PanScales parton showers

Rencontres de Moriond
QCD & high-energy interactions
March 2023

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Science and Technology Facilities Council
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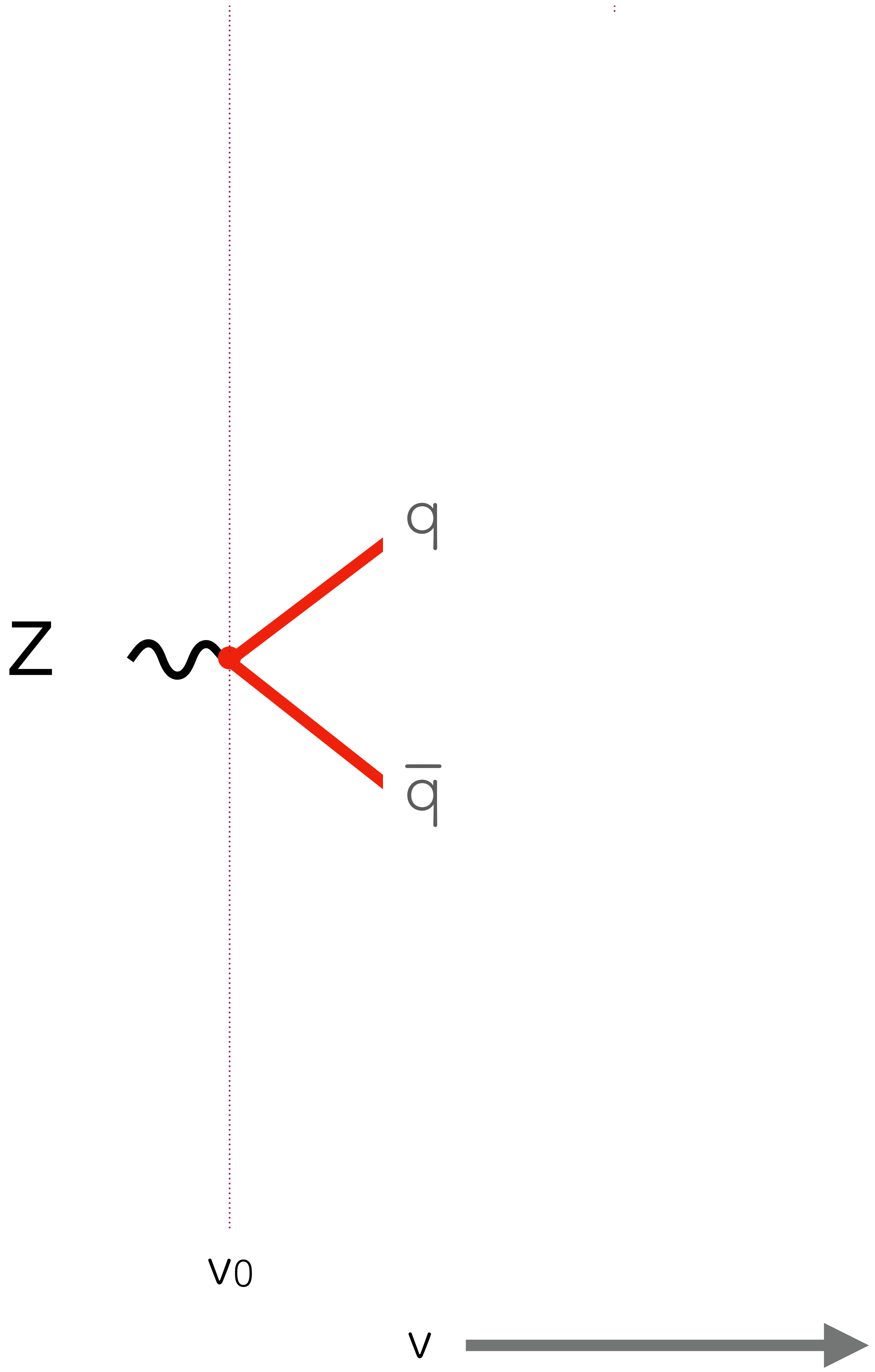
QCD shower: an evolution equation (in **evolution scale v**, e.g. trans.mom.)

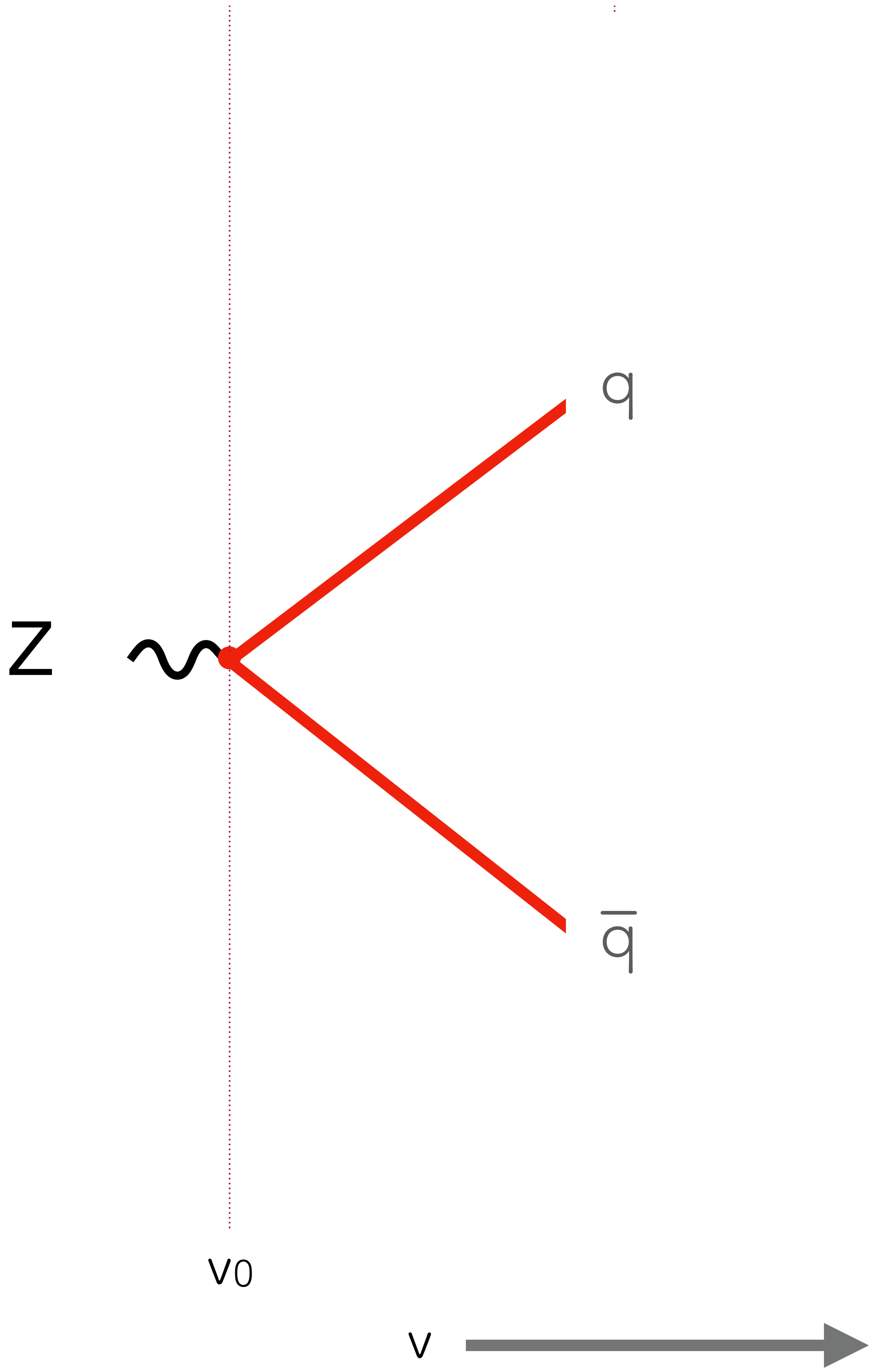


Start with $q\bar{q}$ state.

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

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

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

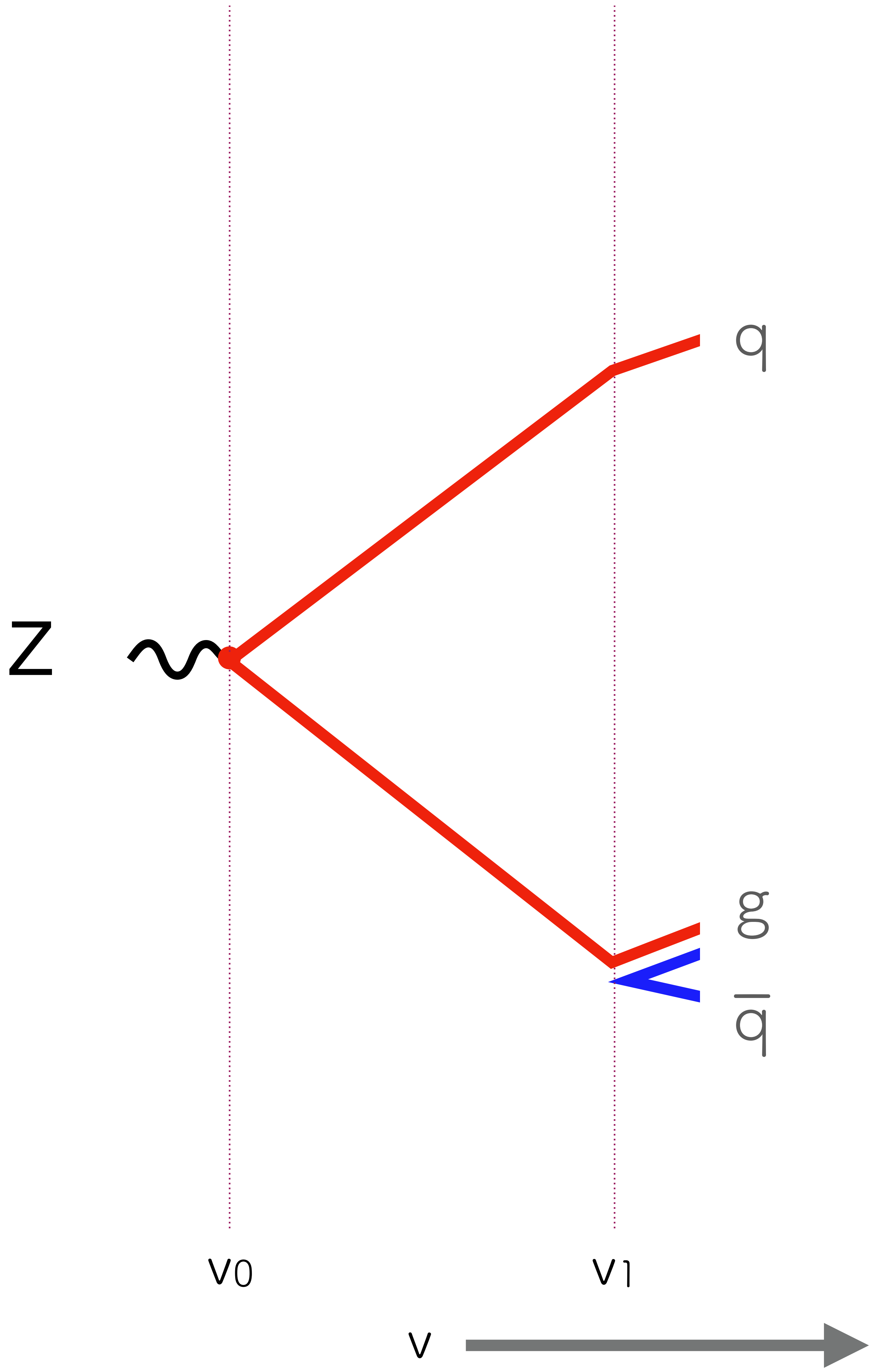


Start with q-qbar state.

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

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

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



Start with q-qbar state.

