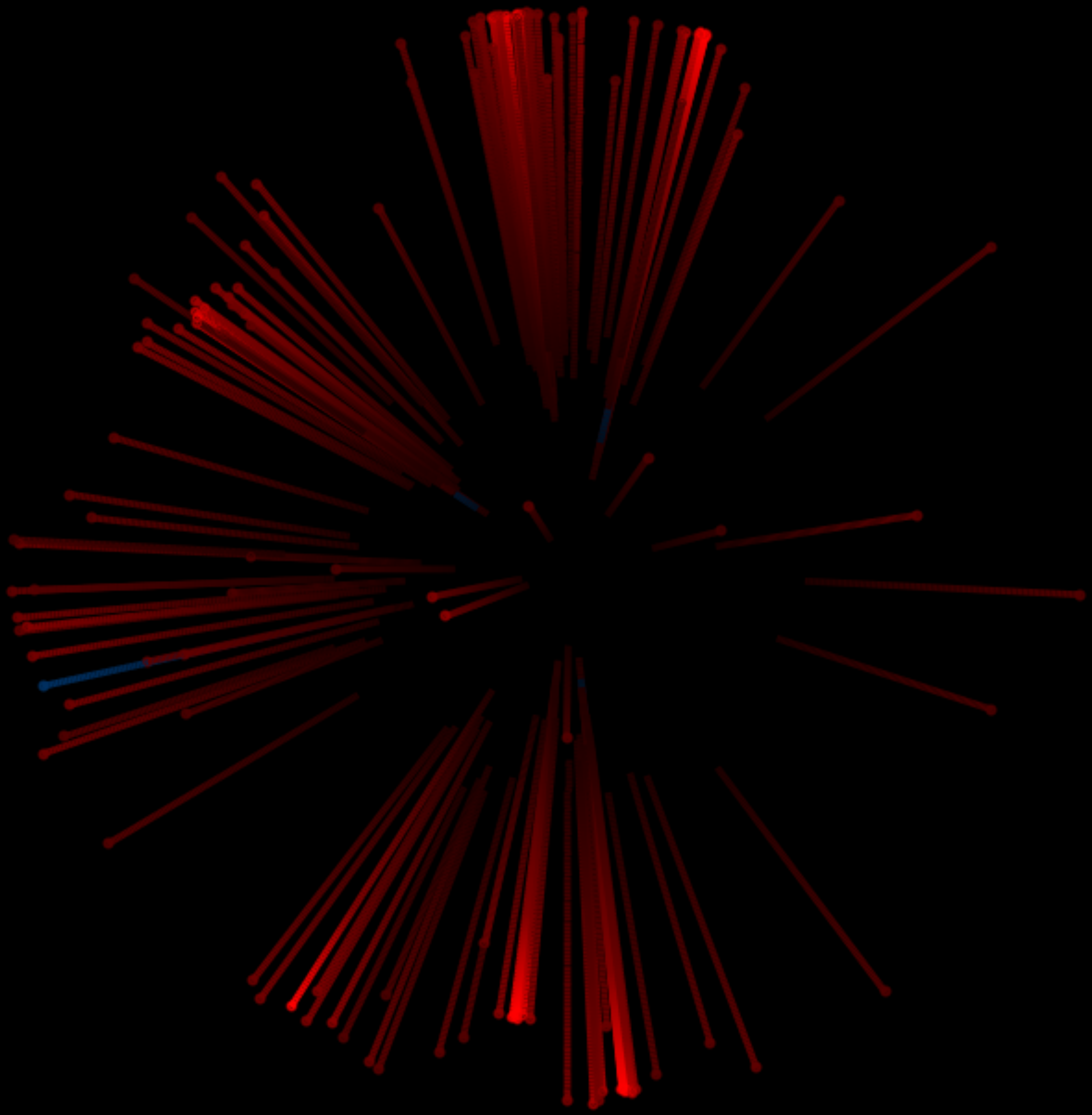
The power and limits of parton showers

KIT Particle Physics Colloquium
via Zoom
June 2021



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

THE ROYAL SOCIETY

UNIVERSITY OF OXFORD

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The context of this talk: LHC physics (colour-coded by directly-probed energy scales)

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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The context of this talk: LHC physics (colour-coded by directly-probed energy scales)

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100 MeV – 4 TeV

top-quark physics
170 GeV – O(TeV)

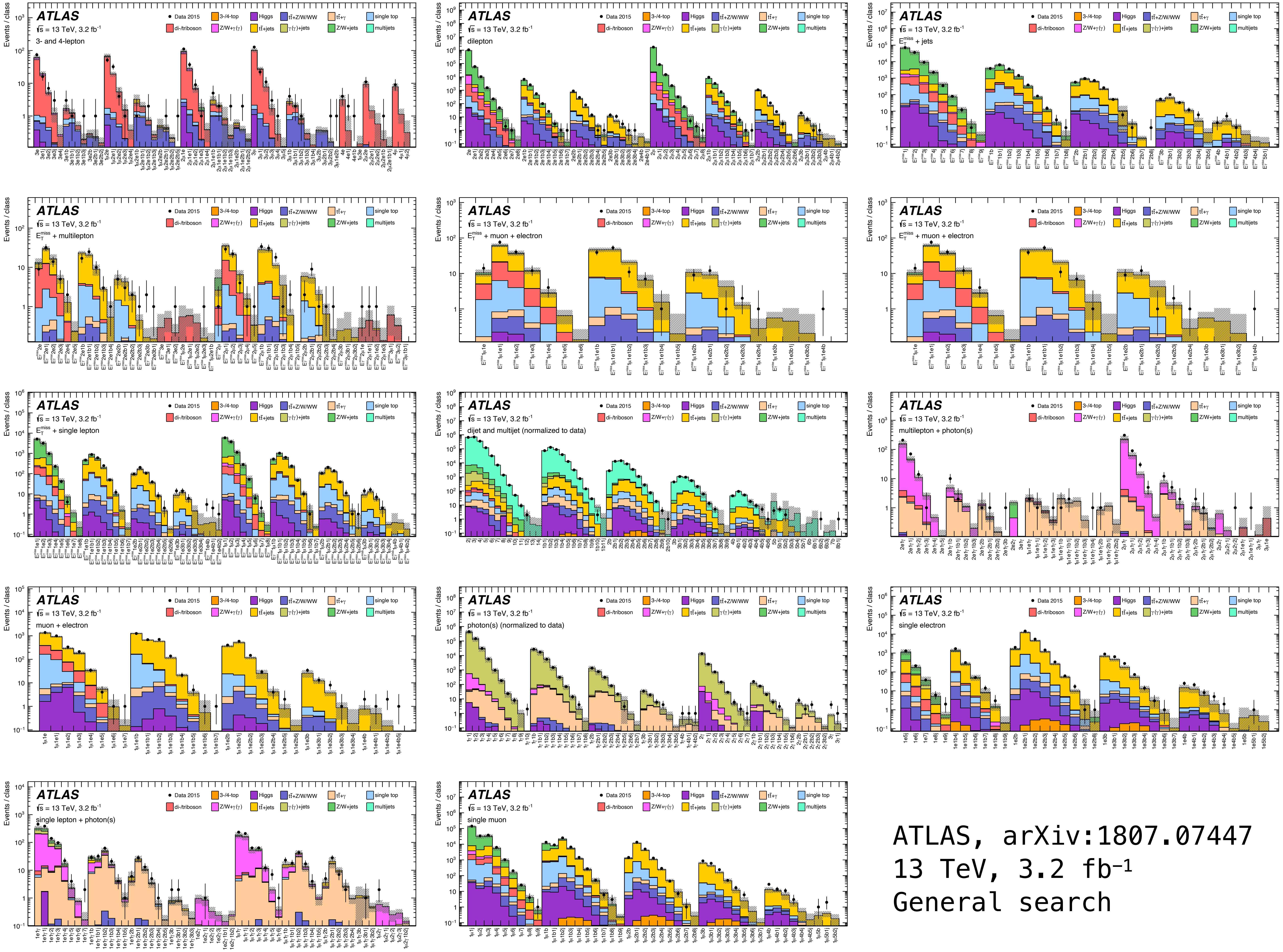
Higgs physics
125 GeV – 500 GeV

direct new-particle searches
100 GeV – 8 TeV

Key high-energy physics goals (my view)

1. Establish the structure of the Higgs sector of the SM
2. Search for signs of physics beyond the SM, direct (incl. dark matter candidates, SUSY, etc.) and indirect
3. Measure SM parameters, proton structure (PDFs), establish theory-data comparison methods, etc.

Broadband searches (here an example with 704 event classes)



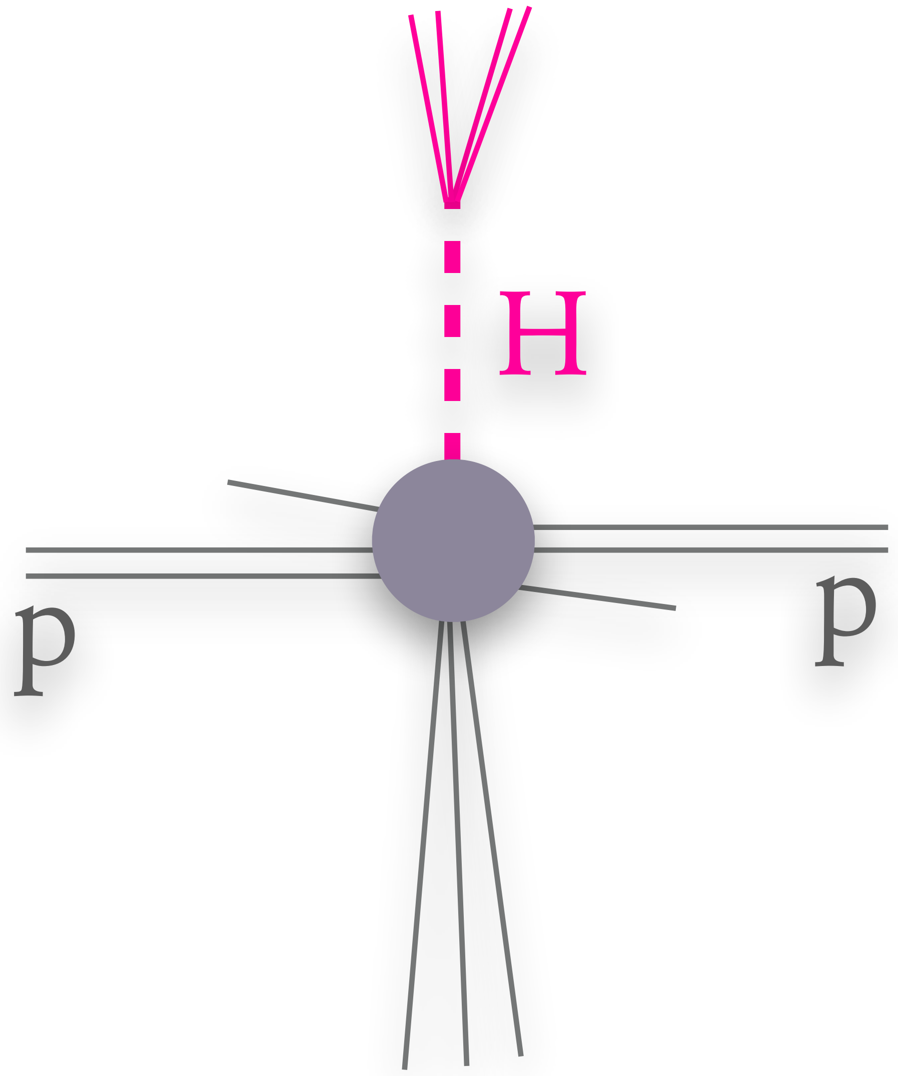
Just one illustration out of many searches at the LHC

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

high p_T Higgs & [SD] jet mass

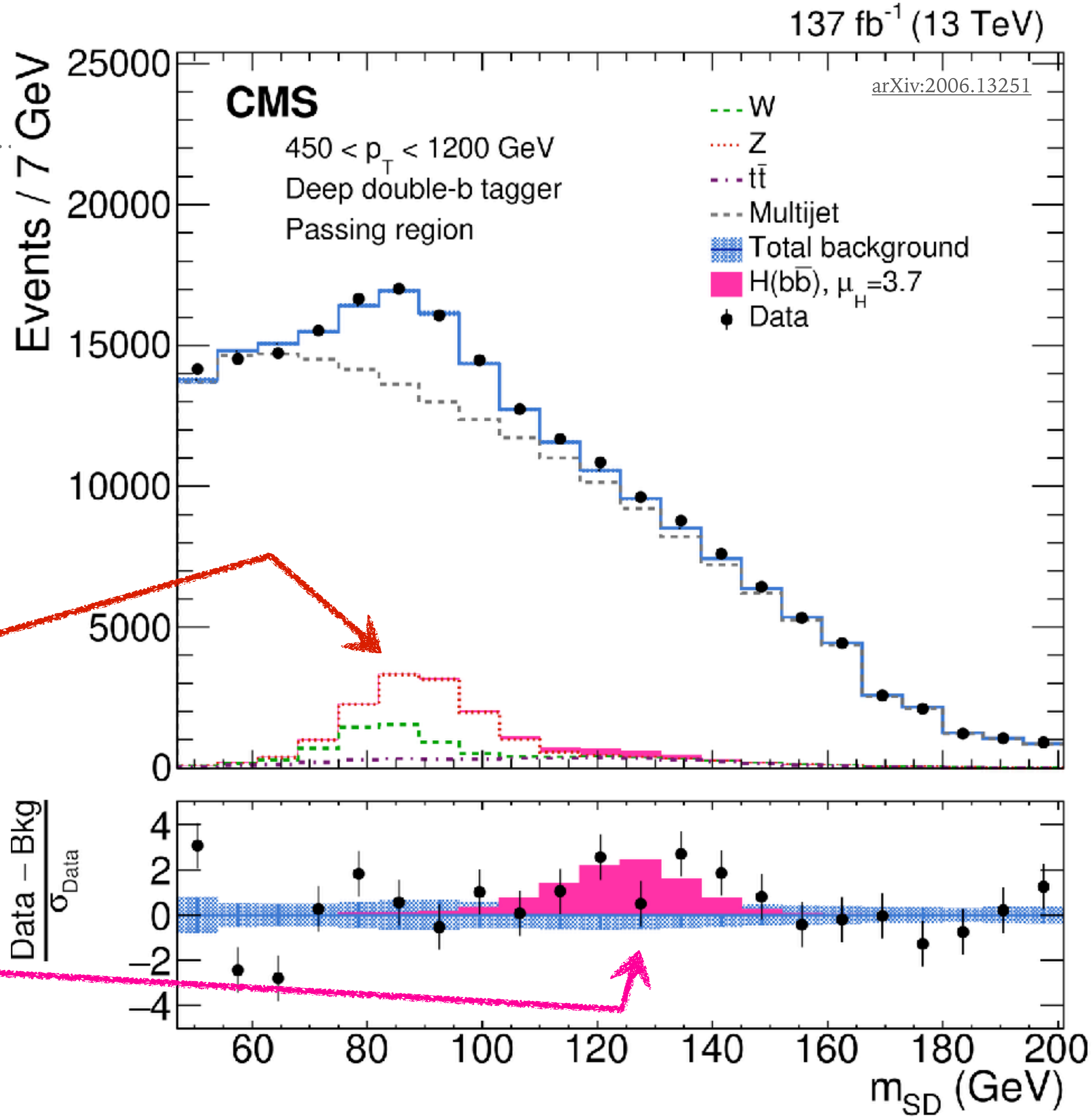
We wouldn't trust electromagnetism if we'd only tested it at one length/momentum scale.

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

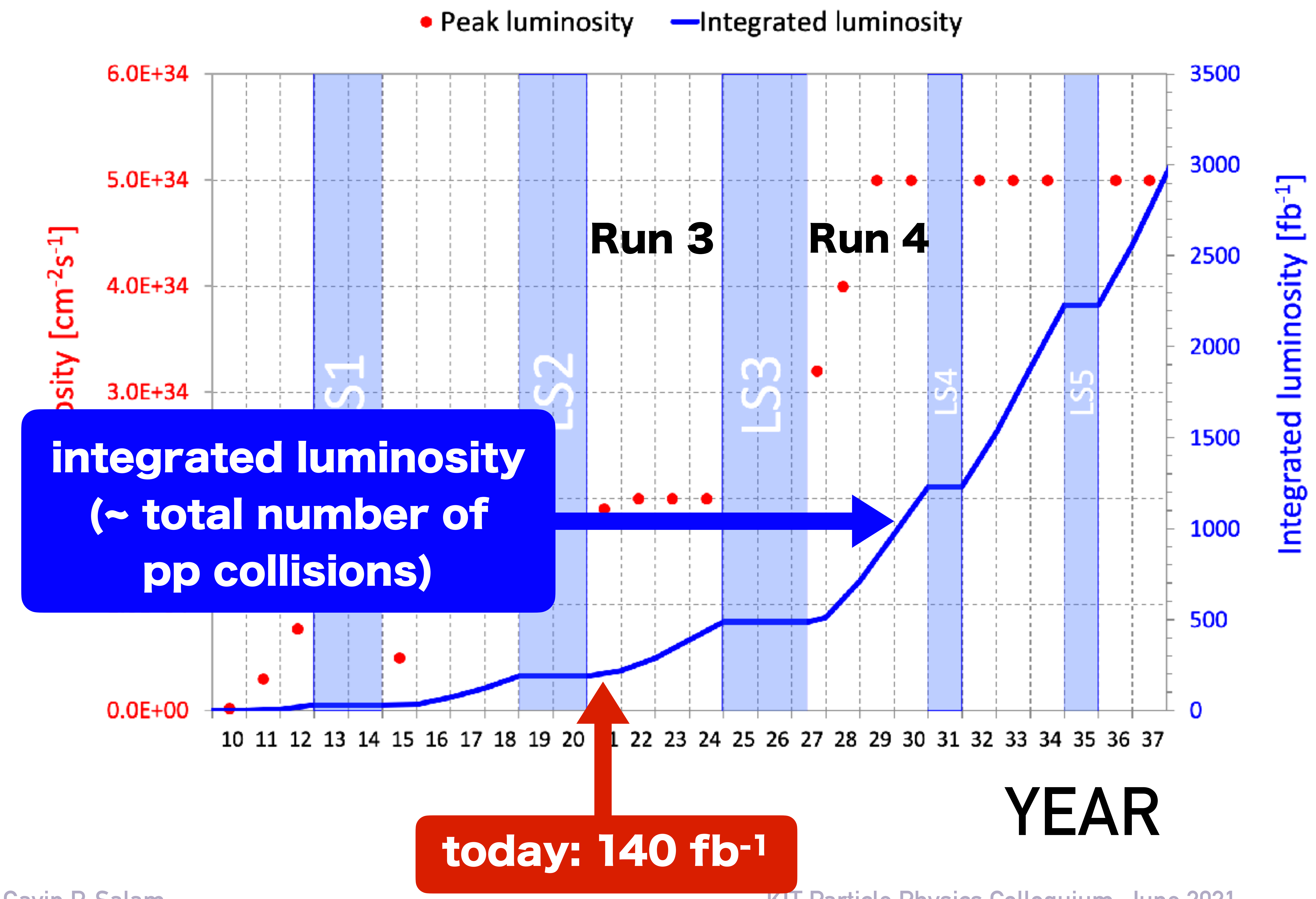


high-p_T
$Z \to bb$

high-p_T
$H \to bb$
(2.5 σ)



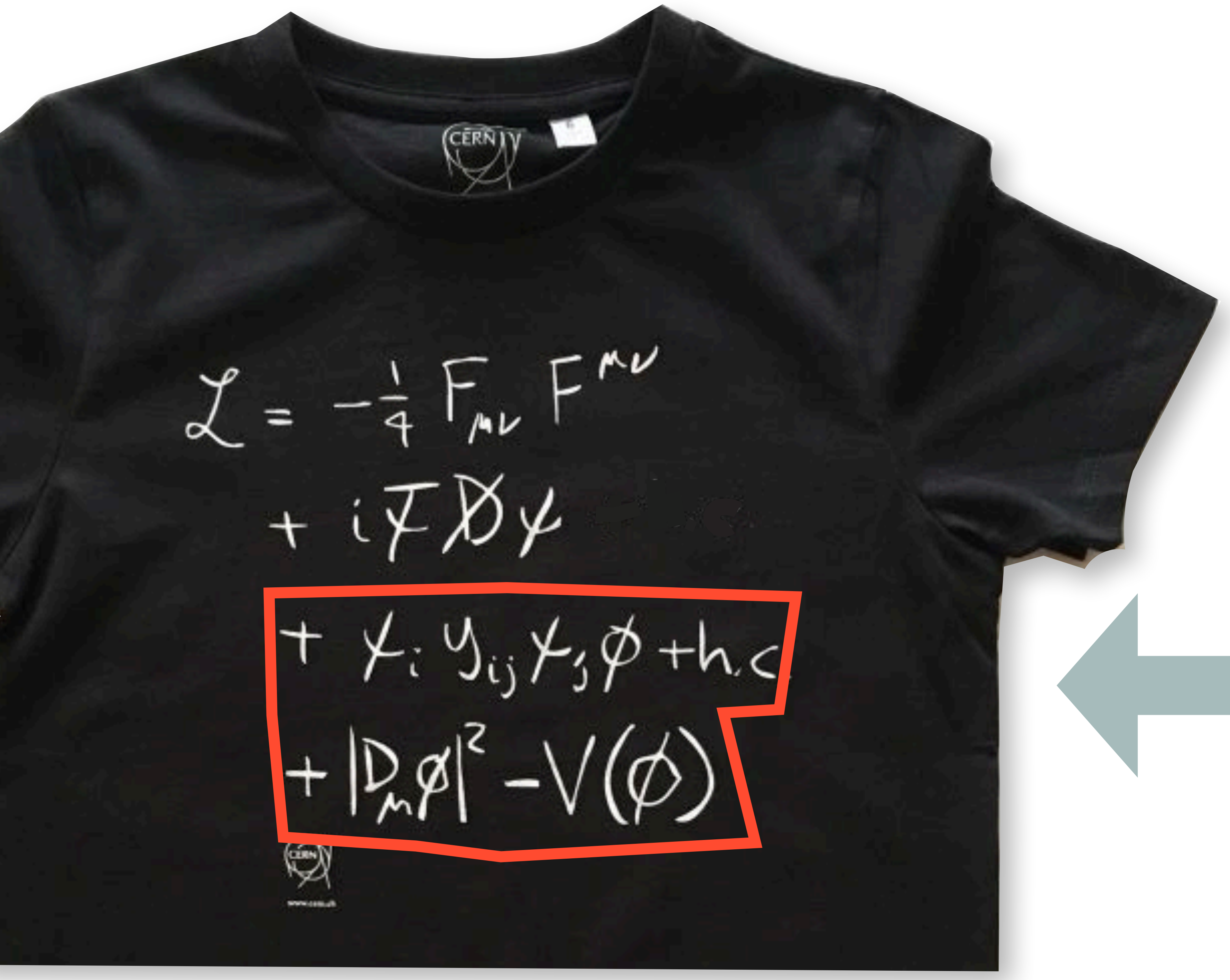
LHC luminosity v. time



year	lumi (fb^{-1})	
2020	140	
2025	450	(× 3)
2030	1200	(× 8)
2037	3000	(× 20)

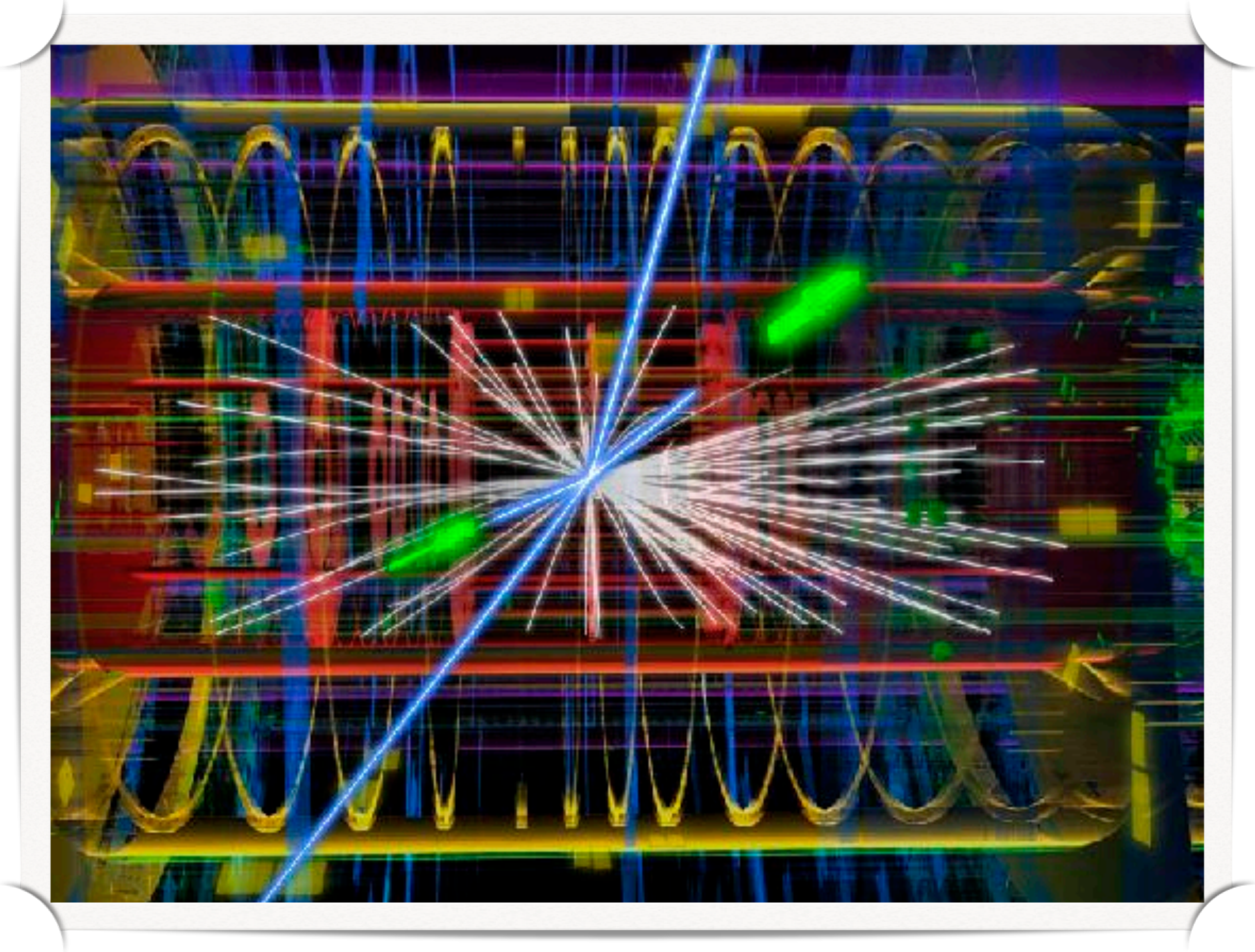
95% of collisions still to be delivered

UNDERLYING THEORY



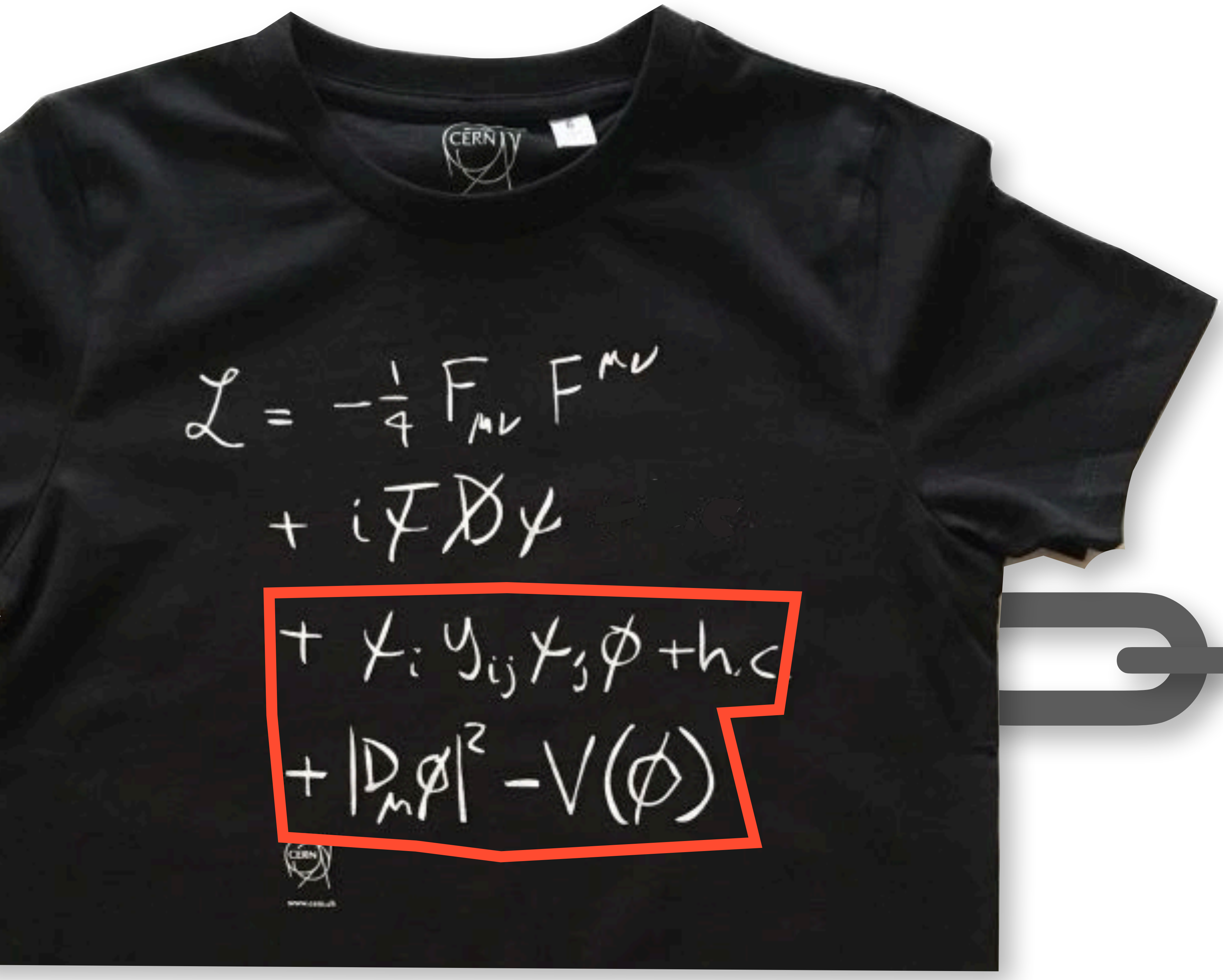
how do you make quantitative connection?

EXPERIMENTAL DATA

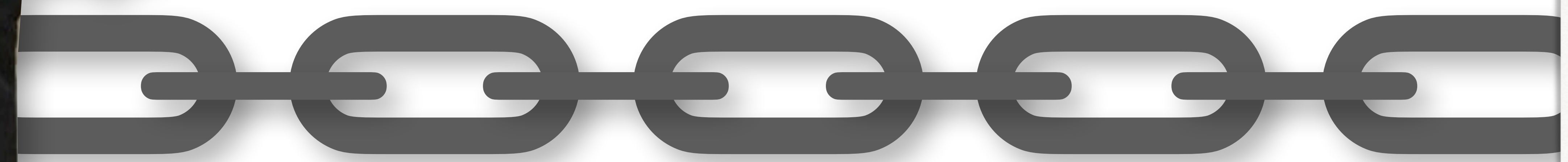


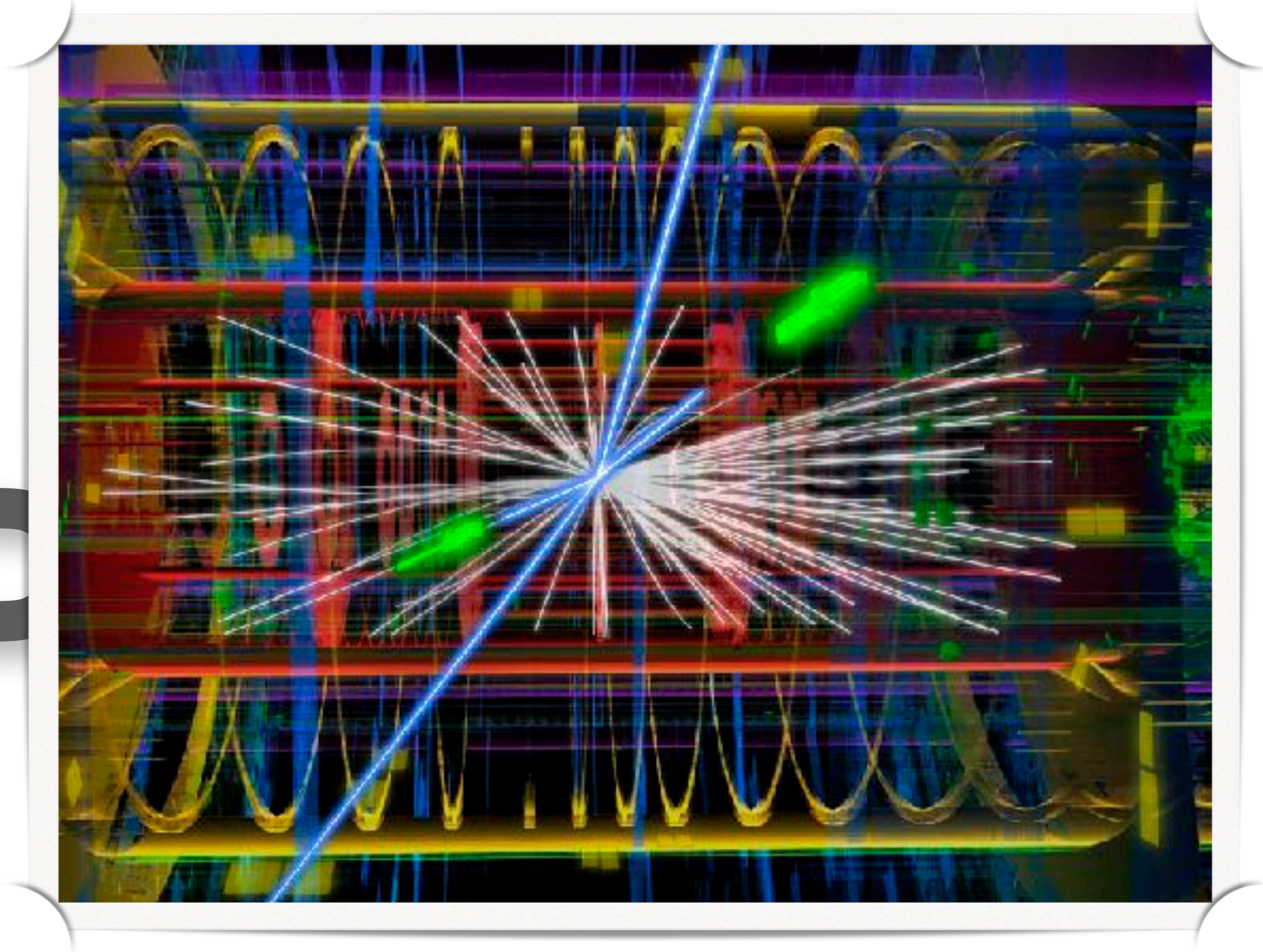
UNDERLYING
THEORY

EXPERIMENTAL
DATA



how do you make quantitative connection?





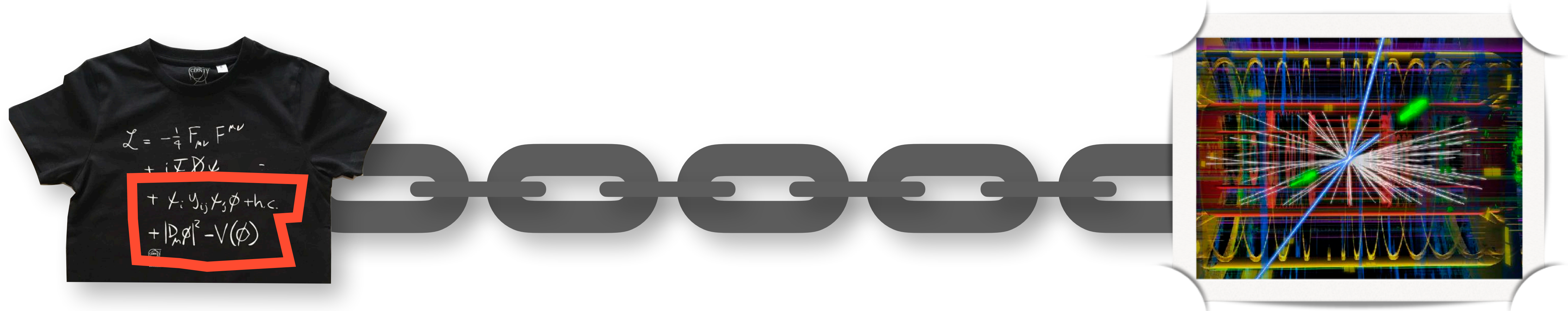
through a chain of experimental and theoretical links

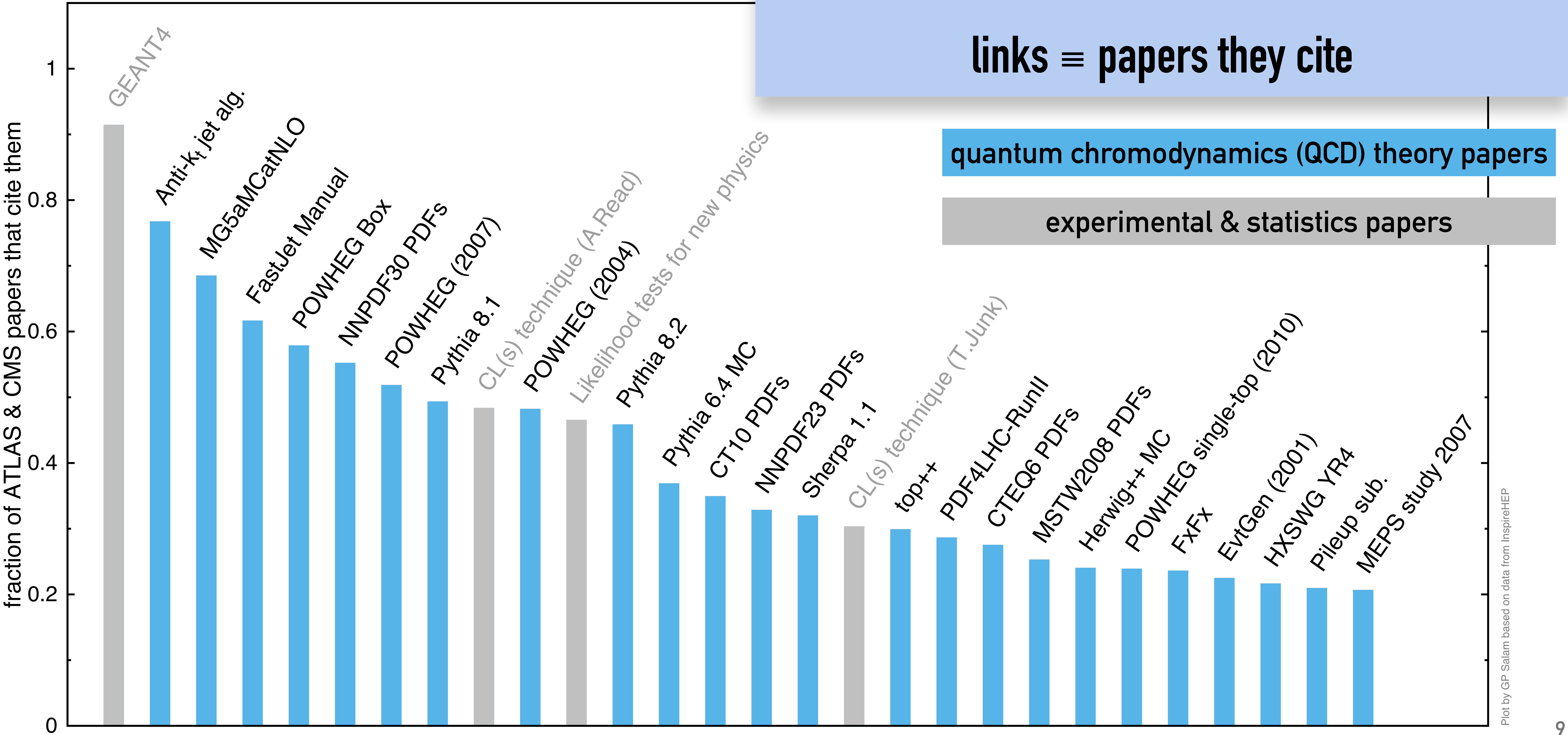
[in particular Quantum Chromodynamics (QCD)]

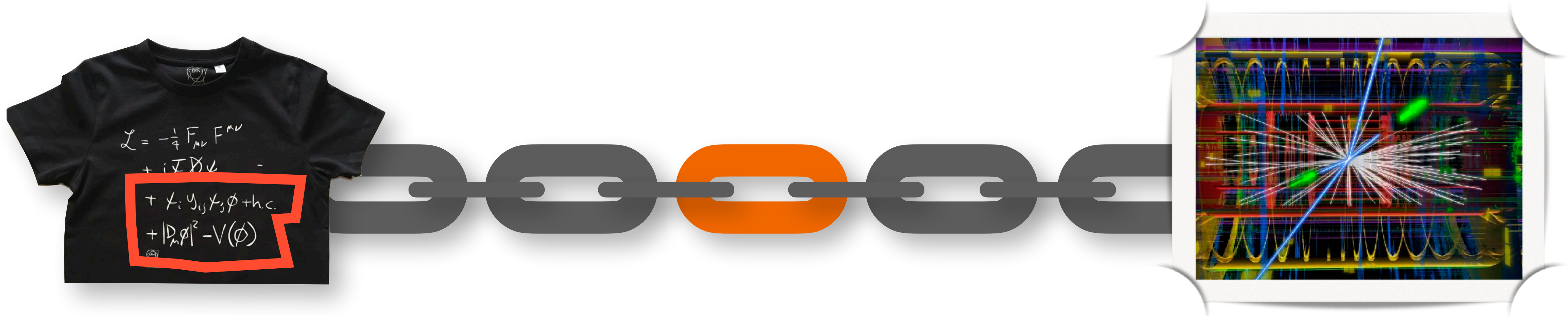
What are the links?

