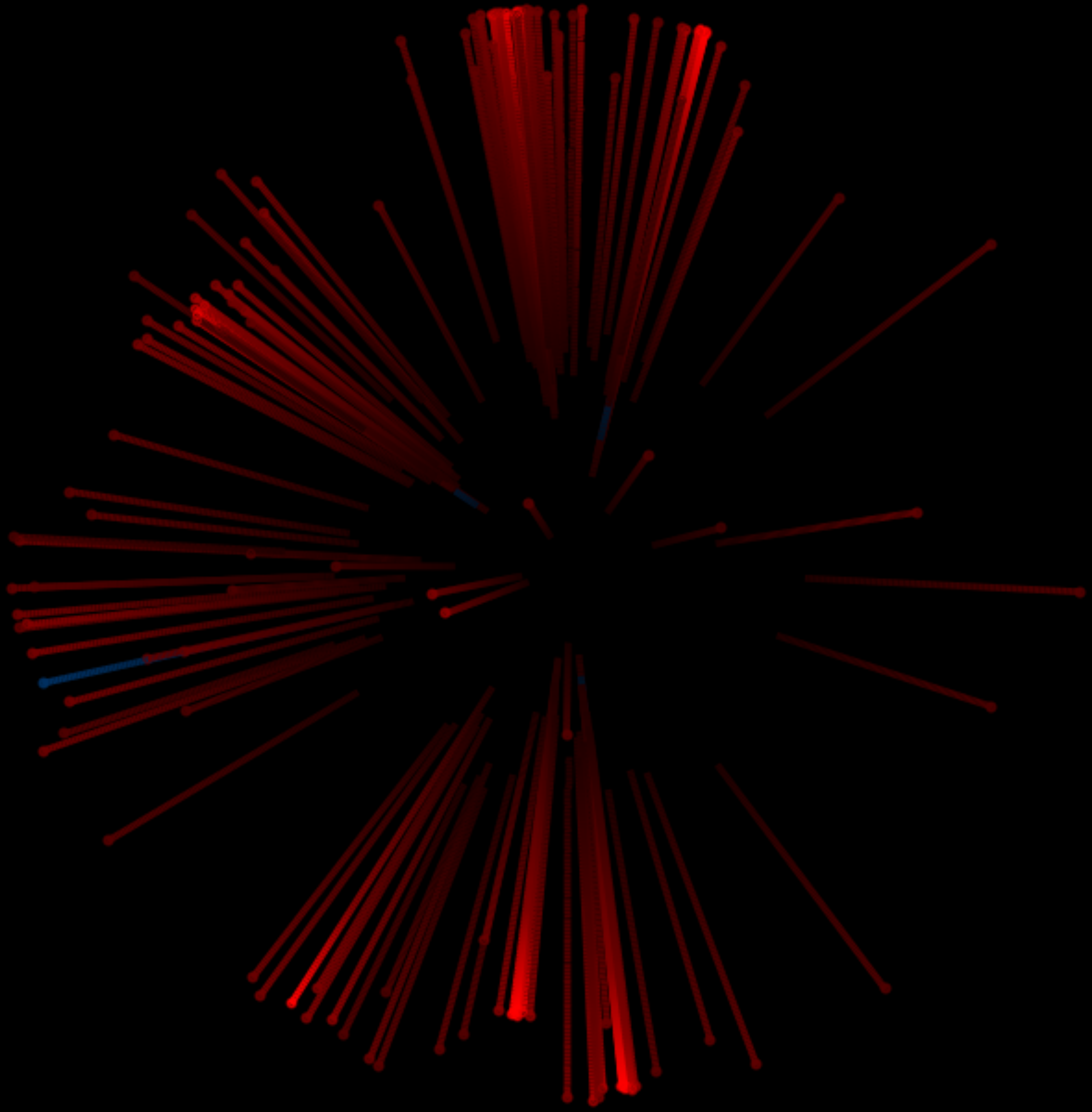
The power and limits of parton showers

DESY Theory Seminar
20 June 2022



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

Science and Technology Facilities Council
THE ROYAL SOCIETY
UNIVERSITY OF OXFORD
European Research Council
Established by the European Commission

The context of this talk: LHC physics

Standard-model physics (QCD & electroweak)

100 MeV – 4 TeV

top-quark physics

170 GeV – O(TeV)

Higgs physics

125 GeV – 500 GeV

direct new-particle searches

100 GeV – 8 TeV

flavour physics (bottom & some charm)

1 – 5 GeV

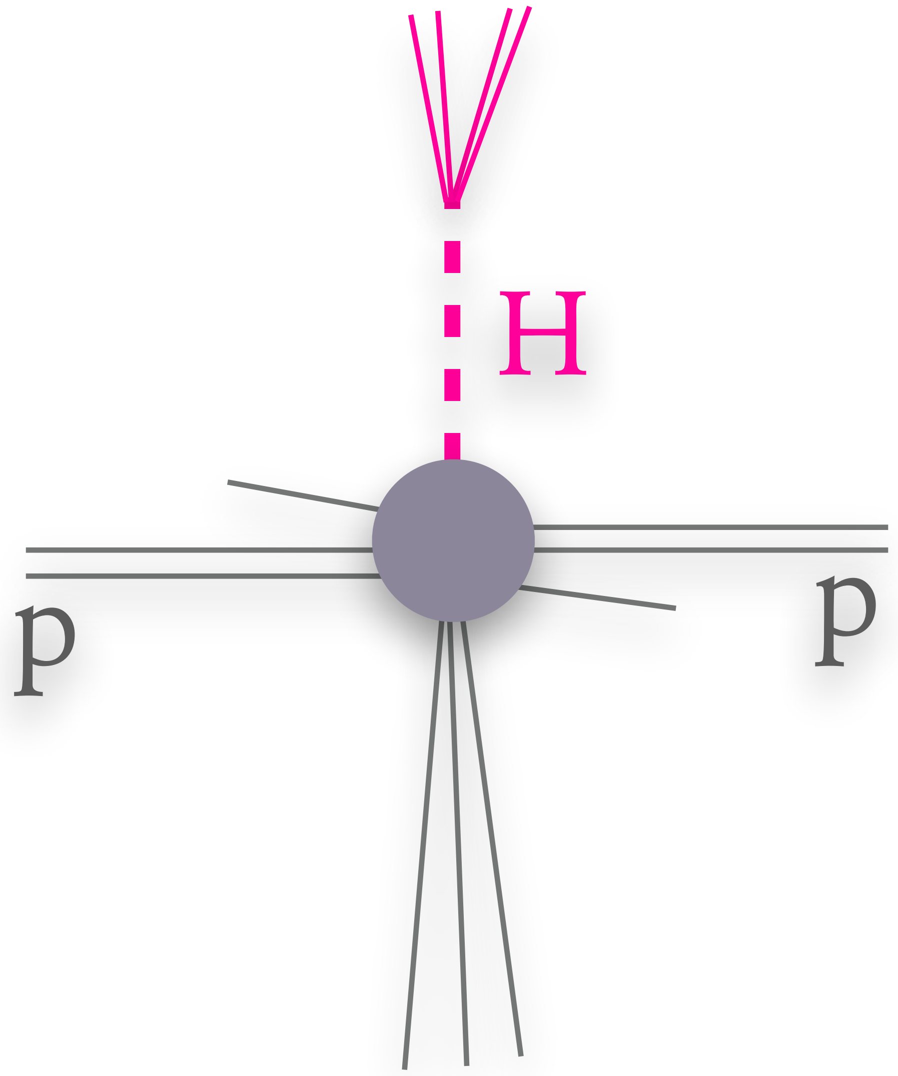
heavy-ion physics

100 MeV - 500 GeV

high p_T Higgs & [SD] jet mass

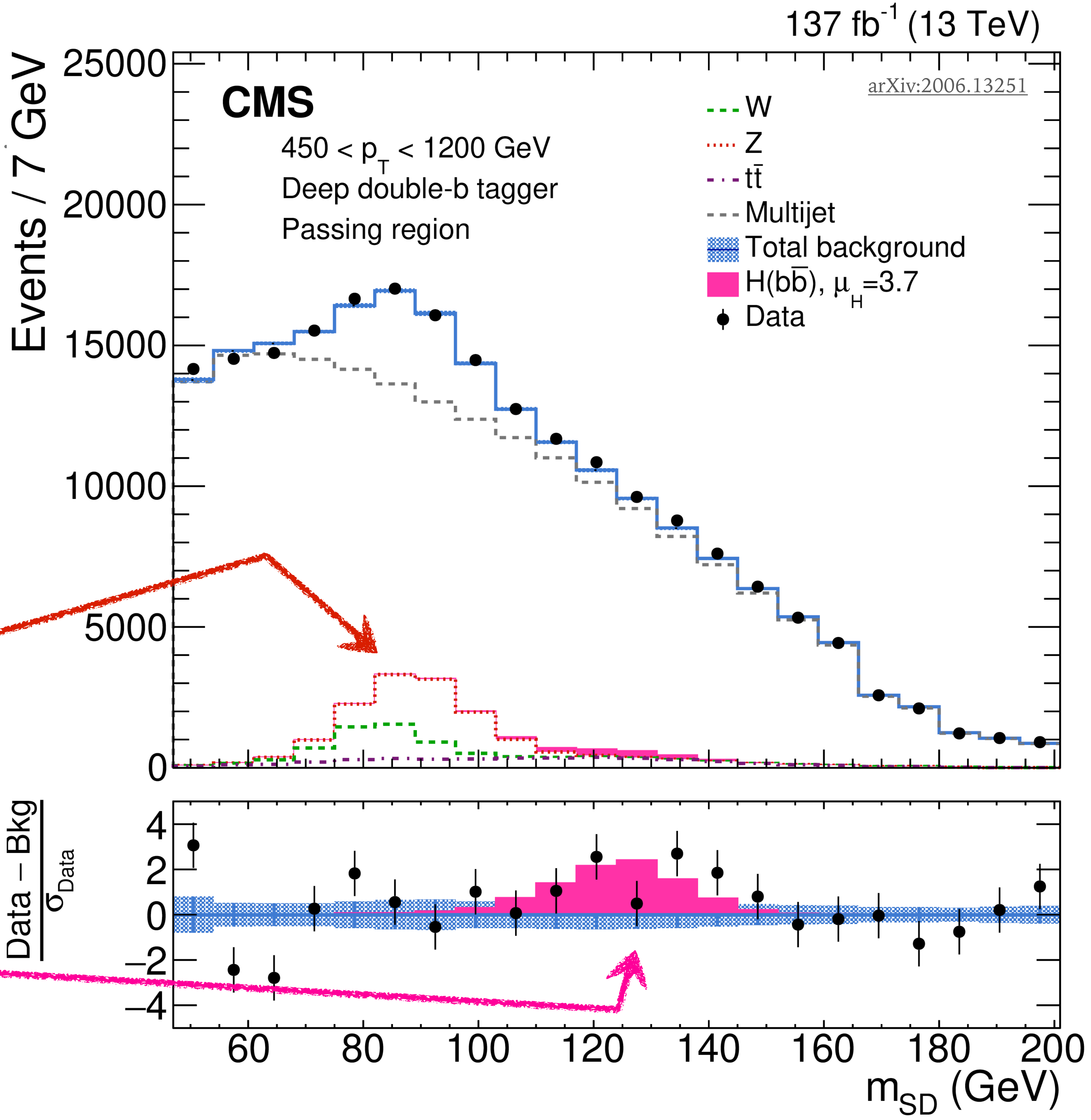
We wouldn’t trust electromagnetism if we’d only tested it at one length/momentum scale.

New Higgs interactions need testing at both low and (here) **high momenta.**



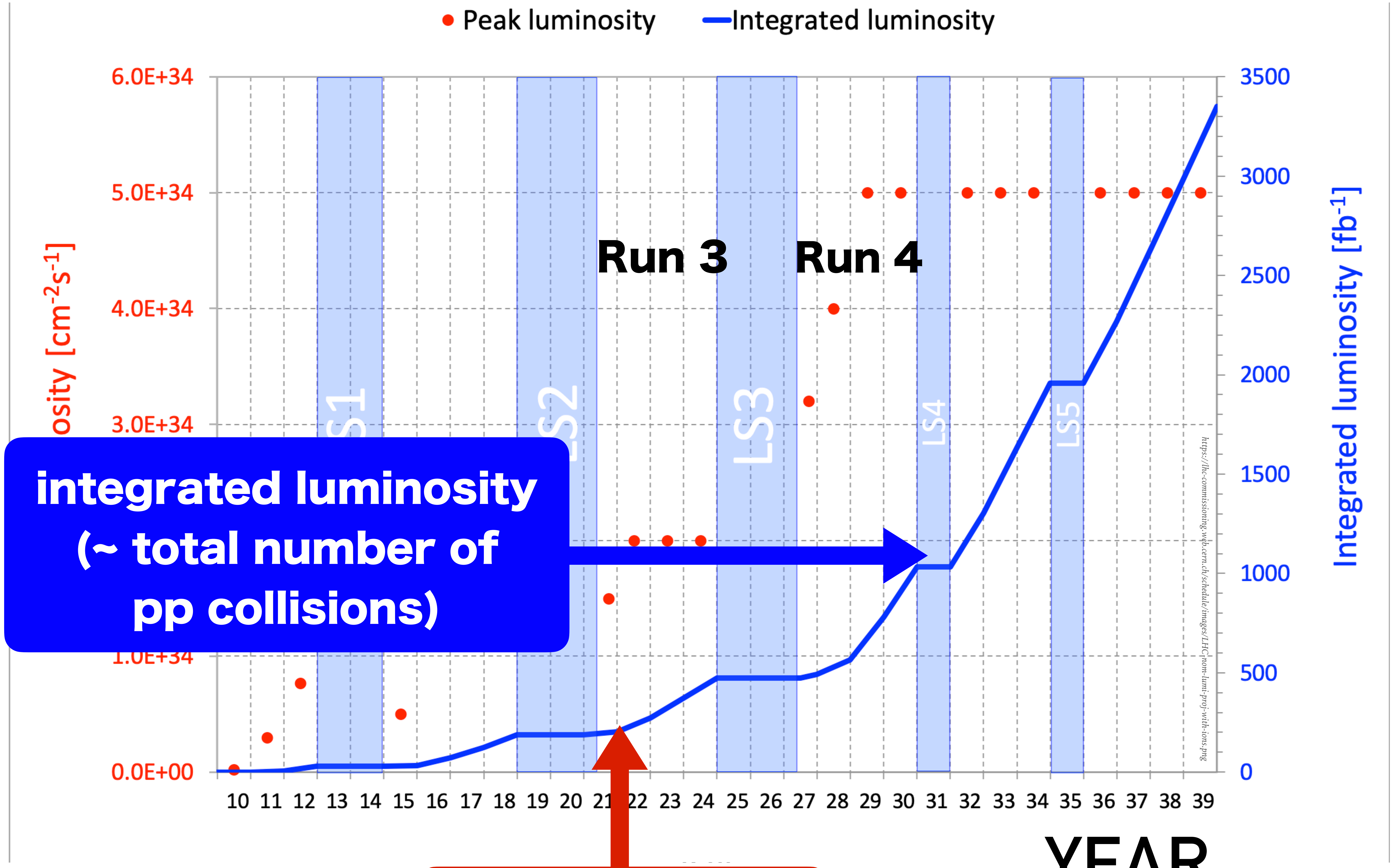
high-p_T
$Z \to bb$

high-p_T
$H \to bb$
(2.5 σ)



arXiv:2006.13251

LHC luminosity v. time



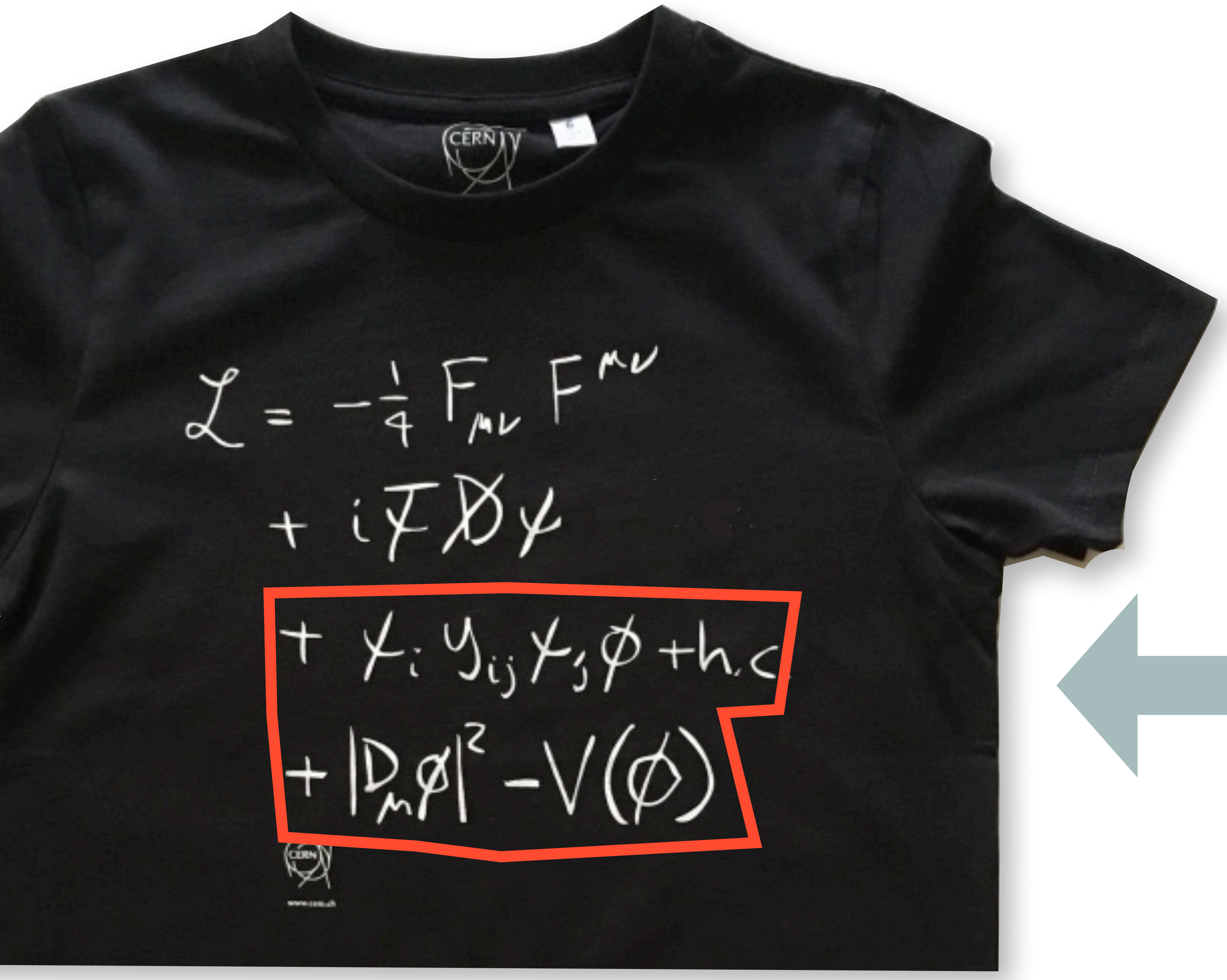
integrated luminosity (~ total number of pp collisions)

today: 140 fb^{-1}

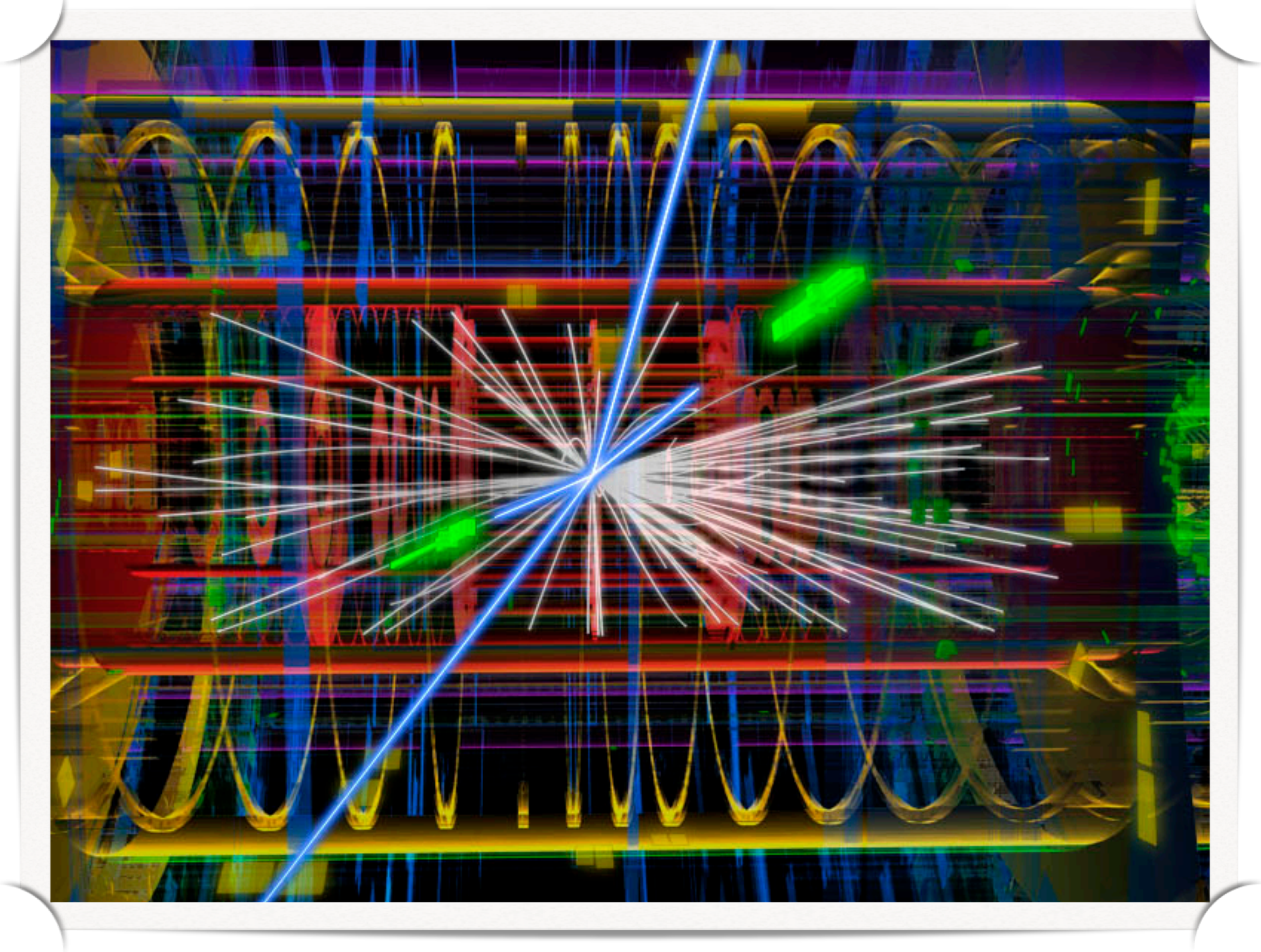
95% of collisions still to be delivered

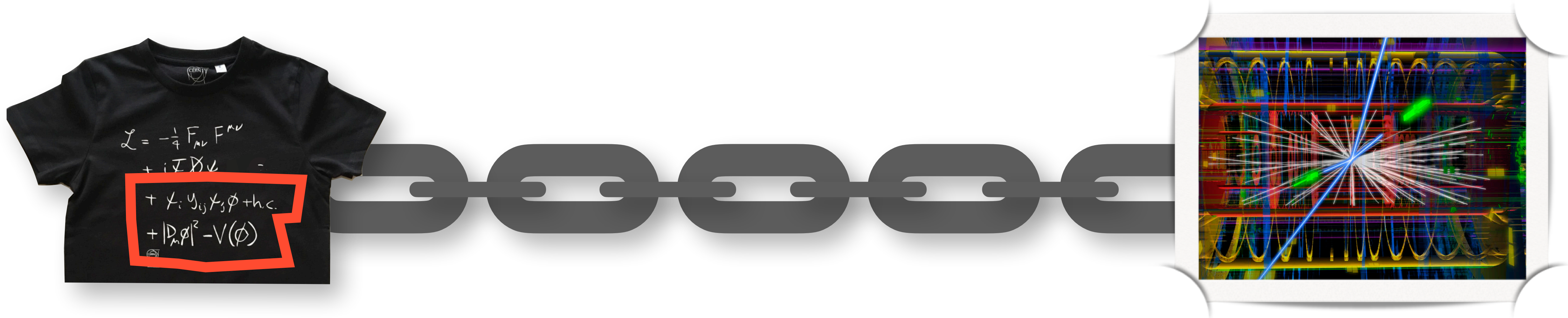
UNDERLYING THEORY

EXPERIMENTAL DATA



how do you make quantitative connection?

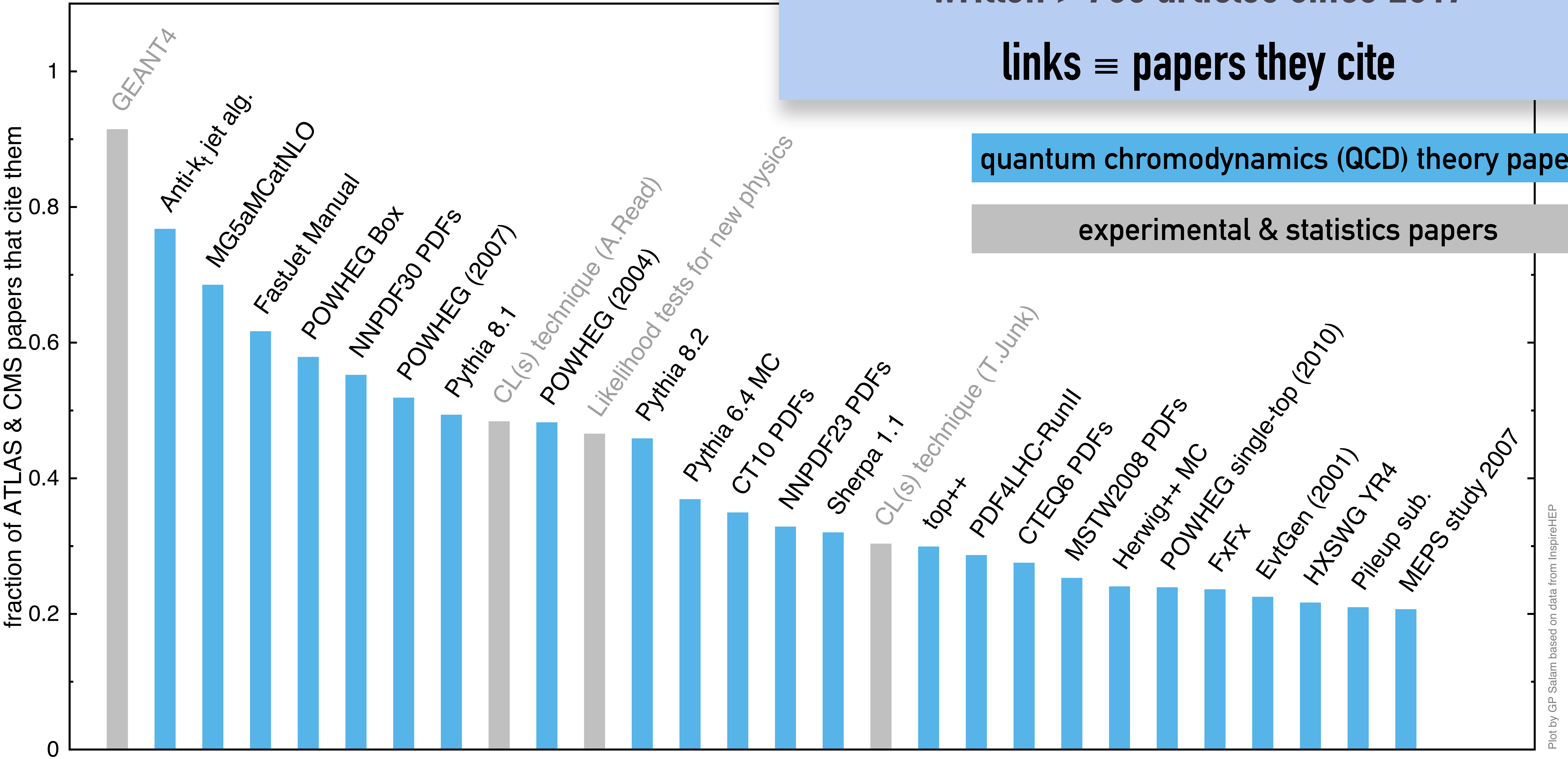




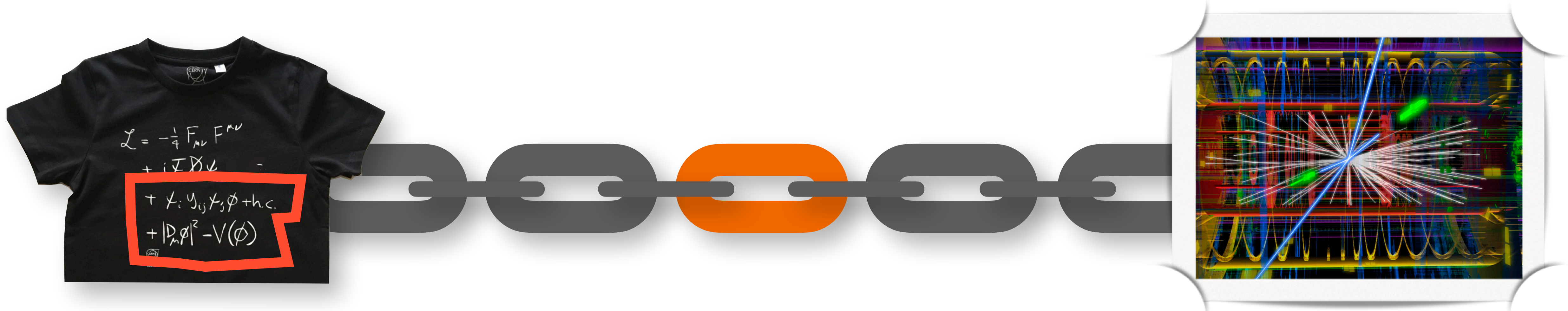
Lagrangian ↔ data

ATLAS and CMS (big LHC expts.) have written >700 articles since 2017

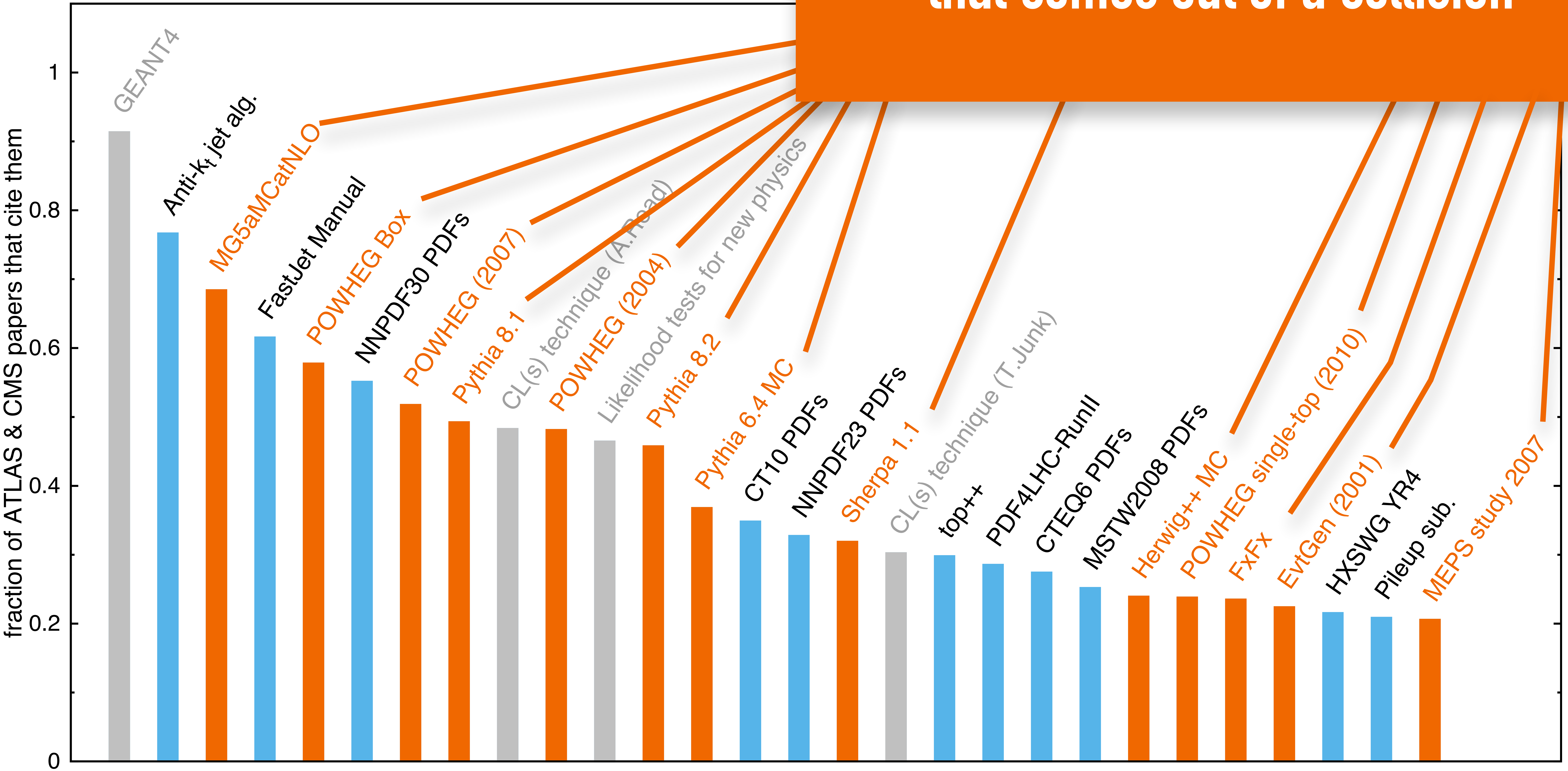
links ≡ papers they cite



Plot by GP Salam based on data from InspireHEP



predicting full particle structure that comes out of a collision



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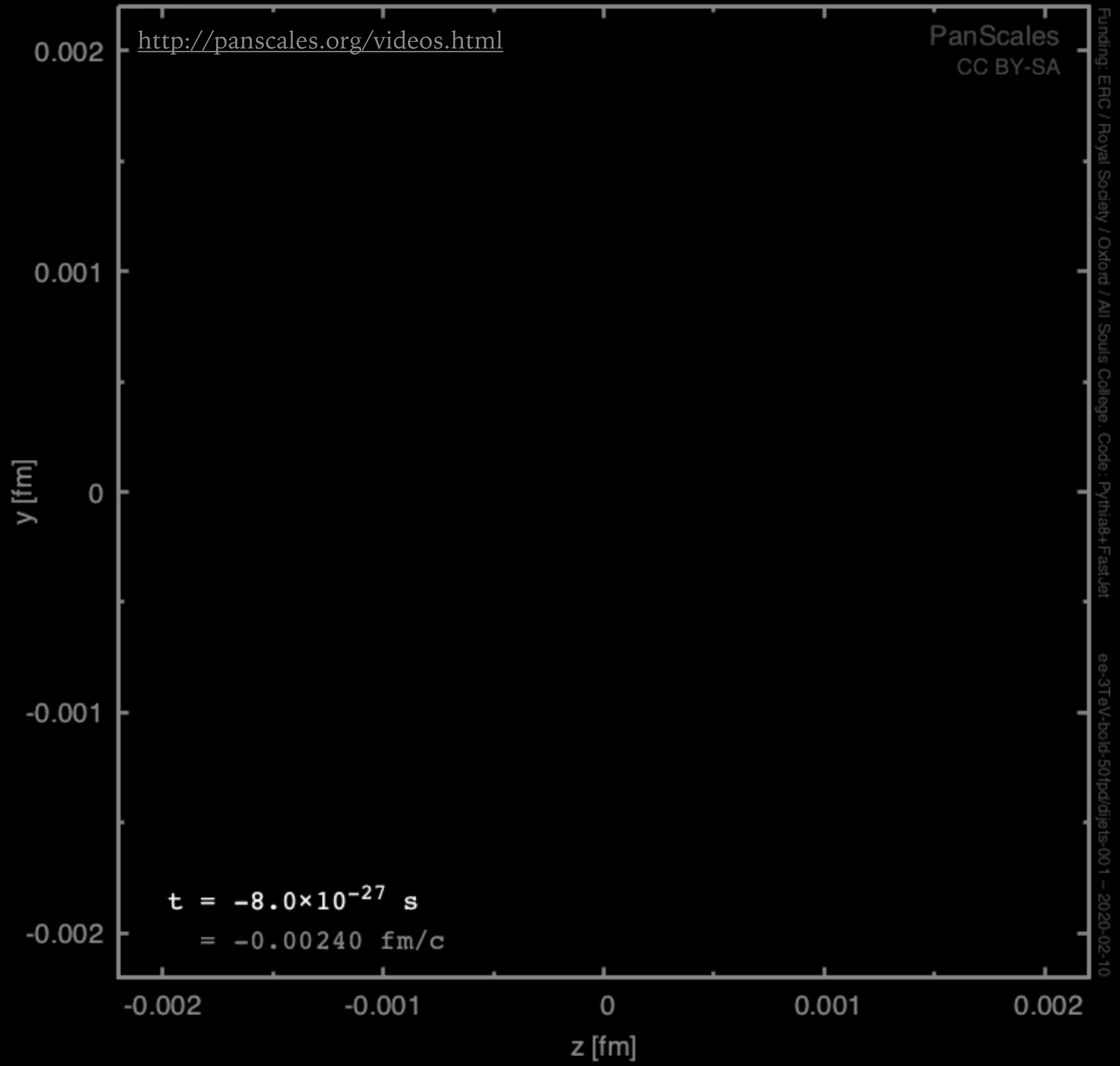