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

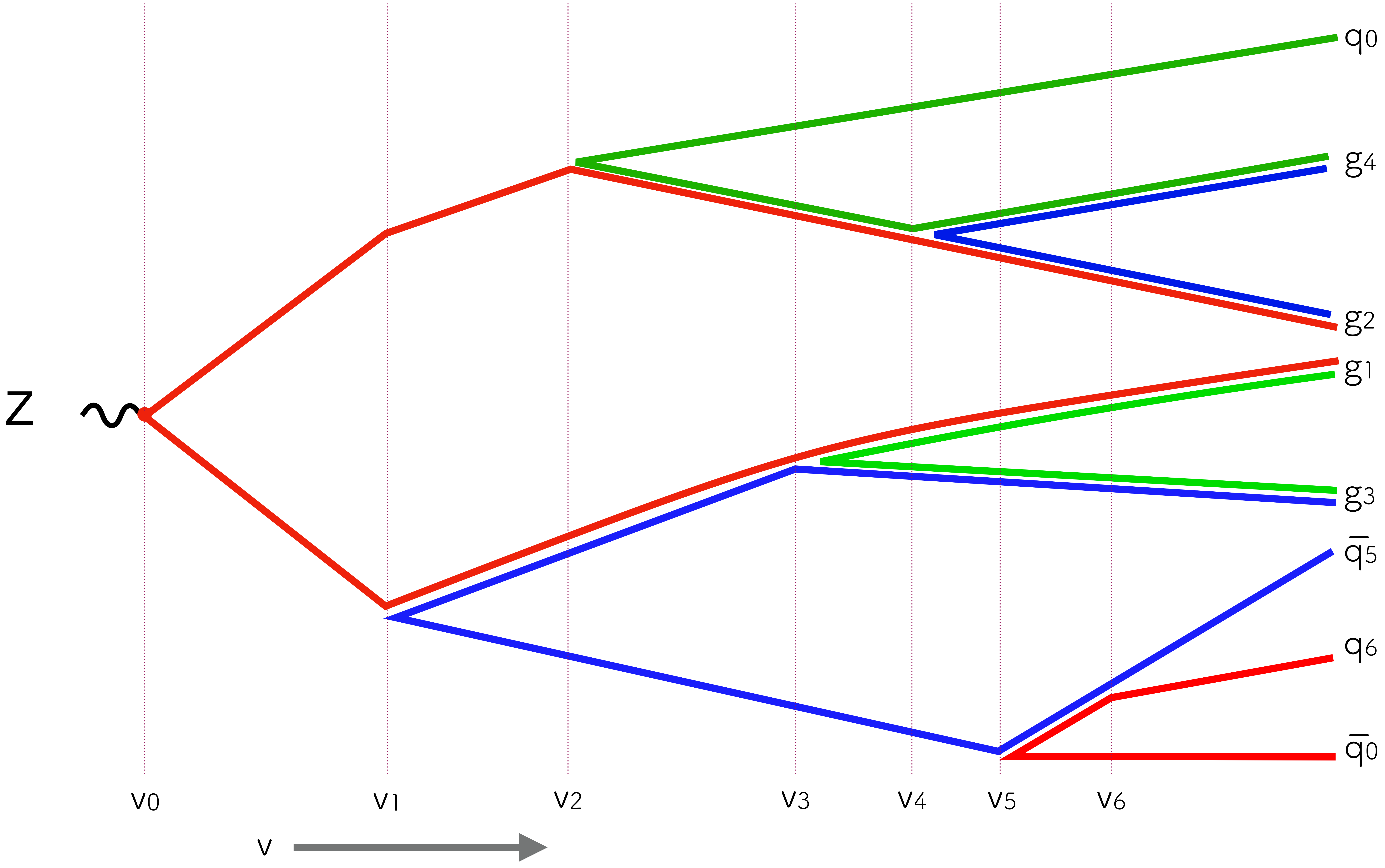
At some point, **state splits** (2→3, i.e. emits gluon). Evolution equation changes

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

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

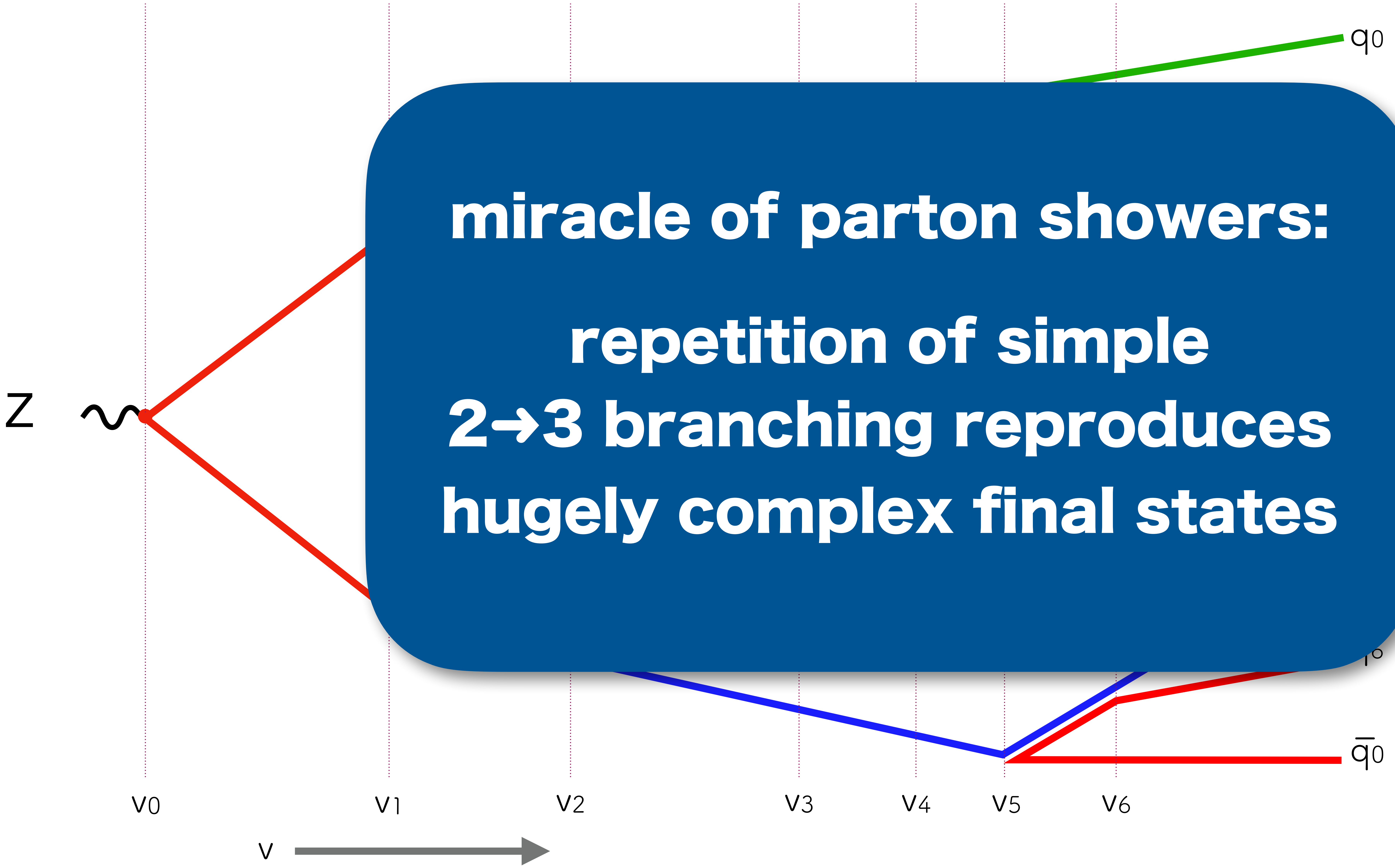
(many showers use a large N_C limit)

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.)

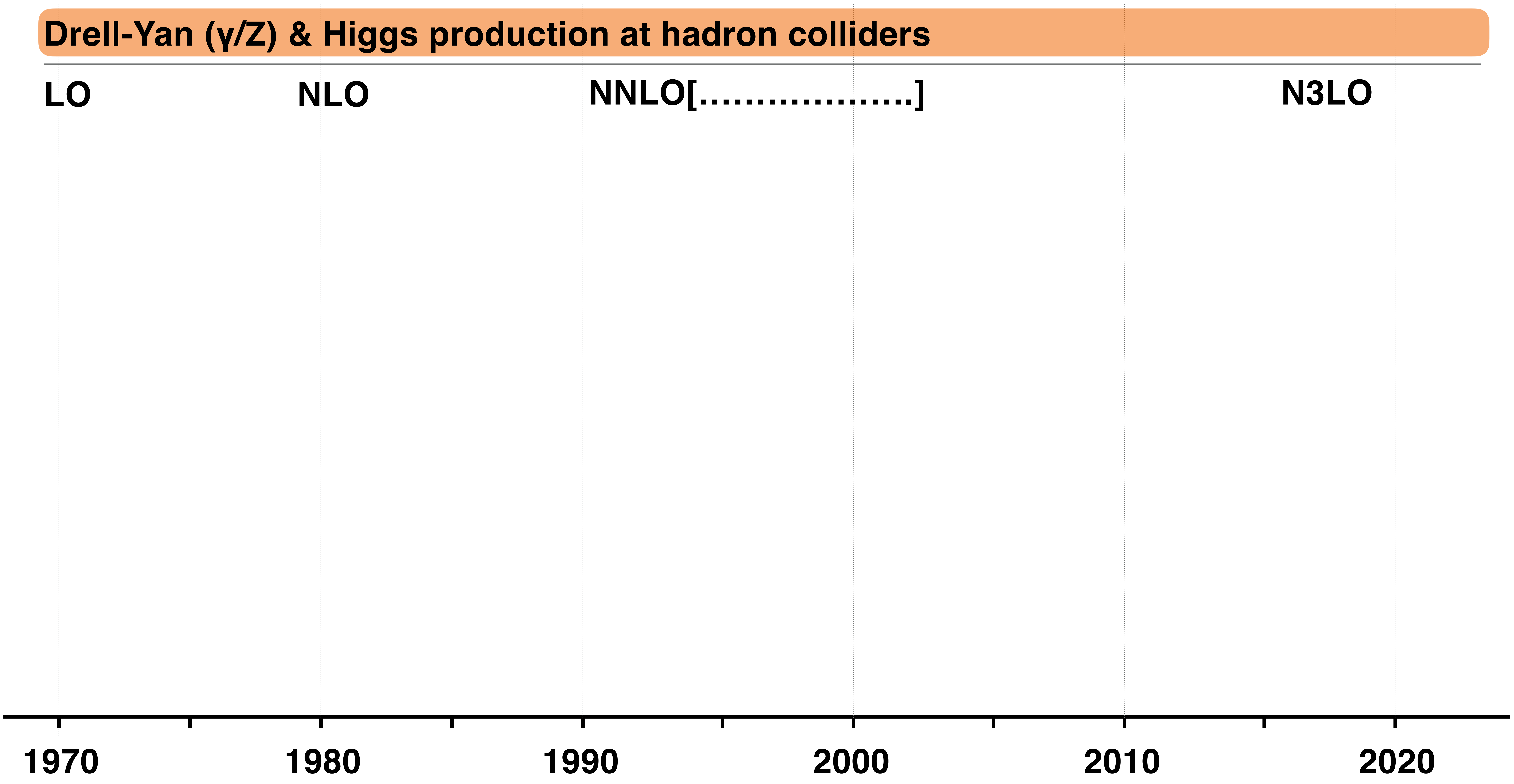


miracle of parton showers:

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



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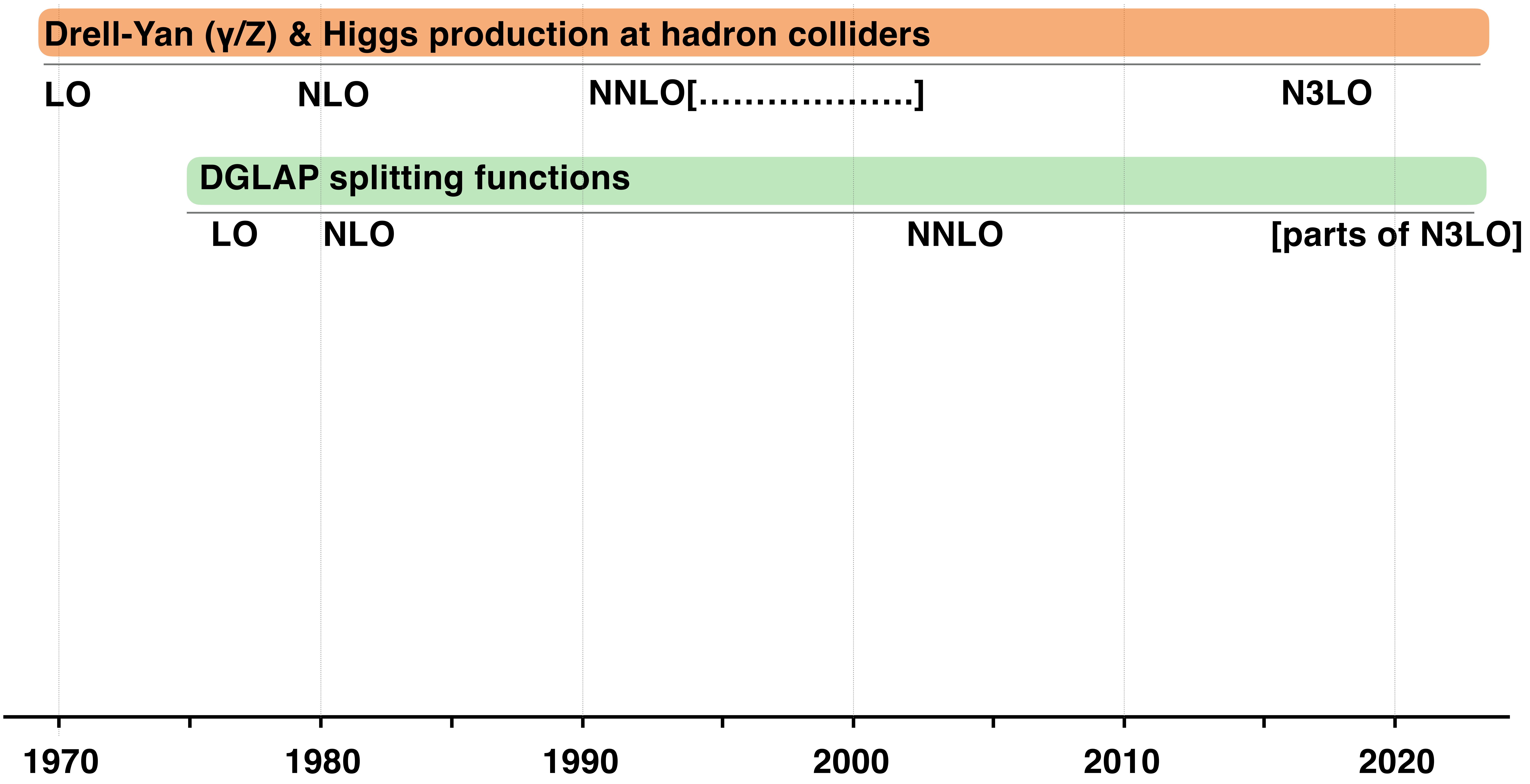