ATLAS and CMS (big LHC expts.) have written 715 articles since 2017

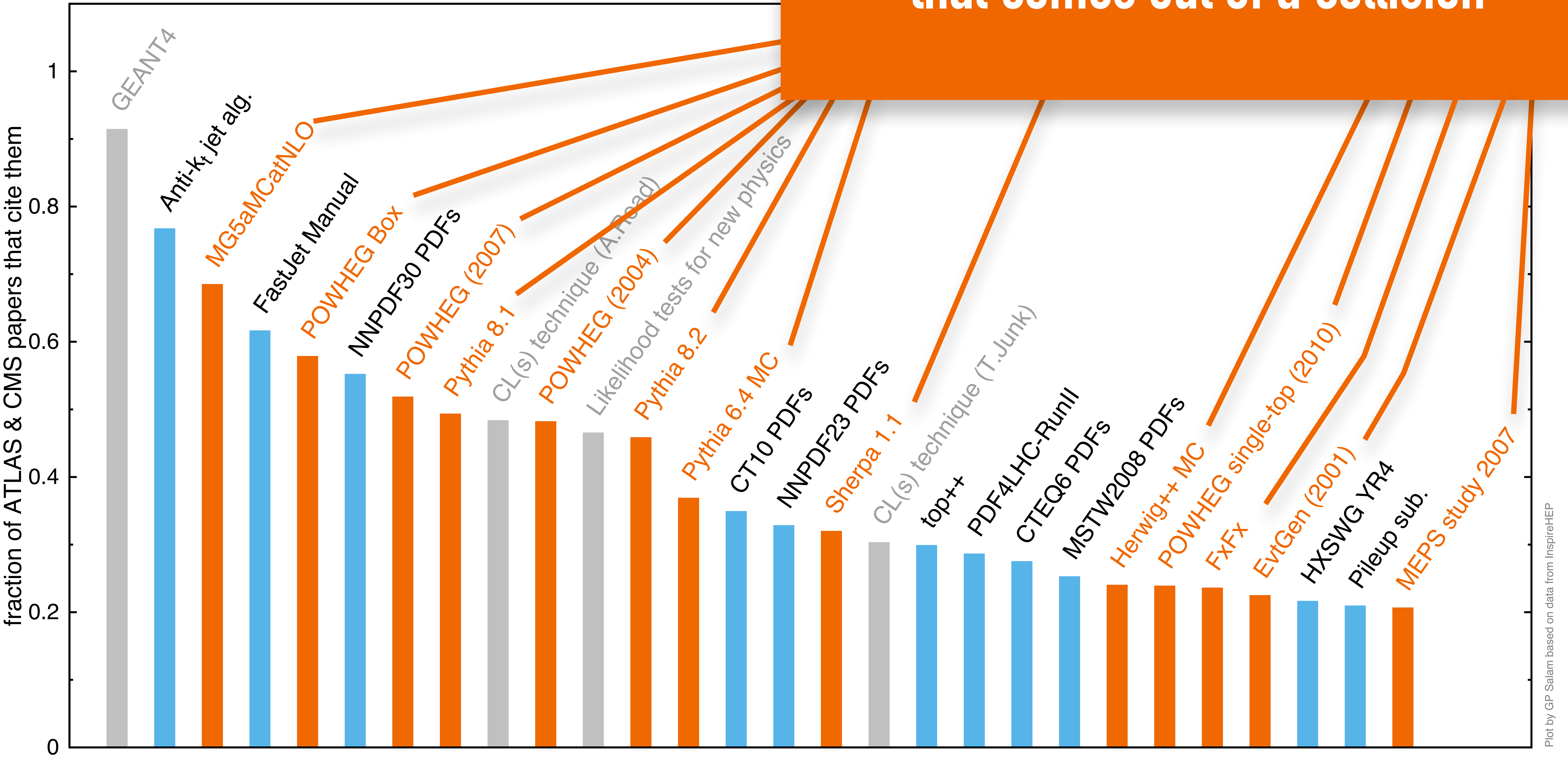
links ≡ papers they cite

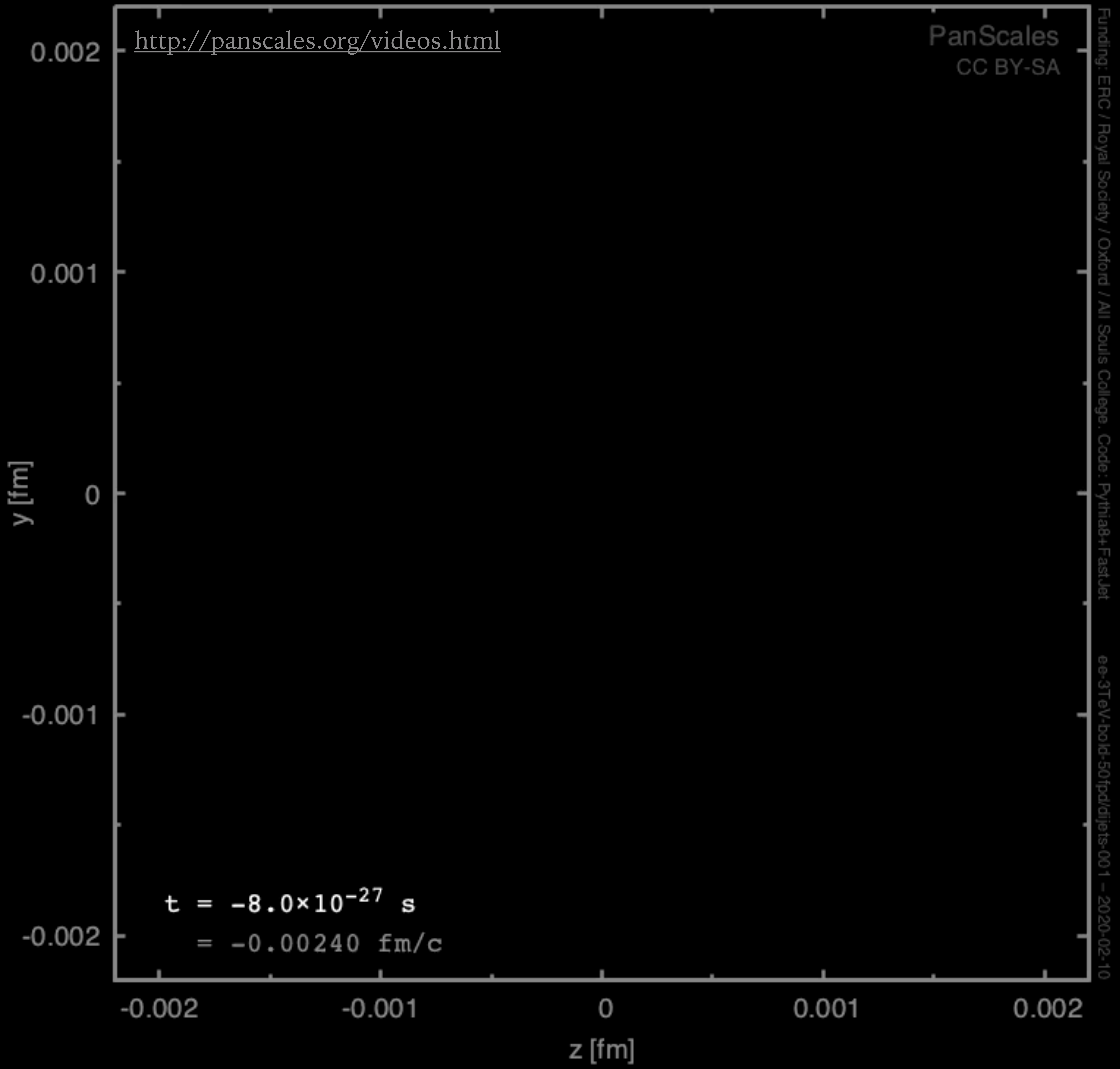






predicting full particle structure that comes out of a collision



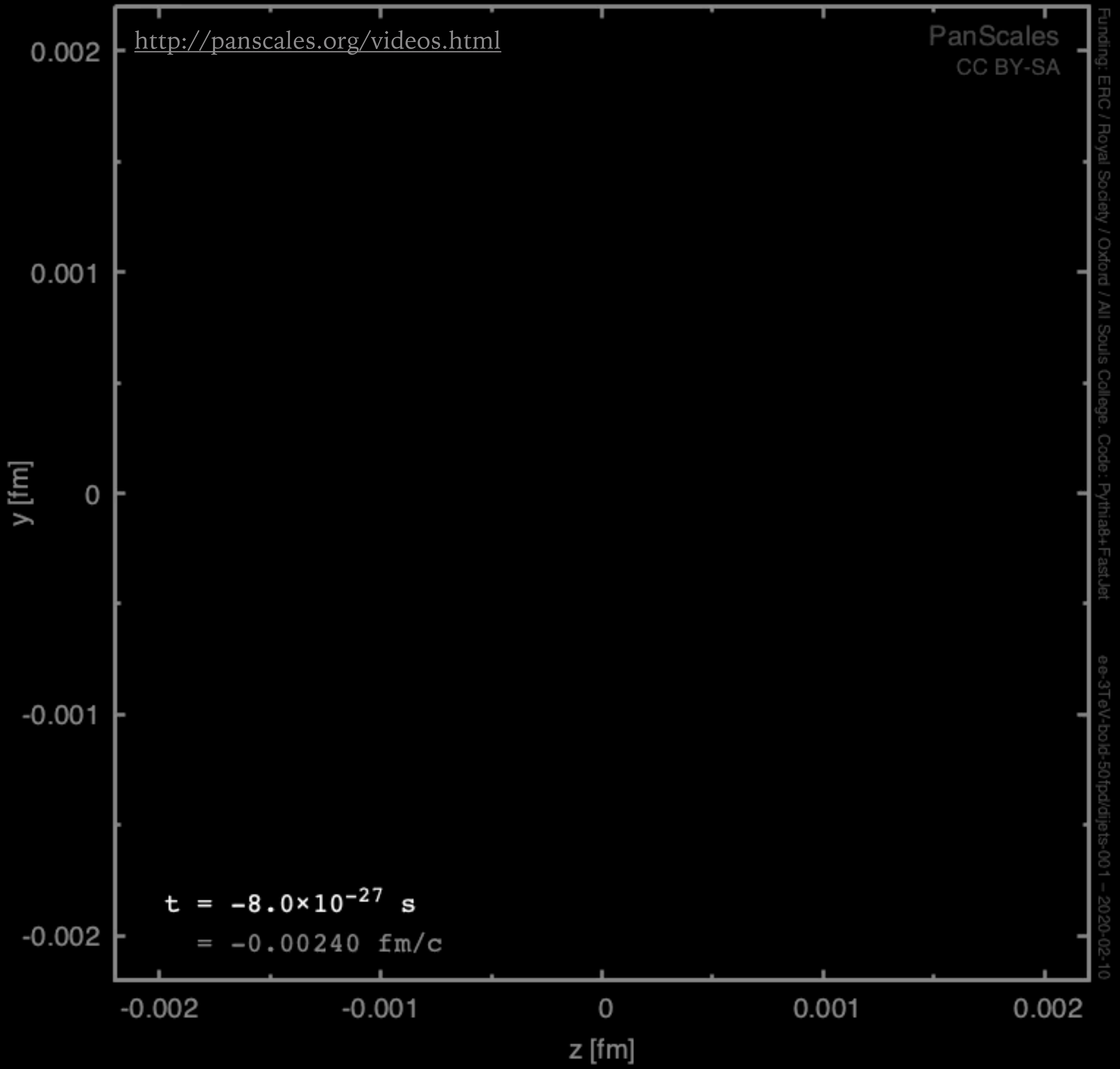


incoming beam particle

intermediate particle (quark or gluon)

final particle (hadron)

Event evolution spans 7 orders of magnitude in space-time



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

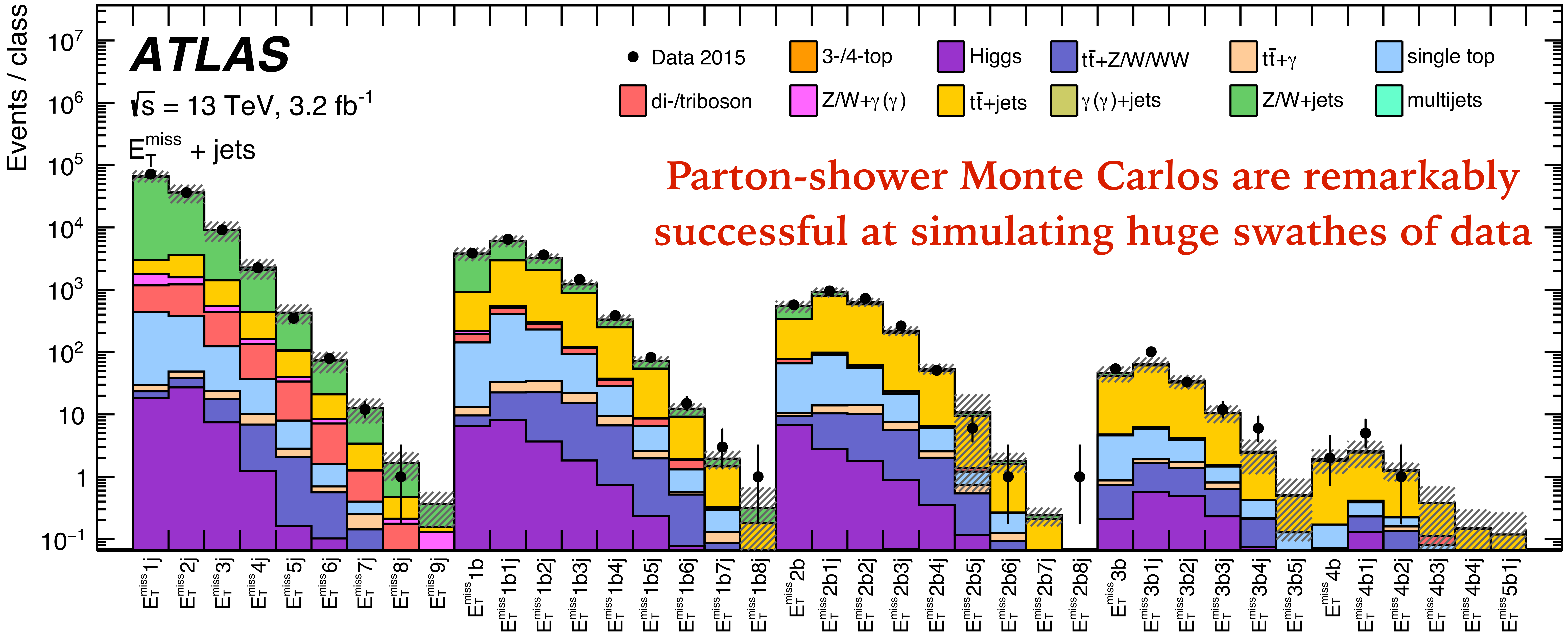
The **2021 High Energy and Particle Physics Prize of the EPS** for an outstanding contribution to High Energy Physics is awarded to **Torbjörn Sjöstrand and Bryan Webber** for the conception, development and realisation of parton shower Monte Carlo simulations, yielding an accurate description of particle 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†)

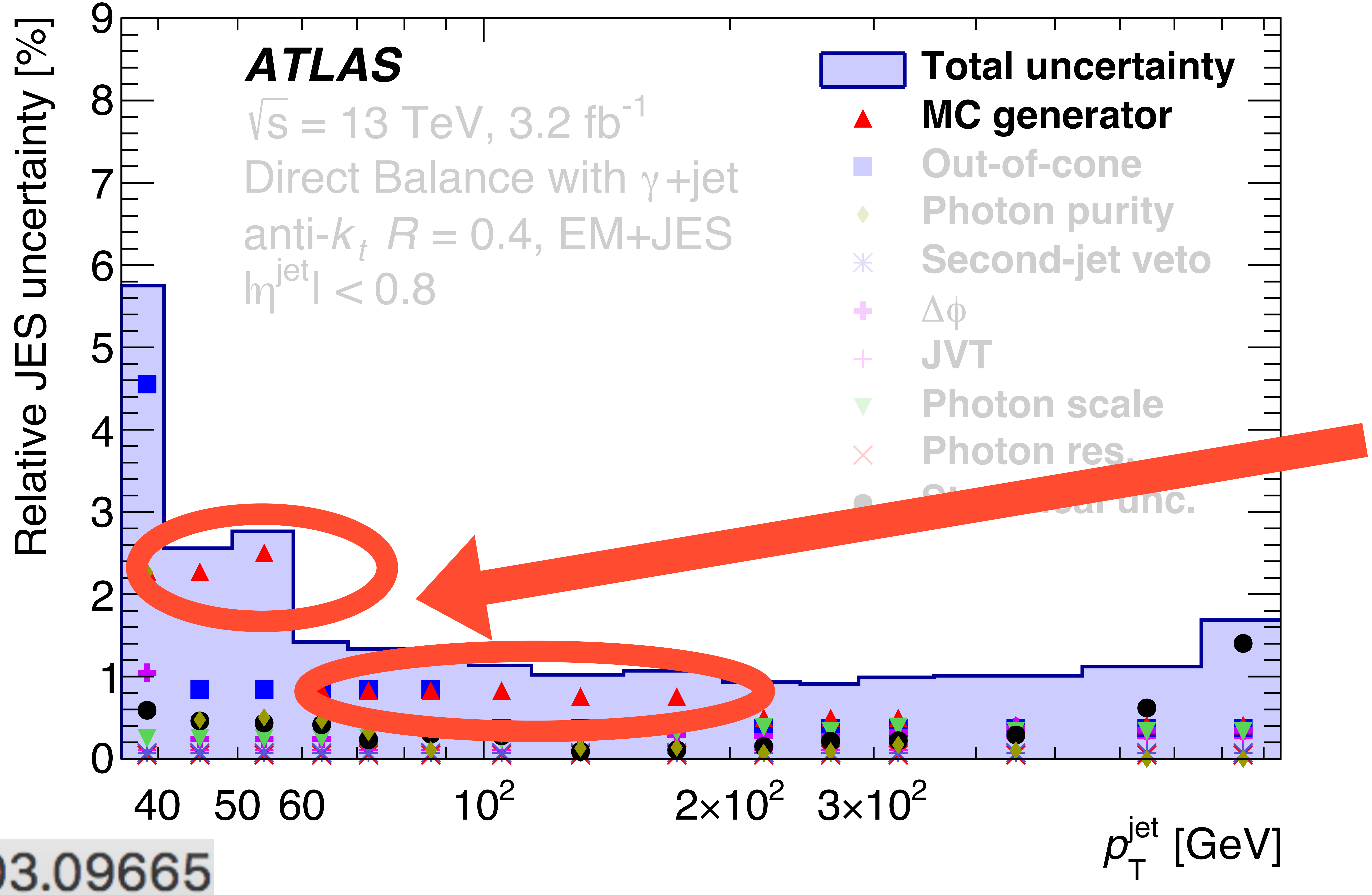
Calculations used in 1807.07447 (ATLAS general search)

Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
$W (\to \ell\nu)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z (\to \ell^+\ell^-)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W (\to q\bar{q})$ + jets	Sherpa 2.1.1	1,2,3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W + \gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
$Z / W + \gamma\gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
γ + jets	Sherpa 2.1.1	0,1,2,3,4j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma$ + jets	Sherpa 2.1.1	0,1,2j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	Pythia 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	Powheg-Box v2	NLO	Pythia 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + WW$	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + \gamma$	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
$t\bar{t} + b\bar{b}$	Sherpa 2.2.0	NLO	Sherpa 2.2.0	NLO	NLO CT10f4	Sherpa default
Single-top (t-channel)	Powheg-Box v1	NLO	Pythia 6.428	app. NNLO	NLO CT10f4	Perugia 2012
Single-top (s- and Wt-channel)	Powheg-Box v2	NLO	Pythia 6.428	app. NNLO	NLO CT10	Perugia 2012
tZ	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
3-top	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
4-top	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
WW	Sherpa 2.1.1	0j@NLO + 1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
WZ	Sherpa 2.1.1	0j@NLO + 1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
ZZ	Sherpa 2.1.1	0,1j@NLO + 2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
Multijets	Pythia 8.186	LO	Pythia 8.186	data	NNPDF2.3LO	A14
Higgs (ggF/VBF)	Powheg-Box v2	NLO	Pythia 8.186	NNLO	NLO CT10	AZNLO
Higgs ($t\bar{t}H$)	MG5_aMC@NLO 2.2.2	NLO	Herwig++	NNLO	NLO CT10	UEEE5
Higgs (W/ZH)	Pythia 8.186	LO	Pythia 8.186	NNLO	NNPDF2.3LO	A14

MC generators work well: e.g. comparison to data in general search



But imperfections matter: e.g. for jet energy calibration (affects ~1500 papers)



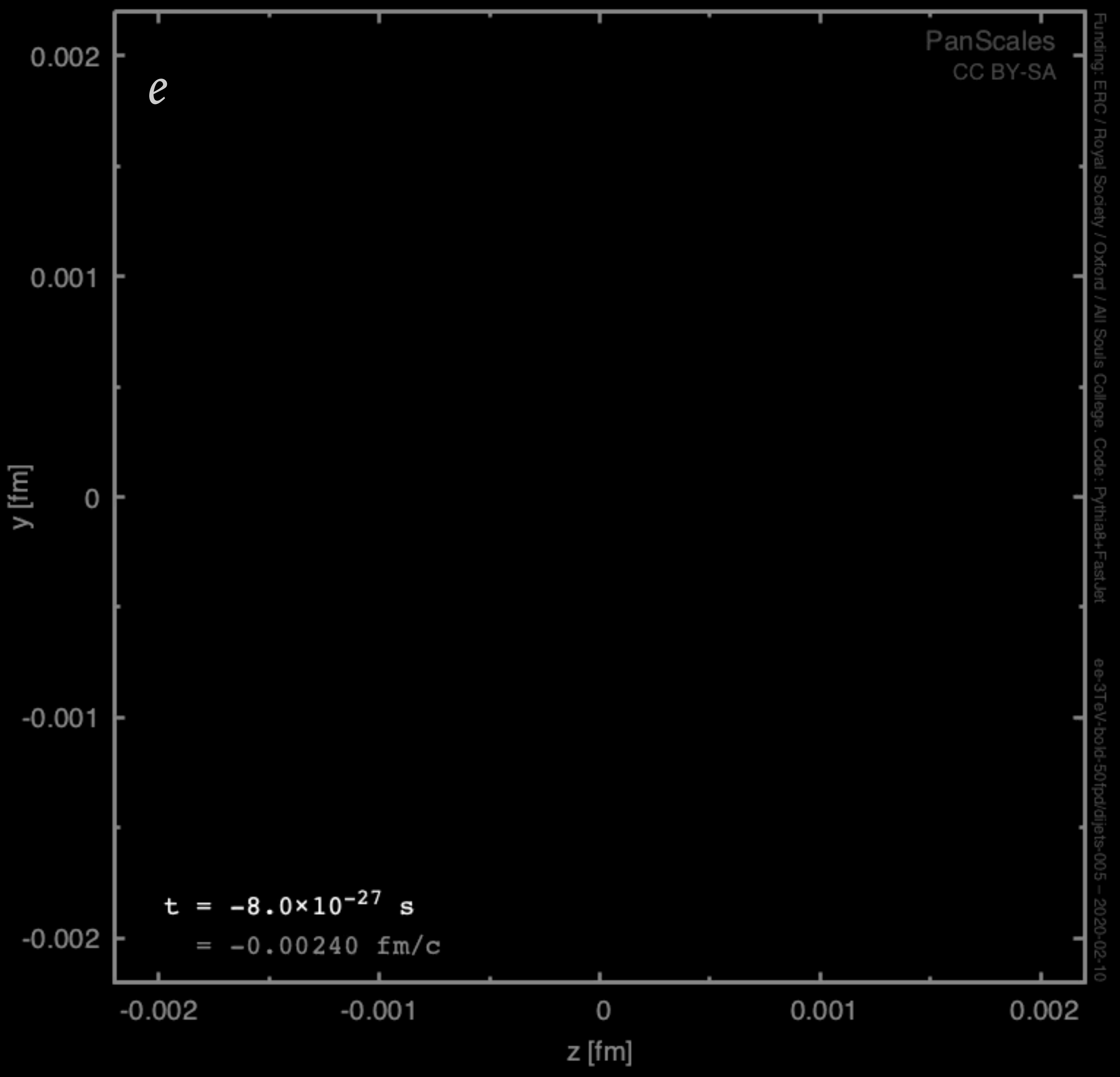
1703.09665

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

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

(here Sherpa v. Pythia)

→ fundamental limit on LHC precision potential


PanScales
CC BY-SA
e
0.002
0.001
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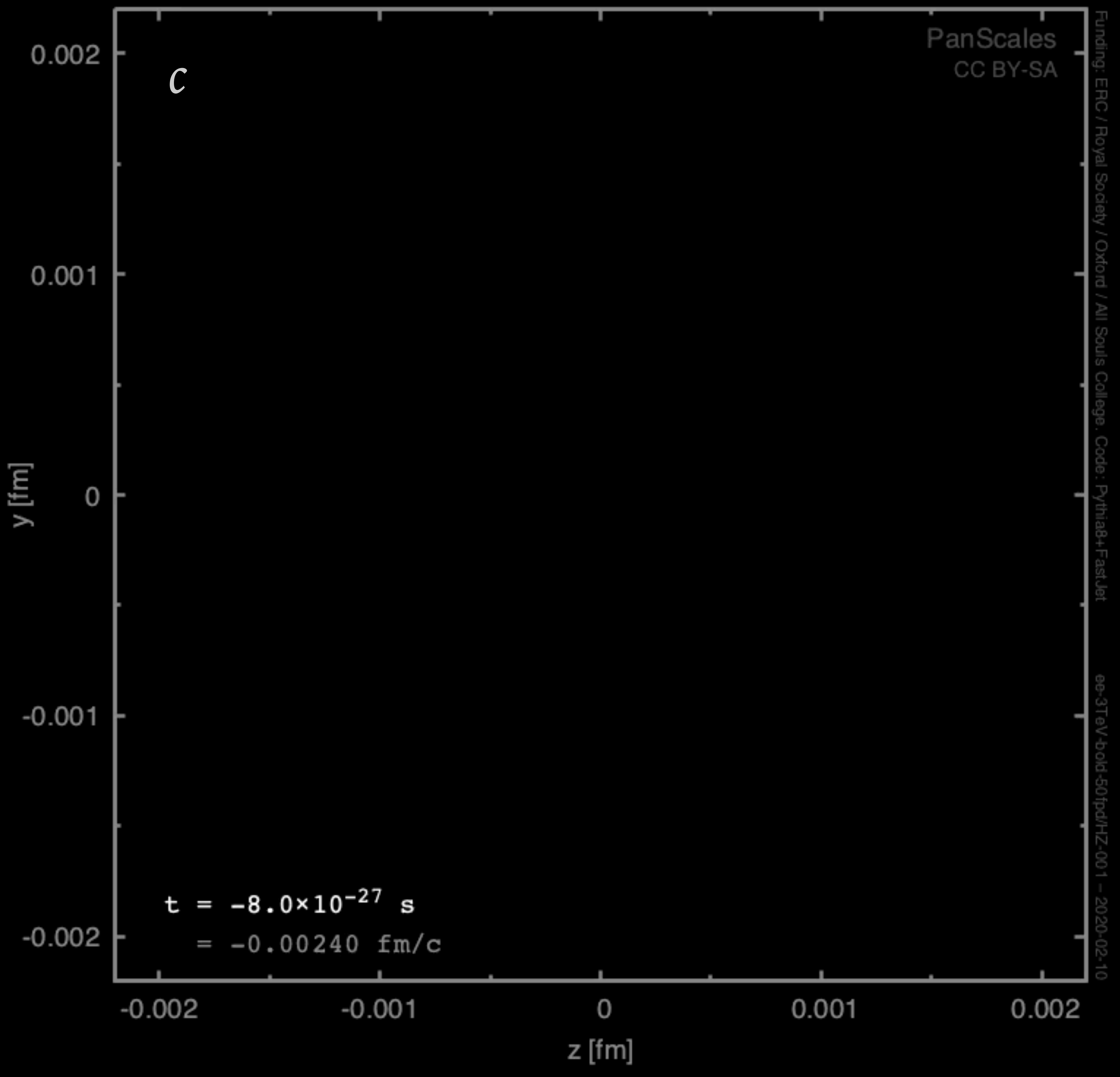
-0.002
y [fm]
-0.002
-0.001
0
0.001
0.002
z [fm]
t = -8.0×10^-27 s
= -0.00240 fm/c
Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet
ee-3TeV-bold-50fpd/dijets-005 – 2020-02-10


PanScales
CC BY-SA
c
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= -0.00240 fm/c
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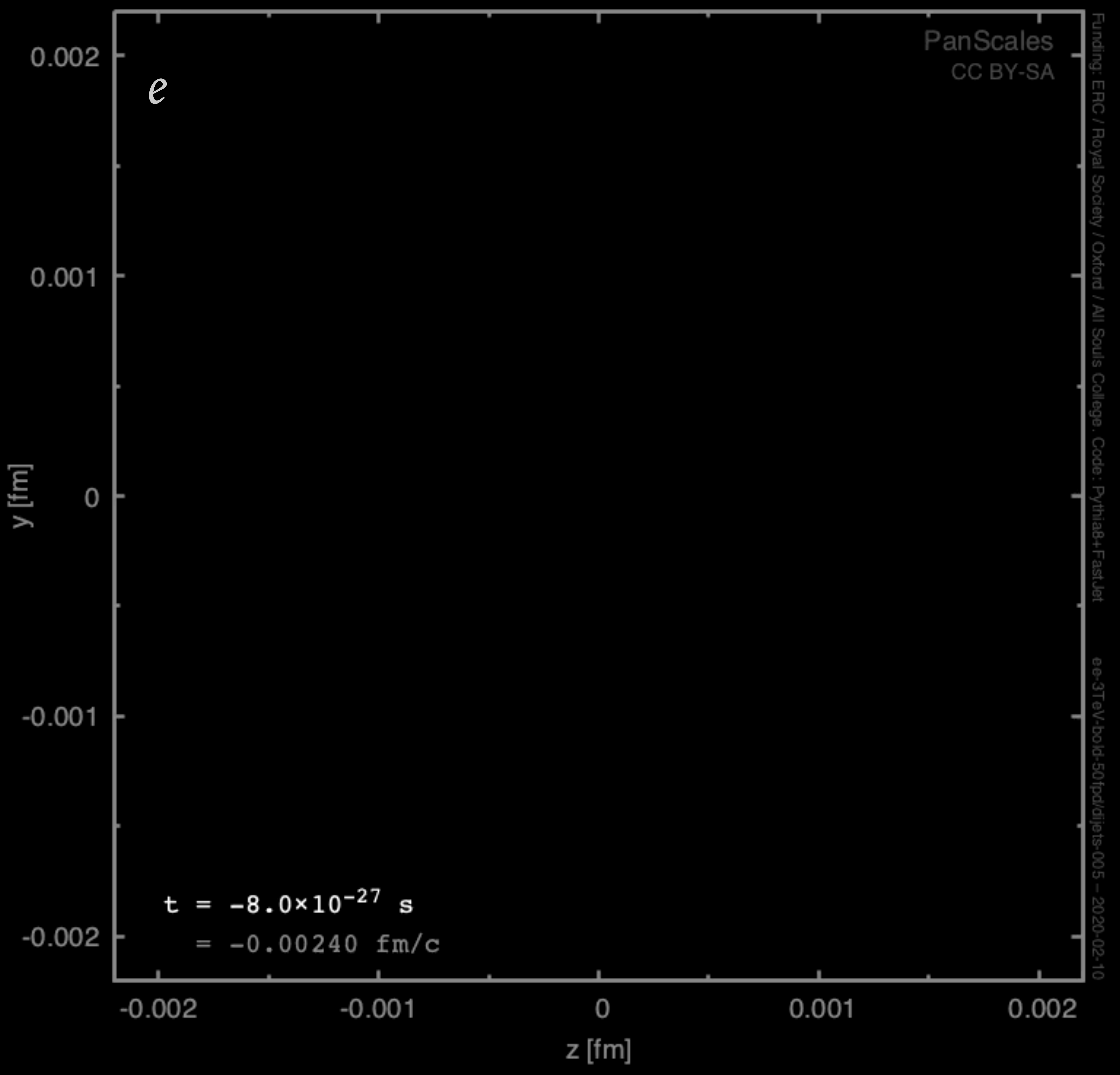
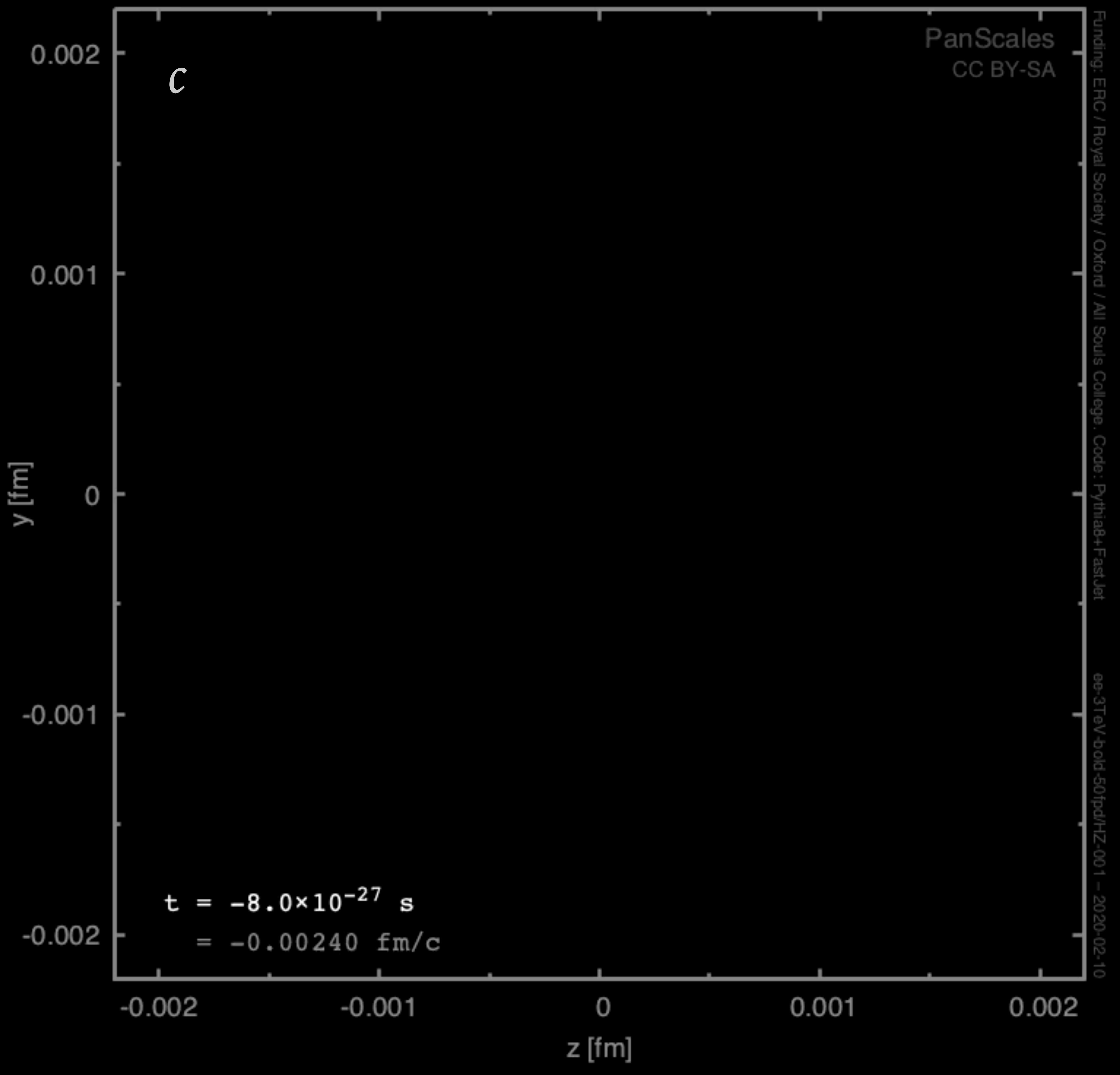
ee-3TeV-bold-50fpd/HZ-001 – 2020-02-10

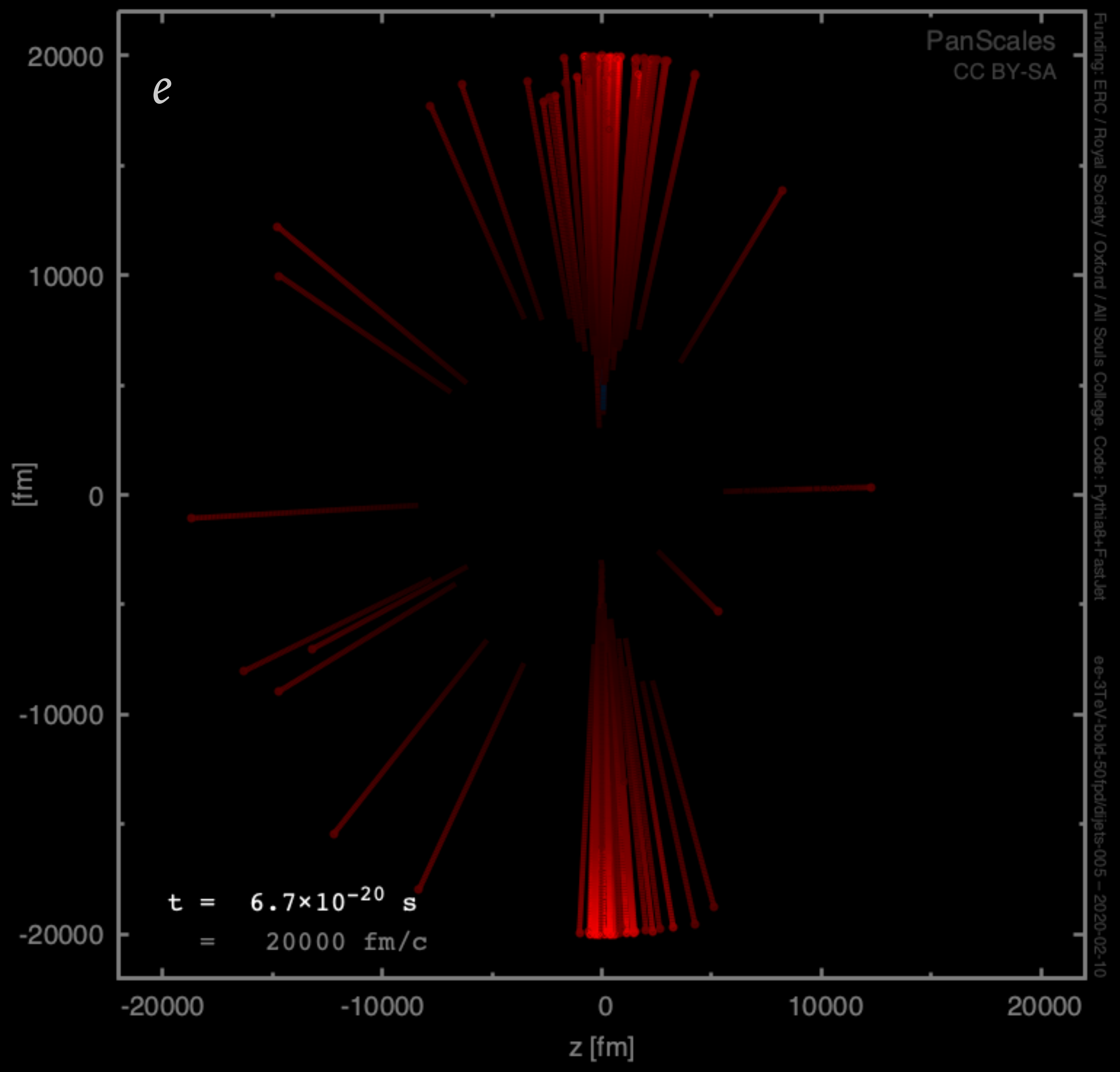
pure QCD event



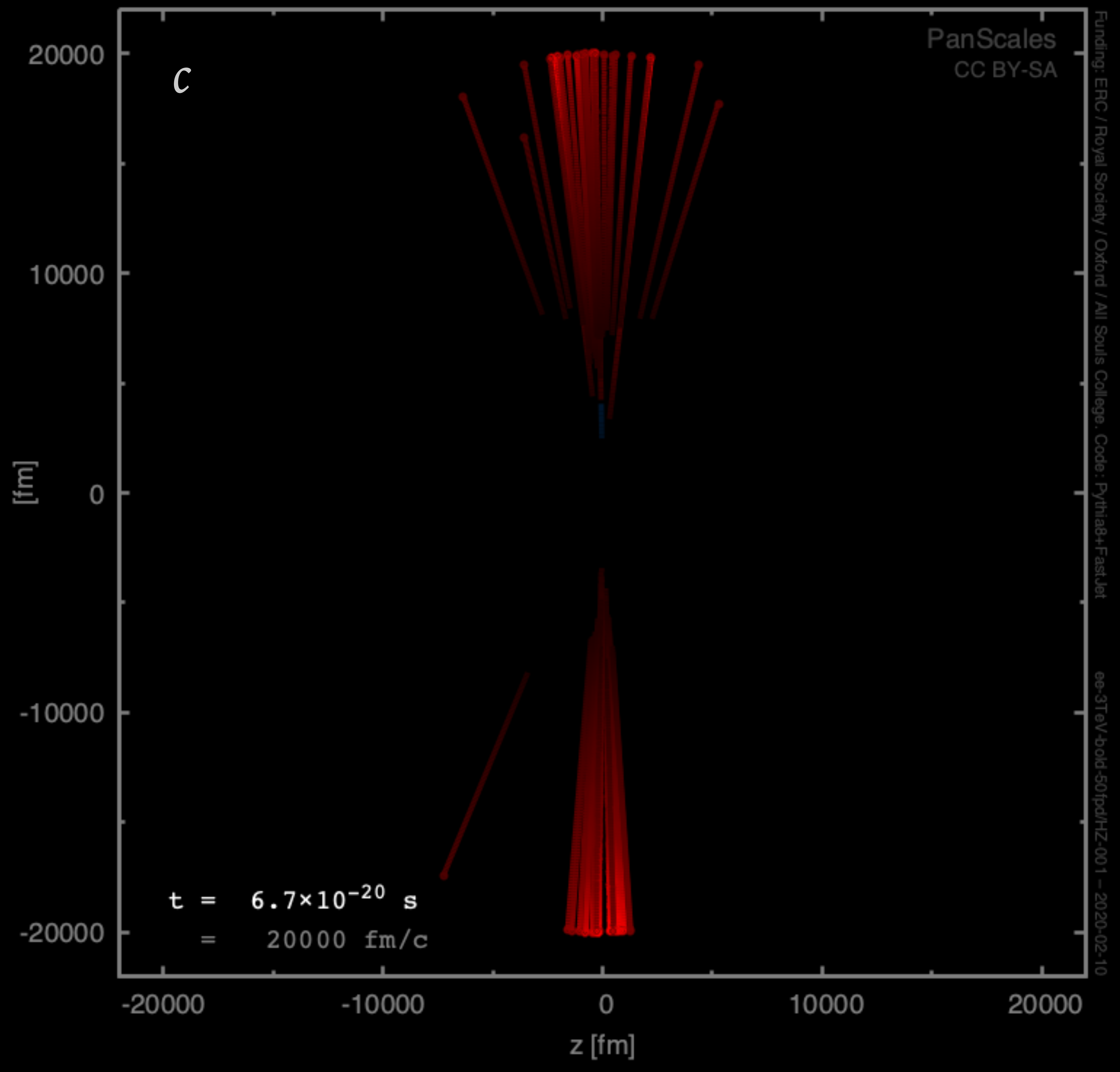
event with Higgs & Z boson decays



pure QCD event

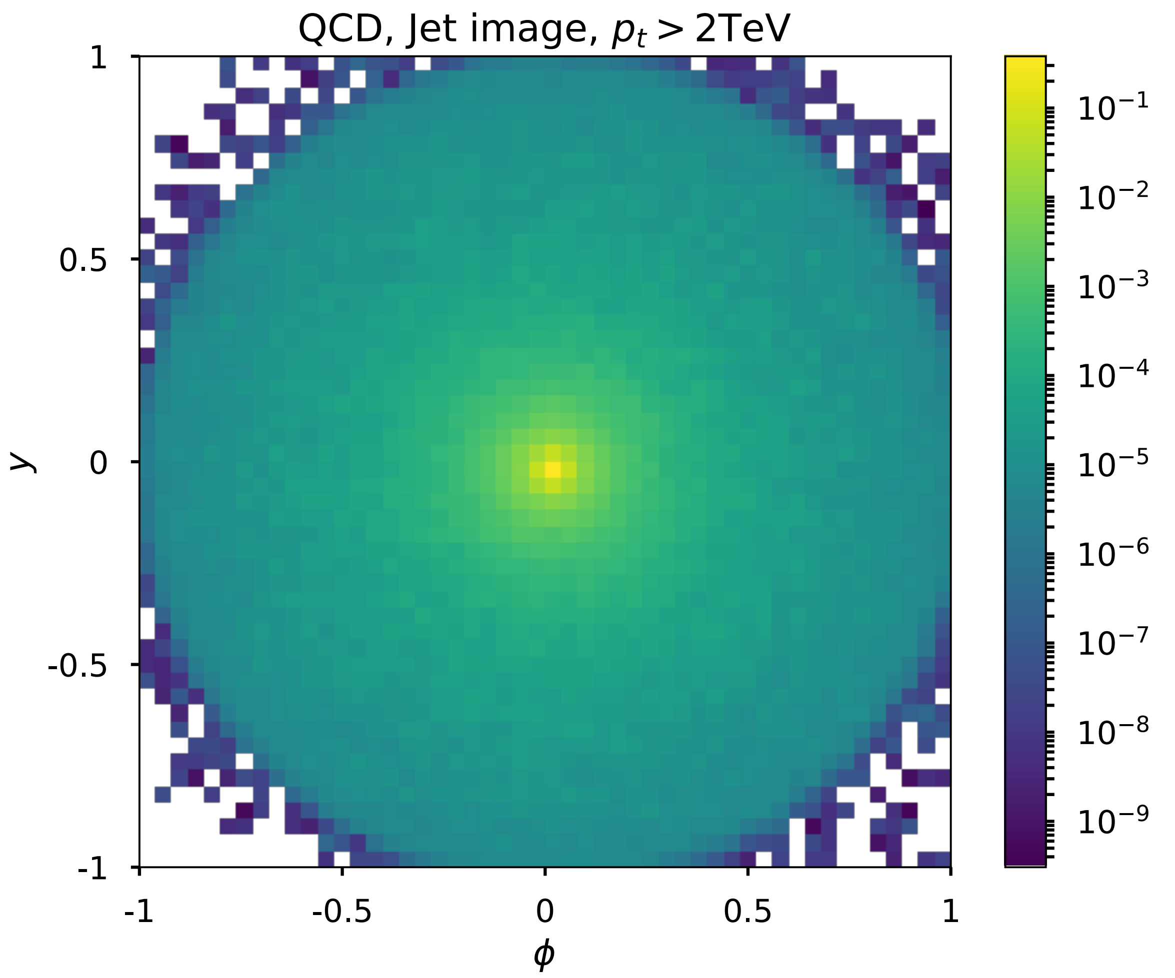


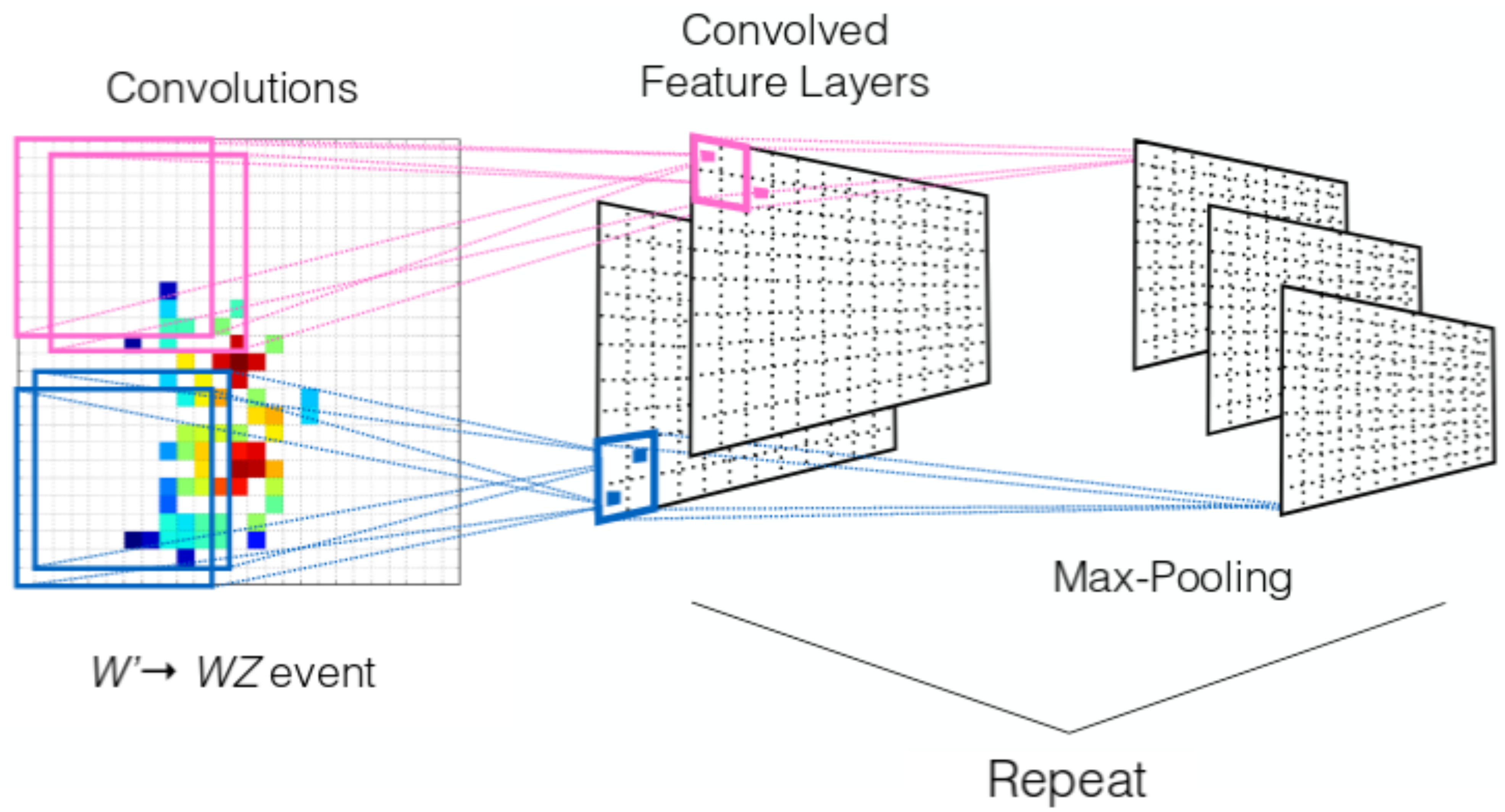
event with Higgs & Z boson decays



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.



