New results for parton showers

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including work 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

Annual Theory Meeting
IPPP Durham, 17/12/2018

at colliders, you can probe

“big unanswered questions”

about fundamental particles & their interactions

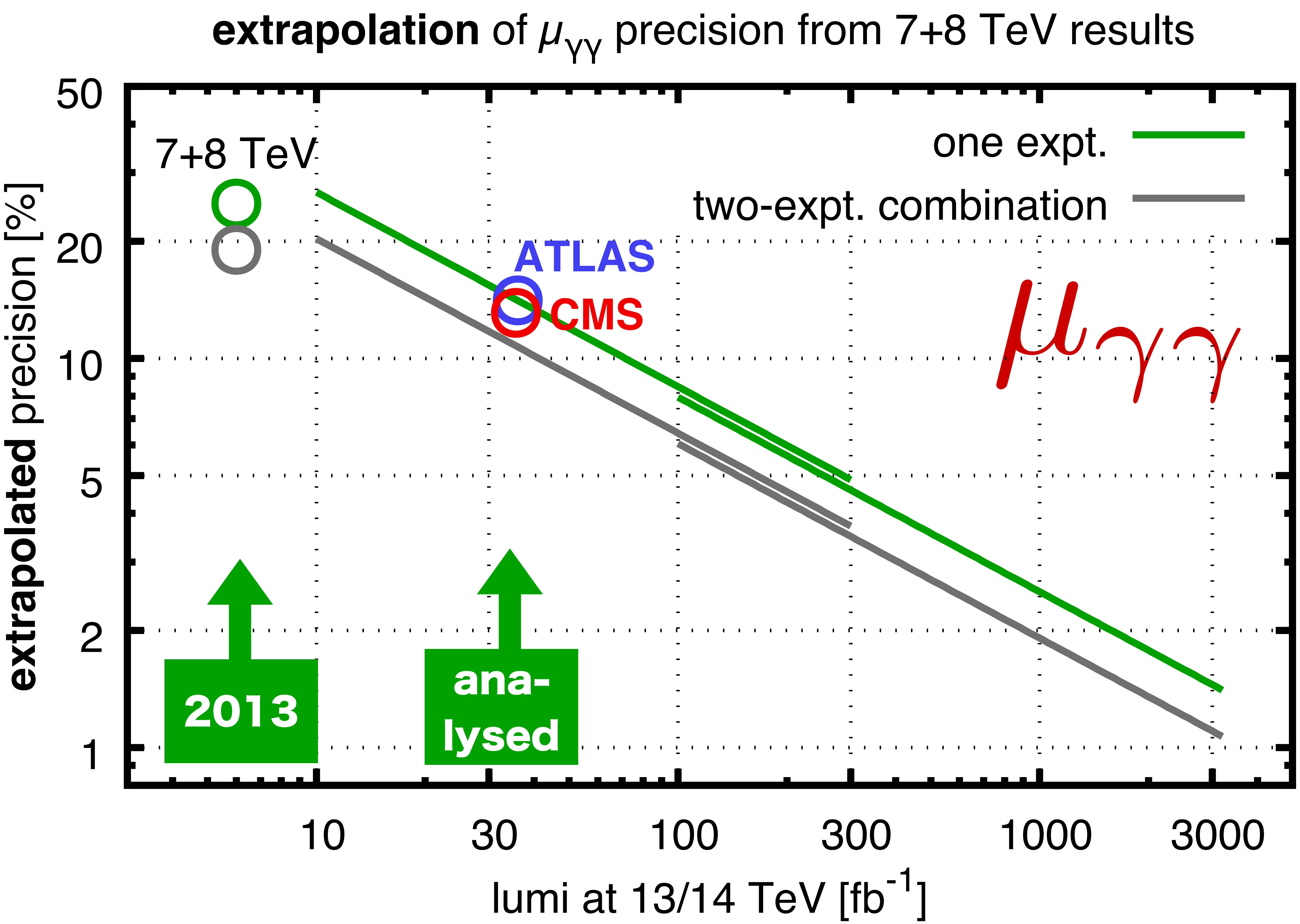
(dark matter, matter-antimatter asymmetry, nature of dark energy, hierarchy of scales…)

and

“big answerable questions”

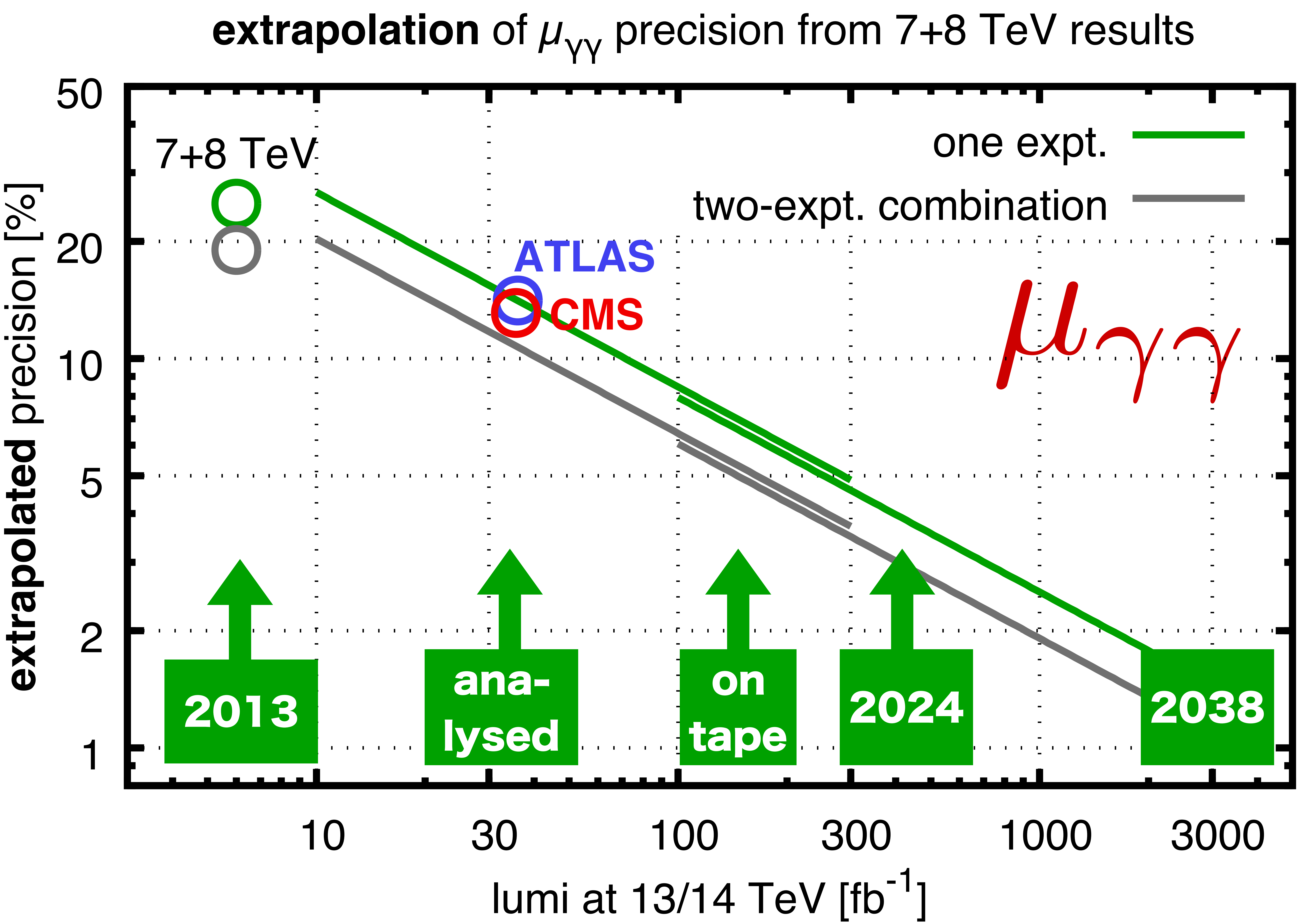
(structure of Higgs sector, determining fundamental parameters of Lagrangian of particle physics)

Higgs precision (H → γγ) : 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

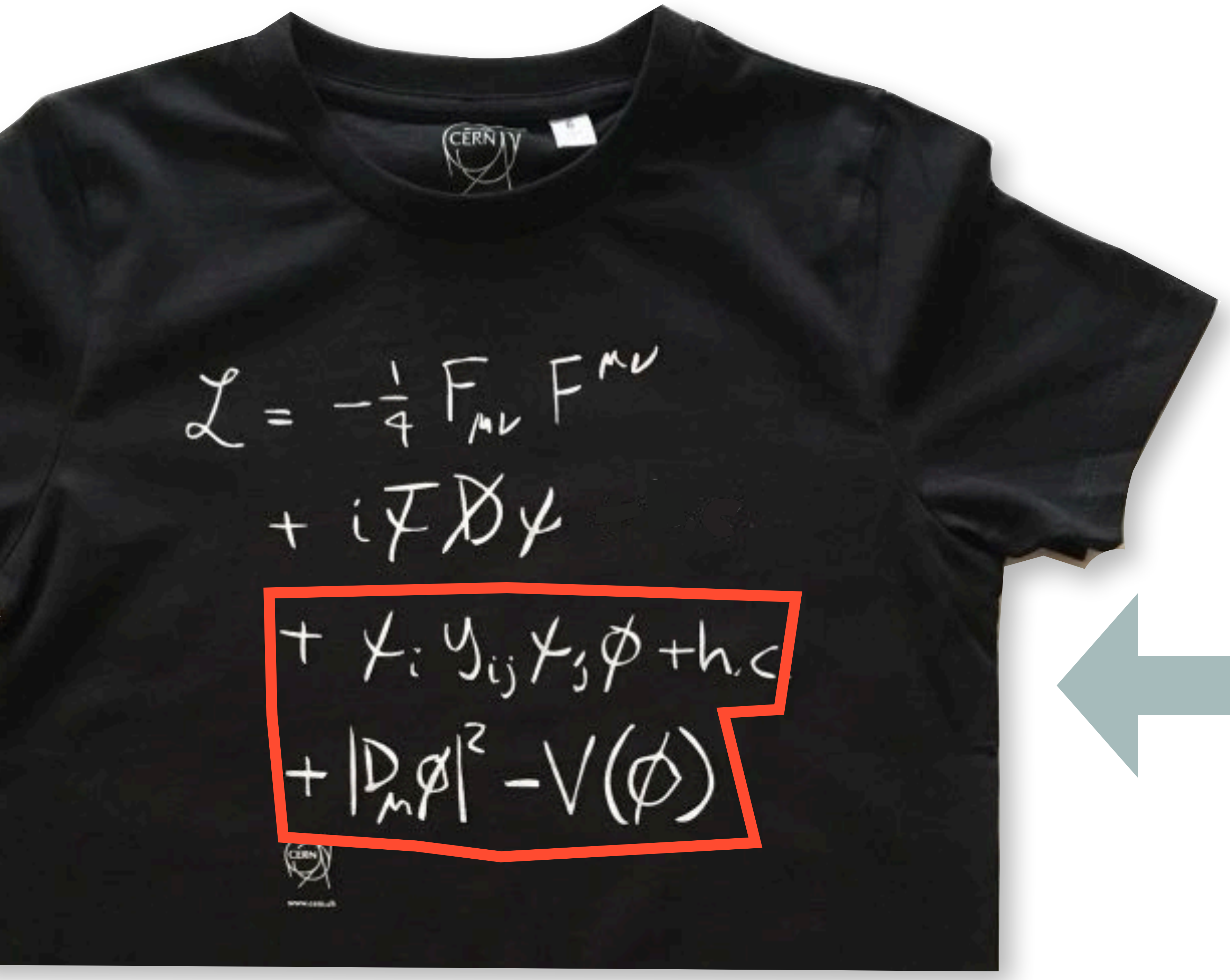
1 fb^{-1} = 10^{14} collisions

how is all of this made quantitative?

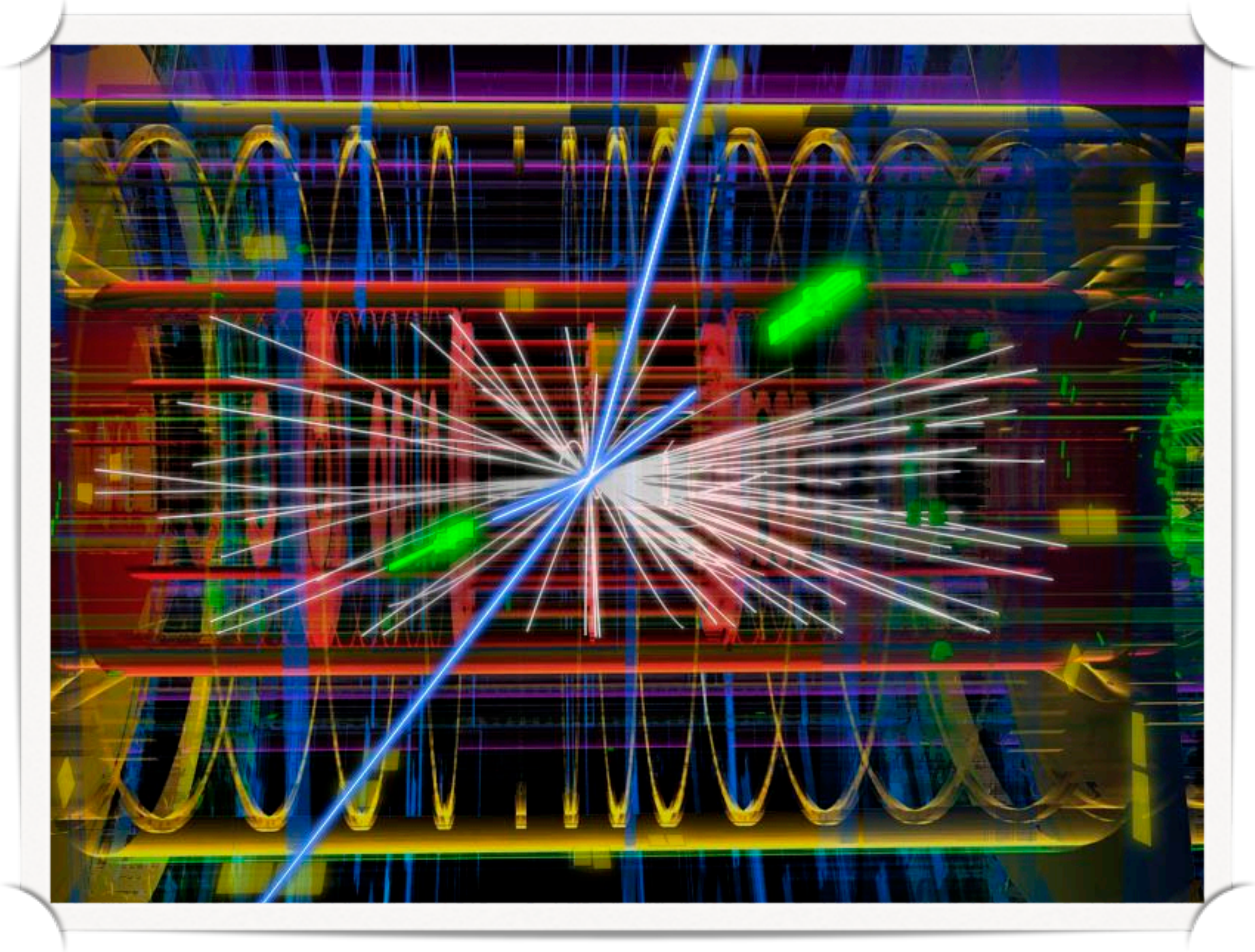
whether new-physics searches, Higgs physics, or other SM studies

UNDERLYING THEORY

EXPERIMENTAL DATA



how do you make quantitative connection?



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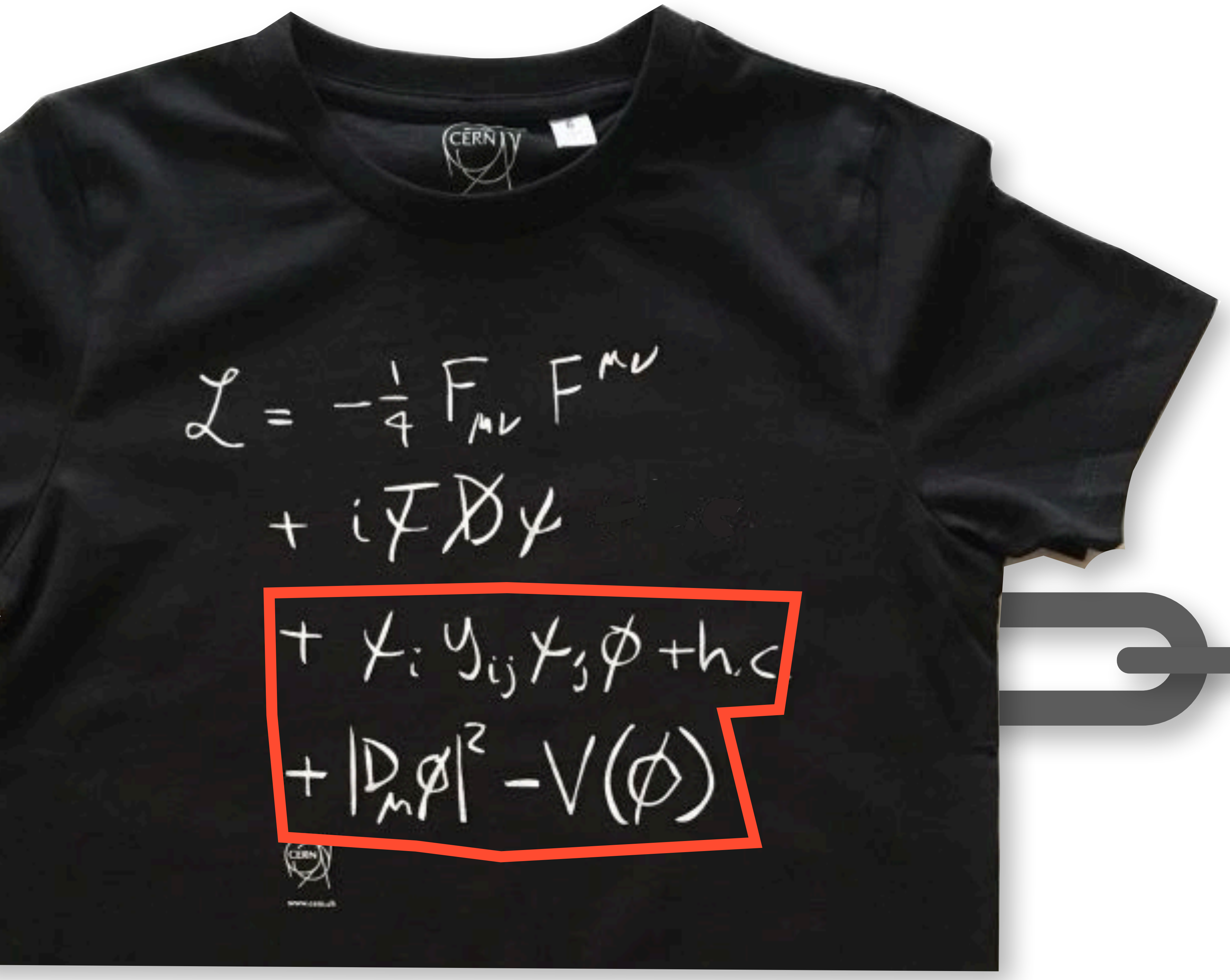

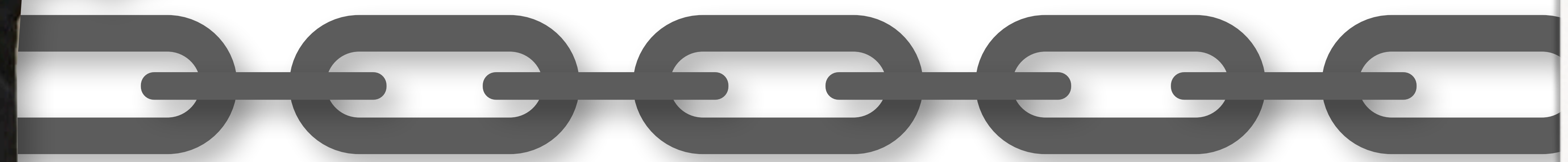

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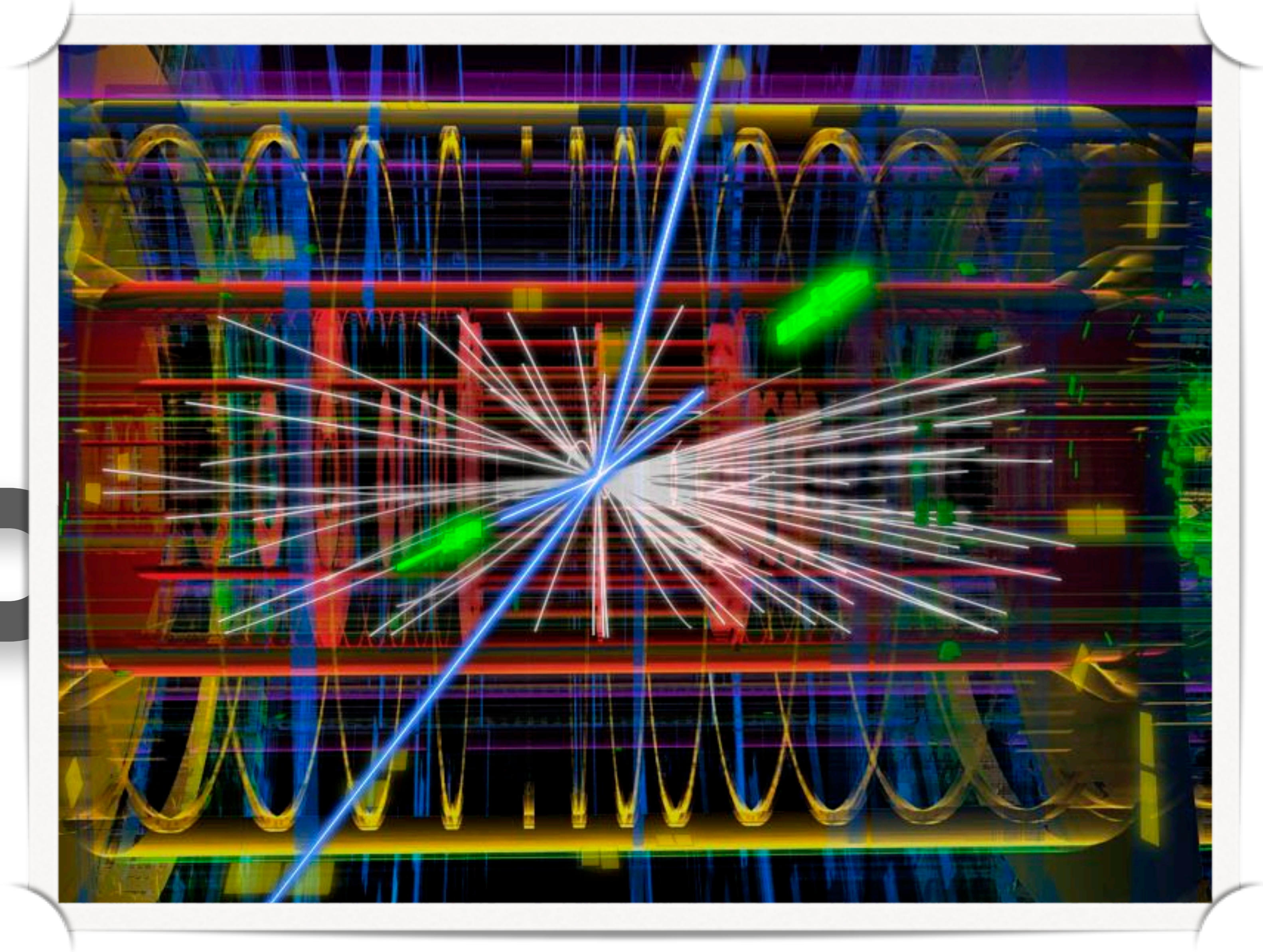


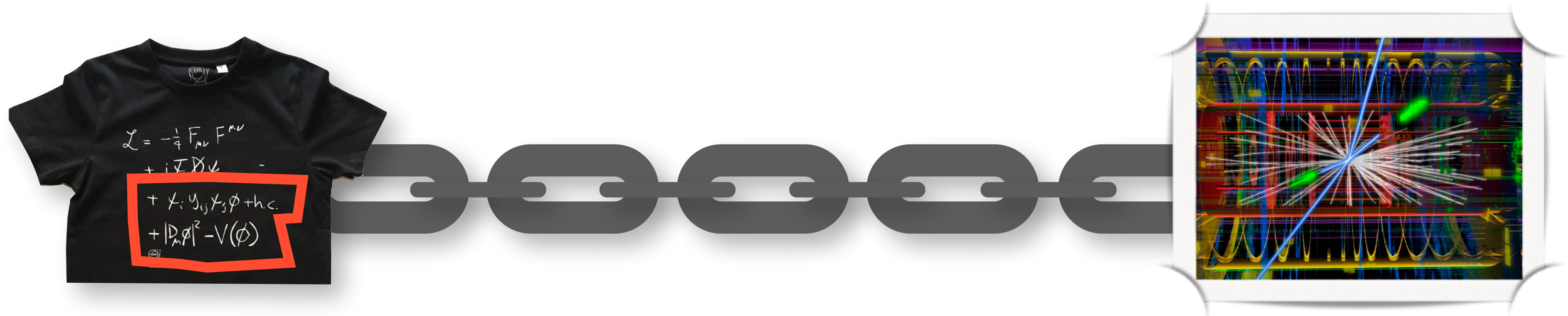
through a chain of experimental and theoretical links

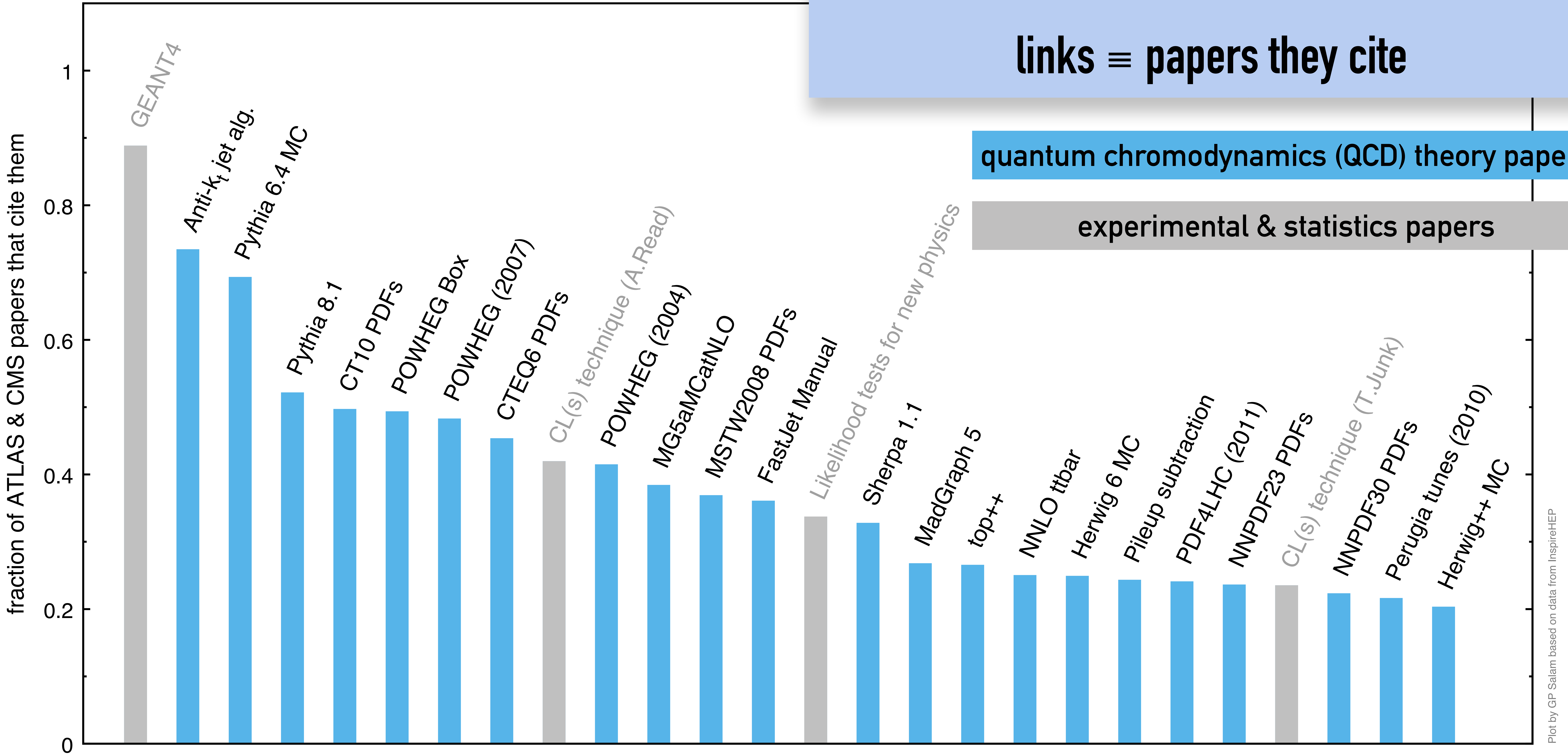
[in particular Quantum Chromodynamics (QCD)]

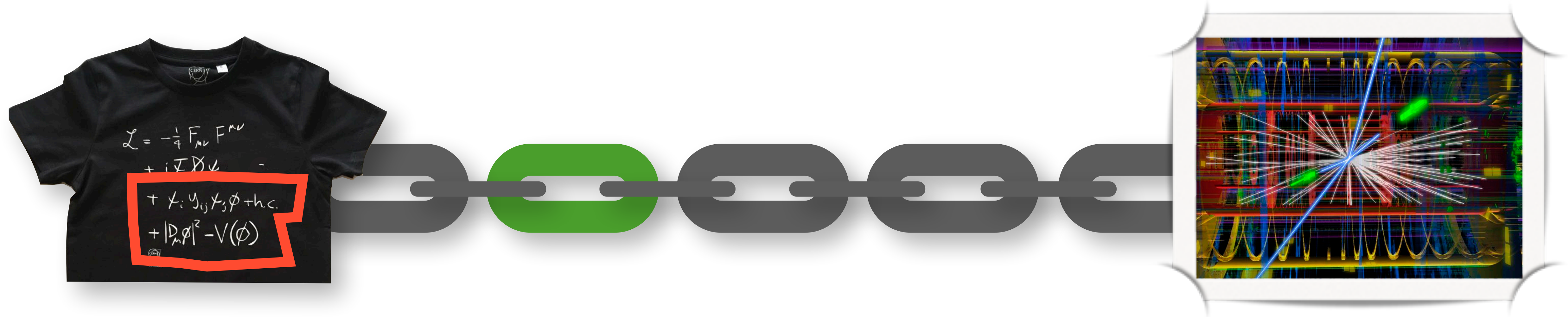
What are the links?

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

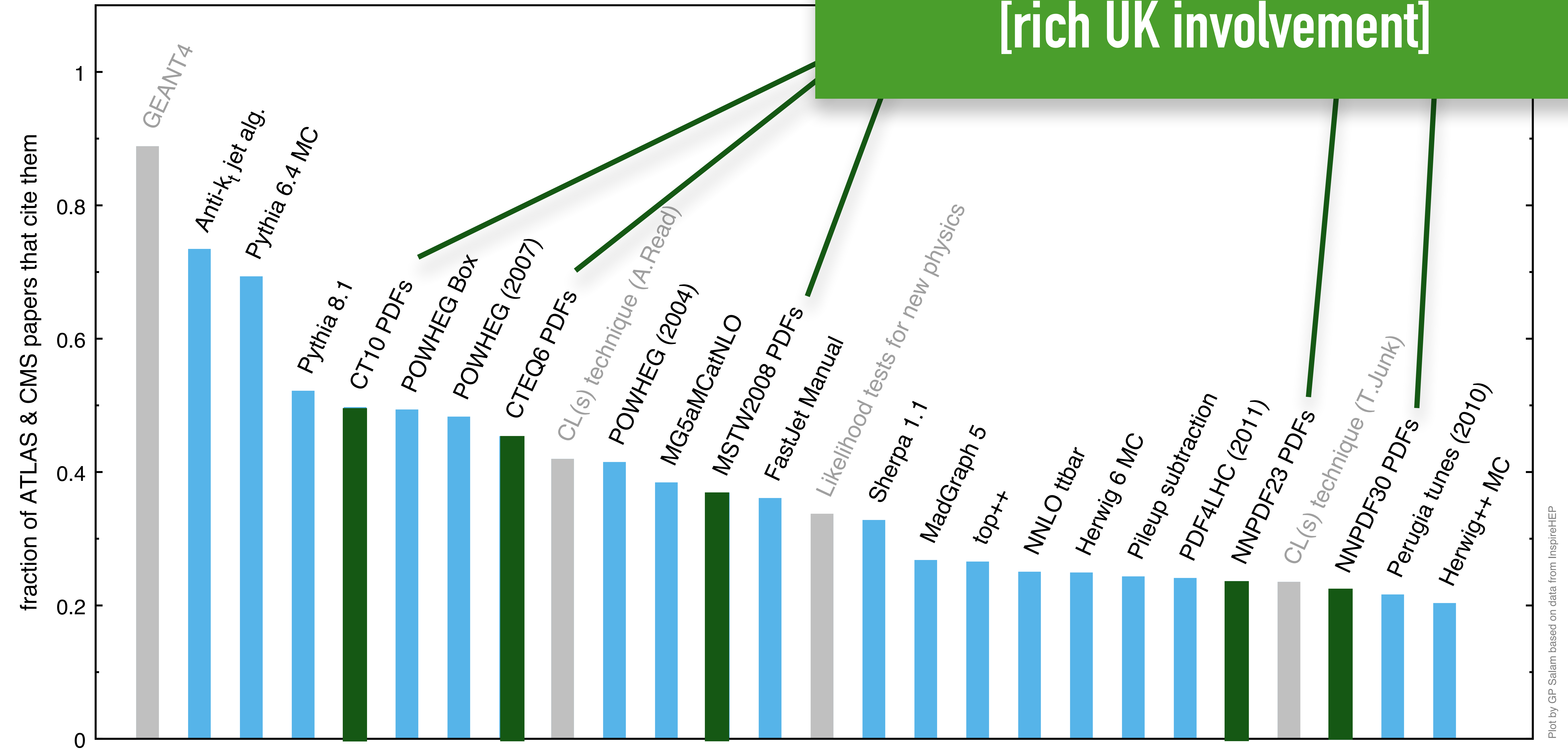
links ≡ papers they cite

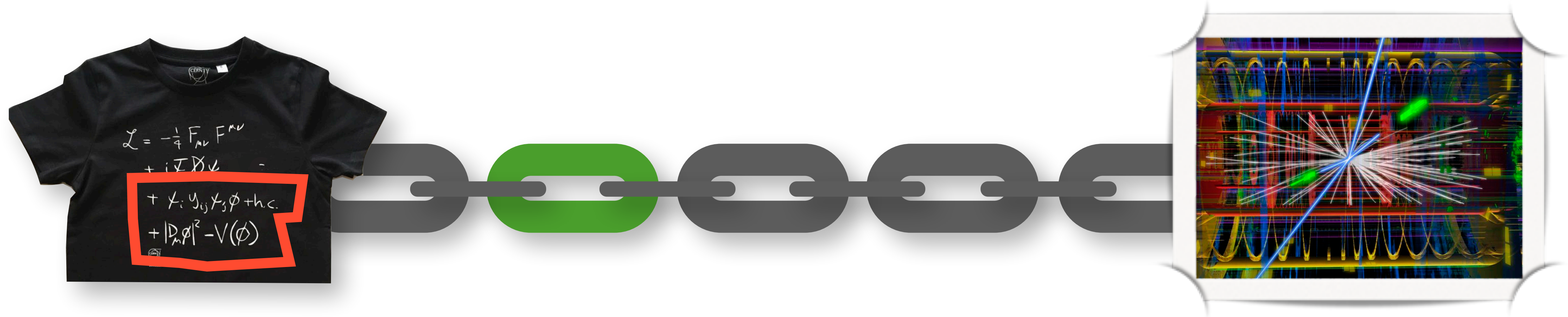






knowing what goes into a collision
i.e. proton structure
[rich UK involvement]