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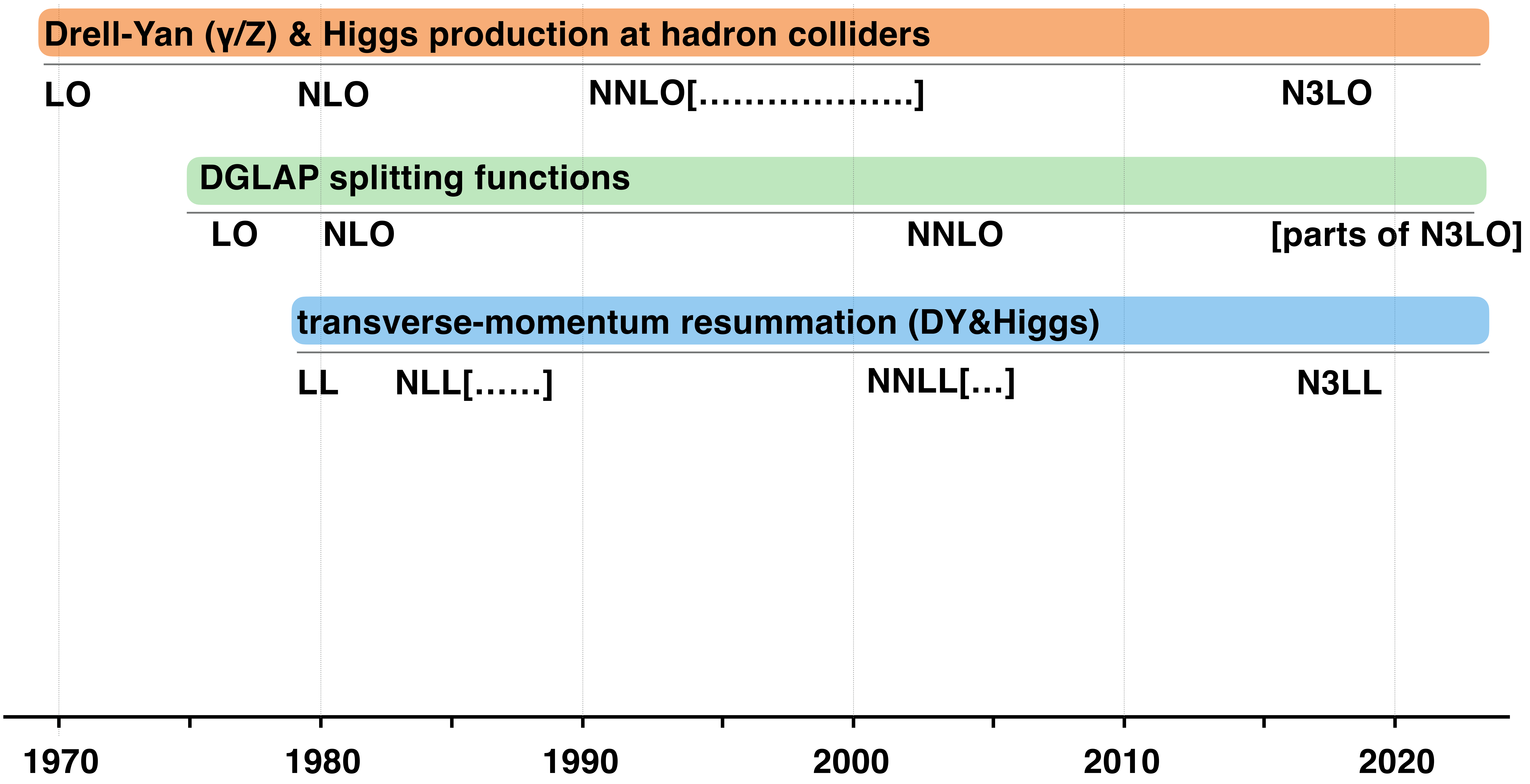

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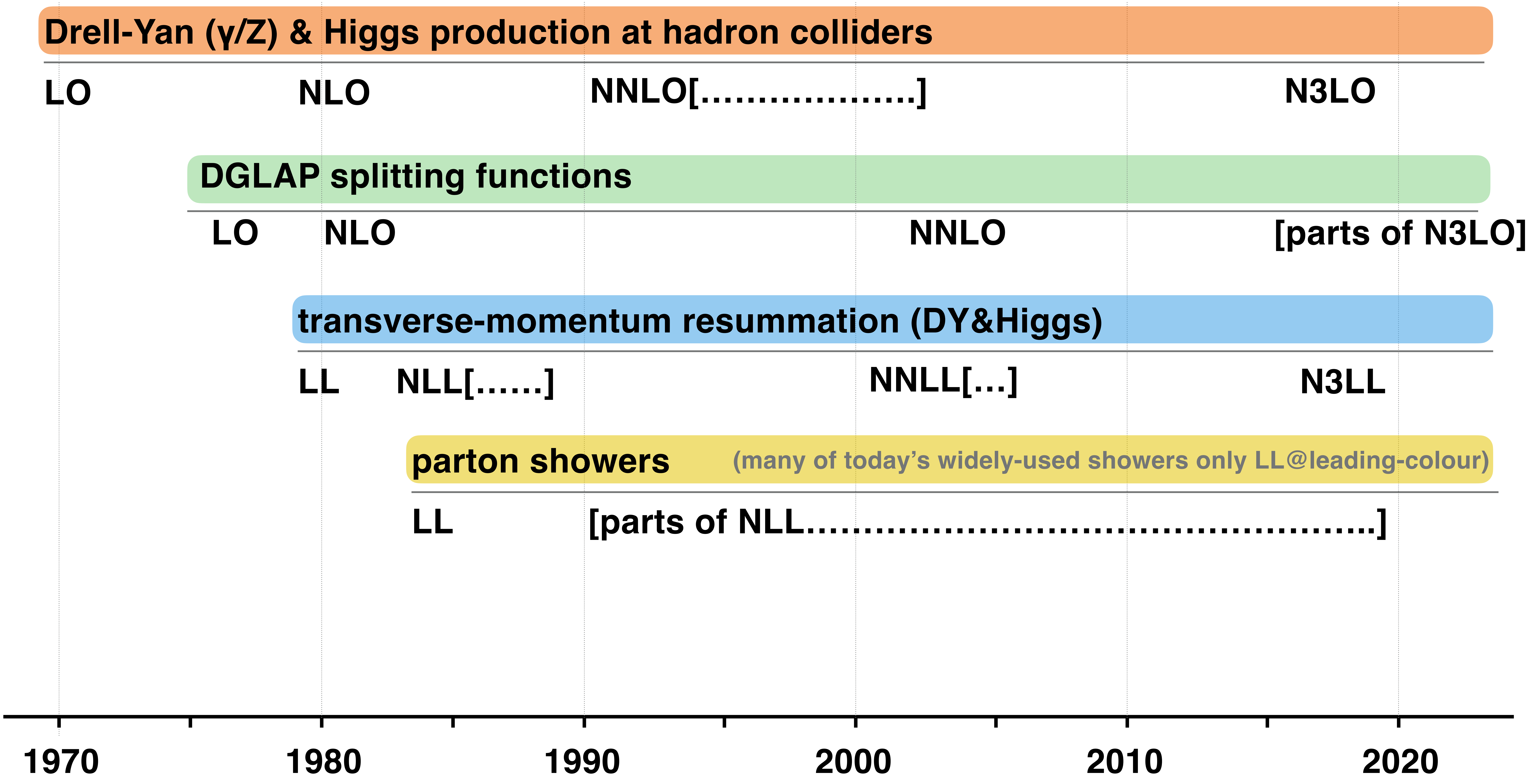

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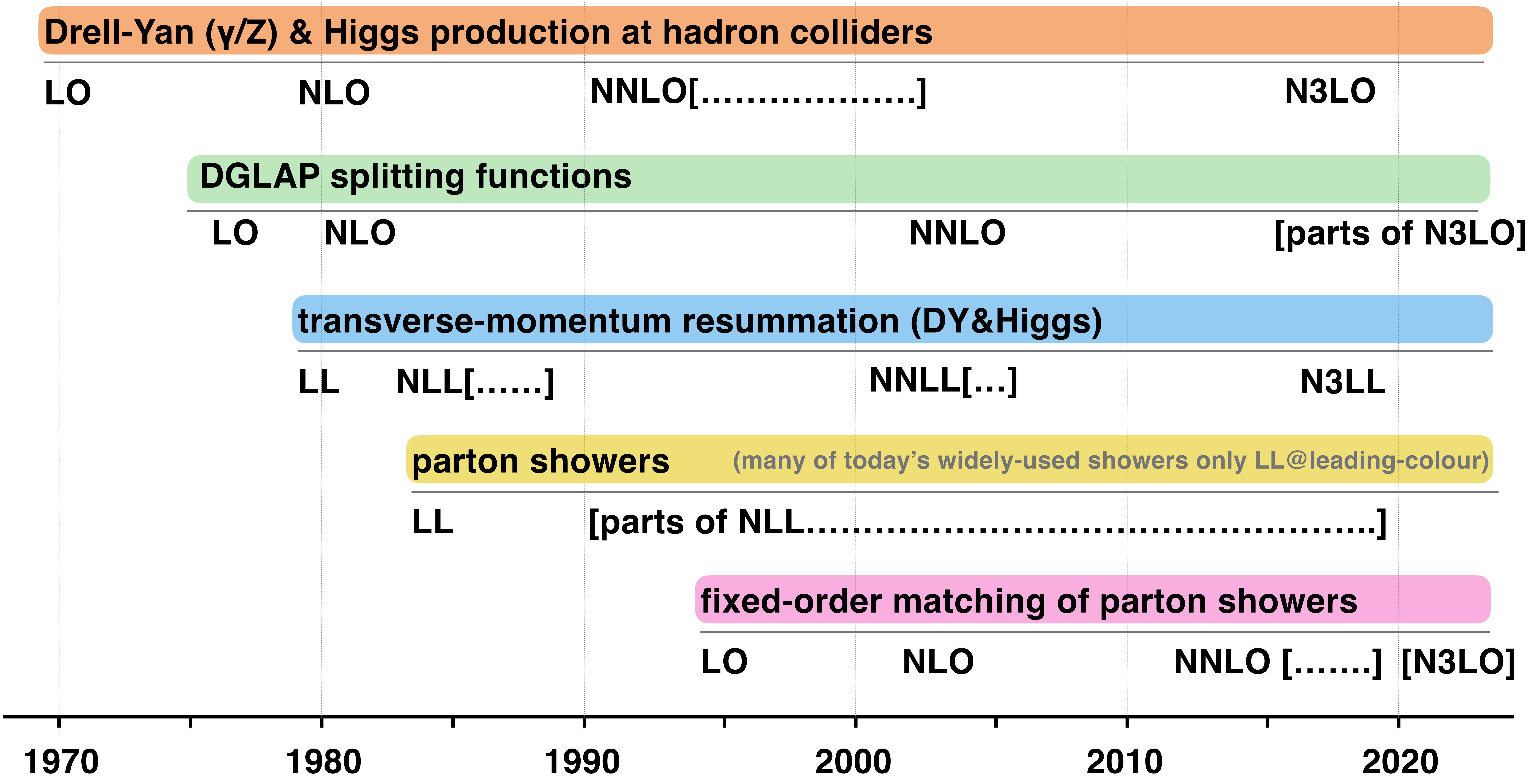

