Insights into the logarithmic accuracy of parton showers

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based mostly on arXiv:1805.09327 with
M. Dasgupta, F. Dreyer, K. Hamilton, P. Monni

** on leave from CERN and CNRS*

European Research Council
Established by the European Commission

THE ROYAL SOCIETY

Southampton HEP group
8/2/2019

at colliders, you can probe

“big unanswered questions”

about fundamental particles & their interactions

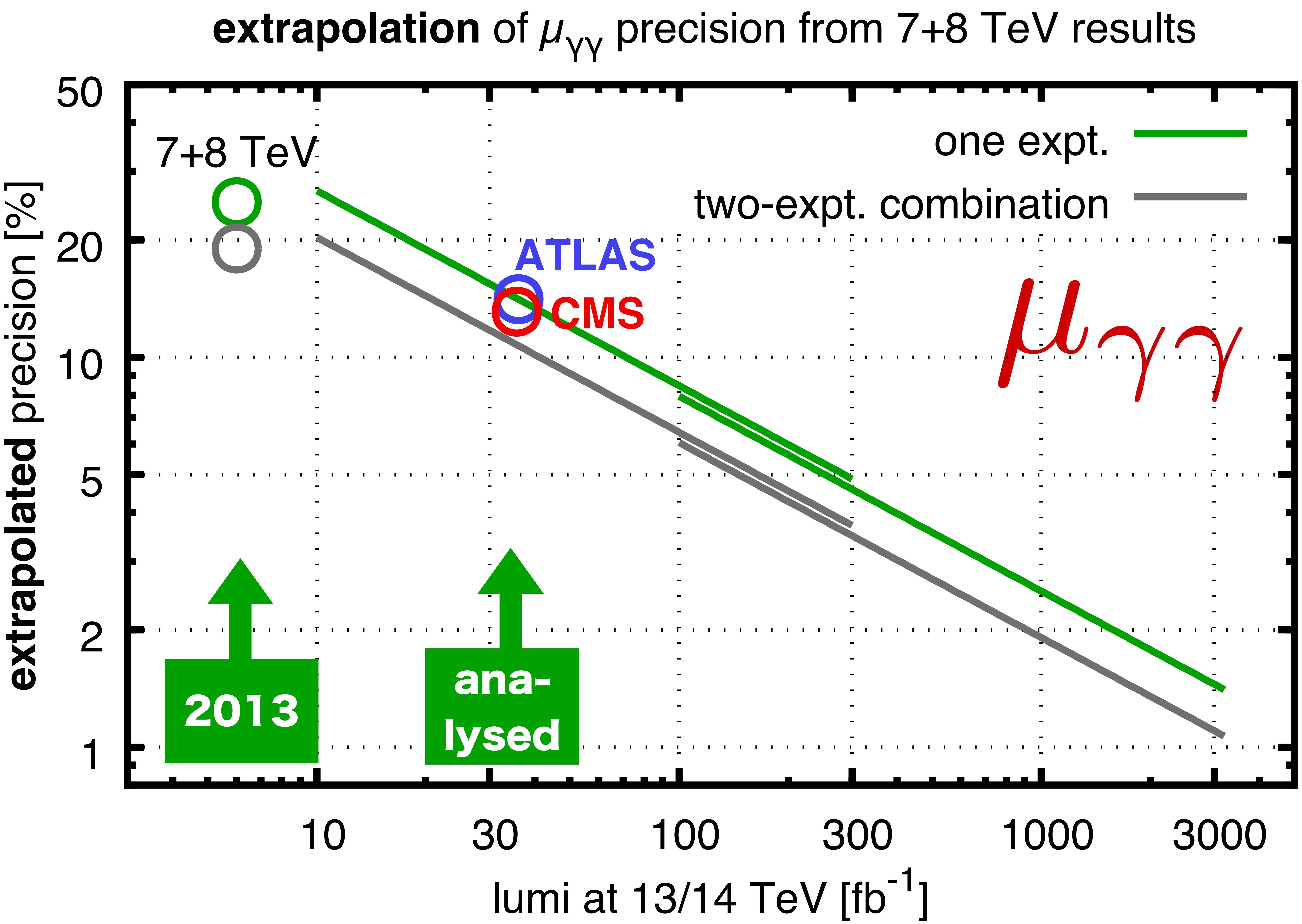
(dark matter, matter-antimatter asymmetry, nature of dark energy, hierarchy of scales…)

and

“big answerable questions”

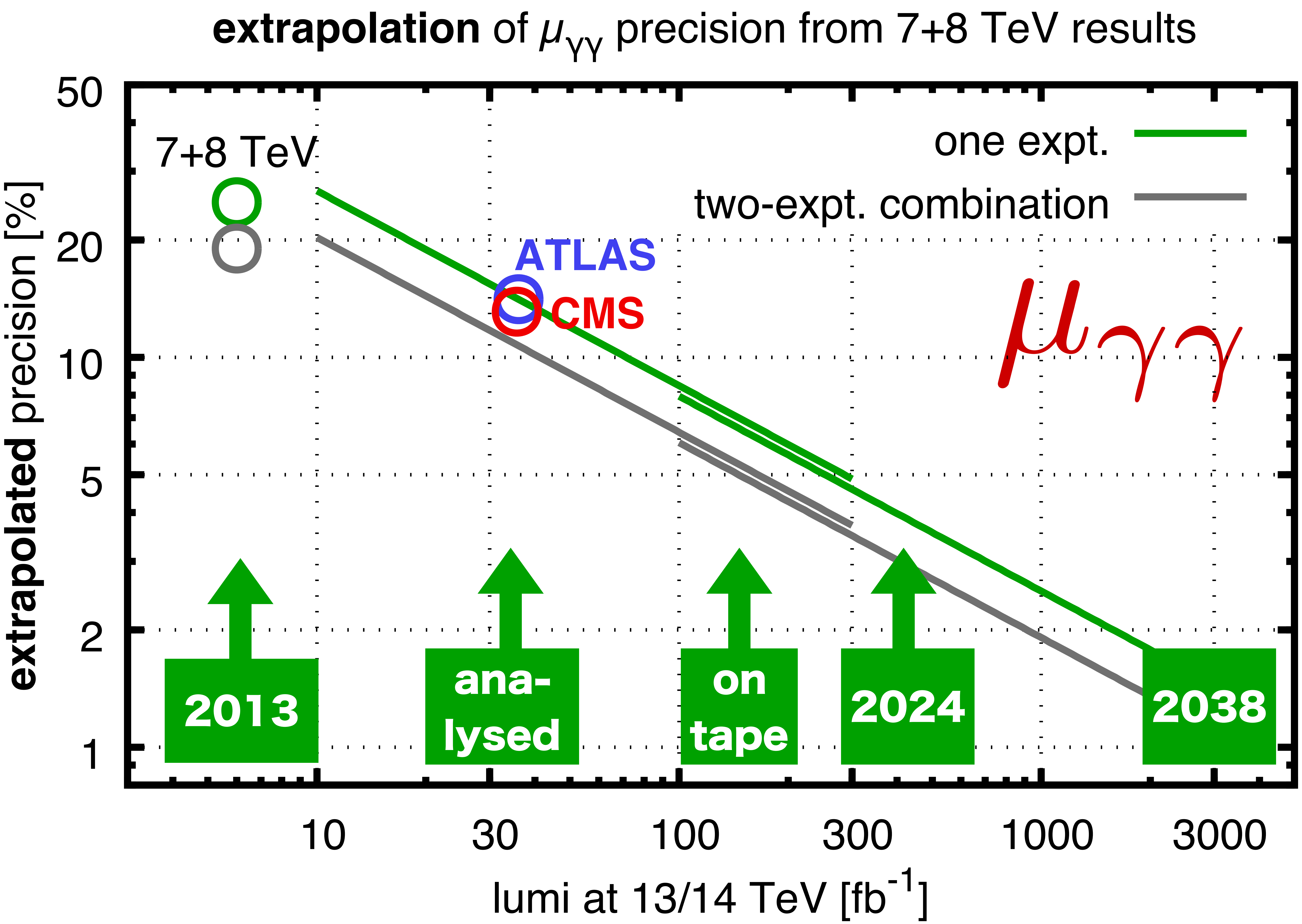
(structure of Higgs sector, determining fundamental parameters of Lagrangian of particle physics)

Higgs precision ($H \to \gamma\gamma$) : optimistic estimate v. luminosity & time



1 fb^{-1} = 10^{14} collisions

Higgs precision (H → γγ) : optimistic estimate v. luminosity & time



The LHC has the statistical potential to take Higgs physics from “observation” to 1–2% precision

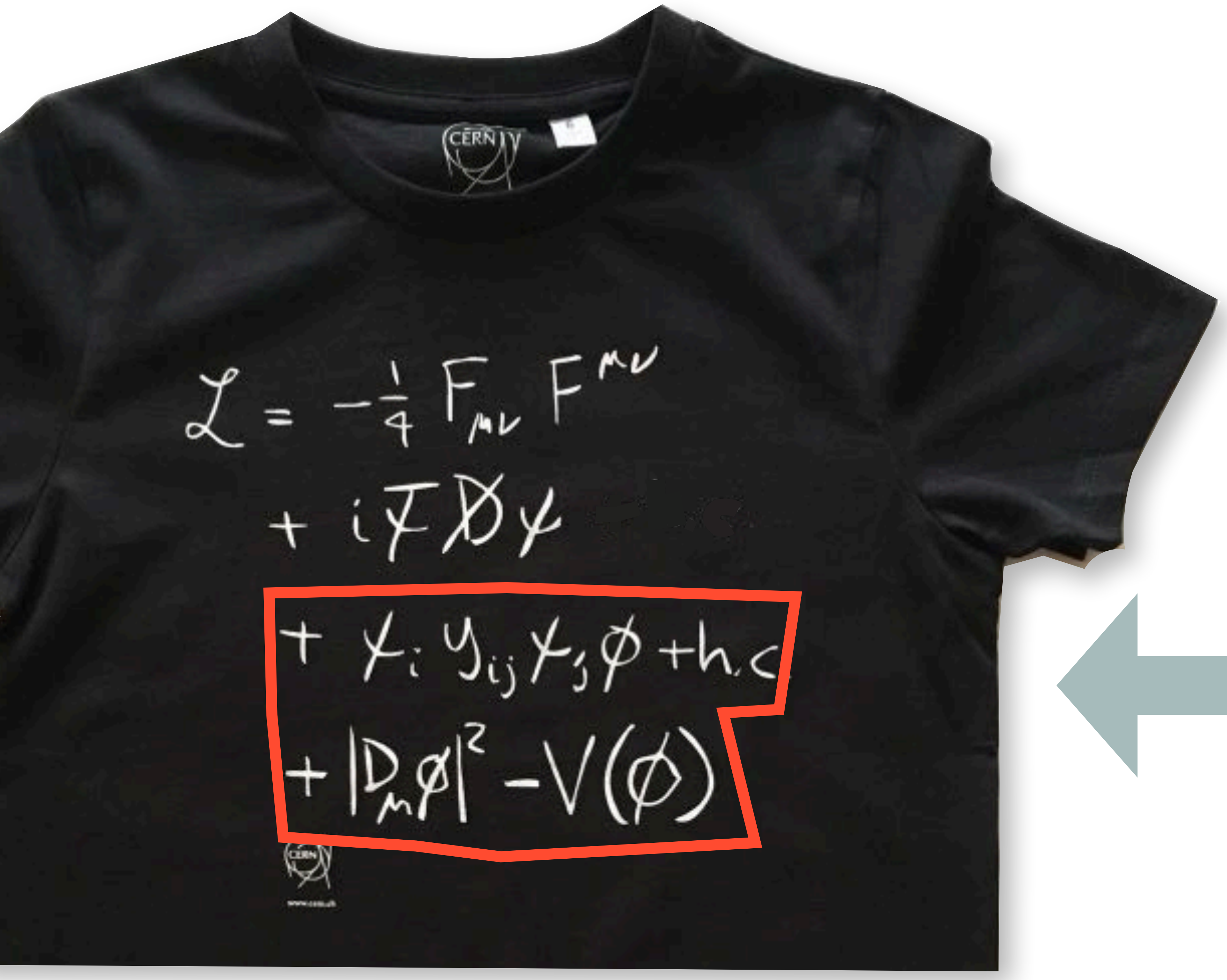
But only if we learn how to connect experimental observations with theory at that precision

1 fb^{-1} = 10^{14} collisions

how is all of this made quantitative?

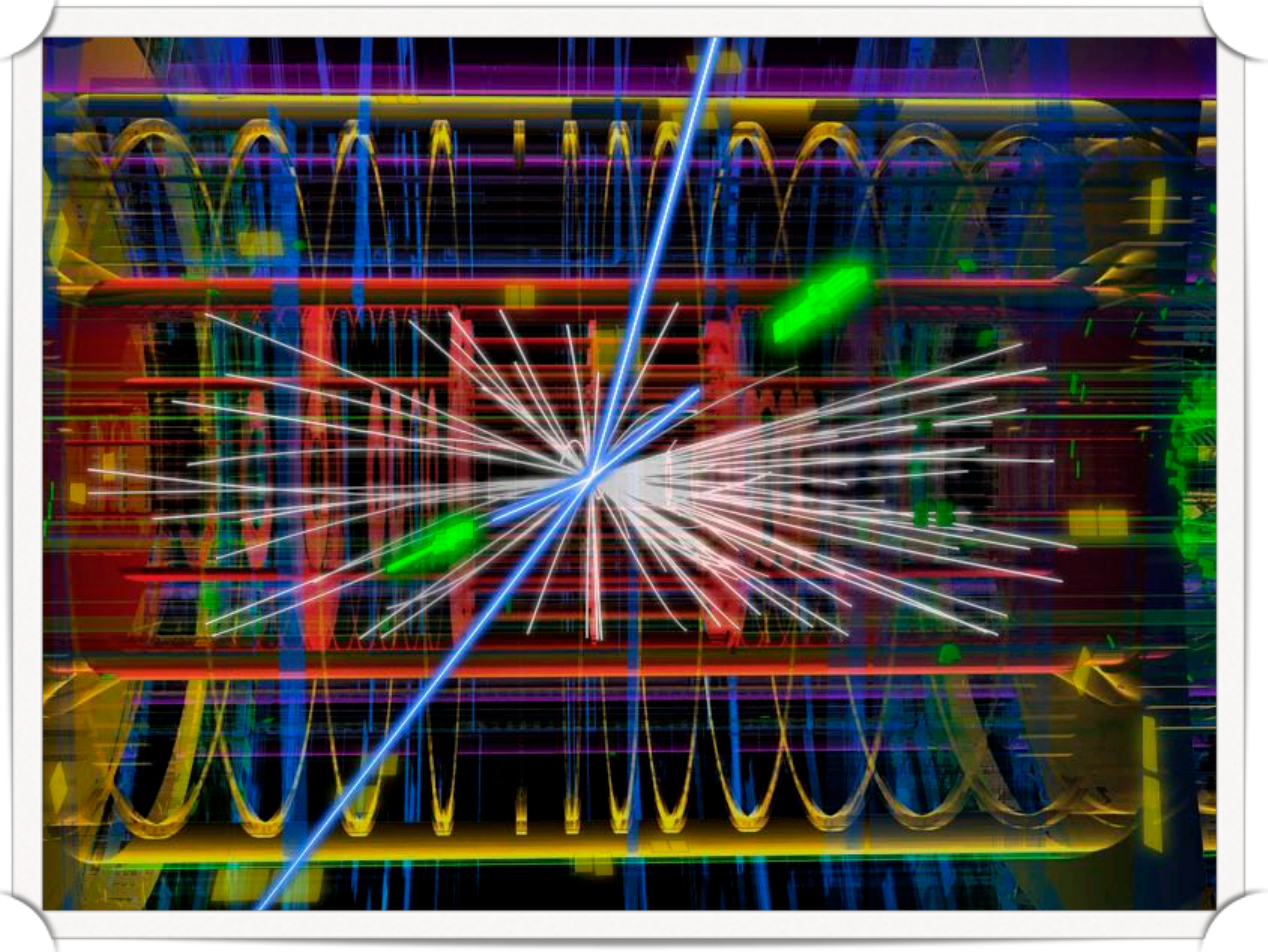
whether new-physics searches, Higgs physics, or other SM studies

UNDERLYING THEORY



how do you make quantitative connection?

EXPERIMENTAL DATA



UNDERLYING
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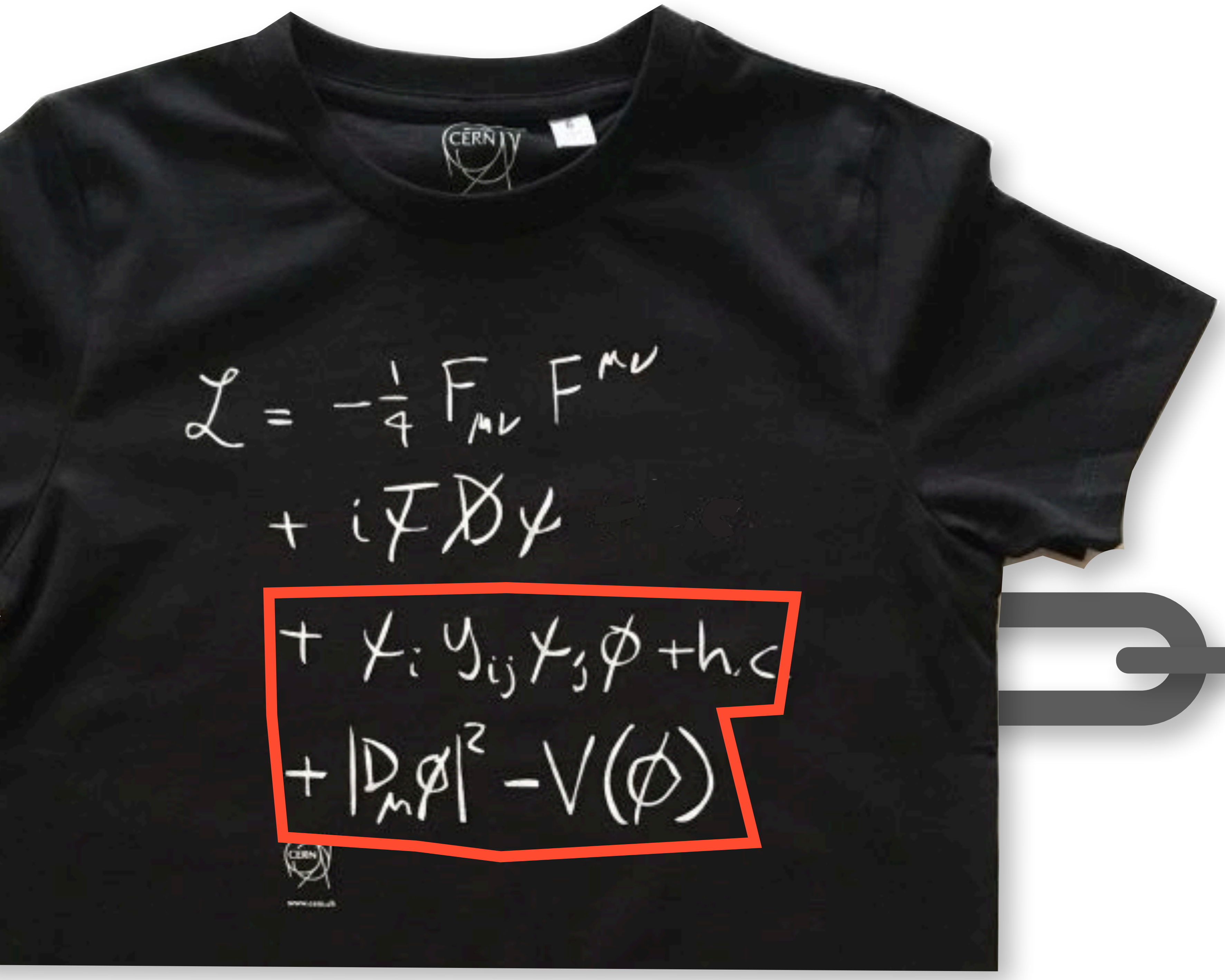

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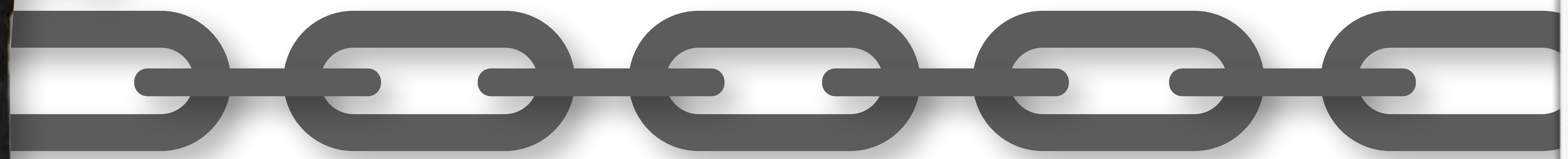
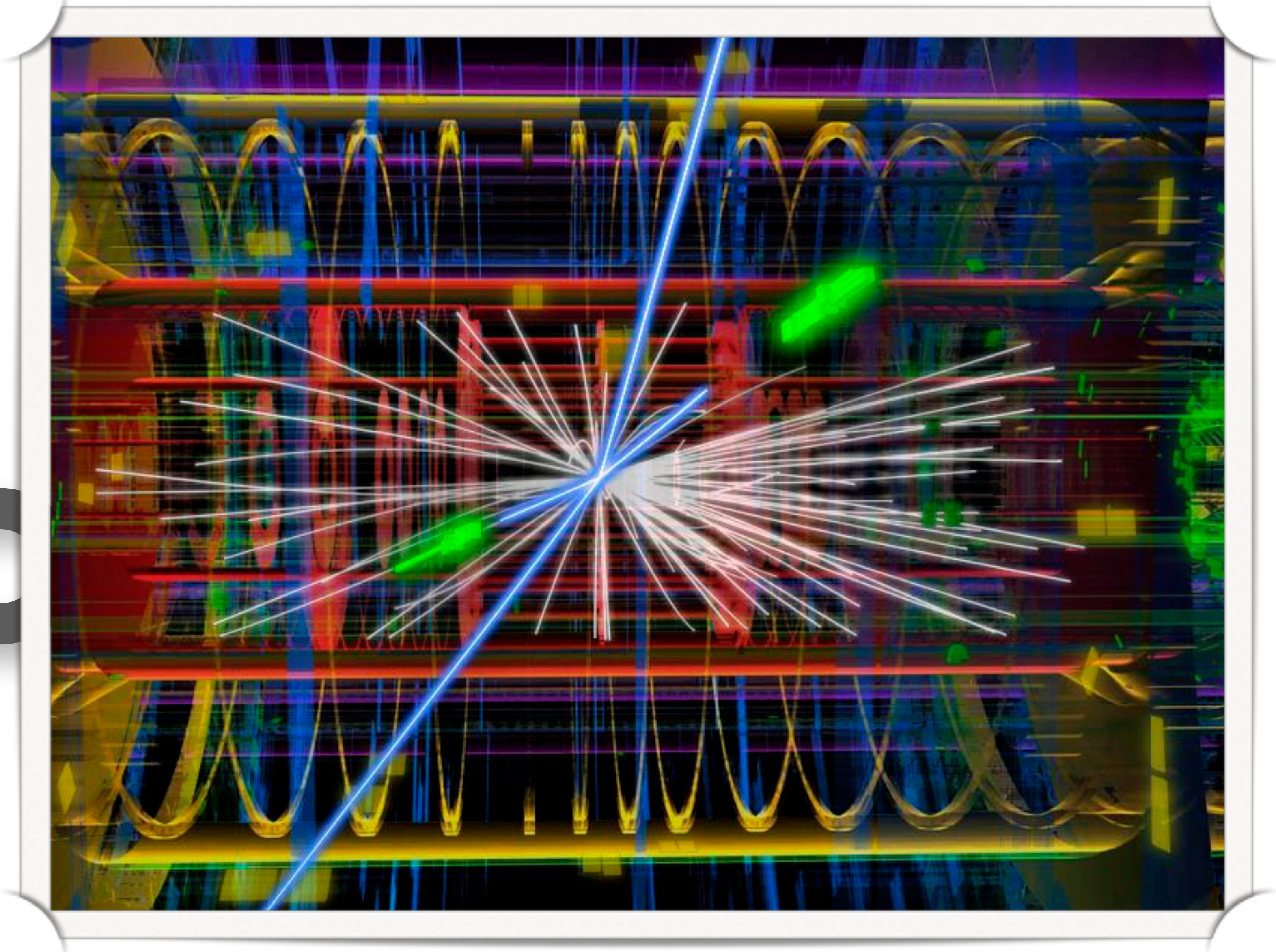
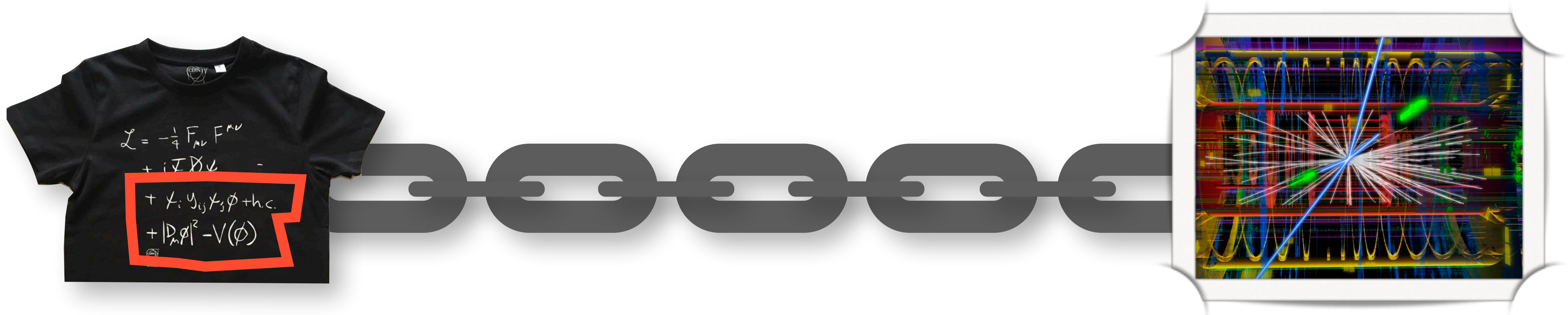




through a chain of experimental and theoretical links

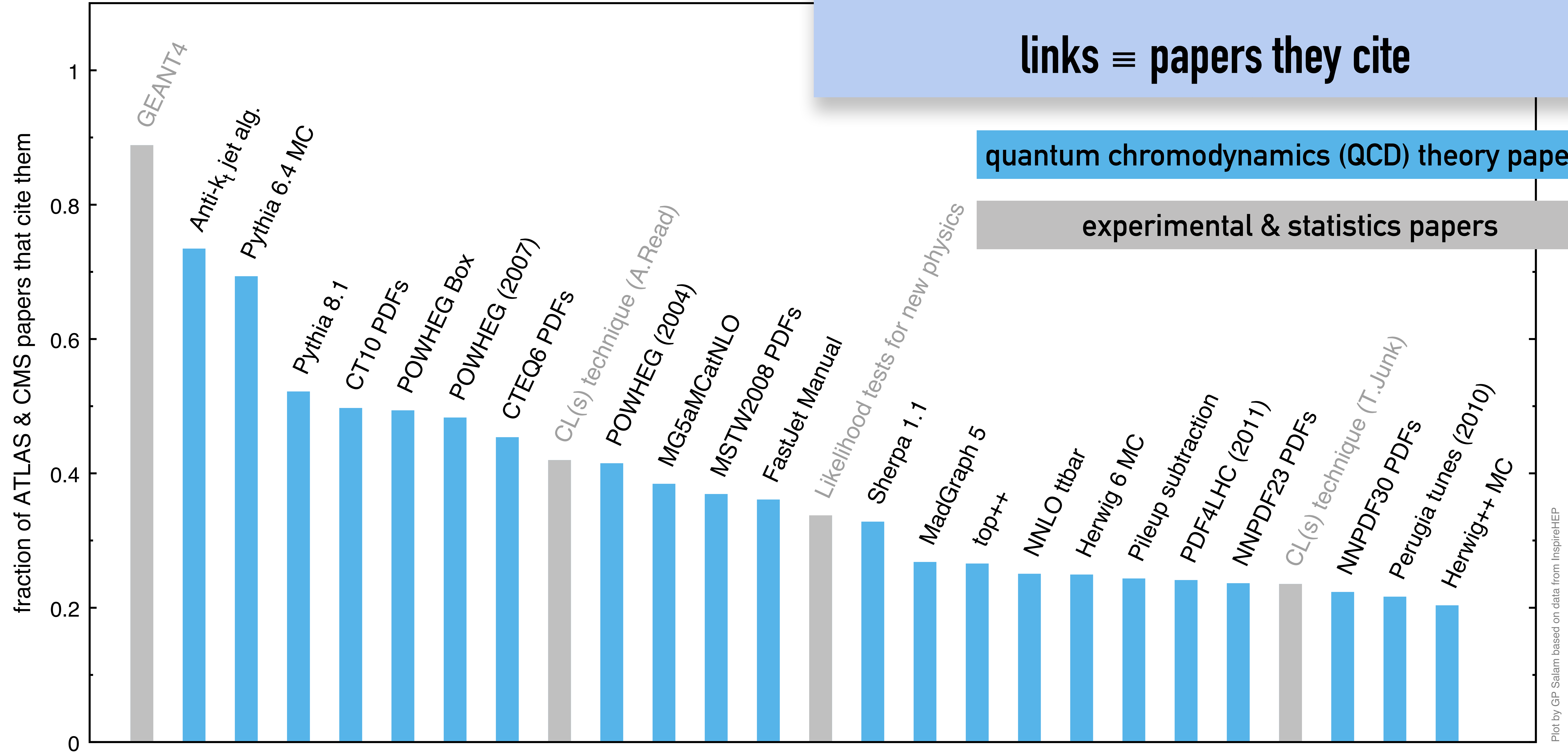
[in particular Quantum Chromodynamics (QCD)]



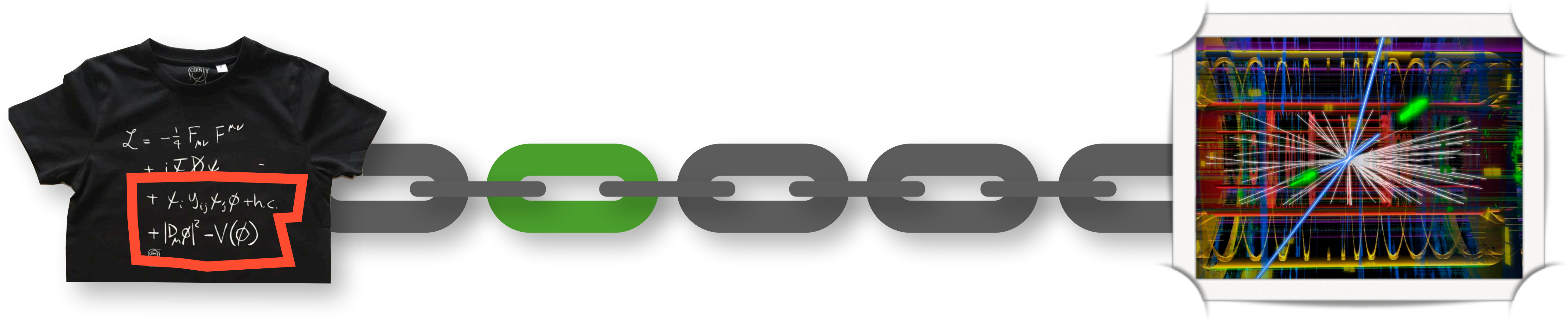
What are the links?

ATLAS and CMS (big LHC expts.) have written 850 articles since 2014

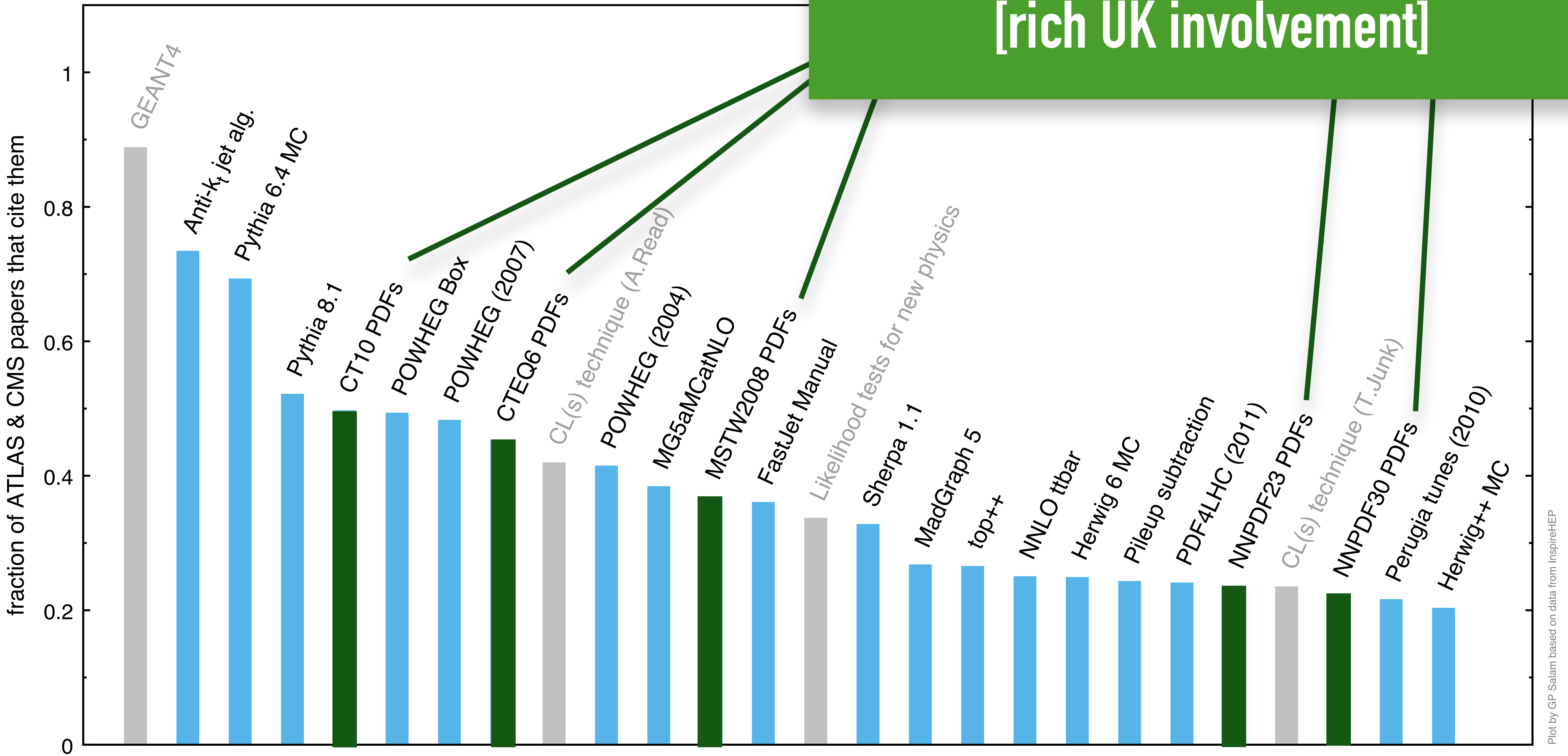
links ≡ papers they cite



Plot by GP Salam based on data from InspireHEP



knowing what goes into a collision
i.e. proton structure
[rich UK involvement]



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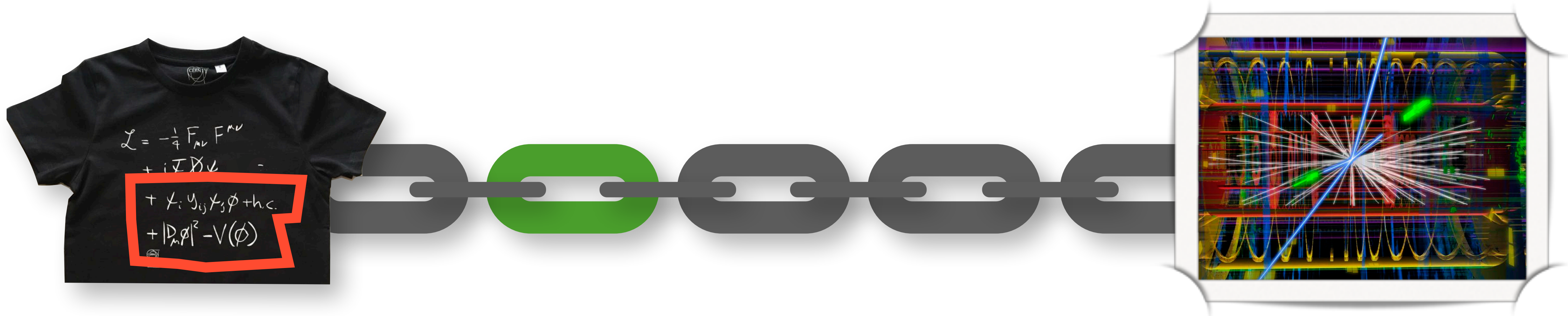

