Ten Years of Higgs Physics

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

New Directions in Theoretical Physics 4, Edinburgh, January 2023

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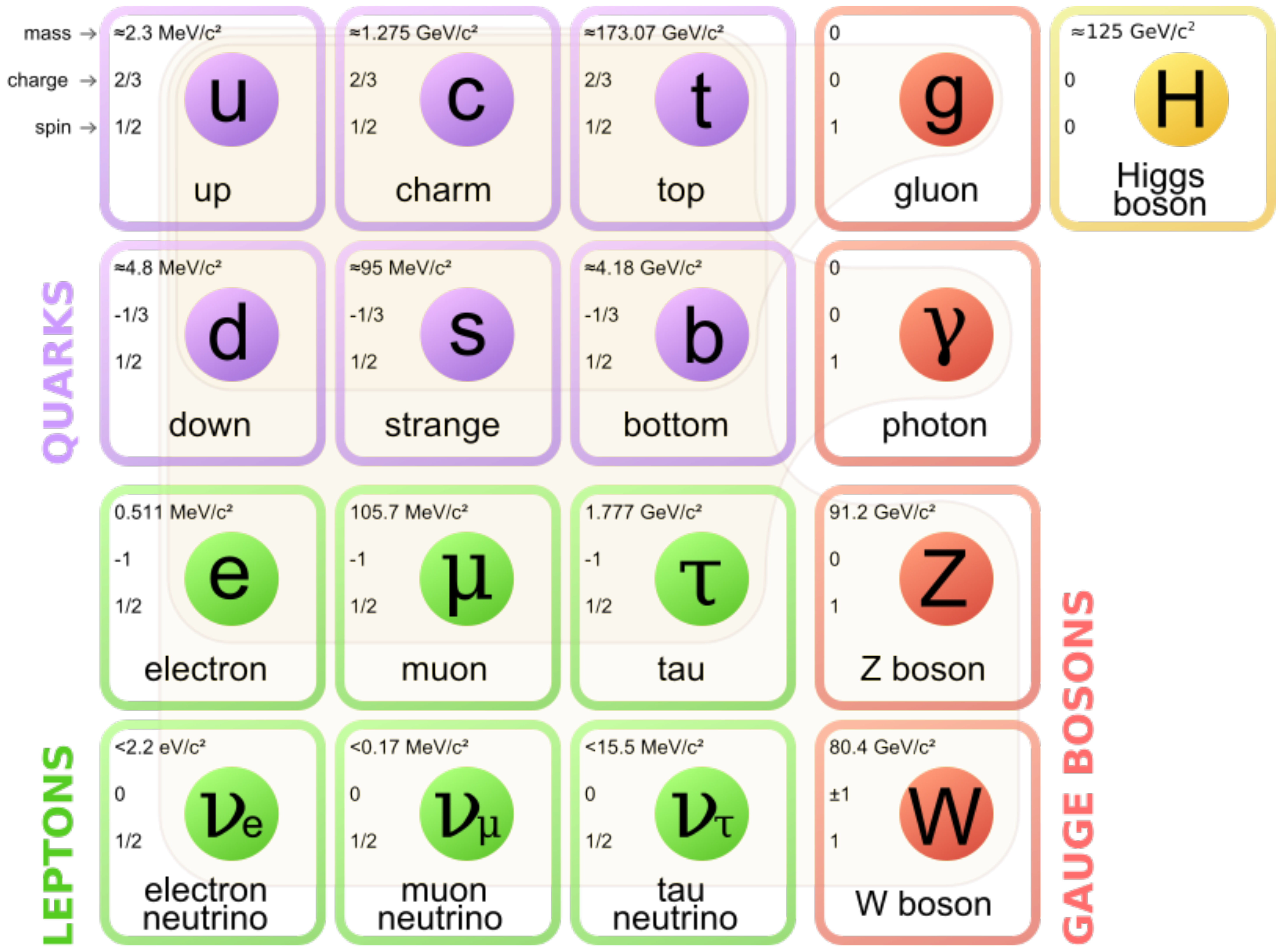
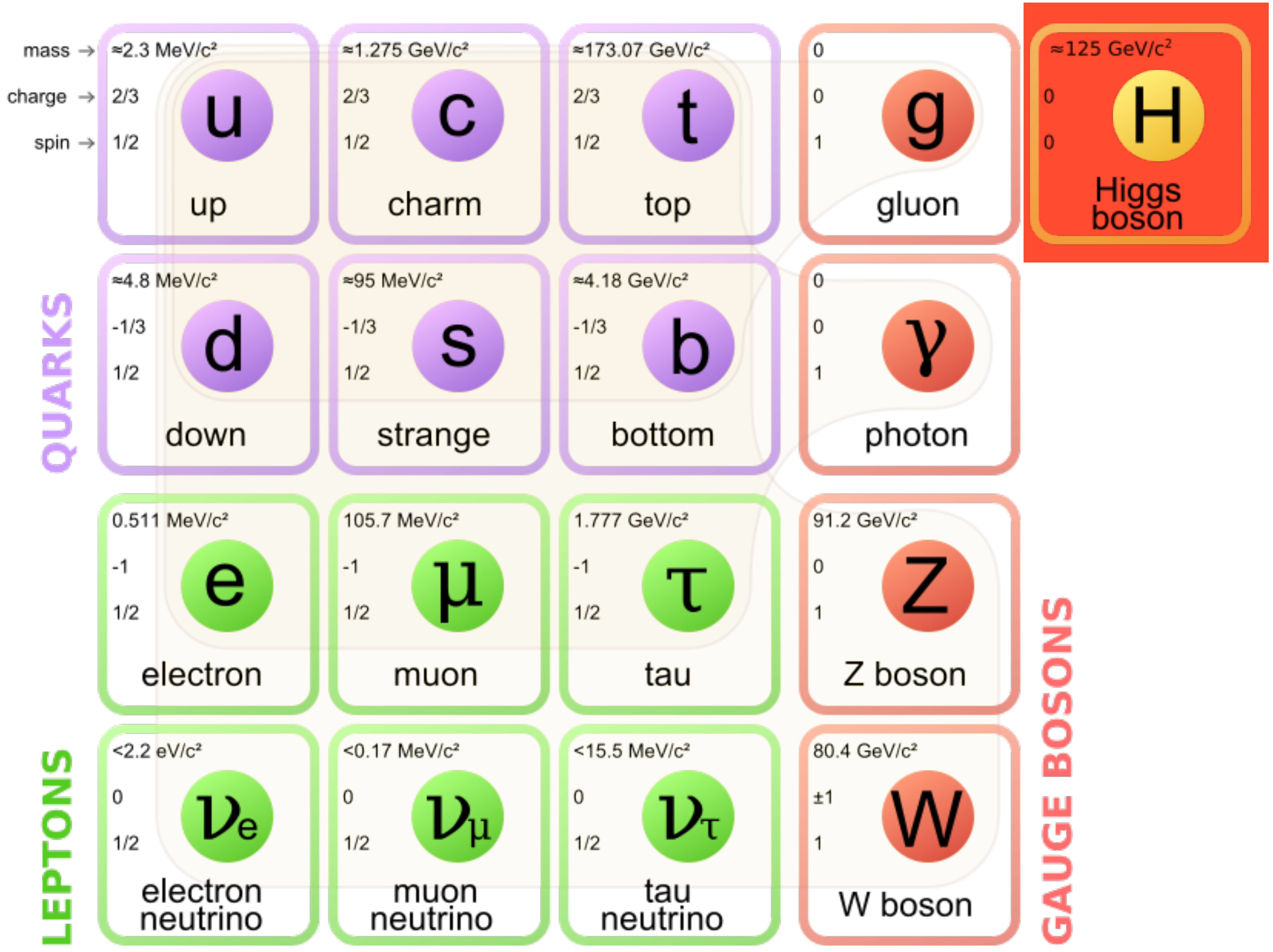
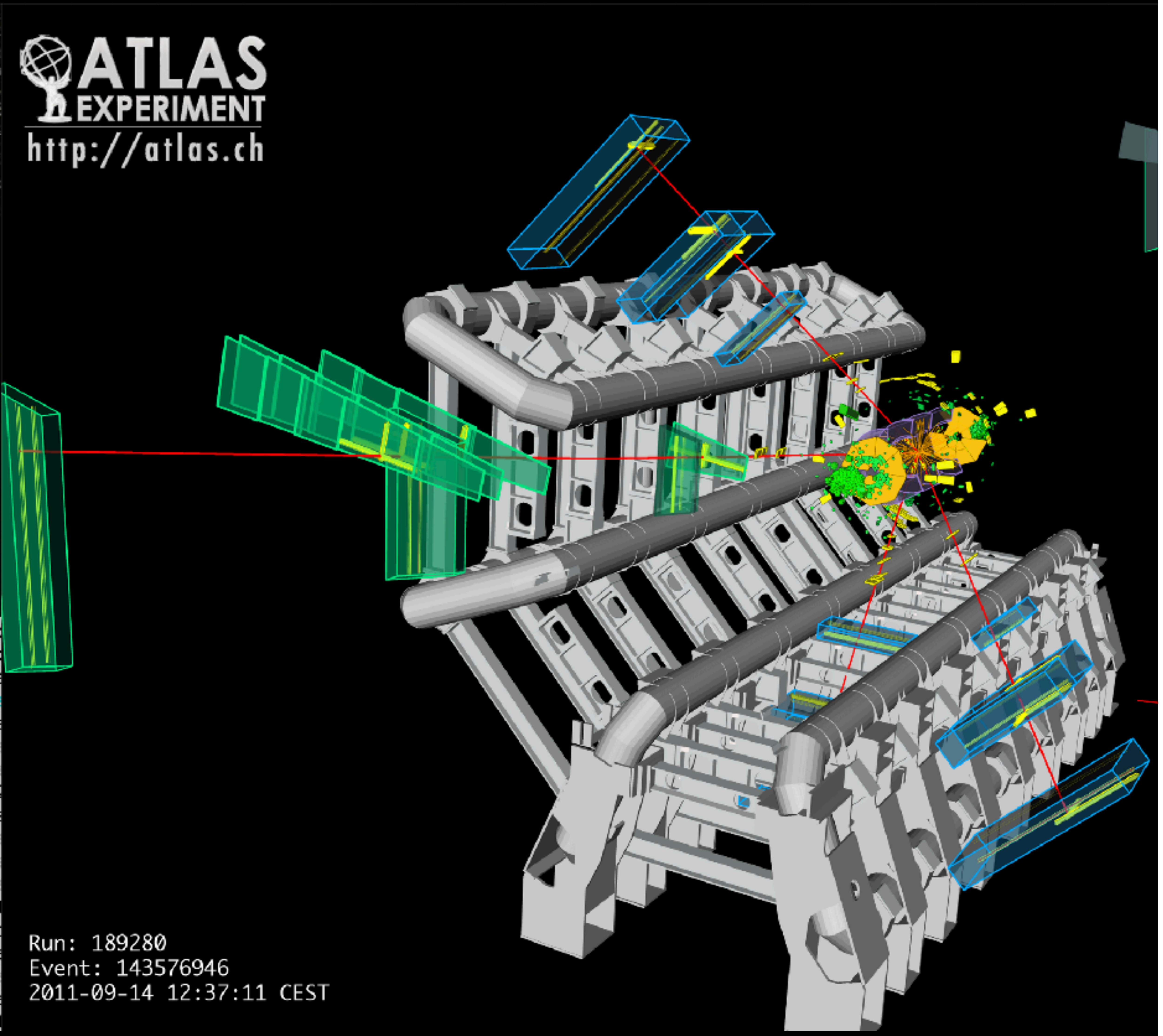
The Higgs boson



The Higgs boson





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ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC):

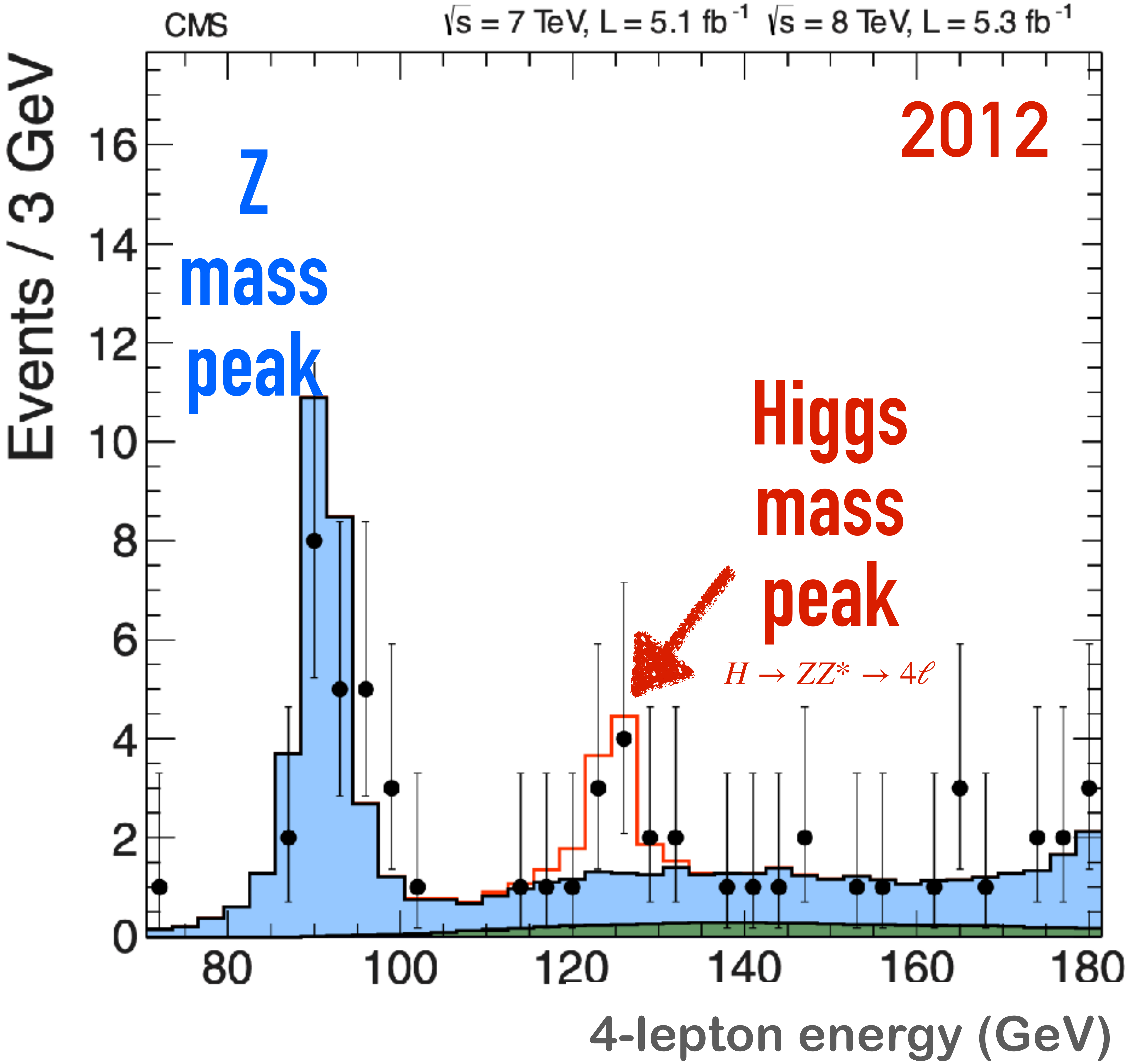
2012 discovery of a Higgs-like boson

Collide protons with protons

Select collision events
with four electrons or muons ("leptons")

Add up their energies
(in their overall centre-of-mass frame)

Plot distribution of that energy



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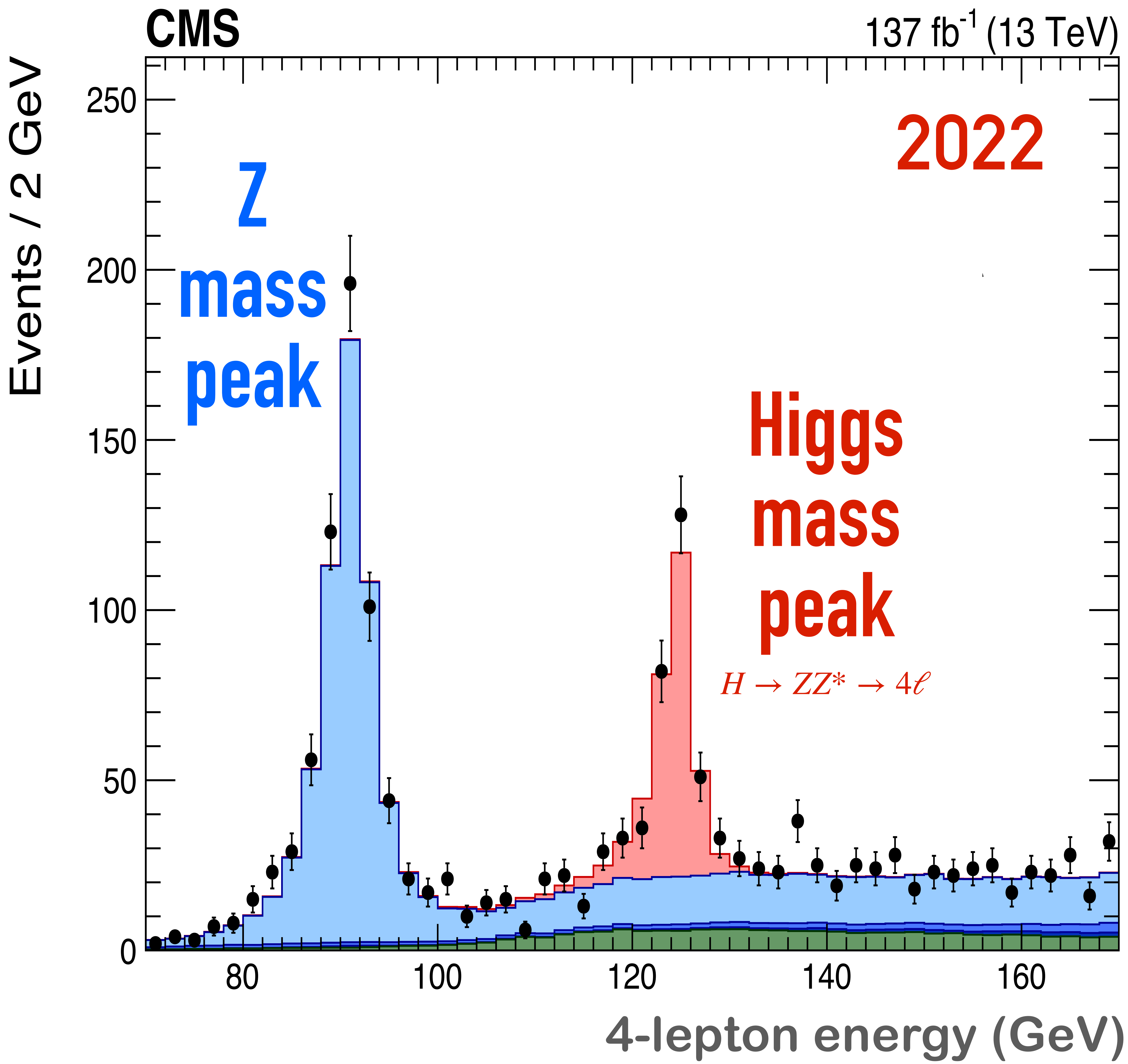

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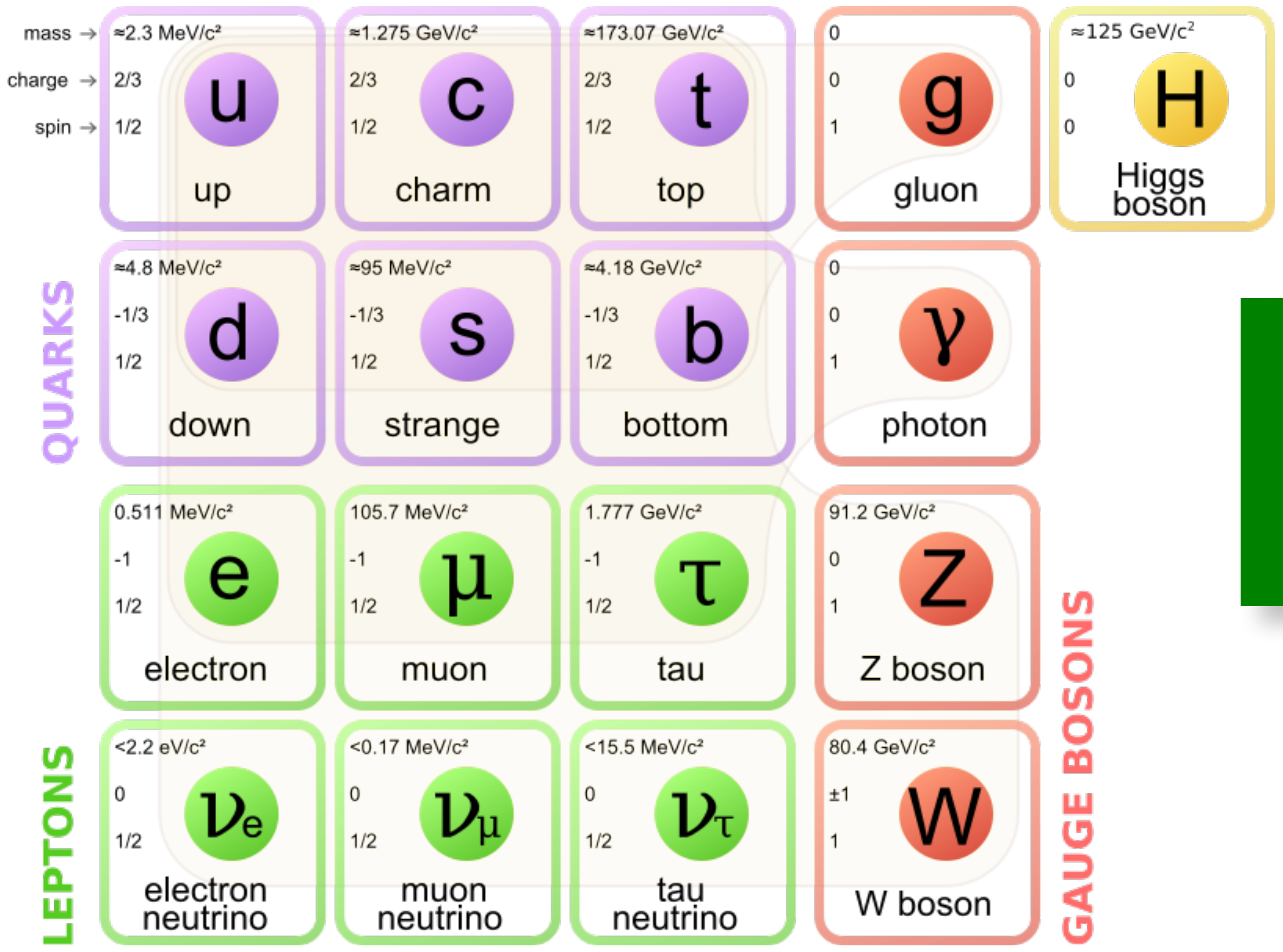
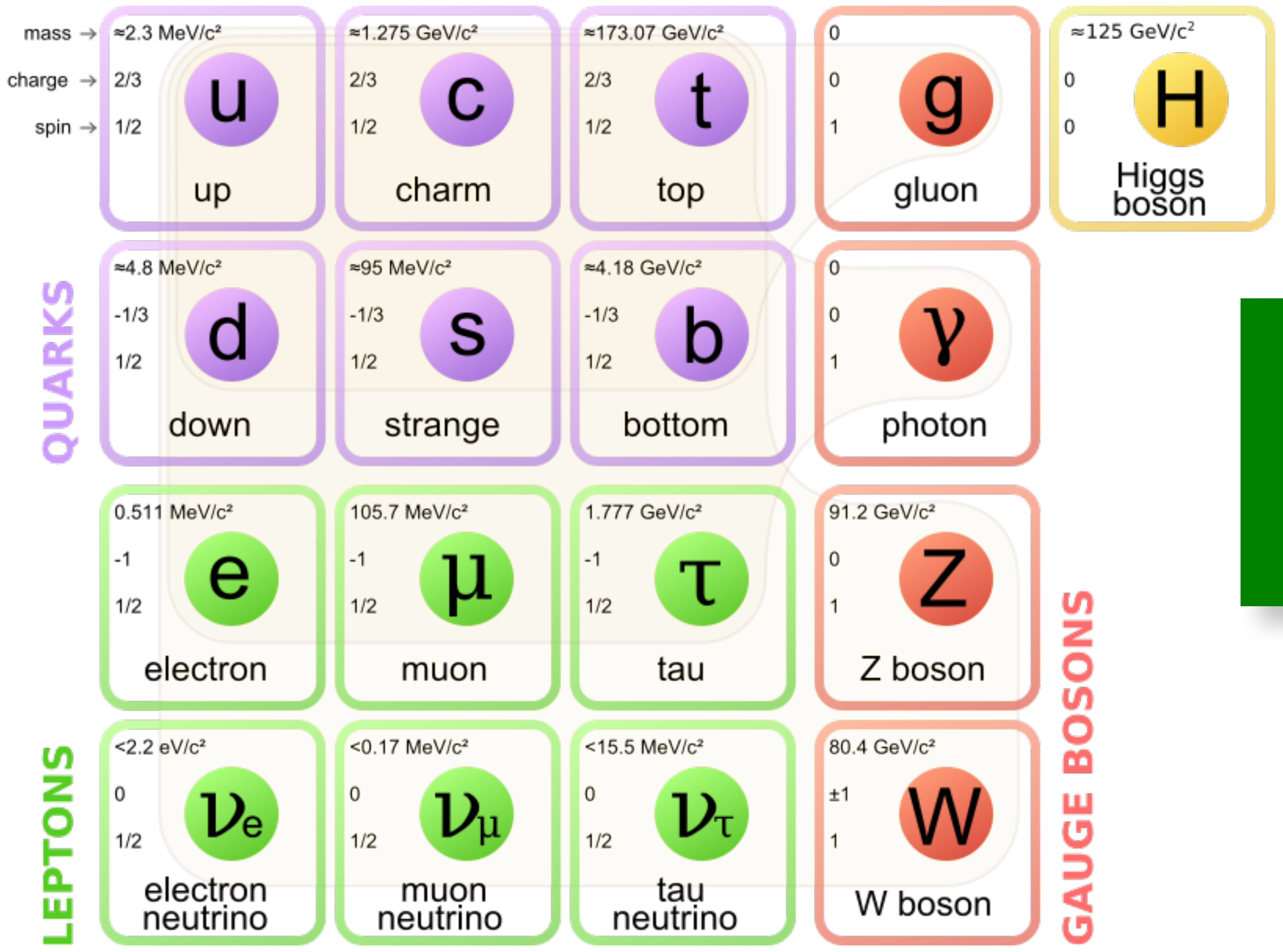
The Higgs boson (2012)



Success!

“The Standard Model is complete”

The Higgs boson (2012)



Success!

“The Standard Model particle set is complete”

particles

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particles

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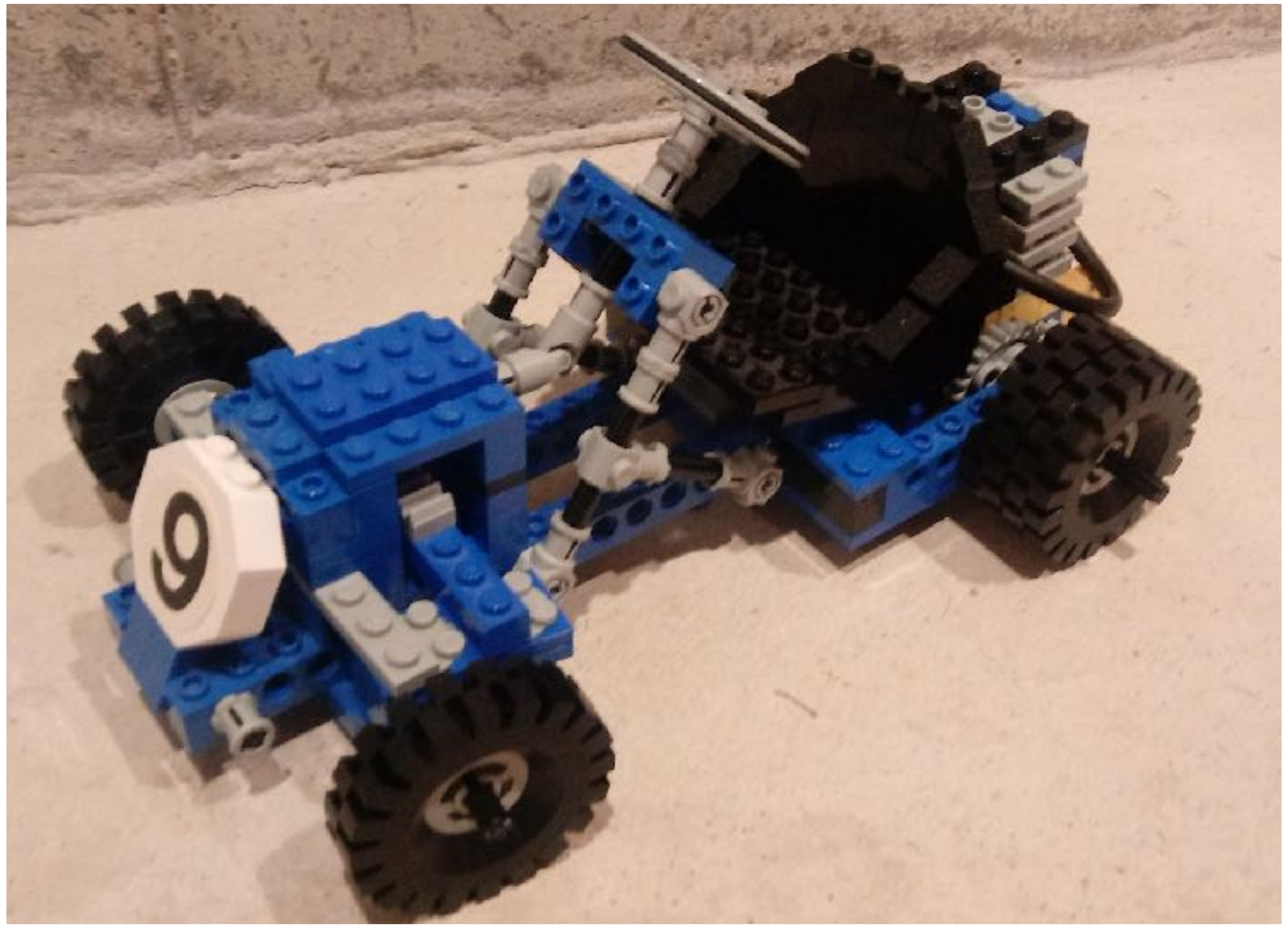
particles + interactions



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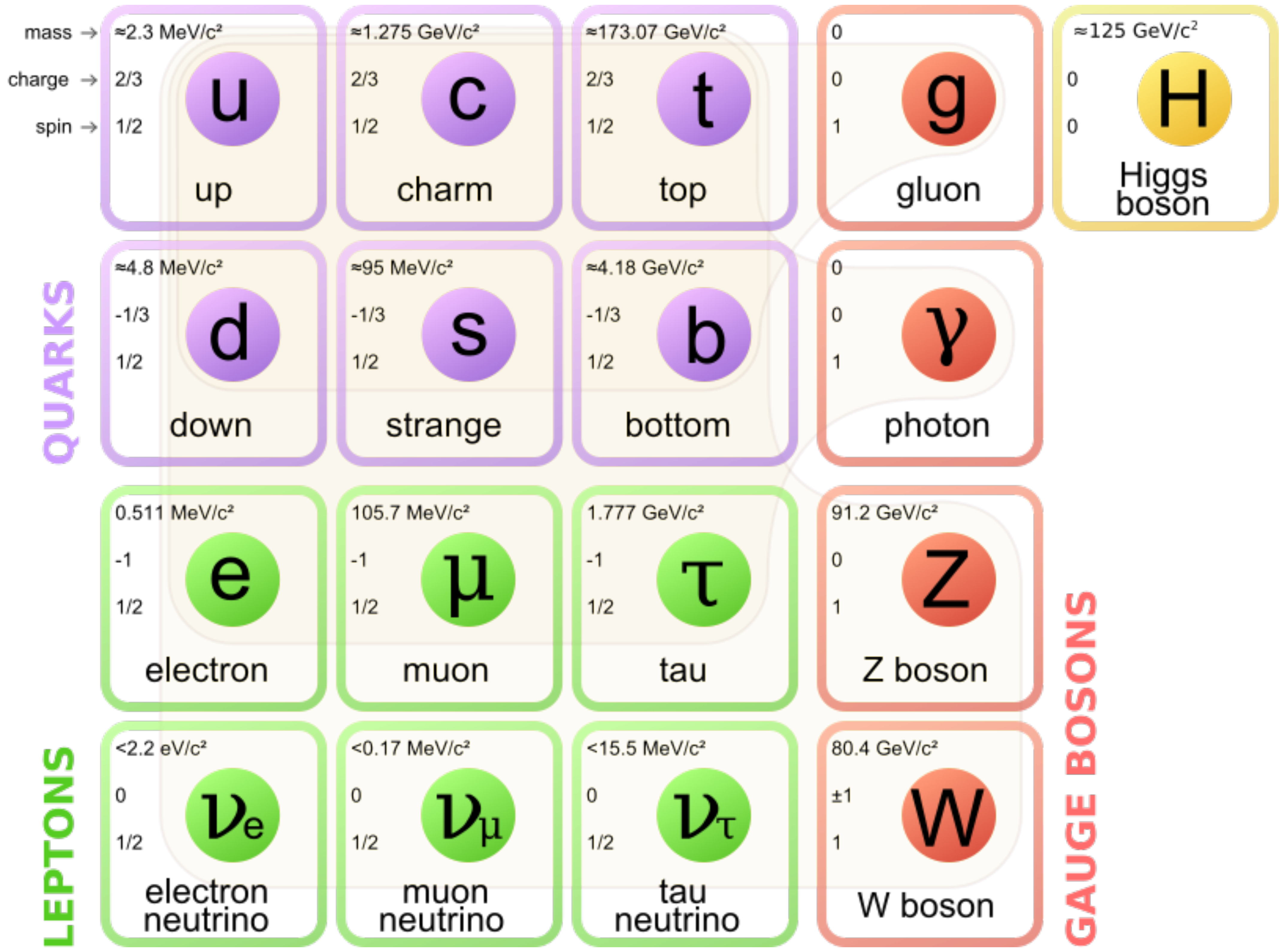
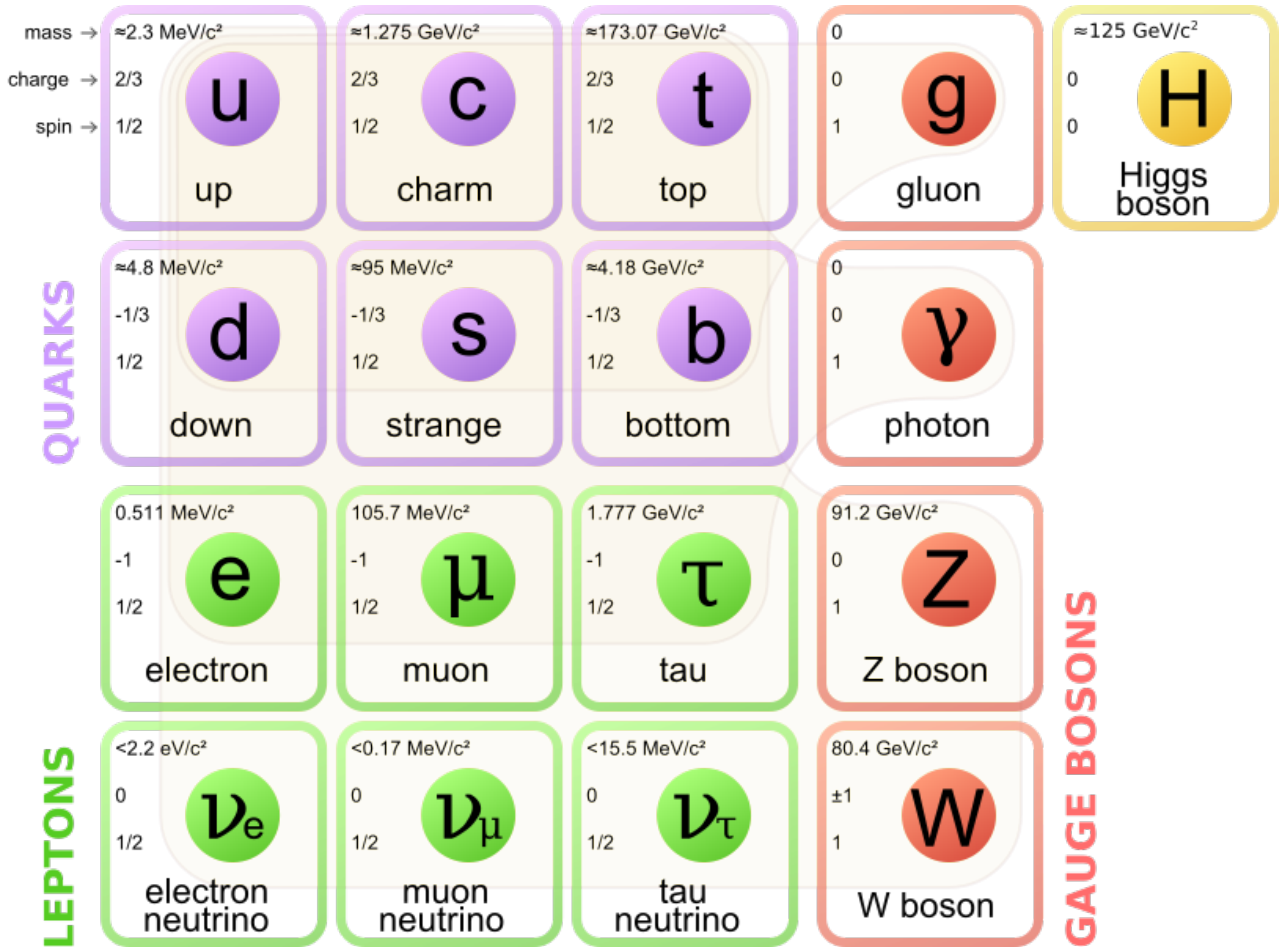
what is the Standard Model?

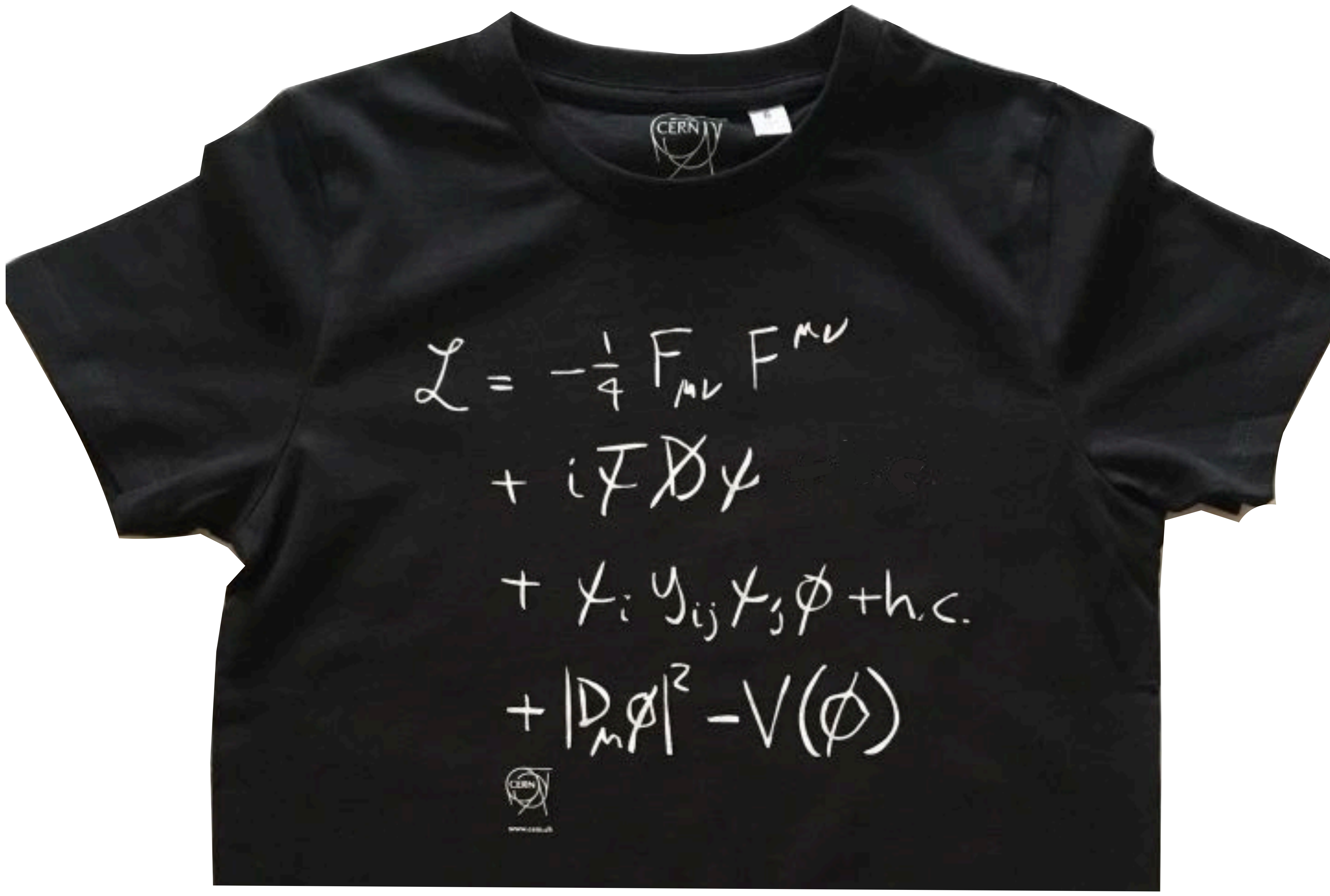


particles

what is the Standard Model?

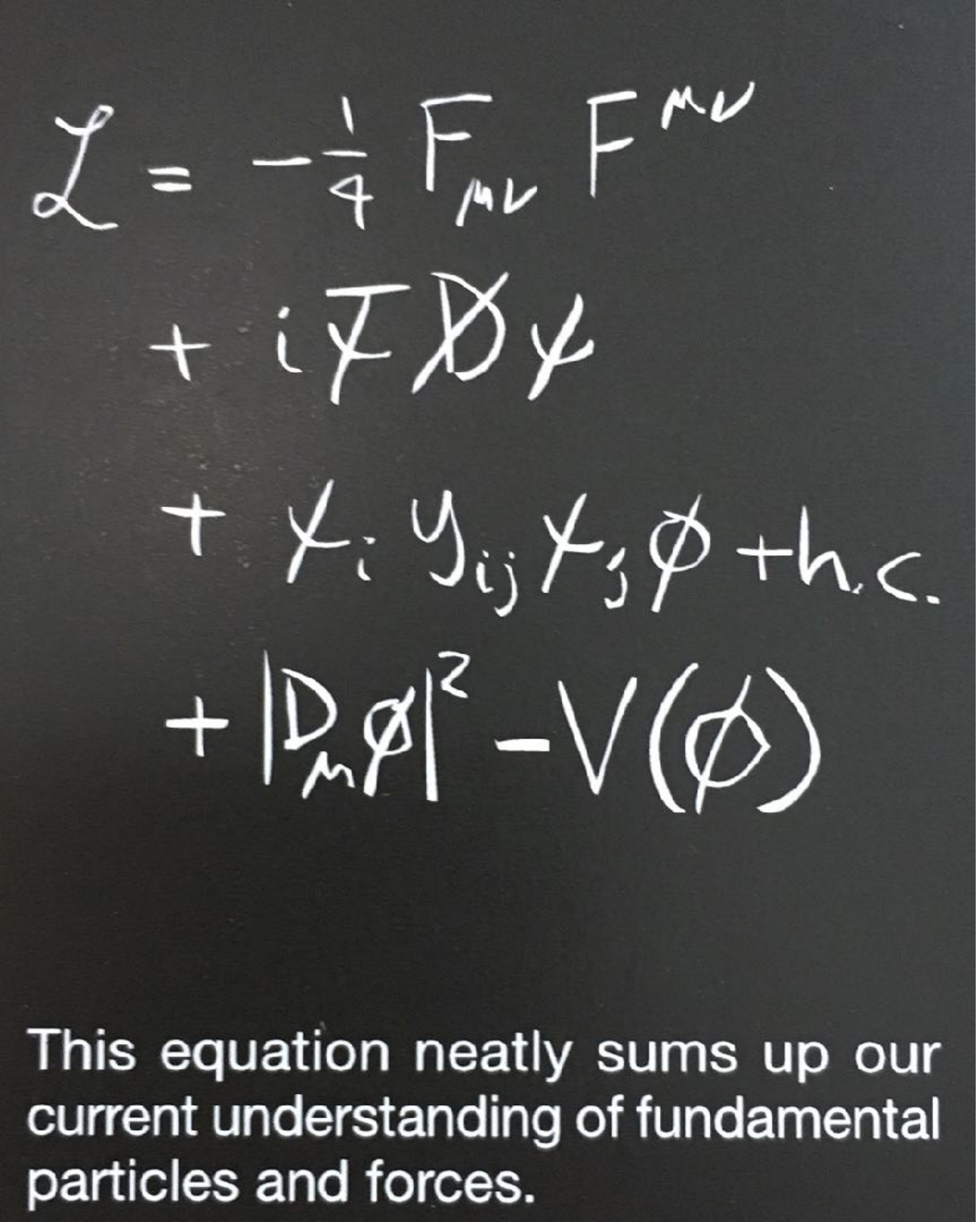


+



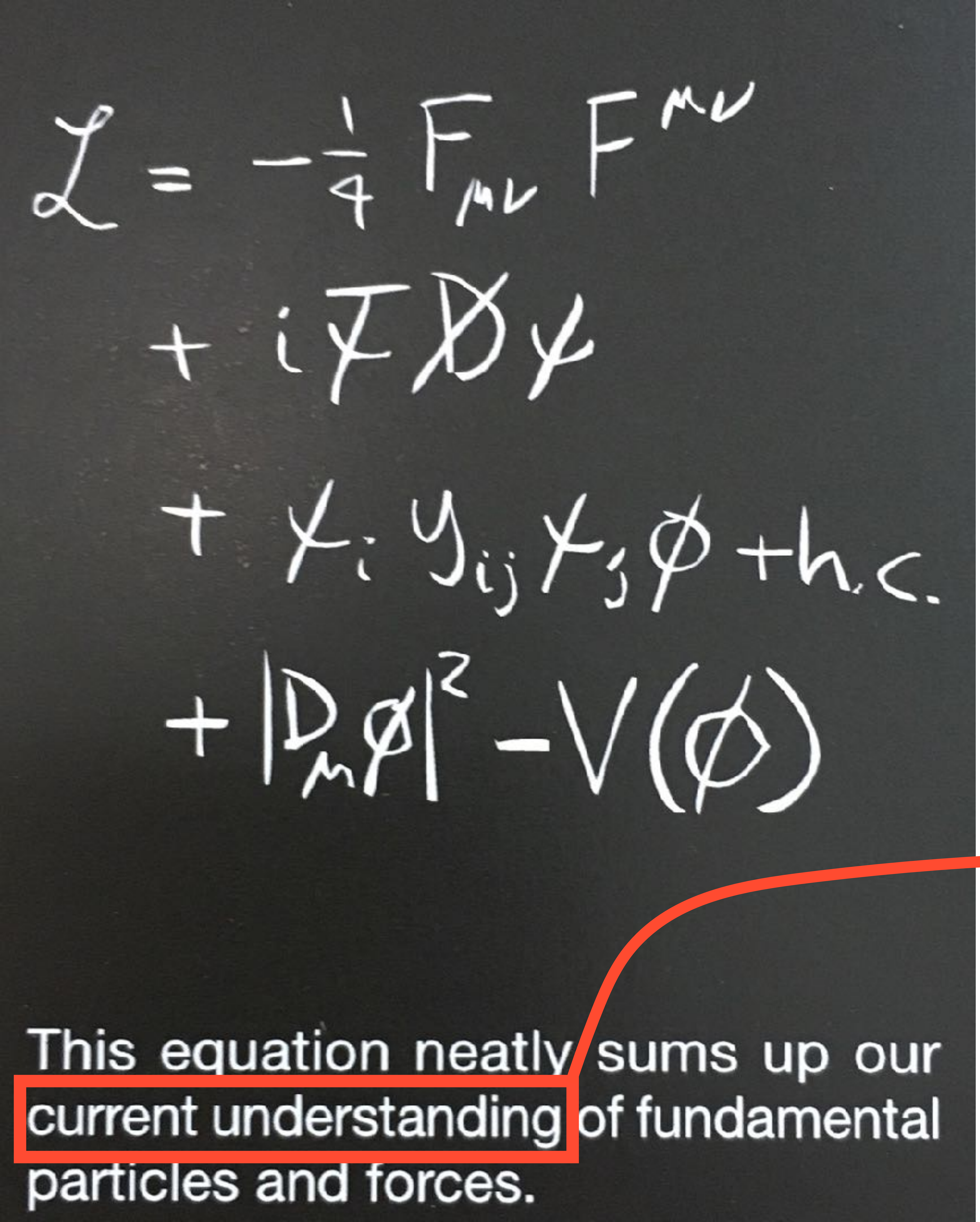
particles

interactions



Standard Model — knowable unknowns

These T-shirts come with a little explanation

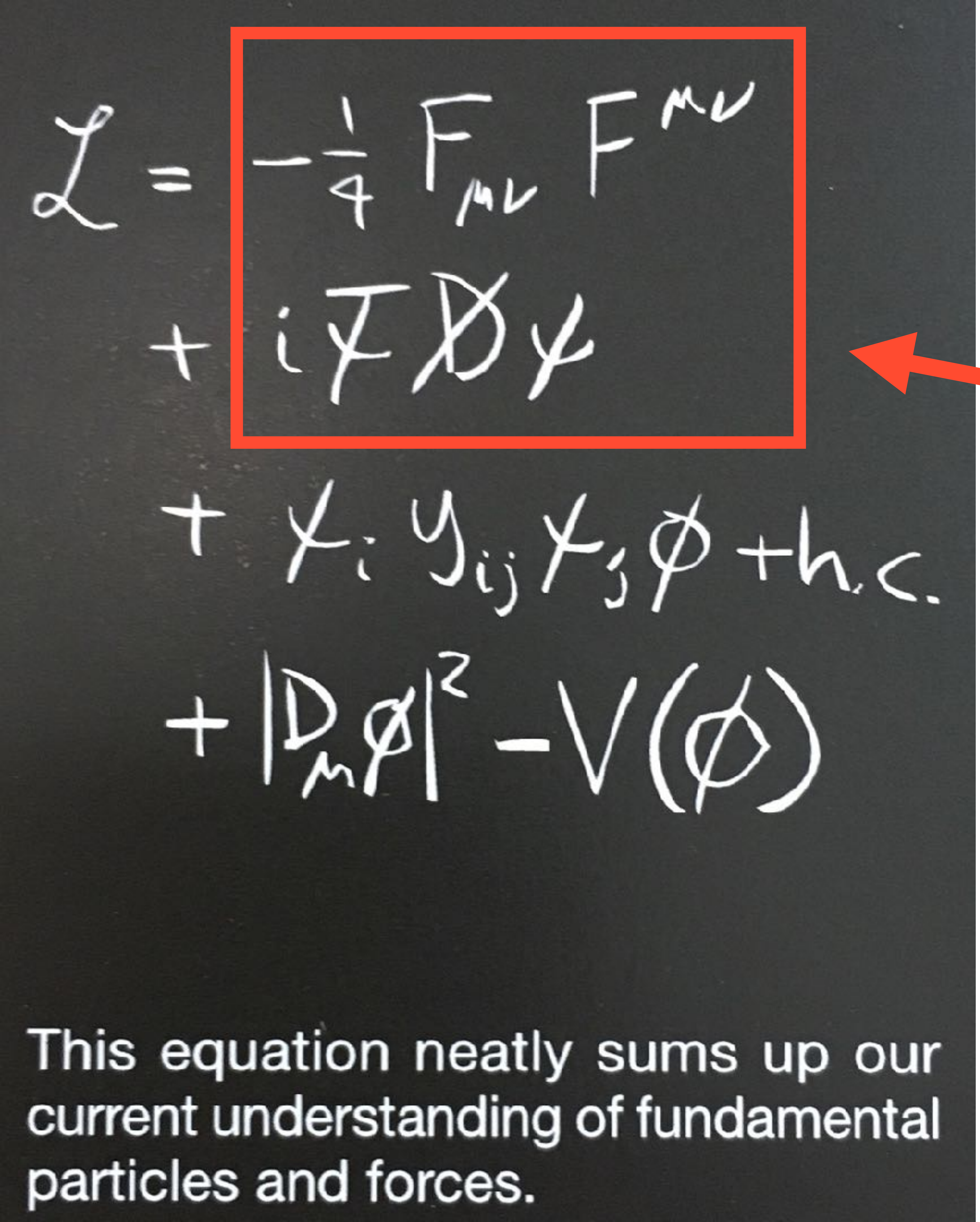


These T-shirts come with a little explanation

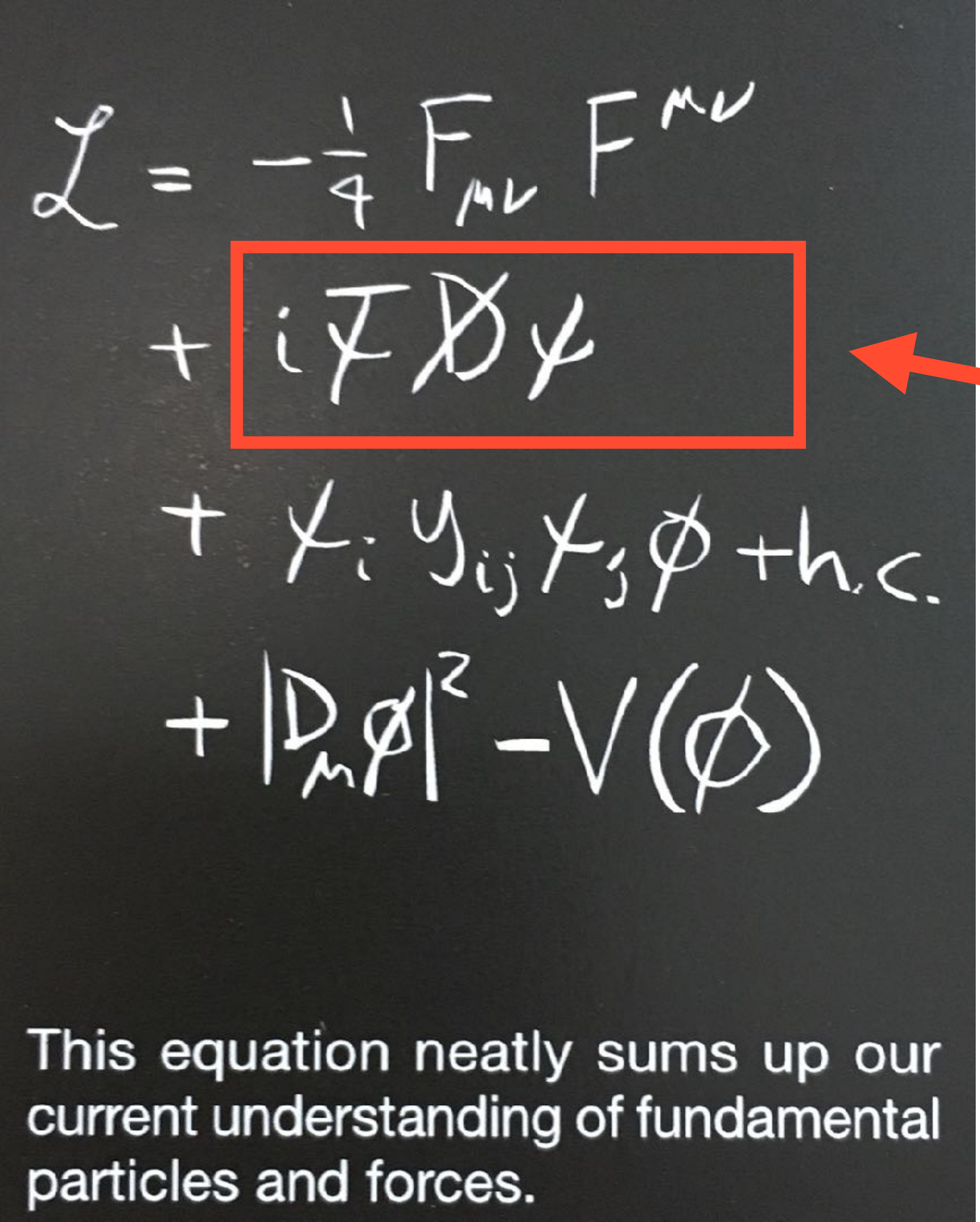
"understanding" = knowledge ?

