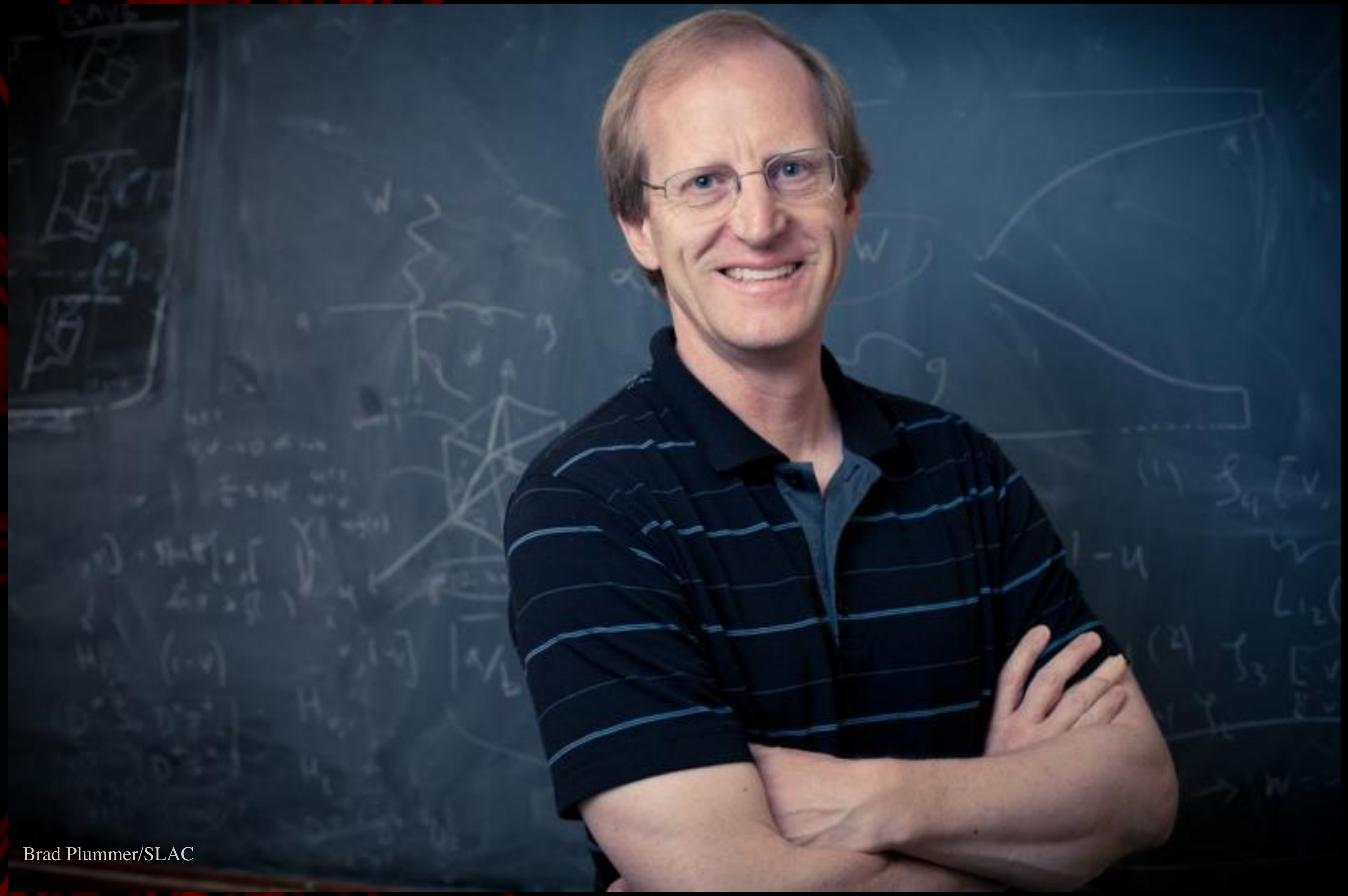
Making perturbative QFT physical

Lancefest
24 June 2026
Higgs Centre, Edinburgh



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

UNIVERSITY OF OXFORD

Science and Technology Facilities Council

THE ROYAL SOCIETY

The promise of perturbative QFT

Follow the rules (Feynman diagrams)

Ask a computer to work through maths

Out comes a prediction

Ask the computer to draw more diagrams, work harder, and you get more accuracy

Does it live up to the promise? [#1]

incredibly powerful, e.g. differential scattering cross-sections from first few orders of perturbative expansion in the strong coupling α_s

$$\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \cdots$$

NLO

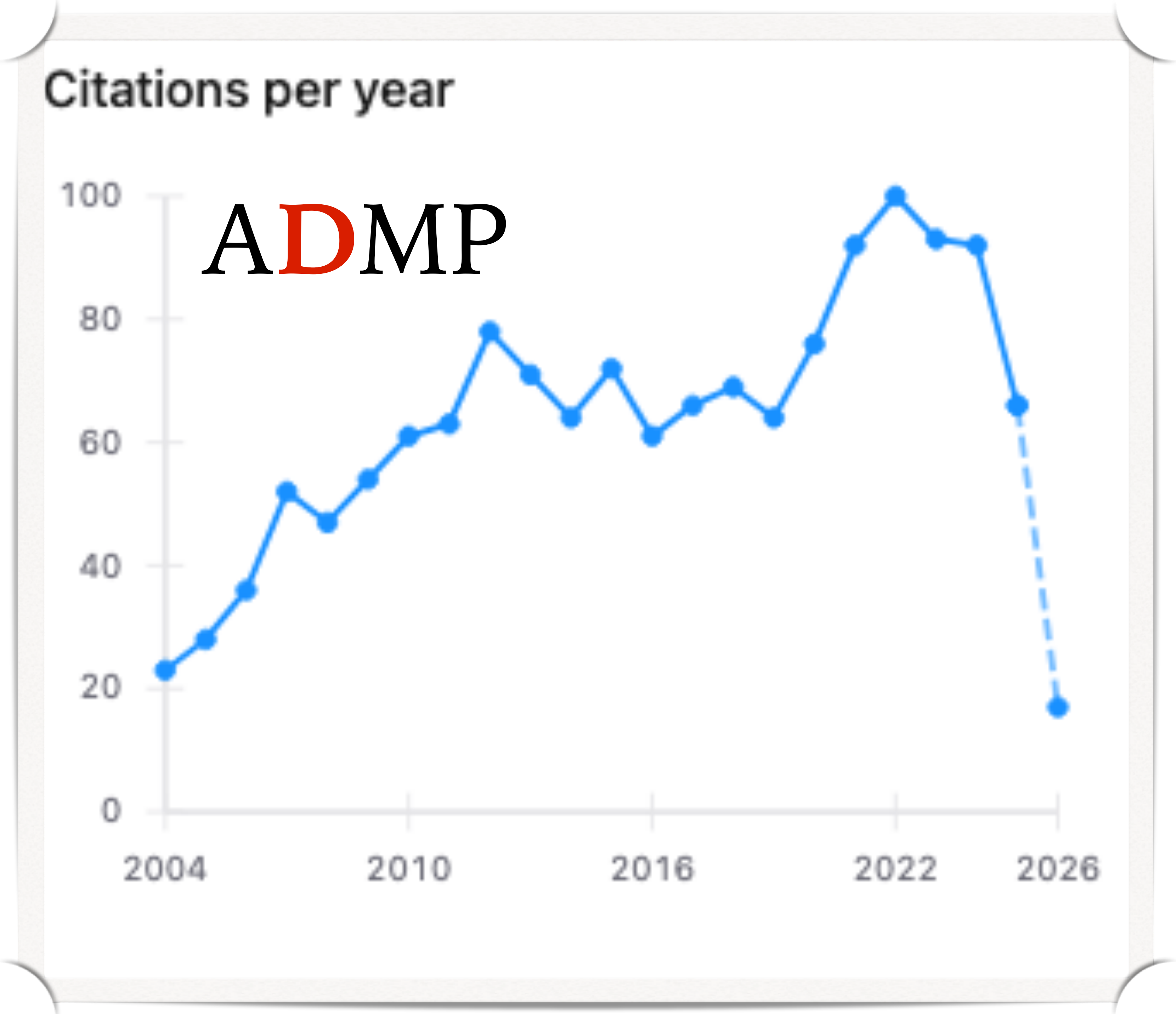
→ e.g. BDDK hep-ph/9403226
BDK hep-ph/9708239
BlackHat, 0803.4180

→ Solution of the 1-loop problem

Does it live up to the promise? [#1]

incredibly powerful, e.g. differential scattering cross-sections from first few orders of perturbative expansion in the strong coupling α_s

$$\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \cdots$$



NLO NNLO

NNLO → e.g. ADMP hep-ph/0312266

NLO → e.g. BDDK hep-ph/9403226
BDK hep-ph/9708239
BlackHat, 0803.4180

→ Solution of the 1-loop problem

Does it live up to the promise? [#1]

incredibly powerful, e.g. differential scattering cross-sections from first few orders of perturbative expansion in the strong coupling α_s

$$\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \cdots$$

Eight loop form factors, amplitudes and patterns in planar $\mathcal{N} = 4$ super-Yang-Mills theory

Lance J. Dixon[a,*] **and Zhenjie Li**[a]
[a] *SLAC National Accelerator Laboratory, Stanford, CA 94309, USA*
E-mail: lance@slac.stanford.edu, munuxilee@gmail.com

The simplest nontrivial amplitude in planar $\mathcal{N} = 4$ super-Yang-Mills theory is six-gluon scattering in the maximally-helicity-violating configuration. It has been computed to 8 loops with the help of antipodal duality, which relates it to the three-point form factor of a protected operator, the chiral stress tensor super-multiplet, represented also as $\mathrm{tr}\phi^2$. In this talk, we describe the computation to 8 loops of another three-point form factor, for the operator $\mathrm{tr}\phi^3$. This form factor lives in the same restricted space of polylogarithms as the $\mathrm{tr}\phi^2$ form factor. We also report on all-order patterns for sequences of coefficients in the symbols of these polylogarithmic results, for the leading discontinuity of the $\mathrm{tr}\phi^3$ form factor.

NLO NNLO

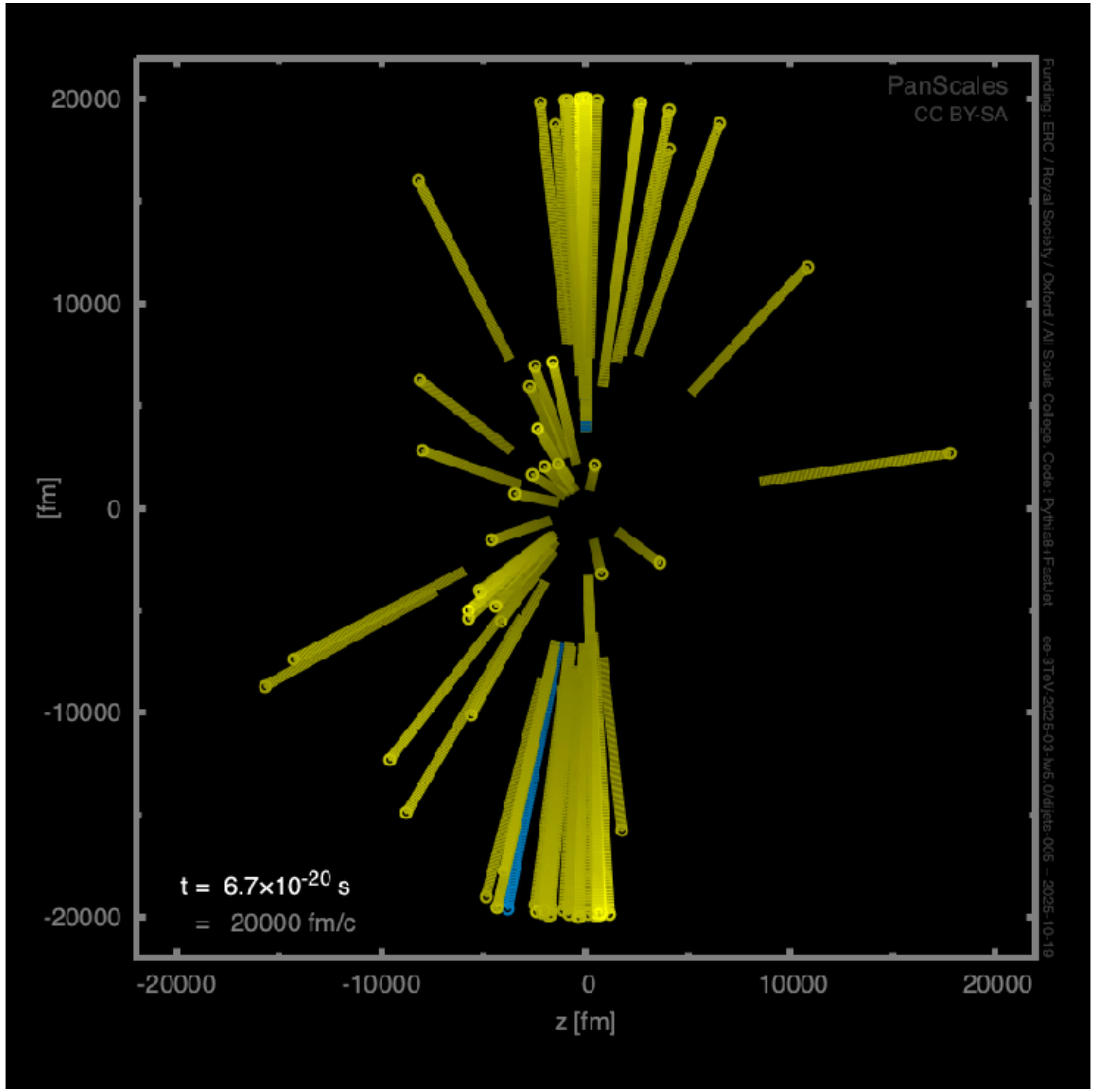
NNLO → e.g. ADMP hep-ph/0312266

NLO → e.g. BDDK hep-ph/9403226
BDK hep-ph/9708239
BlackHat, 0803.4180

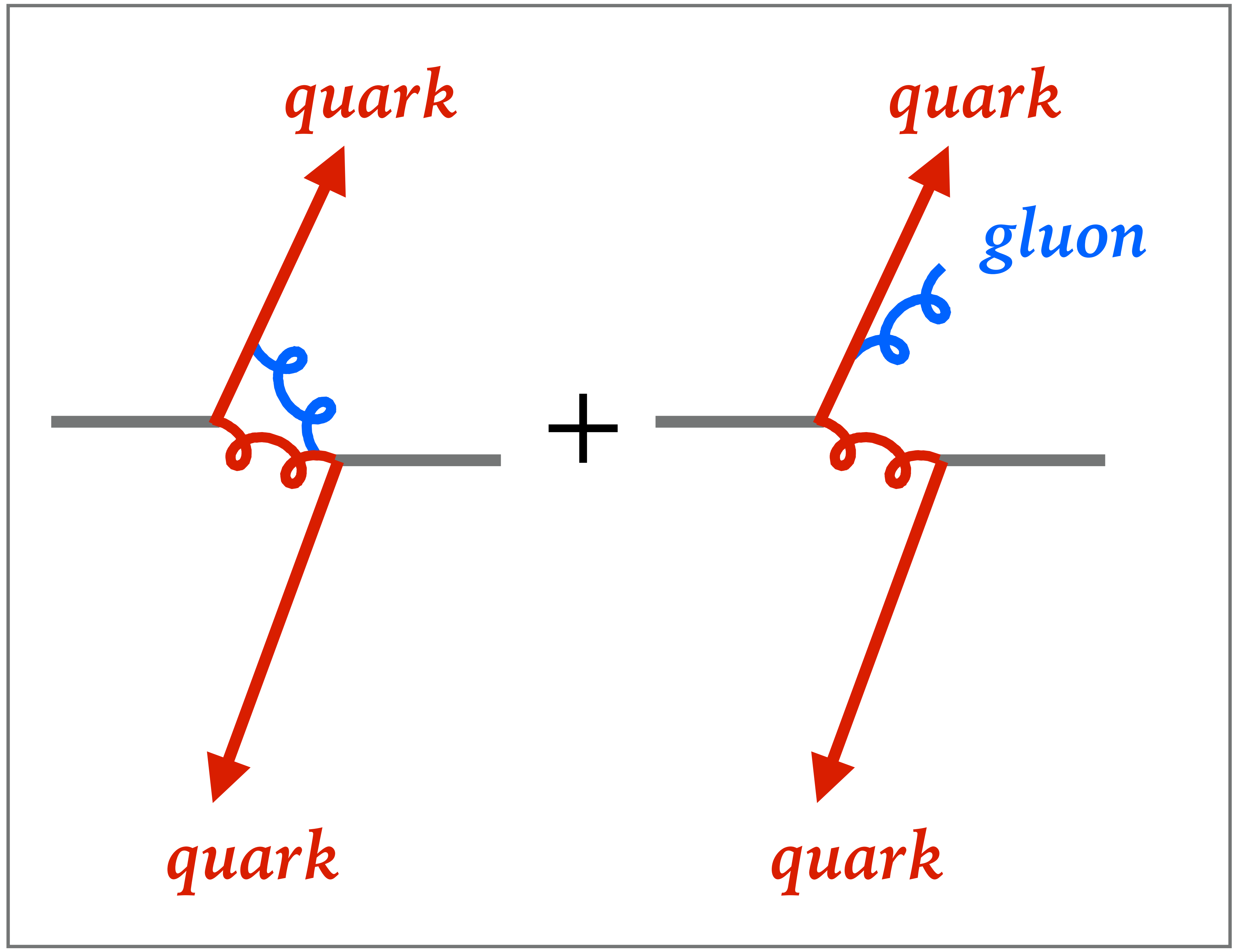
→ Solution of the 1-loop problem

Does it live up to the promise? [#2]

The problem: real events and power-house calculational tool look totally different



$\neq$



next-to-leading order

What a NLO calculation gives you (here, Event2, $e^+e^- \to q\bar{q}$)

LO (2-particle) tree-level event

```
 with weight     1.00000
 px, py, pz, E =   -1.32   -1.38  -49.96   50.00
 px, py, pz, E =    1.32    1.38   49.96   50.00
```

What a NLO calculation gives you (here, Event2, $e^+e^- \to q\bar{q}$)

LO (2-particle) tree-level event
with weight 1.00000

px, py, pz, E =	-1.32	-1.38	-49.96	50.00
px, py, pz, E =	1.32	1.38	49.96	50.00

LO event ($q\bar{q}$)

What a NLO calculation gives you (here, Event2, $e^+e^- \to q\bar{q}$)

LO (2-particle) tree-level event
with weight 1.00000
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

NLO (3-particle) tree-level event
with **weight 16.7749**
px, py, pz, E = -1.60 -1.75 -49.87 49.93
px, py, pz, E = 1.31 1.36 49.25 49.29
px, py, pz, E = 0.30 0.39 0.62 0.79

LO event ($q\bar{q}$)

NLO event, with real emission
~ LO event + extra soft gluon
and **large positive weight**

What a NLO calculation gives you (here, Event2, $e^+e^- \to q\bar{q}$)

LO (2-particle) tree-level event
with weight 1.00000
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

NLO (3-particle) tree-level event
with **weight 16.7749**
px, py, pz, E = -1.60 -1.75 -49.87 49.93
px, py, pz, E = 1.31 1.36 49.25 49.29
px, py, pz, E = 0.30 0.39 0.62 0.79

NLO (2-particle) virtual subtraction event
with **weight -1.5868**
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

NLO (2-particle) virtual subtraction event
with **weight -15.1855**
px, py, pz, E = -1.61 -1.75 -49.94 50.00
px, py, pz, E = 1.61 1.75 49.94 50.00

NLO (2-particle) virtual finite event
with weight 0.0501, multiplying (alphas/2pi)
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

LO event ($q\bar{q}$)

NLO event, with real emission
~ LO event + extra soft gluon
and **large positive weight**

