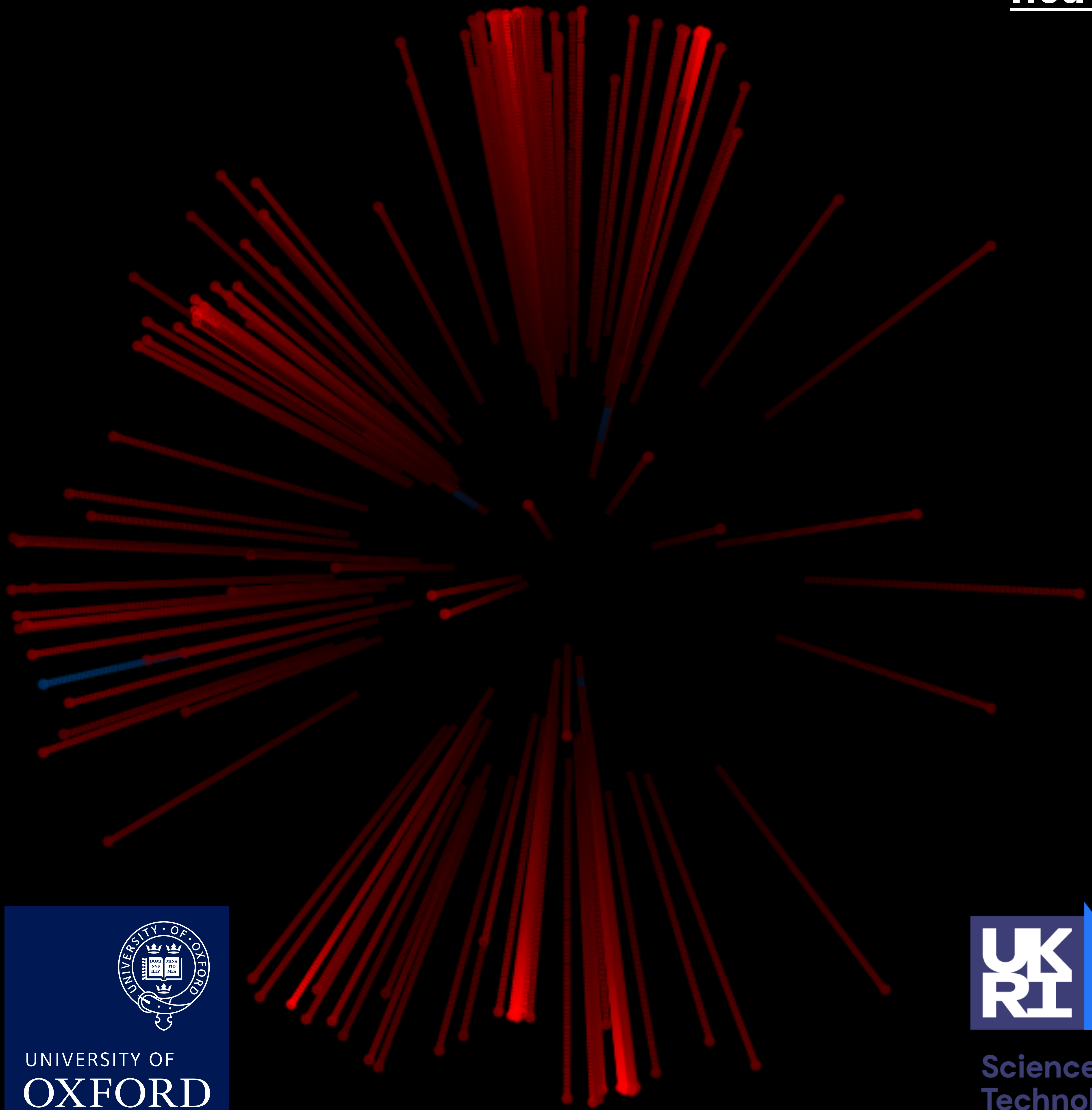
Towards Accurate Parton Showers

Research Training Group – Physics of the Heaviest Particles at the LHC
RWTH Aachen University
January 2025



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

UNIVERSITY OF OXFORD

Science and Technology Facilities Council

THE ROYAL SOCIETY

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

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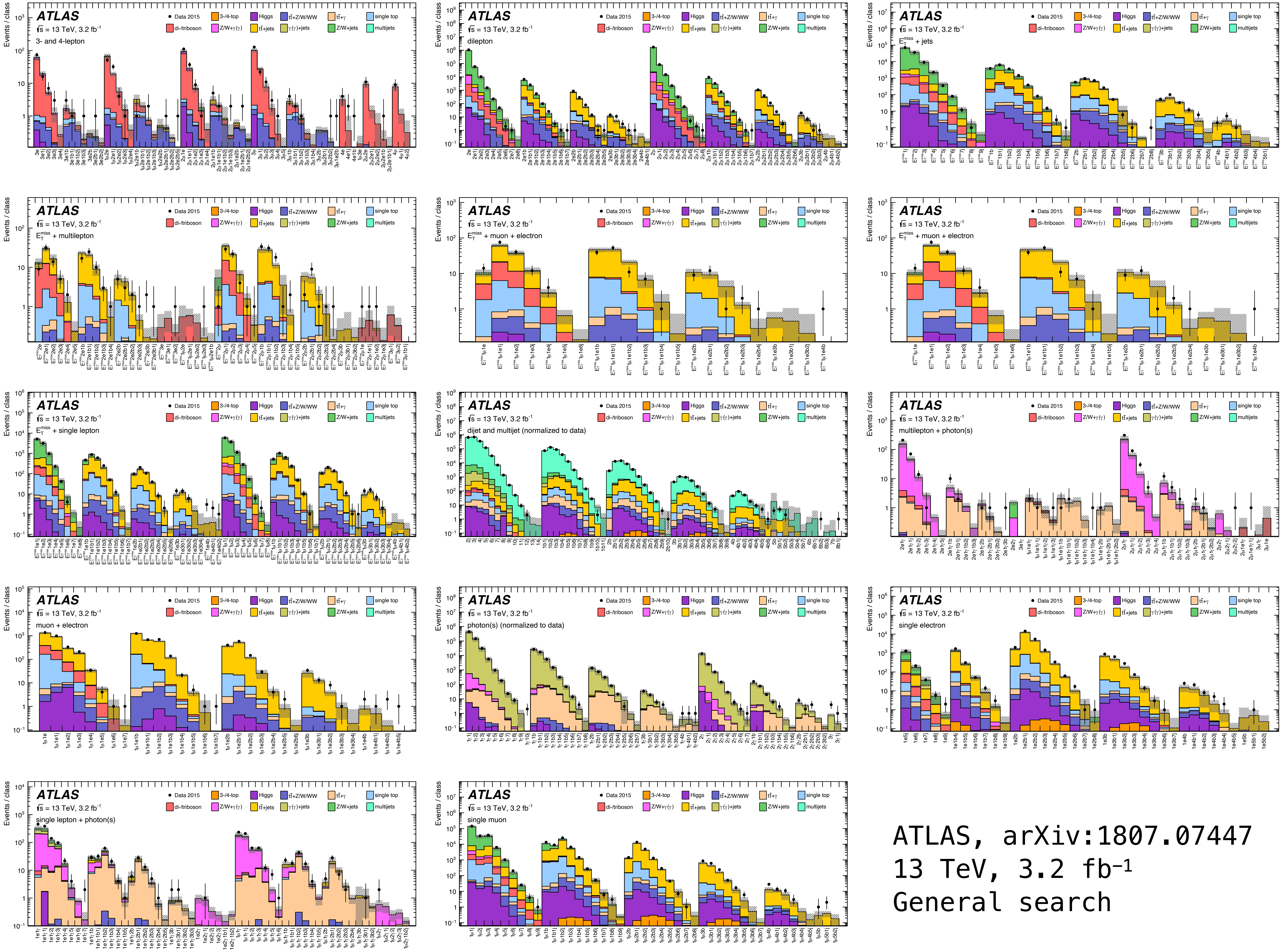
E.g. broadband searches (here an example with 704 event classes, >36000 bins)

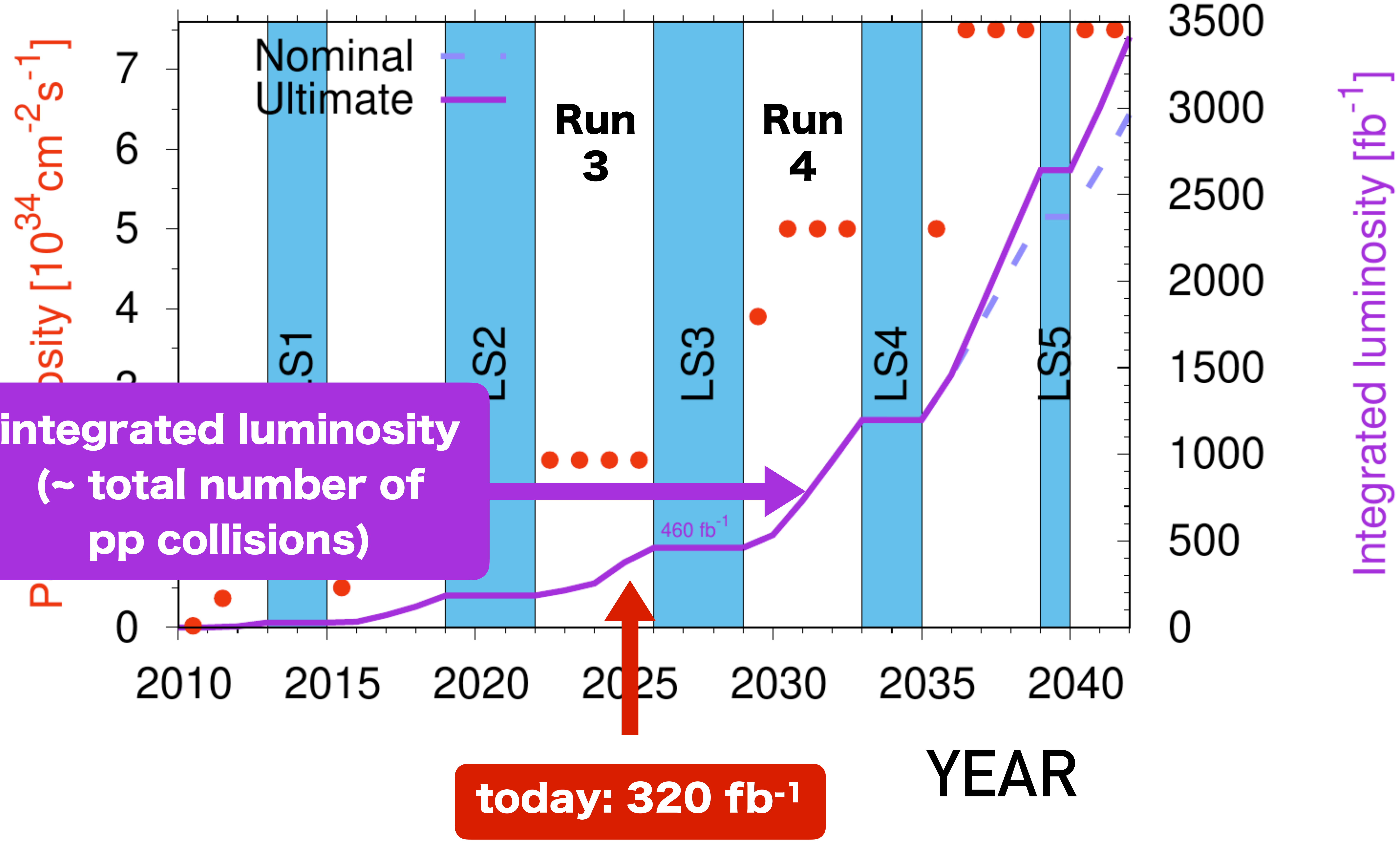


Just one illustration out of many searches at the LHC

ATLAS, arXiv:1807.07447
13 TeV, 3.2 fb^{-1}
General search

http://lhc-commissioning.web.cern.ch/schedule/images/2024/rampup_2023_YETS15weeks_NoIon_MDs_ULT.png

LHC luminosity v. time

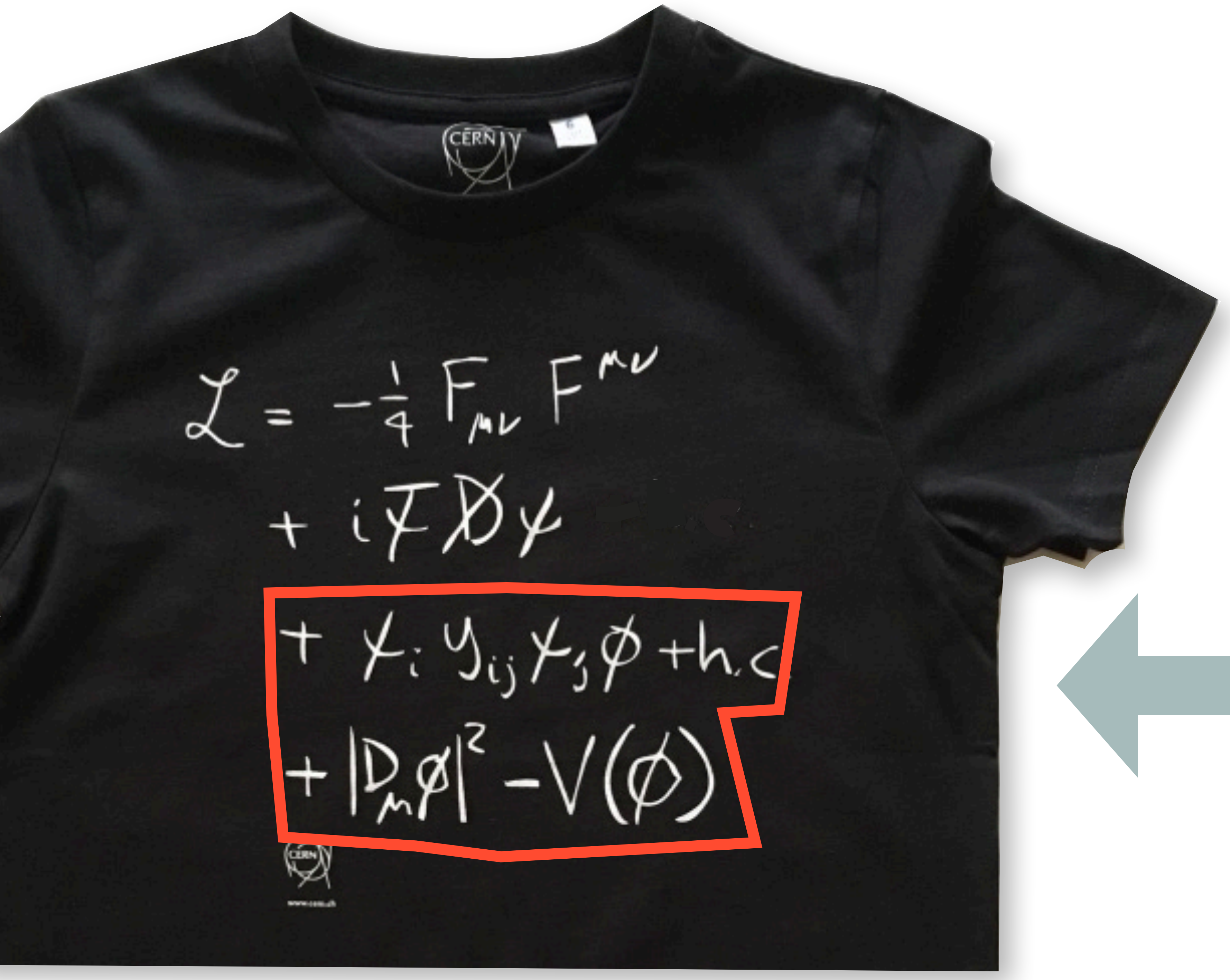


≳ 90% of collisions still to be delivered

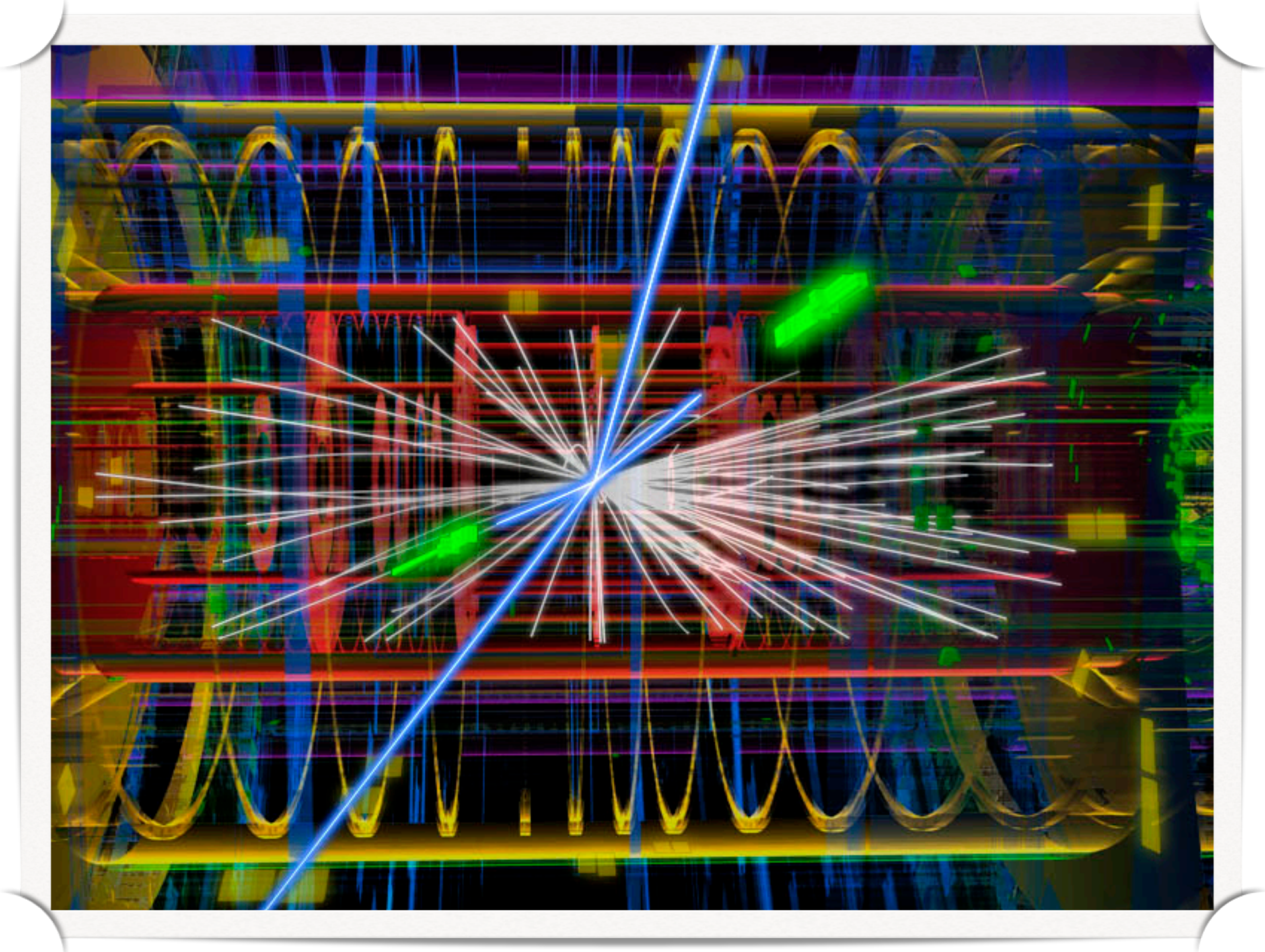
with vastly improved detectors

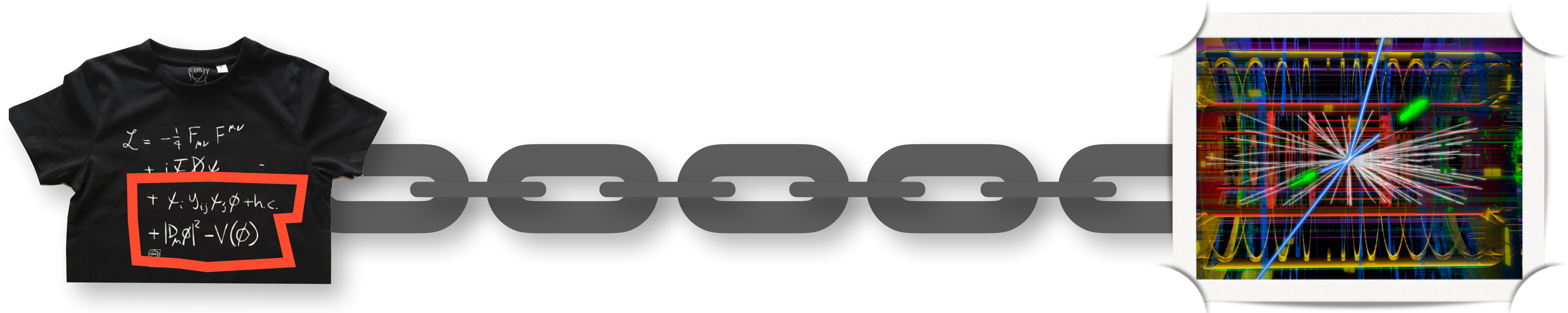
UNDERLYING THEORY

EXPERIMENTAL DATA



how do you make quantitative connection?

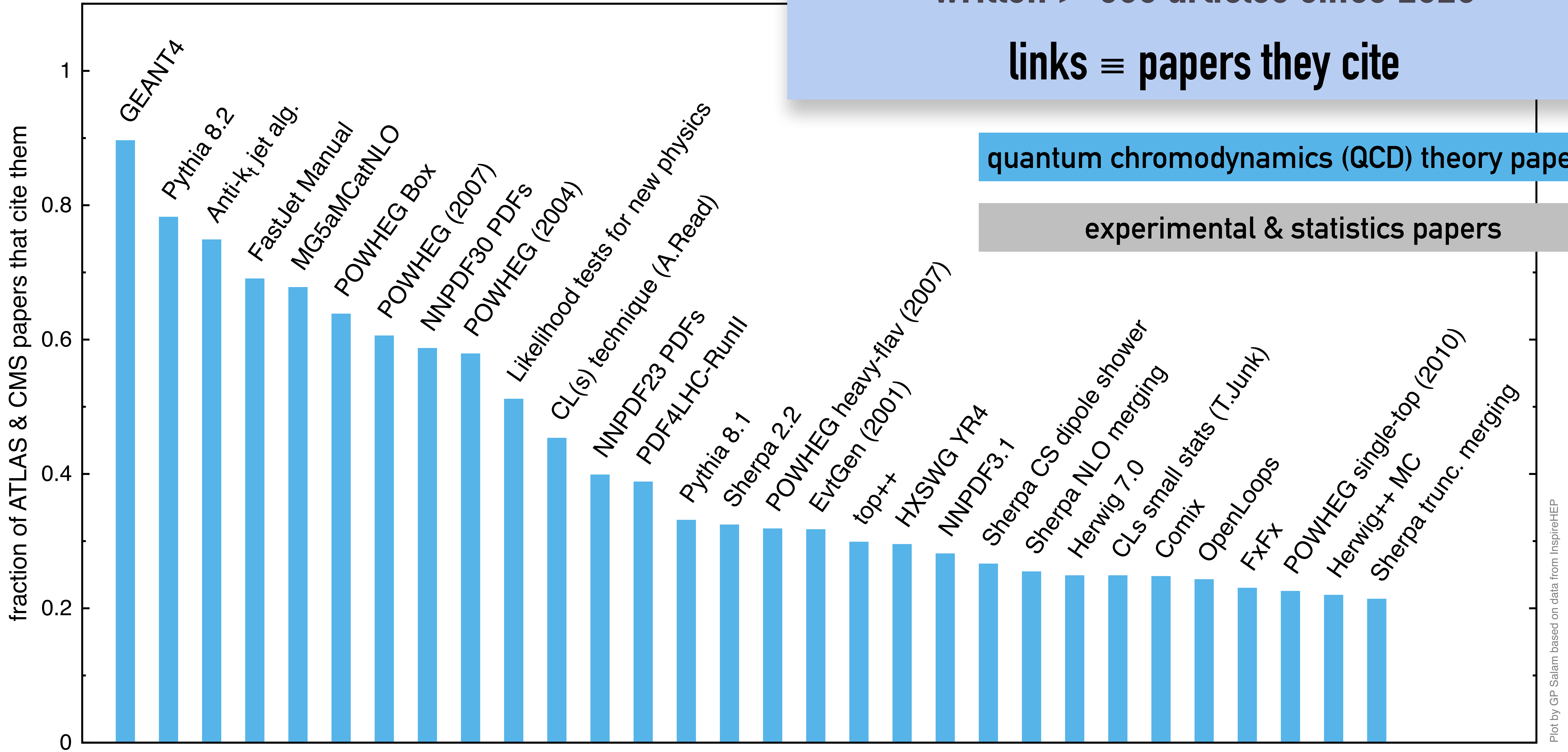


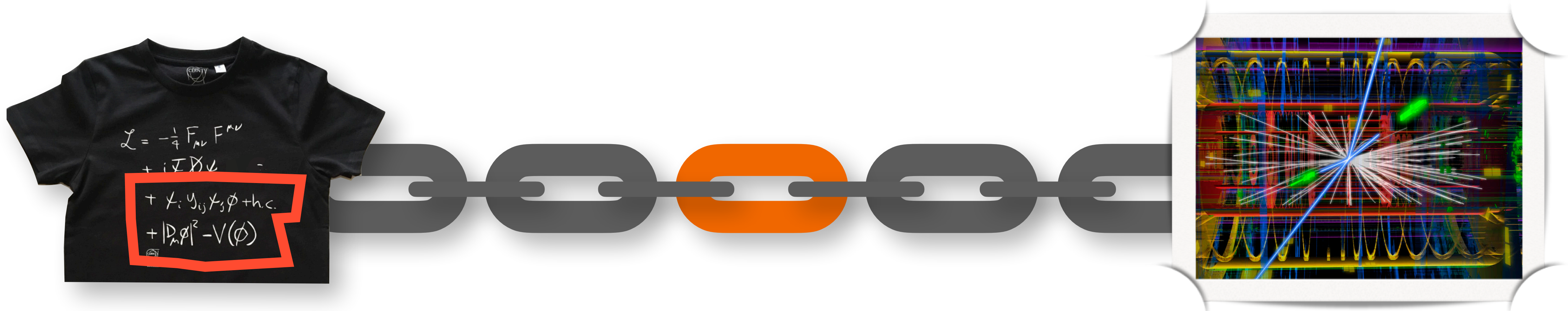


Lagrangian ↔ data

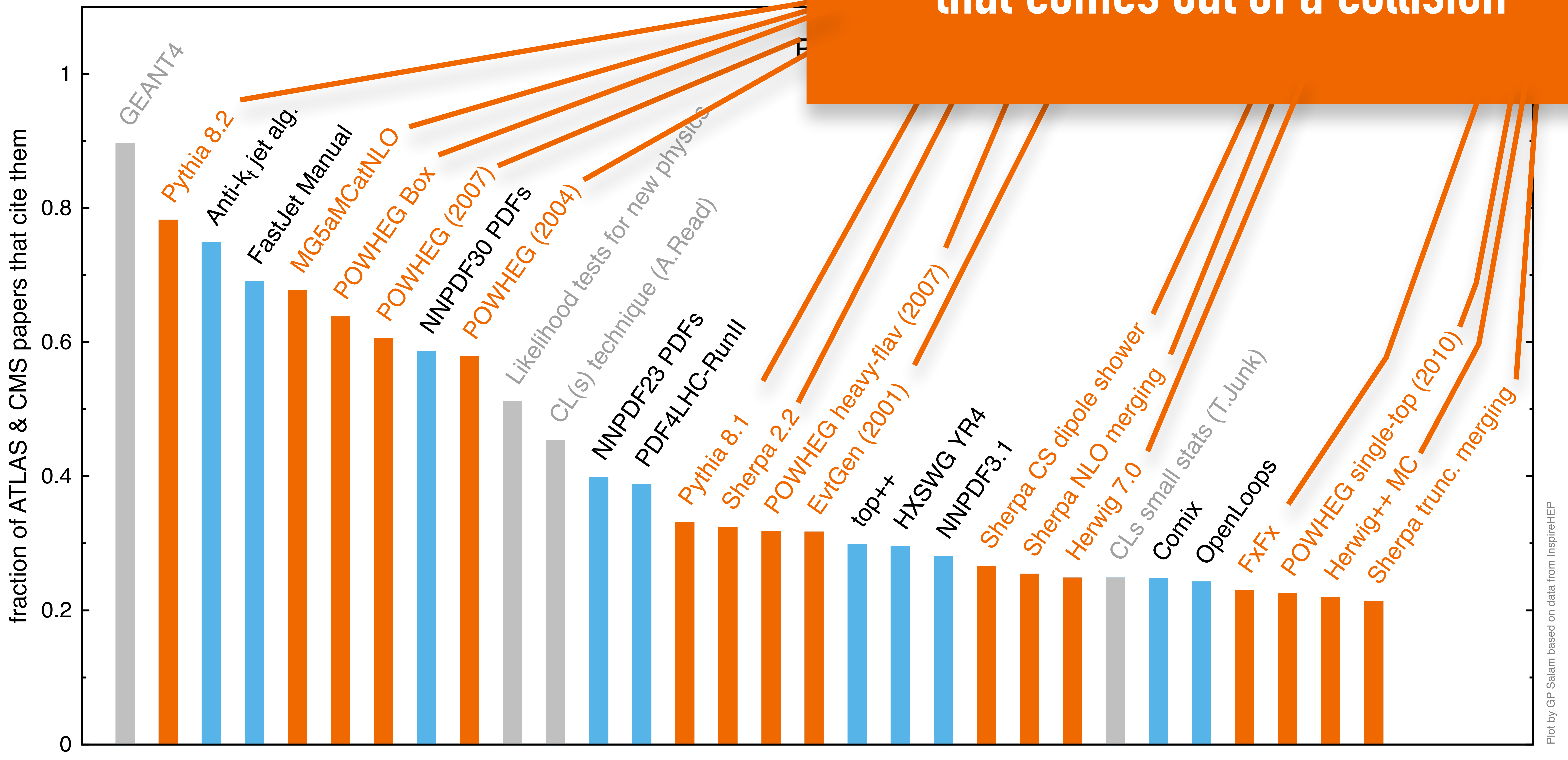
ATLAS and CMS (big LHC expts.) have written > 800 articles since 2020

links ≡ papers they cite





predicting full particle structure that comes out of a collision



simulations use General Purpose Monte Carlo event generators

THE BIG 3

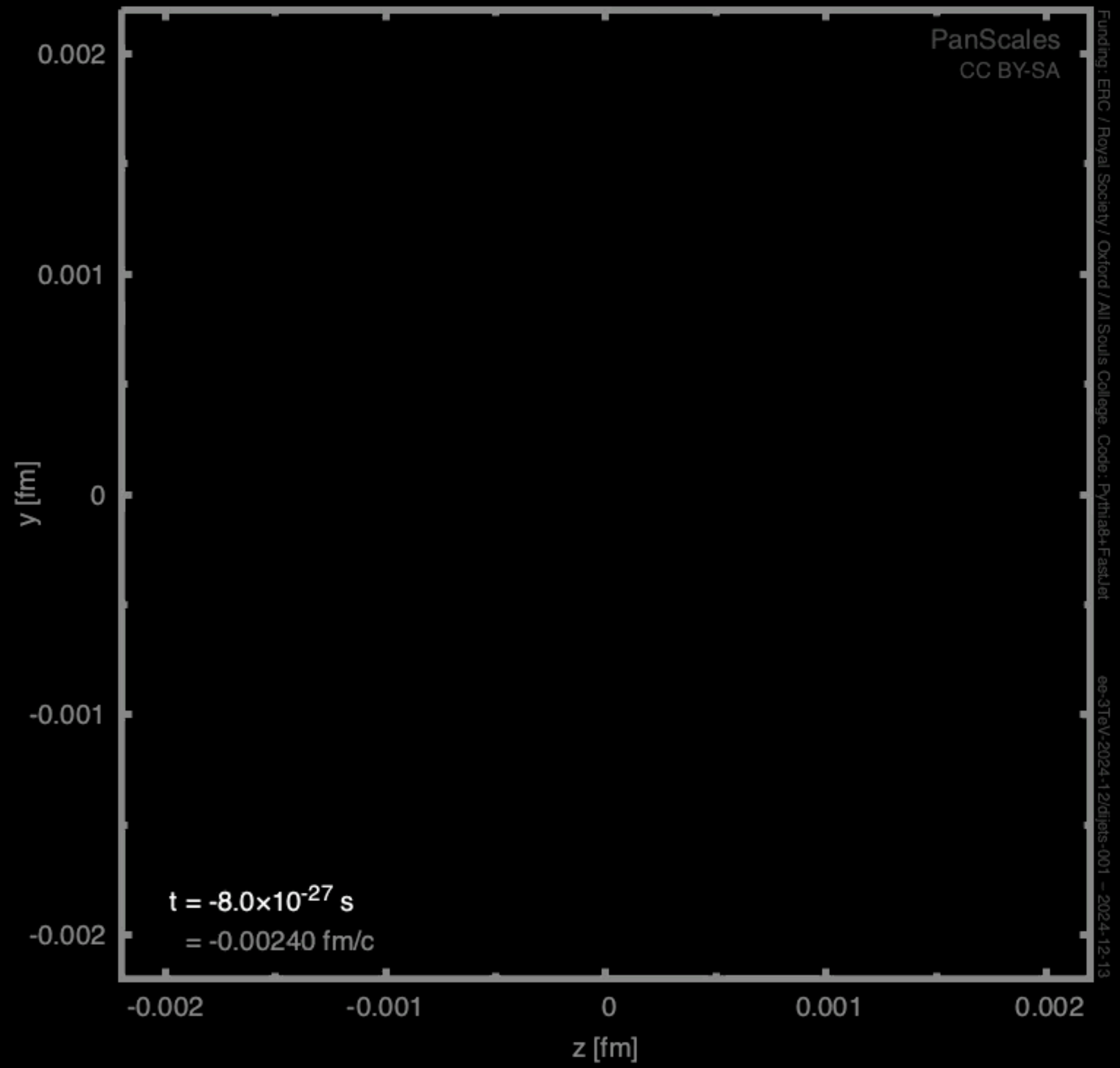
Herwig 7 **Pythia 8** **Sherpa 2**

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†)

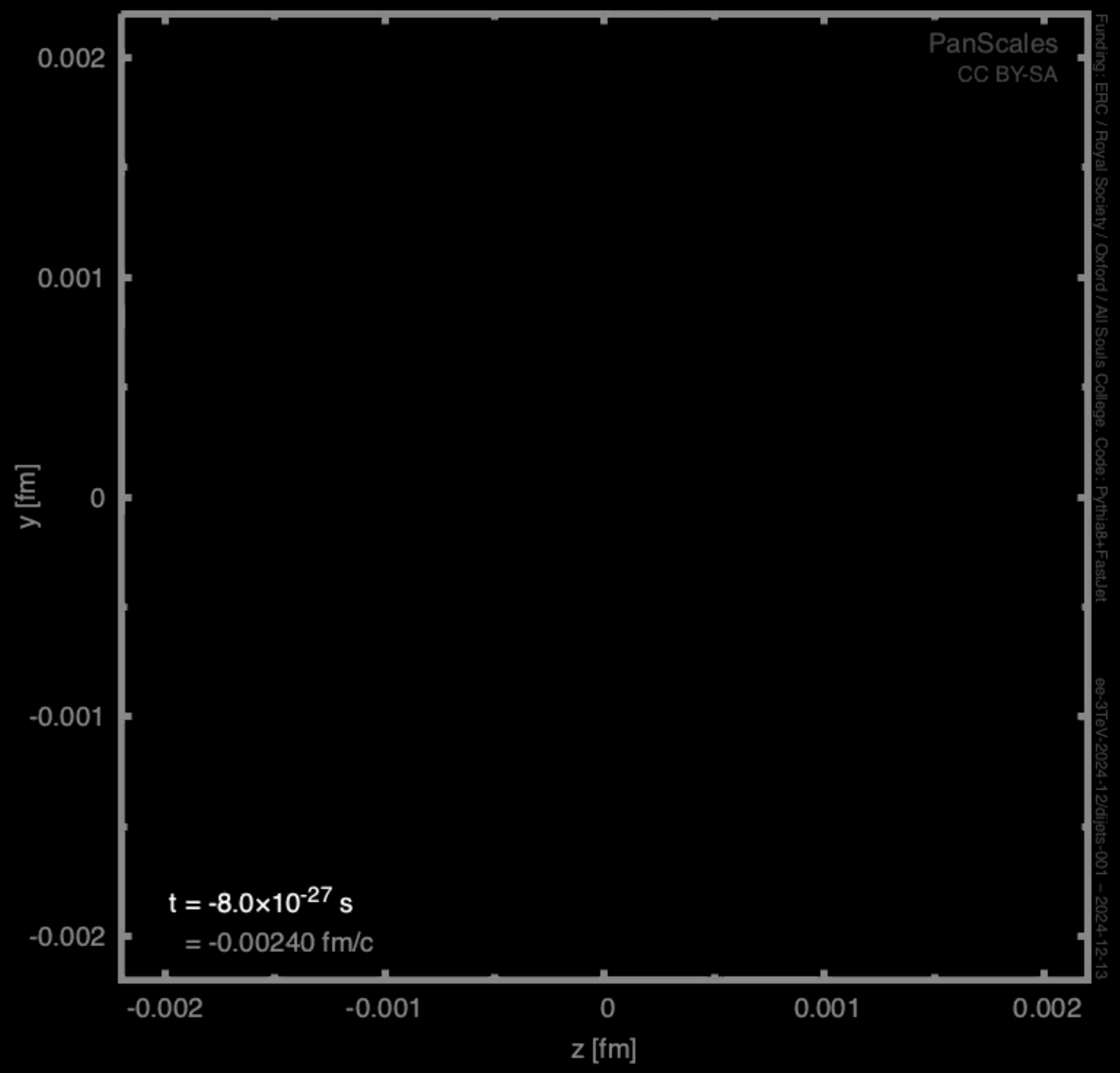


incoming beam particle

intermediate particle (quark or gluon)

final particle (hadron)

Event evolution spans 7 orders of magnitude in space-time



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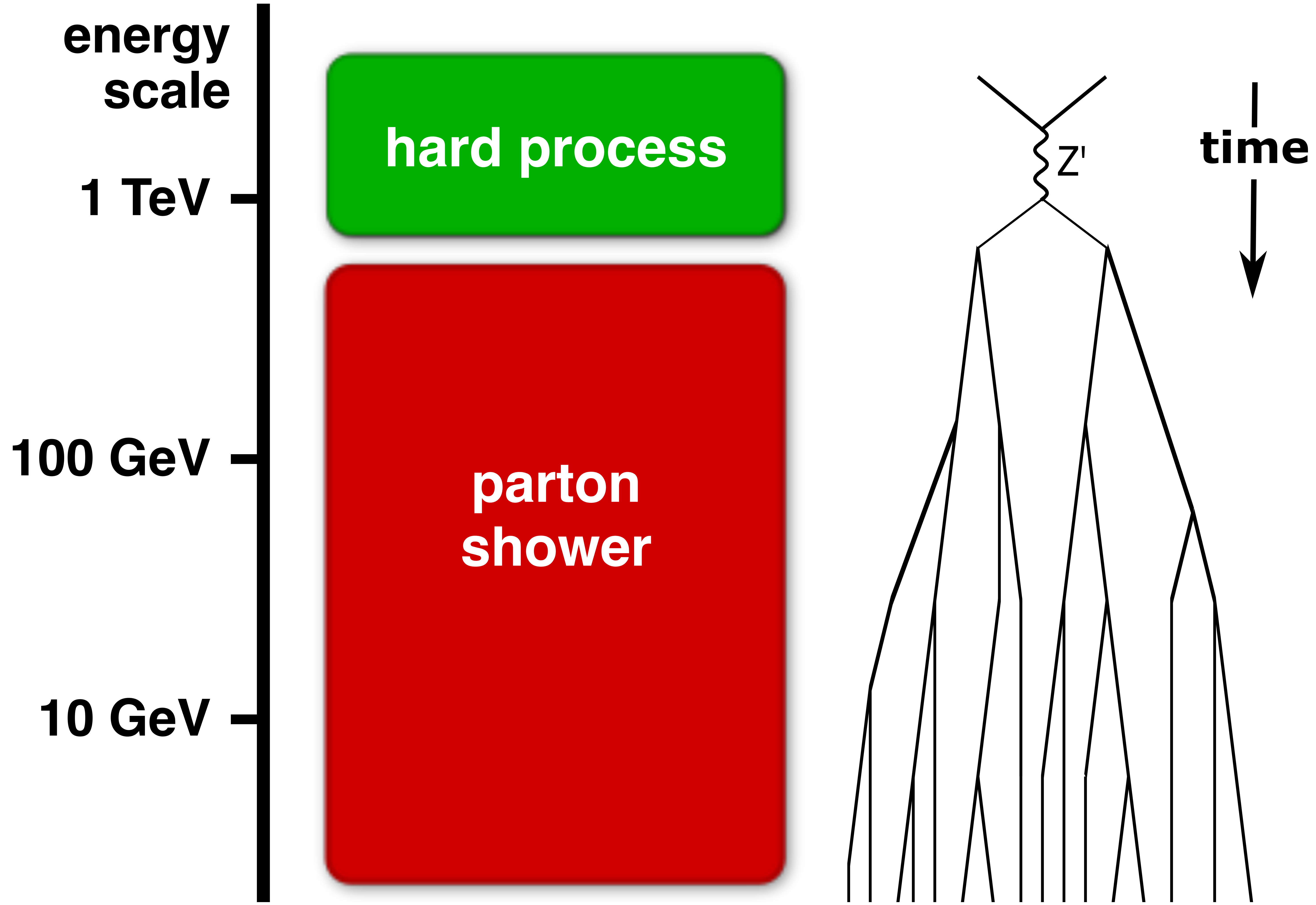
schematic view of key components of QCD predictions and Monte Carlo event simulation



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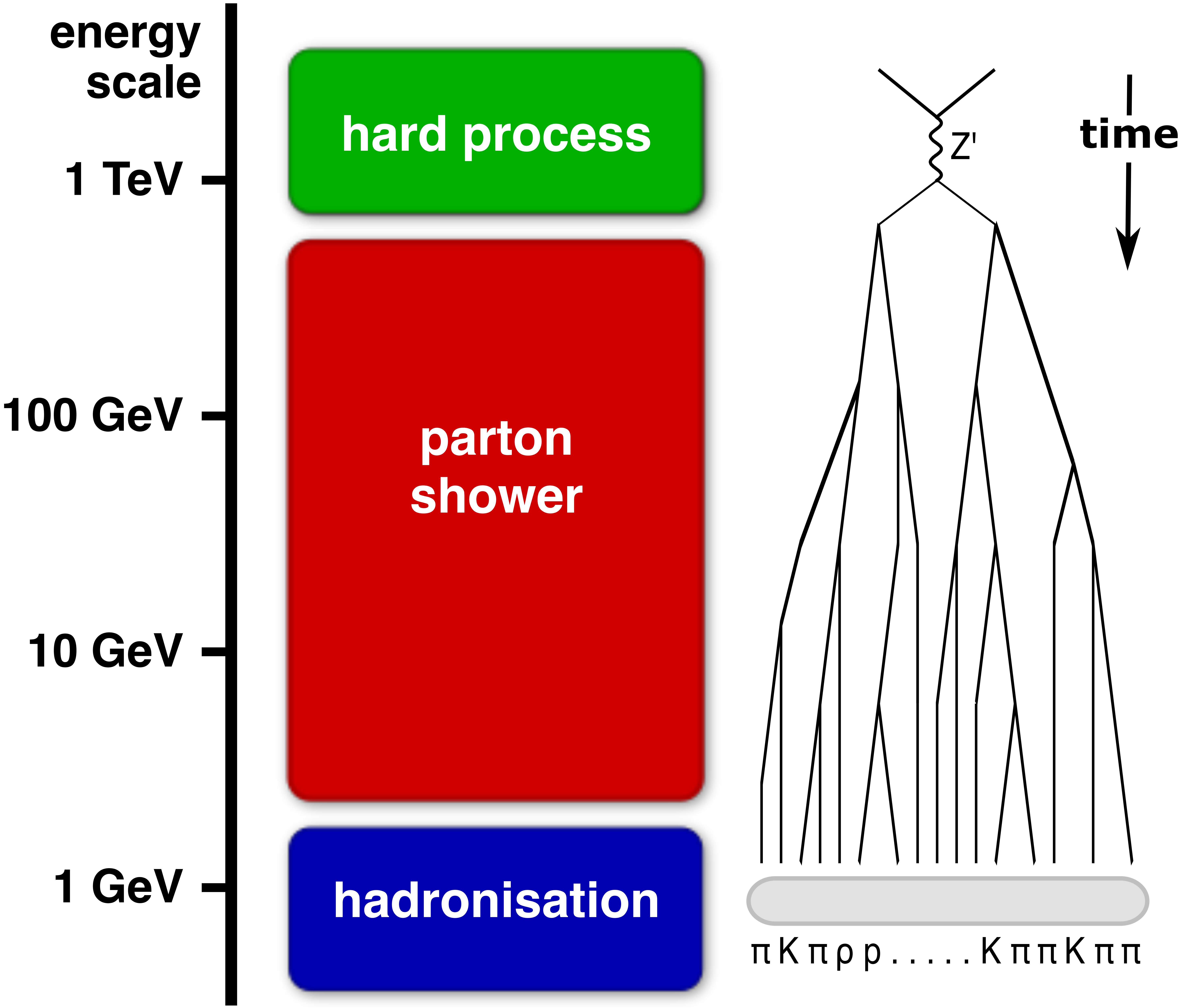
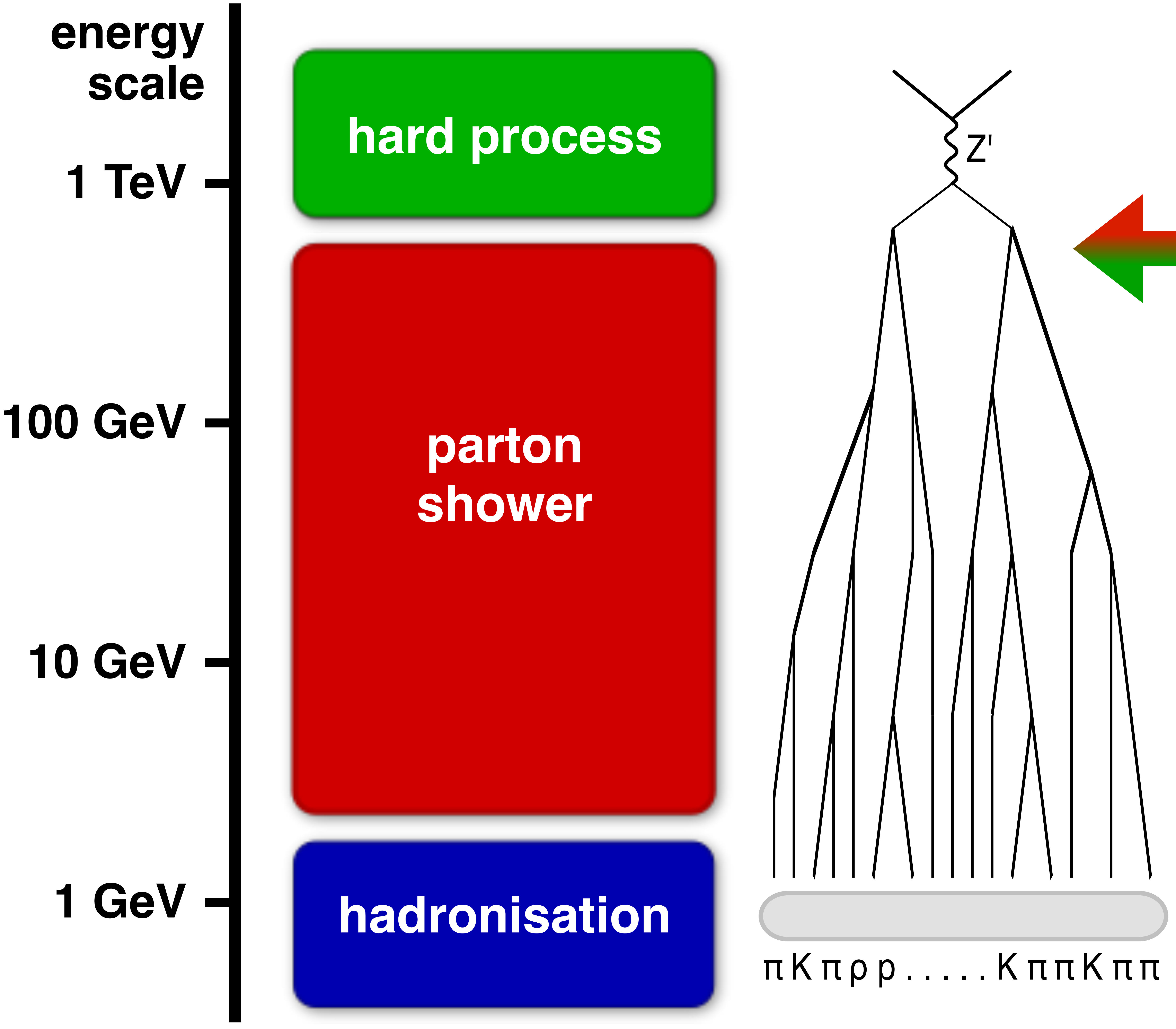


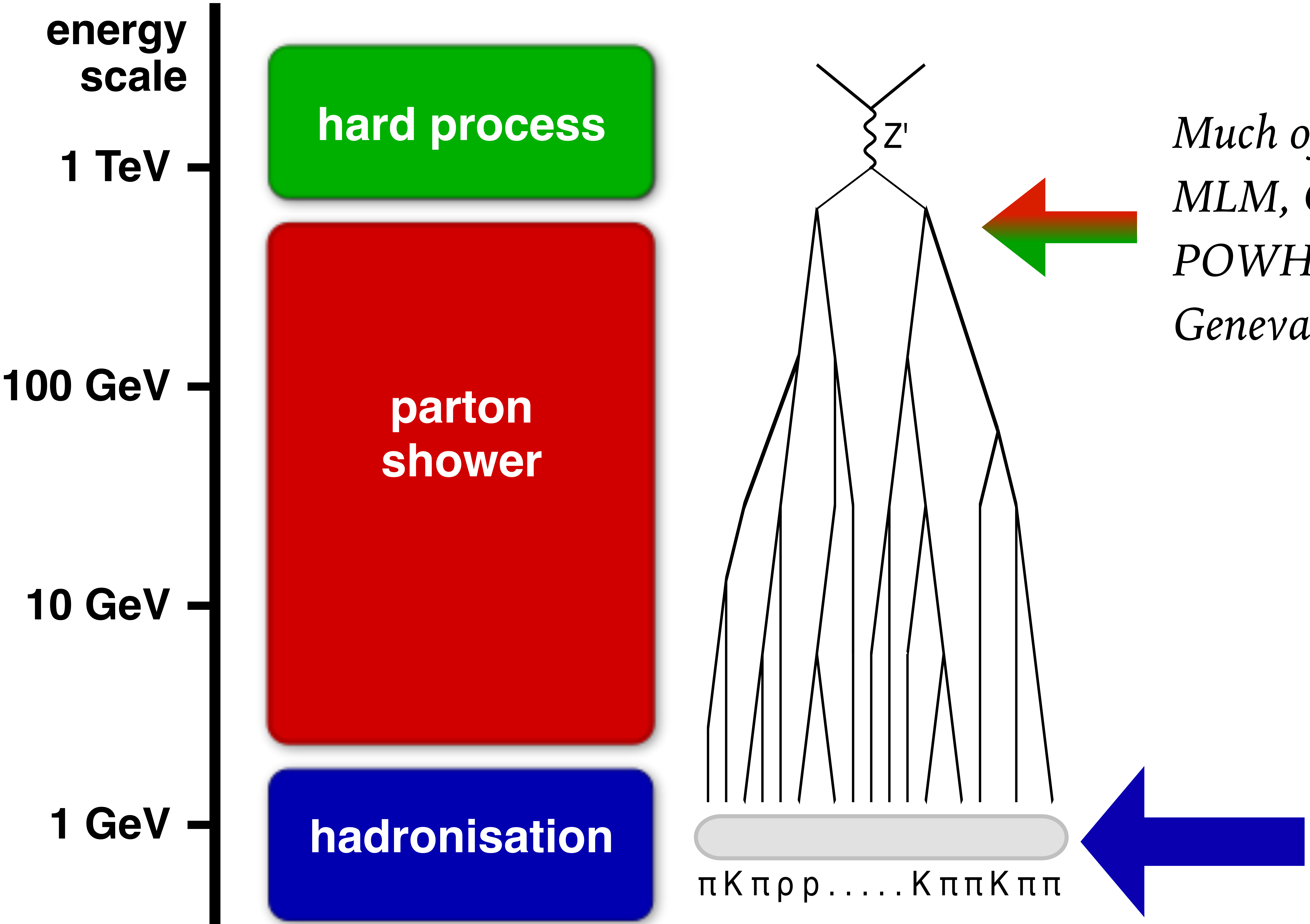
schematic view of key components of QCD predictions and Monte Carlo event simulation

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



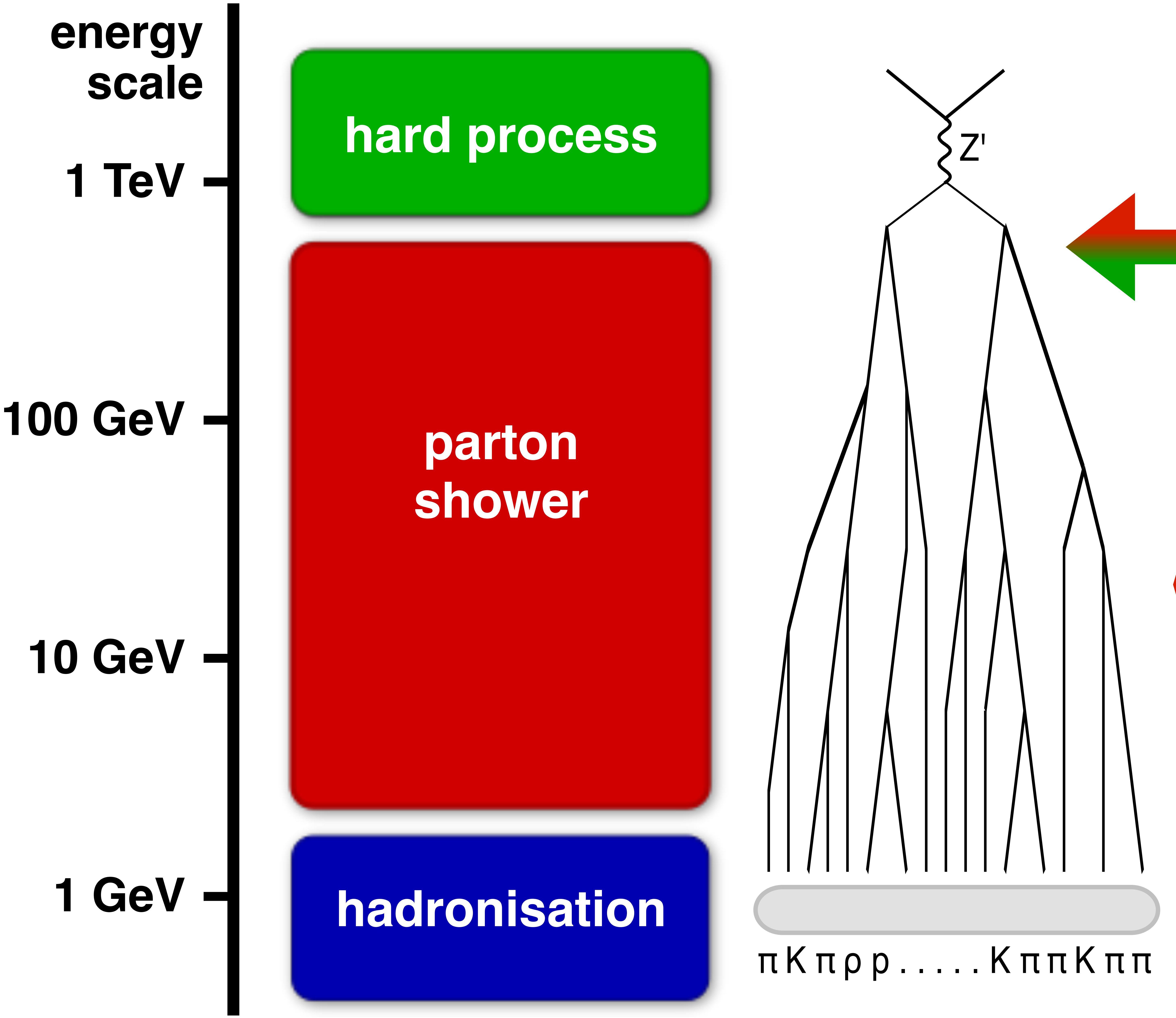
Much of past 20 years' work: MLM, CKKW, MC@NLO, POWHEG, MIN(N)LO, FxFx, Geneva, UNNLOPS, Vincia, etc.

