# Insights into the logarithmic accuracy of parton showers

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based mostly on arXiv:1805.09327 with
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* *on leave from CERN and CNRS*

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THE ROYAL SOCIETY

**Cambridge HEP group**
**4/6/2019**

*at colliders, you can probe*

**"big unanswered questions"**

about fundamental particles & their interactions

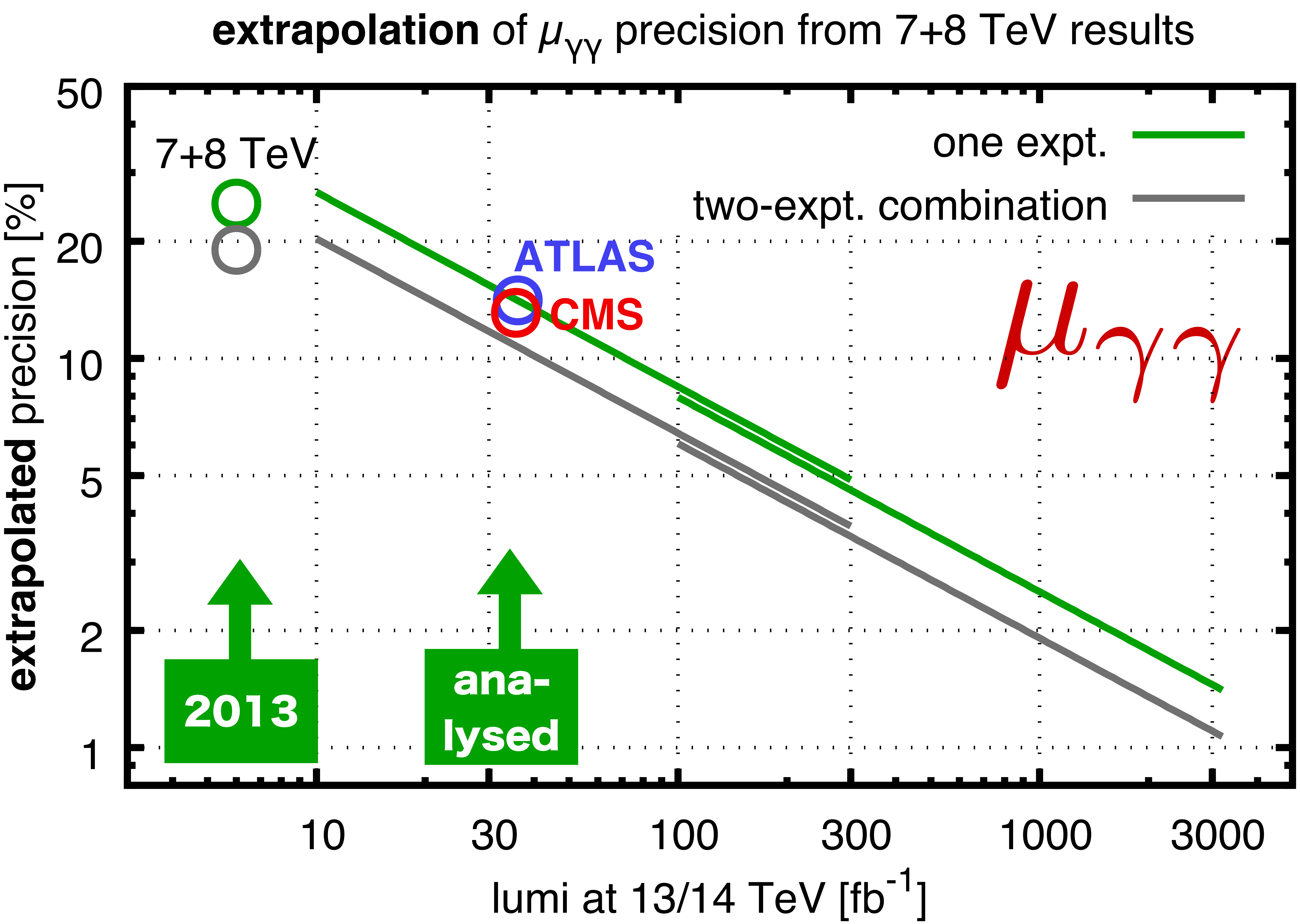
(dark matter, matter-antimatter asymmetry, fine-tuning / hierarchy of scales…)

*and*

**"big answerable questions"**

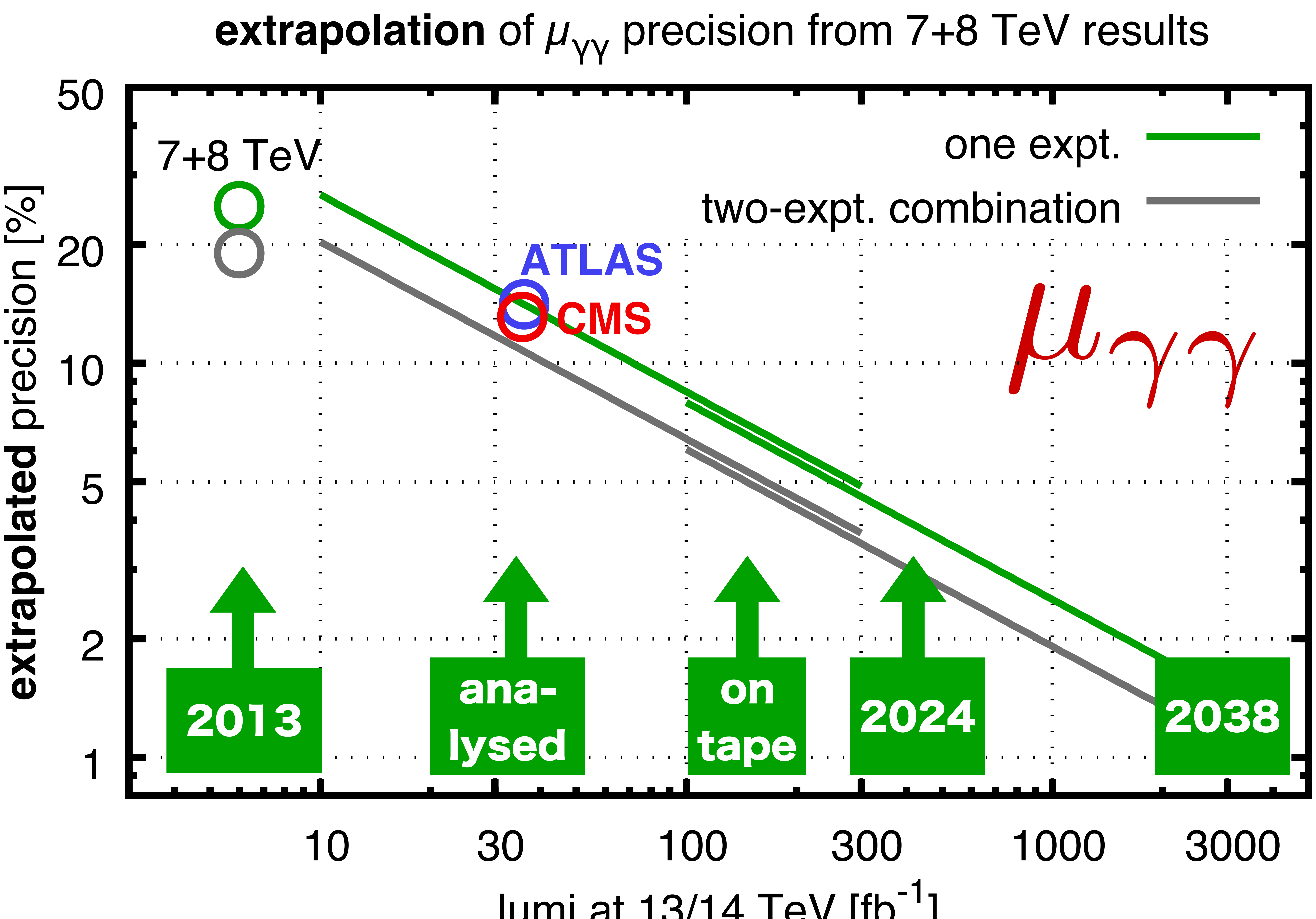
(structure of Higgs sector, determining fundamental parameters of Lagrangian of particle physics)

# 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

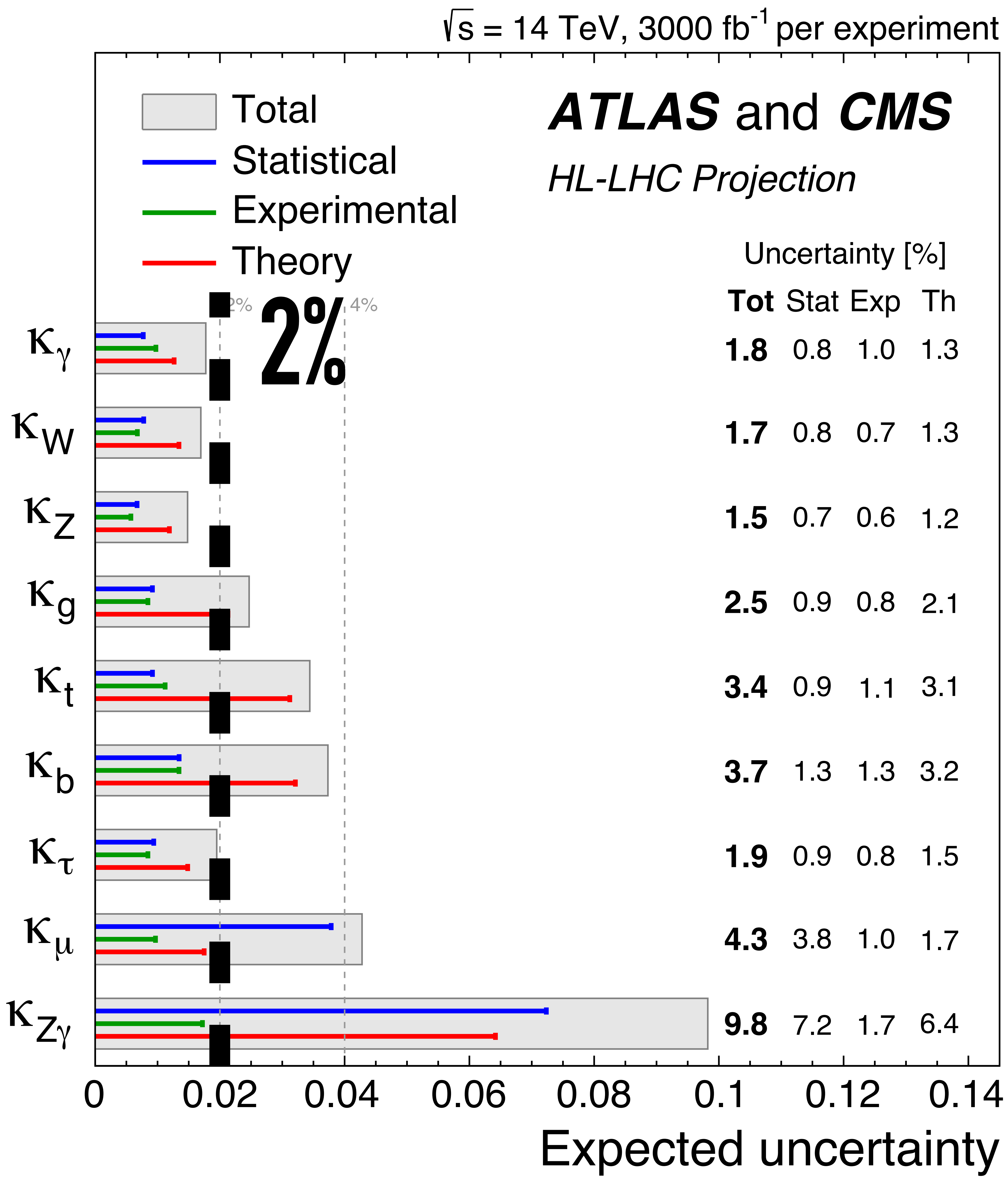



The LHC has the statistical potential to take Higgs physics from "observation" to 1–2% precision

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

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

# HL-LHC official Higgs coupling projections (by ~2036)




We wouldn't consider electromagnetism established (textbook level) if we only knew it to 10%

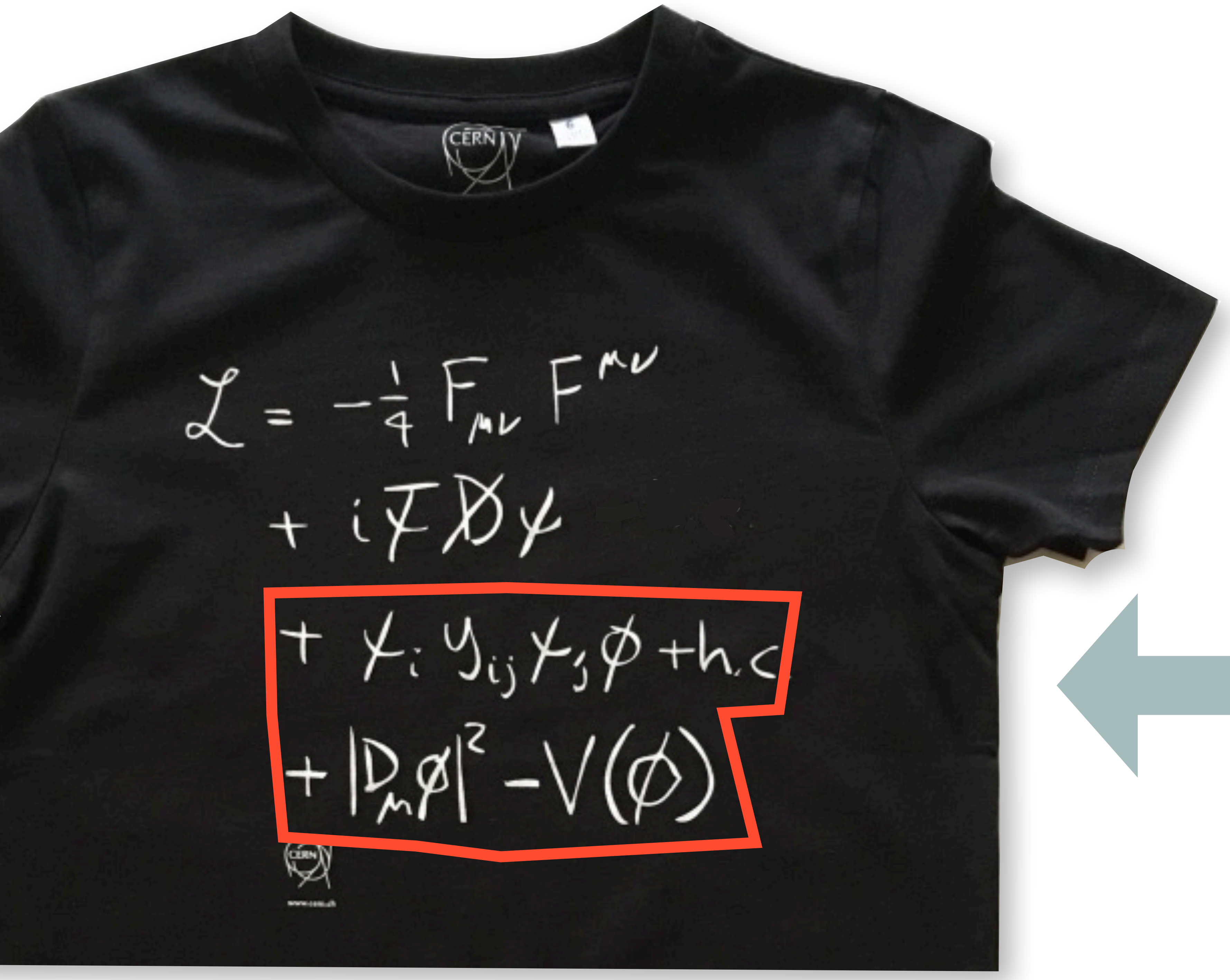
HL-LHC can deliver 1–2% for a range of couplings
**if theoretical interpretations can be made sufficiently accurate**

# how is all of this made quantitative?

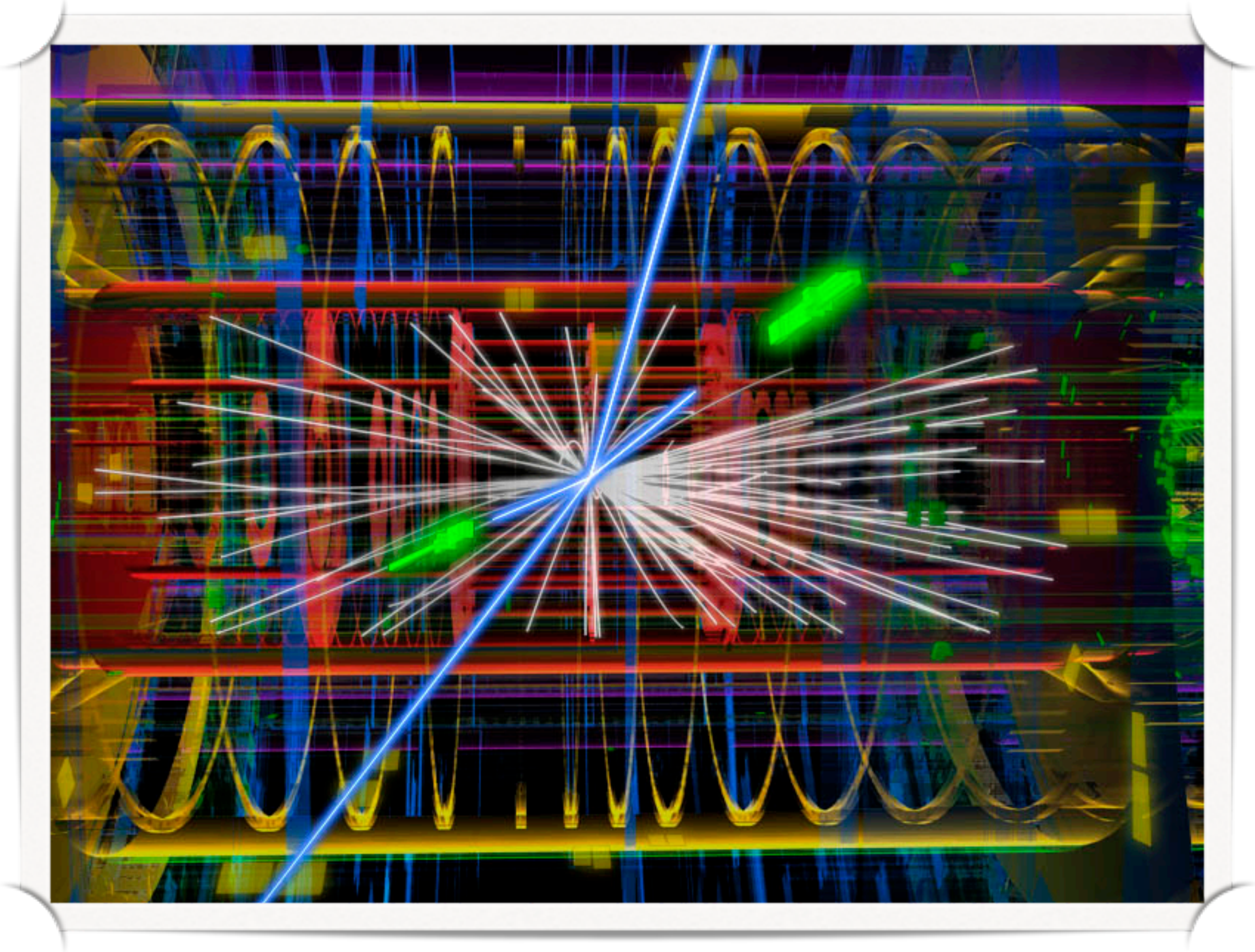
whether new-physics searches, Higgs physics, or other SM studies

# UNDERLYING THEORY

# EXPERIMENTAL DATA

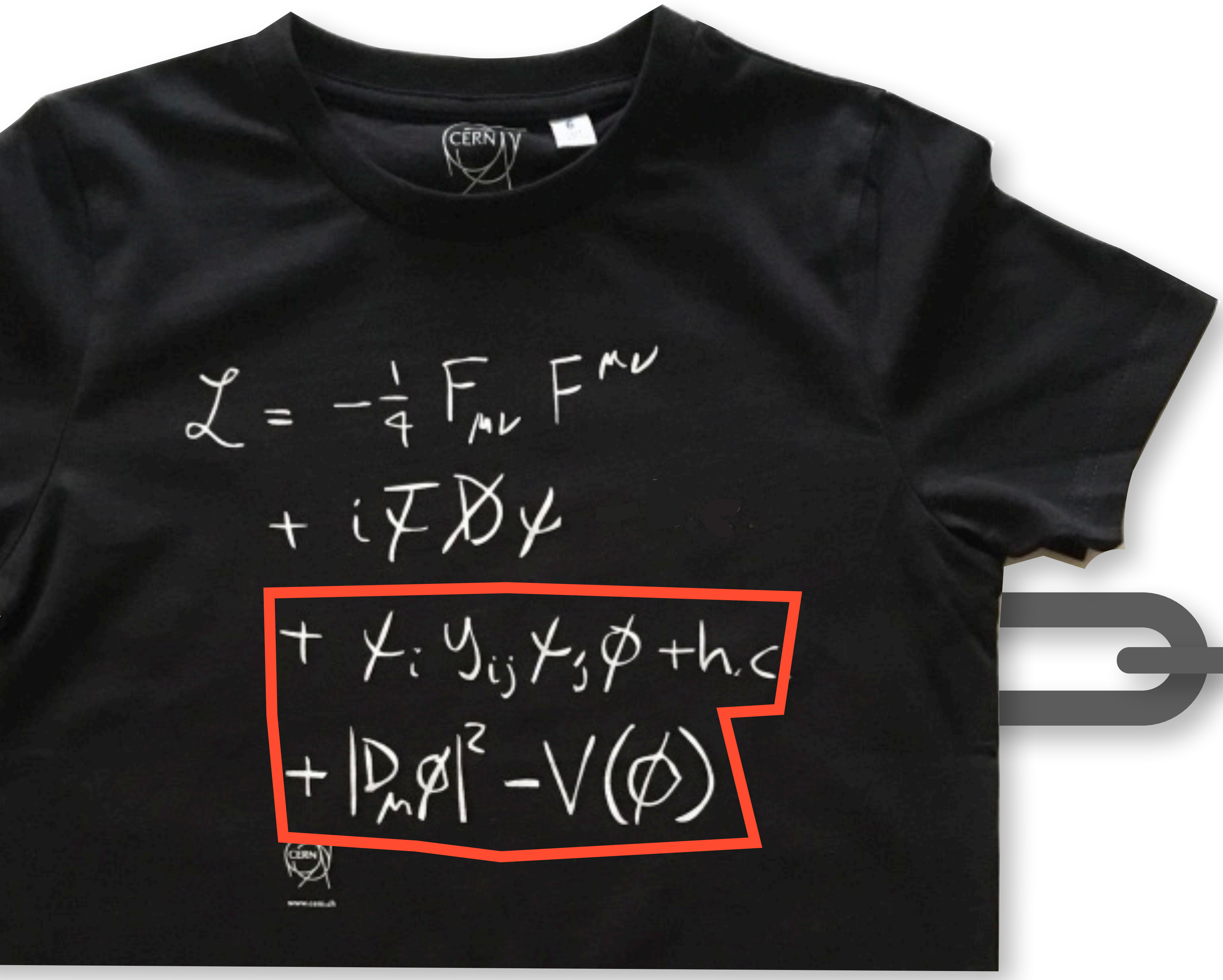


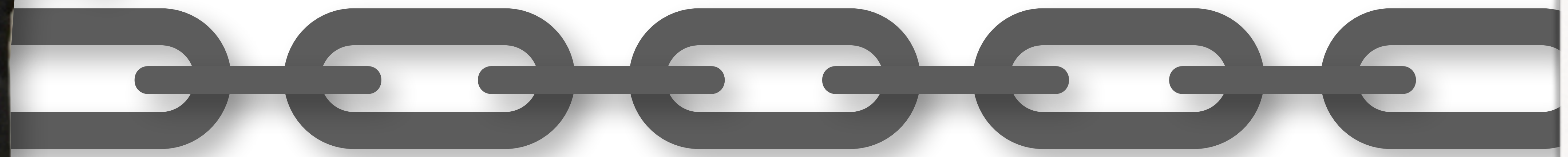

*how do you make quantitative connection?*

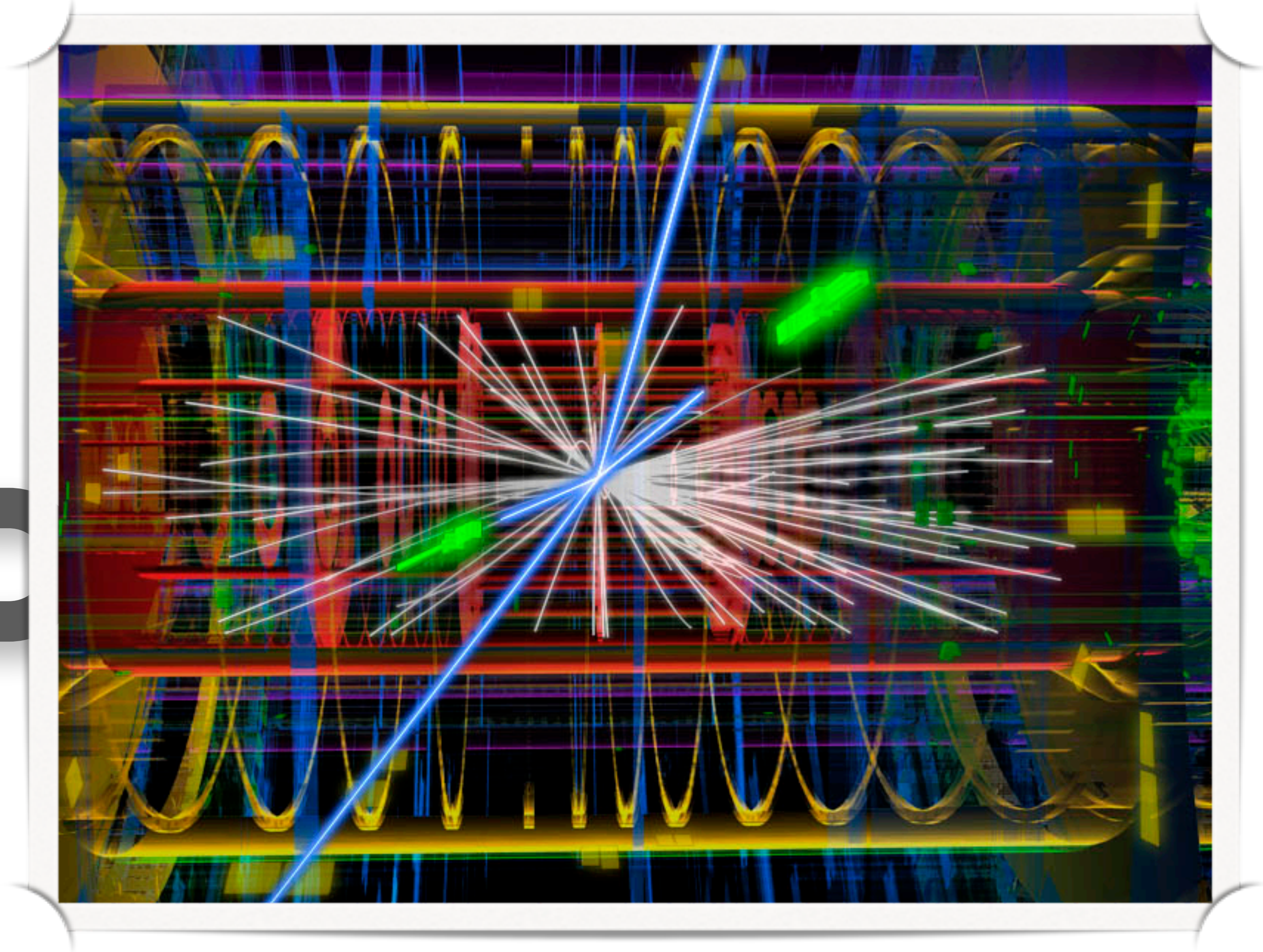


UNDERLYING THEORY

EXPERIMENTAL DATA



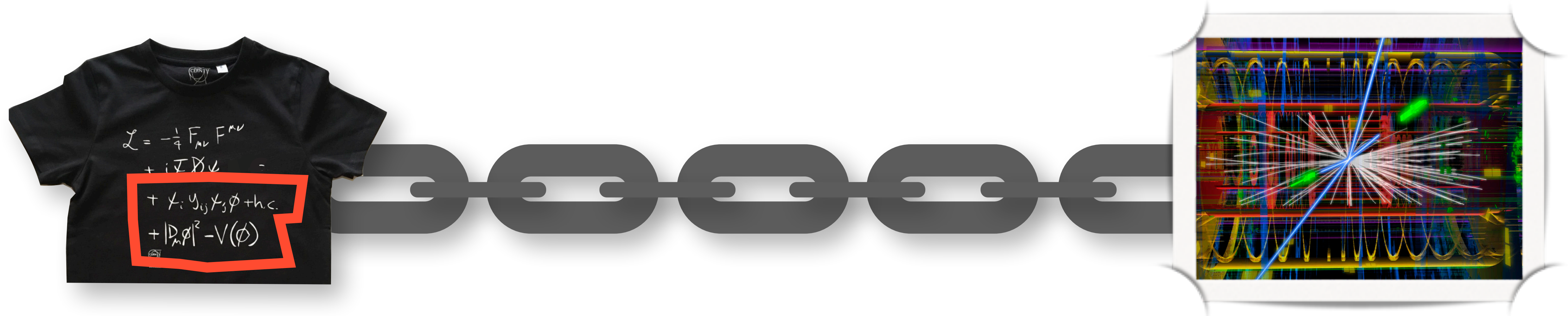





*how do you make quantitative connection?*

*through a chain of experimental and theoretical links*

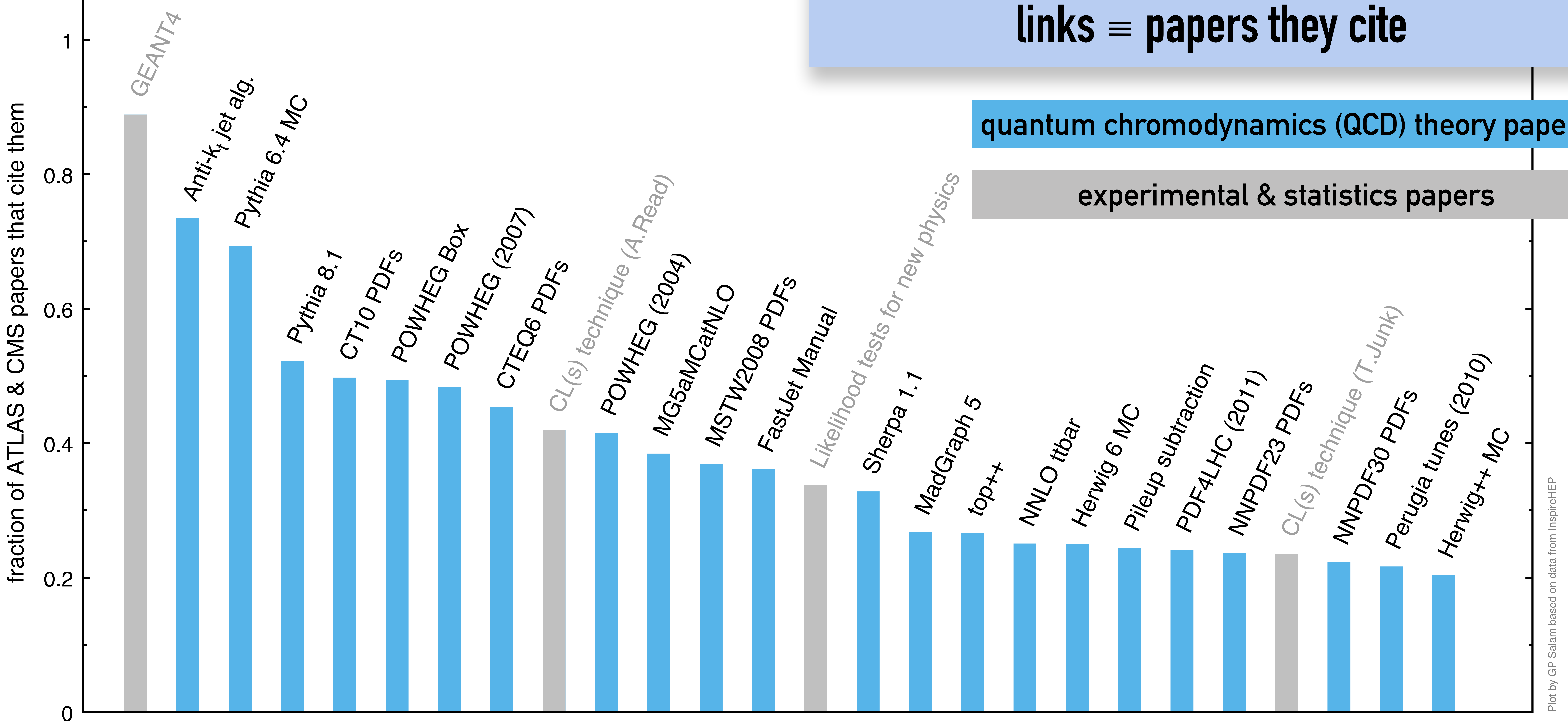
*[in particular Quantum Chromodynamics (QCD)]*

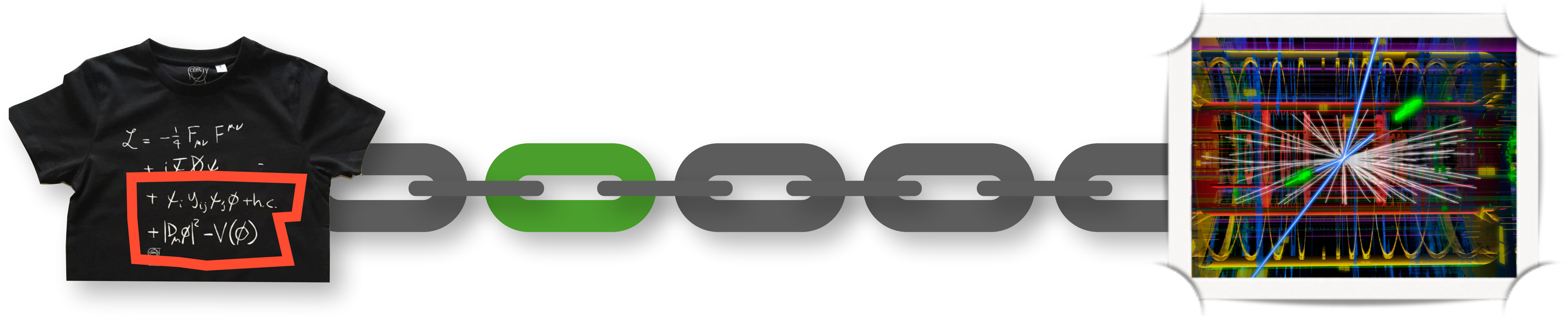


# What are the links?

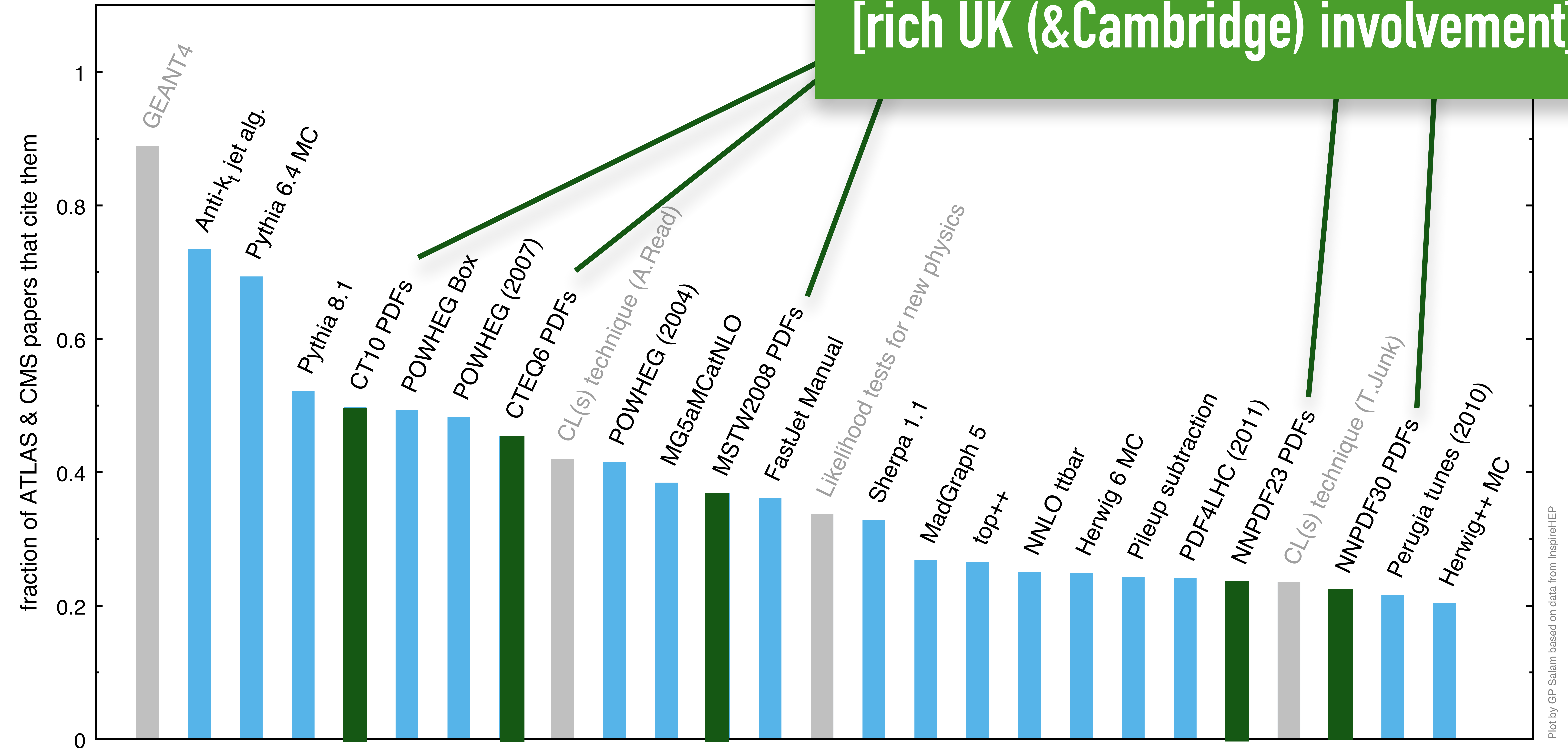
ATLAS and CMS (big LHC expts.) have written O(1000) articles since 2014