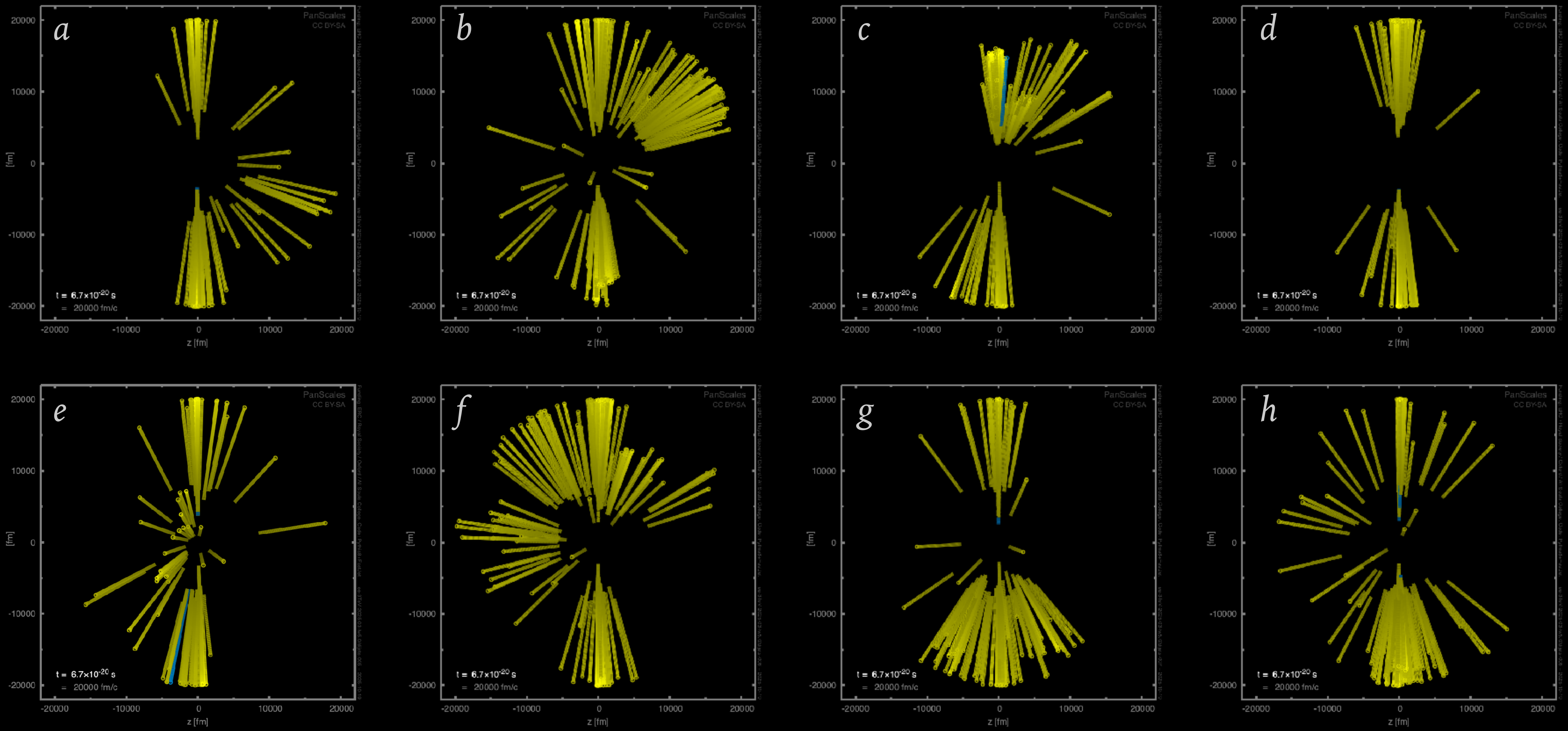
NLO event, “virtual” correction
~ LO event
and **large negative weight**

event weights are ~ probabilities

- real life doesn't have negative probabilities
- real life doesn't have (near-)divergent probabilities
- you can avoid these problems in perturbation theory if you ask very limited kinds of questions, i.e. nearly always summing real & virtual divergences (infrared safe, single momentum scale)*
- but experiments don't limit themselves to those kinds of questions

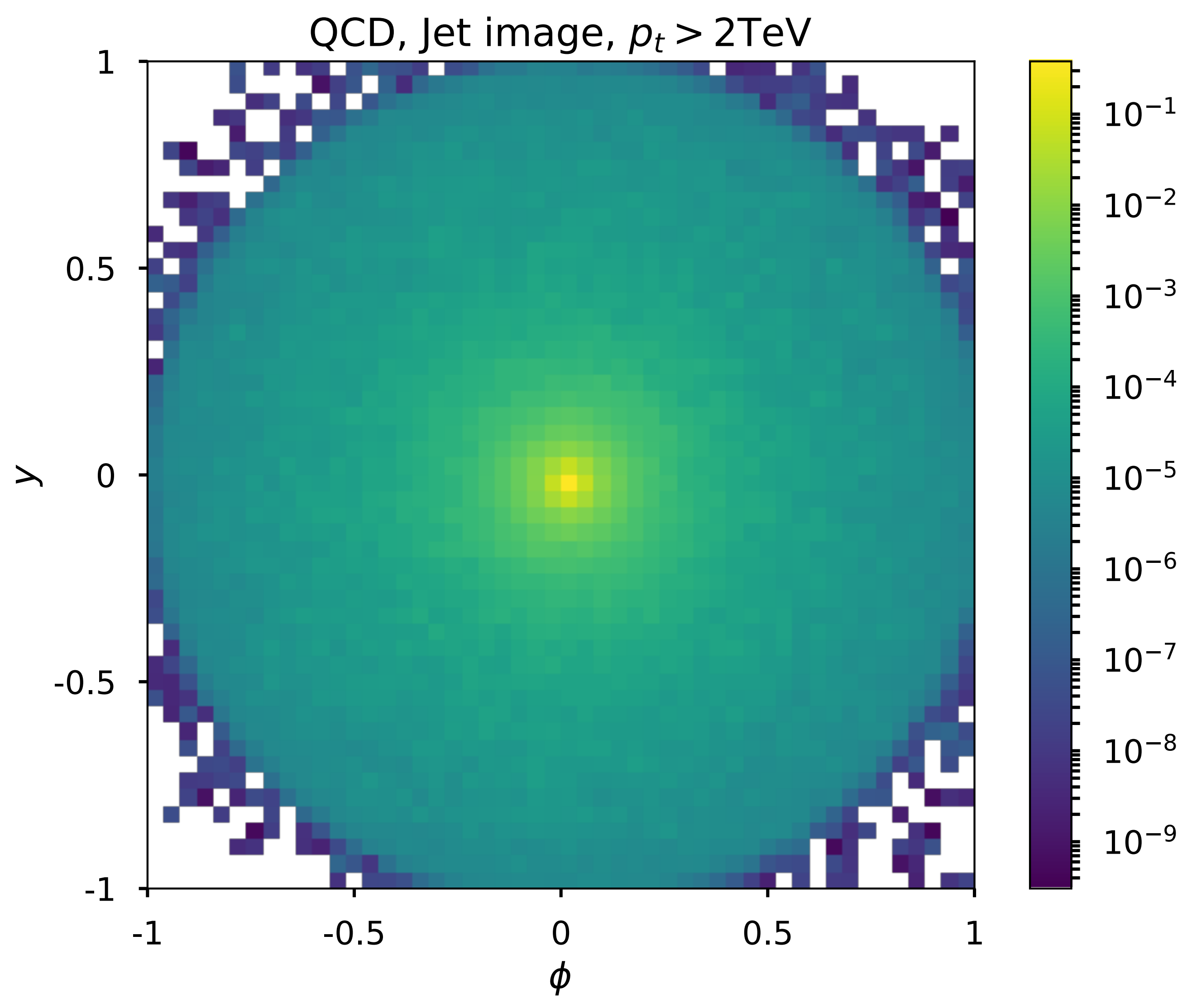
can we be flexible with the questions we ask, yet still get the benefits of perturbation theory?

* though there can still be nasty surprises, cf. Chen et al 2102.07607, GPS & Slade 2106.08329

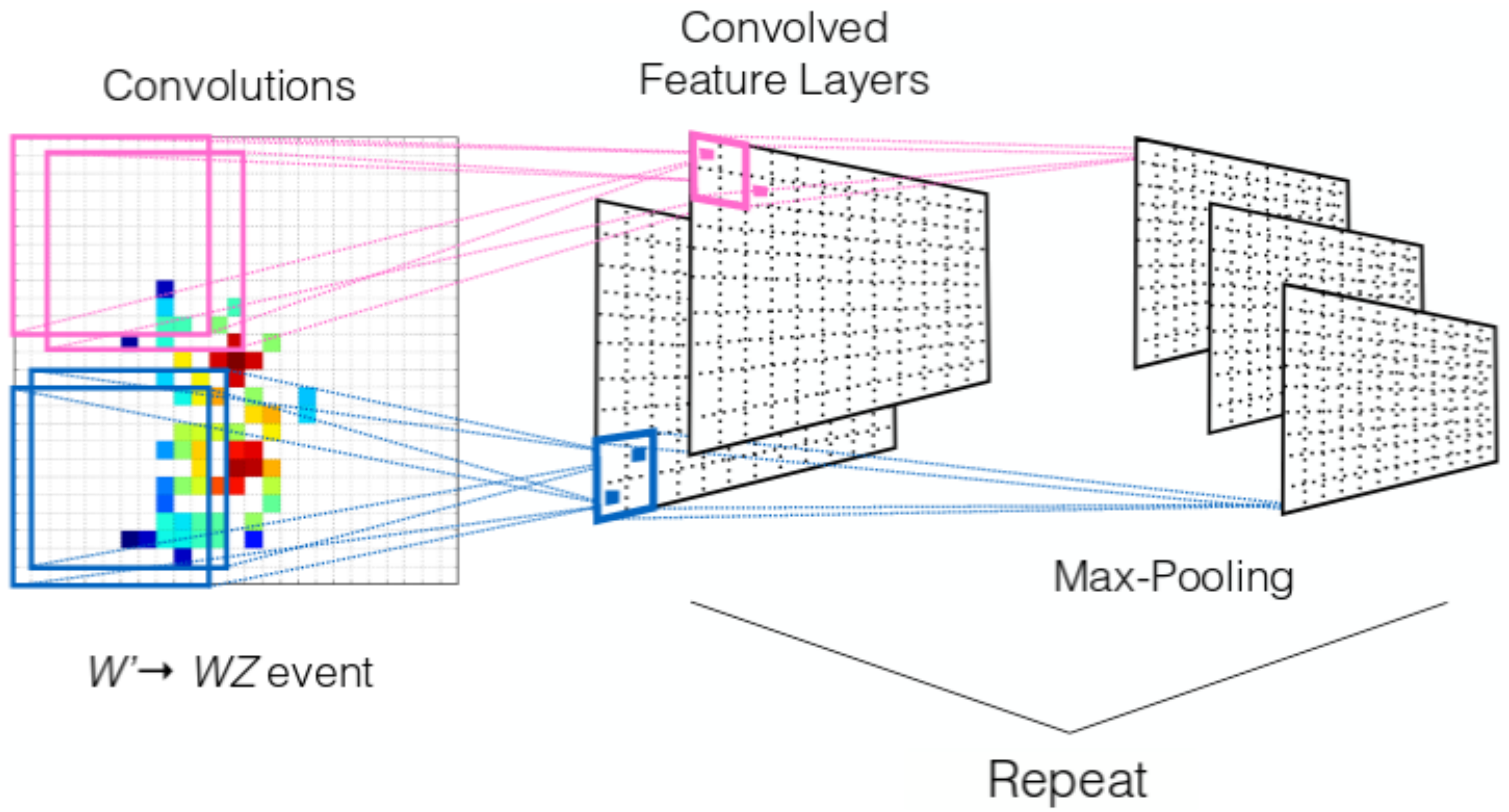


a
b
c
d
e
f
g
h
PanScales
CC BY-SA
t = 6.7×10^-20 s
= 20000 fm/c
z [fm]
[fm]
20000
10000
0
-10000
-20000

Did the jet of particles come from a quark or a W/Z/H-boson? → Use machine learning

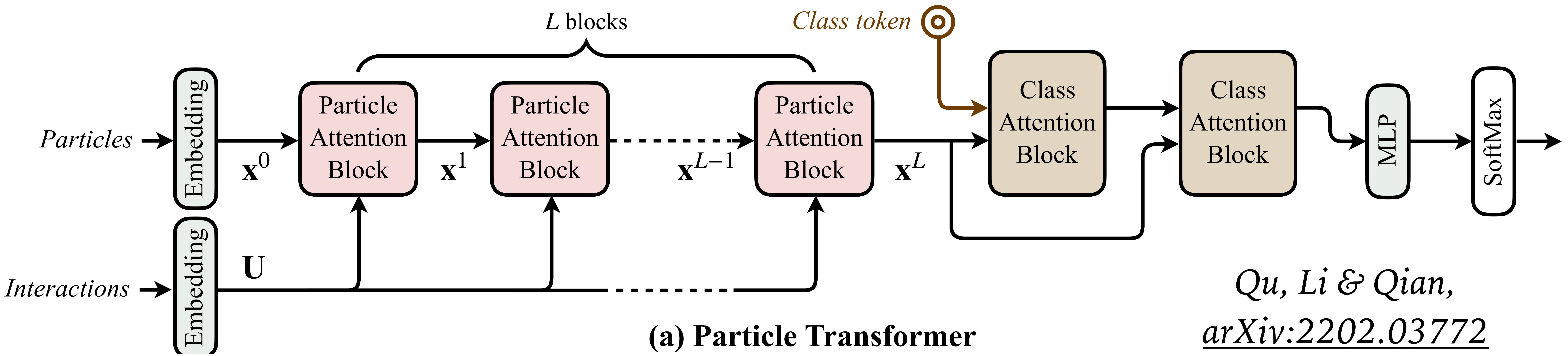


2021 Young Experimental Physicist
EPS HEPP prize



[Cogan, Kagan, Strauss, Schwartzman JHEP 1502 (2015) 118]

[de Oliveira, Kagan, Mackey, Nachman, Schwartzman JHEP 1607 (2016) 069]

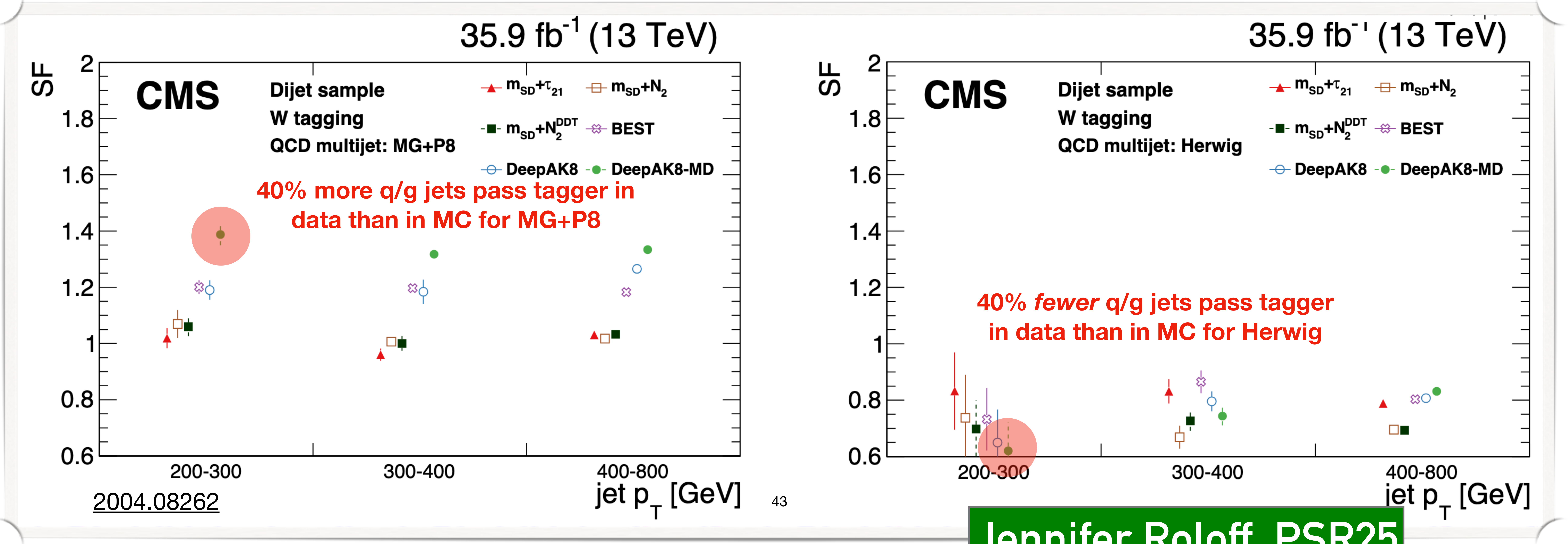


(a) Particle Transformer

Qu, Li & Qian, arXiv:2202.03772

We want machine learning to be accurate

- even simplest ML methods exacerbate sensitivity to imperfections in predictions
- how do we get (perturbative) QFT to be accurate even with ML?



Jennifer Roloff, PSR25

Physical predictions for any one observable: resummation (e.g. EEC collinear limit)

In the collinear limit, $z \to 0$, the perturbative contributions to the EEC exhibits a single logarithmic series

$$\frac{d\sigma}{dz} = \sum_{L=1}^{\infty} \sum_{j=-1}^{L-1} \left(\frac{\alpha_s(\mu)}{4\pi}\right)^L c_{L,j} \mathcal{L}^j(z) + \dots\,, \qquad (4)$$

where $\mathcal{L}^{-1}(z) = \delta(z)$ and $\mathcal{L}^j(z) = \left[\ln^j z/z\right]_+$ for $j \geq 0$ denotes a standard plus distribution. The ellipses denote

Dixon, Moult, Zhu, 1905.01310

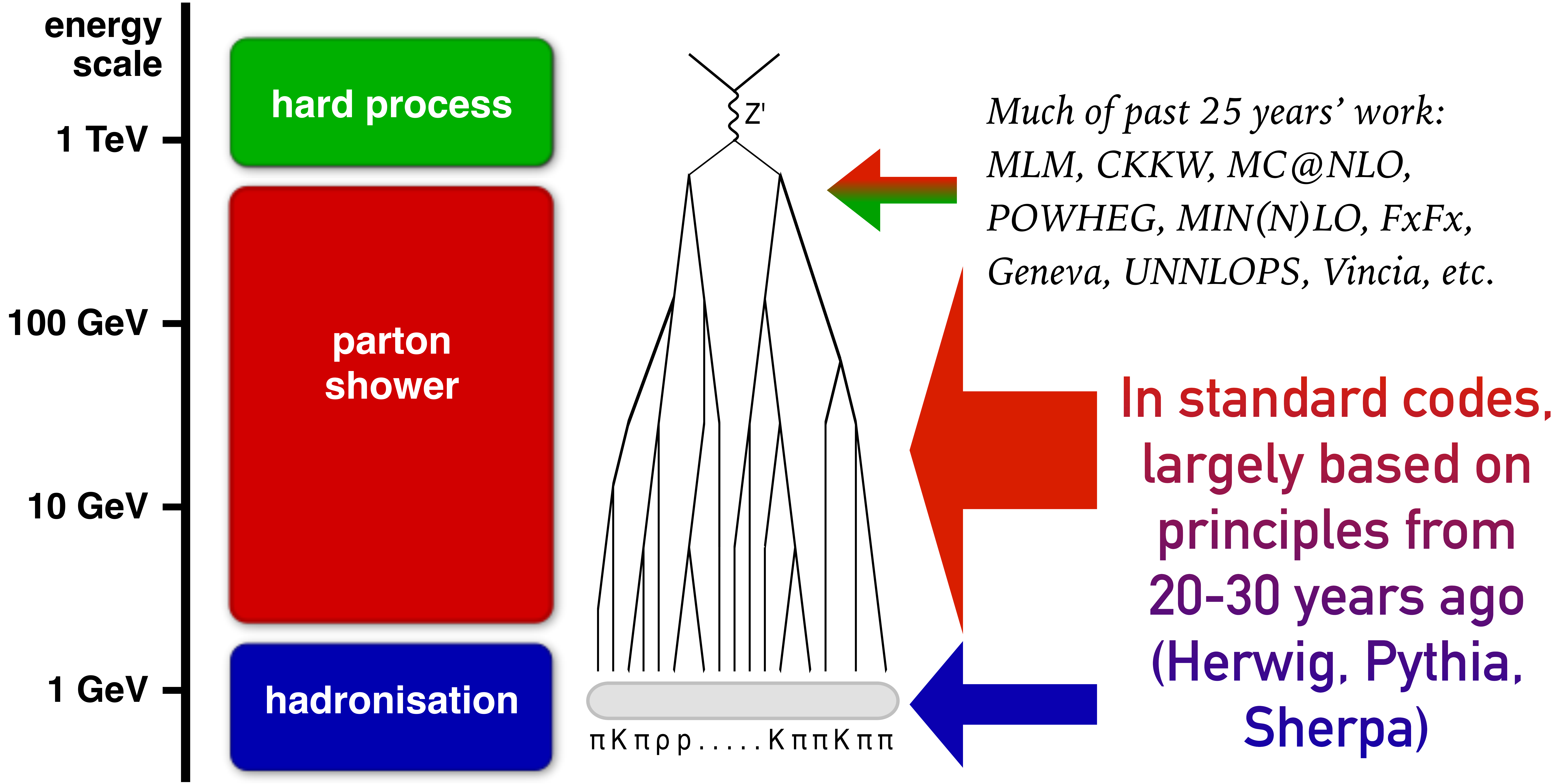
$$0 \leq z = \frac{1-\cos\chi}{2} \leq 1$$

$$\frac{d\vec{J}_{\rm LL}(\ln\frac{zQ^2}{\mu^2},\mu)}{d\ln\mu^2} = \vec{J}_{\rm LL}(\ln\frac{zQ^2}{\mu^2},\mu)\cdot\int_0^1 dy\, y^2\, \widehat{P}_T^{(0)}(y)$$

All-order formulation often involves a differential equation in some scale

$$\vec{J}_{\rm LL}(\ln\frac{zQ^2}{\mu^2},\mu) = (1,1)\cdot V\left[\left(\frac{\alpha_s(\sqrt{z}Q)}{\alpha_s(\mu)}\right)^{-\frac{\vec{\gamma}_T^{(0)}}{\beta_0}}\right]_D V^{-1}\,,$$