— incoming beam particle

— intermediate particle (quark or gluon)

— final particle (hadron)

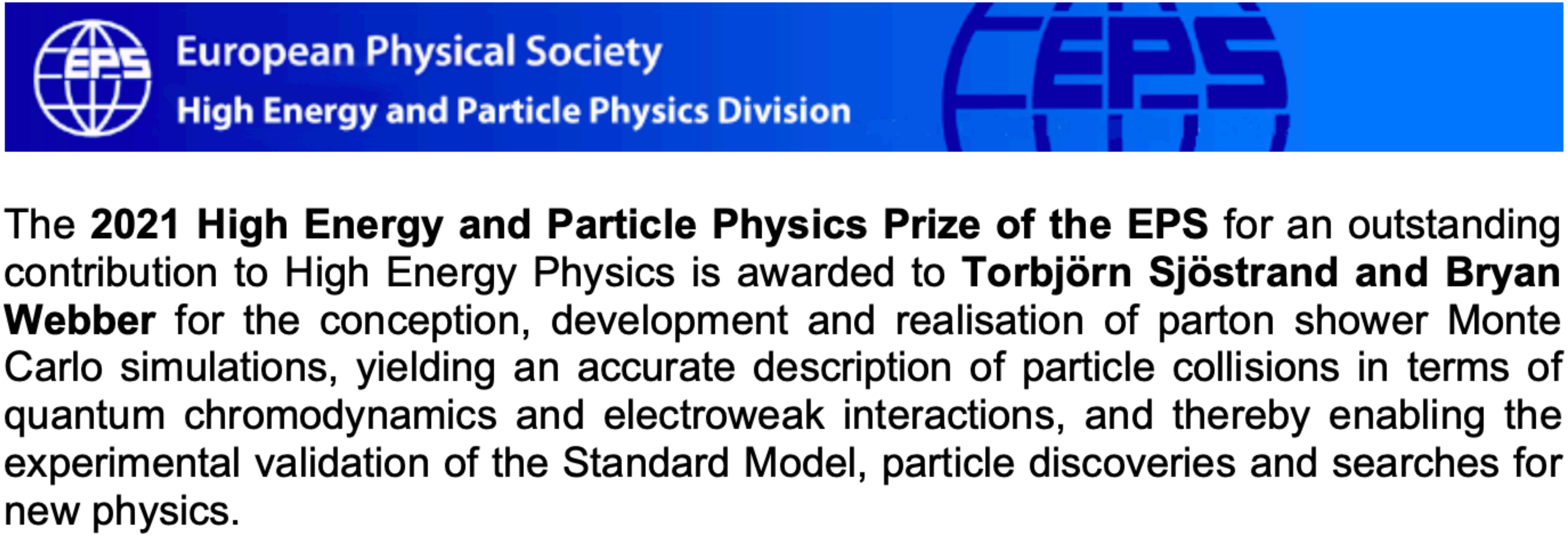
Event evolution spans 7 orders of magnitude in space-time

simulations use General Purpose Monte Carlo event generators

THE BIG 3

Herwig 7 **Pythia 8** **Sherpa 2**

used in ~95% of ATLAS/CMS publications
they do an amazing job of simulation vast swathes of data;
collider physics would be unrecognisable without them



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†)

Elements of a Monte Carlo event generator

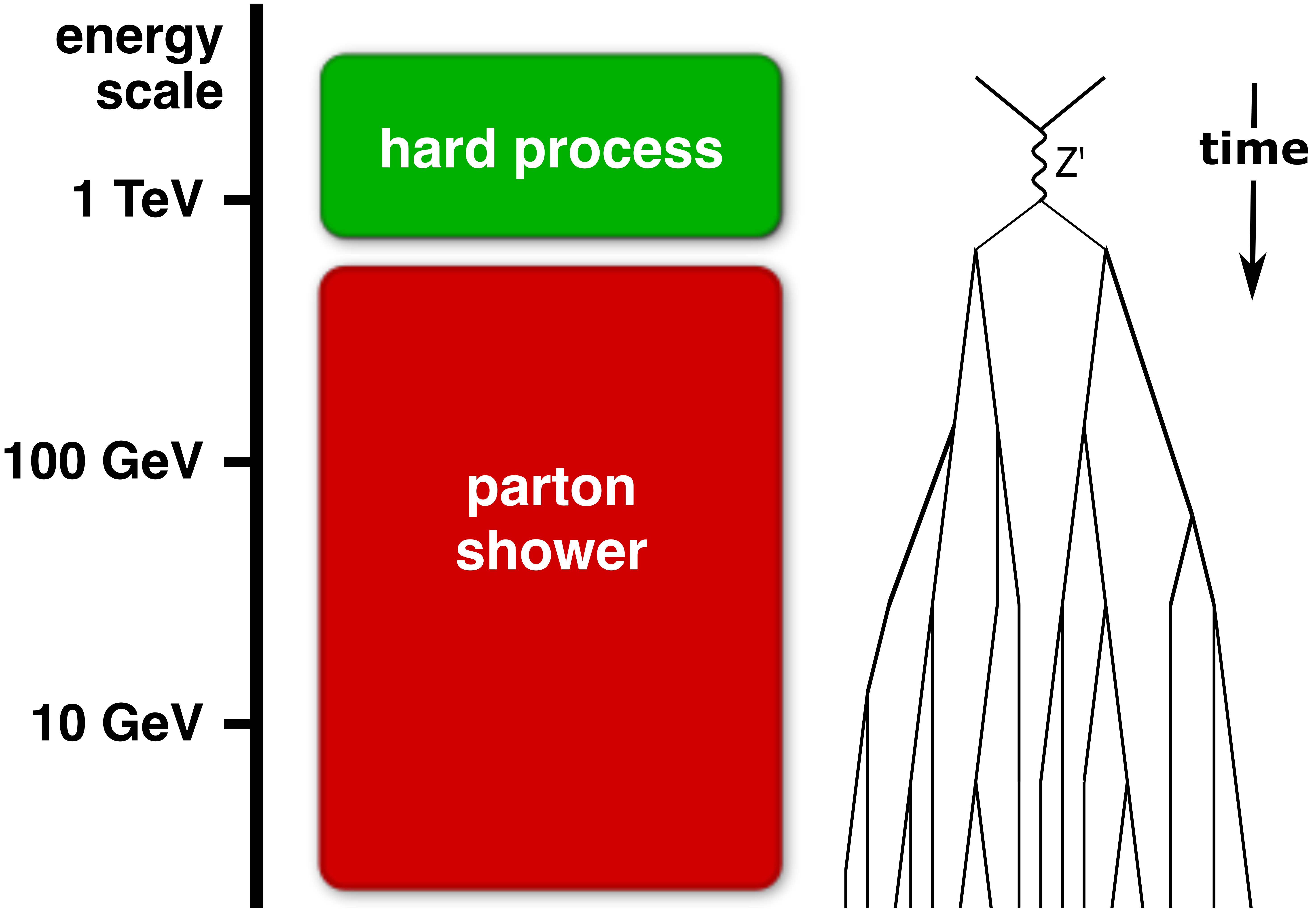
energy
scale

1 TeV

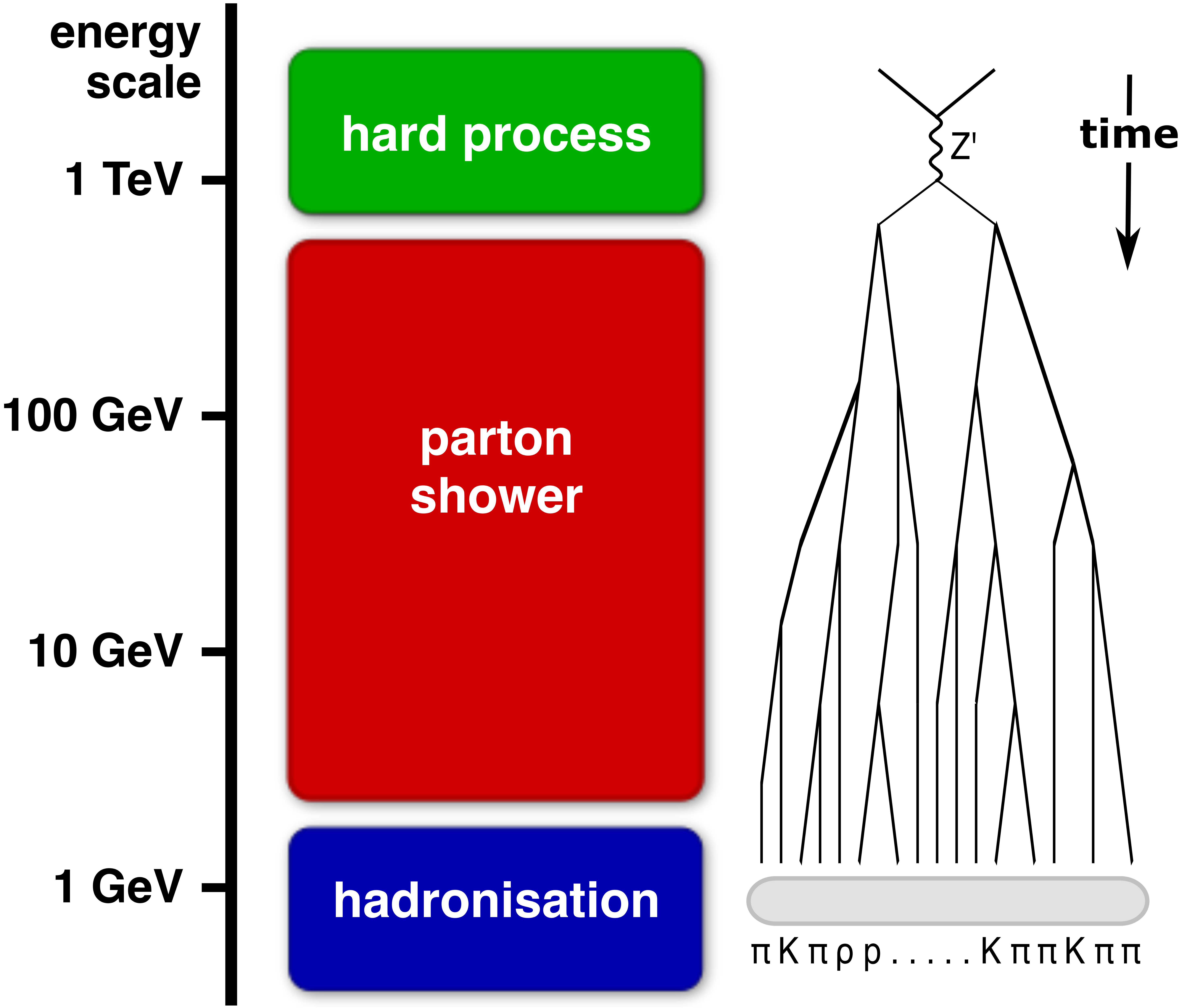
hard process

time

schematic view of key components of QCD predictions and Monte Carlo event simulation

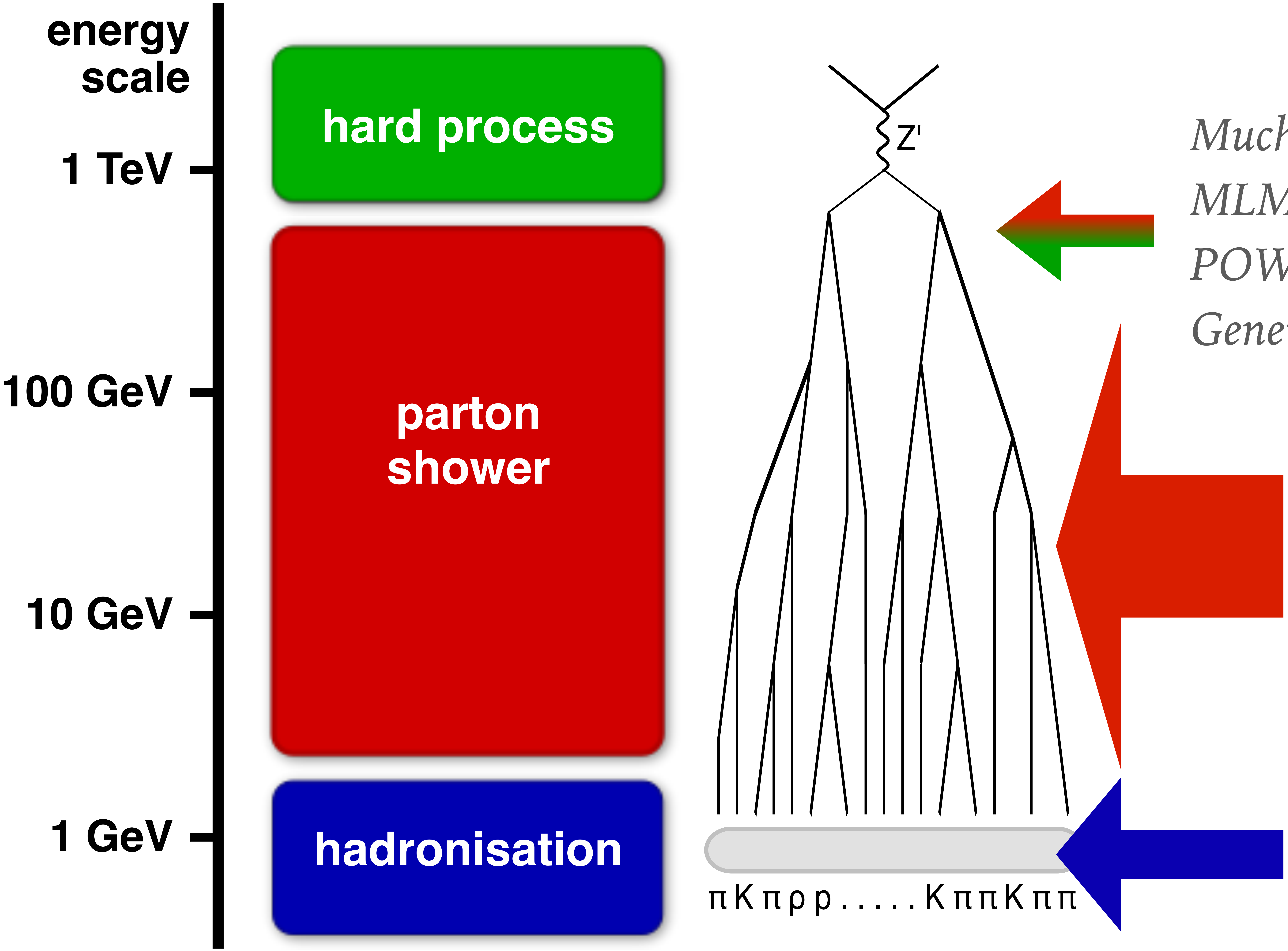


schematic view of key components of QCD predictions and Monte Carlo event simulation



schematic view of key components of QCD predictions and Monte Carlo event simulation

pattern of particles in MC can be directly compared to pattern in experiment



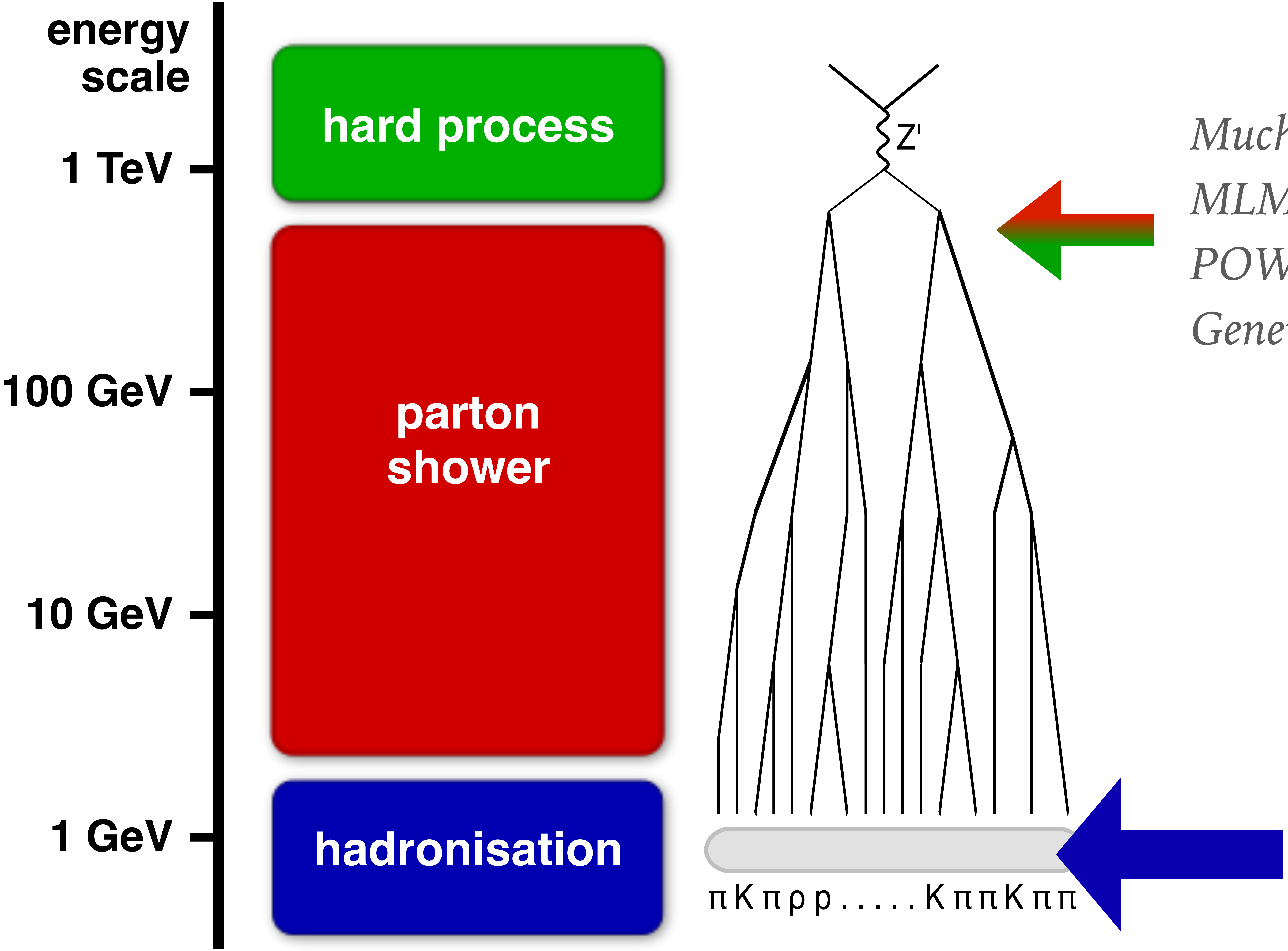
hard process

parton shower

hadronisation

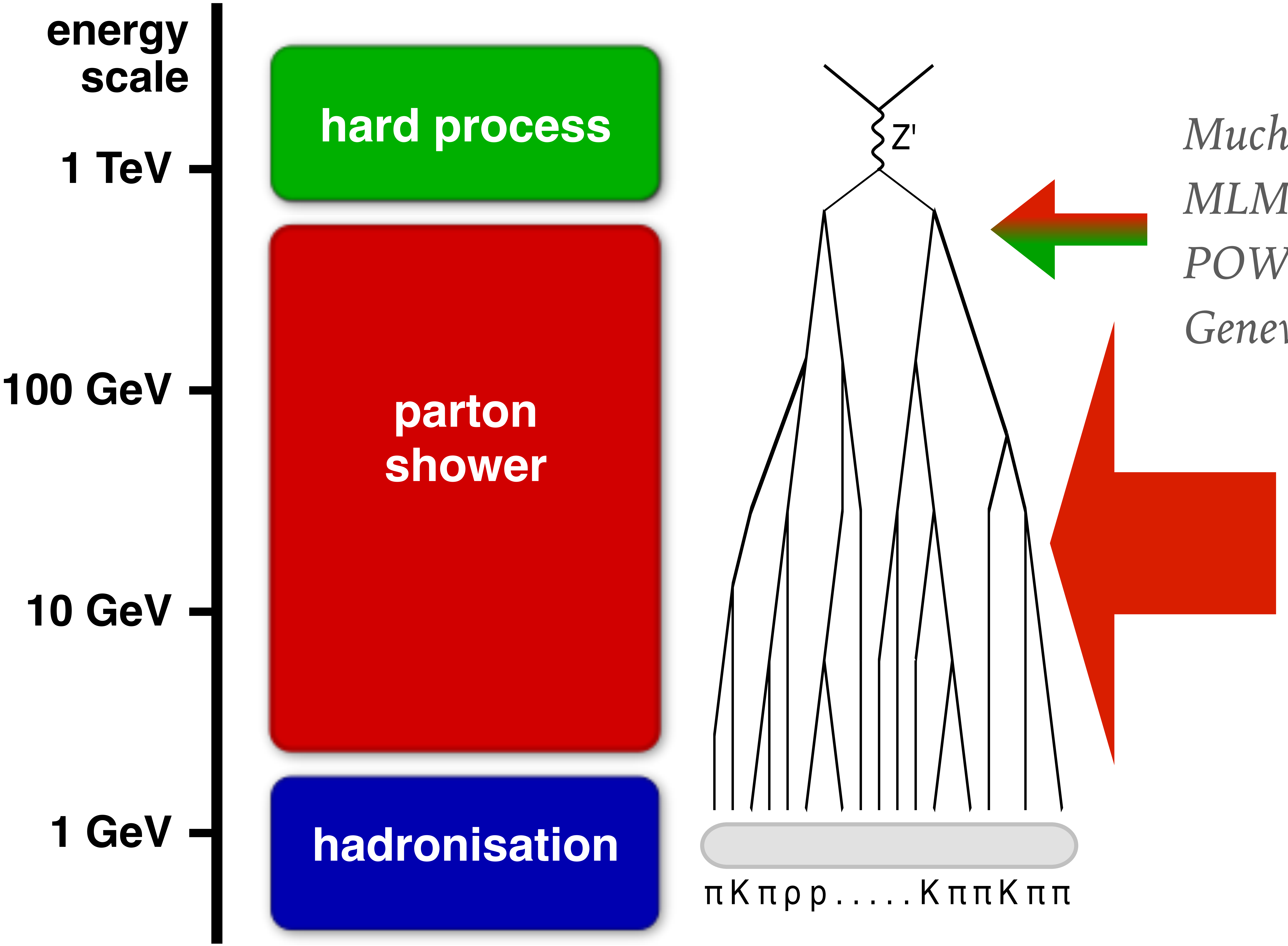
Much of past 20 years' work: MLM, CKKW, MC@NLO, POWHEG, MIN(N)LO, FxFx, Geneva, UNNLOPS, Vincia, etc.

Largely based on principles from 20-30 years ago



Much of past 20 years' work: MLM, CKKW, MC@NLO, POWHEG, MINLO, FxFx, Geneva, UNNLOPS, Vincia, etc.

for new ideas (including connections with heavy-ion collisions) see work by Gustafson, Lönnblad, Sjöstrand

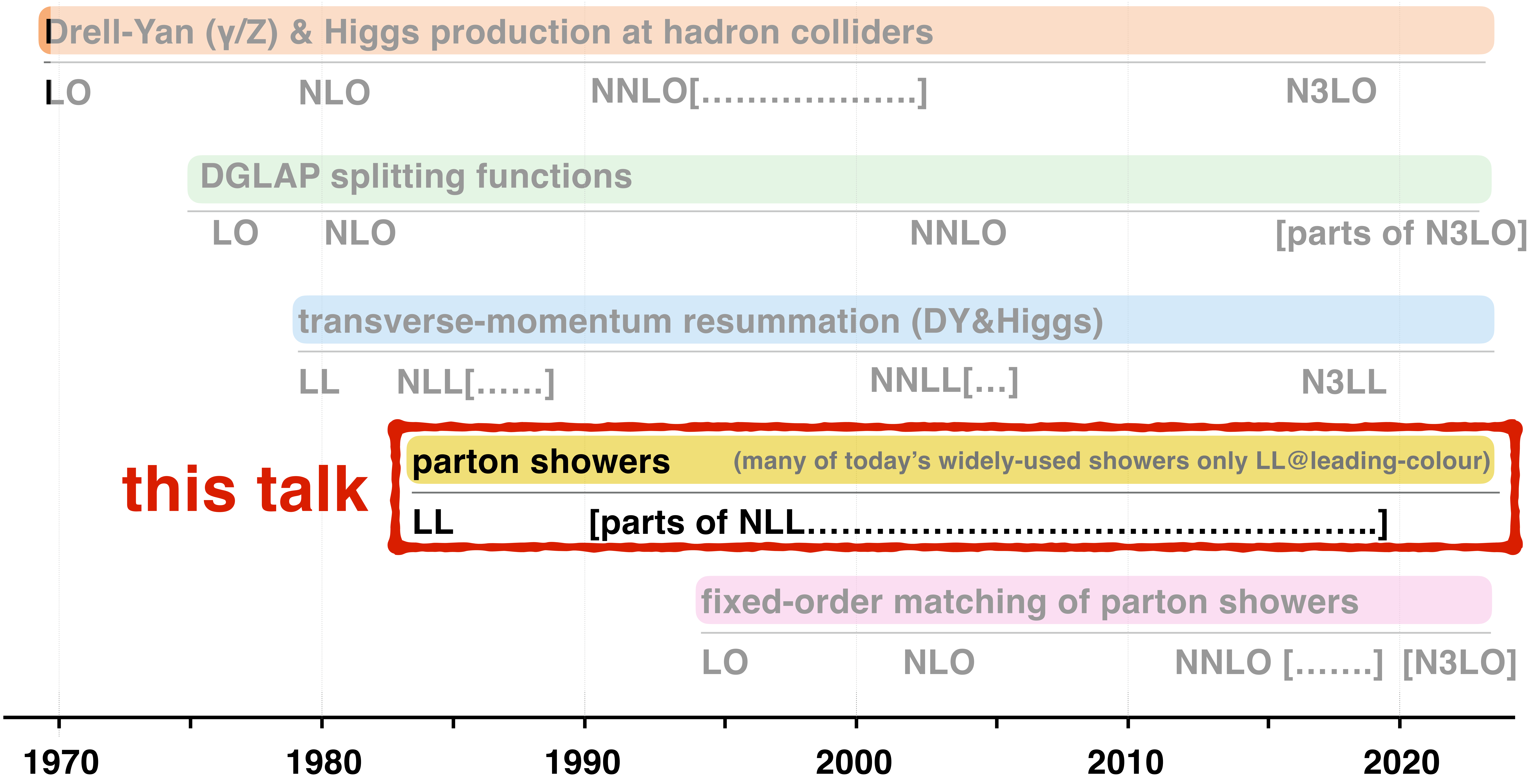


Much of past 20 years' work: MLM, CKKW, MC@NLO, POWHEG, MINLO, FxFx, Geneva, UNNLOPS, Vincia, etc.