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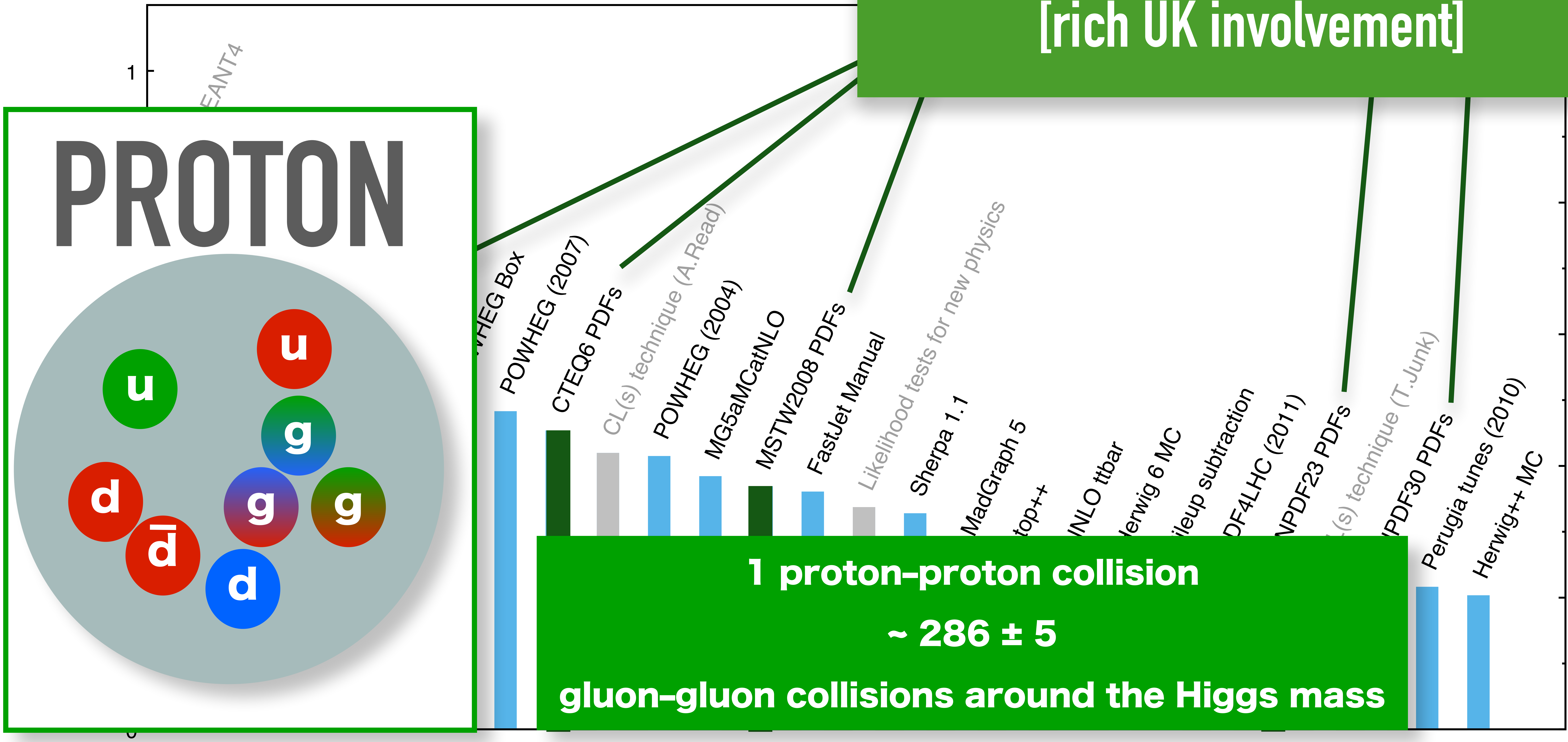
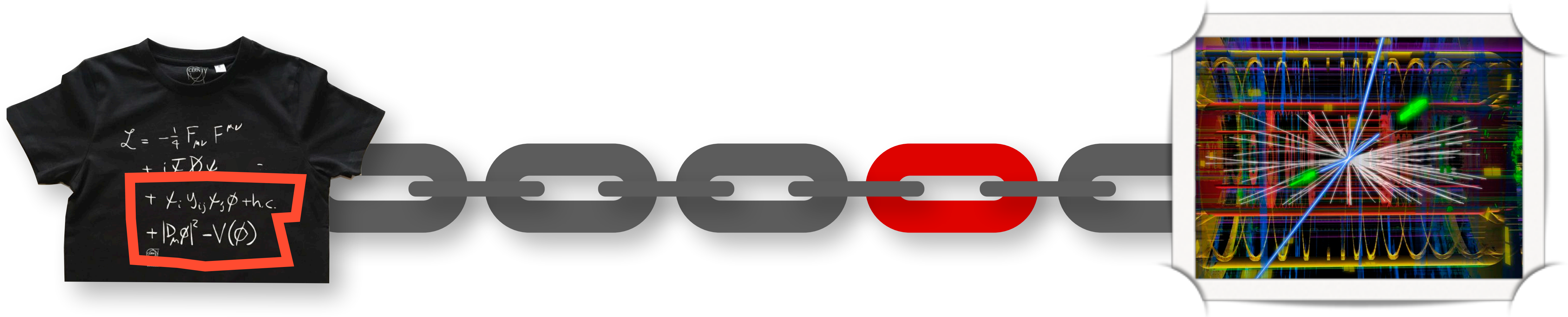
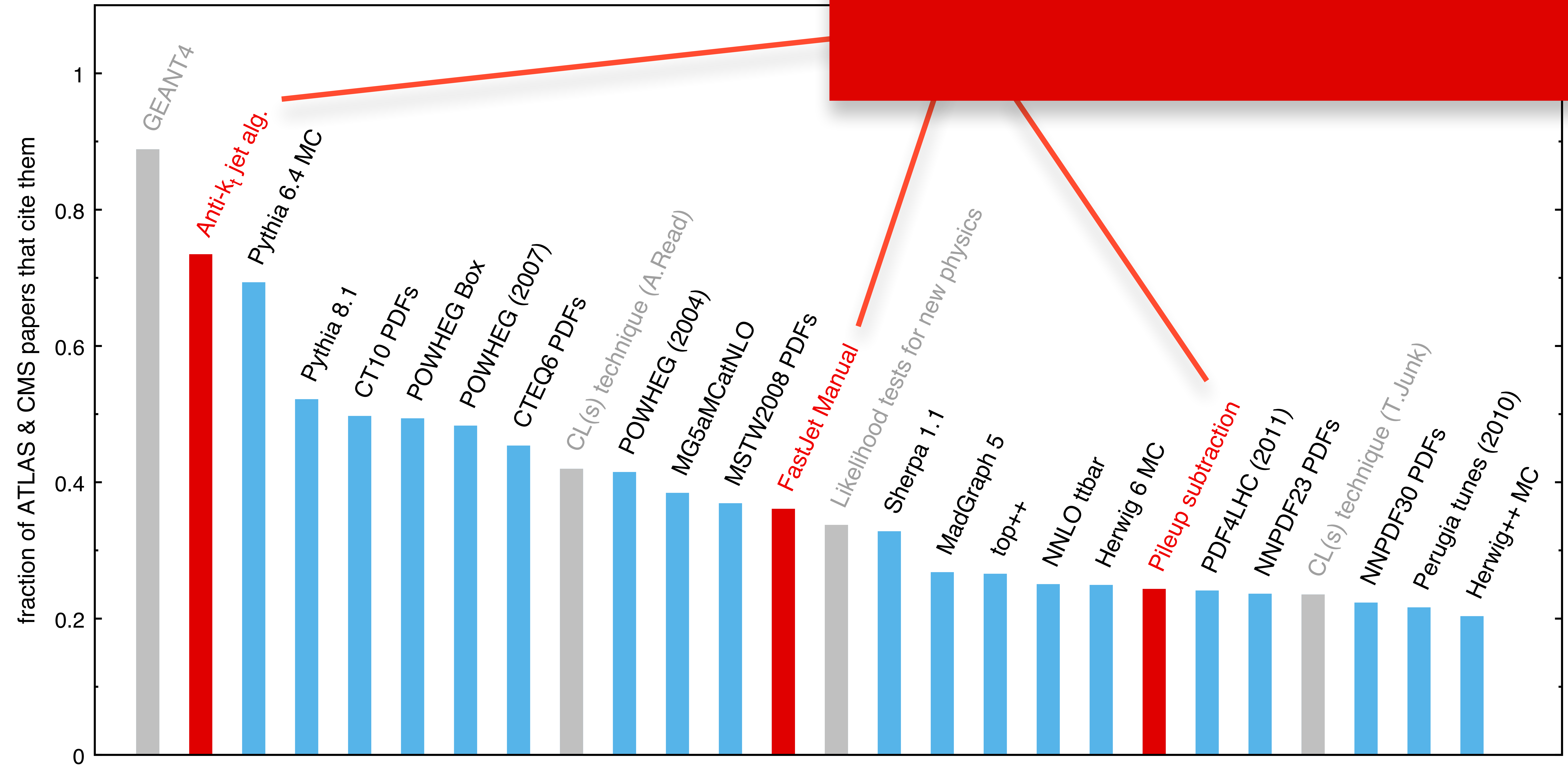


1 proton-proton collision
~ 286 ± 5
gluon-gluon collisions around the Higgs mass

Plot by GP Salam based on data from InspireHEP

organising event information ("jets")





Plot by GP Salam based on data from InspireHEP

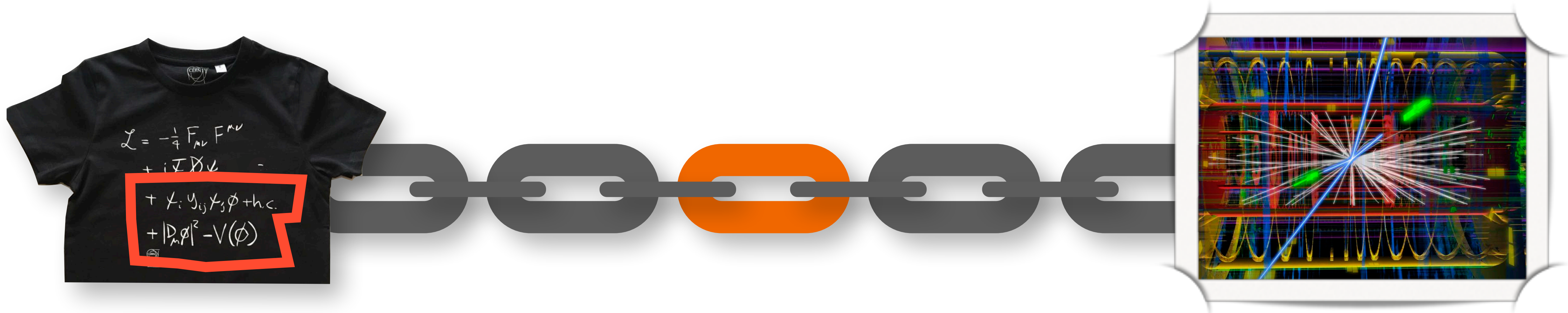

CMS Experiment at the LHC, CERN
Simulated event at 13 TeV centre-of-mass energy
Y
x
z

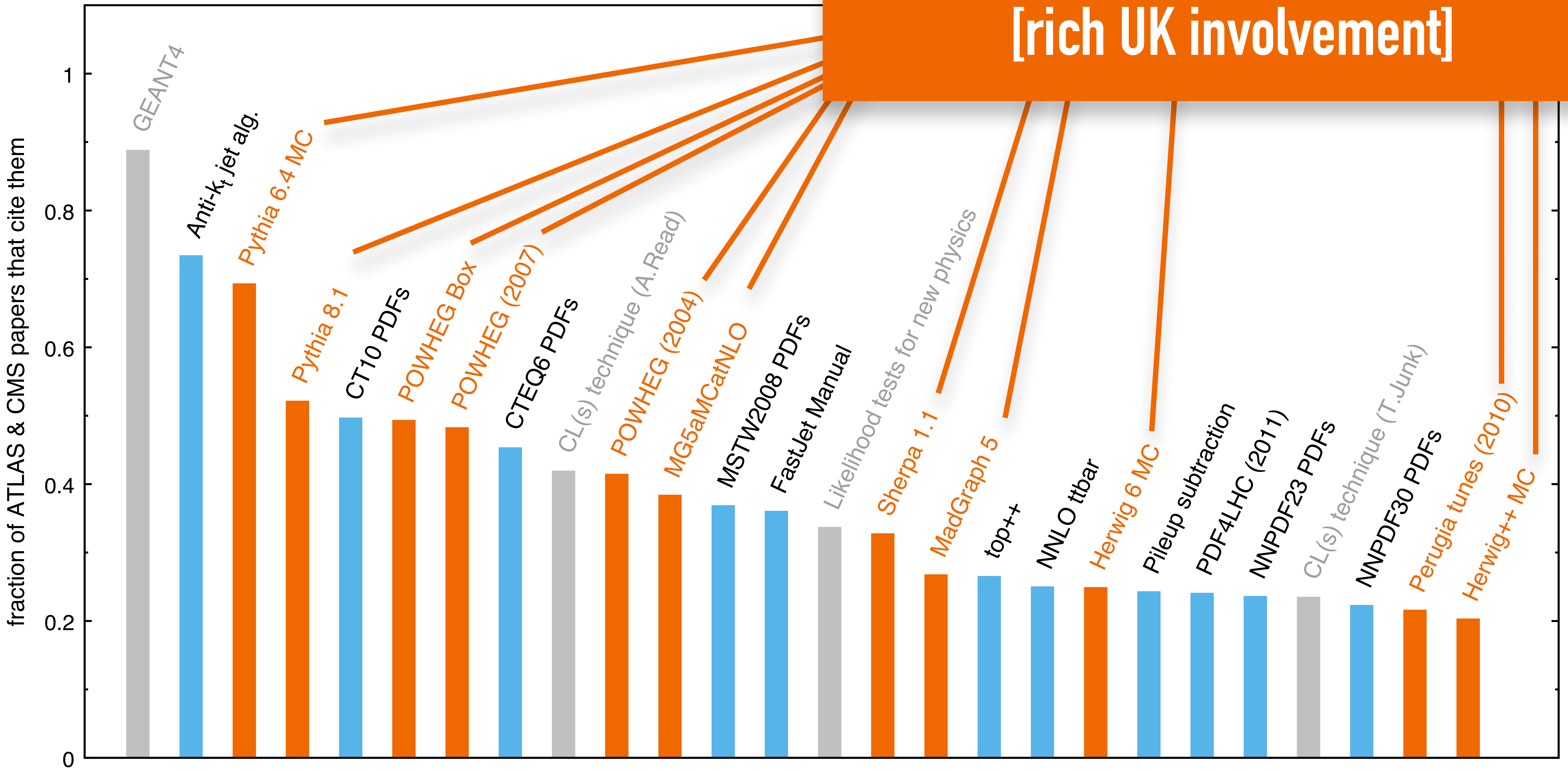

CMS
CMS Experiment at the LHC, CERN
Simulated event at 13 TeV centre-of-mass energy
Y
x
z

the question of organising information from hundreds of particles will come back later

predicting full particle structure that comes out of a collision

[rich UK involvement]





Plot by GP Salam based on data from InspireHEP

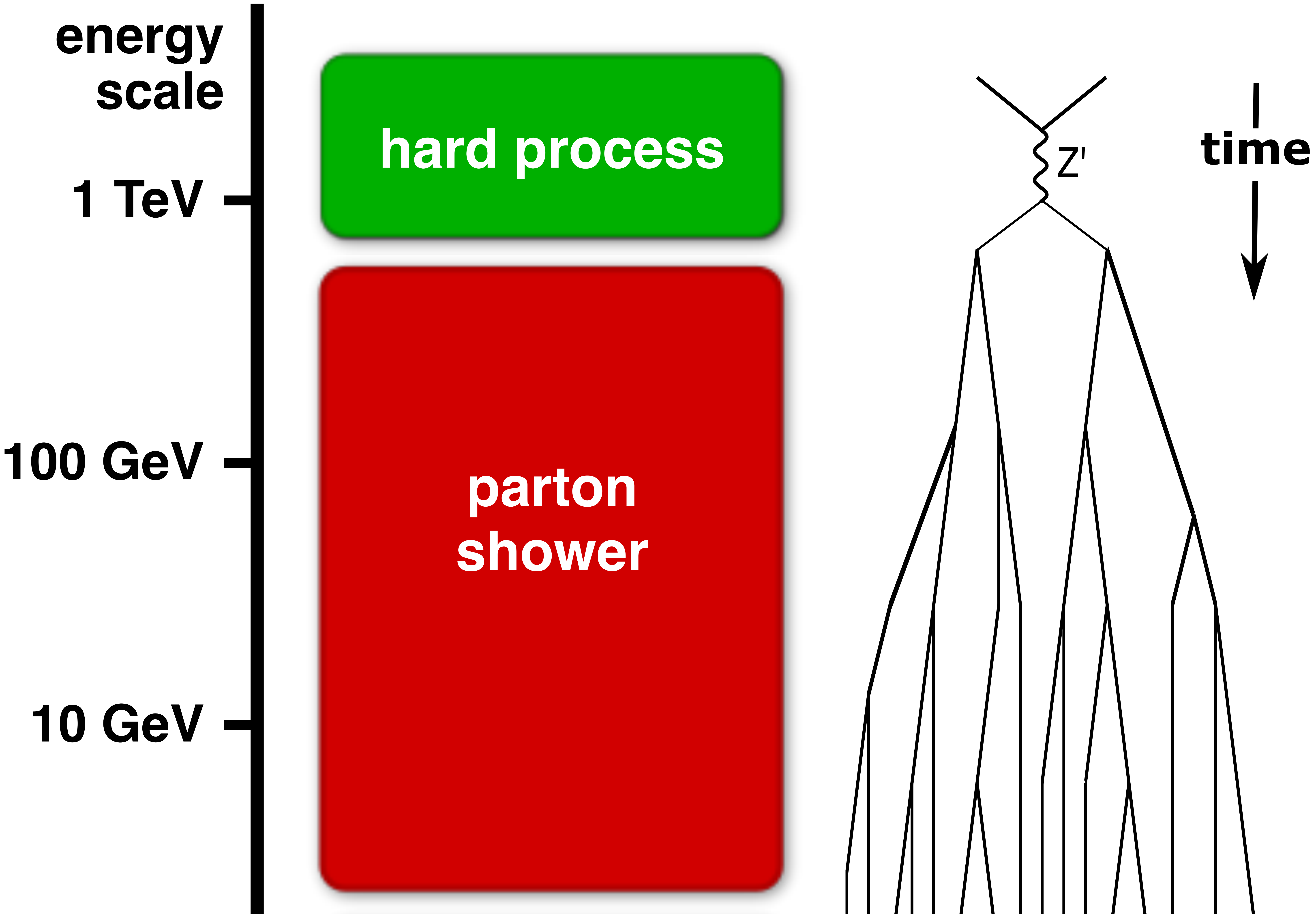
energy scale

1 TeV

hard process

time

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



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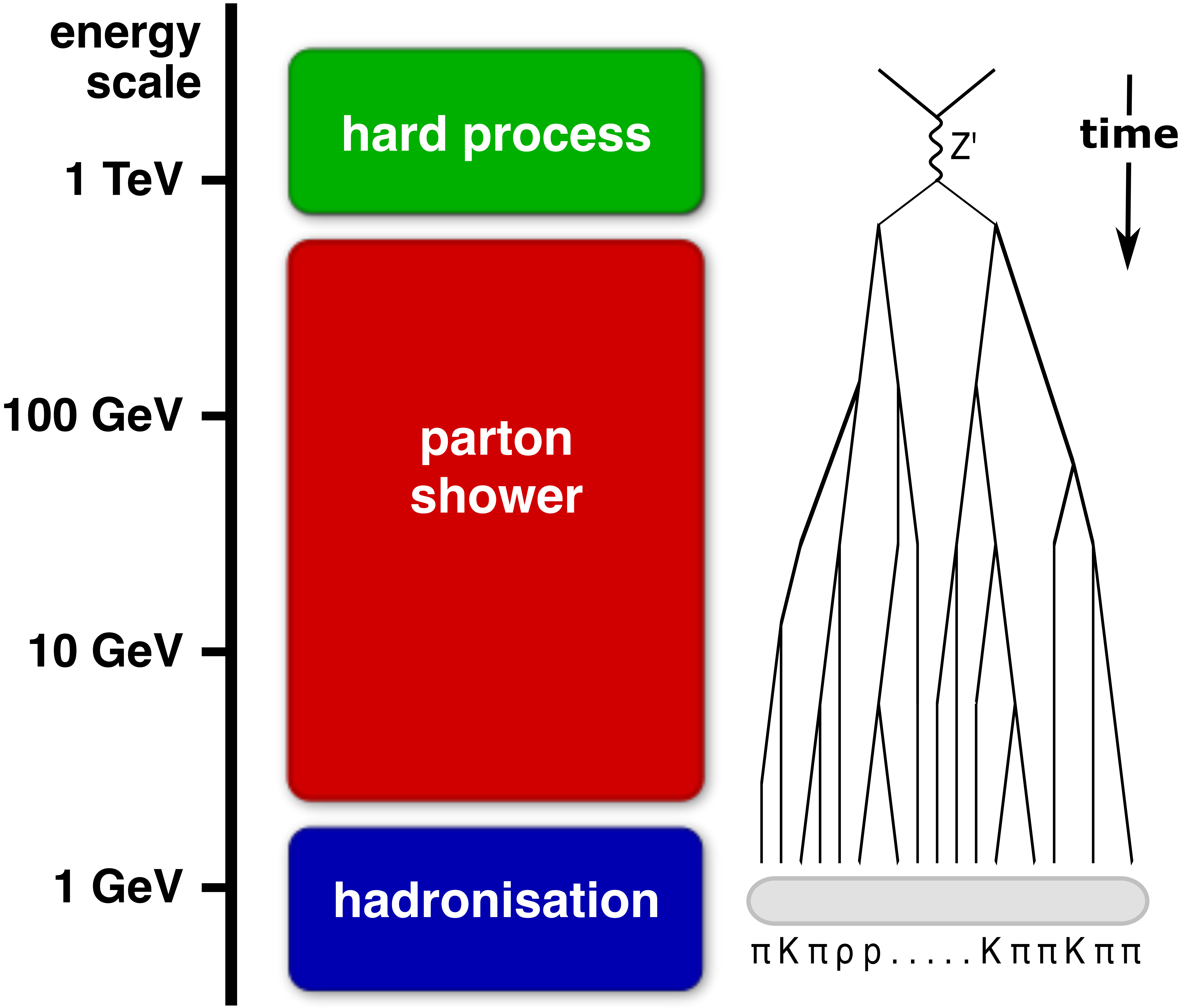


hard process

parton shower

hadronisation

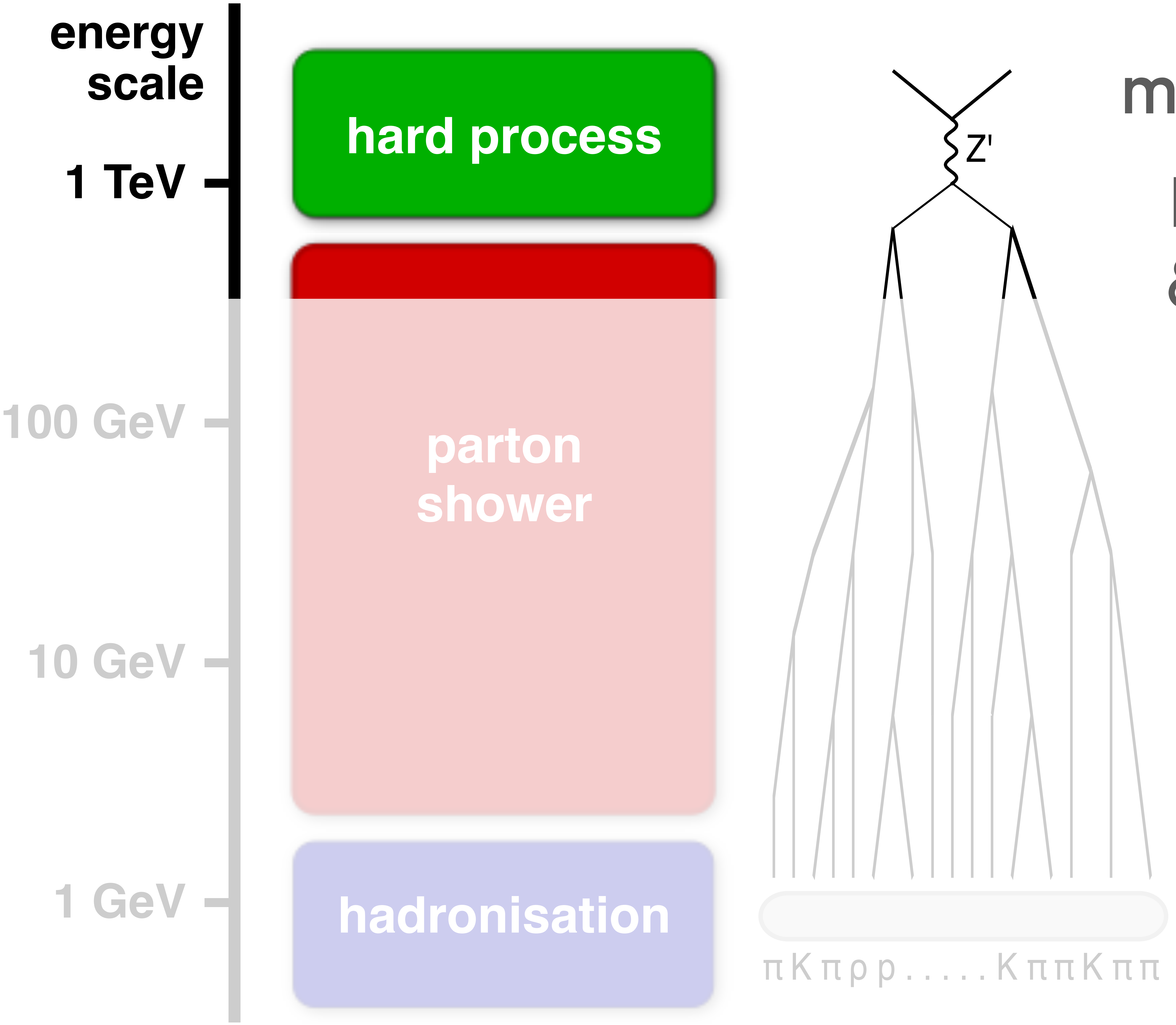
schematic view of key components of QCD predictions and Monte Carlo event simulation

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

general purpose Monte Carlo event generators:
THE BIG 3

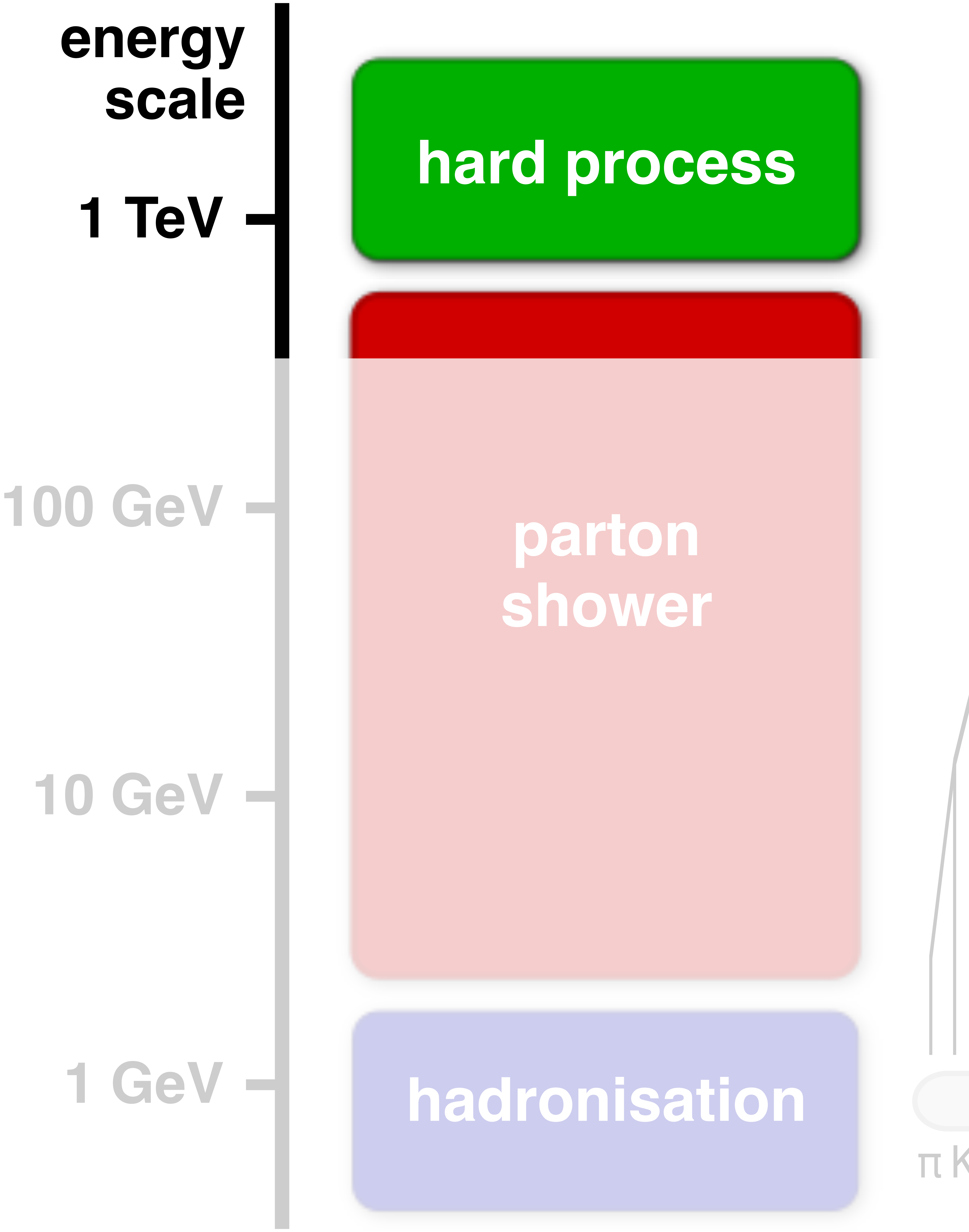
Herwig 7 **Pythia 8** **Sherpa 2**

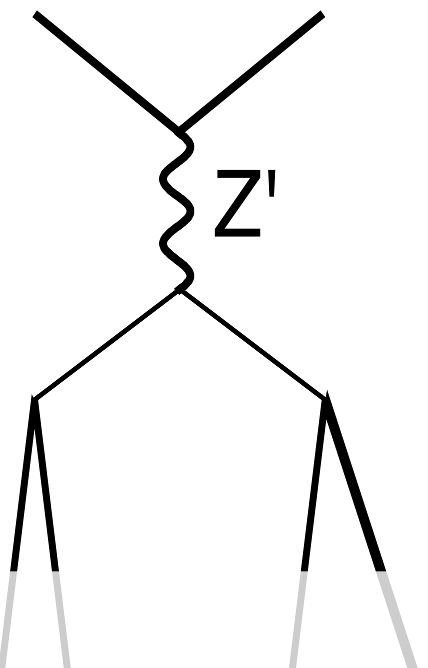
they do an amazing job of simulation vast swathes of data; collider physics would be unrecognisable without them



major advances of past 20yrs:

hard process (NLO, NNLO)
& its interface with shower





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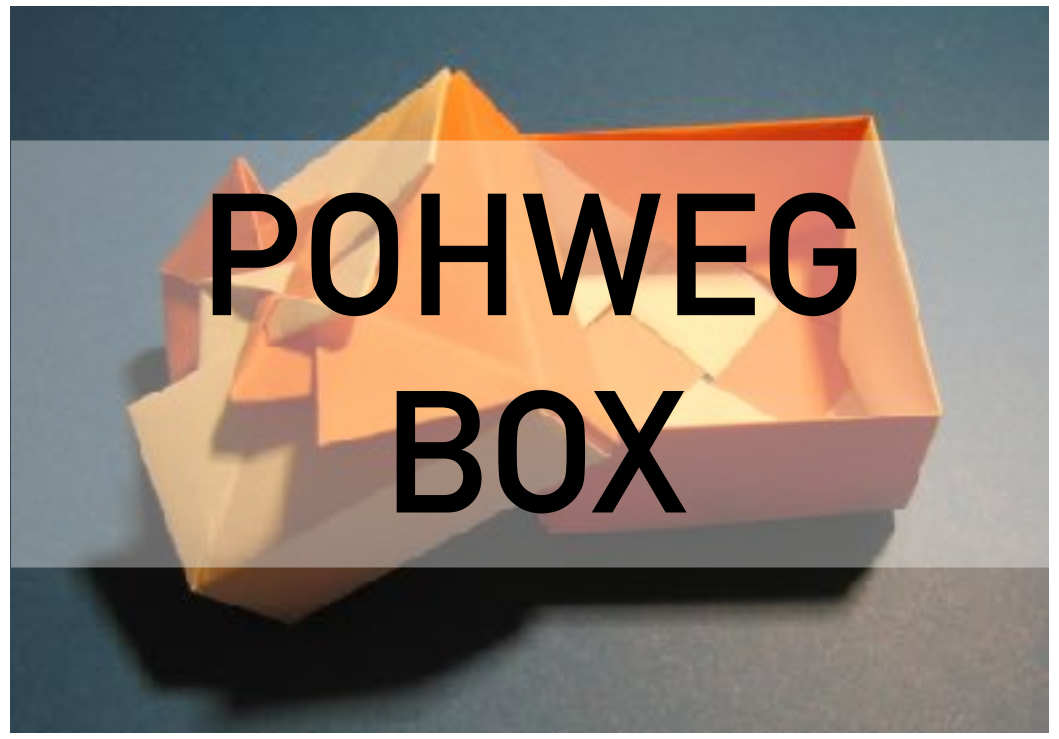


MadGraph5_aMC@NLO

MC@NLO
(in Herwig&Sherpa)

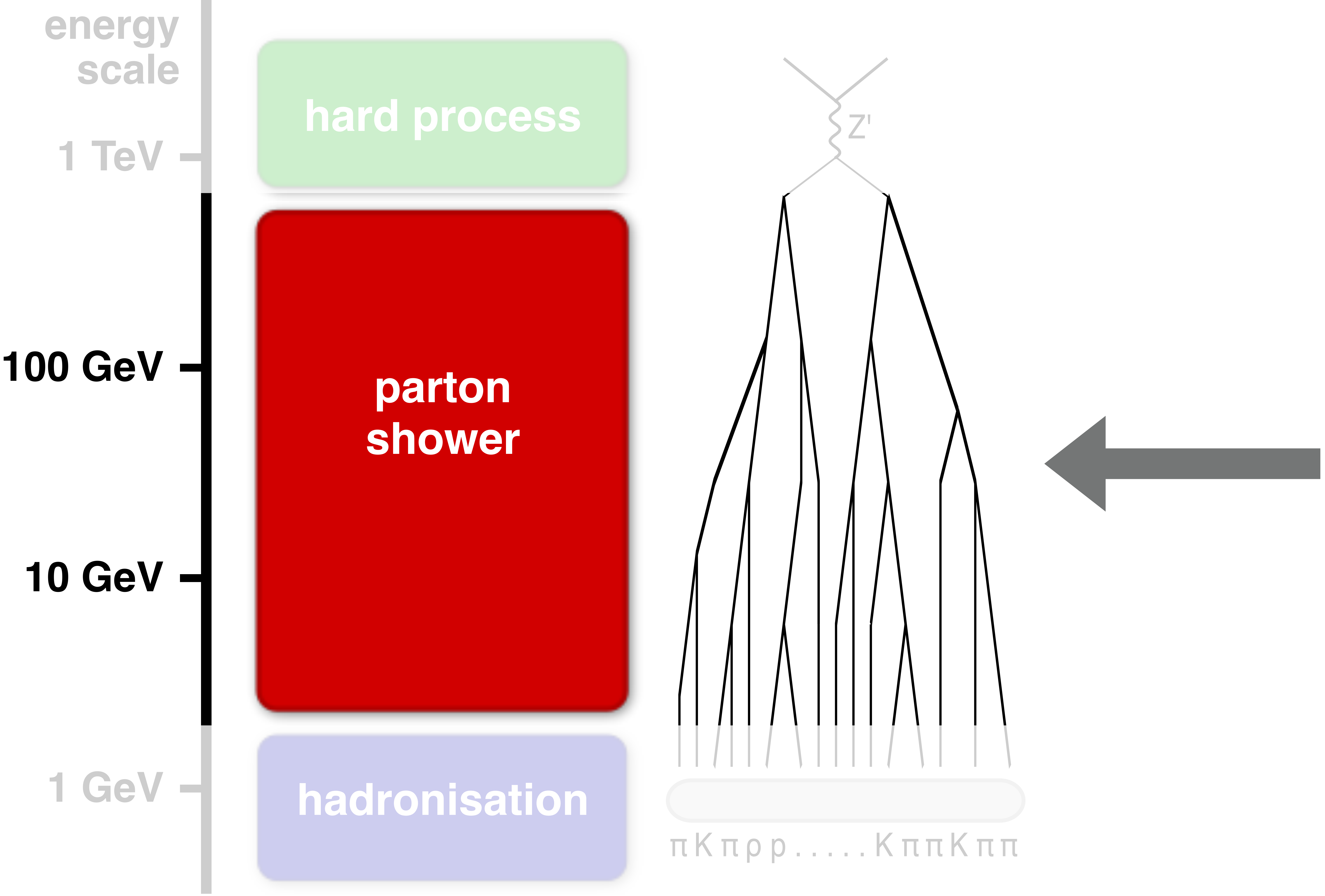
MINLO

MLM, CKKW
Vincia, FxFx

UNNLOPS

GENEVA

[...]



energy scale

1 TeV

100 GeV

10 GeV

1 GeV

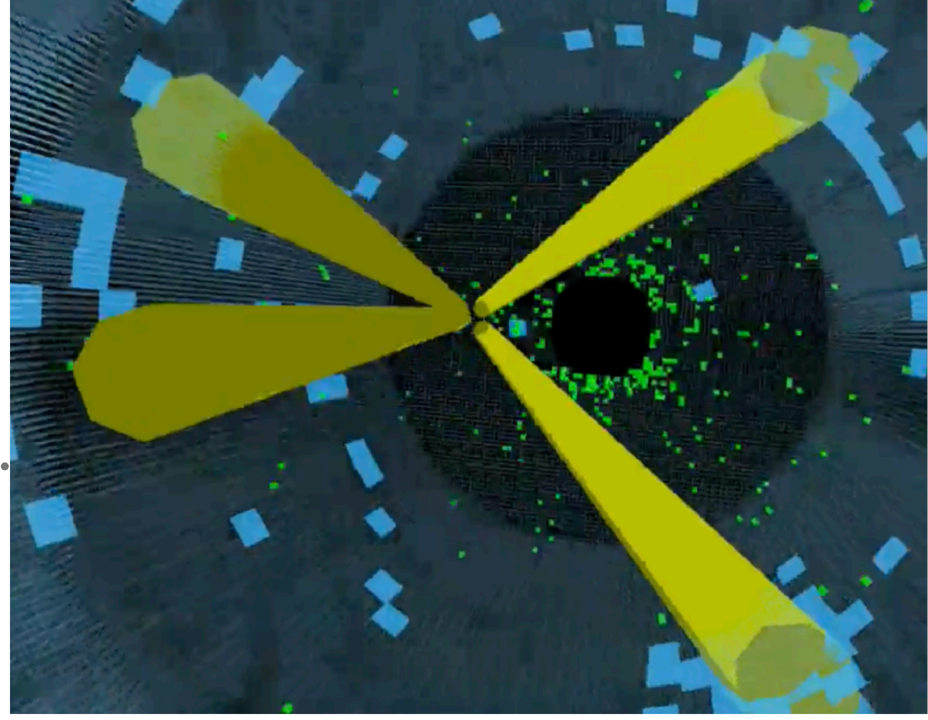
hard process

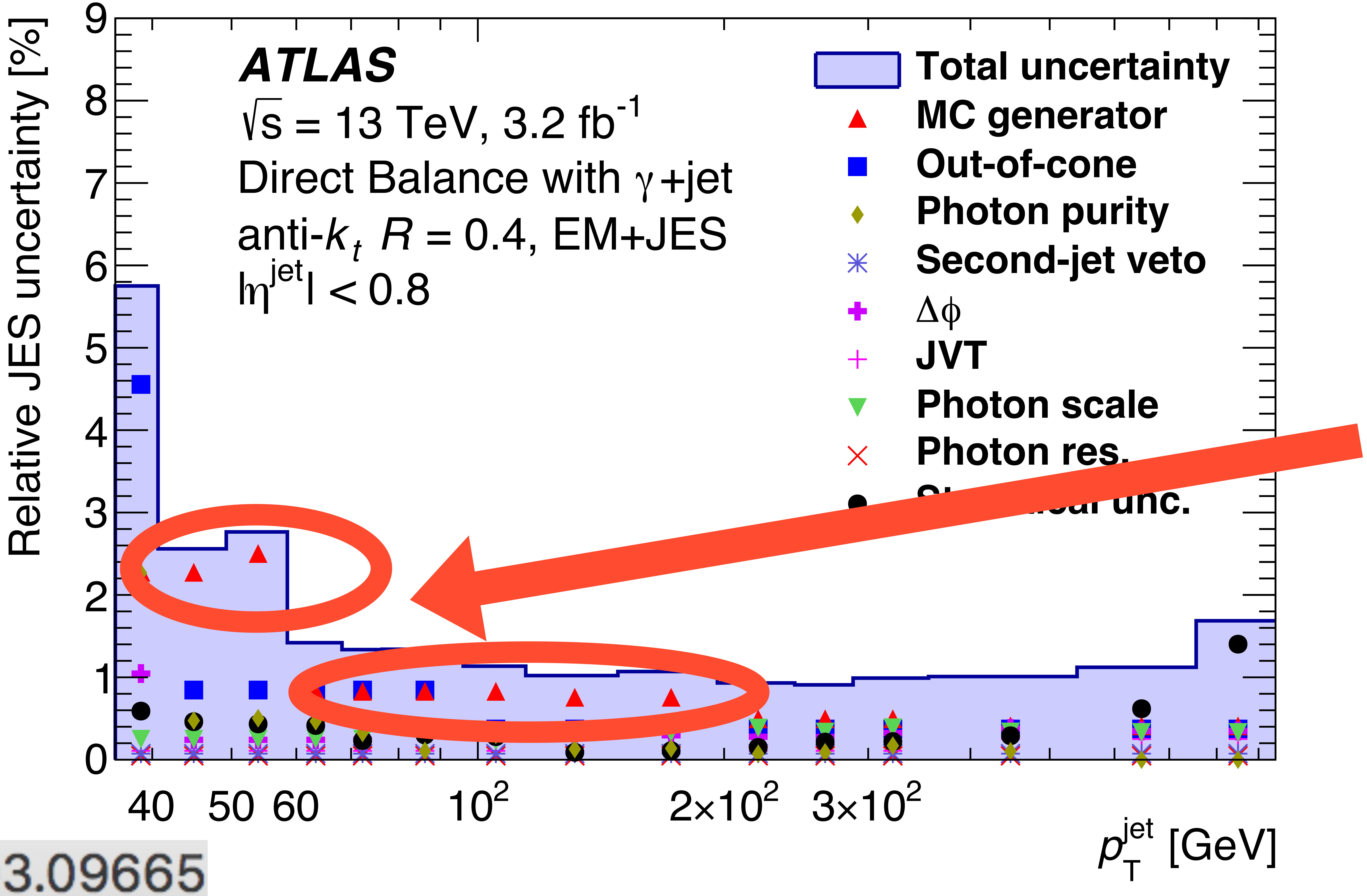
parton shower

hadronisation

this talk

Fundamental experimental calibrations (jets)