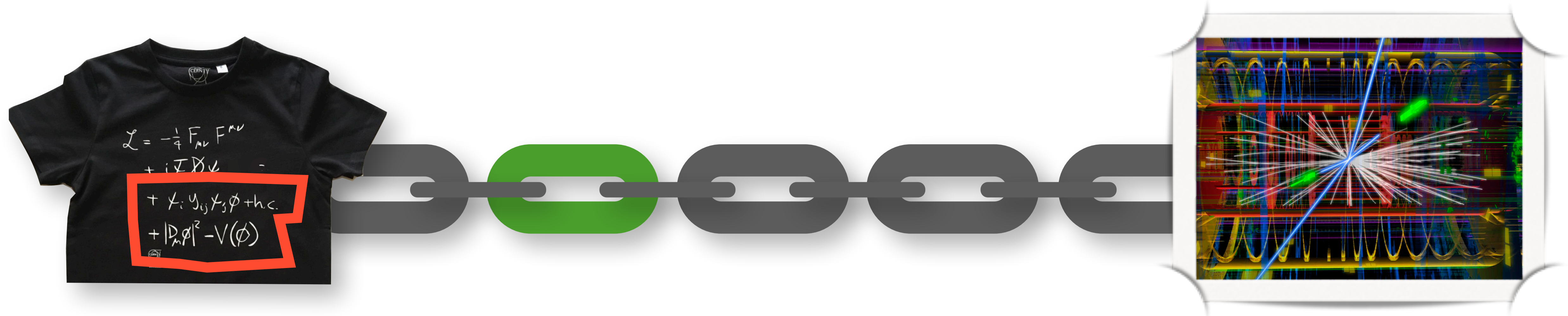
**links ≡ papers they cite**





# knowing what goes into a collision
# i.e. proton structure
# [rich UK (&Cambridge) involvement]





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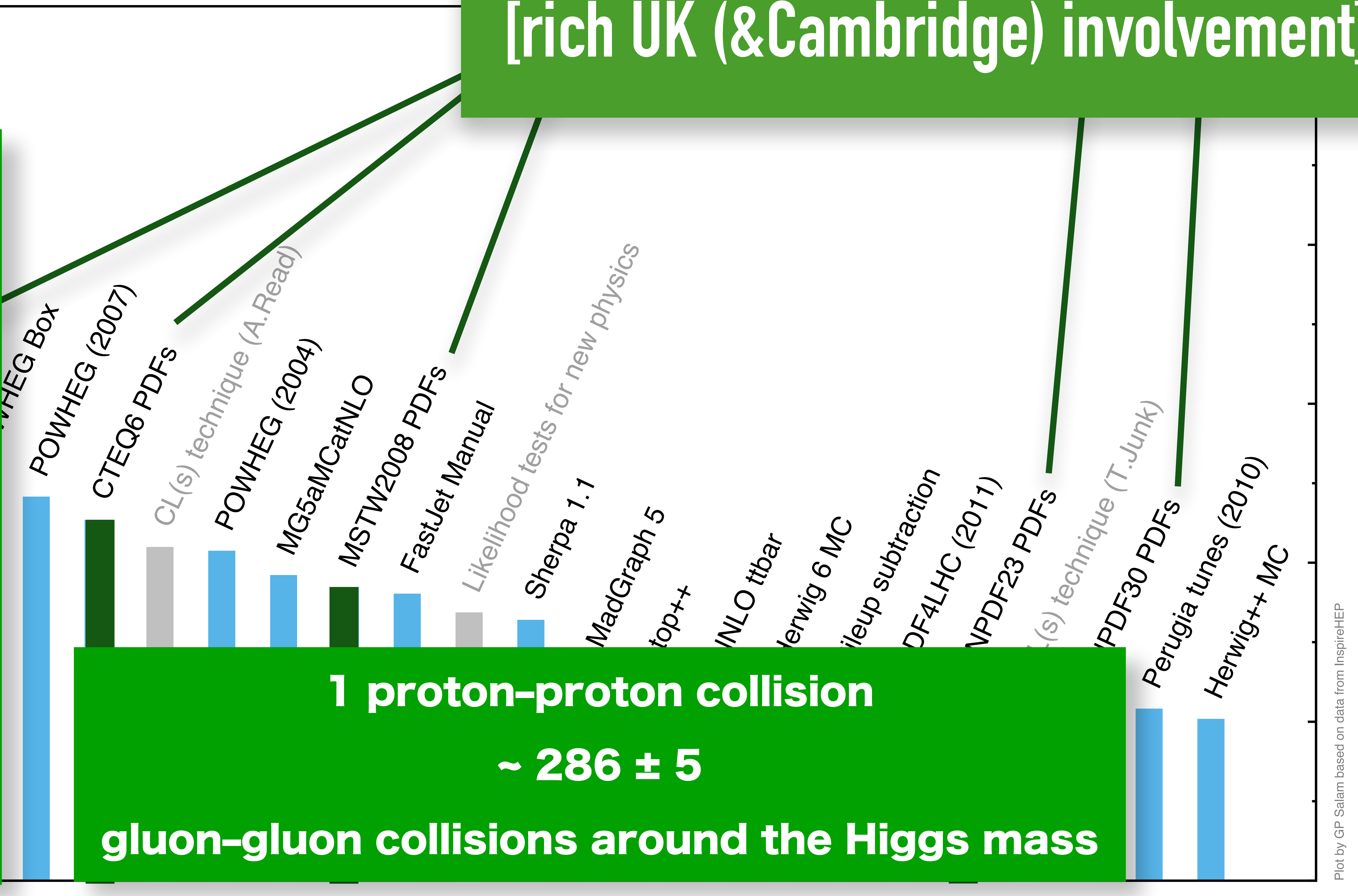
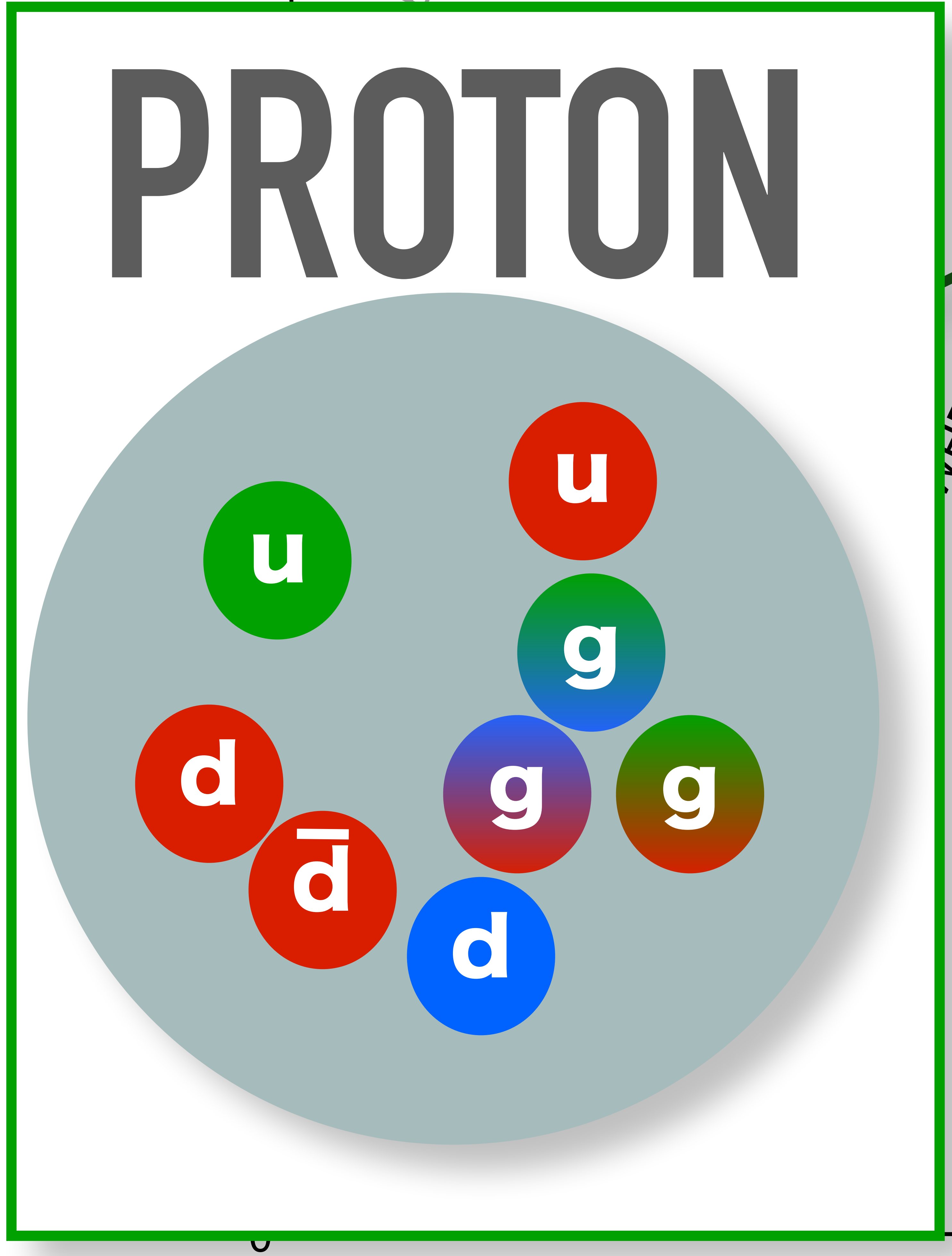
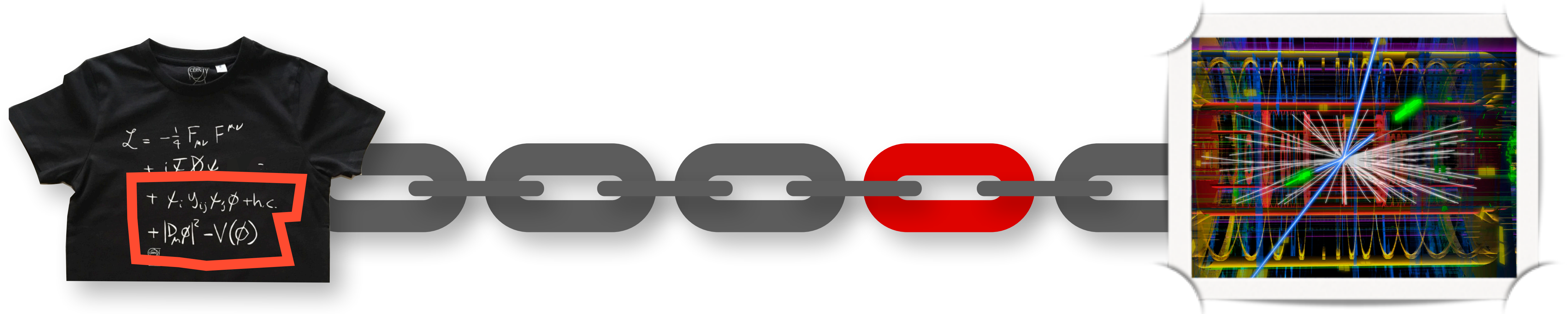
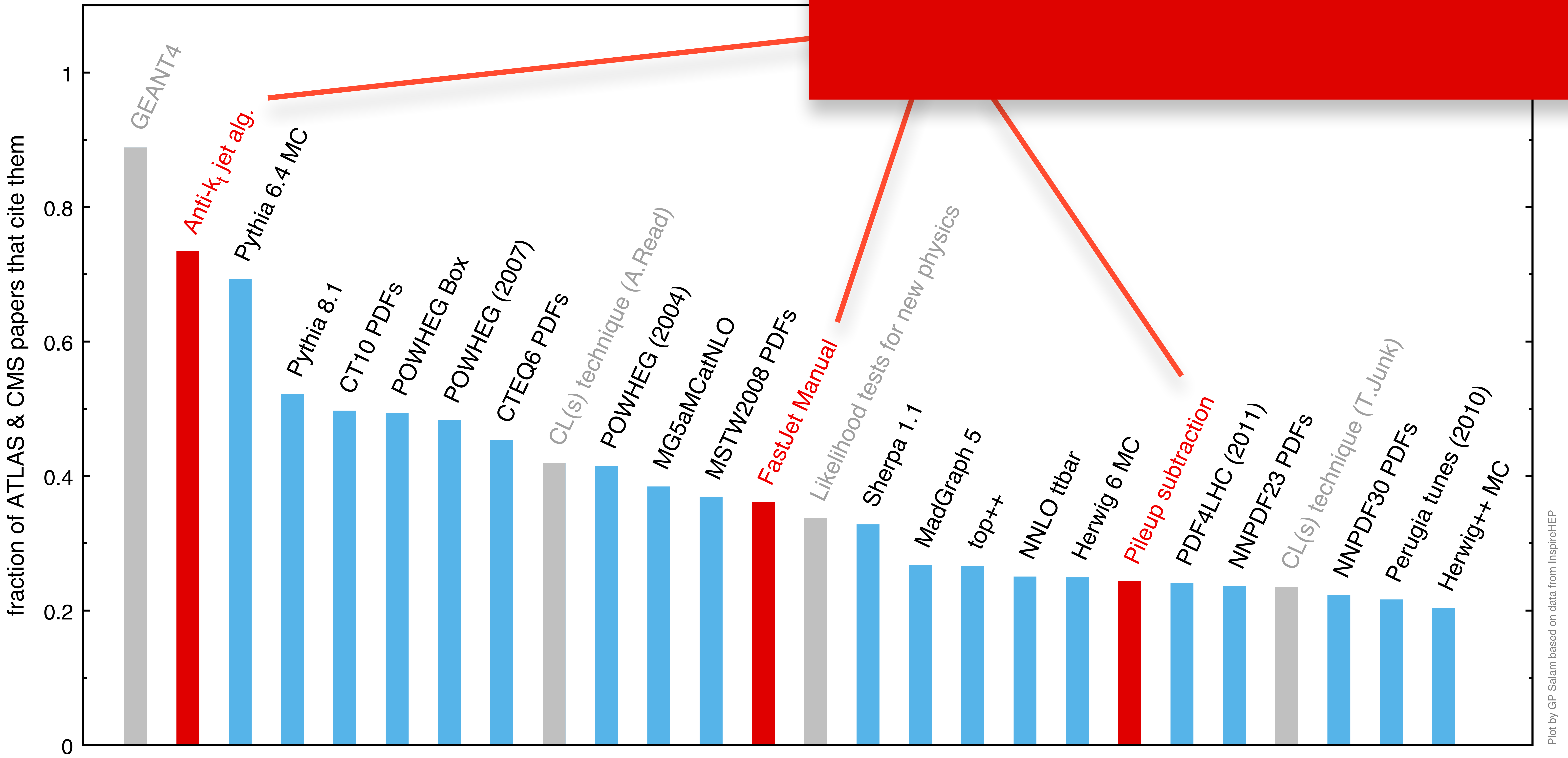



1 proton-proton collision
~ 286 ± 5
gluon-gluon collisions around the Higgs mass



# organising event information ("jets")

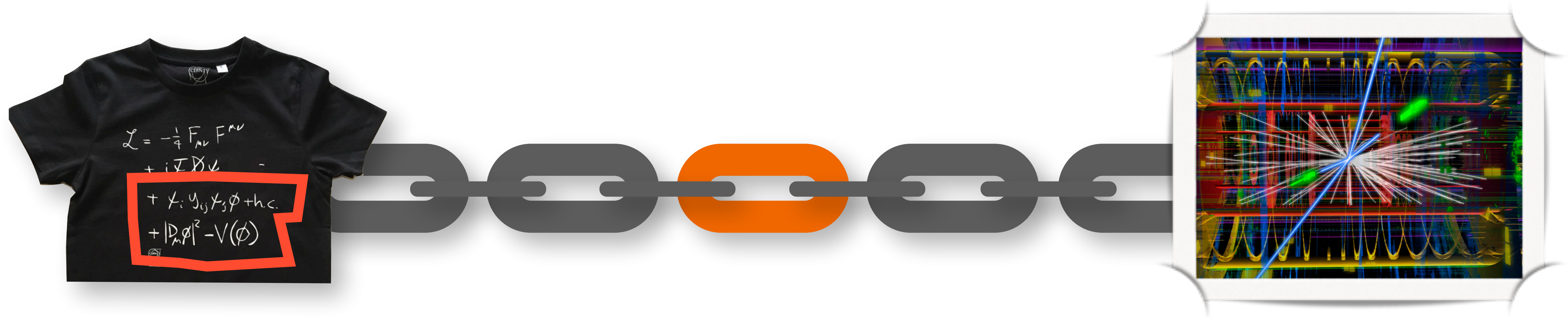


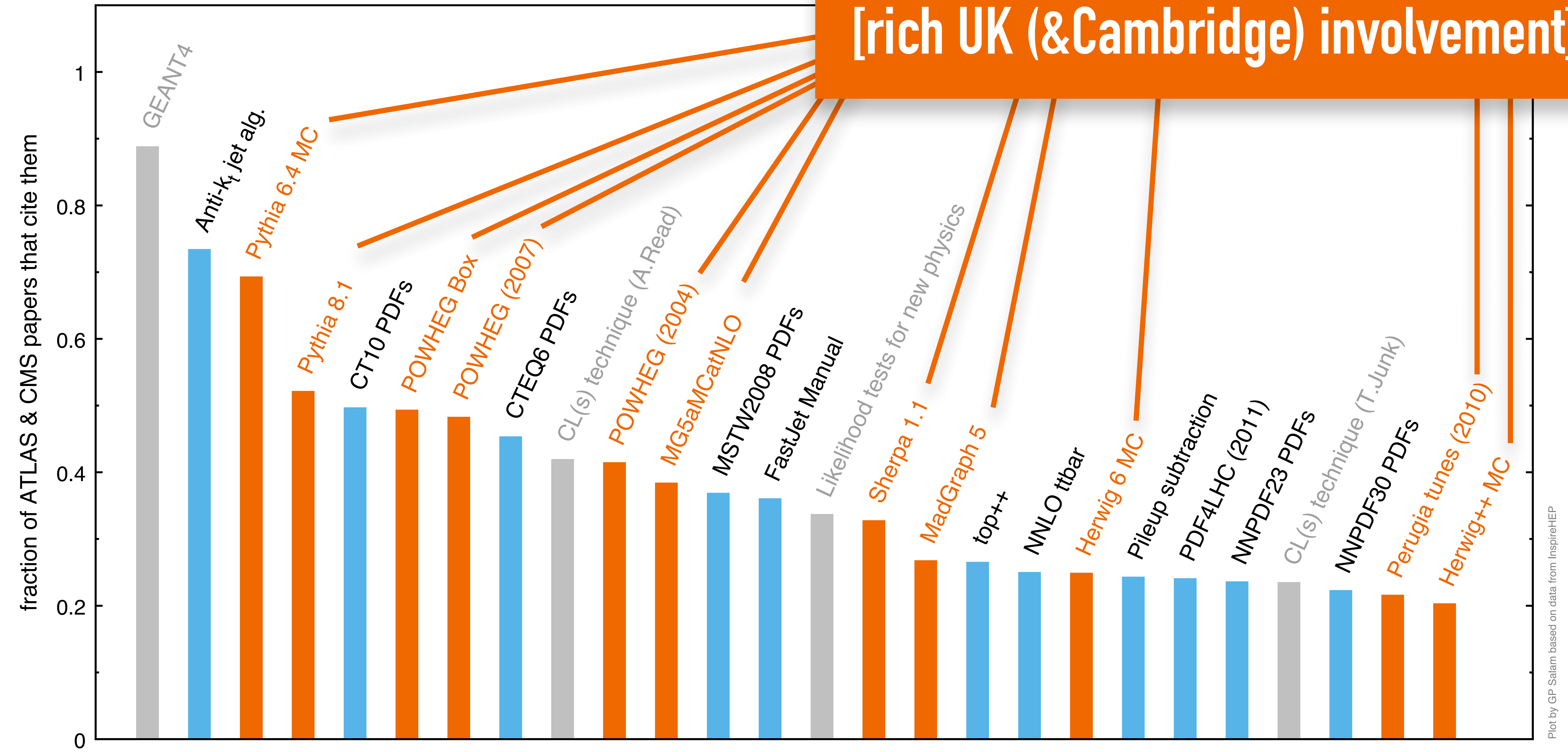
CMS Experiment at the LHC, CERN
Simulated event at 13 TeV centre-of-mass energy


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

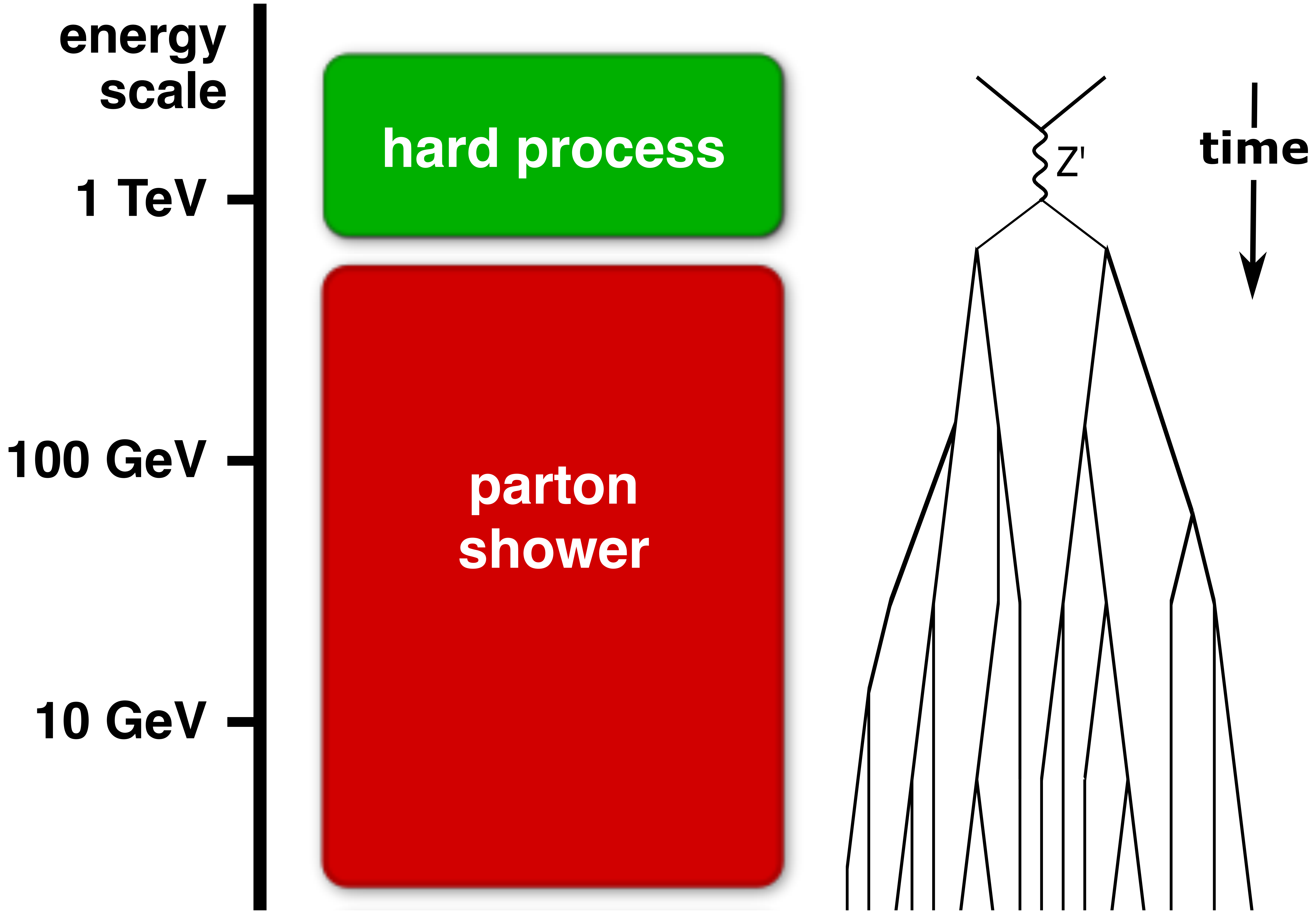
*the question of organising information in events will come back later*

# predicting full particle structure that comes out of a collision [rich UK (&Cambridge) involvement]






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

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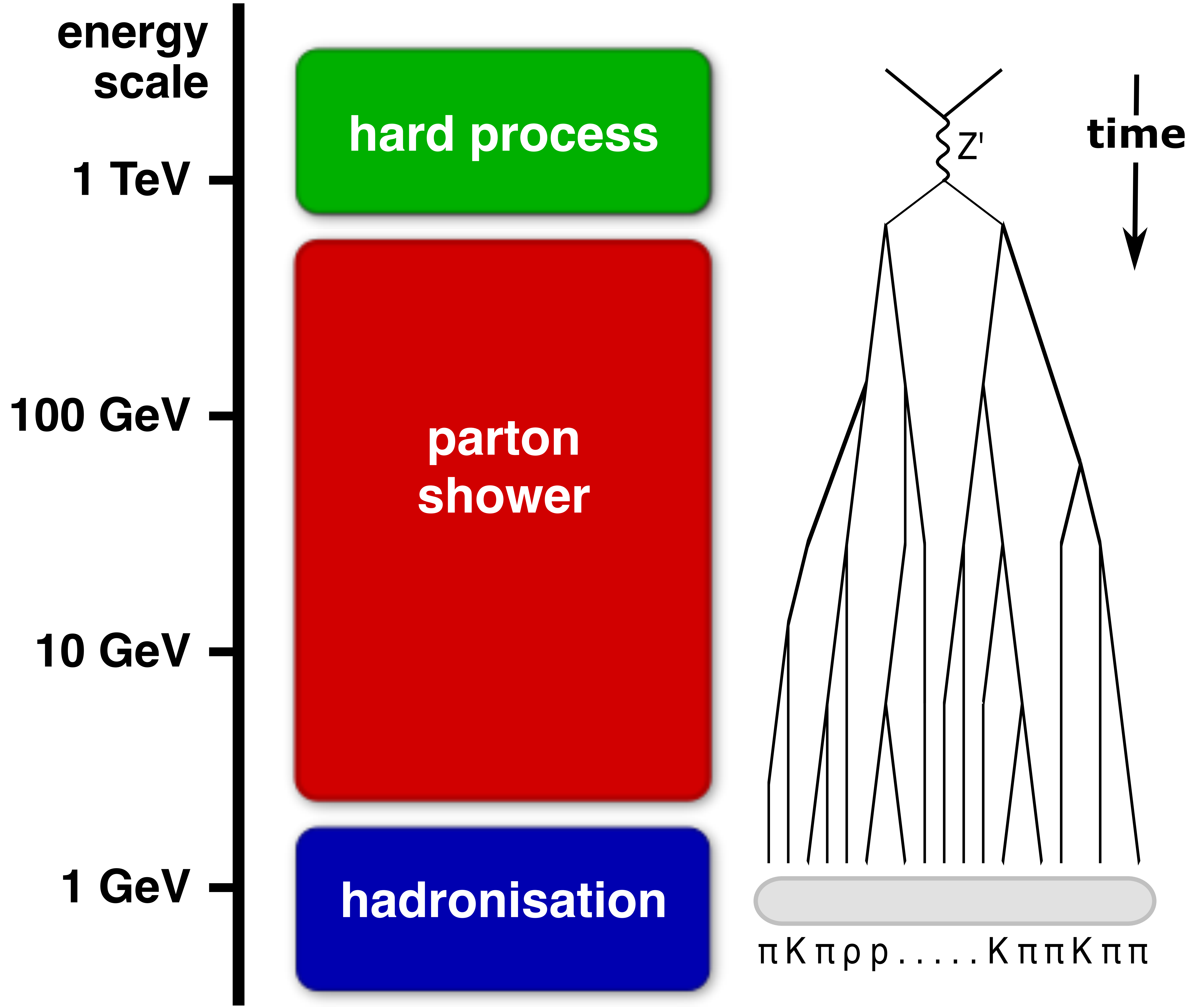


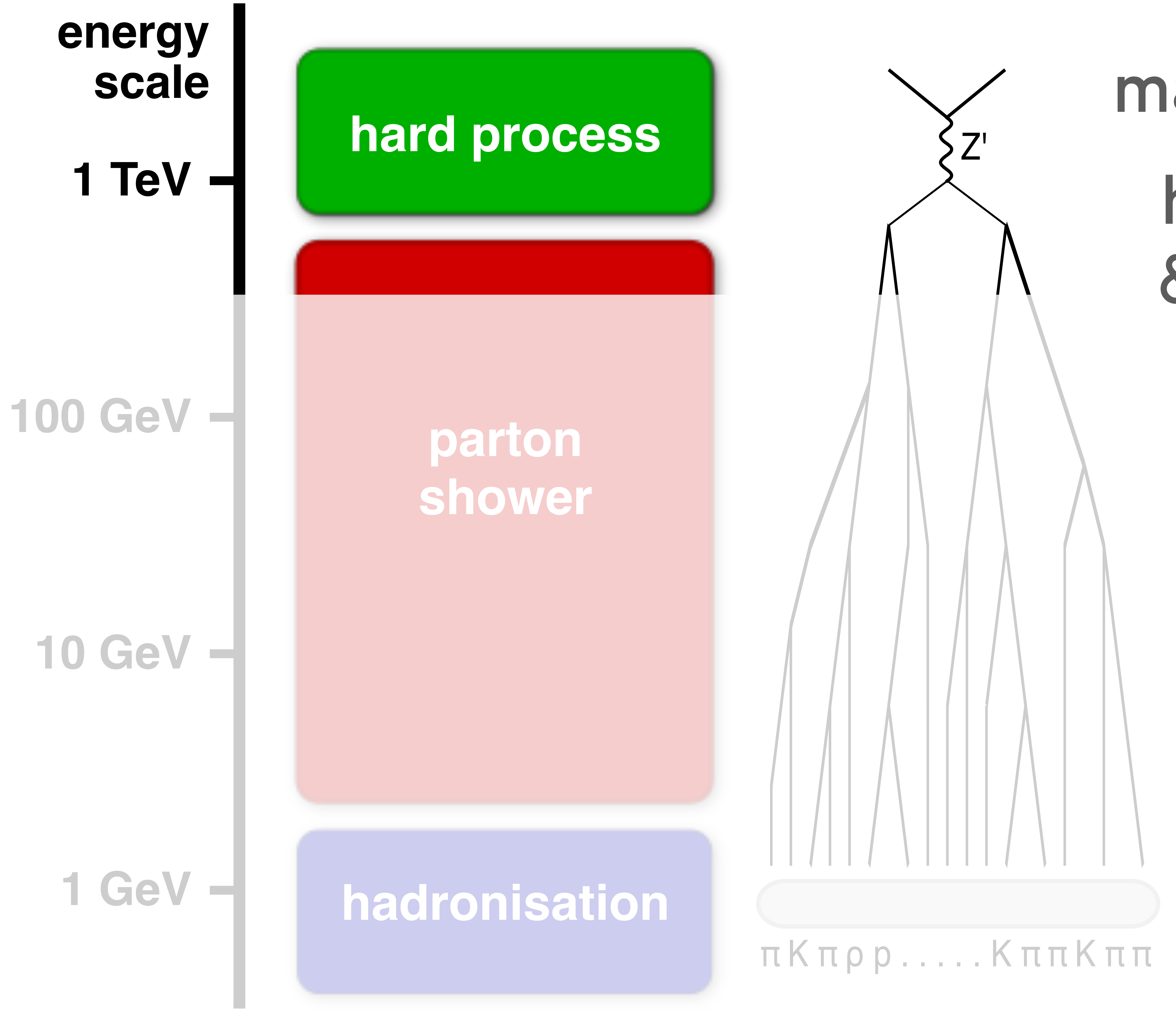

schematic view of key components of QCD predictions and Monte Carlo event simulation

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

# general purpose Monte Carlo event generators: THE BIG 3

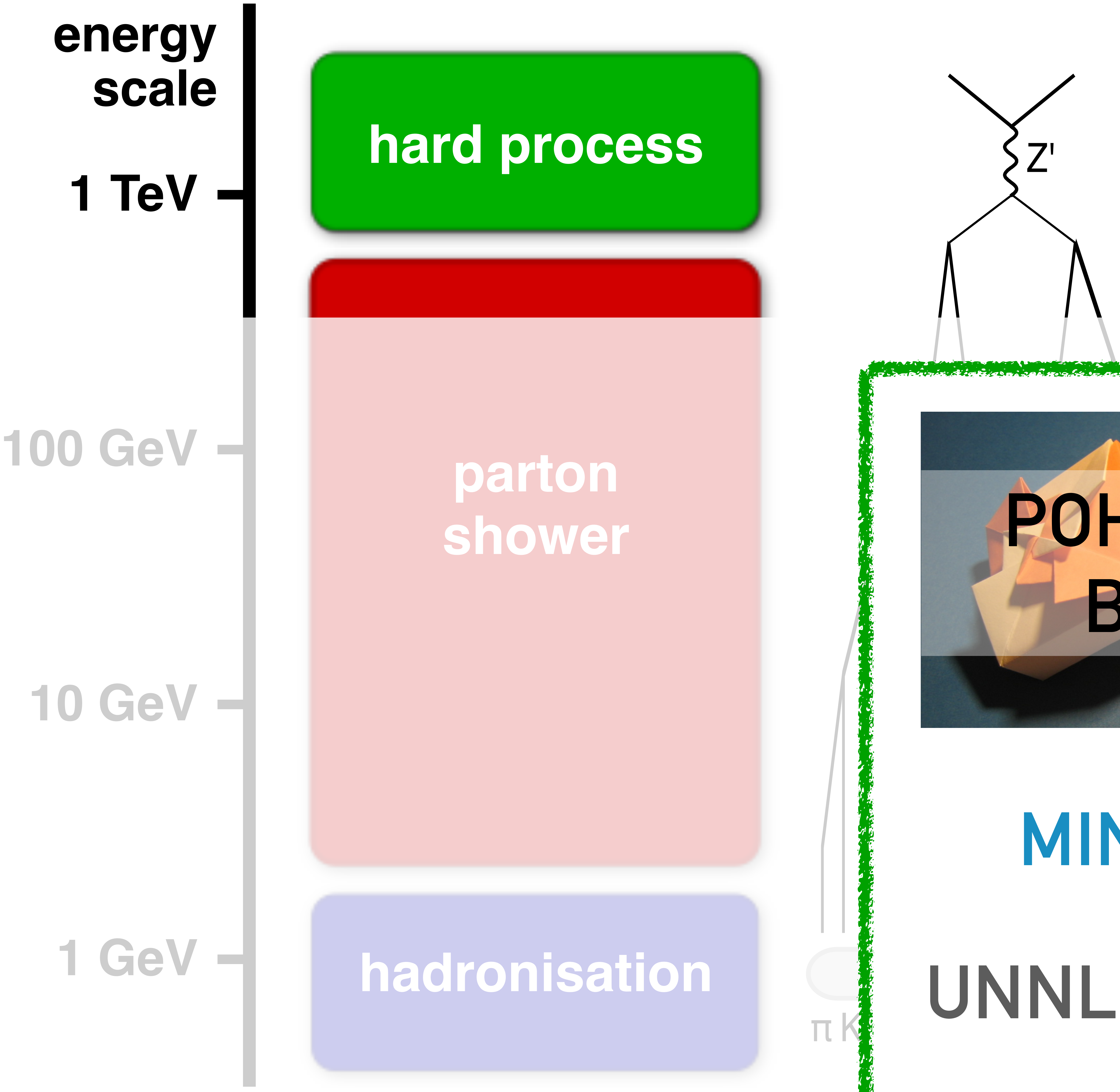
Herwig 7 Pythia 8 Sherpa 2

they do an amazing job of simulating 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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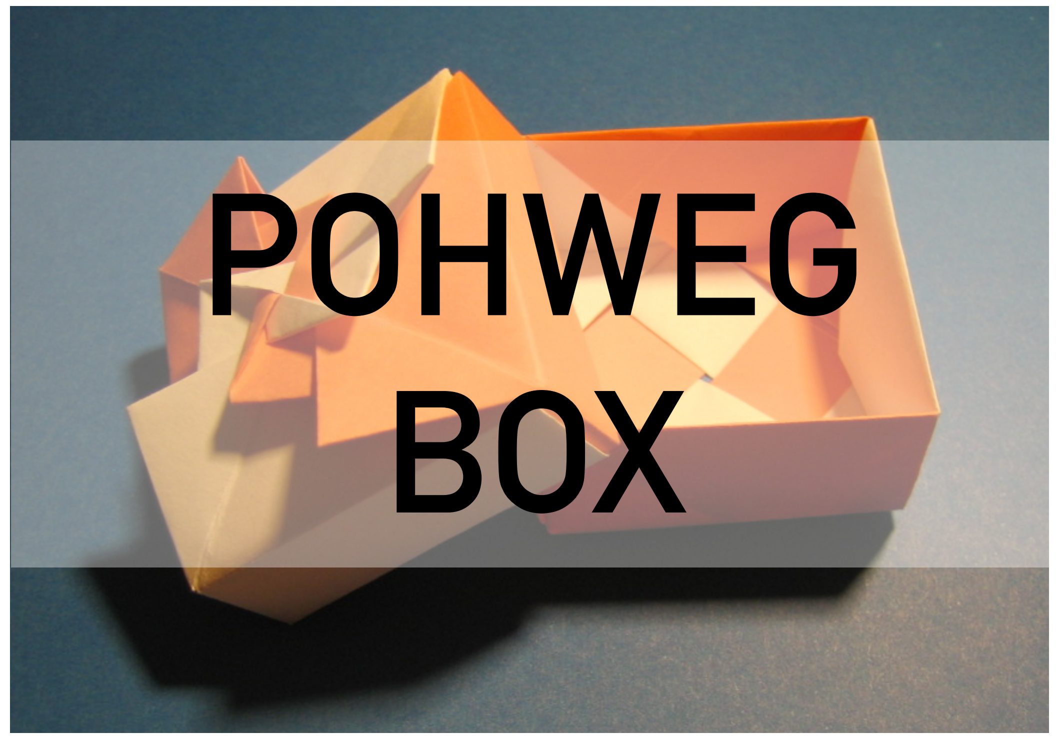



MadGraph5_aMC@NLO

MC@NLO
(in Herwig&Sherpa)

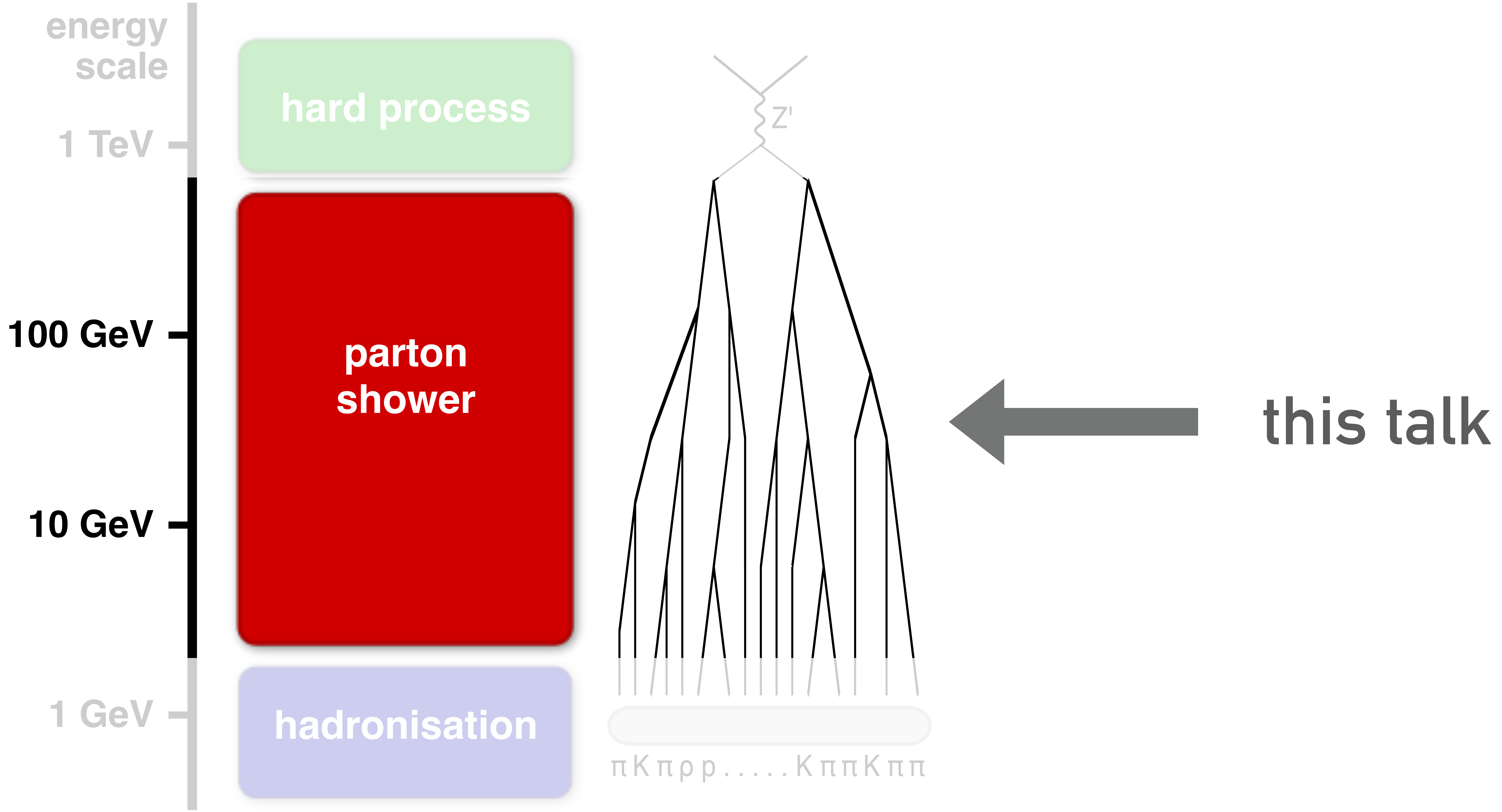
MINLO

MLM, CKKW
Vincia, FxFx

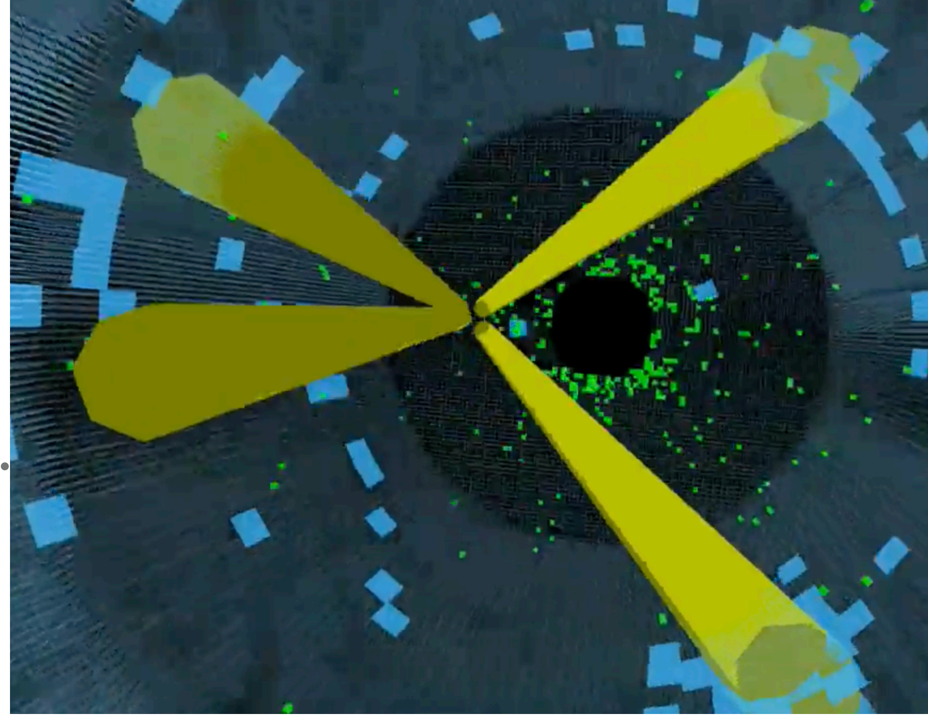
UNNLOPS

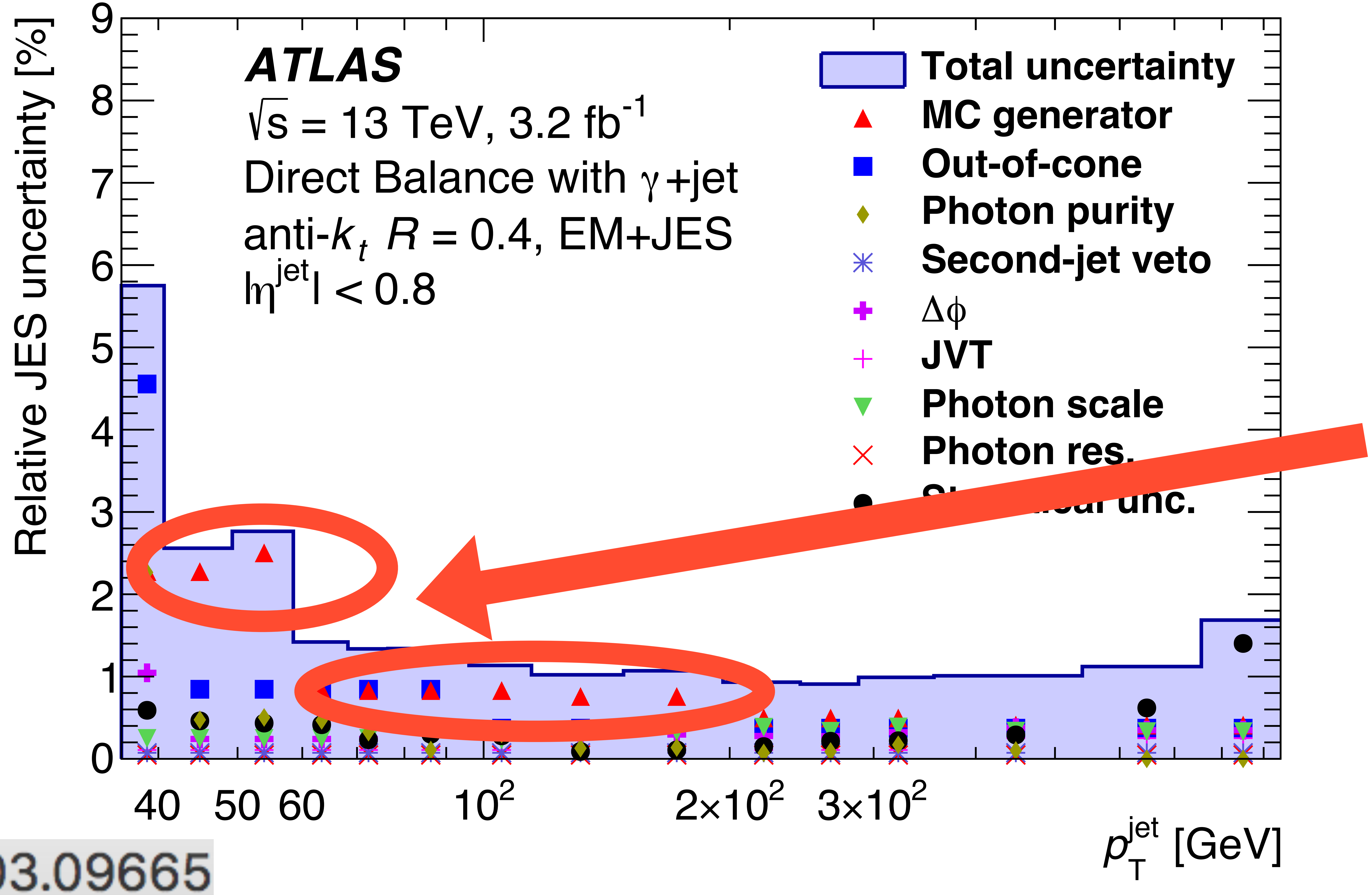
GENEVA

[...]