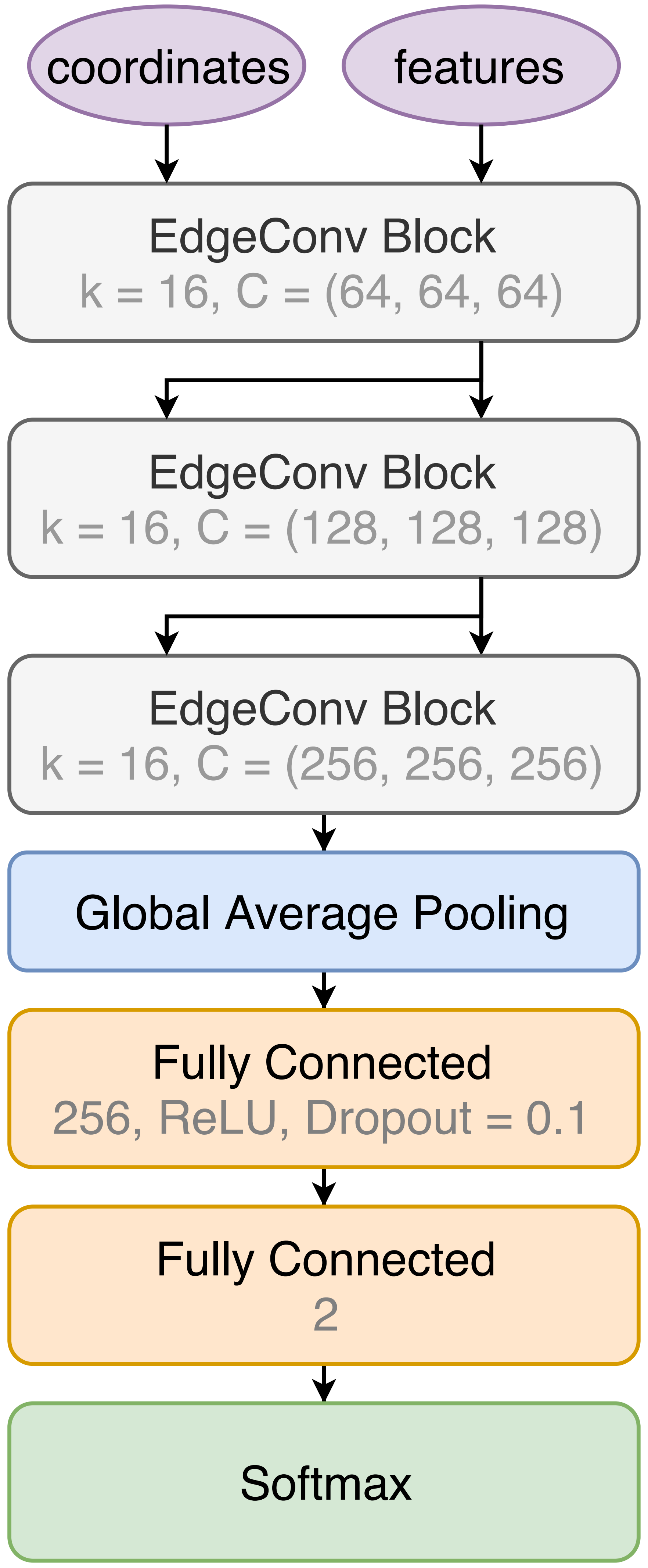


[Cogan, Kagan, Strauss, Schwartzman JHEP 1502 (2015) 118]

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

↓

2021 Young Experimental Physicist Prize EPS HEPP prize

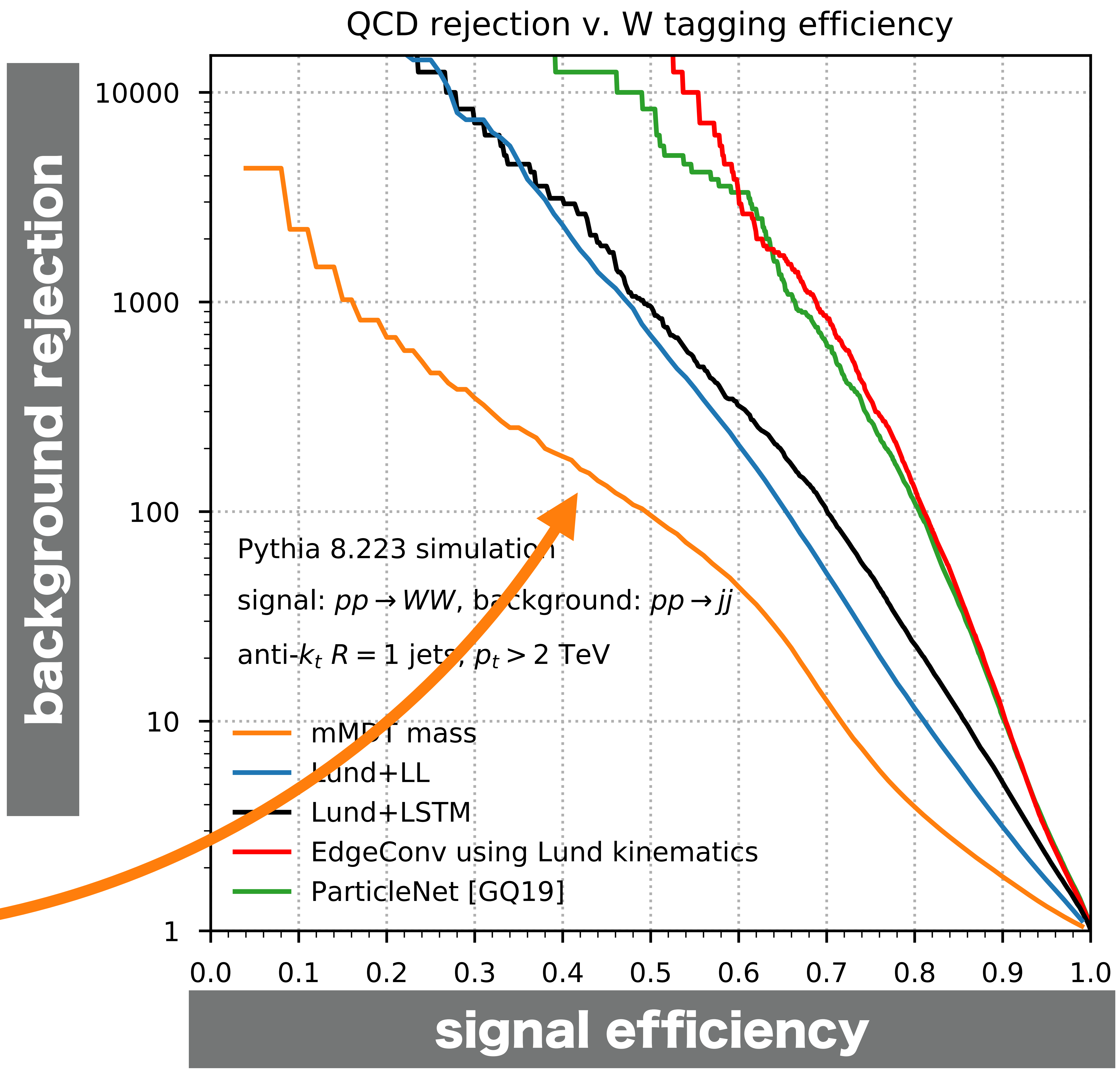


(a) ParticleNet

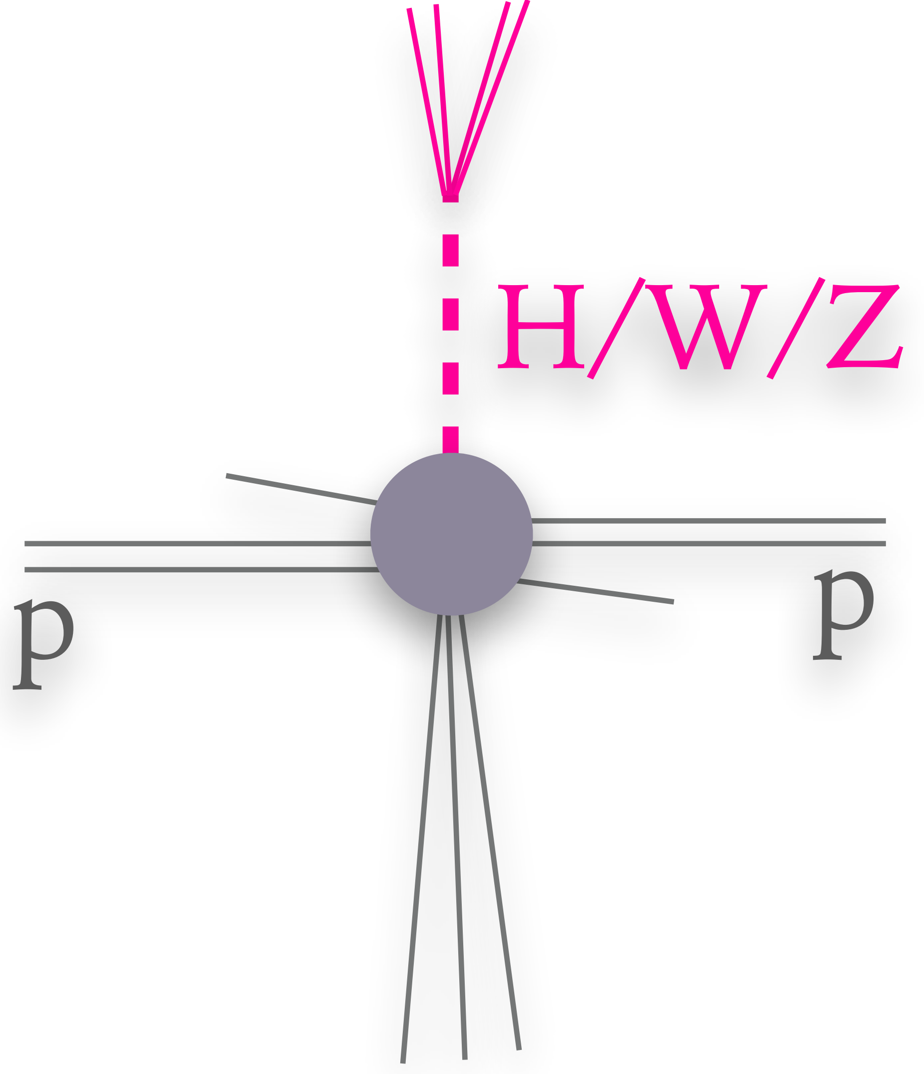
Qu & Guskos, arXiv:1902.08570

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

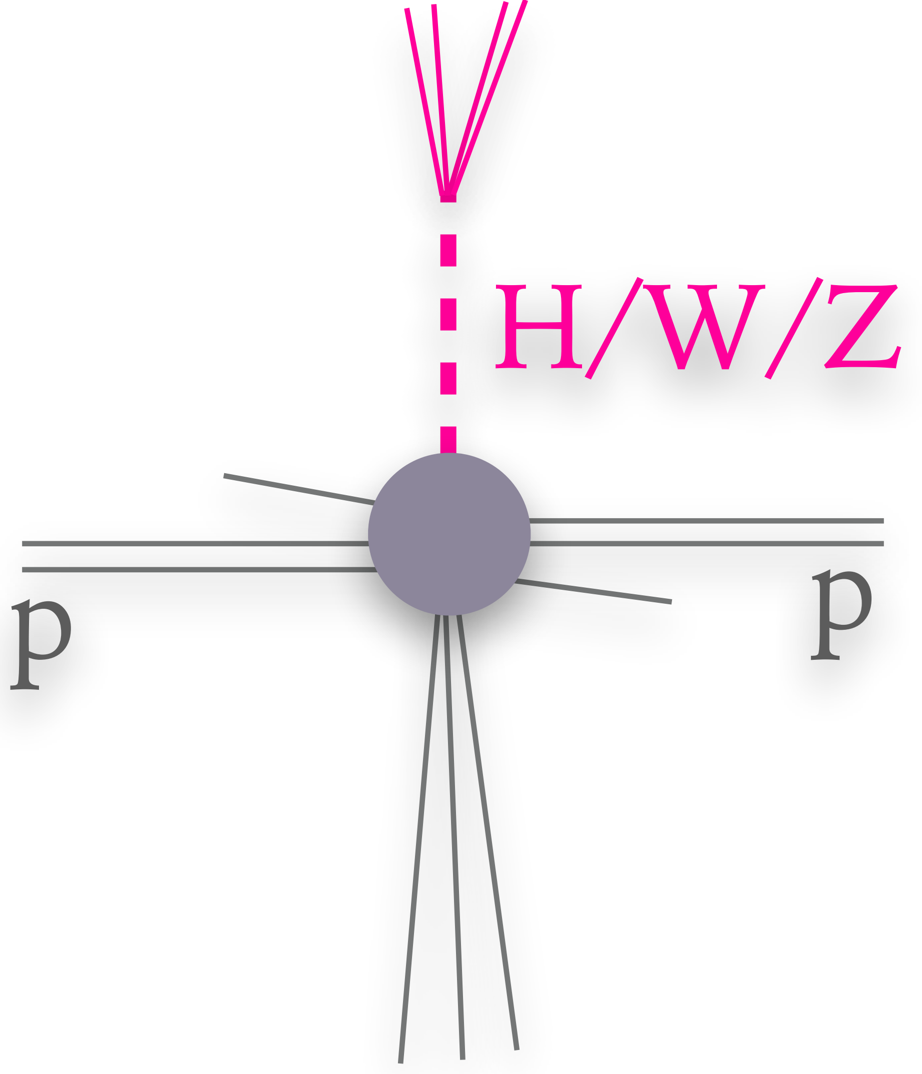
adapted from Dreyer & Qu [2012.08526]



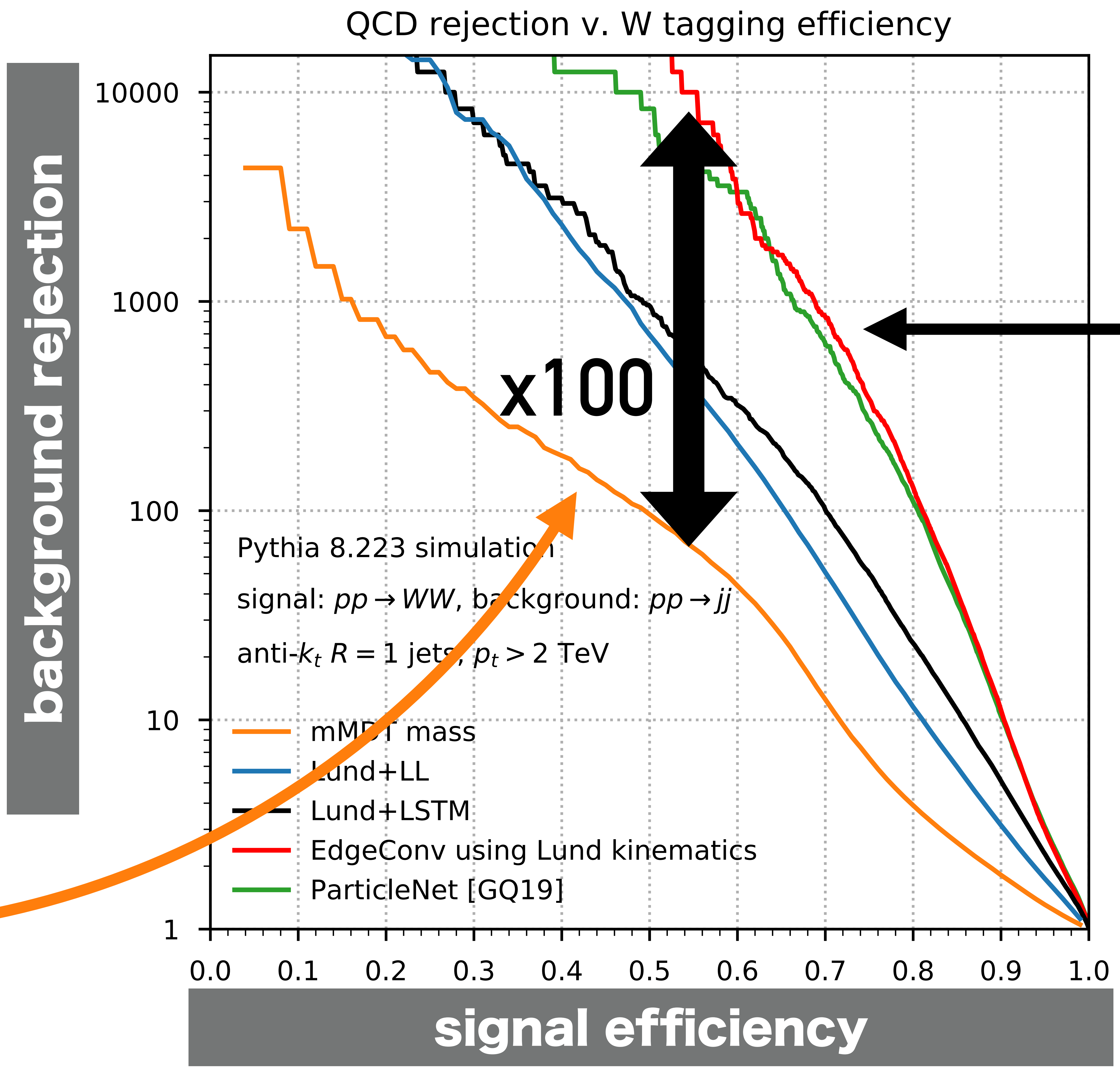
QCD rejection with just jet mass (SD/mMDT) i.e. 2008 tools & their 2013/14 descendants



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

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)

can we trust machine learning? A question of confidence in the training…

“

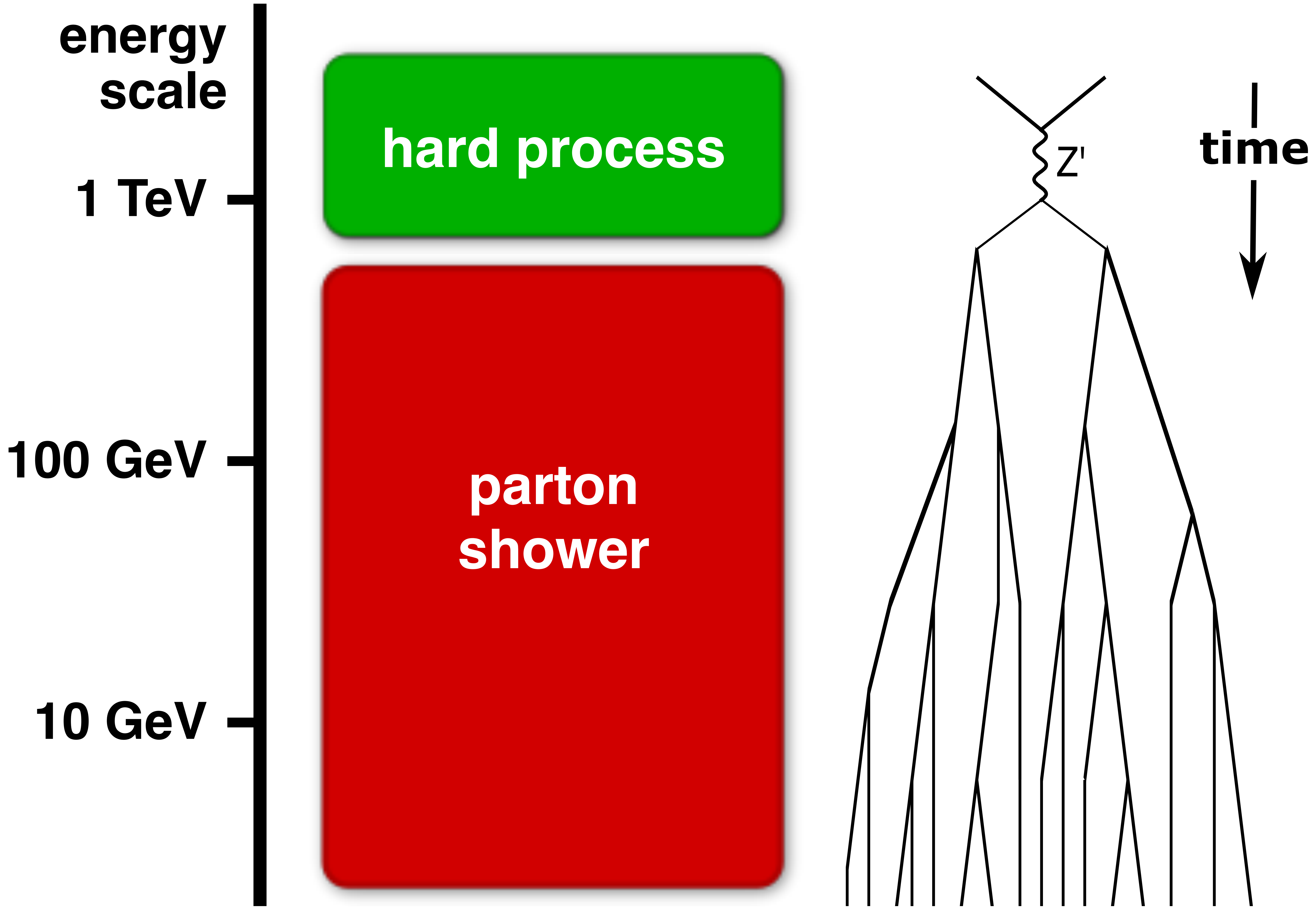
Unless you are highly confident in the information you have about the markets, you may be better off ignoring it altogether

- Harry Markowitz (1990 Nobel Prize in Economics)

[via S Gukov]

Elements of a Monte Carlo event generator

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



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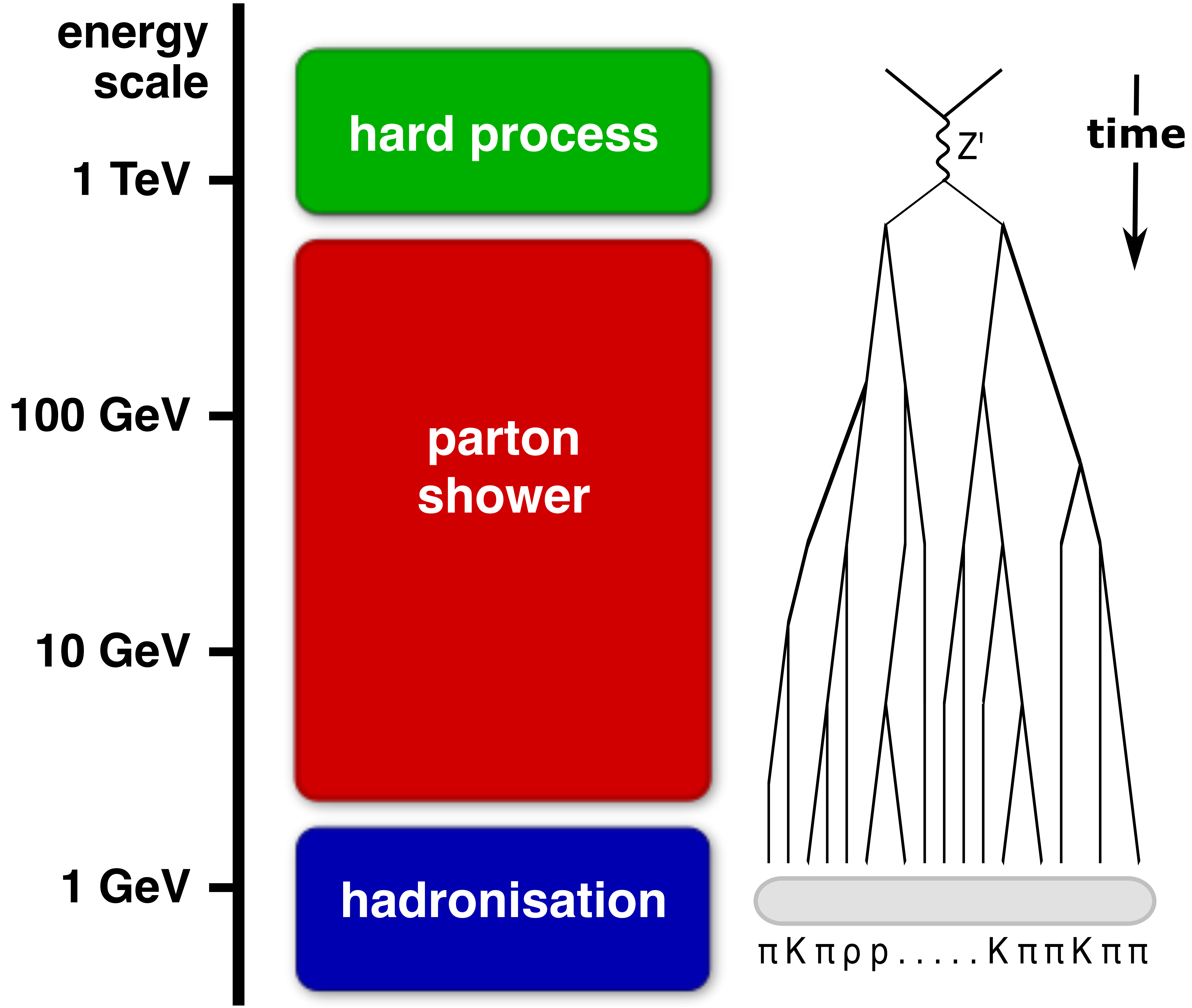
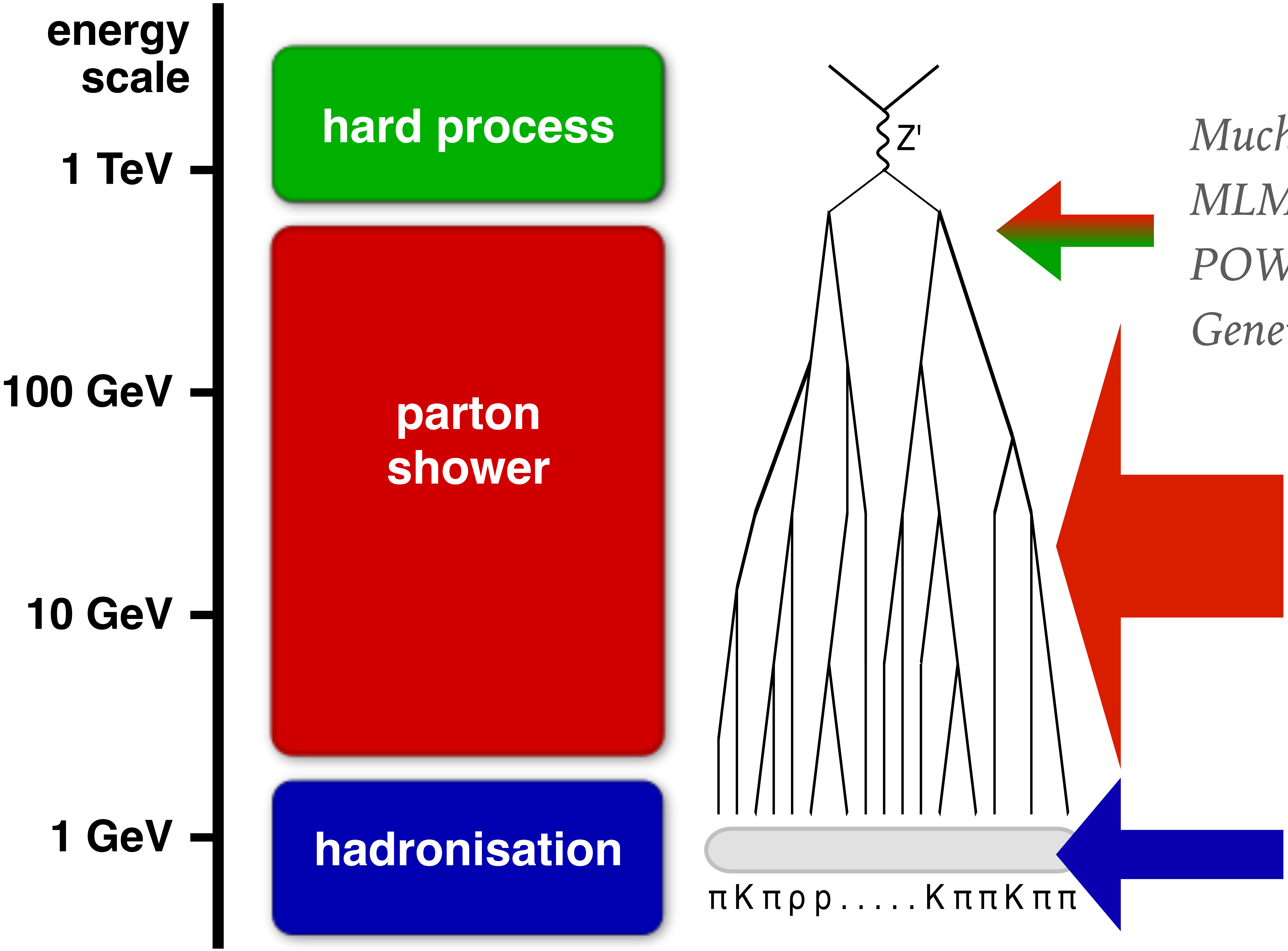


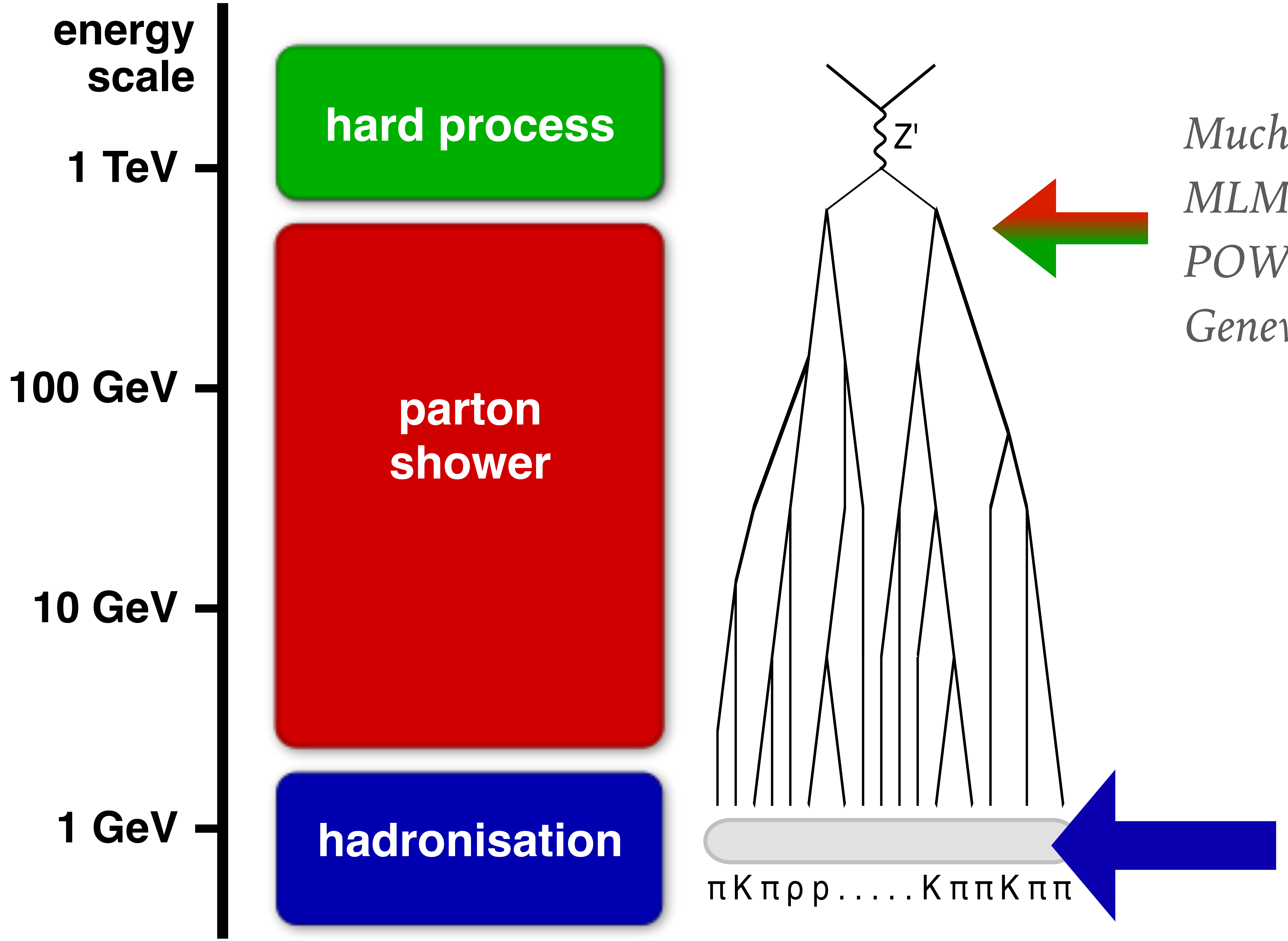
schematic view of key components of QCD predictions and Monte Carlo event simulation

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



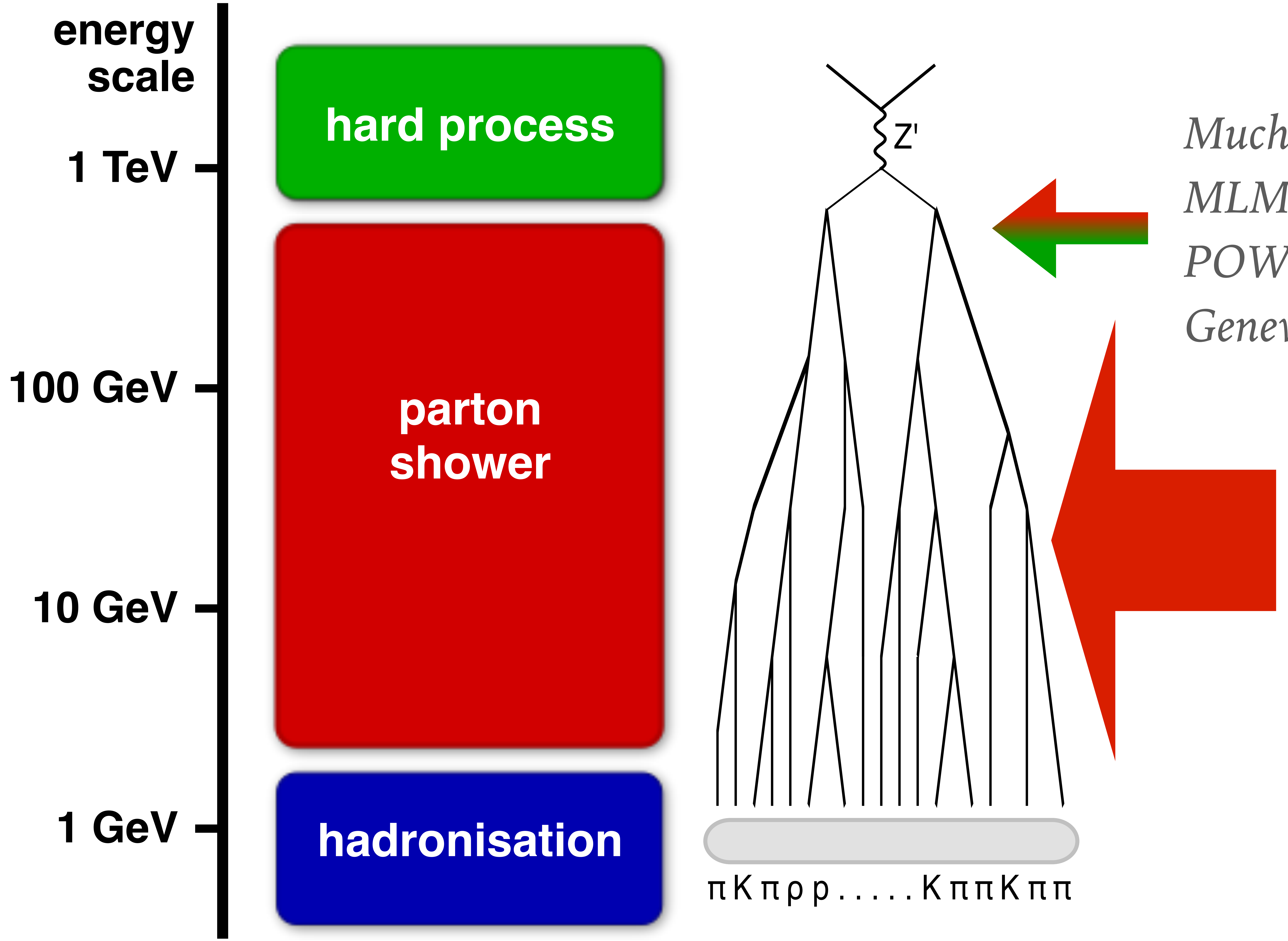
Much of past 20 years' work: MLM, CKKW, MC@NLO, POWHEG, MIN(N)LO, FxFx, Geneva, UNNLOPS, Vincia, etc.