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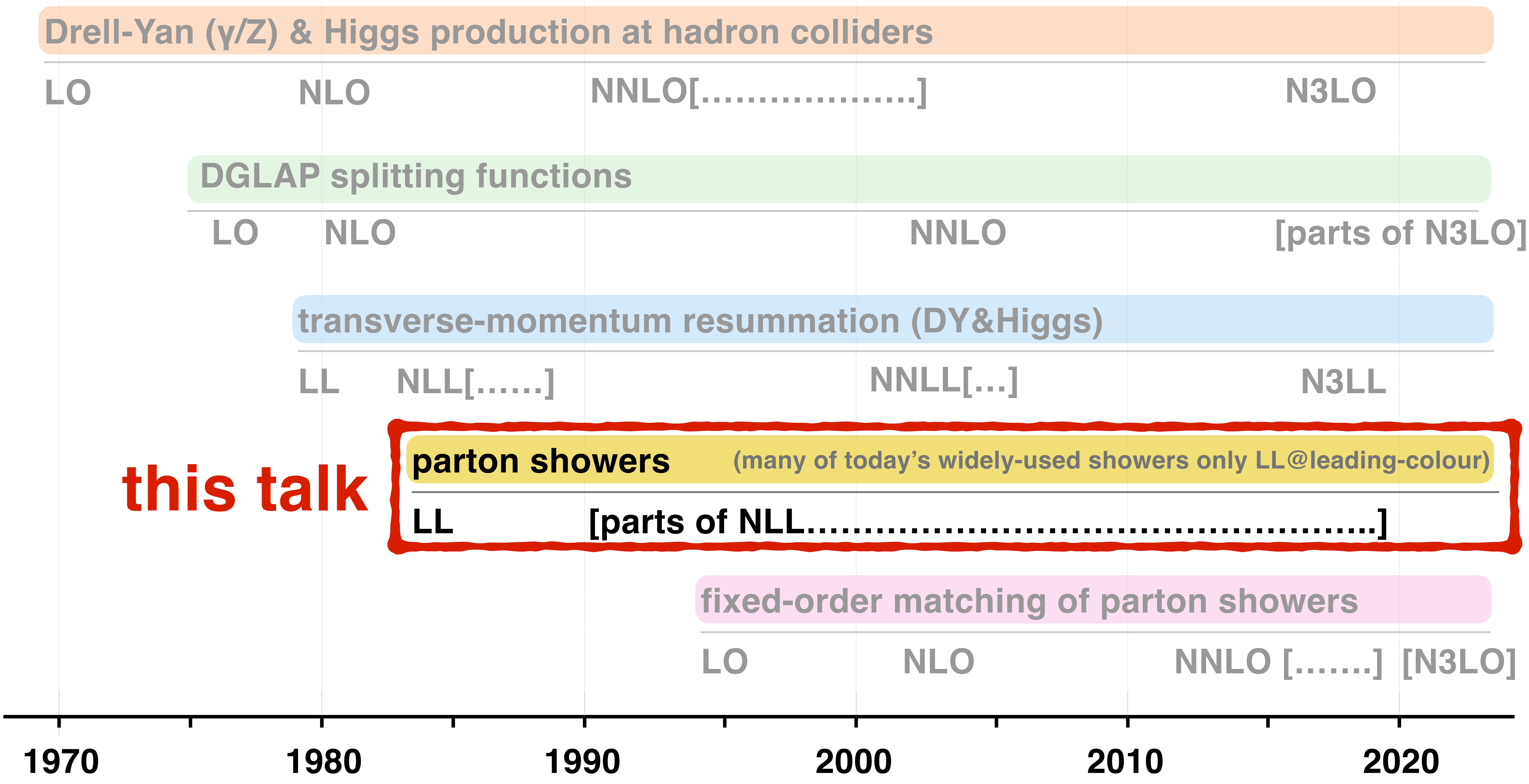
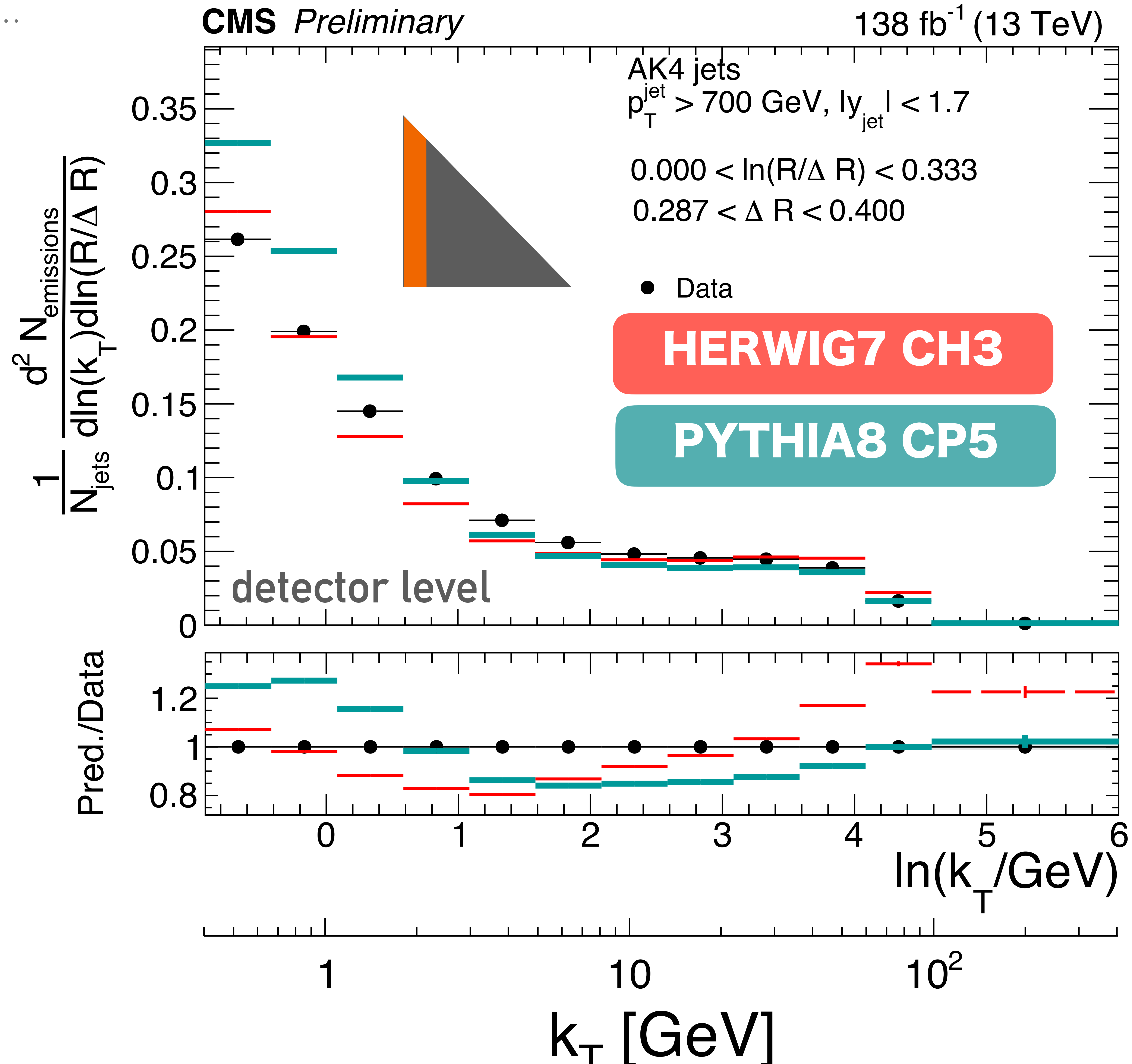


Are showers good enough?

- 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
(Negro & Rossini talks; also ATLAS & ALICE)



We want to design guaranteed NLL showers

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

A Matrix Element condition

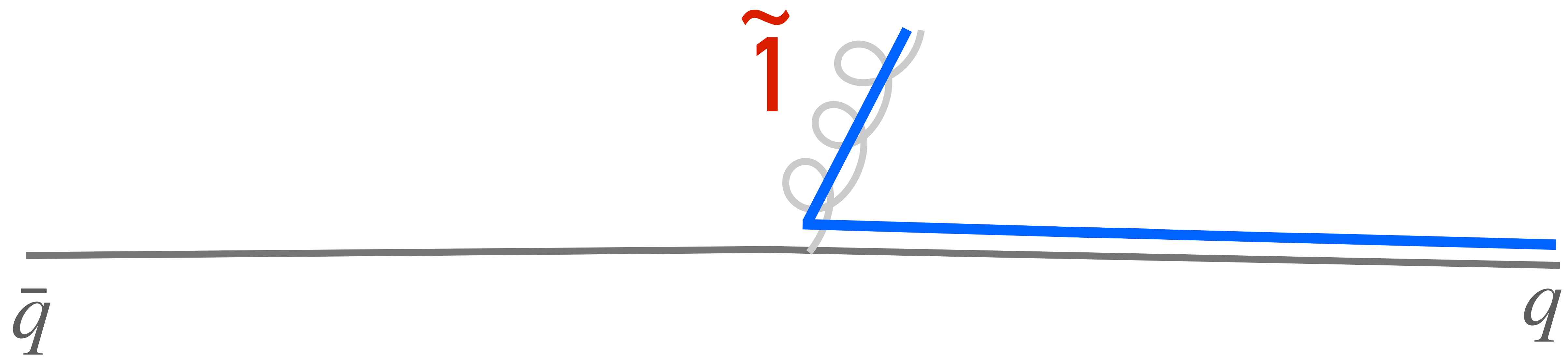
- correctly reproduce n-parton tree-level matrix element for arbitrary configurations, so long as all emissions well separated in the Lund diagram
- supplement with unitarity, 2-loop running coupling & cusp anomalous dimension

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:



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

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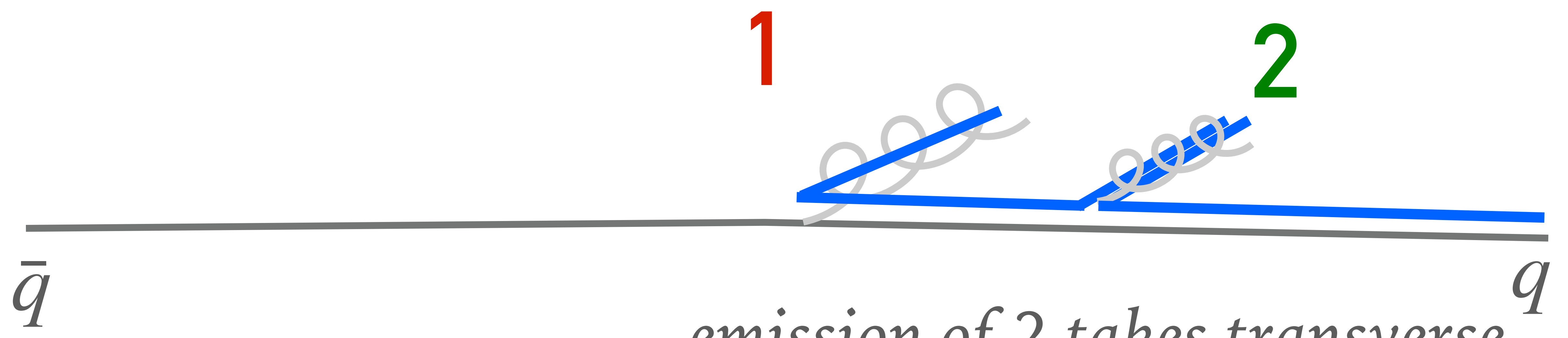

emission of 2 takes transverse recoil from 1

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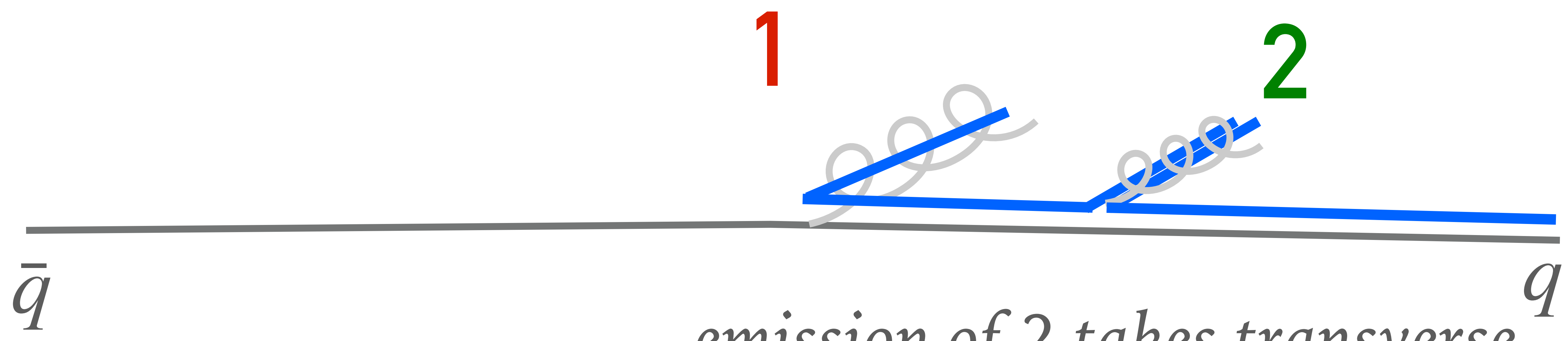
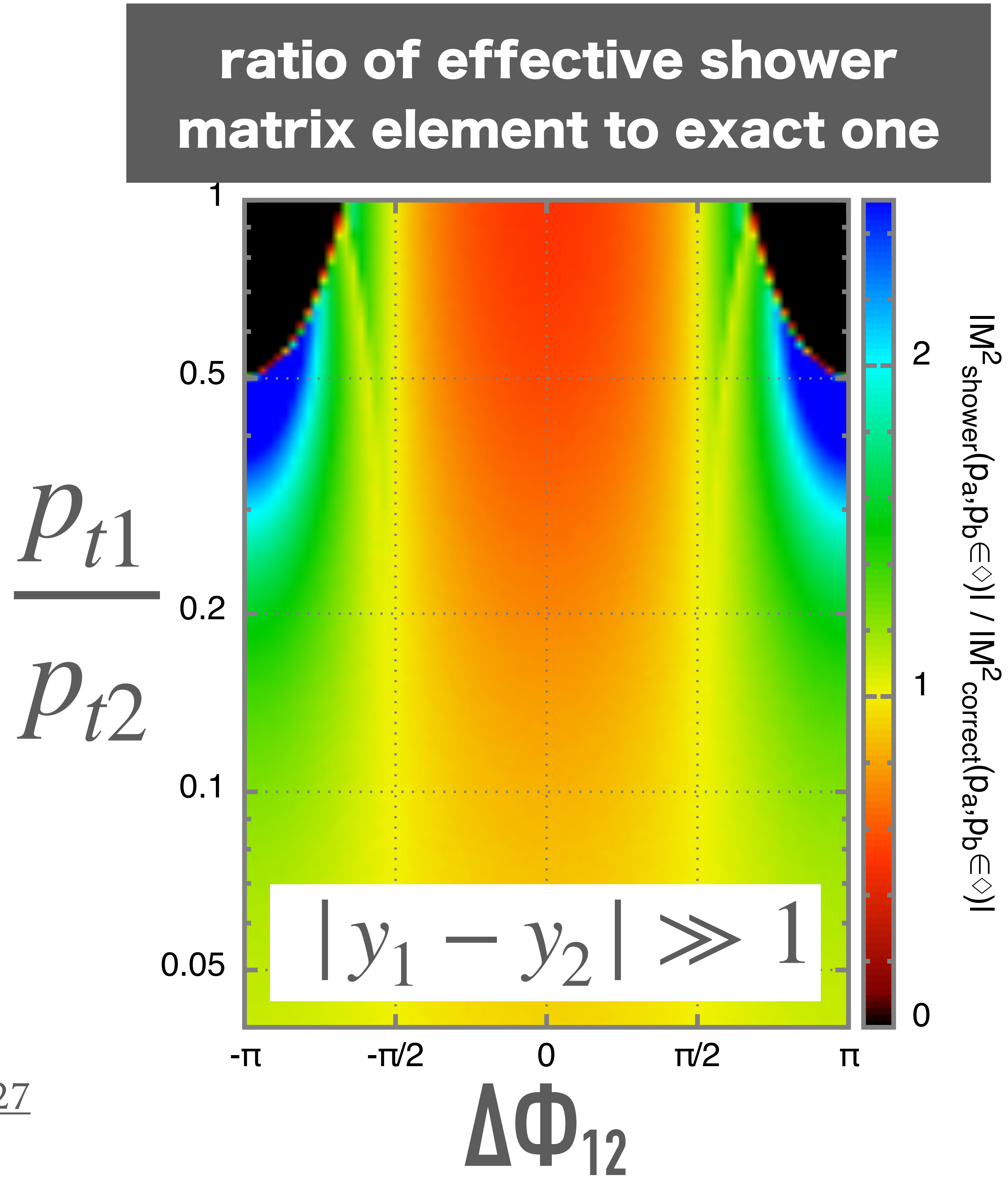


