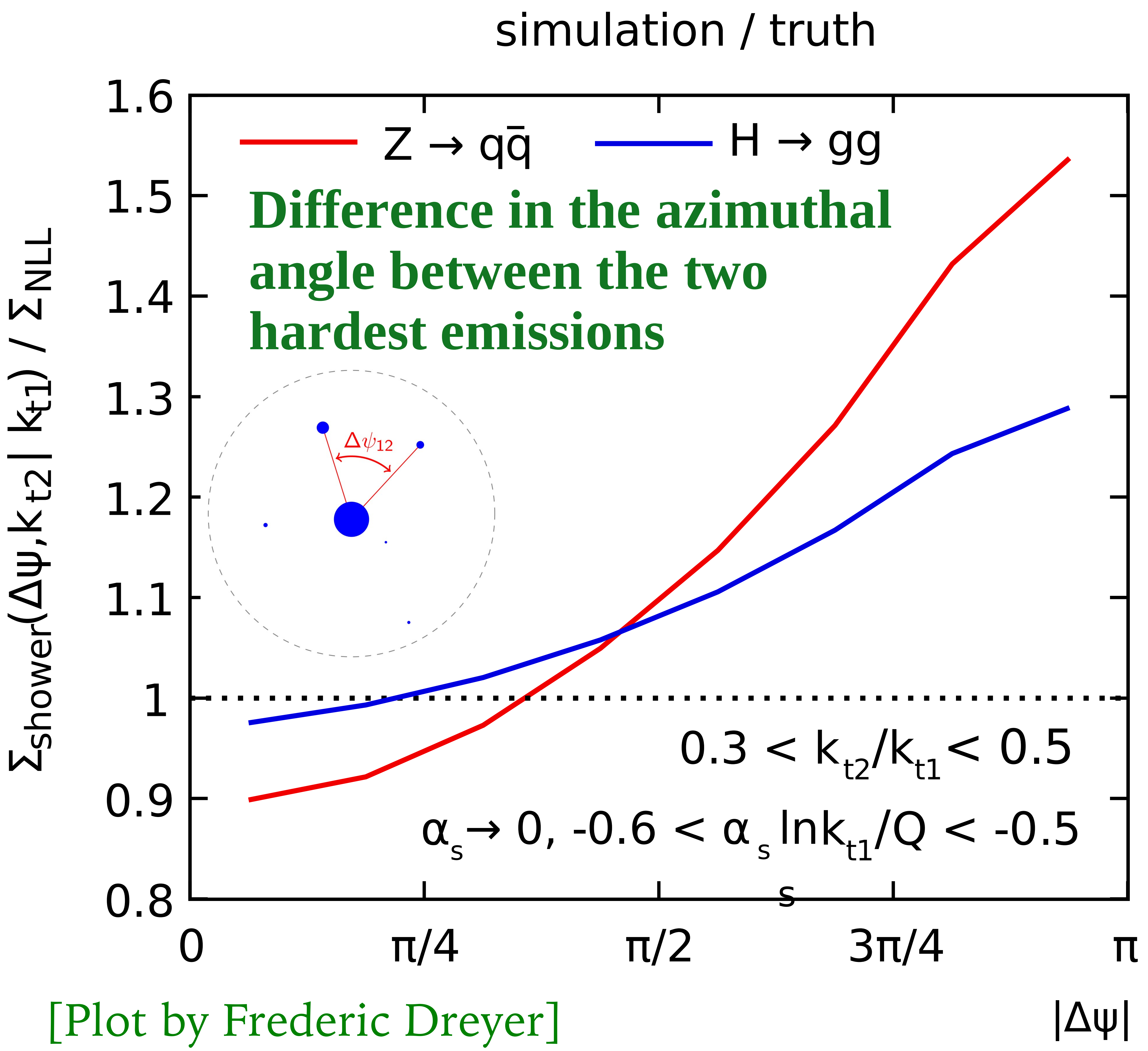
Parton shower (and its interplay with hadronisation) leading source of systematic uncertainty of JES

[CMS, 1910.08819]

JES largest uncertainty in **top**-mass extractions

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	$^{+0.68}_{-0.73}$

SMC as limiting factor in HEP: BSM searches



[Plot by Frederic Dreyer]

Unphysical differences in the **radiation pattern** from quark and gluon jets induced by parton showers jeopardizes **Machine Learning** applications for boosted objects tagging, limiting **new physics** searches

Unless you are highly confident in the information you have about the markets, you may be better off ignoring it altogether

Harry Markowitz (1990 Nobel Prize in Economics)


Melissa van Beekveld
NIKHEF


Mrinal Dasgupta
Manchester


Basem El-Menoufi
Monash


Silvia Ferrario Ravasio
CERN


Keith Hamilton
Univ. Coll. London


Jack Helliwell
Oxford


Alexander Karlberg
CERN


Pier Monni
CERN


Gavin Salam
Oxford


Ludovic Scyboz
Monash


Alba Soto-Ontoso
CERN


Grégory Soyez
IPhT, Saclay

PanScales

A project to bring logarithmic understanding and accuracy to parton showers


Silvia Zanoli
Oxford

Former members


Frédéric Dreyer

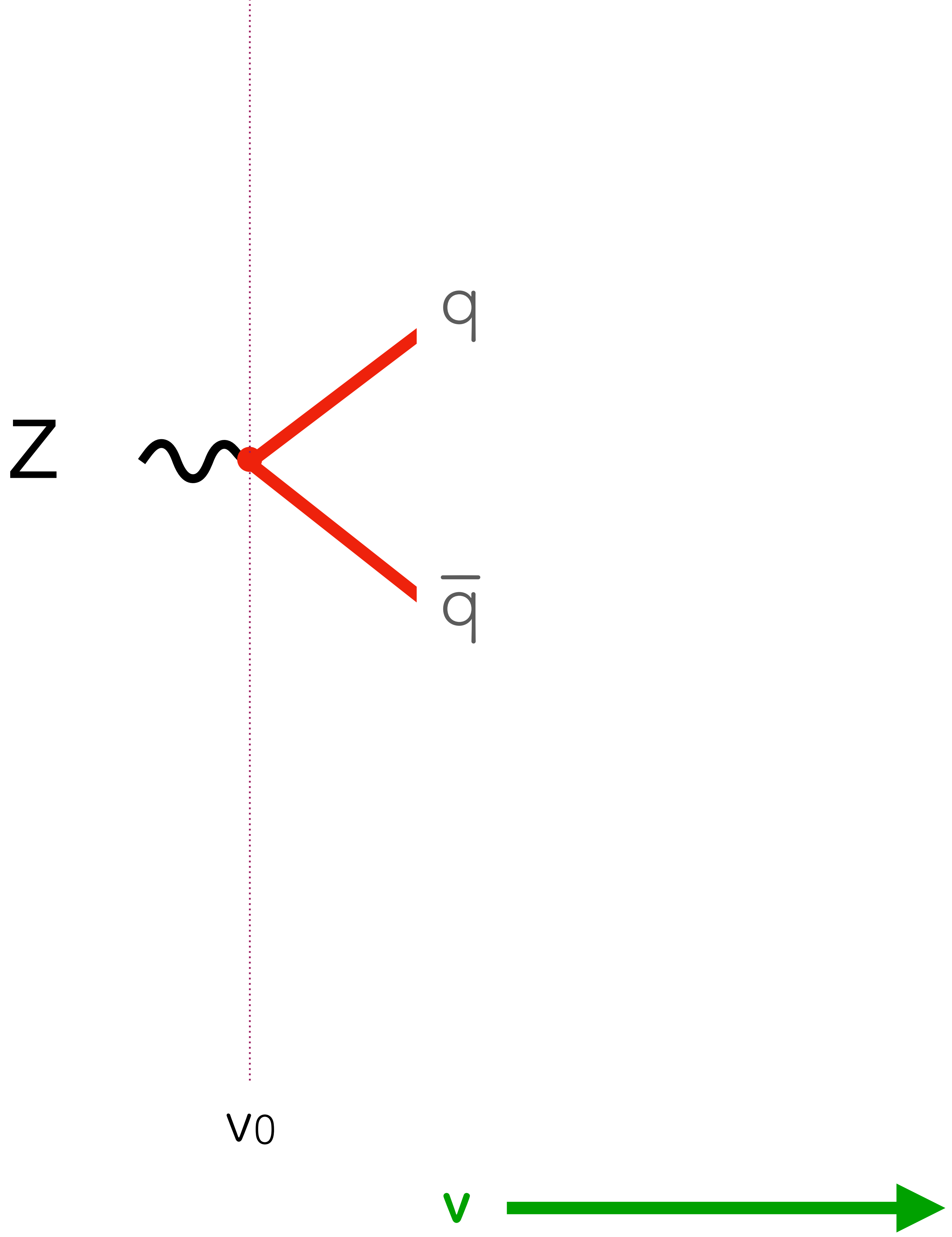

Rok Medves


Rob Verheyen

Scarlett Woolnough

Parton Showers in a nutshell

Dipole showers [Gustafson, Pettersson, ’88] are the most used shower paradigm



Start with $q\bar{q}$ state produced at a **hard scale** v_0.

Throw a random number to determine down to what **scale** state persists unchanged

$$\Delta(v_0, v) = \exp\left(-\int_{v}^{v_0} dP_{q\bar{q}}(\Phi) \right)$$

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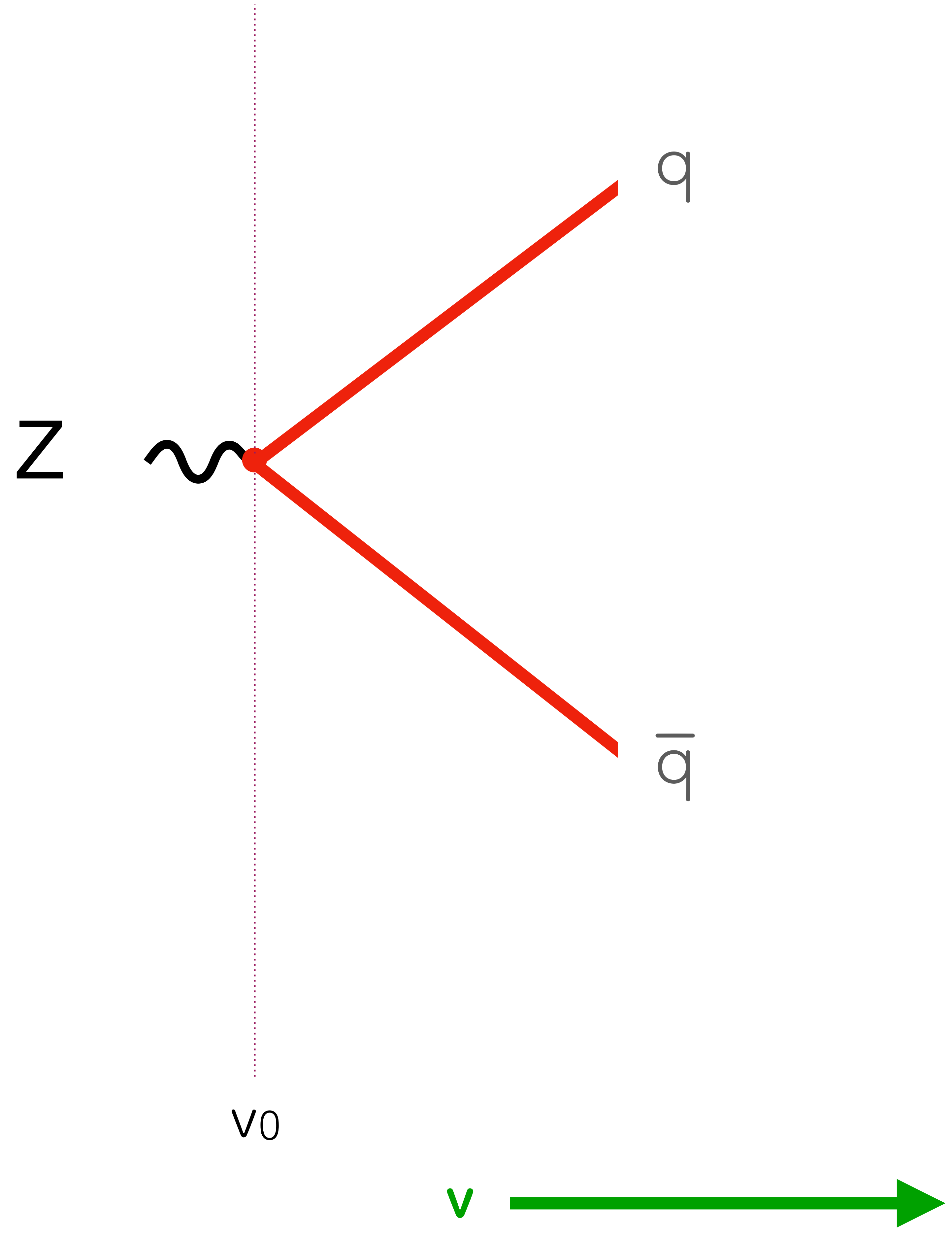

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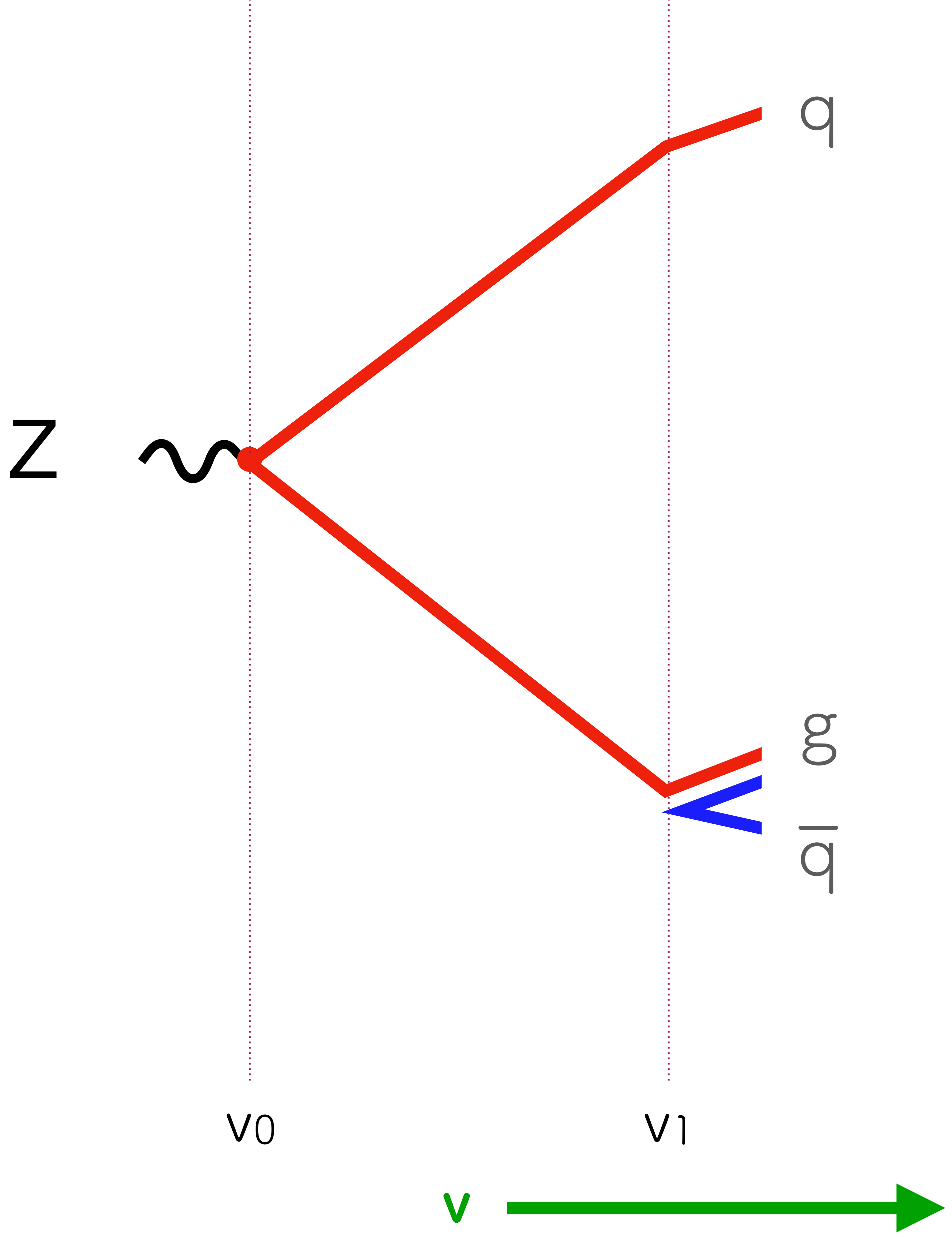


Start with $q\bar{q}$ state produced at a hard scale v_0.

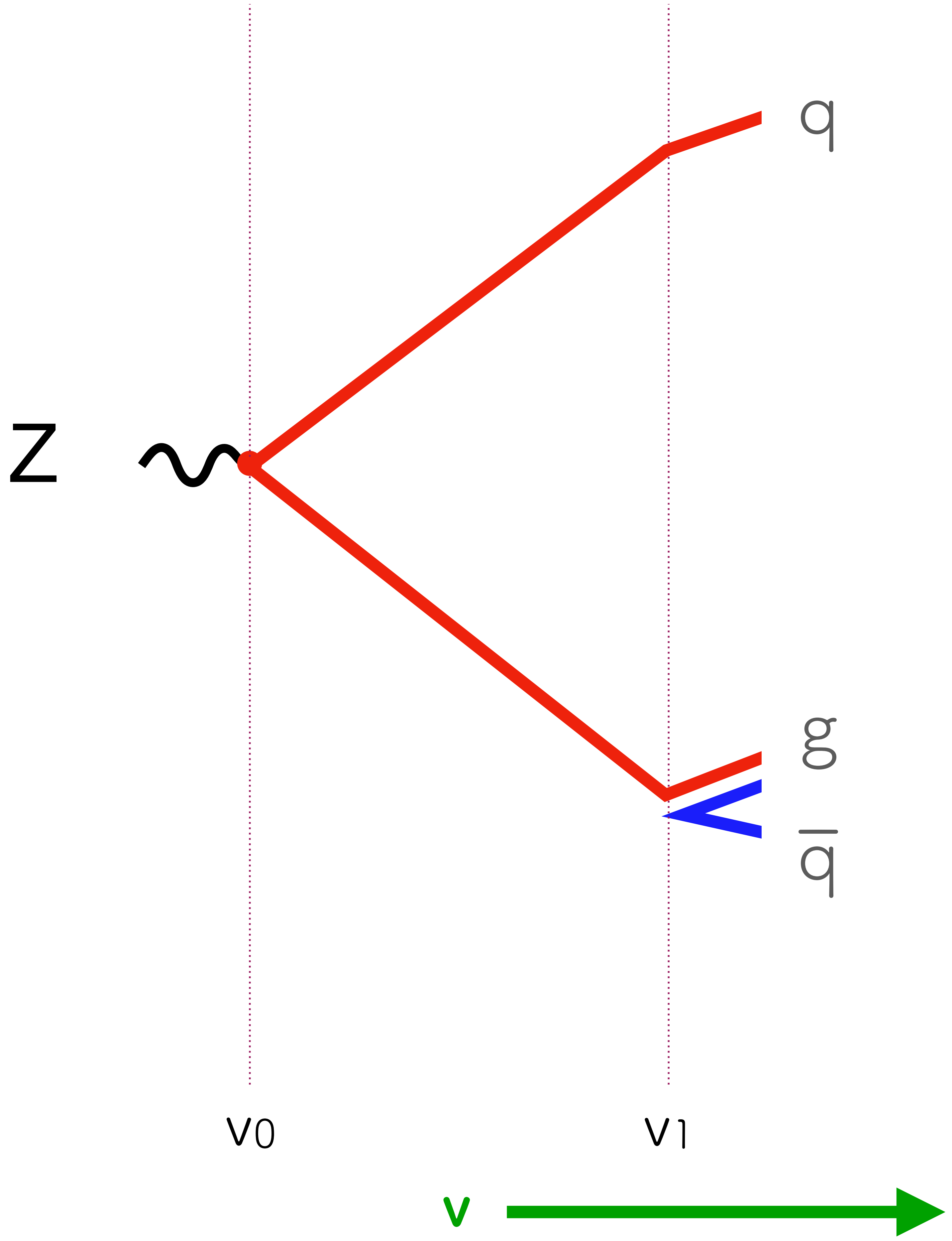
Throw a random number to determine down to what **scale** state persists unchanged

At some point, **state splits** (2→3, i.e. emits gluon) at a scale $v_1 < v_0$. The kinematic (rapidity and azimuth) of the gluon is chosen according to

$$dP_{q\bar{q}}(\Phi(v_1)) \qquad \Phi = \{v, \eta, \varphi\}$$

Parton Showers in a nutshell

Dipole showers [Gustafson, Pettersson, ’88] are the most used shower paradigm



Start with $q\bar{q}$ state produced at a **hard scale** v_0.

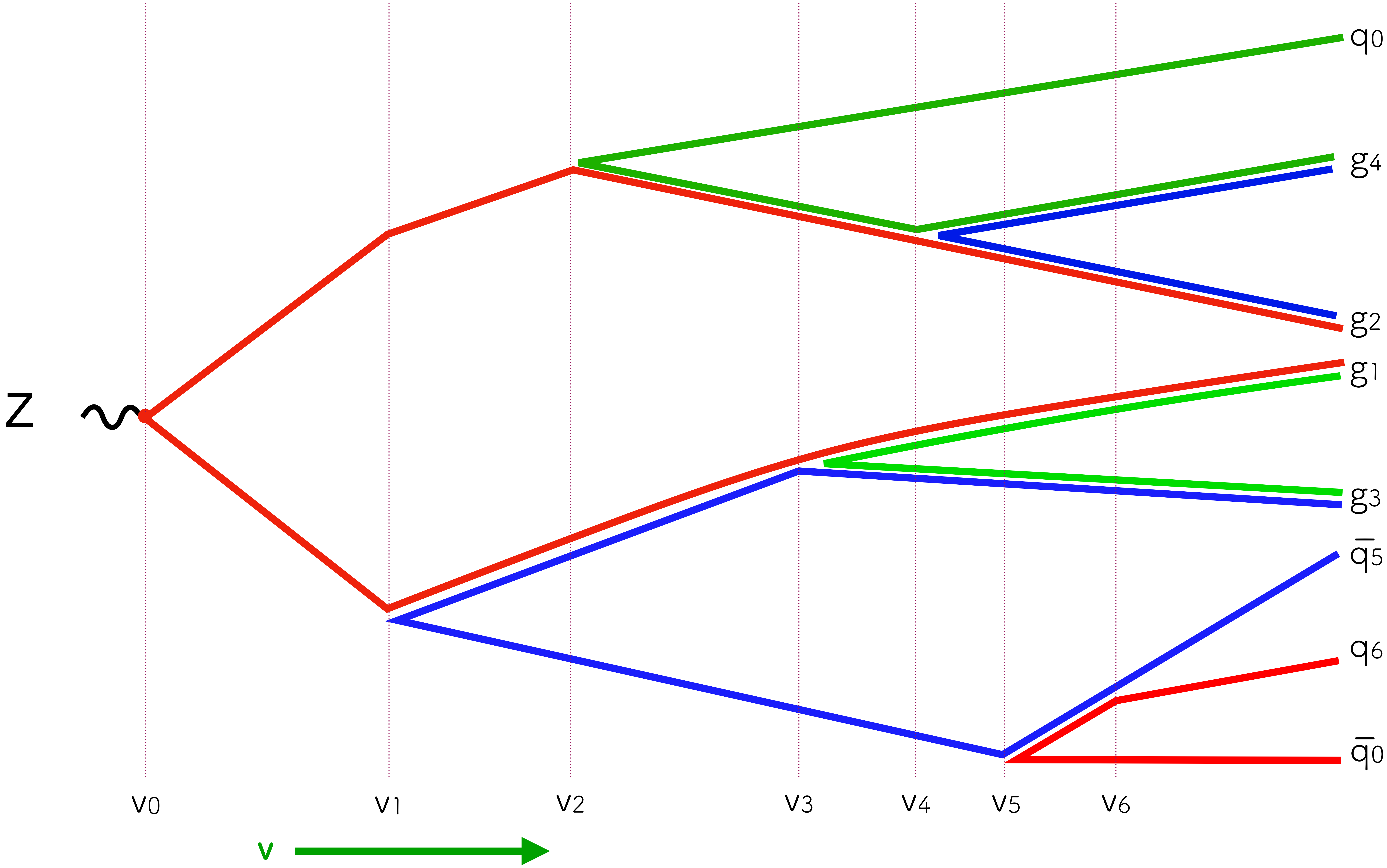
Throw a random number to determine down to what **scale** state persists unchanged

At some point, **state splits** (2→3, i.e. emits gluon) at a scale $v_1 < v_0$.

The gluon is part of two dipoles (qg), $(g\bar{q})$.

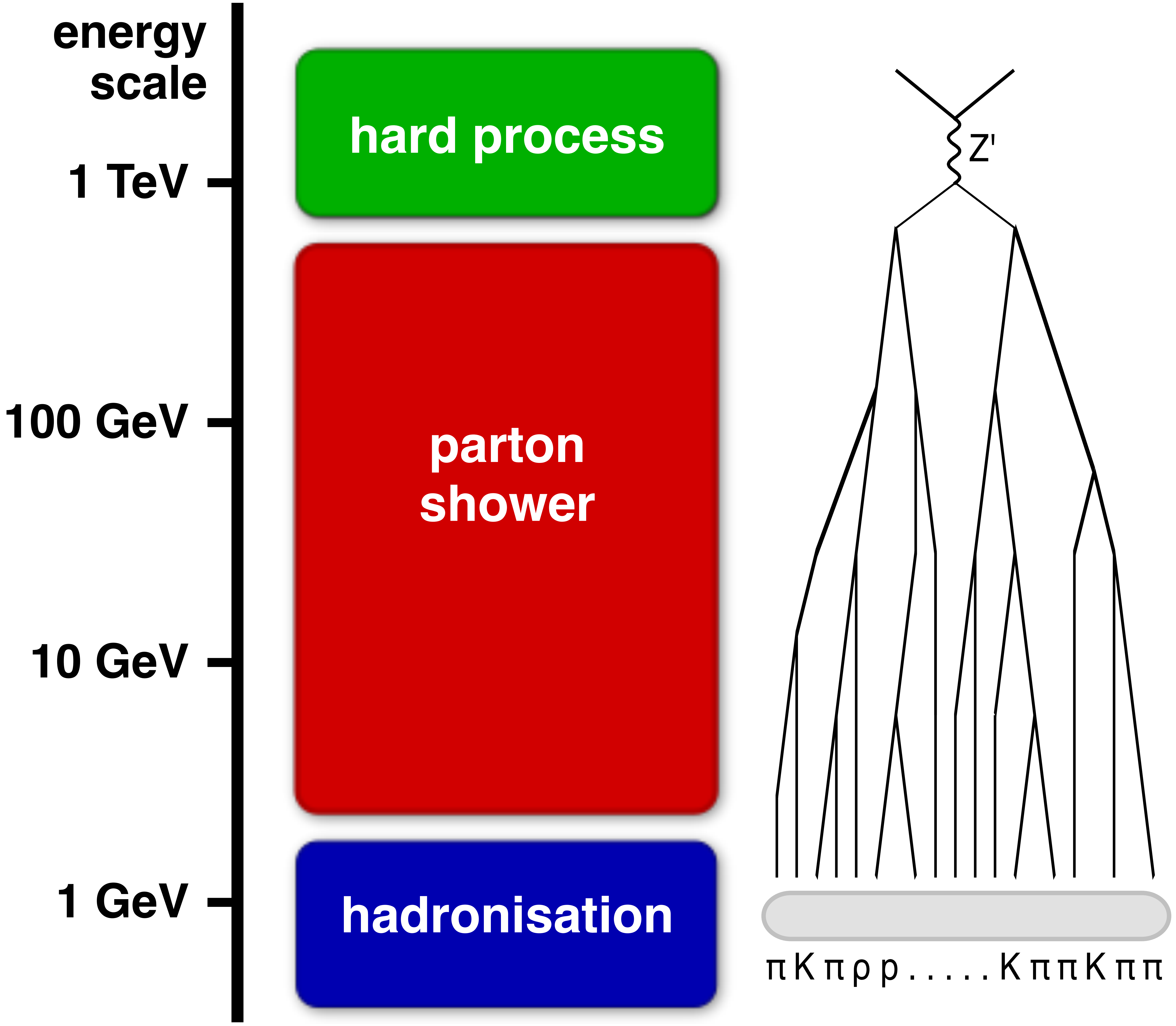
Iterate the above procedure for both dipoles independently, using v_1 as starting scale.

Parton Showers in a nutshell



self-similar evolution continues until it reaches a non-perturbative scale

What should a Parton Shower achieve?



- **Parton showers** evolve collider events from $Q \approx \mathcal{O}(\text{TeV})$ to $\Lambda \approx 1\text{GeV}$
- During this evolution, large logarithms $L = \log Q/\Lambda$ will arise.
- Logarithmic accuracy to assess showers

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

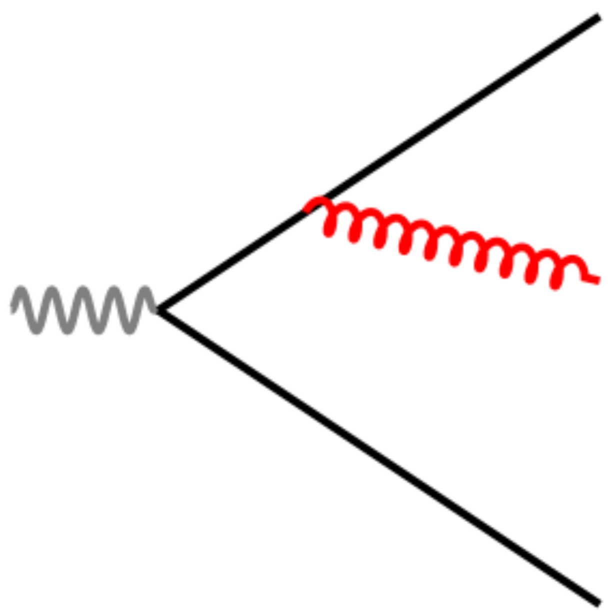
E.g. $O = \frac{p_{\perp,Z}}{m_Z}$ and $p_{\perp,Z} \approx 1\,\text{GeV}$,

$|\alpha_s L| = 0.55$:

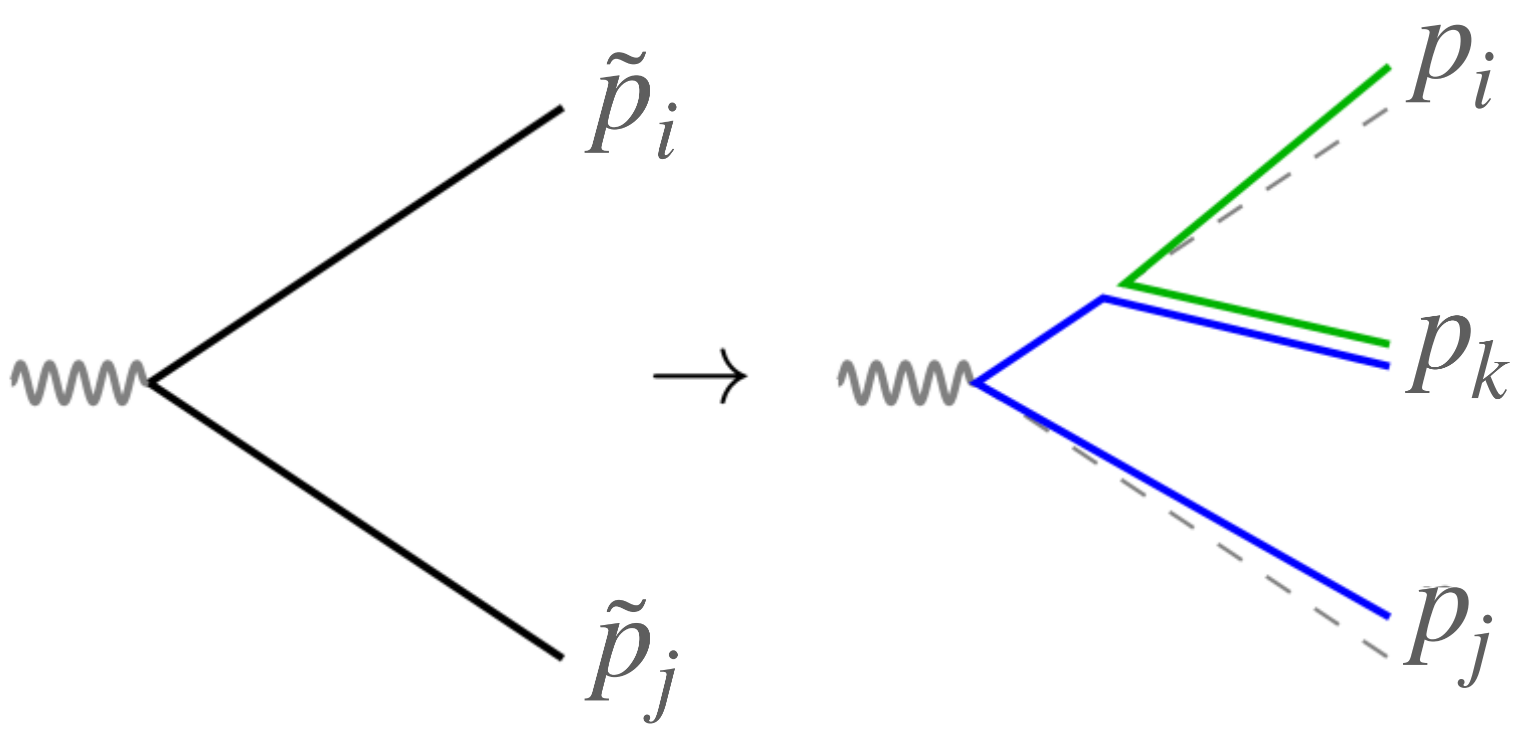
Next-to-Leading Logarithms are $\mathcal{O}(1)$

Which degrees of freedom does a parton shower have?

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



viewed as



$$\mathrm{d}\mathcal{P}_{\tilde{i}\tilde{j}\to ijk} \sim \frac{\alpha_s}{2\pi}\underbrace{\frac{\mathrm{d}v^2}{v^2}\mathrm{d}\bar{\eta}\frac{\mathrm{d}\varphi}{2\pi}}_{\text{Phase-space}}\underbrace{\left[g(\bar{\eta})z_iP_{ik}(z_i)+g(-\bar{\eta})z_jP_{jk}(z_j)\right]}_{\text{Splitting factor}}$$

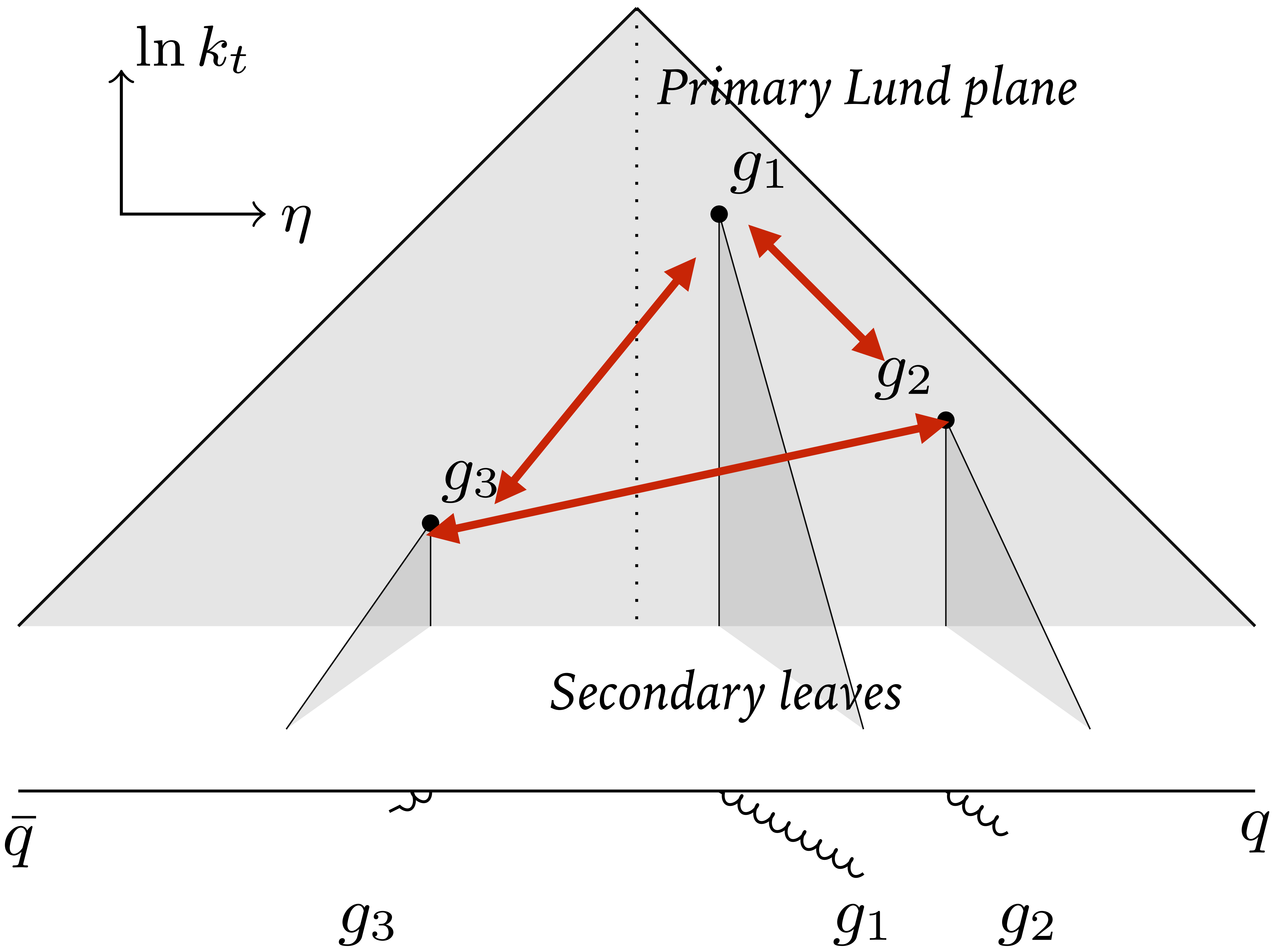
- **1** Evolution variable: v
- **2** Recoil scheme: $\tilde{p}_{i,j} \to p_{i,j,k}$
- **3** Partitioning of dipole: $\bar{\eta}$

These choices affect the logarithmic accuracy of the shower

Dissecting the structure of NLL showers

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

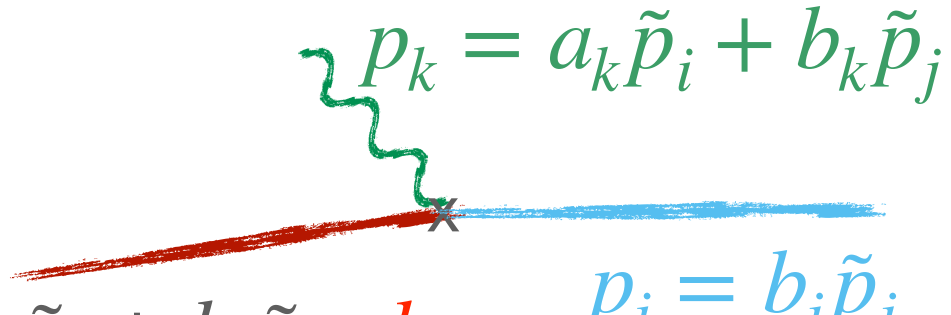
PanScales criterium: a new emission cannot affect previous ones if they are well-separated in at least one direction of the Lund plane



What do state-of-the-art dipole shower implement?

