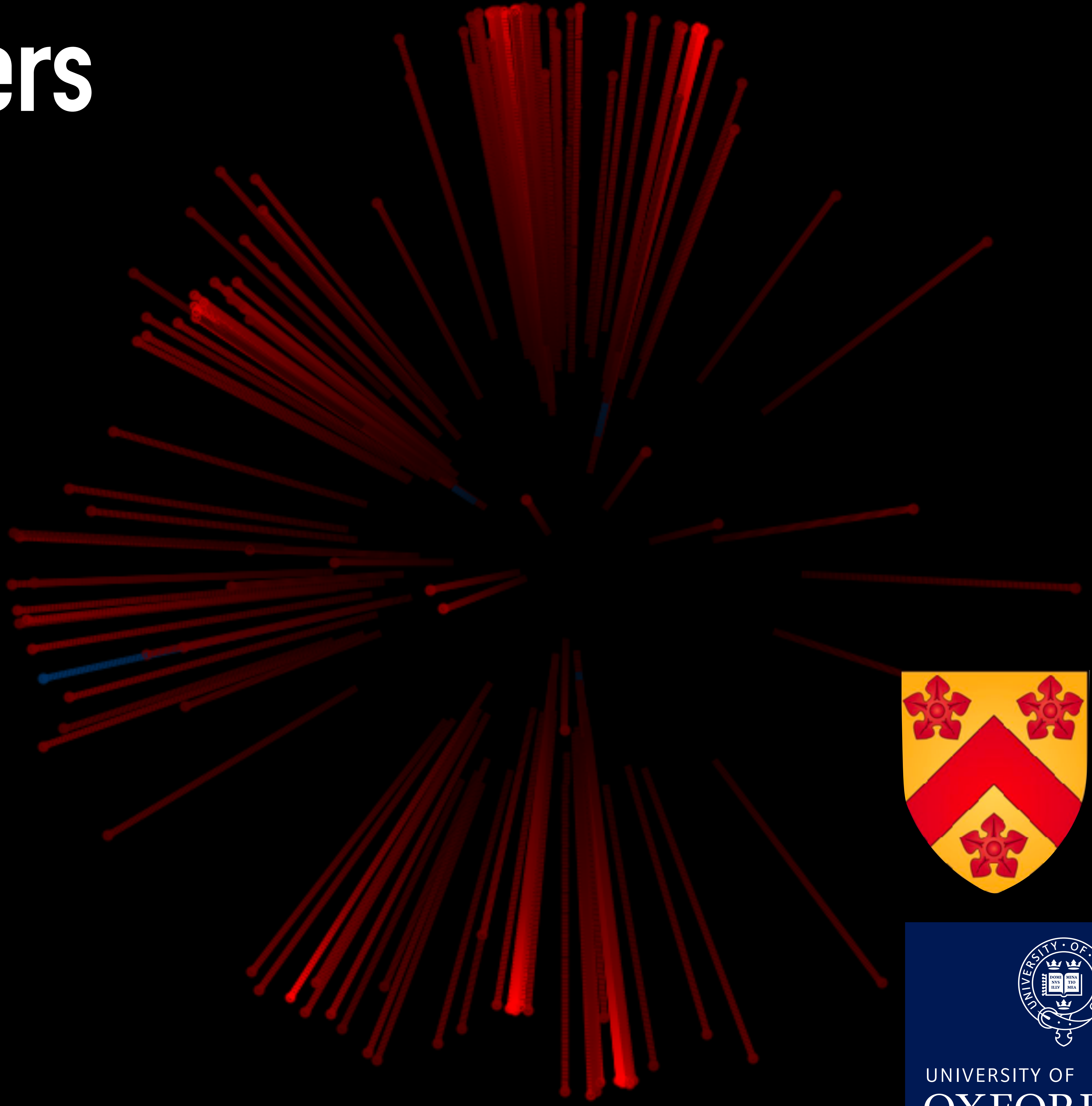
PanScales parton showers

QCD@LHC
IPPP, Durham
September 2023



Gavin Salam
Rudolf Peierls Centre for Theoretical Physics
& All Souls College, Oxford

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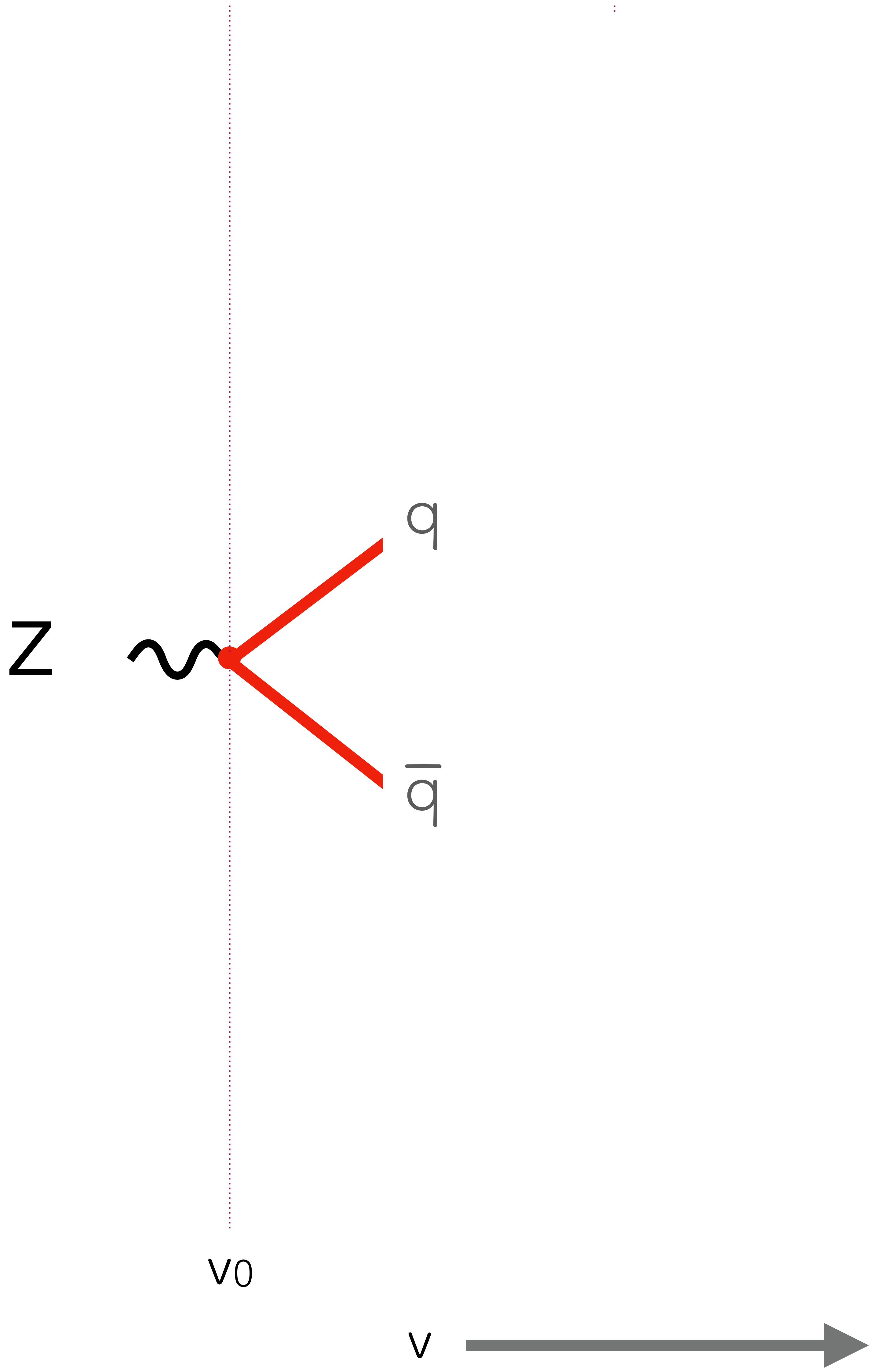
QCD shower: an evolution equation (in evolution scale v, e.g. trans.mom.)



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

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

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

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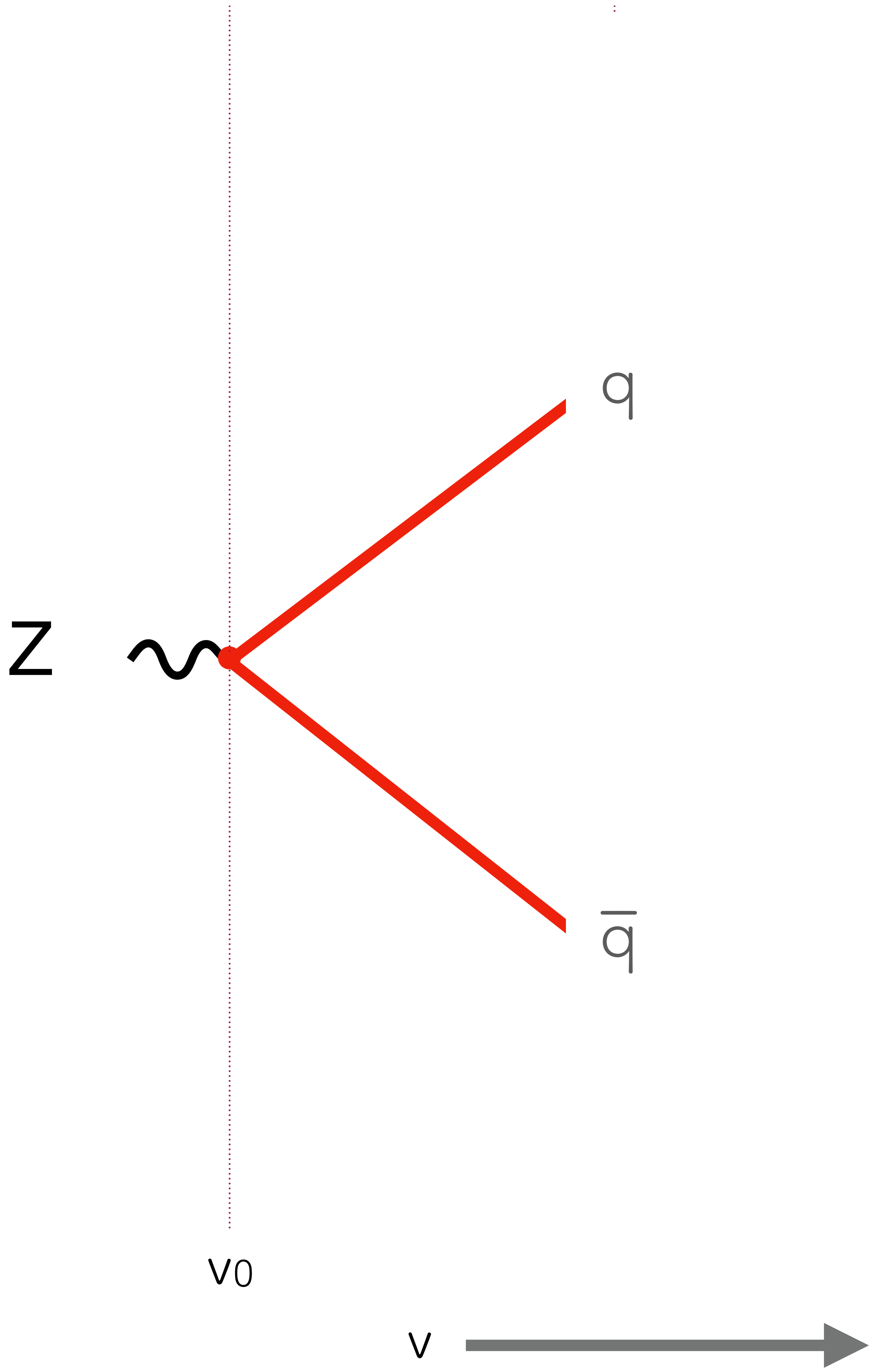

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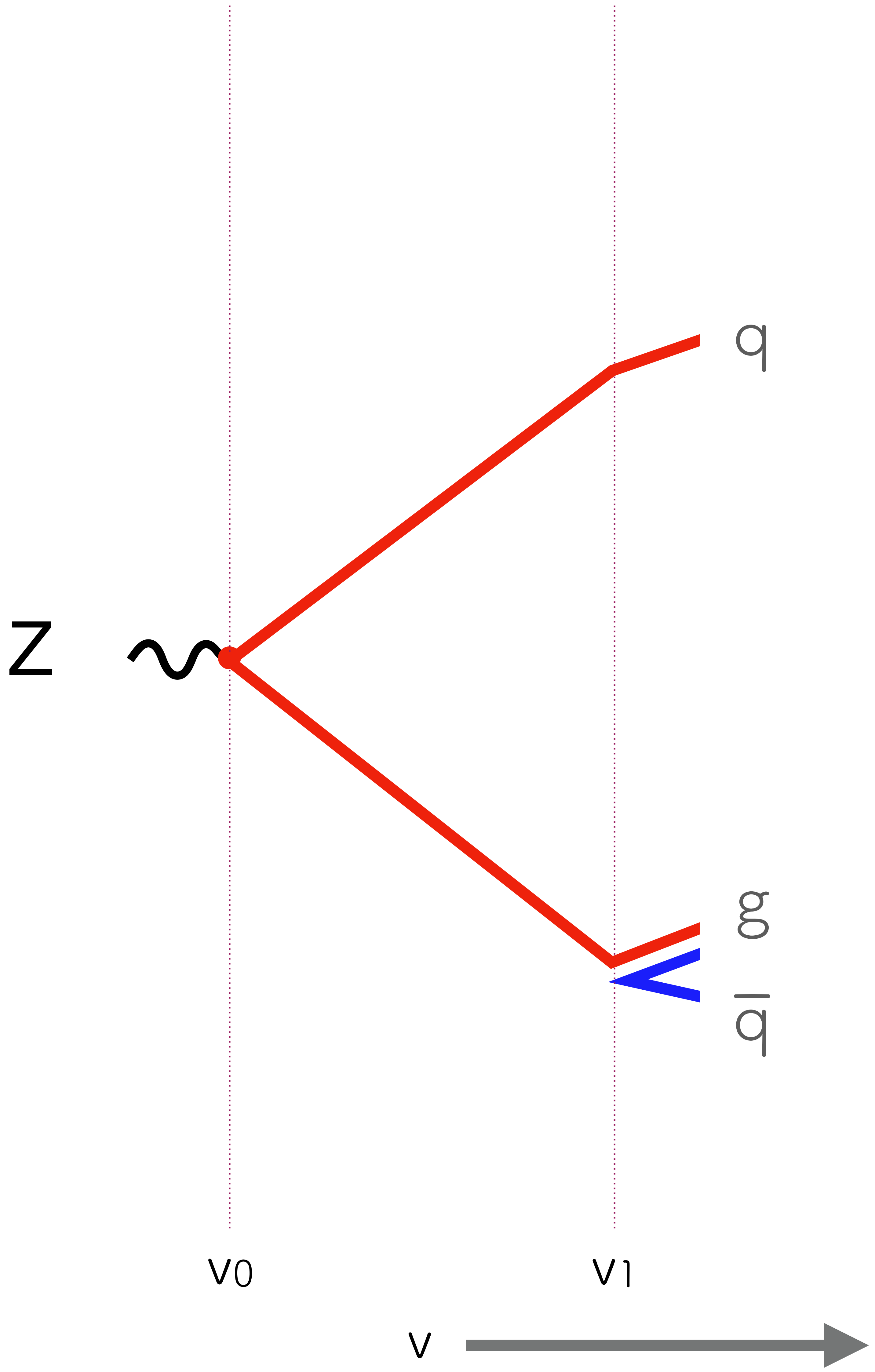
QCD shower: an evolution equation (in **evolution scale v**, e.g. trans.mom.)



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

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

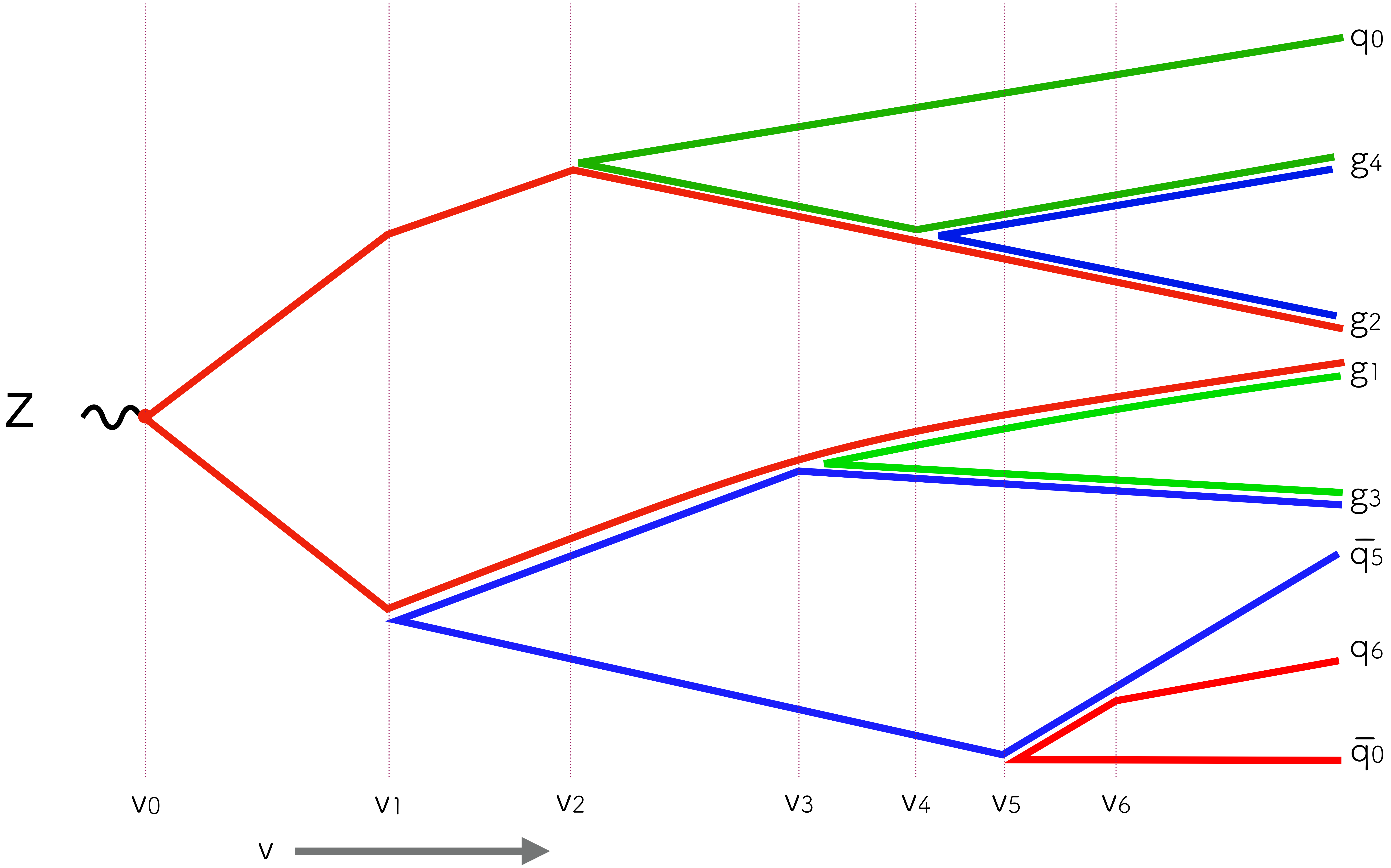
At some point, **state splits** (2→3, i.e. emits gluon). Evolution equation changes

$$\frac{dP_3(v)}{dv} = -\left[f_{2\to 3}^{qg}(v) + f_{2\to 3}^{g\bar{q}}(v)\right] P_3(v)$$

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

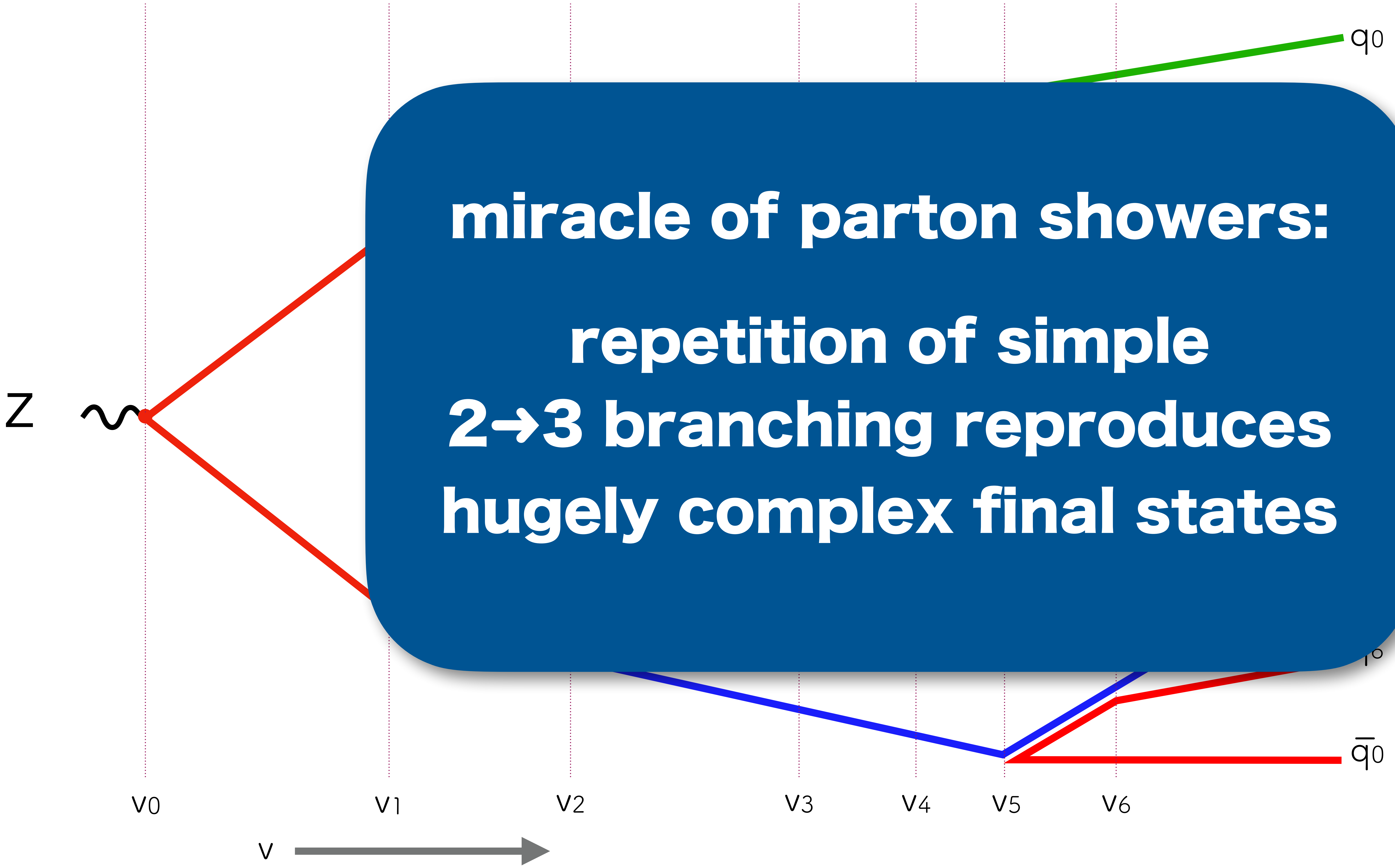
(many showers use a large N_C limit)

QCD shower: an evolution equation (in evolution scale v, e.g. trans.mom.)



