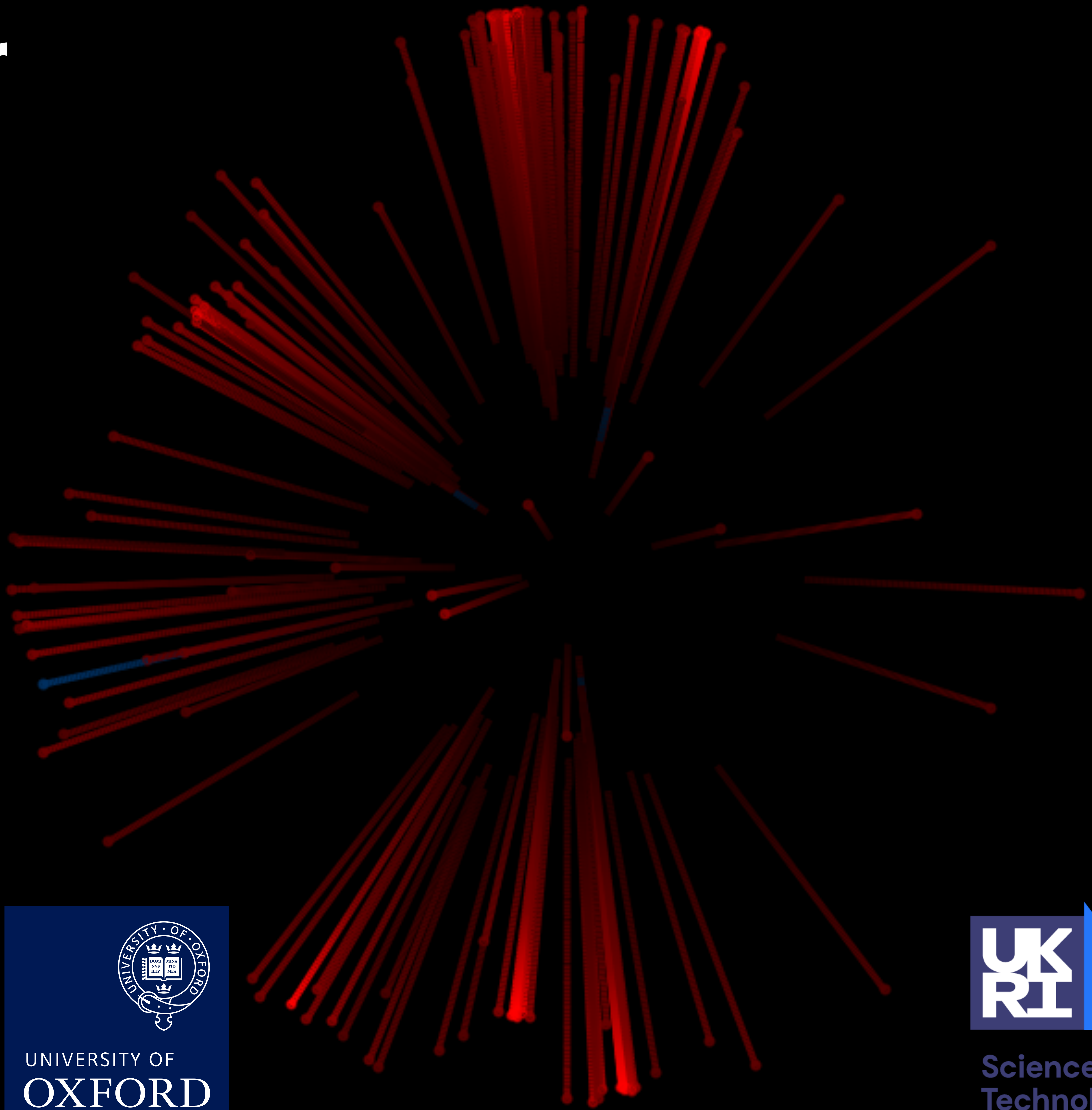
From perturbative QFT to physical collider predictions

UCLA seminar
March 21, 2025



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

UNIVERSITY OF OXFORD

Science and Technology Facilities Council

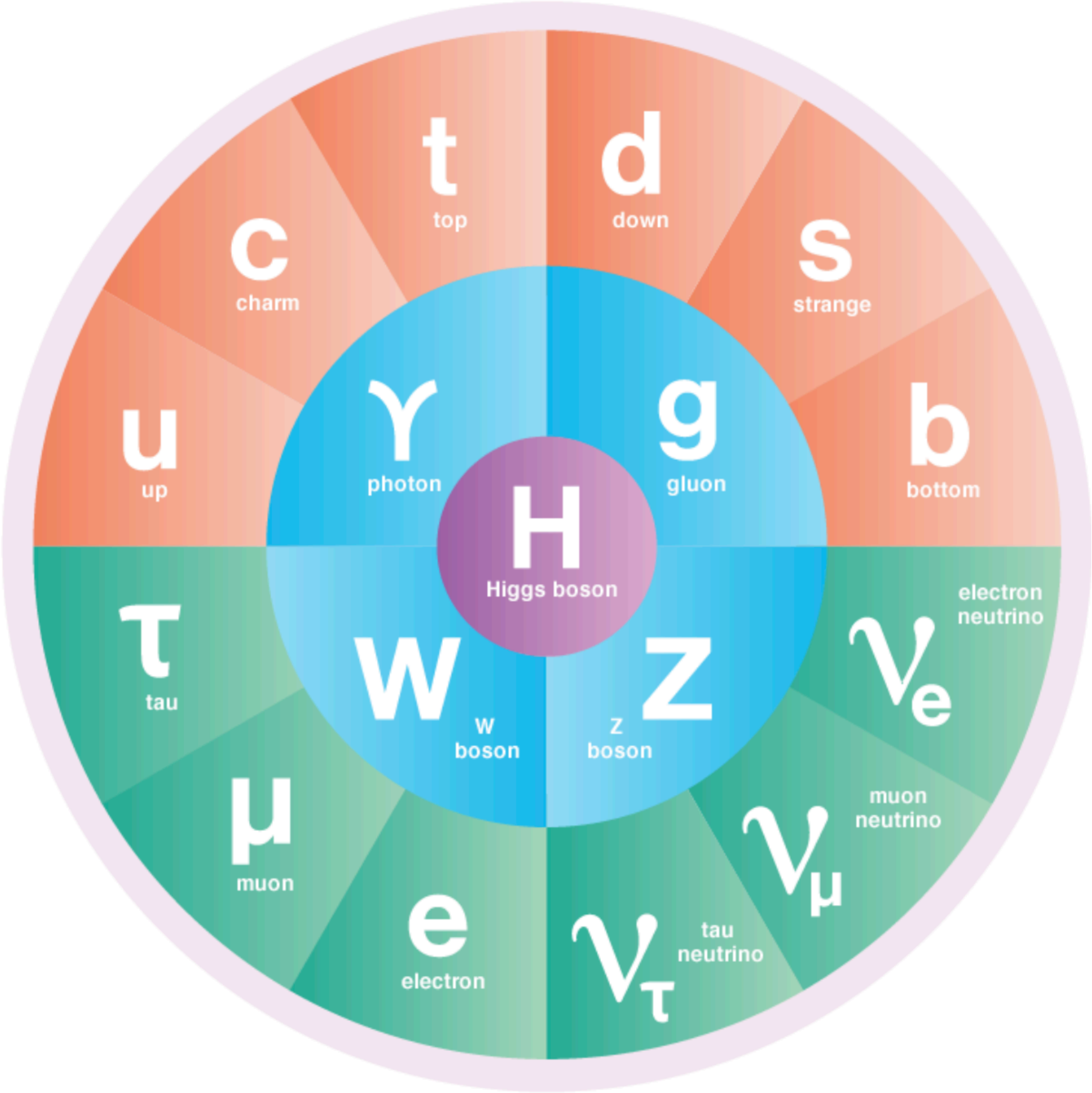
THE ROYAL SOCIETY

What are the fundamental forces and building blocks of the universe?

Why do they have the properties that we observe?

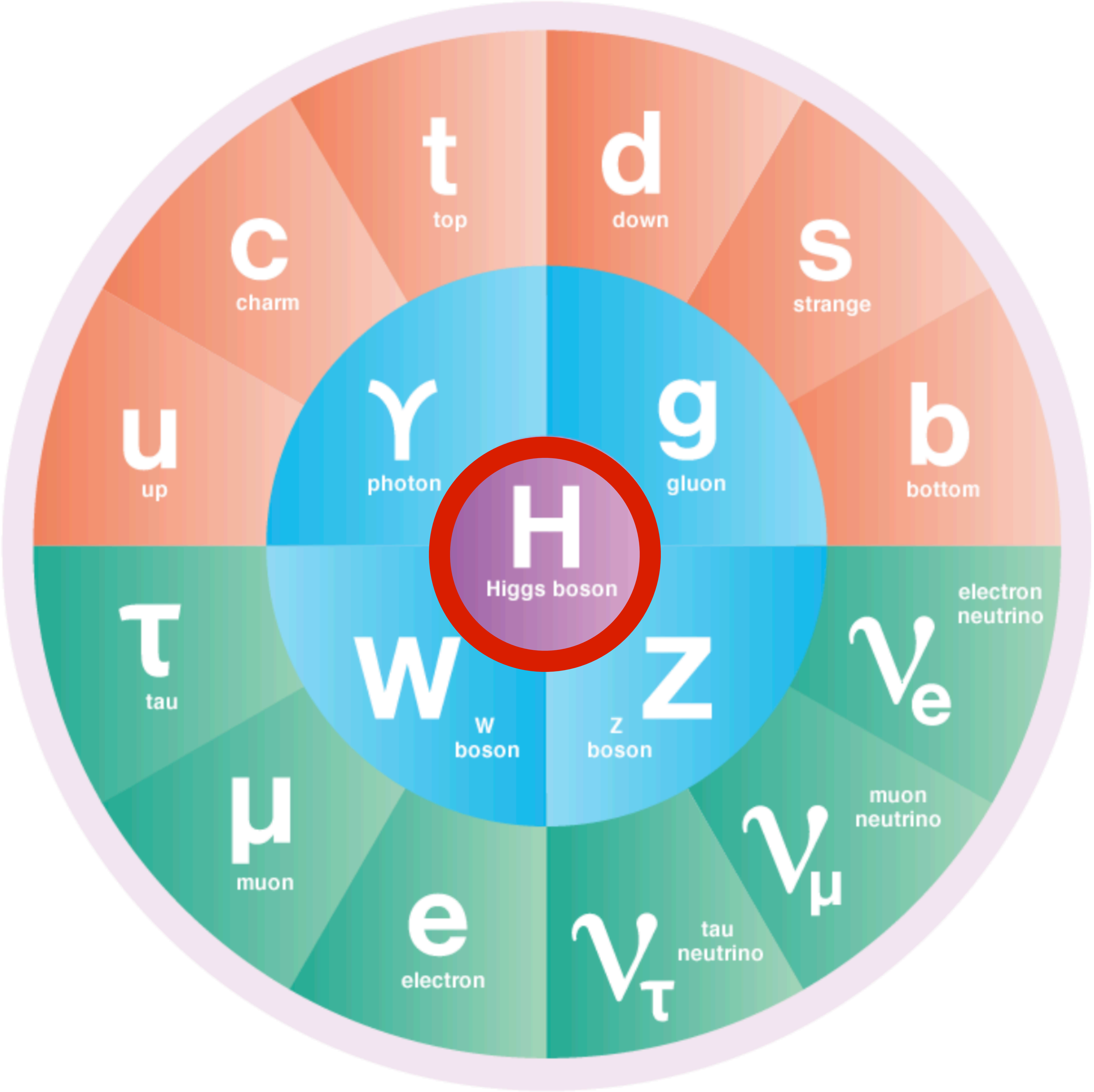
The Standard Model (SM)

https://www.symmetrymagazine.org/standard-model/



particles

The Standard Model (SM)

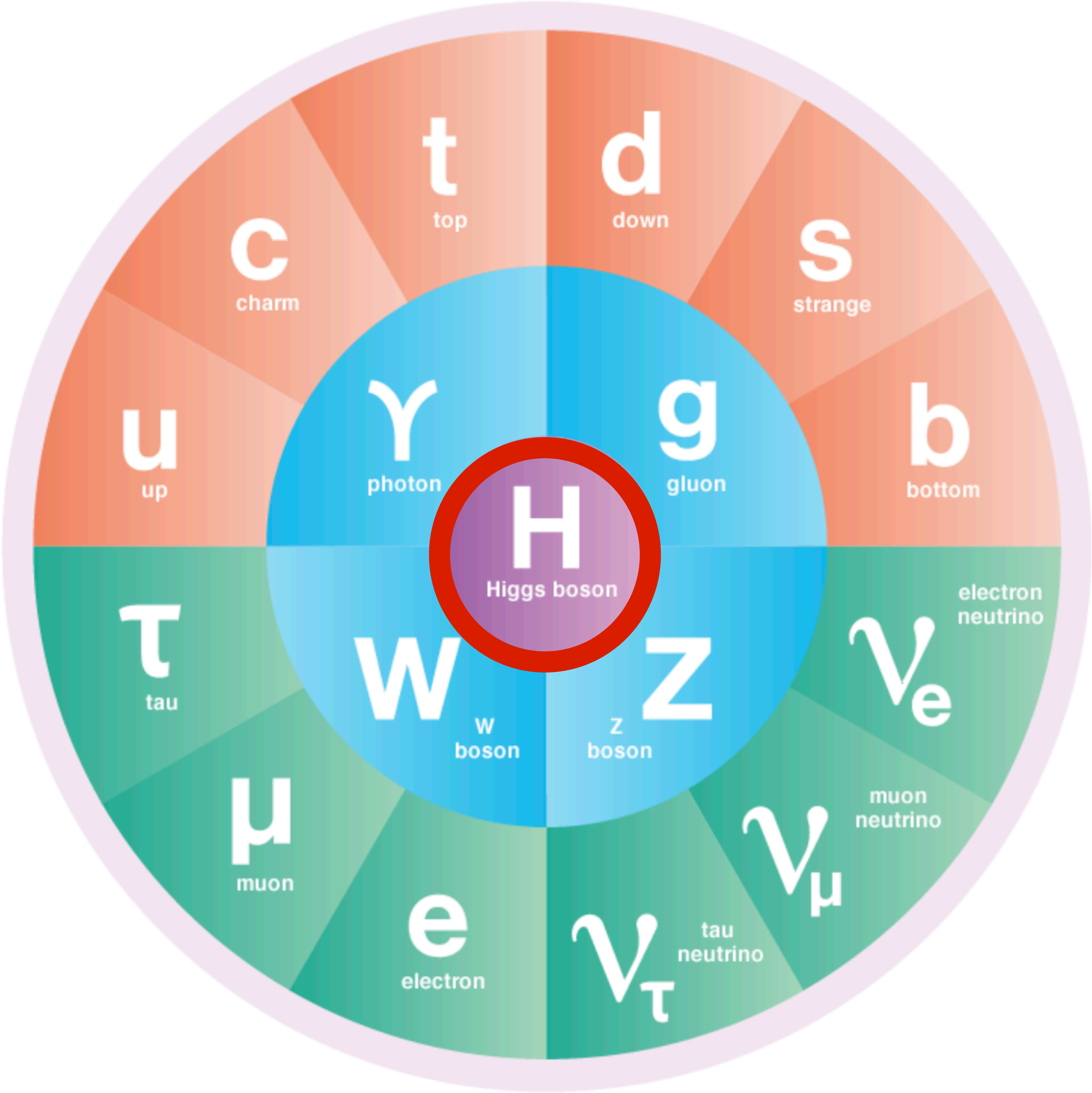


https://www.symmetrymagazine.org/standard-model/

particles

"the standard-model (SM) is complete"

The Standard Model (SM)



https://www.symmetrymagazine.org/standard-model/

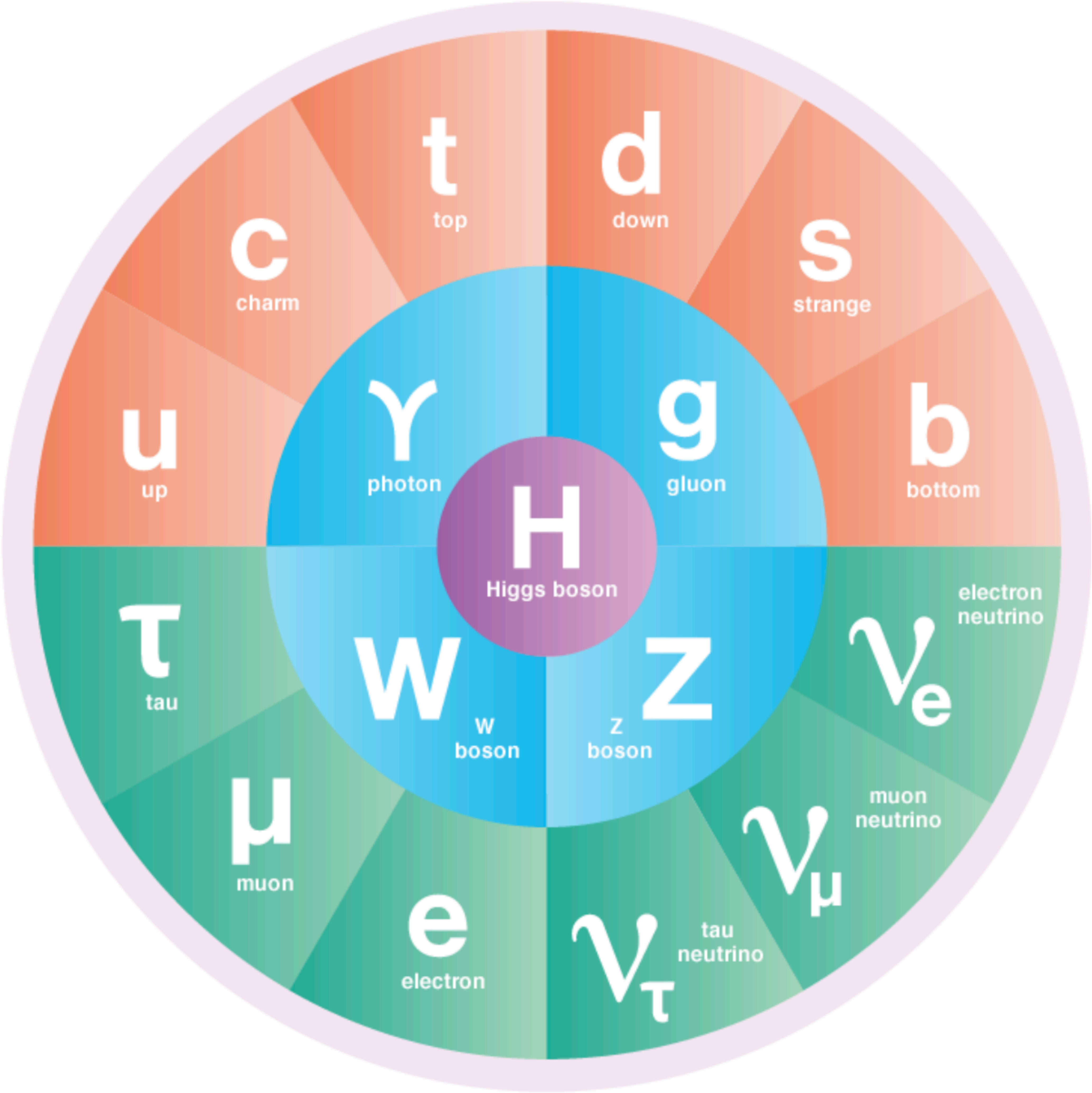
particles

"the standard-model (SM)
is complete"

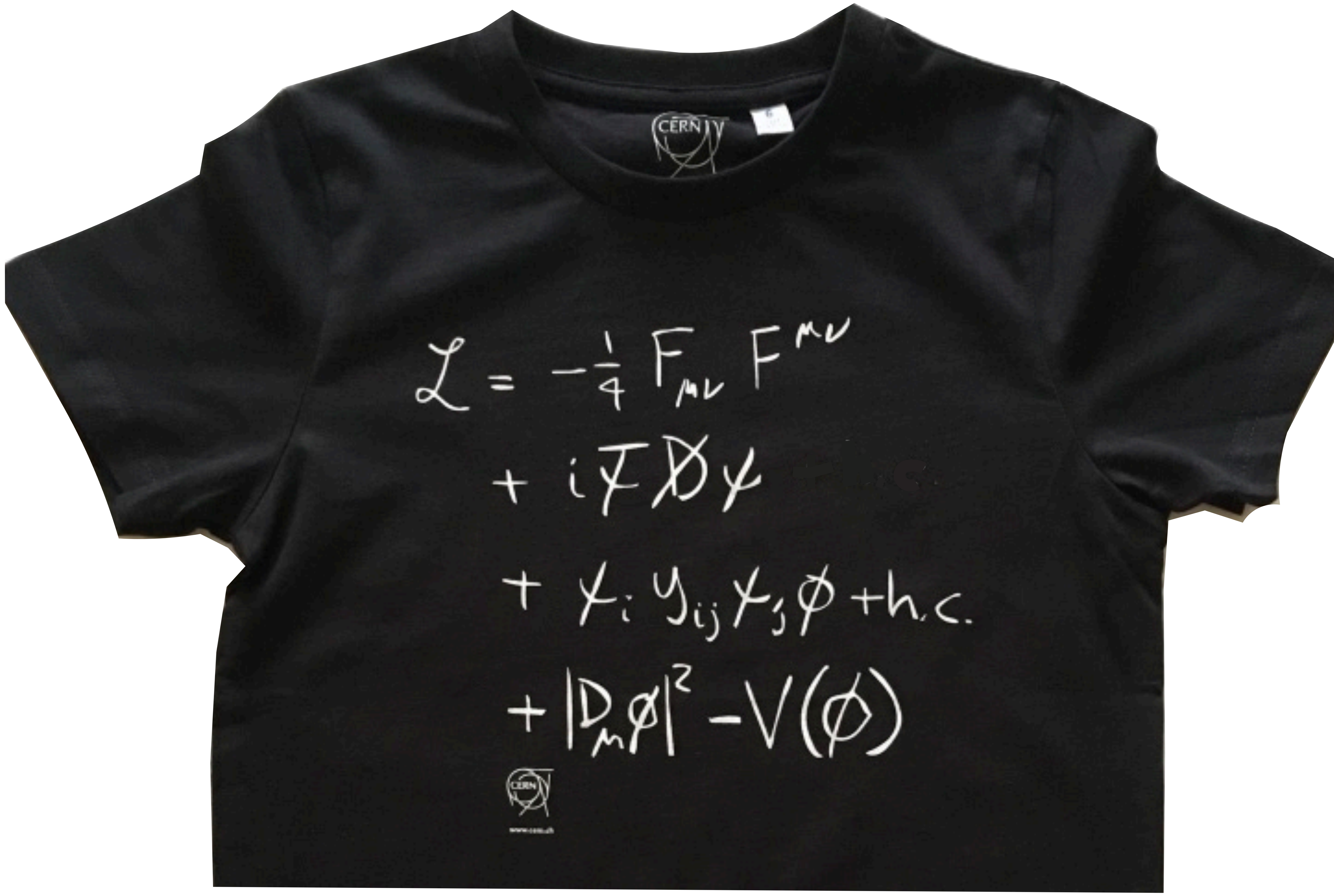
?

The Standard Model (SM)

https://www.symmetrymagazine.org/standard-model/

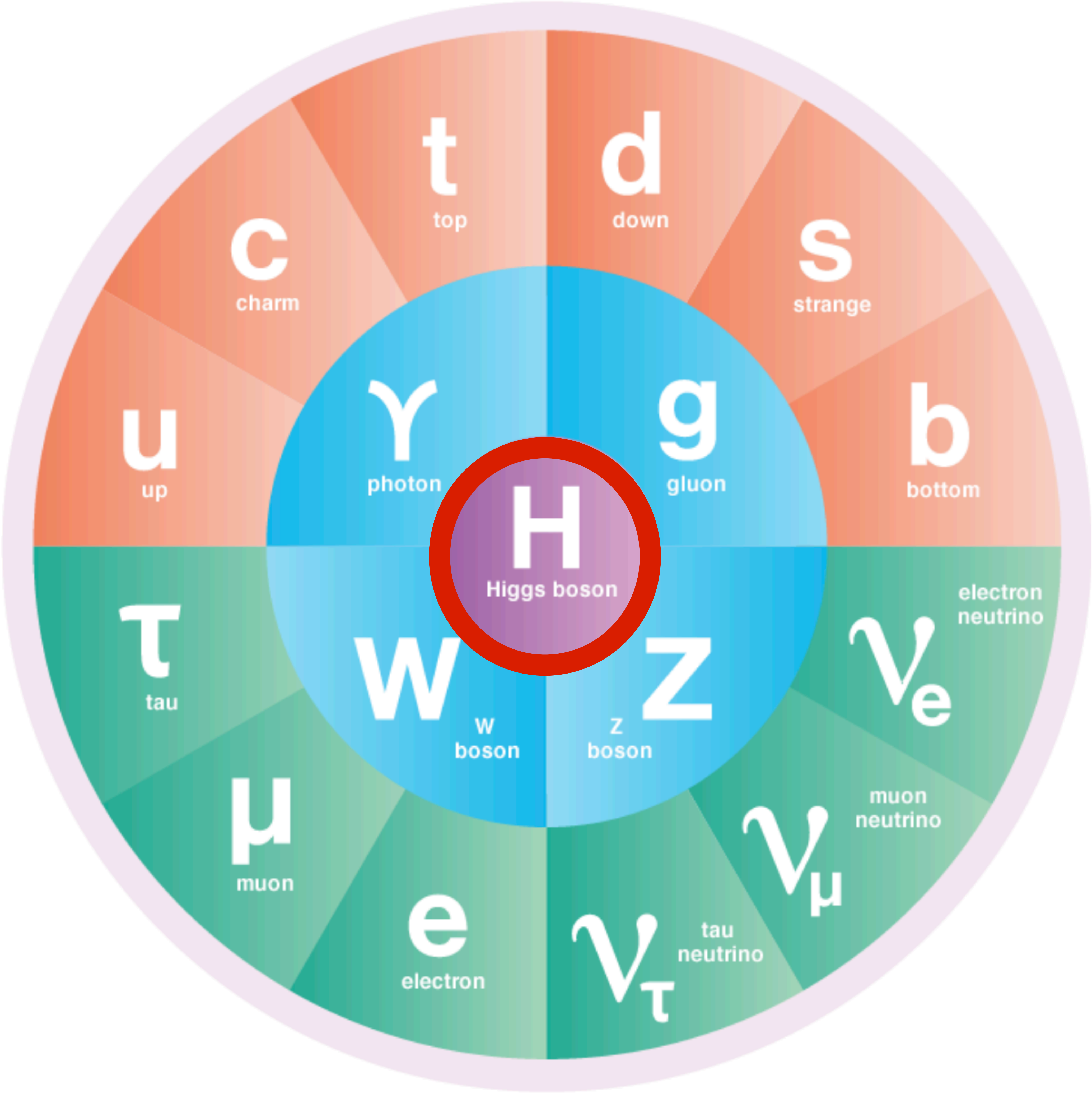


particles



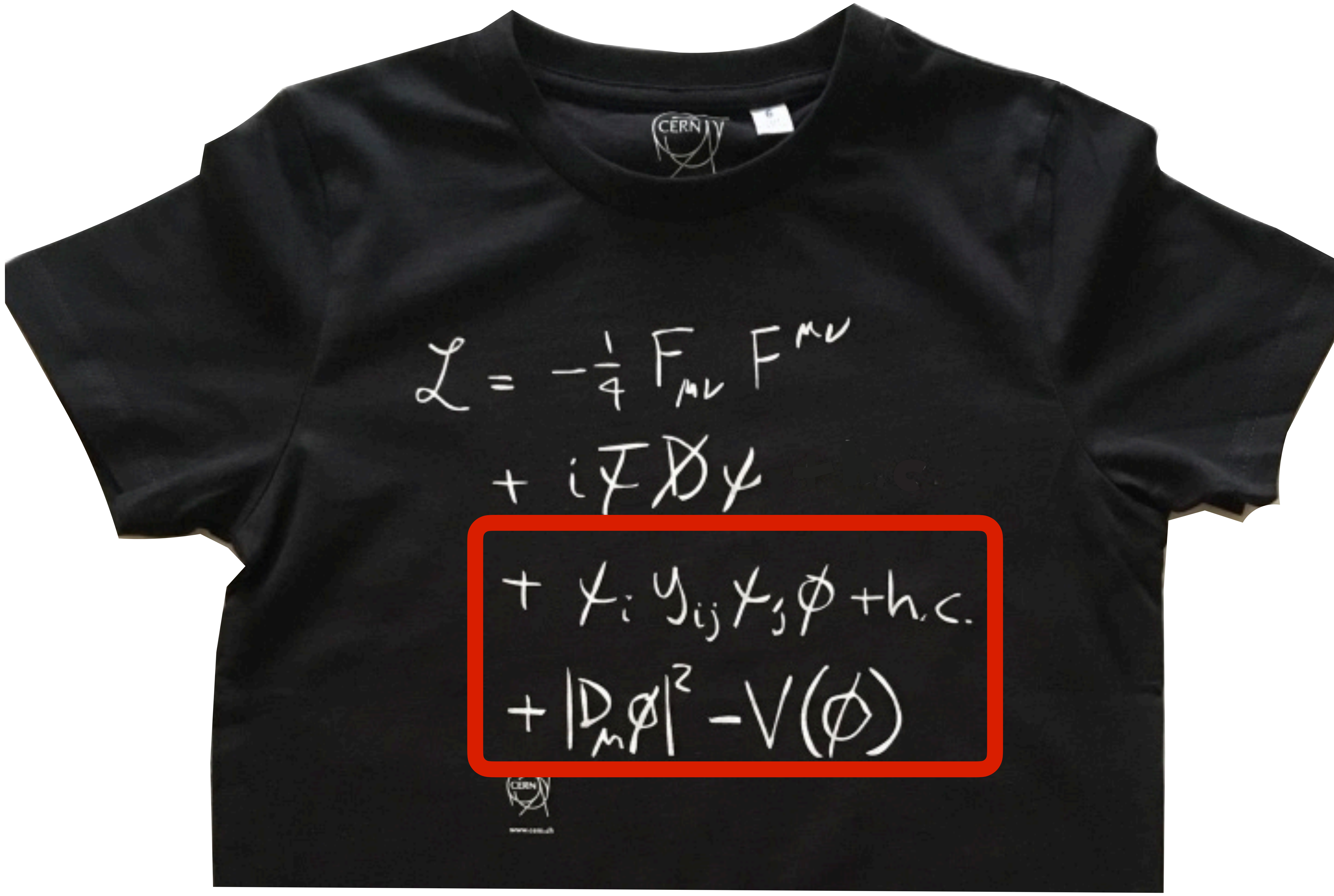
interactions

The Standard Model (SM)



https://www.symmetrymagazine.org/standard-model/

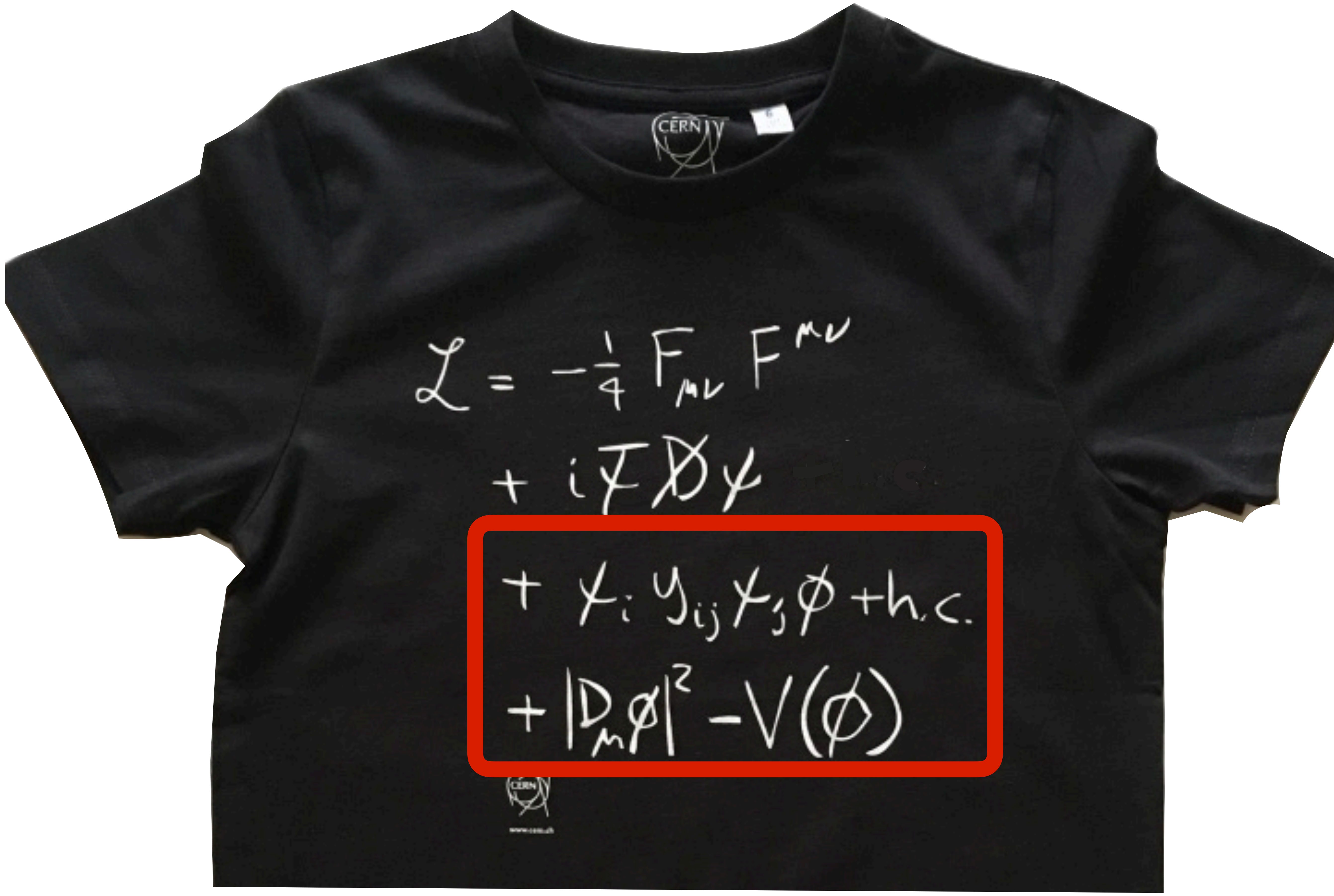
particles



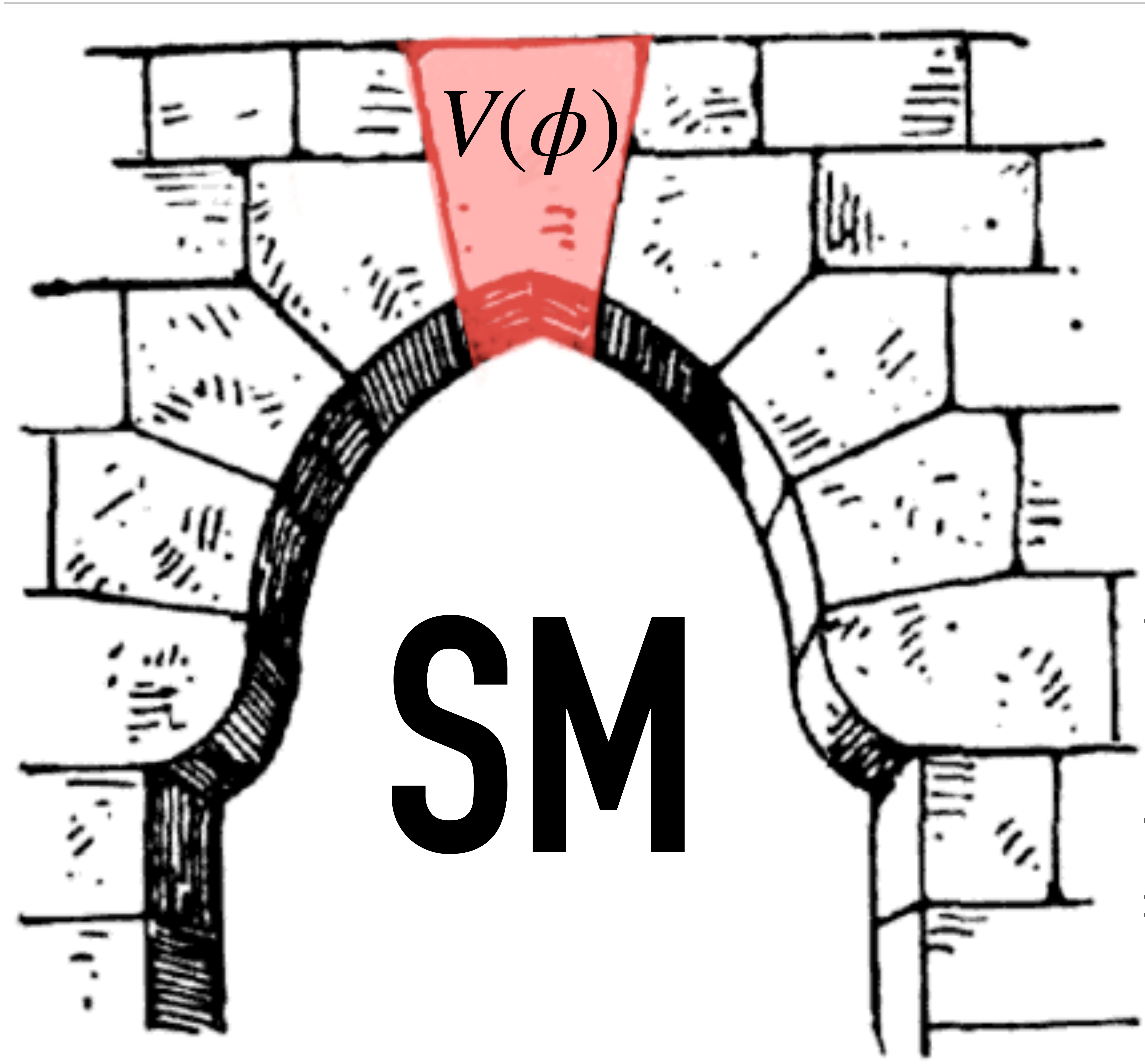
interactions

The Standard Model (SM)

our experimental exploration of the Higgs-related SM interactions is only just starting



interactions



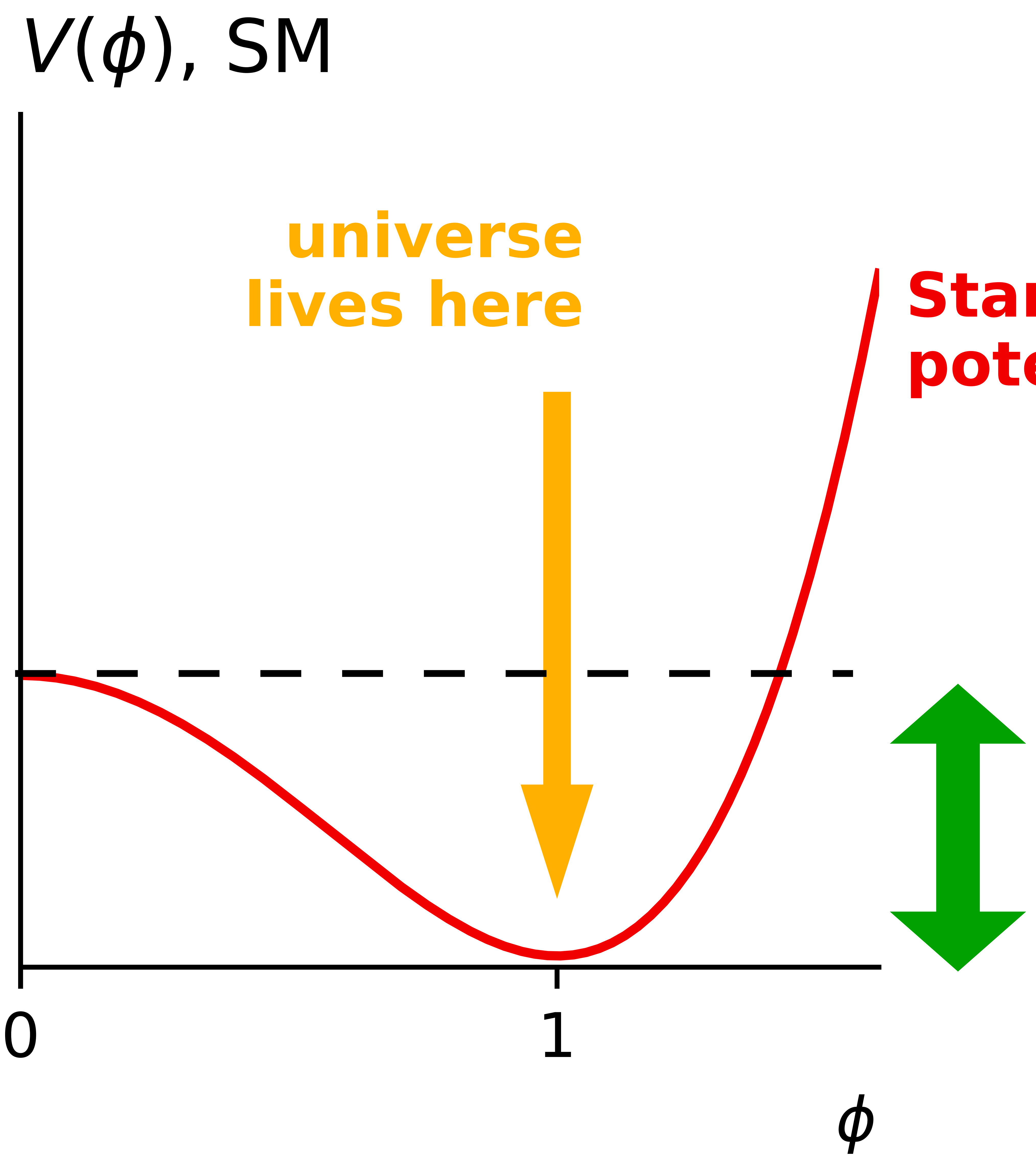
Public Domain, https://commons.wikimedia.org/w/index.php?curid=9502309

unique among all the fields we know, the Higgs field is the only one that is non-zero "classically"

Why?
Higgs potential?