emission of 2 takes transverse recoil from 1

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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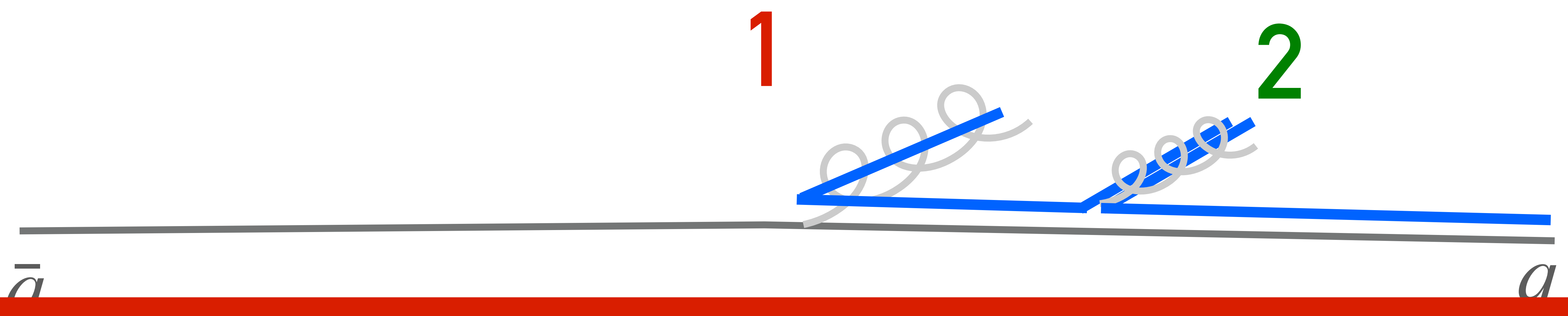


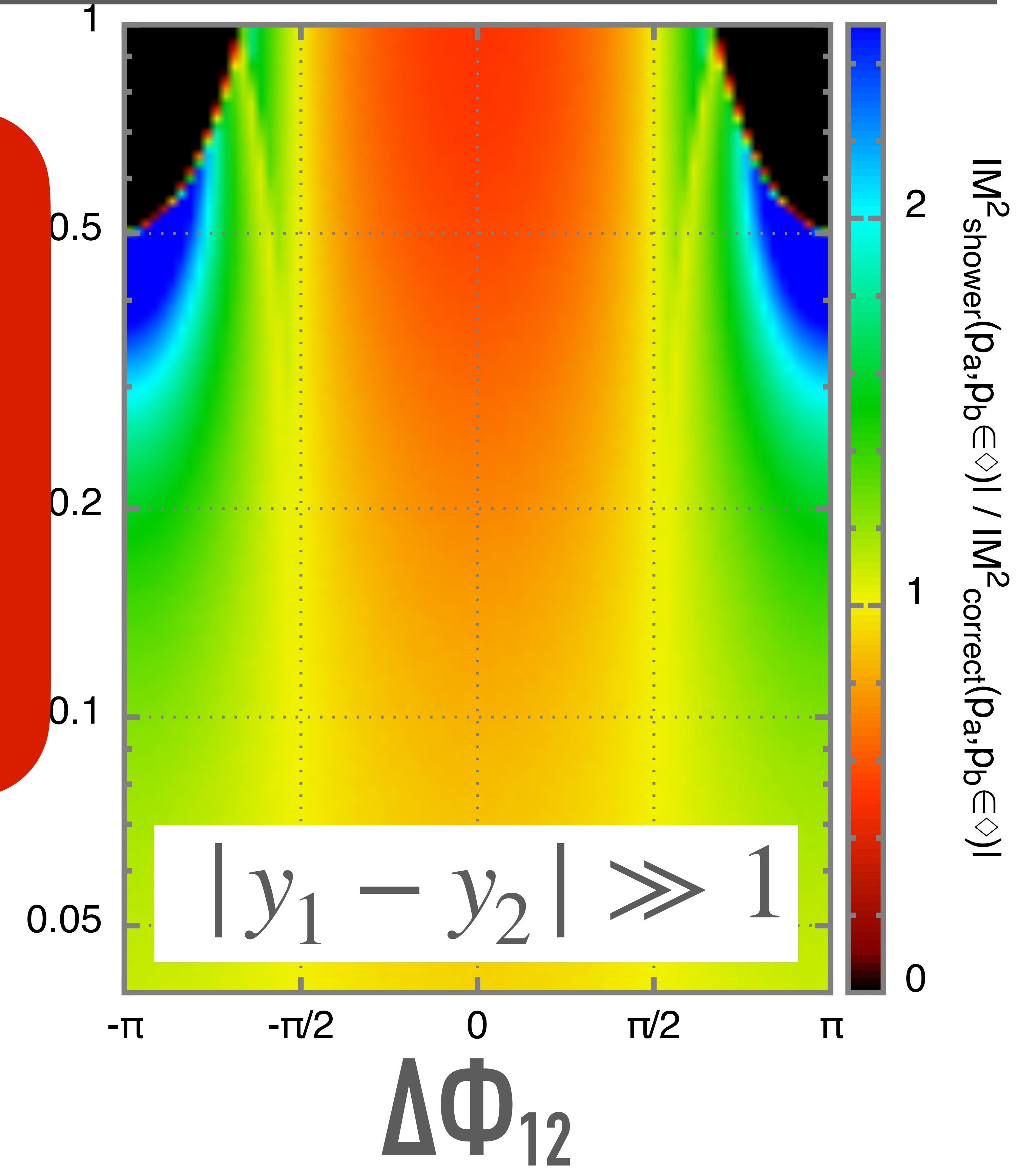
Sh
pa
fro

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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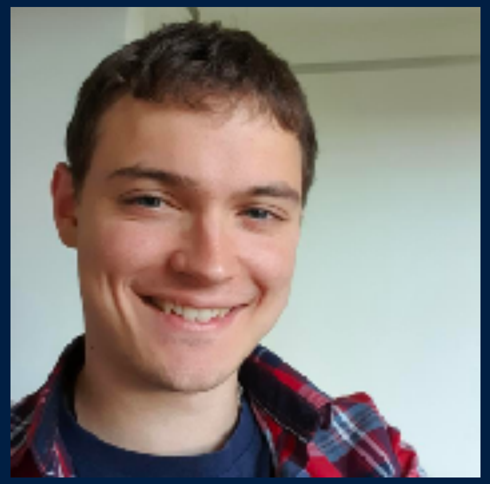
Oxford