1 **Evolution variable**: transverse momentum $v \sim k_\perp$

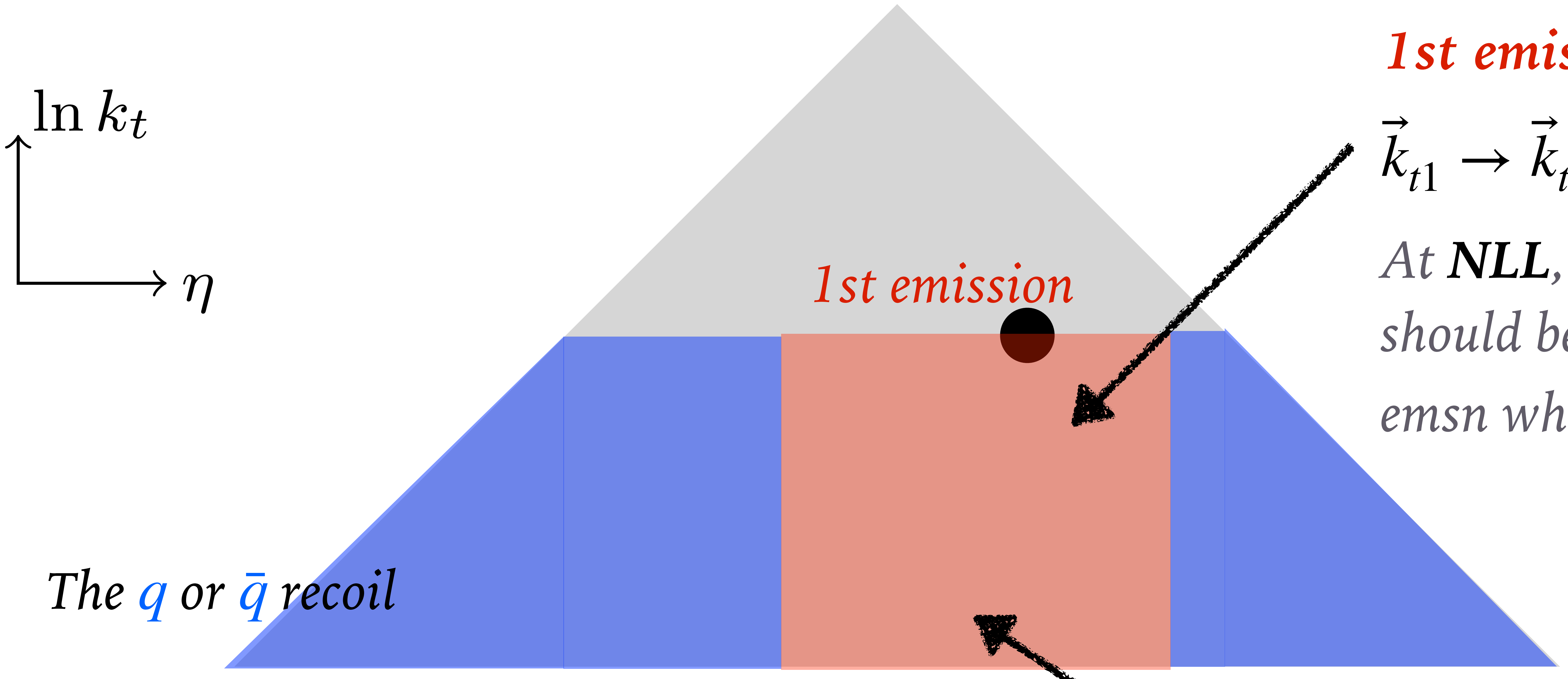
2 **Recoil scheme**: fully local, with one parton absorbing the (majority of) the $k_\perp$ recoil



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

Let's study the $\mathcal{O}(\alpha_s^2)$-expansion of this shower.

How well state-of-the-art dipole shower populate the Lund plane?

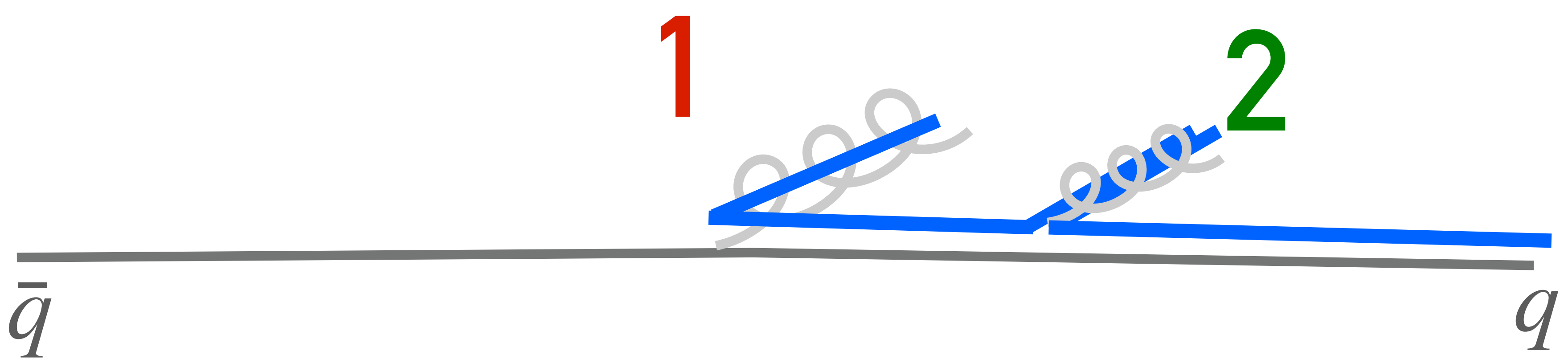


1st emission recoils

$\vec{k}_{t1} \to \vec{k}_{t1} - \vec{k}_{t2}$

At ***NLL****, the 1st emission should be unaffected by other emsn when* $|\eta_1 - \eta_2| \gg 1$

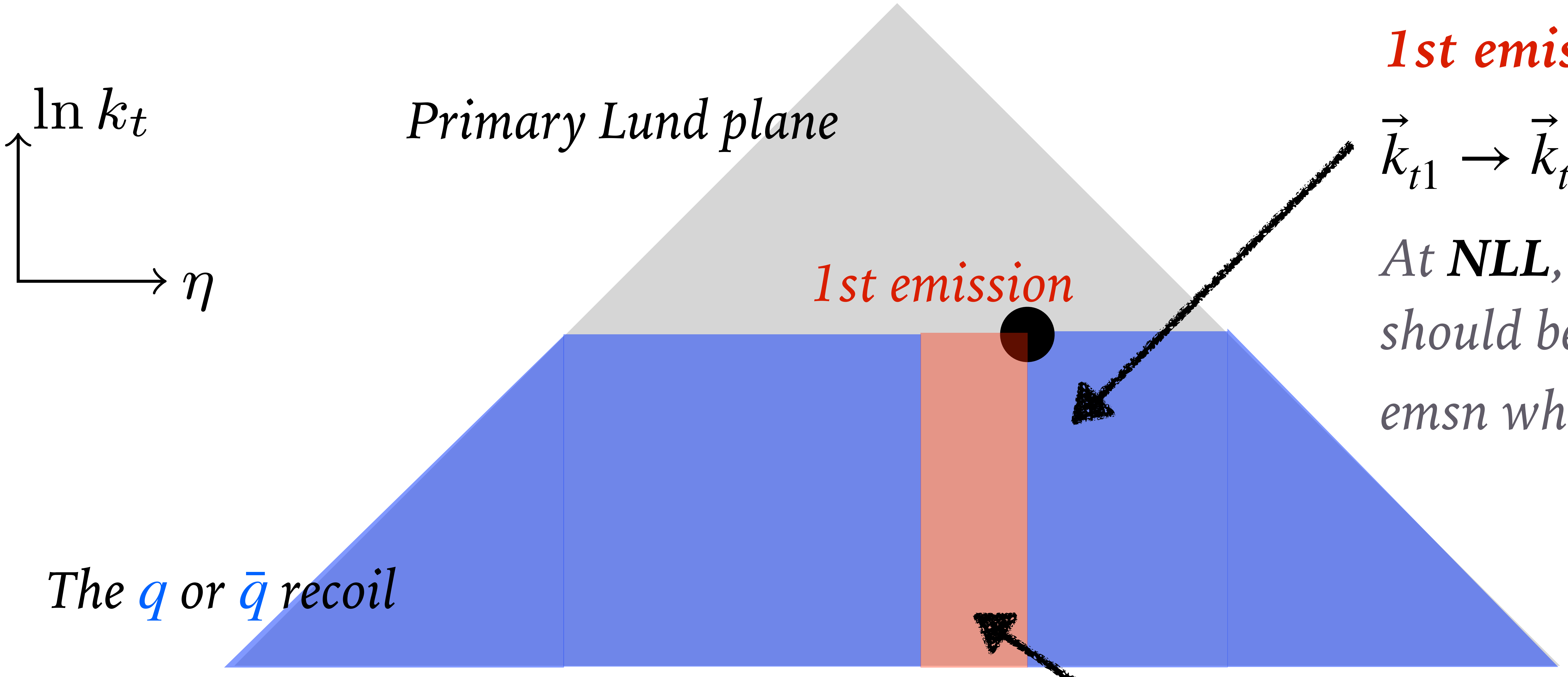
if $k_{t2} \ll k_{t1}$*, the recoil is not an issue:* ***LL is OK****!*



1805.09327 Dasgupta, Dreyer, Hamilton, Monni, Salam

Building a NLL shower

__Dipole-partitioning__ in the event frame reduces but does not solve the problem



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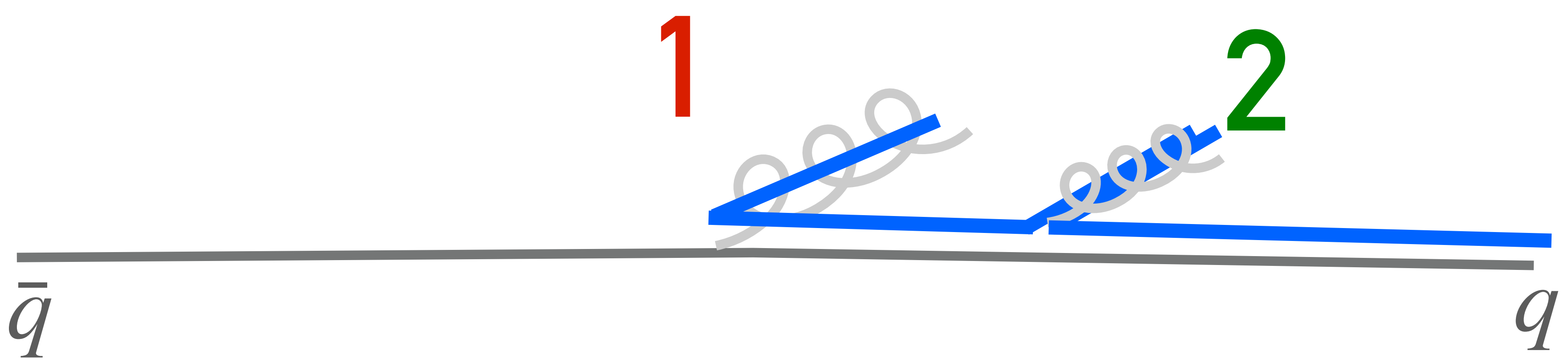


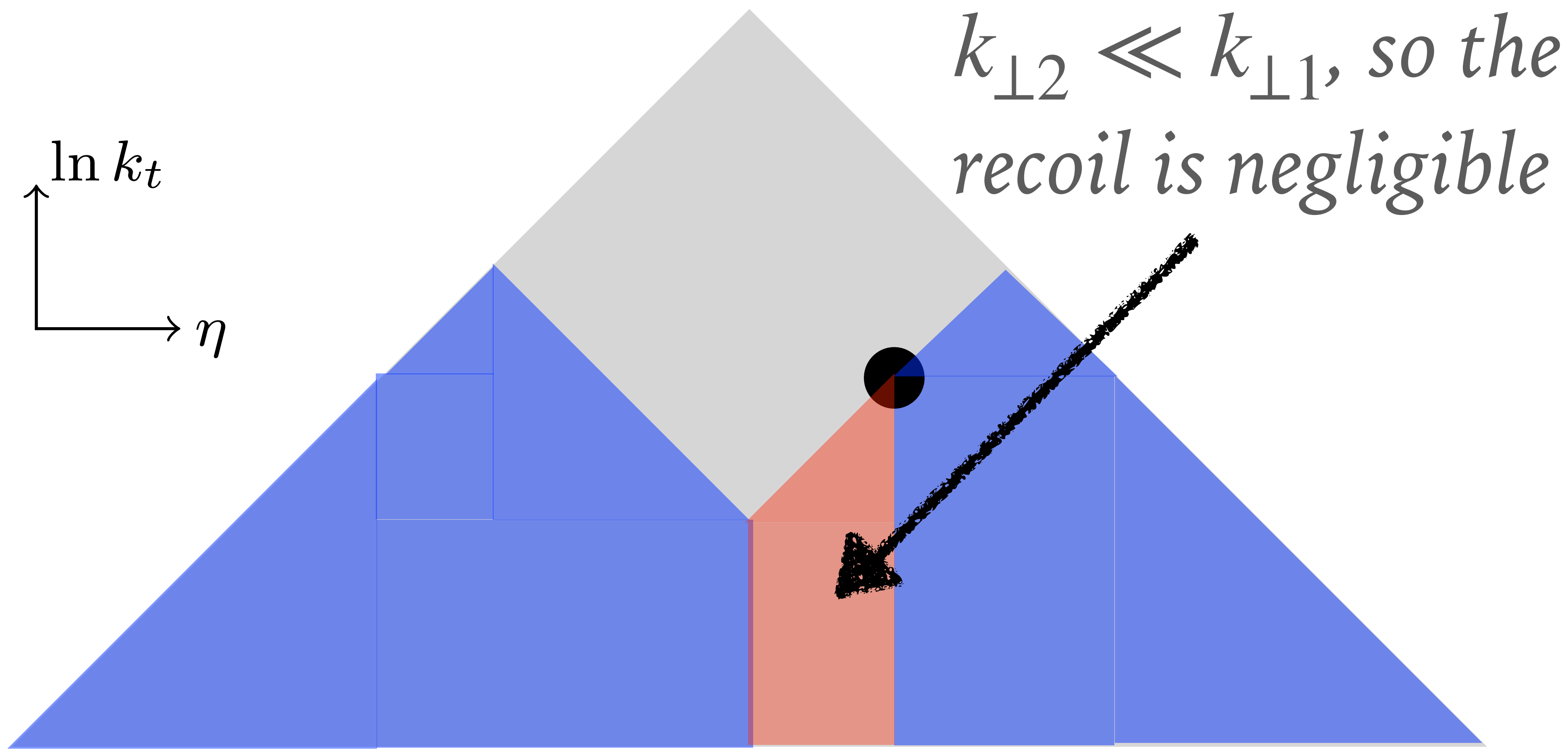
2002.11114 Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez

Building a NLL shower

2002.11114 Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez

Dipole-partitioning in the event frame

PanLocal($0 < \beta < 1$)



$k_{\perp 2} \ll k_{\perp 1}$, so the recoil is negligible

Evolution variable: $v \sim k_\perp e^{-\beta|y|}$

Deductor by Nagy & Soper 0912.4534 follows a similar approach (with $\beta = 1$)

Building a NLL shower

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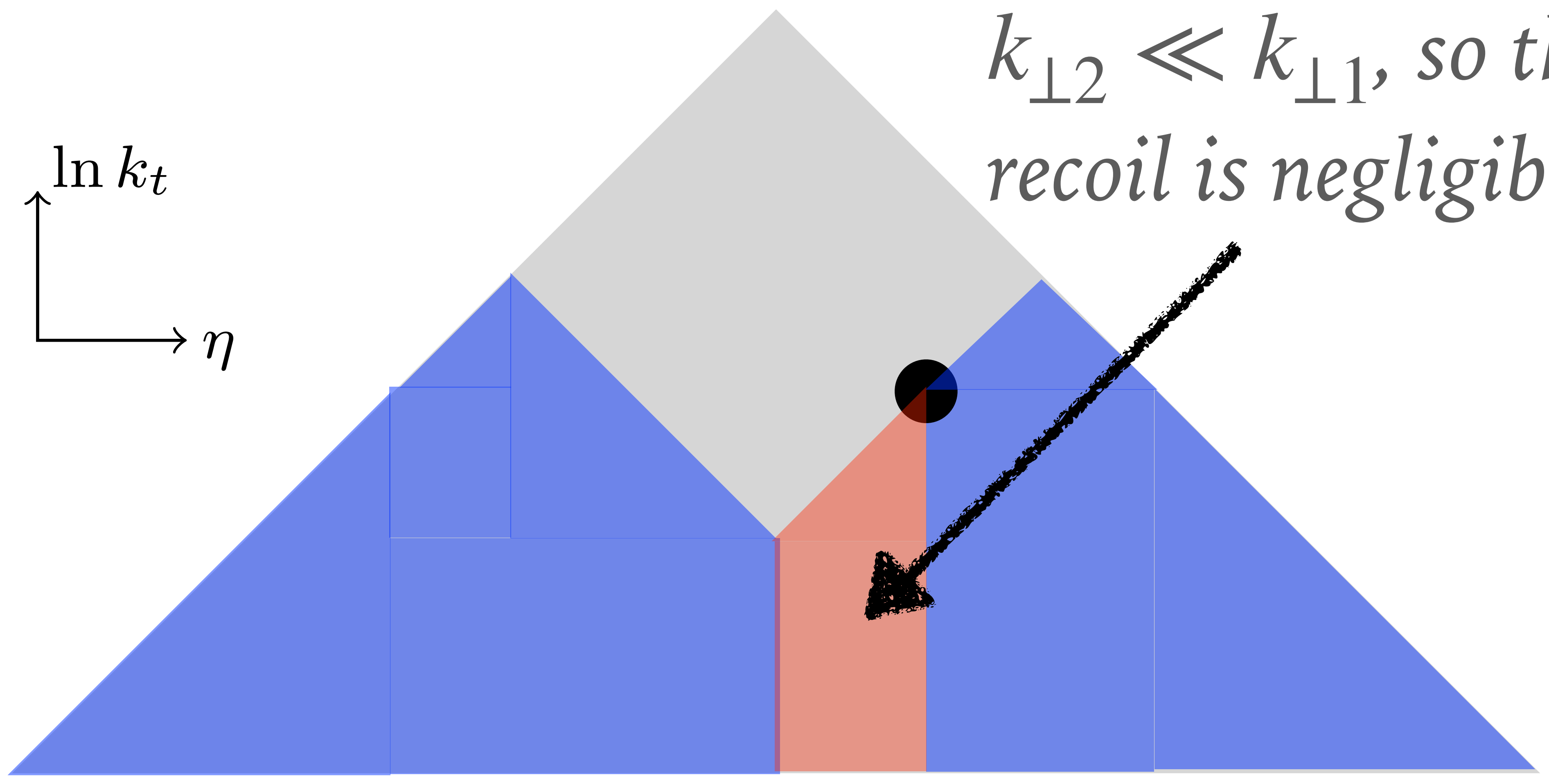

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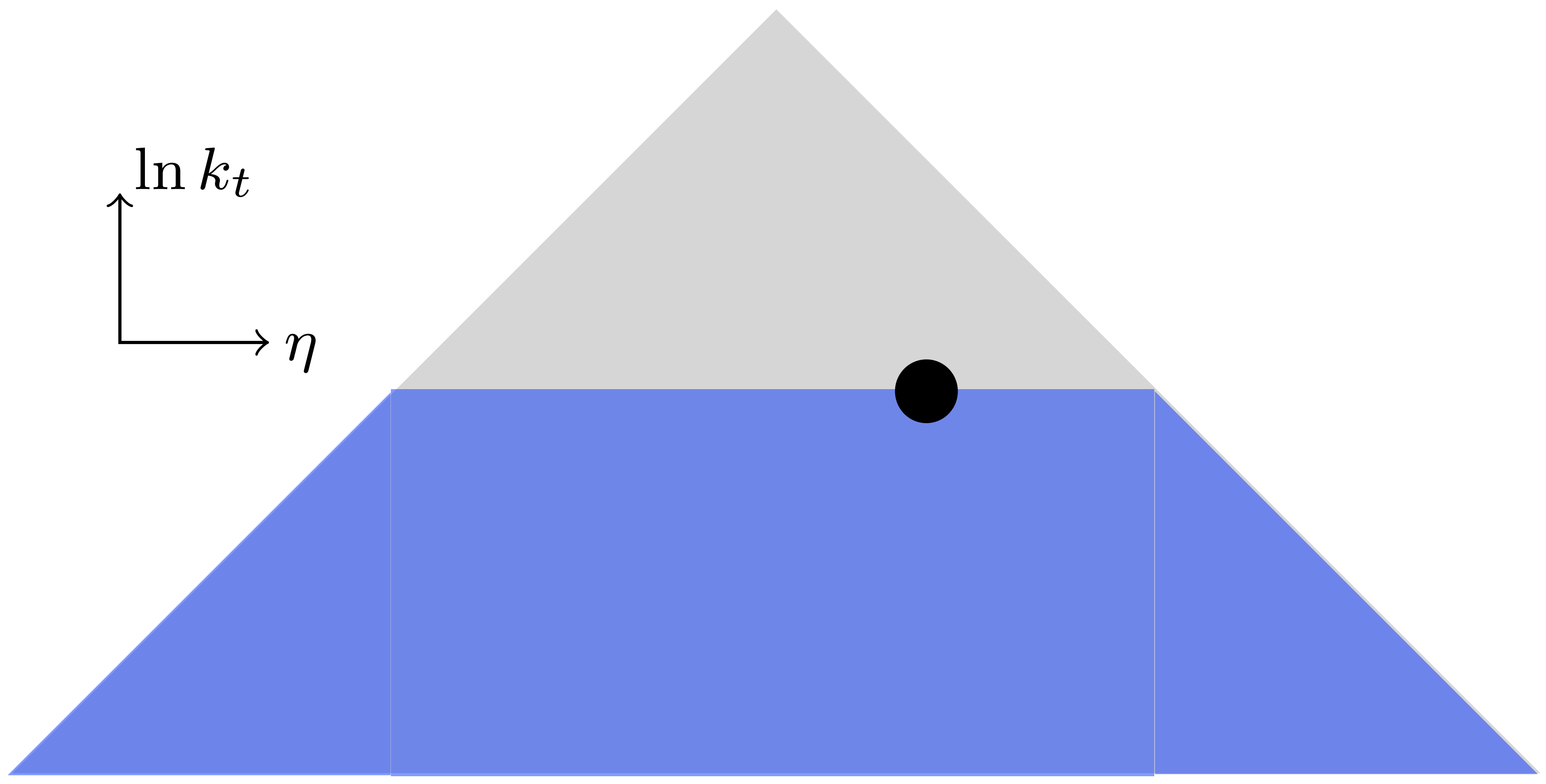
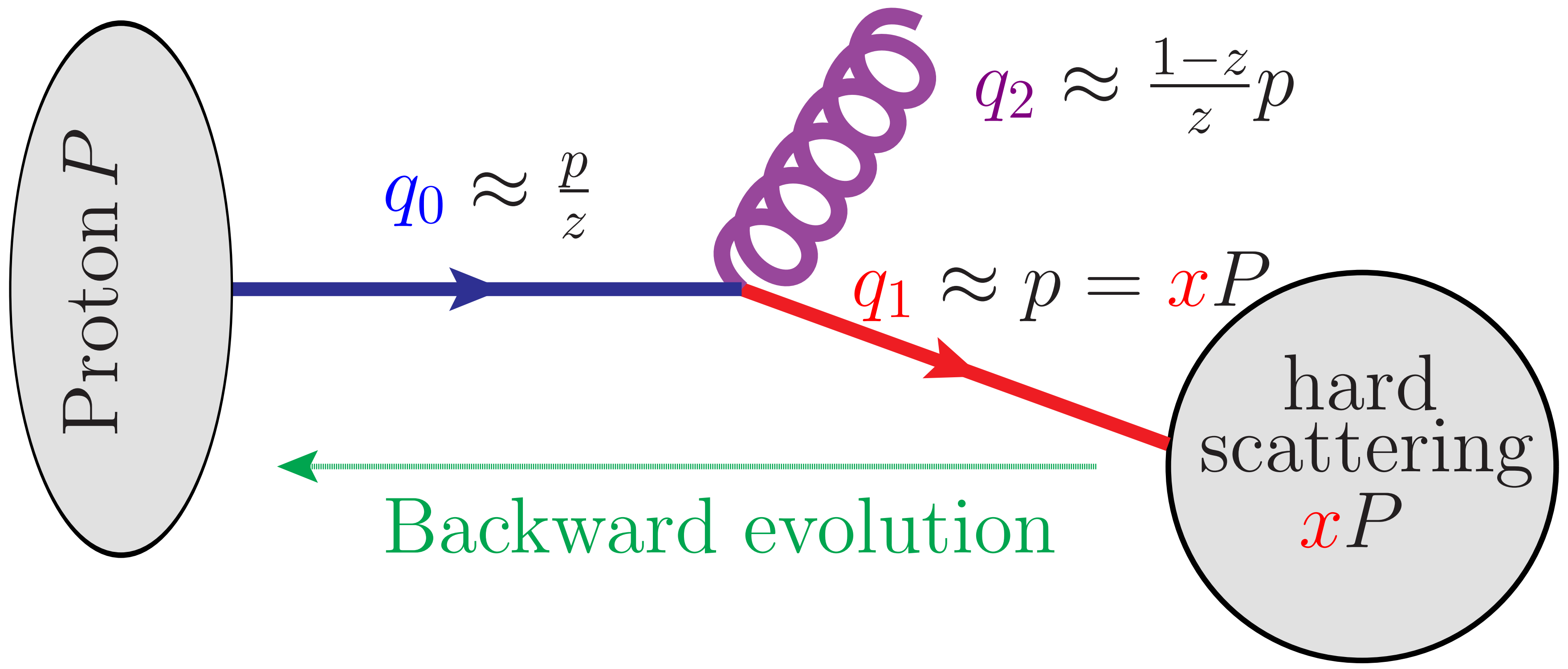


Recoil: $k_{\perp}$ is redistributed among all the partons in the event (mainly the hardest)

Deductor by Nagy & Soper 0912.4534 follows a similar approach (with $\beta = 1$)

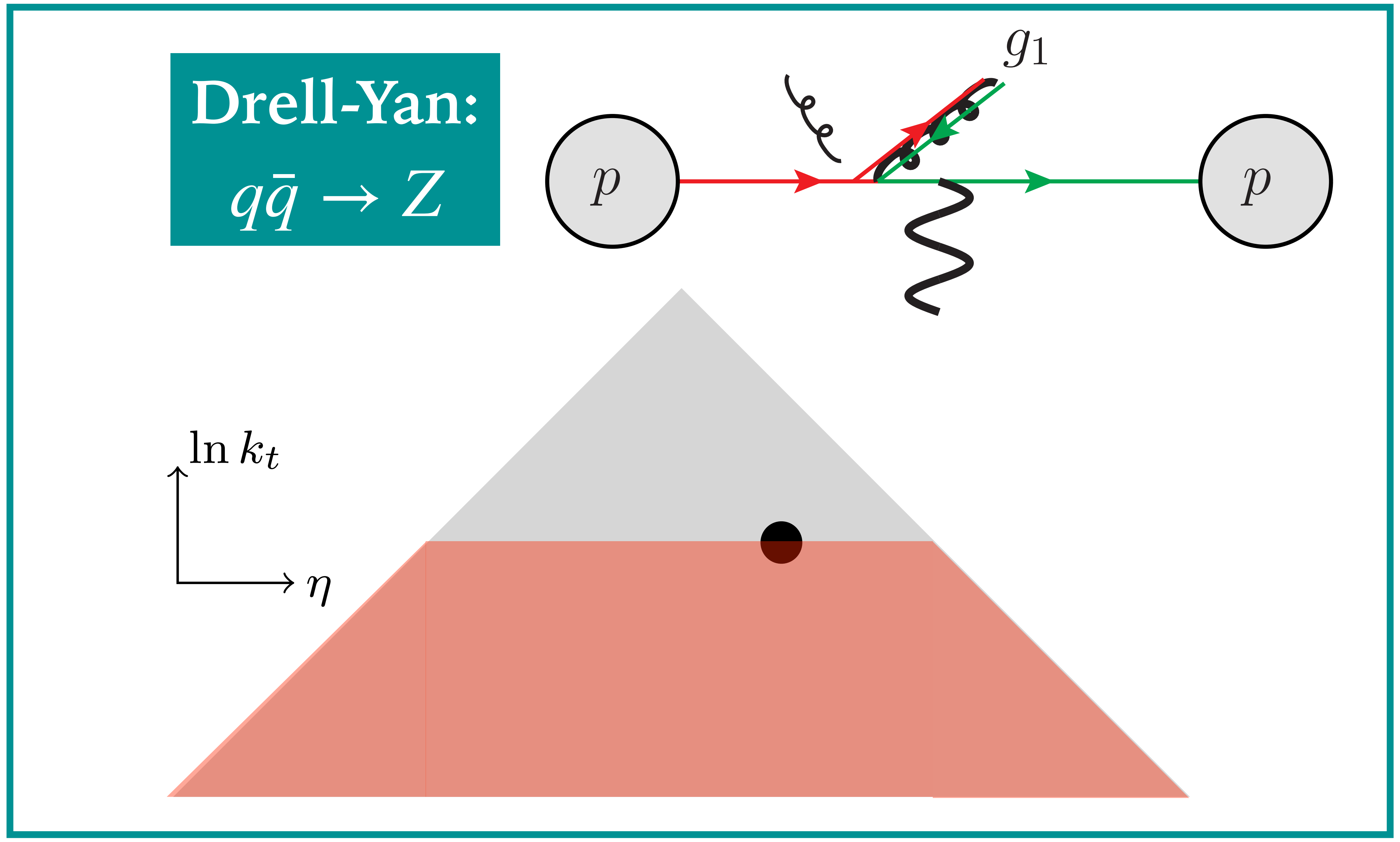
Holguin, Forshaw and Plätzer 2003.06400, and Alaric by Herren et al. 2208.06057 follow a similar approach

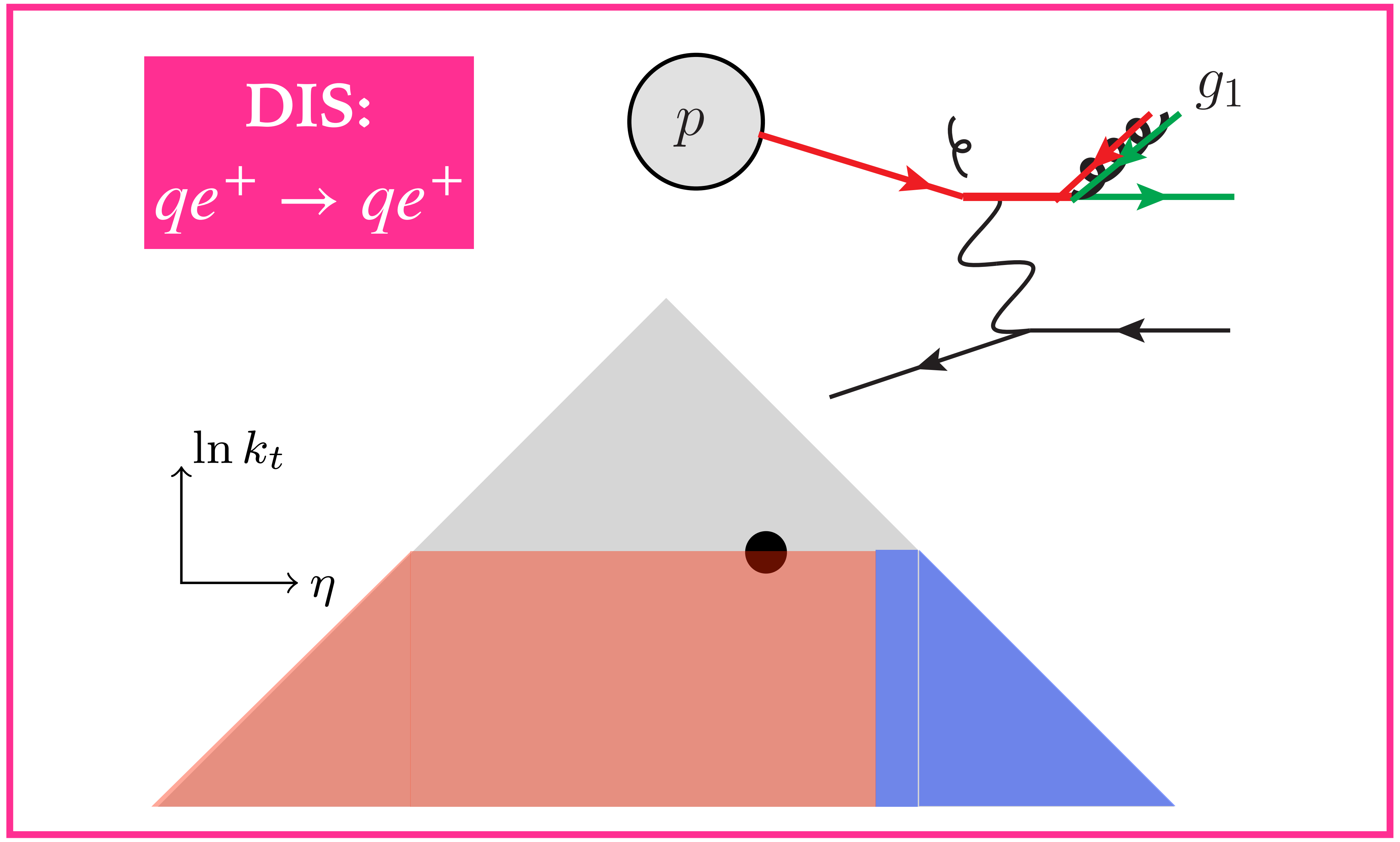
Initial-state radiation in common dipole showers



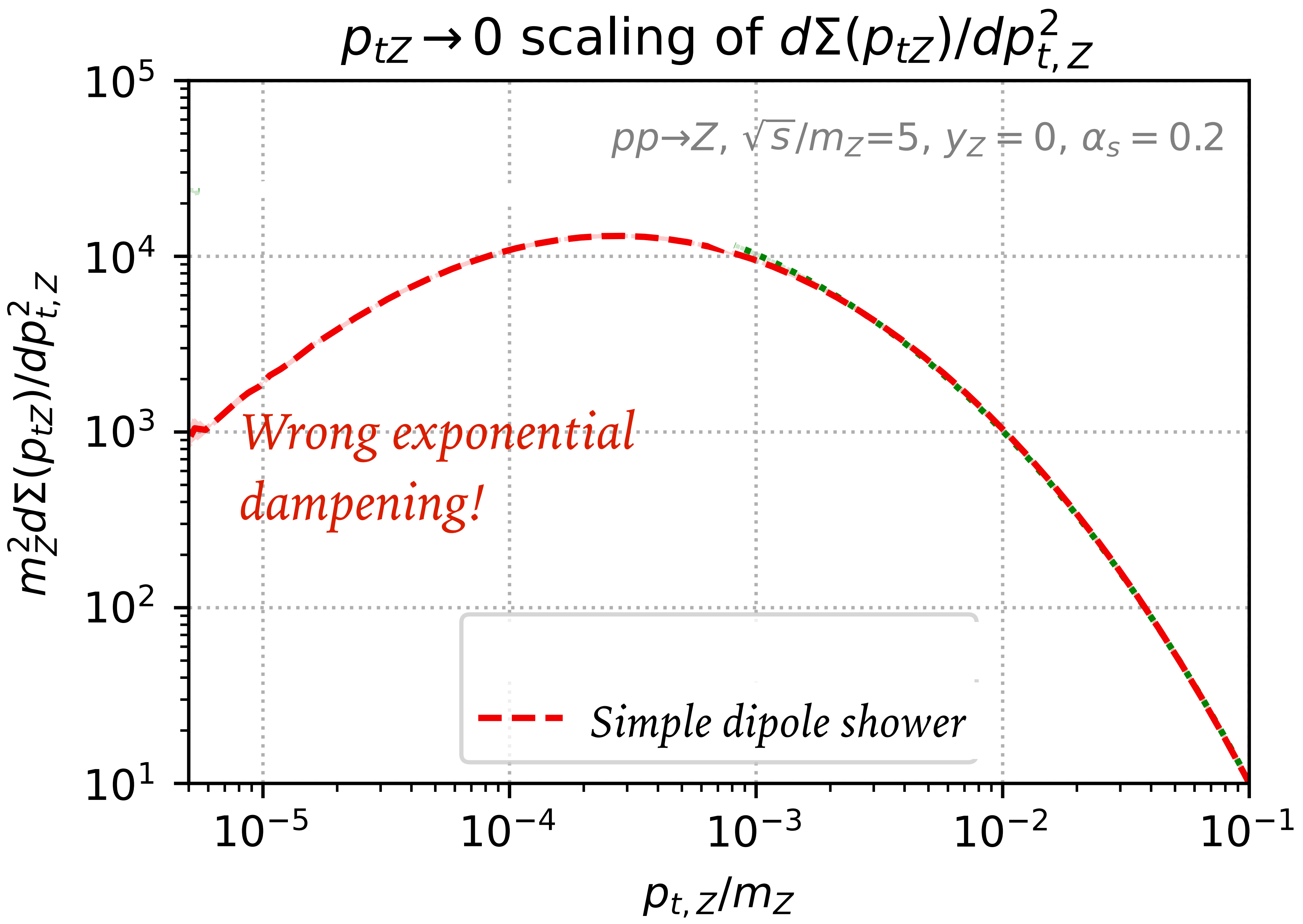
Initial-state radiation: assignement of p_T recoil is more delicate as the emitter cannot take it!

In many dipole-showers the final-state **colour parter** takes it: issue of the recoil even worse!


Drell-Yan:
$q\bar{q} \to Z$

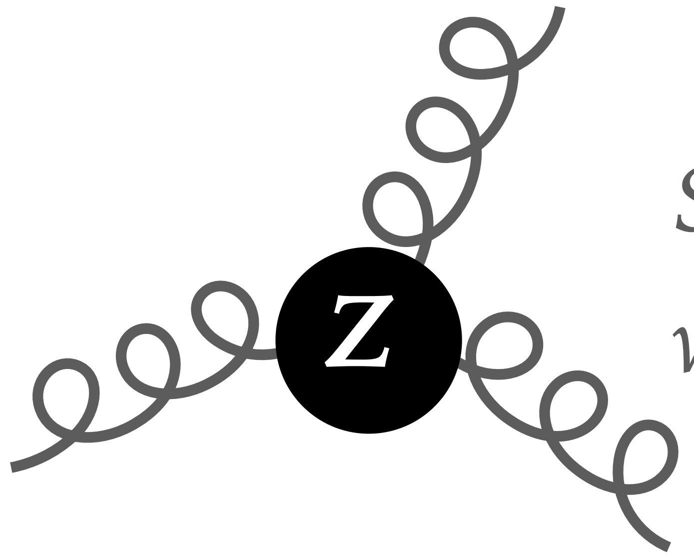

DIS:
$qe^+ \to qe^+$

Transverse momentum of the Z boson in common dipole showers



Wrong exponential dampening!