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

QCD shower: an evolution equation (in evolution scale v, e.g. trans.mom.)



miracle of parton showers:

repetition of simple 2→3 branching reproduces hugely complex final states

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

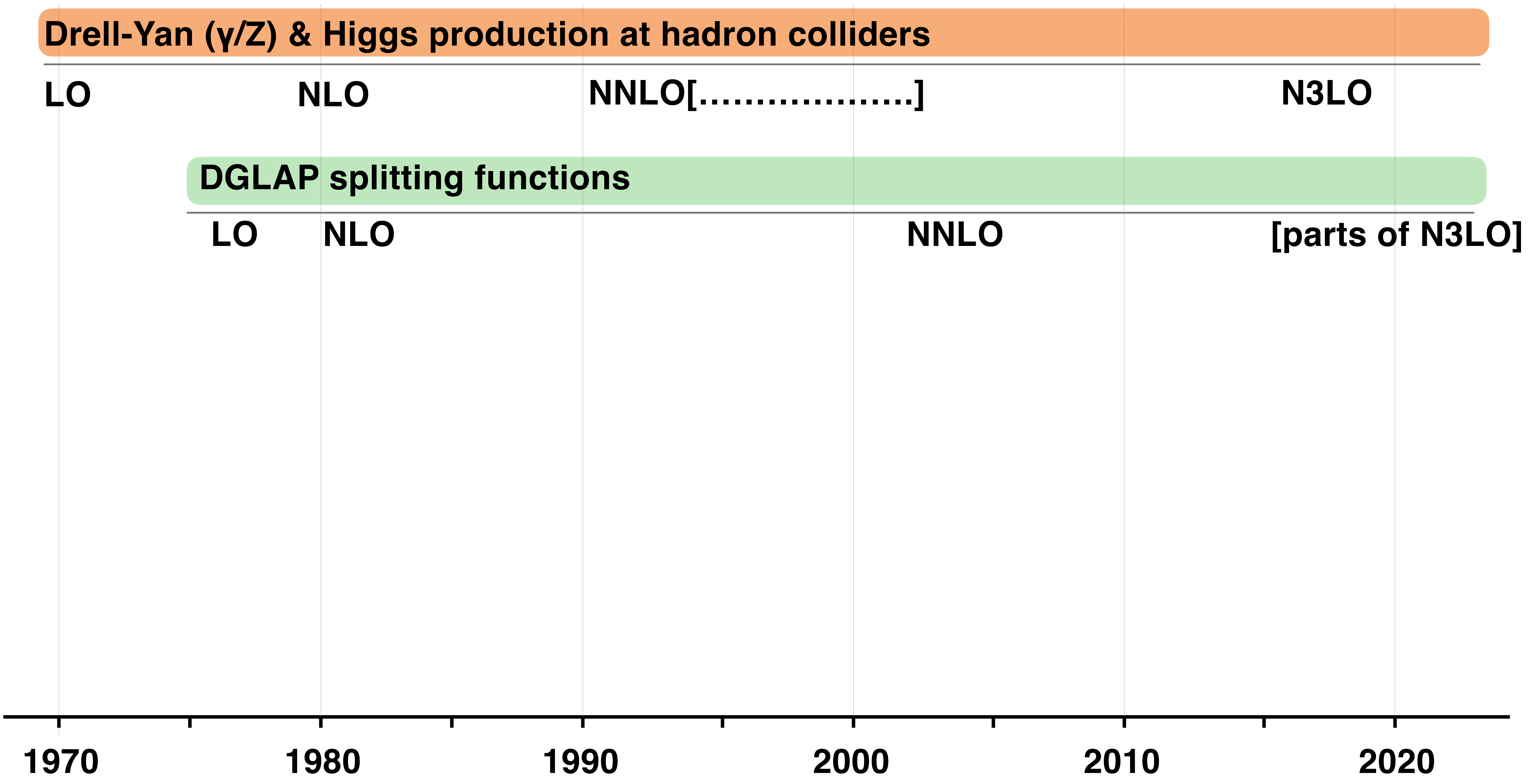
selected collider-QCD accuracy milestones

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

LO **NLO** **NNLO[……………….]** **N3LO**

1970 **1980** **1990** **2000** **2010** **2020**

selected collider-QCD accuracy milestones



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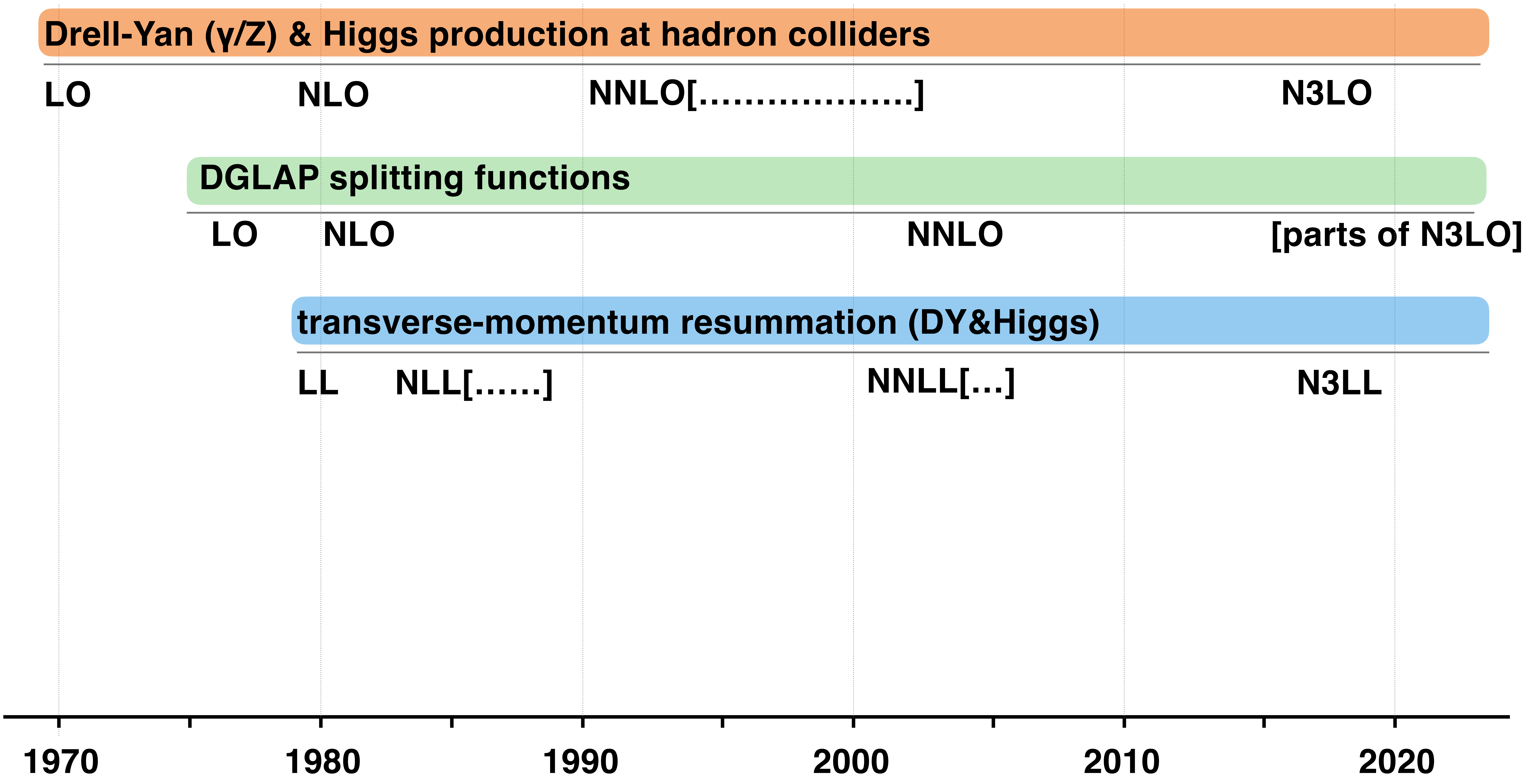

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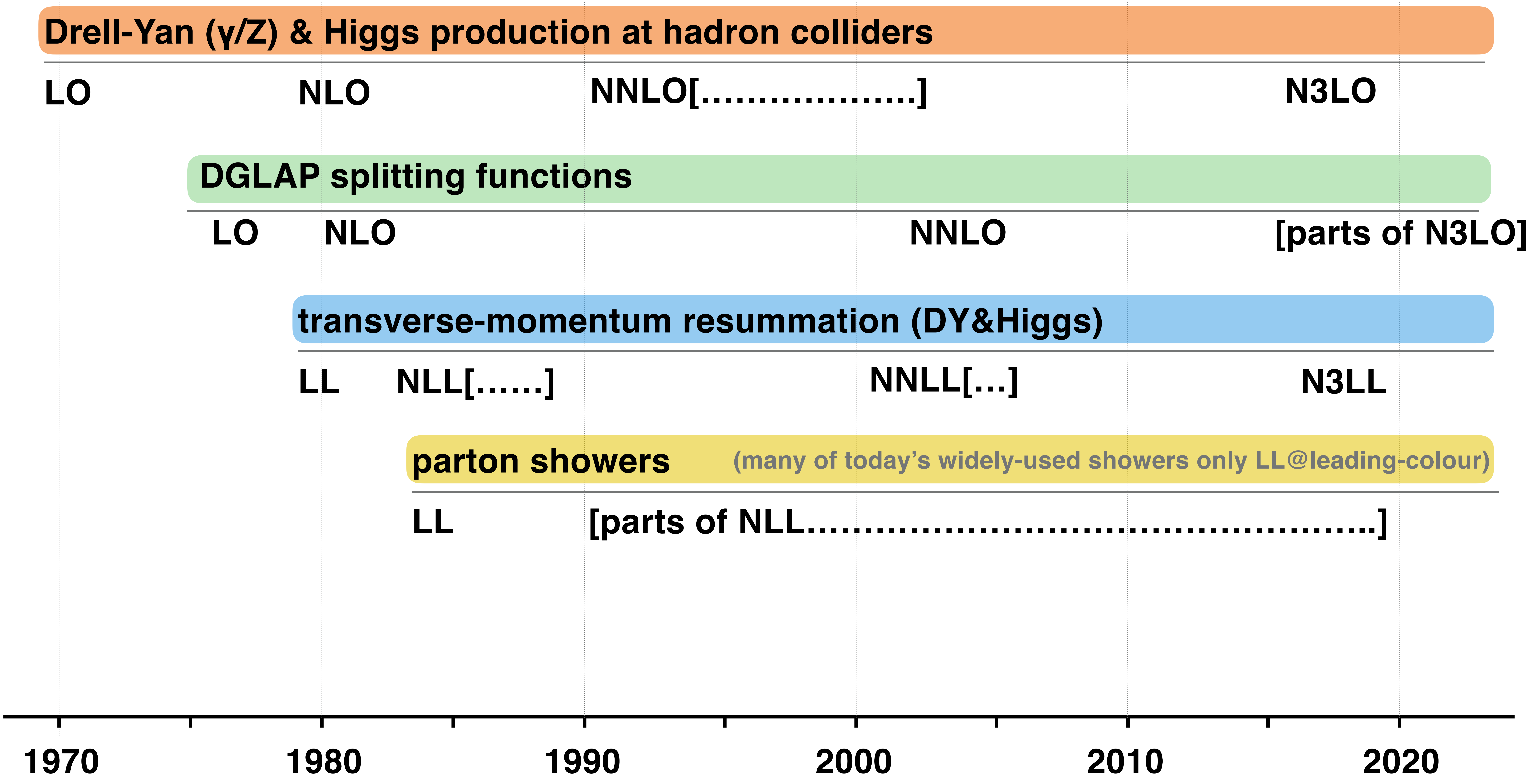

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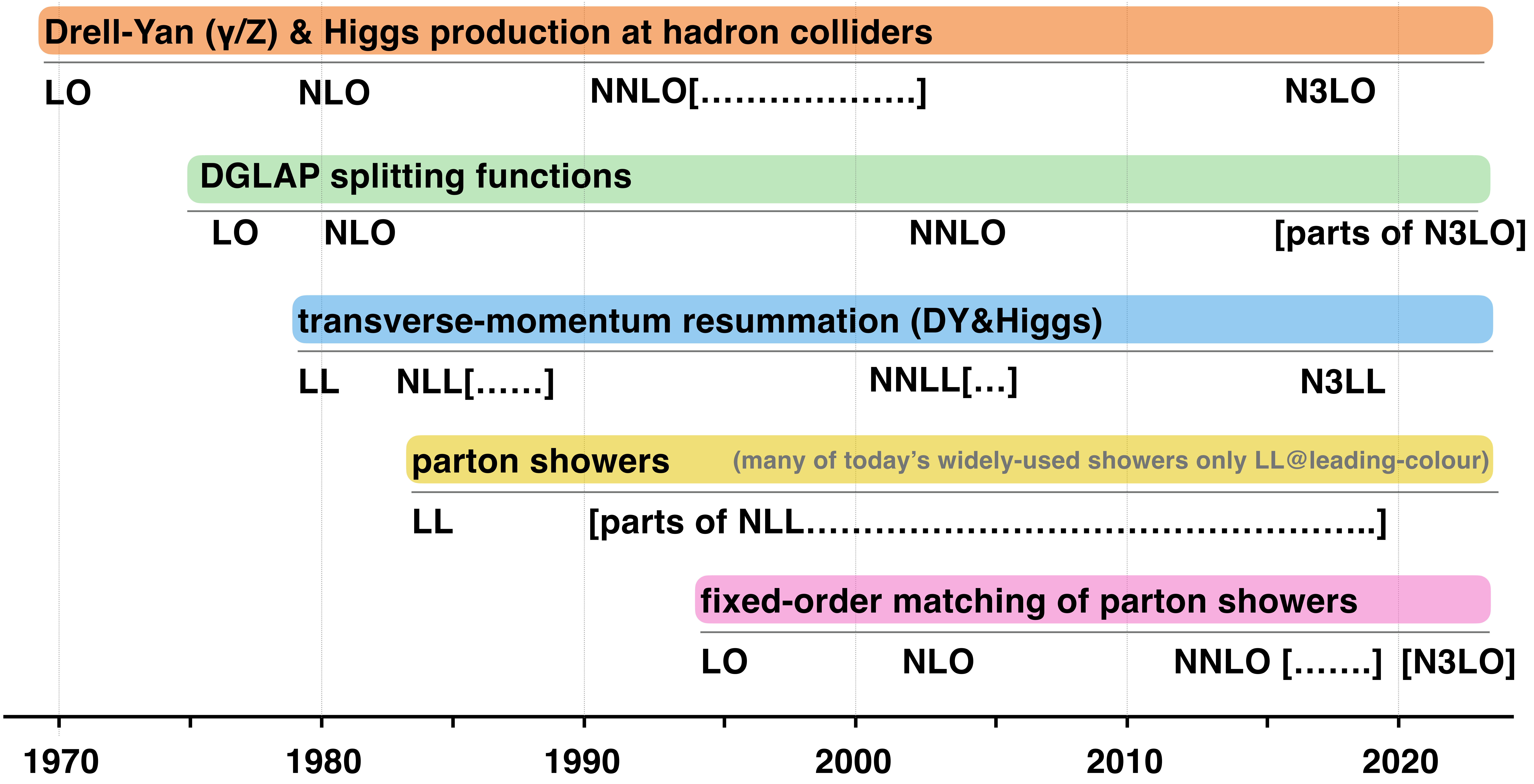