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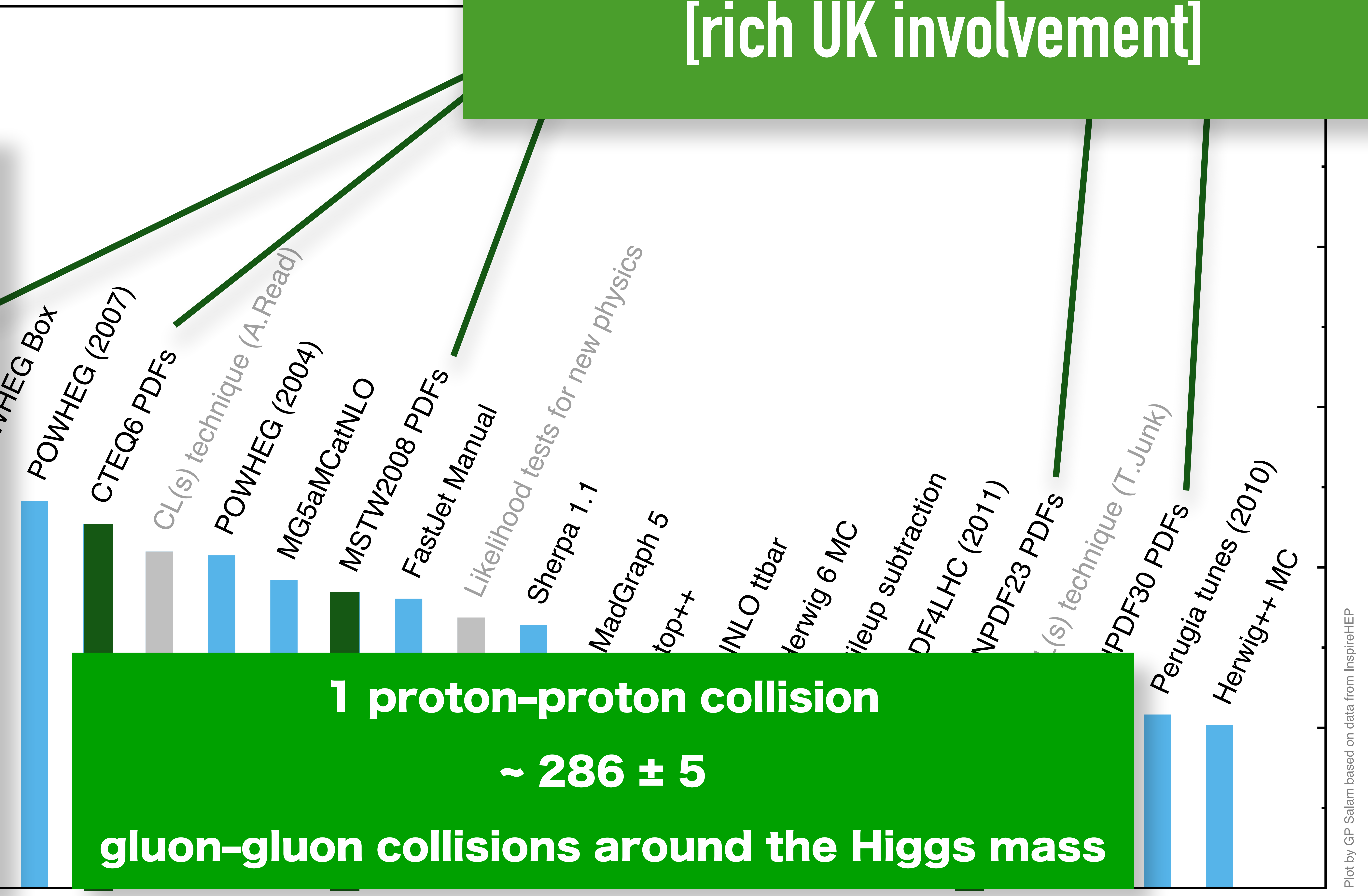
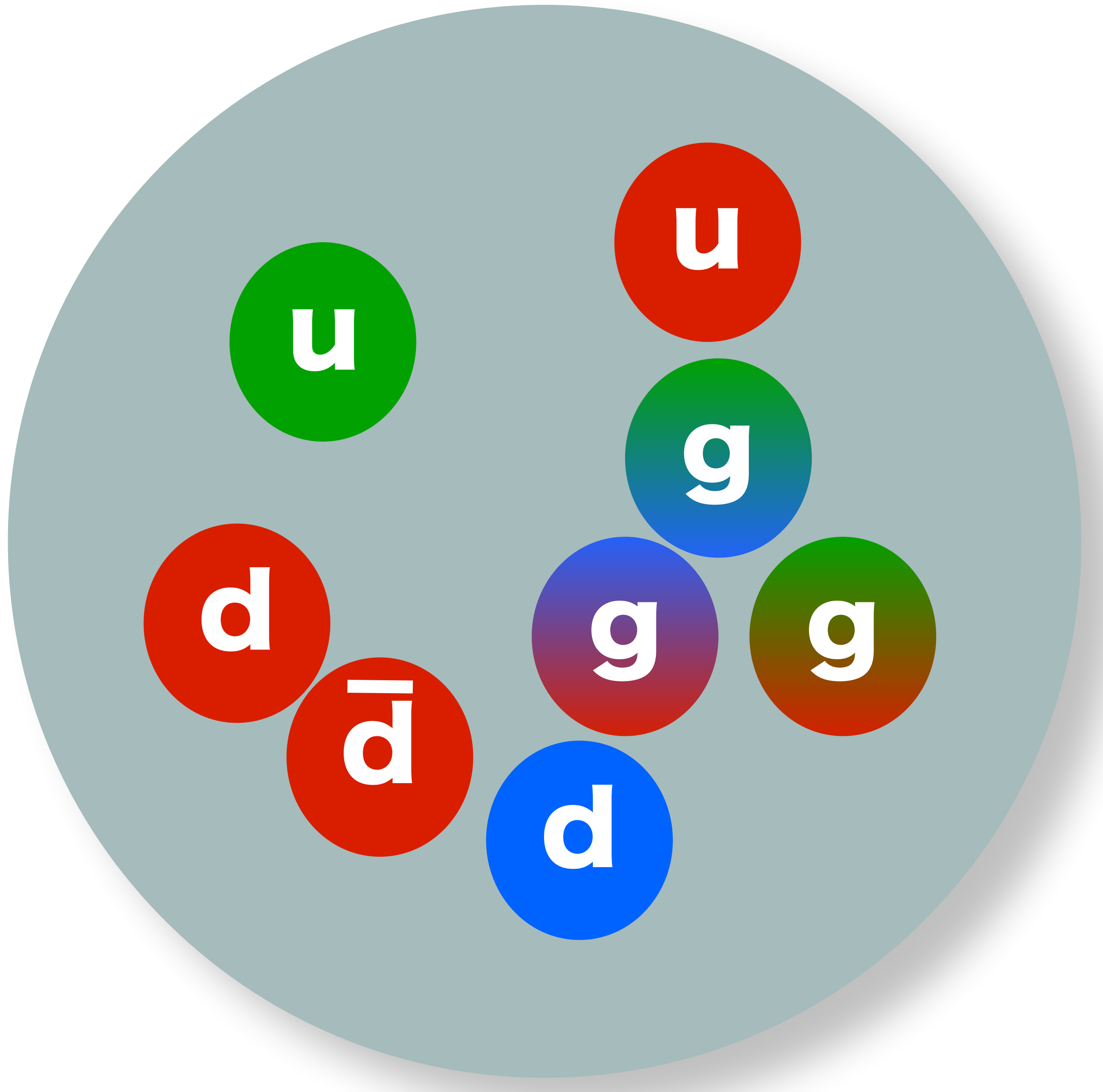
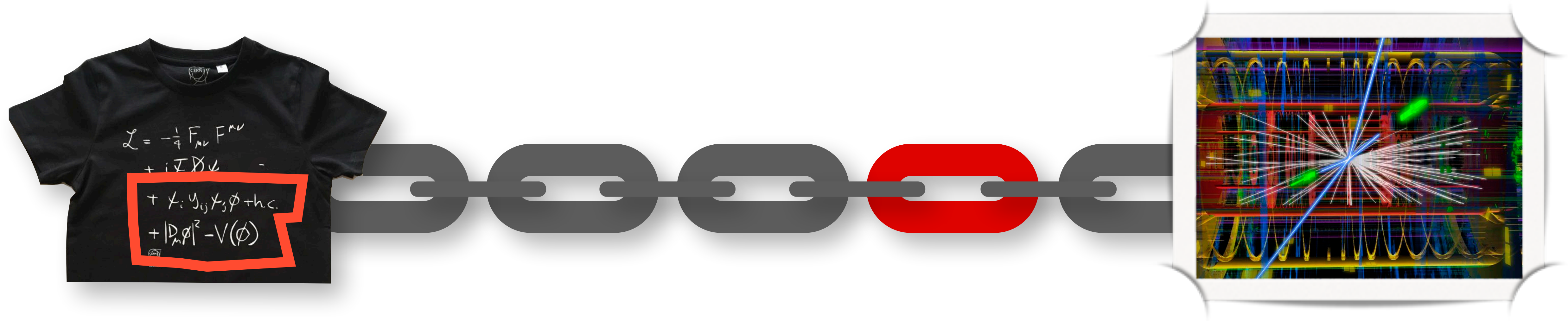


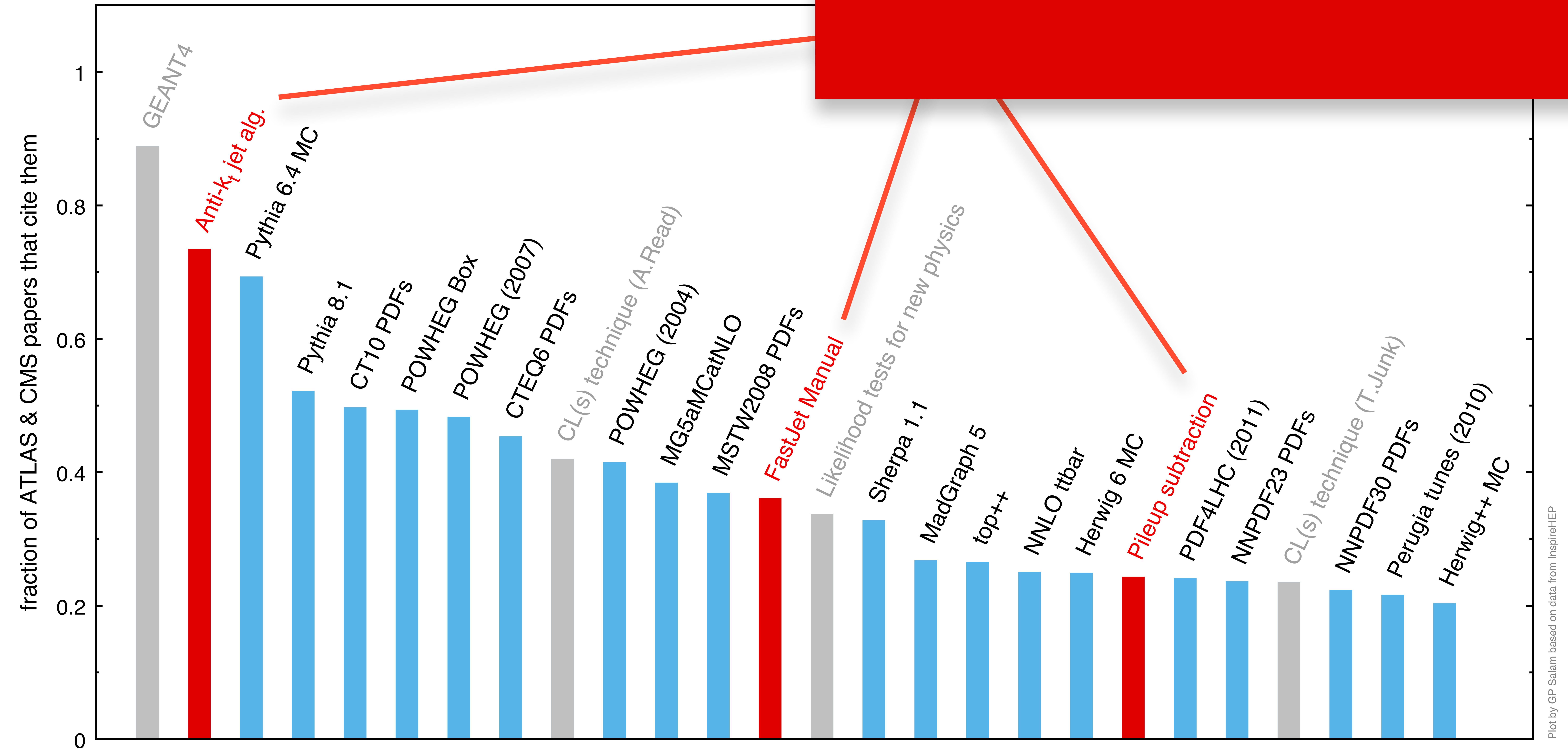
PROTON



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

organising event information ("jets")



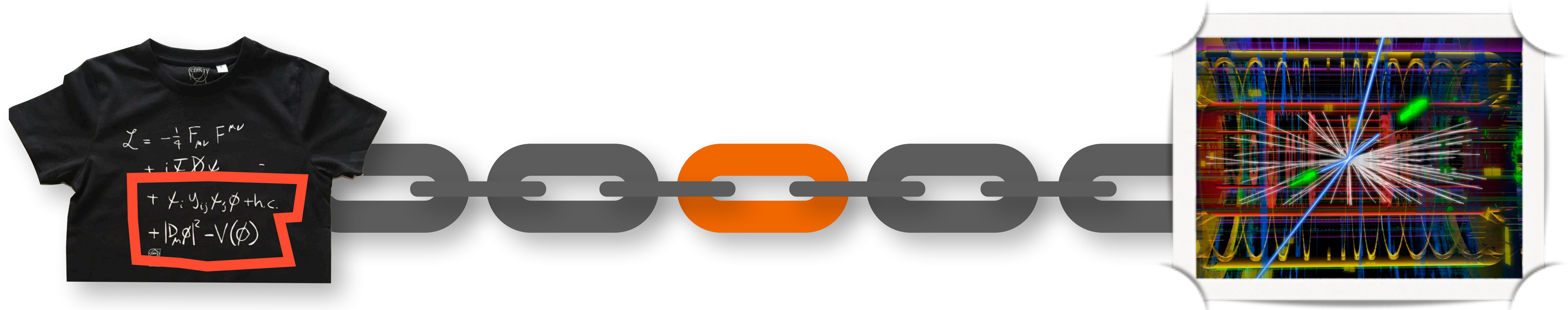


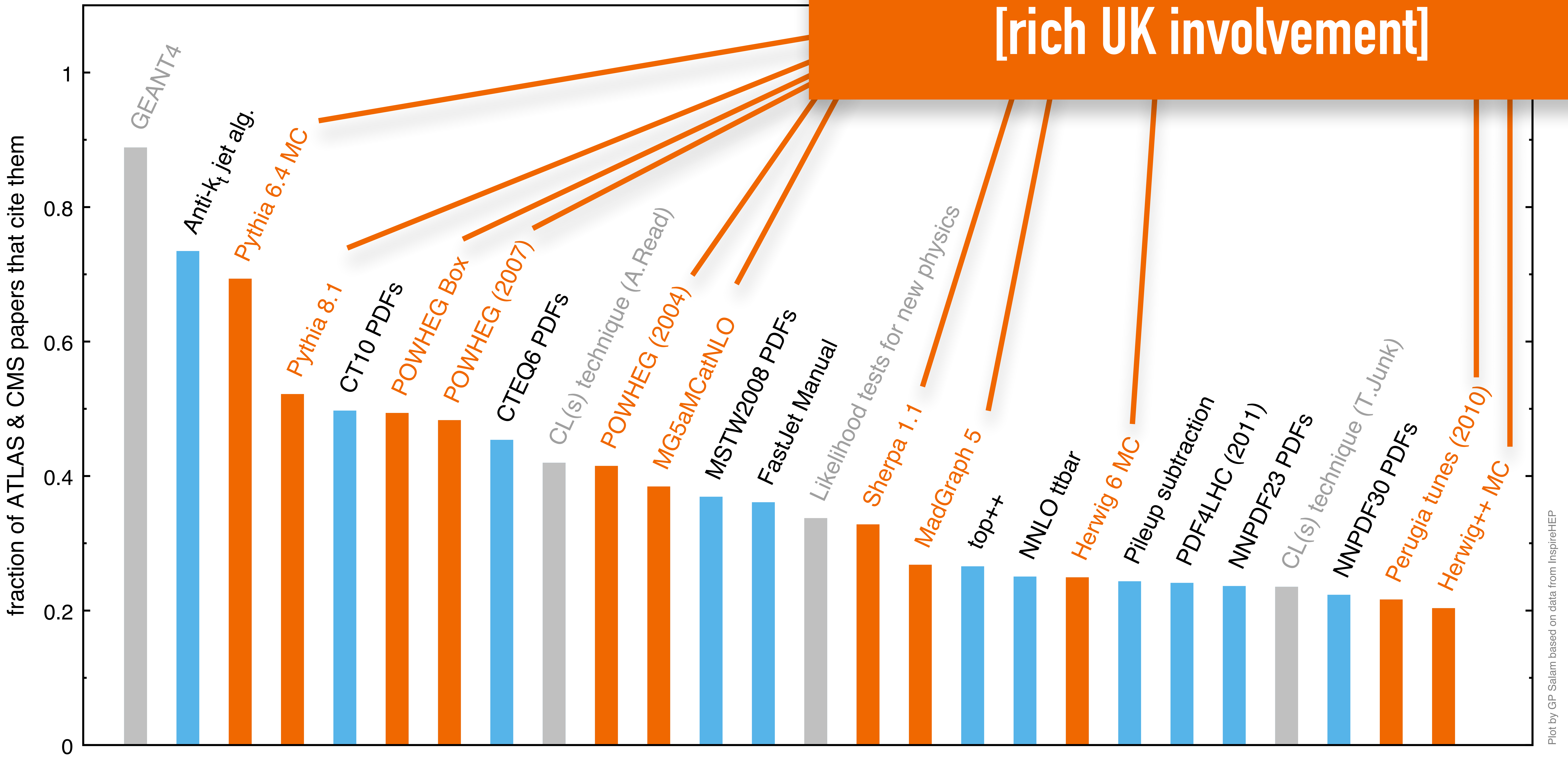

CMS Experiment at the LHC, CERN
Simulated event at 13 TeV centre-of-mass energy


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

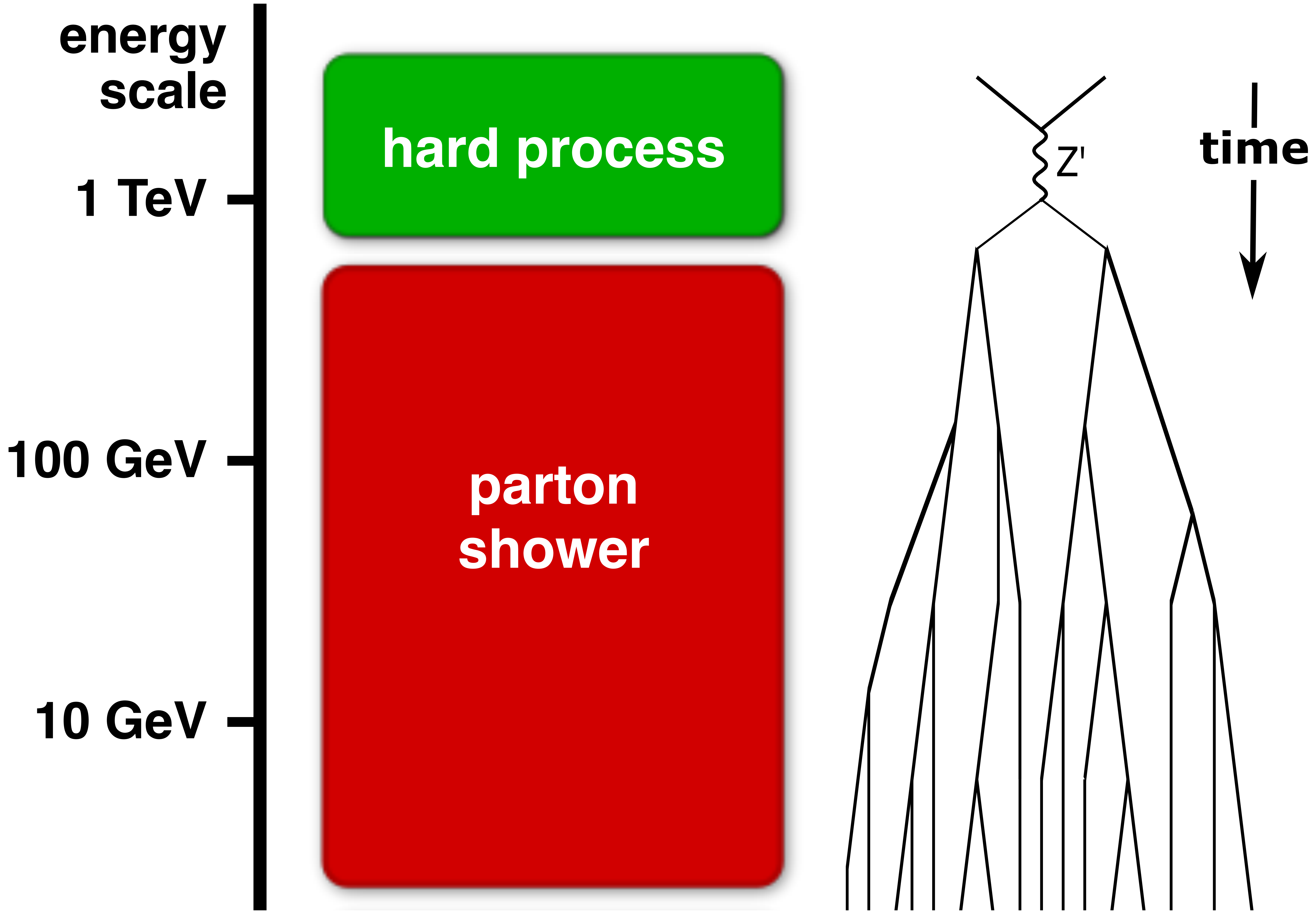
the question of organising information from hundreds of particles will come back later

predicting full particle structure that comes out of a collision [rich UK involvement]





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



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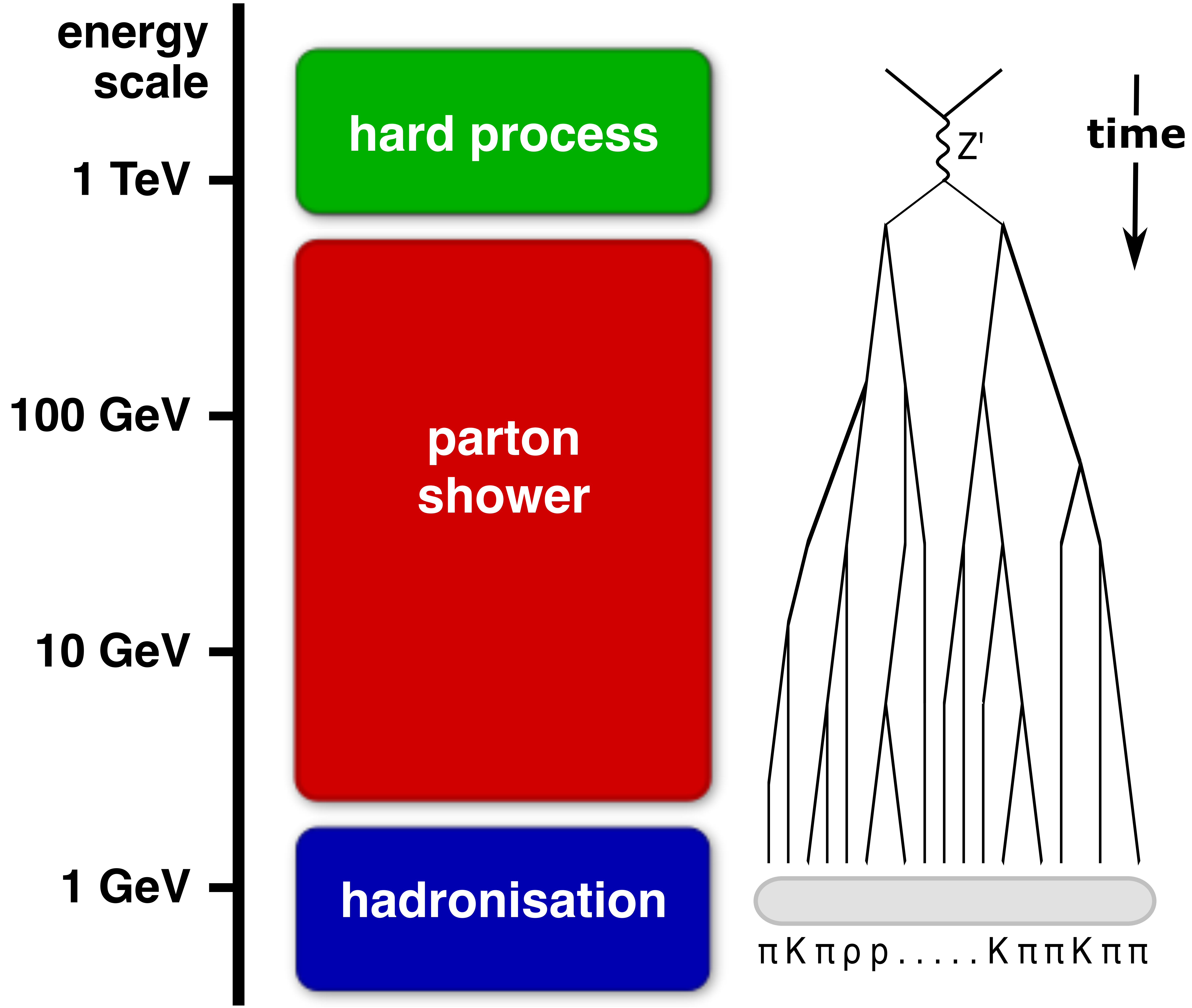


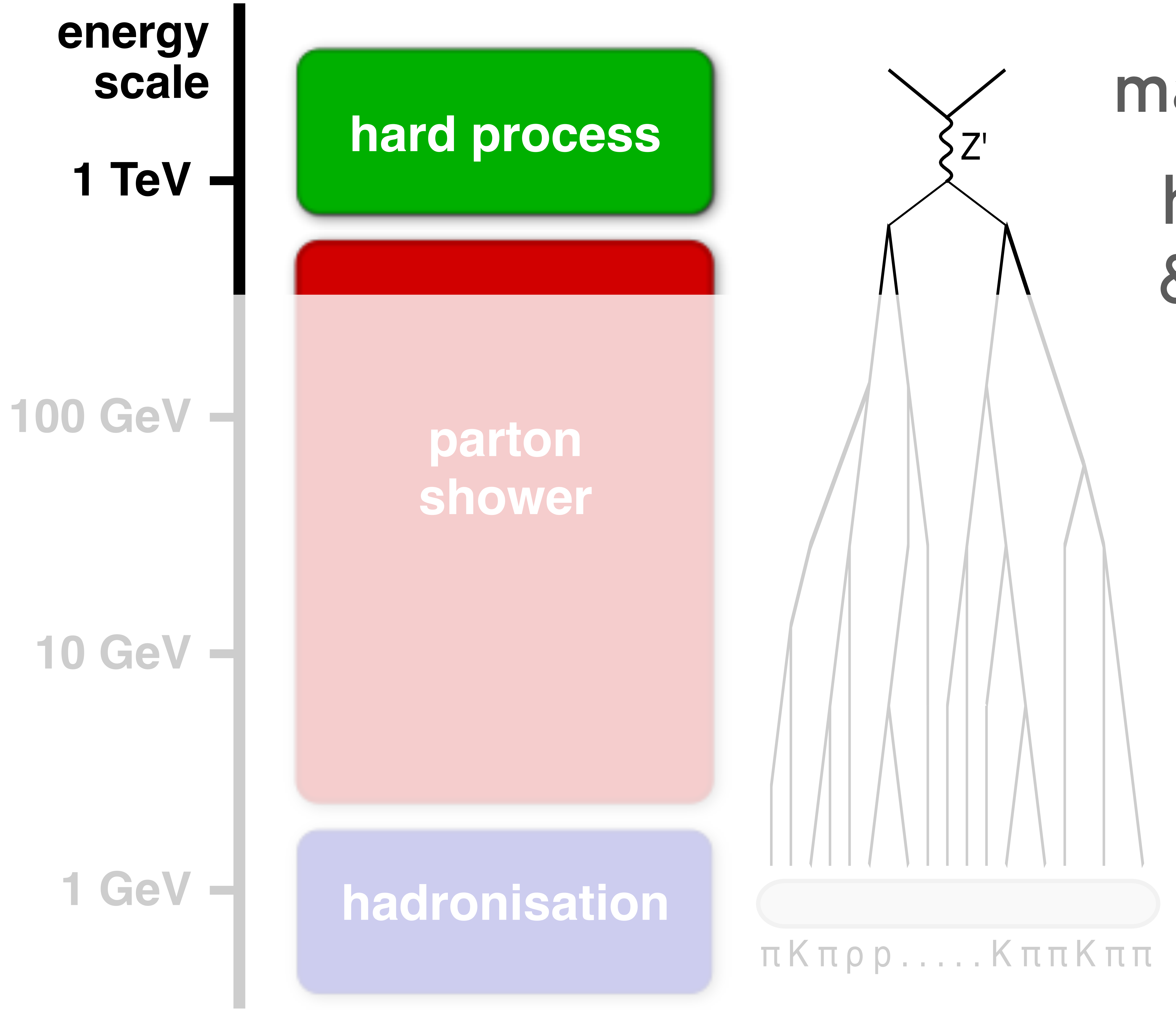
schematic view of key components of QCD predictions and Monte Carlo event simulation

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

general purpose Monte Carlo event generators: THE BIG 3

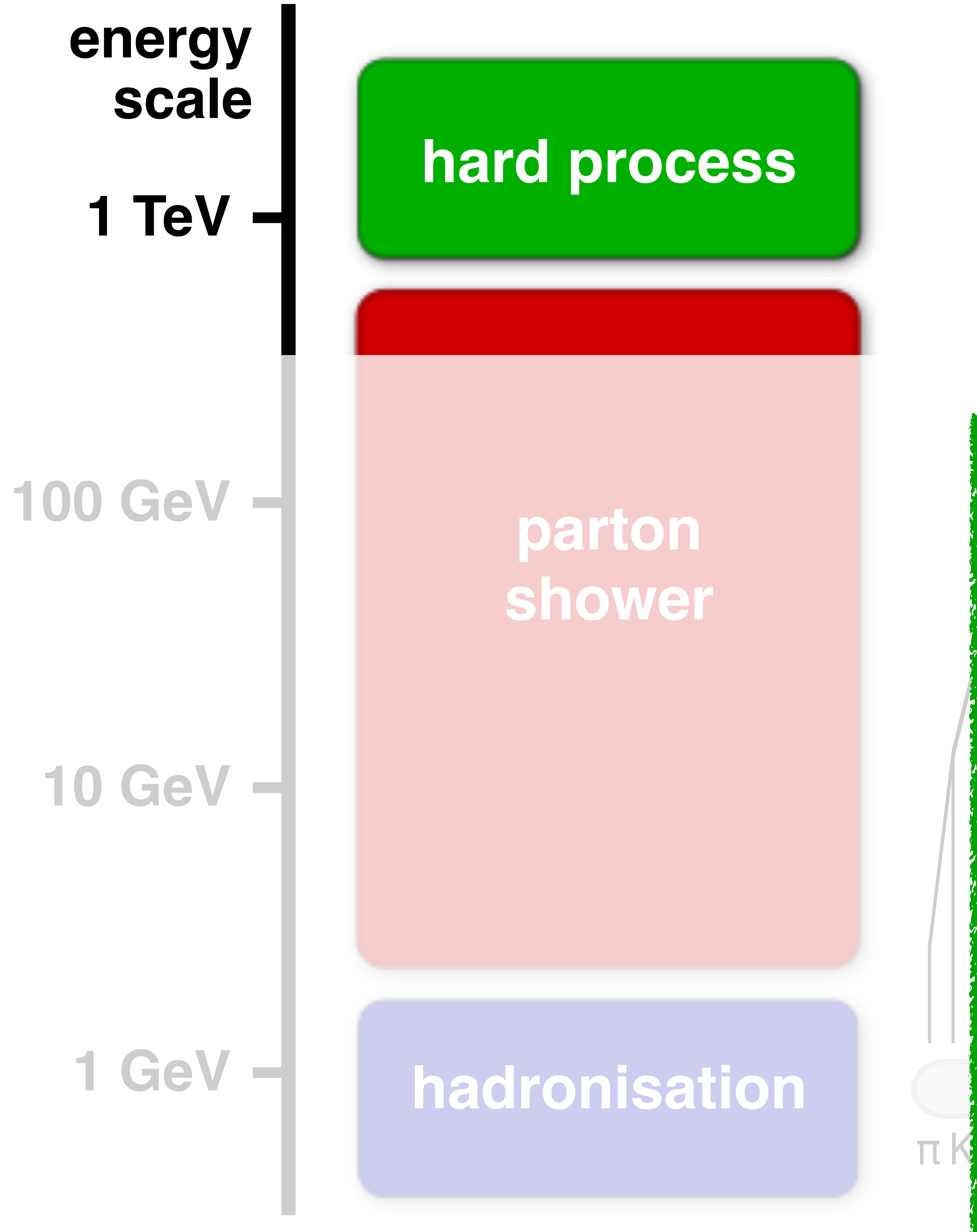
Herwig 7 | Pythia 8 | Sherpa 2

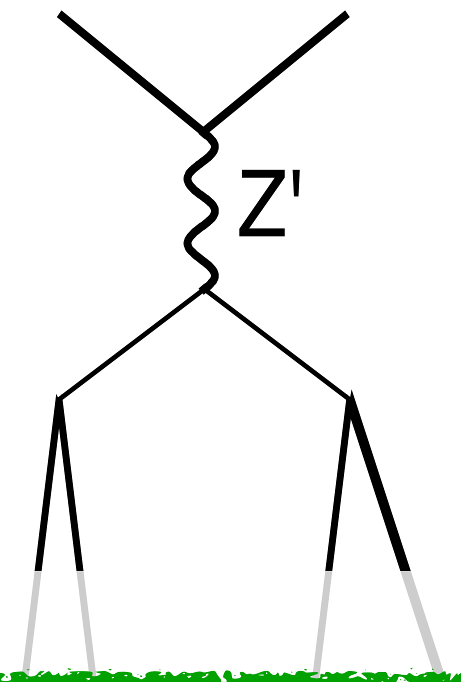
they do an amazing job of simulation vast swathes of data; collider physics would be unrecognisable without them



major advances of past 20yrs:

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





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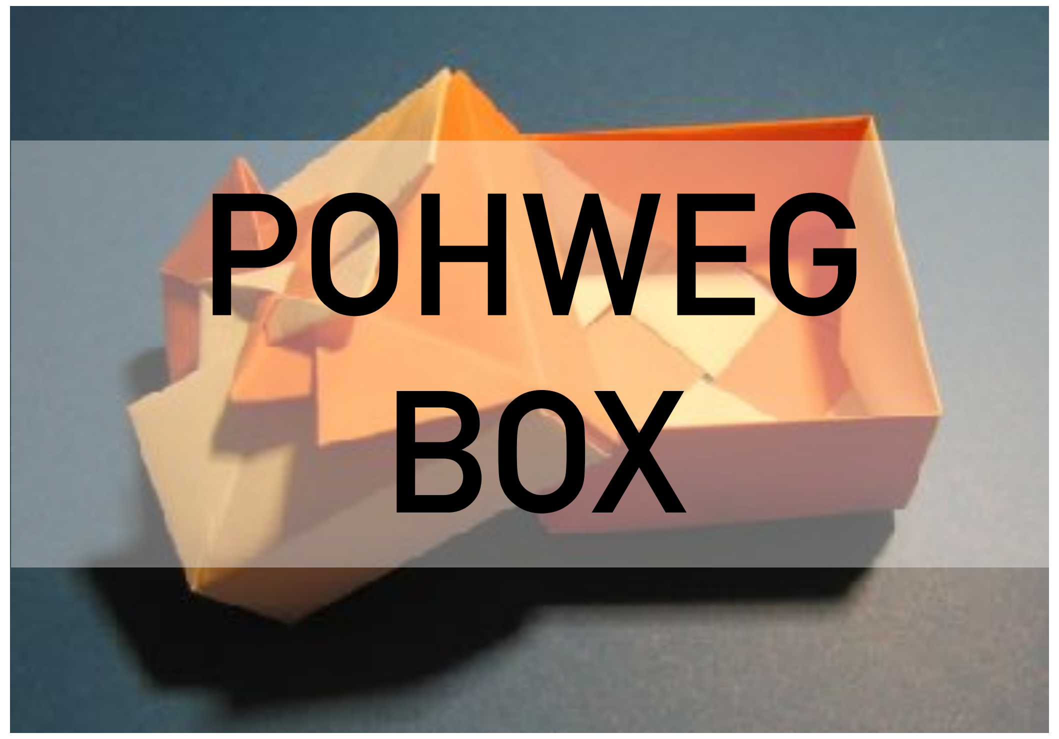


MadGraph5_aMC@NLO

MC@NLO
(in Herwig&Sherpa)