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

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

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

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

[easy to implement in Monte Carlo approach]

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

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

[easy to implement in Monte Carlo approach]

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

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 $\{t_1 = 0.51, t_2 = 1.71\}$**

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

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

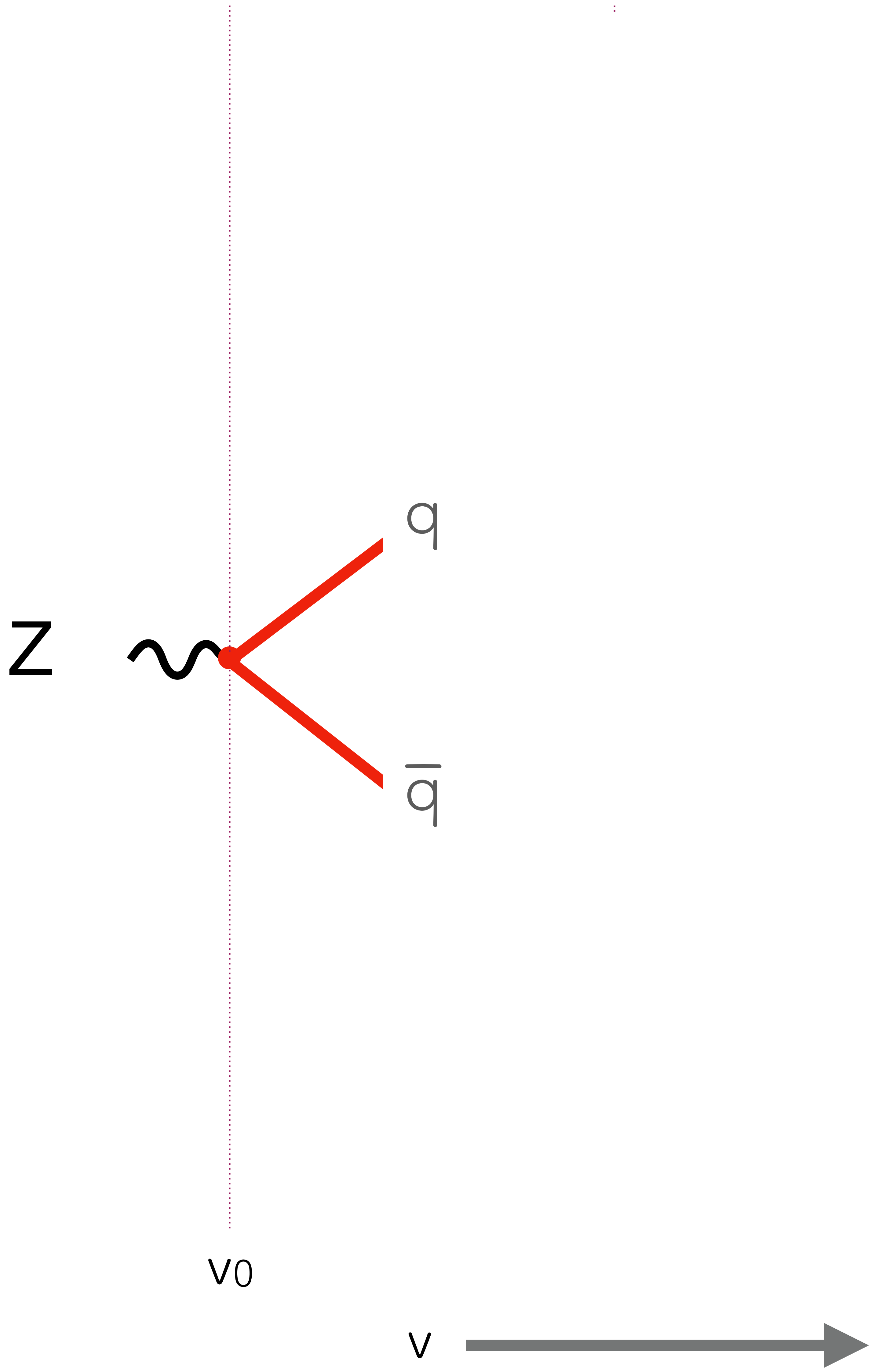
b. Choose random number r $(0 < r < 1)$ and find t_{n+1} that satisfies

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

[i.e. randomly sample exponential distribution]

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

QCD shower: an evolution equation (in evolution scale v, e.g. 1/trans.mom.)

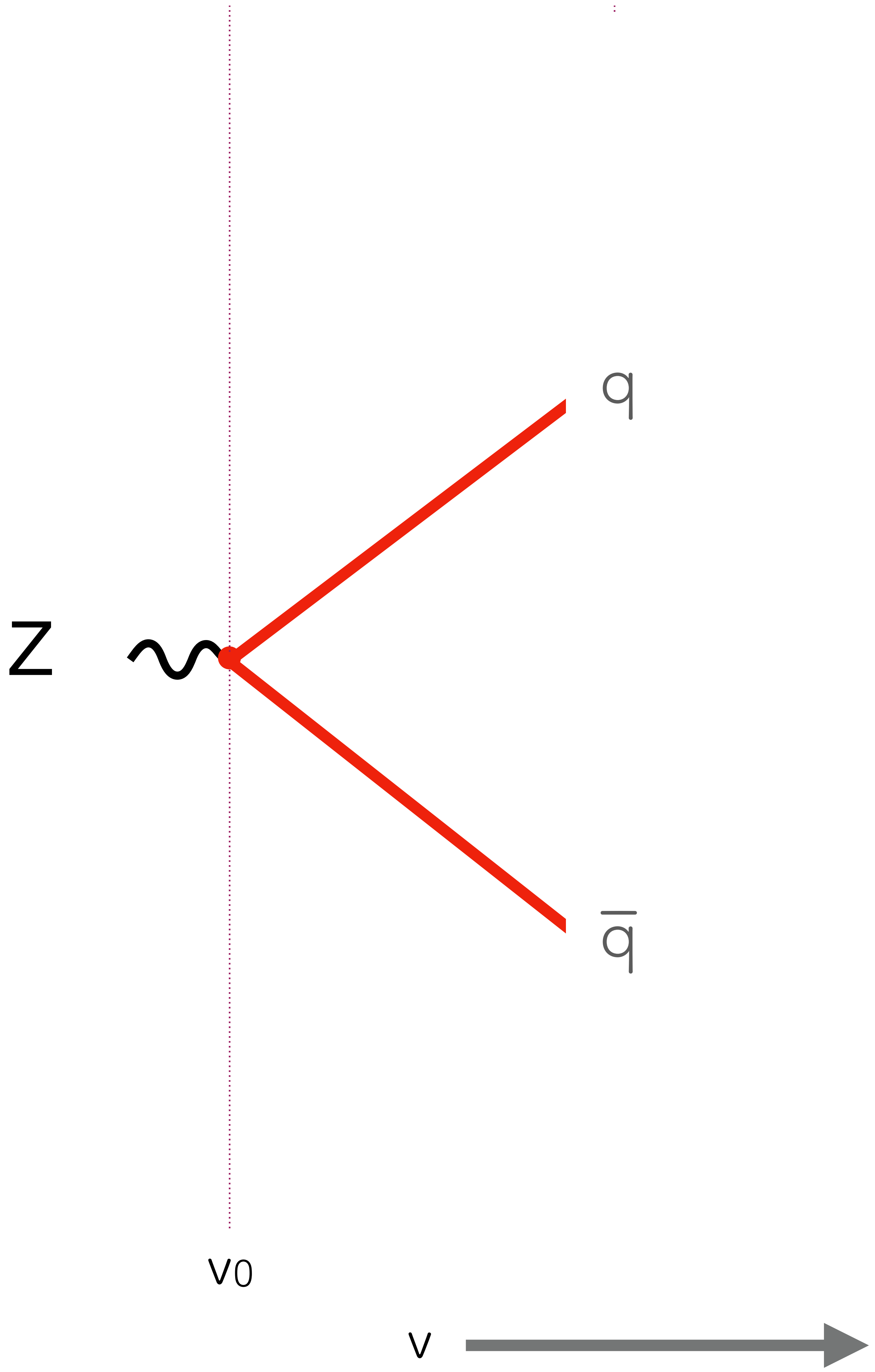


Start with q-qbar state.

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. 1/trans.mom.)



Start with q-qbar state.

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

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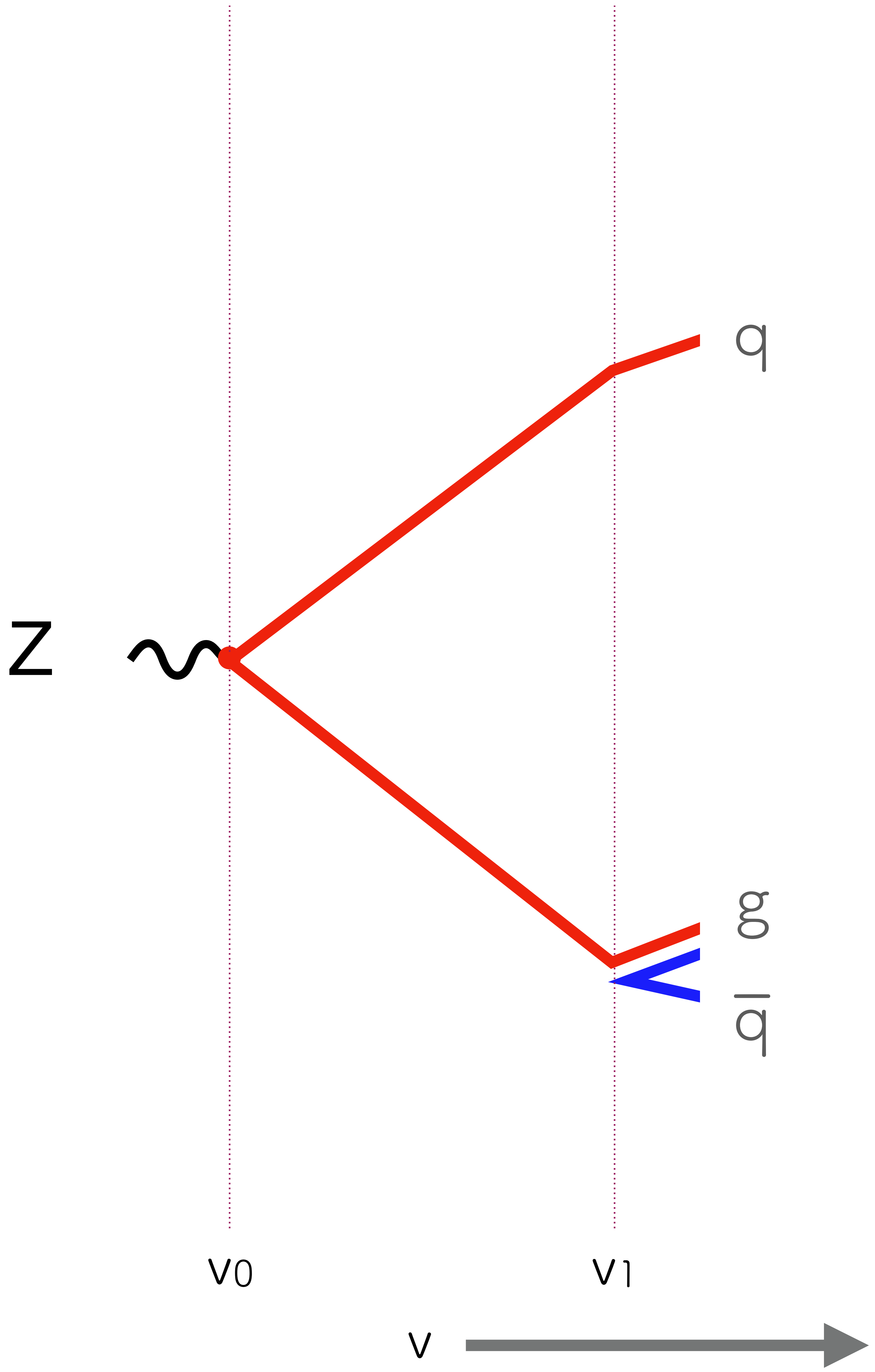


Start with q-qbar state.

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

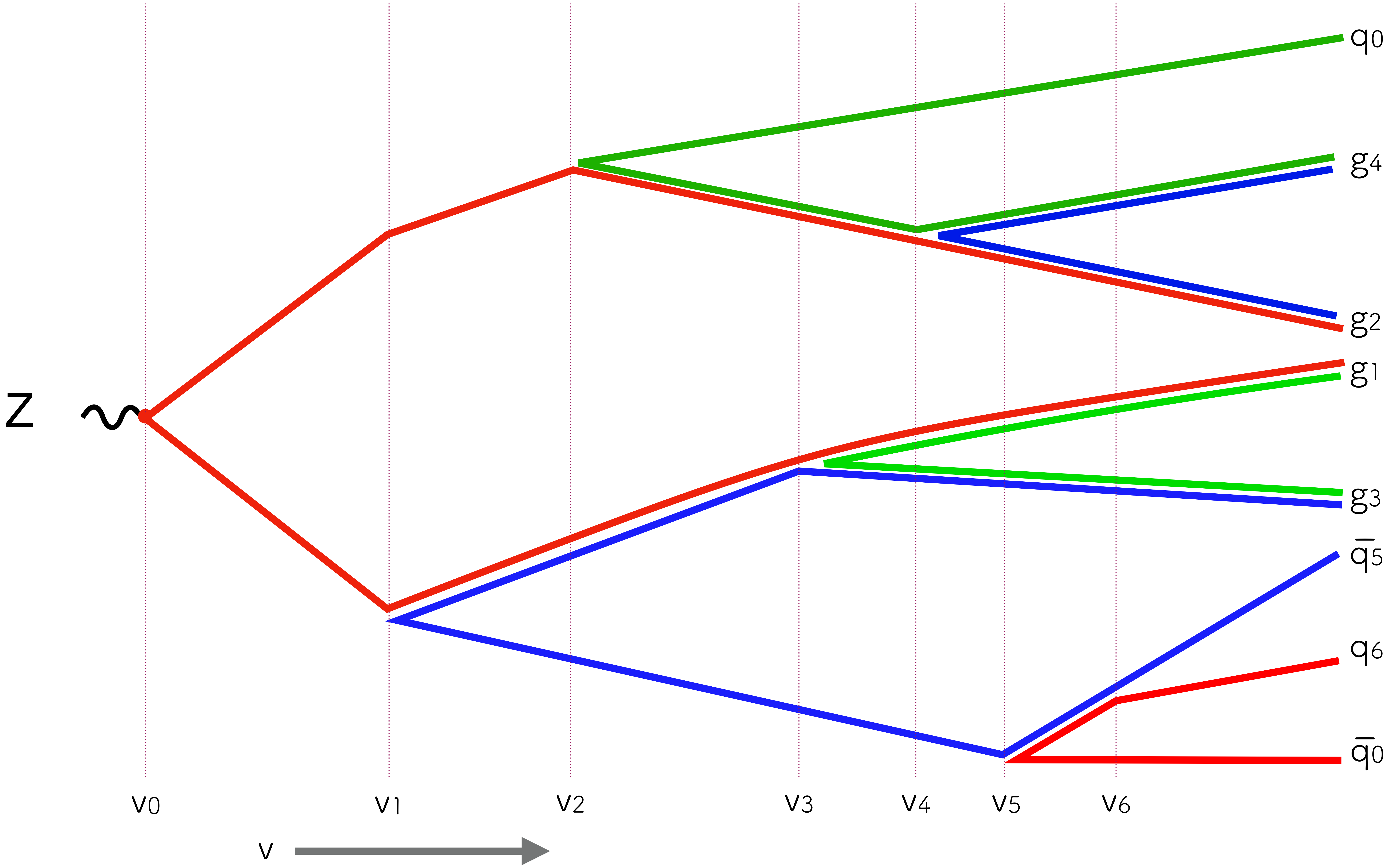
At some point, **state splits** (2→3, i.e. emits gluon). Evolution equation changes

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

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

(many showers use a large N_C limit)

QCD shower: an evolution equation (in evolution scale v, e.g. 1/trans.mom.)



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

what does a parton shower achieve?

not just a question of ingredients,
but also the final result of assembling them together

what **should** a parton shower achieve?

not just a question of ingredients,
but also the final result of assembling them together

it's a complicated issue…

- 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

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- 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]

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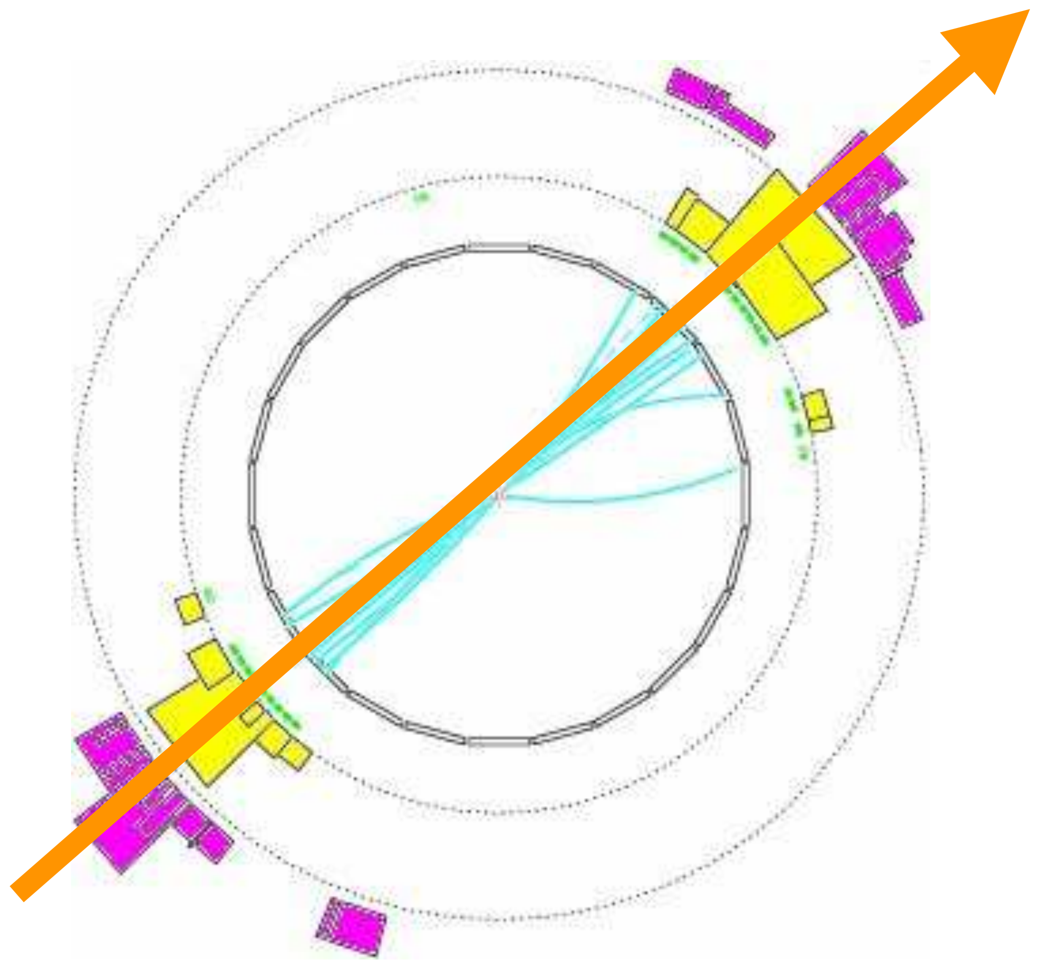
  [machine learning might "learn" many such features]

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

The standard answer so far

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)

$$\sigma(\ln B < -L) = \sigma_{tot} \exp\left[Lg_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \alpha_s^2 g_4(\alpha_s L) + \cdots\right]$$

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

LL ~ $O(\frac{1}{\alpha})$ NLL ~ $O(1)$ NNLL ~ $O(\alpha)$ N^{3}LL ~ $O(\alpha^2)$

Catani, Trentadue, Turnock & Webber '93 → NLL

Becher & Schwartz '08 → N^{3}LL

Until not so long ago: nobody was sure of the accuracy (probably "LL")

In the past you sometimes saw statements like "*Following standard practice to improve the logarithmic accuracy of the parton shower, the soft enhanced term of the splitting functions is rescaled by* $1+\alpha_s(t)/(2\pi)K$" [$K \sim A_2$ in cusp anomalous dimension]

Questions:

1) Which is it? LL or better? Is better than LL even possible?
2) For what observables does accuracy hold?
3) What good is it to know that some handful of observables is LL (or whatever) when you want to calculate arbitrary observables?
4) Does LL even mean anything when you do machine learning?
5) Why only "LL" when analytic resummation can do so much better?
6) Do better ingredients (e.g. higher-order splitting functions) make better showers?

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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

Our proposal for investigating shower accuracy

Resummation

Establish logarithmic accuracy for main classes of resummation:

- global event shapes (thrust, broadening, angularities, jet rates, energy-energy correlations, …)
- non-global observables (cf. Banfi, Corcella & Dasgupta, hep-ph/0612282)
- fragmentation / parton-distribution functions
- multiplicity, cf. original Herwig angular-ordered shower from 1980's

Matrix elements

Establish in what sense iteration of (e.g. 2→3) splitting kernel reproduces *N*-particle tree-level matrix elements *for any N*.
Because this kind of info is exploited by machine-learning algorithms.

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Because this kind of info is exploited by machine-learning algorithms.

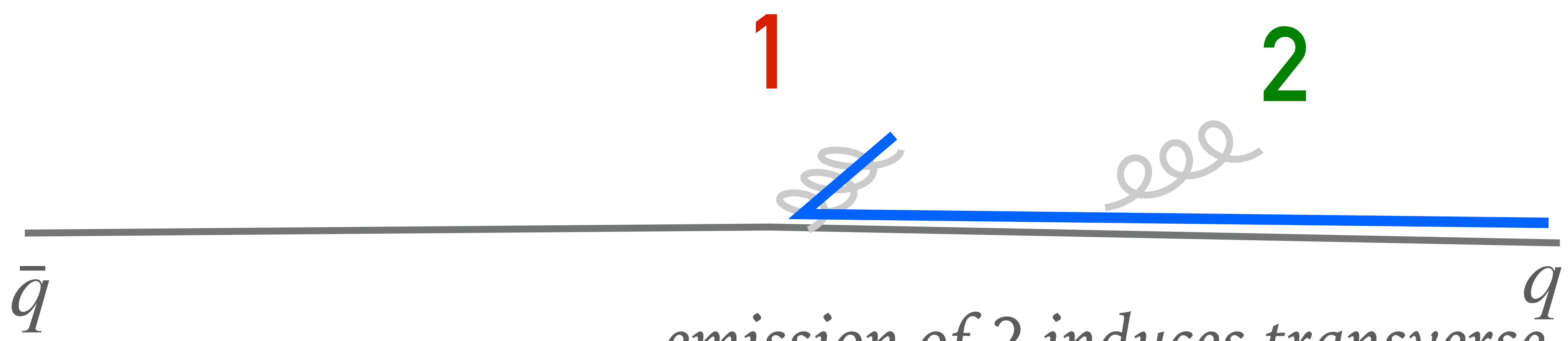
Baseline "NLL" requirements

Aim for NLL, control of $\alpha_s^n L^n$

Aim for NDL, i.e. $\alpha_s^n L^{2n-1}$

Aim for correctness when all particles well separated in Lund diagram

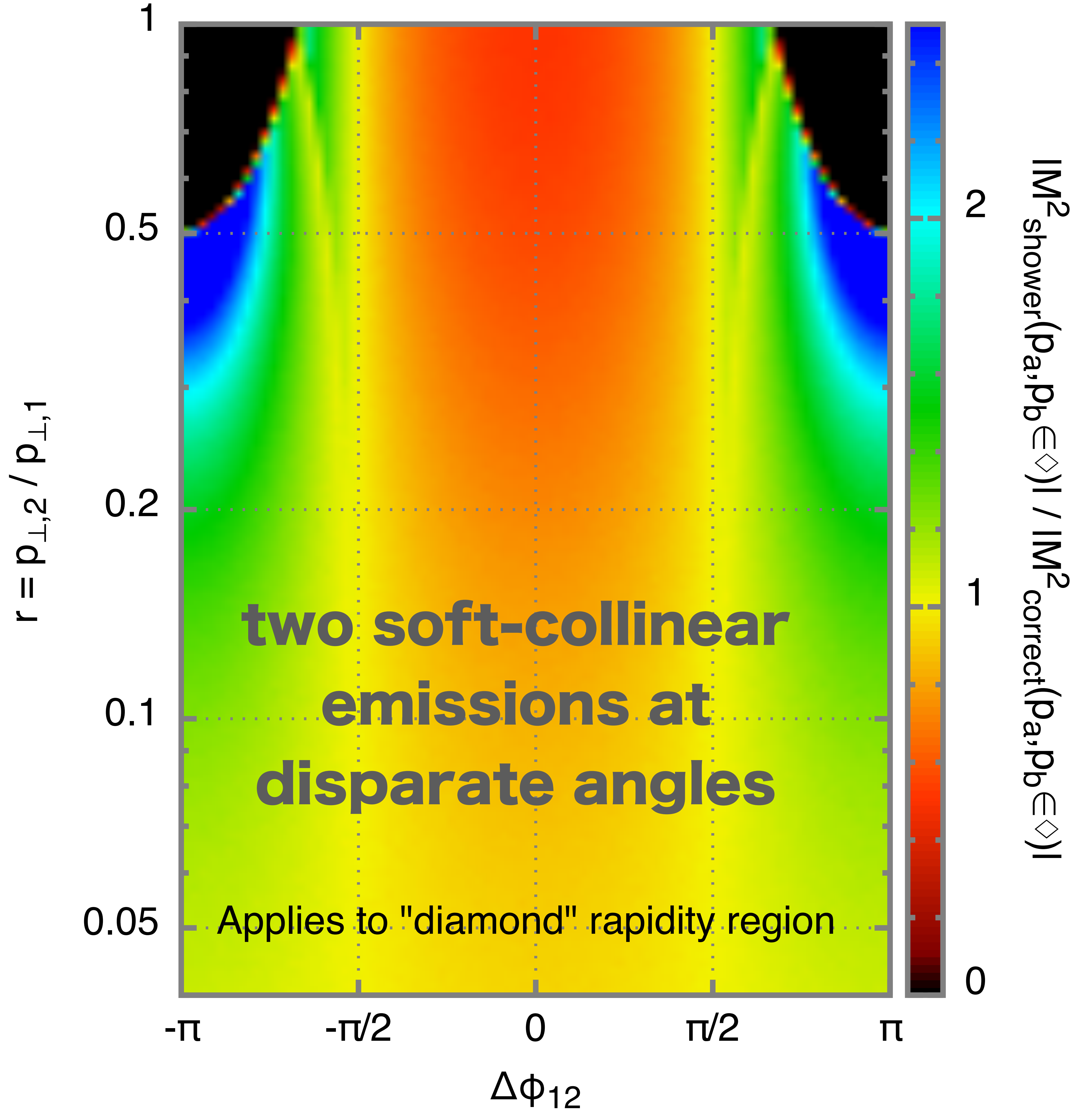
Step 1: might existing (dipole) showers be OK (i.e. NLL)?



emission of 2 induces transverse recoil in 1

Observable	$\mathrm{NLL}_{\ln\Sigma}$ discrepancy
$\sqrt{y_3^{\mathrm{cam}}}$	$-0.18277\,\bar{\alpha}^2 L^2$
FC_1	$-0.066934\,\bar{\alpha}^2 L^2$
B_T	$-0.0167335\,\bar{\alpha}^2 L^2$
vector p_t sum	$-0.250\,\bar{\alpha}^3 L^3$

ratio of effective shower matrix element to exact one



Dasgupta, Dreyer, Hamilton, Monni & GPS 1805.09327

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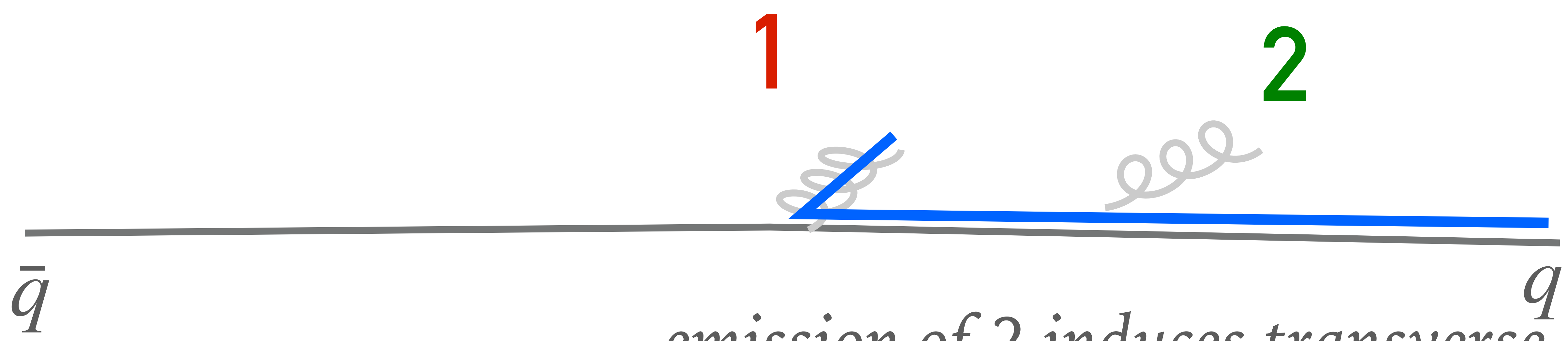
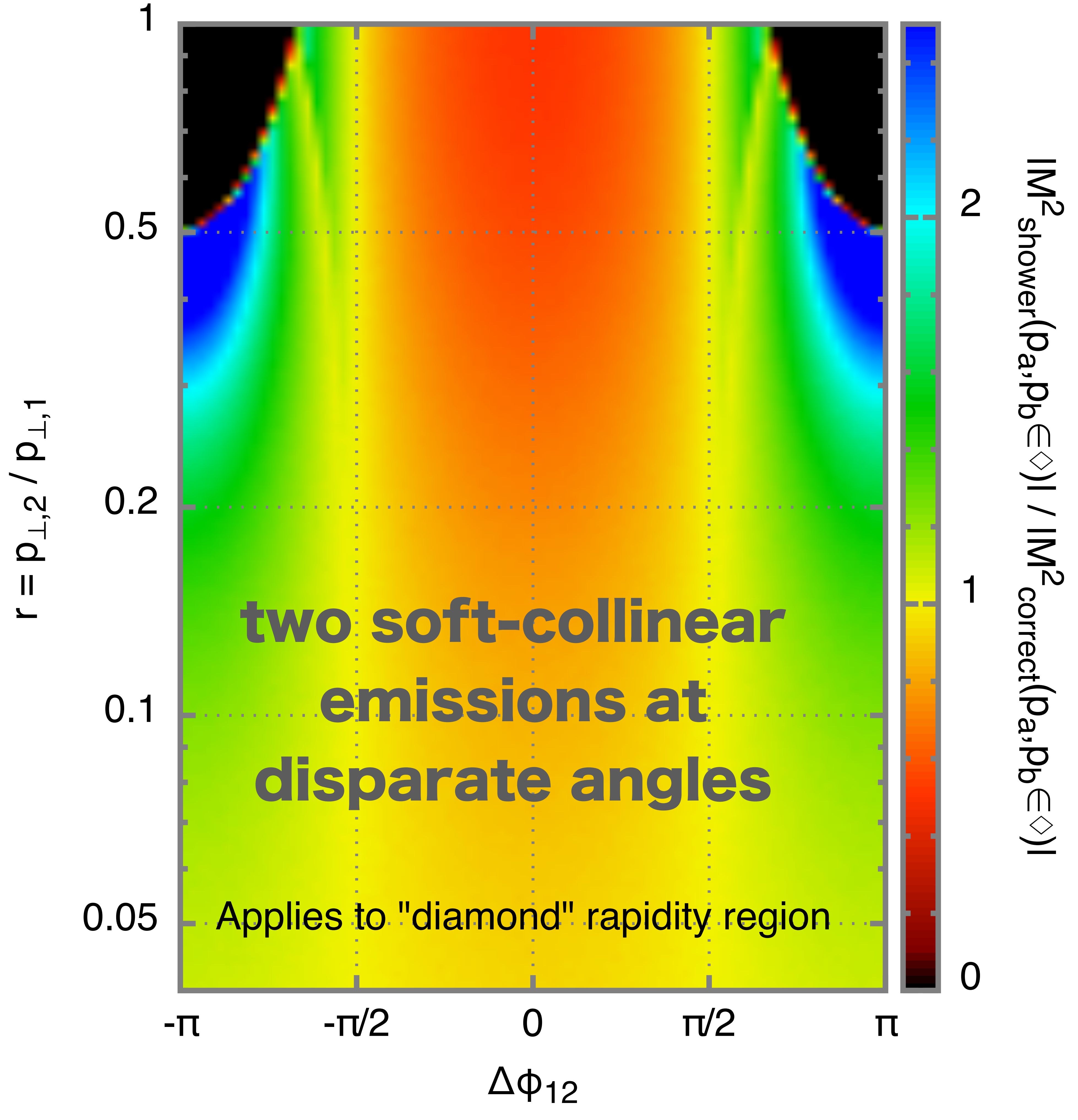


emission of 2 induces transverse recoil in 1

Observable	Σ discrepancy
$\sqrt{\ldots}$ [illegible]	…77 $\bar{\alpha}^2 L^2$
[illegible]	…066934 $\bar{\alpha}^2 L^2$
[illegible]	$-0.0167335\,\bar{\alpha}^2 L^2$
vector p_t …	$-0.250\,\bar{\alpha}^3 L^3$

Correct answer is 0
Not NLL

ratio of effective shower matrix element to exact one



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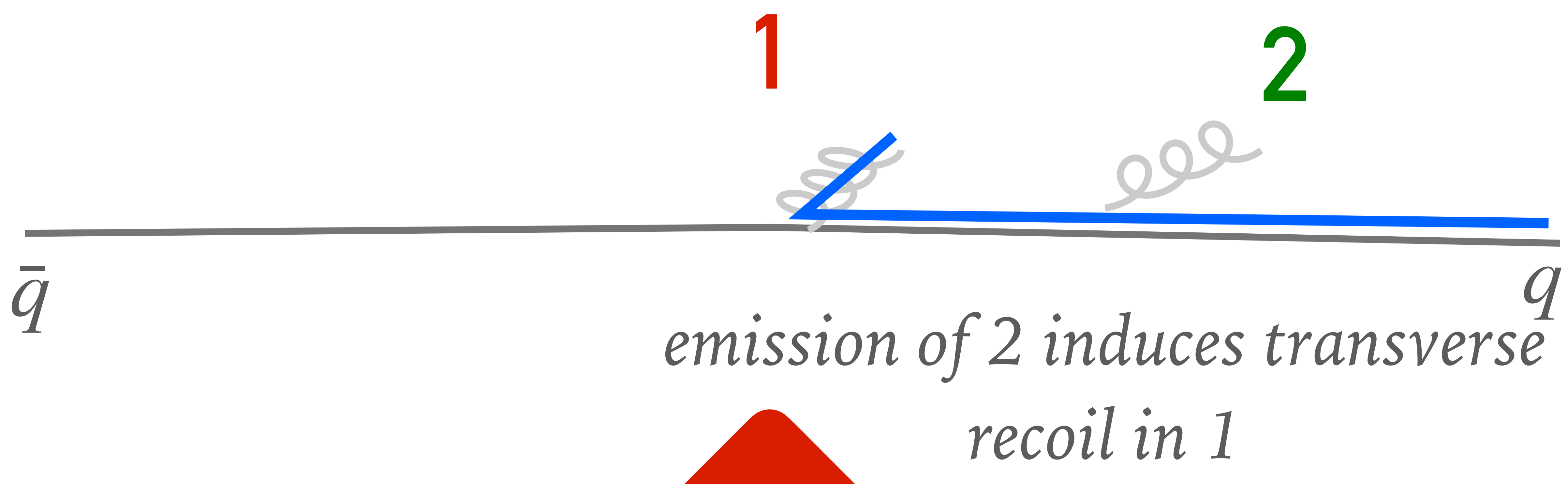

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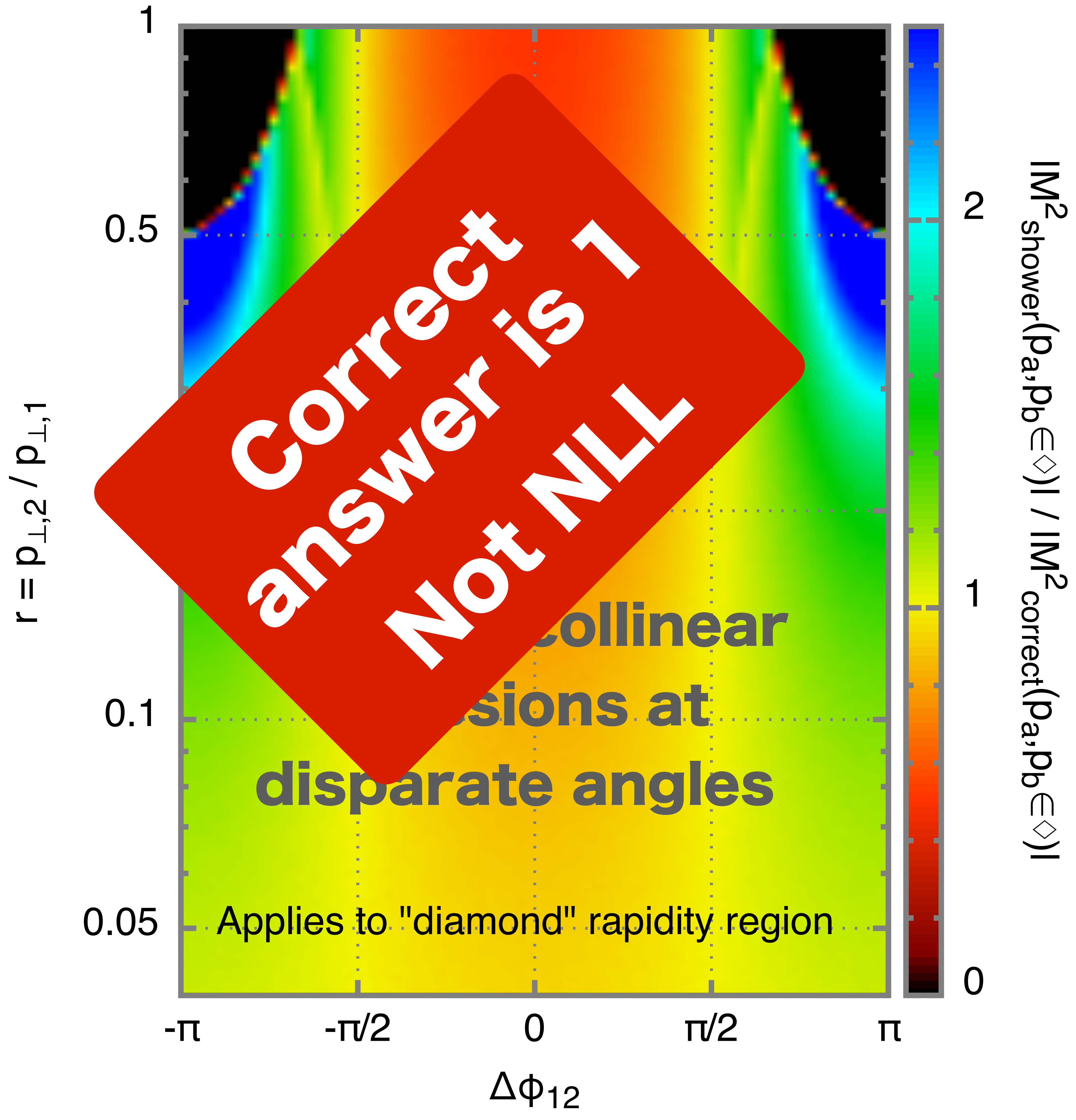
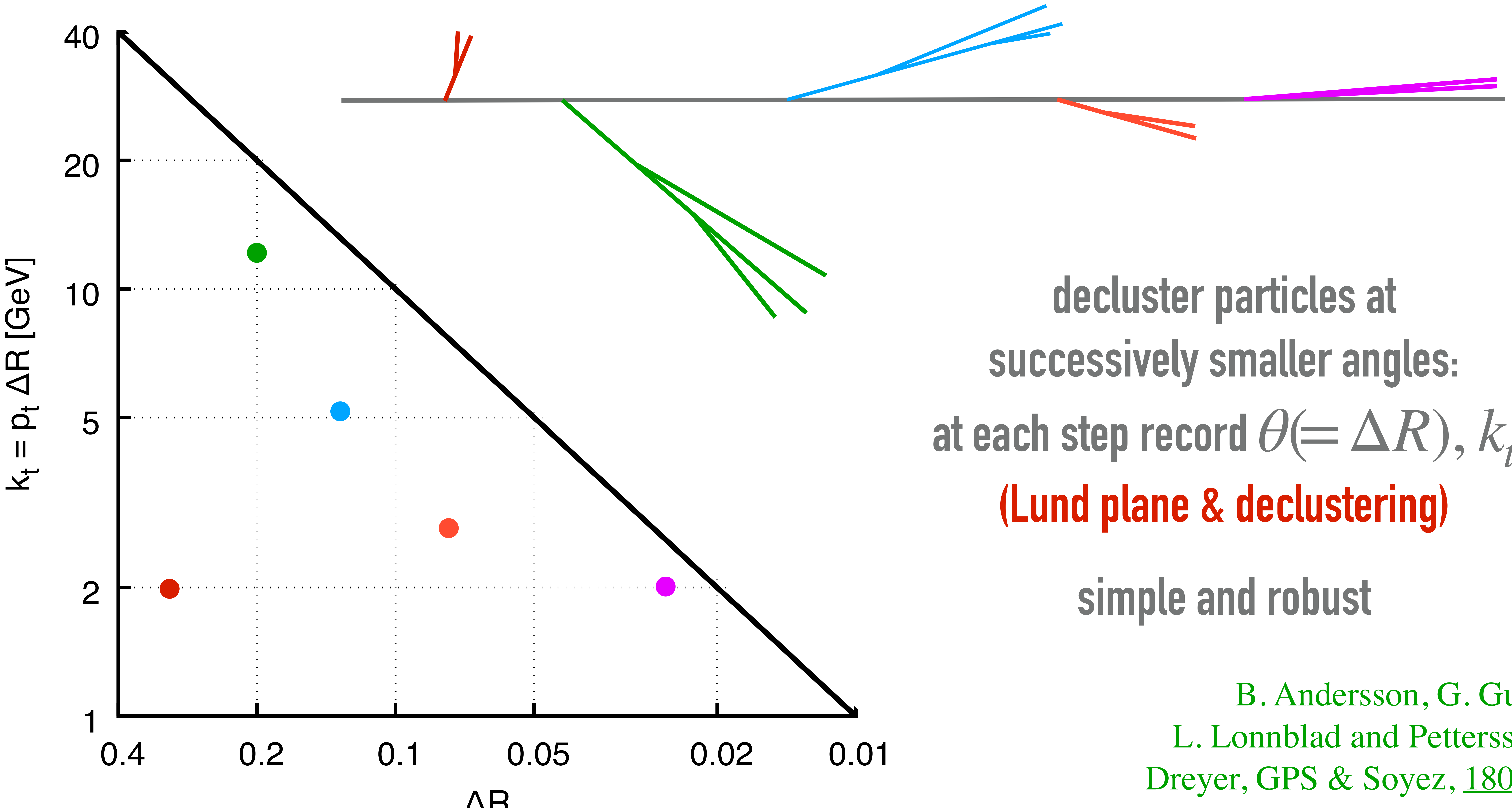


Dasgupta, Dreyer, Hamilton, Monni & GPS 1805.09327

Step 2: find way to organise phase space of arbitrary events (for future tests)