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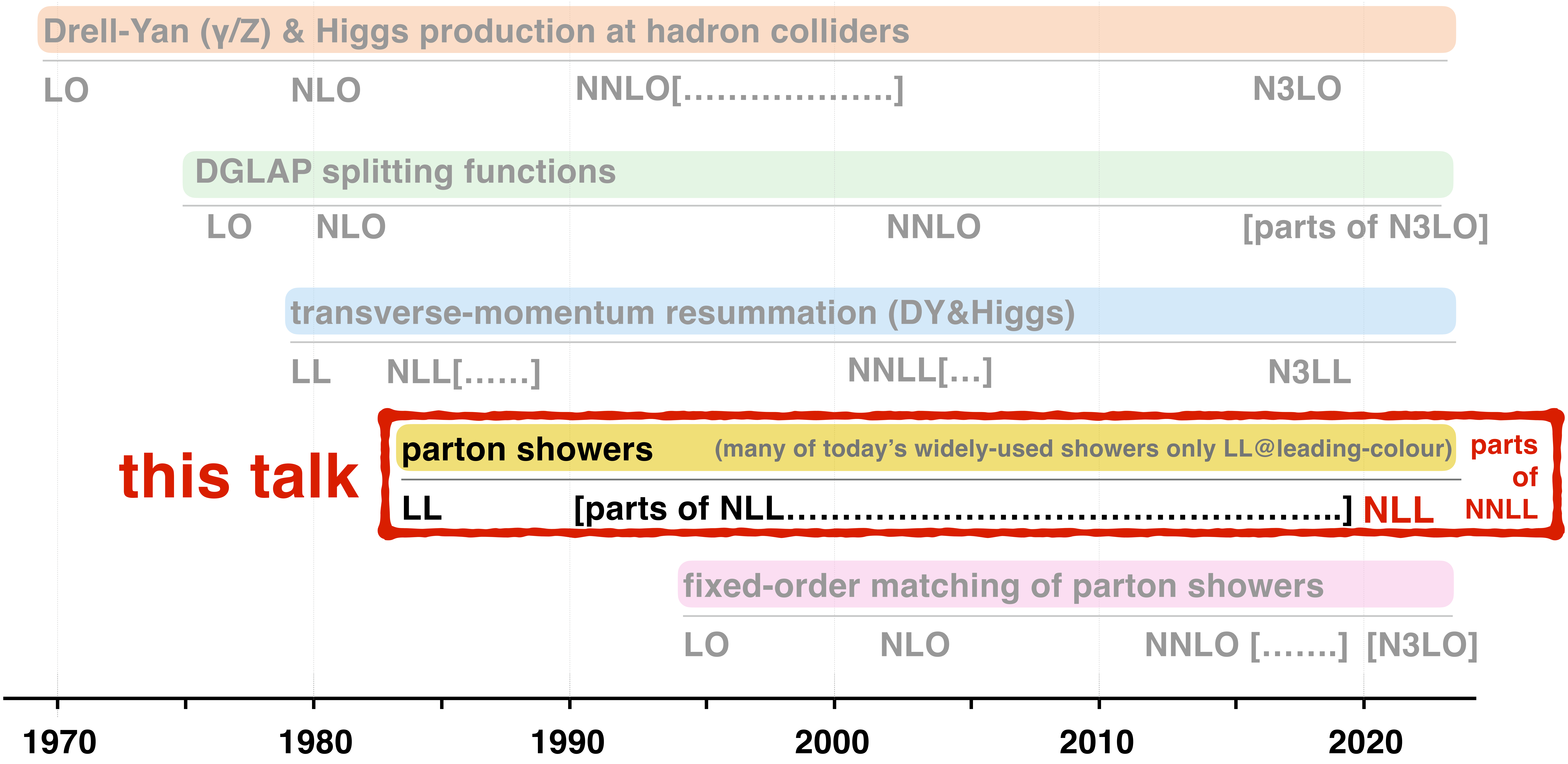
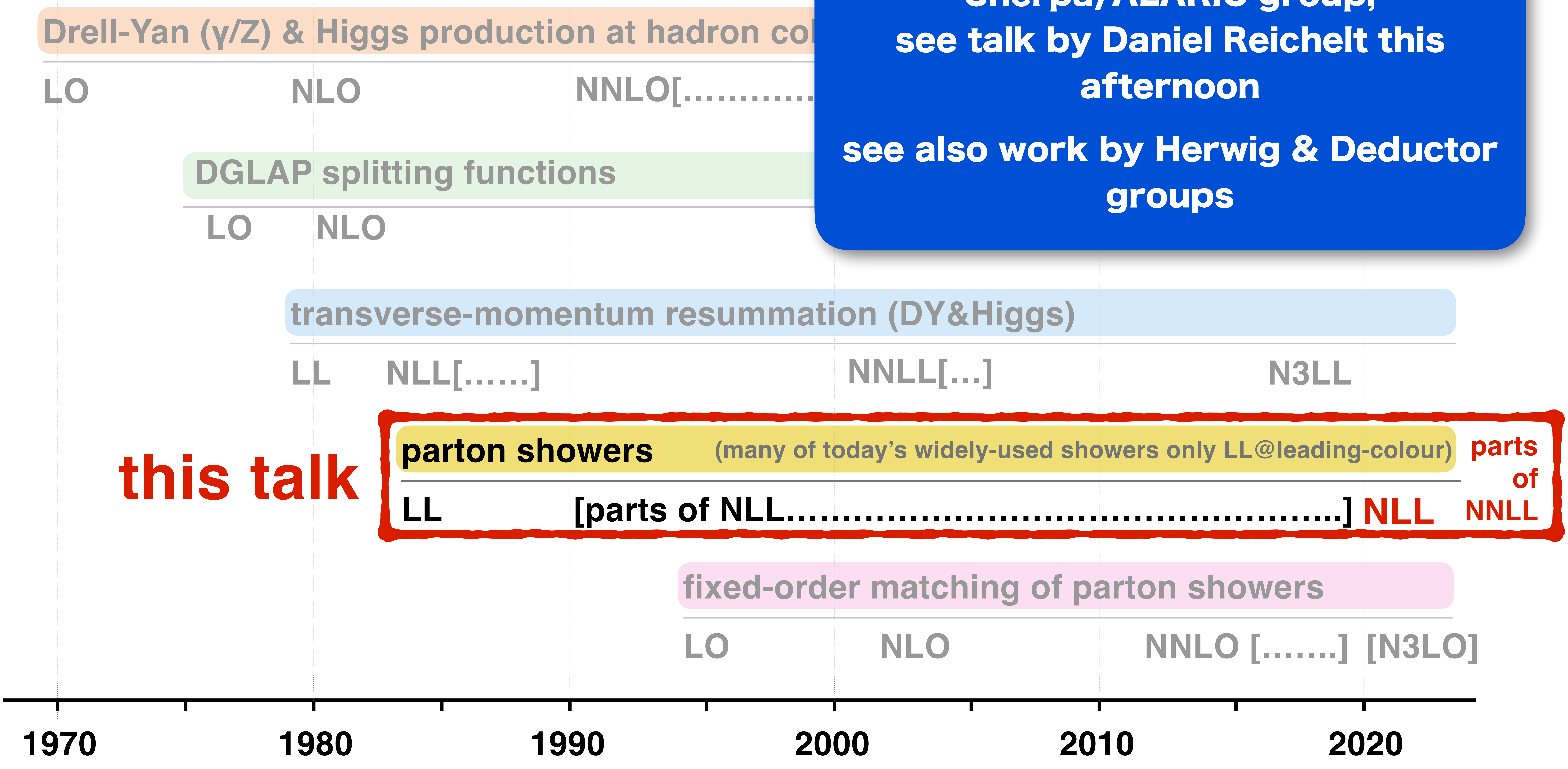


selected collider-QCD accuracy milestones

For related recent results from Sherpa/ALARIC group, see talk by Daniel Reichelt this afternoon

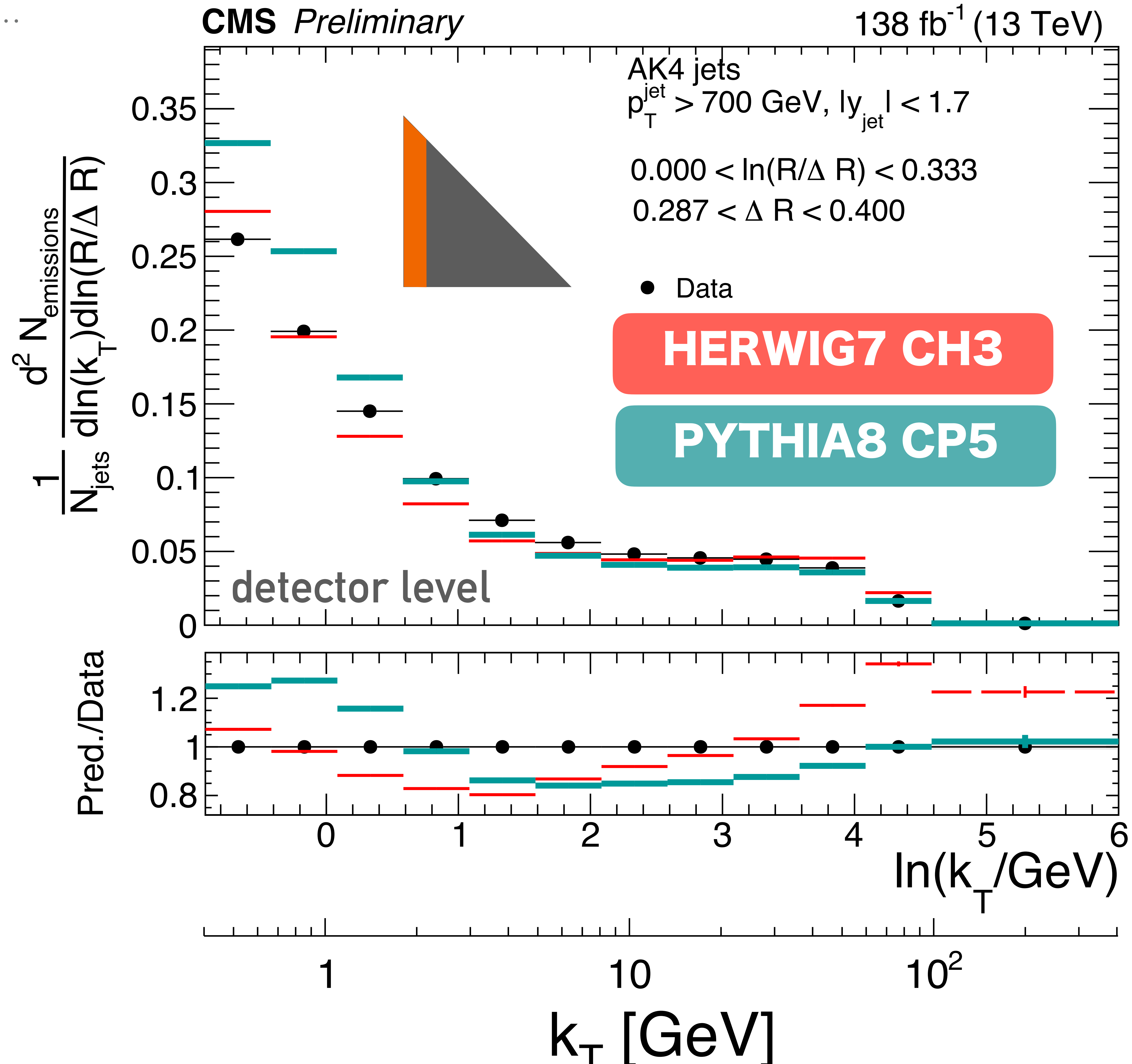
see also work by Herwig & Deductor groups



Are showers good enough?

- ➤ showers do an amazing job on many observables
- ➤ but various places see 10–30% discrepancies between showers and data
- ➤ feeds into many analyses (e.g. via jet-energy scale)
- ➤ as machine learning makes use of ever more information in jets & whole event, we want simulations to get it right

Lund Plane
(Recent CMS results; also ATLAS & ALICE)



Step 1: design guaranteed NLL showers

Dasgupta, Dreyer, Hamilton, Monni, GPS '18
ibid + Soyez '20

A Matrix Element condition

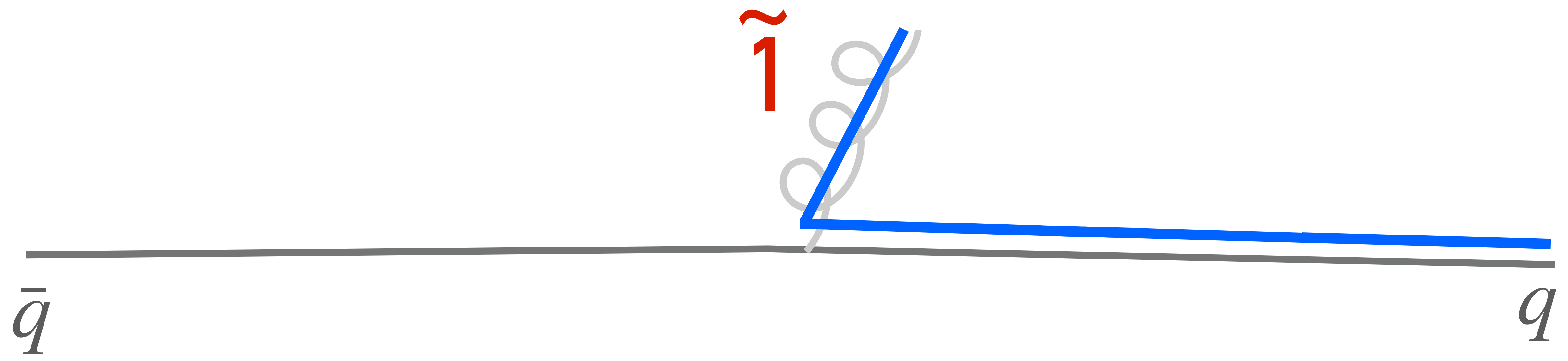
- correctly reproduce n-parton tree-level matrix element for arbitrary configurations, so long as all emissions well separated in the Lund diagram
- supplement with unitarity, 2-loop running coupling & cusp anomalous dimension

Resummation condition: reproduce NLL results for all standard resummations

- global event shapes
- non-global observables
- fragmentation functions
- multiplicities
- …

1. Recoil: the core of any shower

Dipole showers conserve momentum at each step. Traditional dipole-local recoil:



$$d\mathcal{P}^{\rm FS}_{\tilde{\imath}\to ik} = \frac{\alpha_s(k_\perp^2)}{2\pi}\frac{dk_\perp^2}{k_\perp^2}\frac{dz}{z}\frac{d\varphi}{2\pi}N^{\rm sym}_{ik}\left[zP_{\tilde{\imath}\to ik}(z)\right]$$

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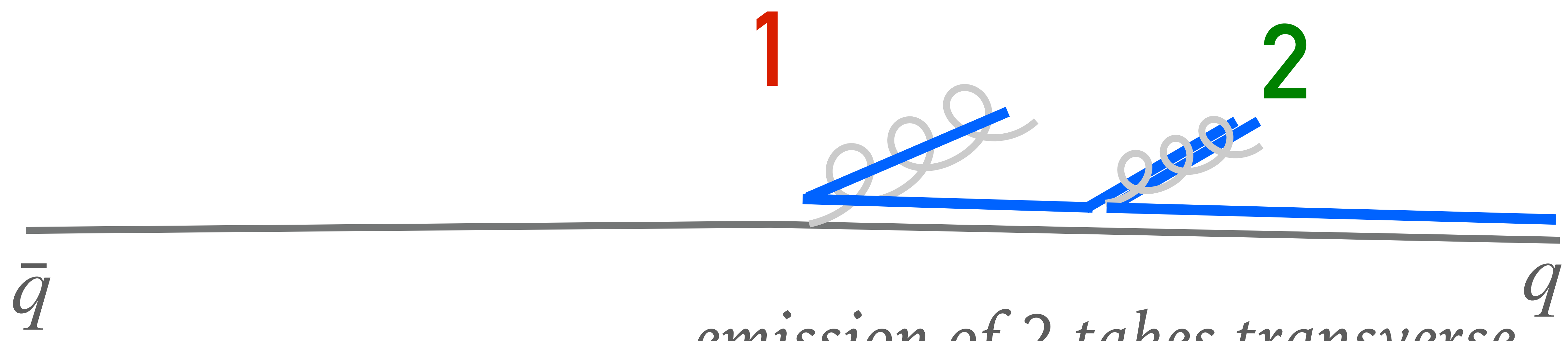

emission of 2 takes transverse recoil from 1

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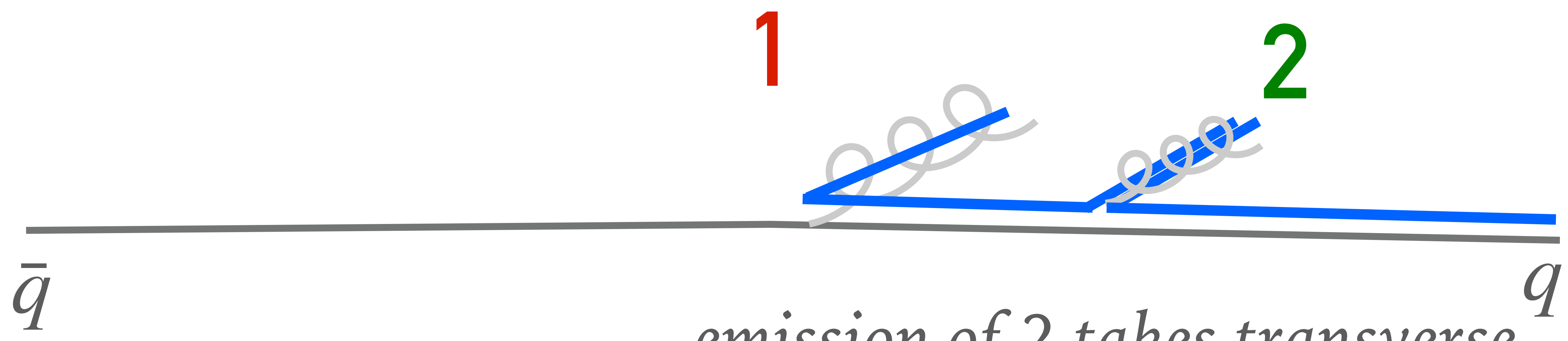
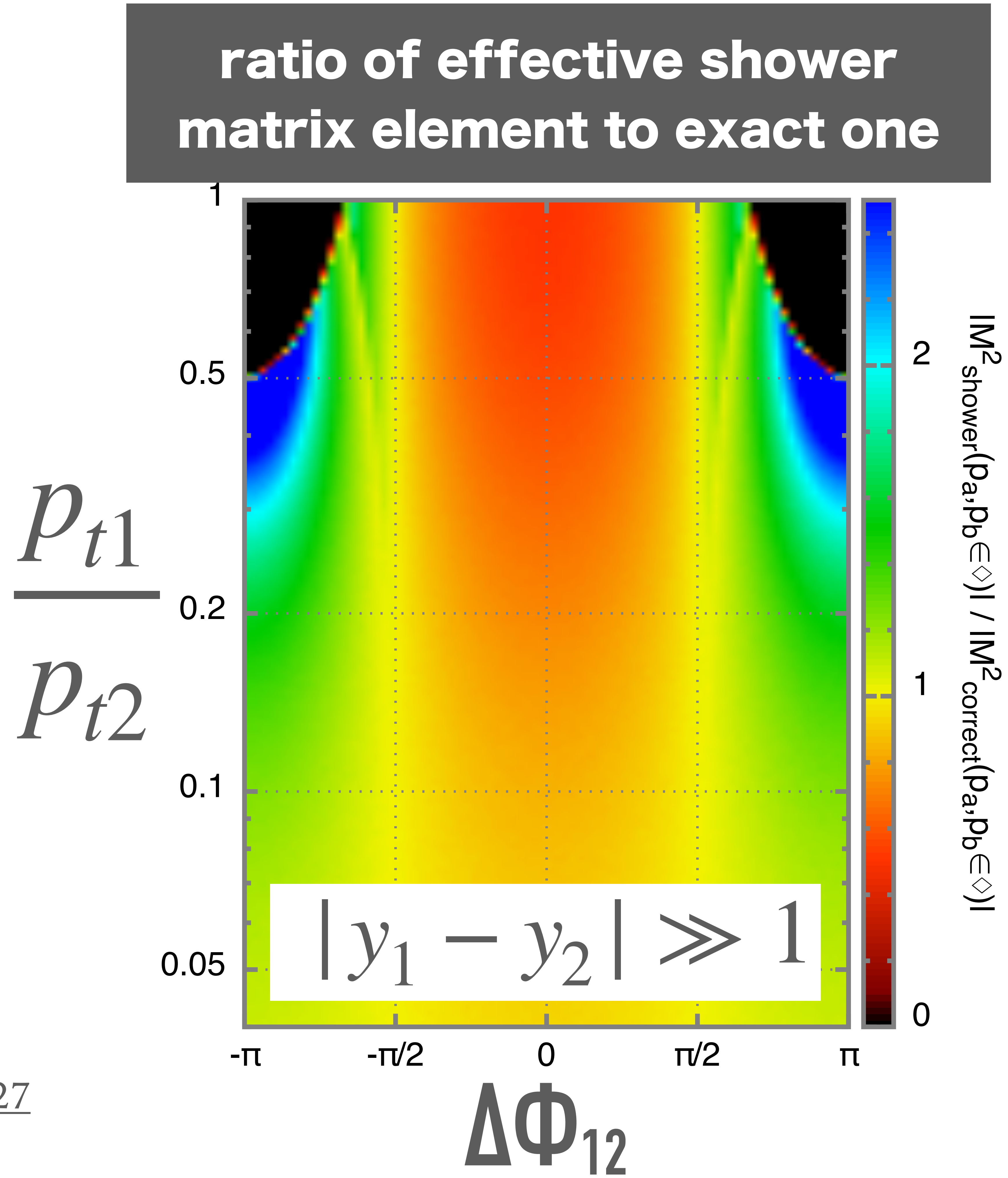


emission of 2 takes transverse recoil from 1

Shower initially generated matrix element for particle $\tilde{1}$, whose momentum differs (by ~ 50%) from final particle 1.

Matrix element is incorrect wrt final momentum 1.