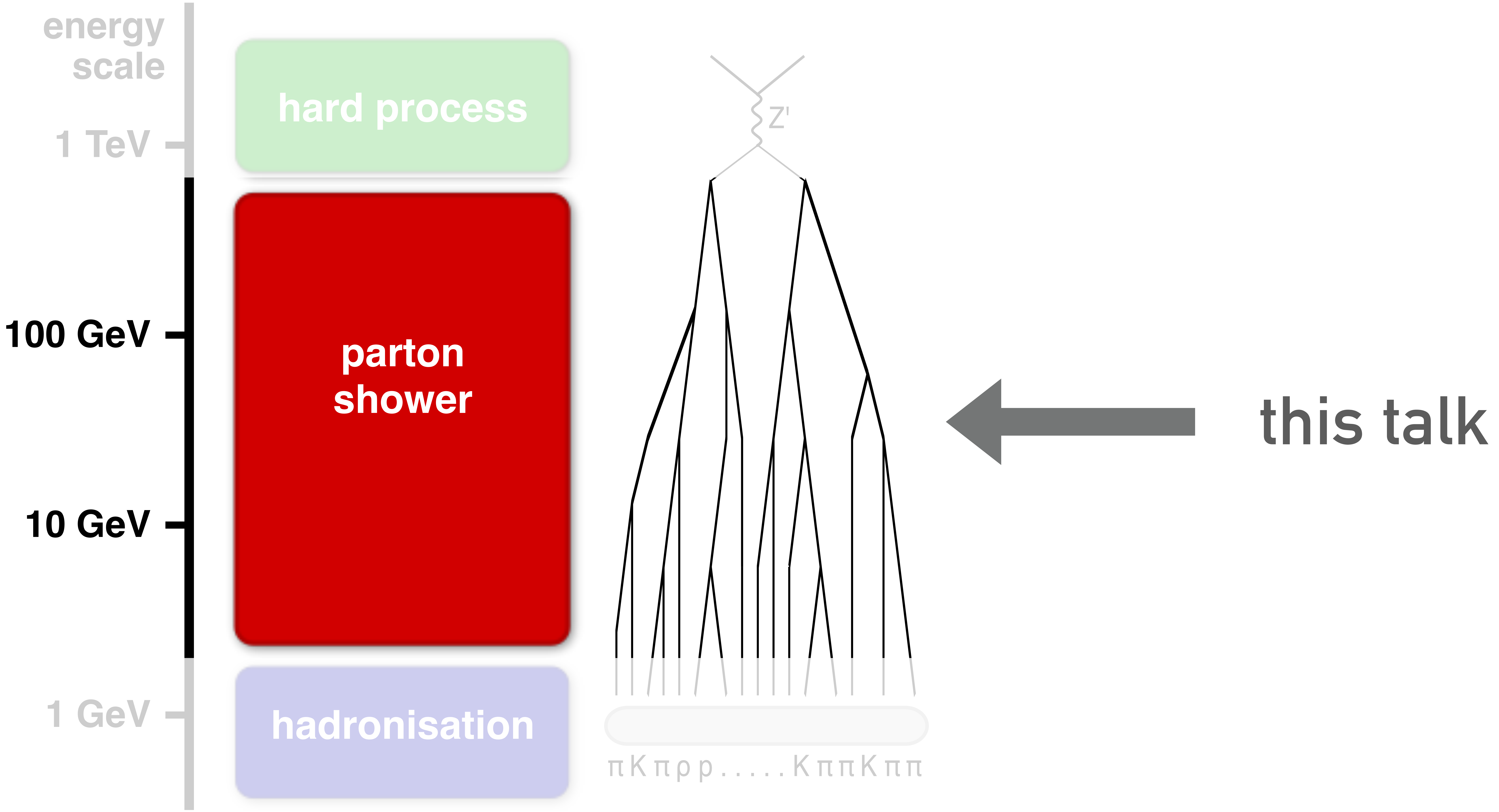
MINLO

MLM, CKKW
Vincia, FxFx

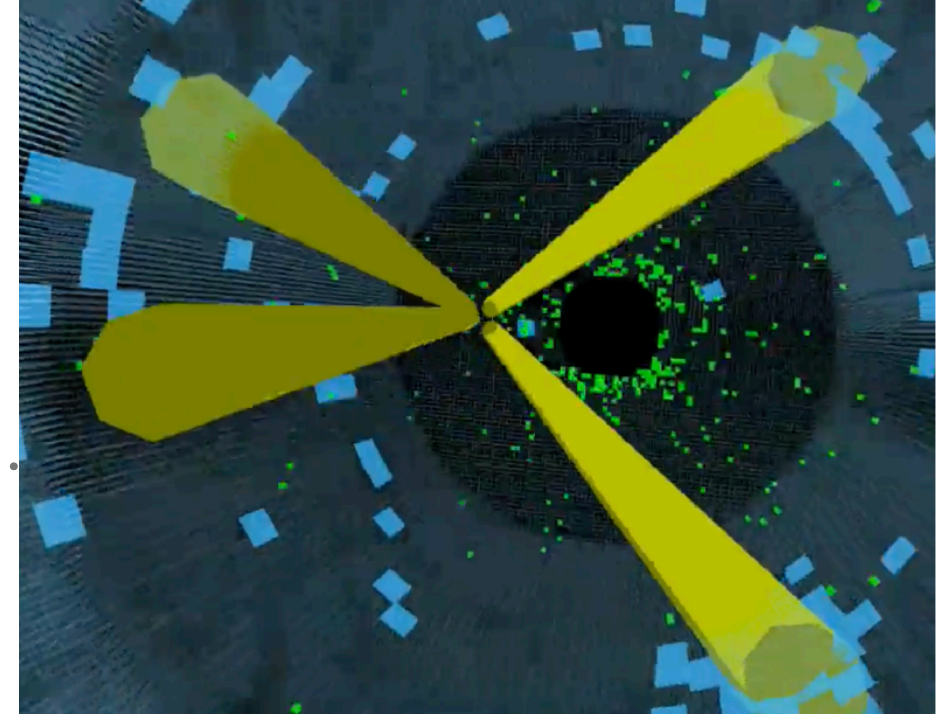
UNNLOPS

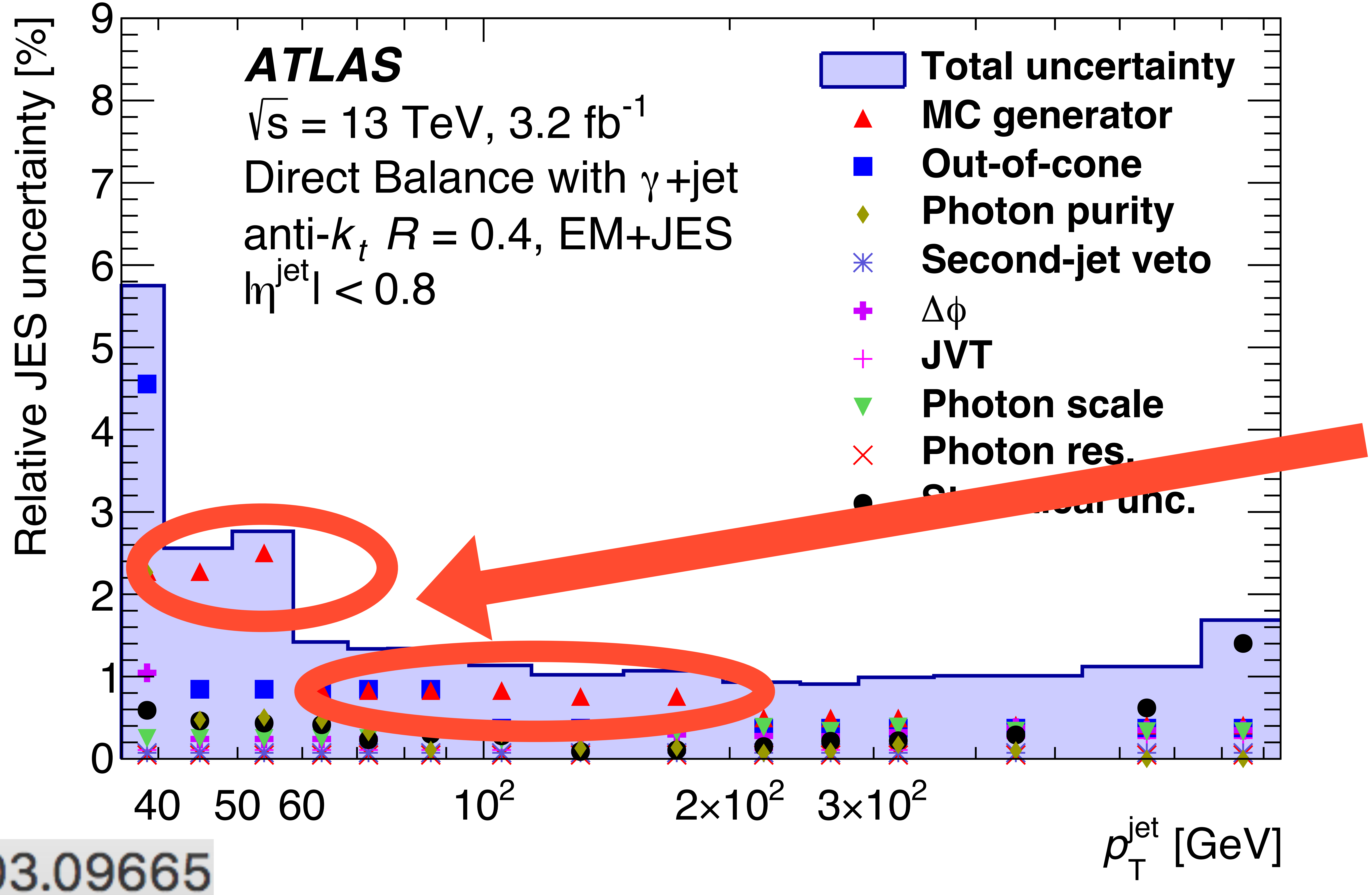
GENEVA

[...]


energy scale
1 TeV
100 GeV
10 GeV
1 GeV
hard process
parton shower
hadronisation
Z'
π K π ρ p . . . . . K π π K π π
this talk

Fundamental experimental calibrations (jets)





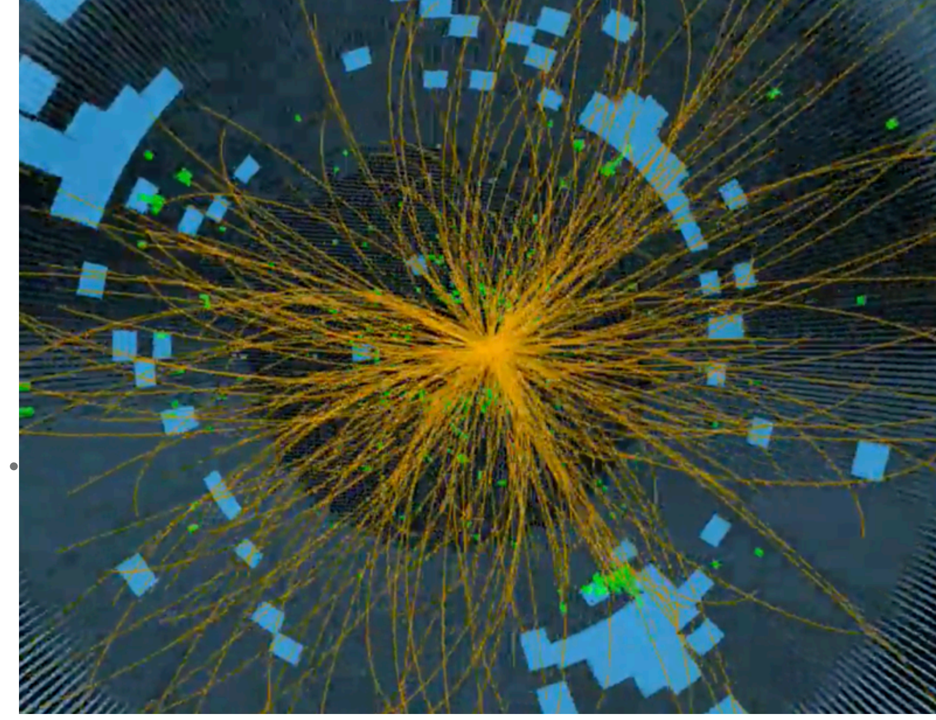
1703.09665

Jet energy scale, which feeds into hundreds of other measurements

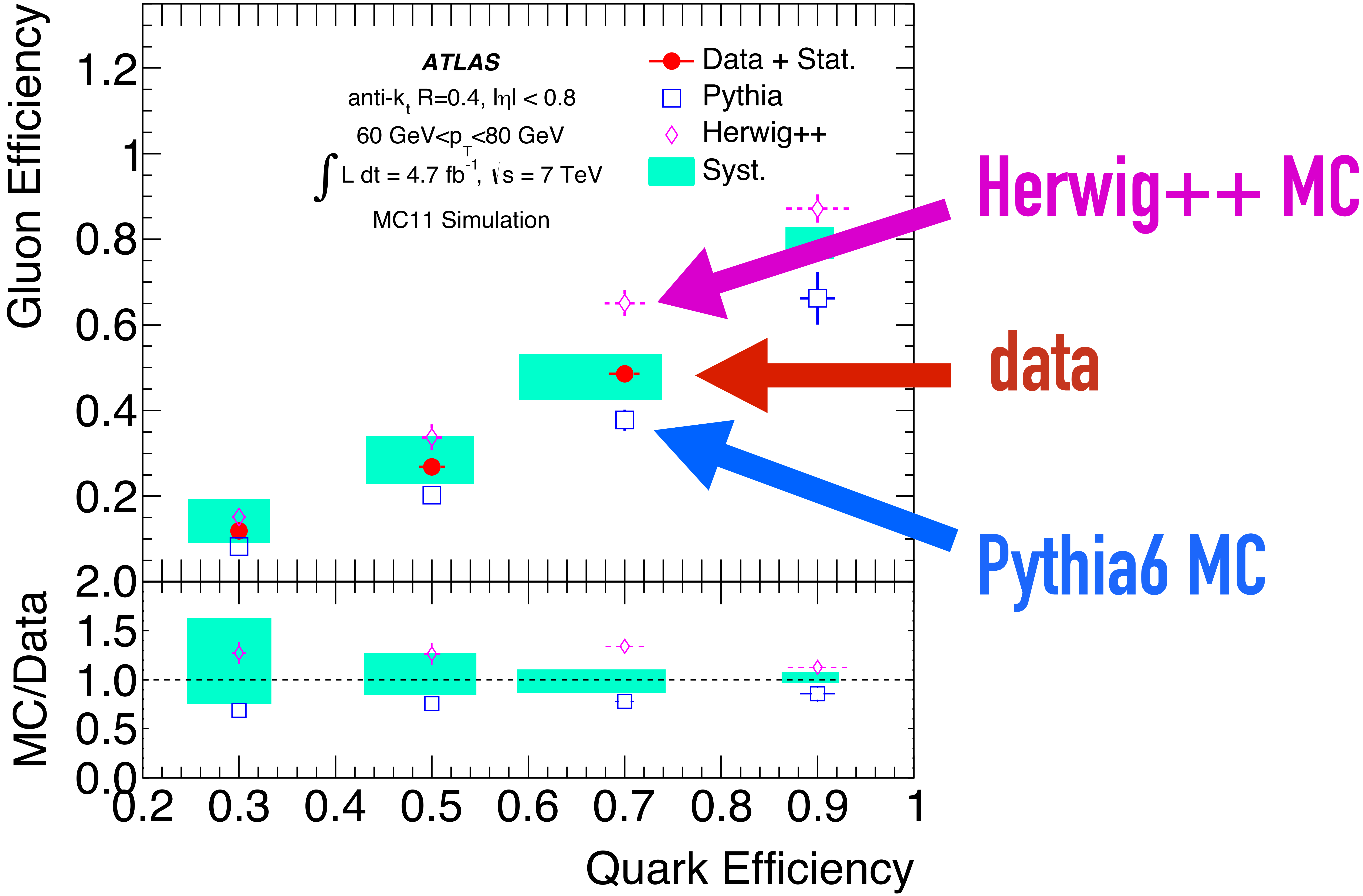
Largest systematic errors (1–2%) come from differences between MC generators

(here Sherpa v. Pythia)

→ fundamental limit on LHC precision potential



using full event information (quark/gluon tagging)



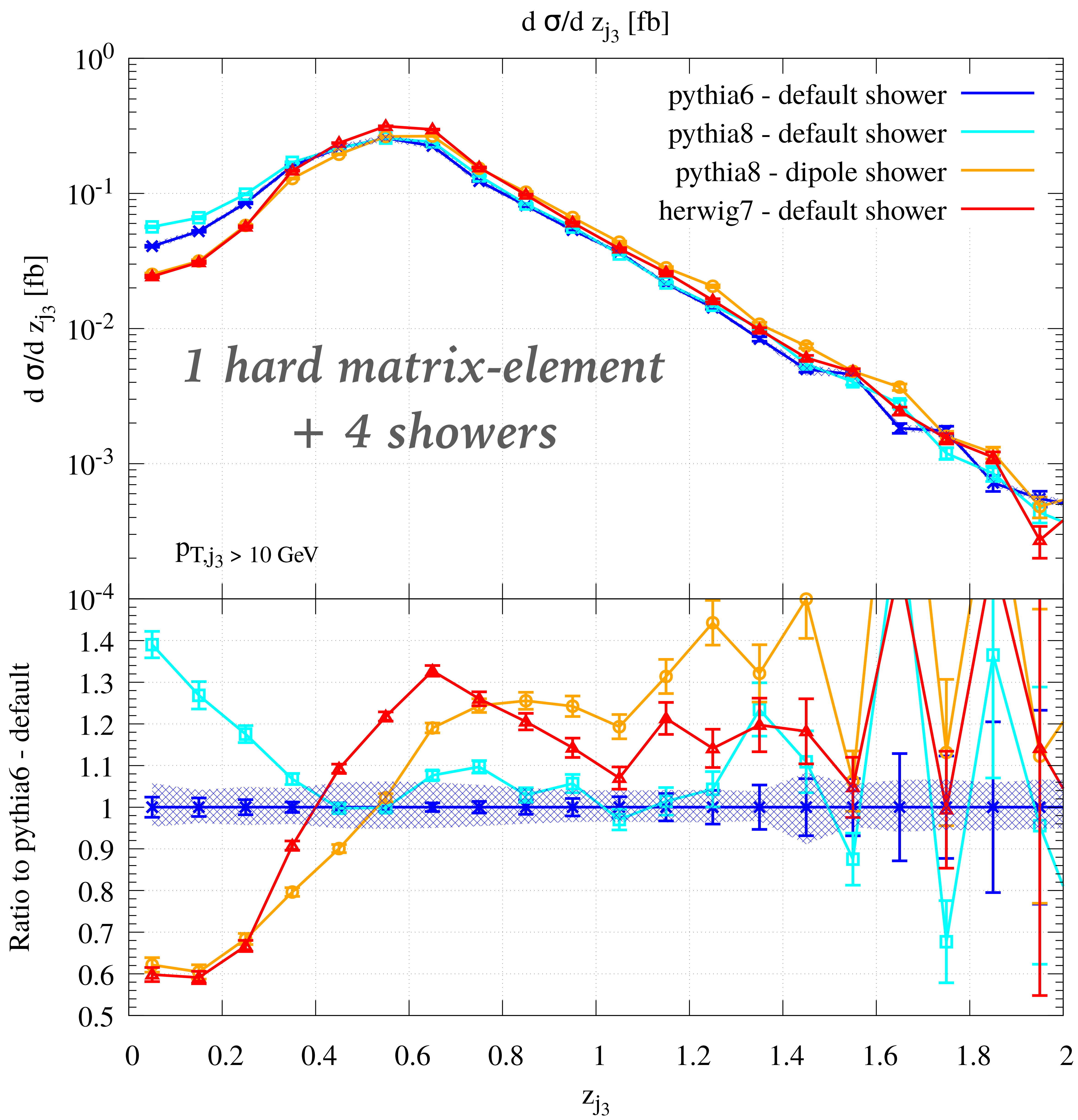
use more info → become more sensitive to MC limitations

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)

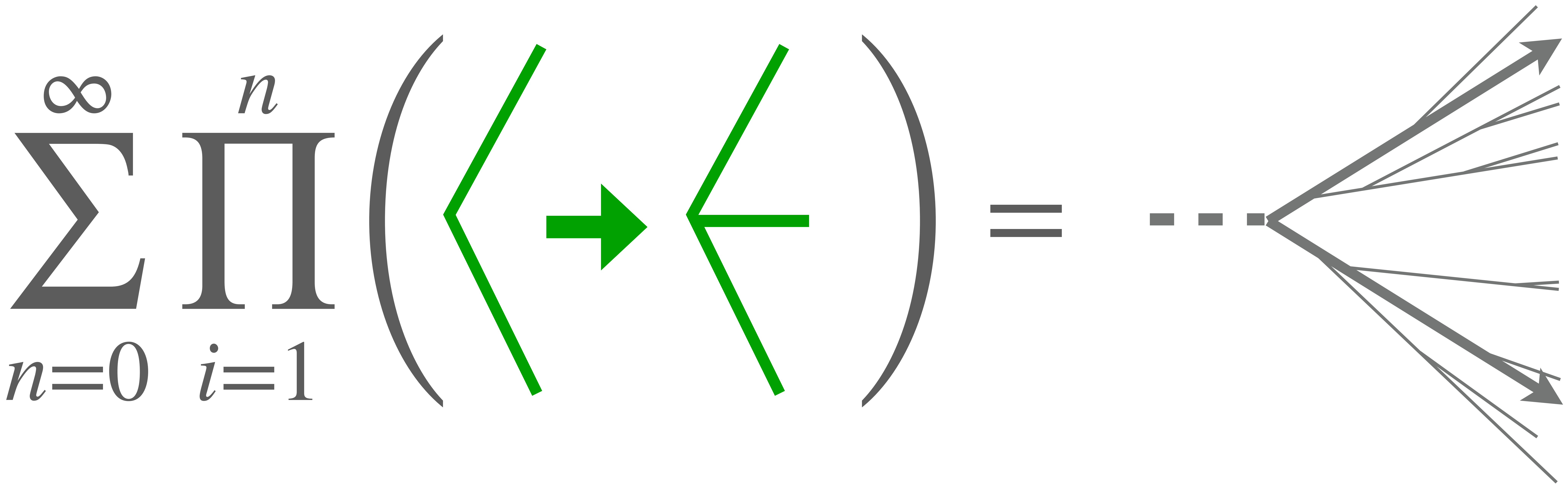
Parton structure also gets in way of better (NNLOPS) hard-process + shower matching schemes

what is a parton shower?

illustrate with dipole / antenna showers

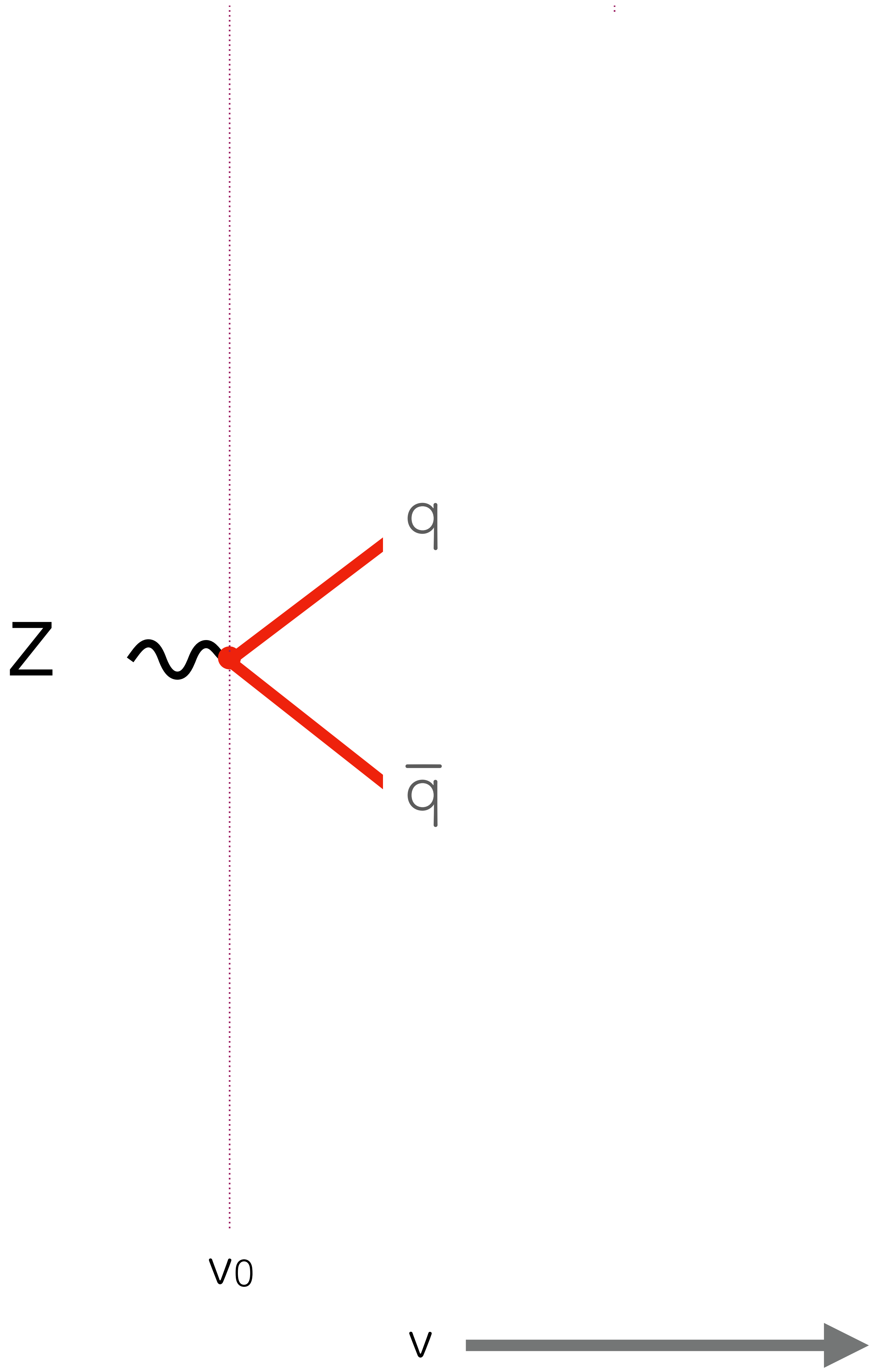
Gustafson & Pettersson 1988, Ariadne 1992, main Sherpa & Pythia8 showers, option in Herwig7, Vincia shower & (partially) Deductor shower

At its simplest



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

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

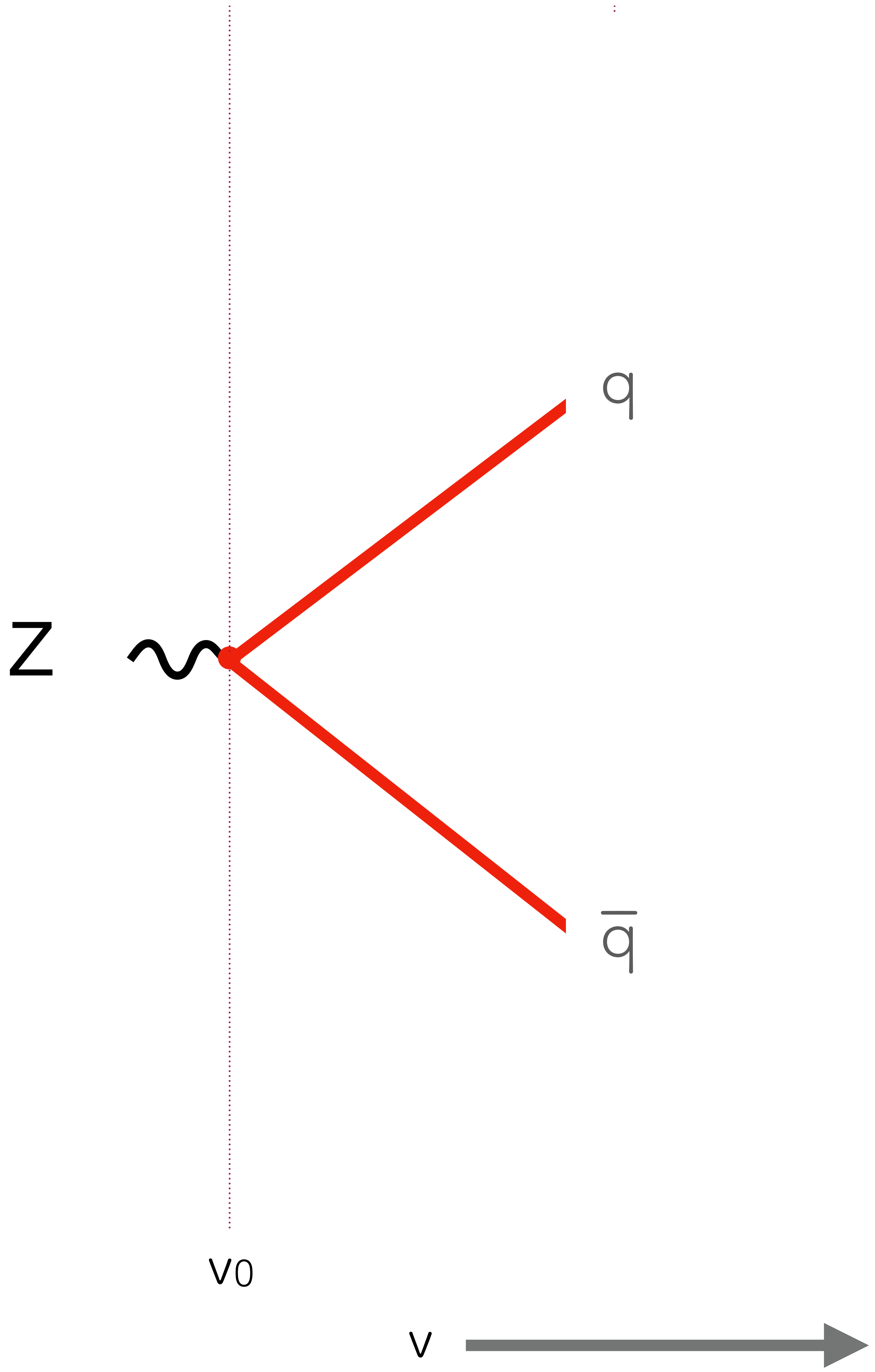


Start with q-qbar state.

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

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

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



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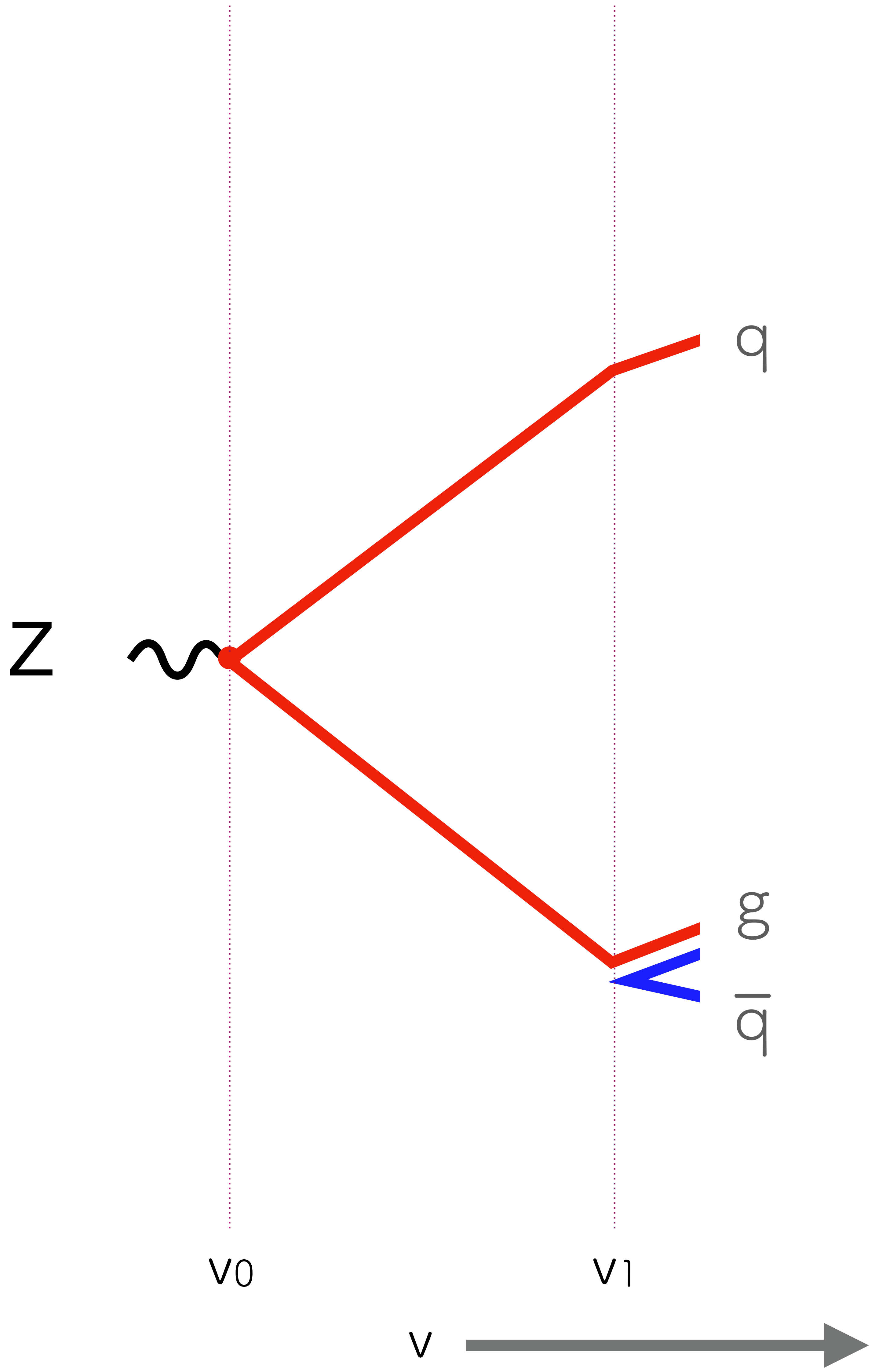


Start with q-qbar state.

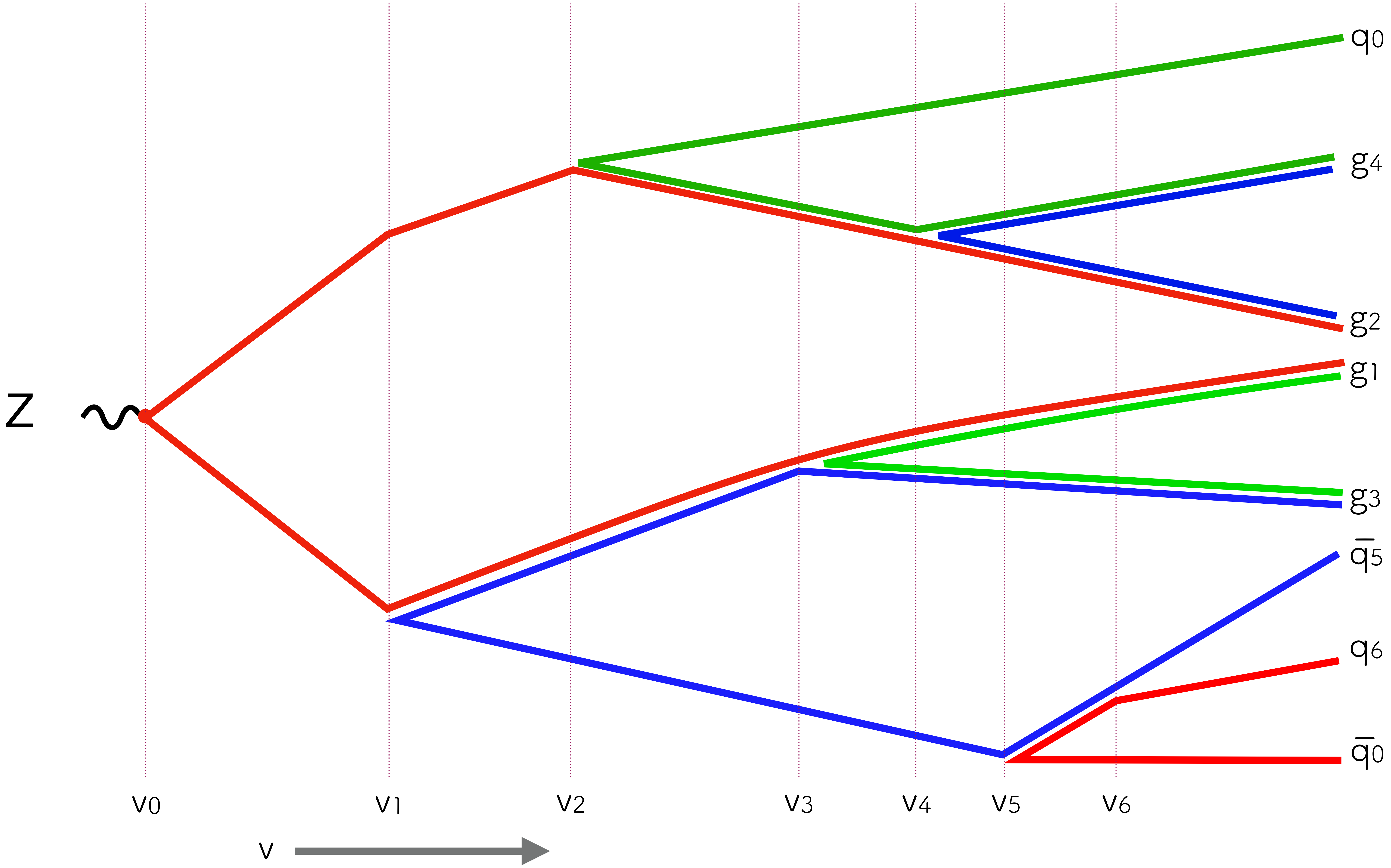
Evolve a step in v and throw a random number to decide if state remains unchanged

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

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

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

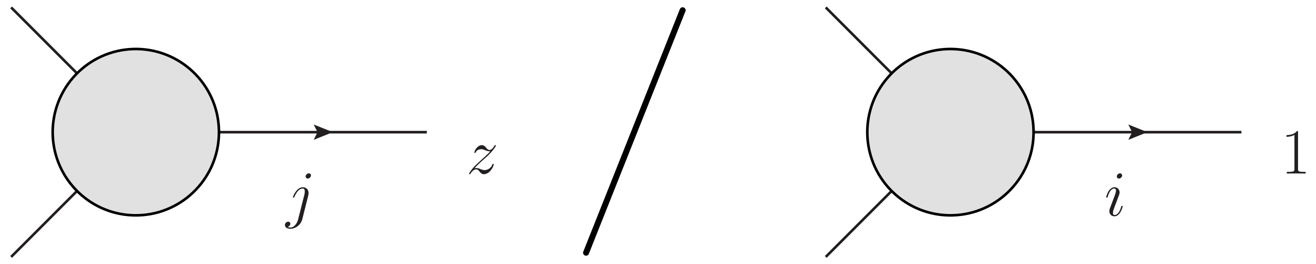
recent directions of parton-shower work?