"understanding" = assumption ?

What does it mean?



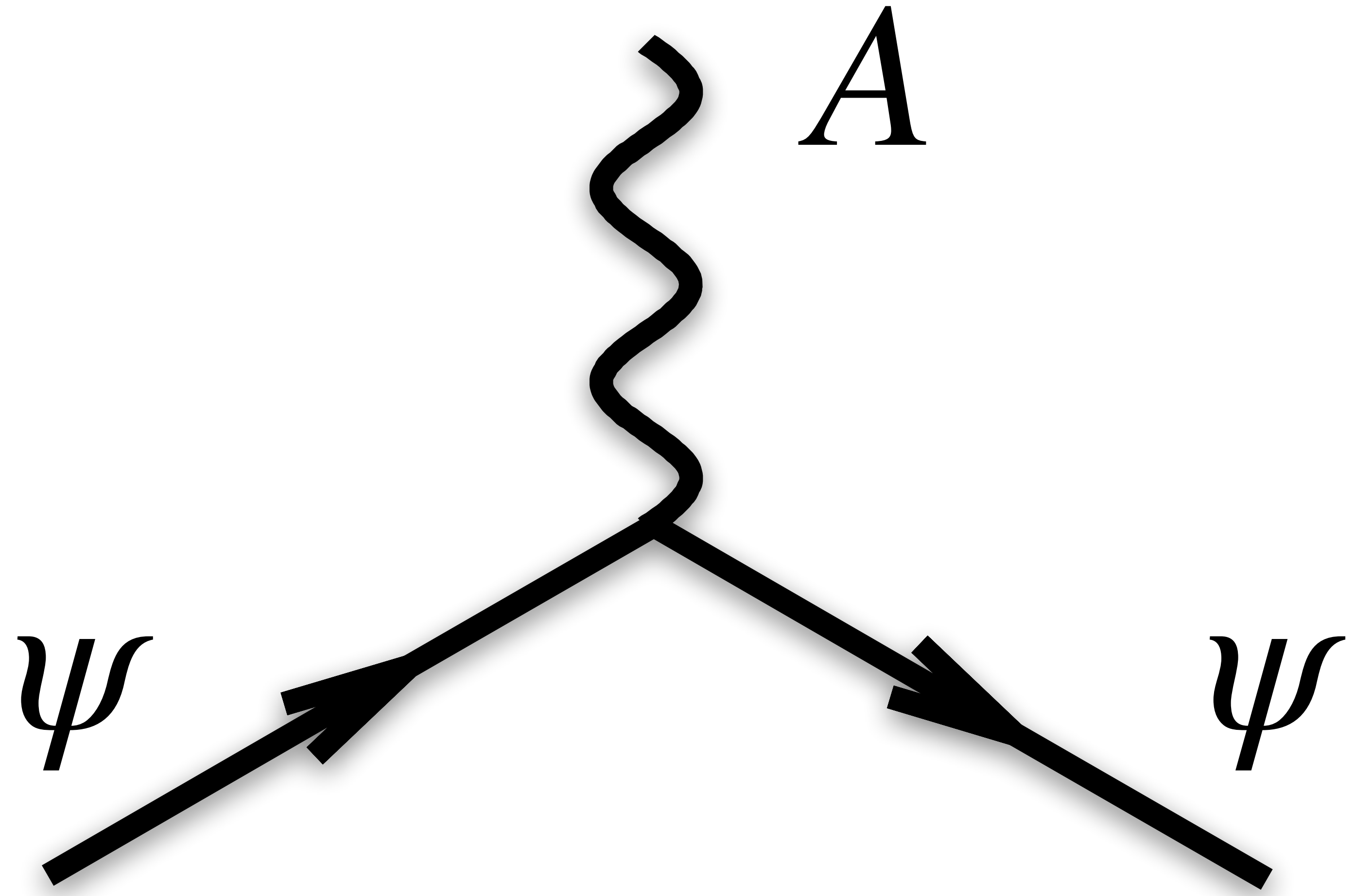
Quantum formulation of Maxwell's equations, (and their analogues for the weak and strong forces).



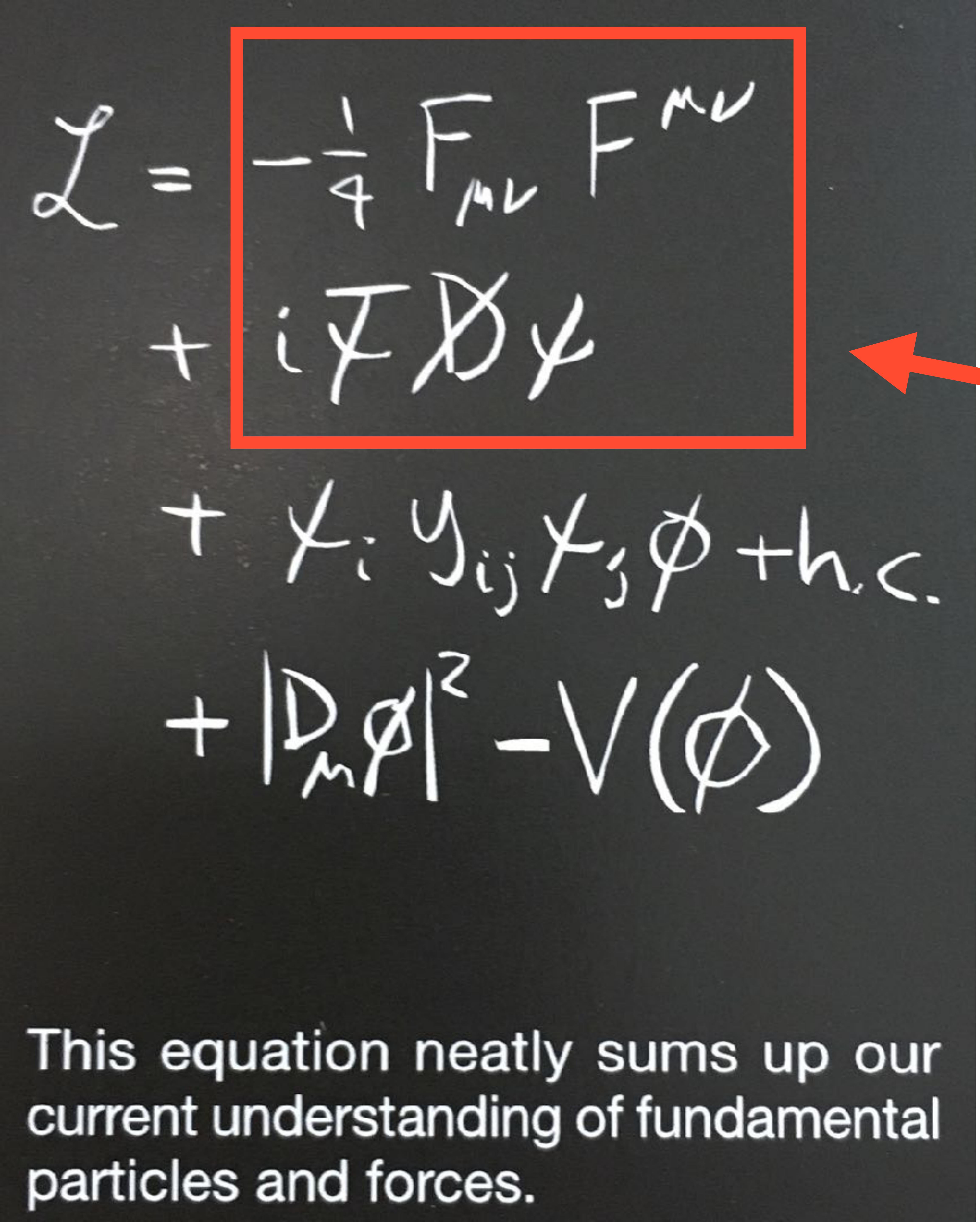
What does it mean?

ψ = fermion (e.g. electron) field

$D \sim eA$(=photon field) $+ \cdots$



tells you there's an electron-photon interaction vertex

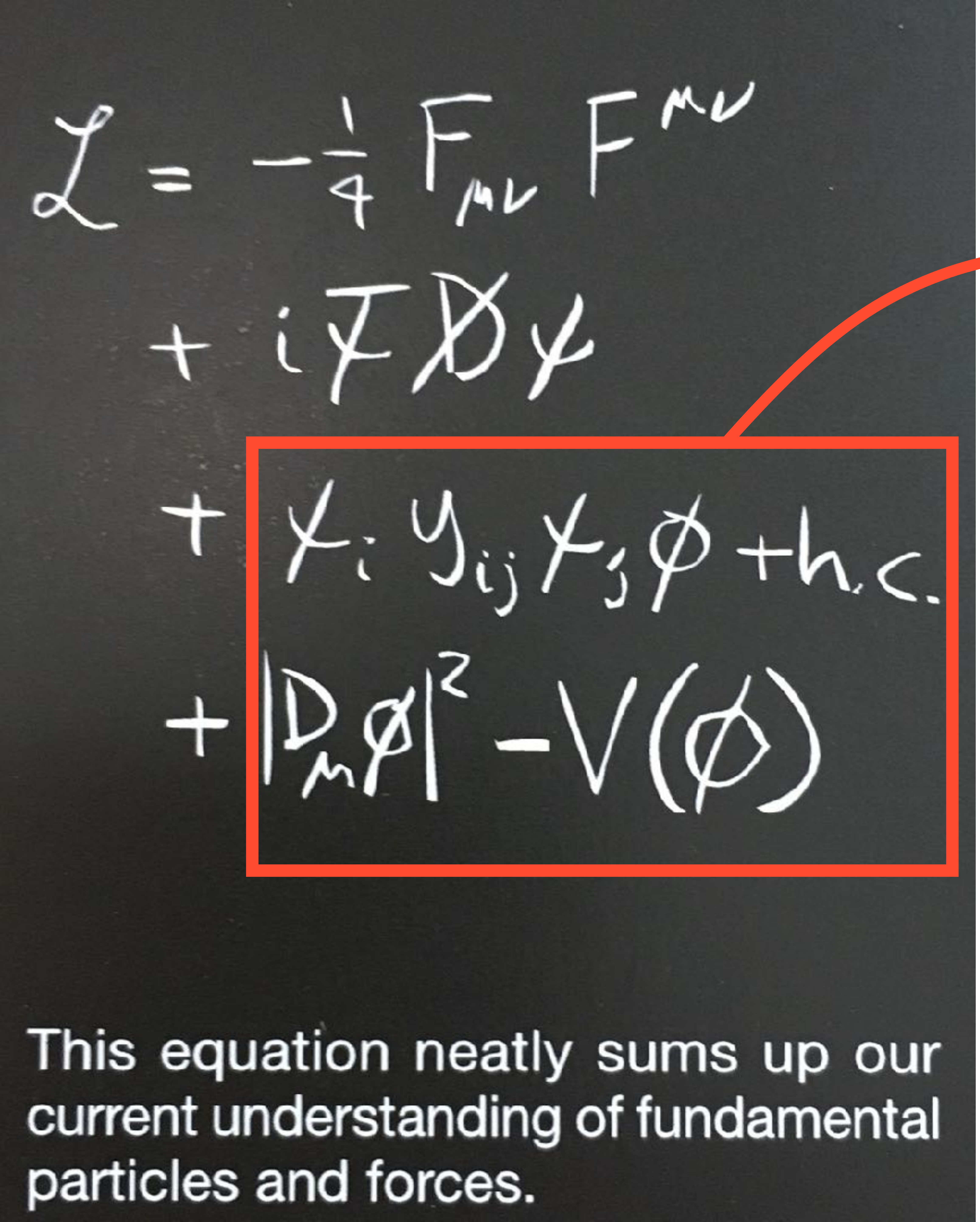


What does it mean?

many experiments have probed these so-called "gauge" interactions (in classical form, they date back to 1860s)

Describe electromagnetism, full electroweak theory & the strong force.

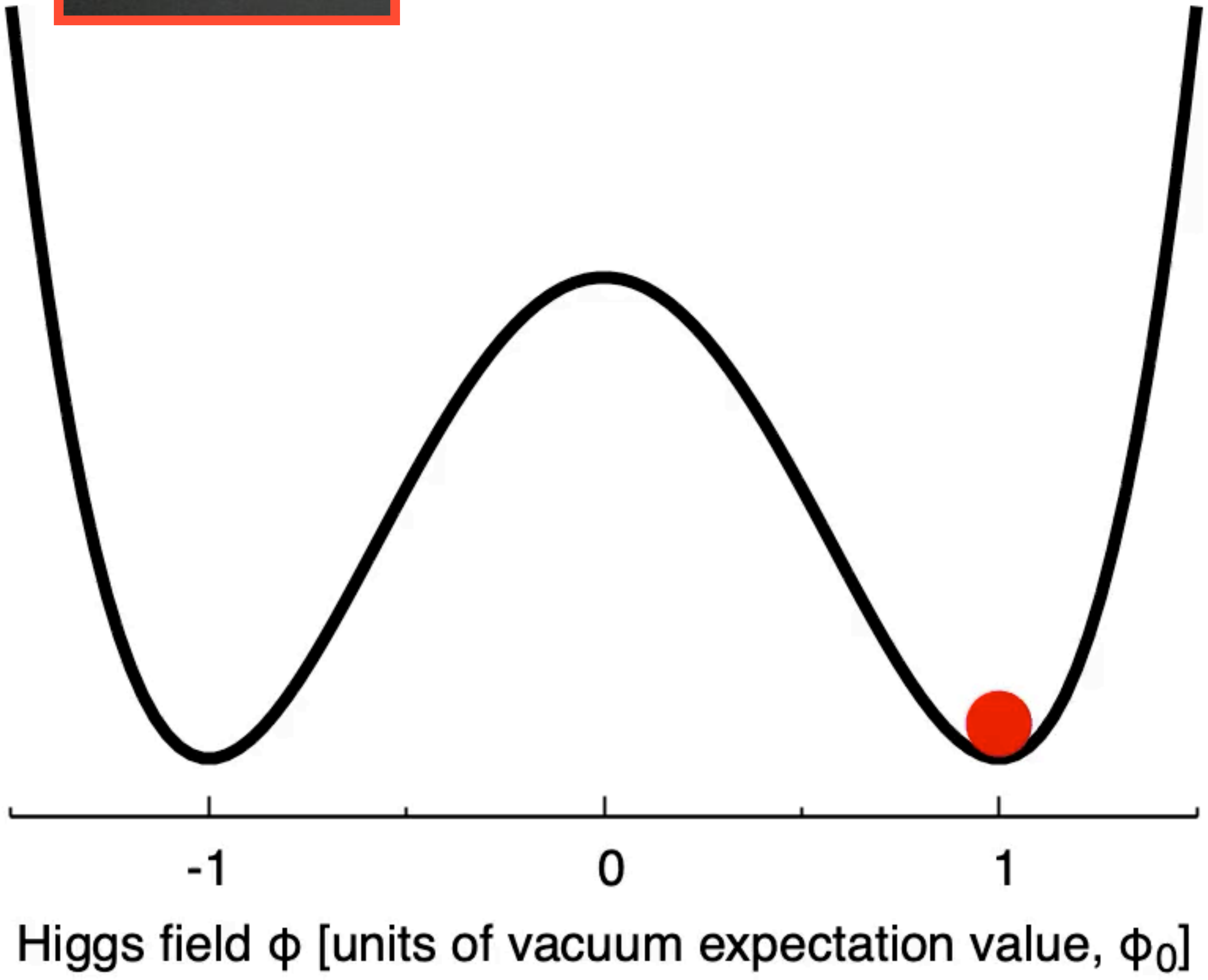
They work to high precision (best tests go up to 1 part in 10^8)



Higgs sector

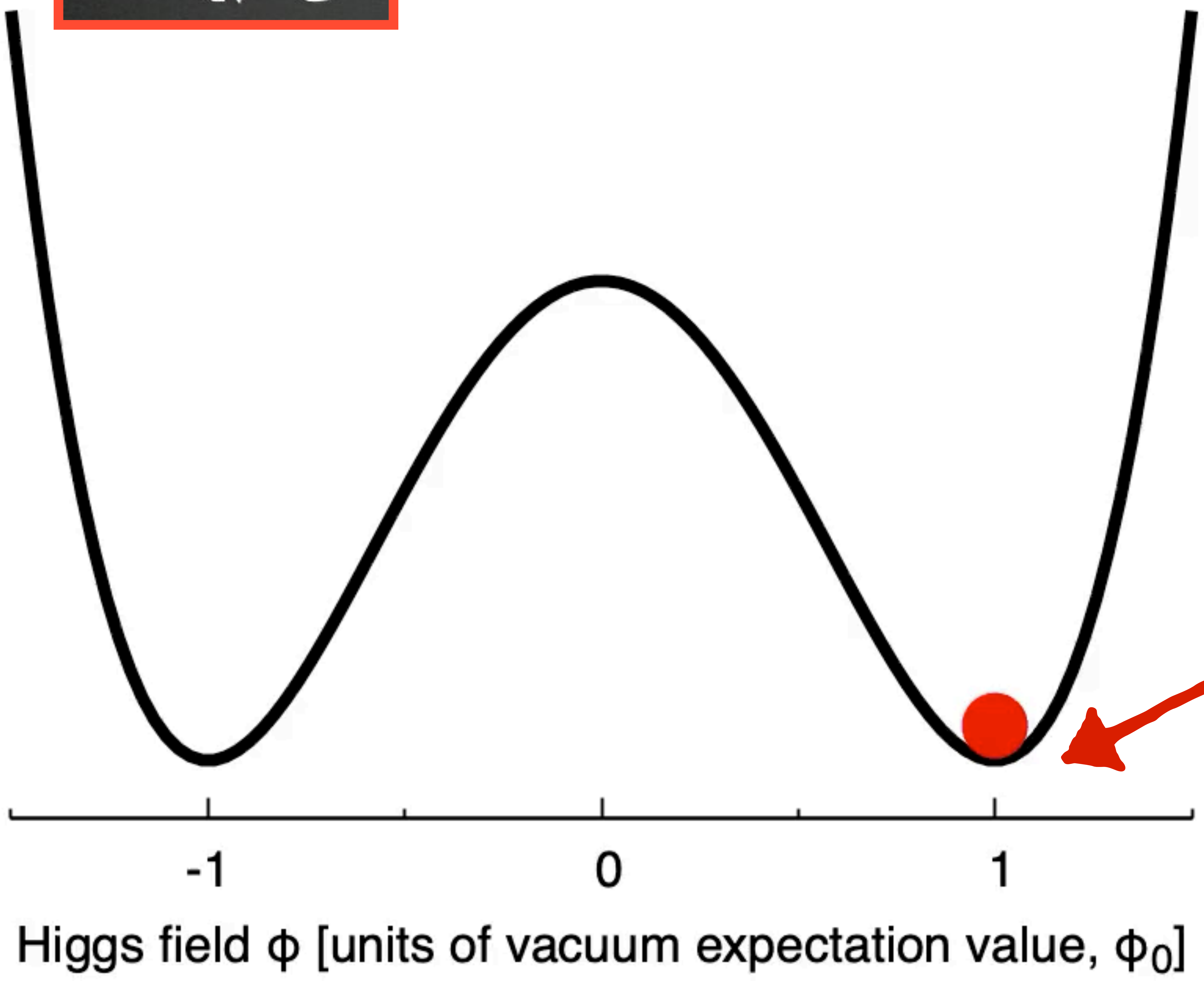
until 10 years ago none of these terms had ever been directly observed.

$$= -\mu^2\phi^2 + \lambda\phi^4$$



- φ is a field at every point in space (plot shows potential vs. 1 of 4 components, at 1 point in space)

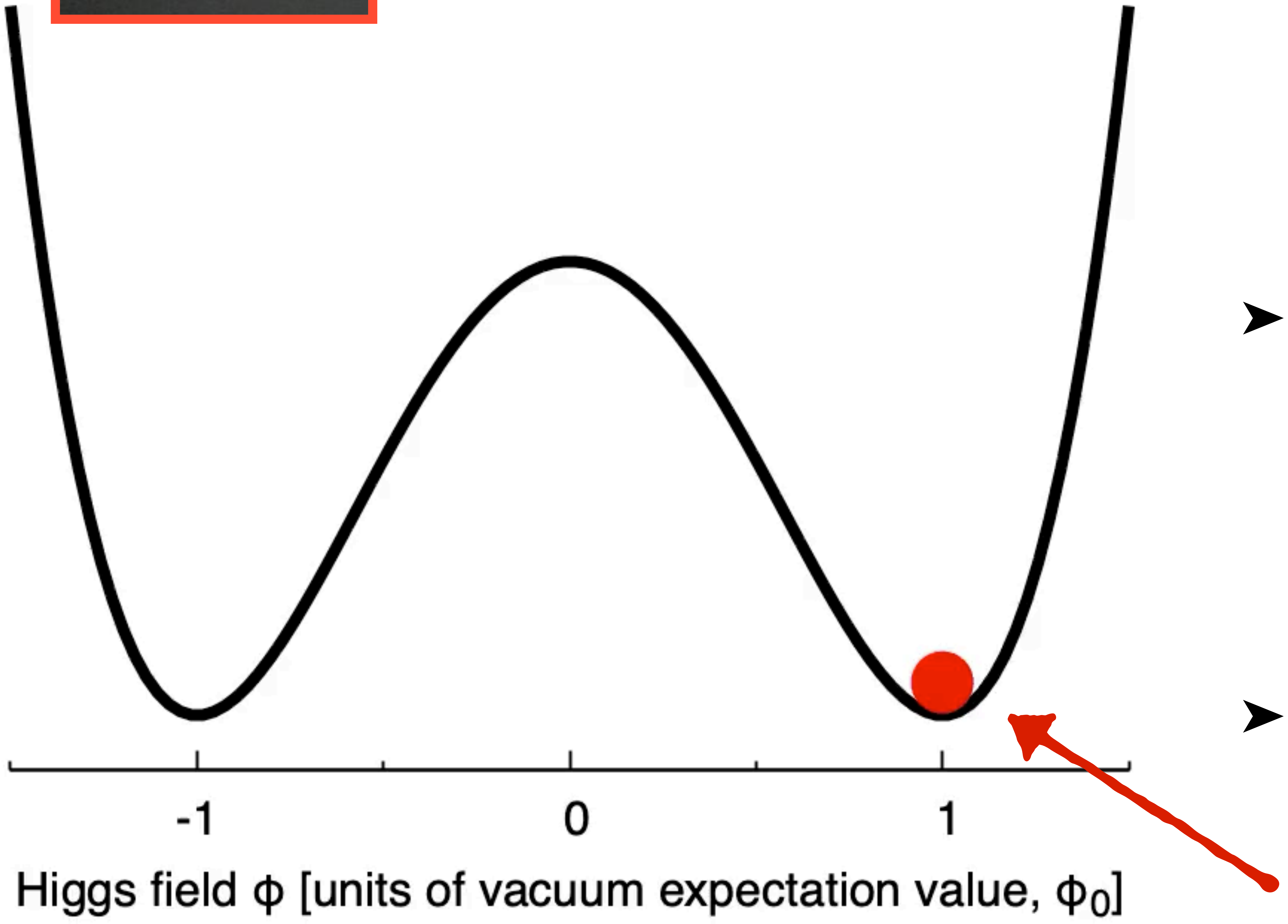
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



- φ is a field at every point in space (plot shows potential vs. 1 of 4 components, at 1 point in space)
- Our universe sits at minimum of V(φ), at

$$\phi = \phi_0 = \frac{\mu}{\sqrt{2\lambda}}$$

$$= -\mu^2\phi^2 + \lambda\phi^4$$



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- Our universe sits at minimum of V(φ), at

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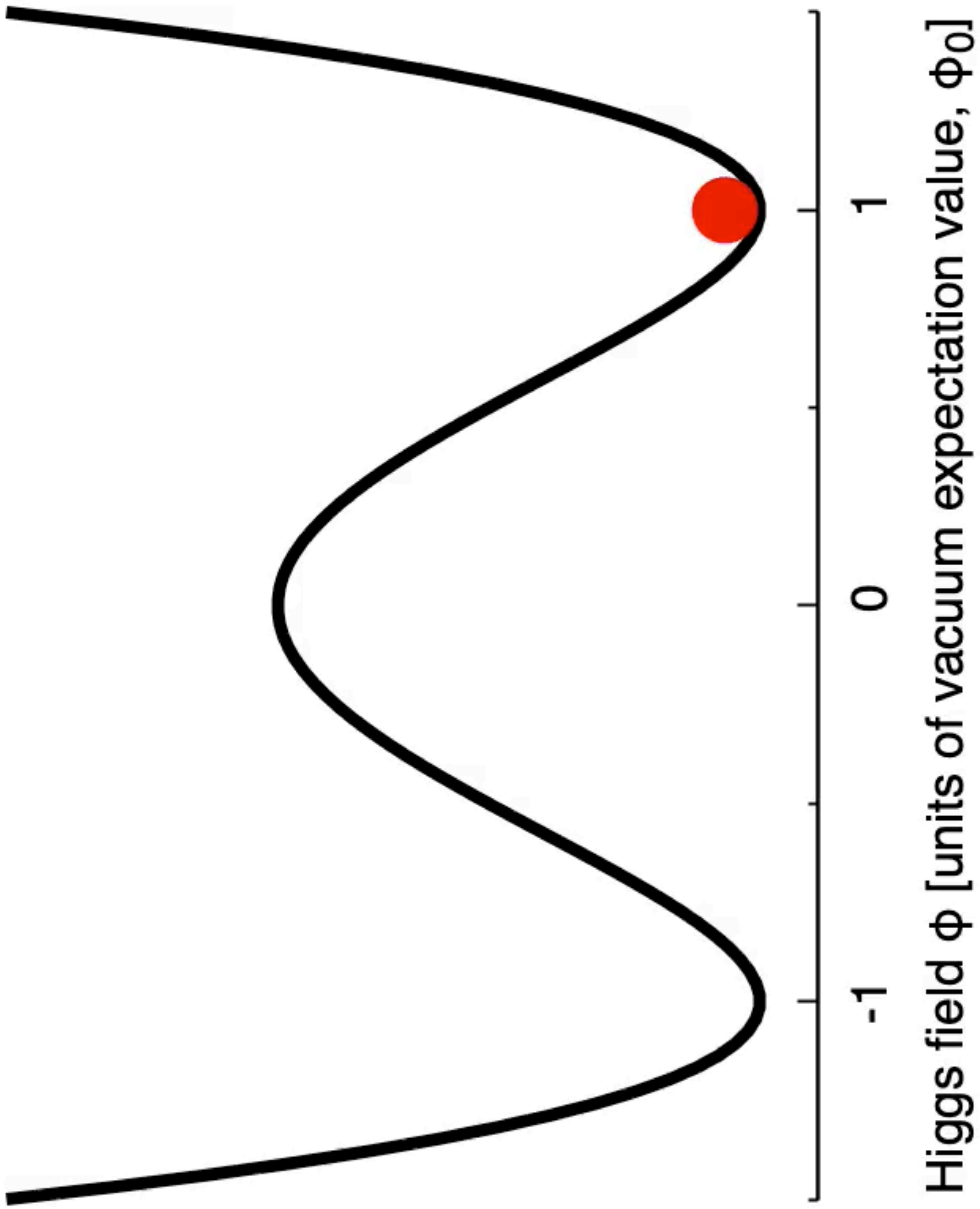
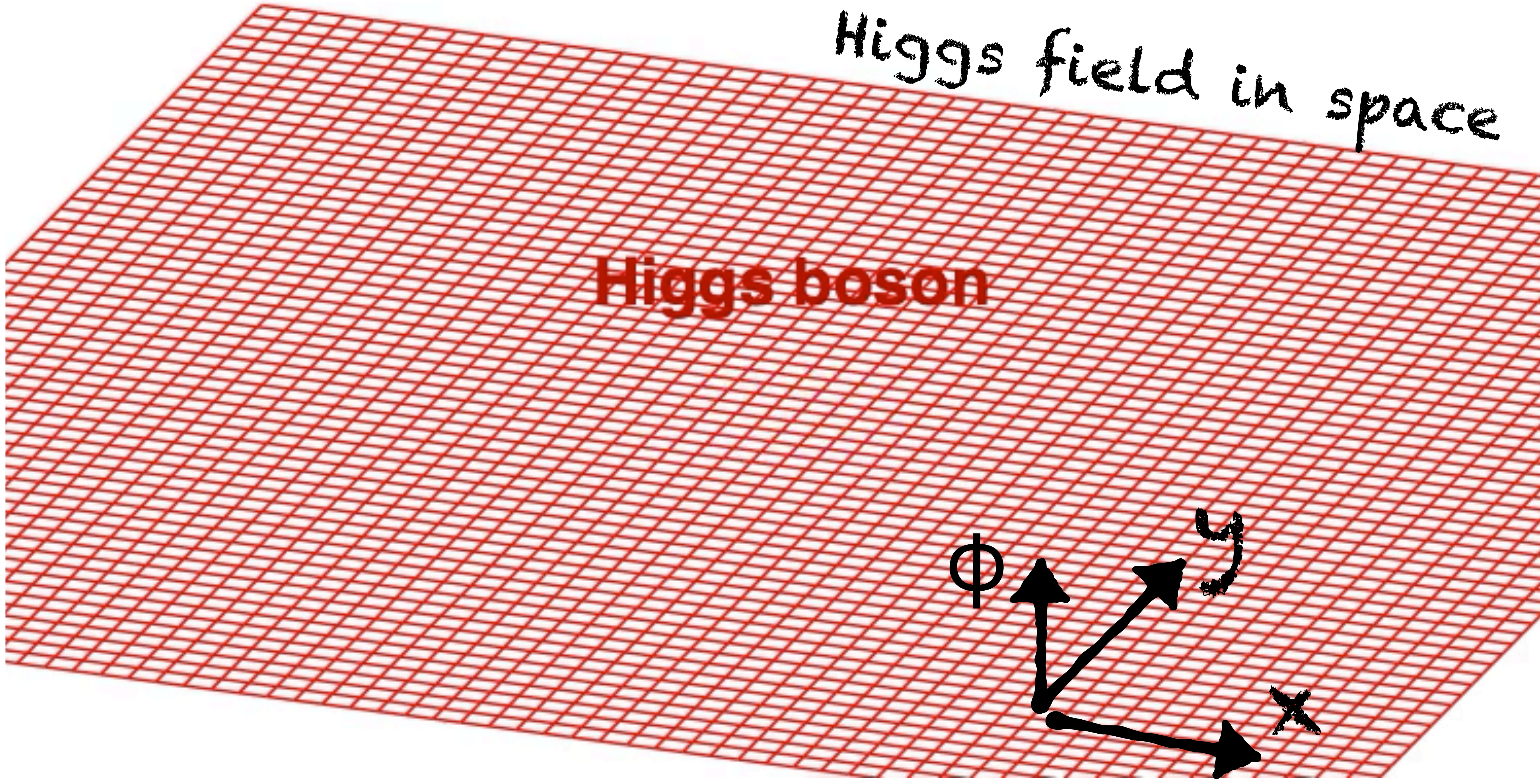
- Excitation of the φ field around φ_0 is a Higgs boson ($\varphi = \varphi_0 + H$)

$$\varphi = \varphi_0 + H$$

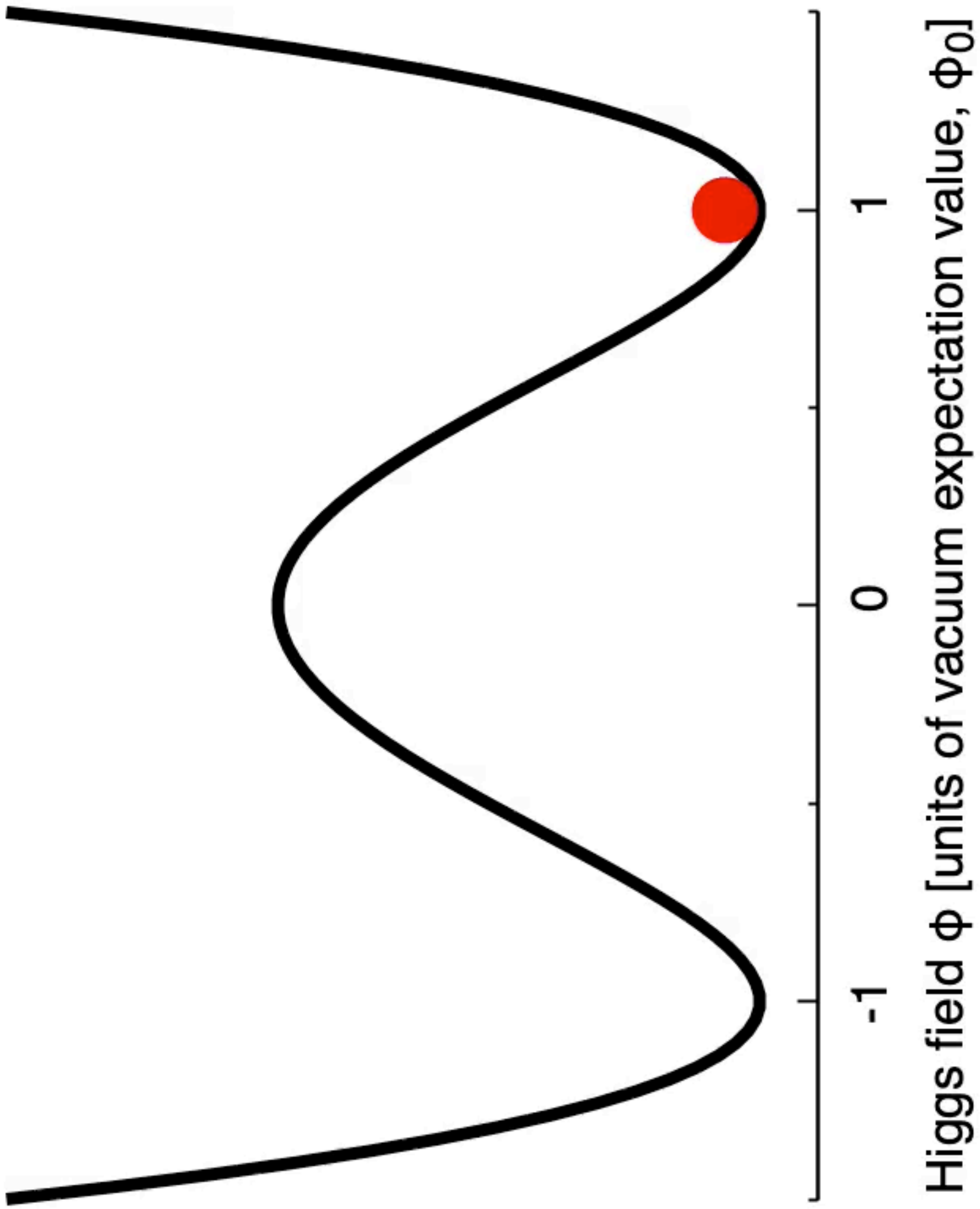


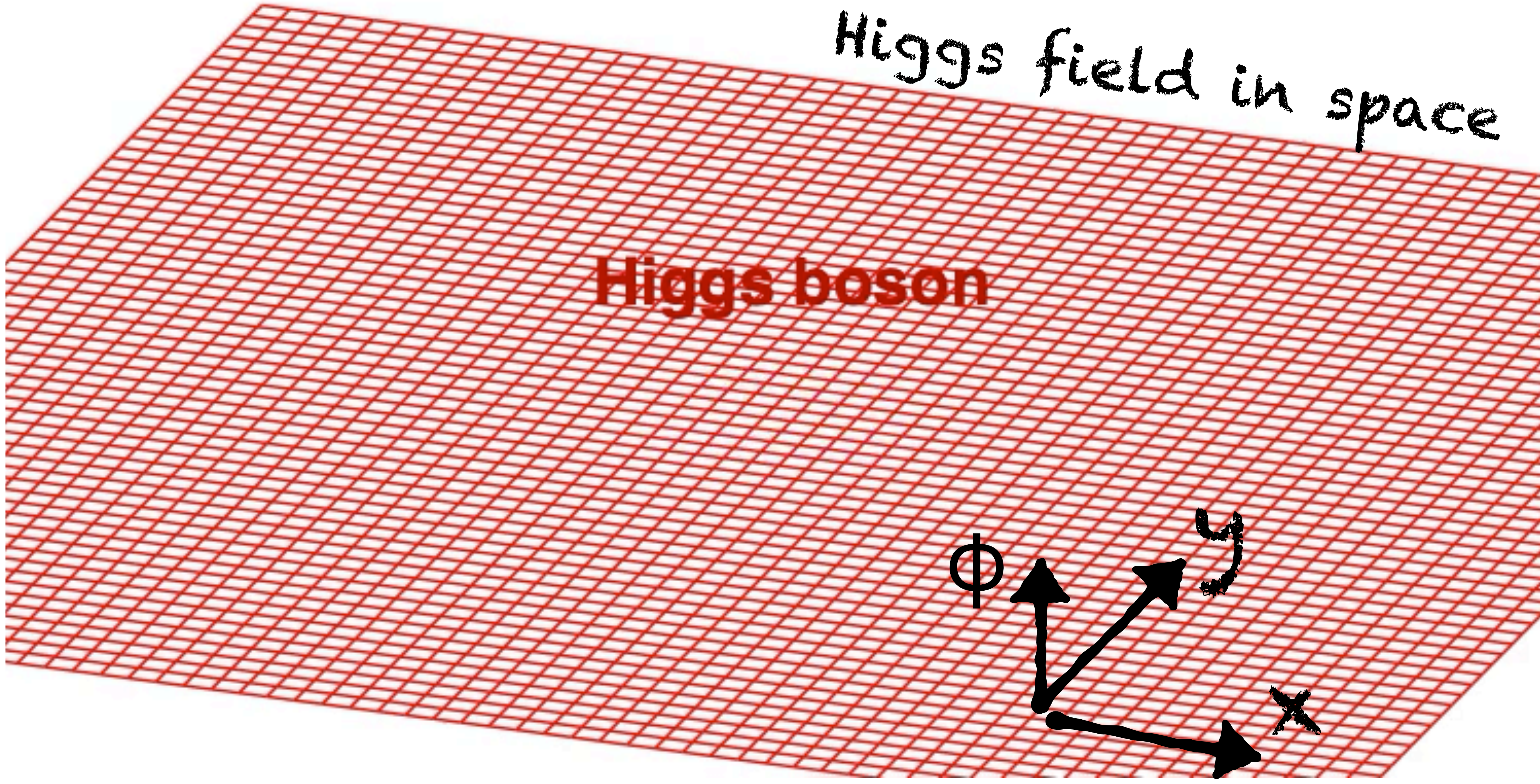


Higgs field can be different at each point in space

A Higgs boson at a given point in space is a localised fluctuation of the field

$$\varphi = \varphi_0 + H$$





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$$\varphi = \varphi_0 + H$$

established

(2012 Higgs boson discovery)

$\varphi = \varphi_0 + H$

established
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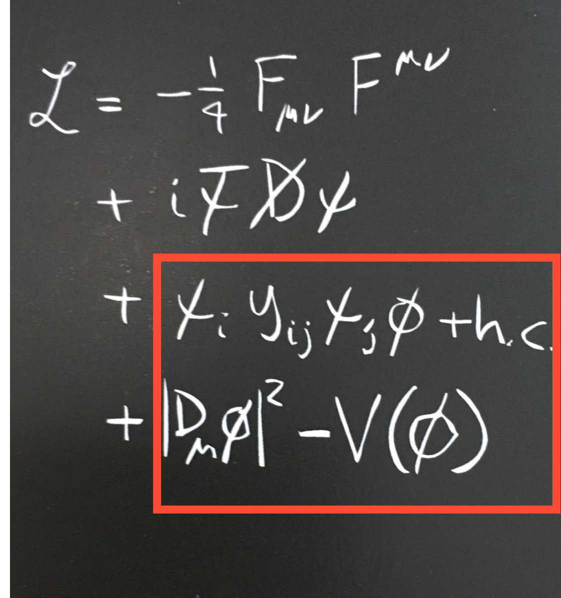
$= -\mu^2\phi^2 + \lambda\phi^4$

hypothesis

what terms are there in the Higgs sector?
2. Gauge–Higgs term

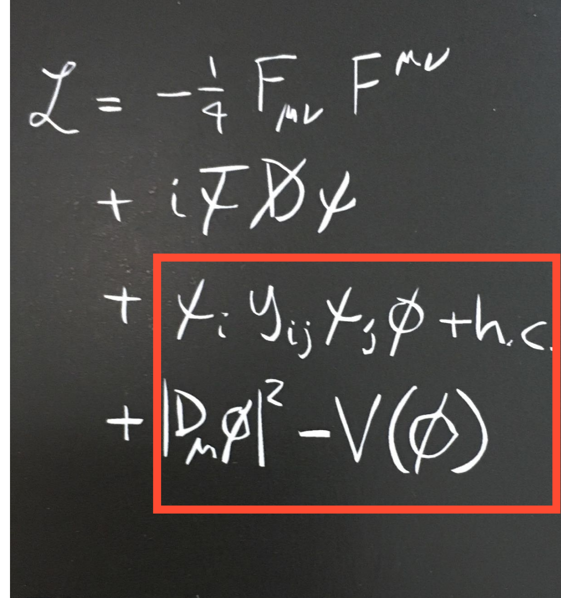


This equation neatly sums up our current understanding of fundamental particles and forces.

$$\rightarrow \overbrace{g^2\phi_0^2}^{\textit{constants}}\ \overbrace{Z_\mu Z^\mu}^{\textit{fields}} + \overbrace{2g^2\phi_0}^{\textit{constants}}\ \overbrace{H\, Z_\mu Z^\mu}^{\textit{fields}} + \ldots$$

Z-boson mass term — *HZZ interaction term*

$$D_\mu = (\partial_\mu + Z_\mu + \ldots) \qquad [\phi^2 = (\phi_0 + H)^2 = \phi_0^2 + 2\phi_0 H + \ldots]$$