Which can be solved analytically or numerically

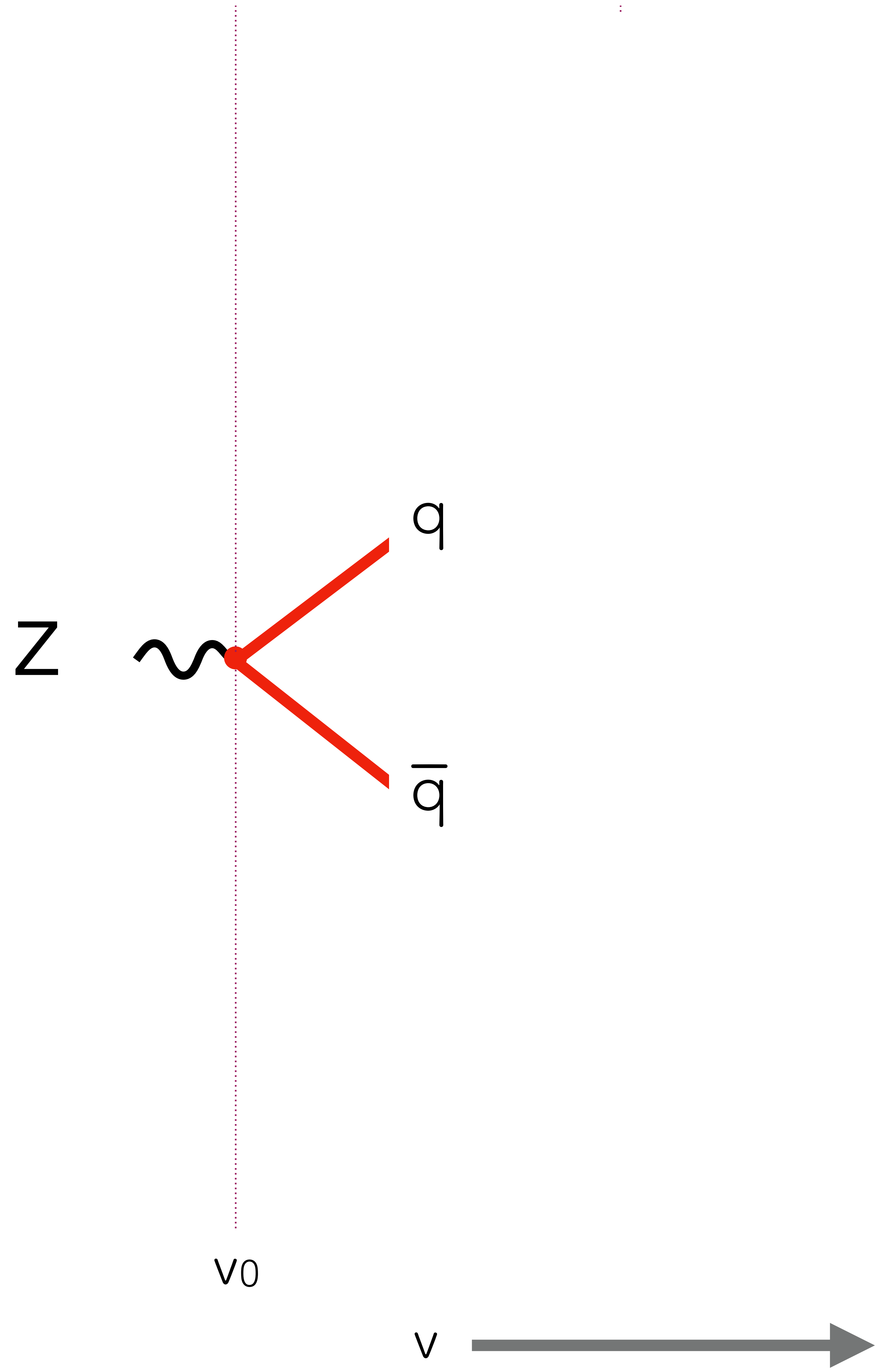

energy scale
1 TeV
100 GeV
10 GeV
1 GeV
hard process
parton shower
hadronisation
Z'
π K π ρ p . . . . . K π π K π π
Much of past 25 years' work:
MLM, CKKW, MC@NLO,
POWHEG, MIN(N)LO, FxFx,
Geneva, UNNLOPS, Vincia, etc.
In standard codes,
largely based on
principles from
20-30 years ago
(Herwig, Pythia,
Sherpa)

parton showers: the ultimate differential equation

discussion today is in the large-NC limit

there are also various approaches for subleading-NC terms

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

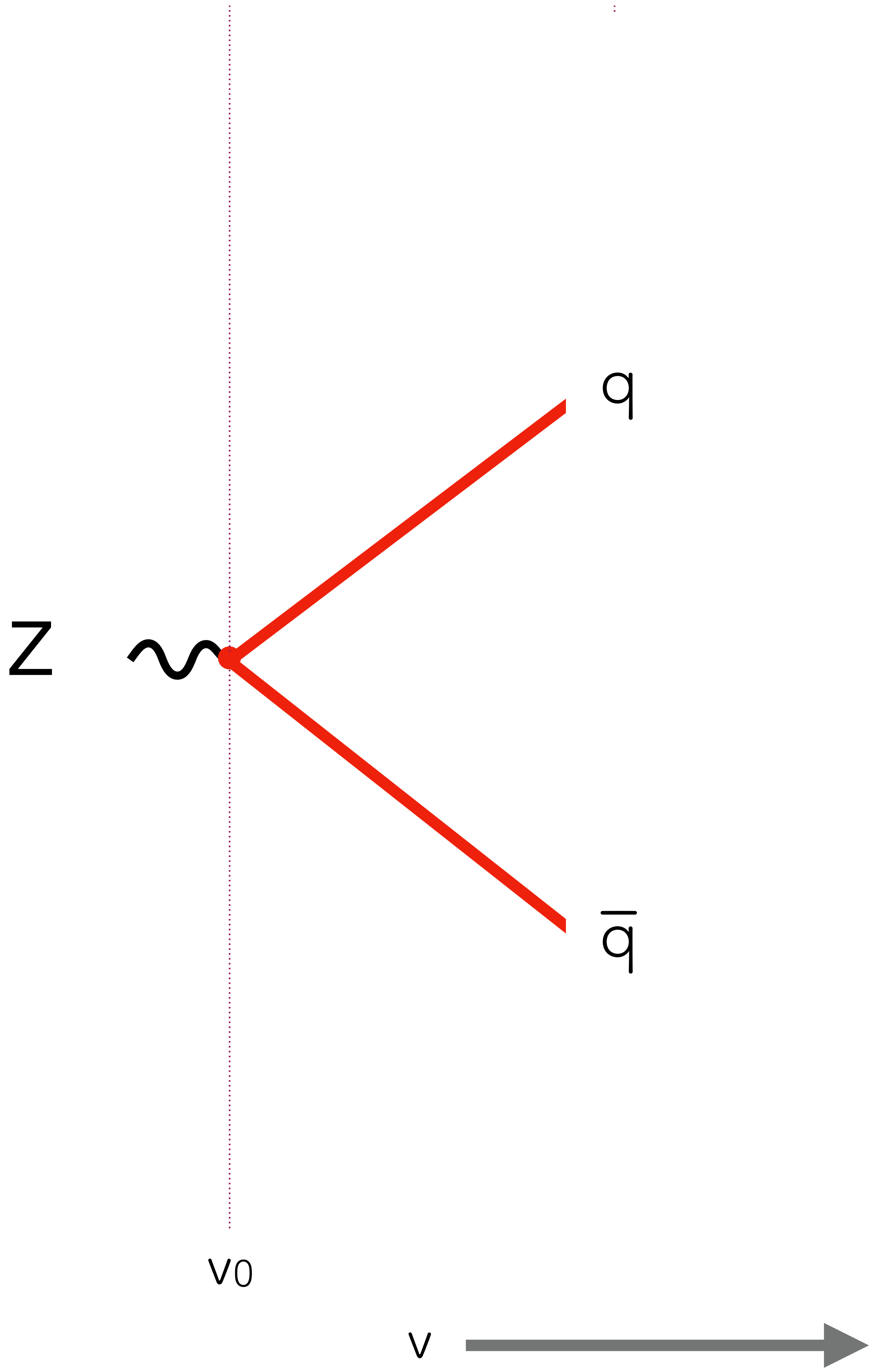


Start with quark (q) antiquark ($\bar{q}$) state.

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

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

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

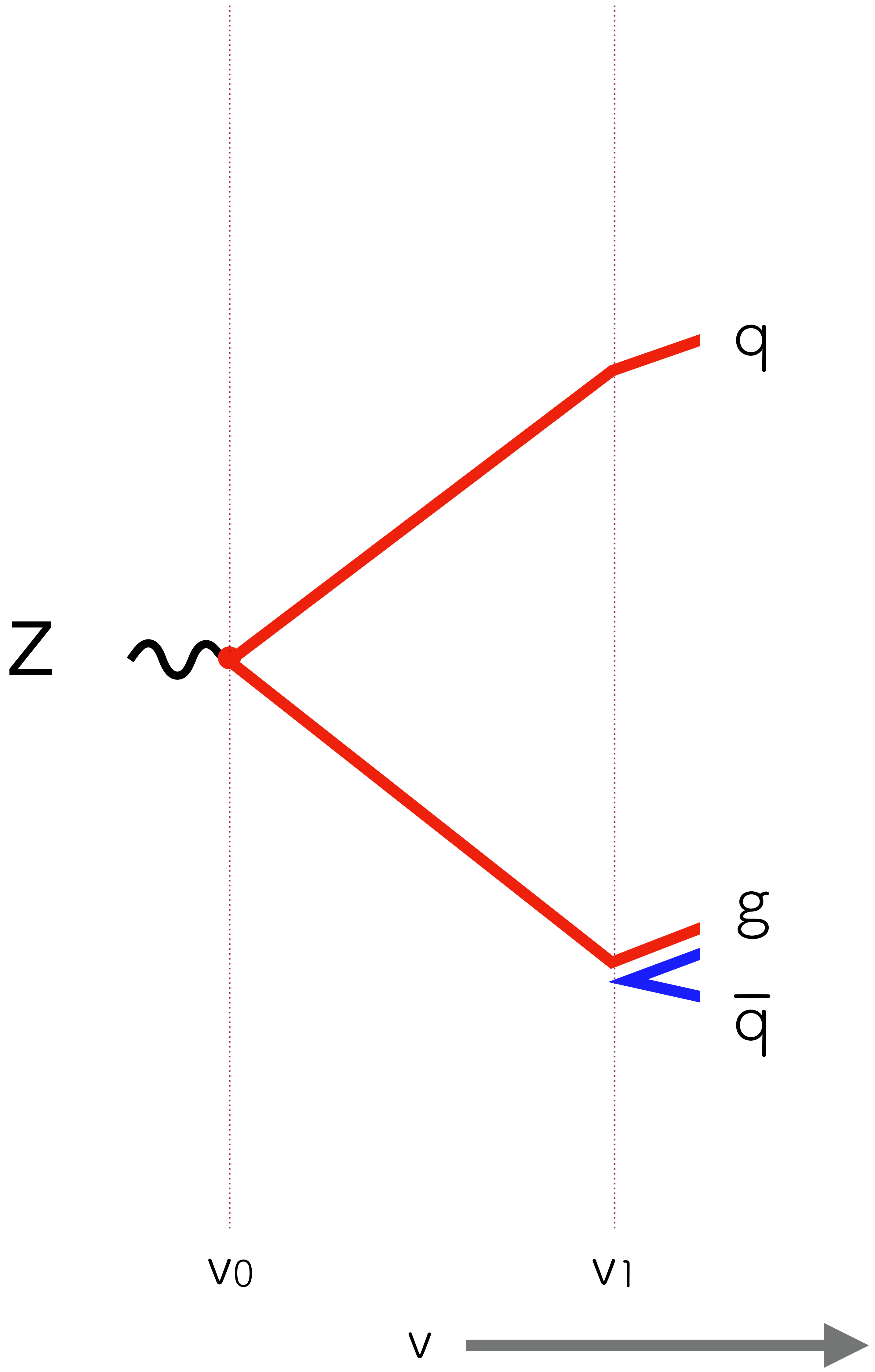


Start with quark (q) antiquark ($\bar{q}$) state.

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

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

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



Start with quark (q) antiquark ($\bar{q}$) state.

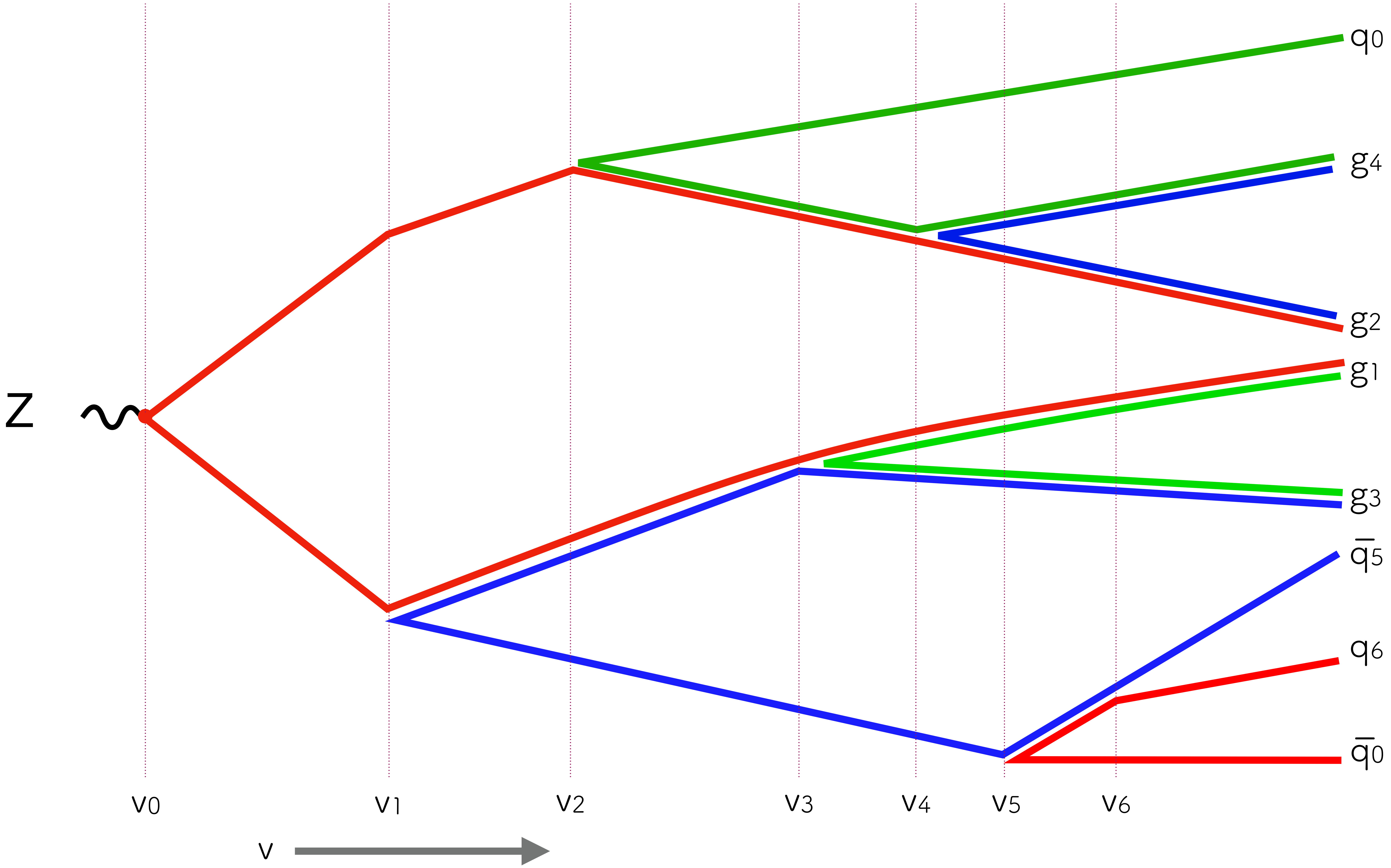
Throw a random number to determine down to what scale state persists unchanged

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

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

gluon (g) here is drawn as two colour lines

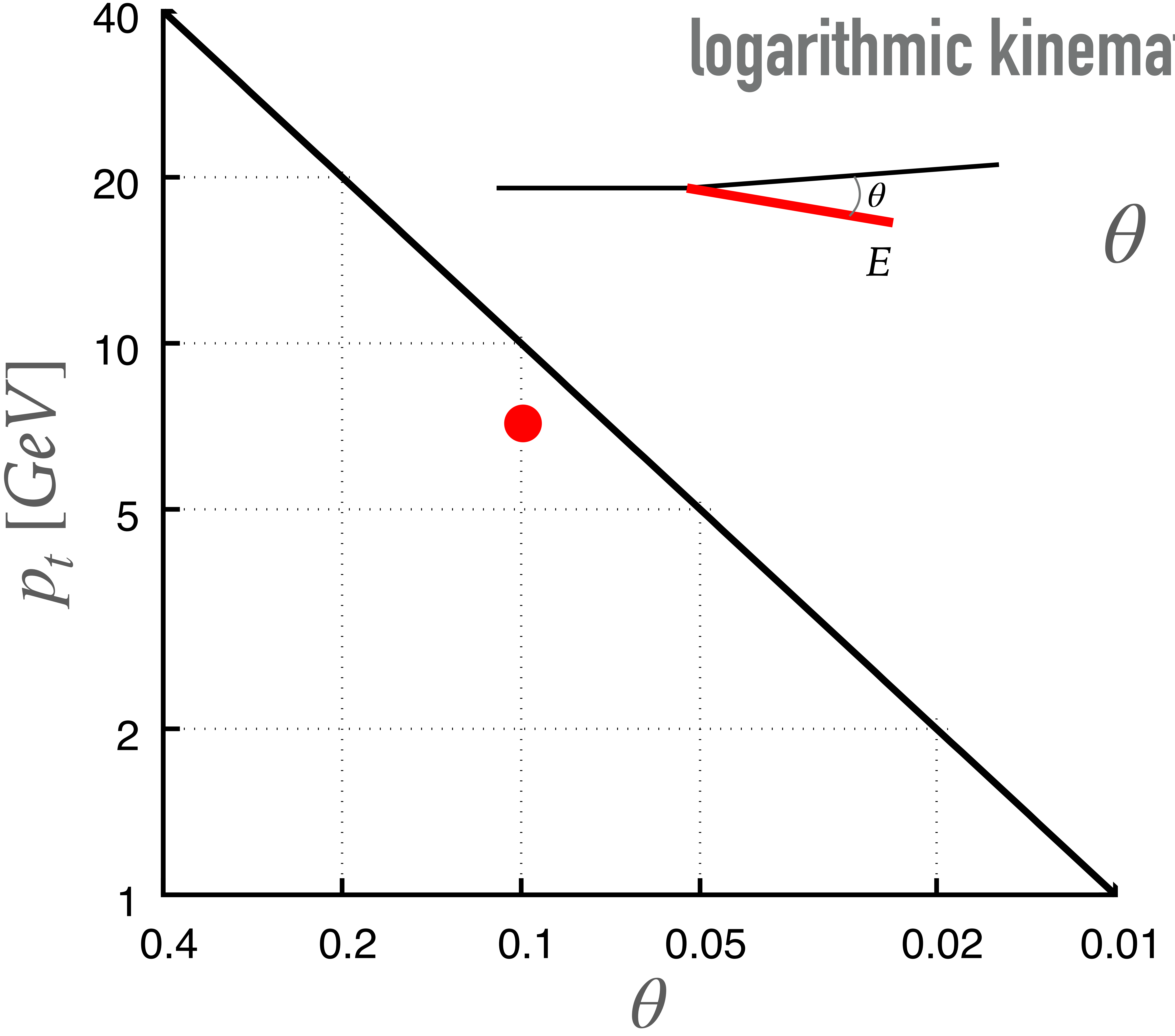
QCD parton shower: an evolution equation (in evolution scale v, e.g. trans.mom.)