In standard codes, largely based on principles from 20-30 years ago



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



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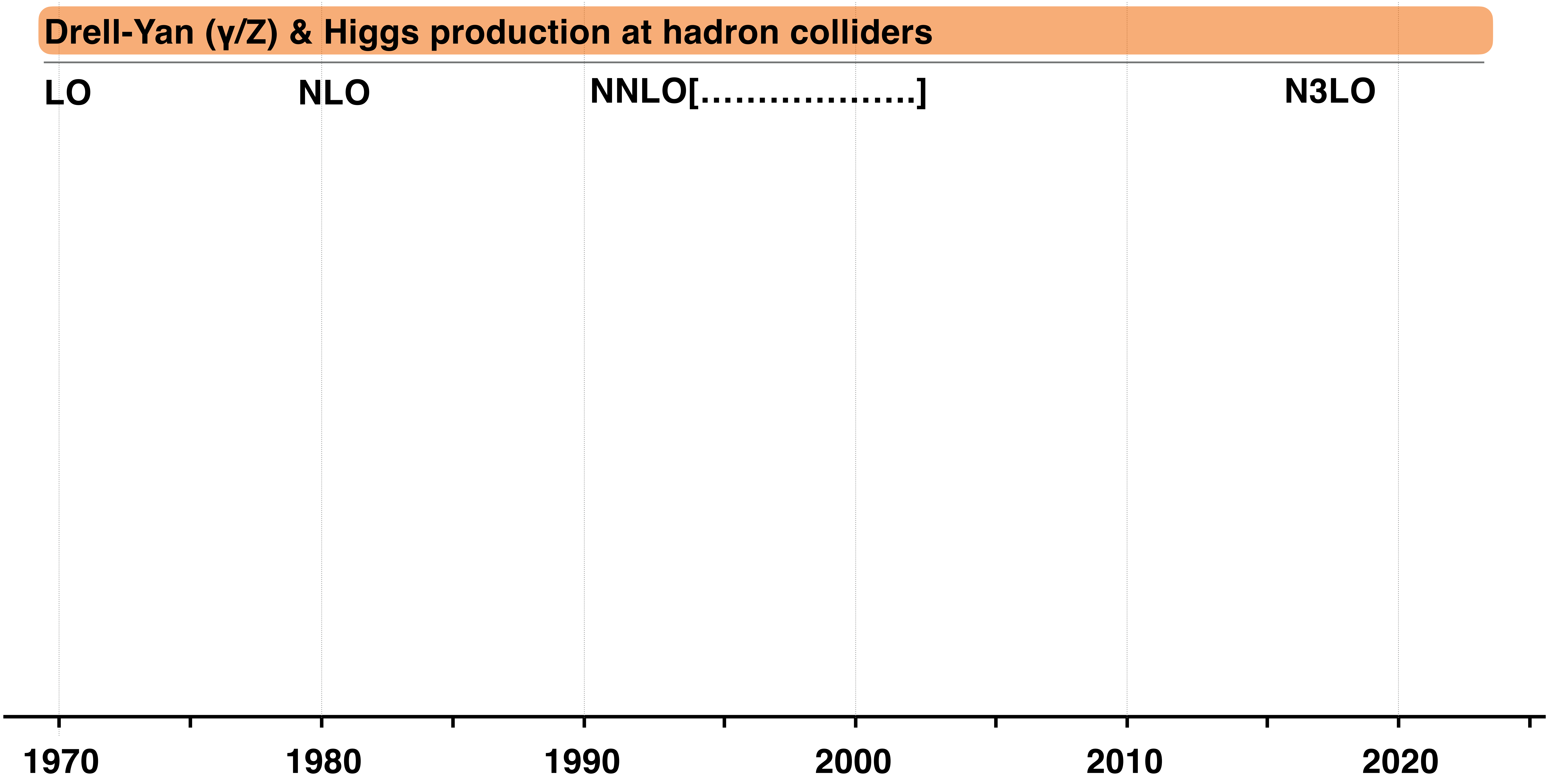
This talk

Status of parton showers

selected collider-QCD accuracy milestones



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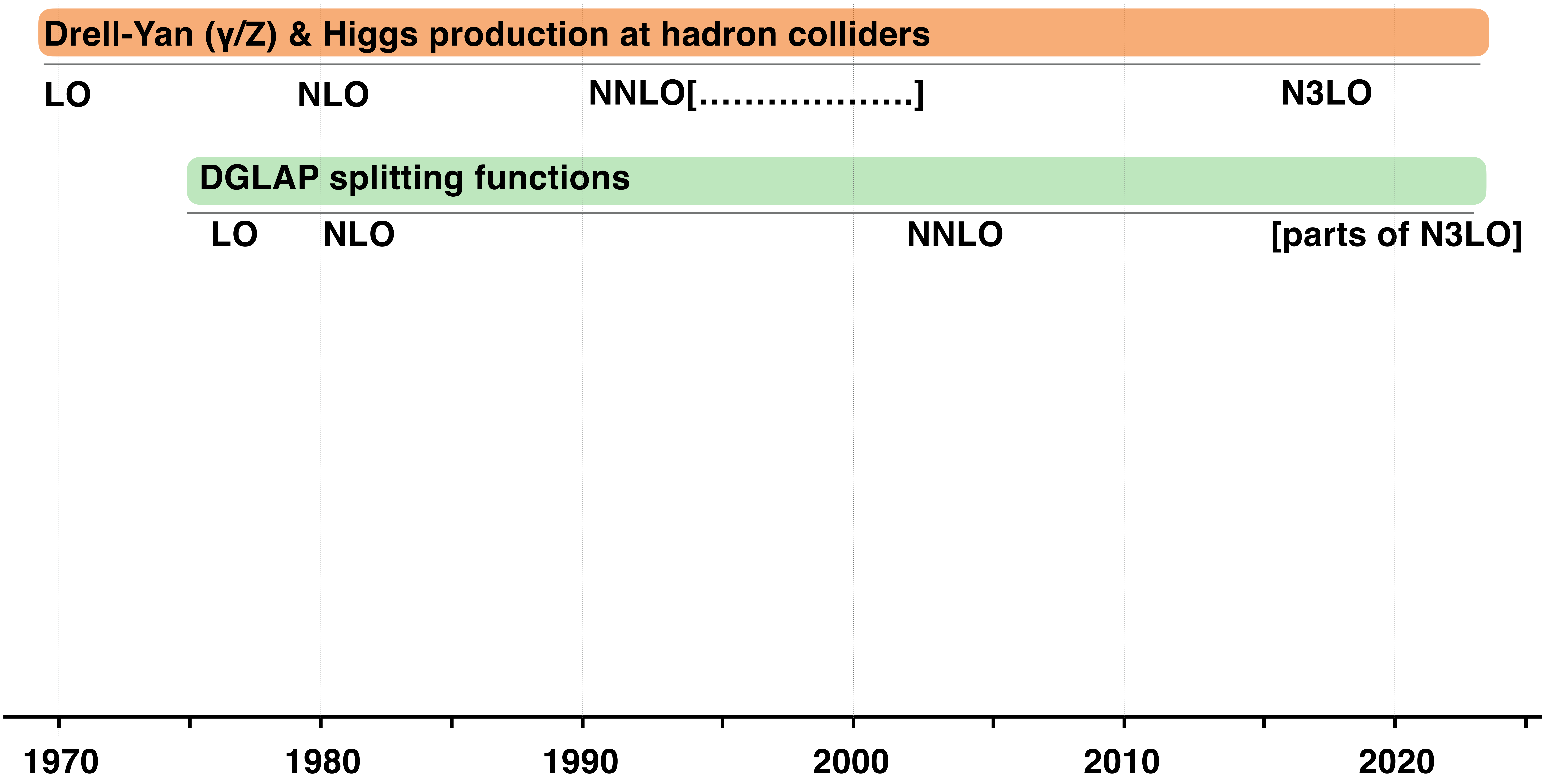

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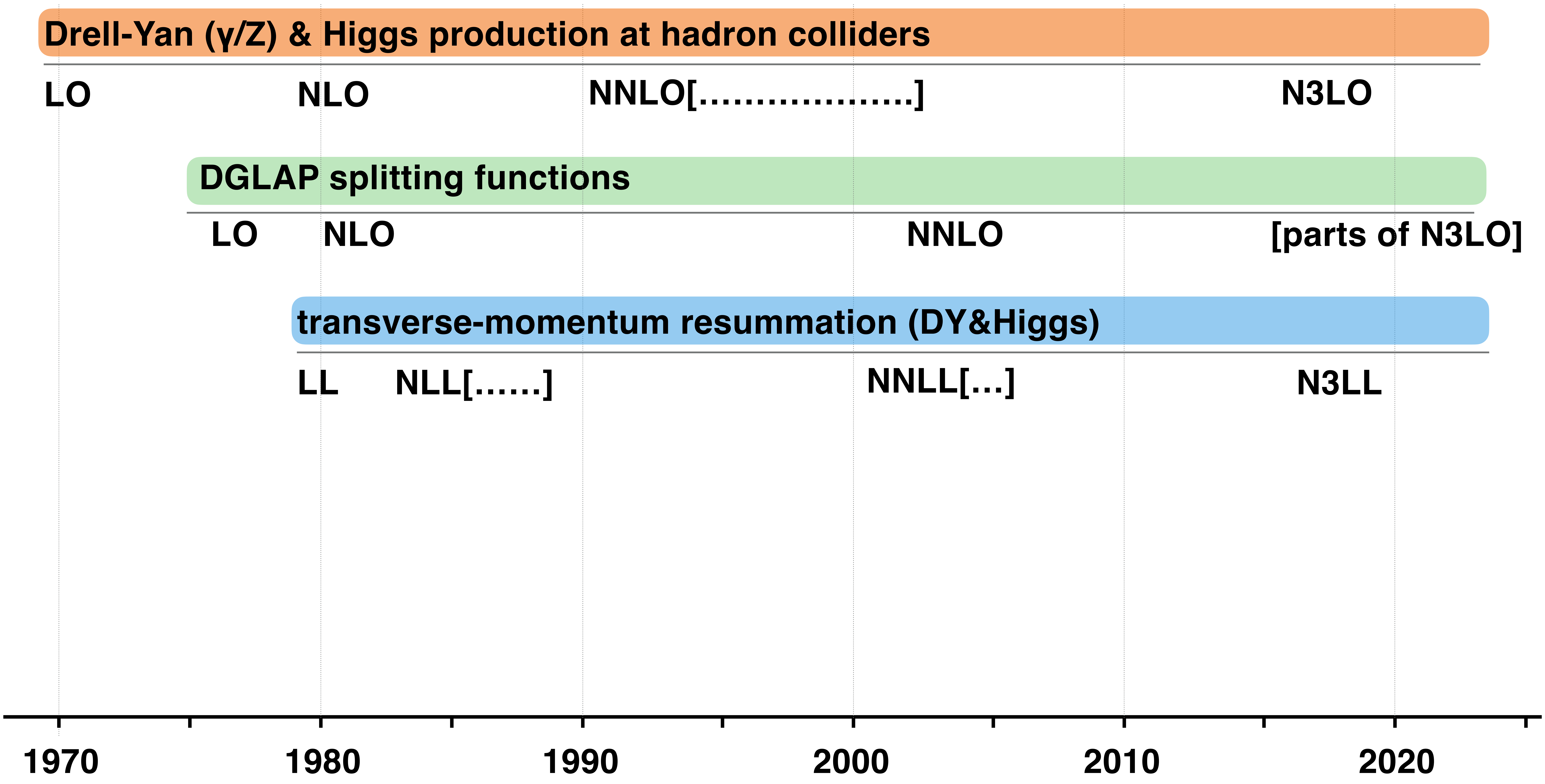

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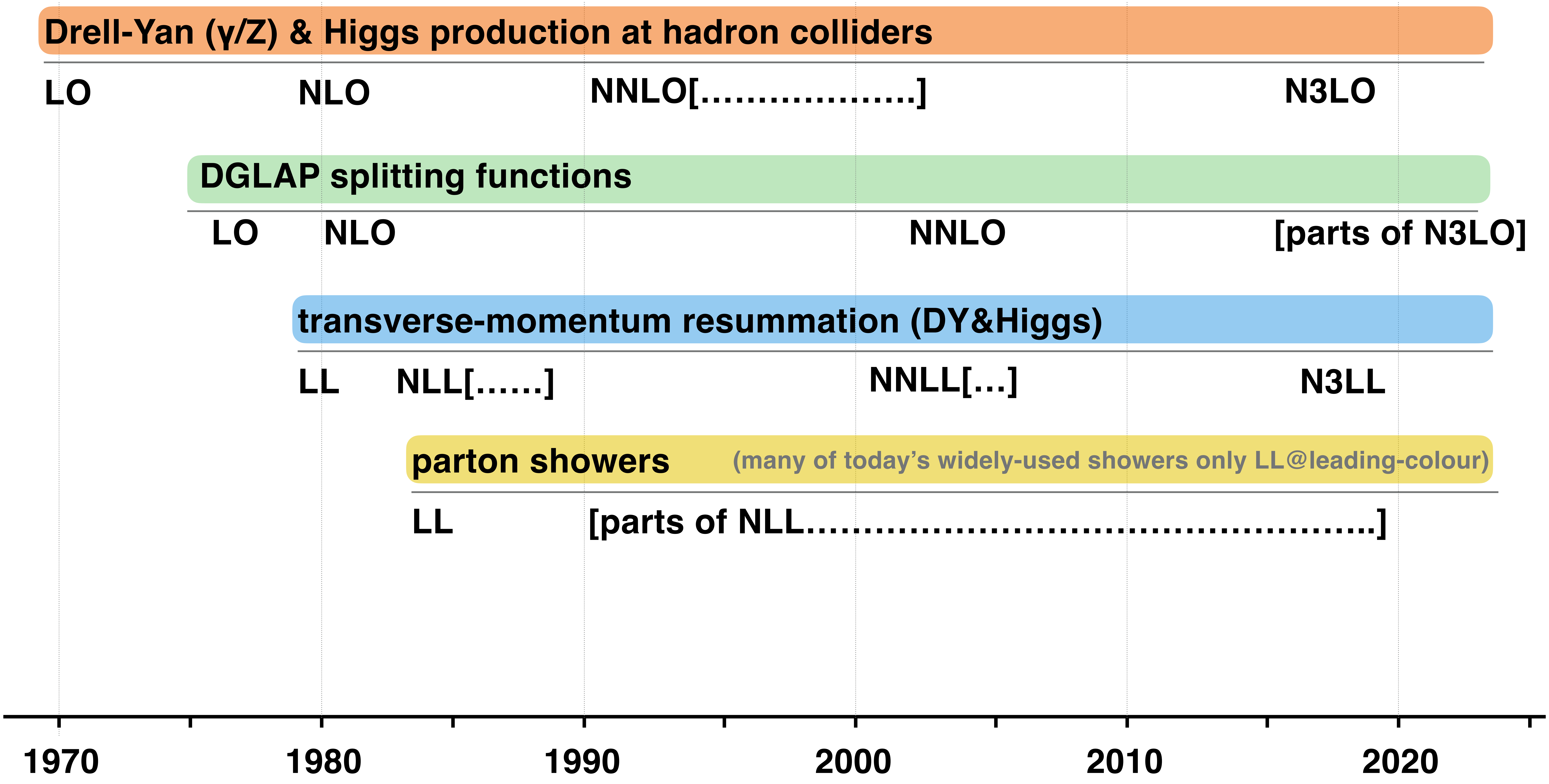

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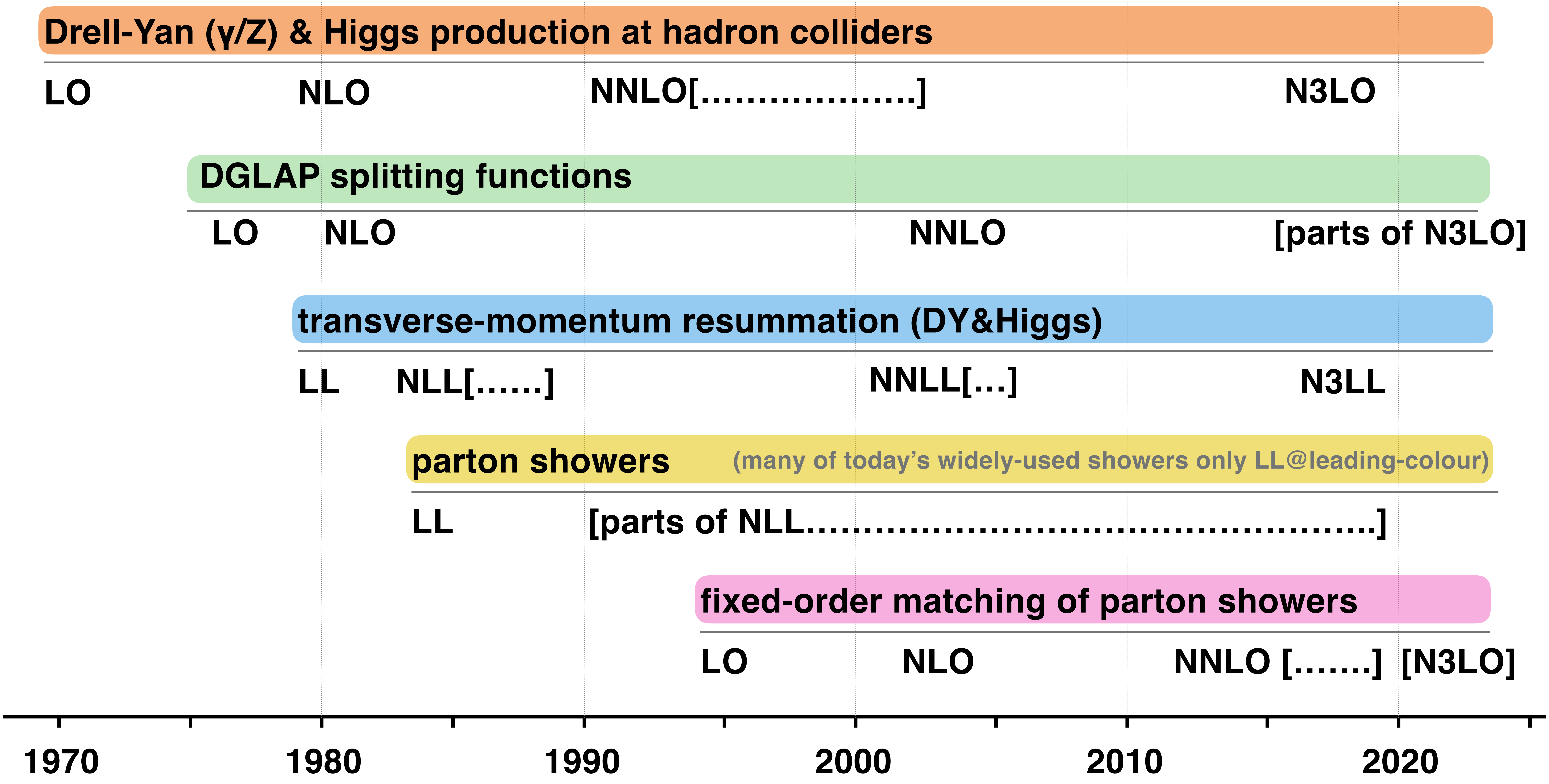

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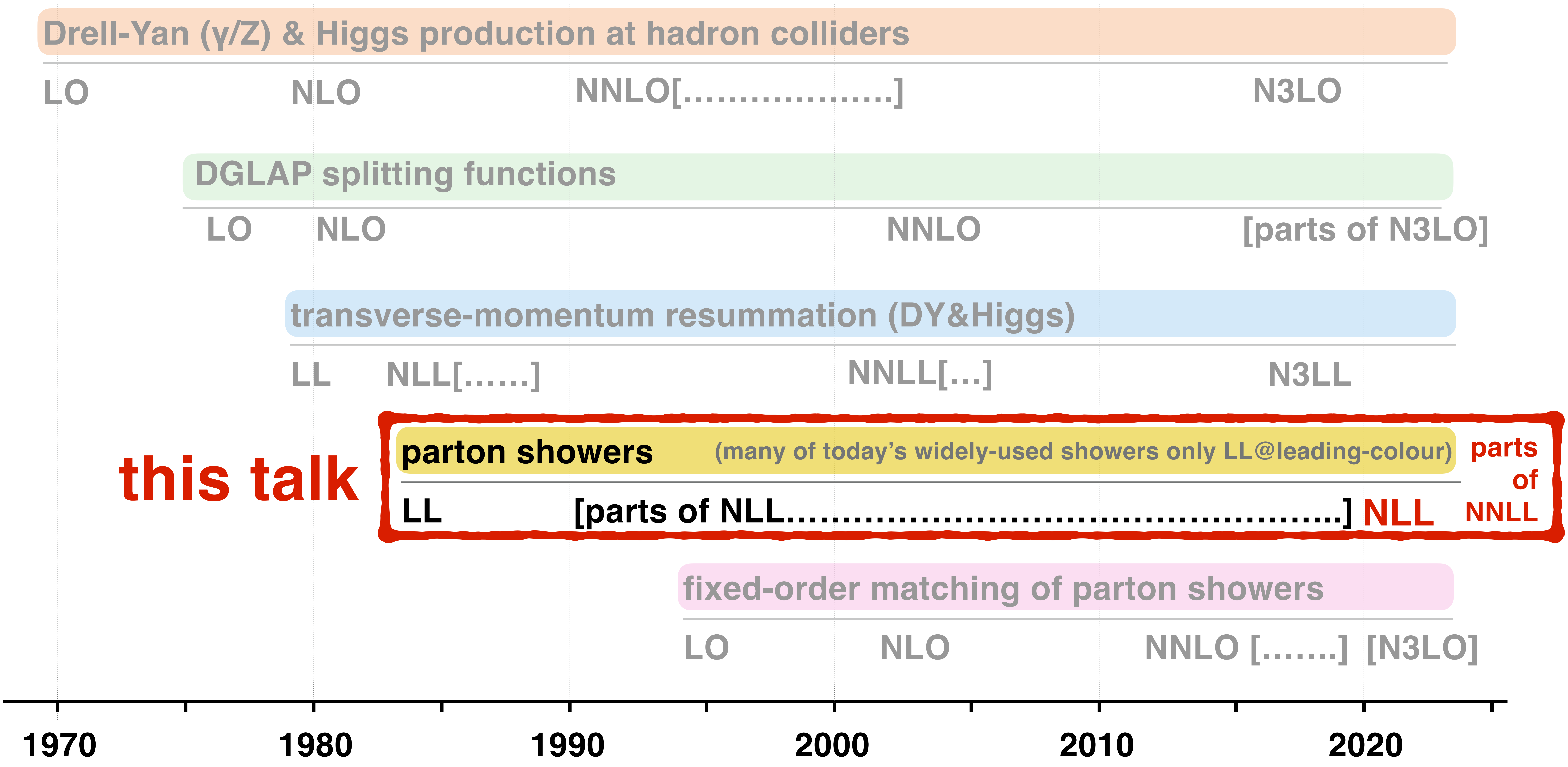
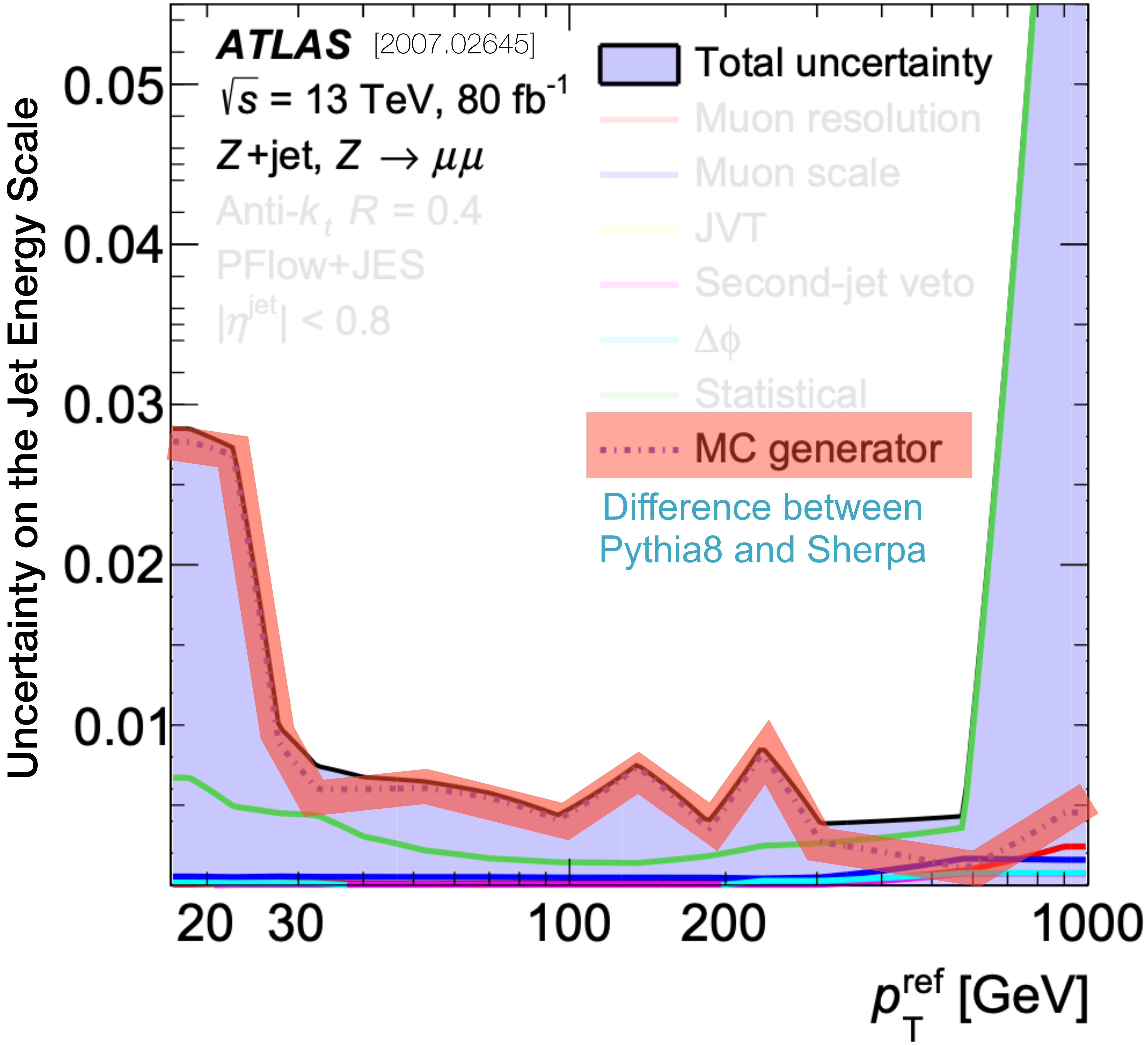


Parton Shower accuracy matters: e.g. for jet energy calibration (affects ~1500 papers)



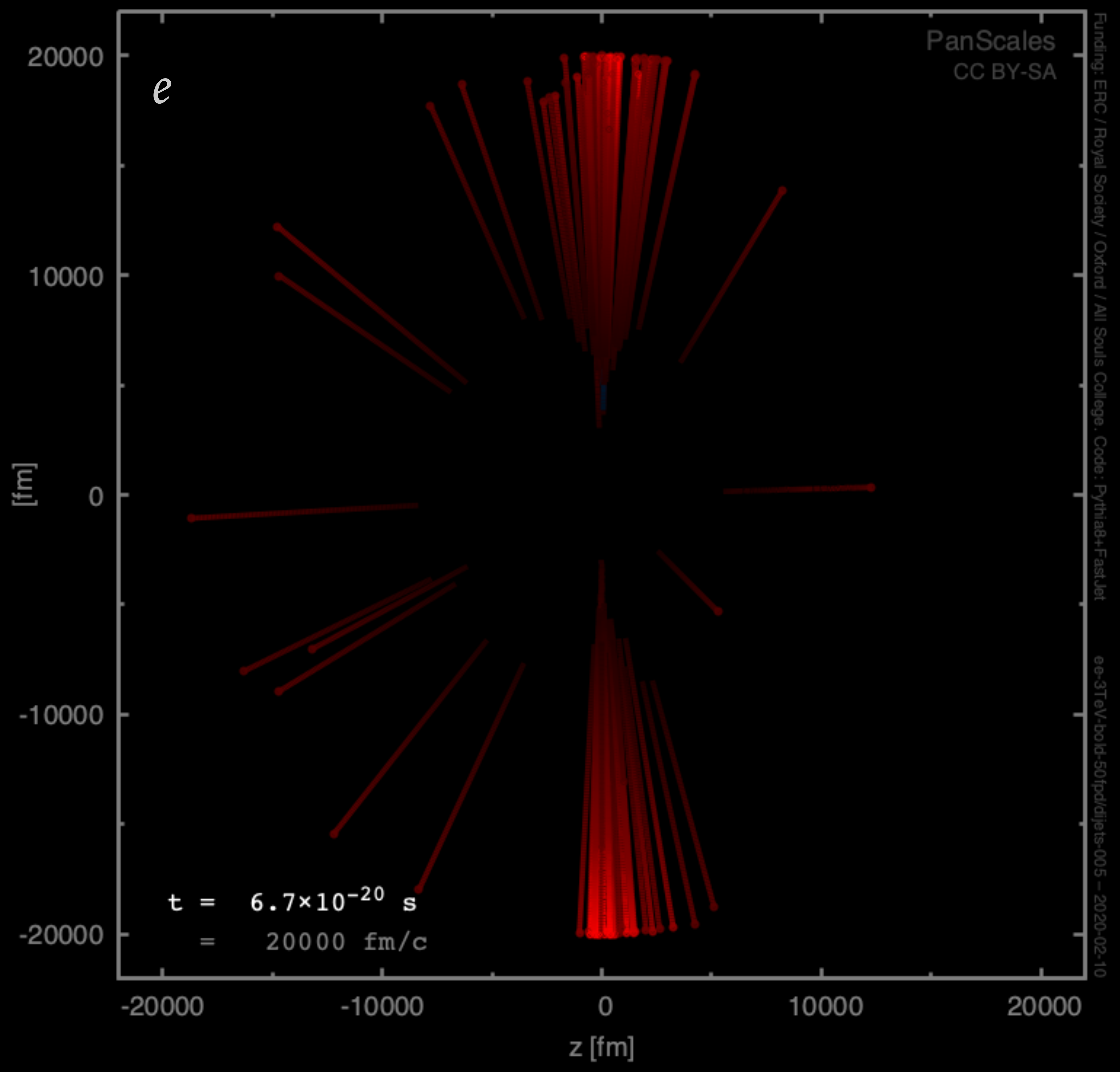
Jet energy calibration uncertainty feeds into 75% of ATLAS & CMS measurements

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

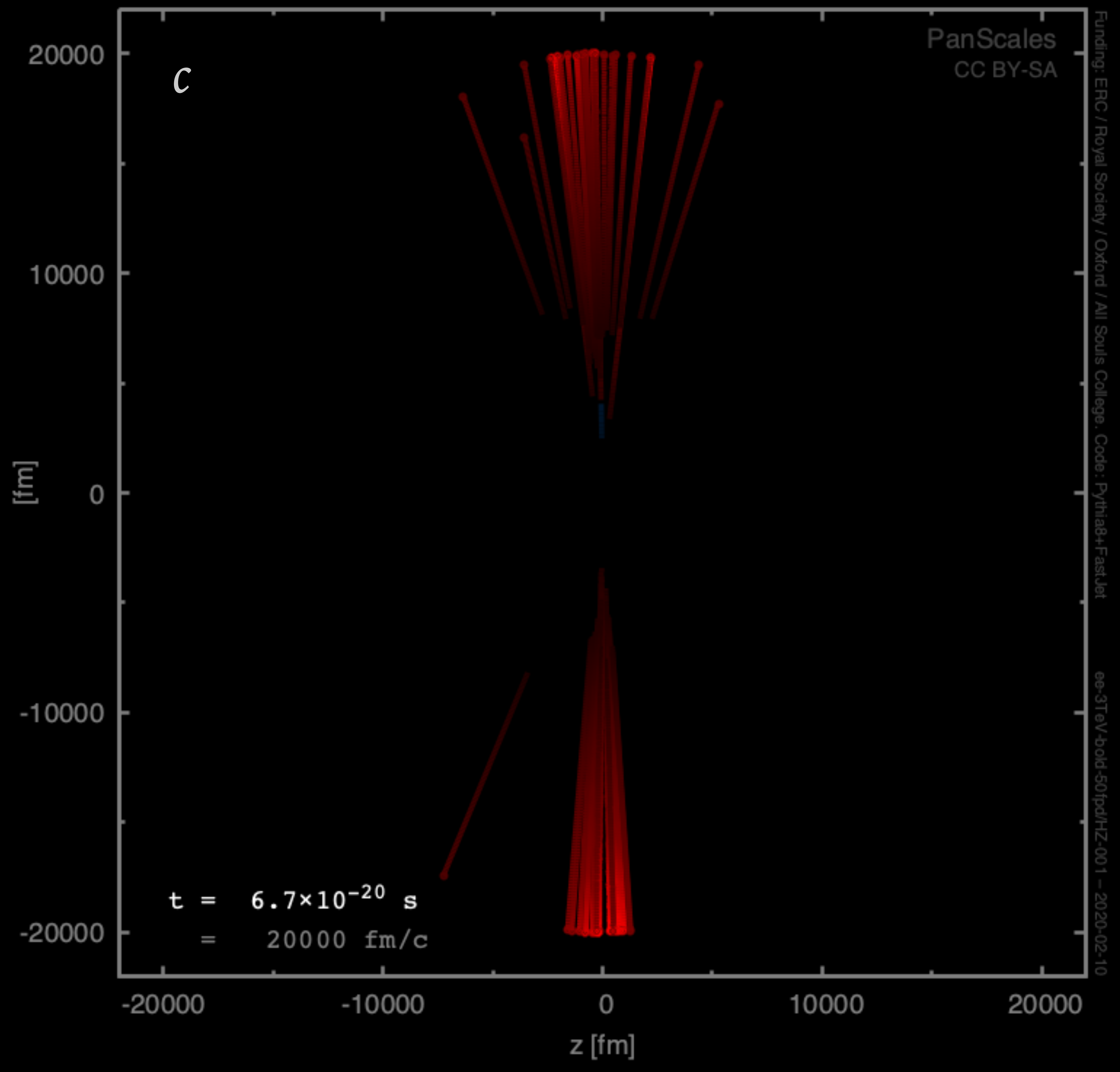
(here Sherpa2 v. Pythia8)

→ fundamental limit on LHC precision potential

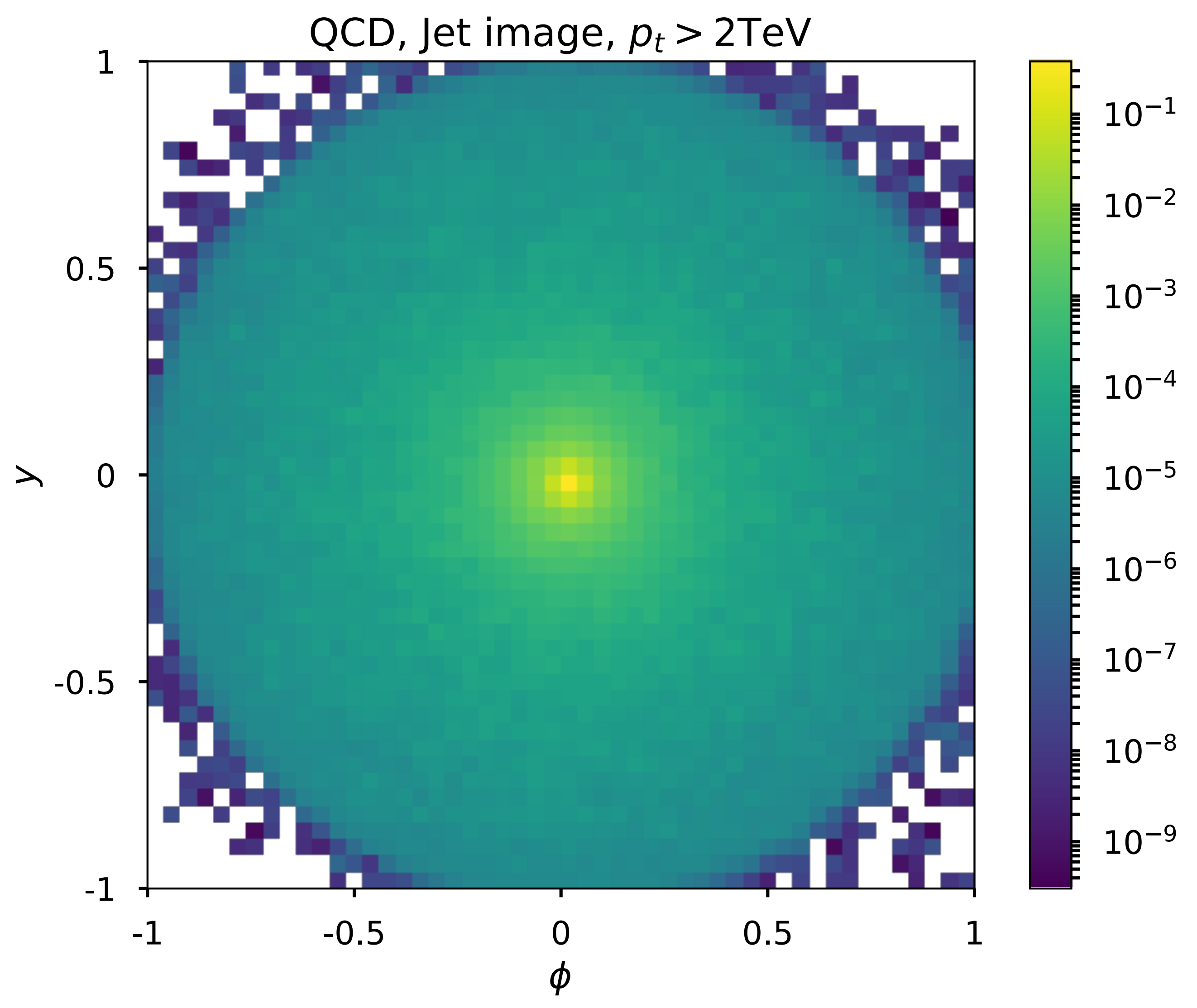
pure QCD event



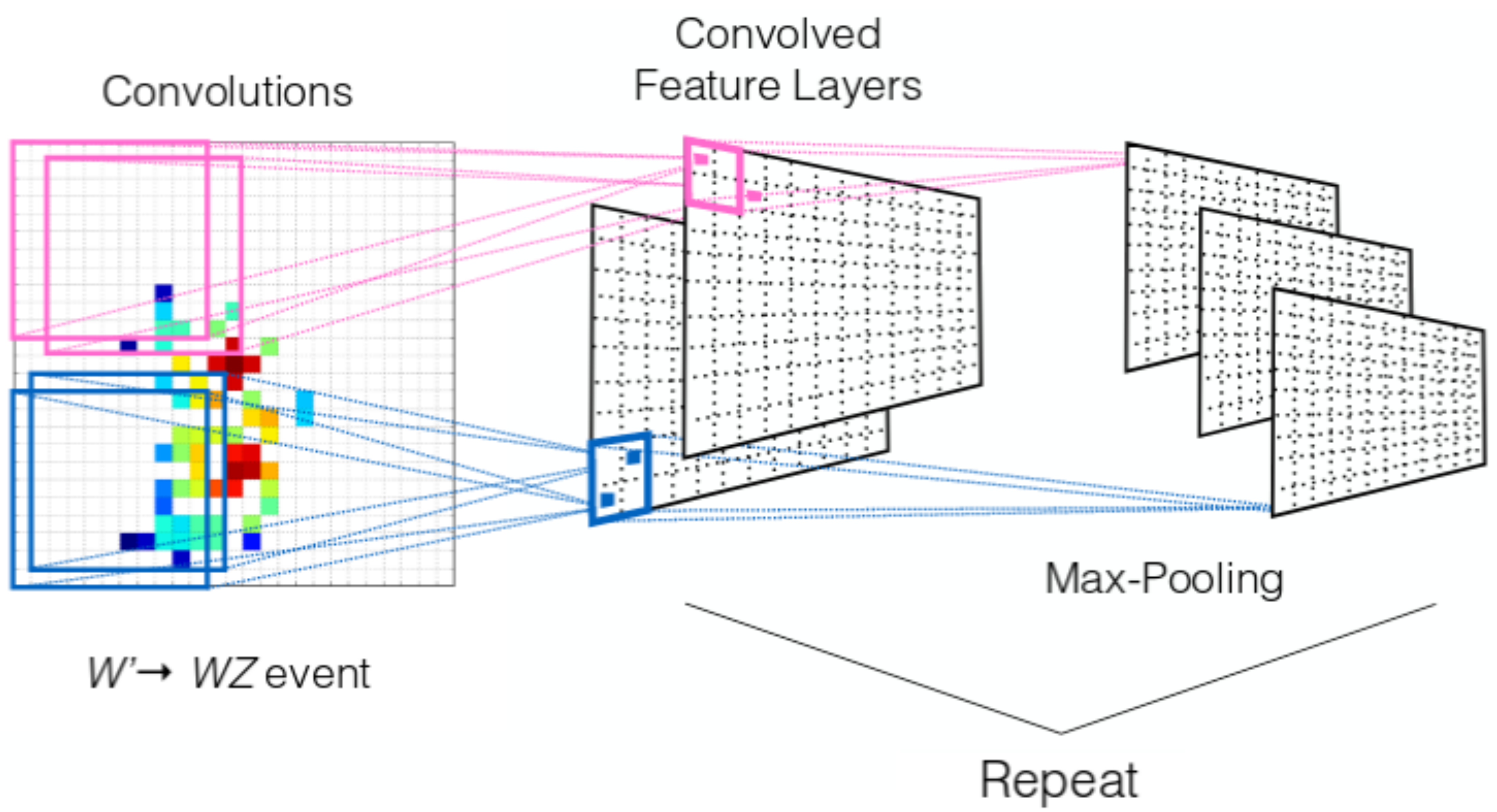
event with Higgs & Z boson decays



Machine learning and jet/event structure

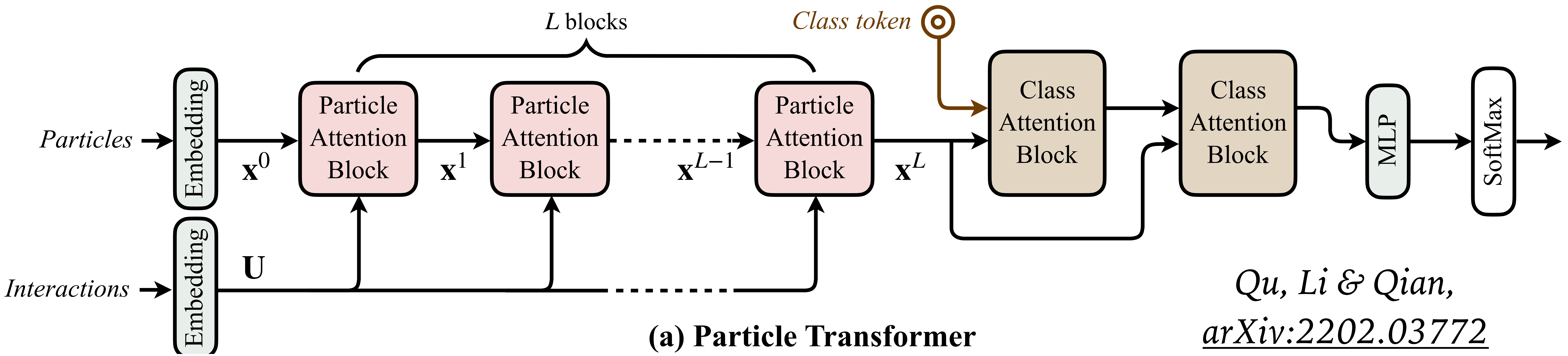


2021 Young Experimental Physicist
EPS HEPP prize



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

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

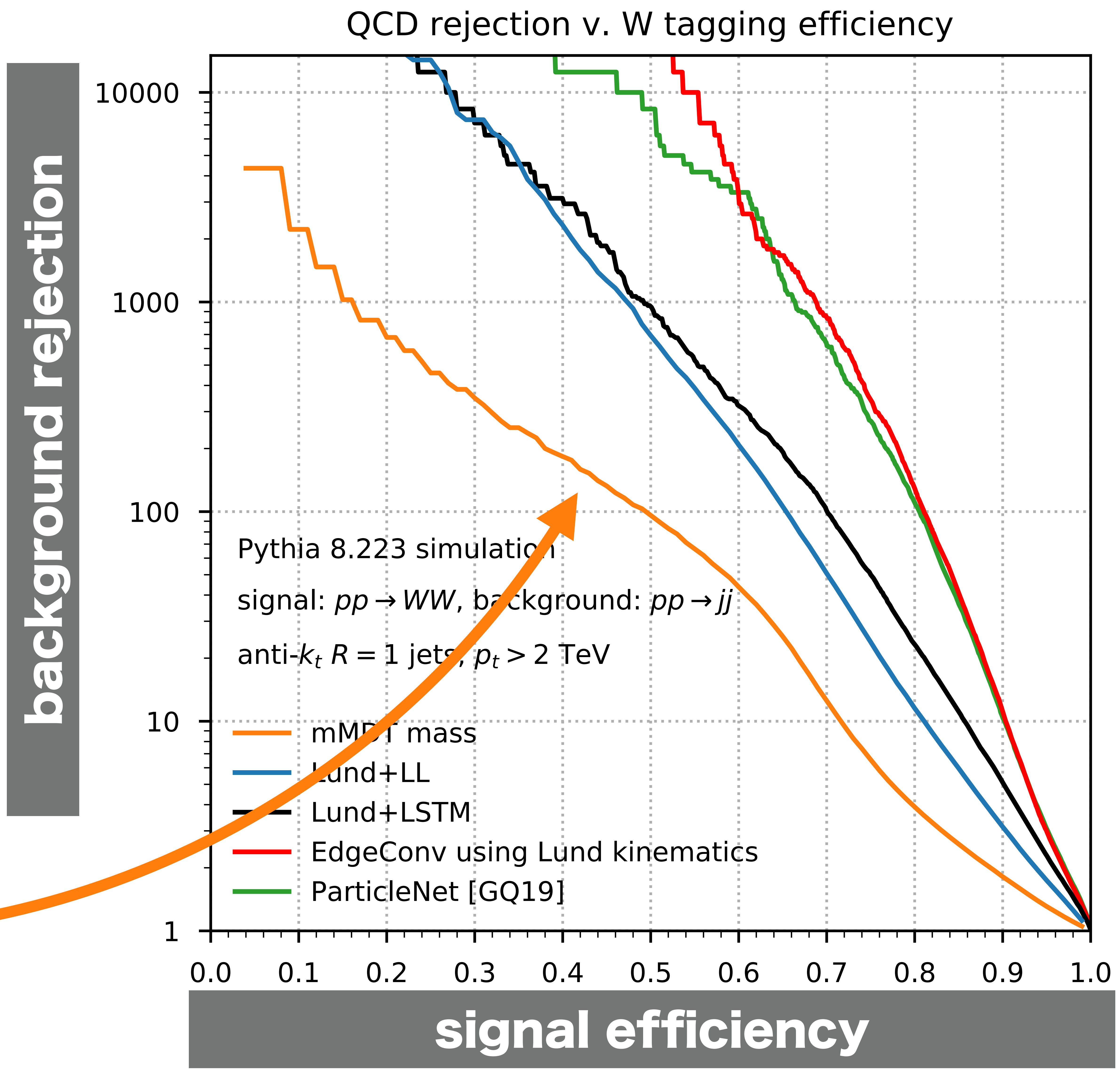


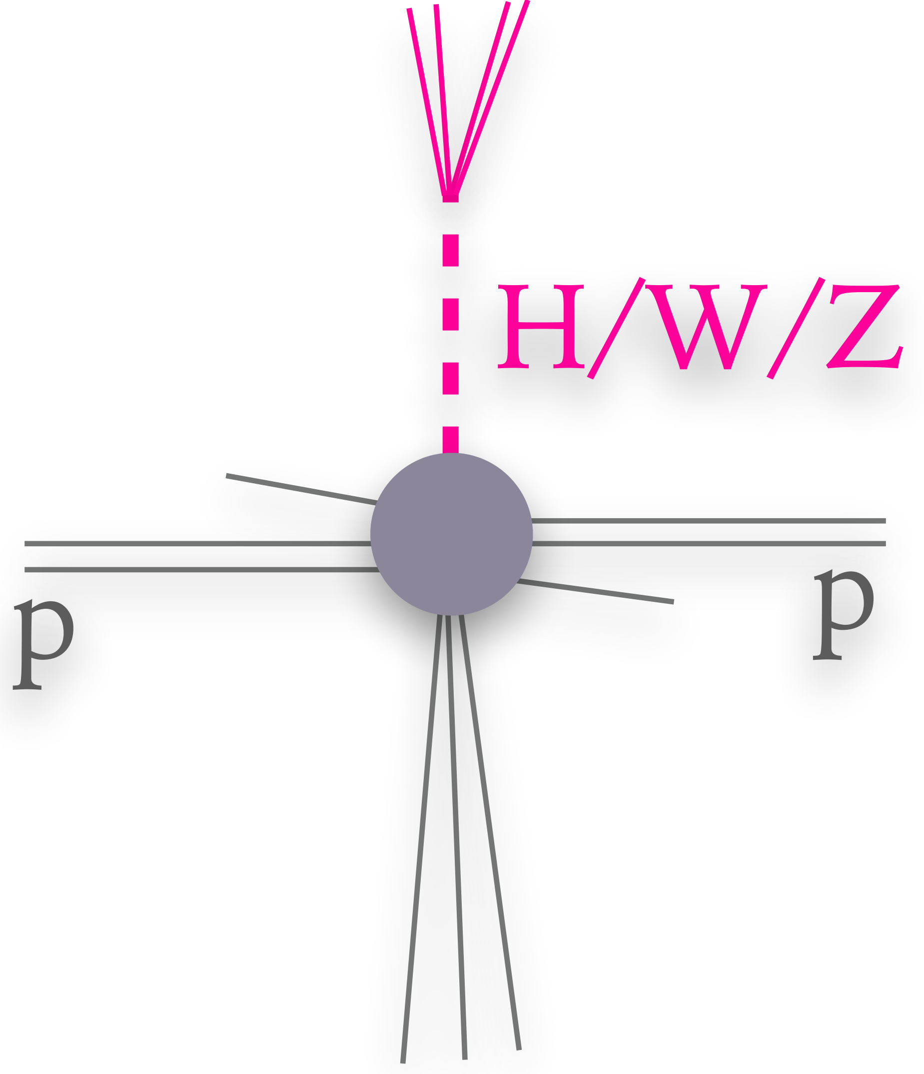
(a) Particle Transformer

Qu, Li & Qian, arXiv:2202.03772

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

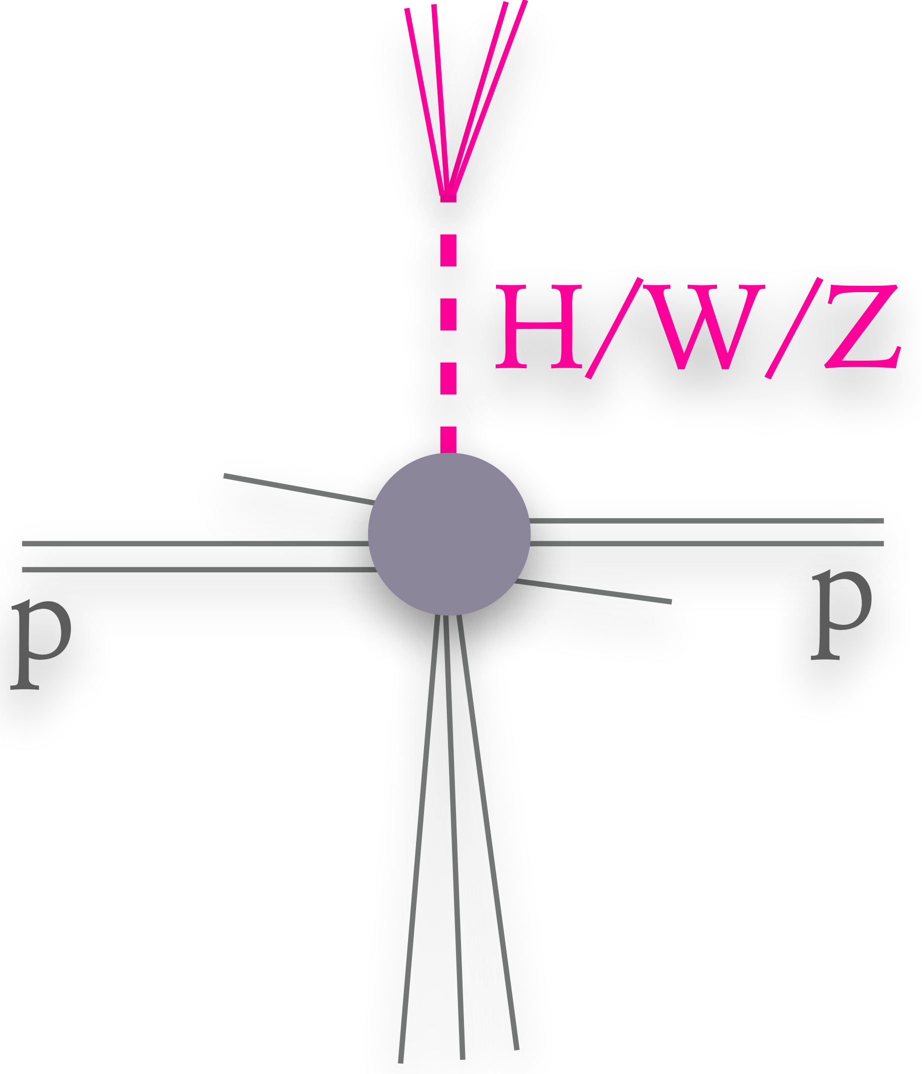
adapted from Dreyer & Qu 2012.08526





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

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



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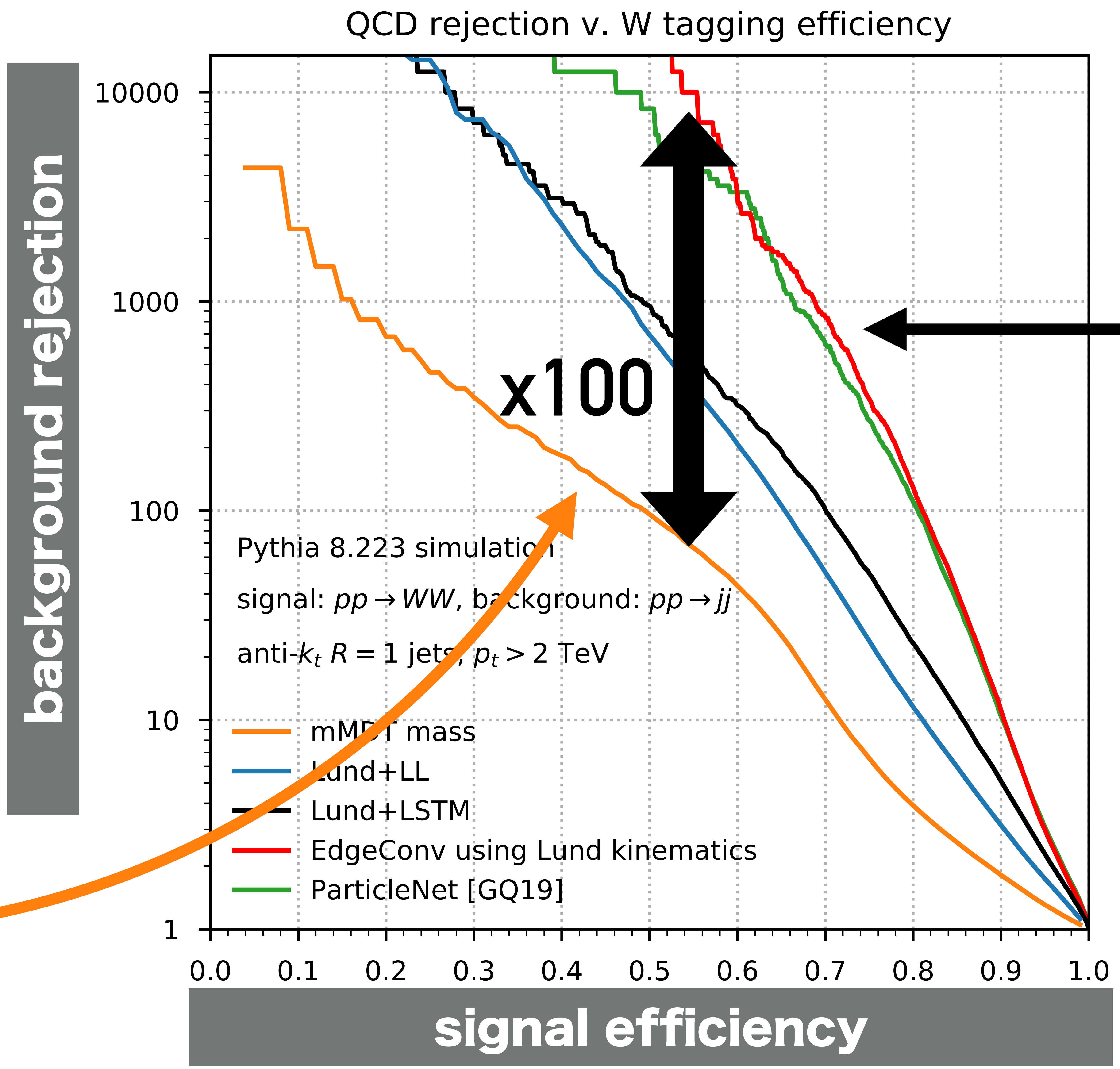


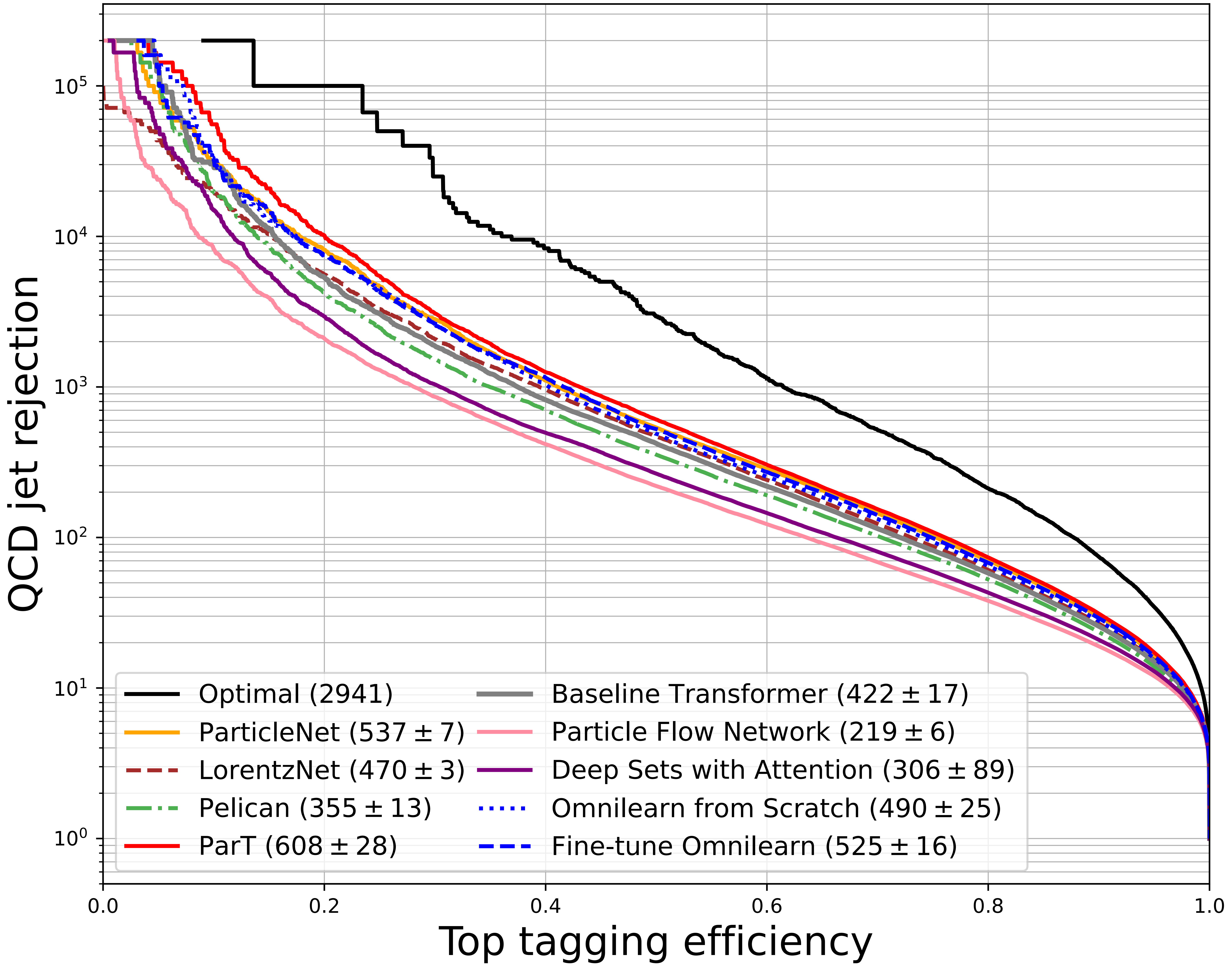
QCD rejection with just jet mass (SD/mMDT) i.e. 2008 tools & their 2013/14 descendants

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

100x better

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

Machine learnig can probably still deliver even more



cf. recent study that uses generative model as "Optimal" discriminator and compares performance of other approaches

Geuskens et al, 2411.02628

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

Example of radioactive decay (limit of long half-life)

Constant decay rate μ per unit time, total time $t_{\max}$. Find distribution of emissions.