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

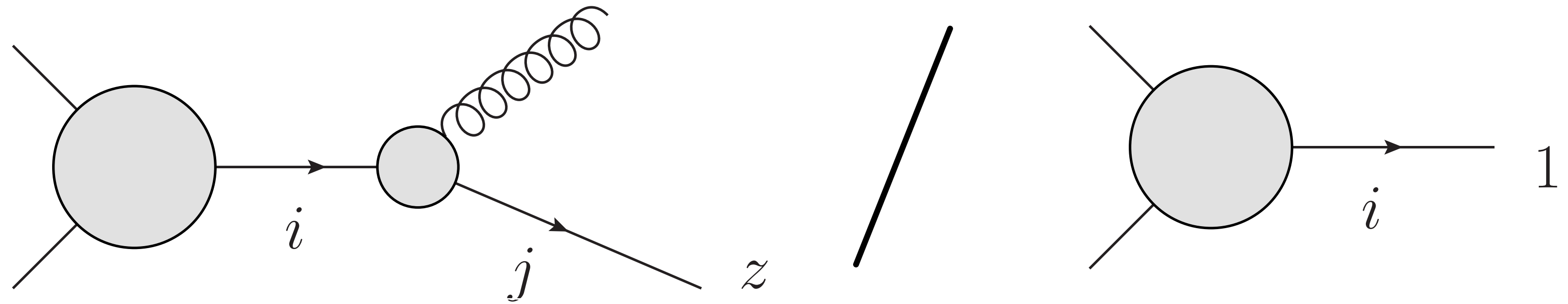
Including 1→ 3 splittings (≡ 2→4)

- 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

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

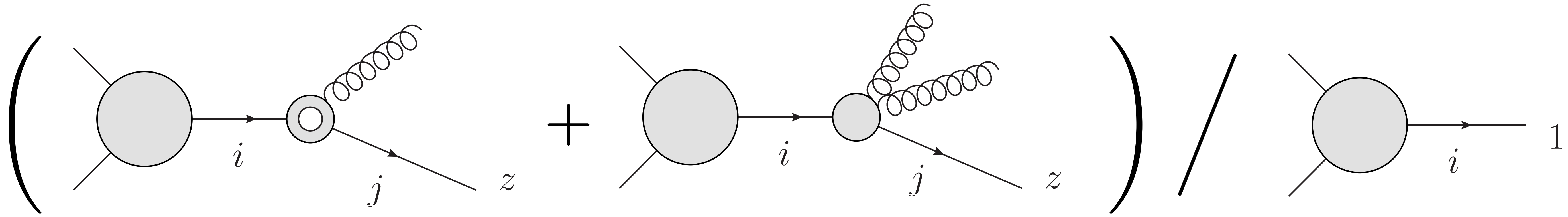


$$D_{ji}^{(1)}(z,\mu) = -\frac{1}{\varepsilon}P_{ji}^{(0)}(z) \qquad \leftrightarrow$$



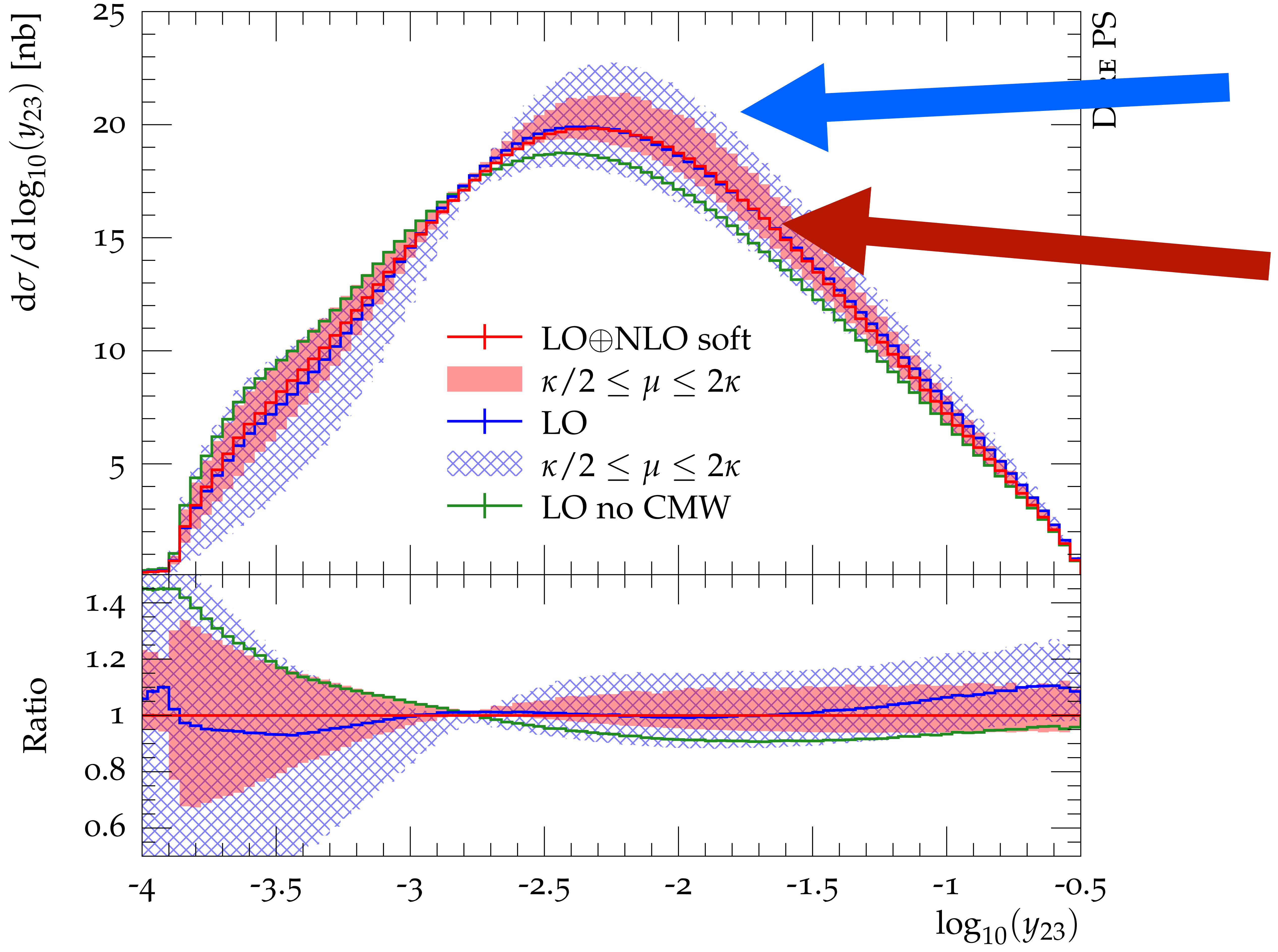
$$D_{ji}^{(2)}(z,\mu) = -\frac{1}{2\varepsilon}P_{ji}^{(1)}(z) + \frac{\beta_0}{4\varepsilon^2}P_{ji}^{(0)}(z) + \frac{1}{2\varepsilon^2}\int_z^1 \frac{\mathrm{d}x}{x}P_{jk}^{(0)}(x)P_{ki}^{(0)}(z/x)$$

$\leftrightarrow$



Equations from slides by Höche

Including 1→ 3 splittings



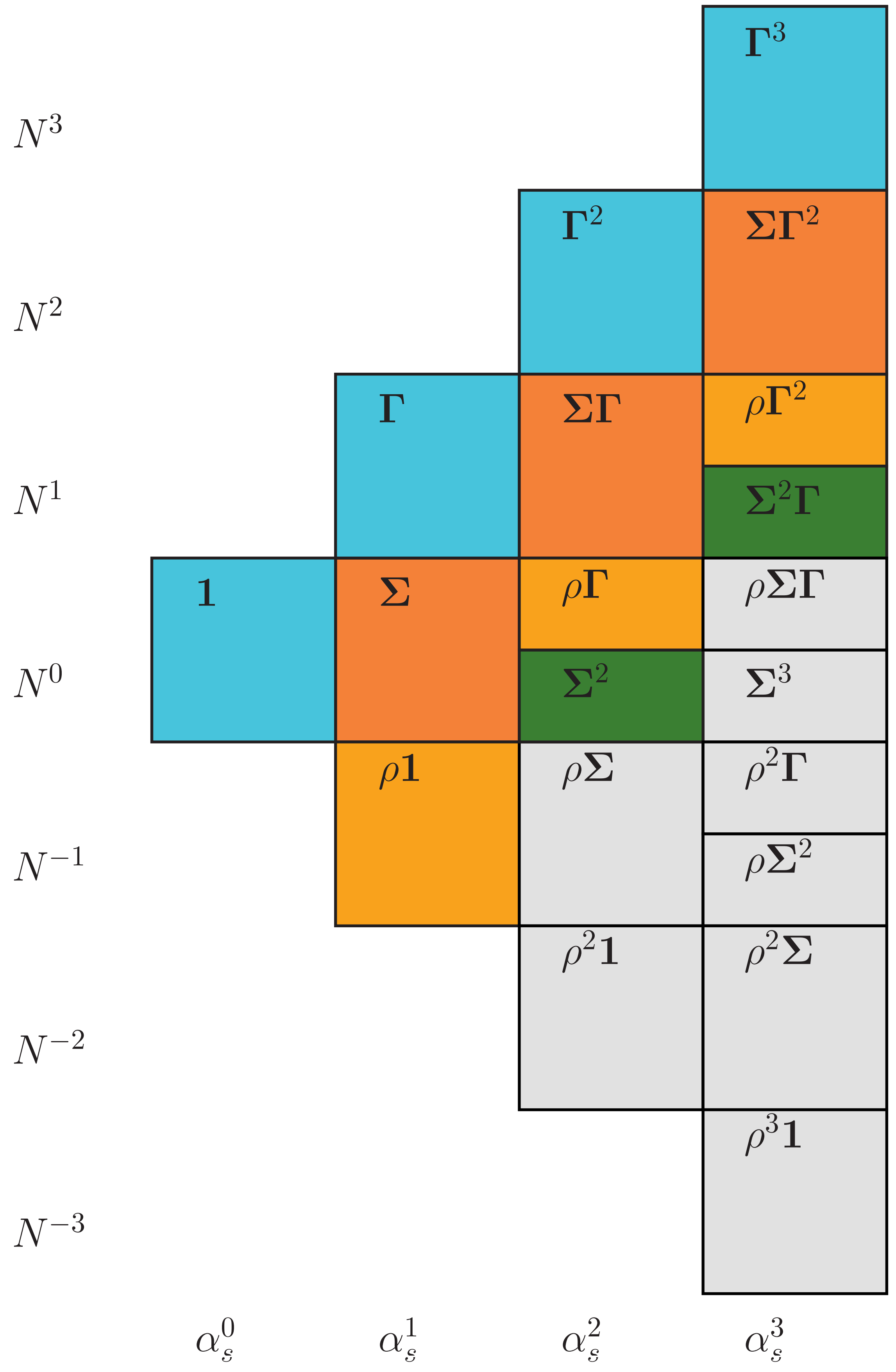
just 1→2 splittings

+ 1→3 soft splittings

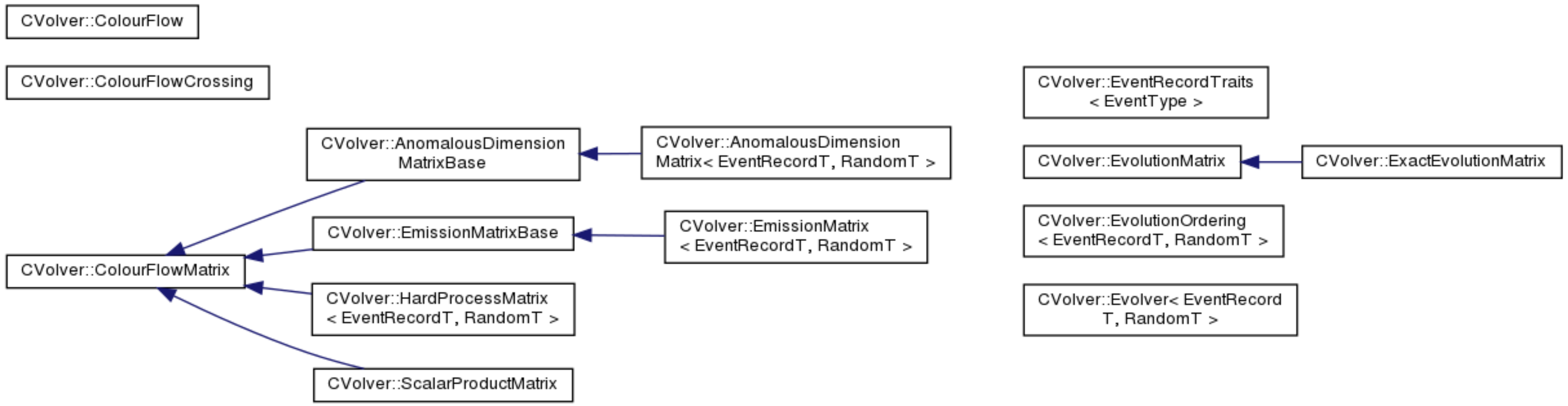
Dulat, Höche & Prestel, 1805.03757

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



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

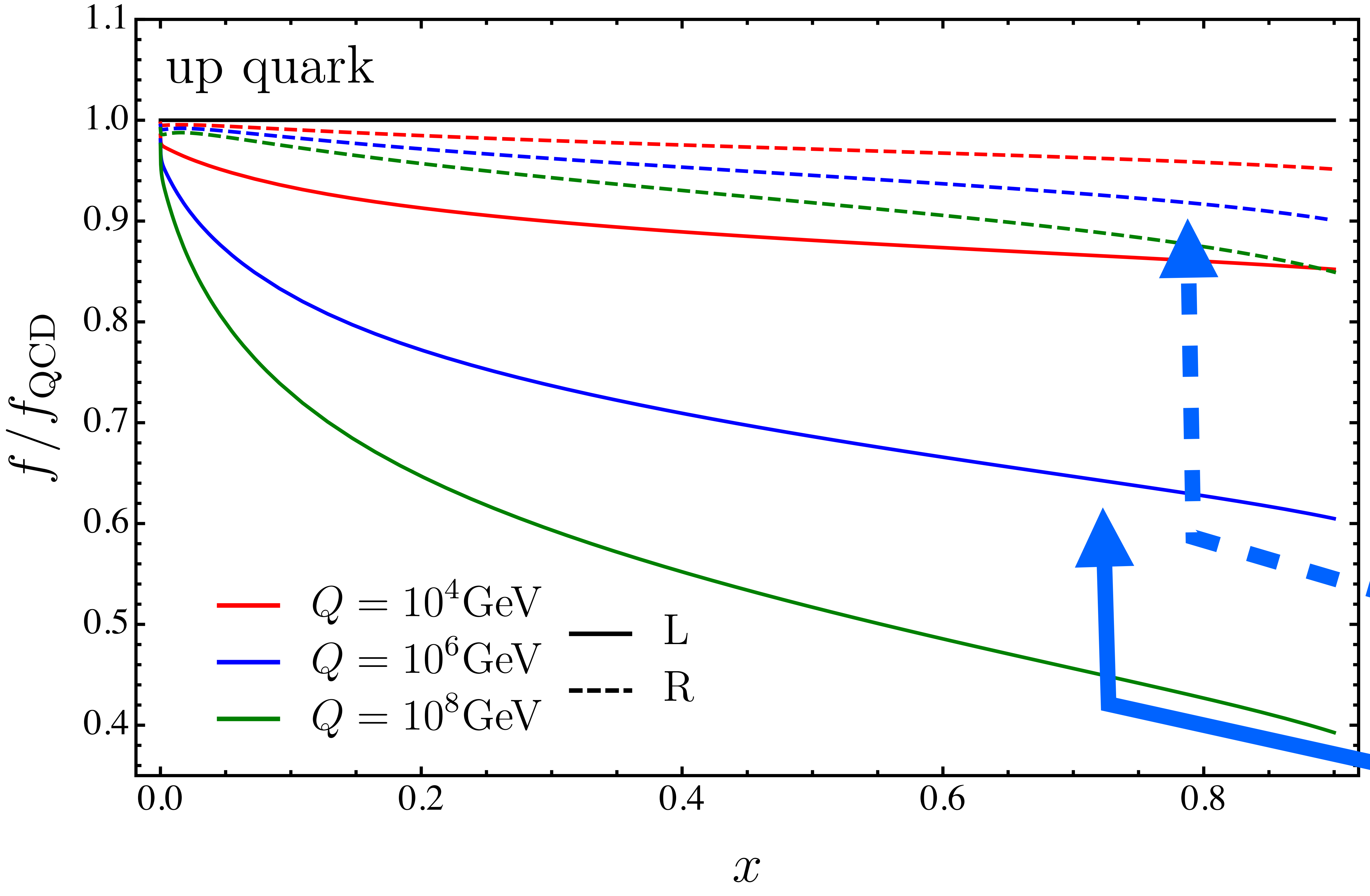


Plugin approach can accommodate anything from (N)GLs to full parton showers.

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

EW showers (esp. beyond LHC)

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



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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  [machine learning might "learn" many such features]

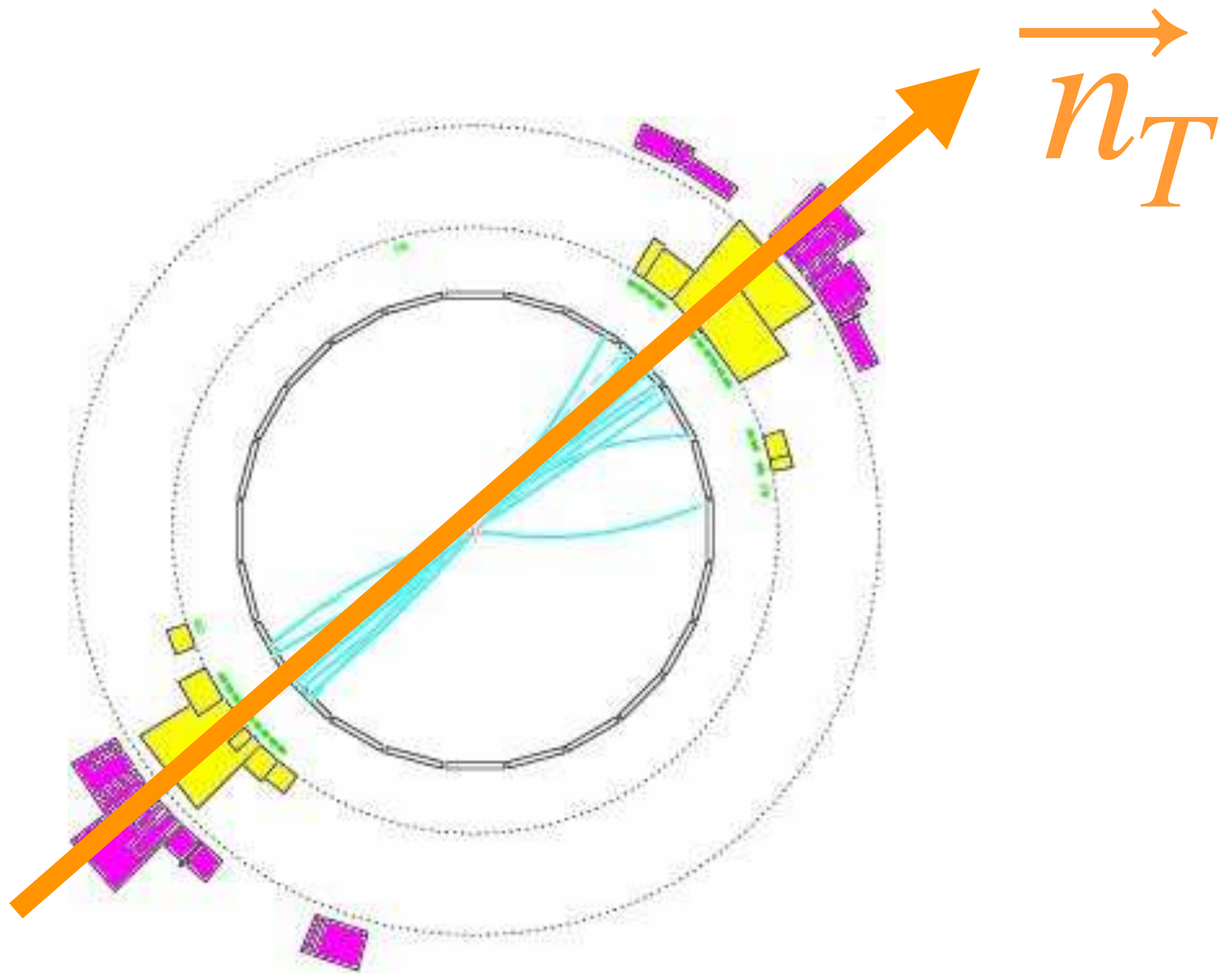
how can you prescribe correctness & accuracy of the answer, when the questions you ask can be arbitrary?

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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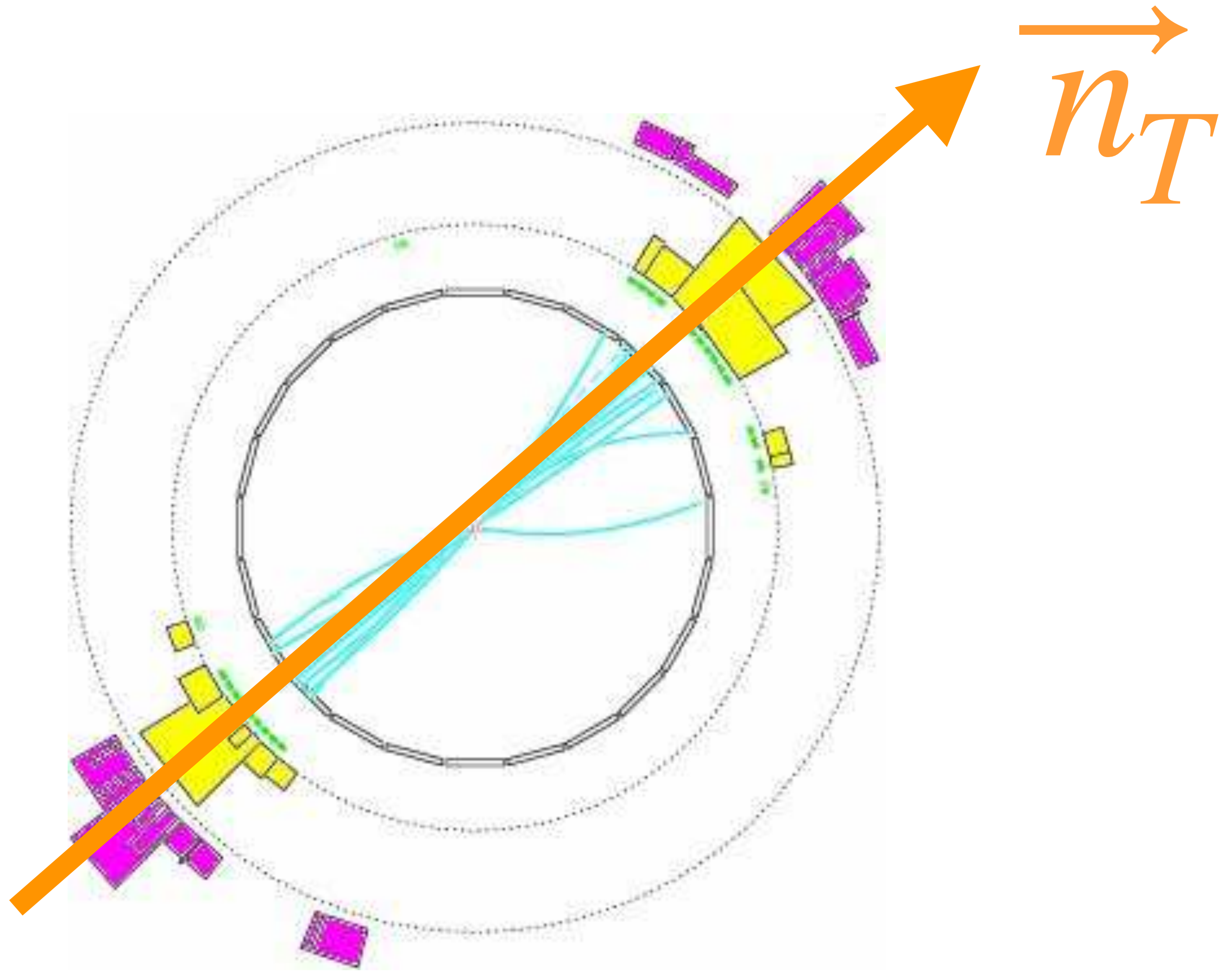


2-jet event: $T \simeq 1$

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

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

Catani, Trentadue, Turnock & Webber '93 → NLL

Becher & Schwartz '08 → N^{3}LL

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. $2 \to 3$) 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

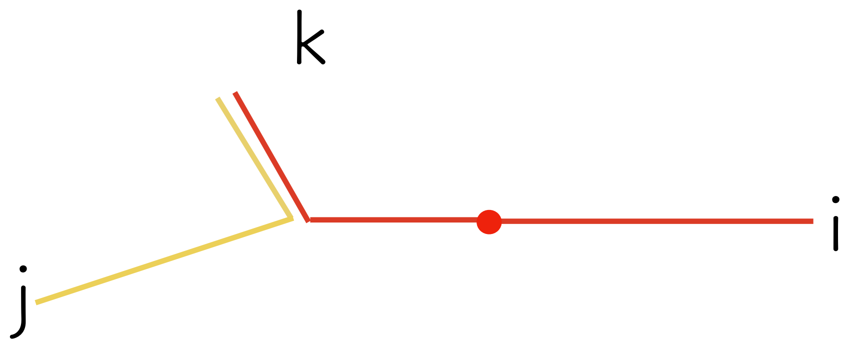
and they'll be limited to fixed order for simplicity
(though it's easy enough to generalise to an all-order study)

Matrix element for single emission: it's correct

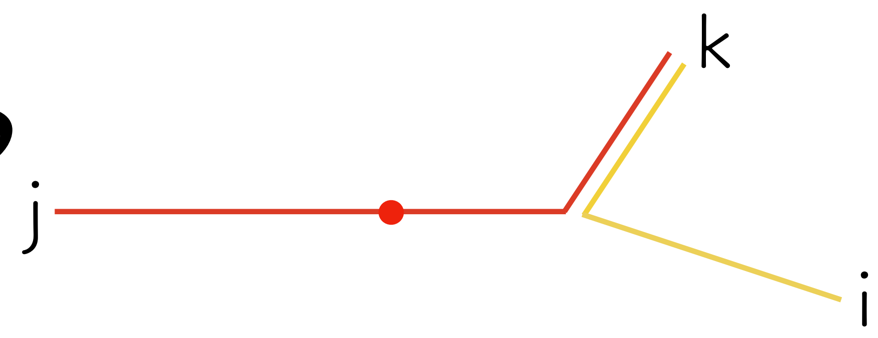
j emits, i spectates

i emits, j spectates

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



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



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

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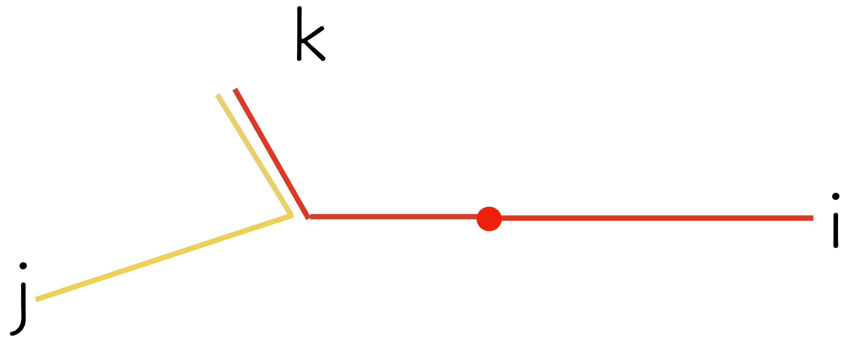

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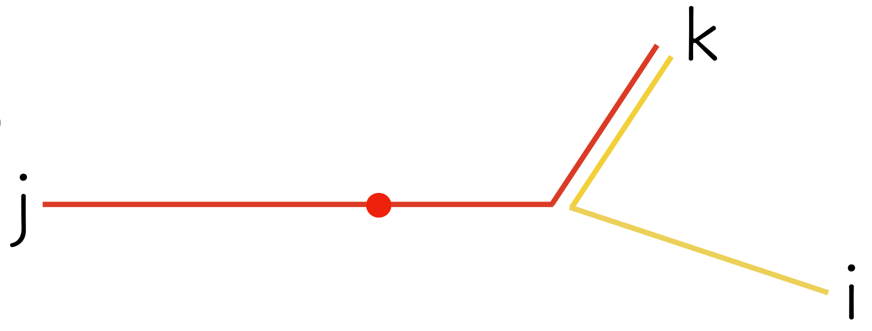

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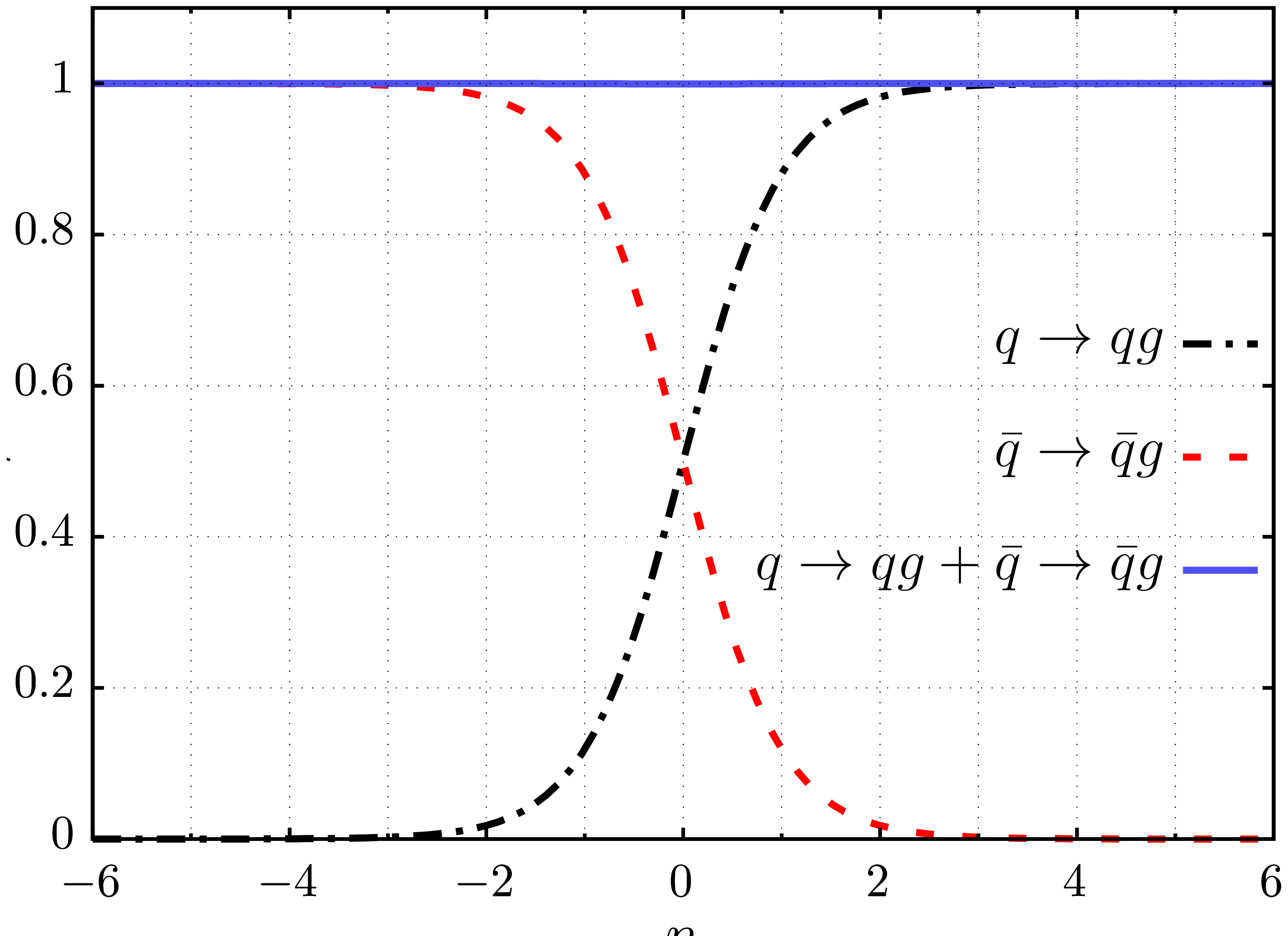
ratio to full matrix element



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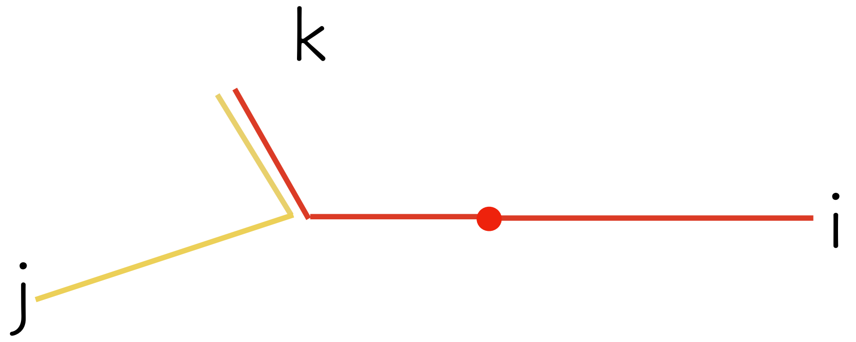

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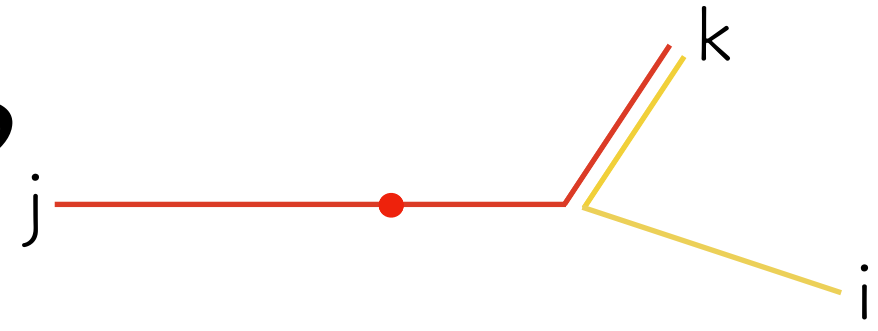