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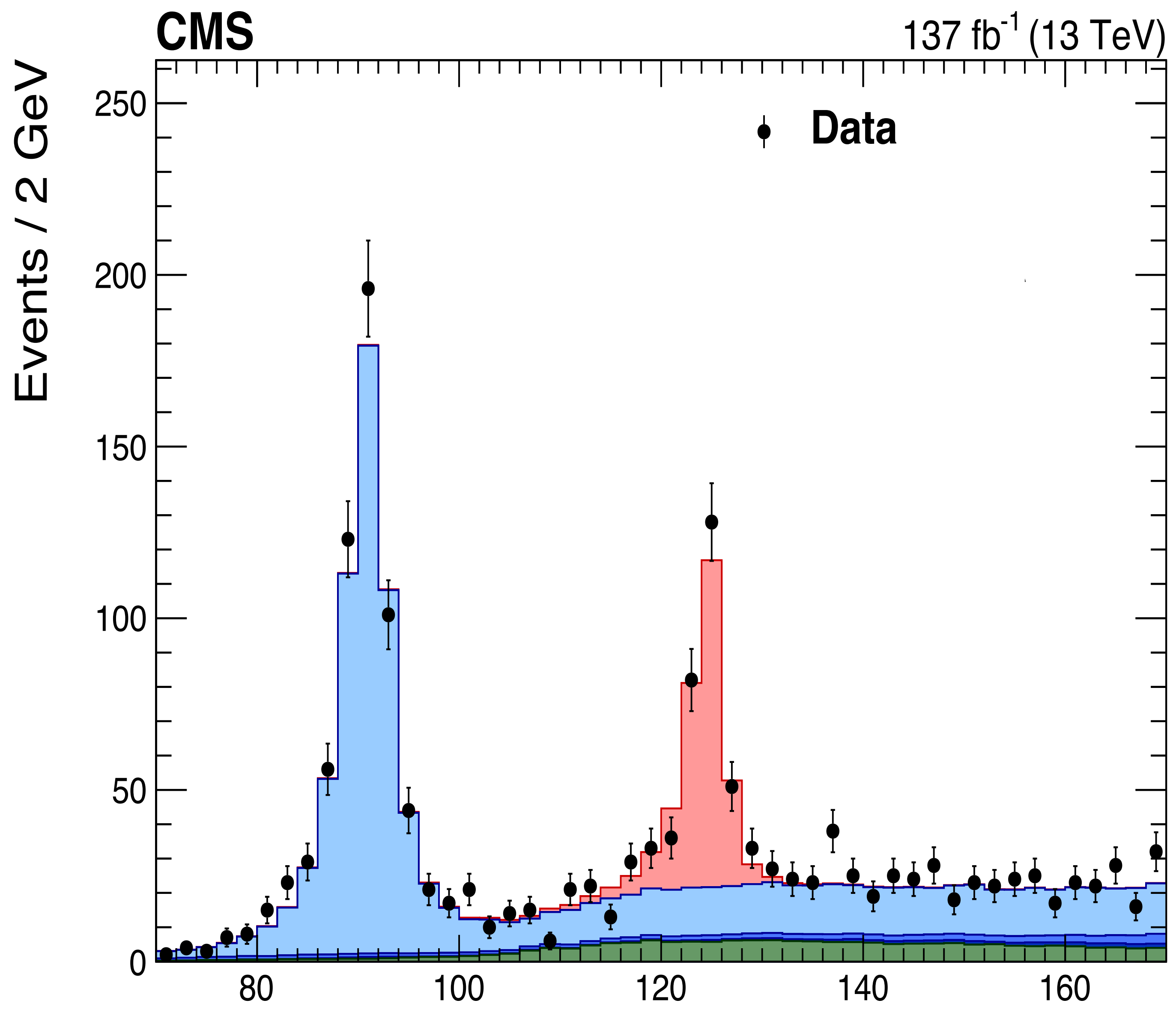
Z-boson mass term

ZZH interaction term



Higgs mechanism predicts specific relation between Z-boson mass and HZZ interaction

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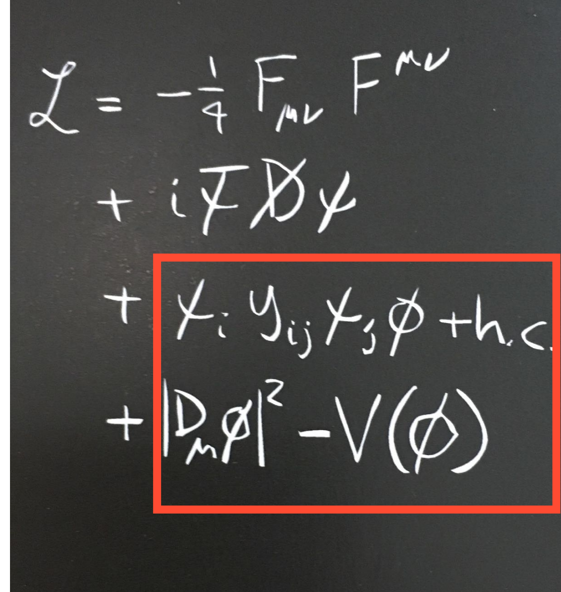

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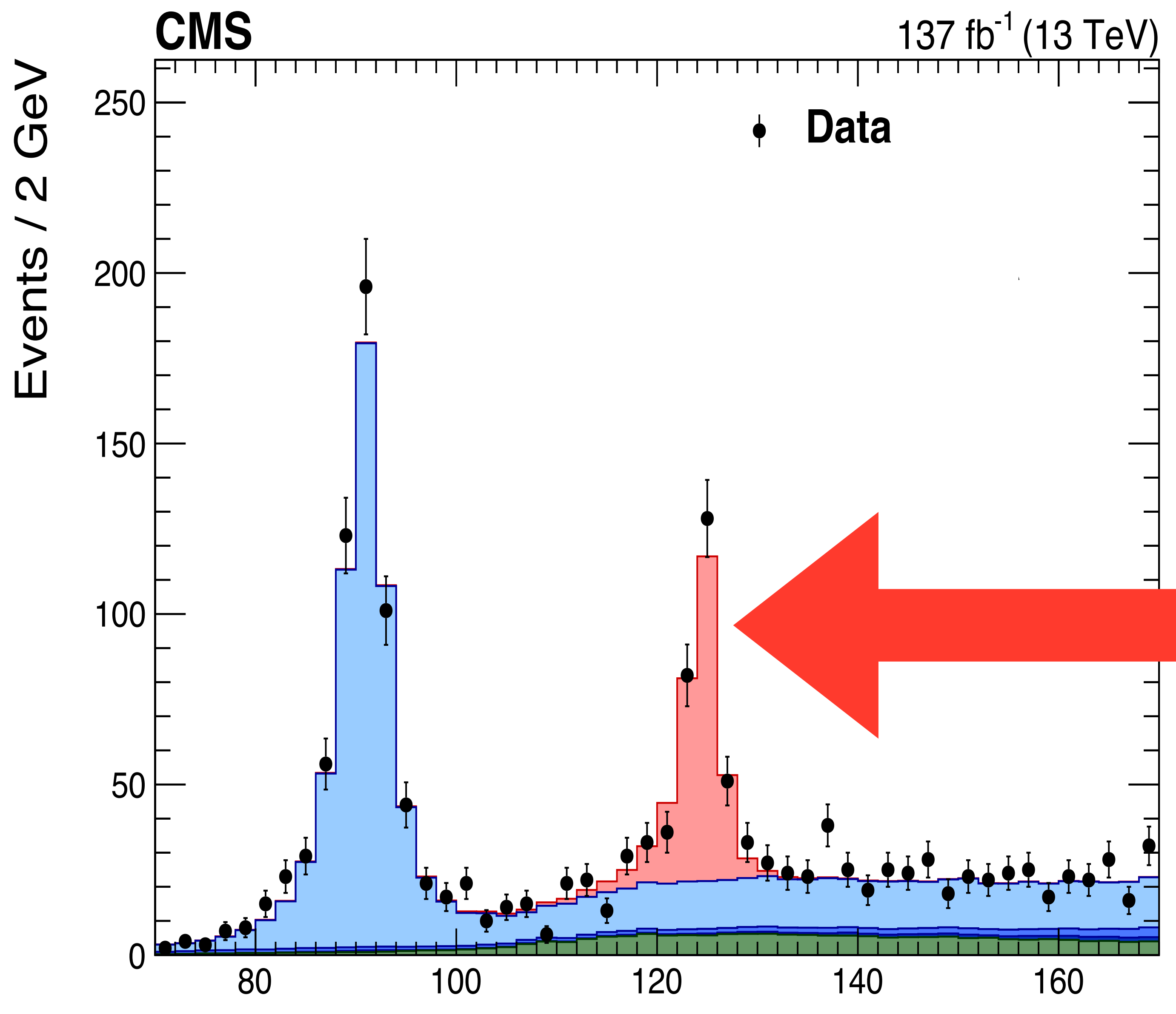

H → ZZ*
ratio to SM=0.94 ± 0.11
confirms Higgs-origin for Z mass

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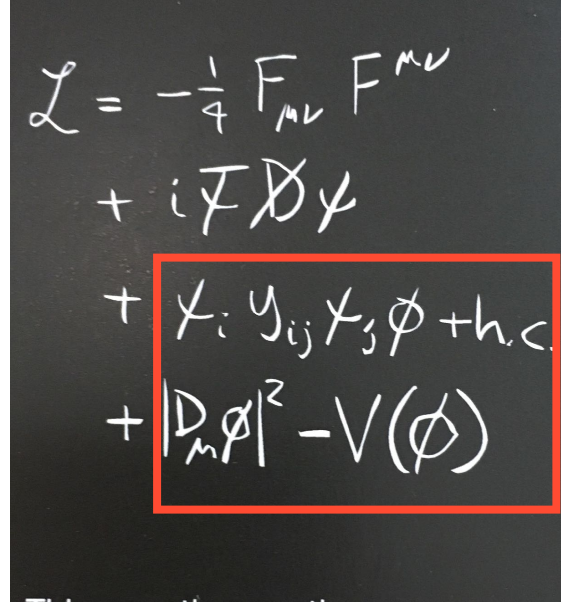

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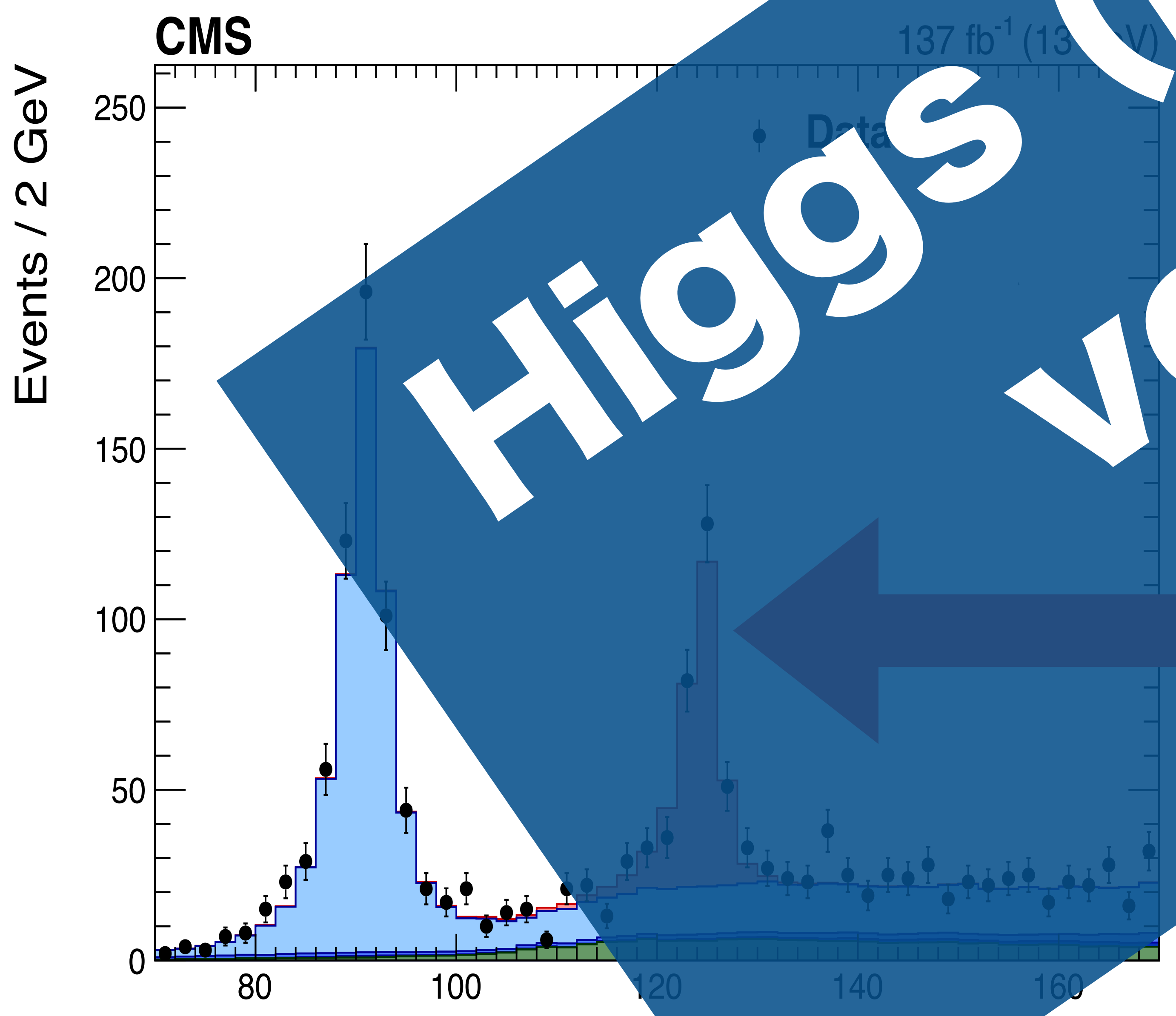
$$\rightarrow g^2 \phi_0^2 Z_\mu Z^\mu + 2 g^2 \phi_0 H Z_\mu Z^\mu + \ldots$$

Z-boson mass term

ZZH interaction term

Higgs (BEH) mechanism for vector boson mass = 2013 Nobel prize



4 lepton

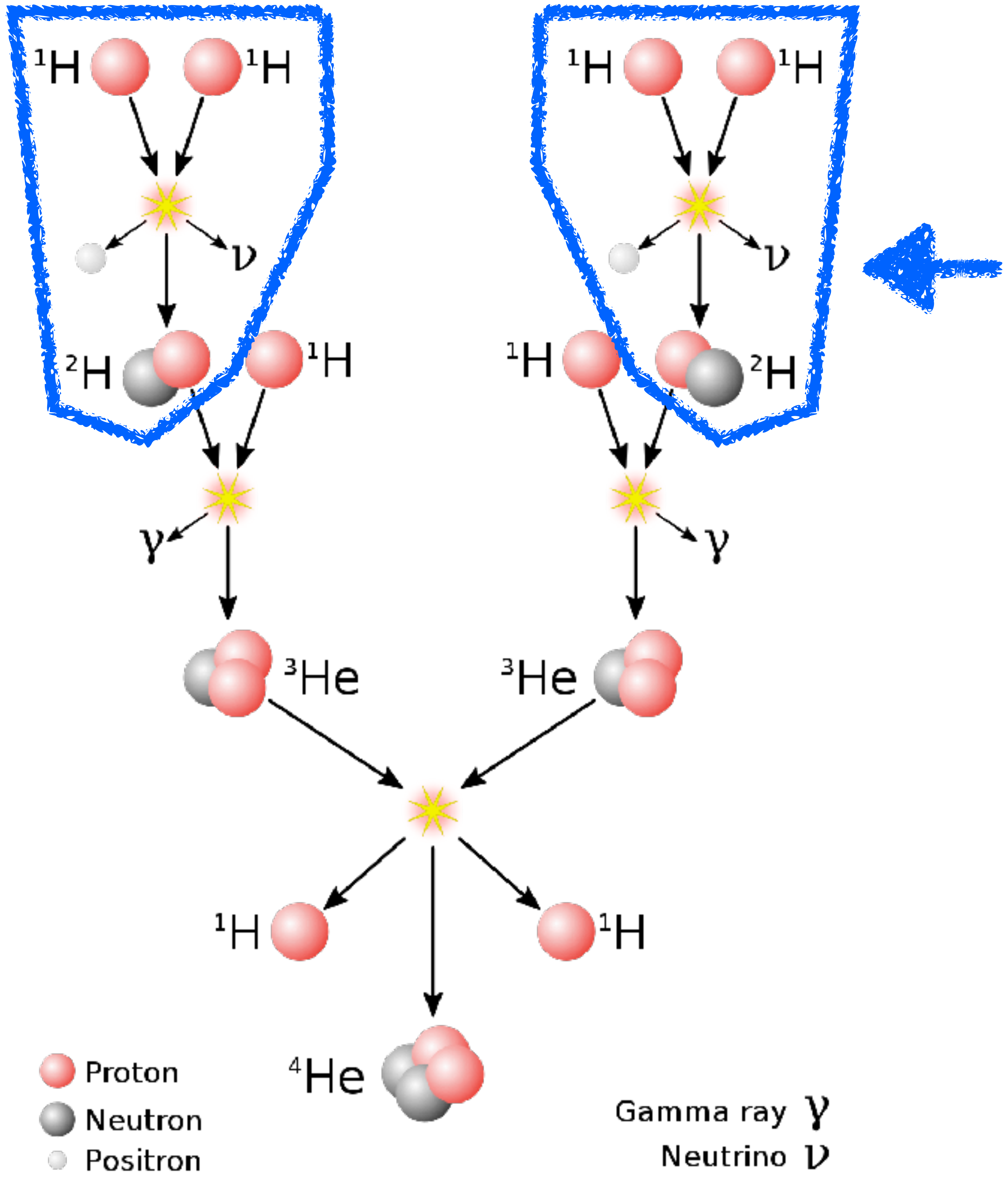
H → ZZ*

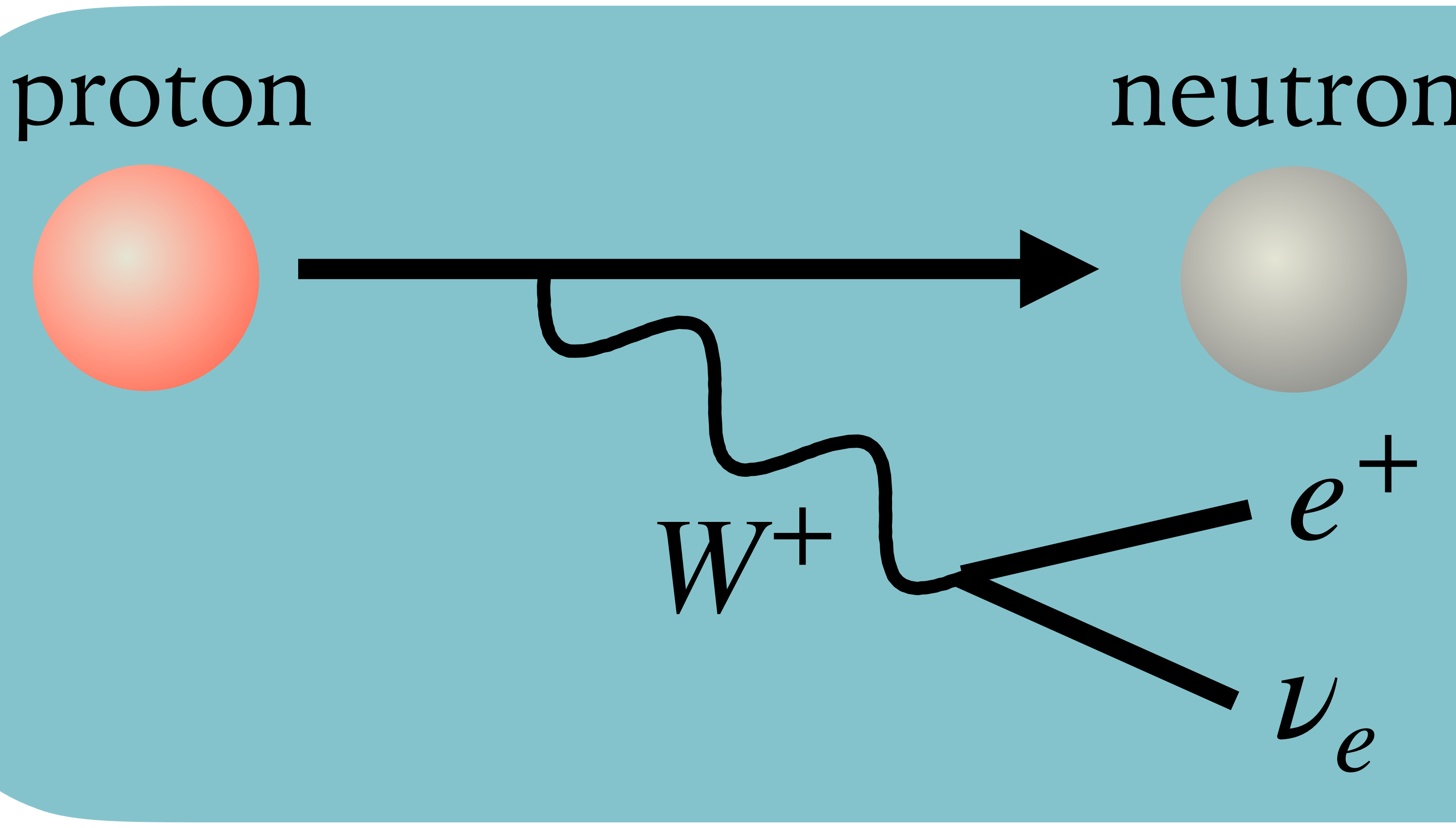
ratio to SM=0.94 ± 0.11

confirms Higgs-origin for Z mass

Higgs mechanism predicts specific relation between Z-boson mass and HZZ interaction

Higgs similarly generates W-boson mass: affects temperature of stars like our sun





$$\text{rate} \sim \frac{1}{m_W^4}$$

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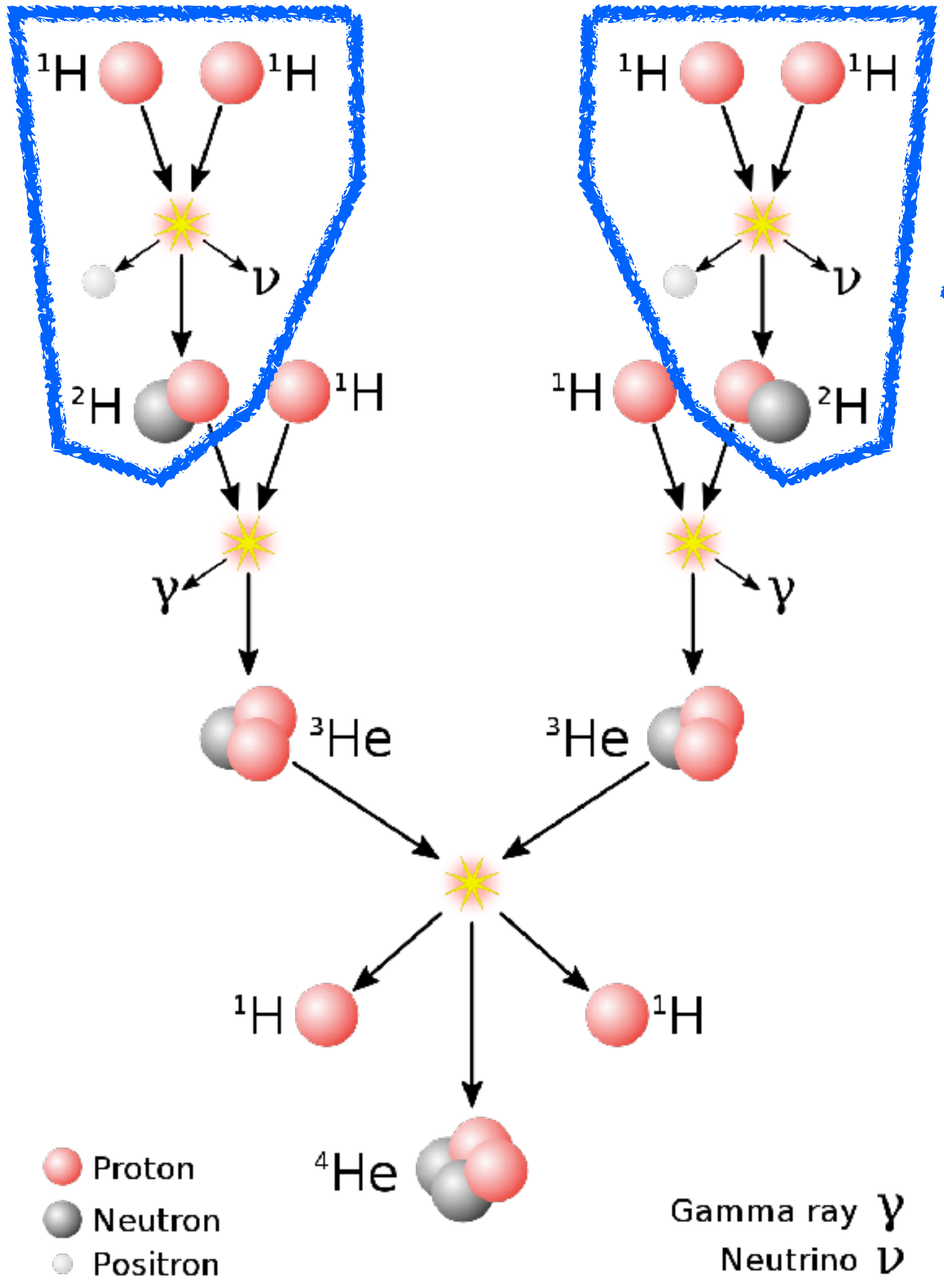

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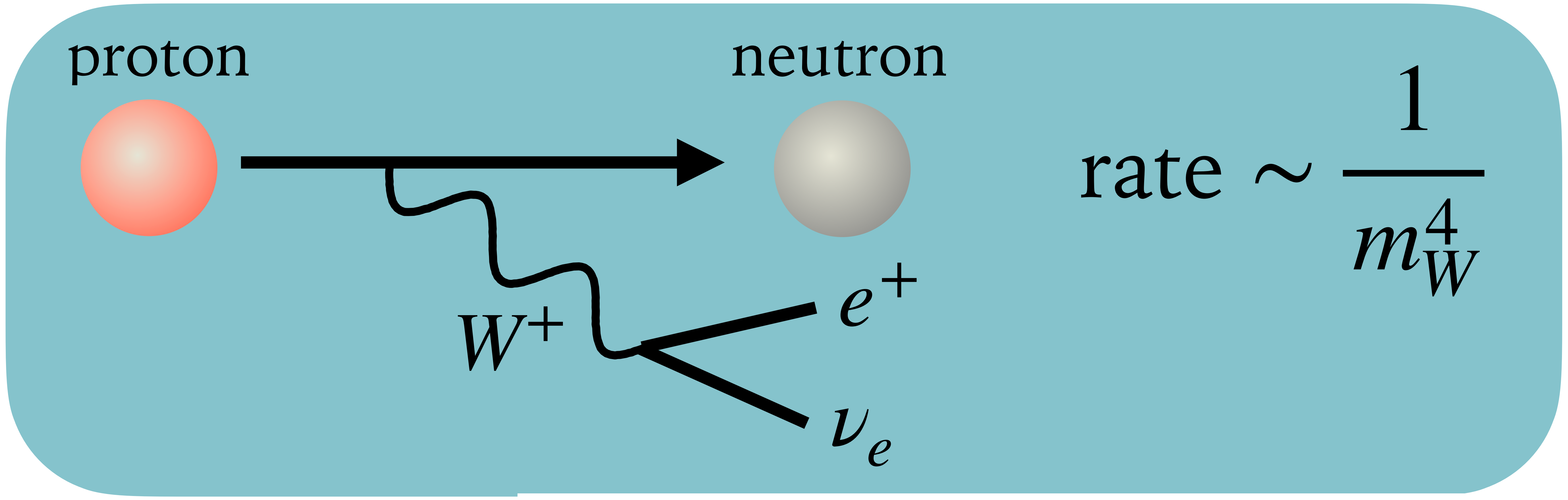
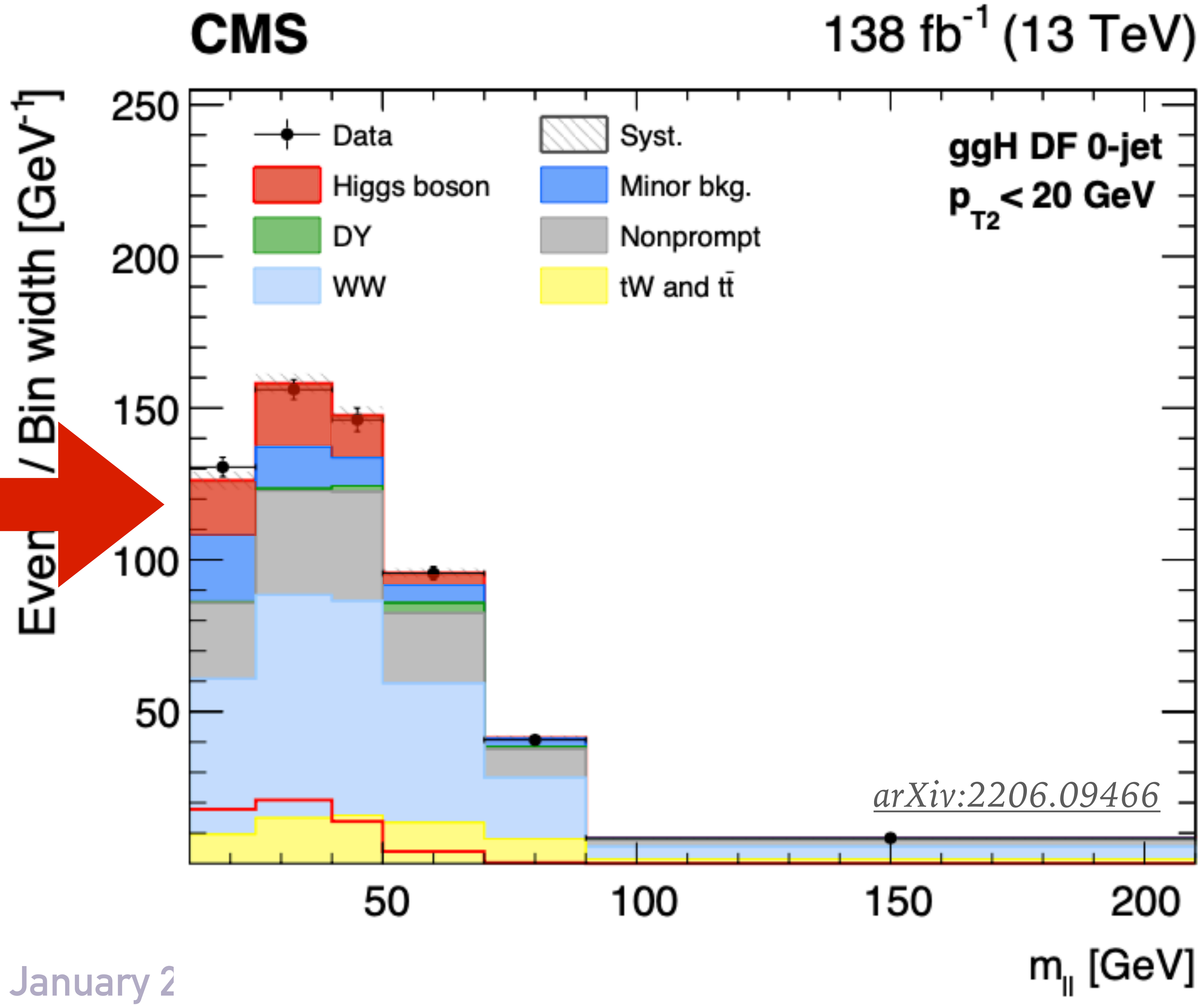
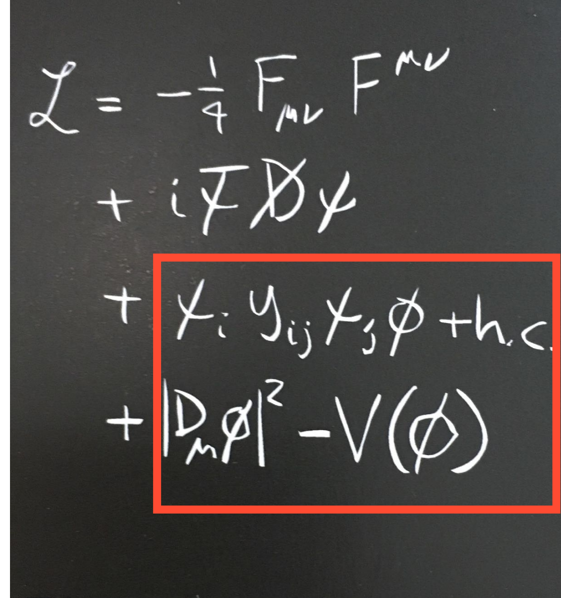


H → WW*

ratio to SM = 0.95 ± 0.10



what terms are there in the Higgs sector?
3. Fermion–Higgs (Yukawa) term



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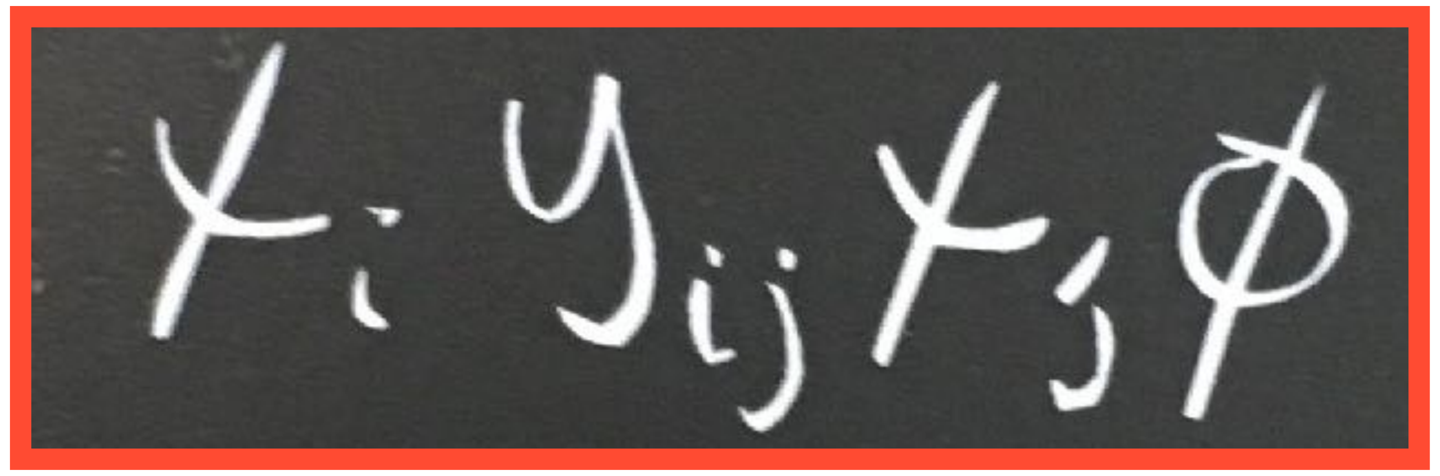

$$\rightarrow \quad y_{ij}\,\phi_0\,\psi_i\,\psi_j \;+\; y_{ij}\,H\,\psi_i\,\psi_j$$

fermion mass term

$m_i = y_{ii}\phi_0$

Higgs-fermion-fermion interaction term;

coupling $\sim y_{ii}$

i	y_i	i	y_i
u	$2 \cdot 10^{-5}$	d	$3 \cdot 10^{-5}$
c	$8 \cdot 10^{-3}$	s	$6 \cdot 10^{-4}$
b	$3 \cdot 10^{-2}$	t	1
ν_e	$\sim 10^{-13}$?	e	$3 \cdot 10^{-6}$
ν_μ		μ	$6 \cdot 10^{-4}$
ν_τ		τ	$1 \cdot 10^{-4}$

$$\phi = \phi_0 + H$$

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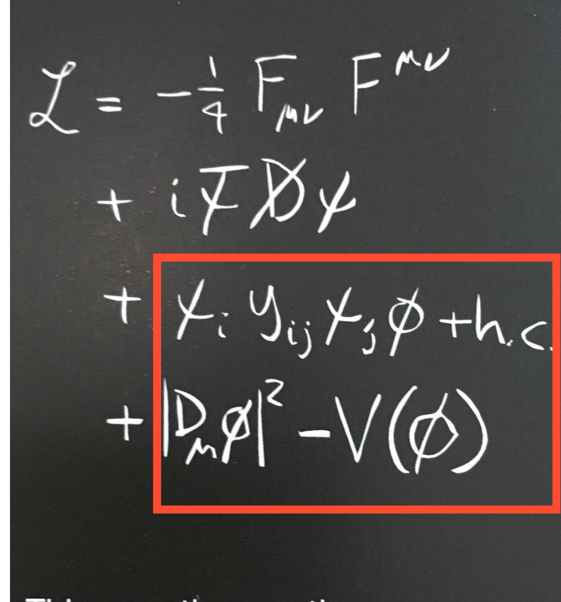

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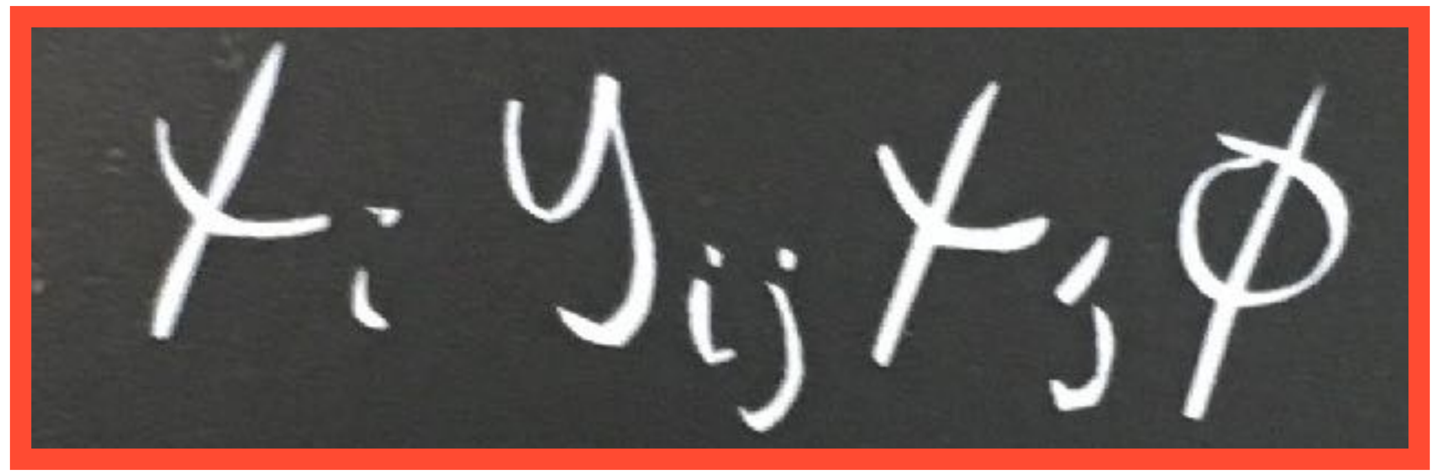

$\rightarrow \quad y_{ij}\,\phi_0\,\psi_i\,\psi_j \quad + \quad y_{ij}\,H\,\psi_i\,\psi_j$

fermion mass term

$m_i = y_{ii}\phi_0$

Higgs-fermion-fermion interaction term; coupling $\sim y_{ii}$

the subject of the next few slides

i	y_i	i	y_i
u	$2 \cdot 10^{-5}$	d	$3 \cdot 10^{-5}$
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$\phi = \phi_0 + H$

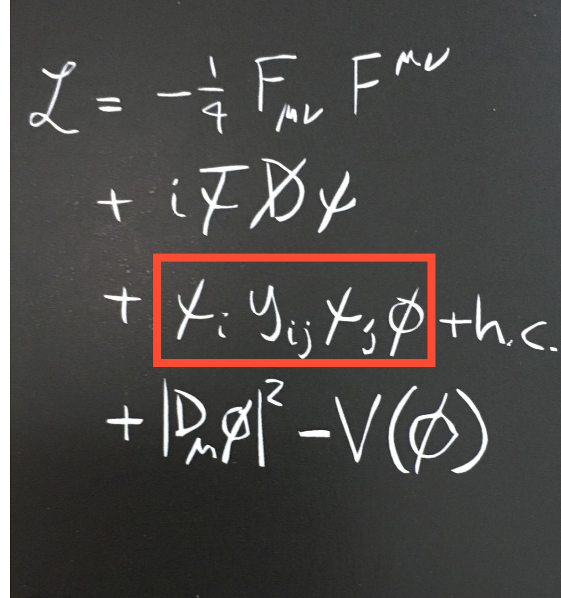
Yukawa interaction hypothesis

Yukawa couplings ~ fermion mass

first fundamental interaction that we probe at the quantum level where interaction strength (y_{ij}) not quantised

(i.e. no underlying unit of conserved charge across particles)

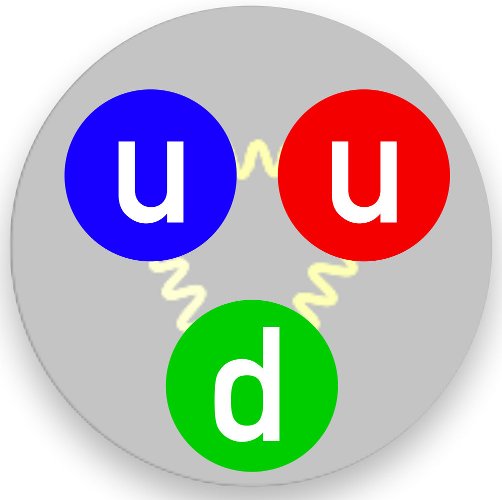
Why do Yukawa couplings matter?
(1) Because, within SM **conjecture**, they're what give masses to all **quarks**



This equation neatly sums up our current understanding of fundamental particles and forces.

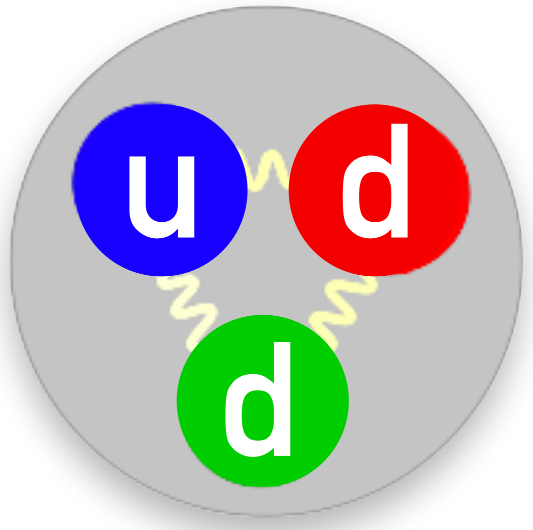
Up quarks (mass ~ 2.2 MeV) are lighter than
down quarks (mass ~ 4.7 MeV)

proton
mass = 938.3MeV



proton (up+up+down): 2.2 + 2.2 + 4.7 + … = 938.3 MeV
neutron (up+down+down): 2.2 + 4.7 + 4.7 + … = 939.6 MeV

neutron
mass = 939.6MeV

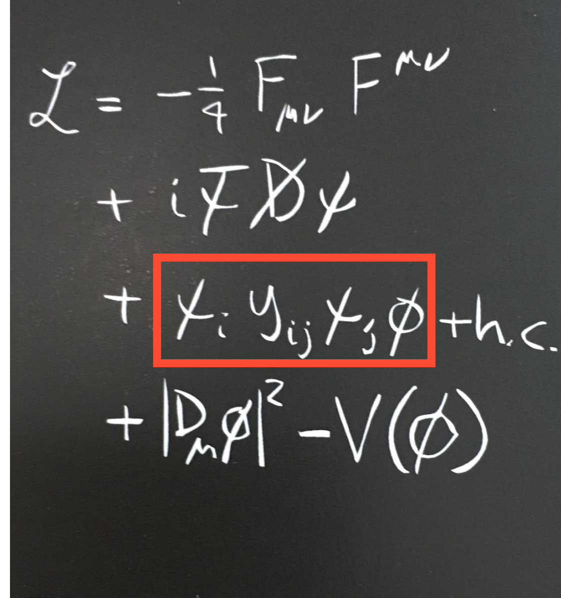


So protons are **lighter** than neutrons,
→ protons are stable.

Which gives us the hydrogen atom,
& chemistry and biology as we know it

Why do Yukawa couplings matter?