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

illustration by K. Hamilton

jet with $R = 0.4$, $p_t = 200$ *GeV*



logarithmic kinematic plane whose two variables are

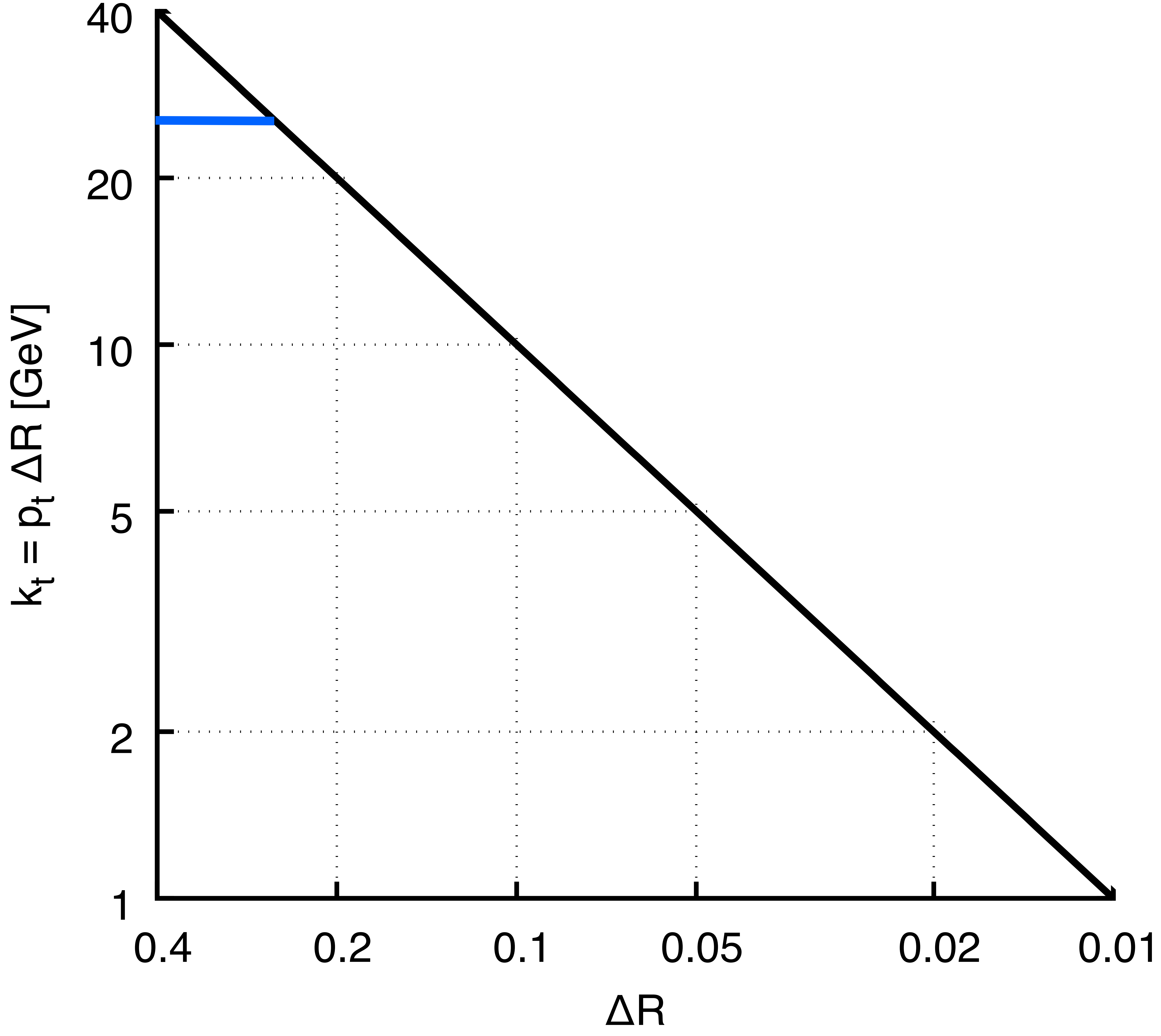
$$\theta \ (or \ \eta = -\ln\tan\frac{\theta}{2})$$

$$p_t = E\theta$$

Introduced for understanding Parton Shower Monte Carlos by B. Andersson,G. Gustafson L. Lonnblad and Pettersson 1989

The Lund Plane

jet with $R = 0.4$, $p_t = 200$ GeV

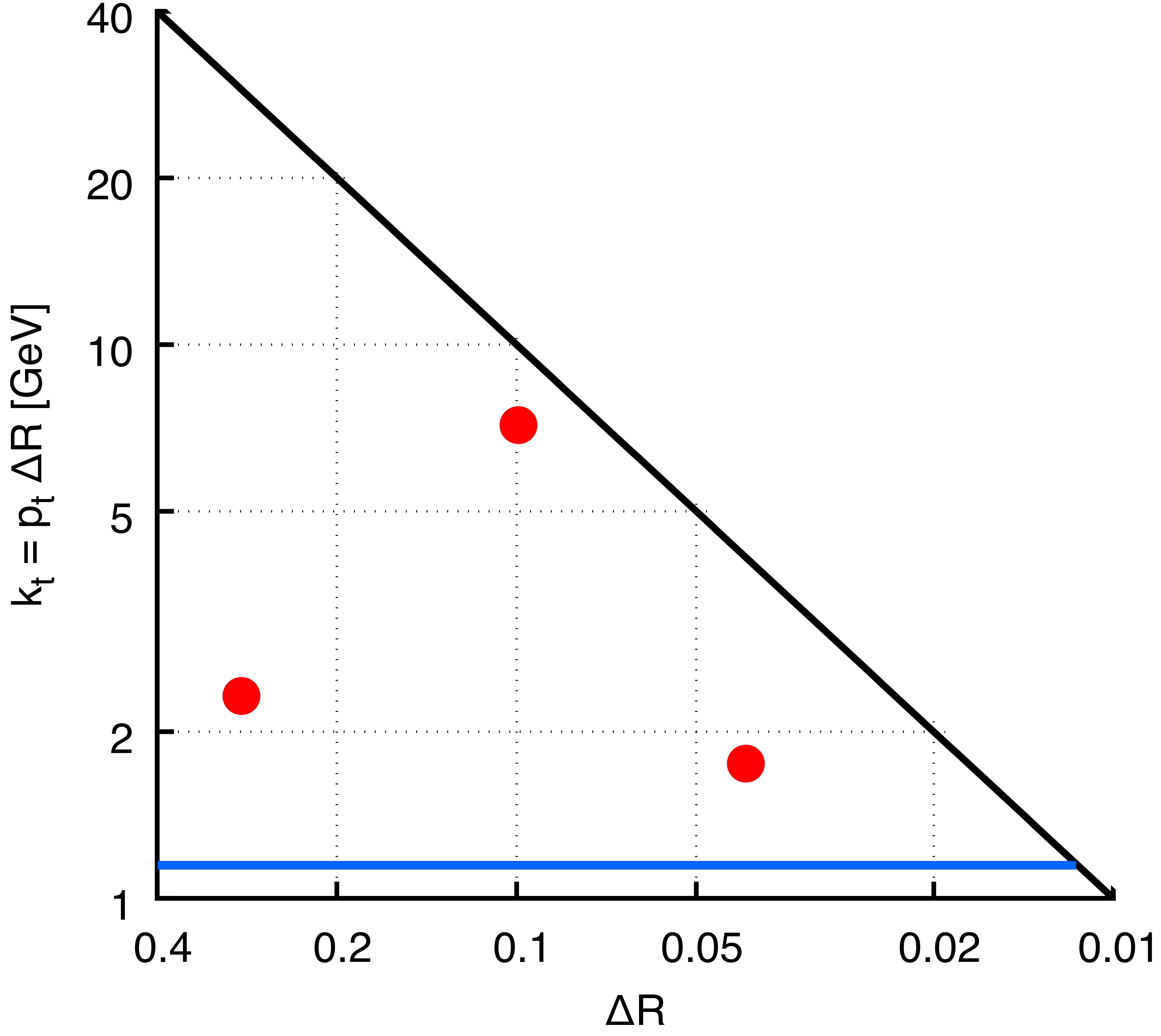


Parton shower is "differential equation" in one variable

You need to **choose** how one variable maps onto the two "logarithmic" dimensions of the Lund plane

A form of scheme choice

jet with $R = 0.4$, $p_t = 200$ GeV

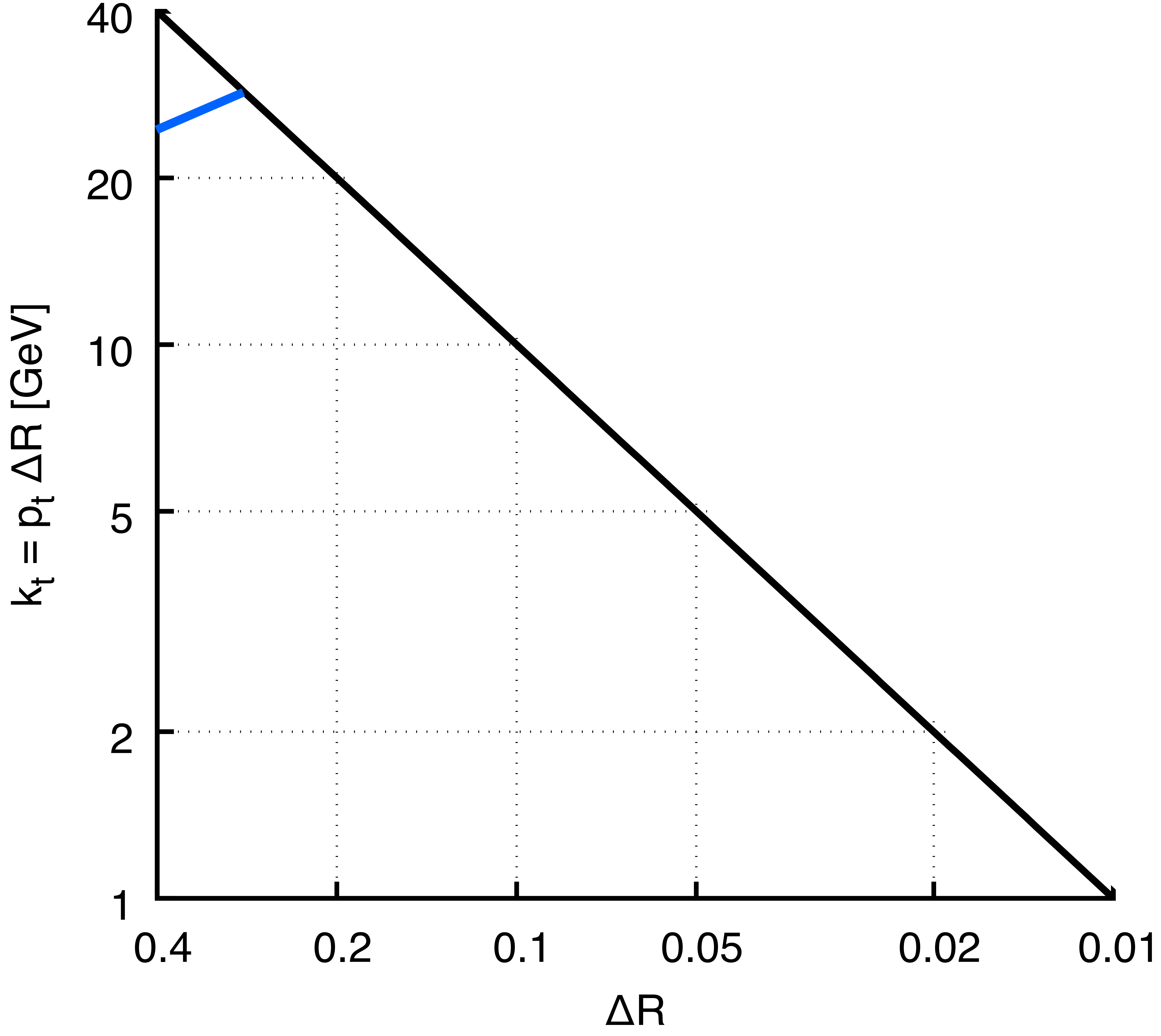


Parton shower is “differential equation” in one variable

You need to **choose** how one variable maps onto the two “logarithmic” dimensions of the Lund plane

A form of scheme choice

jet with $R = 0.4$, $p_t = 200$ GeV

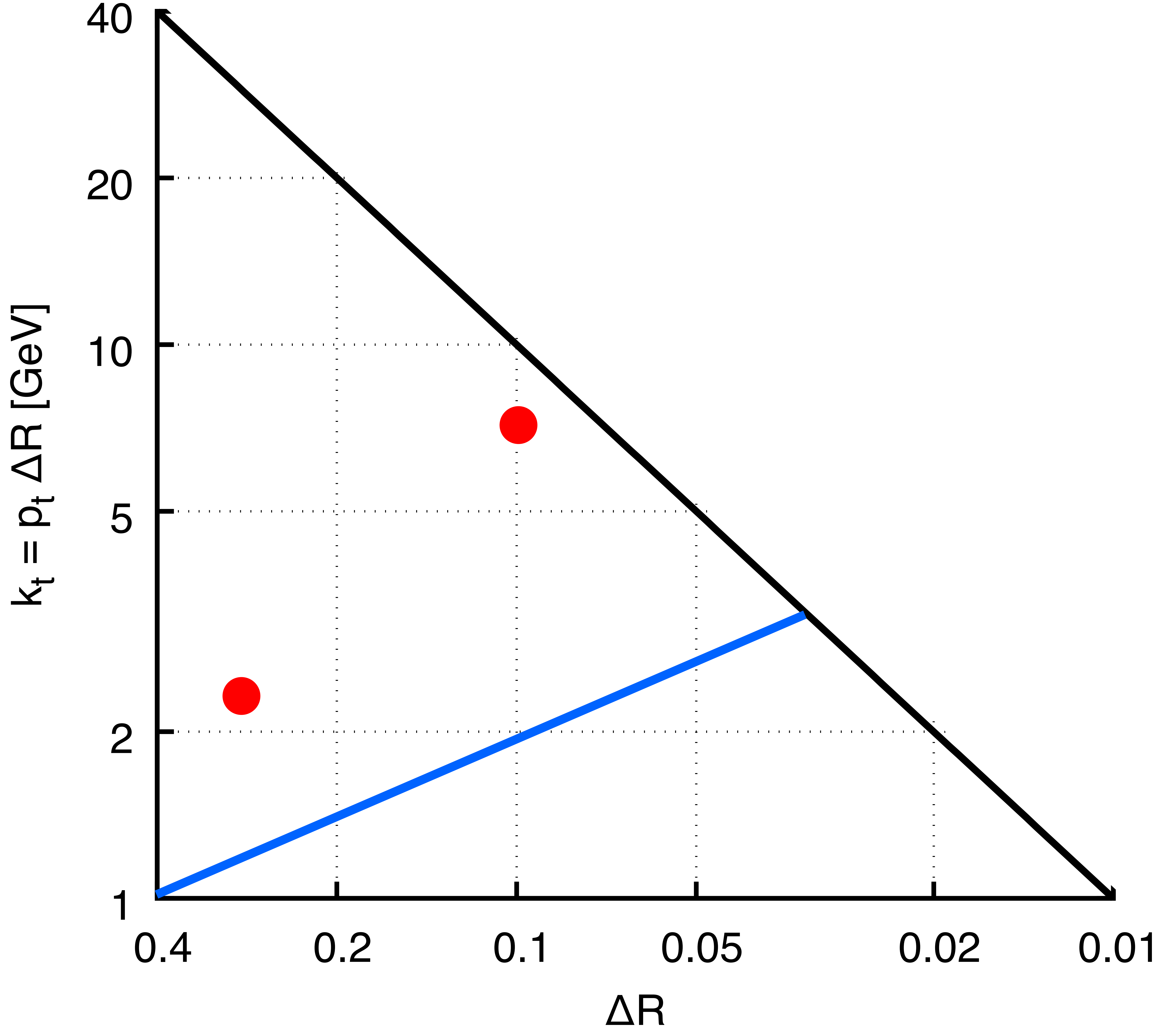


Parton shower is "differential equation" in one variable

You need to **choose** how one variable maps onto the two "logarithmic" dimensions of the Lund plane

A form of scheme choice — **up to the order you control, results should be independent of the scheme choice.**

jet with $R = 0.4$, $p_t = 200$ GeV

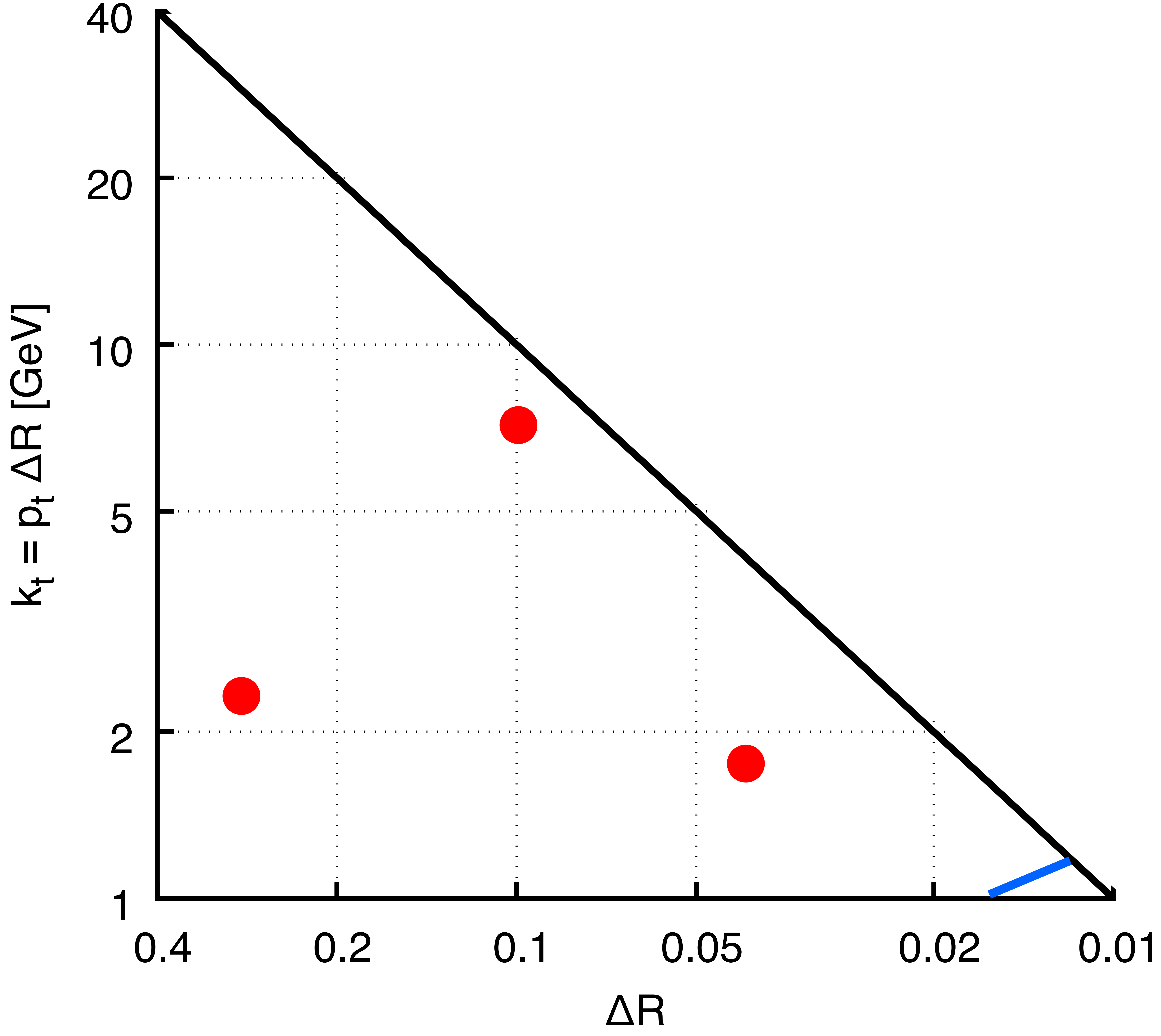


Parton shower is "differential equation" in one variable

You need to **choose** how one variable maps onto the two "logarithmic" dimensions of the Lund plane

A form of scheme choice — **up to the order you control, results should be independent of the scheme choice.**

jet with $R = 0.4$, $p_t = 200$ GeV



Parton shower is "differential equation" in one variable

You need to **choose** how one variable maps onto the two "logarithmic" dimensions of the Lund plane

A form of scheme choice — **up to the order you control, results should be independent of the scheme choice.**

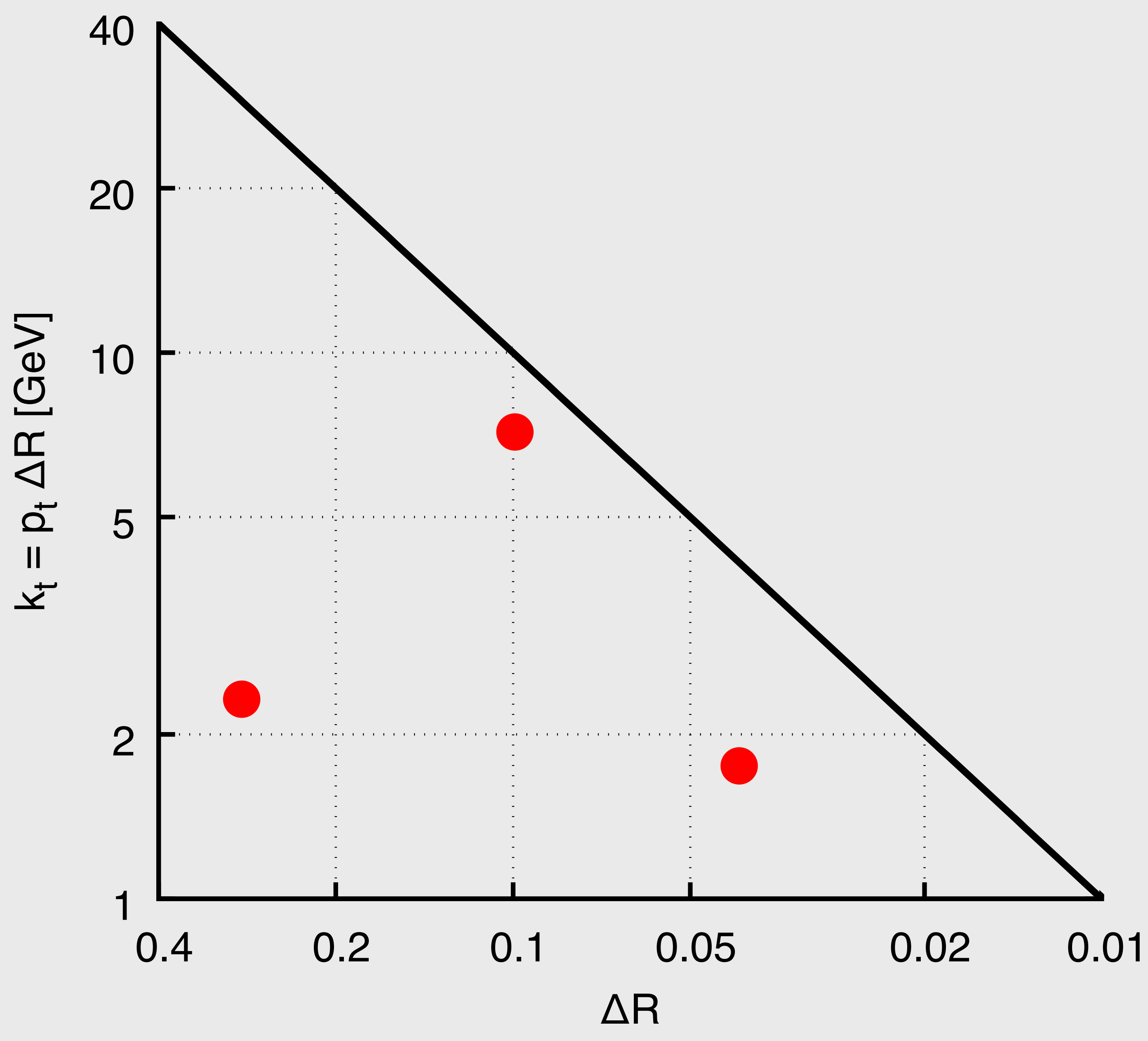
NLL: the foundation

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
  (because those configurations are the most likely ones)