1703.09665

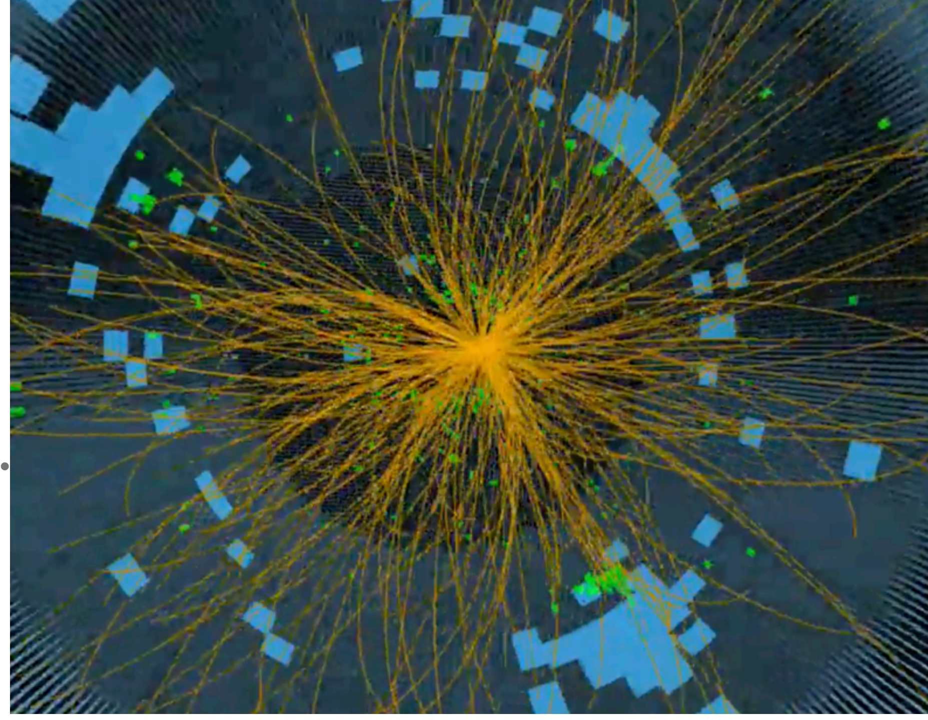
Jet energy scale, which feeds into hundreds of other measurements

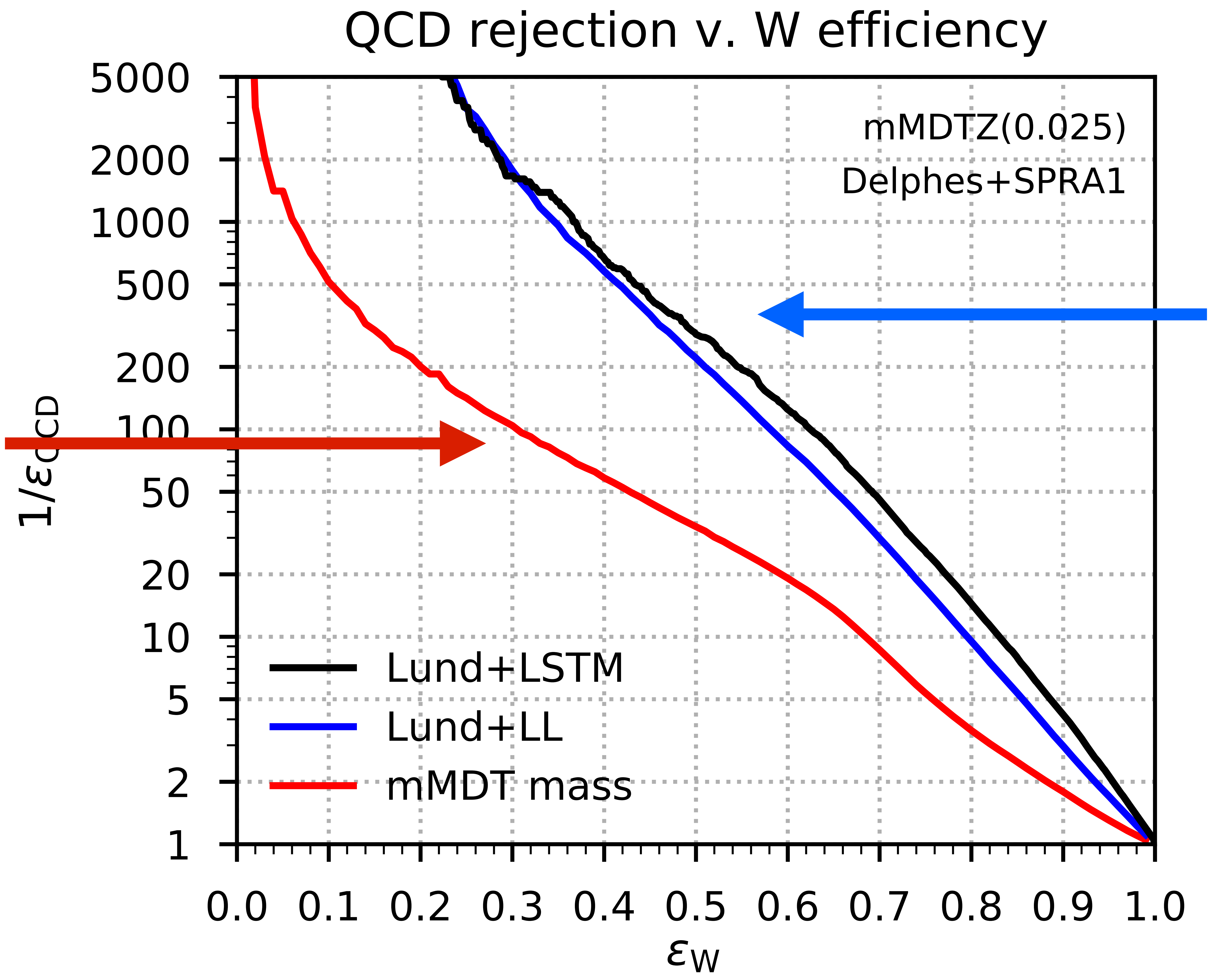
Largest systematic errors (1–2%) come from differences between MC generators

(here Sherpa v. Pythia)

→ fundamental limit on LHC precision potential

using full event information: jet substructure for W tagging





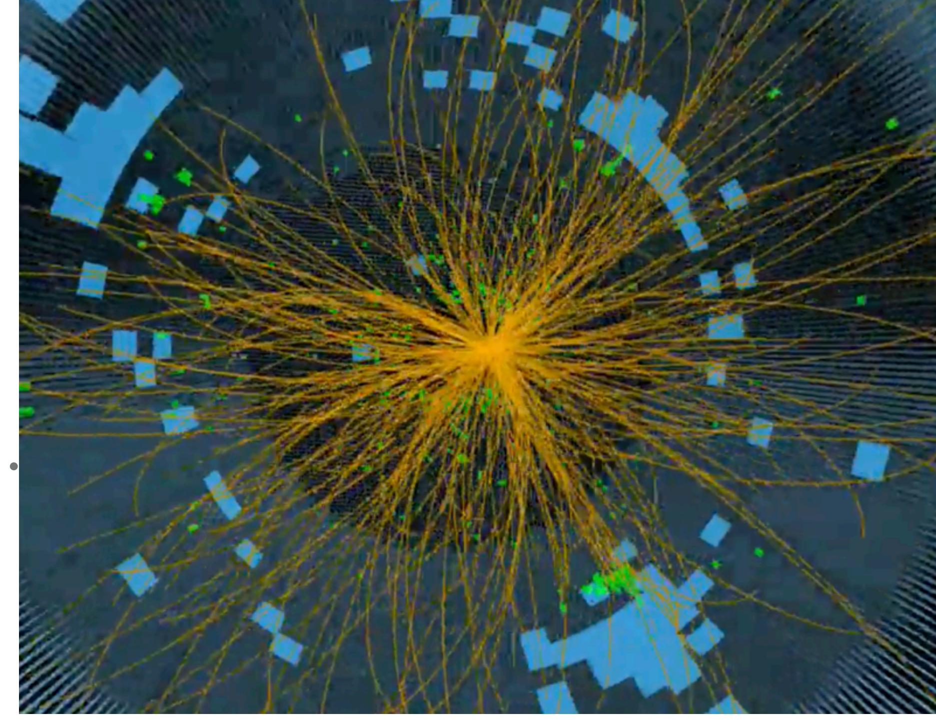
QCD rejection with just jet mass

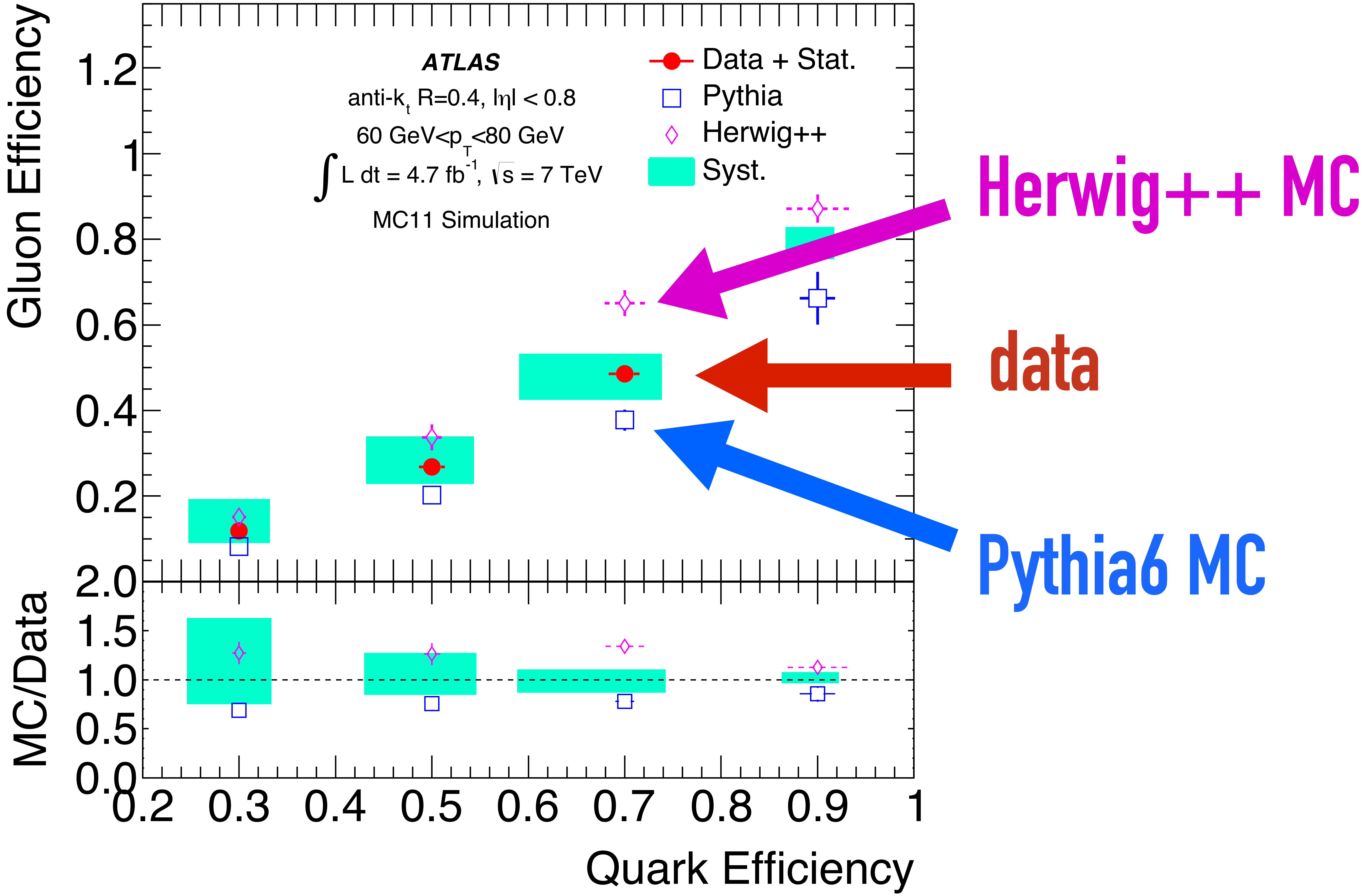
QCD rejection with use of full jet substructure

5–10x better

taken from Dreyer, GPS & Soyez '18

using full event information (quark/gluon tagging)





Herwig++ MC

data

Pythia6 MC

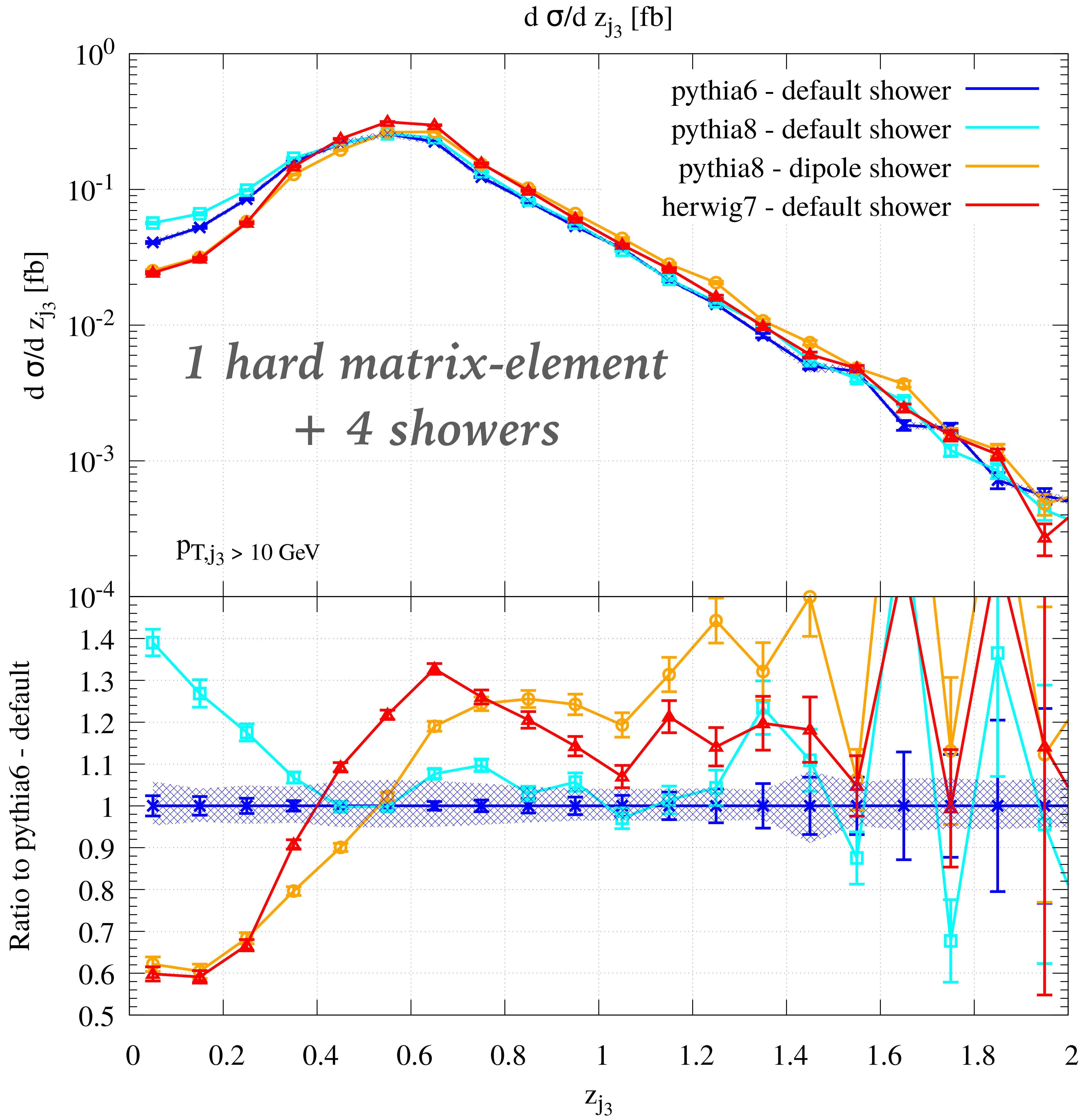
use more info →
become more sensitive
to MC limitations

**up to 35% differences
in MCs v. data**

a concern given trend
towards use of
maximal info,
e.g. with machine
learning

1405.6583

Matching with hard process is hitting a limit (e.g. Jäger, Karlberg, Scheller 1812.05118)



Limits effectiveness of current matching methods (here POWHEG)

Parton structure also gets in way of better (NNLOPS) hard-process + shower matching schemes

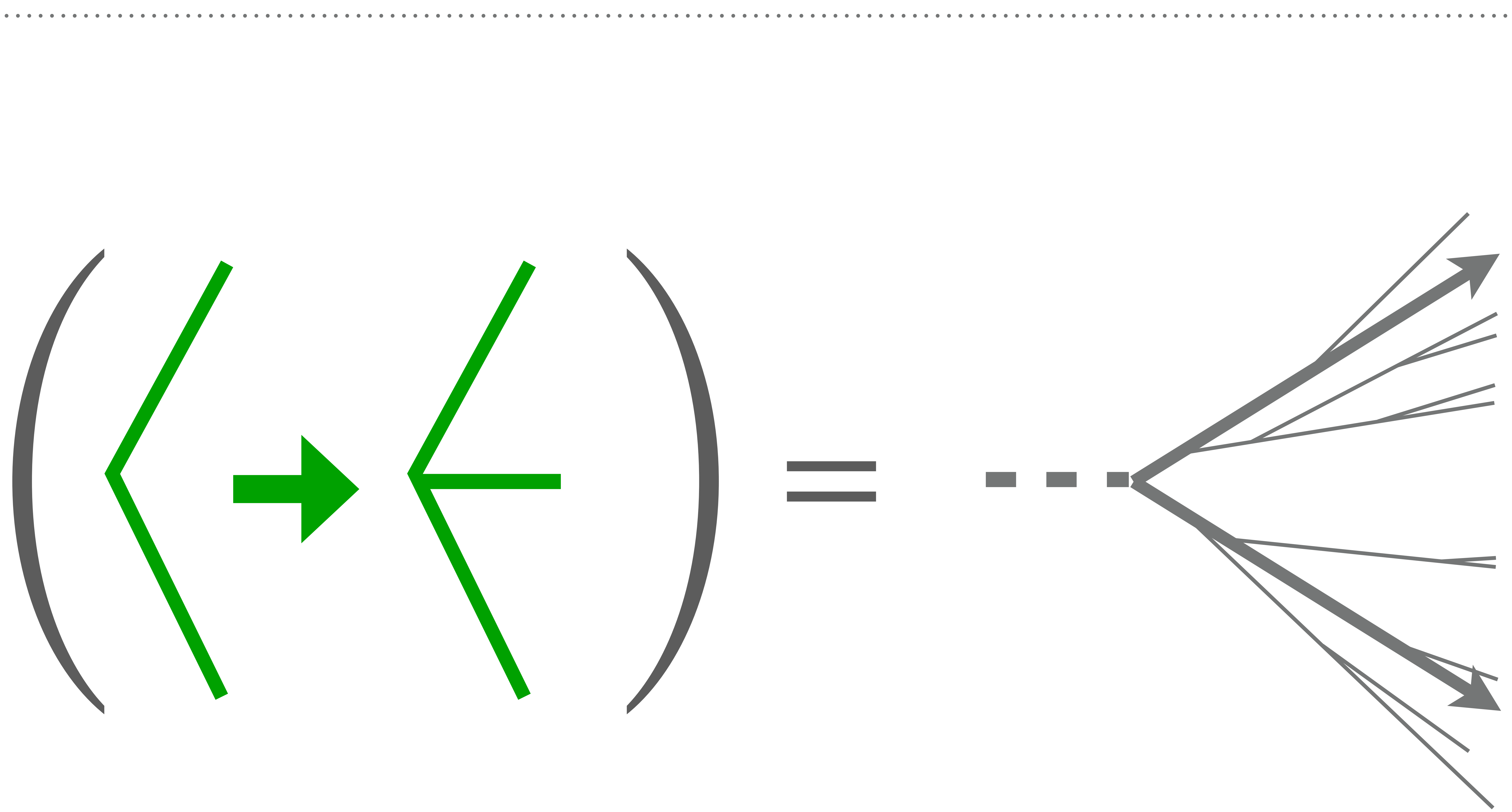
what is a parton shower?

illustrate with dipole / antenna showers

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

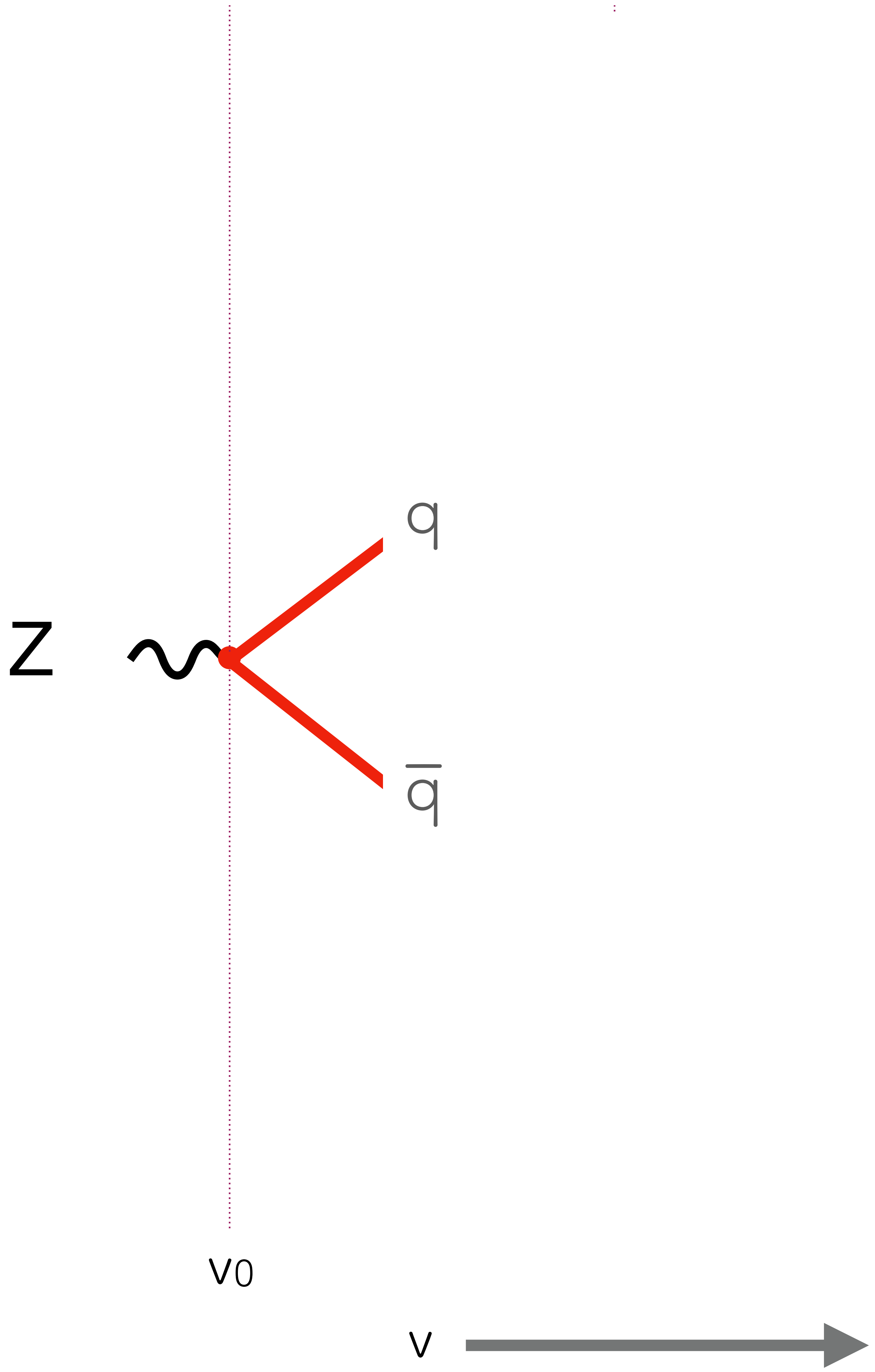
At its simplest

$$\sum_{n=0}^{\infty}\prod_{i=1}^{n}$$



iteration of 2→3 (or 1→2) splitting kernel

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

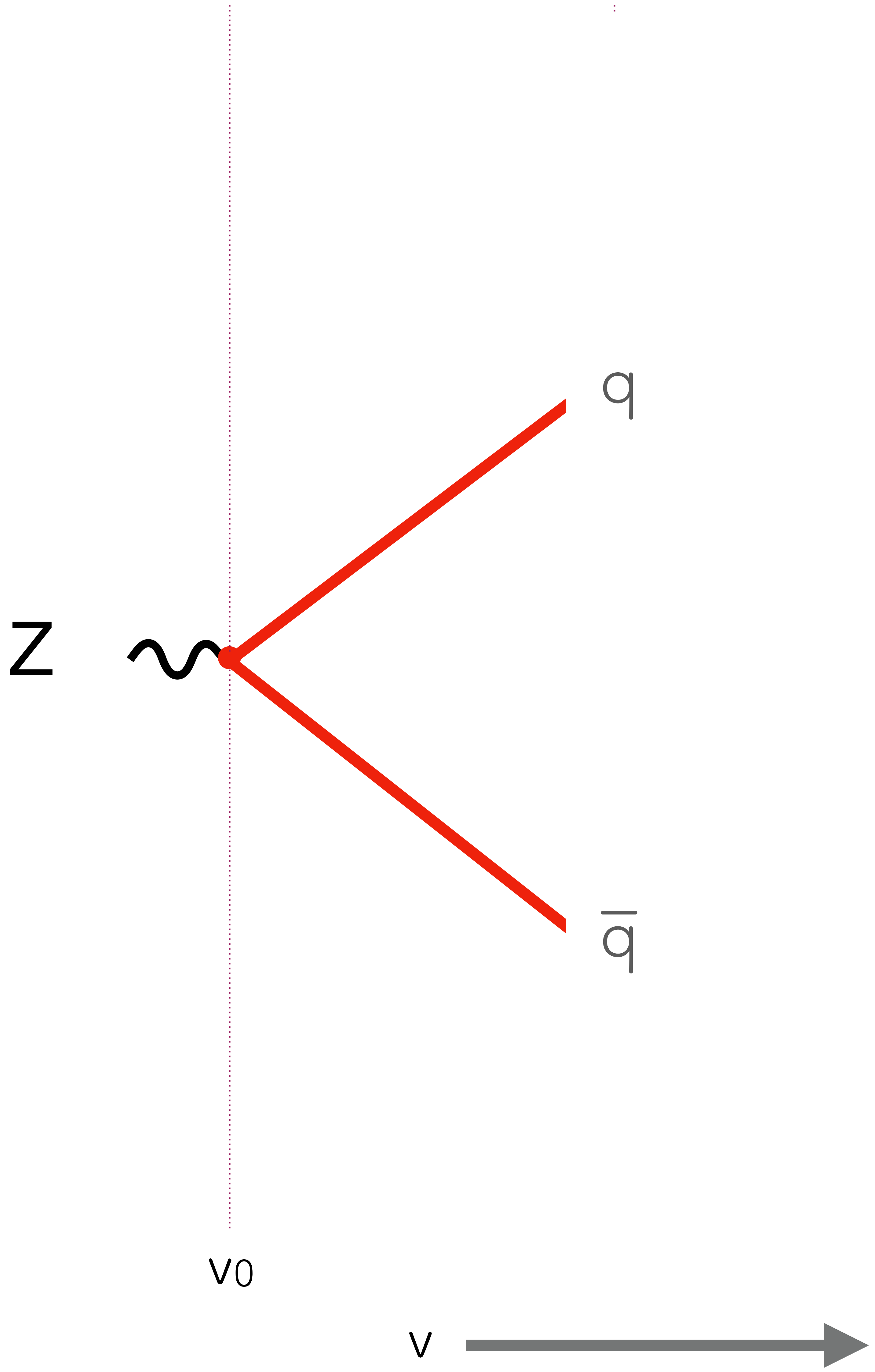


Start with q-qbar state.

Evolve a step in v and throw a random number to decide if state remains unchanged

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

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



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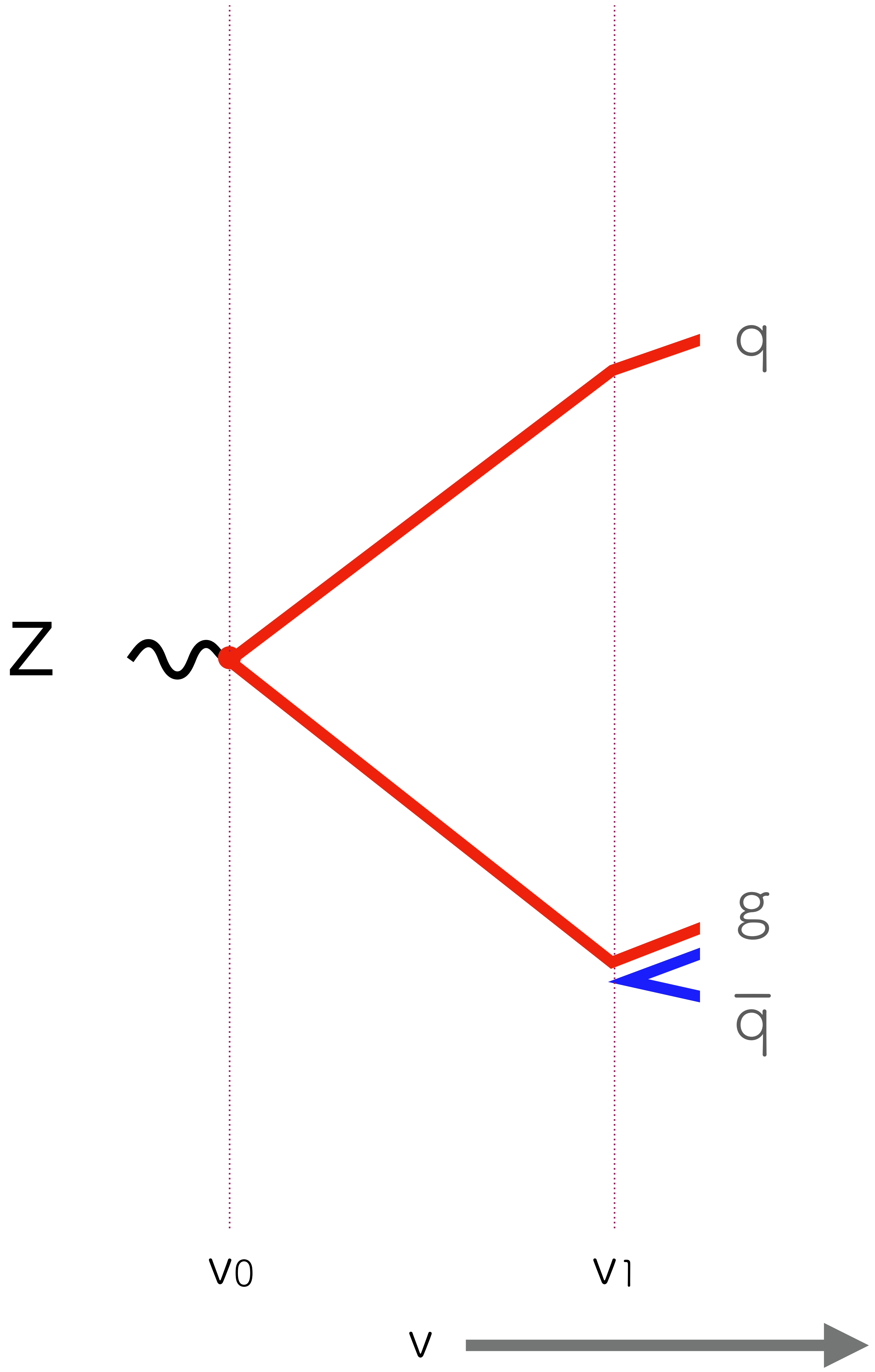


Start with q-qbar state.

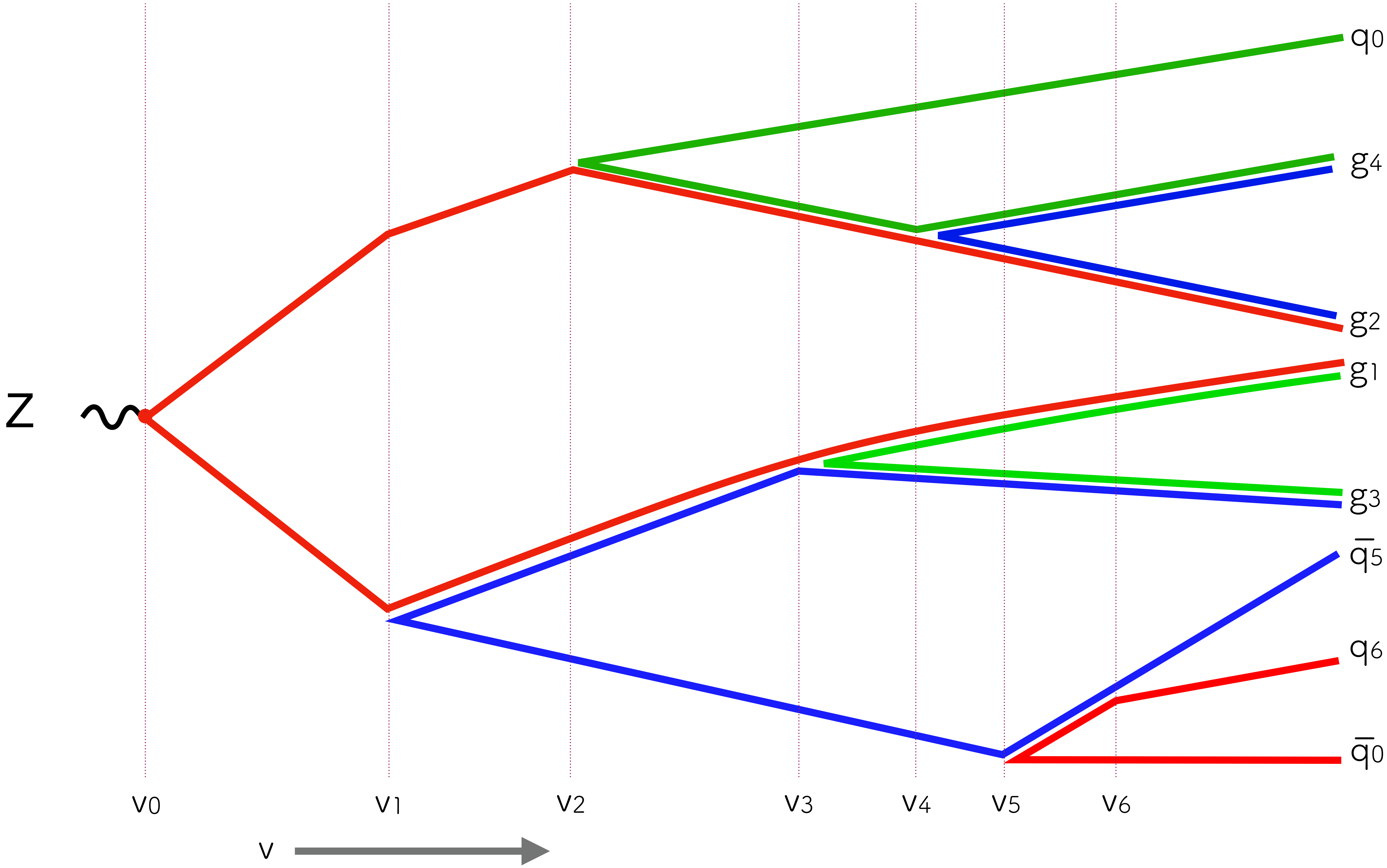
Evolve a step in v and throw a random number to decide if state remains unchanged

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

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

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

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



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

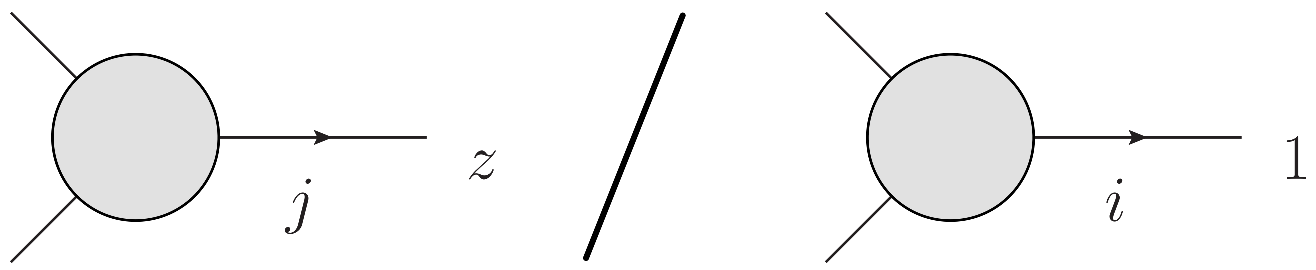
recent directions of parton-shower work?