(2) Because, within SM **conjecture**, they're what give masses to all **leptons**



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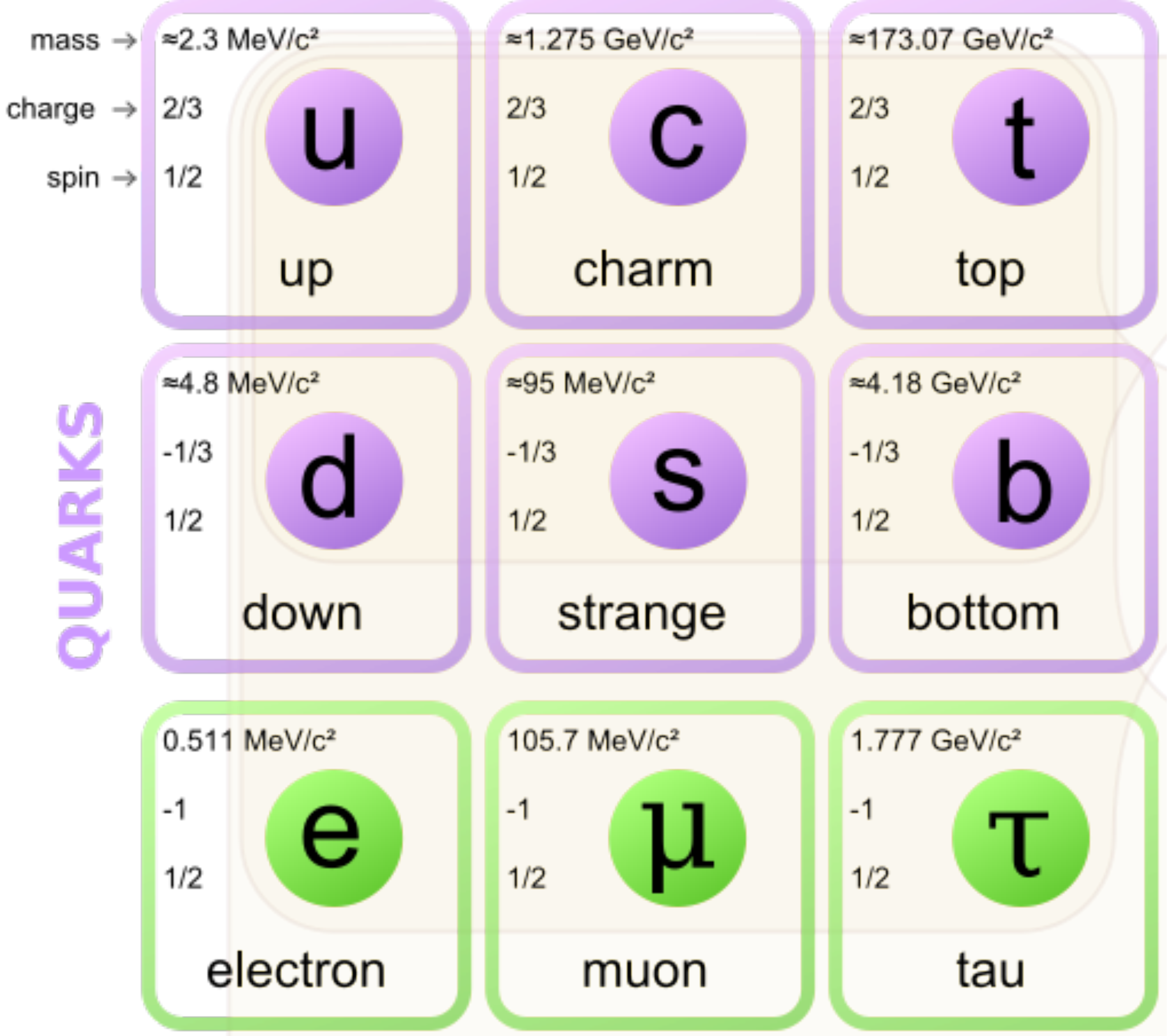
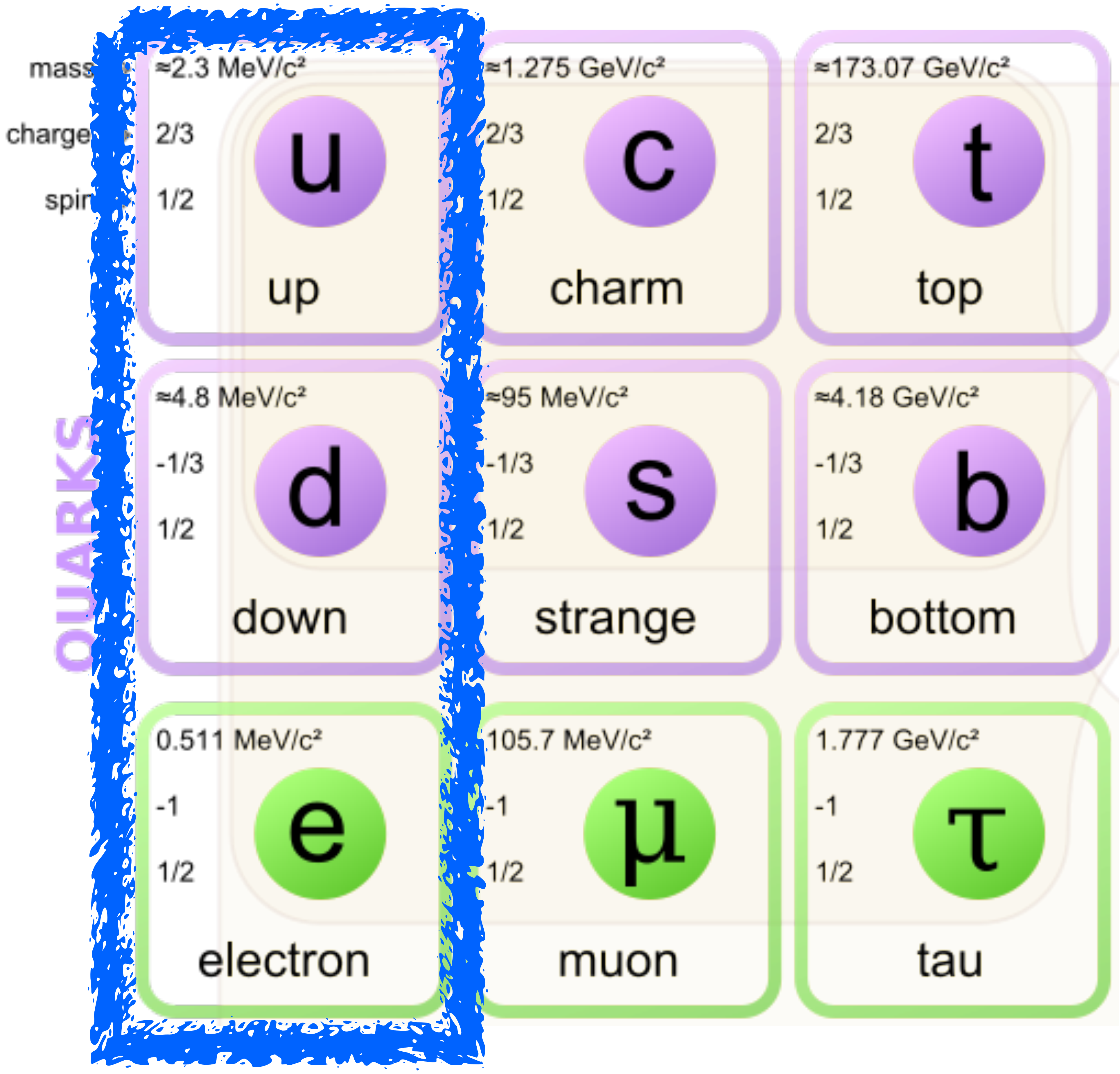
Bohr radius

$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c\alpha} \propto \frac{1}{y_e}$$

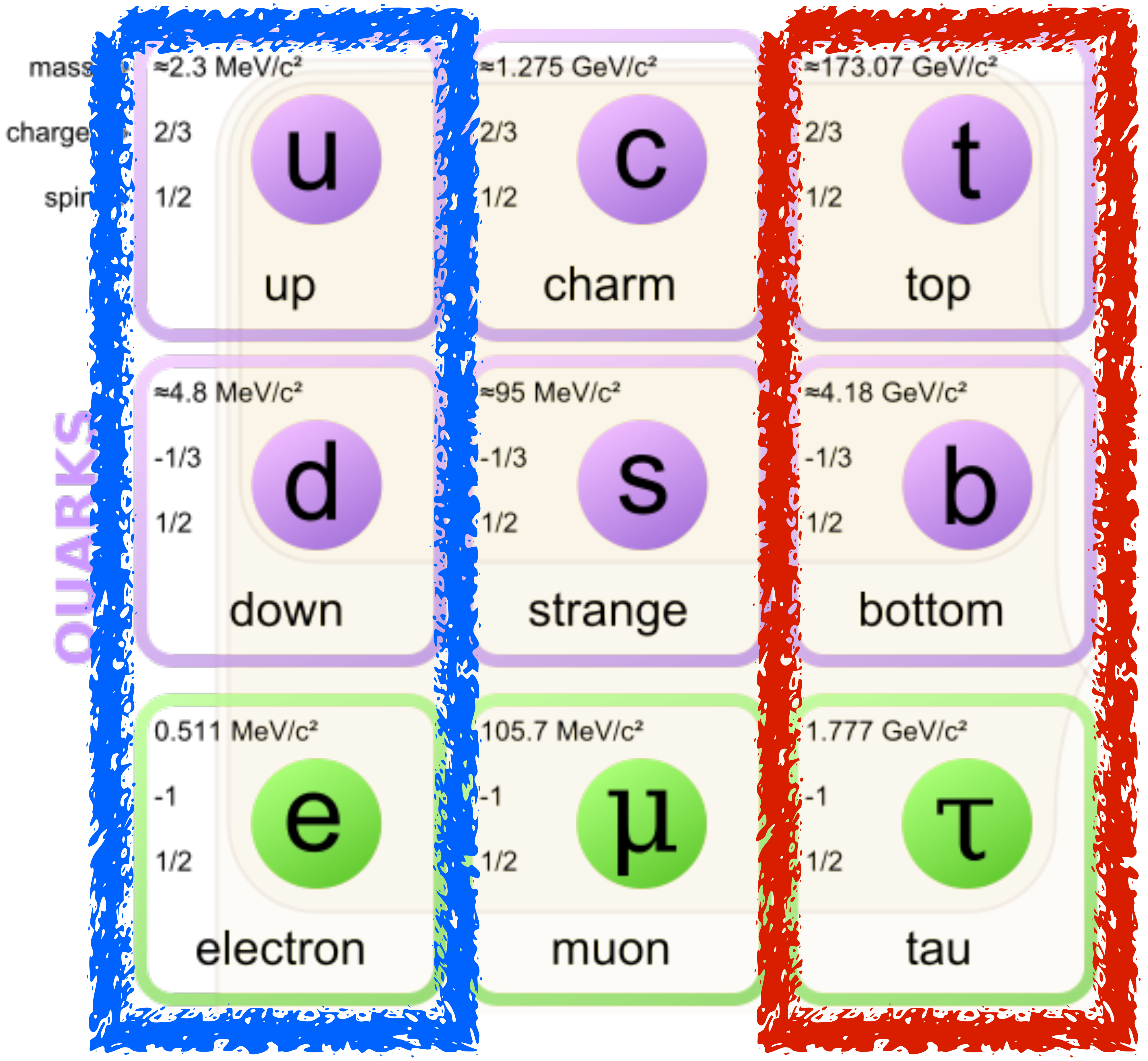
electron mass determines size of all atoms

it sets energy levels of all chemical reactions


mass →
charge →
spin →
QUARKS
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau



1st generation (us) has low mass because of weak interactions with Higgs field (and so with Higgs bosons): **too weak to test today**

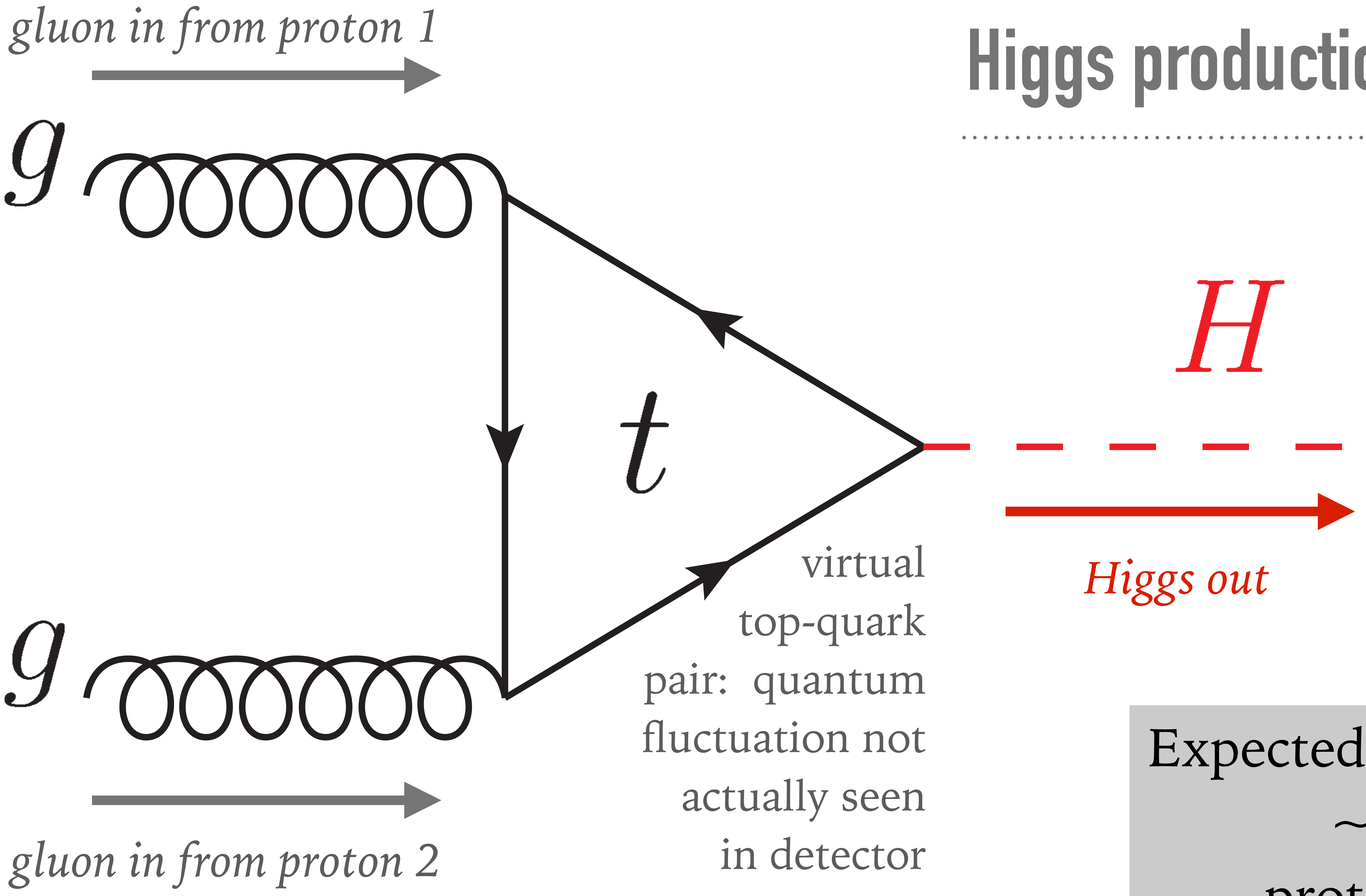


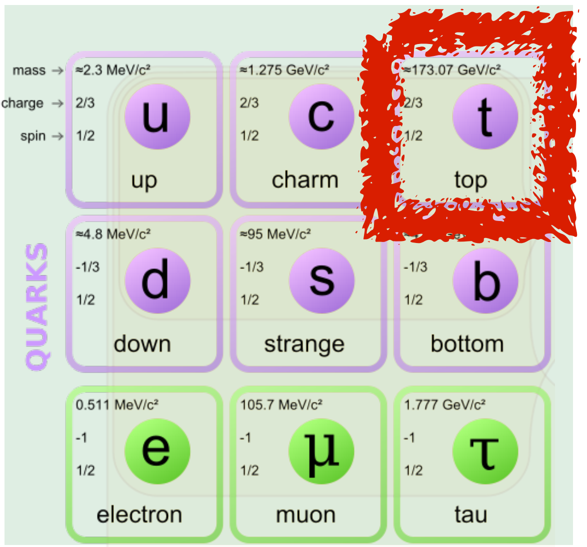
1st generation (us) has low mass because of weak interactions with Higgs field (and so with Higgs bosons): **too weak to test today**

3rd generation (us) has high mass because of strong interactions with Higgs field (and so with Higgs bosons): **can potentially be tested**

what underlying processes tell us about Yukawa interactions?

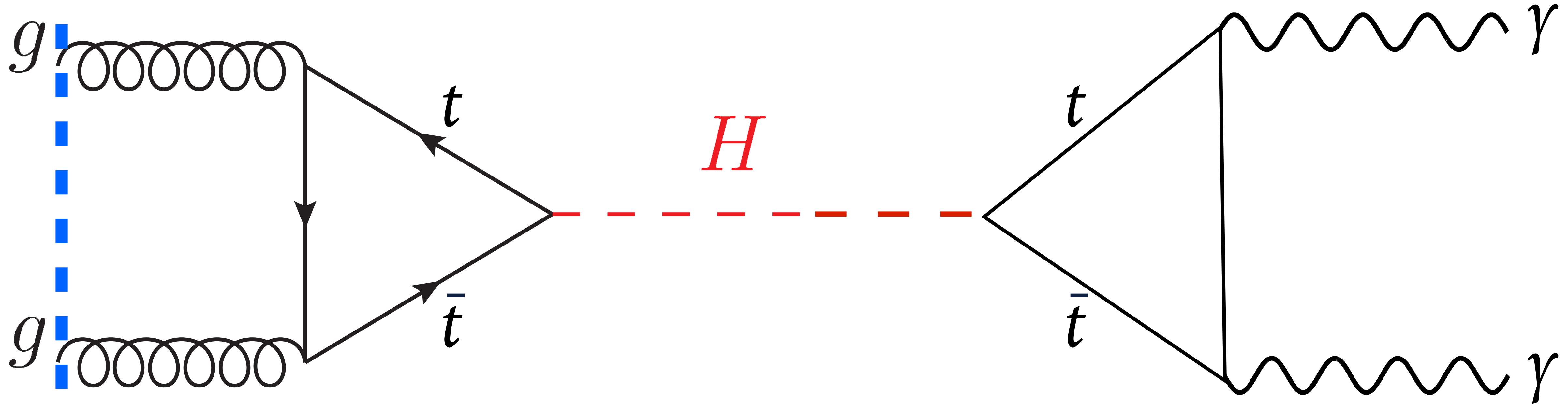
Higgs production: the dominant channel





Expected to happen once for every ~2 billion inelastic proton–proton collisions

LHC data consistent with that already at discovery in 2012


g
g
t
$\bar{t}$
H
t
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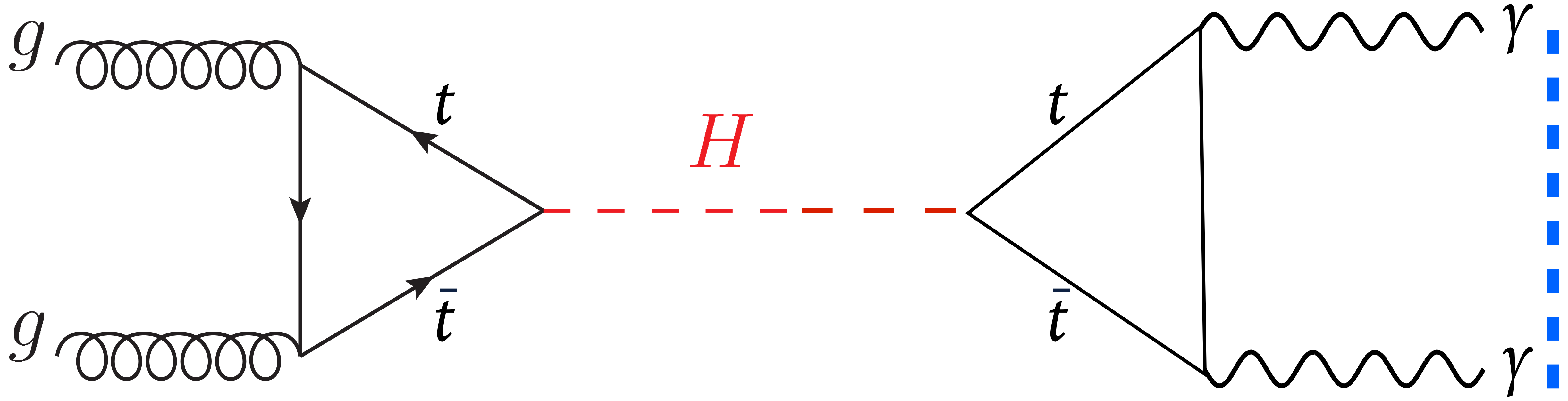
γ
γ


luon
gluo
ϕ
y
x
Higgs field in space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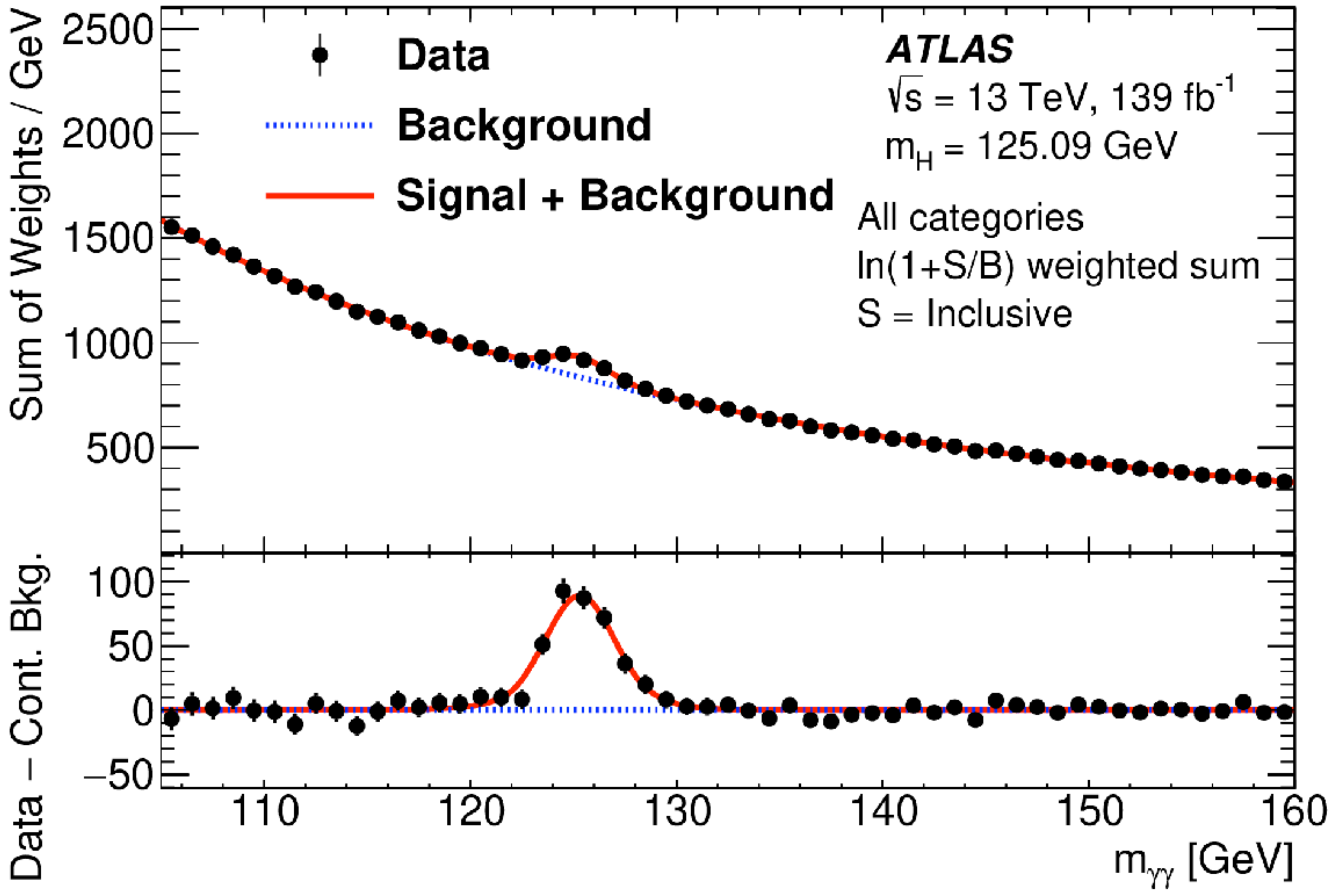
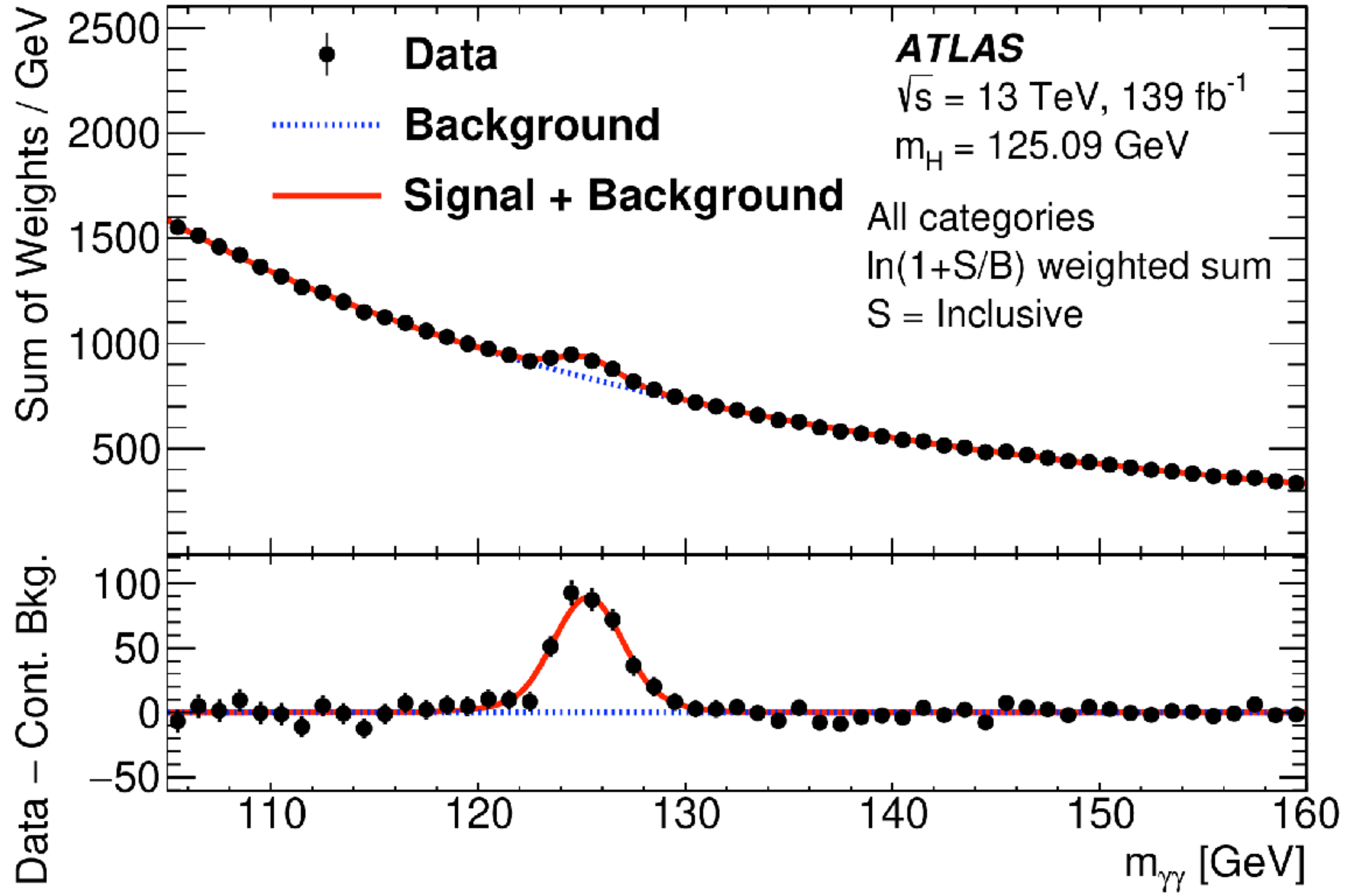
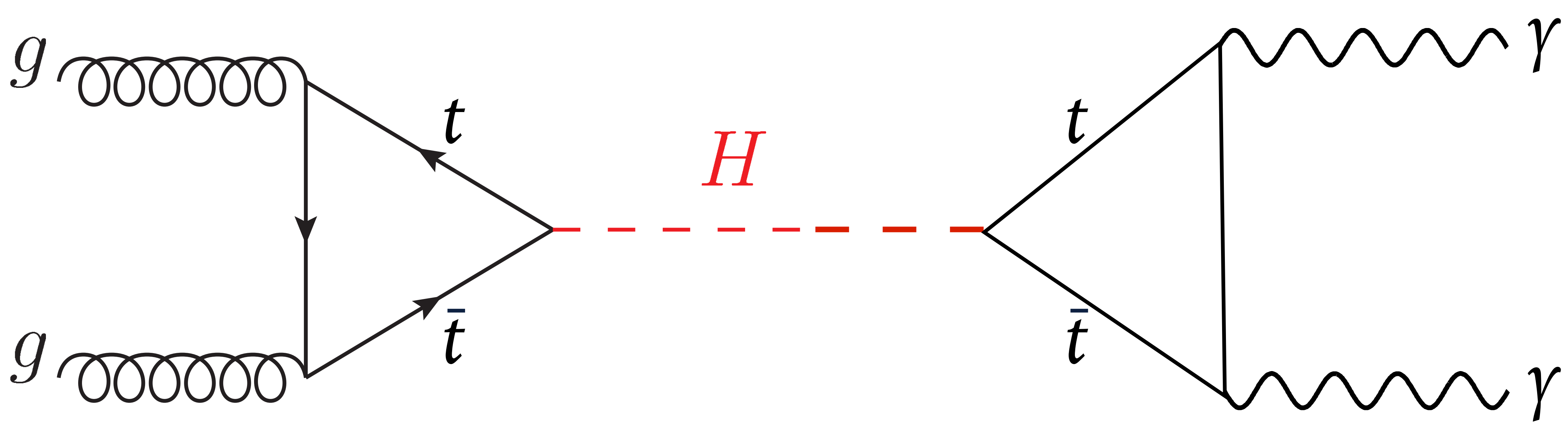


$H \to \gamma\gamma$

ratio to SM
= 1.04 ± 0.10



Data
Background
Signal + Background
ATLAS
√s = 13 TeV, 139 fb^{-1}
m_H = 125.09 GeV
All categories
ln(1+S/B) weighted sum
S = Inclusive
Sum of Weights / GeV
Data – Cont. Bkg.
$m_{\gamma\gamma}$ [GeV]



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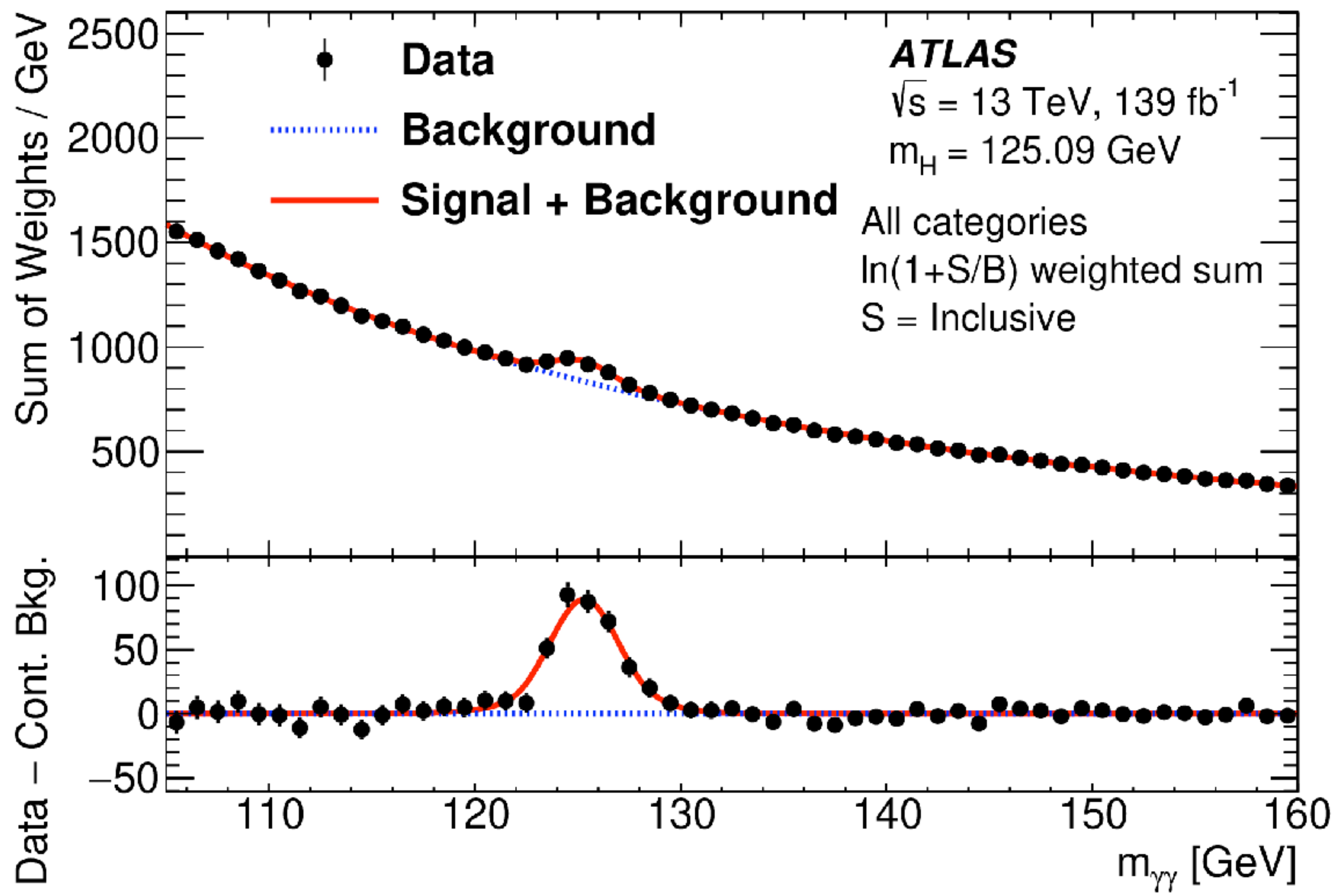
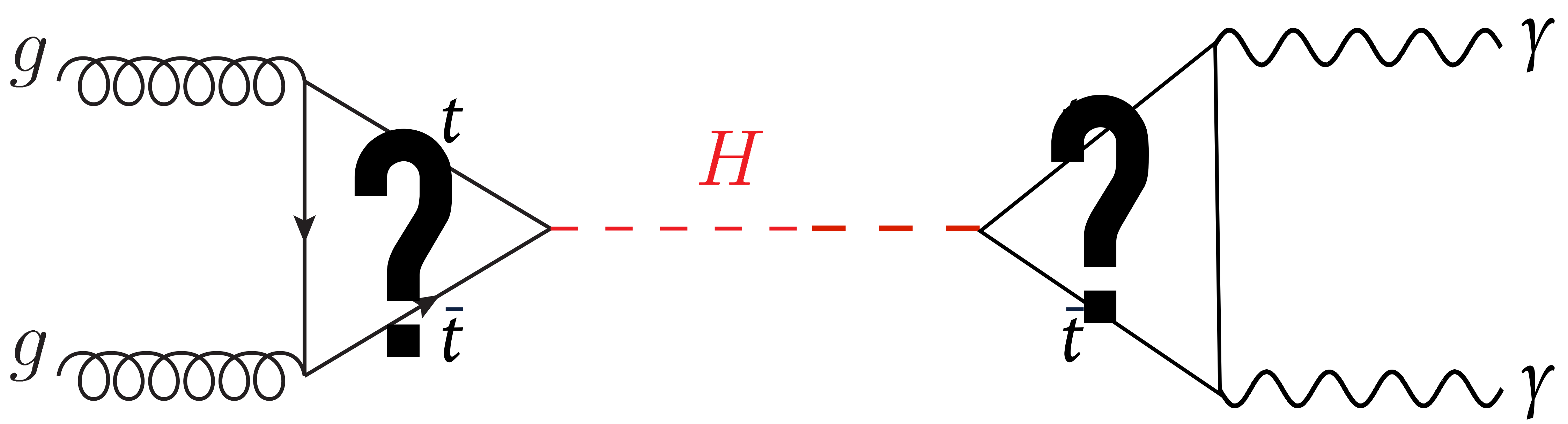
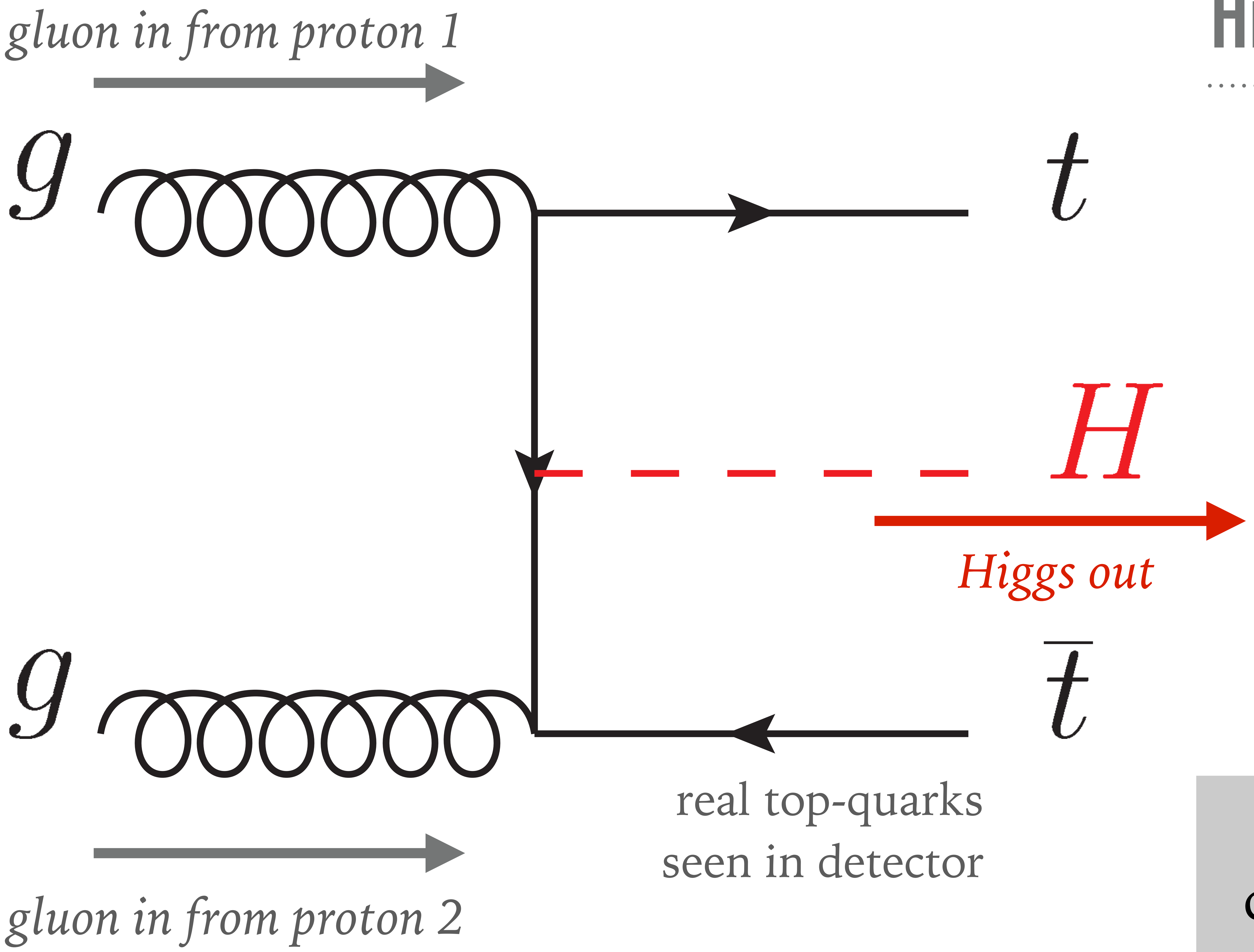




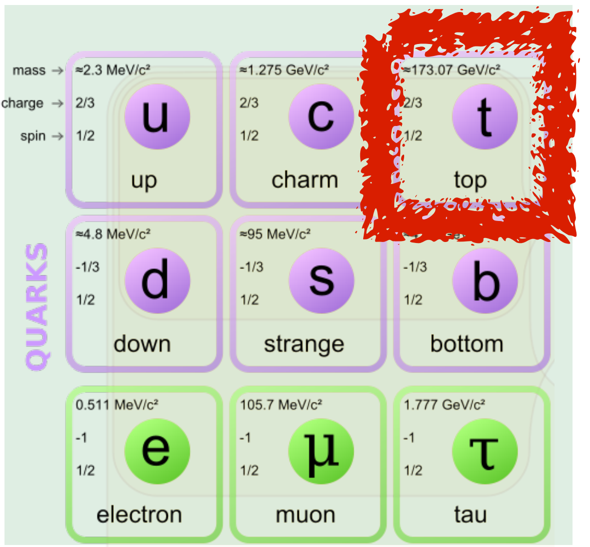
but how can you be sure the Higgs boson is really being radiated off a top-quark, i.e. that you're actually seeing a Yukawa coupling?

Higgs production: the ttH channel

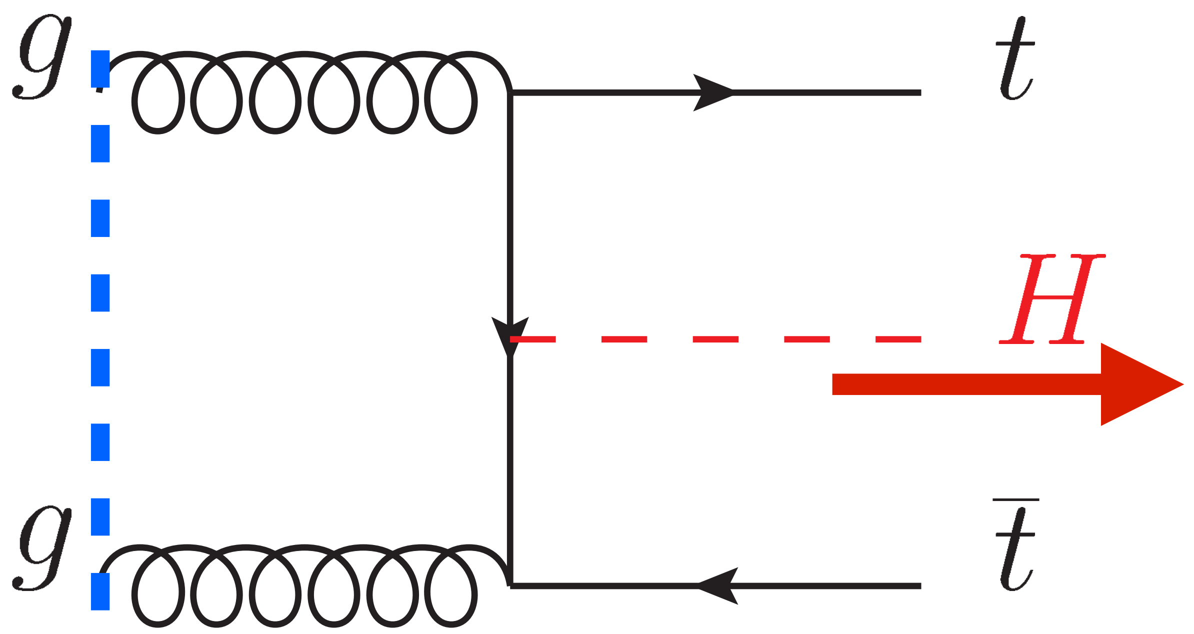


If SM top-Yukawa hypothesis is correct, expect 1 Higgs for every 1600 top-quark pairs.

(rather than 1 Higgs for every 2 billion pp collisions)



https://cern.ch/gsalam/higgs




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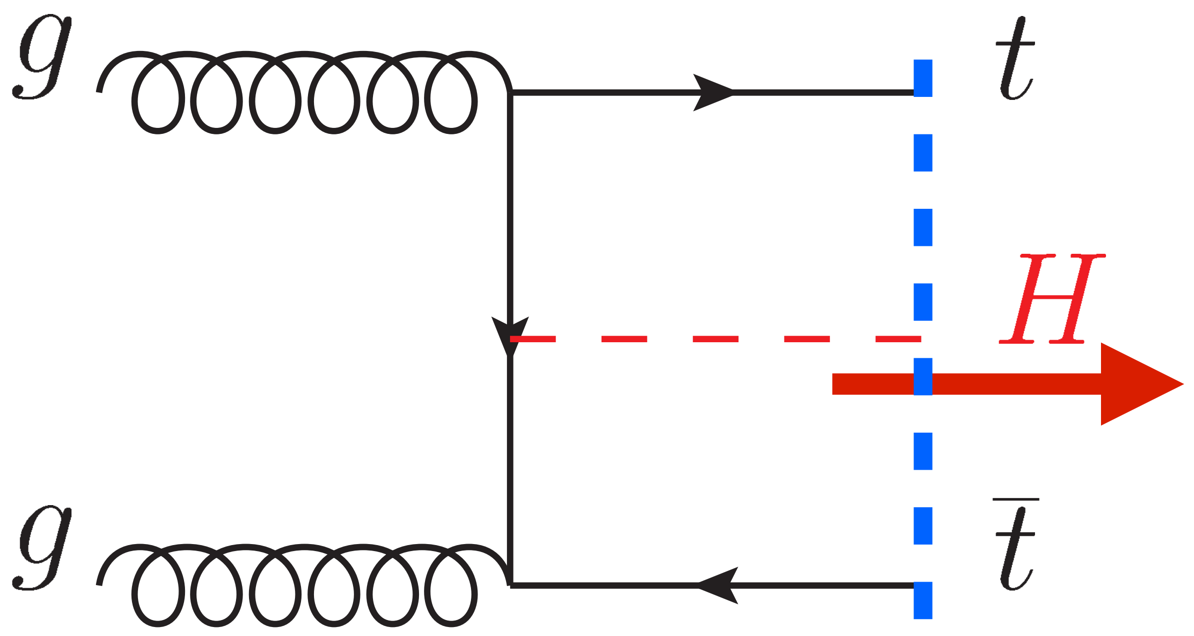
luon
gluo
φ
y
x
Higgs field in space


g
t
H
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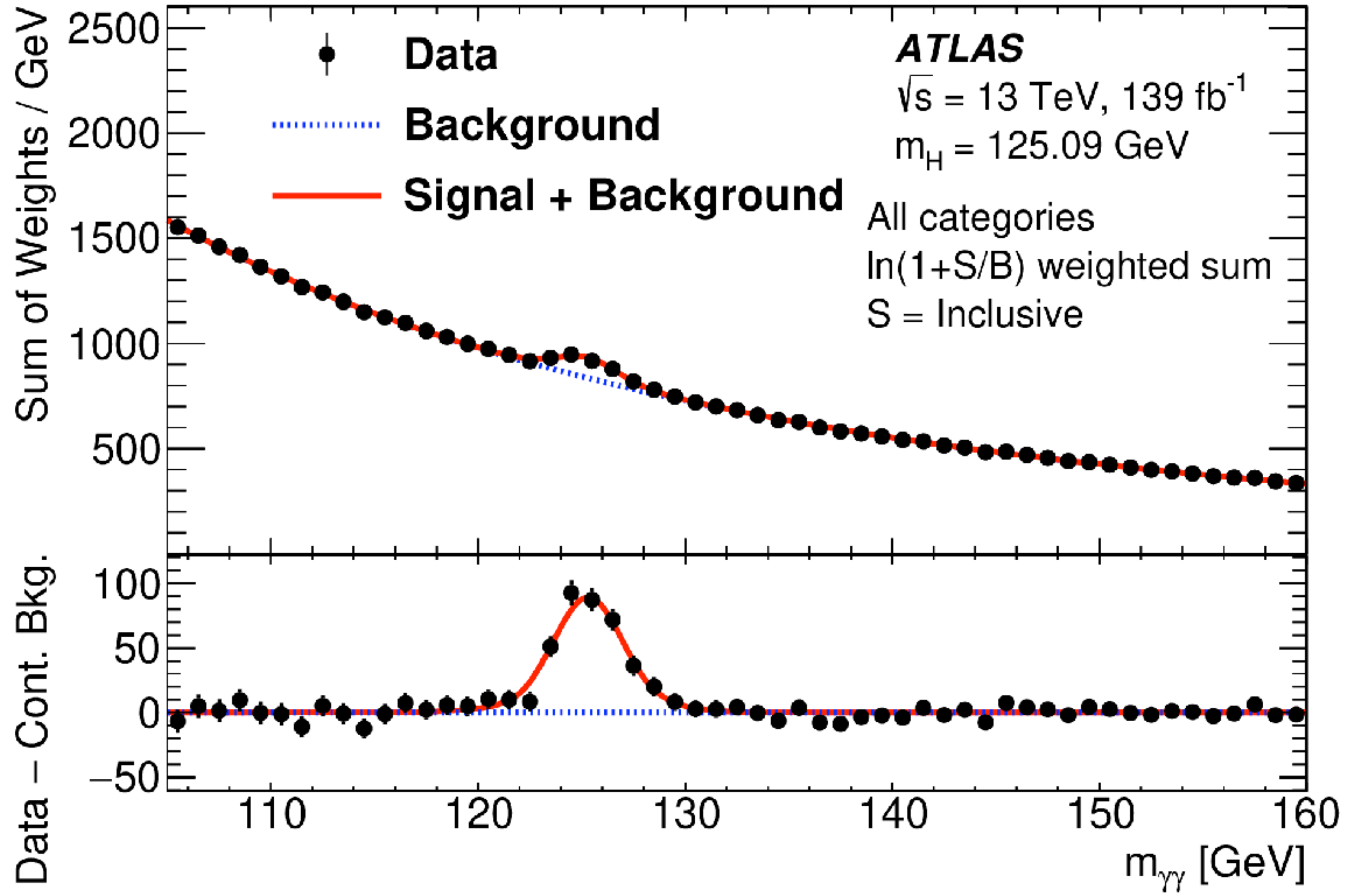
$\bar{t}$

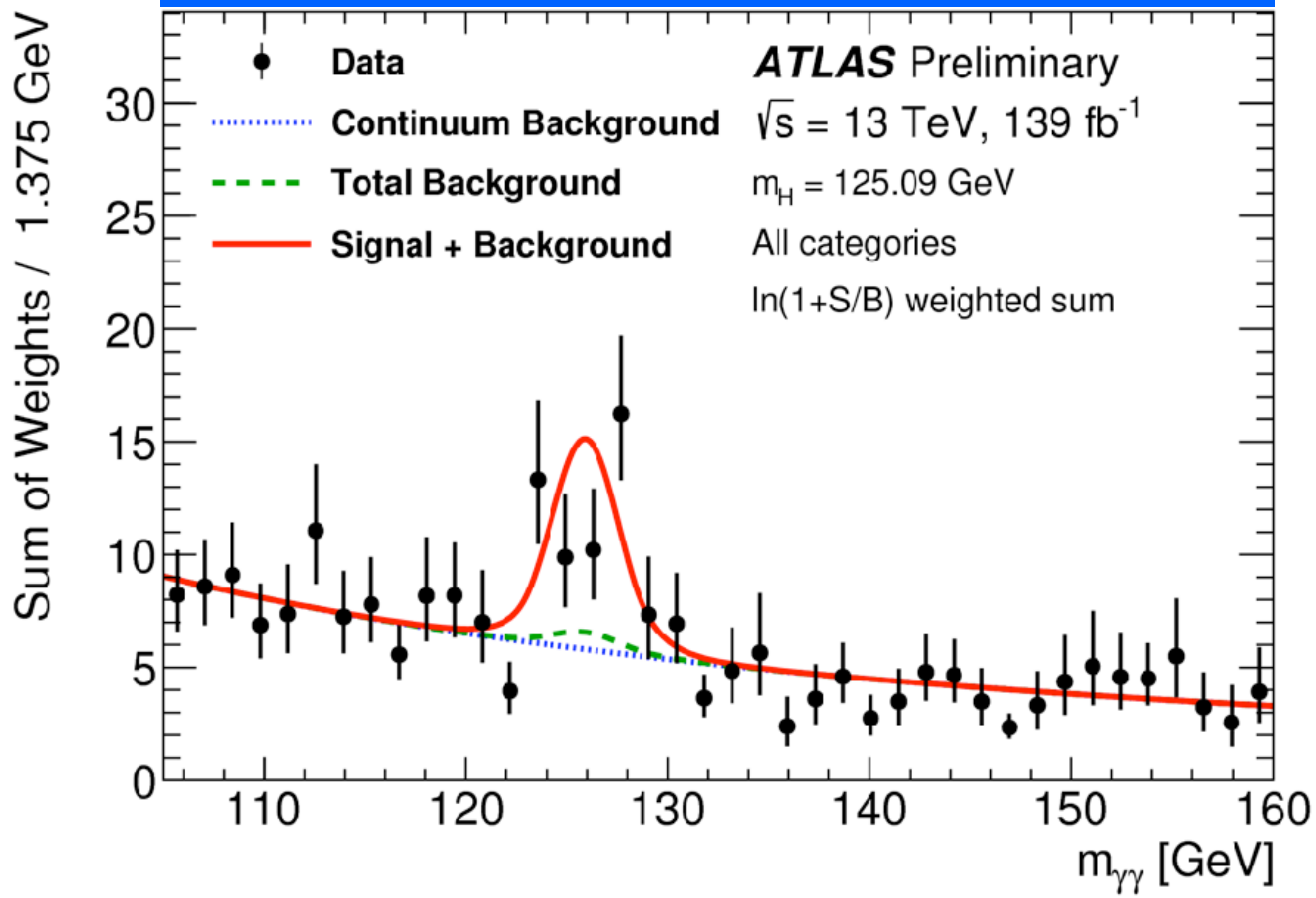

luon
gluo
φ
y
x
Higgs field in space

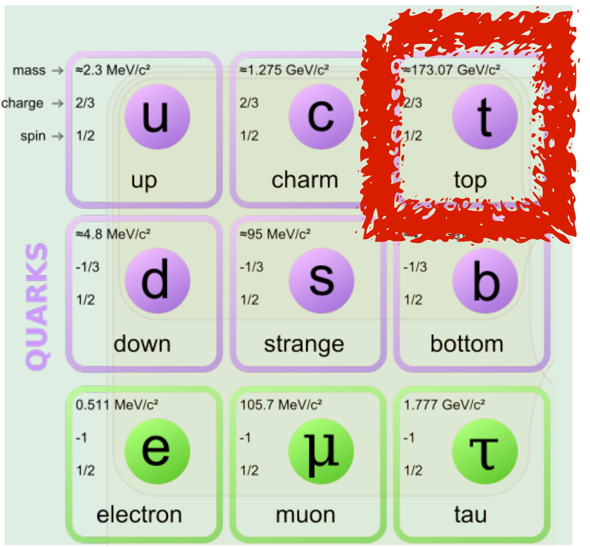
since 2018: ATLAS & CMS see events with top-quarks & Higgs simultaneously

across all events



in events with top quarks



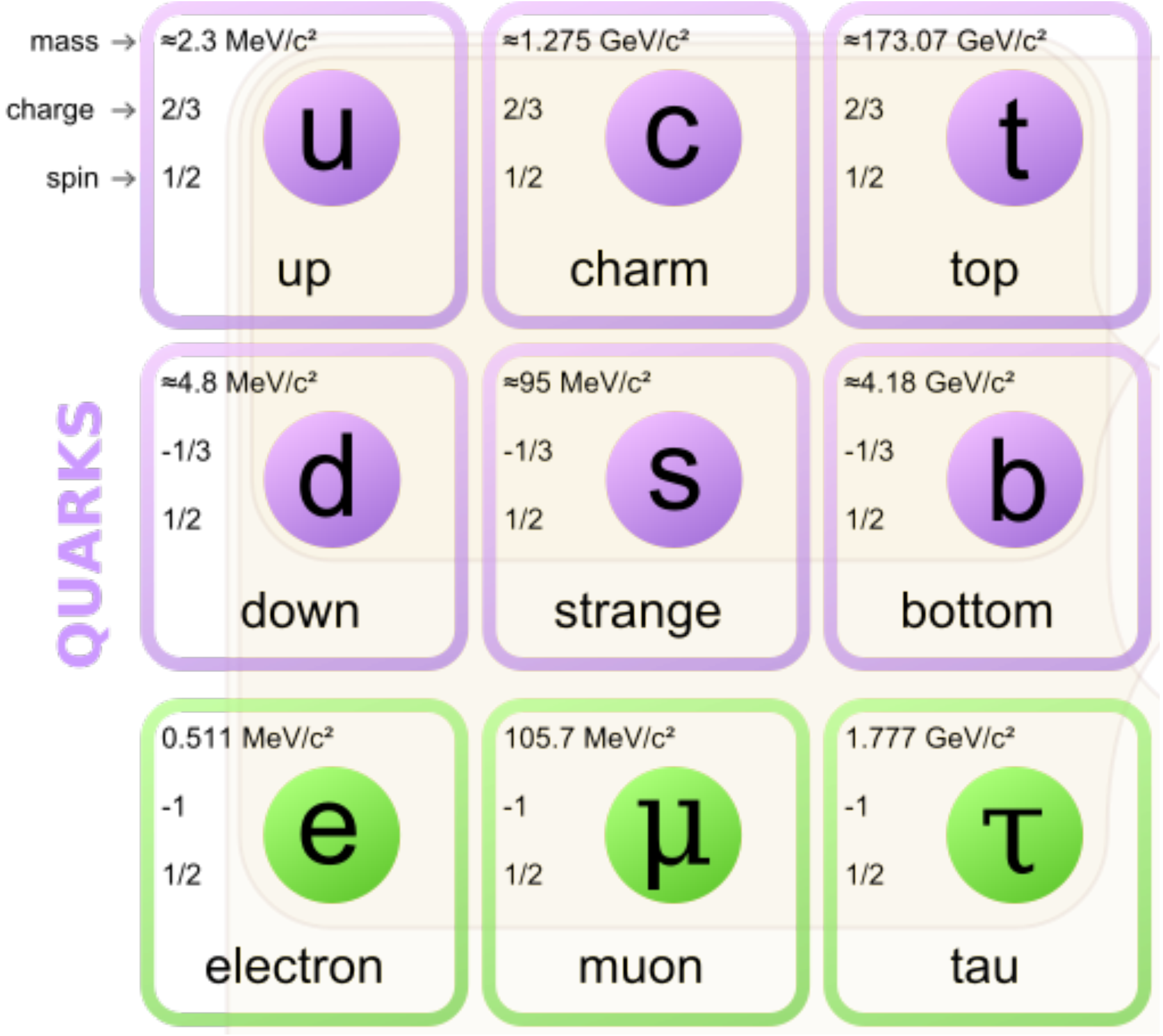


enhanced fraction of Higgs bosons in events with top quarks

→ direct observation of Higgs interaction with tops

(consistent with SM to c. ±25%)