1. write as coupled evolution equations for probability P_0, P_1, P_2 , etc., of having 0,1,2,… emissions

$$\frac{dP_n}{dt} = -\mu P_n(t) + \mu P_{n-1}(t)$$

$n \to n+1$ $\quad$ $n-1 \to n$

[easy to implement in Monte Carlo approach]

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Monte Carlo solution (repeat following procedure many times to get distribution of n, $\{t_i\}$)

a. start with $n = 0$, $t_0 = 0$

b. Choose random number r $(0 < r < 1)$ and find t_{n+1} that satisfies

$$r = e^{-\mu(t_{n+1}-t_n)}$$

[i.e. randomly sample exponential distribution]

c. If $t_{n+1} < t_{max}$, increment n, go to step b

Monte Carlo worked example

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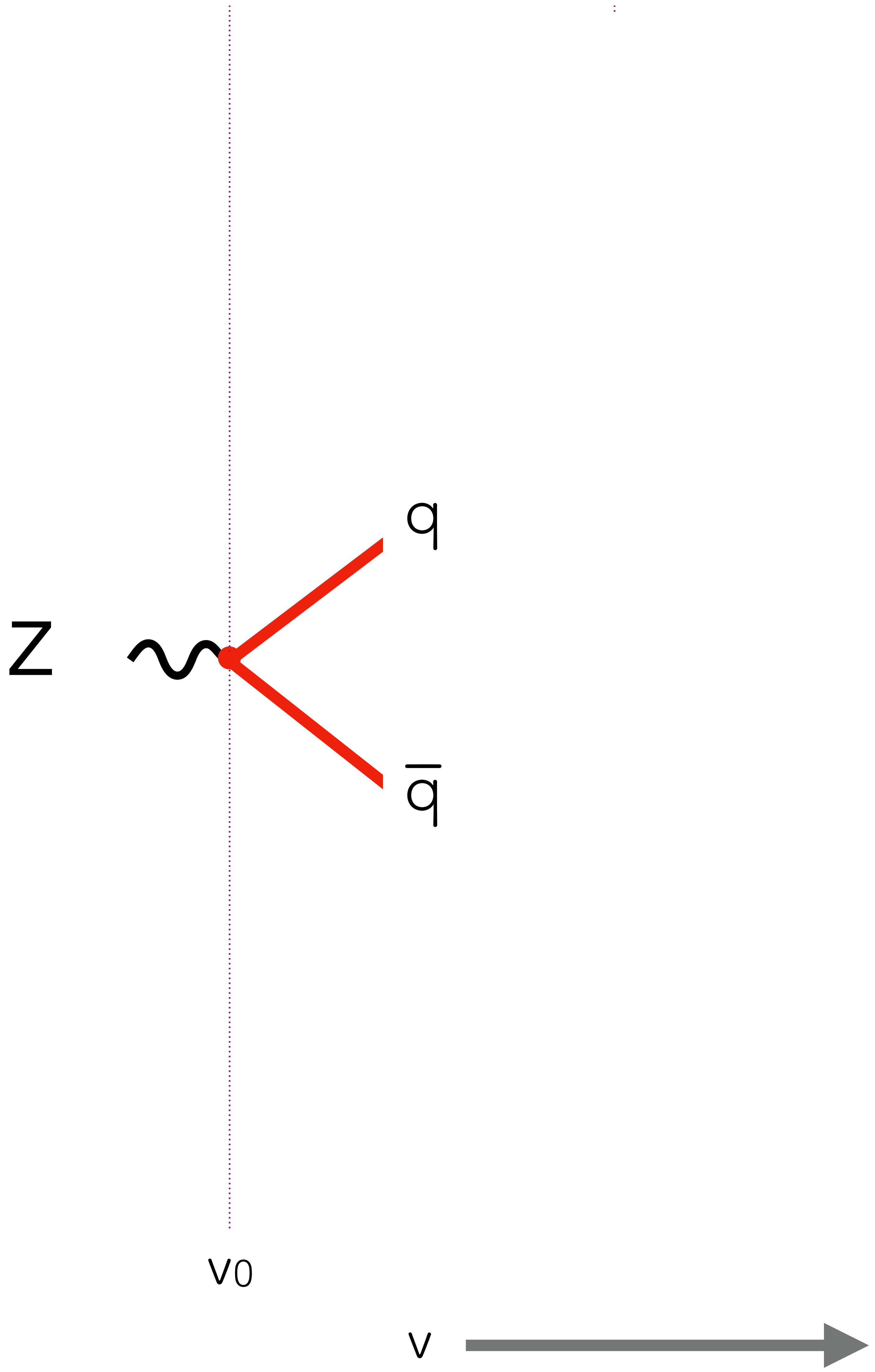
c. If $t_{n+1} < t_{\max}$, increment n, go to step b

E.g. for decay rate $\mu = 1$, total time $t_{\max} = 2$

- start with $n = 0, t_0 = 0$
- random number $r = 0.6 \;\rightarrow\; t_1 = t_0 + \log(1/r) = 0.51$ [emission 1]
- random number $r = 0.3 \;\rightarrow\; t_2 = t_1 + \log(1/r) = 1.71$ [emission 2]
- random number $r = 0.4 \;\rightarrow\; t_3 = t_2 + \log(1/r) = 2.63$ [$> t_{\max}$, so stop]
- **This event has two emissions at times** $\{t_1 = 0.51,\, t_2 = 1.71\}$

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

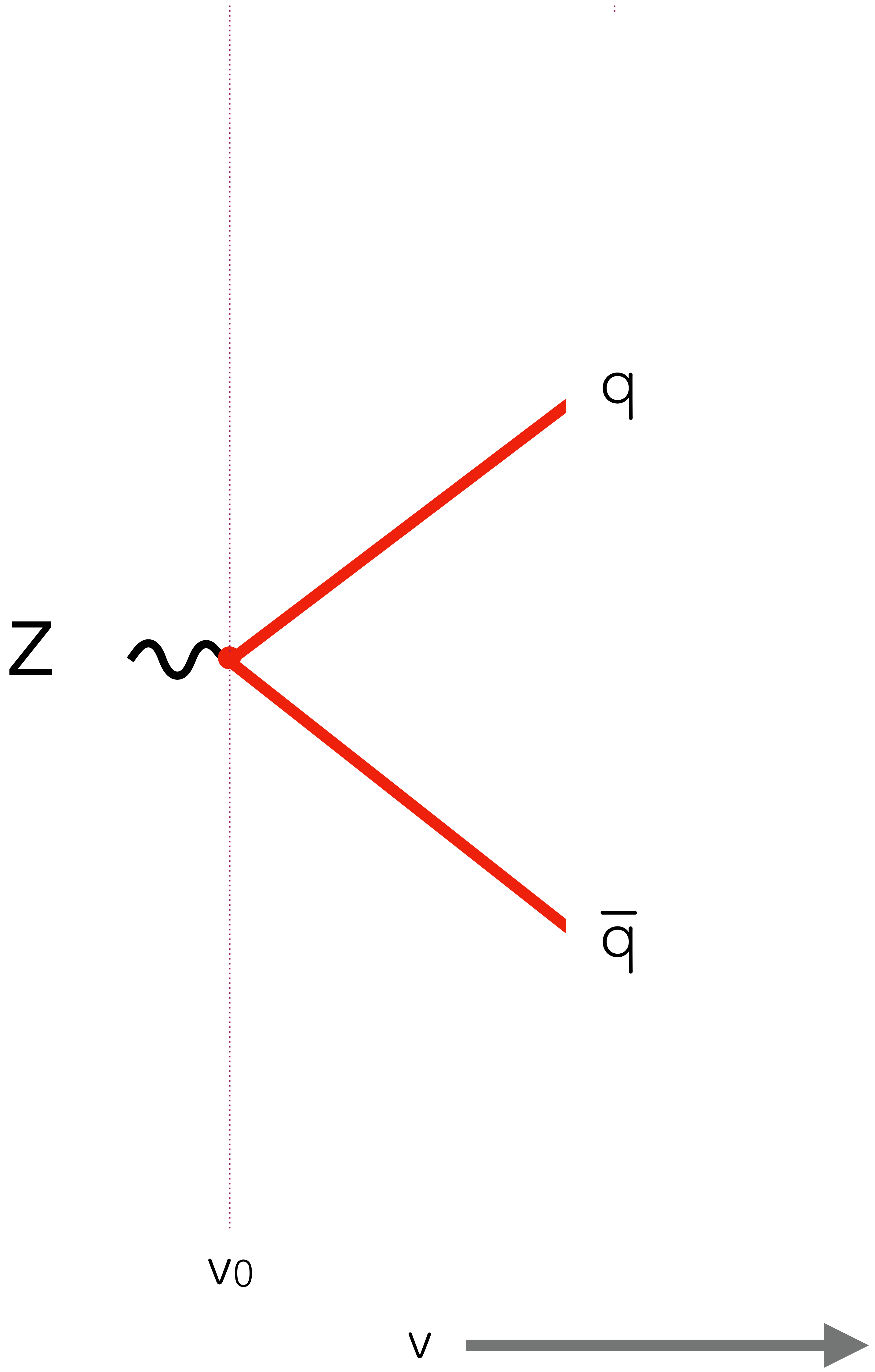


Start with $q\bar{q}$ state.

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

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

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

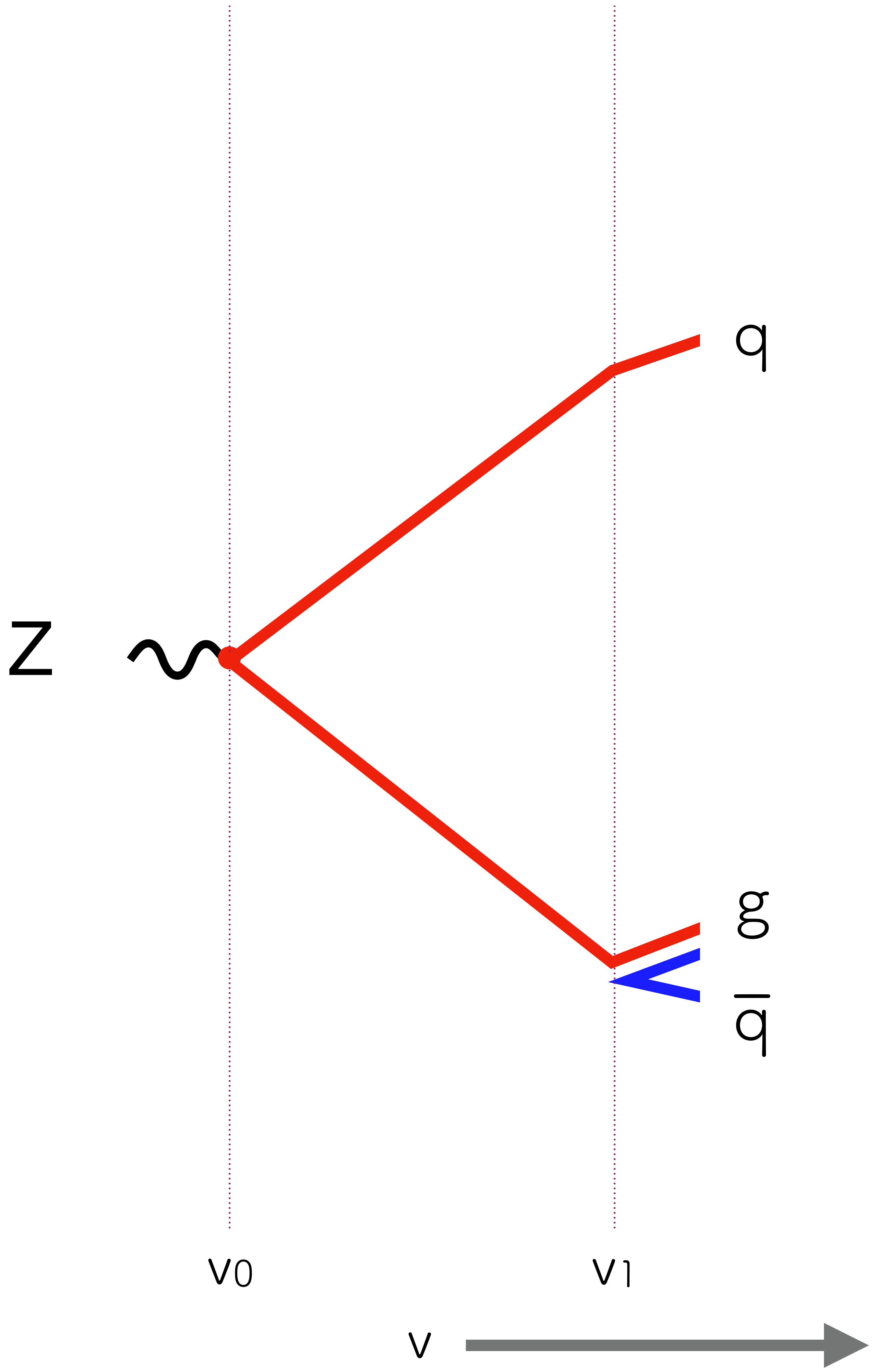


Start with q-qbar state.

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

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

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

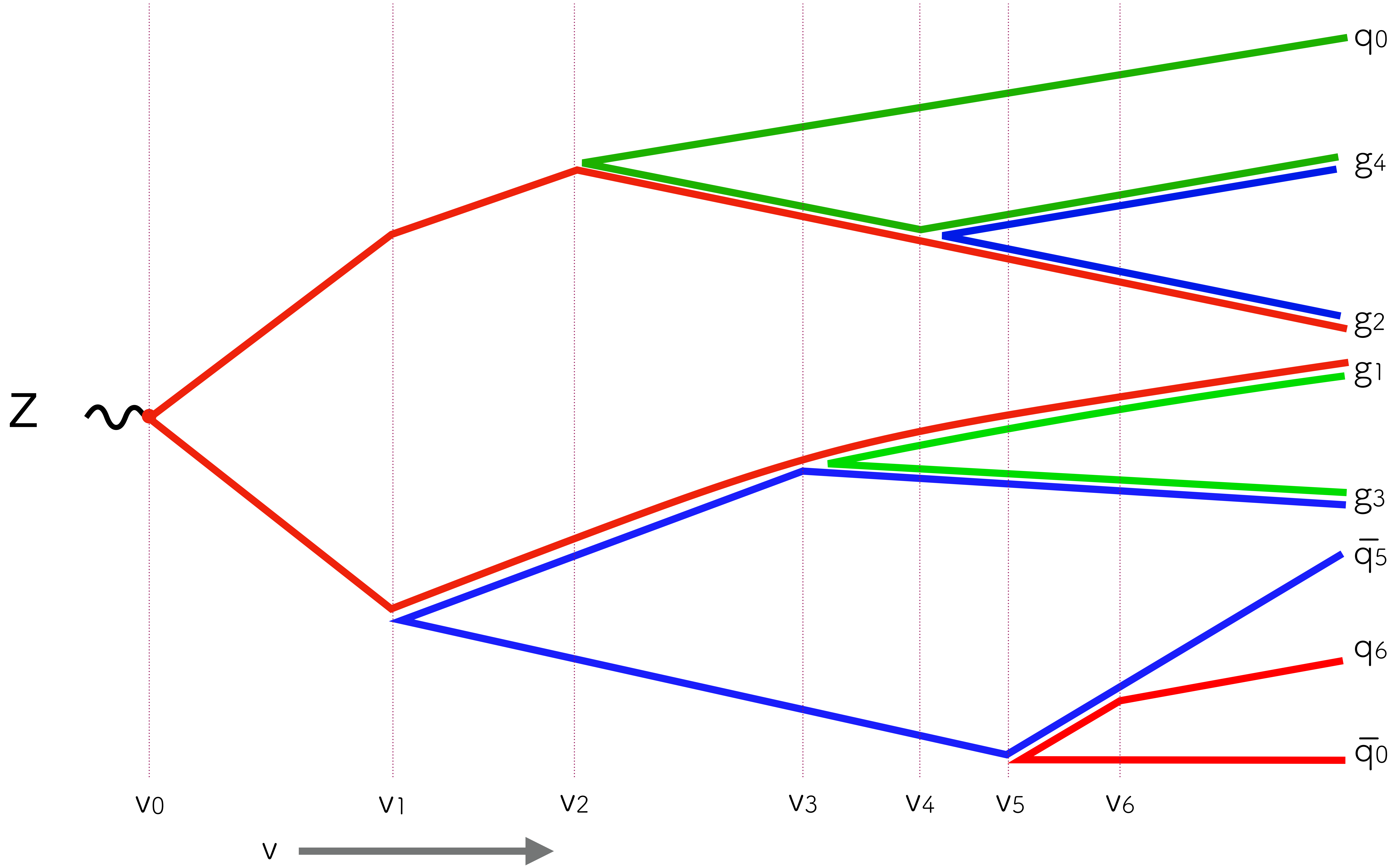
At some point, **state splits** (2→3, i.e. emits gluon). Evolution equation changes

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

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.)

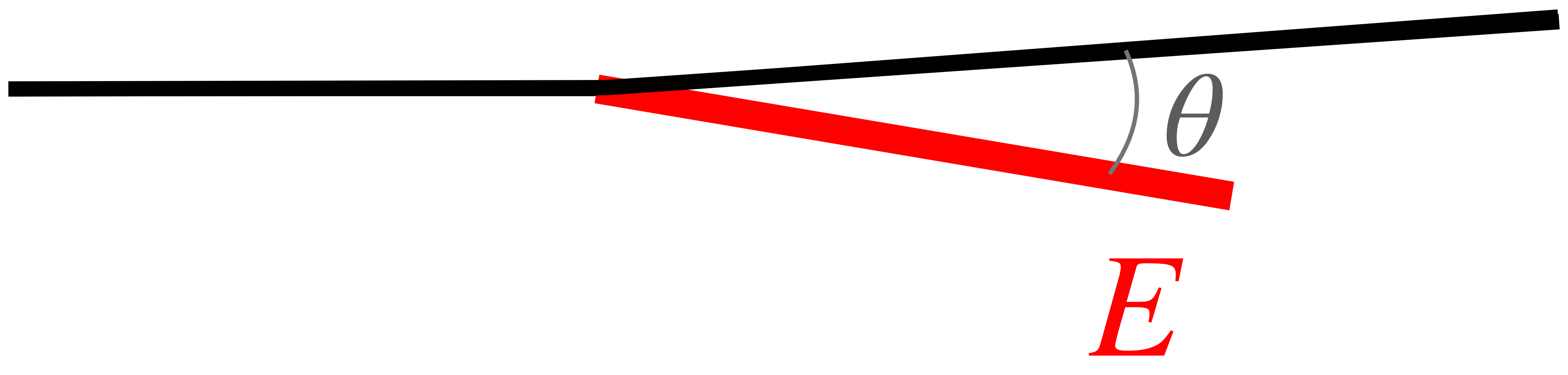


self-similar evolution continues until it reaches a non-perturbative scale

the Lund plane

organisation of phase space that highlights QCD divergences and logarithms

Phase space: two key variables (+ azimuth)



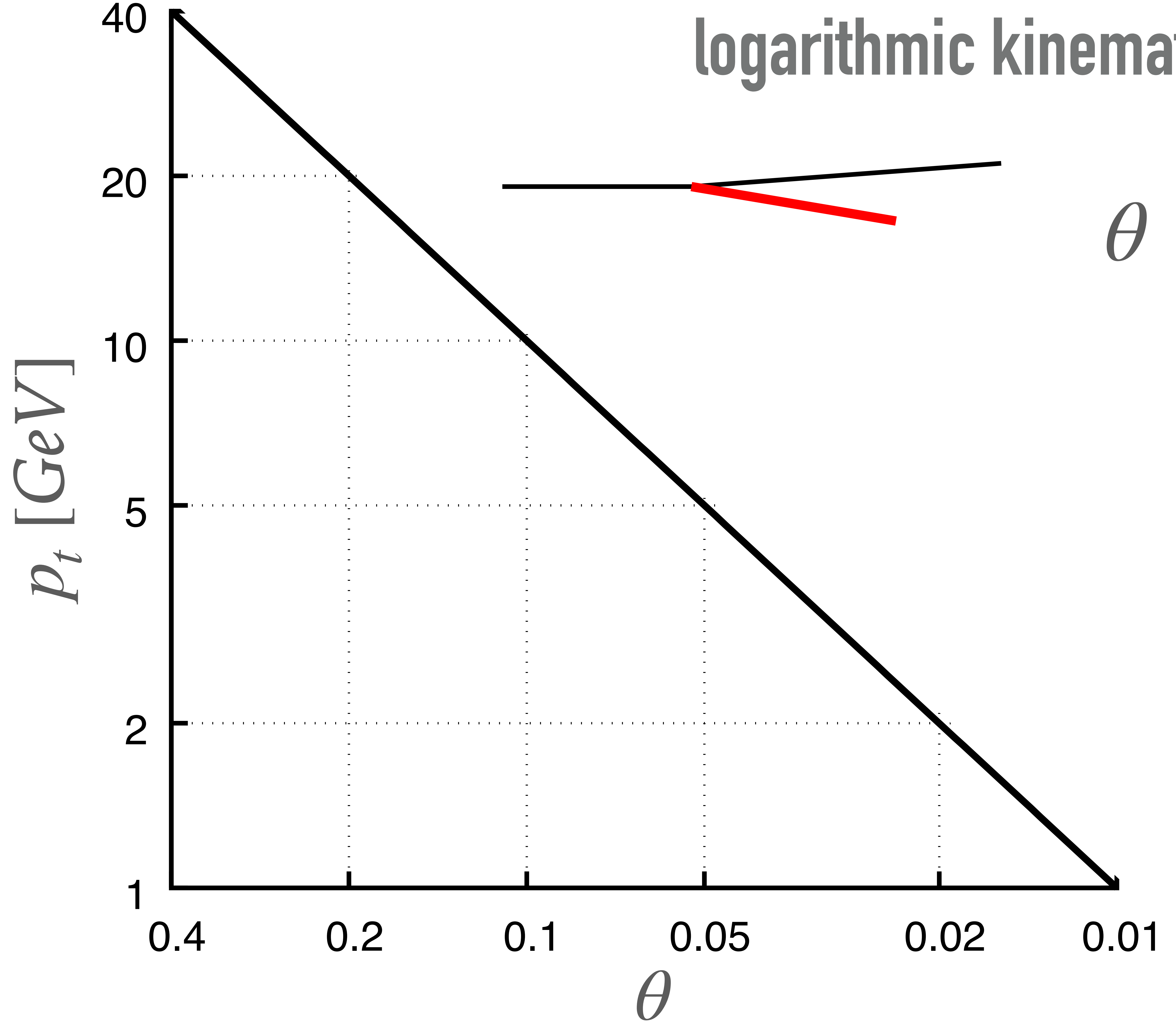
θ (or $\eta = -\ln\tan\frac{\theta}{2}$)   *$\eta$ is called (pseudo)rapidity*

$p_t = E\theta$ *p_t (or $p_\perp$) is a transverse momentum*

$$d\Phi|M^2| = \frac{2\alpha_s(p_t)C}{\pi}\frac{d\theta}{\theta}\frac{dp_t}{p_t}\frac{d\phi}{2\pi}$$

emission probability in low-energy, small-angle limit

jet with R= 0.4, p_t = 200 GeV



logarithmic kinematic plane whose two variables are

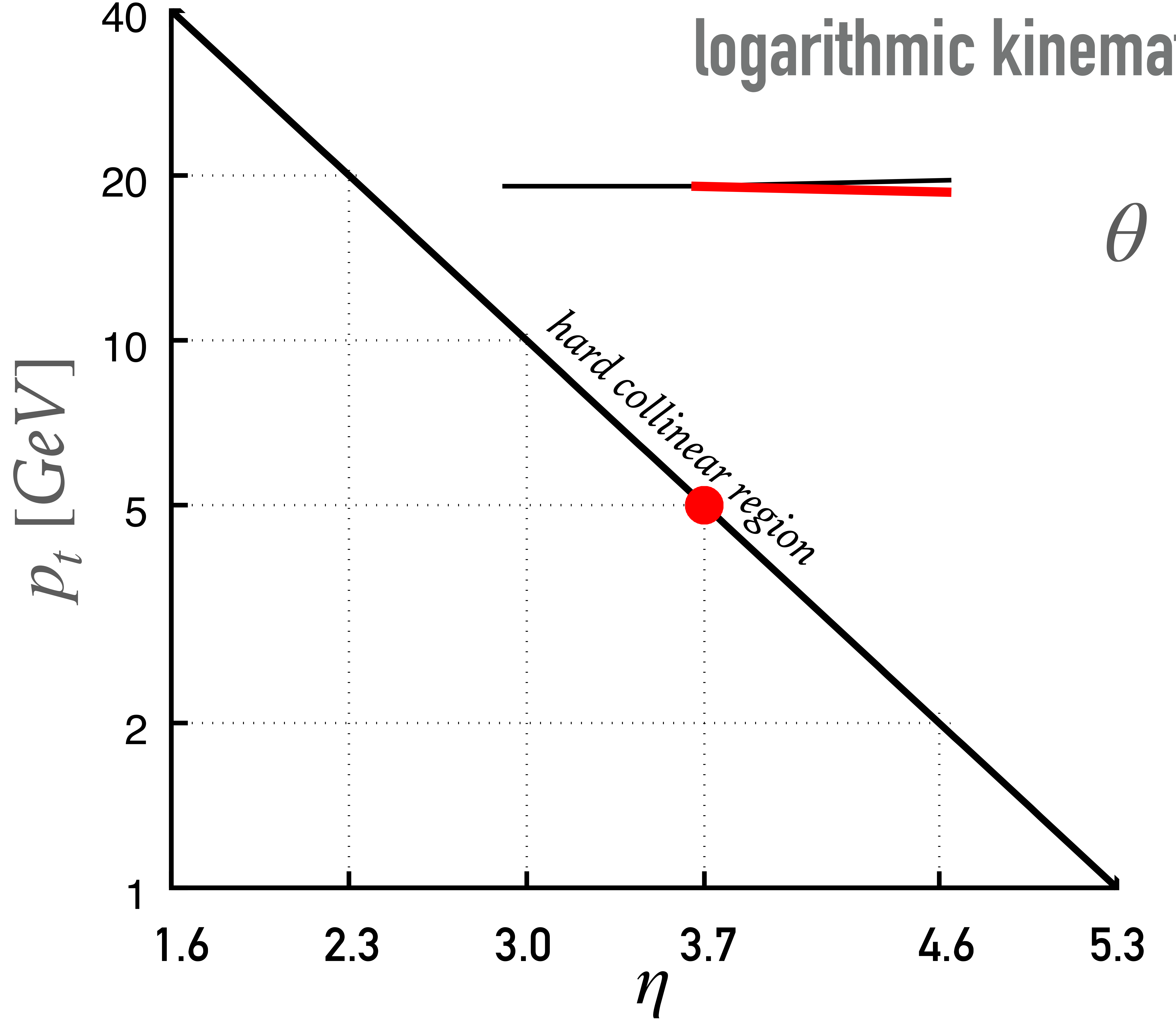
$$\theta \ (or\ \eta = -\ln\tan\frac{\theta}{2})$$

$$p_t = E\theta$$

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



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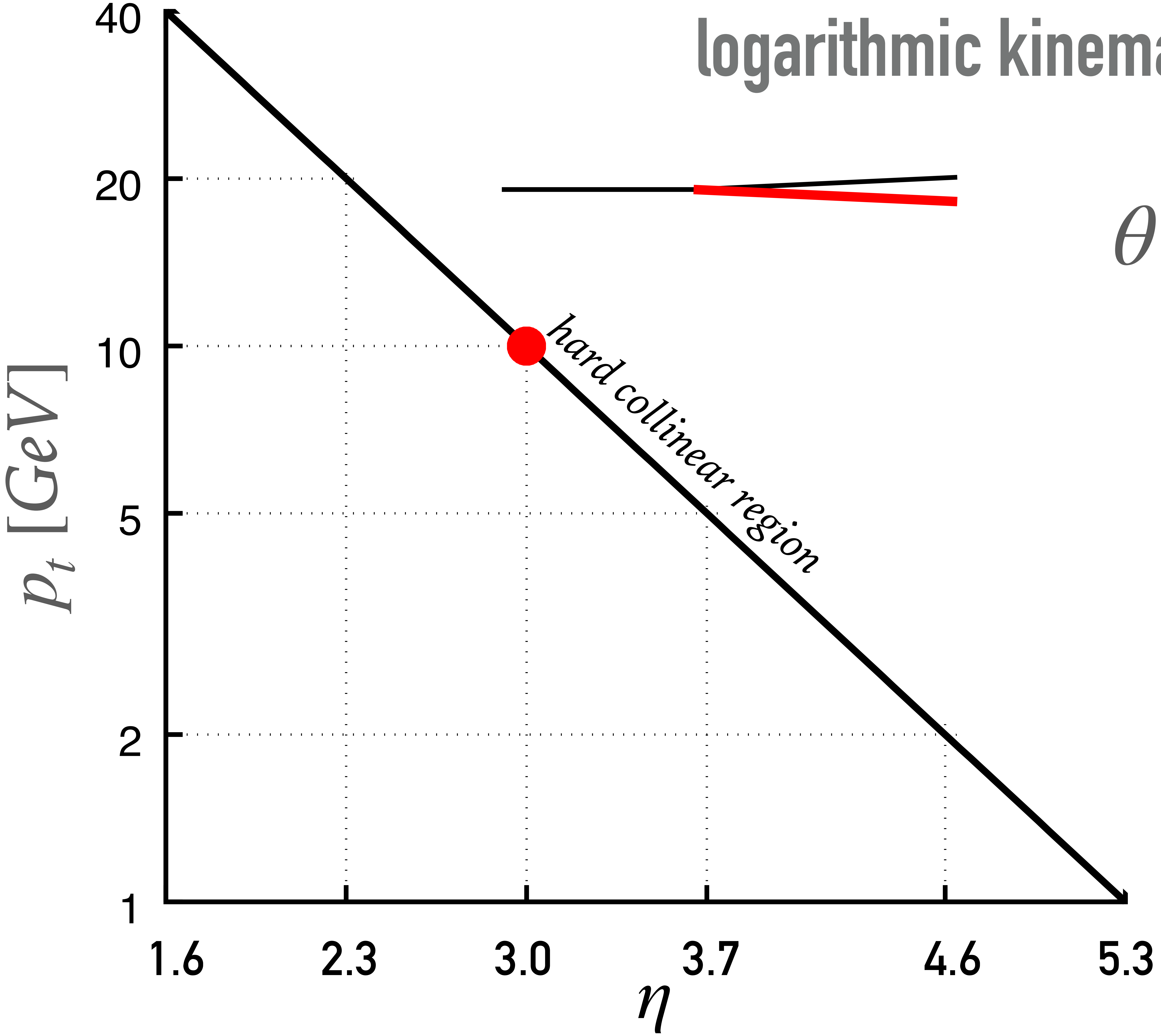

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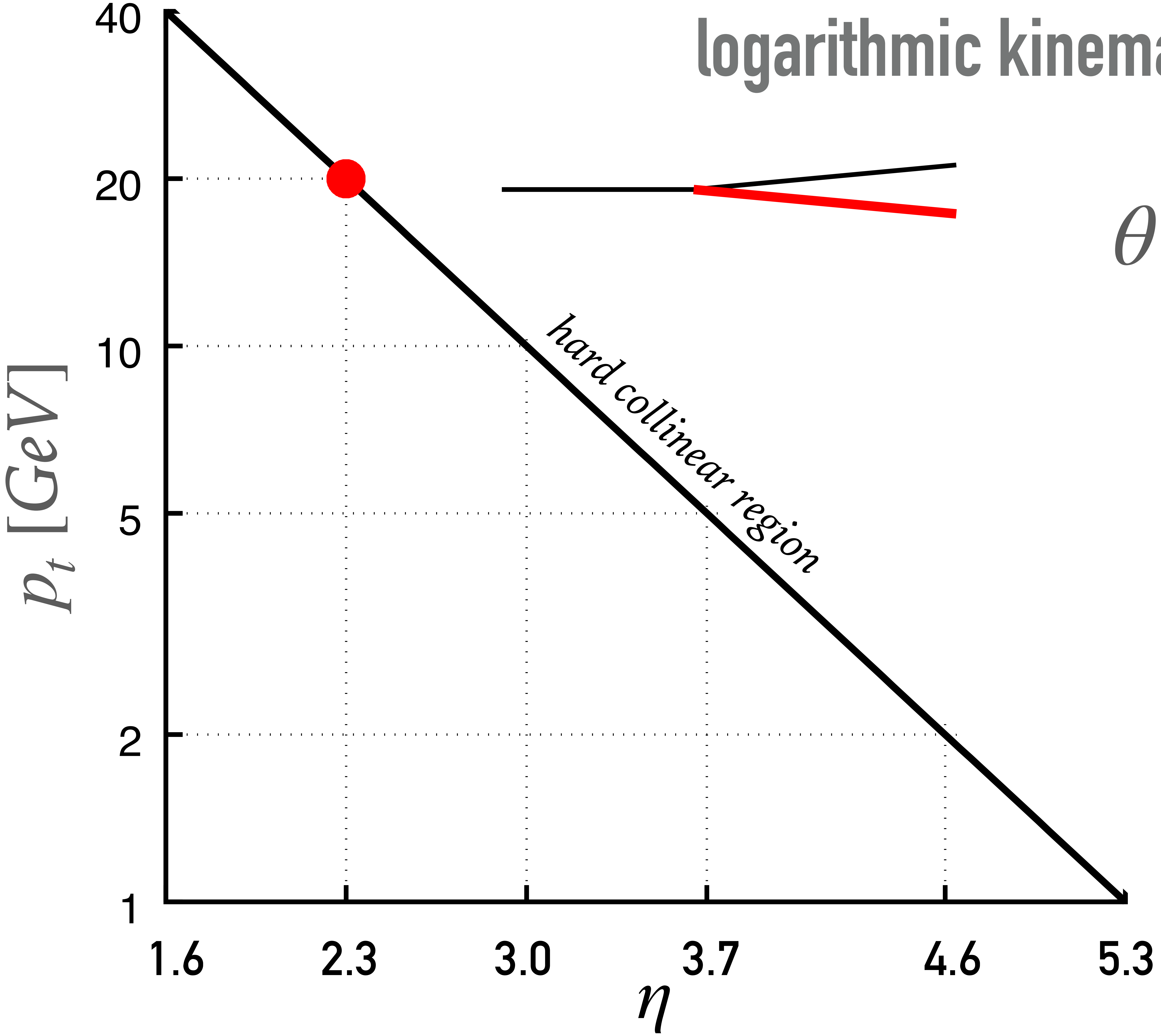

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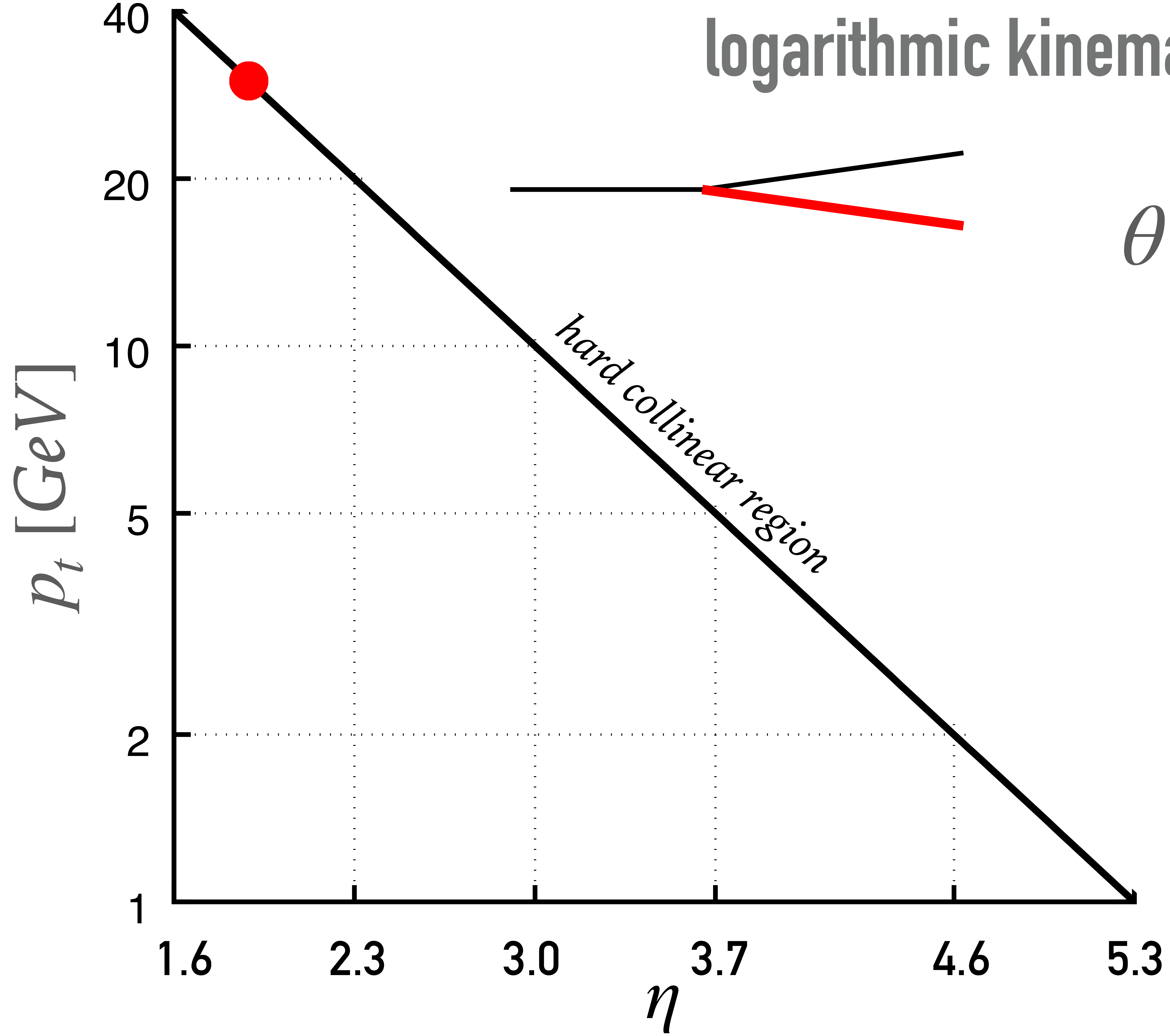

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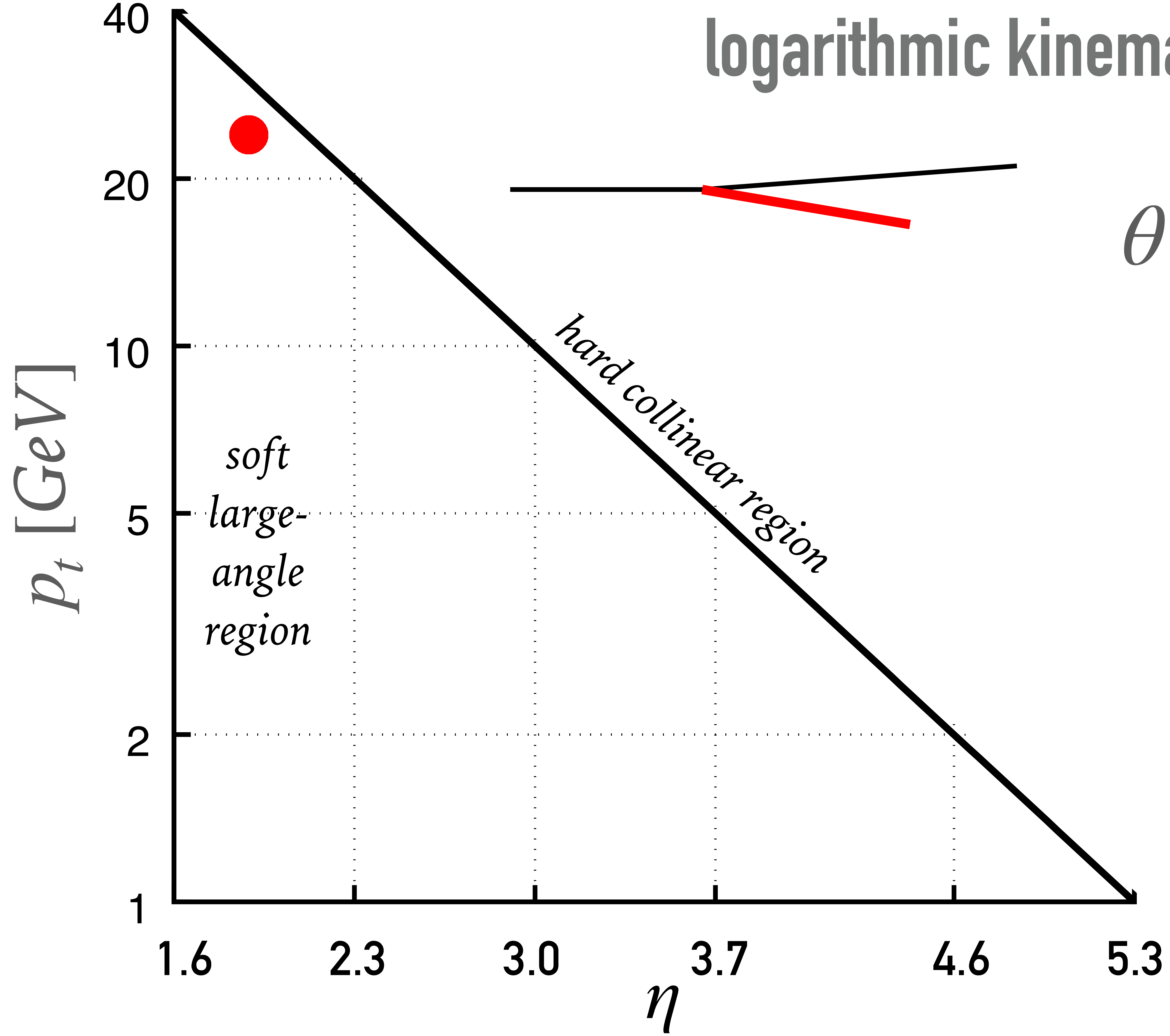

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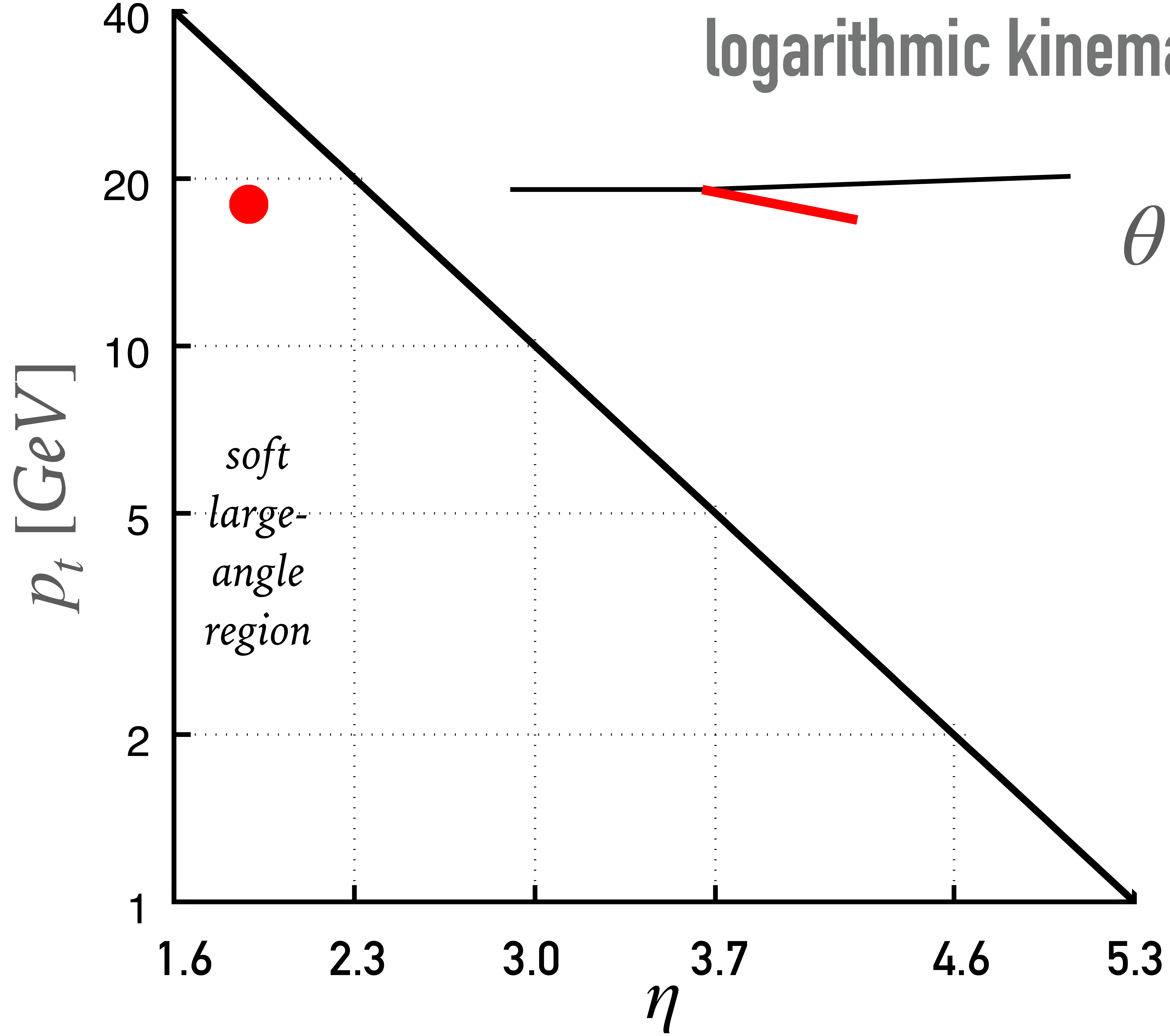
The Lund Plane

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

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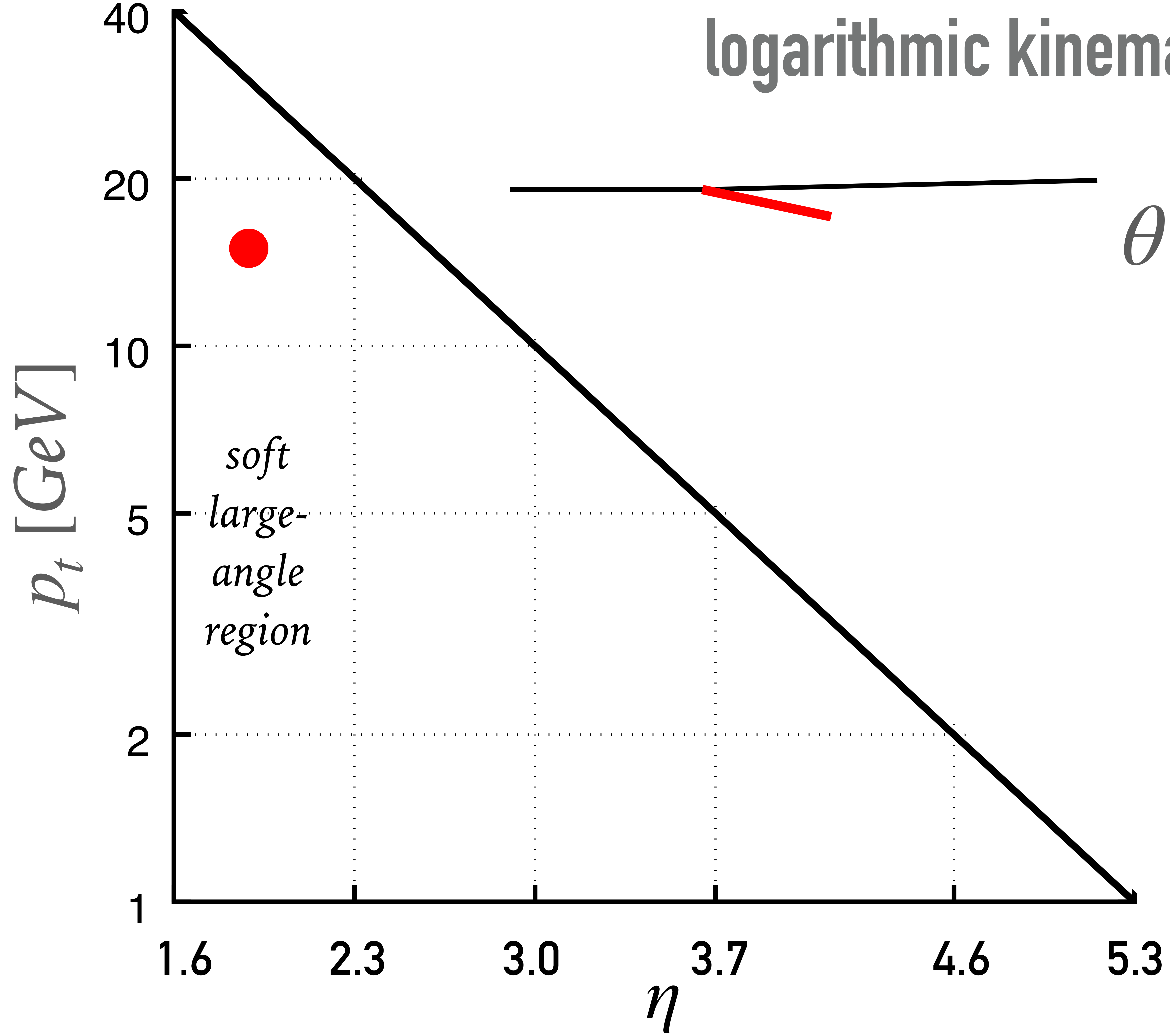

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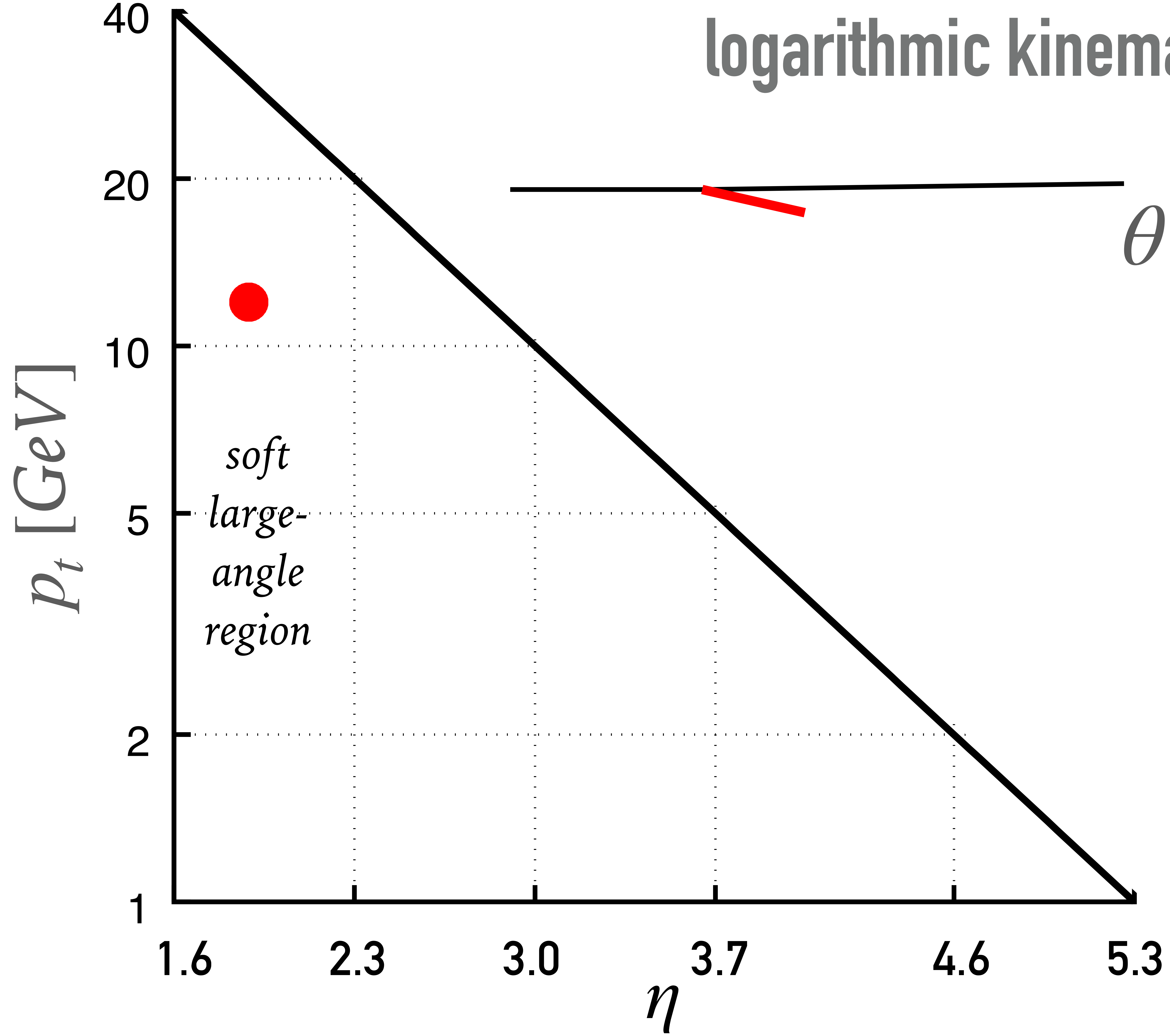

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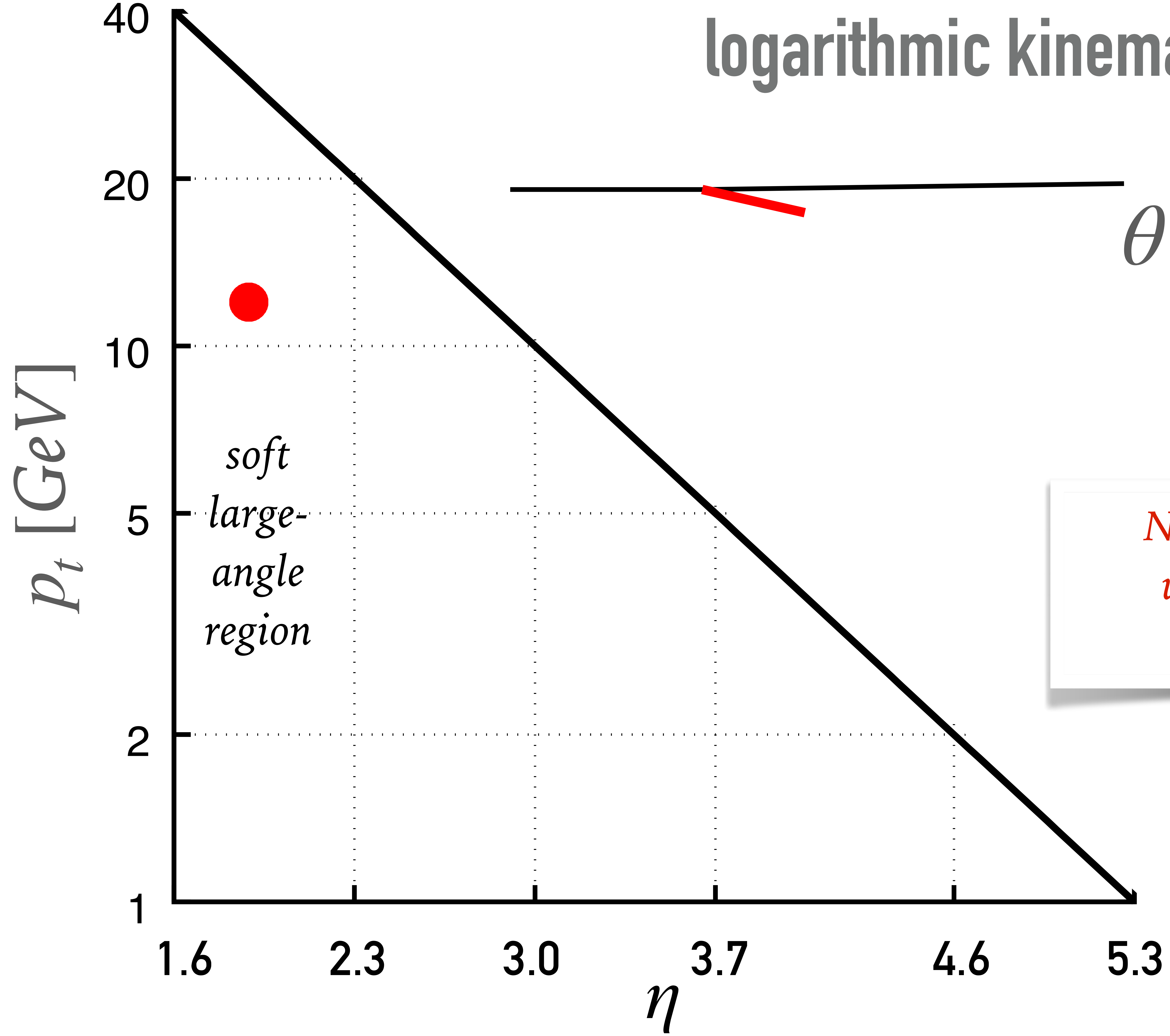

logarithmic kinematic plane whose two variables are

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NB: Lund plane can be constructed event-by-event using Cambridge/Aachen jet clustering sequence,
cf. Dreyer, GPS & Soyez '18