1. including 2 → 4 (or 1→ 3) splittings
2. subleading colour corrections (dipole picture is large N_C)
3. EW showers

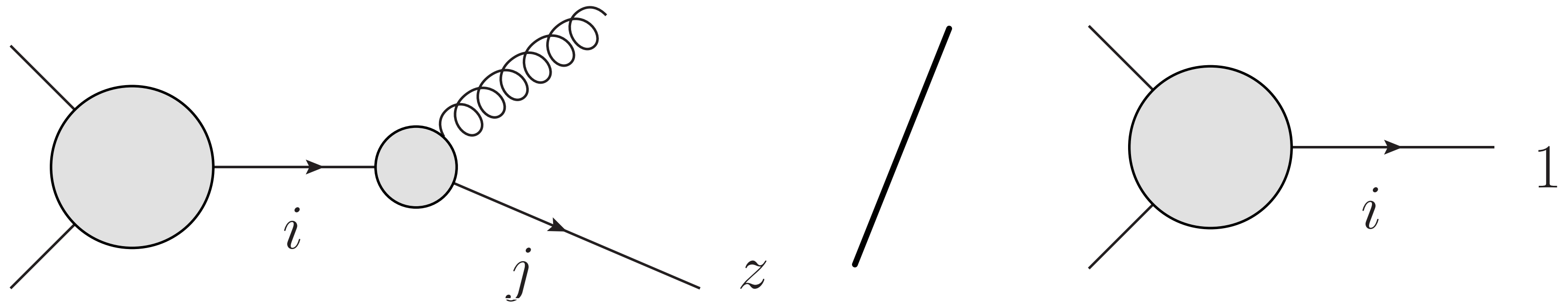
Including 1→ 3 splittings (≡ 2→4)

- Jadach et al, e.g. 1504.06849, 1606.01238
- Li & Skands, 1611.00013
- Höche, Krauss & Prestel, 1705.00982, Höche & Prestel, 1705.00742, Dulat, Höche & Prestel, 1805.03757

$$D_{ji}^{(0)}(z,\mu) = \delta_{ij}\delta(1-z) \qquad \leftrightarrow$$

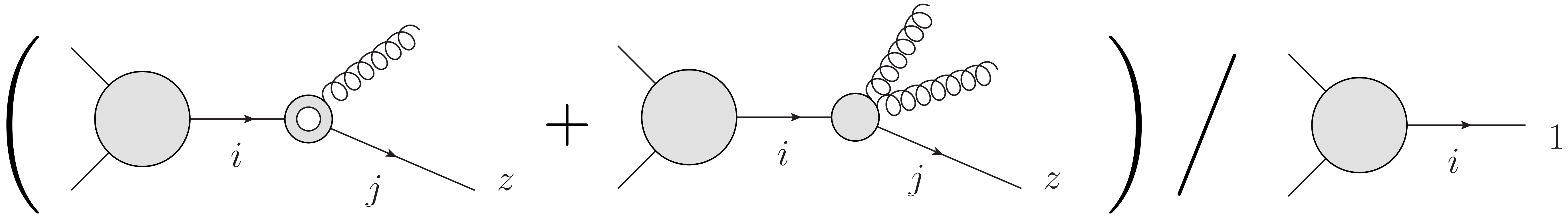


$$D_{ji}^{(1)}(z,\mu) = -\frac{1}{\varepsilon}P_{ji}^{(0)}(z) \qquad \leftrightarrow$$



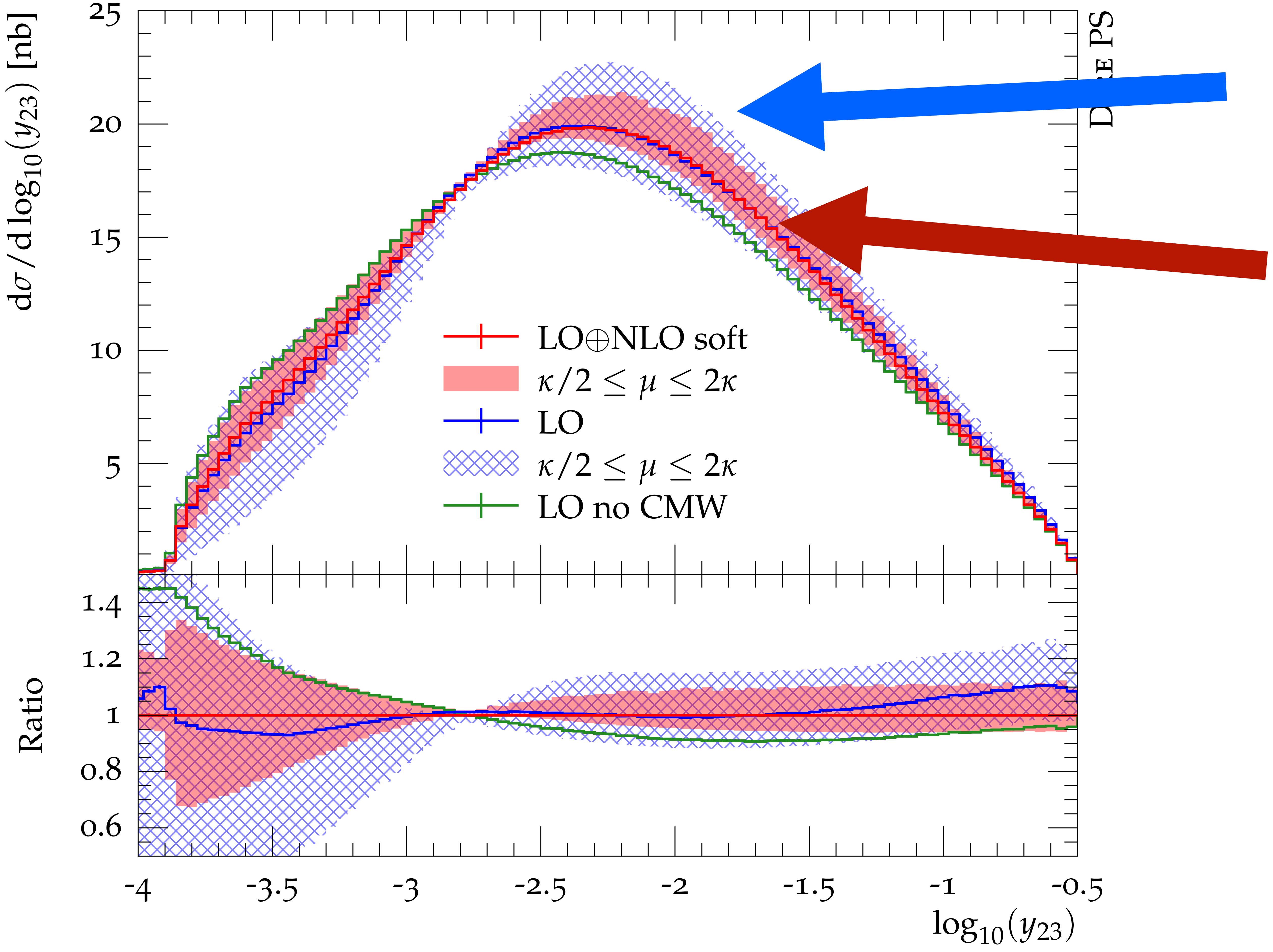
$$D_{ji}^{(2)}(z,\mu) = -\frac{1}{2\varepsilon}P_{ji}^{(1)}(z) + \frac{\beta_0}{4\varepsilon^2}P_{ji}^{(0)}(z) + \frac{1}{2\varepsilon^2}\int_z^1 \frac{\mathrm{d}x}{x}P_{jk}^{(0)}(x)P_{ki}^{(0)}(z/x)$$

$$\leftrightarrow$$



Equations from slides by Höche

Including 1→ 3 splittings

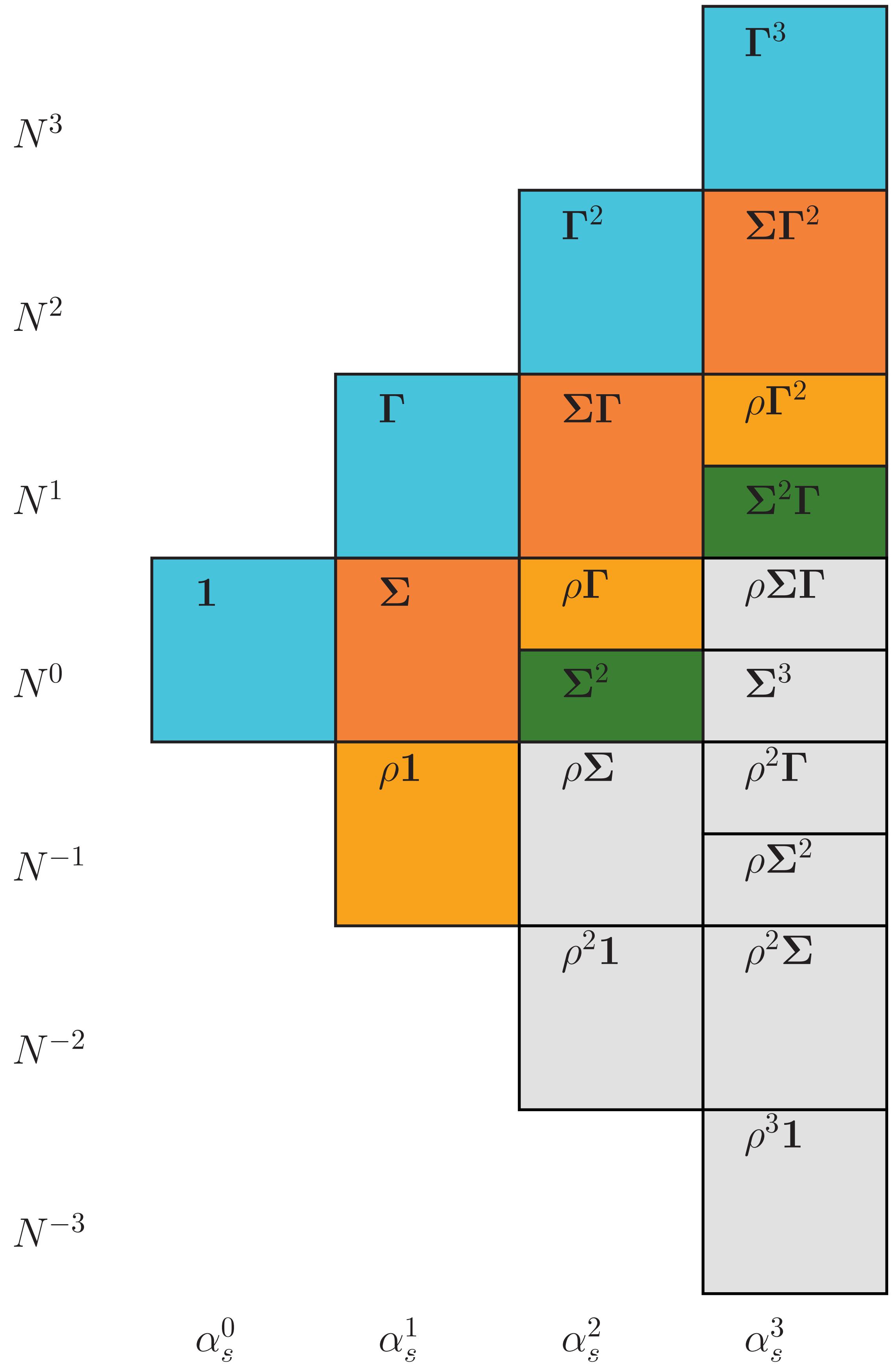


just 1→2 splittings

+ 1→3 soft splittings

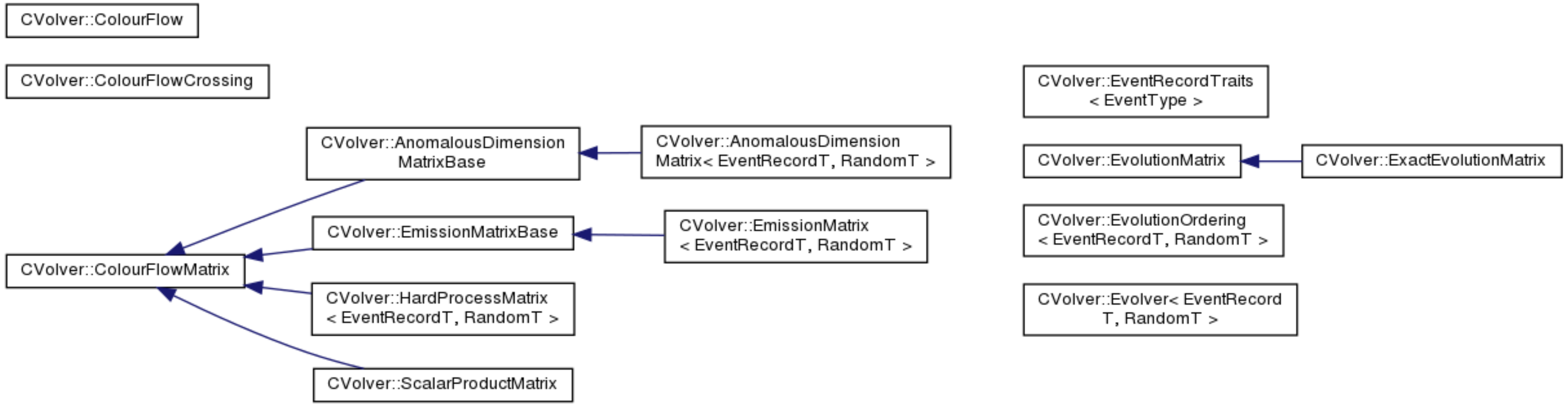
Dulat, Höche & Prestel, 1805.03757

Hierarchy of subleading colour corrections



Angeles, De Angelis, Forshaw, Plätzer, Seymour – JHEP 05 (2018) 044
Gieseke, Kirchgaesser, Plätzer, Siodmok – arXiv:1808.06770
De Angelis, Forshaw, Plätzer – arXiv:181y.xxxxx
Forshaw, Holguin, Plätzer – arXiv:181y.xxxxx
Plätzer, Sjödahl, Thorén, arXiv:1808.00332

$$\mathbf{A}_n(E) = \mathbf{V}(E,E_n)\mathbf{D}_n\mathbf{A}_{n-1}(E_n)\mathbf{D}_n^\dagger\mathbf{V}^\dagger(E,E_n)\theta(E-E_n)$$

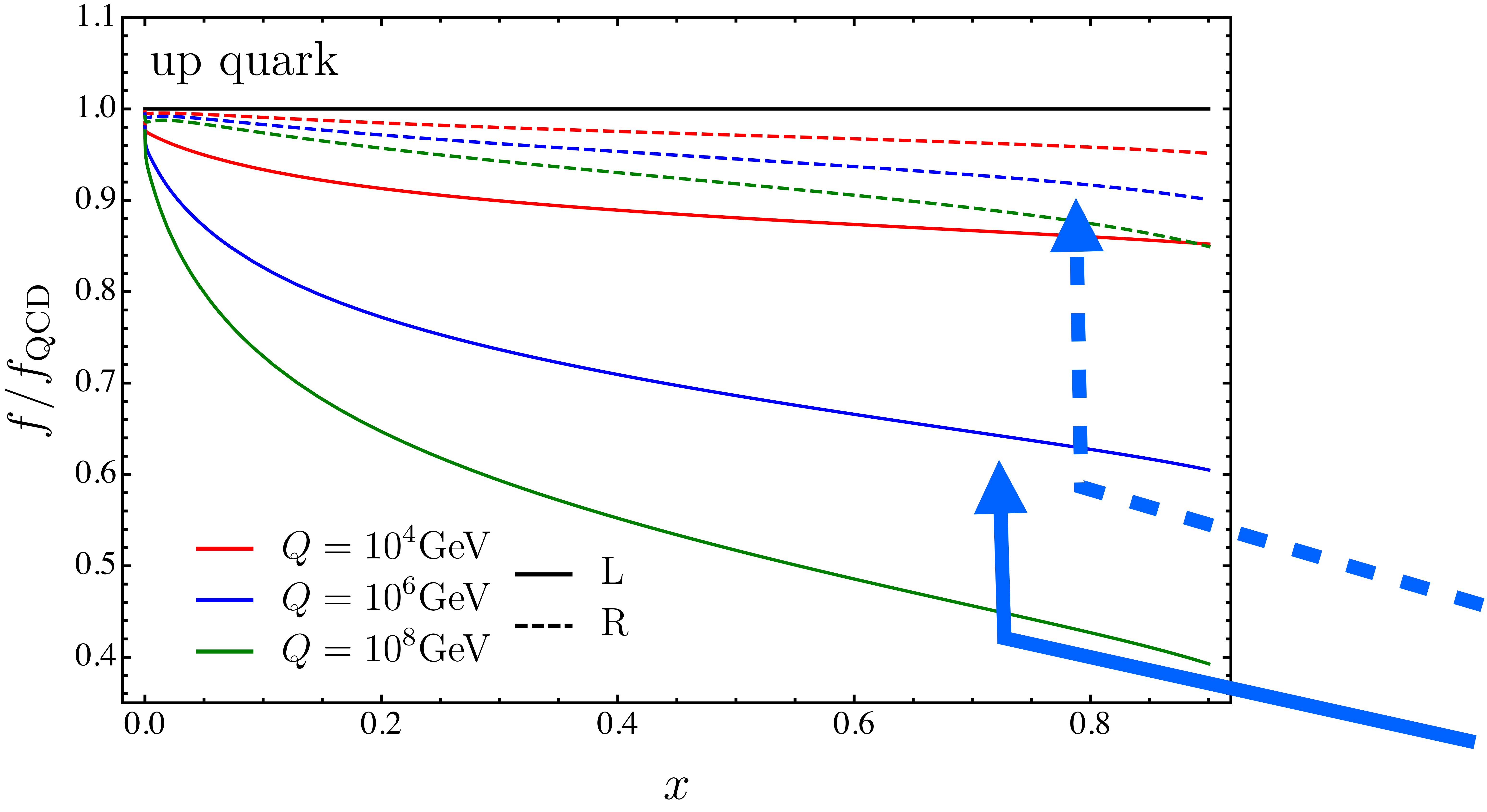


Plugin approach can accommodate anything from (N)GLs to full parton showers.

cf. also work by Hatta & Ueda, 1304.6930; Nagy & Soper papers; some subleading colour also in DIRE2 work

Bauer, Ferland & Webber, 1703.08562, 1808.08831
see also Chen, Han & Tweedie, 1611.00788
& Sjostrand & collab

EW showers (esp. beyond LHC)



W & Z emissions come with double logarithms

$$\alpha_{EW} \ln^2 \frac{Q}{m_W}$$

right-handed up quarks

left-handed up quarks

W emission affects only left-handed quarks

→ strong polarisation of quarks in unpolarised proton (at high enough energies)

what does a parton shower achieve?

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

Dasgupta, Dreyer, Hamilton, Monni & GPS, 1805.09327

what **should** a parton shower achieve?

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

Dasgupta, Dreyer, Hamilton, Monni & GPS, 1805.09327

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

  [machine learning might "learn" many such features]

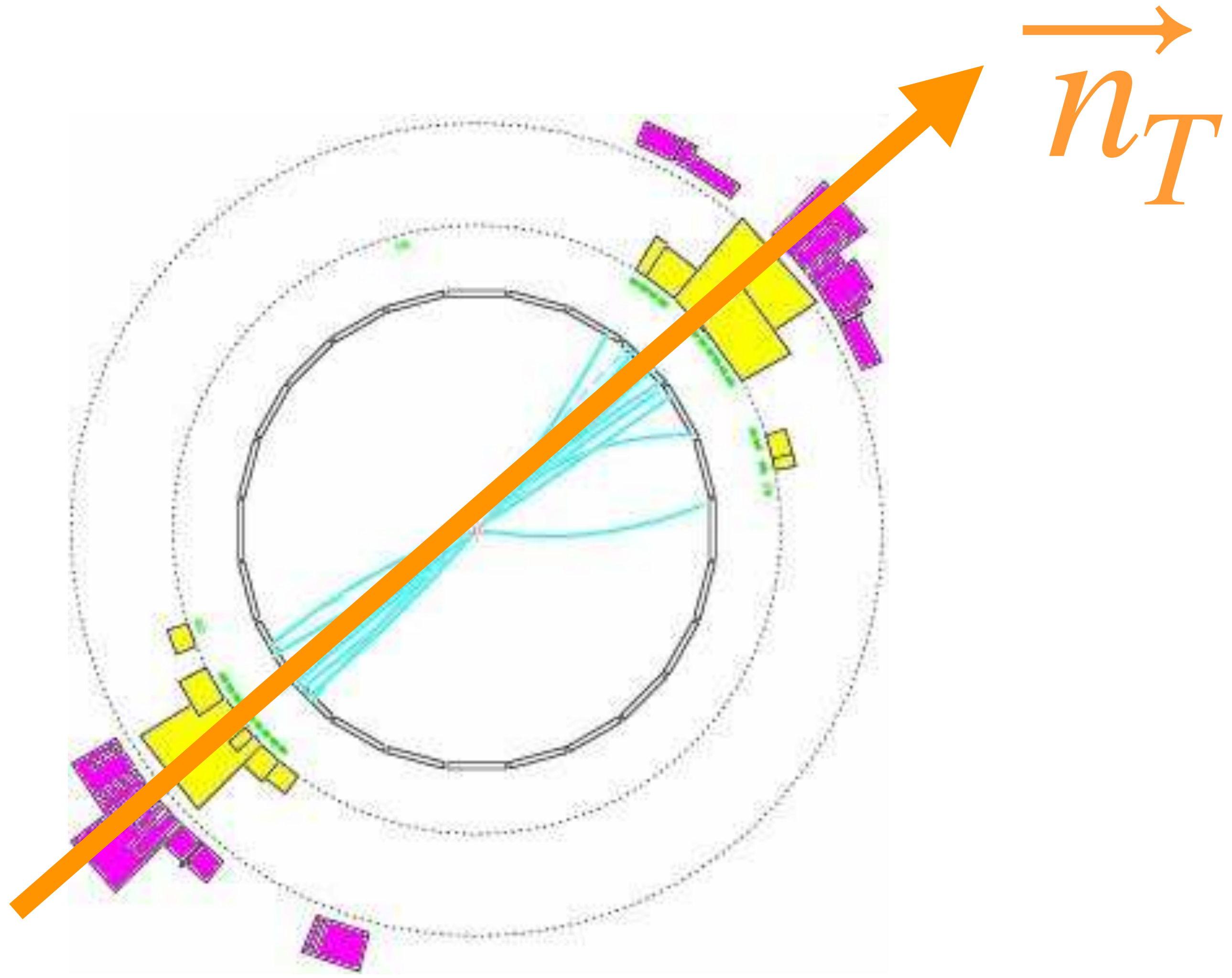
how can you prescribe correctness & accuracy of the answer, when the questions you ask can be arbitrary?

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. for (famous) "Thrust"

$$T = \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_i . \vec{n}_T|}{\sum_i |\vec{p}_i|}$$



2-jet event: $T \simeq 1$

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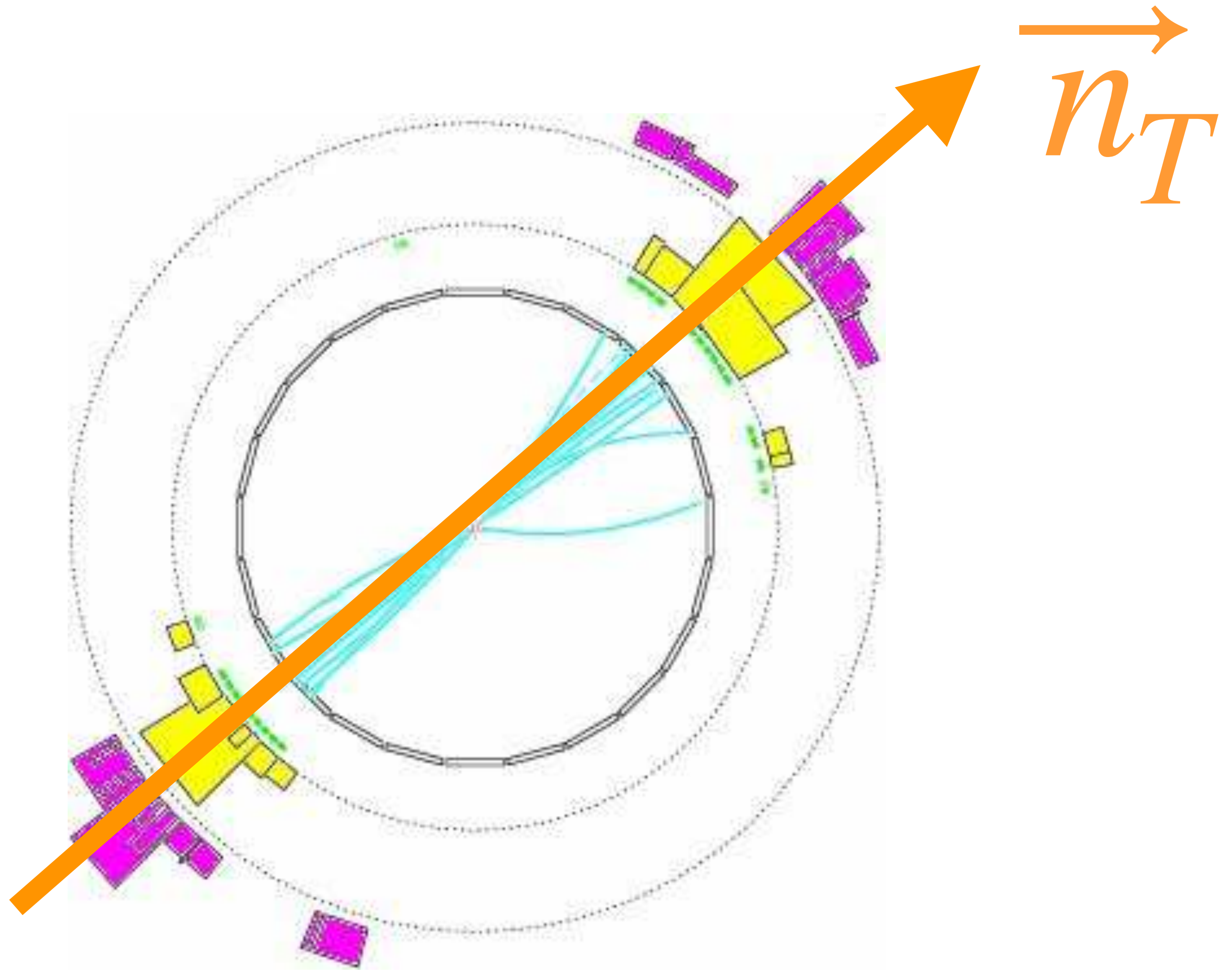


2-jet event: $T \simeq 1$

$$\sigma(1 - T < e^{-L}) = \sigma_{tot} \exp\left[\underbrace{Lg_1(\alpha_s L)}_{\text{LL}} + \underbrace{g_2(\alpha_s L)}_{\text{NLL}} + \underbrace{\alpha_s g_3(\alpha_s L)}_{\text{NNLL}} + \underbrace{\alpha_s^2 g_4(\alpha_s L)}_{\text{N}^3\text{LL}} + \cdots\right]$$

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

Catani, Trentadue, Turnock & Webber ’93 → NLL

Becher & Schwartz ’08 → N³LL

The standard answer so far

Sometimes you may see 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* $1+a_s(t)/(2\pi)K$"

Questions:

1) Which is it? LL or better?
2) For what known observables does this statement 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?

Our proposal for “minimal” criteria for a shower

Resummation

Establish logarithmic accuracy for all known 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*.

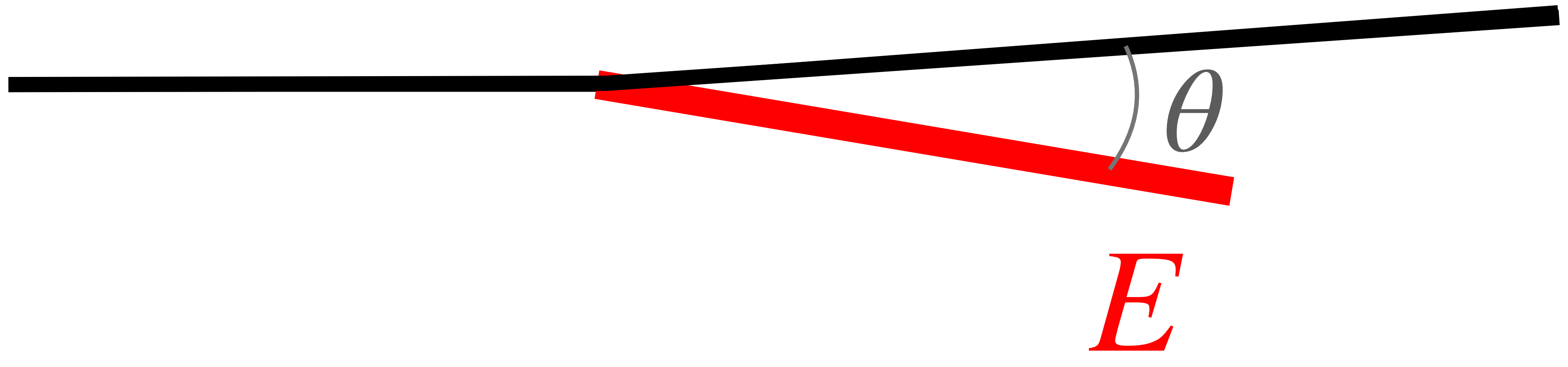
Examine two showers

- **Pythia8** shower: because it's the most widely used
- **DIRE** shower (2015 version, with just 2→3 splitting), because it's unique in being available for two General Purpose MC programs (Pythia8 & Sherpa2)

The results I'll talk about will be the same for both

and they'll be limited to fixed order for simplicity
(though it's easy enough to generalise to an all-order study)

Phase space: two key variables (+ azimuth)



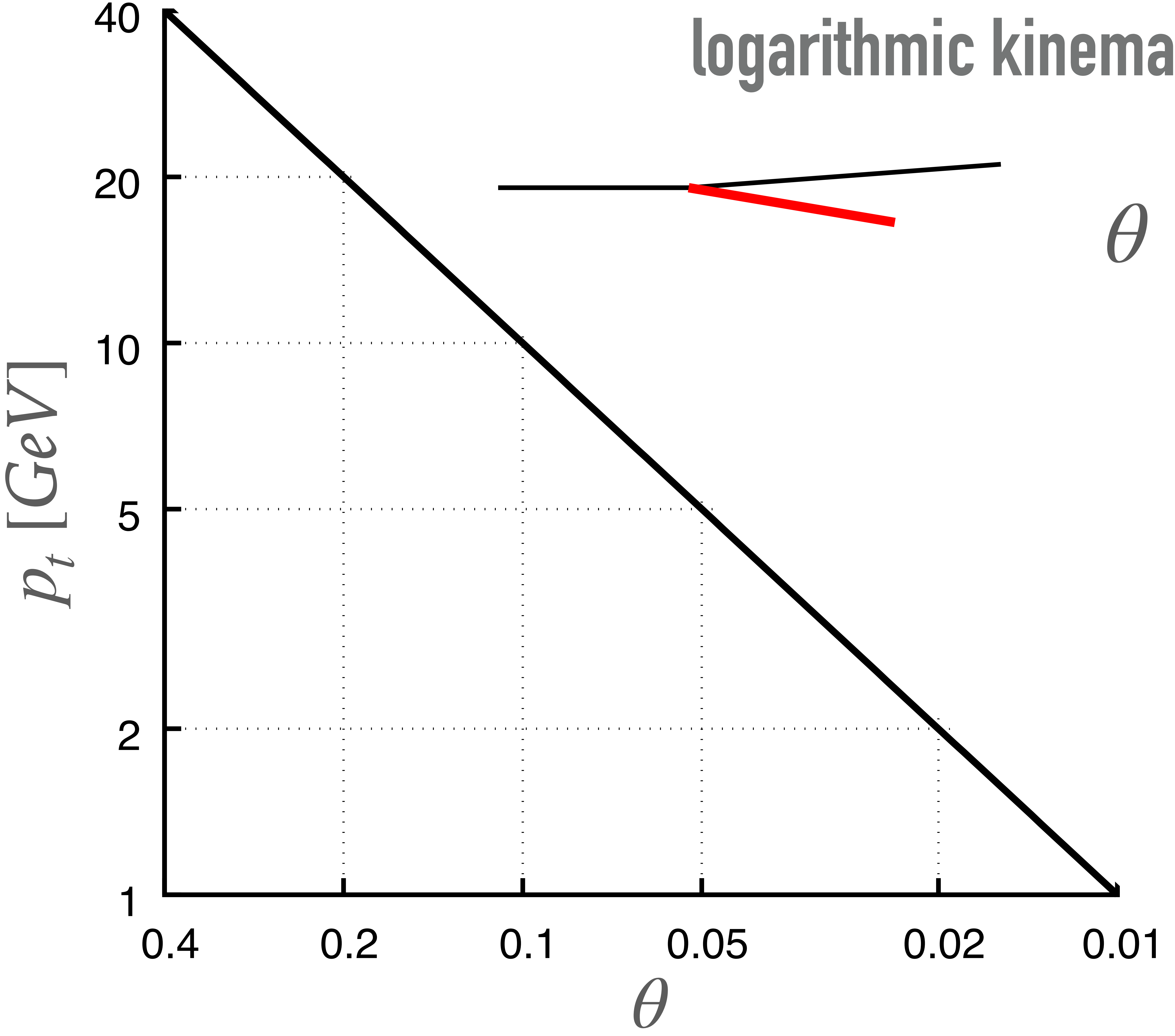
$$\theta\ (or\ \eta = -\ln\tan\frac{\theta}{2})$$

η is called (pseudo)rapidity

$$p_t = E\theta$$

p_t (or $p_\perp$) is called transverse momentum

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

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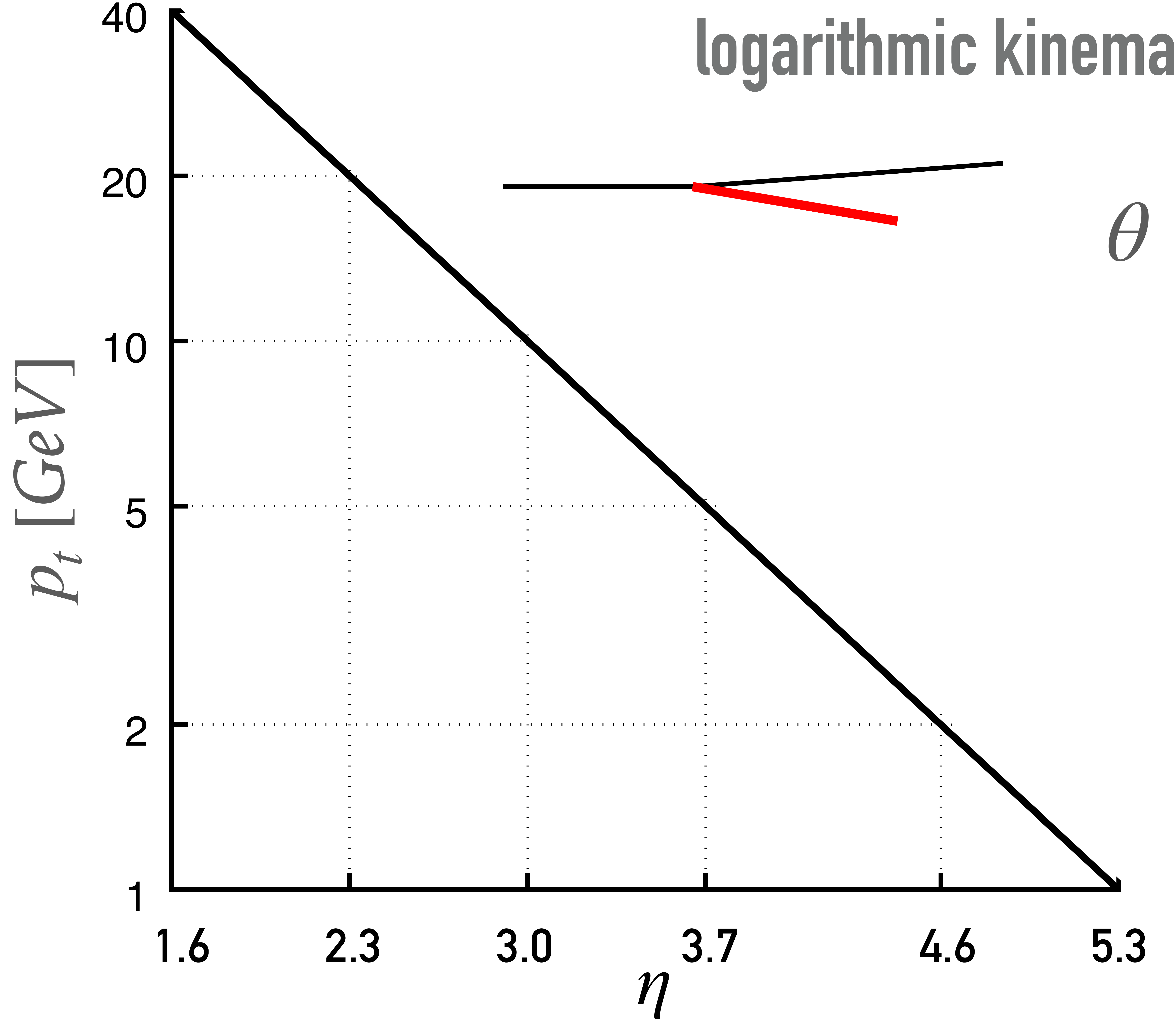

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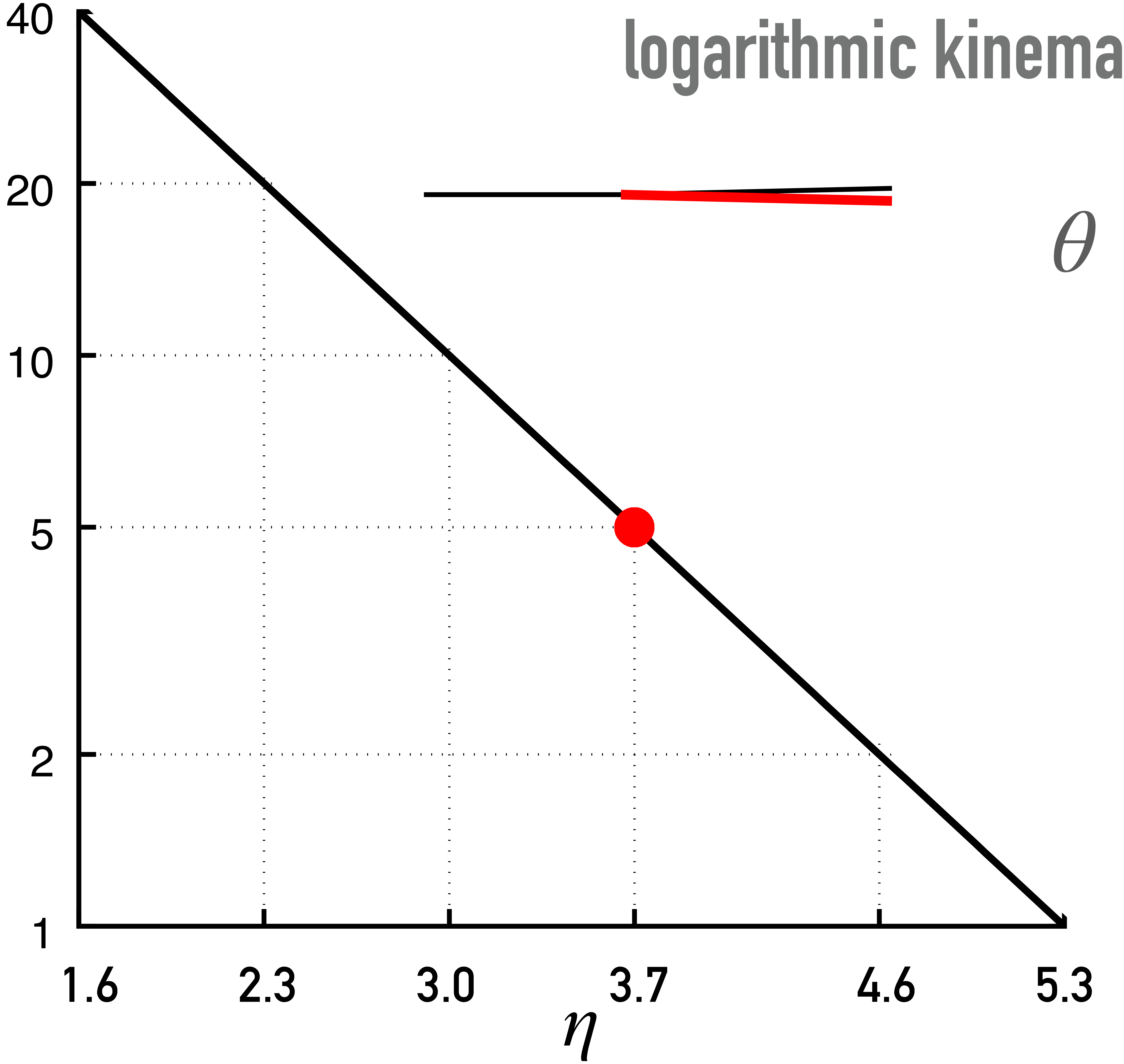

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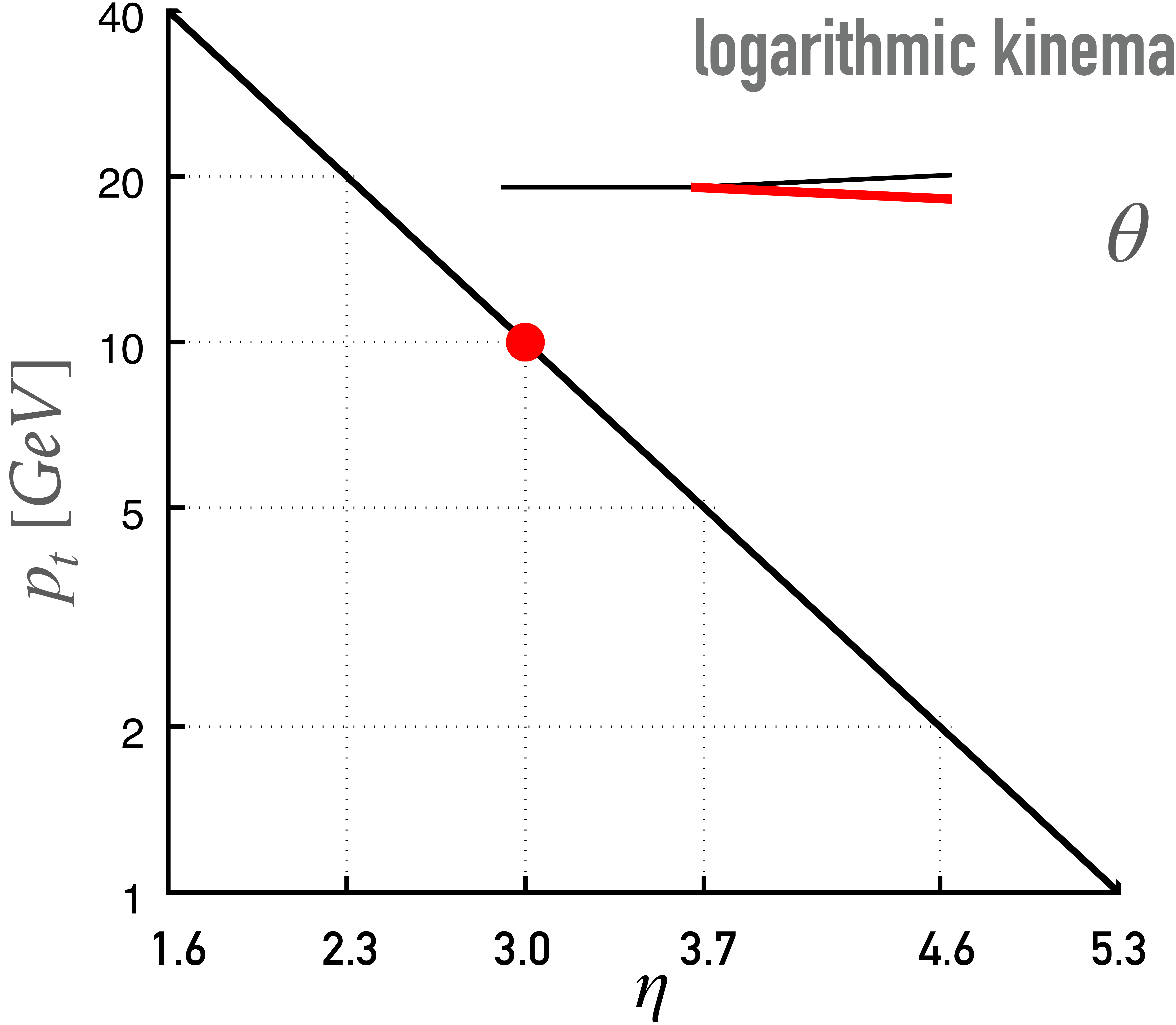