Discovery of 3rd generation Yukawa interactions by ATLAS & CMS



Discovery $\equiv 5\sigma \simeq \pm 20\,\%$

† in part with approach from Butterworth, Davison, Rubin & GPS '08

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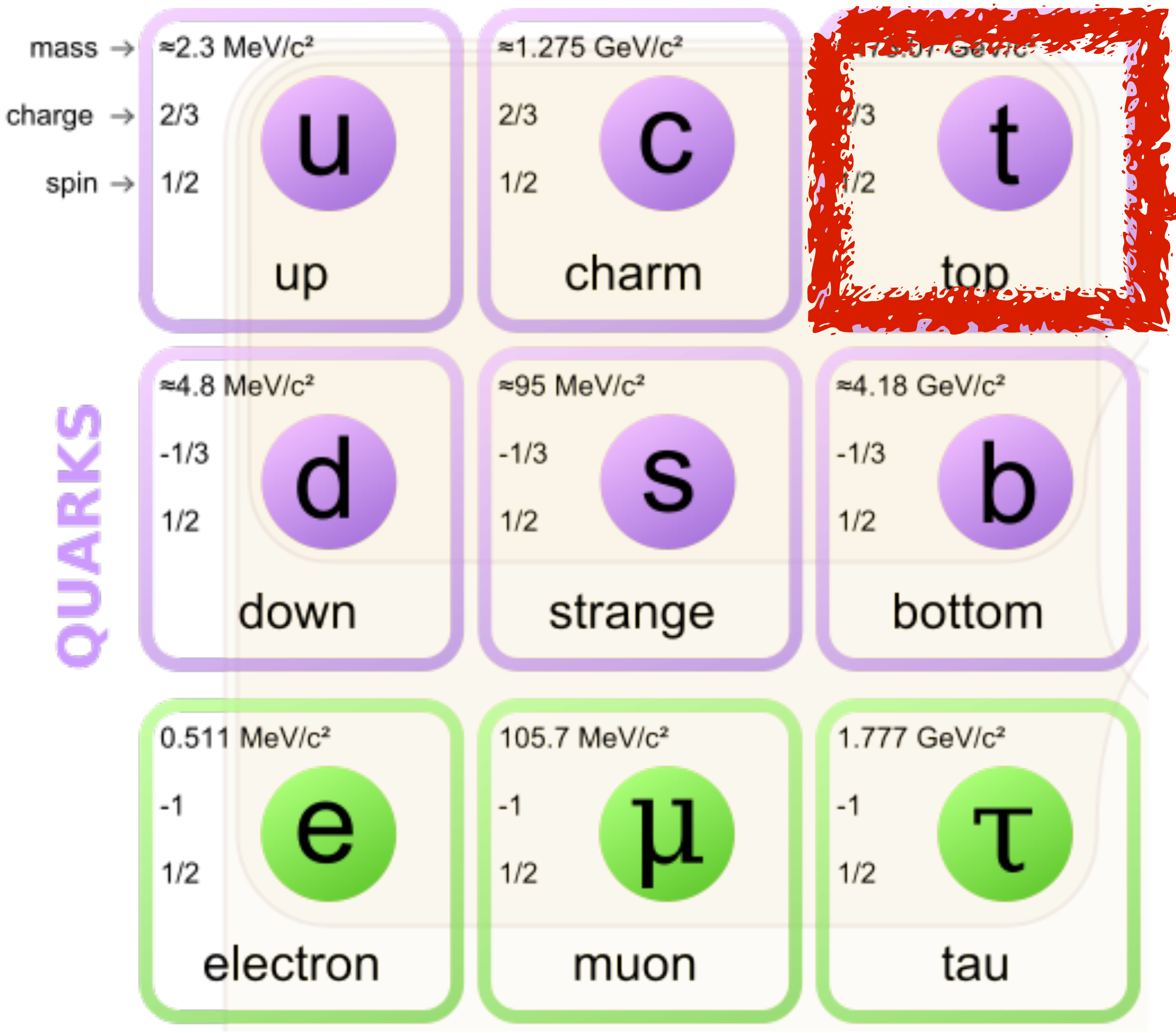

by observing *H* in association with top quarks

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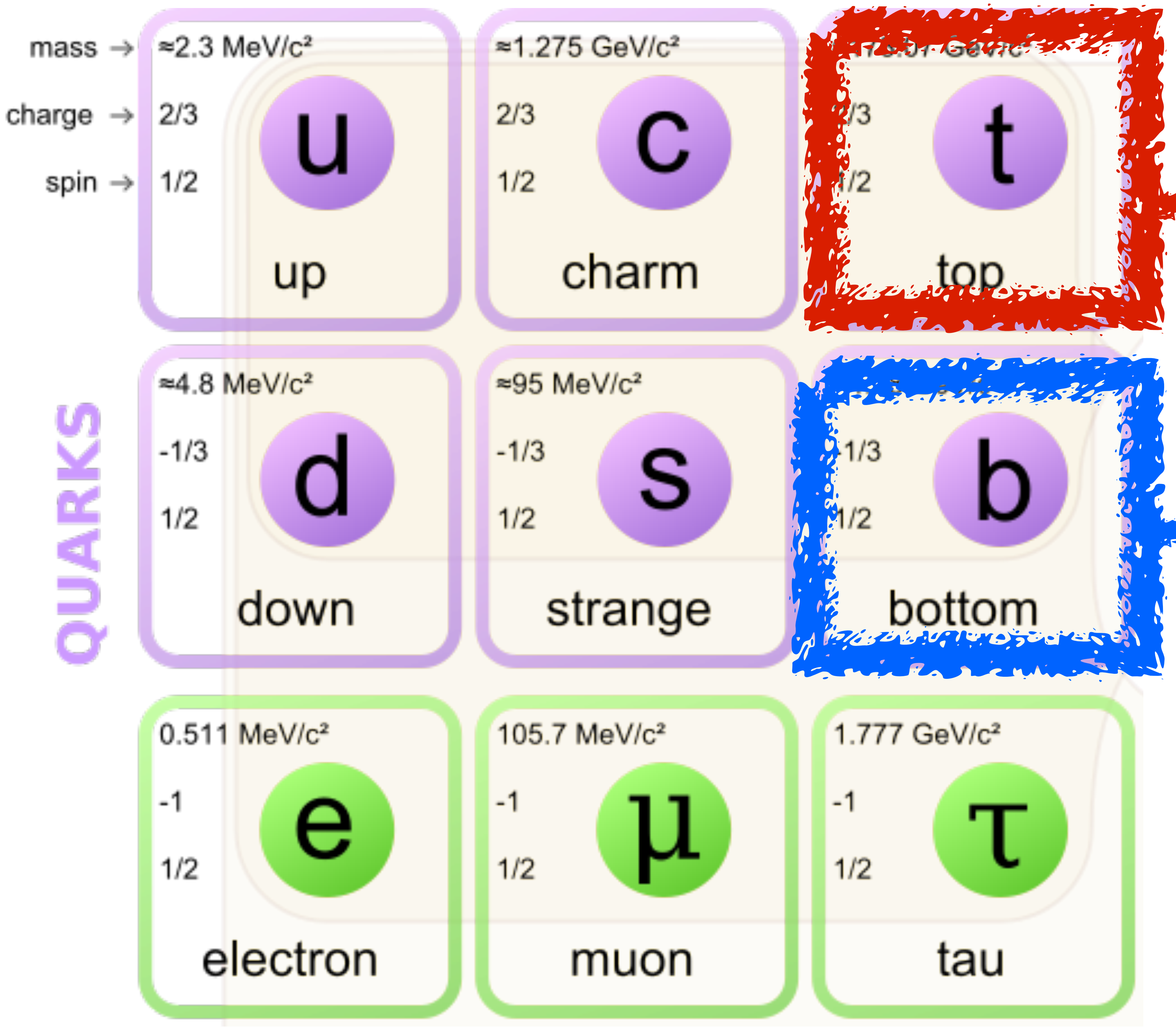
Discovery of 3rd generation Yukawa interactions by ATLAS & CMS



by observing H in association with top quarks

by observing $H \to b\bar{b}$ decays†

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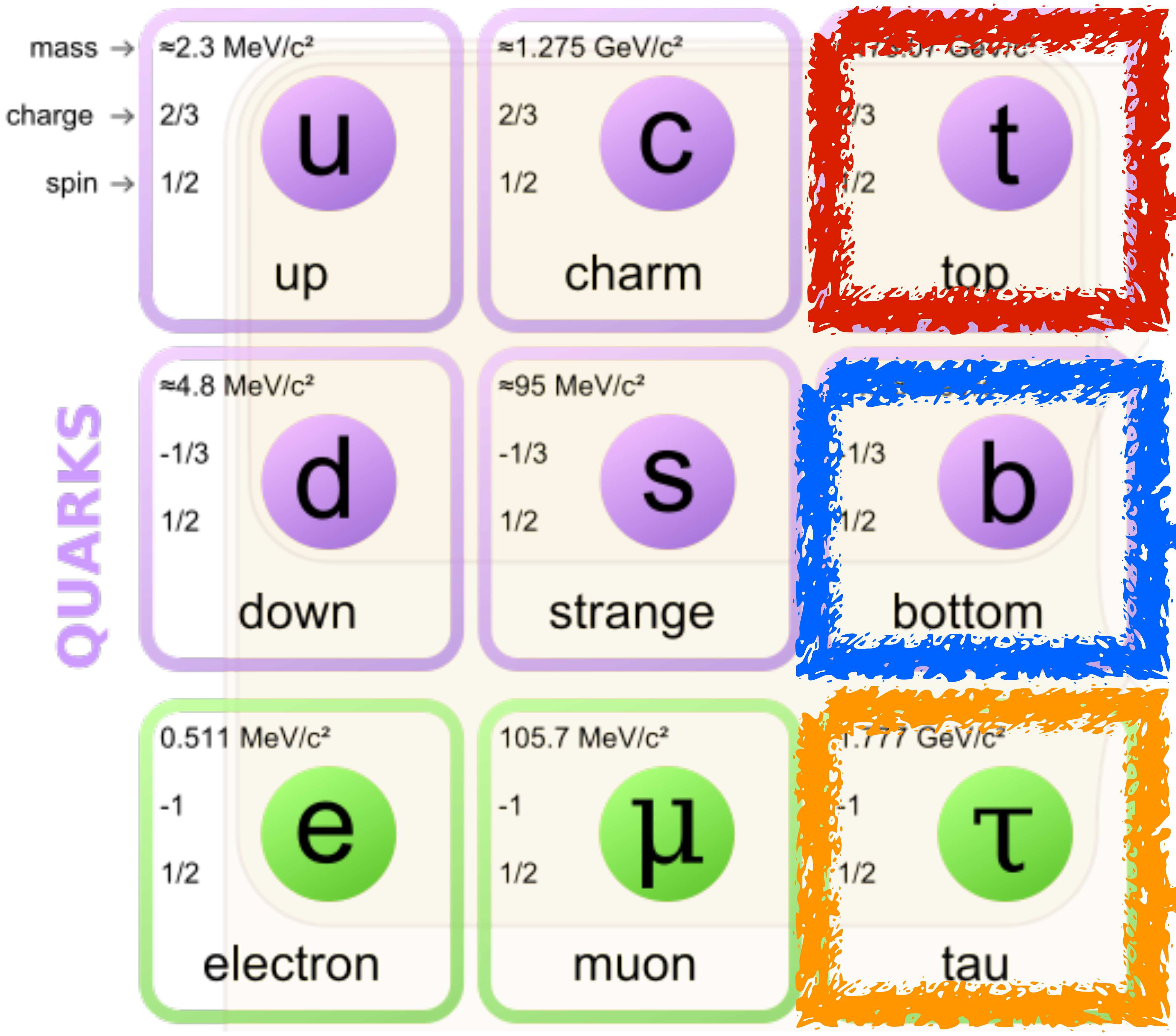


by observing H in association with top quarks

by observing $H \to b\bar{b}$ decays†

by observing $H \to \tau^+\tau^-$ decays

Discovery $\equiv 5\sigma \simeq \pm 20\,\%$

†in part with approach from Butterworth, Davison, Rubin & GPS ‘08

what's the message?

The >5σ observations of the ttH process and of H → ττ and H→ bb decays, independently by ATLAS and CMS, **firmly establish the existence of a new kind of fundamental interaction**, Yukawa interactions.

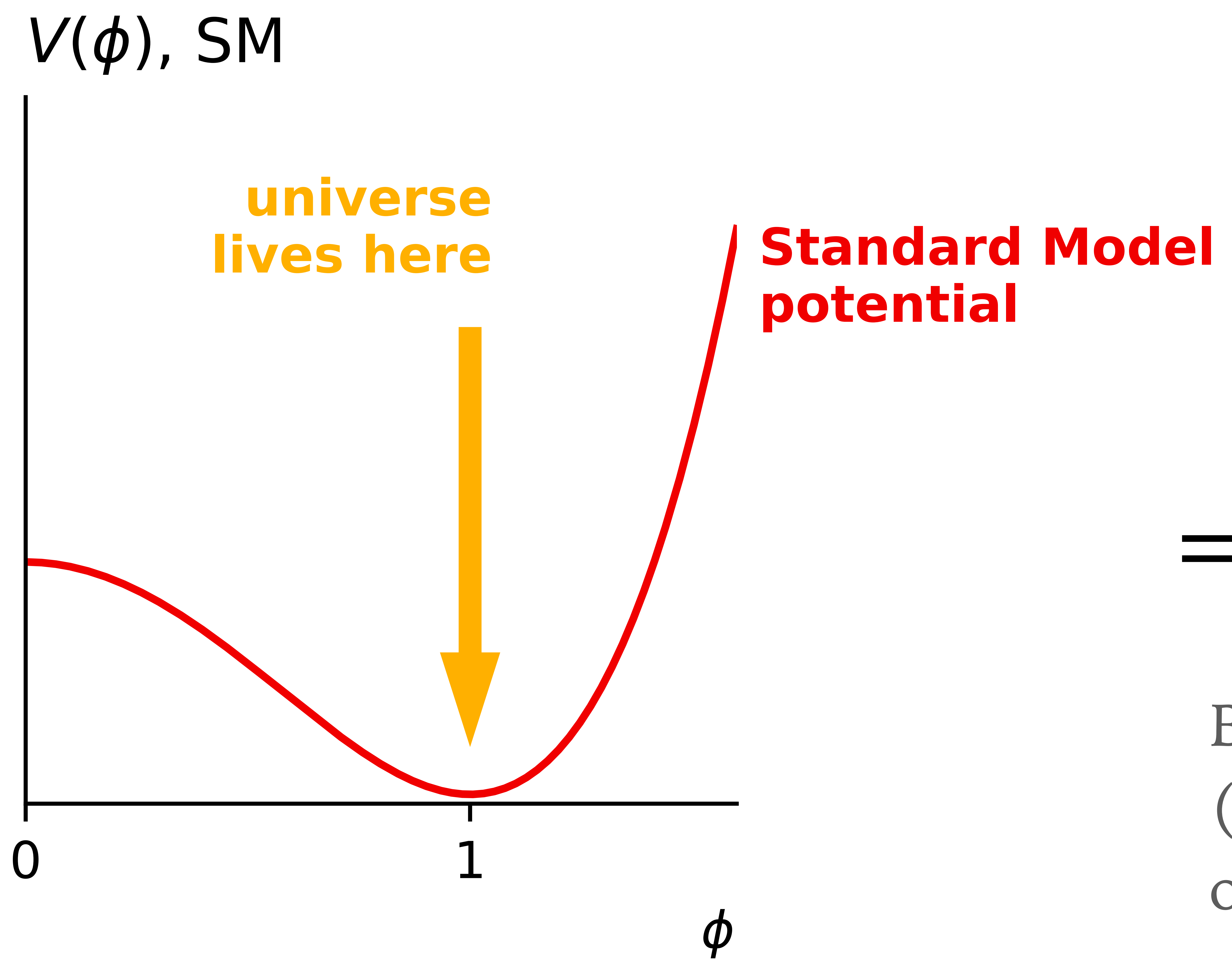
Yukawa interactions are important because they are:

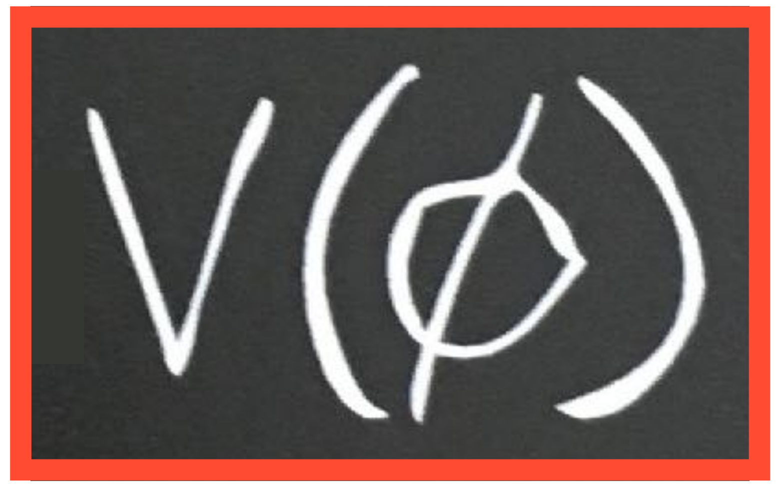
(1) **qualitatively unlike any quantum interaction probed before**
(effective charge not quantised, not conserved)

(2) hypothesized to be responsible for the **stability of hydrogen**, and for determining the **size of atoms** and the energy scales of chemical reactions.

Equivalently this is a **fifth force, the "Higgs force"**

Higgs potential, keystone of the SM — what can we observe experimentally?





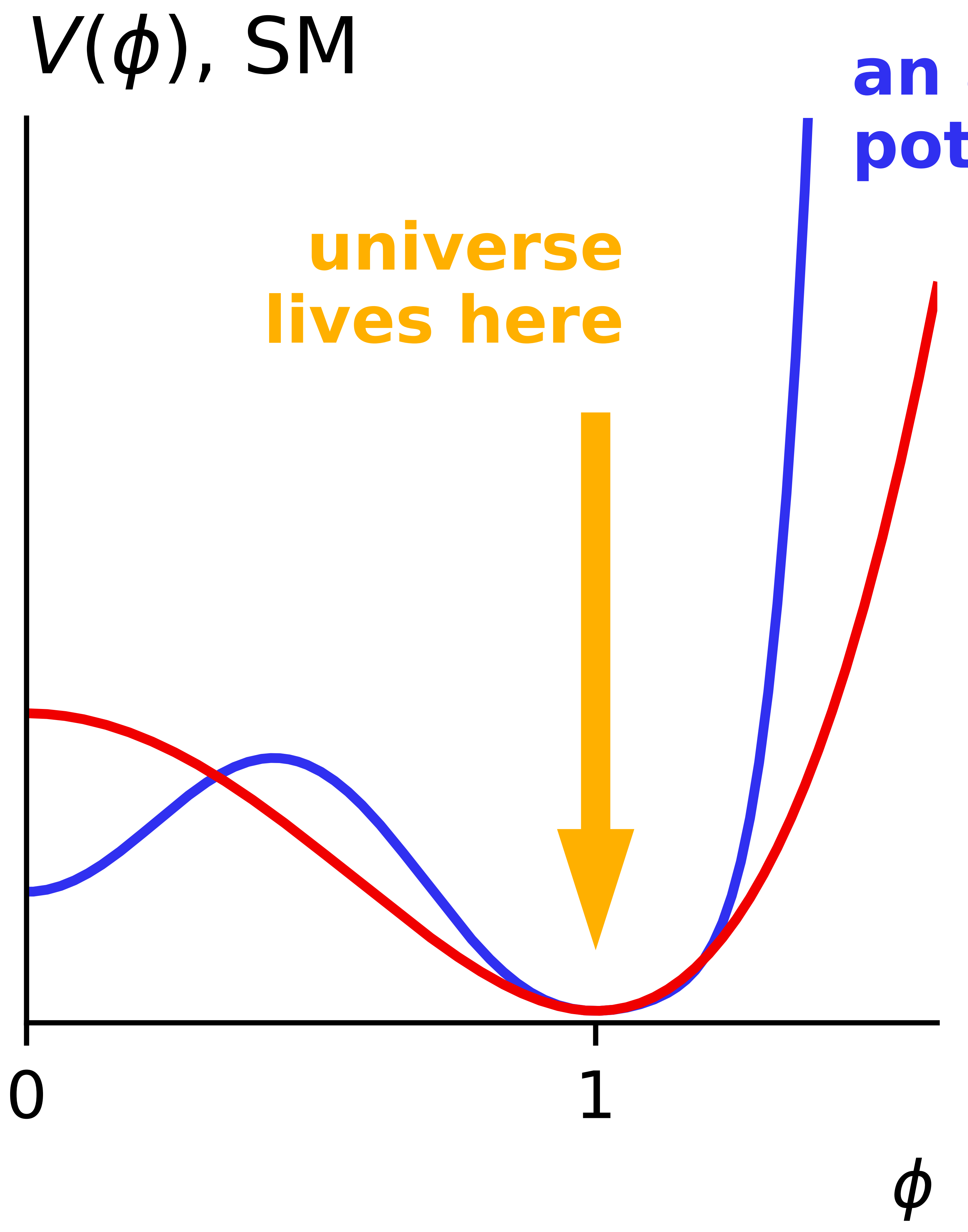
$$= -\mu^2\phi^2 + \lambda\phi^4$$

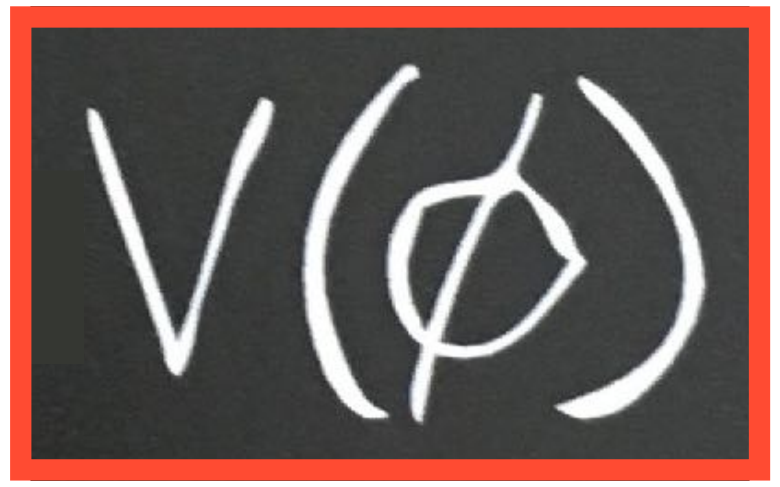
$$= V(\phi_0) + m^2H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

By trying to observe triple-Higgs interaction (e.g. H → HH) it's possible to get a handle on the third derivative of the potential

NB: realistic alternative models tend to involve additional Higgs-like fields; plot adapted from Nature perspective with Wang & Zanderighi

Higgs potential, keystone of the SM — what can we observe experimentally?





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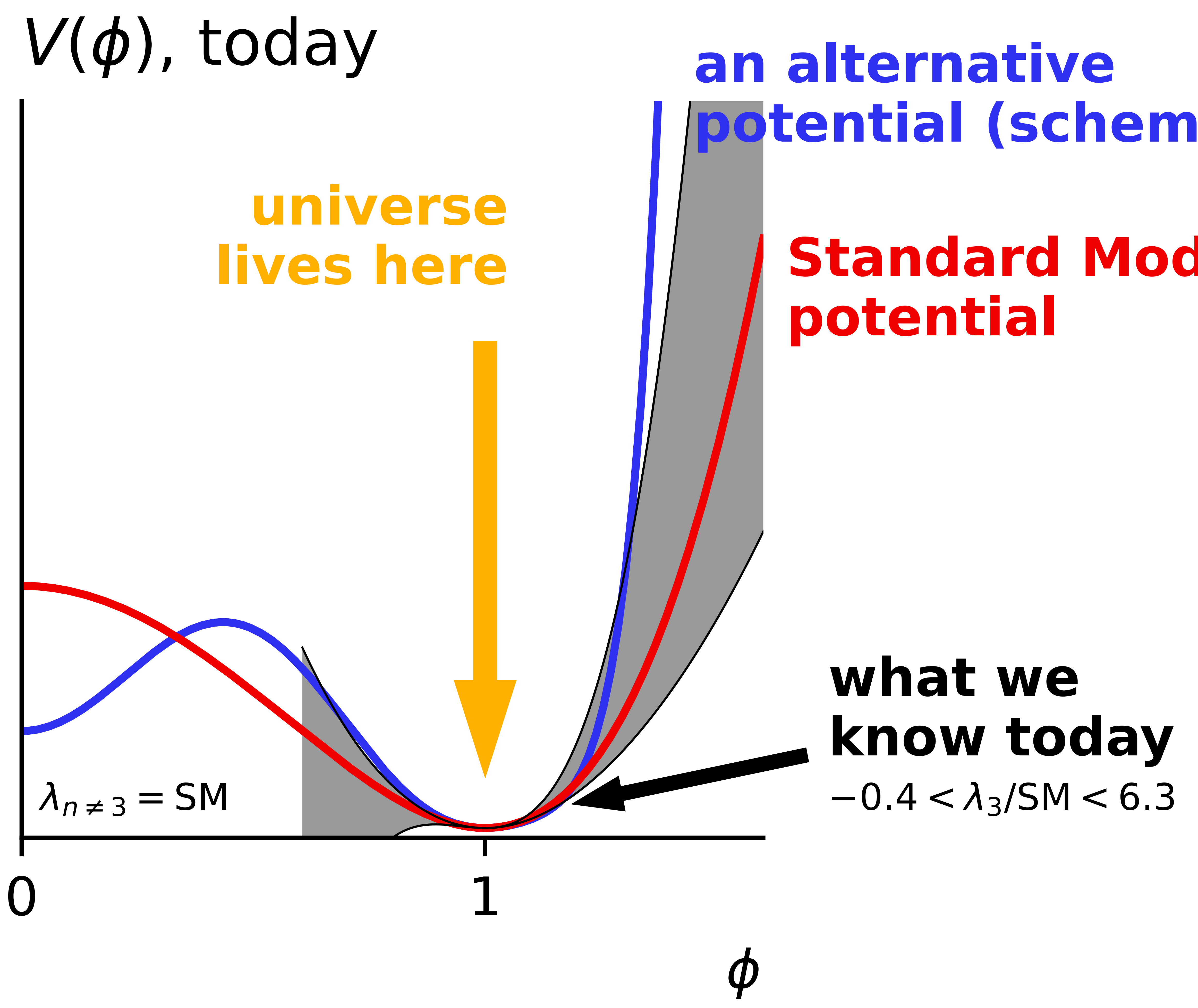

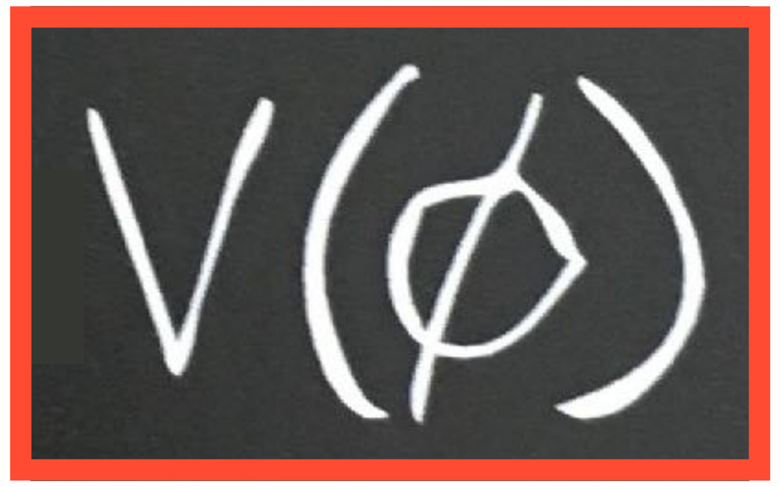

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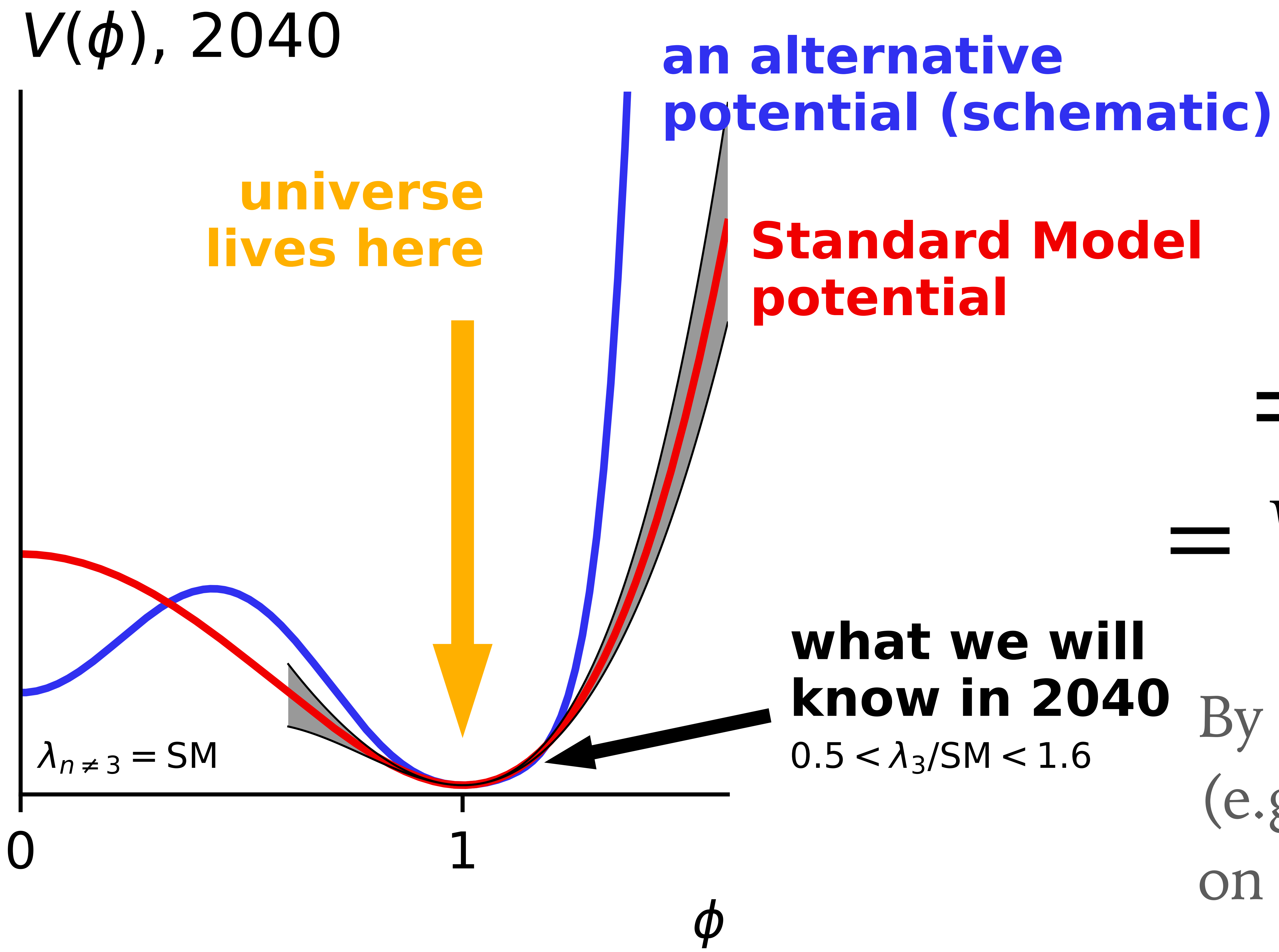

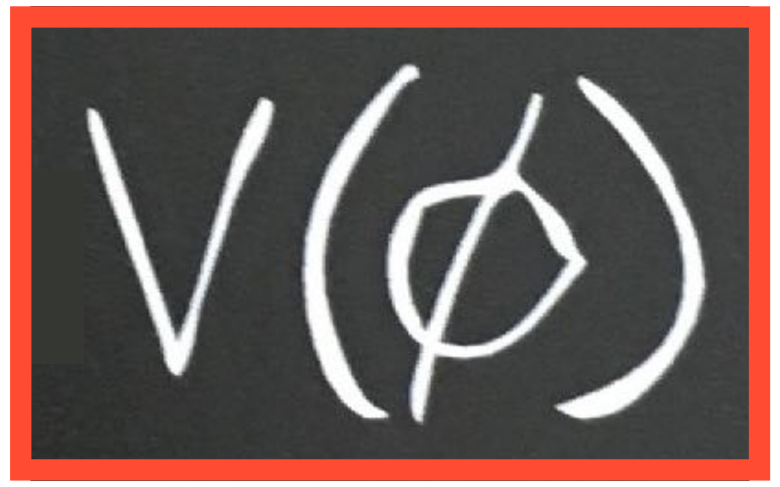

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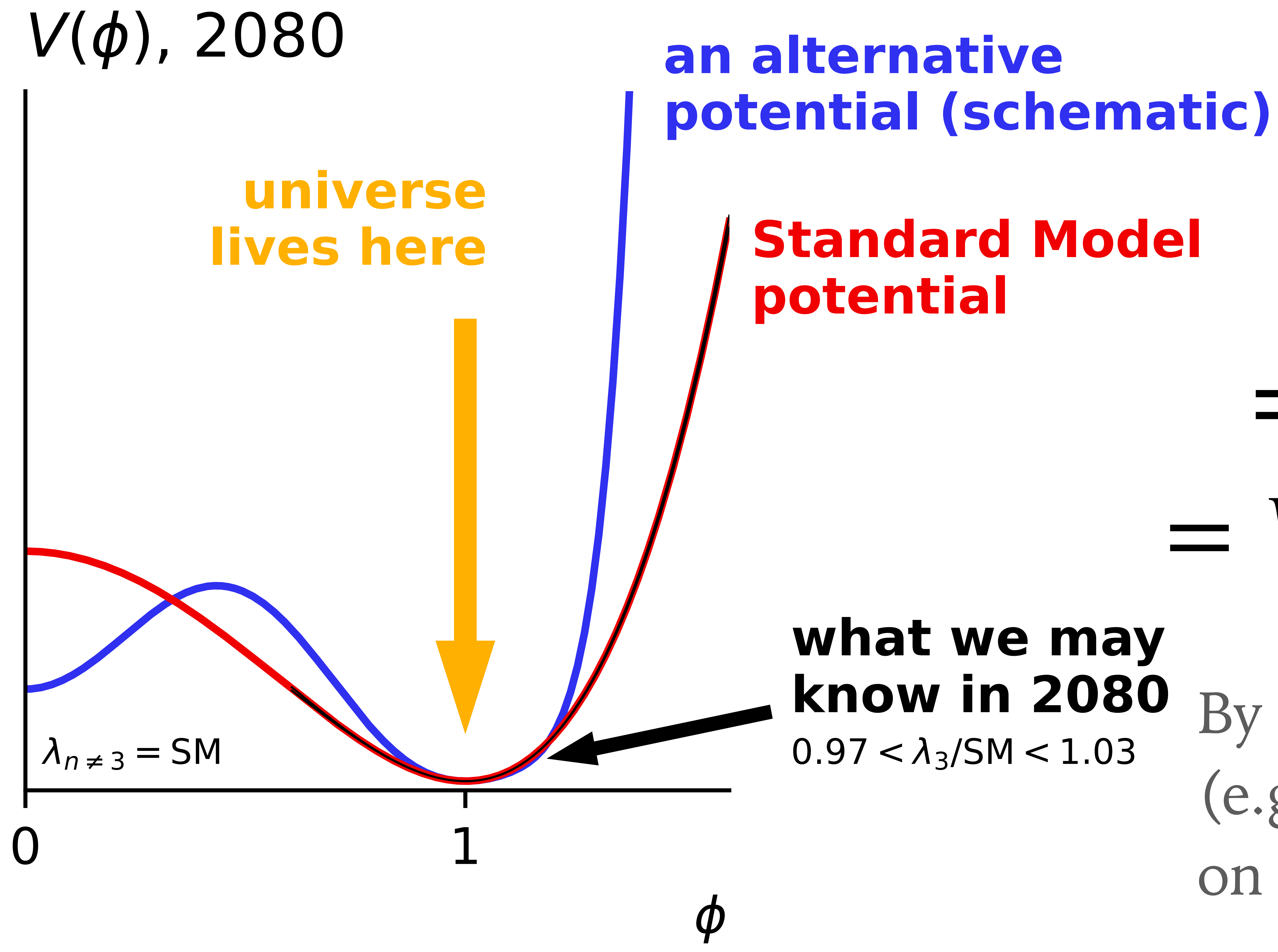

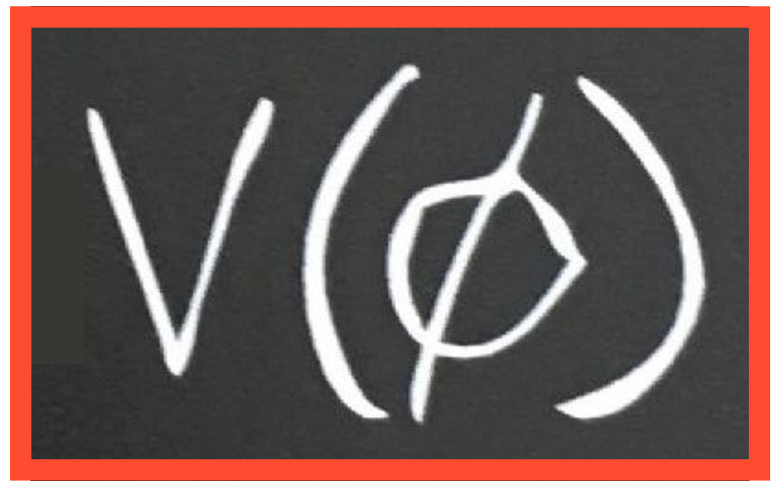

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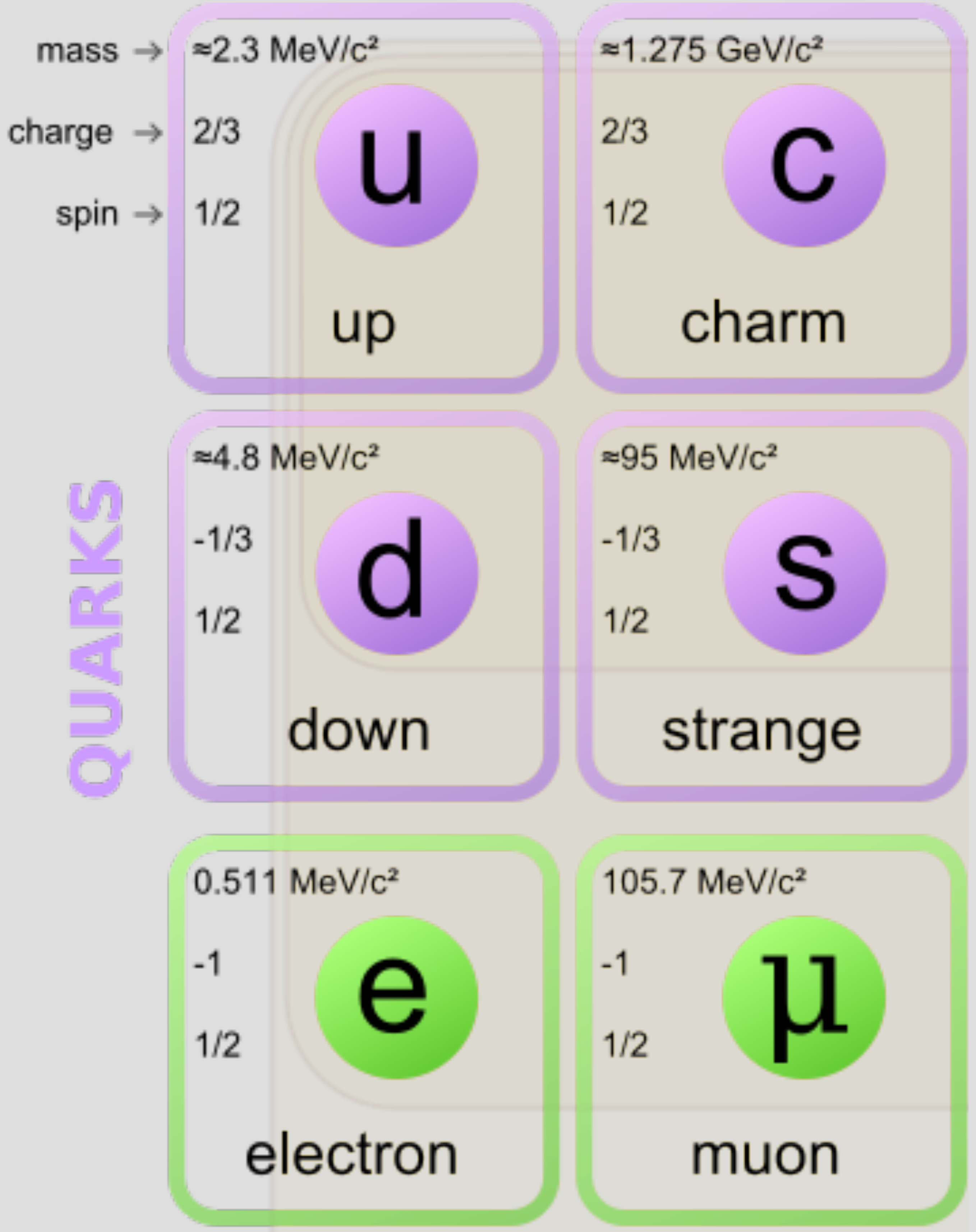
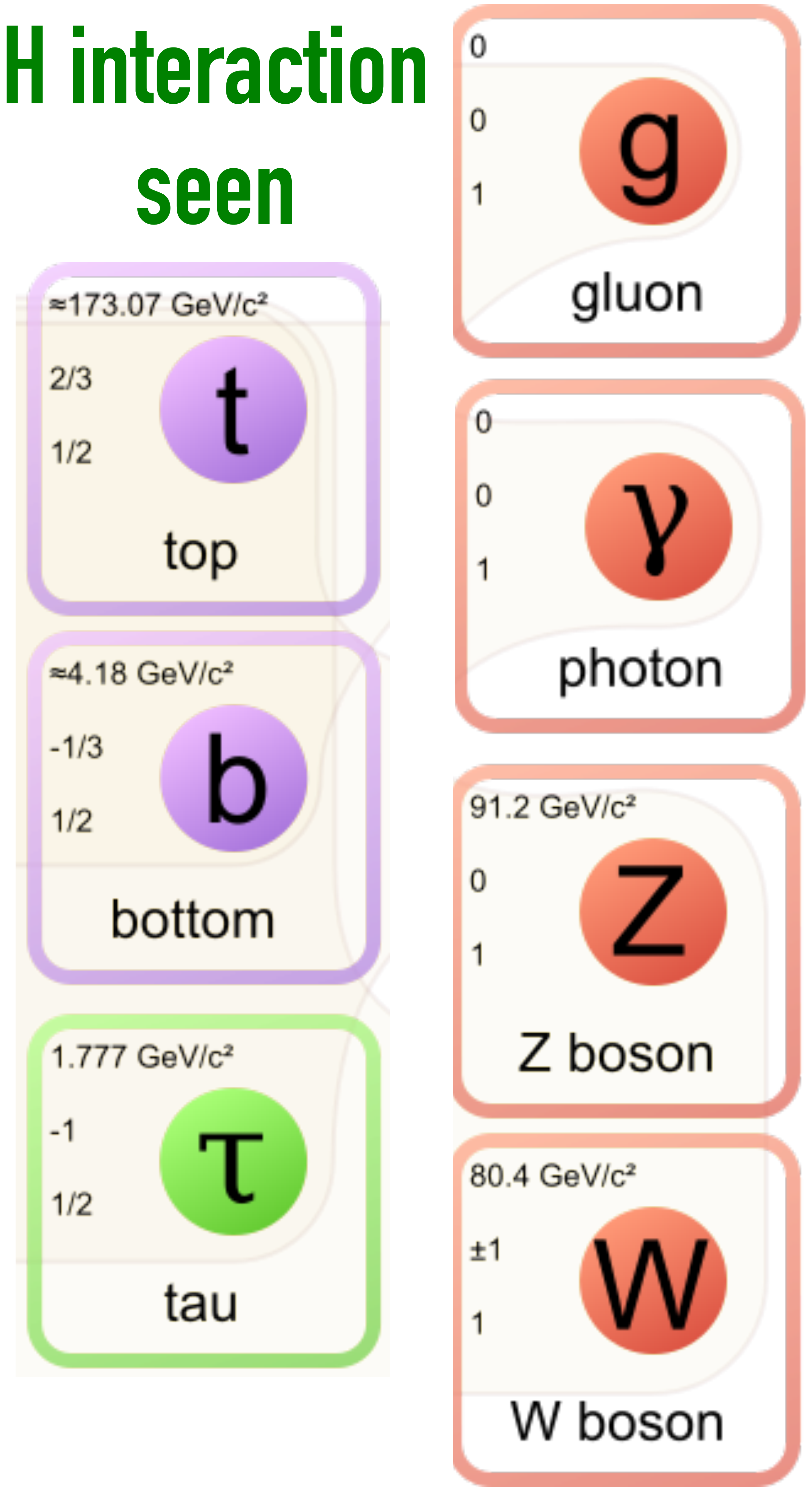
H interaction not yet seen



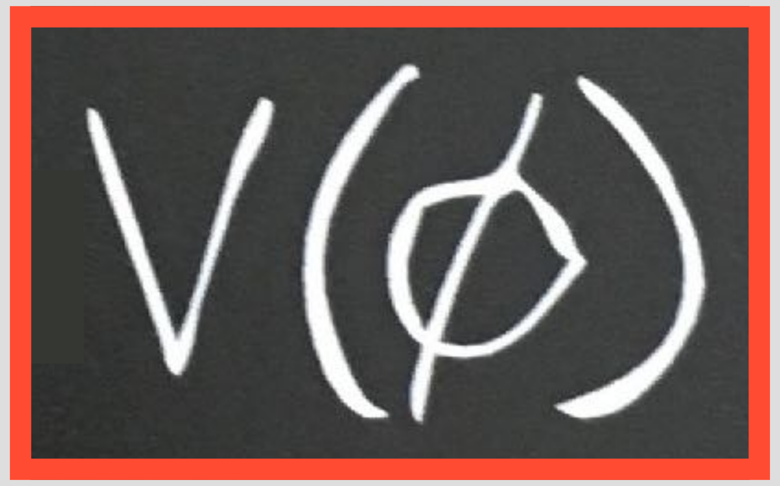
Are Yukawa interactions responsible for all fermion masses?

H interaction seen



Do these interactions follow the Standard Model to better than current ~10% accuracy?