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

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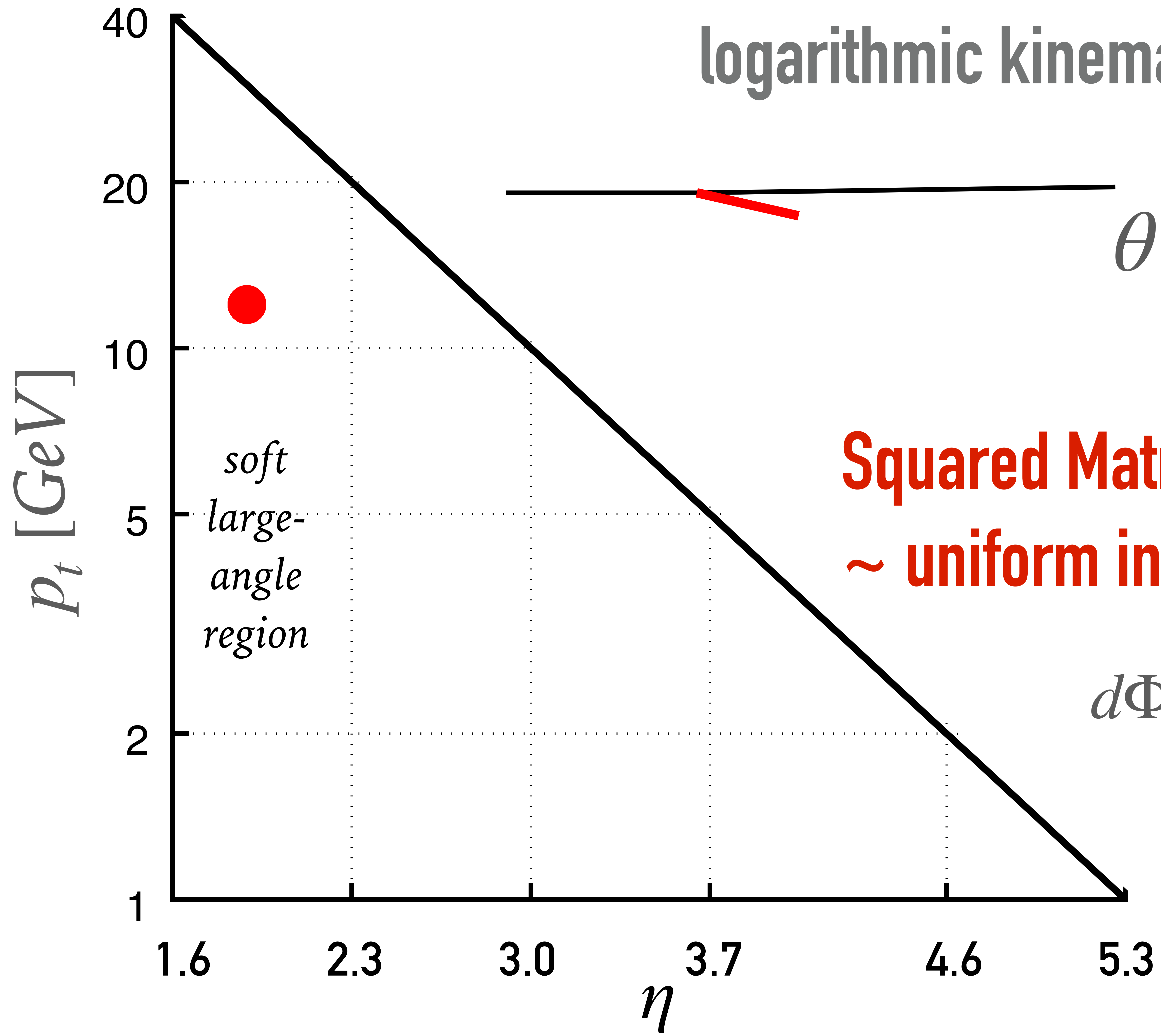

logarithmic kinematic plane whose two variables are

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

$$p_t = E\theta$$

Squared Matrix Element × phasespace

~ uniform in ln pt and η

$$d\Phi|M^2| = \frac{2\alpha_s(p_t)C}{\pi}\frac{dp_t}{p_t}\frac{d\theta}{\theta}\frac{d\phi}{2\pi}$$

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

The Lund Plane

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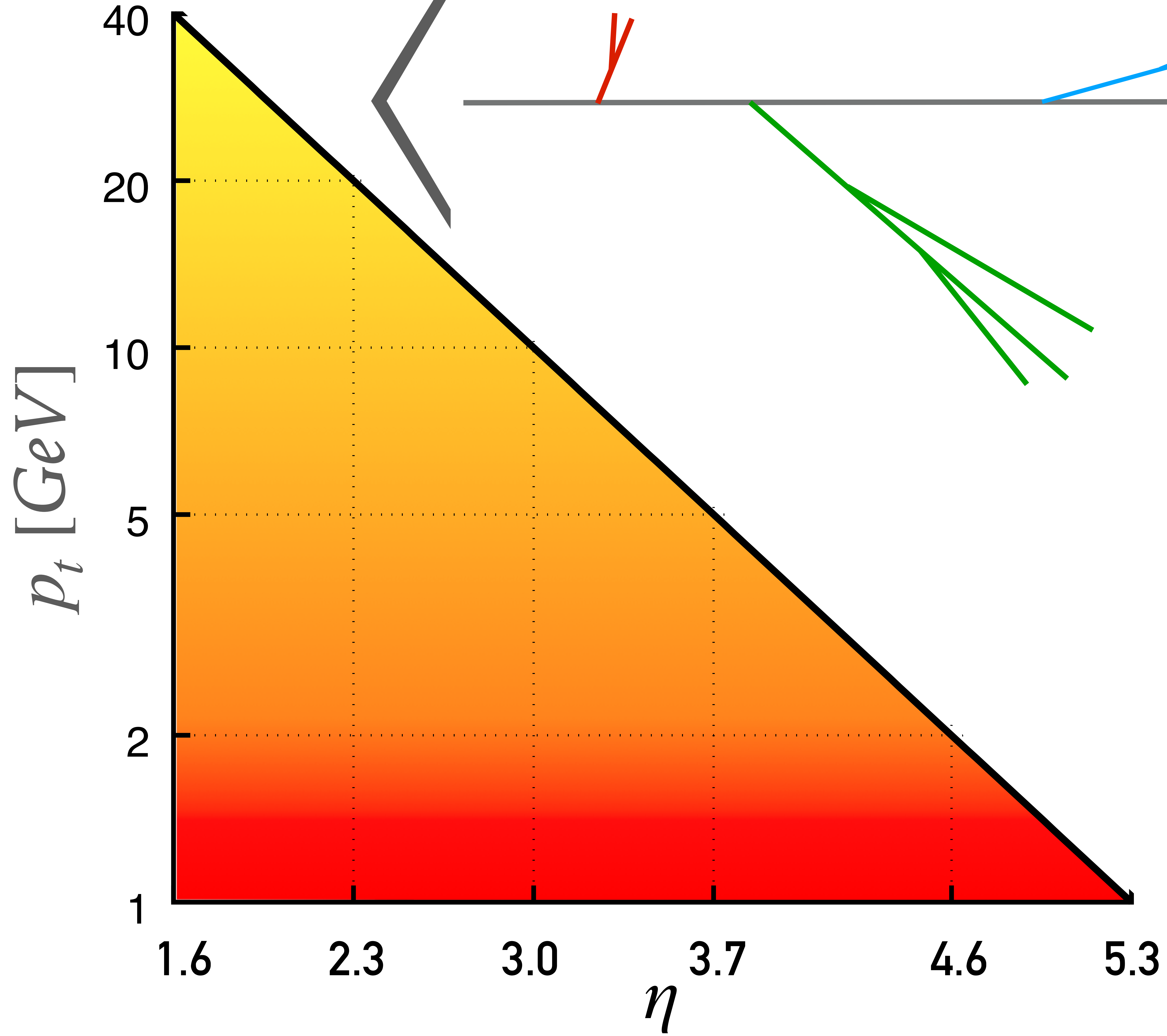
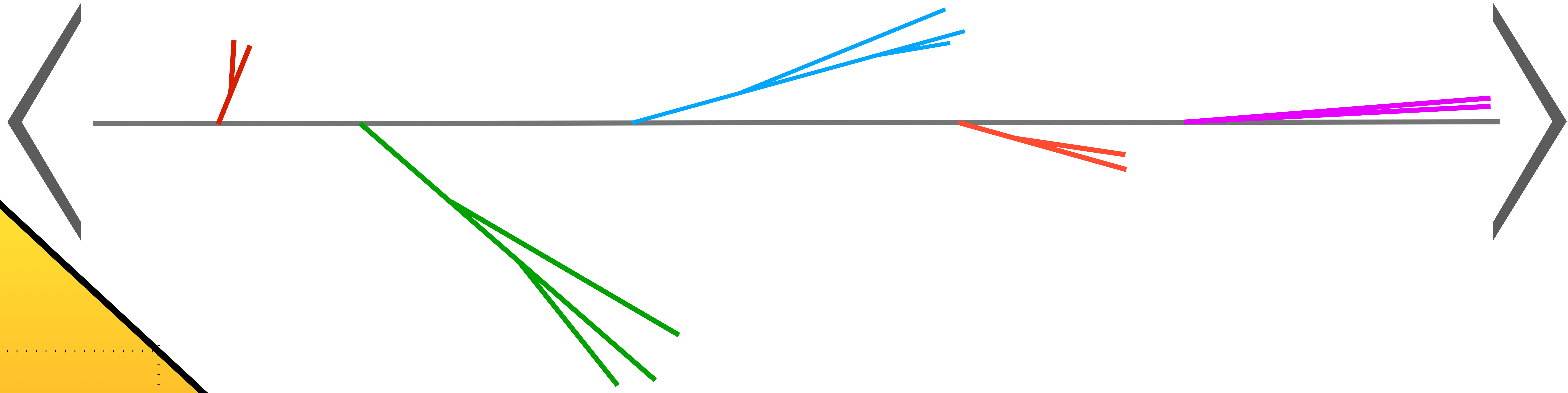




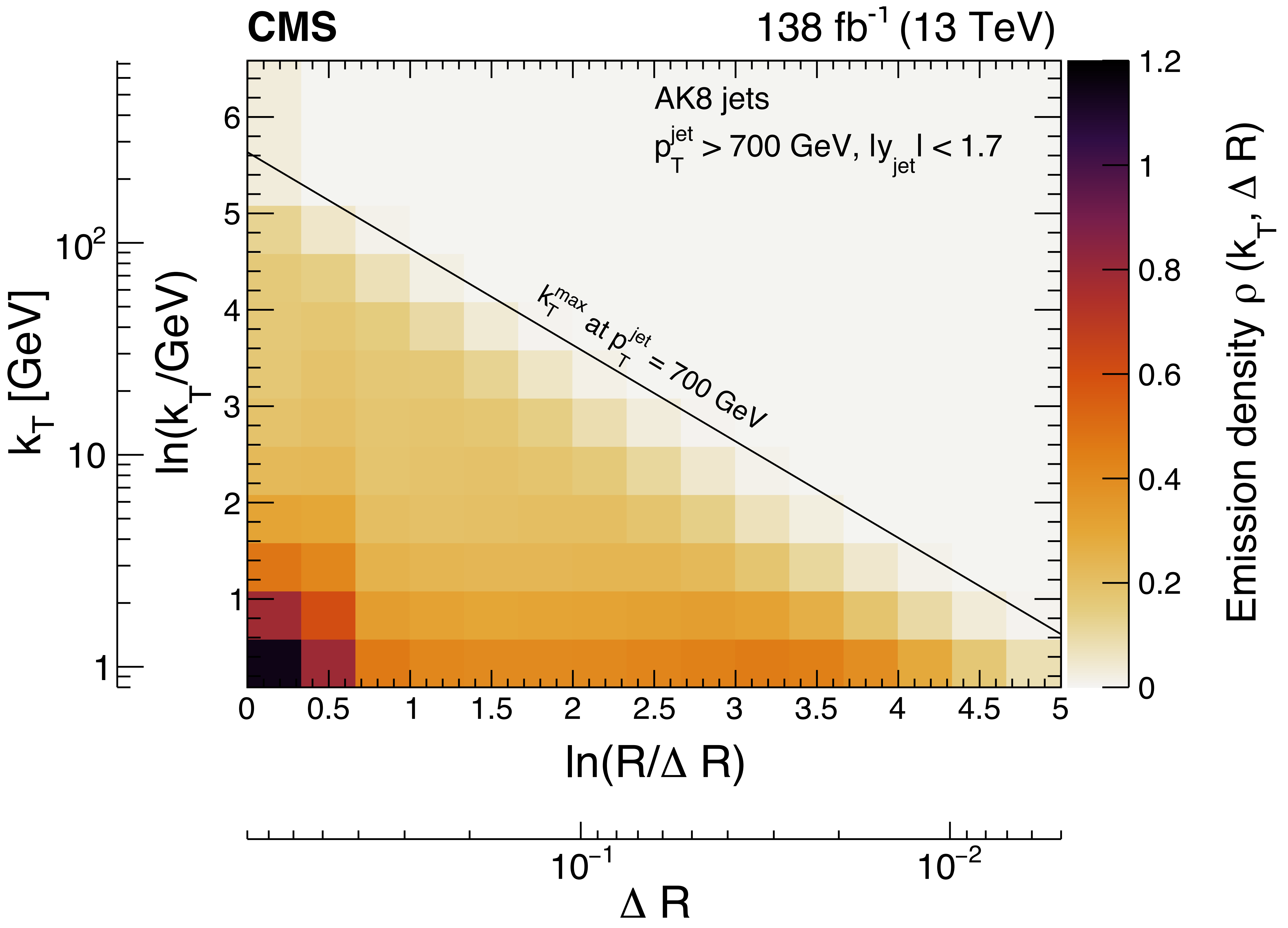
average over many jets:

Lund plane density

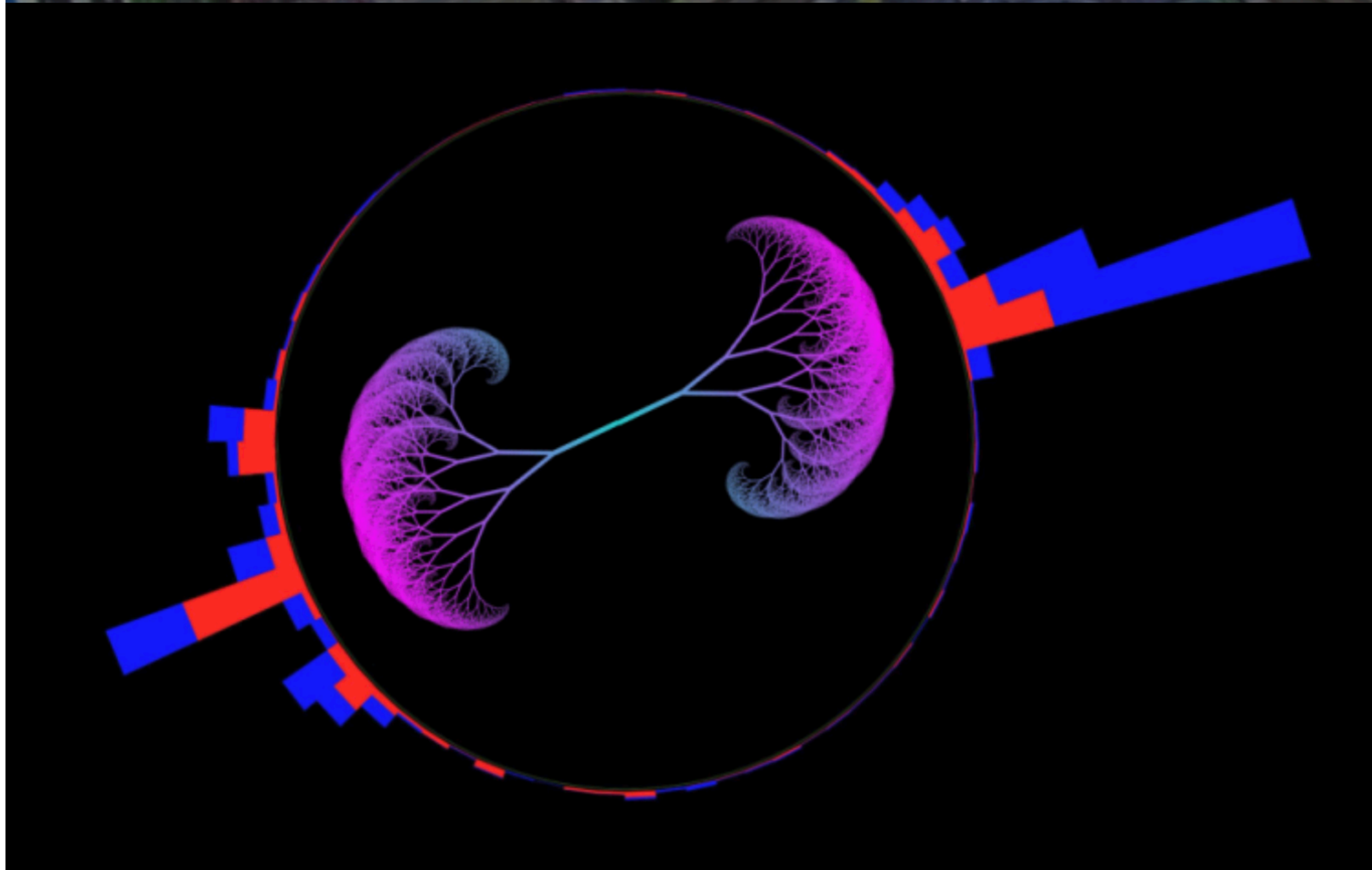
5th heavy-ion workshop @ CERN, 1808.03689

Dreyer, Soyez & GPS, 1807.04758 (for pp applications)

constructing the Lund plane



arXiv:2312.16343



https://cms.cern/news/fractal-tree-quarks-and-gluons

logarithmic accuracy

Logarithmic accuracy: a schematic intro

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

The language of "logarithmic accuracy", widespread for problem with disparate momentum scales, comes from analytical resummations.

E.g. if you place a strong constraint on the Z-boson transverse momentum, $p_{tZ} \ll m_Z$

$$\sigma(p_{t,Z} < p_t) \sim \sigma_{tot} \exp\left[-c\,.\,\alpha_s \ln^2 \frac{m_Z}{p_t}\right]$$

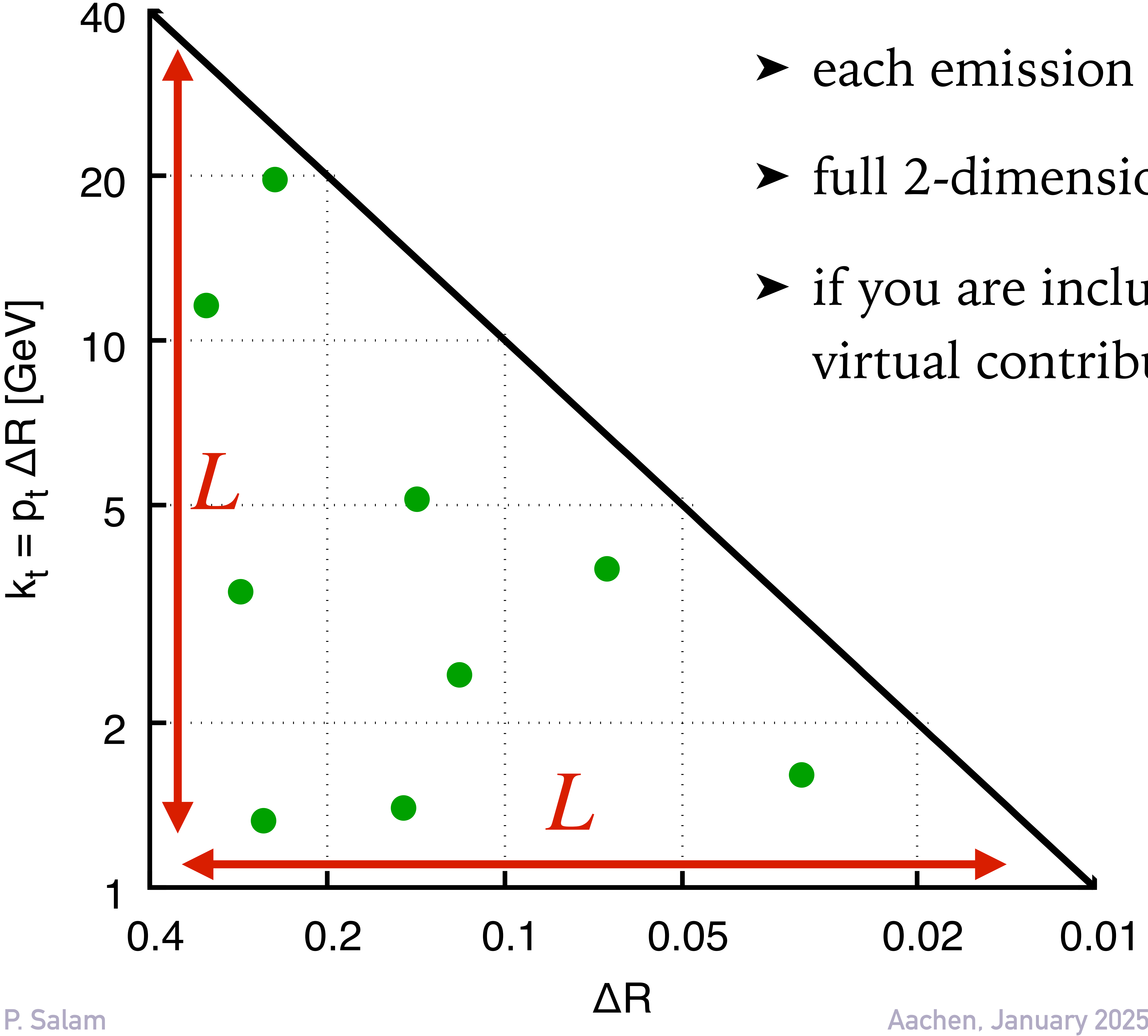
$$\alpha_s \ll 1$$

$$L \equiv \ln \frac{m_Z}{p_t} \gg 1$$

$$\alpha_s L \sim 1 \text{ or } \alpha_s L^2 \sim 1$$

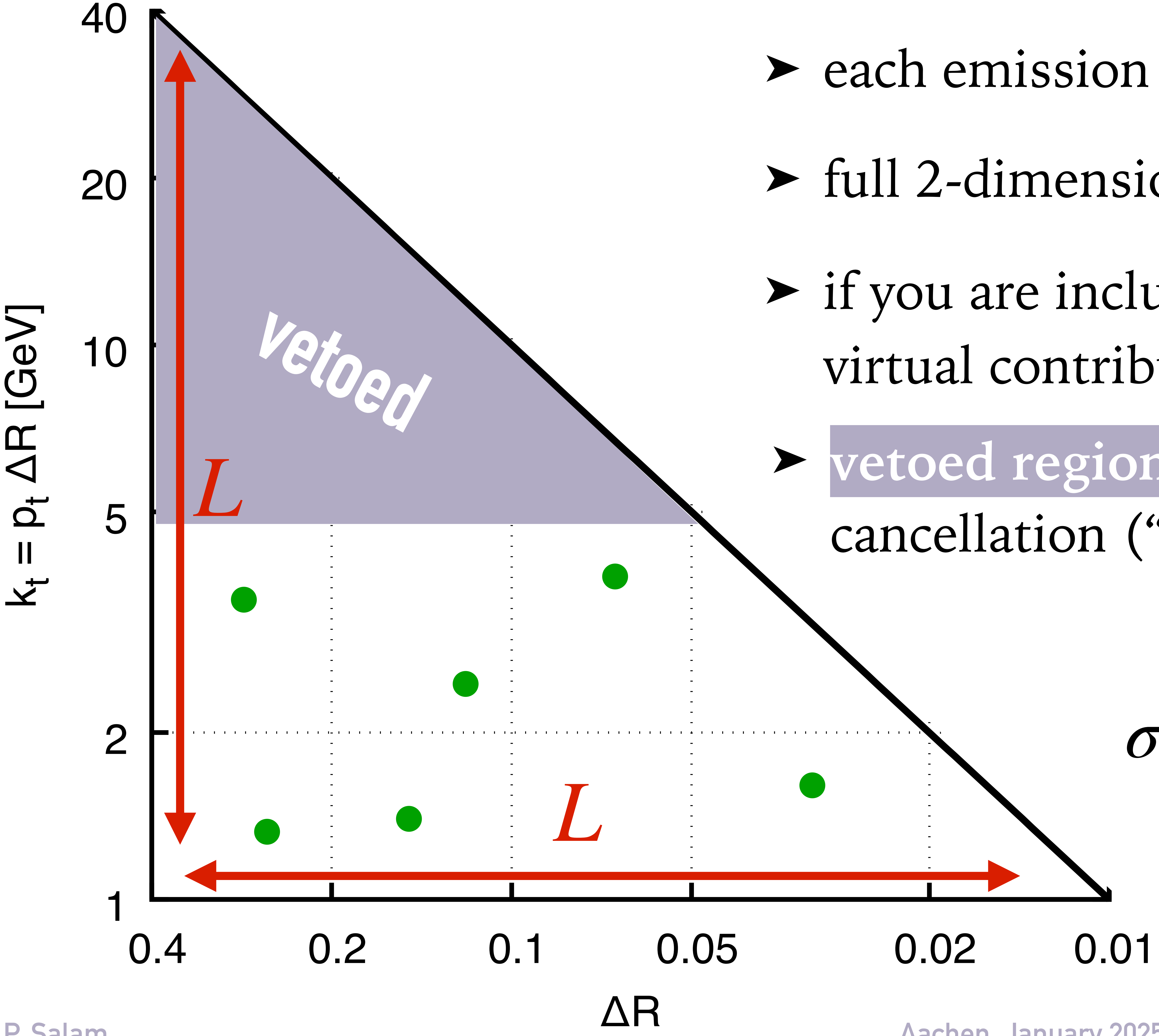
NB: in the next slides L will always be the logarithmic of a ratio of momentum scales, often defined < 0

Double (or leading) logarithms: $\alpha_s^n L^{2n}$



- each emission "costs" a power of α_s
- full 2-dimensions of phase space → factor of L^2
- if you are inclusive, real $\alpha_s L^2$ terms cancel against virtual contributions (unitarity)

Double (or leading) logarithms: $\alpha_s^n L^{2n}$



- each emission "costs" a power of α_s
- full 2-dimensions of phase space → factor of L^2
- if you are inclusive, real $\alpha_s L^2$ terms cancel against virtual contributions (unitarity)
- vetoed regions of phase space break the cancellation ("Sudakov" form factor)

$$\sigma(p_{t,Z} < e^L) \sim \sigma_{tot} \exp\left[-c \cdot \alpha_s L^2\right]$$

Logarithmic accuracy hierarchy, with $\alpha_s L \sim 1$ (as used in this talk)

[depending on observable, take log of cross section, possibly also Fourier/etc. transform]

$$\alpha_s L^2 + \alpha_s^2 L^3 + \alpha_s^3 L^4 + \cdots \equiv \alpha_s^n L^{n+1} \sim \frac{1}{\alpha_s}$$ leading logarithms (LL)

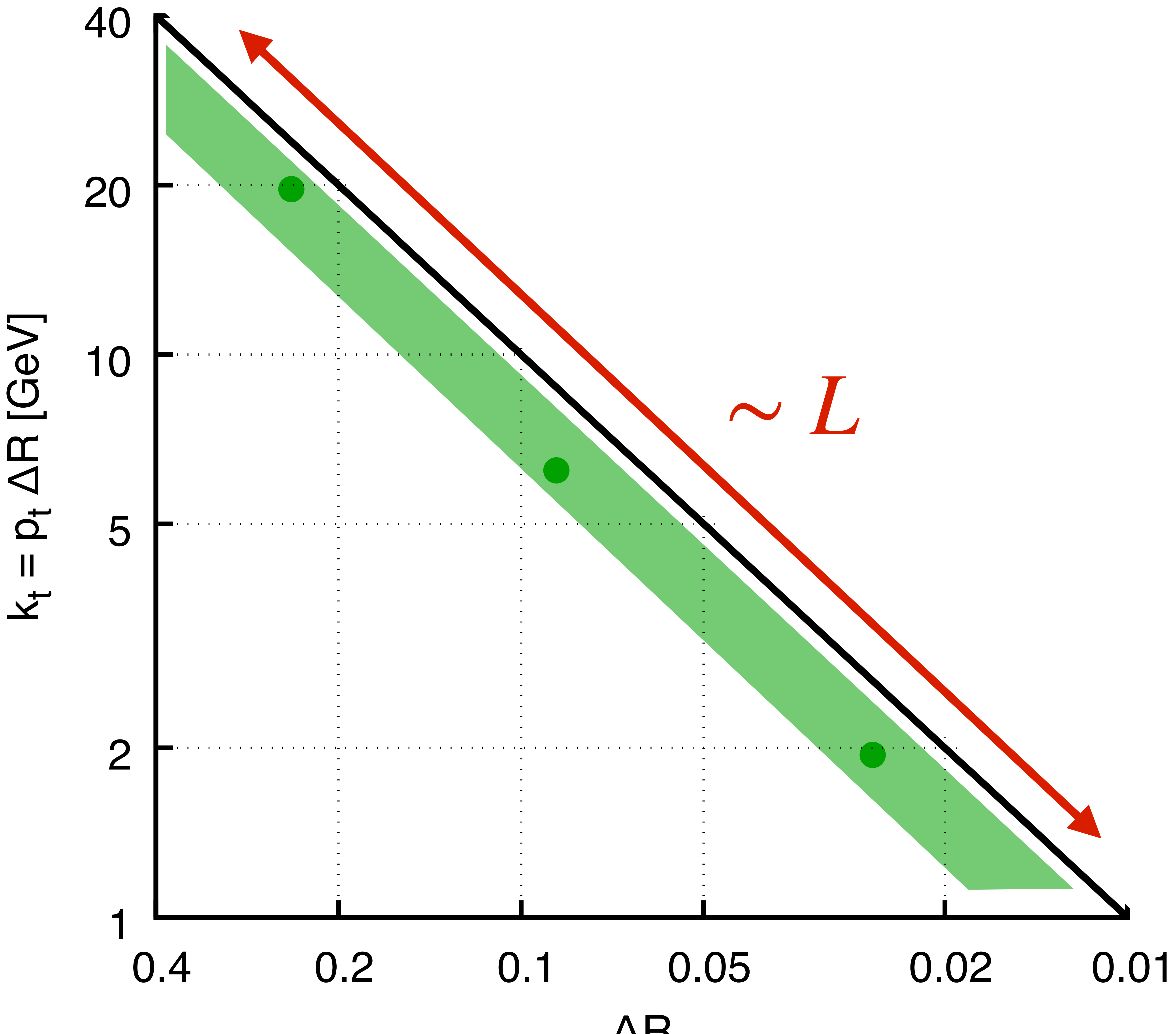
$$\alpha_s L + \alpha_s^2 L^2 + \alpha_s^3 L^3 + \cdots \equiv \alpha_s^n L^n \sim 1$$ next-to-leading logarithms (NLL)

[also called *single logarithms*, SL]

$$\alpha_s + \alpha_s^2 L + \alpha_s^3 L^2 + \cdots \equiv \alpha_s^n L^{n-1} \sim \alpha_s$$ next-to-next-to-leading logarithms (NNLL)

etc.

sources of NLL terms: $\alpha_s^n L^n$



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- 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

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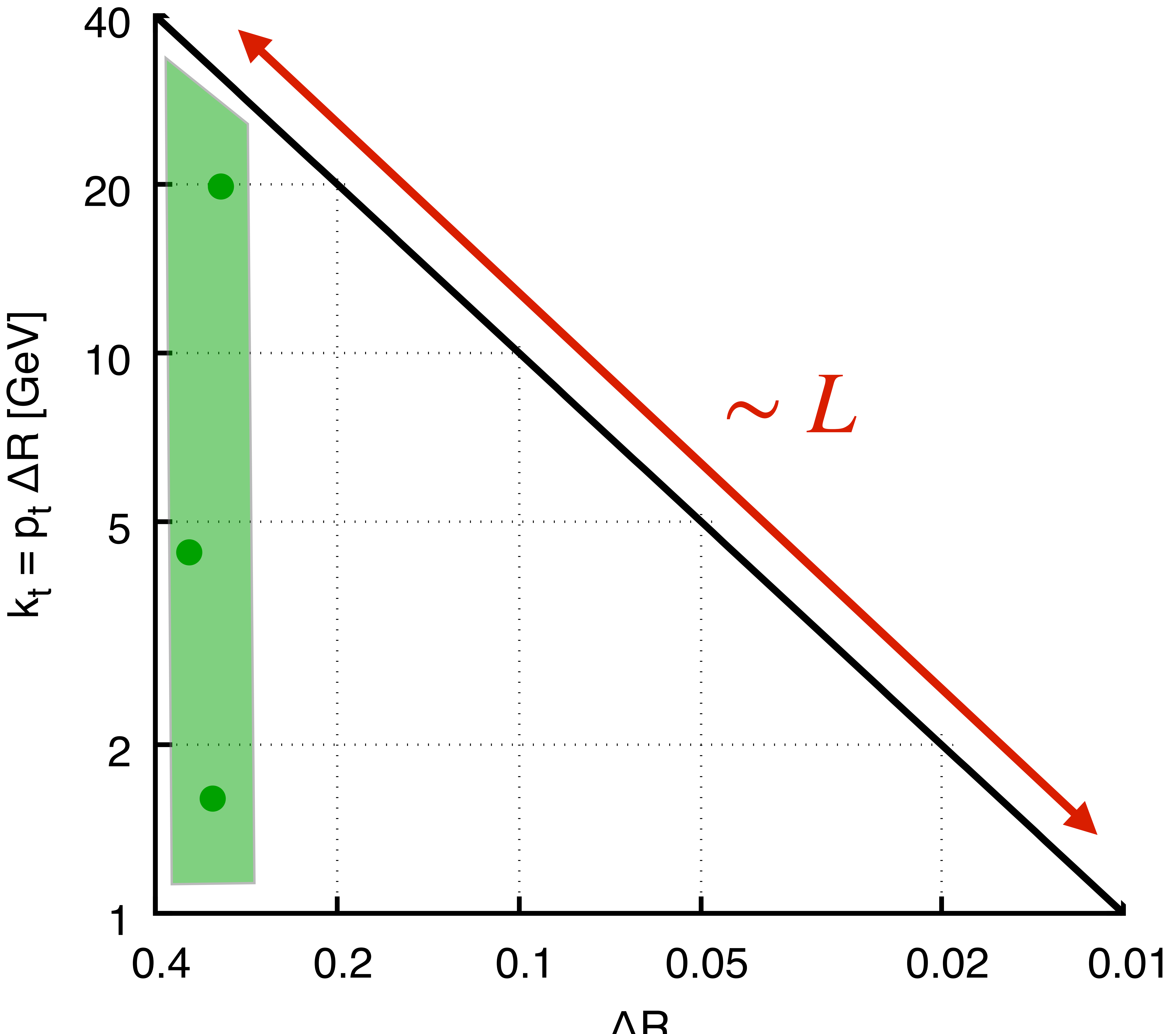

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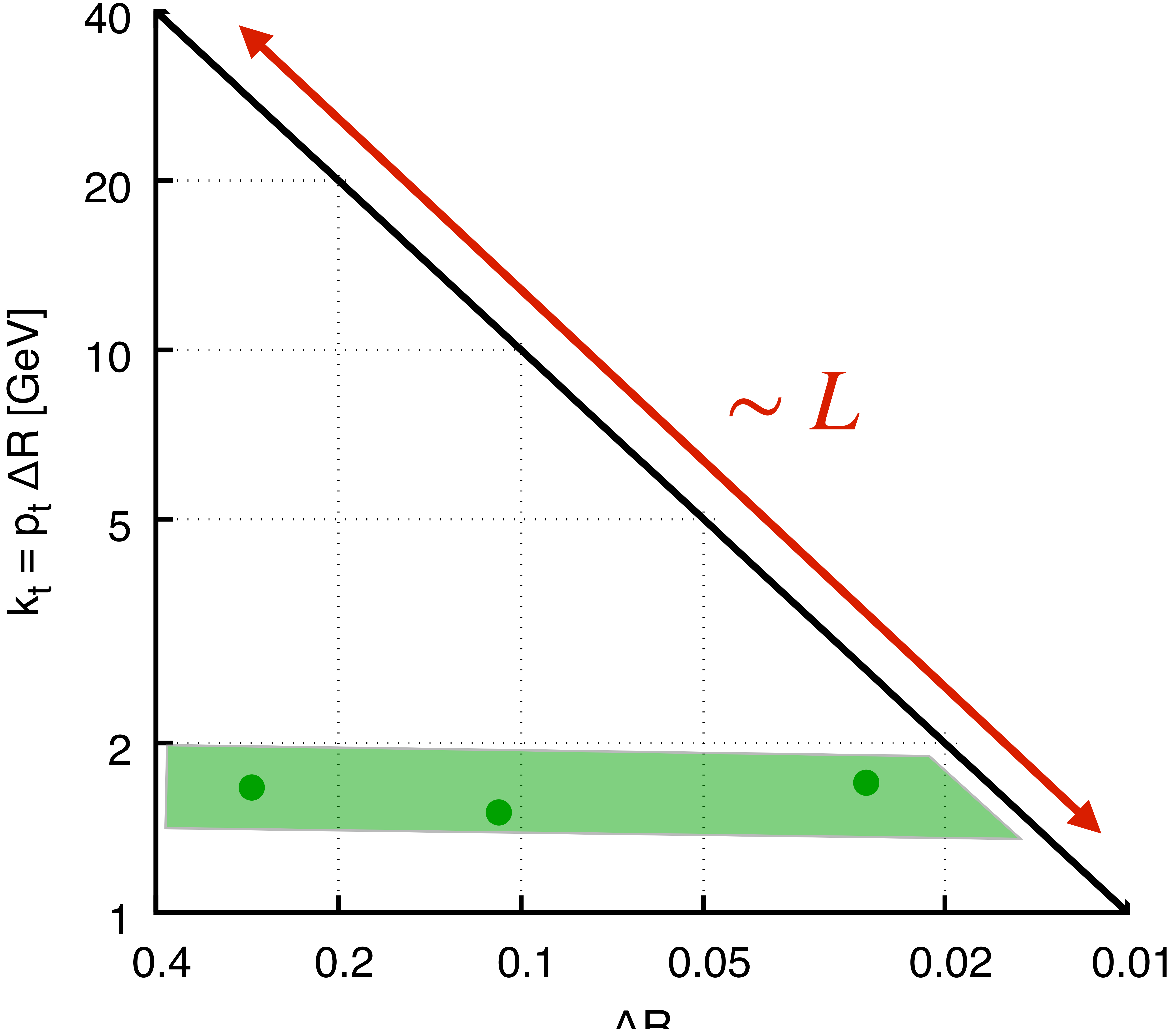

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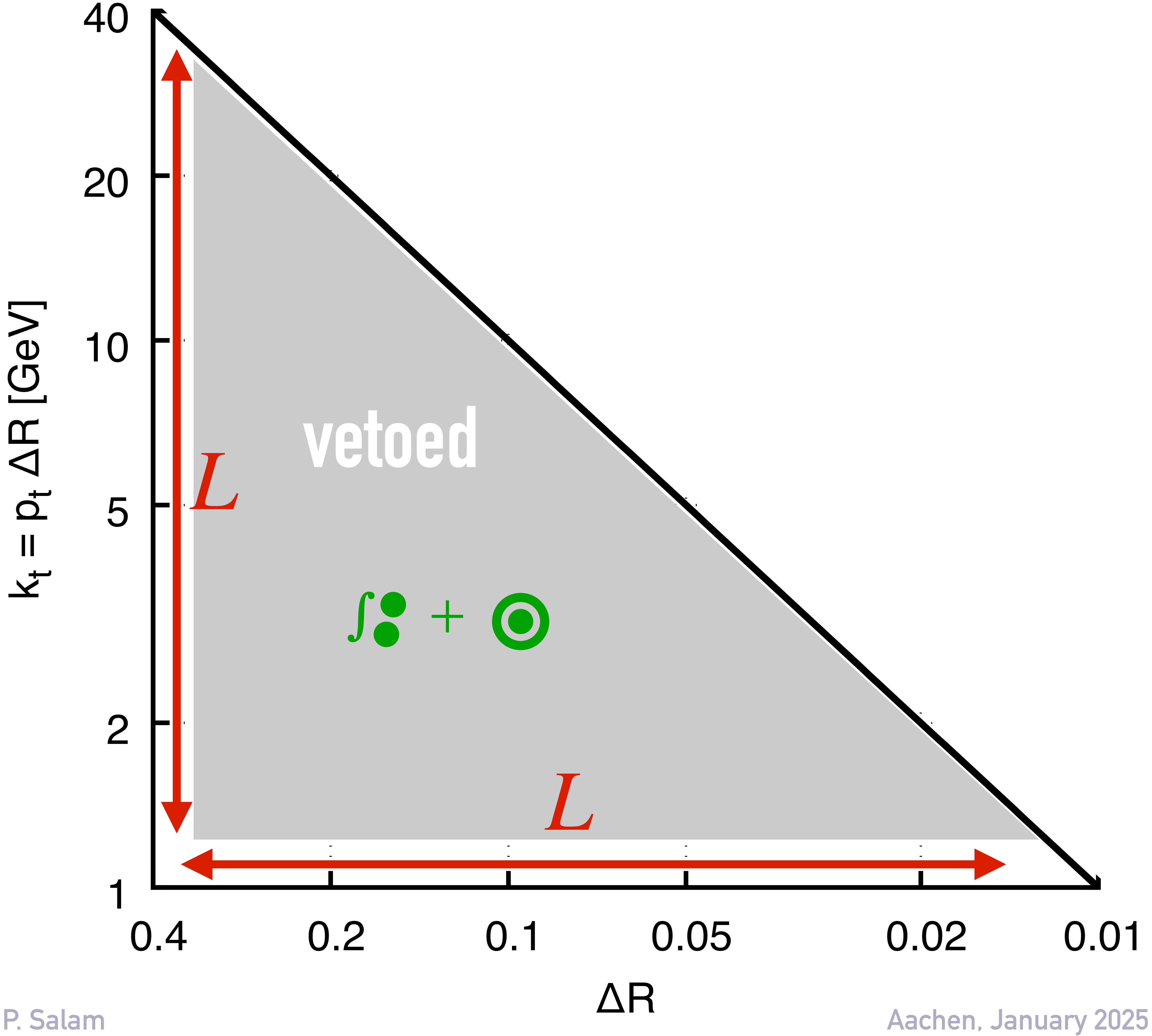


In soft-collinear vetoed region (size L^2), need control of all α_s^2 terms, i.e. summed-integrated

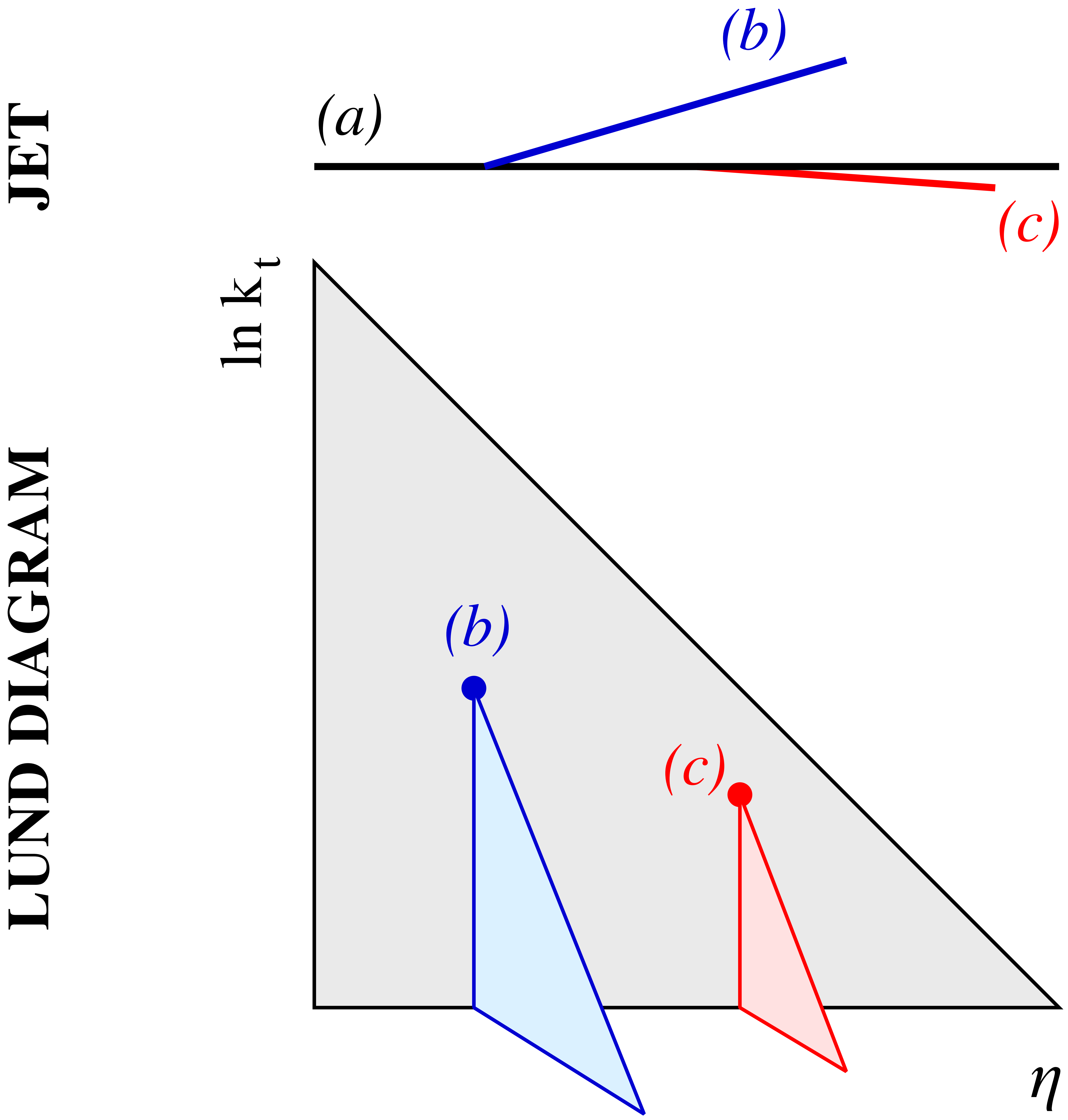
- ➤ tree-level double-soft
- ➤ 1-loop single-soft

Combination that we need corresponds to 2nd order cusp anomalous dimension ("CMW scheme")

$\rightarrow \alpha_s^2 L^2$

(and, with running coupling, etc. $\alpha_s^n L^n$)

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



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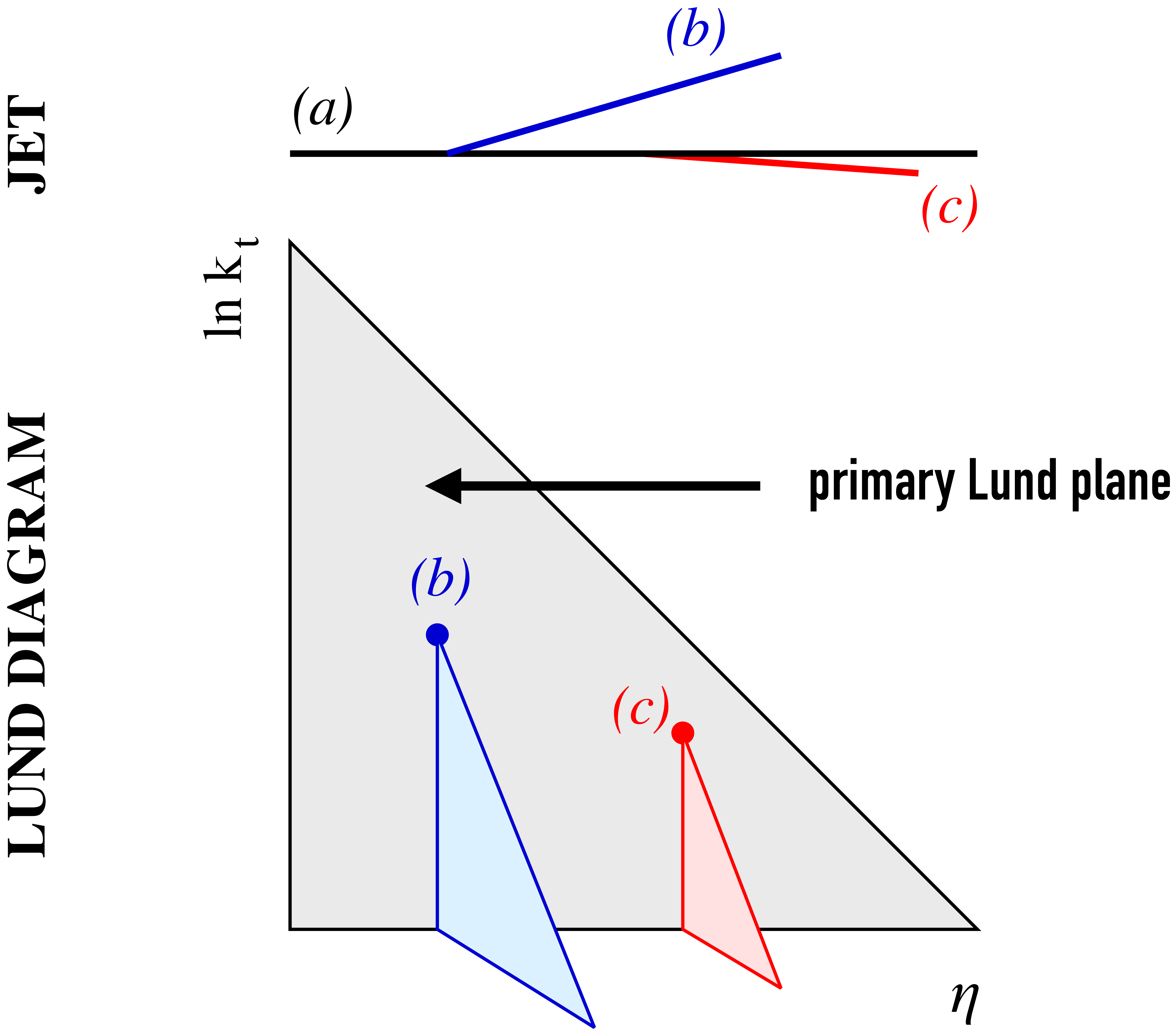

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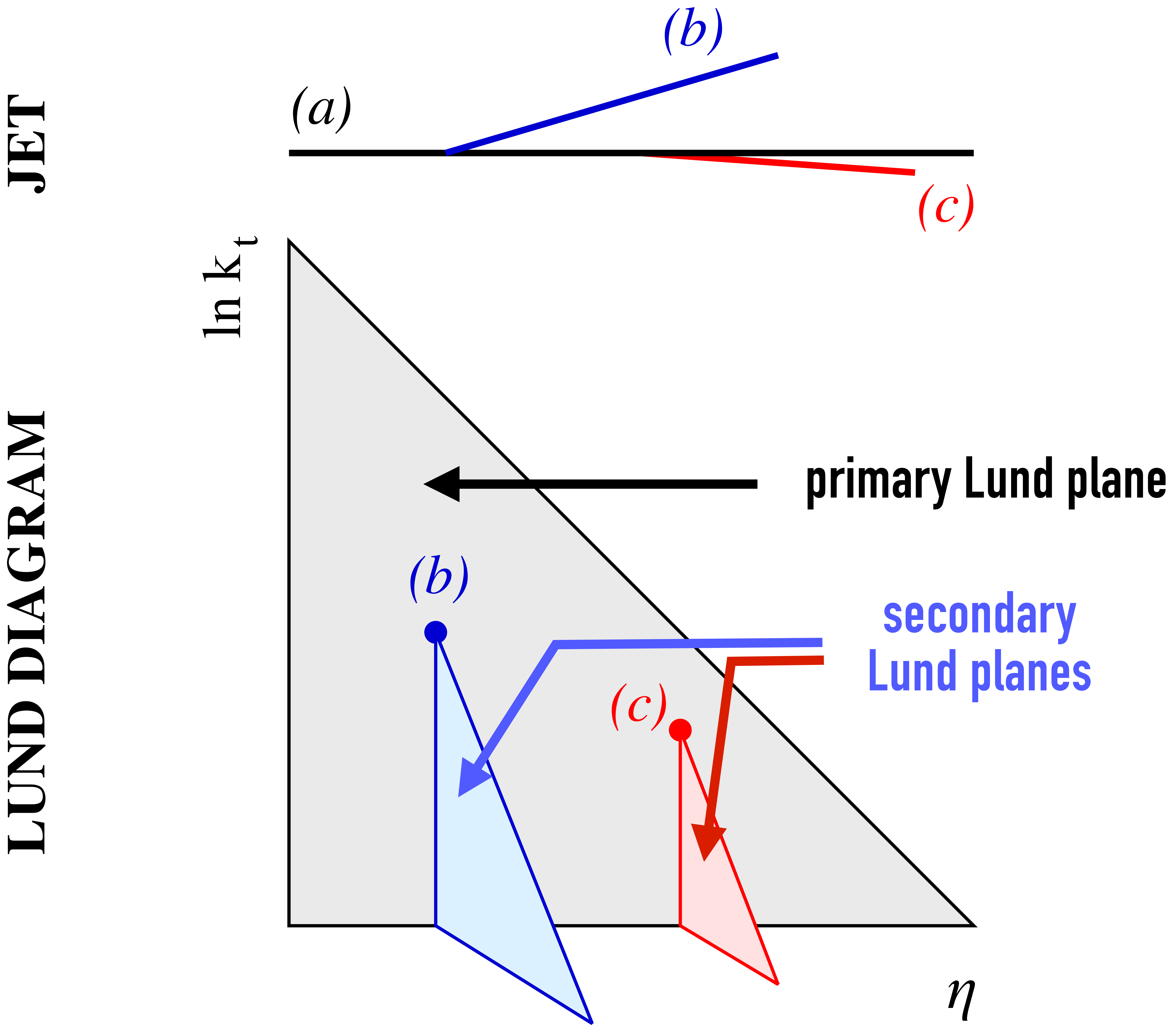

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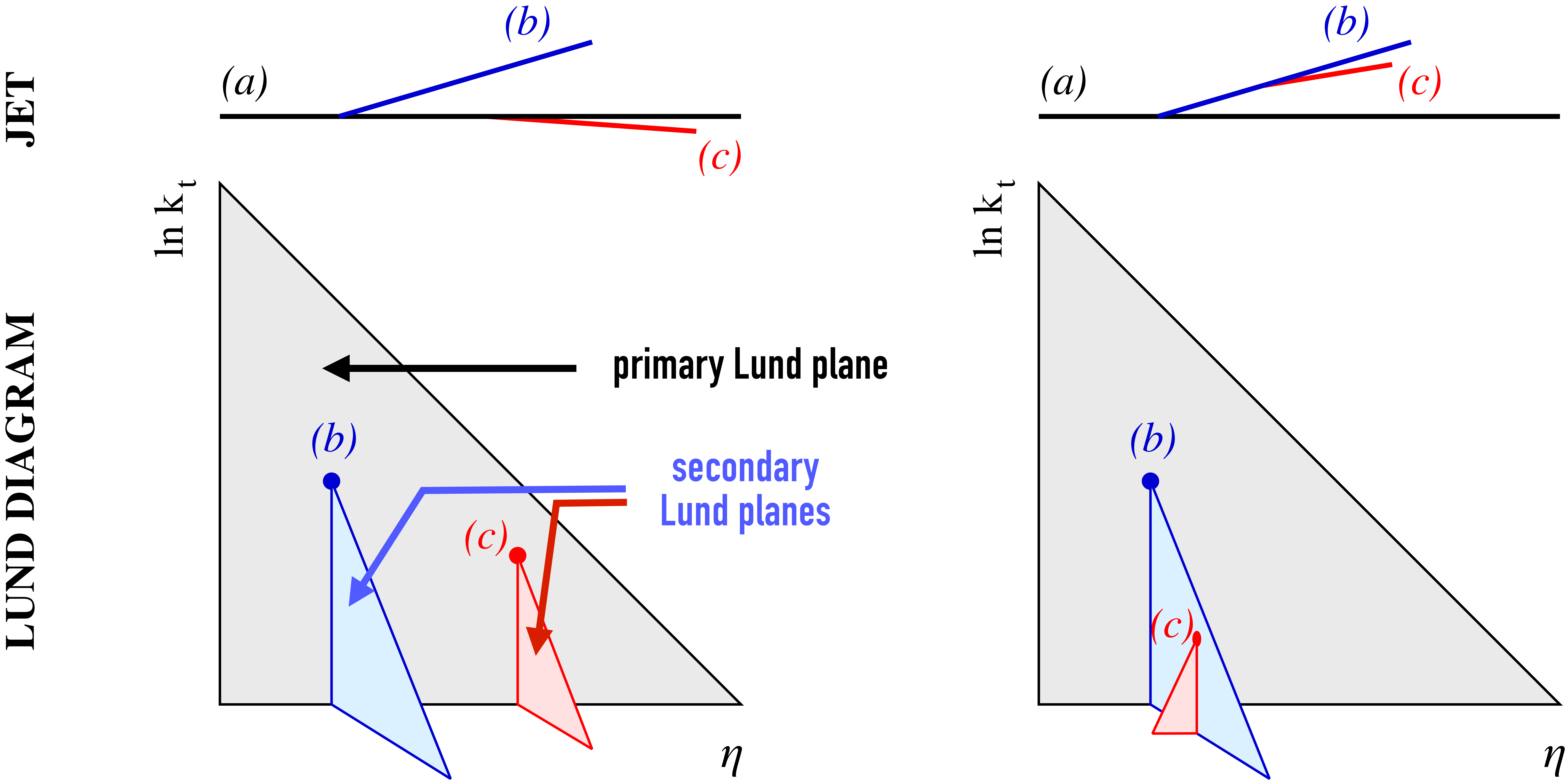