Keystone of SM

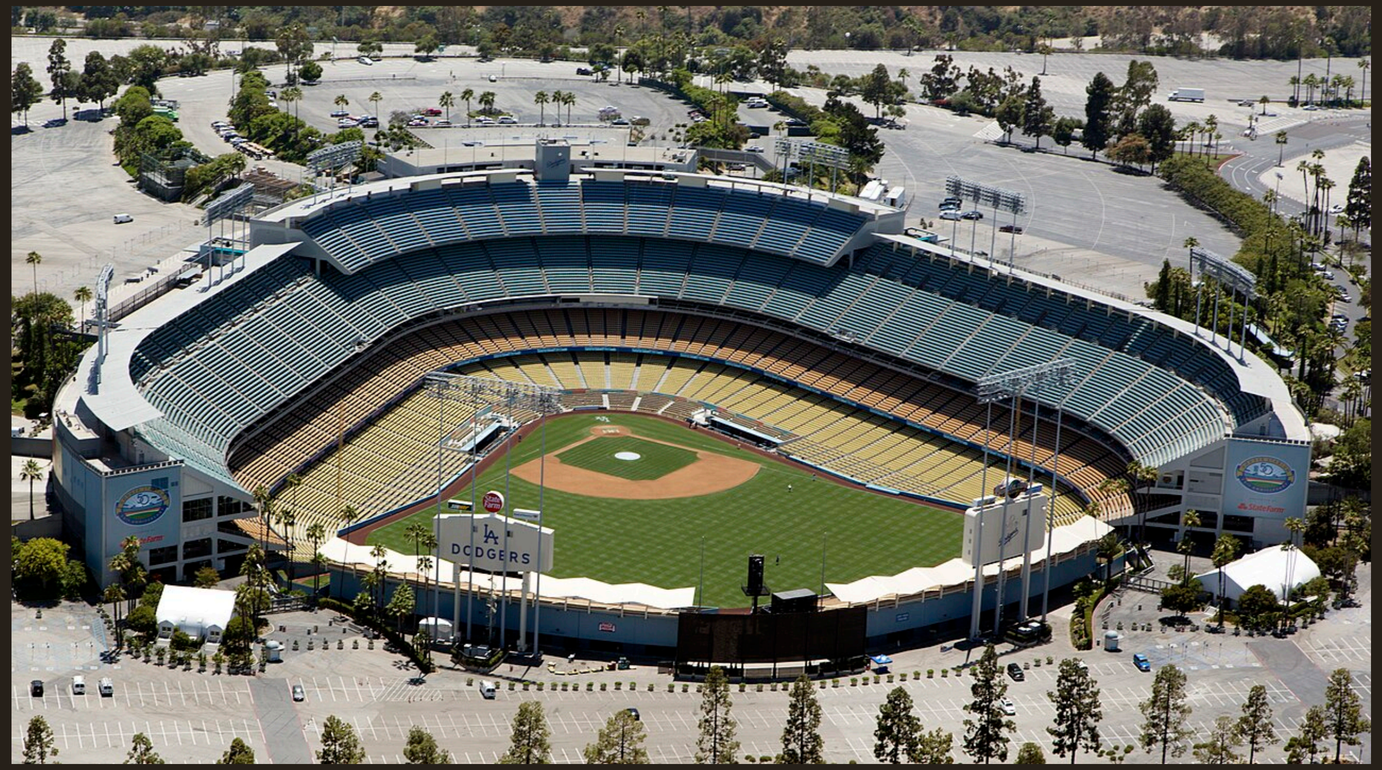
Higgs potential – remember: it's an energy density



Corresponds to an energy density of 1.5×10^{10} GeV/fm^3

$E = mc^2 \rightarrow$ Mass density of 2.6×10^{28} kg/m^3
i.e. >**40 billion times nuclear density**

https://en.wikipedia.org/wiki/Globe#/media/File:World_Globe_Map.jpg
https://en.wikipedia.org/wiki/Old_fashioned_glass#/media/File:Old_Fashioned_Glass.jpg
Dodger Stadium: By Carol M. Highsmith - Library of CongressCatalog: http://lccn.loc.gov/2013632695



https://en.wikipedia.org/wiki/Globe#/media/File:World_Globe_Map.jpg
https://en.wikipedia.org/wiki/Old_fashioned_glass#/media/File:Old_Fashioned_Glass.jpg
Dodger Stadium: By Carol M. Highsmith - Library of CongressCatalog: http://lccn.loc.gov/2013632695

Earth at neutron star density

https://en.wikipedia.org/wiki/Globe#/media/File:World_Globe_Map.jpg
https://en.wikipedia.org/wiki/Old_fashioned_glass#/media/File:Old_Fashioned_Glass.jpg
Dodger Stadium: By Carol M. Highsmith - Library of CongressCatalog: http://lccn.loc.gov/2013632695

Earth at neutron star density

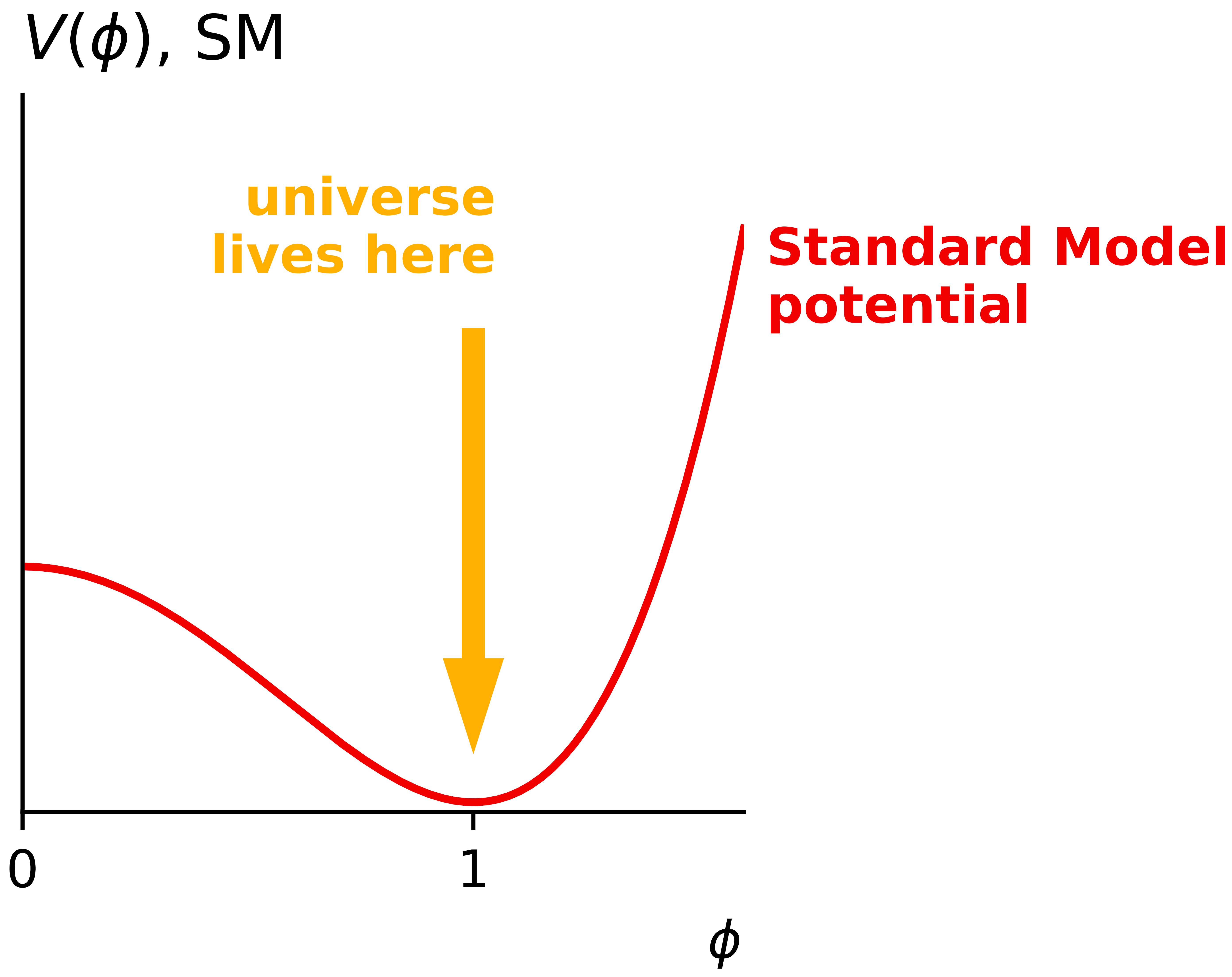
Earth at Higgs potential density

g
g
H
H
H
λ_3
luon
gluo
ϕ
y
x
Higgs field in space


g
g
H
λ_3
H
H
luon
gluo
φ
y
x
Higgs field in space


g
g
H
λ_3
H
H
luon
gluo
Φ
y
x
Higgs field in space

Higgs potential

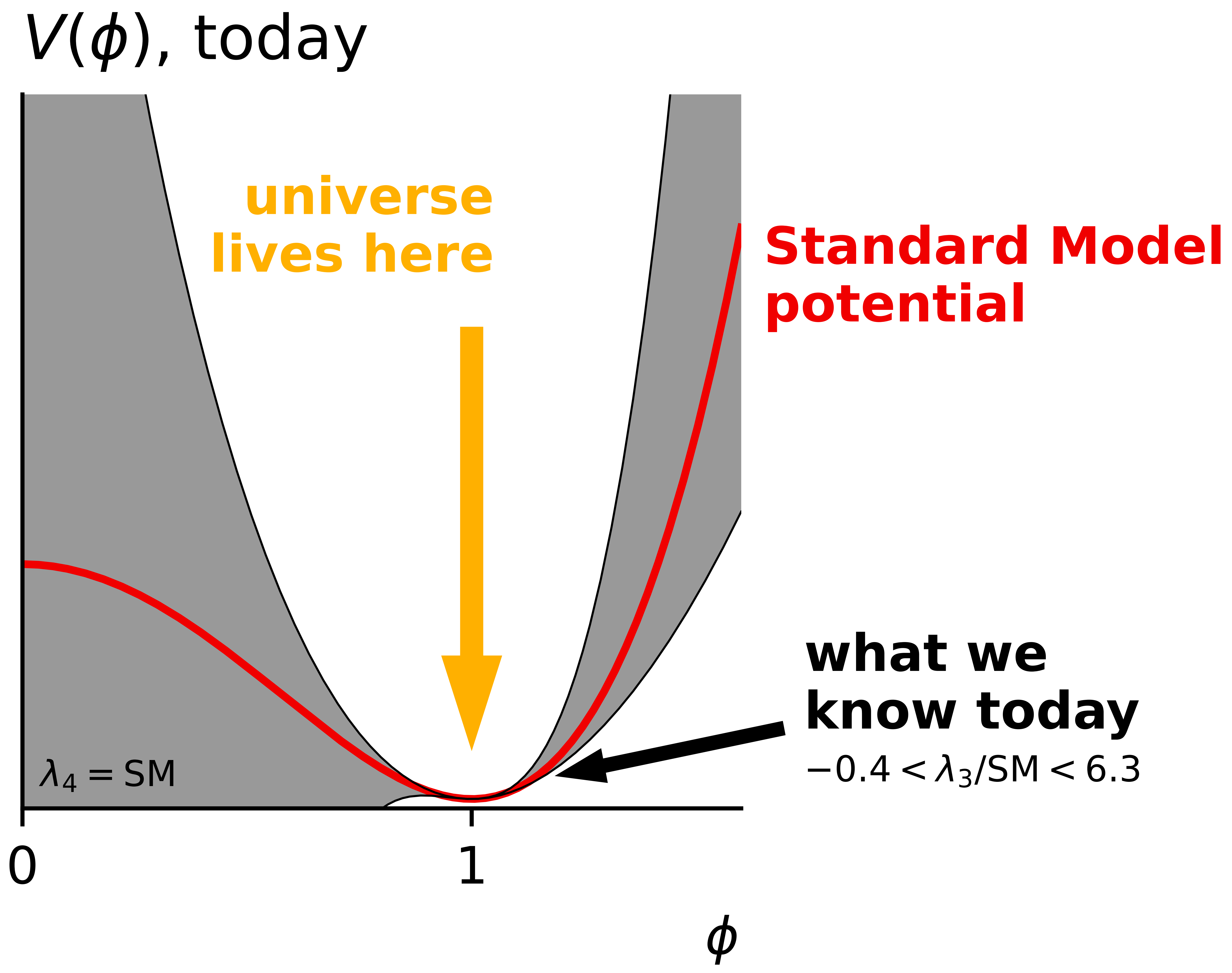


Studying H→HH probes specific mathematical property of the potential's shape:

its third derivative (λ_3), i.e. how asymmetric it is at the minimum

[reconstruction in plot assumes higher derivatives as in SM]

Higgs potential

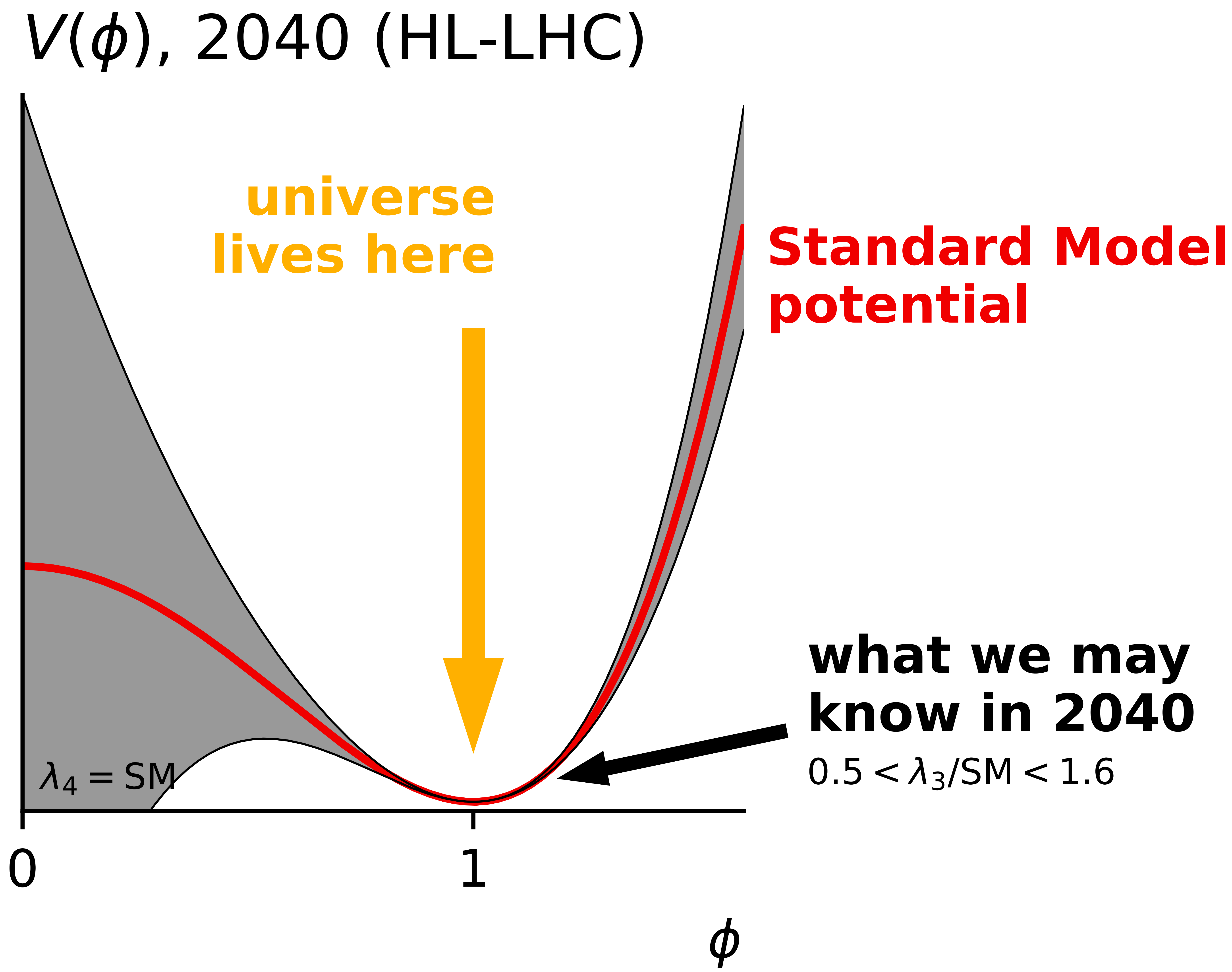


Studying H→HH probes specific mathematical property of the potential's shape:

its third derivative (λ_3), i.e. how asymmetric it is at the minimum

[reconstruction in plot assumes higher derivatives as in SM]

Higgs potential

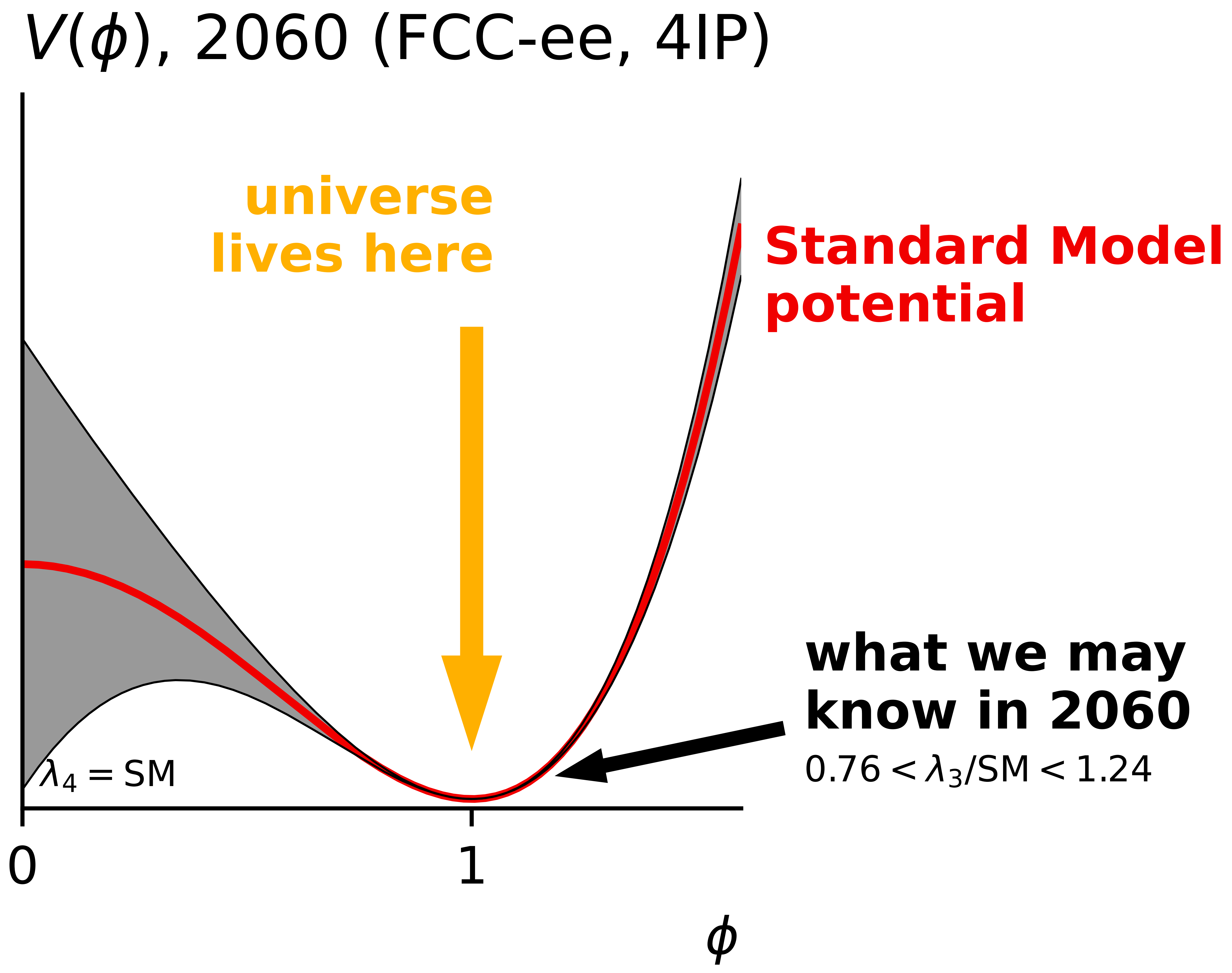


Studying H→HH probes specific mathematical property of the potential's shape:

its third derivative (λ_3), i.e. how asymmetric it is at the minimum

[reconstruction in plot assumes higher derivatives as in SM]

Higgs potential

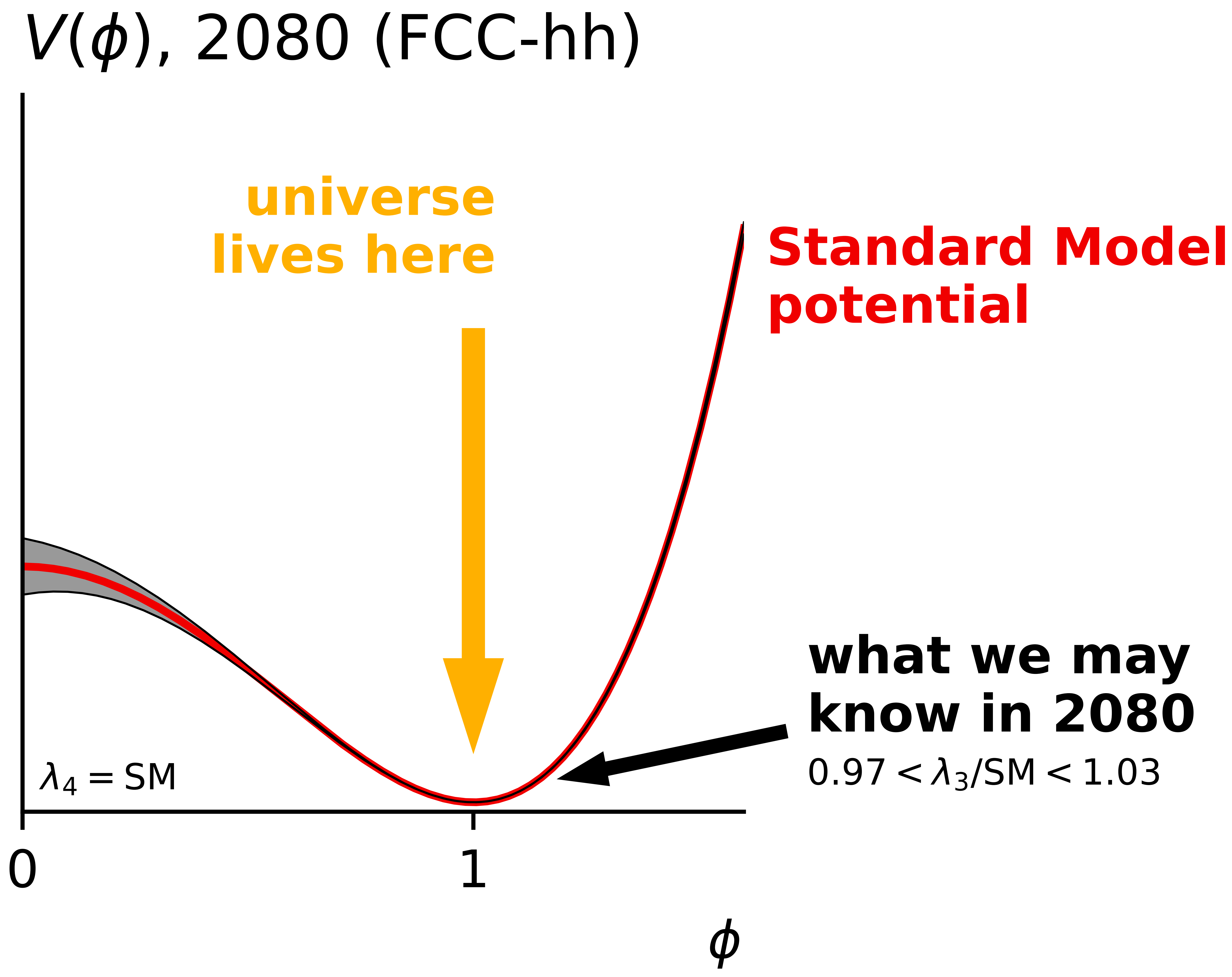


Studying H→HH probes specific mathematical property of the potential's shape:

its third derivative (λ_3), i.e. how asymmetric it is at the minimum

[reconstruction in plot assumes higher derivatives as in SM]

Higgs potential



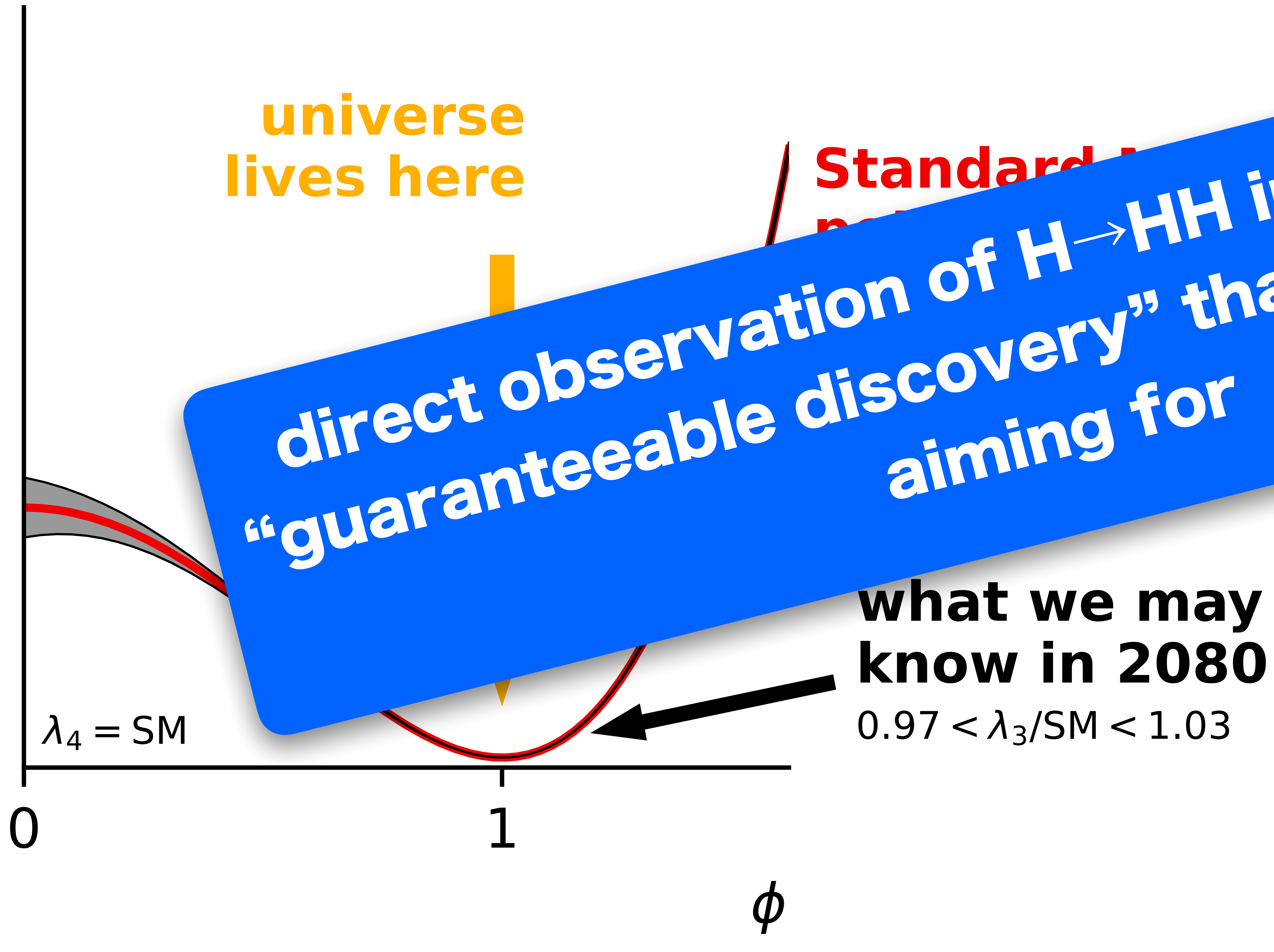
Studying H→HH probes specific mathematical property of the potential's shape:

its third derivative (λ_3), i.e. how asymmetric it is at the minimum

[reconstruction in plot assumes higher derivatives as in SM]

Higgs potential

$V(\phi)$, 2080 (FCC-hh)

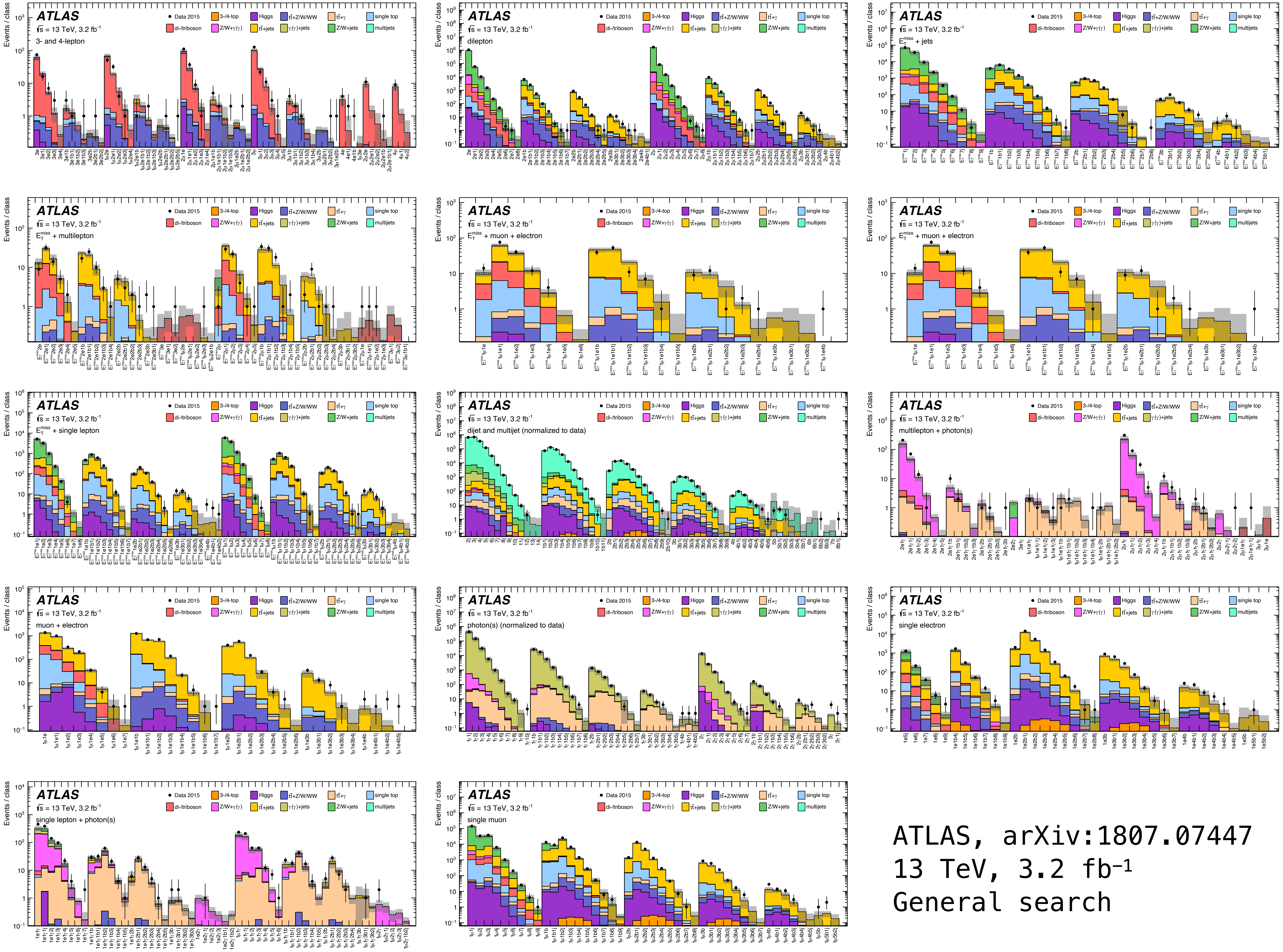


direct observation of H→HH interaction is a "guaranteeable discovery" that HEP should be aiming for

Studying H→HH probes spe… …tical property …'s shape: …ive (λ_3), …metric it is at the minimum

[reconstruction in plot assumes higher derivatives as in SM]

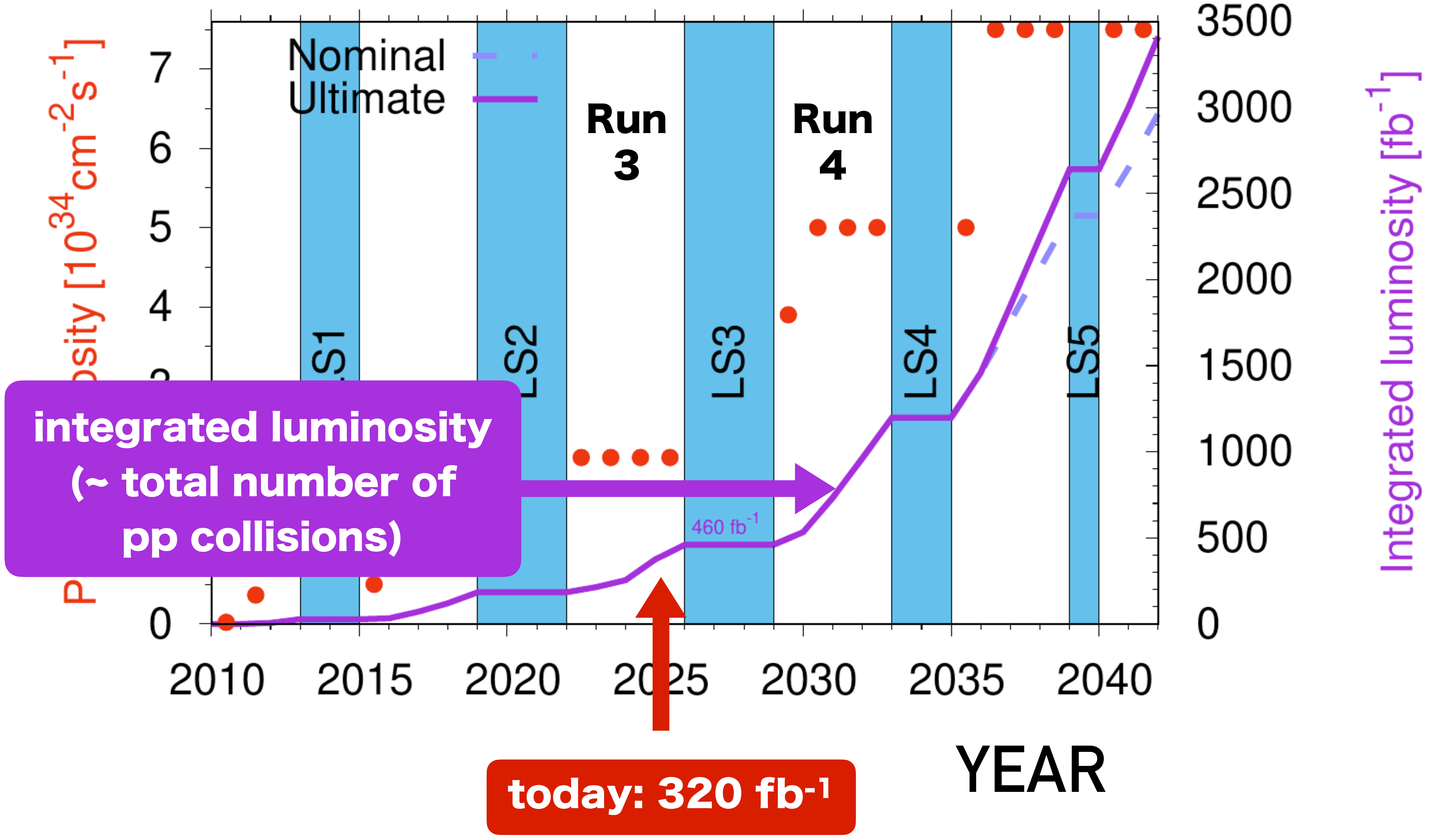
E.g. broadband searches (here an example with 704 event classes, >36000 bins)



Just one illustration out of many searches at the LHC

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

LHC luminosity v. time

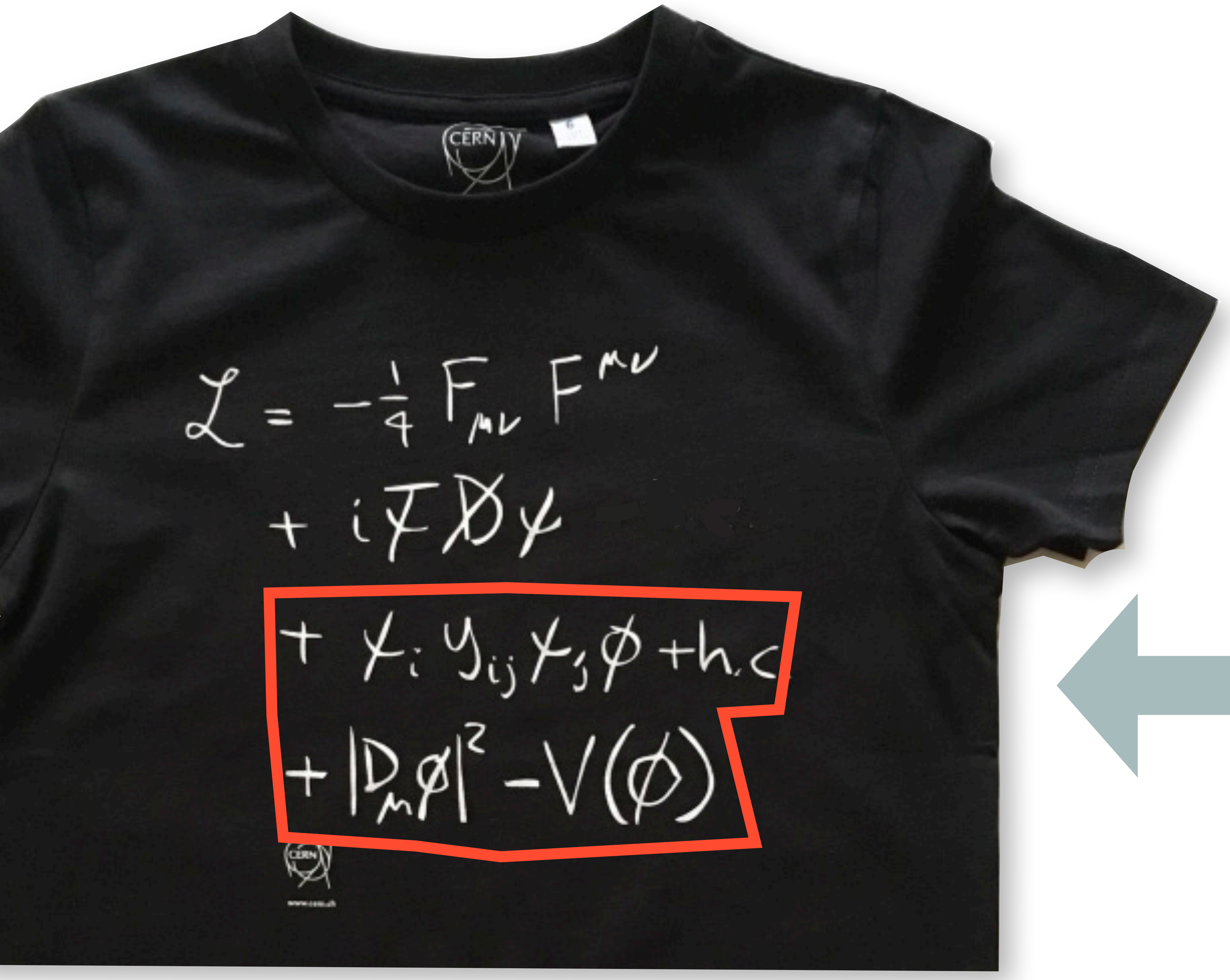


≳ 90% of collisions still to be delivered

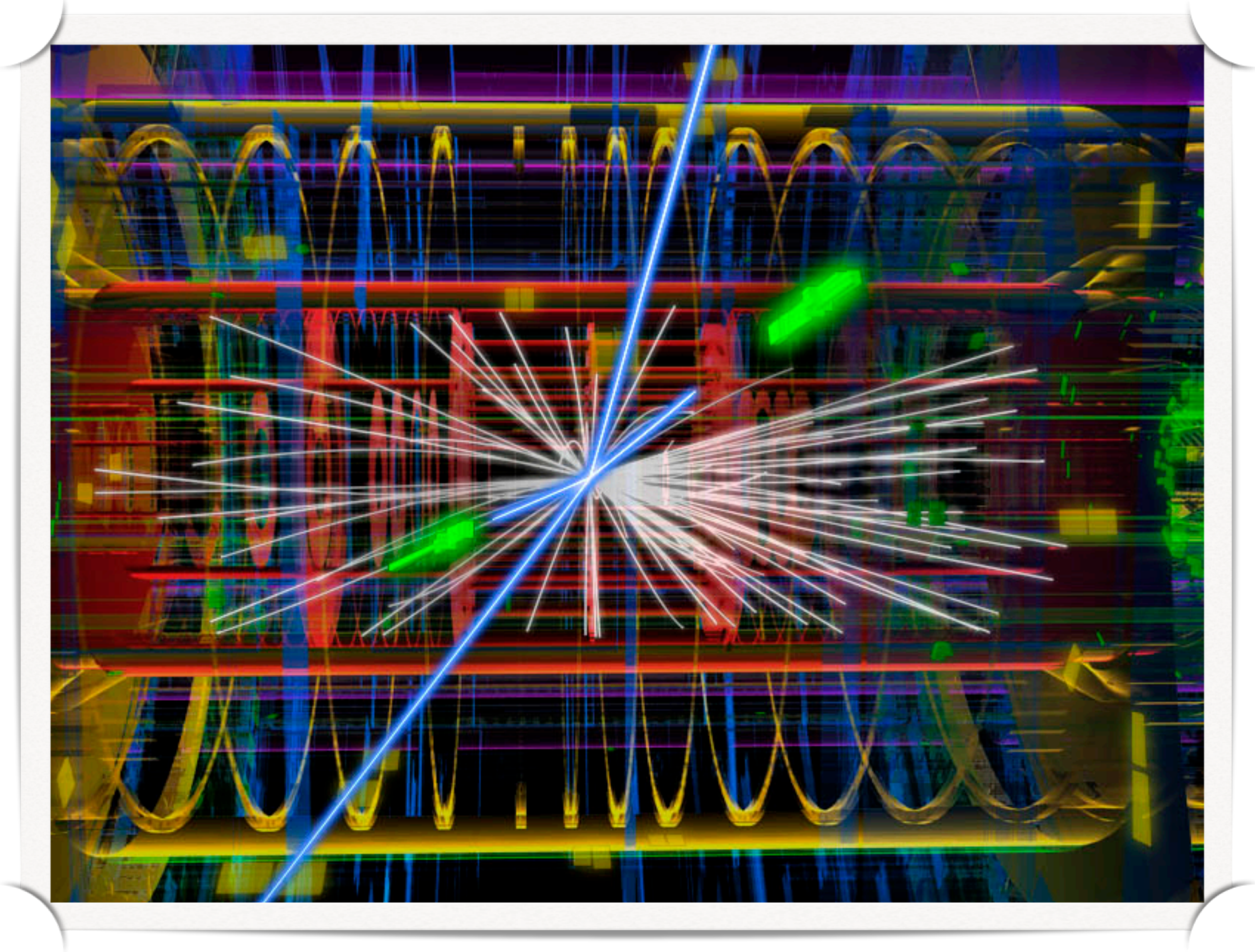
with vastly improved detectors

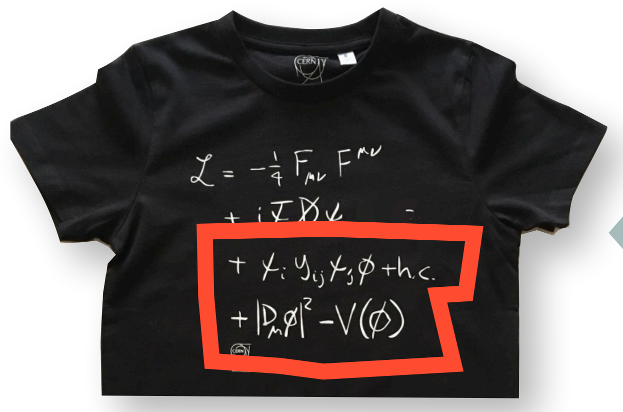
UNDERLYING THEORY

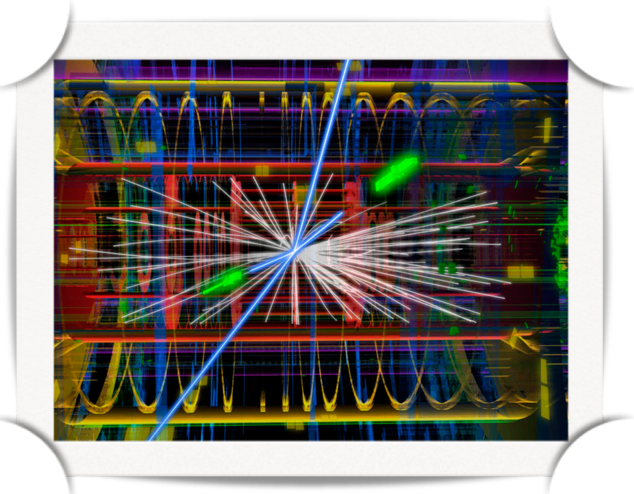
EXPERIMENTAL DATA



how do you make quantitative connection?