This talk

Status of parton showers

selected collider-QCD accuracy milestones



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

this talk

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

LL **[parts of NLL……………………………………]**

fixed-order matching of parton showers

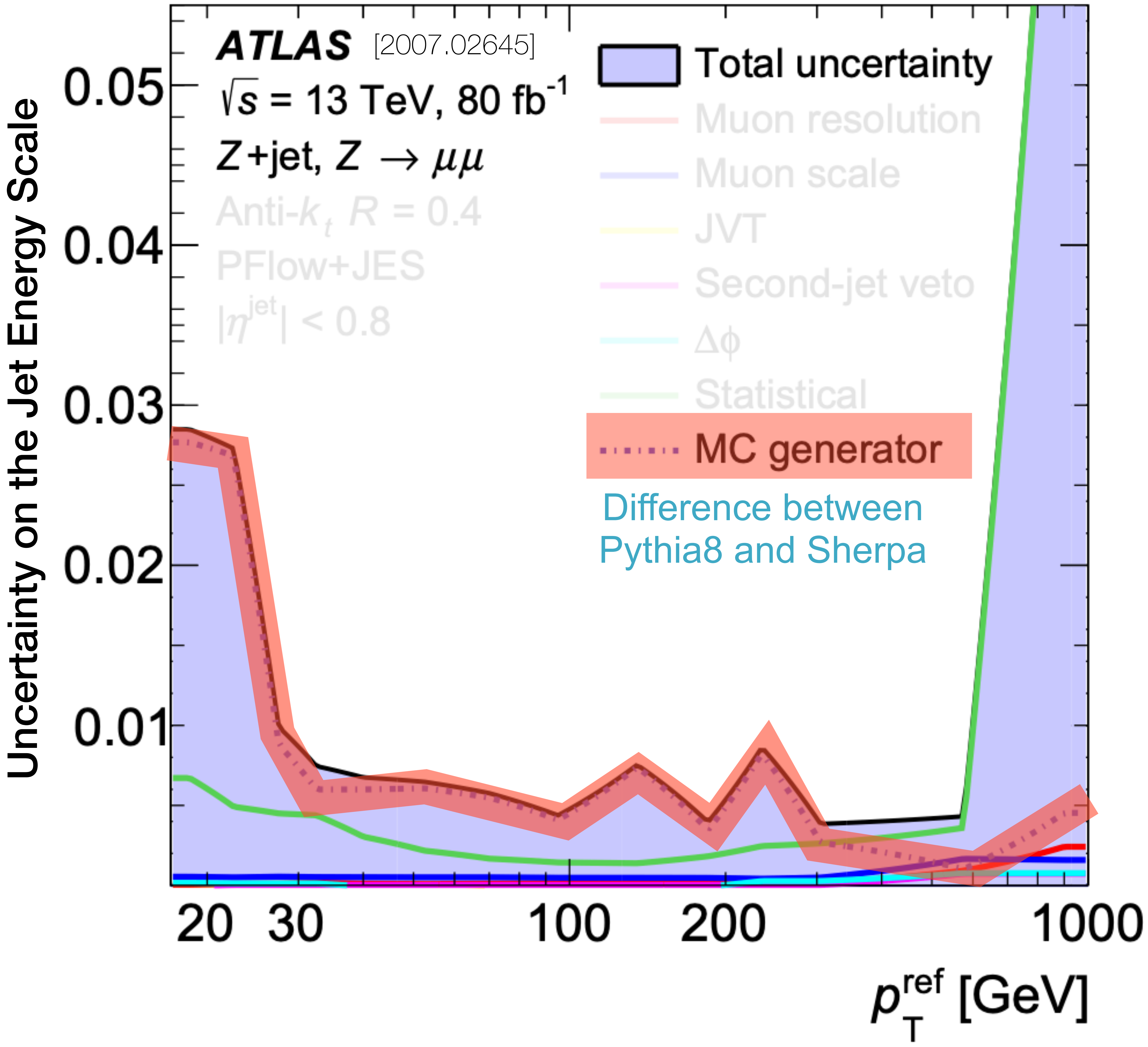
LO NLO NNLO […….] [N3LO]

Many groups active on [QCD] parton showers in past 20 years

- Pythia shower [Sjöstrand & Skands ’04, Cabouat & Sjostrand, ’17]
- Sherpa shower [Schumann & Krauss ’07]
- Deductor shower [Nagy & Soper ’07 - ’22]
- Vincia shower [Giele, Kosower & Skands ’07, Li & Skands ’16, …]
- Dire shower [Höche & Prestel ’15, …]
- Herwig angular-ordered showers [Gieseke, Stephens, Webber ’03, Bewick et al ’19, …]
- Herwig dipole showers [Plätzer & Gieseke ’09, Forshaw, Holguin & Plätzer ’20, …]

Various directions: new formulations of classic shower ideas, alternative kinematic recoil, improved colour-handling, improved spin-handling, higher-order splitting kernels, …

Parton Shower accuracy matters: e.g. for jet energy calibration (affects ~1500 papers)



Jet energy calibration uncertainty feeds into 75% of ATLAS & CMS measurements

Largest systematic errors (1–2%) come from differences between MC generators

(here Sherpa2 v. Pythia8)

→ fundamental limit on LHC precision potential

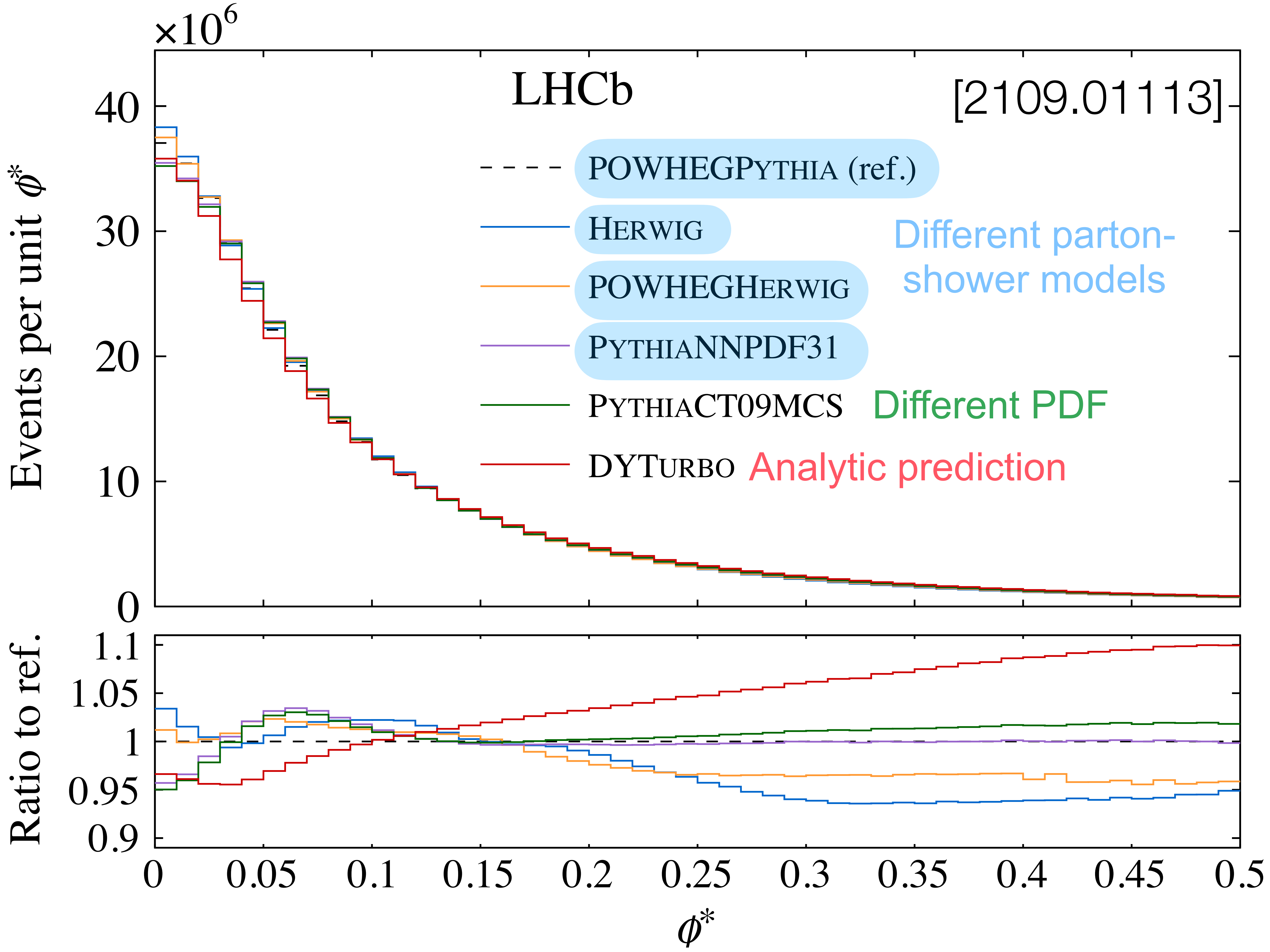
Parton Shower accuracy matters: e.g. for W mass extraction

Consider measurement of W boson mass

Measurements of p_T^Z in $Z/\gamma^* \to l^+l^-$ decays used to validate the MC predictions for p_T^W

The envelope of shifts in m_W originating from differences in these shower predictions is the dominant theory uncertainty (11 MeV)

$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \ \text{MeV}$$



[2109.01113]

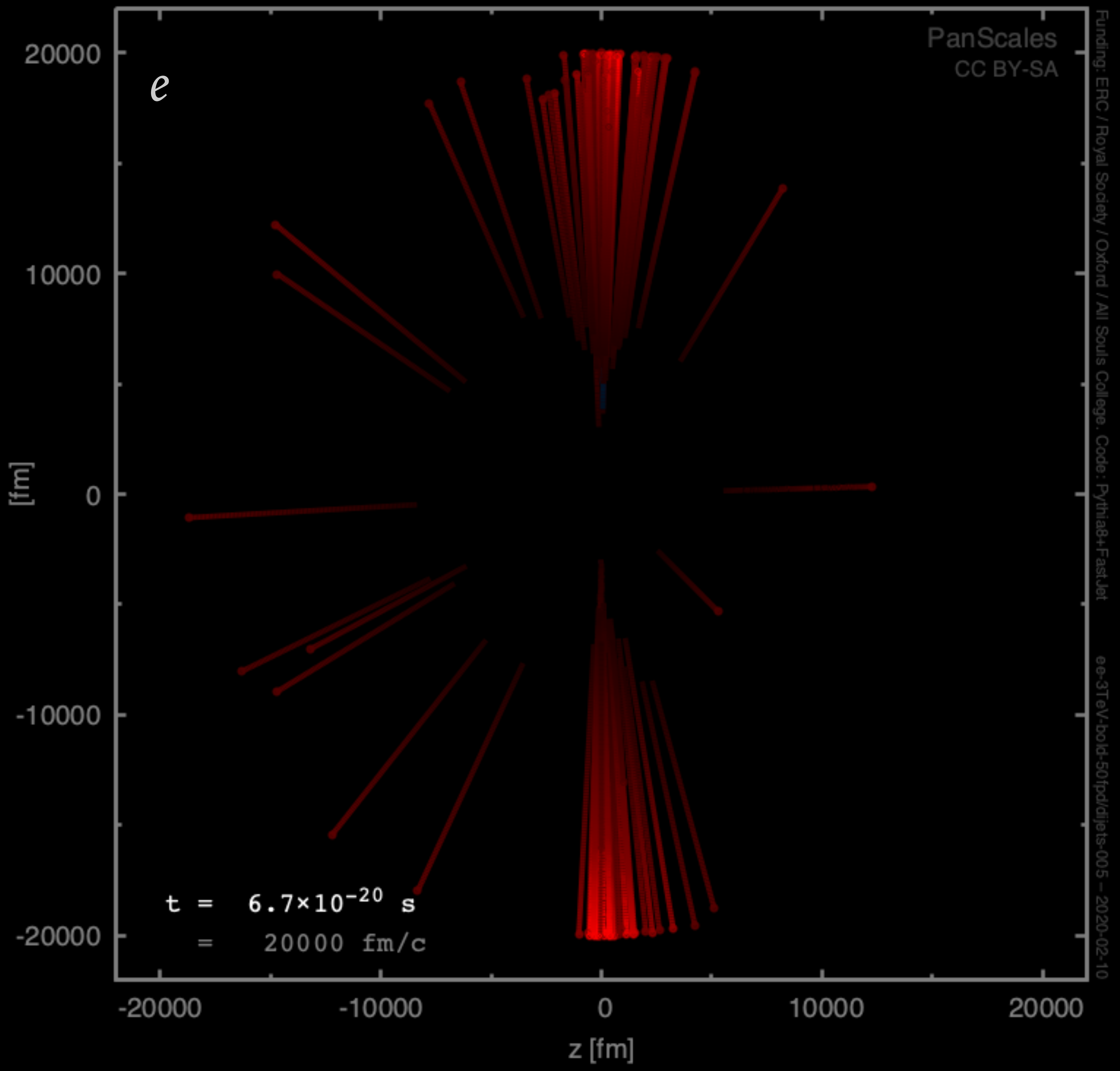
Different parton-shower models

Different PDF

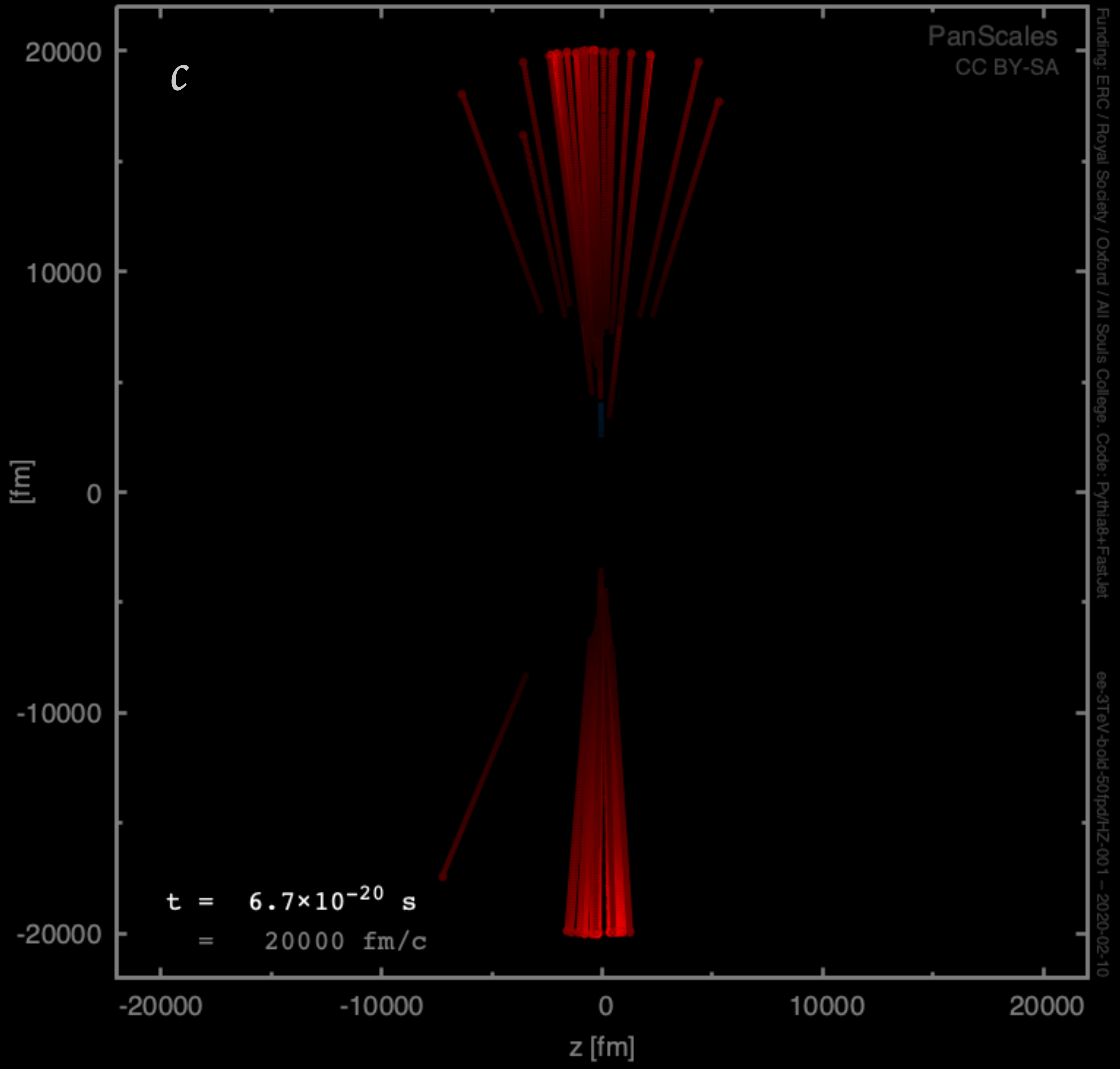
Analytic prediction

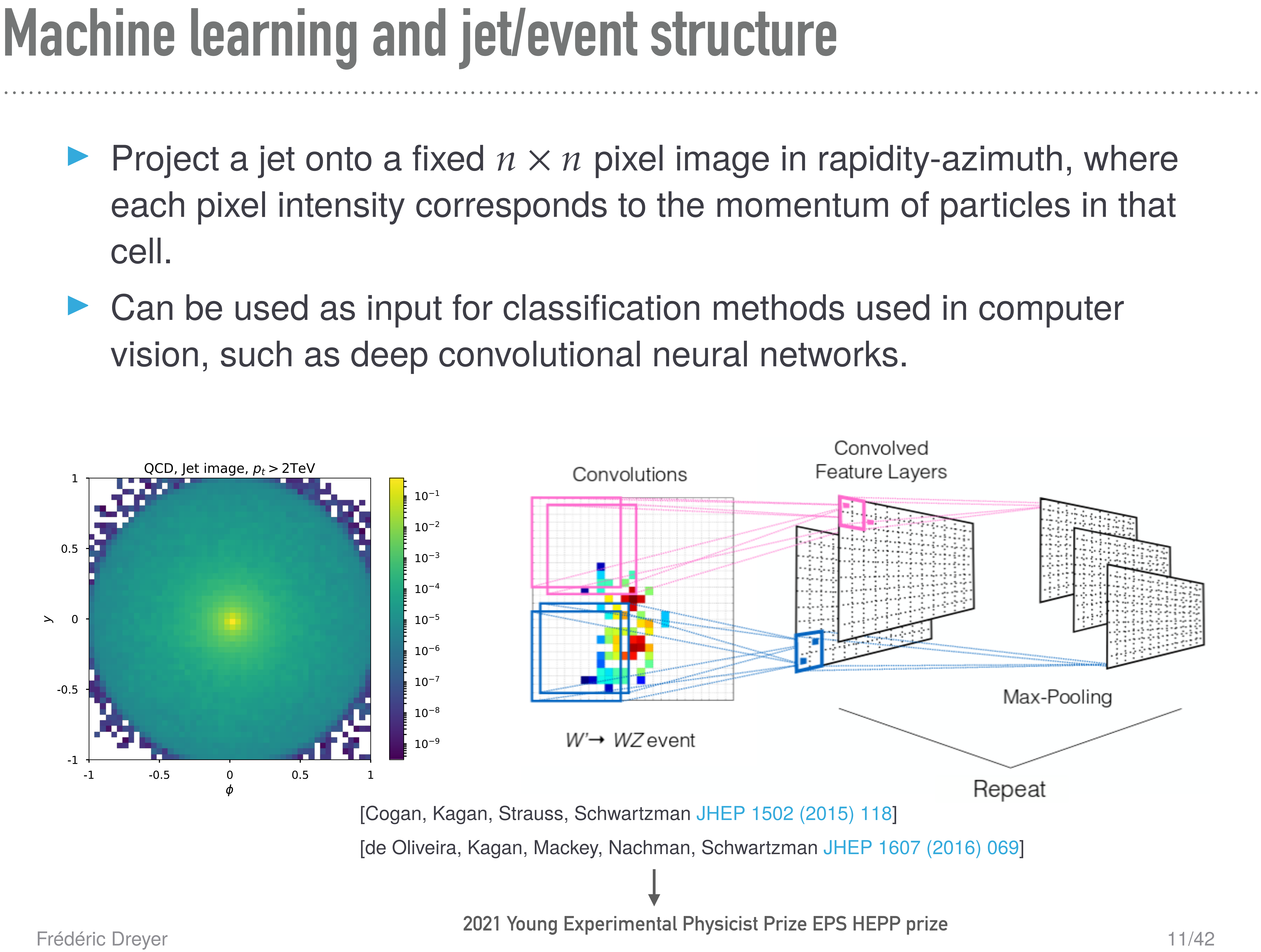
$$\phi^* = \frac{\tan((\pi - \Delta\phi)/2)}{\cosh(\Delta\eta/2)} \sim \frac{p_T^Z}{m_{ll}}$$ [1009.1580]

pure QCD event



event with Higgs & Z boson decays





Machine learning and jet/event structure

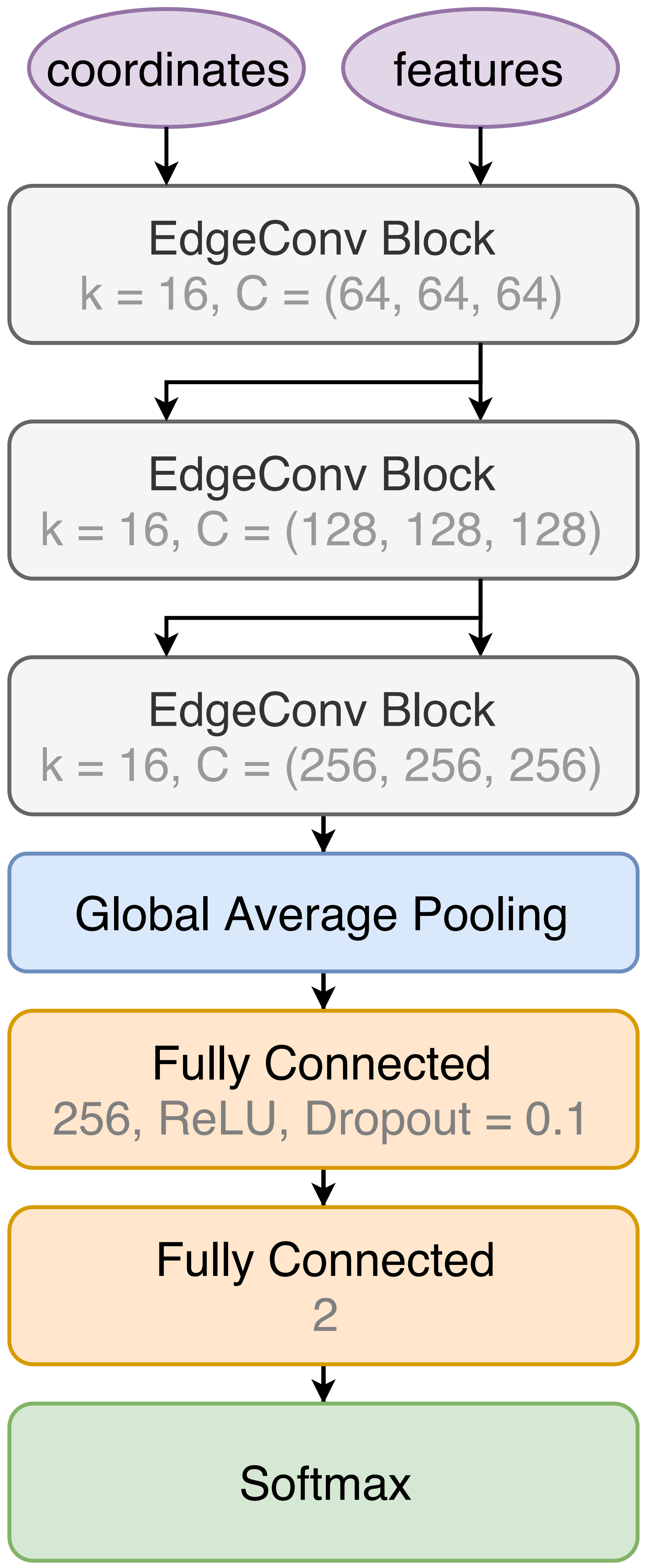
- Project a jet onto a fixed $n \times n$ pixel image in rapidity-azimuth, where each pixel intensity corresponds to the momentum of particles in that cell.
- Can be used as input for classification methods used in computer vision, such as deep convolutional neural networks.

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

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

↓

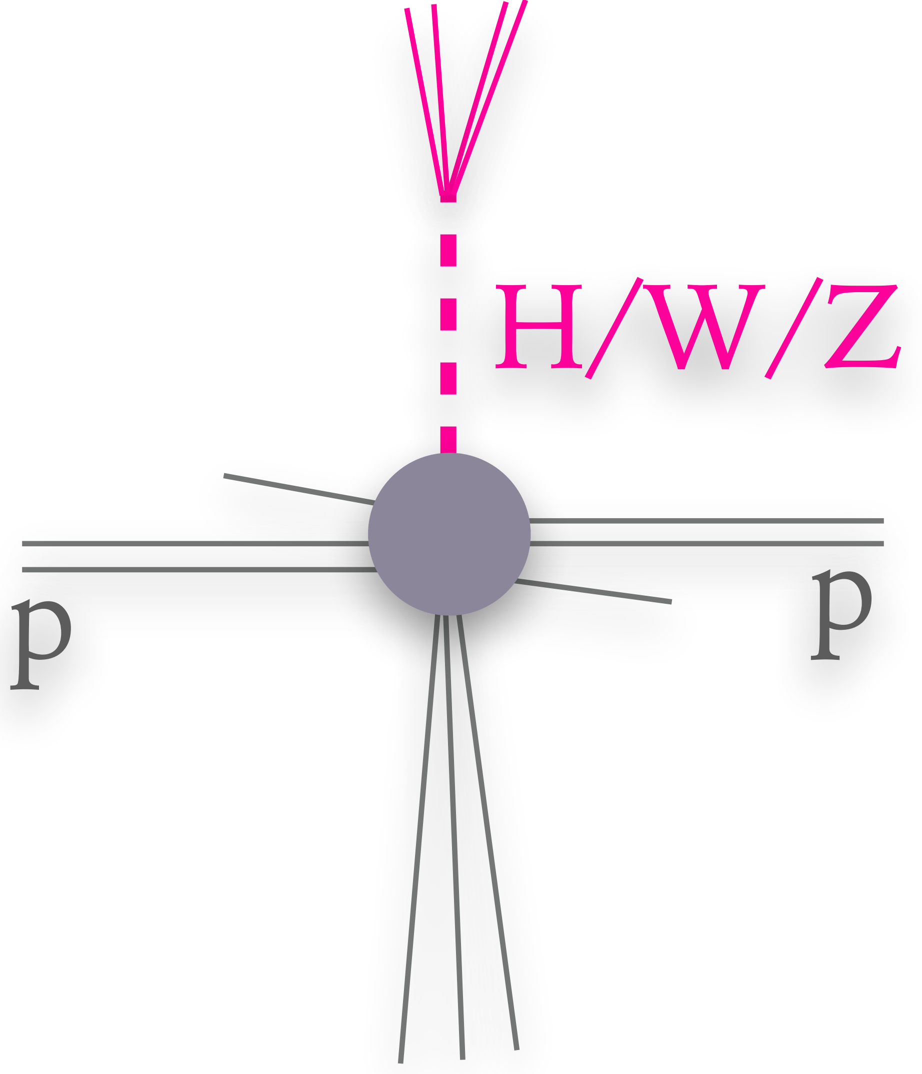
2021 Young Experimental Physicist Prize EPS HEPP prize



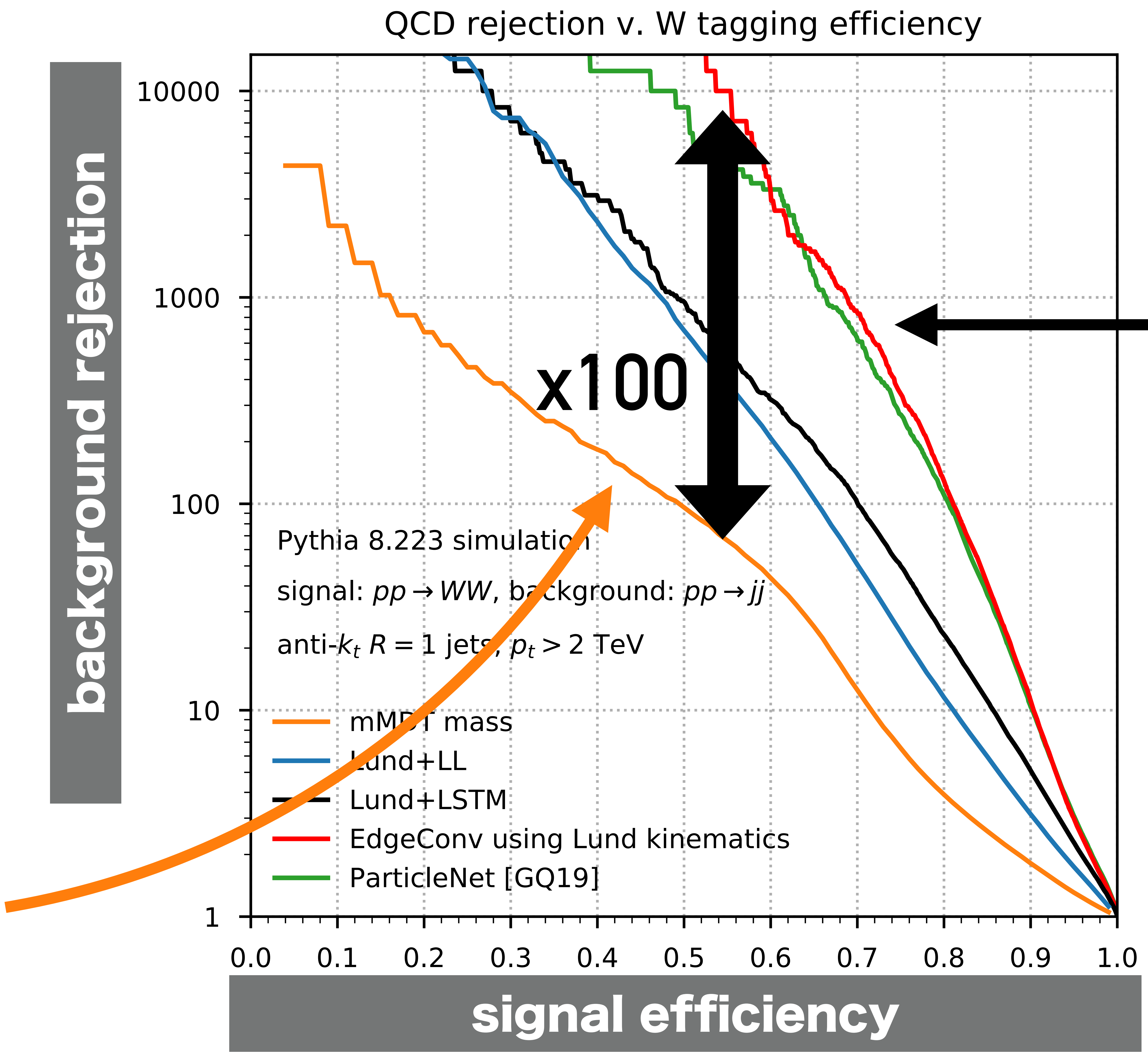
(a) ParticleNet

Qu & Guskos, arXiv:1902.08570

using full jet/event information for H/W/Z-boson tagging



adapted from
Dreyer & Qu
2012.08526



QCD rejection
with use of full jet
substructure
(2021 tools)

100x better

QCD rejection with
just jet mass
(SD/mMDT)
i.e. 2008 tools &
their 2013/14
descendants

First started to be exploited
by Thaler & Van Tilburg with
"N-subjettiness" (2010/11)

can we trust machine learning? A question of confidence…

> 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)*

[via S Gukov]

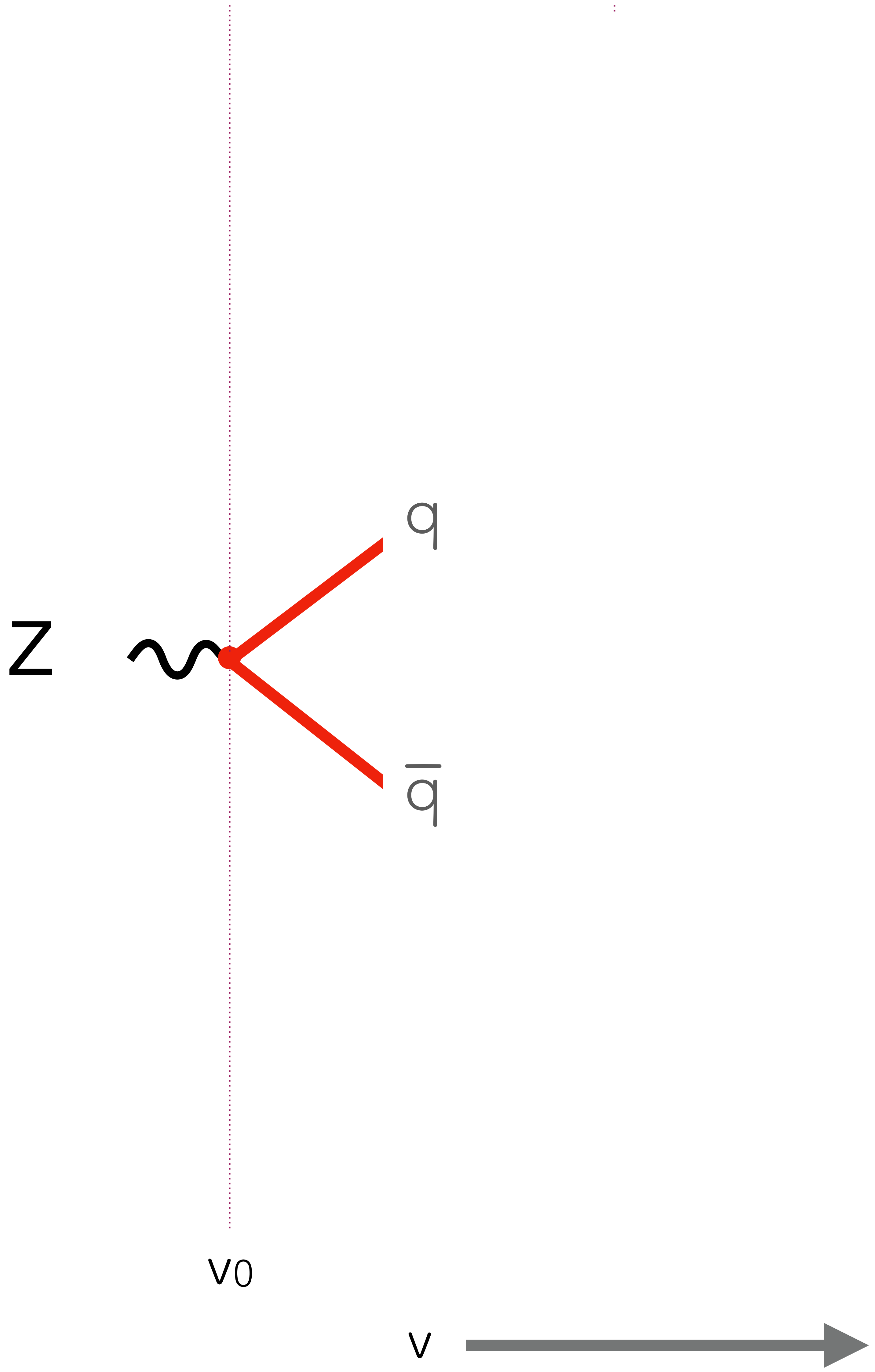
parton shower basics

---

illustrate with dipole / antenna showers

*Gustafson & Pettersson 1988, Ariadne 1992, main Sherpa & Pythia8 showers, option in Herwig7,
Vincia & Dire showers & (partially) Deductor shower*

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

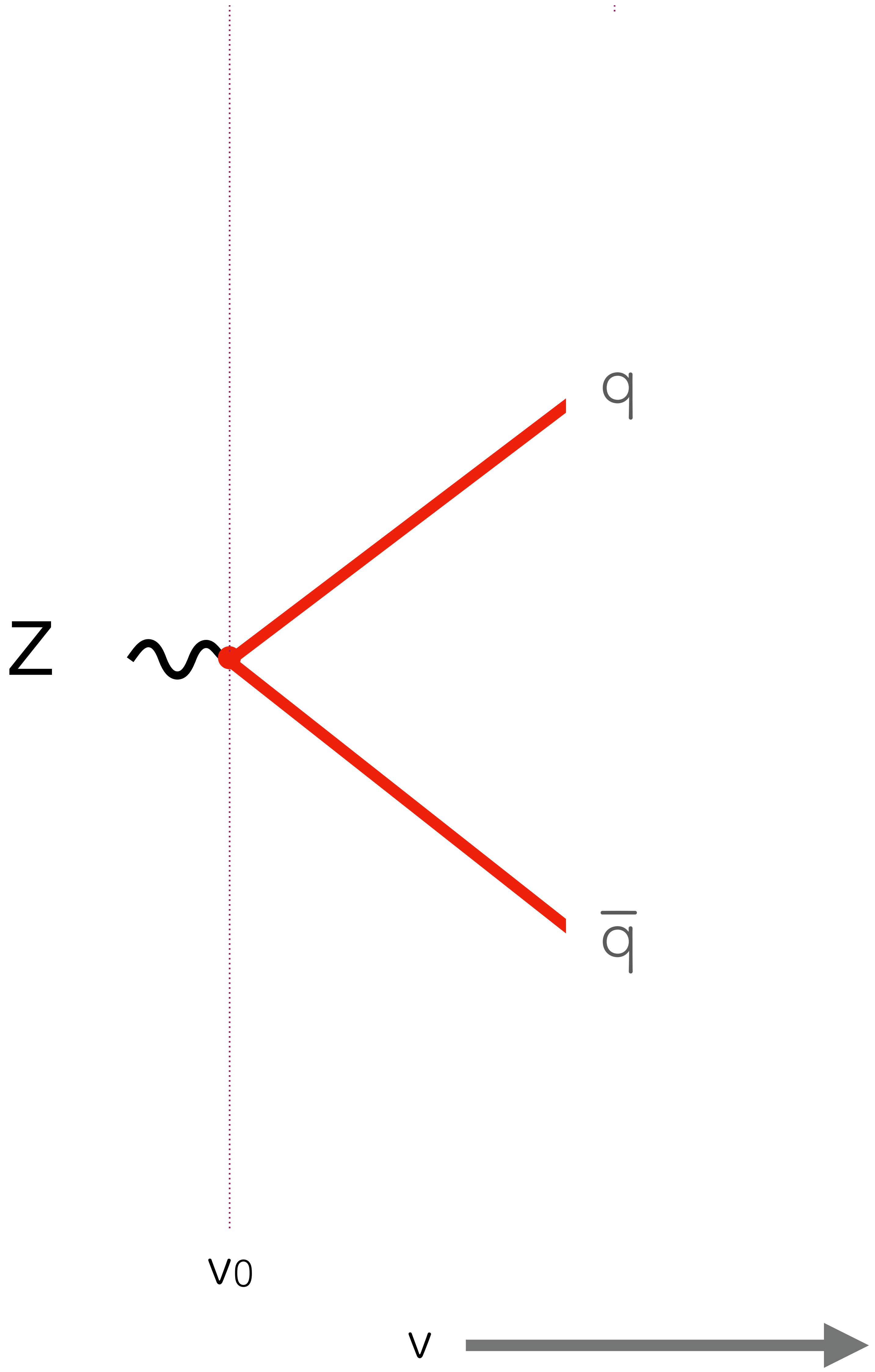


Start with $q\bar{q}$ state.