- supplement with unitarity, 2-loop running coupling & cusp anomalous dimension



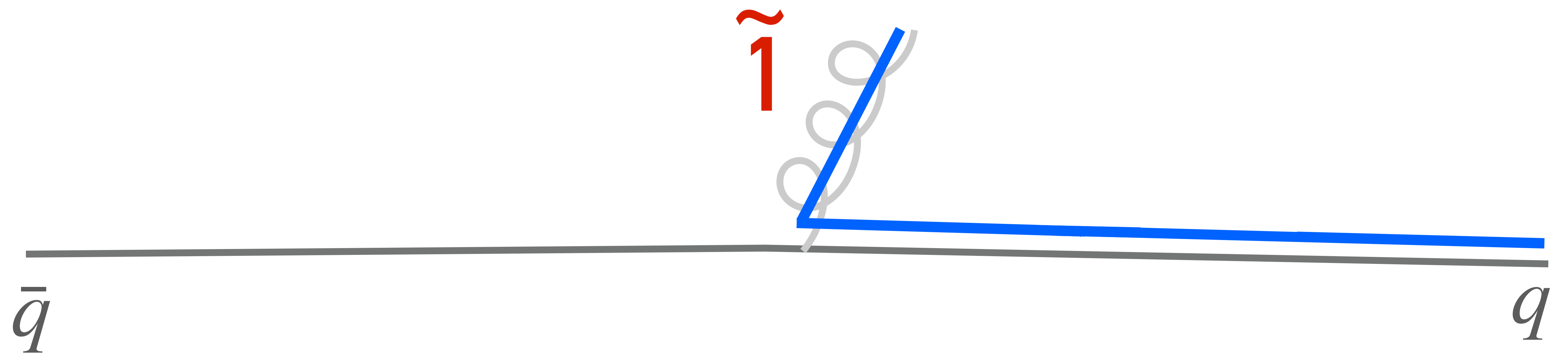
Resummation condition:

reproduce NLL ($\alpha_s^n L^n$) results for all standard resummations

- global event shapes
- non-global observables
- fragmentation functions ($\alpha_s^n L^n$ just leading log)
- multiplicities ($\alpha_s^n L^{2n-1}$)
- …

1. Recoil: the core of any shower

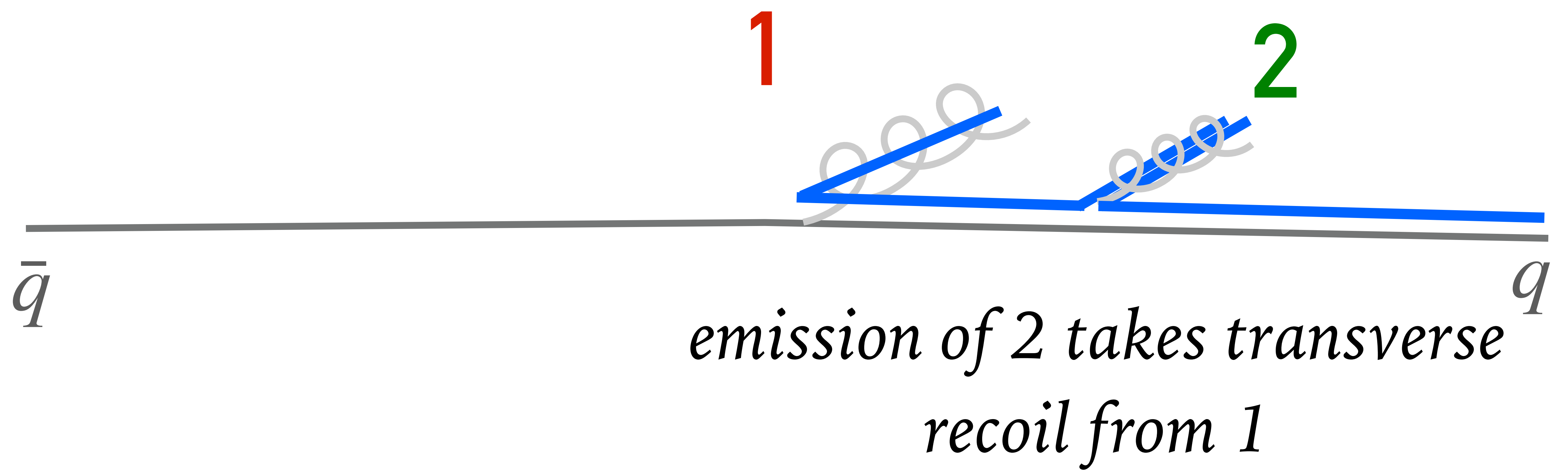
Dipole showers conserve momentum at each step. Traditional dipole-local recoil:



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

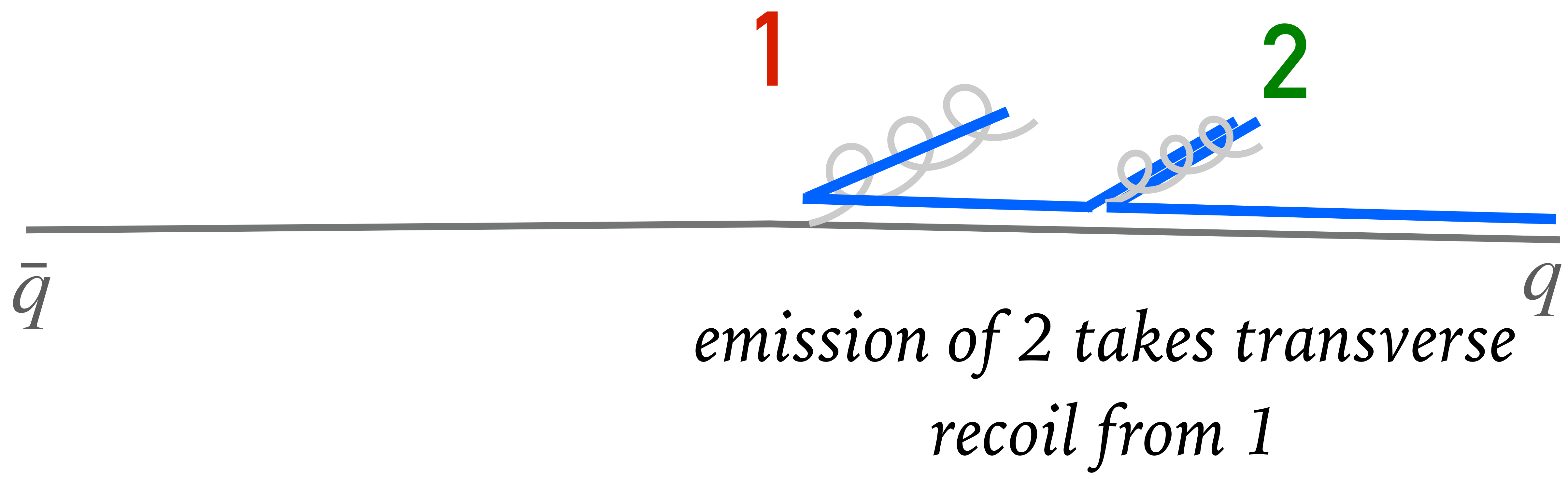
1. Recoil: the core of any shower

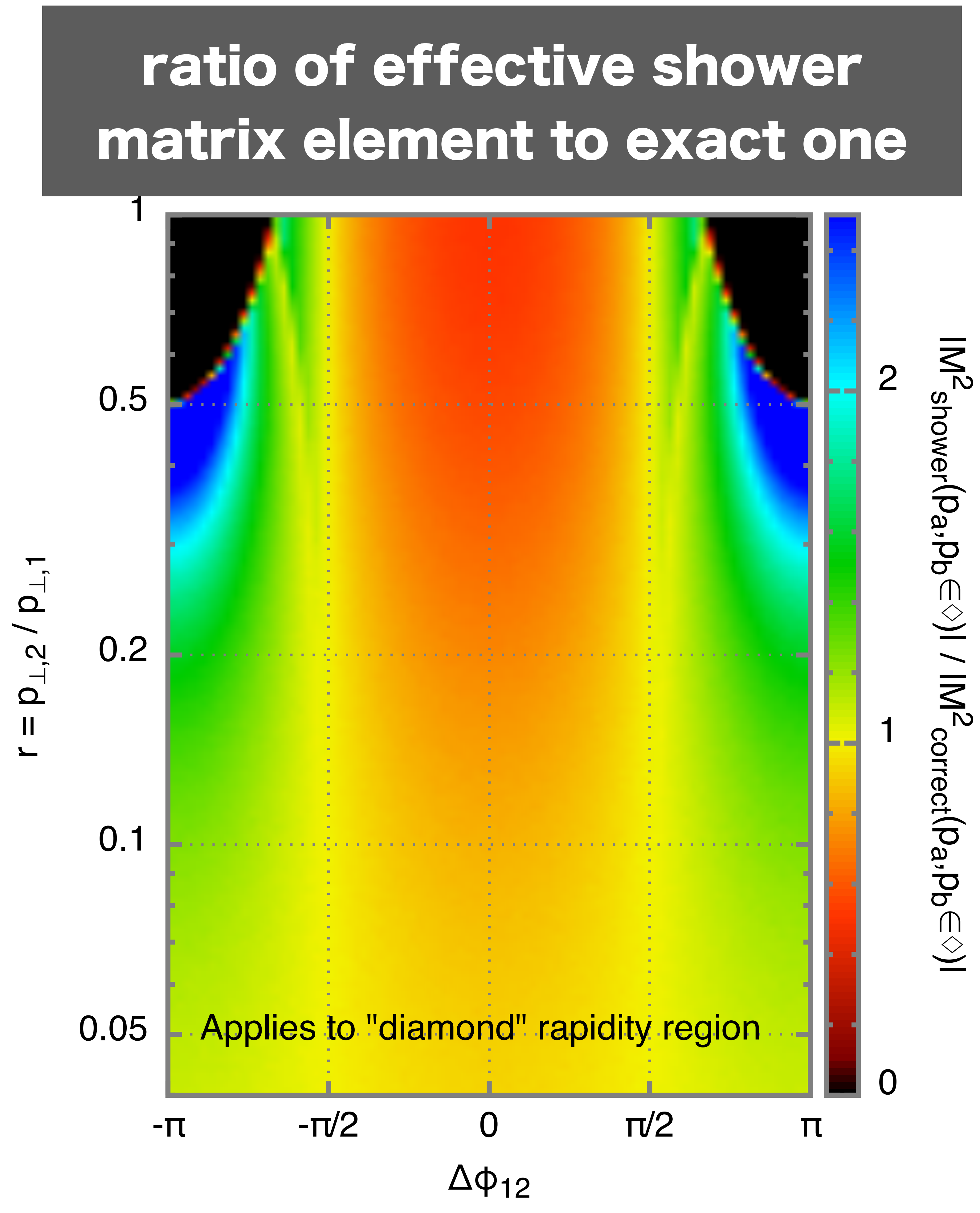
Dipole showers conserve momentum at each step. Traditional dipole-local recoil:



1. Recoil: the core of any shower

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





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

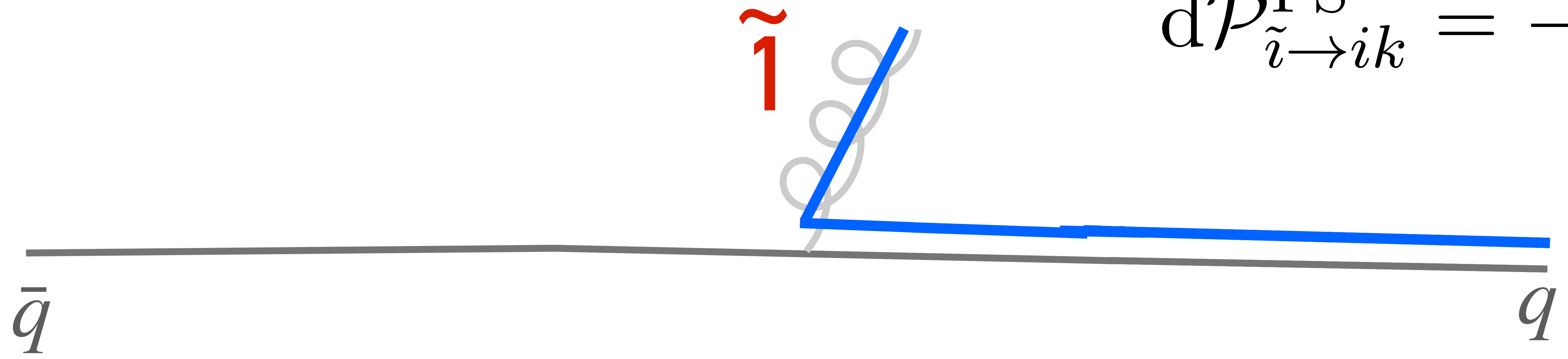
Matrix element is incorrect wrt final momentum 1.

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

1. Correct recoil rule: no side effects on other distant emissions

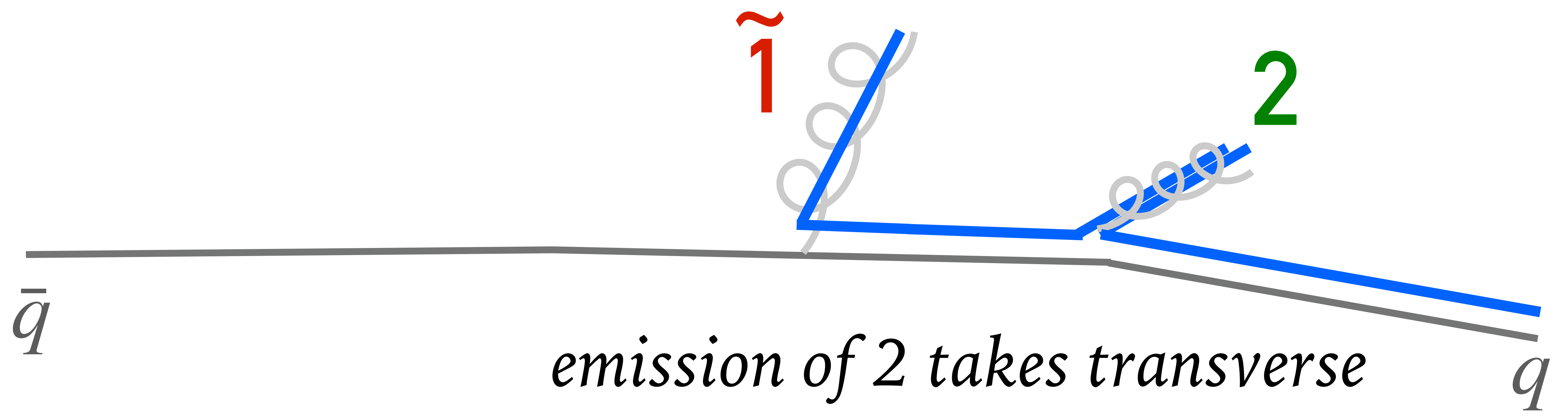
One approach

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



1. Correct recoil rule: no side effects on other distant emissions

One approach

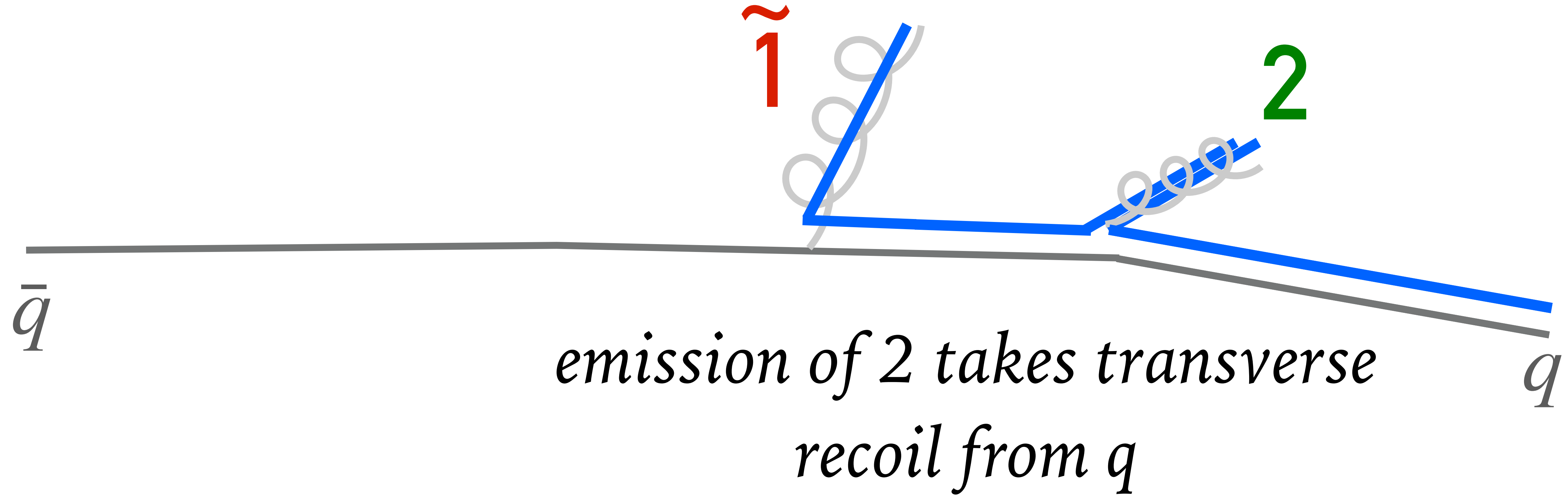


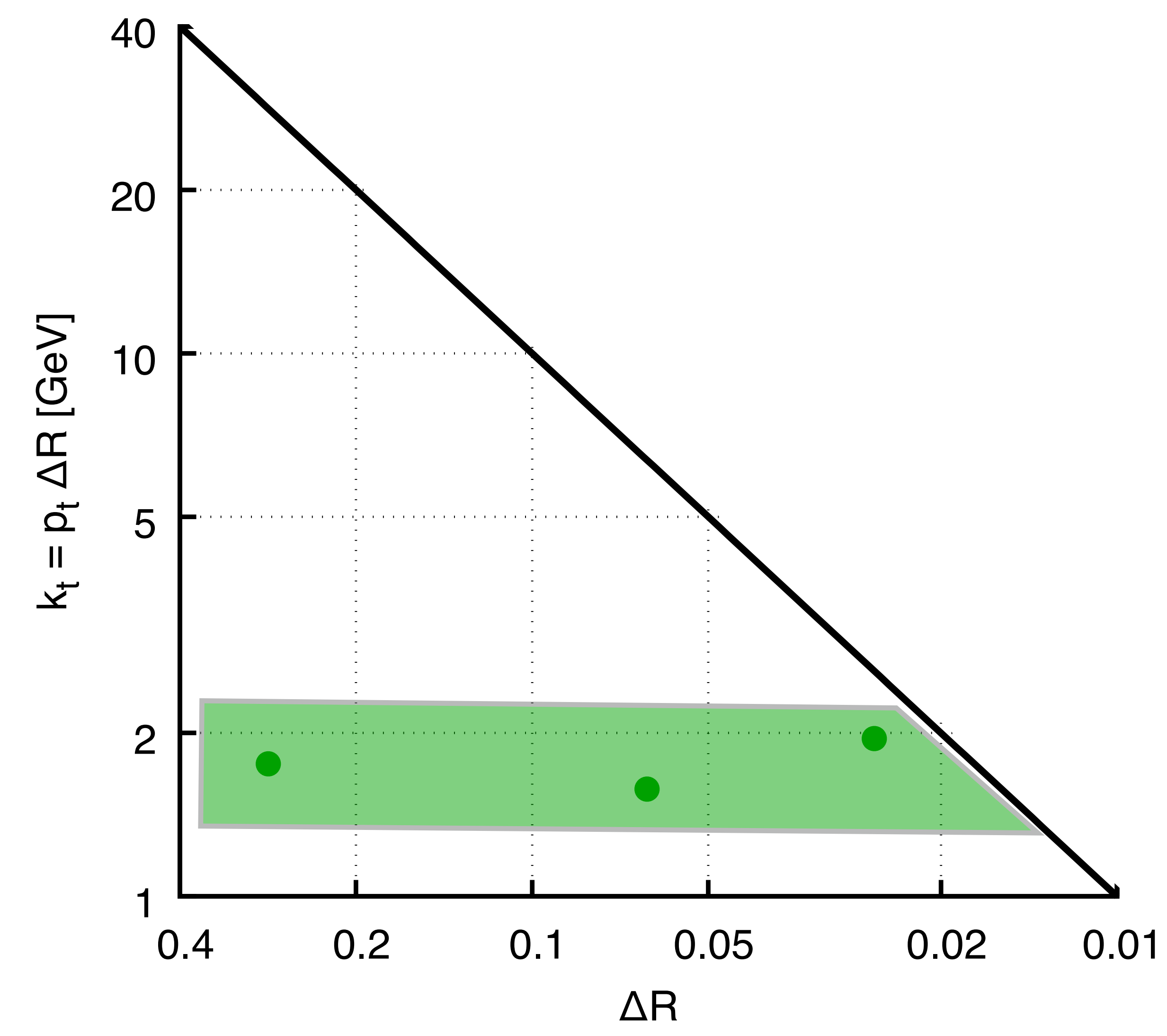
emission of 2 takes transverse recoil from q