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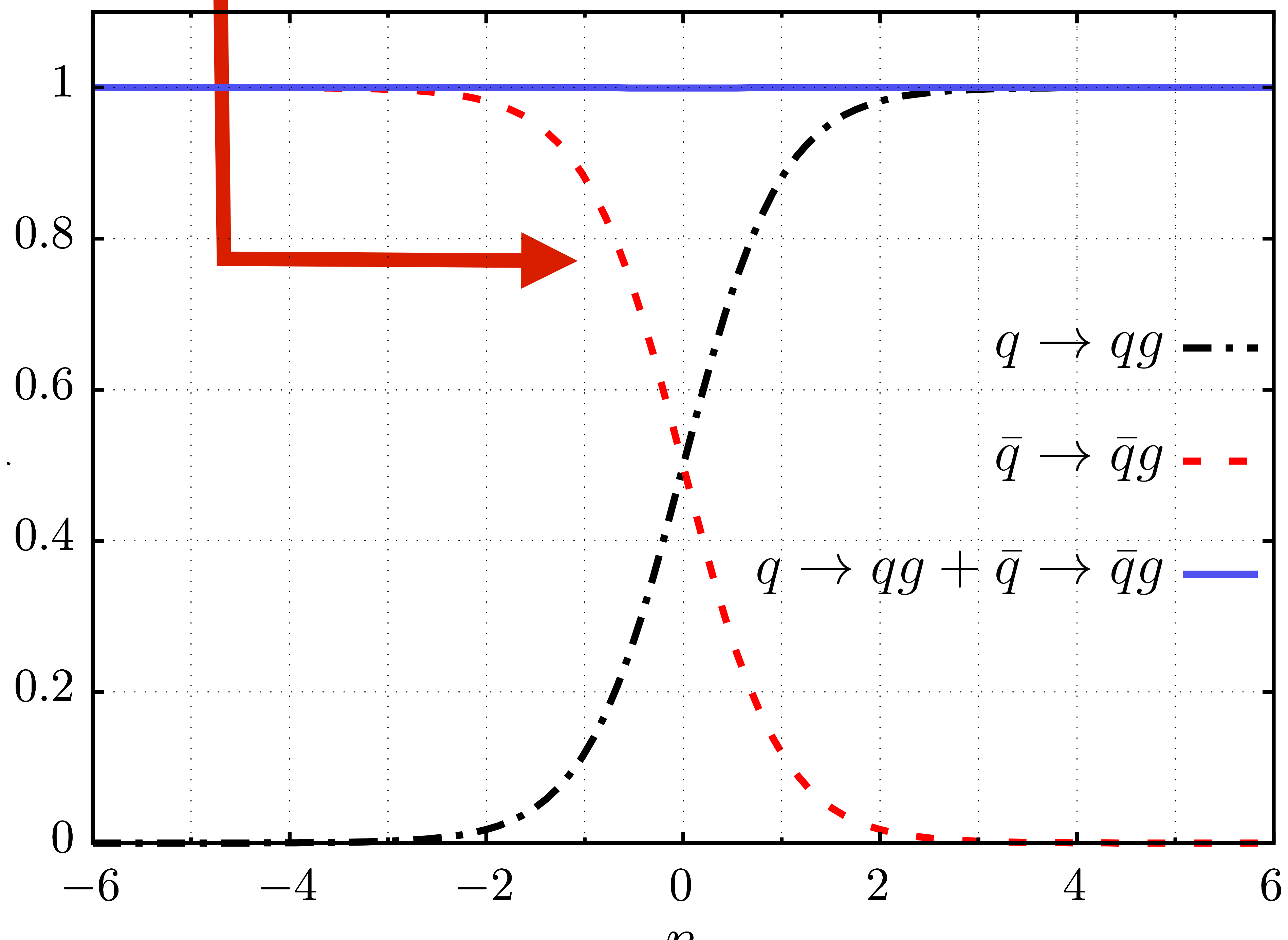

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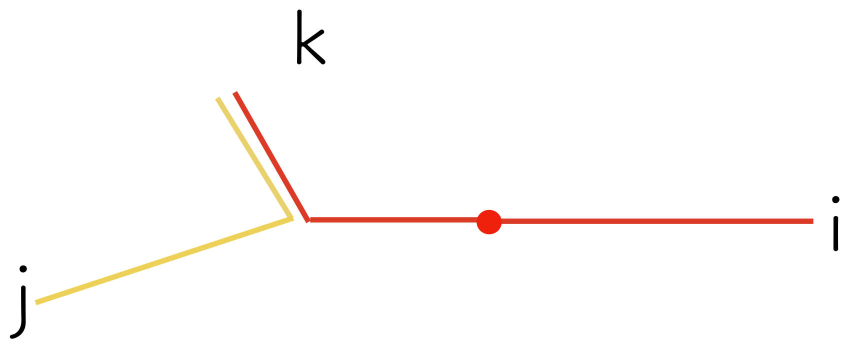

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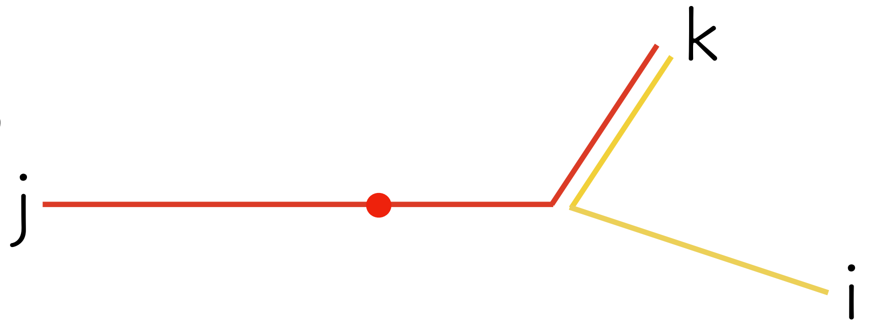

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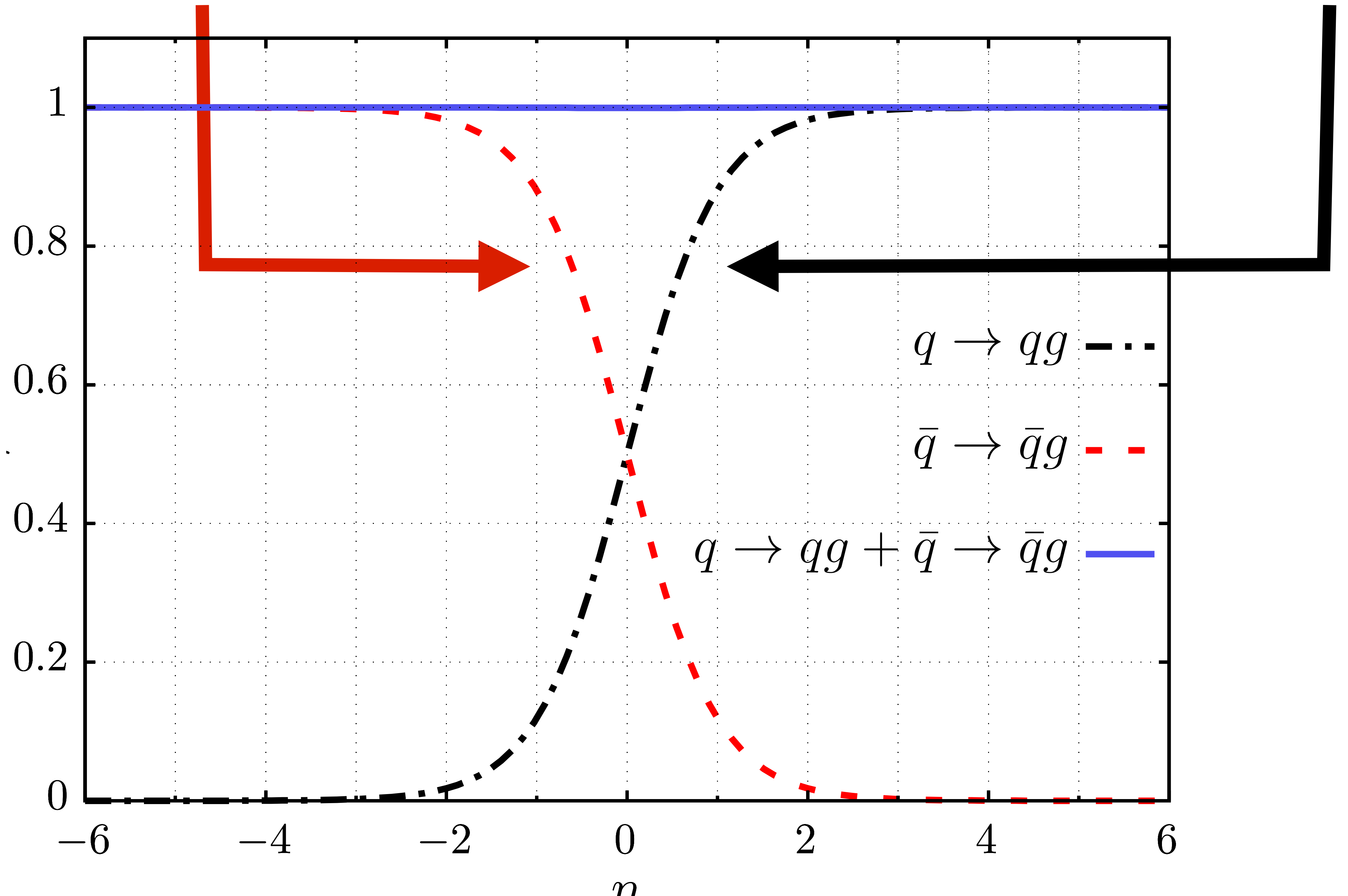

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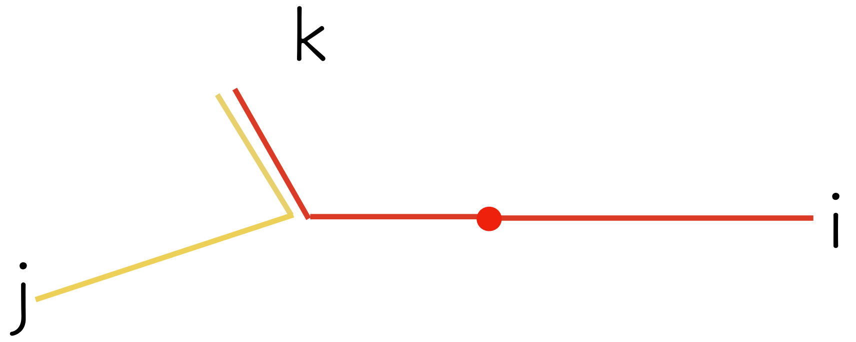
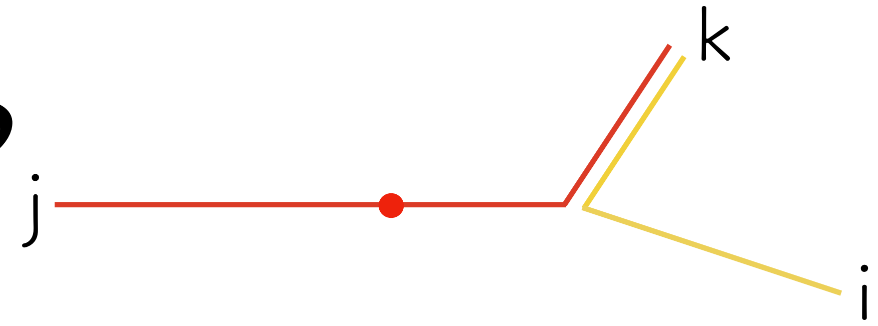
$$d\mathcal{P}_{\tilde{i}\tilde{j}\to ikj} = d\mathcal{P}$$  $$+ \; d\mathcal{P}$$ 

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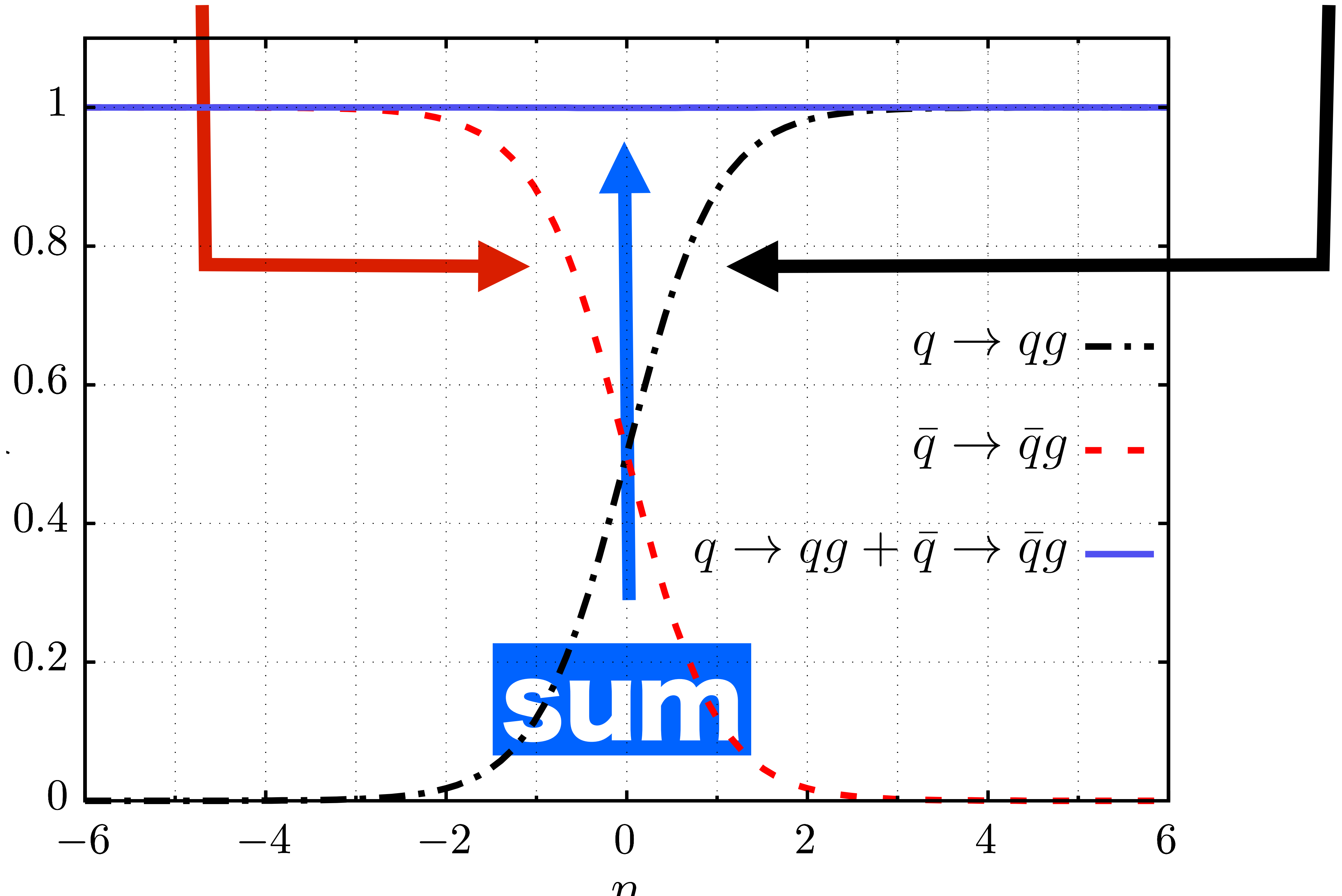
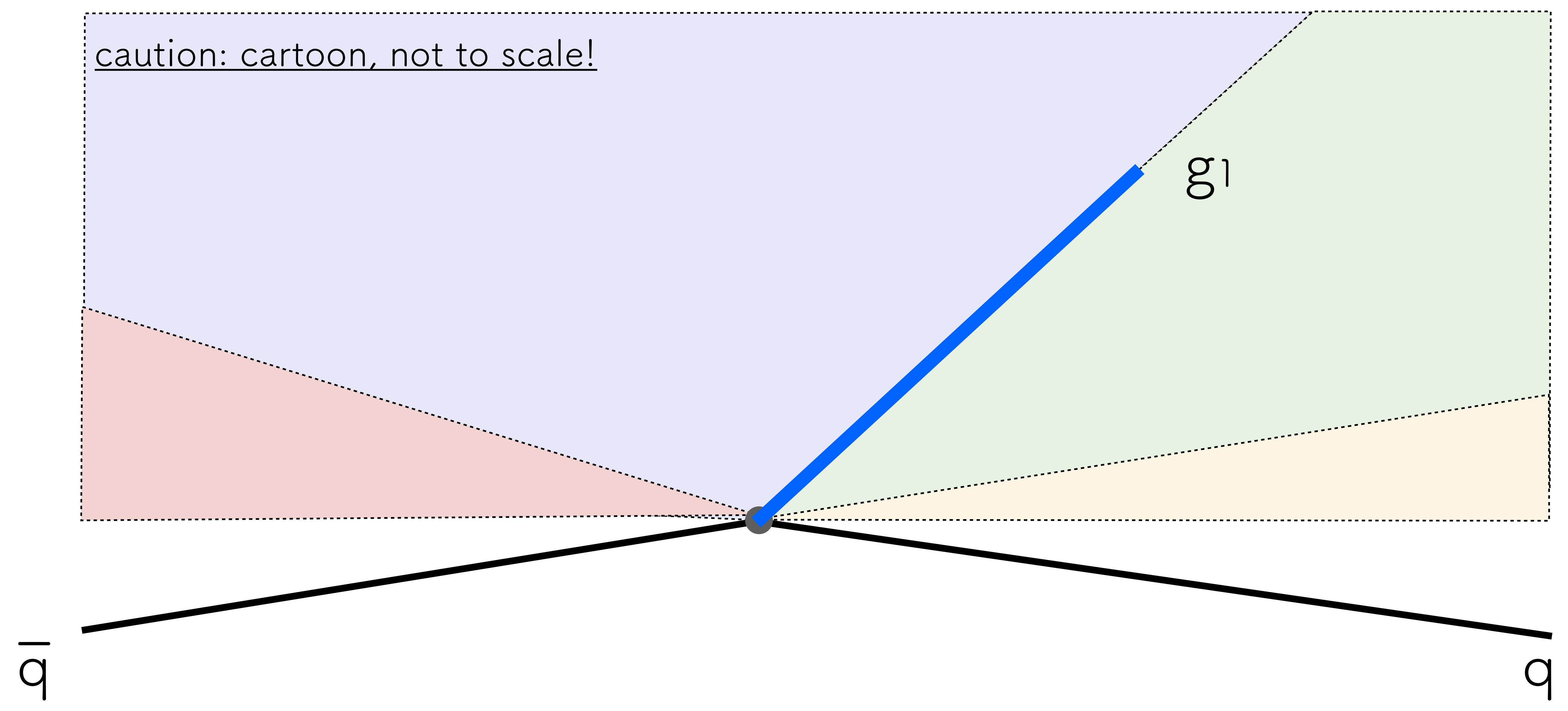


Two emissions



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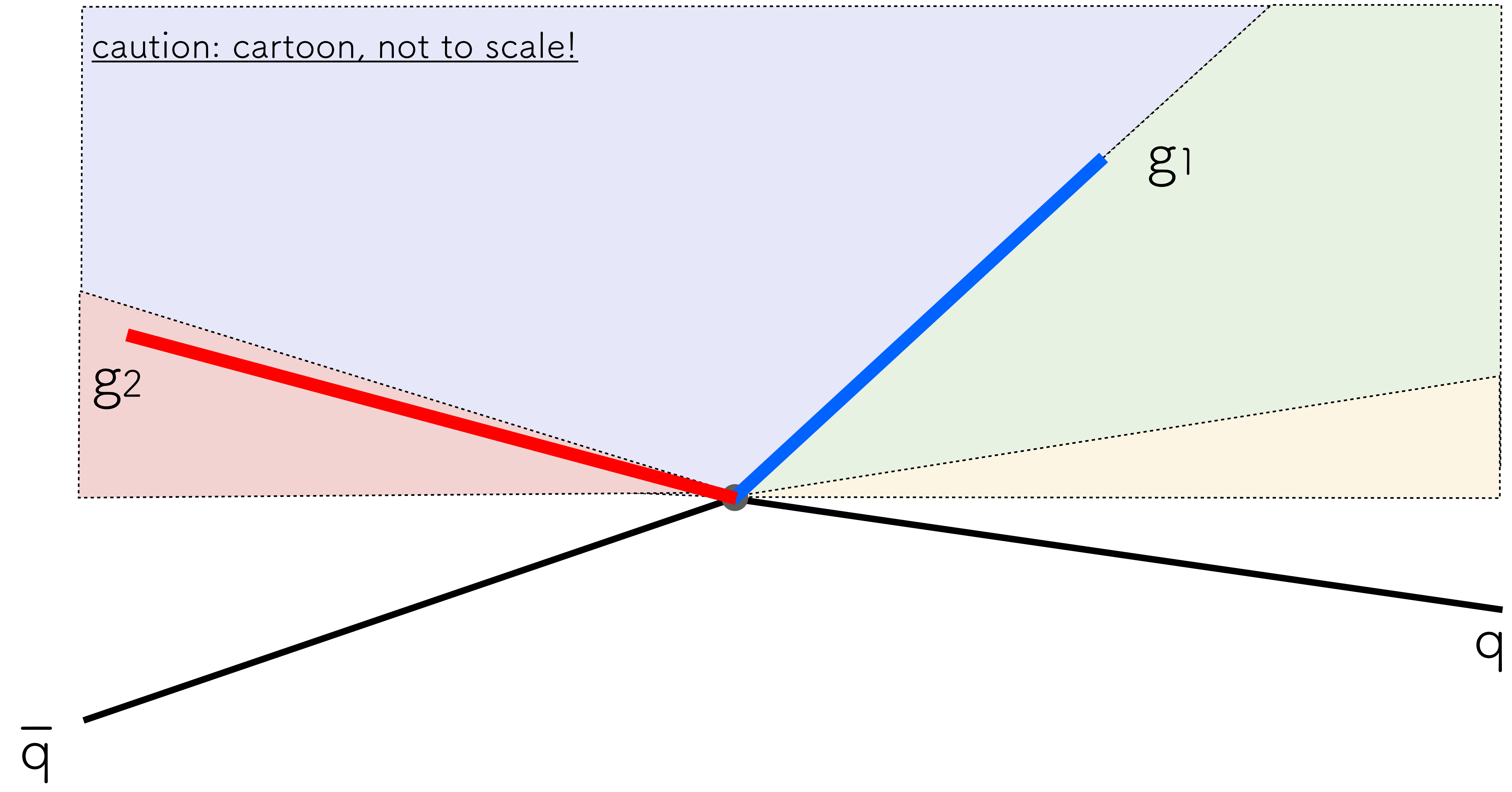
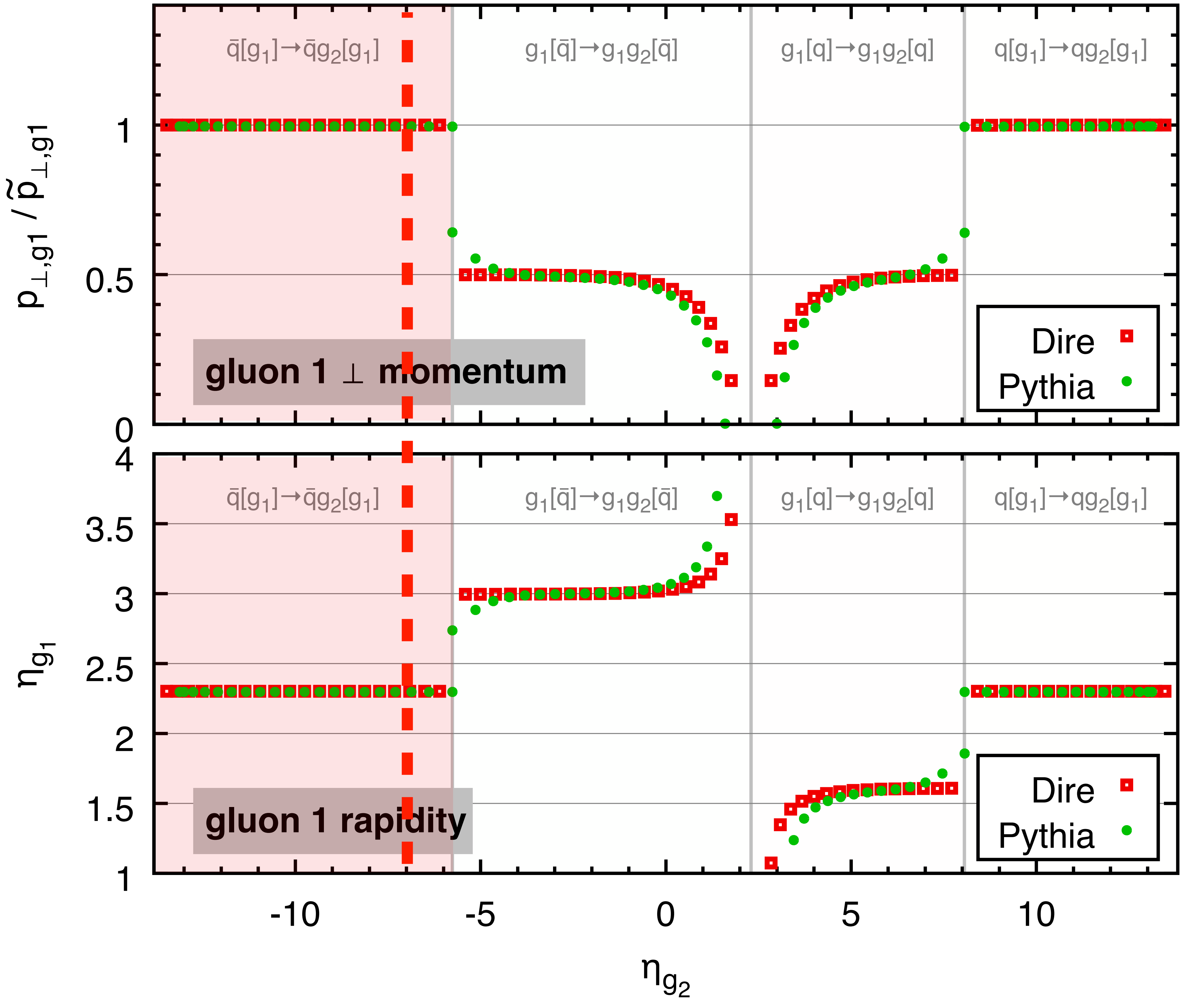


impact of gluon-2 emission on gluon-1 momentum



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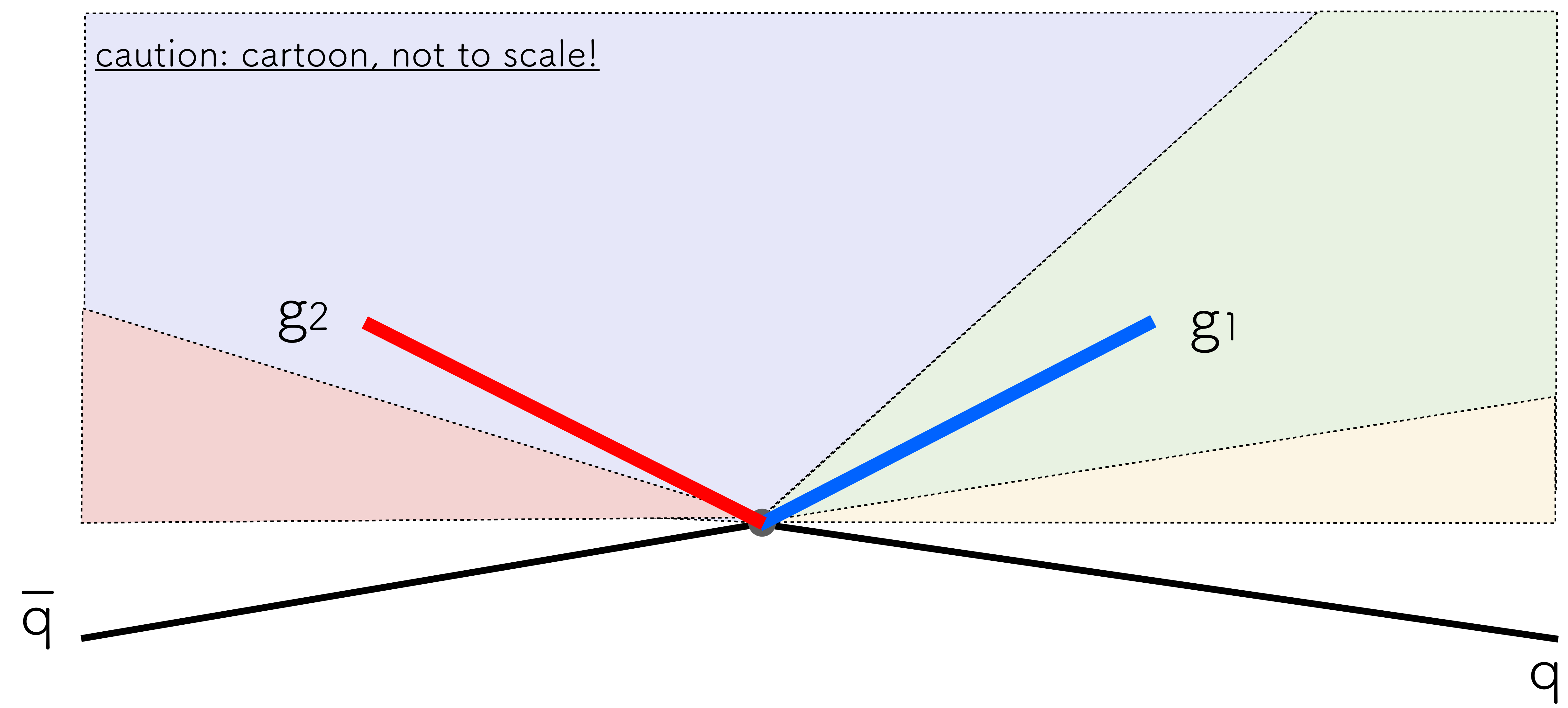

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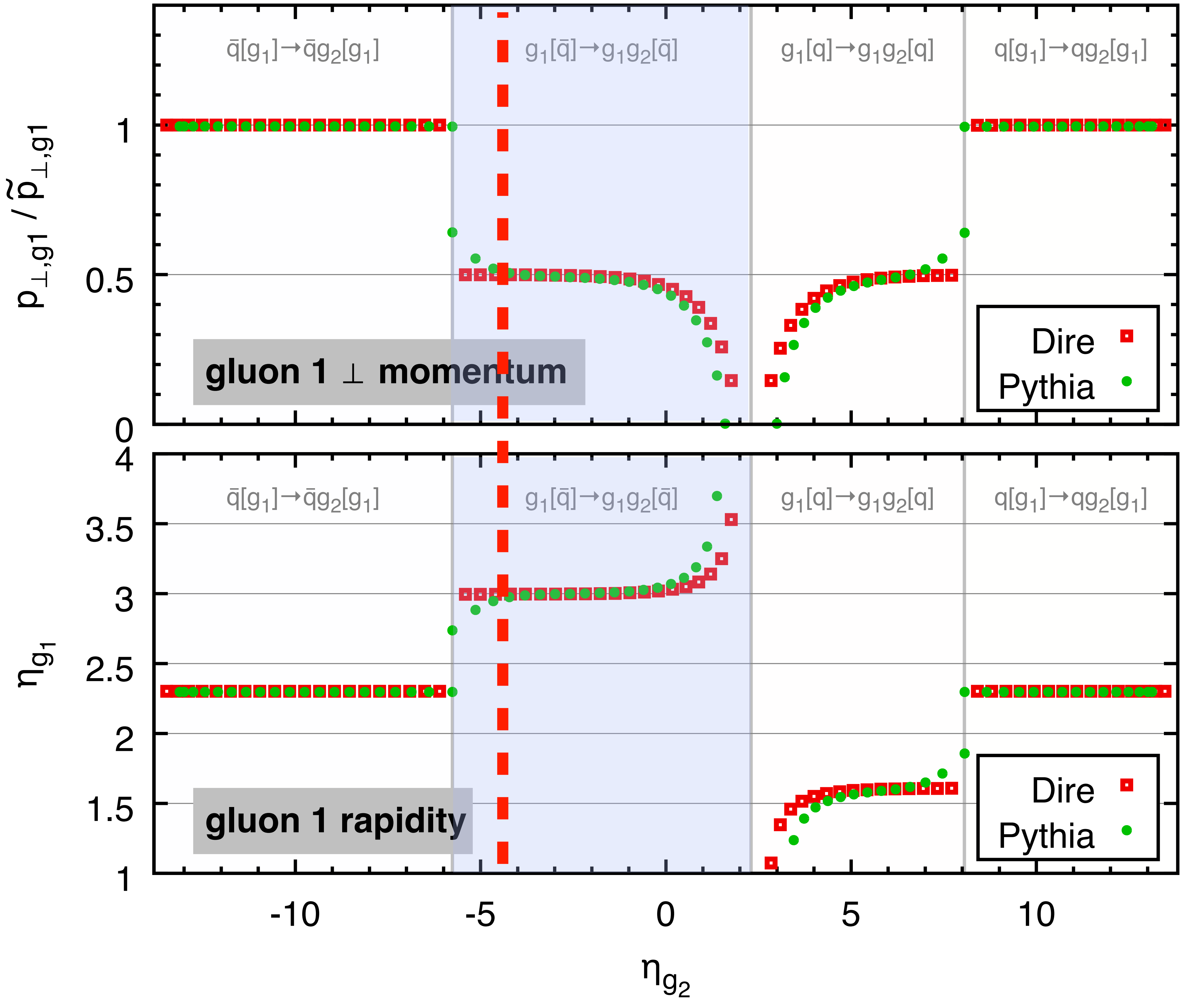

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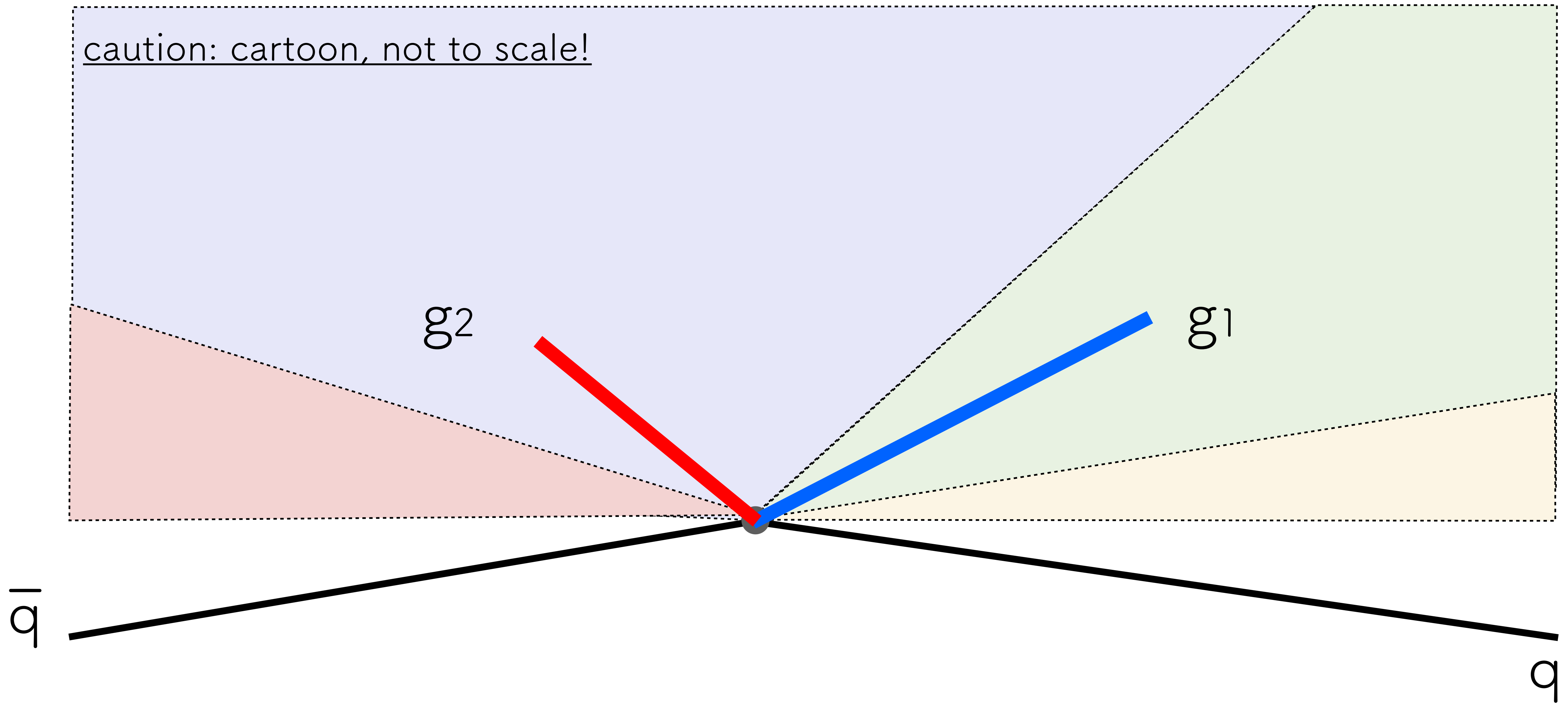