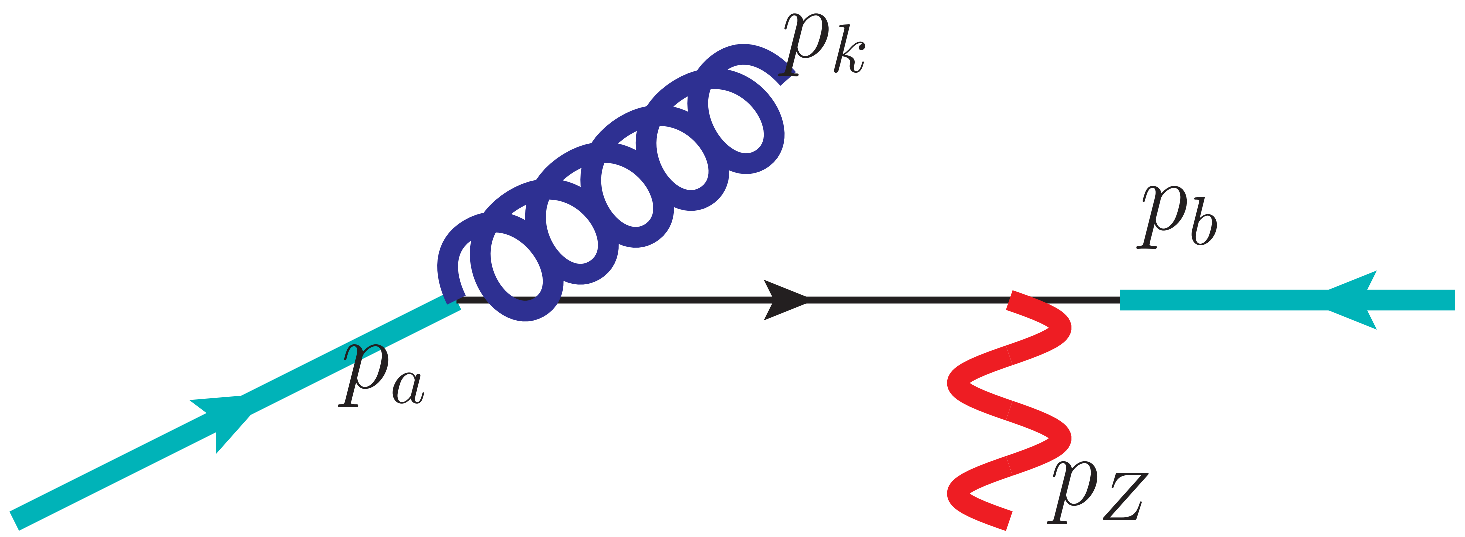
Power-scaling behaviour of the **Z boson $p_\perp$** in Drell Yan [Parisi, Petronzio NPB 154 (1979) 427-440] not achieved



Small p_T region enhanced by emissions with “largish” p_T that cancel vectorially

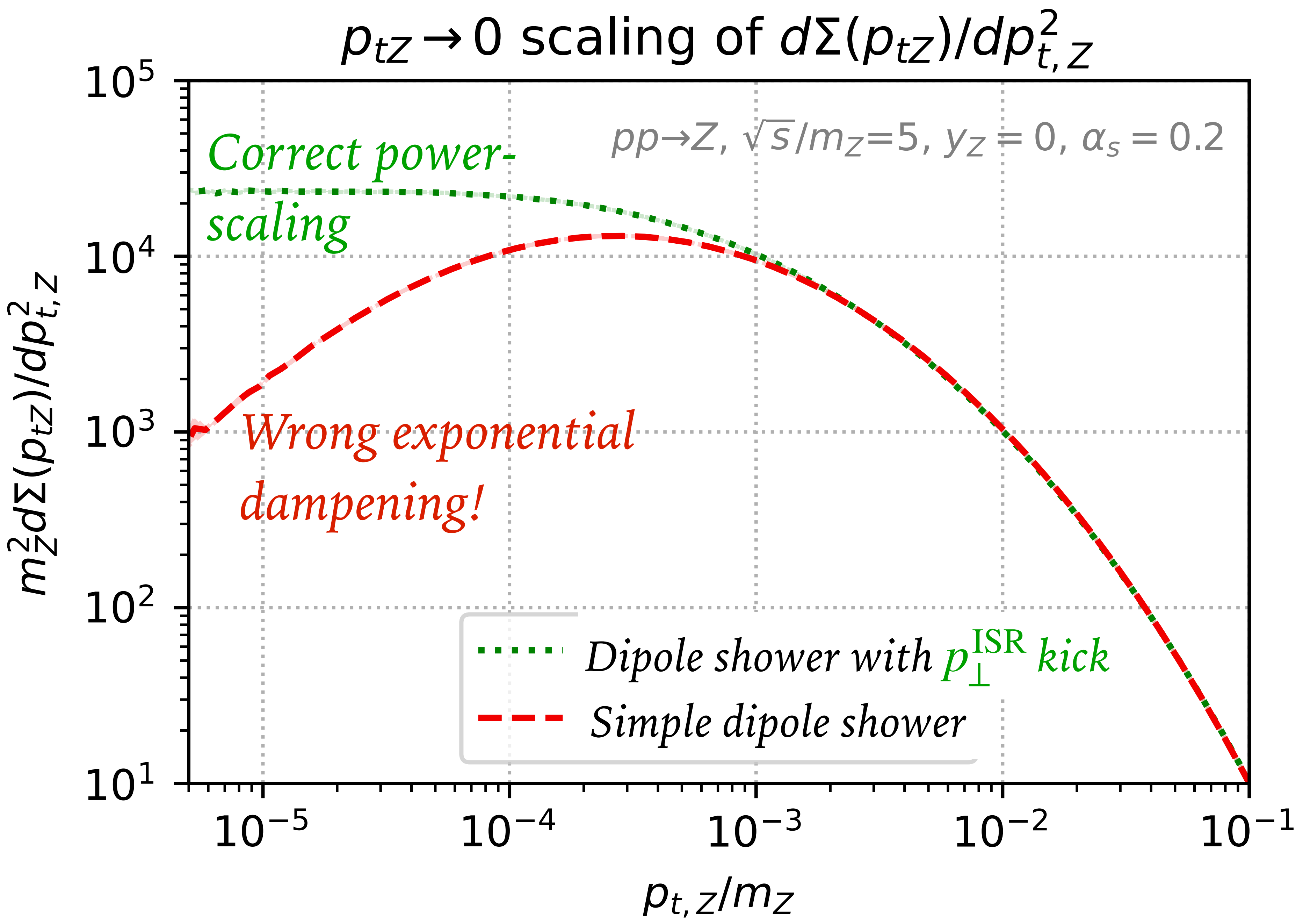
van Beekveld, S.F.R., Hamilton, Salam, Soto-Ontoso, Soyez, Verheyen, 2207.09467

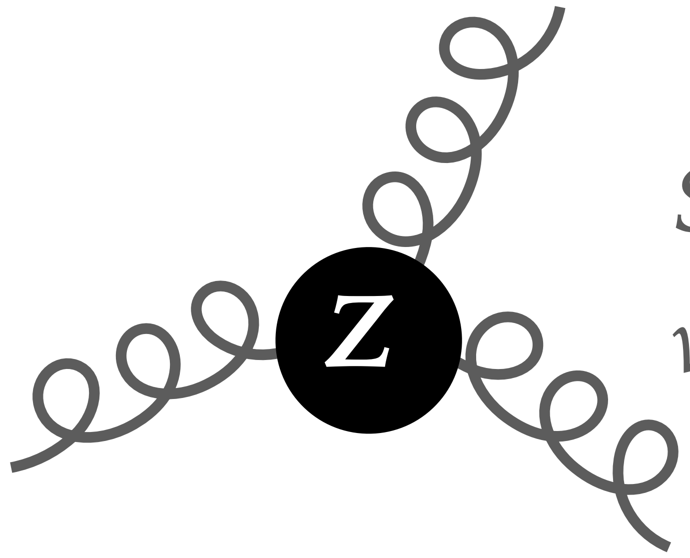
Transverse momentum of the Z boson in common dipole showers



Transverse kick to the incoming parton when it emits, and then perform global boost and rotations to realign it with the z axis. [Plätzer and Gieseke 0909.5593]

Power-scaling behaviour of the **Z boson $p_\perp$** in Drell Yan [Parisi, Petronzio NPB 154 (1979) 427-440]





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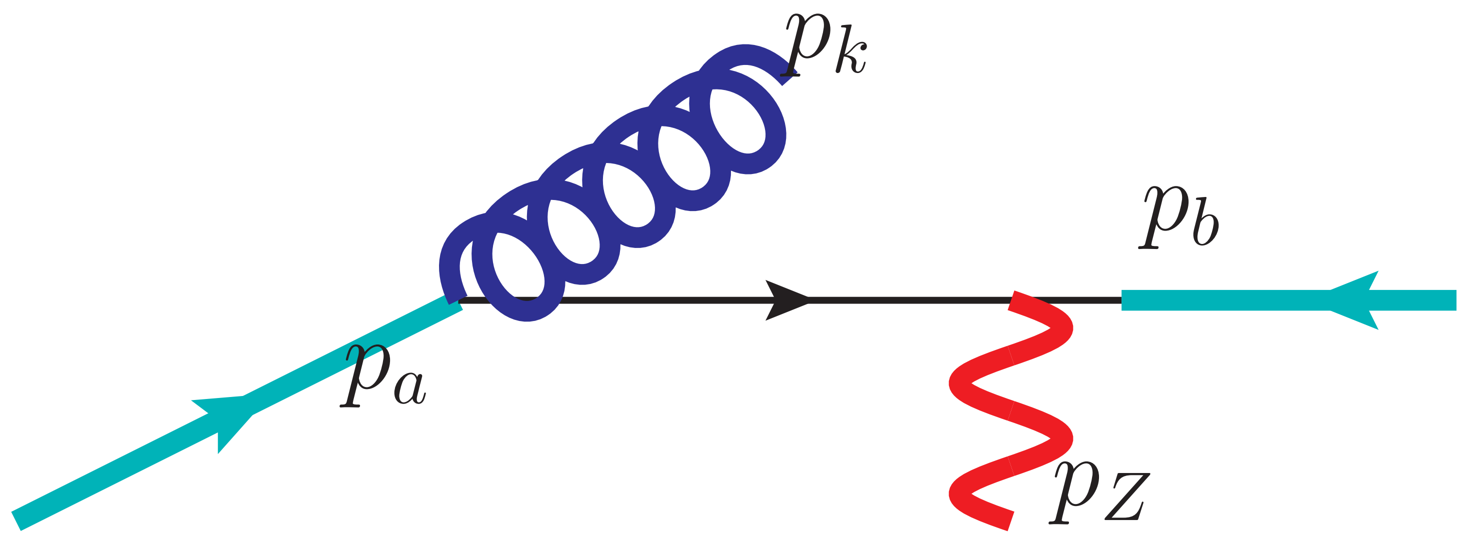

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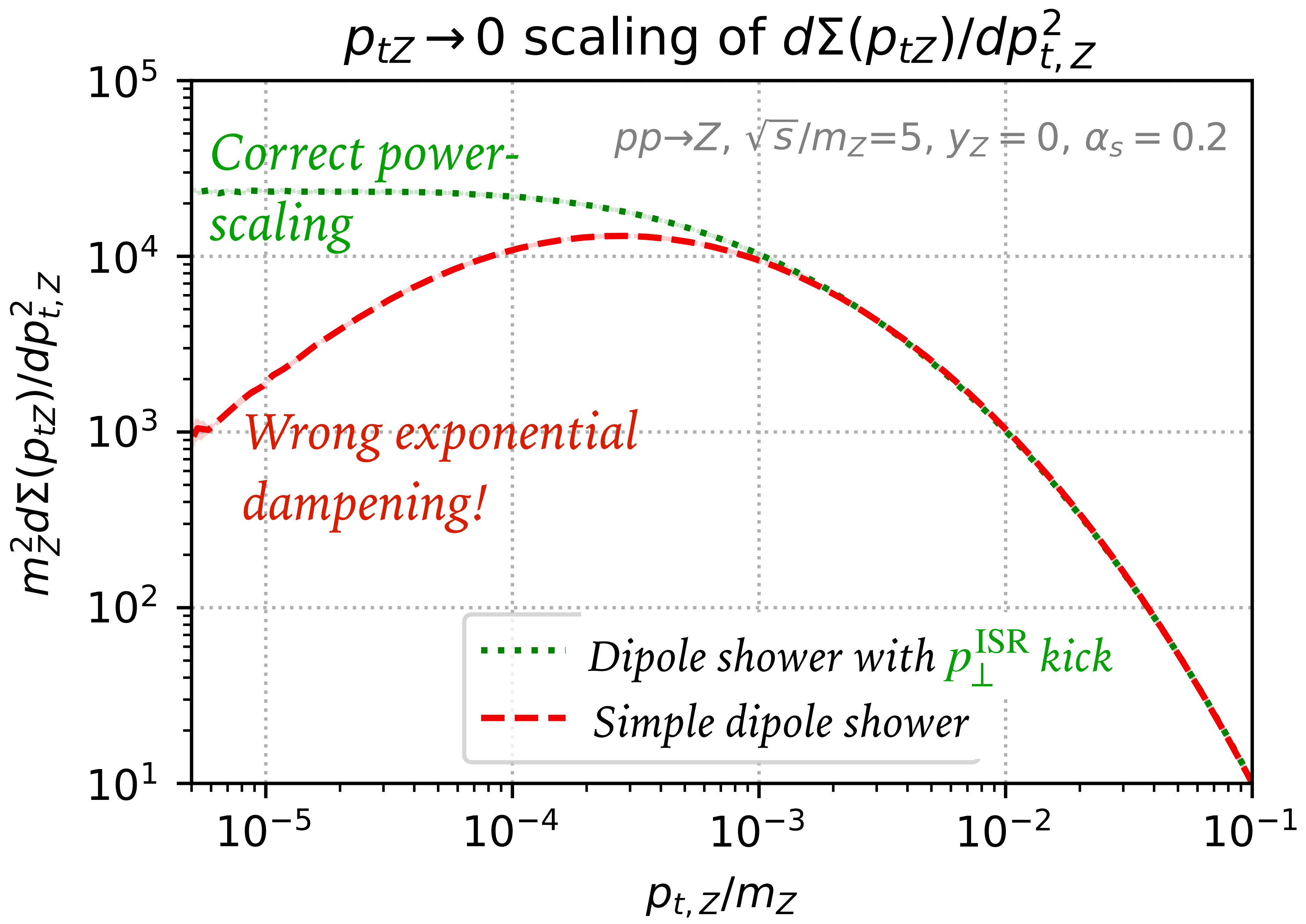
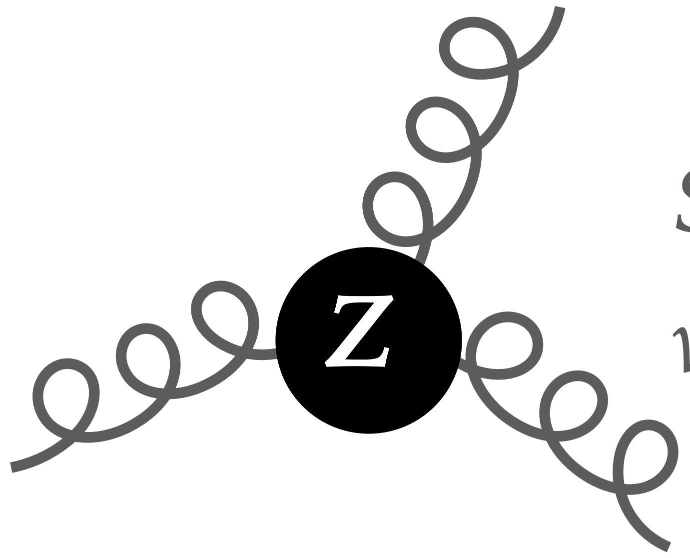
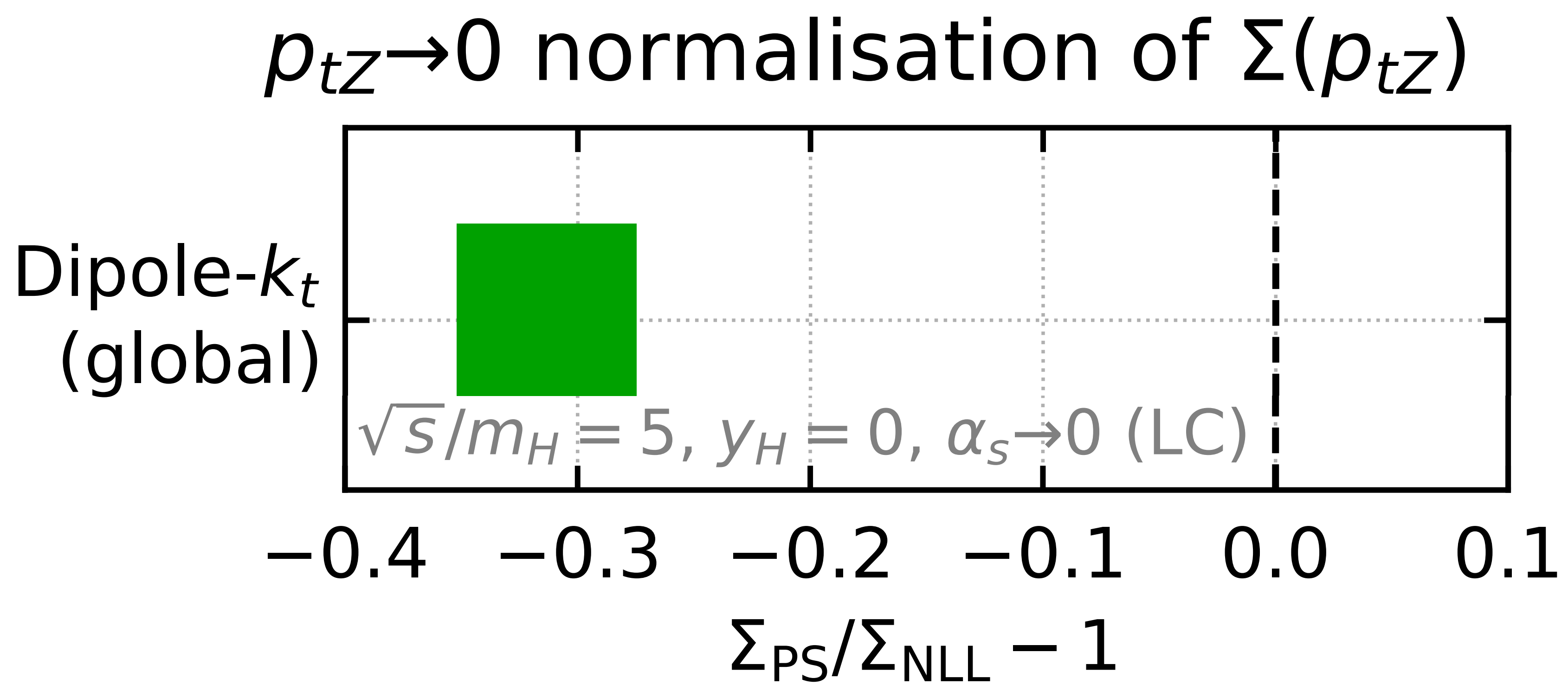
Power-scaling behaviour of the **Z boson $p_\perp$** in Drell Yan [Parisi, Petronzio NPB 154 (1979) 427-440], but the wrong normalisation!





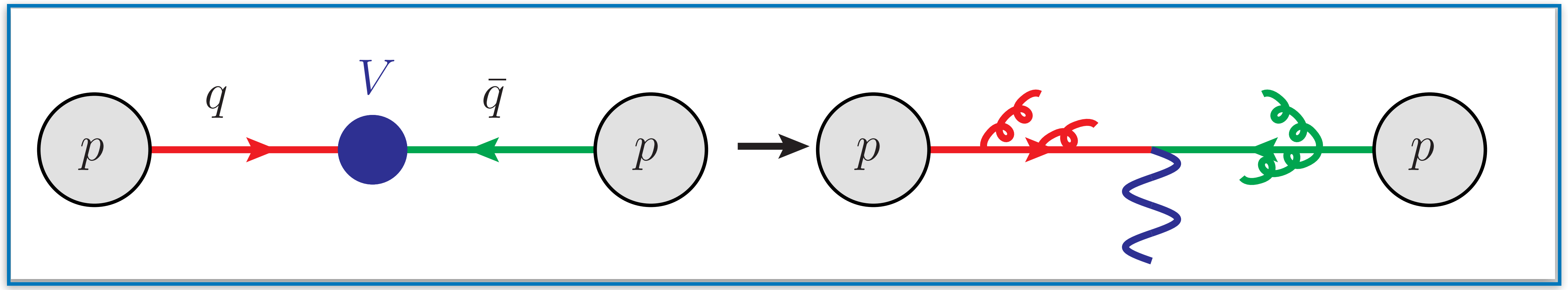
Small p_T region enhanced by emissions with “largish” p_T that cancel vectorially



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

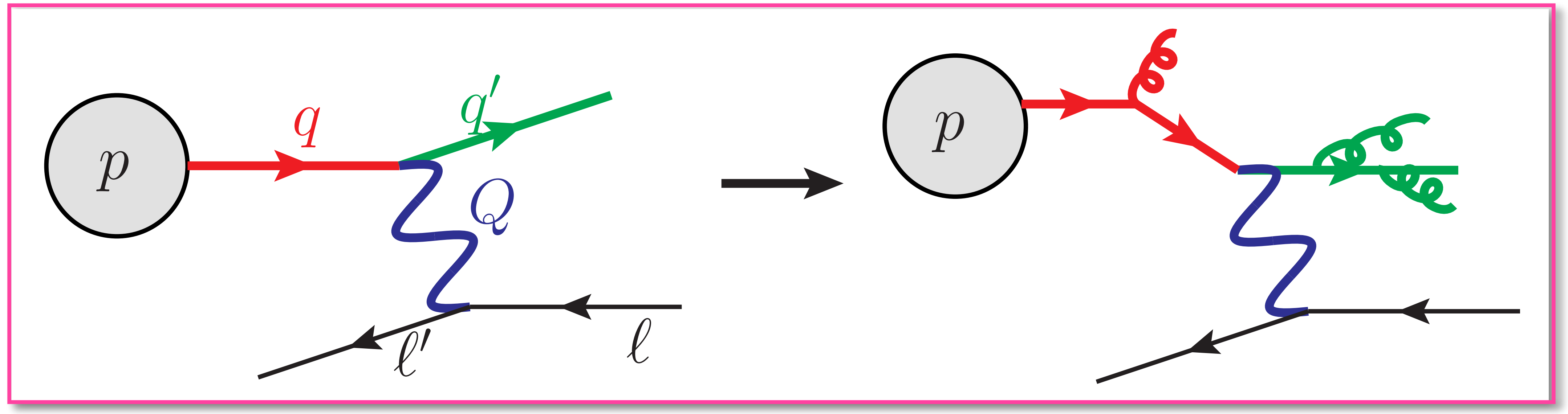
Initial-state radiation in the PanScales showers

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



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

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

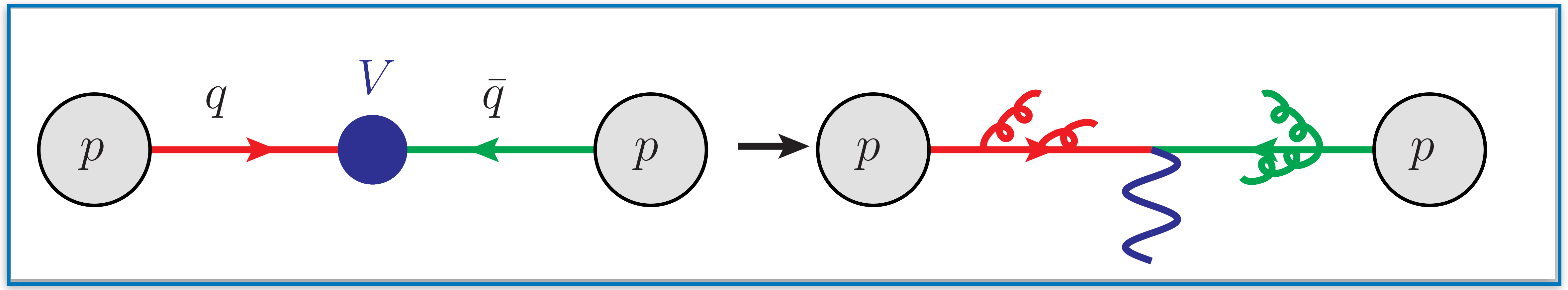


In **DIS**, the final-state quark (and its children) absorbs the $k_\perp$ recoil for all the ISR emissions.

van Beekveld, S.F.R., 2305.08645

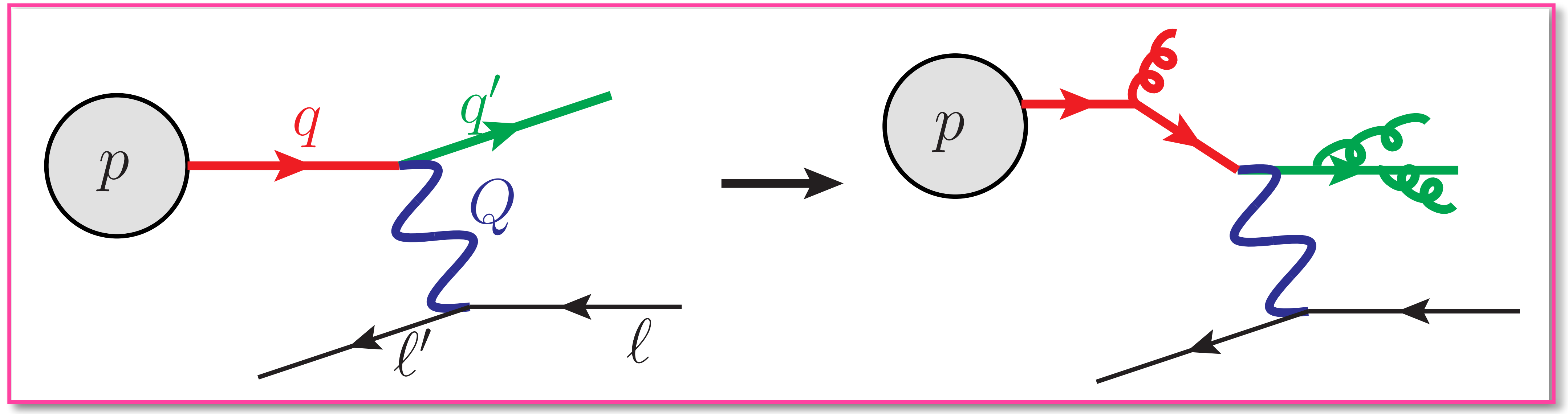
Initial-state radiation in the PanScales showers

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



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

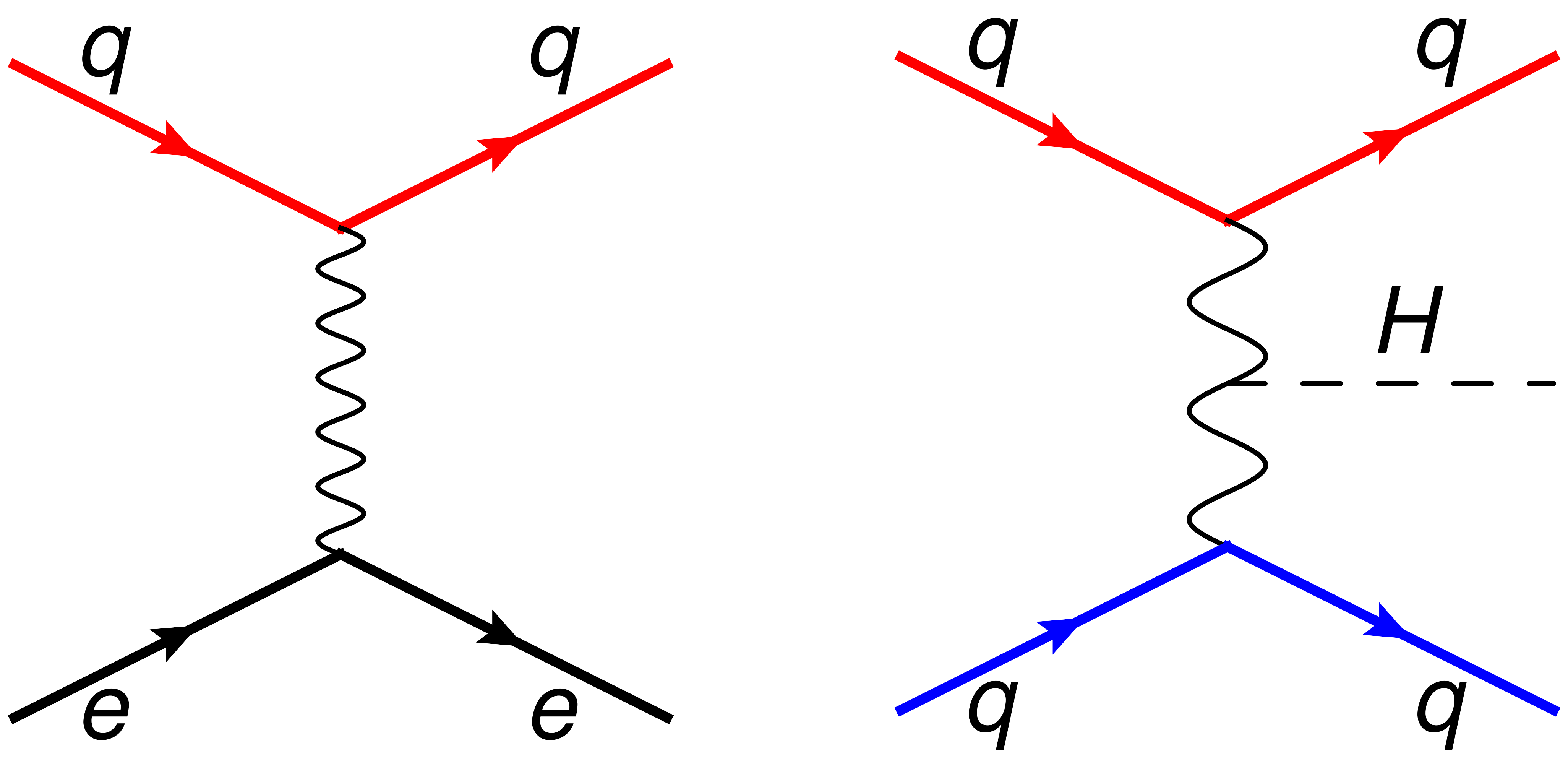
van Beekveld, S.F.R., Salam, Soto-Ontoso, Soyez, Verheyen, 2205.02237



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

van Beekveld, S.F.R., 2305.08645

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



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

Initial-state radiation in the PanScales showers

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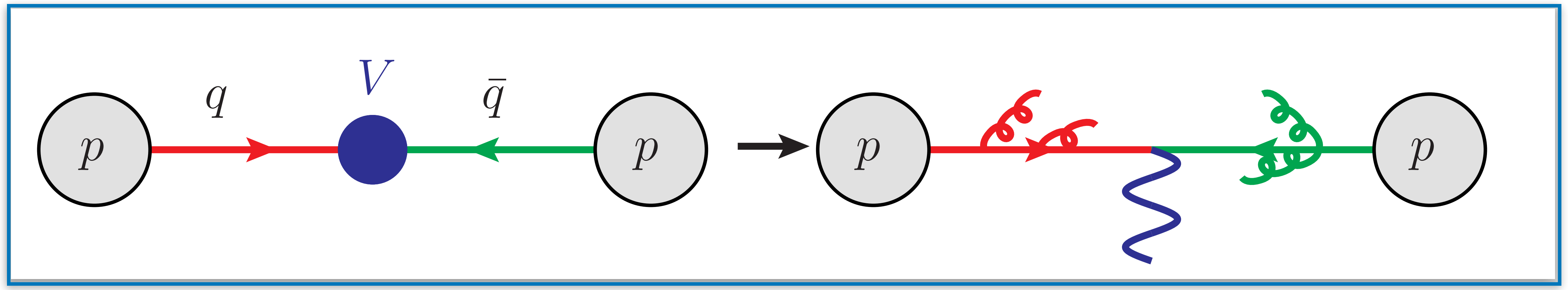

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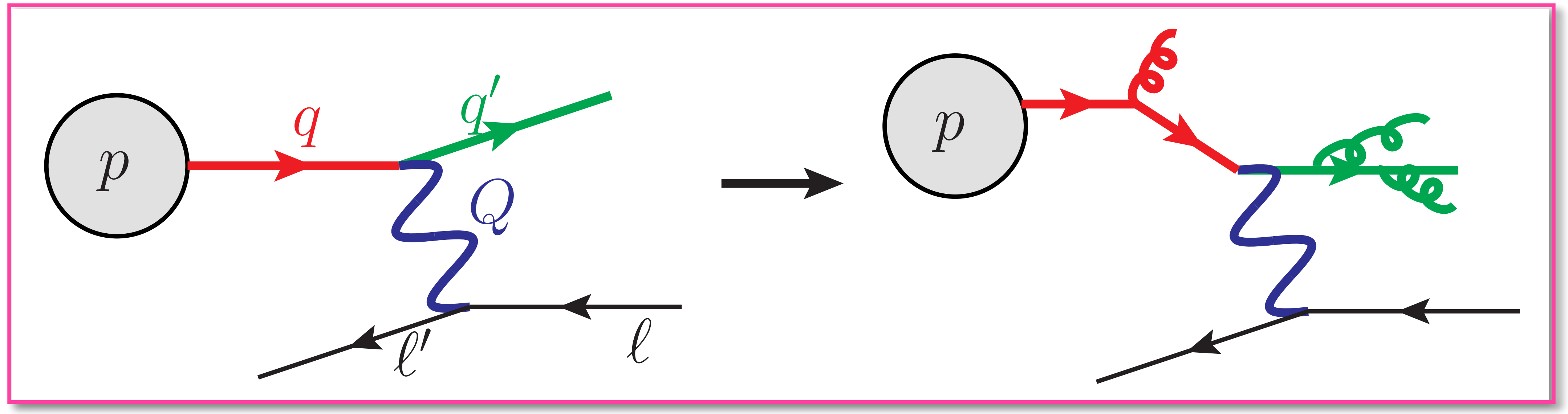

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van Beekveld, S.F.R., 2305.08645

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

Initial-state radiation in the PanScales showers

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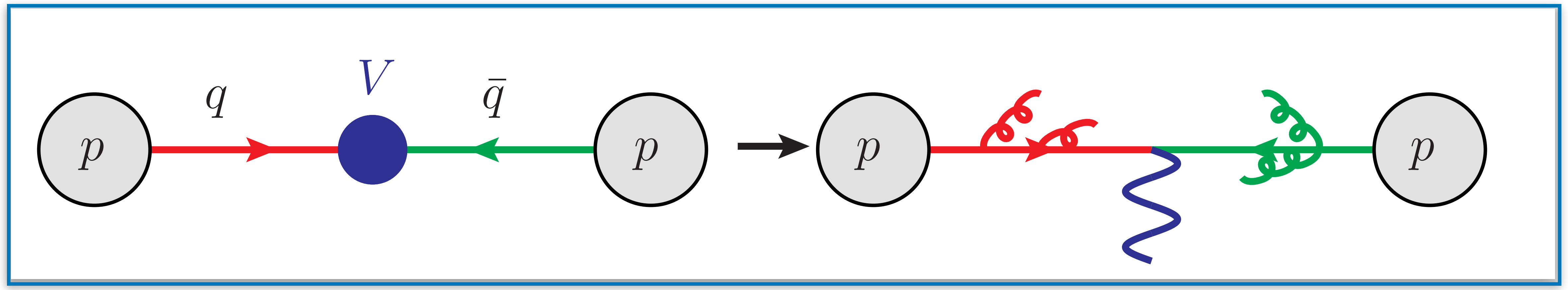

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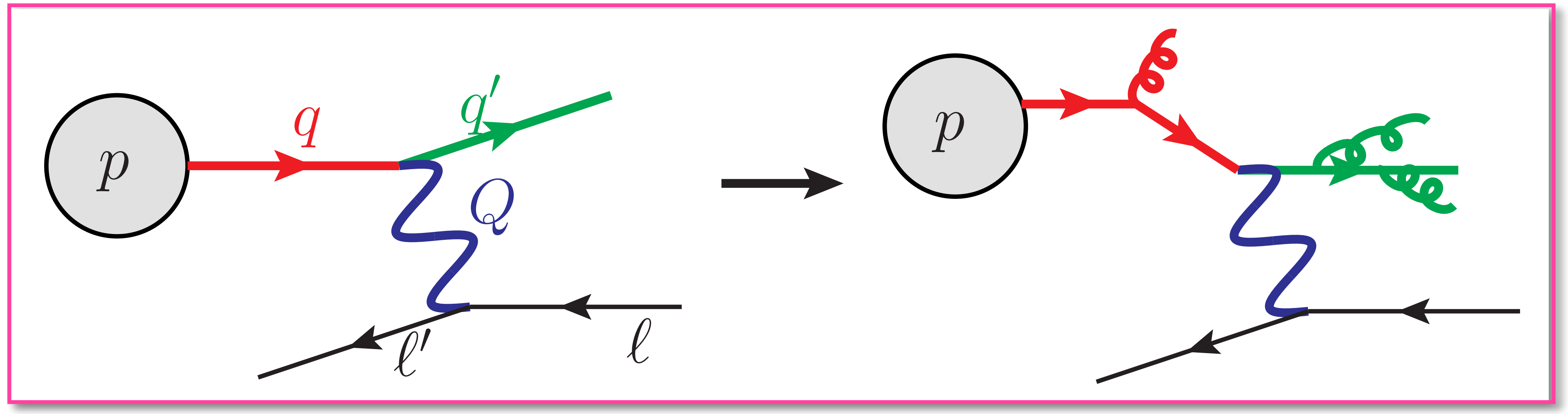

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van Beekveld, S.F.R., 2305.08645

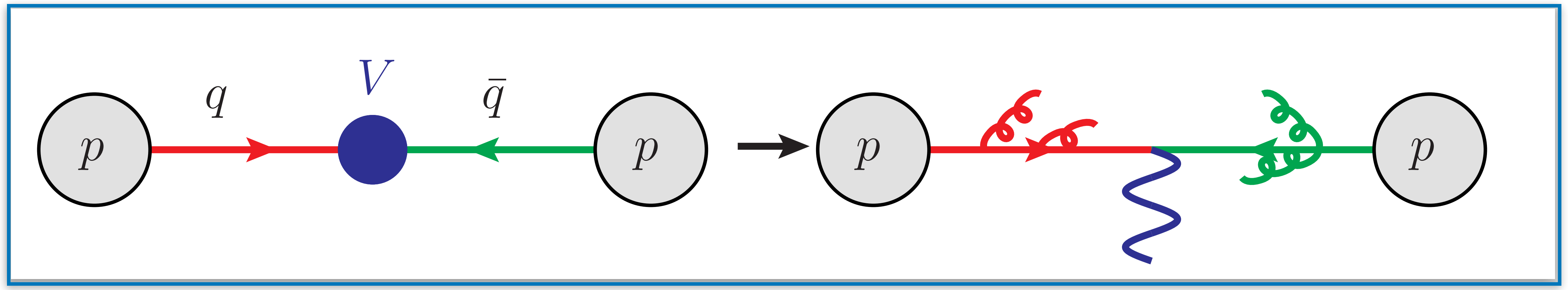
PanGlobal → The k_t recoil of an emission is never conserved locally within the dipole