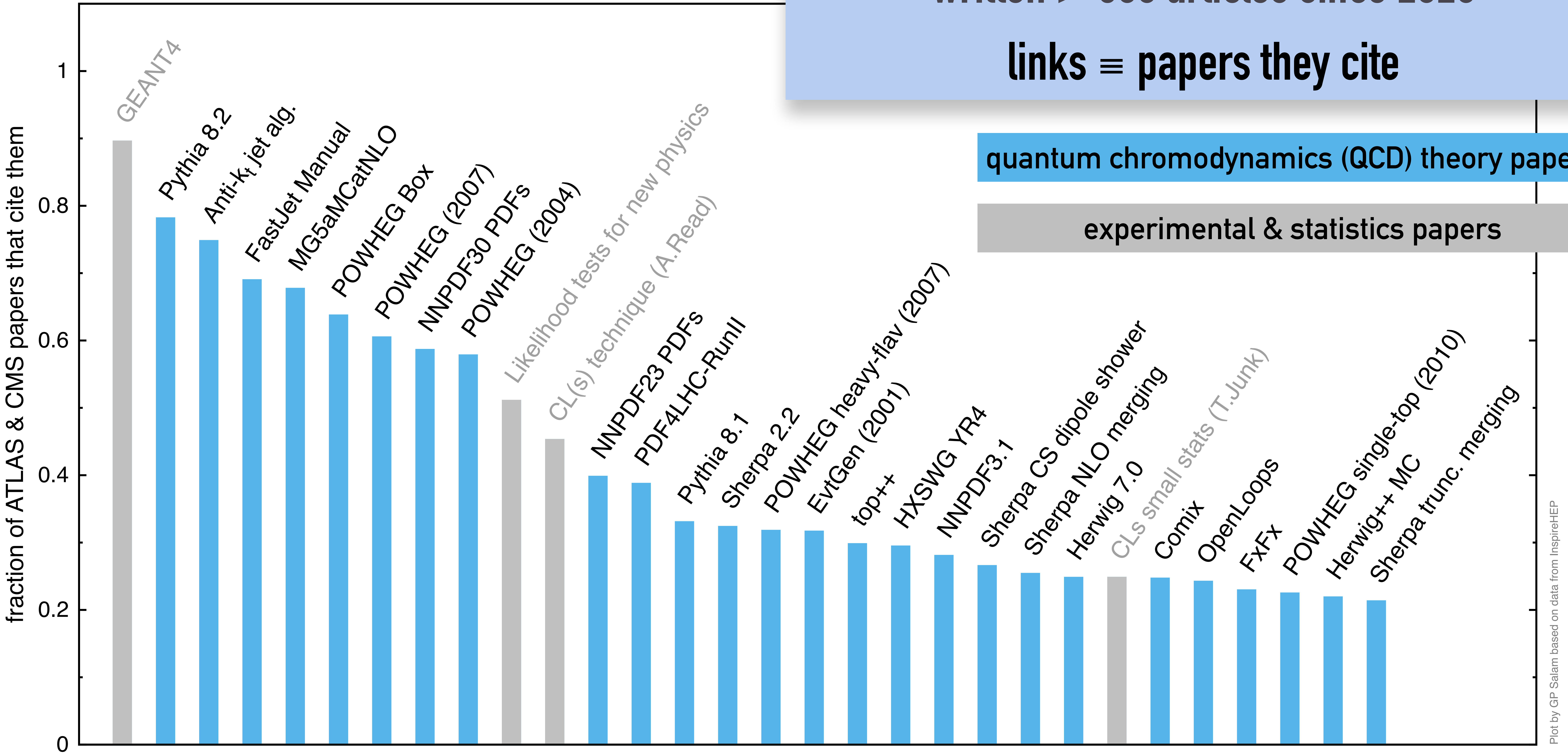


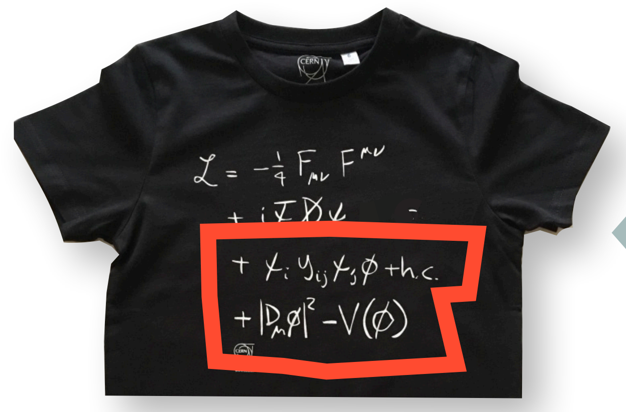


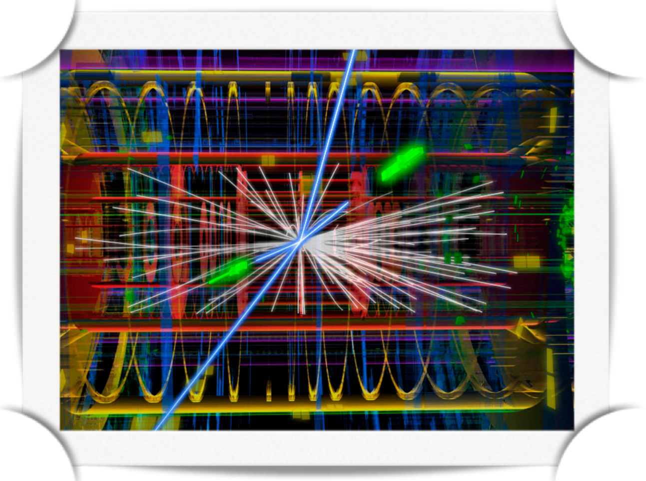
Lagrangian ↔ data

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

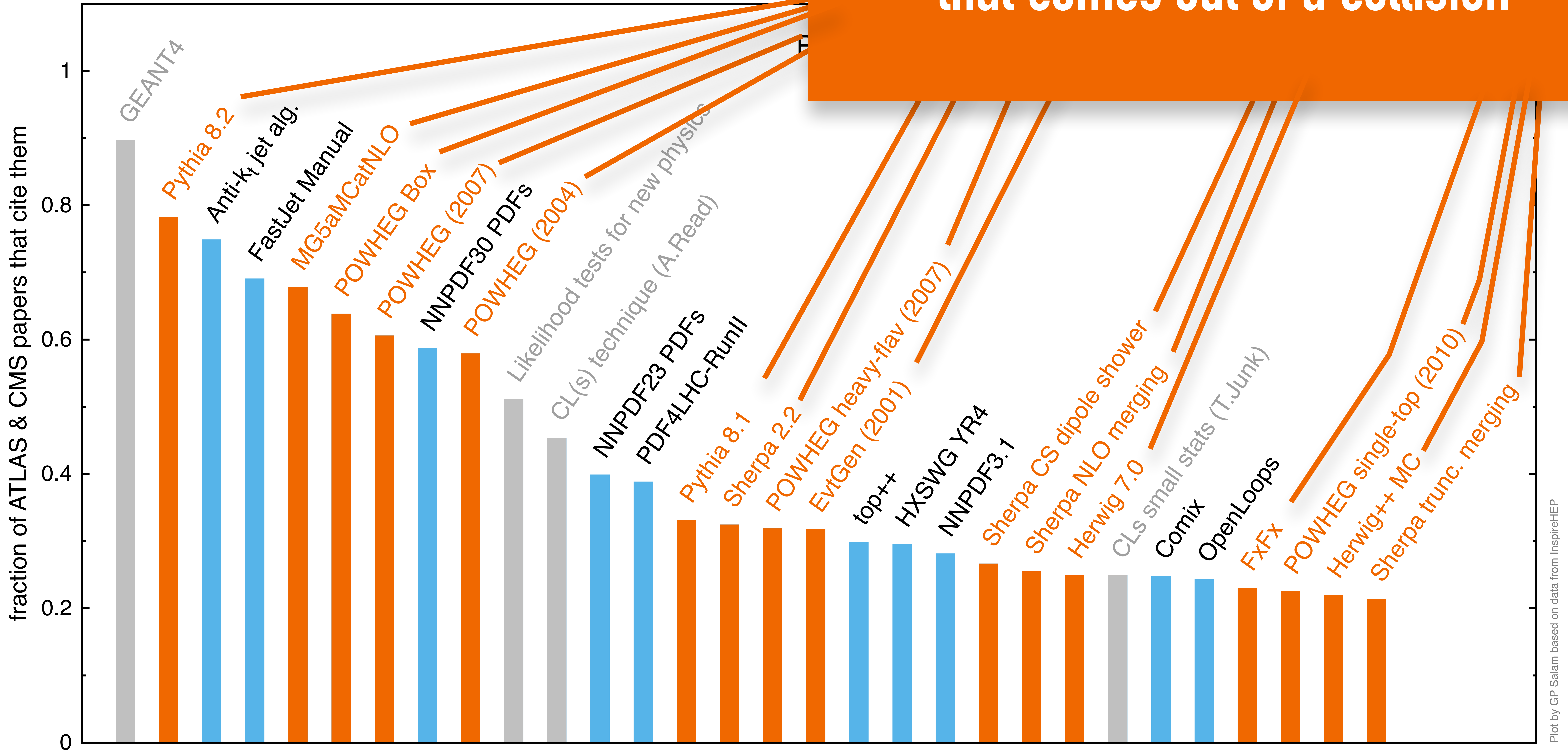
links ≡ papers they cite







predicting full particle structure that comes out of a collision



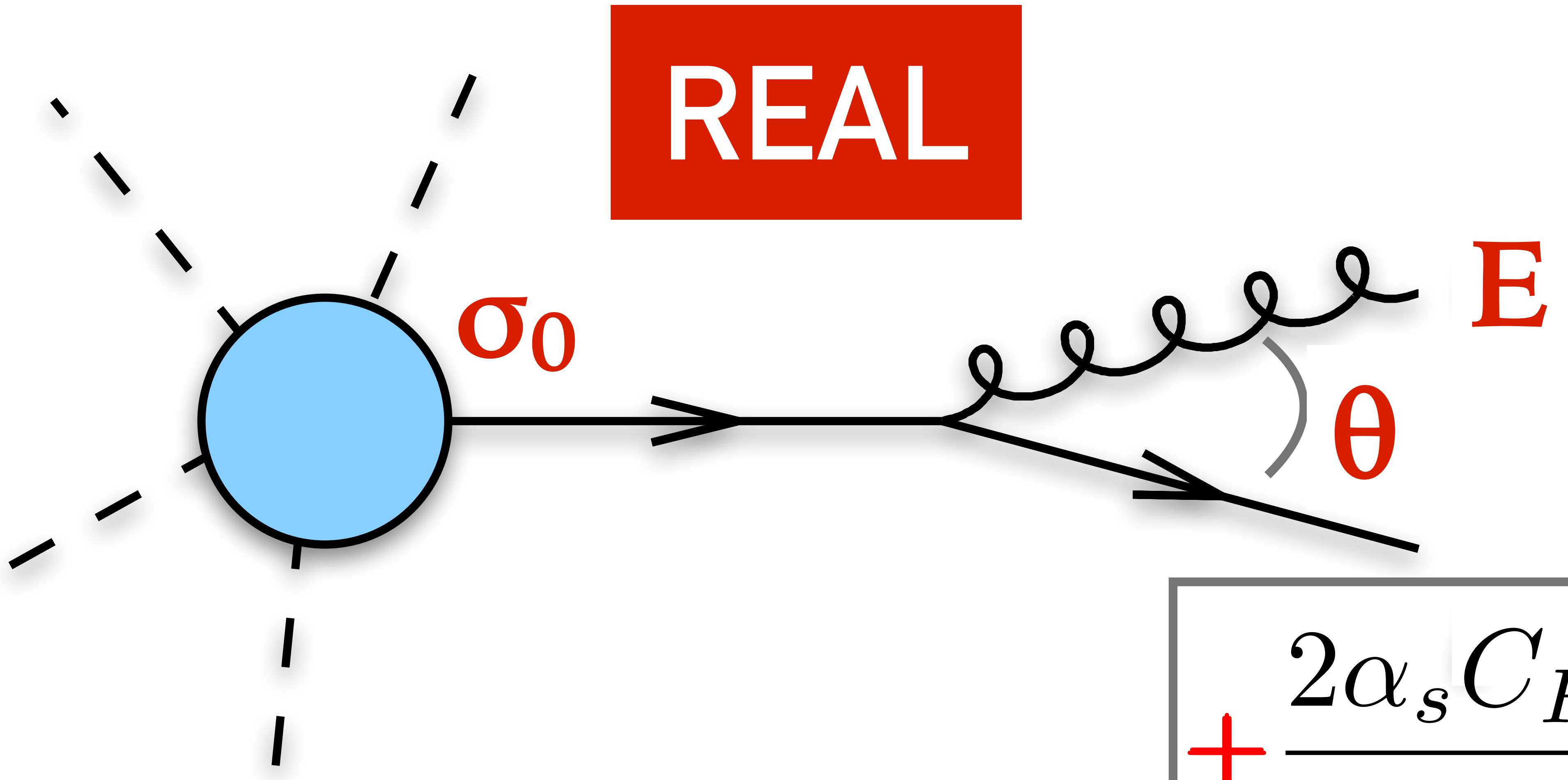
Why not just plain (N)NLO?

i.e. get scattering cross-sections from first few orders of perturbative expansion in the strong coupling α_s

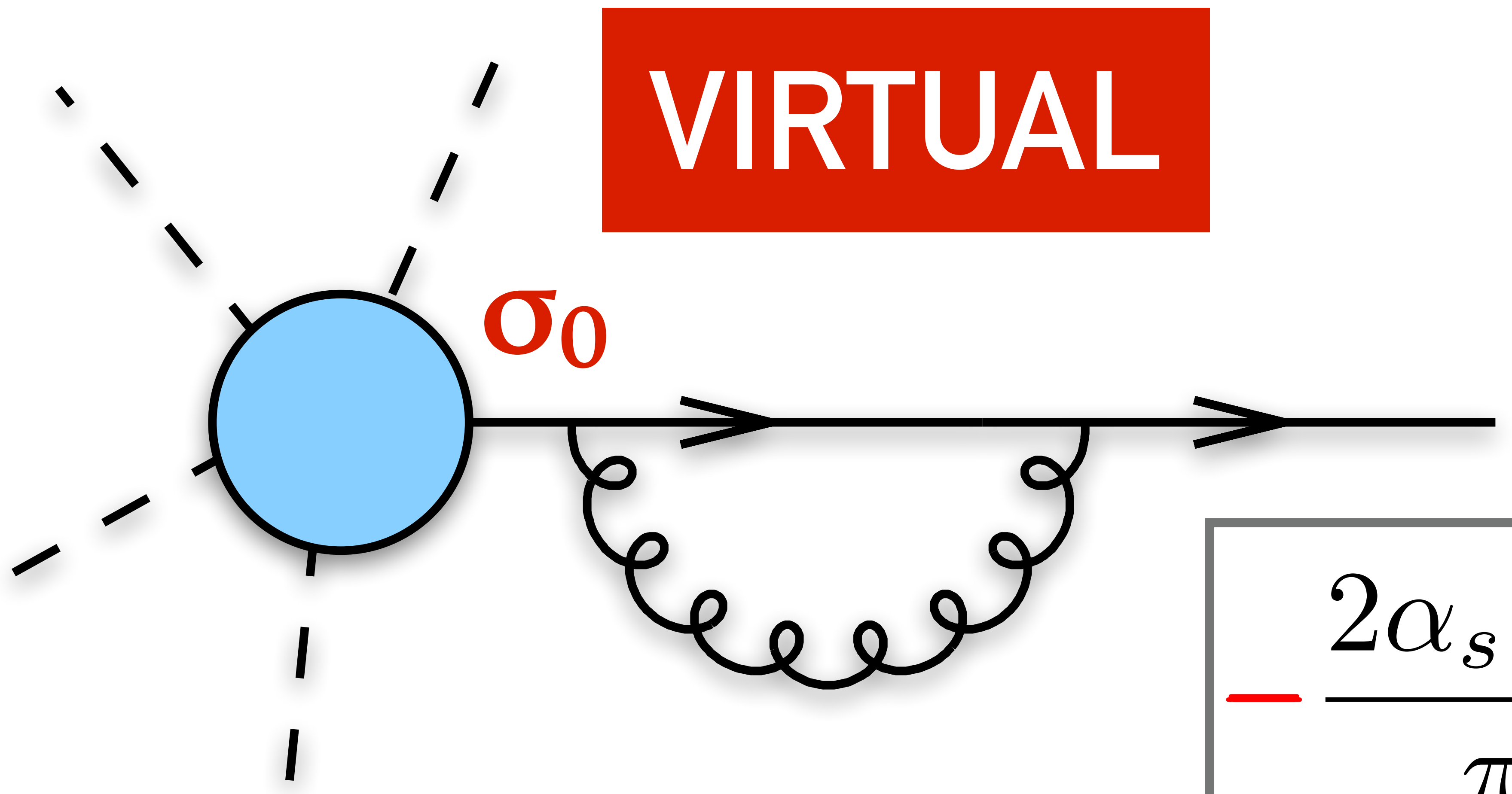
$$\sigma = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \cdots$$

LO NLO NNLO

What kind of contributions do we get at NLO?



$$+\frac{2\alpha_s C_F}{\pi}\frac{dE}{E}\frac{d\theta}{\theta}$$



$$-\frac{2\alpha_s C_F}{\pi}\frac{dE}{E}\frac{d\theta}{\theta}$$

Divergences are present in both real and virtual diagrams.

They arise when an emission has a small energy ($E \ll 1$) or a small angle ($\theta \ll 1$).

In dim-reg, this brings $1/\varepsilon^2$ for each order in α_s.

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

LO (2-particle) tree-level event

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

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

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

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

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

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

NLO (3-particle) tree-level event
with **weight 893.22103**, multiplying (alphas/2pi)
px, py, pz, E = -1.60 -1.75 -49.87 49.93
px, py, pz, E = 1.31 1.36 49.25 49.29
px, py, pz, E = 0.30 0.39 0.62 0.79

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

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

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

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

NLO (3-particle) tree-level event
with **weight 893.22103**, multiplying (alphas/2pi)
px, py, pz, E = -1.60 -1.75 -49.87 49.93
px, py, pz, E = 1.31 1.36 49.25 49.29
px, py, pz, E = 0.30 0.39 0.62 0.79

NLO (2-particle) virtual subtraction event
with **weight -84.49299**, multiplying (alphas/2pi)
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

NLO (2-particle) virtual subtraction event
with **weight -808.58646**, multiplying (alphas/2pi)
px, py, pz, E = -1.61 -1.75 -49.94 50.00
px, py, pz, E = 1.61 1.75 49.94 50.00

NLO (2-particle) virtual finite event
with weight 2.66667, multiplying (alphas/2pi)
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

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

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

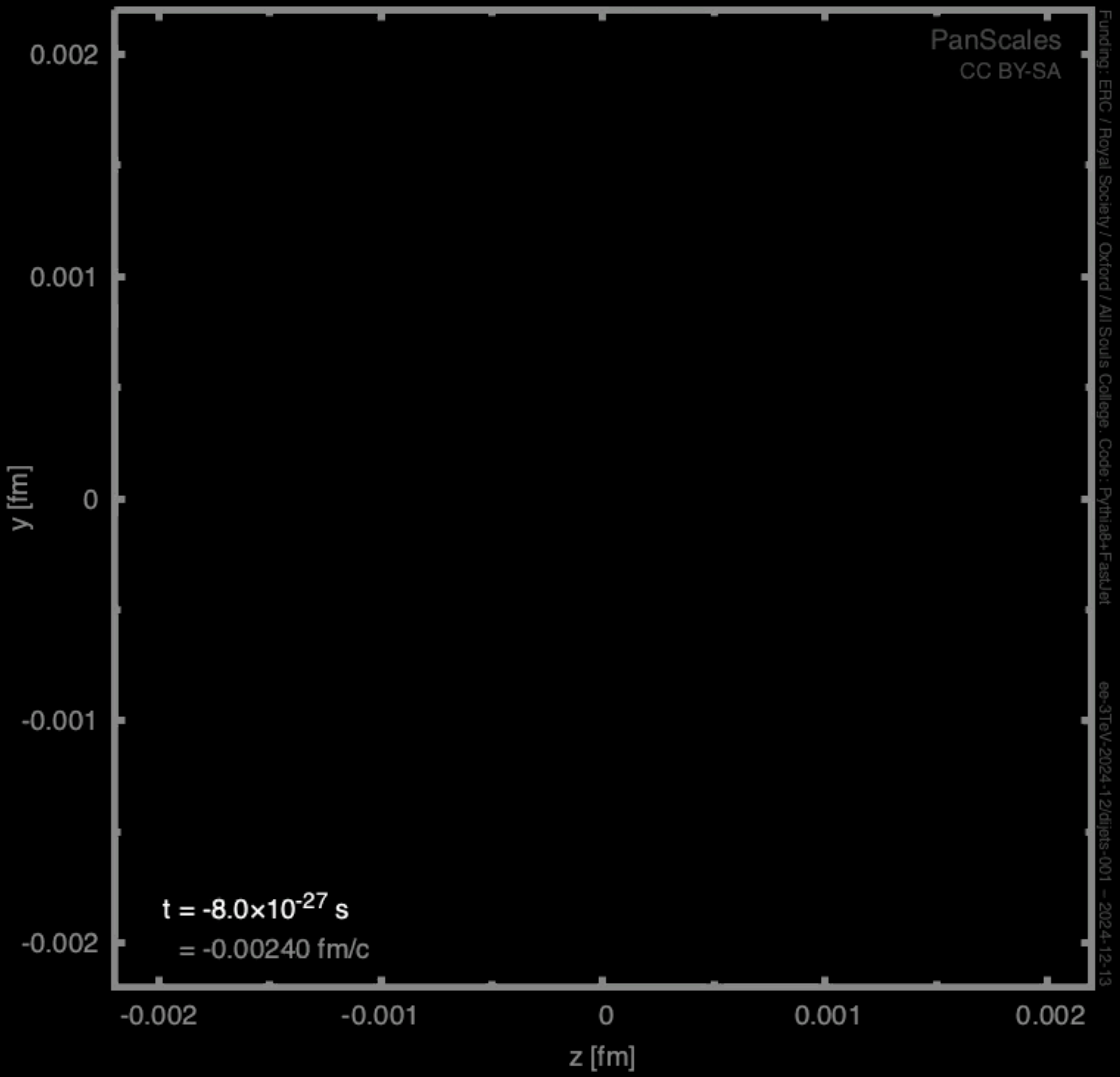
NLO event, “virtual” correction
~ LO event
and **large negative weight**

event weights are ~ probabilities

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

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

What actually happens in a collision?

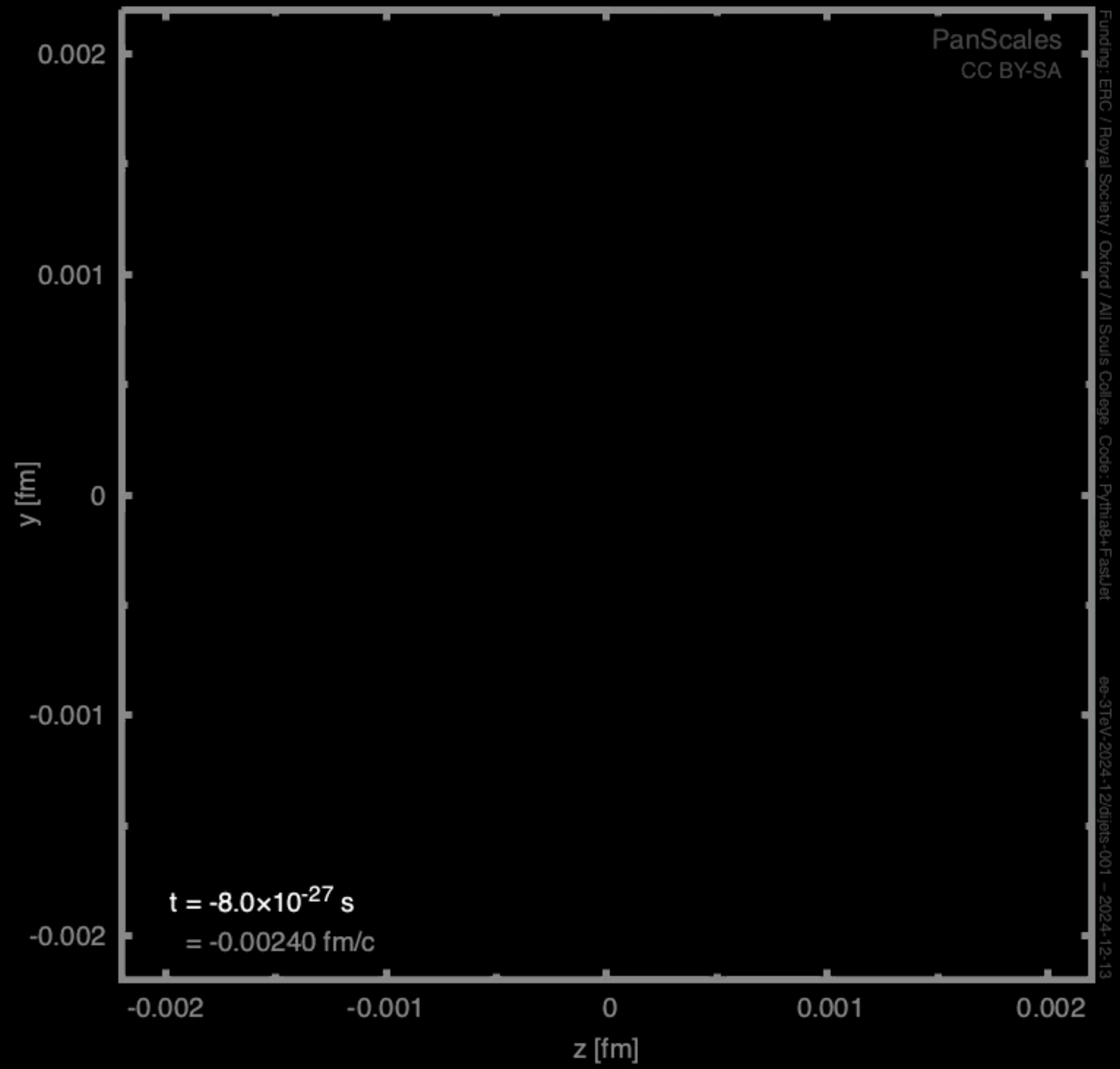


incoming beam particle

intermediate particle (quark or gluon)

final particle (hadron)

Event evolution spans 7 orders of magnitude in space-time



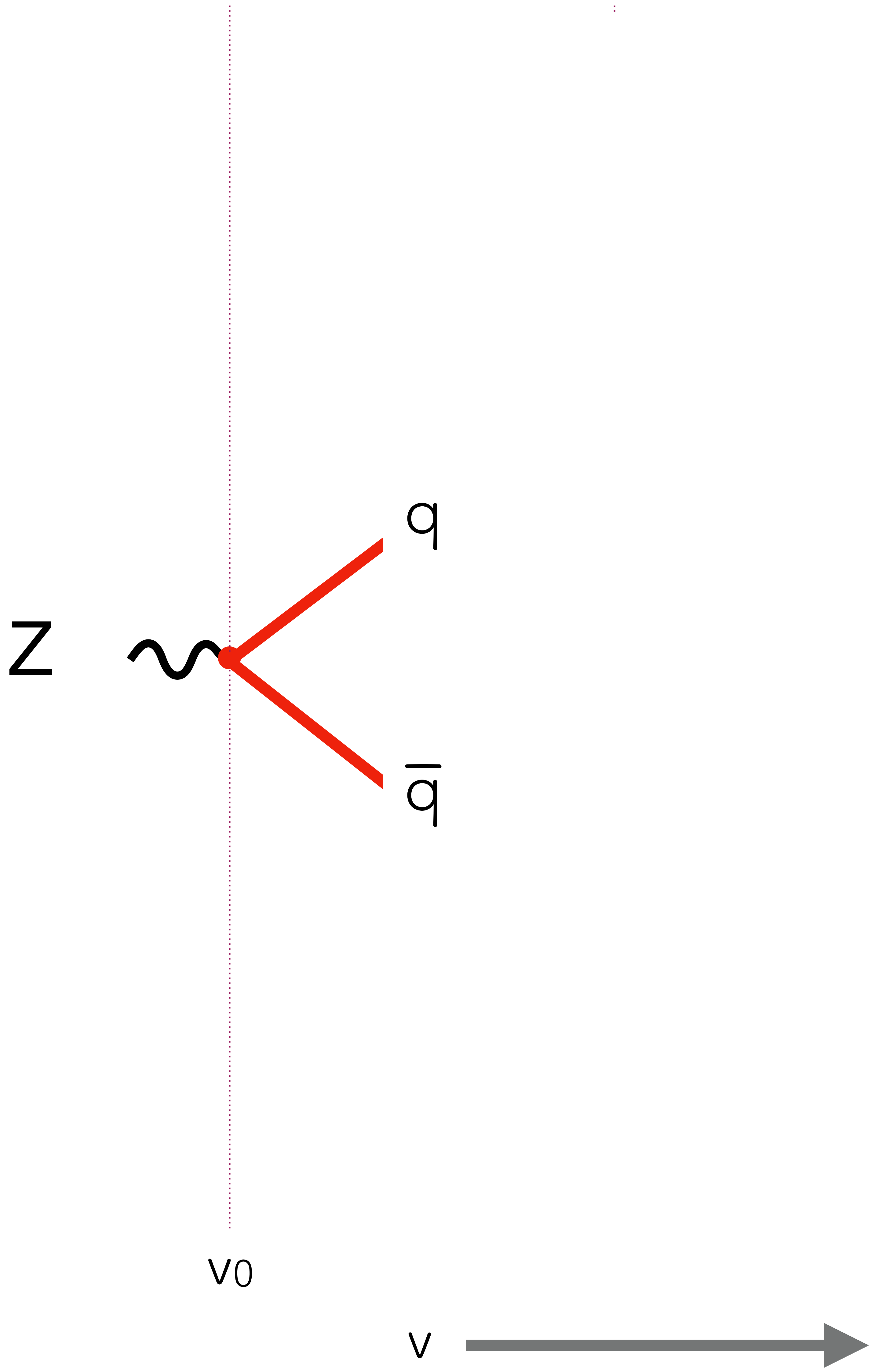
incoming beam particle

intermediate particle (quark or gluon)

final particle (hadron)

Event evolution spans 7 orders of magnitude in space-time

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

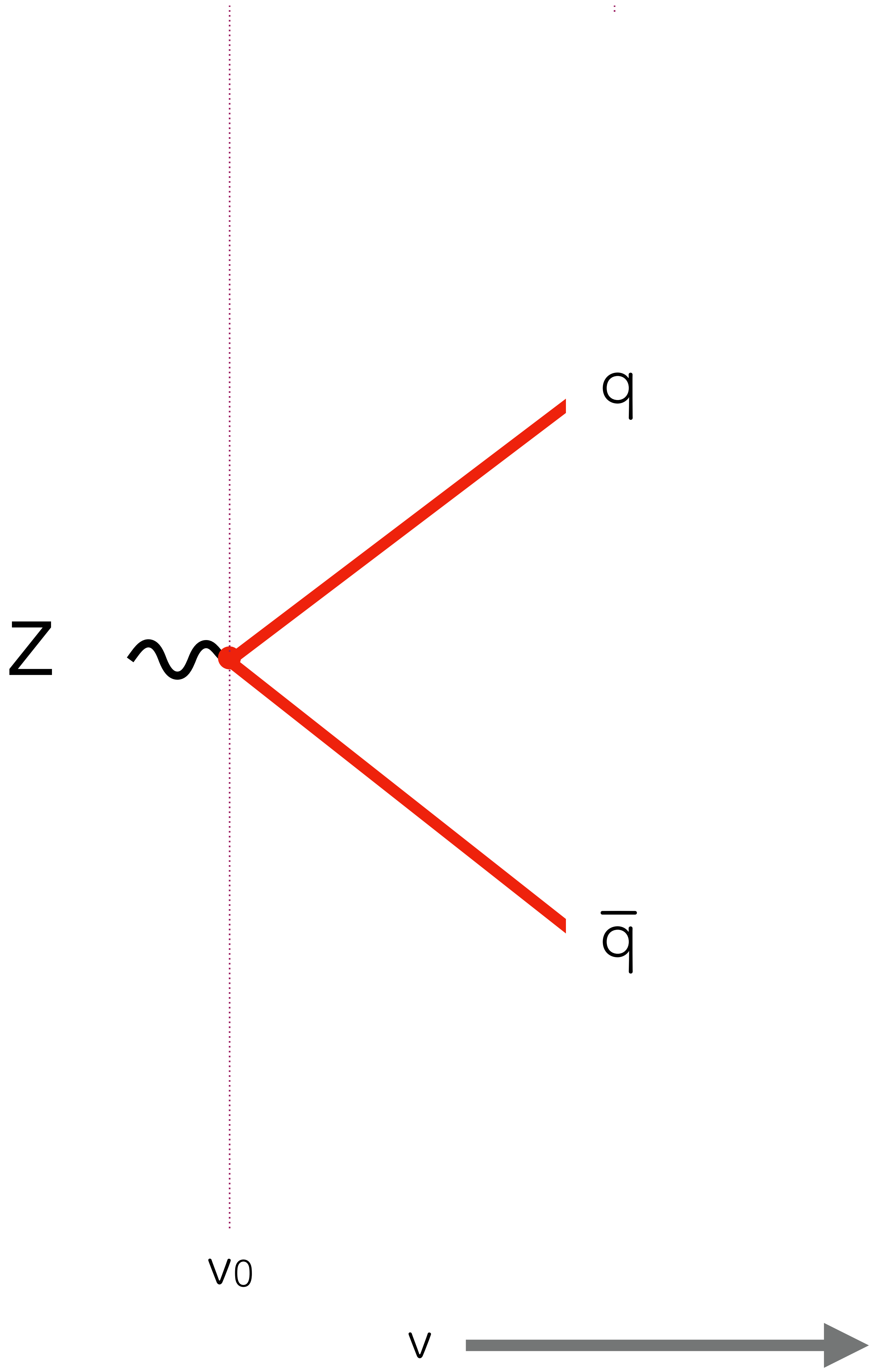


Start with $q\bar{q}$ state.

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

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

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

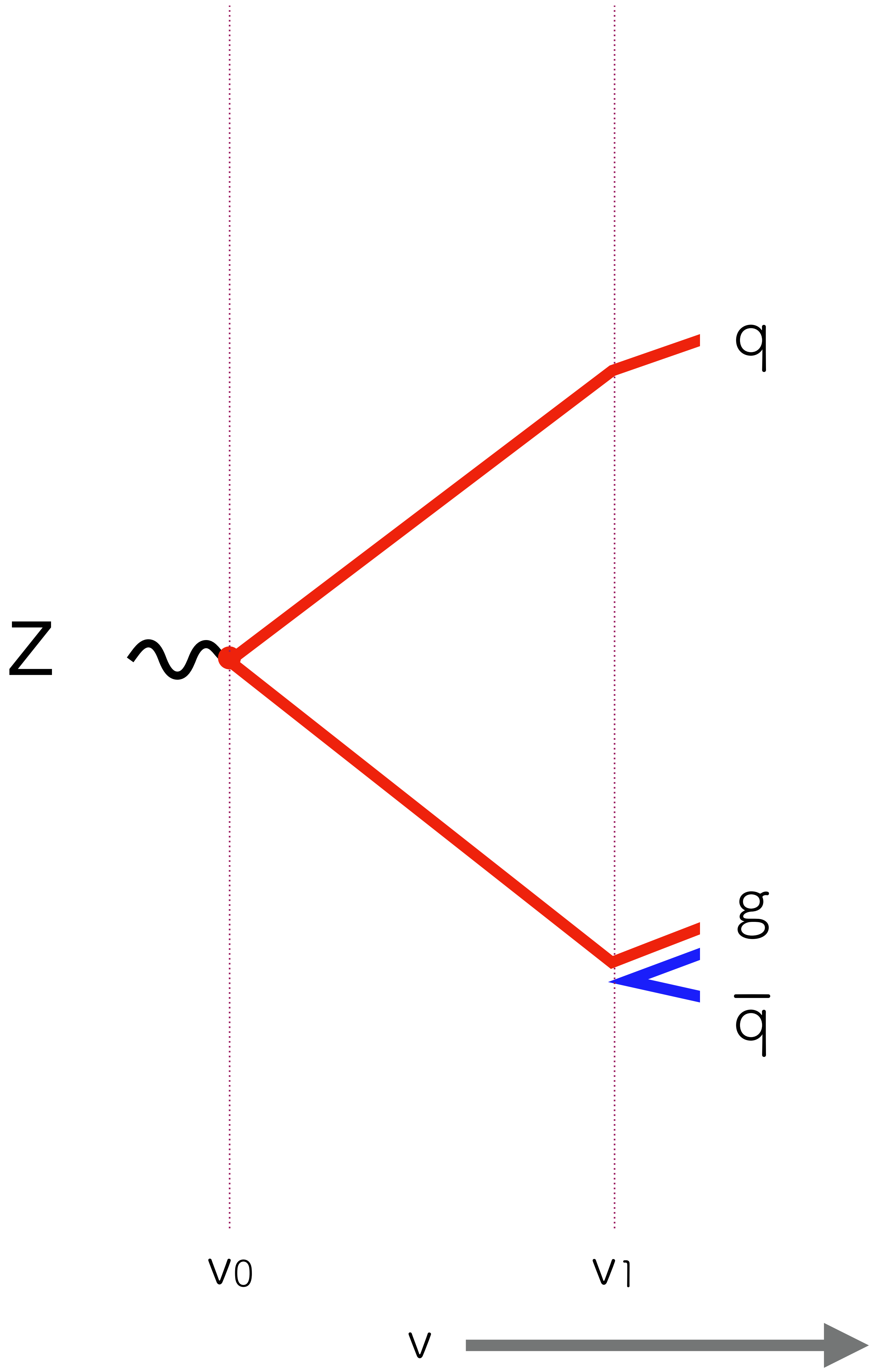


Start with q-qbar state.

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



Start with q-qbar state.

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

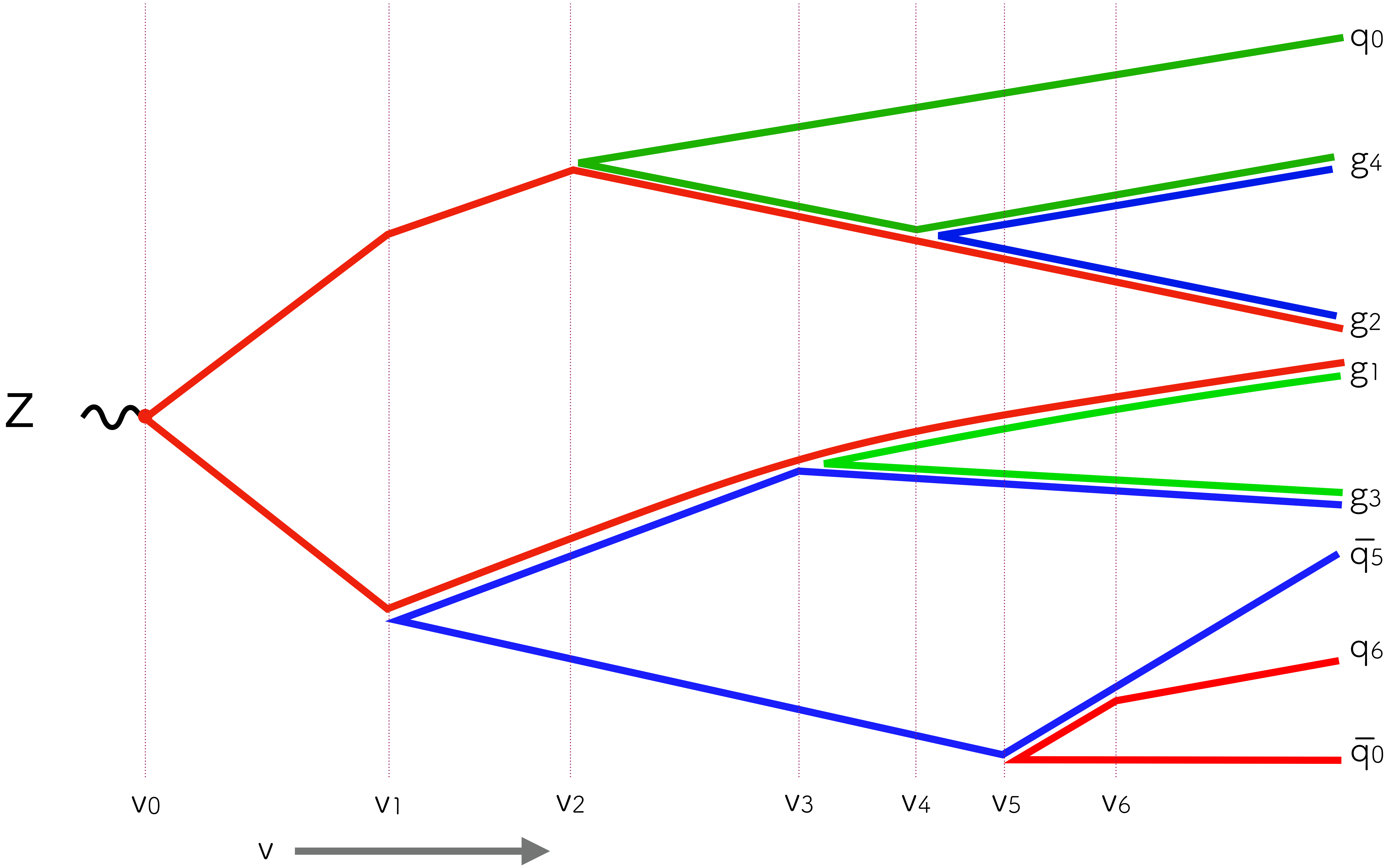
At some point, **state splits** (2→3, i.e. emits gluon). Evolution equation changes

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

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

(many showers use a large N_C limit)

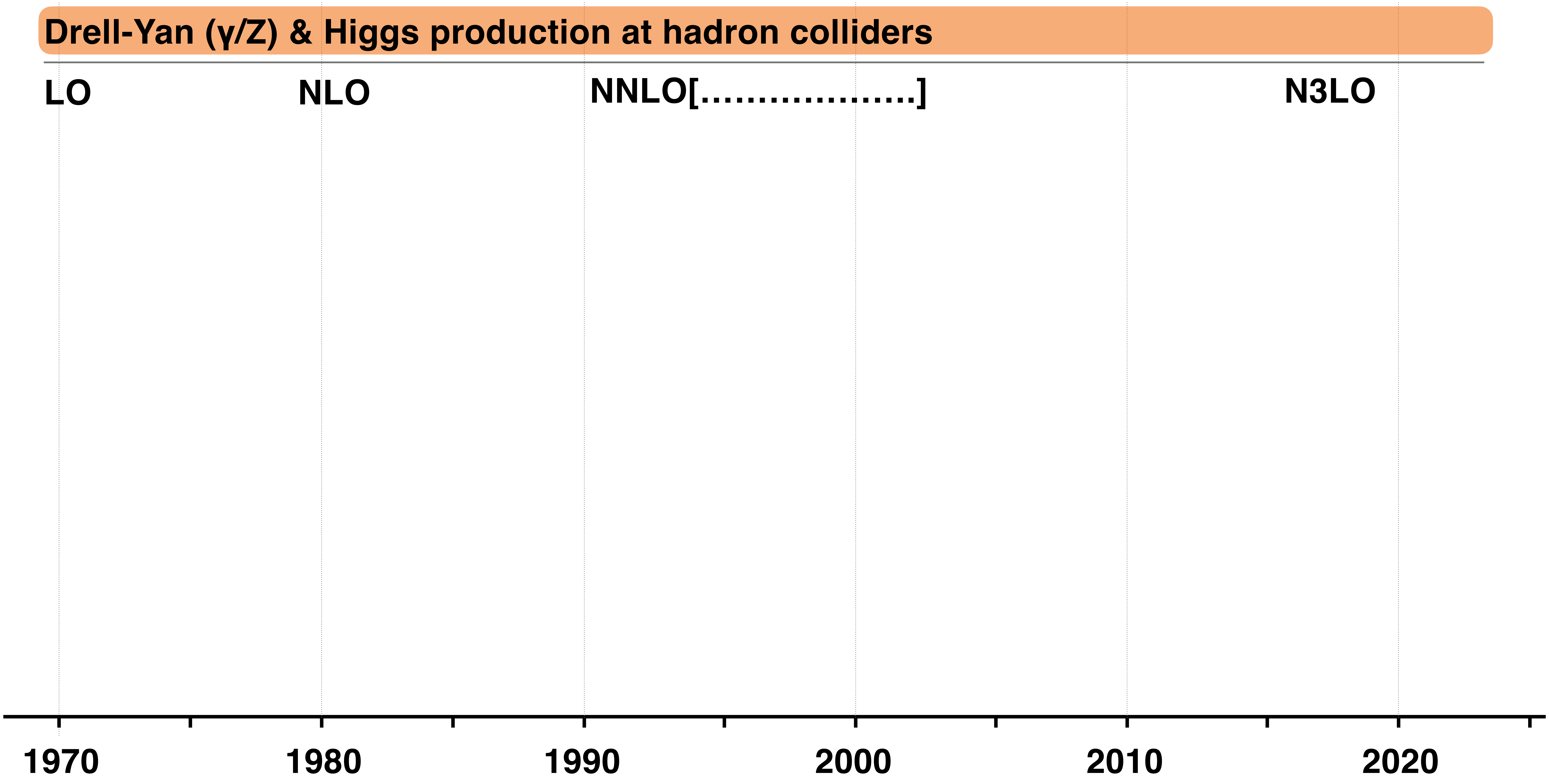
QCD **parton shower**: an evolution equation (in **evolution scale v**, e.g. trans.mom.)