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.)

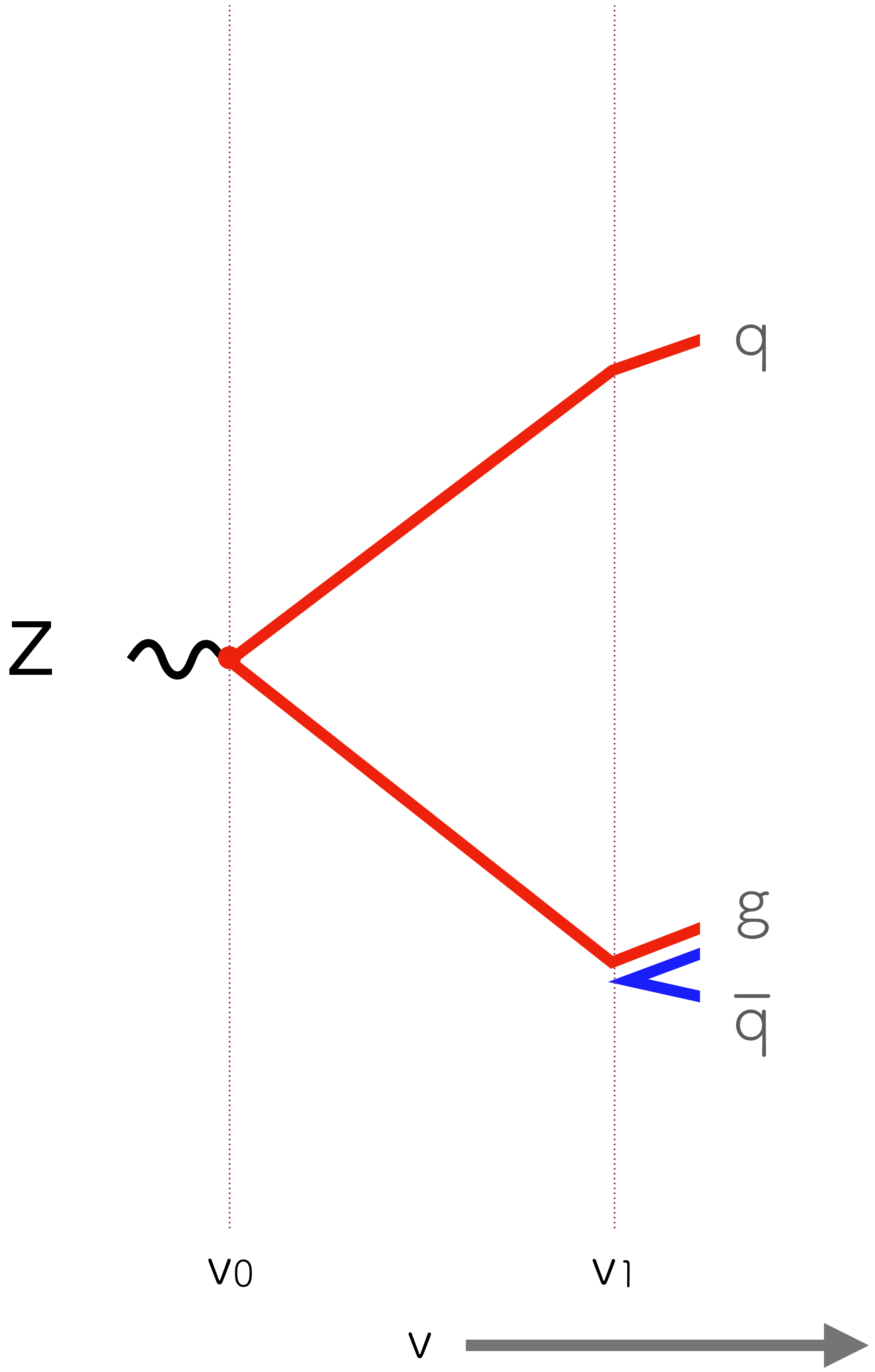


Start with q-qbar state.

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

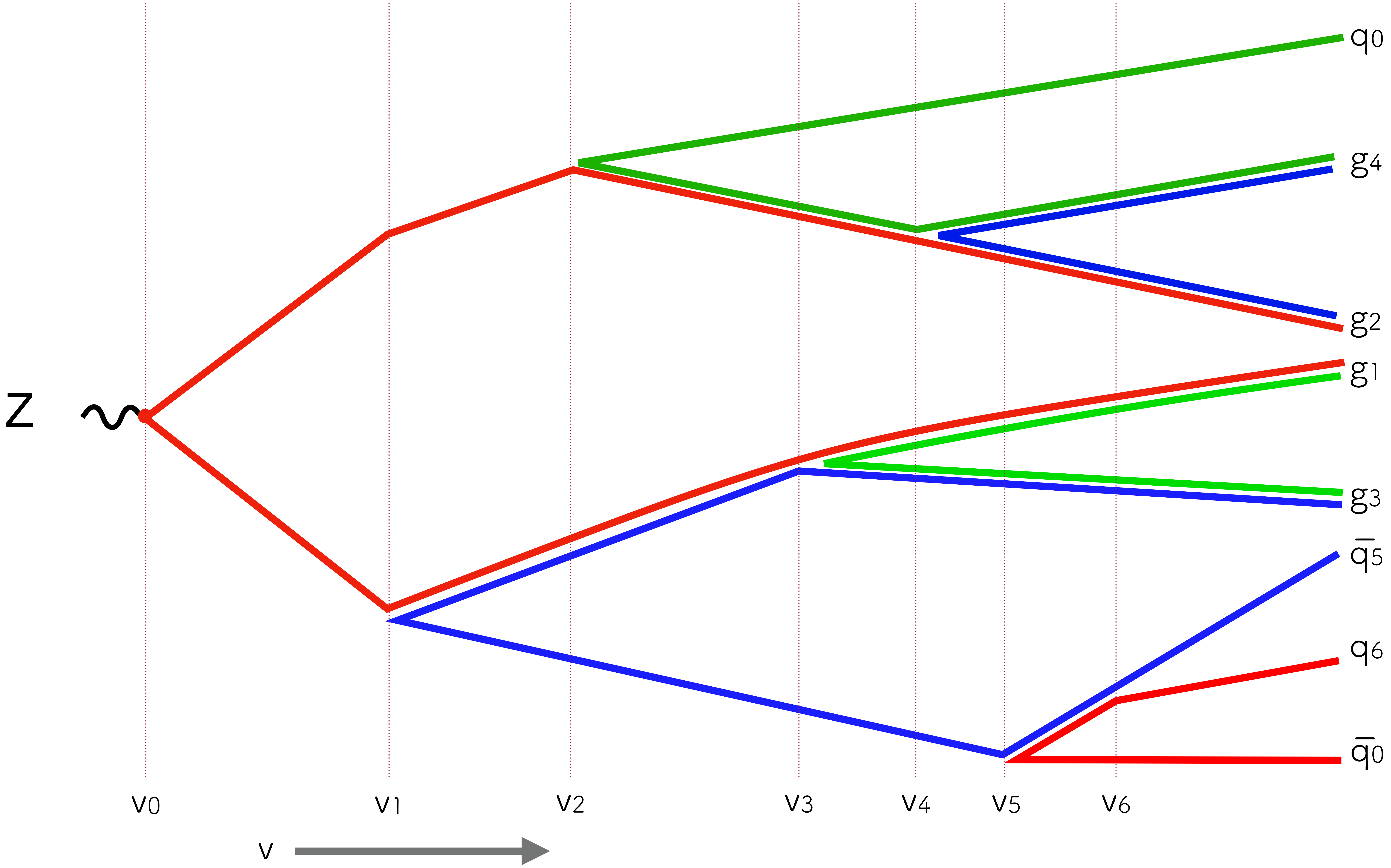
At some point, **state splits** (2→3, i.e. emits gluon). Evolution equation changes

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

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

(many showers use a large N_C limit)

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



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

logarithmic accuracy

How do you defined the accuracy of a parton shower?

- For a total cross section, e.g. for Higgs production, it's easy to talk about systematic improvements (LO, NLO, NNLO, …). But they're restricted to that one observable
- With a parton shower (+hadronisation) you produce a "realistic" full set of particles. You can ask questions of arbitrary complexity:
  - the multiplicity of particles
  - the total transverse momentum with respect to some axis (broadening)
  - the angle of 3rd most energetic particle relative to the most energetic one

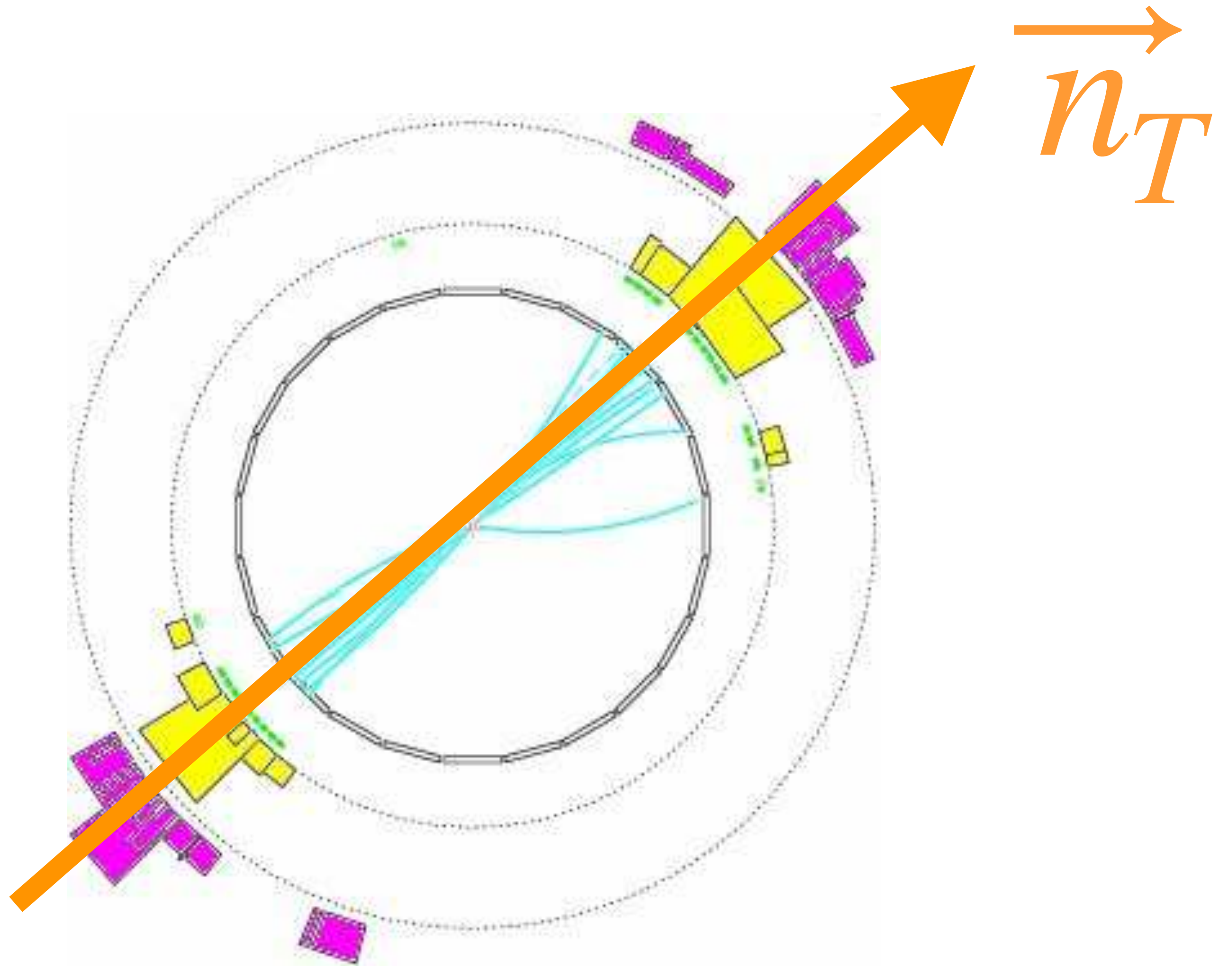
    [machine learning might "learn" many such features]

how can you prescribe correctness & accuracy of the answer, when the questions you ask can be arbitrary?

Logarithmic accuracy: a schematic intro

It’s common to hear that **showers are Leading Logarithmic (LL)** accurate.

That language, widespread for multiscale problems, comes from analytical resummations. E.g. transverse momentum broadening



$$B = \frac{\sum_i |\vec{p}_i \times \vec{n}_T|}{\sum_i |\vec{p}_i|}$$

You can resum cross section for B to be very small (as it is in most events)

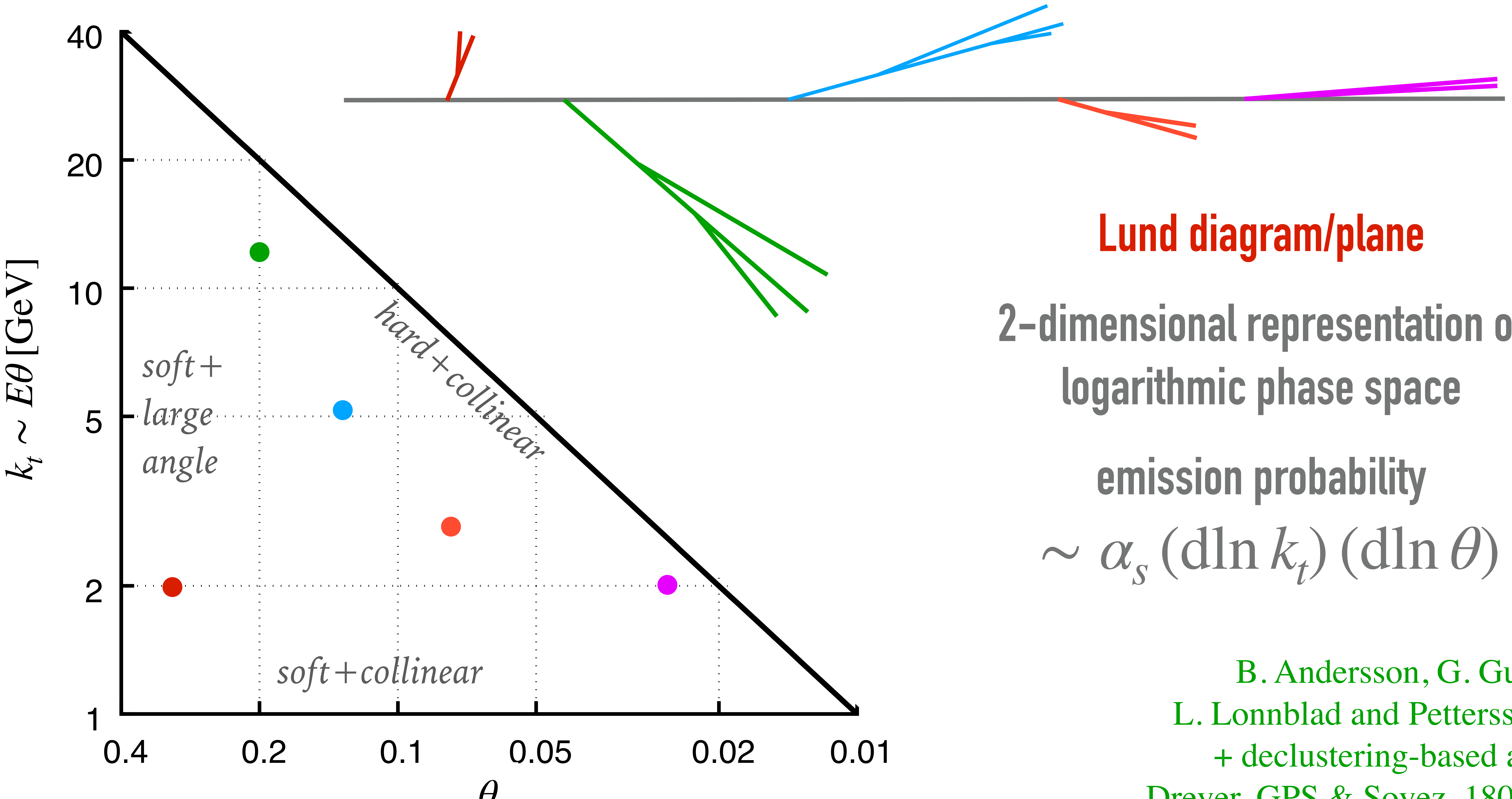
$$\sigma(B < e^L) = \sigma_{tot} \exp\left[\frac{1}{\alpha_s}\underbrace{g_1(\alpha_s L)}_{\text{LL} \sim O(\frac{1}{\alpha})} + \underbrace{g_2(\alpha_s L)}_{\text{NLL} \sim O(1)} + \right.$$

$$[\alpha_s \ll 1,\ \alpha_s L \sim -1]$$

Dokshitzter, Lucenti, Marchesini & GPS ’98

today
concentrate just on LL & NLL
i.e. control of terms up to O(1)

1. origin of logarithms: soft (dE/E) and collinear (dθ/θ) enhancements



Lund diagram/plane

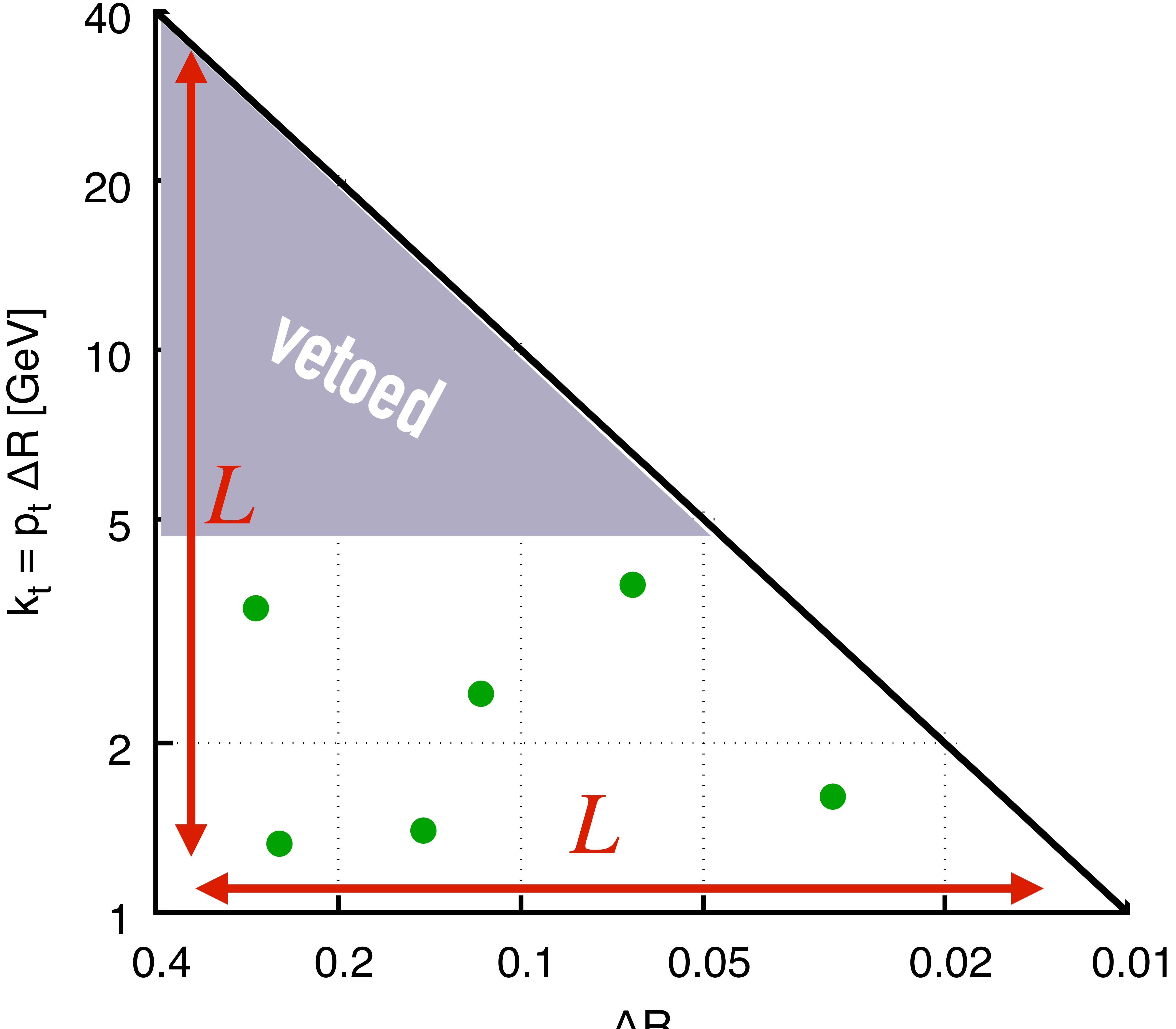
2-dimensional representation of logarithmic phase space

emission probability

$$\sim \alpha_s\,(\mathrm{d}\ln k_t)\,(\mathrm{d}\ln\theta)$$

B. Andersson, G. Gustafson,
L. Lonnblad and Pettersson 1989
+ declustering-based analysis:
Dreyer, GPS & Soyez, 1807.04758

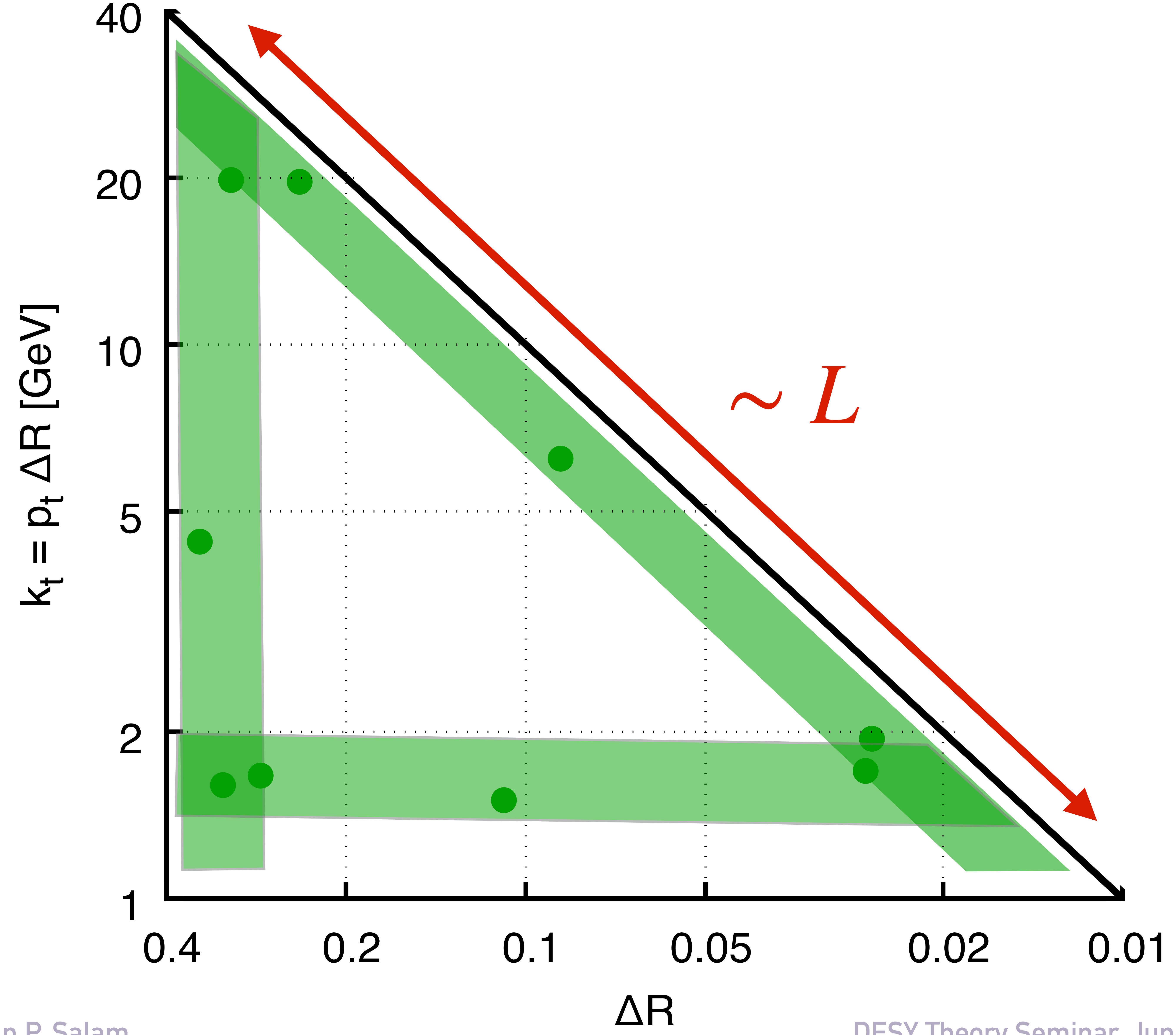
2. classes of logarithmic enhancement: $\alpha_s^n L^{2n}$, $\alpha_s^n L^n$



$\alpha_s^n L^{2n}$:

- each emission “costs” a power of α_s
- full 2-dimensions of phase space → factor of L^2
- vetoed regions of phase space count in similar way (“Sudakov” form factor)

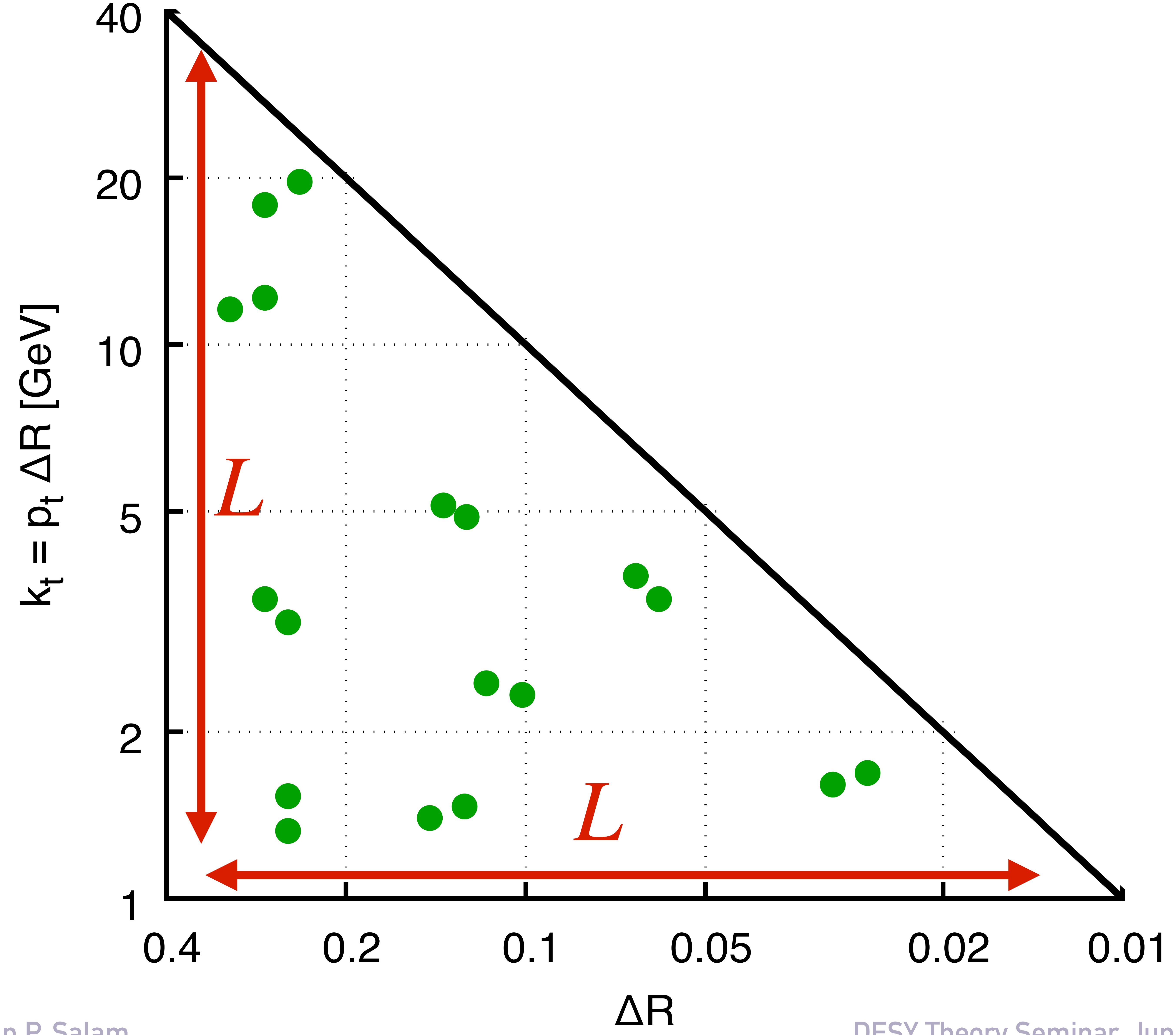
2. classes of logarithmic enhancement: $\alpha_s^n L^{2n}$, $\alpha_s^n L^n$