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

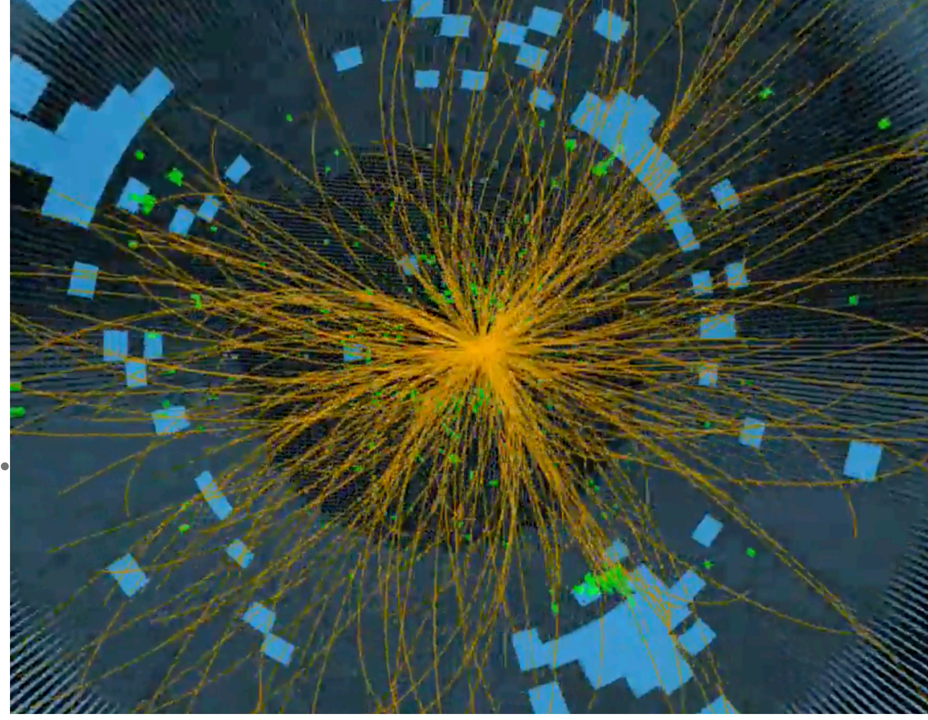
Jet energy scale, which feeds into hundreds of other measurements

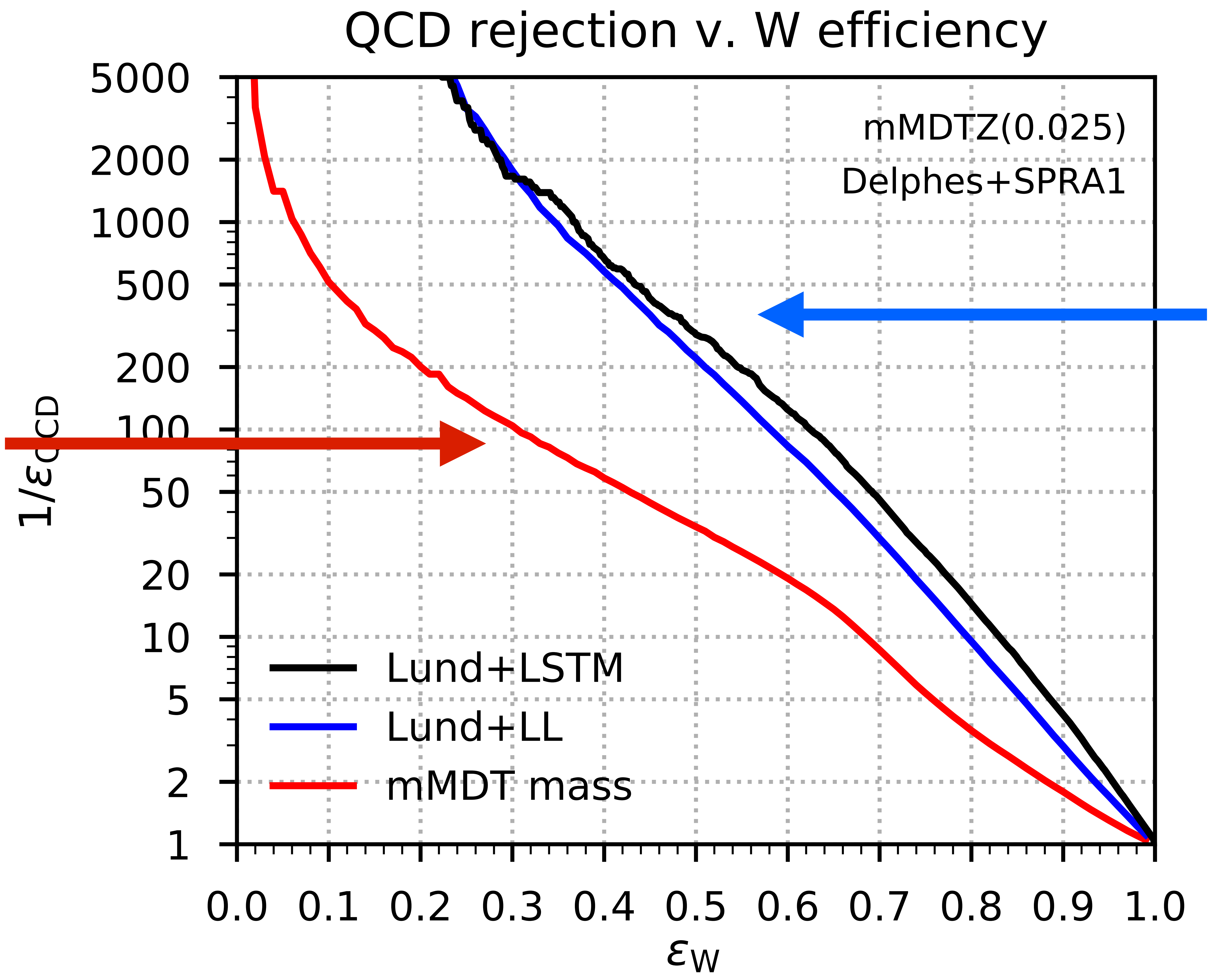
**Largest systematic errors (1–2%) come from differences between MC generators**

(here Sherpa v. Pythia)

→ fundamental limit on LHC precision potential

# using full event information: jet substructure for W tagging





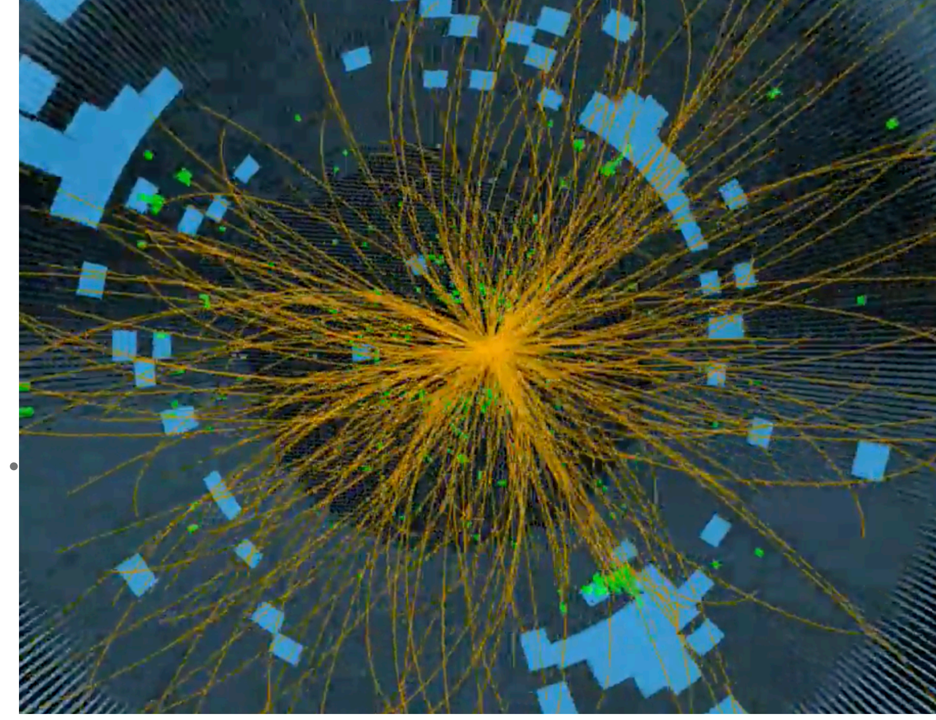

*QCD rejection with just jet mass*

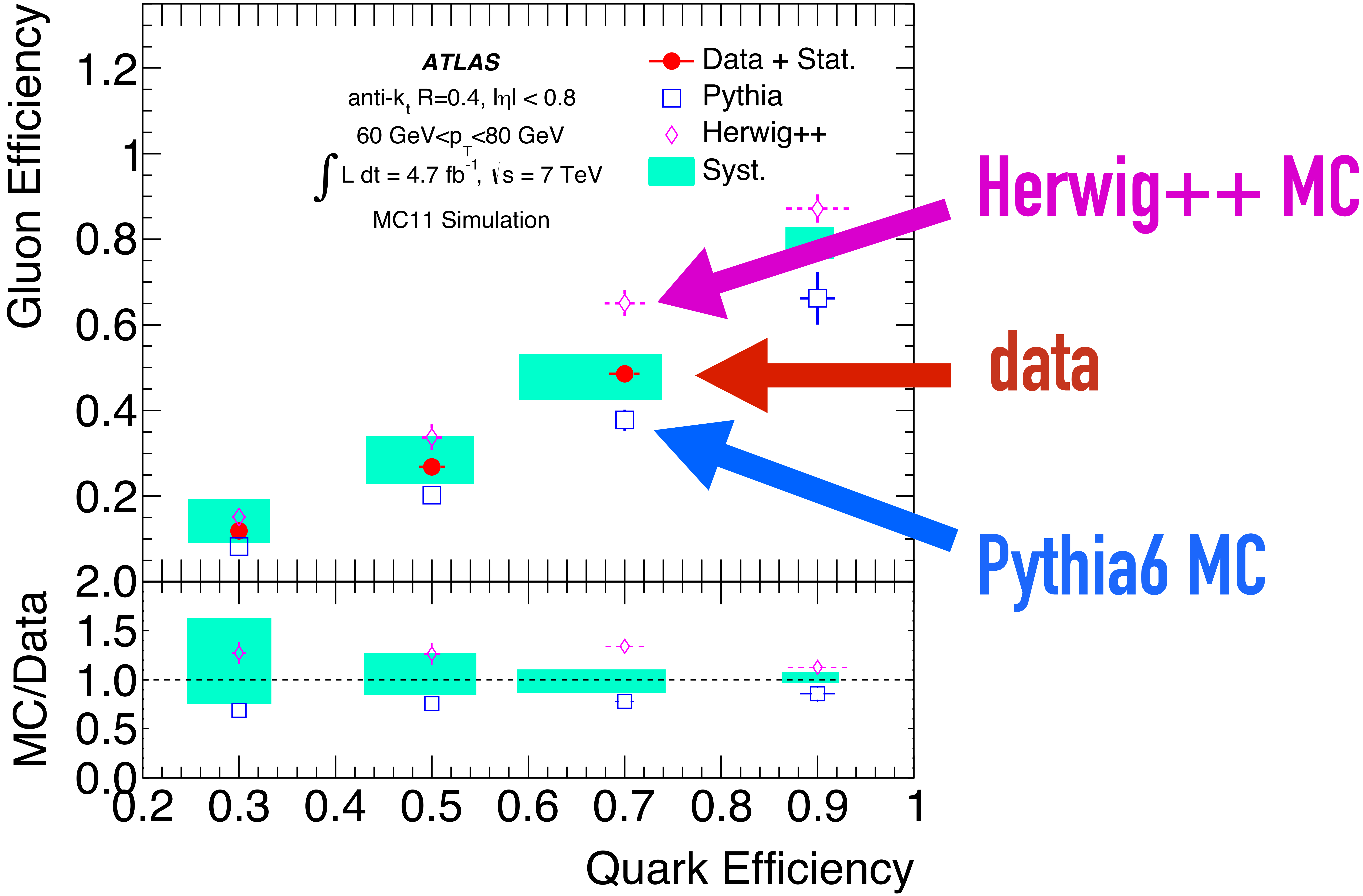
*QCD rejection with use of full jet substructure*

*5–10x better*

*taken from Dreyer, GPS & Soyez '18*

# using full event information (quark/gluon tagging)





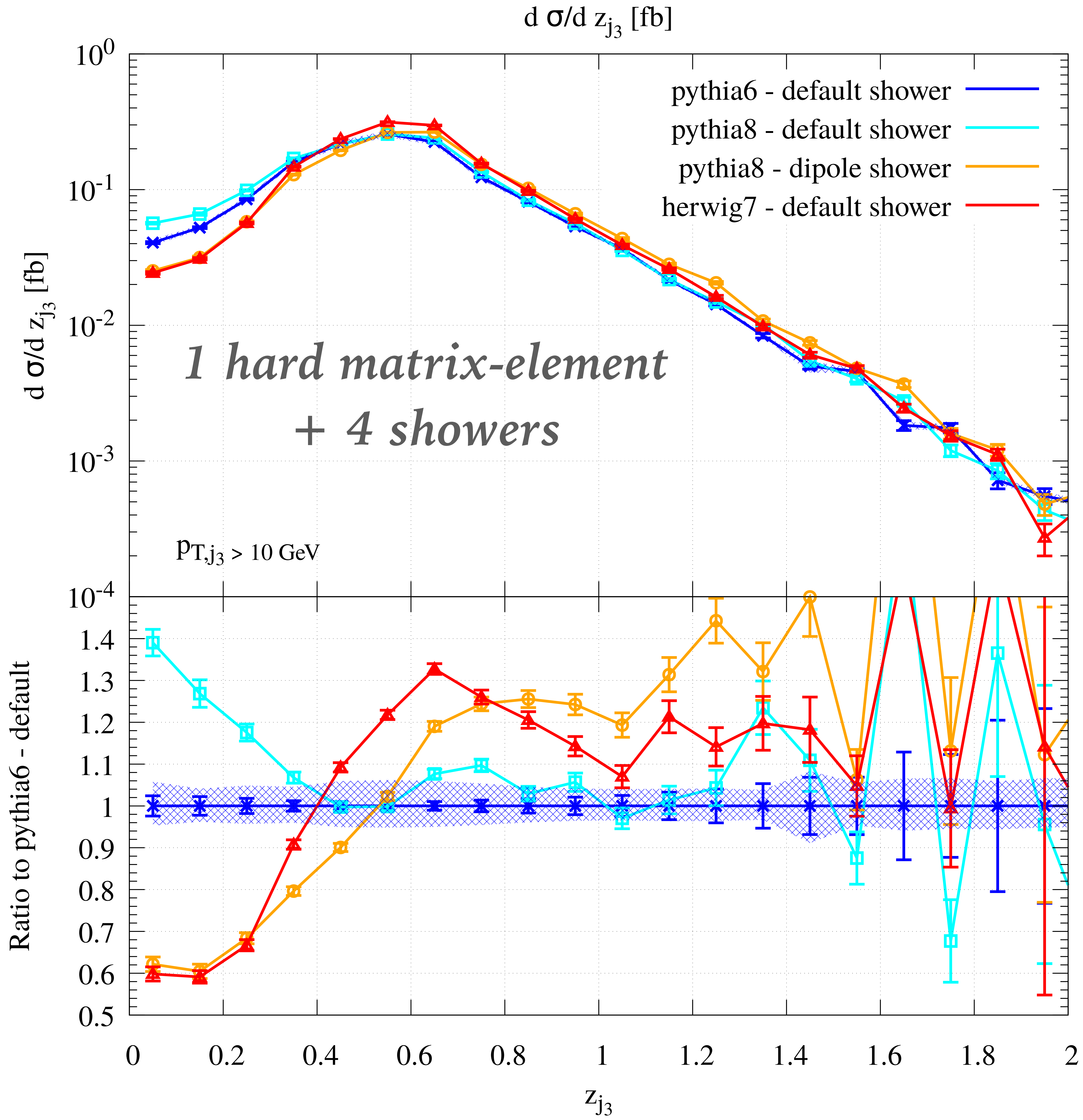

use more info → become more sensitive to MC limitations

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

$$z_{j3} = \left| \frac{y_{j3} - \frac{1}{2}(y_{j1} + y_{j2})}{\Delta y_{j1,j2}} \right|$$

*VBF central jet veto region: $z_{j3} < 0.5$*

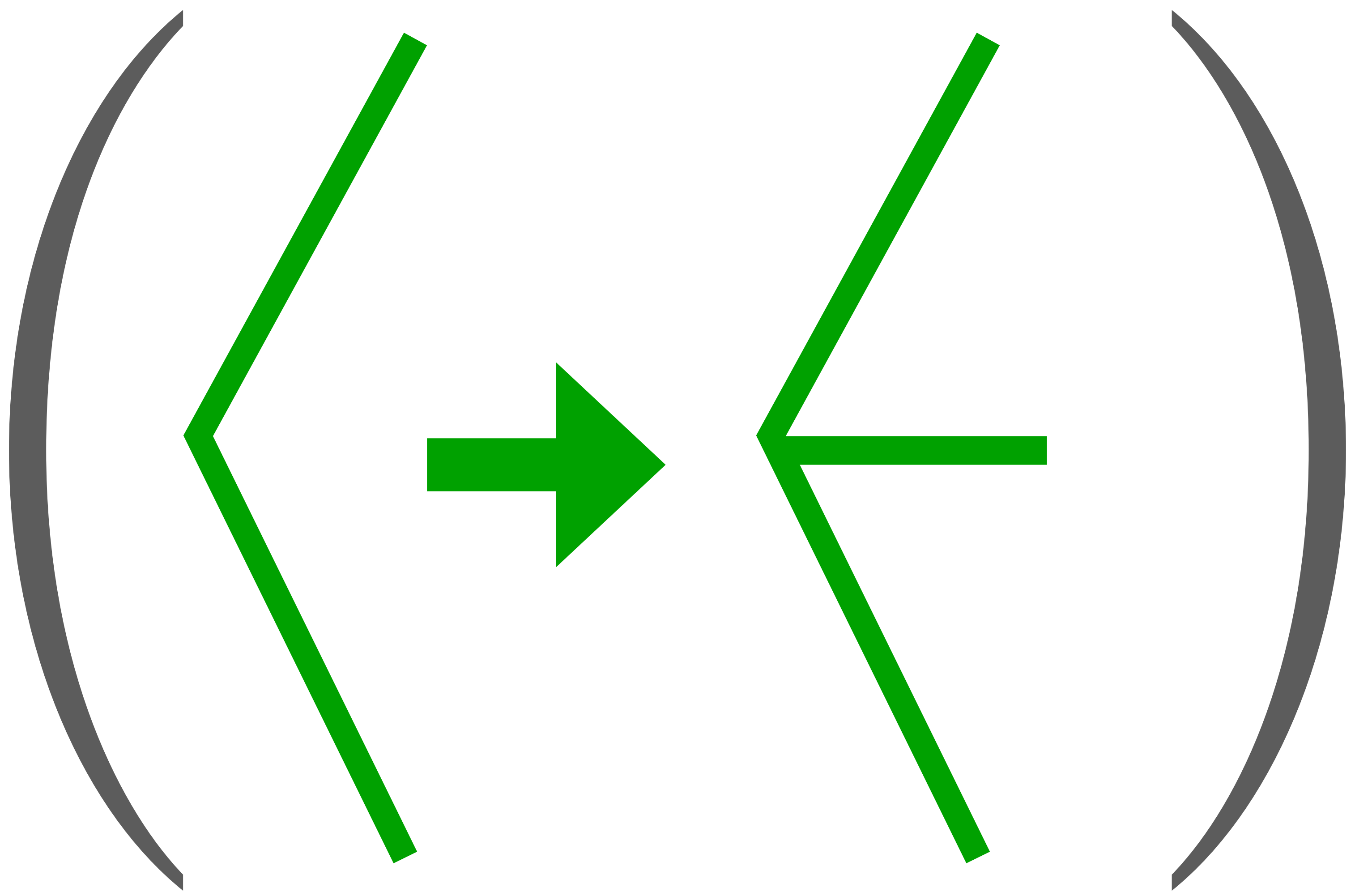
# what is a parton shower?

*illustrate with dipole / antenna showers*

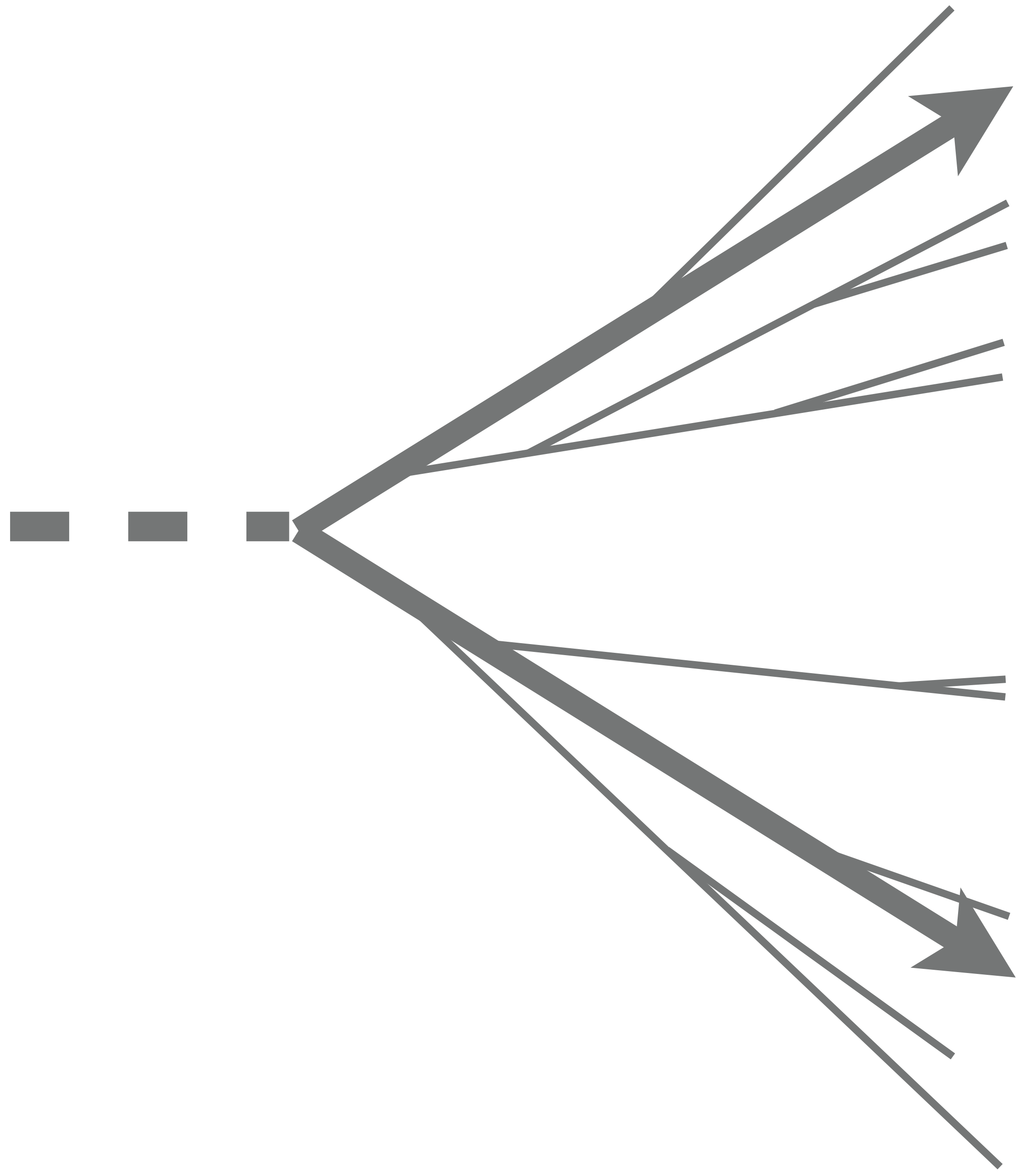
*Gustafson & Pettersson 1988, Ariadne 1992, main Sherpa & Pythia8 showers, option in Herwig7, Vincia shower & (partially) Deductor shower*

# At its simplest

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

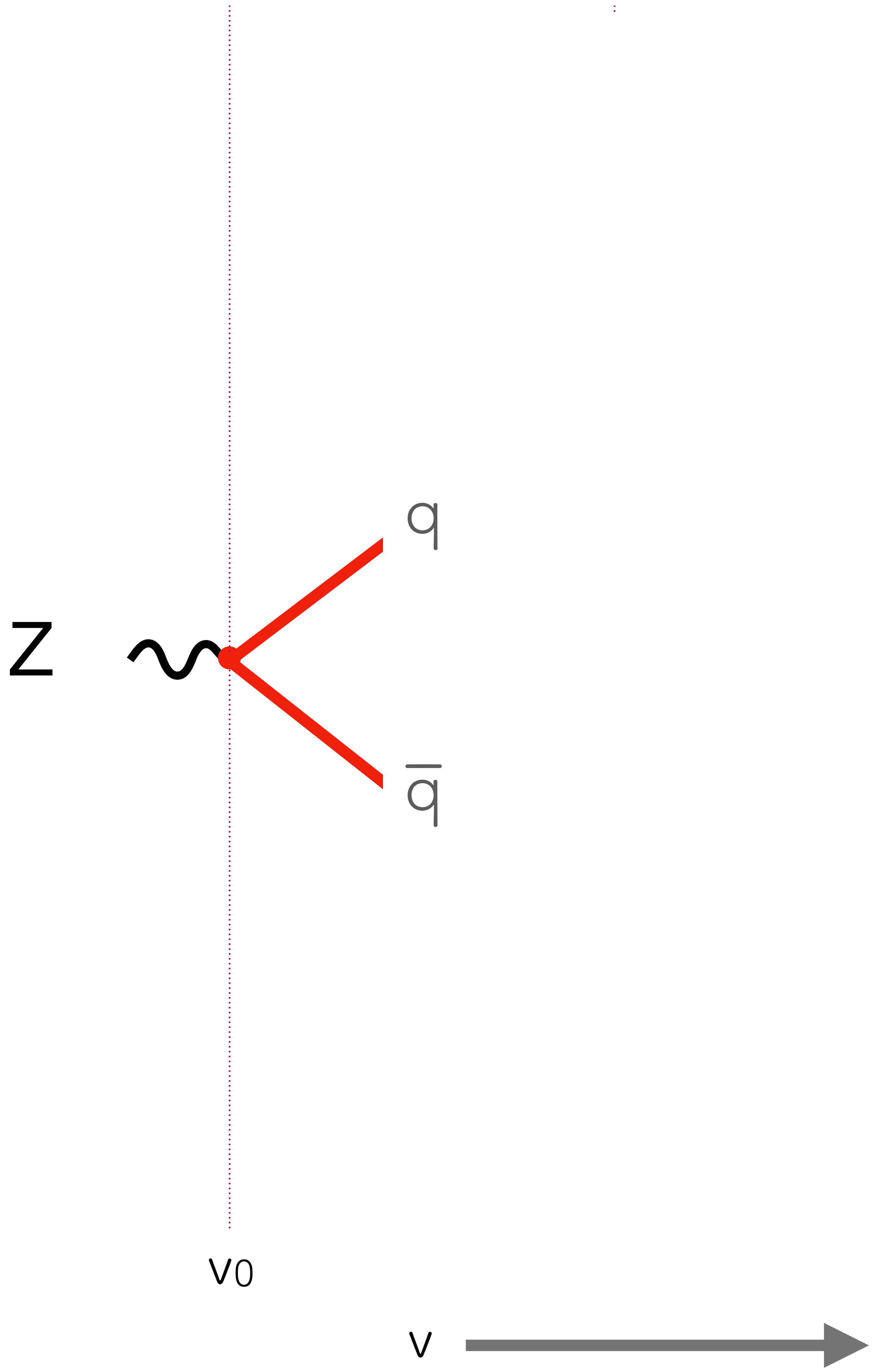


$=$



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

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

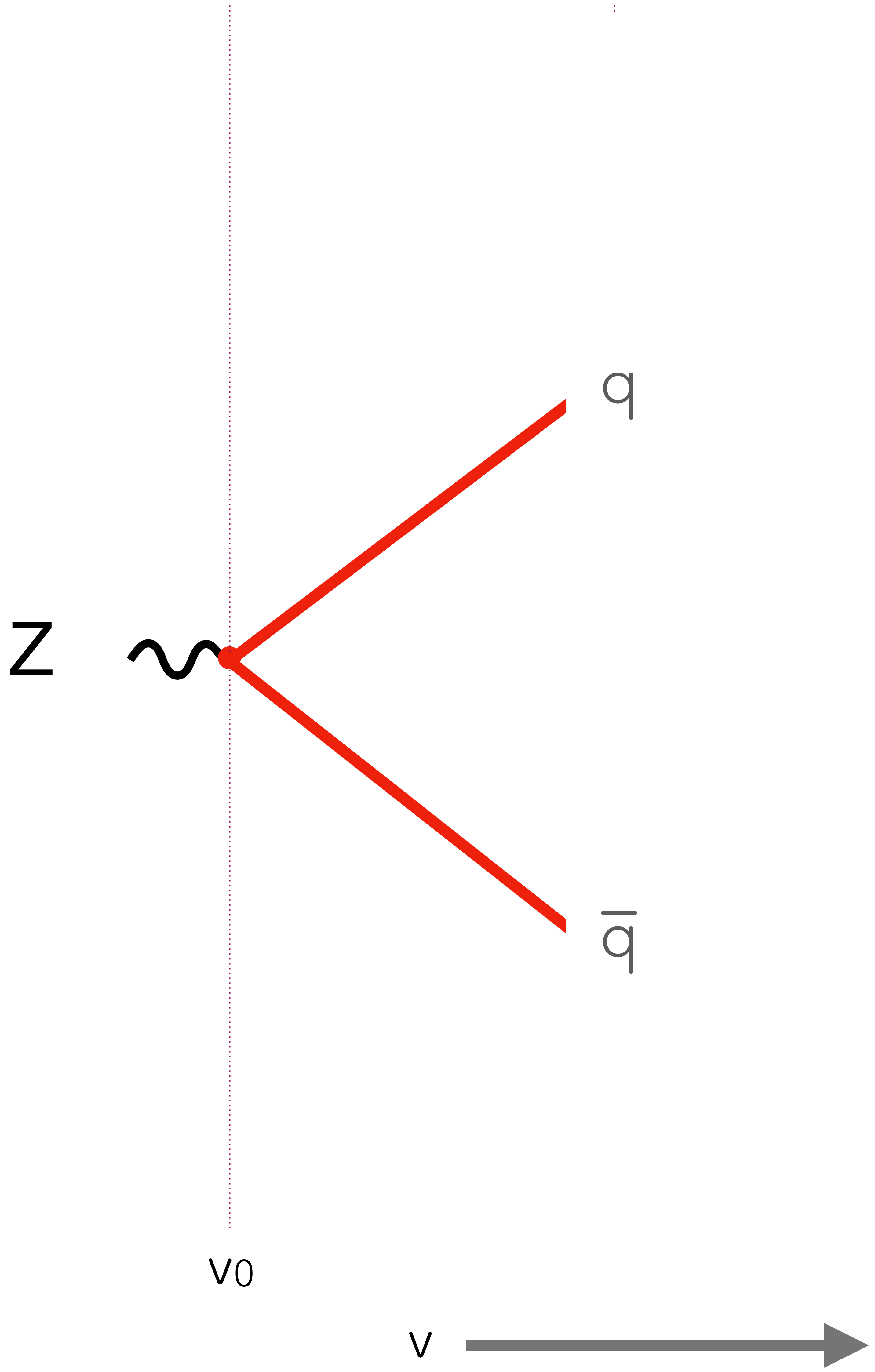



Start with q-qbar state.

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

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

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

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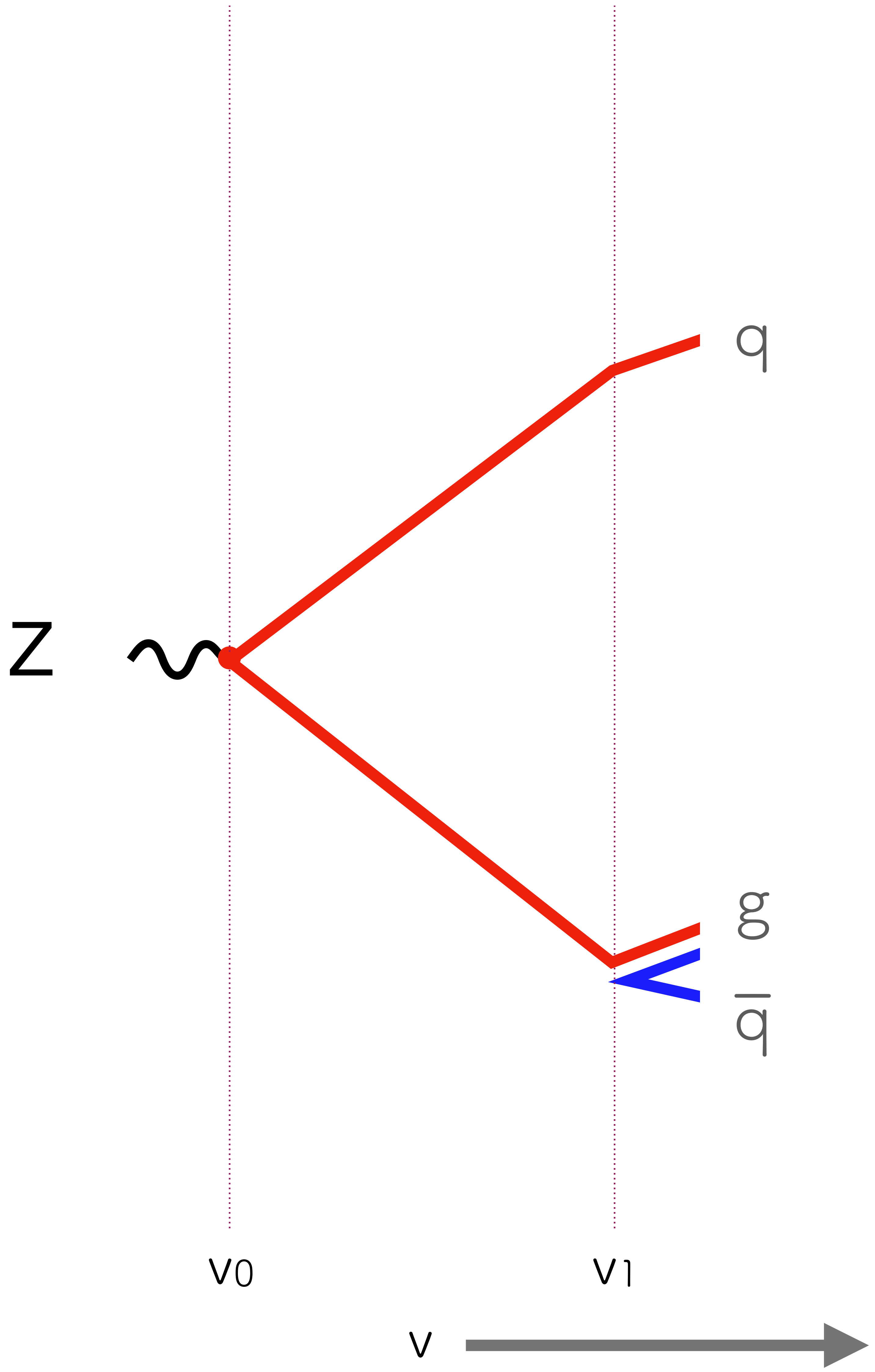



Start with q-qbar state.