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

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

Initial-state radiation in the PanScales showers

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



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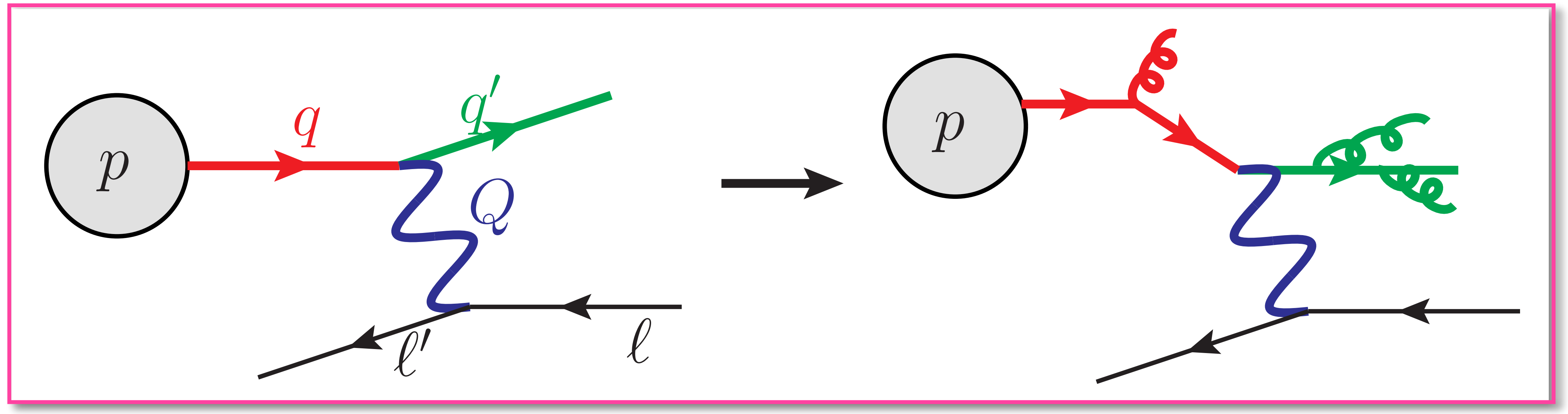


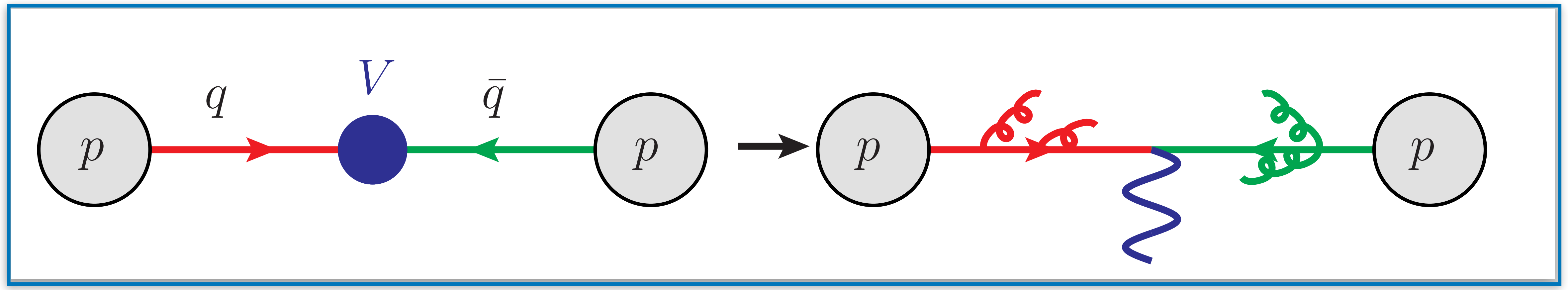
In **DIS**, the final-state quark (and its children) absorbs the $k_\perp$ recoil for all the ISR emissions.

van Beekveld, S.F.R., 2305.08645

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

Initial-state radiation in the PanScales showers

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



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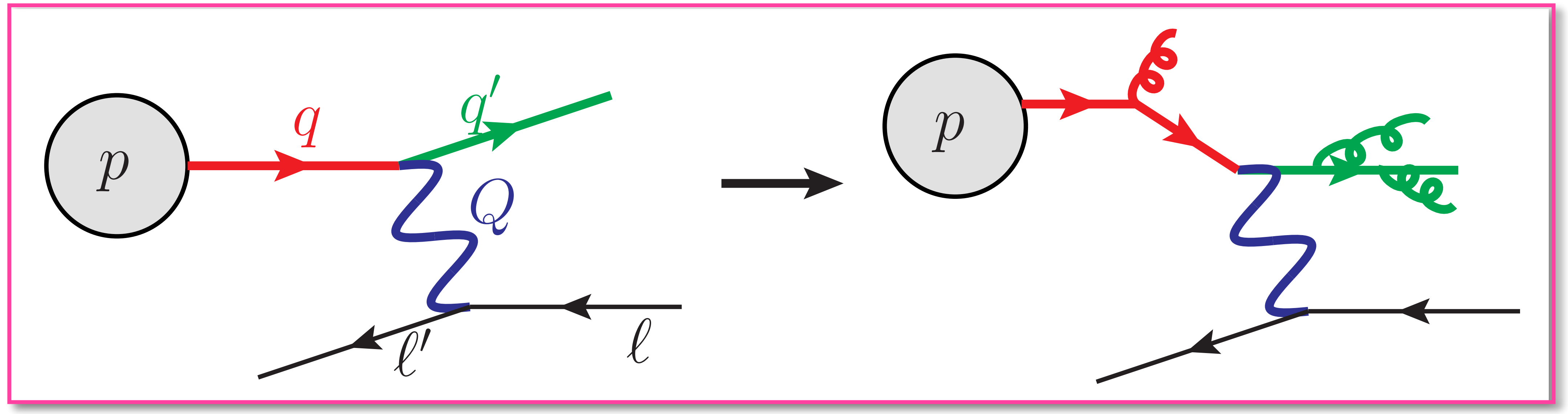

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van Beekveld, S.F.R., 2305.08645

PanLocal

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

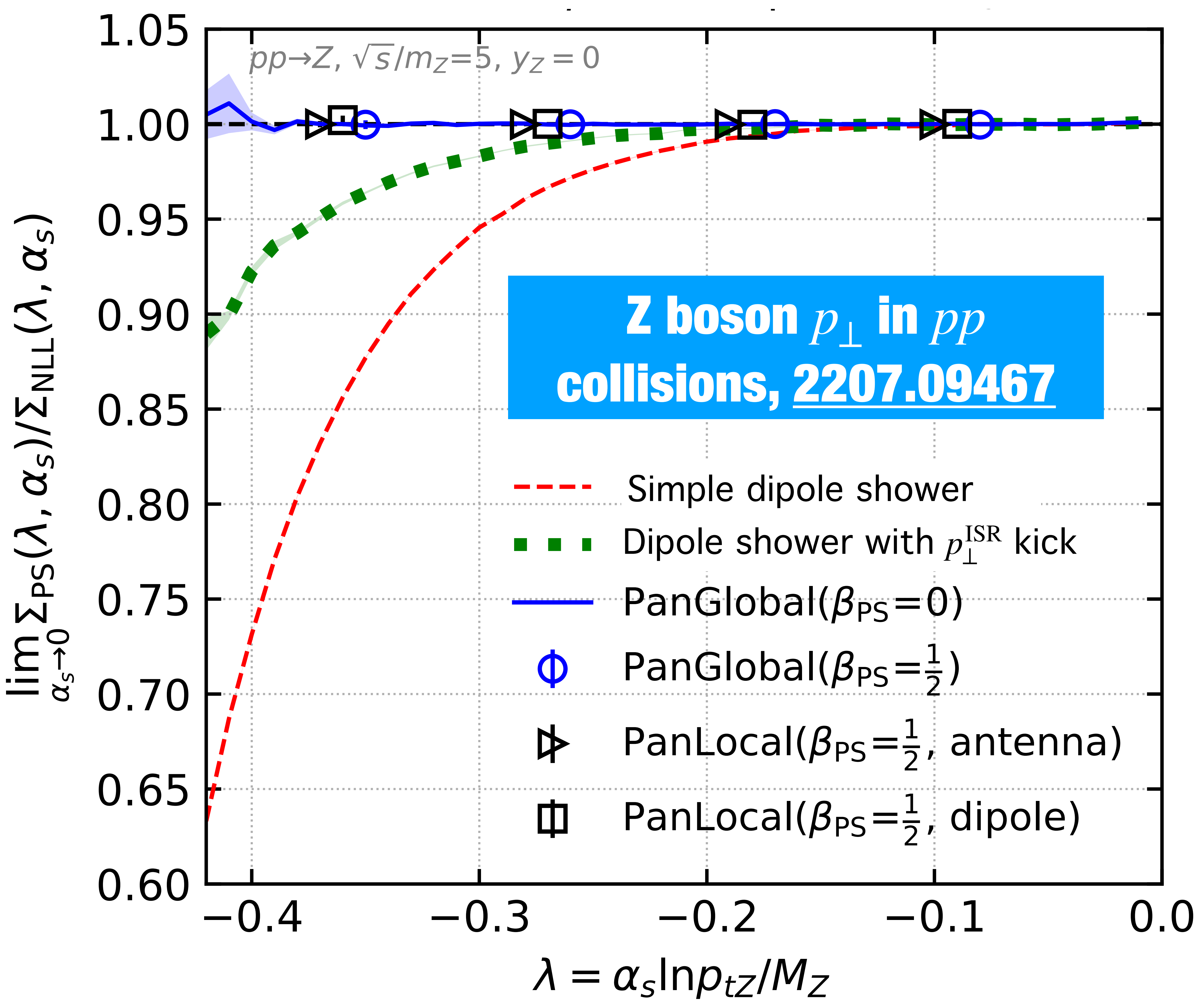
In **colour-singlet** production, we apply a Lorentz transformation to the whole event to realign the incoming partons with the beams. The rapidity of the colour-singlet is preserved.

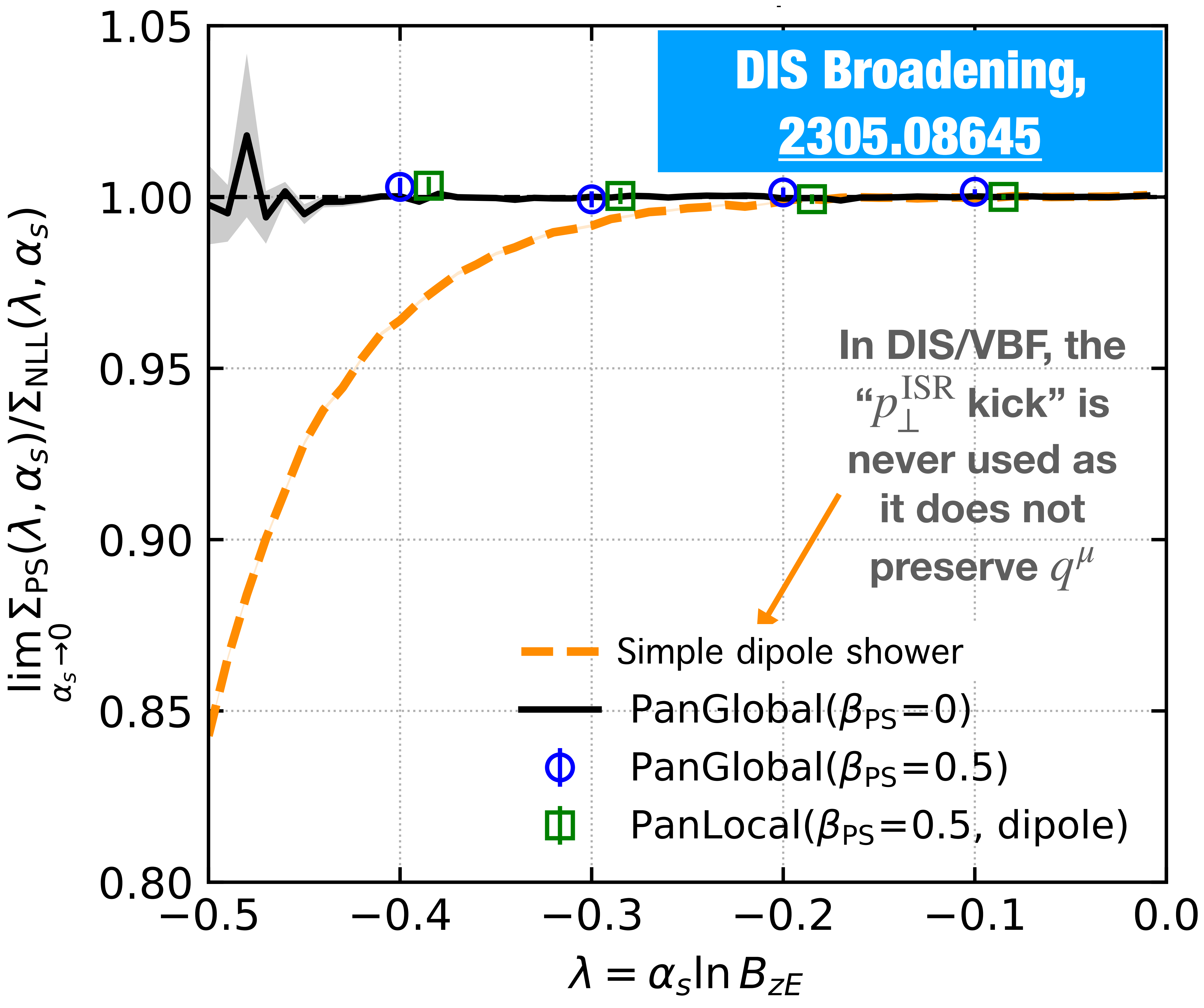
In **DIS**, we apply a Lorentz transformation to all the *partons*, leaving $Q = p_{\text{out}} - p_{\text{in}}$ unchanged. The transform affects mainly partons close in angle to the original final-state quark.

All-orders validation of the PanScales showers

$$\boxed{\lim_{\alpha_s\to 0} \frac{\Sigma_{\mathrm{PS}}}{\Sigma_{\mathrm{NLL}}} \quad \text{at fixed } \lambda = \alpha_s L}$$

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

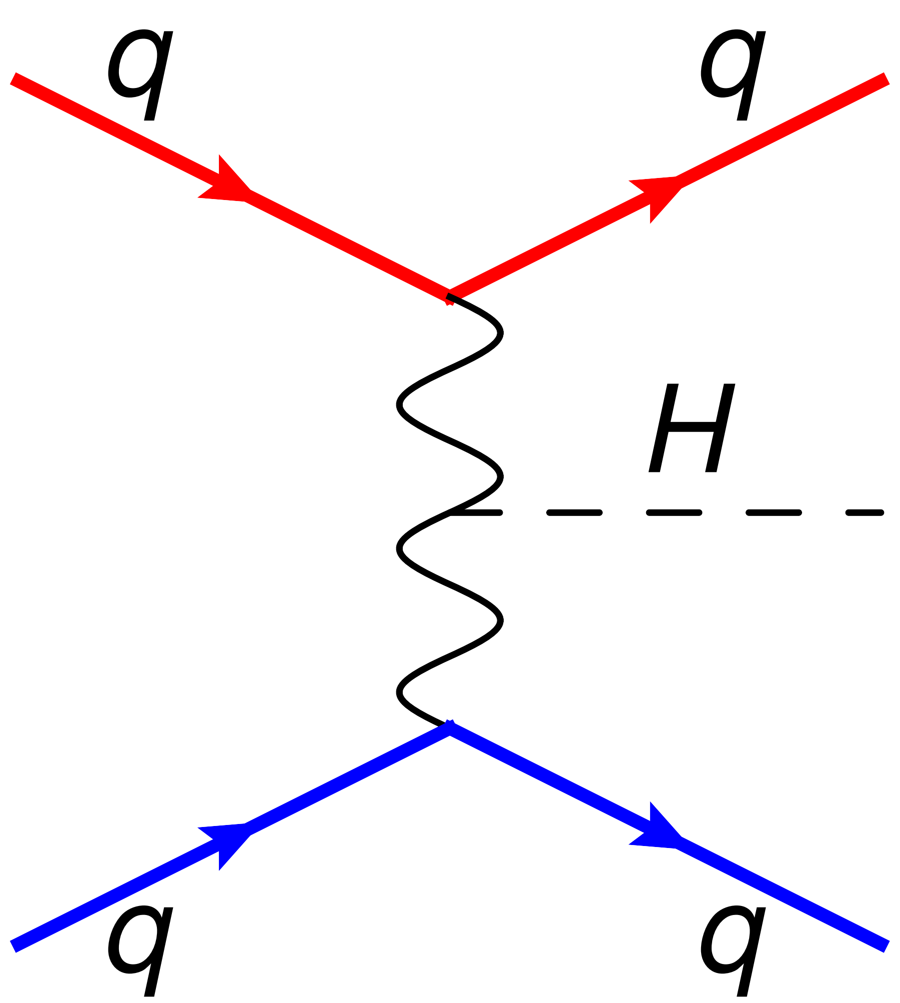

Z boson $p_\perp$ in pp collisions, 2207.09467


DIS Broadening, 2305.08645

In DIS/VBF, the "$p_\perp^{\mathrm{ISR}}$ kick" is never used as it does not preserve q^μ

Exploratory phenomenology for VBF

VBF: boosted Higgs studies, Higgs to invisible/muons measurements. Error budget dominated by PS uncertainty



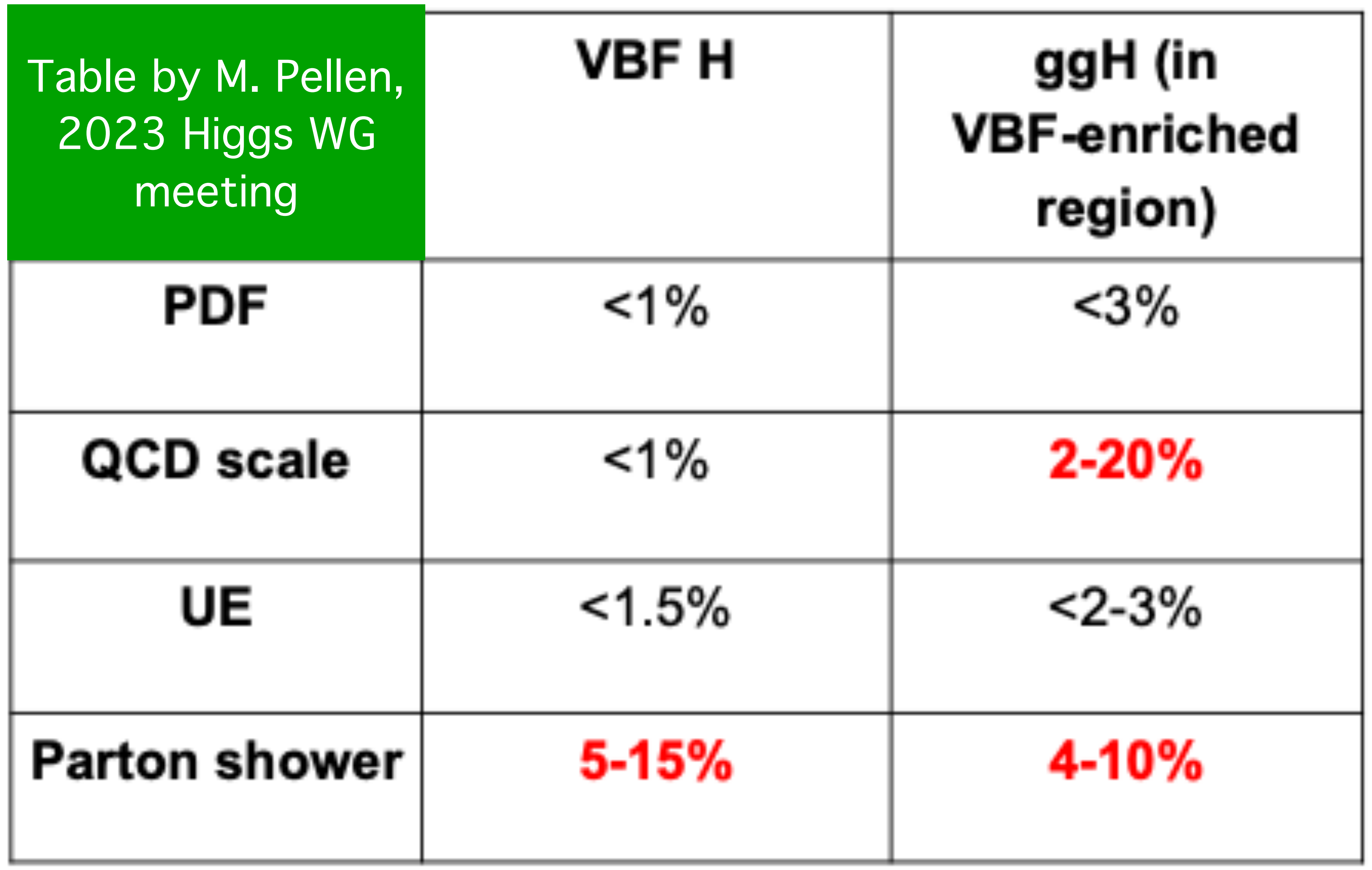
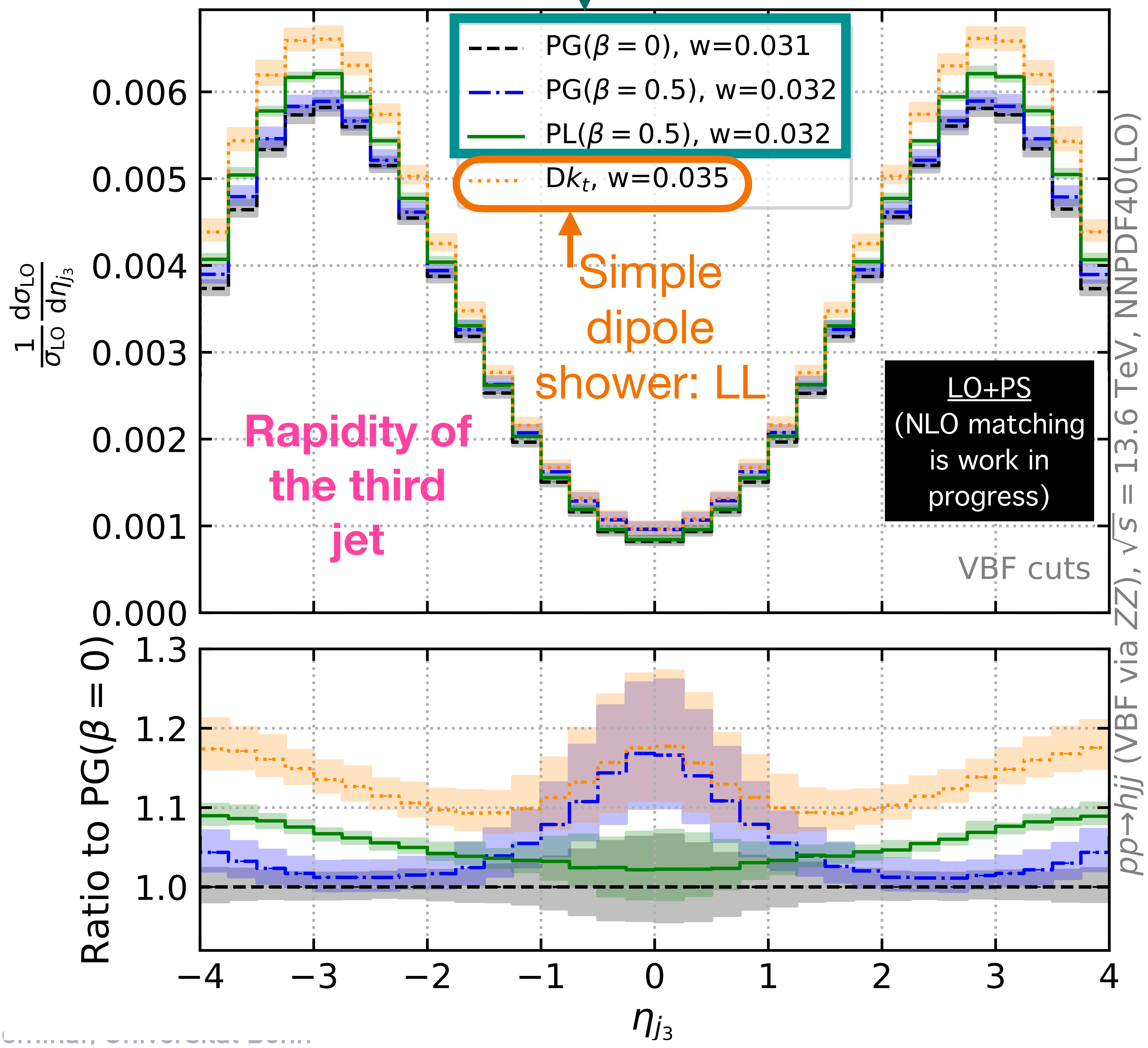


Table by M. Pellen, 2023 Higgs WG meeting	VBF H	ggH (in VBF-enriched region)
PDF	<1%	<3%
QCD scale	<1%	2-20%
UE	<1.5%	<2-3%
Parton shower	5-15%	4-10%

NLL PanScales showers



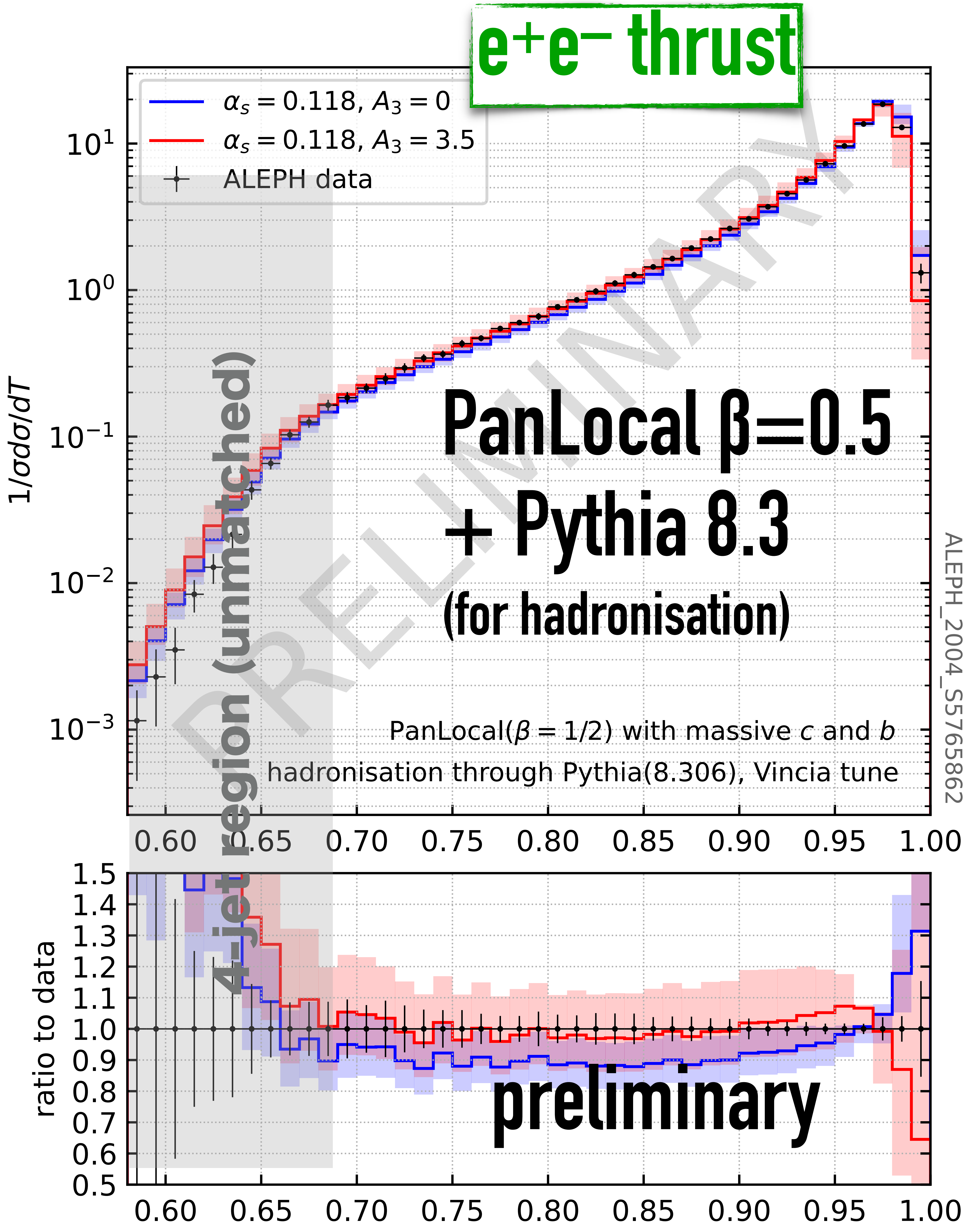
Simple dipole shower: LL

Rapidity of the third jet

LO+PS
(NLO matching is work in progress)

Comparison with LEP data

- **Matching** from Hamilton, Karlberg, Salam, Scyboz, Verheyen: 2301.09645
- preliminary treatment of **heavy-quark masses** [van Beekveld, SFR, Salam, Soyez, Verheyen, in preparation]
- understand nature of perturbative shower uncertainties
- and interplay with non-perturbative tuning

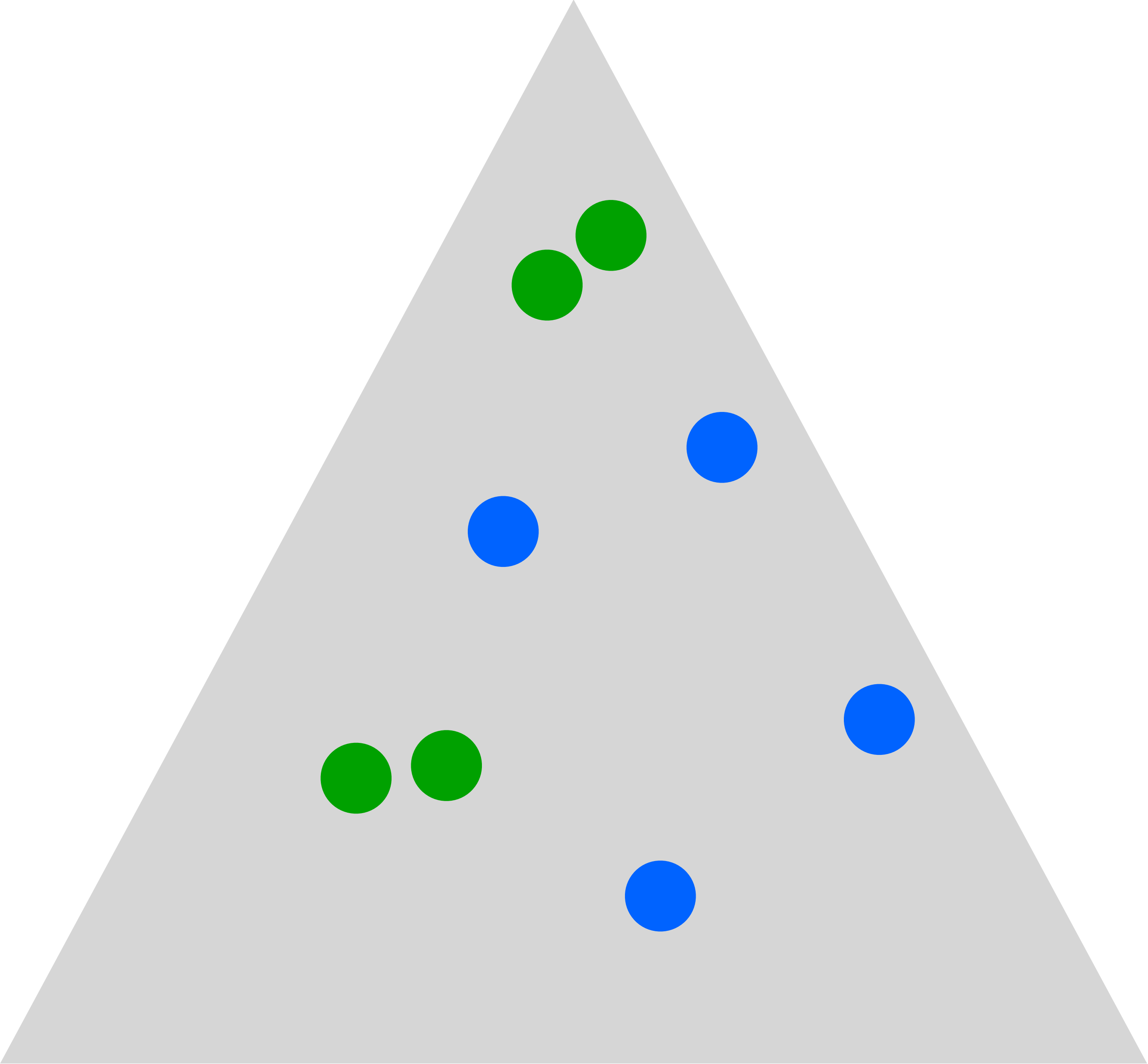


Towards NNLL accuracy

Ferrario Ravasio, Hamilton, Karlberg, GPS, Scyboz, Soyez, 2307.11142

Soft emission — i.e. inclusion of **double-soft current** + associated **virtual corrections**

- any pair of soft emissions with commensurate energy and angles should be produced with the correct [double-soft] matrix element
- probability for any single soft emission should be NLO accurate
- NB: Vincia and Sherpa groups have also explored inclusion of the double-soft current; part of novelty here is doing so to get the log-accuracy benefit.

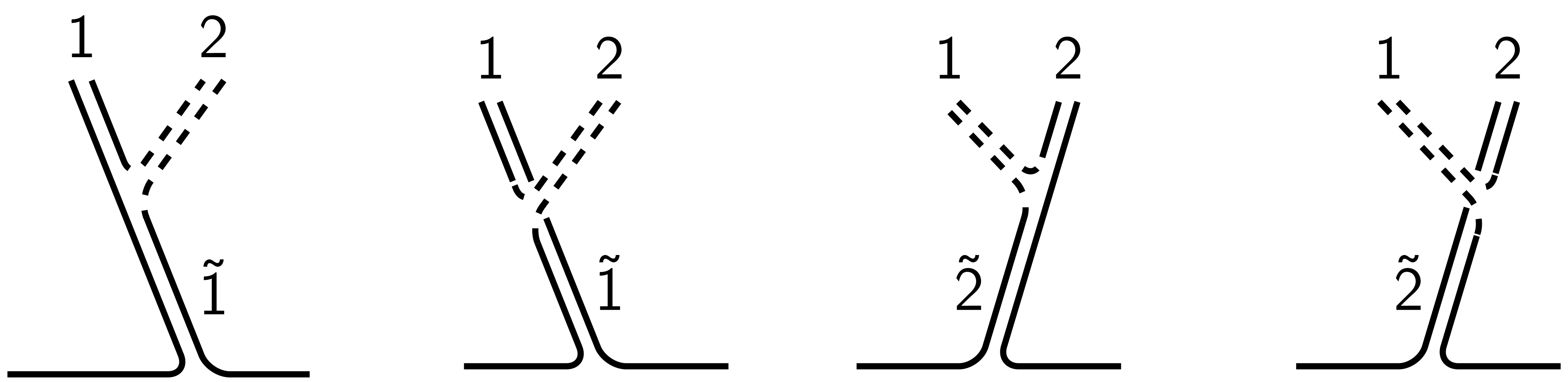


This should maintain NLL accuracy and further achieve

- **NNDL accuracy** for [subjet] multiplicities, i.e. terms $\alpha_s^n L^{2n}$, $\alpha_s^n L^{2n-1}$, $\boldsymbol{\alpha_s^n L^{2n-2}}$
- **Next-to-Single-Log (NSL) accuracy** for non-global logarithms, e.g. energy in a slice, all terms $\alpha_s^n L^n$ and $\boldsymbol{\alpha_s^n L^{n-1}}$ (at leading-N_c)

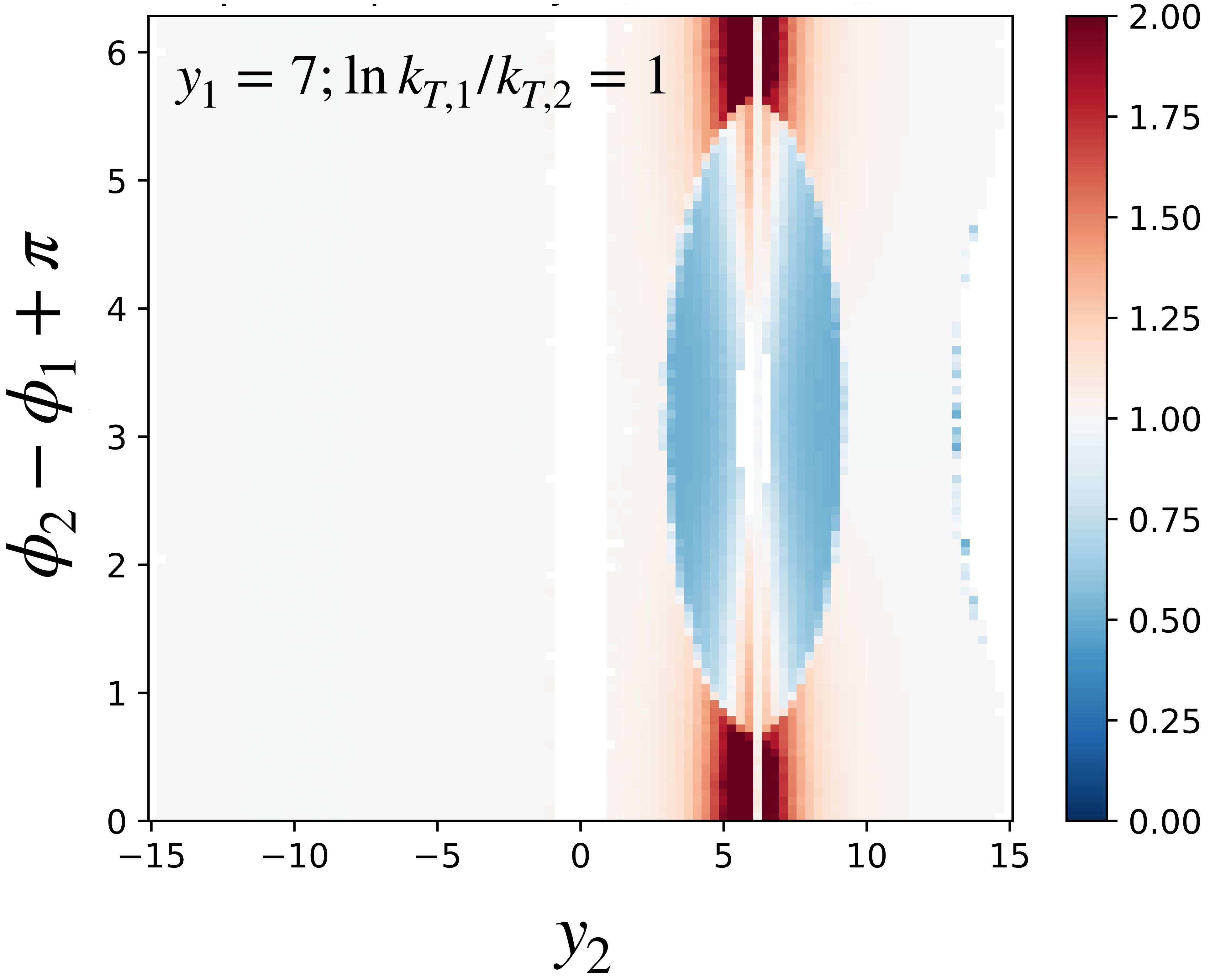
NB: done using PanGlobal, so far just in $e^+e^- \to q\bar{q}$