$\alpha_s^n L^n$:

- each emission "costs" a power of α_s
- some physics effects only involve one-dimensional phase space for emissions — factor of L
- some observables only sensitive to a one-dimensional phase space for emissions

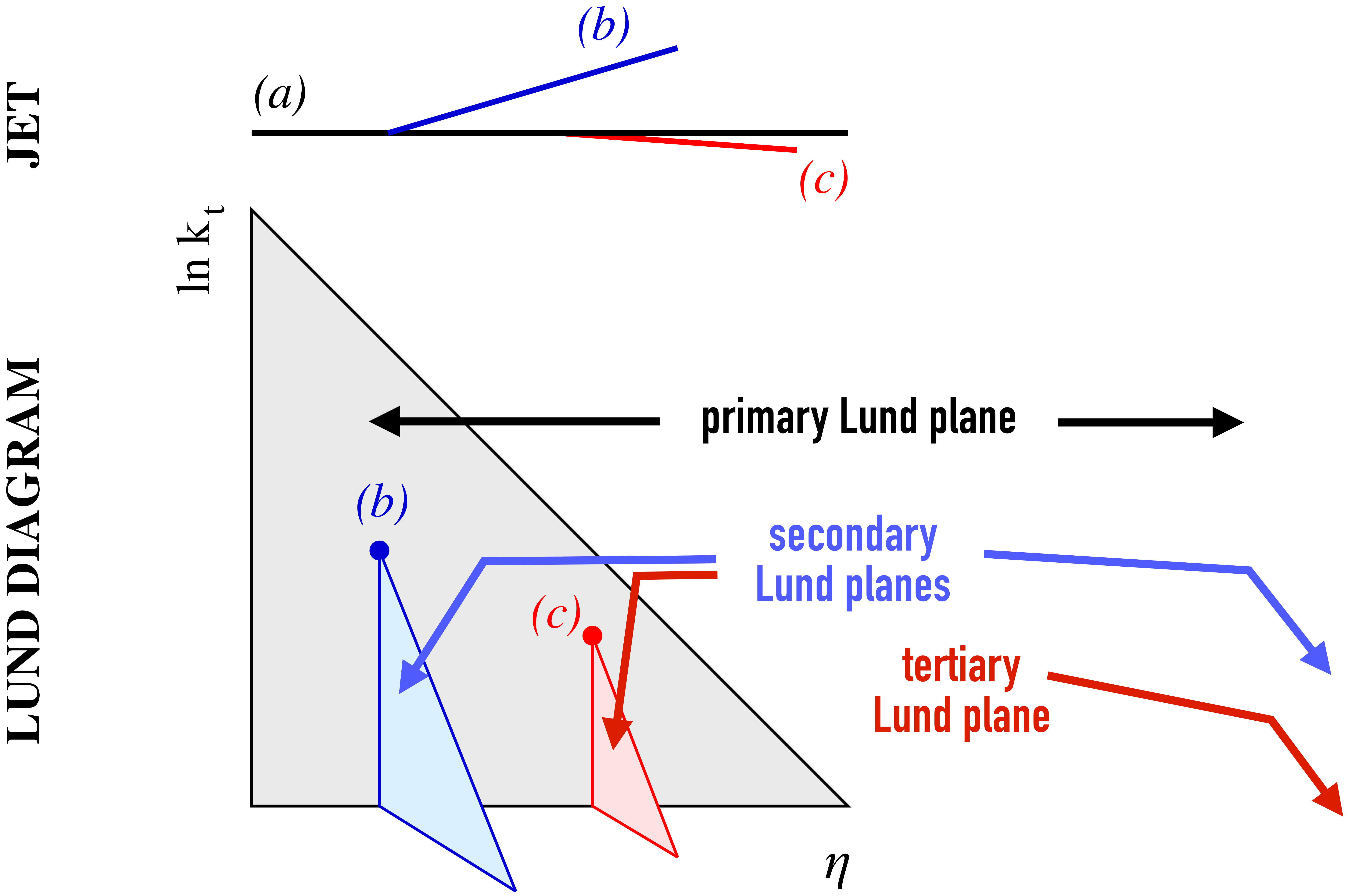
2. classes of logarithmic enhancement: $\alpha_s^n L^{2n}$, $\alpha_s^n L^n$



$\alpha_s^n L^n$:

- a nearby pair of real emissions, or one emission+ one virtual, brings two powers of α_s
- when α_s^2 enhanced by two-dimensional phase space, get $\alpha_s^2 L^2 \times \cdots$
- standard observables (e.g. event shapes) care only about integrated sum of double-real and real-virtual (and overall double-virtual counterpart) = cusp anomalous dimension

3. accuracy needs to hold also for secondary, tertiary, etc. emissions



primary Lund plane

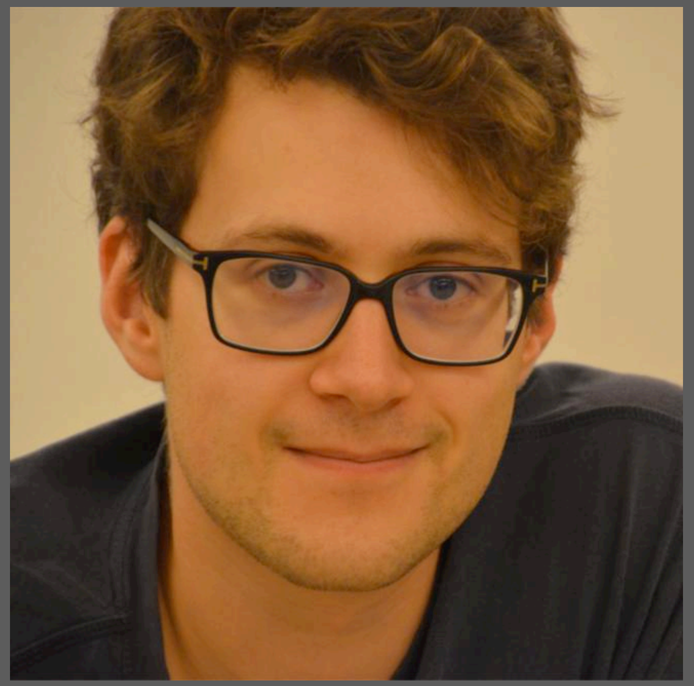
secondary
Lund planes

tertiary
Lund plane

Designing NLL parton showers

defining “NLL” aims
a robust recoil framework
ingredients for specific phase-space regions

Mrinal Dasgupta
Manchester



Frédéric Dreyer
Oxford

Keith Hamilton
Univ. Coll. London

Pier Monni
CERN

Gavin Salam
Oxford

Grégory Soyez
IPhT, Saclay

since 2017

Emma Slade
Oxford (PhD) → GSK.ai

2018–20

Basem El-Menoufi
Manchester

Alexander Karlberg
Oxford

Rok Medves
Oxford (PhD)

Ludovic Scyboz
Oxford

Rob Verheyen
Univ. Coll. London

since 2019

PanScales

A project to bring logarithmic understanding and accuracy to parton showers

Melissa van Beekveld
Oxford

Silvia Ferrario Ravasio
Oxford

Alba Soto-Ontoso
IPhT, Saclay

since 2020

Jack Helliwell
Oxford

since 2022

Defining what we mean by NLL

Dasgupta, Dreyer, Hamilton, Monni, GPS ’18
ibid + Soyez ‘20

A Matrix Element condition

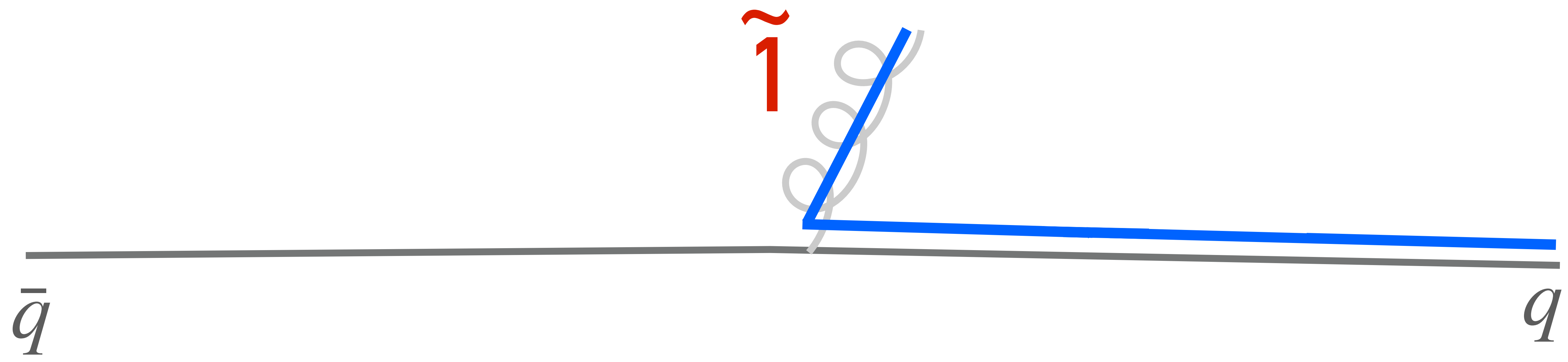
- correctly reproduce *n*-parton tree-level matrix element for arbitrary configurations, so long as all emissions well separated in the Lund diagram
- supplement with unitarity, 2-loop running coupling & cusp anomalous dimension

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

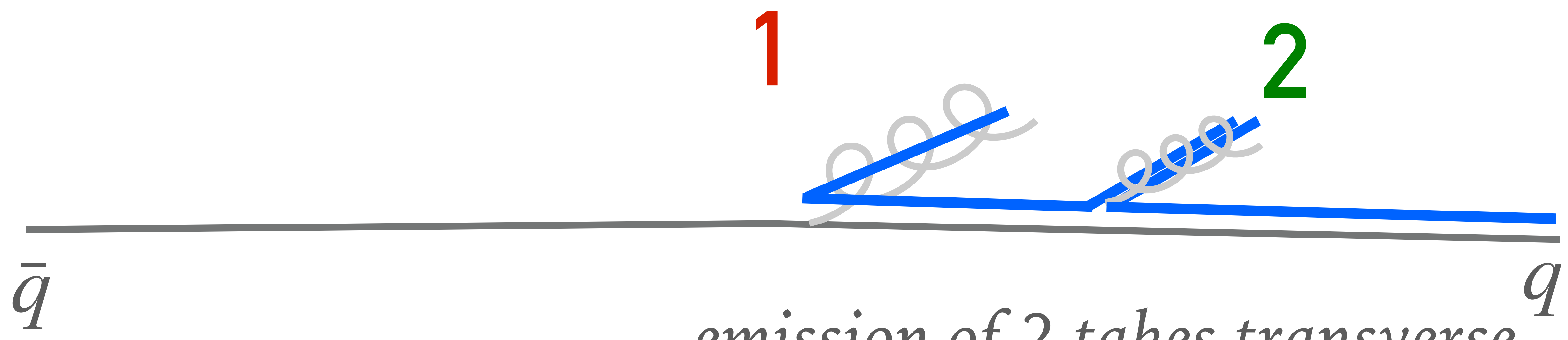
Dipole showers conserve momentum at each step. Traditional dipole-local recoil:



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

1. Recoil: the core of any shower

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



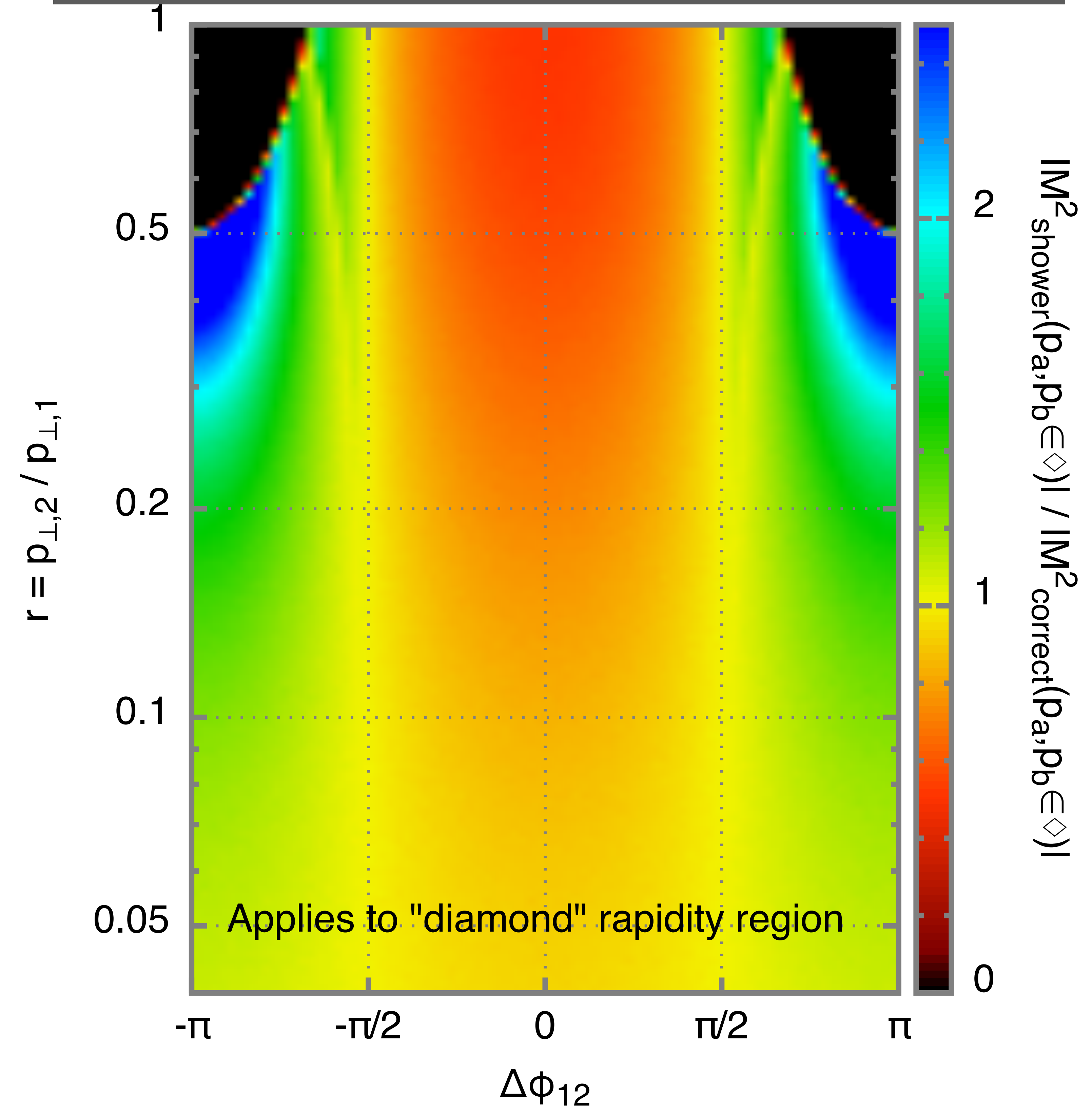
emission of 2 takes transverse recoil from 1

Shower initially generated matrix element for particle $\tilde{1}$, whose momentum differs (by $\sim$ 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

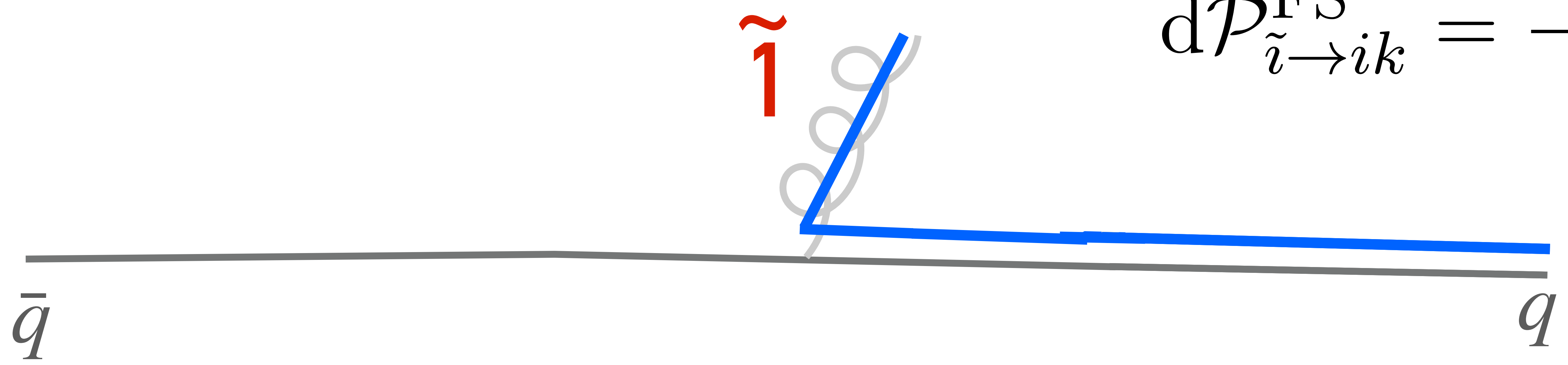
ratio of effective shower matrix element to exact one



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

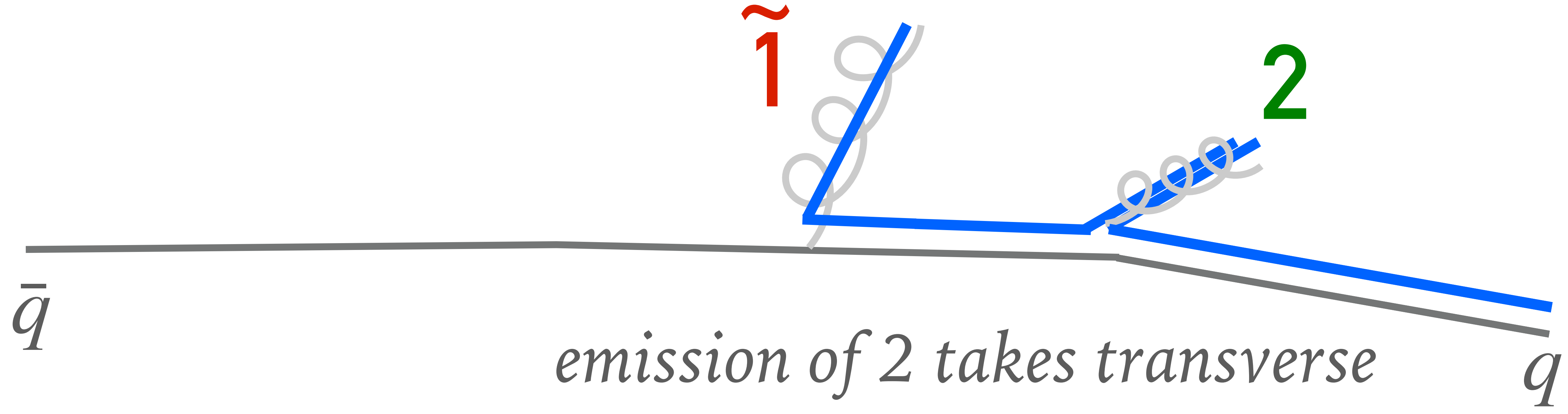
One approach

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

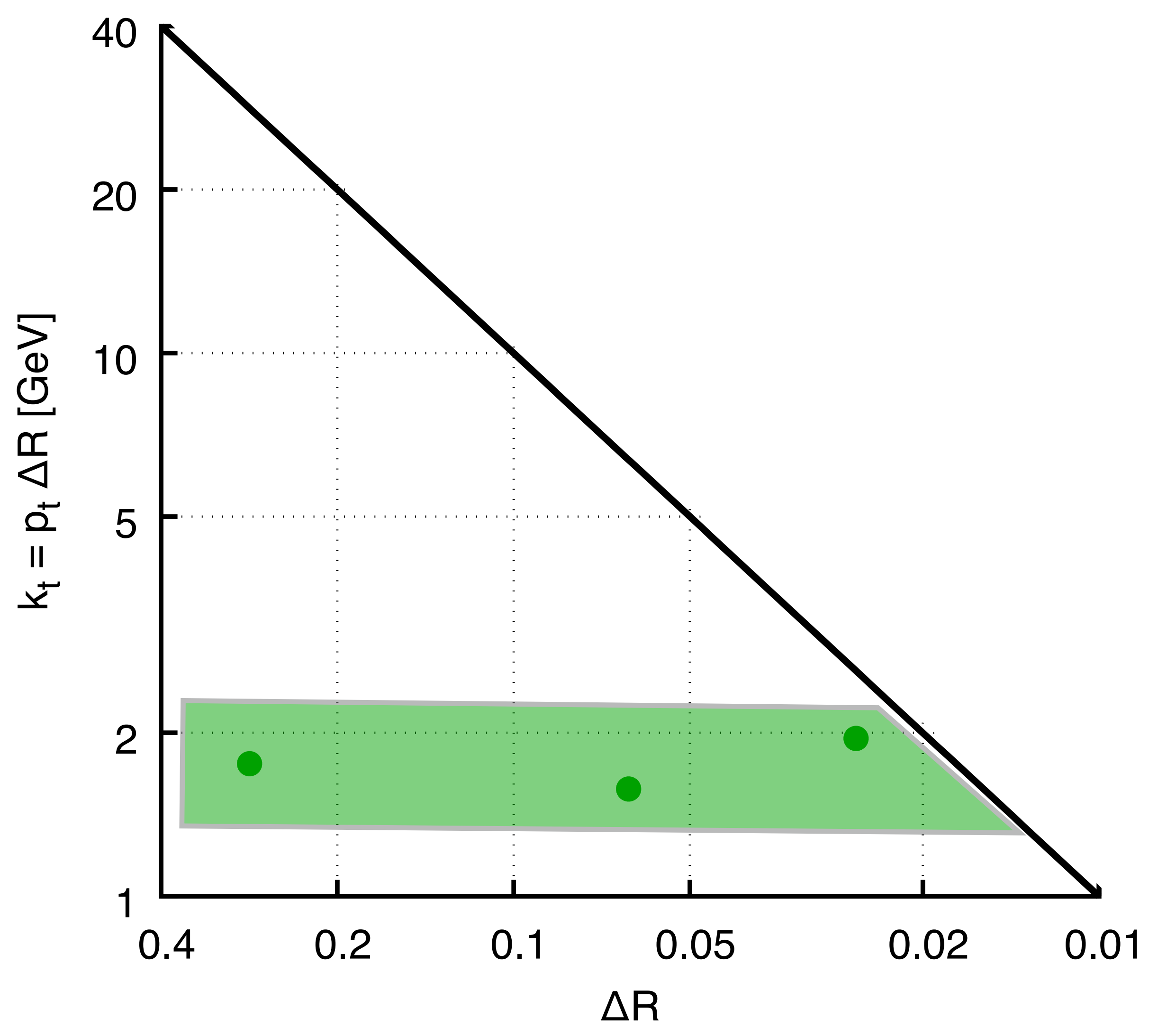


1. Correct recoil rule: no side effects on other distant emissions

One approach



emission of 2 takes transverse recoil from q

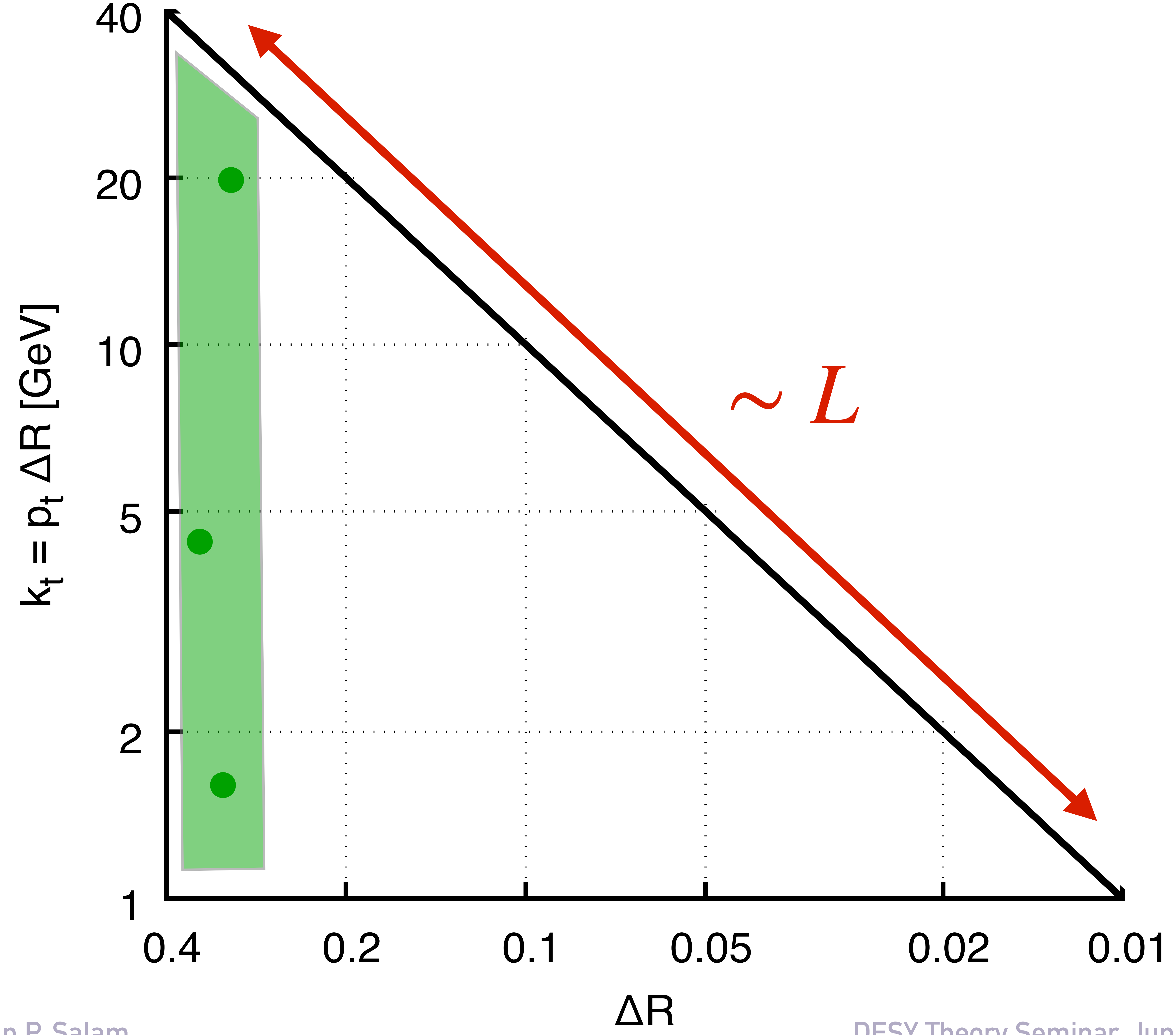


θ_{1q} left almost unchanged if ⊥ recoil from emission of 2 taken by (much harder) q

Can be achieved in multiple ways:

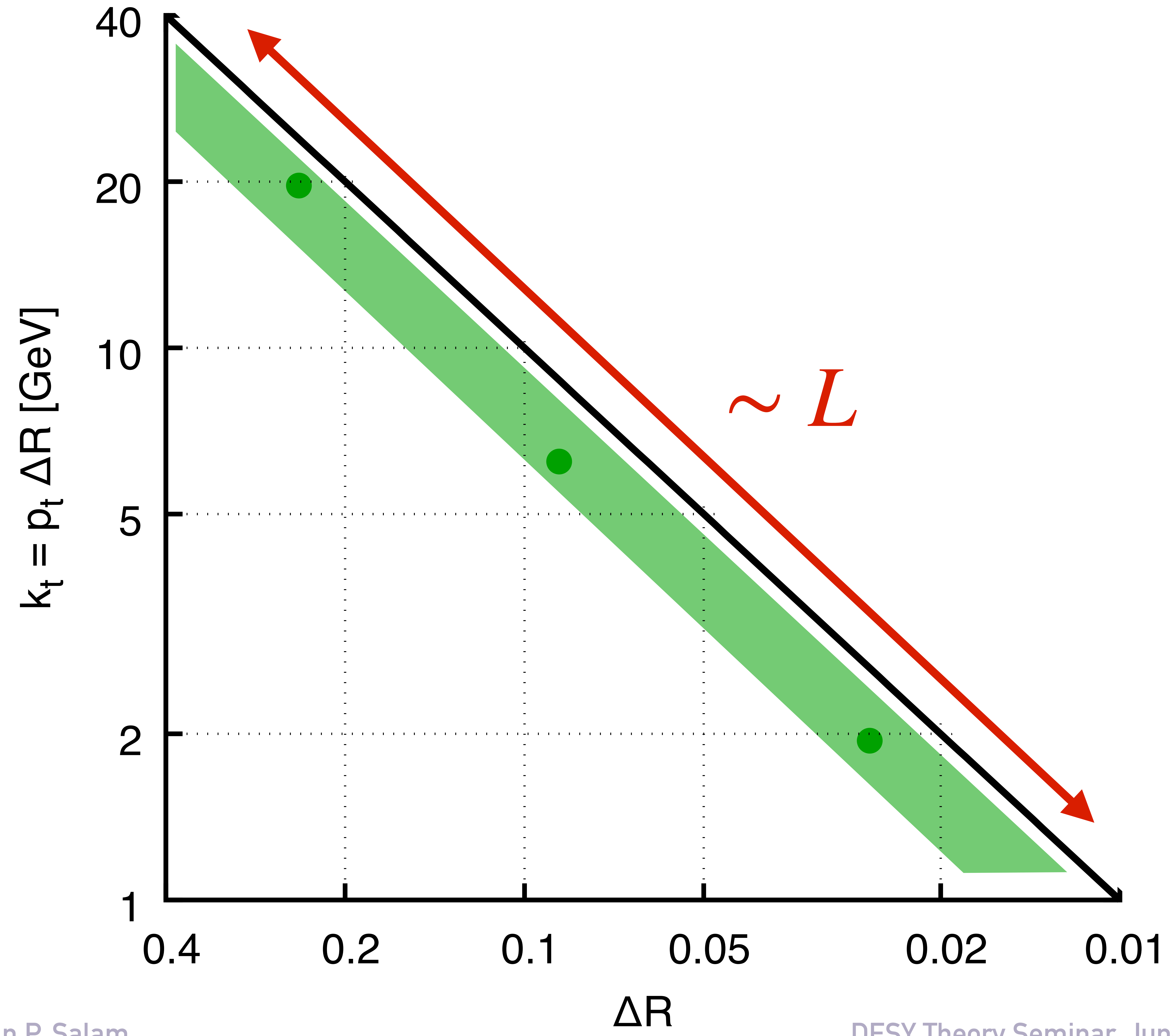
- global transverse recoil
  (Dasgupta et al 2002.11114, "**PanGlobal**"; Holguin Seymour & Forshaw 2003.06400)
- local transverse recoil, with non-standard shower ordering & dipole partition
  ("**PanLocal**"; Nagy & Soper 0912.4534, "Deductor")

2. individual ingredients: (a) large-angle soft (non-global logarithms)



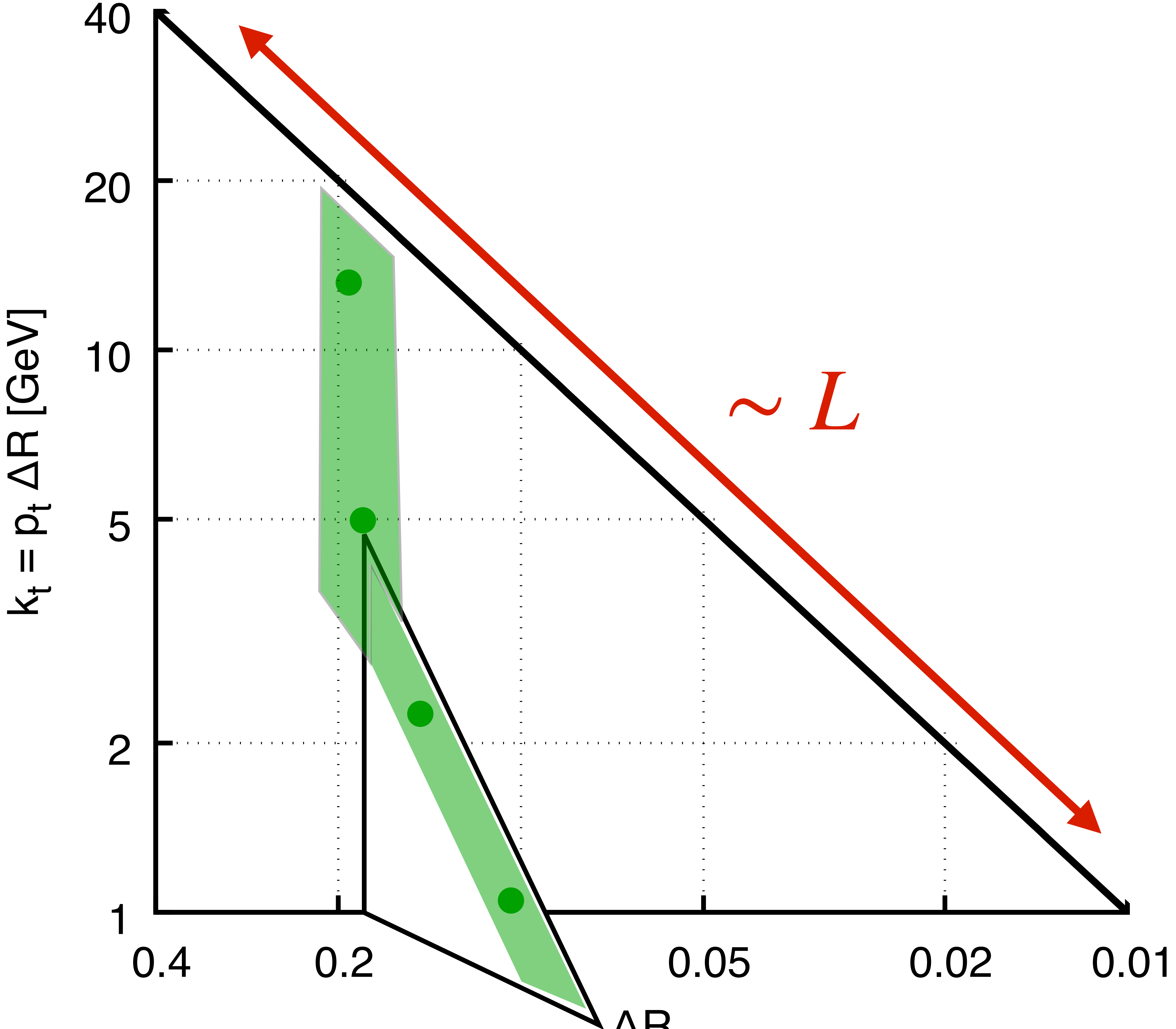
- dipole showers get this right at large N_c “for free”
- (NB: angular ordered showers don’t — Banfi, Corcella & Dasgupta, hep-ph/0612282)