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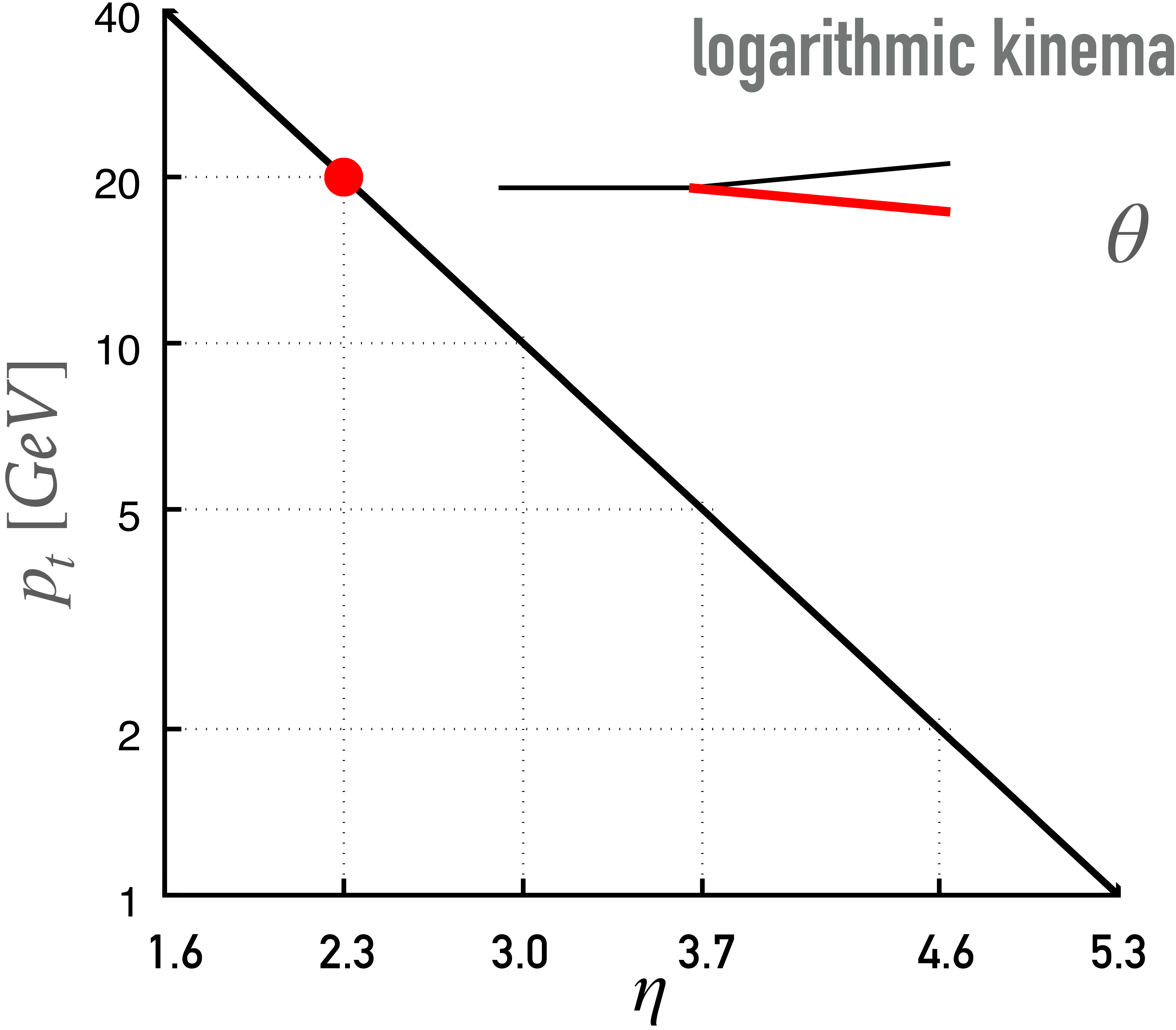
jet with $R = 0.4$, $p_t = 200$ *GeV*



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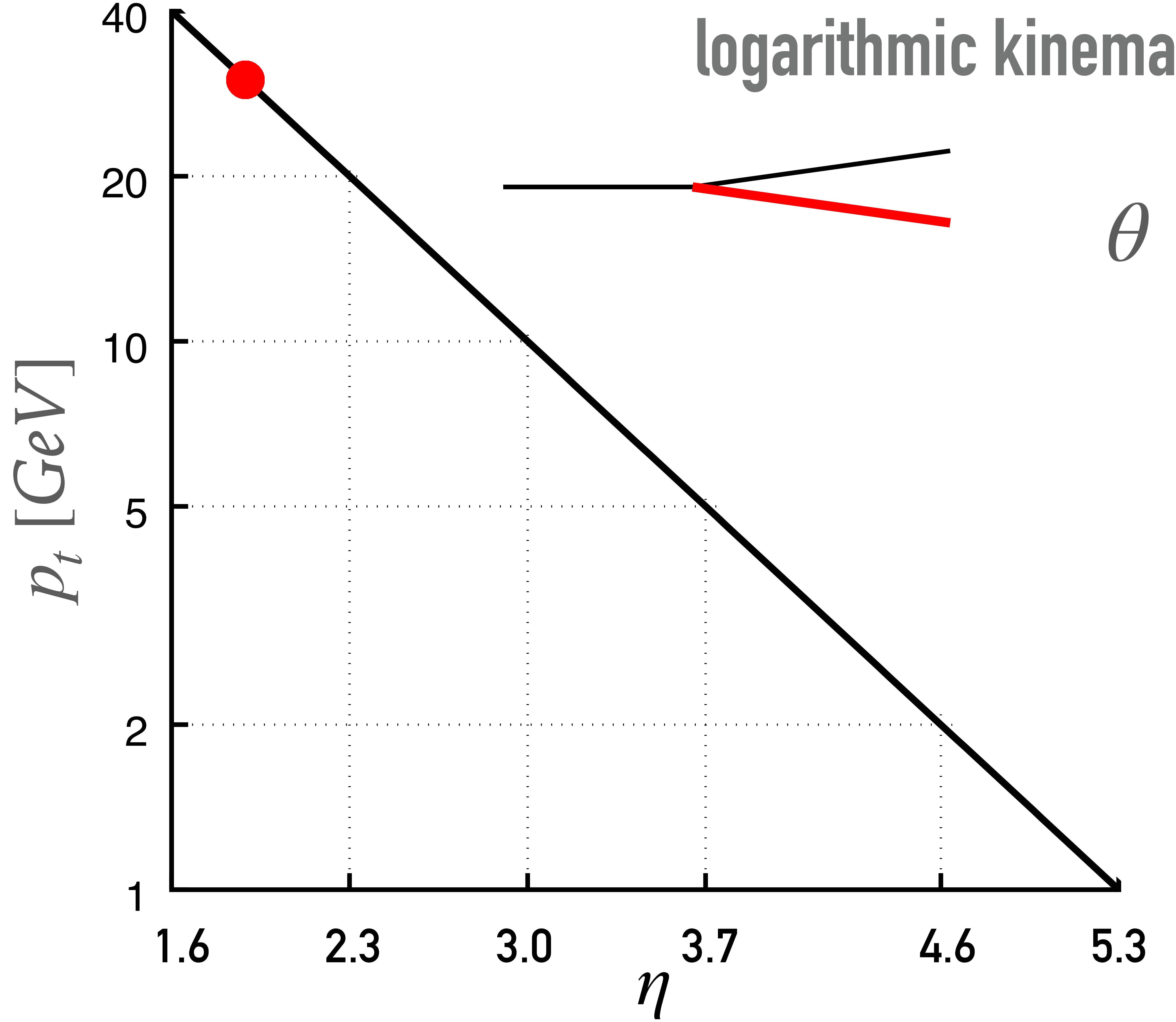

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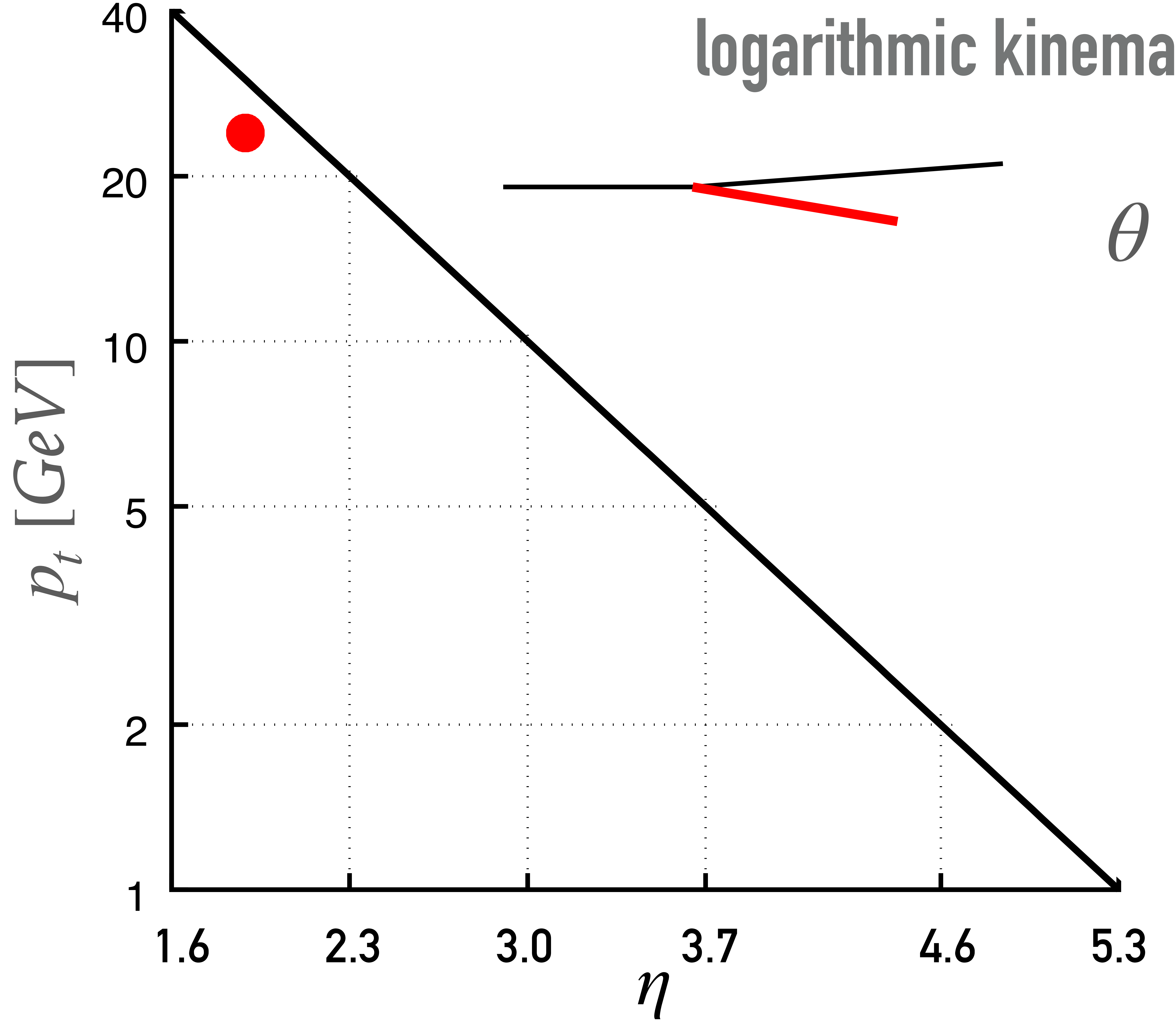

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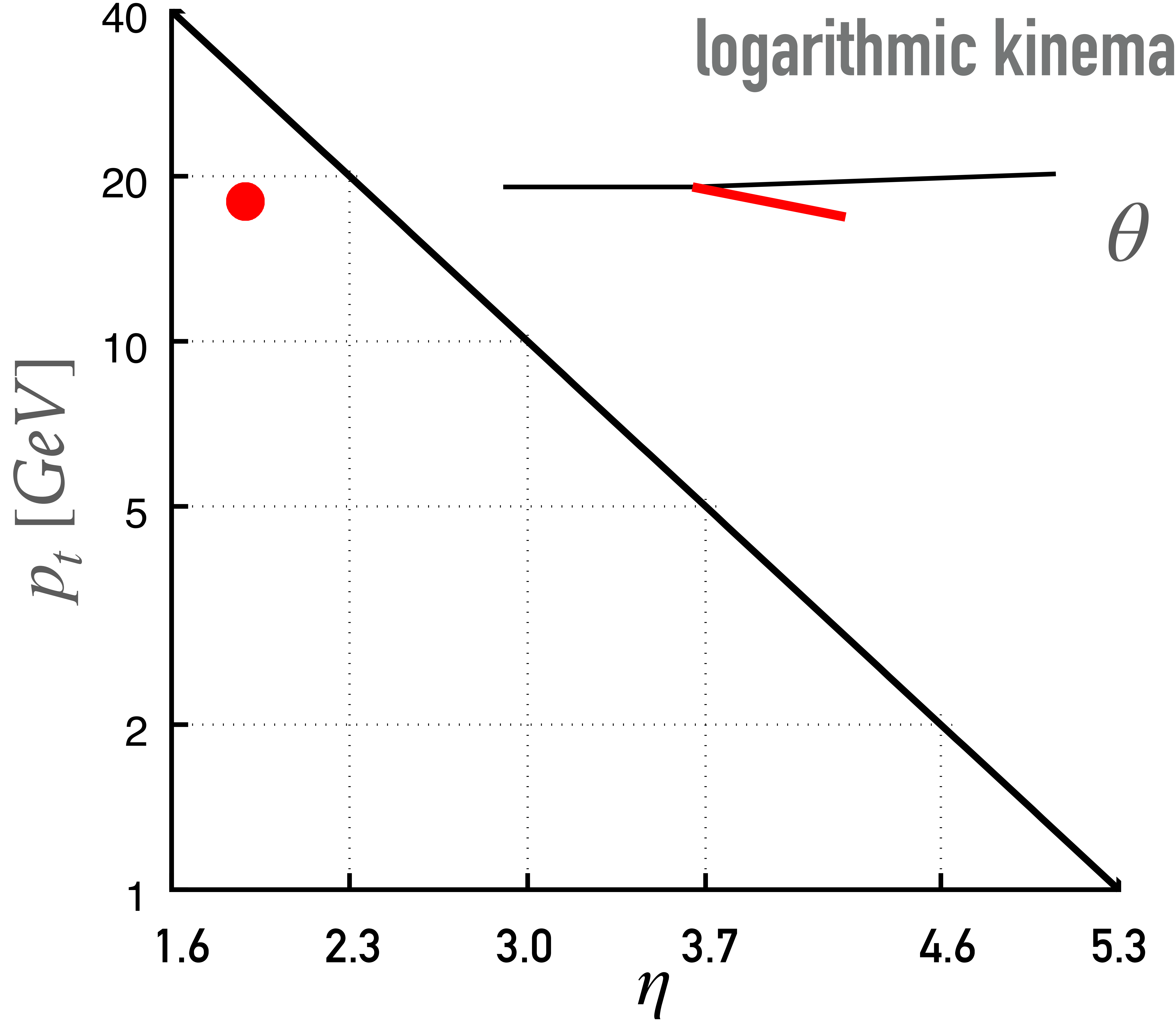

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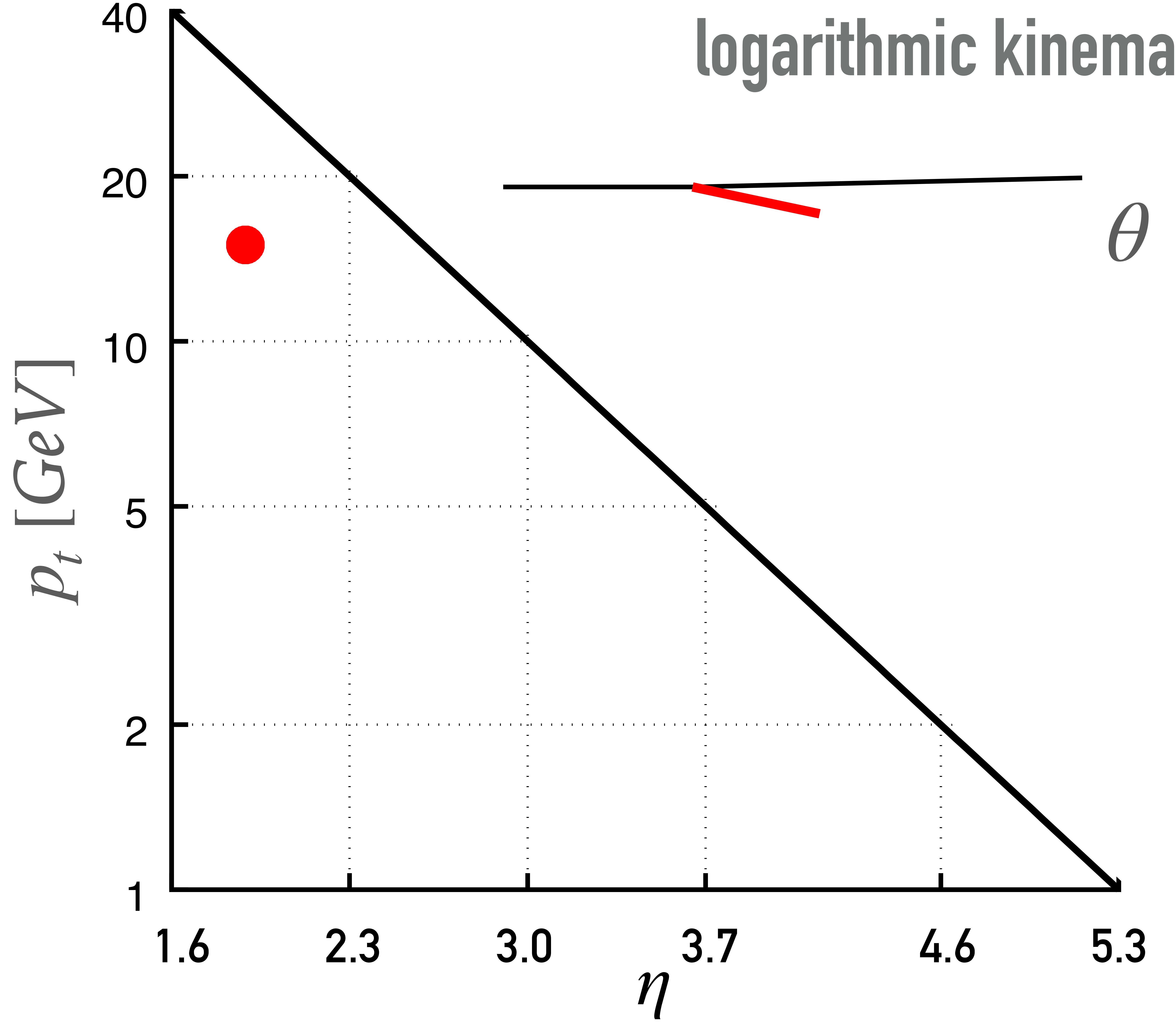

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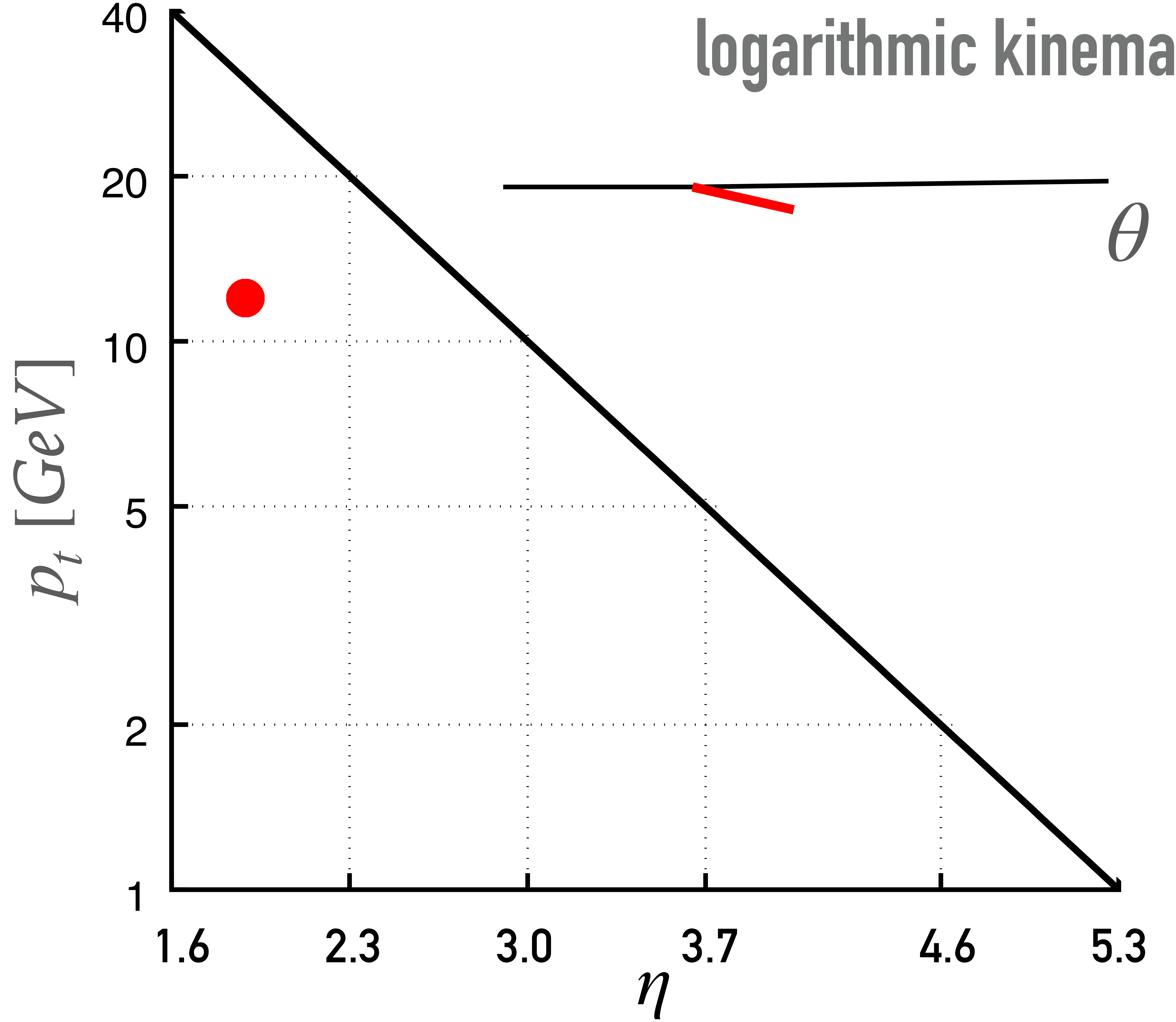

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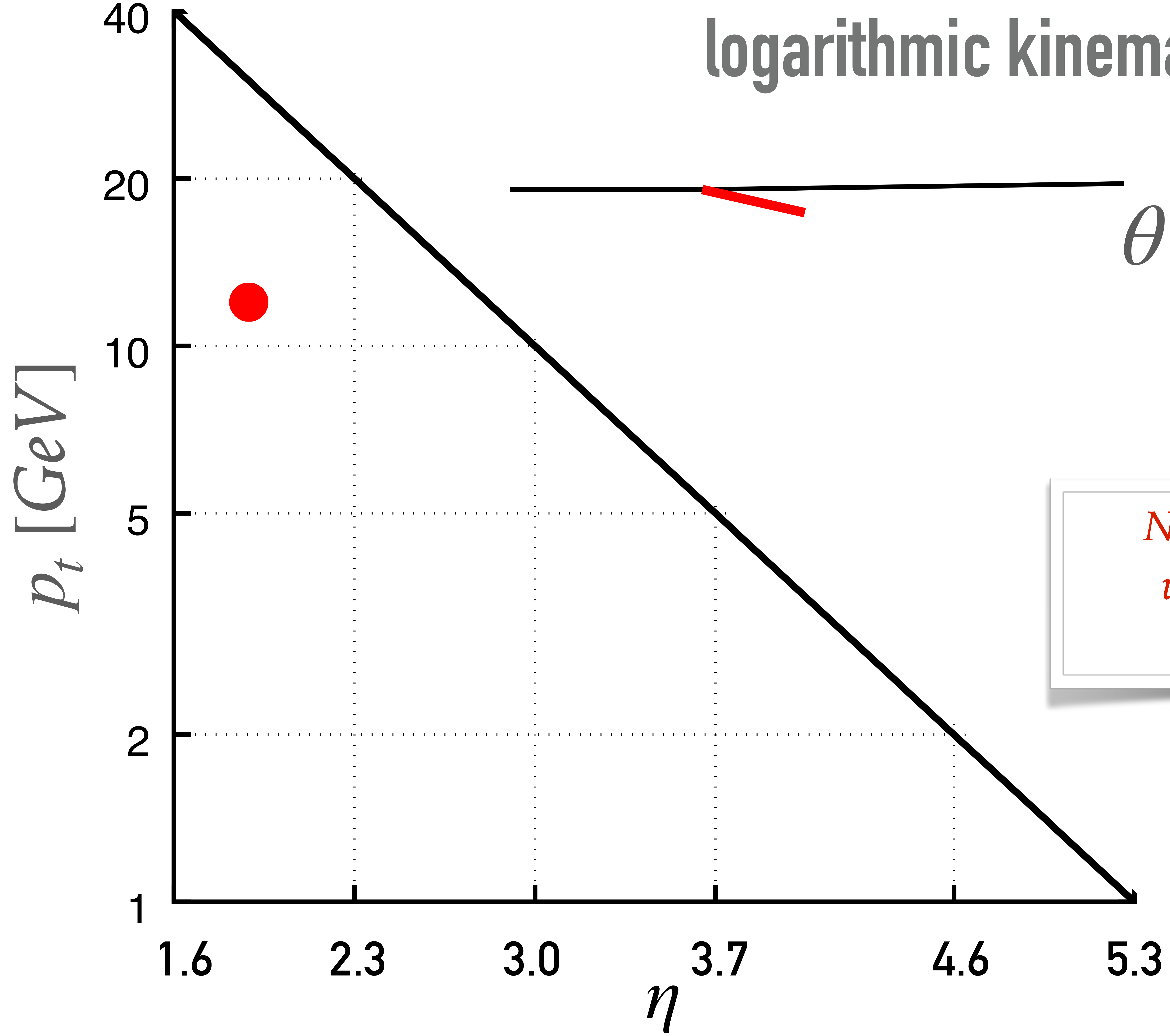

logarithmic kinematic plane whose two variables are

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NB: Lund plane can be constructed event-by-event using Cambridge/Aachen jet clustering sequence,

cf. Dreyer, GPS & Soyez '18

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

The Lund Plane

Matrix element for single emission (low energy ≡ "soft")

coupling *colour factor*

splitting probability →

$$dP = \frac{2\alpha_s C}{\pi} \frac{dp_\perp}{p_\perp} d\eta$$

Uniform density of emission in logarithmic (Lund) plane, except

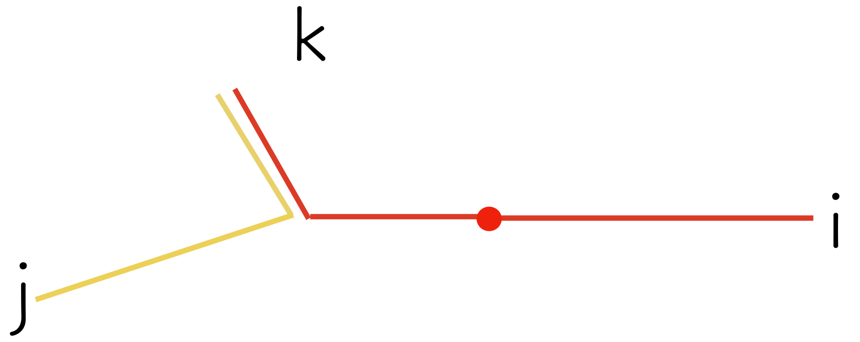
- ➤ for running coupling effects (which we will ignore in the rest of this talk)
- ➤ effects near edges of Lund plane (we'll also ignore those)

Matrix element for single emission in Dire / Pythia8: it's correct

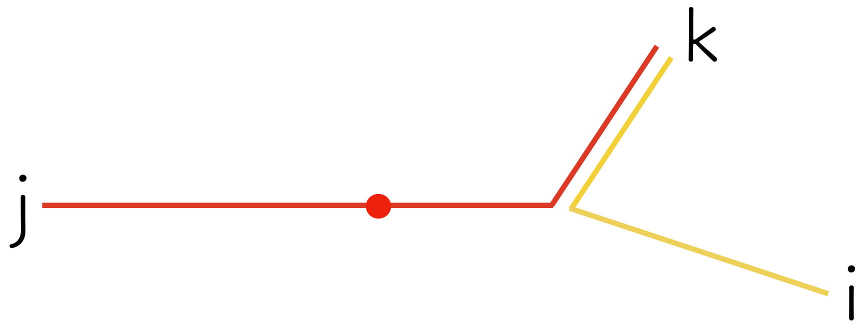
j emits, i spectates

i emits, j spectates

$$d\mathcal{P}_{\tilde{i}\tilde{j}\to ikj} = d\mathcal{P}$$



$$+ \; d\mathcal{P}$$



$$= \frac{2\alpha_{\mathrm{s}} C}{\pi} \frac{dp_\perp}{p_\perp} d\eta \, \frac{e^{-2\eta}}{1+e^{-2\eta}} + \frac{2\alpha_{\mathrm{s}} C}{\pi} \frac{dp_\perp}{p_\perp} d\eta \, \frac{e^{2\eta}}{1+e^{2\eta}}$$

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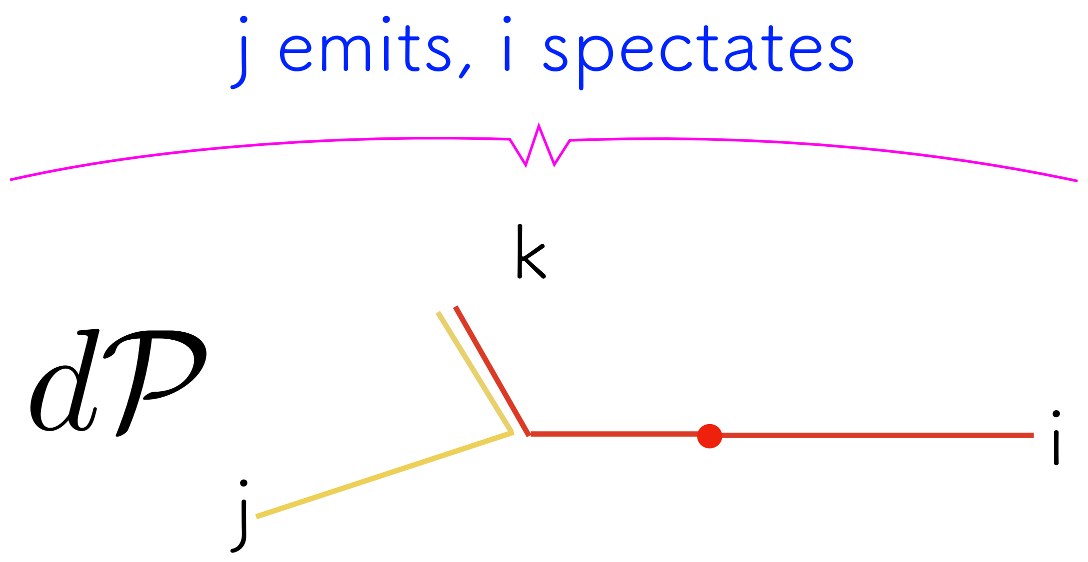

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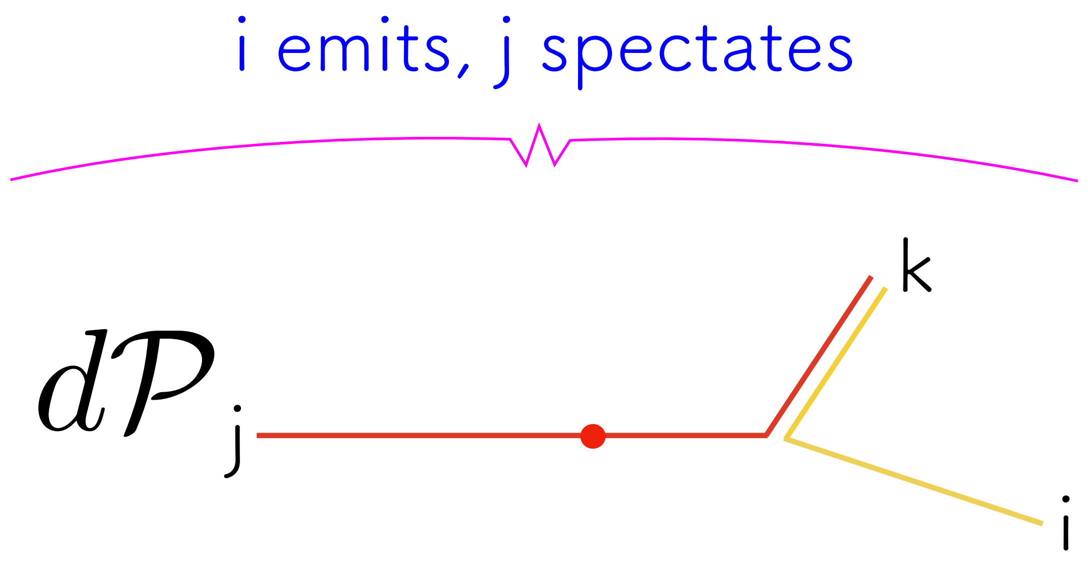
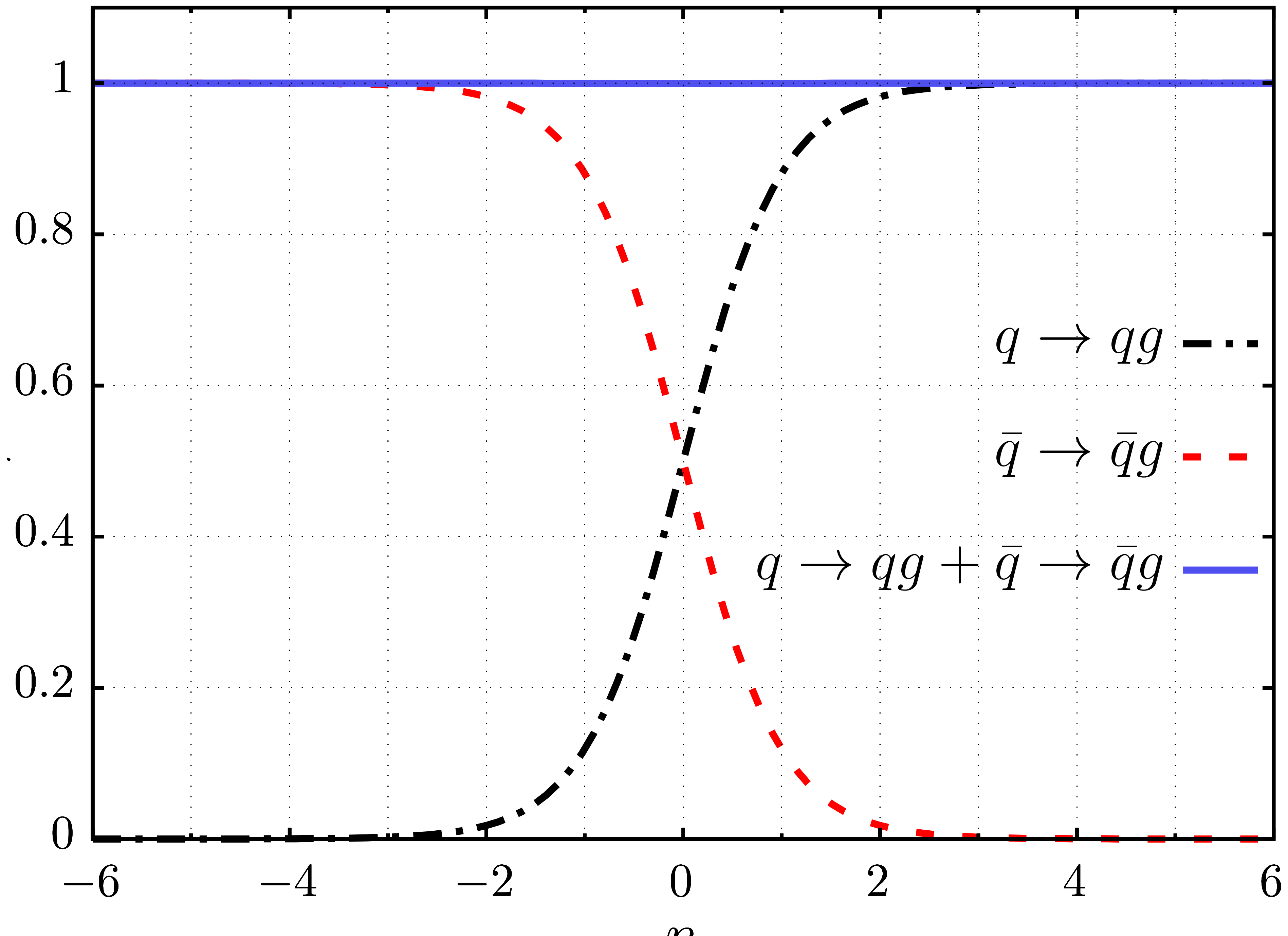


$$= \frac{2\alpha_s C}{\pi}\frac{dp_\perp}{p_\perp}d\eta\,\frac{e^{-2\eta}}{1+e^{-2\eta}} + \frac{2\alpha_s C}{\pi}\frac{dp_\perp}{p_\perp}d\eta\,\frac{e^{2\eta}}{1+e^{2\eta}}$$

ratio to full matrix element



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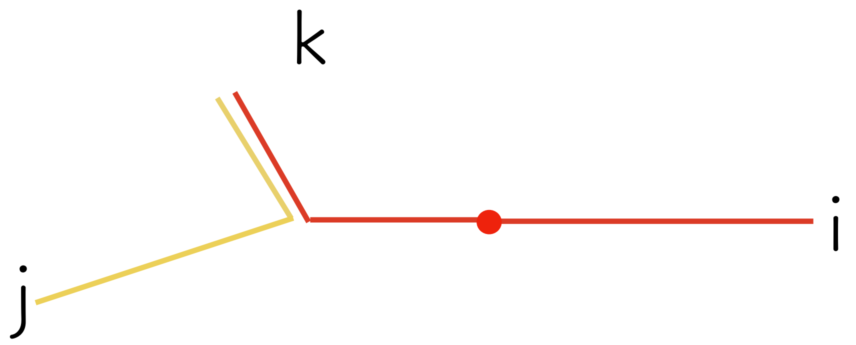

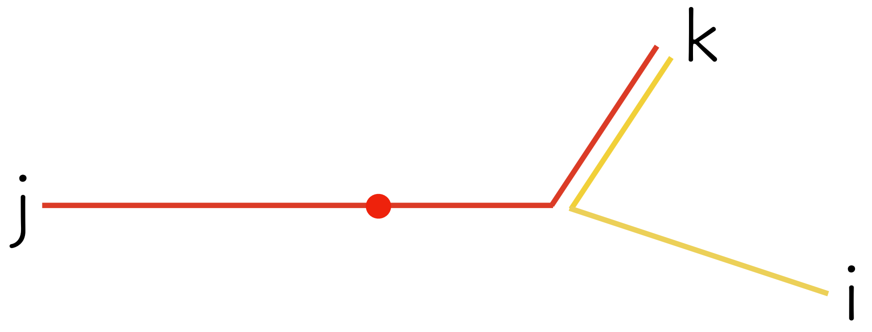

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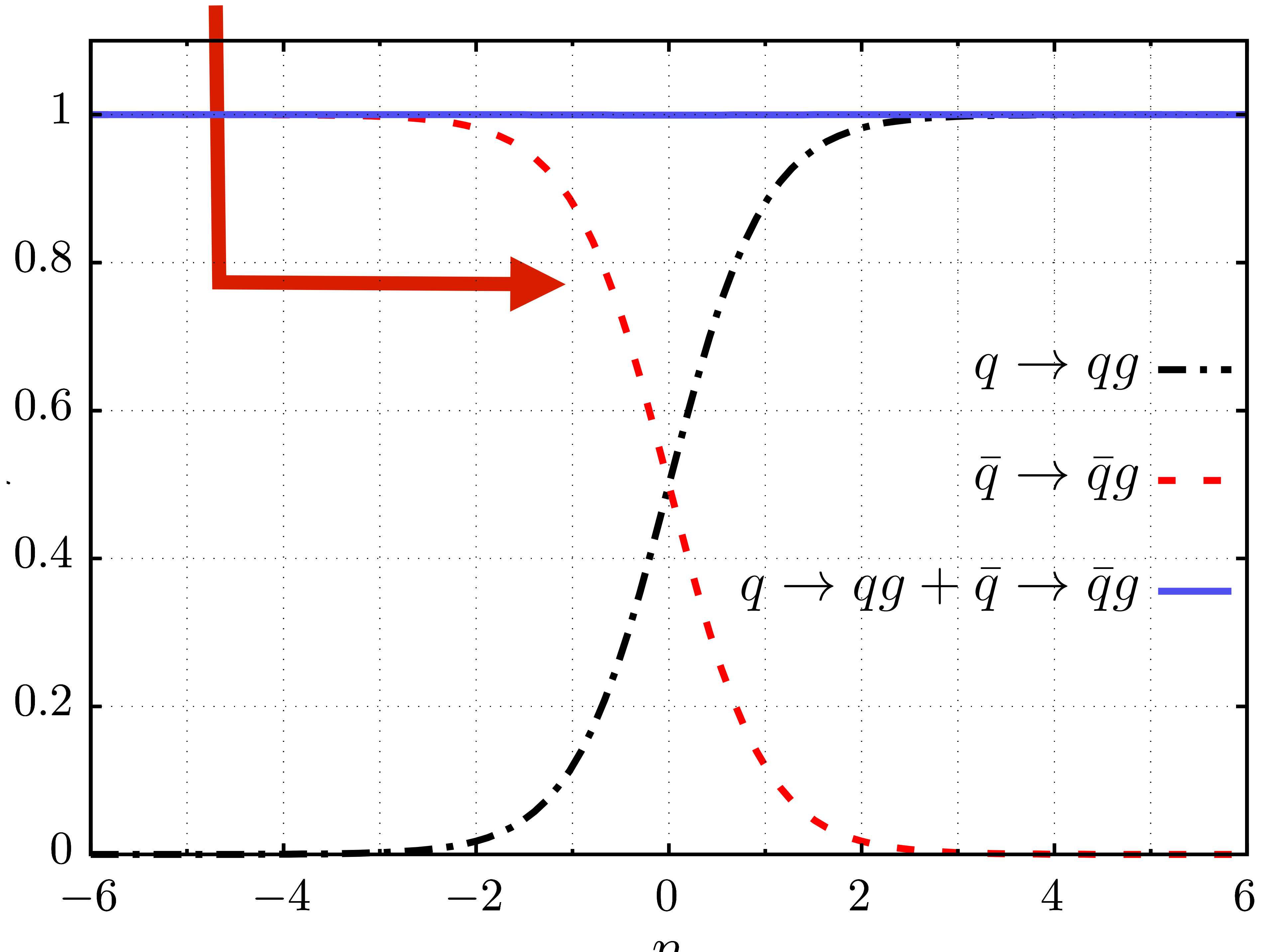