1. Real corrections: pair of soft emissions



- a given two-emission configuration can come from several shower histories
- **accept a given emission with exact double-soft $M^{(\mathrm{DS})}_{\mathrm{exact}}$ divided by shower's effective double-soft matrix element** summed over the histories h that could have produced that configuration

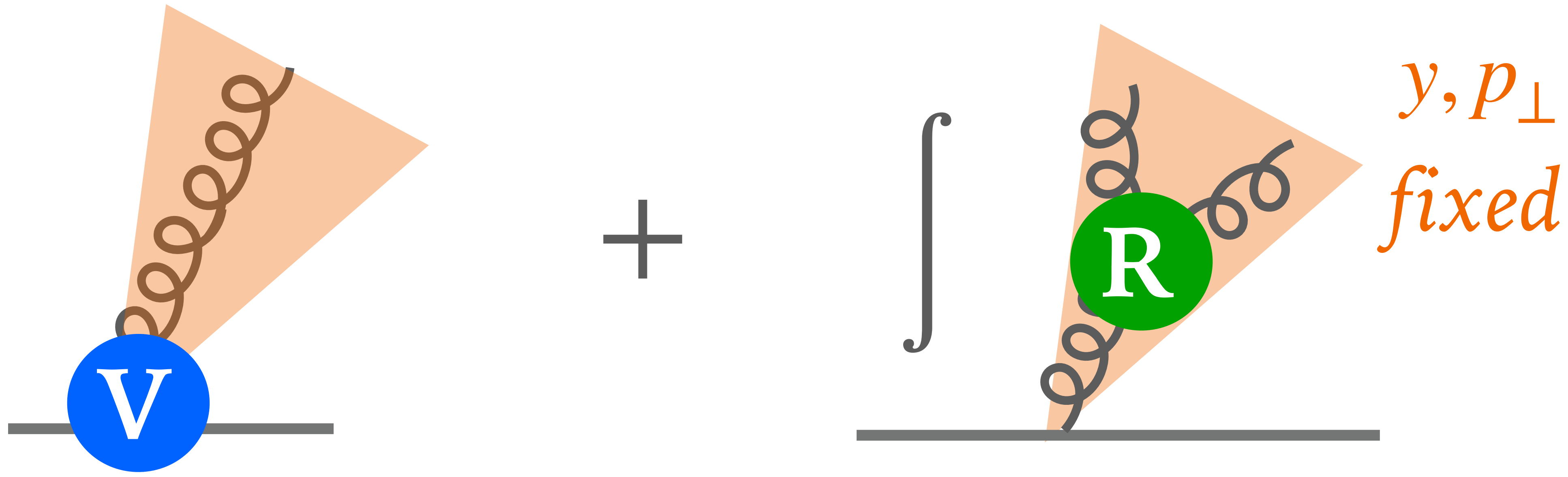
Double-soft acceptance P_{accept}



$$P_{\mathrm{accept}} = \frac{M^{(\mathrm{DS})}_{\mathrm{exact}}}{\sum_h M^{(\mathrm{DS})}_{h,\mathrm{PS}}}$$

Virtual corrections in parton showers

- For a soft emission

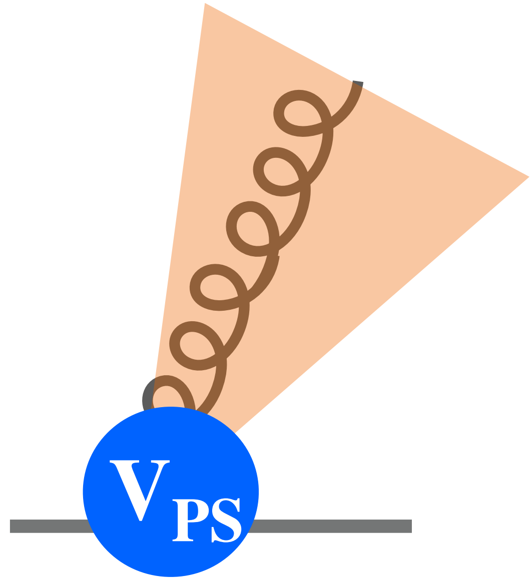


$$= \frac{\alpha_s}{2\pi} K_{\mathrm{CMW}}$$

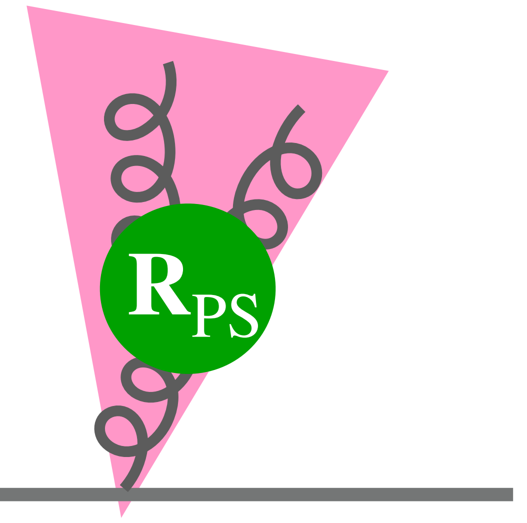
- **Catani**, **Marchesini** and **Webber** defined the "CMW" scheme for the coupling in the shower [*Nucl.Phys.B* 349 (1991) 635-654]

$$\alpha_s^{\mathrm{CMW}} = \alpha_s \left(1 + \frac{\alpha_s}{2\pi} K_{\mathrm{CMW}} \right)$$

At fixed "shower variables", but the rapidity and $p_\perp$ of the jet can vary



$$\equiv \frac{\alpha_s}{2\pi} K_{\mathrm{CMW}} - \int$$



This ensures

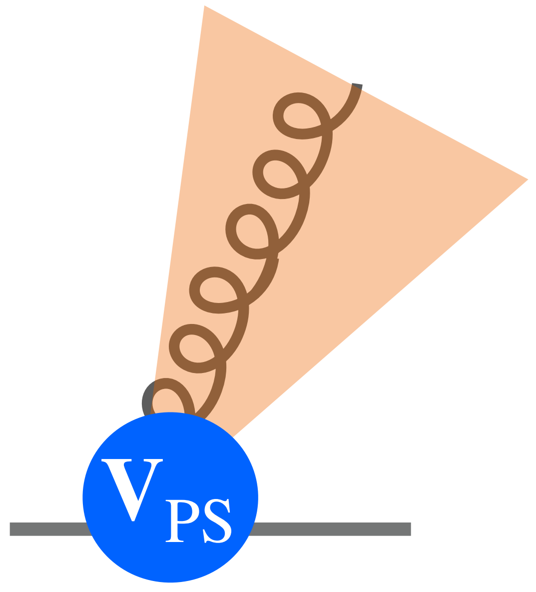
$$\mathbf{V}_{\mathbf{PS}} + \int \mathbf{R}_{\mathbf{PS}} = \frac{\alpha_s}{2\pi} K_{\mathrm{CMW}}$$

"on average"

2. Virtual corrections for soft emissions

With our double soft acceptance we have $\mathbf{R}_{\mathbf{PS}} = \mathbf{R}$.

To ensure



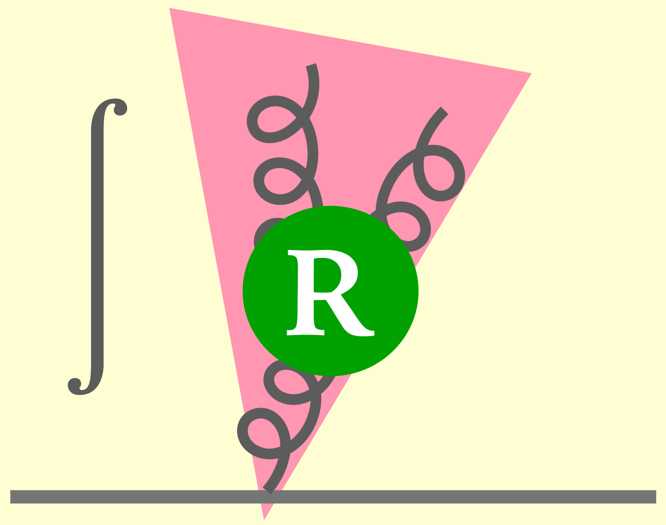
$$= \frac{\alpha_s}{2\pi} K_{\mathrm{CMW}} - \int$$

We modify the CMW scheme

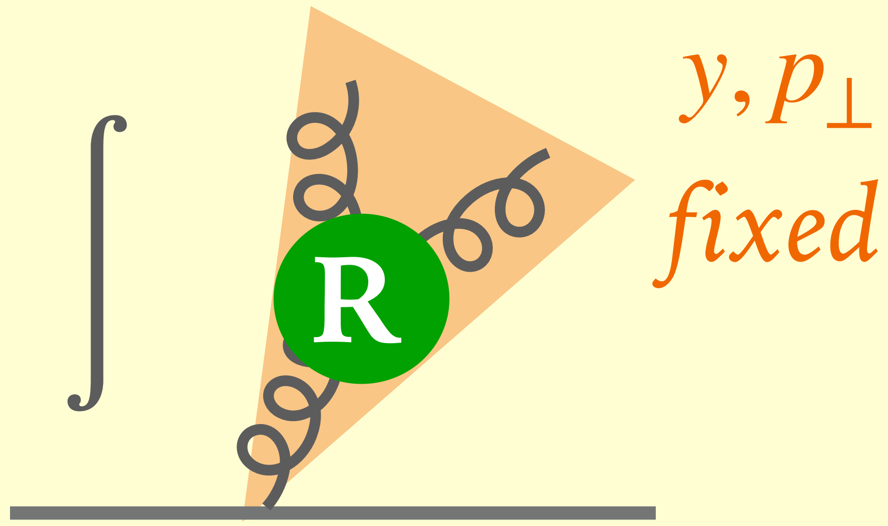
$$K_{\mathrm{CMW}} \rightarrow K_{\mathrm{CMW}} + \Delta K(\Phi^{(1)}_{\mathrm{PS}})$$

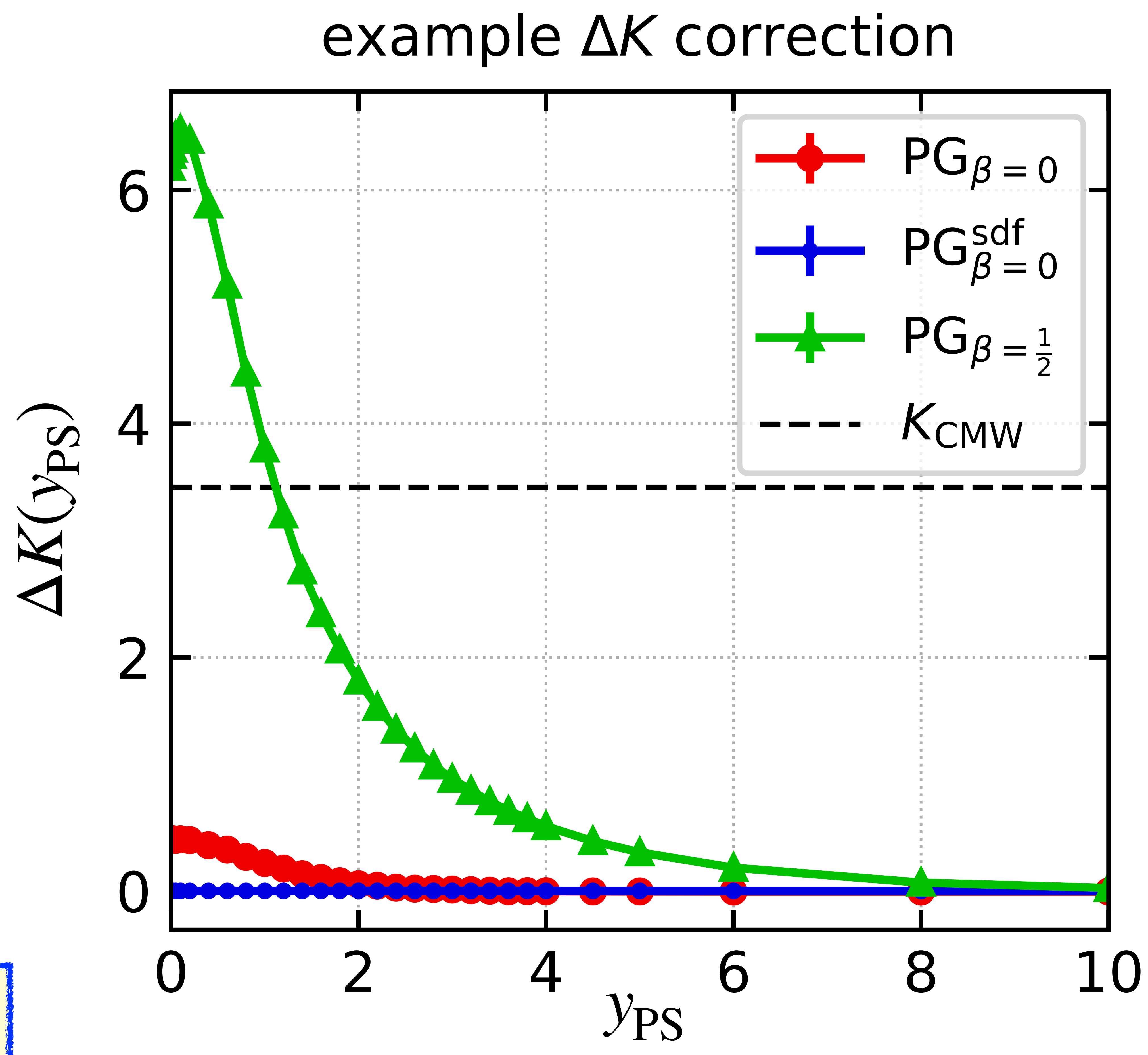
fixed "shower variables"

$$\frac{\alpha_s}{2\pi} \Delta K(\Phi^{(1)}_{\mathrm{PS}}) = \int$$



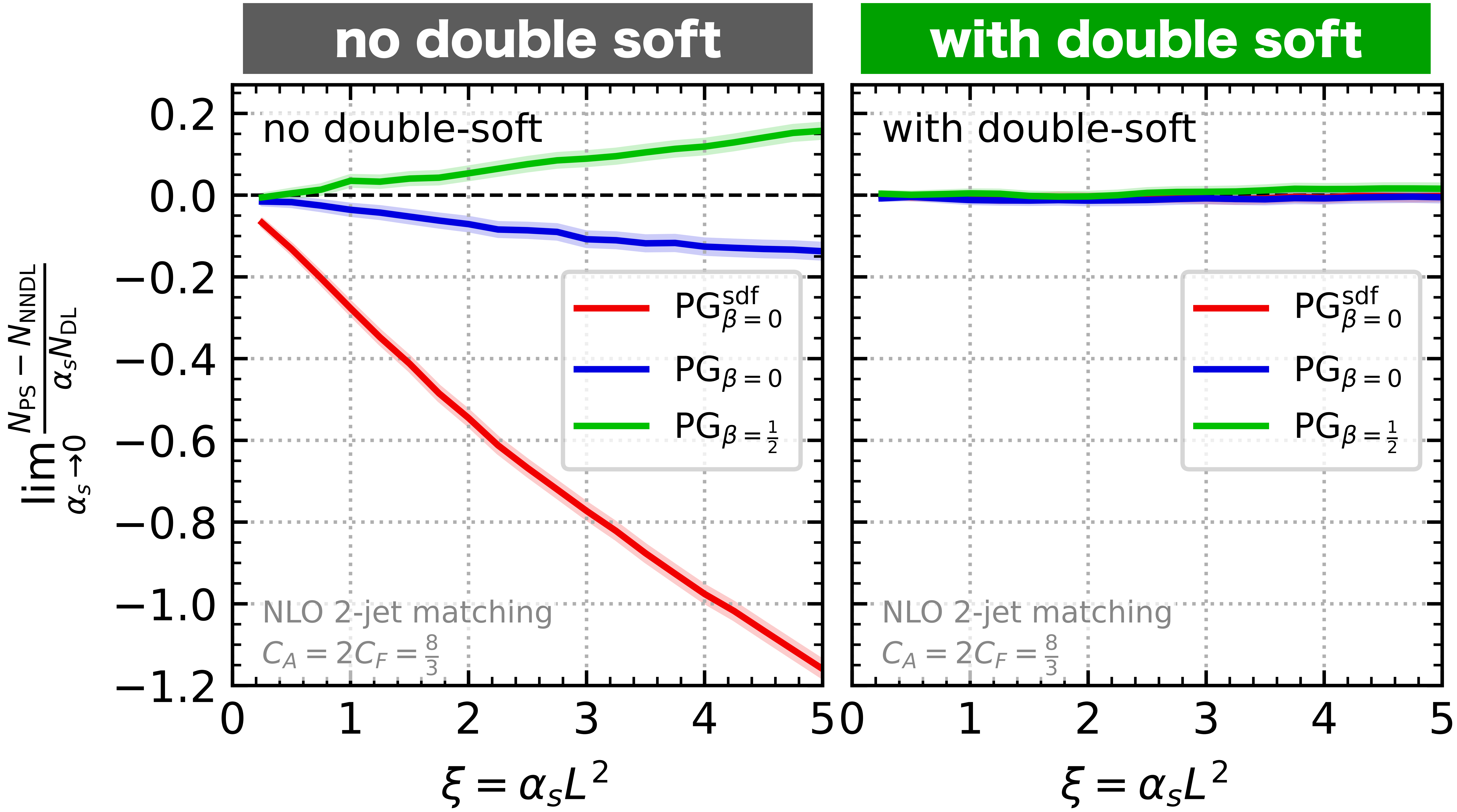
$$- \int$$





ΔK vanishes for large rapidities since virtual corrections to soft-collinear emissions are OK for NLL showers

NNDL subjet multiplicity

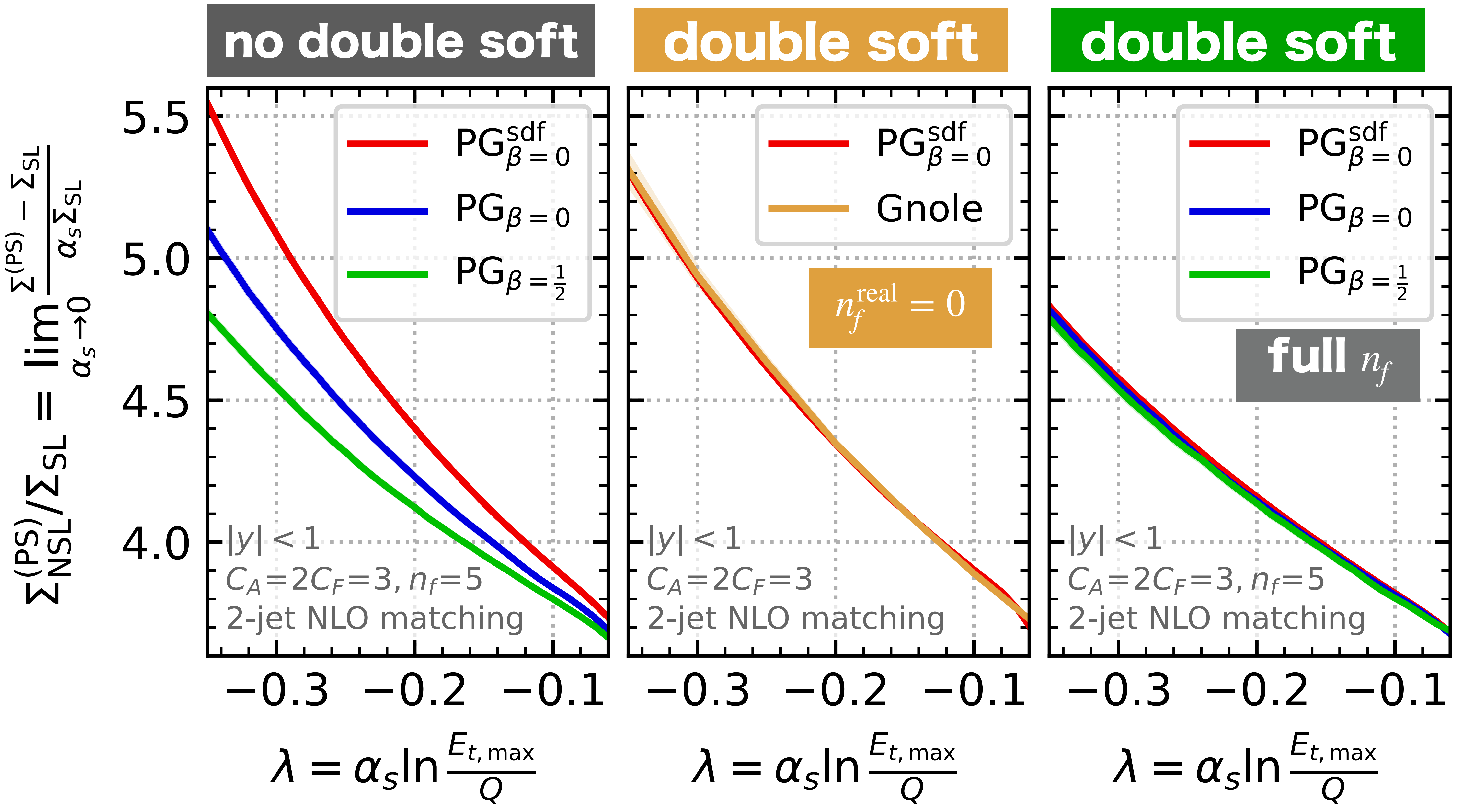


$$\lim_{\alpha_s \to 0} \frac{N_{\rm PS} - N_{\rm NNDL}}{\alpha_s N_{\rm DL}}\bigg|_{\text{fixed } \alpha_s L^2}$$

- **NNDL ($\alpha_s^n L^{2n-2}$)** analytic resummation = Medves, Soto Ontoso, Soyez, 2205.02861
- $\alpha_s \to 0$ limit to isolate NNDL terms.
- **Double soft necessary for NNDL agreement**

S.F.R., Hamilton, Karlberg, Salam, Scyboz, Soyez
2307.11142

NSL for the energy flow in a rapidity slice



$$\Sigma^{(\mathrm{PS})}_{\mathrm{NSL}} = \lim_{\alpha_s \to 0} \left. \frac{\Sigma^{(\mathrm{PS})} - \Sigma_{\mathrm{SL}}}{\alpha_s} \right|_{\text{fixed } \alpha_s L}, \qquad L \equiv \ln \frac{E_{t,\max}}{Q}$$

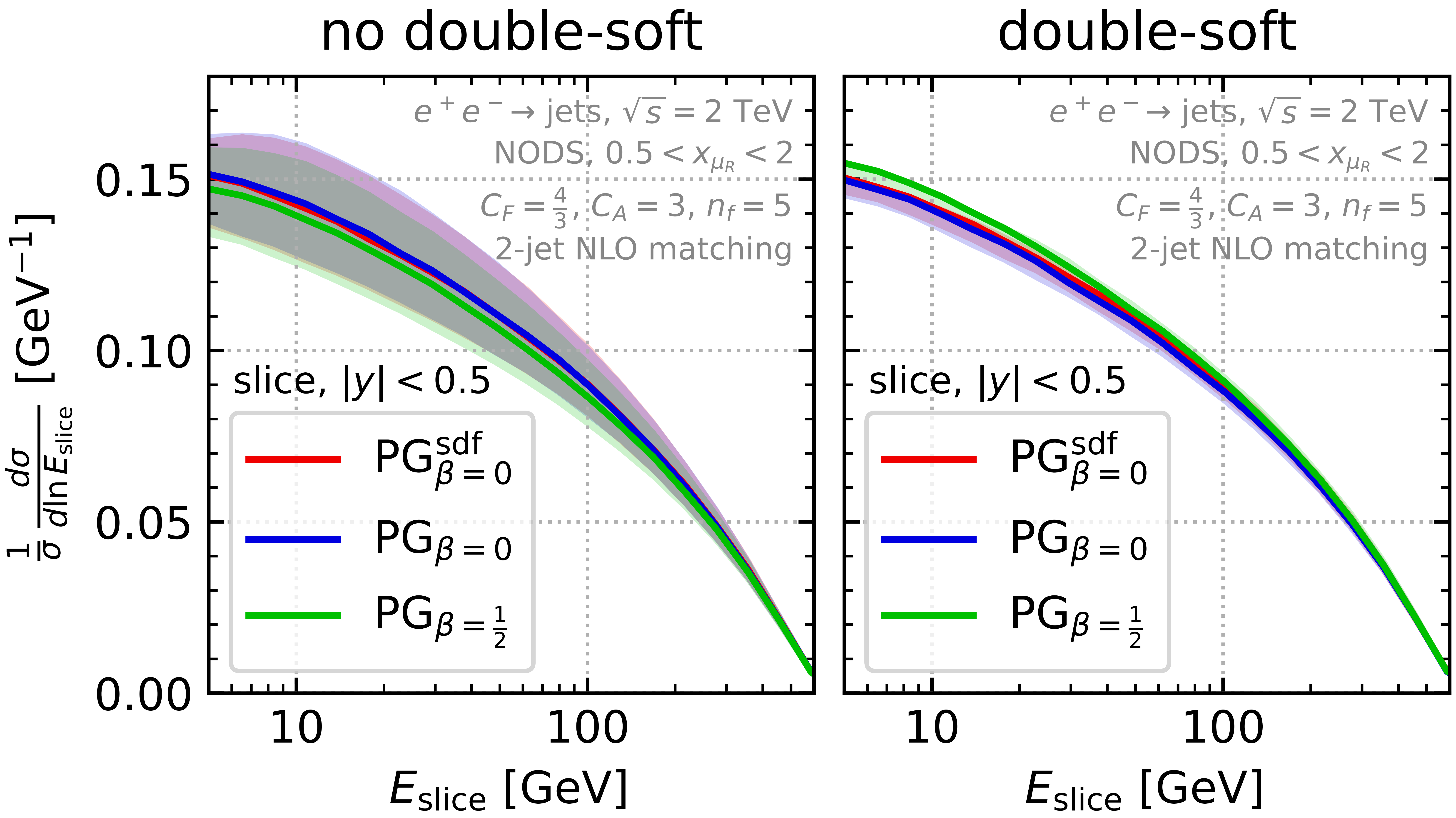
- **NSL ($\alpha_s^n L^{n-1}$)** = Banfi, Dreyer, Monni, 2104.06416, 2111.02413 **(“Gnole”)** [NB: see also Becher, Schalch, Xu, 2307.02283]
- **NSL agreement with Gnole for $n_f^{\mathrm{real}} = 0$**
- First large-N_c **full-n_f** results for NSL non-global logs

S.F.R., Hamilton, Karlberg, Salam, Scyboz, Soyez 2307.11142

NSL Pheno outlook

S.F.R., Hamilton, Karlberg, Salam, Scyboz, Soyez
2307.11142

- Energy flow in slice between two 1 TeV jets
- **Double-soft reduces uncertainty band**



Uncertainty here is estimated varying the renormalisation scale

$$\alpha_s^{\mathrm{CMW}}(k_t; x_R) = \alpha_s(x_R k_t)\left(1 + \frac{\alpha_s(x_R k_t)}{2\pi}(K_{\mathrm{CMW}} + \Delta K(\Phi)) + 2\alpha_s(x_R k_t) b_0 (1-z) \ln x_R\right)$$

Conclusions

- **PanScales is first validated NLL shower**
  - benefits of LL → NLL include reduced uncertainties (reliable estimate uncertainties)
  - NLO matching in place for some simple processes
  - for realistic applications we also need massive quarks (in progress) and tuning
- **Higher log accuracy is one of the next frontiers**
  - first results with double-soft (+ virtual) corrections!
  - brings NNDL multiplicity and NSL non-global logarithms
- **Public code**
  - https://gitlab.com/panscales/panscales-0.X

BACKUP

Next steps

Towards a complete public shower usable for phenomenology

Public NLL shower (for lepton collisions, colour-singlet production in pp collisions, DIS, VBF) and interface to Pythia8.3 soon!

Going beyond NLL

SciPost Physics Codebases Submission

CERN-TH-2023-???, OUTP-23-???

PanScales logarithmic tests and associated numerical techniques

Melissa van Beekveld[1], Mrinal Dasgupta[2], Silvia Ferrario Ravasio[3], Keith Hamilton[4], Jack Helliwell[1], Basem Kamal El-Menoufi[2,5], Alexander Karlberg[3], Rok Medves[1], Pier Francesco Monni[3], Gavin P. Salam[1,6], Ludovic Scyboz[1,5], Alba Soto-Ontoso[3], Gregory Soyez[7], Rob Verheyen

Next steps

Towards a complete public shower usable for phenomenology

hadron collisions:
more complex processes & associated tests

Heavy quarks & resonances
Essential for phenomenology

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

Interface to Pythia

uncertainty estimates

Next steps

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

Next-to-leading non-global logarithms in QCD

Banfi, Dreyer and Monni, 2104.06416, 2111.02413

Lund and Cambridge multiplicities

Medves, Soto-Ontoso, Soyez, 2205.02861, 2212.05076

Groomed jet mass studies

Anderle, Dasgupta, El-Menoufi, Guzzi, Helliwell, 2007.10355; Dasgupta, El-Menoufi, Helliwell 2211.03820

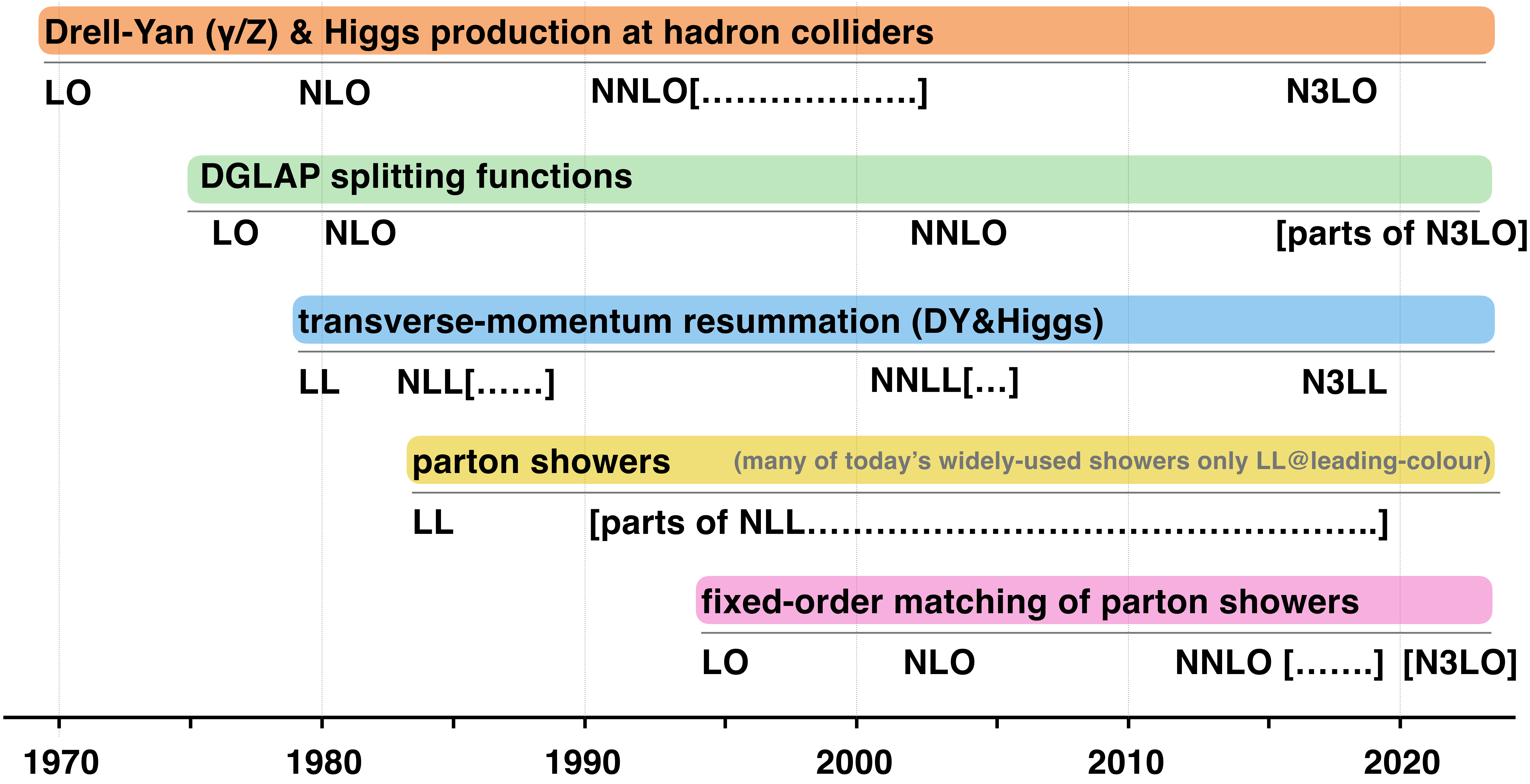
[see also SCET work, Frye, Larkoski, Schwartz & Yan, 1603.09338 + …]

Dissecting the collinear structure of quark splitting at NNLL

Dasgupta, El-Menoufi, 2109.07496

It's time for better Parton Showers!

Slide from G. Salam



Drell-Yan (γ/Z) & Higgs production at hadron colliders

LO NLO NNLO[……………….] N3LO

DGLAP splitting functions

LO NLO NNLO [parts of N3LO]

transverse-momentum resummation (DY&Higgs)

LL NLL[……] NNLL[…] N3LL

parton showers (many of today's widely-used showers only LL@leading-colour)

LL [parts of NLL…………………………………….]

fixed-order matching of parton showers

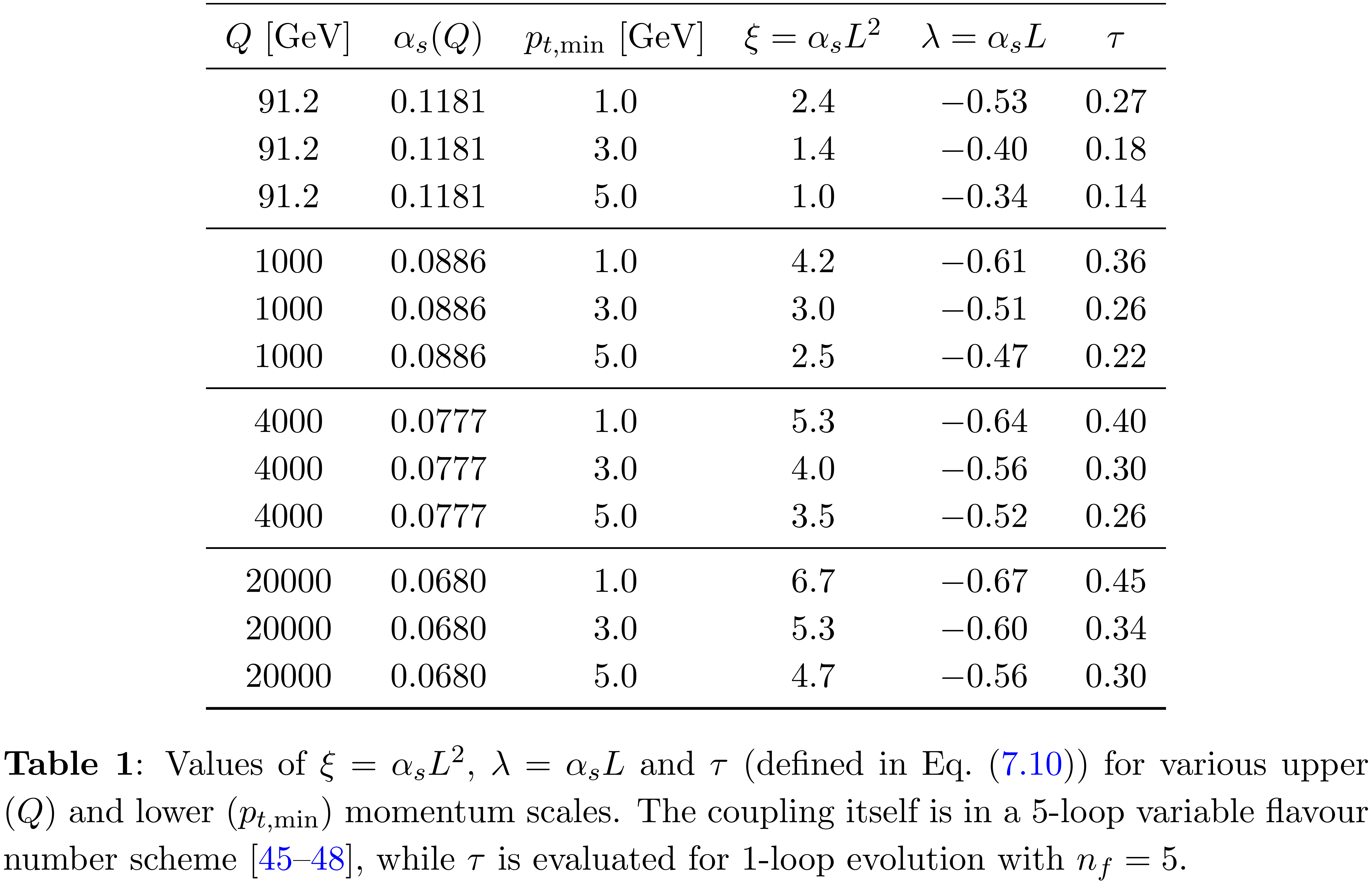
LO NLO NNLO […….] [N3LO]

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

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

Slide from G. Salam

how large are the logarithms?