Melissa van Beekveld


Jack Helliwell


Rok Medves


Frederic Dreyer


GPS


Ludo Scyboz

CERN


Mrinal Dasgupta


Gregory Soyez


Pier Monni


Alexander Karlberg


Alba Soto Ontoso


Silvia Ferrario Ravasio

UCL


Keith Hamilton


Rob Verheyen

Manchester

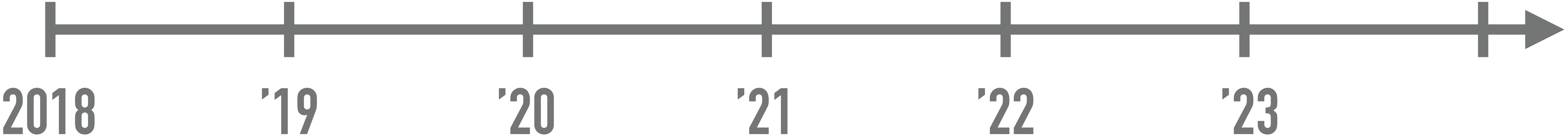

Basem El-Menoufi

PanScales

A project to bring logarithmic understanding and accuracy to parton showers

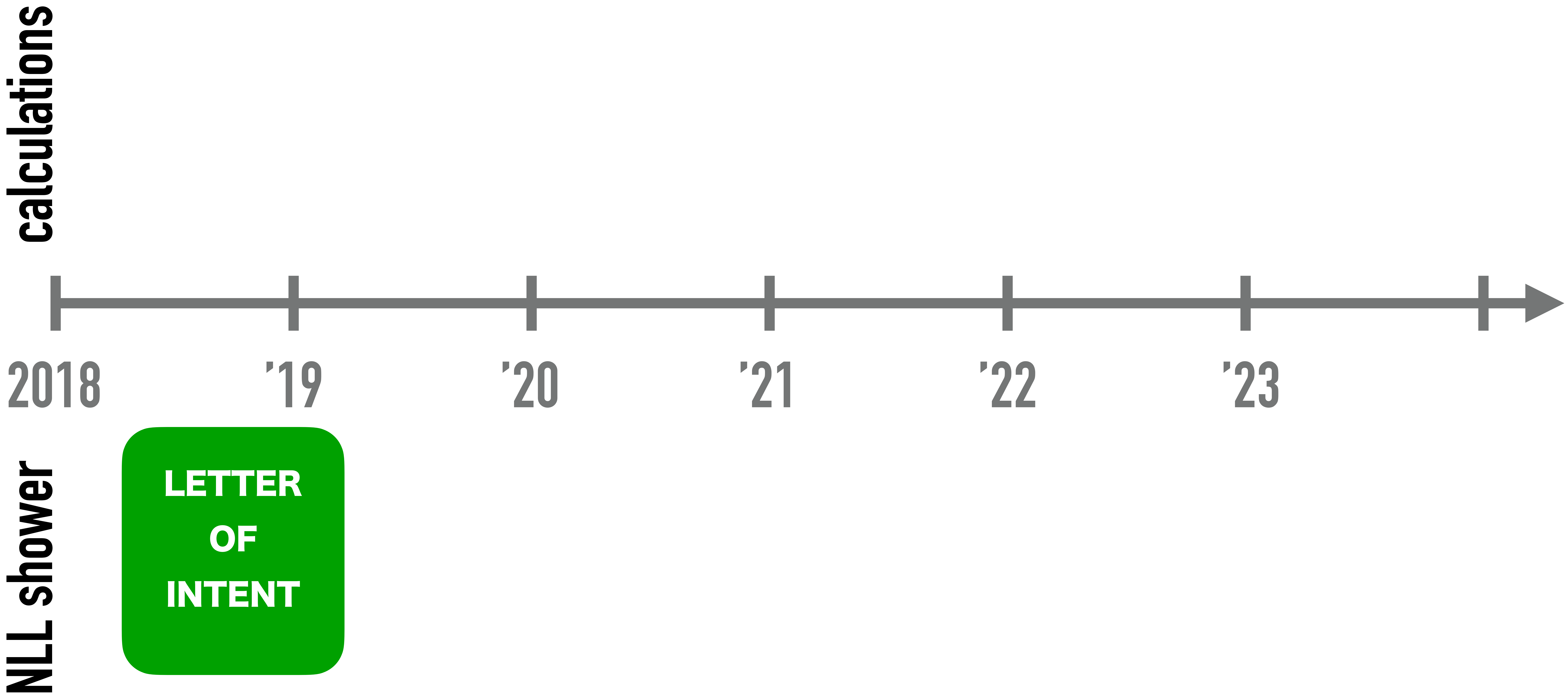
PanScales timeline

calculations

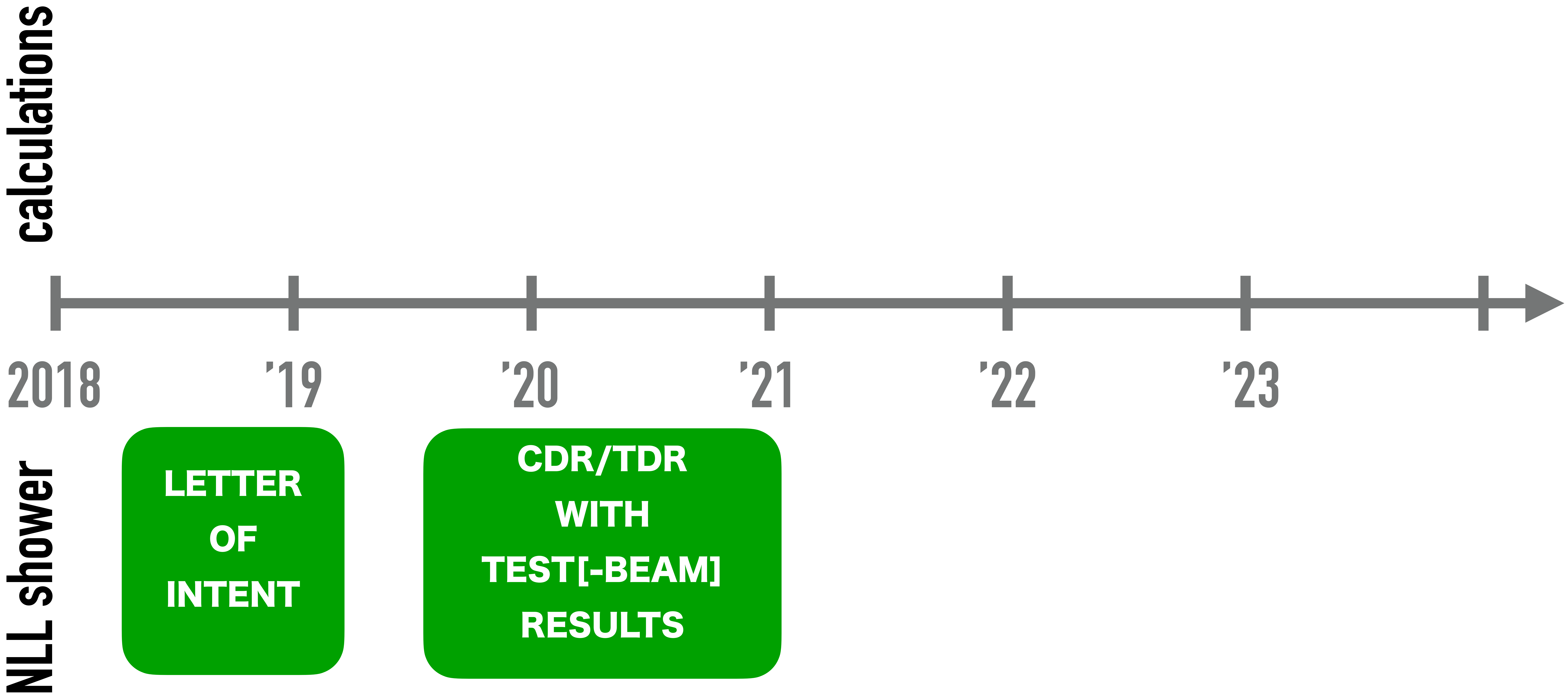


NLL shower

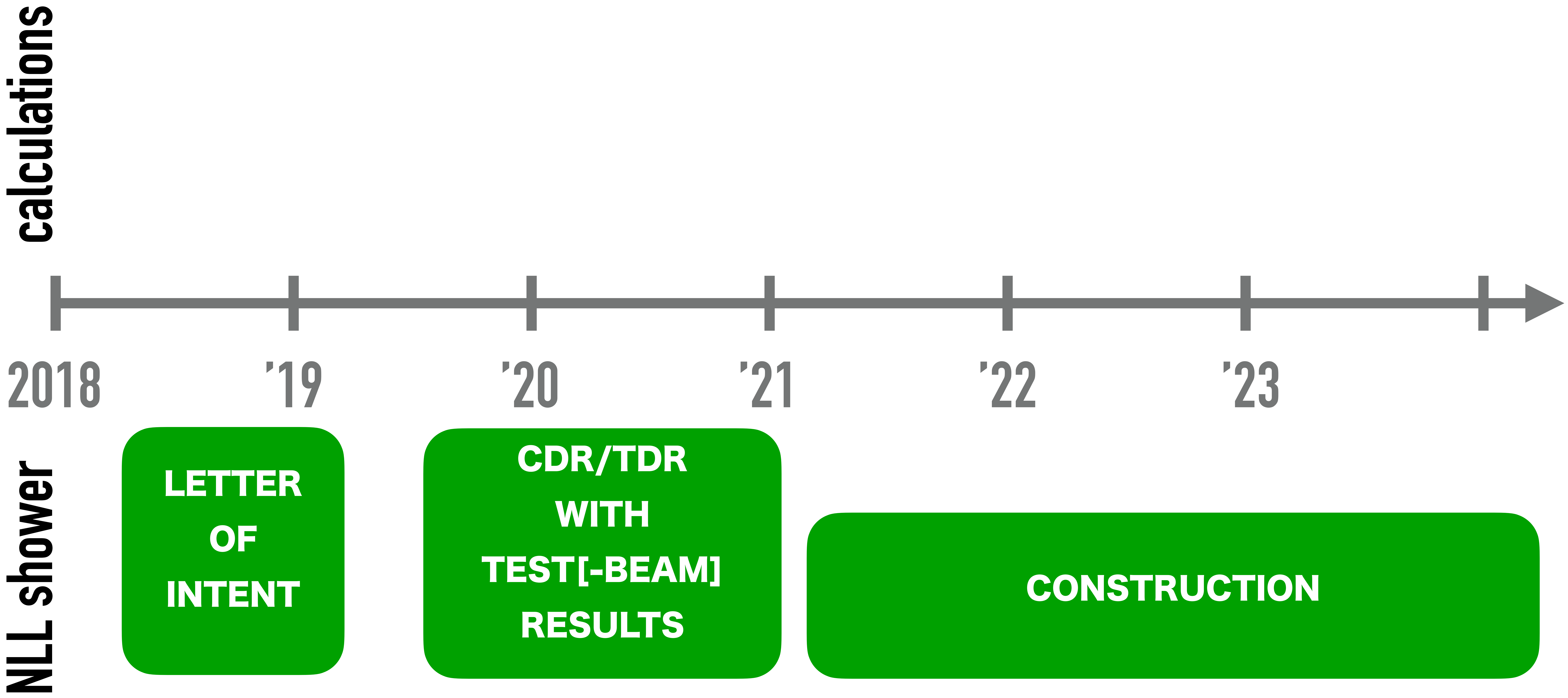
PanScales timeline



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

2018 '19 '20 '21 '22 '23

NLL shower

LETTER OF INTENT

CDR/TDR WITH TEST[-BEAM] RESULTS

CONSTRUCTION

COMMISSIONING

CONSTRUCTION

PanLocal

$k_t\sqrt{\theta}$ ordered

Recoil

⊥: local

+: local

–: local

Dipole partition

event CoM

PanGlobal

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

Recoil

⊥: global

+: local

–: local

Dipole partition

event CoM

Colour

nested ordered double soft (NODS)

Designed to ensure LL are full colour (also gets many NLL at full colour)

Spin

for correct azimuthal structure in collinear and soft→collinear

[Collins-Knowles extended to soft sector]

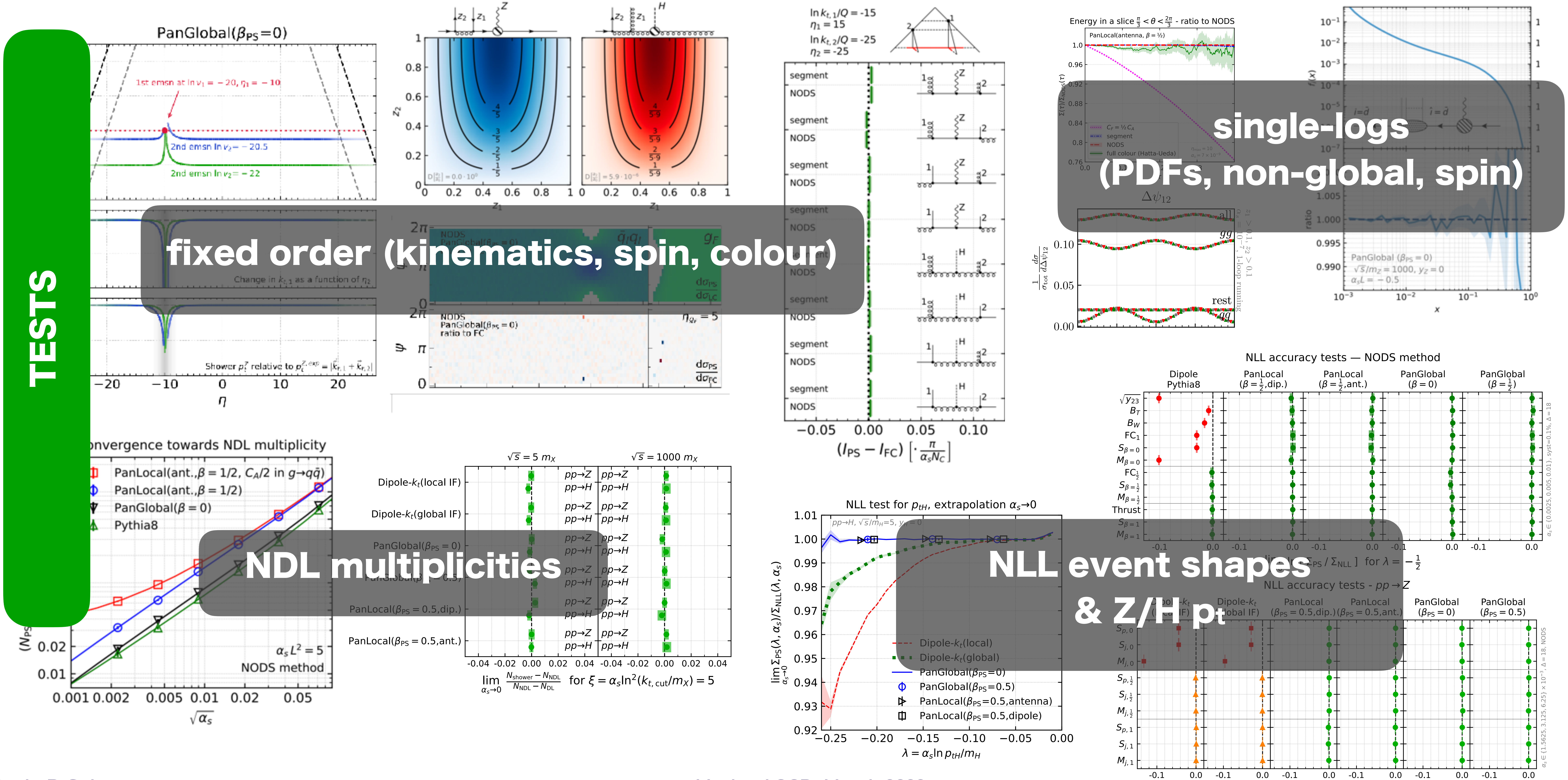
e^+e^-: Dasgupta, Dreyer, Hamilton, Monni, GPS & Soyez, 2002.11114; pp: van Beekveld, Ferrario Ravasio, GPS, Soto Ontoso, Soyez, Verheyen, 2205.02237; & pp tests, ibid + Hamilton: 2207.09467

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



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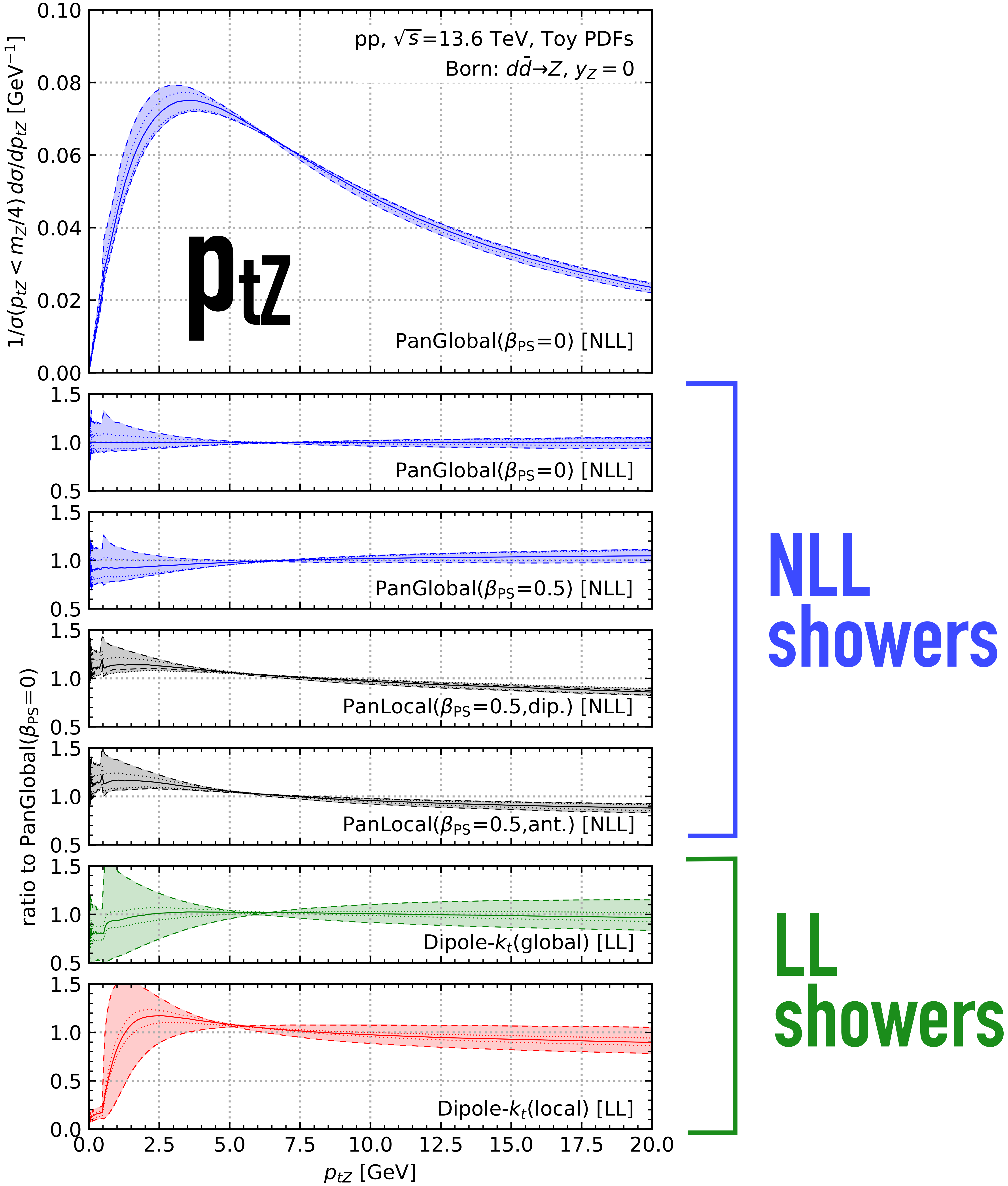