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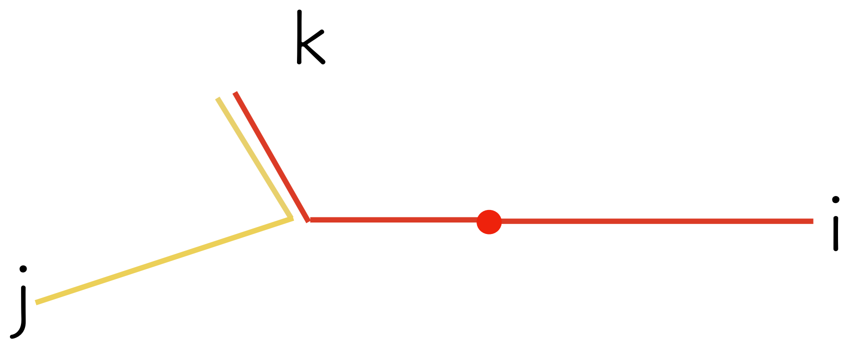

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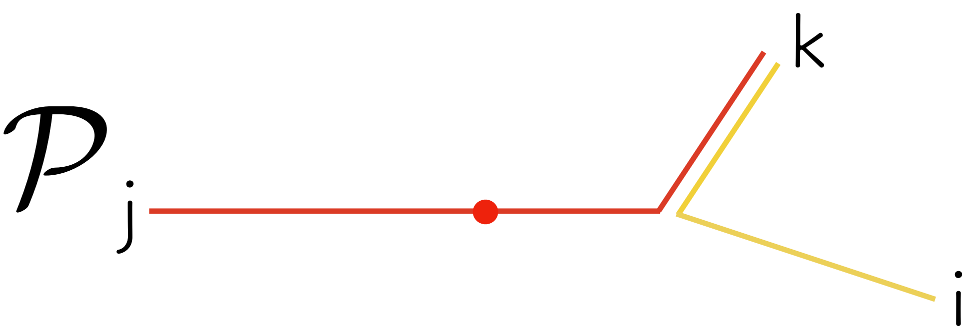

$$= \frac{2\alpha_s C}{\pi}\frac{dp_\perp}{p_\perp}d\eta\boxed{\frac{e^{-2\eta}}{1+e^{-2\eta}}} + \frac{2\alpha_s C}{\pi}\frac{dp_\perp}{p_\perp}d\eta\boxed{\frac{e^{2\eta}}{1+e^{2\eta}}}$$

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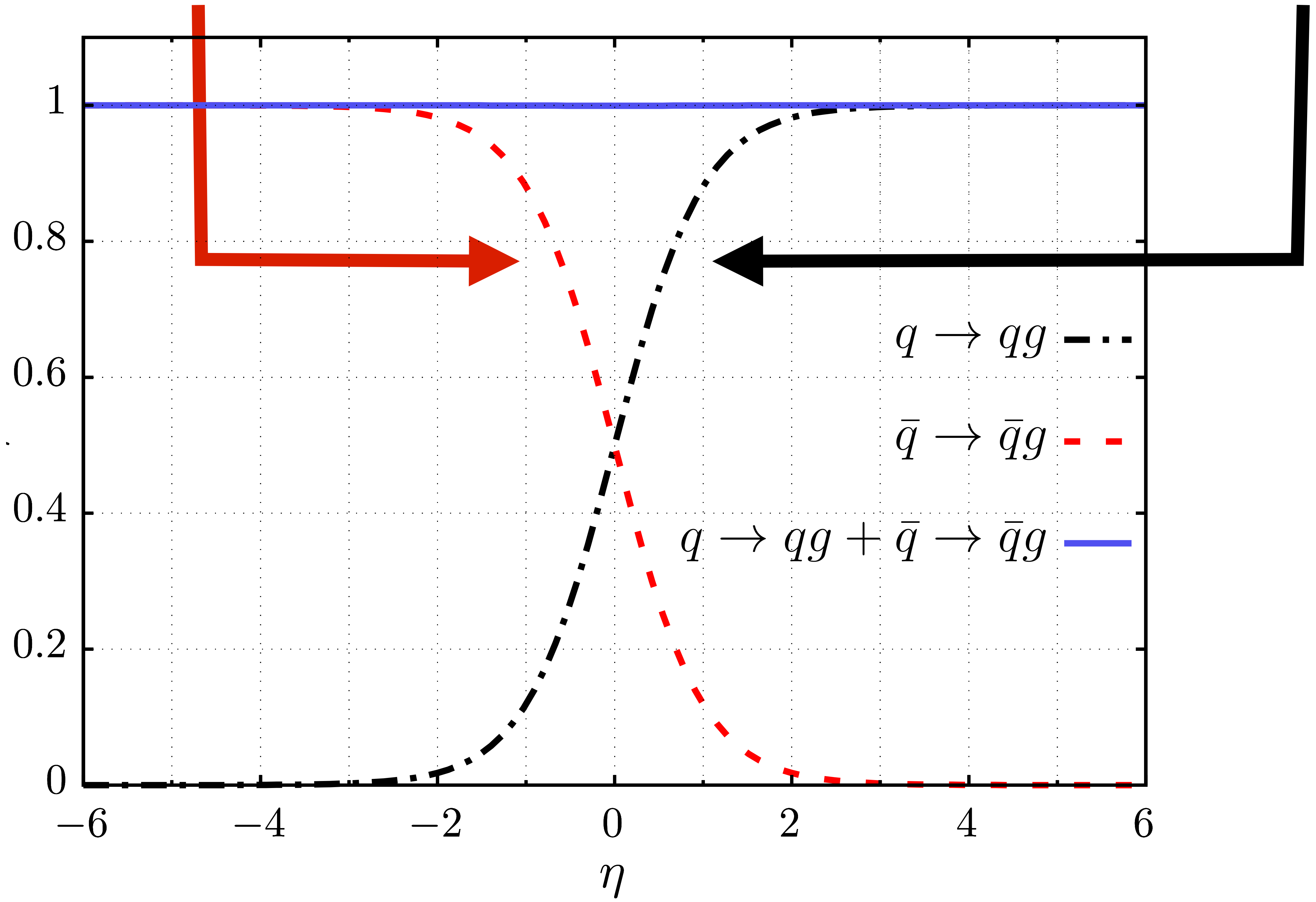

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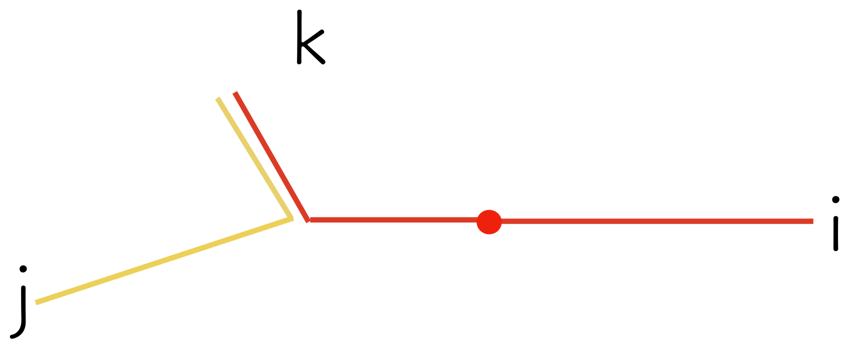
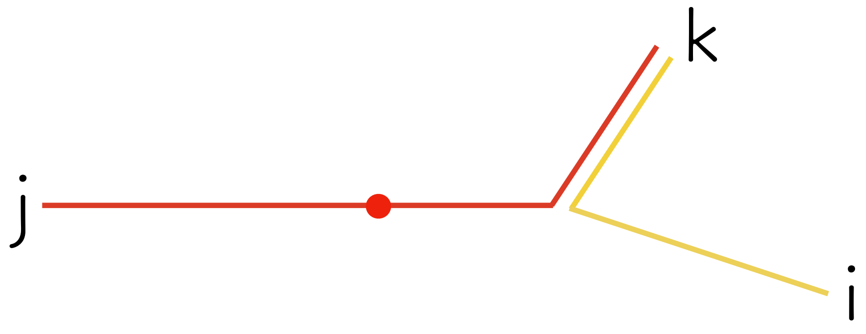
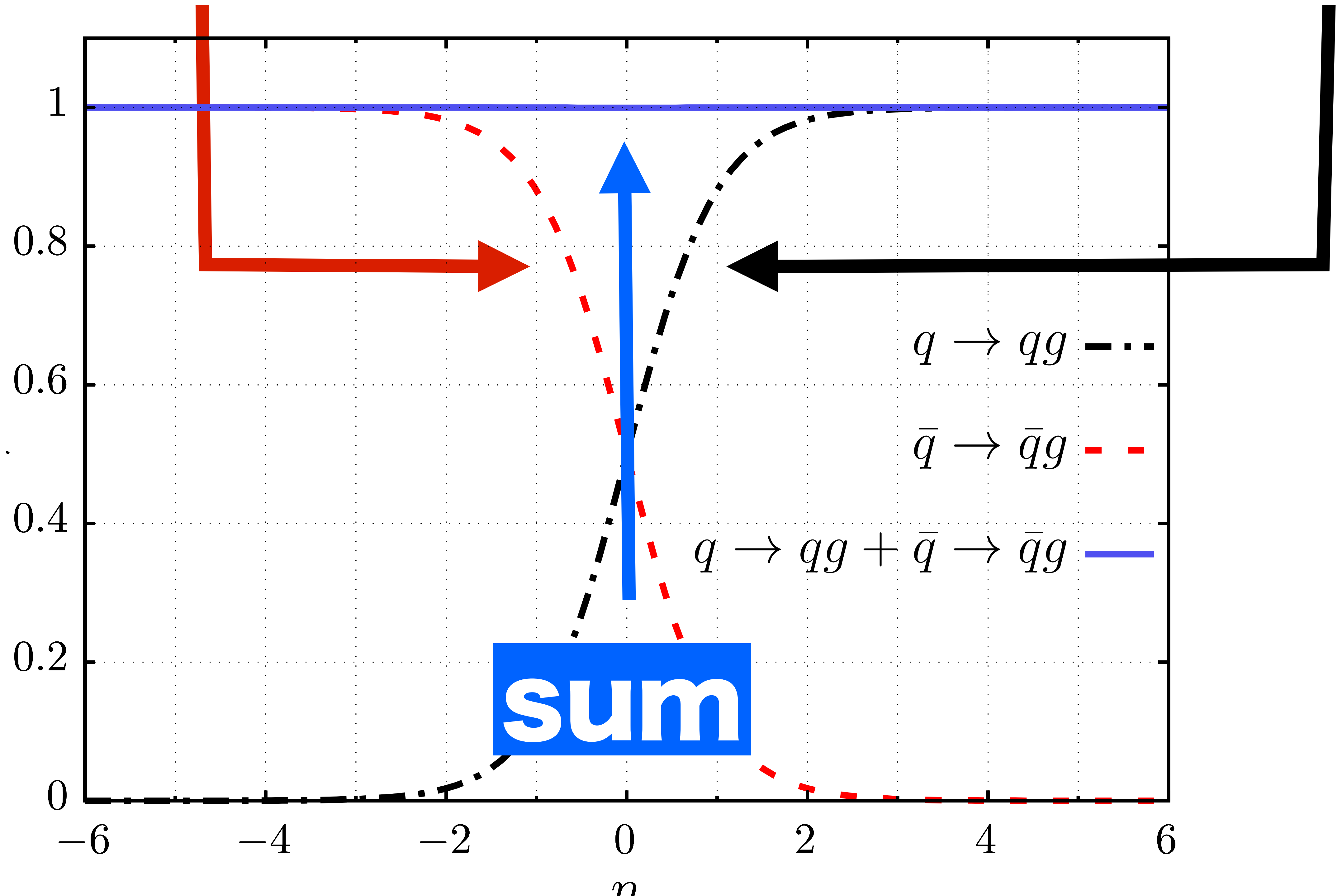




$$= \frac{2\alpha_s C}{\pi}\frac{dp_\perp}{p_\perp}\,d\eta\,\boxed{\frac{e^{-2\eta}}{1+e^{-2\eta}}} + \frac{2\alpha_s C}{\pi}\frac{dp_\perp}{p_\perp}\,d\eta\,\boxed{\frac{e^{2\eta}}{1+e^{2\eta}}}$$

ratio to full matrix element



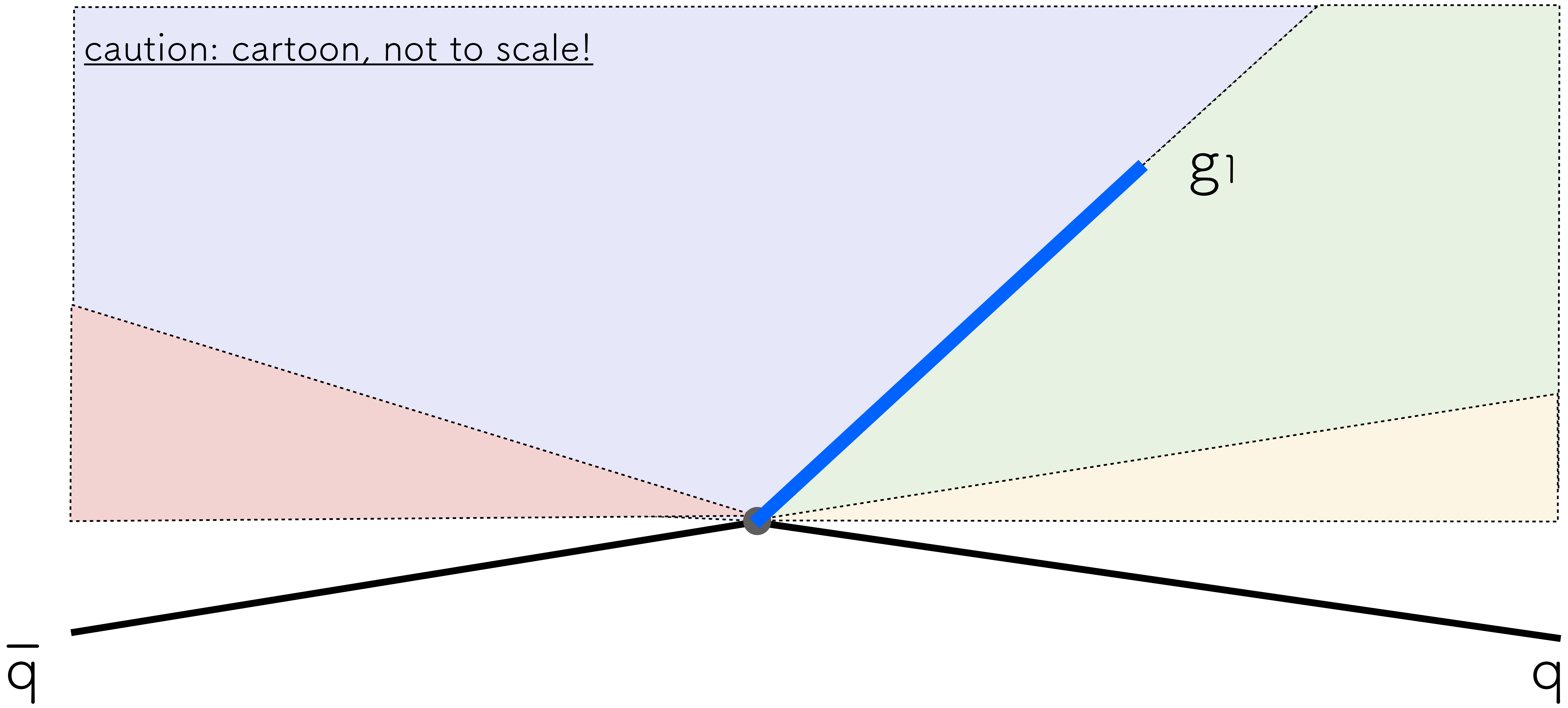
Matrix element for two emissions (low energy ≡ “soft”)

$$dP = \frac{1}{2!}\left(\frac{2\alpha_s C}{\pi}\frac{dp_{\perp,1}}{p_{\perp,1}}d\eta_1\right)\left(\frac{2\alpha_s C}{\pi}\frac{dp_{\perp,2}}{p_{\perp,1}}d\eta_2\right)$$

Double-emission density is square of single-emission formula

- in large parts of phase space
- specifically in parts of primary Lund plane that are well separated in η (this is a consequence of “angular ordering”)

Two emissions in dipole showers (Dire / Pythia8)



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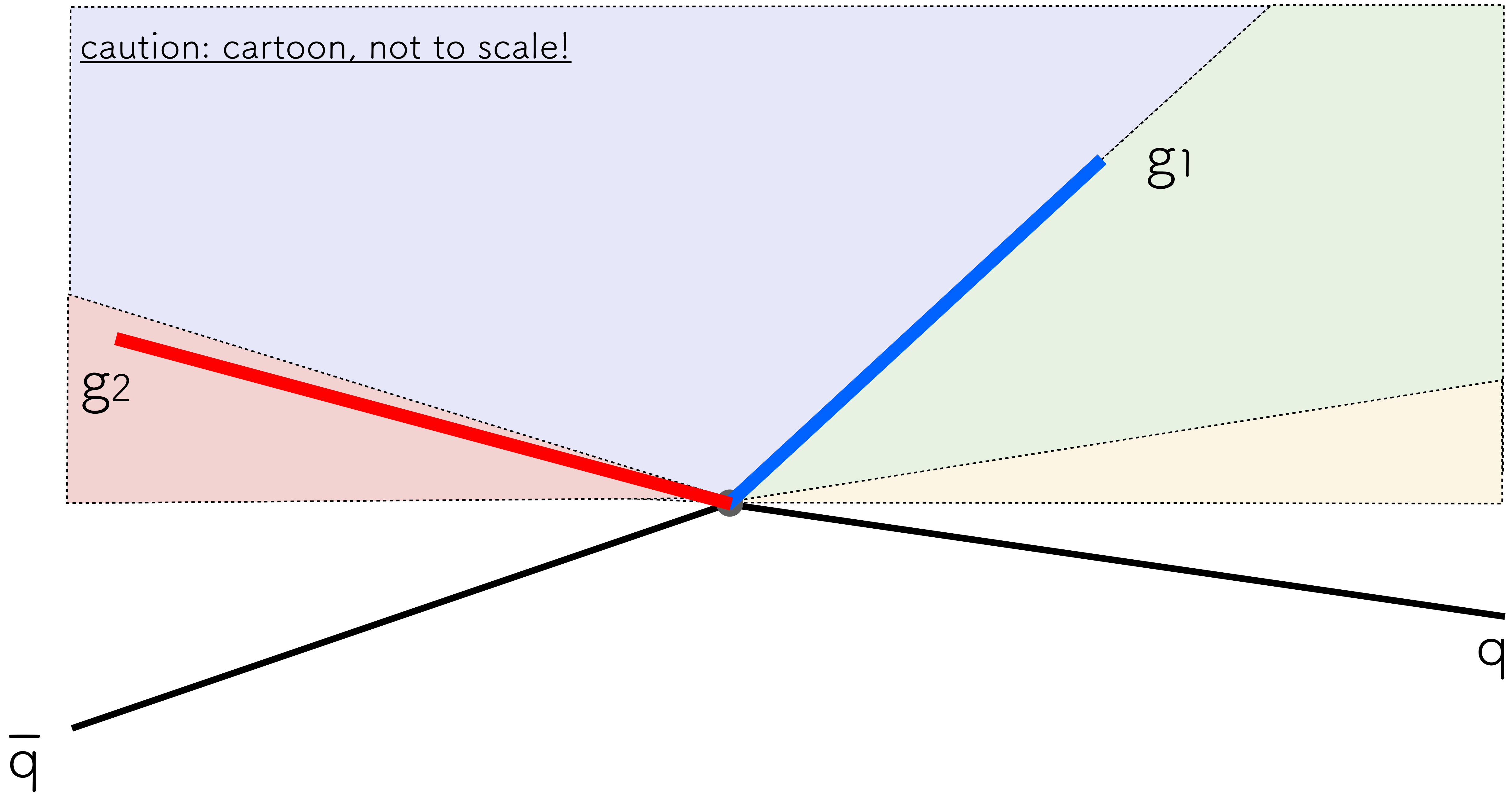
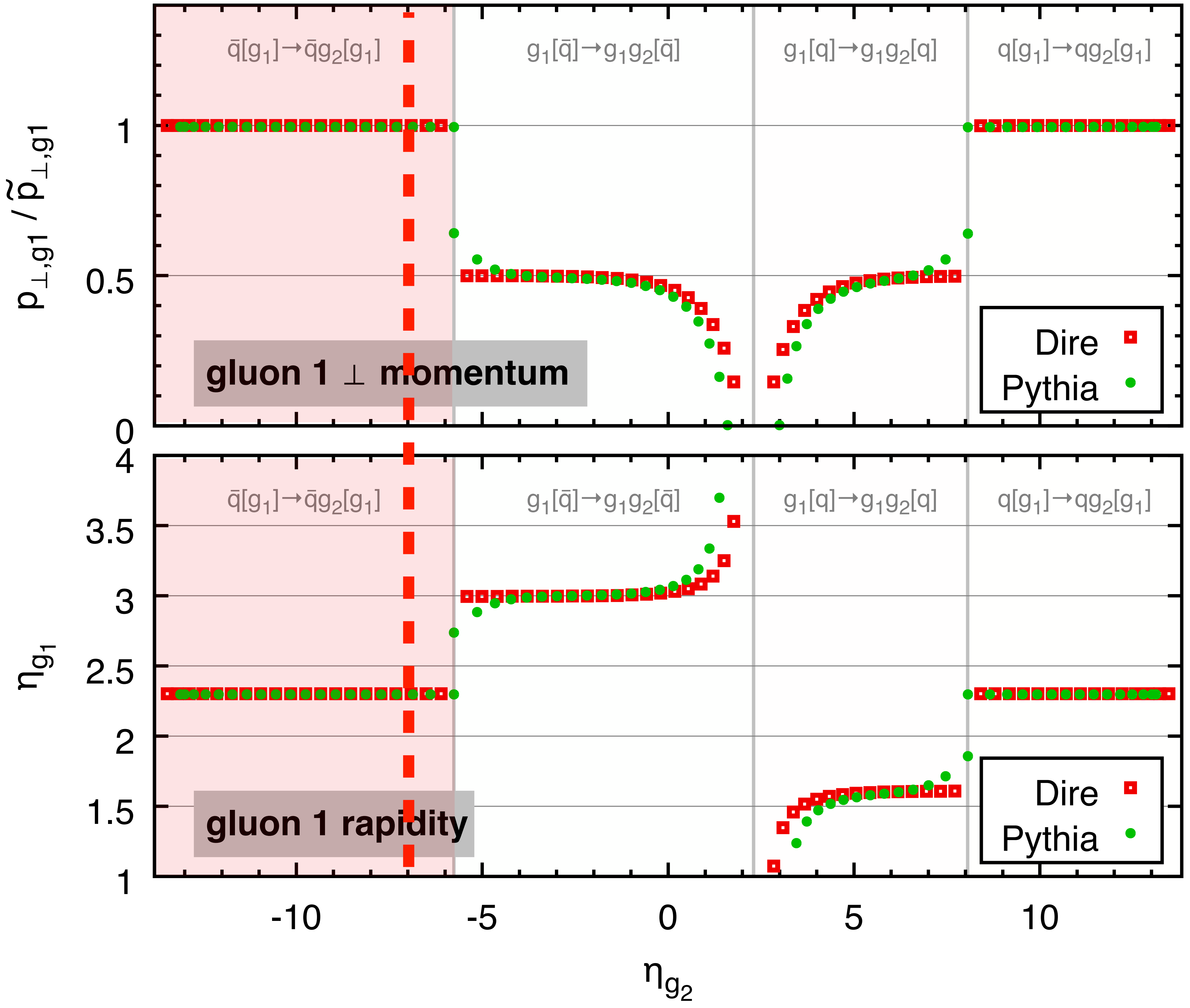


impact of gluon-2 emission on gluon-1 momentum



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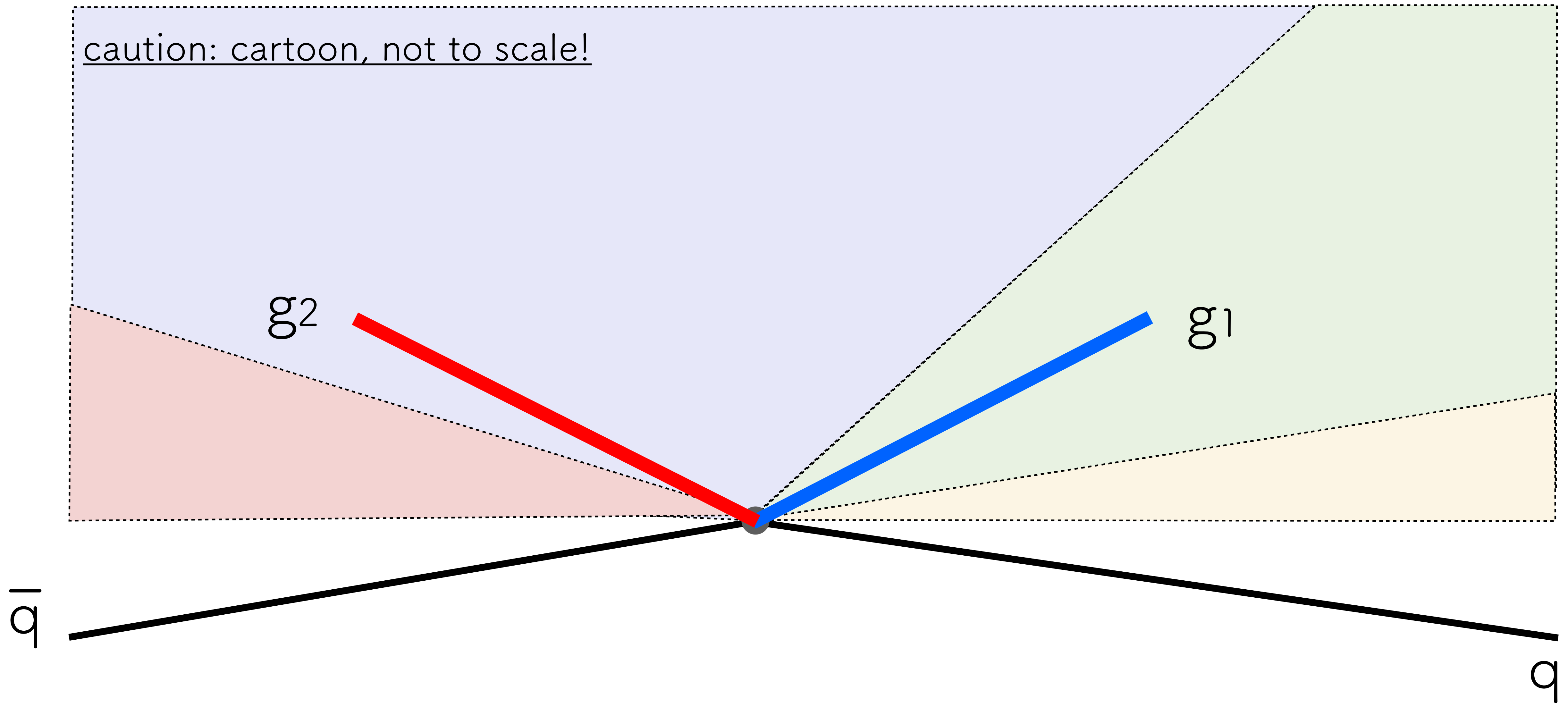

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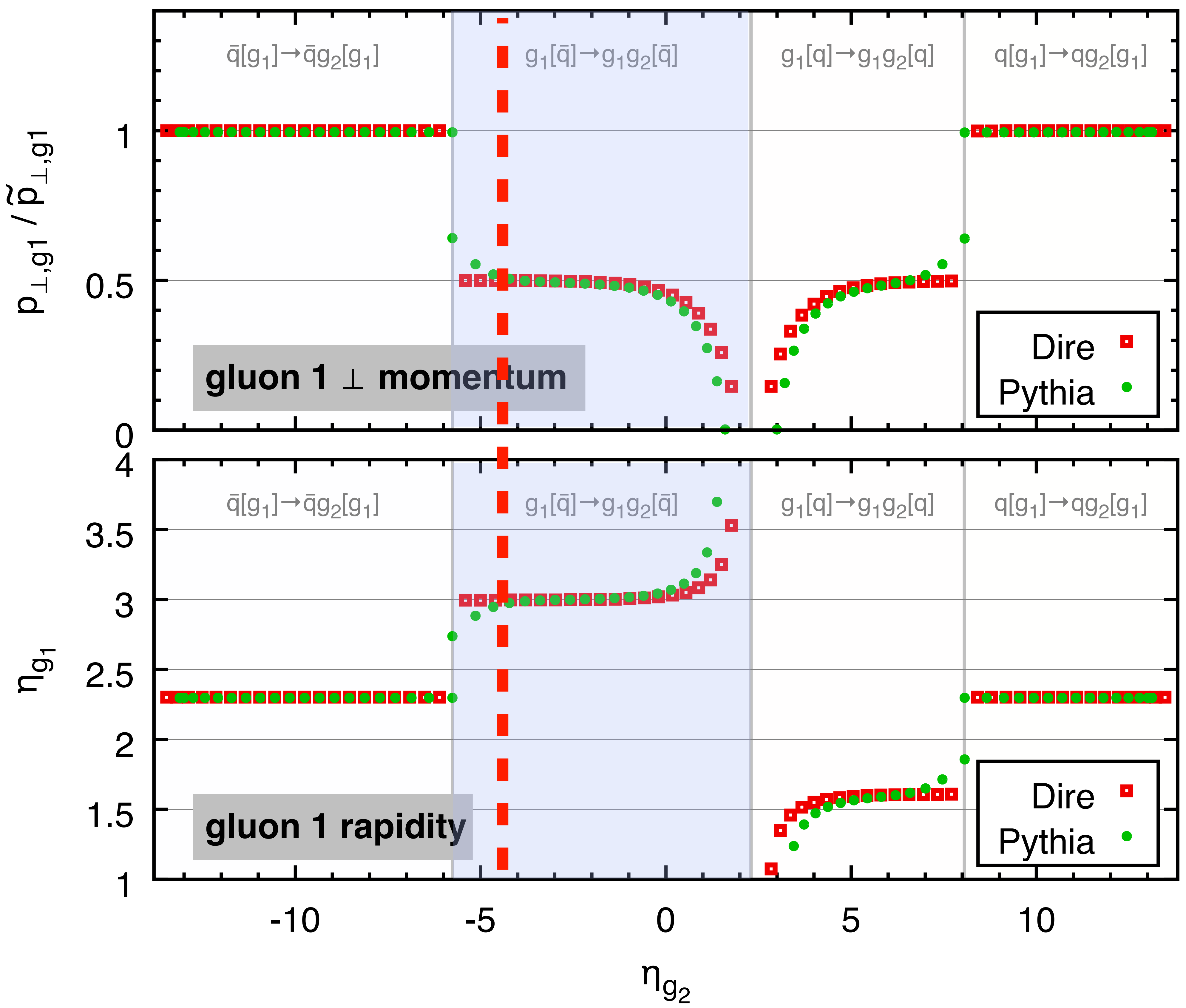

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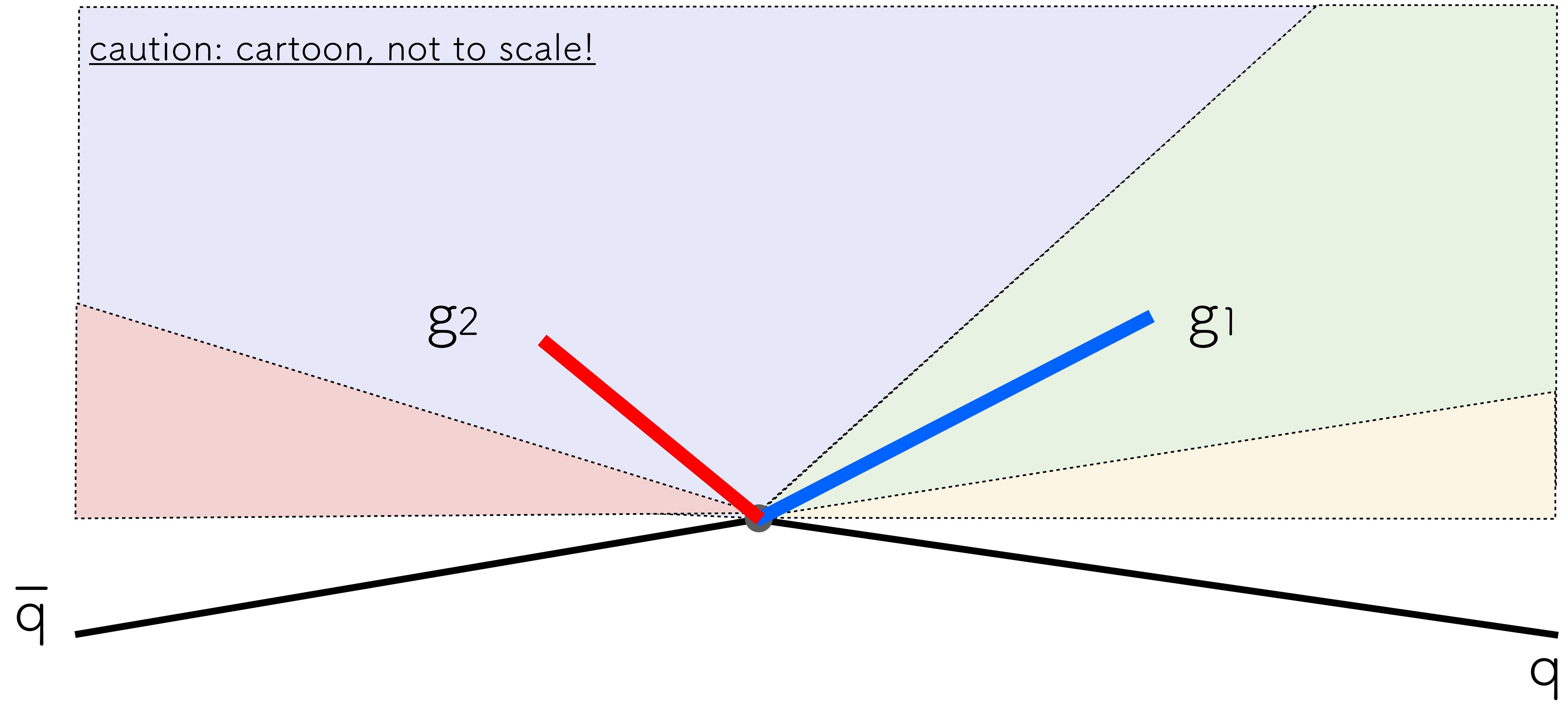

caution: cartoon, not to scale!