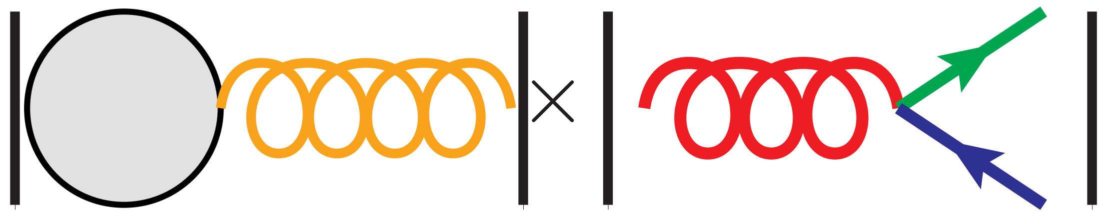
Q [GeV]	$\alpha_s(Q)$	$p_{t,\min}$ [GeV]	$\xi = \alpha_s L^2$	$\lambda = \alpha_s L$	τ
91.2	0.1181	1.0	2.4	−0.53	0.27
91.2	0.1181	3.0	1.4	−0.40	0.18
91.2	0.1181	5.0	1.0	−0.34	0.14
1000	0.0886	1.0	4.2	−0.61	0.36
1000	0.0886	3.0	3.0	−0.51	0.26
1000	0.0886	5.0	2.5	−0.47	0.22
4000	0.0777	1.0	5.3	−0.64	0.40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

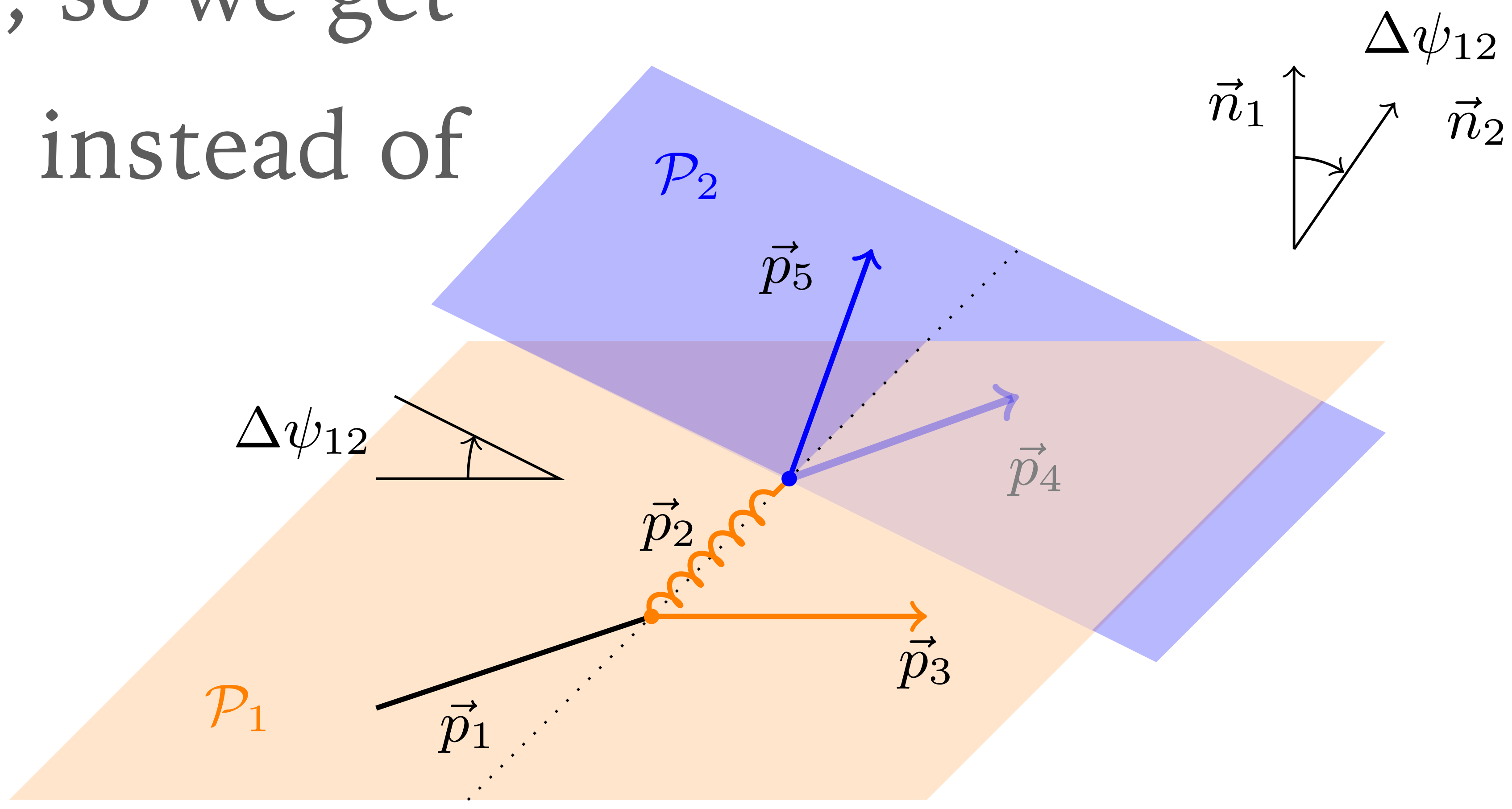
Shower emission probability are polarisations-averaged at every step, so we get

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

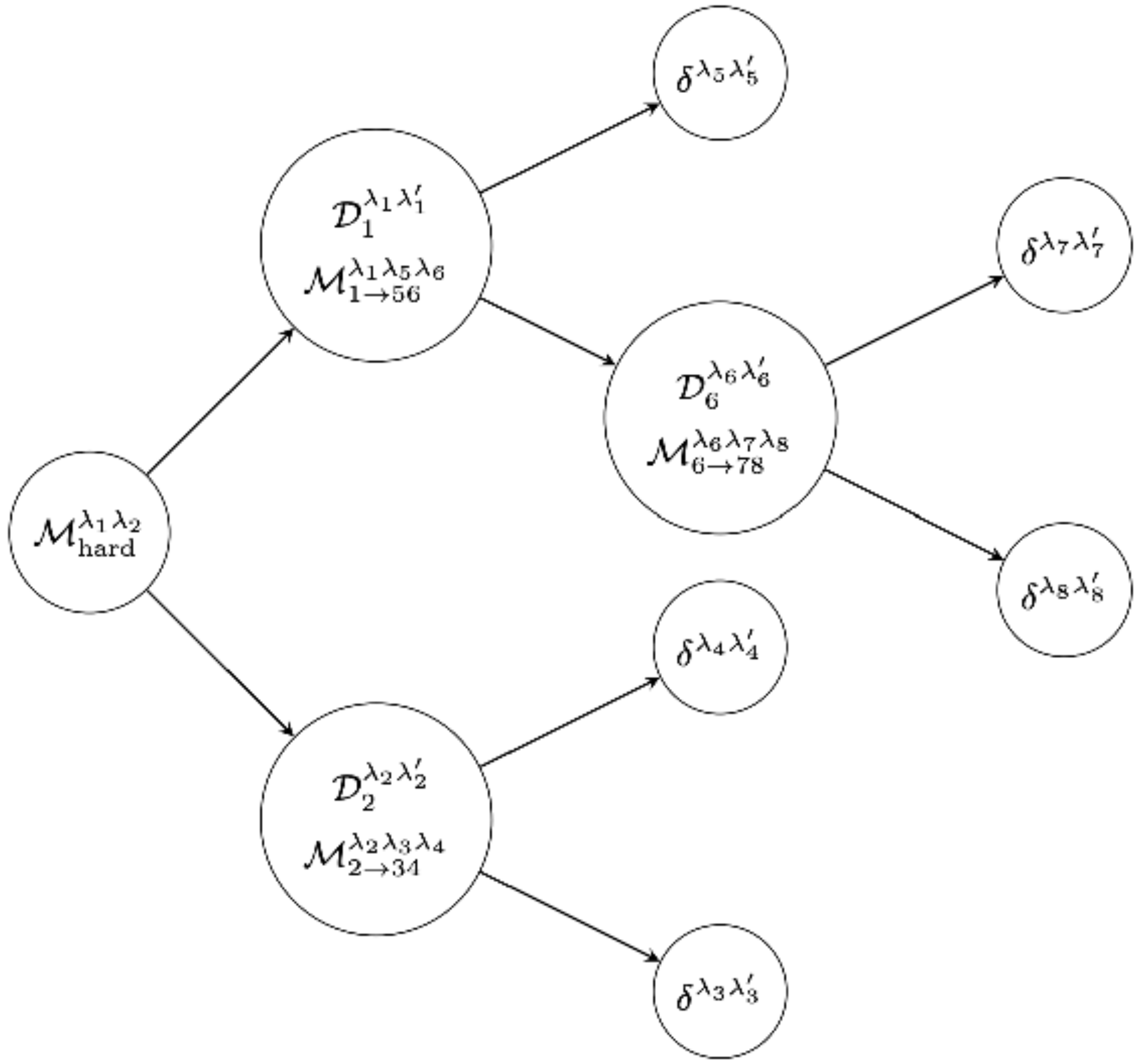


instead of

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



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.

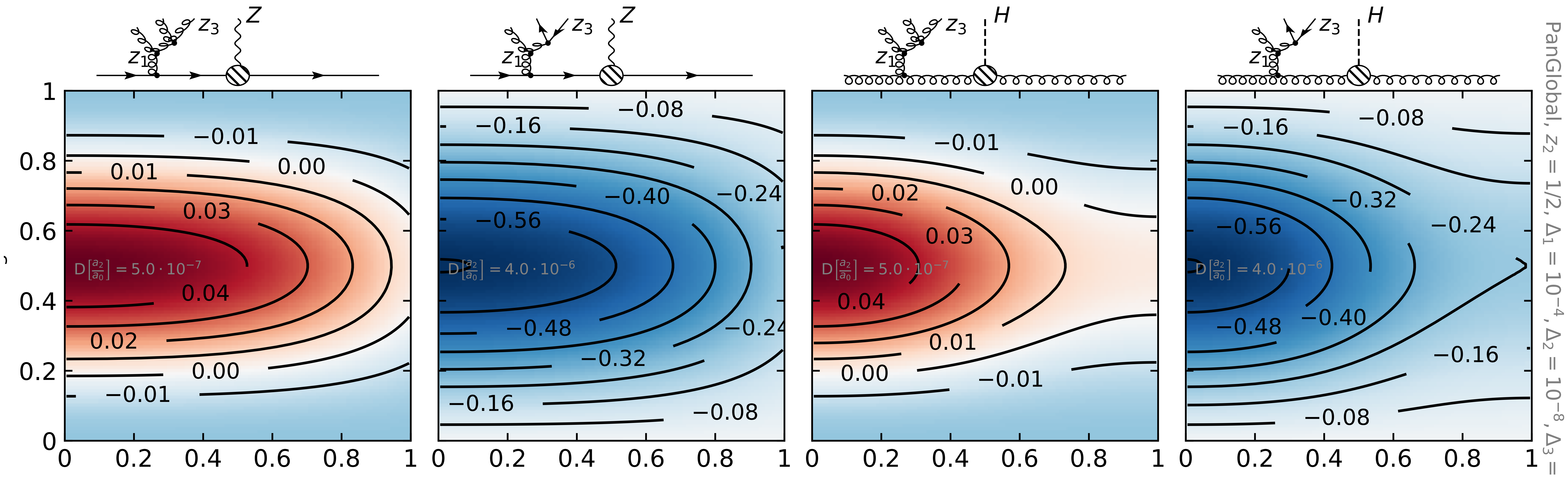
Soft and collinear spin in PanScales

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]**

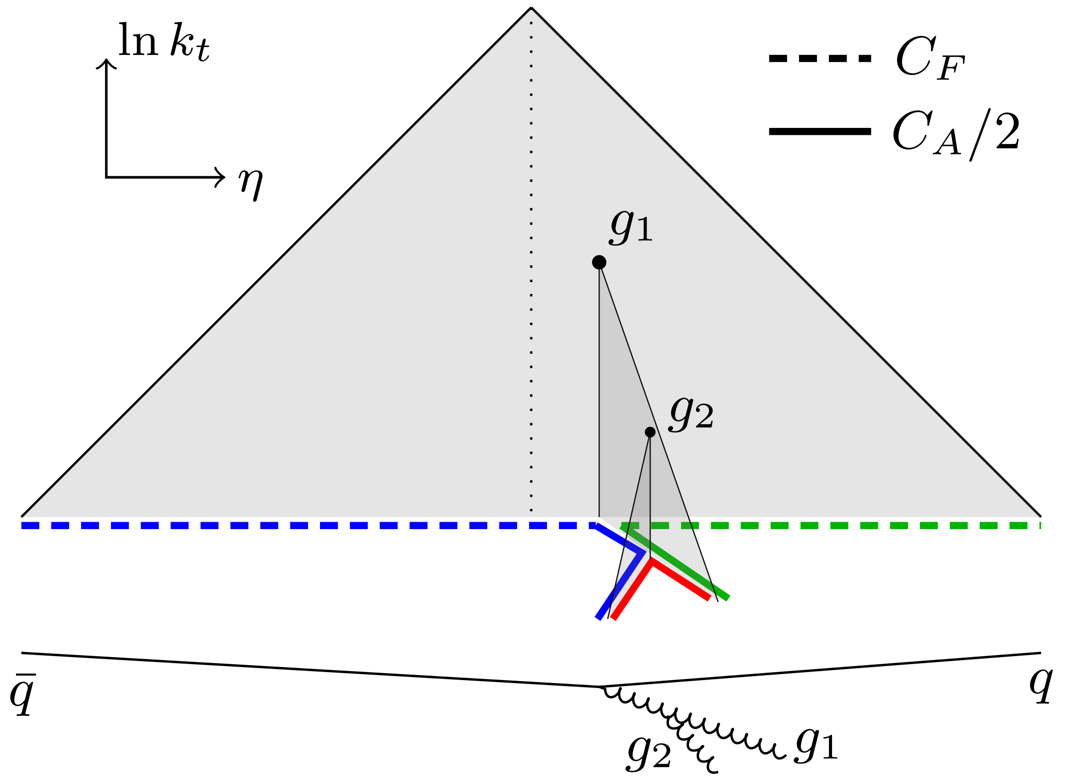
Also for hadron-collisions **[van Beekveld, SFR, Salam, Soto-Ontoso, Soyez, Verheyen ’22]**



Colour in the PanScales showers

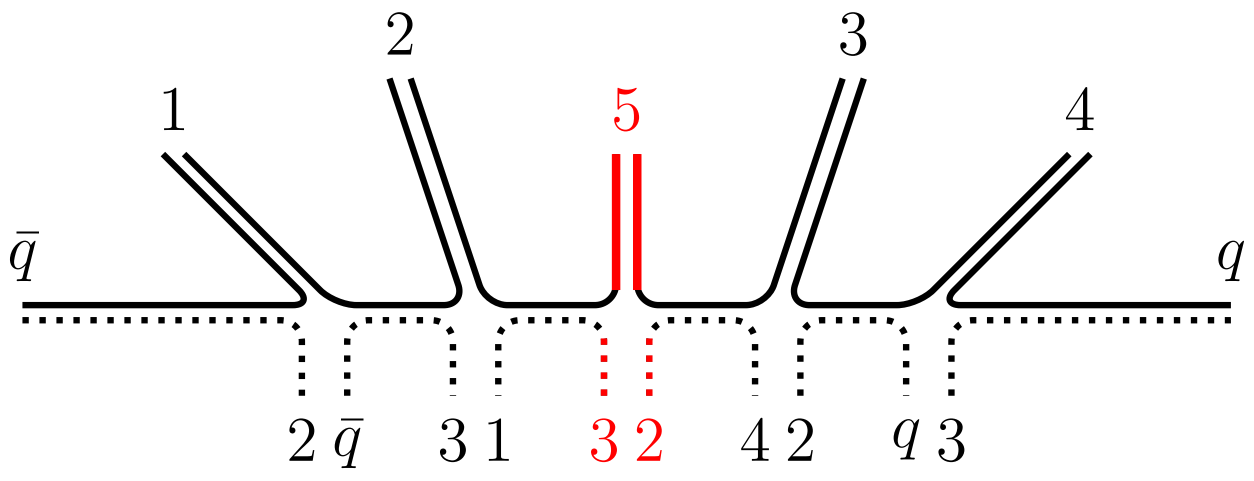
Hamilton, Medves, Salam, Scyboz, Soyez, 2011.10054 [FSR]
van Beekveld, SFR, Salam, Soto-Ontoso, Soyez, Verheyen [generalisation to ISR]

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

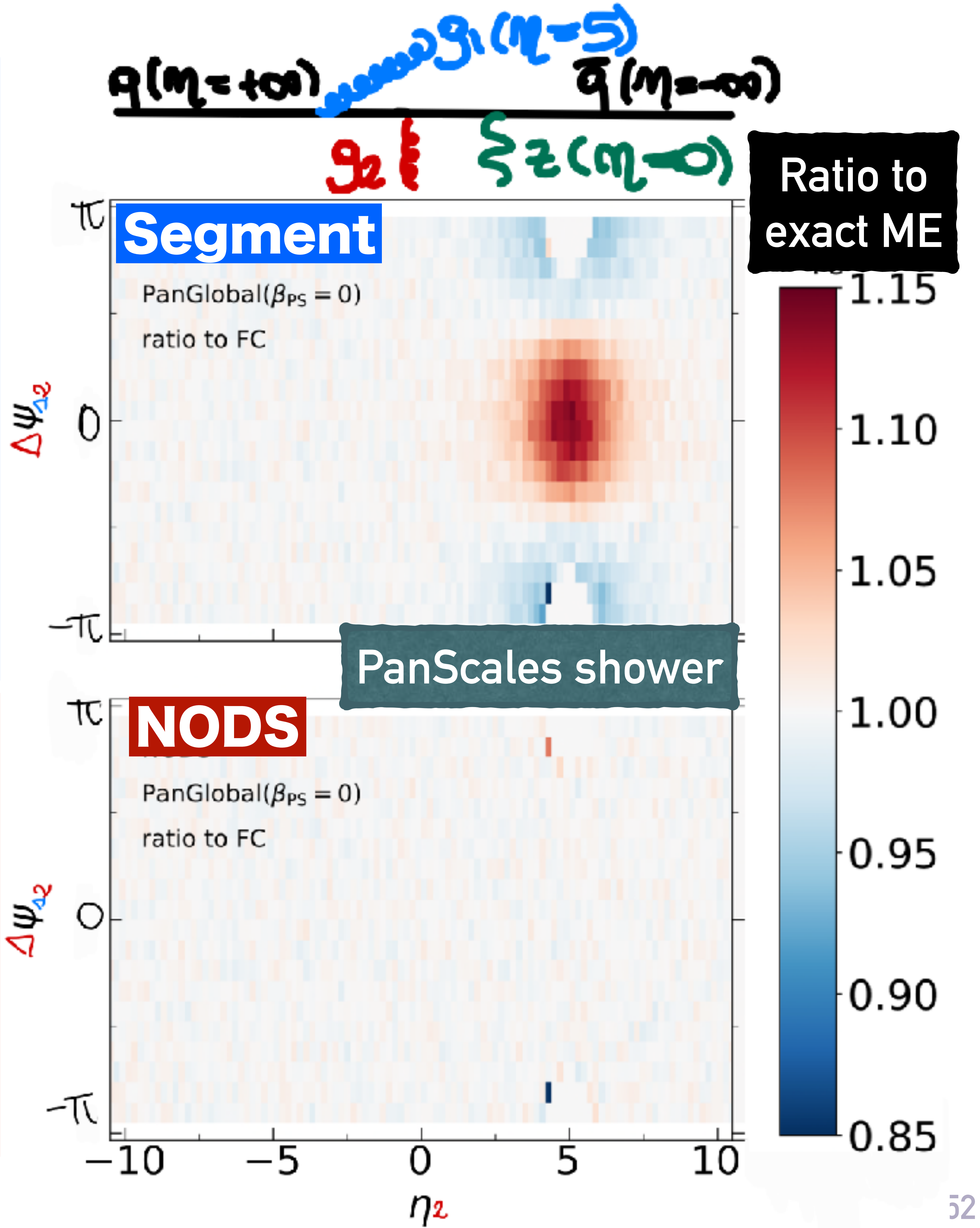


$$\bar{q}[-\infty, C_F, \eta_1^L, C_A, \eta_2^L, +\infty]_{g_2}$$
$$g_2[-\infty, C_A, \eta_2^R, C_A, +\infty]_{g_1}$$
$$g_1[-\infty, C_A, \eta_1^R, C_F, +\infty]_q$$
$$\eta_L = \max(0,\eta), \quad \eta_R = \min(0,\eta)$$

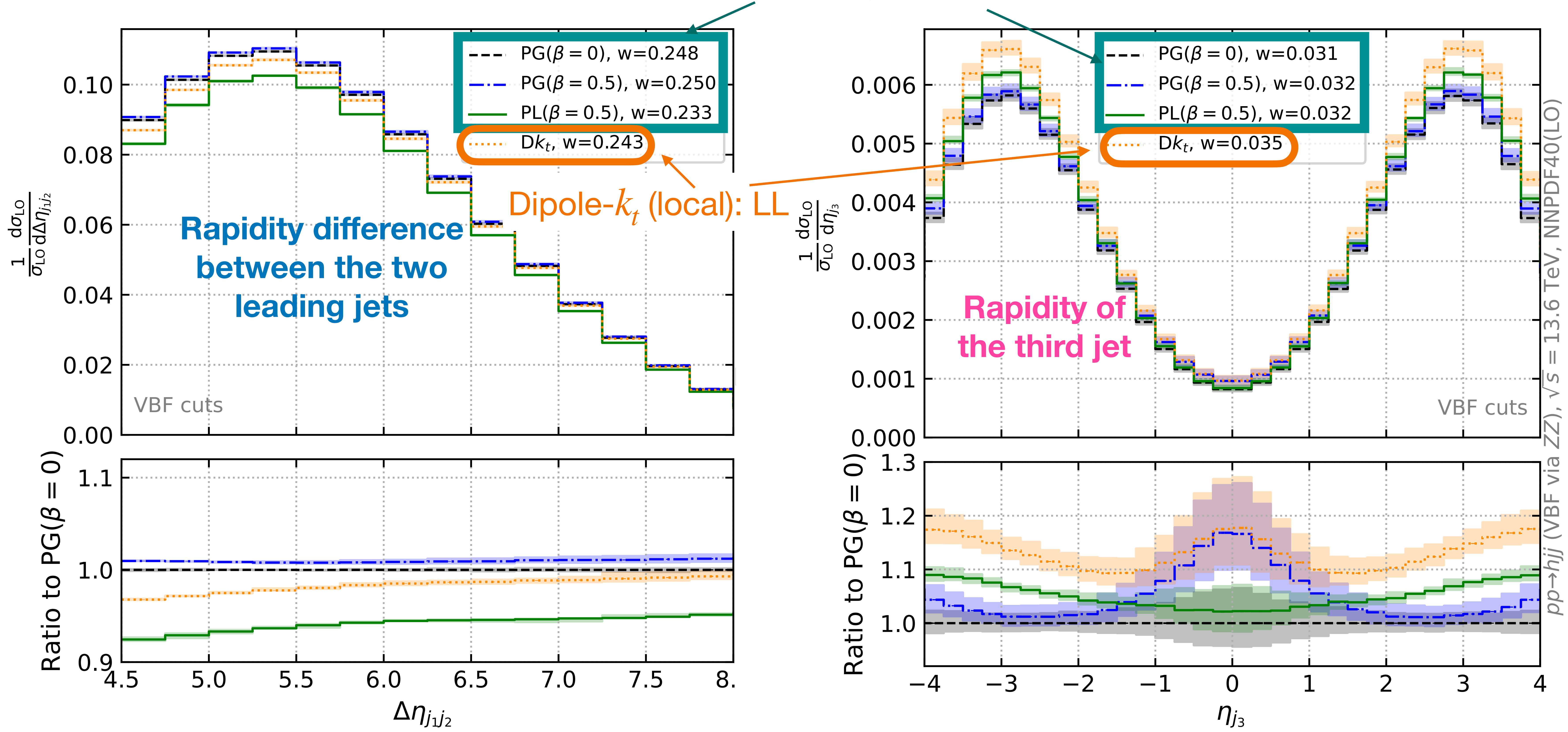
NODS: nested (double soft) matrix element corrections assuming last emission is the softest



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



Exploratory phenomenology for VBF

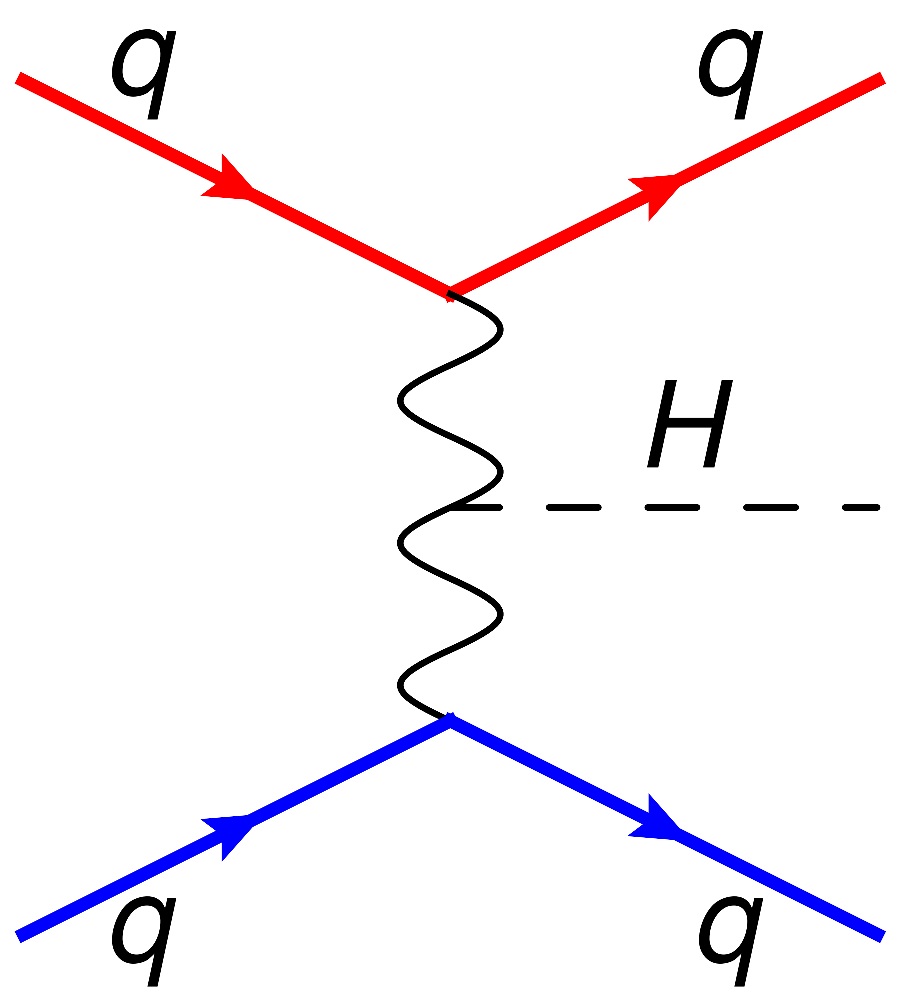


NLL PanScales showers

Dipole-k_t (local): LL

Rapidity difference between the two leading jets

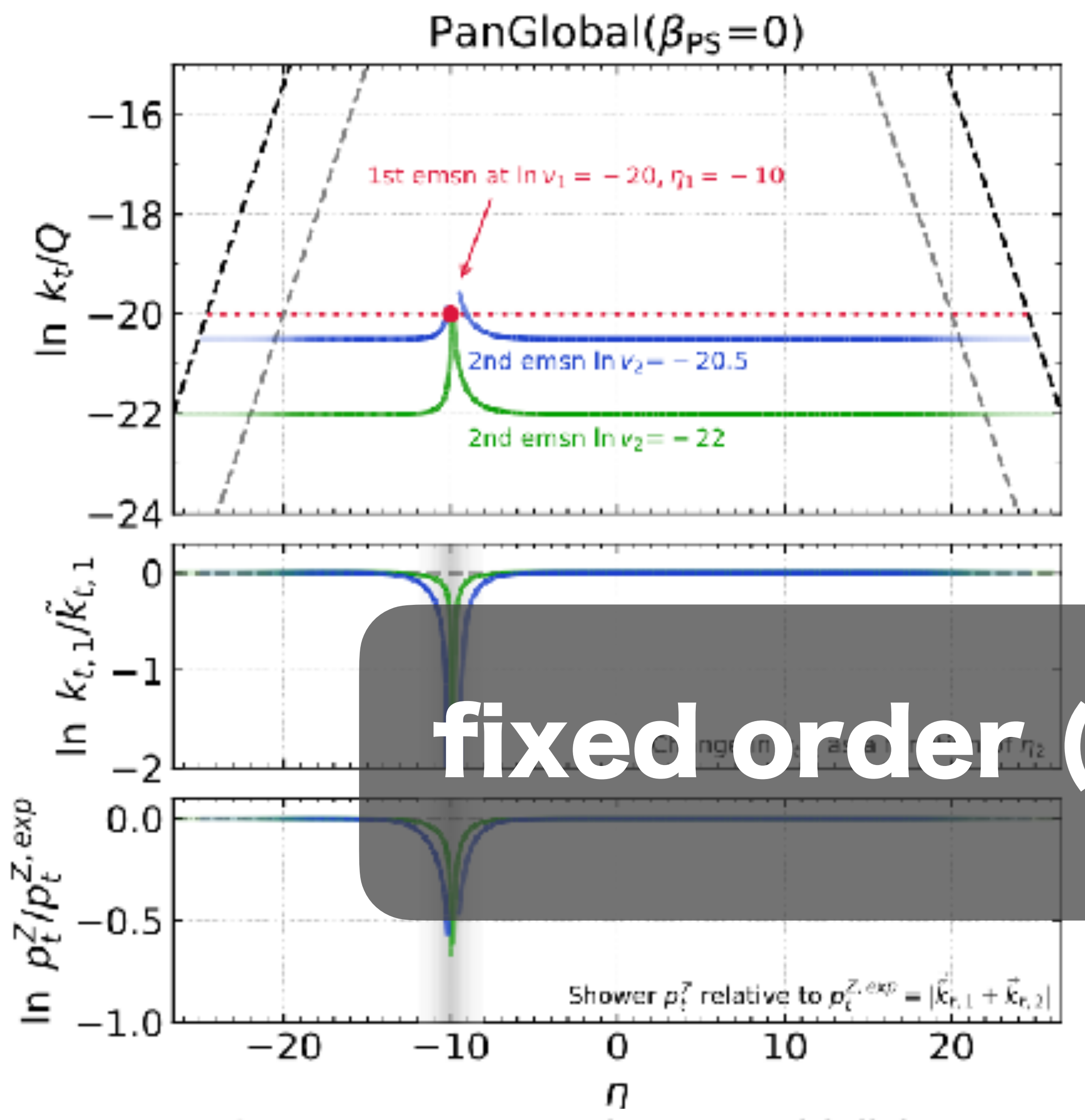
Rapidity of the third jet

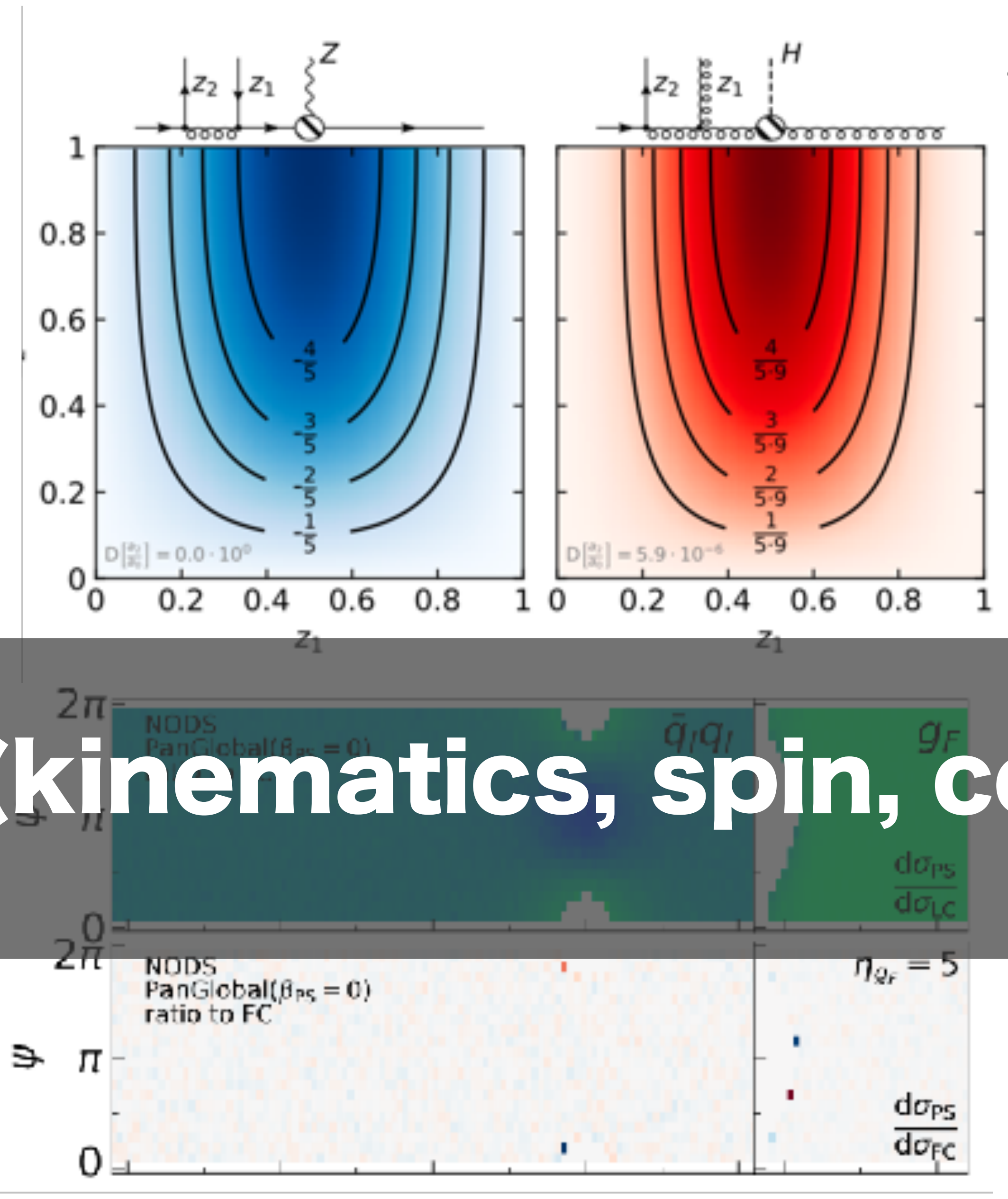


LO events obtained thanks to our **Pythia8.3** [2203.11601] interface!

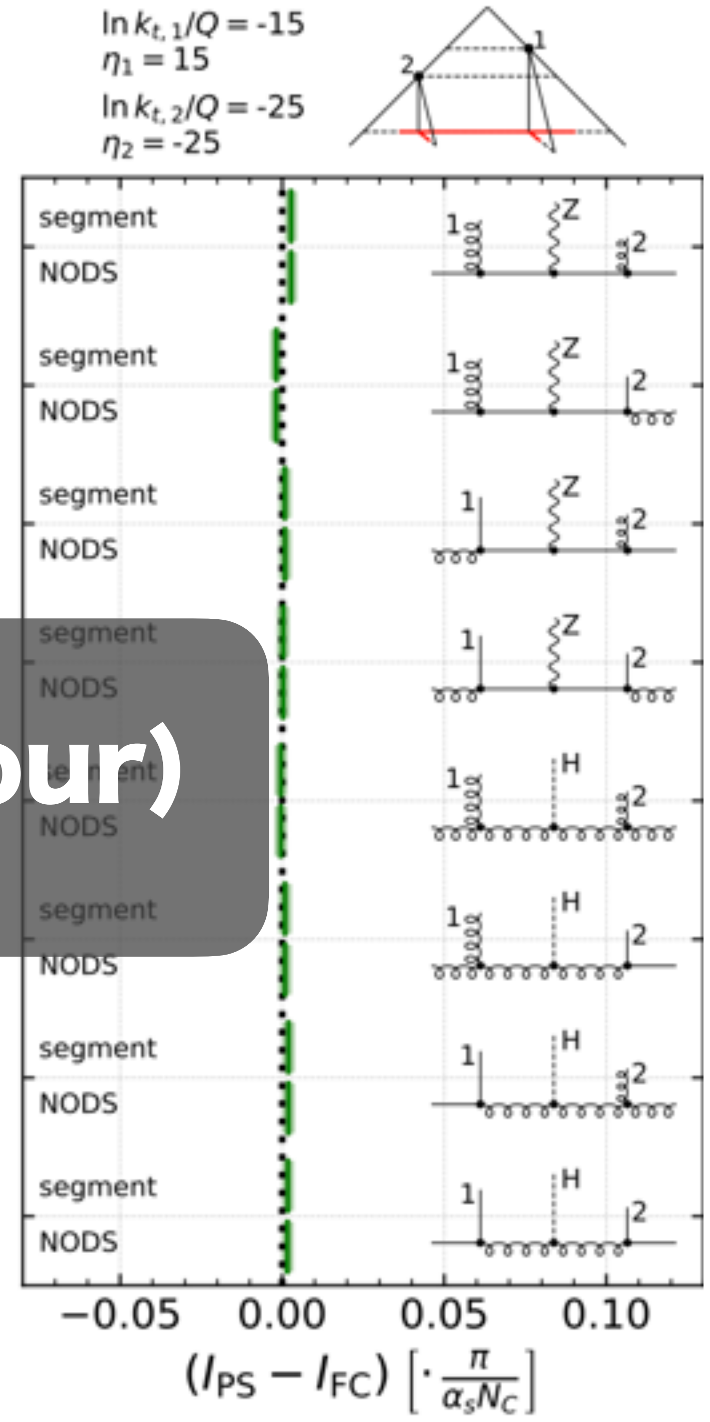
- For inclusive observables, differences have the same size of NLO corrections. LL shower lies between the NLL predictions.
- For exclusive observables, the LL shower lies outside the band spanned by the NLL showers

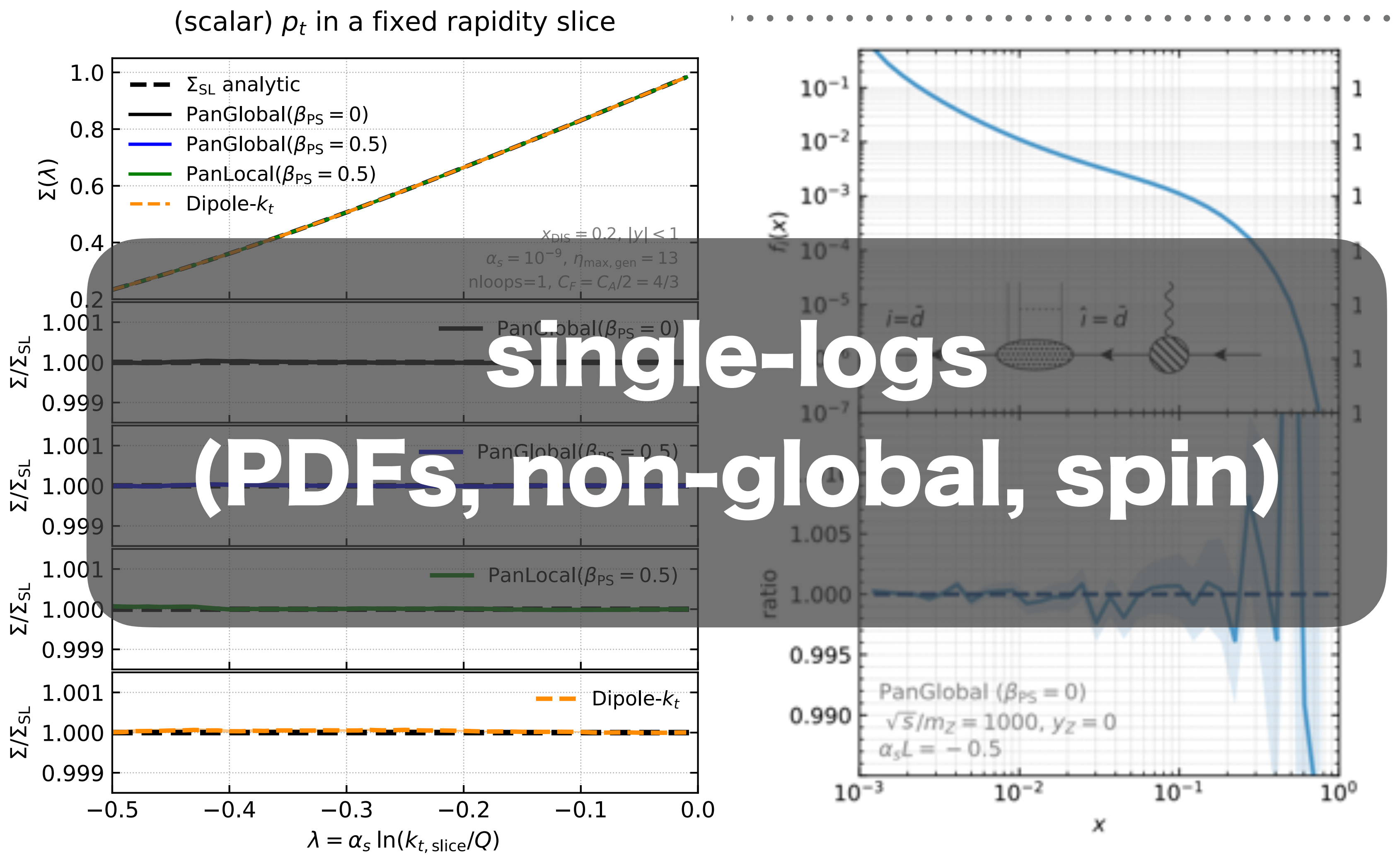
All-orders validation of the PanScales showers