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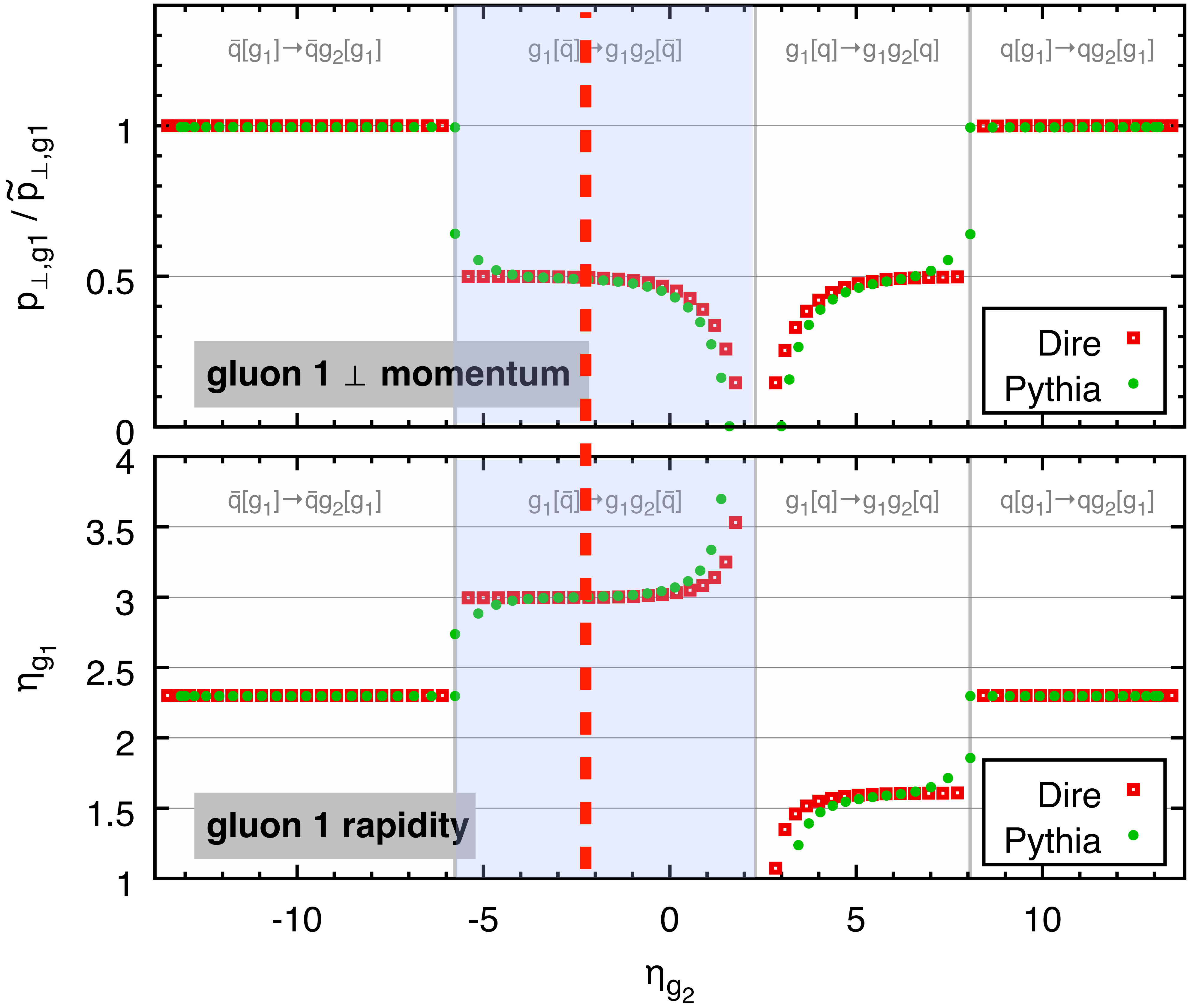

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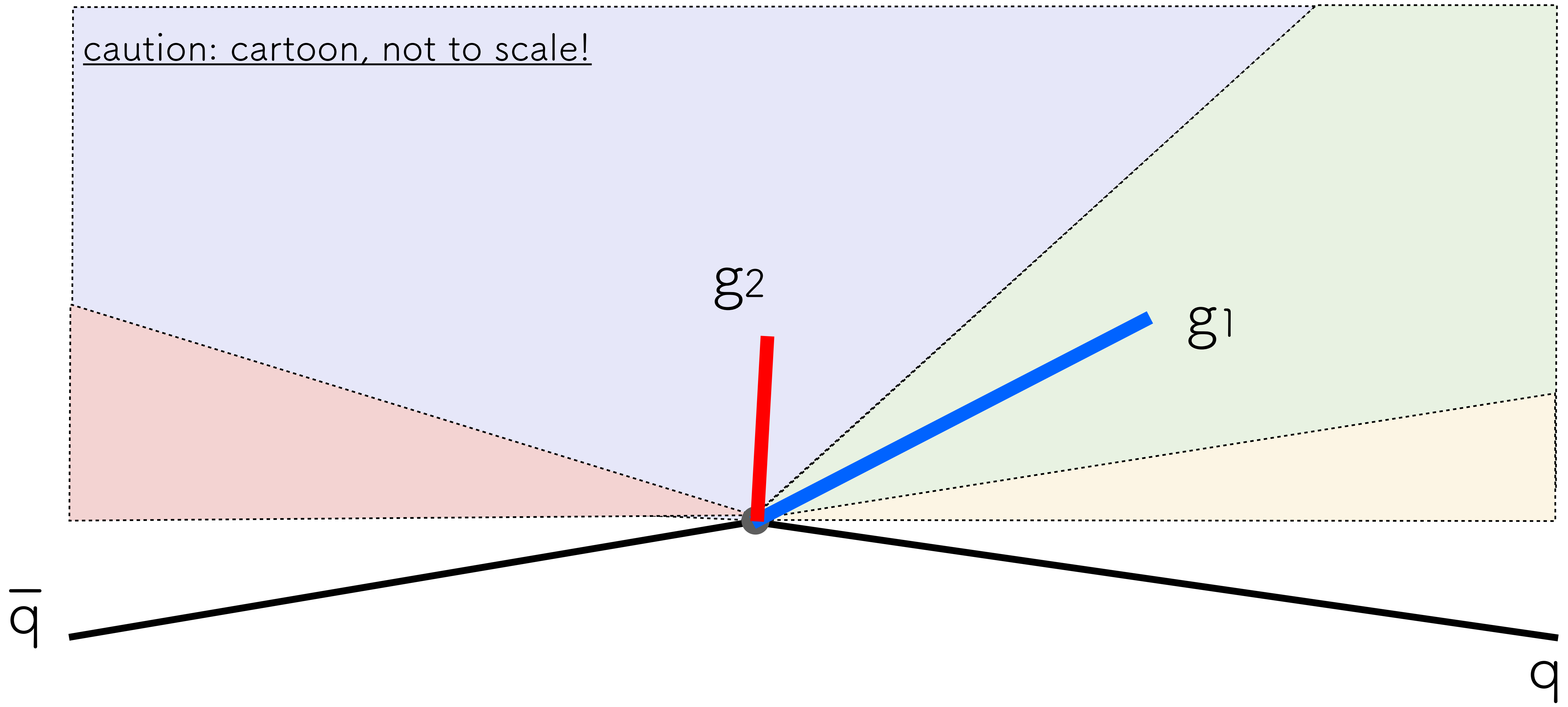

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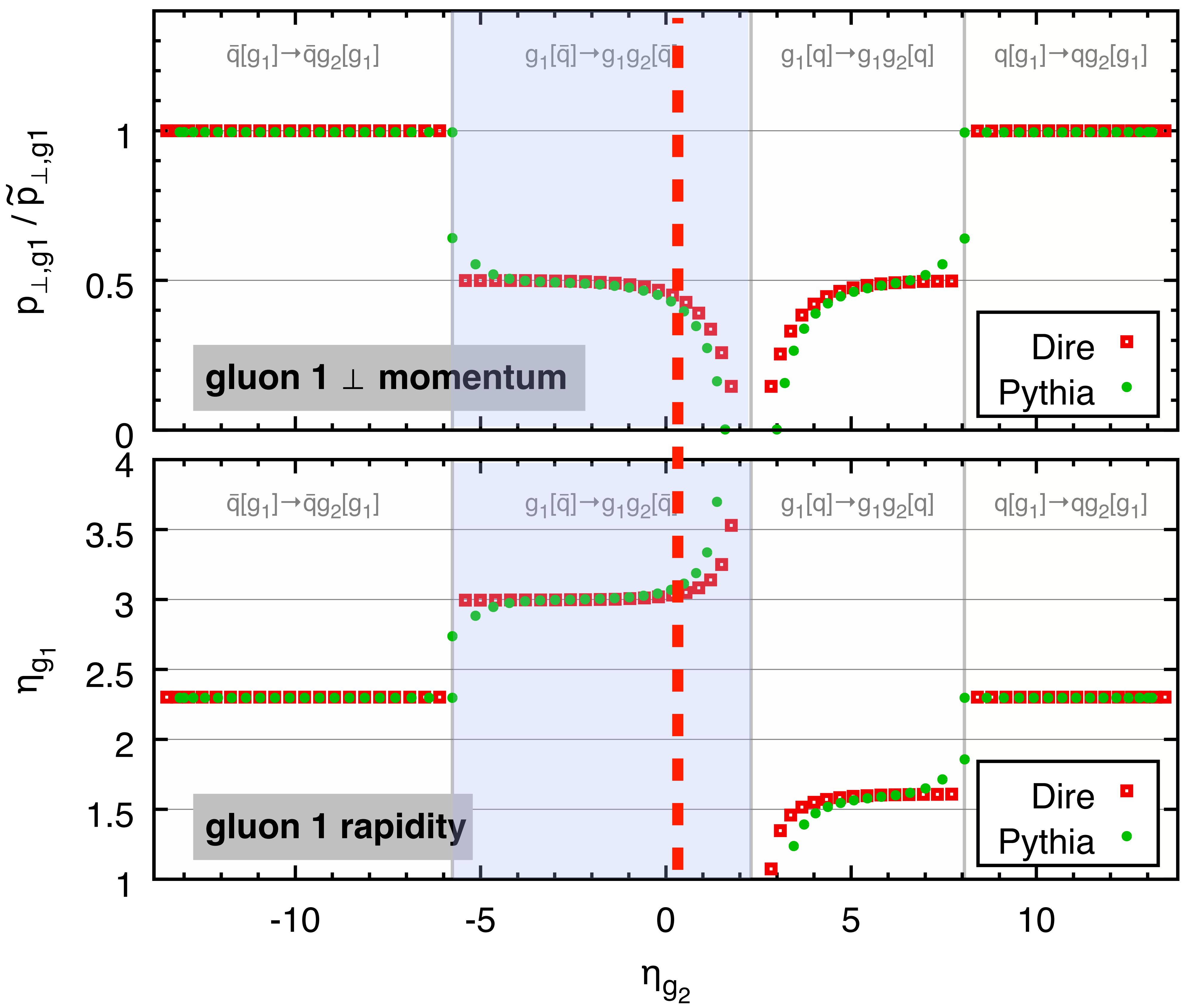

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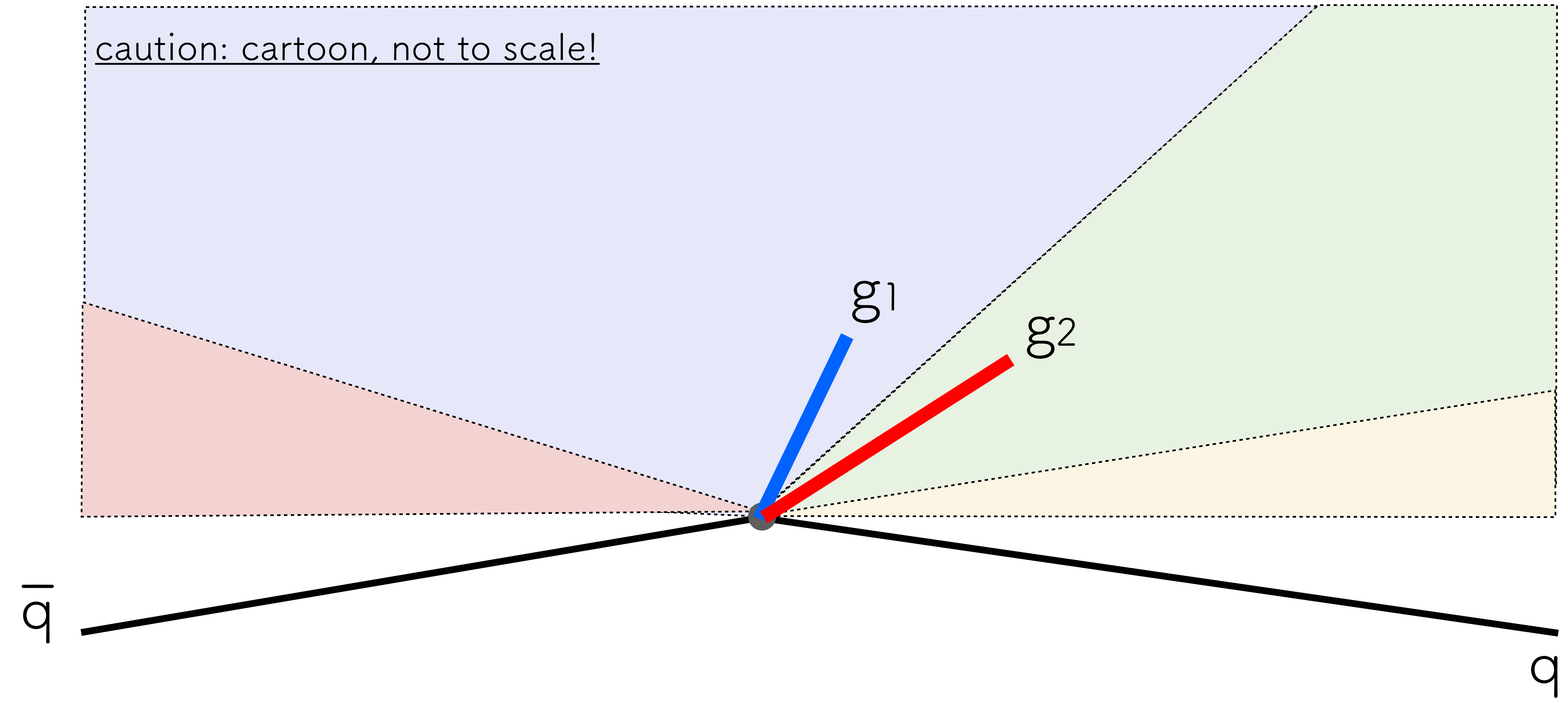

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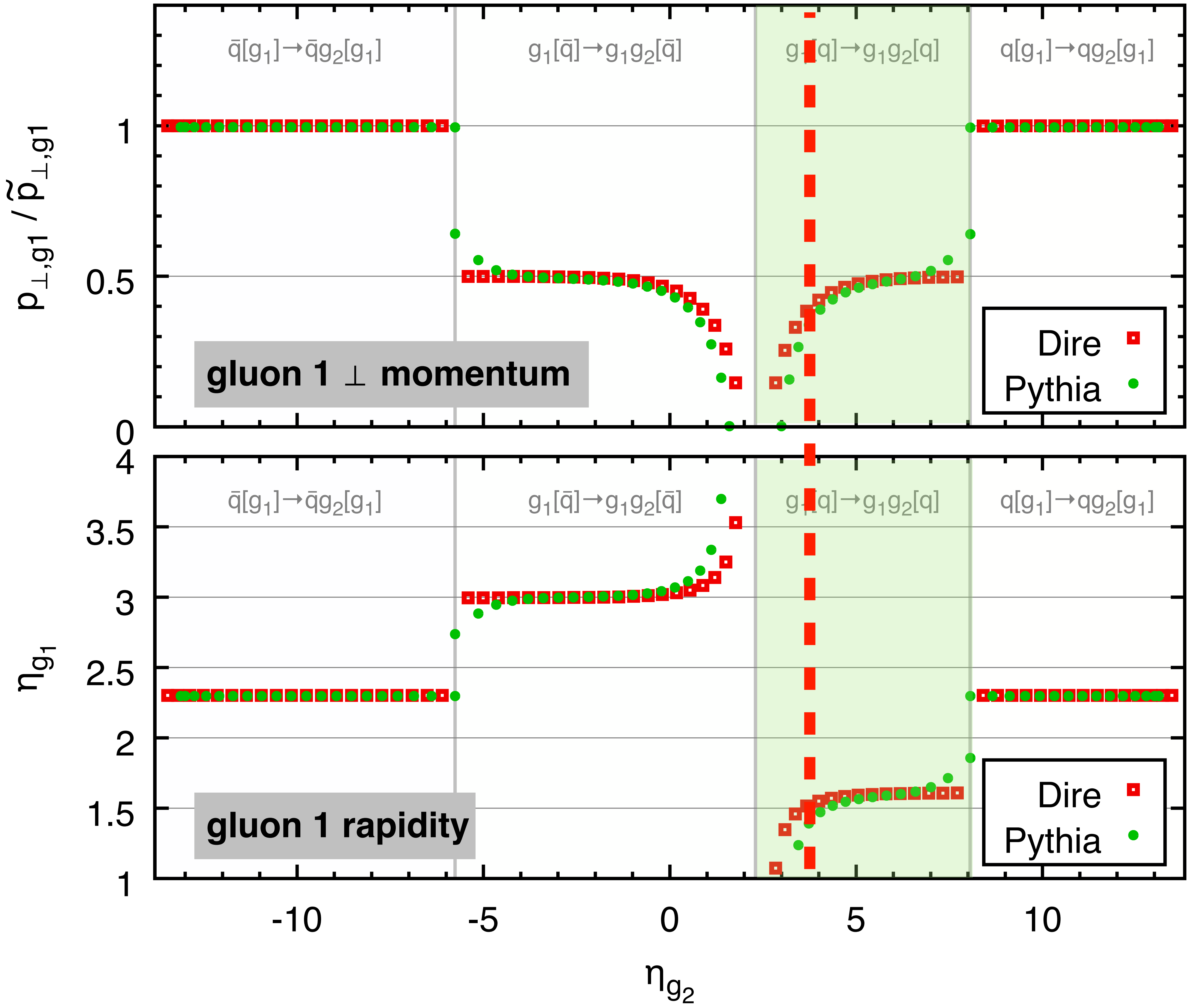

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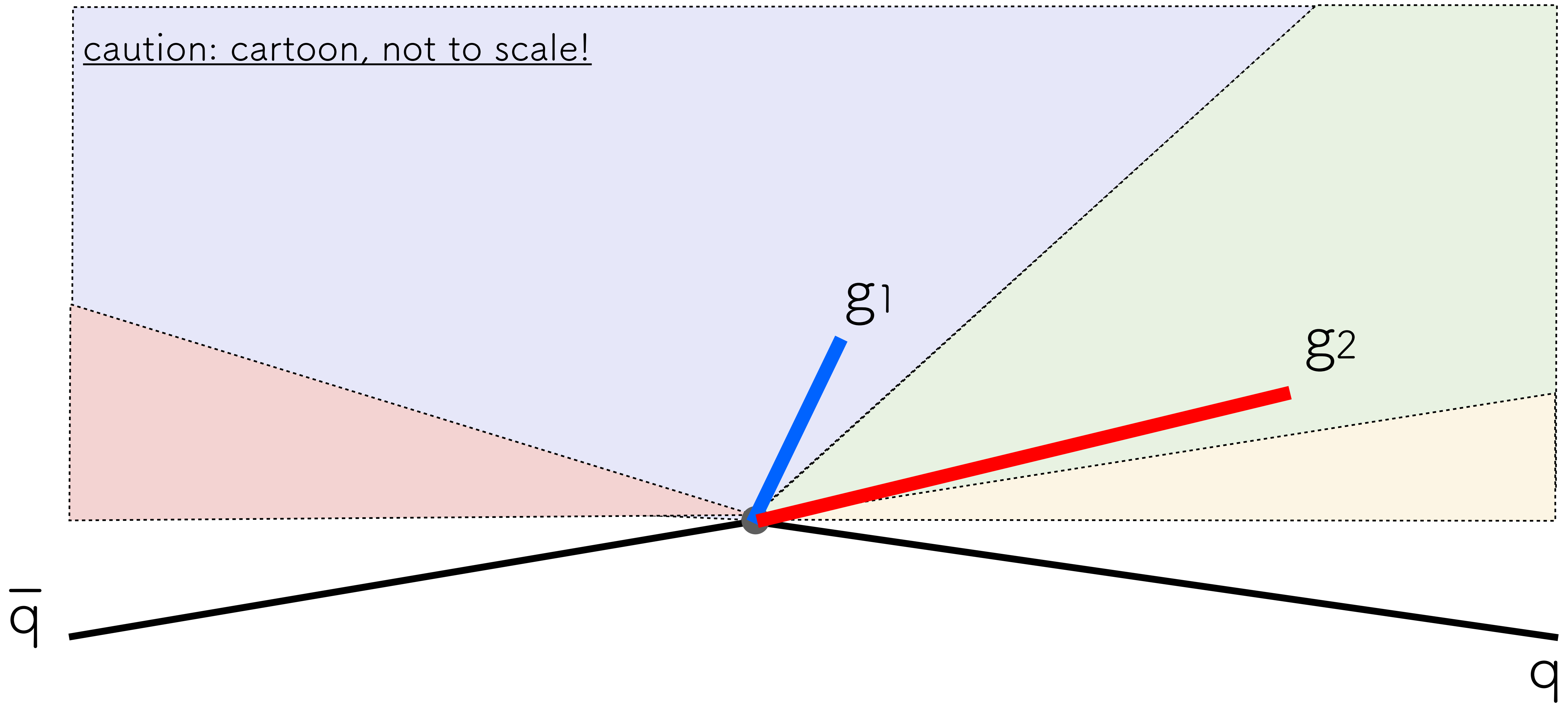

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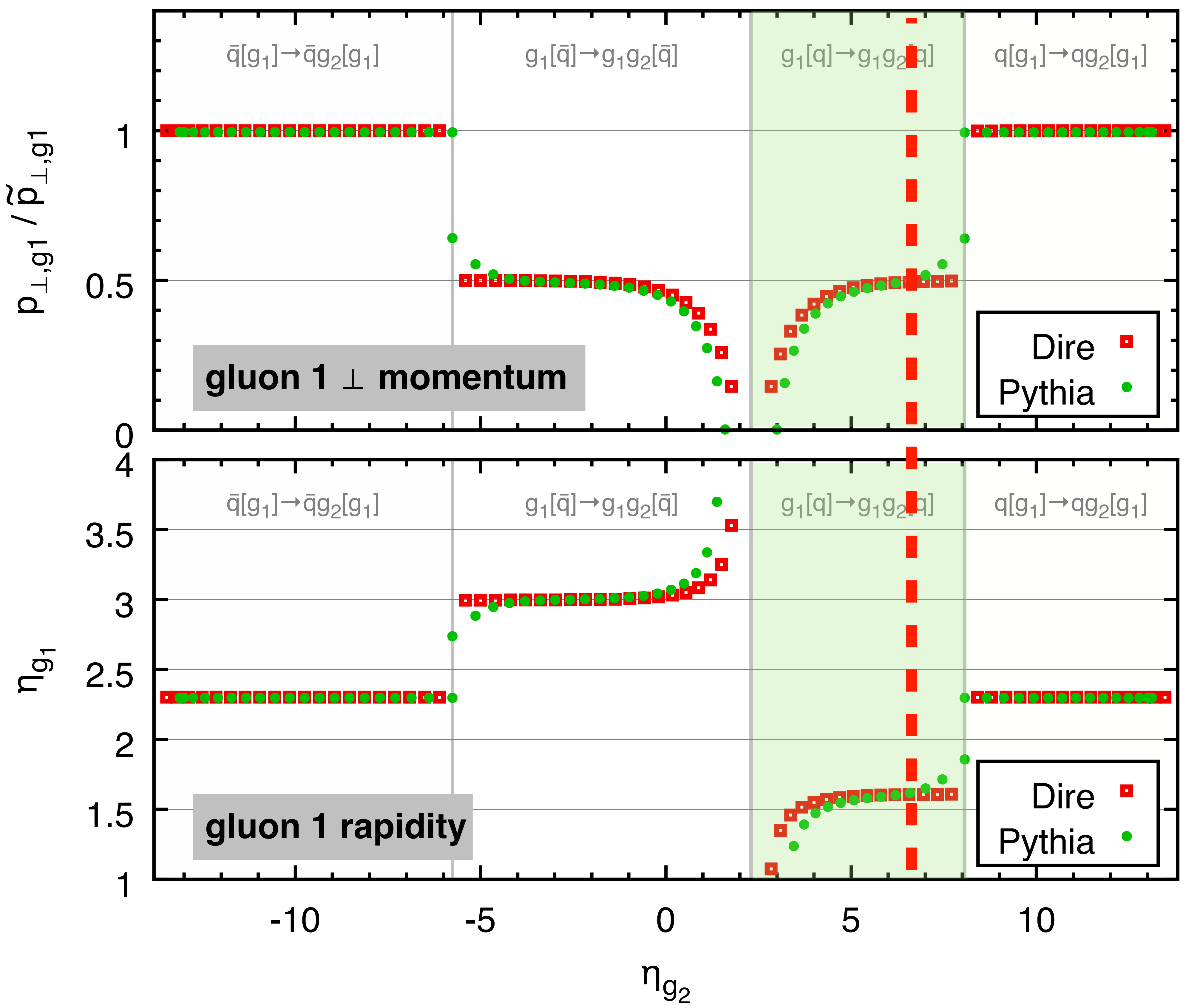

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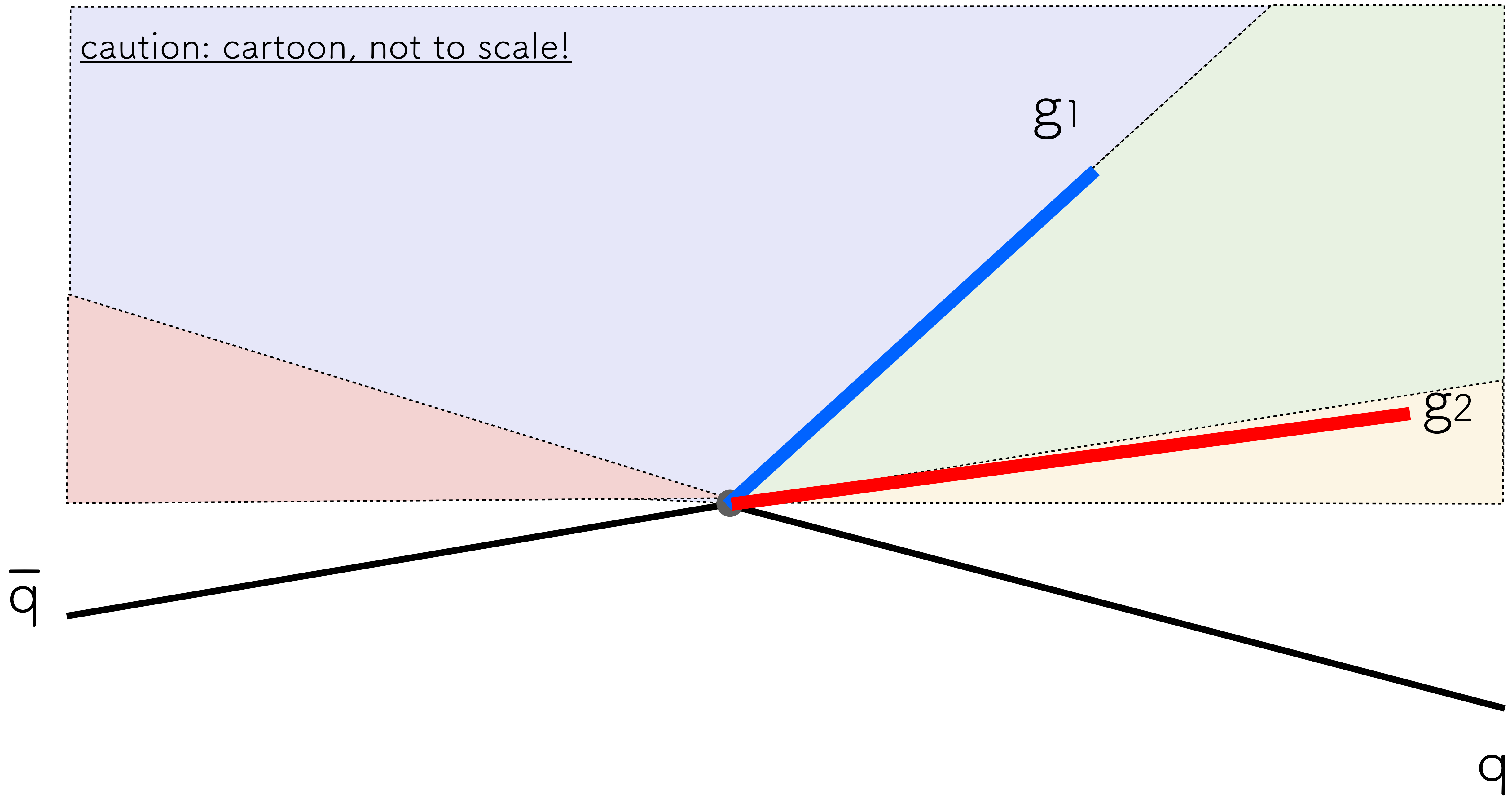

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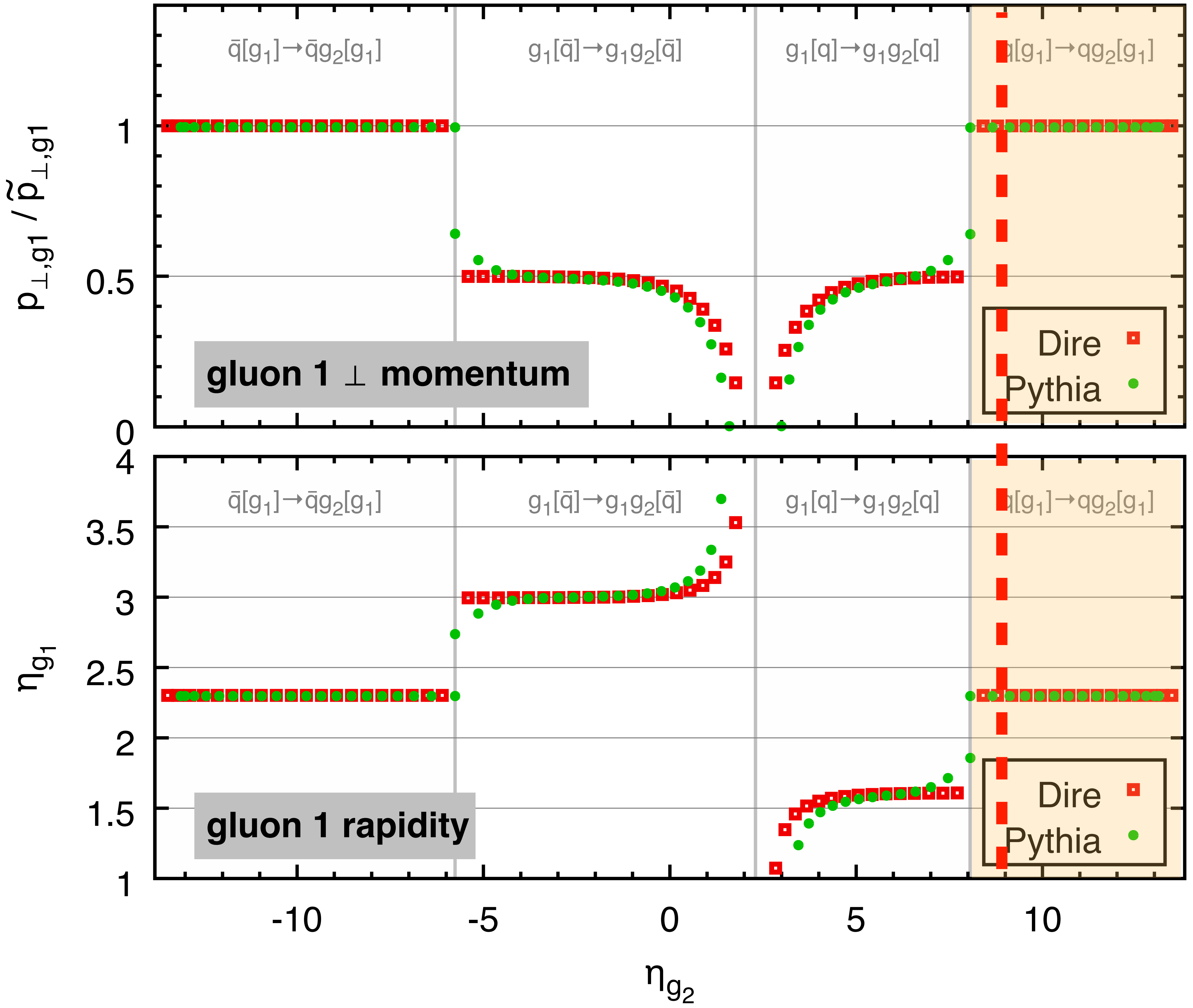

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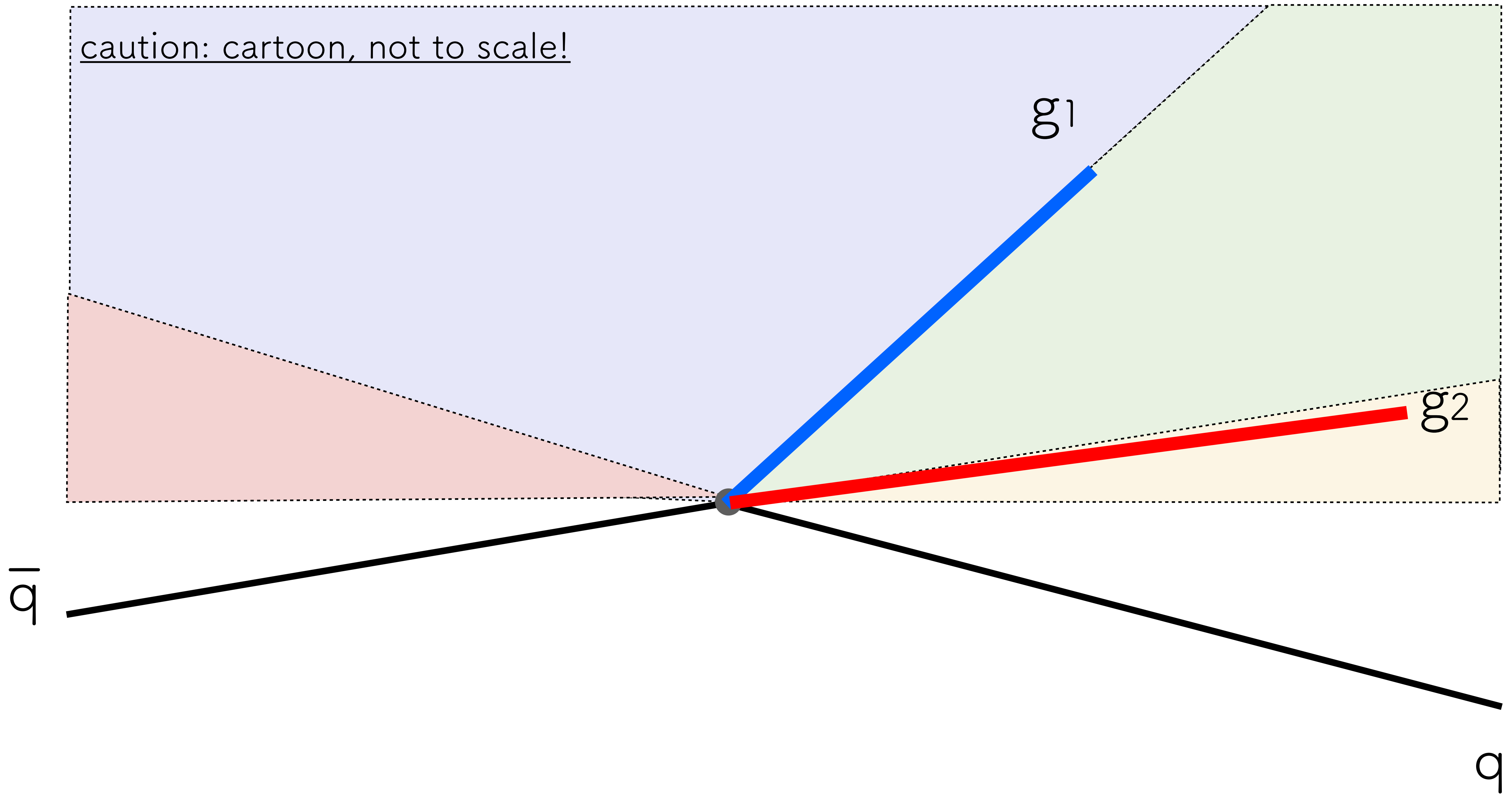