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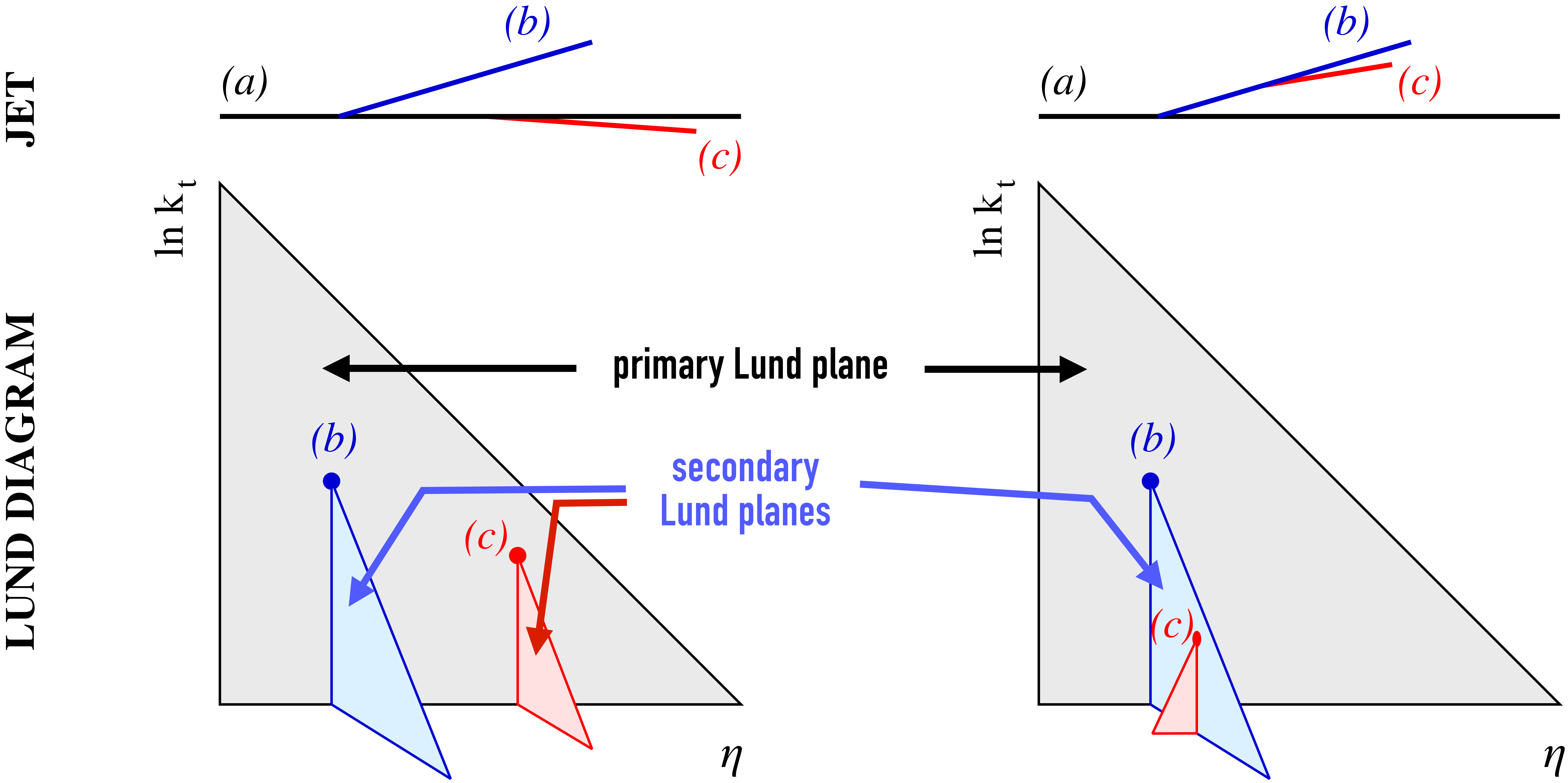

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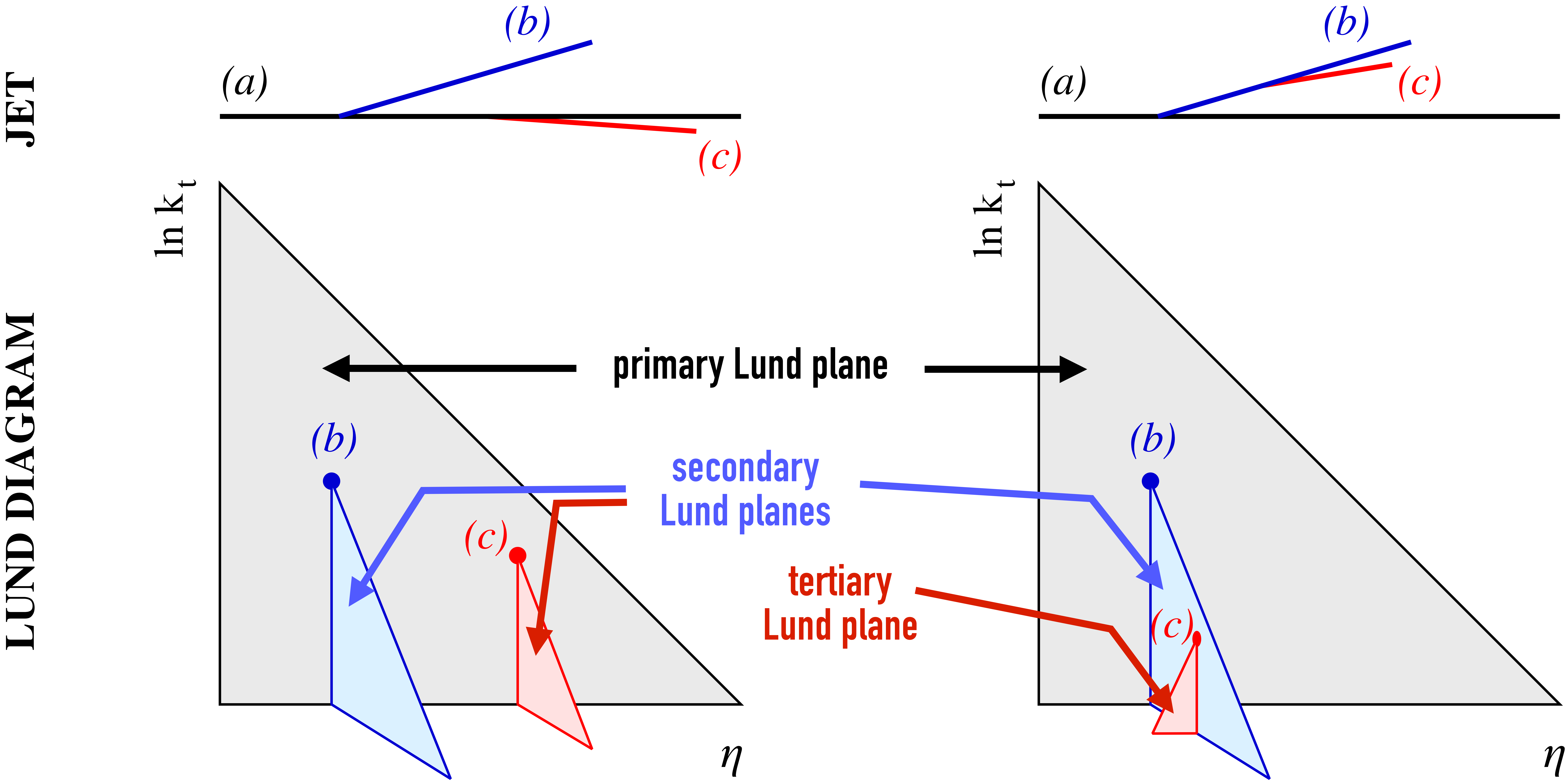


Designing NLL parton showers

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


Mrinal Dasgupta
Manchester


Keith Hamilton
Univ. Coll. London

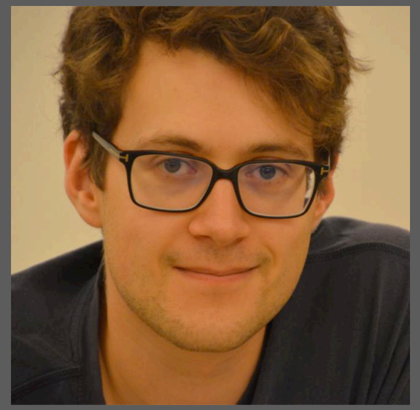

Pier Monni
CERN


GPS
Oxford


Grégory Soyez
IPhT, Saclay

since 2017

former members


Frédéric Dreyer


Rob Verheyen


Rok Medves


Emma Slade


Basem El-Menoufi
Monash


Alexander Karlberg
CERN


Ludovic Scyboz
Monash

since 2019


Melissa van Beekveld
NIKEHF


Silvia Ferrario Ravasio
CERN


Alba Soto-Ontoso
Granada

since 2020

PanScales

A project to bring logarithmic understanding and accuracy to parton showers


Jack Helliwell
Monash

since 2022


Silvia Zanoli
Oxford

since 2023


Nicolas Schalch
Oxford

since 2024

European Research Council
Established by the European Commission

ERC funded
2018–2024

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 family of observable

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- 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 family of 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**
  - **the angle of 3rd most energetic particle relative to the most energetic one**

    [machine learning might "learn" many such features]

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  [machine learning might "learn" many such features]

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

Defining what we mean by NLL

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

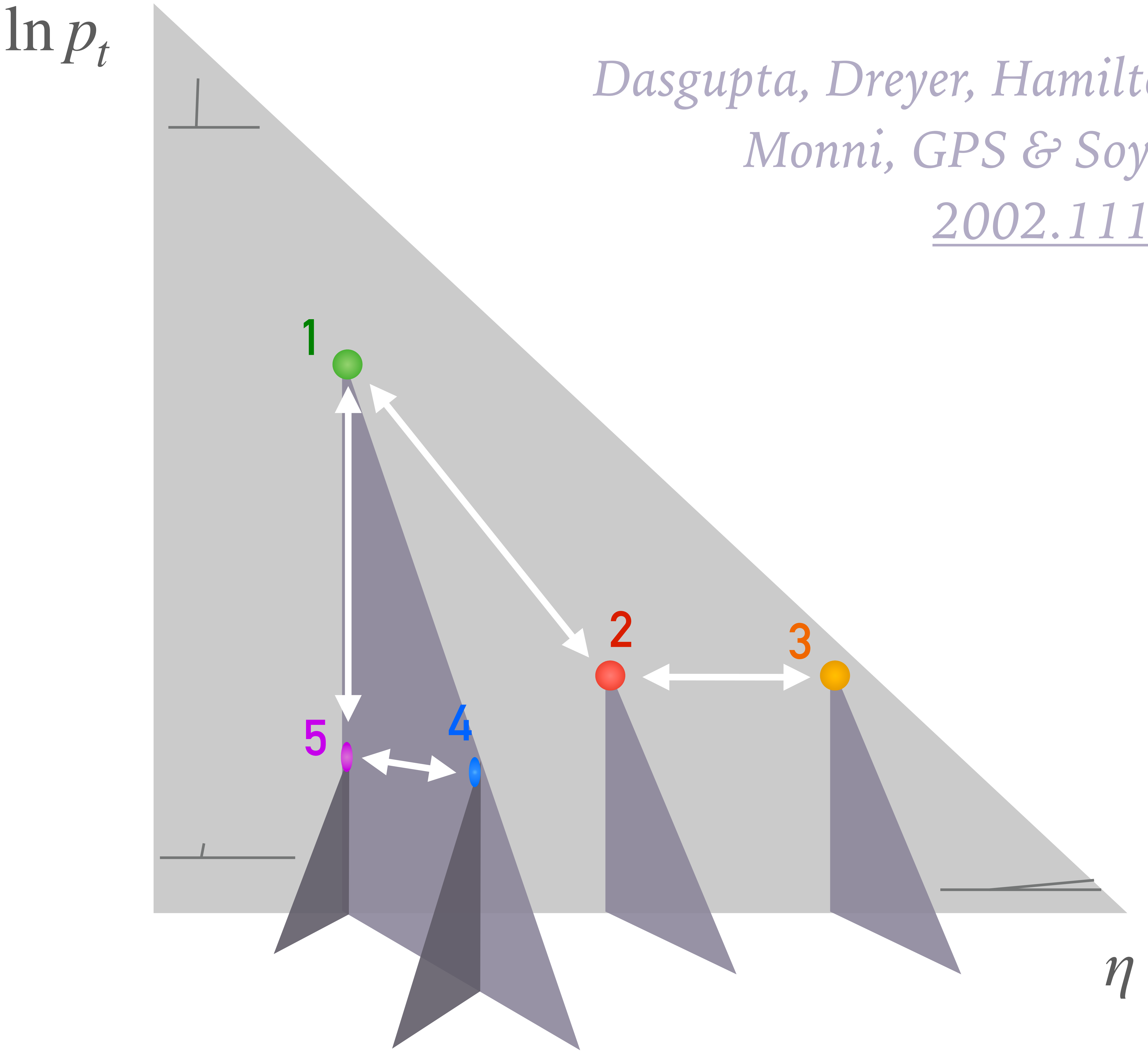
A Matrix Element condition

- 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
- …

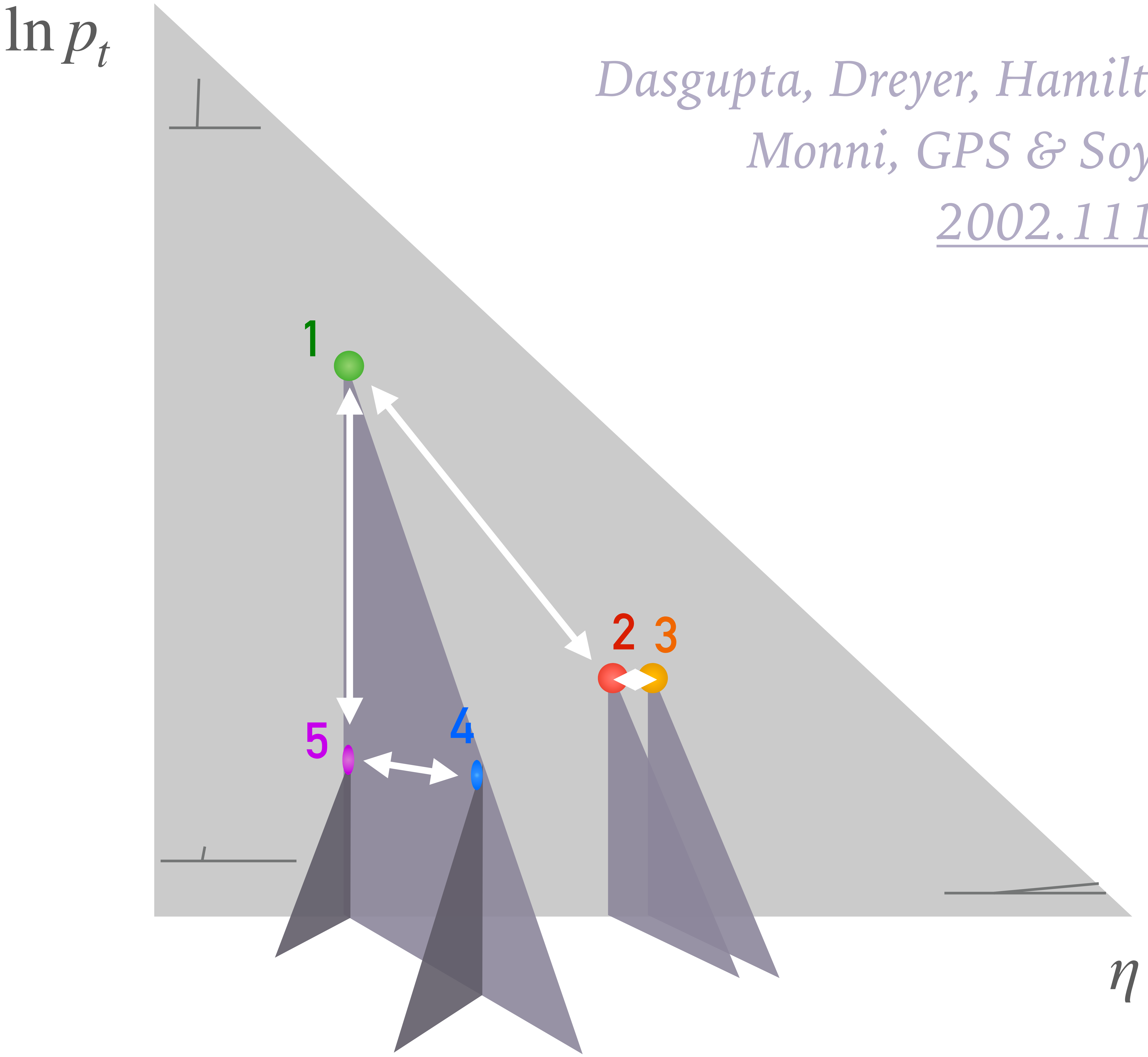
When do we require effective shower $|M^2|$ to be correct?



Dasgupta, Dreyer, Hamilton, Monni, GPS & Soyez, 2002.11114

- a shower with simple (parton) 1→2 or (dipole) 2→3 splittings can't reproduce full matrix element
- but QCD has amazing factorisation properties — simplifications in presence of energy or angular ordering
- **we should be able to reproduce $|M^2|$ when all emissions well separated in Lund diagram** $d_{12} \gg 1$, $d_{23} \gg 1$, $d_{15} \gg 1$, etc.

When do we require effective shower $|M^2|$ to be correct?

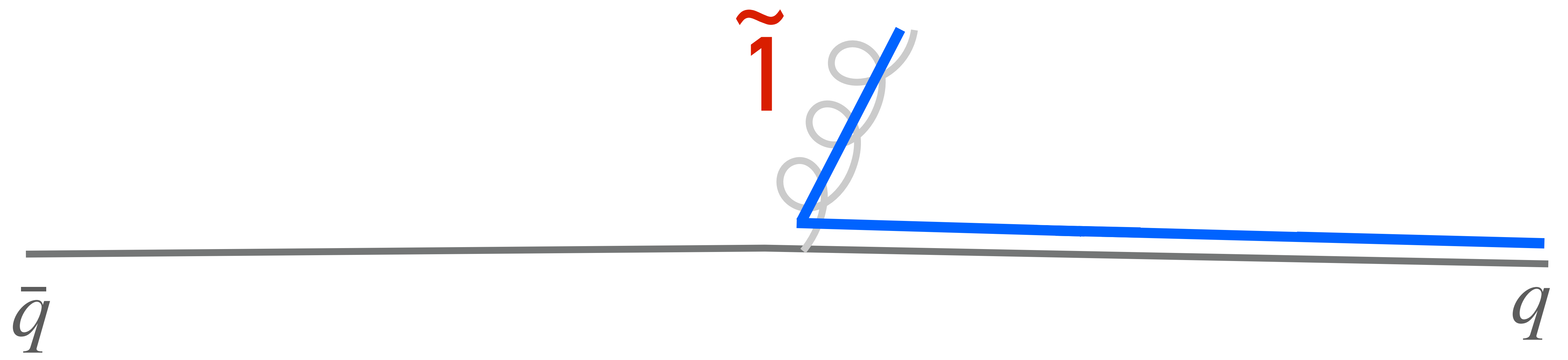


Dasgupta, Dreyer, Hamilton, Monni, GPS & Soyez, 2002.11114

- a shower with simple 1→2 or 2→3 splittings can't reproduce full matrix element
- but QCD has amazing factorisation properties — simplifications in presence of energy or angular ordering
- **At NLL we are allowed to make a mistake (by $\mathcal{O}(1)$ factor) when a pair is close by,** e.g. $d_{23} \sim 1$

1. Recoil: the core of any shower

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



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

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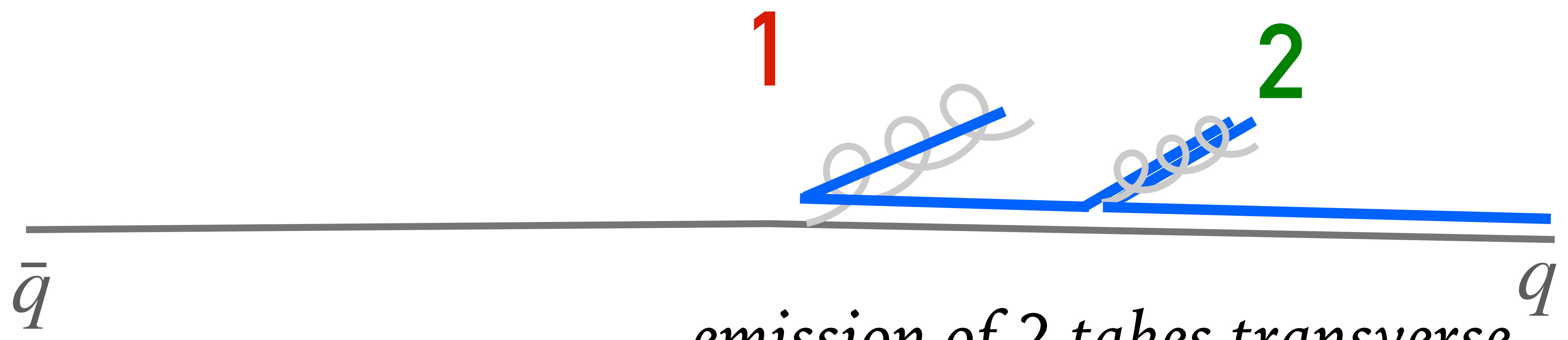

emission of 2 takes transverse recoil from 1

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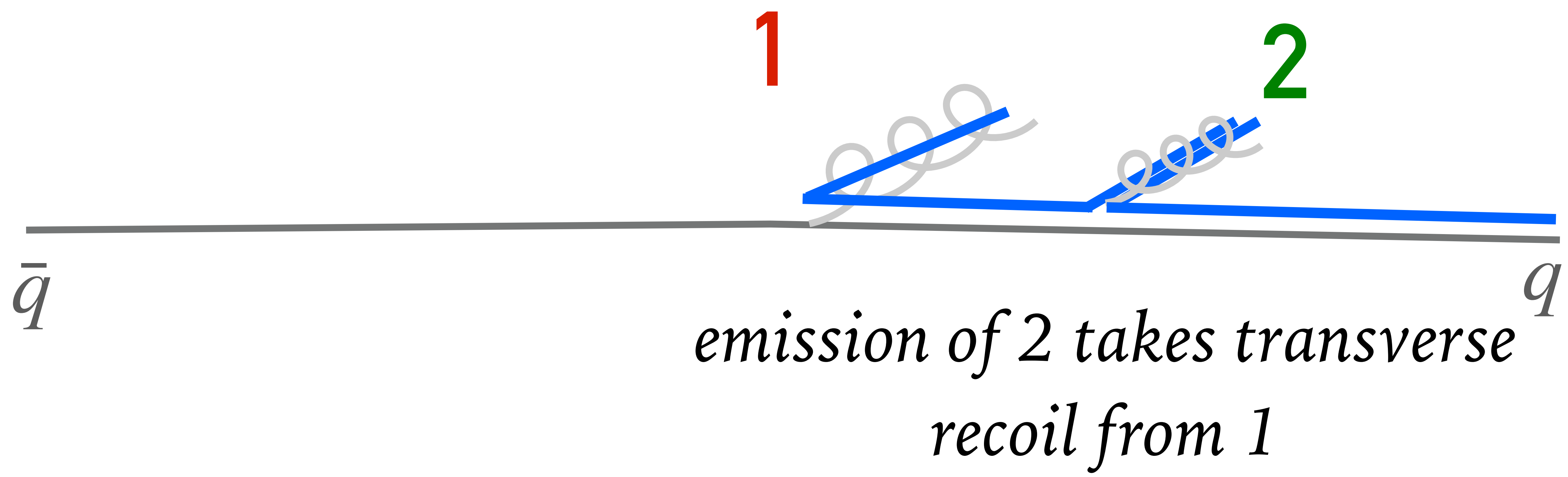
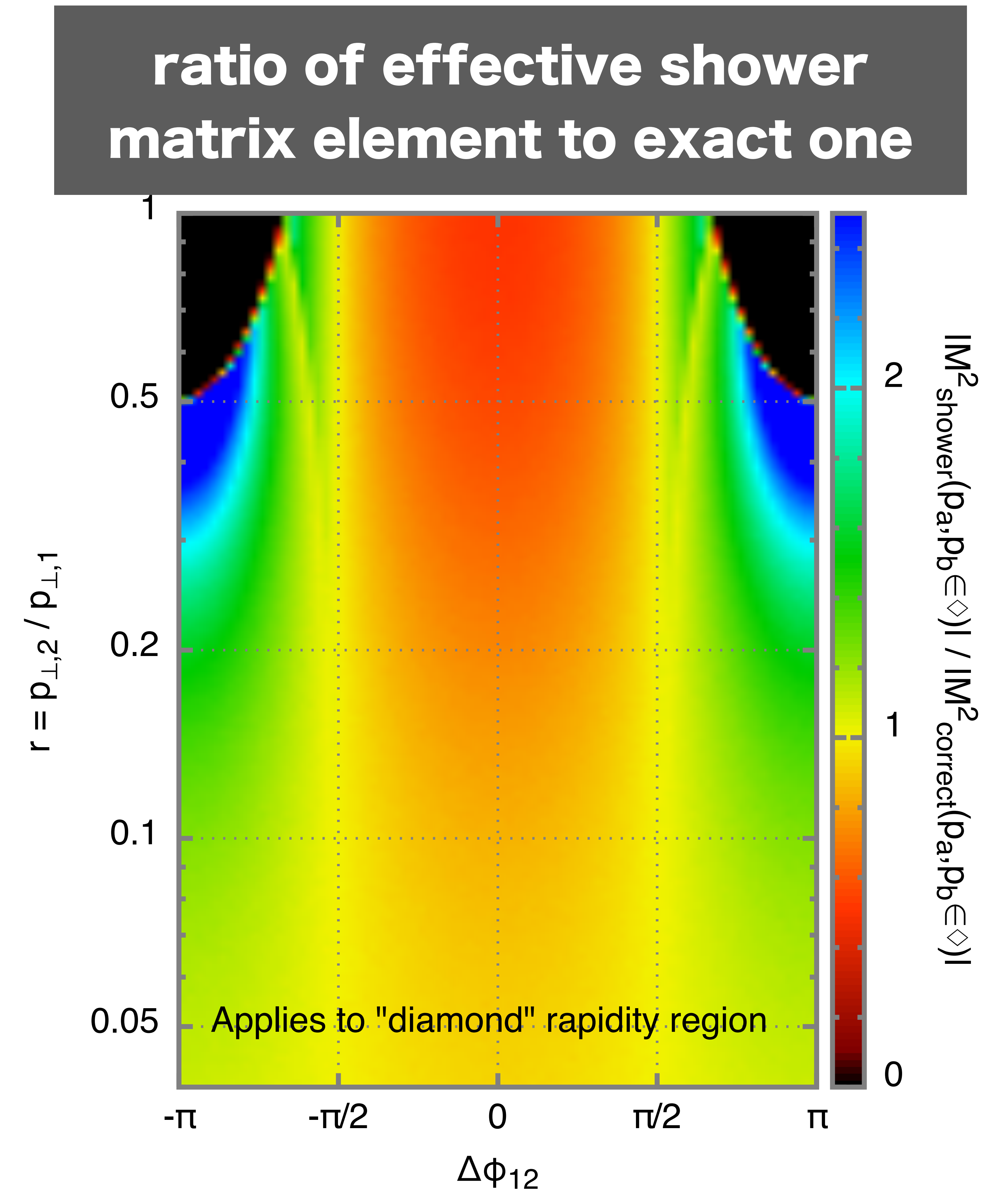




Shower initially generated matrix element for particle $\tilde{1}$, whose momentum differs (by $\sim$ 50%) from final particle 1.

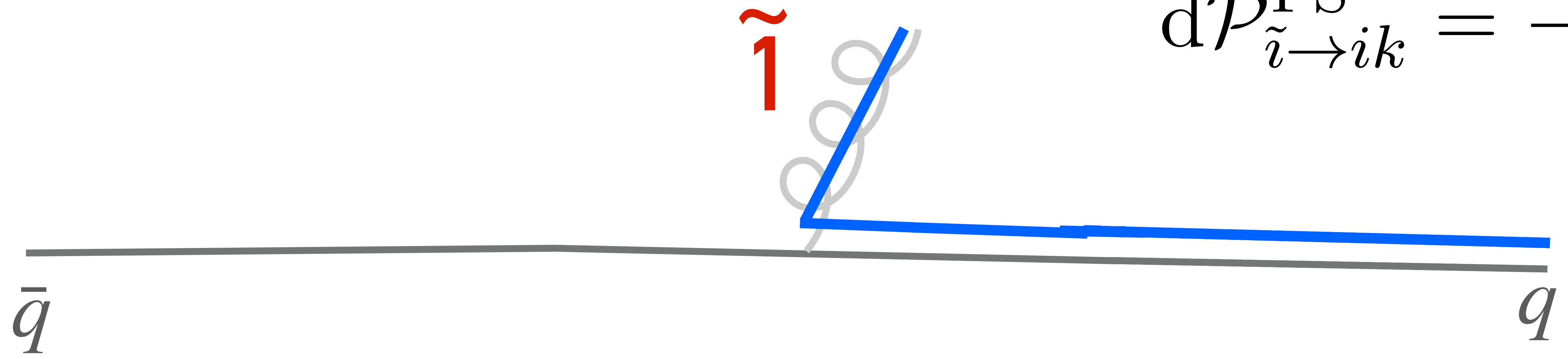
Matrix element is incorrect wrt final momentum 1.

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

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

One approach

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



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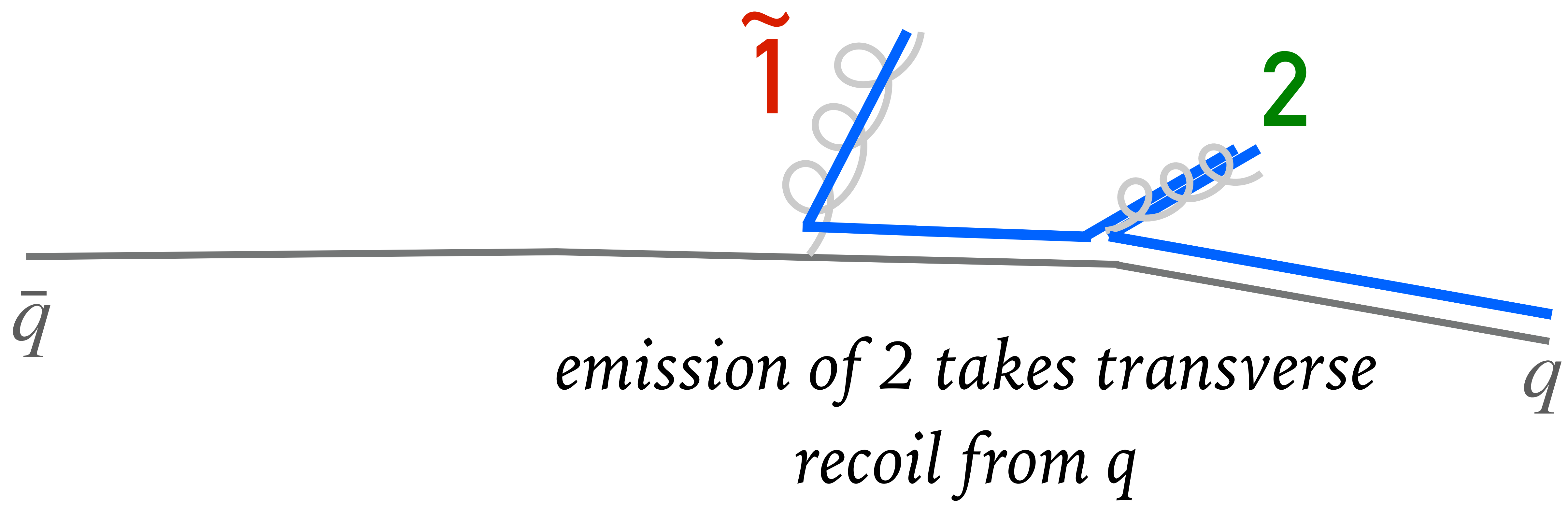

θ_{1q} left almost unchanged if ⊥ recoil from emission of 2 taken by (much harder) q

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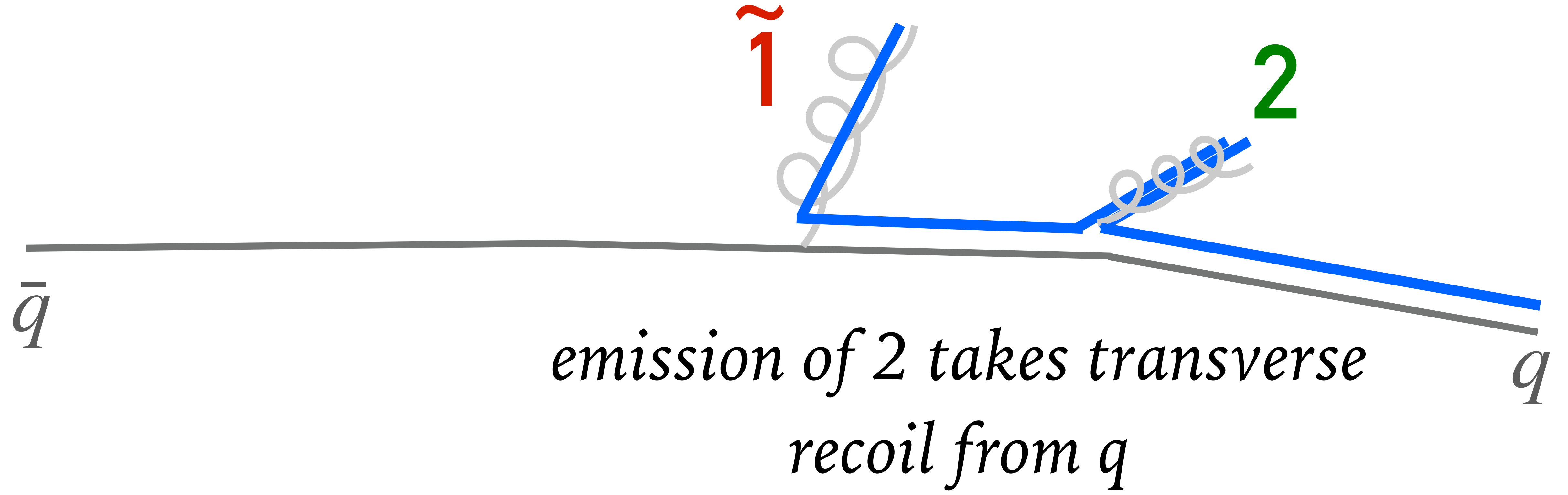
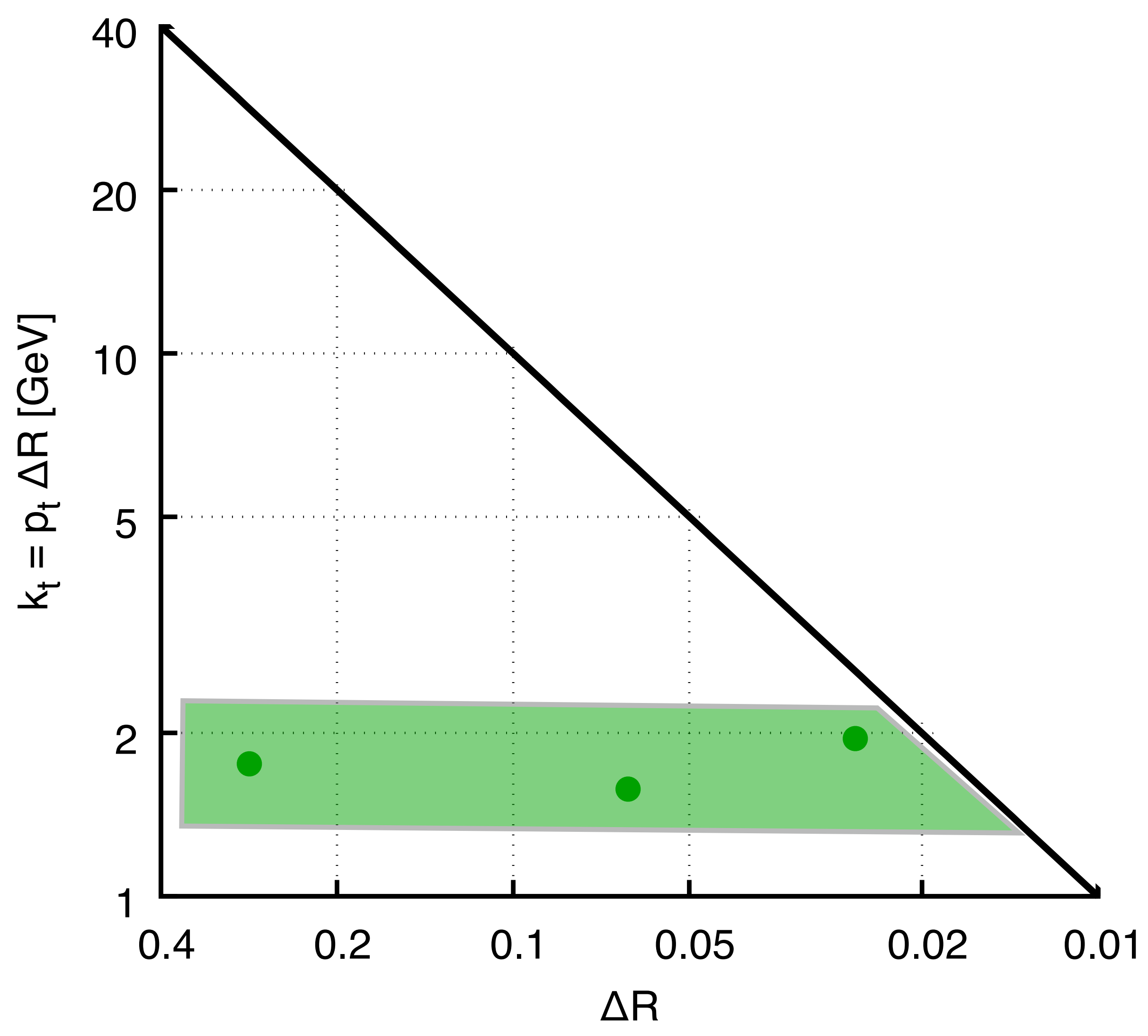




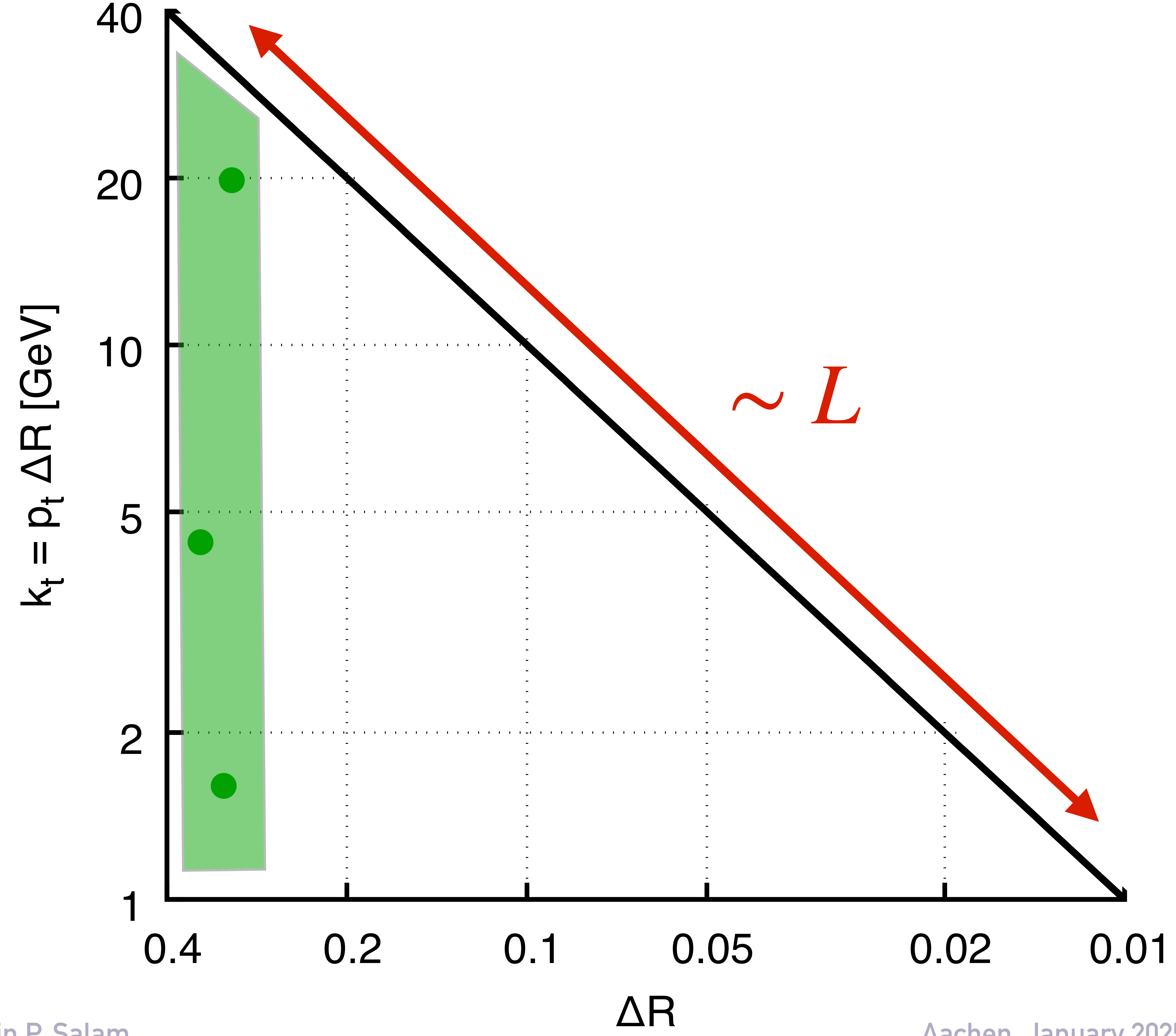
θ_{1q} left almost unchanged if ⊥ recoil from emission of 2 taken by (much harder) q

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)

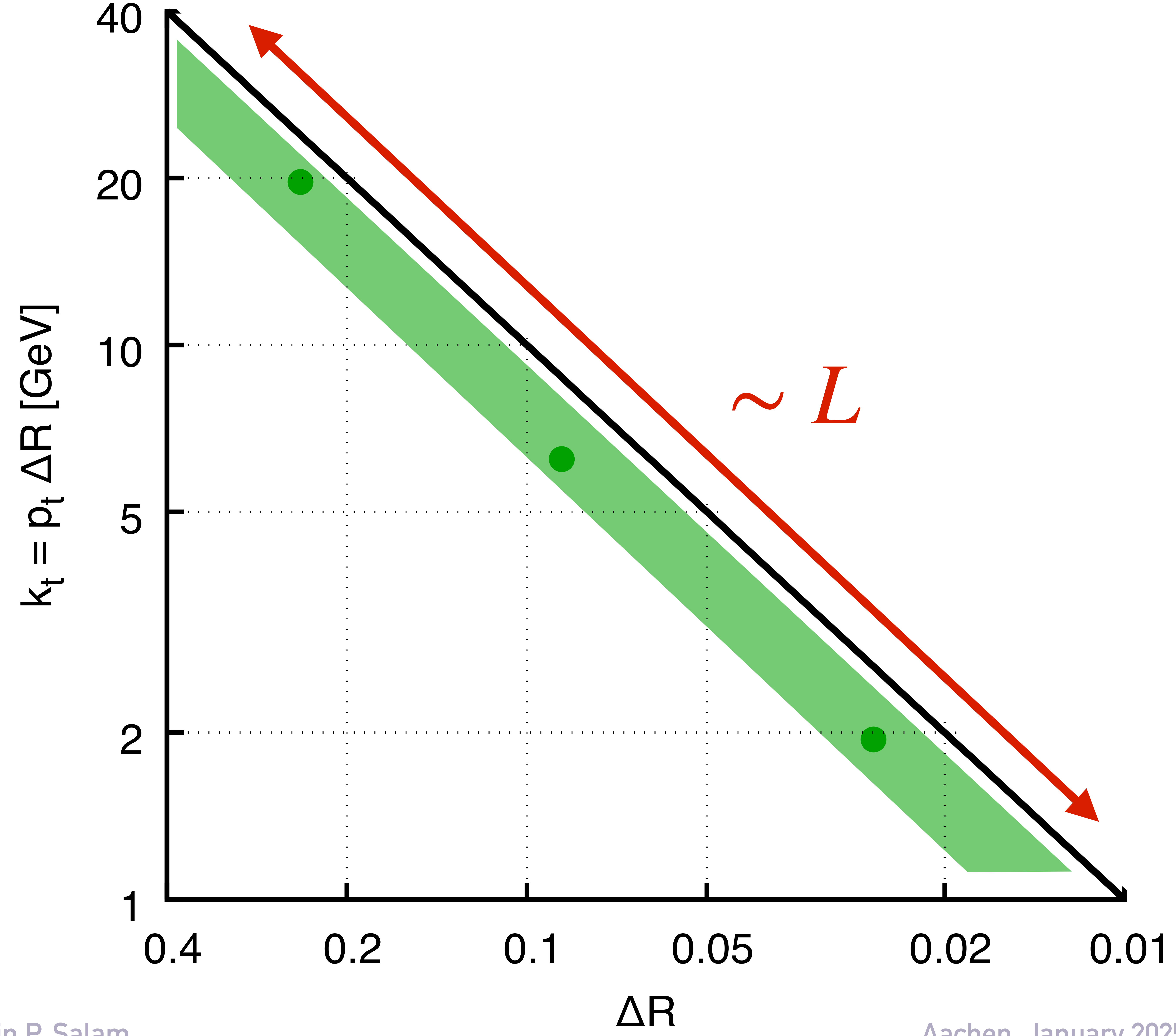
➤ local transverse recoil, with non-standard shower ordering & dipole partition
("**PanLocal**"; Nagy & Soper 0912.4534 + ⋯, "Deductor")

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



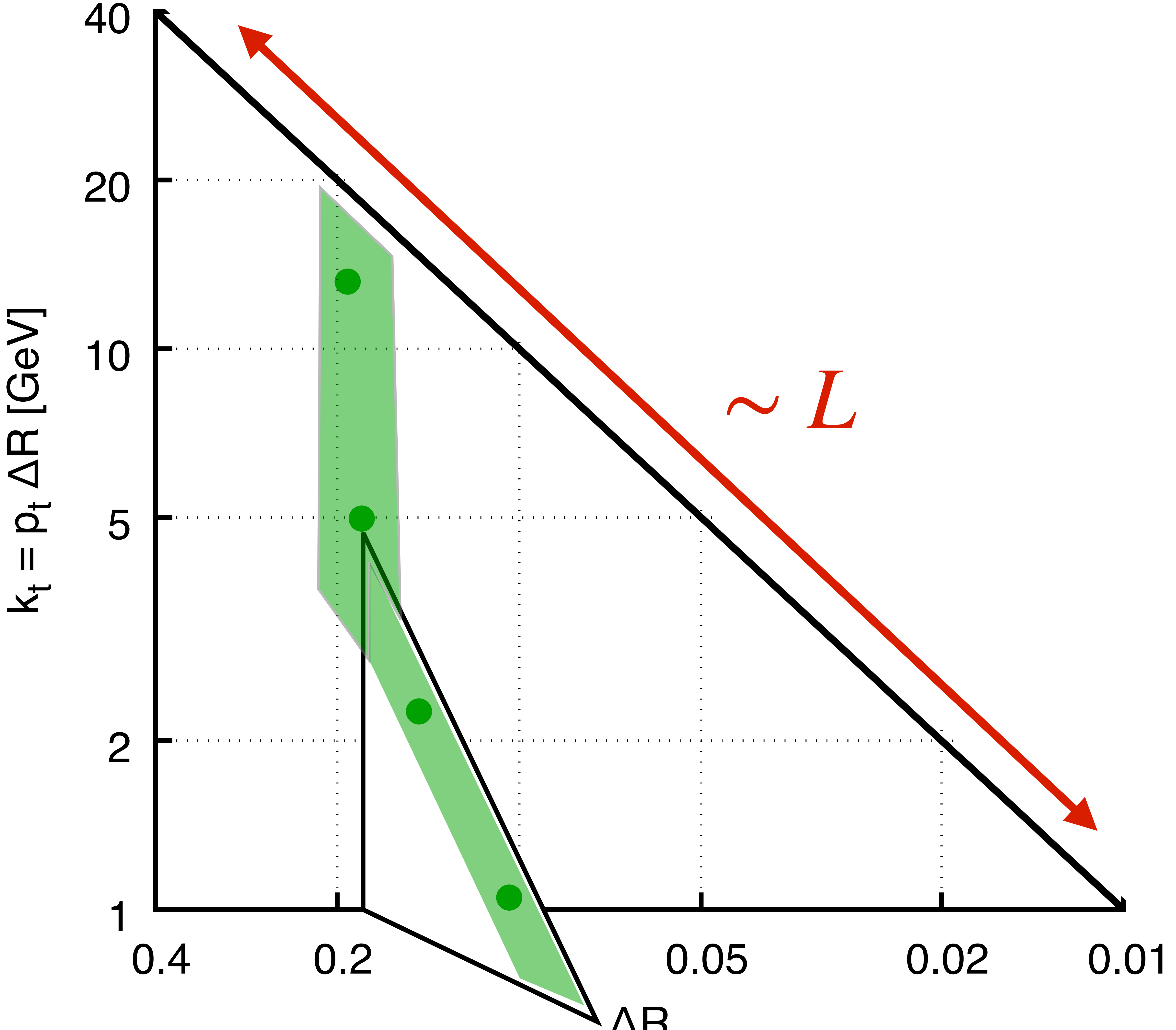
- dipole showers get this right at large N_c "for free"
- (NB: angular ordered "parton" showers don't — cf. Banfi, Corcella & Dasgupta, hep-ph/0612282)

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



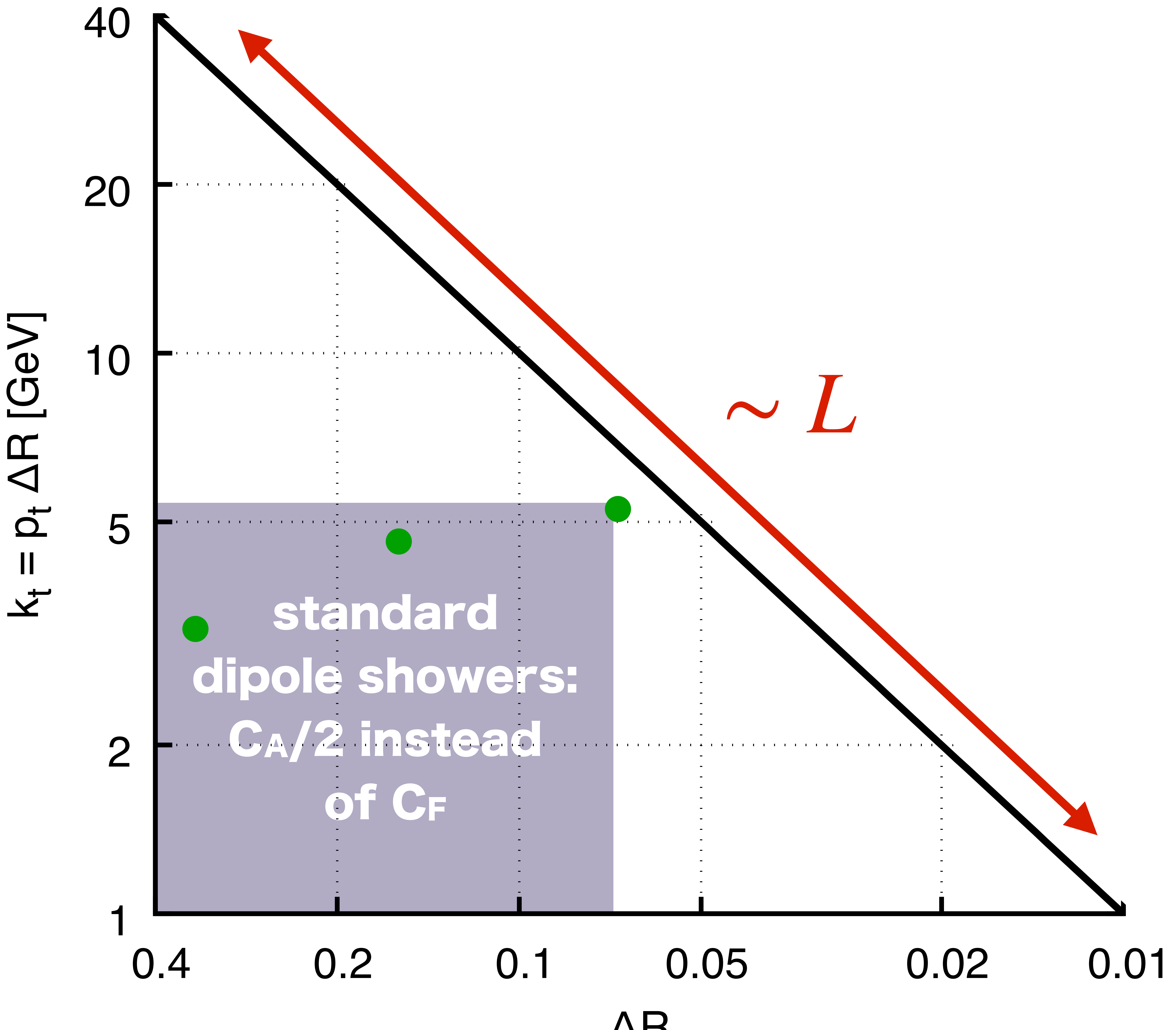
- recipe proposed long ago by Collins ('86)
- implemented in Herwig showers (Deductor & CVolver frameworks also discuss it)
- Included in PanScales showers: Karlberg, GPS, Scyboz, Verheyen, 2103.16526

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 ($\text{LL} \times 1/N_c^2 \sim \text{NLL}$)

  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

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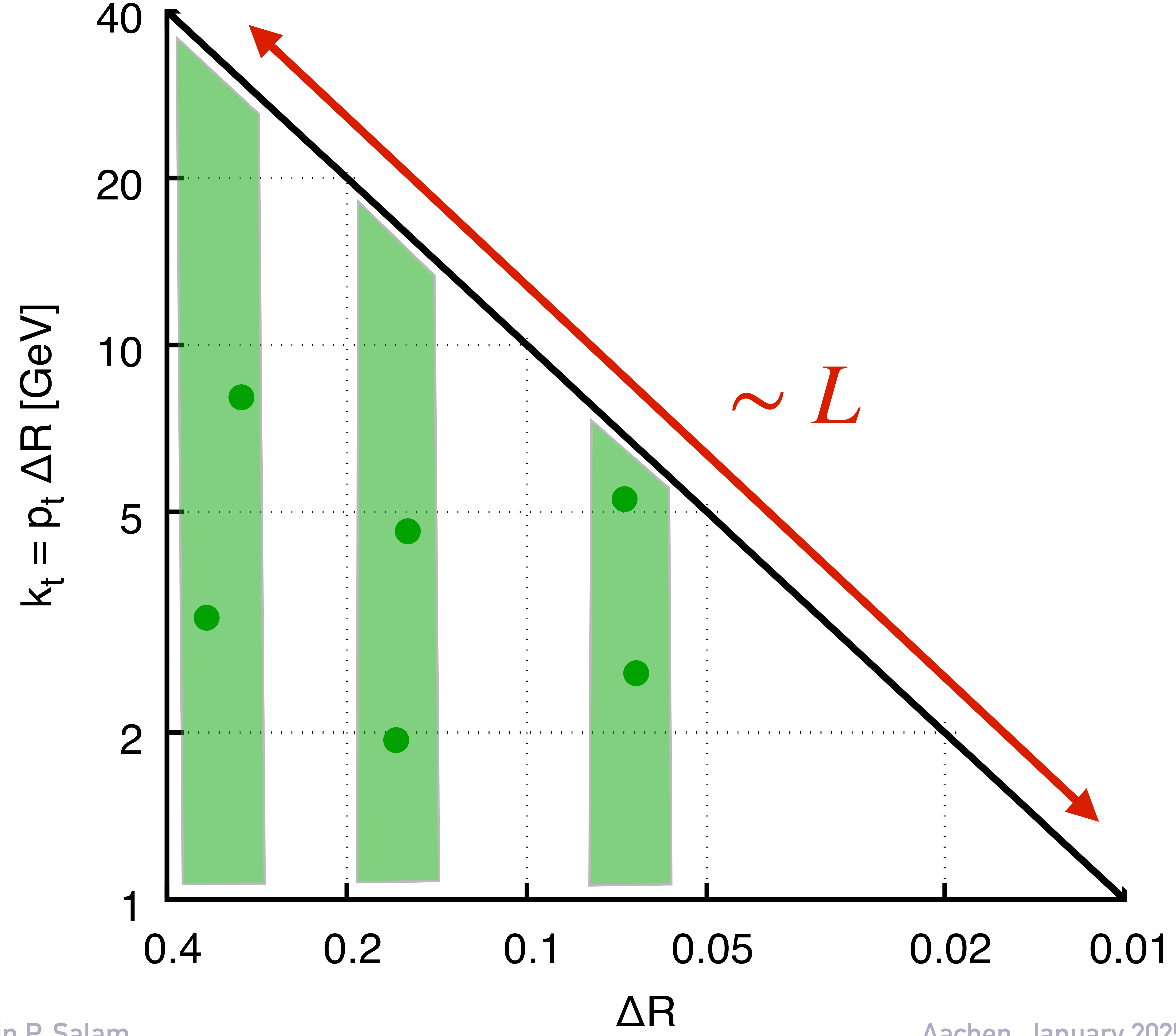