2. individual ingredients: (b) hard-collinear spin correlations



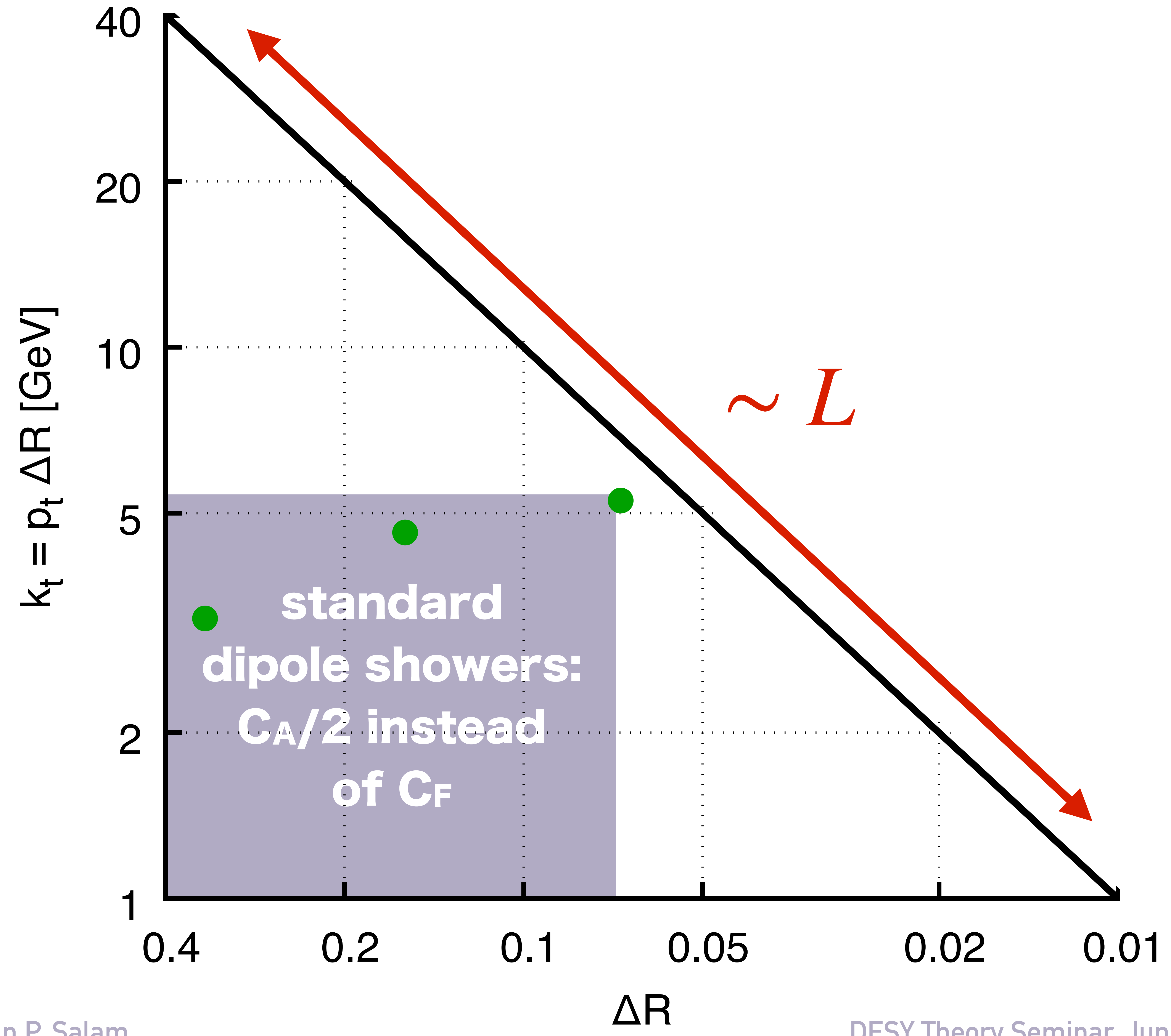
- recipe proposed long ago by Collins ('86)
- implemented in Herwig showers (Deductor & CVolver frameworks also discuss it)
- Included in PanScales showers: Karlberg, GPS, Scyboz, Verheyen, 2103.16526

2. individual ingredients: (c) soft, then hard-collinear spin correlations



- explicitly excluded from Collins recipe ('86)
- (Deductor & CVolver frameworks could in principle get it, but not implemented)
- Efficient & simple large-N_c scheme introduced and implemented in PanScales showers: Hamilton, Karlberg, GPS, Scyboz, Verheyen, 2103.16526

2. individual ingredients: (d) colour, beyond leading-N_c limit



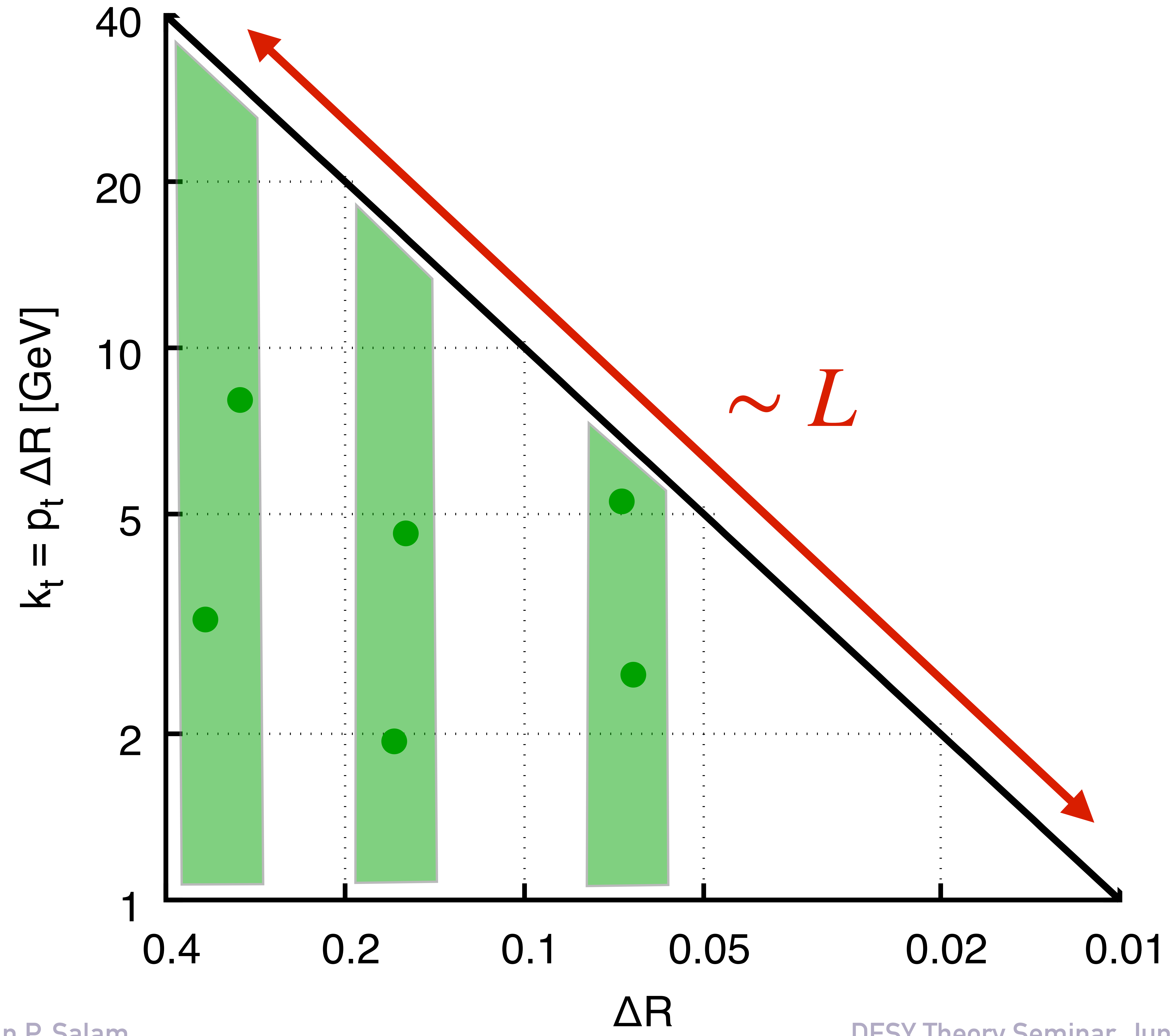
- Standard showers have wrong subleading colour terms at LL ($\mathrm{LL} \times 1/N_c^2 \sim \mathrm{NLL}$)

Gustafson '93
Dasgupta et al '18

- Angular ordering ("coherence") points to correct solution when all emissions well separated in angle

Friberg, Gustafson, Hakkinen '96
Hamilton, Medves, GPS, Scyboz, Soyez, 2011.10054
Forshaw, Holguin & Platzer, 2011.15087

2. individual ingredients: (d) colour, beyond leading-N_c limit



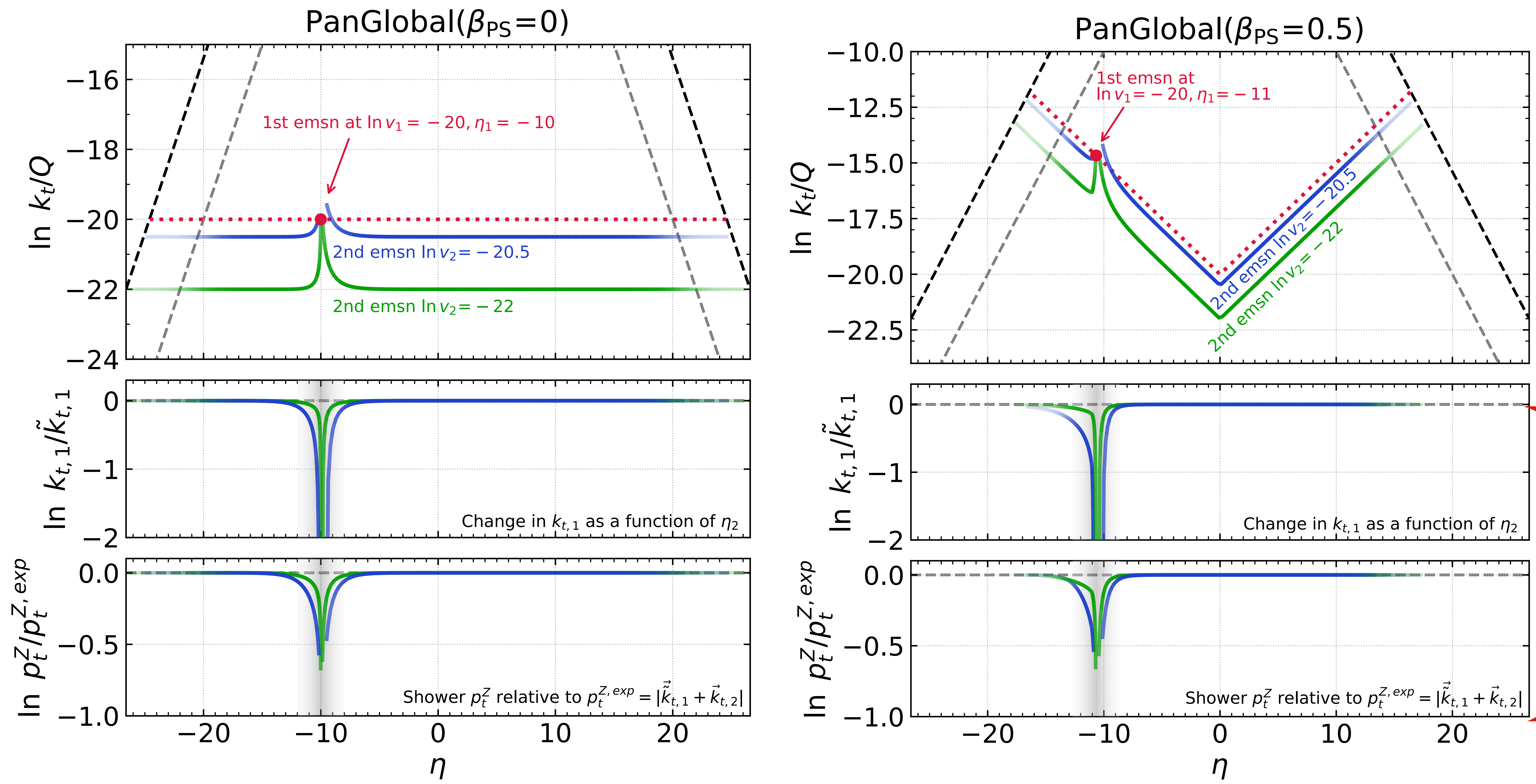
PanScales approach

- Systematic expansion, with full colour for up to n emissions in any vertical slice
- Implemented for $n = 1$ & 2 (segment & "NODS" methods)
- difference between them gives estimate of residual systematic error

Hamilton, Medves, GPS, Scyboz, Soyez, 2011.10054

(NB: coherence-violating logarithms with initial partons & complex final state not addressed so far in PanScales)

2. individual ingredients: (e) all of the above, **with initial-state hadrons**



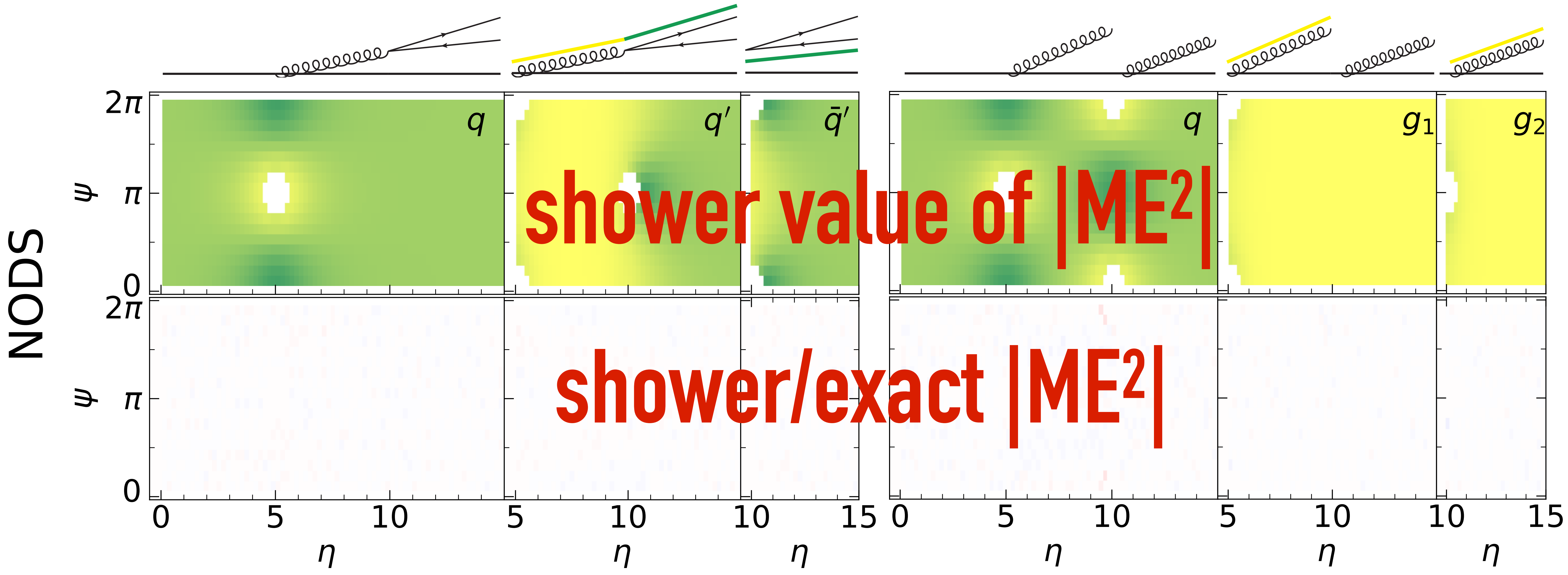
checks of correct recoil

van Beekveld, Ferrario Ravasio, GPS, Soto-Ontoso, Soyez, Verheyen, 2205.02237

Testing NLL showers

matrix element tests
all-order resummation comparisons

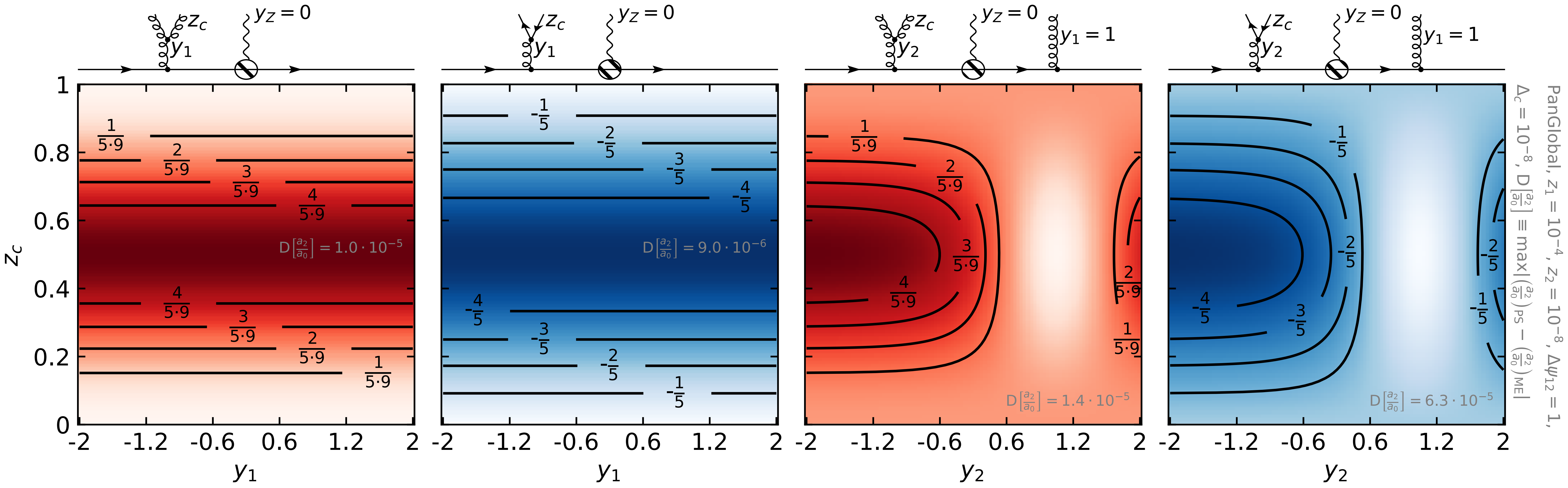
Test class 1: tree-level (2nd/3rd-order) expansion of shower v. factorised matrix element



shower value of $|ME^2|$

shower/exact $|ME^2|$

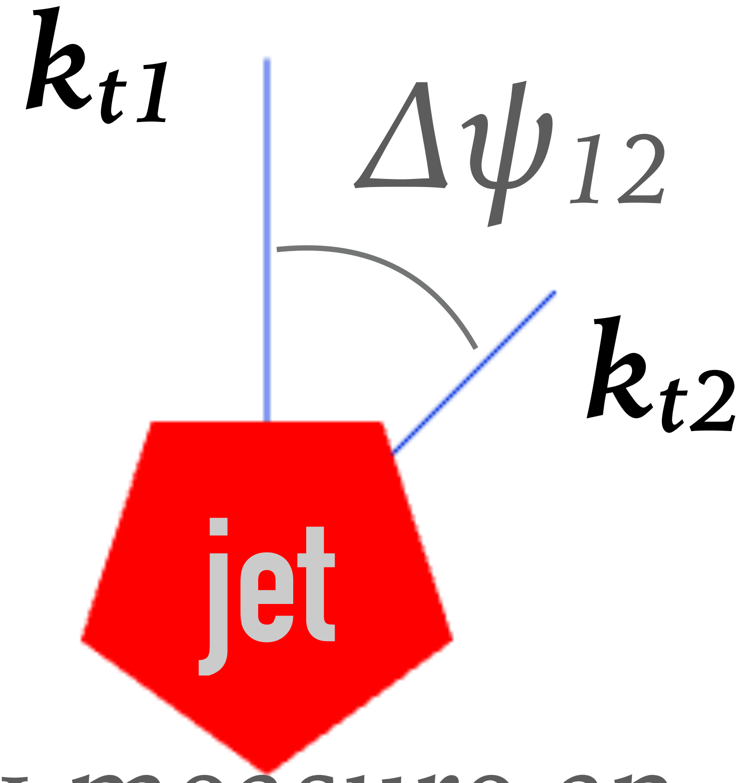
colour



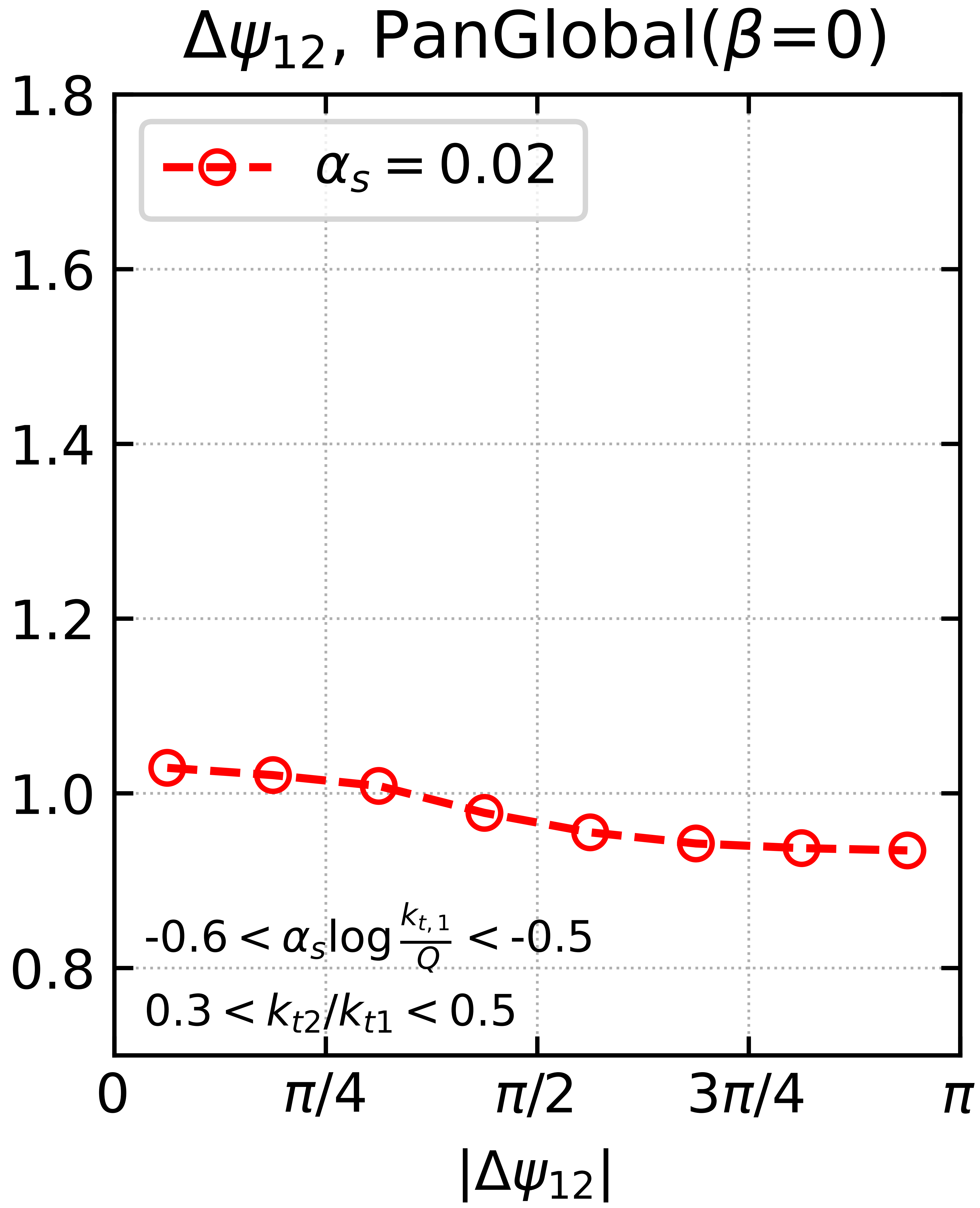
spin

- semi-analytically (recoil checks)
- numerically (colour & spin)

Test class 2: full shower v. all-order NLL

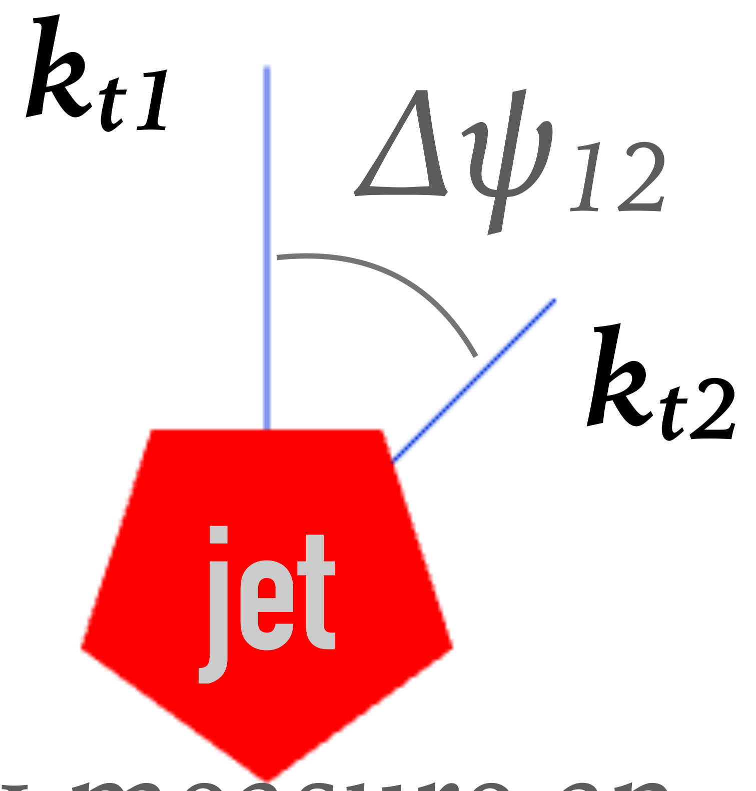


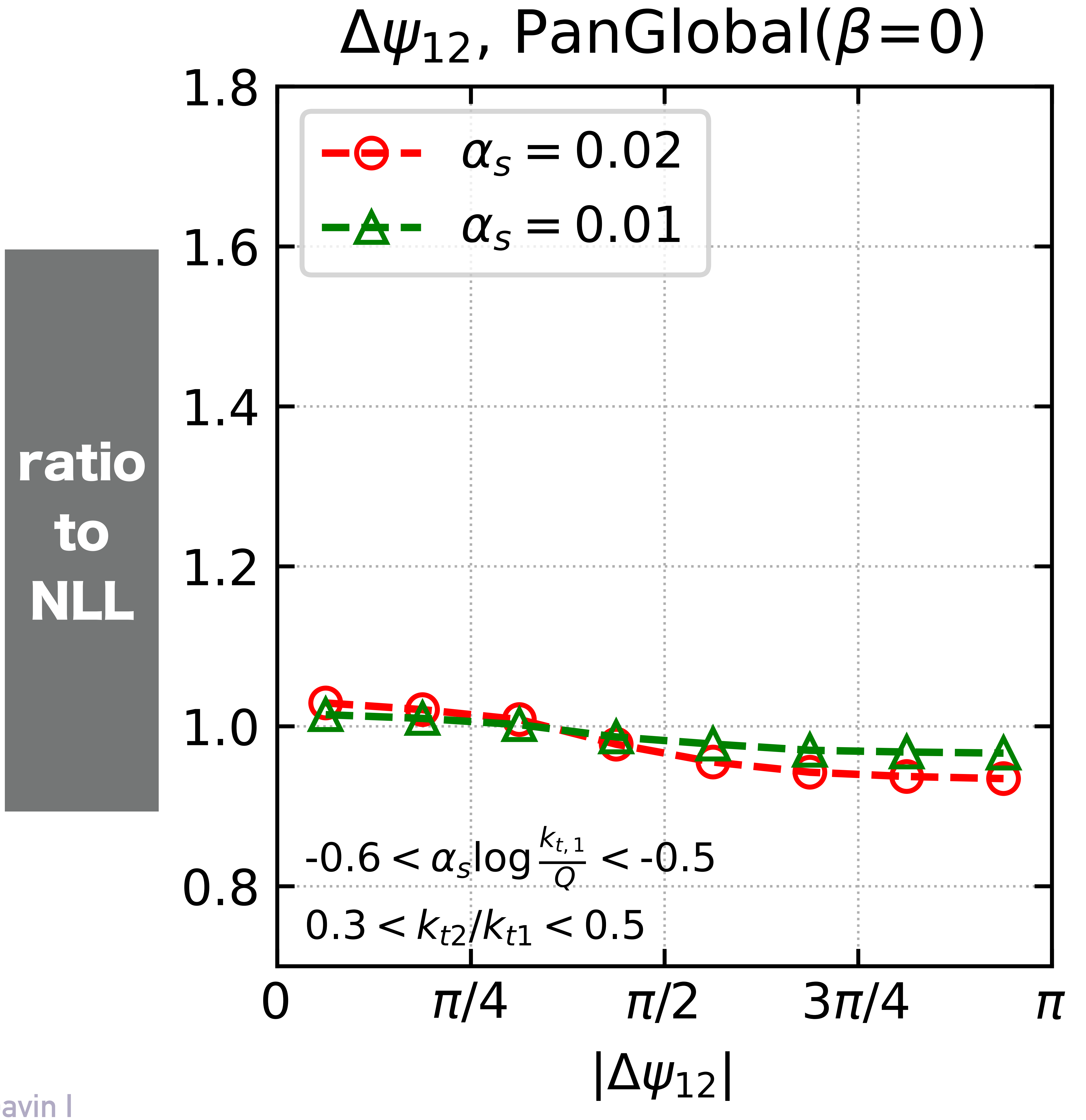
ratio to NLL



- run full shower with specific value of $\alpha_s(Q)$ & measure an observable: azimuth between two highest-k_t emissions (soft-collinear)
- ratio to NLL should be flat ≡ 1
- it isn't: have we got an NLL mistake? Or a residual subleading (NNLL) term?