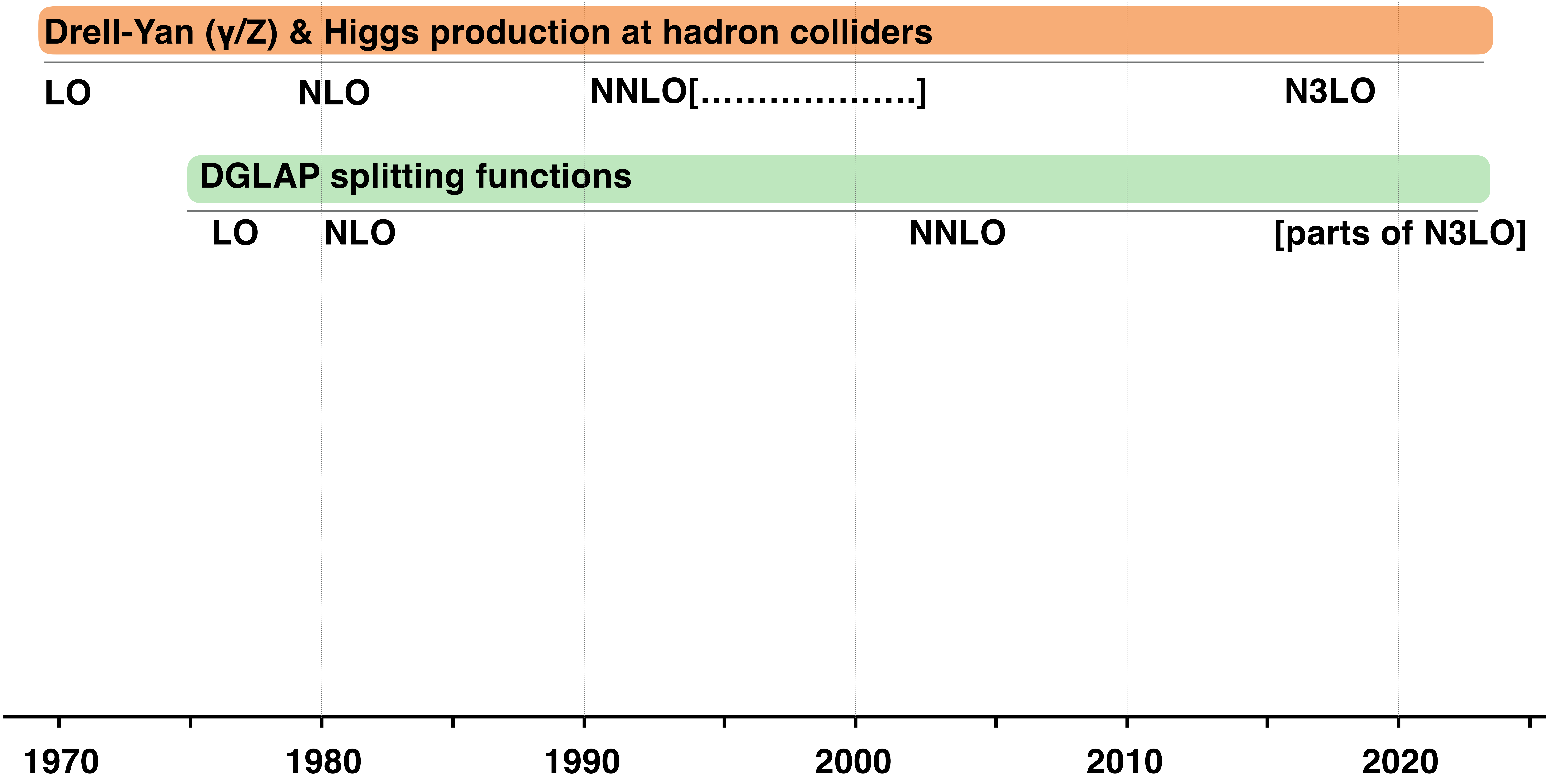
self-similar evolution continues until it reaches a non-perturbative scale

(made tractable in part by large-N_C limit, with non-interfering colour dipoles)

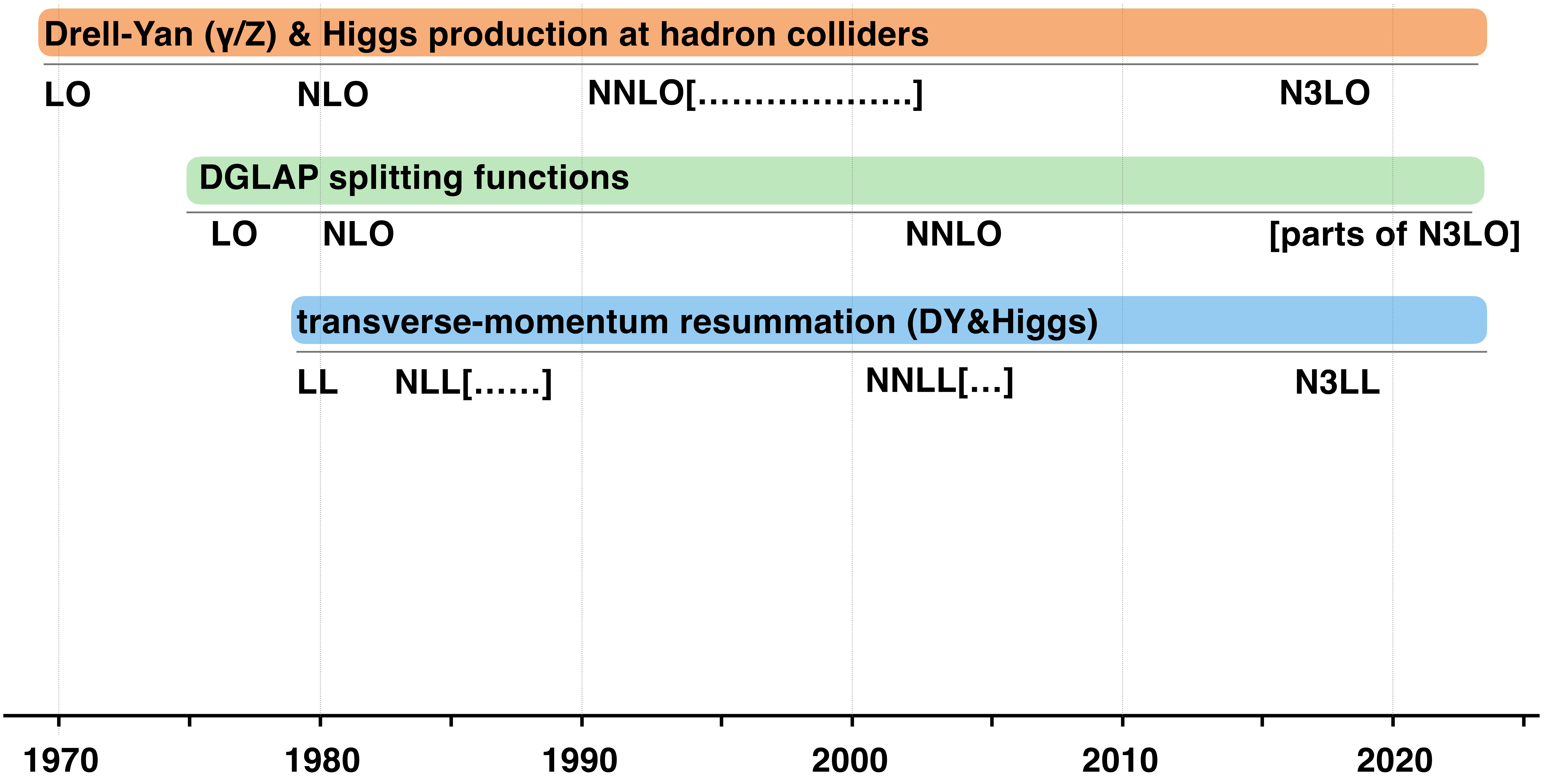
selected collider-QCD accuracy milestones



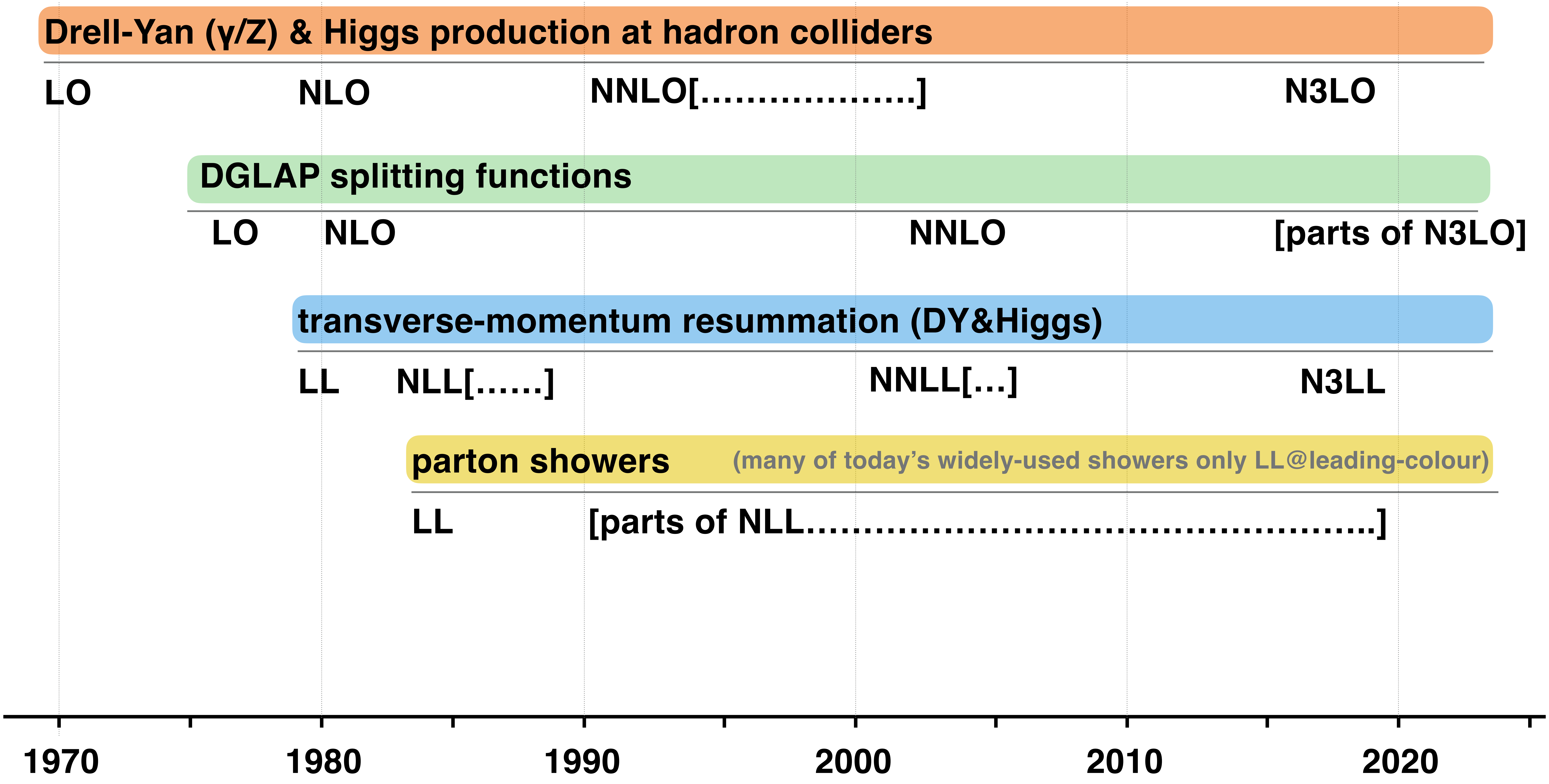
selected collider-QCD accuracy milestones



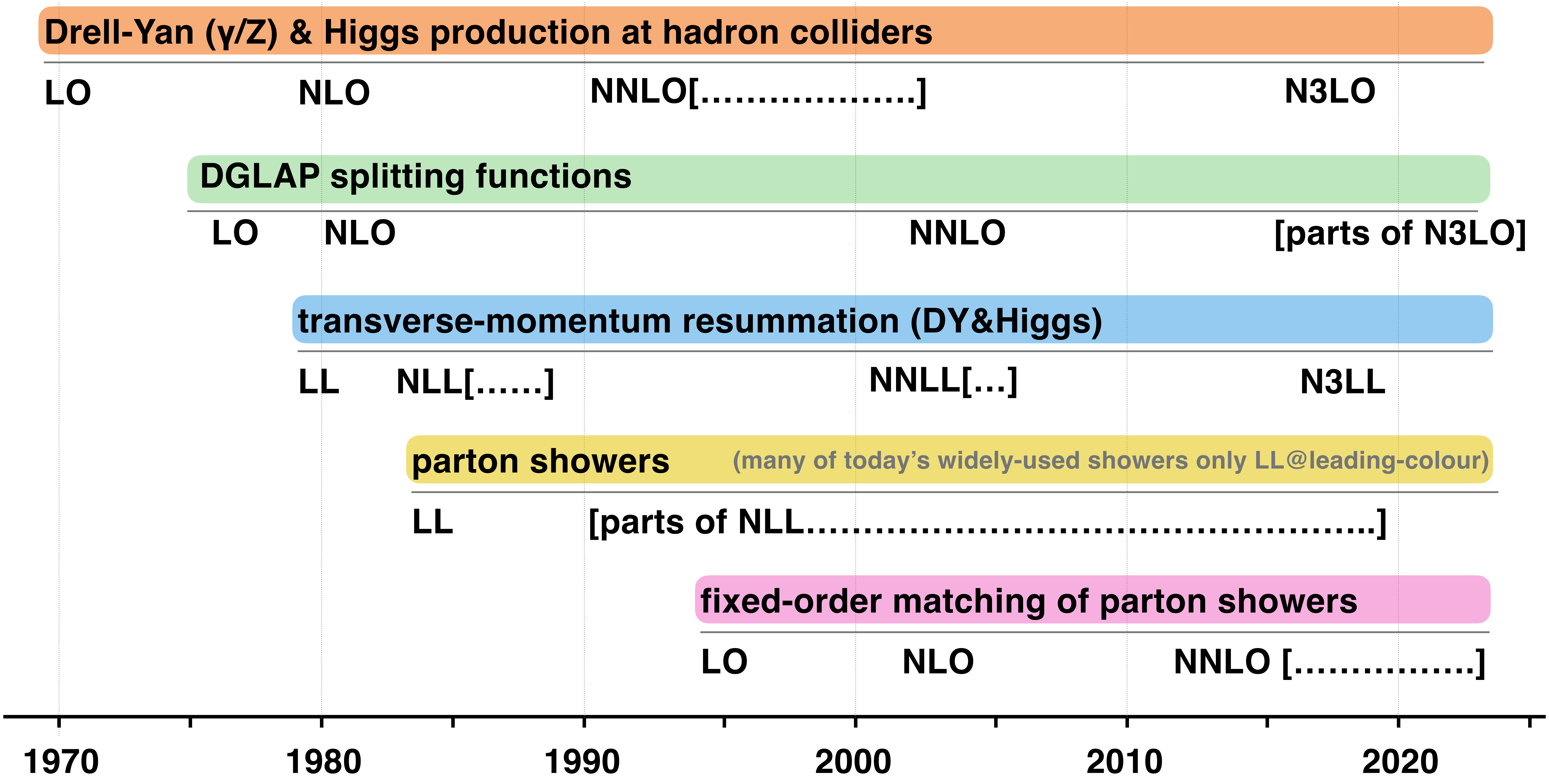
selected collider-QCD accuracy milestones



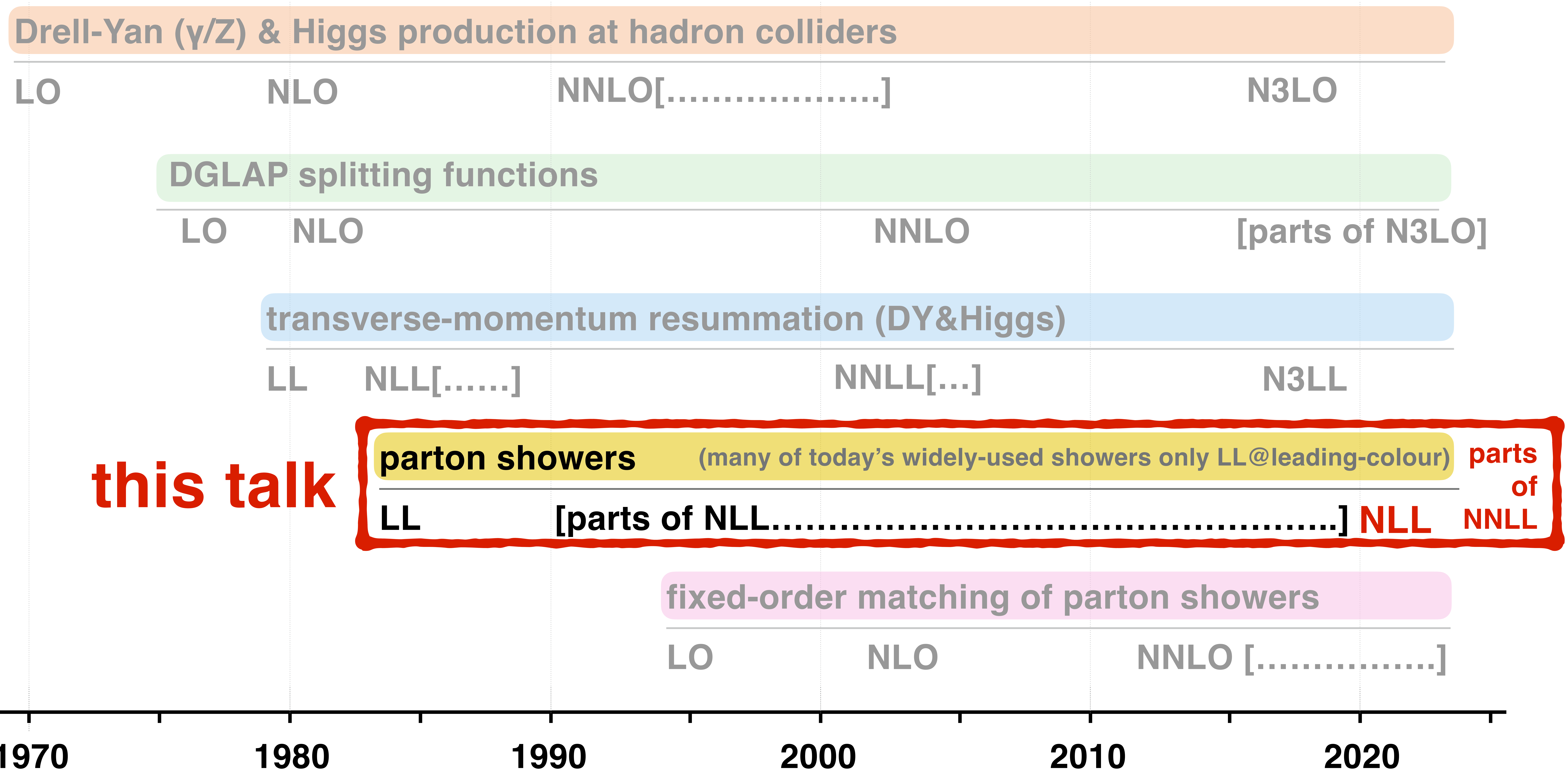
selected collider-QCD accuracy milestones



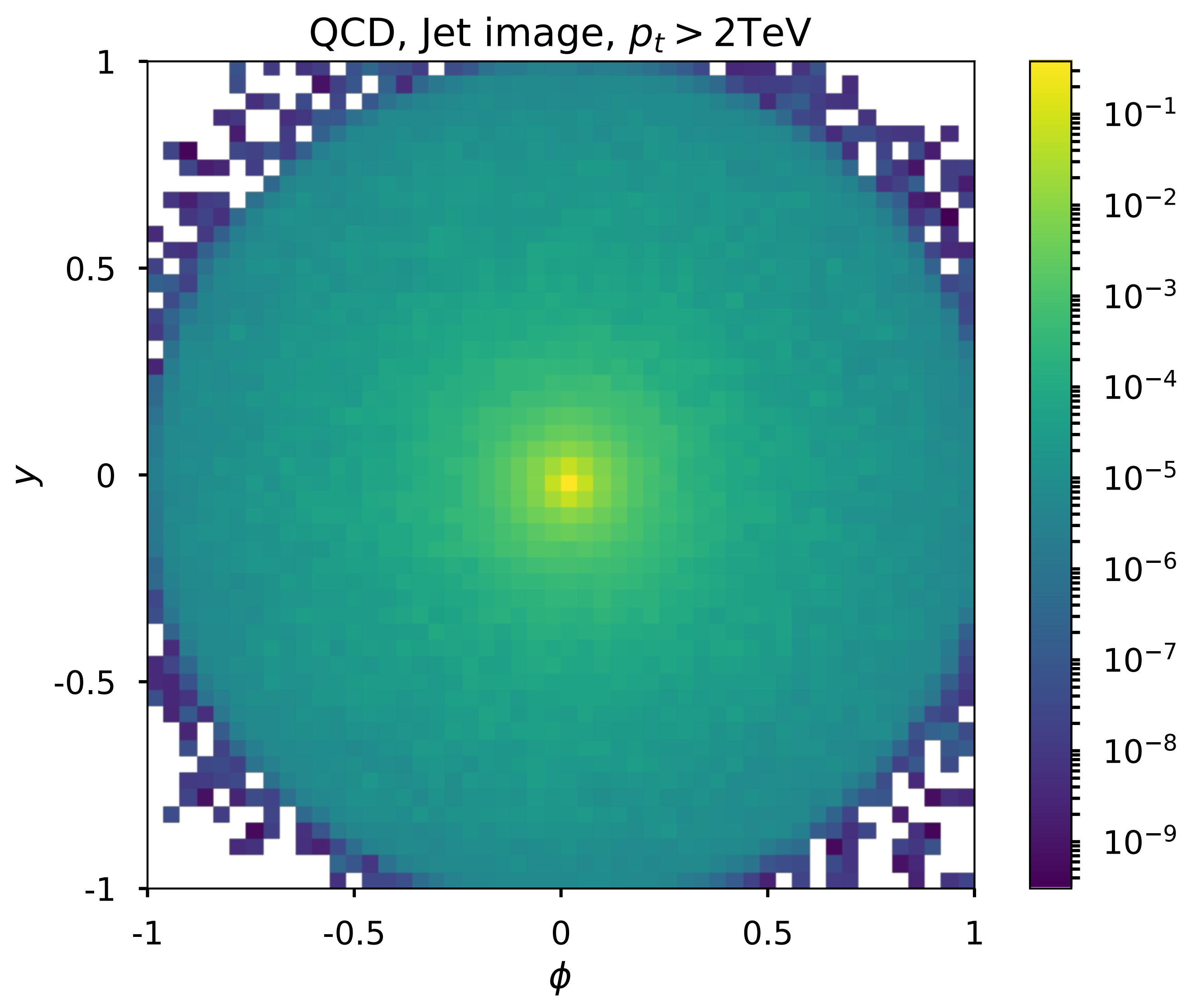
selected collider-QCD accuracy milestones



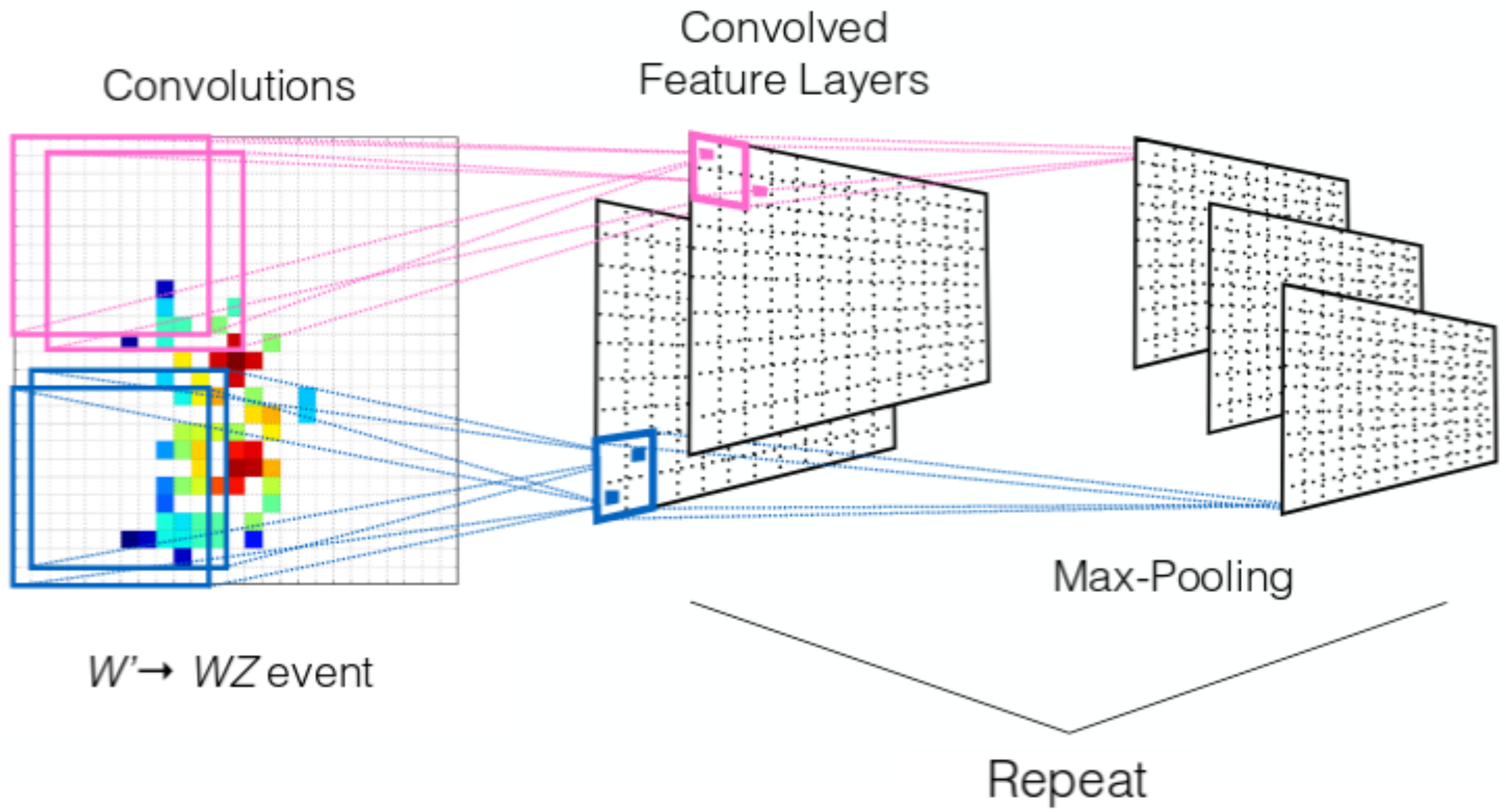
selected collider-QCD accuracy milestones



Machine learning and jet/event structure

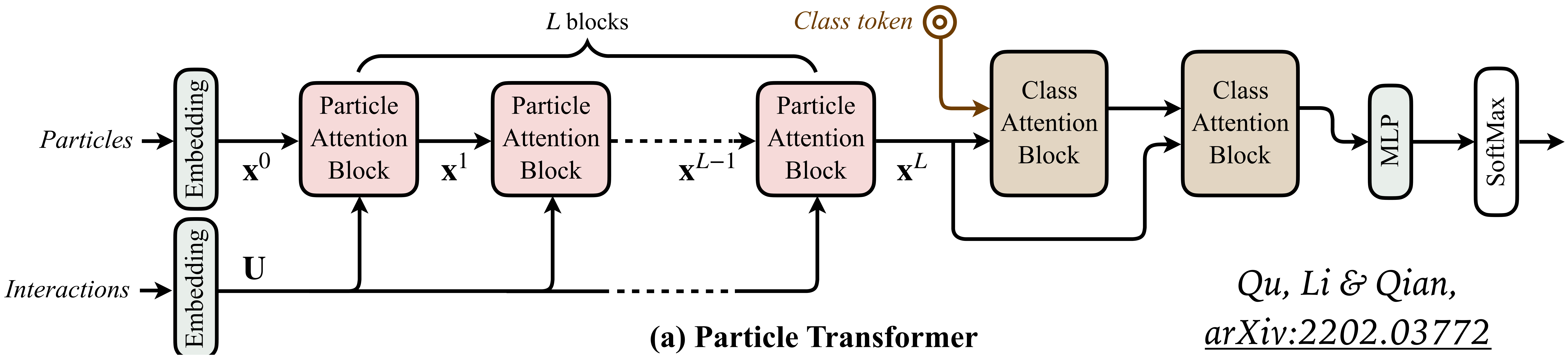


2021 Young Experimental Physicist
EPS HEPP prize



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

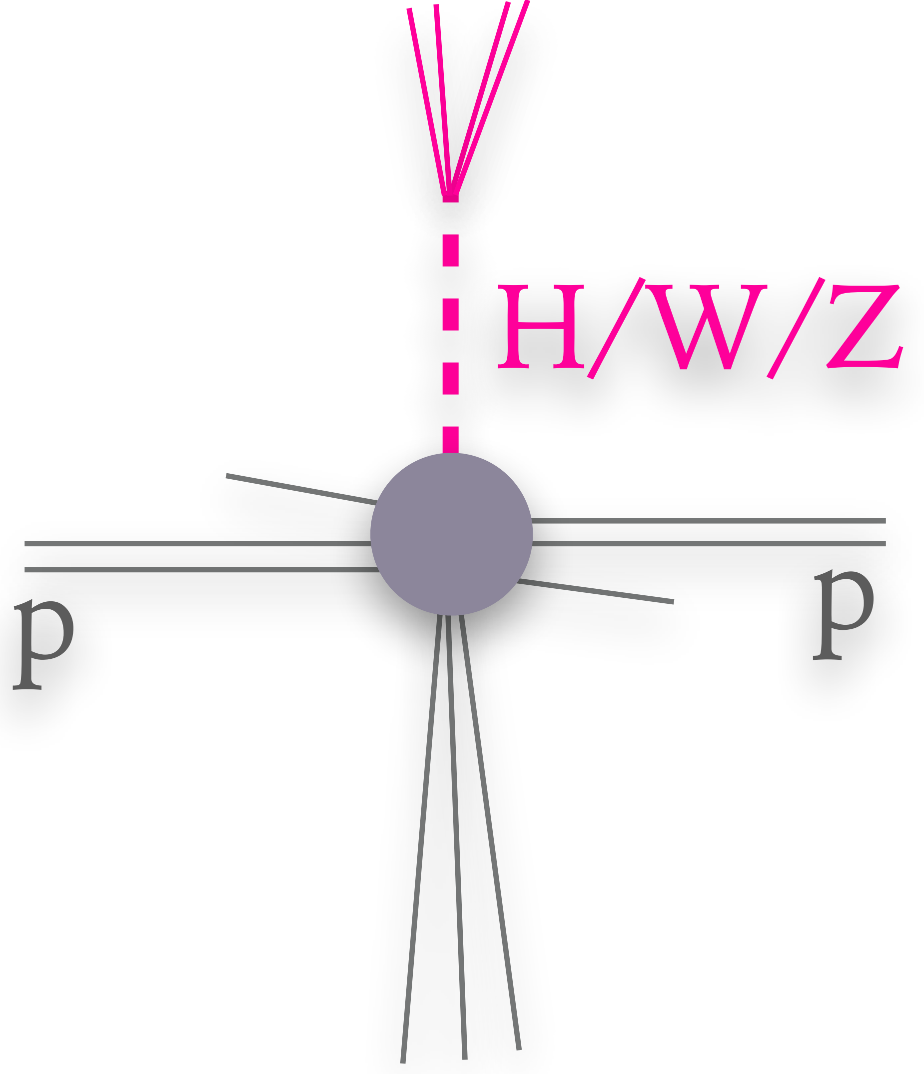
[de Oliveira, Kagan, Mackey, Nachman, Schwartzman JHEP 1607 (2016) 069]



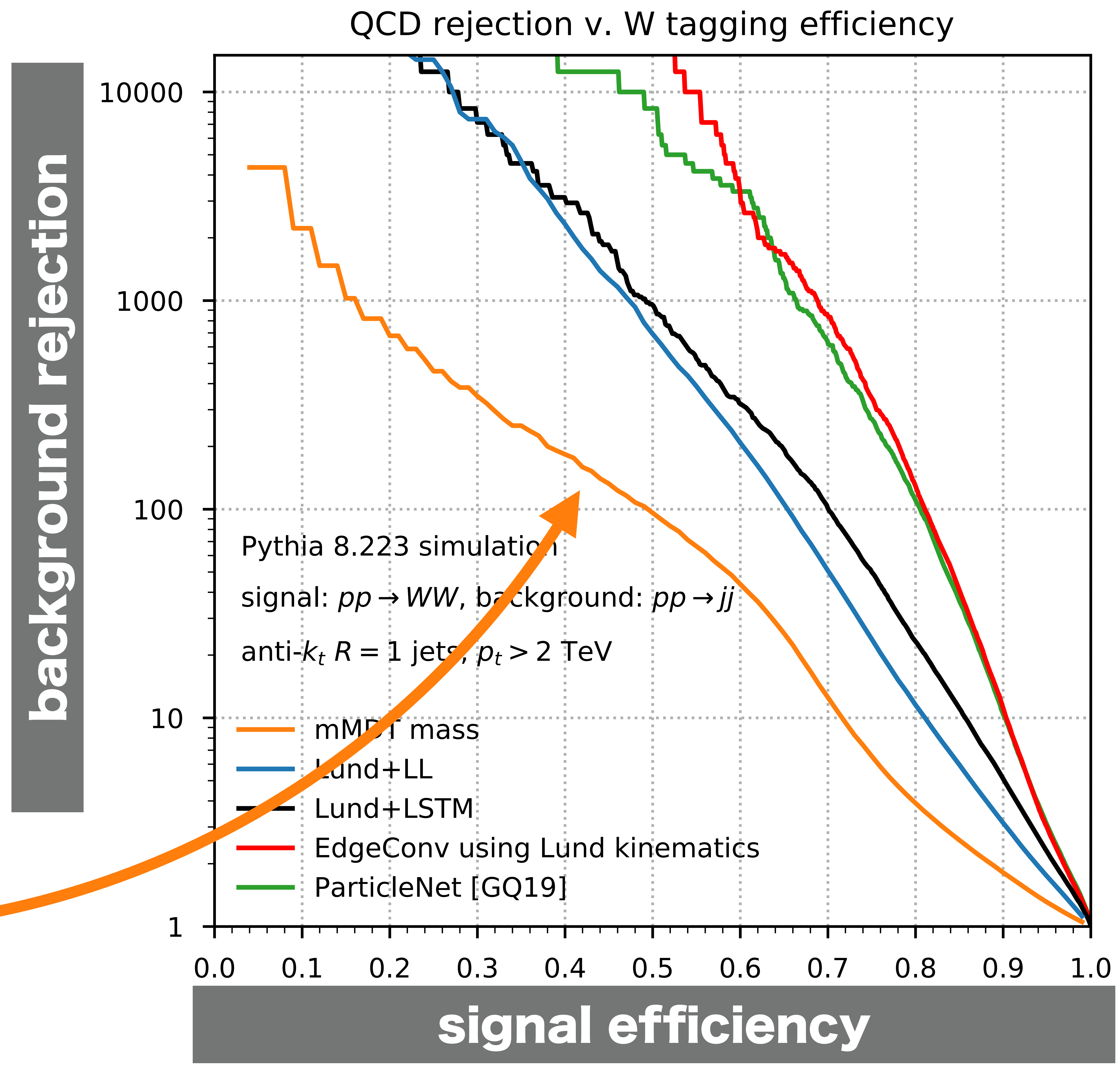
(a) Particle Transformer

Qu, Li & Qian, arXiv:2202.03772

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



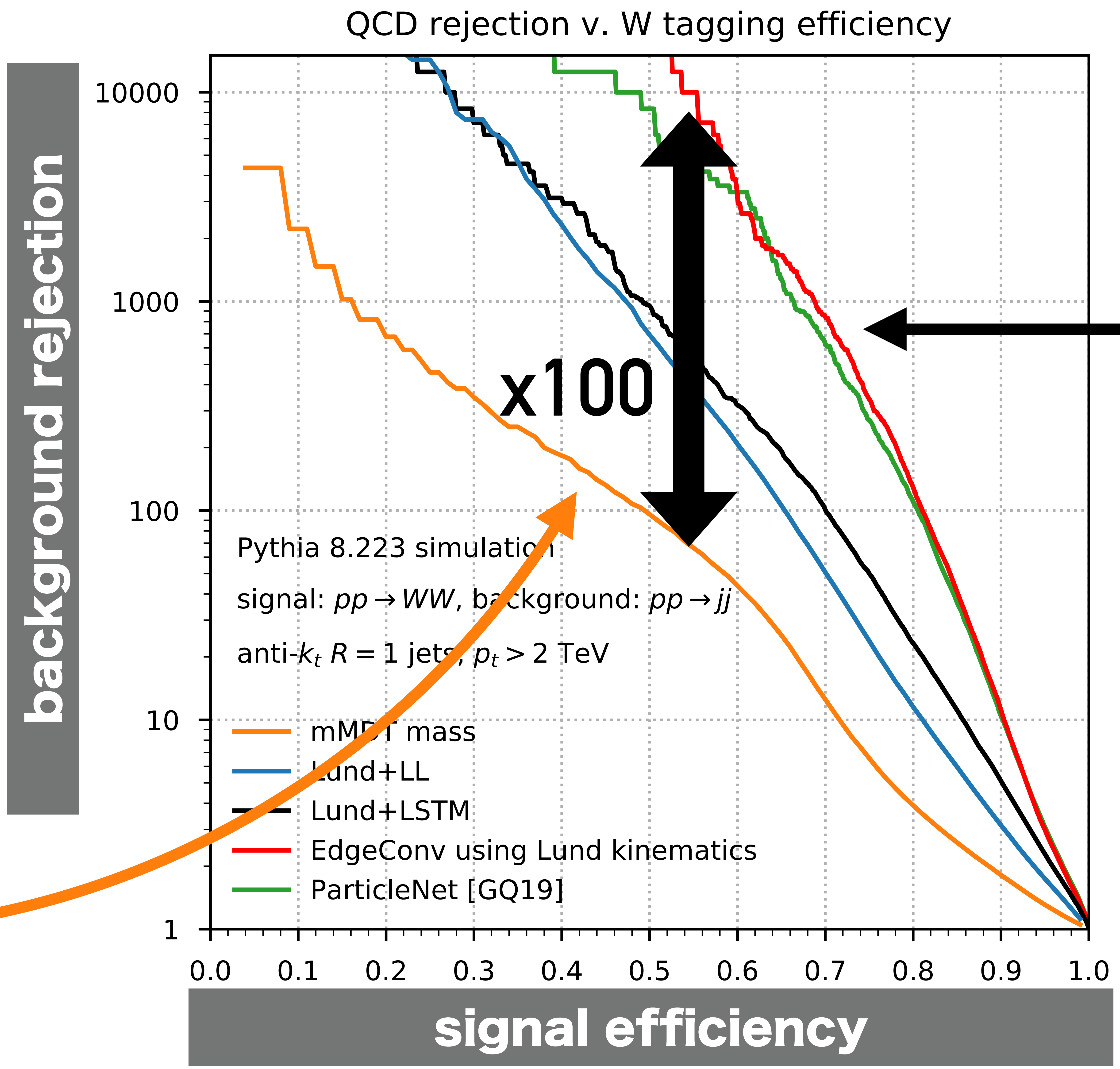
adapted from Dreyer & Qu [2012.08526](#)

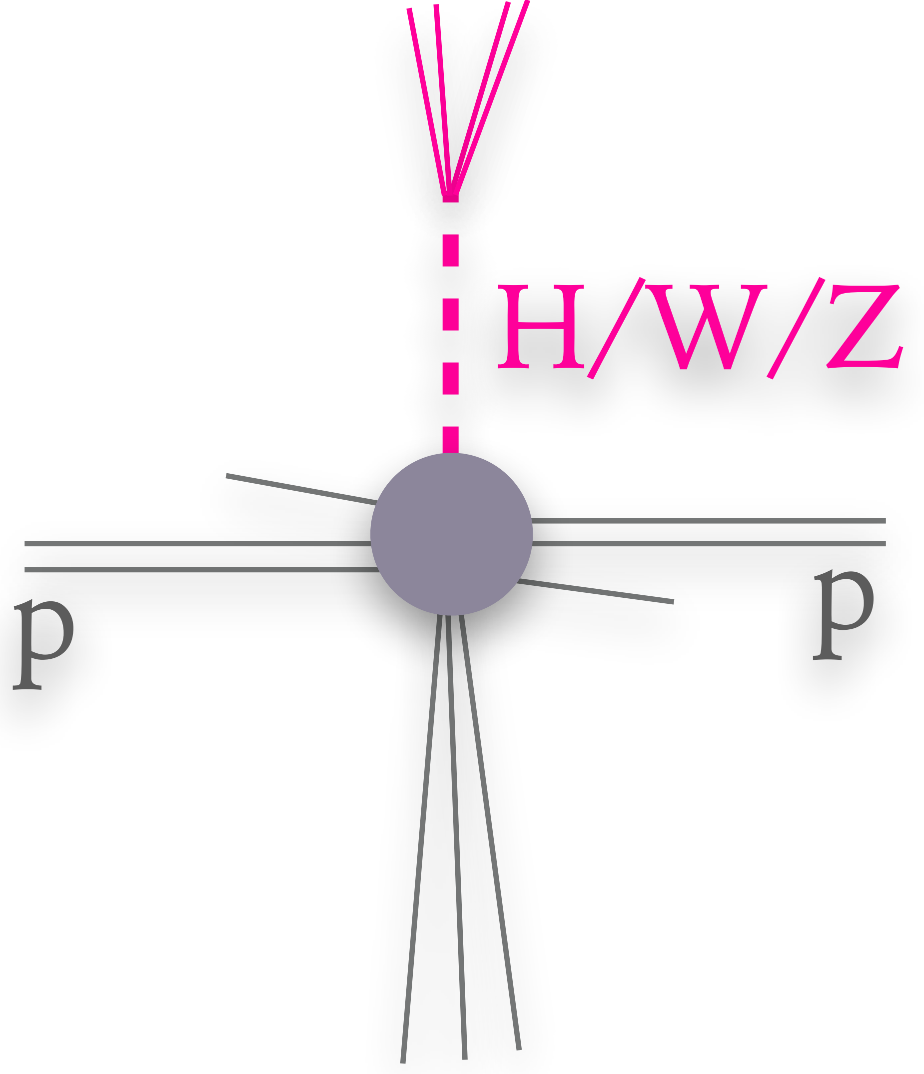


QCD rejection with just jet mass (SD/mMDT) i.e. 2008 tools & their 2013/14 descendants

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

adapted from Dreyer & Qu *2012.08526*





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

100x better

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

First started to be exploited by Thaler & Van Tilburg with "N-subjettiness" (2010/11) can we make perturbative QCD simultaneously physical and systematically improvable?

Mrinal Dasgupta
Manchester

Keith Hamilton
Univ. Coll. London

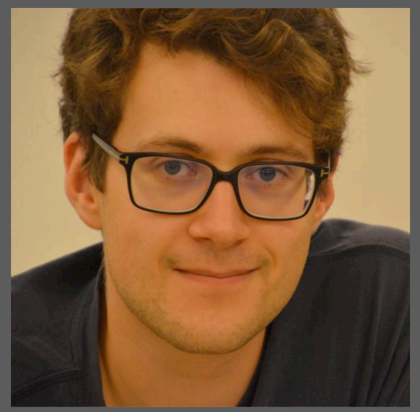
Pier Monni
CERN

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

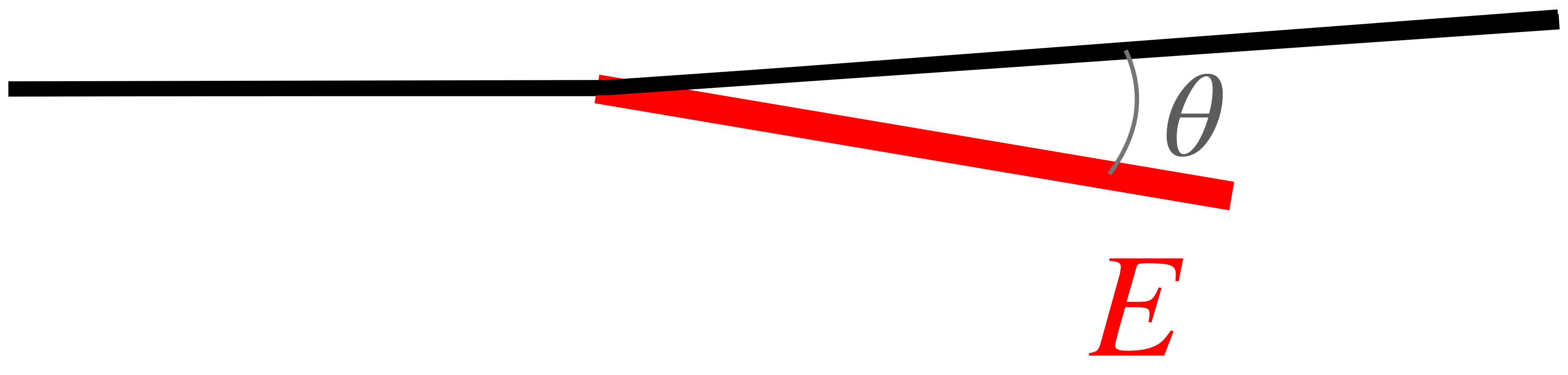
ERC funded
2018–2024

the Lund plane

organisation of phase space that highlights QCD divergences and logarithms

Original concept: B. Andersson, G. Gustafson L. Lonnblad and Pettersson, 1989
Event-by-event definition: Dreyer, GPS & Soyez, 1807.04758

Phase space: two key variables (+ azimuth)

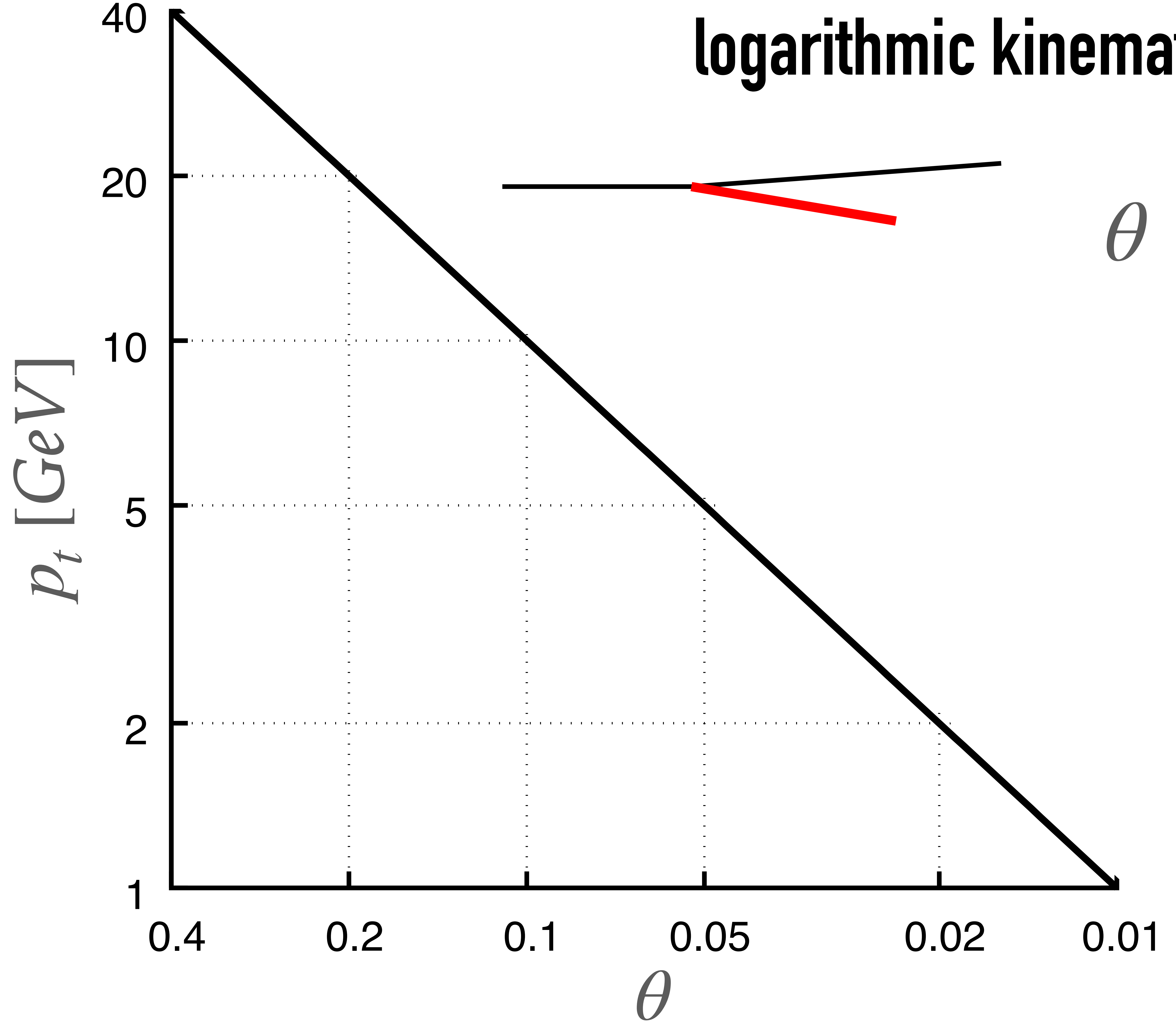


$\theta \ (or\ \eta = -\ln\tan\frac{\theta}{2})$ — *η is called (pseudo)rapidity*