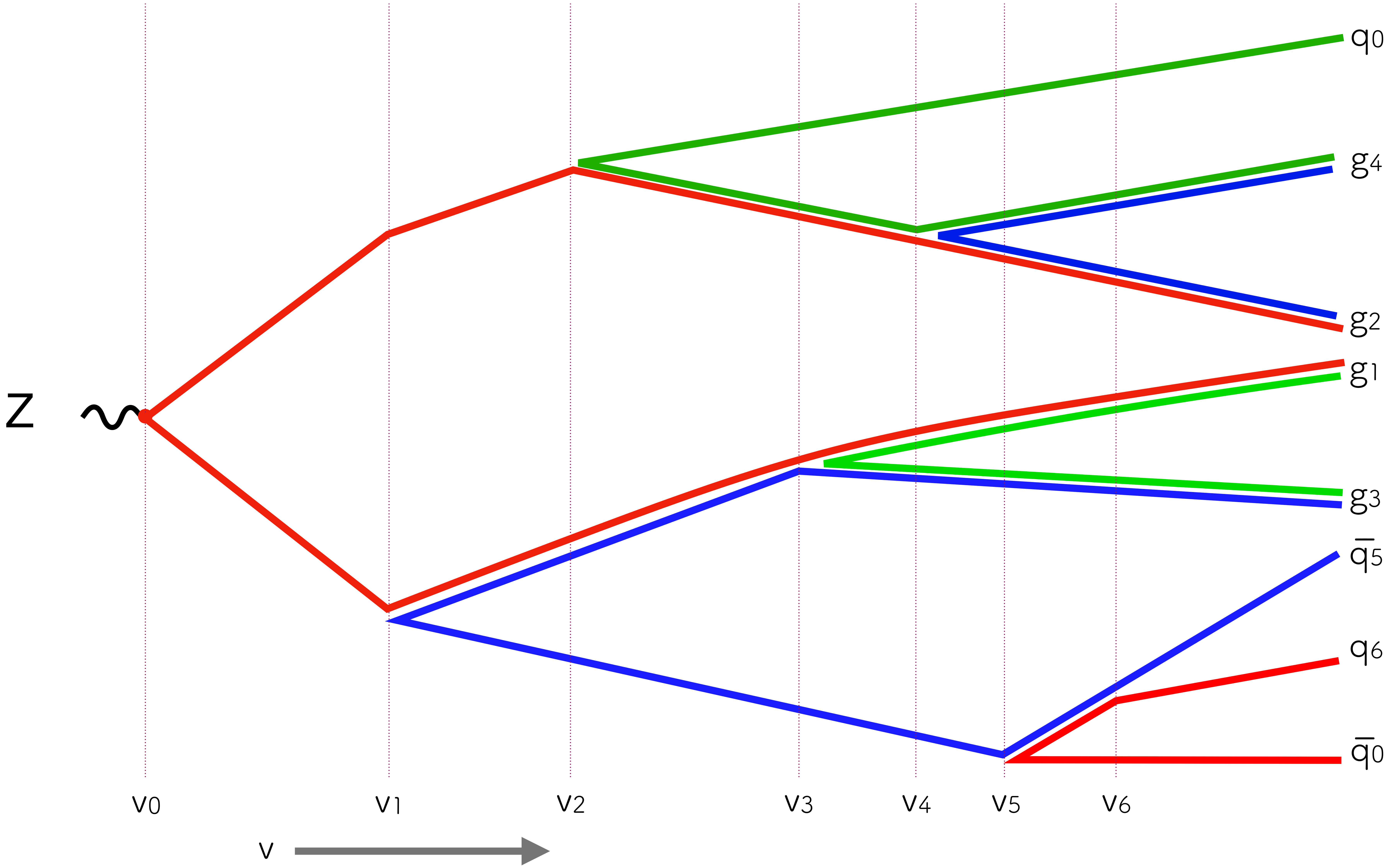
Evolve a step in v and throw a random number to decide if state remains unchanged

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

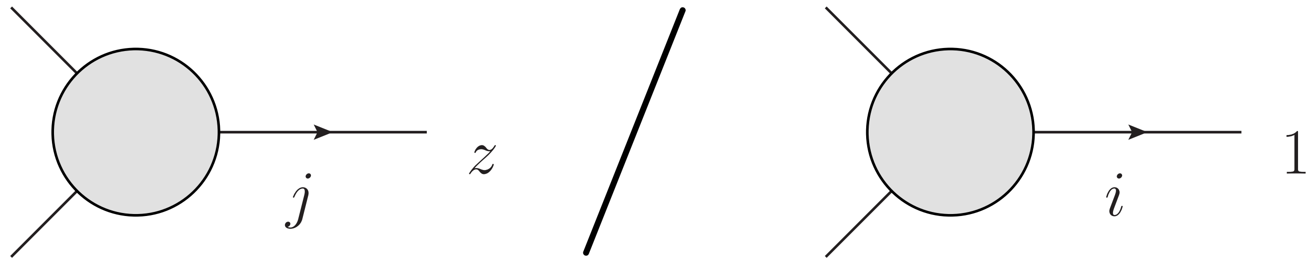
# recent directions of parton-shower work?

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

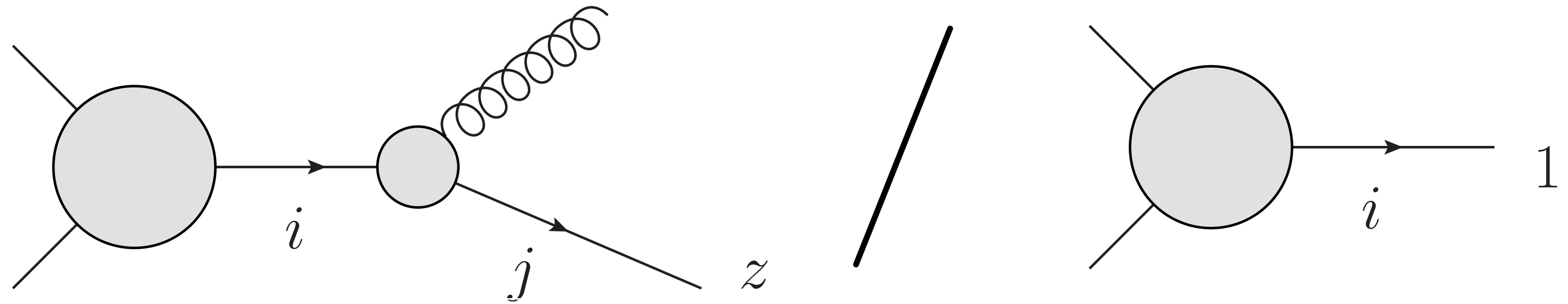
# Including 1→ 3 splittings (≡ 2→4)

- 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

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

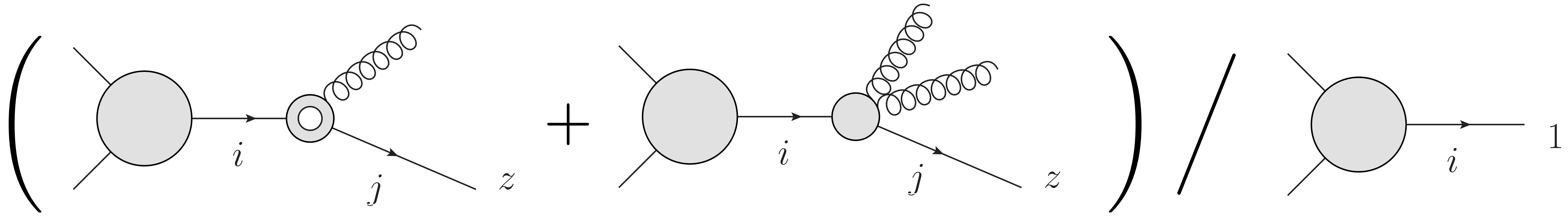



$$D_{ji}^{(1)}(z,\mu) = -\frac{1}{\varepsilon}P_{ji}^{(0)}(z) \qquad \leftrightarrow$$



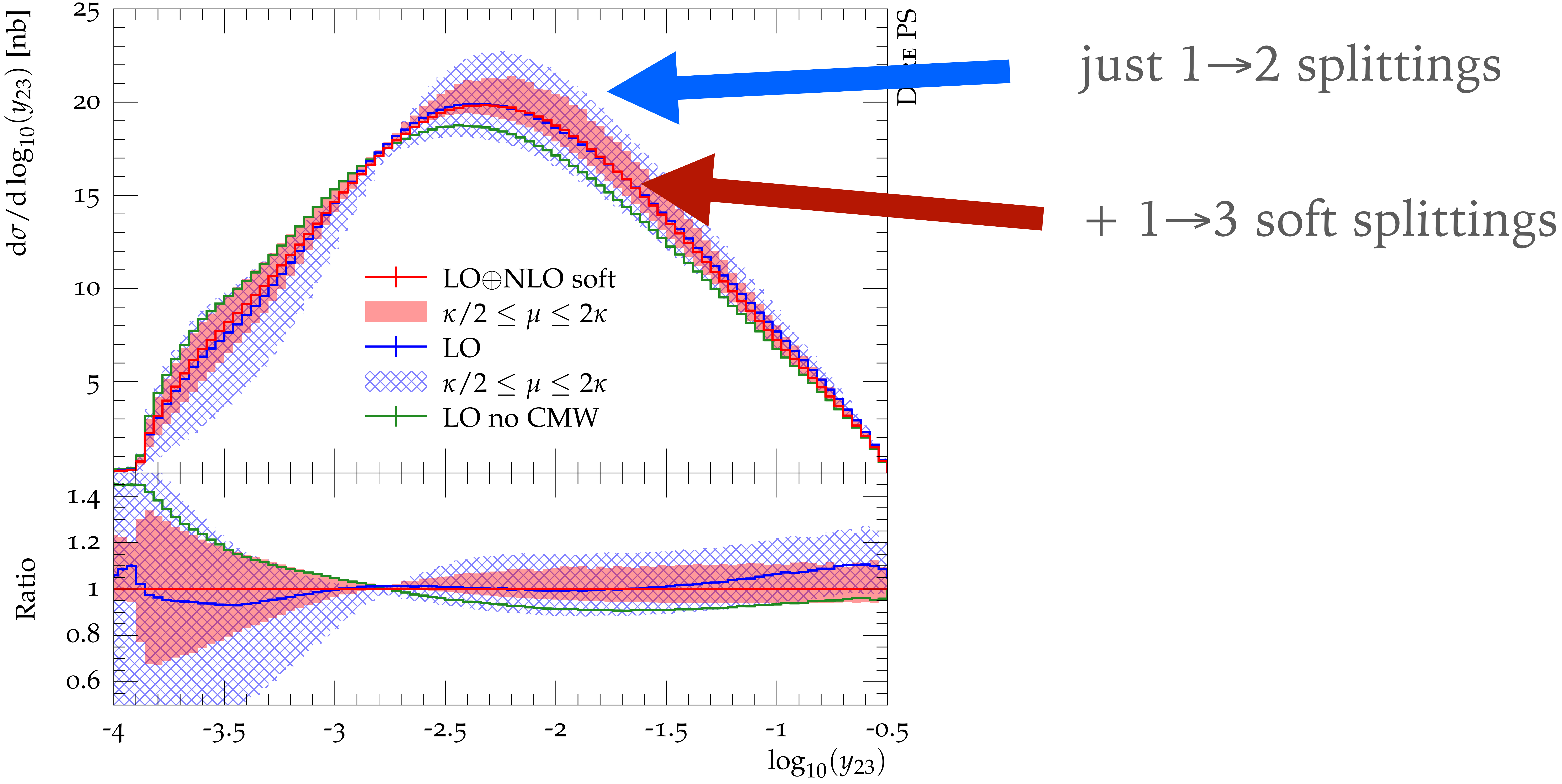

$$D_{ji}^{(2)}(z,\mu) = -\frac{1}{2\varepsilon}P_{ji}^{(1)}(z) + \frac{\beta_0}{4\varepsilon^2}P_{ji}^{(0)}(z) + \frac{1}{2\varepsilon^2}\int_z^1 \frac{\mathrm{d}x}{x}P_{jk}^{(0)}(x)P_{ki}^{(0)}(z/x)$$

$\leftrightarrow$




*Equations from slides by Höche*

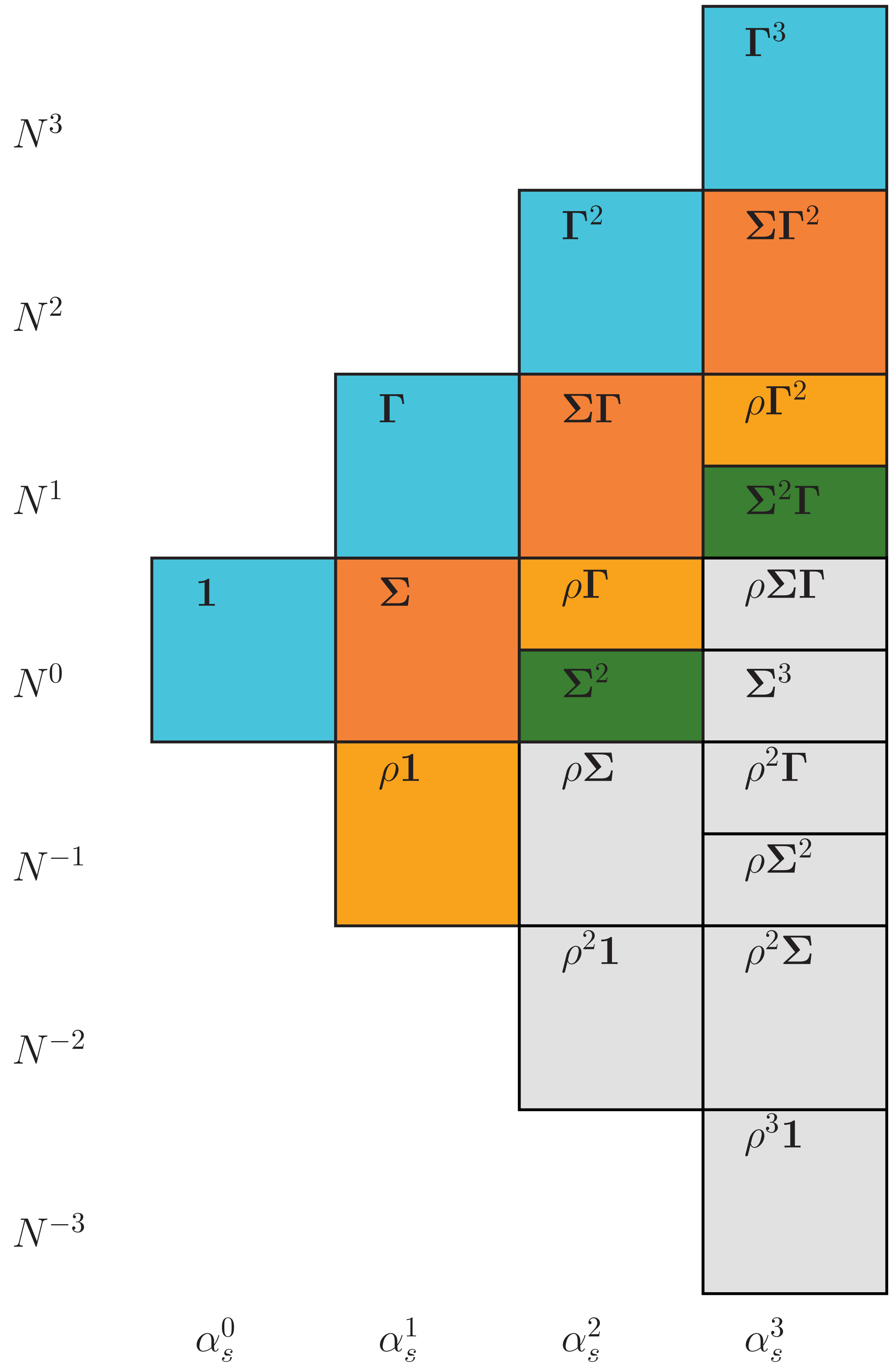
# Including 1→ 3 splittings



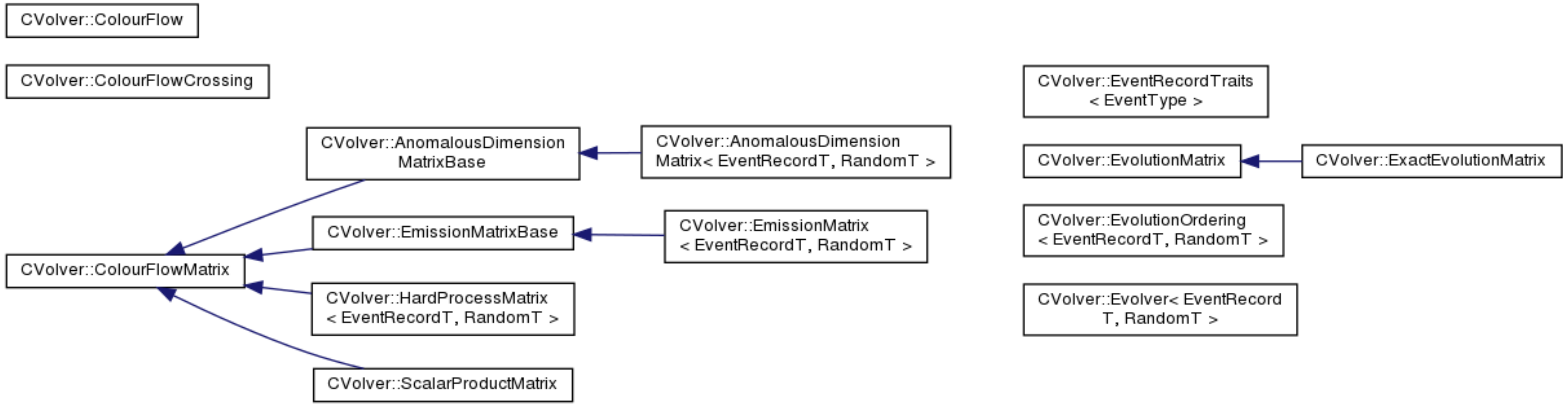

*Dulat, Höche & Prestel, 1805.03757*

# 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




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

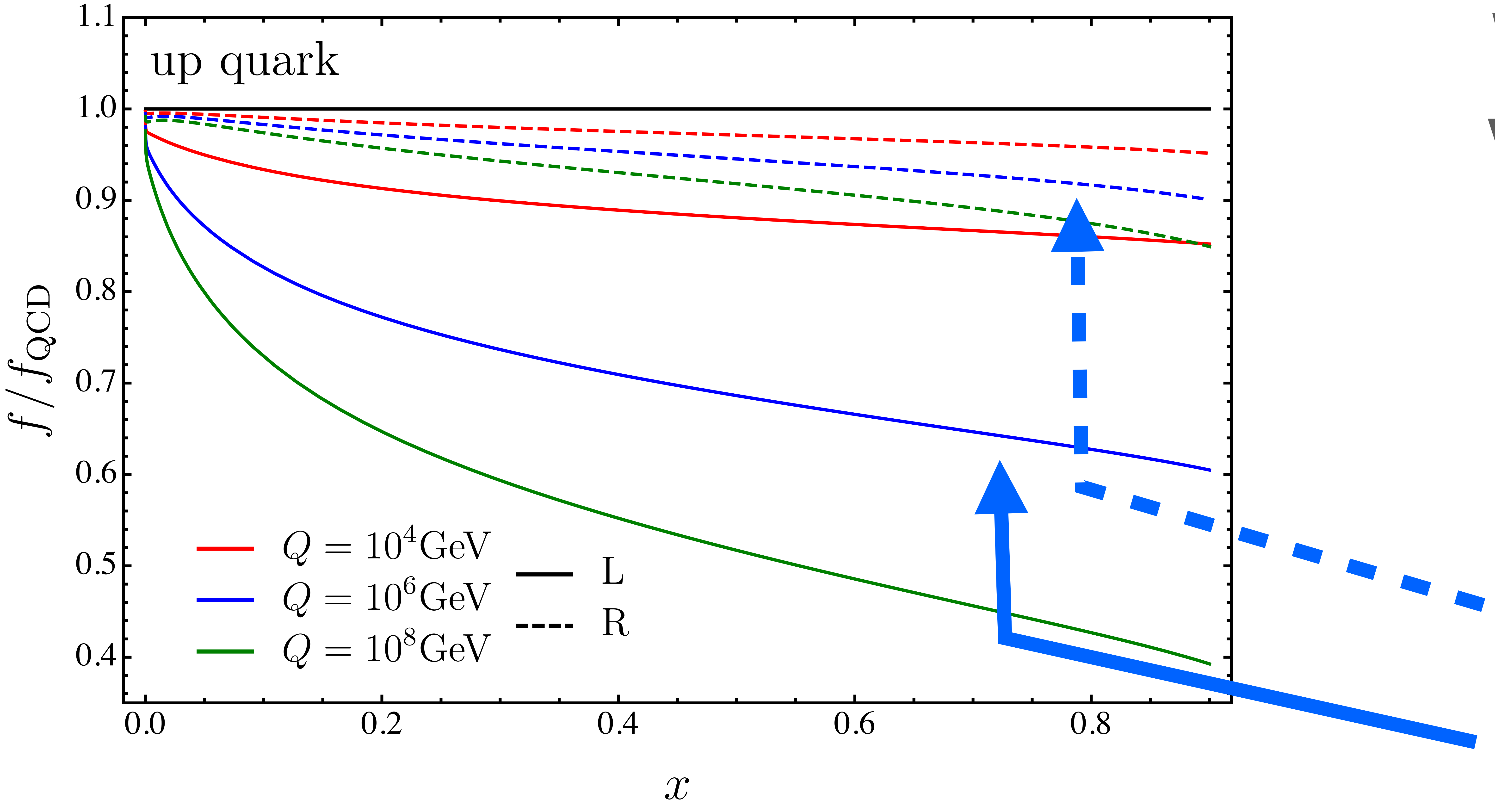



Plugin approach can accommodate anything from (N)GLs to full parton showers.

*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

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

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]*

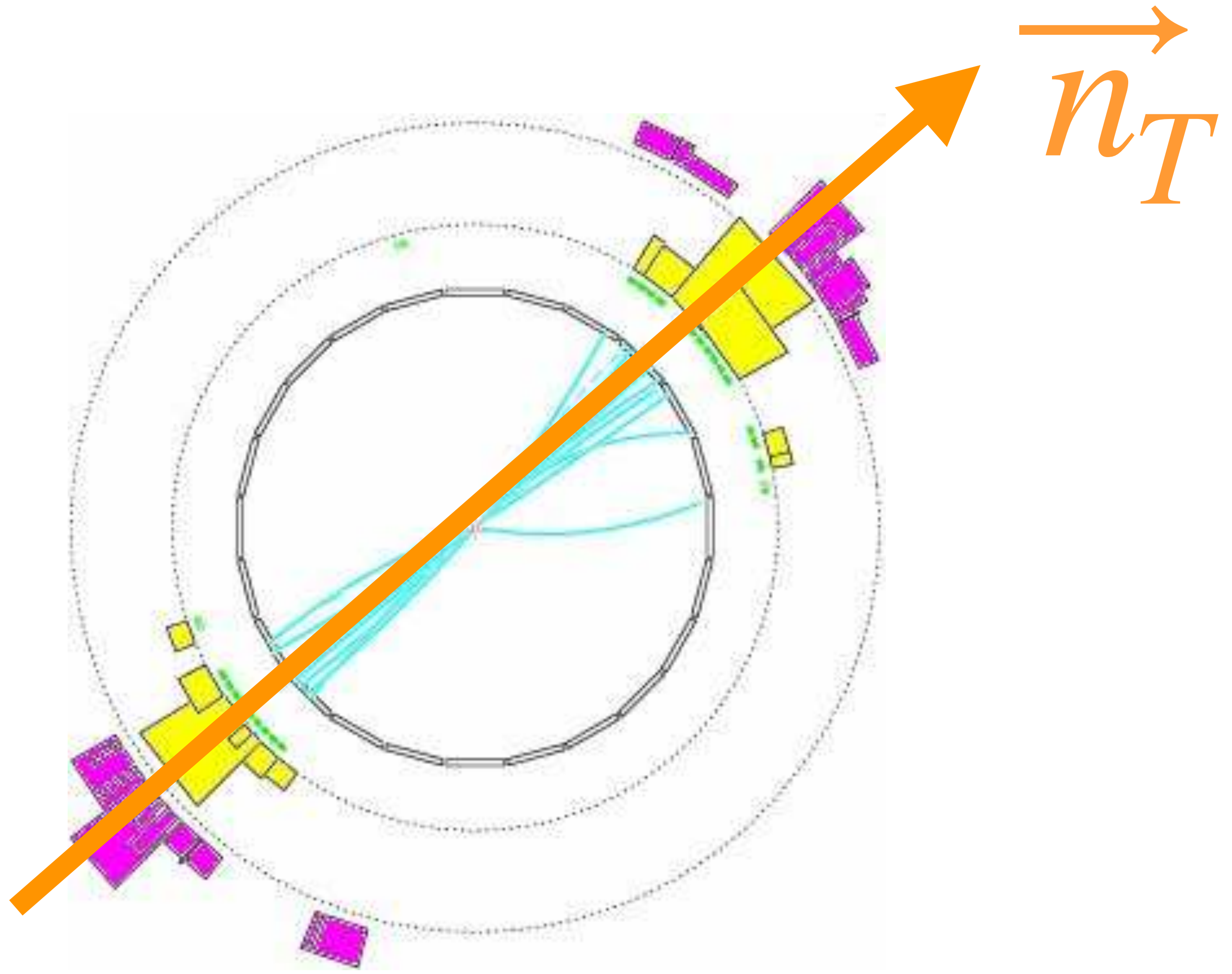
**how can you prescribe correctness & accuracy of the answer, when the questions you ask can be arbitrary?**

# 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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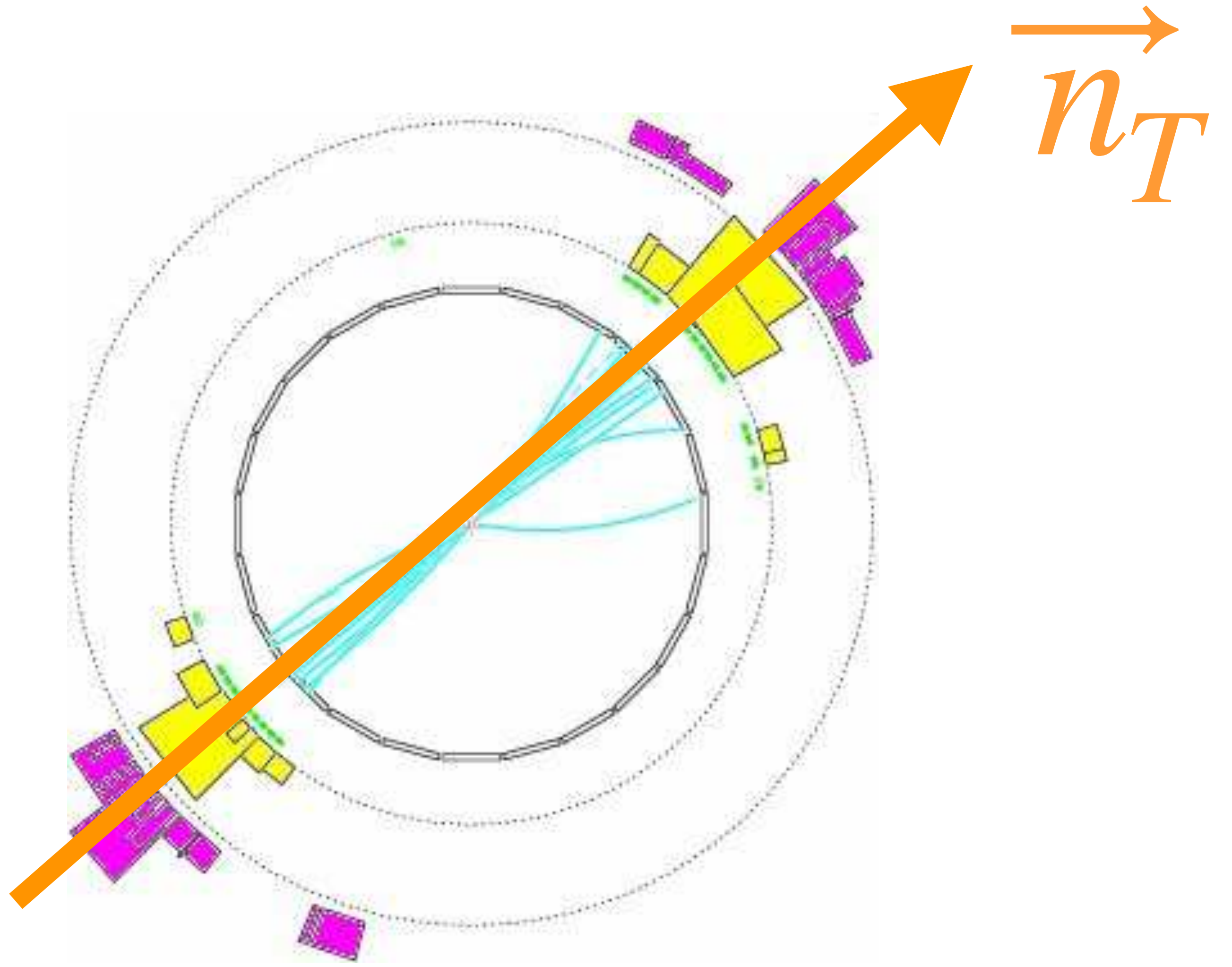
That language, widespread for multiscale problems, comes from analytical resummations. E.g. for (famous) "Thrust"

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




2-jet event: $T \simeq 1$

$$\sigma(1 - T < e^{-L}) = \sigma_{tot} \exp\left[\underbrace{L g_1(\alpha_s L)}_{\text{LL}} + \underbrace{g_2(\alpha_s L)}_{\text{NLL}} + \underbrace{\alpha_s g_3(\alpha_s L)}_{\text{NNLL}} + \underbrace{\alpha_s^2 g_4(\alpha_s L)}_{\text{N}^3\text{LL}} + \cdots\right]$$

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

*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* $1+\alpha_s(t)/(2\pi)K$"

**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*.

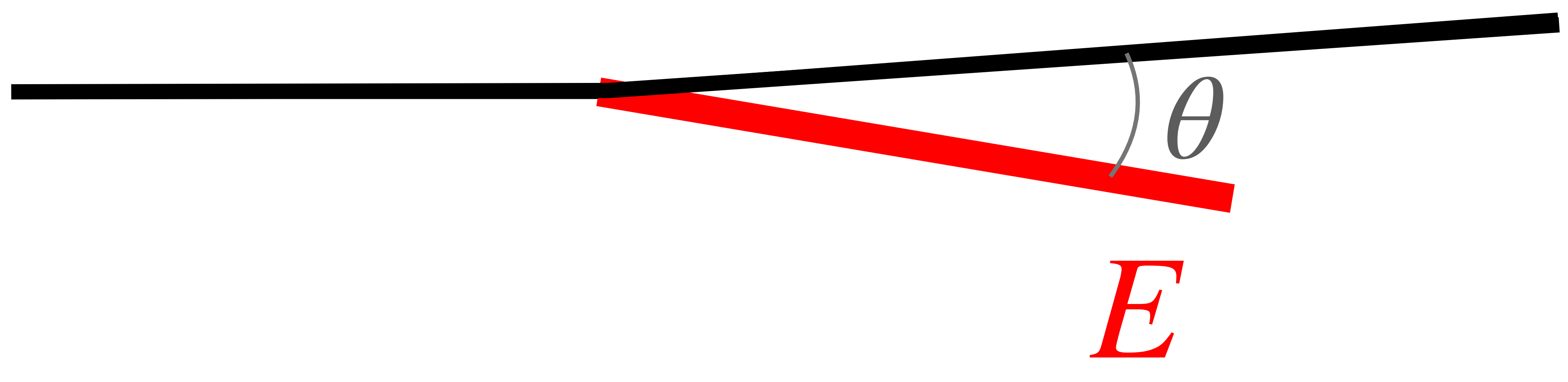
# Examine two showers

- **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)



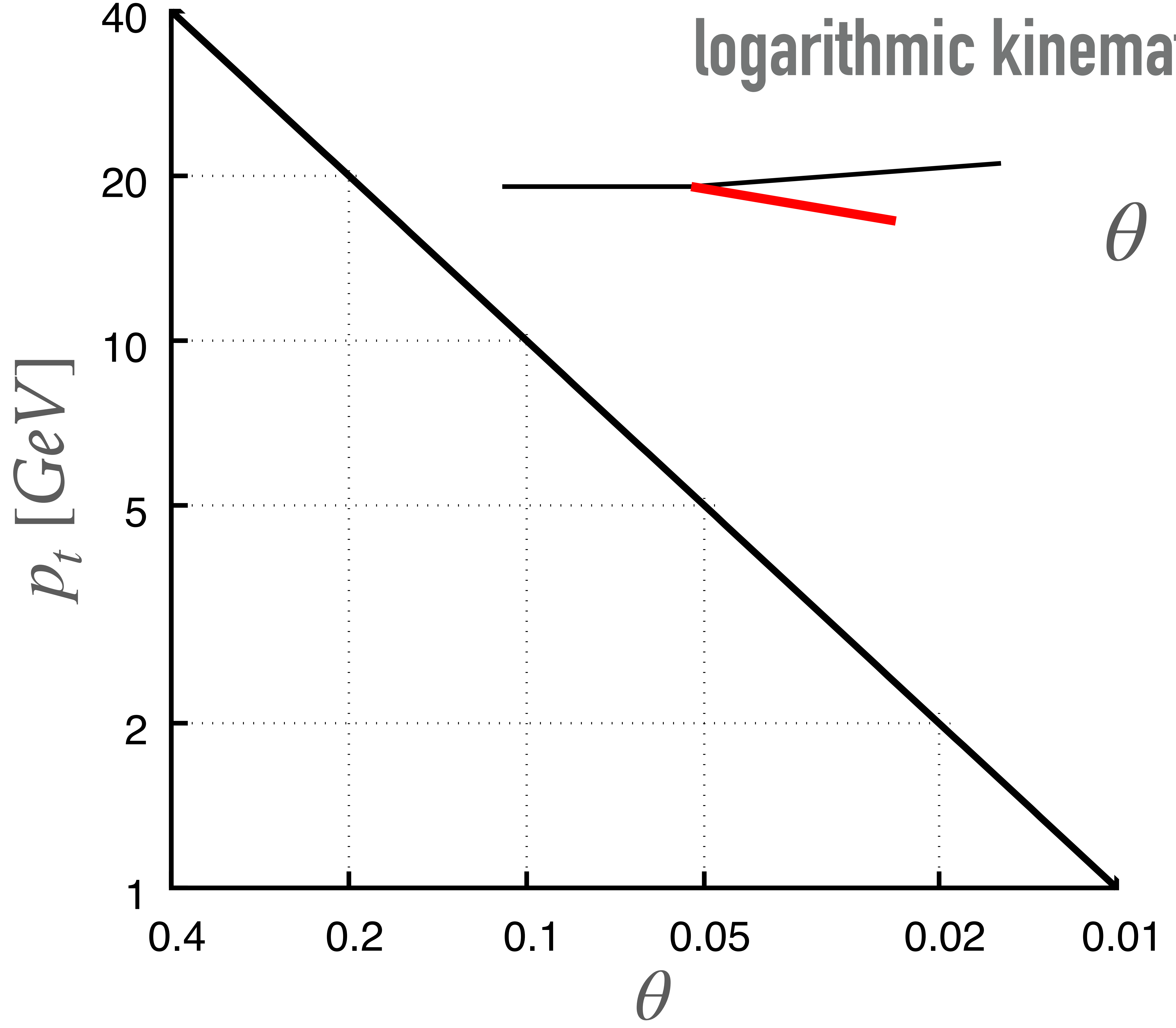

$$\theta \ (or \ \eta = -\ln\tan\frac{\theta}{2})$$

*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**

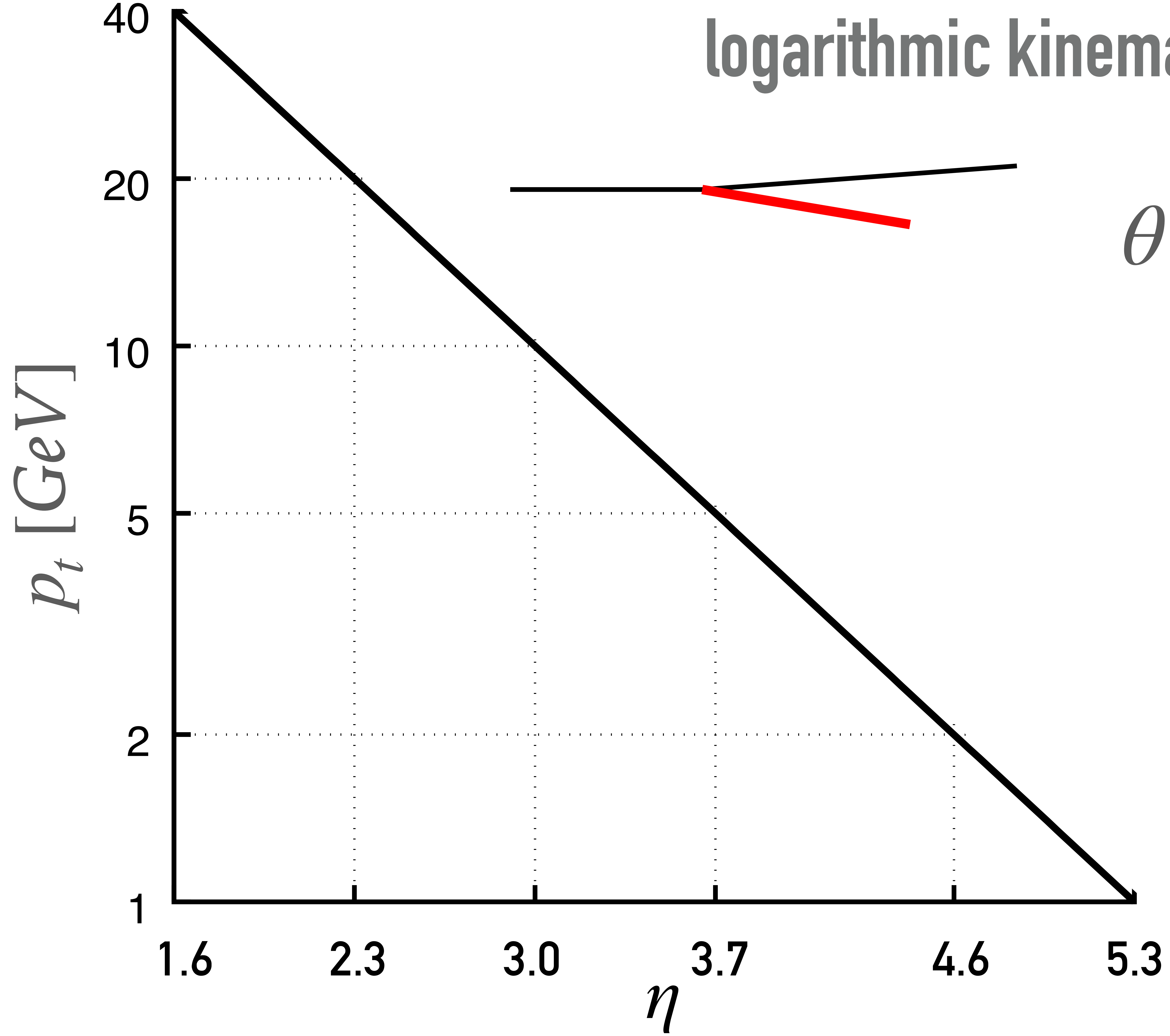
$$\theta \ (or \ \eta = -\ln\tan\frac{\theta}{2})$$

$$p_t = E\theta$$

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

# The Lund Plane

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

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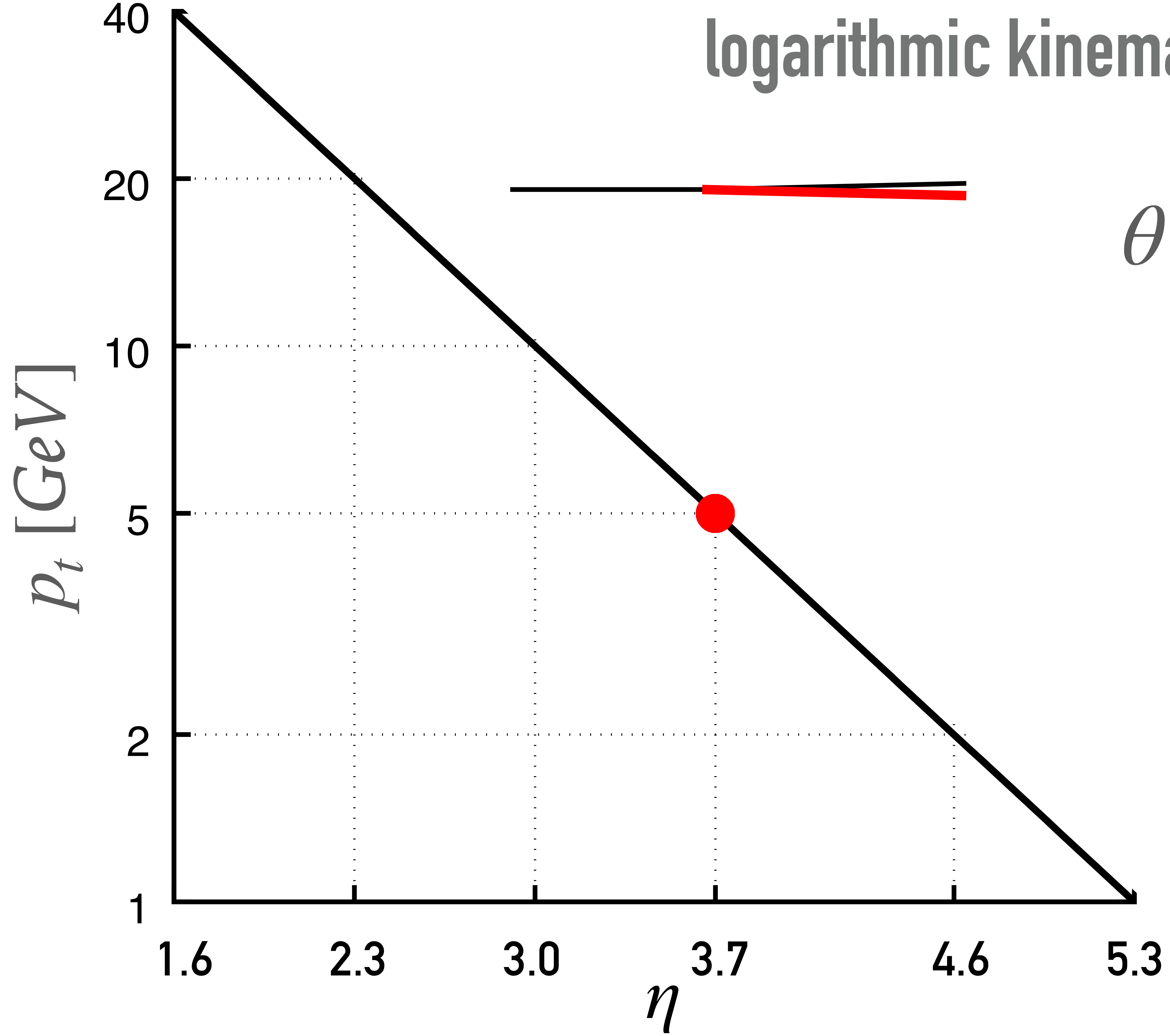
# The Lund Plane