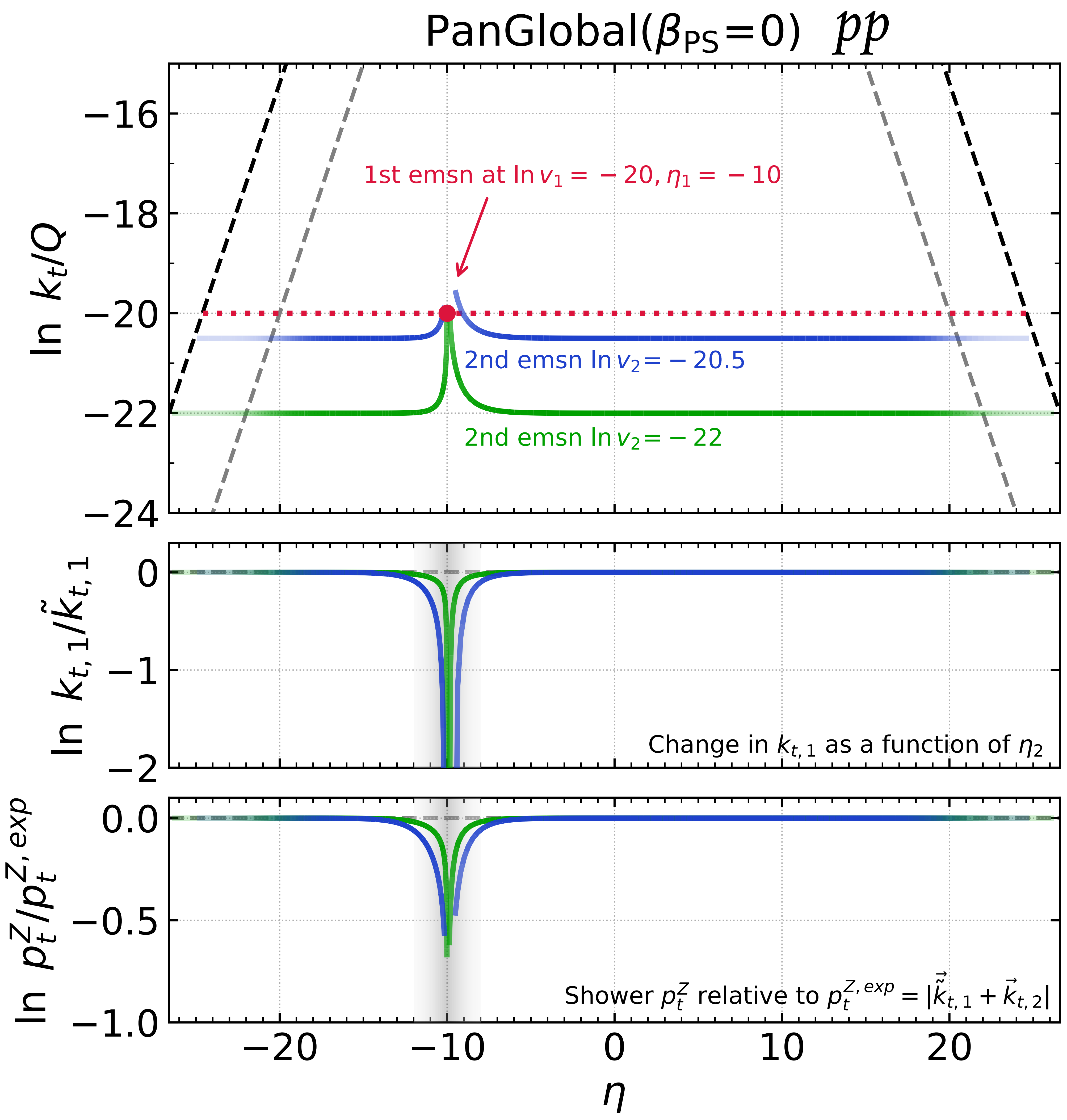
PanScales approach

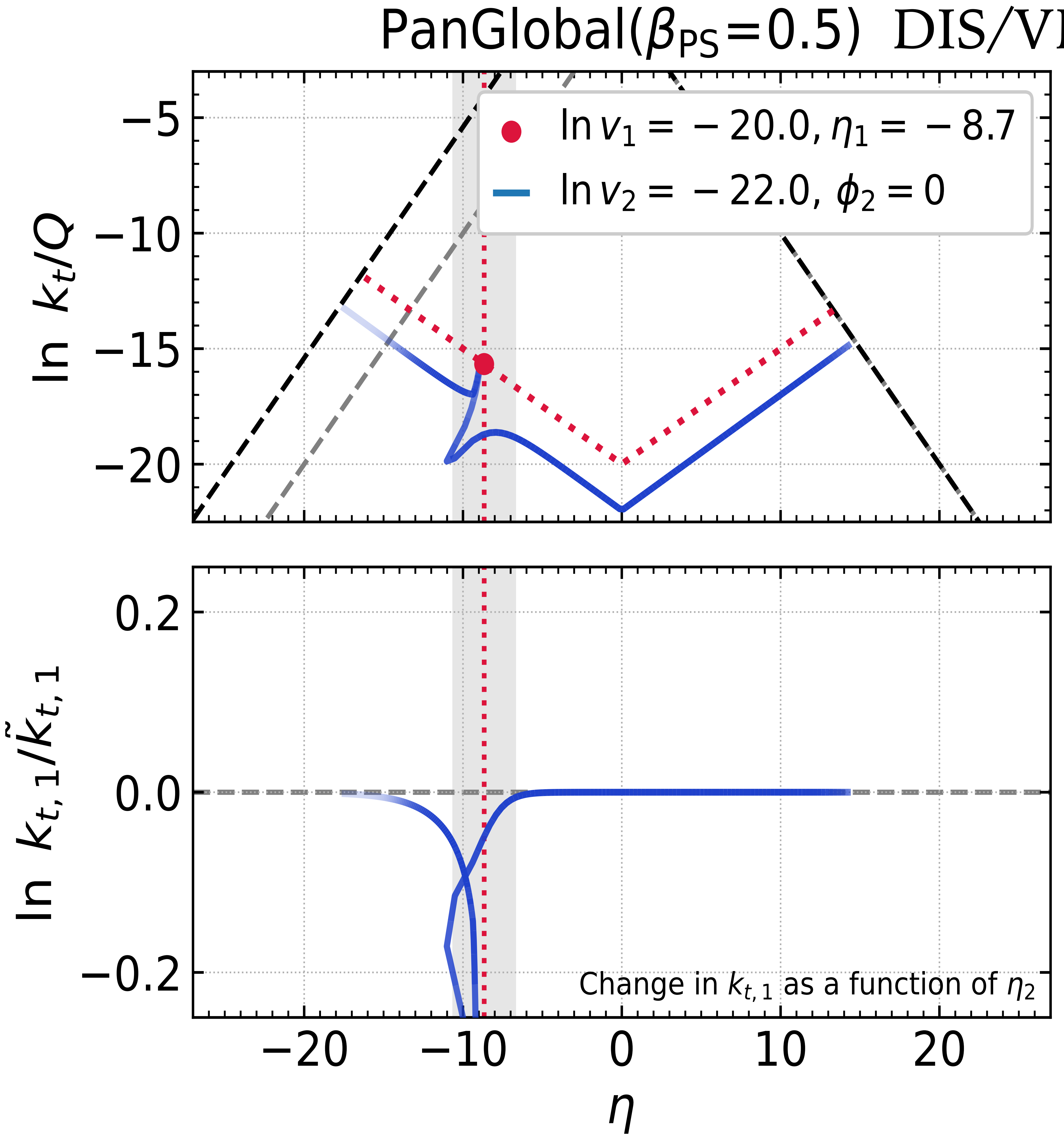
- Systematic expansion, with full colour for up to n emissions in any vertical slice
- Implemented for $n = 1$ & 2 (segment & "NODS" methods)
- difference between them gives estimate of residual systematic error

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





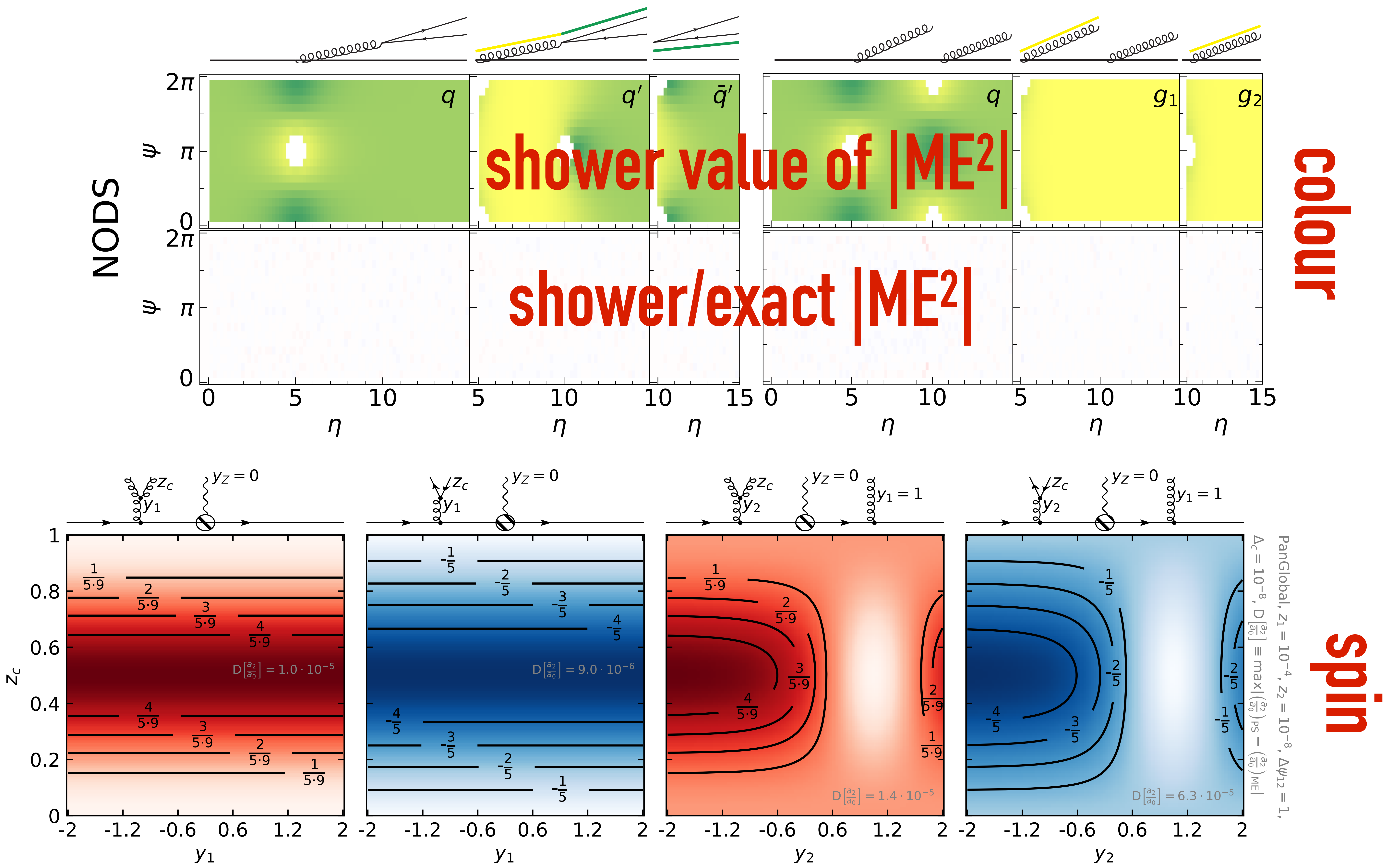
checks of correct recoil

pp: van Beekveld, Ferrario Ravasio, GPS, Soto-Ontoso, Soyez, Verheyen, 2205.02237
DIS: van Beekveld, Ferrario Ravasio, 2305.08645

Testing NLL showers

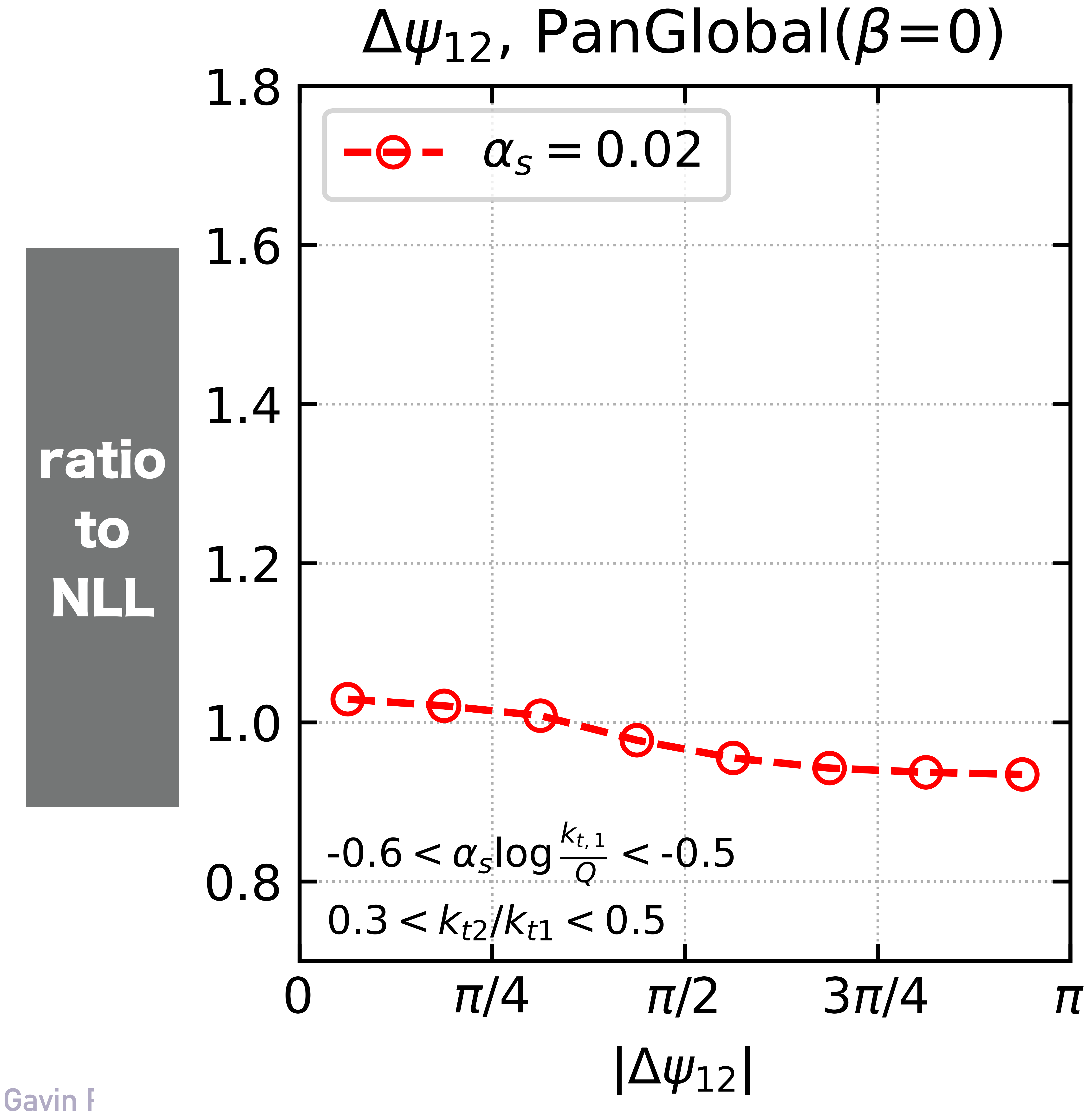
matrix element tests
all-order resummation comparisons

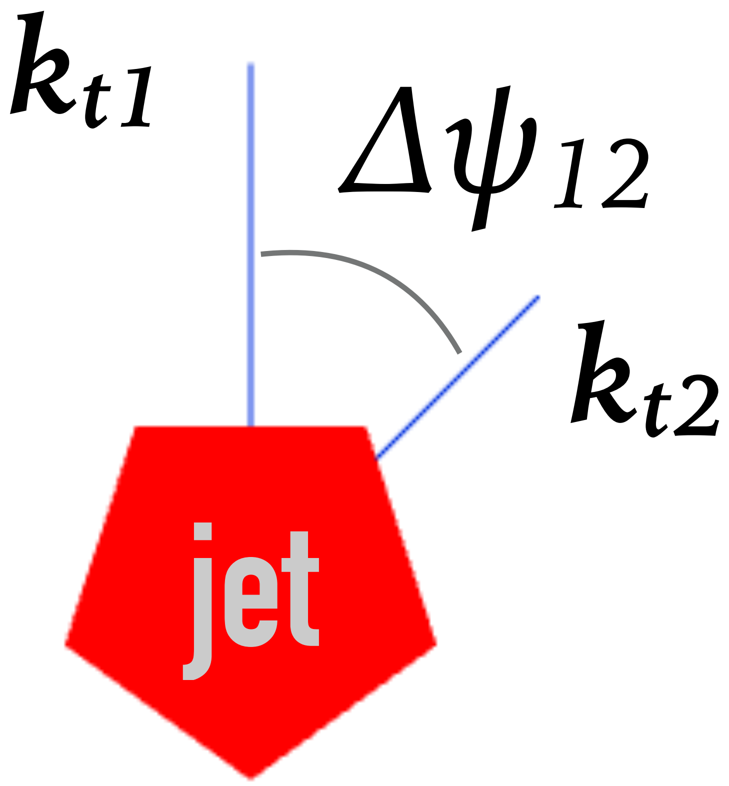
Test class 1: tree-level (2nd/3rd-order) expansion of shower v. factorised matrix element



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

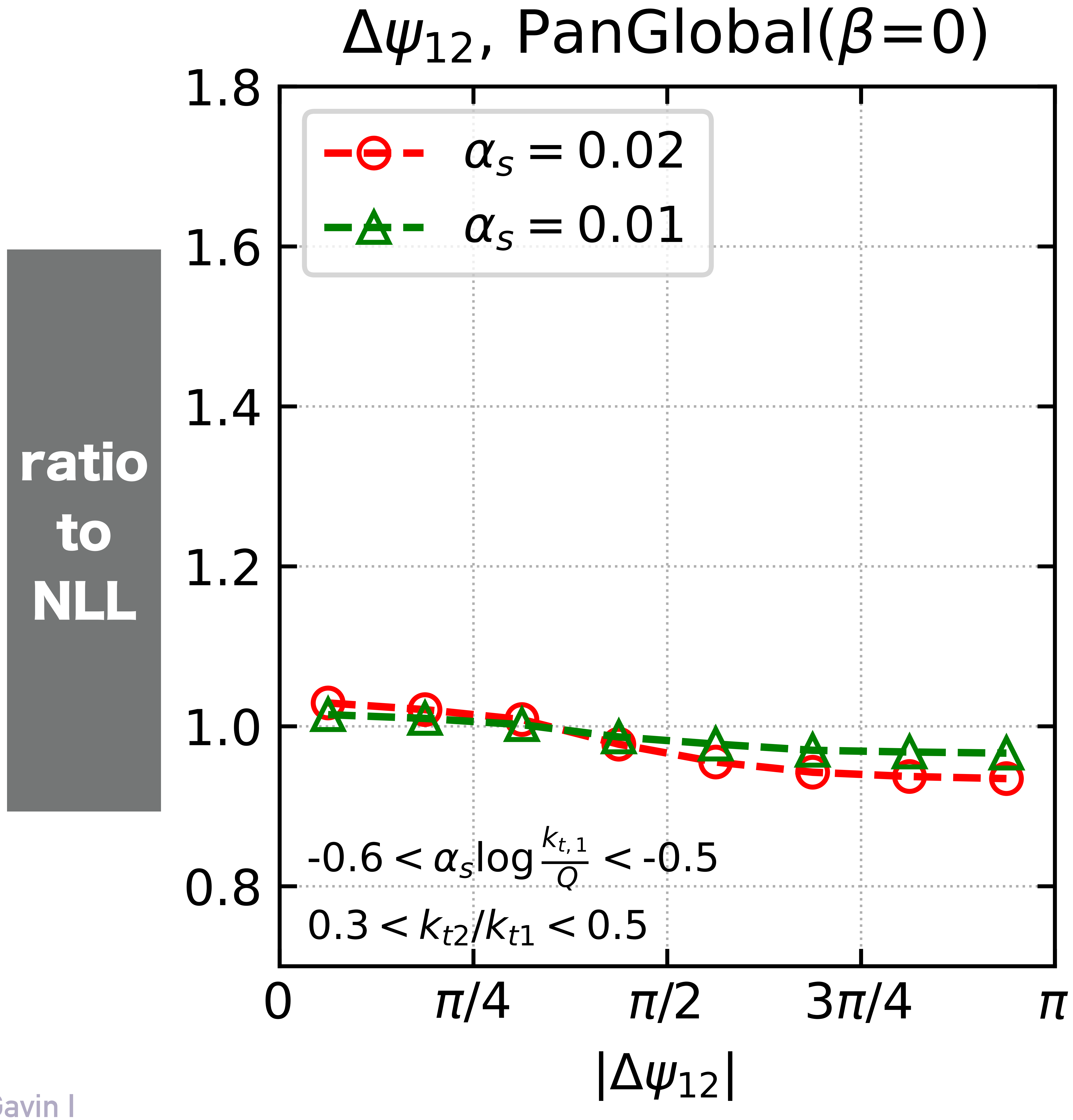
Test class 2: full shower v. all-order NLL

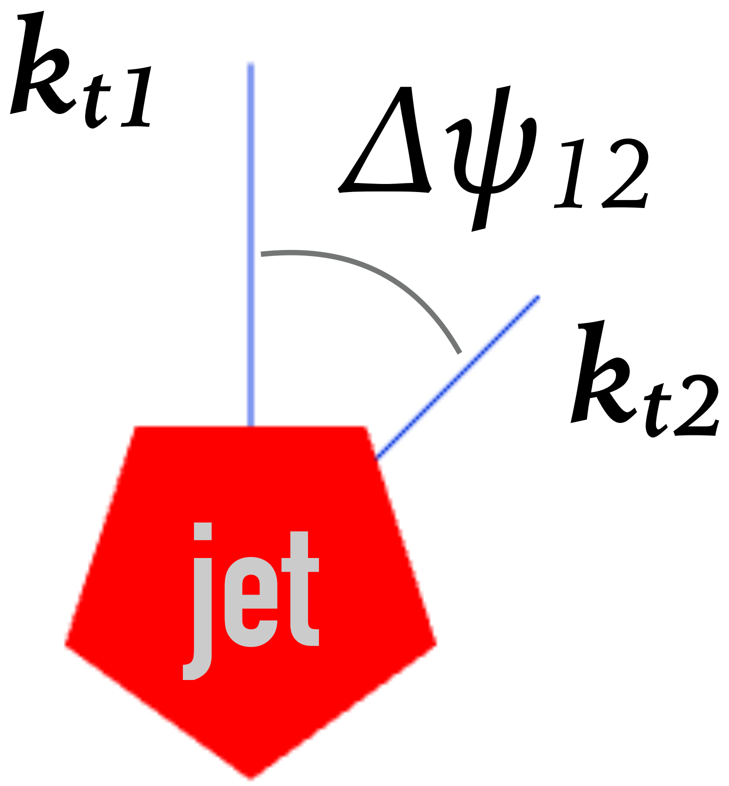




- run full shower with specific value of $\alpha_s(Q)$ & measure an observable: azimuth between two highest-k_t emissions (soft-collinear)
- ratio to NLL should be flat $\equiv 1$
- it isn't: have we got an NLL mistake? Or a residual subleading (NNLL) term?

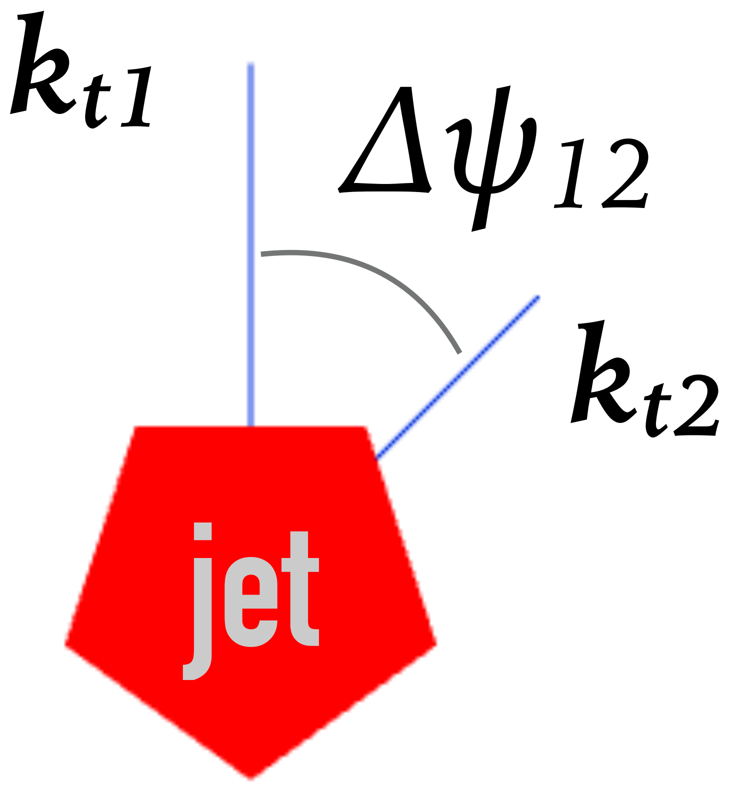
Tests (2): full shower v. all-order NLL

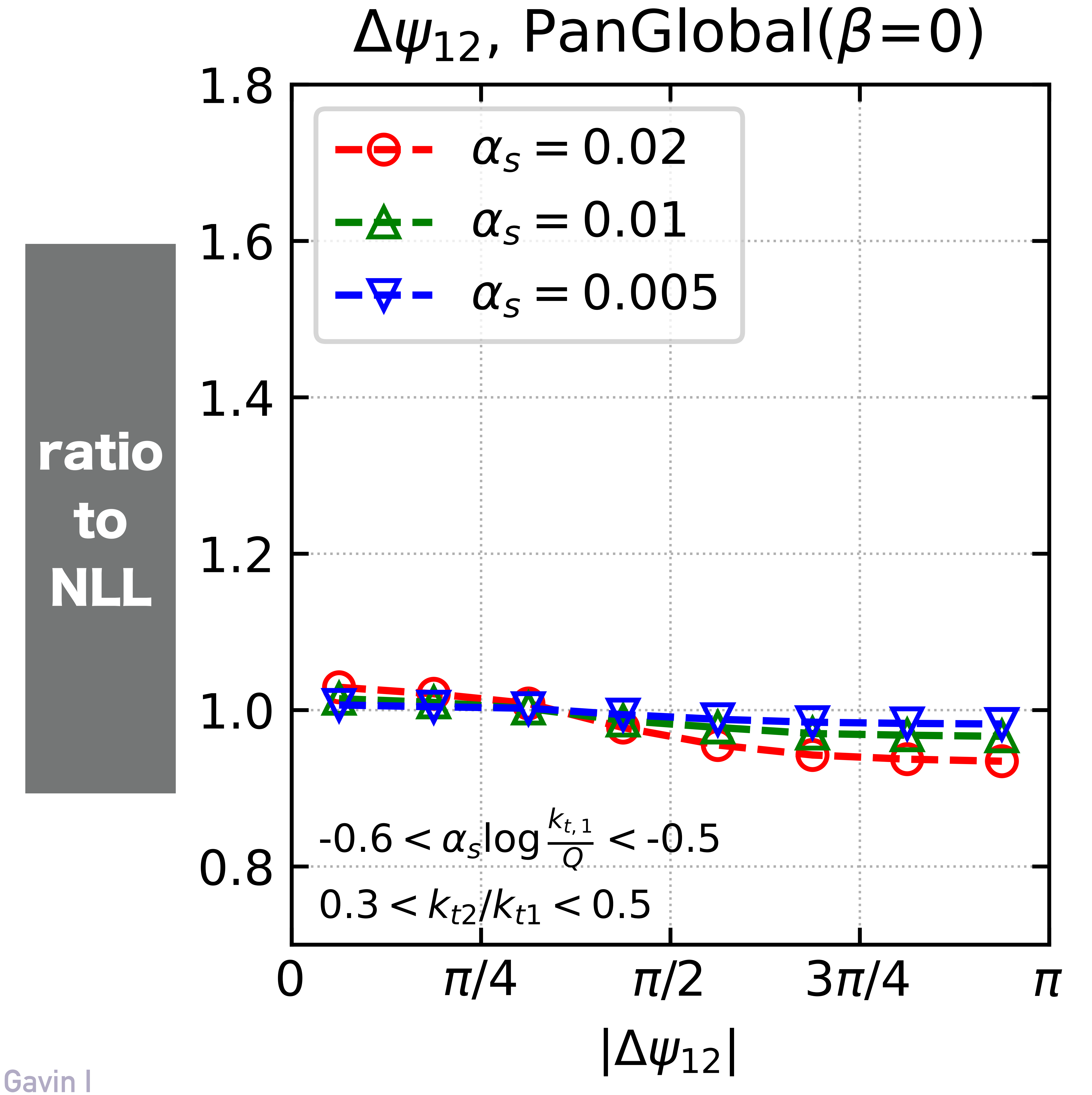




- run full shower with specific value of $\alpha_s(Q)$ & measure an observable: azimuth between two highest-k_t emissions (soft-collinear)
- ratio to NLL should be flat ≡ 1
- it isn't: have we got an NLL mistake? Or a residual subleading (NNLL) term?
- try reducing $\alpha_s(Q)$, while keeping constant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

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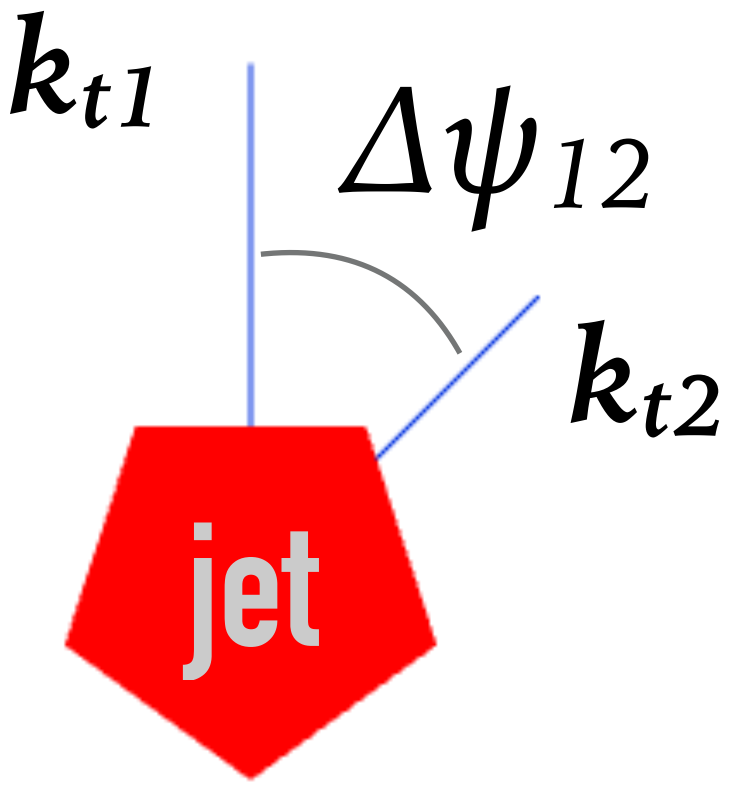
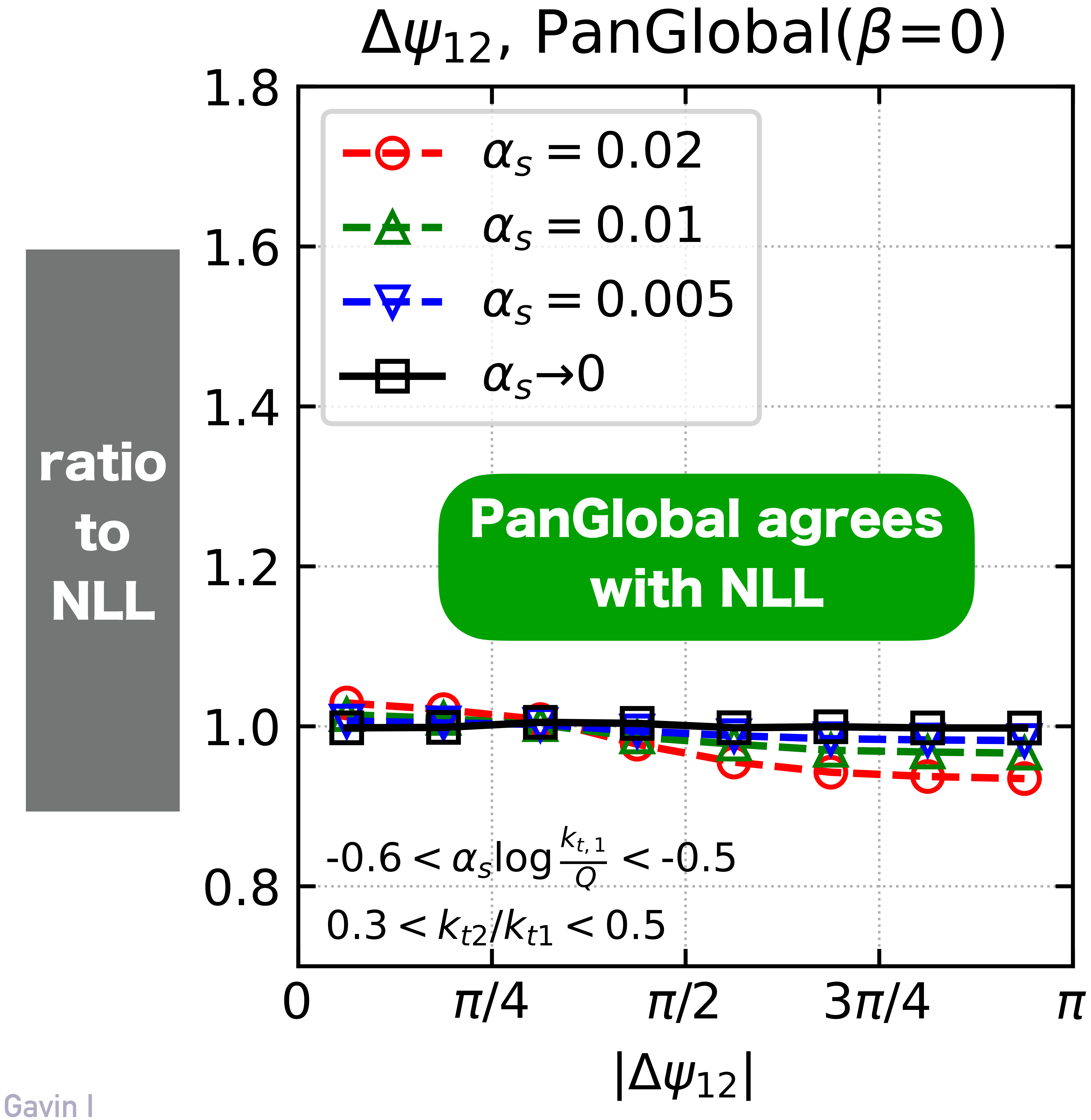
Tests (2): full shower v. all-order NLL

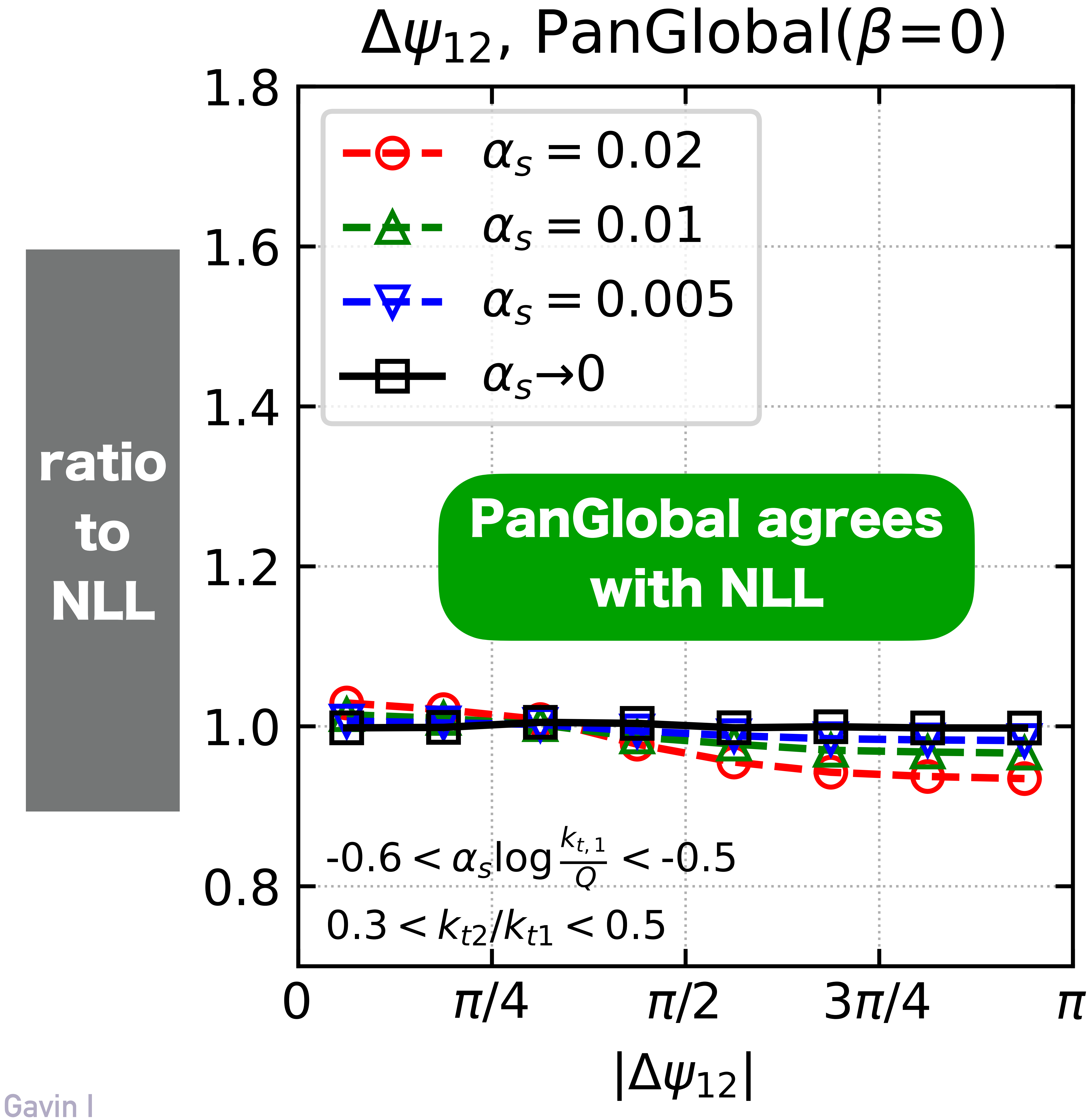


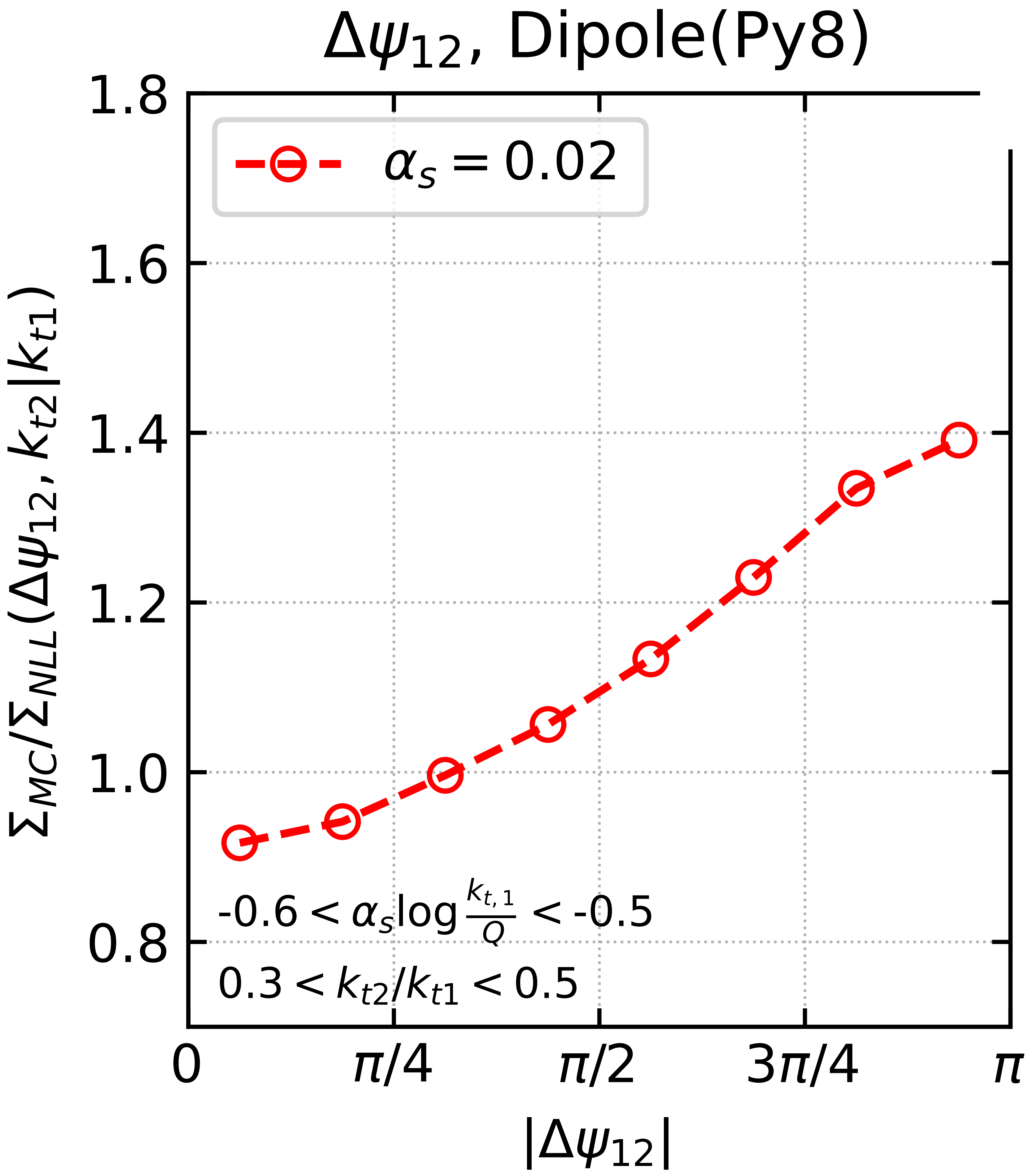


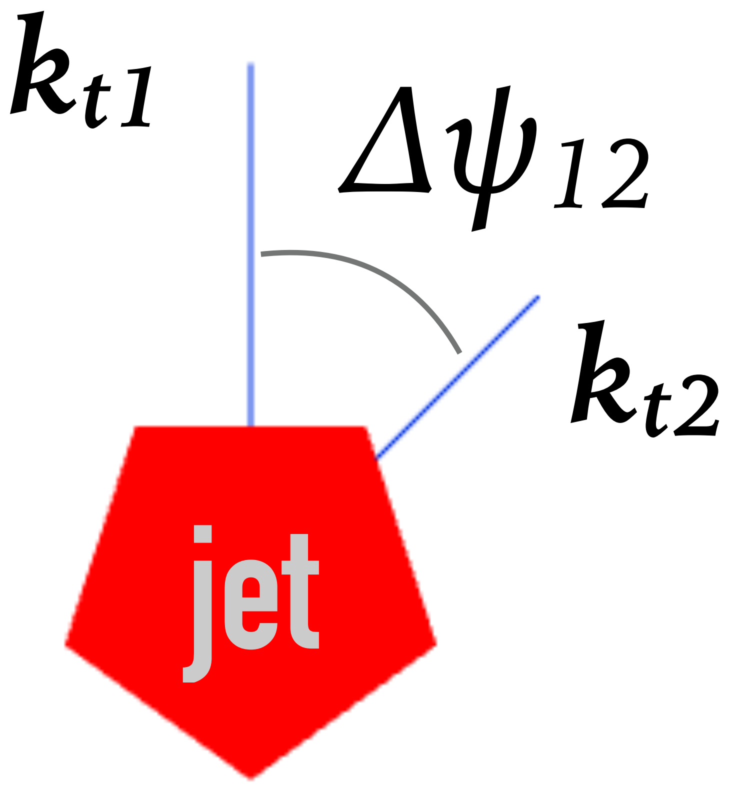
- run full shower with specific value of $\alpha_s(Q)$ & measure an observable: azimuth between two highest-k_t emissions (soft-collinear)
- ratio to NLL should be flat ≡ 1
- it isn't: have we got an NLL mistake? Or a residual subleading (NNLL) term?
- try reducing $\alpha_s(Q)$, while keeping constant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