First observed: Andersson, Gustafson, Sjogren ’92
Closely related effect present for Z p_t: Nagy & Soper 0912.4534
Impact on log accuracy across many observables: Dasgupta, Dreyer, Hamilton, Monni, GPS, 1805.09327

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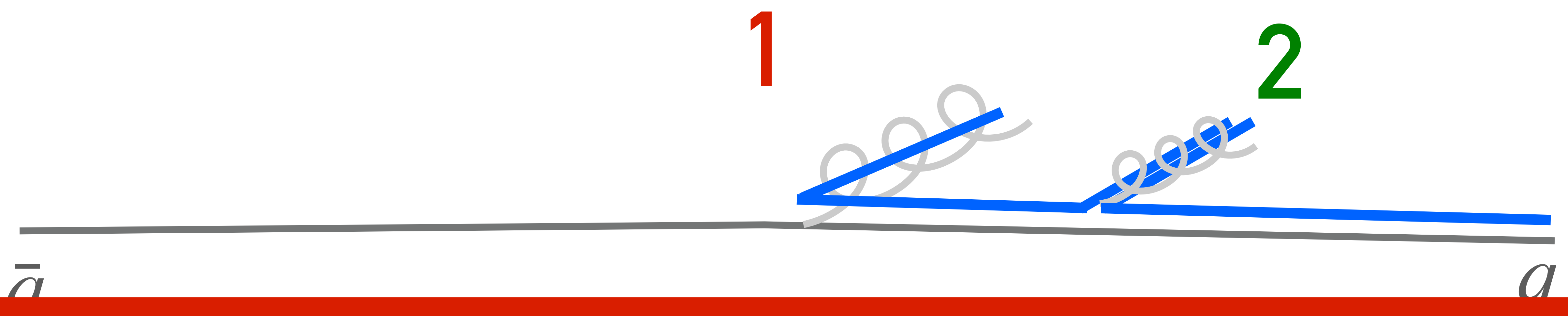


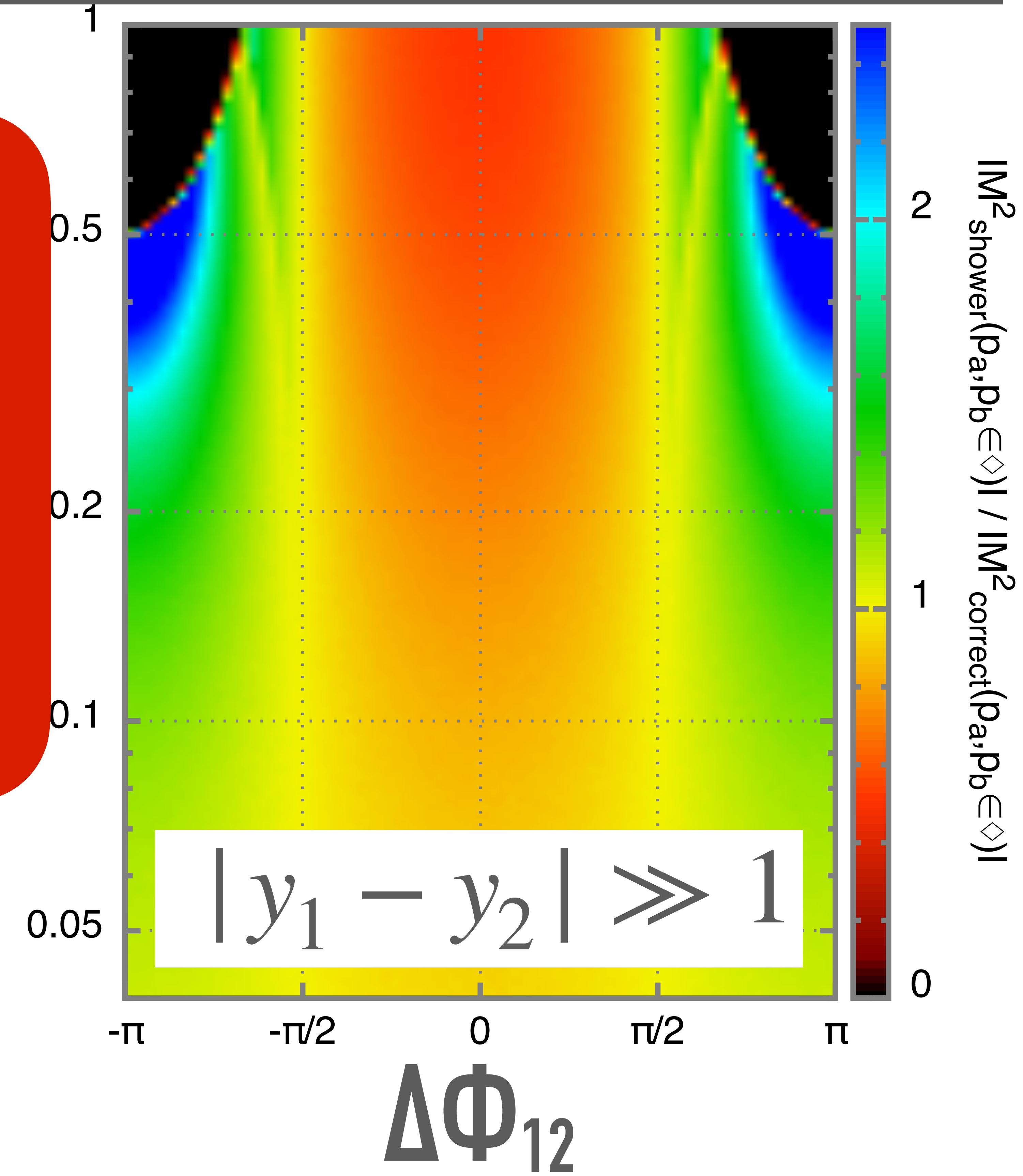
Sh
pa
fro

design principle for new showers:

recoil & other shower design should respect absence of cross-talk between disparate scales (e.g. angles), i.e. QCD factorisation

Matrix element is incorrect wrt final momentum 1.

ratio of effective shower matrix element to exact one



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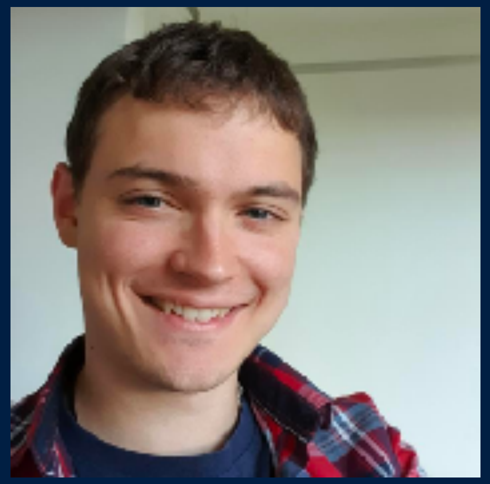
Oxford


Melissa van Beekveld


Jack Helliwell


Rok Medves


Frederic Dreyer


GPS


Ludo Scyboz

UCL


Keith Hamilton


Rob Verheyen

Saclay


Gregory Soyez

CERN


Silvia
Ferrario Ravasio


Alexander
Karlberg


Pier Monni


Alba
Soto Ontoso

Manchester


Mrinal Dasgupta

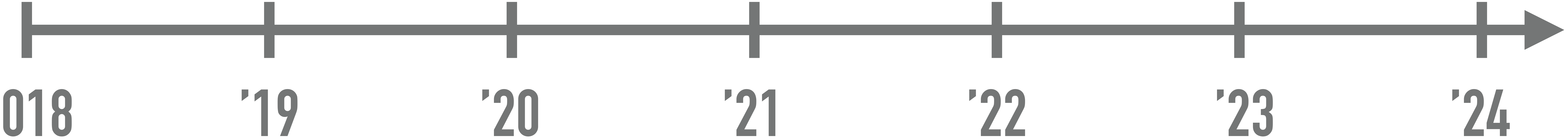

Basem El-Menoufi

PanScales current & recent members

A project to bring logarithmic understanding and accuracy to parton showers

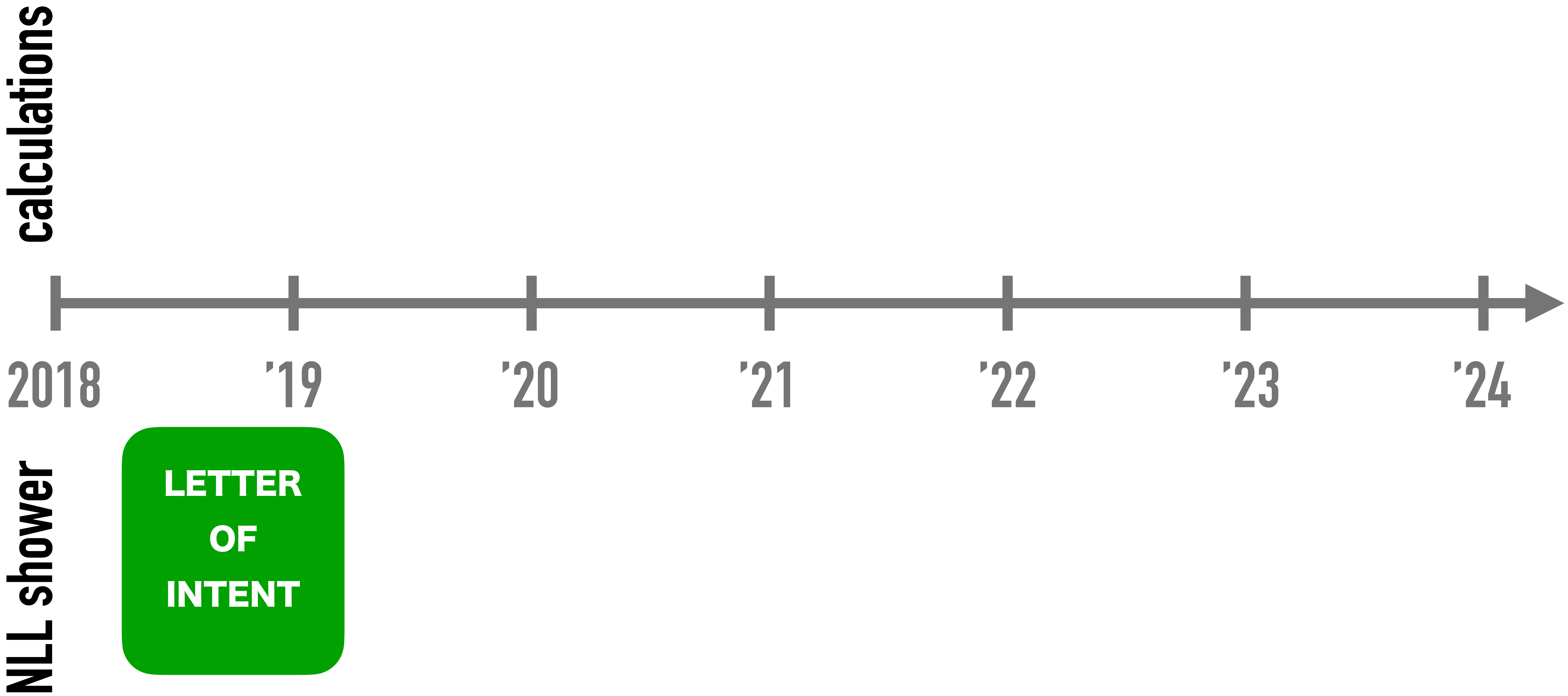
PanScales timeline

calculations

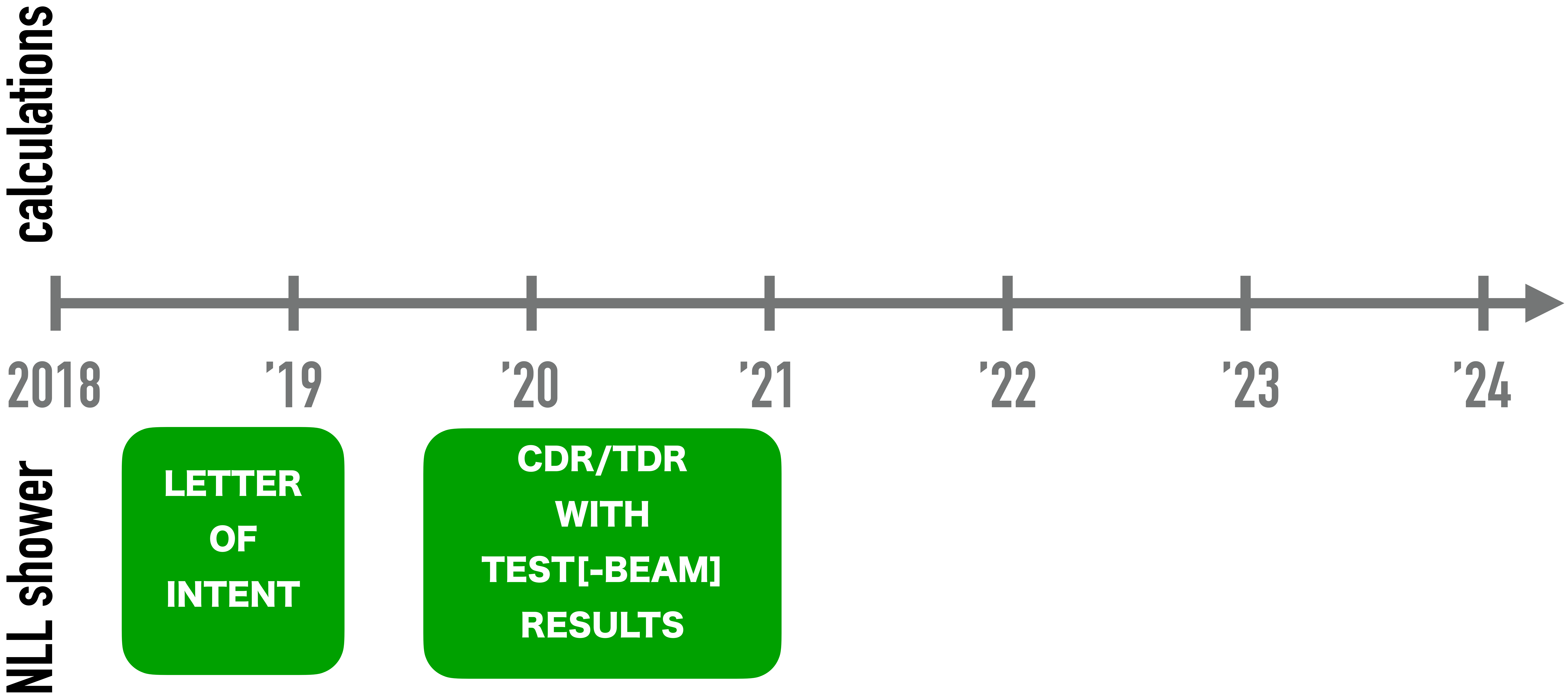


NLL shower

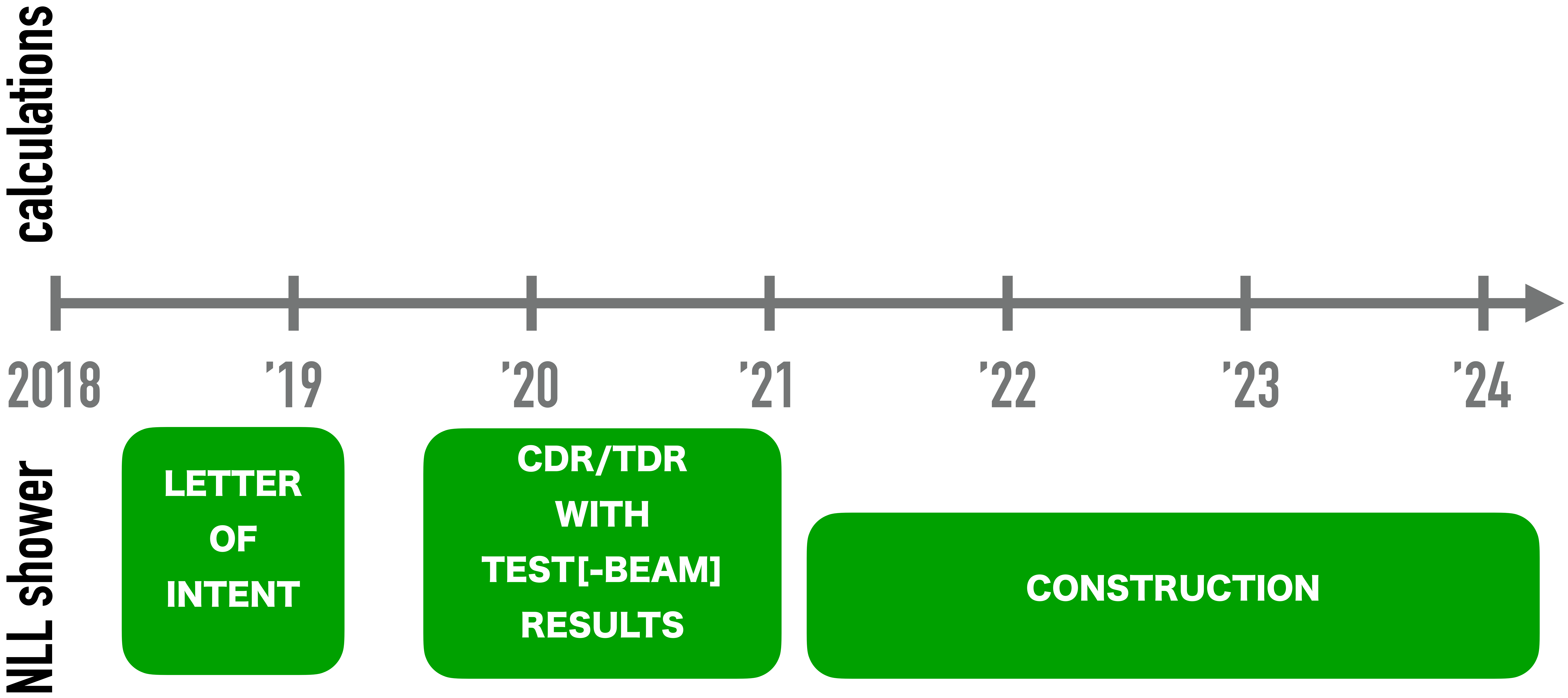
PanScales timeline



PanScales timeline



PanScales timeline



PanScales timeline

PanScales timeline

calculations

R&D for UPGRADE

Dasgupta, El Menoufi, 2109.07496
Medves, Soto Ontoso, Soyez, 2205.02861, 2212.05076
Banfi, Dreyer, Monni, 2104.06416, 2111.02413
van Beekveld, Dasgupta, El-Menoufi, Helliwell, Monni, 2307.15734

2018 | ’19 | ’20 | ’21 | ’22 | ’23 | ’24

NLL shower

LETTER OF INTENT

CDR/TDR WITH TEST[-BEAM] RESULTS

COMMISSIONING

CONSTRUCTION

CONSTRUCTION

PanLocal	PanGlobal	Colour	Spin
$k_t\sqrt{\theta}$ ordered	k_t or $k_t\sqrt{\theta}$ ordered	nested ordered double soft (NODS)	for correct azimuthal structure in collinear and soft→collinear
Recoil ⊥: local +: local −: local	**Recoil** ⊥: global +: local −: local	Designed to ensure LL are full colour (also gets many NLL at full colour)	[Collins-Knowles extended to soft sector]
Dipole partition event CoM	**Dipole partition** event CoM		

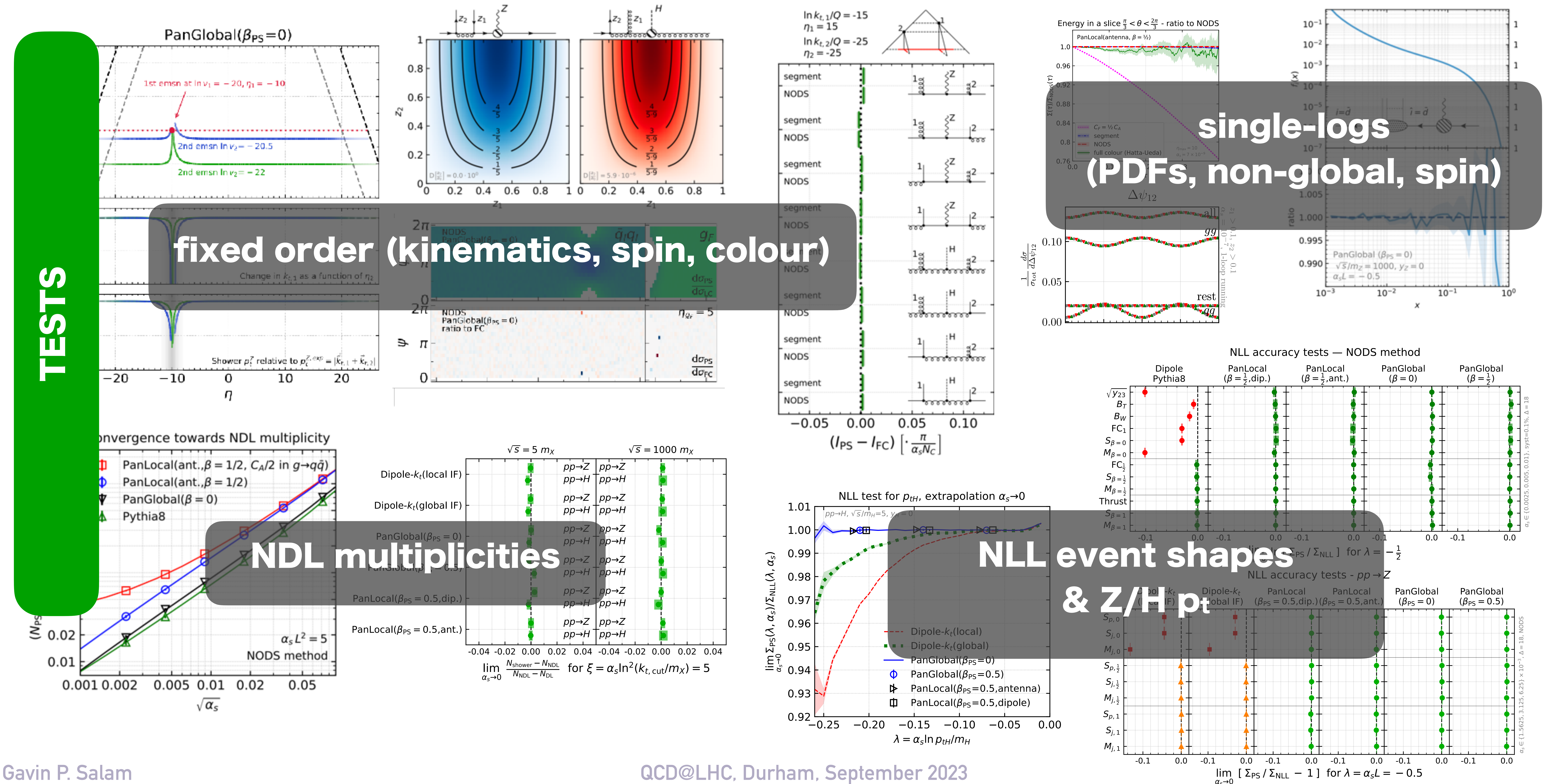
e^+e^-: Dasgupta, Dreyer, Hamilton, Monni, GPS & Soyez, 2002.11114; pp: van Beekveld, Ferrario Ravasio, GPS, Soto Ontoso, Soyez, Verheyen, 2205.02237; & pp tests, ibid + Hamilton: 2207.09467; DIS+VBF, van Beekveld, Ferrario Ravasio 2305.08645