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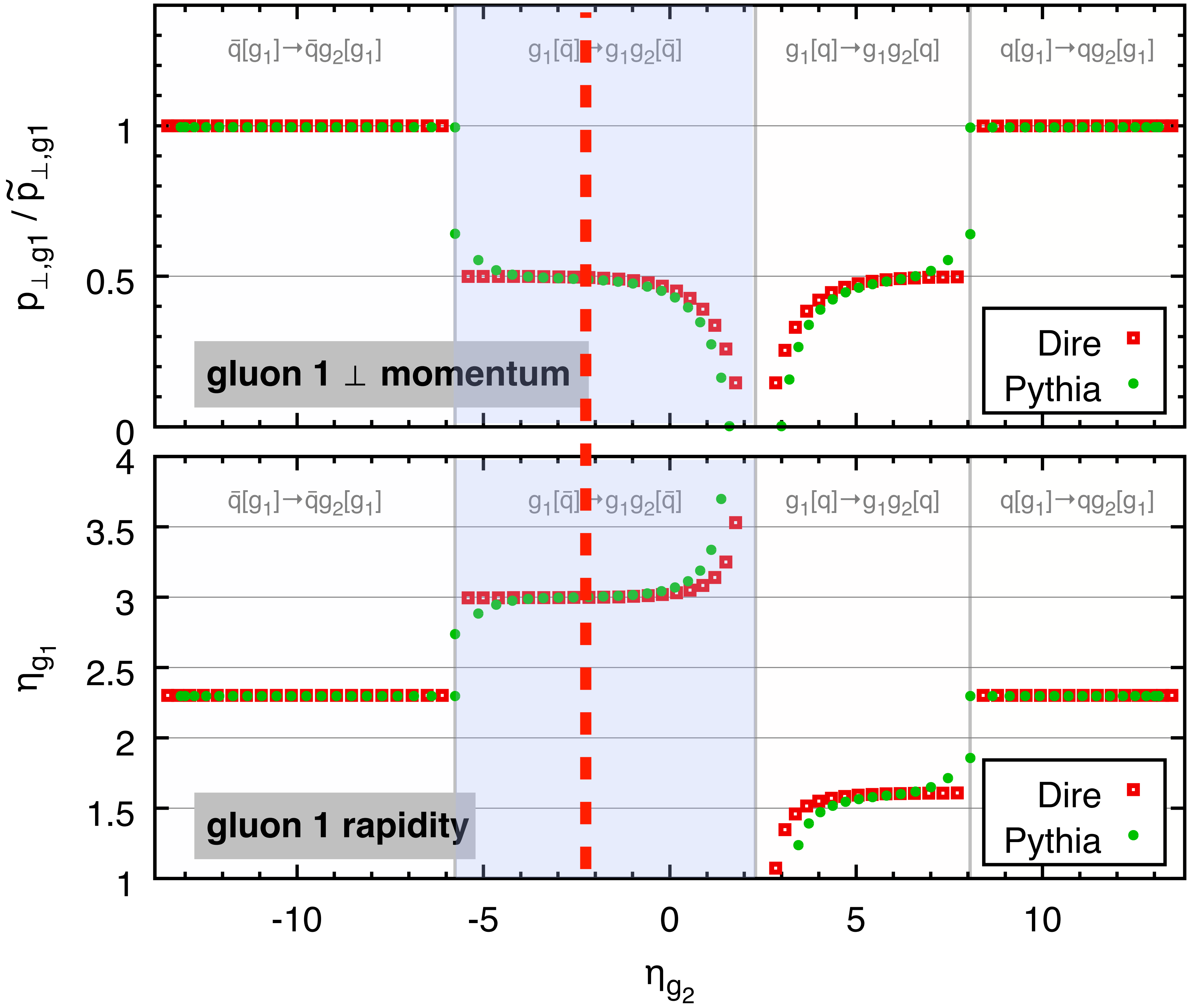

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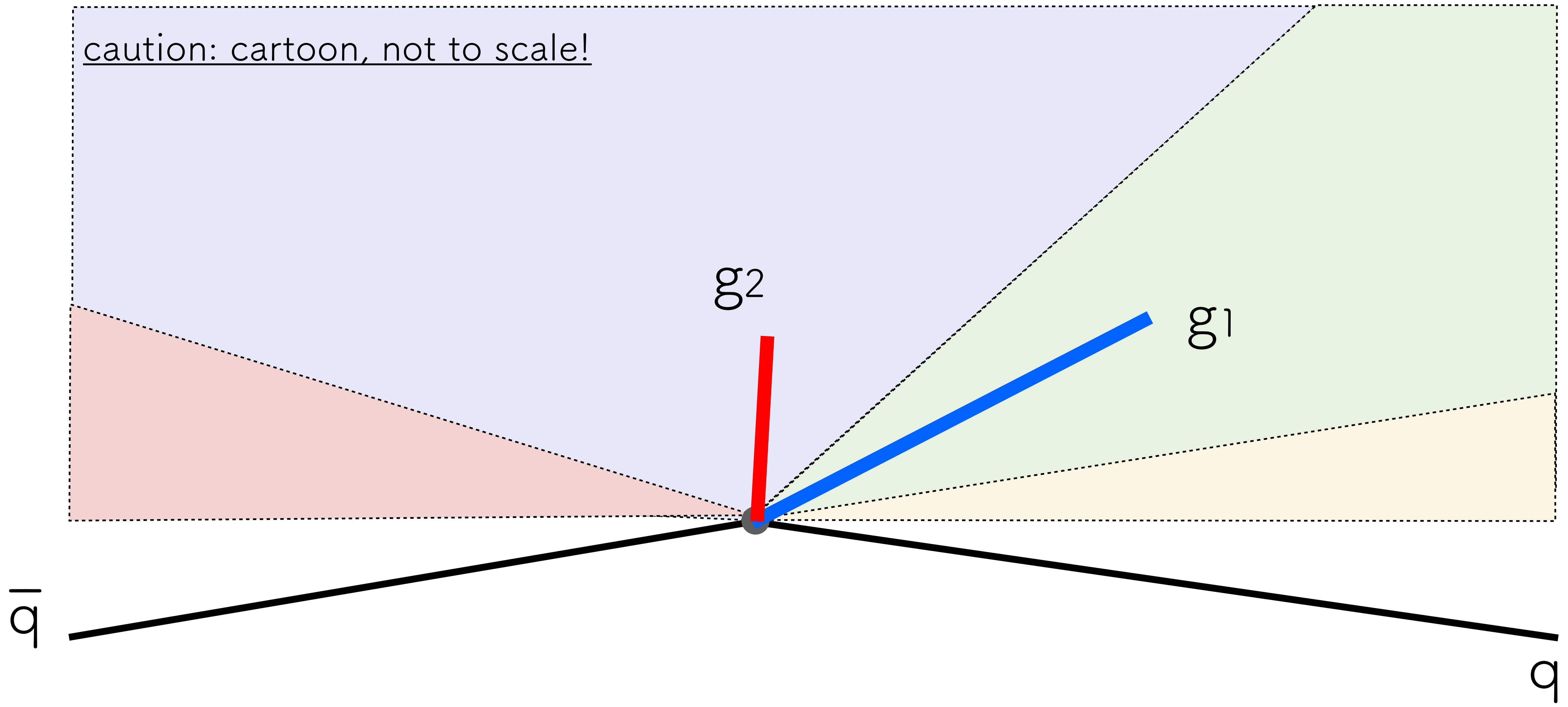

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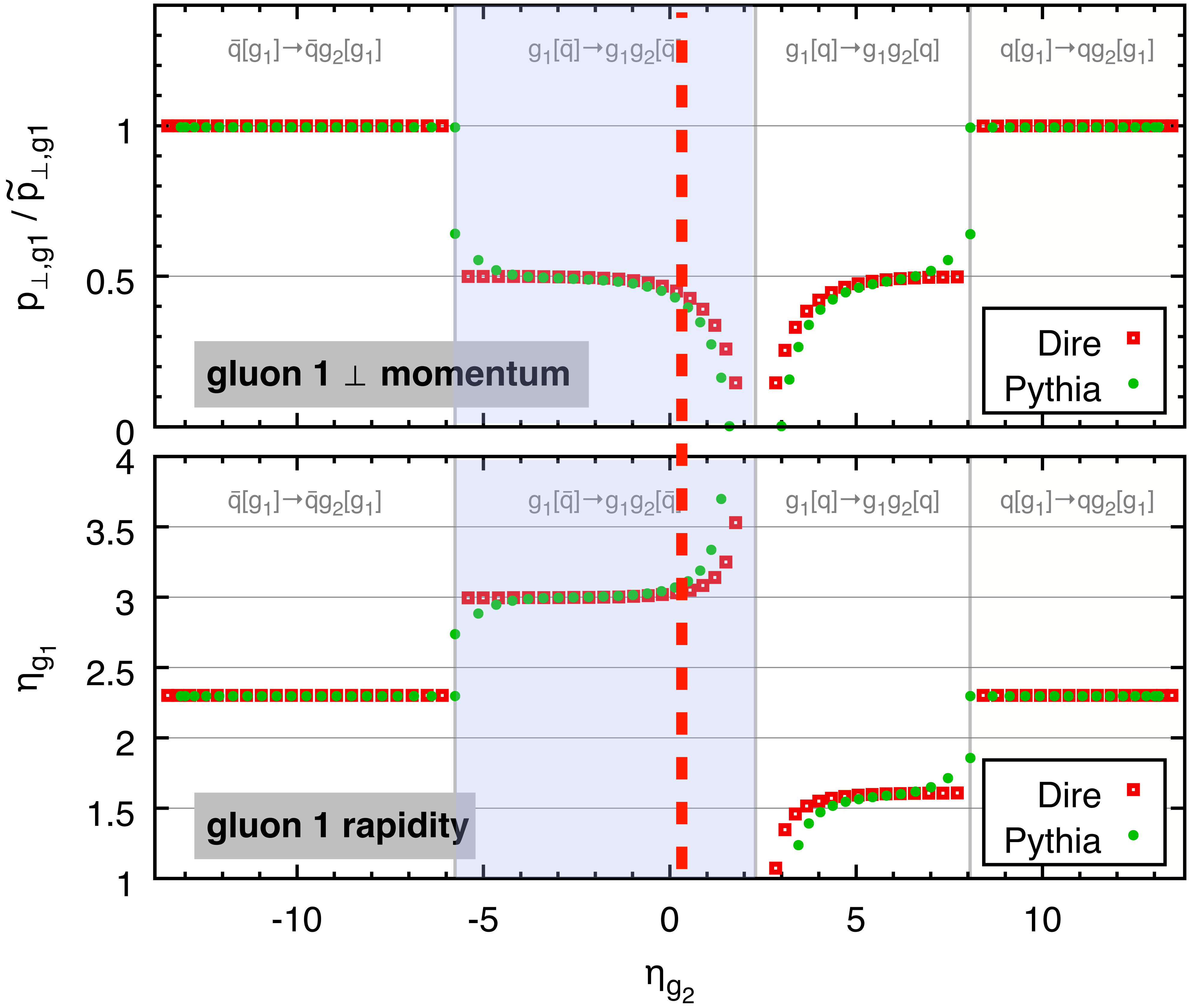

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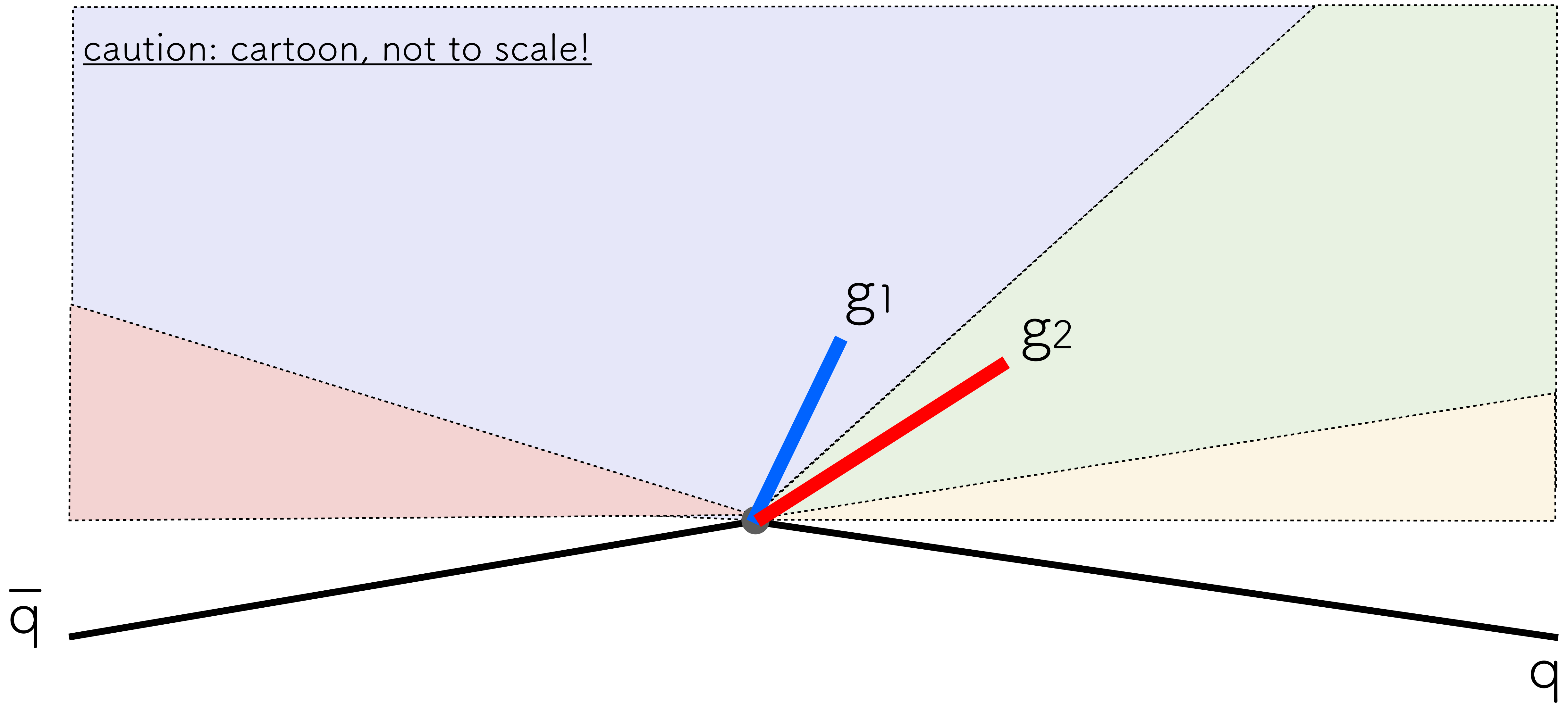

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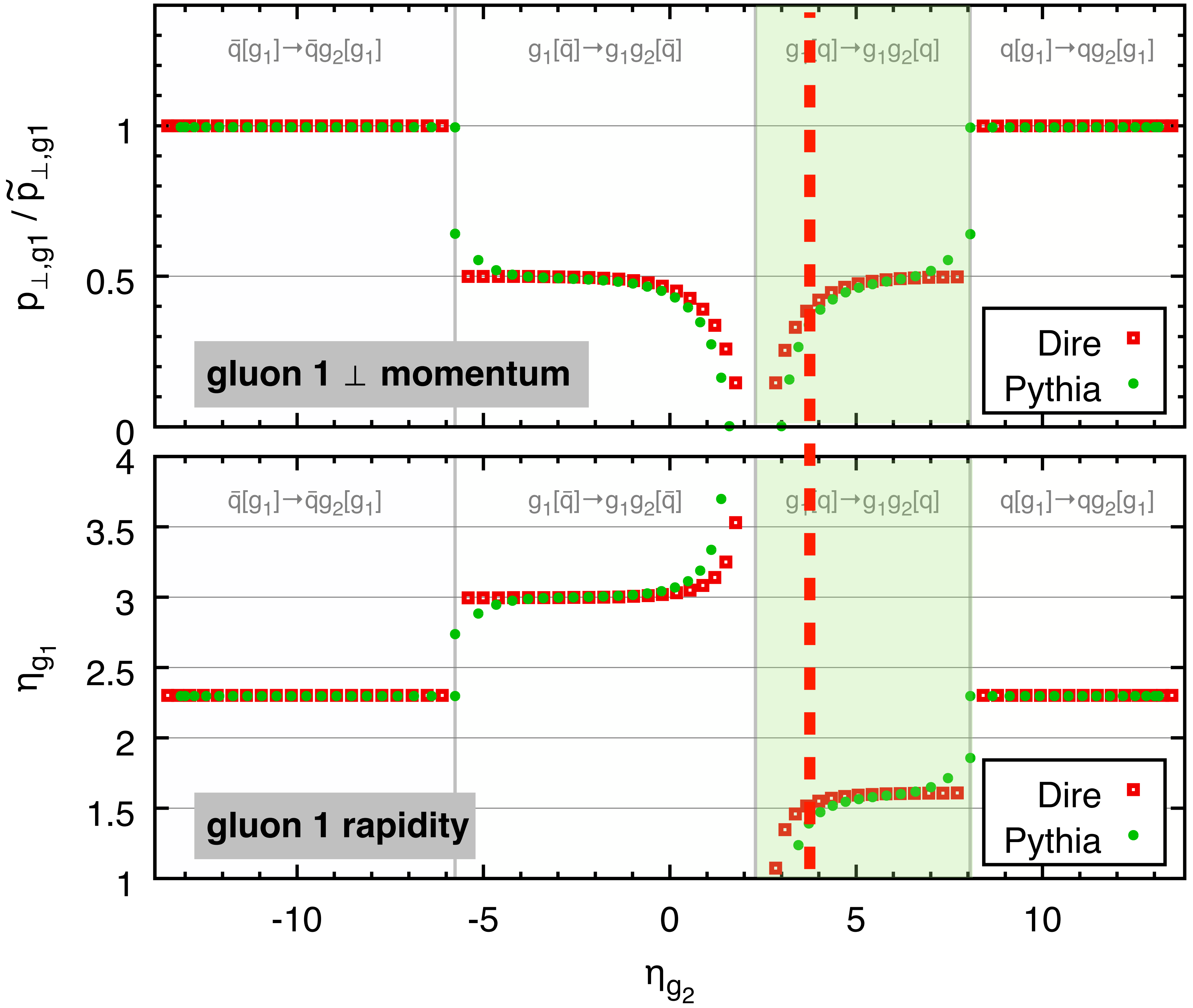

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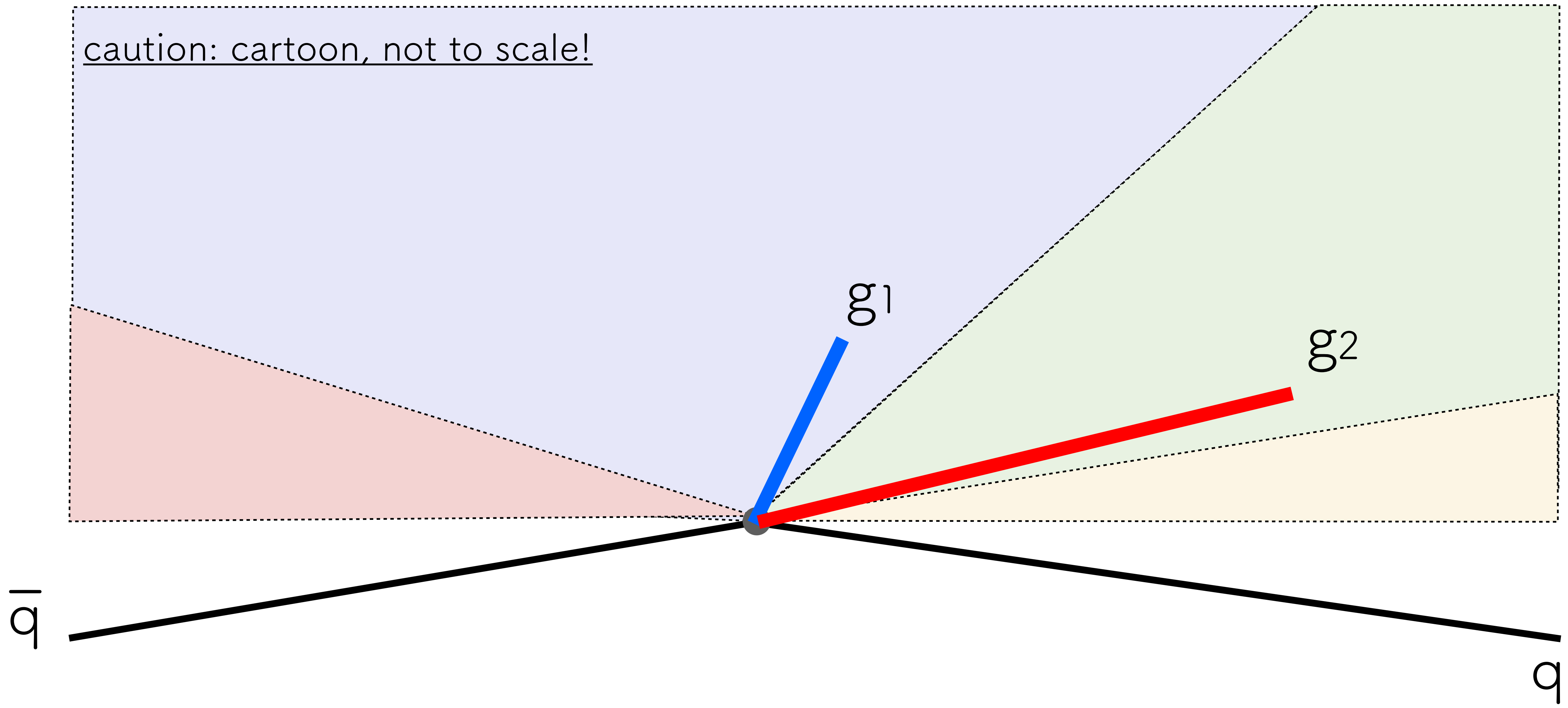

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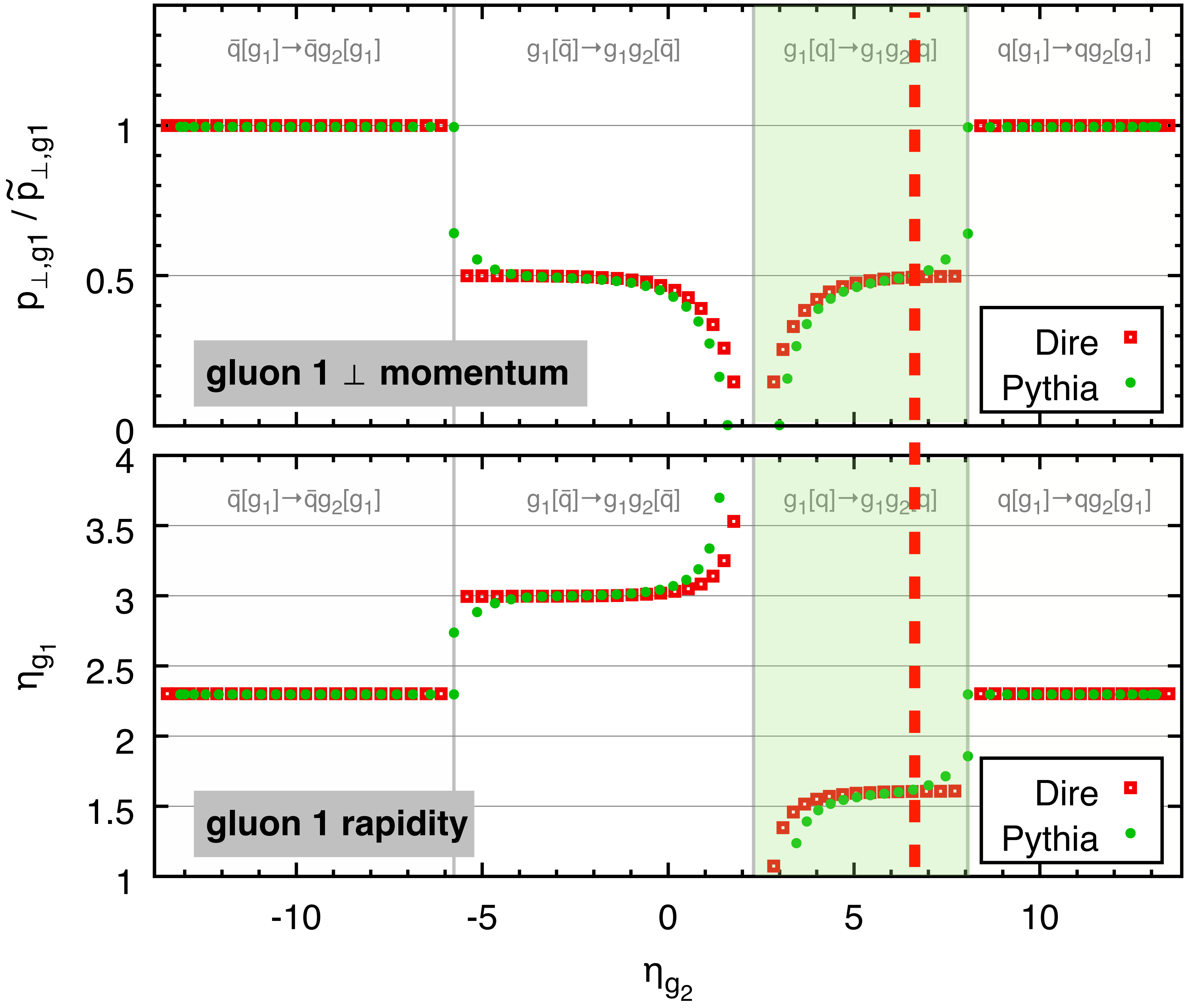

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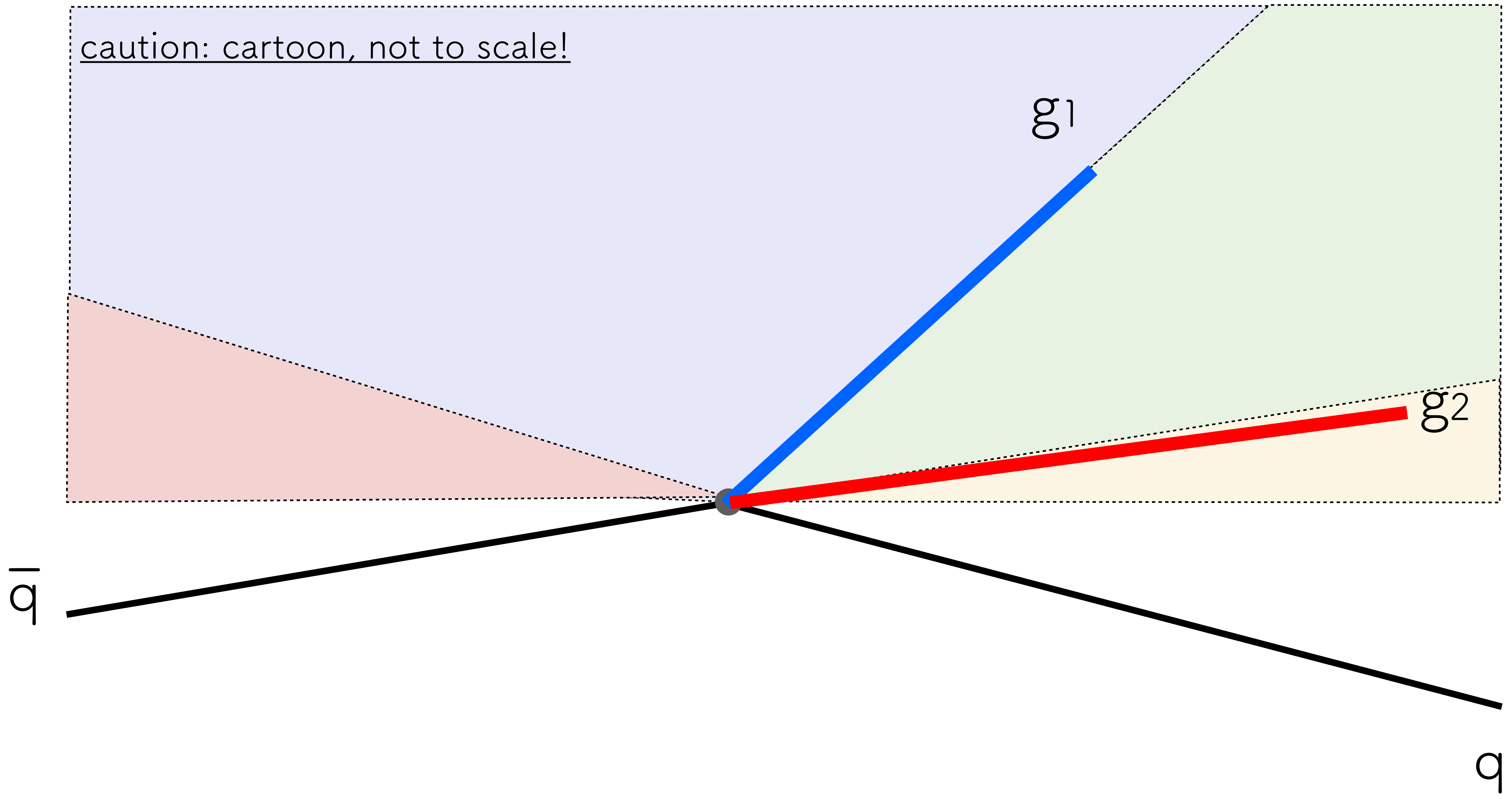

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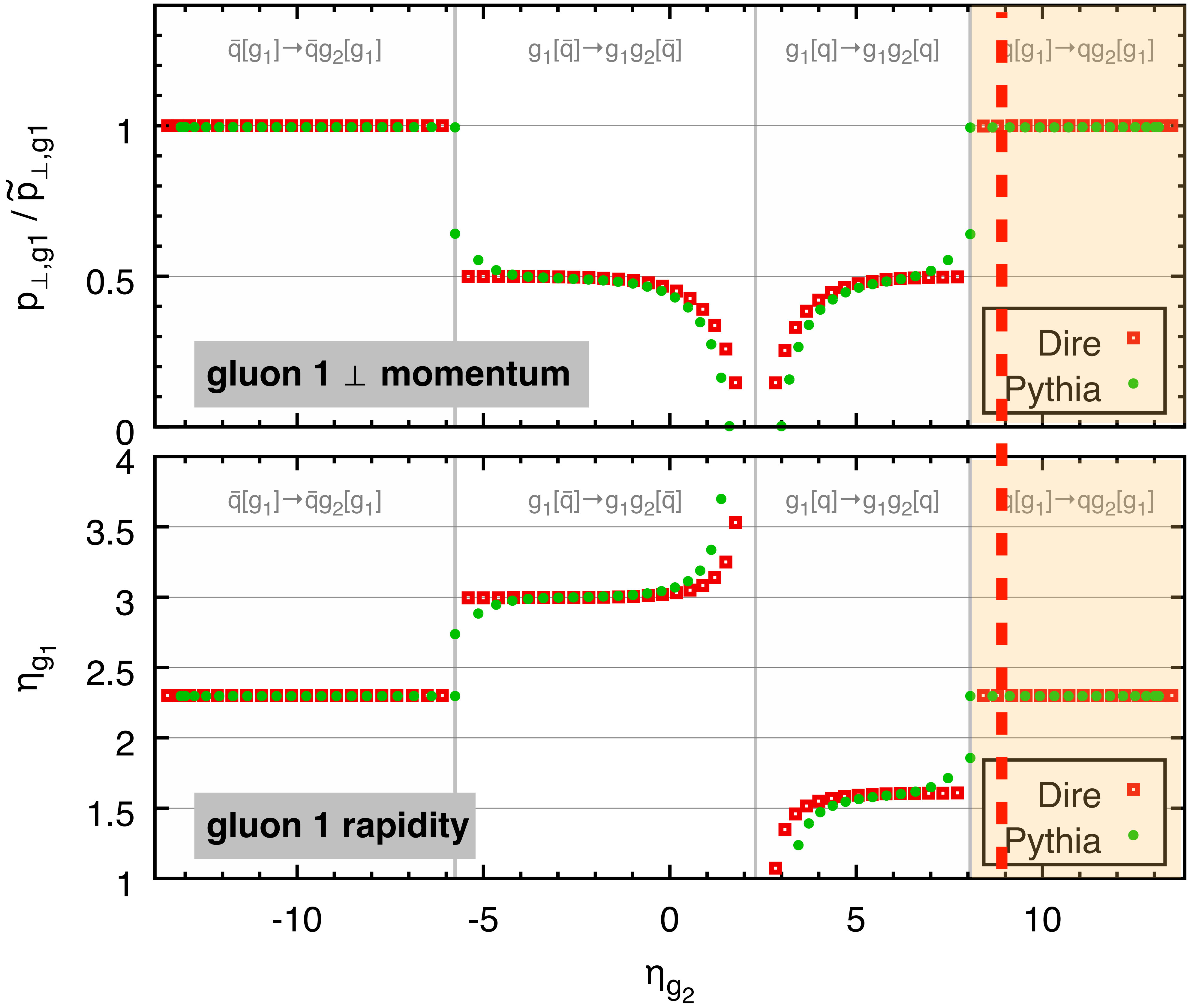

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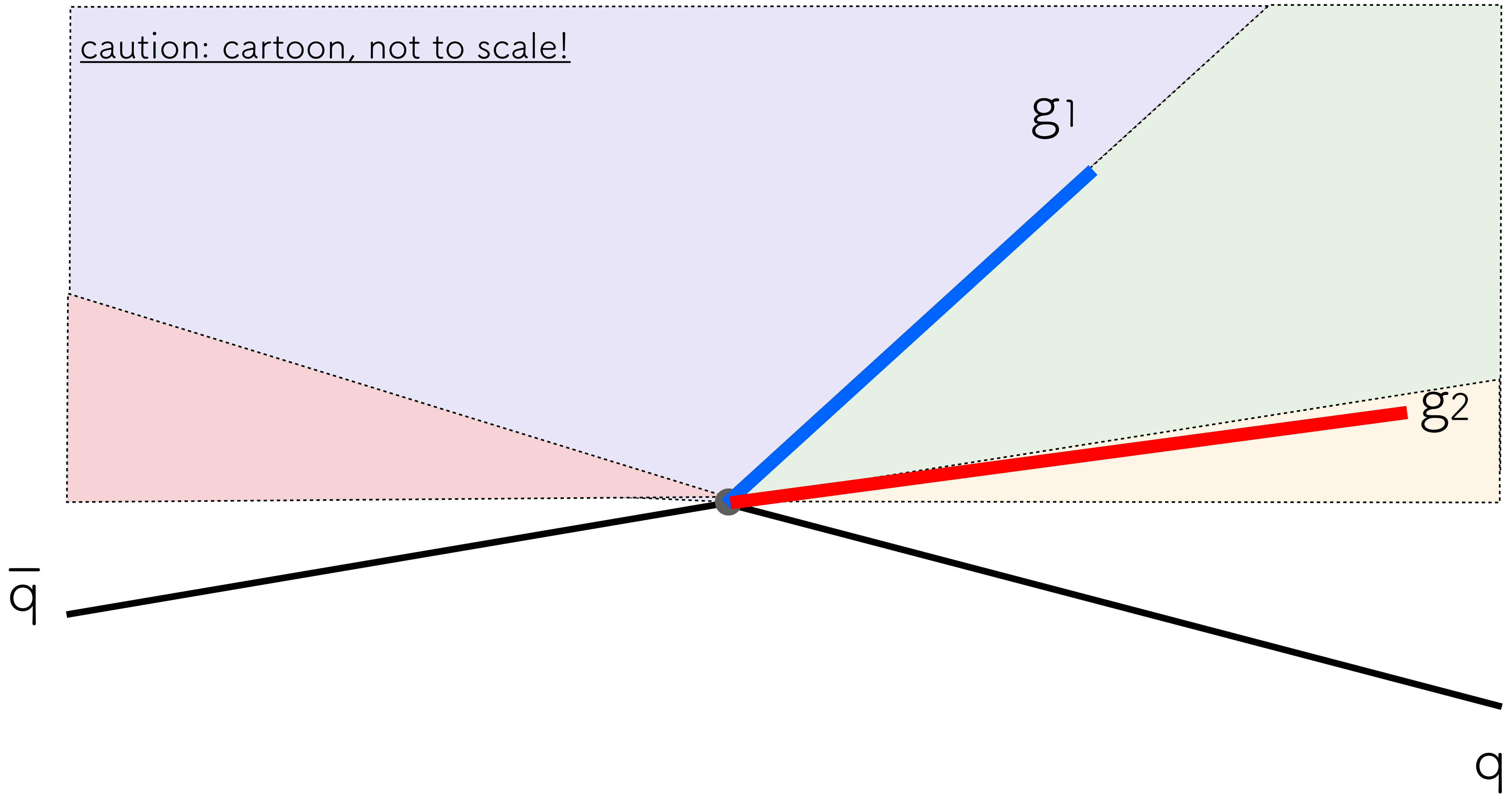
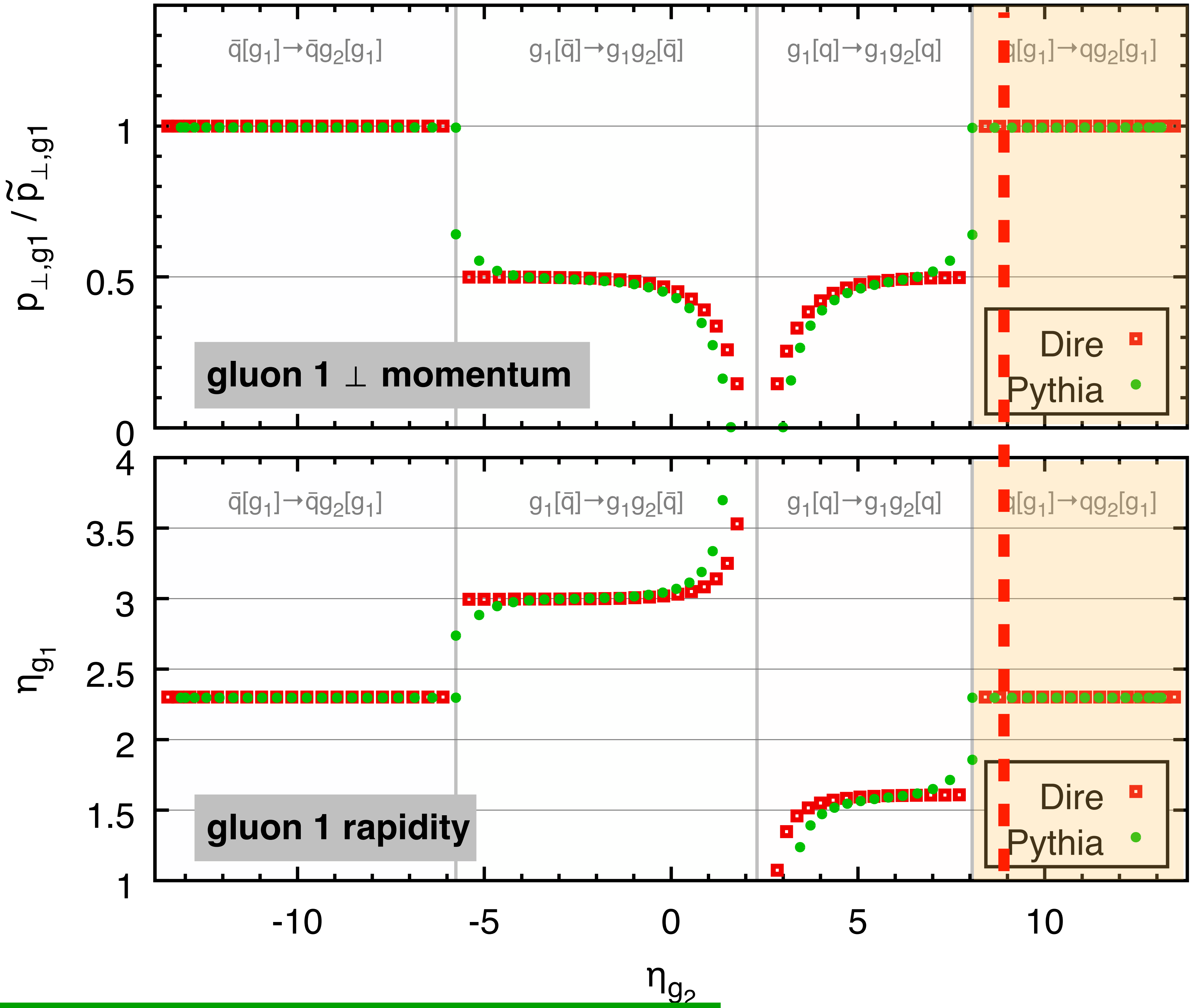


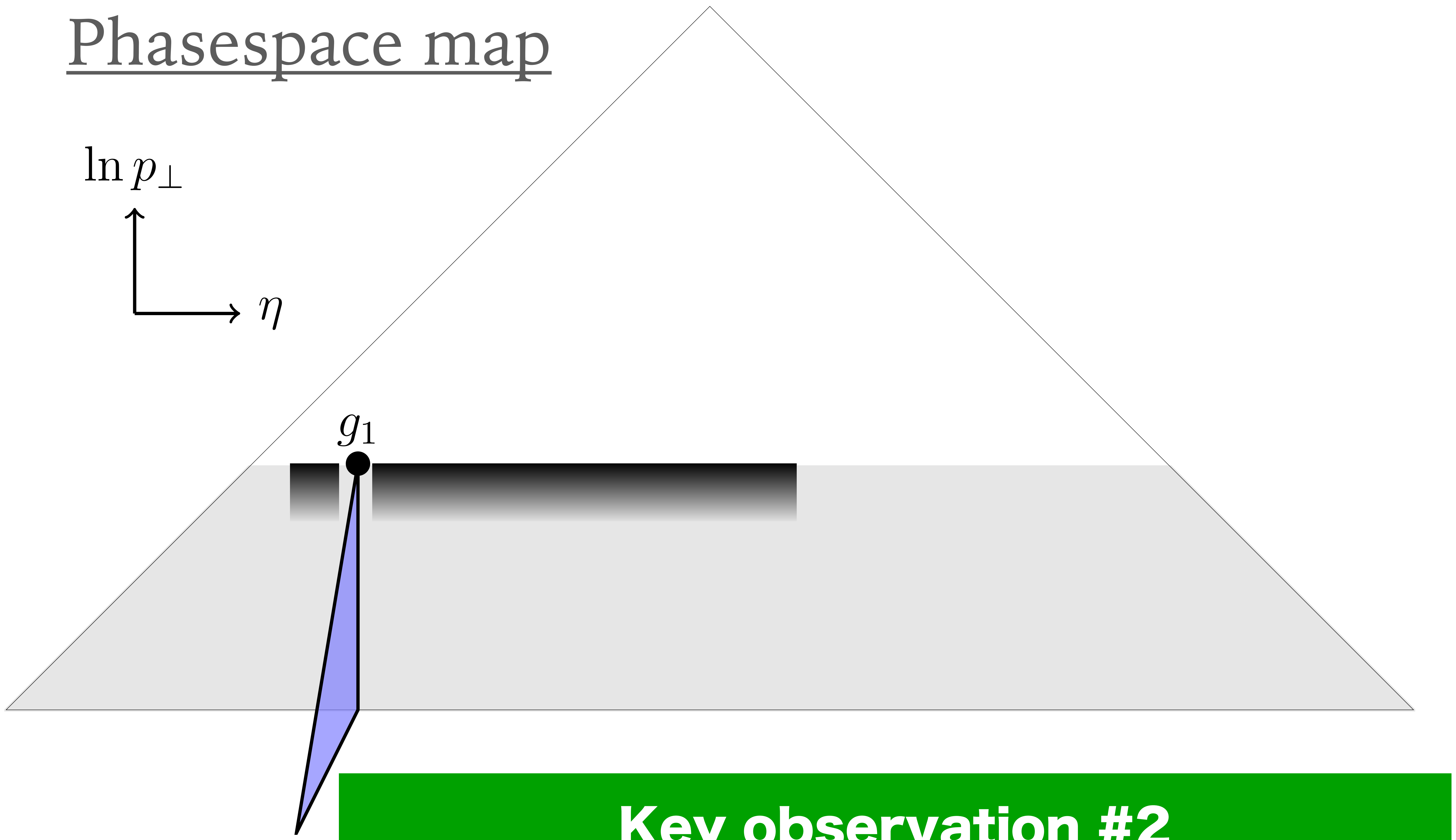

impact of gluon-2 emission on gluon-1 momentum

Key observation #1

highly non-trivial cross talk between emissions

also noticed in 1992 by Andersson, Gustafson & Sjogren → special "fudge" in Ariadne