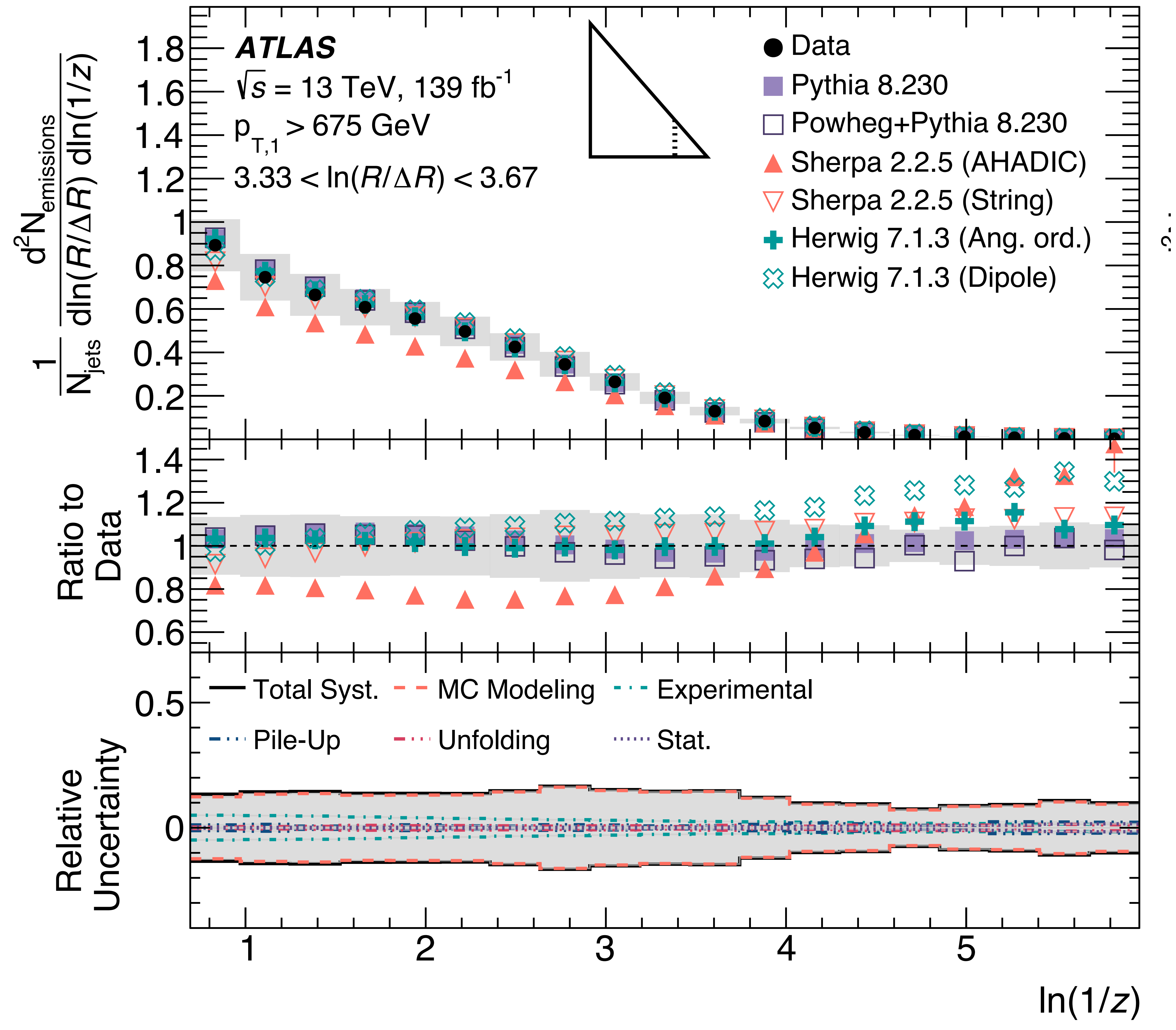


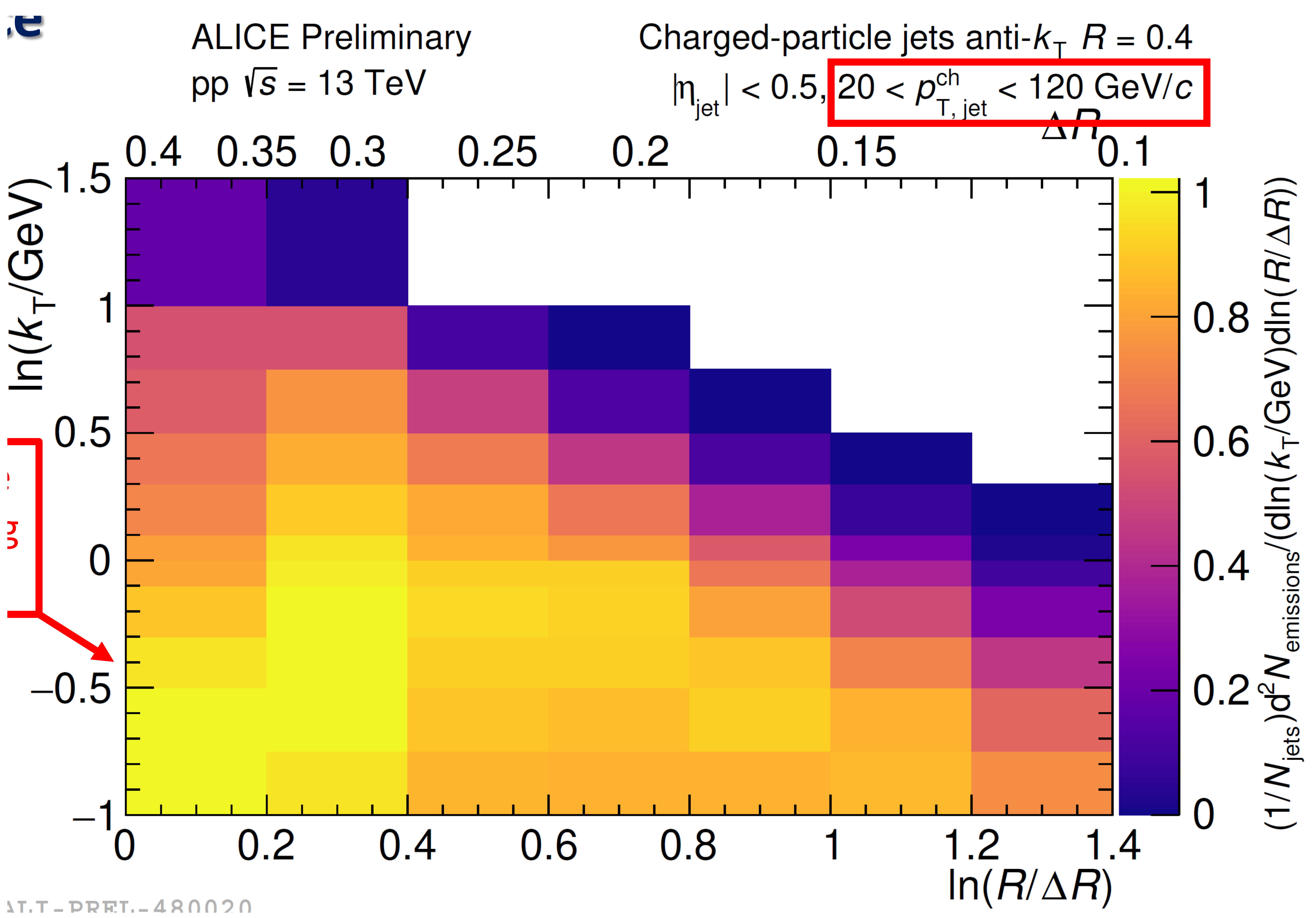
decluster particles at
successively smaller angles:
at each step record $\theta (= \Delta R), k_t$
(Lund plane & declustering)

simple and robust

B. Andersson, G. Gustafson,
L. Lonnblad and Pettersson 1989
Dreyer, GPS & Soyez, 1807.04758

Lund plane turns out to be powerful for **measurements** of jet substructure





+ calculations in Lifson, GPS & Soyez , 2007.06578

Step 3a: identify some core principles for NLL showers

1. for a new emission k, when it is generated far in the Lund diagram from any other emission $(|d_{ki}^{Lund}| \gg 1)$, **it should not modify the kinematics (Lund coordinates) of any preceding emission** by more than an amount $\exp(-p|d_{ki}^{Lund}|)$, where $p = \mathcal{O}(1)$

2. when k is distant from other emissions, generate it with matrix element and phasespace (and associated Sudakov)

$$\frac{d\Phi_k}{d\Phi_{k-1}} \frac{|M_{1\ldots k}|^2}{|M_{1\ldots(k-1)}|^2}$$

[simple forms known from factorisation properties of matrix-elements]

3. emission k **should not impact $d\Phi \times |M|^2$ ratio for subsequent distant emissions *unless***
   a. they are at commensurate angle (or on k's Lund "leaf"), or
   b. k was a hard collinear splitting, which can affect other hard collinear splittings (cross-talk on same leaf ≡ DGLAP, cross-talk on other leaves ≡ spin correlations)

Step 3b: design proof-of-principle showers (final-state, leading colour)

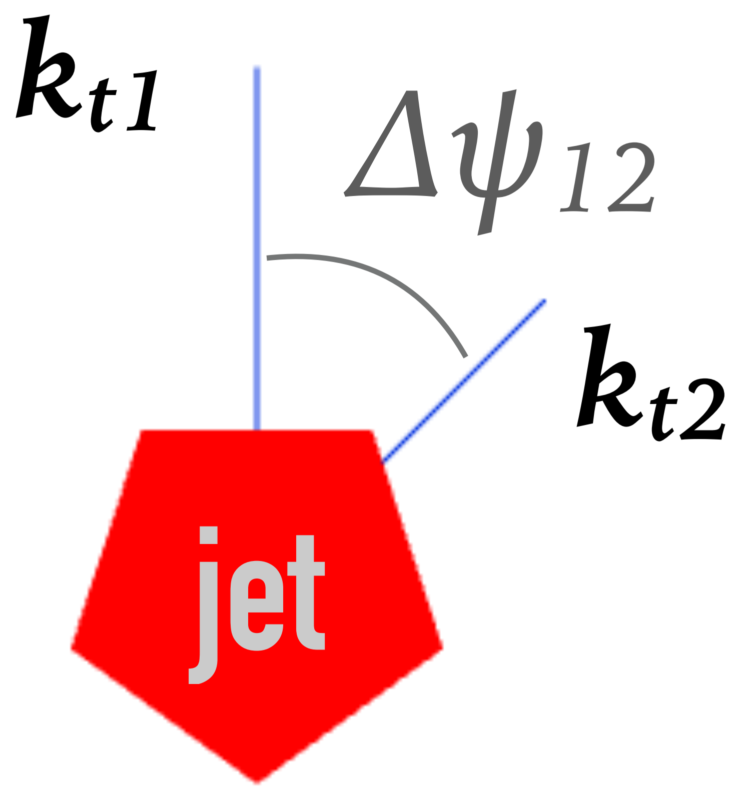
Degrees of freedom

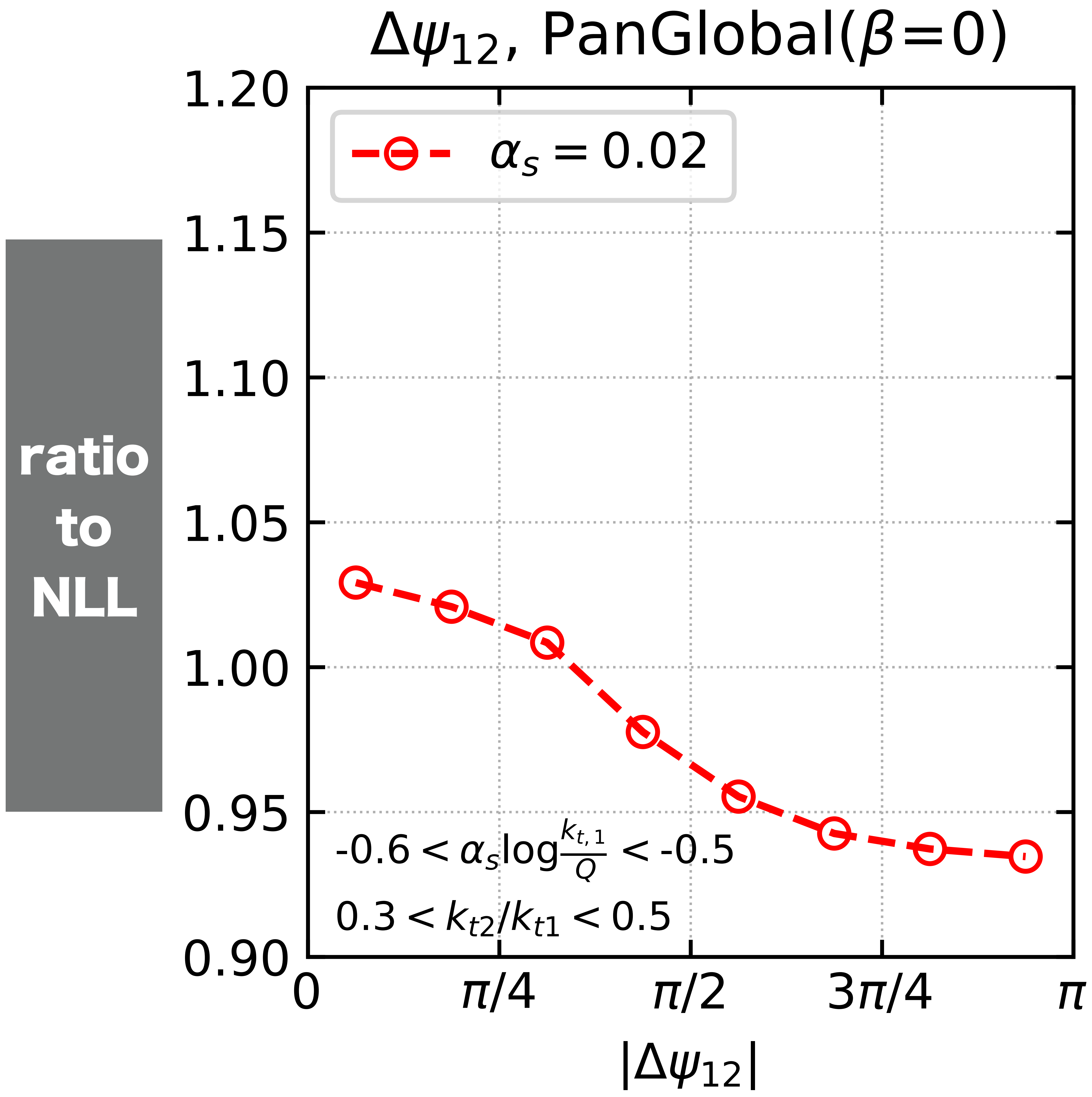
- the order in which emissions are generated: in decreasing $v = k_t \theta^\beta$, with β a parameter that sets the class of ordering variable ($\beta = 0$ gives standard k_t-ordered showers).
- how other partons' momenta change when a gluon is emitted (recoil scheme)

Candidate showers

- **PanGlobal showers:** transverse recoil shared across all particles in the event, expected to be NLL for $0 \leq \beta < 1$.
- **PanLocal showers:** all recoil shared locally within dipole, expected to be NLL for $0 < \beta < 1$. (NB: assignment of transverse recoil between dipole ends differs from standard dipole/antenna showers)

Step 3c: test new showers against NLL calculations





- run full shower with specific value of $\alpha_s(Q)$
- ratio to NLL should be flat ≡ 1
- it isn't: have we got an NLL mistake? Or a residual subleading (NNLL) term?

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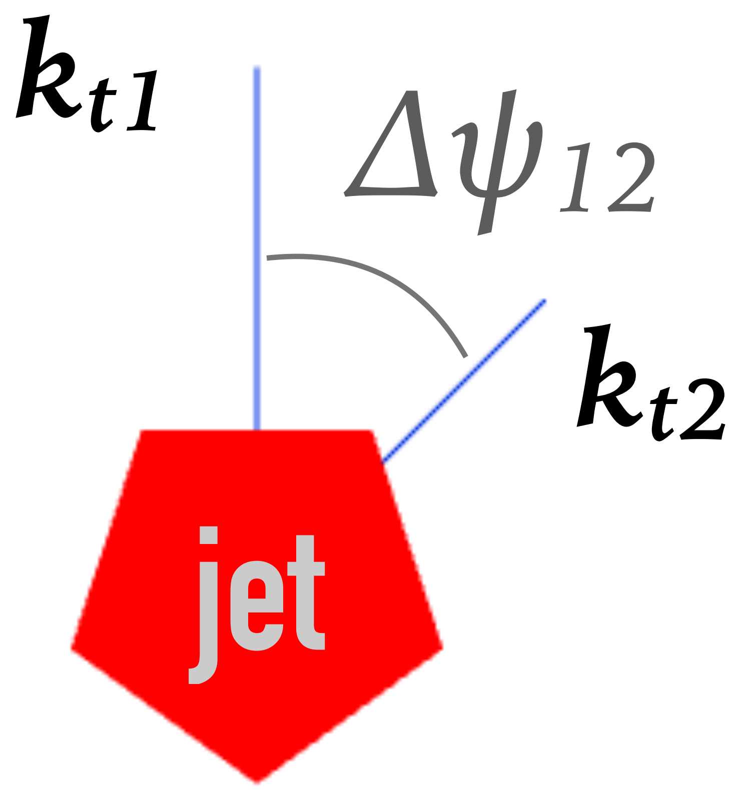

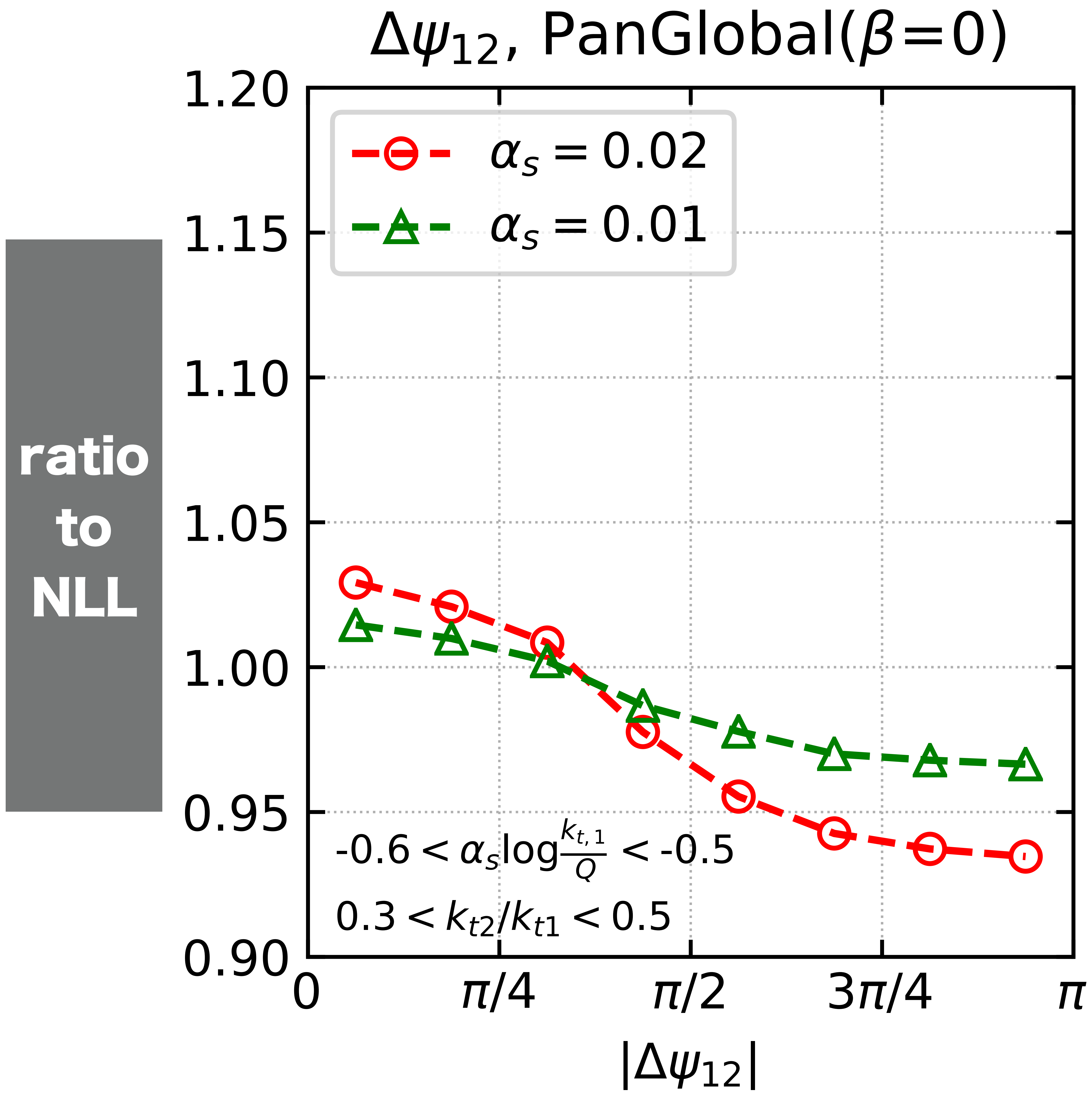

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- try halving $\alpha_s(Q)$, while keeping constant $\alpha_s L$ [$L \equiv \ln k_{t1}/Q$]
- NLL effects, $(\alpha_s L)^n$, should be unchanged, subleading ones, $\alpha_s(\alpha_s L)^n$, halved

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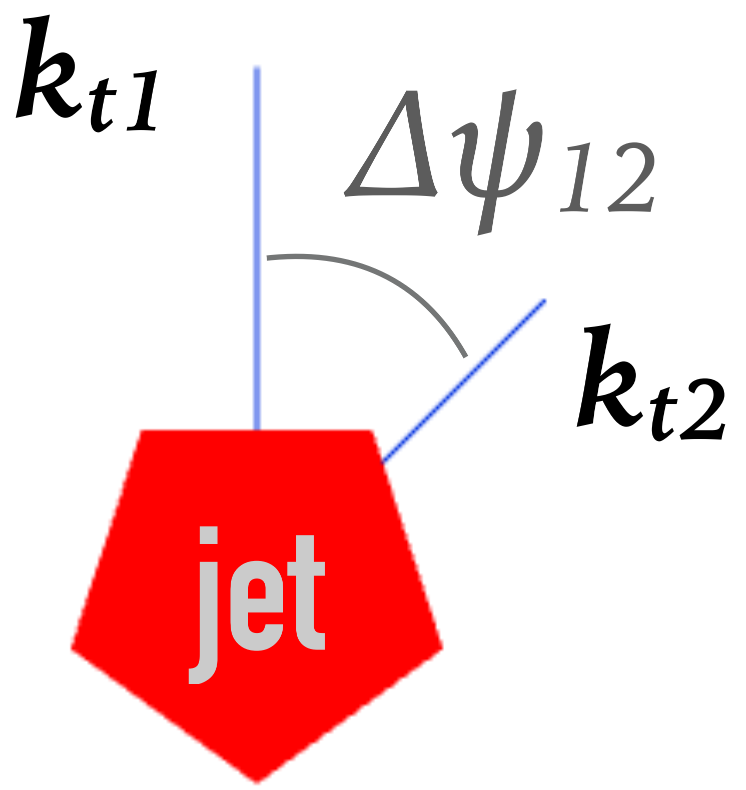
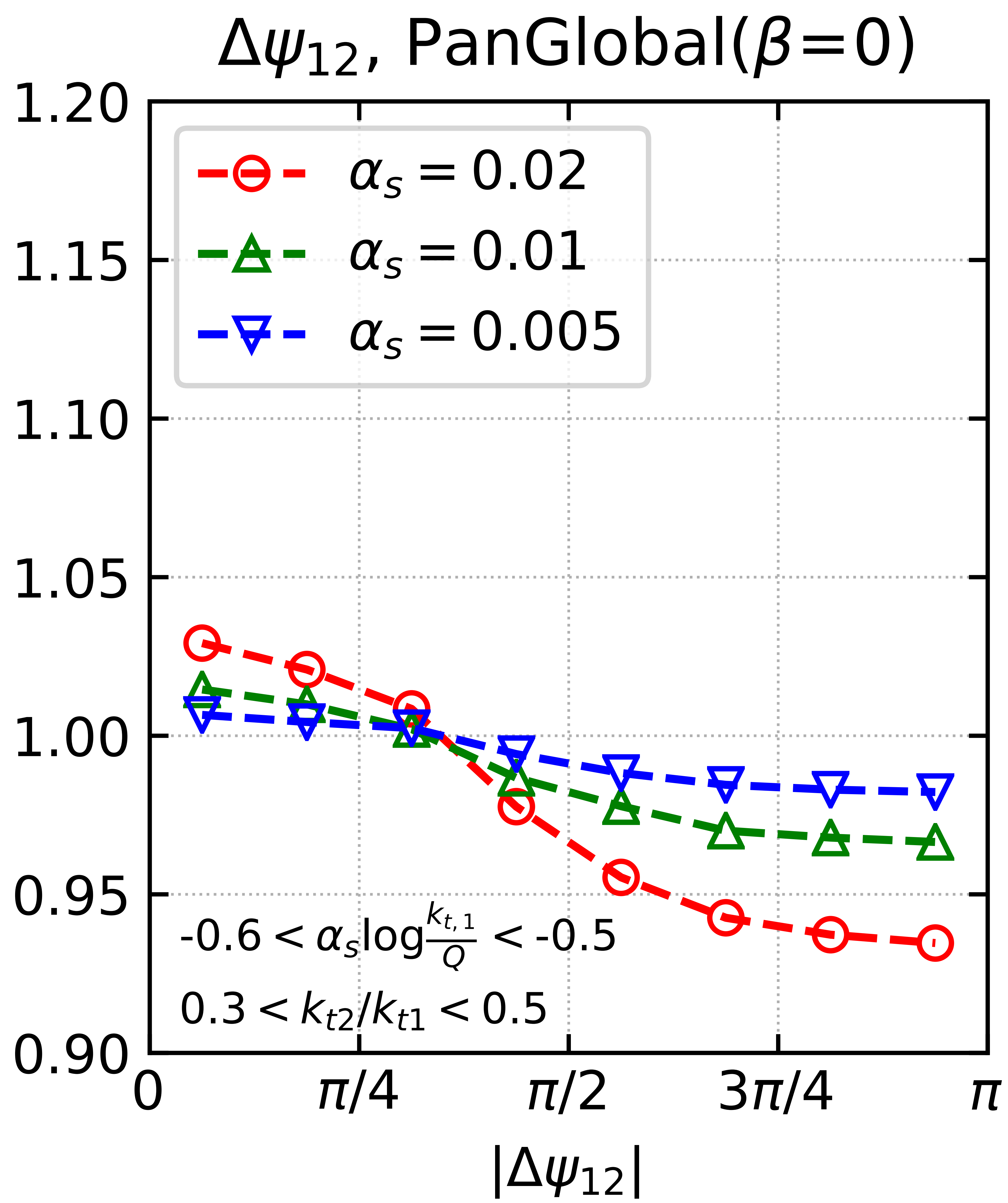


ratio to NLL



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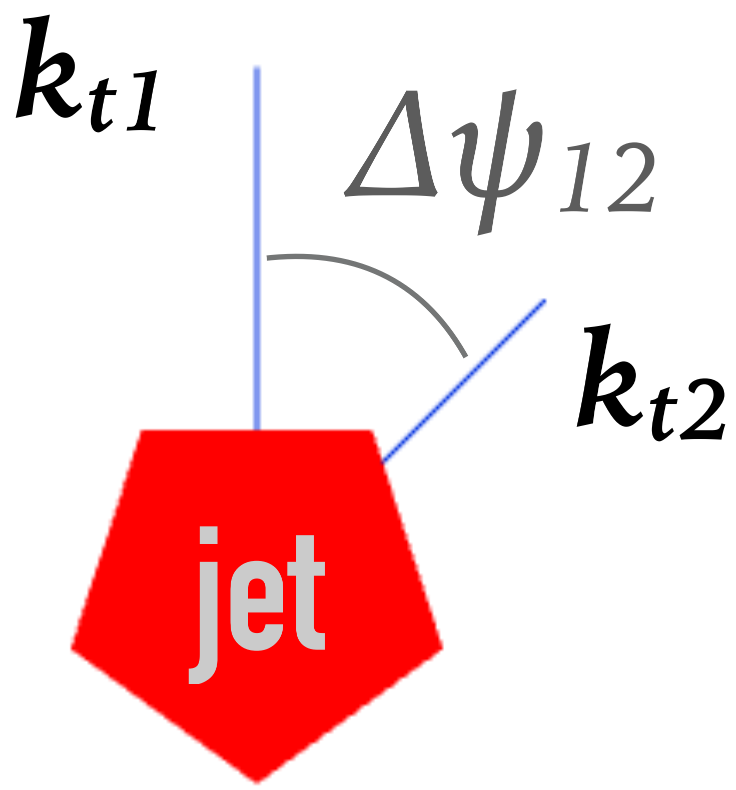

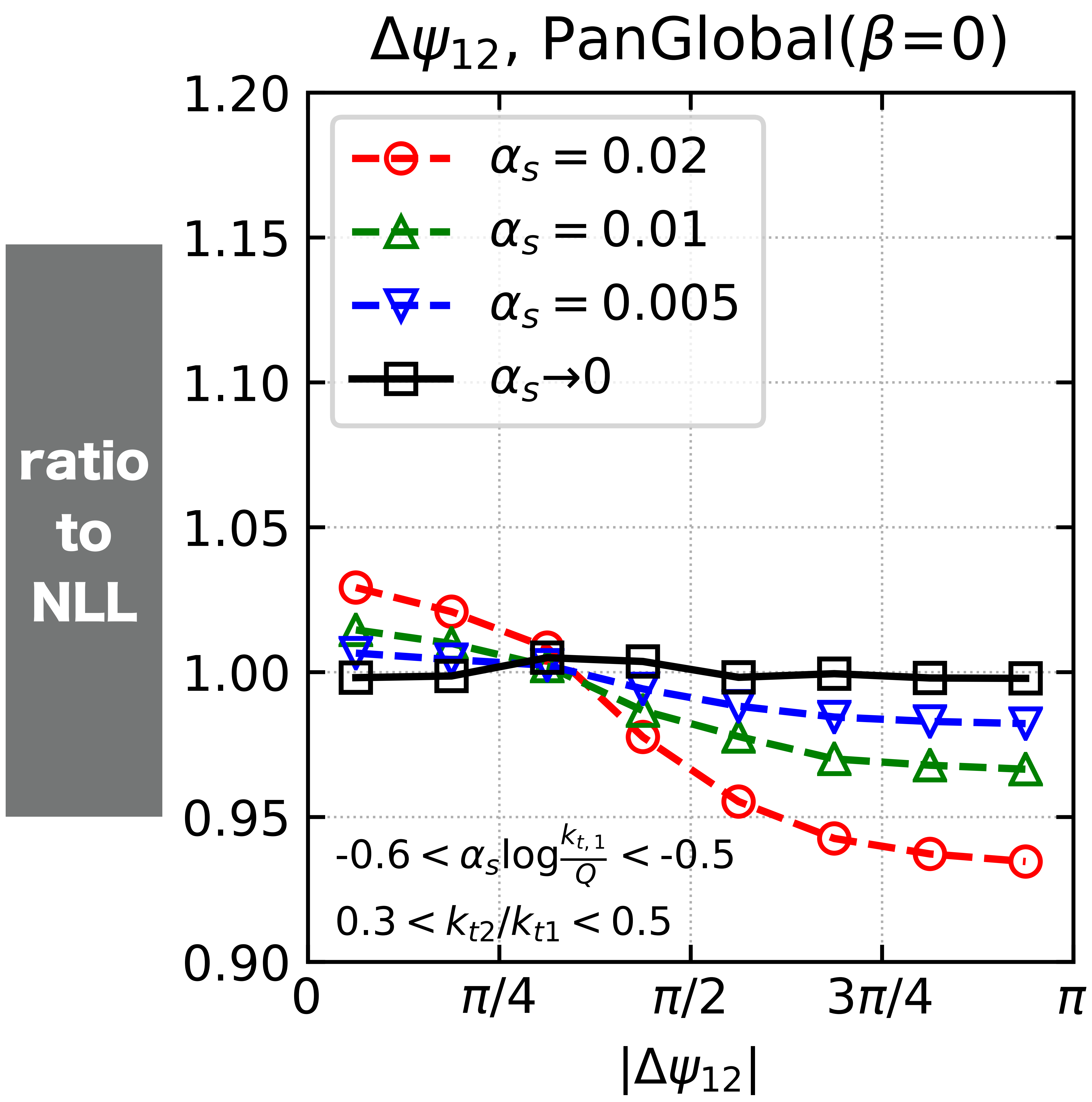

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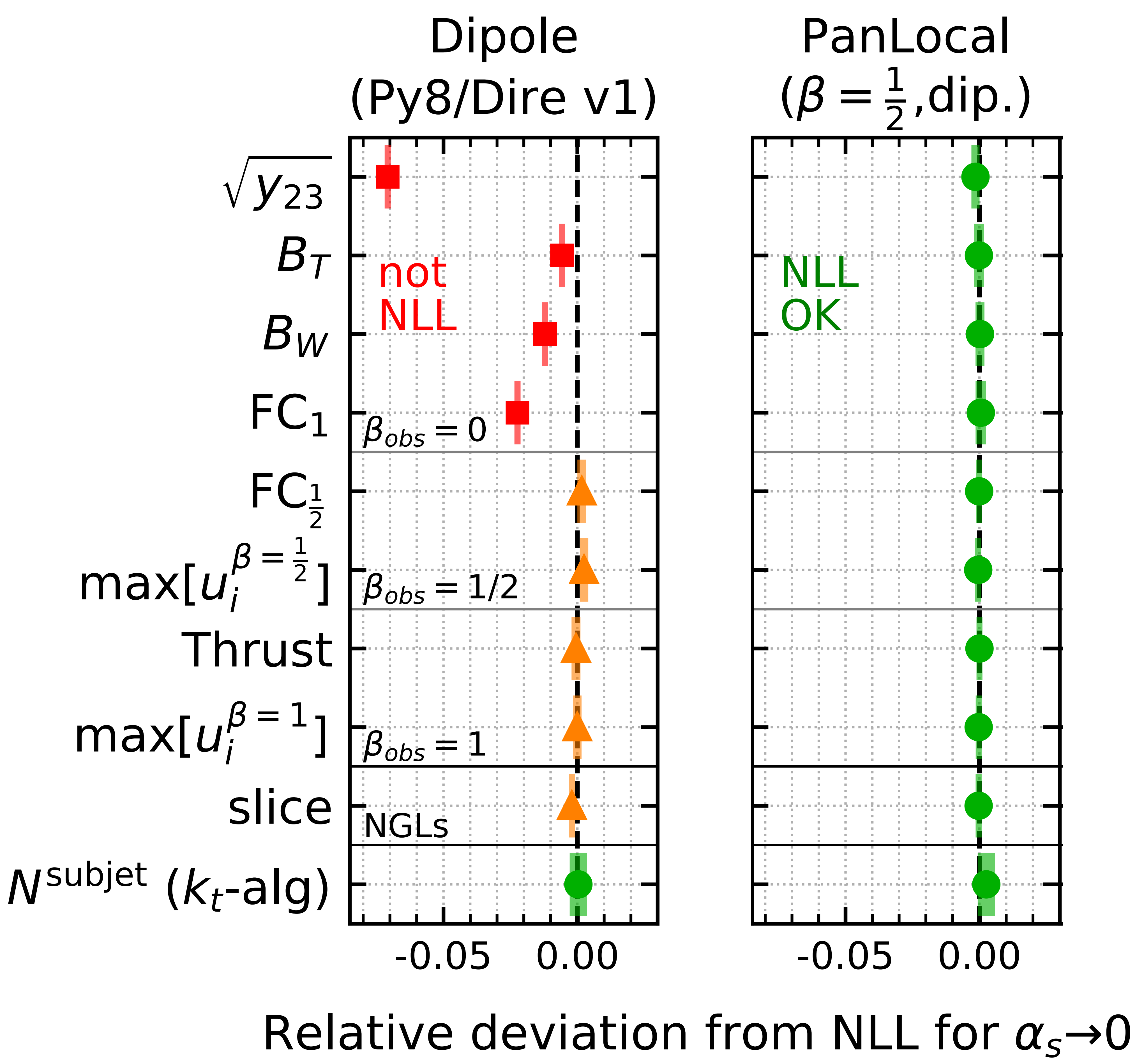
✓ **extrapolation $\alpha_s \to 0$ agrees with NLL**

Step 3c: test new showers against NLL calculations — for many observables

Dasgupta, Dreyer, Hamilton, Monni, GPS, Soyez, 2002.11114 (Phys.Rev.Lett.)

standard parton showers

new "PanScales" parton showers, designed specifically to achieve NLL accuracy



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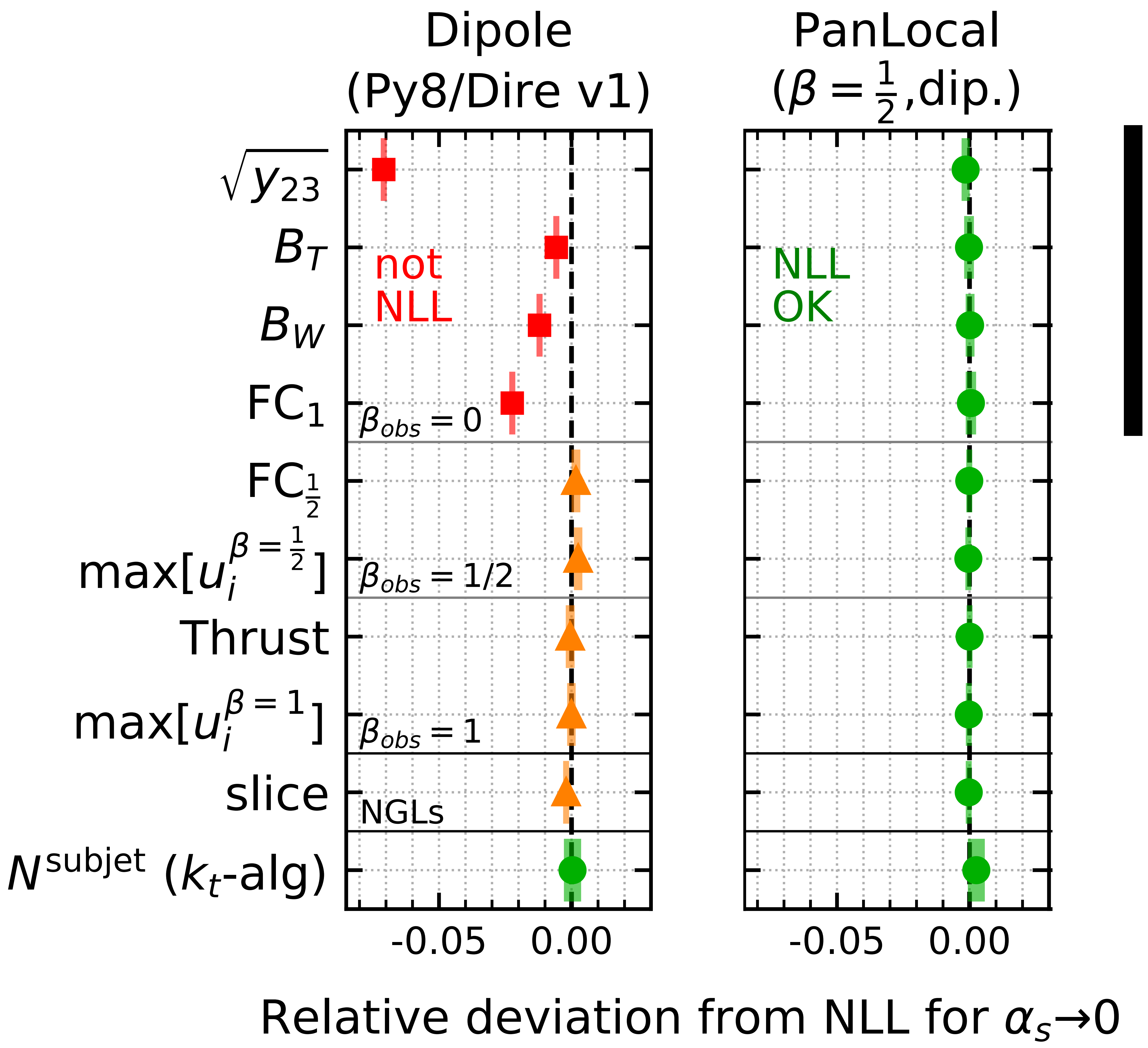

Event shapes sensitive to transverse momentum (jet broadenings, jet clustering transitions)

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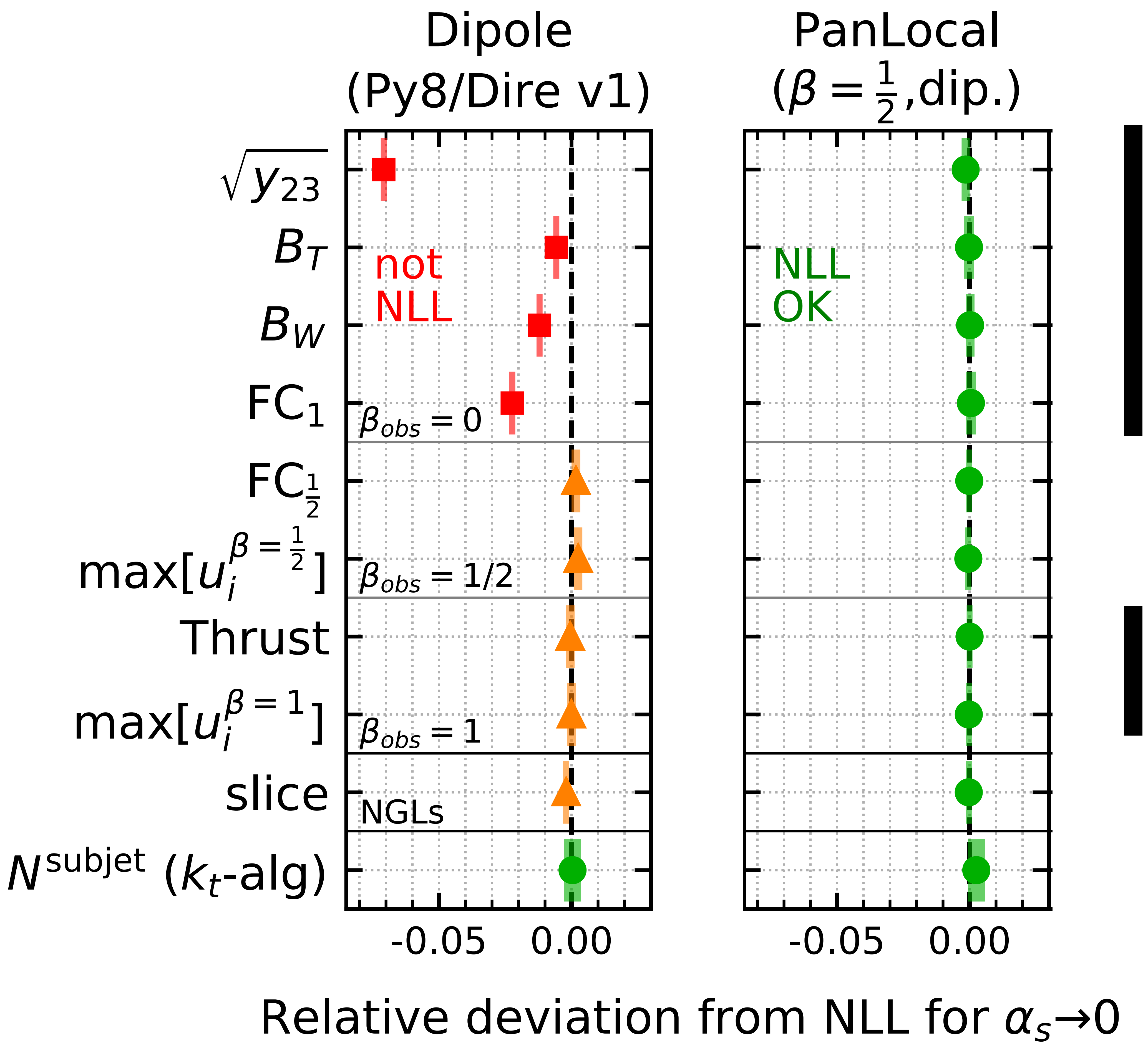