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

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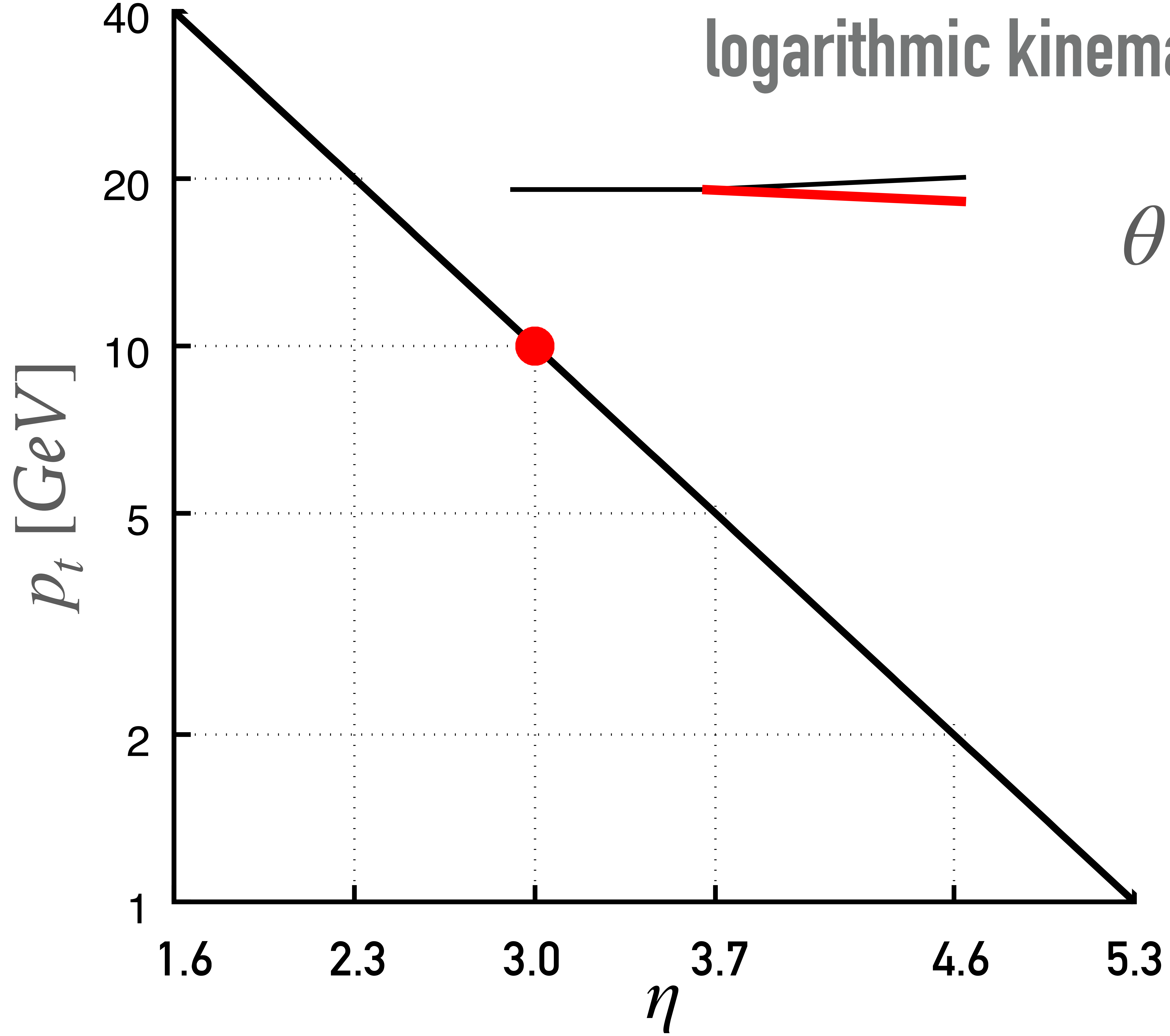


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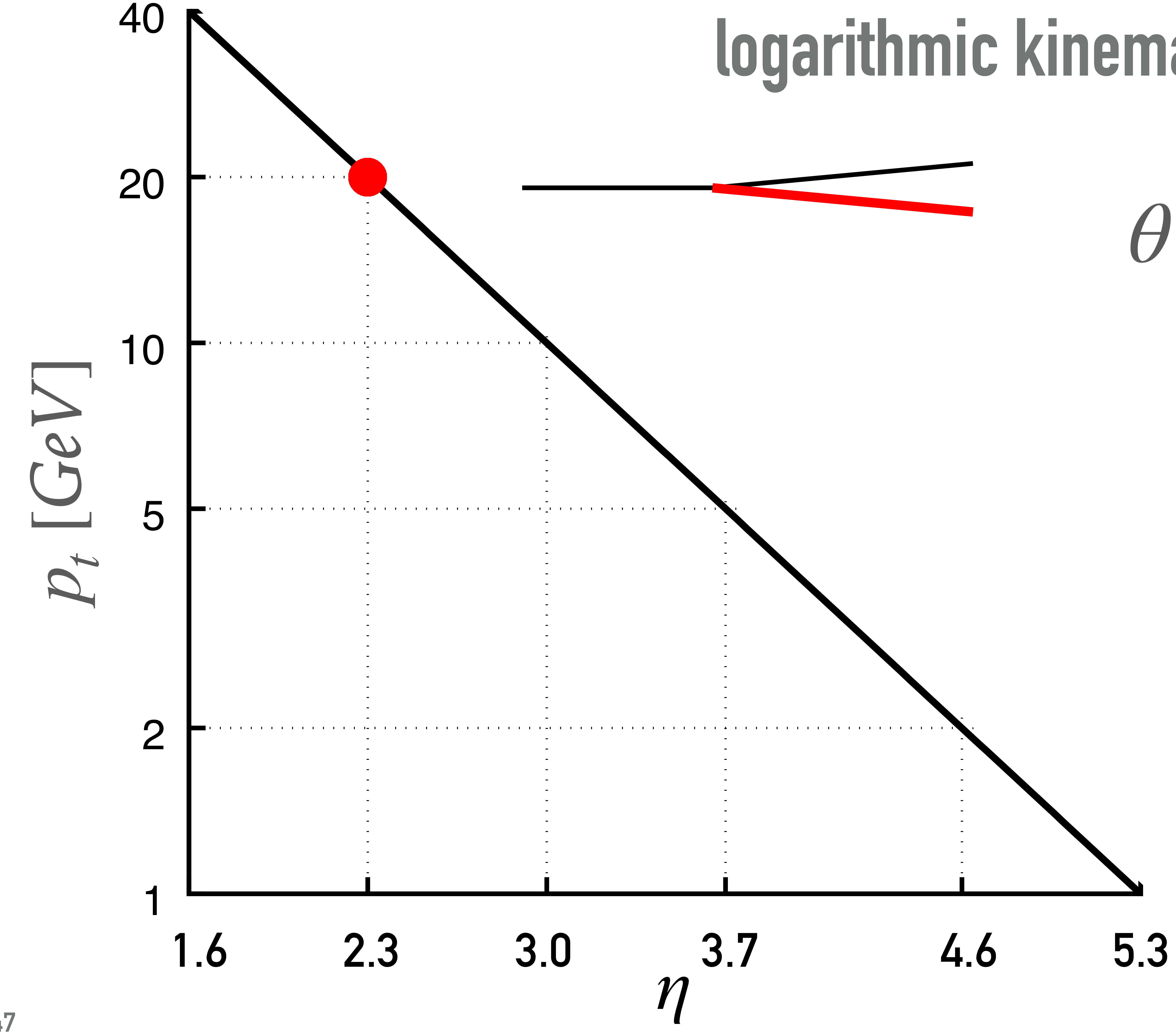


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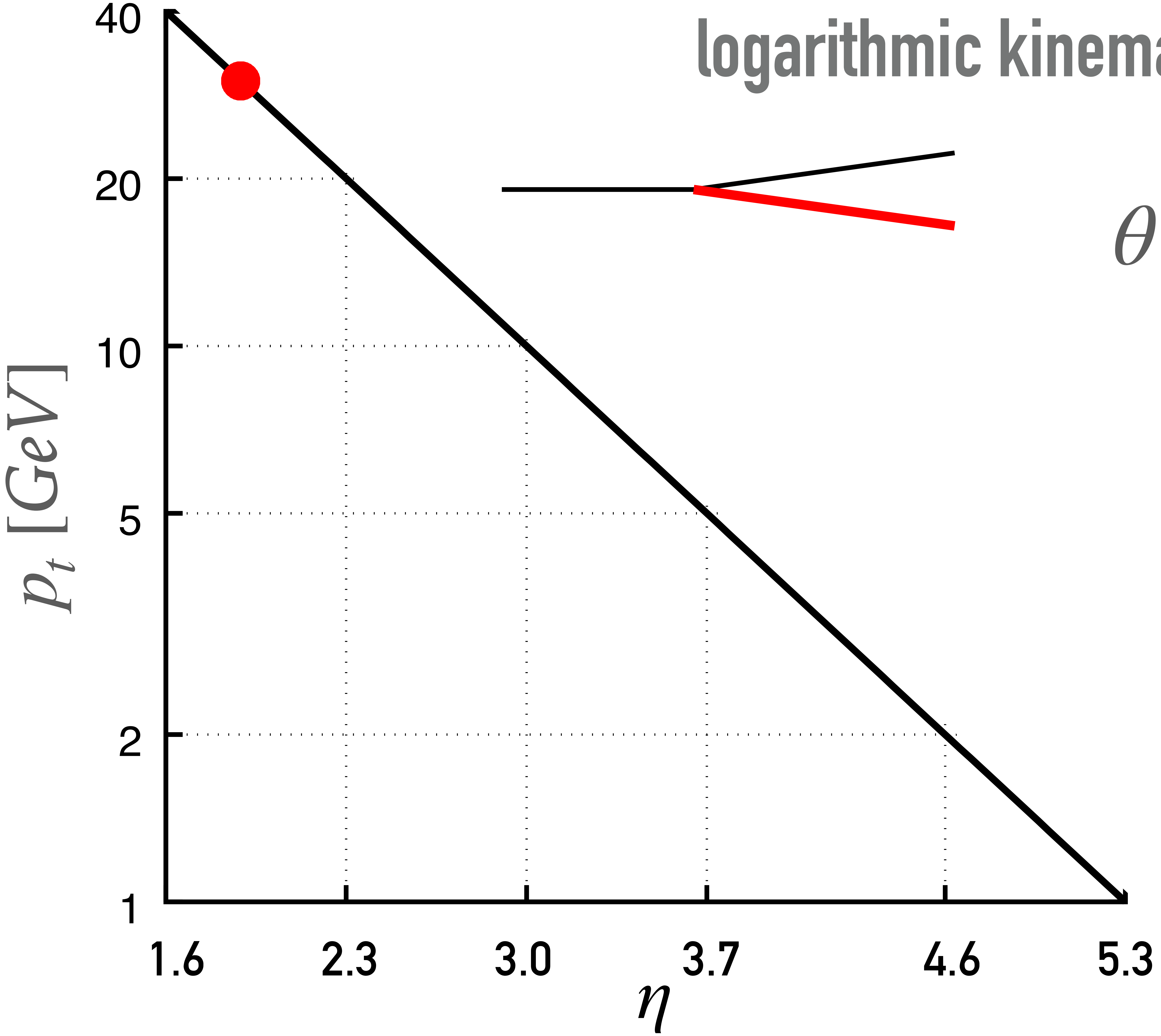


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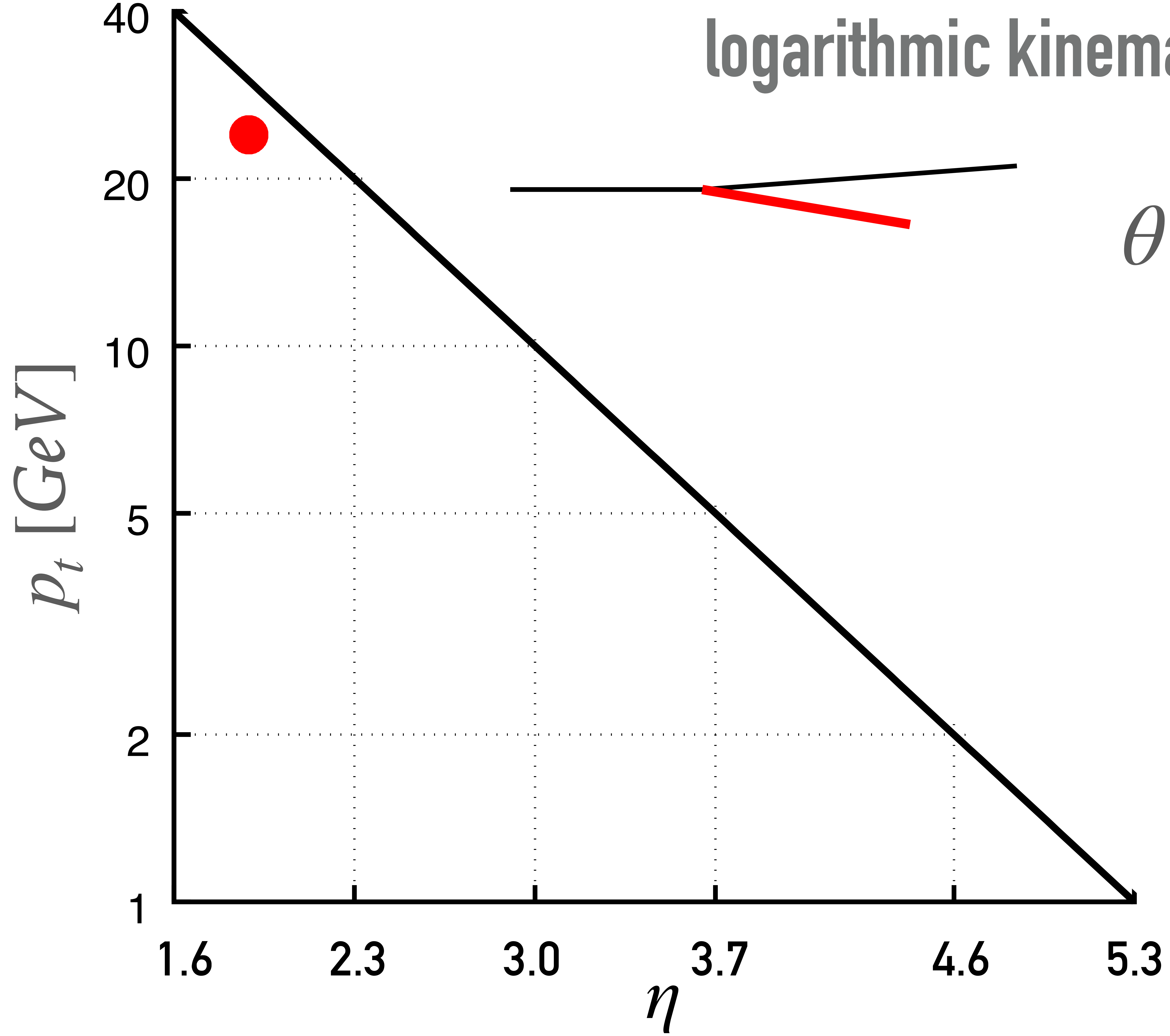
*jet with $R = 0.4$, $p_t = 200$ GeV*

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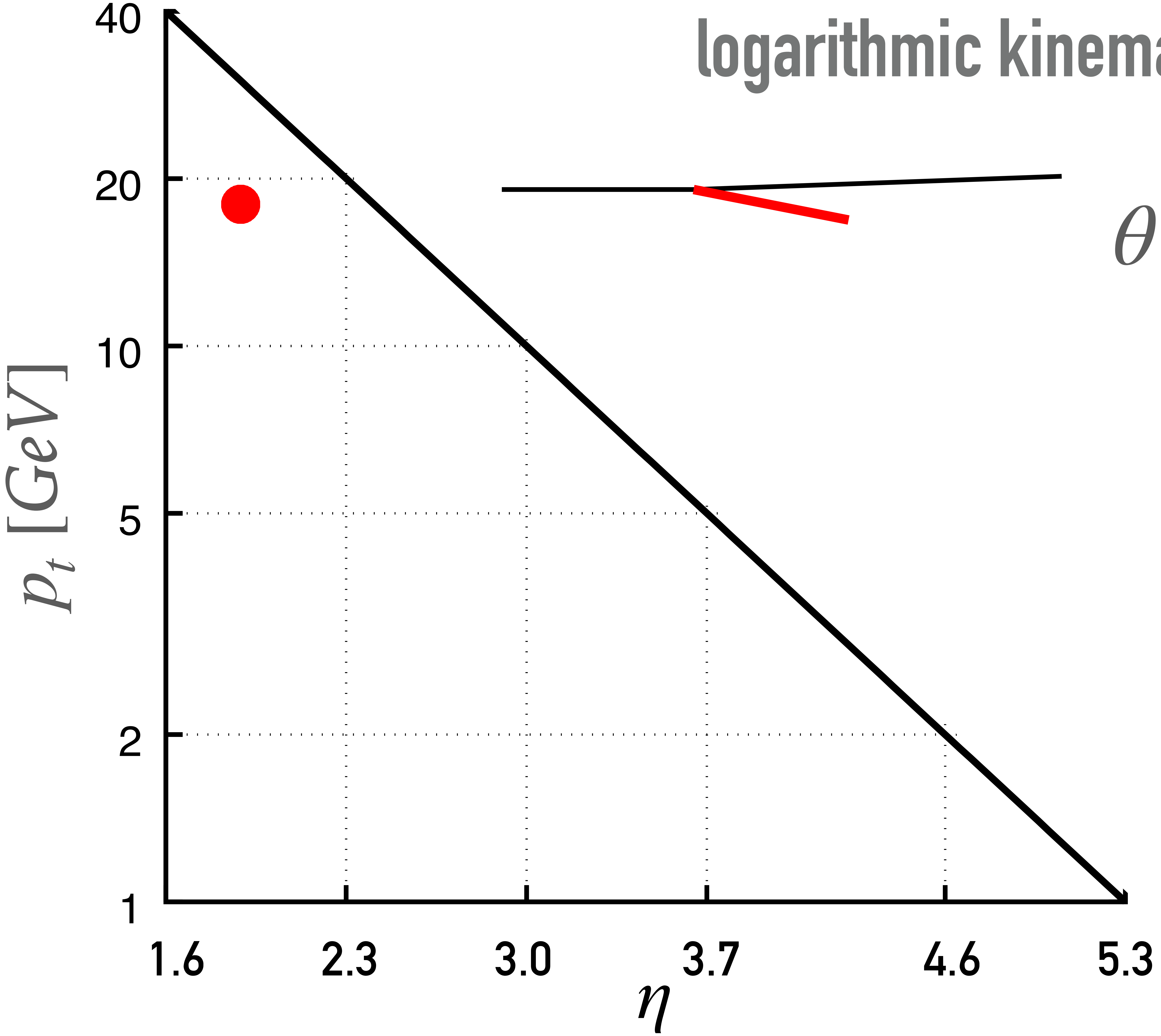


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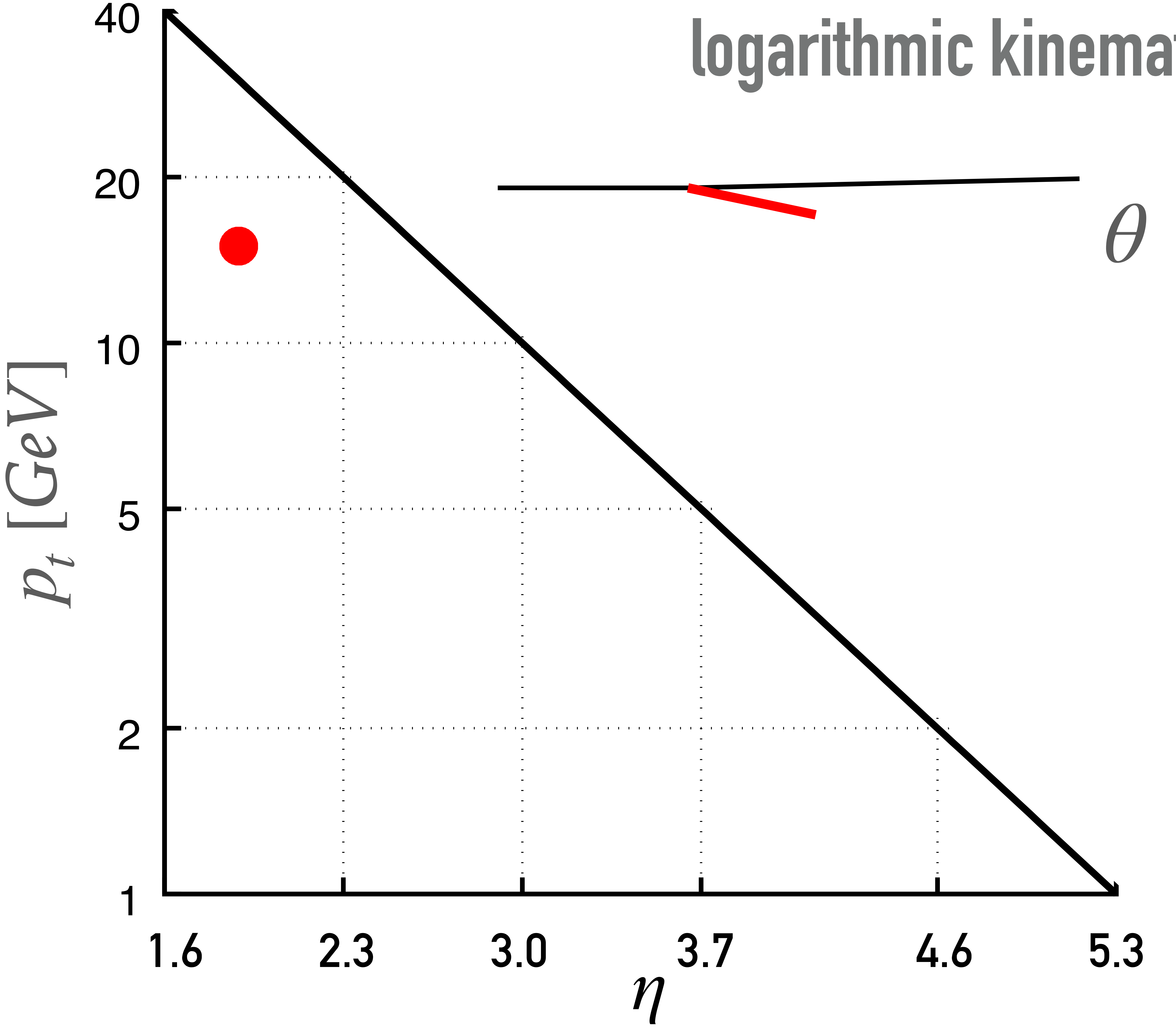


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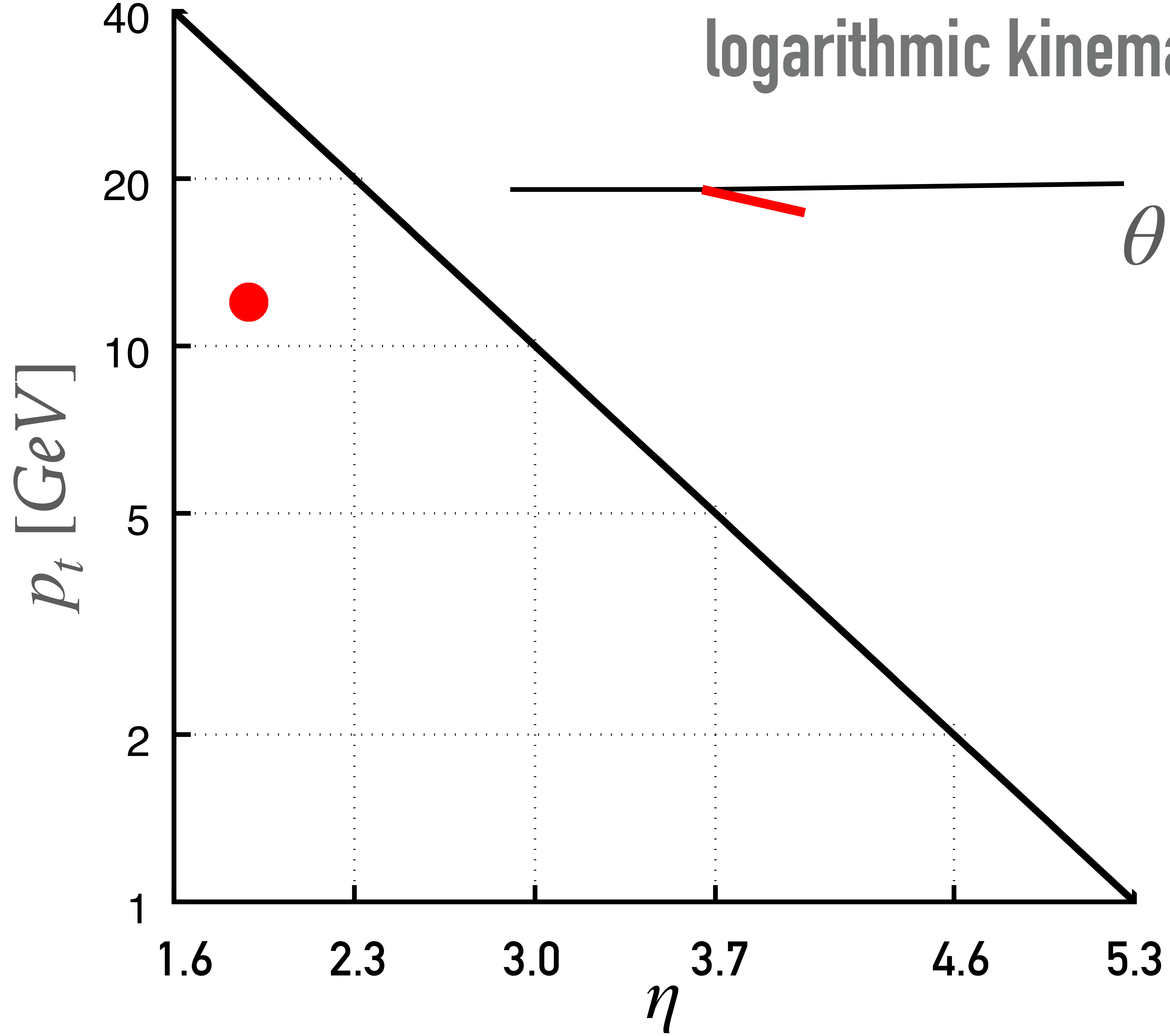


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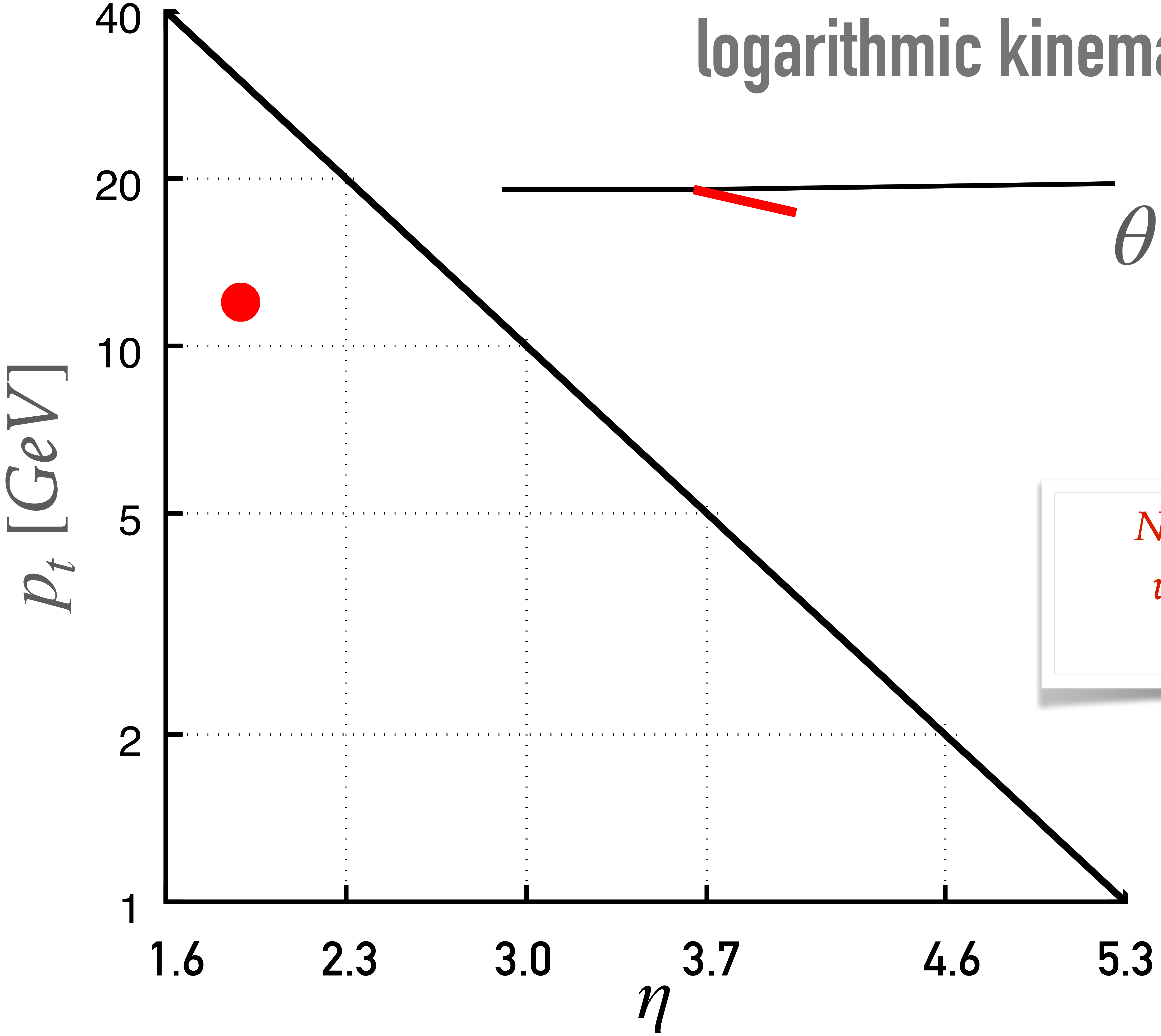



**logarithmic kinematic plane whose two variables are**

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

$$p_t = E\theta$$

*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

# 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)

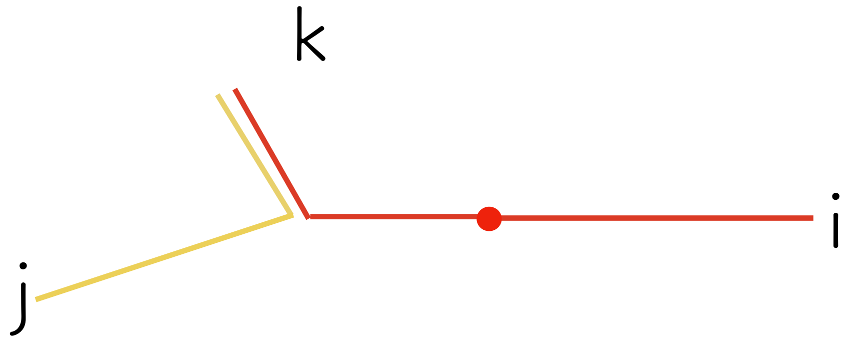
➤ effects near edges of Lund plane (we'll also ignore those)

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

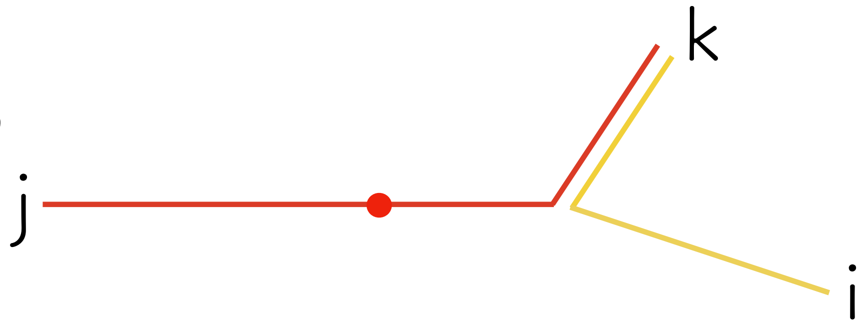
j emits, i spectates

i emits, j spectates

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




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




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

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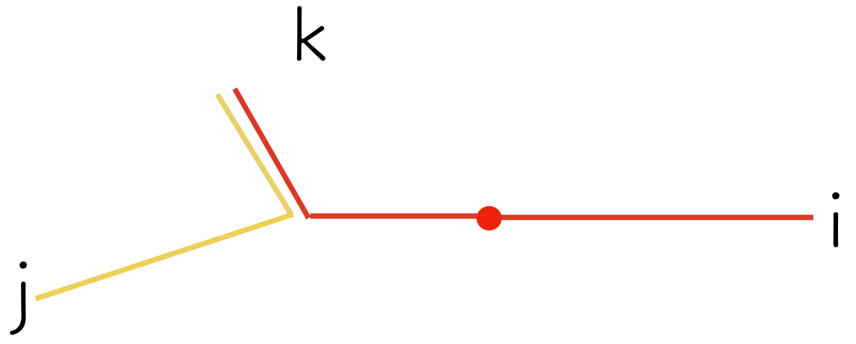
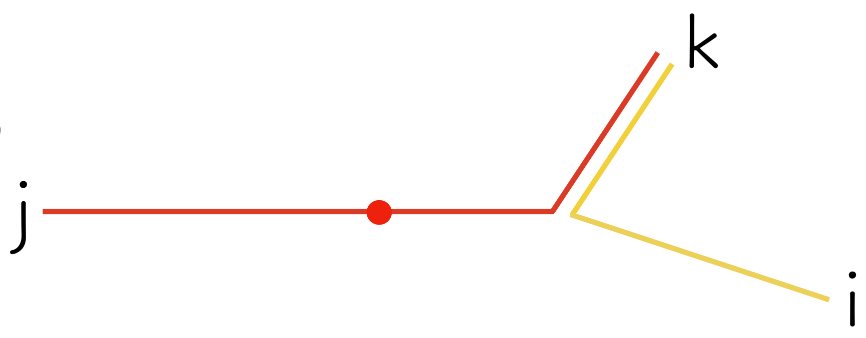
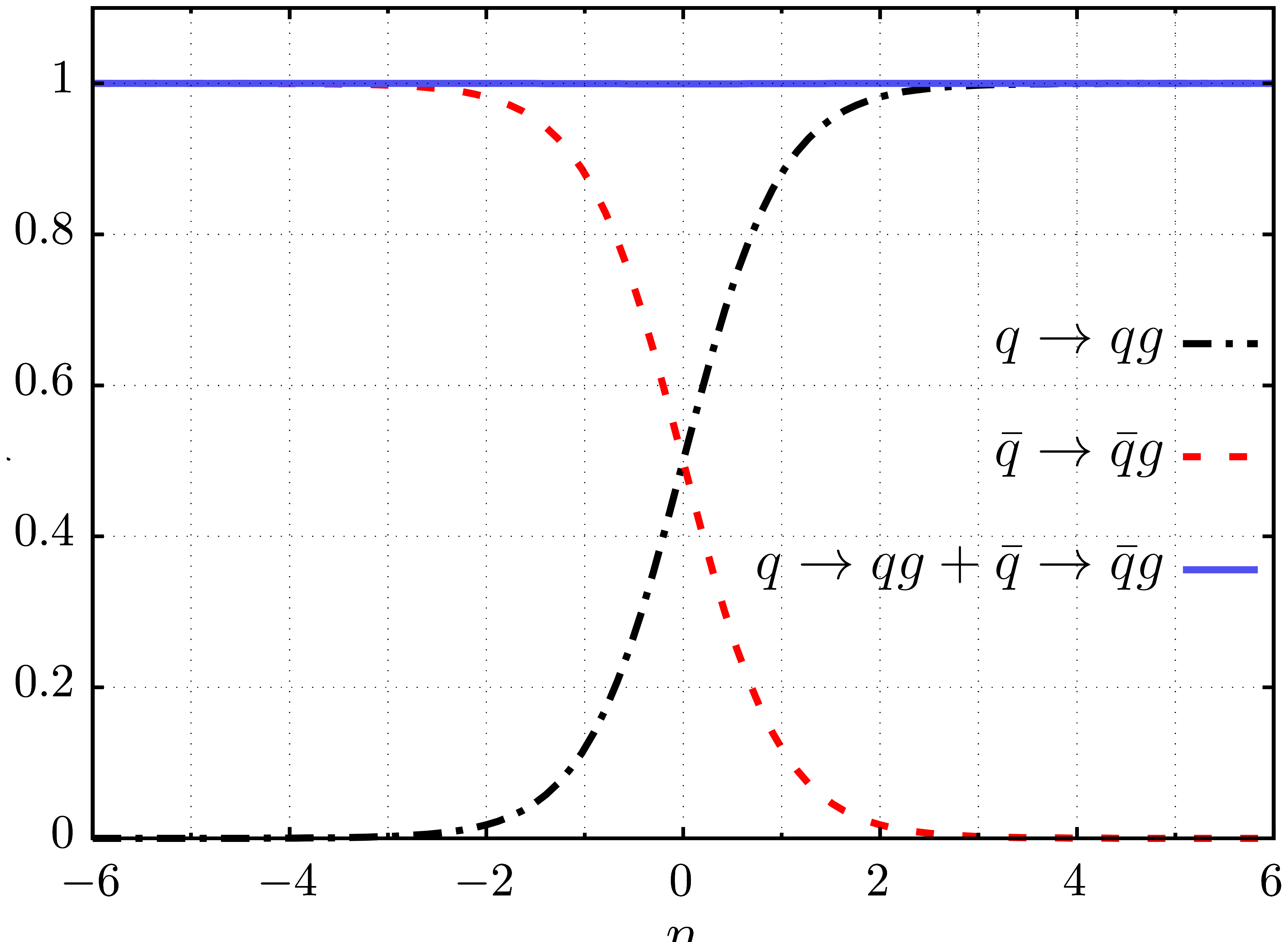



$$+\ d\mathcal{P}$$




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

**ratio to full matrix element**



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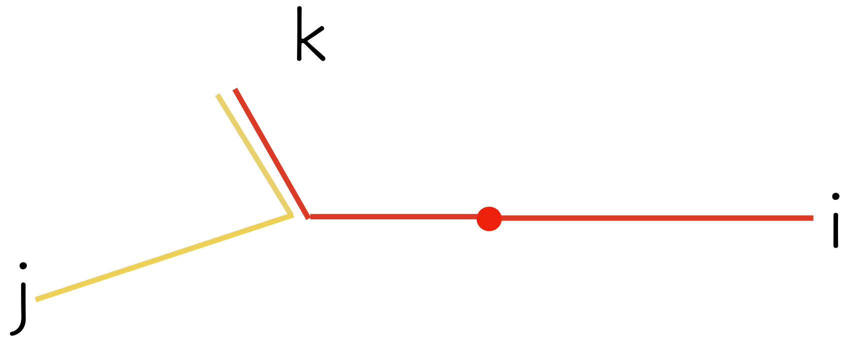
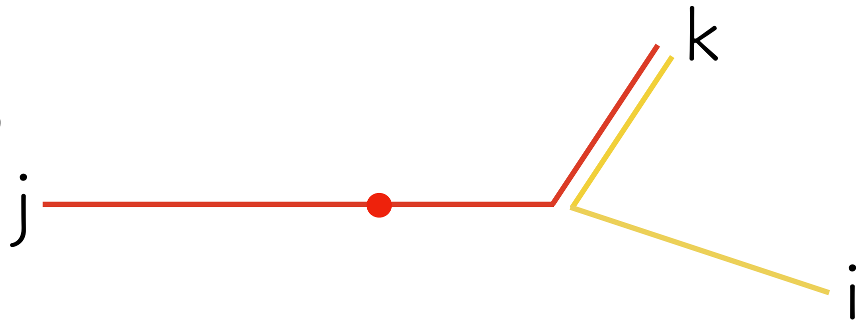
j emits, i spectates

i emits, j spectates

$$dP_{\tilde{i}\tilde{j}\to ikj} = dP$$




$$+ \; dP$$




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

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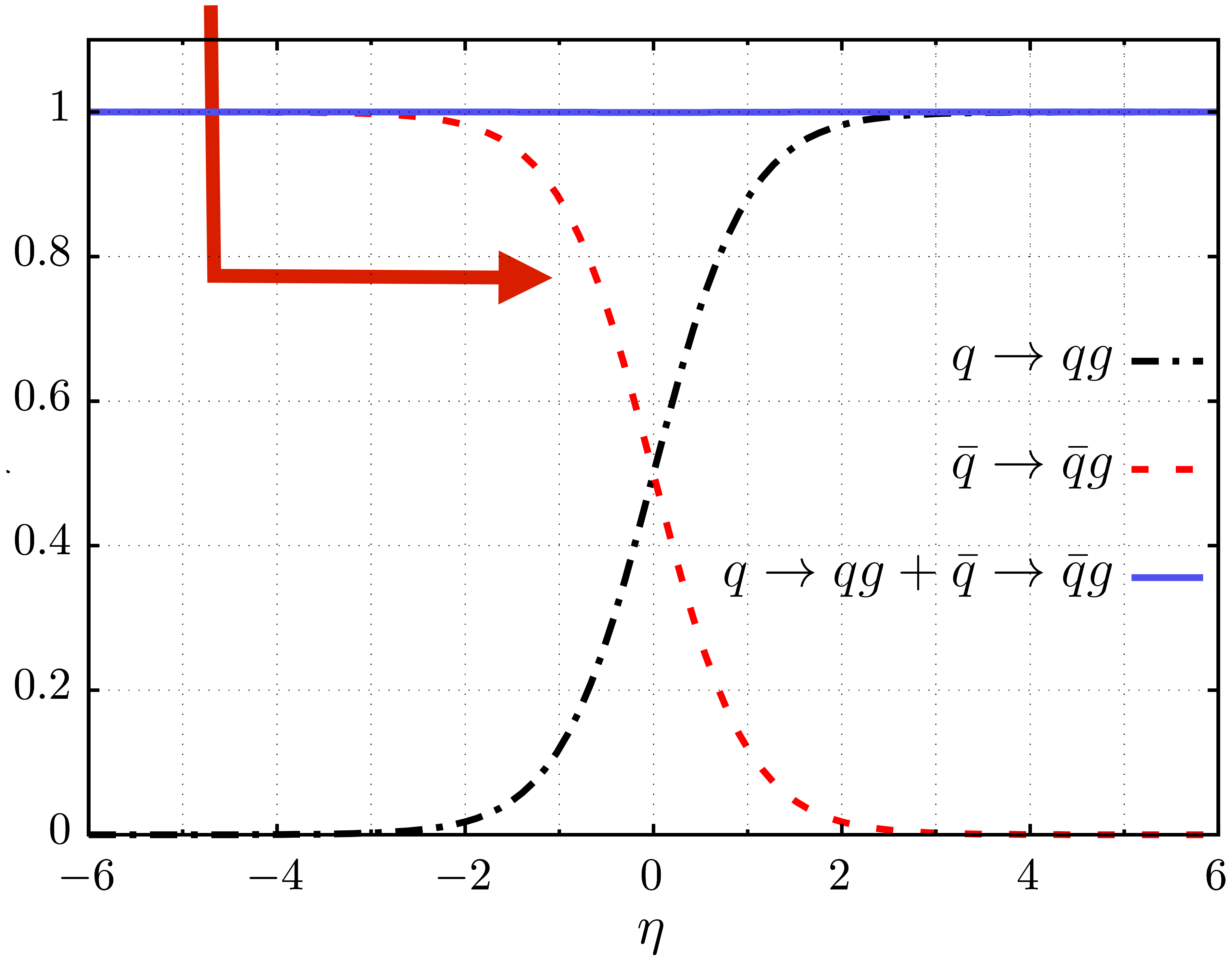