$p_t = E\theta$ — *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

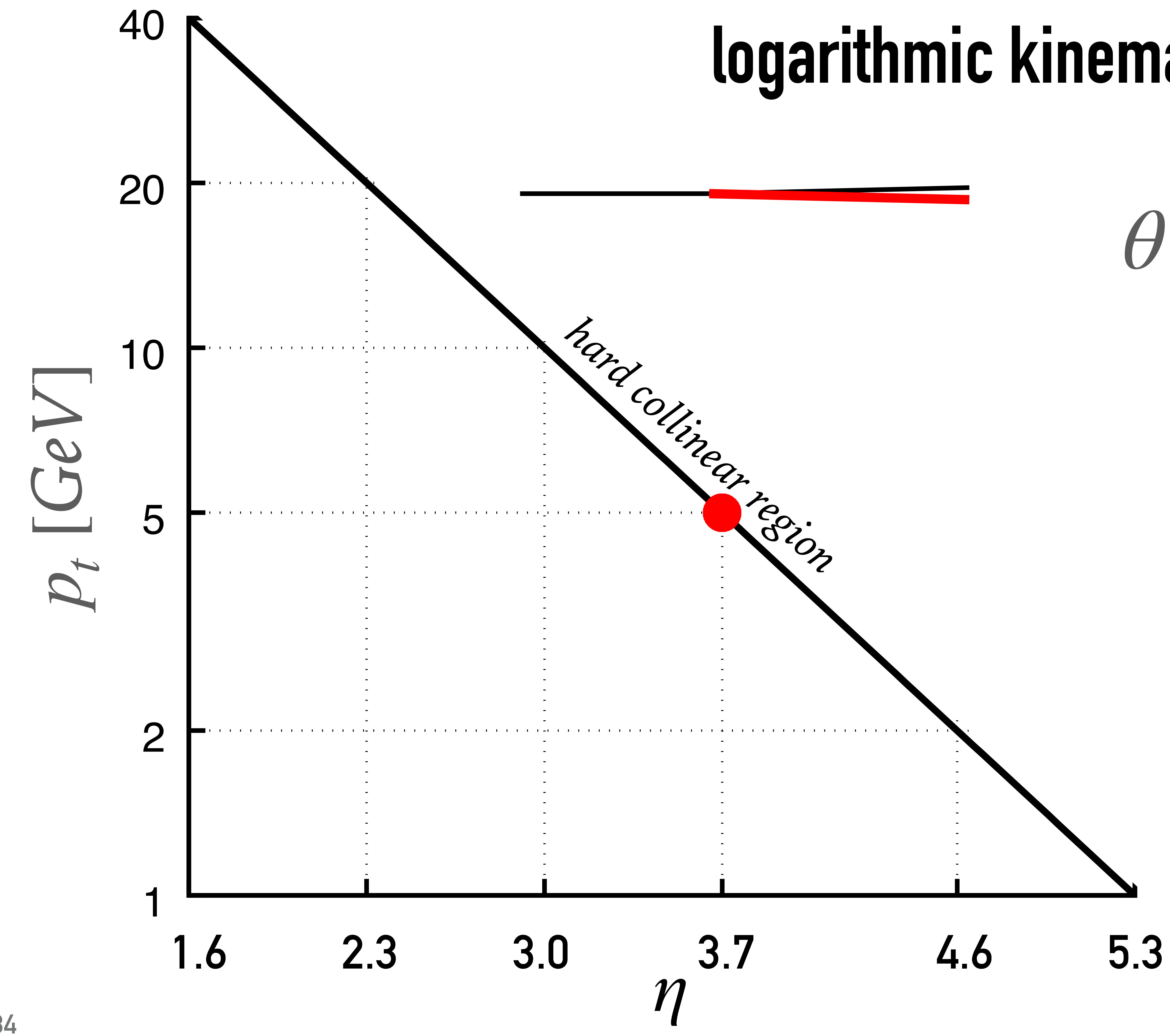
$$\theta \ (or\ \eta = -\ln\tan\frac{\theta}{2})$$

$$p_t = E\theta$$

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*



logarithmic kinematic plane whose two variables are

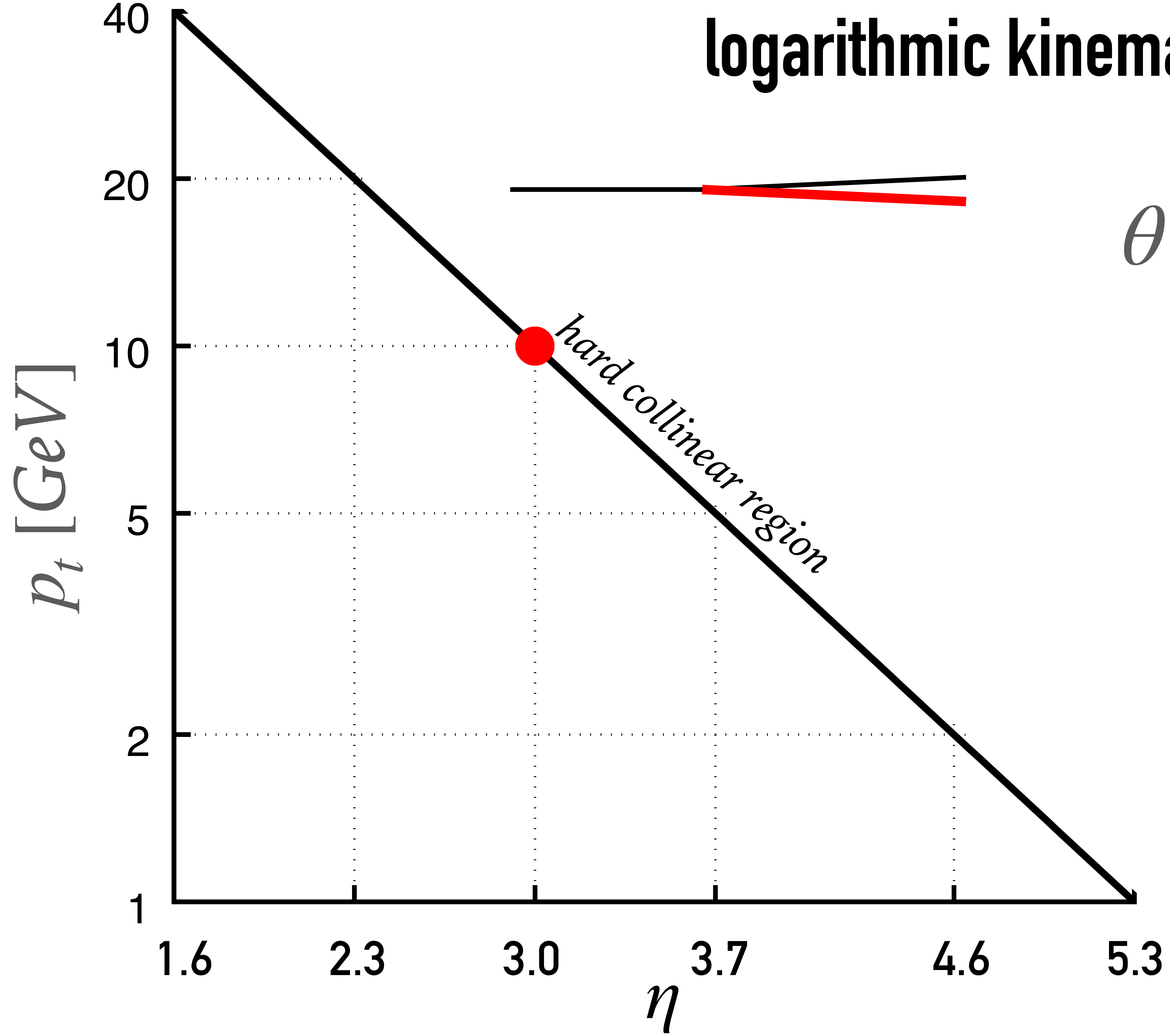
$$\theta \ (or \ \eta = -\ln \tan \frac{\theta}{2})$$

$$p_t = E\theta$$

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*



logarithmic kinematic plane whose two variables are

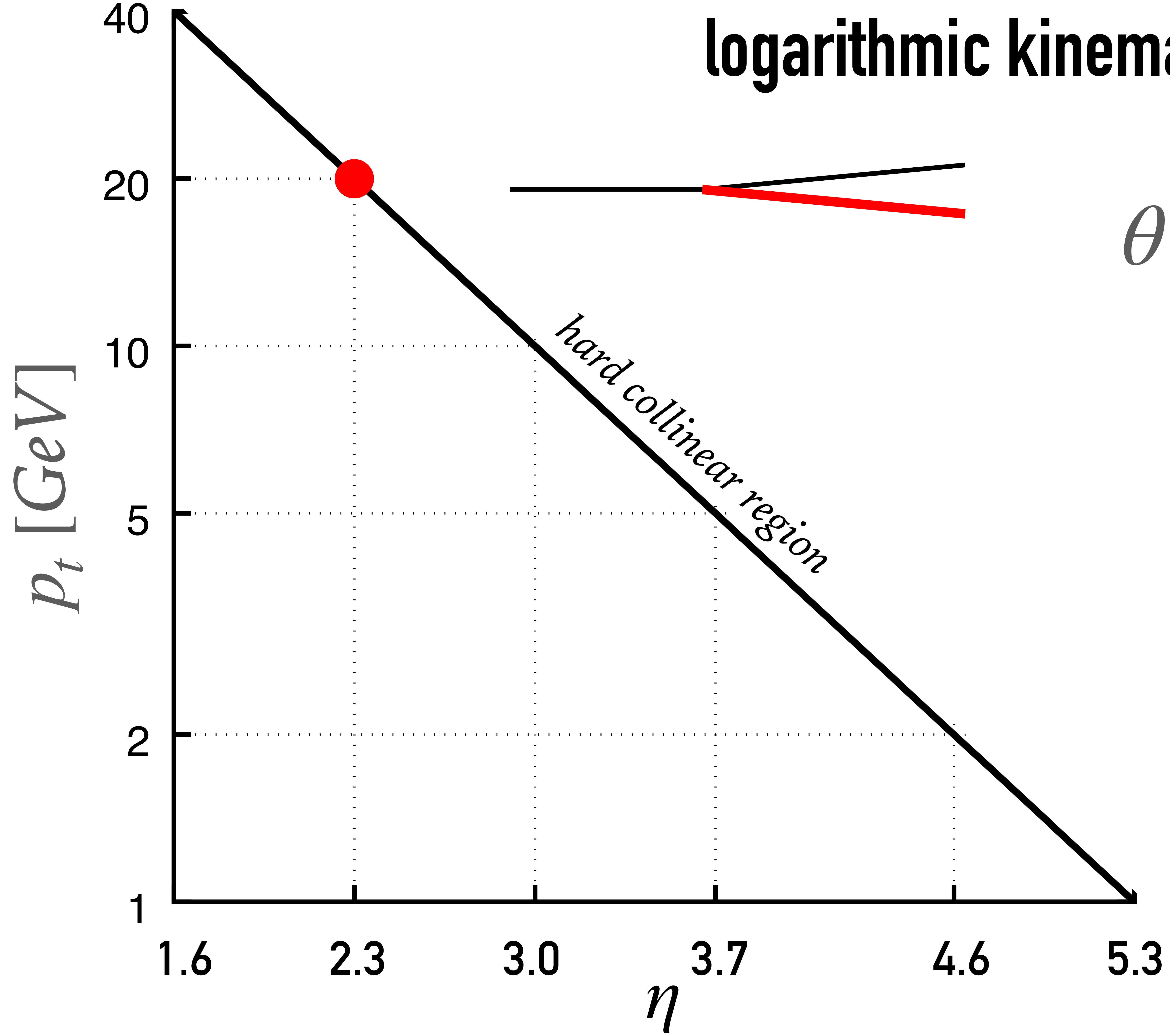
$$\theta \ (or\ \eta = -\ln\tan\frac{\theta}{2})$$

$$p_t = E\theta$$

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*



logarithmic kinematic plane whose two variables are

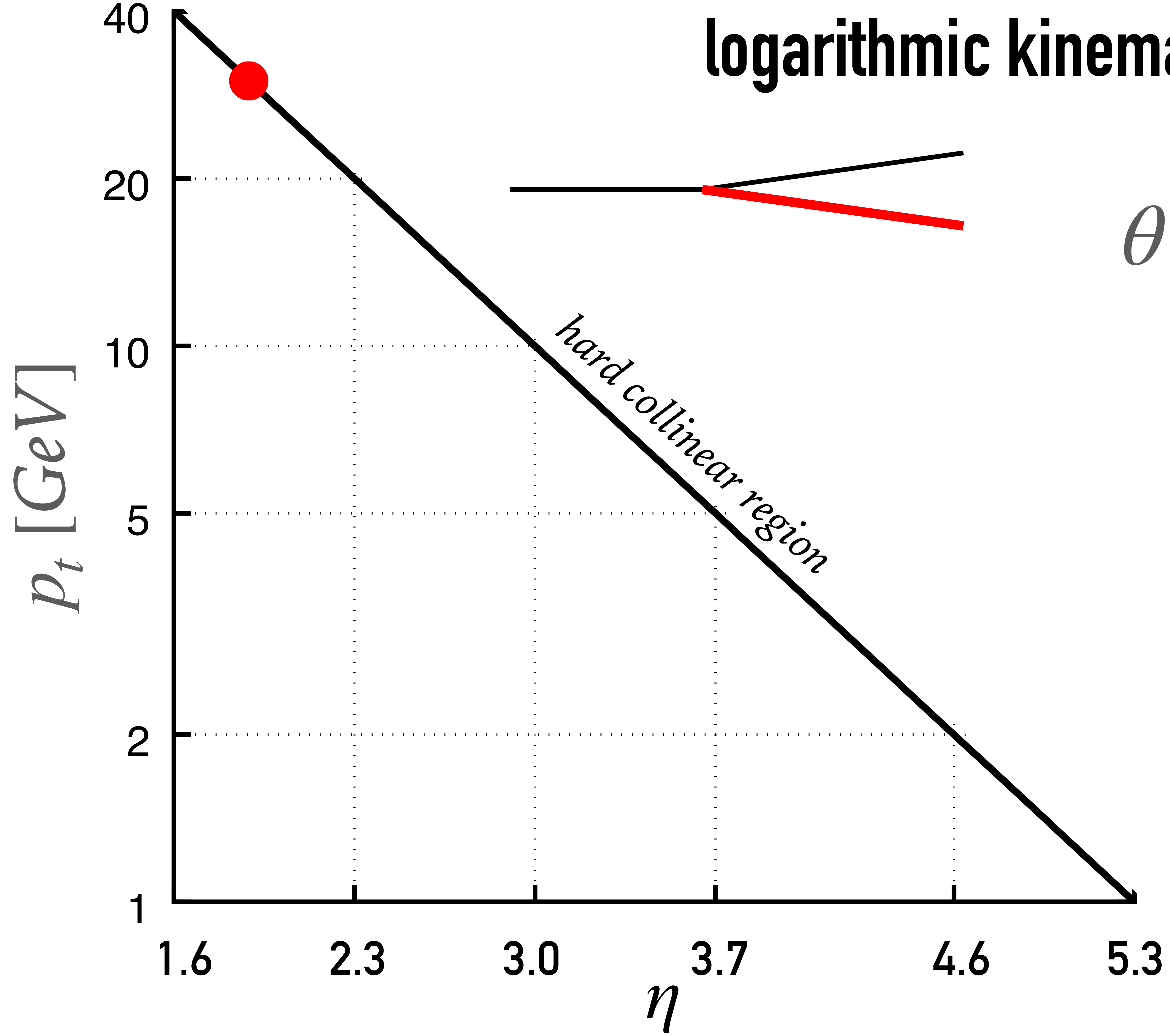
$$\theta \ (or\ \eta = -\ln\tan\frac{\theta}{2})$$

$$p_t = E\theta$$

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



logarithmic kinematic plane whose two variables are

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

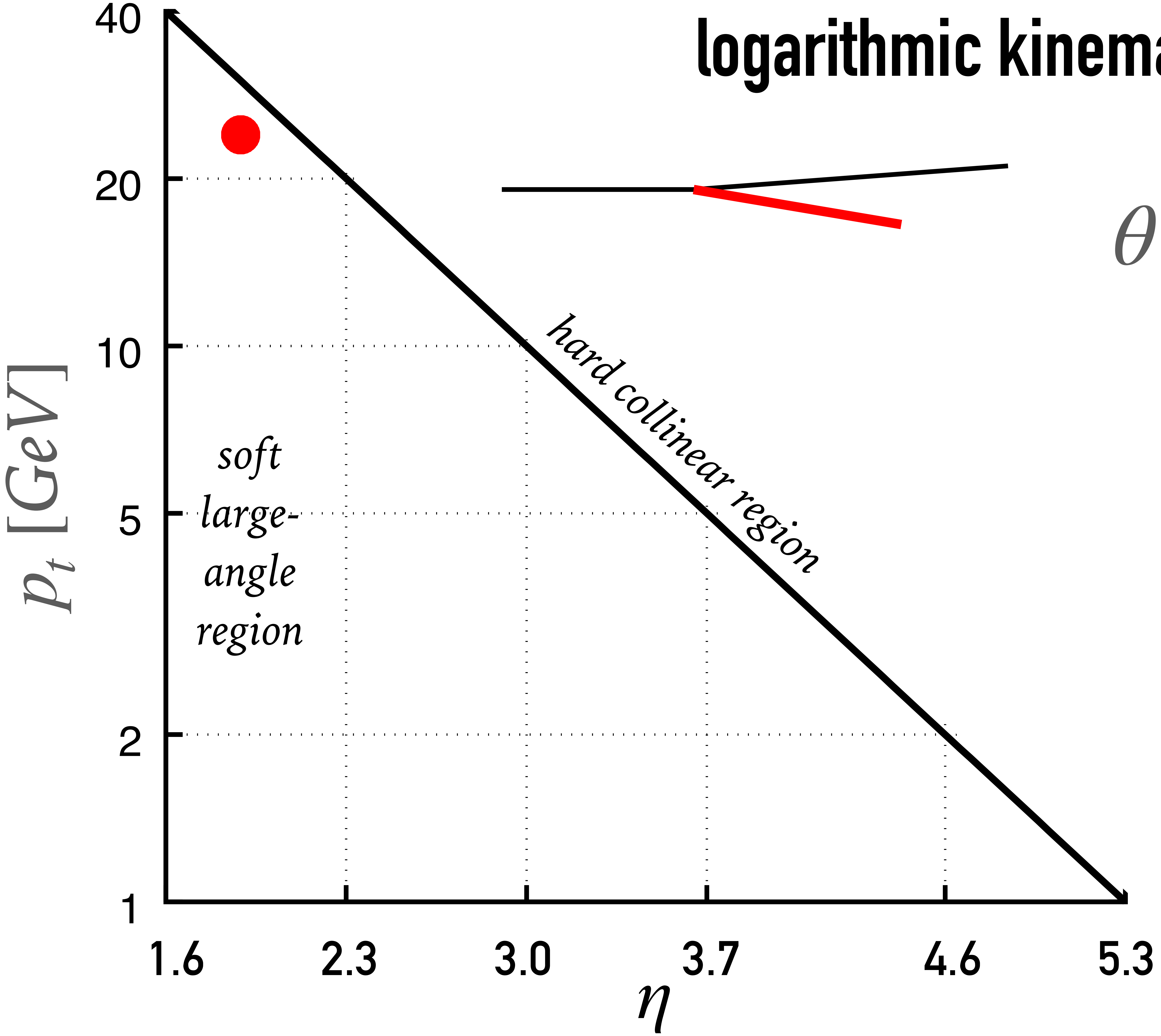
$$p_t = E\theta$$

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

The Lund Plane

The Lund Plane

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



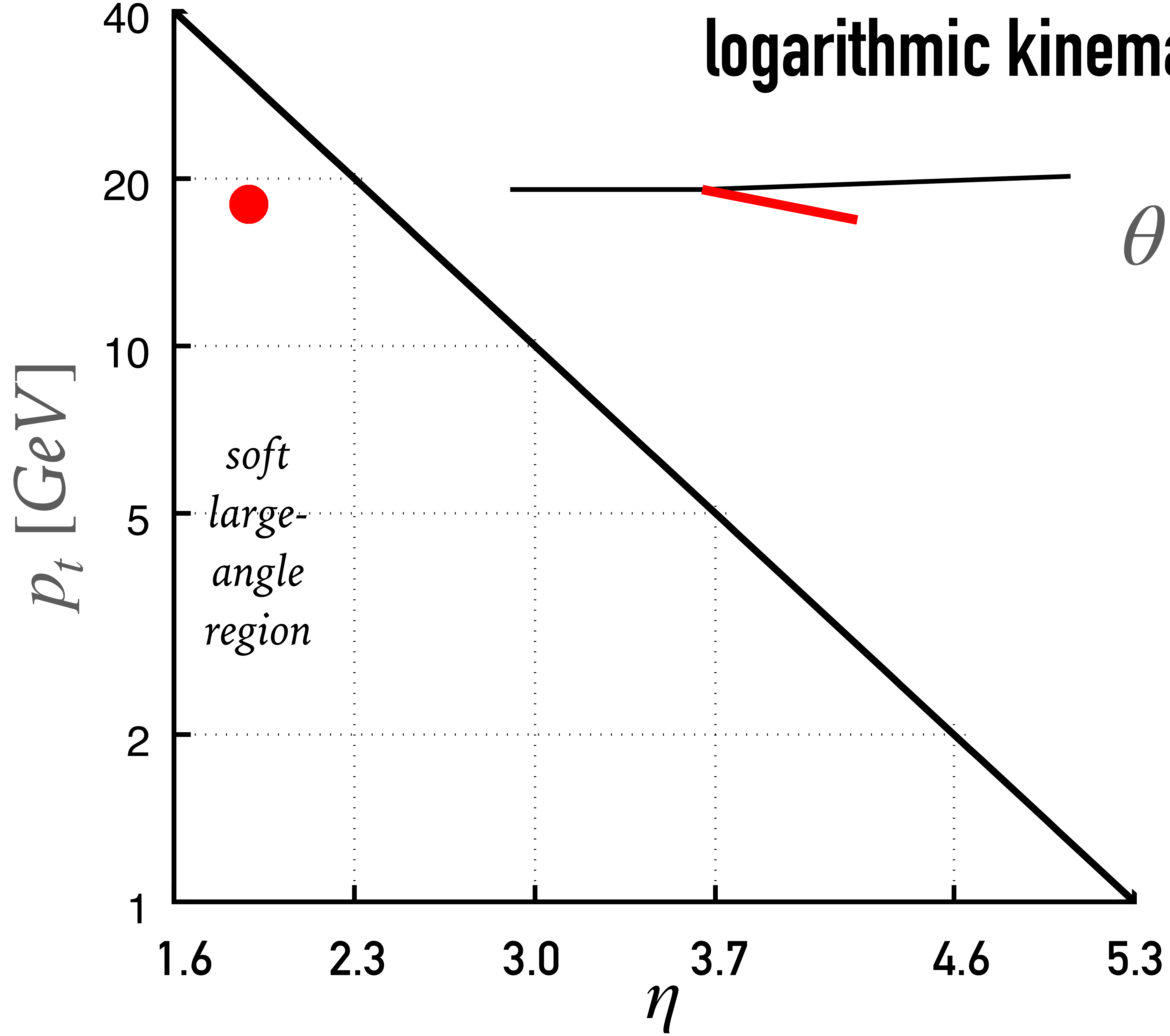
logarithmic kinematic plane whose two variables are

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

$$p_t = E\theta$$

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

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



logarithmic kinematic plane whose two variables are

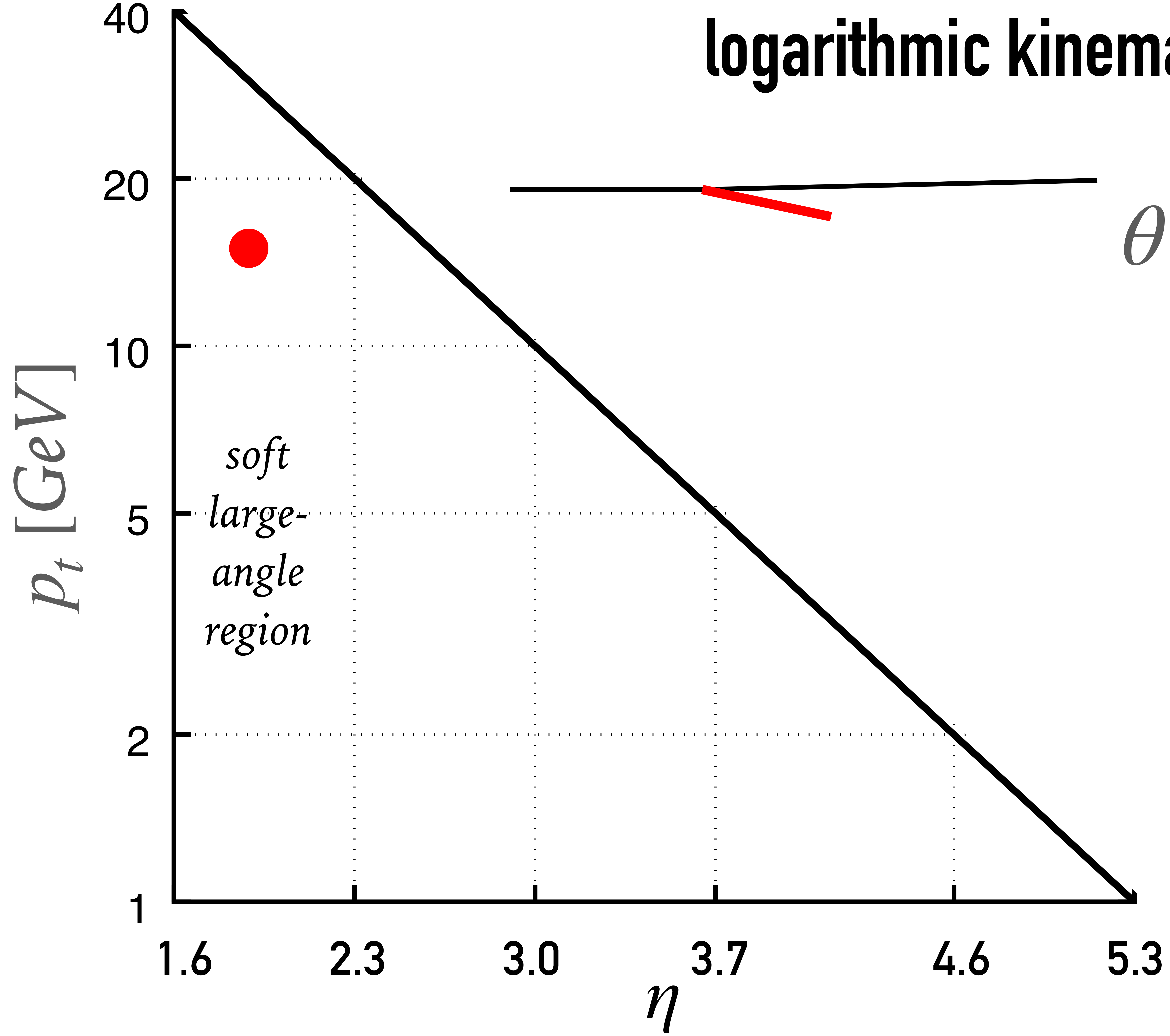
$$\theta \ (or\ \eta = -\ln \tan \frac{\theta}{2})$$

$$p_t = E\theta$$

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



logarithmic kinematic plane whose two variables are

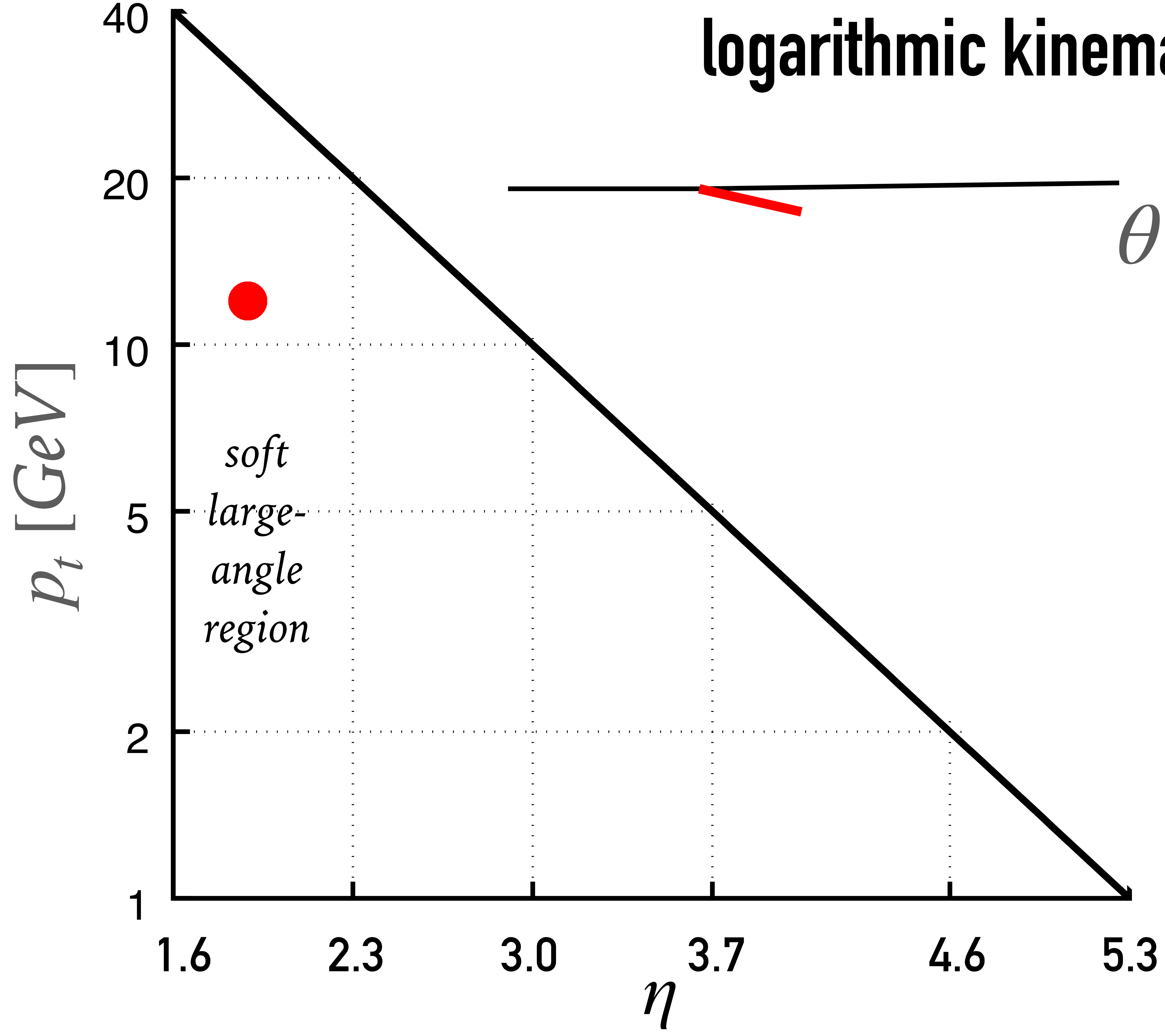
$$\theta \ (or\ \eta = -\ln\tan\frac{\theta}{2})$$

$$p_t = E\theta$$

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*



logarithmic kinematic plane whose two variables are

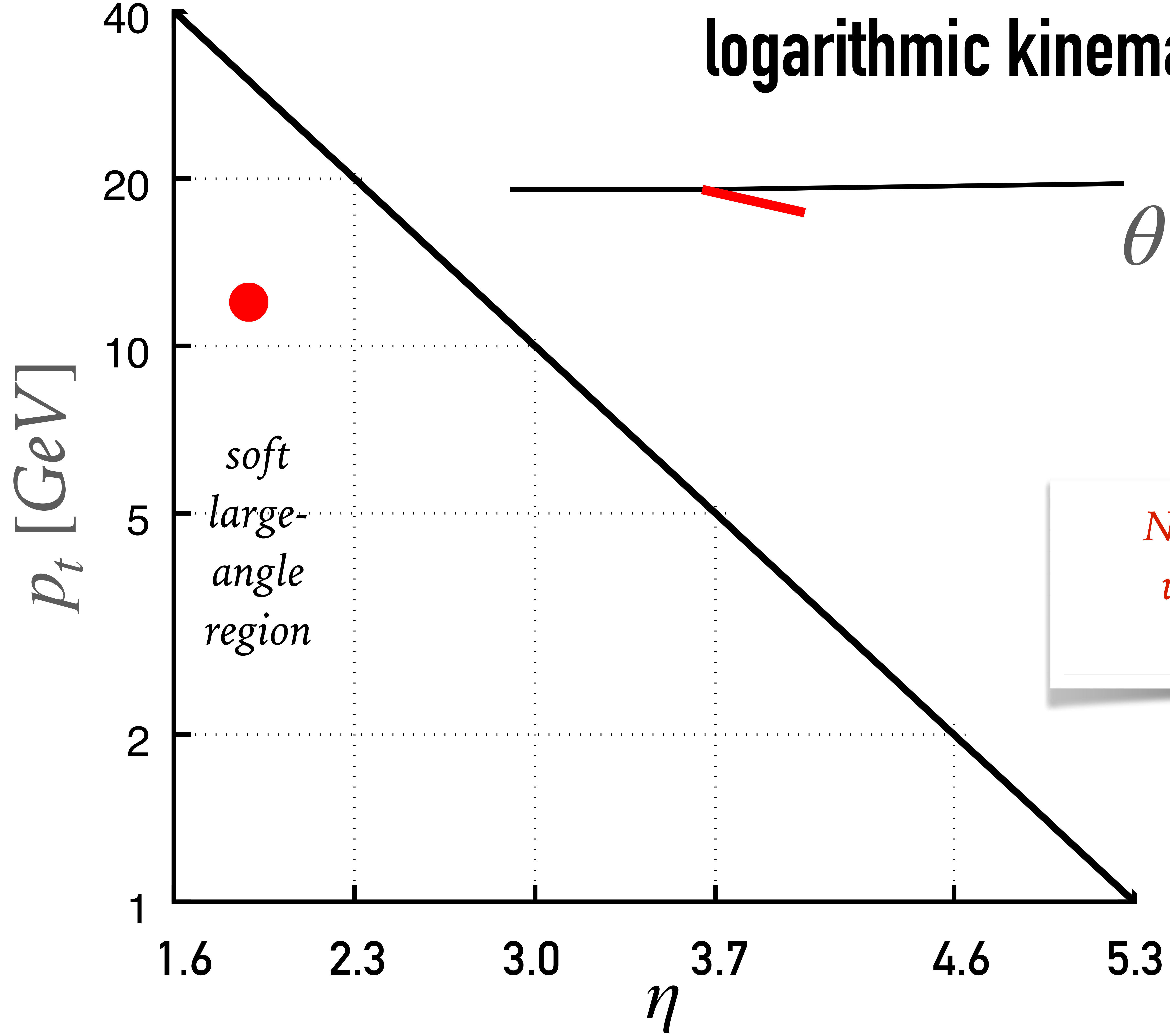
$$\theta \; (or\; \eta = -\ln \tan \frac{\theta}{2})$$

$$p_t = E\theta$$

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



logarithmic kinematic plane whose two variables are

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

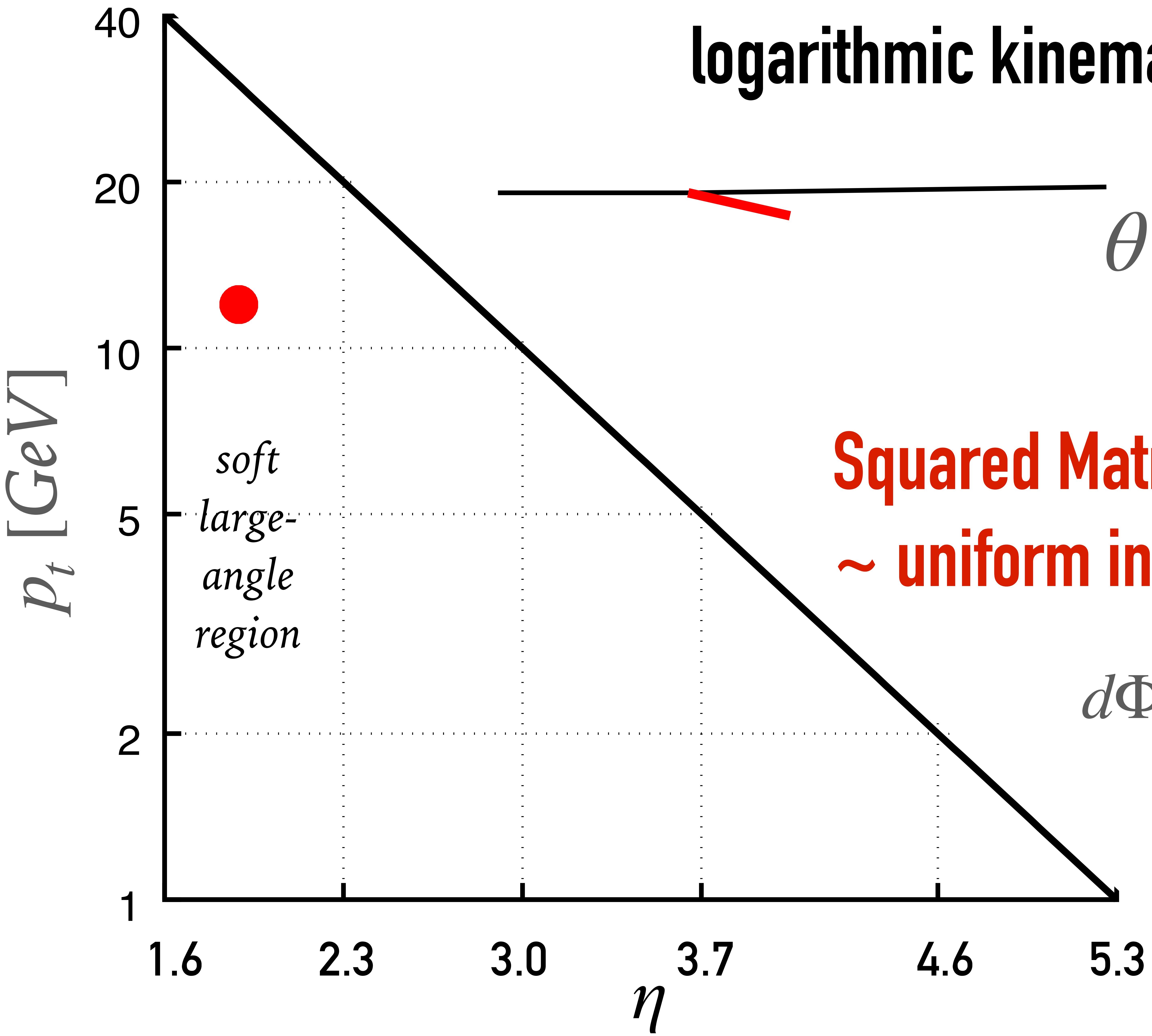
$$p_t = E\theta$$

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

The Lund Plane

jet with R = 0.4, p_t = 200 GeV



logarithmic kinematic plane whose two variables are

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

$$p_t = E\theta$$

Squared Matrix Element × phasespace

~ uniform in ln pt and η

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

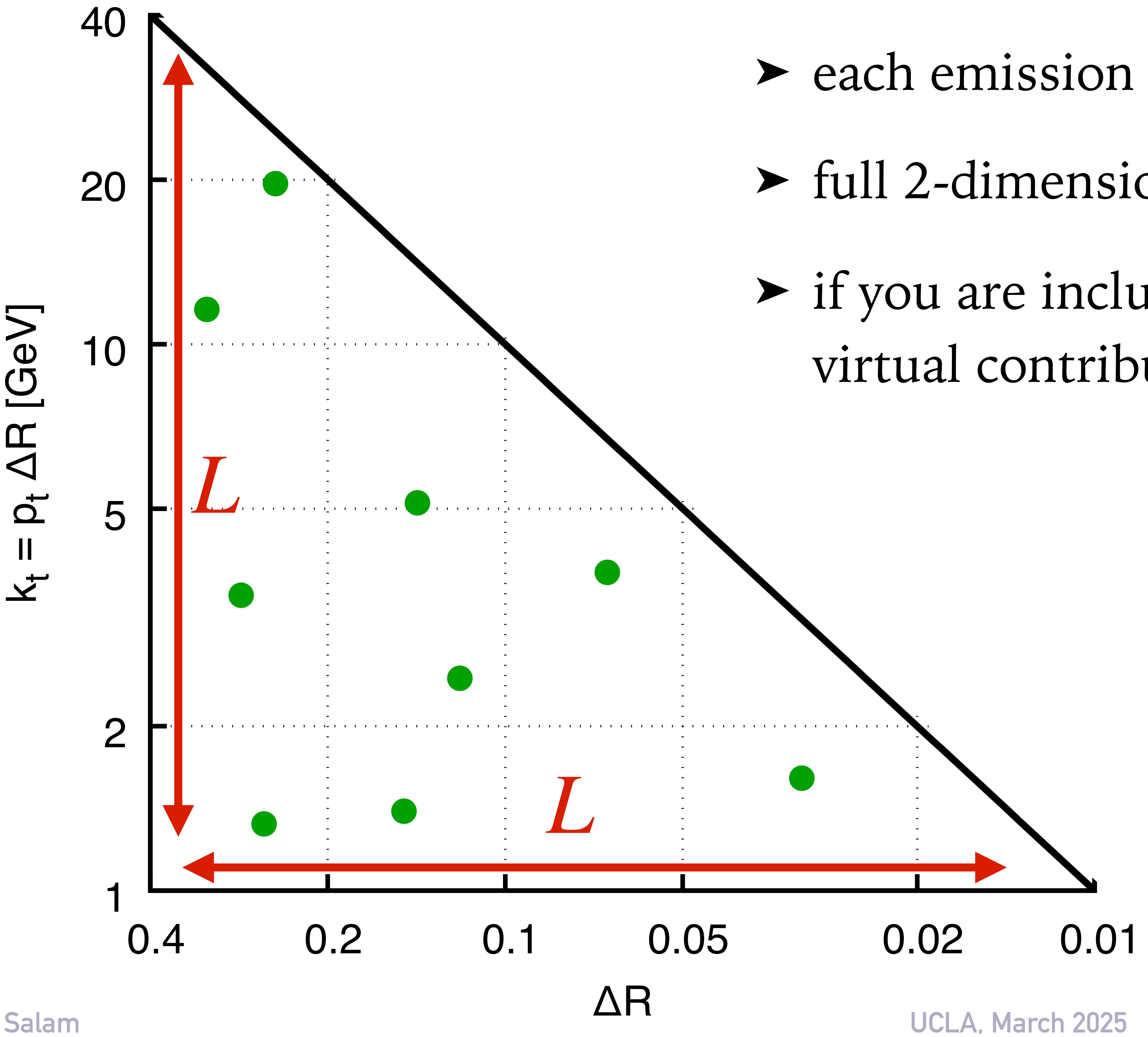
Introduced for understanding Parton Shower Monte Carlos by B. Andersson, G. Gustafson L. Lonnblad and Pettersson 1989

The Lund Plane

Element #1: criteria for accuracy

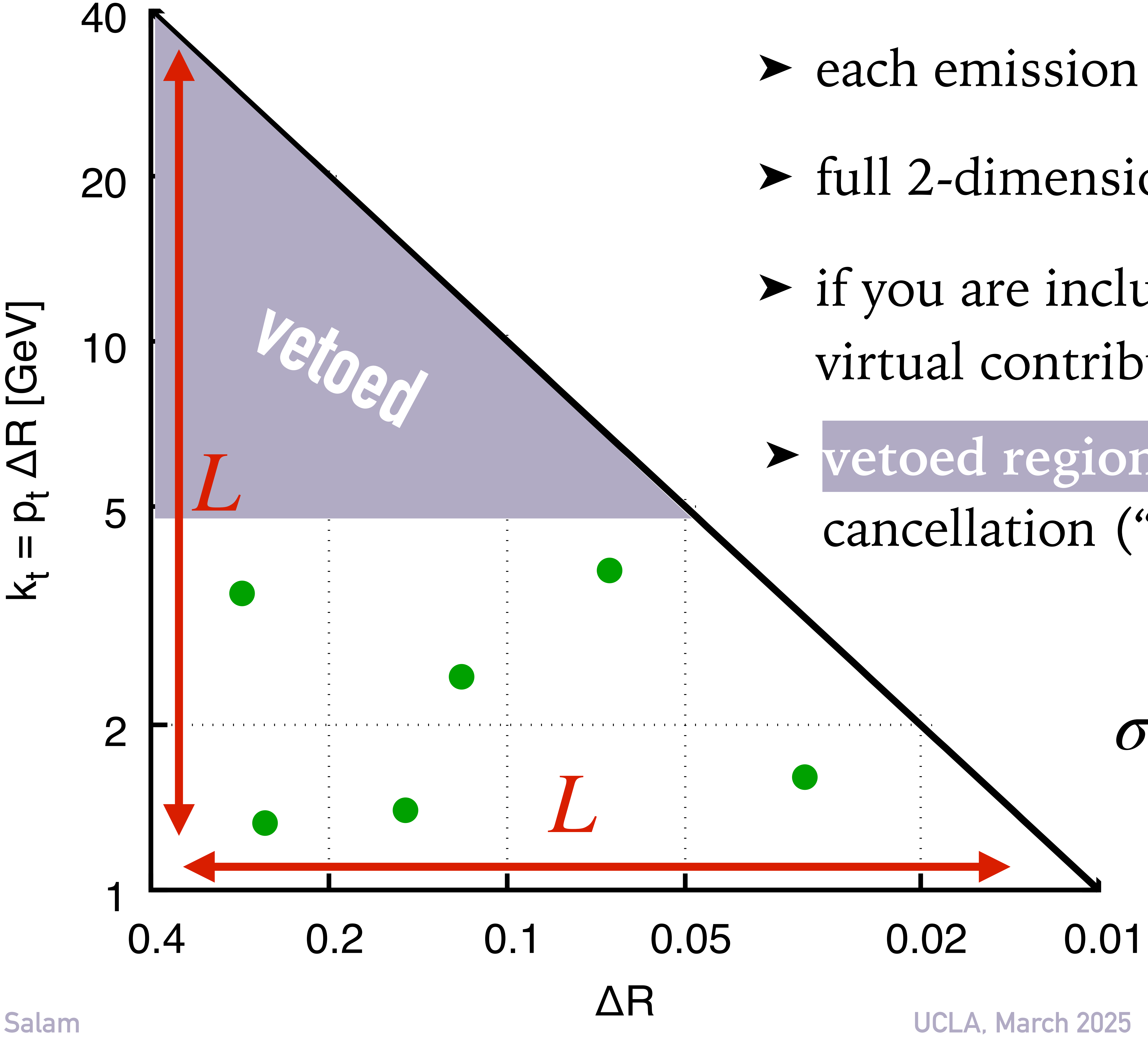
parton showers span disparate scales
natural language is "logarithmic" accuracy

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.