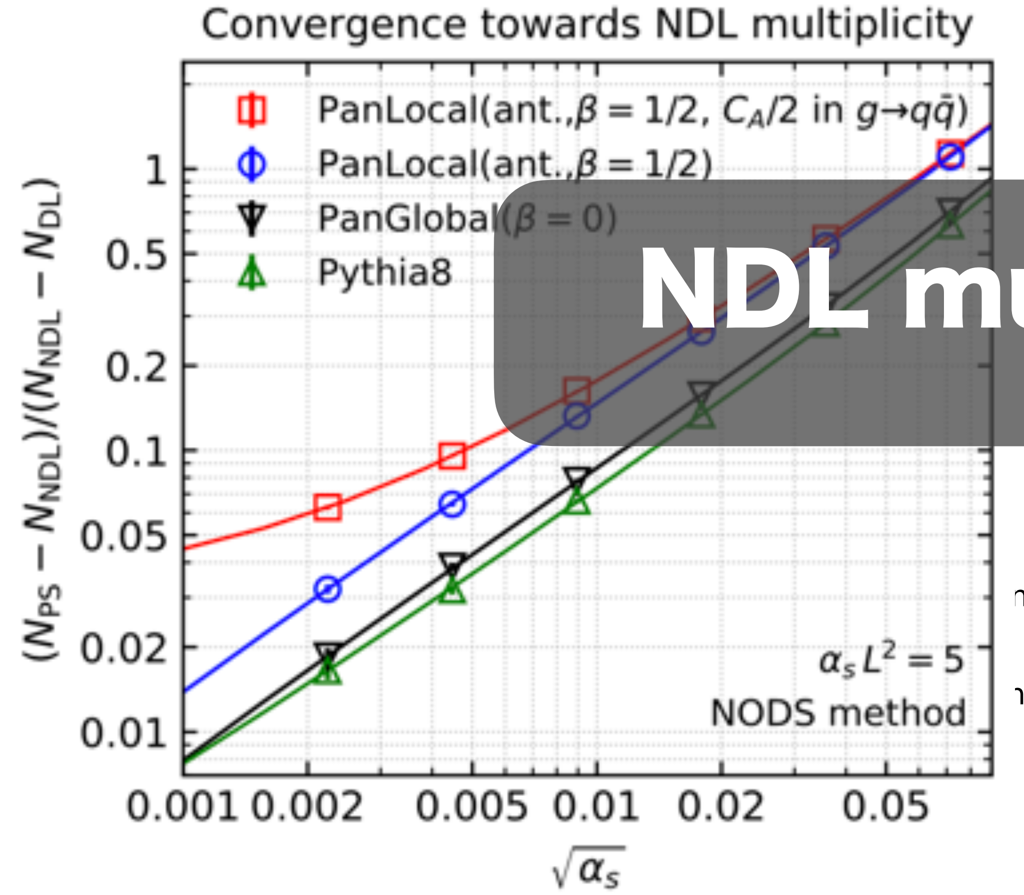


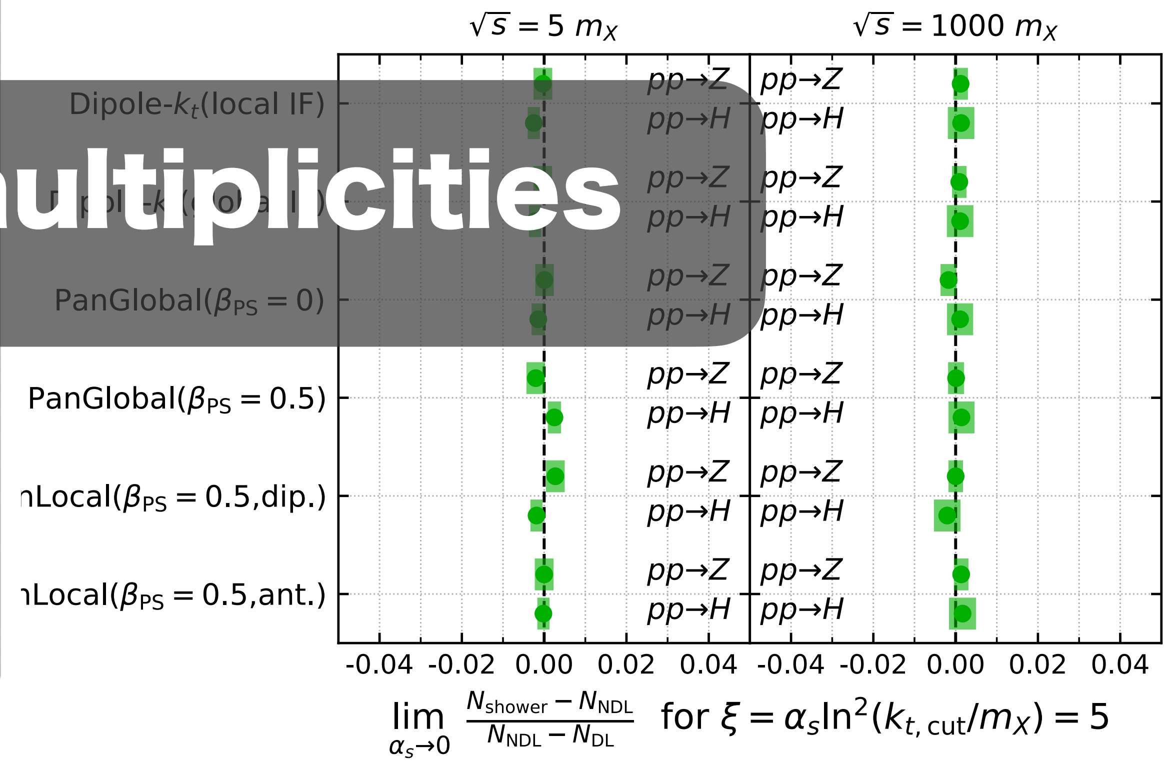
fixed order (kinematics, spin, colour)



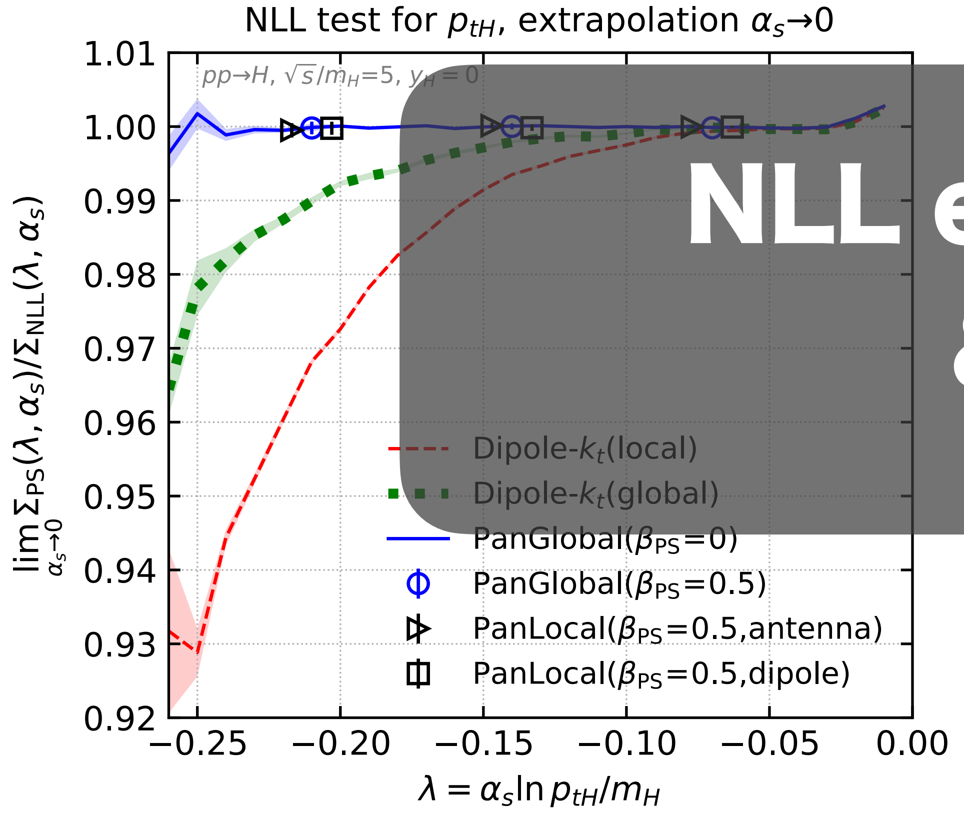


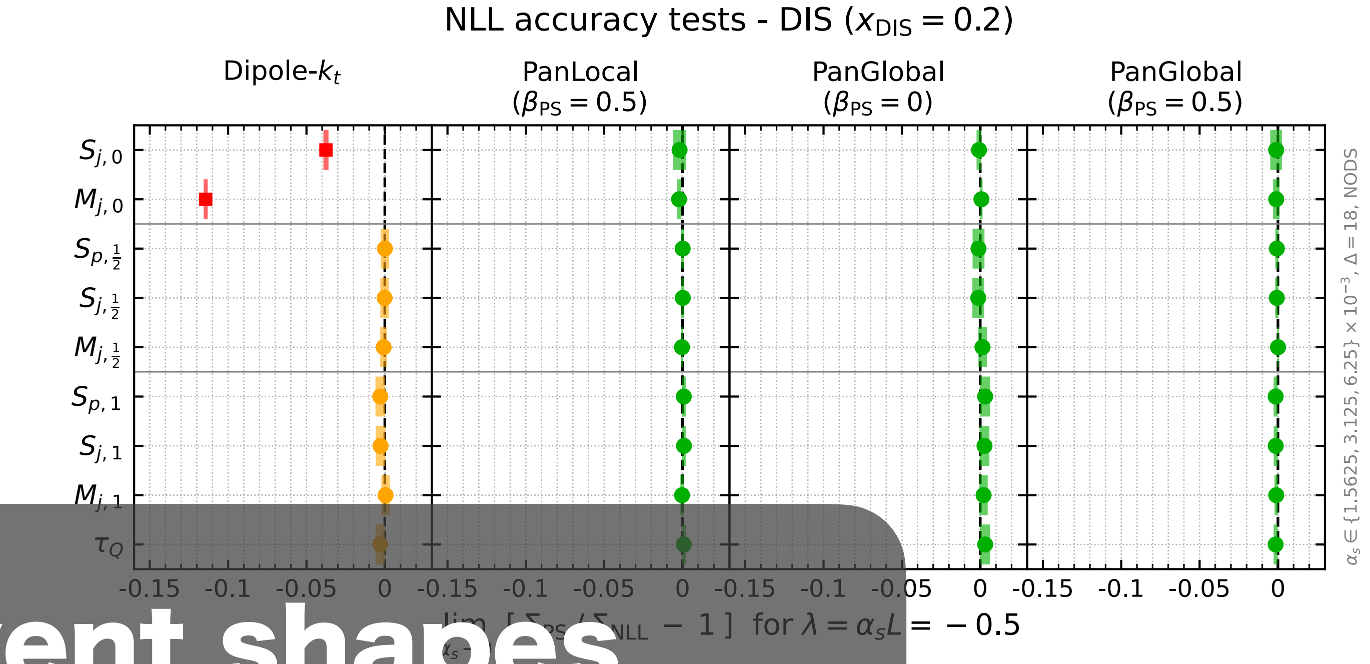
single-logs (PDFs, non-global, spin)

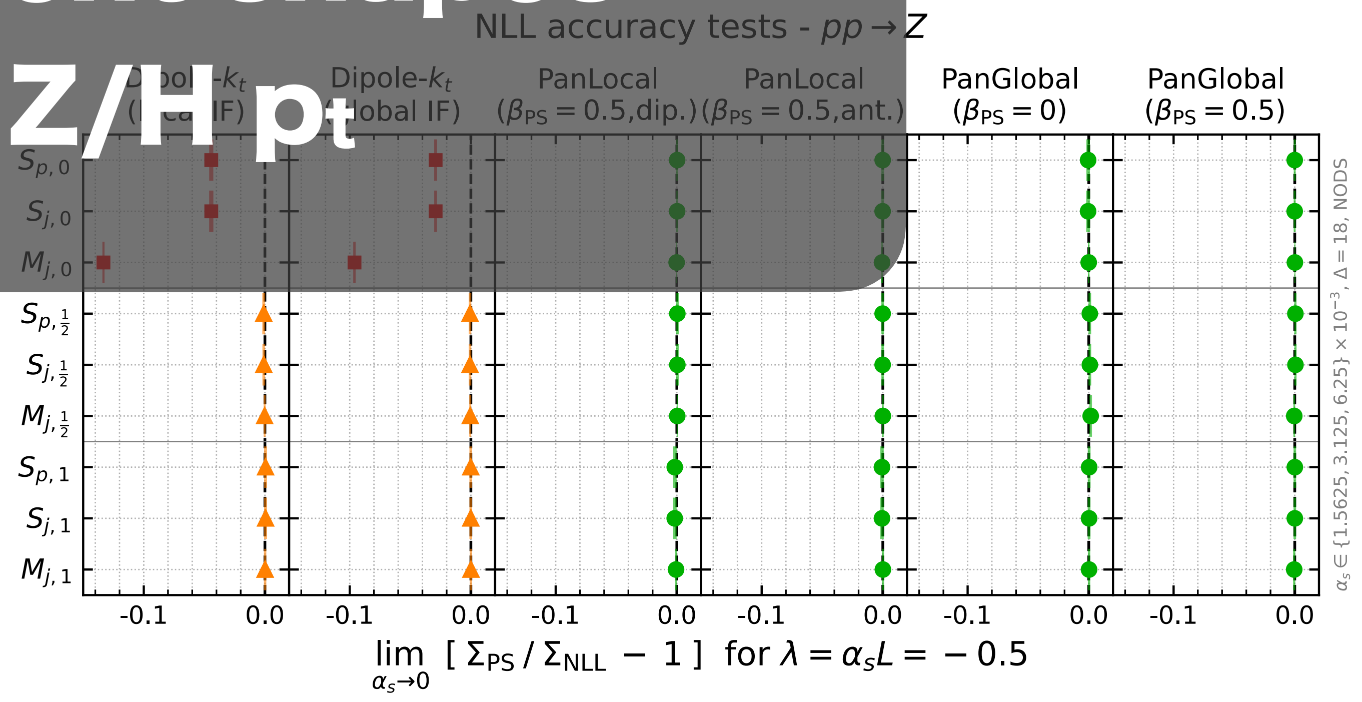




NDL multiplicities







NLL event shapes & Z/H p_t

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

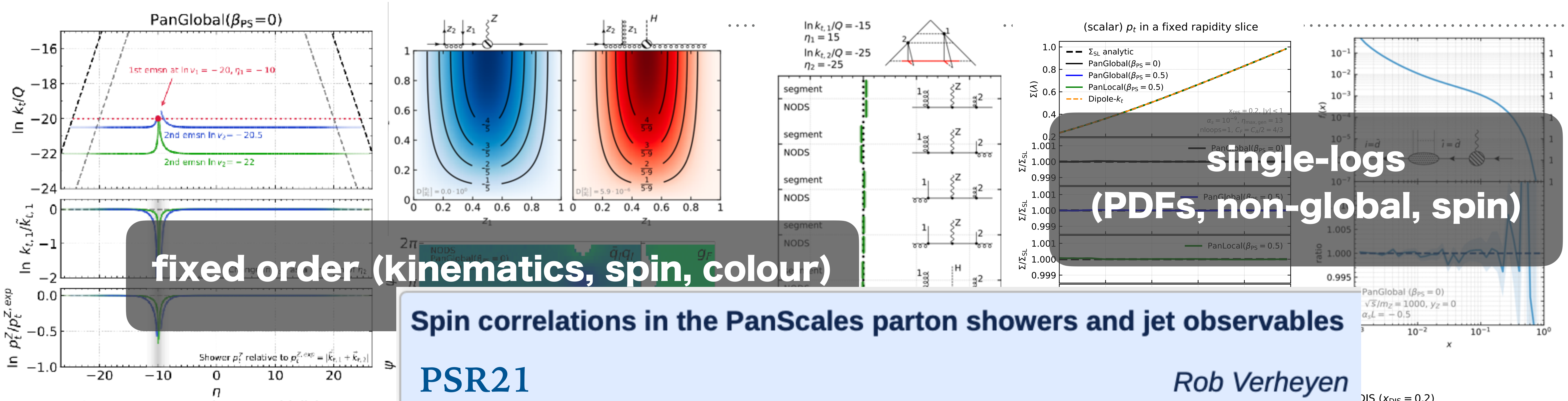
Colour in e^+e^- 2011.10054 and in pp 2205.02237

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

All-orders tests for pp 2207.09467

DIS NLL tests 2305.08645

All-orders validation of the PanScales showers



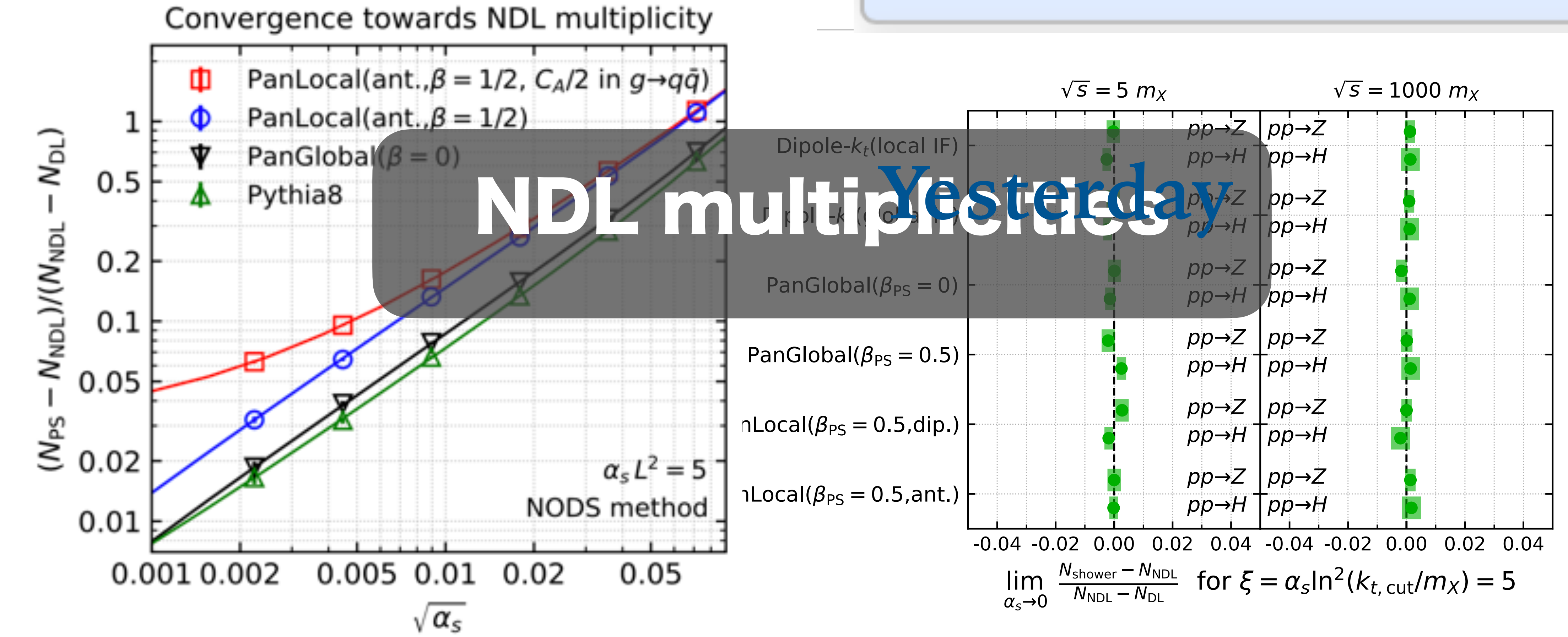
fixed order (kinematics, spin, colour)

single-logs (PDFs, non-global, spin)

Spin correlations in the PanScales parton showers and jet observables

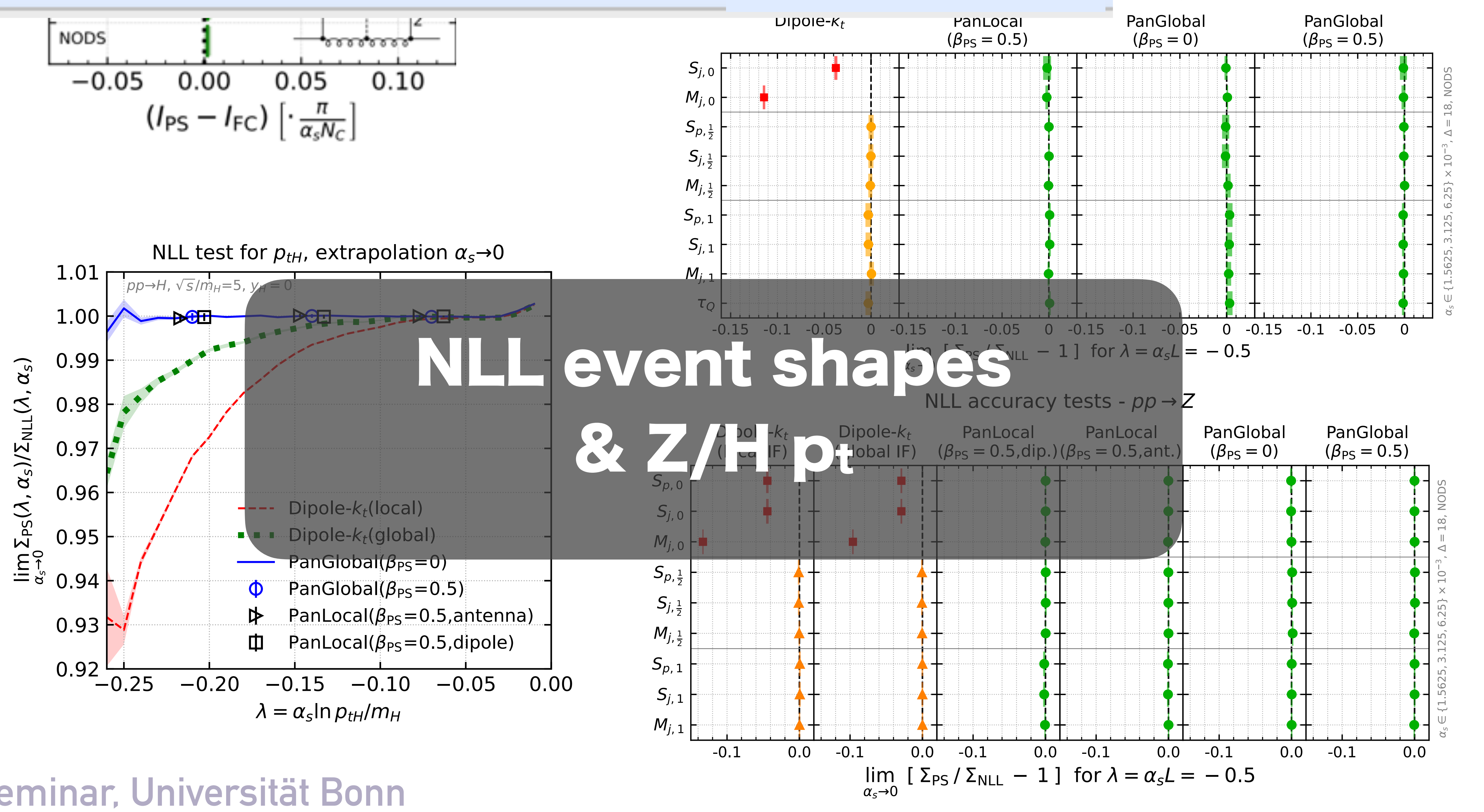
PSR21

Rob Verheyen



NDL multiplicities

Yesterday



NLL event shapes & Z/H p_t

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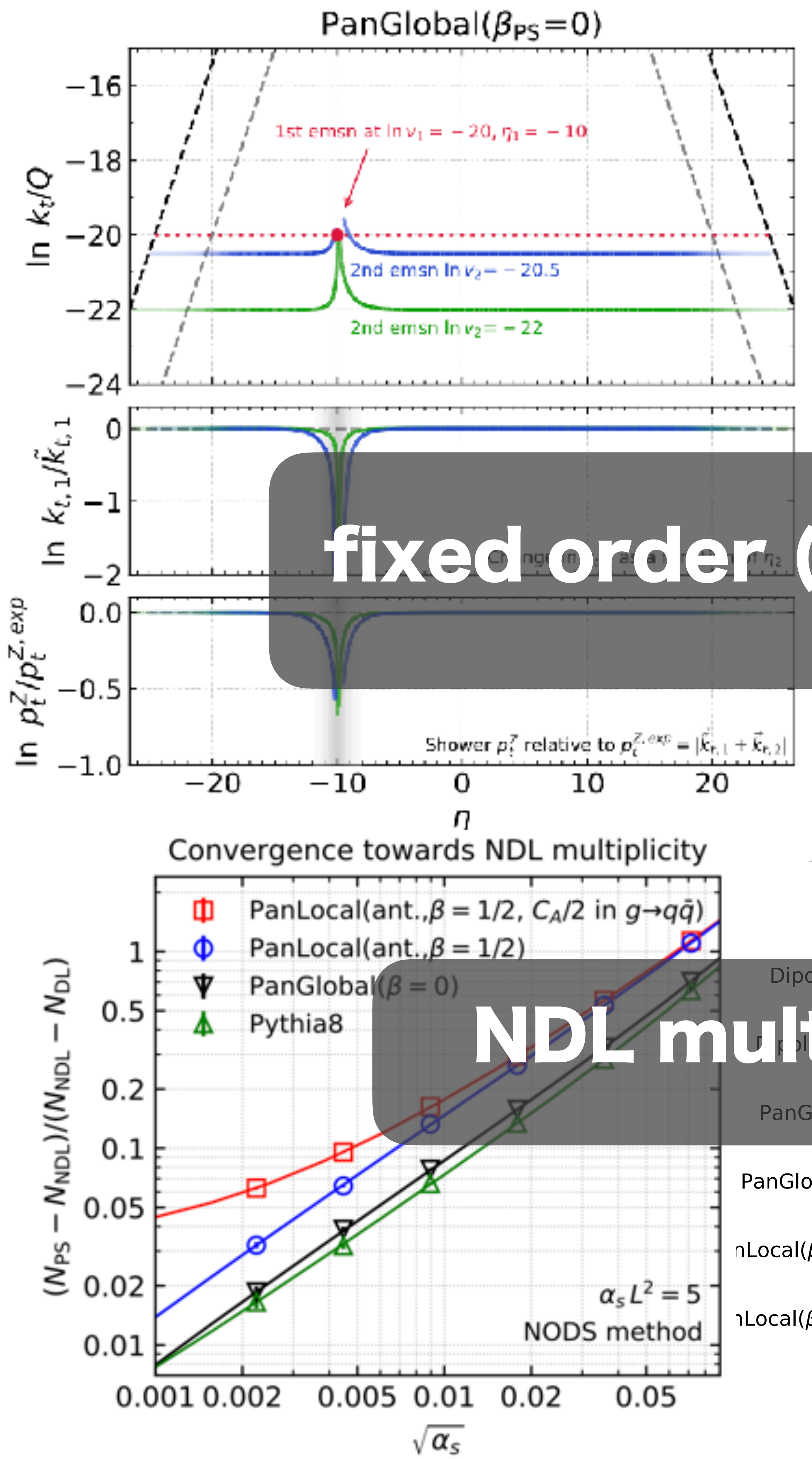
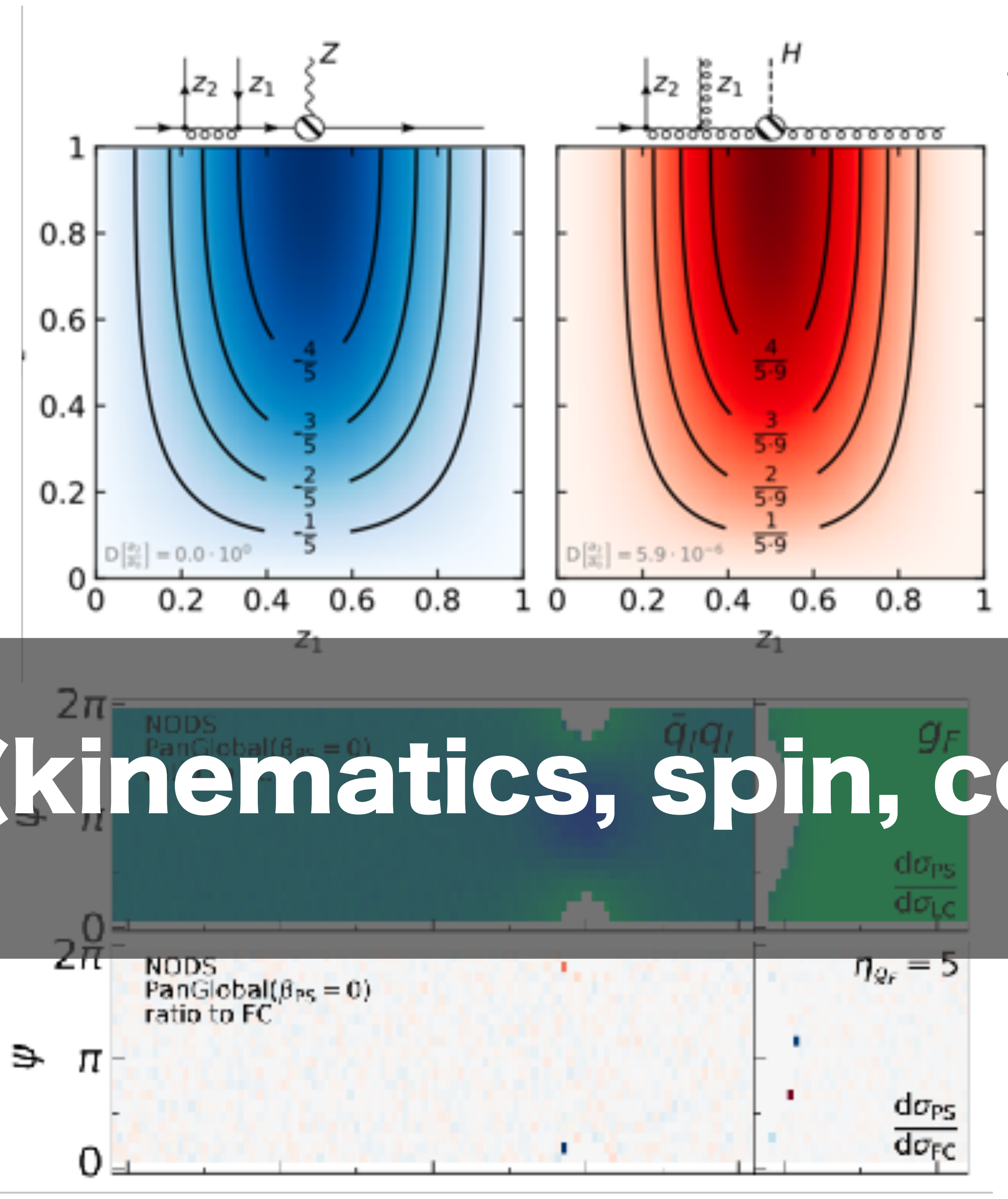
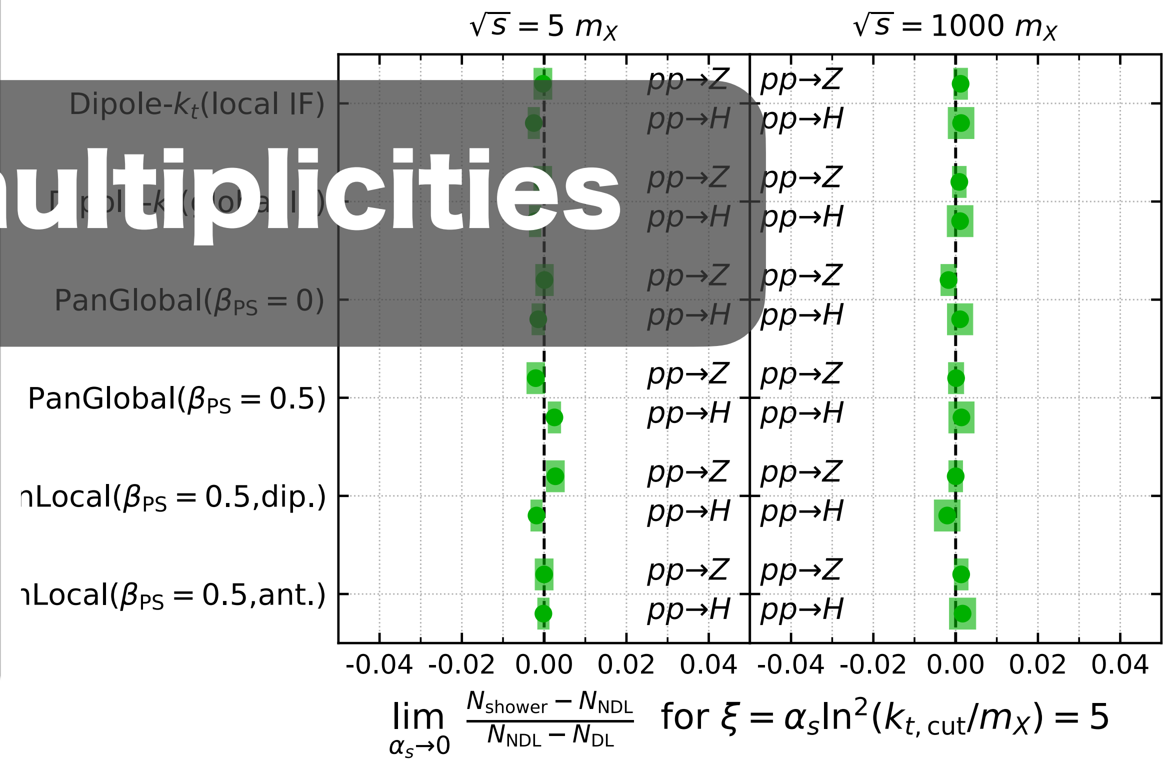
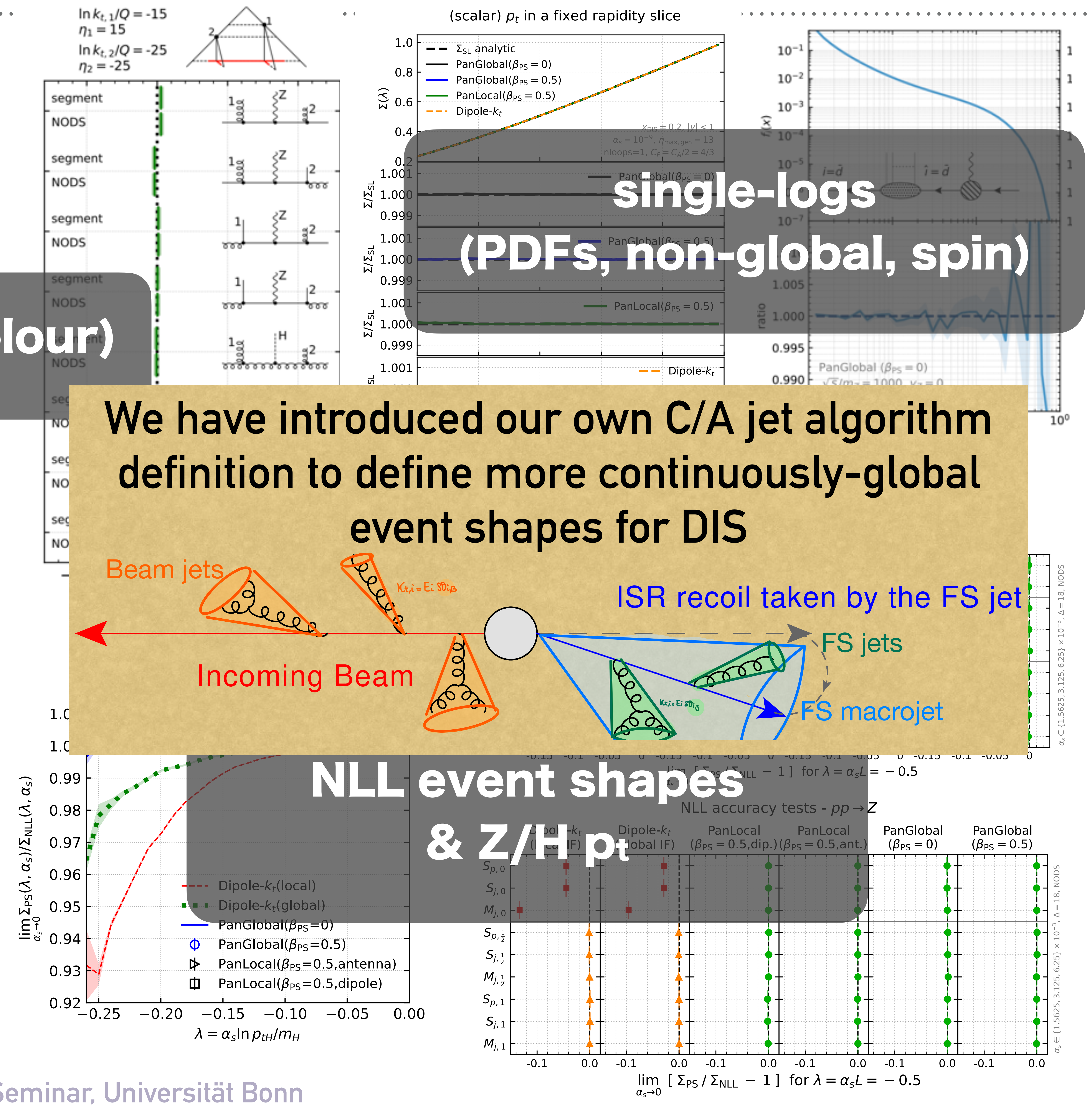








fixed order (kinematics, spin, colour)

single-logs (PDFs, non-global, spin)

NDL multiplicities

NLL event shapes & Z/H p_t

We have introduced our own C/A jet algorithm definition to define more continuously-global event shapes for DIS