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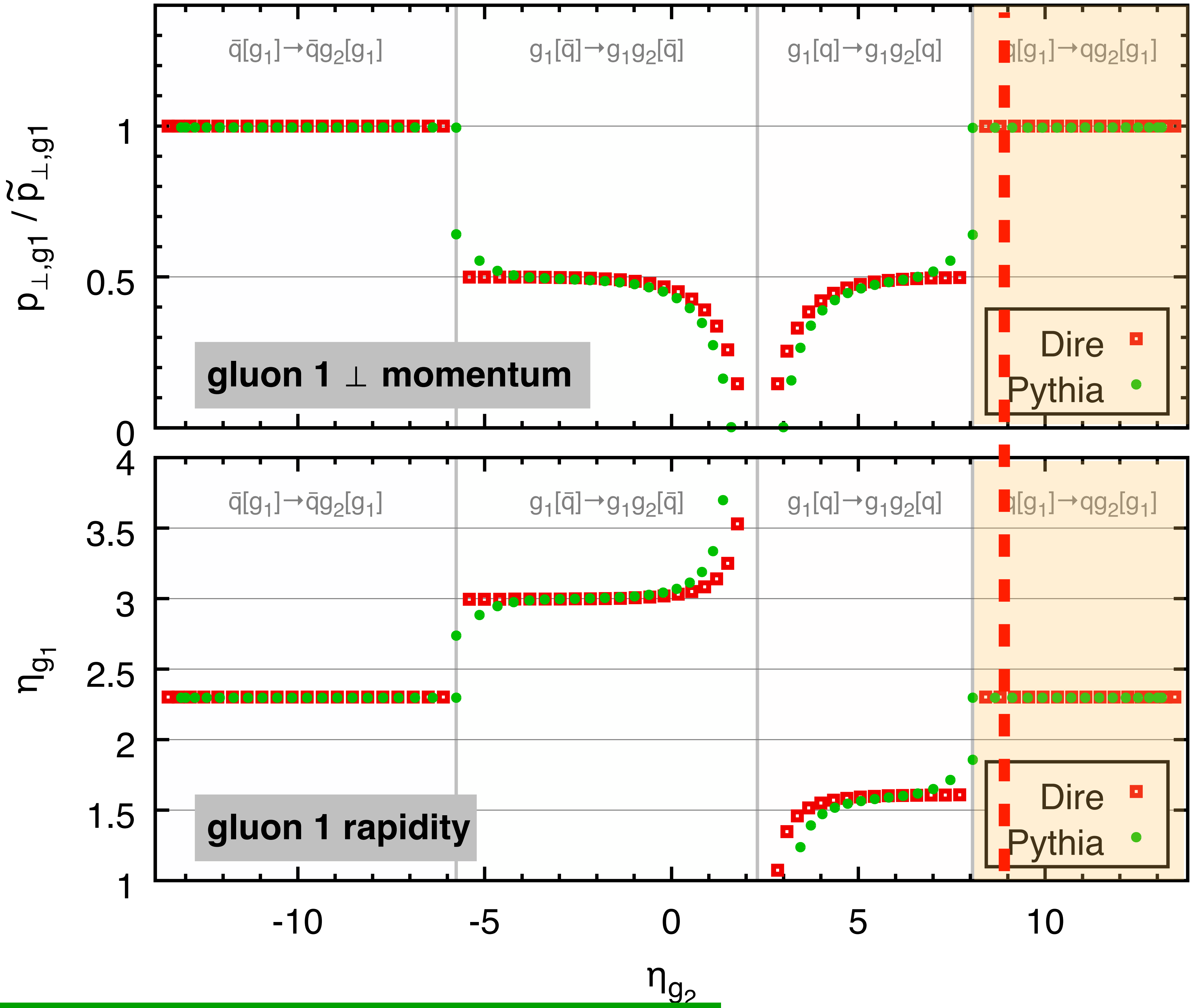


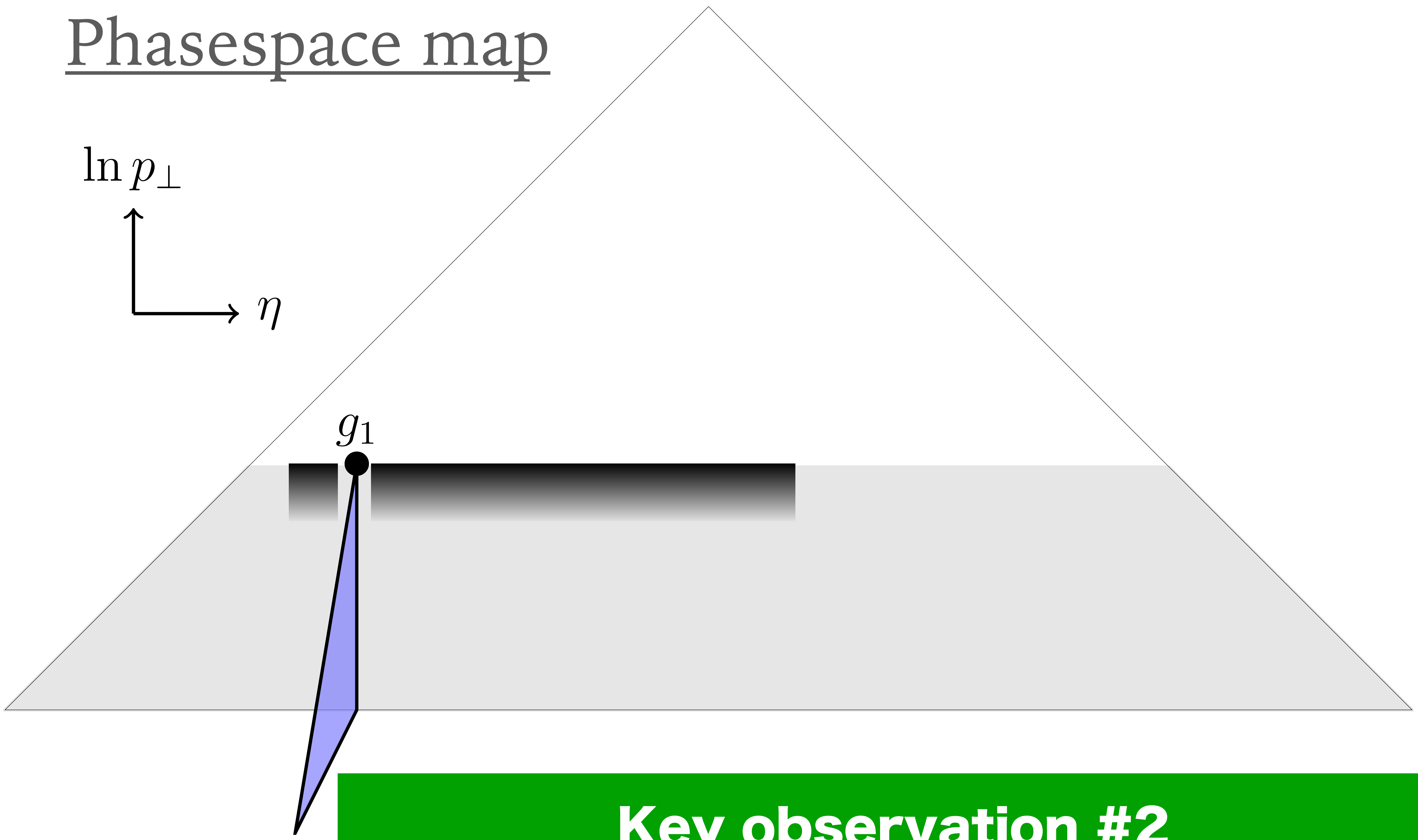
Key observation #1

highly non-trivial cross talk between emissions

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

Two emissions matrix-element

Phasespace map

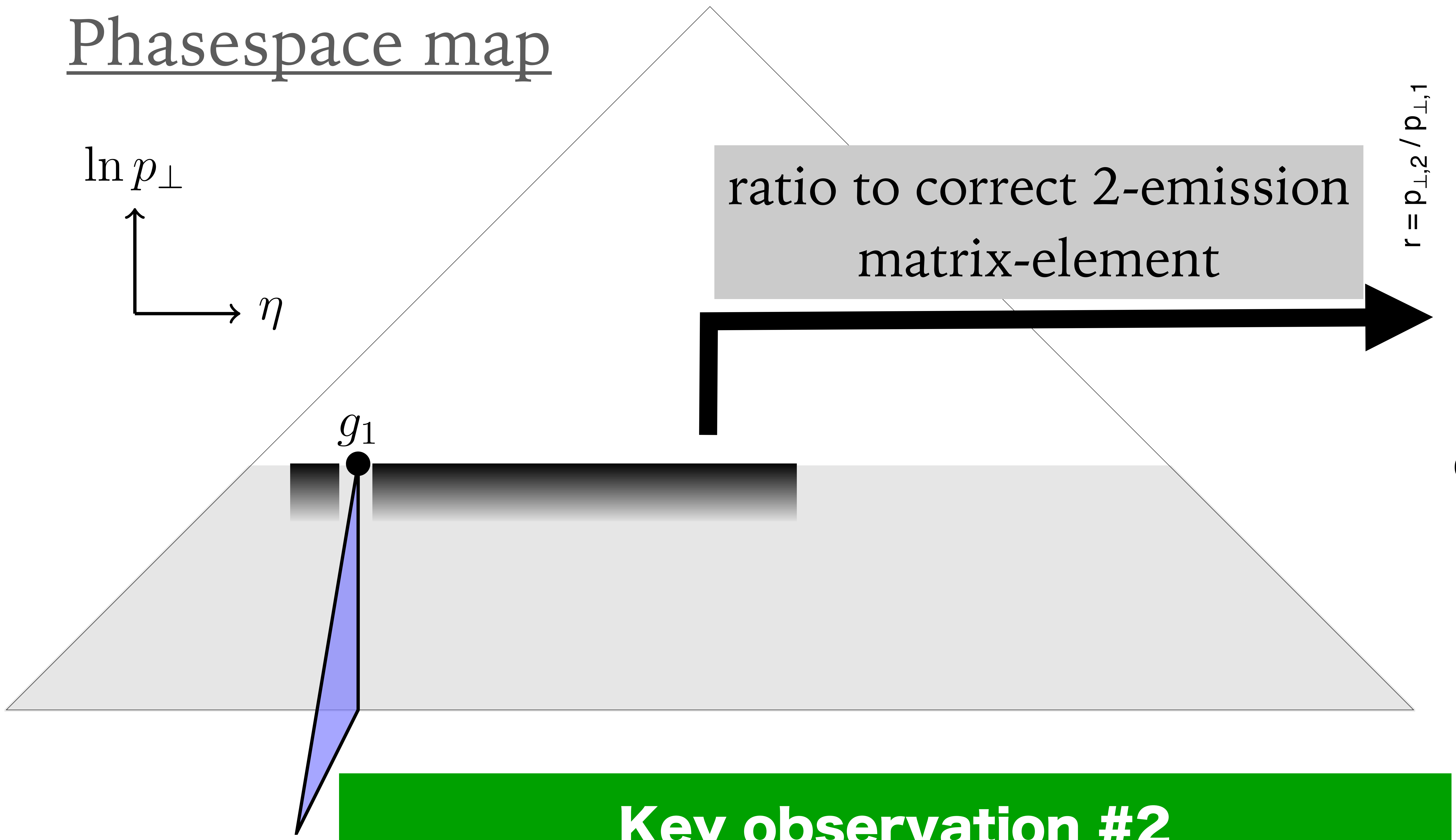


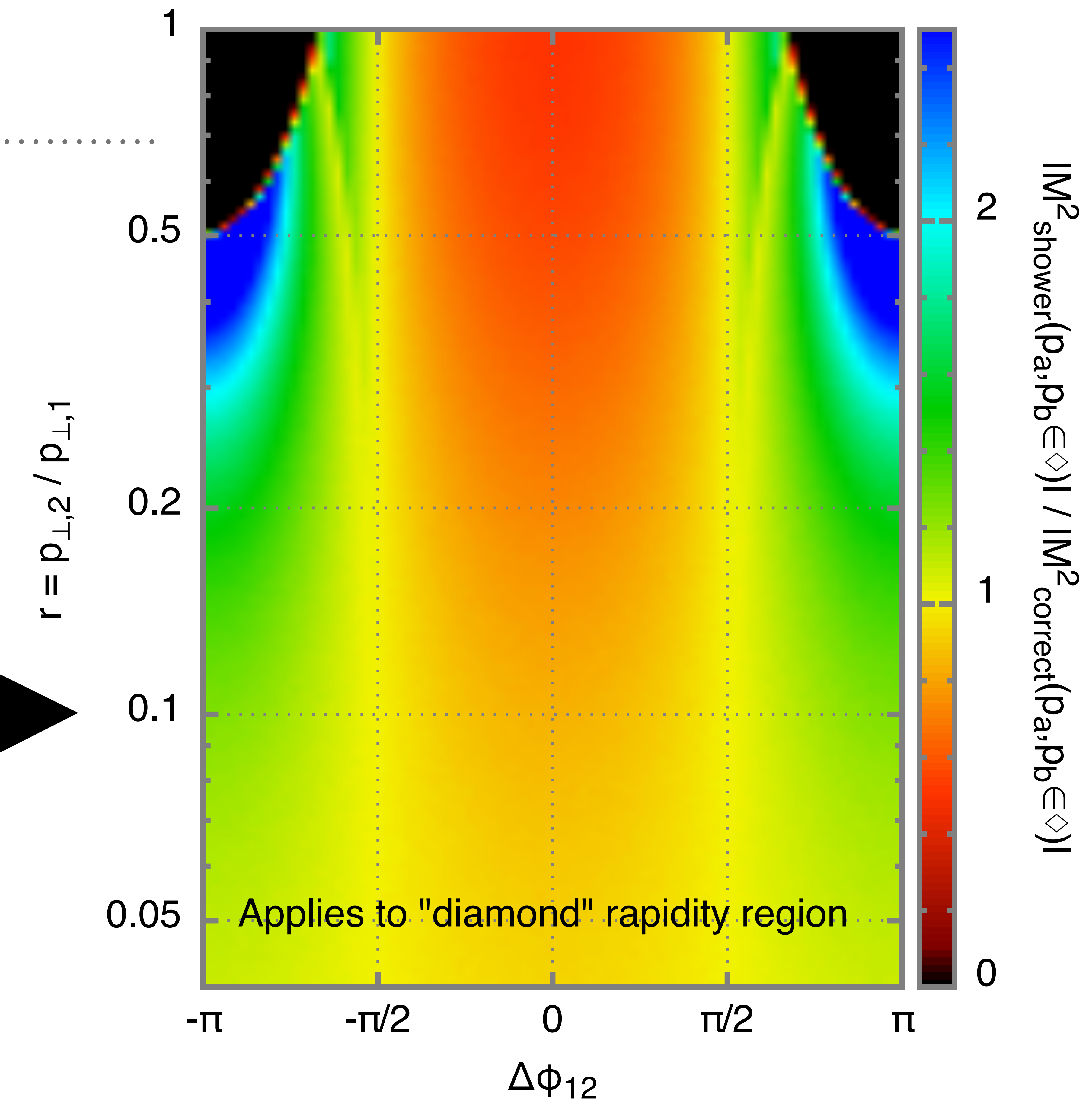
Key observation #2

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





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	$\mathrm{NLL}_{\ln\Sigma}$ 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.

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

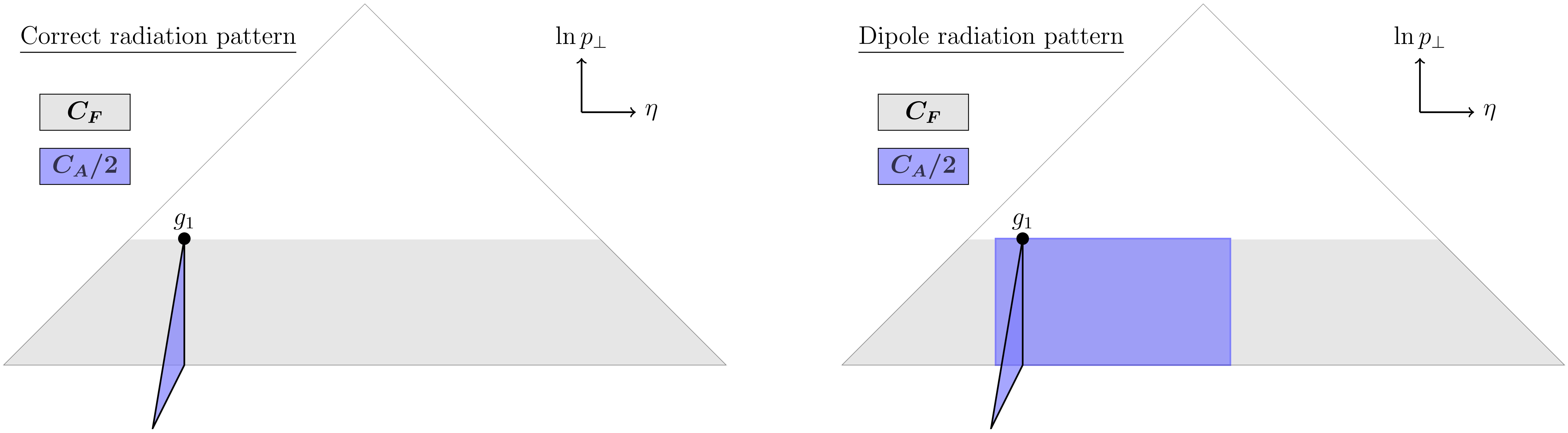
(because all these observables are quite inclusive)

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)

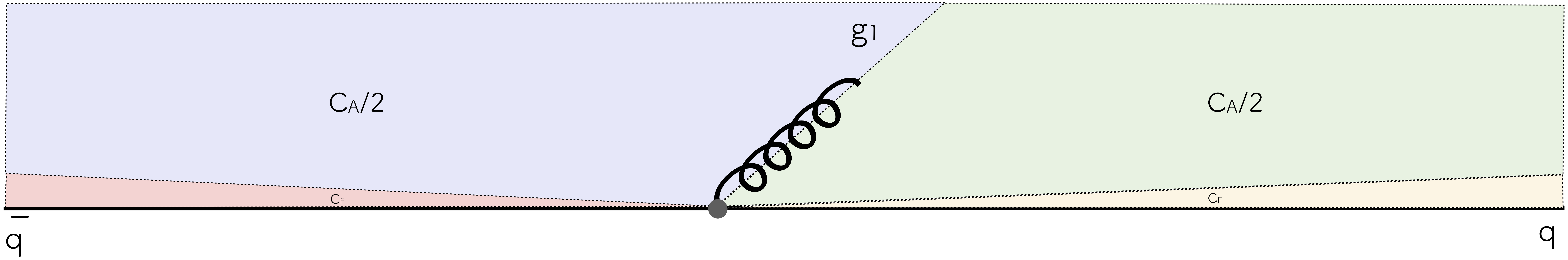


Key observation #3

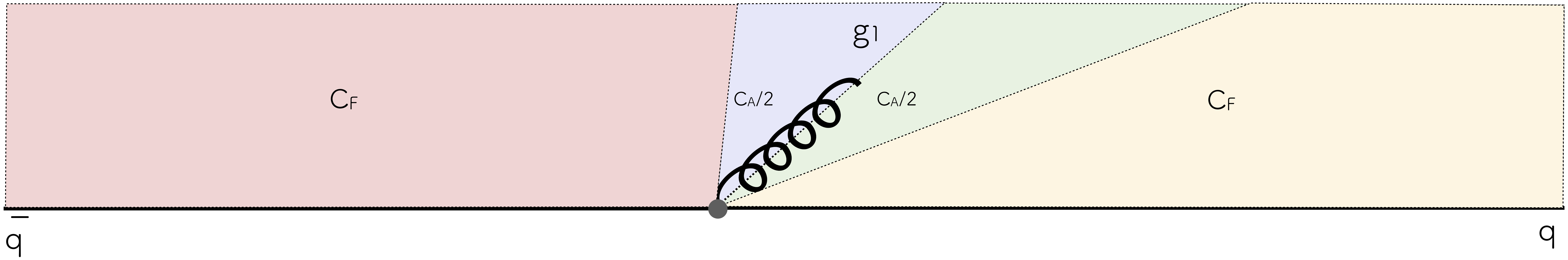
C_F v. $C_A/2$ issues occurs over a large area → double (leading) log effects?

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

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

closing

Conclusions

Parton showers are a crucial element in collider physics

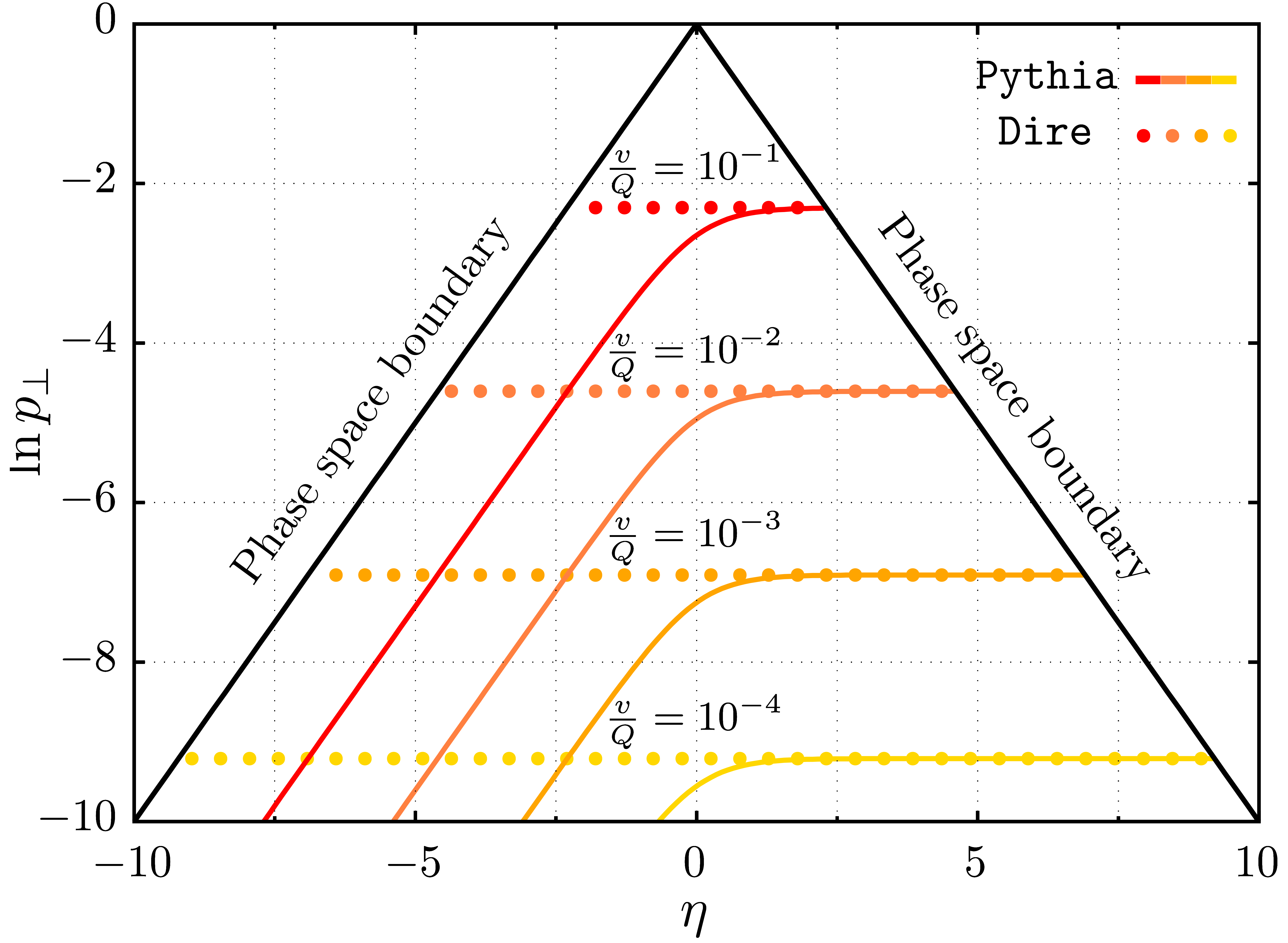
Seeing many developments (subleading colour for non-global logarithms, multi-particle emission kernels, etc.)

<u>But maybe we need to go back to foundations:</u>

- ➤ 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

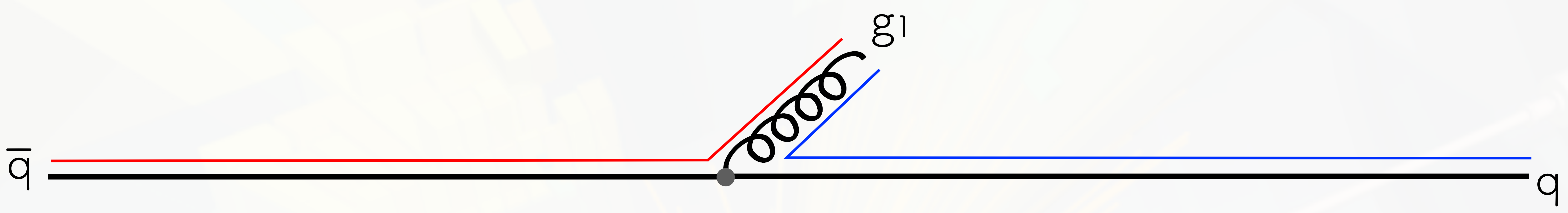
BACKUP

Constant evolution variable contours in the Lund plane

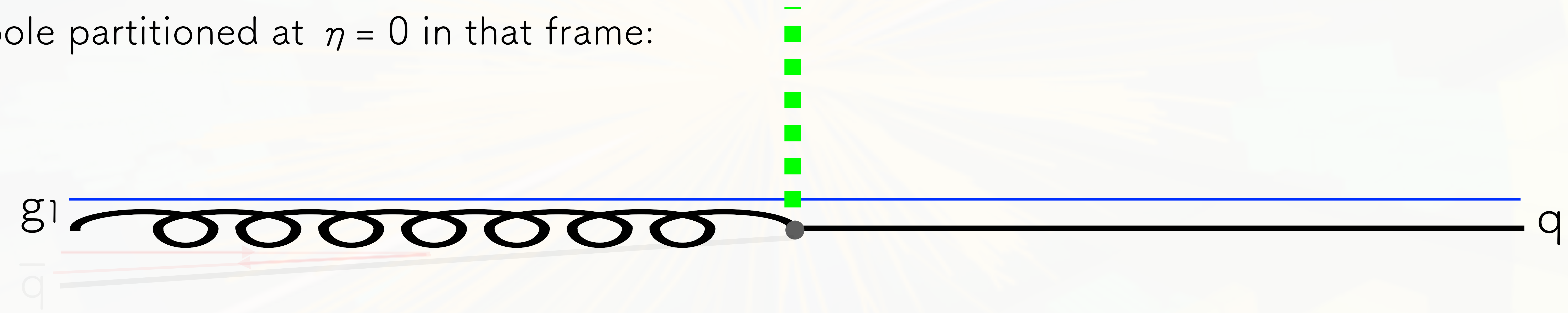


two soft emissions : boost dipole partitions back into the event COM

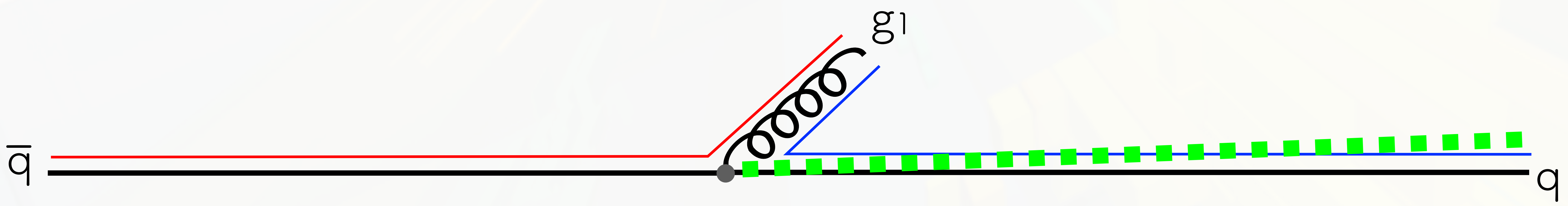
- Consider we emitted **soft gluon g_1** from **hard** $q\bar{q}$, so we end up with a $\bar{q}g_1$ and a g_1q dipole:



- 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:



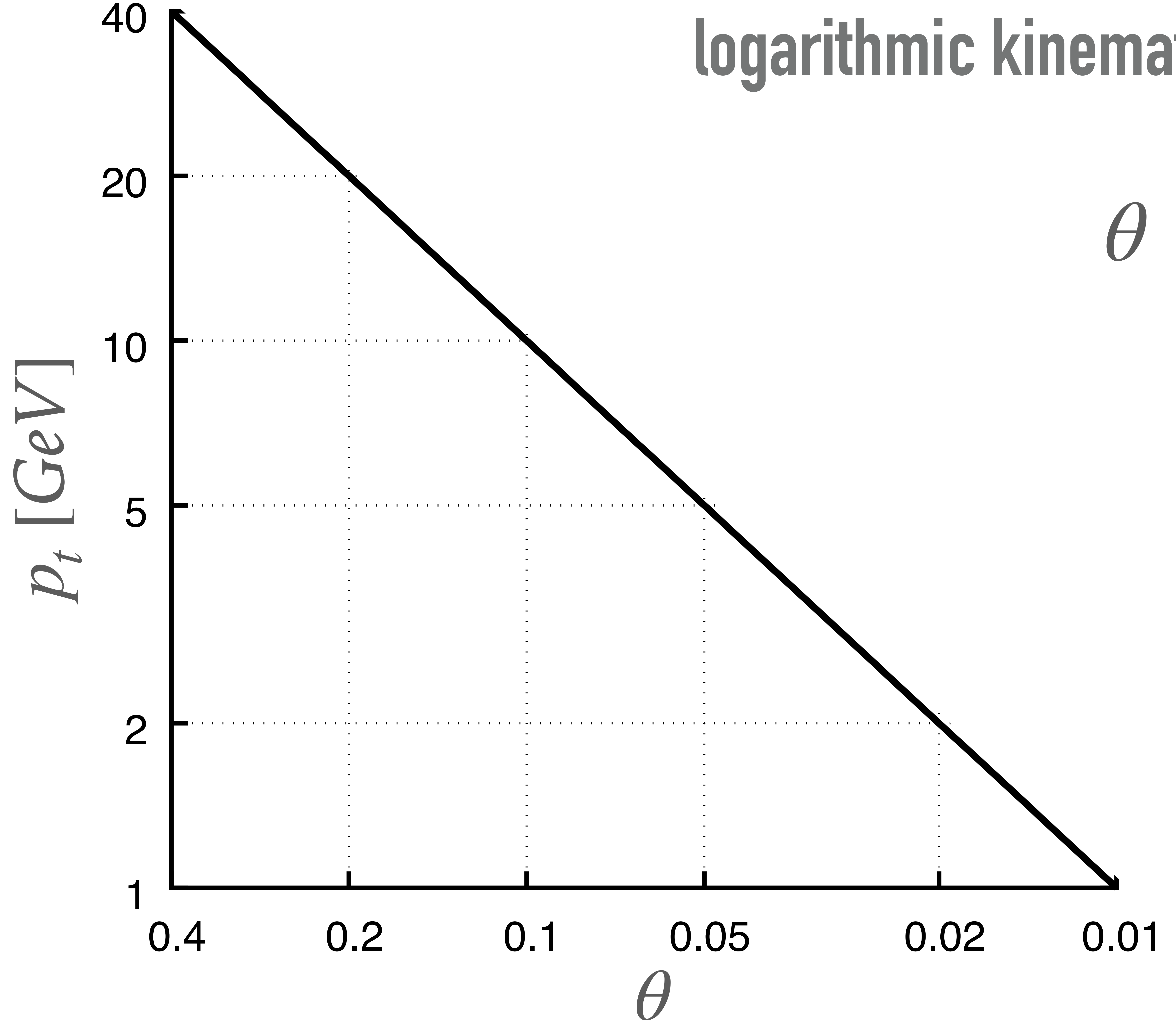
- To get us back to the event COM from the g_1q dipole COM undo the same **BIG BOOST** ⟵



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

g_1

jet with R= 0.4, p_t = 200 GeV



logarithmic kinematic plane whose two variables are

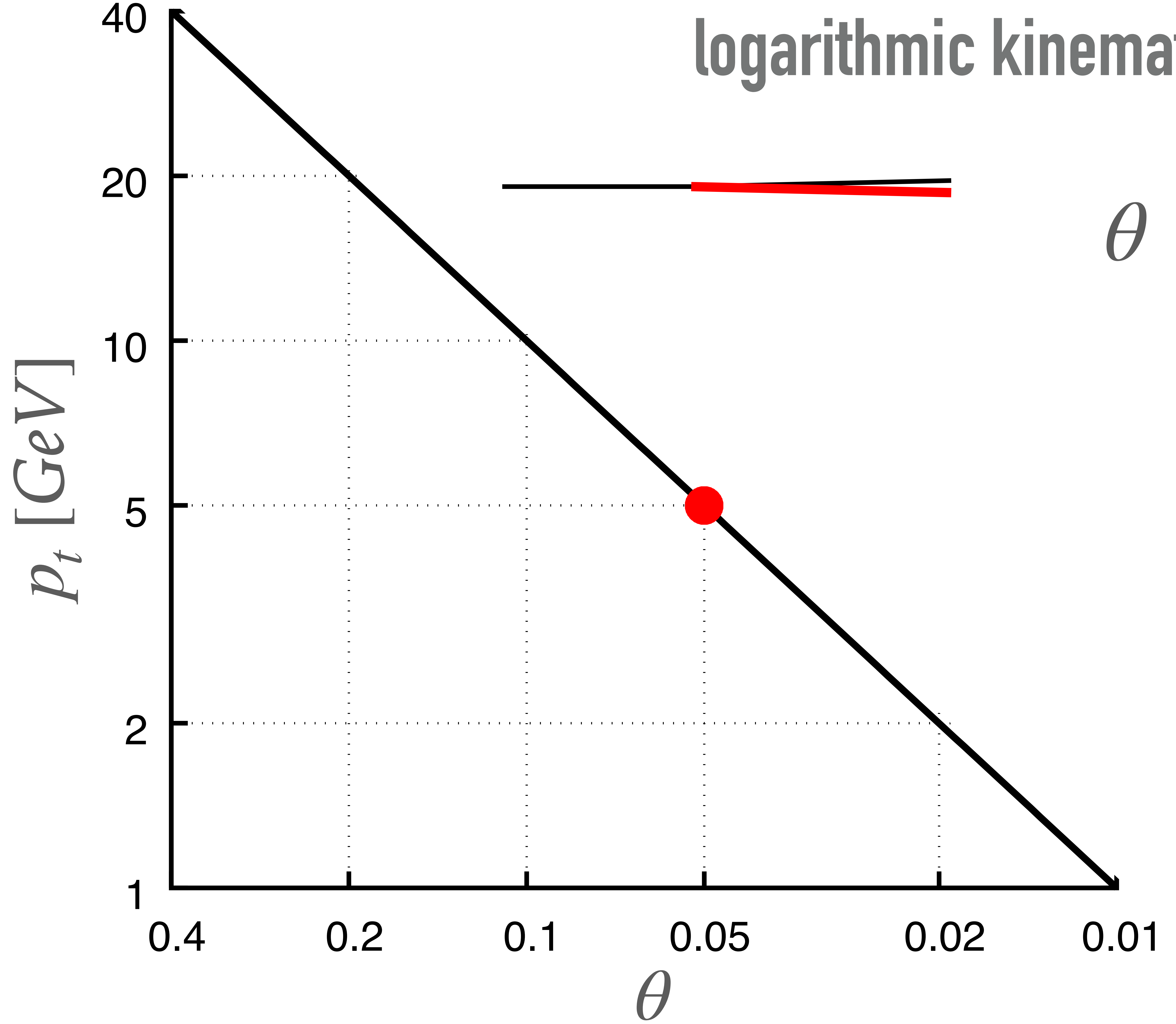
$$\theta \ (or\ \eta = -\ln\tan\frac{\theta}{2})$$

$$p_t = E\theta$$

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

The Lund Plane

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



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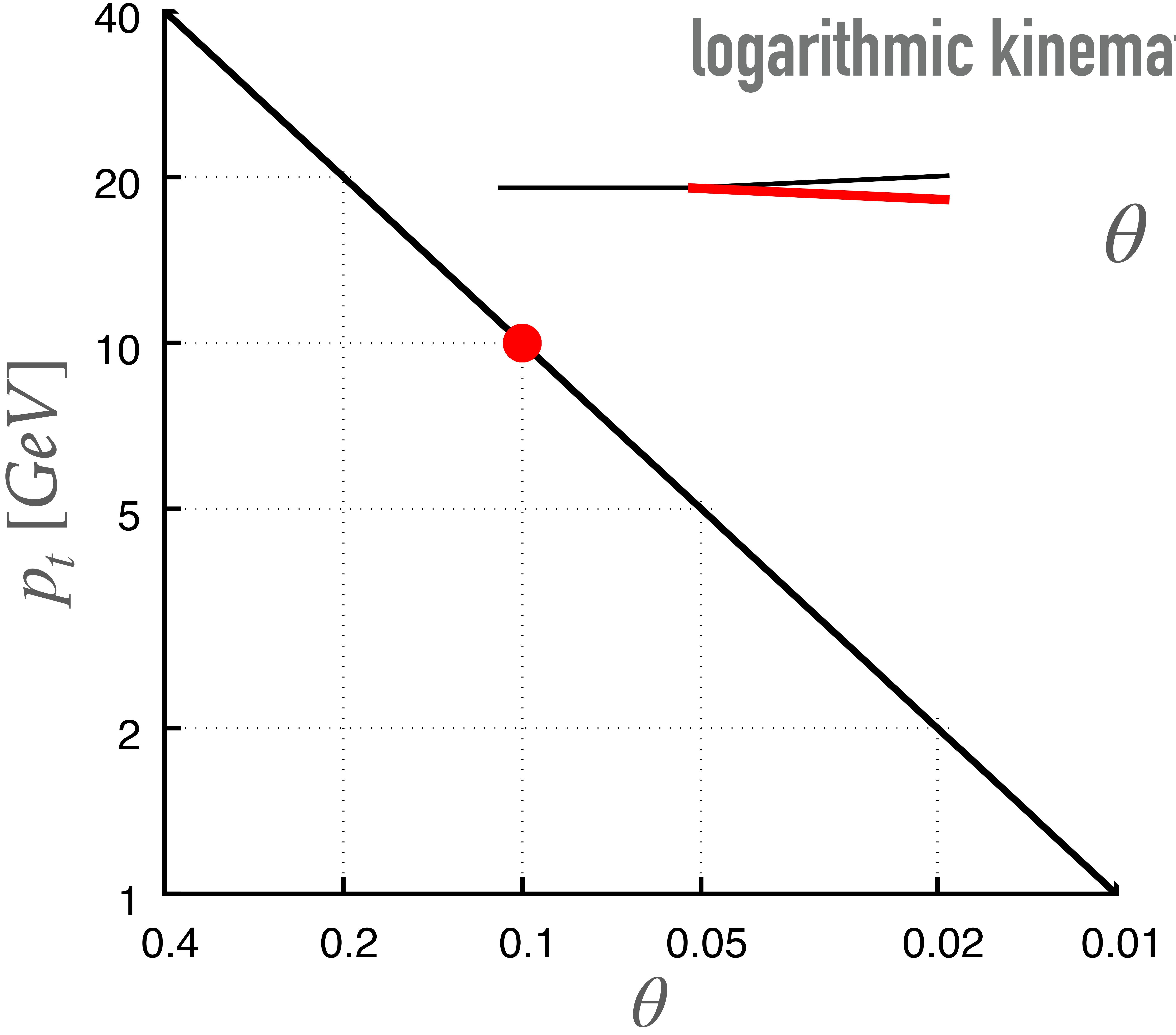