Defining what we mean by NLL

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

A Matrix Element condition

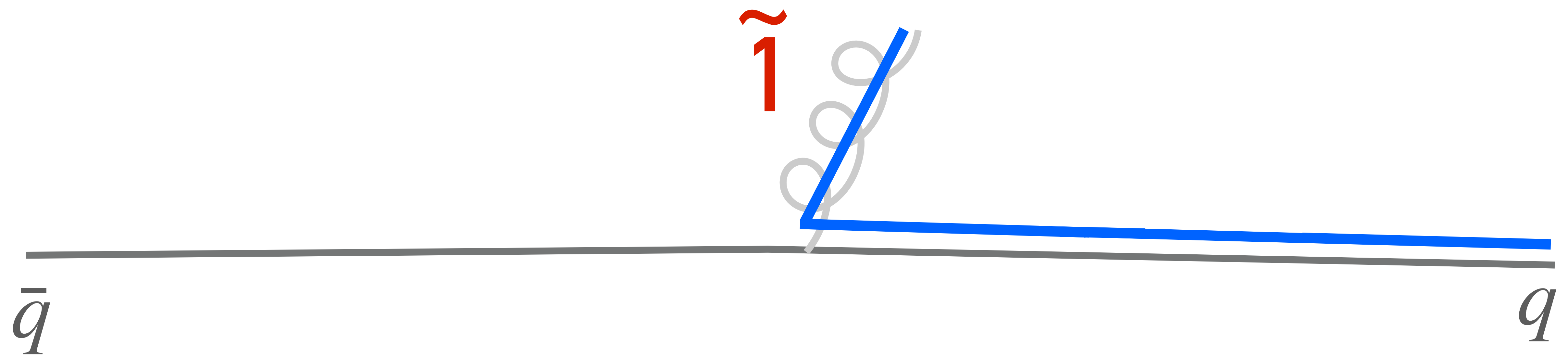
- correctly reproduce n-parton tree-level matrix element for arbitrary configurations, so long as all emissions well separated in the Lund diagram
(because those configurations are the most likely ones)
- supplement with unitarity, 2-loop running coupling & cusp anomalous dimension

Resummation condition: reproduce NLL results for all standard resummations

- global event shapes
- non-global observables
- fragmentation functions
- multiplicities
- …

1. Recoil: the core of any shower

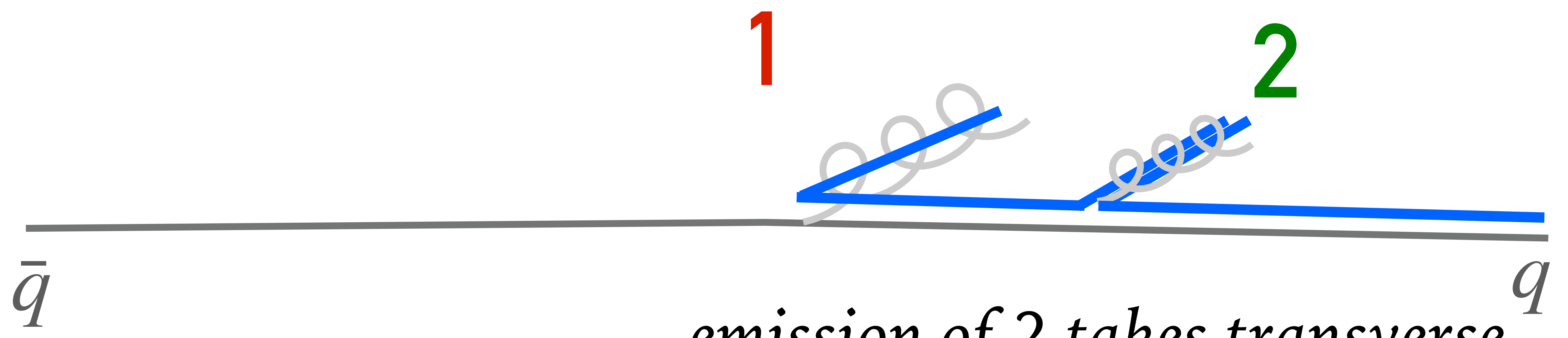
Dipole showers conserve momentum at each step. Traditional dipole-local recoil:



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

1. Recoil: the core of any shower

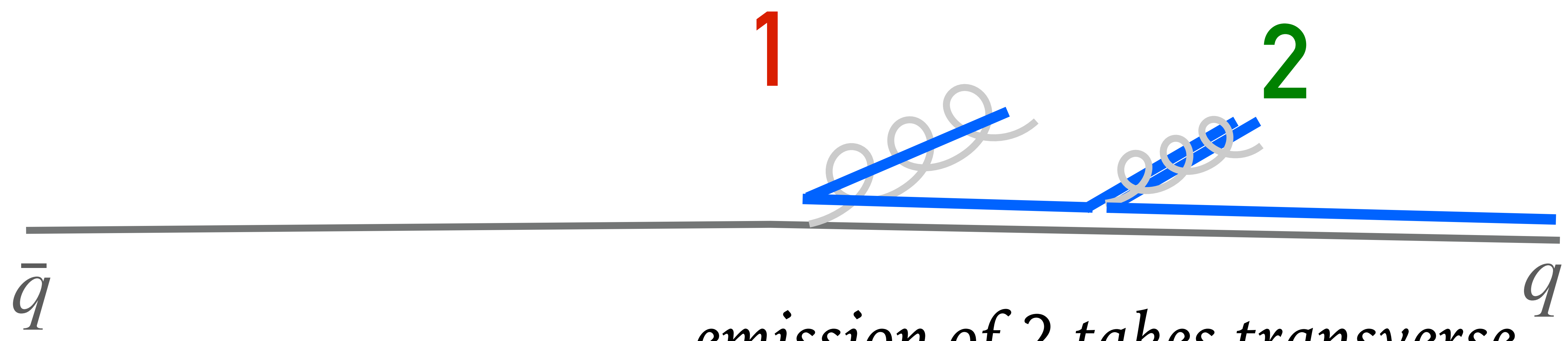
Dipole showers conserve momentum at each step. Traditional dipole-local recoil:

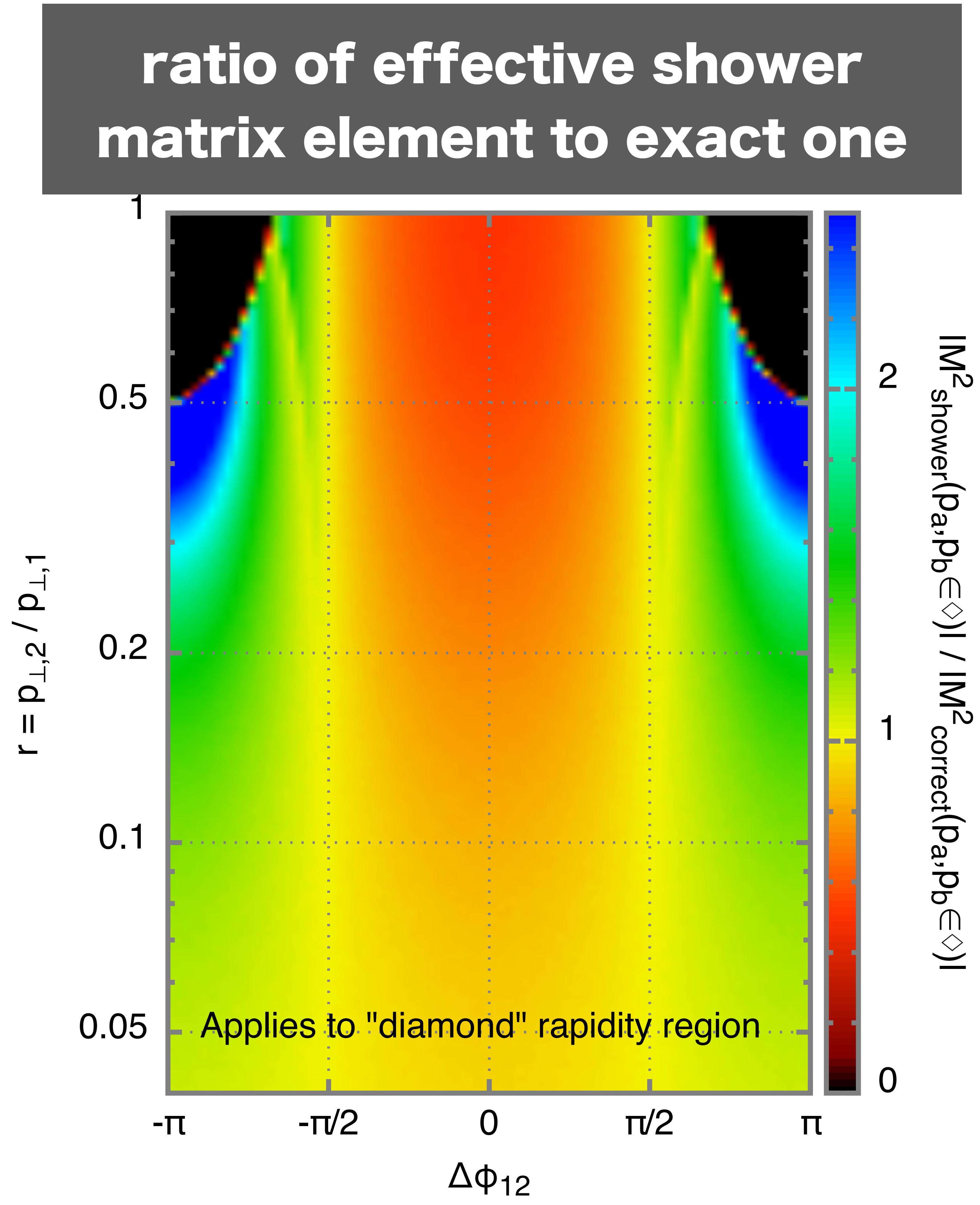


emission of 2 takes transverse recoil from 1

1. Recoil: the core of any shower

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





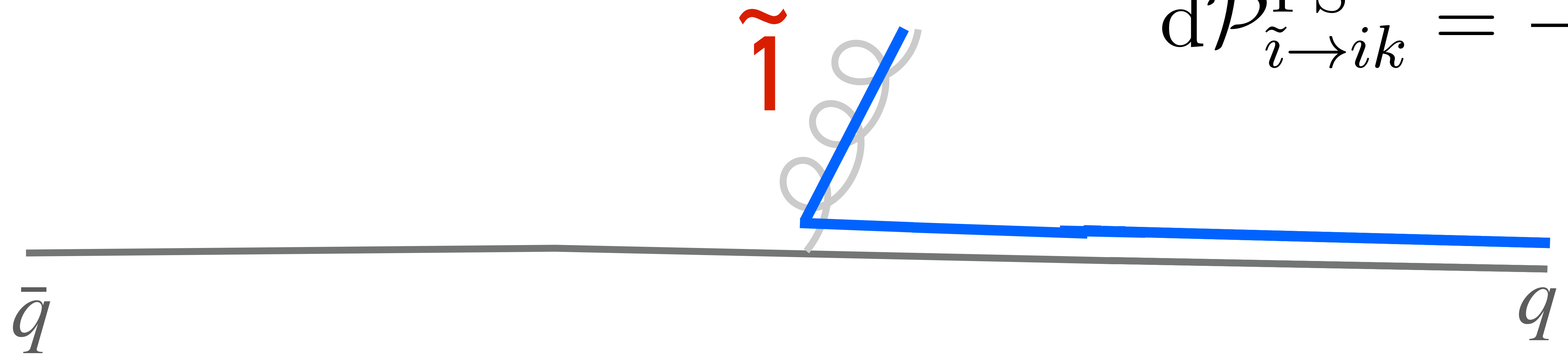
Shower initially generated matrix element for particle $\tilde{1}$, whose momentum differs (by ~ 50%) from final particle 1.

Matrix element is incorrect wrt final momentum 1.

First observed: Andersson, Gustafson, Sjogren '92
Closely related effect present for Z p_t: Nagy & Soper 0912.4534
Impact on log accuracy across many observables: Dasgupta, Dreyer, Hamilton, Monni, GPS, 1805.09327

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

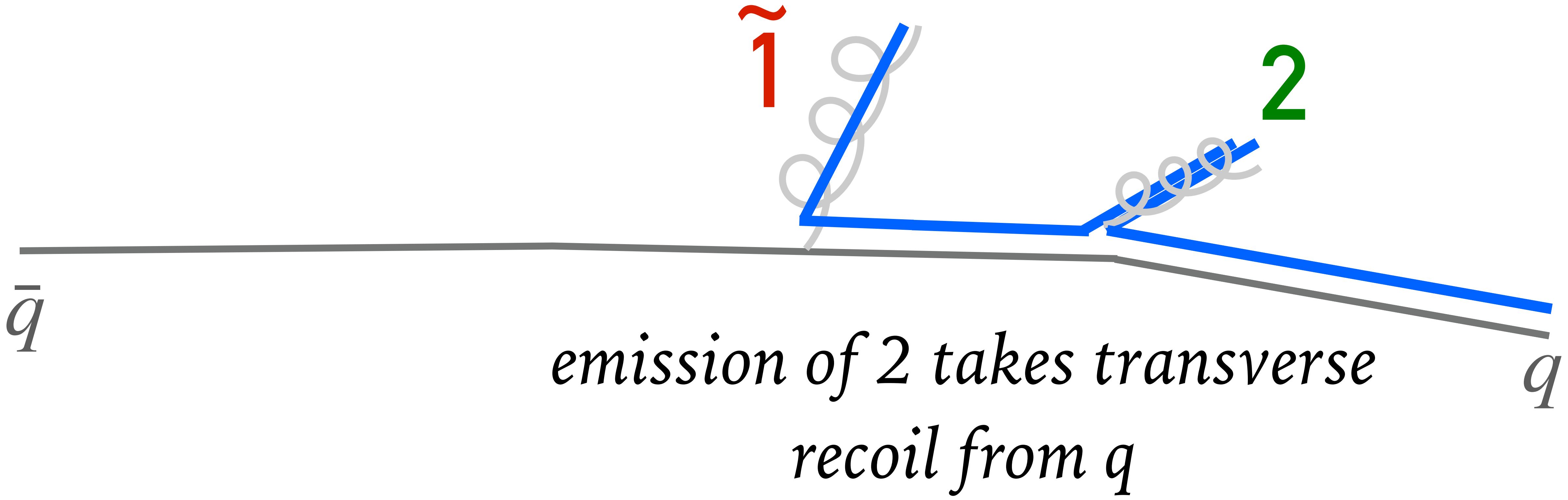
One approach



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

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

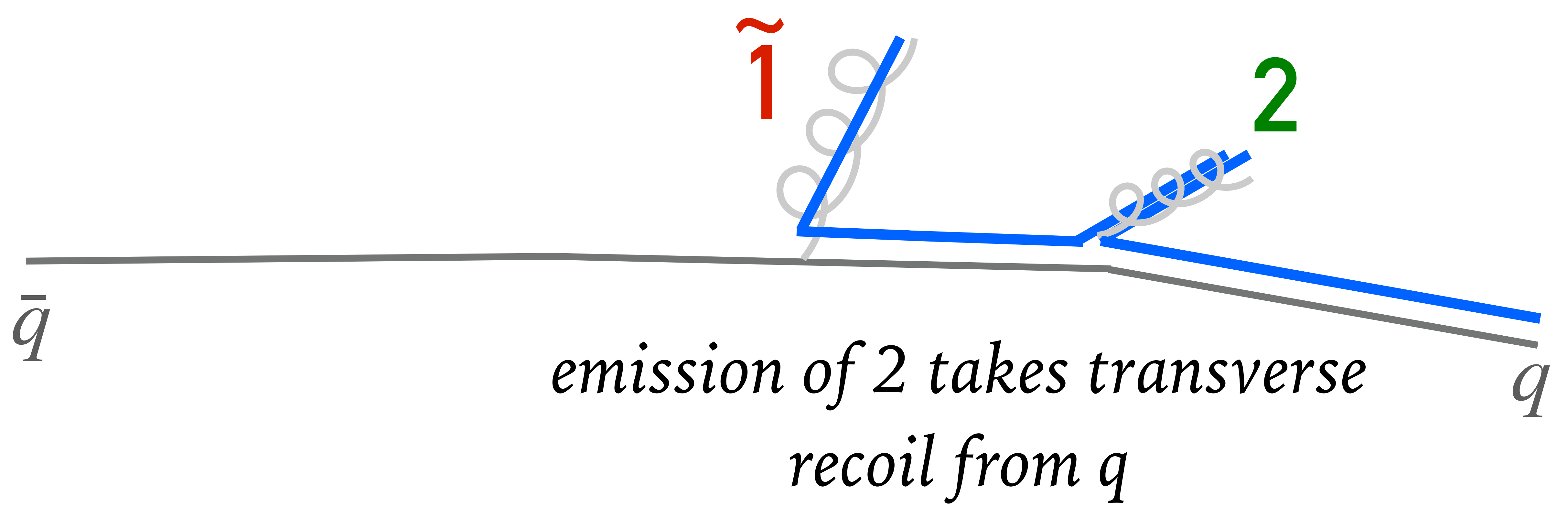
One approach

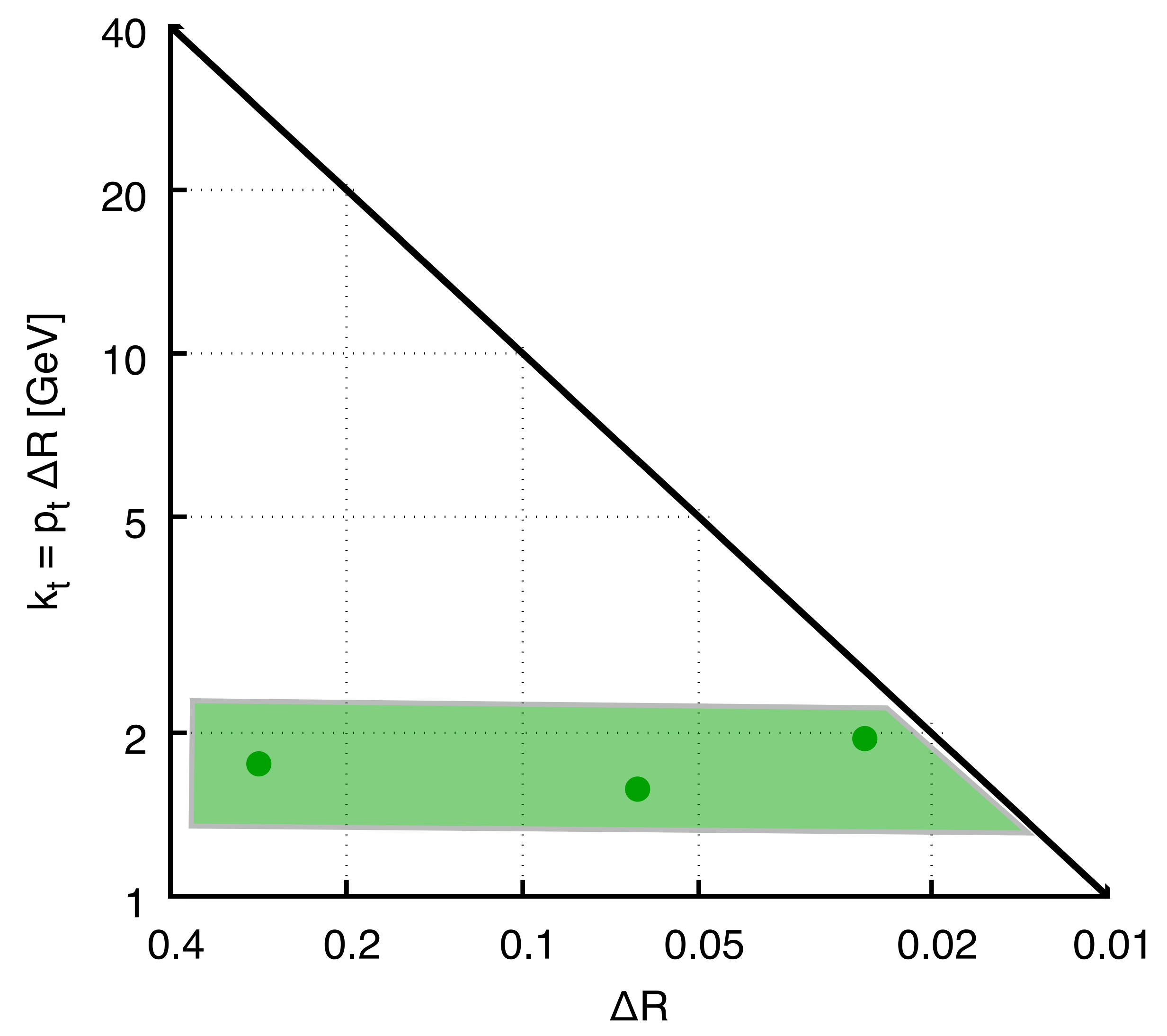


θ_{1q} left almost unchanged if ⊥ recoil from emission of 2 taken by (much harder) q

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

One approach





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

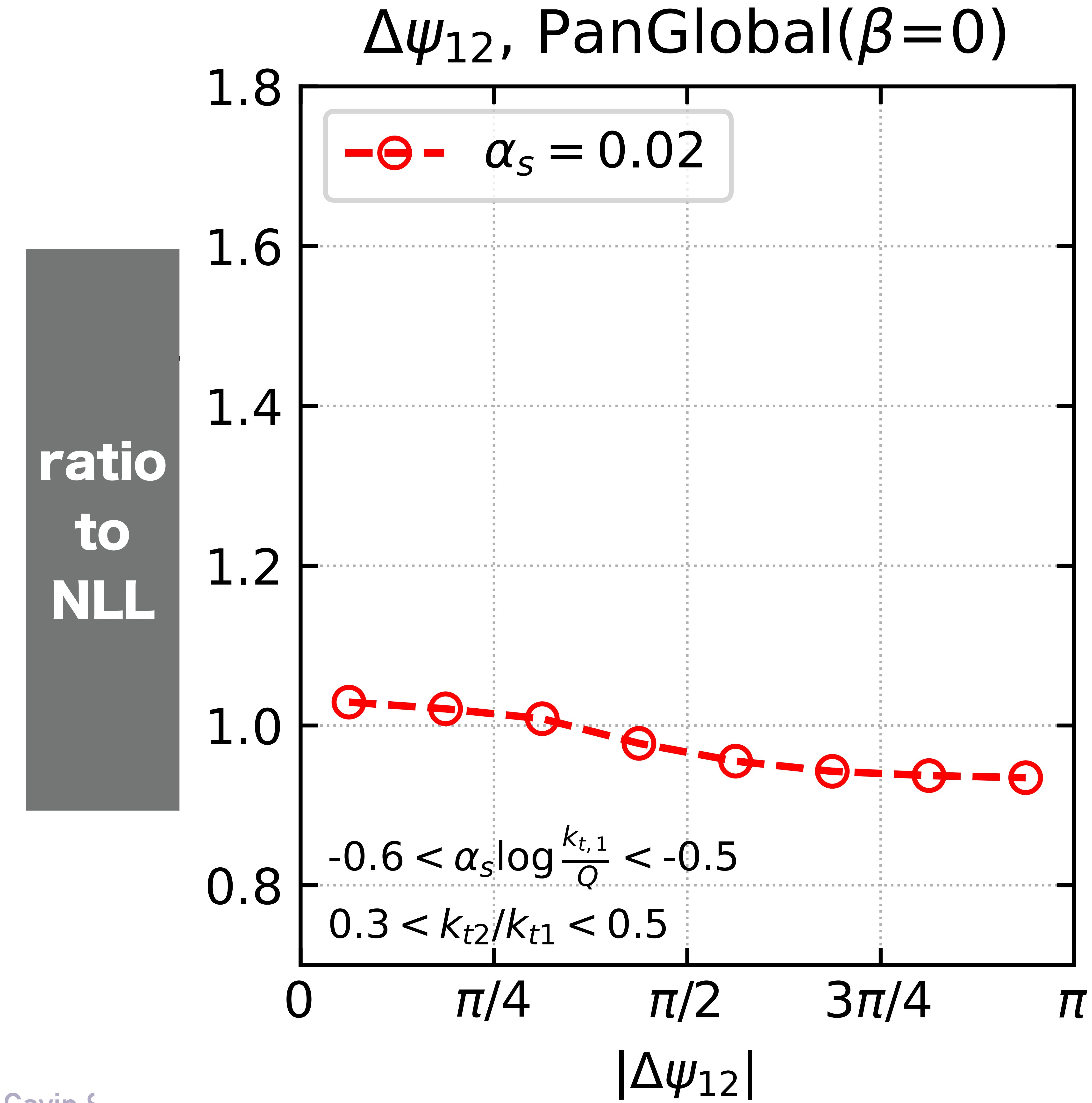
Can be achieved in multiple ways:

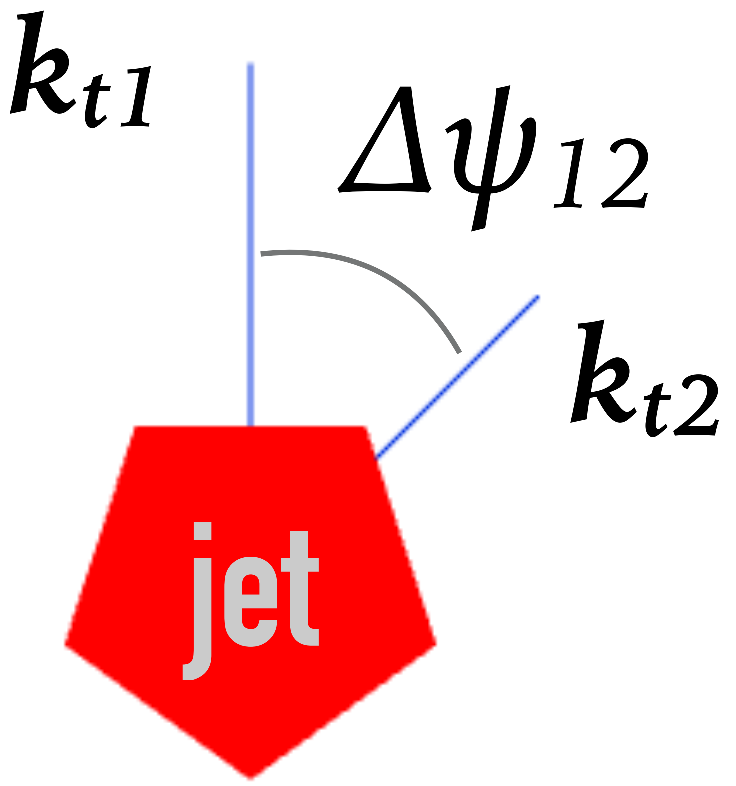
- global transverse recoil (Dasgupta et al 2002.11114, "**PanGlobal**"; Holguin Seymour & Forshaw 2003.06400; Alaric 2208.06057 + ⋯, Apollo, 2403.19452)
- local transverse recoil, with non-standard shower ordering & dipole partition (2002.11114 "**PanLocal**"; Nagy & Soper 0912.4534 + ⋯, "Deductor")

Element #2: testing correctness

Parton showers operate at all orders and mix many effects. How can you separate out just the orders you aim to control to test they're correct?

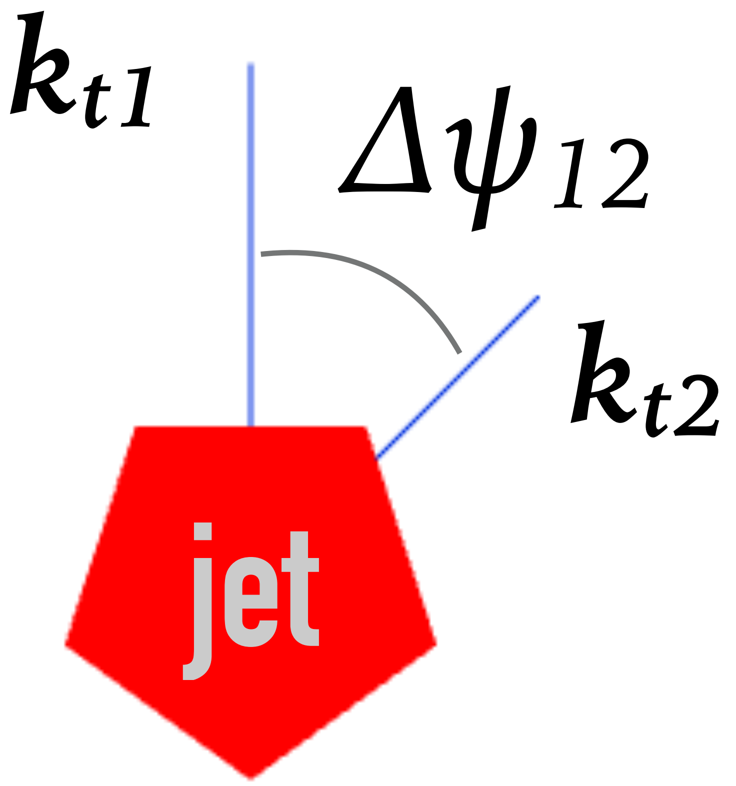
Test class 2: full shower v. all-order NLL



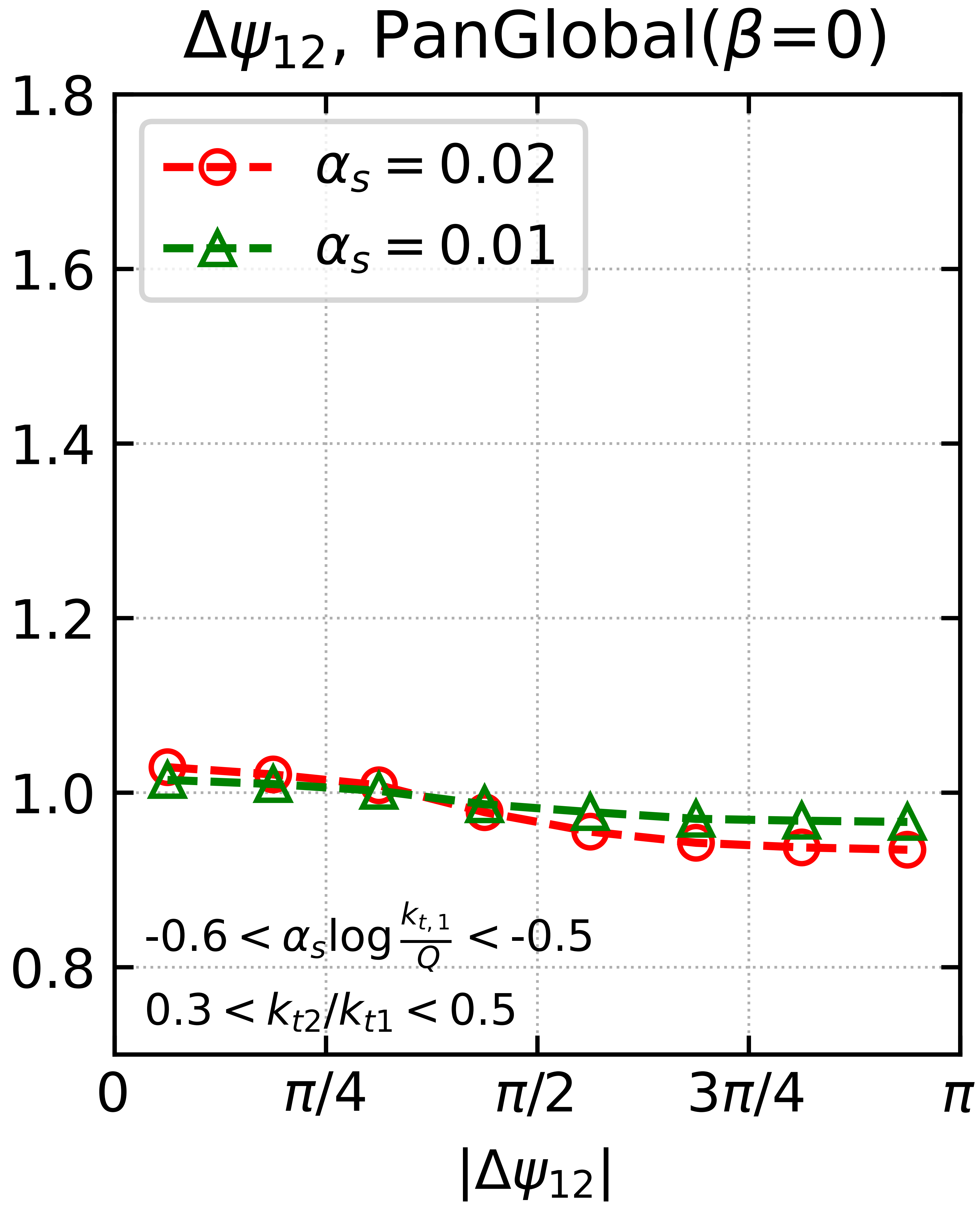


- run full shower with specific value of $\alpha_s(Q)$ & measure an observable: azimuth between two highest-k_t emissions (soft-collinear)
- ratio to NLL should be flat $\equiv 1$
- it isn't: have we got an NLL mistake? Or a residual subleading (NNLL) term?

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

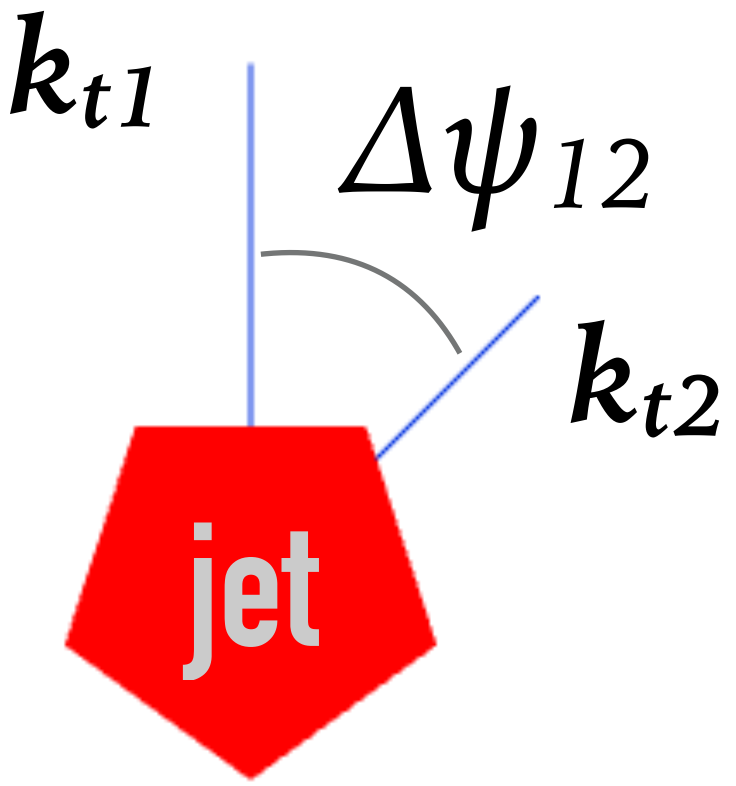


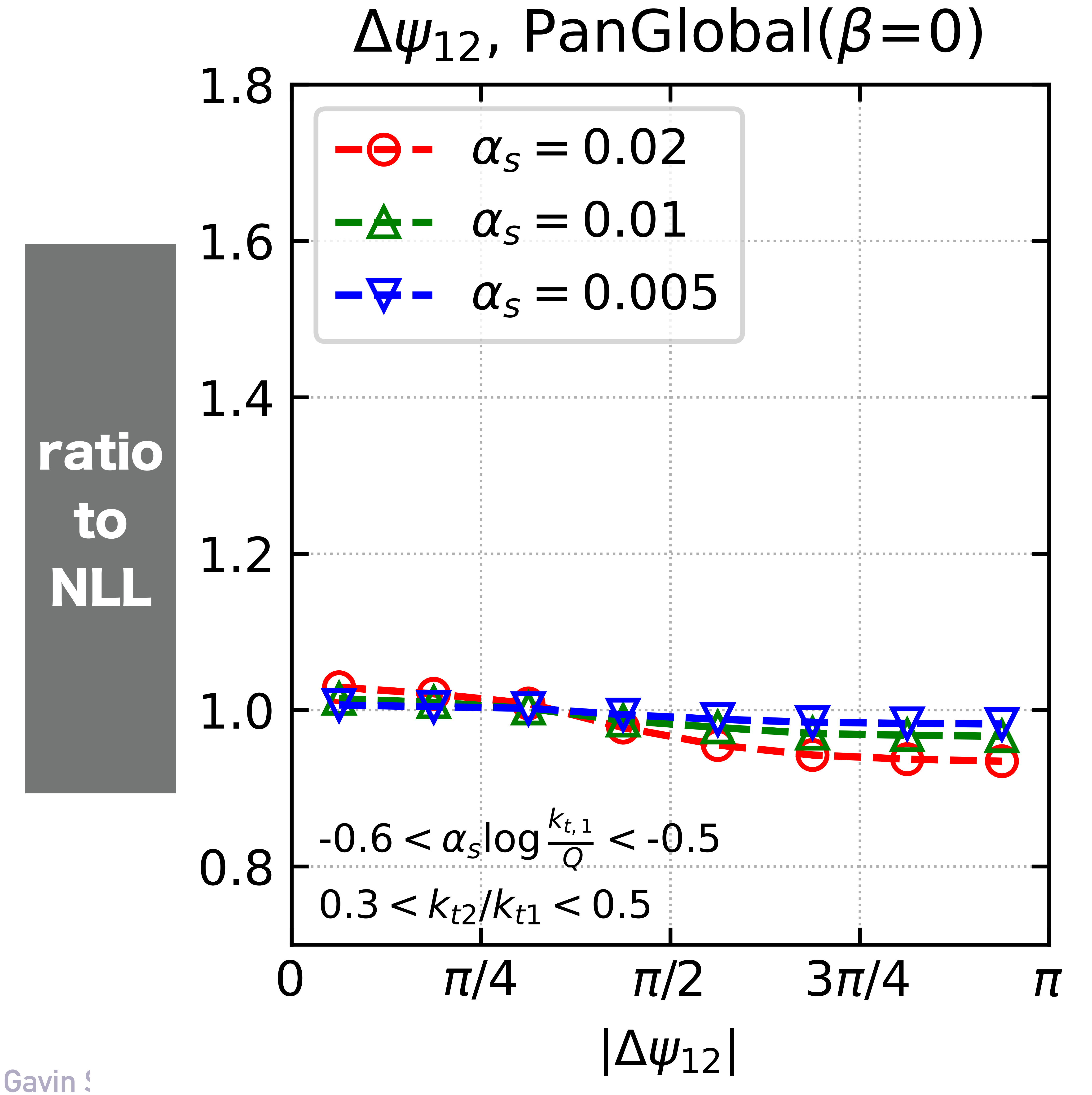
ratio to NLL



- run full shower with specific value of $\alpha_s(Q)$ & measure an observable: azimuth between two highest-k_t emissions (soft-collinear)
- ratio to NLL should be flat ≡ 1
- it isn't: have we got an NLL mistake? Or a residual subleading (NNLL) term?
- 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, $\alpha_s(\alpha_s L)^n$, $\to 0$

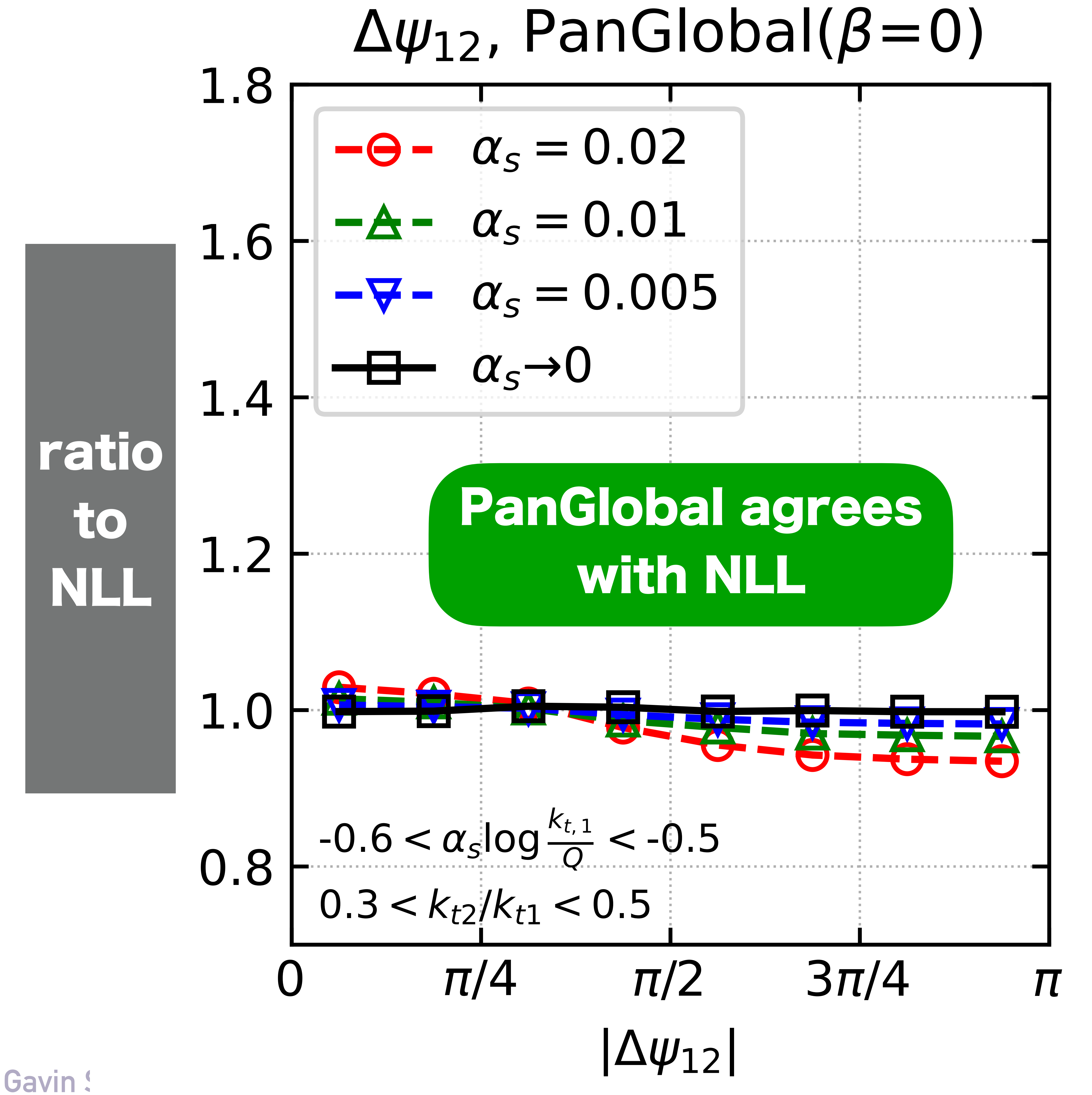
Tests (2): full shower v. all-order NLL

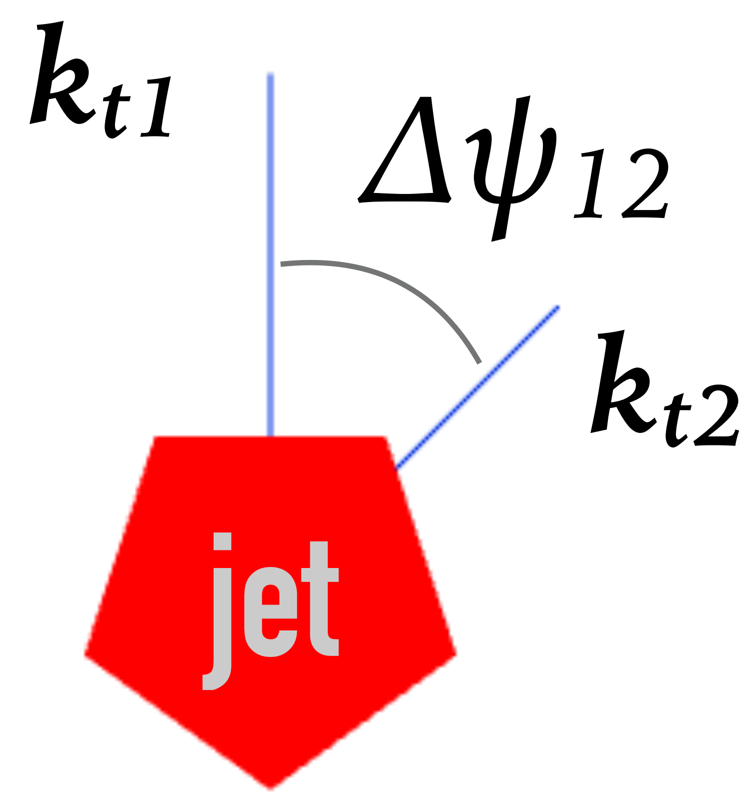




- run full shower with specific value of $\alpha_s(Q)$ & measure an observable: azimuth between two highest-k_t emissions (soft-collinear)
- ratio to NLL should be flat $\equiv 1$
- it isn't: have we got an NLL mistake? Or a residual subleading (NNLL) term?
- try reducing $\alpha_s(Q)$, while keeping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