θ_{1q} left almost unchanged if ⊥ recoil from emission of 2 taken by (much harder) q

1. Correct recoil rule: no side effects on other distant emissions

One approach





θ_{1q} left almost unchanged if ⊥ recoil from emission of 2 taken by (much harder) q

Can be achieved in multiple ways:

- global transverse recoil
  (Dasgupta et al 2002.11114, "**PanGlobal**"; Holguin Seymour & Forshaw 2003.06400; Alaric 2208.06057 + ⋯, Apollo, 2403.19452)
- local transverse recoil, with non-standard shower ordering & dipole partition
  (2002.11114 "**PanLocal**"; Nagy & Soper 0912.4534 + ⋯, "Deductor")

June 2026 slide from Melissa van Beekveld

	Alaric	Apollo	FHP	Panscales
Available for e+e-?	NLL	NLL	NLL	Partial NNLL
Available for pp?	NLL (no numerical proof beyond colour singlet)	No	No	NLL (no numerical proof beyond colour singlet)
Available for DIS?	No	No	No	NLL
Recoil distribution	Global for soft, local pT for collinear	As Alaric's soft map, different ord. variable	Global	Local (PanLocal) and global (PanGlobal) variants
Splitting functions at LO	Soft with special ref. direction, +coll remainder	Antenna functions	AP with sharp partitioning	AP with smooth partitioning
Spin correlations	Yes in e+e-	No	Yes in e+e-	Yes at NLL
Corrections beyond LC	No	No	No	Yes at NLL (NODS)
NLO matching available?	Yes in e+e-, using S-MC@NLO at exact colour	Yes in e+e- on paper, not yet implemented	Yes in e+e-	Yes for CS (dBNLO, P2B or positive weights ESME)
Multi-jet merging?	In e+e-; 5 jets (NLO), in pp; 3 jets (LO)	No	No	No
Particle masses?	Yes in e+e-	No	No	Yes in e+e-
Resonances?	Yes in e+e-	No	No	No
Publicly available?	Python codes, should become part of Sherpa	No, but should become part of Pythia8	No, but should become part of Herwig	Yes, interfaced to Pythia8

N^pLL

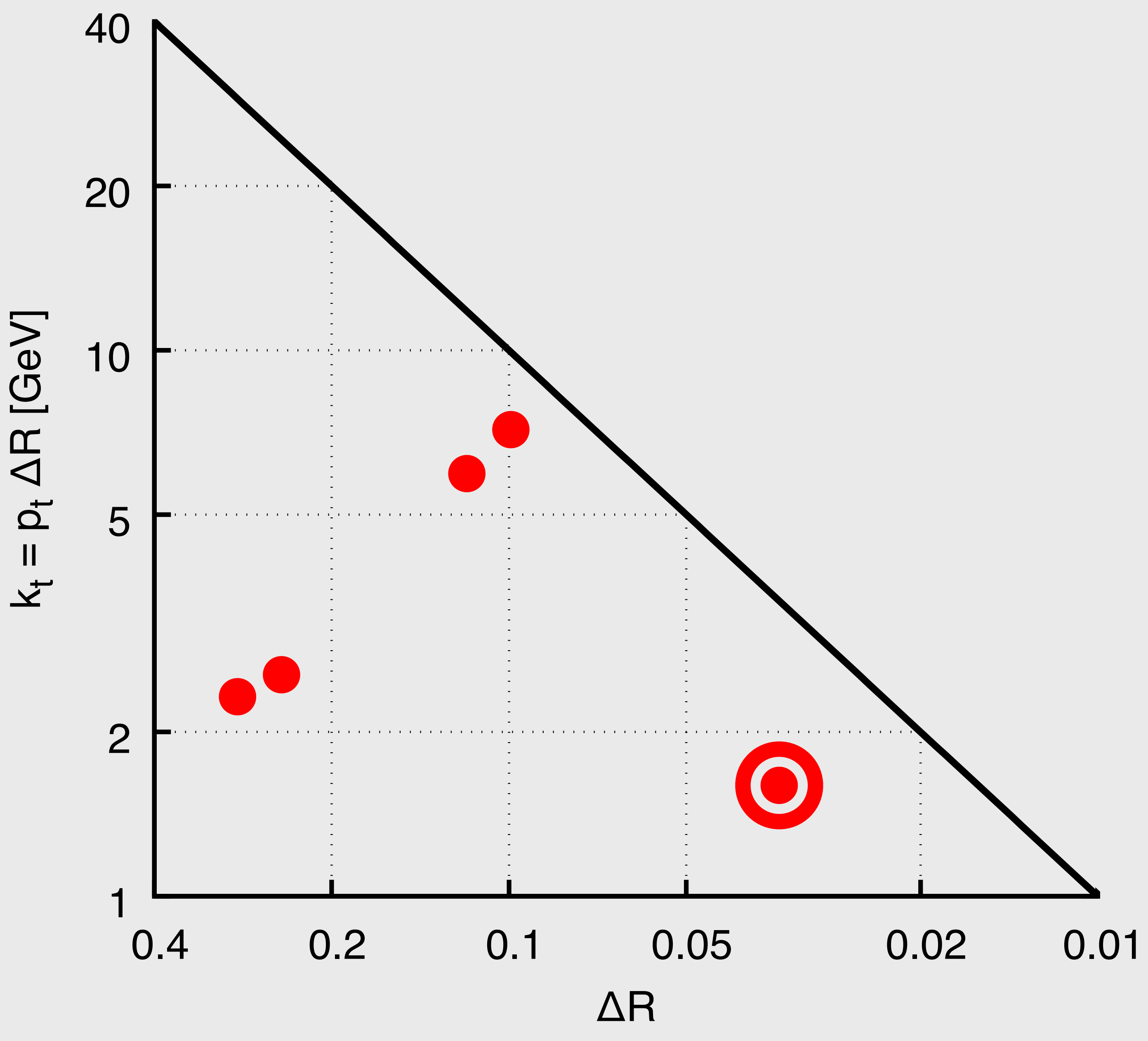
A Matrix Element condition

- correctly reproduce n-parton tree-level matrix element for arbitrary configurations, so long as all groups of up to $\boldsymbol{p}$ emissions are well separated in the Lund diagram
- For groups of $\boldsymbol{k}$ emissions, be accurate up to $\boldsymbol{p-k}$ loops
- supplement with unitarity, $\boldsymbol{p+1}$-loop running coupling & cusp anomalous dimension

Resummation condition:

reproduce N^pLL ($\alpha_s^n L^{n+1-p}$) results for all standard resummations

- global event shapes
- non-global observables
- fragmentation functions ($\alpha_s^n L^{n+1-p} \equiv N^{p-1}LL$)
- multiplicities ($\alpha_s^n L^{2n-p}$)
- …



Melissa van Beekveld
NIKHEF

Mrinal Dasgupta
Manchester

Basem El-Menoufi
Turin

Silvia Ferrario Ravasio
Turin

Keith Hamilton
Univ. Coll. London

Jack Helliwell
Monash

Alexander Karlberg
Oxford

Pier Monni
CERN

GPS
Oxford

Nicolas Schalch
Oxford

Ludovic Scyboz
Monash

Alba Soto-Ontoso
Granada

Grégory Soyez
IPhT, Saclay

Silvia Zanoli
Oxford

PanScales

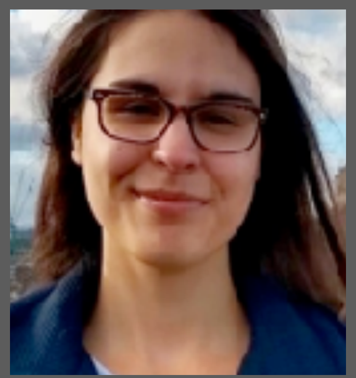
A project to bring logarithmic understanding and accuracy to parton showers

former members

Frédéric Dreyer

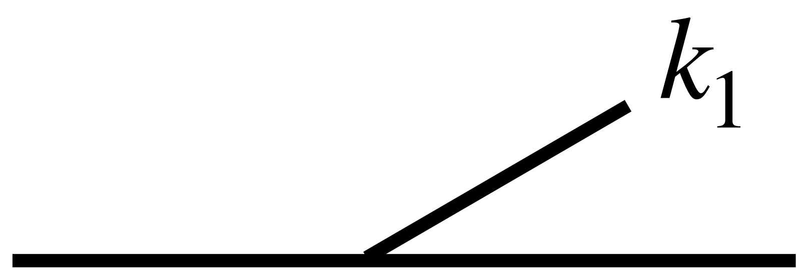
Rob Verheyen

Rok Medves



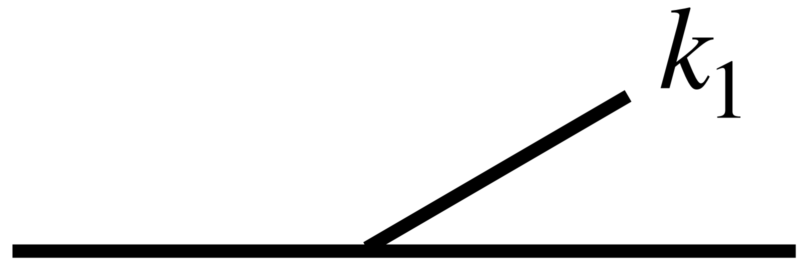
Emma Slade

Towards NNLL: each new emission's distribution conditional on previous emission

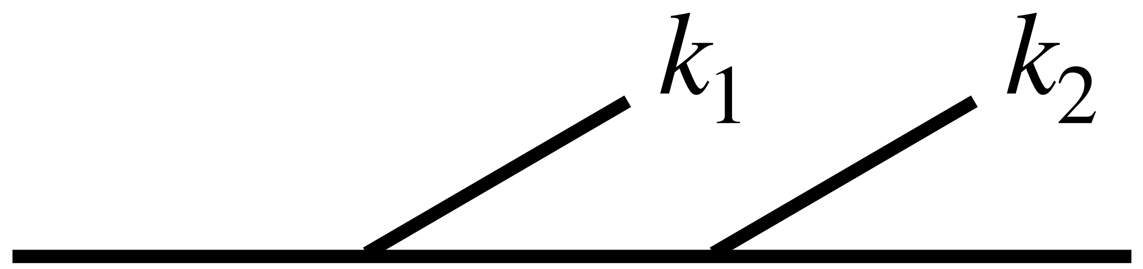


Distribute k_1 according to $M^2(k_1)$

Towards NNLL: each new emission's distribution conditional on previous emission

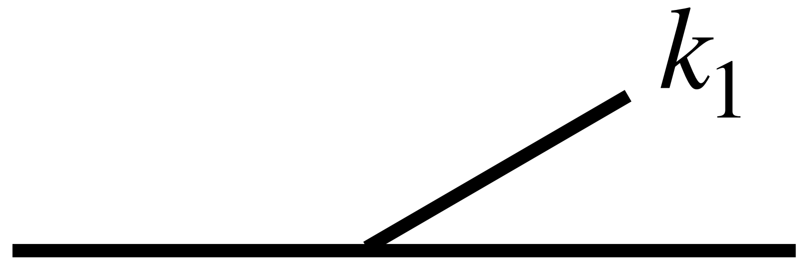


Distribute k_1 according to $M^2(k_1)$

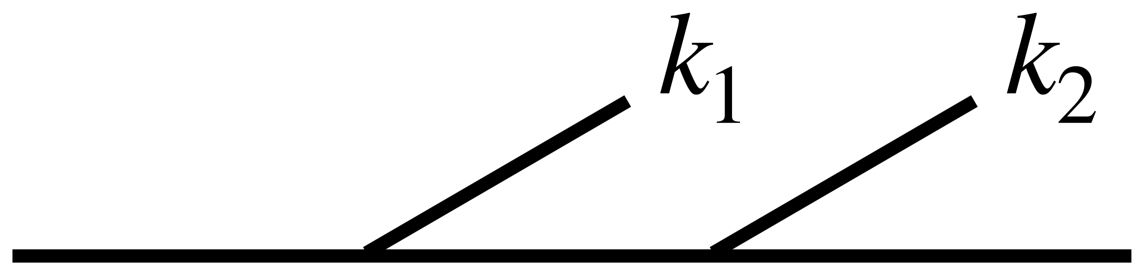


Distribute k_2 according to $M^2(k_1, k_2)/M^2(k_1)$

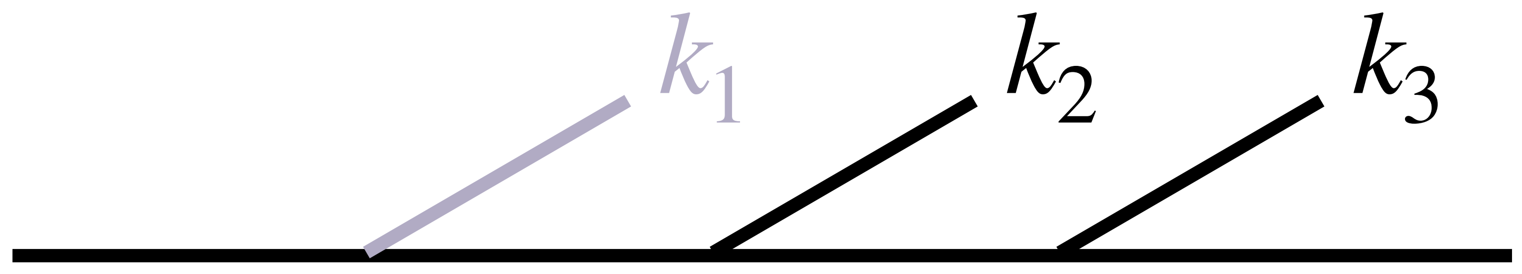
Towards NNLL: each new emission's distribution conditional on previous emission



Distribute k_1 according to $M^2(k_1)$

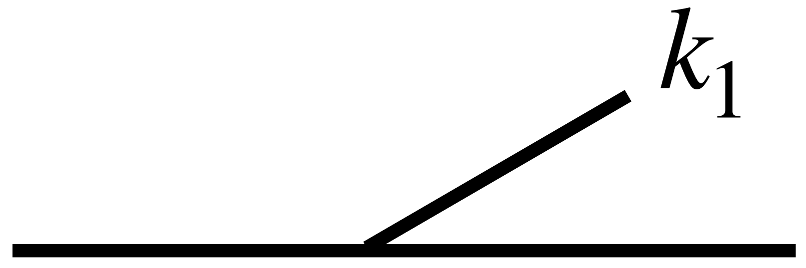


Distribute k_2 according to $M^2(k_1, k_2)/M^2(k_1)$

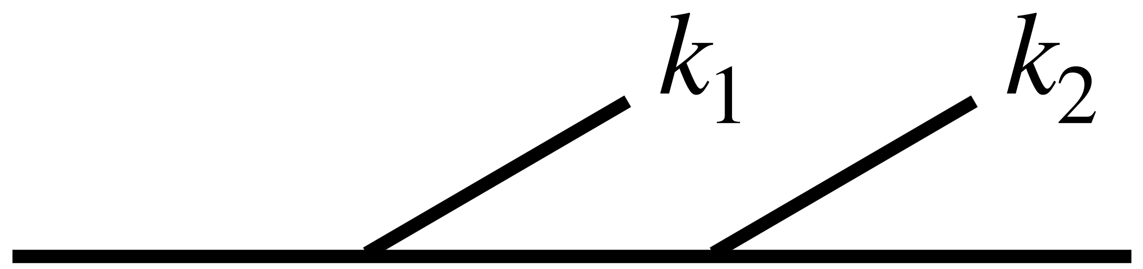


Distribute k_3 according to $M^2(k_2, k_3)/M^2(k_2)$

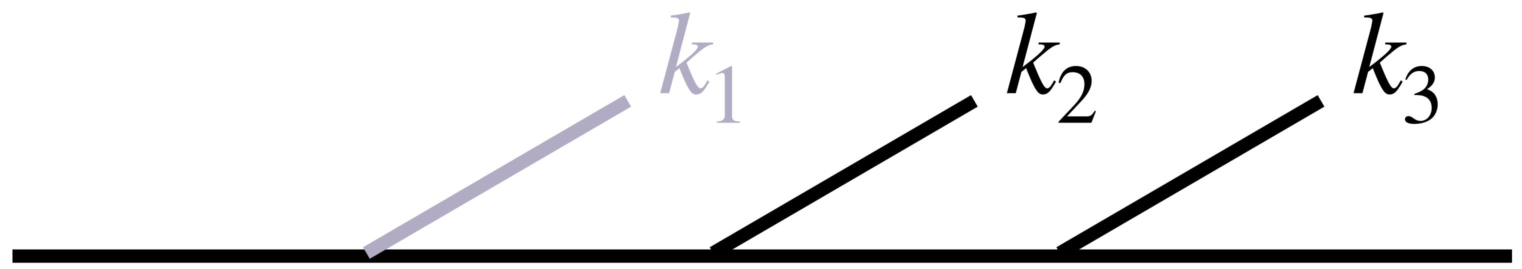
Towards NNLL: each new emission's distribution conditional on previous emission