Hamilton, Medves, GPS, Scyboz, Soyez, 2011.10054

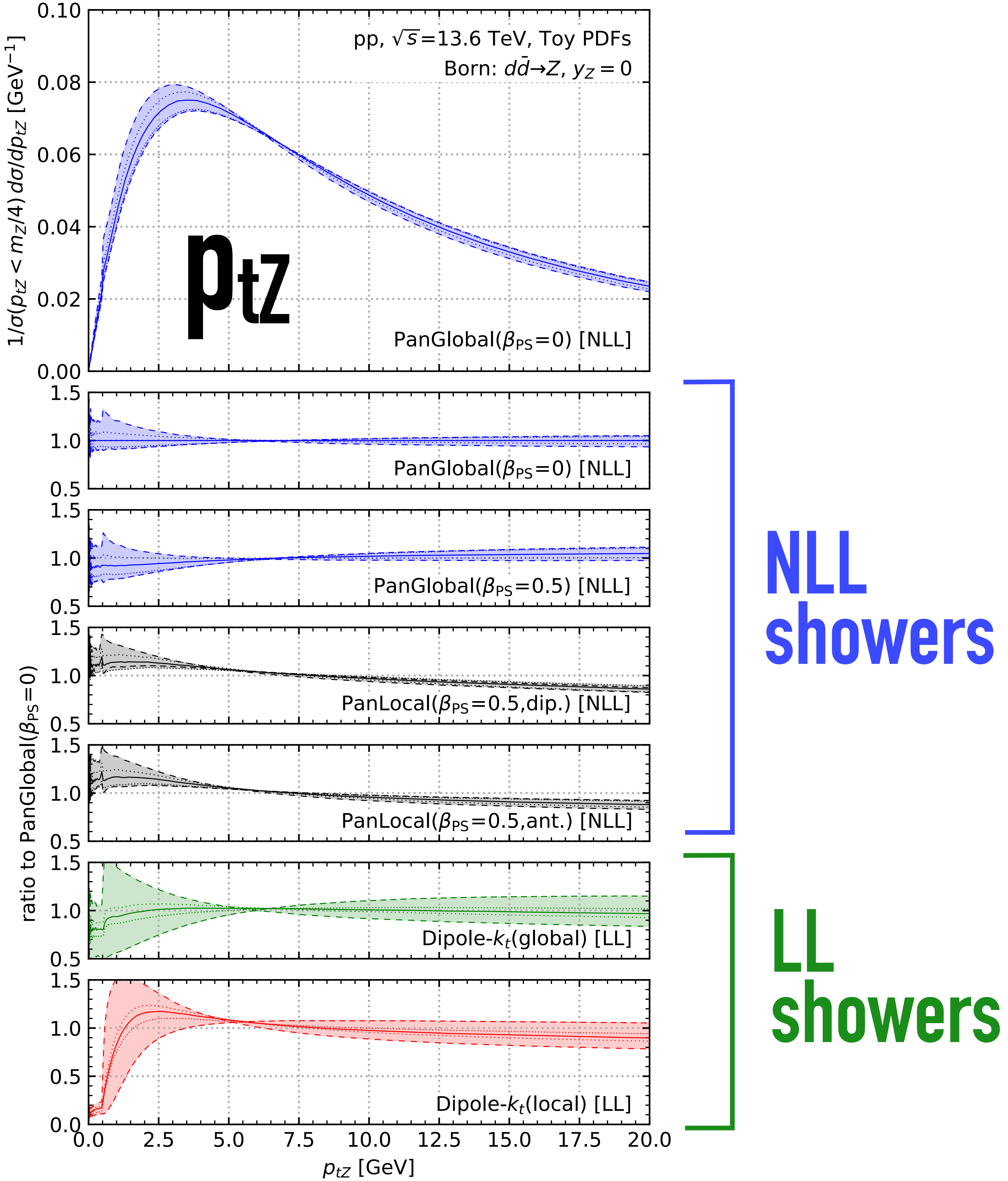
Karlberg, GPS, Scyboz, Verheyen, 2011.10054; ibid + Hamilton, 2111.01161

& pp extensions: van Beekveld et al, 2205.02237

a selection of the logarithmic accuracy tests



COMMISSIONING

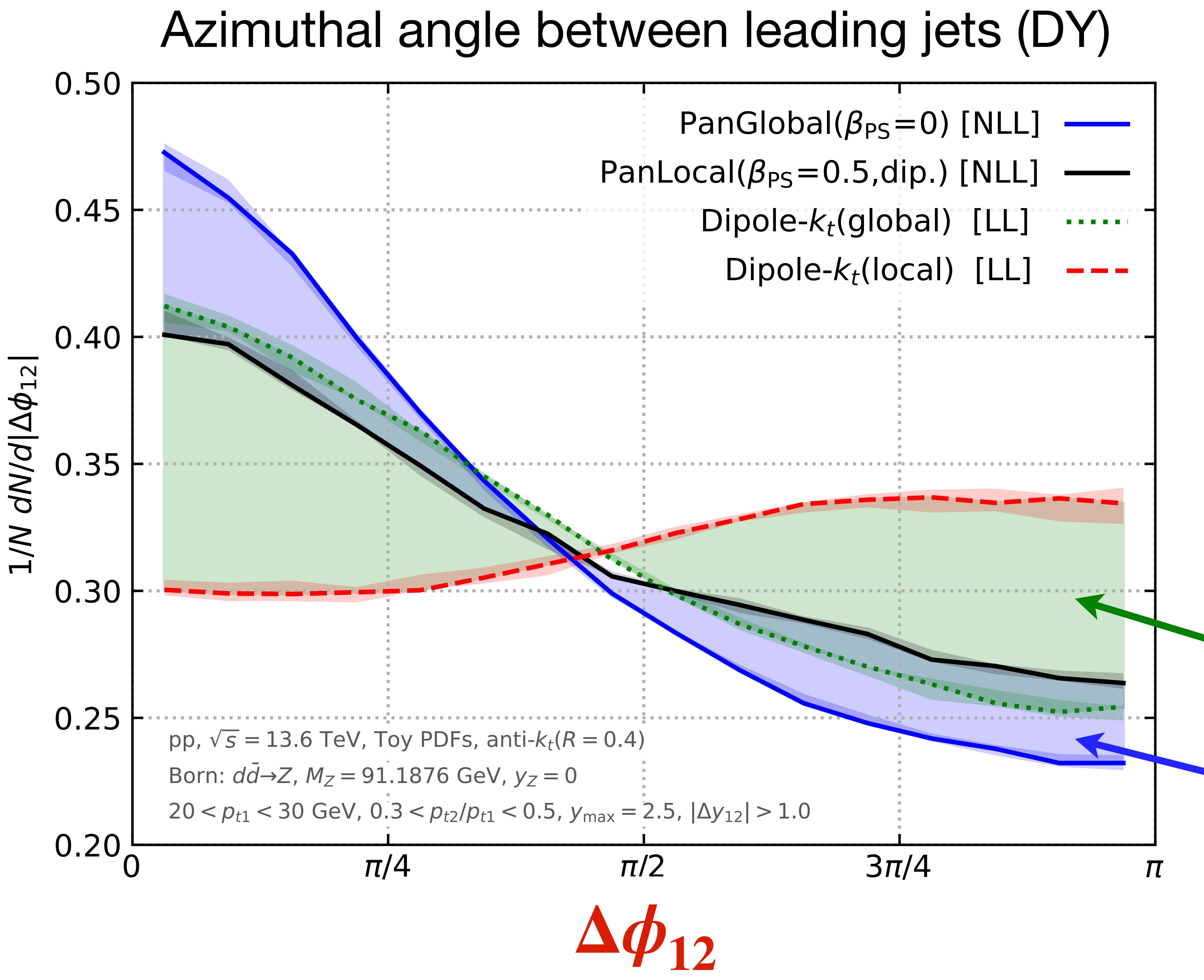


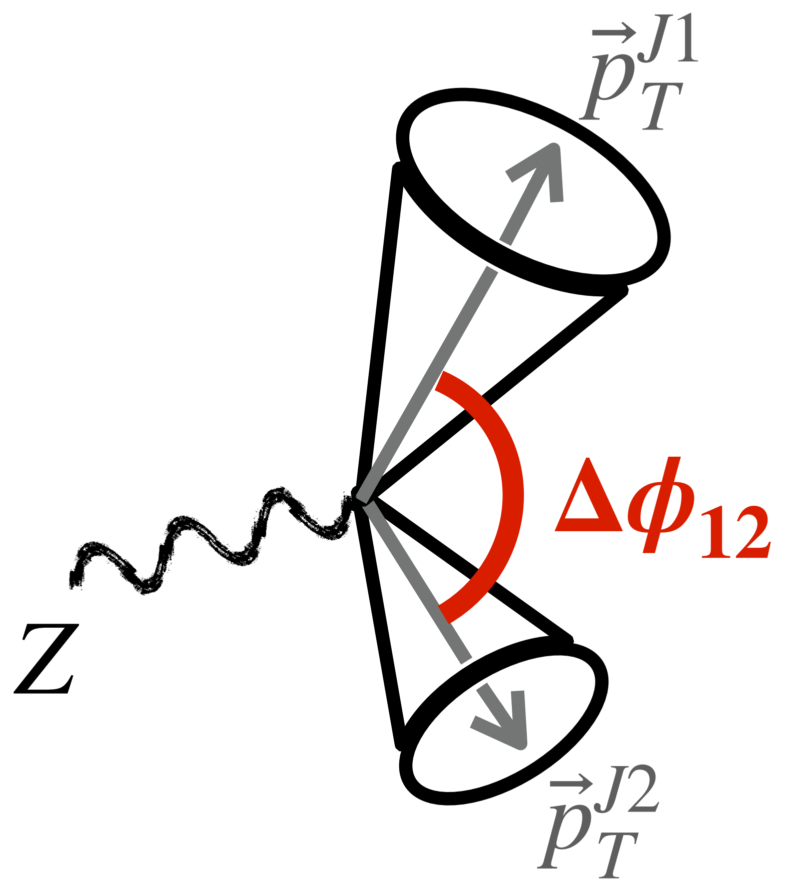
for inclusive quantities like p_{tZ}, advantage of NLL shower is partly in reduction of uncertainties

van Beekveld, Ferrario Ravasio, GPS, Soto Ontoso, Soyez, Verheyen, Hamilton: 2207.09467

$m_{\ell\ell} = m_Z$

COMMISSIONING



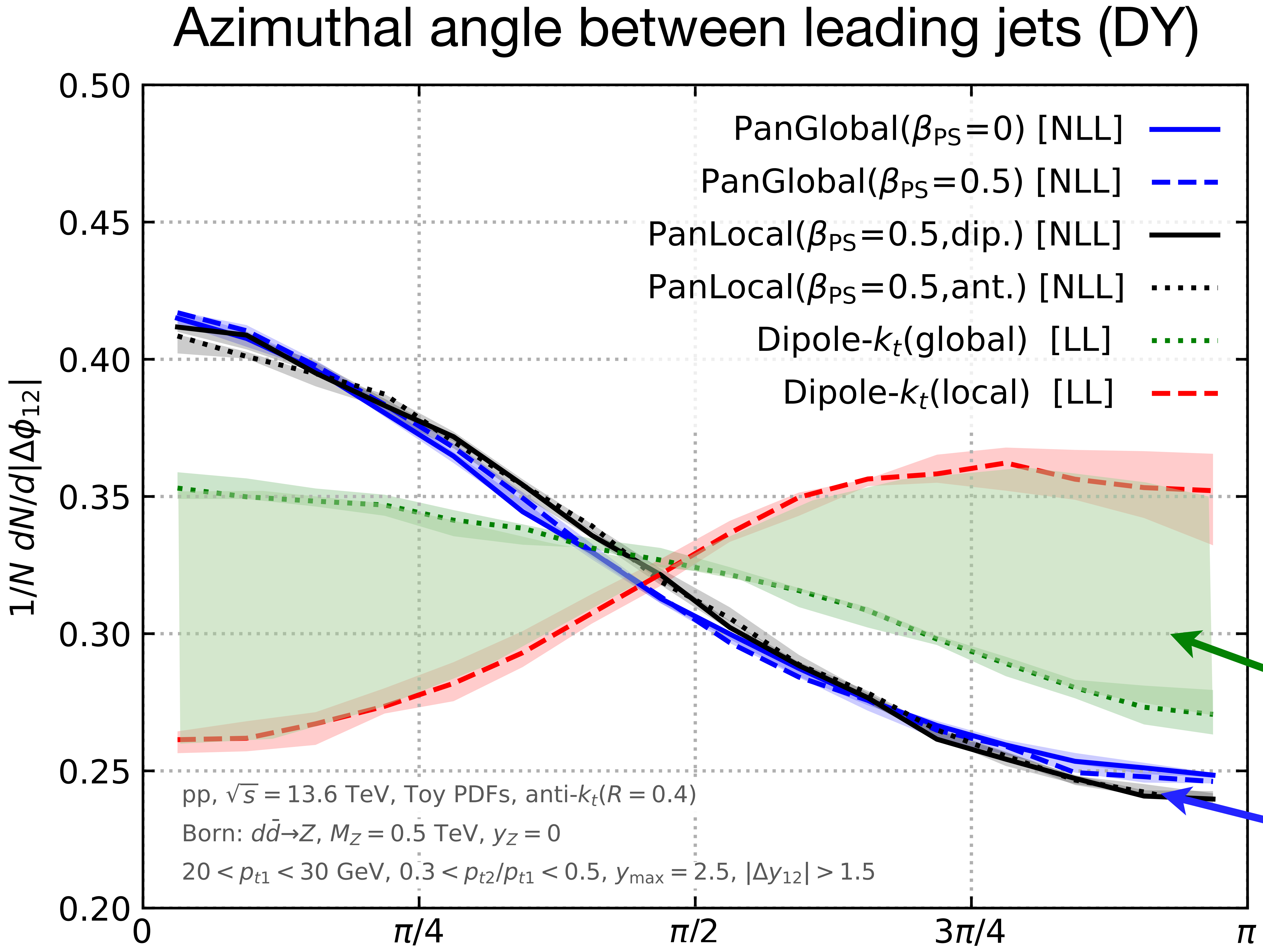


for more exclusive quantities, also see clear shape differences in going to NLL

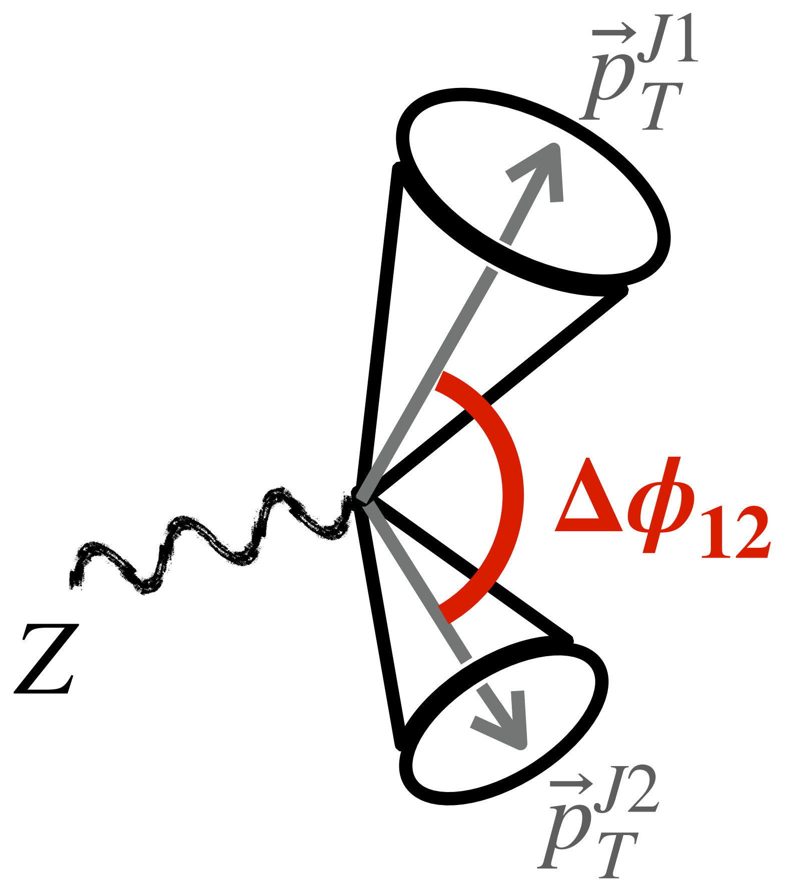
van Beekveld, Ferrario Ravasio, GPS, Soto Ontoso, Soyez, Verheyen, Hamilton: 2207.09467

$m_{\ell\ell} = 500\,\mathrm{GeV}$

COMMISSIONING



$\Delta\phi_{12}$



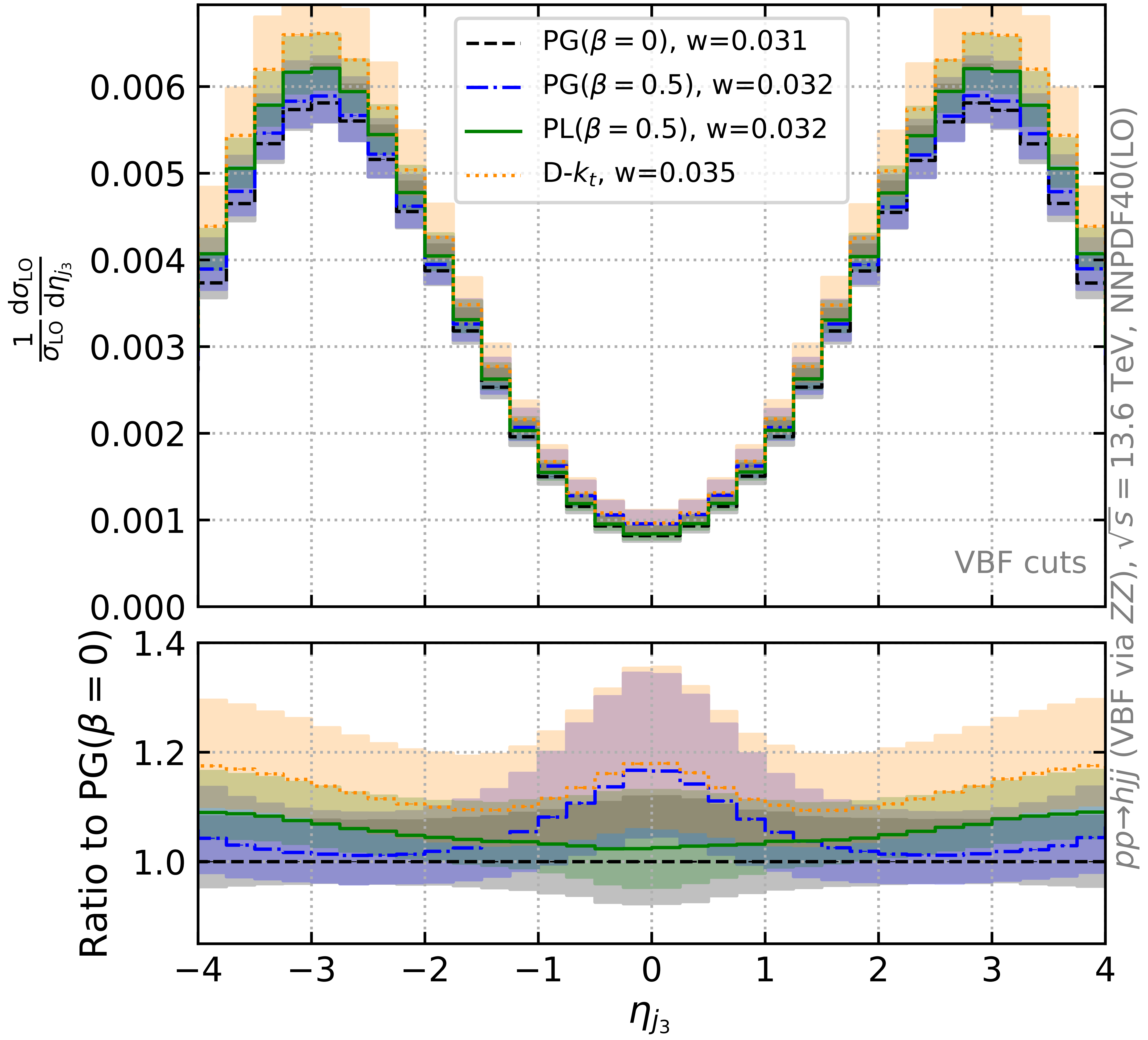
for more exclusive quantities, also see clear shape differences in going to NLL

especially at larger scales

LL showers

NLL showers

van Beekveld, Ferrario Ravasio, GPS, Soto Ontoso, Soyez, Verheyen, Hamilton: 2207.09467