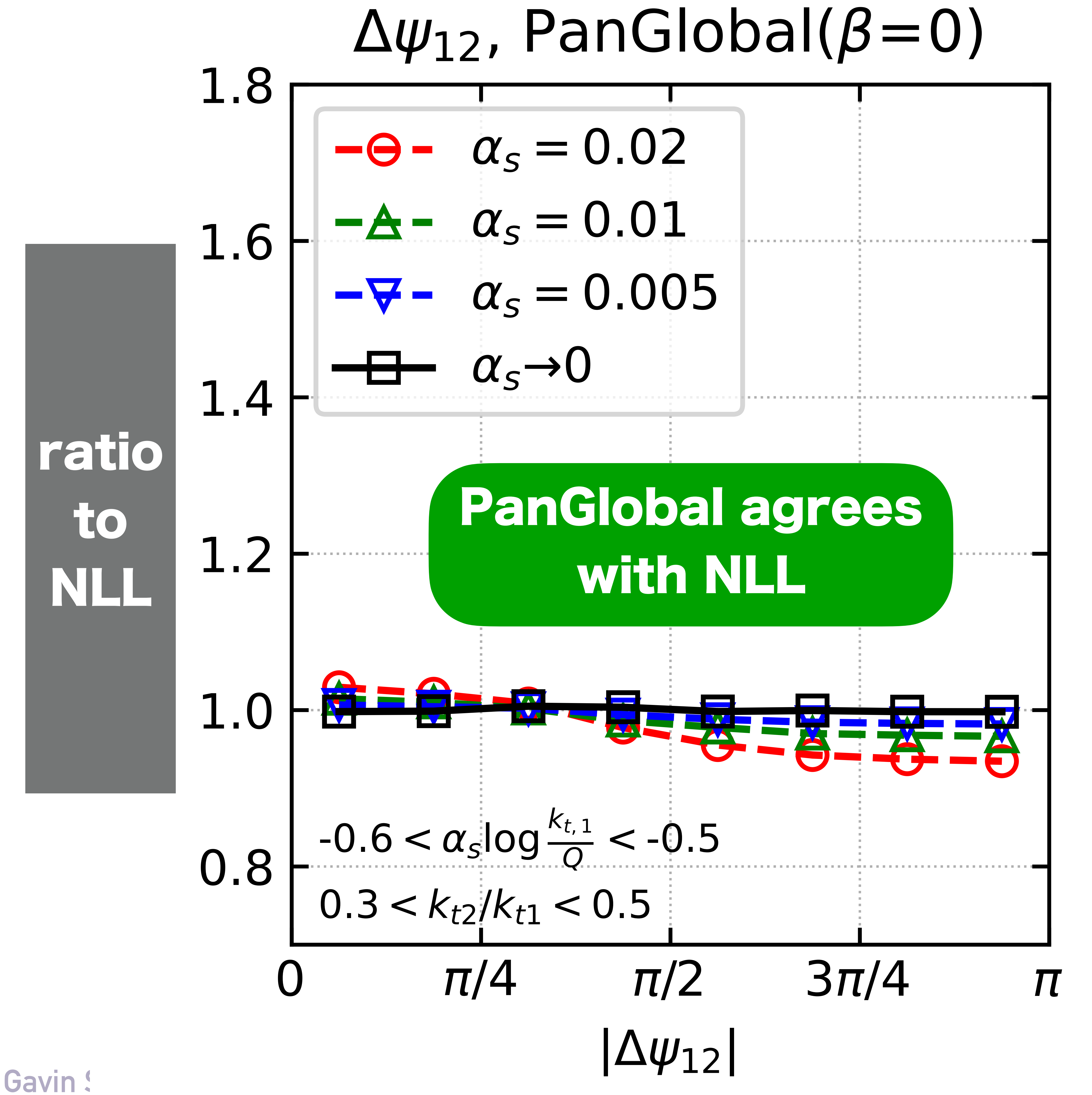


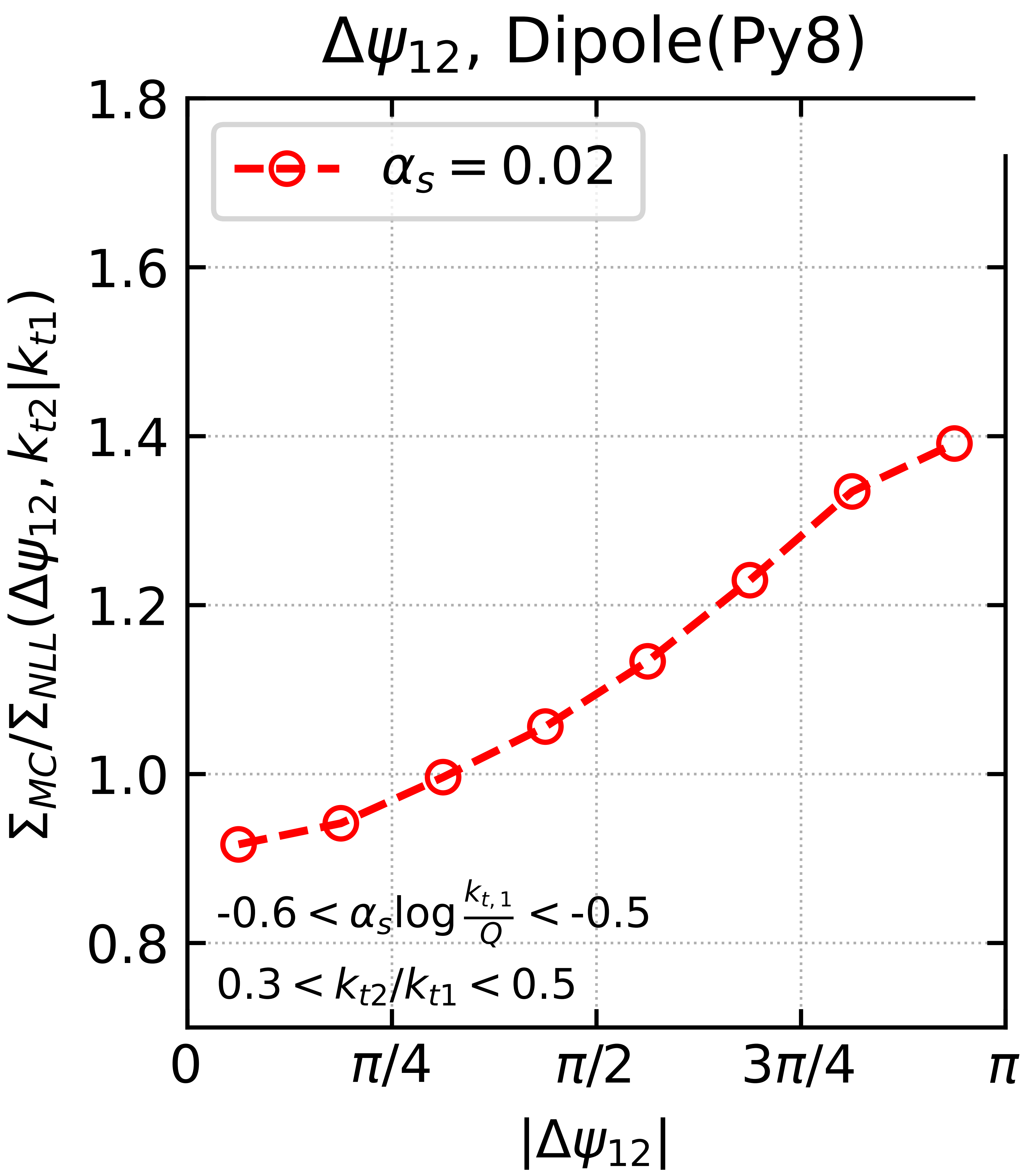


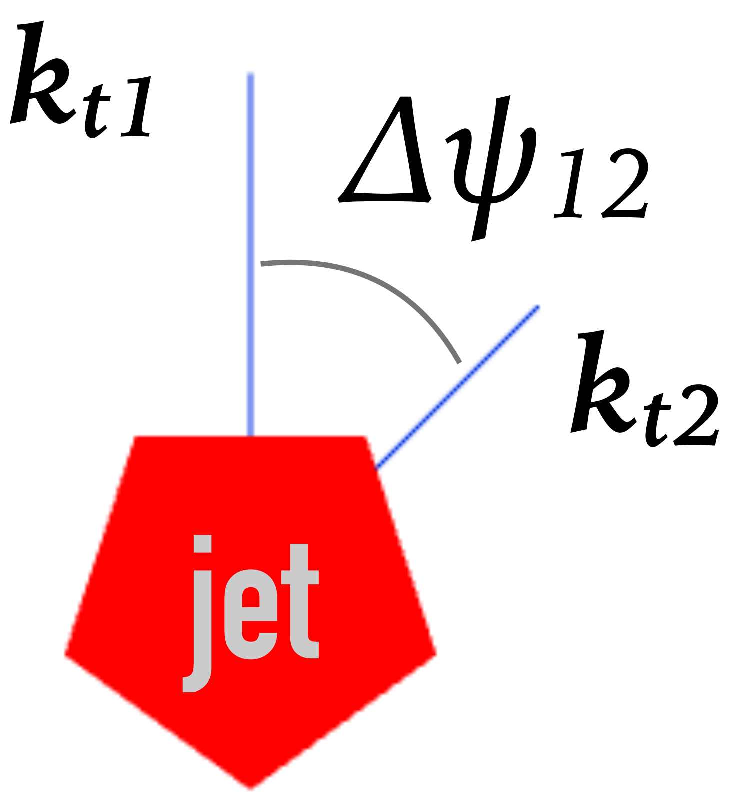
- run full shower with specific value of $\alpha_s(Q)$ & measure an observable: azimuth between two highest-k_t emissions (soft-collinear)
- ratio to NLL should be flat $\equiv 1$
- it isn't: have we got an NLL mistake? Or a residual subleading (NNLL) term?
- try reducing $\alpha_s(Q)$, while keeping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

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

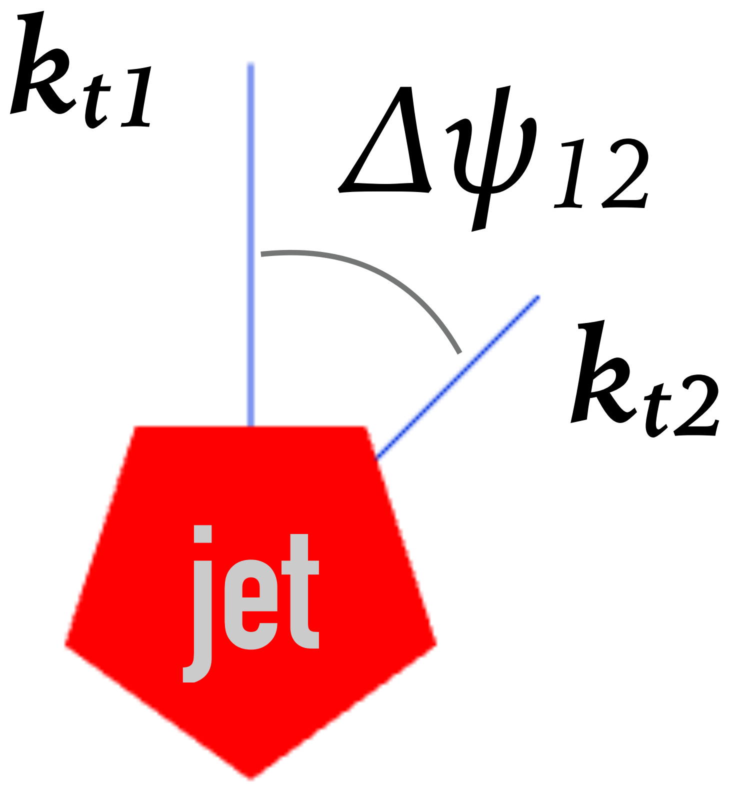
Tests (2): full shower v. all-order NLL



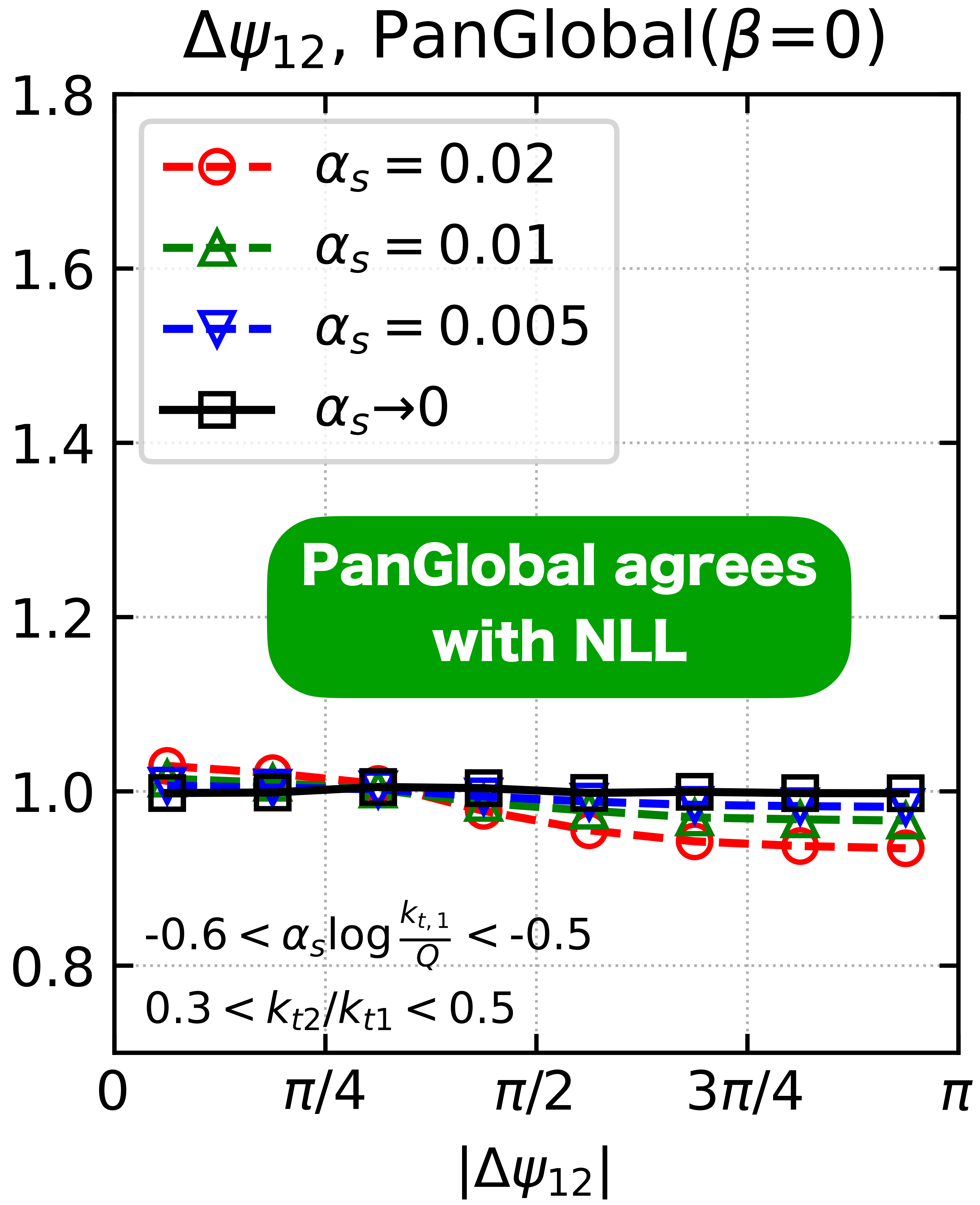


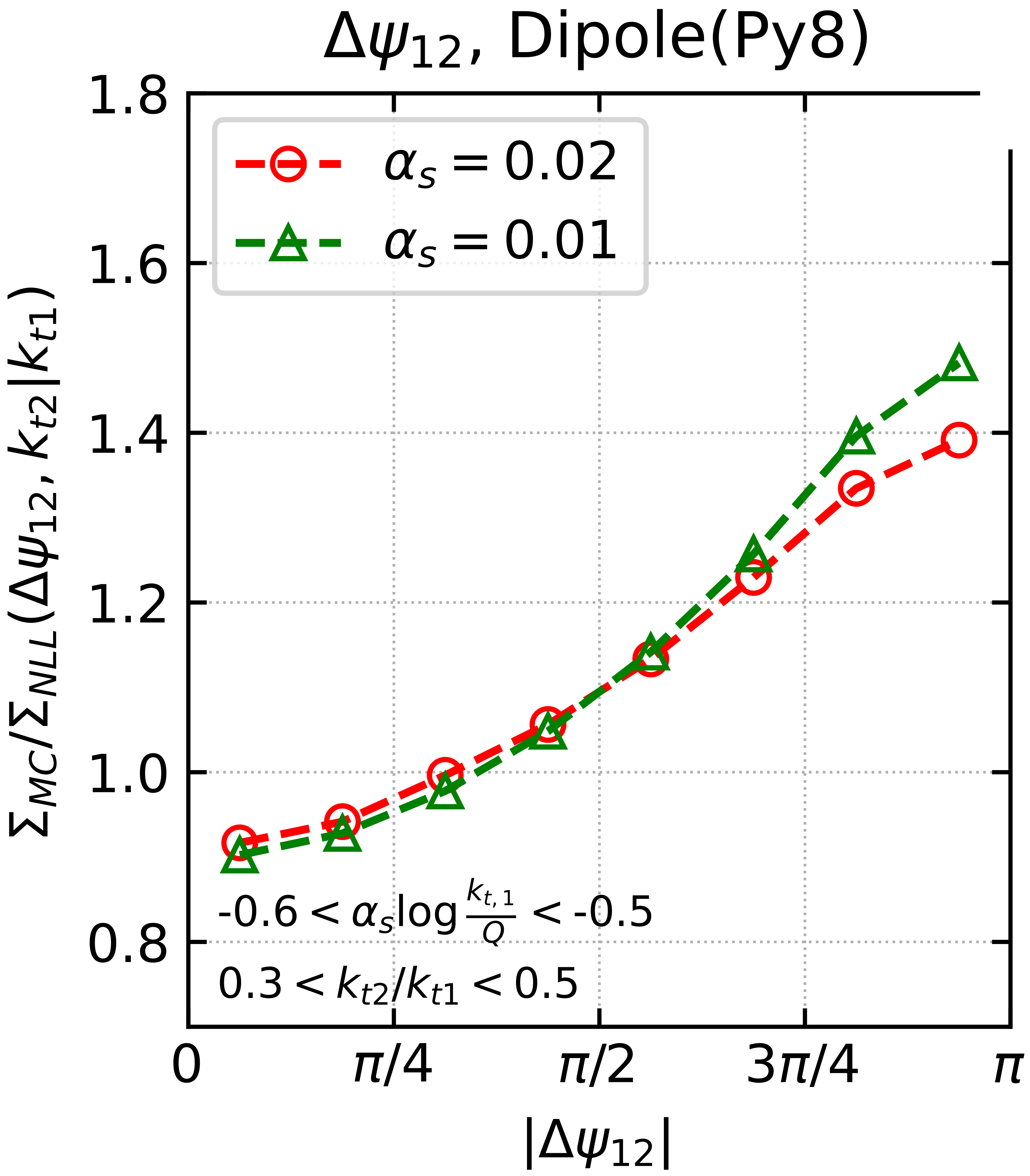


Tests (2): full shower v. all-order NLL

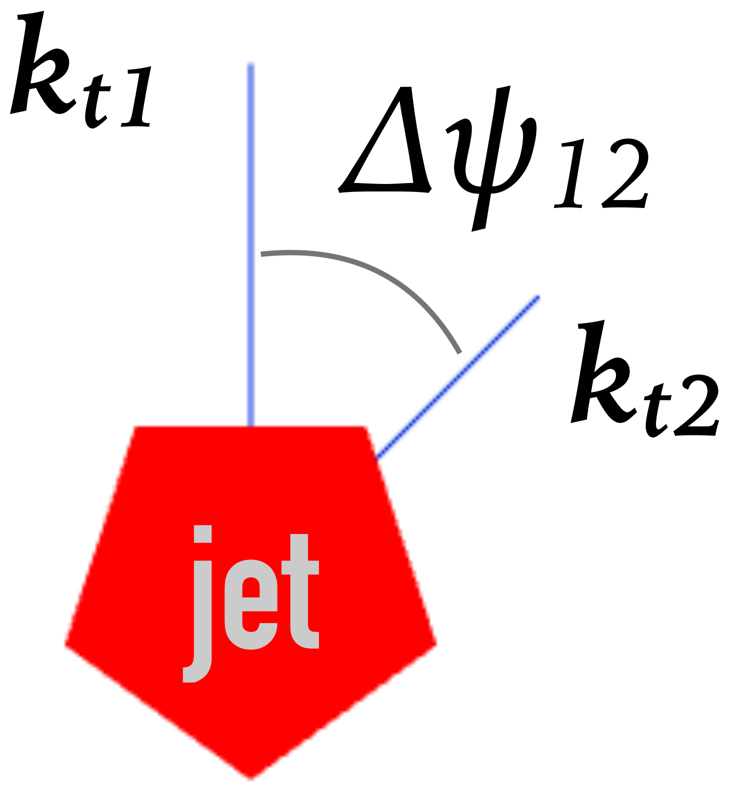


ratio to NLL

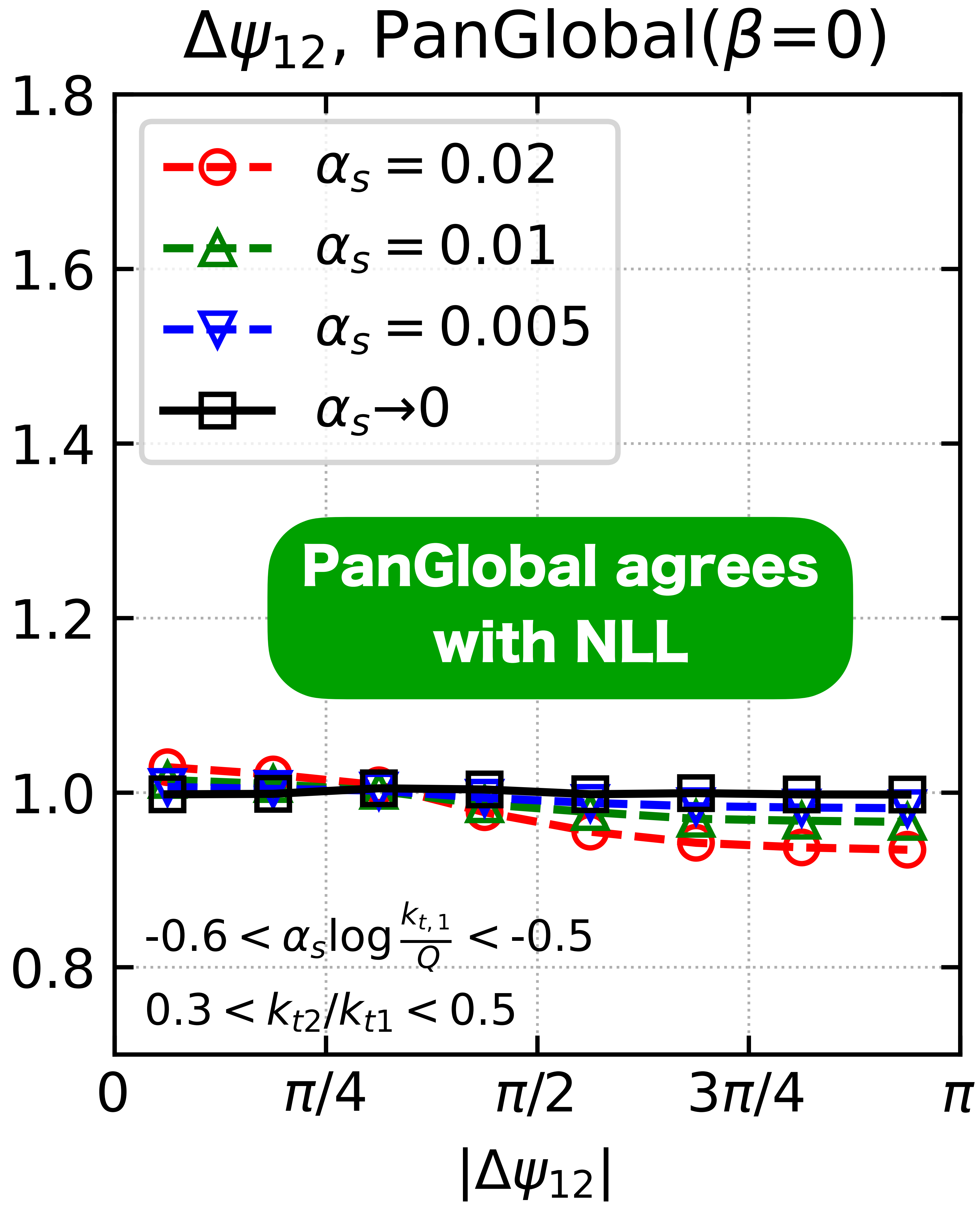


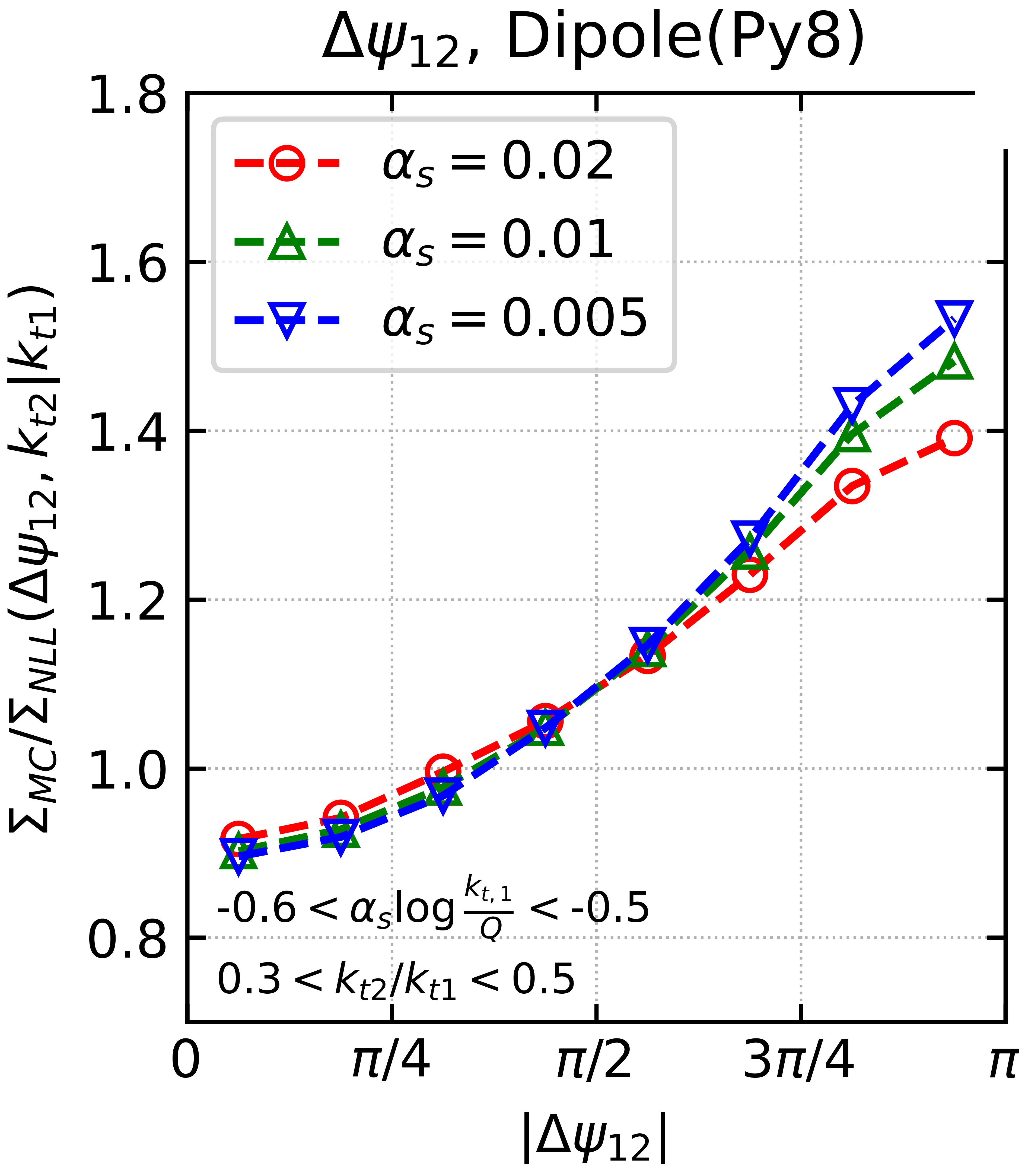


Tests (2): full shower v. all-order NLL

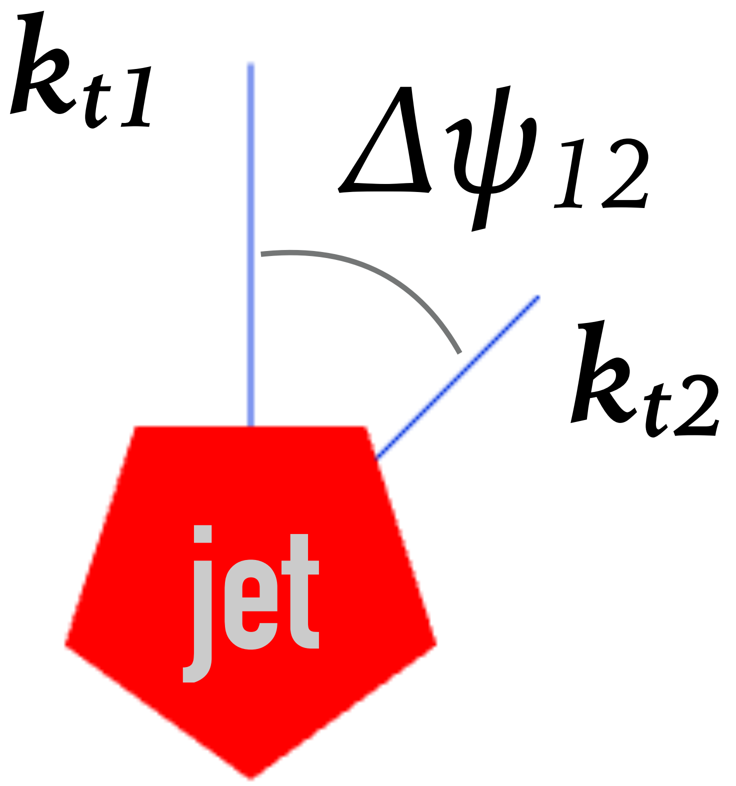


ratio to NLL

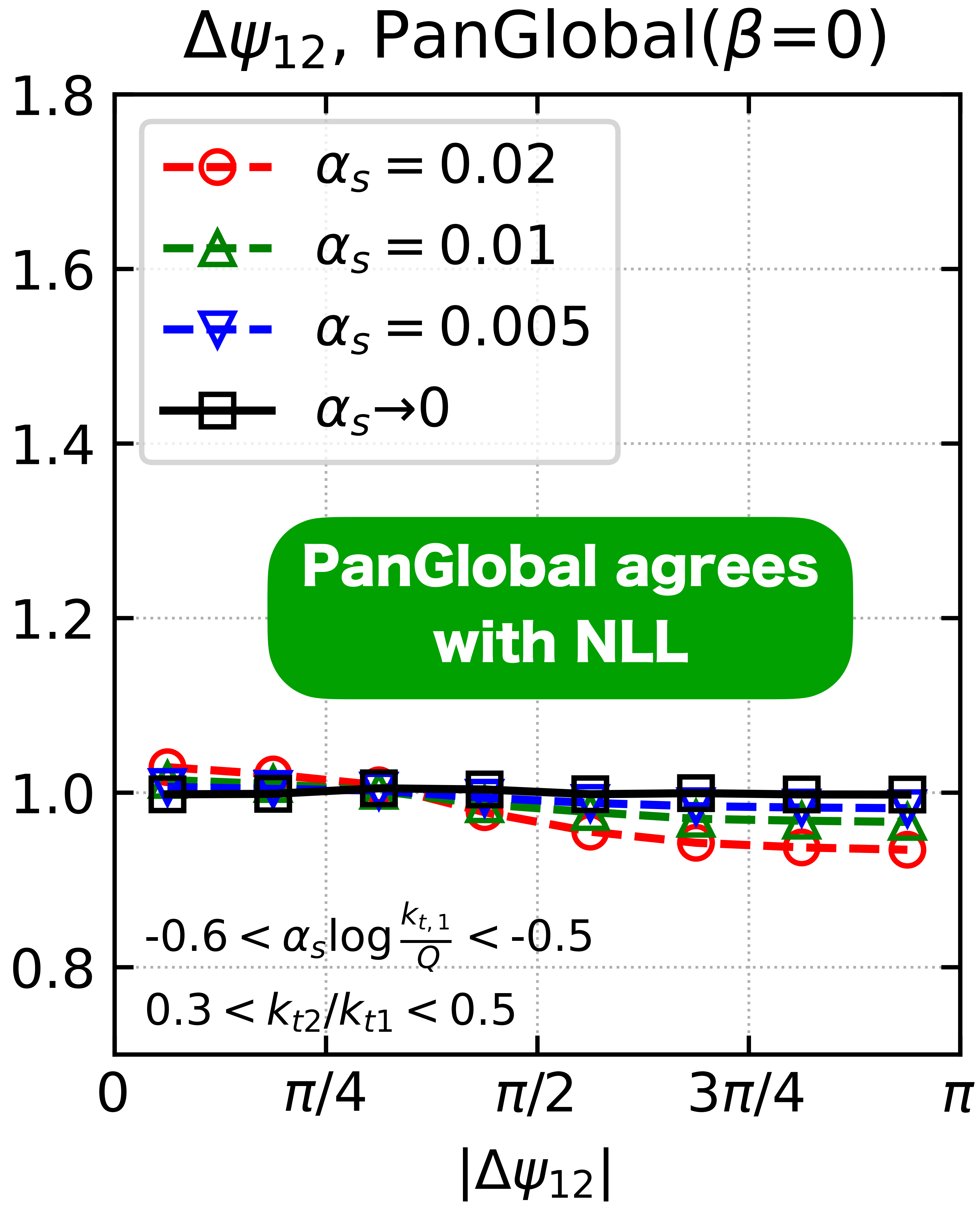




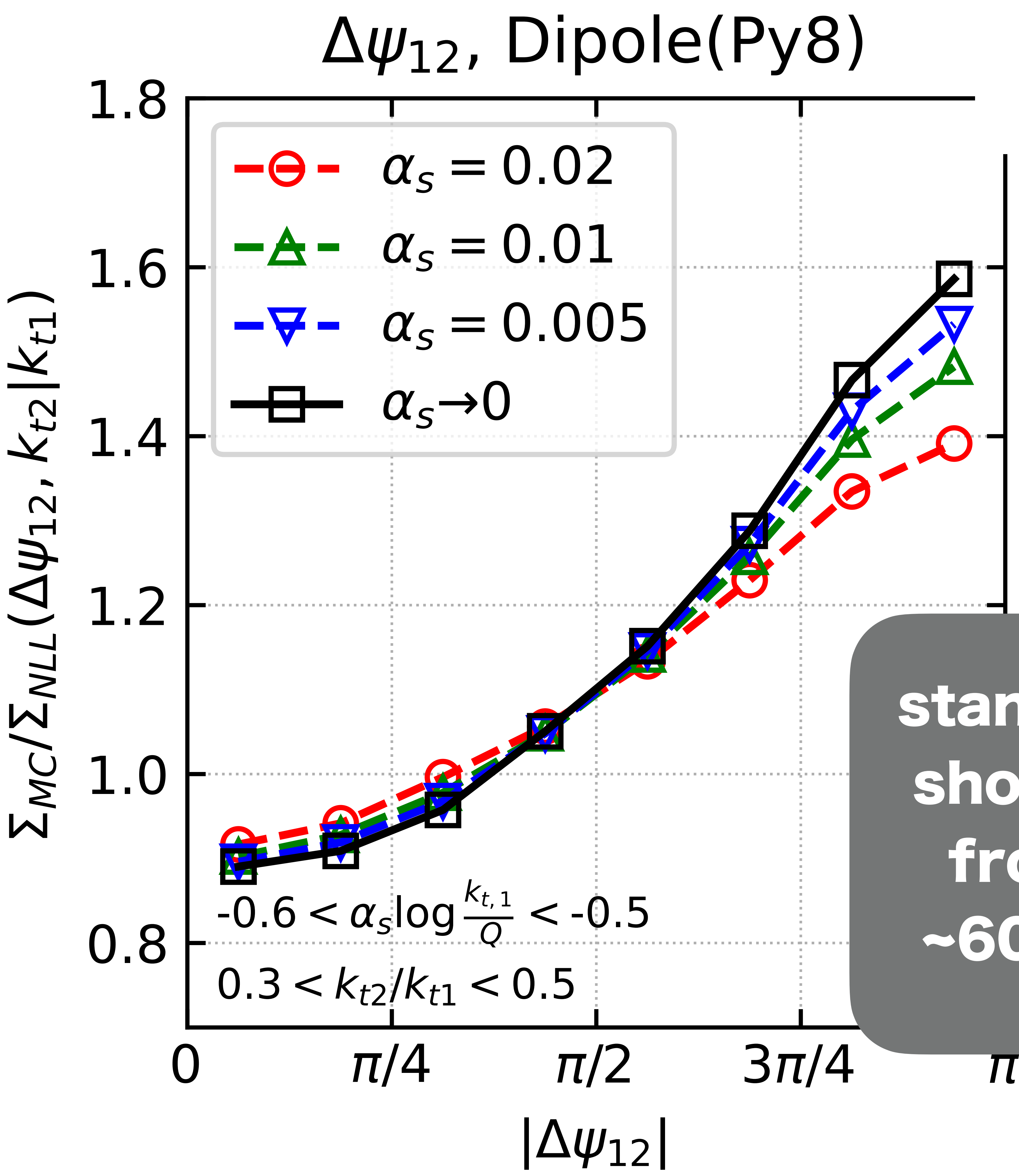
Tests (2): full shower v. all-order NLL



ratio to NLL

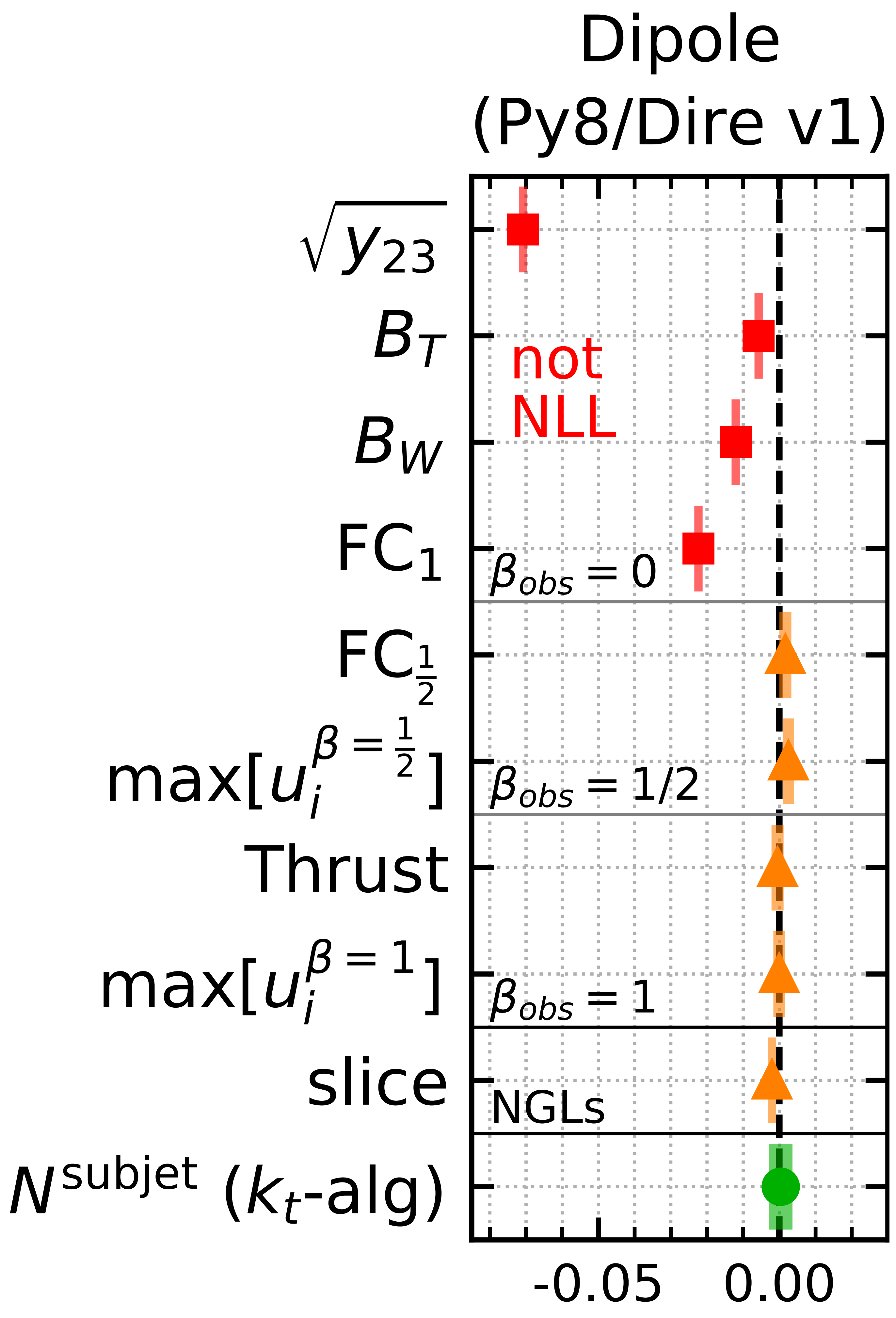


PanGlobal agrees with NLL



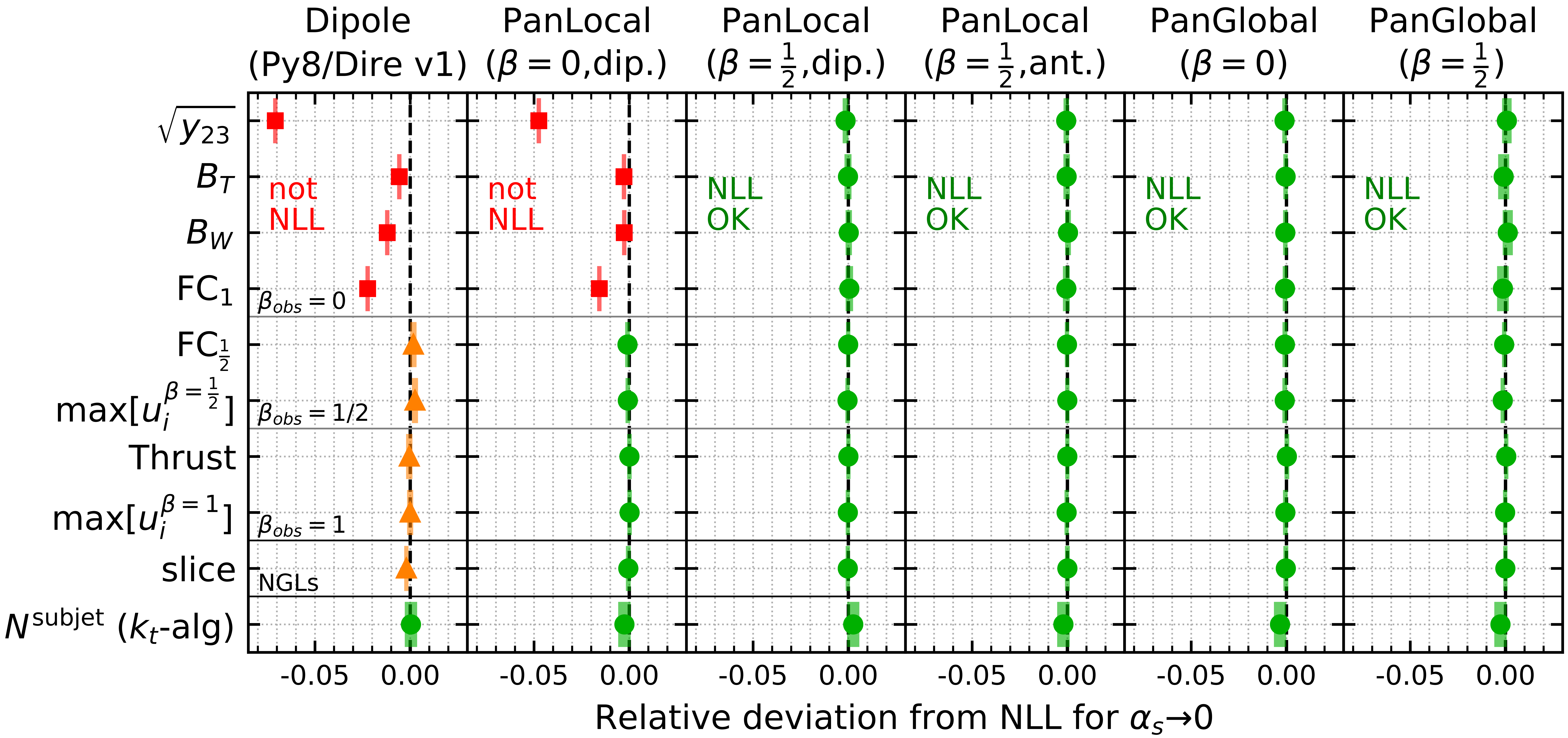
standard dipole shower differs from NLL by ~60%, i.e. O(1)

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



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

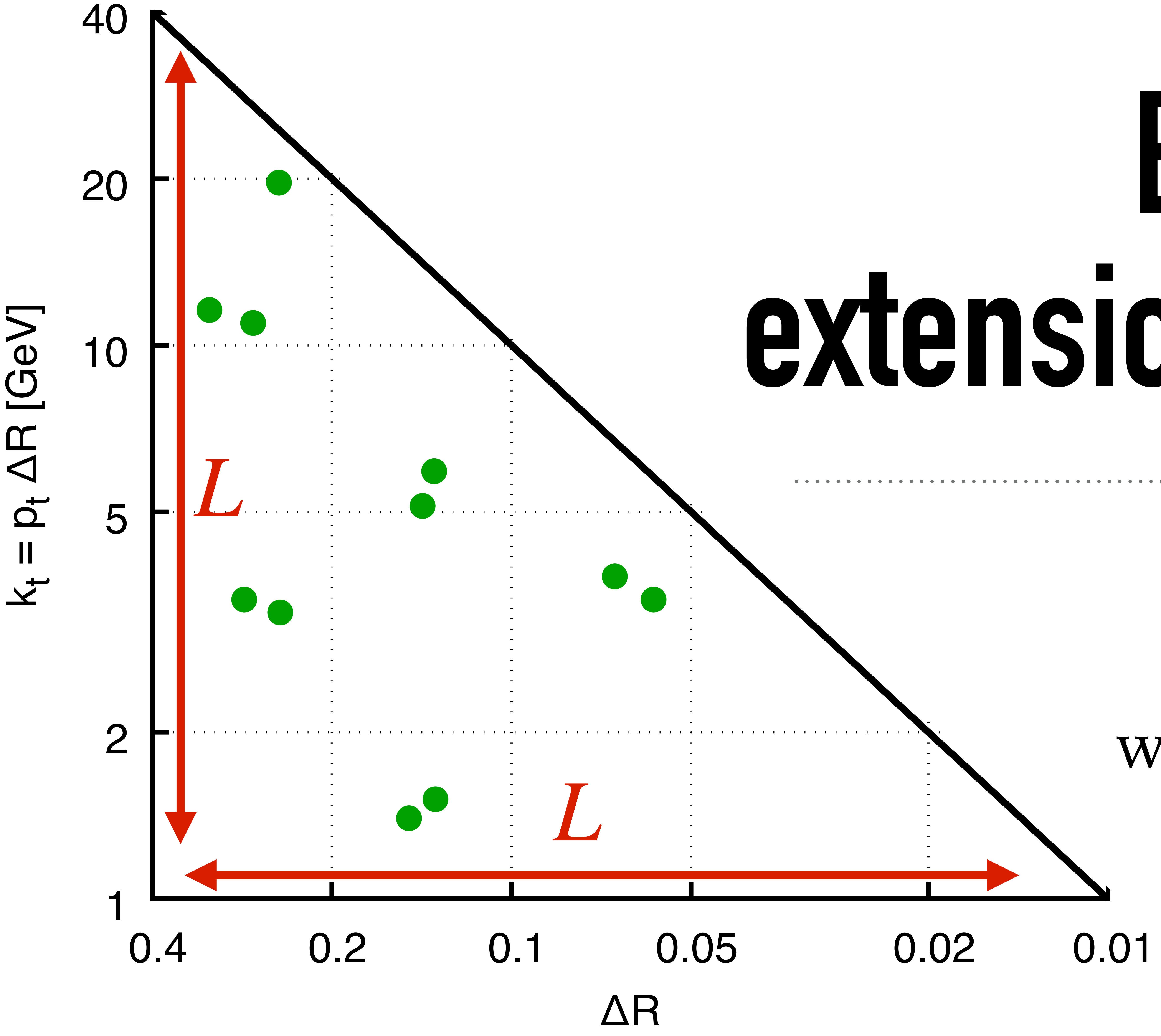
Christian T Preuss
Department of Physics, University of Wuppertal, 42119 Wuppertal, Germany
E-mail: preuss@uni-wuppertal.de

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]

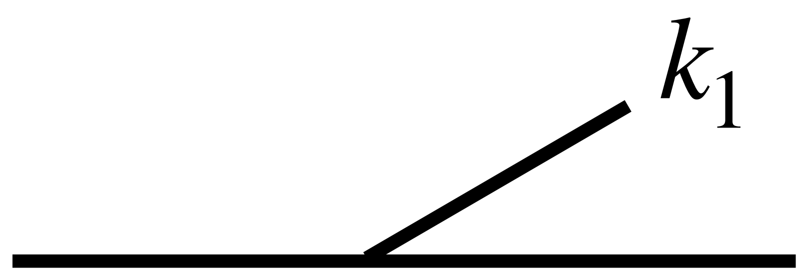
slide from Pier Monni



Element #3: extension to higher orders

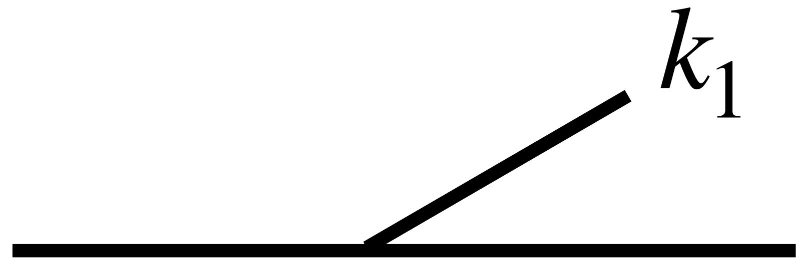
E.g. at NNLL, effective matrix element should be correct even where there are pairs of emissions close by in the Lund plane