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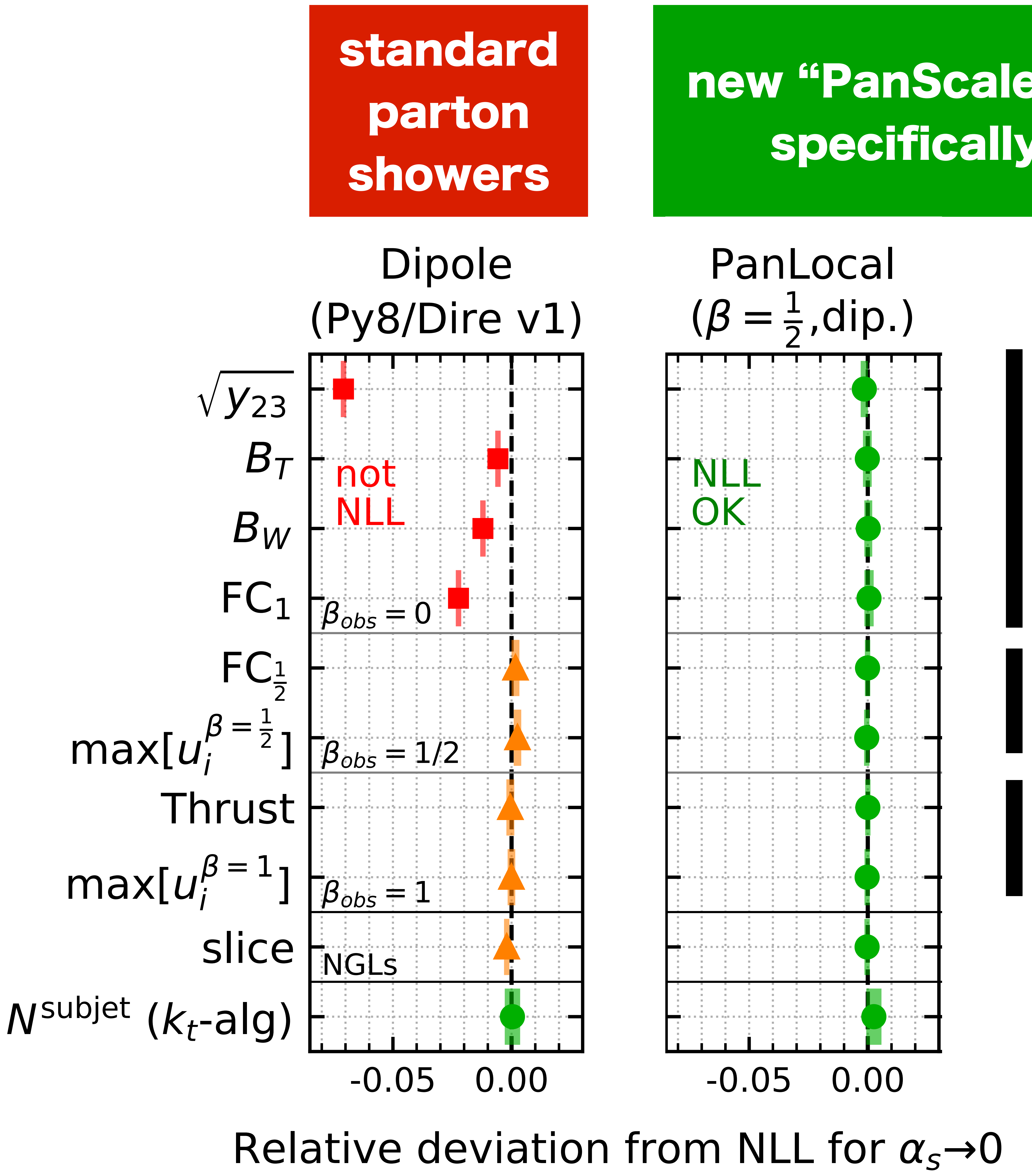

Event shapes sensitive to transverse momentum (jet broadenings, jet clustering transitions)

Event shapes that probe $p_t\, e^{-0.5|\eta|}$ (like $\beta = 0.5$ ordering variable)

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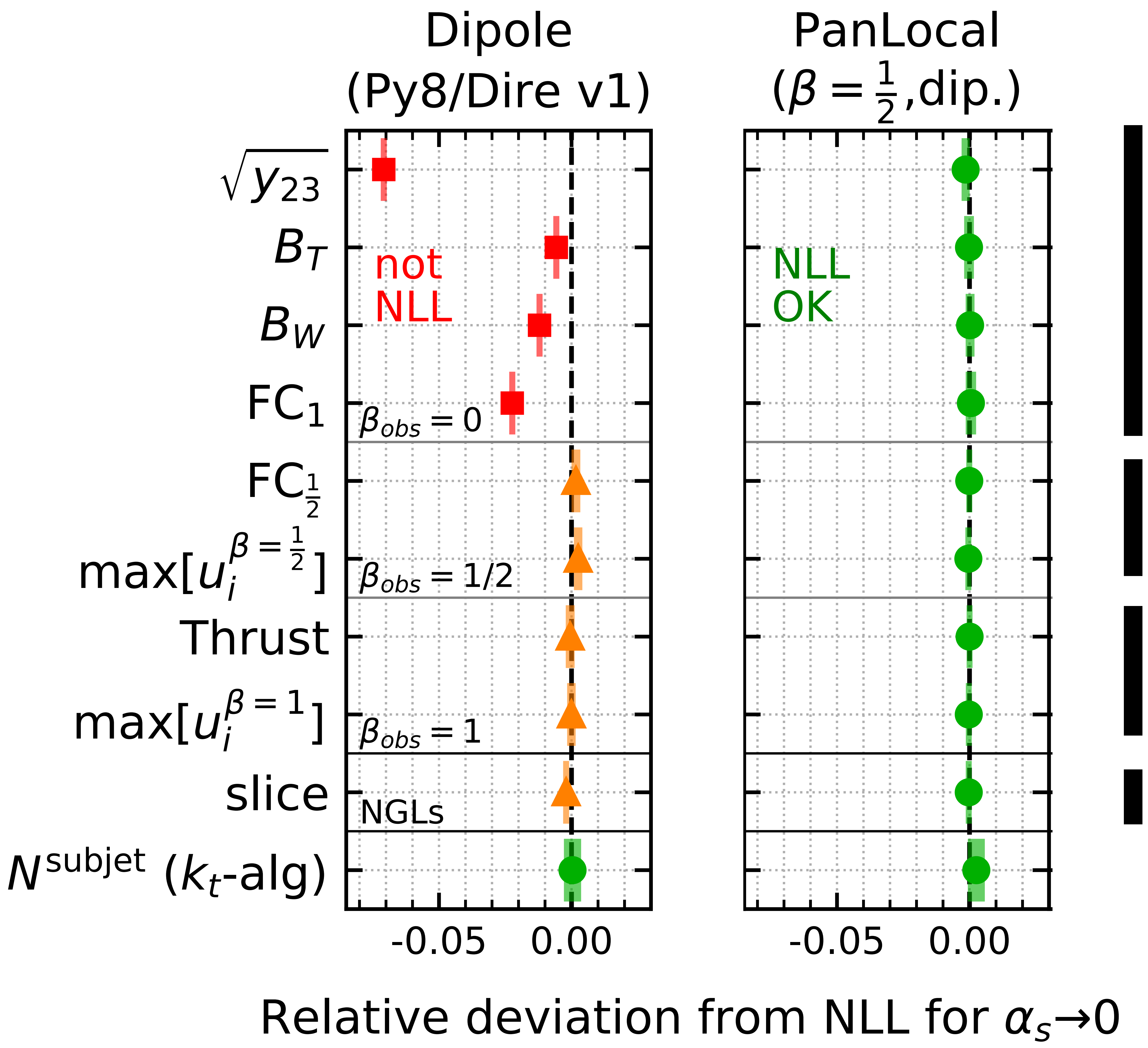

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probe of non-global logarithms

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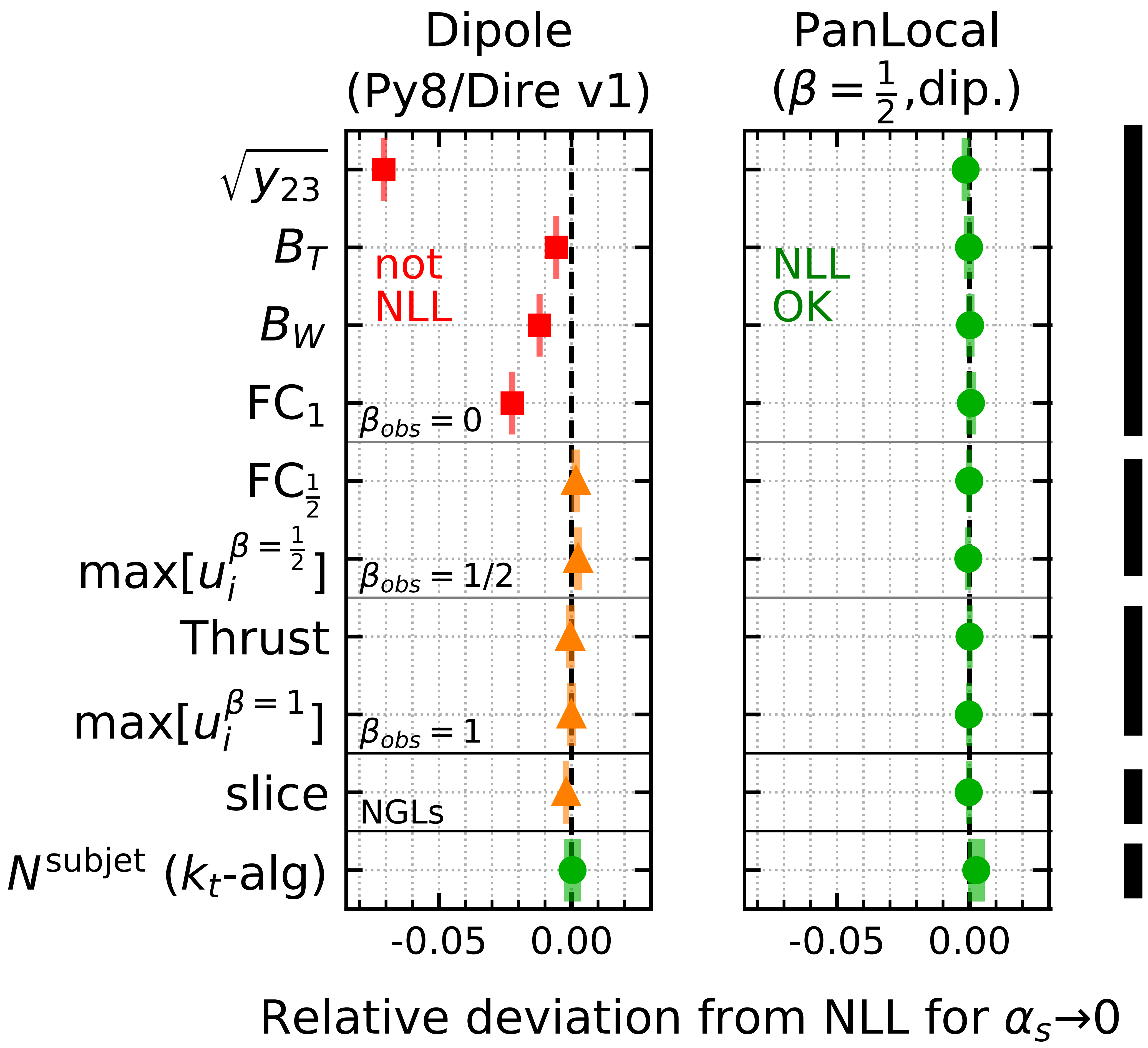

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standard jet multiplicity (probe of full recursive shower structure)

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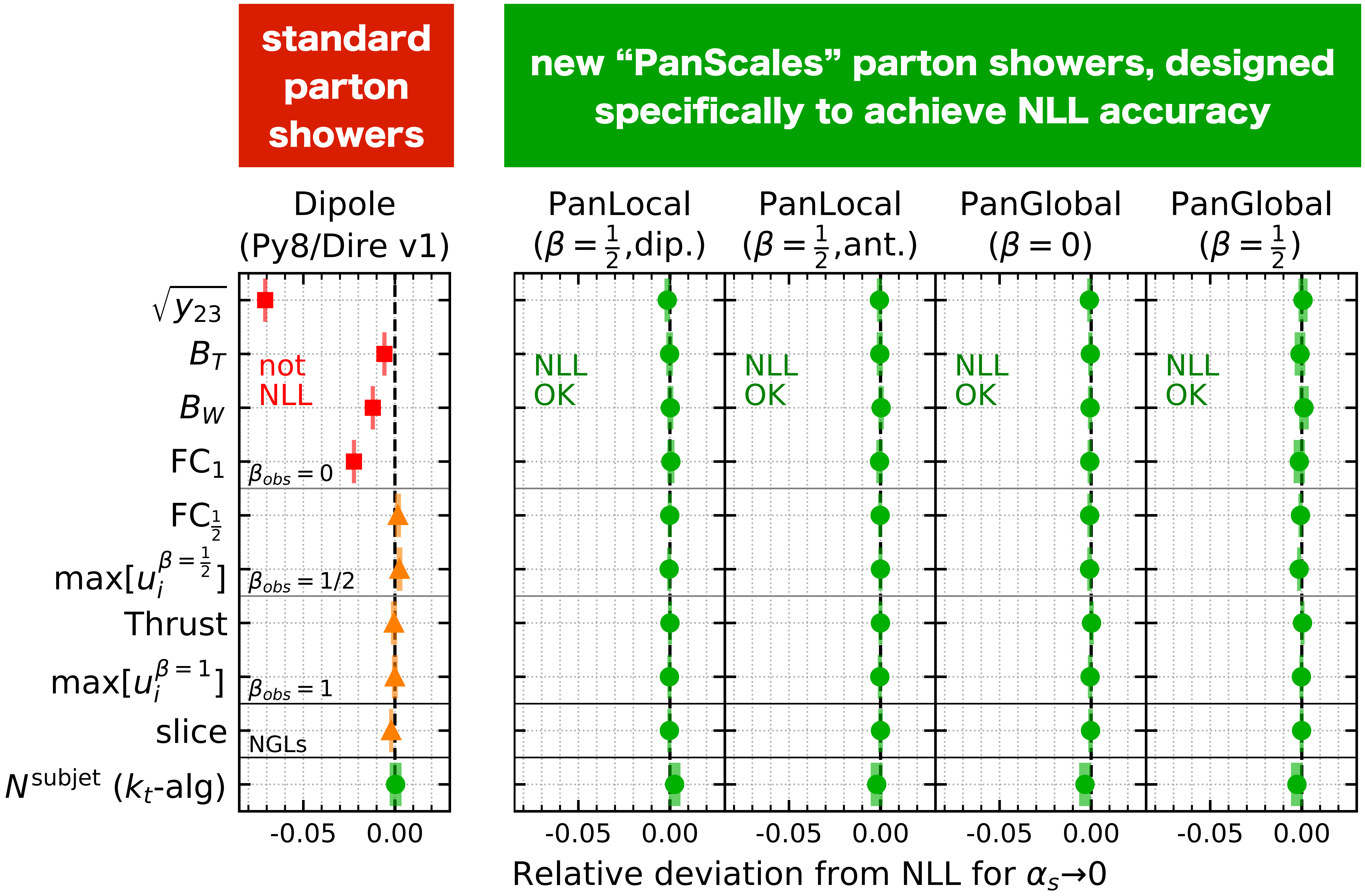
Dasgupta, Dreyer, Hamilton, Monni, GPS, Soyez, 2002.11114 (Phys.Rev.Lett.)



All PanScales shower that are expected to agree with NLL pass these tests

(Standard dipole showers don't)

see also Bewick, Ferrario Ravasio, Richardson and Seymour 1904.11866, Forshaw, Holguin & Plätzer, 2003.06400 and Nagy & Soper, 2011.04777

Next steps beyond proof of concept NLL final-state shower

Towards a complete e^+e^- NLL shower

Including initial hadrons

Going beyond NLL

Public code

Next steps beyond proof of concept NLL final-state shower

Towards a complete e^+e^- NLL shower

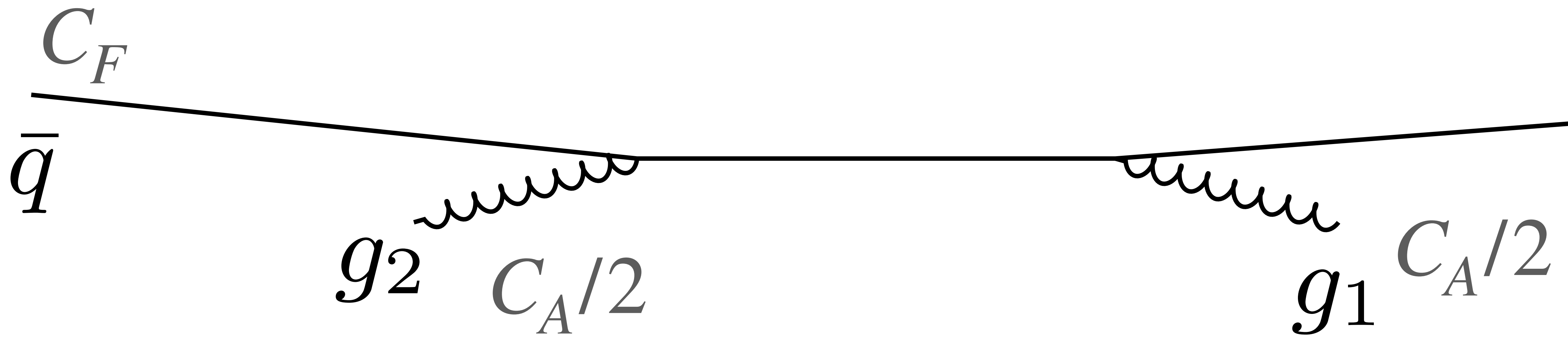
Colour
Standard dipole showers have wrong subleading-colour terms at LL

Spin
Our NLL matrix-element condition means that we need spin correlations

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

Heavy quarks
Also needed for phenomenology

Colour in parton showers: leading colour and beyond



Most showers (and all NLL candidates) use concept of colour dipoles, valid when squared number of colours, $N_C^2 = 9 \gg 1$

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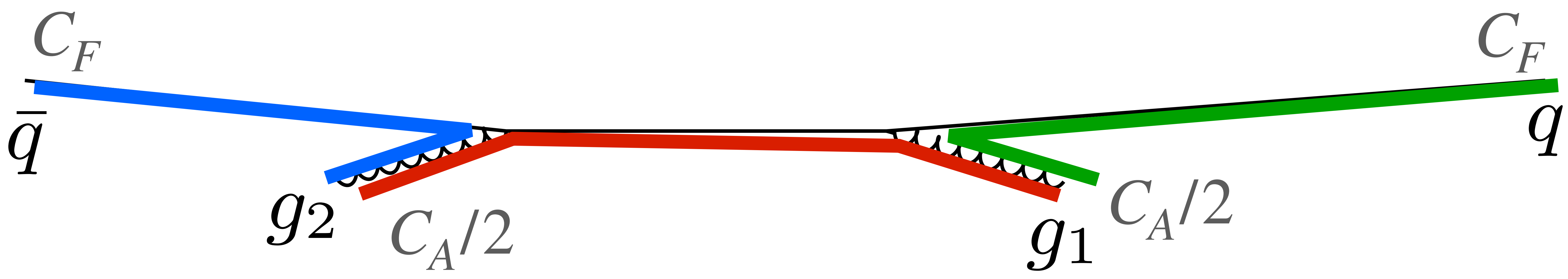

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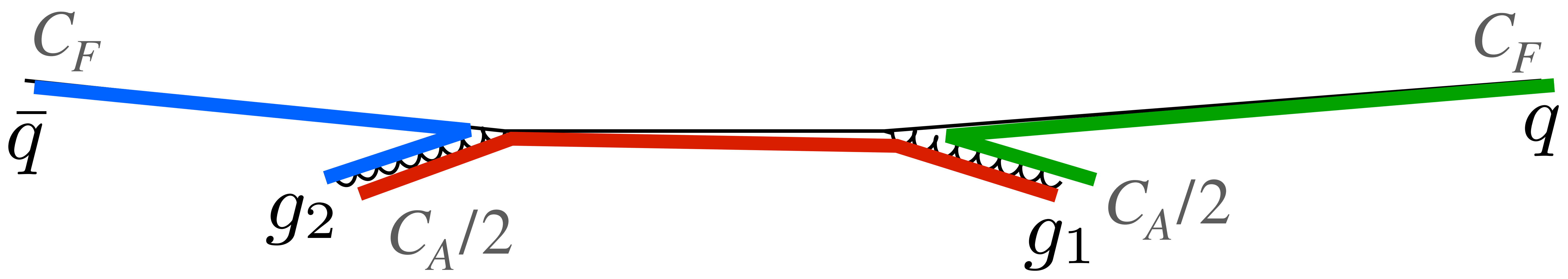

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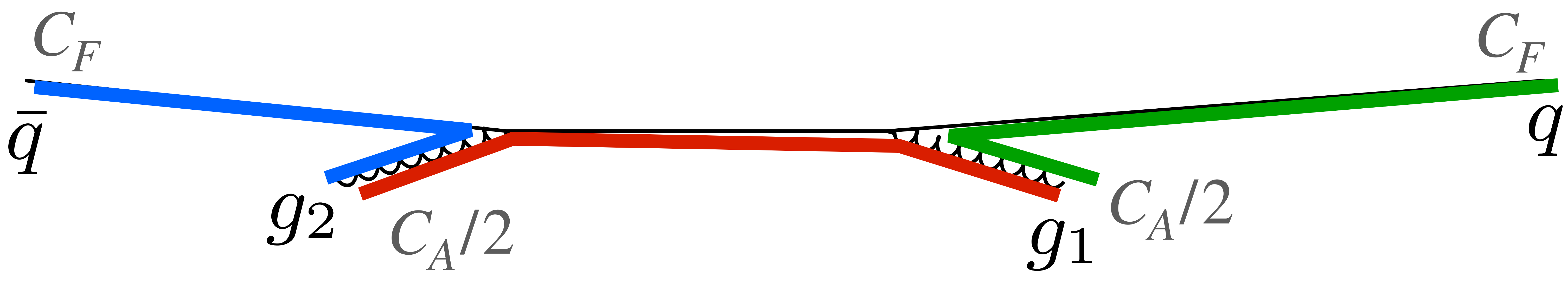

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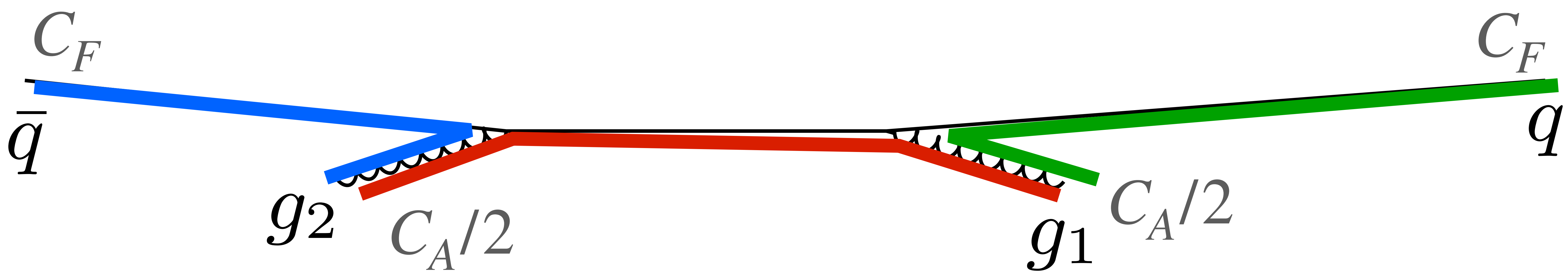
- Standard showers replace $C_A/2 \to C_F = N_C/2 - 1/2N_C$ for each half that ends in a q ("Colour Factor from Emitter" – CFFE)

Approach 1

Solve the complete colour problem, as $1/N_C^2$ expansion (Nagy& Soper 1908.11420 + …, de Angelis Forshaw & Plätzer 2007.09648 + …)

Colour in parton showers: leading colour and beyond



Most showers (and all NLL candidates) use concept of colour dipoles, valid when squared number of colours, $N_C^2 = 9 \gg 1$

- Large-N_C means that each dipole radiates with colour factor $C_A/2 = N_C/2$
- Standard showers replace $C_A/2 \to C_F = N_C/2 - 1/2N_C$ for each half that ends in a q ("Colour Factor from Emitter" – CFFE)

Approach 1

Solve the complete colour problem, as $1/N_C^2$ expansion (Nagy& Soper 1908.11420 + …, de Angelis Forshaw & Plätzer 2007.09648 + …)

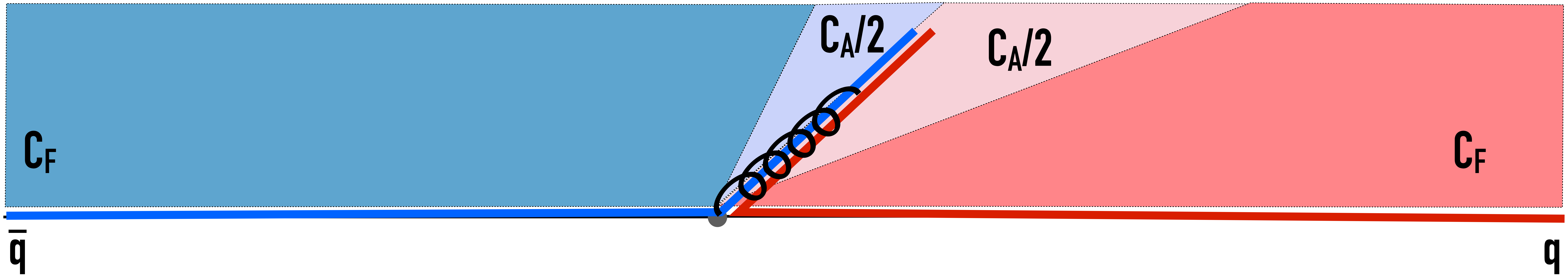
Approach 2

Solve the problem as it matters for logarithmic accuracy (see also Holguin, Forshaw & Plätzer, 2011.15087)

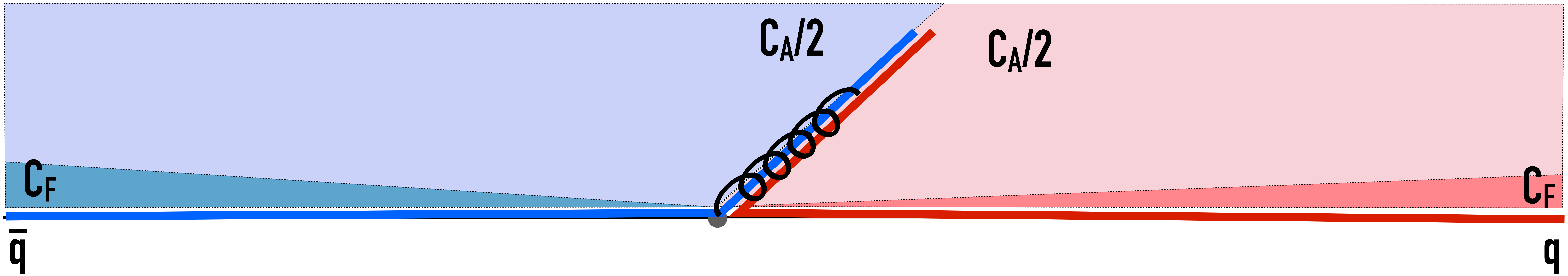
Angular-ordered v. standard dipole colour

Dasgupta, Dreyer, Hamilton, Monni & GPS 1805.09327

Correct physical (angular-ordered) picture



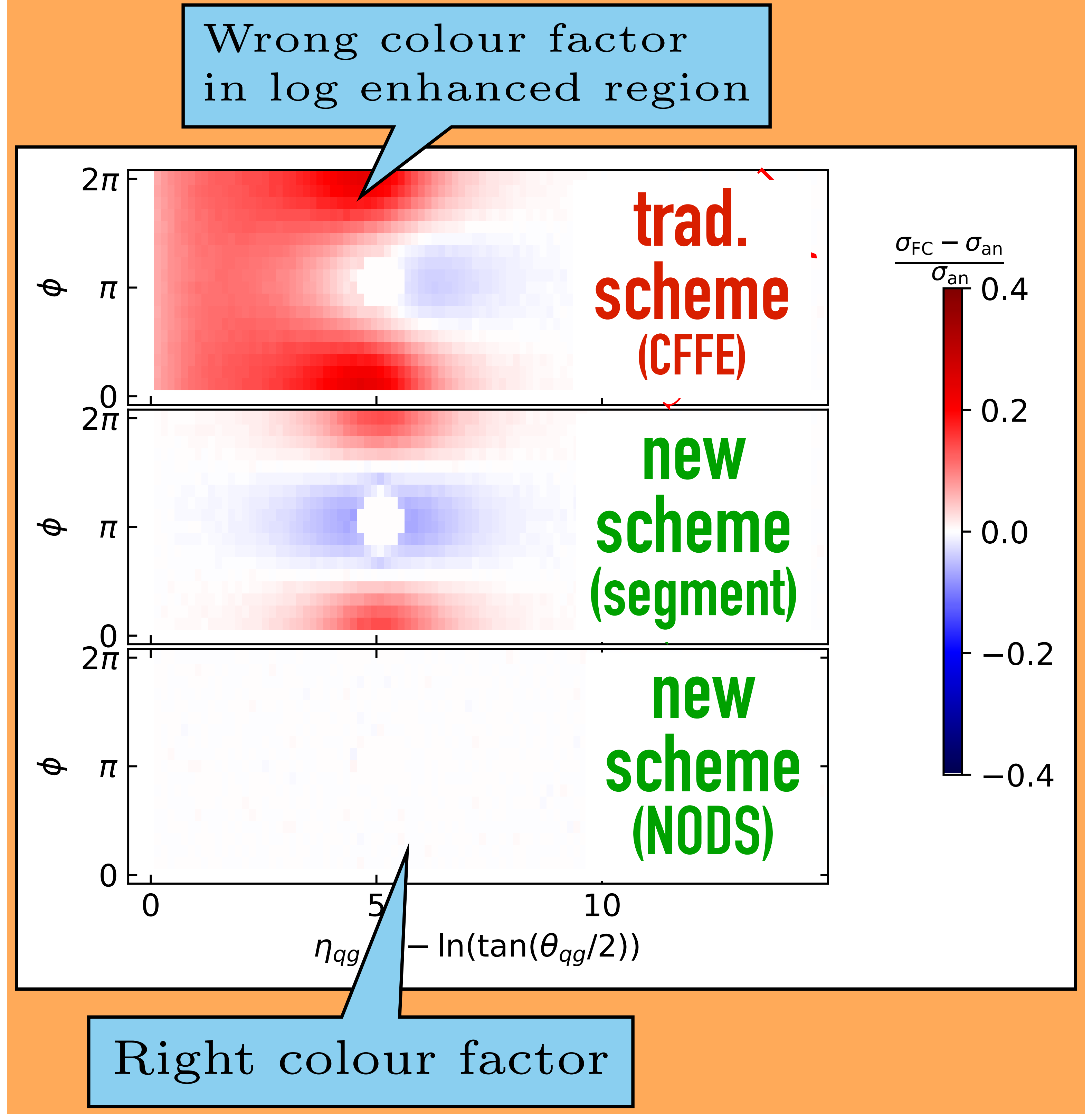
Standard dipole showers — colour factor from emitter (CFFE)



New simple, fast colour algorithms: segment & NODS

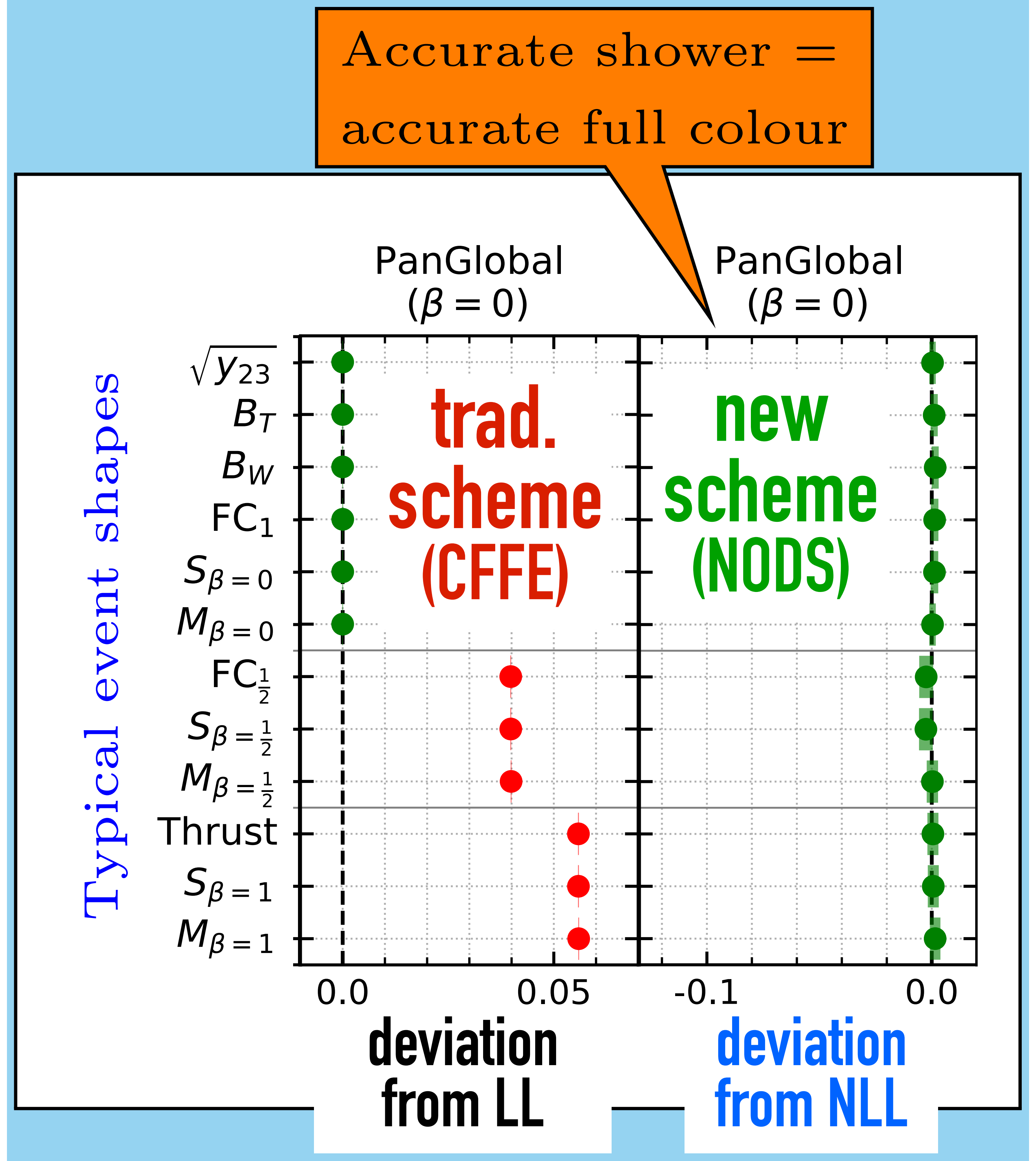
Hamilton, Medves, GPS, Scyboz & Soyez, 2011.10054

- Evaluate correctness based on how well schemes reproduce known matrix element: $q\bar{q}g_1 \to q\bar{q}g_1 + g$ example



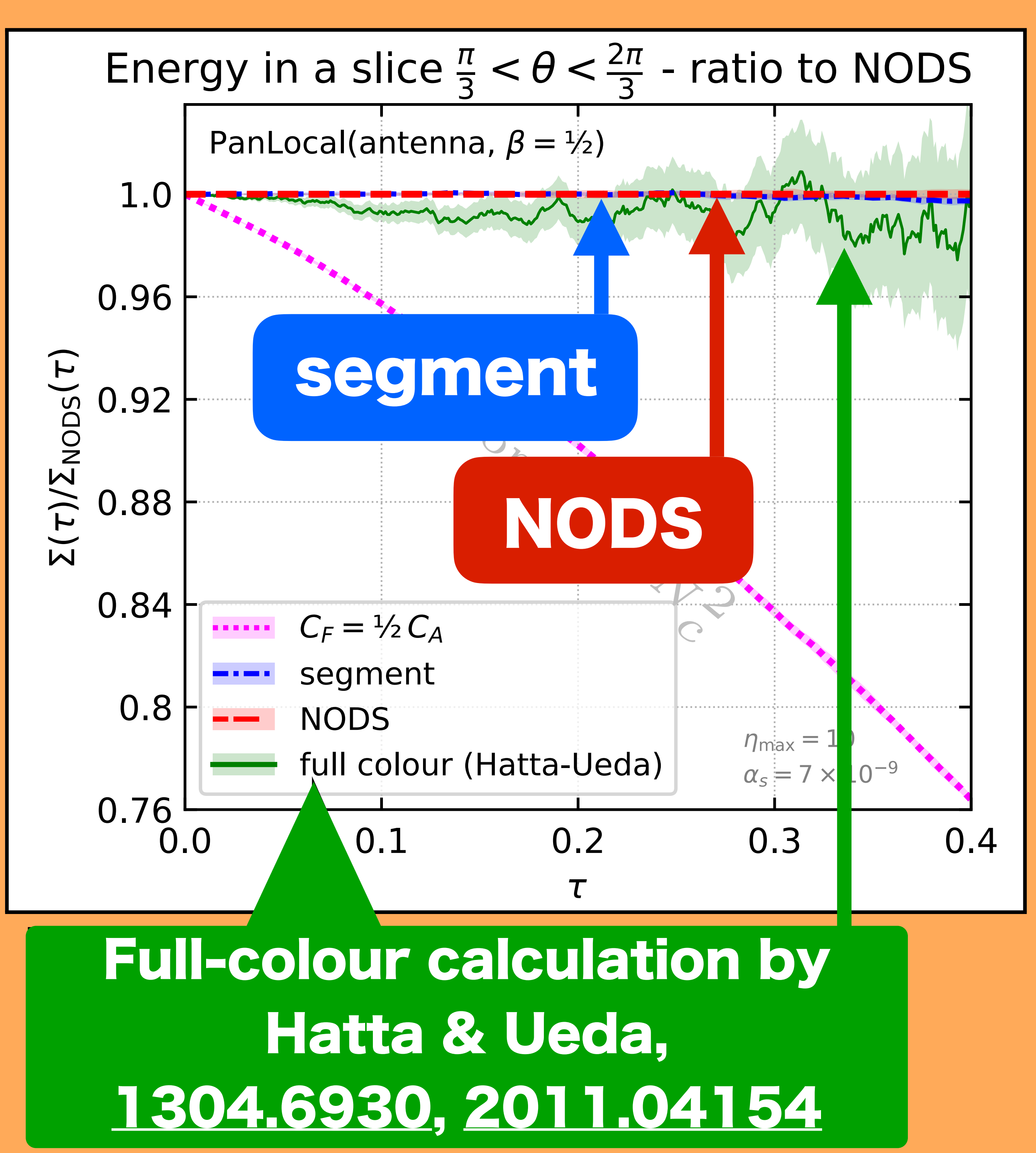
Slide from Rok Medves LHCP poster

- Algorithms reproduce NLL resummation



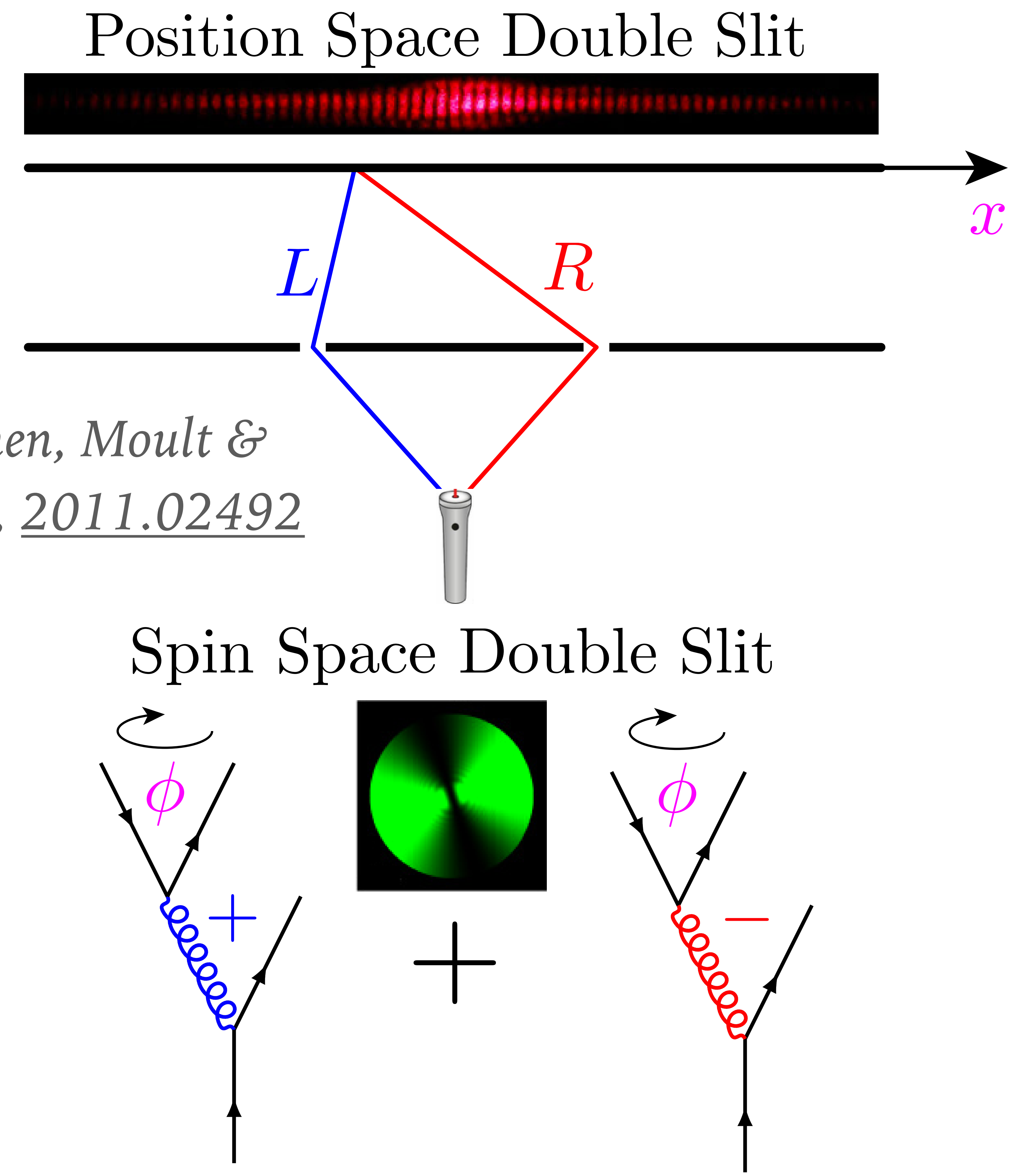
- LL: Resums terms $\alpha_s^n L^{n+1}$
- NLL: Resums terms $\alpha_s^n L^n$

- Testing non-global observables: Radiation into rapidity slice



- NODS/Segment schemes don't reproduce full-colour NLL for non-global logarithms. **Open question**: why do they come so close numerically?