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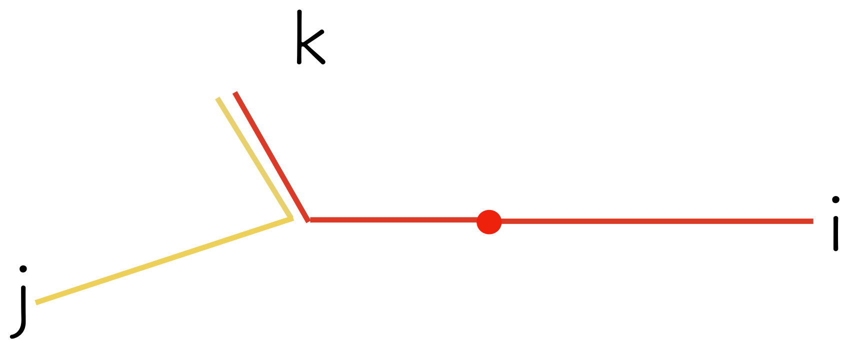
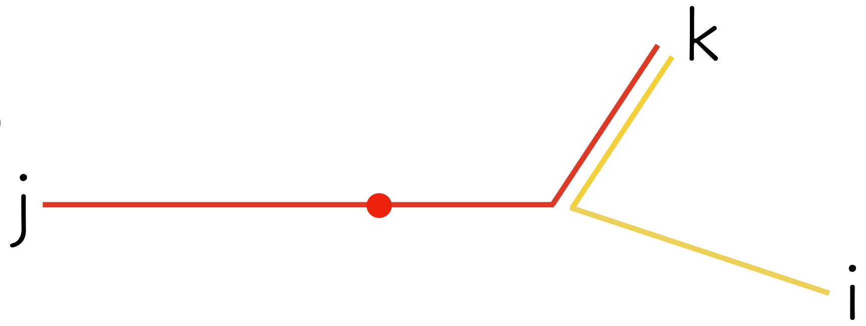
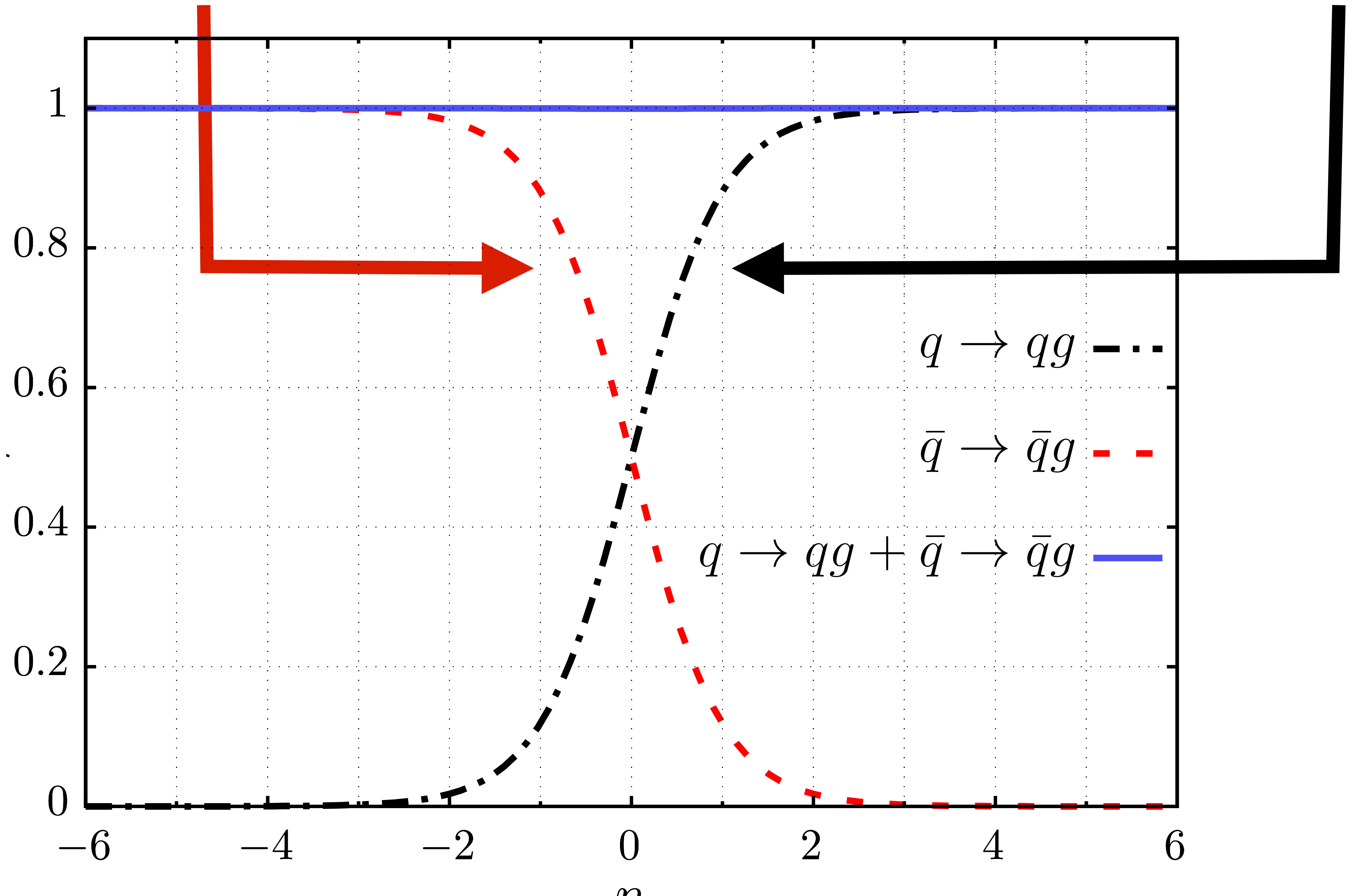



$$+ \; d\mathcal{P}$$




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

**ratio to full matrix element**



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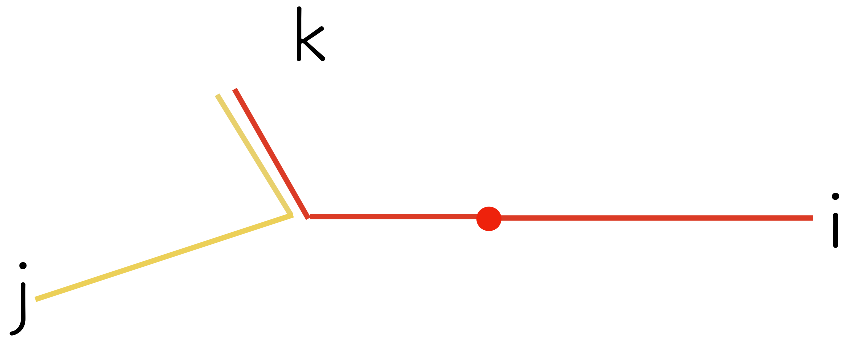
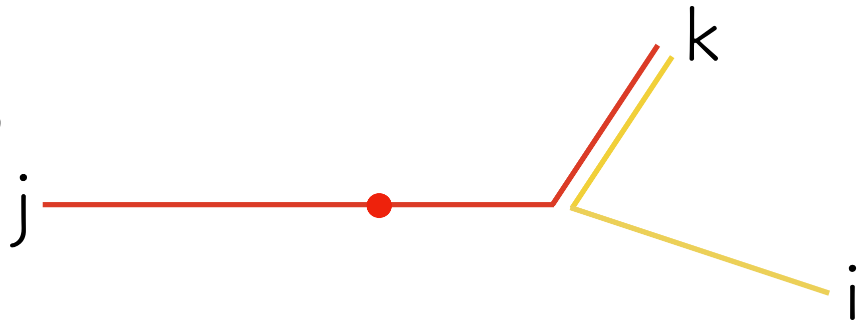
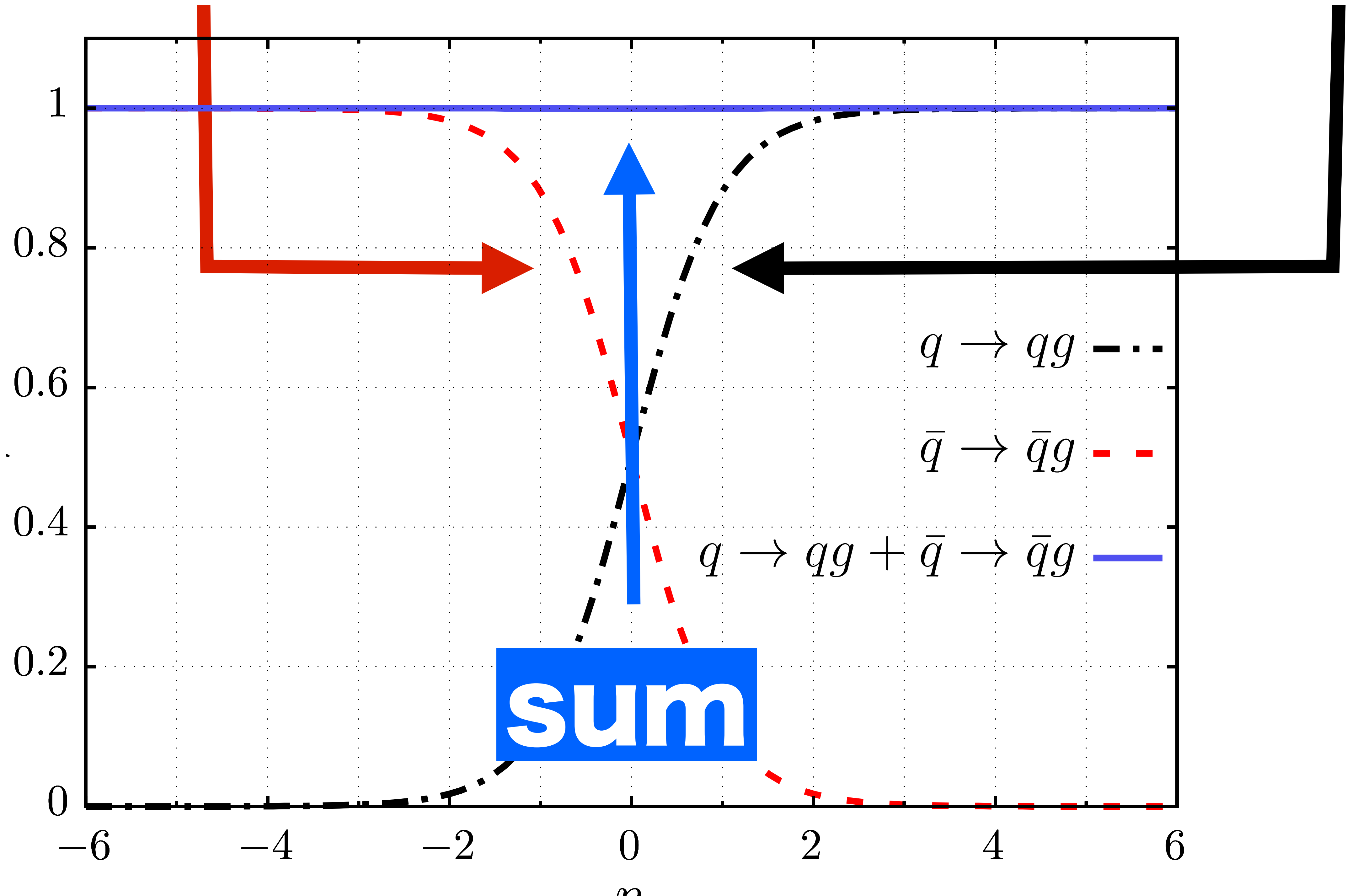



$$+ \; dP$$




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

**ratio to full matrix element**



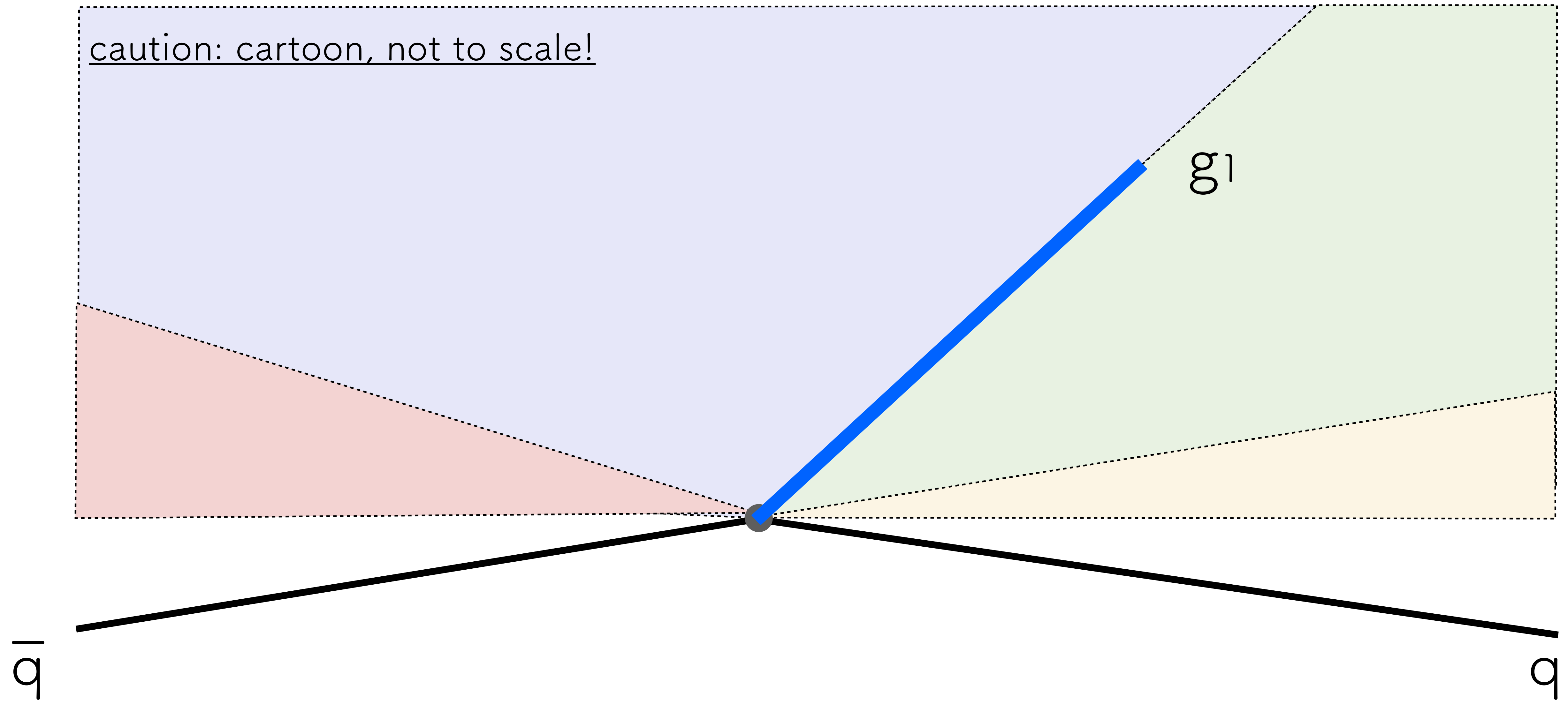
# Matrix element for two emissions (low energy ≡ "soft")

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

**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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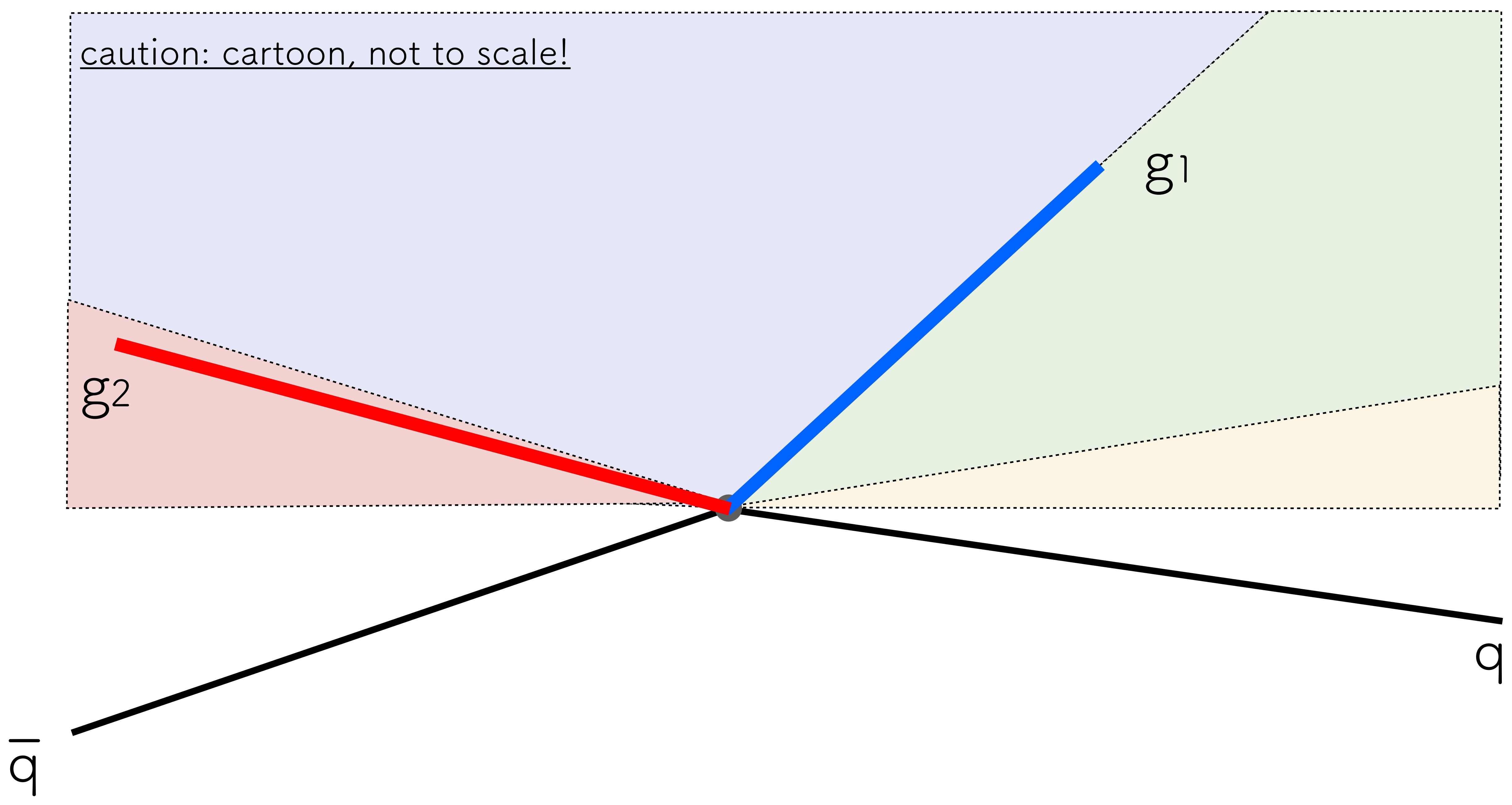
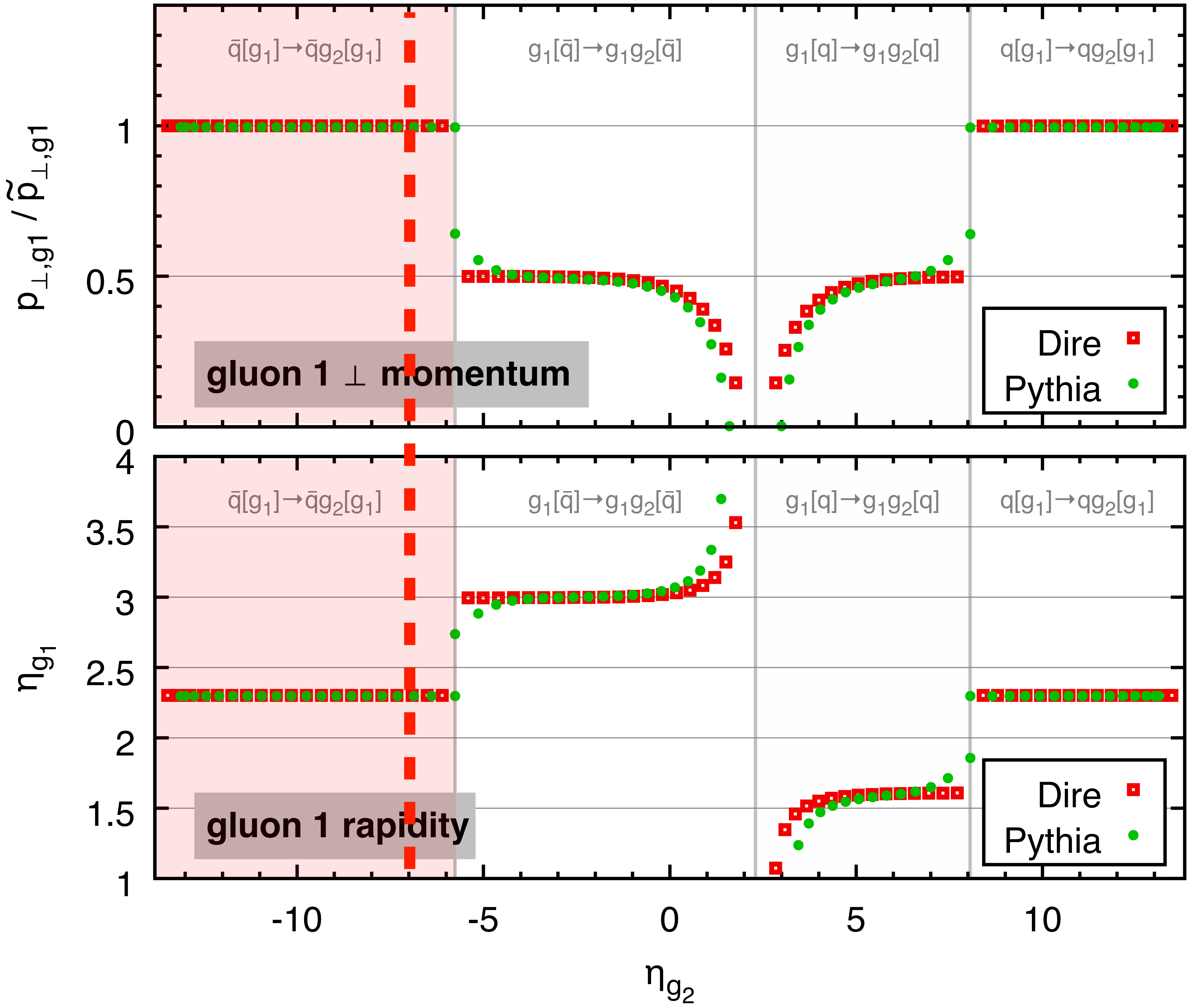



impact of gluon-2 emission on gluon-1 momentum



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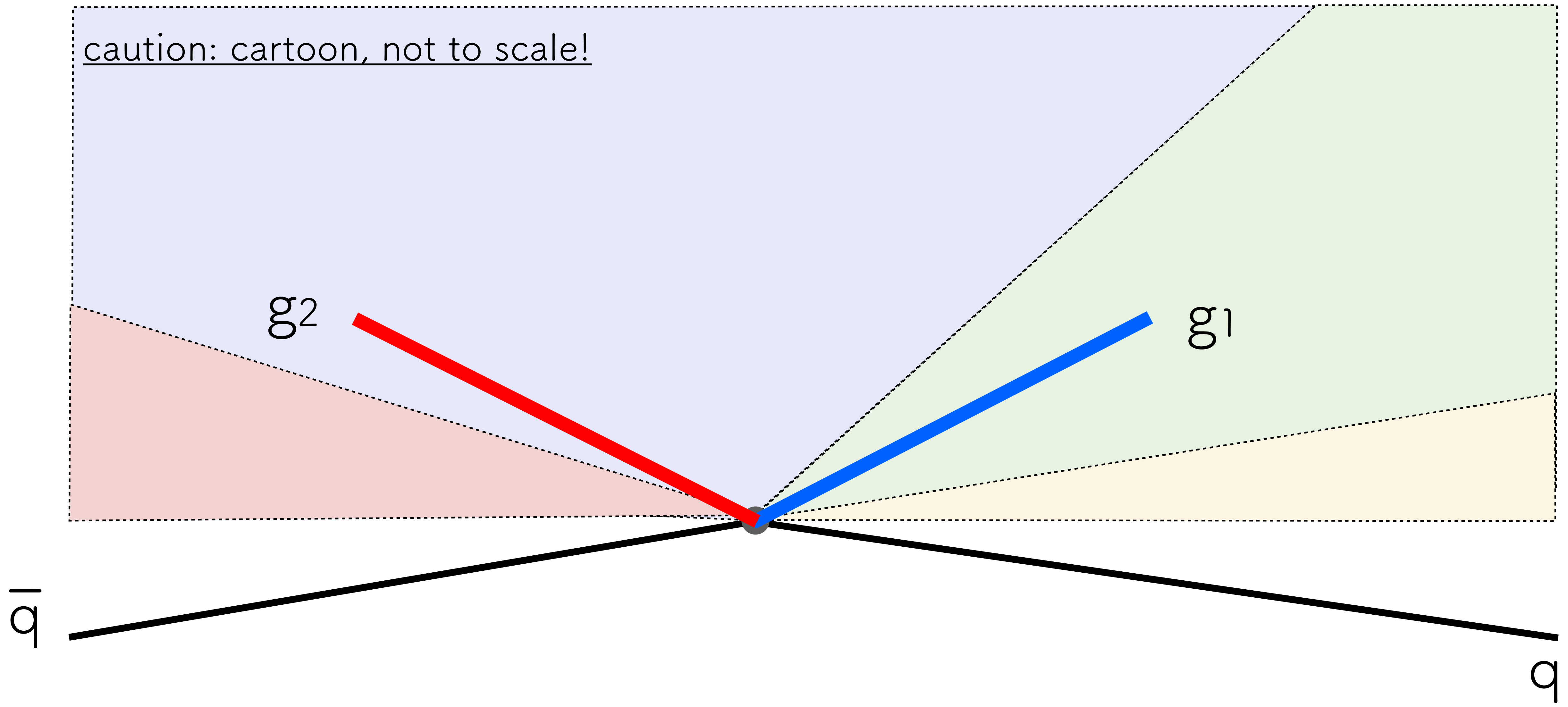


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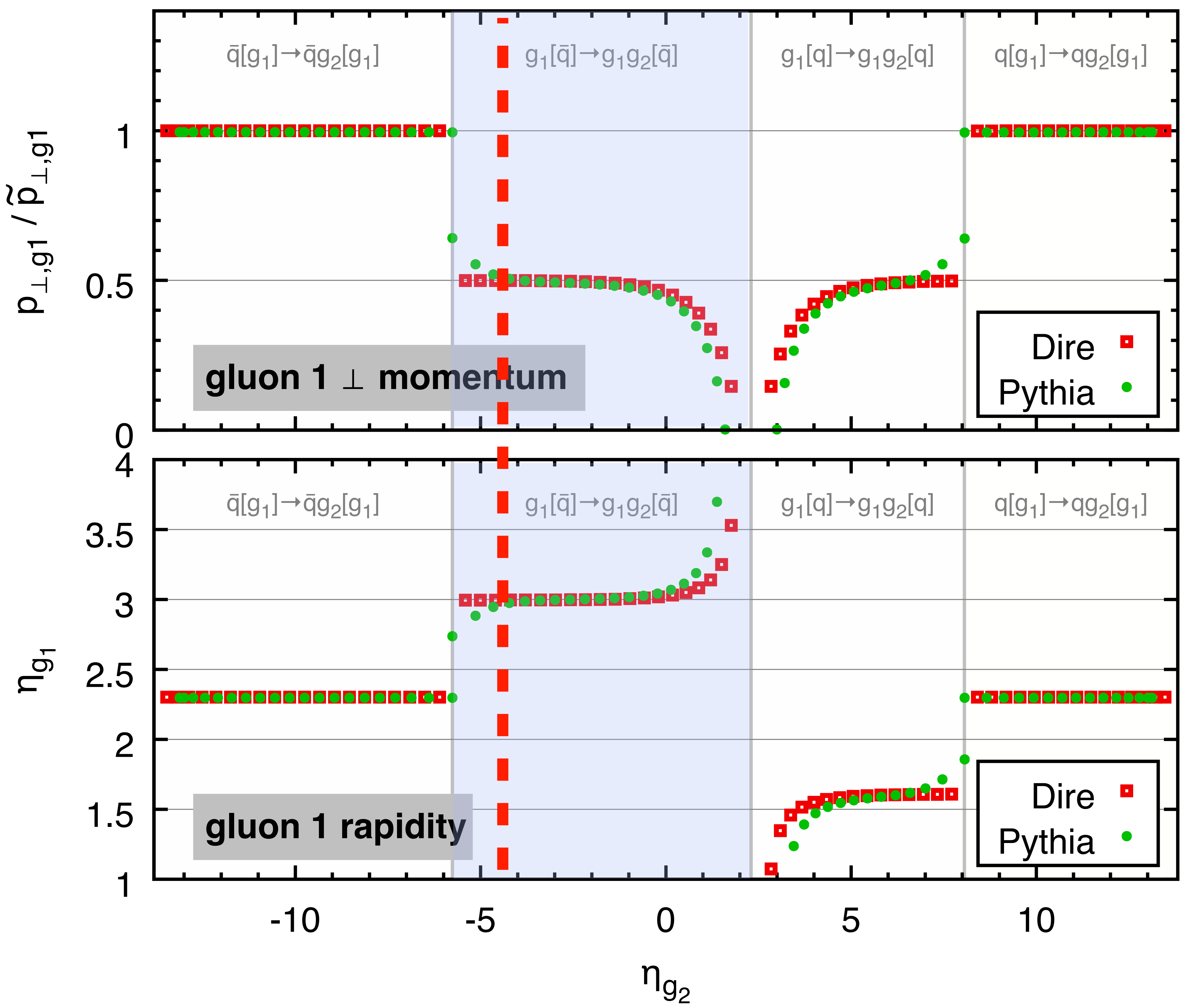

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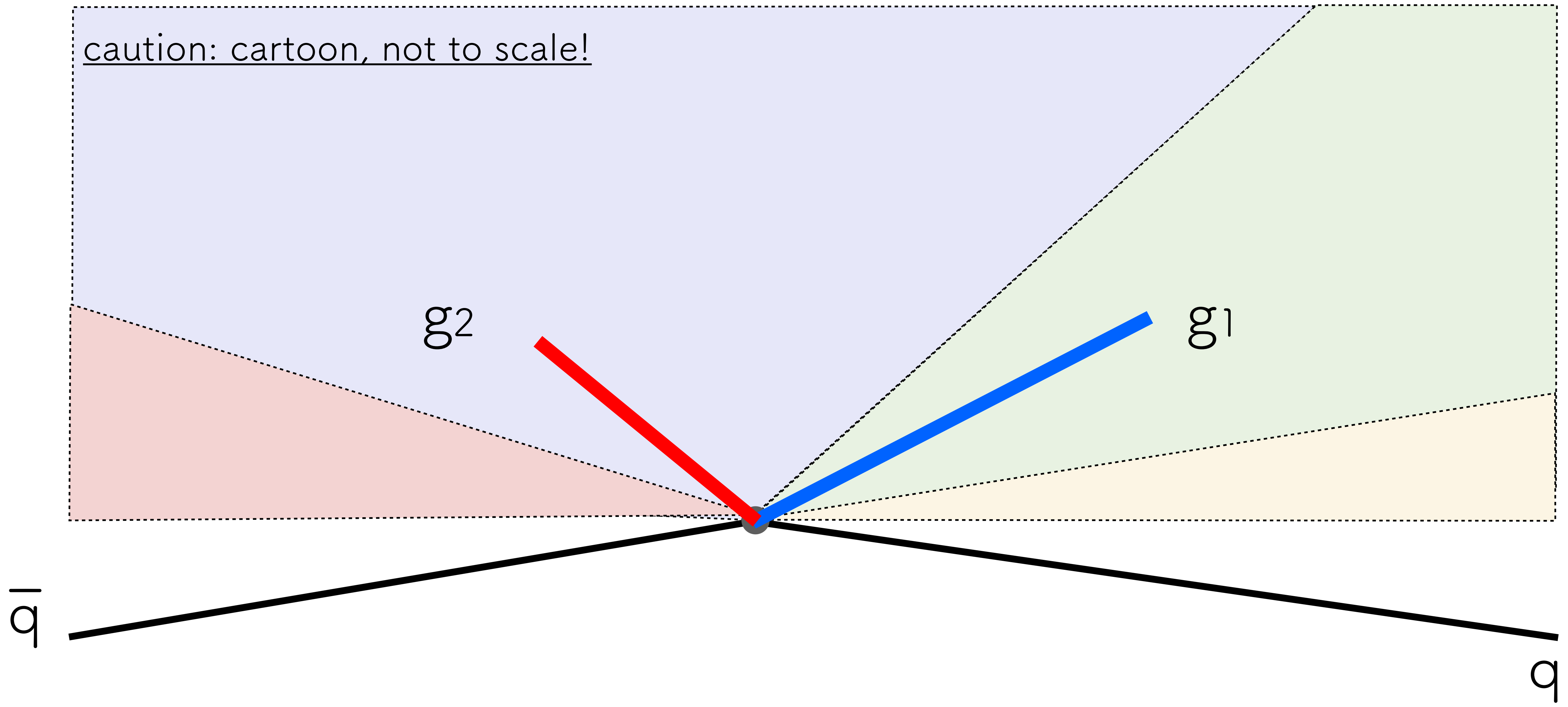


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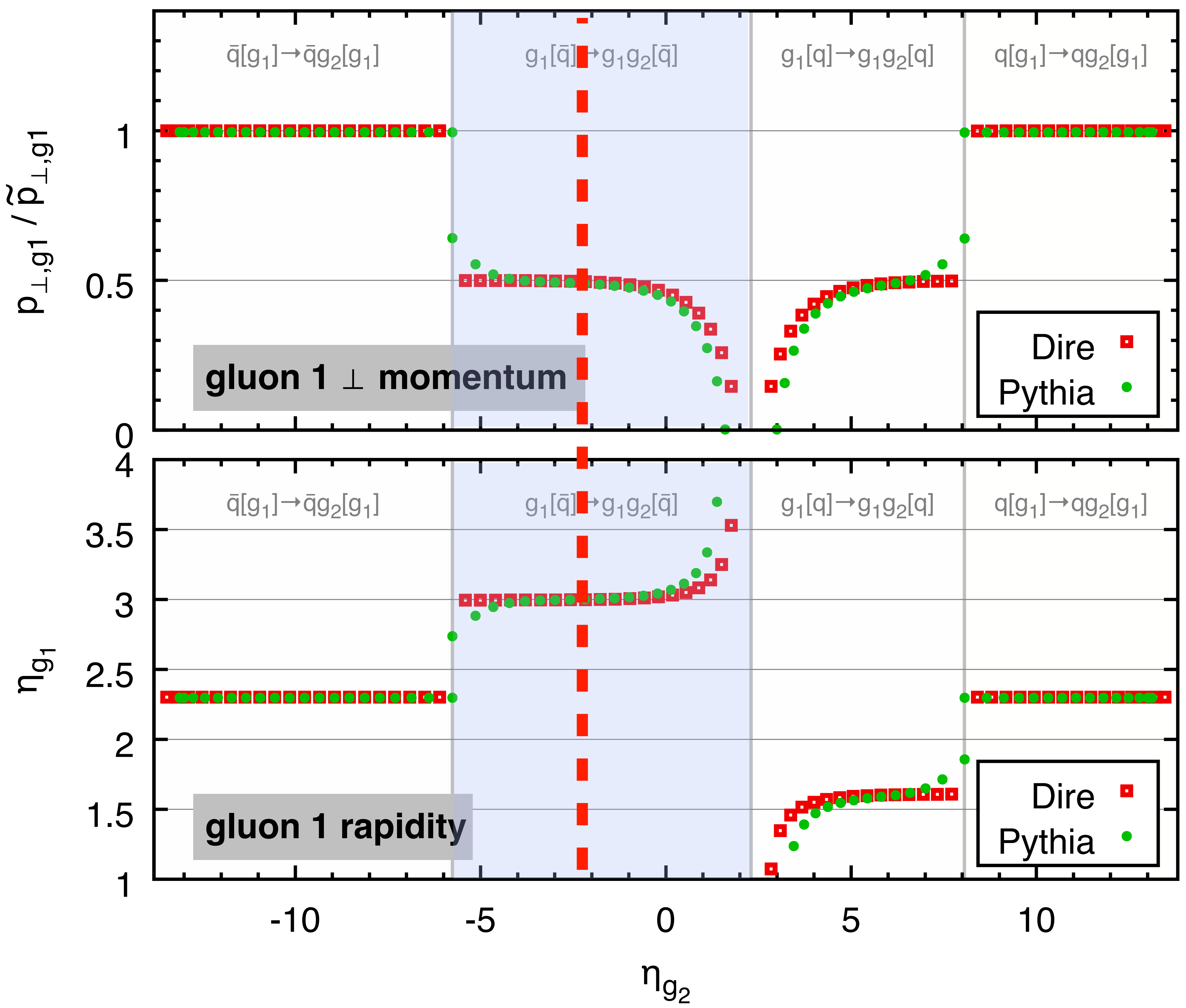