Tests (2): full shower v. all-order NLL

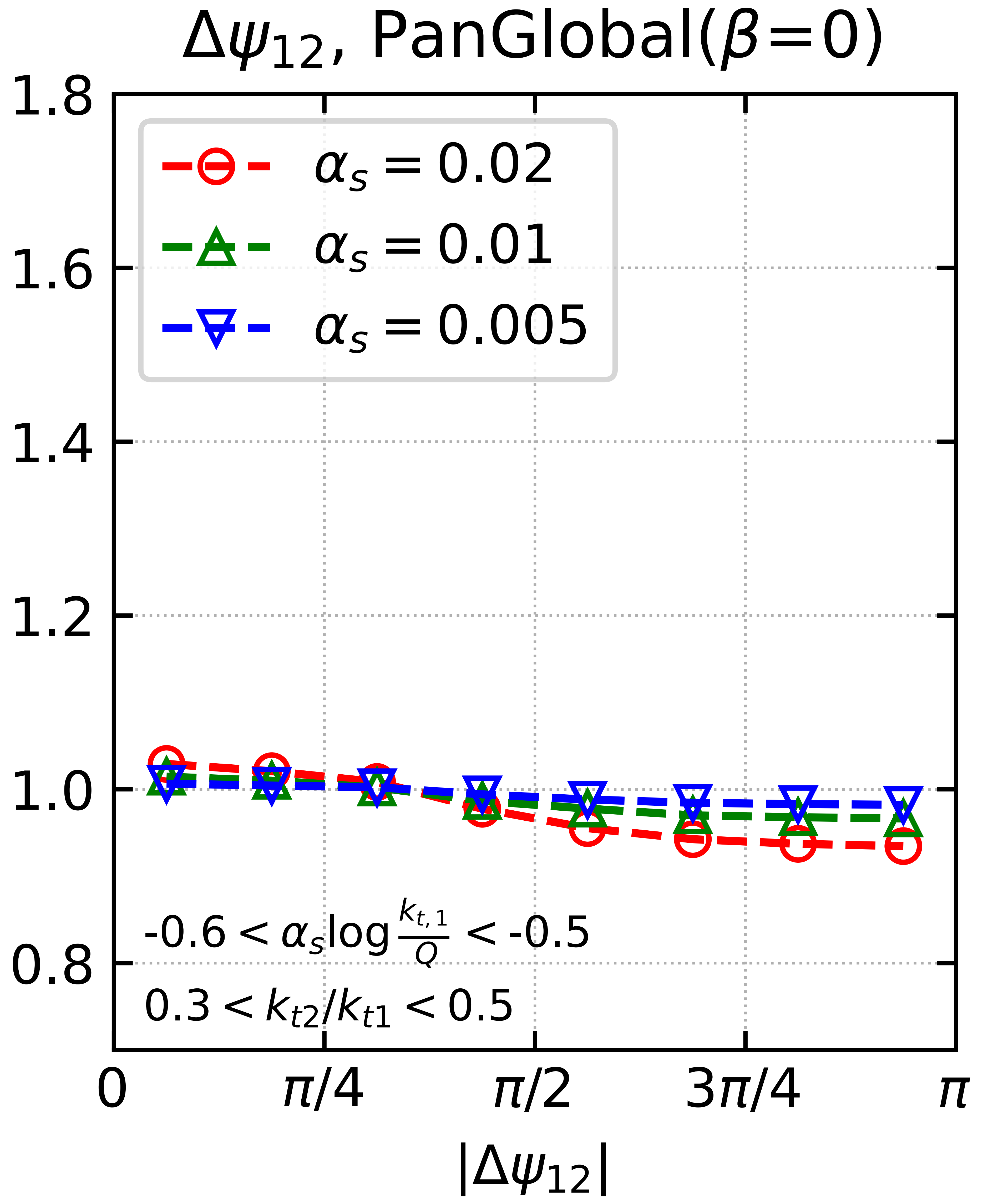


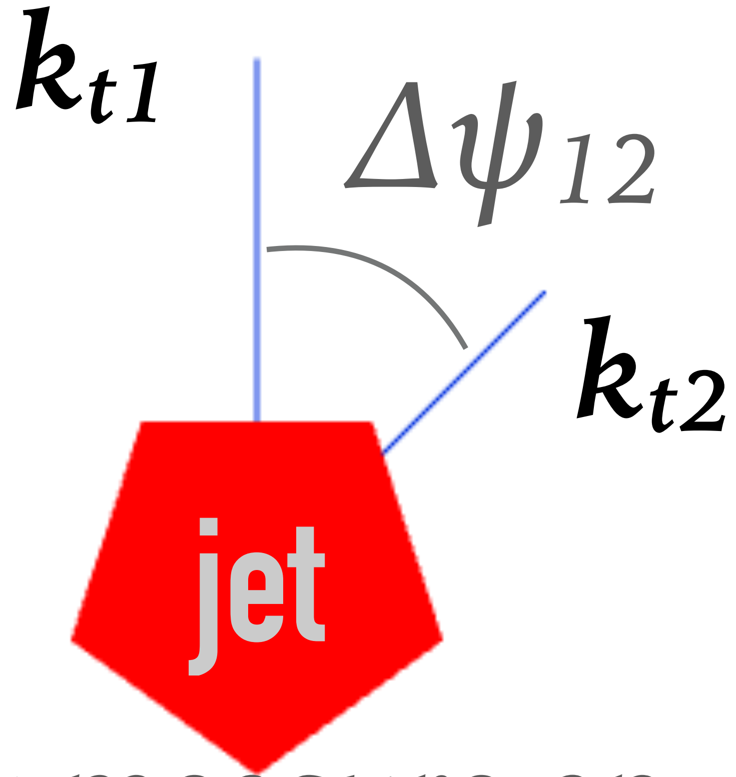


- run full shower with specific value of $\alpha_s(Q)$ & measure an observable: azimuth between two highest-k_t emissions (soft-collinear)
- ratio to NLL should be flat ≡ 1
- it isn't: have we got an NLL mistake? Or a residual subleading (NNLL) term?
- try reducing $\alpha_s(Q)$, while keeping constant $\alpha_s L$ [$L \equiv \ln k_{t1}/Q$]
- NLL effects, $(\alpha_s L)^n$, should be unchanged, subleading ones, $\alpha_s(\alpha_s L)^n$, → 0

Tests (2): full shower v. all-order NLL

ratio to NLL





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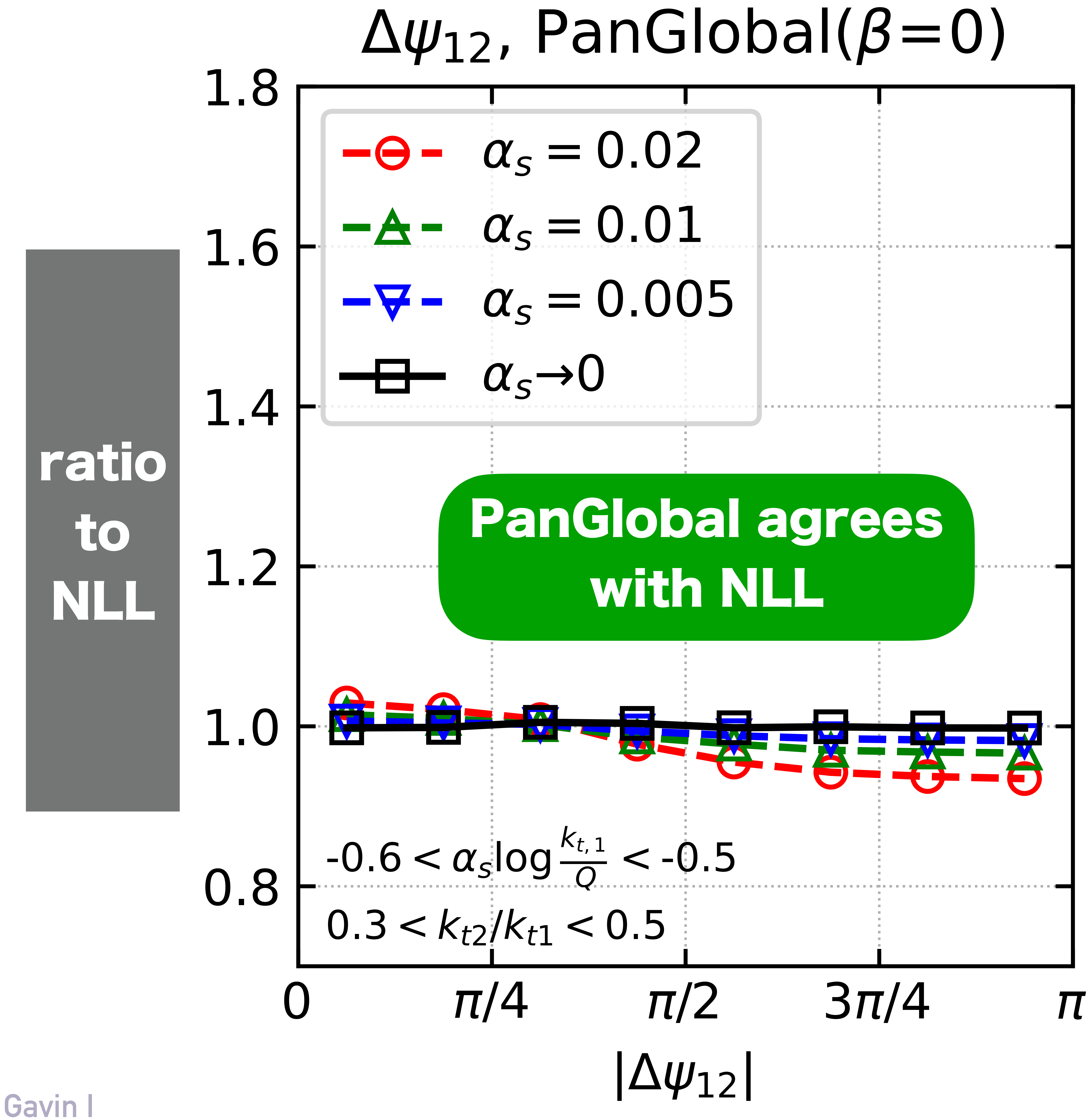

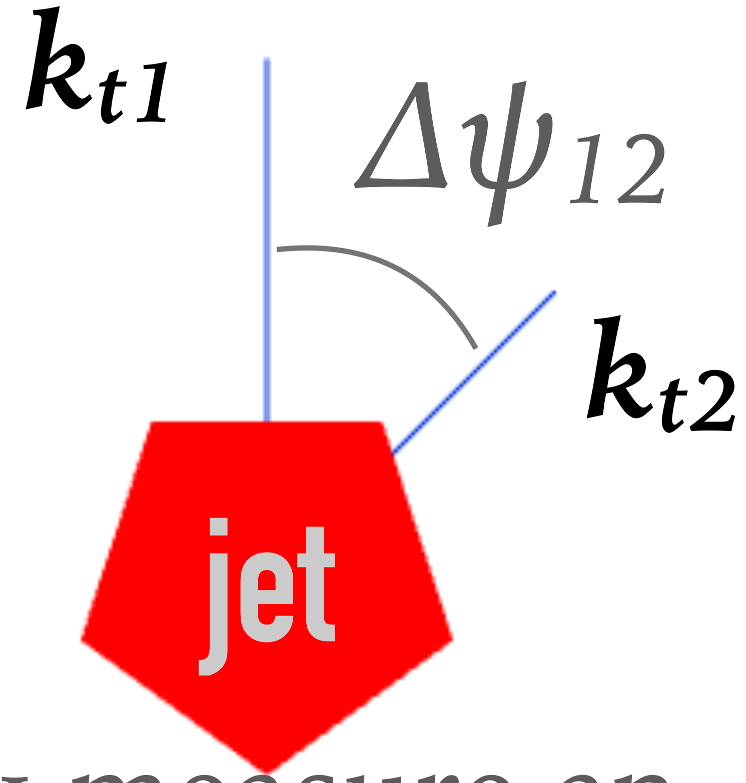

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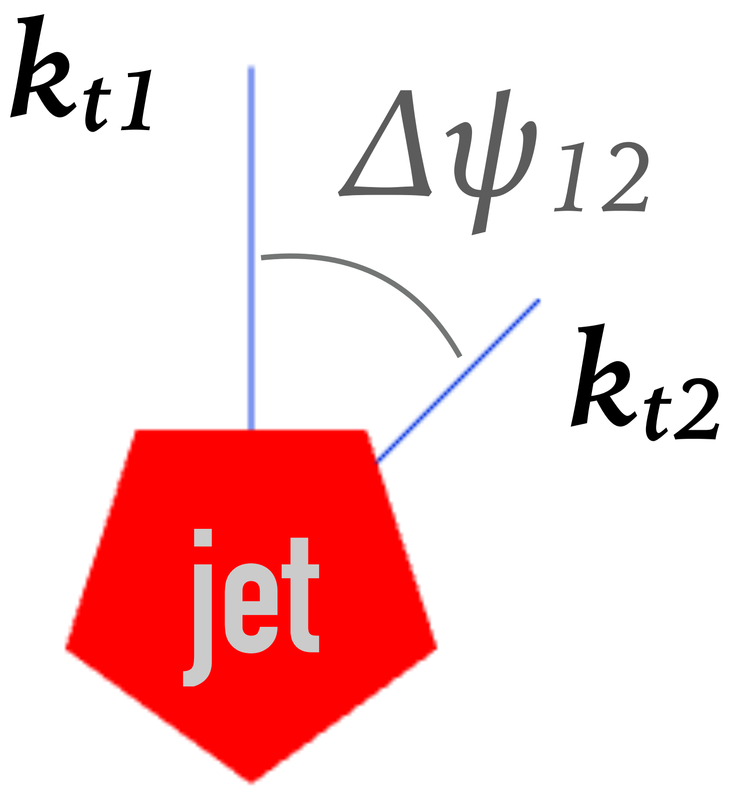
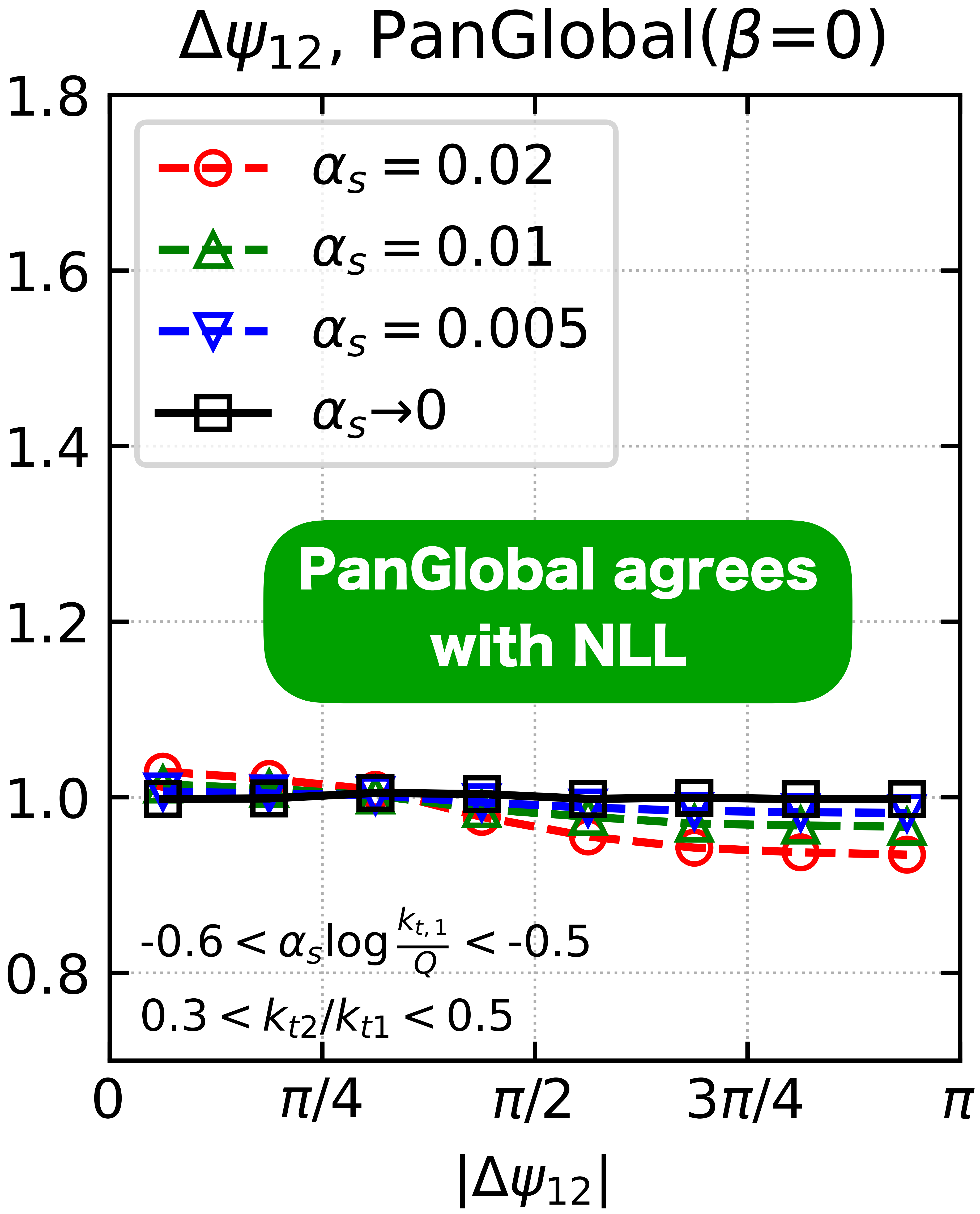
- try reducing $\alpha_s(Q)$, while keeping constant $\alpha_s L$ [$L \equiv \ln k_{t1}/Q$]

✓ **extrapolation $\alpha_s \to 0$ agrees with NLL**

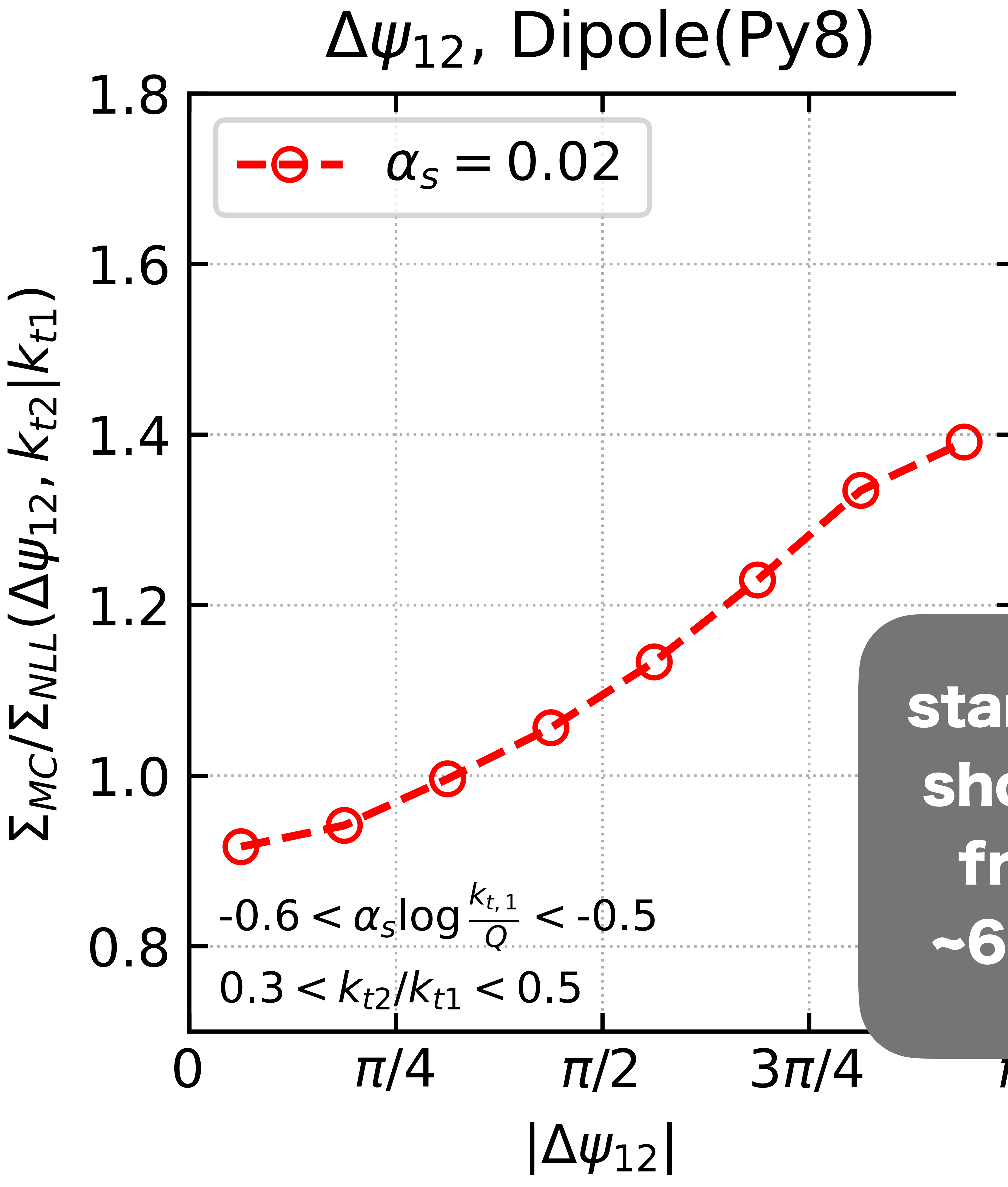
Tests (2): full shower v. all-order NLL



ratio to NLL

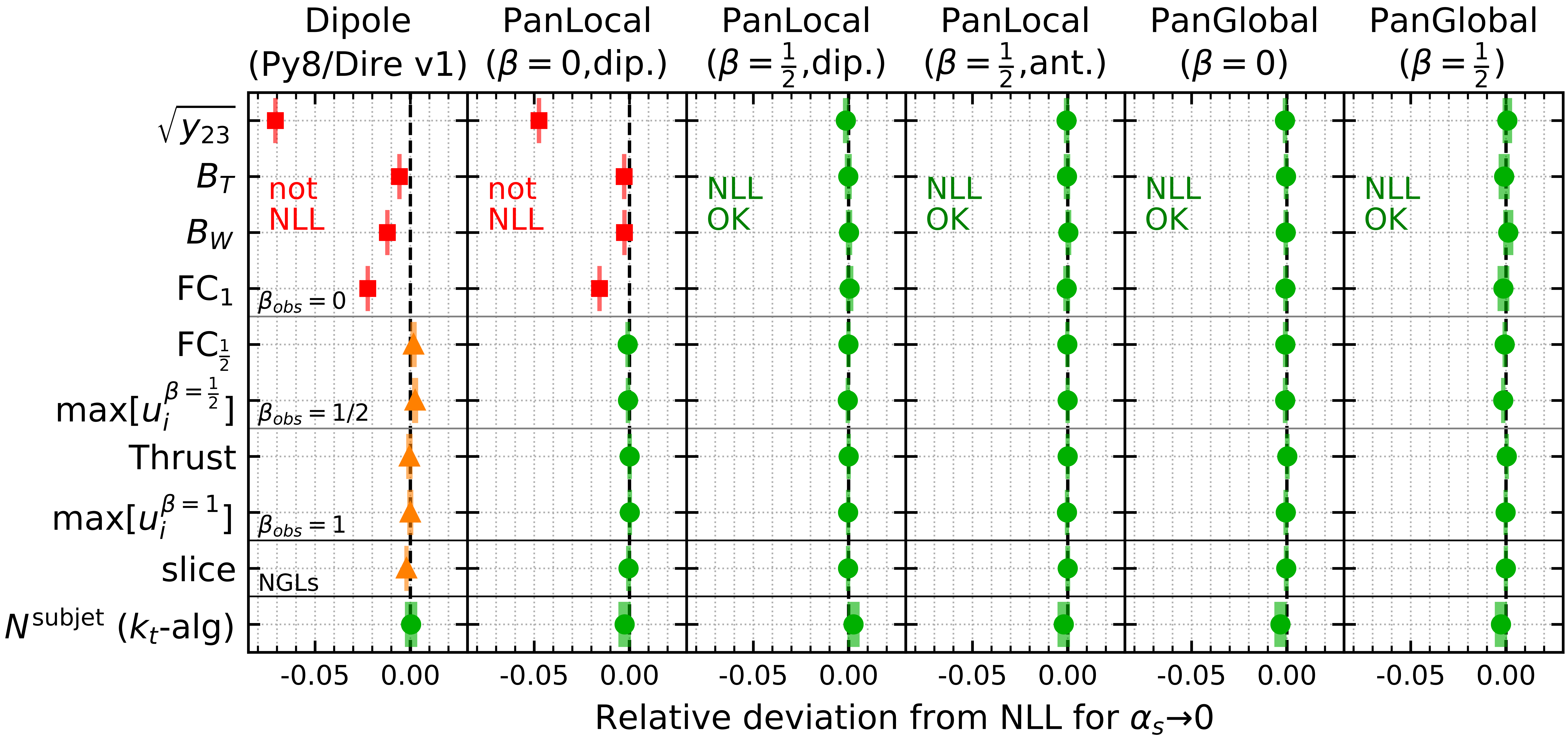


PanGlobal agrees with NLL

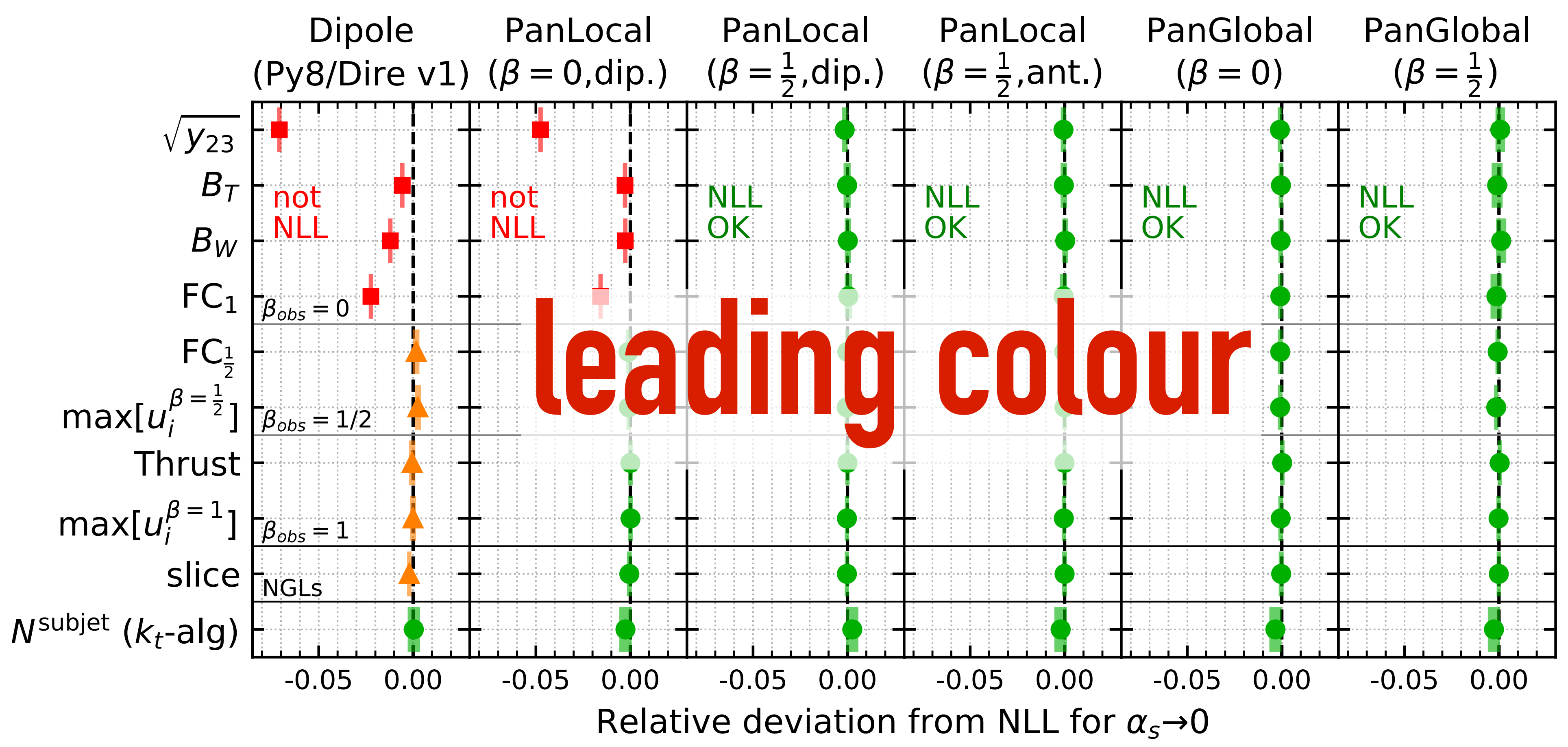


standard dipole shower differs from NLL by ~60%, i.e. O(1)

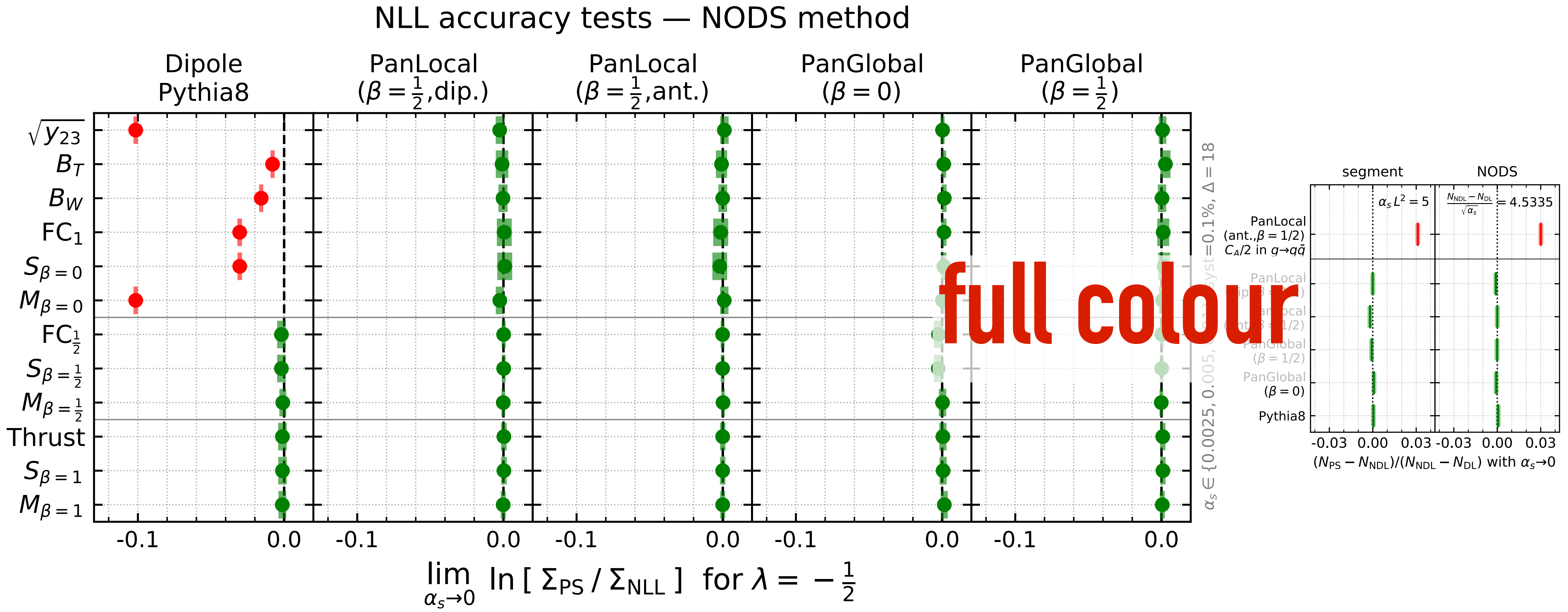
Test class 2: full shower v. all-order NLL — many observables



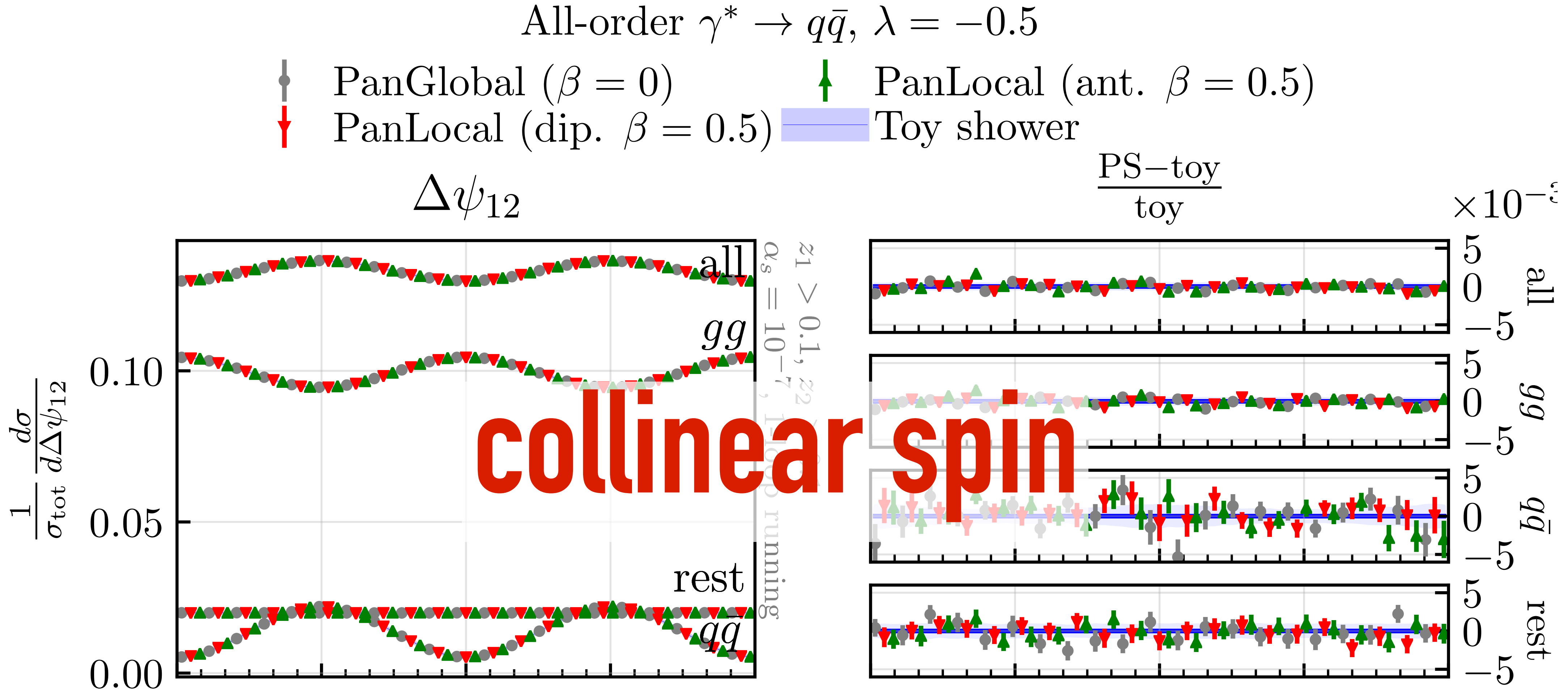
Test class 2: full shower v. all-order NLL — many observables