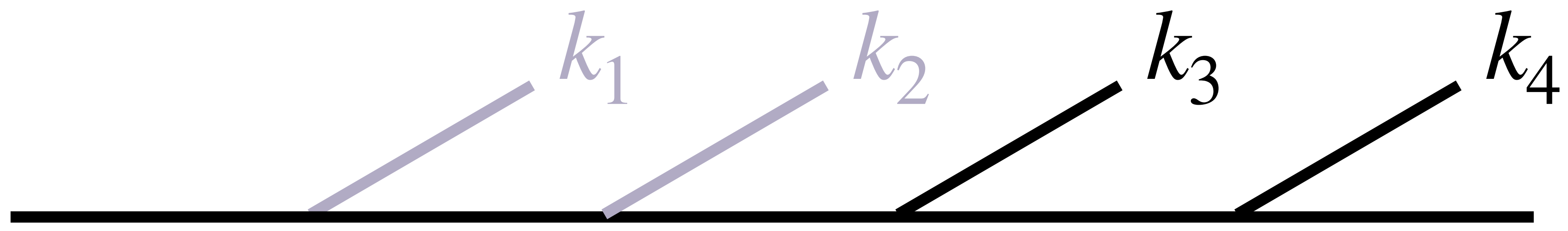
Distribute k_1 according to $M^2(k_1)$



Distribute k_2 according to $M^2(k_1, k_2)/M^2(k_1)$

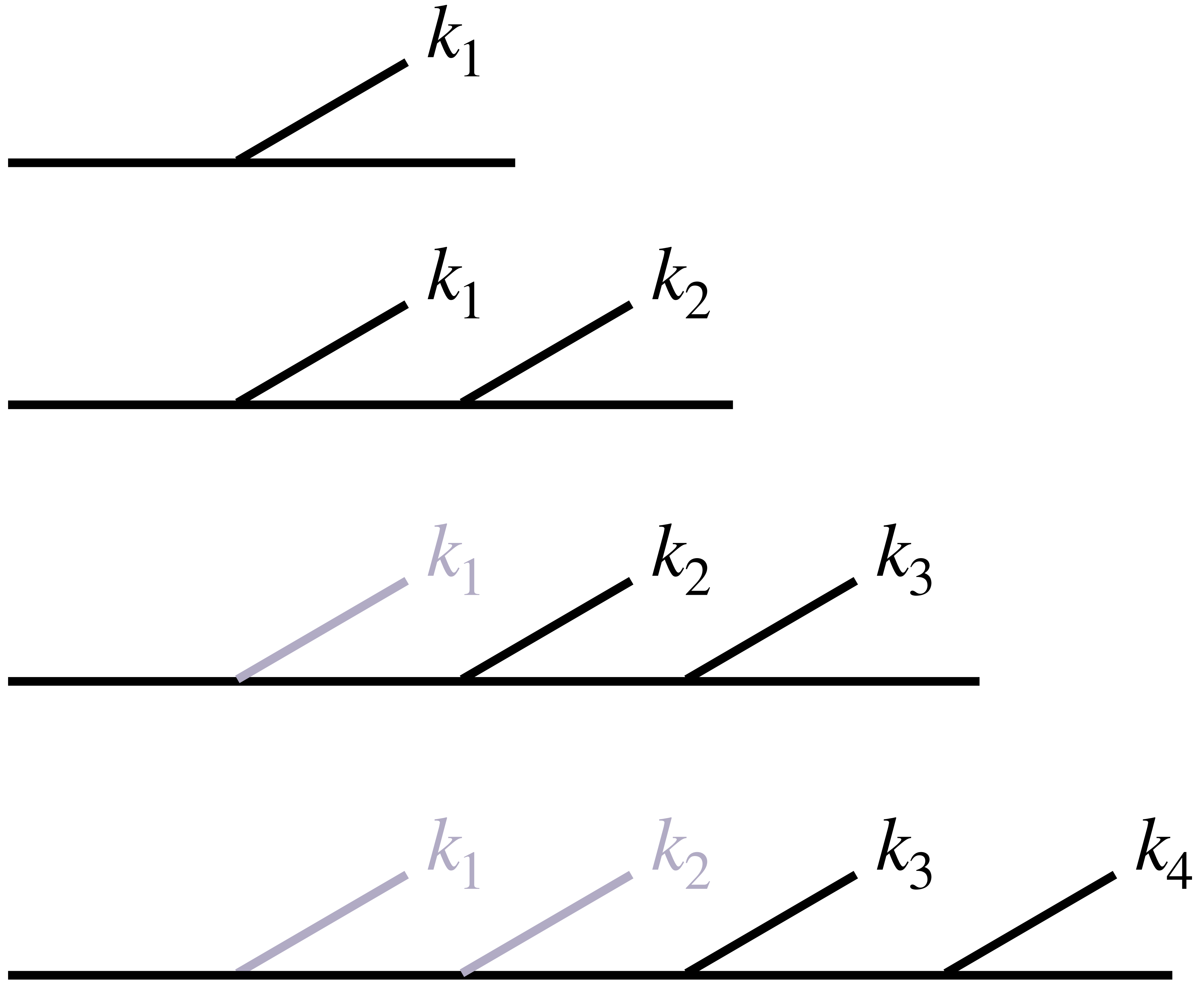


Distribute k_3 according to $M^2(k_2, k_3)/M^2(k_2)$



Distribute k_4 according to $M^2(k_3, k_4)/M^2(k_3)$

Towards NNLL: each new emission's distribution conditional on previous emission



Distribute k_1 according to $M^2(k_1)$

Distribute k_2 according to $M^2(k_1, k_2)/M^2(k_1)$

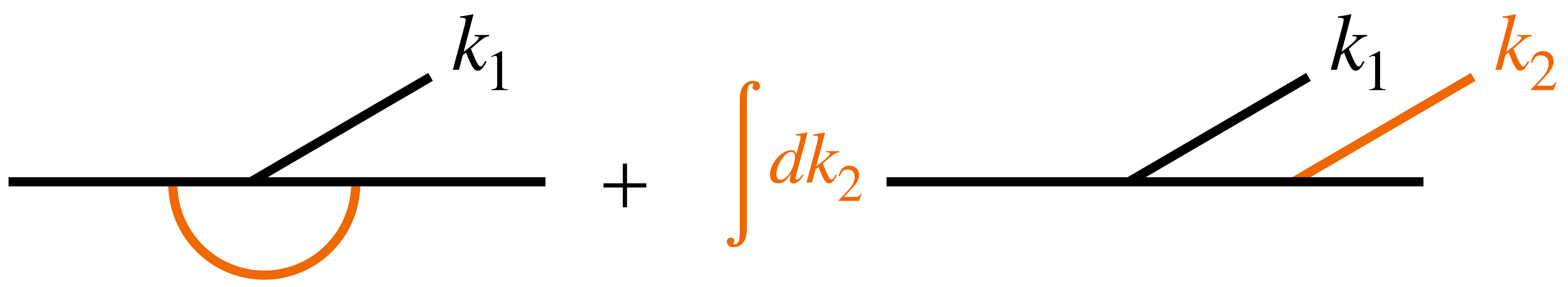
Distribute k_3 according to $M^2(k_2, k_3)/M^2(k_2)$

Distribute k_4 according to $M^2(k_3, k_4)/M^2(k_3)$

Relies on factorisation: e.g. $M^2(k_1, k_2, k_3, k_4)/M^2(k_1, k_2, k_3) \to M^2(k_3, k_4)/M^2(k_3)$
if 3 and 4 well separated in Lund plane from 1 and 2

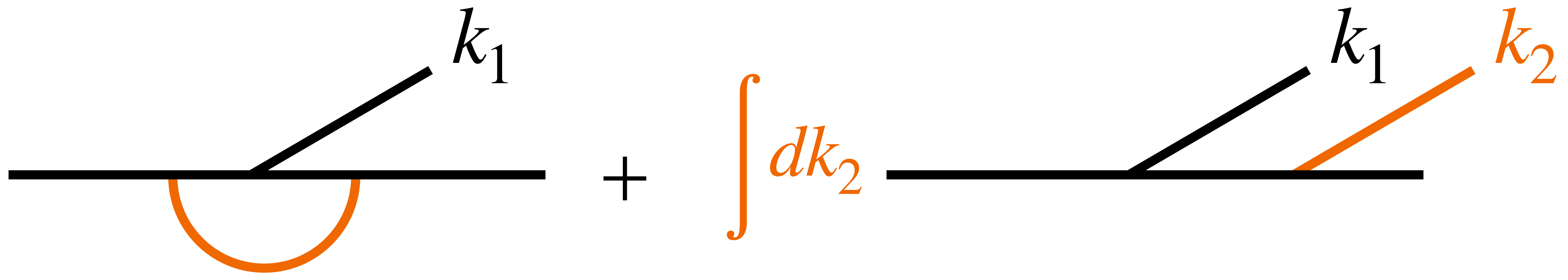
[factorised matrix elements given in Dokshitzer, Marchesini & Oriani '92, Campbell & Glover, hep-ph/9710255, Catani & Grazzini hep-ph/9810389, etc.]

Account for virtual corrections associated with each emission

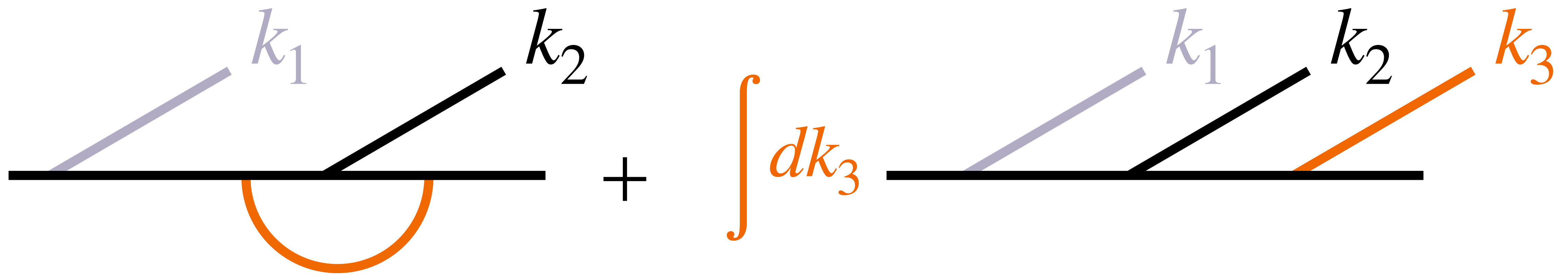


NLO correction to k_1 emission intensity sums loop correction and all possible scenarios for the next emission

Account for virtual corrections associated with each emission



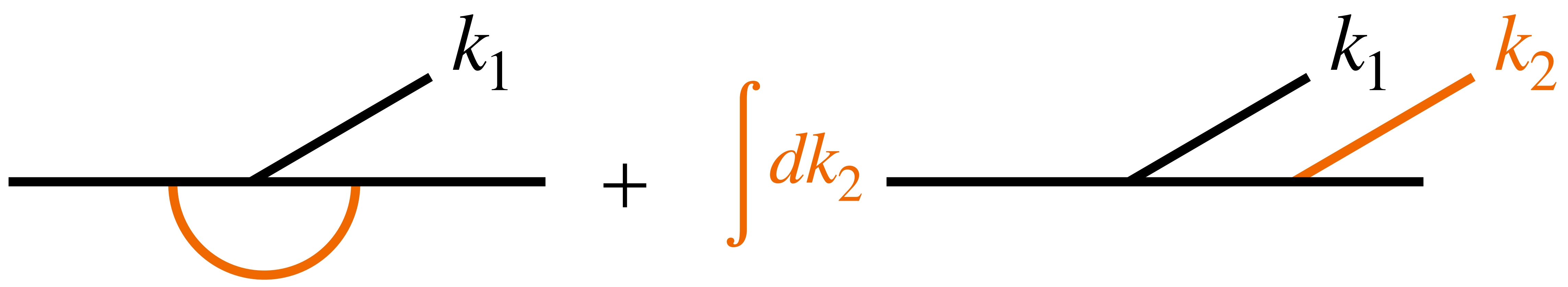
NLO correction to k_1 emission intensity sums loop correction and all possible scenarios for the next emission



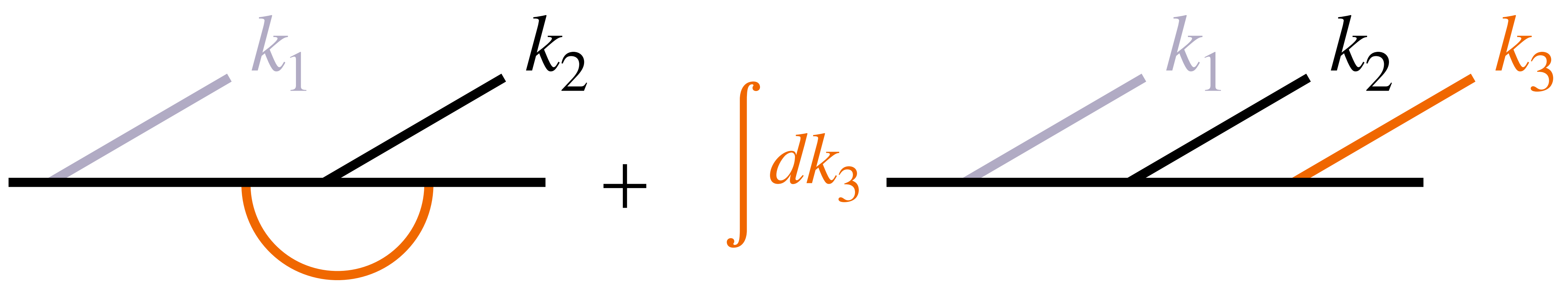
NLO correction to k_2 emission intensity sums loop correction and all possible scenarios for the next emission

etc.

Account for virtual corrections associated with each emission



NLO correction to k_1 emission intensity sums loop correction and all possible scenarios for the next emission



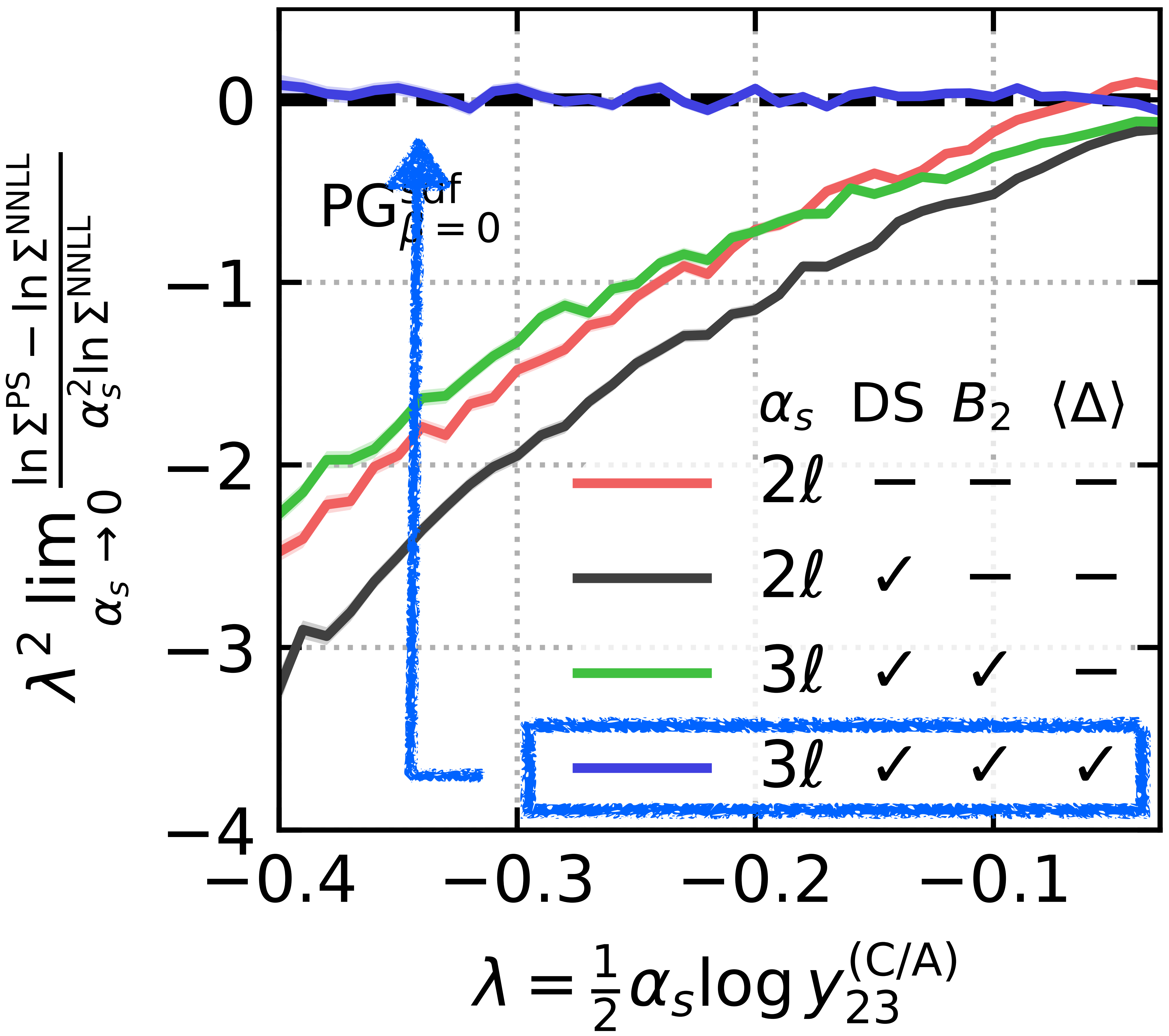
NLO correction to k_2 emission intensity sums loop correction and all possible scenarios for the next emission

etc.

Again relies on factorisation, e.g. when 1 and 2 are well separated in the Lund plane + careful nesting, cf. van Beekveld, Dasgupta, El-Menoufi, Helliwell, Monni, GPS 2409.08316 (see also Hartgring, Laenen & Skands, 1303.4974, Campbell et al 2108.07133 at fixed order)

Testing NNLL for event shapes (so far only for e+e− collisions)

Difference relative to known NNLL

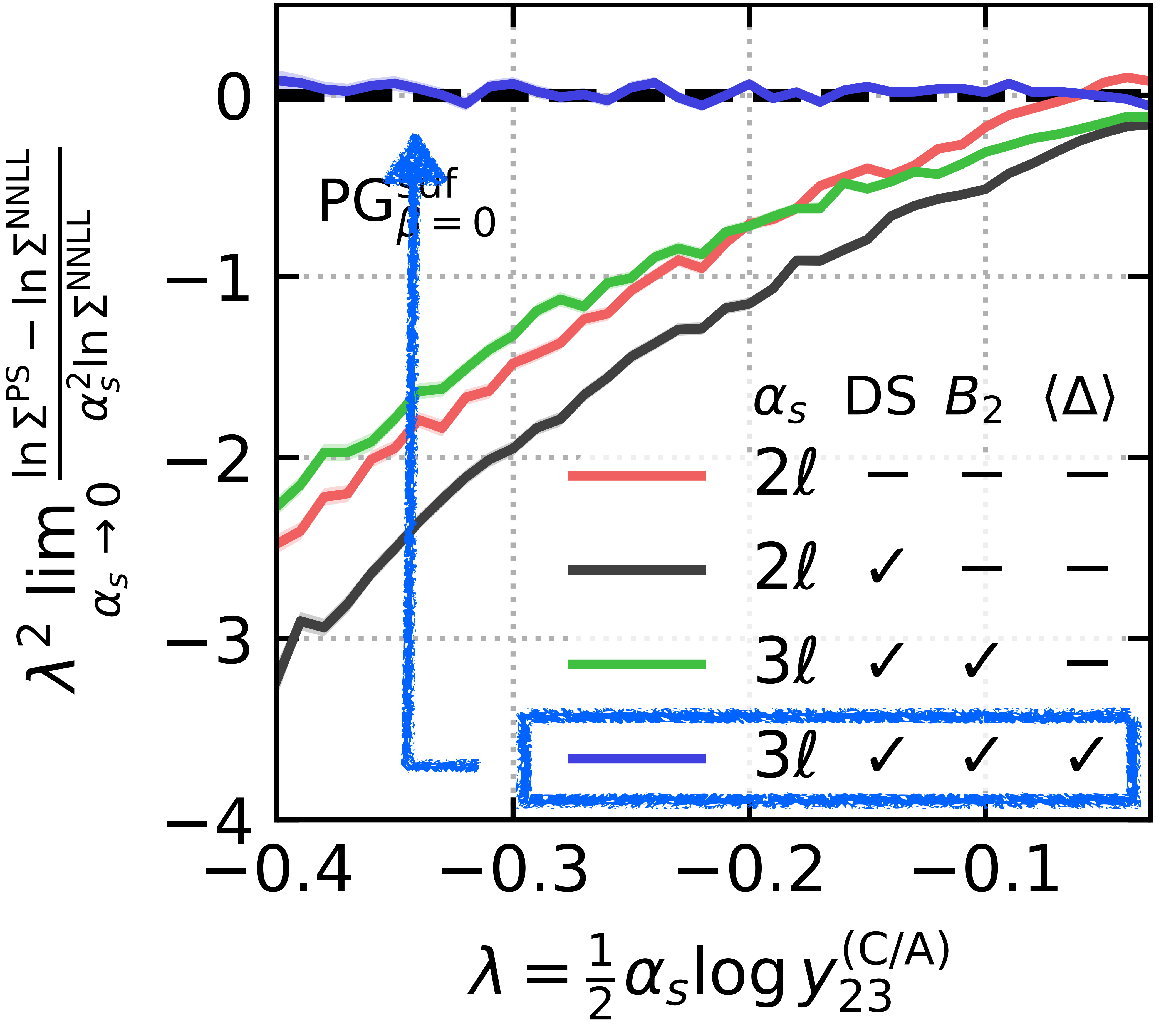


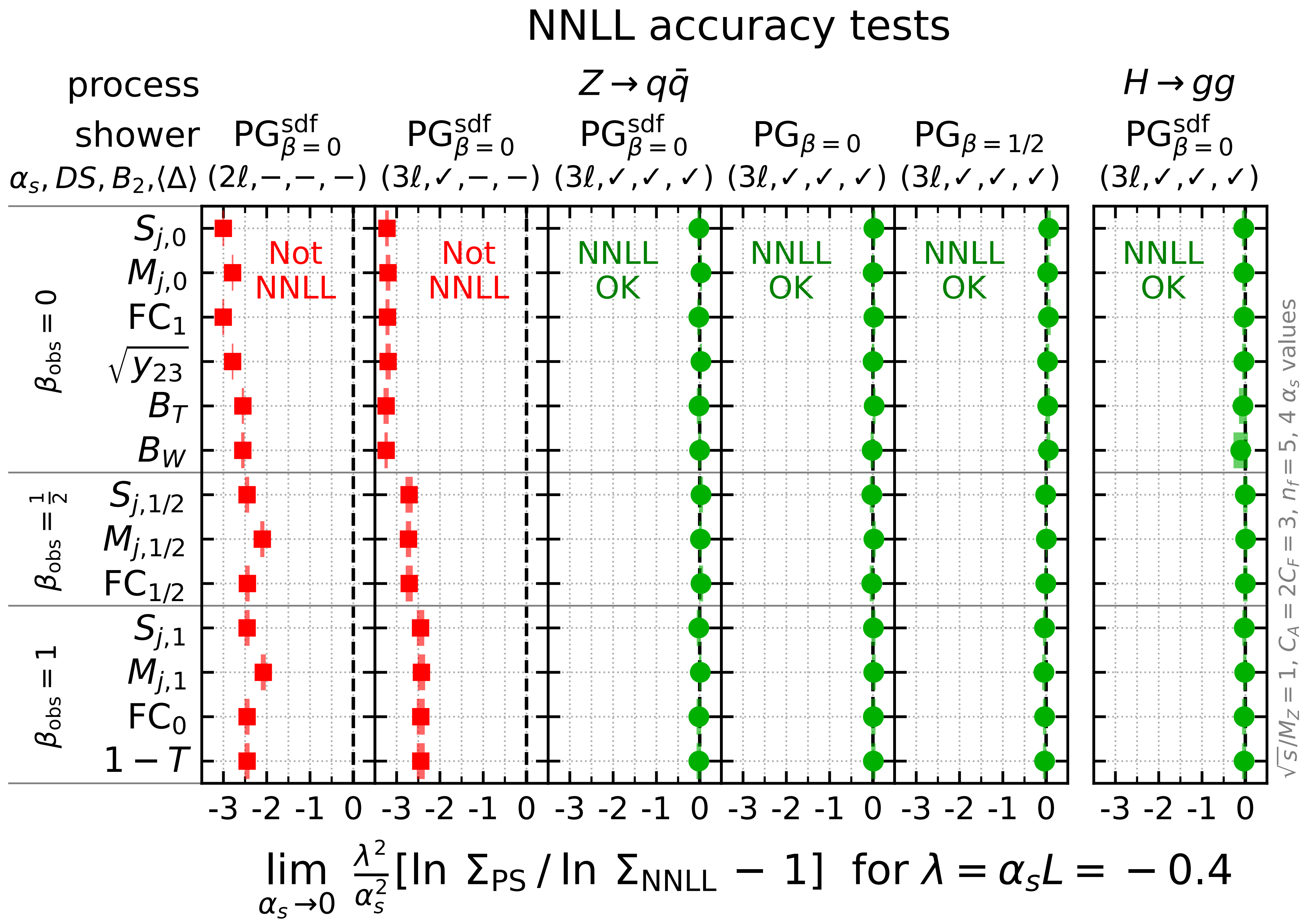
need to analyse and account for all possible sources of NNLL contribution