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

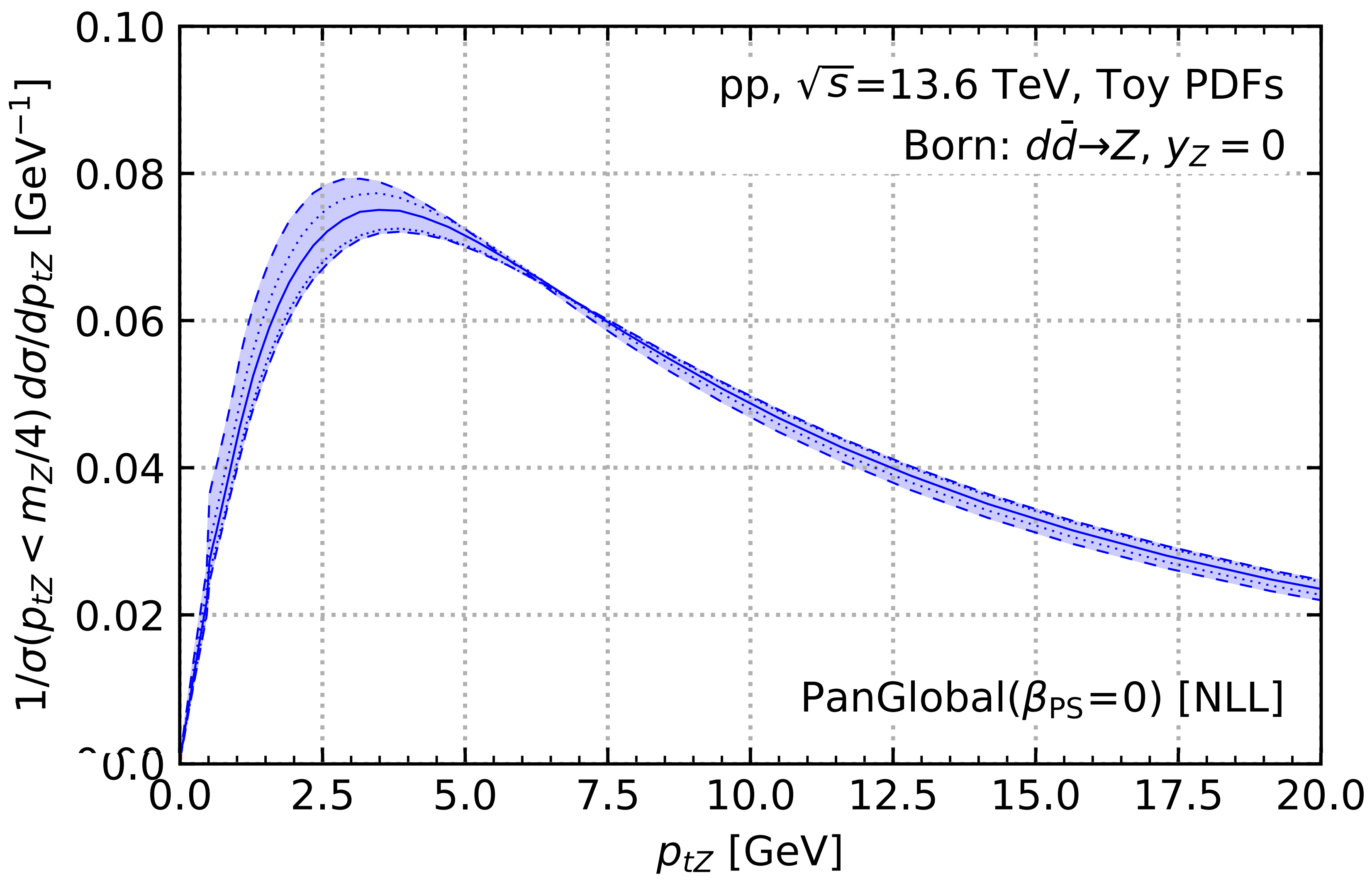
Colour in e^+e^- 2011.10054 and in pp 2205.02237

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

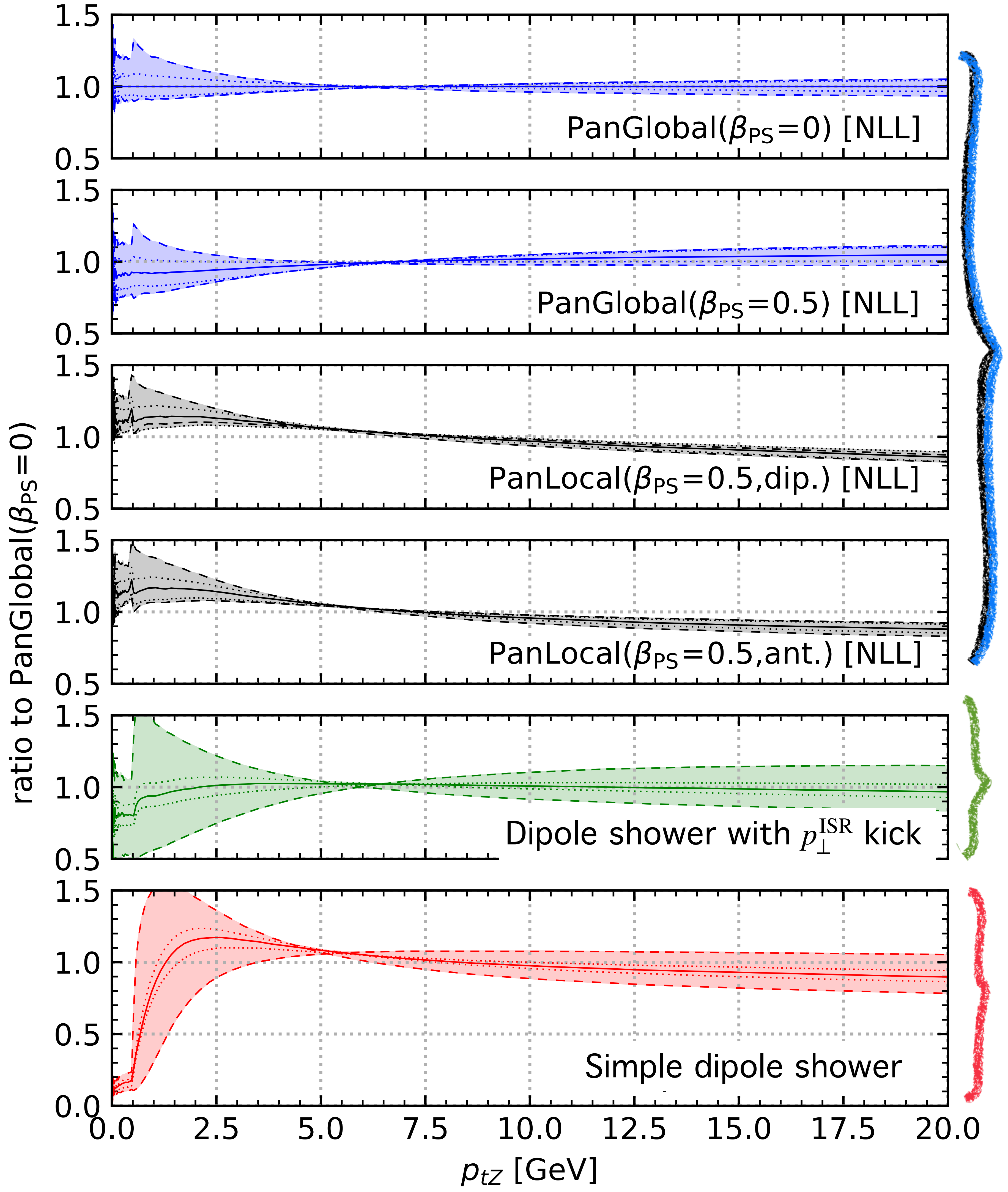
All-orders tests for pp 2207.09467

DIS NLL tests 2305.08645

Transverse-momentum of the Z boson



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



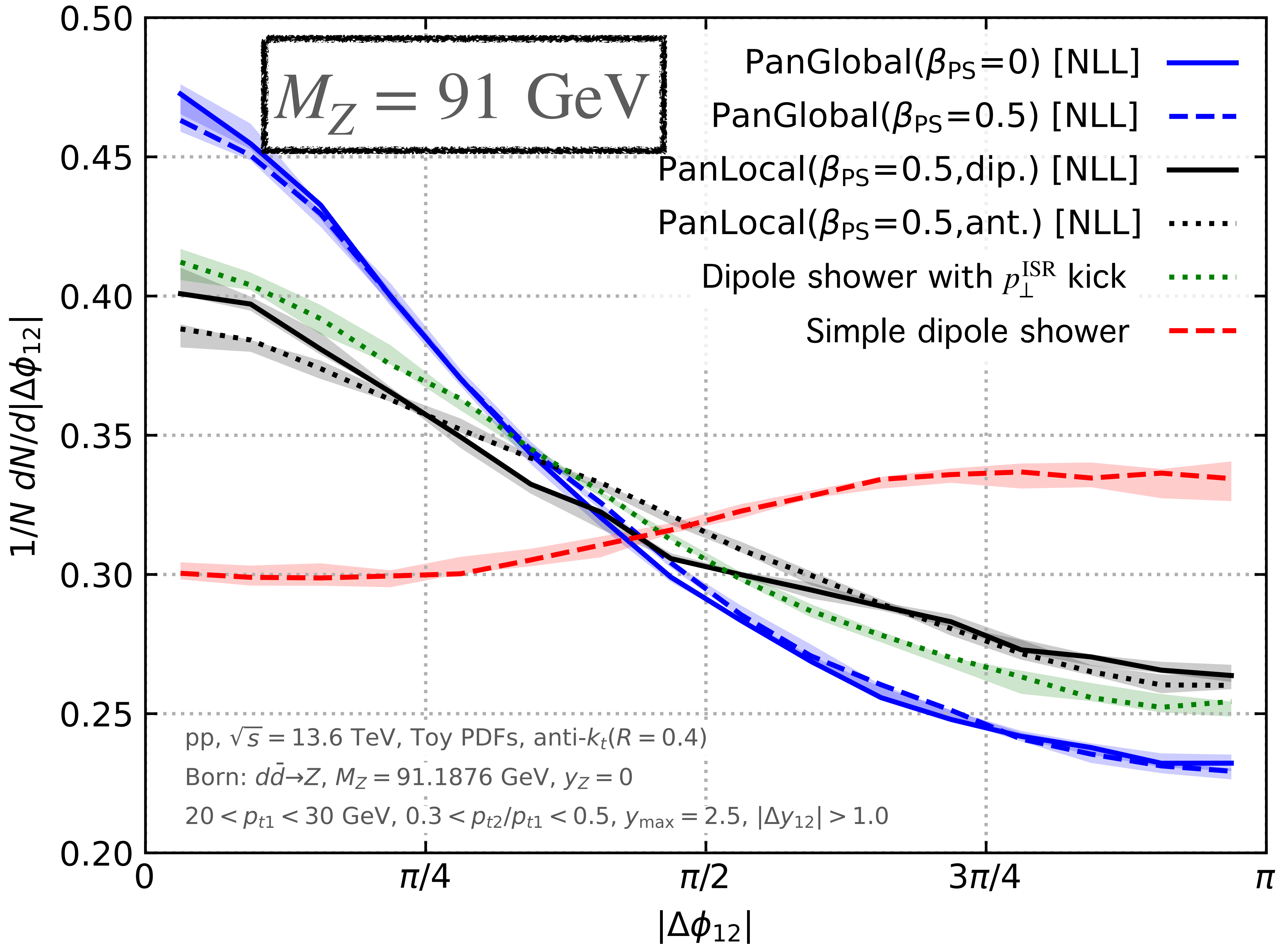
PanScales NLL showers with global [blue] or local [black] recoil. At small pTZ, the spectrum is power-suppressed with the correct normalisation.

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

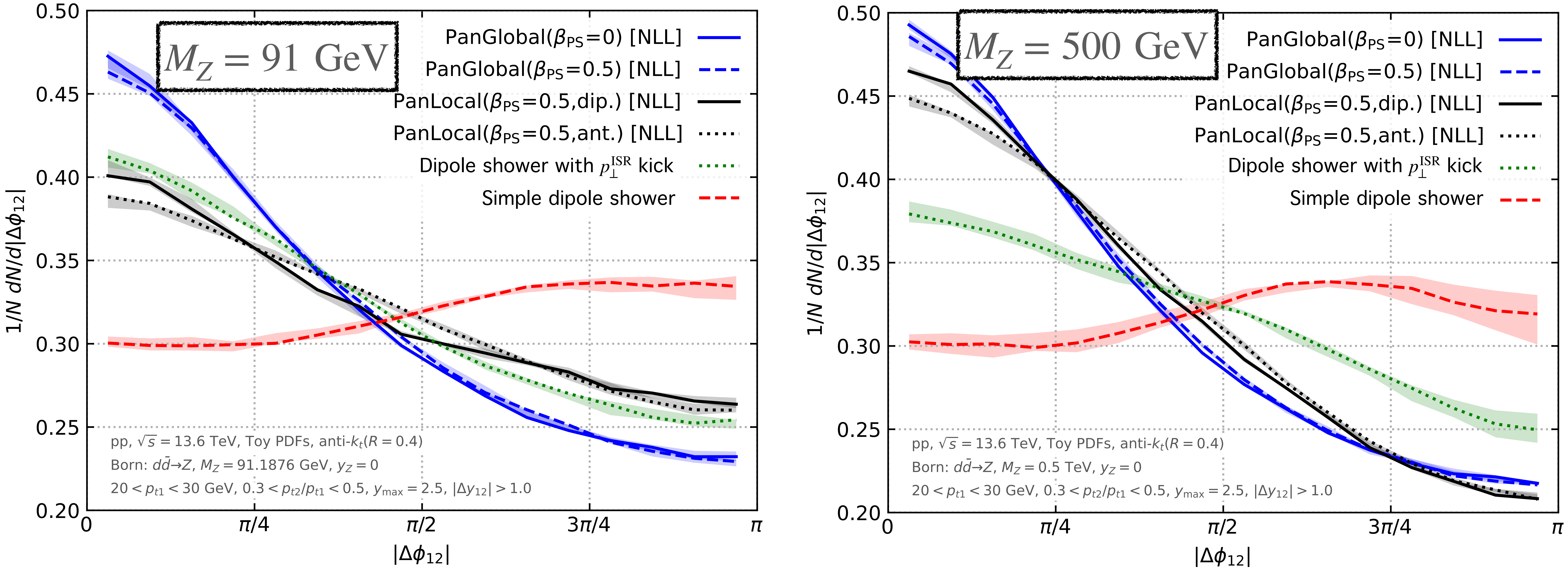
LL shower. At small pTZ, the spectrum is EXPONENTIALLY suppressed!

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

Azimuthal correlations between the two leading jets in DY

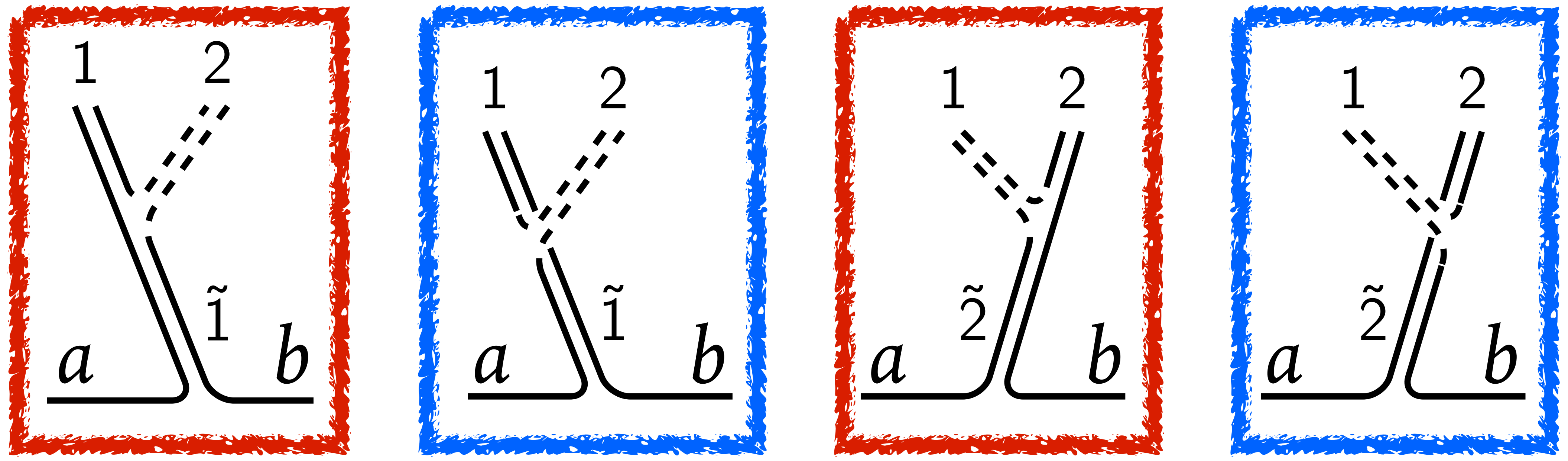


Azimuthal correlations between the two leading jets in DY



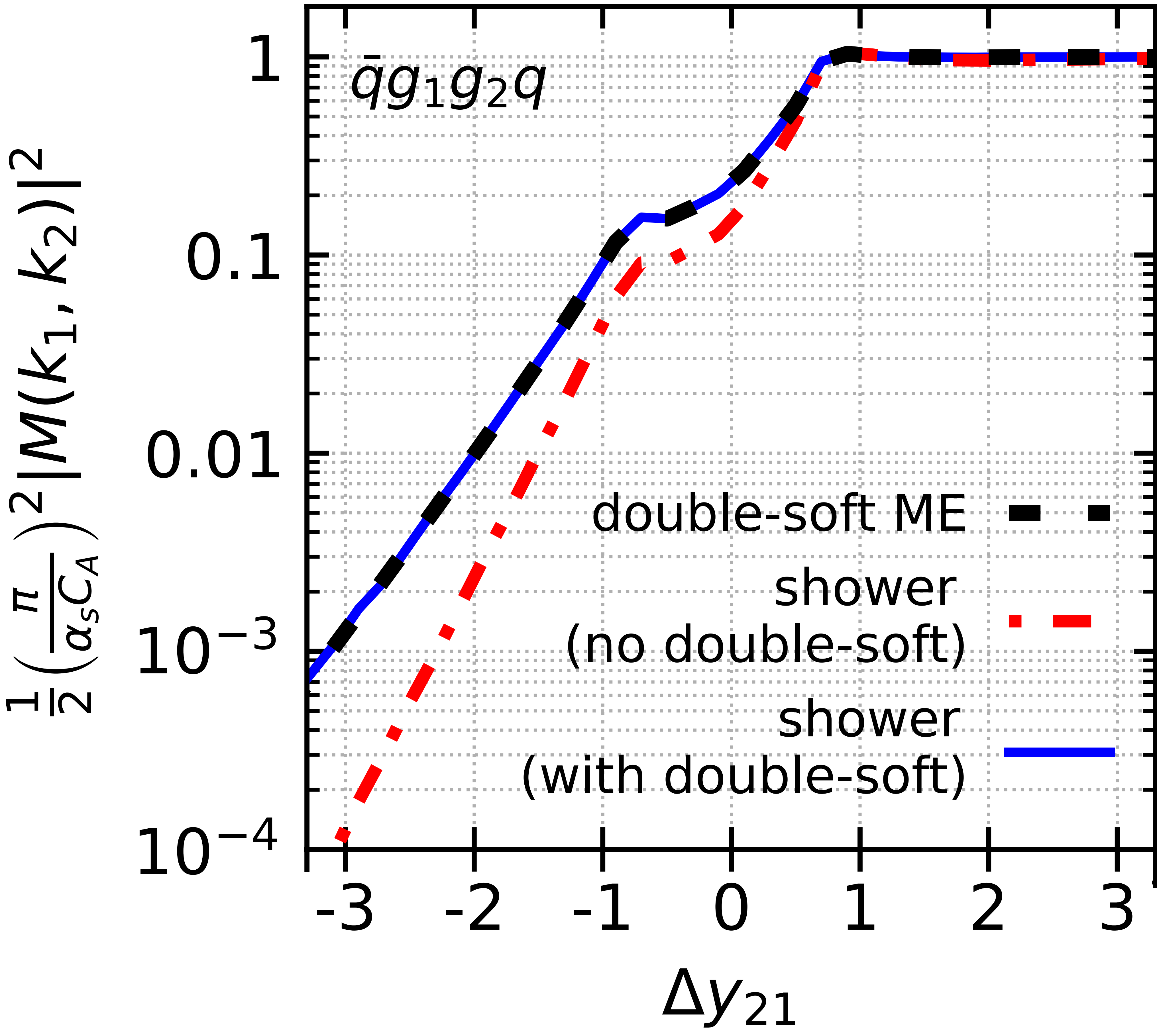
- Impossible to tune a **LL shower** to reproduce a NLL across several energy scales (at 91 GeV subleading effects are more sizeable and the shower is more tunable than at 500 GeV!)
- Difference among PS larger than scale uncertainty, and hence should be used to estimate **PS uncertainties**, until we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

2. Get the colour ordering

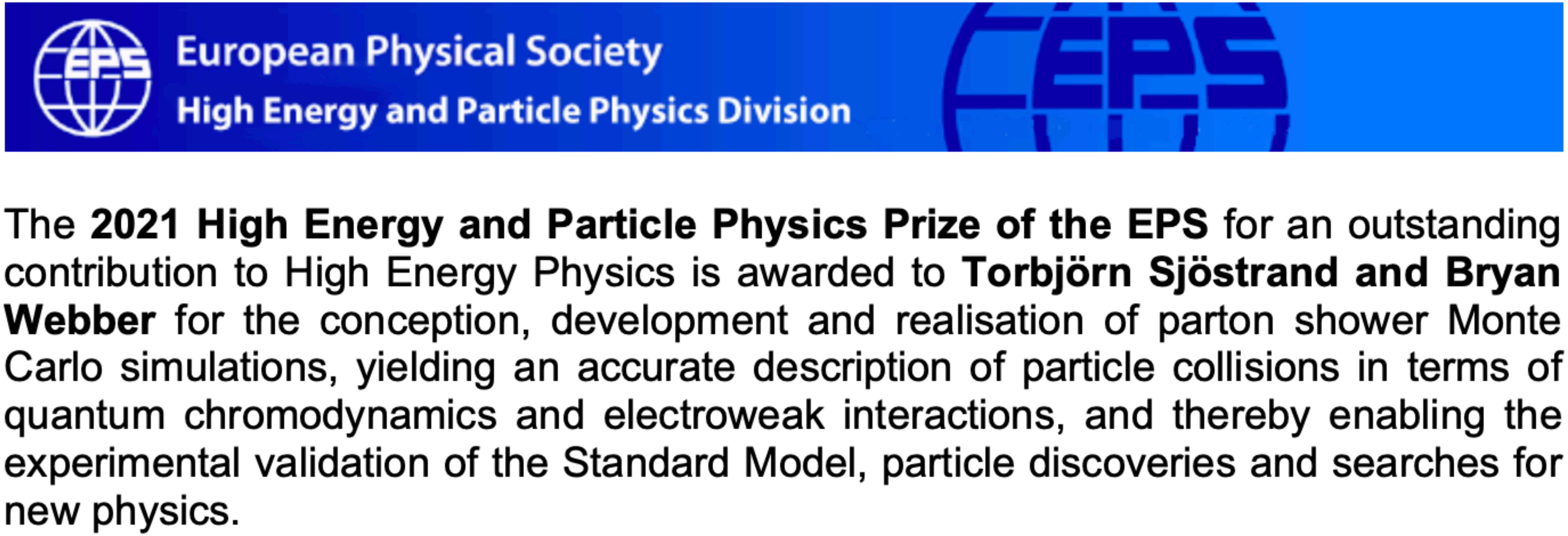


- There are two colour orderings *a12b*, *a21b*
- relative fractions $F^{(12)}$ and $F^{(21)}$ of the two must be correct in order to get correct next soft emission (large-N_c)
- If shower produces more of the ***12*** ordering than is correct, then allow for **swap of ordering** (similarly for gg v. $q\bar{q}$)

matrix-element test,
a12b colour ordering



$$P_{\text{swap}} = \frac{F^{(12)}_{\text{shower}} - F^{(12)}_{\text{DS}}}{F^{(12)}_{\text{shower}}}$$



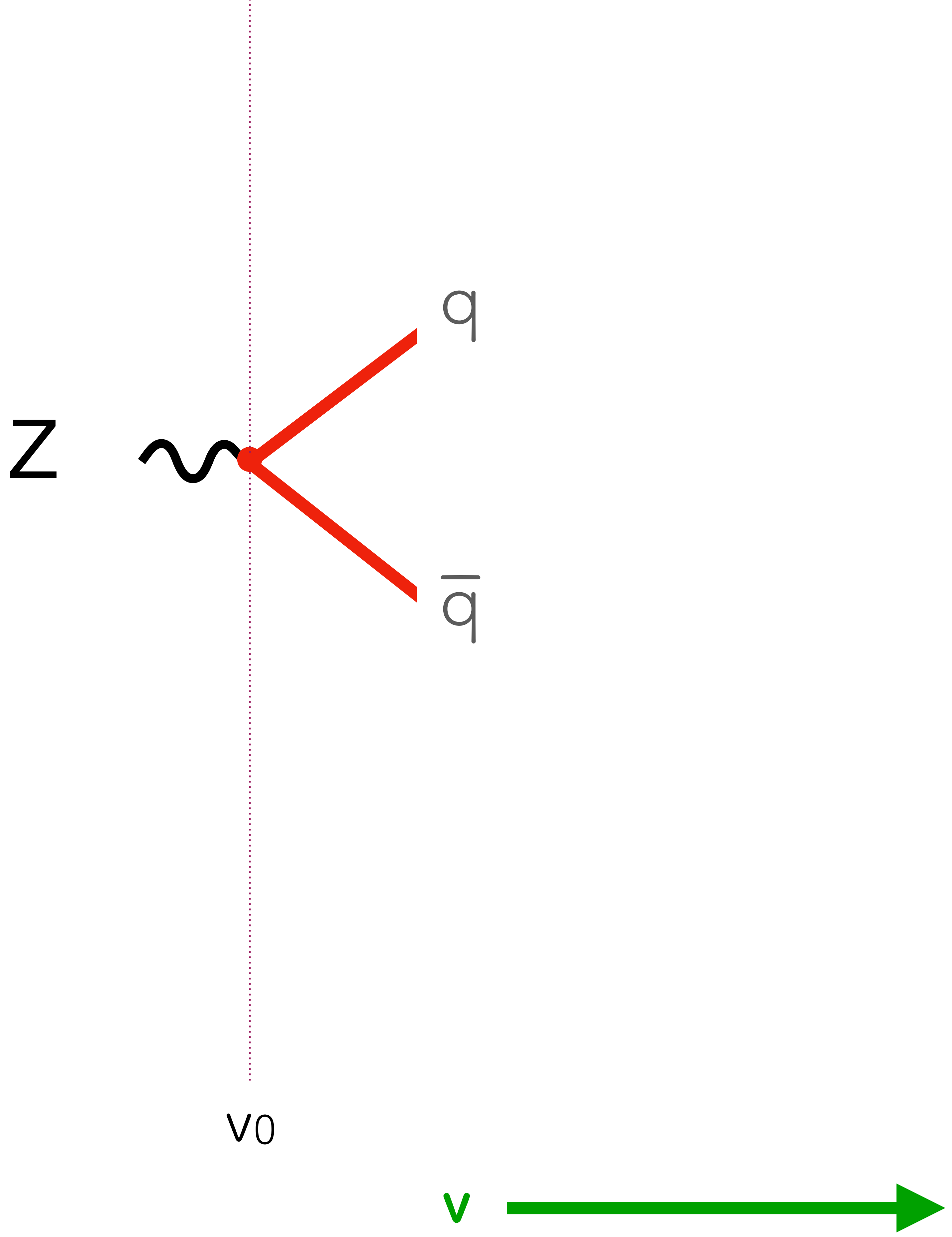
European Physical Society
High Energy and Particle Physics Division

The **2021 High Energy and Particle Physics Prize of the EPS** for an outstanding contribution to High Energy Physics is awarded to **Torbjörn Sjöstrand and Bryan Webber** for the conception, development and realisation of parton shower Monte Carlo simulations, yielding an accurate description of particle collisions in terms of quantum chromodynamics and electroweak interactions, and thereby enabling the experimental validation of the Standard Model, particle discoveries and searches for new physics.

Torbjörn Sjöstrand: founding author of Pythia
Byran Webber: founding author of Herwig (with Marchesini†)

Parton Showers in a nutshell

Dipole showers [Gustafson, Pettersson, ’88] are the most used shower paradigm



Start with $q\bar{q}$ state.

Throw a random number to determine down to what **scale** state persists unchanged

$$\frac{dP_2(v)}{dv} = -f^{q\bar{q}}_{2\to 3}(v)\, P_2(v)$$

Parton Showers in a nutshell

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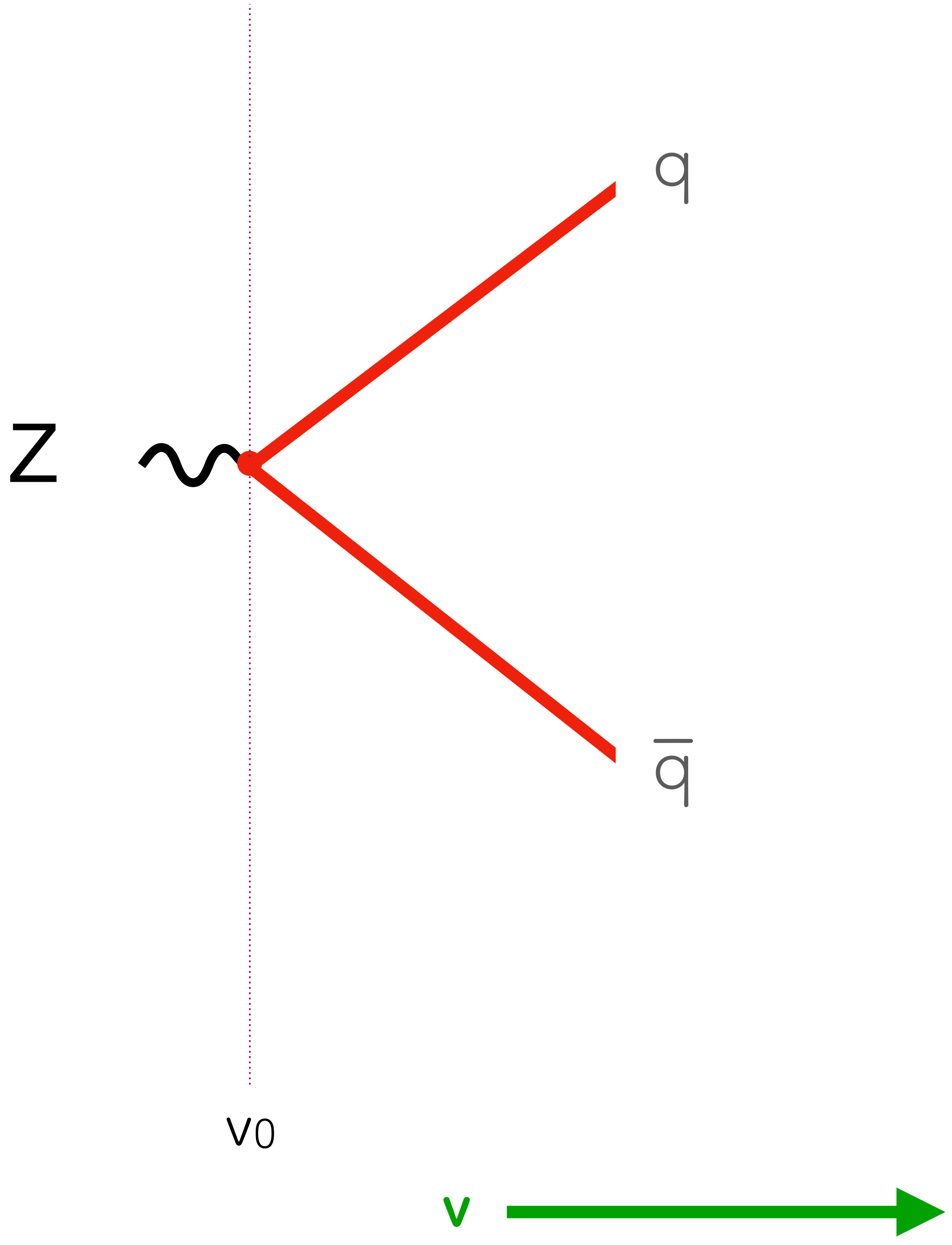

Start with $q\bar{q}$ state.

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$$\frac{dP_2(v)}{dv} = -\, f_{2\to3}^{q\bar{q}}(v)\, P_2(v)$$

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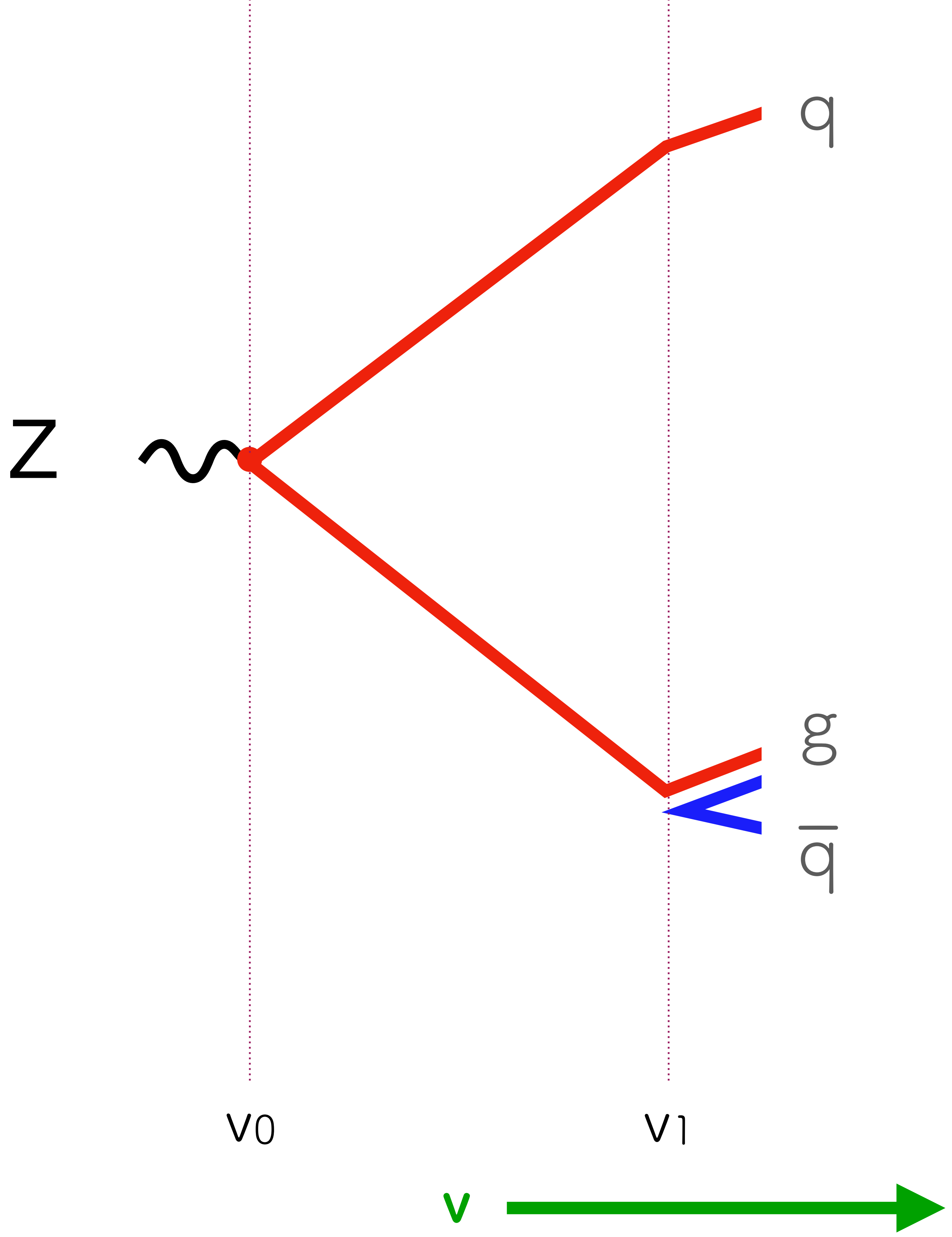


Start with $q\bar{q}$ state.

Throw a random number to determine down to what **scale** state persists unchanged

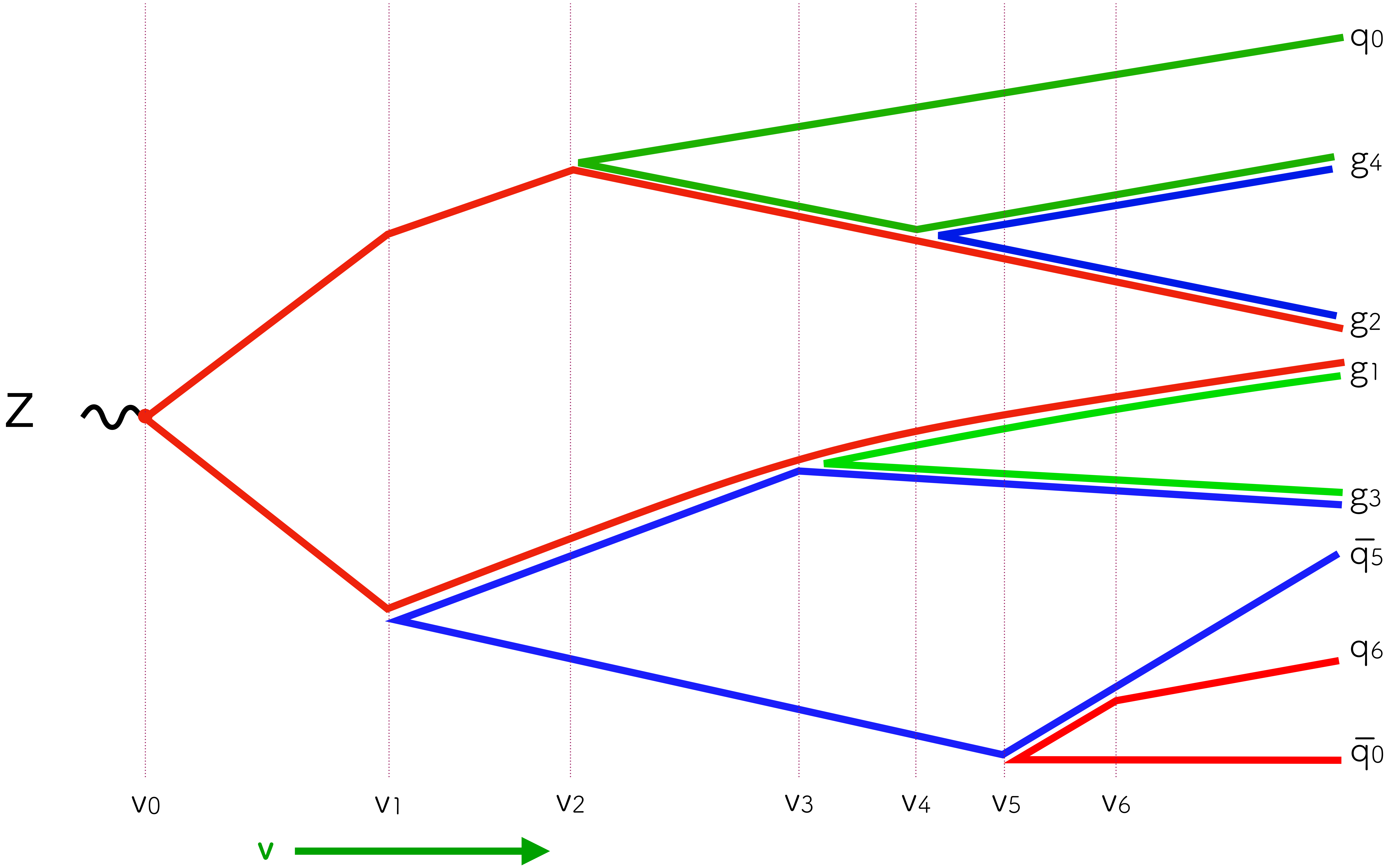
At some point, **state splits** (2→3, i.e. emits gluon). Evolution equation changes

$$\frac{dP_3(v)}{dv} = -\left[f^{qg}_{2\to3}(v) + f^{g\bar{q}}_{2\to3}(v)\right] P_3(v)$$

gluon is part of two dipoles (qg), $(g\bar{q})$, each treated as independent

(many showers use a large N$_C$ limit)

Parton Showers in a nutshell



self-similar evolution continues until it reaches a non-perturbative scale