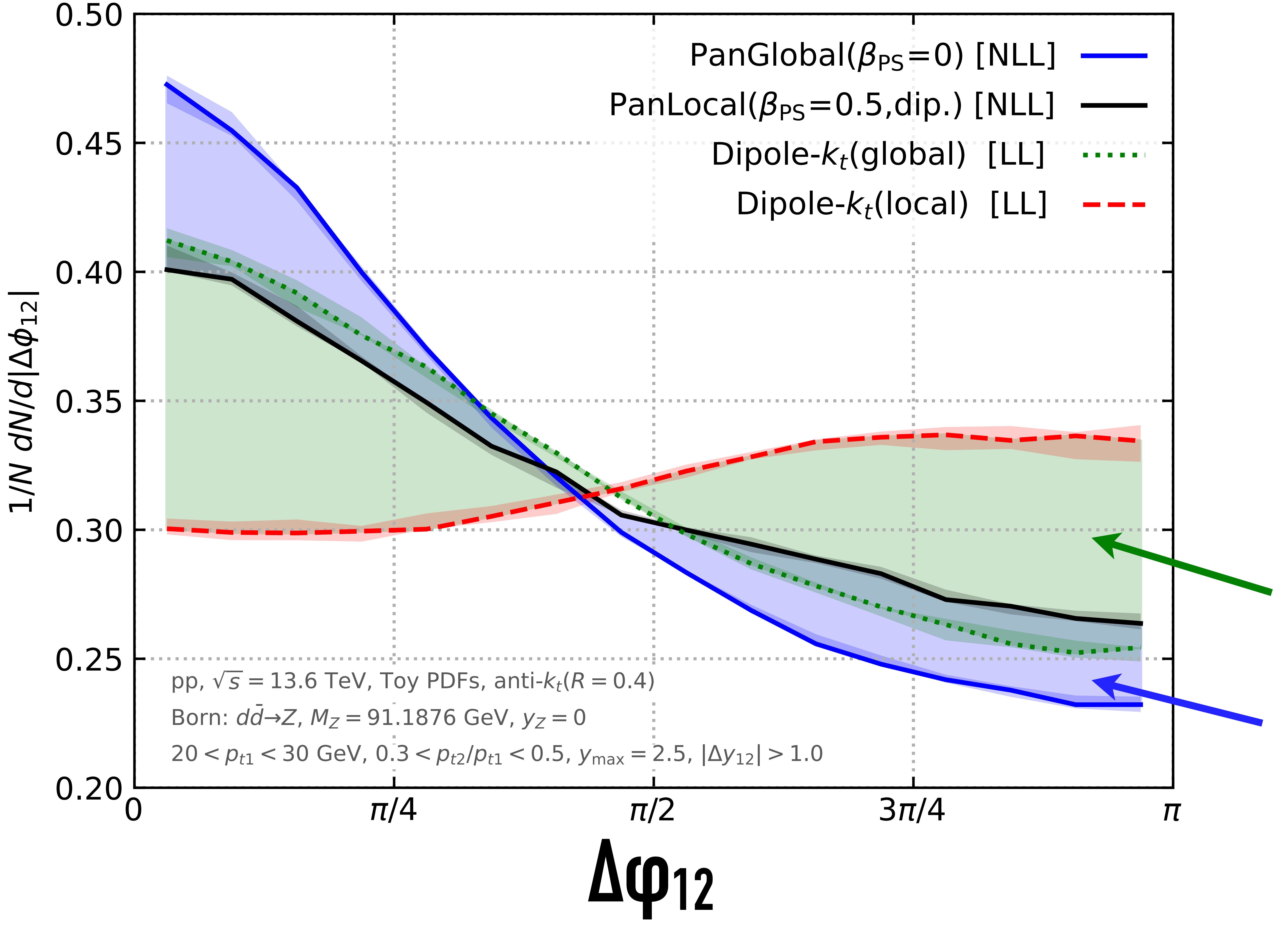
for inclusive quantities like p_{tZ}, advantage of NLL shower is partly in reduction of uncertainties

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

$m_{\ell\ell} = m_Z$

Azimuthal angle between leading jets (DY)

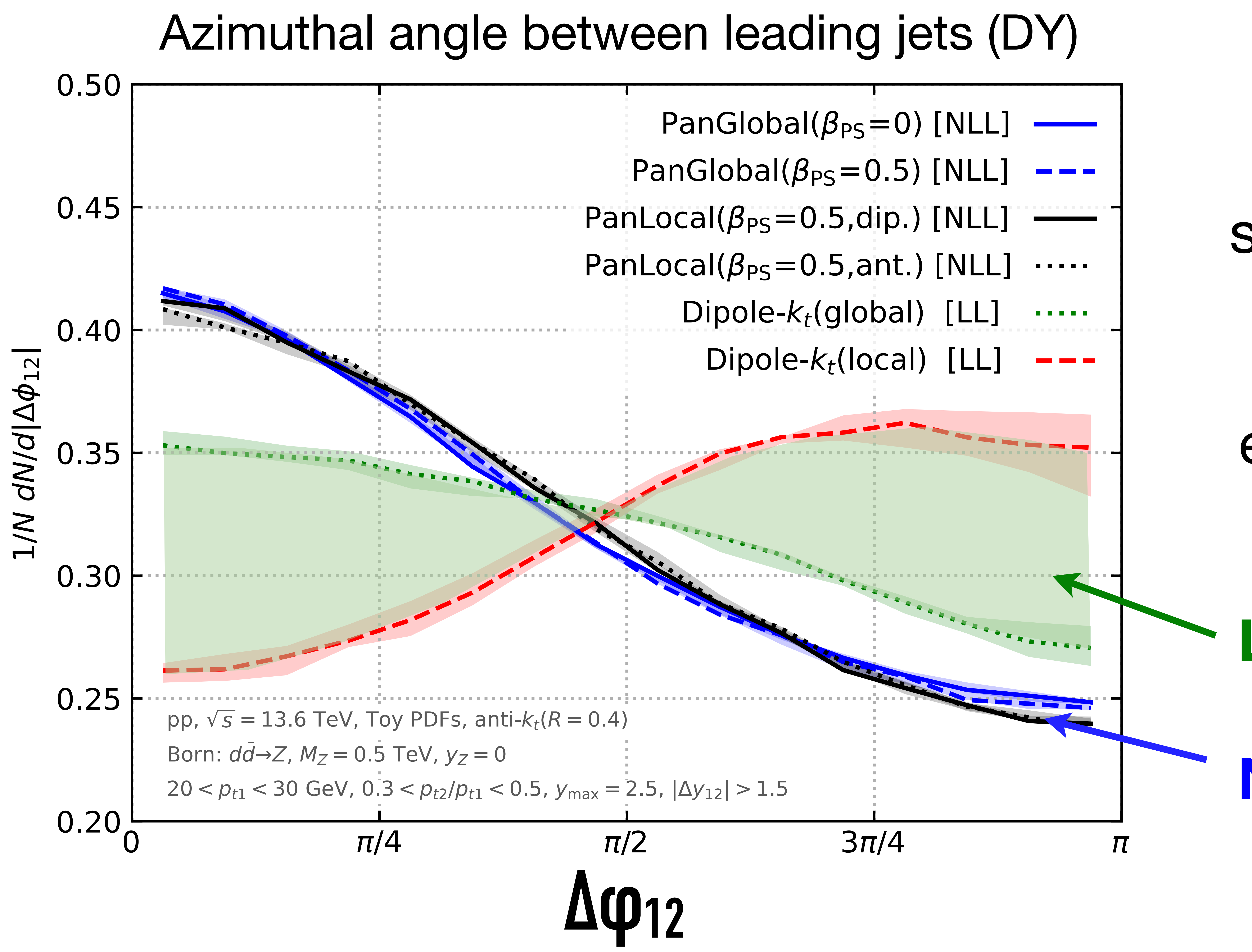
COMMISSIONING



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

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

especially at larger scales

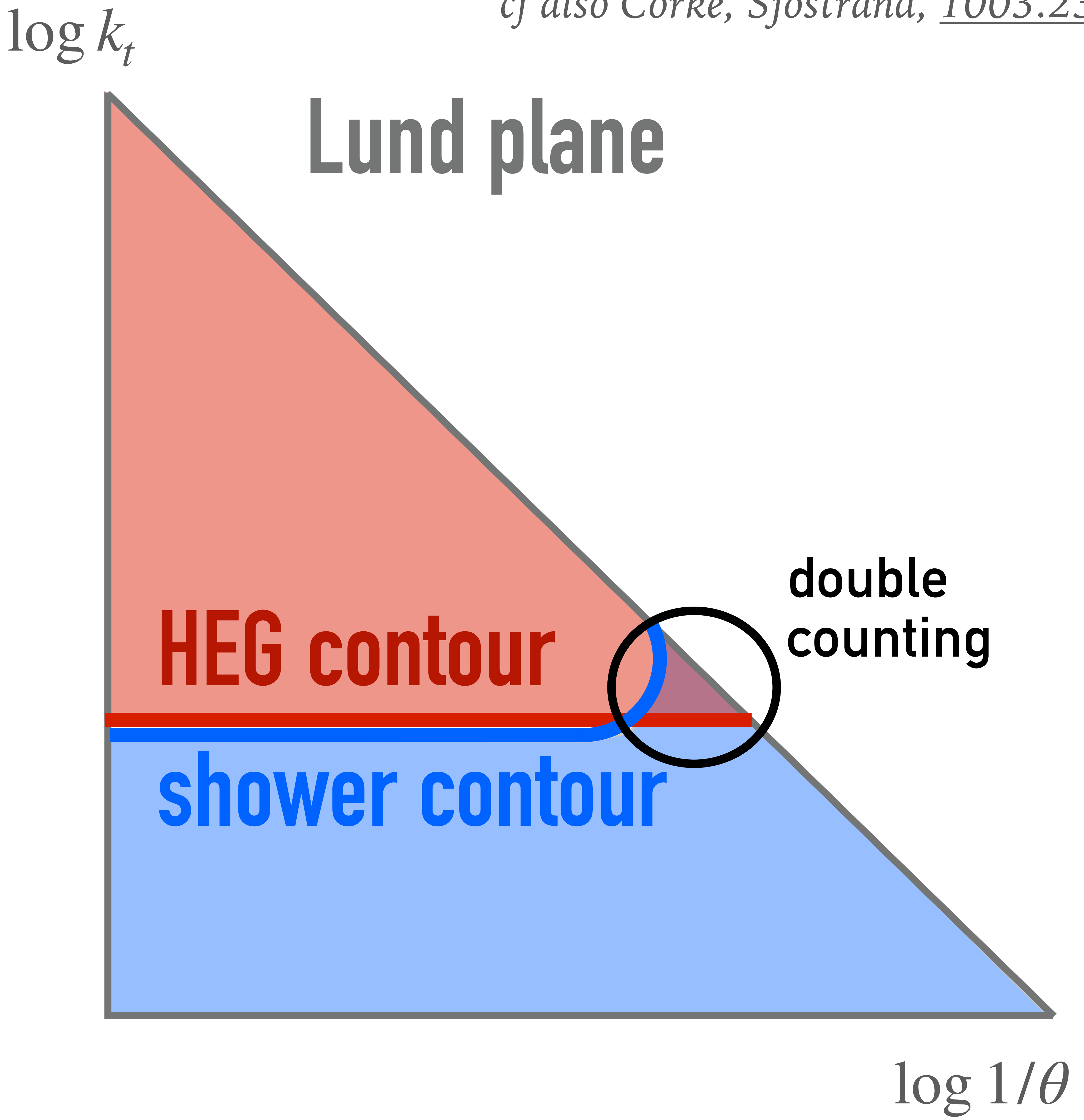
van Beekveld, Ferrario Ravasio, GPS, Soto Ontoso, Soyez, Verheyen, Hamilton: 2207.09467