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

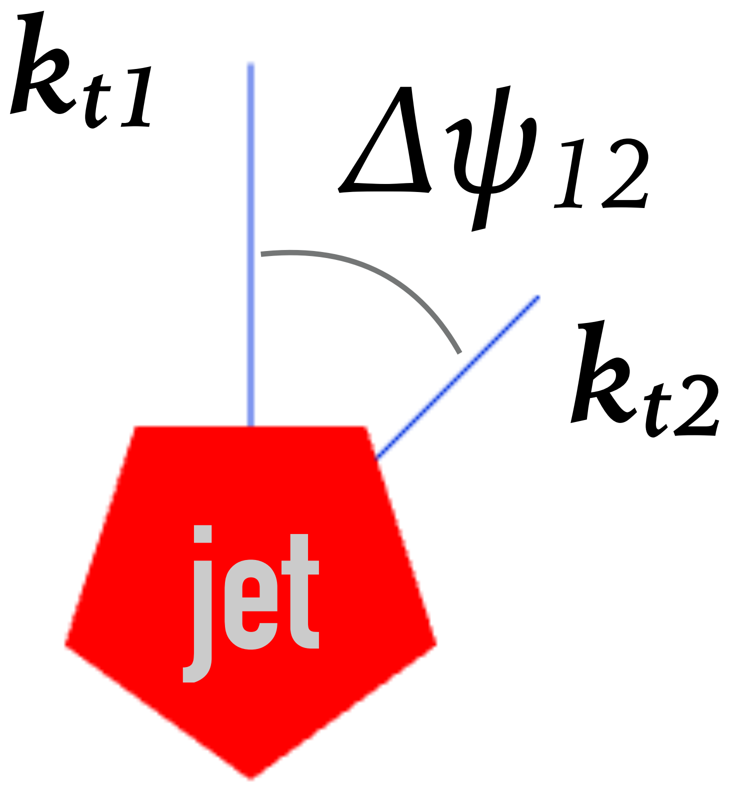
Tests (2): full shower v. all-order NLL



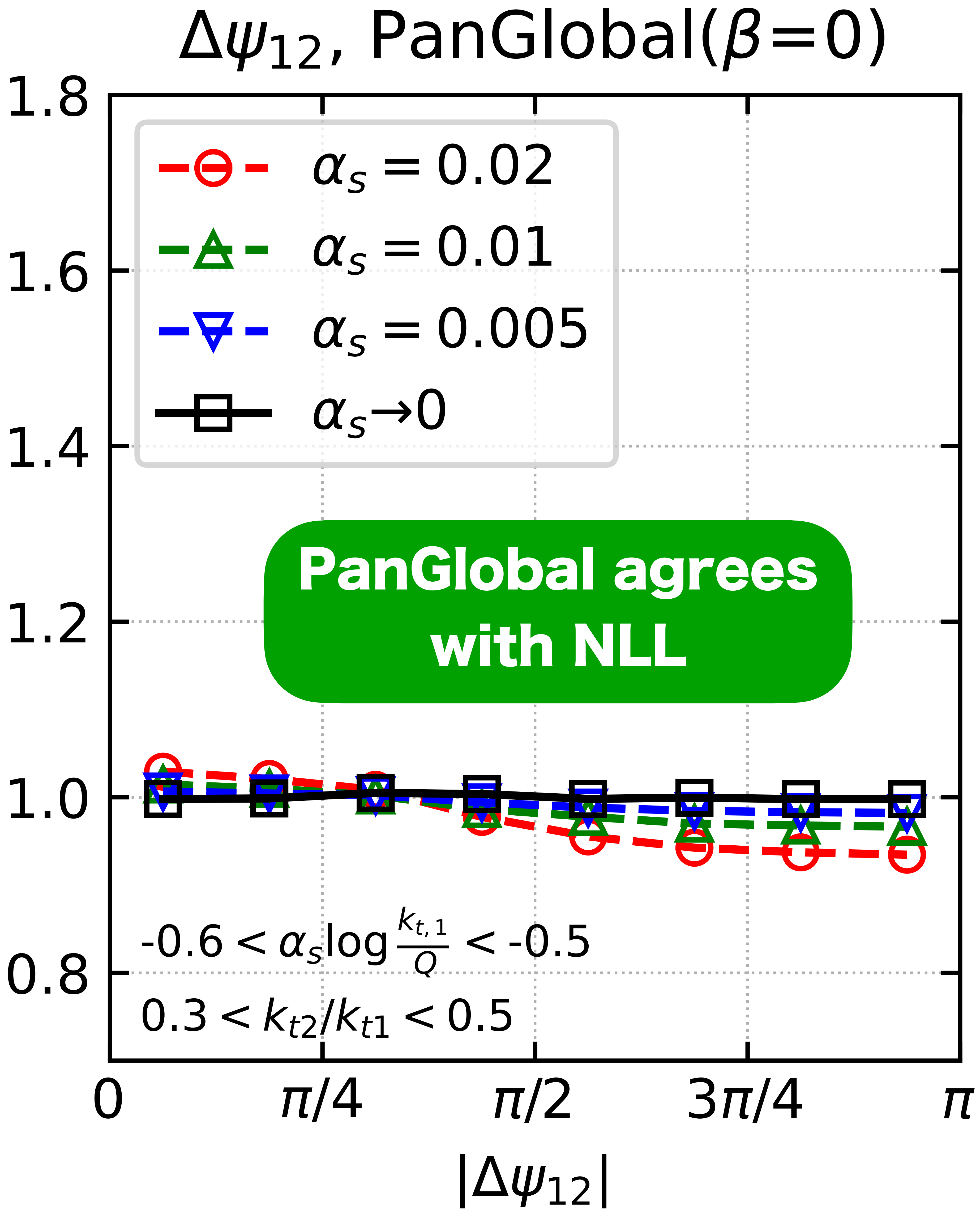


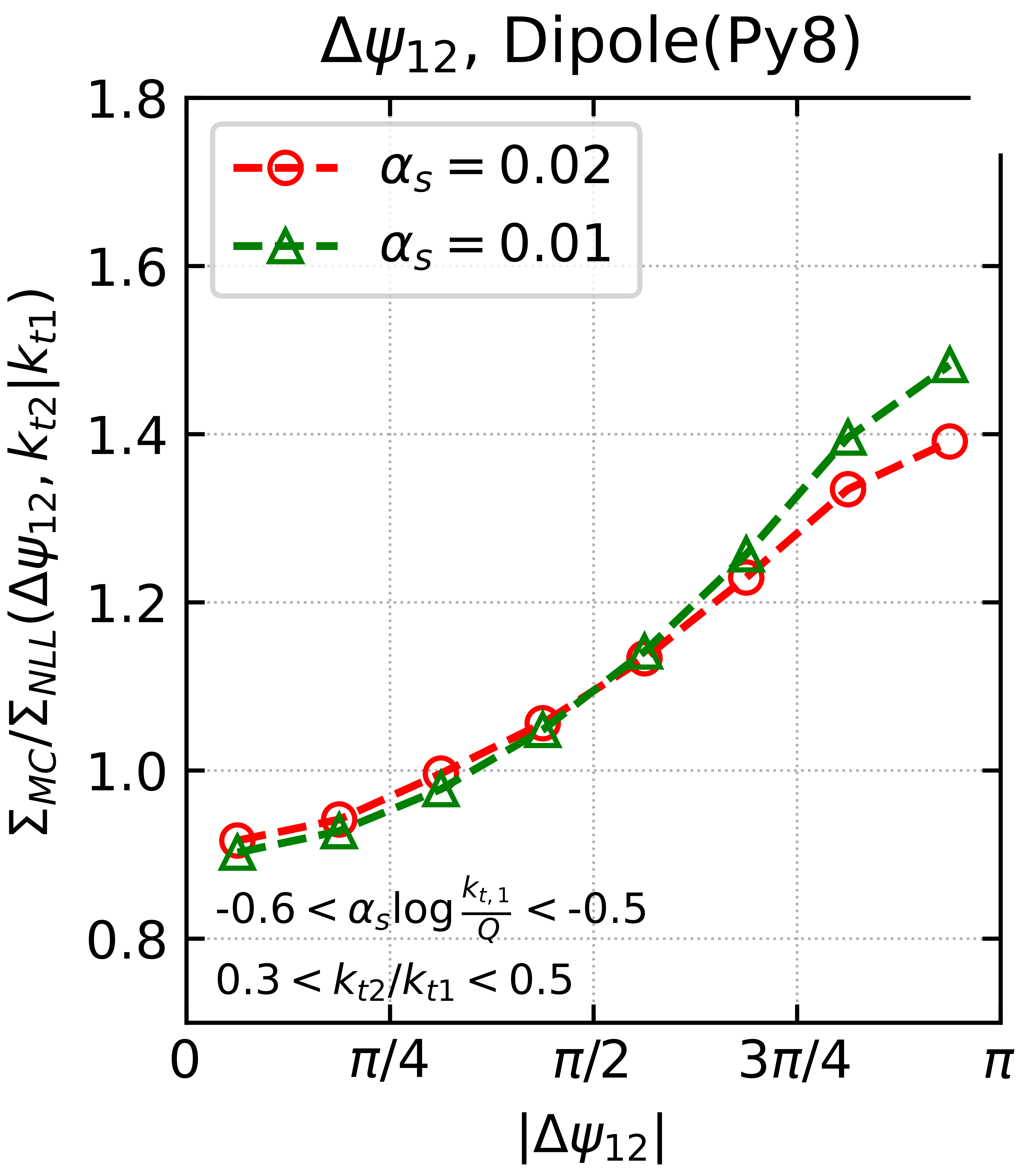


Tests (2): full shower v. all-order NLL



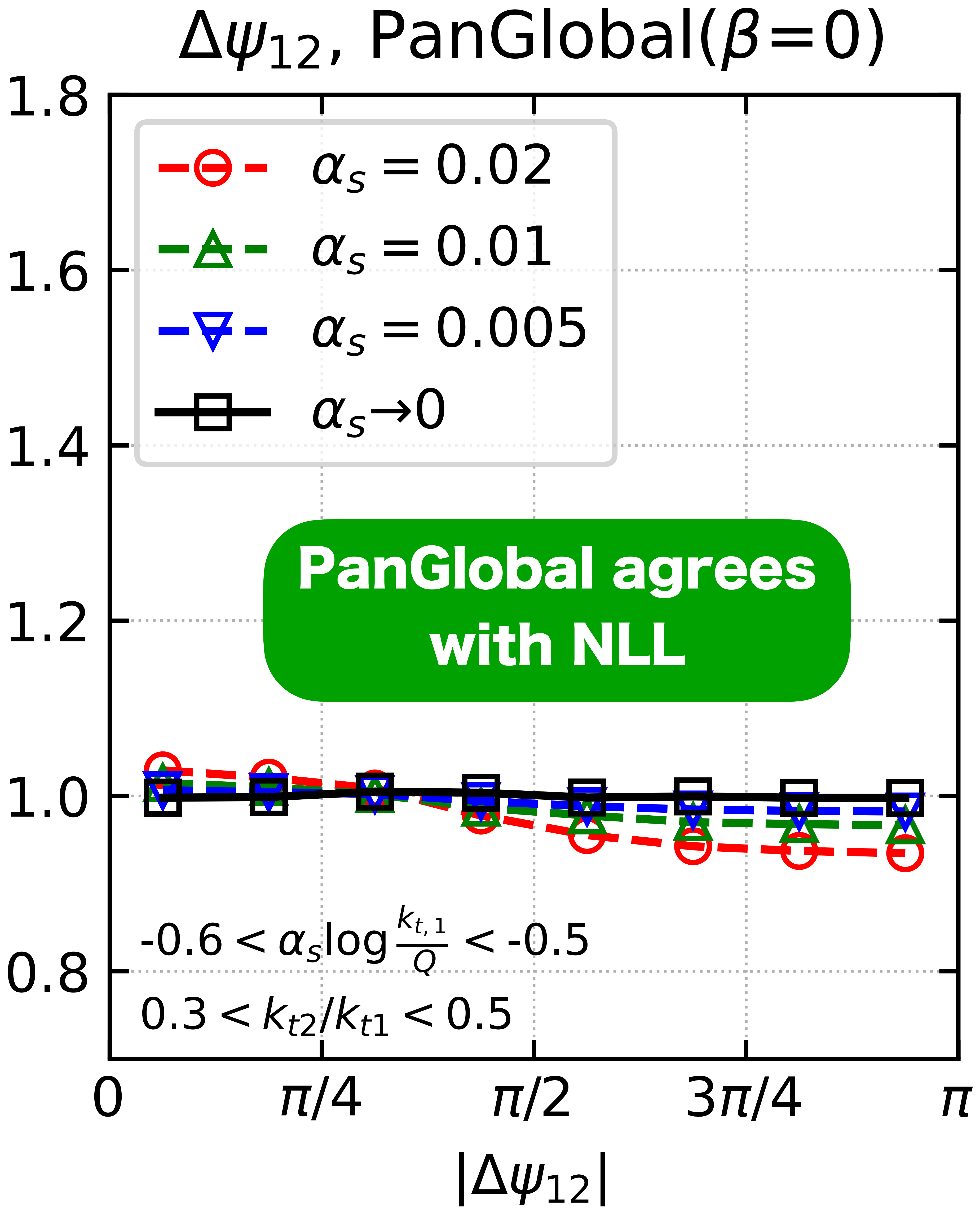
ratio to NLL

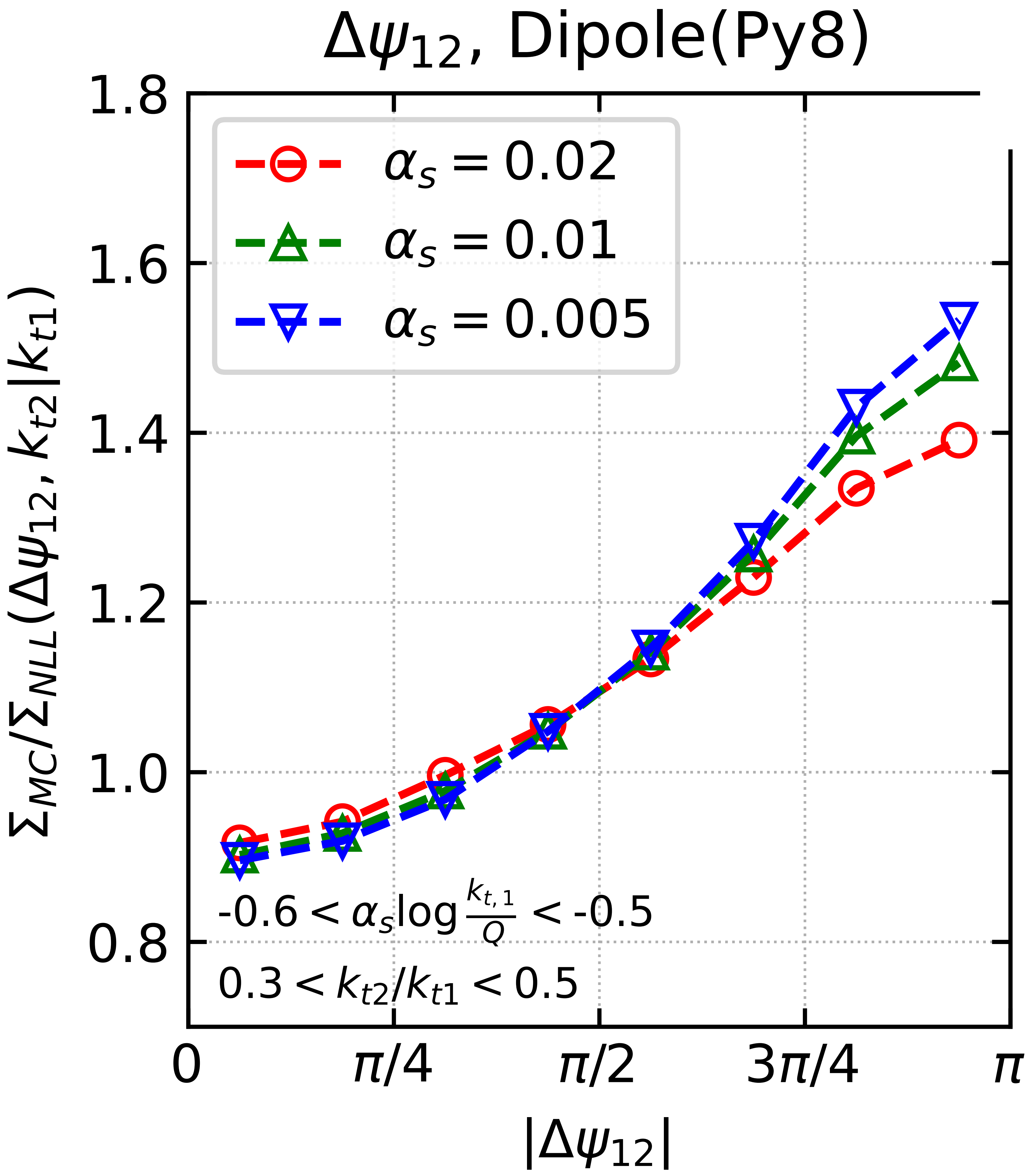


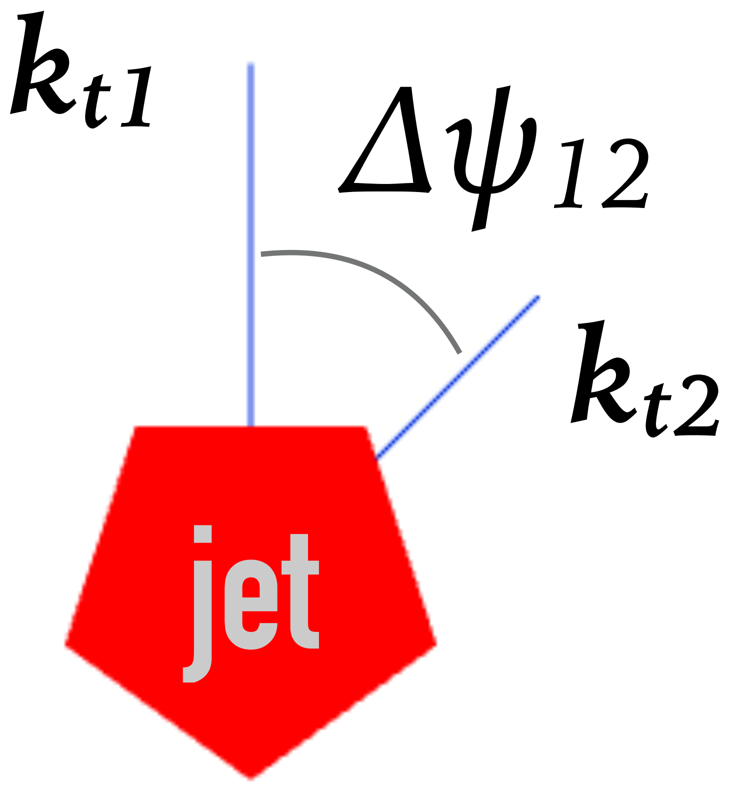


Tests (2): full shower v. all-order NLL

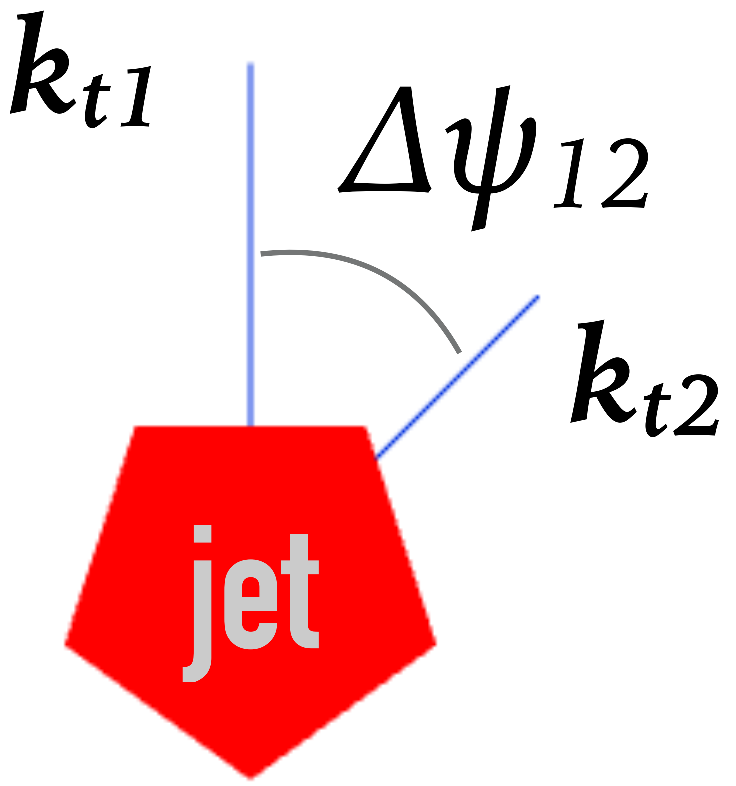
ratio to NLL



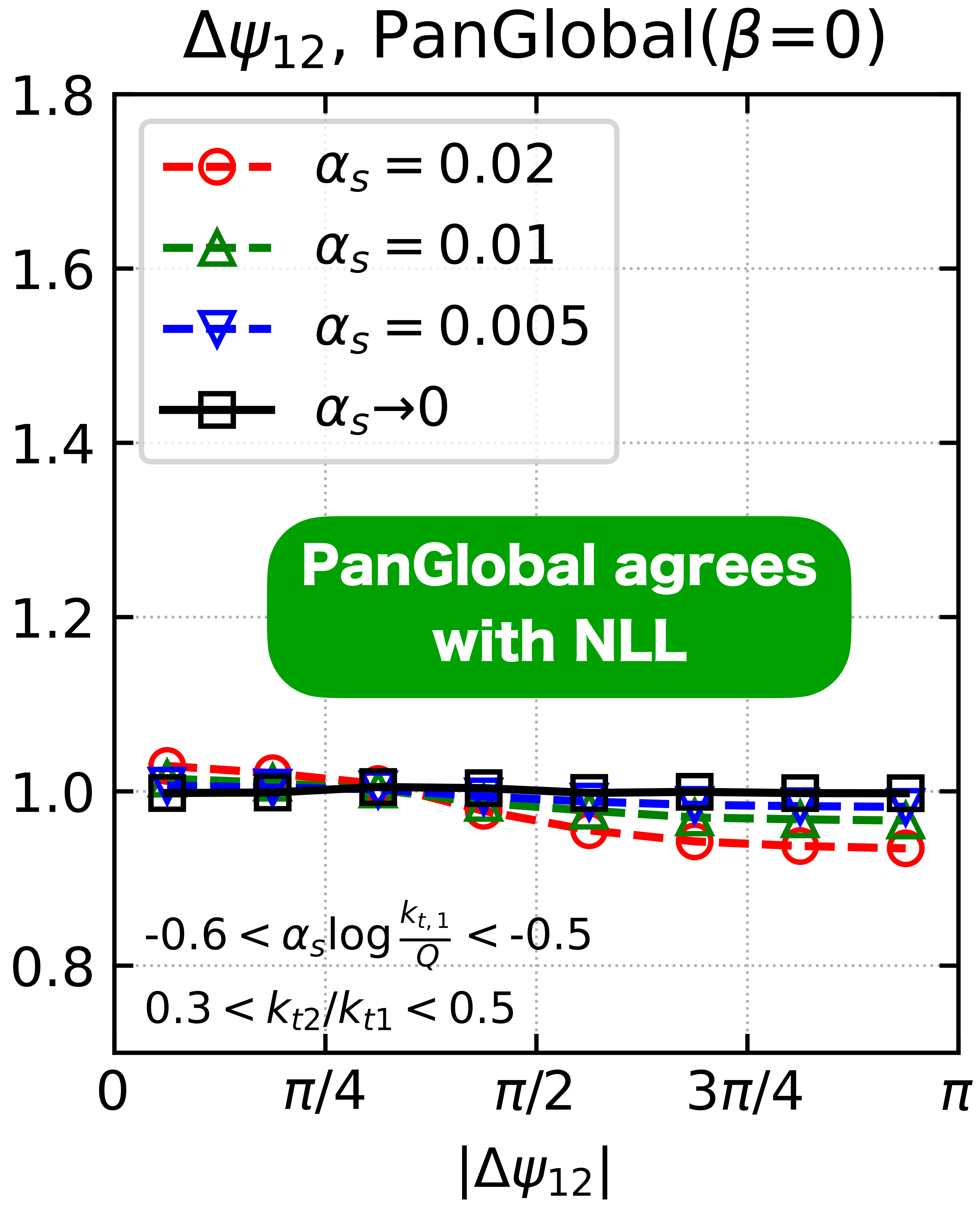




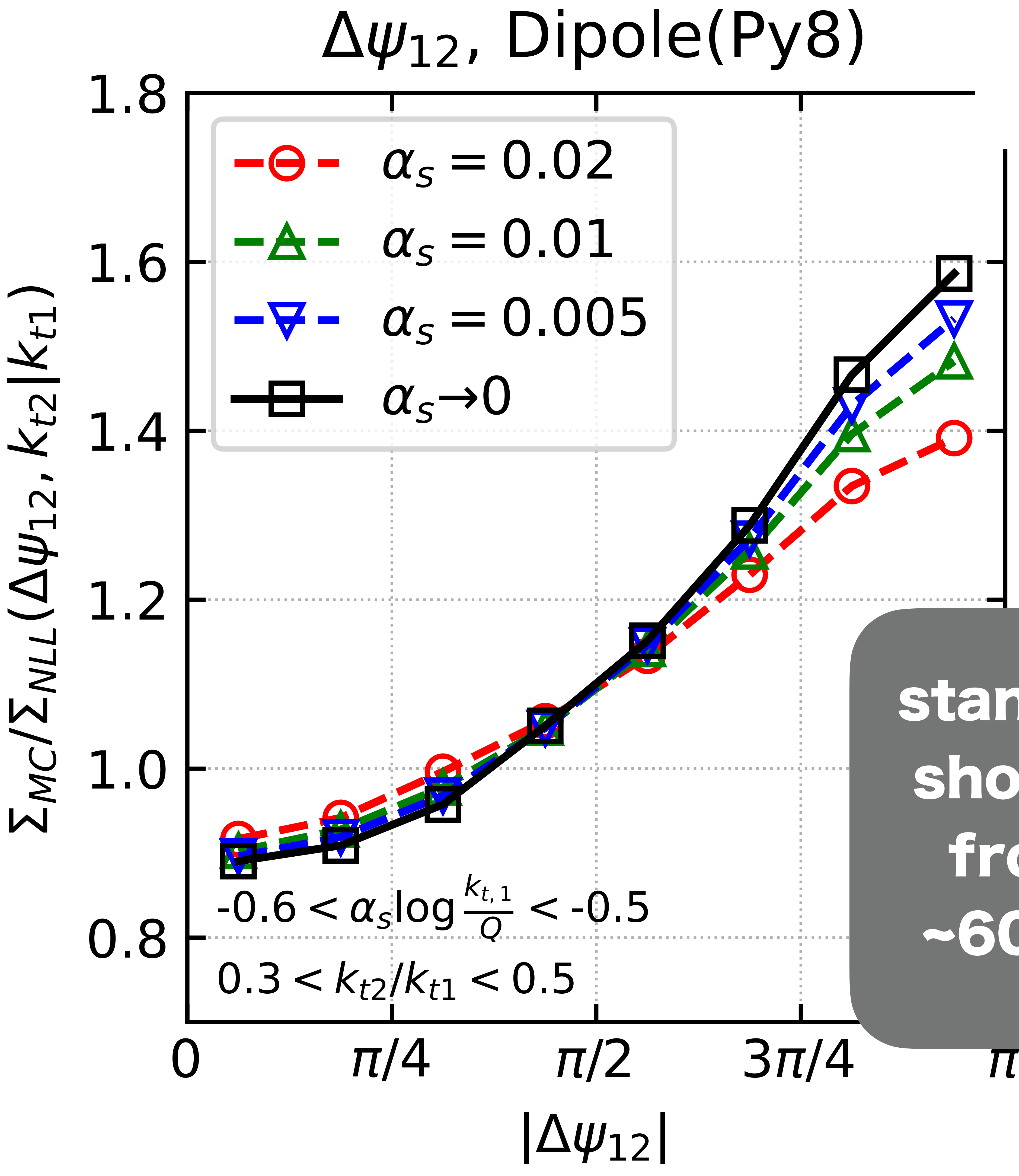
Tests (2): full shower v. all-order NLL



ratio to NLL

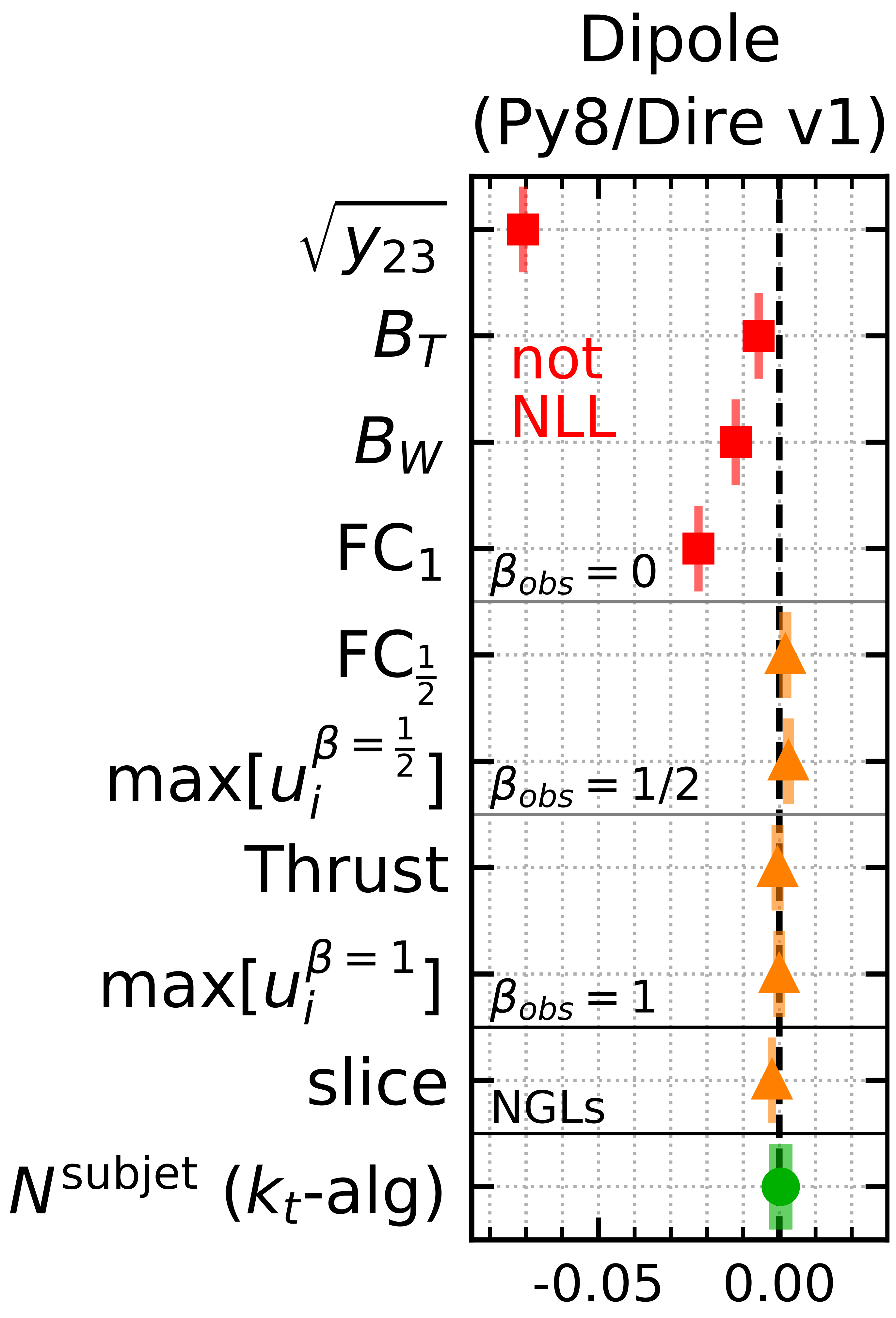


PanGlobal agrees with NLL



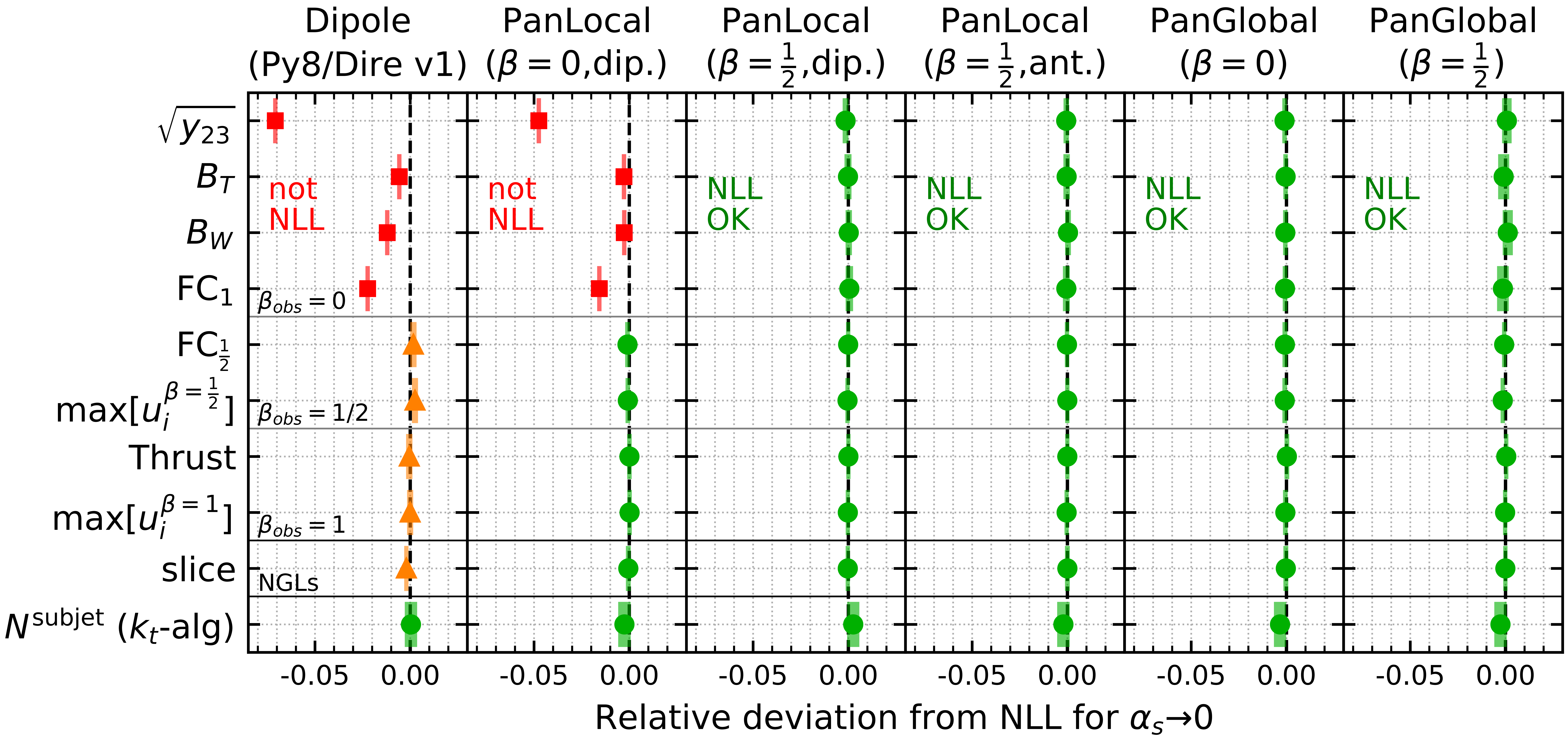
standard dipole shower differs from NLL by ~60%, i.e. O(1)

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



Relative deviation from NLL for $\alpha_s \to 0$

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



PanScales status mid-2023: e^+e^- → jets, pp→ Z/W/H, DIS (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

NLL is quickly becoming the standard for parton showers

PanScales

Parton showers beyond leading logarithmic accuracy

Mrinal Dasgupta,[1] Frédéric A. Dreyer,[2] Keith Hamilton,[3] Pier Francesco Monni,[4] Gavin P. Salam,[2,*] and Grégory Soyez[5]

slide from Pier Monni

NLL is quickly becoming the standard for parton showers

PanScales

Parton showers beyond leading logarithmic accuracy

Mrinal Dasgupta,[1] Frédéric A. Dreyer,[2] Keith Hamilton,[3] Pier Francesco Monni,[4] Gavin P. Salam,[2,*] and Grégory Soyez[5]

Matching and event-shape NNDL accuracy in parton showers

Keith Hamilton,[a] Alexander Karlberg,[b,c] Gavin P. Salam,[b,d] Ludovic Scyboz,[b] Rob Verheyen[a]

PanScales showers for hadron collisions: all-order validation

Melissa van Beekveld,[a] Silvia Ferrario Ravasio,[a] Keith Hamilton,[b] Gavin P. Salam,[a,c] Alba Soto-Ontoso,[d] Gregory Soyez,[d] Rob Verheyen[b]

Spin correlations in final-state parton showers and jet observables

Alexander Karlberg[1], Gavin P. Salam[1,2], Ludovic Scyboz[1], Rob Verheyen[3]

Colour and logarithmic accuracy in final-state parton showers

Keith Hamilton,[a] Rok Medves,[b] Gavin P. Salam,[b,c] Ludovic Scyboz,[b] Gregory Soyez[d]

Next-to-leading-logarithmic PanScales showers for Deep Inelastic Scattering and Vector Boson Fusion

Melissa van Beekveld,[a] Silvia Ferrario Ravasio,[b]

Building a consistent parton shower

Jeffrey R. Forshaw,[a,b] Jack Holguin,[a,b] Simon Plätzer.[b,c]

Improvements on dipole shower colour

Jack Holguin [a,1], Jeffrey R. Forshaw [b,1], Simon Plätzer [c,2]

[1]Consortium for Fundamental Physics, School of Physics & Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom
[2]Particle Physics, Faculty of Physics, University of Vienna, 1090 Wien, Austria

DEDUCTOR

Summations of large logarithms by parton showers

Zoltán Nagy
DESY, Notkestrasse 85, 22607 Hamburg, Germany *

Davison E. Soper
Institute for Fundamental Science, University of Oregon, Eugene, OR 97403-5203, USA †
(Dated: 18 August 2021)

Summations by parton showers of large logarithms in electron-positron annihilation

Zoltán Nagy
DESY, Notkestrasse 85, 22607 Hamburg, Germany *

Davison E. Soper
Institute for Fundamental Science, University of Oregon, Eugene, OR 97403-5203, USA †
(Dated: 13 November 2020)

Introduction to the PanScales framework, version 0.1

Melissa van Beekveld[1], Mrinal Dasgupta[2], Basem Kamal El-Menoufi[2,3], Silvia Ferrario Ravasio[4], Keith Hamilton[5], Jack Helliwell[6], Alexander Karlberg[4], Rok Medves[6], Pier Francesco Monni[4], Gavin P. Salam[6,7], Ludovic Scyboz[3,6], Alba Soto-Ontoso[4], Gregory Soyez[8], Rob Verheyen[5]

ALARIC

A new approach to color-coherent parton evolution

Florian Herren,[1] Stefan Höche,[1] Frank Krauss,[2] Daniel Reichelt,[2] and Marek Schönherr[2]
[1]*Fermi National Accelerator Laboratory, Batavia, IL, 60510, USA*
[2]*Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK*

A new approach to QCD evolution in processes with massive partons

Benoît Assi and Stefan Höche
Fermi National Accelerator Laboratory, Batavia, IL, 60510

The Alaric parton shower for hadron colliders

Stefan Höche,[1] Frank Krauss,[2] and Daniel Reichelt[2]

APOLLO

A partitioned dipole-antenna shower with improved transverse recoil

Christian T Preuss
Department of Physics, University of Wuppertal, 42119 Wuppertal, Germany
E-mail: preuss@uni-wuppertal.de

Soft spin correlations in final-state parton showers

Keith Hamilton,[a] Alexander Karlberg,[b] Gavin P. Salam,[b,c] Ludovic Scyboz,[b] Rob Verheyen[a]

[… & more]

slide from Pier Monni

towards NNLL
(for now e+e−)

NLL: terms of order $\alpha_s^n L^n \sim 1$ *(residual uncertainties* $\sim \alpha_s \sim 10-20\,\%$ *)*

NNLL: terms of order $\alpha_s^n L^{n-1} \sim \alpha_s$ *(residual uncertainties* $\sim \alpha_s^2 \sim$ *few %)*

FAKULTÄTEN UND EINRICHTUNGEN
Suche

Institut für Theoretische Teilchenphysik und Kosmologie | RWTH AACHEN UNIVERSITY

Institut für Theoretische Teilchenphysik und Kosmologie

English

STUDIUM FORSCHUNG DAS INSTITUT

Das Institut › Seminare › TTK Theorie-Seminar › Seminare WS 24/25

- Seminare
- TTK Theorie-Seminar
  - Seminare WS 24/25
  - Seminare SS 25
  - Seminararchiv
- Teilchen- und Astroteilchenphysik-Kolloquium
- Kolloquium
- Weitere Seminare

TTK Seminare WS 24/25

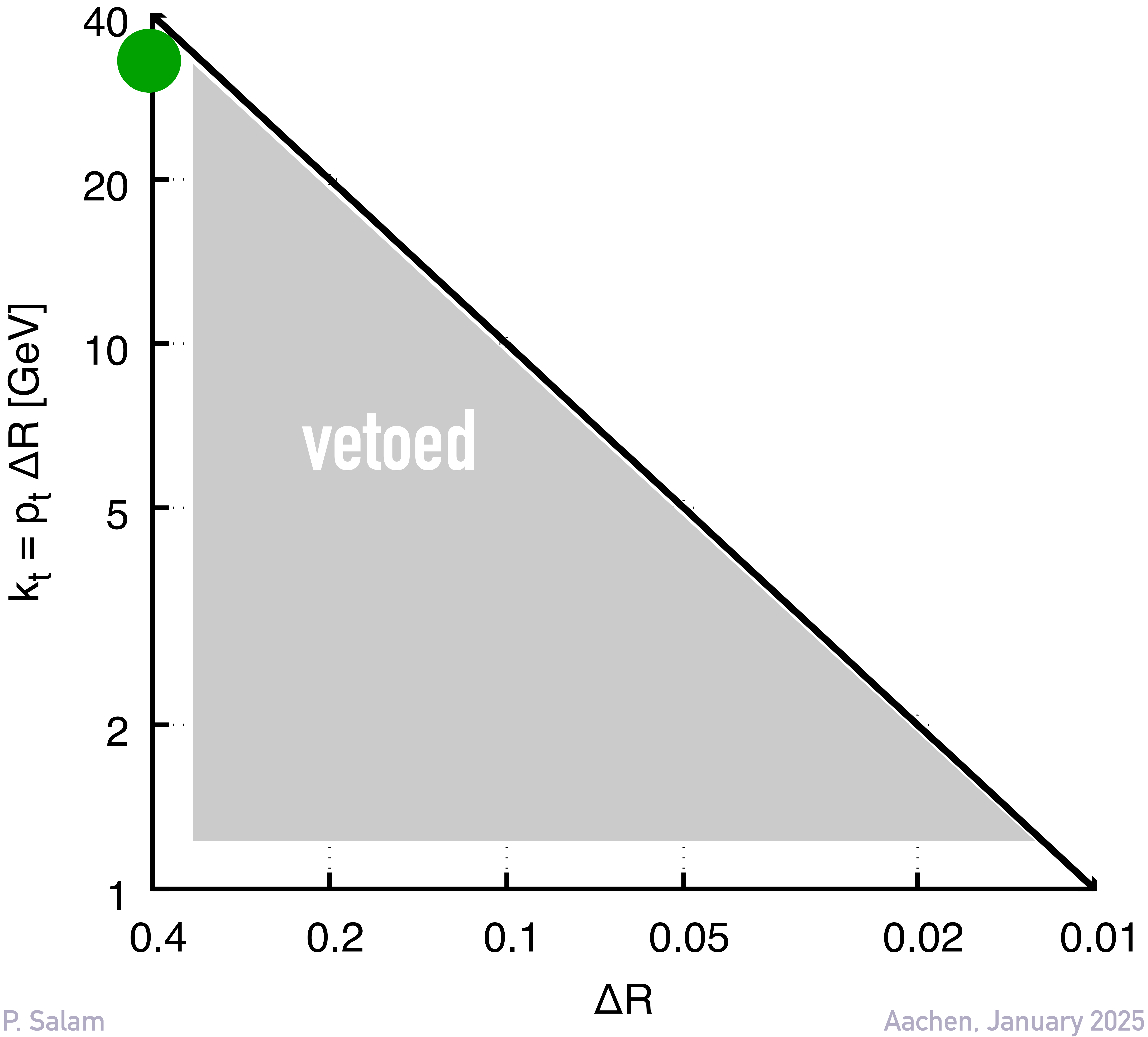
Do. 30.01.2025, 16.30 Uhr

Melissa van Beekveld (NIKHEF, Amsterdam)

The PanScales parton showers: where Monte Carlo and Resummation meet

Host: M. Krämer

sources of NNLL terms: $\alpha_s^n L^{n-1}$



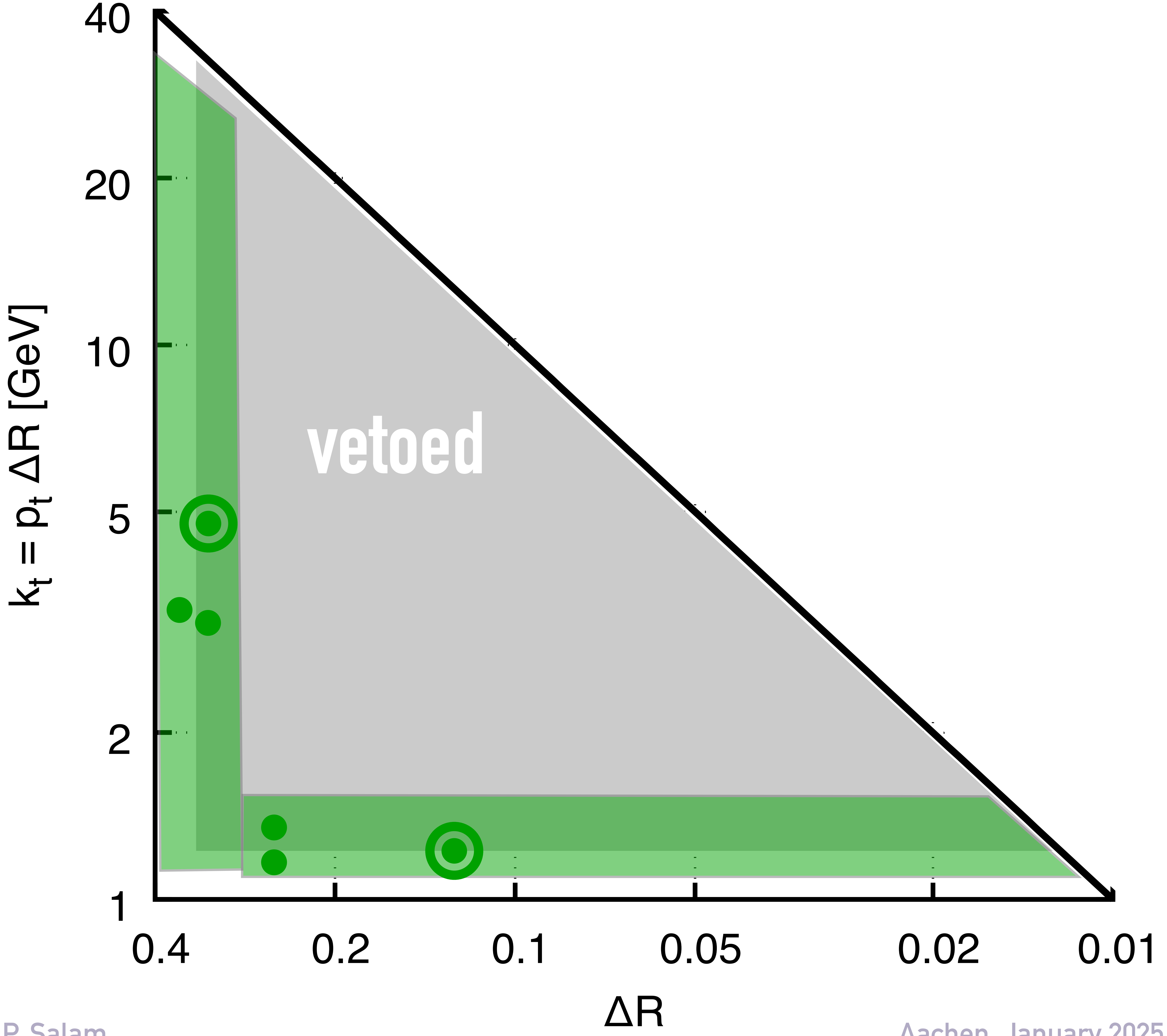
At top of Lund plane (hard 3-jet region), account for Born+1-real and Born 1-loop — i.e. full NLO

$\rightarrow \alpha_s$ ($= \alpha_s^n L^{n-1}$ with $n = 1$)

Must be done in a way that preserves shower logarithmic accuracy

Hamilton, Karlberg, GPS, Scyboz, Verheyen, 2301.09645

sources of NNLL terms: $\alpha_s^n L^{n-1}$



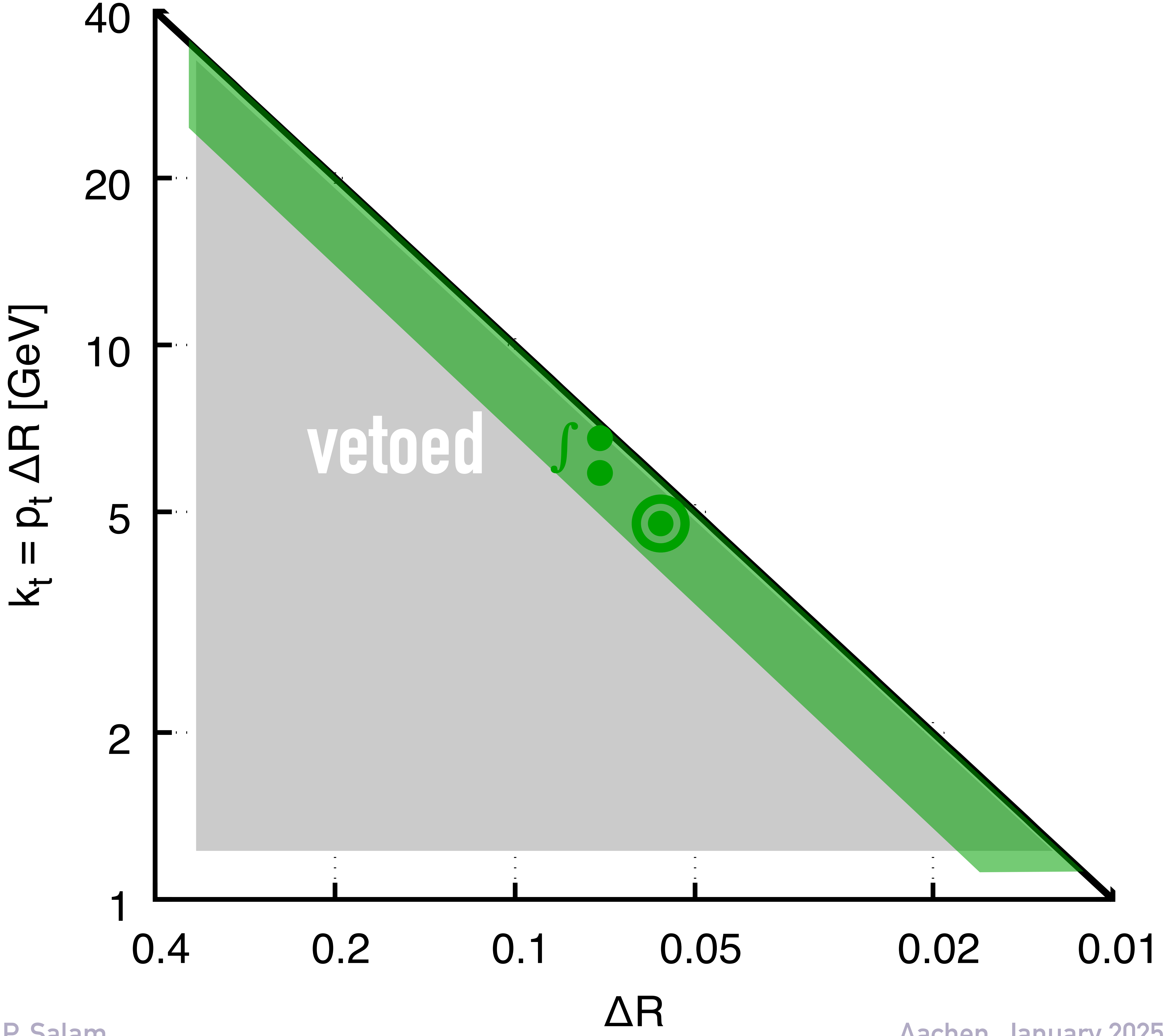
At edges, i.e. regions of size L, account for α_s^2 contributions, both fully differential soft double-real (large-angle and/or collinear), and soft 1-loop single-real

$\rightarrow \alpha_s^2 L$

(and, with running coupling, etc. $\alpha_s^n L^{n-1}$)

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

sources of NNLL terms: $\alpha_s^n L^{n-1}$



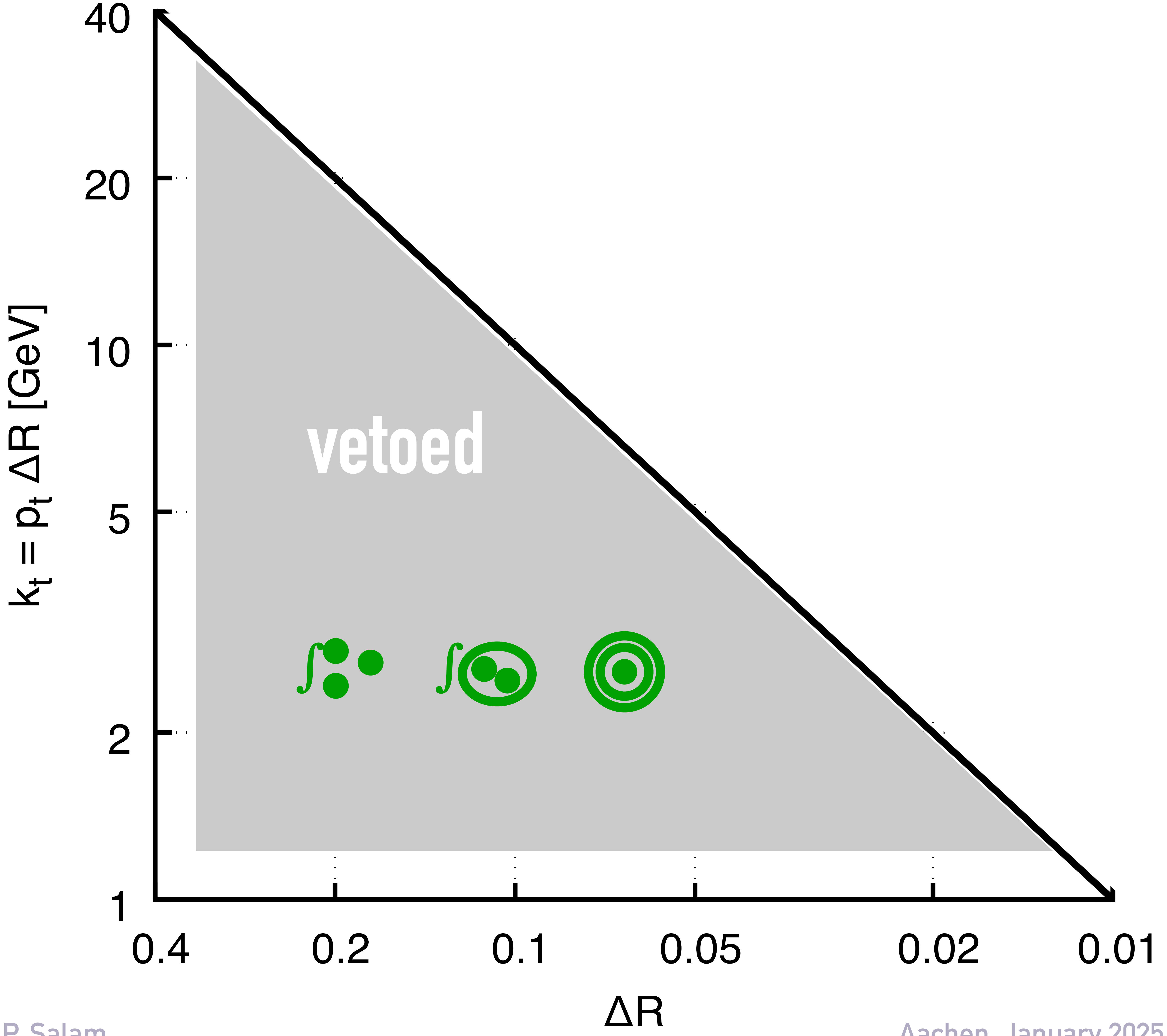
For many observables, at hard collinear edge, only need integrated collinear $1 \to 3$ and one-loop collinear $1 \to 2$

$\to \alpha_s^2 L$

(and, with running coupling, etc. $\alpha_s^n L^{n-1}$)

Dasgupta & El-Menoufi, 2109.07496
van Beekveld, Dasgupta, El-Menoufi, Monni, 2307.15734

sources of NNLL terms: $\alpha_s^n L^{n-1}$



In soft-collinear vetoed region (size L^2), need control of all α_s^3 terms, i.e. summed-integrated

- triple-soft,
- 1-loop double-soft
- 2-loop single-soft

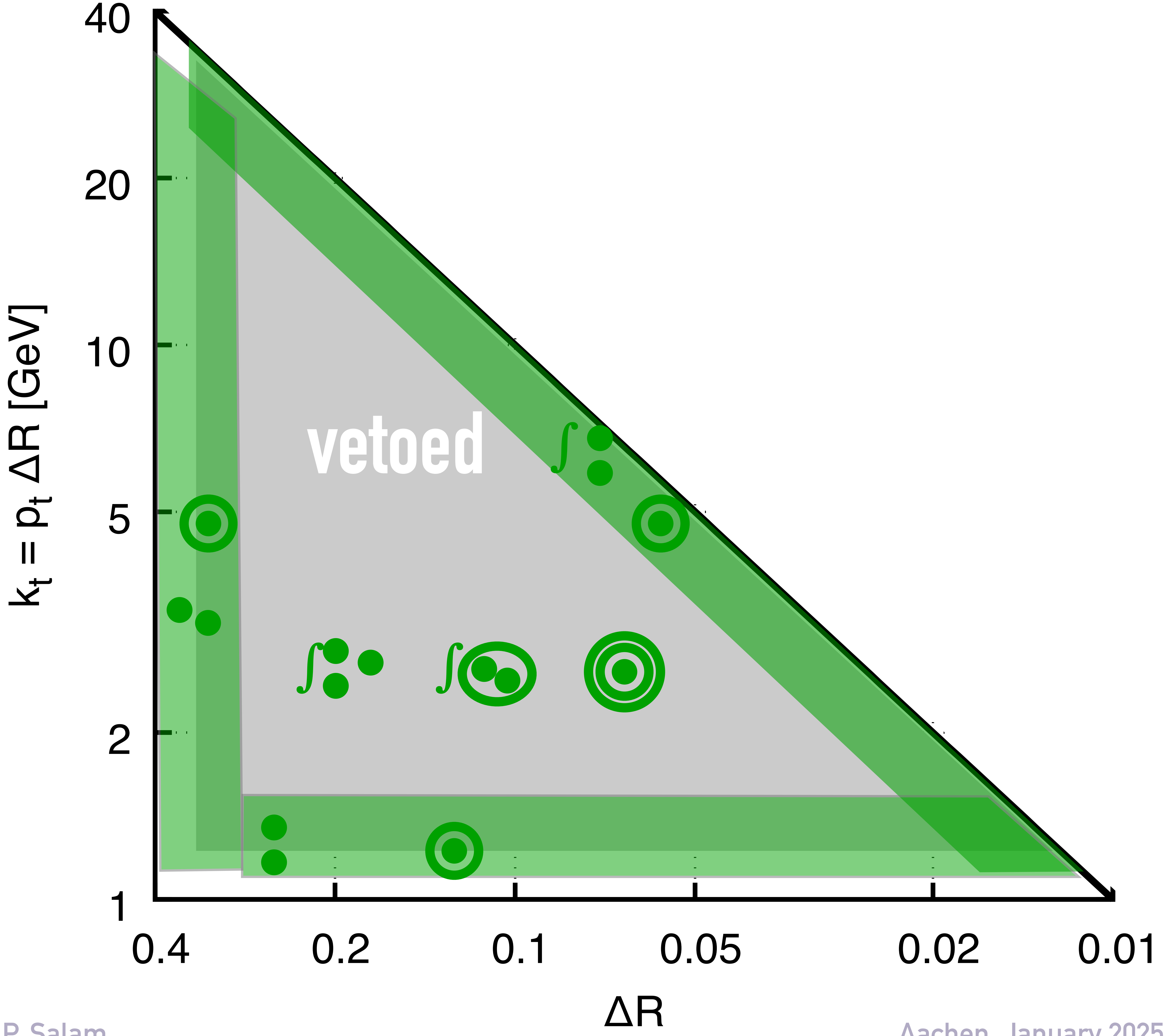
Combination that we need can be deduced from existing work (cf. 3-loop cusp anomalous dimension)

$\rightarrow \alpha_s^3 L^2$

(and, with running coupling, etc. $\alpha_s^n L^{n-1}$)

Banfi, El-Menoufi & Monni 1807.11487
Catani, de Florian, Grazzini, 1904.10365

sources of NNLL terms: $\alpha_s^n L^{n-1}$



Consistent assembly of all the pieces

van Beekveld, Dasgupta, El-Menoufi, Ferrario Ravasio, Hamilton, Helliwell, Karlberg, Monni, GPS, Scyboz, Soto-Ontoso, Soyez, 2406.02661

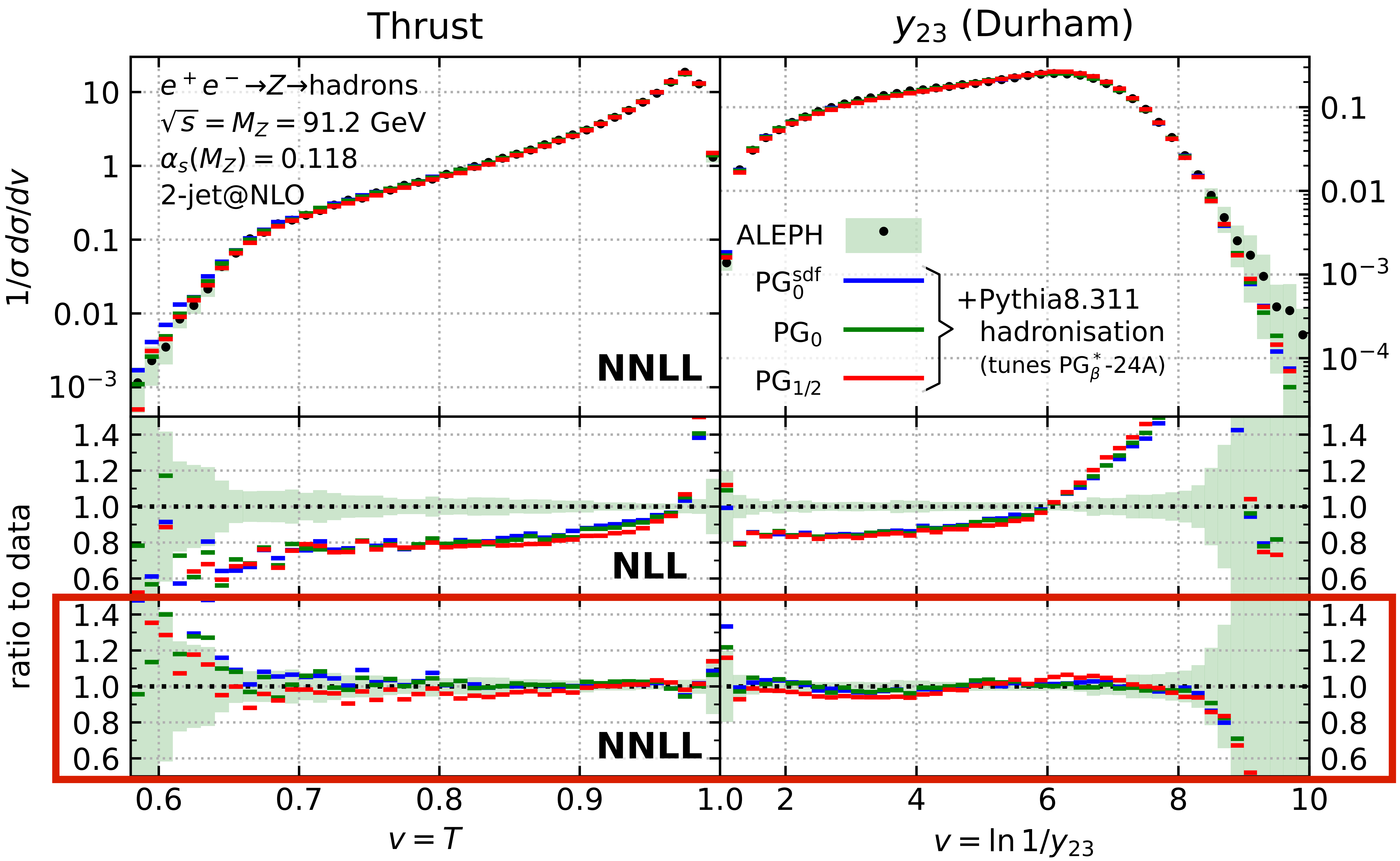
And new NNLL calculations against which to verify the results

non-global logarithms: Banfi, Dreyer, Monni, 2104.06416

subjet multiplicity: Medves, Soyez, Soto Ontoso, 2205.02861

+ wider literature + work in progress

Comparing to LEP event-shape data



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

Conclusions

Took about 35 years to reach full NLL since the birth of parton showers …

Birth of Herwig (with elements of NLL for global observables)

slide from Pier Monni

SIMULATION OF QCD JETS INCLUDING SOFT GLUON INTERFERENCE

G. MARCHESINI
Istituto di Fisica dell'Università di Parma and INFN, Sezione di Milano, Italy

B.R. WEBBER*
CERN, Geneva, Switzerland

Received 21 March 1983
(Revised 14 December 1983)

We present a new Monte Carlo simulation scheme for jet evolution in perturbative QCD which takes into account the results of recent analyses of soft-gluon interference. Therefore, this scheme accounts correctly not only for the leading collinear singularities, as in previous schemes, but also for leading infrared singularities. In this first paper we study the basic features of gluon jet evolution such as: (i) the interference effects and the corresponding depletion of the parton distributions in the soft region; (ii) the approach to asymptopia; (iii) the efficiency of colour screening (preconfinement), which has been questioned recently by Bjorken.

MONTE CARLO SIMULATION OF GENERAL HARD PROCESSES WITH COHERENT QCD RADIATION*

G. MARCHESINI
Dipartimento di Fisica, Università di Parma, INFN, Gruppo Collegato di Parma, Italy

B.R. WEBBER
Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, UK

Received 8 February 1988

In this paper we extend our previous work on the simulation of coherent soft-gluon radiation to hard collisions that involve incoming as well as outgoing coloured partons. Existing simulations correctly sum the leading collinear singularities for initial- and final-state radiation, and in some cases the leading infrared contributions from outgoing partons, but not those for incoming (or the interference between incoming and outgoing). Asymptotically, however, the leading infrared and collinear contributions are comparable, the bulk of gluon emission occurring in the soft region. Furthermore, a correct treatment of leading infrared terms is necessary for the inclusive cancellation of singularities in the Sudakov form factor. We show how such a treatment may be formulated in terms of an angular ordering procedure applicable to all hard processes. We then describe a new Monte Carlo program which incorporates this procedure, together with other new features such as azimuthal correlations due to gluon polarization and interference. The program is designed as a general-purpose event generator, simulating hard lepton–lepton, lepton–hadron and hadron–hadron scattering in a single package. Simulation of soft hadronic collisions and underlying events is also included. We present the predictions of the program for a wide variety of processes, and compare them with analytical results and experimental data.

A MODEL FOR INITIAL STATE PARTON SHOWERS

Torbjörn SJÖSTRAND
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA

Received 25 February 1985

We present a detailed model for exclusive properties of initial state parton showers. A numerically efficient algorithm is obtained by tracing the parton showers backwards, i.e. start with the hard scattering partons and then successively reconstruct preceding branchings in falling sequence of spacelike virtualities Q^2 and rising sequence of parton energies. We show how the Altarelli–Parisi equations can be recast in a form suitable for this, and also discuss the kinematics of the branchings. The complete model is implemented in a Monte Carlo program, and some first results are presented.

Birth of Pythia

Parton showers beyond leading logarithmic accuracy

Mrinal Dasgupta,[1] Frédéric A. Dreyer,[2] Keith Hamilton,[3] Pier Francesco Monni,[4] Gavin P. Salam,[2,*] and Grégory Soyez[5]
[1] *Consortium for Fundamental Physics, School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom*
[2] *Rudolf Peierls Centre for Theoretical Physics, Parks Road, Oxford OX1 3PU, UK*
[3] *Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK*
[4] *CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland*
[5] *Institut de Physique Théorique, Université Paris-Saclay, CNRS, CEA, F-91191, Gif-sur-Yvette, France*

Parton showers are among the most widely used tools in collider physics. Despite their key importance, none so far has been able to demonstrate accuracy beyond a basic level known as leading logarithmic (LL) order, with ensuing limitations across a broad spectrum of physics applications. In this letter, we propose criteria for showers to be considered next-to-leading logarithmic (NLL) accurate. We then introduce new classes of shower, for final-state radiation, that satisfy the main elements of these criteria in the widely used large-N_C limit. As a proof of concept, we demonstrate these showers' agreement with all-order analytical NLL calculations for a range of observables, something never so far achieved for any parton shower.

General principles for a NLL parton shower (formulated for e^+e^-, many extensions will follow)

[ca. 800 papers on the subject of event generators ……………………………………………………]

. . . key steps towards NNLL were just O(5) years away

slide from Pier Monni

Birth of Herwig (with elements of NLL for global observables)

SIMULATION OF QCD JETS INCLUDING SOFT GLUON INTERFERENCE

G. MARCHESINI

Istituto di Fisica dell'Università di Parma
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Received 21 March 1983
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MONTE CARLO SIMULATION OF GENERAL HARD PROCESSES WITH COHERENT QCD RADIATION*

G MARCHESINI

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In this paper we extend our previous work on the simulation of coherent soft-gluon radiation to hard collisions that involve incoming as well as outgoing coloured partons Existing simulations correctly sum the leading collinear singularities for initial- and final-state radiation, and in some cases the leading infrared contributions from outgoing partons, but not those for incoming (or the interference between incoming and outgoing) Asymptotically, however, the leading infrared and collinear contributions are comparable, the bulk of gluon emission occurring in the soft region Furthermore, a correct treatment of leading infrared terms is necessary for the inclusive cancellation of singularities in the Sudakov form factor We show how such a treatment may be formulated in terms of an angular ordering procedure applicable to all hard processes We then describe a new Monte Carlo program which incorporates this procedure, together with other new features such as azimuthal correlations due to gluon polarization and interference The program is designed as a general-purpose event generator, simulating hard lepton–lepton, lepton–hadron and hadron–hadron scattering in a single package Simulation of soft hadronic collisions and underlying events is also included We present the predictions of the program for a wide variety of processes, and compare them with analytical results and experimental data

General principles for NNLL parton showers

A new standard for the logarithmic accuracy of parton showers

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We report on a major milestone in the construction of logarithmically accurate final-state parton showers, achieving next-to-next-to-leading-logarithmic (NNLL) accuracy for the wide class of observables known as event shapes. The key to this advance lies in the identification of the relation between critical NNLL analytic resummation ingredients and their parton-shower counterparts. Our analytic discussion is supplemented with numerical tests of the logarithmic accuracy of three shower variants for more than a dozen distinct event-shape observables in $Z \to q\bar{q}$ and Higgs $\to gg$ decays. The NNLL terms are phenomenologically sizeable, as illustrated in comparisons to data.

A MODEL FOR INITIAL STATE PARTON SHOWERS

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We present a detailed model for exclusive properties of initial state parton showers. A numerically efficient algorithm is obtained by tracing the parton showers backwards, i.e. start with the hard scattering partons and then successively reconstruct preceding branchings in falling sequence of spacelike virtualities Q^2 and rising sequence of parton energies. We show how the Altarelli–Parisi equations can be recast in a form suitable for this, and also discuss the kinematics of the branchings. The complete model is implemented in a Monte Carlo program, and some first results are presented.

Birth of Pythia

Parton showers beyond leading logarithmic accuracy

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Parton showers are among the most widely used tools in collider physics. Despite their key importance, none so far has been able to demonstrate accuracy beyond a basic level known as leading logarithmic (LL) order, with ensuing limitations across a broad spectrum of physics applications. In this letter, we propose criteria for showers to be considered next-to-leading logarithmic (NLL) accurate. We then introduce new classes of shower, for final-state radiation, that satisfy the main elements of these criteria in the widely used large-N_C limit. As a proof of concept, we demonstrate these showers' agreement with all-order analytical NLL calculations for a range of observables, something never so far achieved for any parton shower.

Parton showering with higher-logarithmic accuracy for soft emissions

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The accuracy of parton-shower simulations is often a limiting factor in the interpretation of data from high-energy colliders. We present the first formulation of parton showers with accuracy one order beyond state-of-the-art next-to-leading logarithms, for classes of observable that are dominantly sensitive to low-energy (soft) emissions, specifically non-global observables and subjet multiplicities. This represents a major step towards general next-to-next-to-leading logarithmic accuracy for parton showers.