Collinear spin in parton showers (last but one of NLL ingredients)



Chen, Moult & Zhu, 2011.02492

Quantum mechanical interference in otherwise quasi-classical regime

Algorithm for spin interference in collinear part of parton showers introduced long ago by Collins (1988)

A standard part of Herwig angular ordered showers, which are excellent for collinear regime, but can't do soft sector at NLL (cf. Banfi, Corcella & Dasgupta hep-ph/0612282)

Recoil in normal dipole showers may break the spin correlations (cf. Richardson and Webster, 1807.01955)

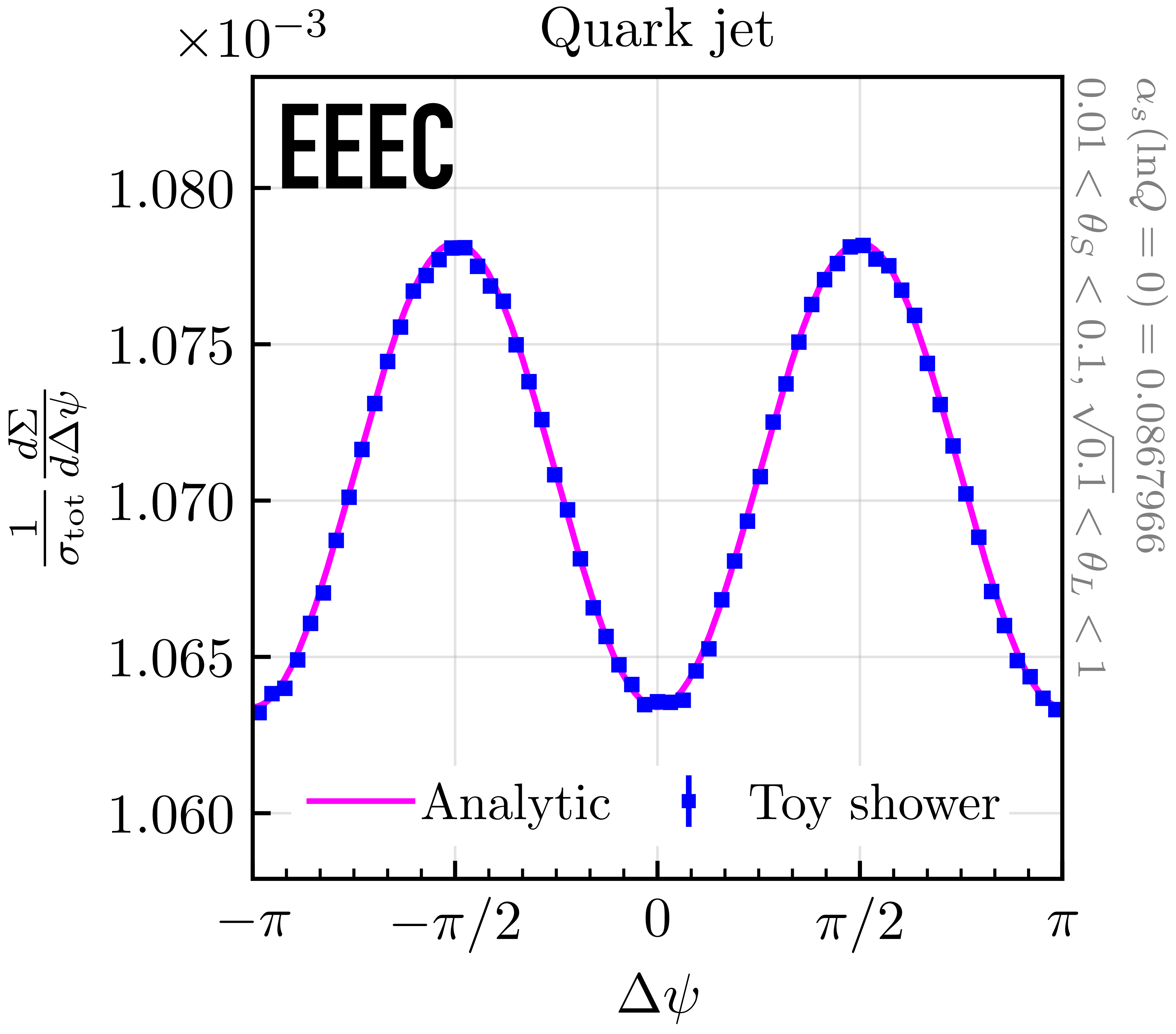
But Collins algorithm and PanScales showers should be compatible.

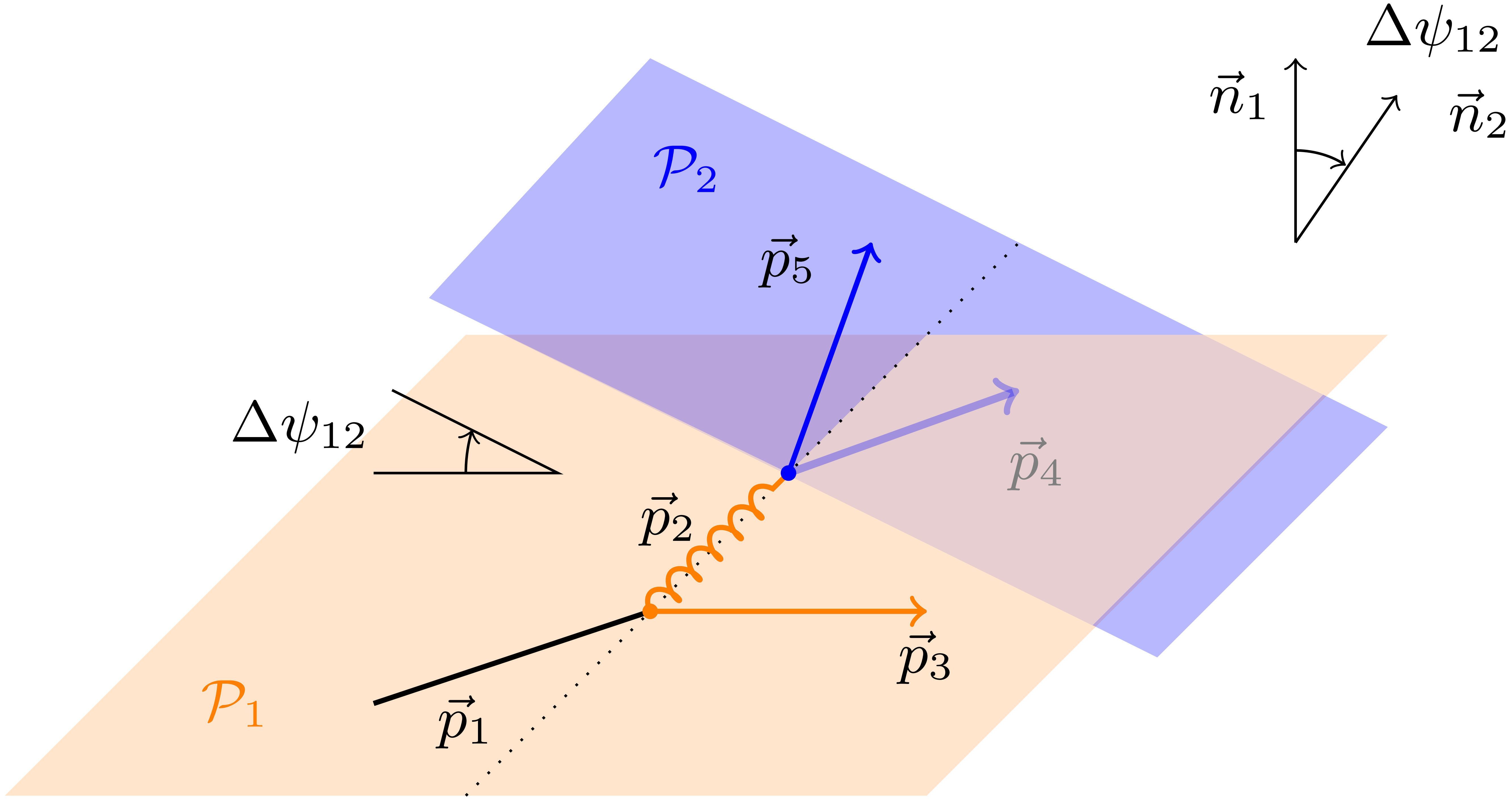
To test spin in shower, you need observables and reference resummations

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

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

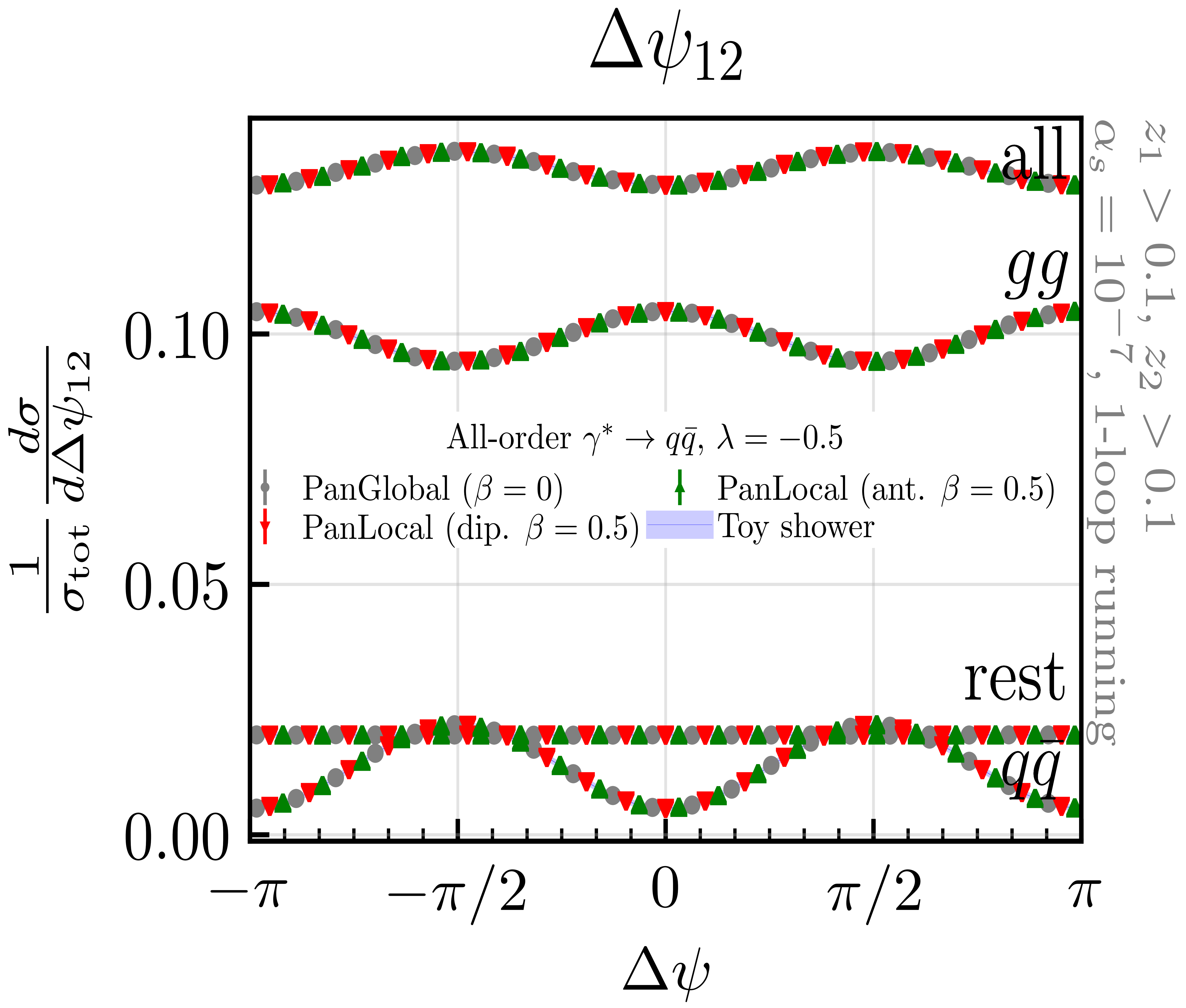
(extending unpolarized Microjets code from Dasgupta, Dreyer, GPS, Soyez 1411.5182)





Karlberg, GPS, Scyboz & Verheyen, 2103.16526

Spin correlations in full shower

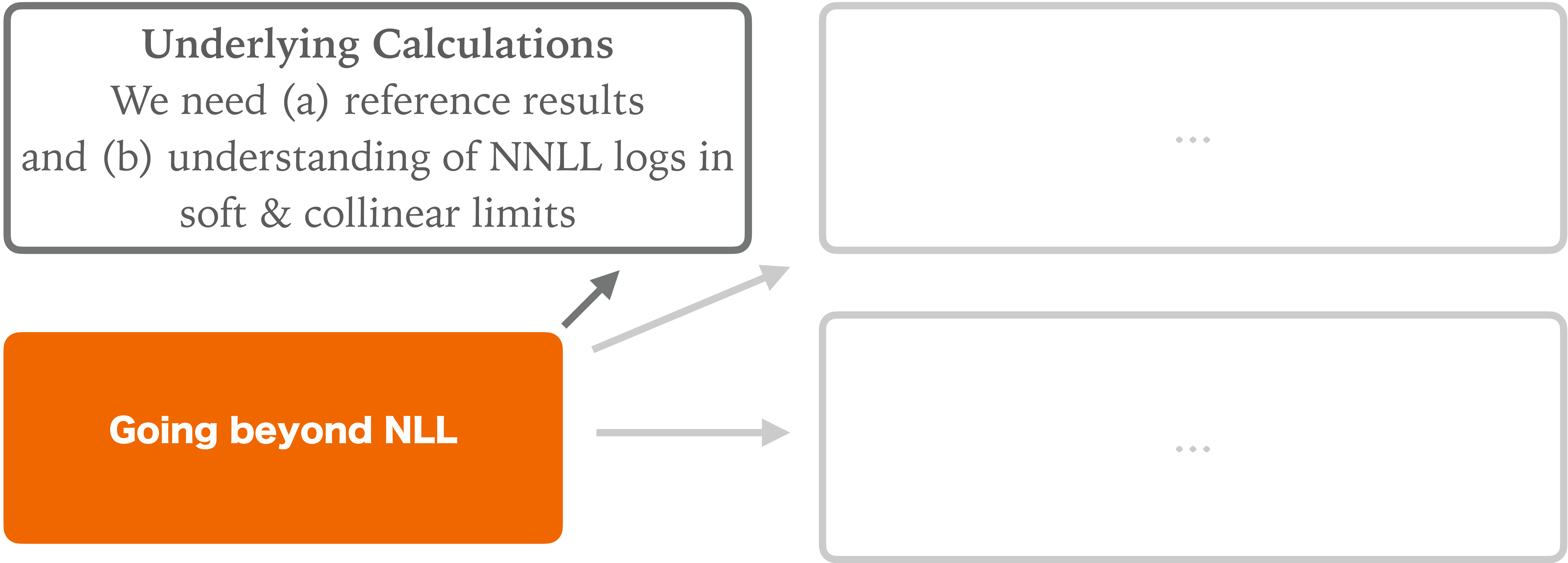


magnitude of spin correlation effects	
EEEC	-0.008
$\Delta\psi_{12},\ z_1, z_2 > 0.1$	-0.025
$\Delta\psi_{12},\ z_1 > 0.1,\ z_2 > 0.3$	-0.042

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

Karlberg, GPS, Scyboz & Verheyen, 2103.16526

Next steps beyond proof of concept NLL final-state shower



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 beyond proof of concept NLL final-state shower

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

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 + …]

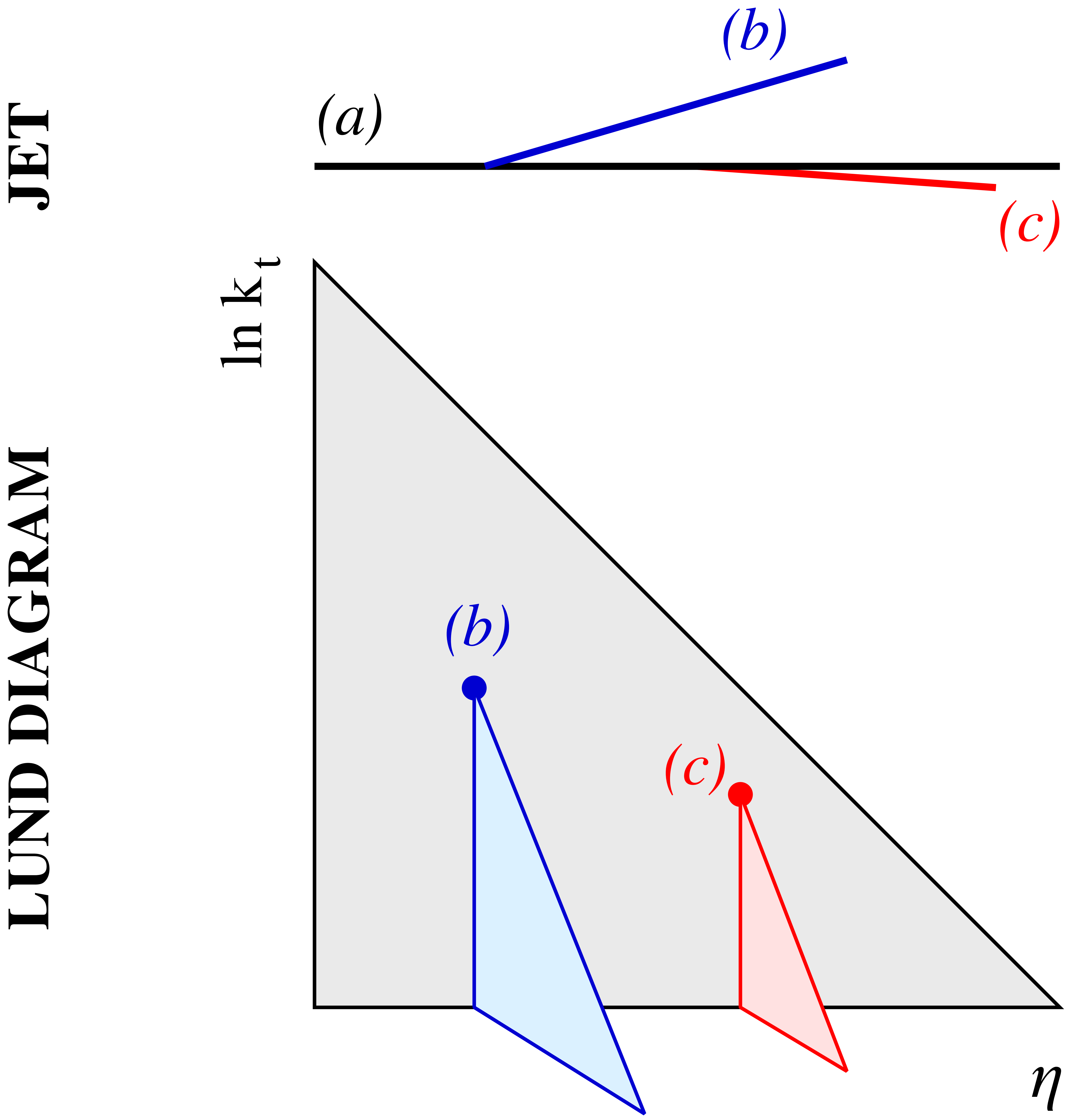
Next-to-leading non-global logarithms in QCD
Banfi, Dreyer and Monni, 2104.06416

Conclusions

conclusions

- Parton showers (and event generators in general), and their predictions of the fine 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 $\equiv$ 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 (so far only for final-state showers)
- Overall message:
  The parton shower part of event generators can be brought under theoretical control, by systematically addressing each of the physical effects that is relevant in different (logarithmic) phase space regions.

BACKUP


JET
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LUND DIAGRAM
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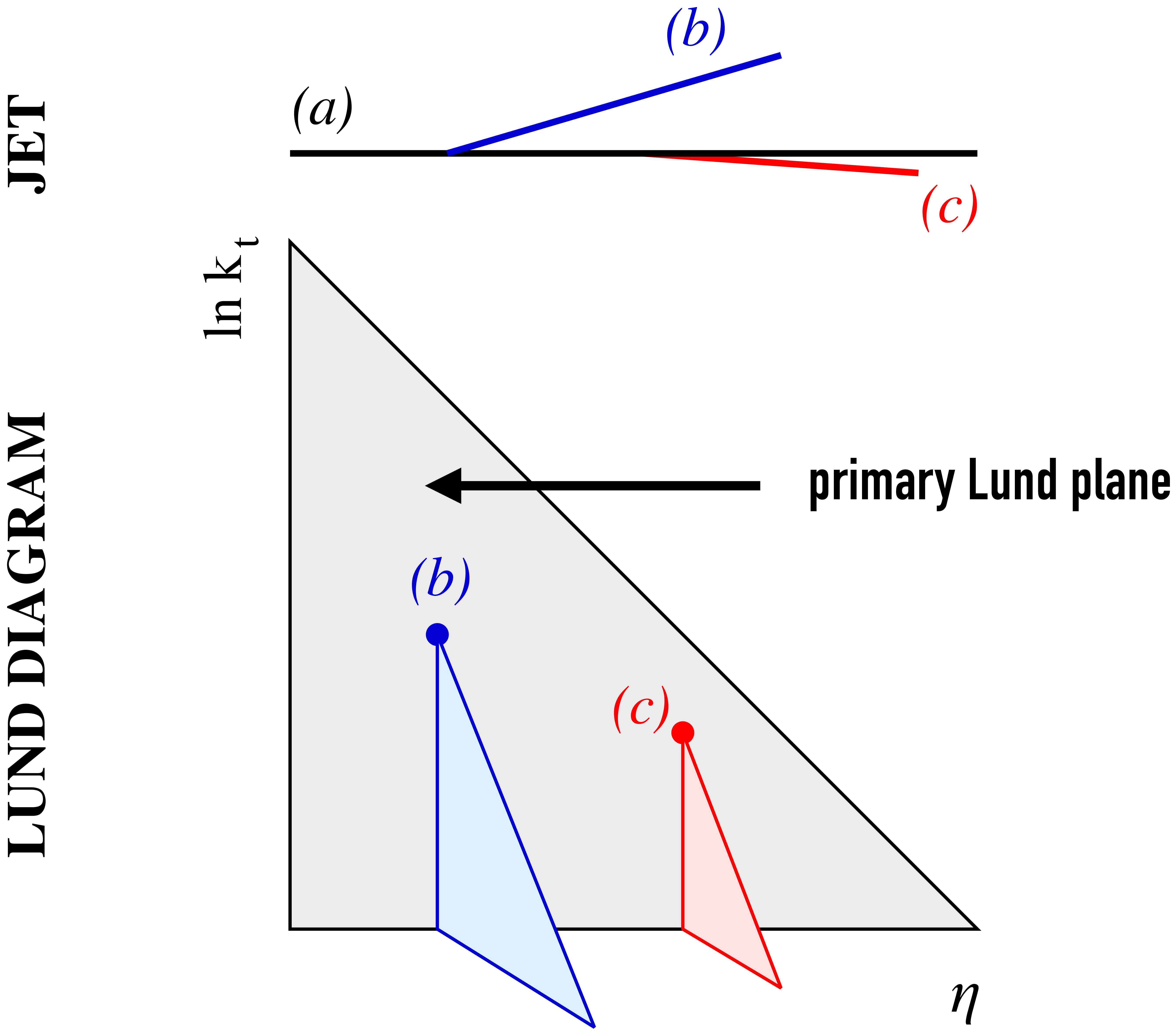
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primary Lund plane
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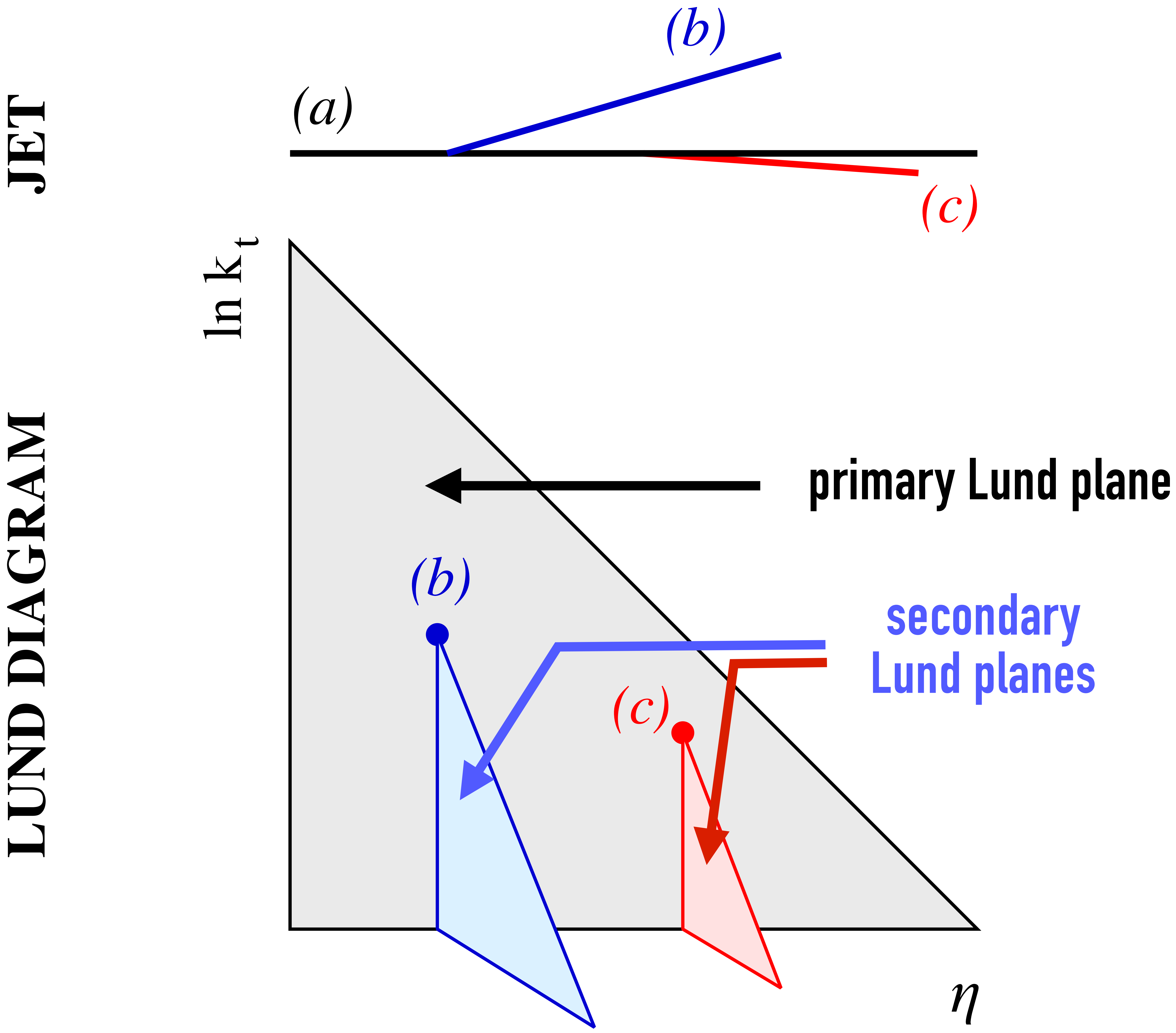
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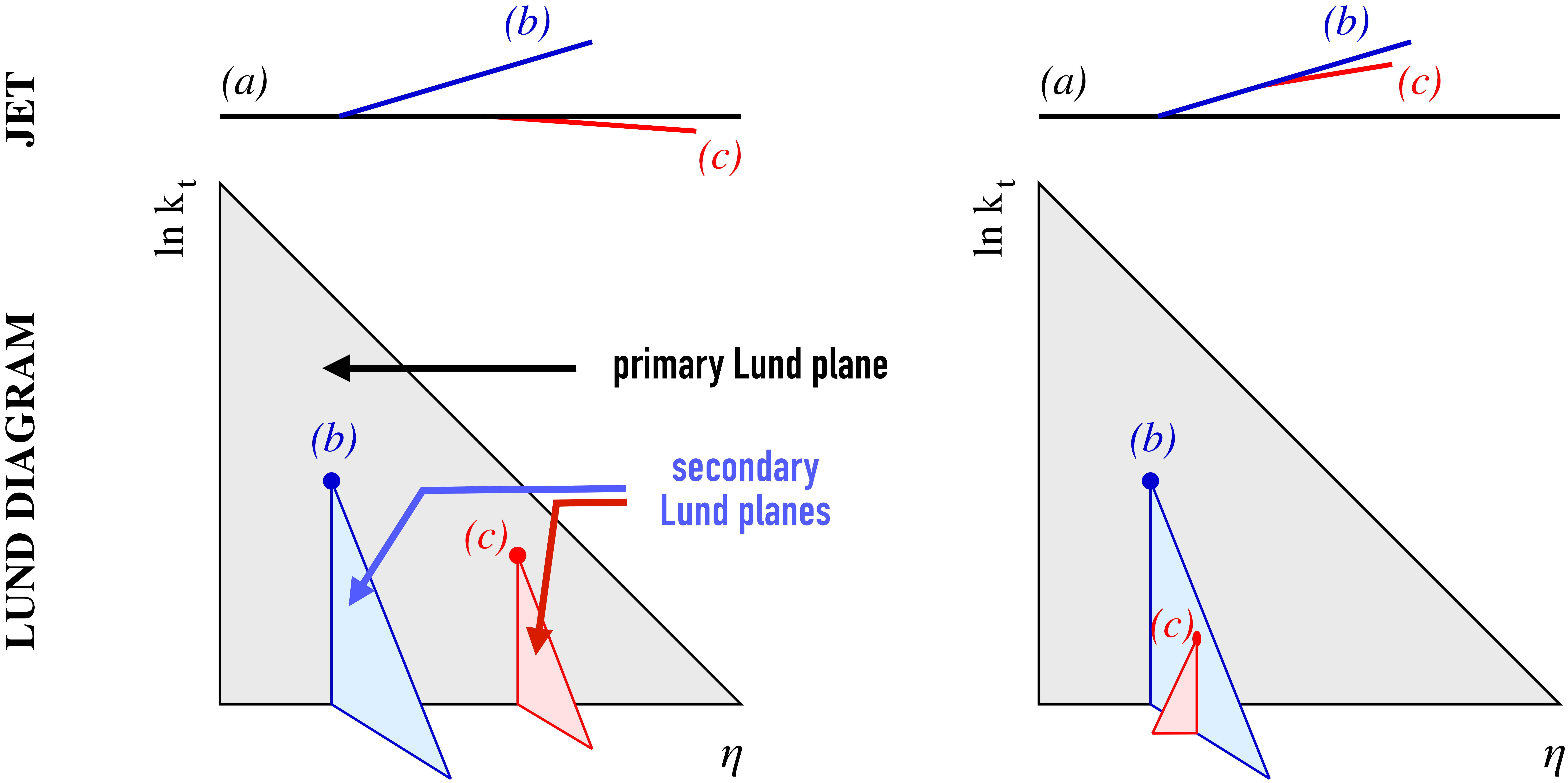
Lund planes
η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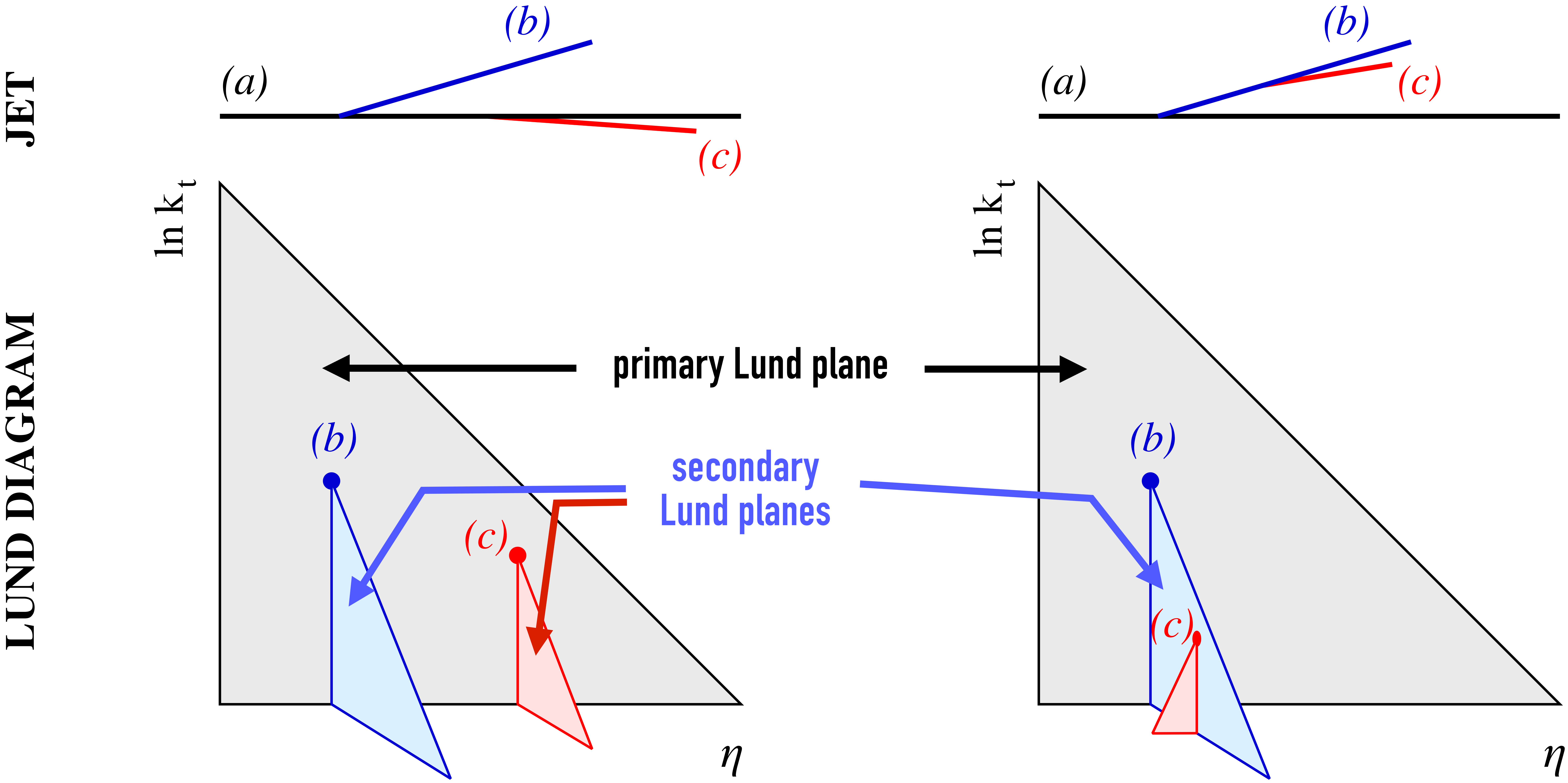
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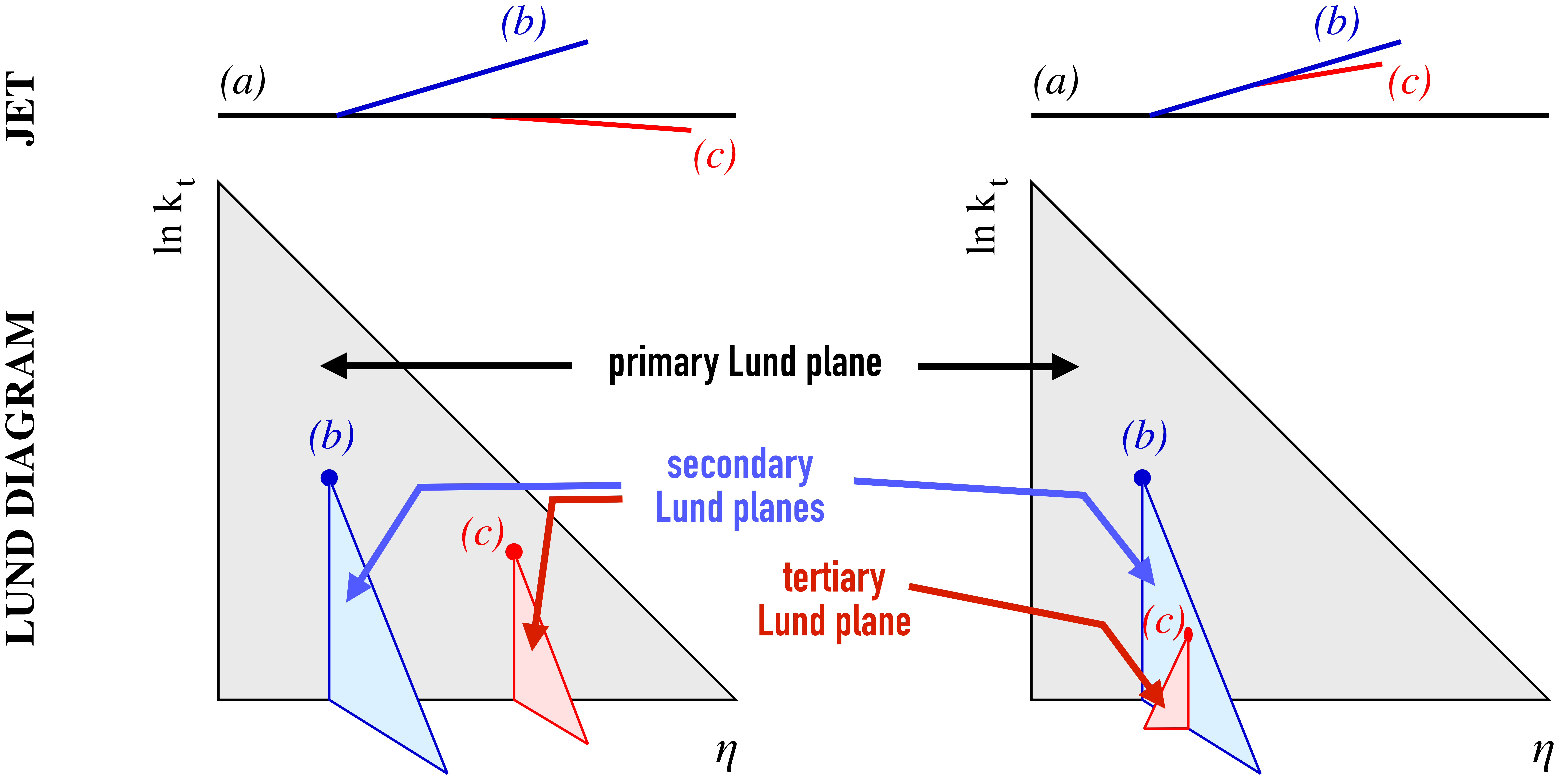
primary Lund plane
secondary
Lund planes


JET
LUND DIAGRAM
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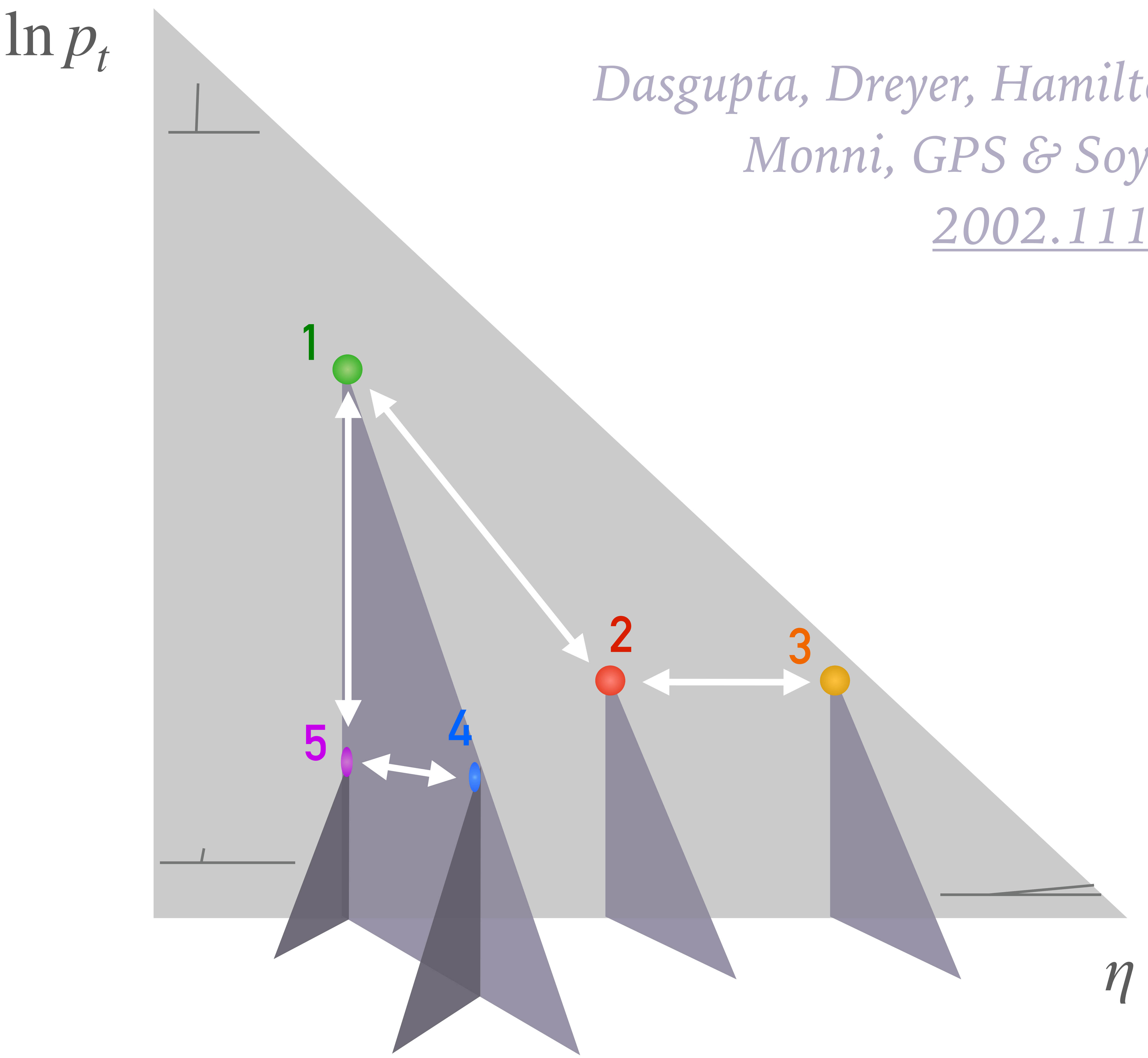
Lund planes
tertiary
Lund plane

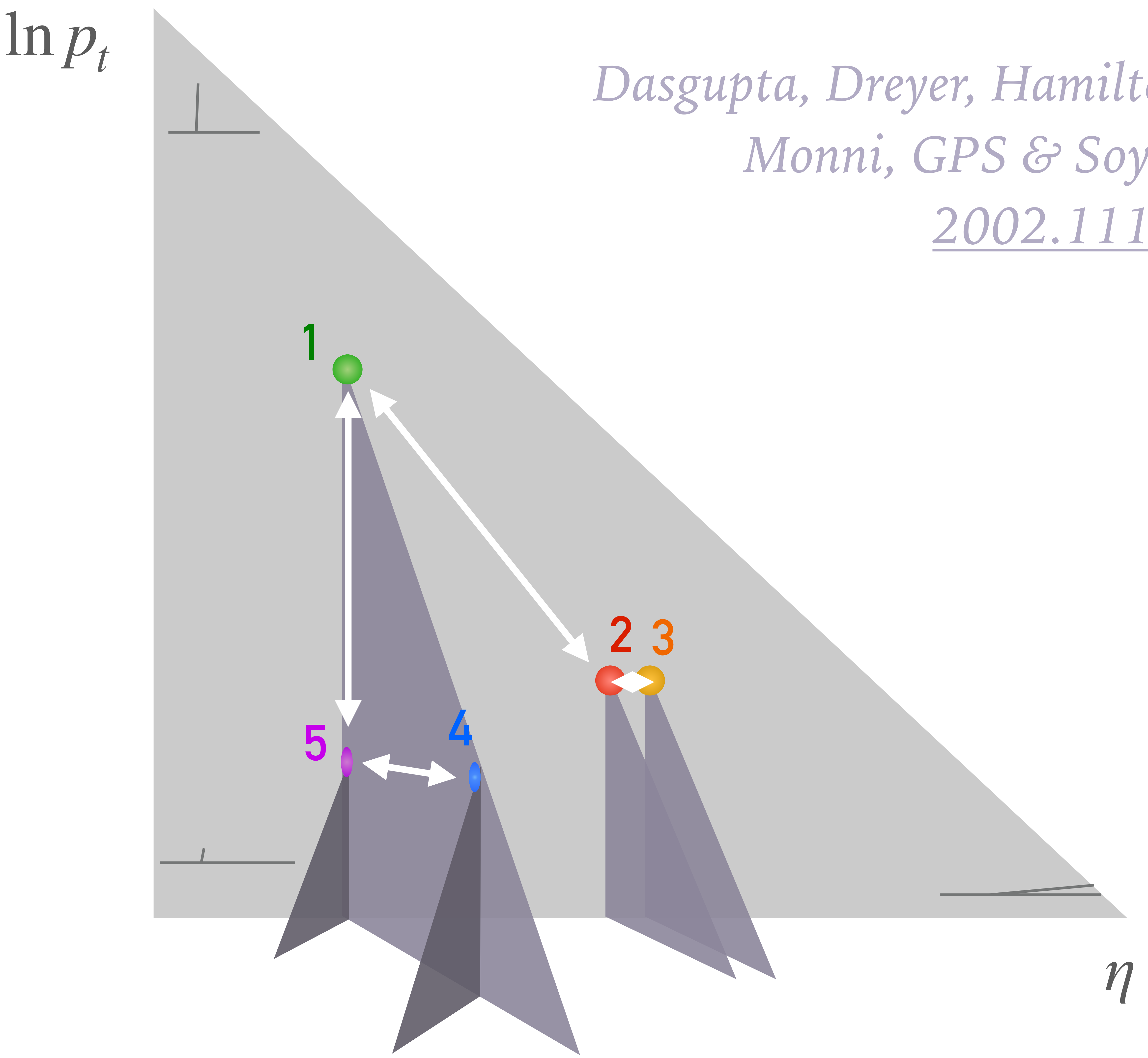
When do we require effective shower $|M^2|$ to be correct?