Higgs potential not yet "seen"

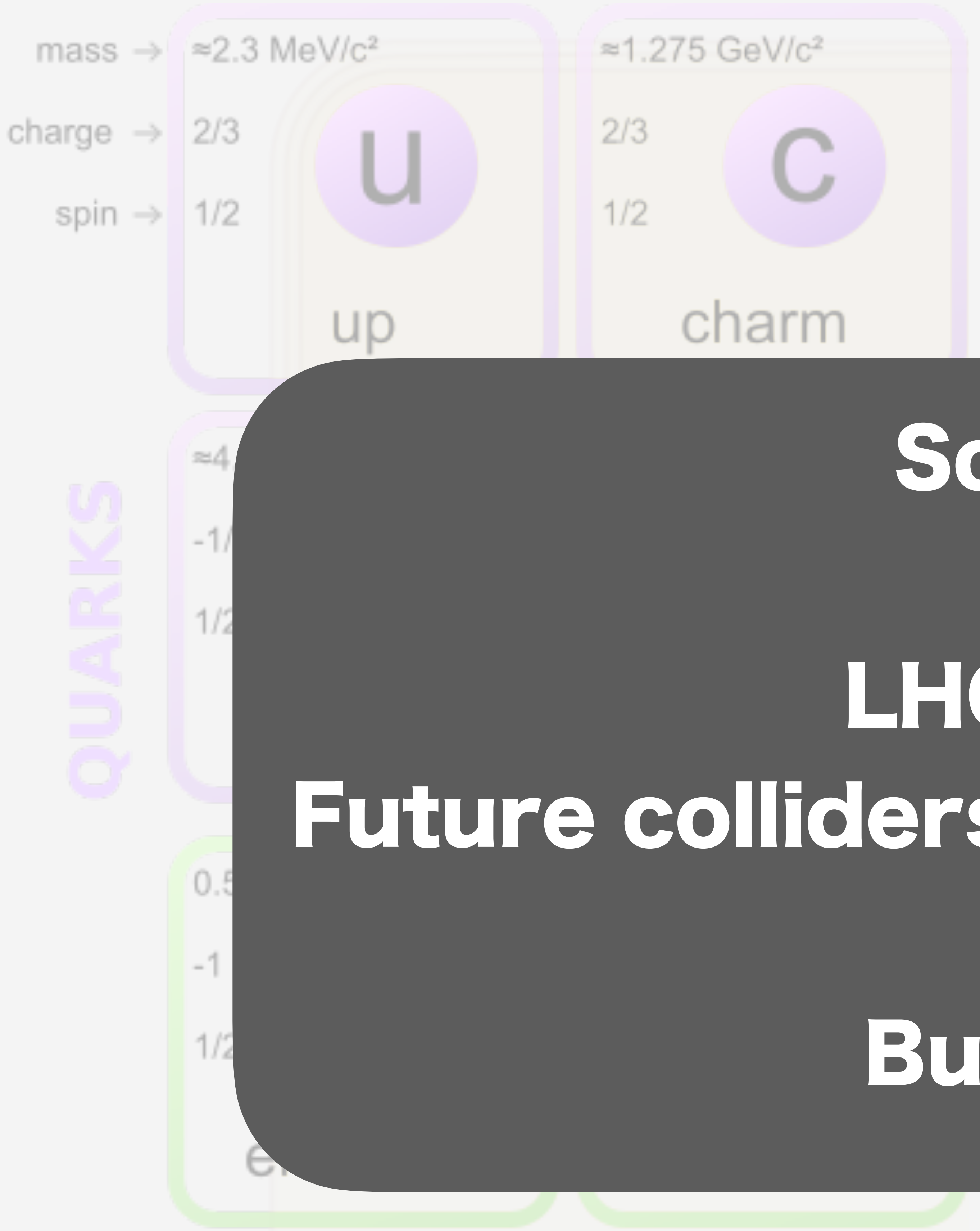


$$= -\mu^2\phi^2 + \lambda\phi^4$$

Is this "toy-model" potential Nature's choice?

Does the Higgs behave as a pointlike (fundamental) particle?

H interaction not yet seen



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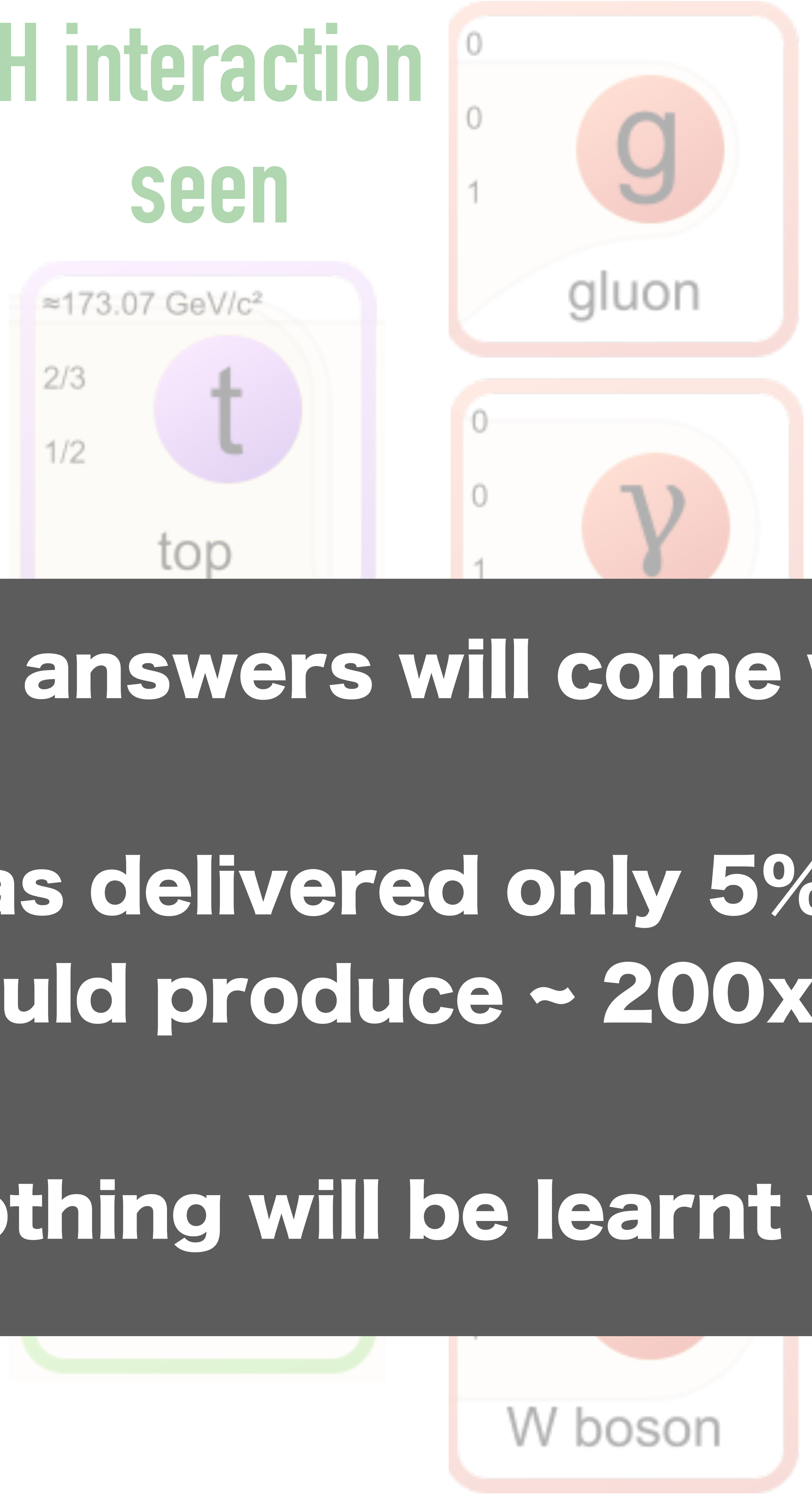


Do these interactions follow the Standard Model to better than current 10% accuracy?

Higgs potential not yet "seen"

ntlike (fundamental) particle?

Some answers will come with more data

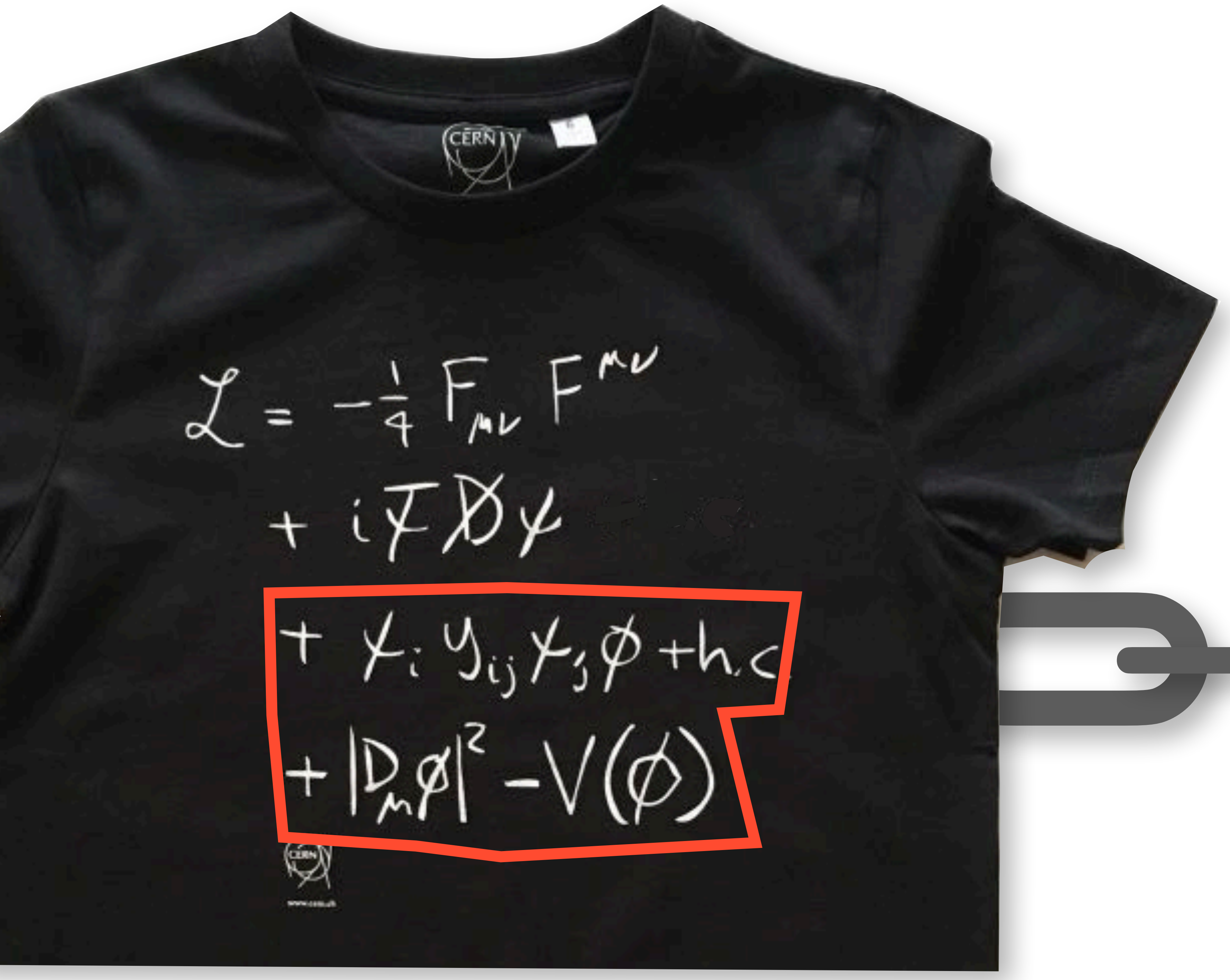
LHC has delivered only 5% of its collisions

Future colliders could produce ~ 200x more Higgses than the LHC

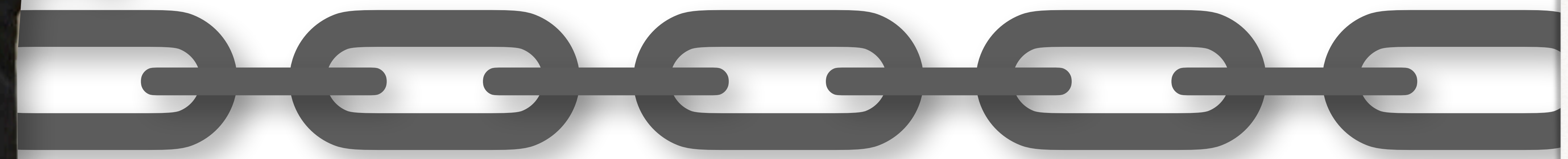
But nothing will be learnt without QCD . . .

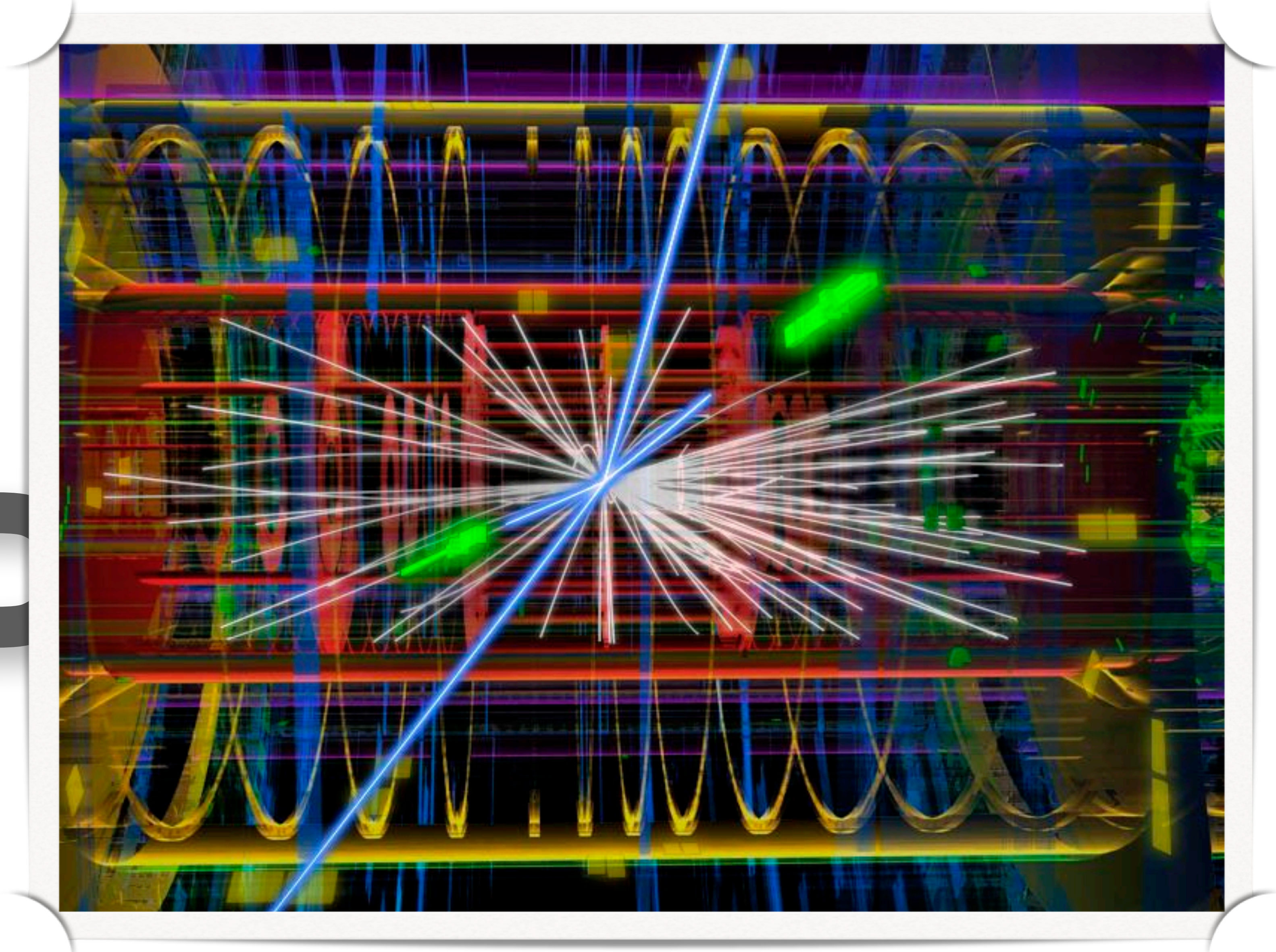
UNDERLYING THEORY

EXPERIMENTAL DATA



how do you make quantitative connection?





What's in the colliding protons? (NNPDF @ Ed.)

novel ways of simulating events (HEJ @ Ed.)

quantum fluctuations during scattering (amplitudes @ Ed.)

adapted from Nature perspective with Wang & Zanderighi

What is the origin of the vast range of quark and lepton masses in the Standard Model?

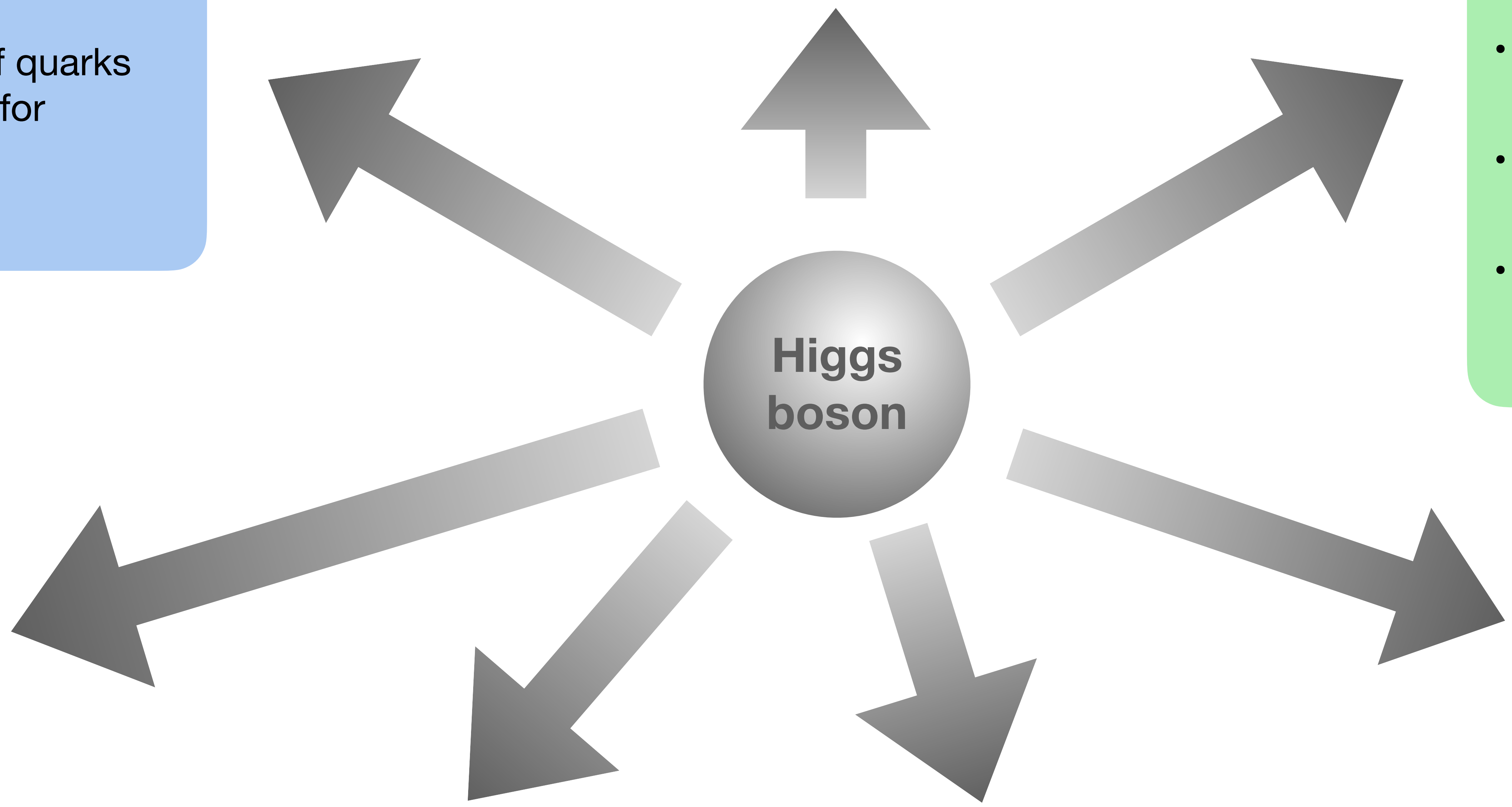
- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs decay into pairs of quarks and leptons with distinct flavours (for example, $H \to \mu^+\tau^-$)?

What is the origin of the early-universe inflation?

- Is the Higgs connected to the mechanism that drives inflation?
- Are there any imprints in cosmological observations?

Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs with the W and Z?



What is dark matter?

- Can the Higgs provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs?

Why is the Higgs field non-zero?

- Supposedly because the Higgs potential makes that the lowest energy state
- Can we verify the SM prediction for the Higgs potential?

The Higgs boson as the mediator of a fifth force

- unlike other electroweak and strong forces, strength of interaction is not quantised
- i.e. does not come in multiples of some elementary charge

Why is there more matter than antimatter in the universe?

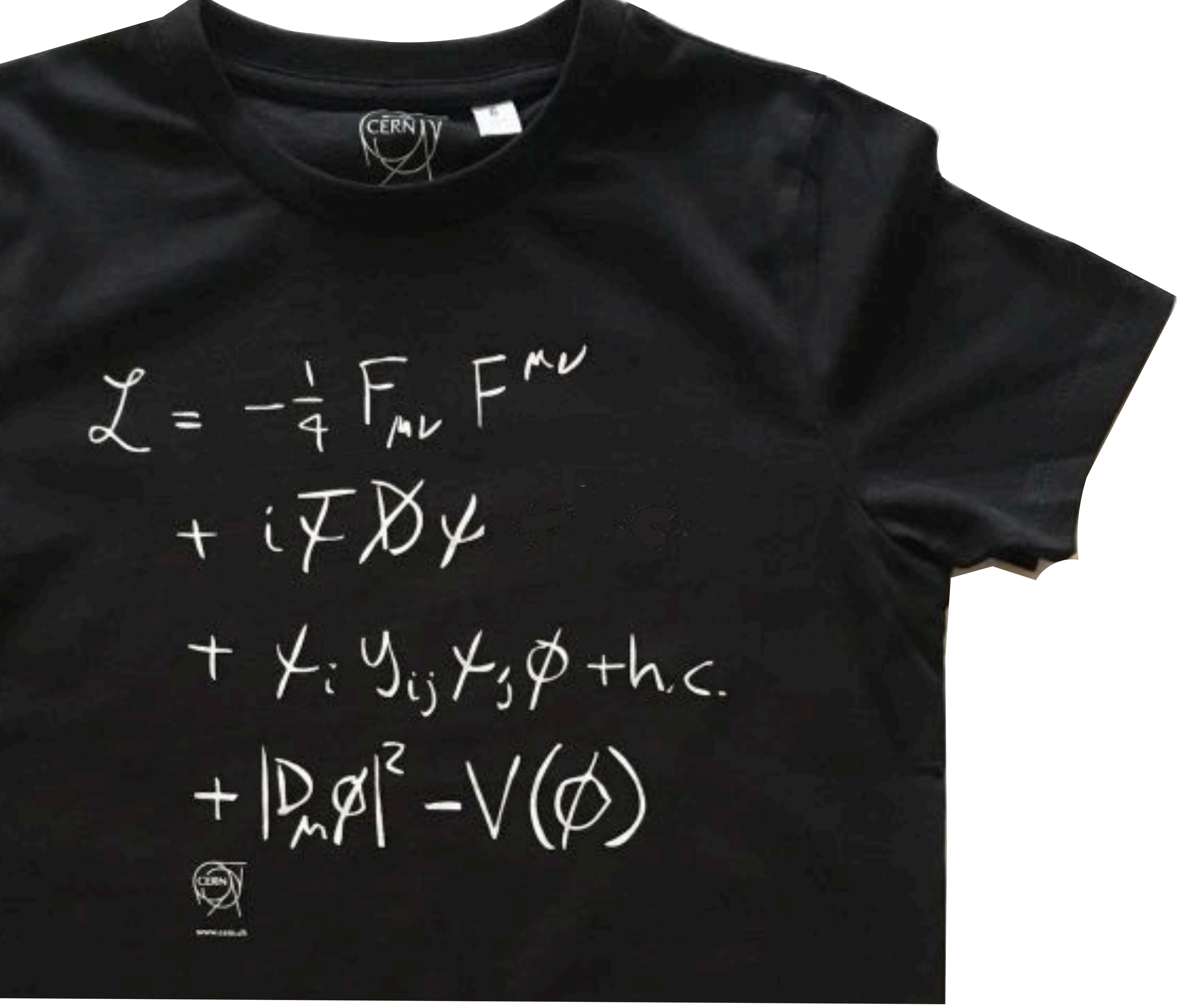
- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-universe electroweak phase transition?
- Are there multiple Higgs sectors?

outlook

Outlook

- Higgs discovery has opened a new chapter in particle physics
- **Interaction with W & Z bosons is the raison d'être for the Higgs mechanism (Nobel prize)**
- **But also involves qualitatively new kind of interaction — Yukawa interactions ("fifth force")**
  - critical to the world as we know it
  - so far probed only to 10–20%, for a subset of the fermions
  - and in only a corner of phase space (low momenta)
- **Huge experimental progress still to come, from (HL)LHC and possible future colliders (e.g. CERN's Future Circular Collider project)**
  - We may find clues to some of the big mysteries of particles physics and cosmology (dark matter, hierarchy problem, early-universe phase transitions)
  - or we may confirm the SM in its remarkable minimality

backup



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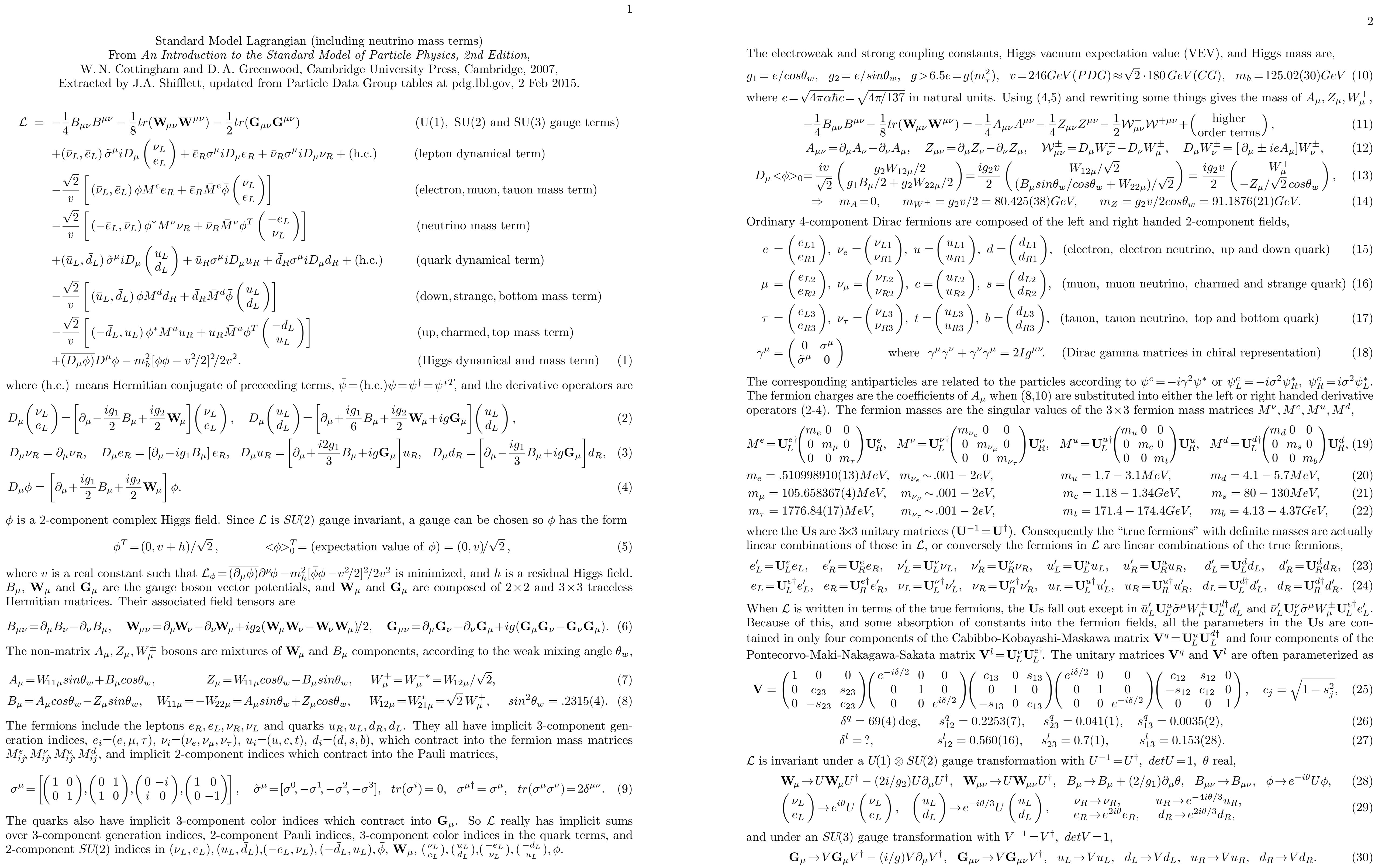


1

Standard Model Lagrangian (including neutrino mass terms)
From *An Introduction to the Standard Model of Particle Physics, 2nd Edition*,
W. N. Cottingham and D. A. Greenwood, Cambridge University Press, Cambridge, 2007,
Extracted by J.A. Shifflett, updated from Particle Data Group tables at pdg.lbl.gov, 2 Feb 2015.

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) \quad \text{(U(1), SU(2) and SU(3) gauge terms)}$$
$$+(\bar\nu_L,\bar e_L)\,\tilde\sigma^\mu iD_\mu\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar e_R\sigma^\mu iD_\mu e_R + \bar\nu_R\sigma^\mu iD_\mu\nu_R + \text{(h.c.)} \quad \text{(lepton dynamical term)}$$
$$-\frac{\sqrt2}{v}\left[(\bar\nu_L,\bar e_L)\,\phi M^e e_R + \bar e_R\bar M^e\bar\phi\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\right] \quad \text{(electron, muon, tauon mass term)}$$
$$-\frac{\sqrt2}{v}\left[(-\bar e_L,\bar\nu_L)\,\phi^* M^\nu\nu_R + \bar\nu_R\bar M^\nu\phi^T\begin{pmatrix}-e_L\\ \nu_L\end{pmatrix}\right] \quad \text{(neutrino mass term)}$$
$$+(\bar u_L,\bar d_L)\,\tilde\sigma^\mu iD_\mu\begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar u_R\sigma^\mu iD_\mu u_R + \bar d_R\sigma^\mu iD_\mu d_R + \text{(h.c.)} \quad \text{(quark dynamical term)}$$
$$-\frac{\sqrt2}{v}\left[(\bar u_L,\bar d_L)\,\phi M^d d_R + \bar d_R\bar M^d\bar\phi\begin{pmatrix}u_L\\ d_L\end{pmatrix}\right] \quad \text{(down, strange, bottom mass term)}$$
$$-\frac{\sqrt2}{v}\left[(-\bar d_L,\bar u_L)\,\phi^* M^u u_R + \bar u_R\bar M^u\phi^T\begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right] \quad \text{(up, charmed, top mass term)}$$
$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar\phi\phi - v^2/2]^2/2v^2. \quad \text{(Higgs dynamical and mass term)} \quad (1)$$

where (h.c.) means Hermitian conjugate of preceeding terms, $\bar\psi = \text{(h.c.)}\psi = \psi^\dagger = \psi^{*T}$, and the derivative operators are

$$D_\mu\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} = \left[\partial_\mu - \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}, \quad D_\mu\begin{pmatrix}u_L\\ d_L\end{pmatrix} = \left[\partial_\mu + \frac{ig_1}{6}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu + ig\mathbf{G}_\mu\right]\begin{pmatrix}u_L\\ d_L\end{pmatrix}, \quad (2)$$
$$D_\mu\nu_R = \partial_\mu\nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1B_\mu]\,e_R, \quad D_\mu u_R = \left[\partial_\mu + \frac{i2g_1}{3}B_\mu + ig\mathbf{G}_\mu\right]u_R, \quad D_\mu d_R = \left[\partial_\mu - \frac{ig_1}{3}B_\mu + ig\mathbf{G}_\mu\right]d_R, \quad (3)$$
$$D_\mu\phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi. \quad (4)$$

ϕ is a 2-component complex Higgs field. Since $\mathcal{L}$ is $SU(2)$ gauge invariant, a gauge can be chosen so ϕ has the form

$$\phi^T = (0, v+h)/\sqrt2, \qquad <\phi>_0^T = \text{(expectation value of }\phi) = (0,v)/\sqrt2, \quad (5)$$

where v is a real constant such that $\mathcal{L}_\phi = \overline{(\partial_\mu\phi)}\partial^\mu\phi - m_h^2[\bar\phi\phi - v^2/2]^2/2v^2$ is minimized, and h is a residual Higgs field. B_μ, $\mathbf{W}_\mu$ and $\mathbf{G}_\mu$ are the gauge boson vector potentials, and $\mathbf{W}_\mu$ and $\mathbf{G}_\mu$ are composed of 2×2 and 3×3 traceless Hermitian matrices. Their associated field tensors are

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu + ig_2(\mathbf{W}_\mu\mathbf{W}_\nu - \mathbf{W}_\nu\mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu\mathbf{G}_\nu - \partial_\nu\mathbf{G}_\mu + ig(\mathbf{G}_\mu\mathbf{G}_\nu - \mathbf{G}_\nu\mathbf{G}_\mu). \quad (6)$$

The non-matrix $A_\mu, Z_\mu, W_\mu^\pm$ bosons are mixtures of $\mathbf{W}_\mu$ and B_μ components, according to the weak mixing angle θ_w,

$$A_\mu = W_{11\mu}sin\theta_w + B_\mu cos\theta_w, \quad Z_\mu = W_{11\mu}cos\theta_w - B_\mu sin\theta_w, \quad W_\mu^+ = W_\mu^{-*} = W_{12\mu}/\sqrt2, \quad (7)$$
$$B_\mu = A_\mu cos\theta_w - Z_\mu sin\theta_w, \quad W_{11\mu} = -W_{22\mu} = A_\mu sin\theta_w + Z_\mu cos\theta_w, \quad W_{12\mu} = W_{21\mu}^* = \sqrt2 W_\mu^+, \quad sin^2\theta_w = .2315(4). \quad (8)$$

The fermions include the leptons e_R, e_L, ν_R, ν_L and quarks u_R, u_L, d_R, d_L. They all have implicit 3-component generation indices, $e_i = (e,\mu,\tau)$, $\nu_i = (\nu_e,\nu_\mu,\nu_\tau)$, $u_i = (u,c,t)$, $d_i = (d,s,b)$, which contract into the fermion mass matrices $M^e_{ij}, M^\nu_{ij}, M^u_{ij}, M^d_{ij}$, and implicit 2-component indices which contract into the Pauli matrices,

$$\sigma^\mu = \left[\begin{pmatrix}1&0\\0&1\end{pmatrix},\begin{pmatrix}0&1\\1&0\end{pmatrix},\begin{pmatrix}0&-i\\i&0\end{pmatrix},\begin{pmatrix}1&0\\0&-1\end{pmatrix}\right], \quad \tilde\sigma^\mu = [\sigma^0, -\sigma^1, -\sigma^2, -\sigma^3], \quad tr(\sigma^i) = 0, \quad \sigma^{\mu\dagger} = \sigma^\mu, \quad tr(\sigma^\mu\sigma^\nu) = 2\delta^{\mu\nu}. \quad (9)$$

The quarks also have implicit 3-component color indices which contract into $\mathbf{G}_\mu$. So $\mathcal{L}$ really has implicit sums over 3-component generation indices, 2-component Pauli indices, 3-component color indices in the quark terms, and 2-component $SU(2)$ indices in $(\bar\nu_L,\bar e_L), (\bar u_L,\bar d_L), (-\bar e_L,\bar\nu_L), (-\bar d_L,\bar u_L), \bar\phi, \mathbf{W}_\mu, \binom{\nu_L}{e_L}, \binom{u_L}{d_L}, \binom{-e_L}{\nu_L}, \binom{-d_L}{u_L}, \phi$.

2

The electroweak and strong coupling constants, Higgs vacuum expectation value (VEV), and Higgs mass are,

$$g_1 = e/cos\theta_w, \quad g_2 = e/sin\theta_w, \quad g > 6.5e = g(m_z^2), \quad v = 246GeV(PDG) \approx \sqrt2\cdot180\,GeV(CG), \quad m_h = 125.02(30)GeV \quad (10)$$

where $e = \sqrt{4\pi\alpha\hbar c} = \sqrt{4\pi/137}$ in natural units. Using (4,5) and rewriting some things gives the mass of $A_\mu, Z_\mu, W_\mu^\pm$,

$$-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) = -\frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{2}\mathcal{W}^-_{\mu\nu}\mathcal{W}^{+\mu\nu} + \begin{pmatrix}\text{higher}\\ \text{order terms}\end{pmatrix}, \quad (11)$$
$$A_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu, \quad \mathcal{W}^\pm_{\mu\nu} = D_\mu W^\pm_\nu - D_\nu W^\pm_\mu, \quad D_\mu W^\pm_\nu = [\partial_\mu \pm ieA_\mu]W^\pm_\nu, \quad (12)$$
$$D_\mu<\phi>_0 = \frac{iv}{\sqrt2}\begin{pmatrix}g_2W_{12\mu}/2\\ g_1B_\mu/2 + g_2W_{22\mu}/2\end{pmatrix} = \frac{ig_2v}{2}\begin{pmatrix}W_{12\mu}/\sqrt2\\ (B_\mu sin\theta_w/cos\theta_w + W_{22\mu})/\sqrt2\end{pmatrix} = \frac{ig_2v}{2}\begin{pmatrix}W^+_\mu\\ -Z_\mu/\sqrt2\,cos\theta_w\end{pmatrix}, \quad (13)$$
$$\Rightarrow \quad m_A = 0, \quad m_{W^\pm} = g_2v/2 = 80.425(38)GeV, \quad m_Z = g_2v/2cos\theta_w = 91.1876(21)GeV. \quad (14)$$

Ordinary 4-component Dirac fermions are composed of the left and right handed 2-component fields,

$$e = \begin{pmatrix}e_{L1}\\ e_{R1}\end{pmatrix}, \ \nu_e = \begin{pmatrix}\nu_{L1}\\ \nu_{R1}\end{pmatrix}, \ u = \begin{pmatrix}u_{L1}\\ u_{R1}\end{pmatrix}, \ d = \begin{pmatrix}d_{L1}\\ d_{R1}\end{pmatrix}, \quad \text{(electron, electron neutrino, up and down quark)} \quad (15)$$
$$\mu = \begin{pmatrix}e_{L2}\\ e_{R2}\end{pmatrix}, \ \nu_\mu = \begin{pmatrix}\nu_{L2}\\ \nu_{R2}\end{pmatrix}, \ c = \begin{pmatrix}u_{L2}\\ u_{R2}\end{pmatrix}, \ s = \begin{pmatrix}d_{L2}\\ d_{R2}\end{pmatrix}, \quad \text{(muon, muon neutrino, charmed and strange quark)} \quad (16)$$
$$\tau = \begin{pmatrix}e_{L3}\\ e_{R3}\end{pmatrix}, \ \nu_\tau = \begin{pmatrix}\nu_{L3}\\ \nu_{R3}\end{pmatrix}, \ t = \begin{pmatrix}u_{L3}\\ u_{R3}\end{pmatrix}, \ b = \begin{pmatrix}d_{L3}\\ d_{R3}\end{pmatrix}, \quad \text{(tauon, tauon neutrino, top and bottom quark)} \quad (17)$$
$$\gamma^\mu = \begin{pmatrix}0&\sigma^\mu\\ \tilde\sigma^\mu&0\end{pmatrix} \quad \text{where} \quad \gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2Ig^{\mu\nu}. \quad \text{(Dirac gamma matrices in chiral representation)} \quad (18)$$

The corresponding antiparticles are related to the particles according to $\psi^c = -i\gamma^2\psi^*$ or $\psi^c_L = -i\sigma^2\psi^*_R$, $\psi^c_R = i\sigma^2\psi^*_L$. The fermion charges are the coefficients of A_μ when (8,10) are substituted into either the left or right handed derivative operators (2-4). The fermion masses are the singular values of the 3×3 fermion mass matrices M^ν, M^e, M^u, M^d,

$$M^e = \mathbf{U}^{e\dagger}_L\begin{pmatrix}m_e&0&0\\0&m_\mu&0\\0&0&m_\tau\end{pmatrix}\mathbf{U}^e_R, \quad M^\nu = \mathbf{U}^{\nu\dagger}_L\begin{pmatrix}m_{\nu_e}&0&0\\0&m_{\nu_\mu}&0\\0&0&m_{\nu_\tau}\end{pmatrix}\mathbf{U}^\nu_R, \quad M^u = \mathbf{U}^{u\dagger}_L\begin{pmatrix}m_u&0&0\\0&m_c&0\\0&0&m_t\end{pmatrix}\mathbf{U}^u_R, \quad M^d = \mathbf{U}^{d\dagger}_L\begin{pmatrix}m_d&0&0\\0&m_s&0\\0&0&m_b\end{pmatrix}\mathbf{U}^d_R, \quad (19)$$
$$m_e = .510998910(13)MeV, \quad m_{\nu_e} \sim .001 - 2eV, \quad m_u = 1.7 - 3.1MeV, \quad m_d = 4.1 - 5.7MeV, \quad (20)$$
$$m_\mu = 105.658367(4)MeV, \quad m_{\nu_\mu} \sim .001 - 2eV, \quad m_c = 1.18 - 1.34GeV, \quad m_s = 80 - 130MeV, \quad (21)$$
$$m_\tau = 1776.84(17)MeV, \quad m_{\nu_\tau} \sim .001 - 2eV, \quad m_t = 171.4 - 174.4GeV, \quad m_b = 4.13 - 4.37GeV, \quad (22)$$

where the $\mathbf{U}$s are 3x3 unitary matrices ($\mathbf{U}^{-1} = \mathbf{U}^\dagger$). Consequently the "true fermions" with definite masses are actually linear combinations of those in $\mathcal{L}$, or conversely the fermions in $\mathcal{L}$ are linear combinations of the true fermions,

$$e'_L = \mathbf{U}^e_L e_L, \quad e'_R = \mathbf{U}^e_R e_R, \quad \nu'_L = \mathbf{U}^\nu_L\nu_L, \quad \nu'_R = \mathbf{U}^\nu_R\nu_R, \quad u'_L = \mathbf{U}^u_L u_L, \quad u'_R = \mathbf{U}^u_R u_R, \quad d'_L = \mathbf{U}^d_L d_L, \quad d'_R = \mathbf{U}^d_R d_R, \quad (23)$$
$$e_L = \mathbf{U}^{e\dagger}_L e'_L, \quad e_R = \mathbf{U}^{e\dagger}_R e'_R, \quad \nu_L = \mathbf{U}^{\nu\dagger}_L\nu'_L, \quad \nu_R = \mathbf{U}^{\nu\dagger}_R\nu'_R, \quad u_L = \mathbf{U}^{u\dagger}_L u'_L, \quad u_R = \mathbf{U}^{u\dagger}_R u'_R, \quad d_L = \mathbf{U}^{d\dagger}_L d'_L, \quad d_R = \mathbf{U}^{d\dagger}_R d'_R. \quad (24)$$

When $\mathcal{L}$ is written in terms of the true fermions, the $\mathbf{U}$s fall out except in $\bar u'_L\mathbf{U}^u_L\tilde\sigma^\mu W^\pm_\mu\mathbf{U}^{d\dagger}_L d'_L$ and $\bar\nu'_L\mathbf{U}^\nu_L\tilde\sigma^\mu W^\pm_\mu\mathbf{U}^{e\dagger}_L e'_L$. Because of this, and some absorption of constants into the fermion fields, all the parameters in the $\mathbf{U}$s are contained in only four components of the Cabibbo-Kobayashi-Maskawa matrix $\mathbf{V}^q = \mathbf{U}^u_L\mathbf{U}^{d\dagger}_L$ and four components of the Pontecorvo-Maki-Nakagawa-Sakata matrix $\mathbf{V}^l = \mathbf{U}^\nu_L\mathbf{U}^{e\dagger}_L$. The unitary matrices $\mathbf{V}^q$ and $\mathbf{V}^l$ are often parameterized as

$$\mathbf{V} = \begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}e^{-i\delta/2}&0&0\\0&1&0\\0&0&e^{i\delta/2}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}\\0&1&0\\-s_{13}&0&c_{13}\end{pmatrix}\begin{pmatrix}e^{i\delta/2}&0&0\\0&1&0\\0&0&e^{-i\delta/2}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}, \quad c_j = \sqrt{1-s_j^2}, \quad (25)$$
$$\delta^q = 69(4)\deg, \quad s^q_{12} = 0.2253(7), \quad s^q_{23} = 0.041(1), \quad s^q_{13} = 0.0035(2), \quad (26)$$
$$\delta^l = ?, \quad s^l_{12} = 0.560(16), \quad s^l_{23} = 0.7(1), \quad s^l_{13} = 0.153(28). \quad (27)$$

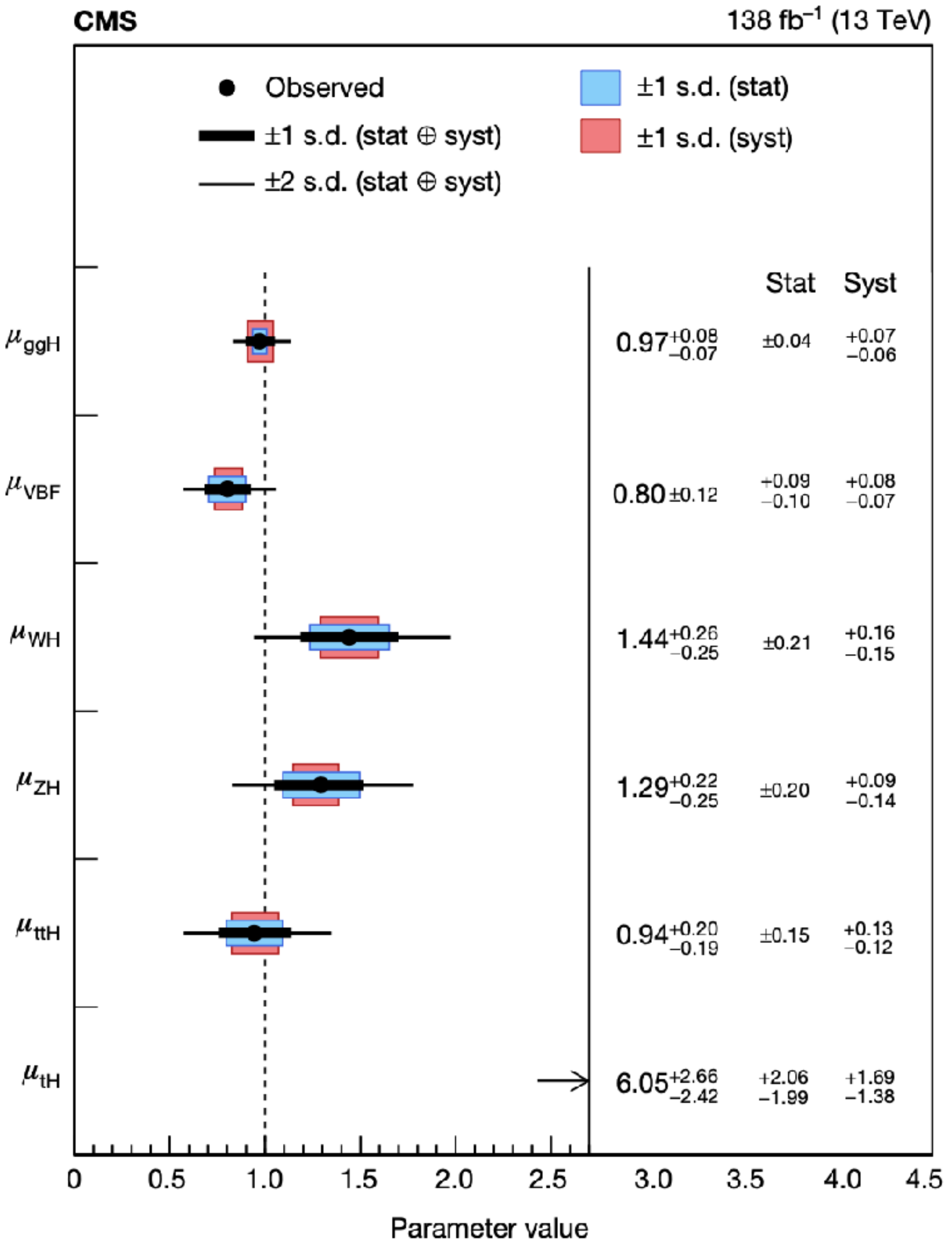
$\mathcal{L}$ is invariant under a $U(1)\otimes SU(2)$ gauge transformation with $U^{-1} = U^\dagger$, $detU = 1$, θ real,