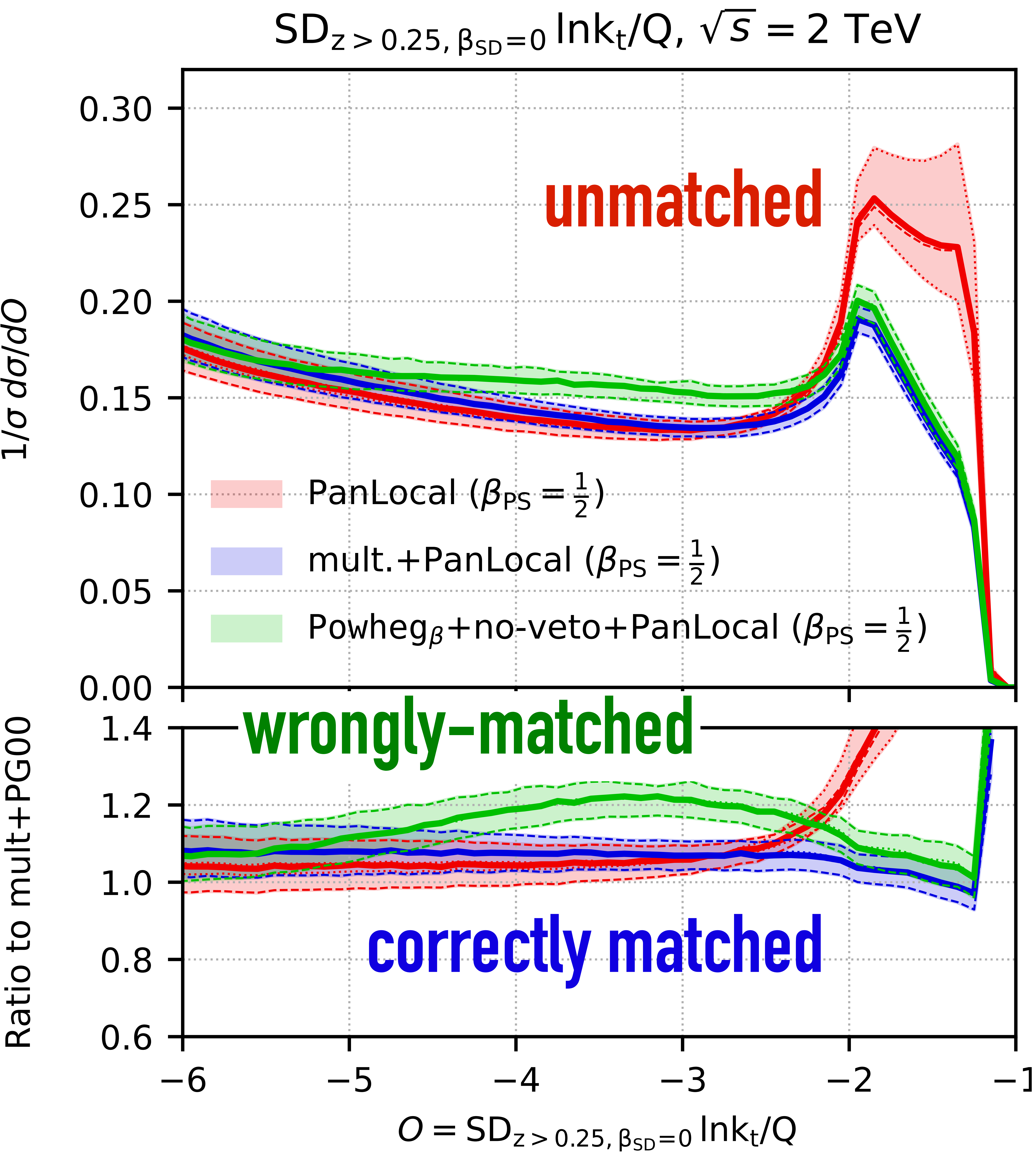
Logarithmic accuracy and NLO matching

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: **these seem straightforward**
- in other schemes, first emission is generated by an external program (POWHEG, MINNLO, Geneva, etc.): **these need more care**





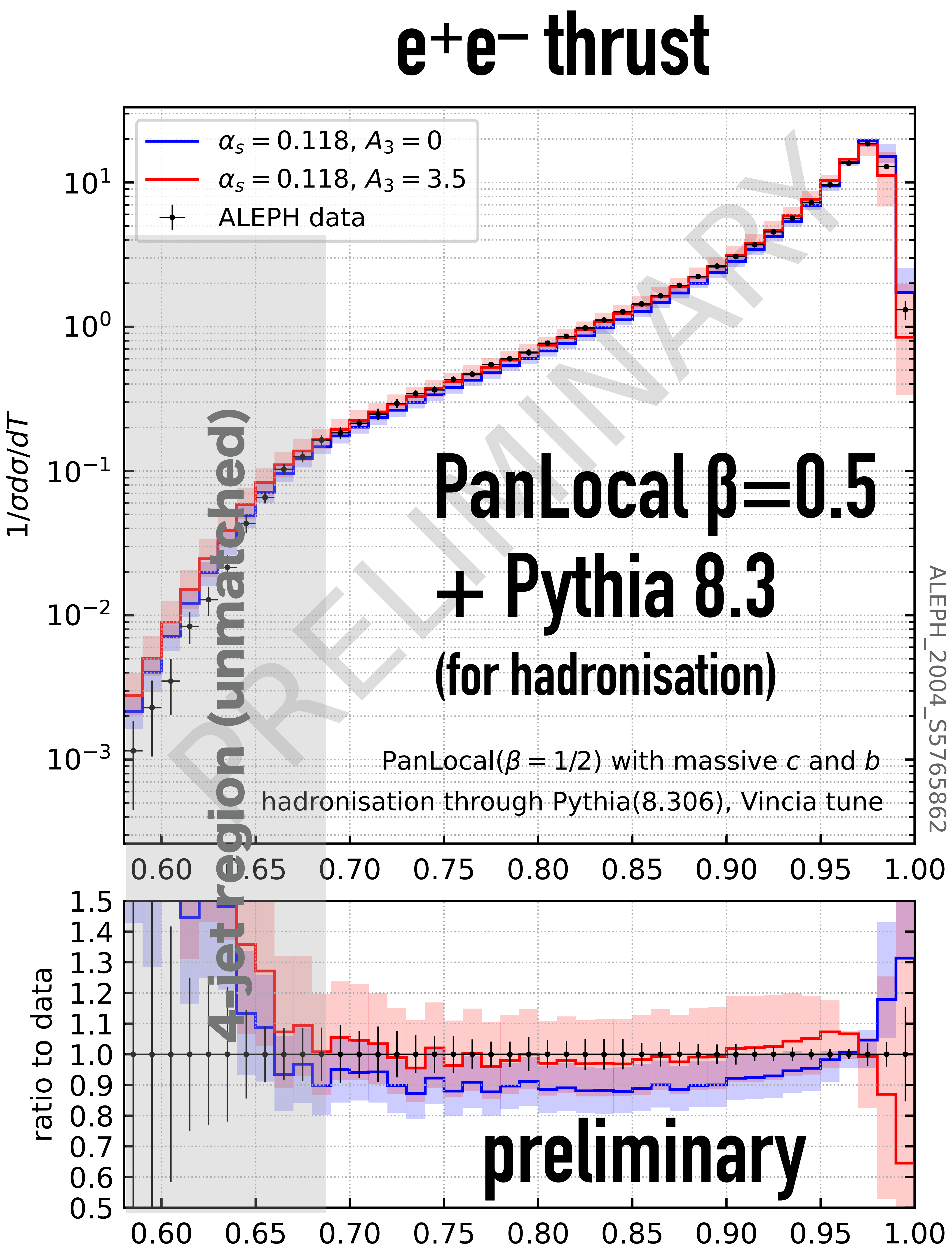
Hamilton, Karlberg, GPS, Scyboz, Verheyen, 2301.09645

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)

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

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.

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
  - NLL is foundation for yet higher accuracies
- **Matching is one of the next frontiers**
  - first results with NLO $e^+e^- \to 2\,\mathrm{jets}$
  - for realistic applications we also need massive quarks and tuning
- **We're on the path towards public code**
  - exact timeline still fuzzy!

backup

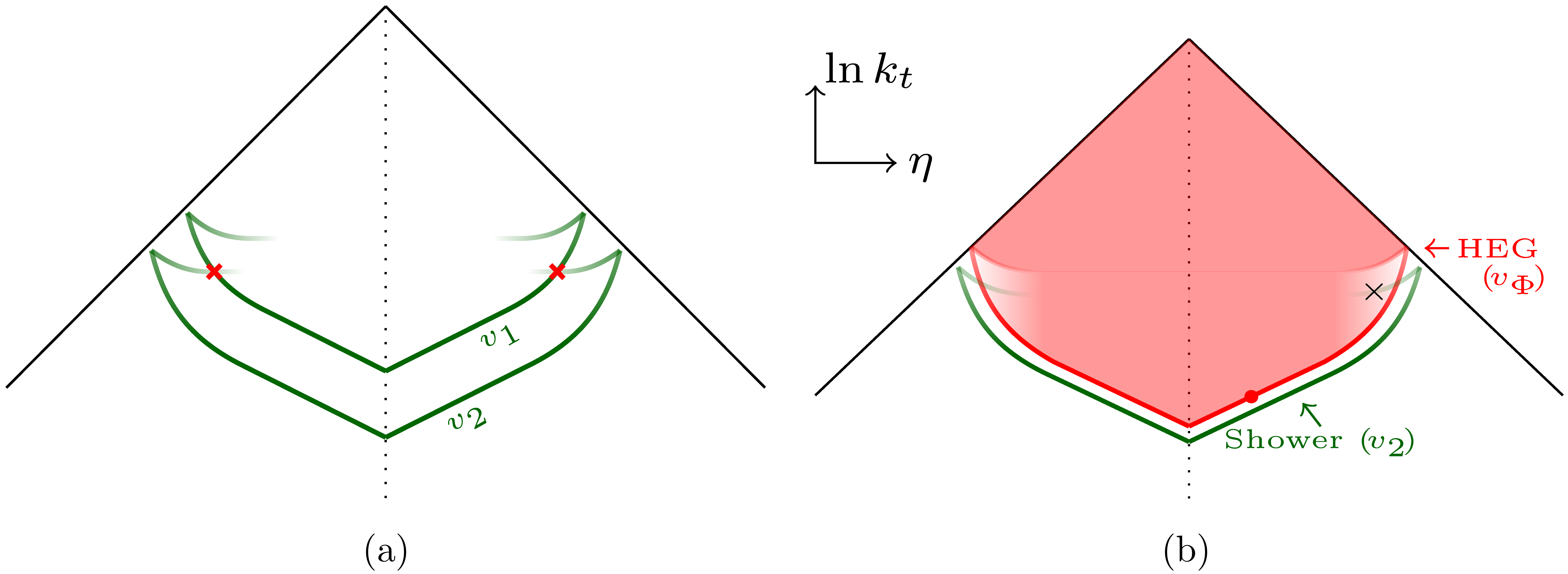
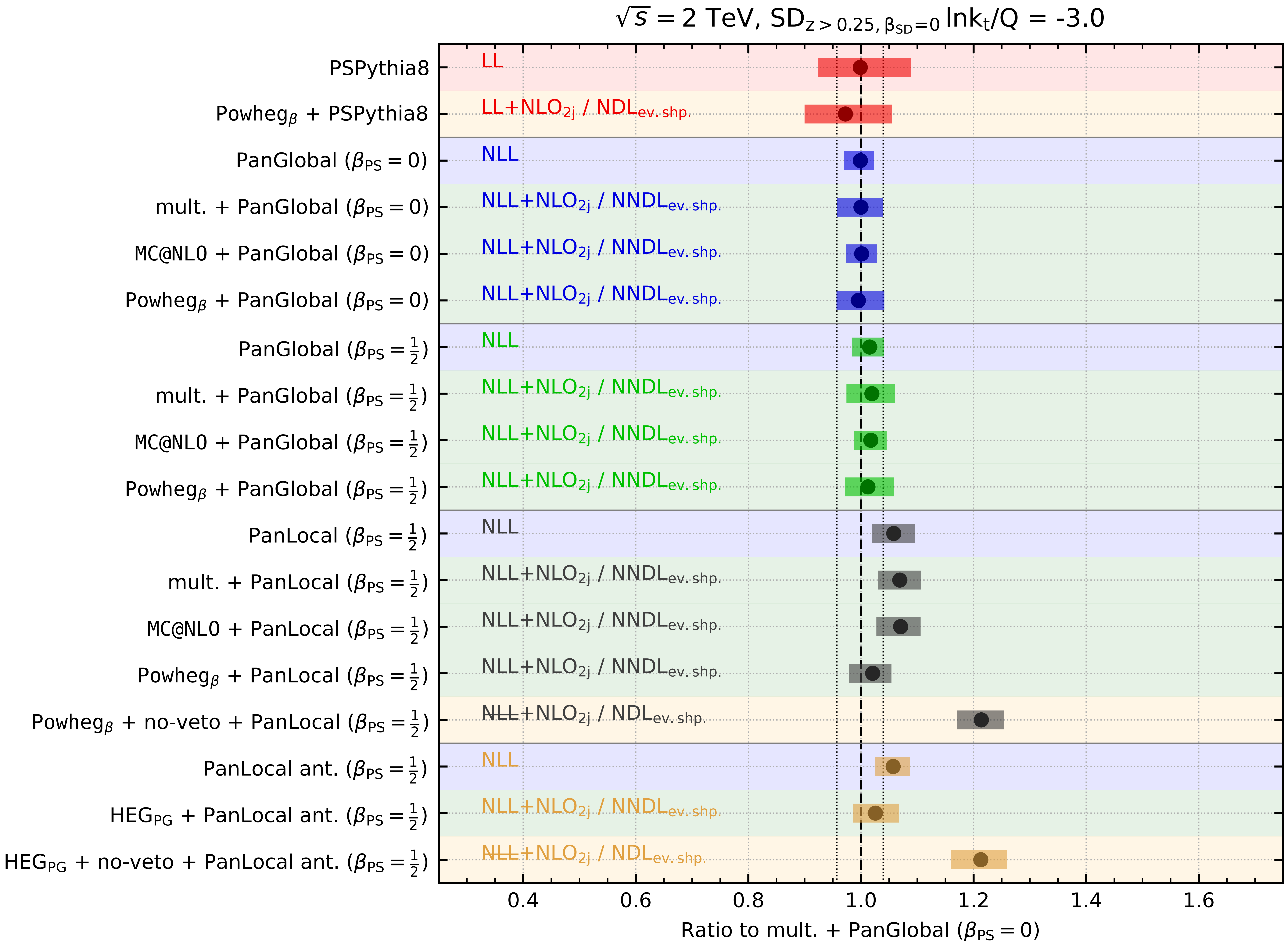


Figure 2: Schematic illustration of the issue associated with gluon asymmetrisation. (a) Contours on the Lund plane, in the PanLocal family of showers, highlighting the fact that a given physical point X in the Lund plane (highlighted with a red cross) can come from two different values of v. The shading 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.


√s = 2 TeV, SD$_{z>0.25,\beta_{SD}=0}$ lnk$_t$/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 ($\beta_{PS}=\frac{1}{2}$)
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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$_{ev. shp.}$
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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

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

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