(some, which don't affect event shapes, are still work in progress)

Testing NNLL for event shapes (so far only for e+e− collisions)

Difference relative to known NNLL



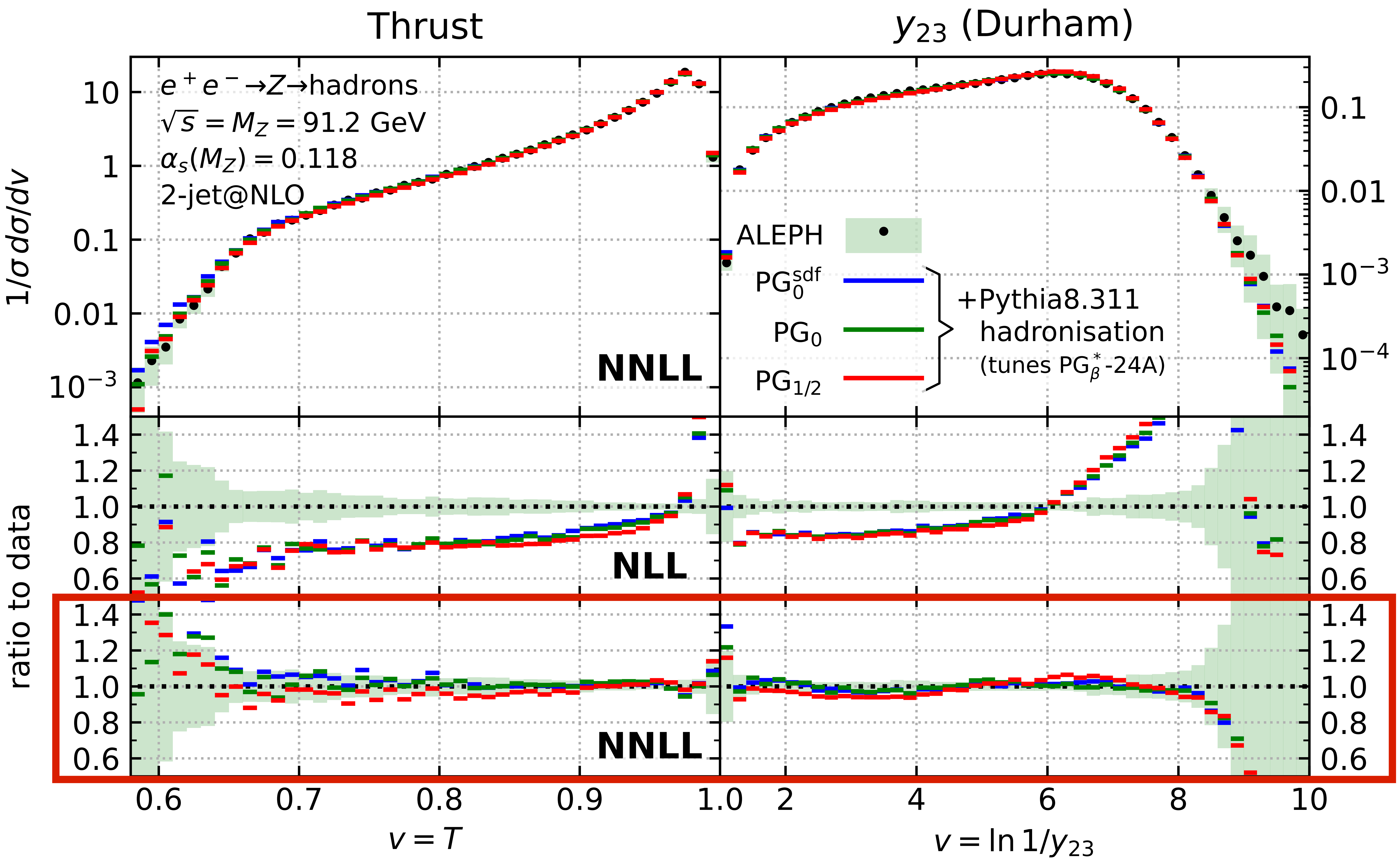


need to analyse and account for all possible sources of NNLL contribution

(some, which don't affect event shapes, are still work in progress)

Comparing to LEP event-shape data

Ferrario Ravasio et al, 2307.11142,
van Beekveld et al, 2406.02661



NNLL brings 20% effects ($\sim \alpha_s$)

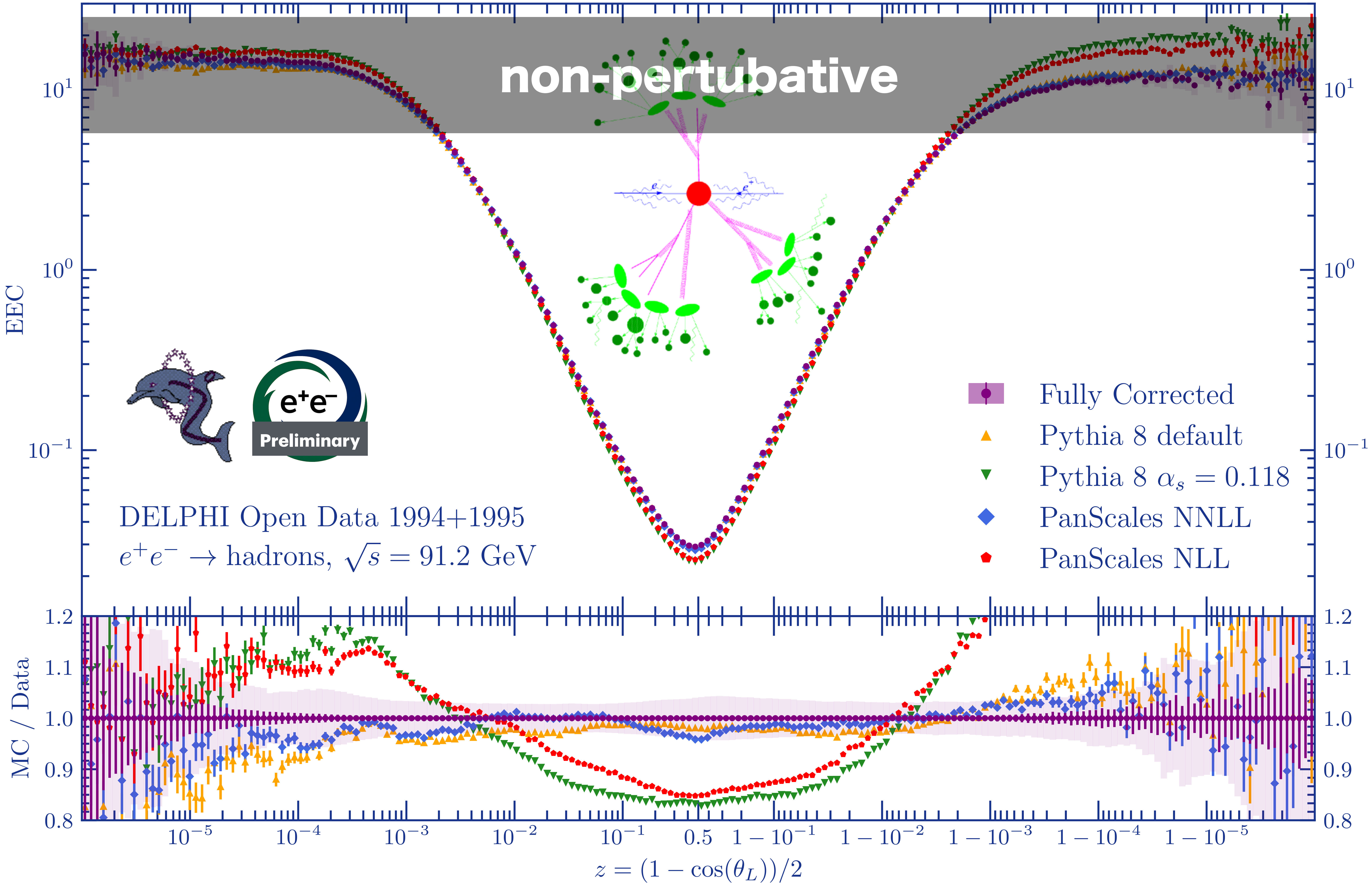
Dramatically improves agreement with data, using a “normal” $\alpha_s = 0.118$

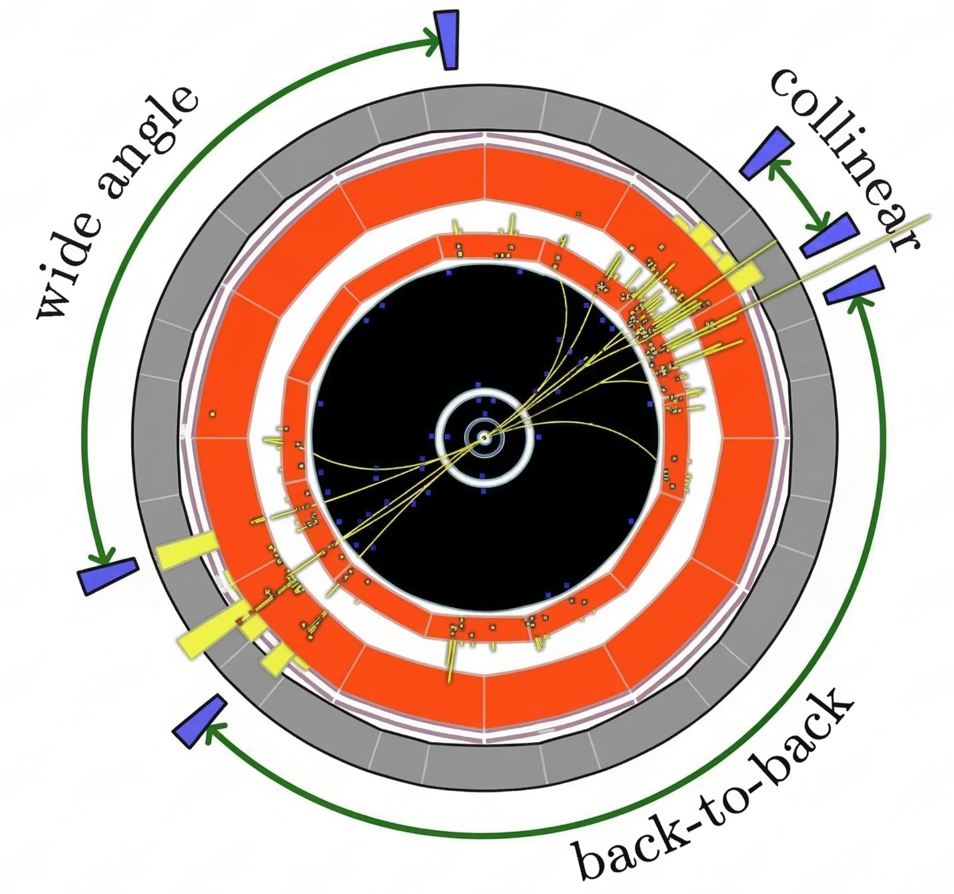
NB: 3-jet @ NLO still missing for robust pheno conclusions

NNLL

for event shapes; not yet general NNLL

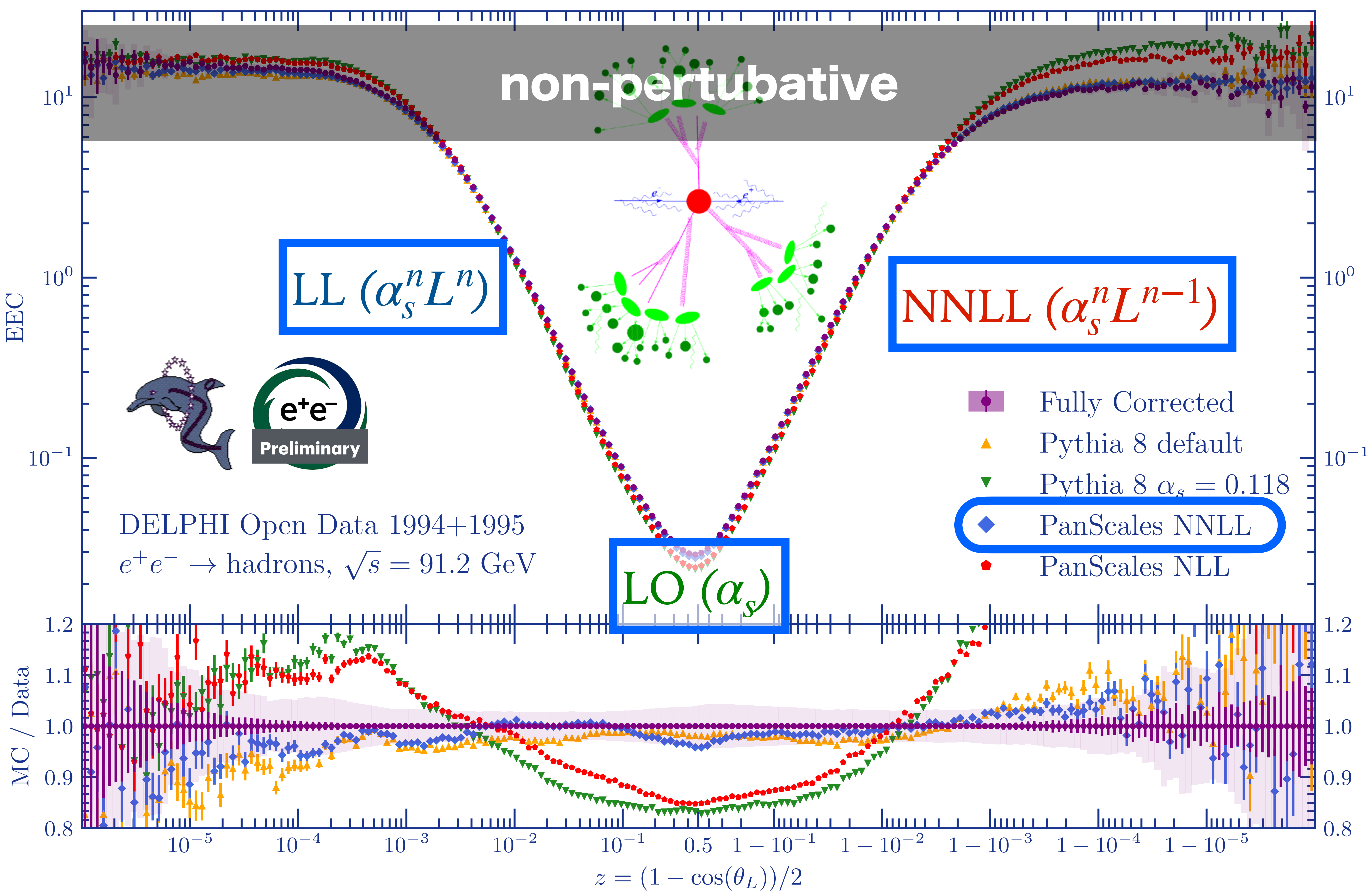
EEC, e+e− Alliance measurement on archived data

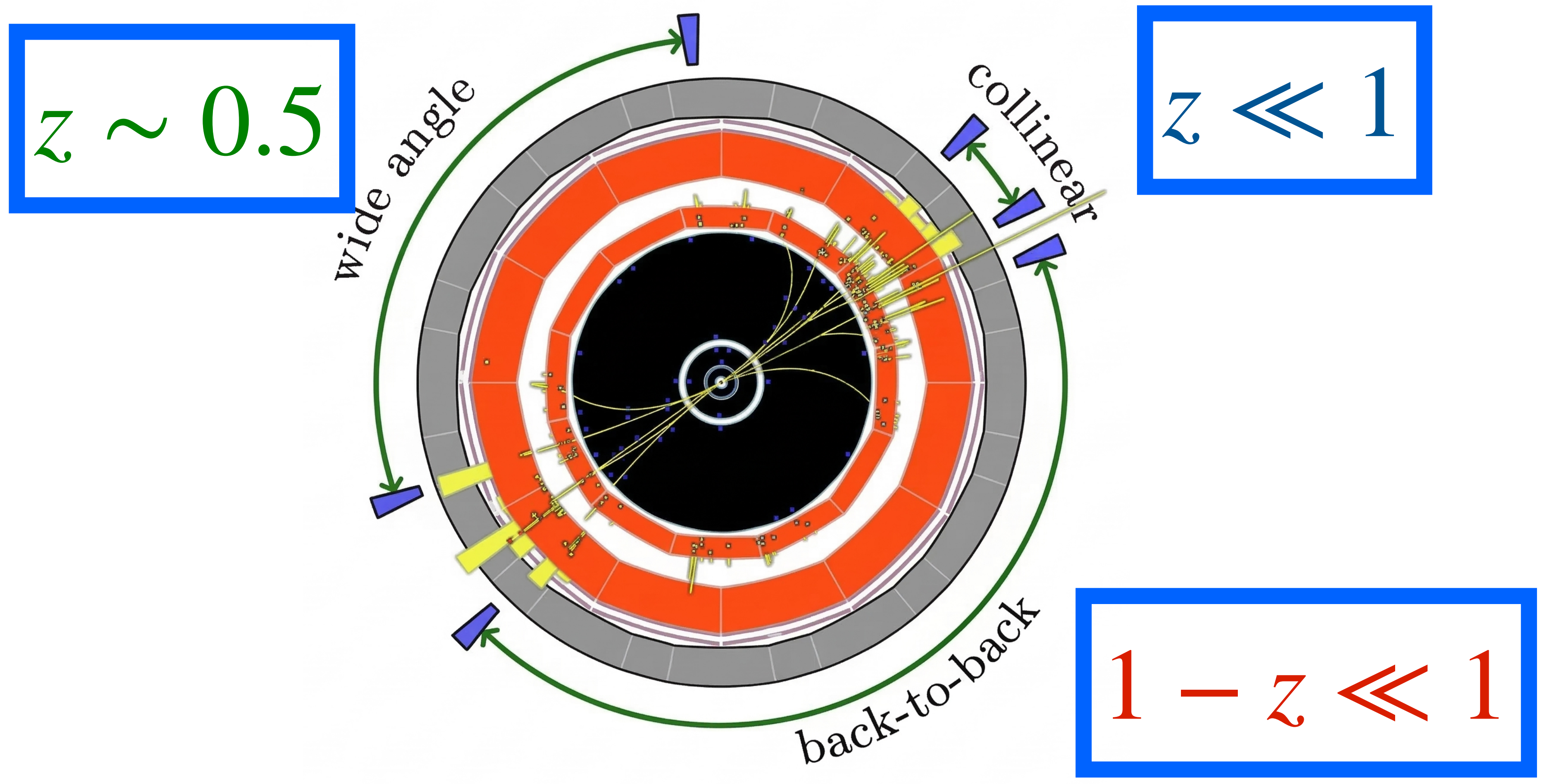




- State-of-the-art PanScales @ NNLL describe the data well without parton shower tuning
  - 3-jets in the ME
- Leading Log Pythia8 generator also describe the data with parton shower tuning

EEC, e+e− Alliance measurement on archived data





- State-of-the-art PanScales @ NNLL describe the data well without parton shower tuning
  - 3-jets in the ME

- Leading Log Pythia8 generator also describe the data with parton shower tuning

Lance Dixon

Philadelphia Eagles, Linebacker

Age: 24y-11m-6d (Jul 18, 2001)	**Country:** US	**Drafted:** Undrafted, PHI, 2025
	College: Toledo	**Agent(s):** Paul Bobbitt

The promise of perturbative QFT

Follow the rules (Feynman diagrams)

Ask a computer to work through maths

Out comes a prediction

Ask the computer to draw more diagrams, work harder, and you get more accuracy

the hope is that the technology that gets developed for "standard" pQFT calculations can be leveraged to get accuracy not just at fixed order, but across the full range of perturbative scales in simulations