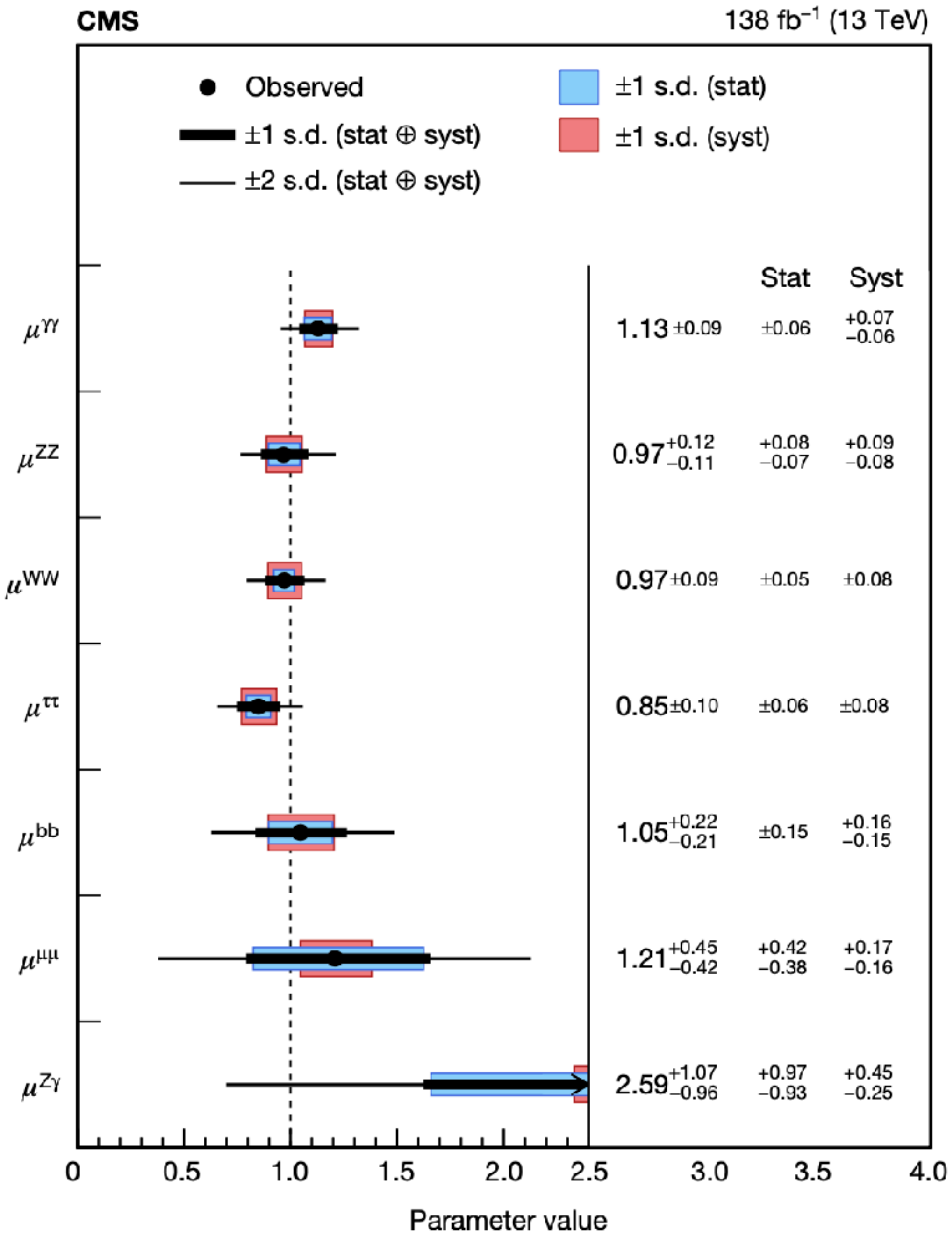
$$\mathbf{W}_\mu \to U\mathbf{W}_\mu U^\dagger - (2i/g_2)U\partial_\mu U^\dagger, \quad \mathbf{W}_{\mu\nu} \to U\mathbf{W}_{\mu\nu}U^\dagger, \quad B_\mu \to B_\mu + (2/g_1)\partial_\mu\theta, \quad B_{\mu\nu} \to B_{\mu\nu}, \quad \phi \to e^{-i\theta}U\phi, \quad (28)$$
$$\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} \to e^{i\theta}U\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}, \quad \begin{pmatrix}u_L\\ d_L\end{pmatrix} \to e^{-i\theta/3}U\begin{pmatrix}u_L\\ d_L\end{pmatrix}, \quad \nu_R \to \nu_R, \quad e_R \to e^{2i\theta}e_R, \quad u_R \to e^{-4i\theta/3}u_R, \quad d_R \to e^{2i\theta/3}d_R, \quad (29)$$

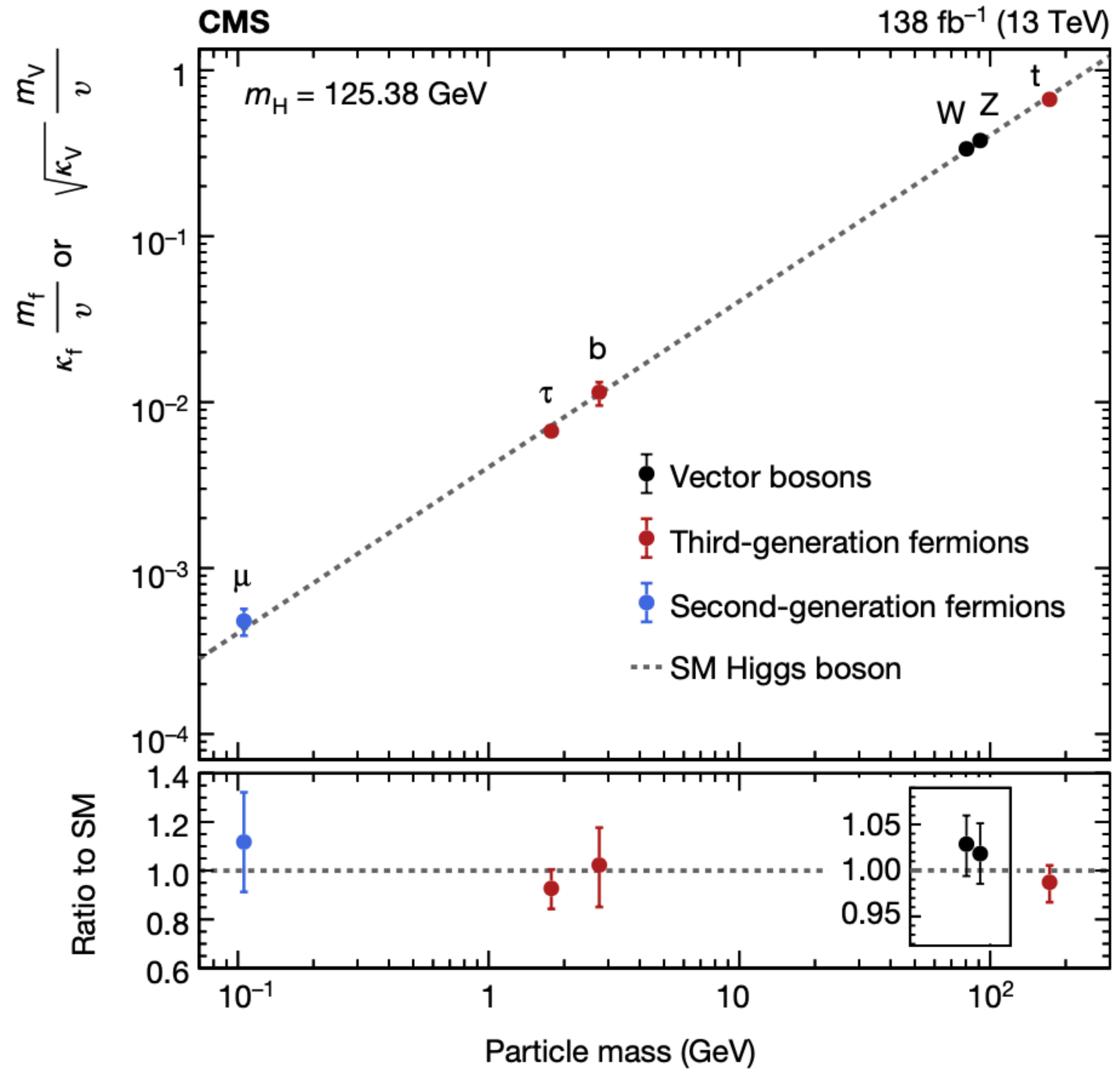
and under an $SU(3)$ gauge transformation with $V^{-1} = V^\dagger$, $detV = 1$,

$$\mathbf{G}_\mu \to V\mathbf{G}_\mu V^\dagger - (i/g)V\partial_\mu V^\dagger, \quad \mathbf{G}_{\mu\nu} \to V\mathbf{G}_{\mu\nu}V^\dagger, \quad u_L \to Vu_L, \quad d_L \to Vd_L, \quad u_R \to Vu_R, \quad d_R \to Vd_R. \quad (30)$$

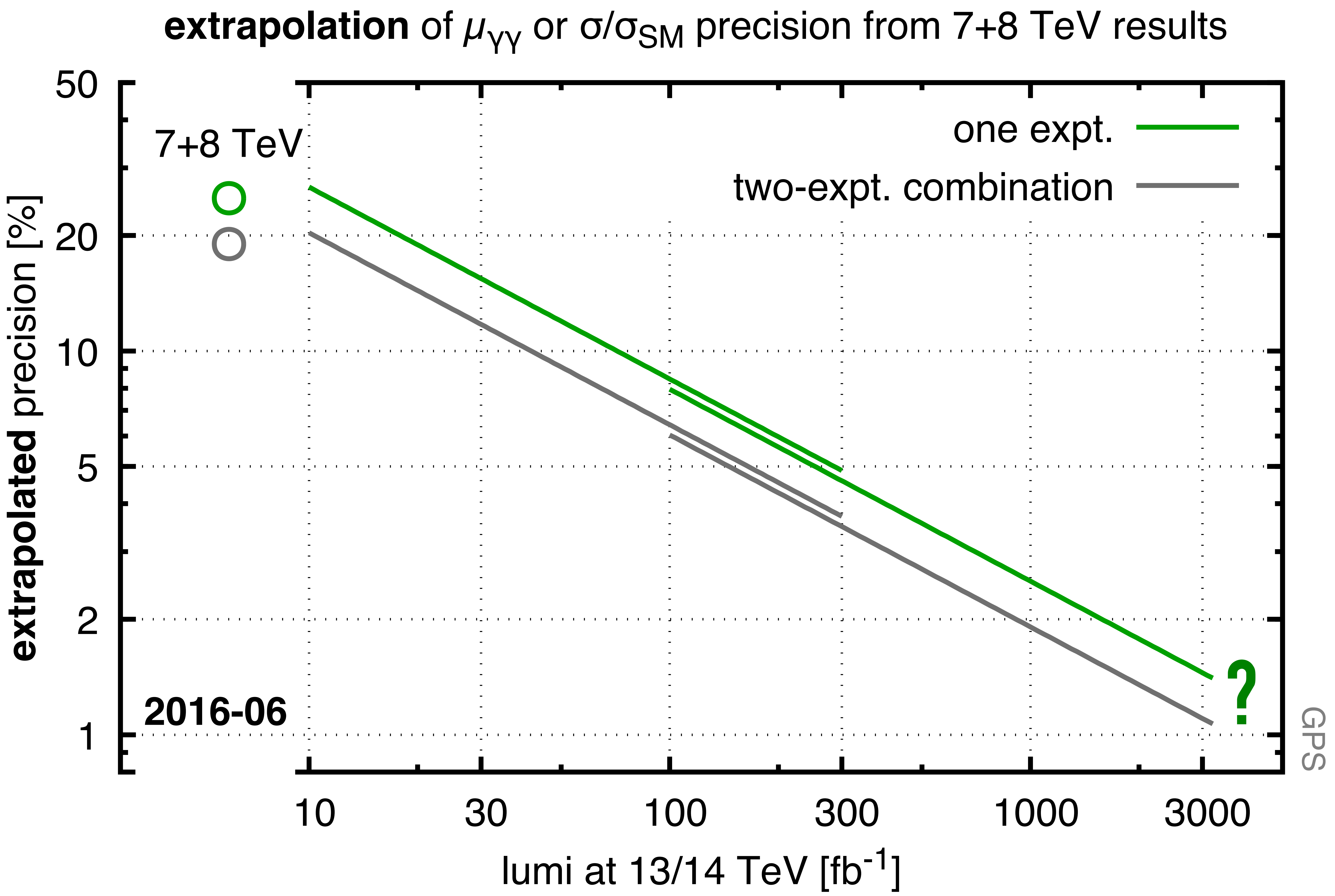
http://einstein-schrodinger.com/Standard_Model.pdf


CMS
138 fb^{-1} (13 TeV)
Observed
±1 s.d. (stat ⊕ syst)
±2 s.d. (stat ⊕ syst)
±1 s.d. (stat)
±1 s.d. (syst)
Stat
Syst
μ_{ggH} $0.97^{+0.08}_{-0.07}$ ±0.04 $^{+0.07}_{-0.06}$
μ_{VBF} 0.80±0.12 $^{+0.09}_{-0.10}$ $^{+0.08}_{-0.07}$
μ_{WH} $1.44^{+0.26}_{-0.25}$ ±0.21 $^{+0.16}_{-0.15}$
μ_{ZH} $1.29^{+0.22}_{-0.25}$ ±0.20 $^{+0.09}_{-0.14}$
μ_{ttH} $0.94^{+0.20}_{-0.19}$ ±0.15 $^{+0.13}_{-0.12}$
μ_{tH} $6.05^{+2.66}_{-2.42}$ $^{+2.06}_{-1.99}$ $^{+1.69}_{-1.38}$
0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5
Parameter value

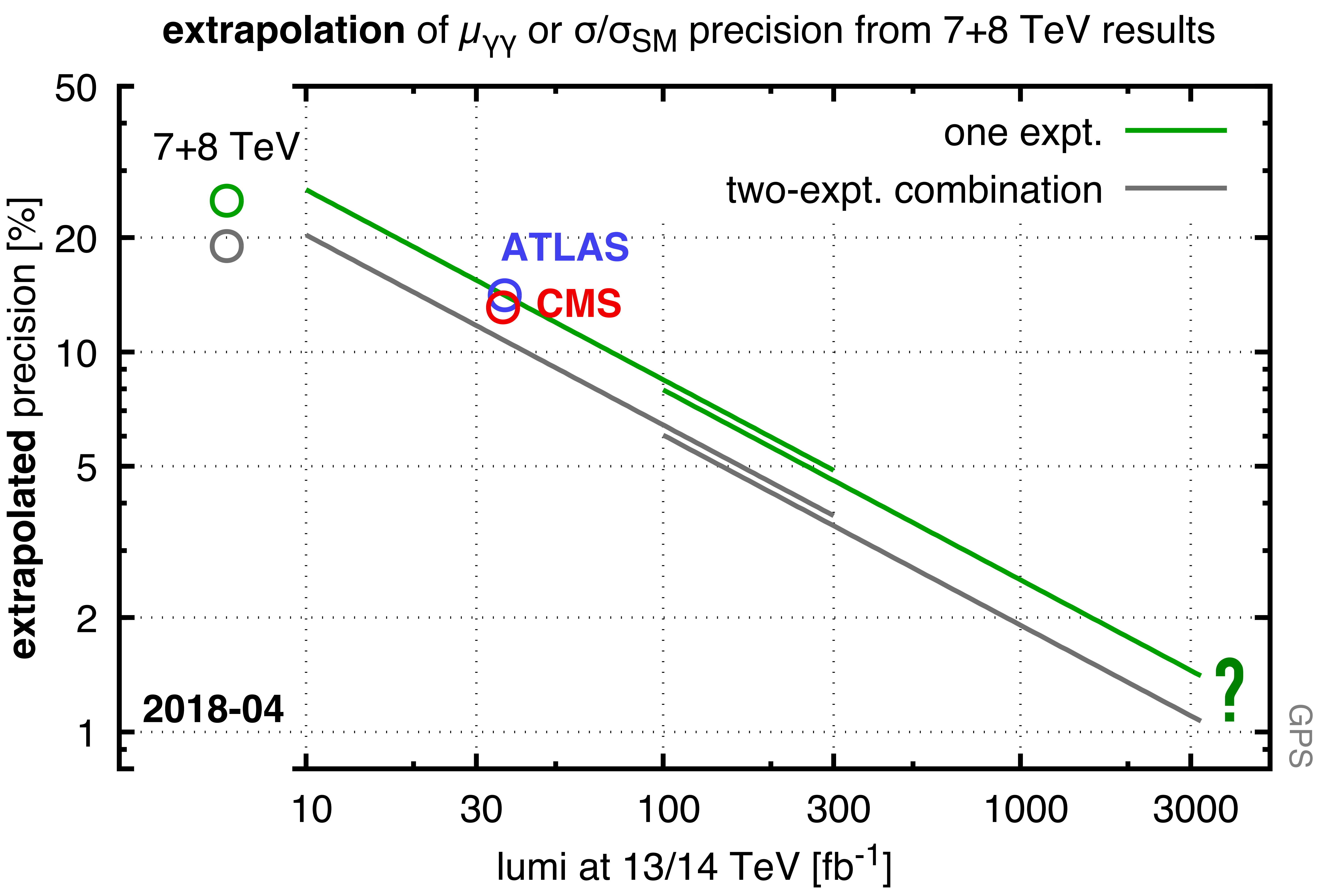

CMS
138 fb^{-1} (13 TeV)
Observed
±1 s.d. (stat ⊕ syst)
±2 s.d. (stat ⊕ syst)
±1 s.d. (stat)
±1 s.d. (syst)
Stat
Syst
$\mu^{\gamma\gamma}$ 1.13±0.09 ±0.06 $^{+0.07}_{-0.06}$
μ^{ZZ} $0.97^{+0.12}_{-0.11}$ $^{+0.08}_{-0.07}$ $^{+0.09}_{-0.08}$
μ^{WW} 0.97±0.09 ±0.05 ±0.08
$\mu^{\tau\tau}$ 0.85±0.10 ±0.06 ±0.08
μ^{bb} $1.05^{+0.22}_{-0.21}$ ±0.15 $^{+0.16}_{-0.15}$
$\mu^{\mu\mu}$ $1.21^{+0.45}_{-0.42}$ $^{+0.42}_{-0.38}$ $^{+0.17}_{-0.16}$
$\mu^{Z\gamma}$ $2.59^{+1.07}_{-0.96}$ $^{+0.97}_{-0.93}$ $^{+0.45}_{-0.25}$
0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
Parameter value


CMS
138 fb^{-1} (13 TeV)
m_H = 125.38 GeV
$\kappa_f \frac{m_f}{v}$ or $\sqrt{\kappa_V} \frac{m_V}{v}$
W
Z
t
b
τ
μ
Vector bosons
Third-generation fermions
Second-generation fermions
SM Higgs boson
Ratio to SM
Particle mass (GeV)

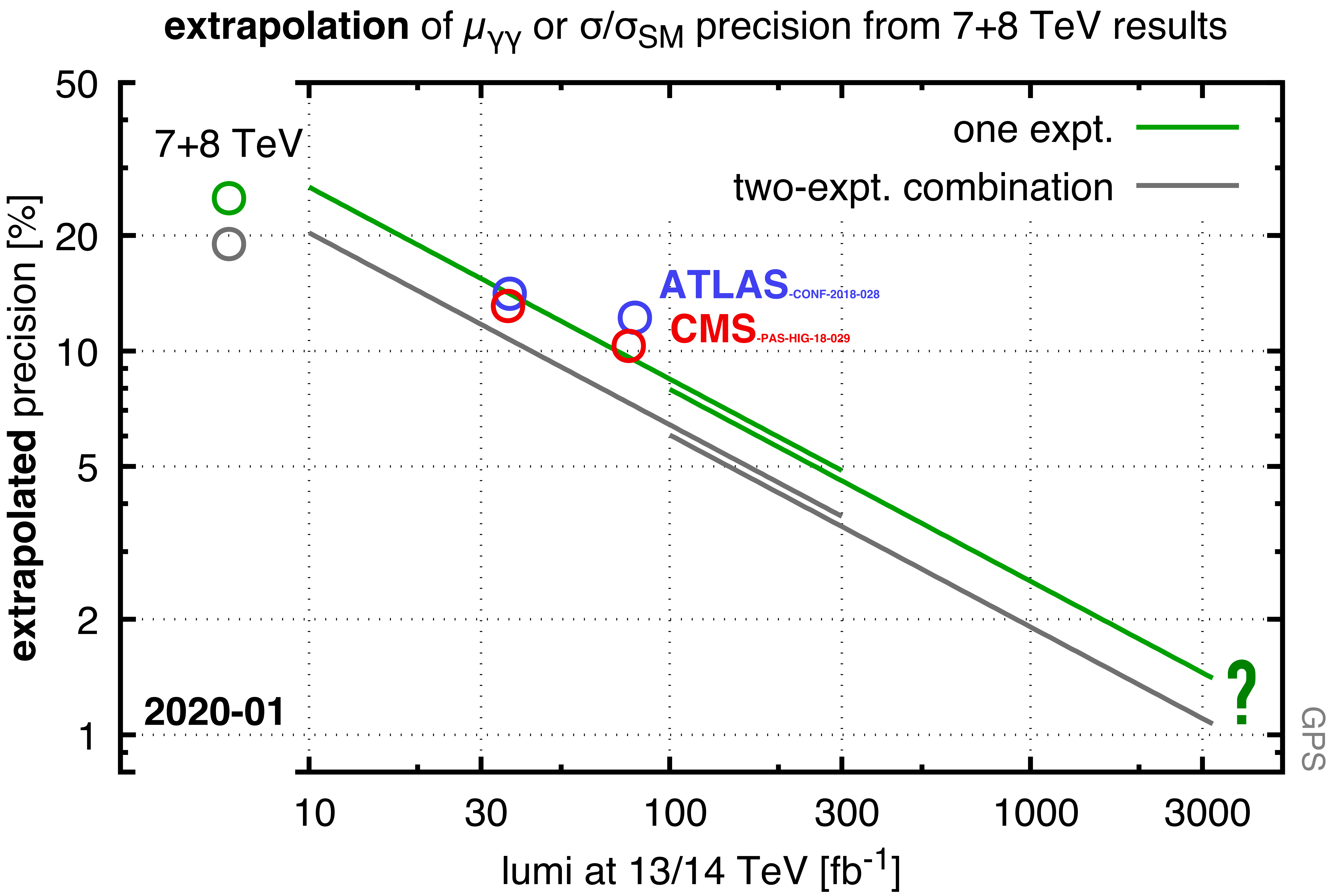
H → γγ, an indirect probe of the top Yukawa, HWW and contact ggH couplings



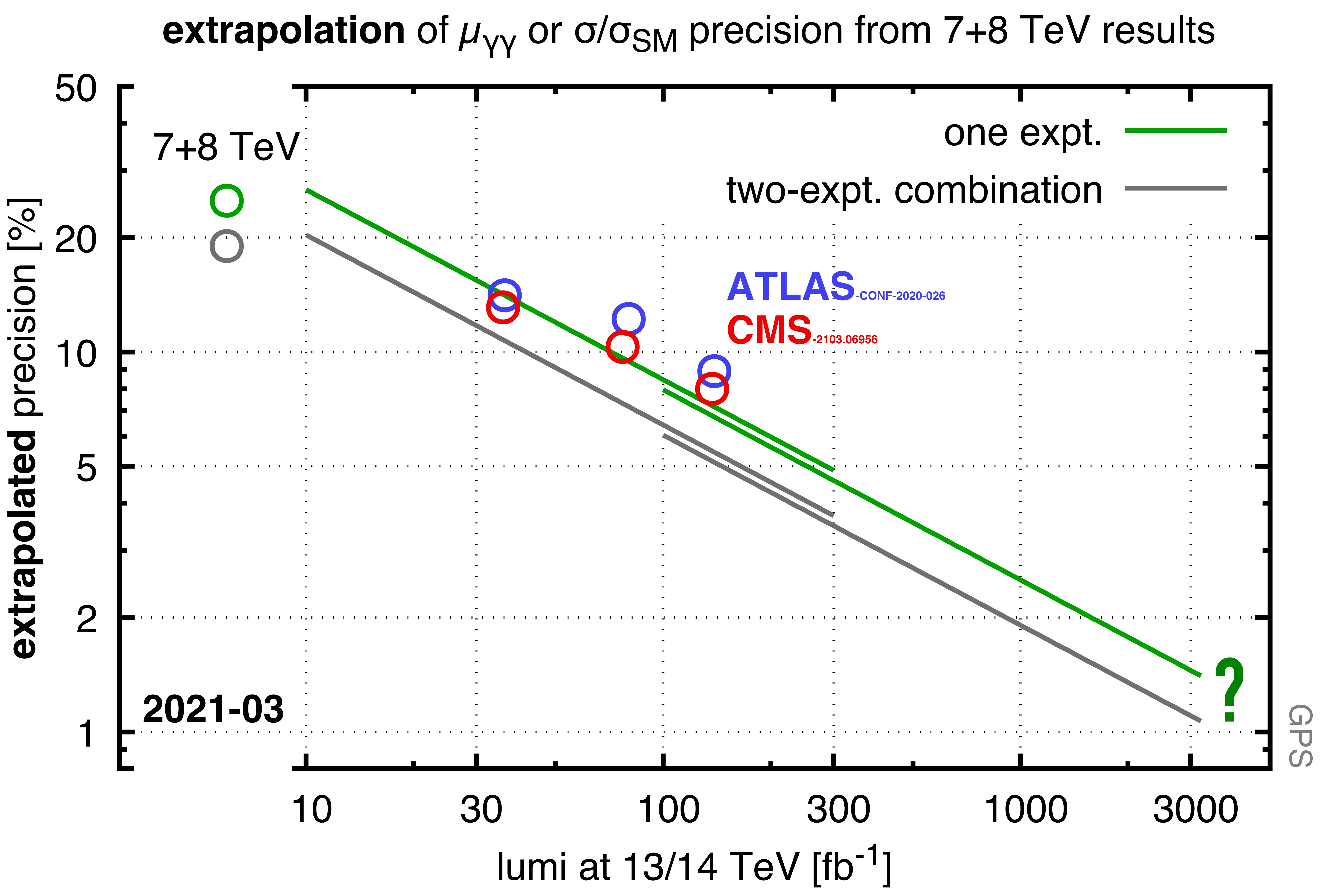
$H \to \gamma\gamma$, an indirect probe of the top Yukawa, HWW and contact ggH couplings



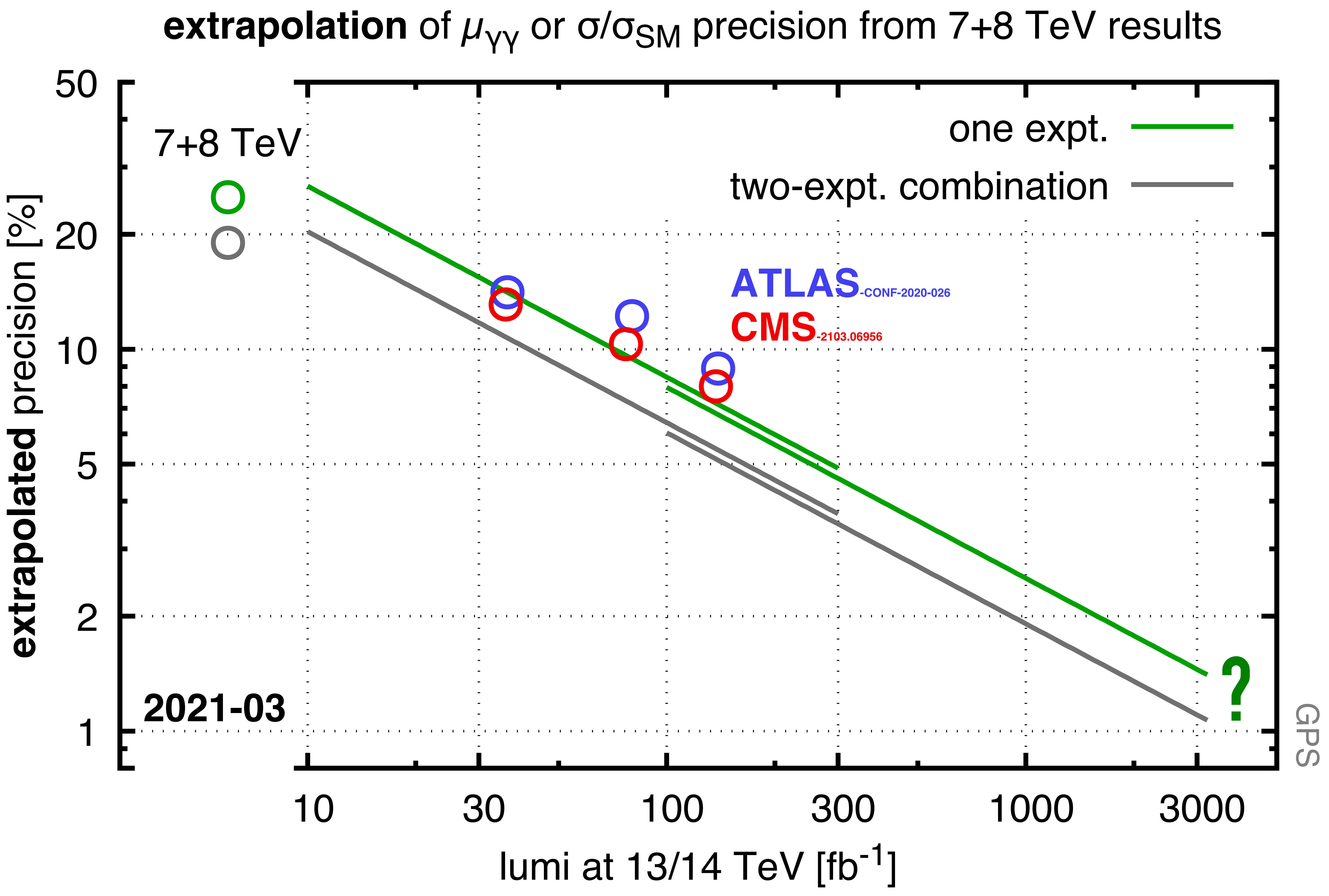
H → γγ, an indirect probe of the top Yukawa, HWW and contact ggH couplings



H → γγ, an indirect probe of the top Yukawa, HWW and contact ggH couplings



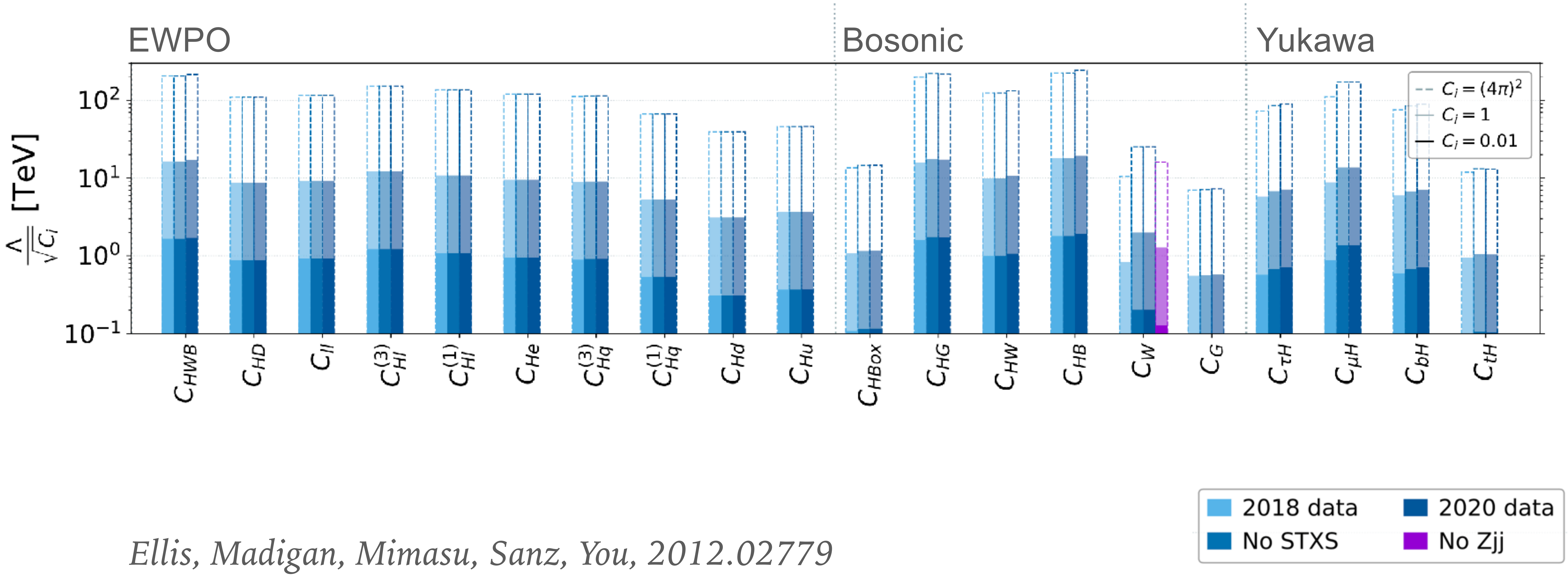
H → γγ, an indirect probe of the top Yukawa, HWW and contact ggH couplings



today's ATLAS and CMS total uncertainties (ratio to SM) are at the 8-9% level

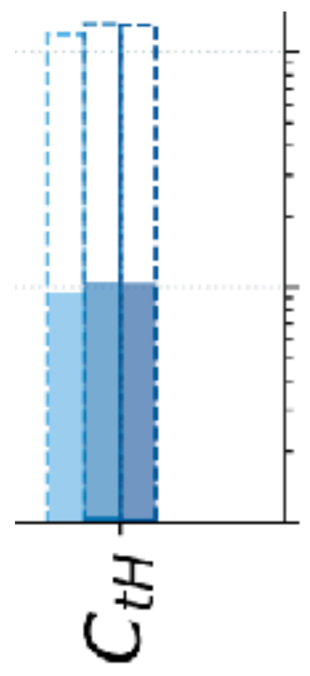
5-7% stat.
3-7% syst.
~5% theo.

We are (indirectly) searching for new physics



Ellis, Madigan, Mimasu, Sanz, You, 2012.02779

We are (indirectly) searching for new physics
Current ~10% agreement with SM places constraint on new physics



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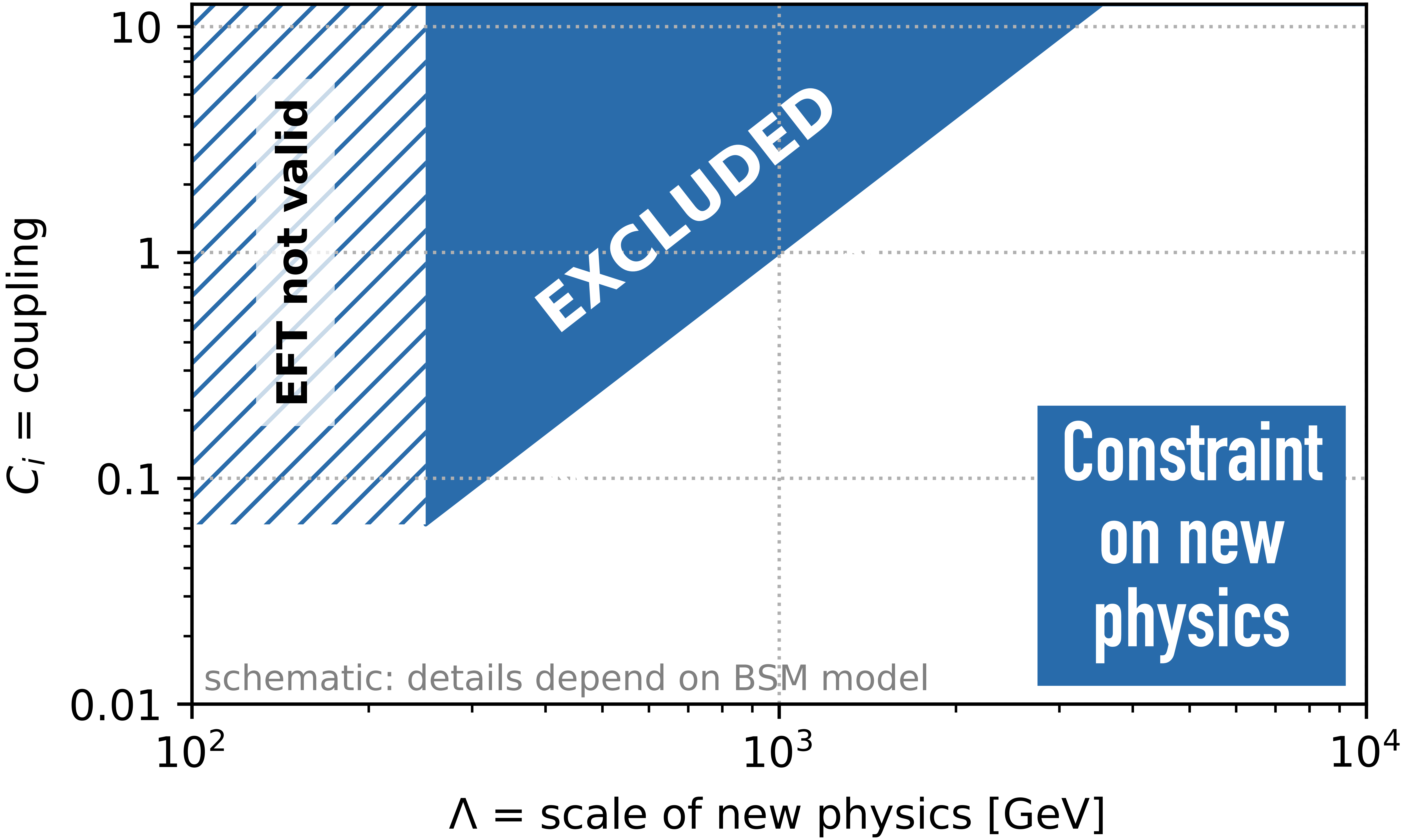

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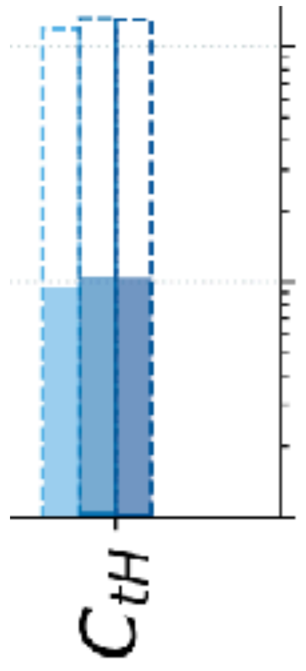
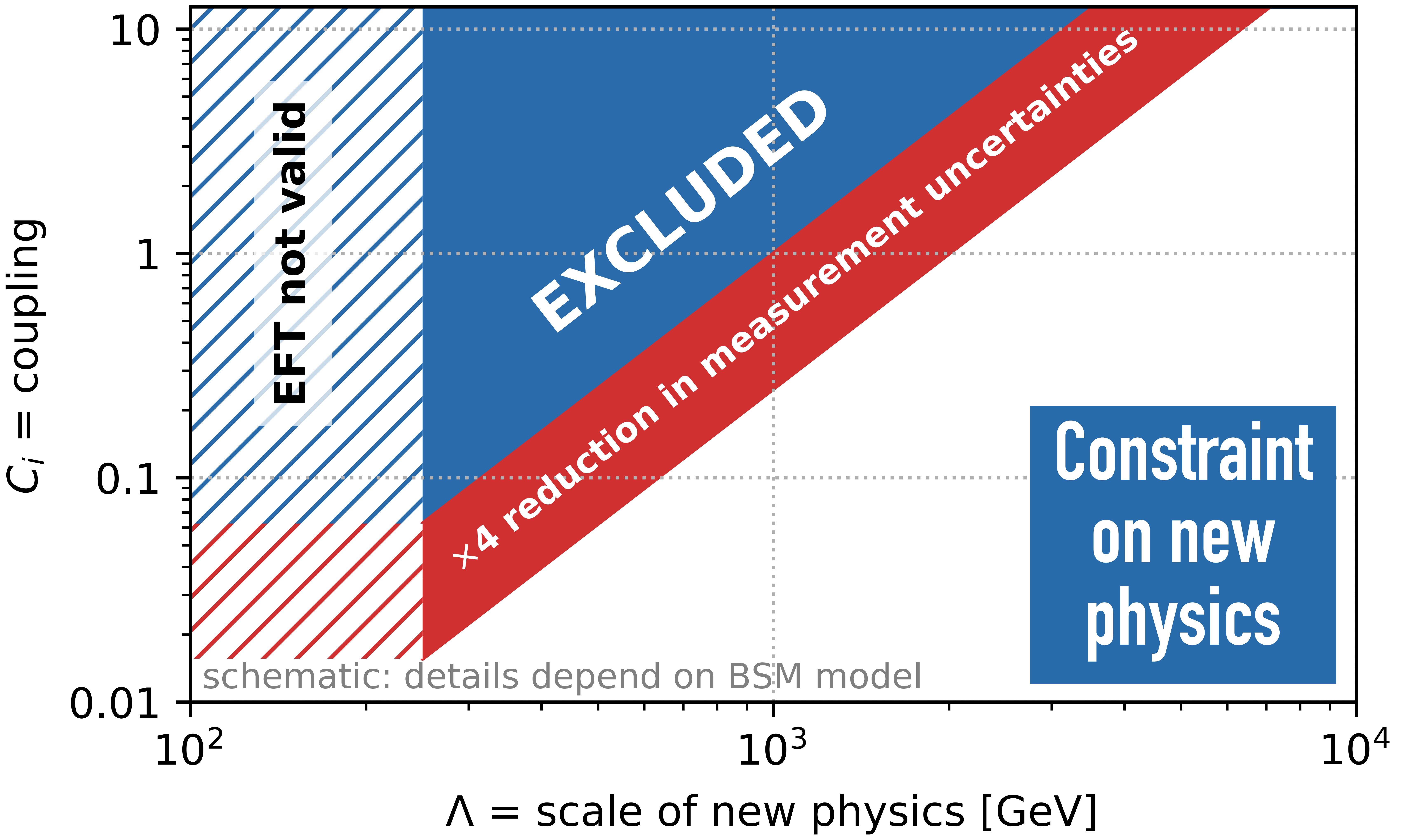


We are (indirectly) searching for new physics
Future ~ 2% measurements at LHC will place stronger constraint on (or discover) new physics



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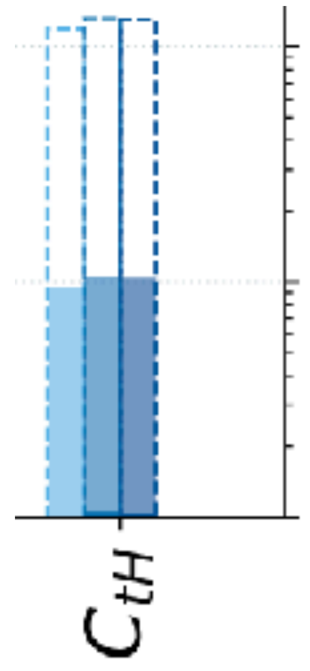
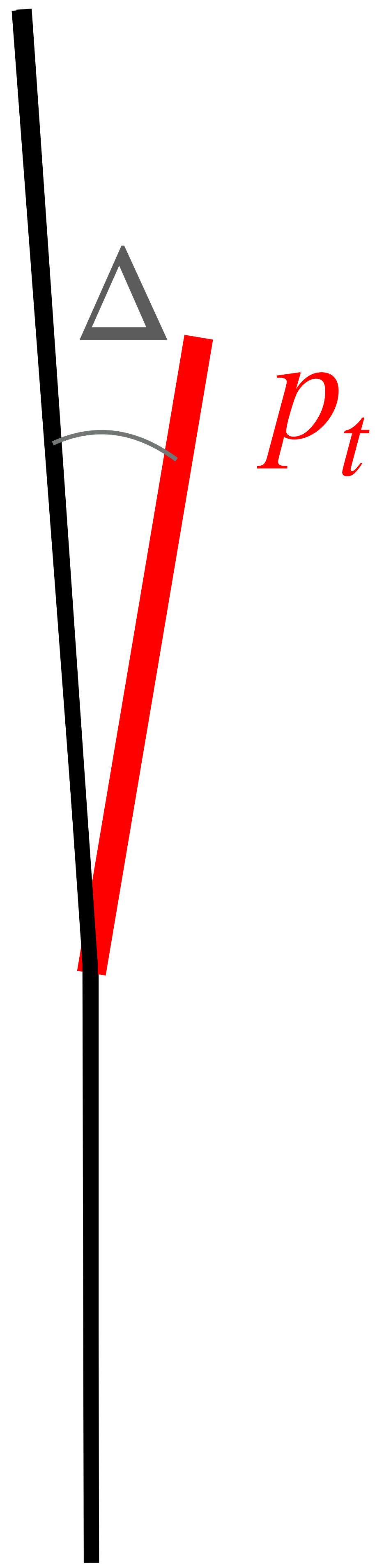


Phase space: two key variables (+ azimuth)

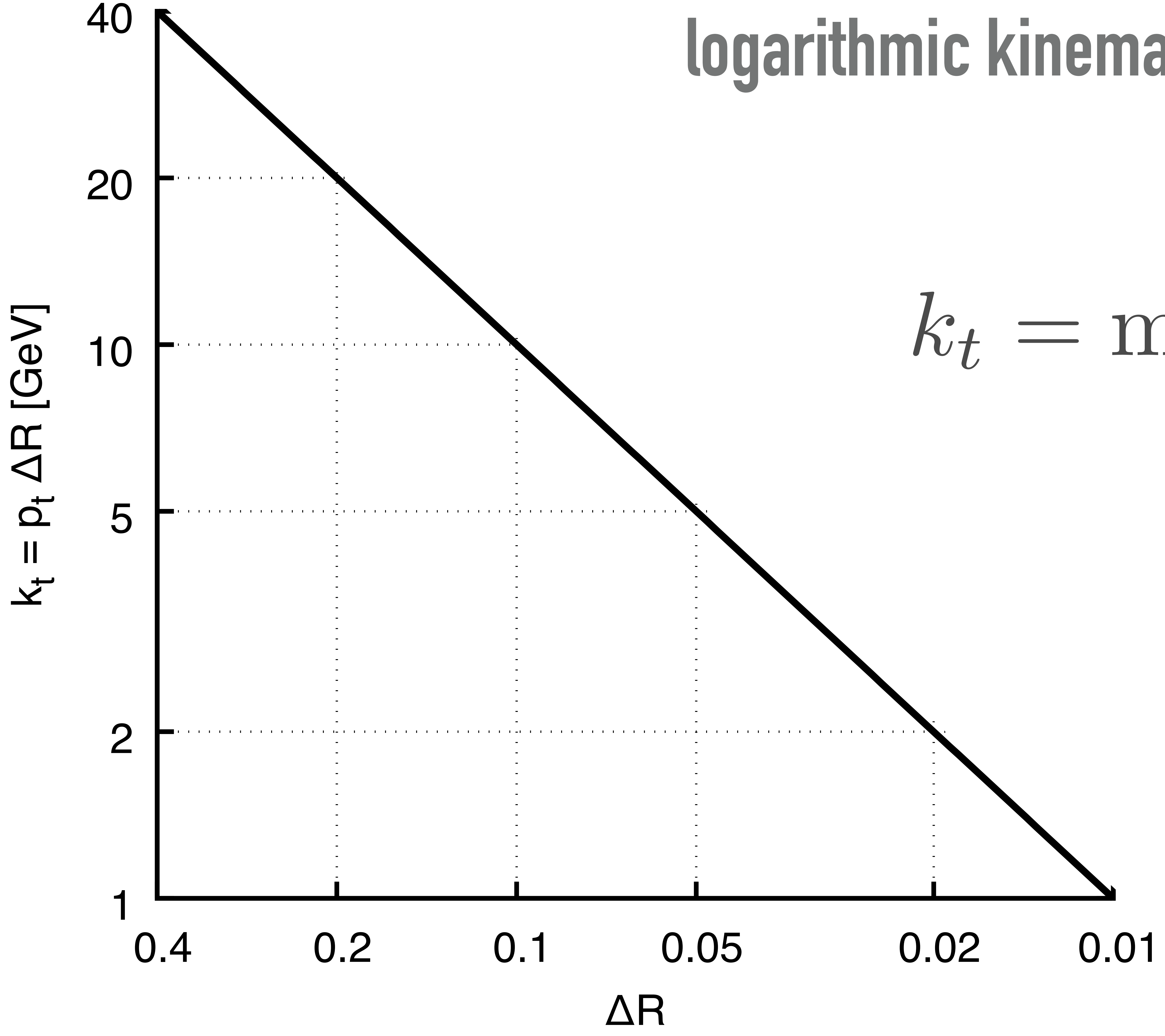


ΔR (or just Δ) — *opening angle of a splitting*

$k_t = p_t \Delta$ — p_t (or $p_\perp$) *is transverse momentum wrt beam*

k_t *is* $\sim$ *transverse momentum wrt jet axis*

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



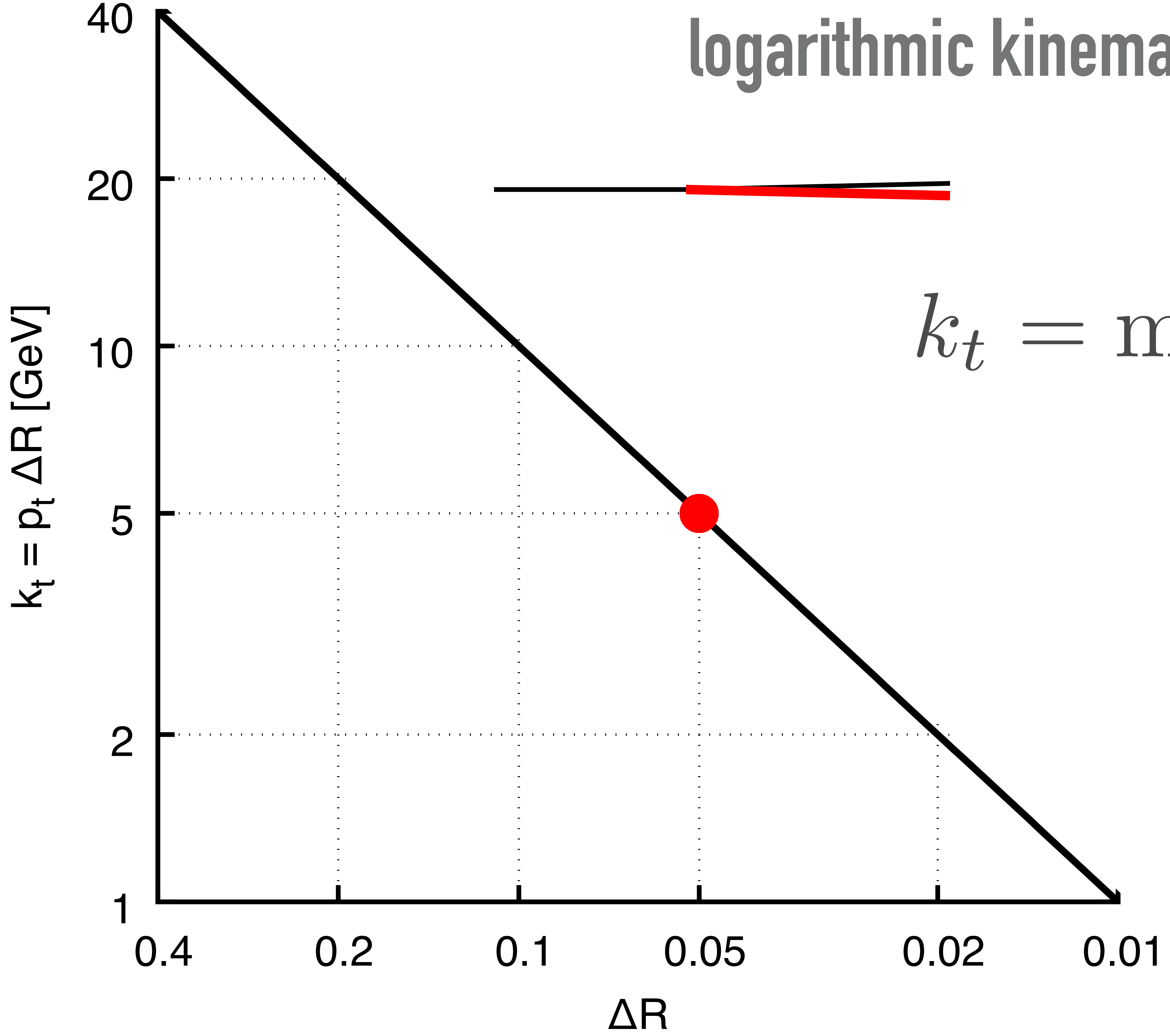
logarithmic kinematic plane whose two variables are

$$\Delta R_{ij}$$

$$k_t = \min(p_{ti}, p_{tj}) \Delta R_{ij}$$

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

The Lund Plane



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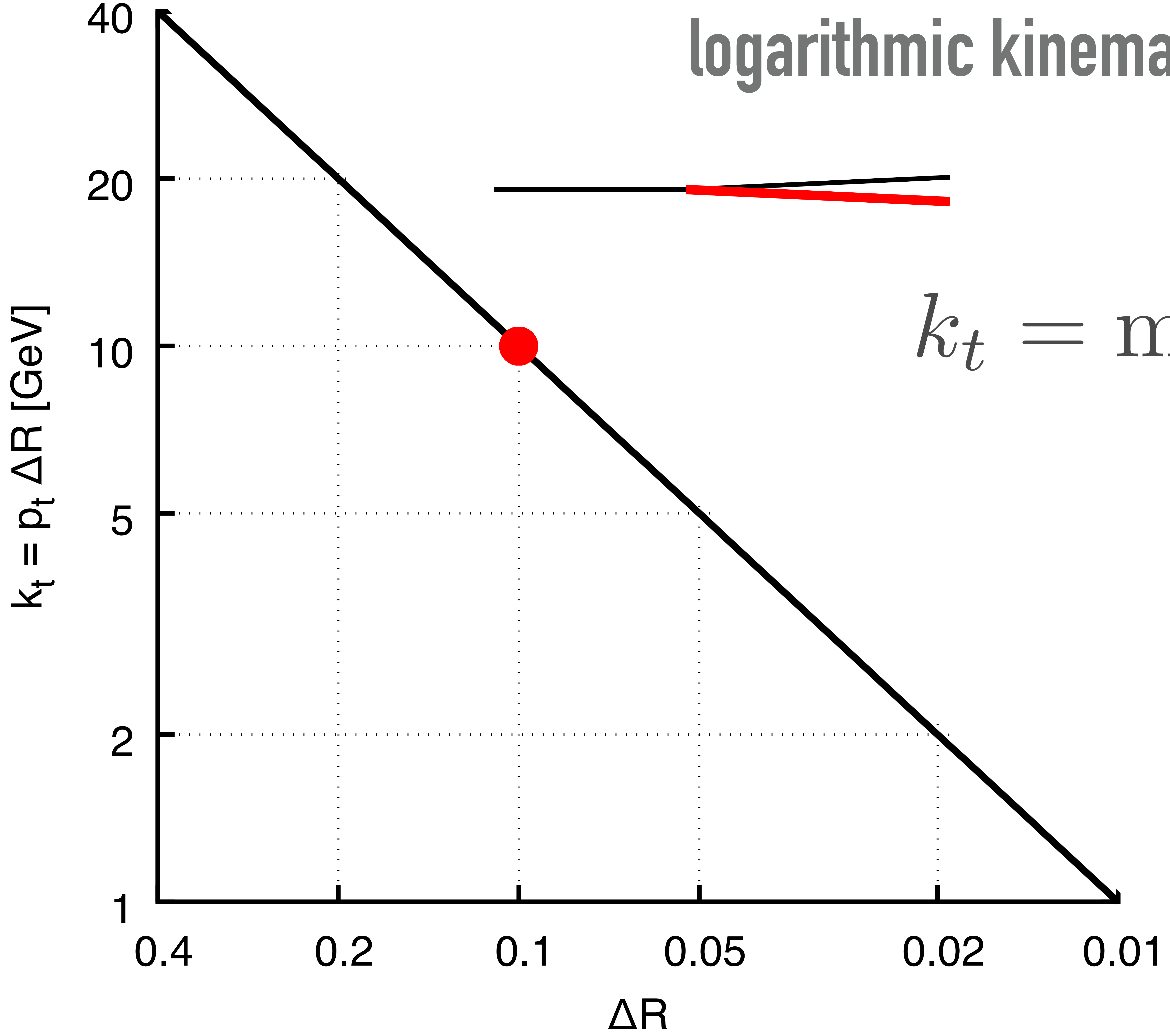