Two emissions matrix-element



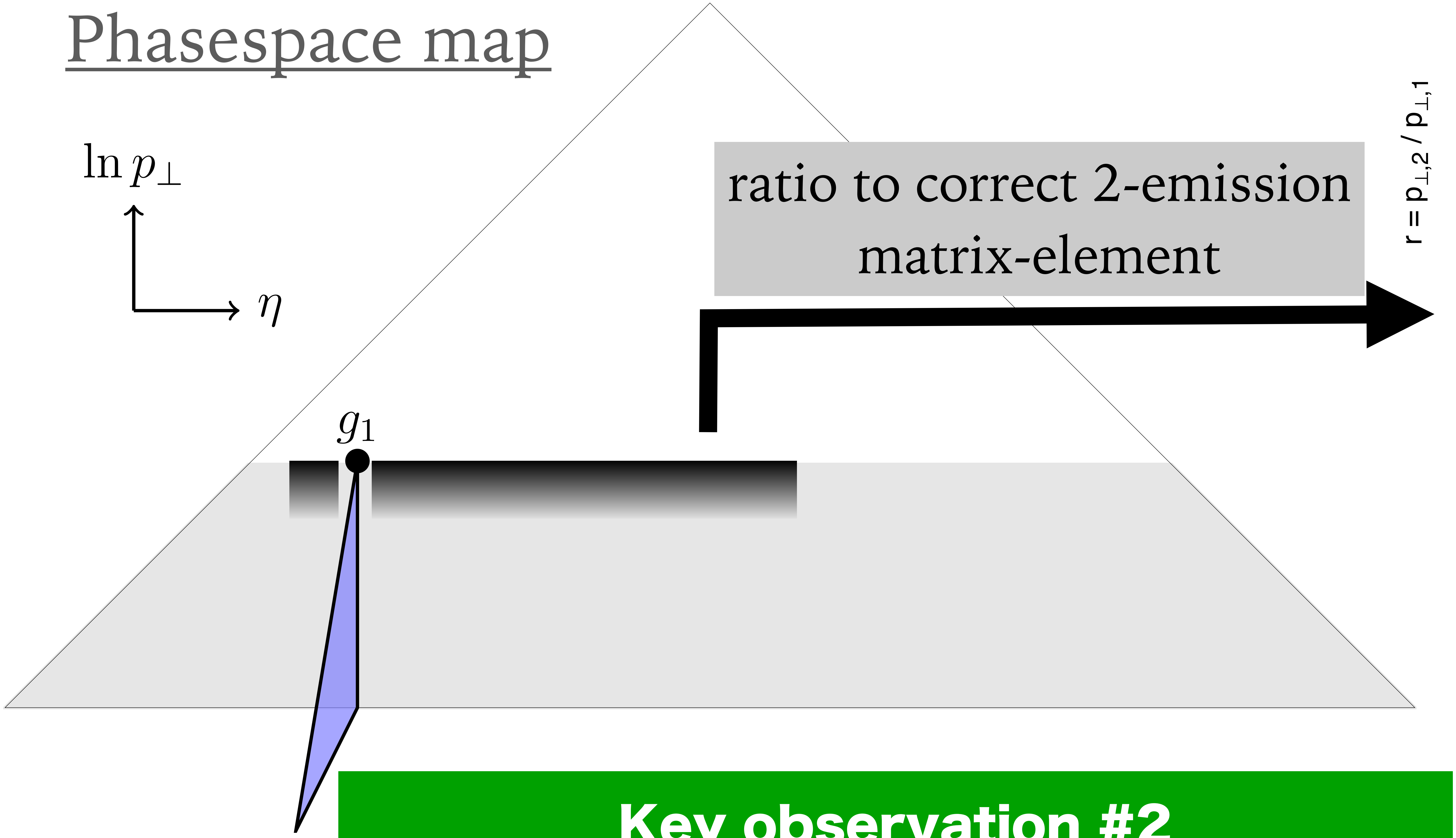
Key observation #2

phasespace where it matters is "NLL"

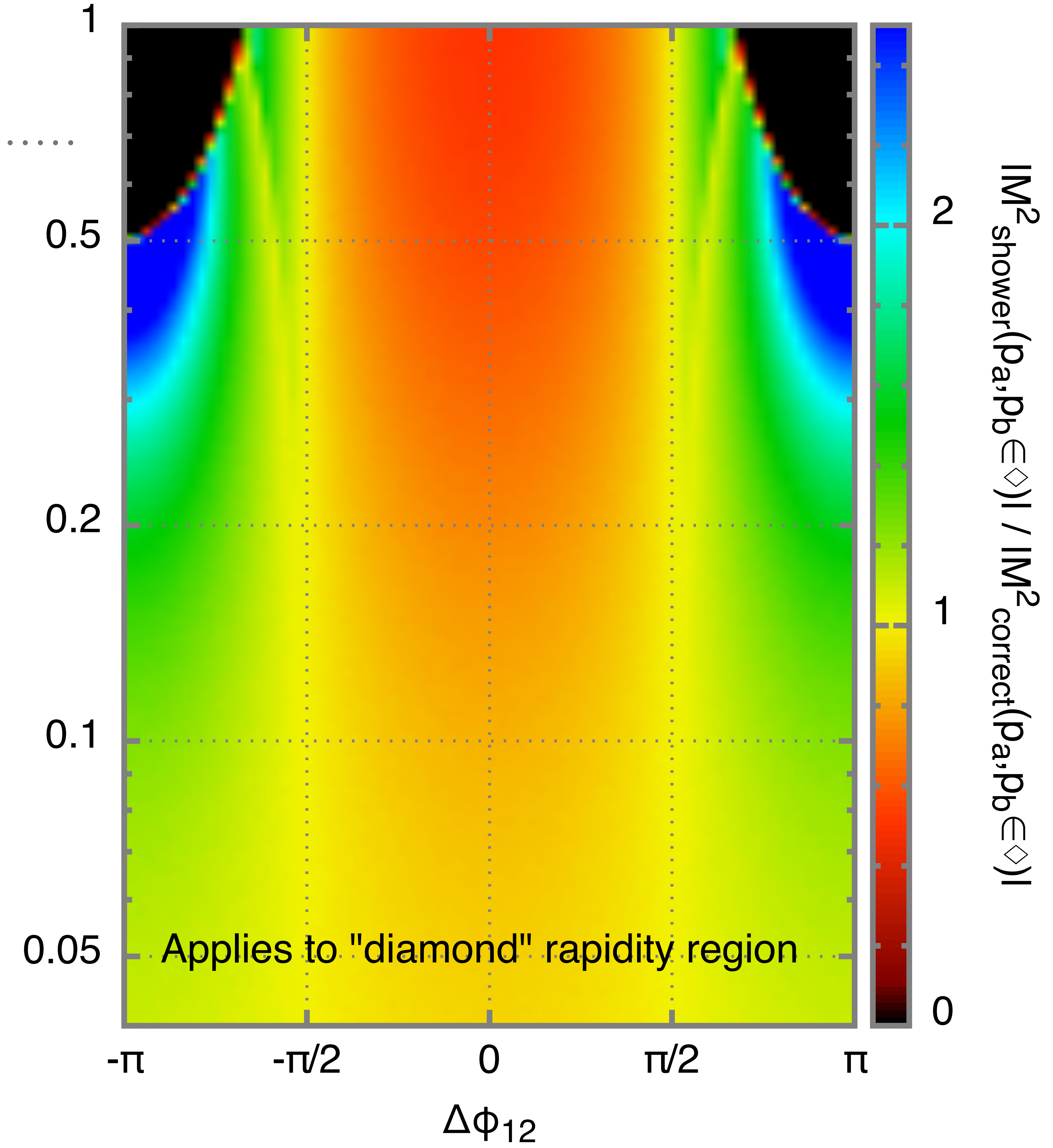
analogous effect commented on by Nagy & Soper for DY recoil, but wider relevance not appreciated?

Two emissions matrix-element

Phasespace map



ratio to correct 2-emission matrix-element


ratio of dipole-shower double-soft ME to correct result

Key observation #2

phasespace where it matters is "NLL"

analogous effect commented on by Nagy & Soper for DY recoil, but wider relevance not appreciated?

Prevents shower from getting NLL accuracy for any e+e- event shape!

Observable	$\text{NLL}_{\ln\Sigma}$ discrepancy
$1-T$	$0.116^{+0.004}_{-0.004}\,\bar{\alpha}^3 L^3$
vector p_t sum	$-0.349^{+0.003}_{-0.003}\,\bar{\alpha}^3 L^3$
B_T	$-0.0167335\,\bar{\alpha}^2 L^2$
y_3^{cam}	$-0.18277\,\bar{\alpha}^2 L^2$
FC_1	$-0.066934\,\bar{\alpha}^2 L^2$

numerically, coefficients are not large compared to other effects, cf.

$$CMW \simeq 0.65\bar{\alpha}^2 L^2$$

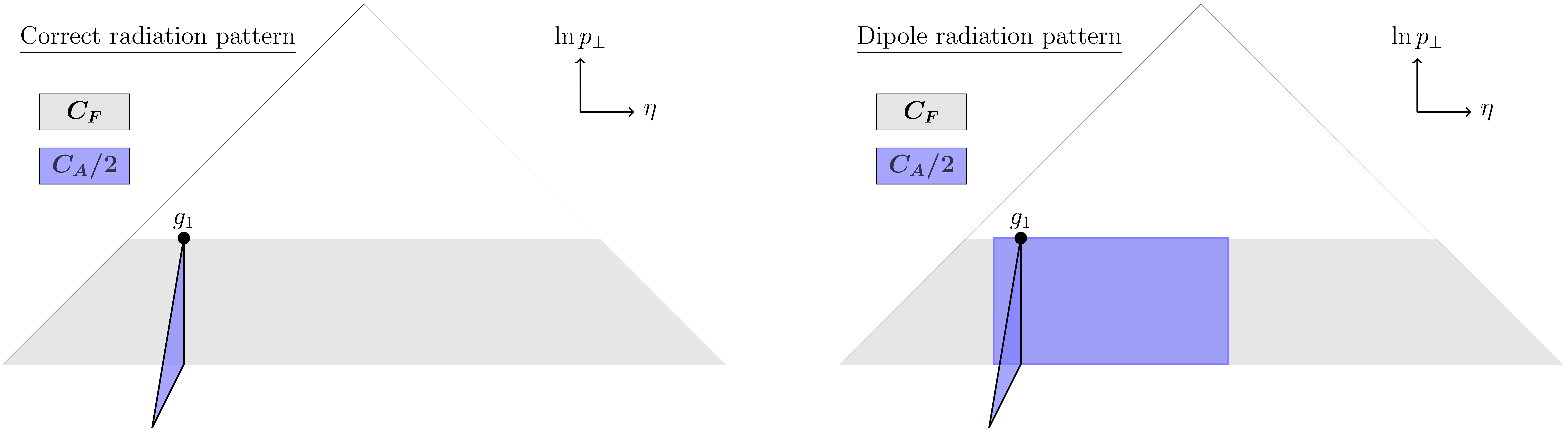
(because all these observables are quite inclusive)

but machine-learning uses all info — including large phasespace regions with 100% deficiencies

probably can't be solved with 1→ 3, because iteration affects 1→ N

so far took $C_F = C_A/2$, i.e. leading N_C limit

In real life they're not equal & common choice for allocating them assigns $C_A/2$ to large part of phasespace that is actually gluon emission from quark (i.e. C_F)

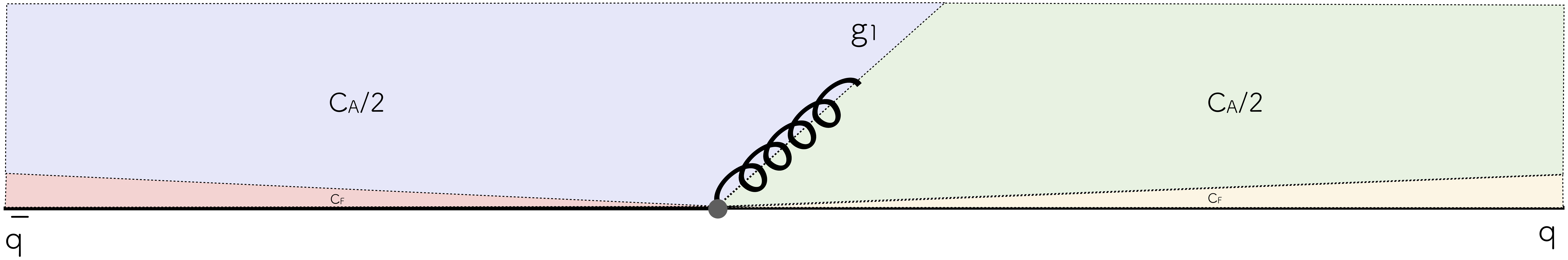


Key observation #3

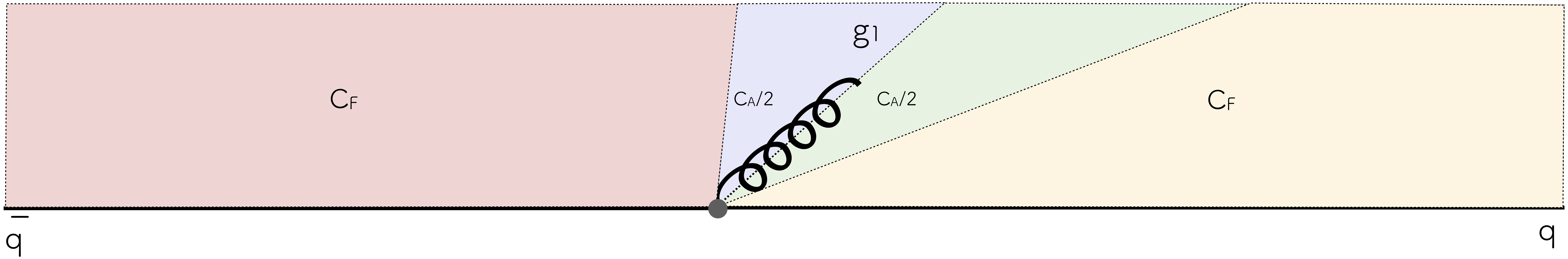
C_F v. $C_A/2$ issues occurs over a large area → double (leading) log effects?

another view of the colour issue

- The dipole shower phase space partitioning of g_2's radiation pattern is:



- Angular ordering implies a partitioning more like the following:



impact on observables?

Has LL subleading-N_C effect on 3-jet rates, thrust, but *not for* things like broadening, 2-jet rate (which are physically close the evolution variable, i.e. transverse momentum).

E.g. for thrust

$$\delta\Sigma(L) = -\frac{1}{64}\bar{\alpha}^2 L^4 \left(\frac{C_A}{2C_F} - 1\right)$$

- no LL effect for events shapes in same LL class as broadening & 2-jet rate
- but it will re-appear for 3-jet rate

closing

Conclusions

Parton showers are a crucial element in collider physics

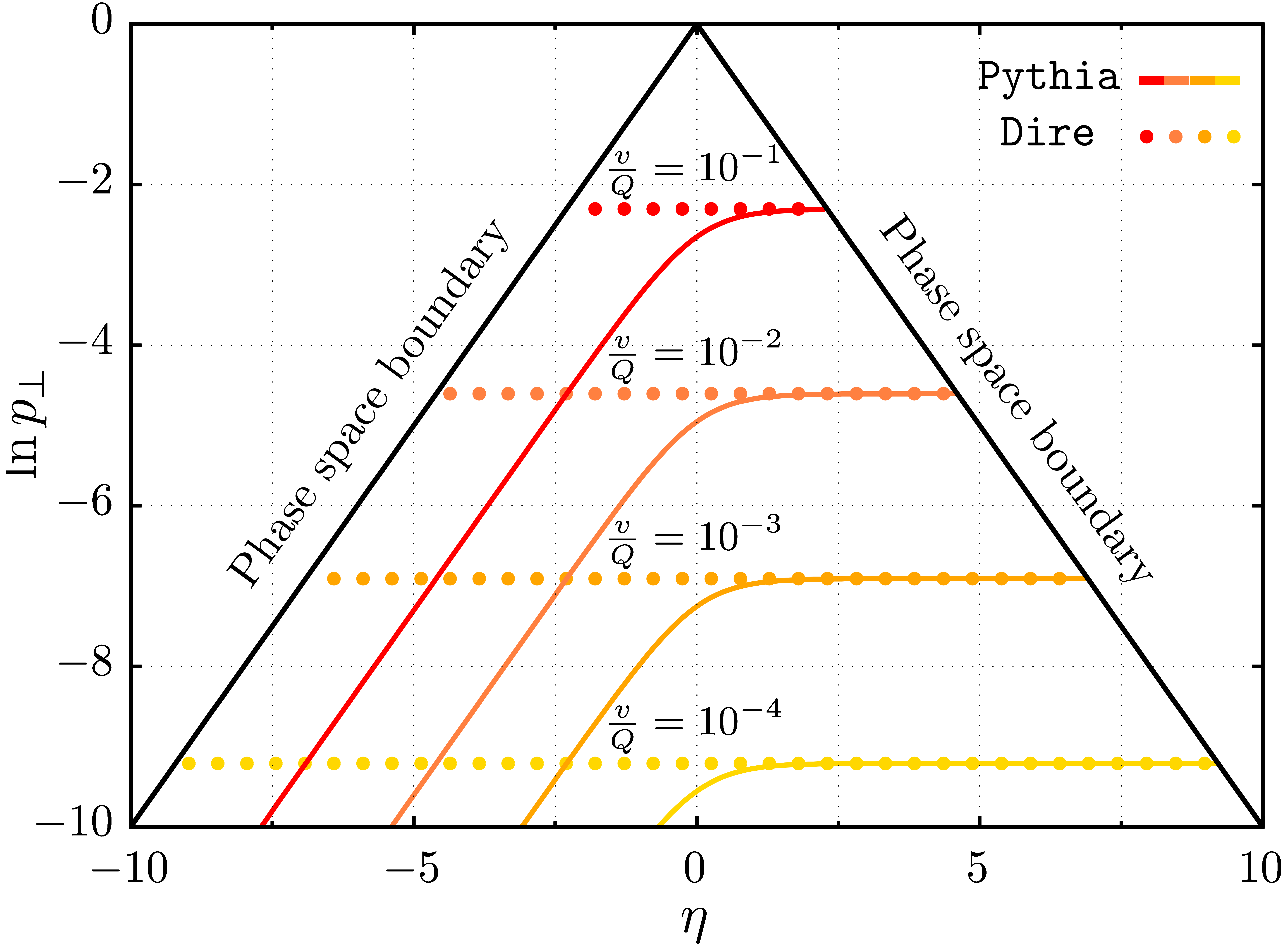
Seeing many developments (subleading colour for non-global logarithms, multi-particle emission kernels, etc.)

But maybe we need to go back to foundations:

- improving parton showers is not just a question of better components (e.g. higher-order splitting kernels)
- question of how components are assembled is equally crucial
- we must identify & state what a parton shower should be achieving
- new studies along these lines are teaching us important things about existing showers

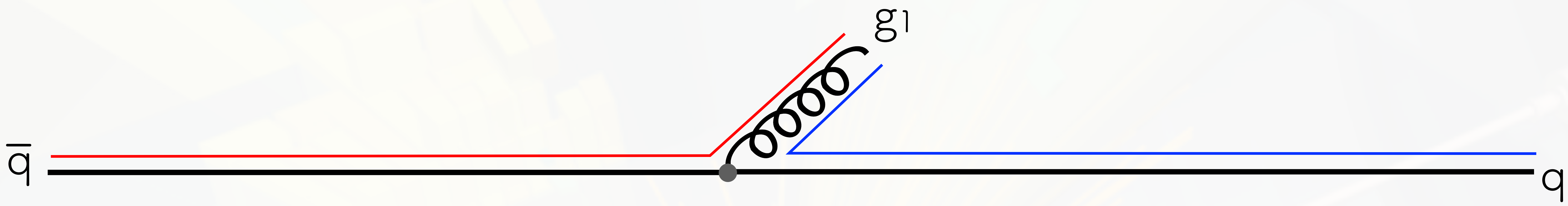
BACKUP

Constant evolution variable contours in the Lund plane

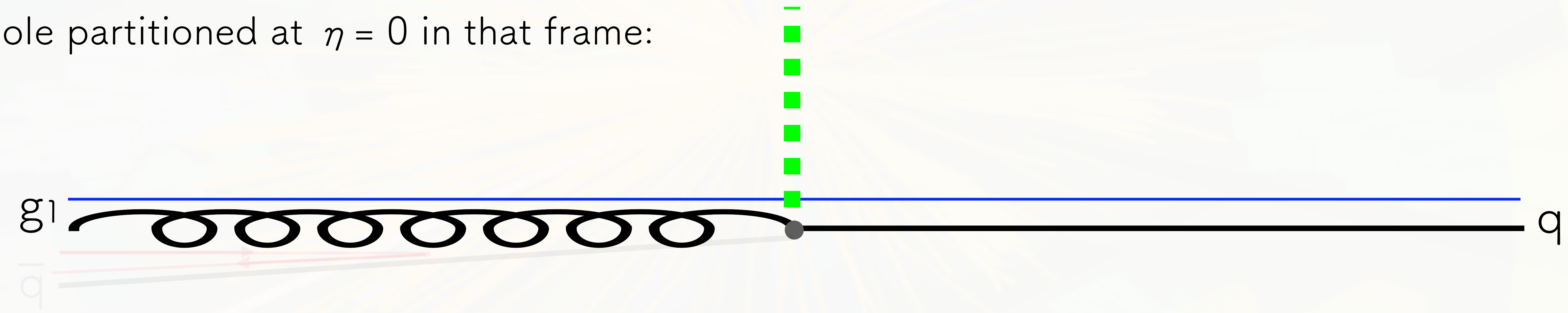


two soft emissions : boost dipole partitions back into the event COM

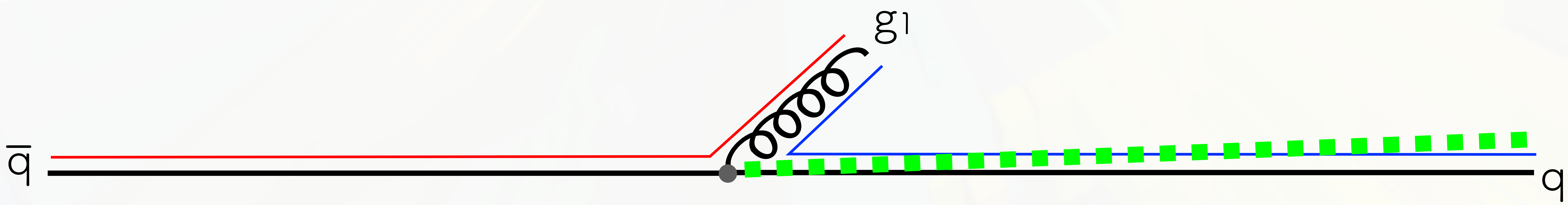
- Consider we emitted **soft gluon g_1** from **hard** $q\bar{q}$, so we end up with a $\bar{q}g_1$ and a g_1q dipole:



- To get us from the event COM to the g_1q dipole COM [blue line] requires a **BIG BOOST** ⟶
- Dipole partitioned at $\eta = 0$ in that frame:



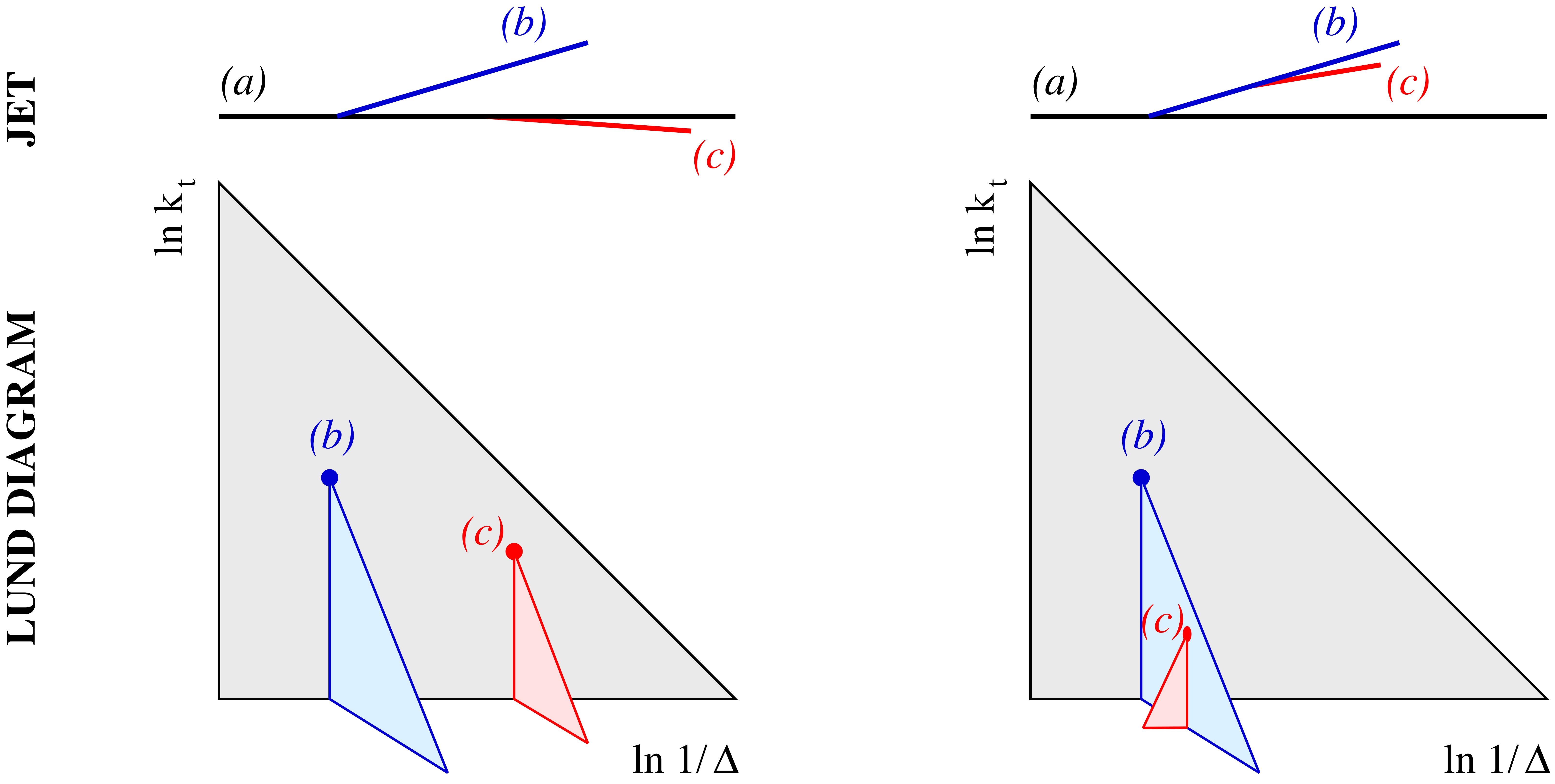
- To get us back to the event COM from the g_1q dipole COM undo the same **BIG BOOST** ⟵



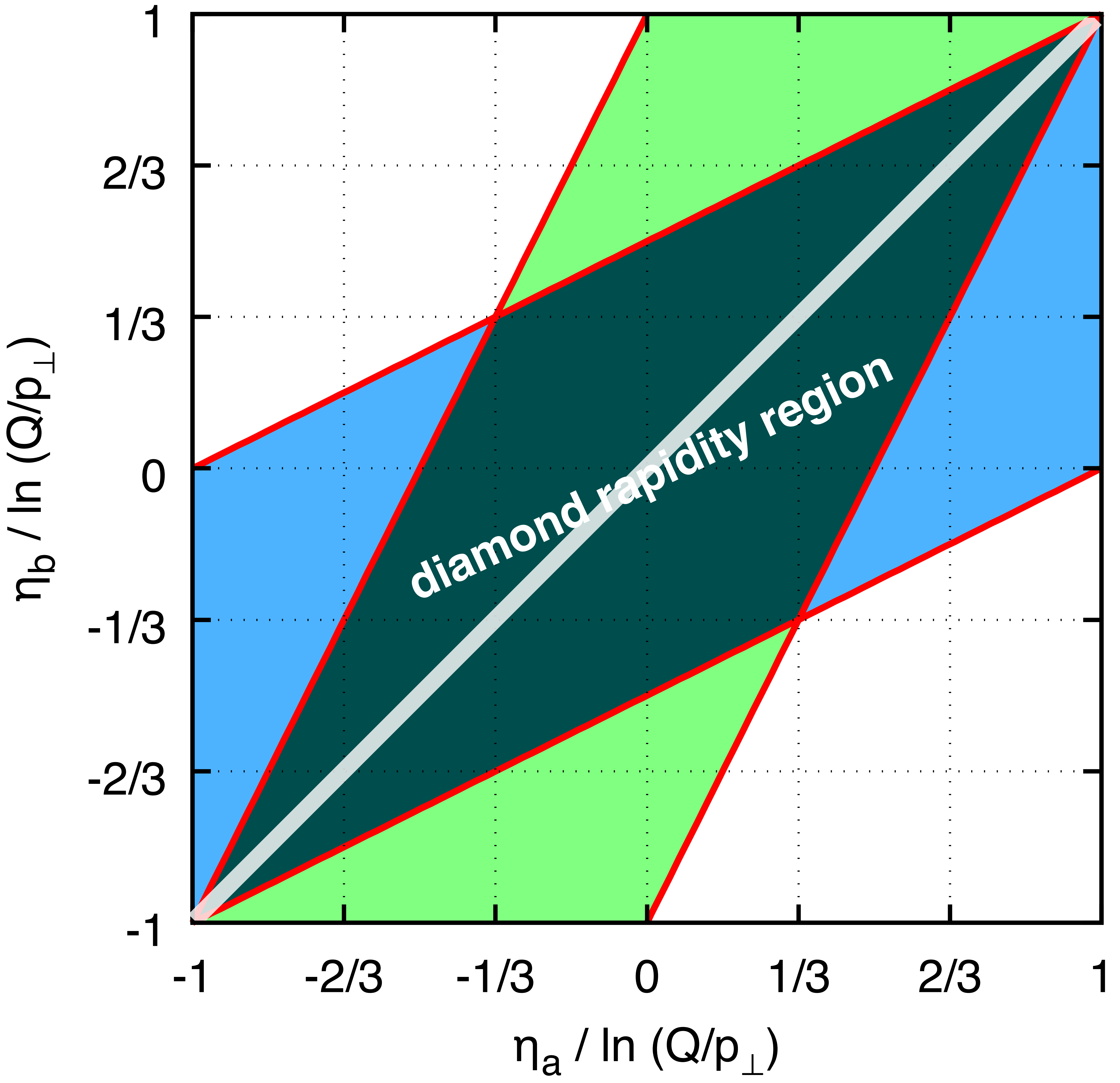
- In event COM partition comes out very close to q ; instead of equidistant in angle between g_1 & q

g_1

organise phasespace: Lund diagrams



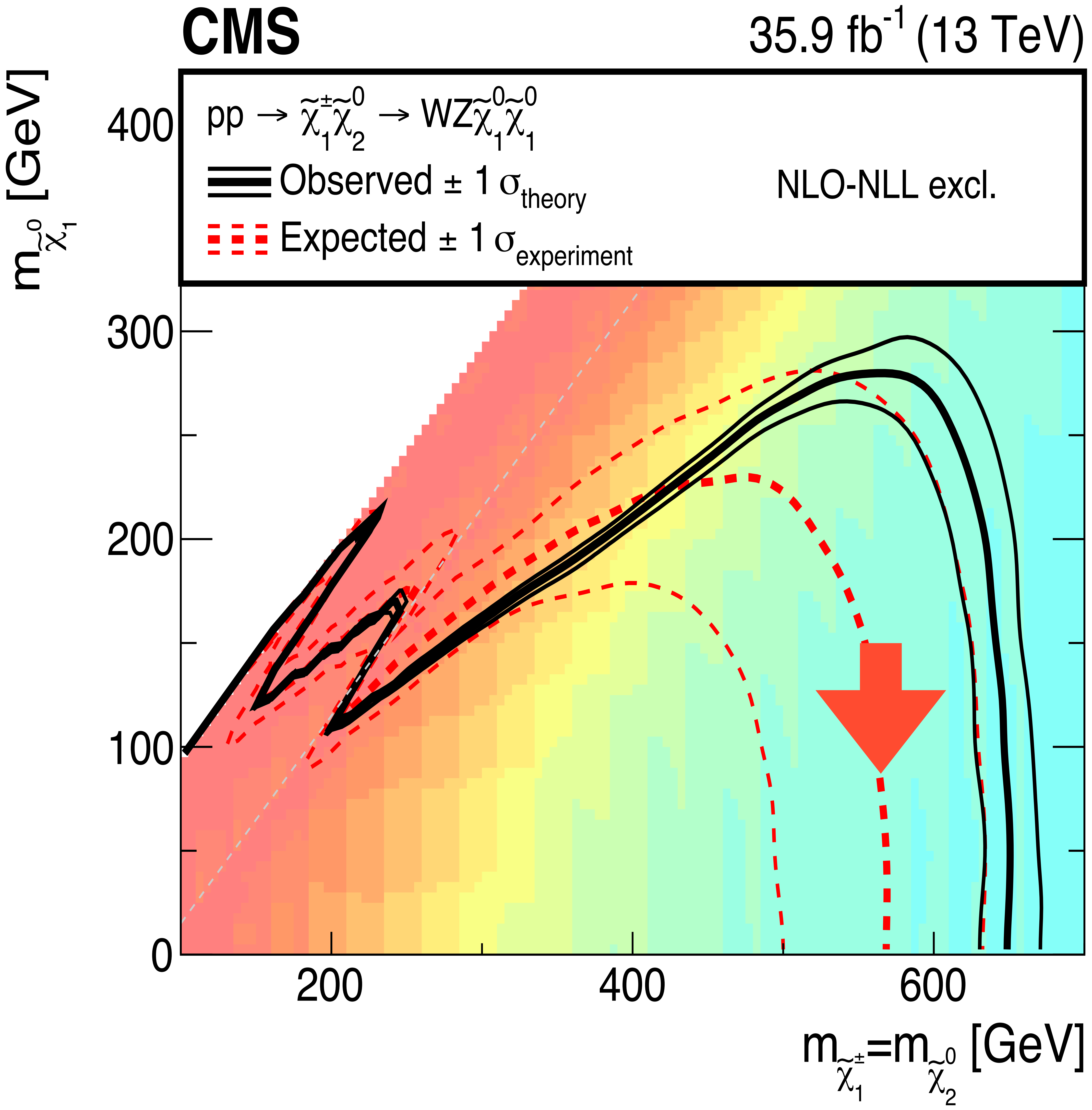
Diamond rapidity region where dipole showers introduce “wrong” correlations



$$\frac{dP_{2,\text{shower}}(p_a, p_b \in \diamond)}{d\eta_a\, d\eta_b\; d^2\boldsymbol{p}_{\perp,a} d^2\boldsymbol{p}_{\perp,b}} = \frac{1}{2!}\left(\frac{\alpha_s C_A}{2\pi^2}\right)^2 \int \frac{d^2\boldsymbol{p}_{\perp,1}}{{p_{\perp,1}}^2} \int_{p_{\perp,2}<p_{\perp,1}} \frac{d^2\boldsymbol{p}_{\perp,2}}{{p_{\perp,2}}^2} \int_{\diamond} d\eta_1 d\eta_2 \times$$

$$\times \left[\delta^2(\boldsymbol{p}_{\perp,1} - \boldsymbol{p}_{\perp,2} - \boldsymbol{p}_{\perp,a})\,\delta^2(\boldsymbol{p}_{\perp,2} - \boldsymbol{p}_{\perp,b})\delta(\eta_a - \eta_1)\delta(\eta_b - \eta_2) + (a \leftrightarrow b)\right]\ .$$

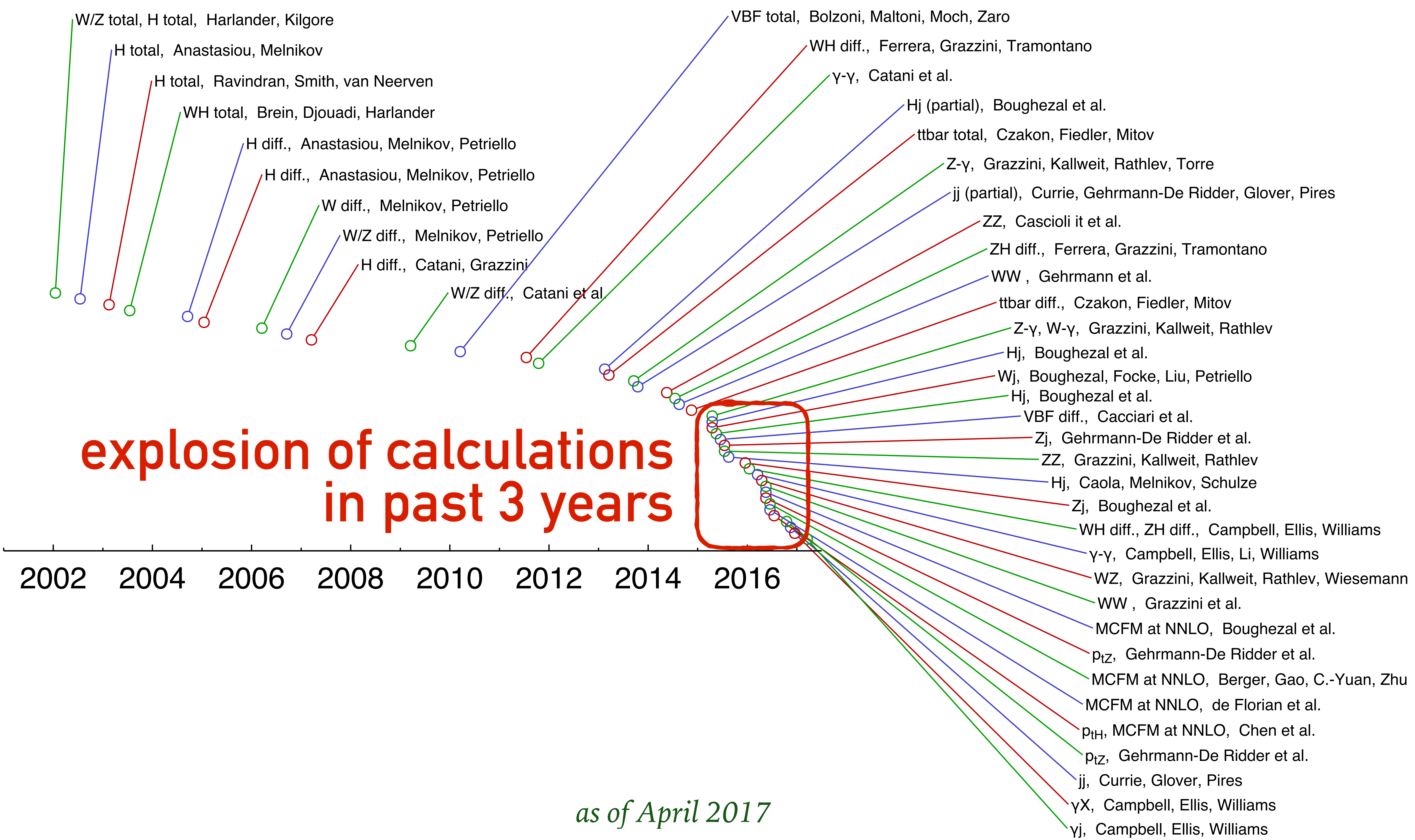
The path forward: collect 20–30x more collisions by ~2035



- Suppose we had a choice between
  - HL-LHC (14 TeV, $3ab^{-1}$)
  - or going to higher c.o.m. energy but limited to $80fb^{-1}$.
- How much energy would we need to equal the HL-LHC?

today's reach (13 TeV, $80fb^{-1}$)	HL-LHC reach (14 TeV $3ab^{-1}$)	energy needed for same reach with $80fb^{-1}$
4.7 TeV SSM Z'	6.7 TeV	20 TeV
2 TeV weakly coupled Z'	3.7 TeV	37 TeV
680 GeV chargino	1.4 TeV	54 TeV

Hard processes: to 3rd order (NNLO) in perturbation theory strong coupling constant (α_s)



W/Z total, H total, Harlander, Kilgore
H total, Anastasiou, Melnikov
H total, Ravindran, Smith, van Neerven
WH total, Brein, Djouadi, Harlander
H diff., Anastasiou, Melnikov, Petriello
H diff., Anastasiou, Melnikov, Petriello
W diff., Melnikov, Petriello
W/Z diff., Melnikov, Petriello
H diff., Catani, Grazzini
W/Z diff., Catani et al.
VBF total, Bolzoni, Maltoni, Moch, Zaro
WH diff., Ferrera, Grazzini, Tramontano
γ-γ, Catani et al.
Hj (partial), Boughezal et al.
ttbar total, Czakon, Fiedler, Mitov
Z-γ, Grazzini, Kallweit, Rathlev, Torre
jj (partial), Currie, Gehrmann-De Ridder, Glover, Pires
ZZ, Cascioli it et al.
ZH diff., Ferrera, Grazzini, Tramontano
WW , Gehrmann et al.
ttbar diff., Czakon, Fiedler, Mitov
Z-γ, W-γ, Grazzini, Kallweit, Rathlev
Hj, Boughezal et al.
Wj, Boughezal, Focke, Liu, Petriello
Hj, Boughezal et al.
VBF diff., Cacciari et al.
Zj, Gehrmann-De Ridder et al.
ZZ, Grazzini, Kallweit, Rathlev
Hj, Caola, Melnikov, Schulze
Zj, Boughezal et al.
WH diff., ZH diff., Campbell, Ellis, Williams
γ-γ, Campbell, Ellis, Li, Williams
WZ, Grazzini, Kallweit, Rathlev, Wiesemann
WW , Grazzini et al.
MCFM at NNLO, Boughezal et al.
p_{tZ}, Gehrmann-De Ridder et al.
MCFM at NNLO, Berger, Gao, C.-Yuan, Zhu
MCFM at NNLO, de Florian et al.
p_{tH}, MCFM at NNLO, Chen et al.
p_{tZ}, Gehrmann-De Ridder et al.
jj, Currie, Glover, Pires
γX, Campbell, Ellis, Williams
γj, Campbell, Ellis, Williams

explosion of calculations in past 3 years

as of April 2017