General principles for a NLL parton shower
(formulated for e^+e^-, many extensions will follow)

[ca. 800 papers on the subject of event generators ....]

Outlook

We now have solid foundations for discussing logarithmic accuracy of parton showers

First indications are that full NNLL is essential for precision phenomenology

Several important steps remain:

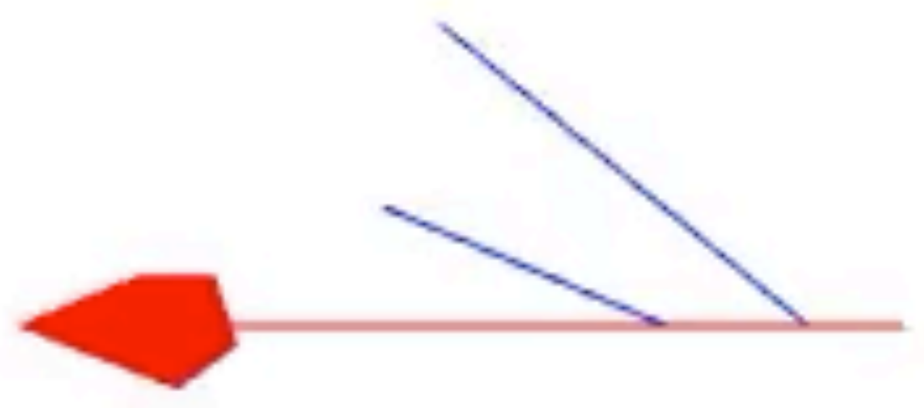
- NNLL for e^+e^-: including fully differential 1→ 3 & 1-loop 1→2 collinear splitting
- NNLL with initial-state hadrons
- log-accurate treatment of quark masses

A further critical missing element for general NNLL is easily available log-consistent (N)NLO matching.

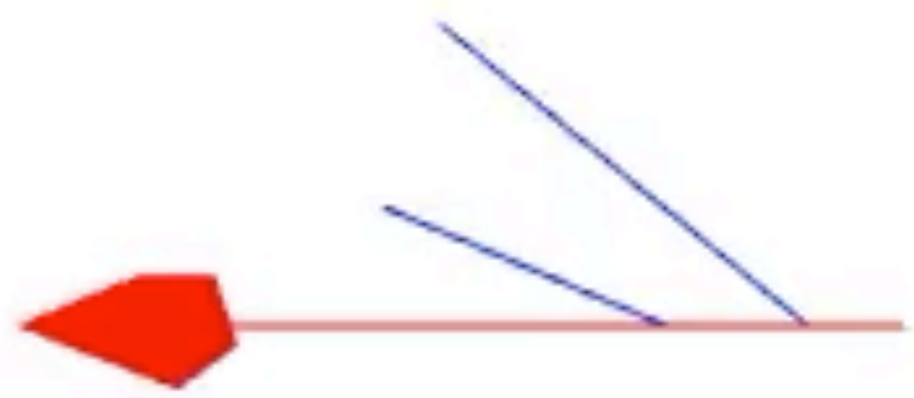
Code is available publicly: https://gitlab.com/panscales/panscales-0.X

backup

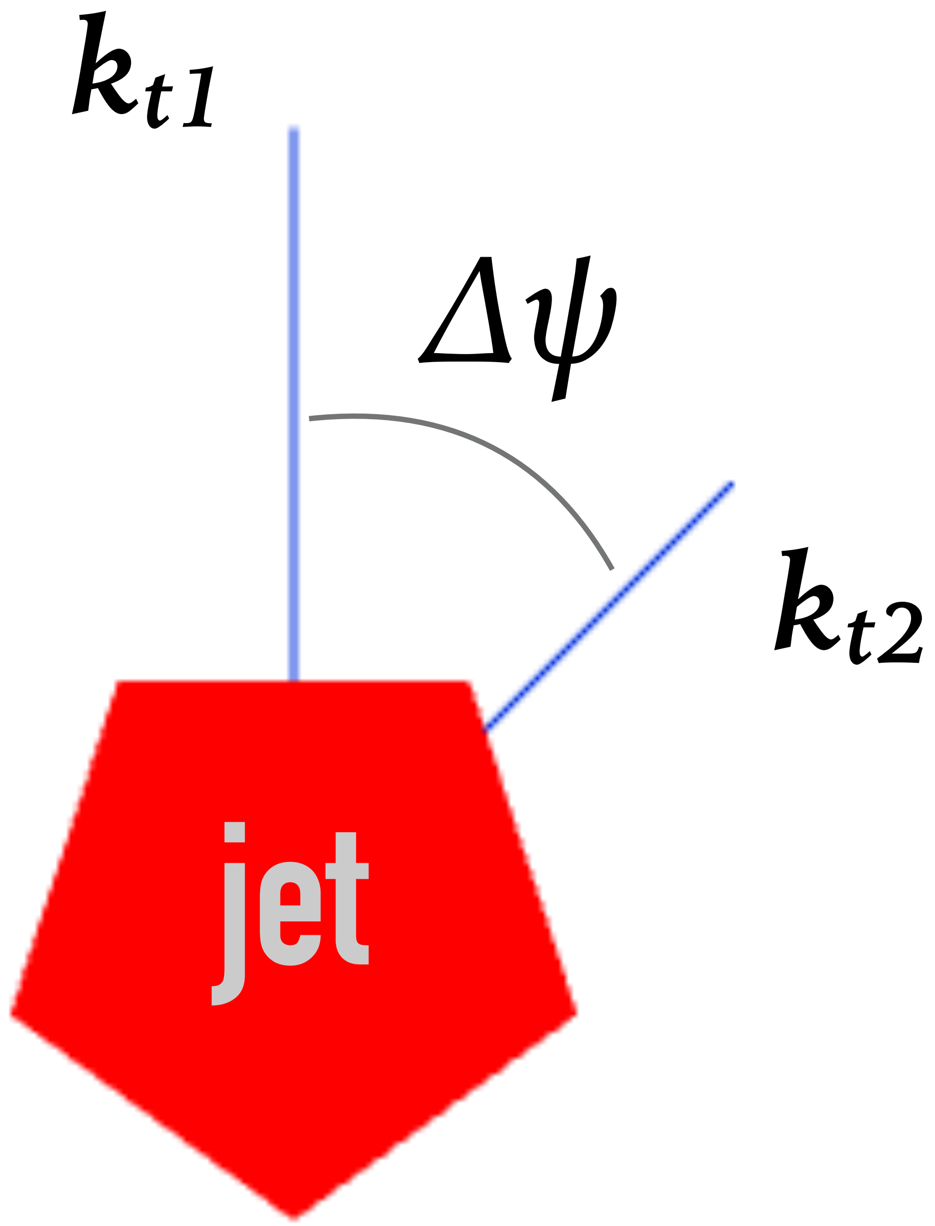
Concrete example: azimuthal structure in jets



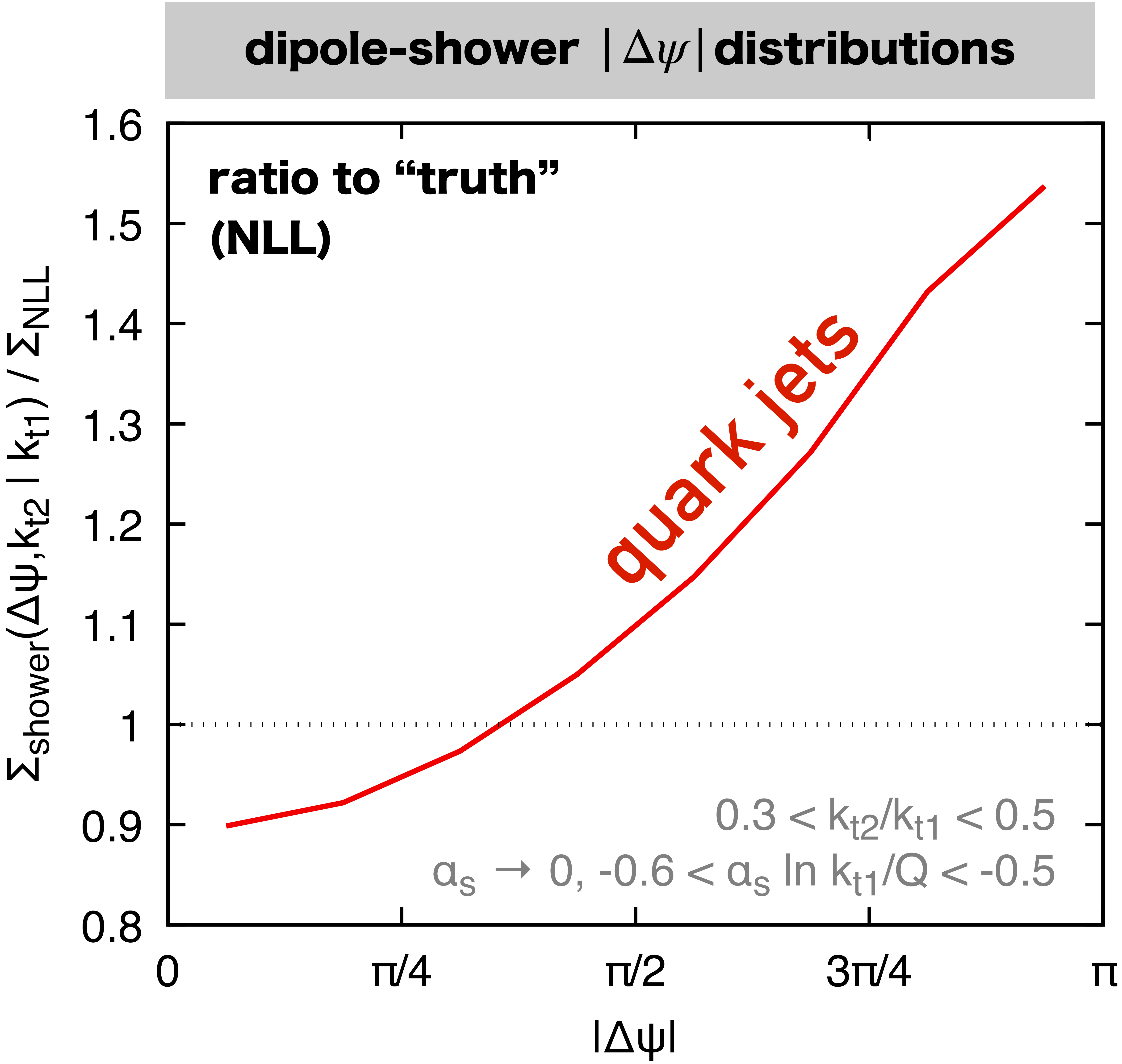
Concrete example: azimuthal structure in jets

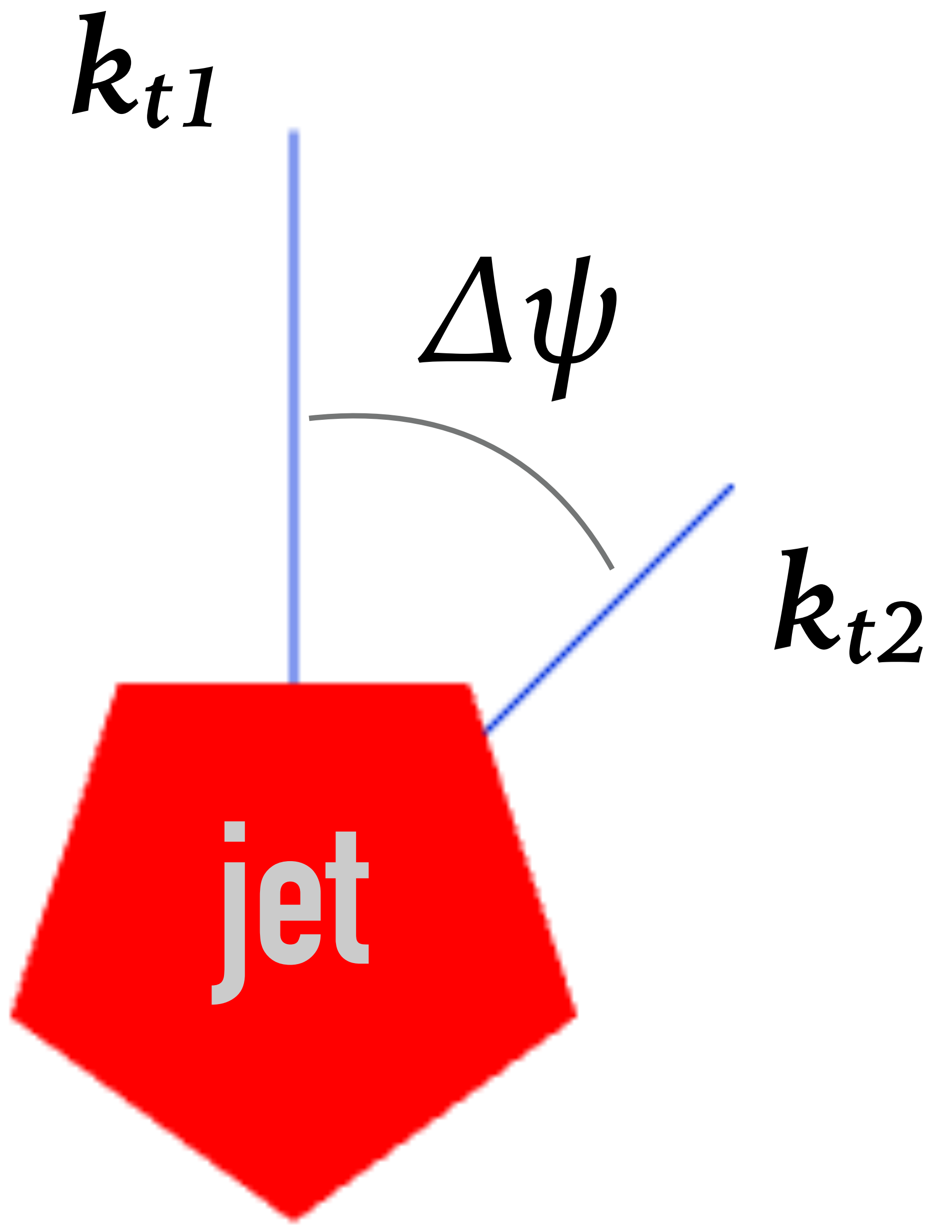


Concrete example: azimuthal structure in jets

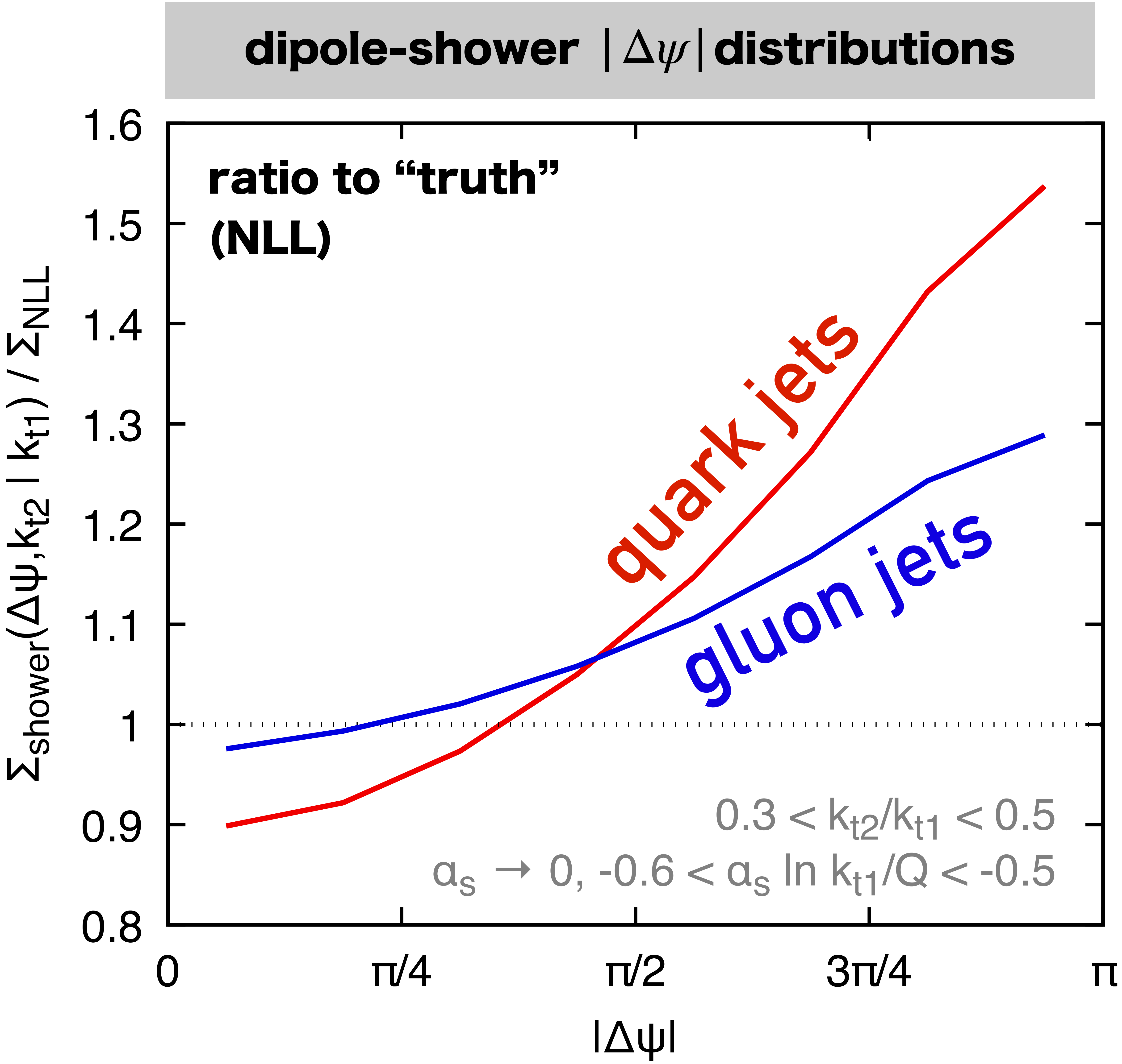


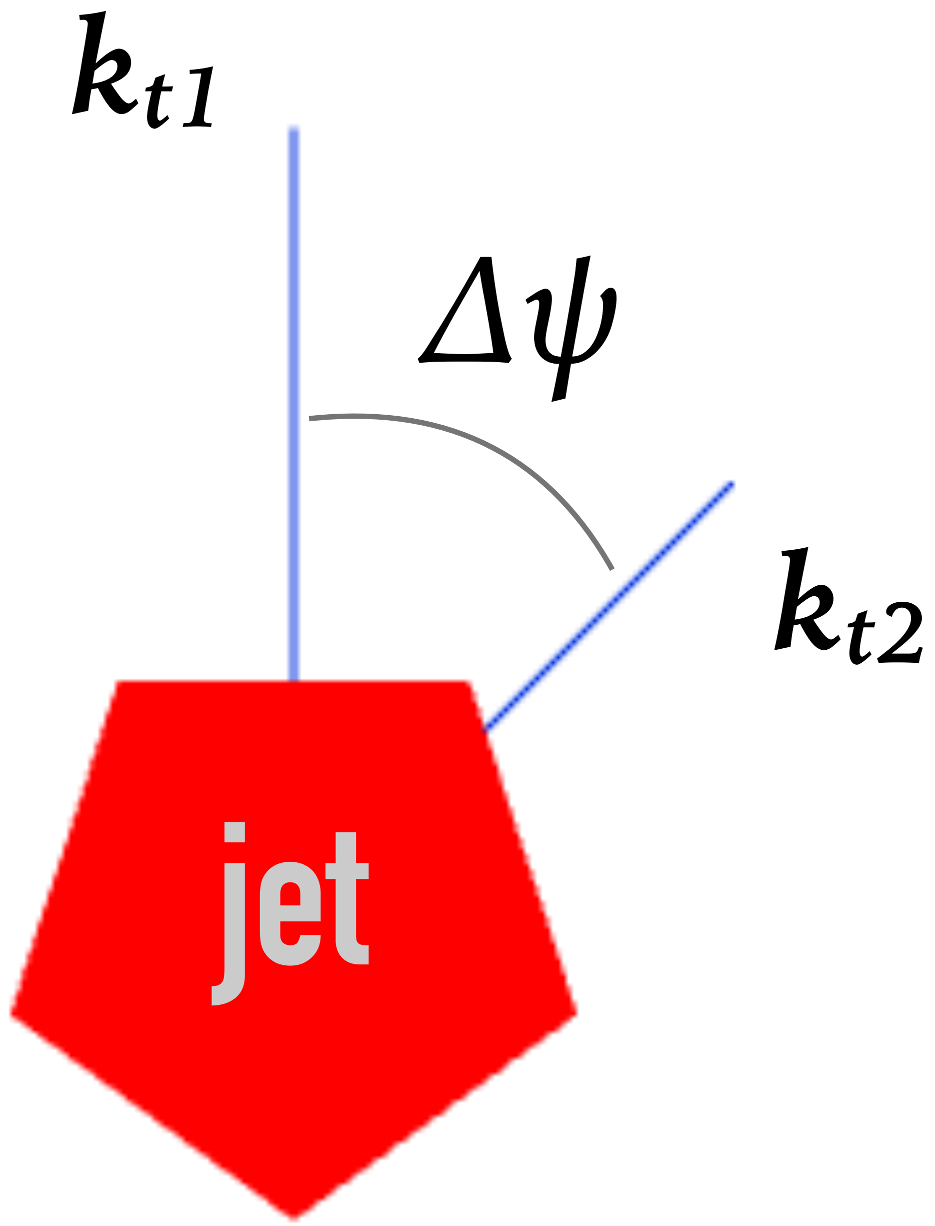
Concrete example: azimuthal structure in jets





Concrete example: azimuthal structure in jets





(machine-learning) quark/gluon discrimination trained on this simulation may **learn to exploit a feature that doesn't exist in real events**

CMS Lund plane measurements

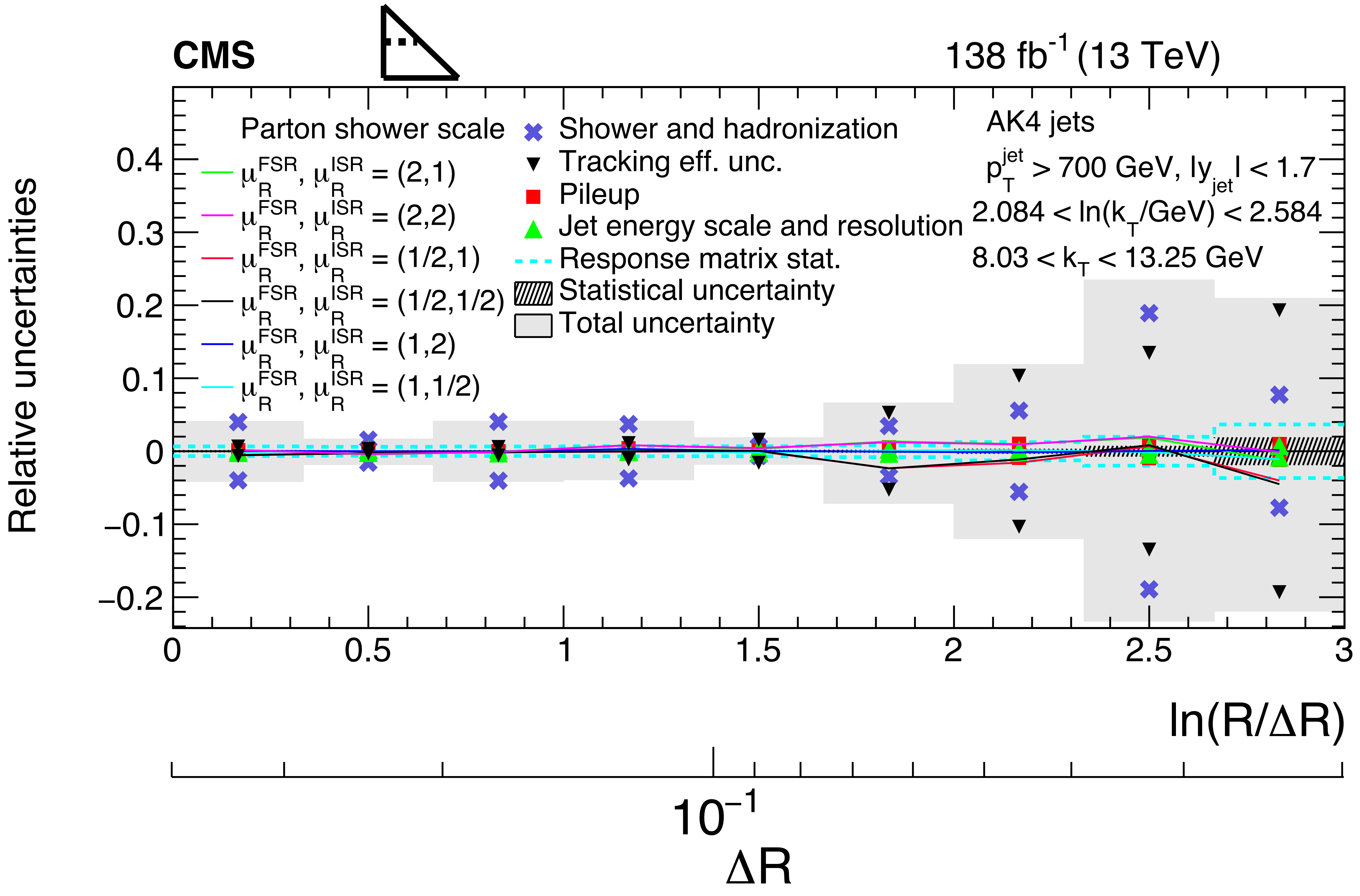
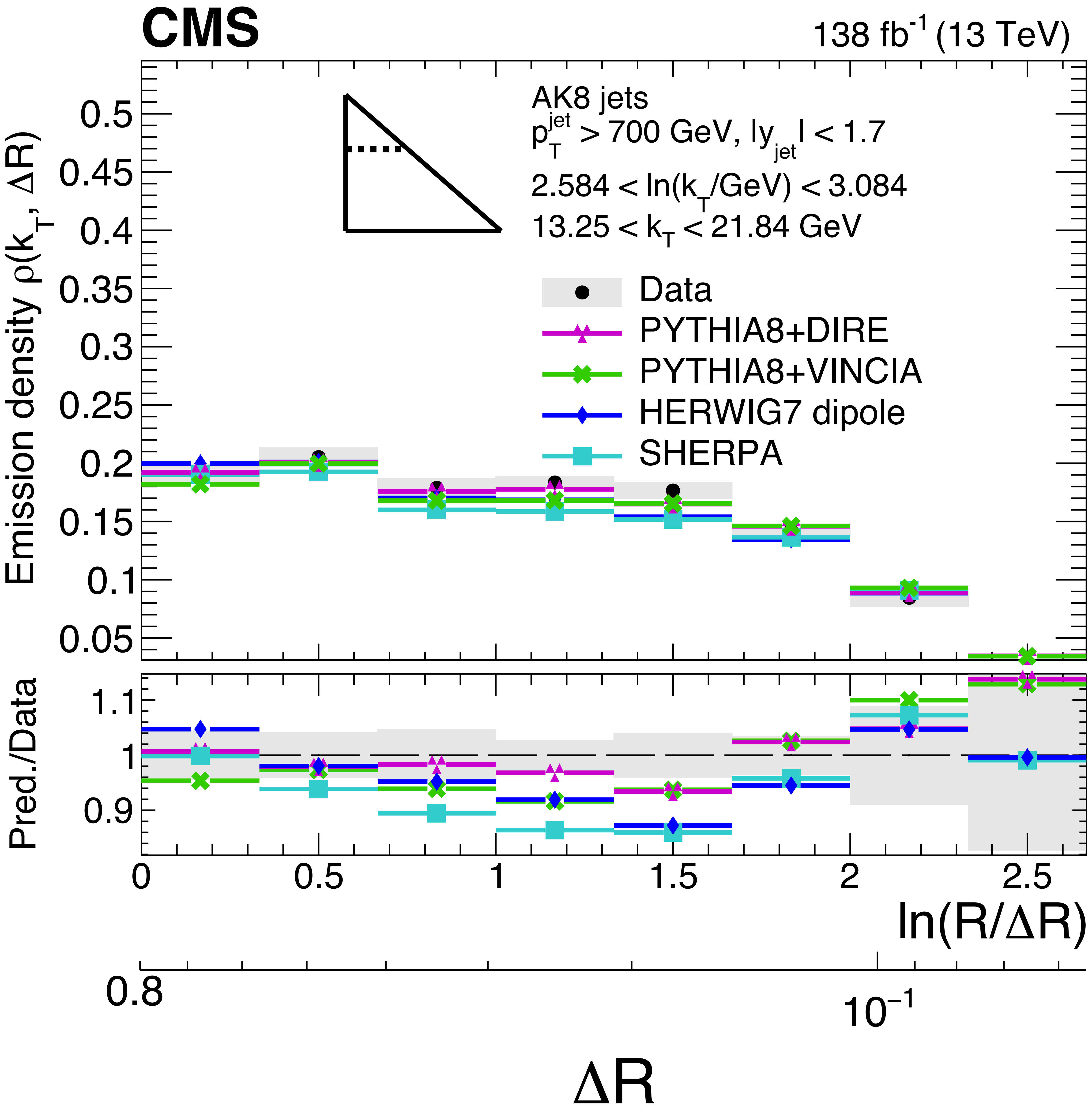
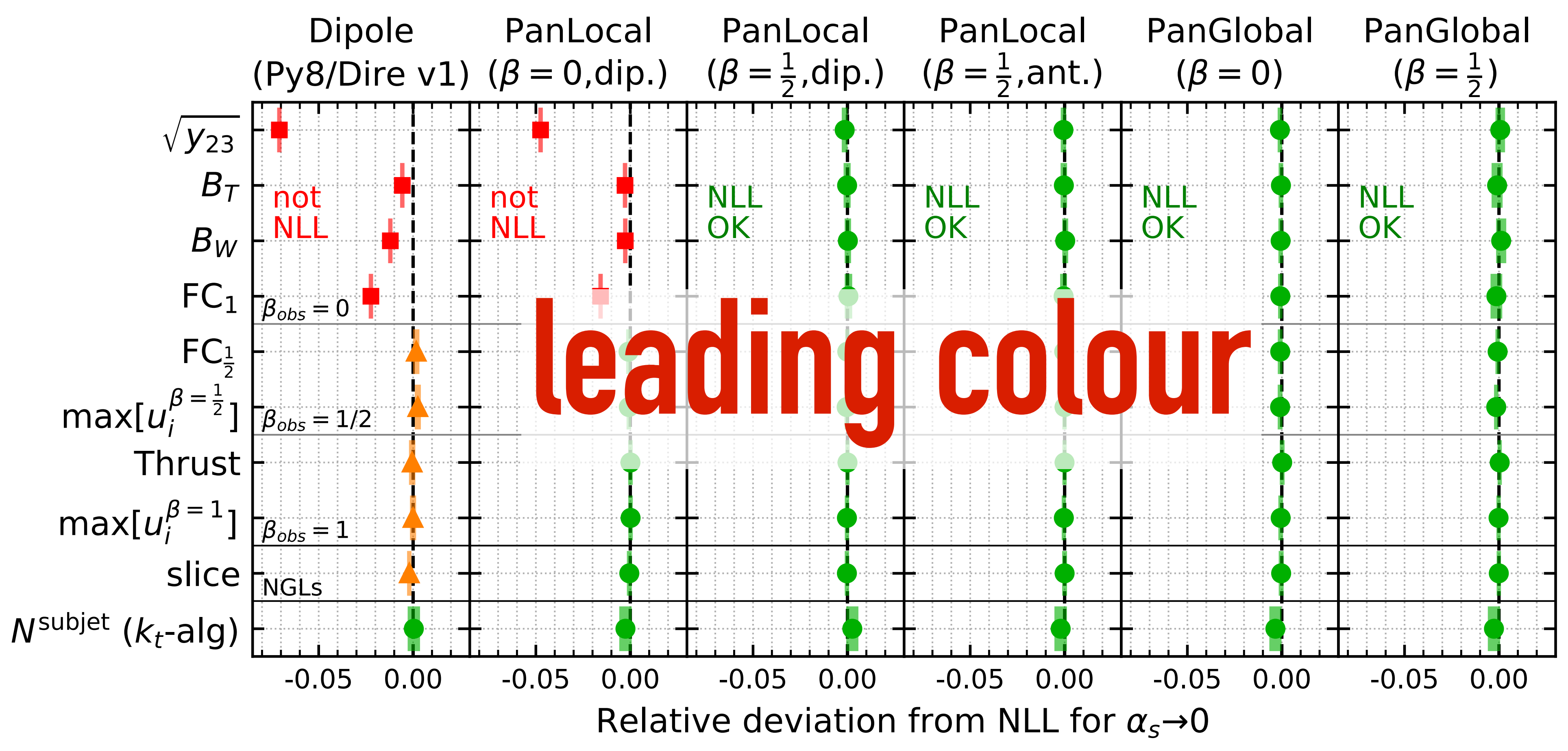
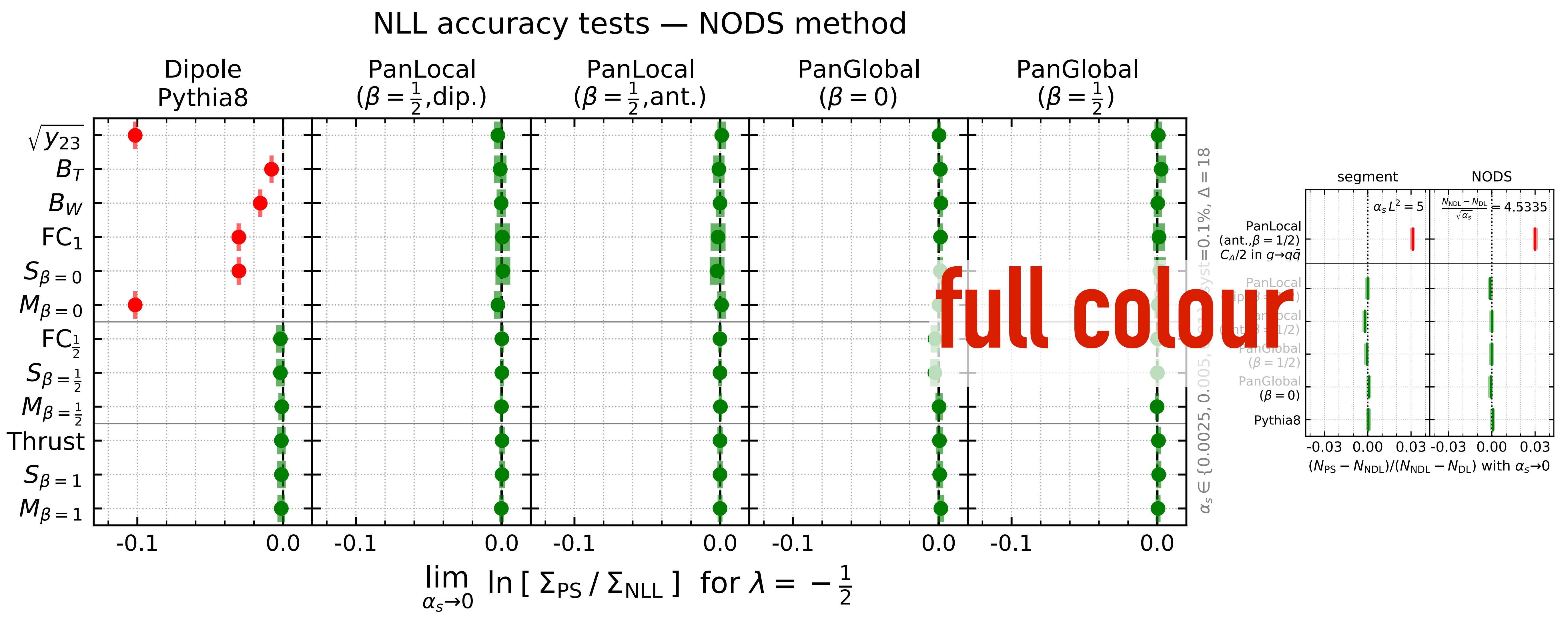


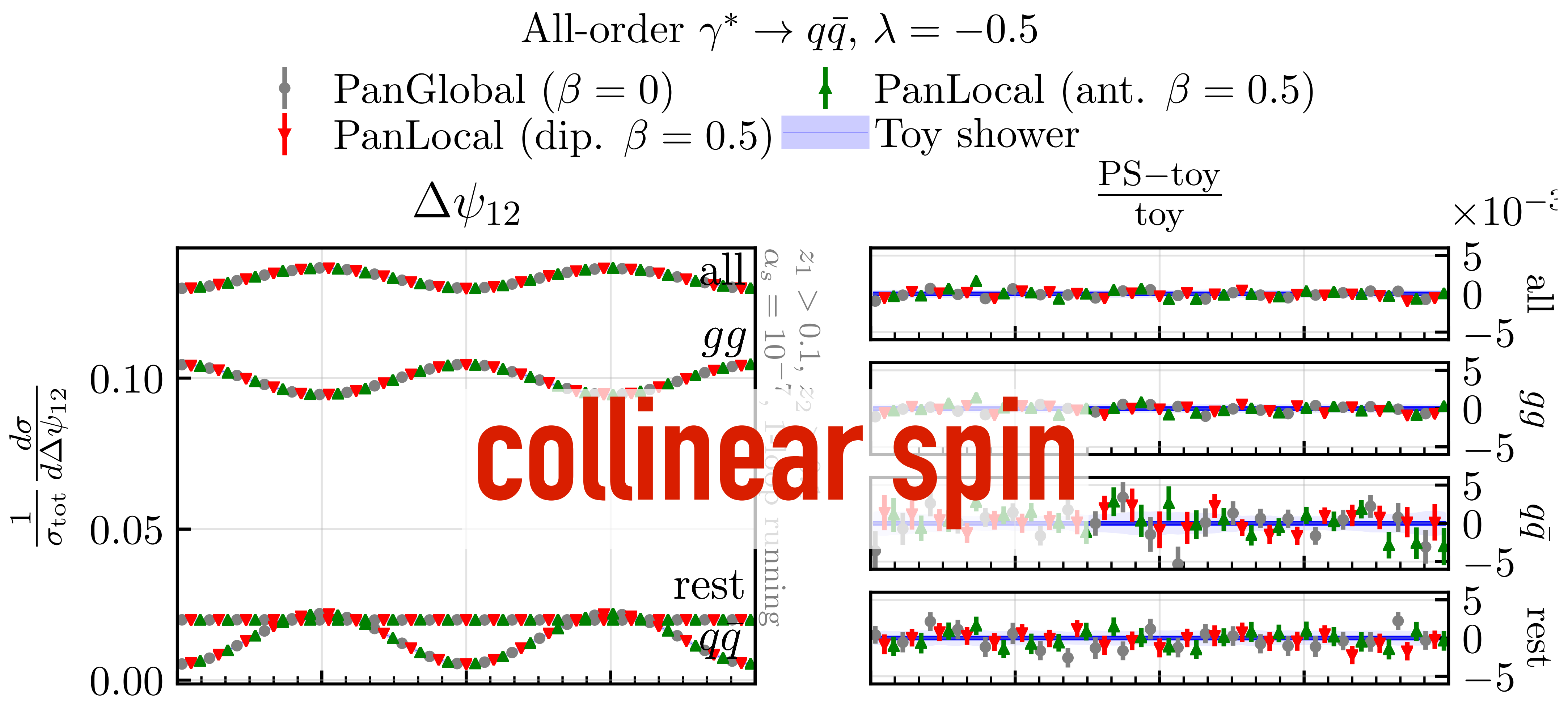
Figure 7: Different components of the systematic uncertainties for AK4 jets for different horizontal slices of the LJP density. The upper plot is for low k_T of $1.09 < k_T < 1.79$ GeV, and the lower plot is for higher k_T of $8.03 < k_T < 13.25$ GeV. The total experimental uncertainty is represented by the filled area. The statistical uncertainties in the data are represented by the hashed band.

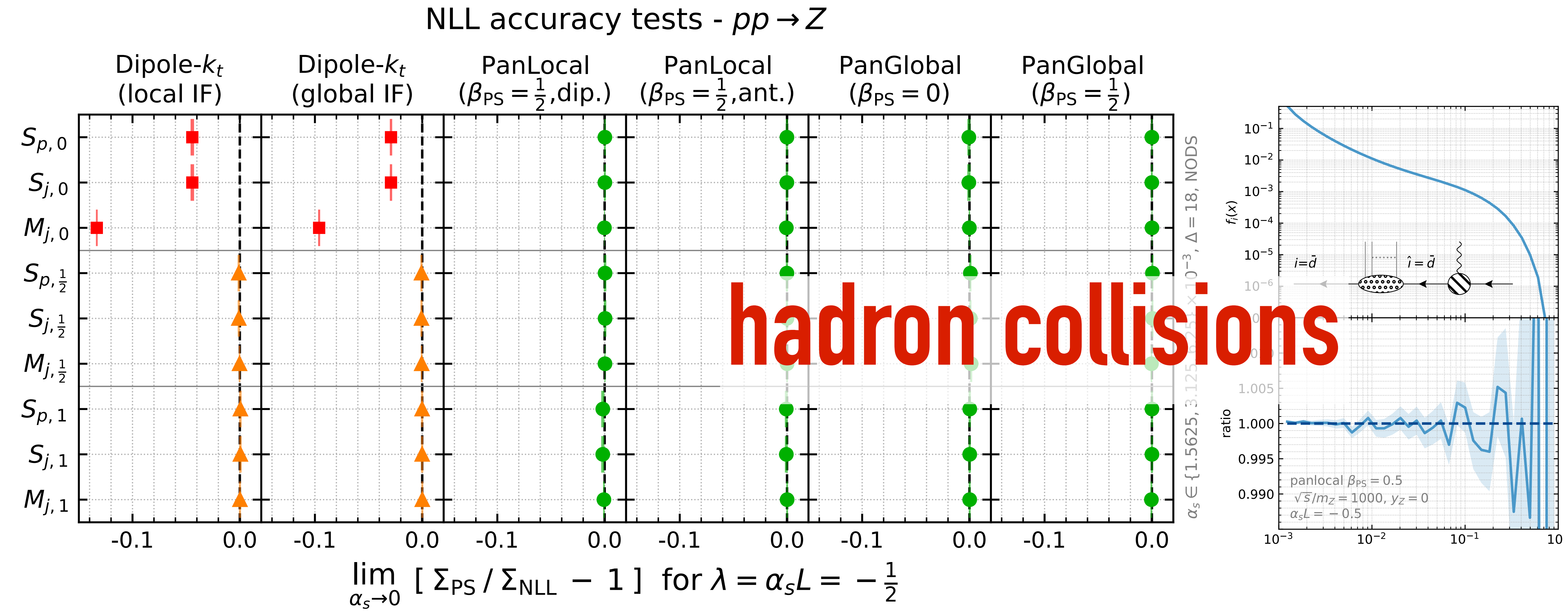


Test class 2: full shower v. all-order NLL — many observables

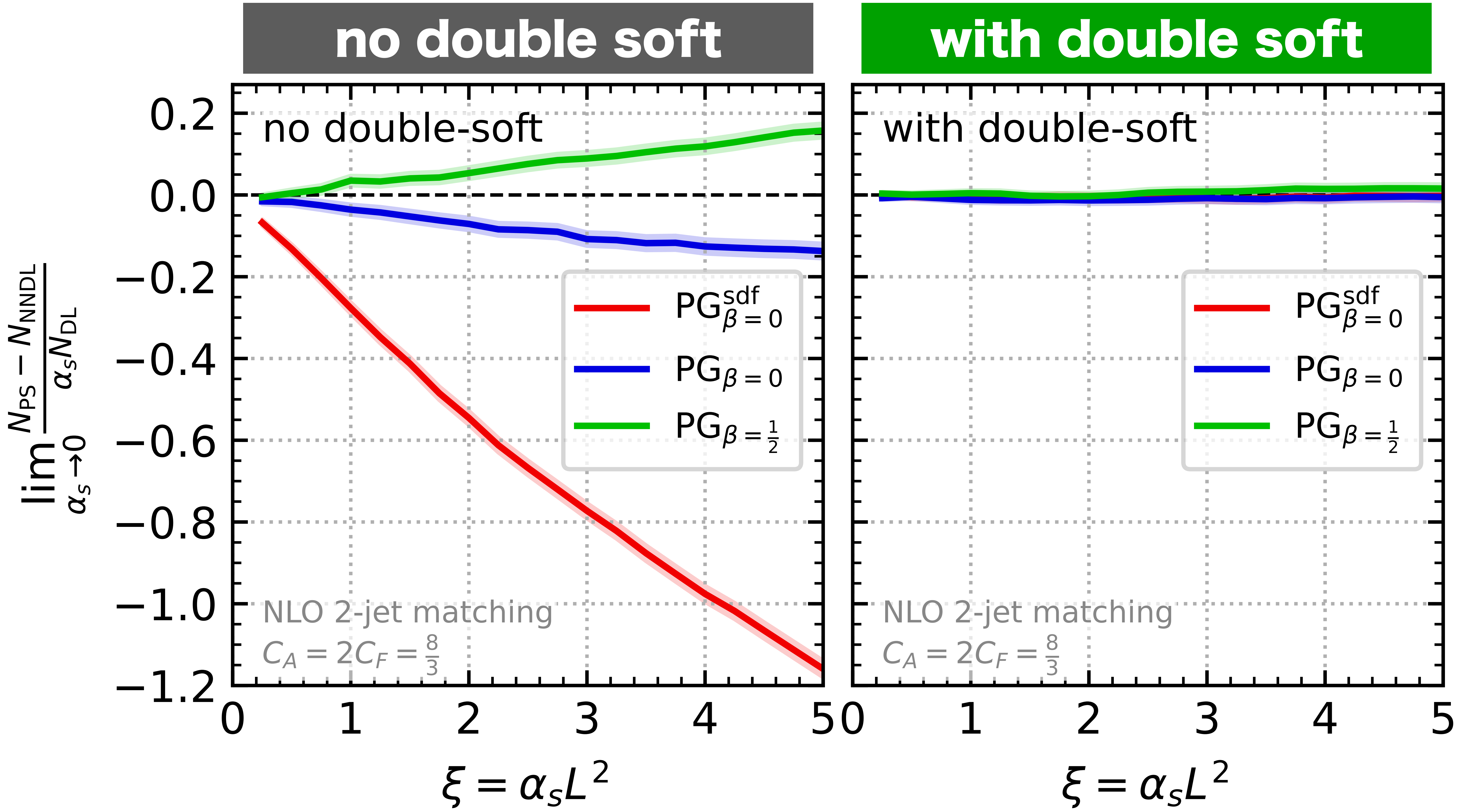








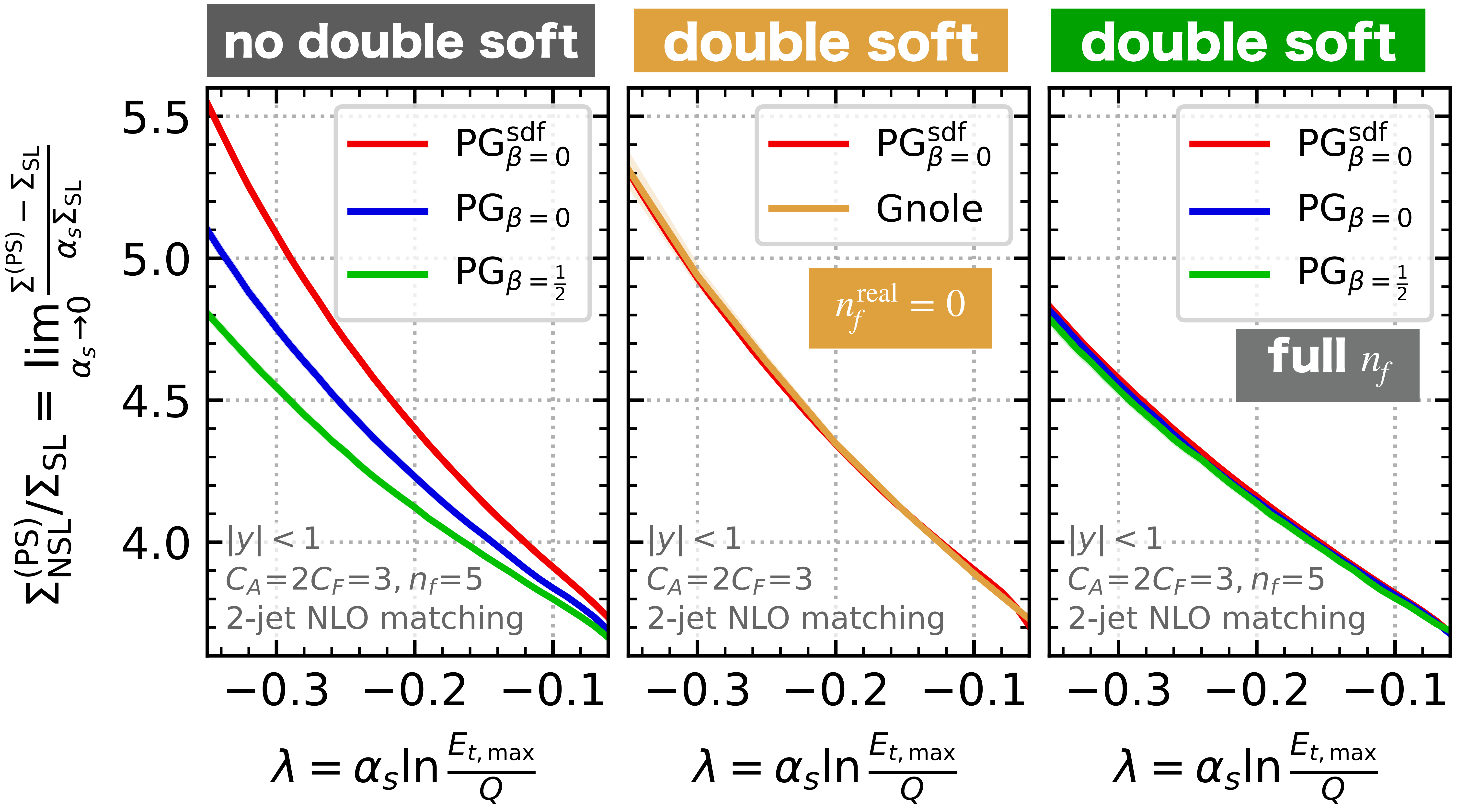
Log test #1: NNDL Lund subjet multiplicity



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

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

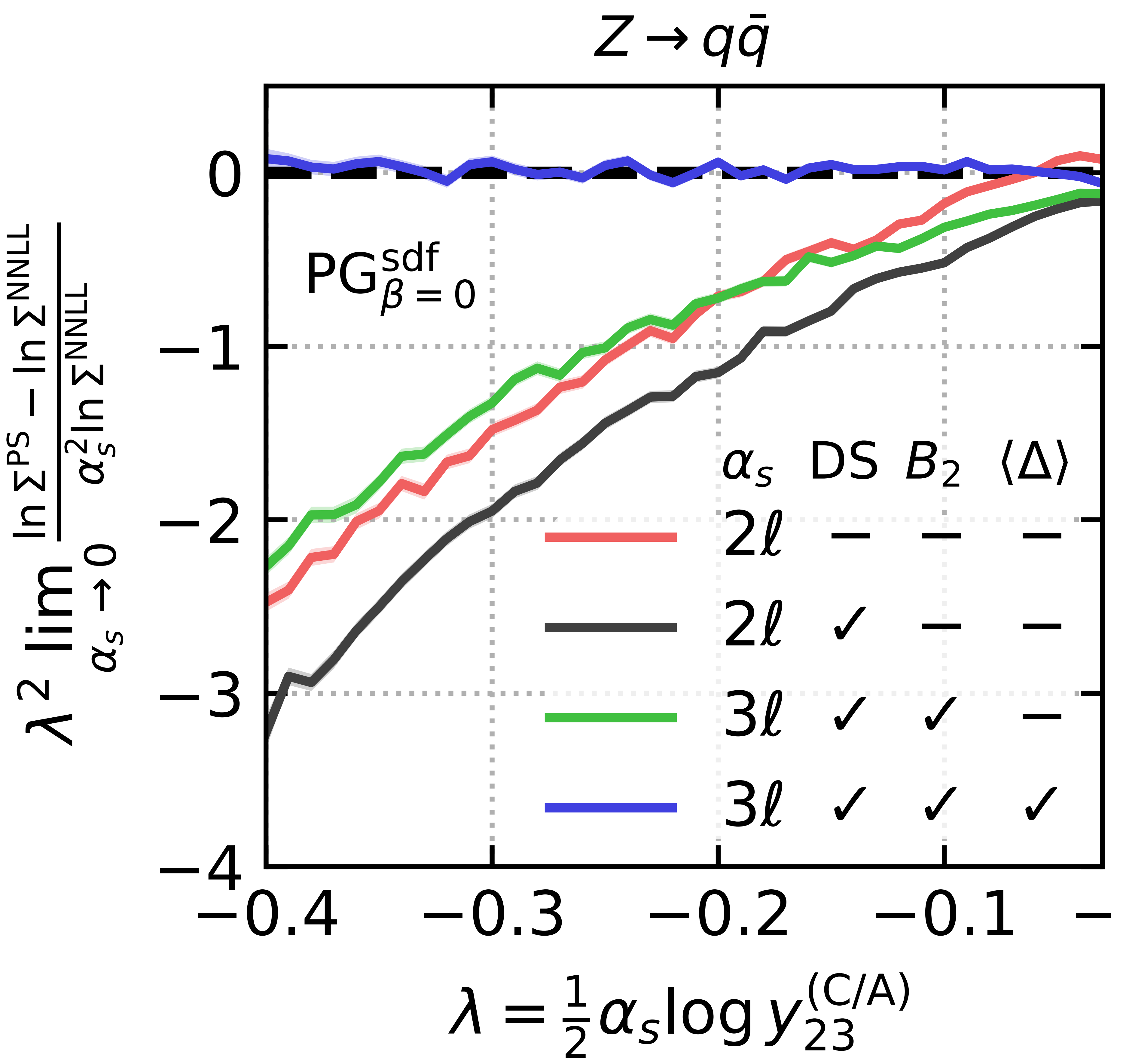
Log test #2: NSL for energy flow in slice

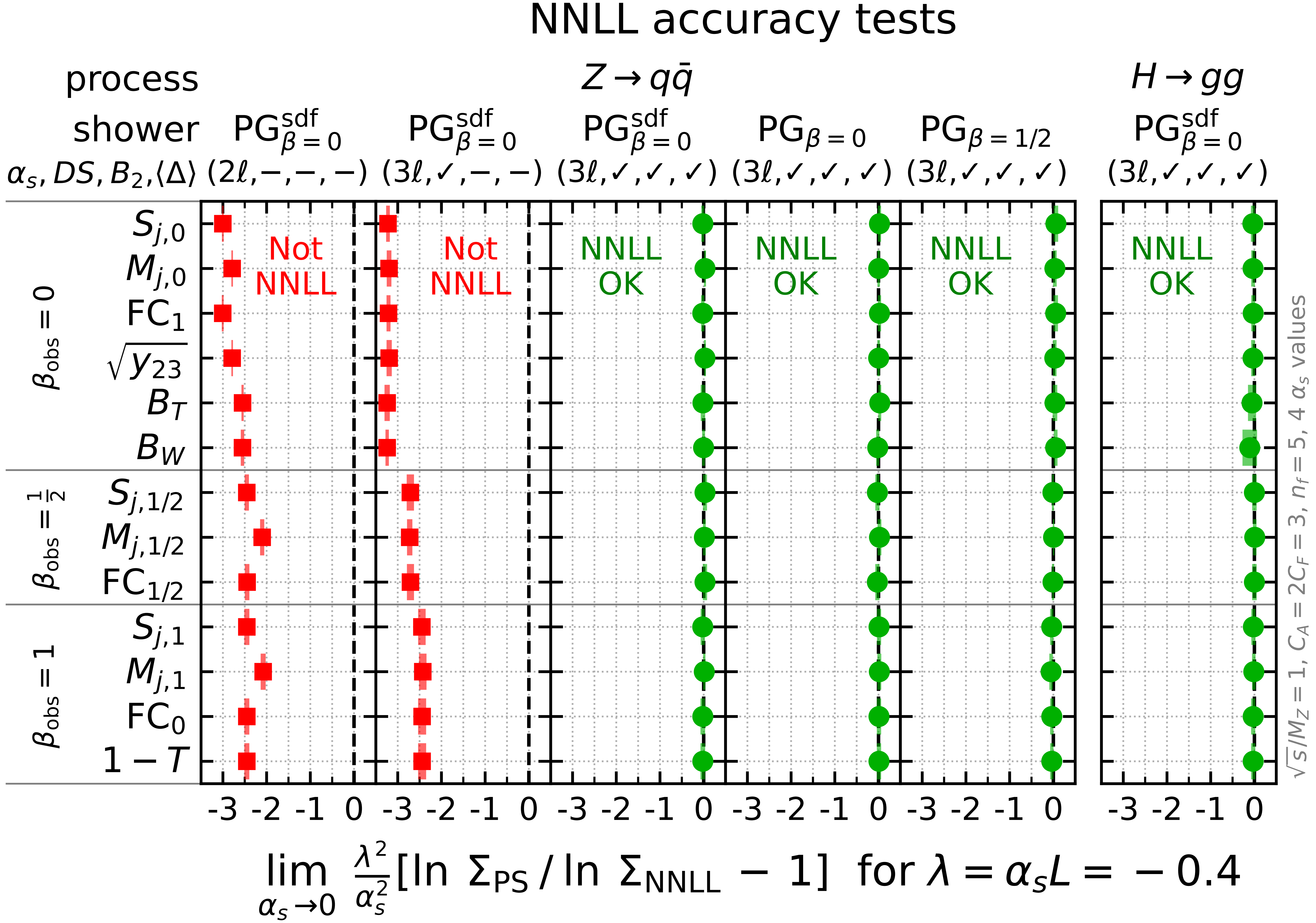


$$\Sigma^{(\mathrm{PS})}_{\mathrm{NSL}} = \lim_{\alpha_s \to 0} \left. \frac{\Sigma^{(\mathrm{PS})} - \Sigma_{\mathrm{SL}}}{\alpha_s} \right|_{\text{fixed } \alpha_s L}, \qquad L \equiv \ln \frac{E_{t,\max}}{Q}$$

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

Log test #3: NNLL global event shapes





van Beekveld, Dasgupta, El-Menoufi, Ferrario Ravasio, Hamilton, Helliwell, Karlberg, Monni, GPS, Scyboz, Soto-Ontoso, Soyez, 2406.02661