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
- **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
- **we are allowed to make a mistake (by $\mathcal{O}(1)$ factor) when a pair is close by,** e.g. $d_{23} \sim 1$

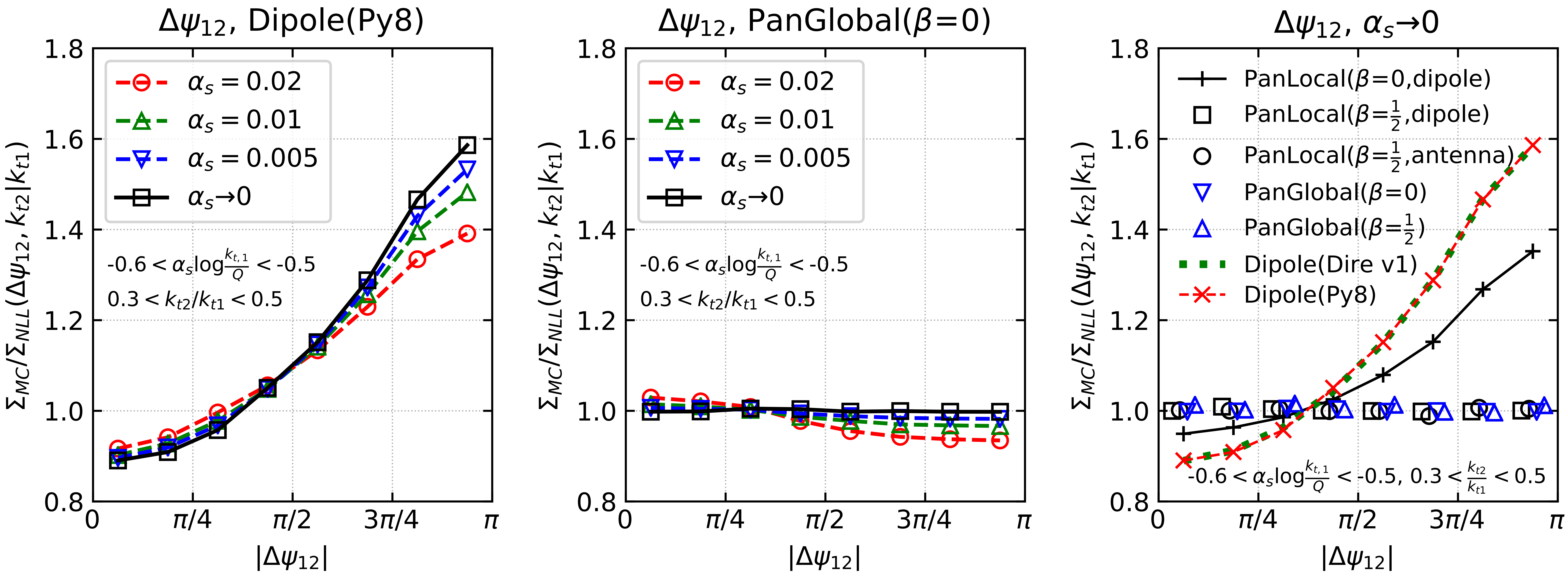


FIG. 1. Left: distribution for the difference in azimuthal angle between the two highest-k_t primary Lund declusterings in the Pythia8 dipole shower algorithm, normalised to the NLL result [53], [51]§ 4; successively smaller α_s values keep fixed $\alpha_s \ln k_{t1}$. Middle: the same for the PanGlobal($\beta = 0$) shower. Right: the $\alpha_s \to 0$ limit of the ratio for multiple showers. This observable directly tests part of our NLL (squared) matrix-element correctness condition. A unit value for the ratio signals success.

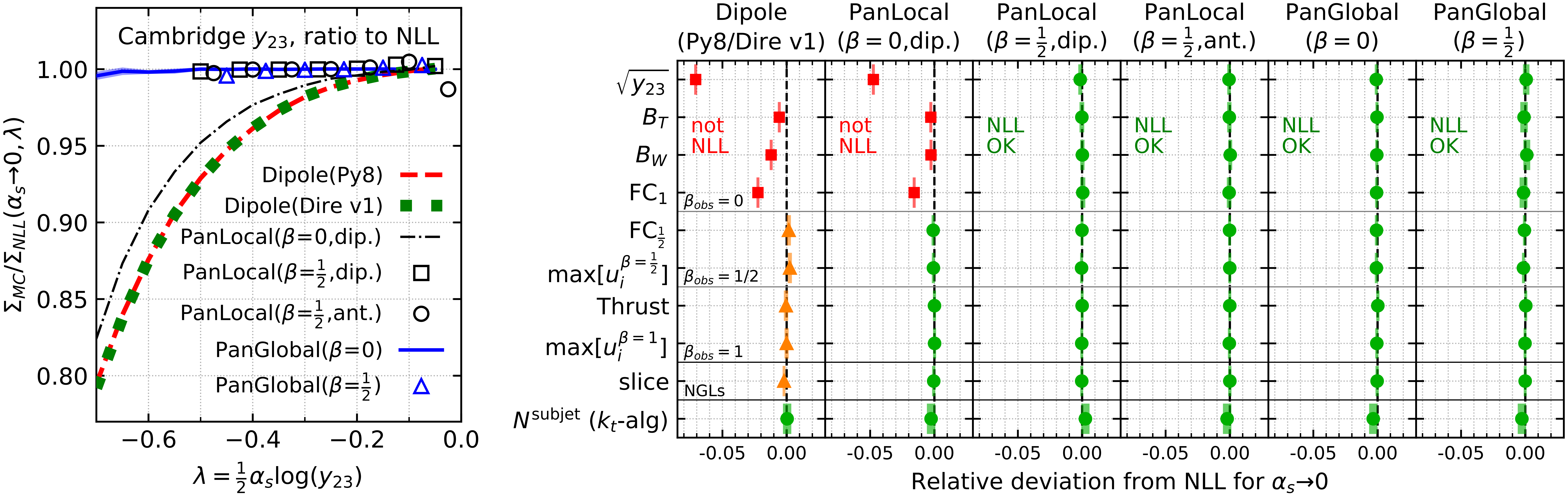


FIG. 2. Left: ratio of the cumulative y_{23} distribution from several showers divided by the NLL answer, as a function of $\alpha_s \ln y_{23}/2$, for $\alpha_s \to 0$. Right: summary of deviations from NLL for many shower/observable combinations (either $\Sigma_{\text{shower}}(\alpha_s \to 0, \alpha_s L = -0.5)/\Sigma_{\text{NLL}} - 1$ or $(N^{\text{subjet}}_{\text{shower}}(\alpha_s \to 0, \alpha_s L^2 = 5)/N^{\text{subjet}}_{\text{NLL}} - 1)/\sqrt{\alpha_s}$). Red squares indicate clear NLL failure; amber triangles indicate NLL fixed-order failure that is masked at all orders; green circles indicate that all NLL tests passed.

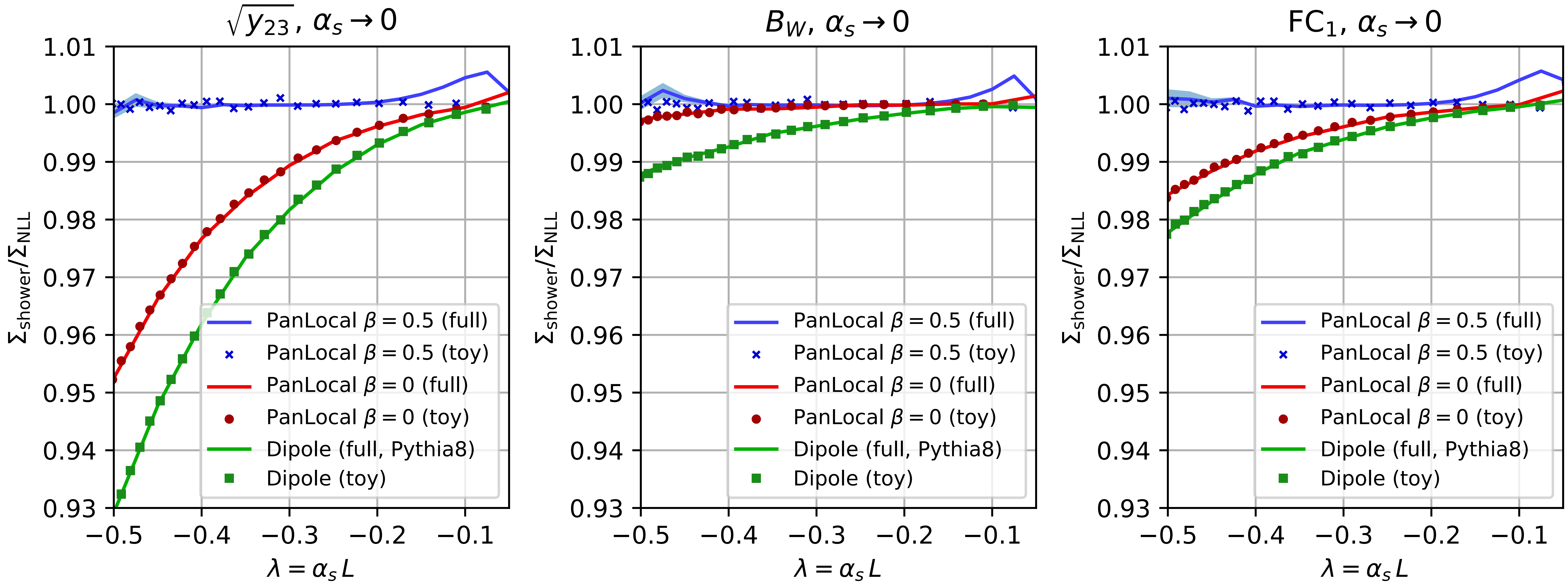


FIG. 3. Comparison of the ratio $\Sigma_{\rm shower}/\Sigma_{\rm NLL}$ between the toy shower and the full shower for three reference observables ($\sqrt{y_{23}}$, B_W and FC_1), in the limit $\alpha_s \to 0$, as a function of $\alpha_s L$. For the full showers the figure shows the ratio of the shower prediction to the full NLL result, while for the toy shower it shows the ratio to the CAESAR-like toy shower. Three full showers are shown in each plot, each compared to the corresponding toy shower. The PanLocal full showers are shown in their dipole variants (identical conclusions hold for the antenna variant). Small (0.5%) issues at $\lambda \gtrsim -0.1$ are a consequence of the fact that for the largest of the α_s values used in the extrapolation, the corresponding L values do not quite satisfy $e^L \ll 1$.

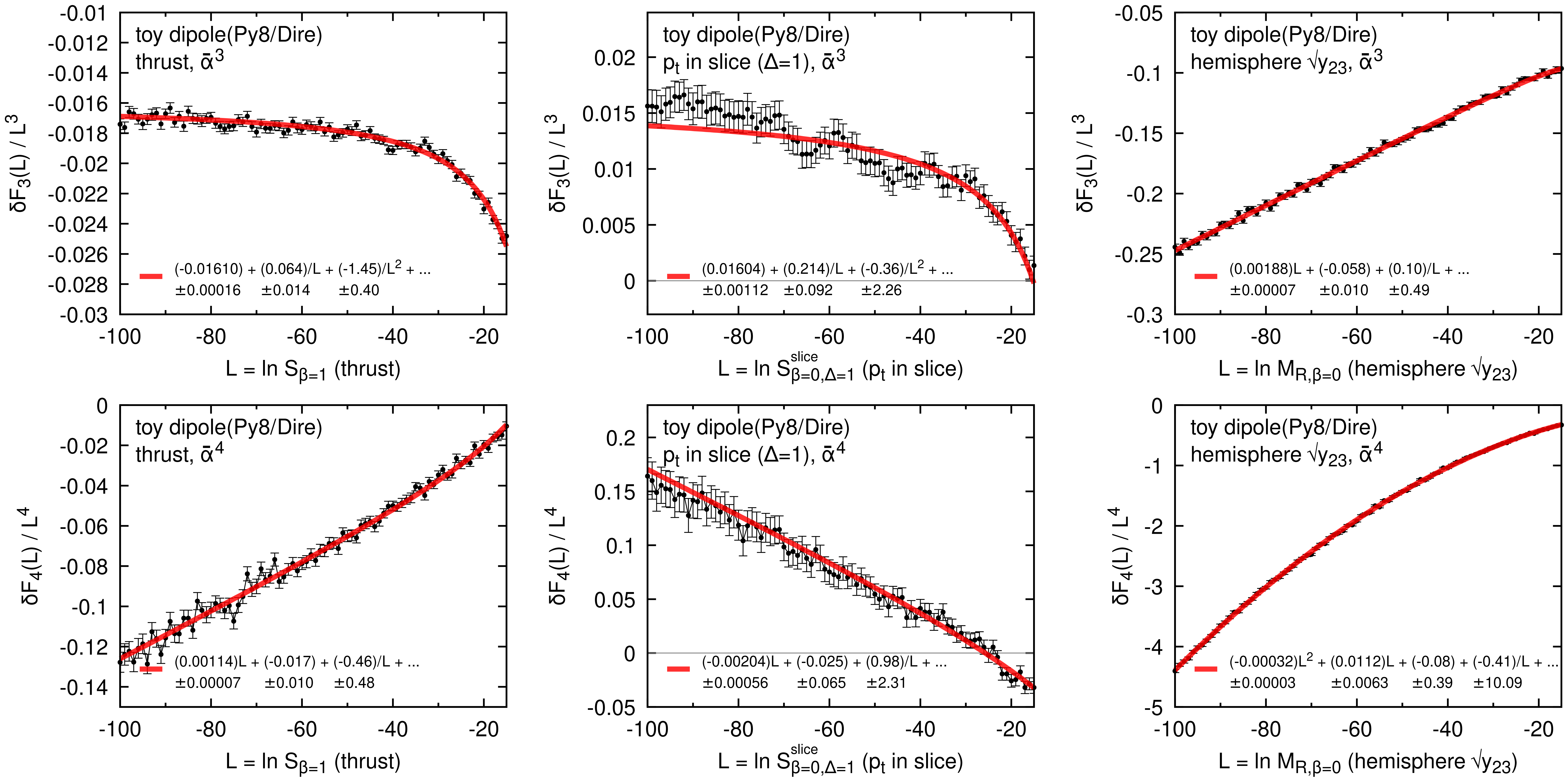


FIG. 4. Fixed order results from the toy implementation of the standard dipole showers. The plots show the difference between the toy dipole shower and the (NLL-correct) CAESAR results for the F_n coefficient of $\bar{\alpha}^n$ in the expansion of Eq. (33), divided by L^n. For an NLL-correct shower, the results should tend to zero for large negative L. The first row shows the result of $n = 3$, the second row that of $n = 4$. The columns correspond to different observables (thrust, slice transverse momentum and hemisphere $\sqrt{y_{23}}$). Observe how the results tend to constants (NLL discrepancy) or demonstrate a linear or even quadratic dependence on L (super-leading logarithms). The coefficients have been fitted taking into account correlations between points, and we include powers down to L^{-3} in the fit of $\delta F_n/L^n$. The fit range is from -100 to -5 and the quoted error includes both the (statistical) fit uncertainty and the difference in coefficients obtained with the range $[-100, -10]$ (added in quadrature).

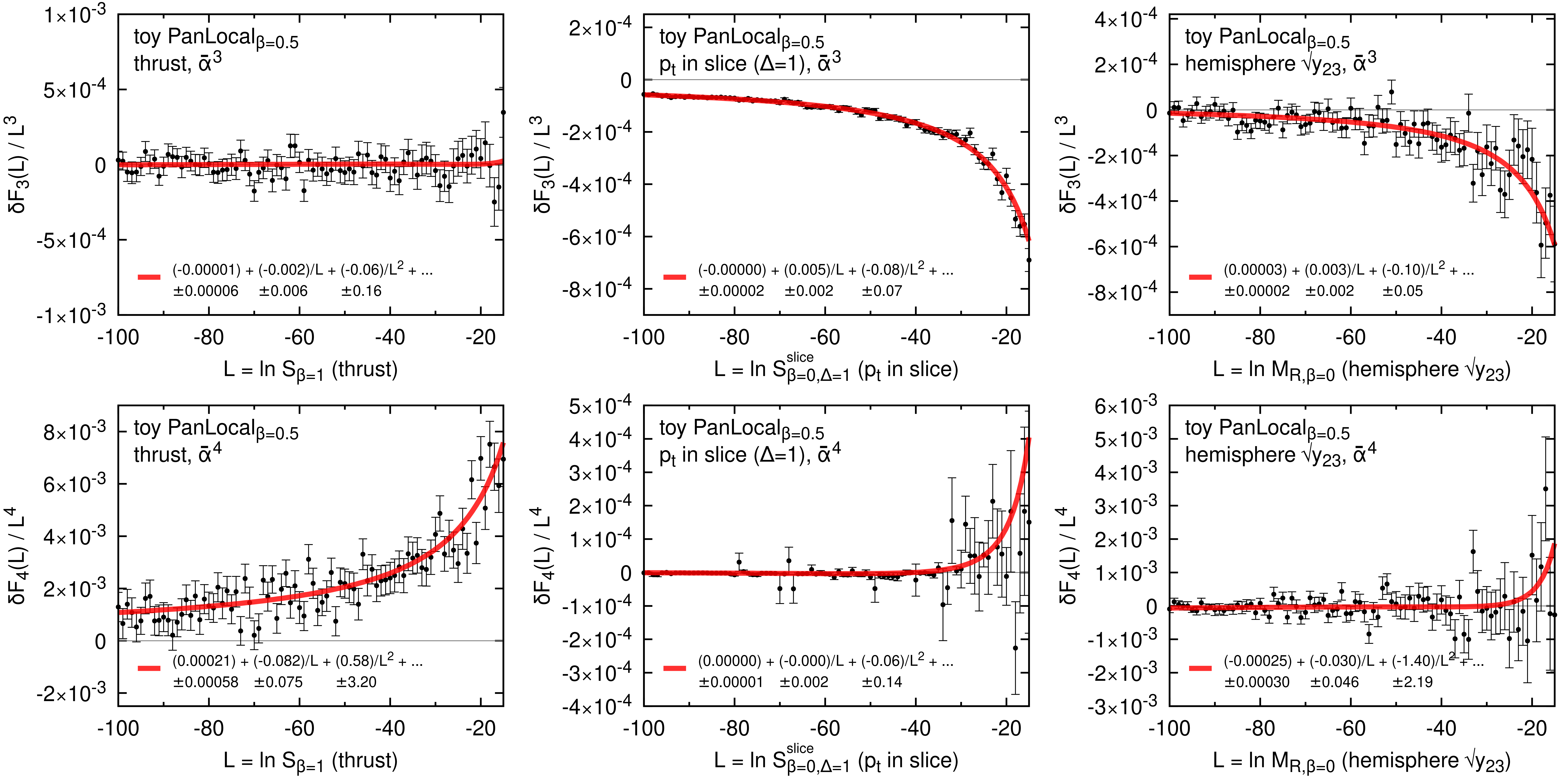


FIG. 5. Analogue of Fig. 4, demonstrating the absence of NLL (or super-leading) issues at fixed order in the toy version of the PanLocal $\beta = 0.5$ shower. At order $\bar{\alpha}^4$, we include fit terms down to L^{-4}.

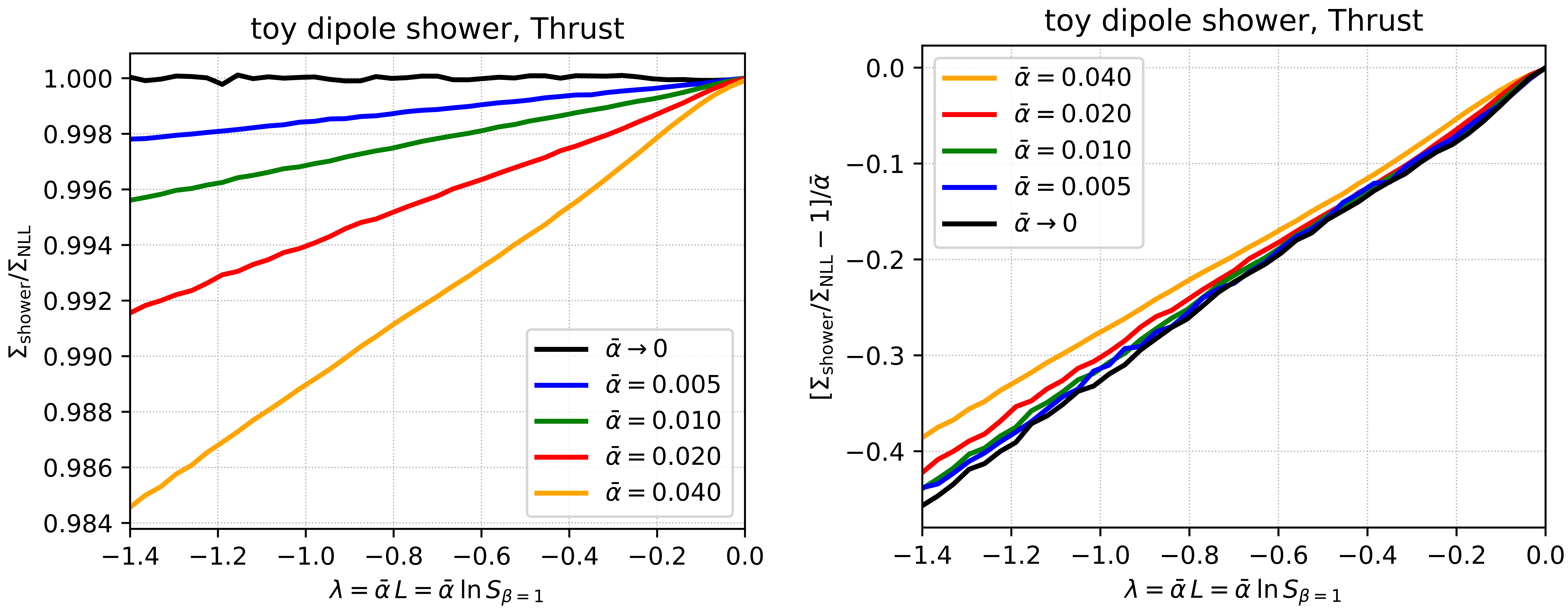


FIG. 7. Toy-shower all-order result for the thrust ($S_{\beta=1}$, Eq. (25)). Left: $\Sigma_{\rm dipole}/\Sigma_{\rm NLL}$, where the NLL result is given by running the CAESAR version of the shower. Four values of $\bar{\alpha}$ are shown, together with the extrapolation to $\bar{\alpha} = 0$, showing that the all-order dipole-shower result (in our usual limit of fixed $\bar{\alpha}L$ and $\bar{\alpha} \to 0$) is consistent with the NLL result, despite the super-leading logarithmic terms that are visible in Fig. 4. Right: $(\Sigma_{\rm dipole}/\Sigma_{\rm NLL} - 1)/\bar{\alpha}$, again for three values of $\bar{\alpha}$ and the extrapolation to $\bar{\alpha} = 0$. The fact that these curves converge is a sign that the all-order (toy) dipole-shower discrepancy with respect to NLL behaves as a term that vanishes proportionally to $\bar{\alpha}$, i.e. as an NNLL term. The results here involve fixed coupling, i.e. they do not include a correction of the form of Eq. (30).

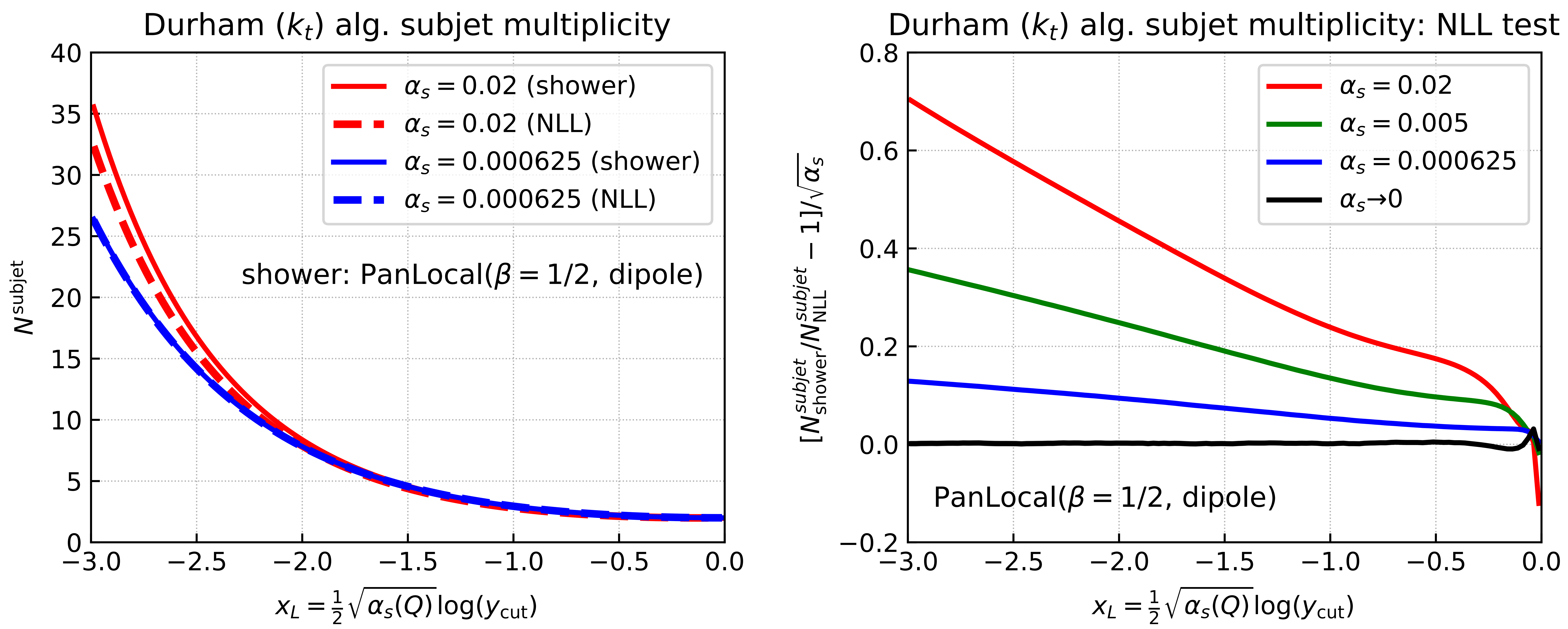
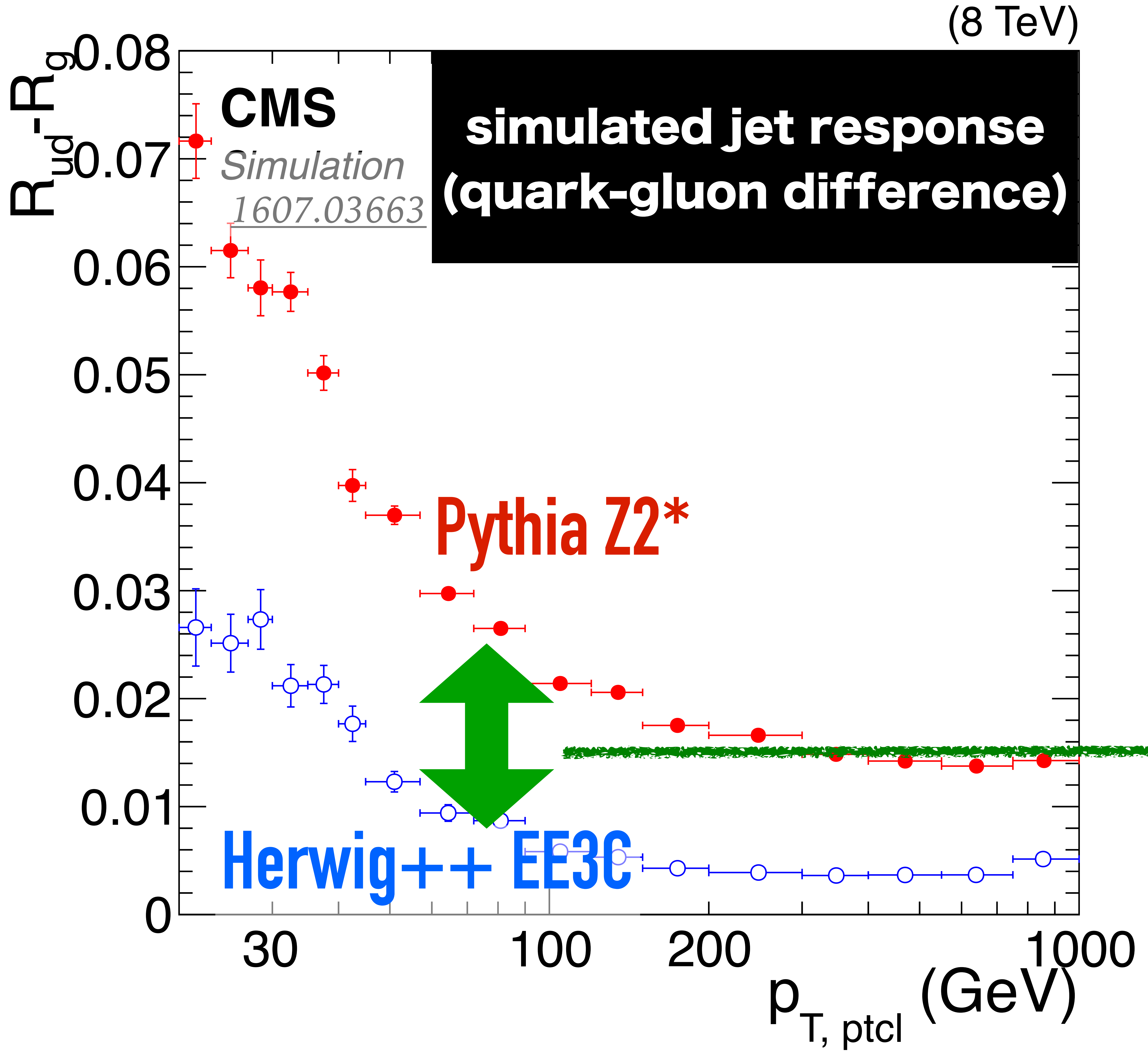
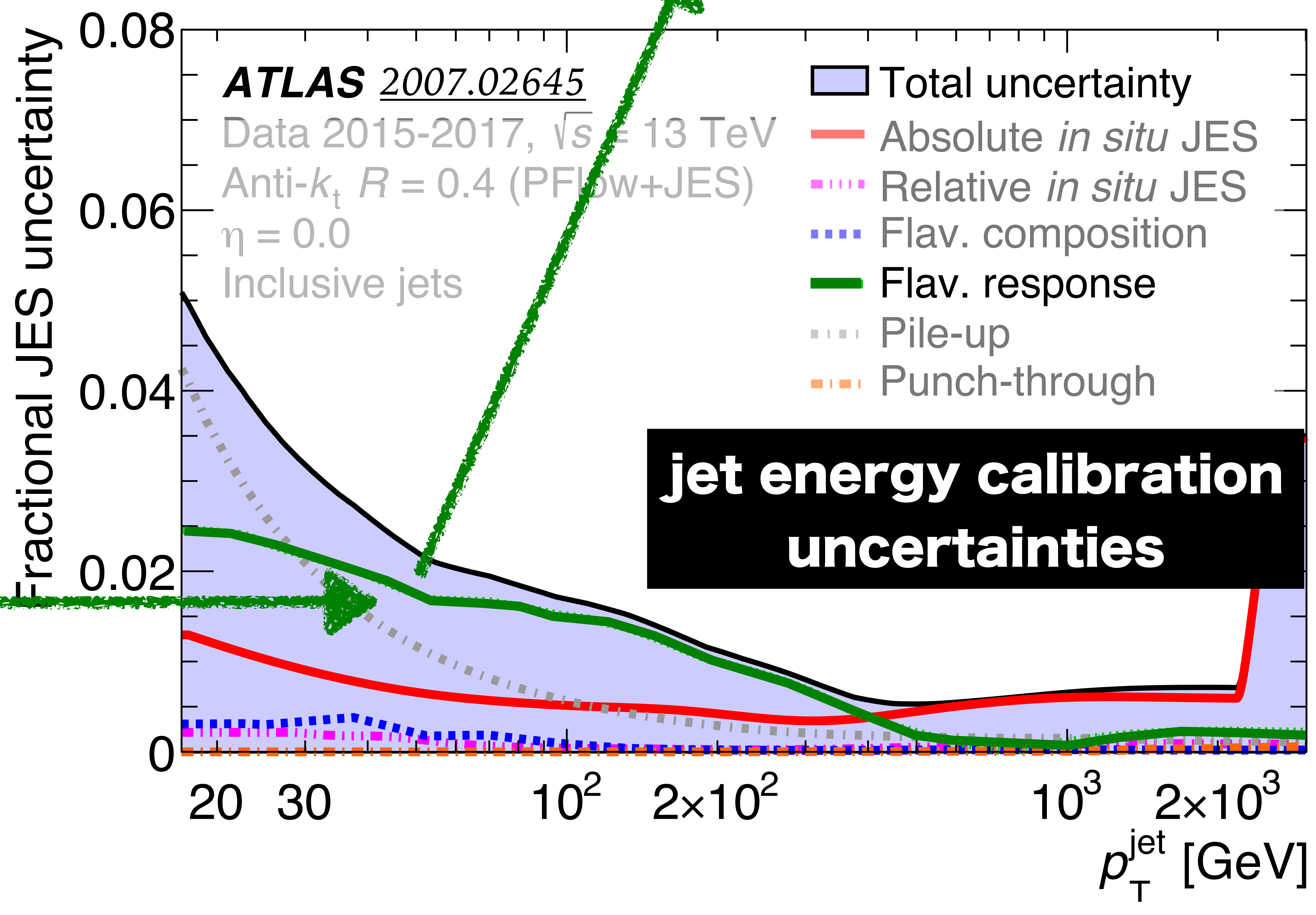


FIG. 8. Checks of the k_t algorithm subjet multiplicity. Left: the multiplicity as a function of $\frac{1}{2}\sqrt{\alpha_s(Q)}\ln y_{cut}$, comparing the PanLocal $\beta = 0.5$ shower (dipole variant) with the NLL prediction, for two choices of α_s. Right: Eq. (50) for the same shower, for several α_s values, together with the $\alpha_s \to 0$ limit.

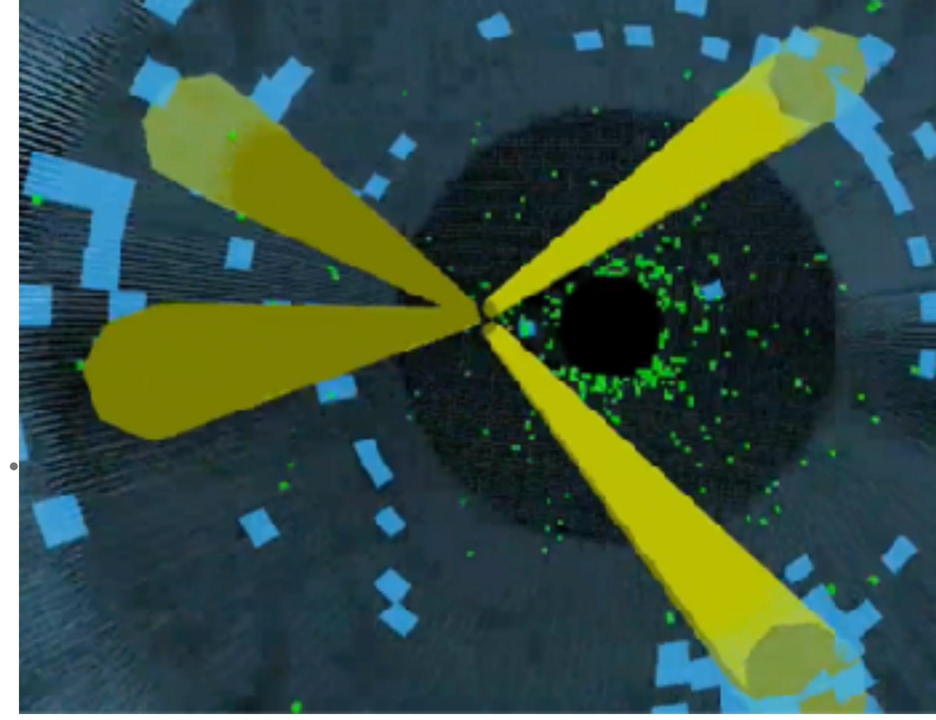
But imperfections matter: e.g. for jet energy calibration (affects ~1500 papers)

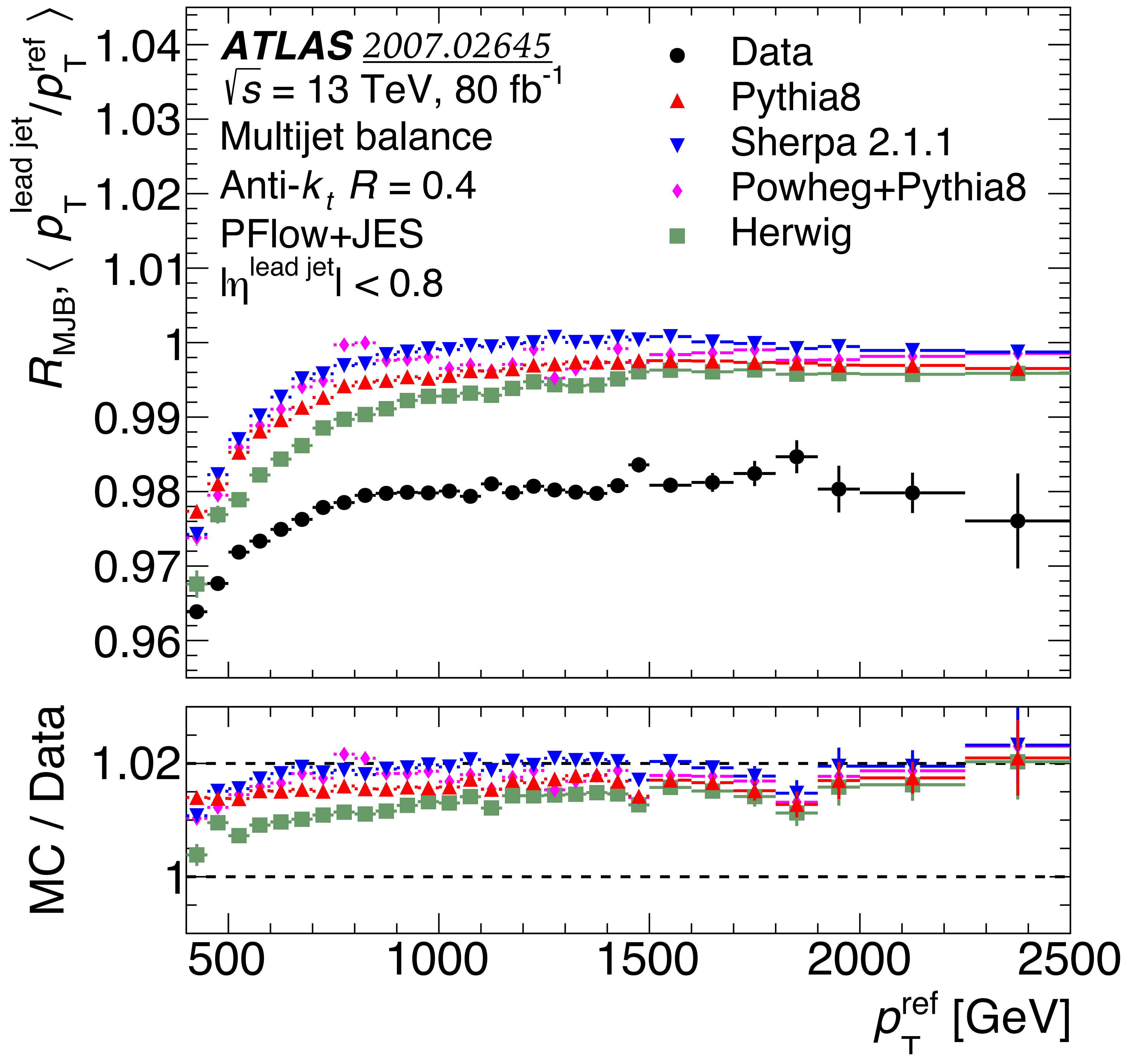
Largest uncertainty source is poor understanding of [parton shower simulations of] quark v. gluon-induced jet responses





Fundamental experimental calibrations (jets)





MJB = multi-jet balance