DIS + Vector-boson fusion

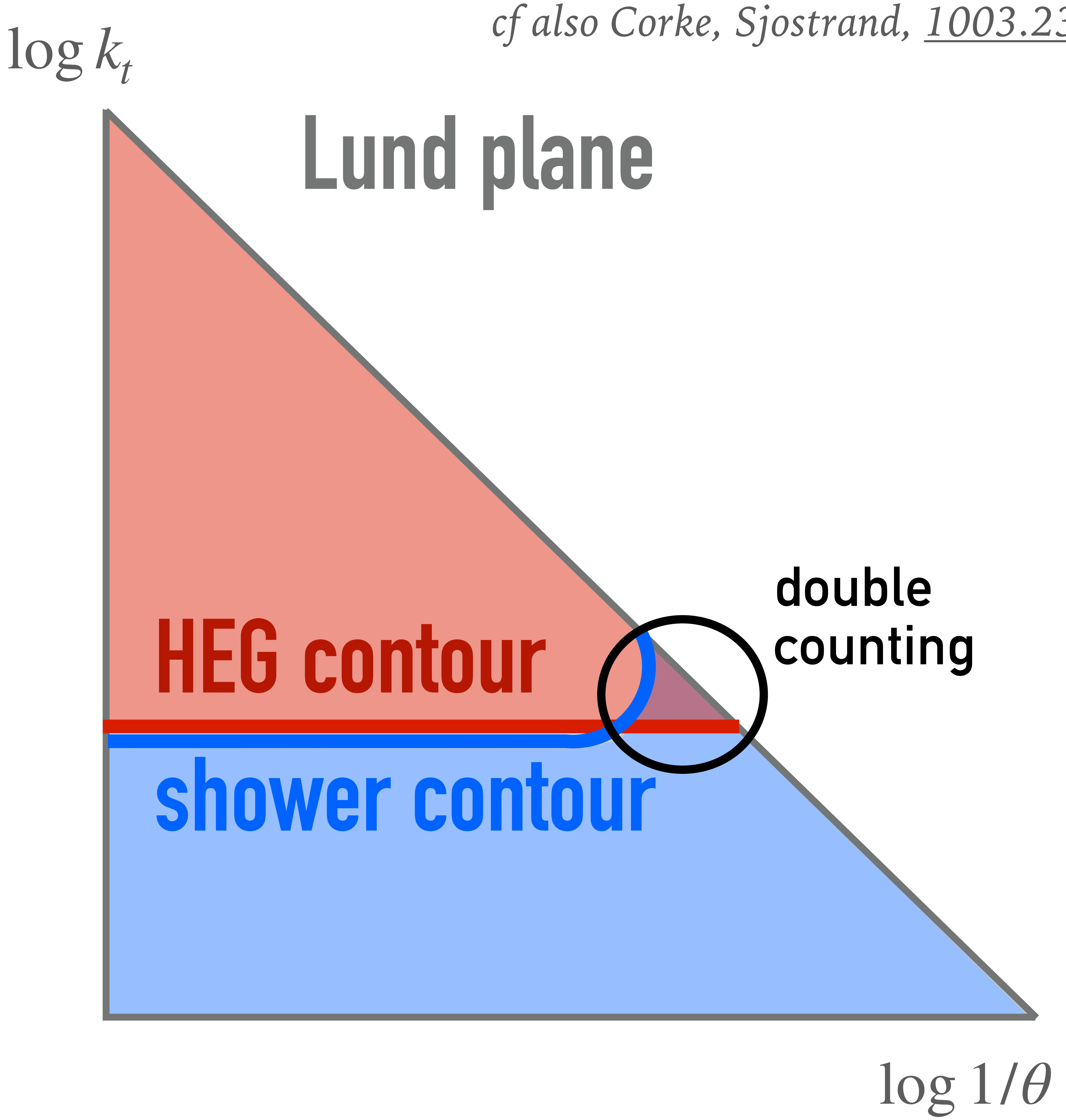
- Conserves vector boson momenta — may facilitate inclusion of higher order corrections via project-to-Born type approaches
- Plot shows 3rd jet η distribution, with correct dip behaviour in the middle

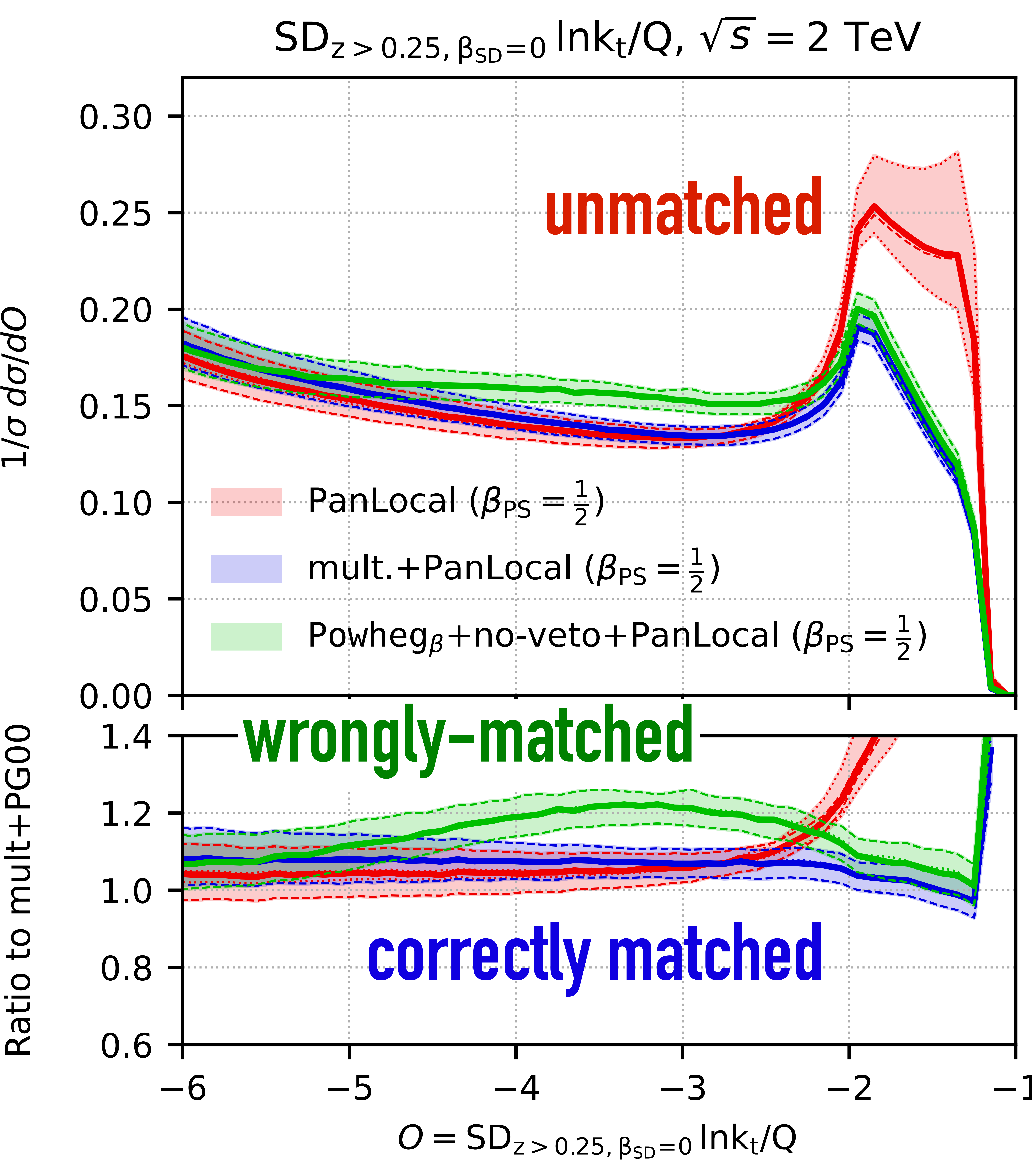
NLO matching and logarithmic accuracy

Hamilton, Karlberg, GPS, Scyboz, Verheyen, 2301.09645

cf also Corke, Sjostrand, 1003.2384

- Proof of concept explored for $e^+e^- \to 2\,\text{jets}$ @ NLO
- some matching schemes supplement shower with pure $\mathcal{O}(\alpha_s)$, e.g. MC@NLO, KrKNLO, MAcNLOPS:
  Shower log accuracy easy to maintain
- in other schemes, first emission is generated by an external program (POWHEG, MINNLO, Geneva, etc.):
  Shower log accuracy subtle to maintain
- NB: concern is not just kinematic mismatch, but also any mismatch in partitioning functions





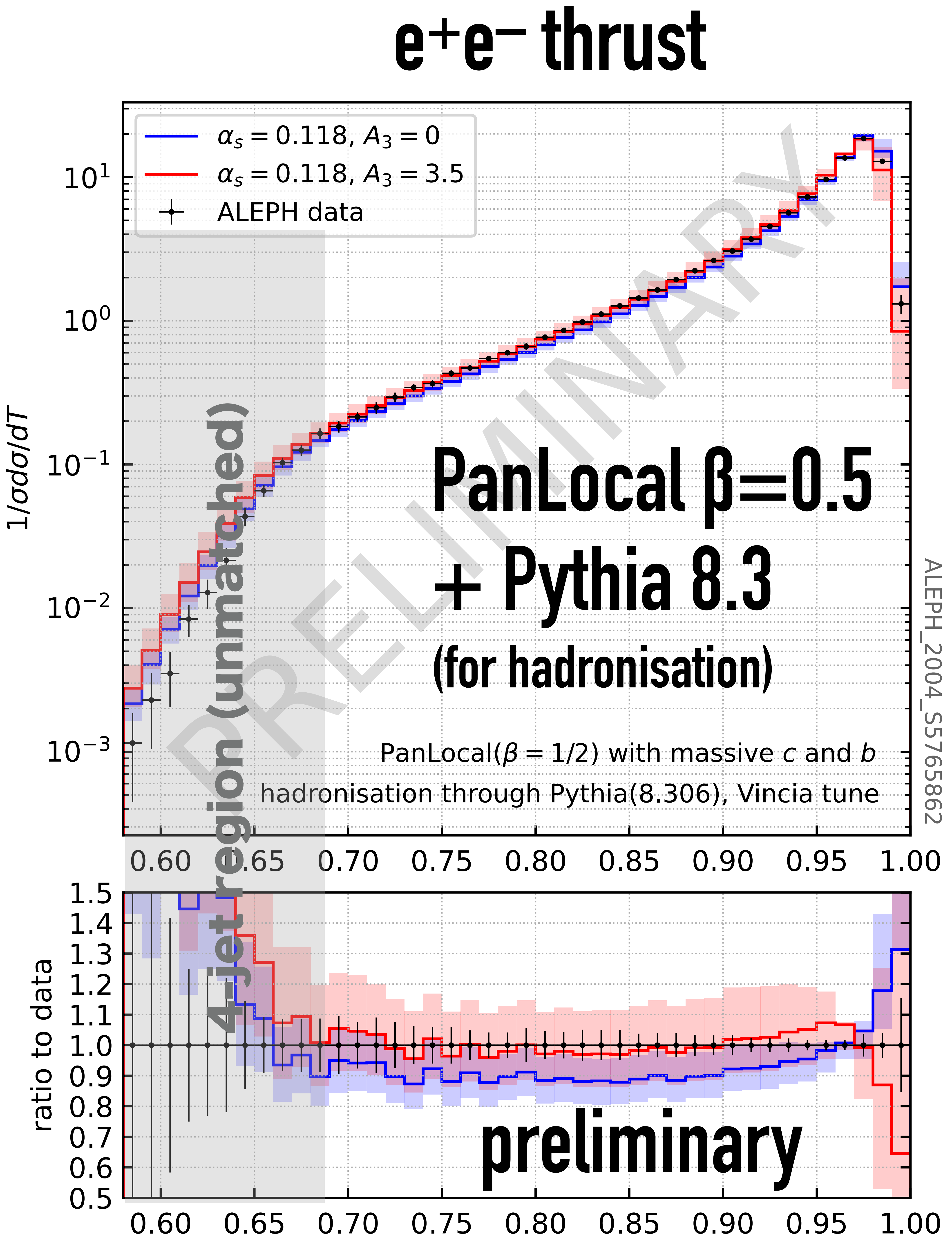
Hamilton, Karlberg, GPS, Scyboz, Verheyen, 2301.09645

Matching & log-accuracy

- Done correctly, **matching augments accuracy** of shower from NLL to NLL + NNDL (for event shapes)
- Done wrongly, it breaks exponentiation structure of shower (impact depends on observable)
- example with significant impact is **SoftDrop transverse momentum** (i.e. jet substructure)

$$\partial_L \Sigma_{\rm SD}(L) = \bar\alpha c\, e^{\bar\alpha c L - \bar\alpha \Delta} - 2\bar\alpha L e^{-\bar\alpha L^2}(1 - e^{-\bar\alpha\Delta})$$

spurious term from wrong matching



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.

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

Latest development: first steps towards NNLL accuracy [PanGlobal only]

Initial focus is on soft emission — i.e. inclusion of double-soft current + associated virtual corrections

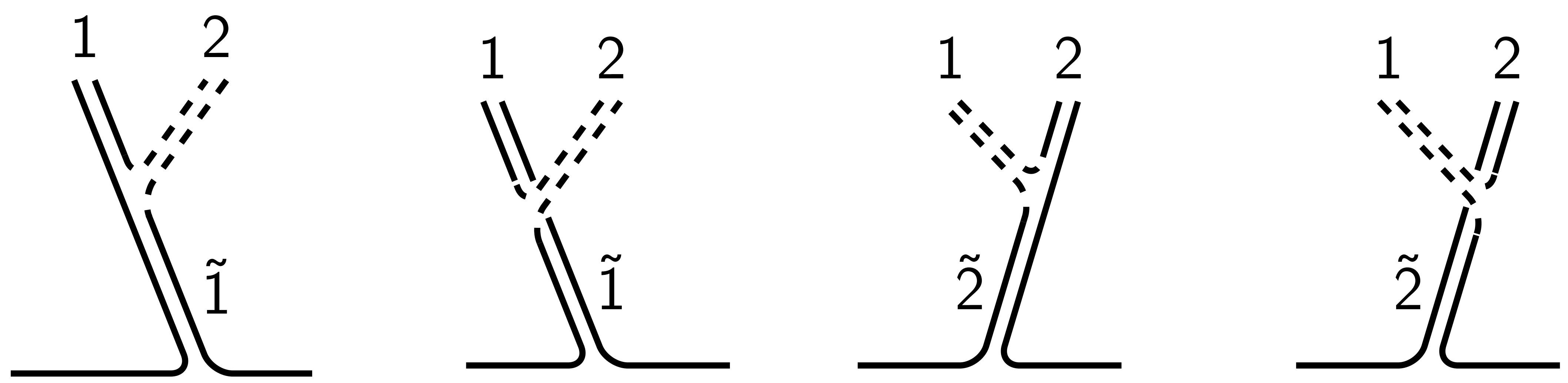
- any pair of soft emissions with commensurate energy and angles should be produced with the correct [double-soft] matrix element
- subsequent (much softer) emissions from that soft pair should also come with the correct matrix element
- probability for any single soft emission should be NLO accurate
- NB: Vincia and Sherpa groups have also explored inclusion of such terms; part of novelty here is doing so in context of shower that satisfies PanScales principles, as needed to get the log-accuracy benefit.

This should maintain NLL accuracy and further achieve

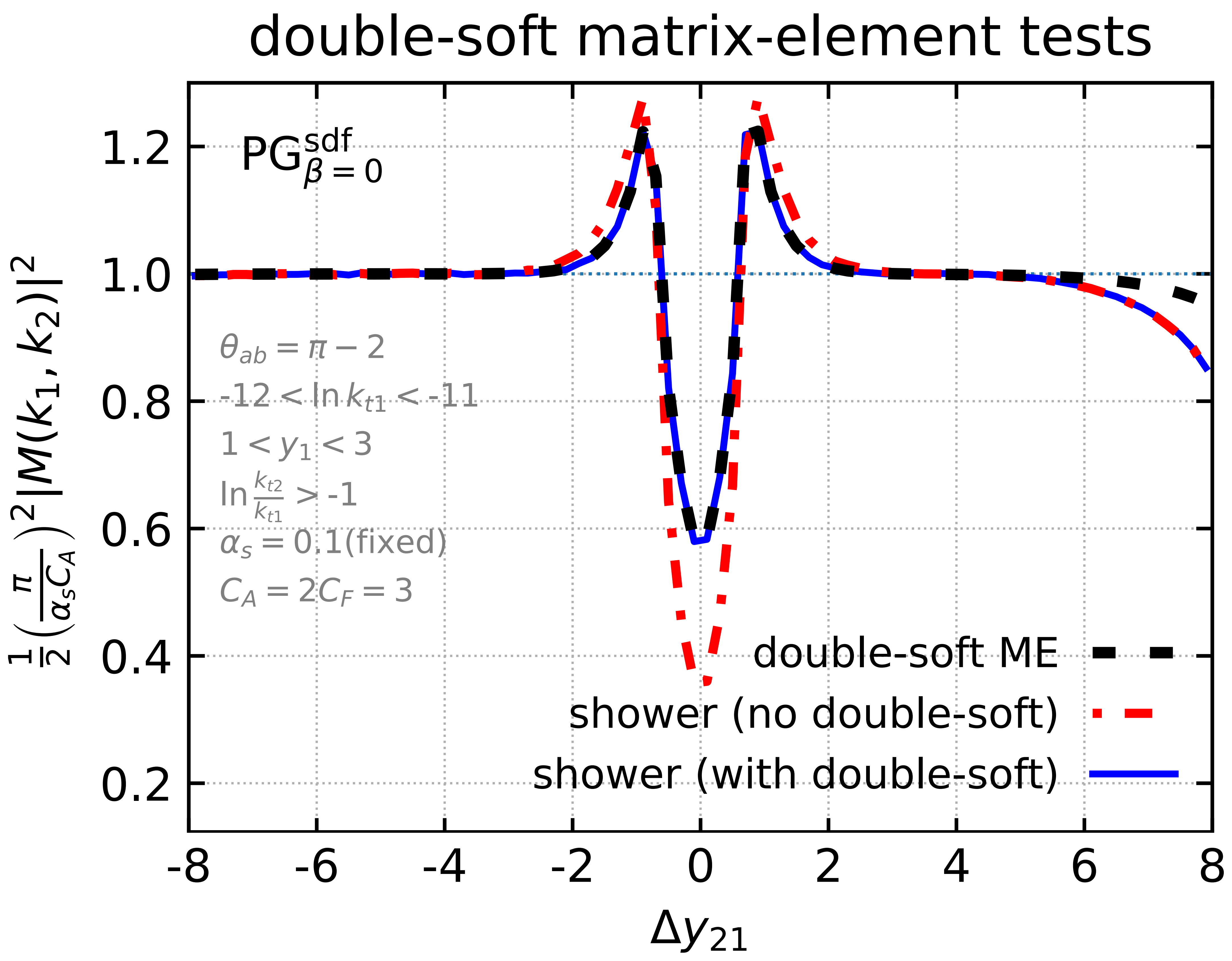
- **NNDL accuracy** for [subjet] multiplicities, i.e. terms $\alpha_s^n L^{2n}$, $\alpha_s^n L^{2n-1}$, $\boldsymbol{\alpha_s^n L^{2n-2}}$
- **Next-to-Single-Log (NSL) accuracy** for non-global logarithms, e.g. energy in a slice, all terms $\alpha_s^n L^n$ and $\boldsymbol{\alpha_s^n L^{n-1}}$ (at leading-N_c)

NB: done using adapted PanGlobal showers [cf. backup], without spin correlations for now

1. Get the double-soft matrix element

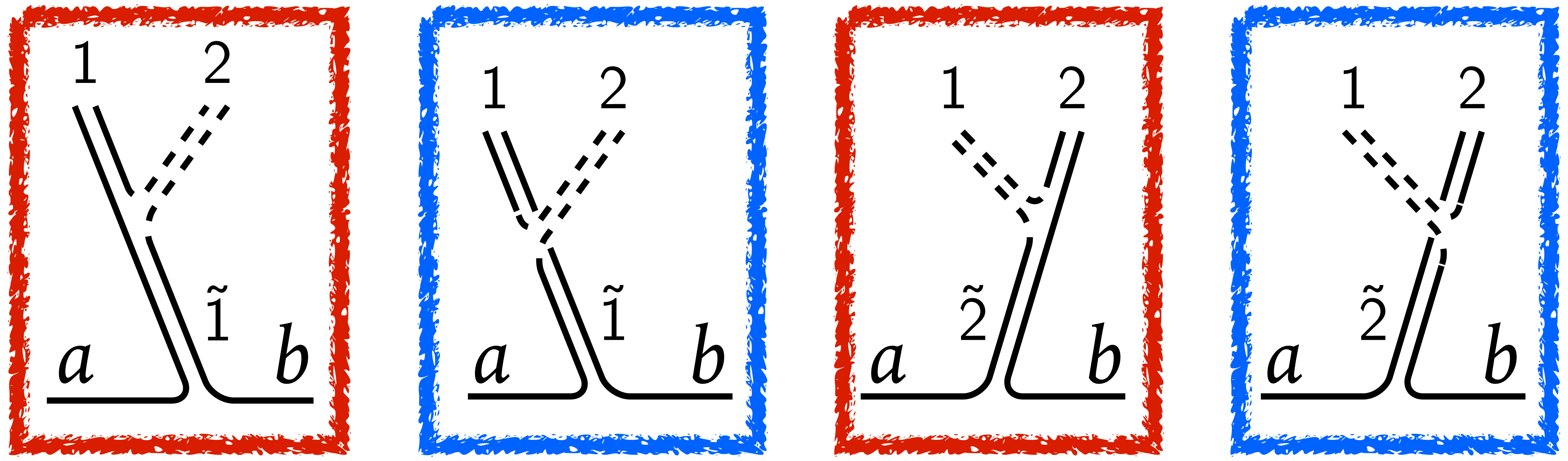


- a given two-emission configuration can come from four histories (two emission orderings × two colour orderings)
- **accept a given emission with true double-soft $|M^2|$ divided by shower's effective double-soft matrix element** summed over the histories, h, that could have produced that configuration