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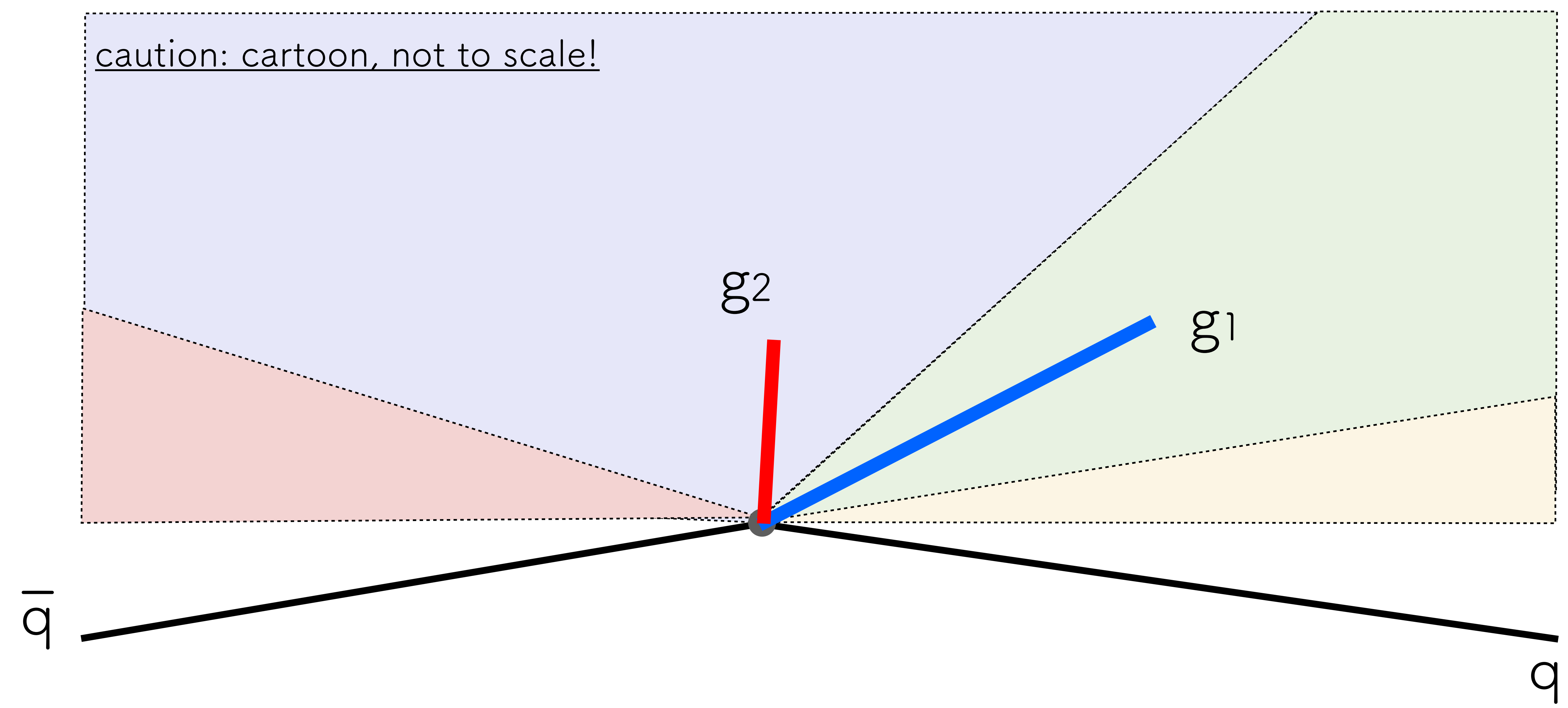


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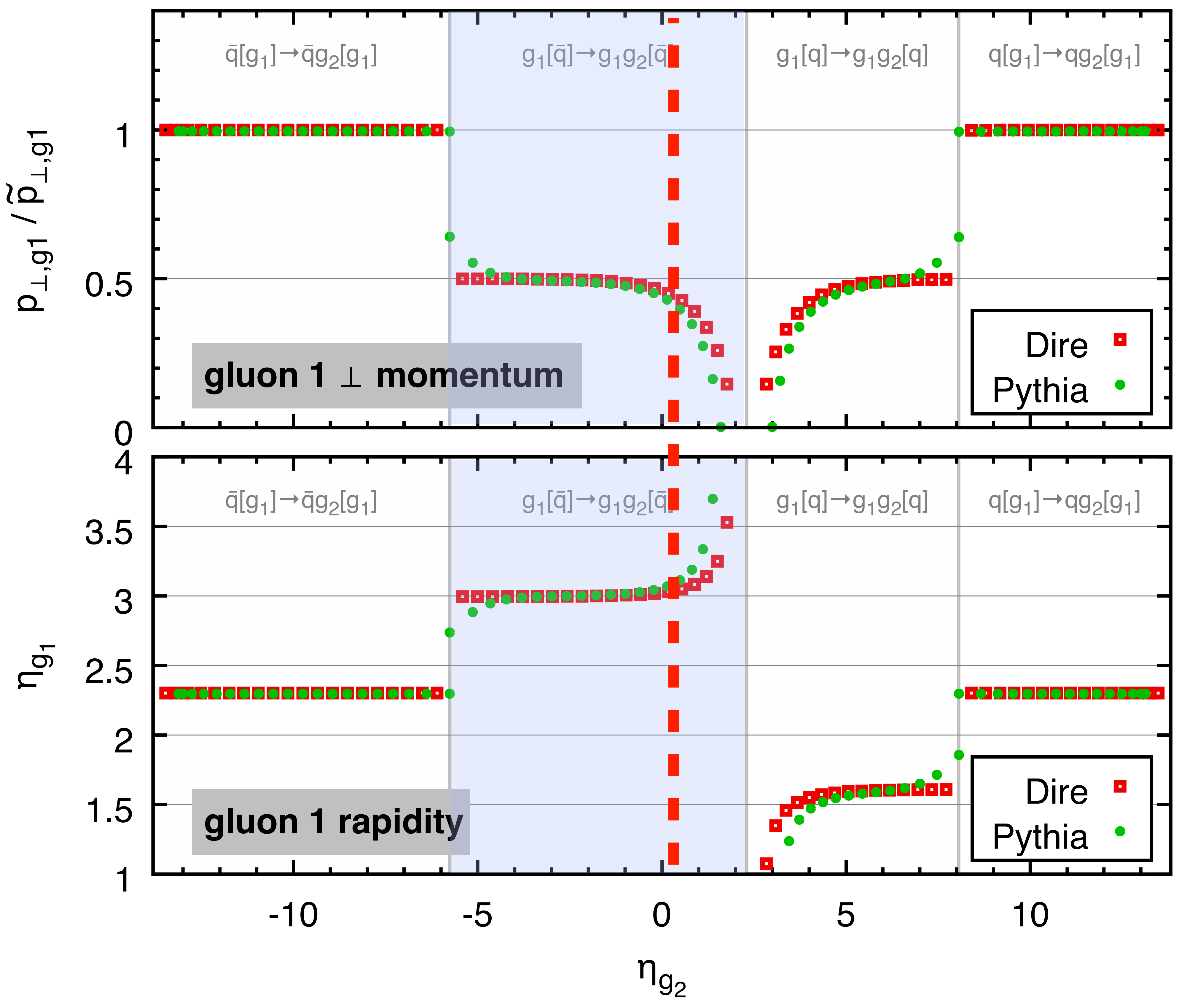

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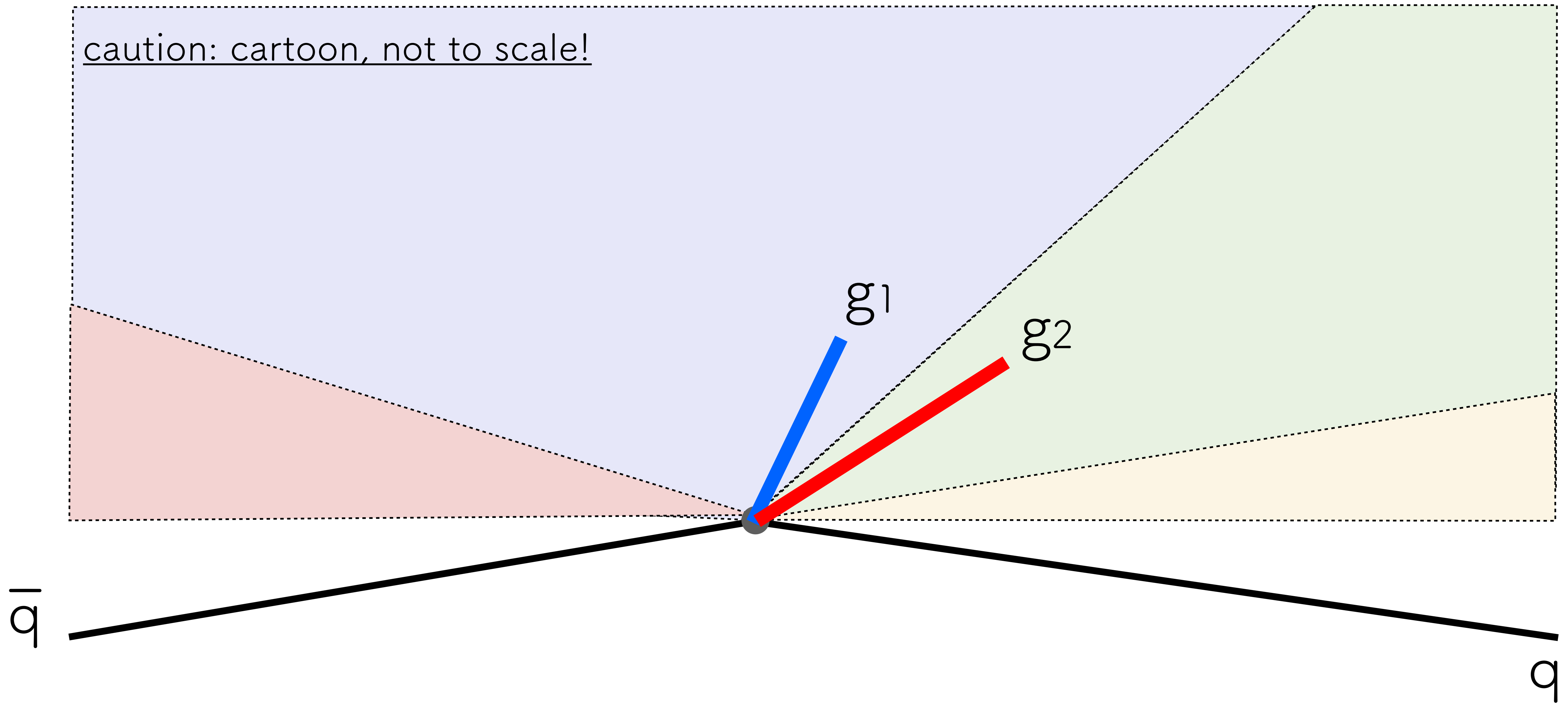


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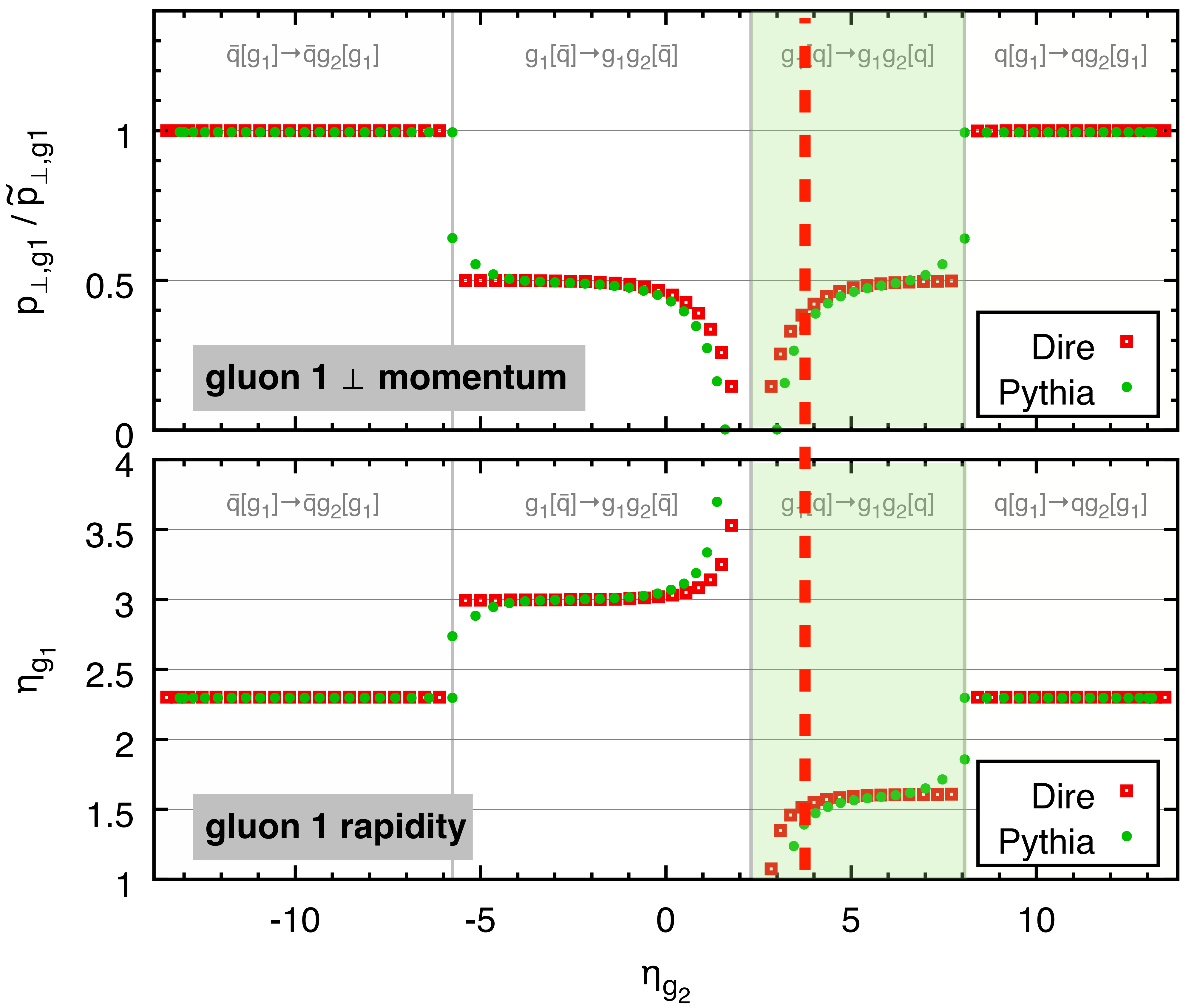

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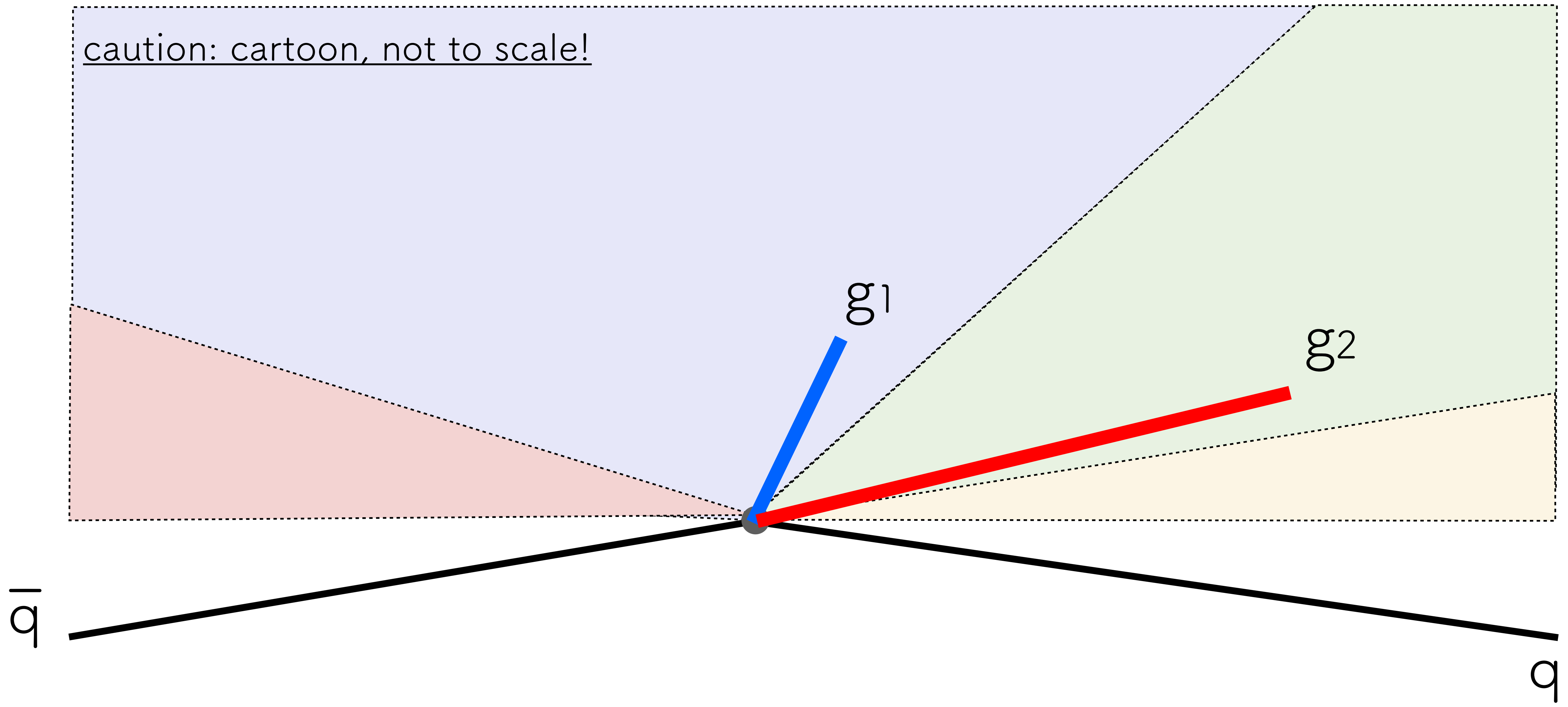


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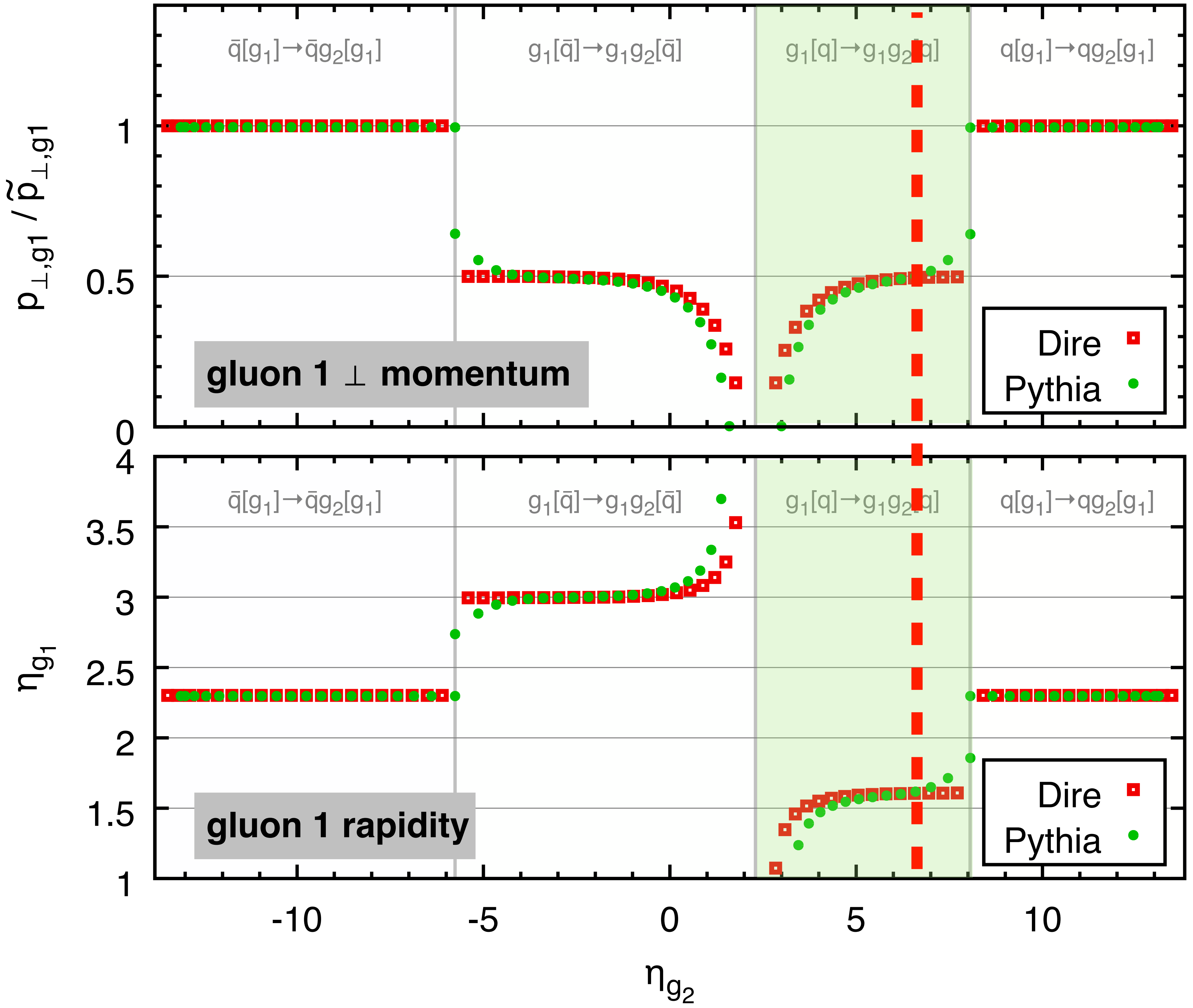

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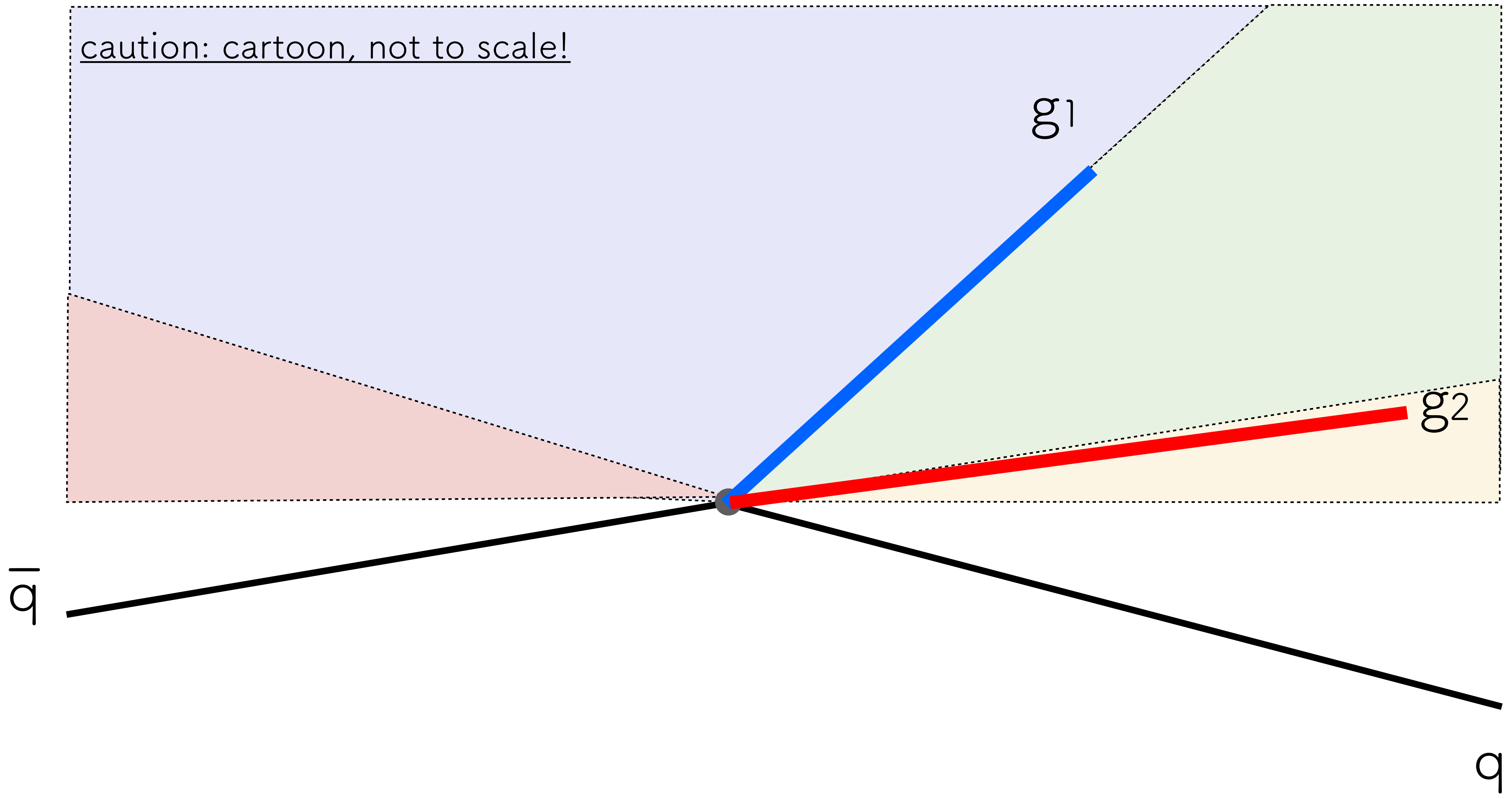


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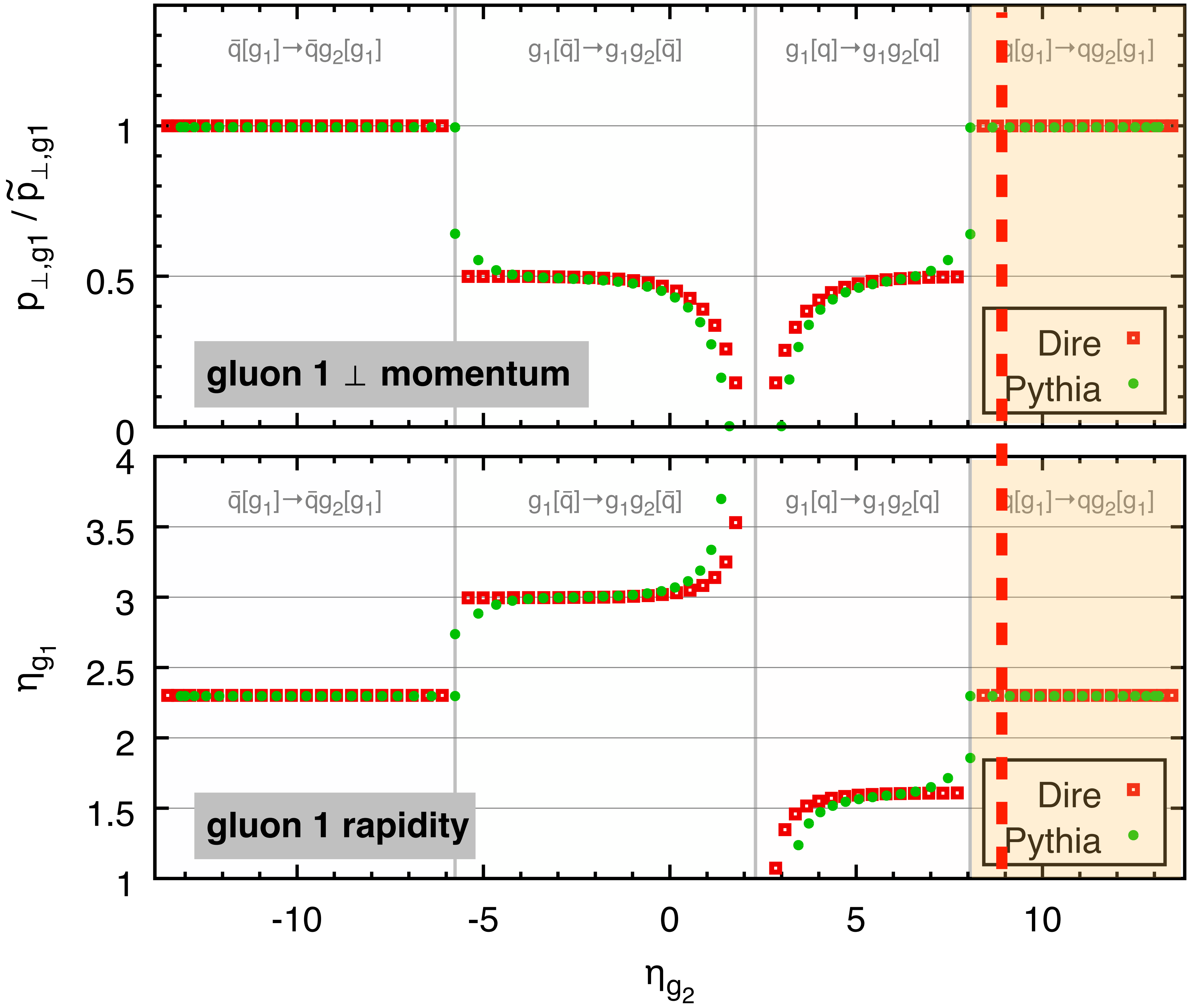

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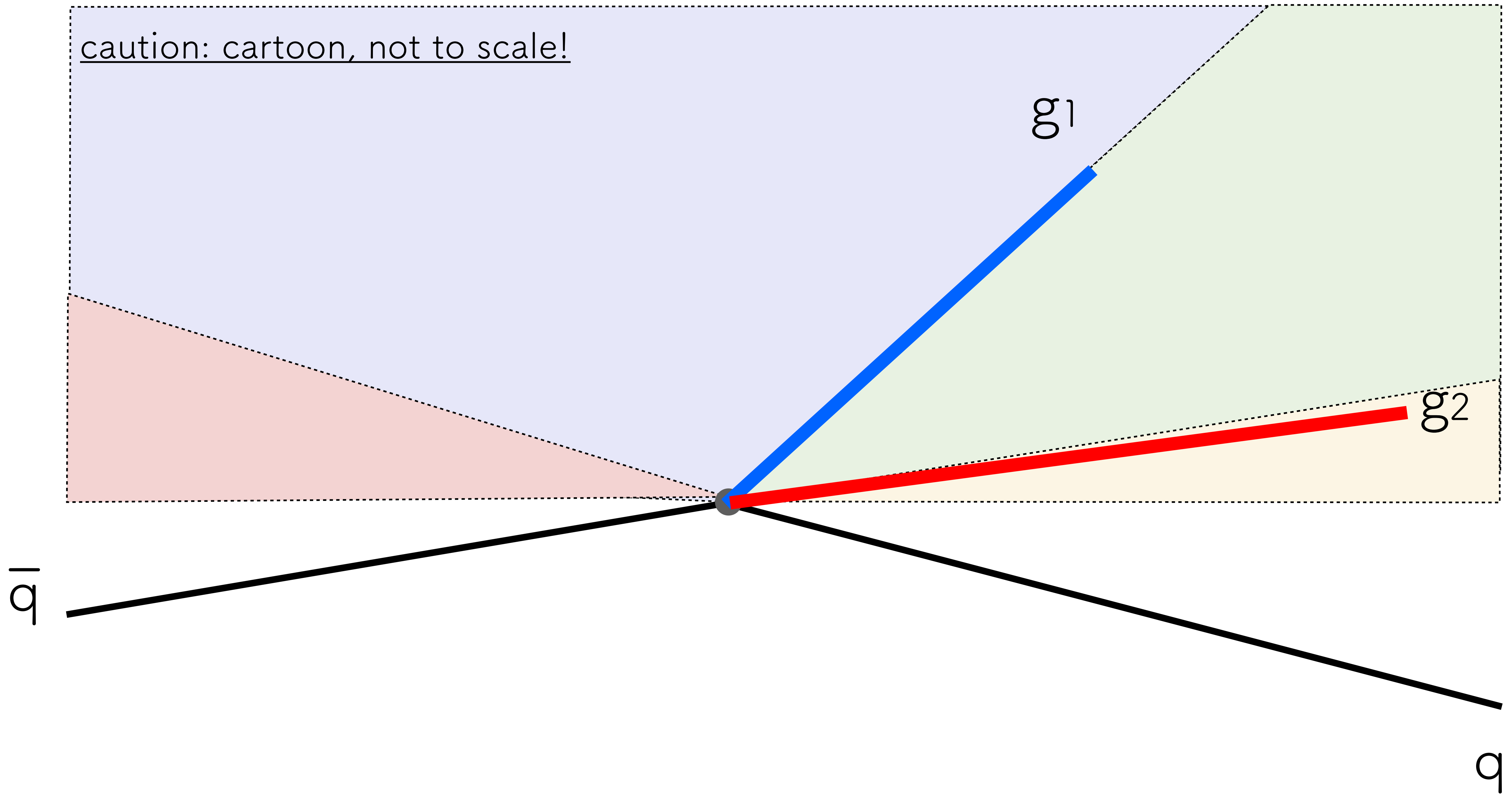


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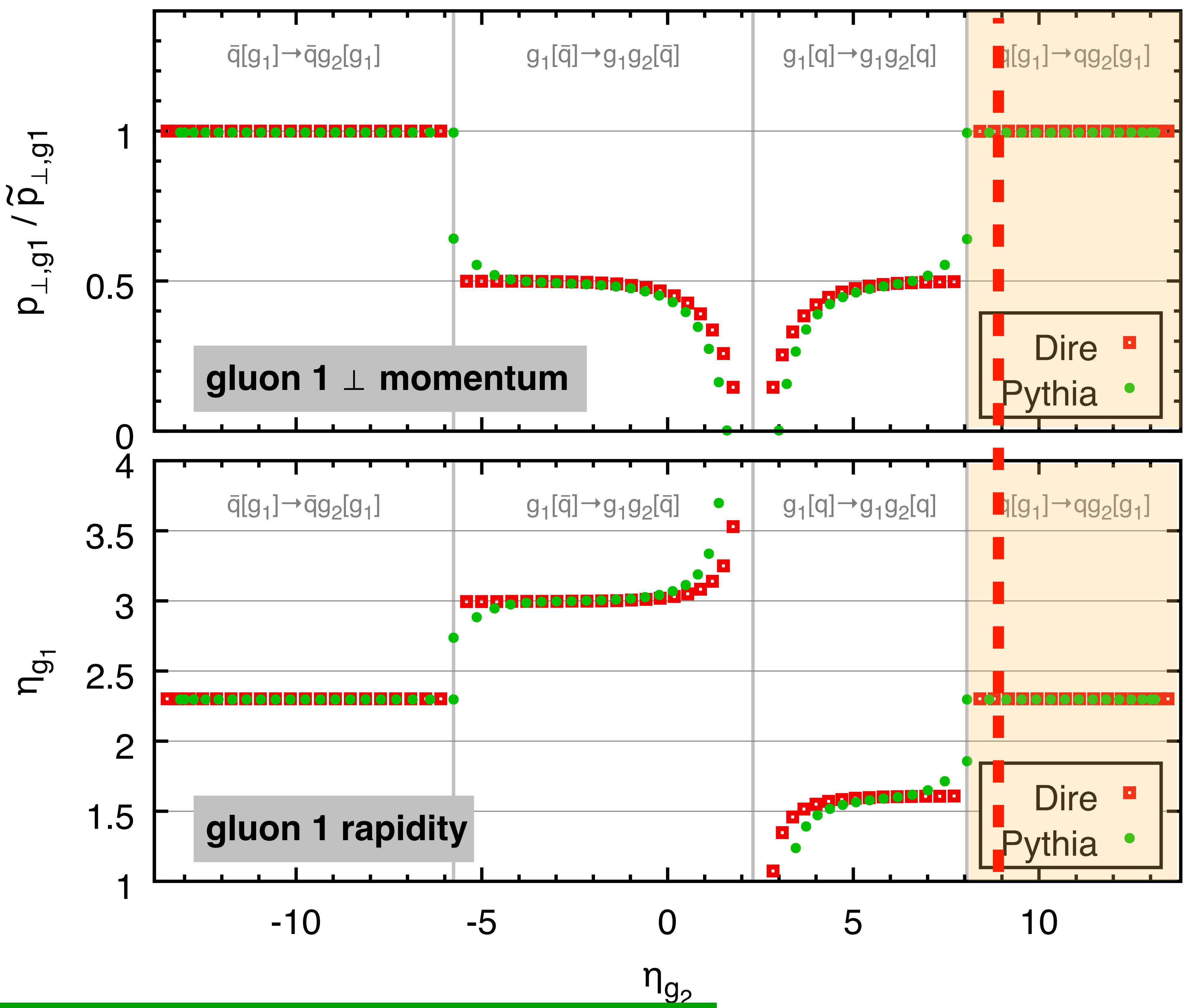



**Key observation #1**

**highly non-trivial cross talk between emissions**

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

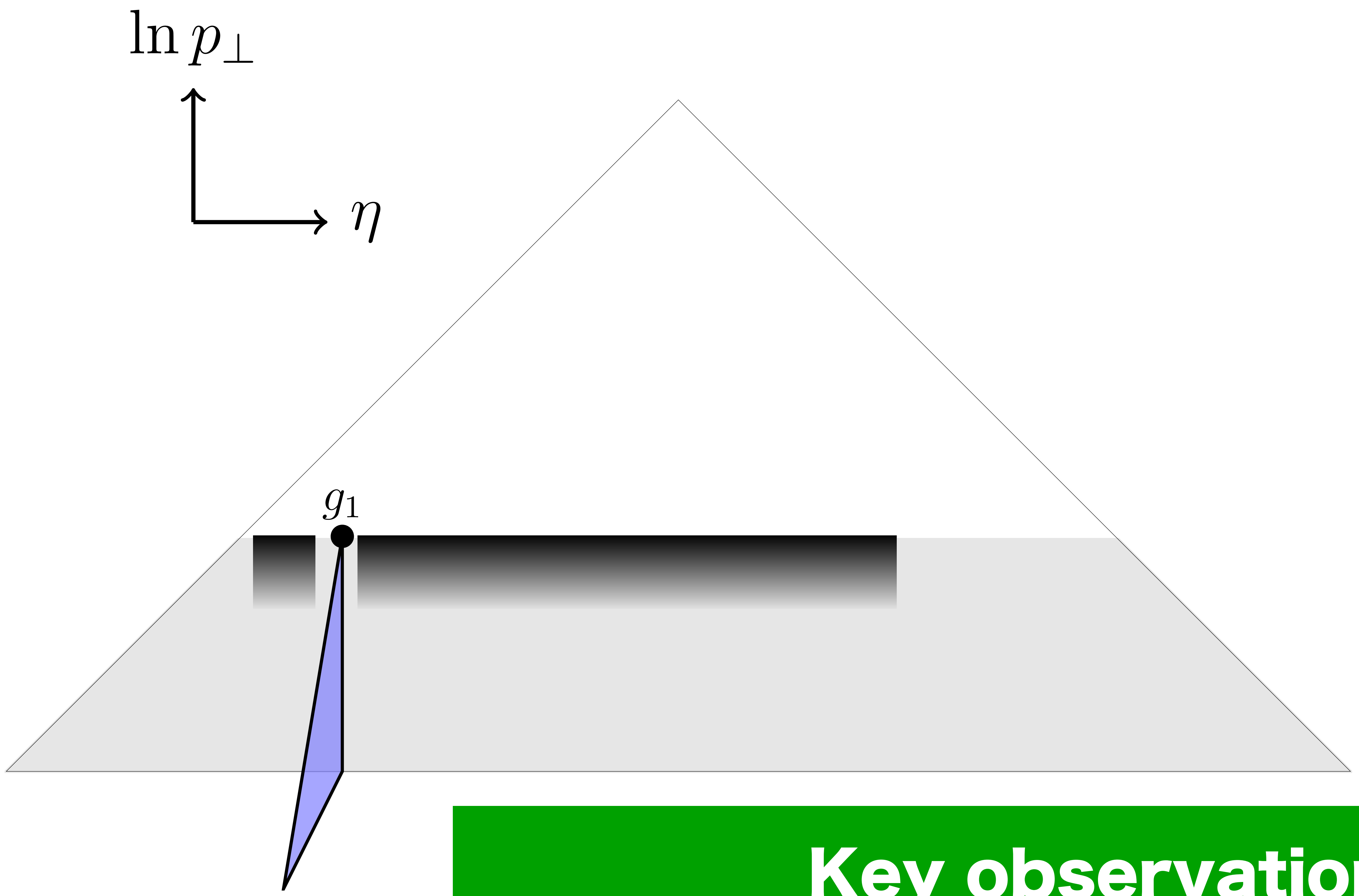
# in equations

$$
\begin{aligned}
&1. \quad \bar{q}[g_1] \to \bar{q}g_2[g_1]: && \boldsymbol{p}_{\perp,g_1} = \widetilde{\boldsymbol{p}}_{\perp,g_1}\,, && \eta_{g_1} = \widetilde{\eta}_{g_1}\,,\\
&2. \quad g_1[\bar{q}] \to g_1 g_2[\bar{q}]: && \boldsymbol{p}_{\perp,g_1} = \widetilde{\boldsymbol{p}}_{\perp,g_1} - \boldsymbol{p}_{\perp,g_2}\,, && \eta_{g_1} = \widetilde{\eta}_{g_1} - \ln\frac{|\boldsymbol{p}_{\perp,g_1}|}{|\widetilde{\boldsymbol{p}}_{\perp,g_1}|}\,,\\
&3. \quad g_1[q] \to g_1 g_2[q]: && \boldsymbol{p}_{\perp,g_1} = \widetilde{\boldsymbol{p}}_{\perp,g_1} - \boldsymbol{p}_{\perp,g_2}\,, && \eta_{g_1} = \widetilde{\eta}_{g_1} + \ln\frac{|\boldsymbol{p}_{\perp,g_1}|}{|\widetilde{\boldsymbol{p}}_{\perp,g_1}|}\,,\\
&4. \quad q[g_1] \to q g_2[g_1]: && \boldsymbol{p}_{\perp,g_1} = \widetilde{\boldsymbol{p}}_{\perp,g_1}\,, && \eta_{g_1} = \widetilde{\eta}_{g_1}
\end{aligned}
$$