Make each new emission's distribution conditional on previous emission

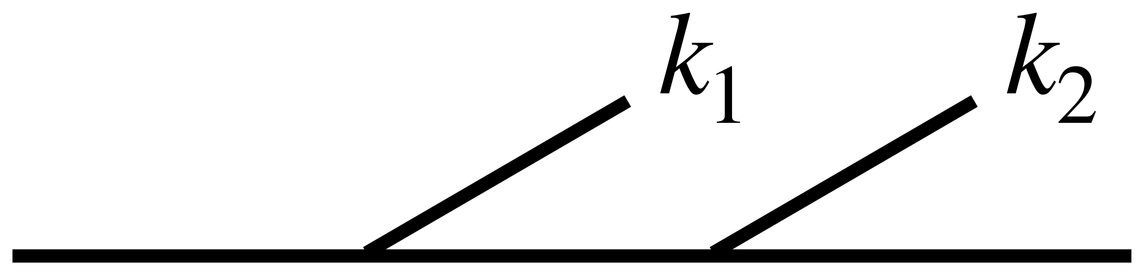


Distribute k_1 according to $M^2(k_1)$

Make each new emission's distribution conditional on previous emission

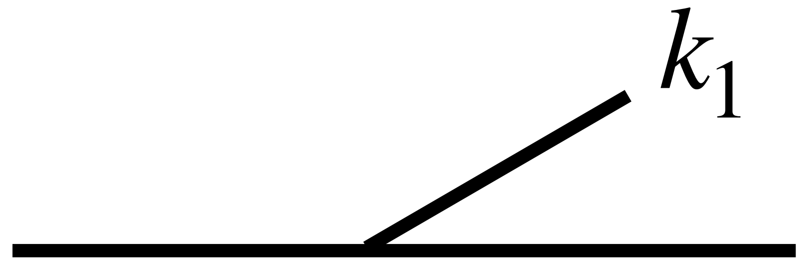


Distribute k_1 according to $M^2(k_1)$

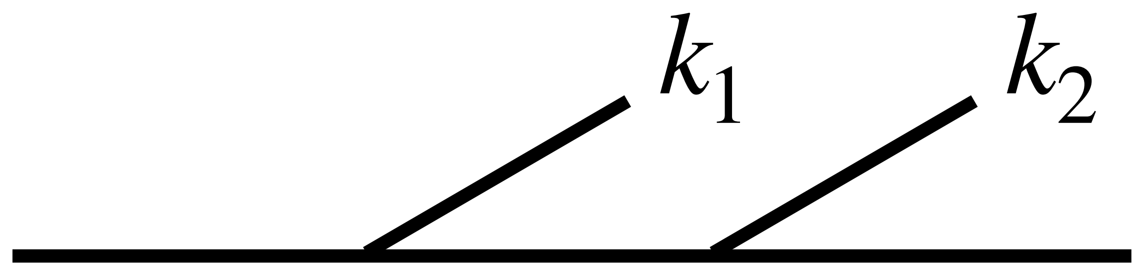


Distribute k_2 according to $M^2(k_1, k_2)/M^2(k_1)$

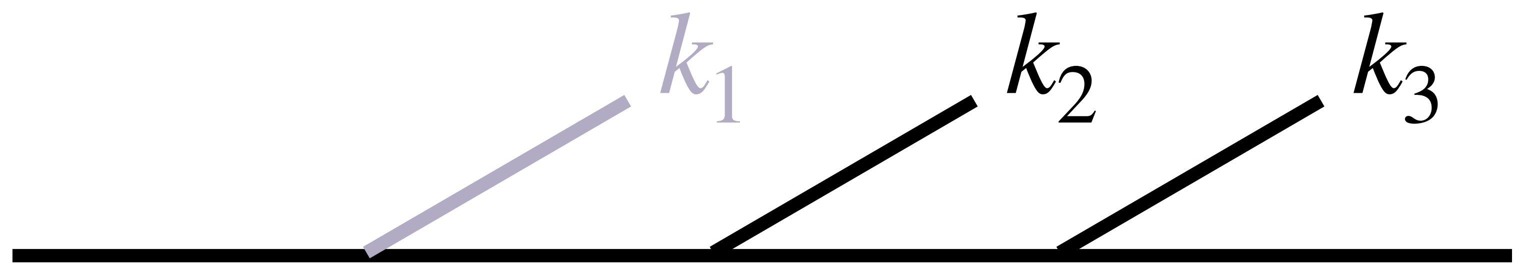
Make each new emission's distribution conditional on previous emission



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

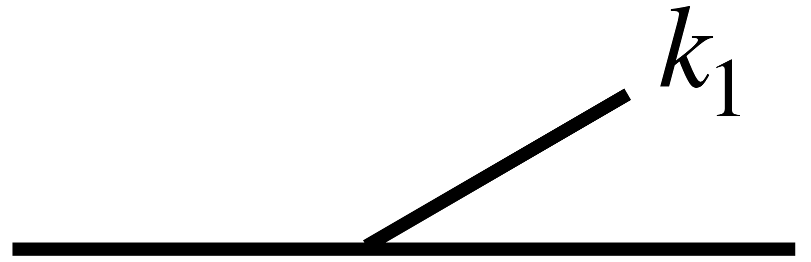


Distribute k_2 according to $M^2(k_1, k_2)/M^2(k_1)$

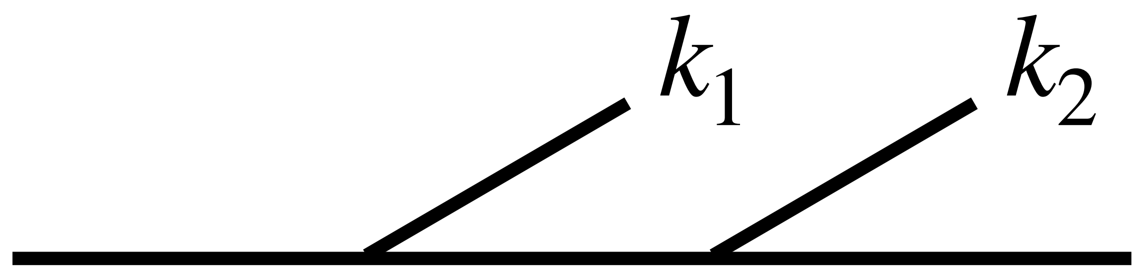


Distribute k_3 according to $M^2(k_2, k_3)/M^2(k_2)$

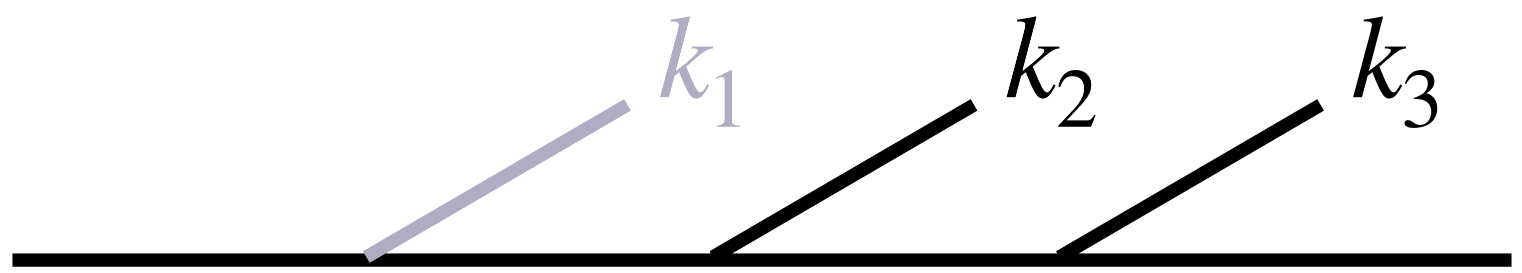
Make each new emission's distribution conditional on previous emission



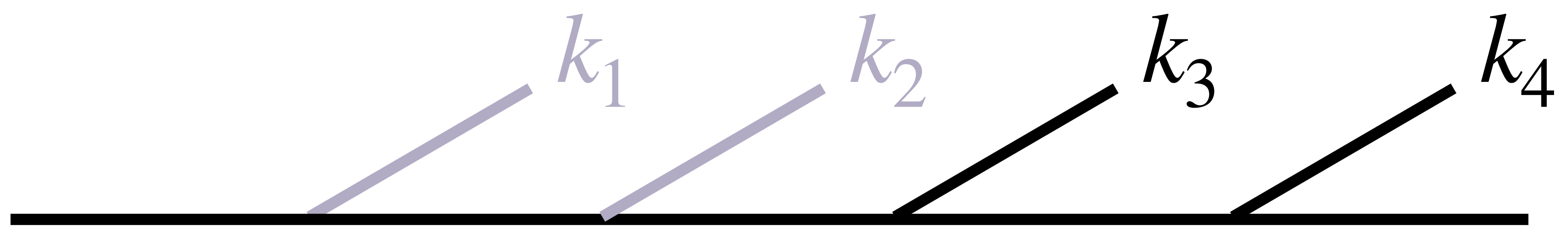
Distribute k_1 according to $M^2(k_1)$



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

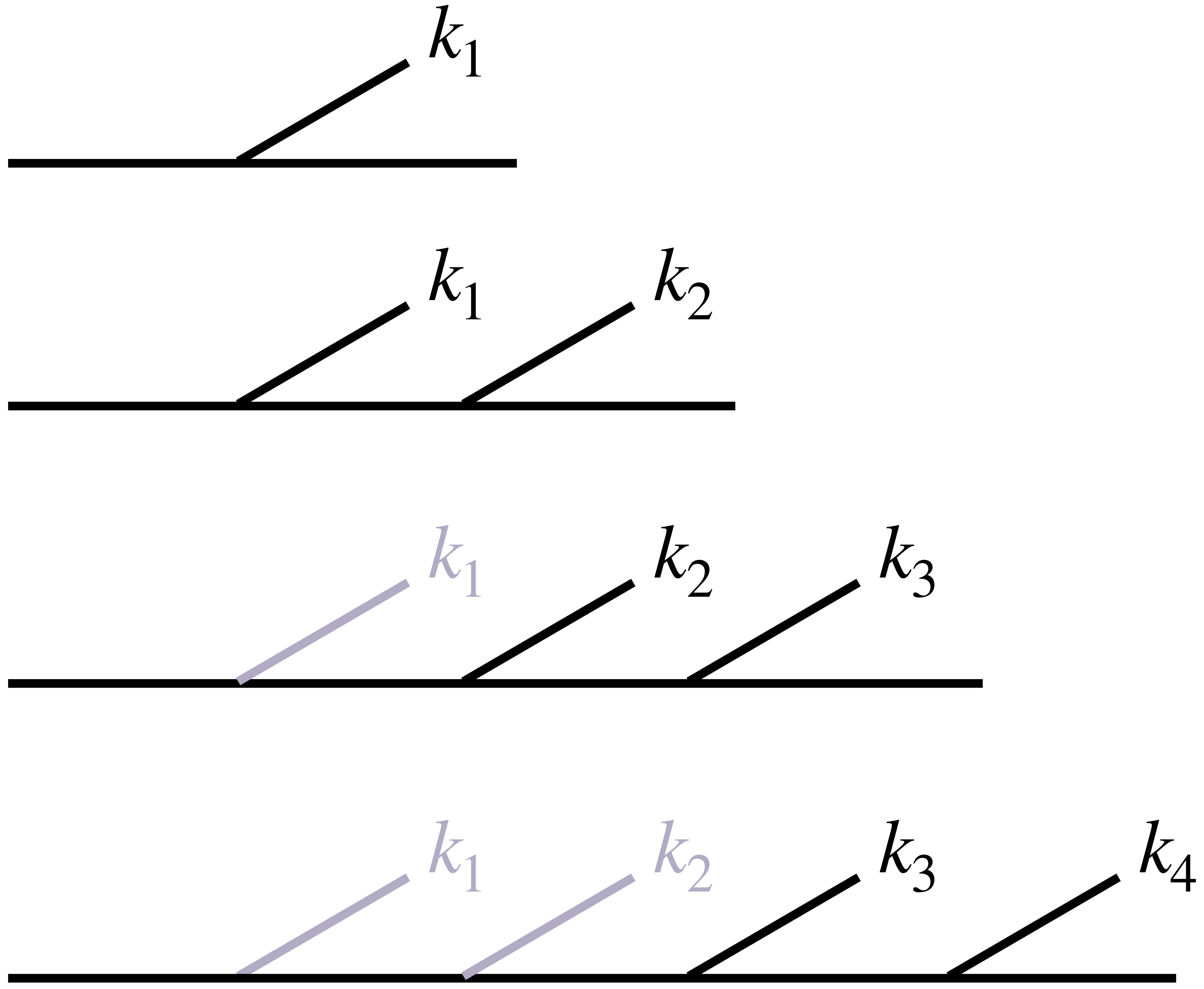


Distribute k_3 according to $M^2(k_2, k_3)/M^2(k_2)$



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

Make each new emission's distribution conditional on previous emission



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

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

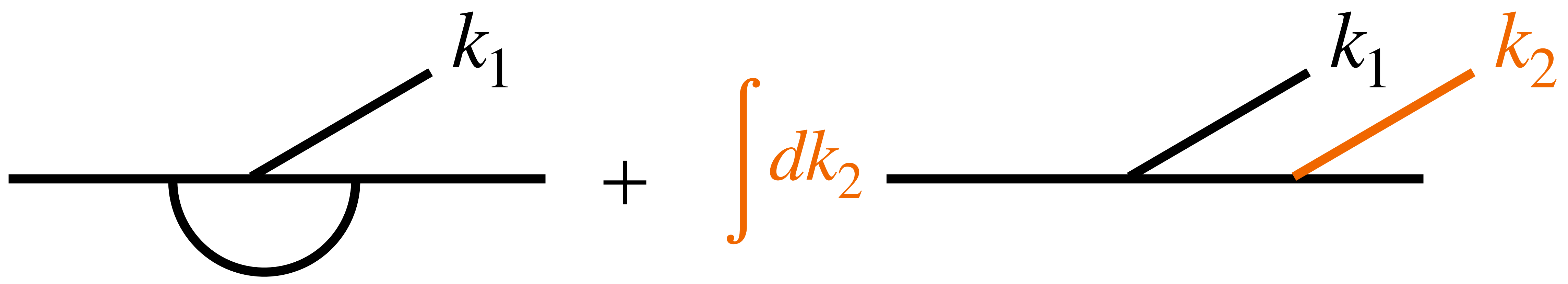
Distribute k_3 according to $M^2(k_2, k_3)/M^2(k_2)$

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

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

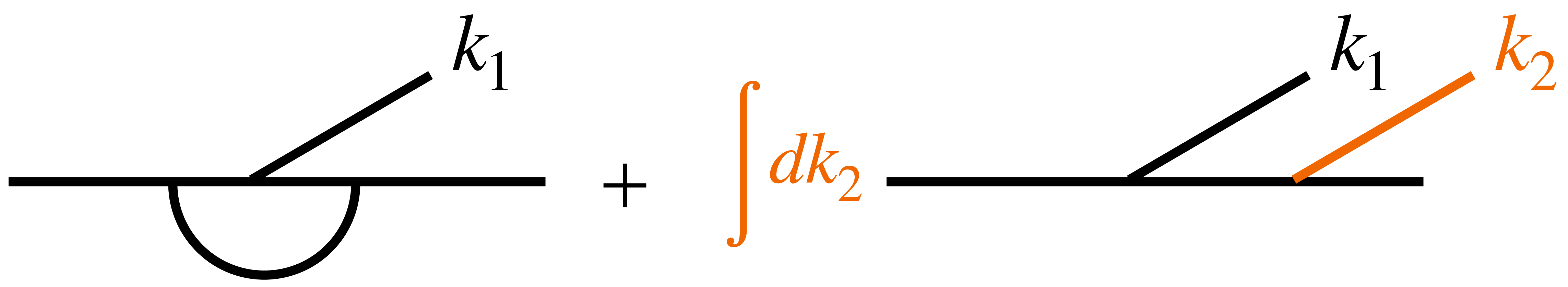
[factorised matrix elements given in Dokshitzer, Marchesini & Oriani '92, Campbell & Glover, hep-ph/9710255, Catani & Grazzini hep-ph/9810389, etc.]

Account for virtual corrections associated with each emission

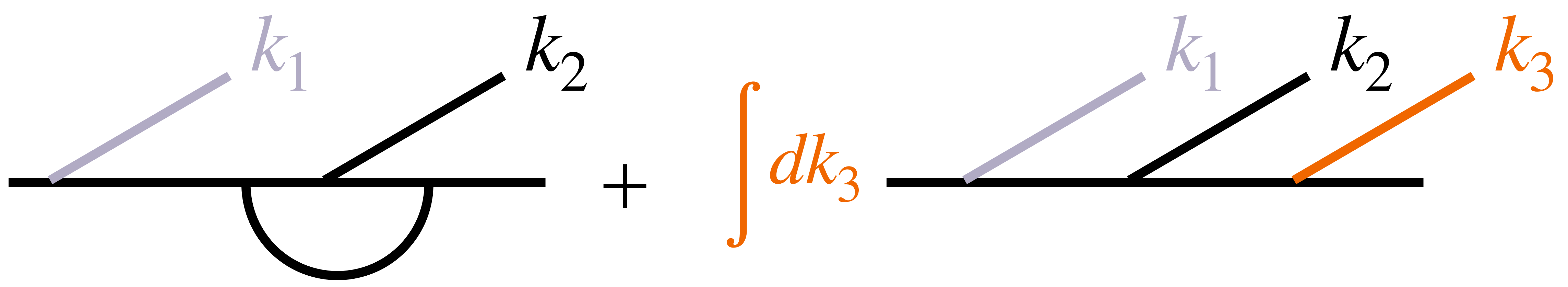


NLO correction to k_1 emission intensity sums loop correction and all possible scenarios for the next emission

Account for virtual corrections associated with each emission



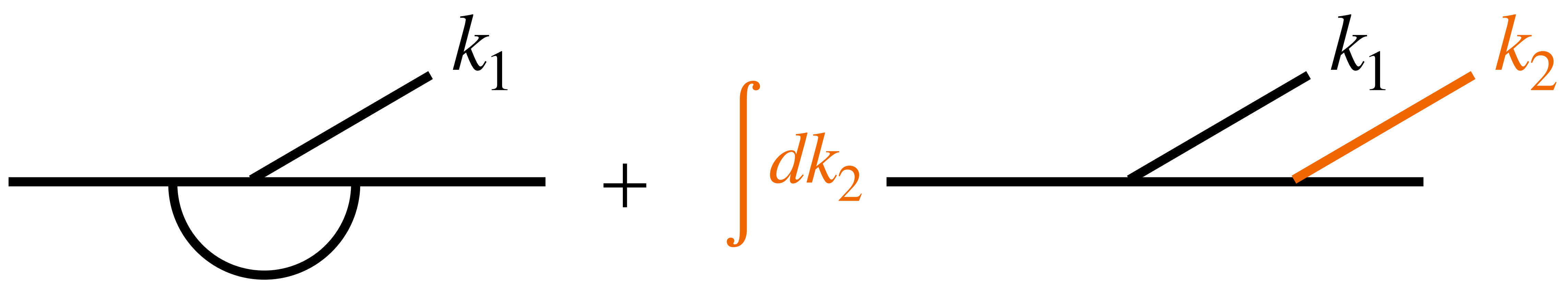
NLO correction to k_1 emission intensity sums loop correction and all possible scenarios for the next emission



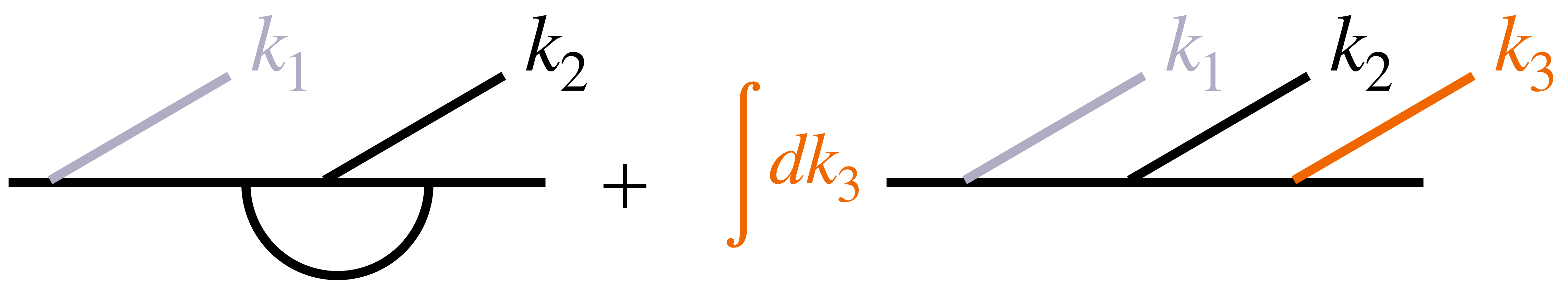
NLO correction to k_2 emission intensity sums loop correction and all possible scenarios for the next emission

etc.

Account for virtual corrections associated with each emission



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

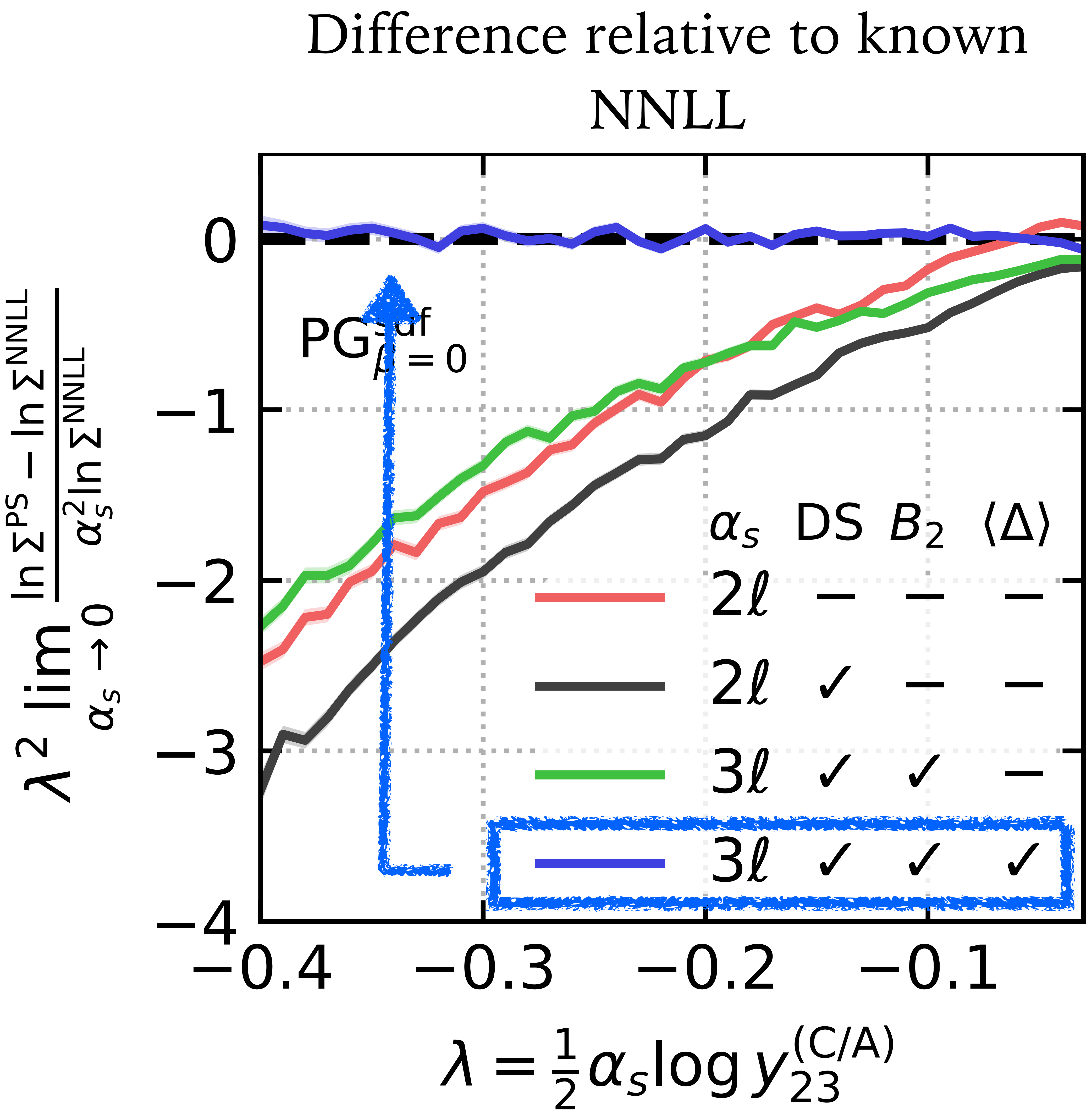


NLO correction to k_2 emission intensity sums loop correction and all possible scenarios for the next emission

etc.

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

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

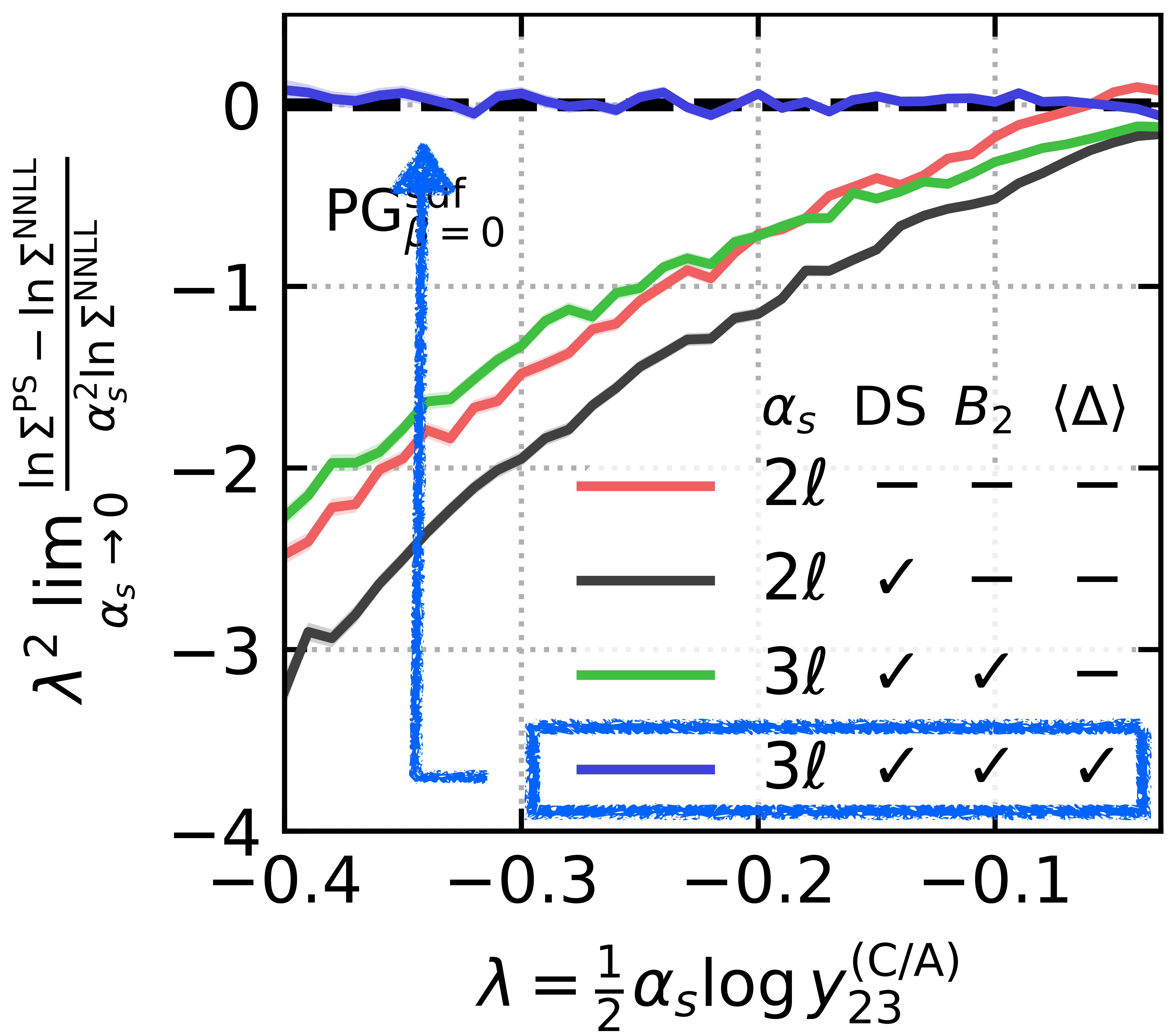


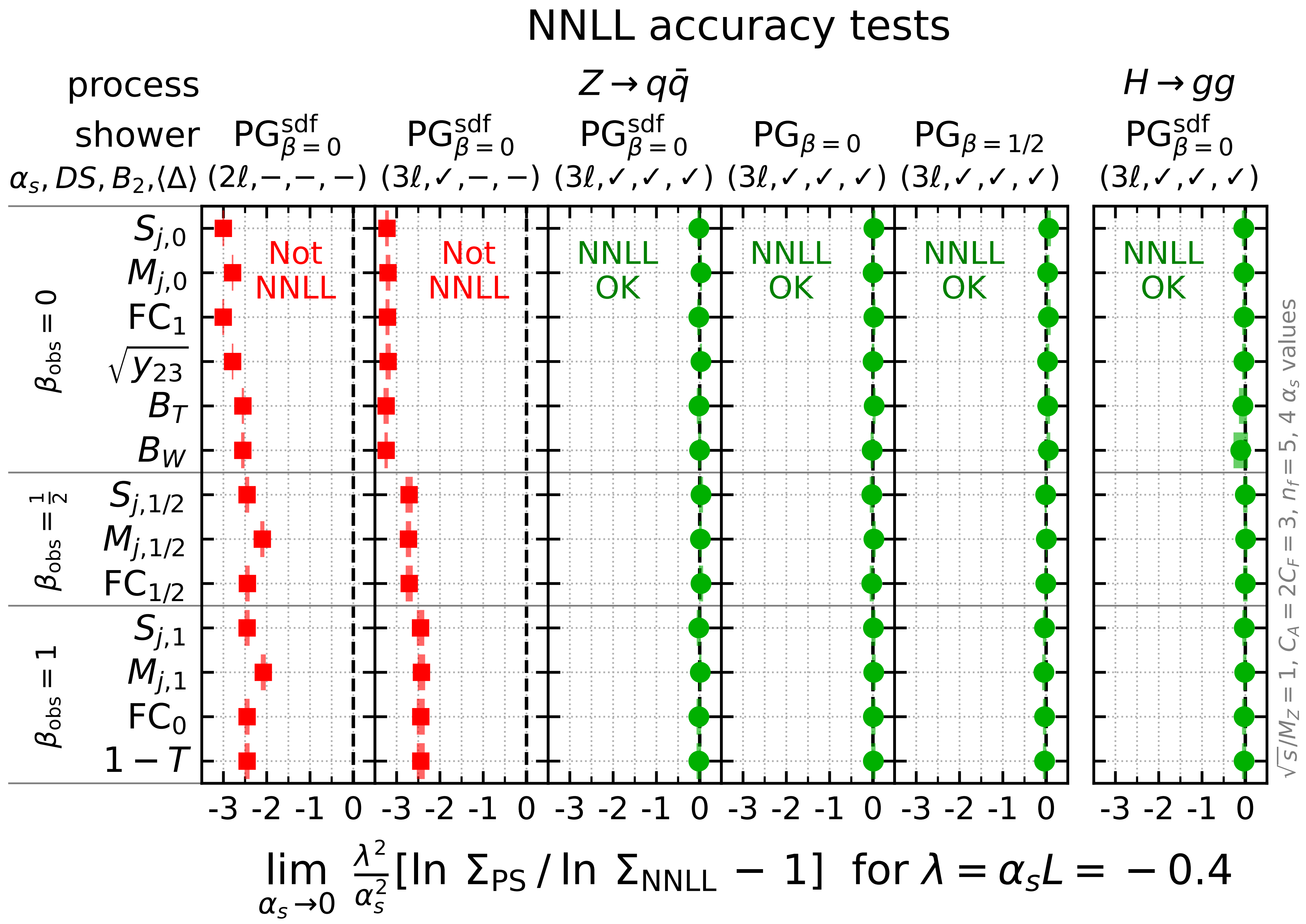
need to analyse and account for all possible sources of NNLL contribution

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

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

Difference relative to known NNLL

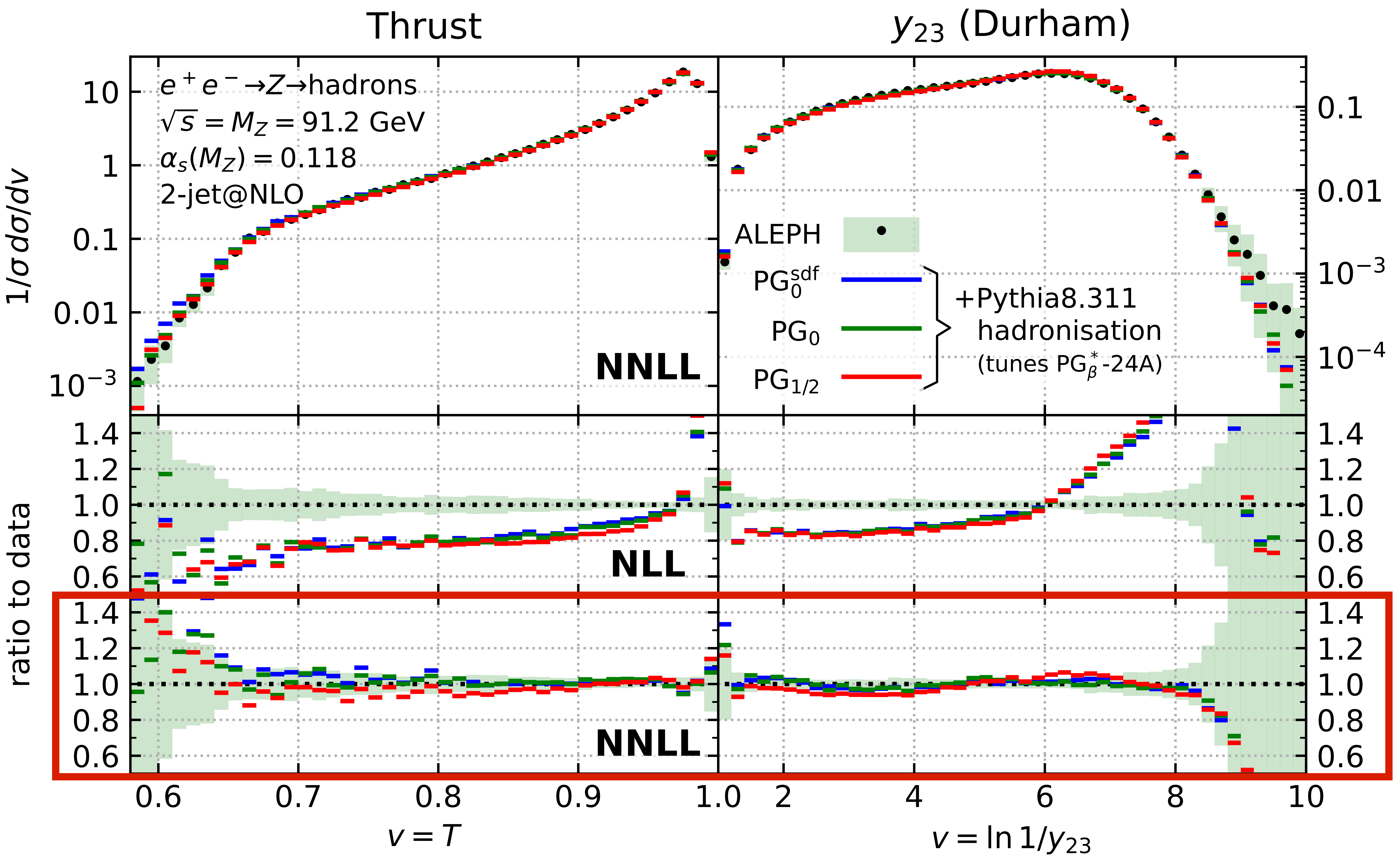




need to analyse and account for all possible sources of NNLL contribution

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

Comparing to LEP event-shape data



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

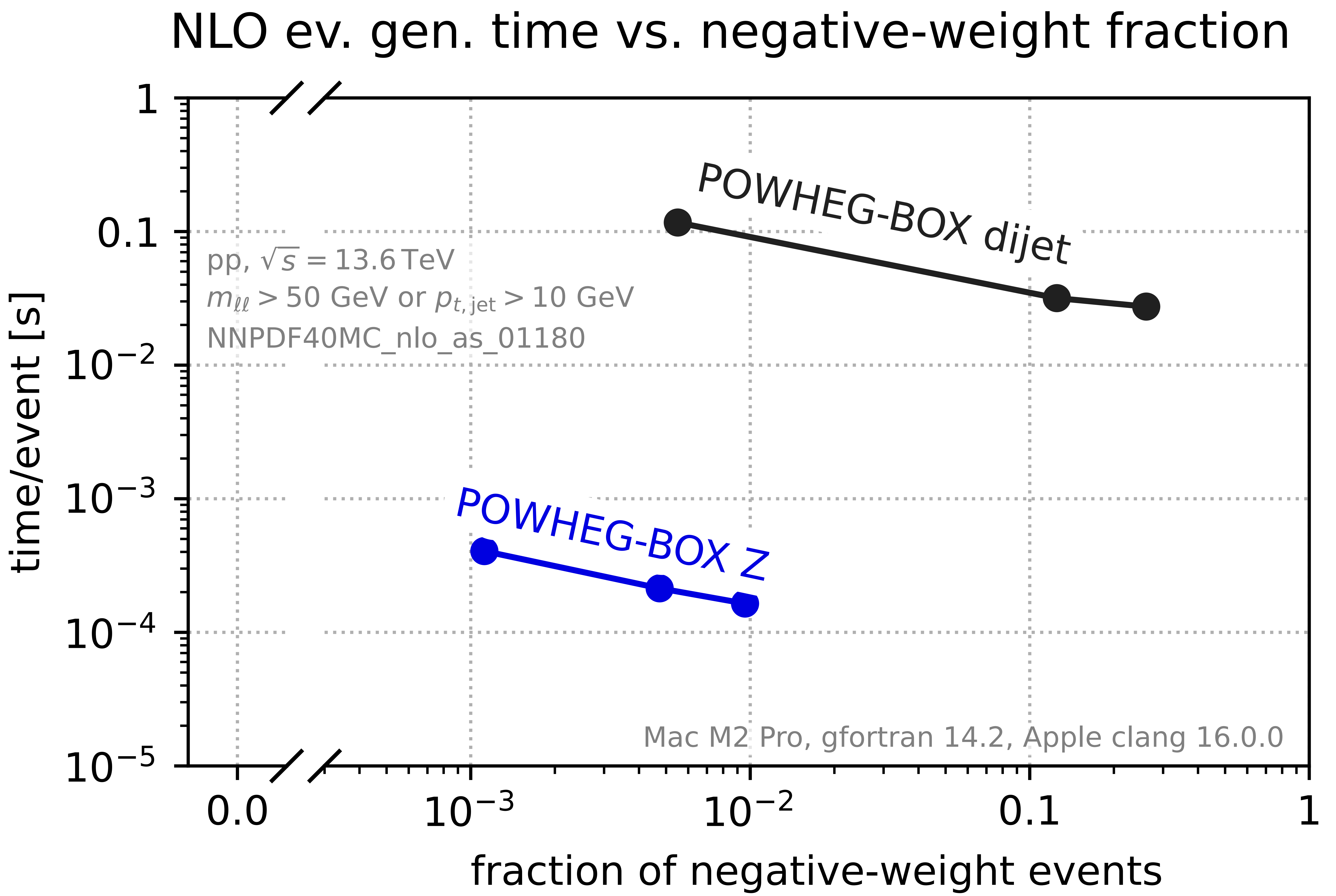
Element #4: positive-definite NLO event normalisation

NLO normalisation of parton shower event rates is a long-solved problem

Frixione-Webber "MC@NLO" hep-ph/0204244

& Nason "POWHEG" hep-ph/0409146

But only if you accept some finite fraction of events with negative "weights" ≡ negative probability

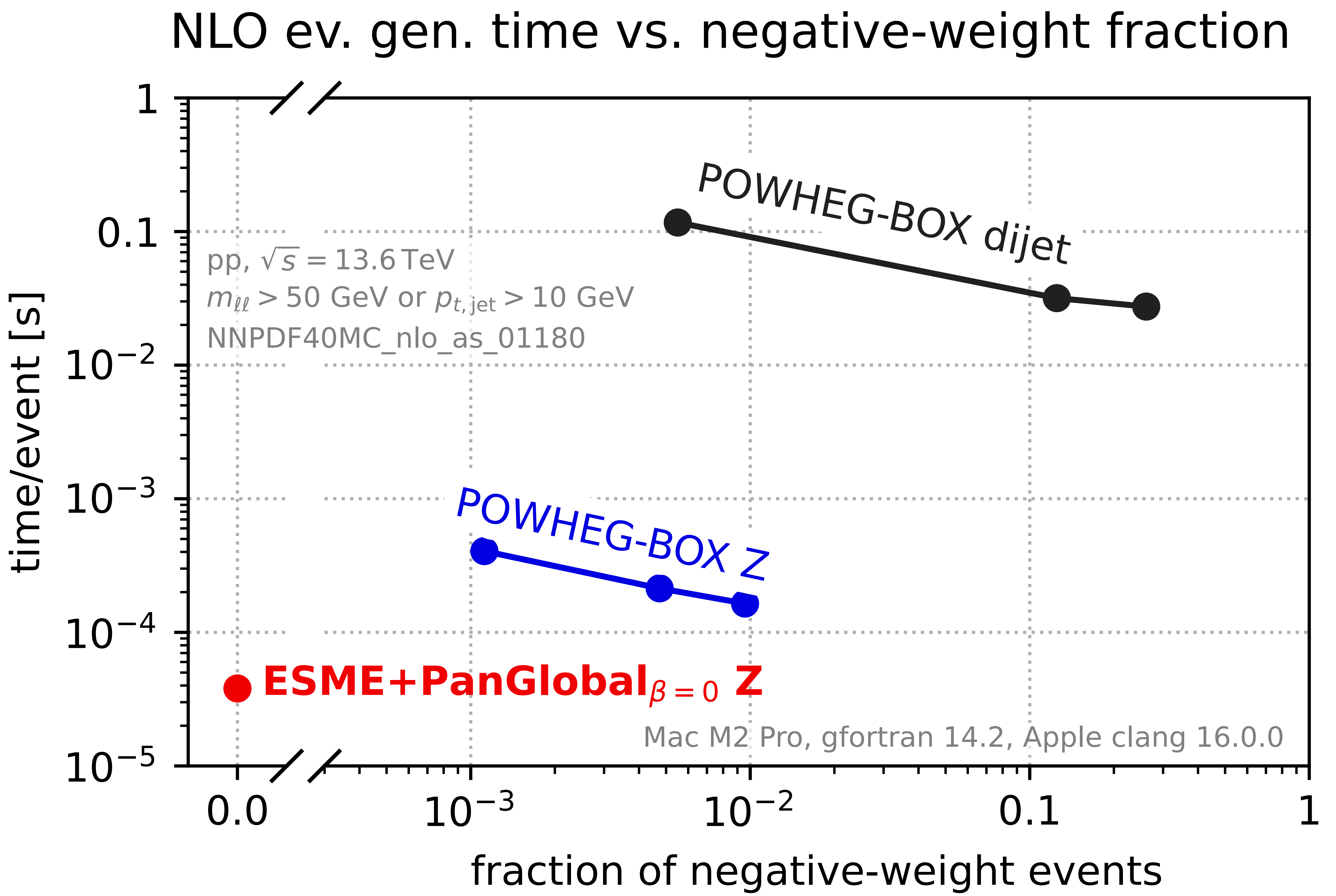


much debated practical problem, affects

1. performance
(negative weights worsen Monte Carlo convergence)

2. machine-learning
(ML expects “physical" training samples)

Existing approaches mitigate, but don’t solve the problem



much debated practical problem, affects

1. performance
(negative weights worsen Monte Carlo convergence)

2. machine-learning
(ML expects "physical" training samples)

Existing approaches mitigate, but don't solve the problem

New approach: **"Exponentiated Subtraction for Matching Events" (ESME)**
guarantees NLO *and* absence of negative-weight events, van Beekveld et al, 2503.nnnnn

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 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.

General principles for NNLL parton showers

A new standard for the logarithmic accuracy of parton showers

Melissa van Beekveld,[1] Mrinal Dasgupta,[2] Basem Kamal El-Menoufi,[3] Silvia Ferrario Ravasio,[4] Keith Hamilton,[5] Jack Helliwell,[6] Alexander Karlberg,[4] Pier Francesco Monni,[4] Gavin P. Salam,[6,7] Ludovic Scyboz,[3] Alba Soto-Ontoso,[4] and Gregory Soyez[8]
[1] *Nikhef, Theory Group, Science Park 105, 1098 XG, Amsterdam, The Netherlands*
[2] *Department of Physics & Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom*
[3] *School of Physics and Astronomy, Monash University, Wellington Rd, Clayton VIC-3800, Australia*
[4] *CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland*
[5] *Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK*
[6] *Rudolf Peierls Centre for Theoretical Physics, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK*
[7] *All Souls College, Oxford OX1 4AL, UK*
[8] *IPhT, Université Paris-Saclay, CNRS UMR 3681, CEA Saclay, F-91191 Gif-sur-Yvette, France*

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

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.

Parton showering with higher-logarithmic accuracy for soft emissions

Silvia Ferrario Ravasio,[1] Keith Hamilton,[2] Alexander Karlberg,[1] Gavin P. Salam,[3,4] Ludovic Scyboz,[3] and Gregory Soyez[1,5]
[1] *CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland*
[2] *Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK*
[3] *Rudolf Peierls Centre for Theoretical Physics, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK*
[4] *All Souls College, Oxford OX1 4AL, UK*
[5] *IPhT, Université Paris-Saclay, CNRS UMR 3681, CEA Saclay, F-91191 Gif-sur-Yvette, France*

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 and so for QCD to be (a) physical and (b) still subject to systematic improvement.

First indications are that full NNLL is essential for precision collider 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
- generalising positive-definite NLO to wider range of processes and to NNLO and beyond

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