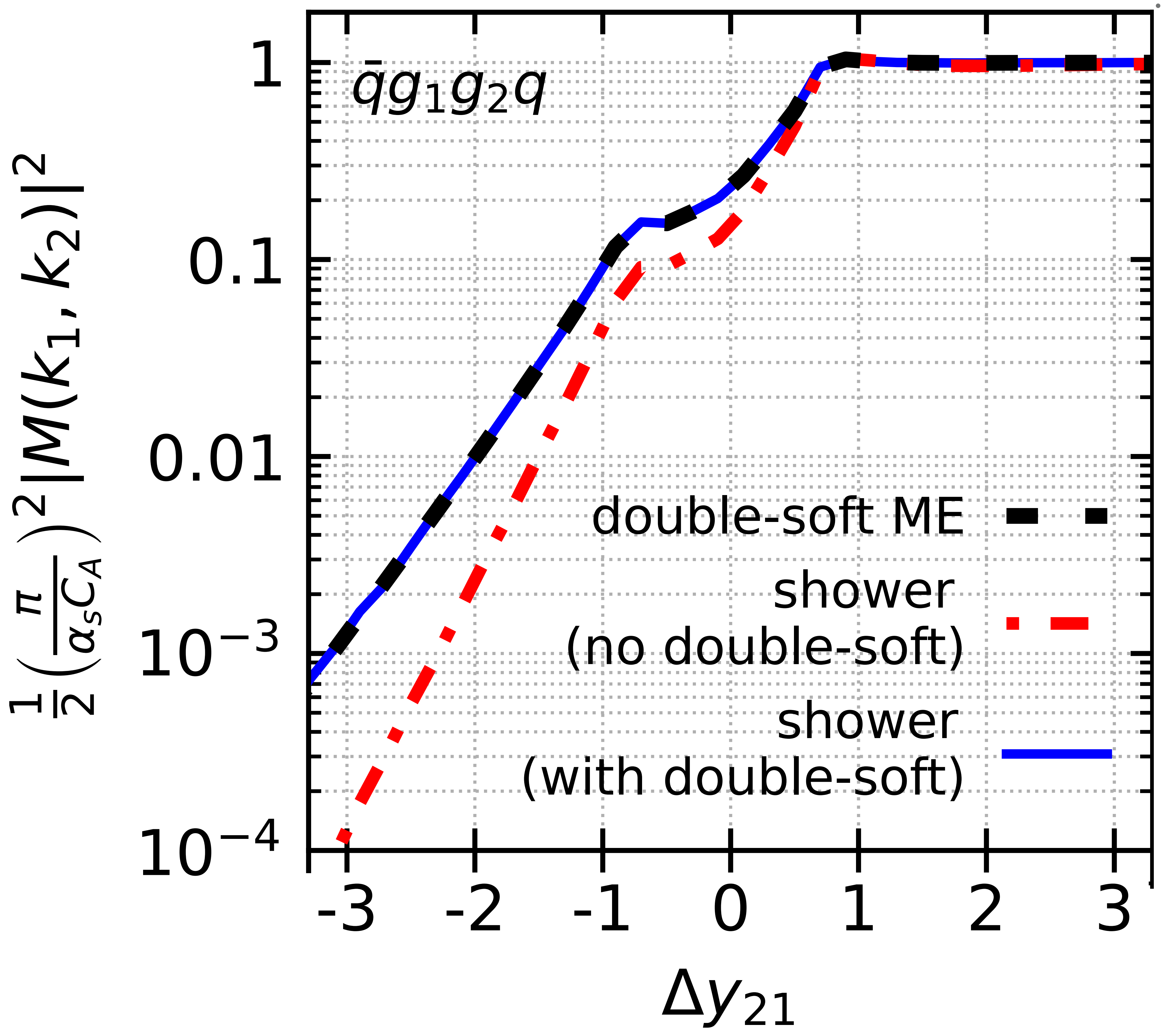
$$P_{\text{accept}} = \frac{|M_{\text{DS}}|^2}{\sum_h |M_{\text{shower},h}|^2}.$$

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



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

3. NLO accurate single-soft emissions

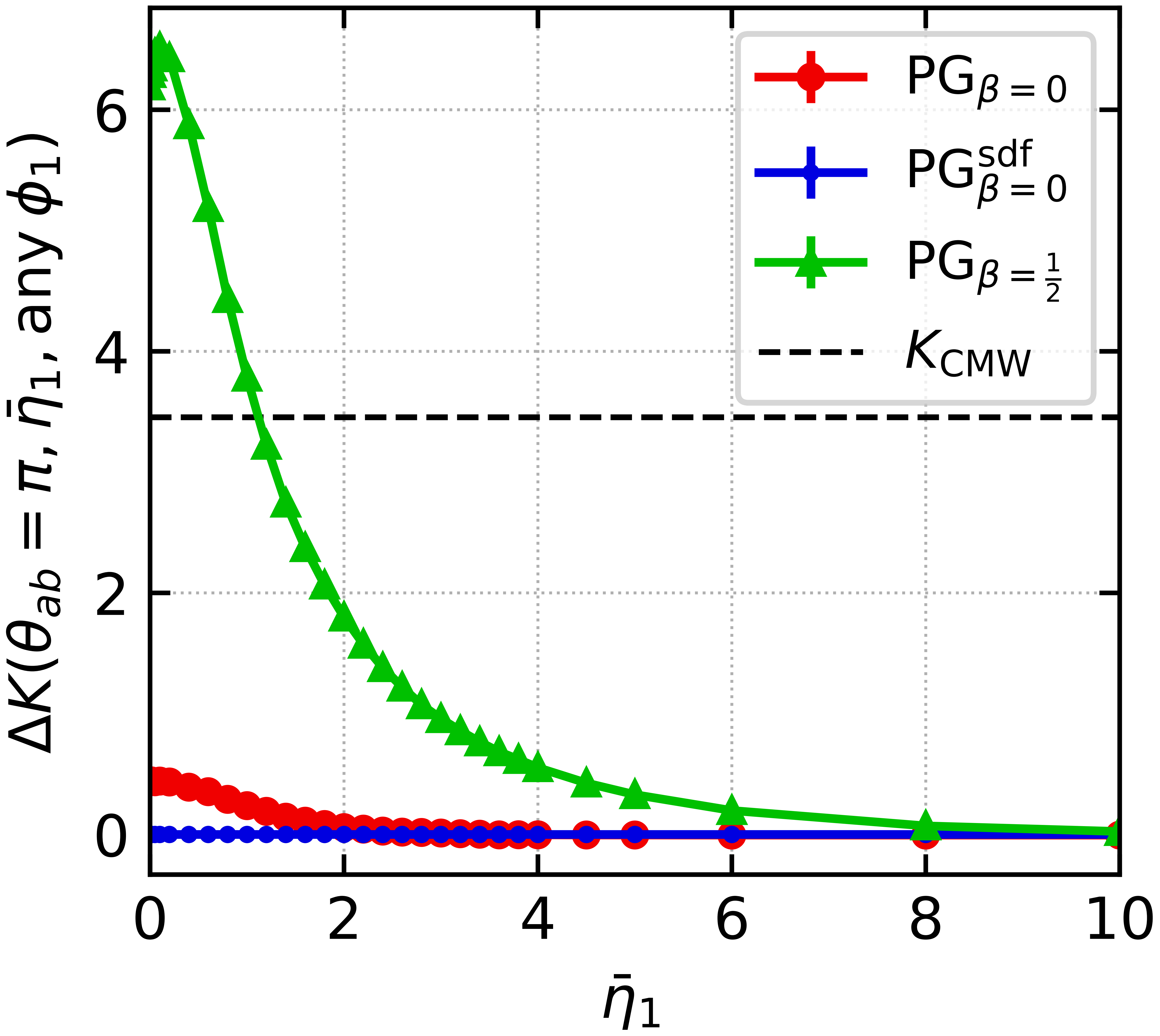
In soft-collinear region, showers already have NLO soft-emission intensity, thanks to

$$\alpha_s + \alpha_s^2 K_{\text{CMW}}/2\pi$$

For most PanScales showers this is not sufficient in the soft large-angle region.

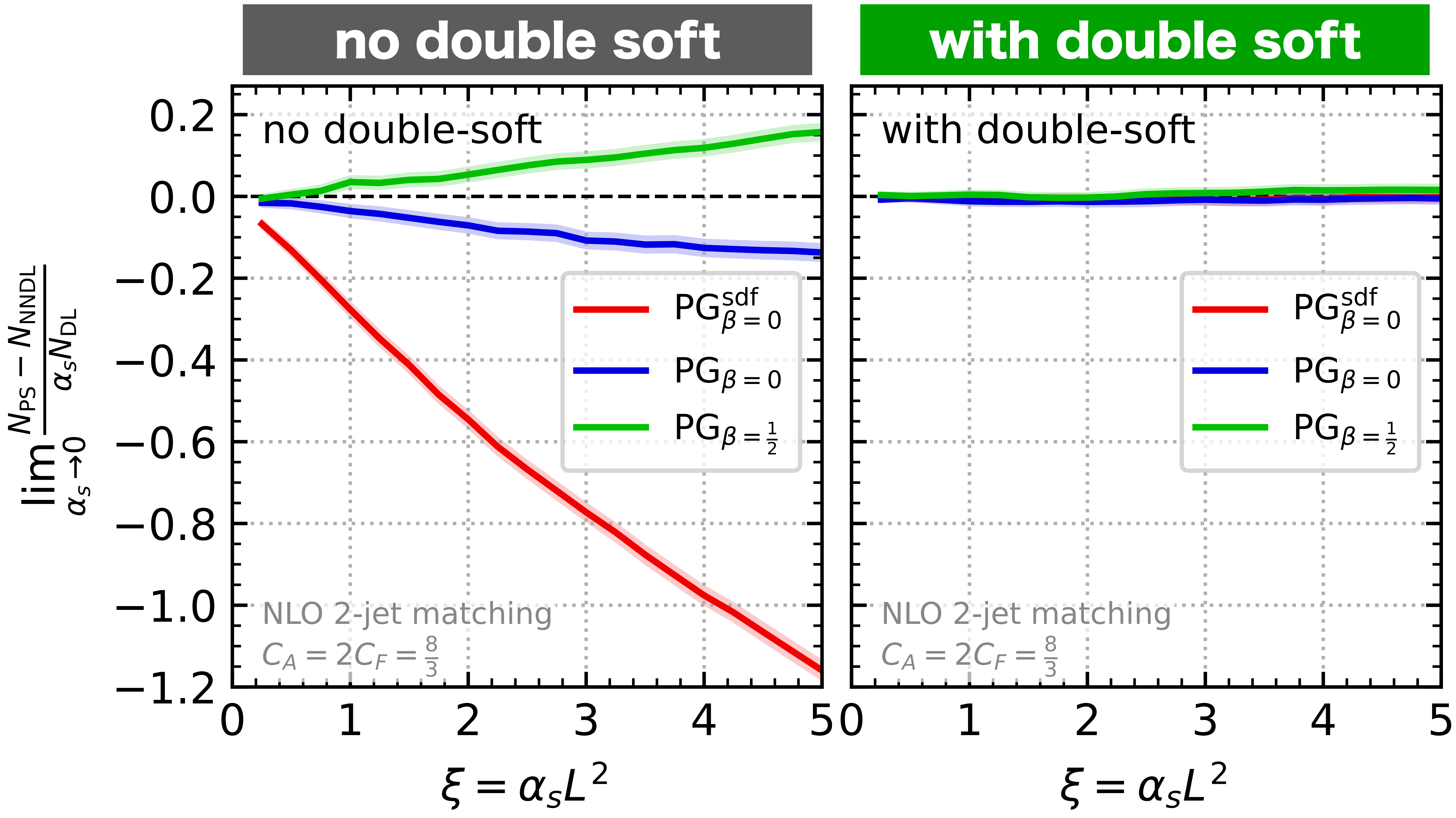
So we must include additional $\alpha_s^2 \Delta K/2\pi$ term in emission intensity (a bit like POWHEG/MC@NLO $\overline{B}$ term, using shower soft-collinear region as counterterm)

example ΔK correction



$$\Delta K = \int_r d\Phi^{(\text{PS})}_{12/\tilde{1}} |M^{(\text{PS})}_{12/\tilde{1}}|^2 - \int_{r_{\text{sc}}} d\Phi^{(\text{PS})}_{12/\tilde{1}_{\text{sc}}} |M^{(\text{PS})}_{12/\tilde{1}_{\text{sc}}}|^2.$$

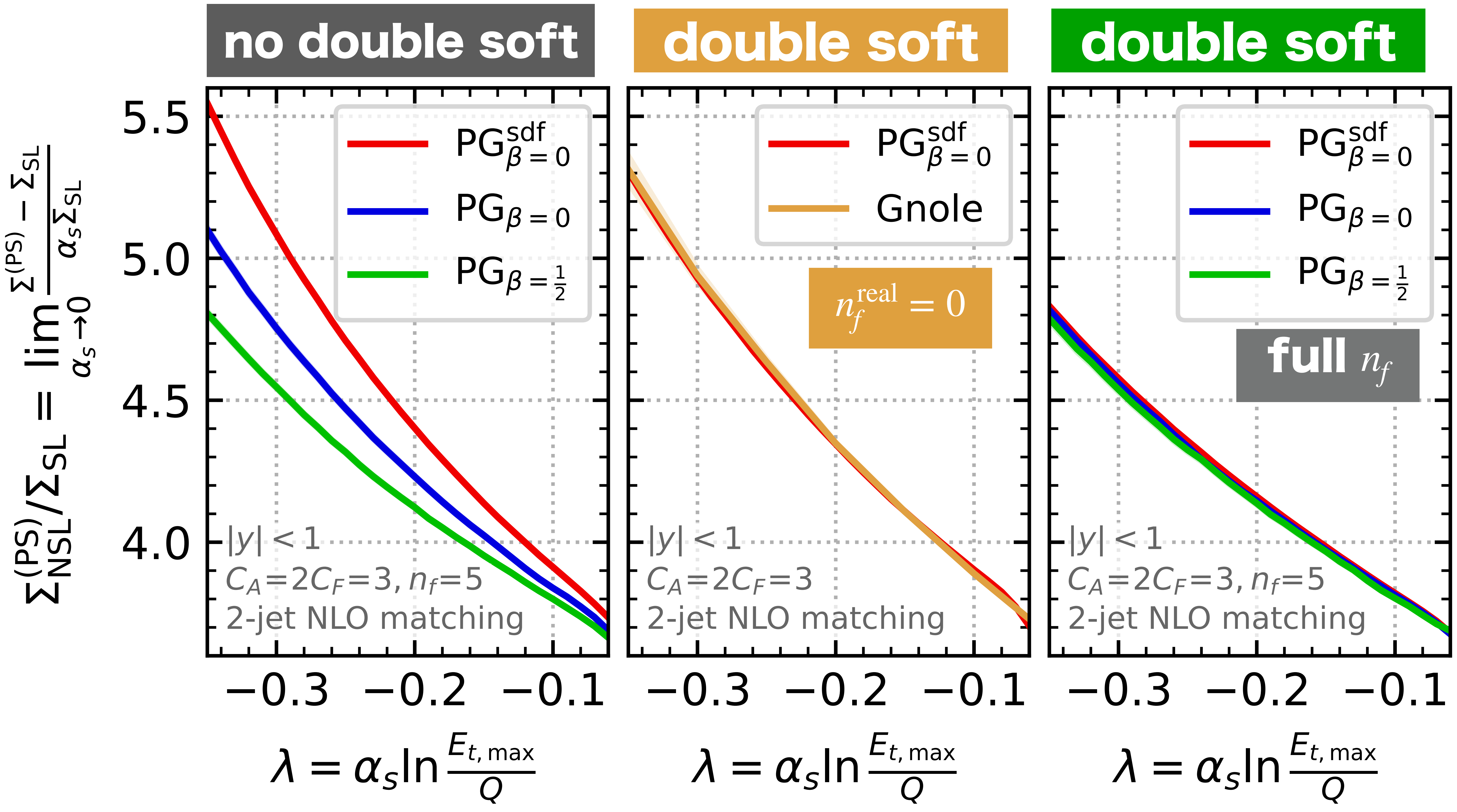
Log test #1: NNDL Lund subjet multiplicity



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

- NNDL ($\alpha_s^n L^{2n-2}$) analytic resummation = Medves, Soto Ontoso, Soyez, 2205.02861
- $\alpha_s \to 0$ limit to isolate NNDL terms (NB $1/\alpha_s$ in denominator makes this harder than NDL/NLL tests).
- Showers without double-soft differ from zero (and each other)
- **Adding double soft brings NNDL agreement**

Log test #2: NSL for energy flow in slice

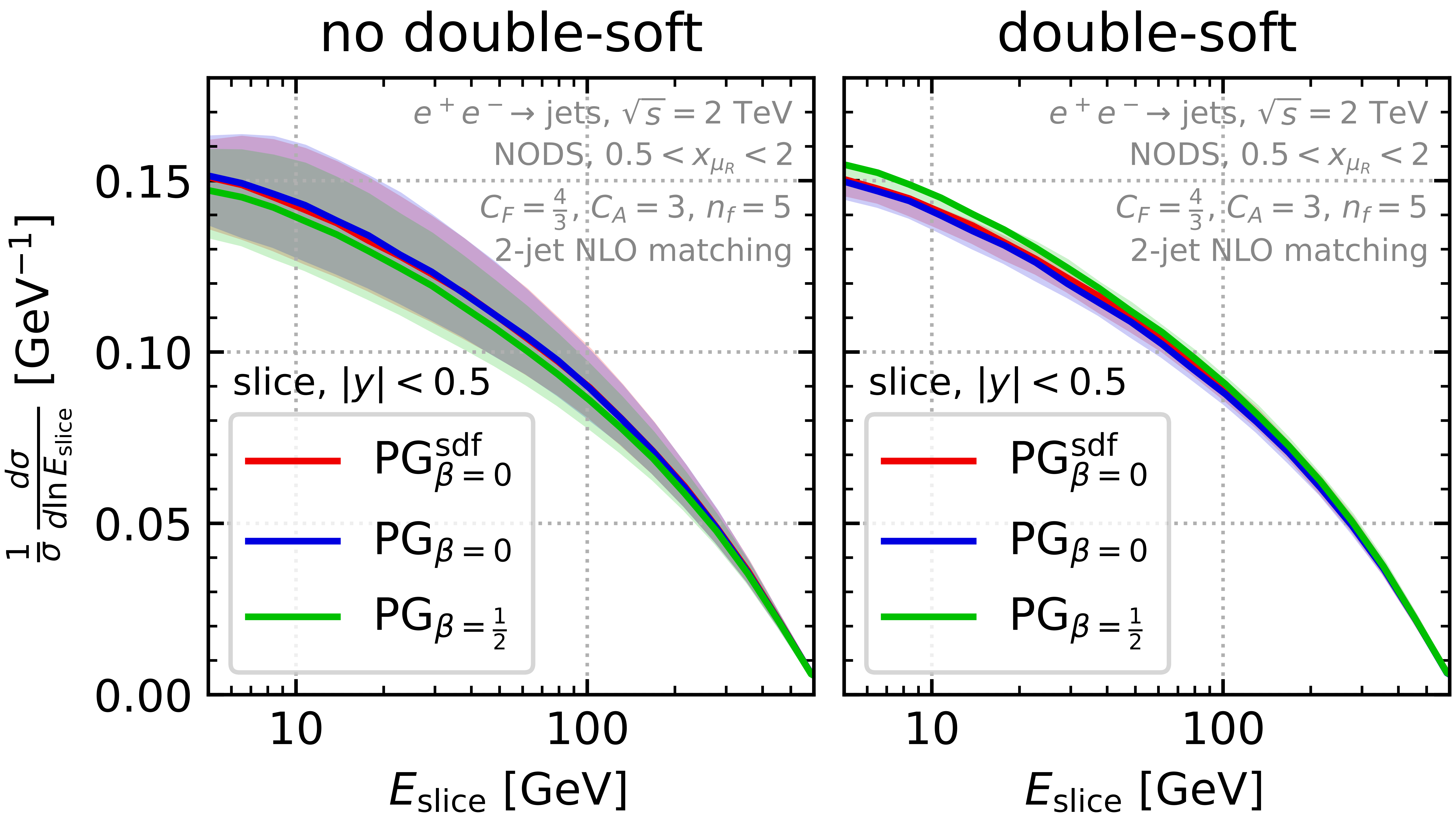


$$\Sigma^{(PS)}_{NSL} = \lim_{\alpha_s \to 0} \frac{\Sigma^{(PS)} - \Sigma_{SL}}{\alpha_s}\bigg|_{\text{fixed } \alpha_s L}, \qquad L \equiv \ln \frac{E_{t,max}}{Q}$$