*With/without tilde: momentum before/after emission of gluon 2*

# Two emissions matrix-element

## Phasespace map



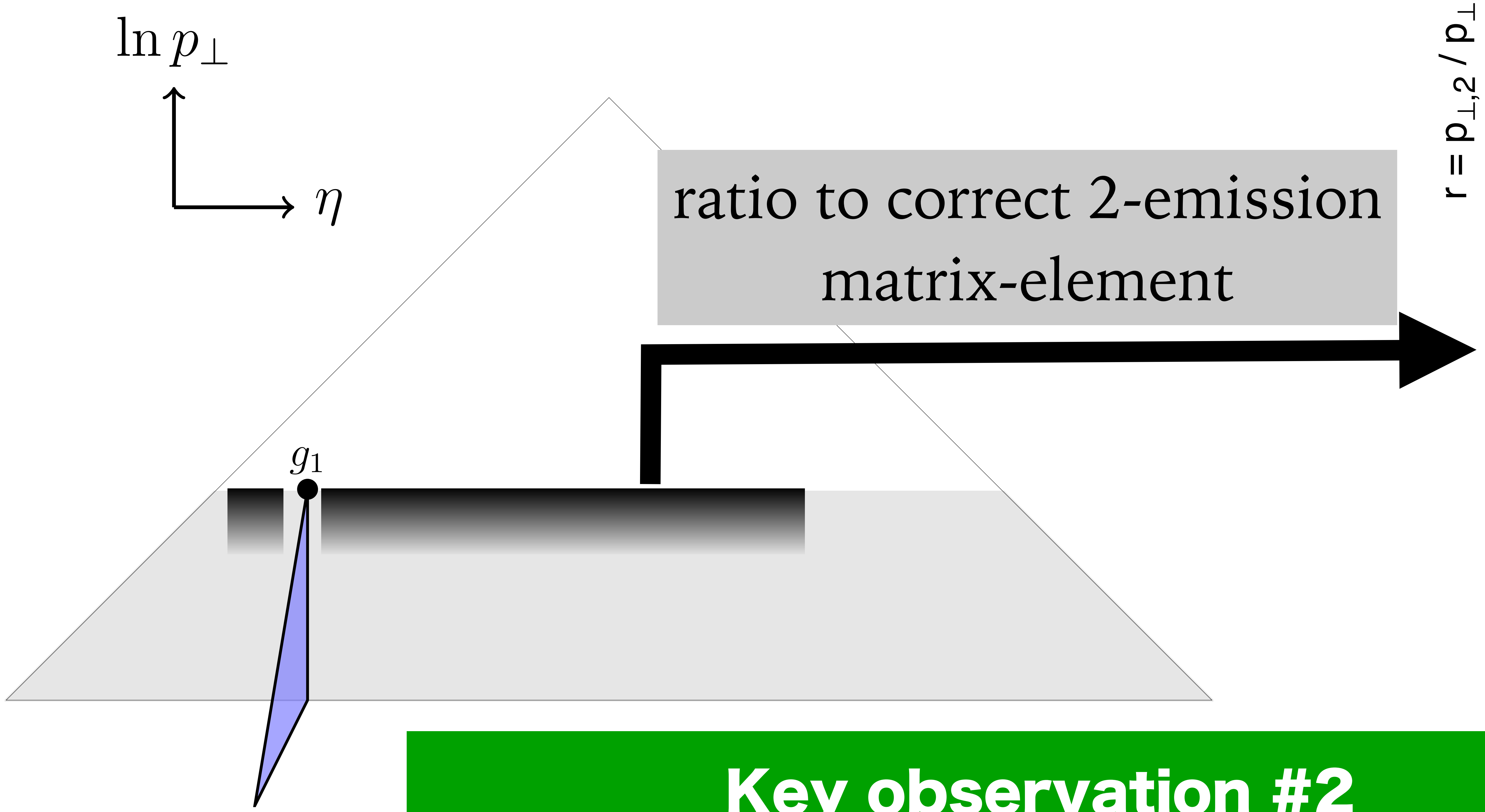

**Key observation #2**

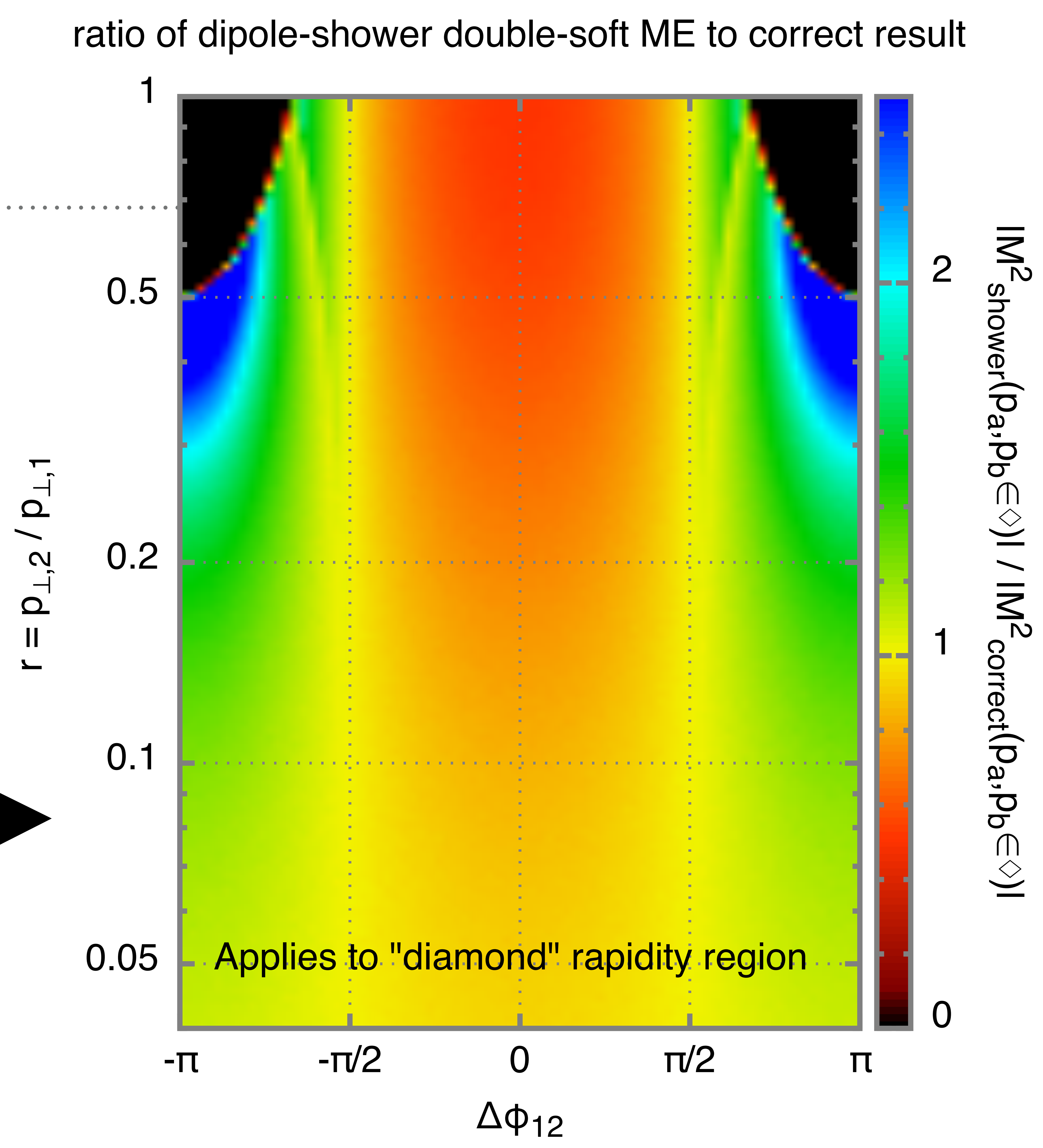
**phasespace where it matters is "NLL"**

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

# Two emissions matrix-element

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?*

# 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 | $-0.349^{+0.003}_{-0.003}\,\bar{\alpha}^3 L^3$ |
| $B_T$ | $-0.0167335\,\bar{\alpha}^2 L^2$ |
| $y_3^{\text{cam}}$ | $-0.18277\,\bar{\alpha}^2 L^2$ |
| $\text{FC}_1$ | $-0.066934\,\bar{\alpha}^2 L^2$ |

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

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

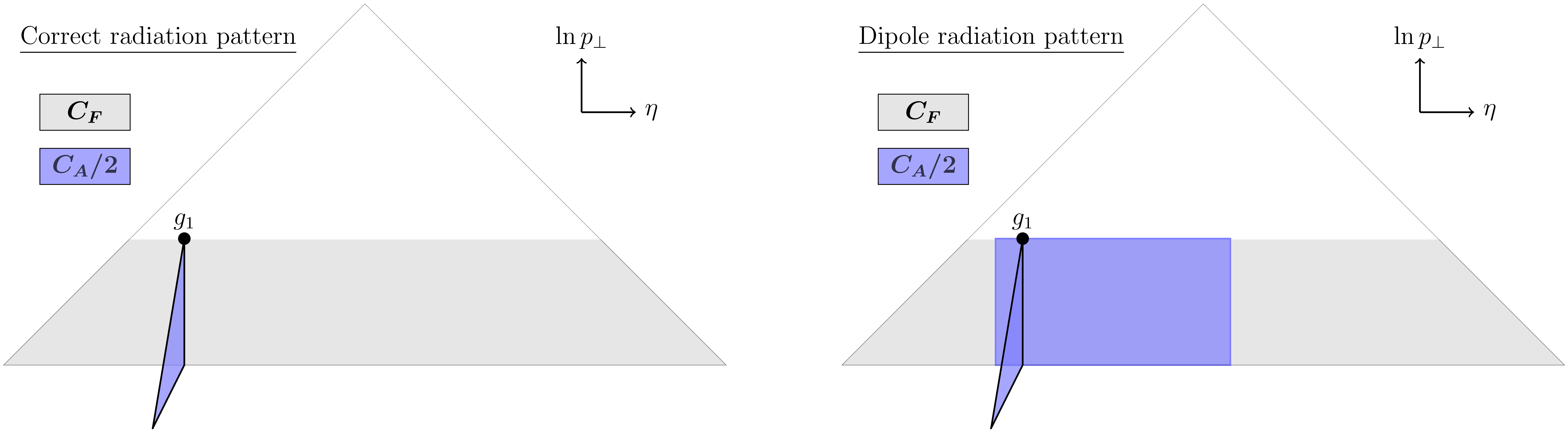
(because all these observables are quite inclusive)

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. $C_F$)

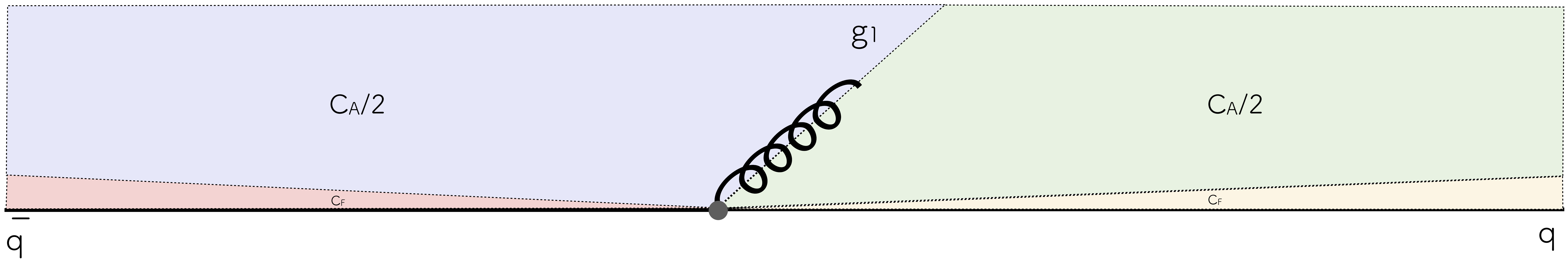



**Key observation #3**

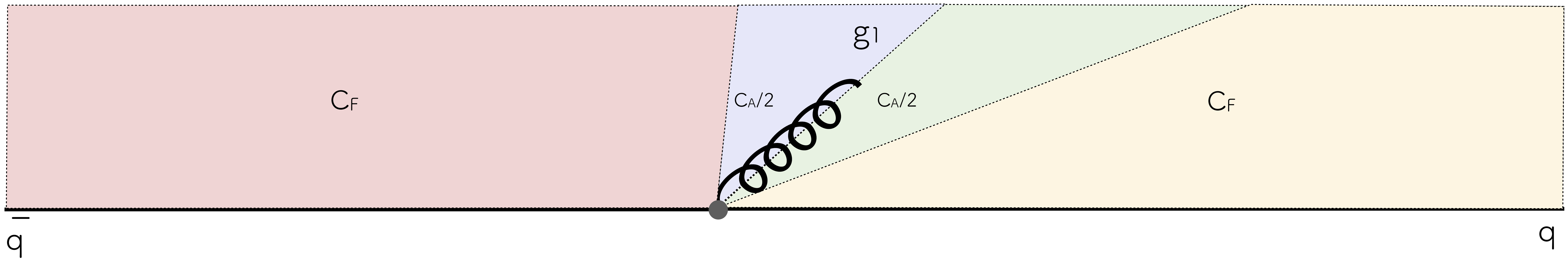
**$C_F$ v. $C_A/2$ issues occurs over a large area → double (leading) log effects?**

# 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

# next steps

# Understanding showers

- **Extend analysis to other showers**
  - E.g. Herwig angular ordered shower variants studied by Bewick, Ravasio-Ferrario, Richardson, Seymour, arXiv:1904.11866
- **Extend analysis to all orders**
  - including a statement of matrix-element properties to be reproduced at all orders
  - extension of analytic/numerical analysis shown here to all-orders, for both recoil issues and colour-factor issues
  - implementing full versions of showers (e.g. Pythia & Dire) & checking that there aren't other "surprises"
    [numerical verification of log-structure with a full shower is highly non-trivial, but important for validating future shower algorithms]

# Developing new showers

- **What ordering variables can / should one be using?**
  - broad conceivable family is $k_t\, e^{-b|\eta|}$ with any b > -1
  - are all allowed?
- **What classes of recoil schemes are allowed?**
  - dipole-local?
  - global?
- **What should be chosen as the baseline colour-factor treatment?**
  - full colour is cumbersome, are there starting points that make it less so?
  - cf. e.g. Gustafson '93, C. Friberg, G. Gustafson and J. Hakkinen, hep-ph/9604347 Giele, Kosower & Skands, arXiv:1102.2126

# closing

# Conclusions

Parton showers are a crucial element in collider physics

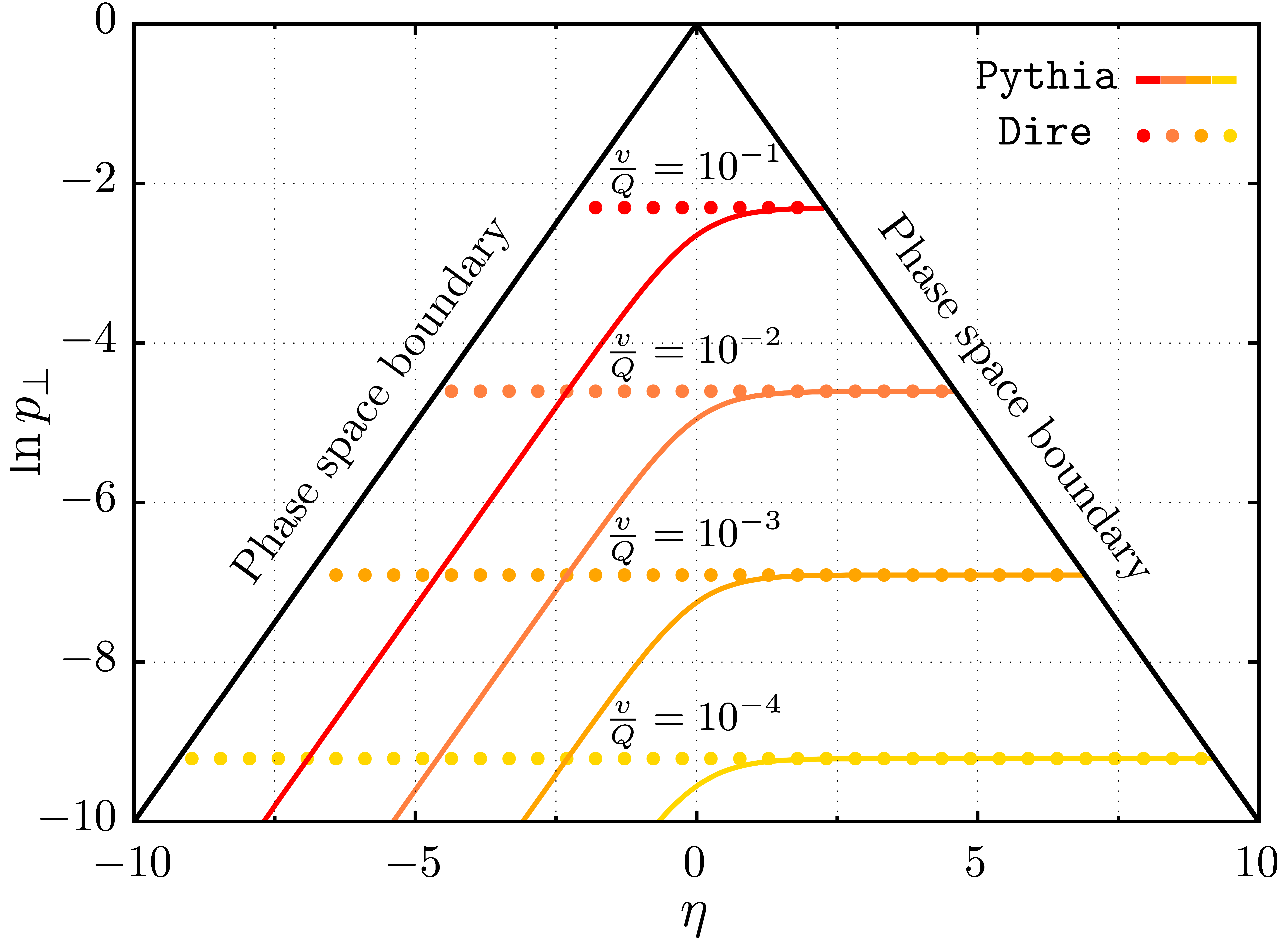
Seeing many developments (subleading colour for non-global logarithms, multi-particle emission kernels, etc.)

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

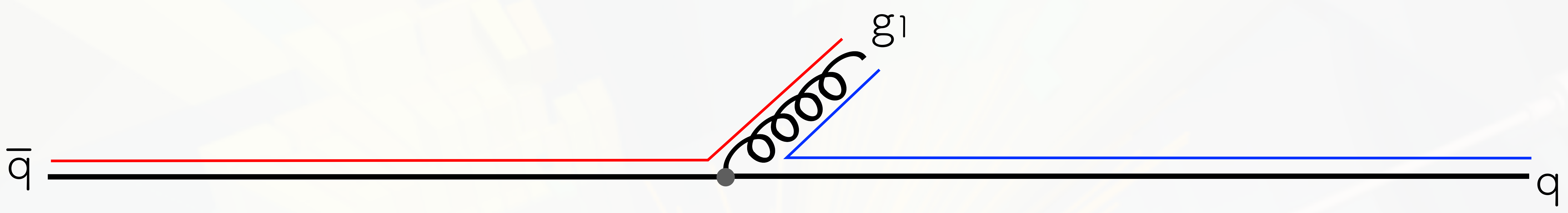
# BACKUP

# Constant evolution variable contours in the Lund plane

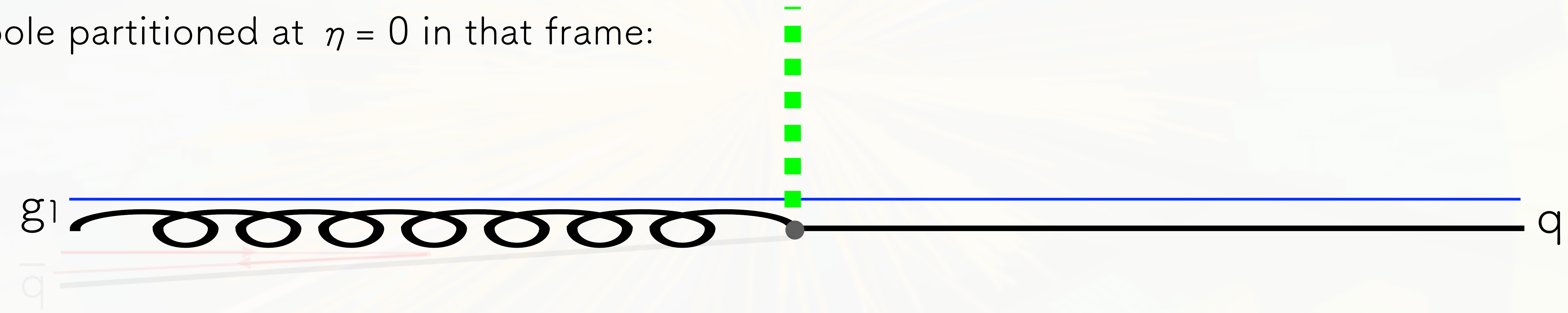


# two soft emissions : boost dipole partitions back into the event COM

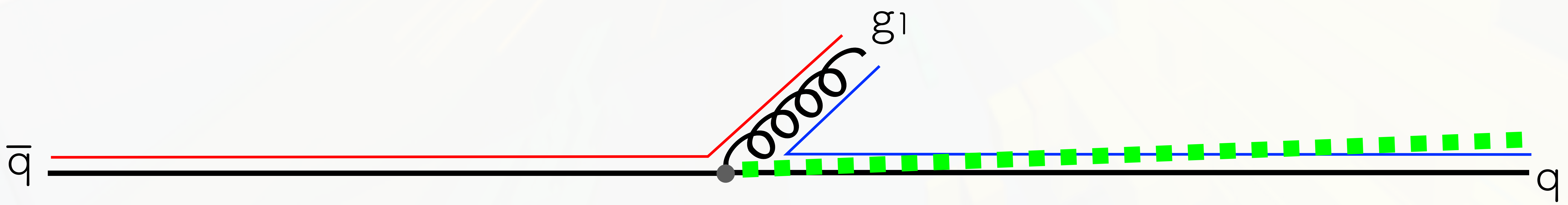
- Consider we emitted **soft gluon $g_1$** from **hard** $q\bar{q}$, so we end up with a $qg_1$ and a $g_1\bar{q}$ dipole:




- 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:



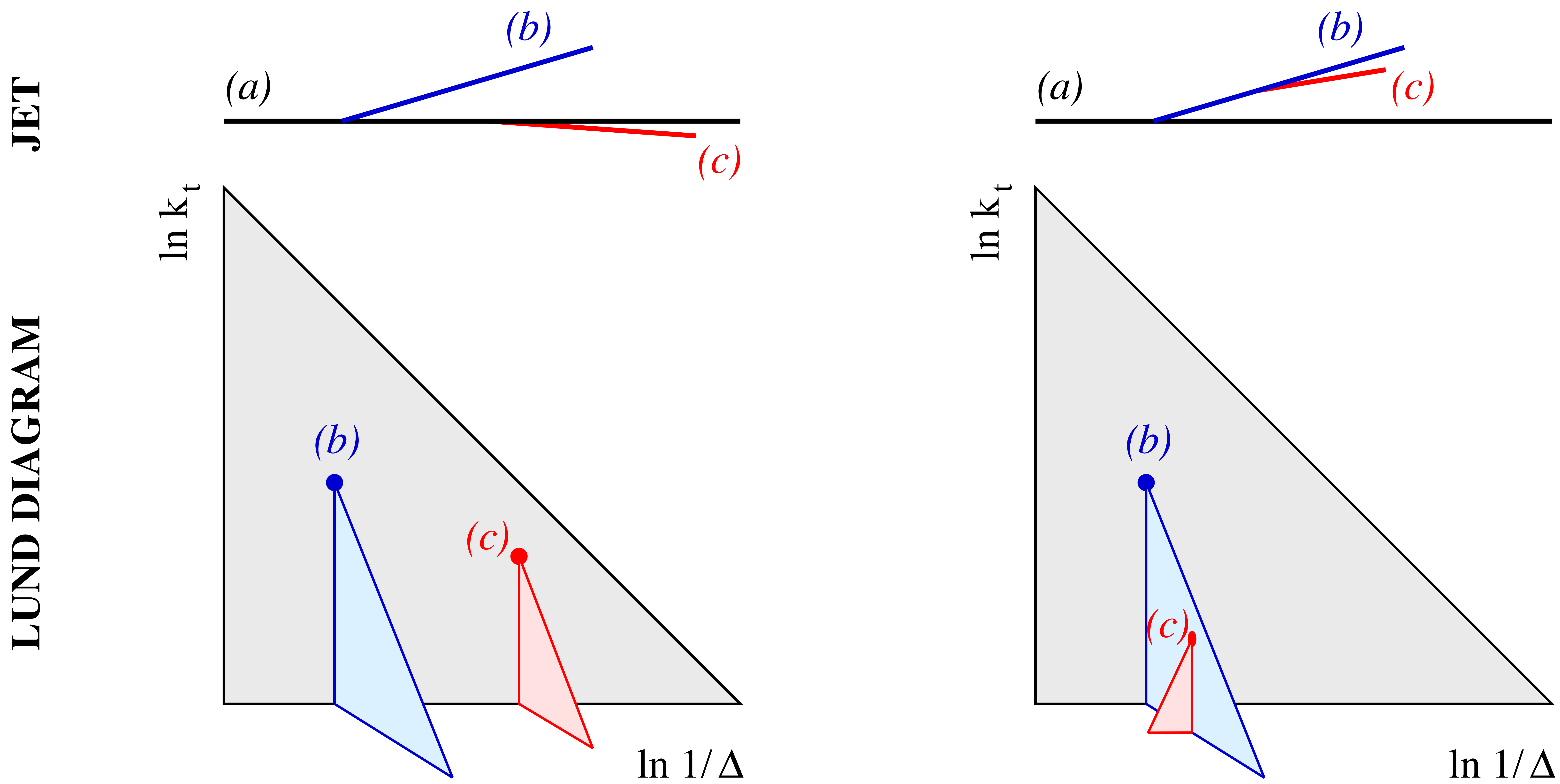

- To get us back to the event COM from the $g_1q$ dipole COM undo the same **BIG BOOST** ⟵



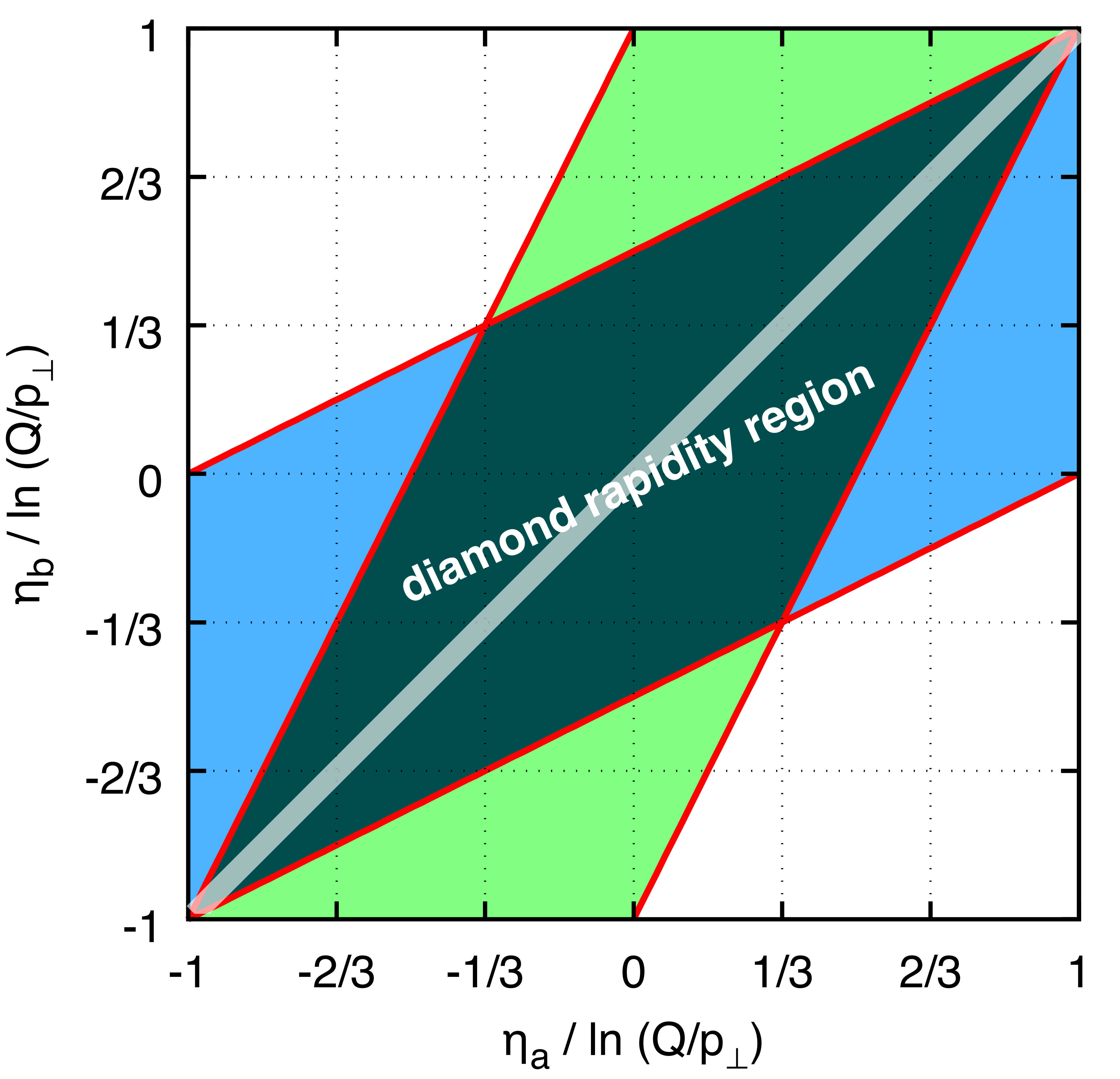

- In event COM partition comes out very close to q ; instead of equidistant in angle between $g_1$ & q

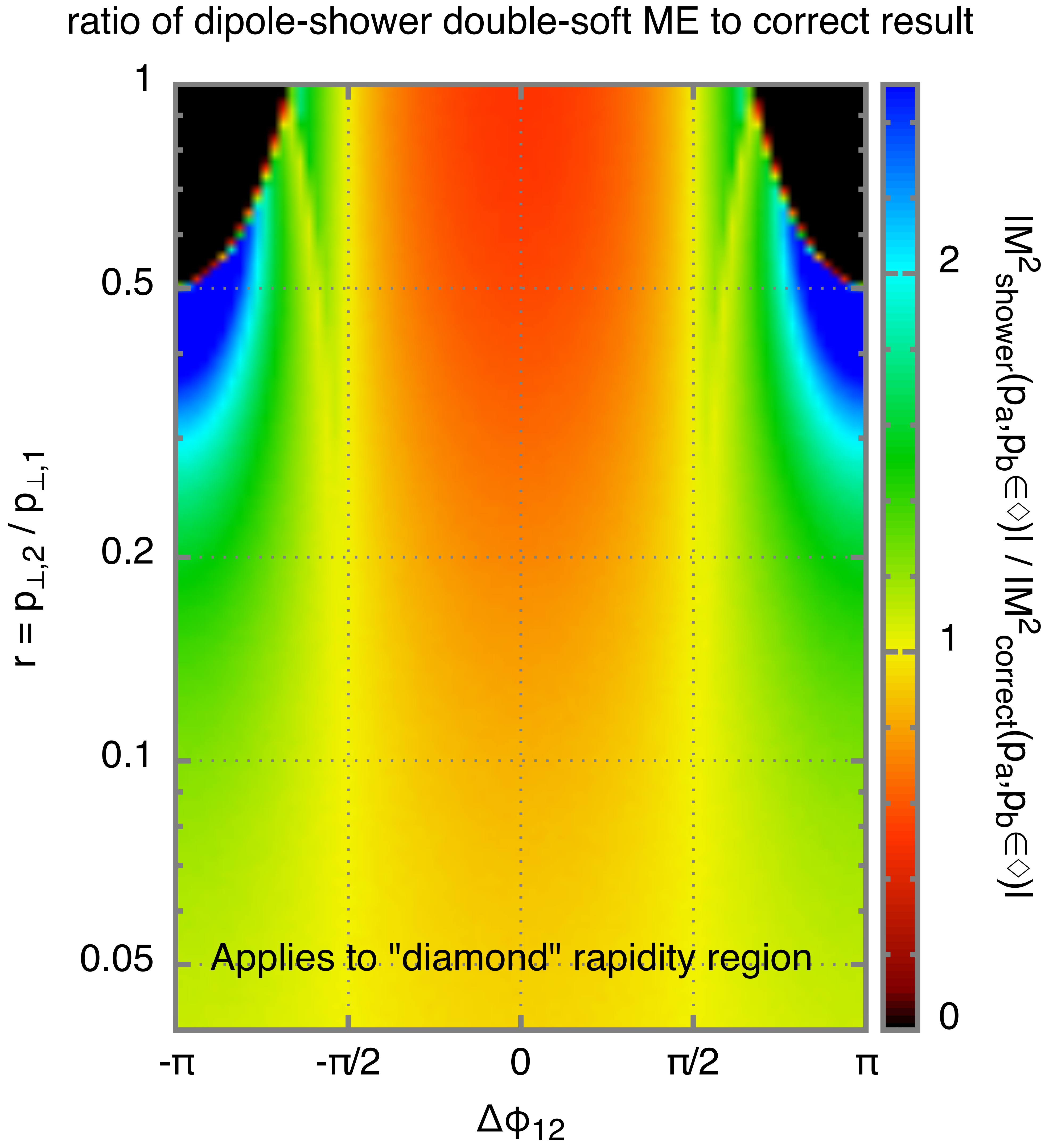
$g_1$

# organise phasespace: Lund diagrams

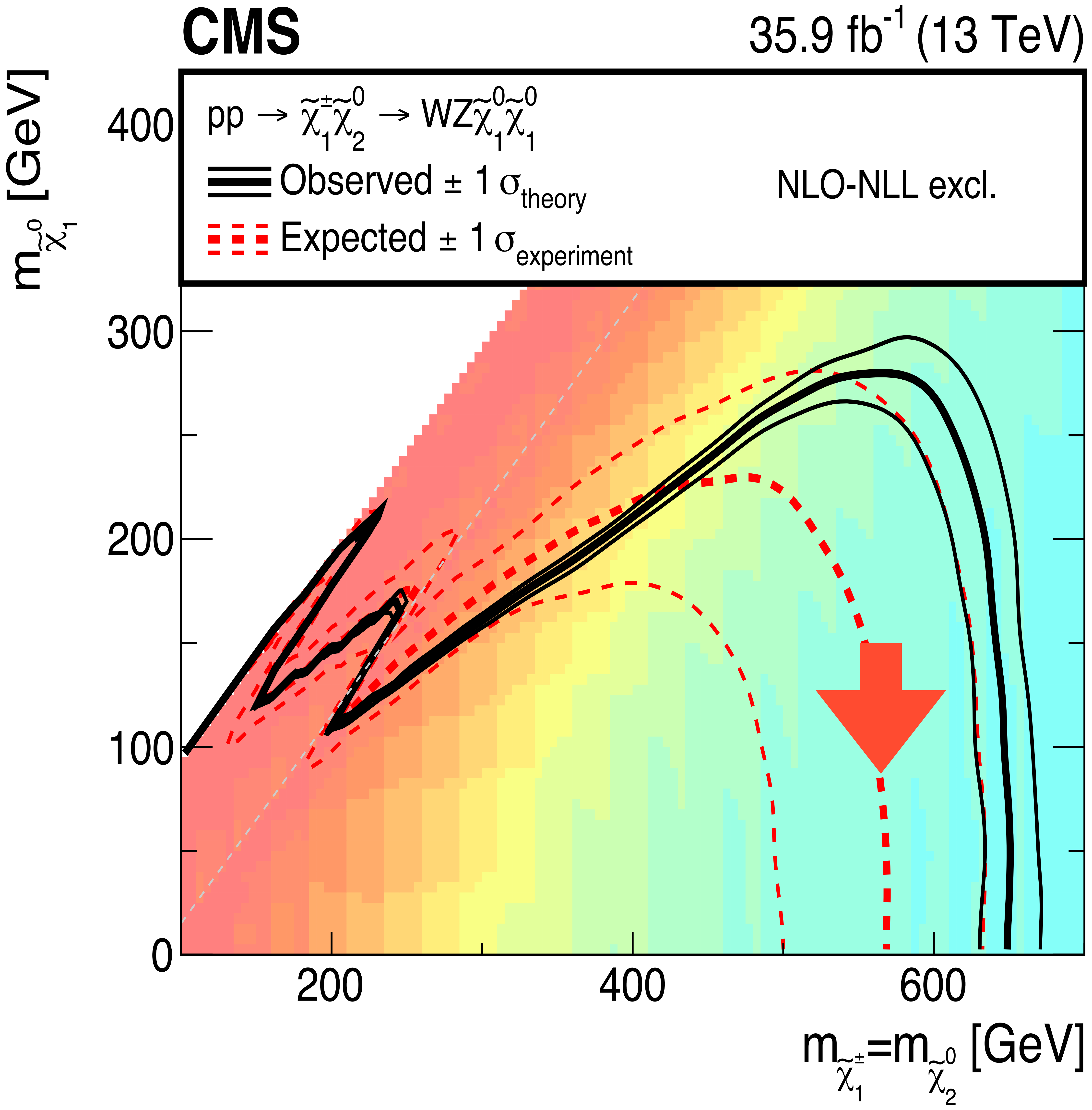


$$\frac{dP_{2,\text{shower}}(p_a, p_b \in \diamond)}{d\eta_a\, d\eta_b\, d^2\boldsymbol{p}_{\perp,a} d^2\boldsymbol{p}_{\perp,b}} = \frac{1}{2!}\left(\frac{\alpha_s C_A}{2\pi^2}\right)^2 \int \frac{d^2\boldsymbol{p}_{\perp,1}}{{p_{\perp,1}}^2} \int_{p_{\perp,2}<p_{\perp,1}} \frac{d^2\boldsymbol{p}_{\perp,2}}{{p_{\perp,2}}^2}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



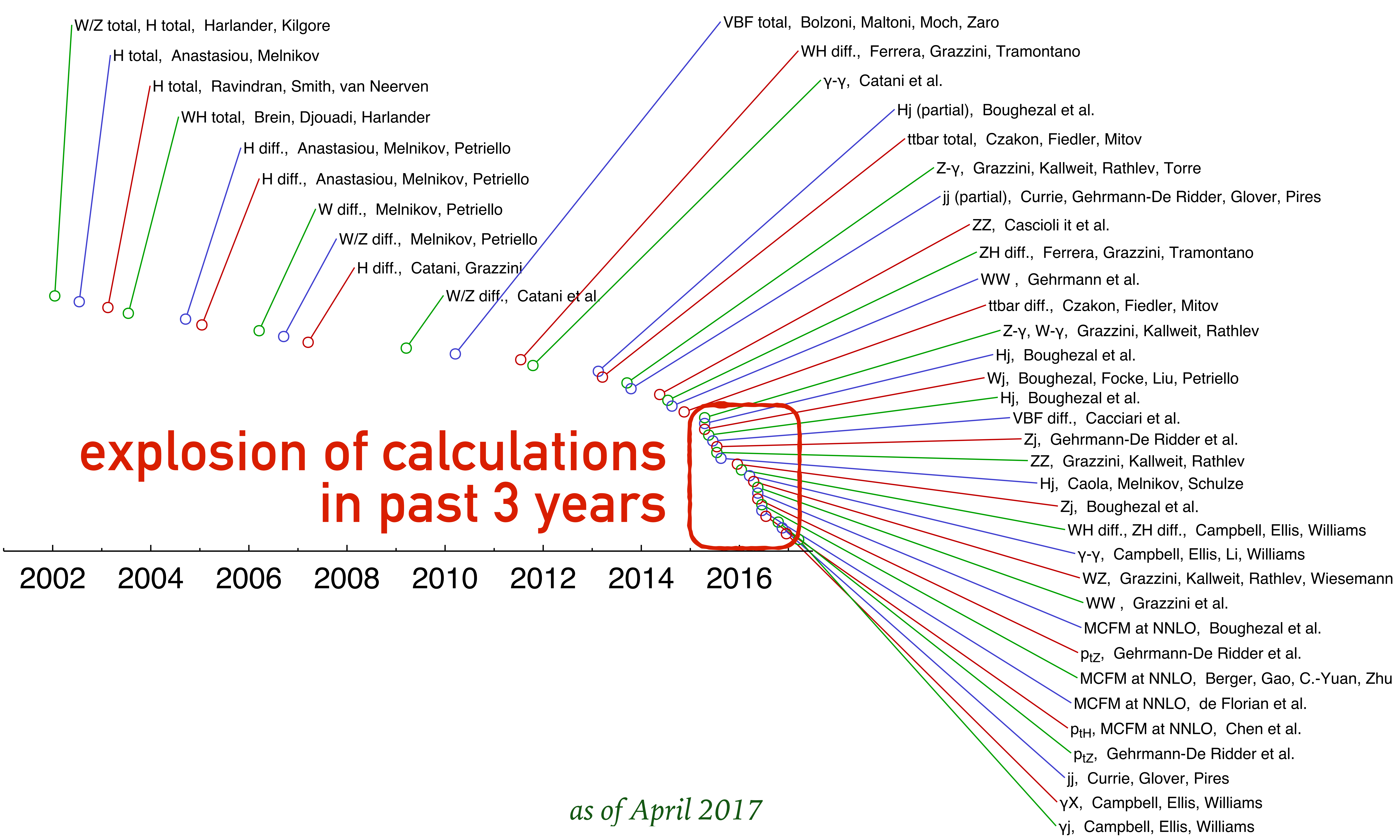
# The path forward: collect 20–30x more collisions by ~2035




- 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 ($\alpha_s$)




**explosion of calculations in past 3 years**

*as of April 2017*