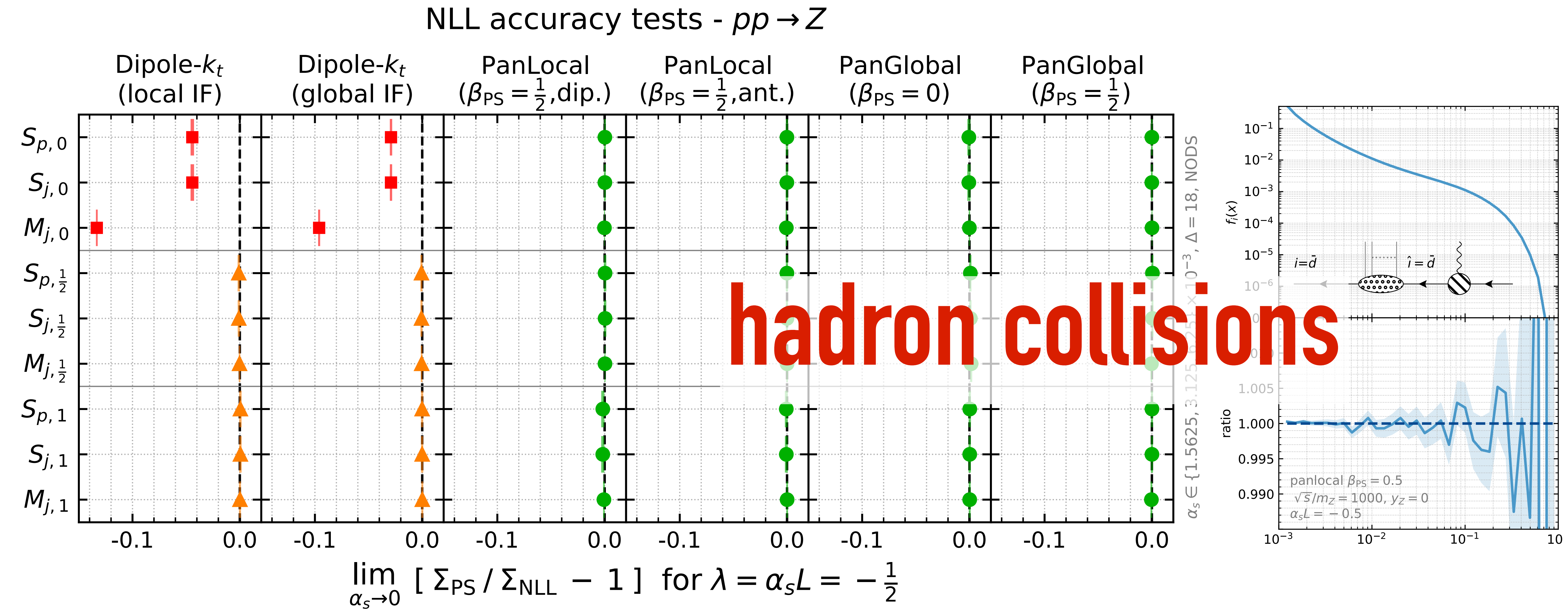
leading colour



full colour



collinear spin



hadron collisions

PanScales status: $e^+e^- \rightarrow$ jets & pp $\rightarrow$ Z/W/H (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

PanLocal	PanGlobal	FHP	Deductor
$k_t\sqrt{\theta}$ ordered	k_t or $k_t\sqrt{\theta}$ ordered	k_t ordered	$k_t\theta$ ("Λ") ordered
Recoil	**Recoil**	**Recoil**	**Recoil**
⊥: local	⊥: global	⊥: global	⊥: local
+: local	+: local	+: local	+: local
–: local	–: local	–: global	–: global
Tests	**Tests**	**Tests**	**Tests**
numerical for many observables	numerical for many observables	analytical for thrust & multiplicity	analytical / numerical for thrust

Dasgupta, Dreyer, Hamilton, Monni, GPS & Soyez 2002.11114
+ subsequent work incl van Beekveld, Ferrario Ravasio, Karlberg, Medves, Scyboz, Soto-Ontoso, Verheyen

Forshaw, Holguin & Plätzer
2003.06400

Nagy & Soper
2011.04777 *(+past decade)*

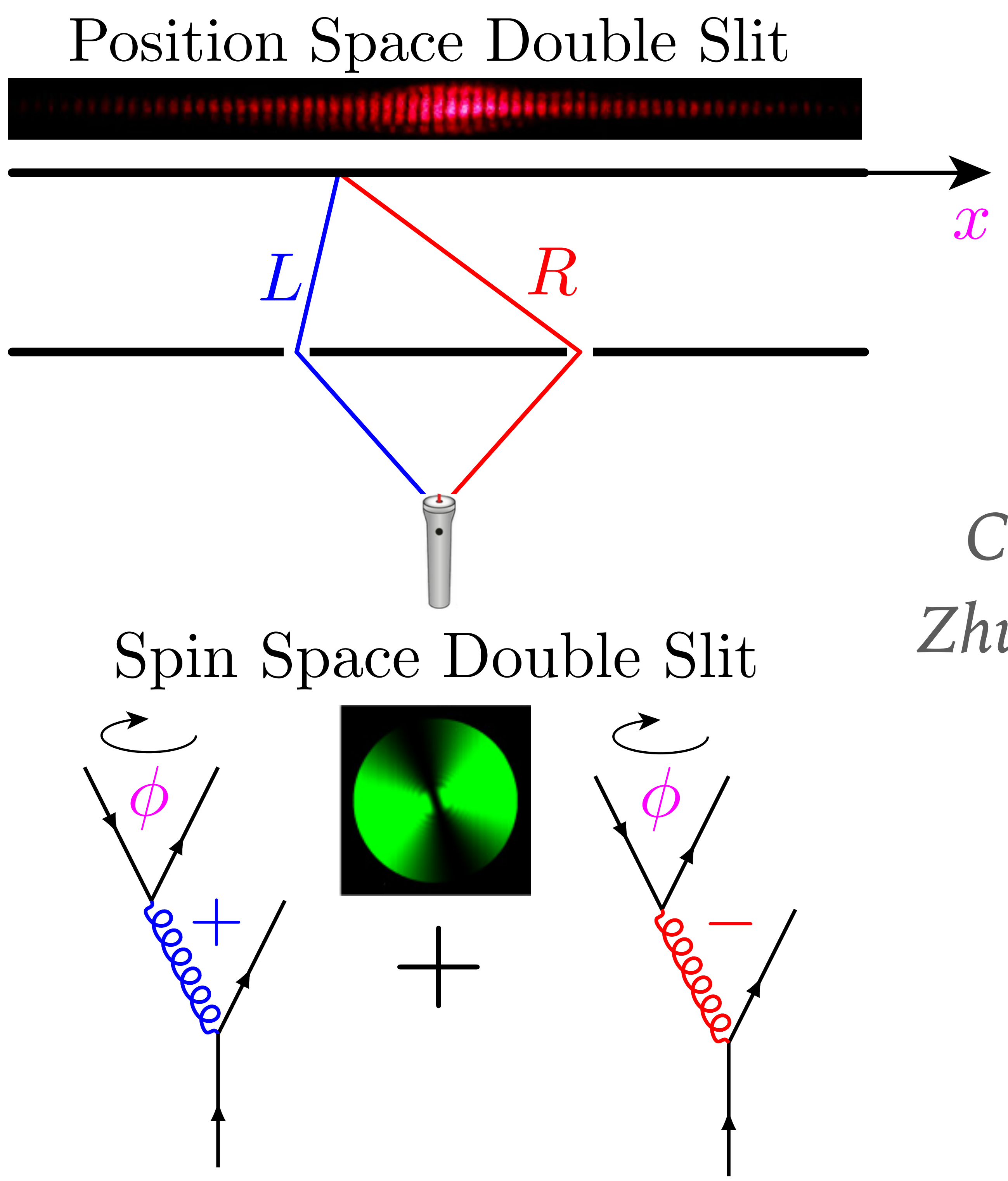
spin-offs

To test spin in shower, you need observables and reference resummations

Energy-energy-energy correlations (EEEC), resummed analytically (Chen, Moult & Zhu,2011.02492)

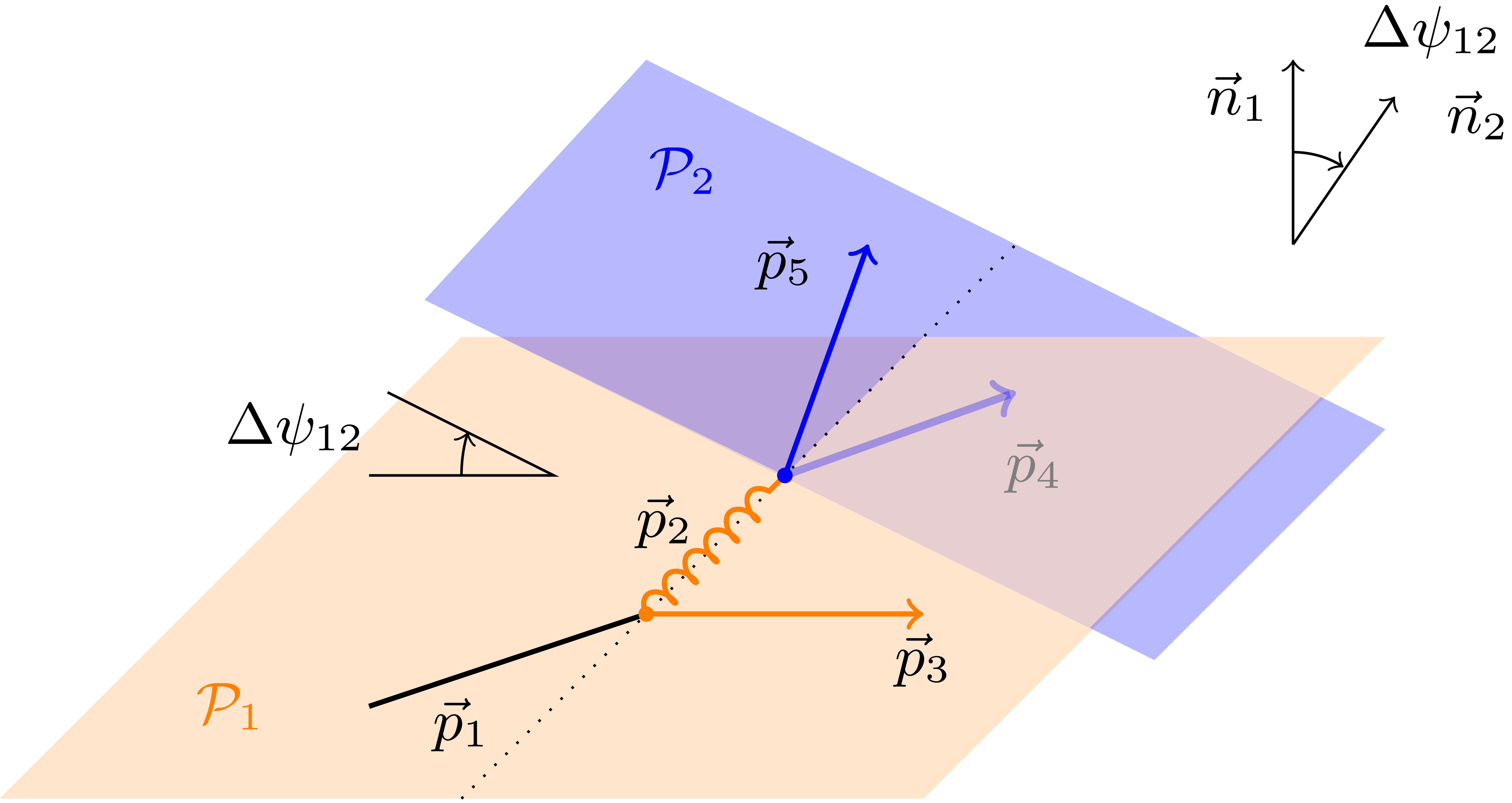
Lund declustering ($\Delta\psi_{12}$, $\Delta\psi_{11'}$), resummed numerically with "toy shower"

(extending unpolarized Microjets code from Dasgupta, Dreyer, GPS, Soyez 1411.5182)



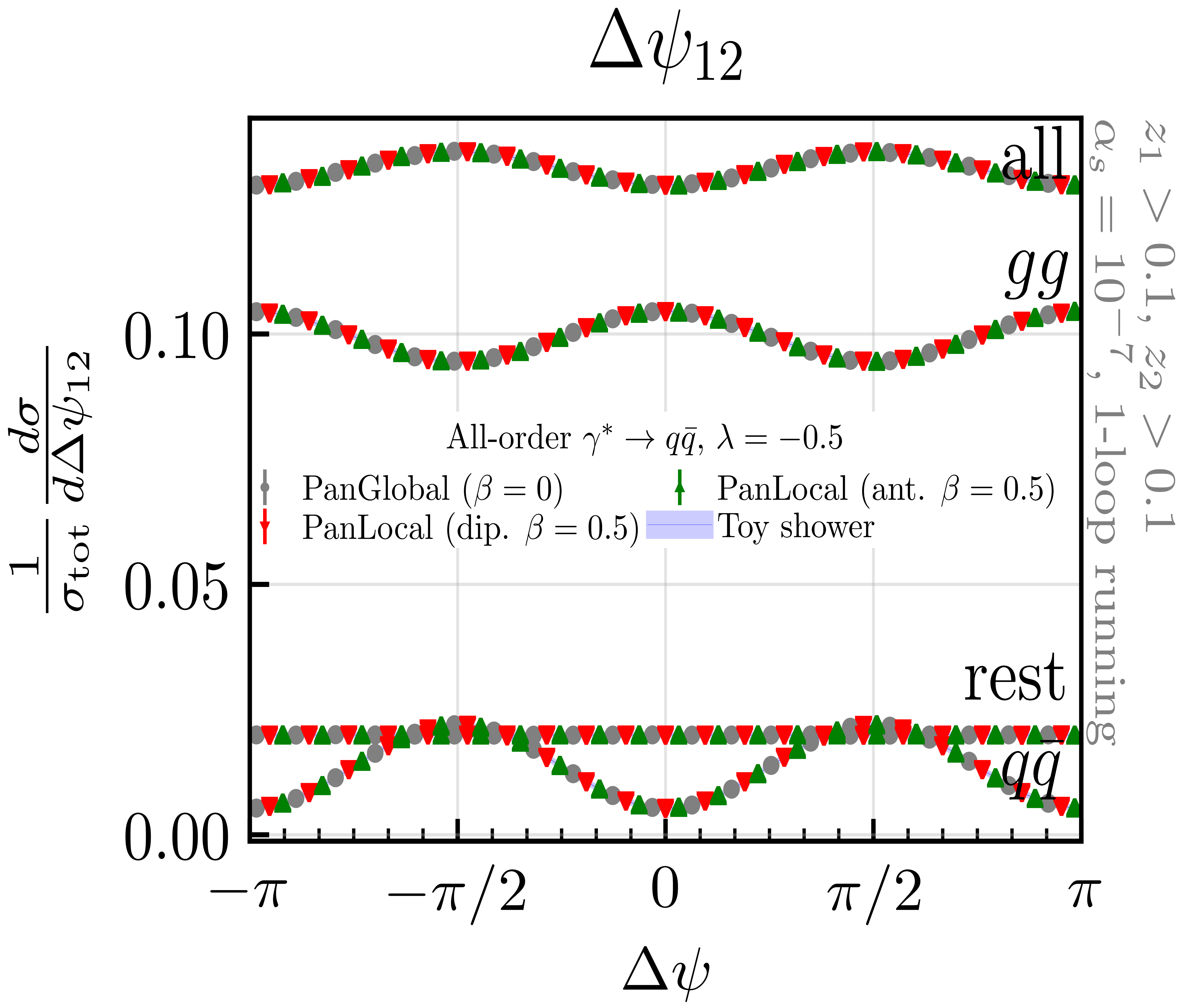
Chen, Moult & Zhu, 2011.02492

Quantum mechanical interference in otherwise quasi-classical regime



Karlberg, GPS, Scyboz & Verheyen, 2103.16526

Spin correlations in full shower

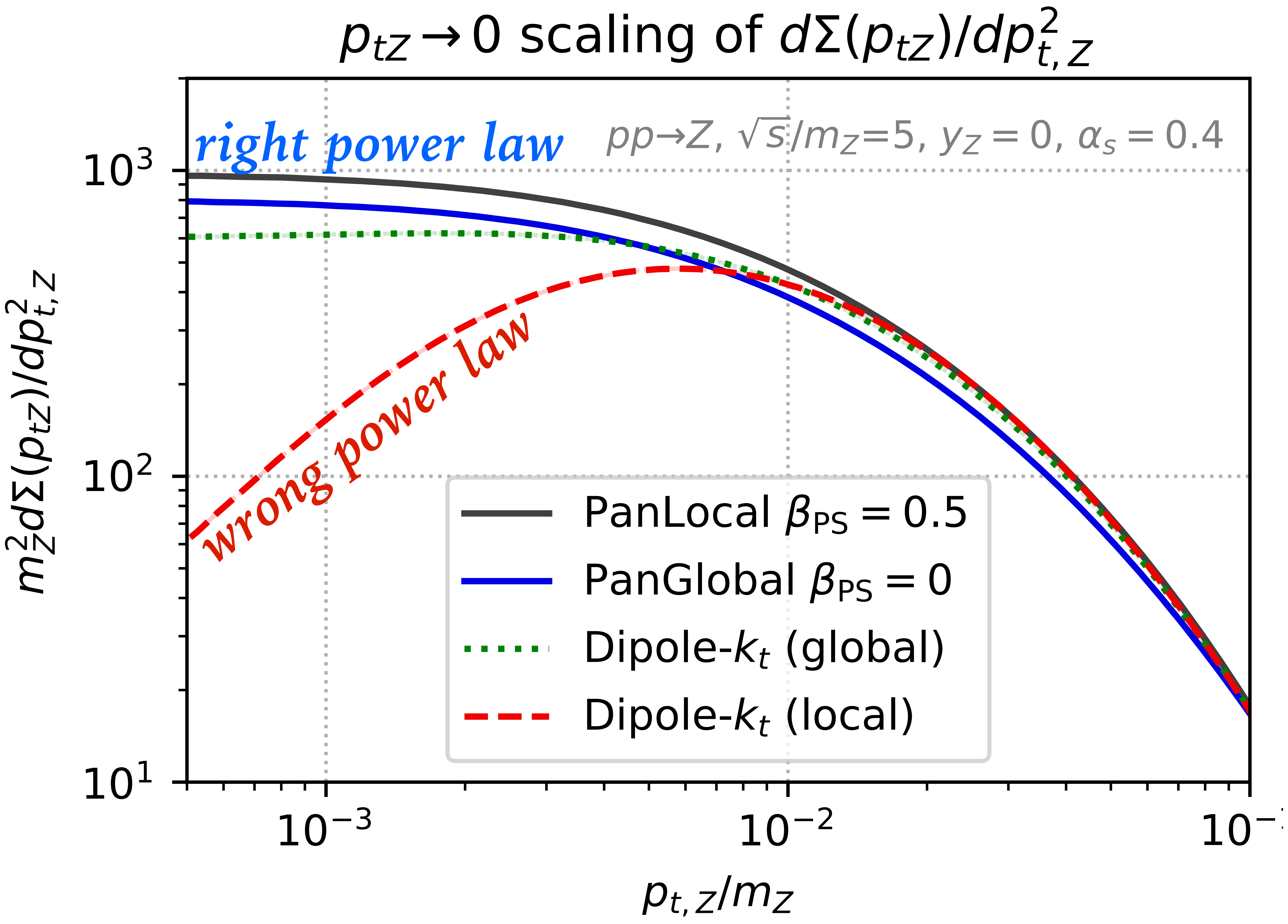


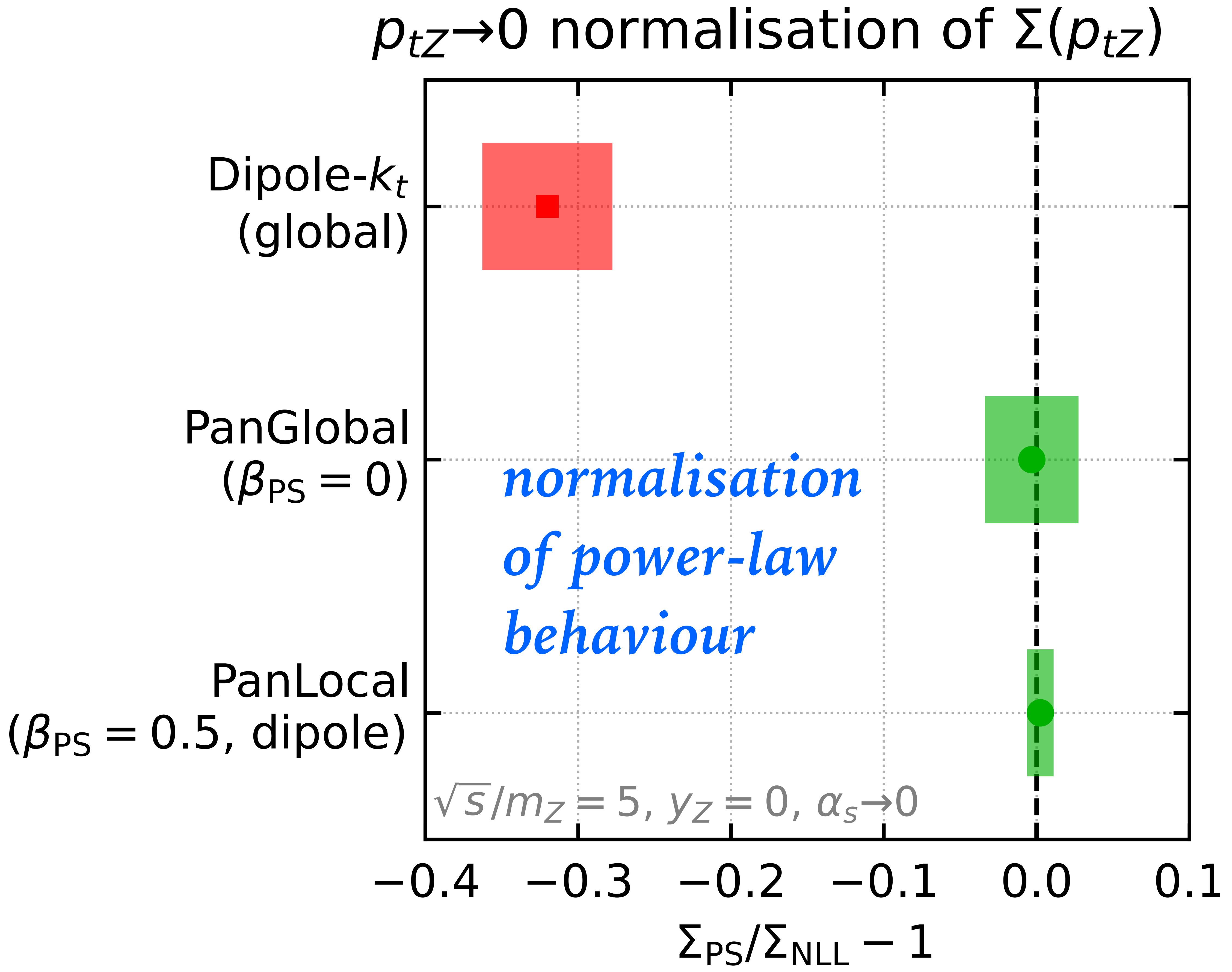
magnitude of spin correlation effects	
EEEC	-0.008
$\Delta\psi_{12},\ z_1, z_2 > 0.1$	-0.025
$\Delta\psi_{12},\ z_1 > 0.1,\ z_2 > 0.3$	-0.042

Lund declustering $\Delta\psi_{12}$ offers interesting prospects for experimental measurements of spin-correlation effects in jets

Karlberg, GPS, Scyboz & Verheyen, 2103.16526

pp → Z + hadrons: small-p_t asymptotics for Z p_t spectrum


$p_{tZ} \to 0$ scaling of $d\Sigma(p_{tZ})/dp_{t,Z}^2$


$p_{tZ} \to 0$ normalisation of $\Sigma(p_{tZ})$

Parisi-Petronzio ’79, predicted power-law scaling of Z p_t spectrum at low p_t.

Which showers reproduce it?

van Beekveld, Ferrario Ravasio, Hamilton,
GPS, Soto-Ontoso, Soyez, to appear

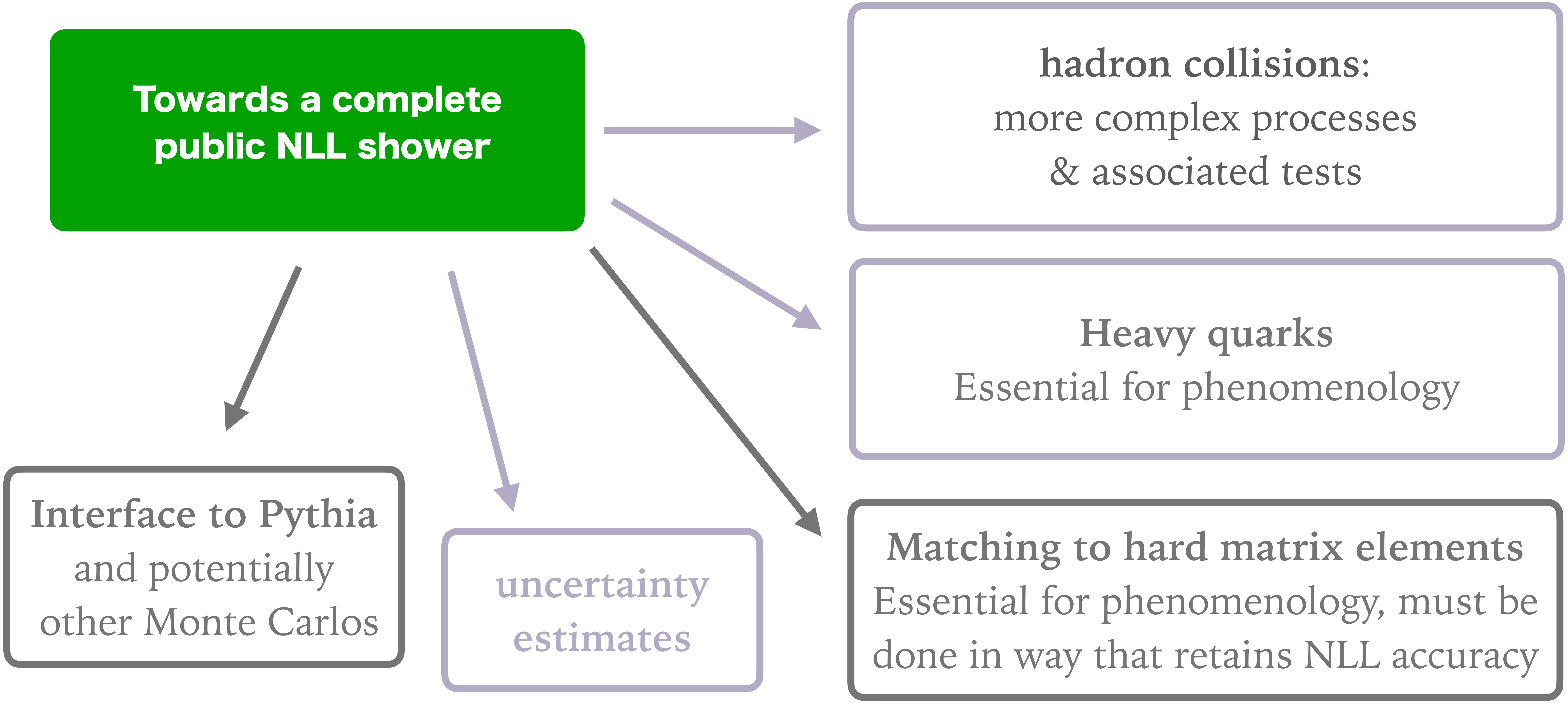
future prospects

Next steps

Towards a complete public NLL shower

Going beyond NLL

Next steps



Towards a complete public NLL shower

hadron collisions:
more complex processes
& associated tests

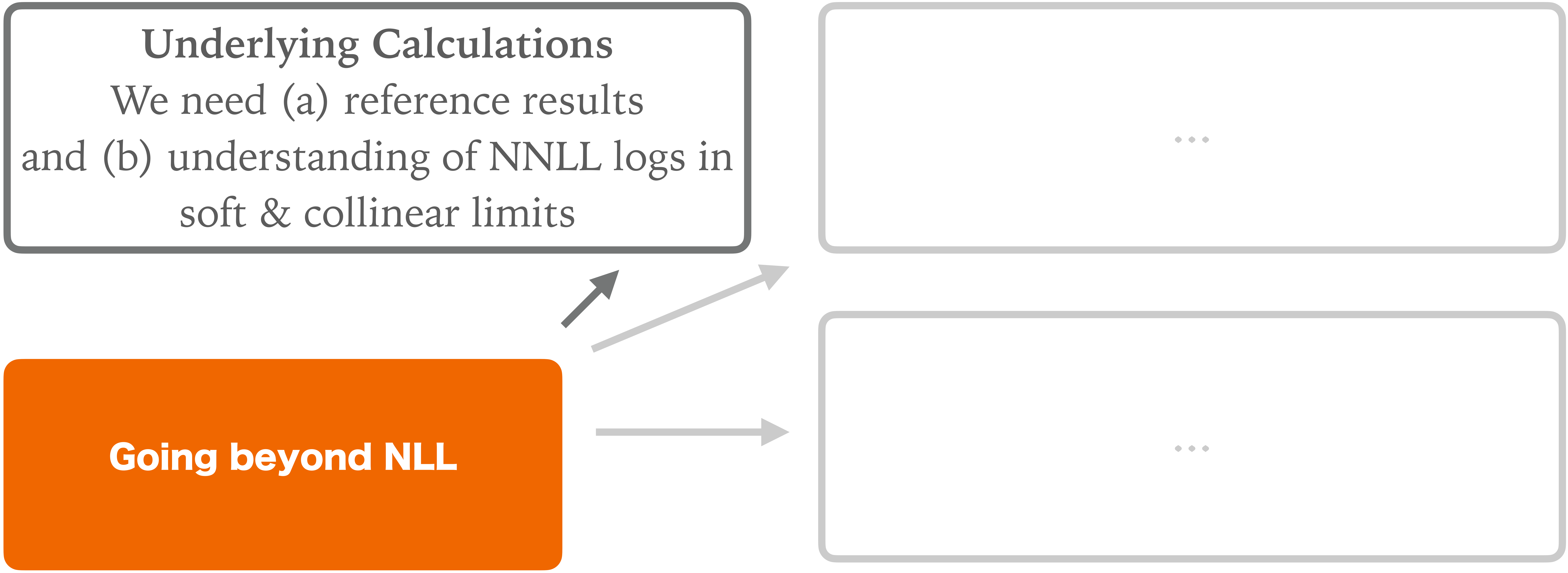
Heavy quarks
Essential for phenomenology

Interface to Pythia
and potentially
other Monte Carlos

uncertainty estimates

Matching to hard matrix elements
Essential for phenomenology, must be done in way that retains NLL accuracy

Next steps



Underlying Calculations

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

…

…

Going beyond NLL

Other groups' work (prior to our NLL understanding): Jadach et al 1103.5015 & 1503.06849, Li & Skands 1611.00013, Höche & Prestel 1705.00742, +Krauss 1705.00982, +Dulat 1805.03757,

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

Lund and Cambridge multiplicities for precision physics
Medves, Soto-Ontoso, Soyez, 2205.02861

Groomed jet mass as a direct probe of collinear parton dynamics
Anderle, Dasgupta, El-Menoufi,
Guzzi, Helliwell, 2007.10355
[see also SCET work, Frye, Larkoski,
Schwartz & Yan, 1603.09338 + …]

Dissecting the collinear structure of quark splitting at NNLL
Dasgupta, El-Menoufi, 2109.07496

Conclusions

conclusions

- Parton showers (and event generators in general), and their predictions of the full structure of events, are an essential part of LHC's very broad physics programme
- Despite their central role, understanding of their accuracy has been elusive
- **Minimal baseline** for progress beyond 1980's technology **is to achieve NLL** accuracy ≡ control of terms $(\alpha_s L)^n$
- We've demonstrated leading-colour NLL is possible, full colour can be included at LL, (and at NLL for most observables), spin correlations fit in nicely, for both final and initial-state showers
- **Next steps:**
  - full phenomenological showers (e.g. including matching, pp processes with jets)
  - mapping out the path towards higher accuracy