- NSL ($\alpha_s^n L^{n-1}$) = Banfi, Dreyer, Monni, 2104.06416, 2111.02413 ("Gnole")
  [NB: see also Becher, Schalch, Xu, 2307.02283]
- **Semi-blind:** only compared to Gnole once three PanGlobal variants agreed with each other
- **NSL agreement with Gnole for $n_f^{real} = 0$**
- **By-product:** First large-N_c full-n_f results for NSL non-global logarithms
  (including ref. results for several observables, cf. backup)

NSL Pheno outlook

- Observable is energy flow in slice between two 1 TeV jets
- Without DS: three PanGlobal variants actually quite close, but large uncertainty band
- **With DS: three variants still close, reduced uncertainty band**



Conclusions

- **PanScales is first validated NLL shower (with spin & full-colour@LL/NLL)**
  - benefits of LL → NLL include reduced uncertainties (and ability to reliably estimate uncertainties)
  - multi-differential soft/collinear observables have enhanced sensitivity to NLL
  - 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
- **We're on the path towards public code**
  - exact timeline still fuzzy, but progress being made

backup

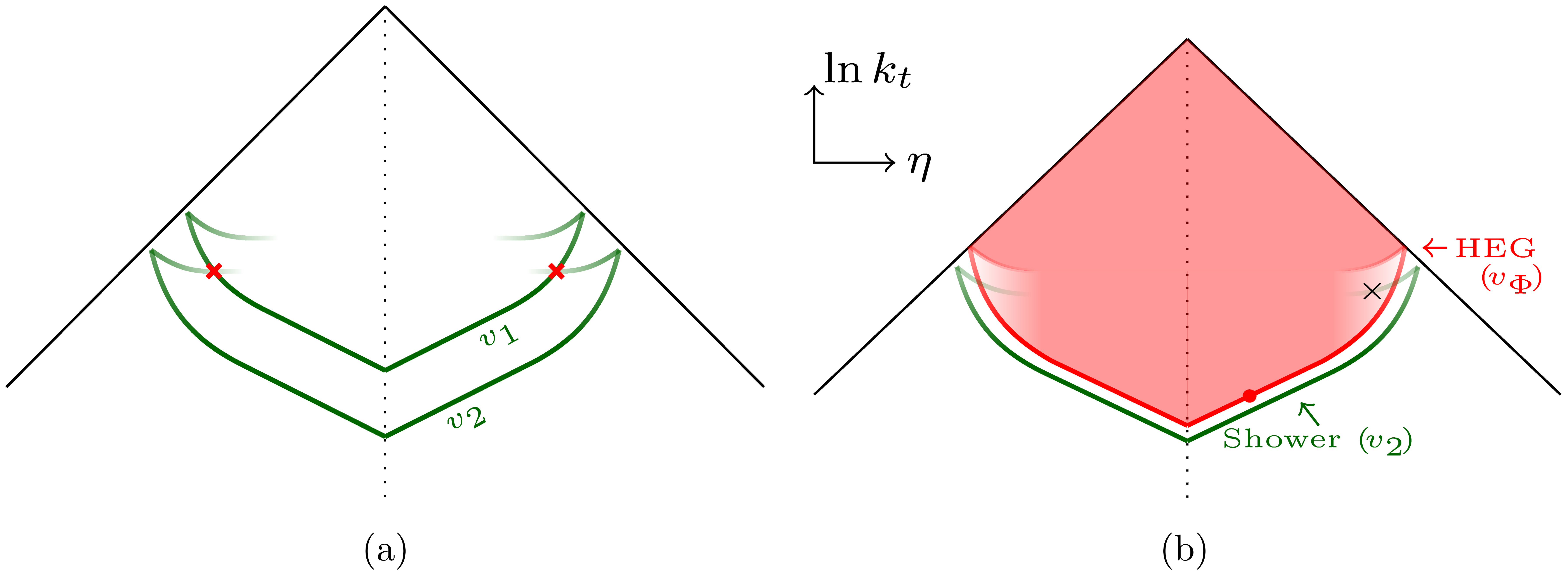
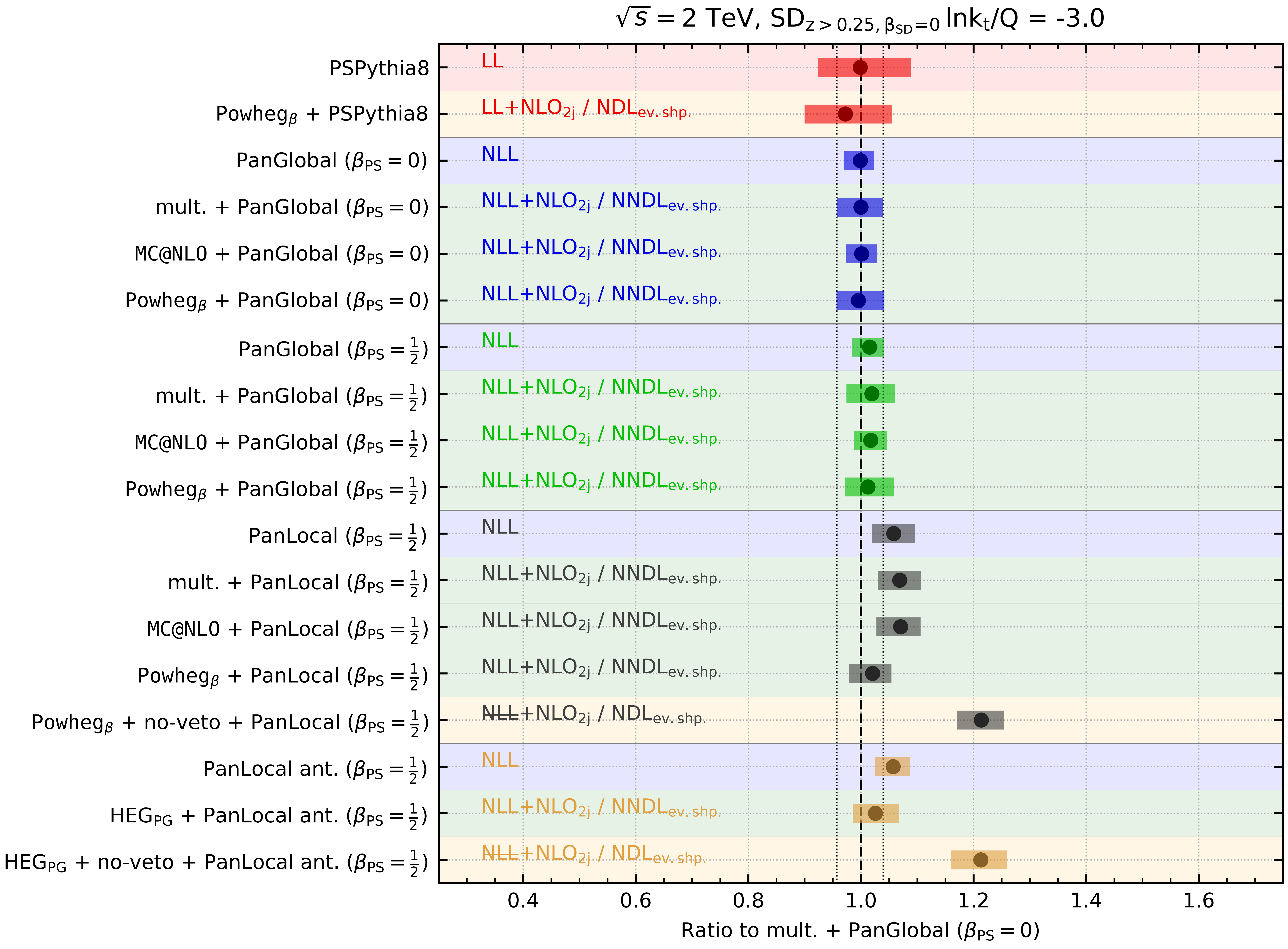


Figure 2: Schematic illustration of the issue associated with gluon asymmetrisation. (a) Contours on the Lund plane, in the PanLocal family of showers, highlighting the fact that a given physical point X in the Lund plane (highlighted with a red cross) can come from two different values of v. The shading of the green curves represents the variation in radiation intensity along the contour. (b) Density plot, at each point in the Lund plane, representing schematically the fraction of the emission intensity at that point that has been excluded once the HEG has reached a given v value (v_Φ) without emitting, and an illustration that as the shower continues there may still be phase-space points (such as that marked with a cross) where the Sudakov has only been partially accounted for. The implications are discussed in the text.


$\sqrt{s} = 2$ TeV, $SD_{z>0.25, \beta_{SD}=0}$ $\ln k_t/Q$ = -3.0
PSPythia8
Powheg$_\beta$ + PSPythia8
PanGlobal ($\beta_{PS} = 0$)
mult. + PanGlobal ($\beta_{PS} = 0$)
MC@NLO + PanGlobal ($\beta_{PS} = 0$)
Powheg$_\beta$ + PanGlobal ($\beta_{PS} = 0$)
PanGlobal ($\beta_{PS} = \frac{1}{2}$)
mult. + PanGlobal ($\beta_{PS} = \frac{1}{2}$)
MC@NLO + PanGlobal ($\beta_{PS} = \frac{1}{2}$)
Powheg$_\beta$ + PanGlobal ($\beta_{PS} = \frac{1}{2}$)
PanLocal ($\beta_{PS} = \frac{1}{2}$)
mult. + PanLocal ($\beta_{PS} = \frac{1}{2}$)
MC@NLO + PanLocal ($\beta_{PS} = \frac{1}{2}$)
Powheg$_\beta$ + PanLocal ($\beta_{PS} = \frac{1}{2}$)
Powheg$_\beta$ + no-veto + PanLocal ($\beta_{PS} = \frac{1}{2}$)
PanLocal ant. ($\beta_{PS} = \frac{1}{2}$)
HEG$_{PG}$ + PanLocal ant. ($\beta_{PS} = \frac{1}{2}$)
HEG$_{PG}$ + no-veto + PanLocal ant. ($\beta_{PS} = \frac{1}{2}$)
LL
LL+NLO$_{2j}$ / NDL$_{ev. shp.}$
NLL
NLL+NLO$_{2j}$ / NNDL$_{ev. shp.}$
NLL+NLO$_{2j}$ / NNDL$_{ev. shp.}$
NLL+NLO$_{2j}$ / NNDL$_{ev. shp.}$
NLL
NLL+NLO$_{2j}$ / NNDL$_{ev. shp.}$
NLL+NLO$_{2j}$ / NNDL$_{ev. shp.}$
NLL+NLO$_{2j}$ / NNDL$_{ev. shp.}$
NLL
NLL+NLO$_{2j}$ / NNDL$_{ev. shp.}$
NLL+NLO$_{2j}$ / NNDL$_{ev. shp.}$
NLL+NLO$_{2j}$ / NNDL$_{ev. shp.}$
~~NLL~~+NLO$_{2j}$ / NDL$_{ev. shp.}$
NLL
NLL+NLO$_{2j}$ / NNDL$_{ev. shp.}$
~~NLL~~+NLO$_{2j}$ / NDL$_{ev. shp.}$
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Ratio to mult. + PanGlobal ($\beta_{PS} = 0$)

Matching — augment from NLL to NLL + NNDL?

Two ways of counting logarithms

$$\ln \Sigma = \underbrace{\alpha_s^n L^{n+1}}_{\text{LL}} + \underbrace{\alpha_s^n L^n}_{\text{NLL}} + \underbrace{\alpha_s^n L^{n-1}}_{\text{NNLL}} + \ldots \text{ (relevant when } \alpha_s L \sim 1)$$

$$\Sigma = \underbrace{\alpha_s^n L^{2n}}_{\text{DL}} + \underbrace{\alpha_s^n L^{2n-1}}_{\text{NDL}} + \underbrace{\alpha_s^n L^{2n-2}}_{\text{NNDL}} + \ldots \text{ (relevant when } \alpha_s L^2 \sim 1)$$

“Split-dipole-frame”

Antenna showers like PanGlobal need to transition between different splitting functions at the two dipole ends

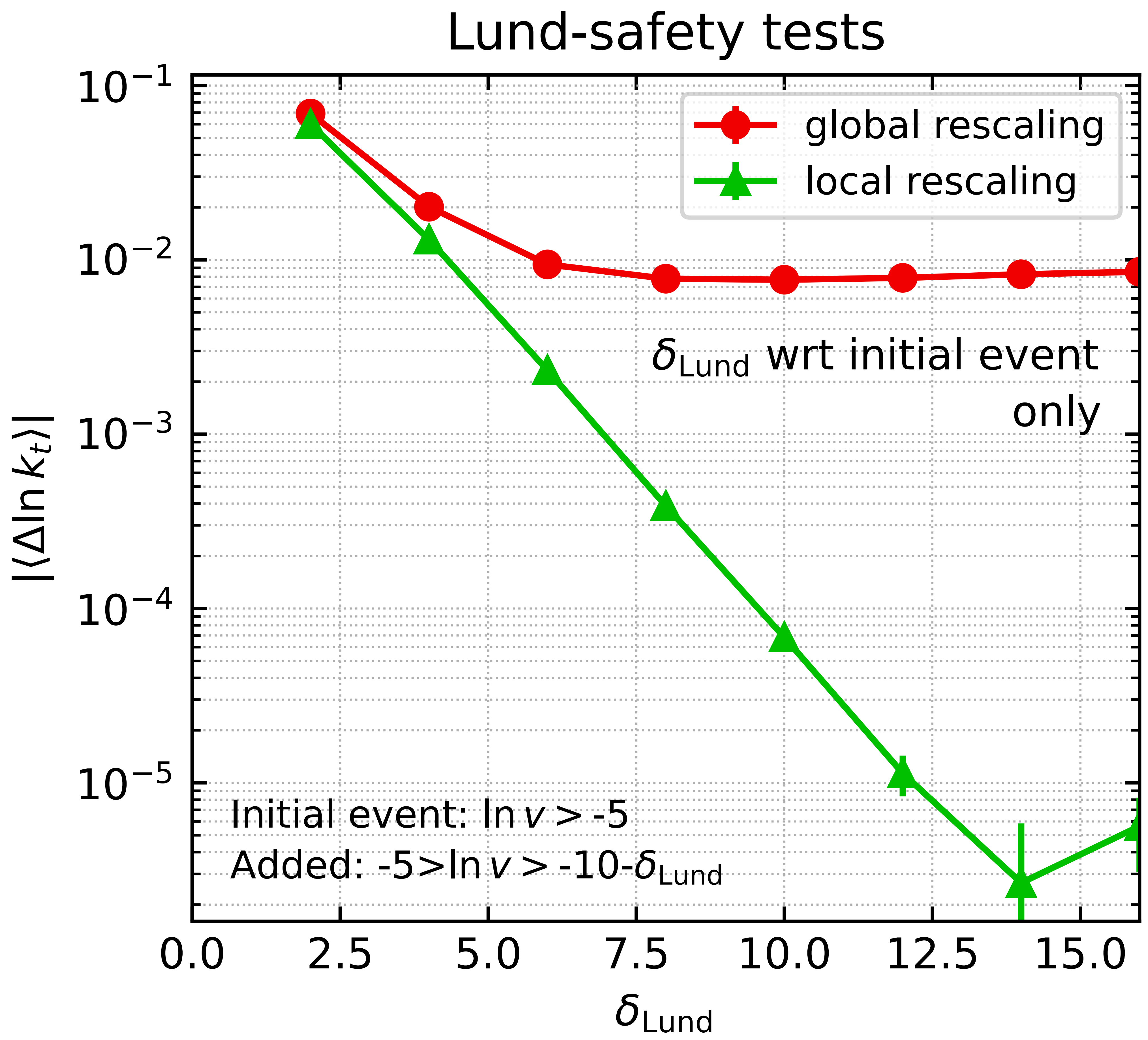
$$\frac{d\mathcal{P}_{n\to n+1}}{d\ln v} = \sum_{\{\tilde{\imath},\tilde{\jmath}\}\in\text{dip}} \int d\bar{\eta}\frac{d\phi}{2\pi}\frac{\alpha_s(k_t)}{\pi}\left(1+\frac{\alpha_s(k_t)K_{\text{CMW}}}{2\pi}\right) \times \left[f(\bar{\eta})a_k P_{\tilde{\imath}\to ik}(a_k) + f(-\bar{\eta})b_k P_{\tilde{\jmath}\to jk}(b_k)\right] . \quad (2)$$

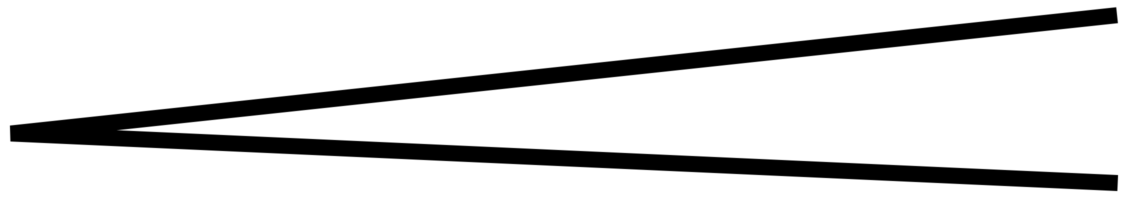
Default PanGlobal choice: $f(\bar{\eta})$ is a function that makes the transition happen around $\bar{\eta} = 0$, i.e. the bisector of the dipole in the frame of the hard system (lab-frame for e^+e^- collisions)

Split Dipole Frame choice: replace $f(\bar{\eta}) \to f(\eta)$, with η the rapidity of the emission in the dipole centre-of-mass frame. Helps ensure longitudinal boost invariance of shower’s effective double-soft current (before inclusion of double-soft ME corrections).

Recent adaptation of the PanGlobal showers

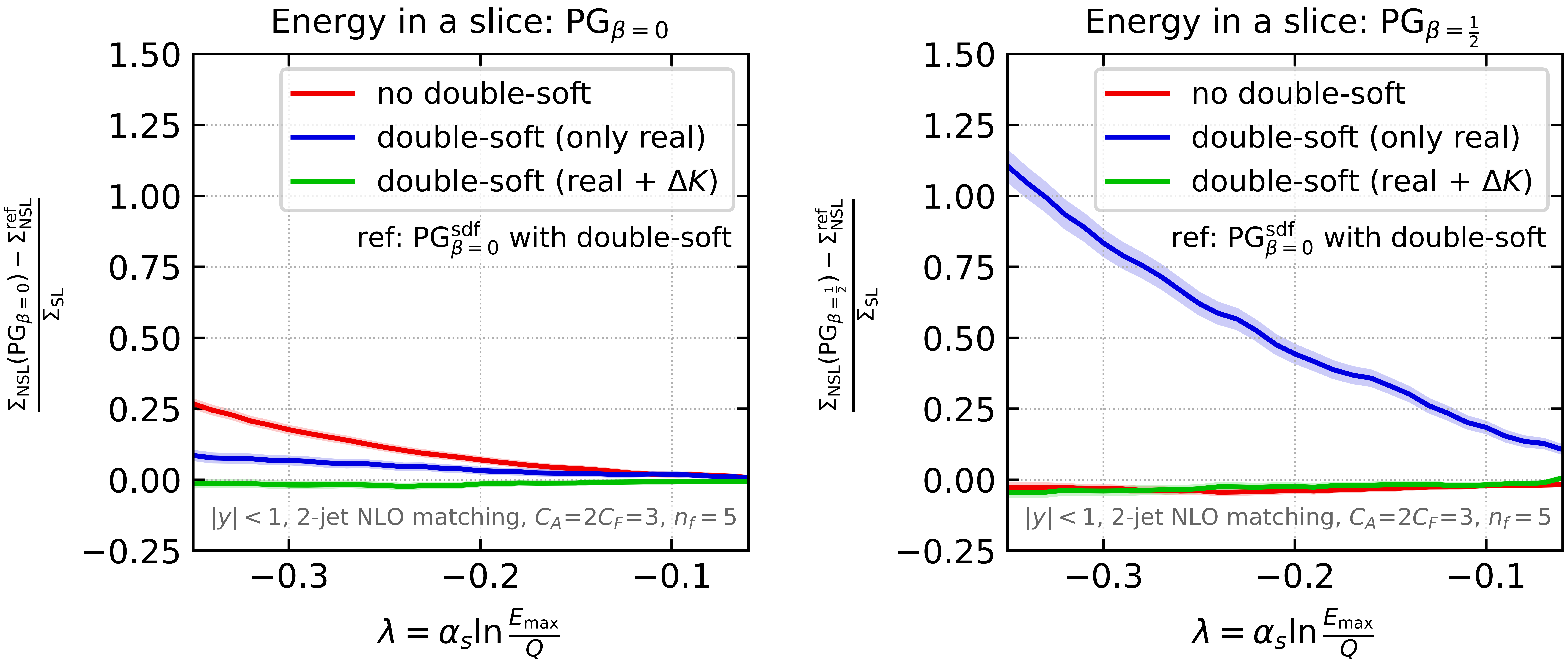
- PanGlobal shower applies a global rescaling and boost to ensure momentum conservation
- We discovered this has issues in the triple collinear region
- We now instead apply, e.g., a dipole-local rescaling to ensure conservation of event invariant mass, then apply a global boost (affects all e^+e^-, pp, DIS, VBF showers)





for very skewed dipole, in-plane ⊥ vector has large energy component. Old PanGlobal variant wrongly propagated that effect to other partons (violation of PanScales conditions, which manifests first at NNLL)

Impact of ΔK on non-global logarithms



Reference results for non-global logarithms