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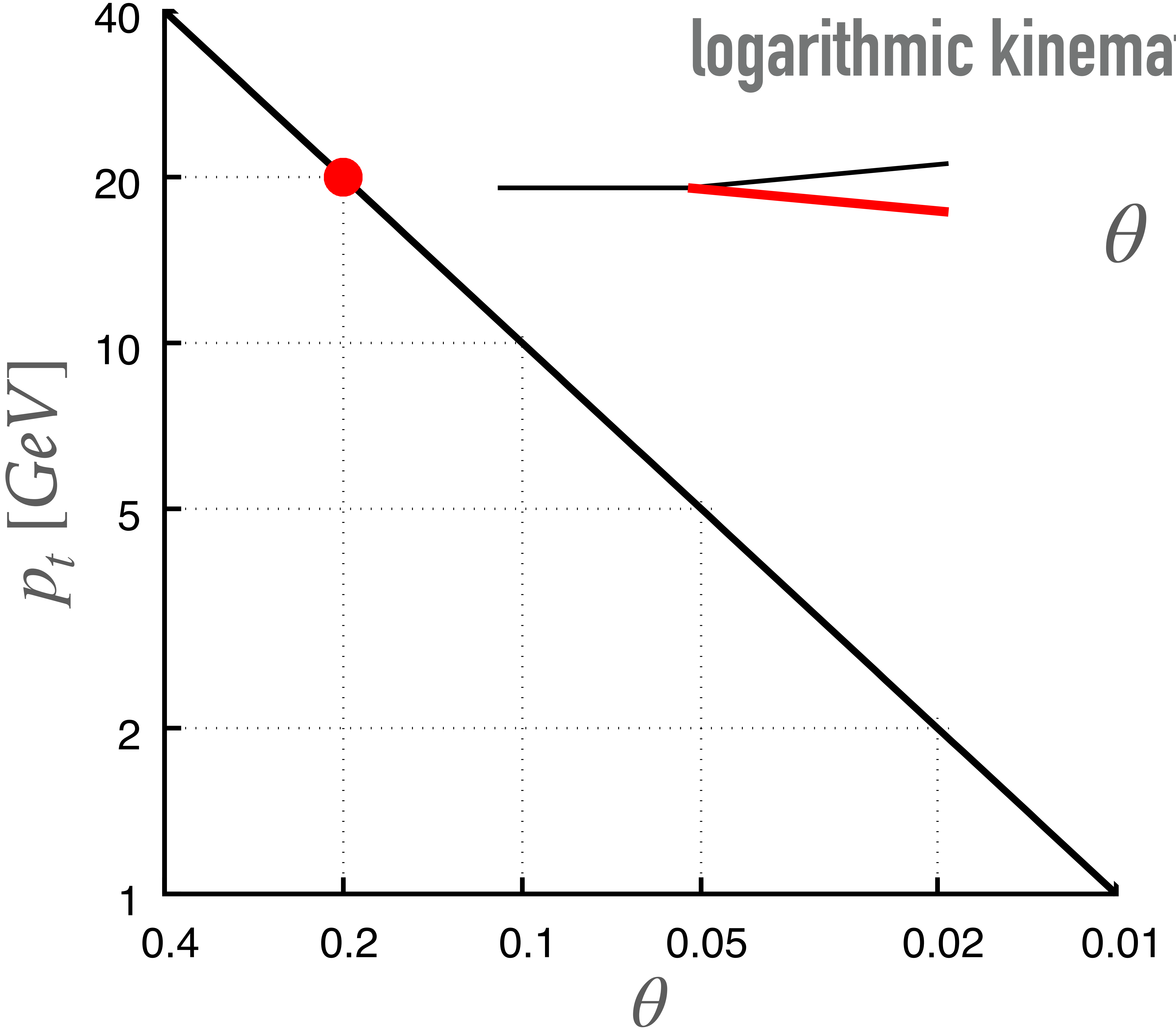

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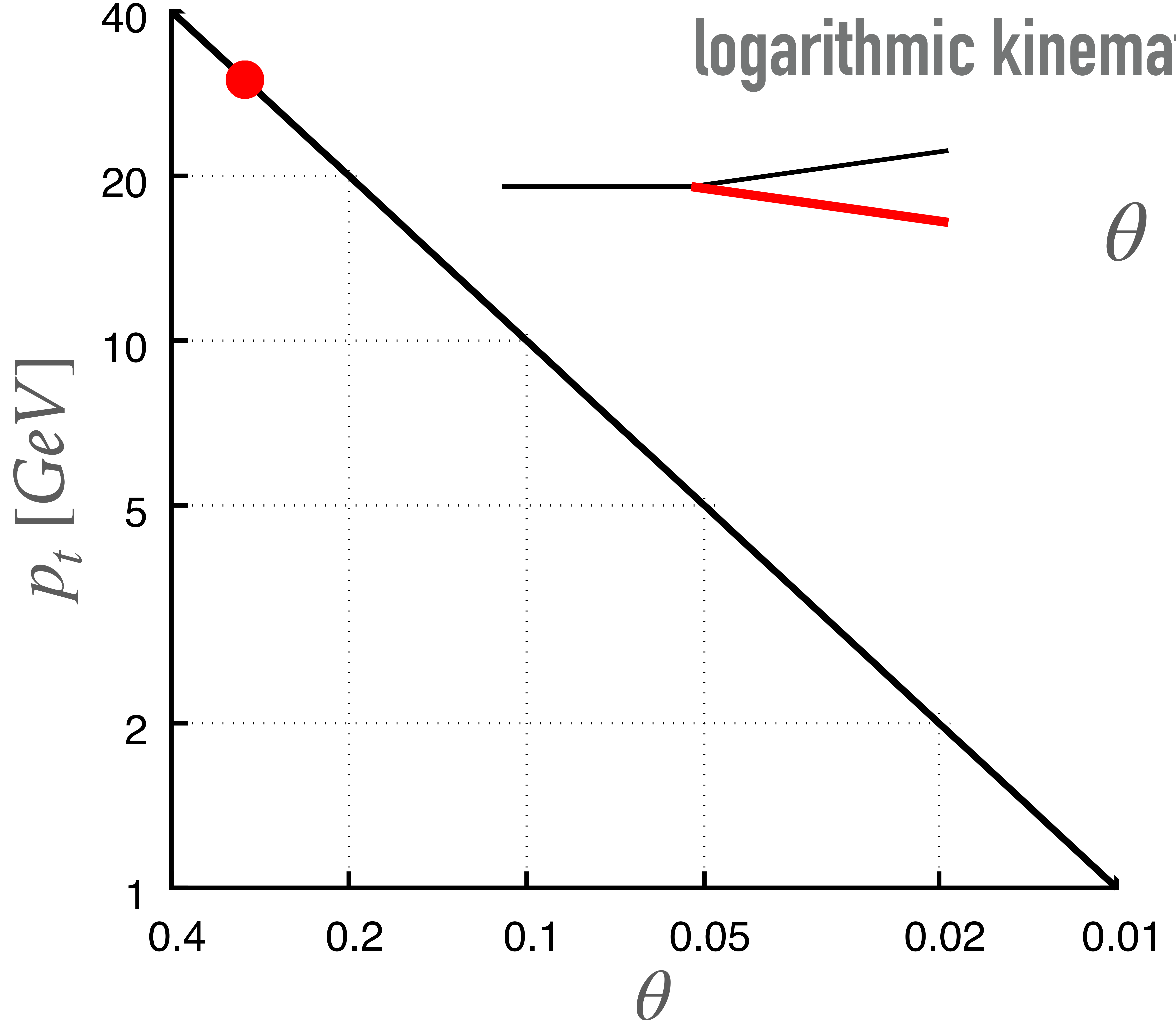

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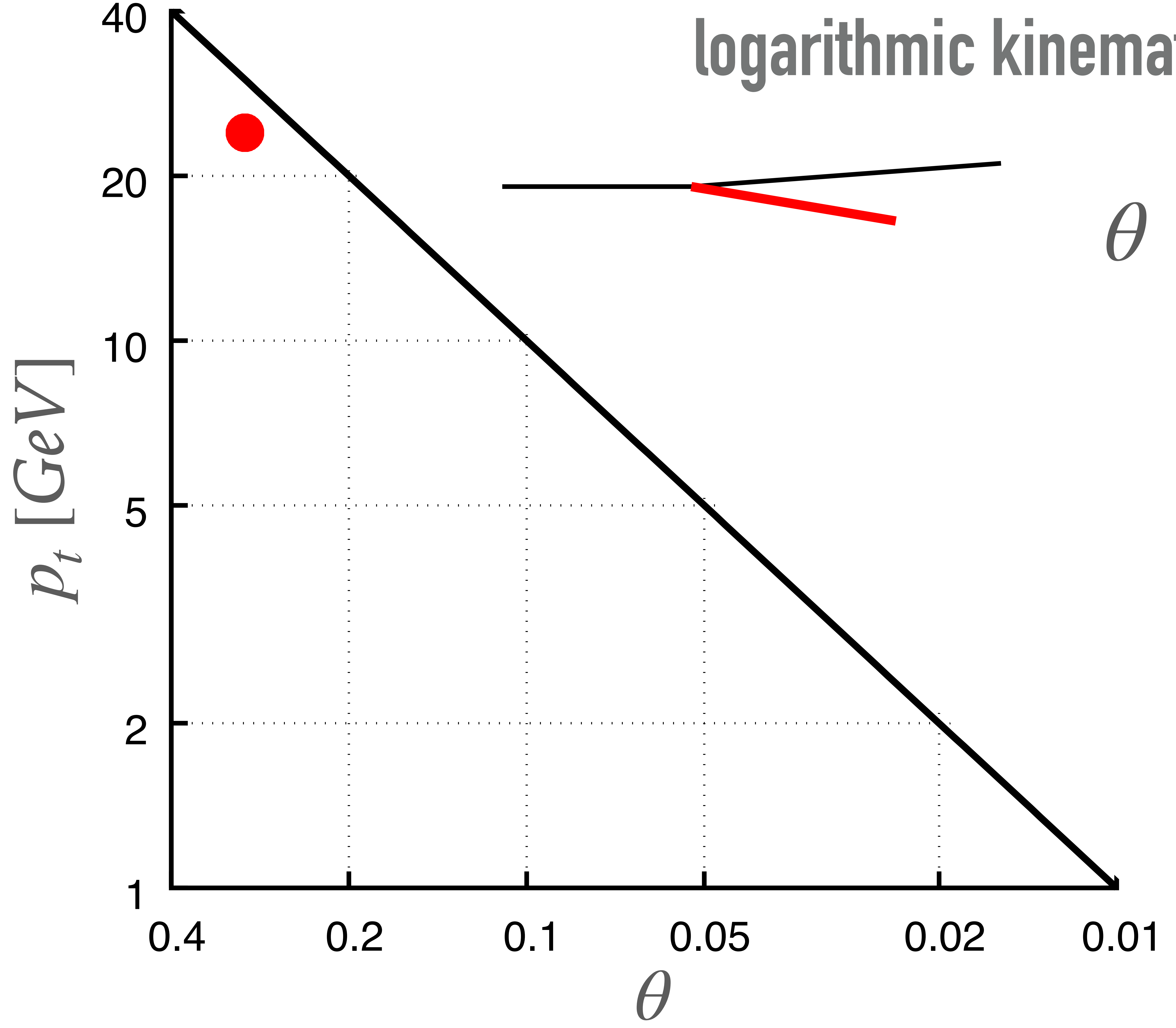

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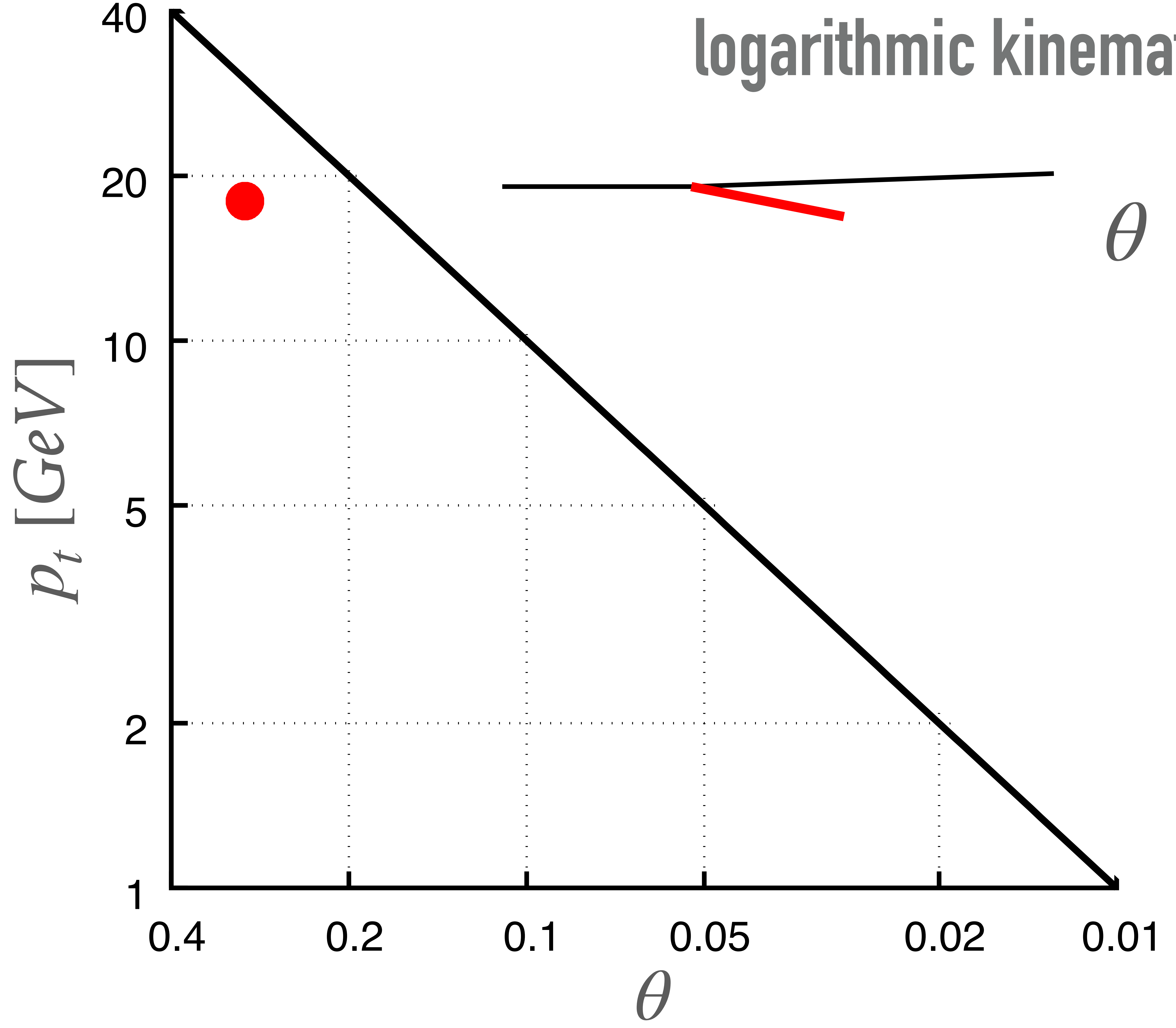

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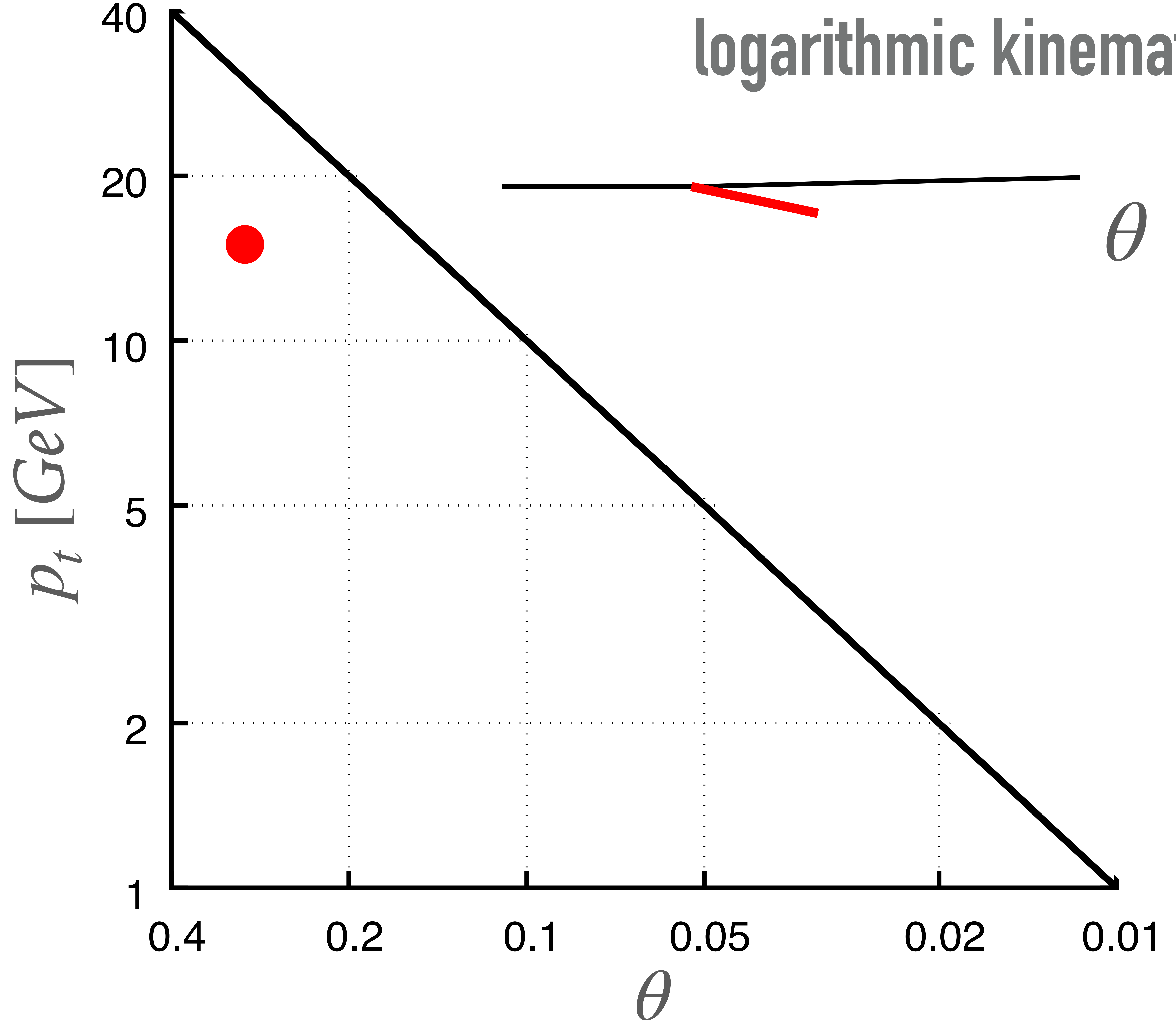

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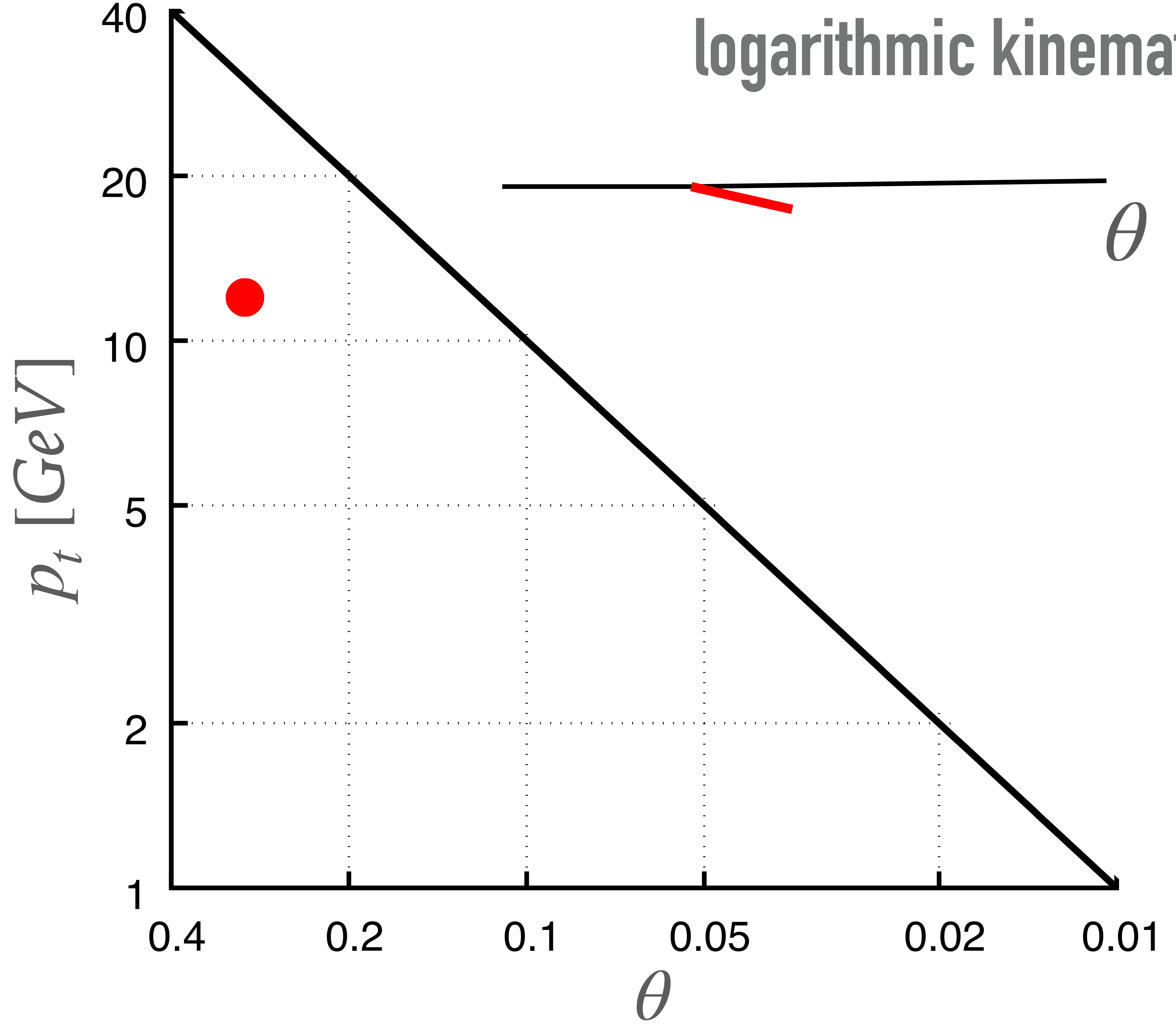

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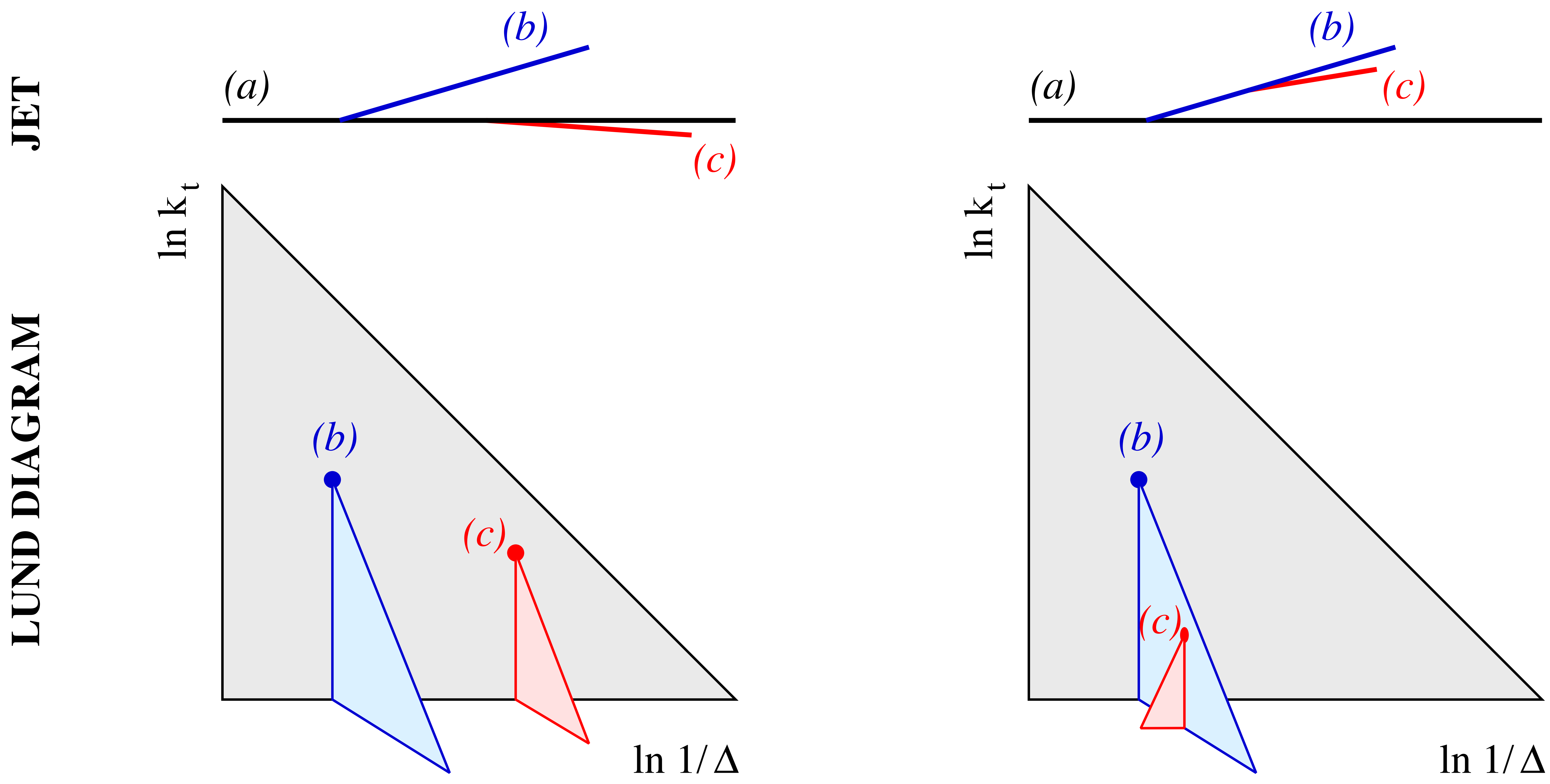
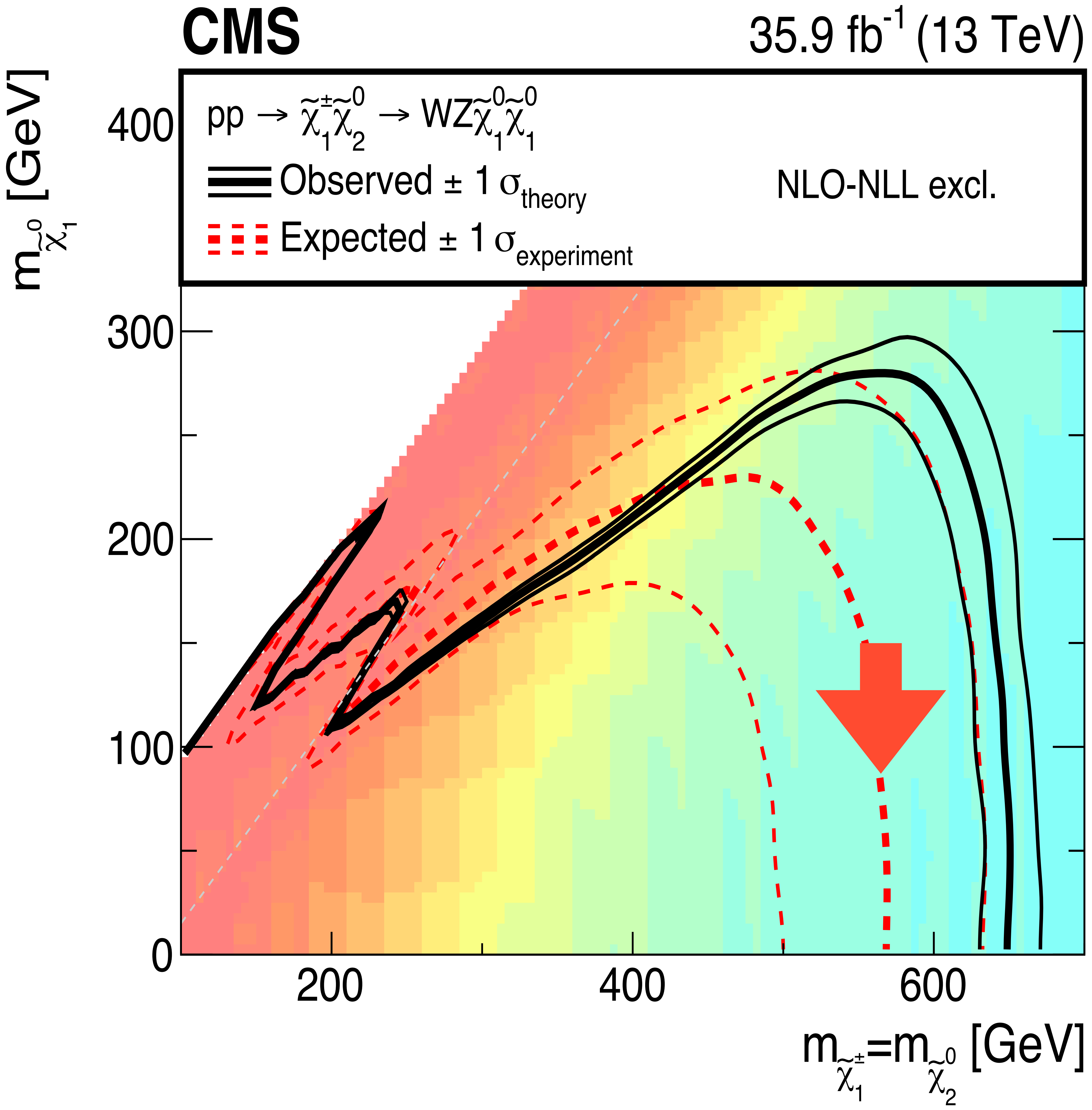
Introduced for understanding Parton Shower Monte Carlos by B. Andersson, G. Gustafson L. Lonnblad and Pettersson 1989

organise phasespace: Lund diagrams



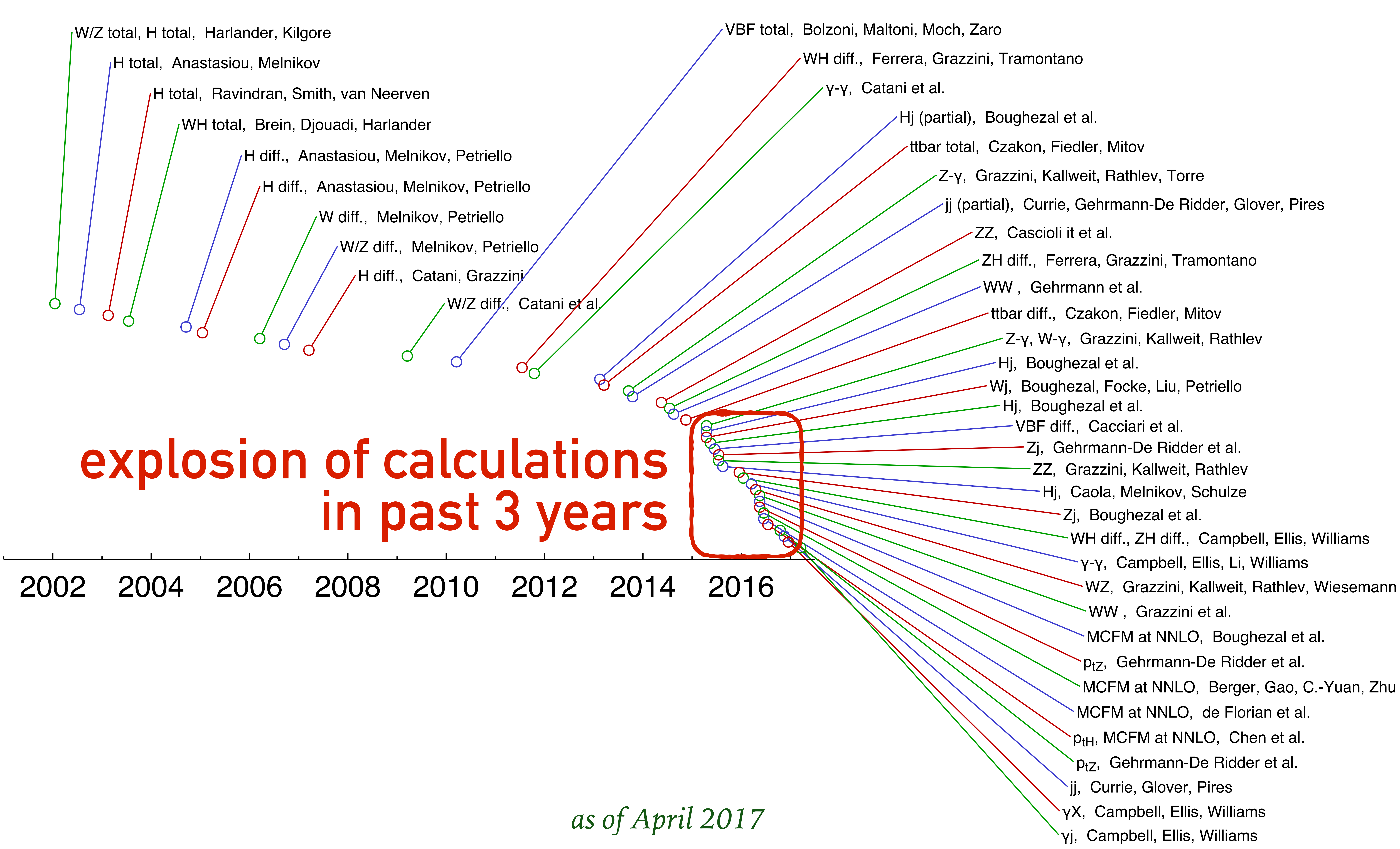
The path forward: collect 20–30x more collisions by ~2035



- 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)



as of April 2017