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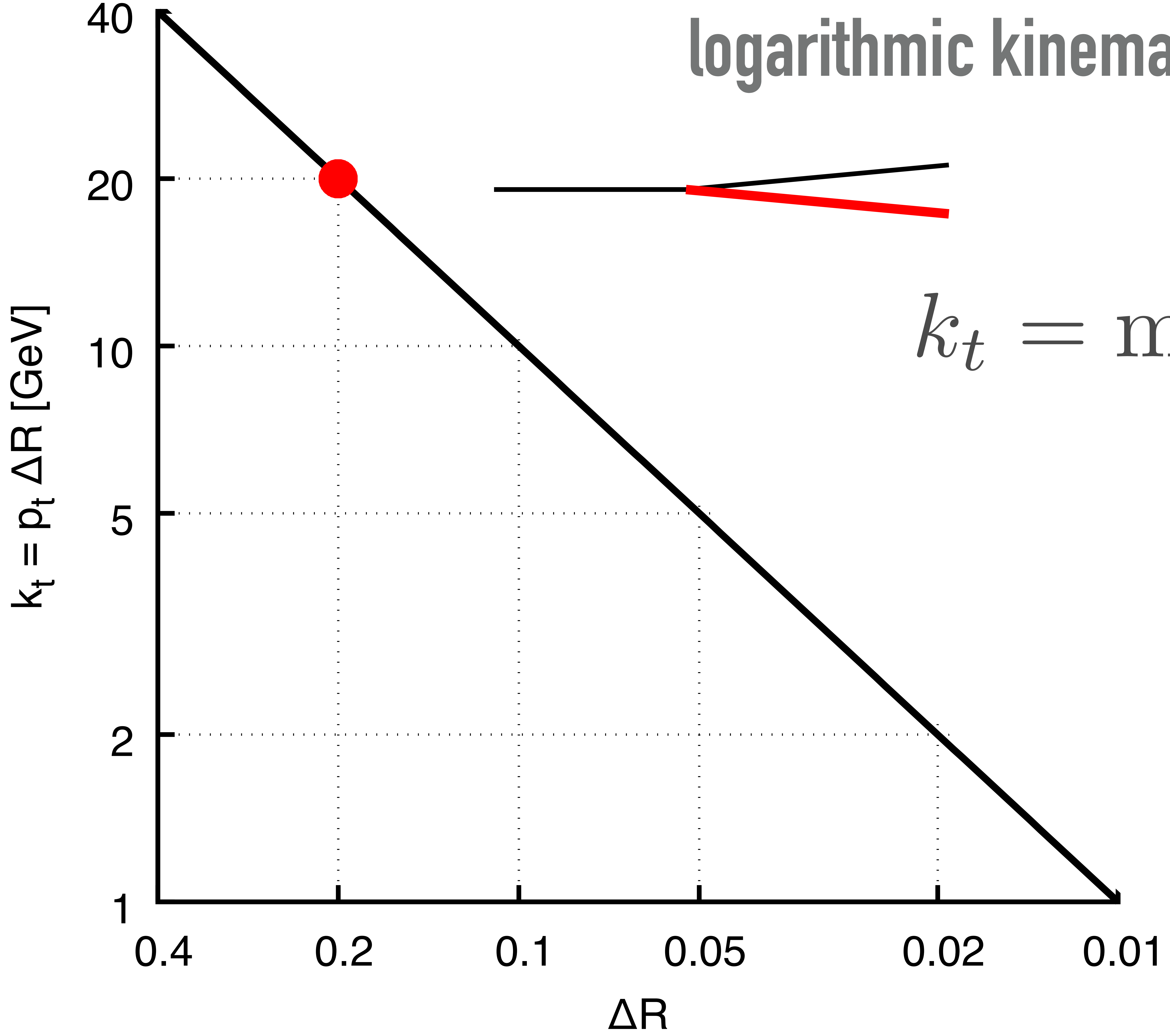

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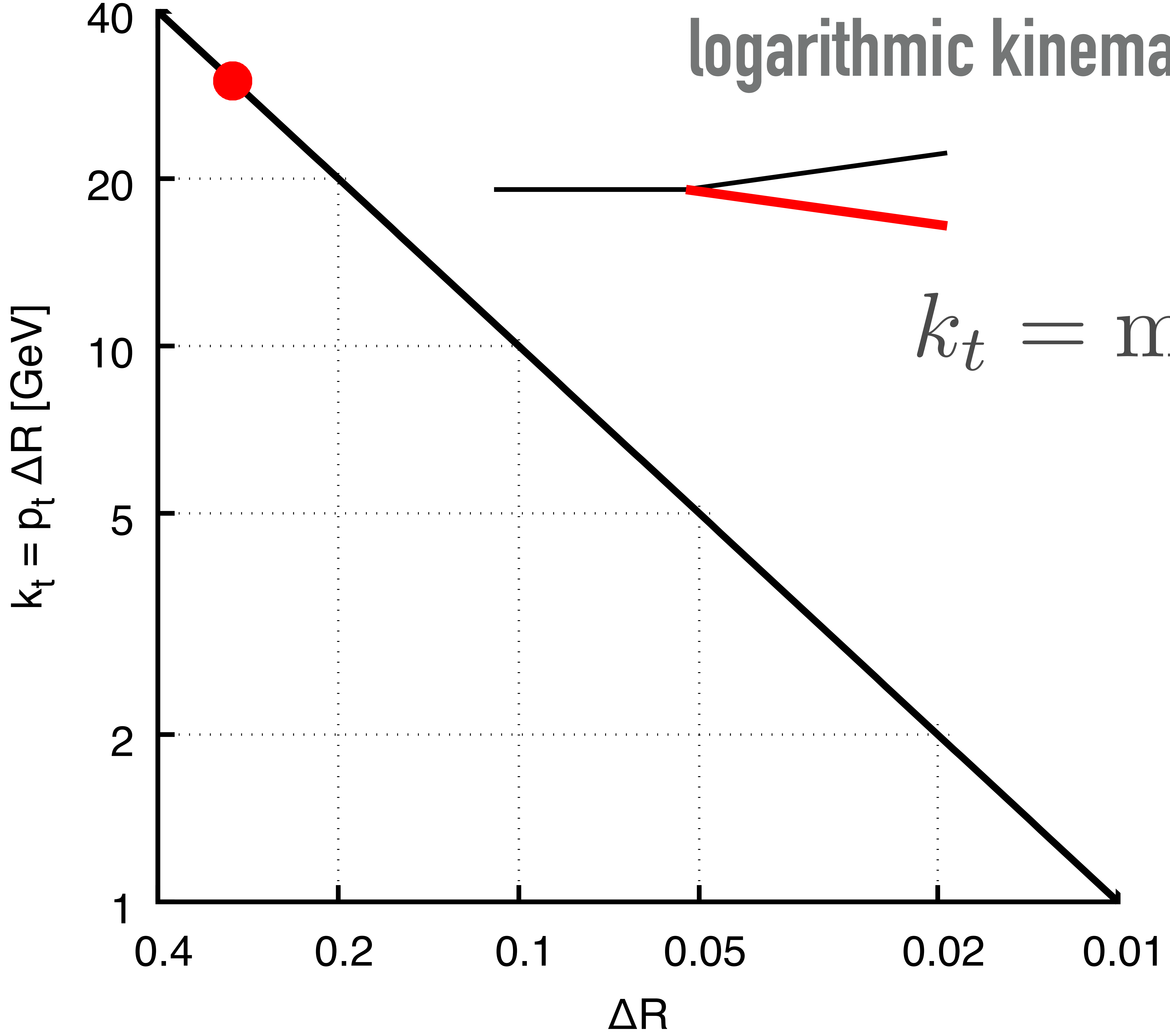
jet with R= 0.4, p_t = 200 GeV



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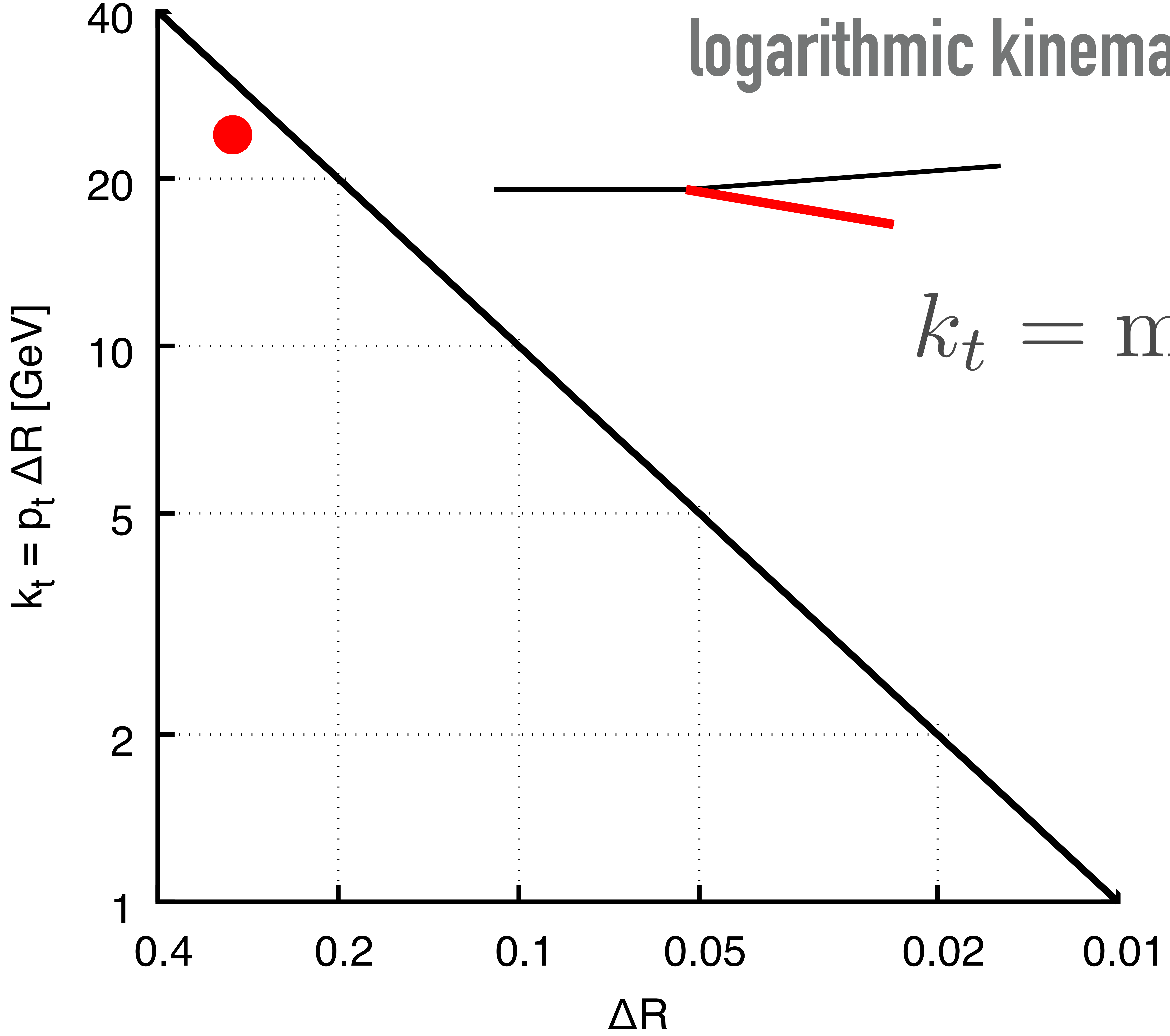

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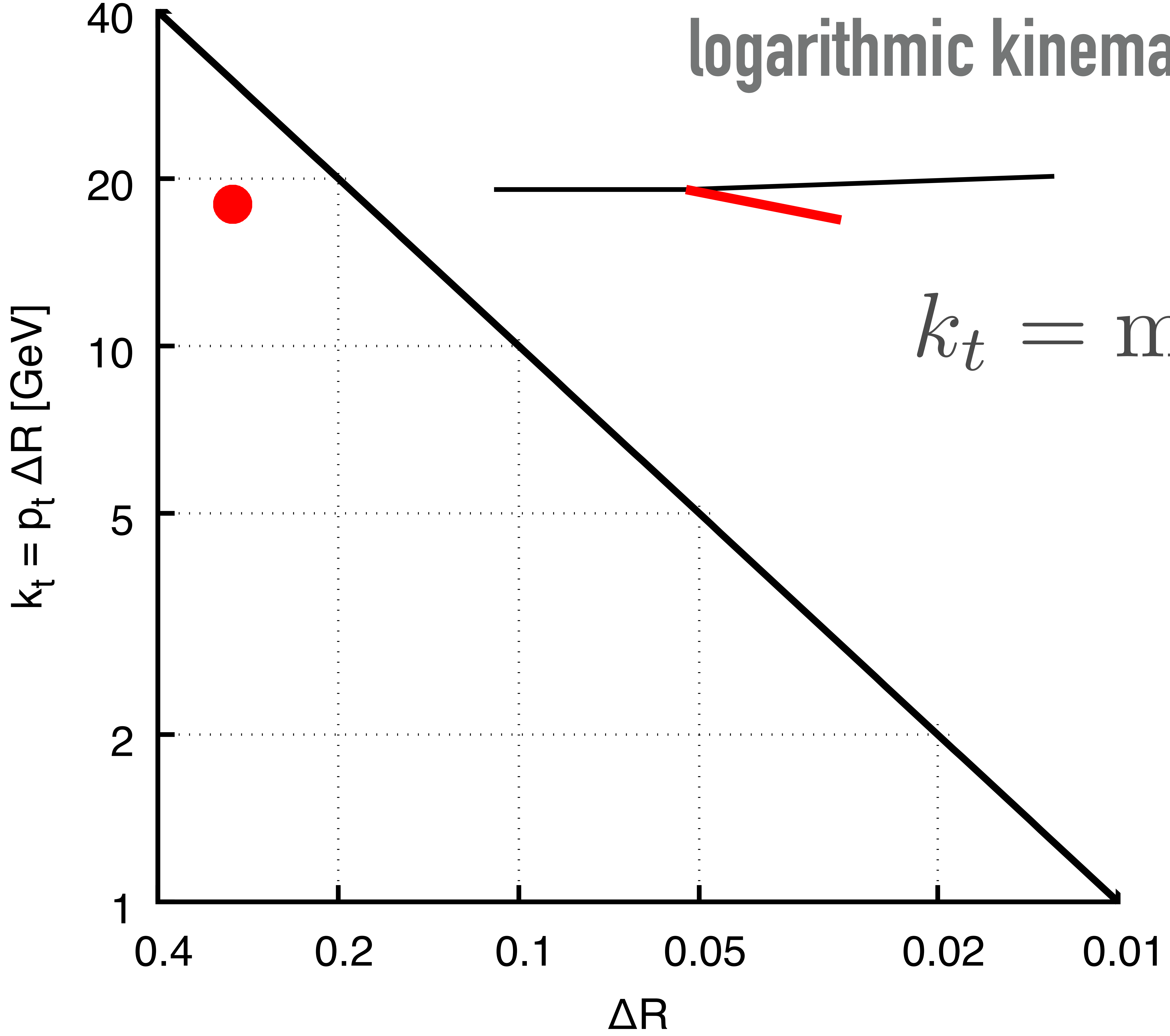
The Lund Plane

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



logarithmic kinematic plane whose two variables are

$$\Delta R_{ij}$$

$$k_t = \min(p_{ti}, p_{tj})\Delta R_{ij}$$

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

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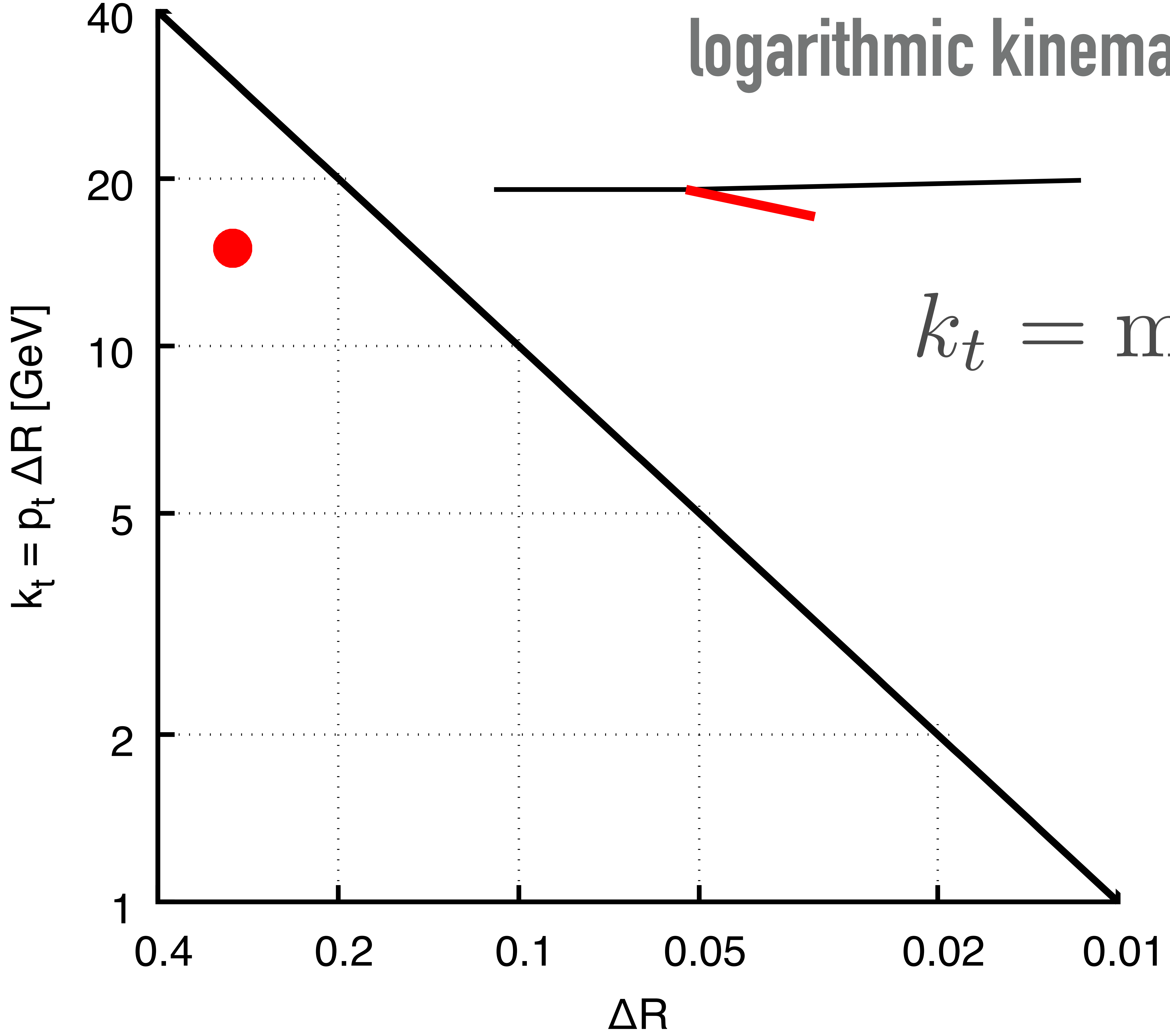

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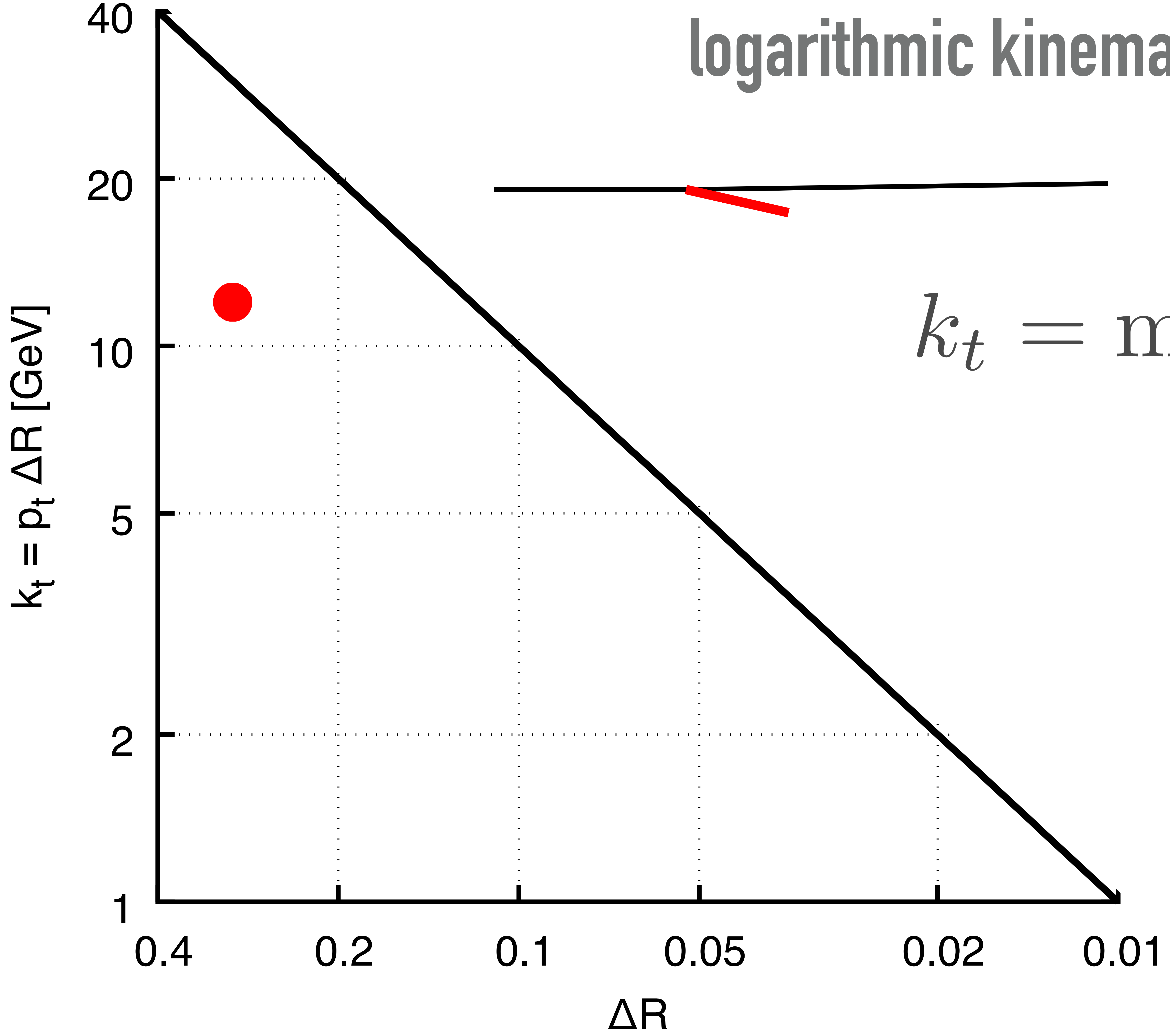

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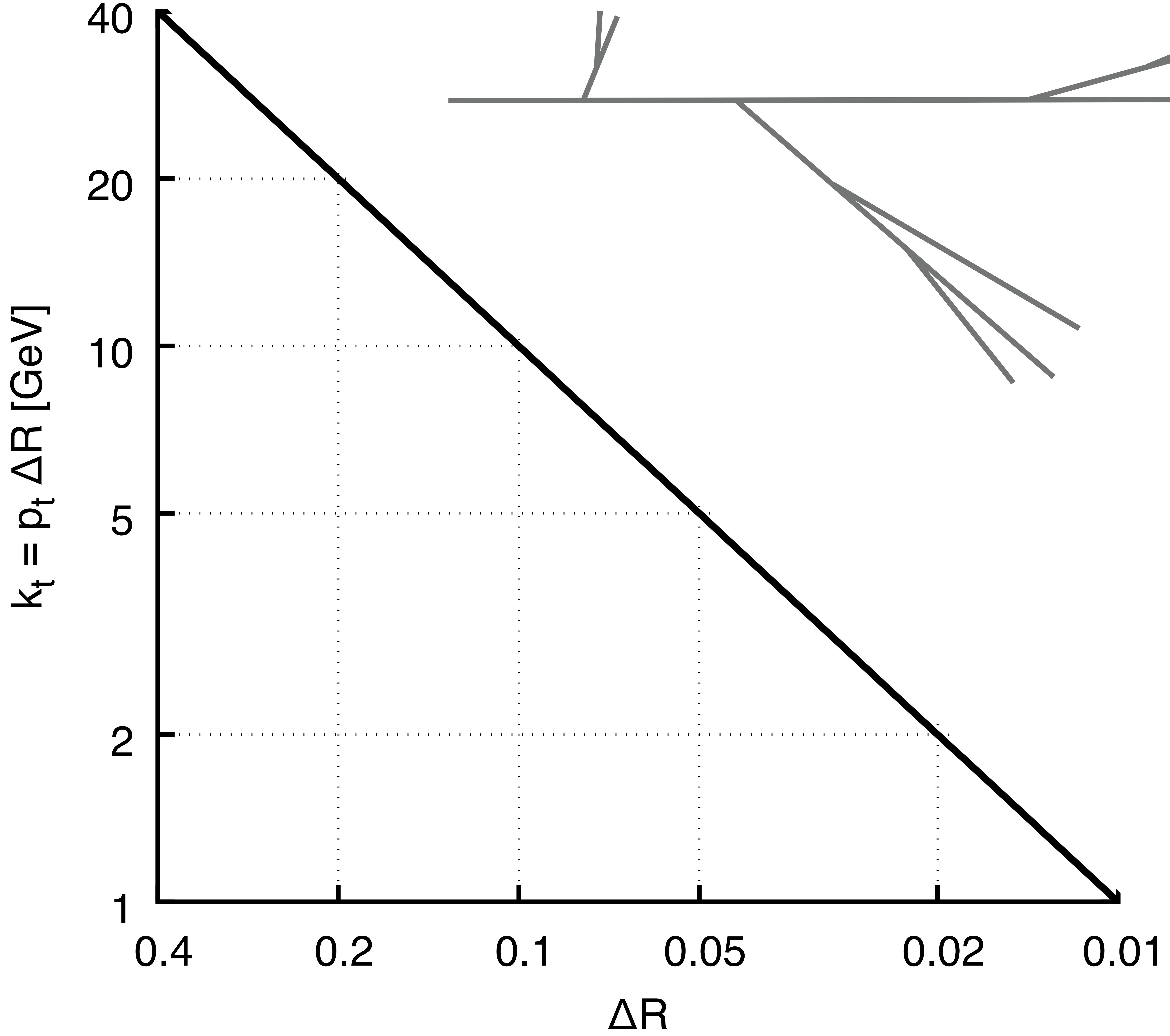
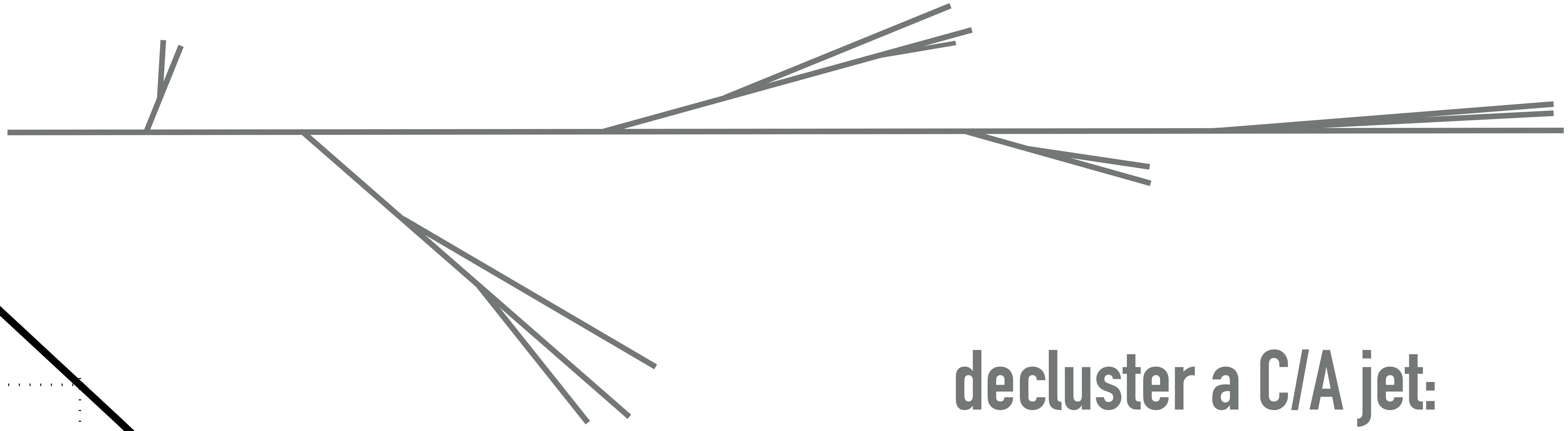


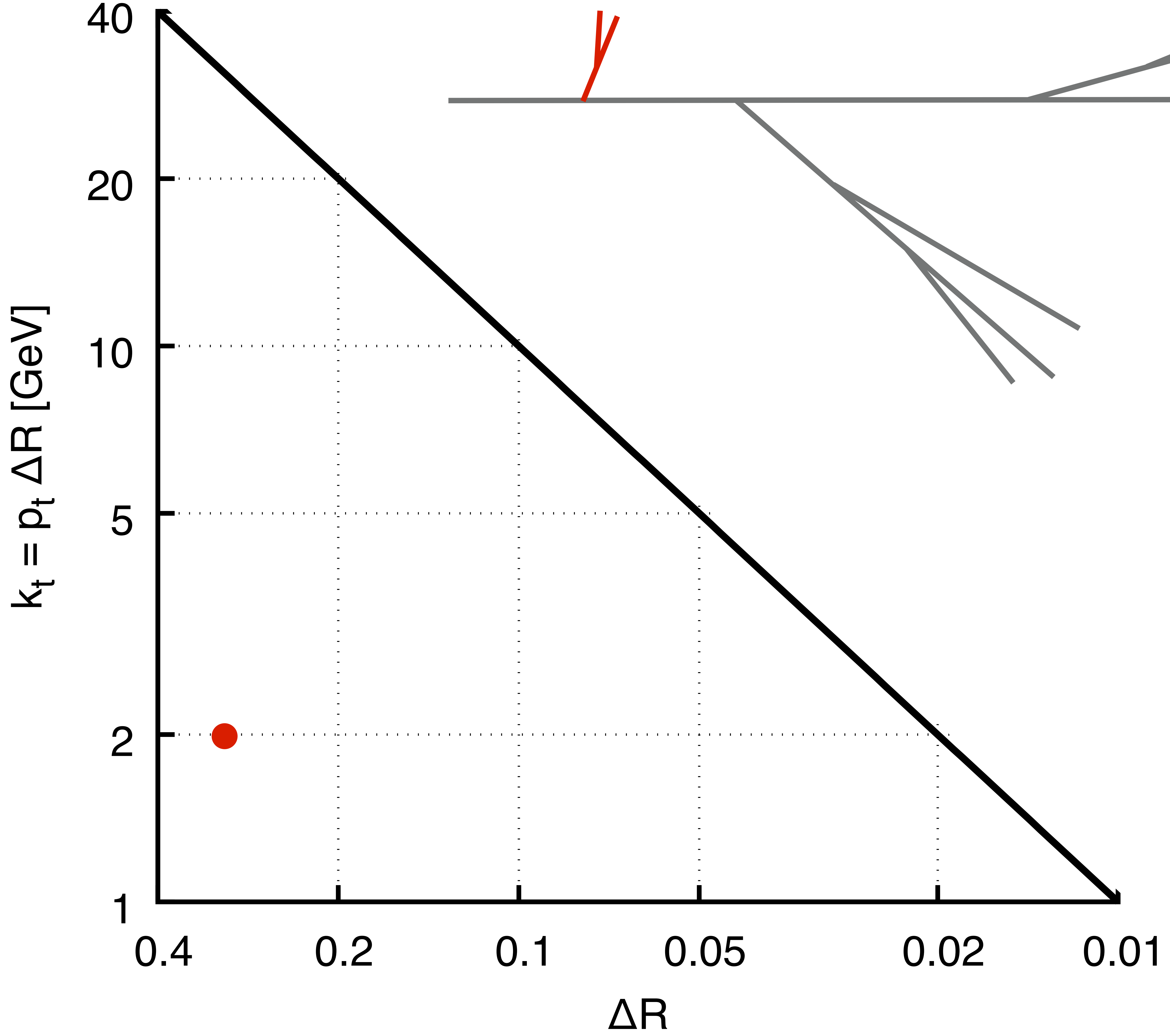


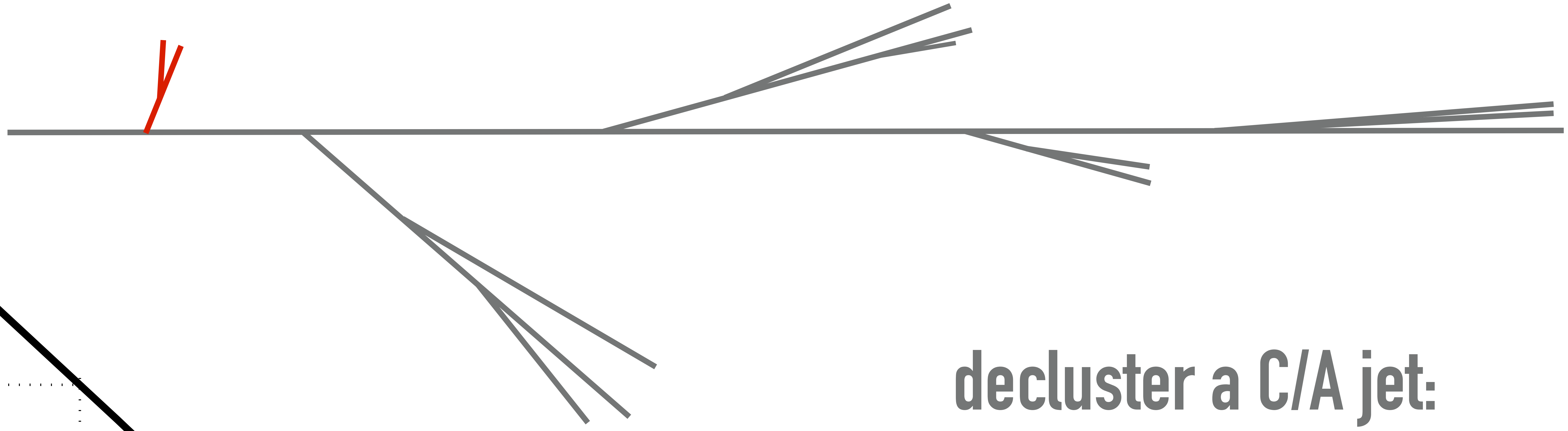
decluster a C/A jet:
at each step record ΔR,kt
as a point in the Lund plane

repeatedly follow harder branch

5th heavy-ion workshop @ CERN, 1808.03689
Dreyer, Soyez & GPS, 1807.04758 (for pp applications)

constructing the Lund plane





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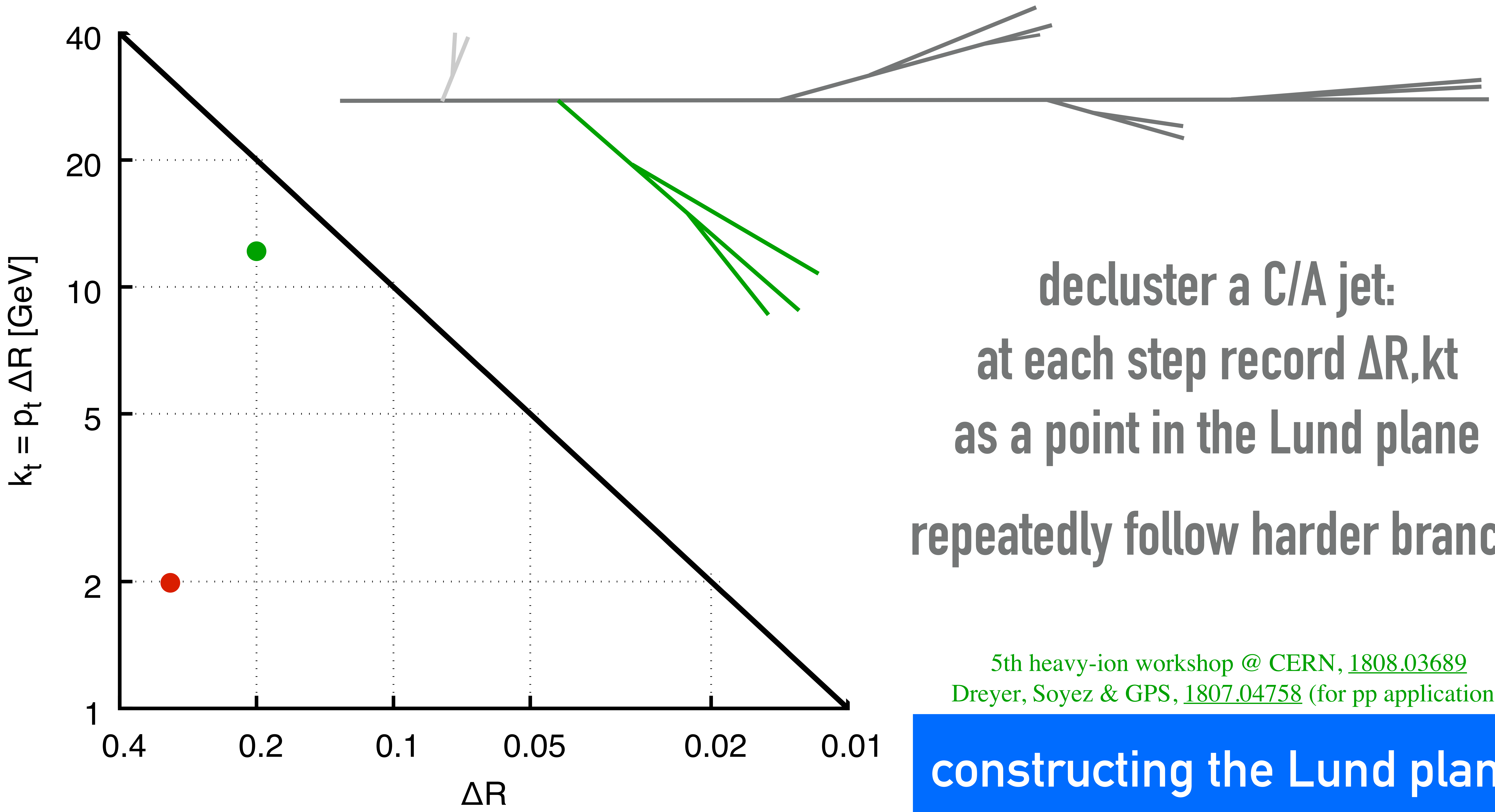

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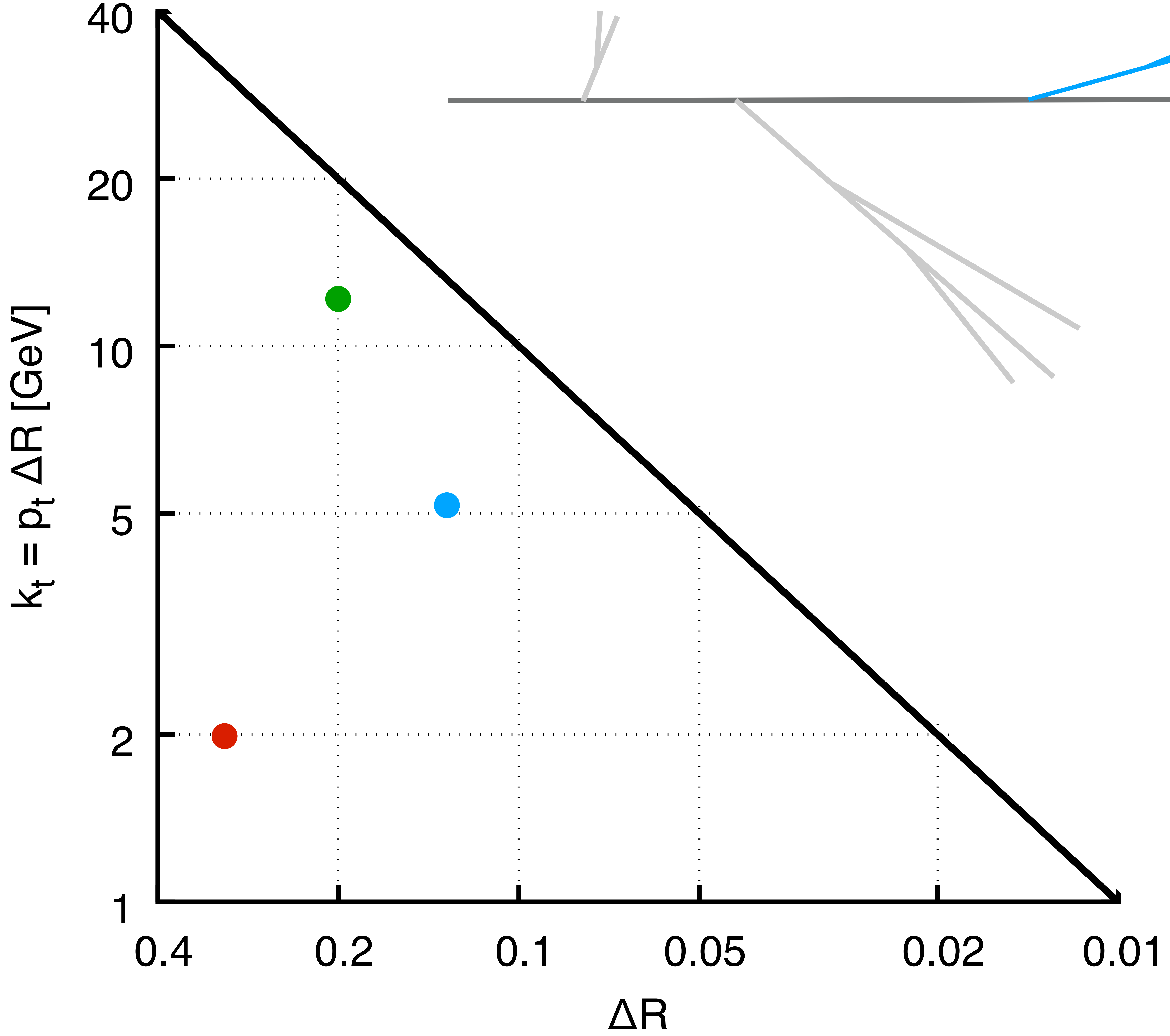

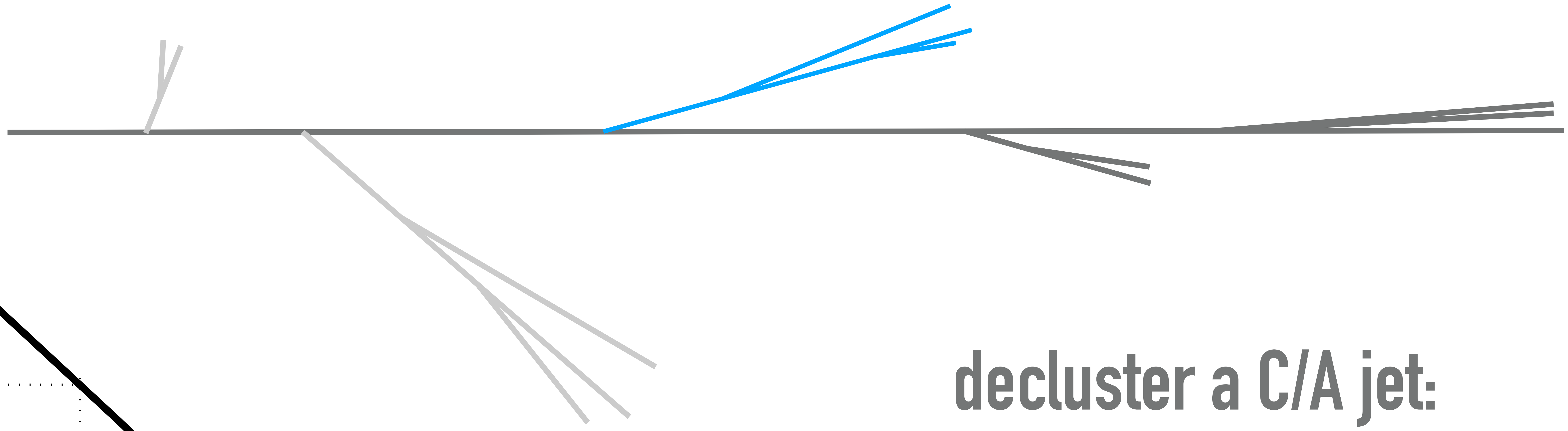

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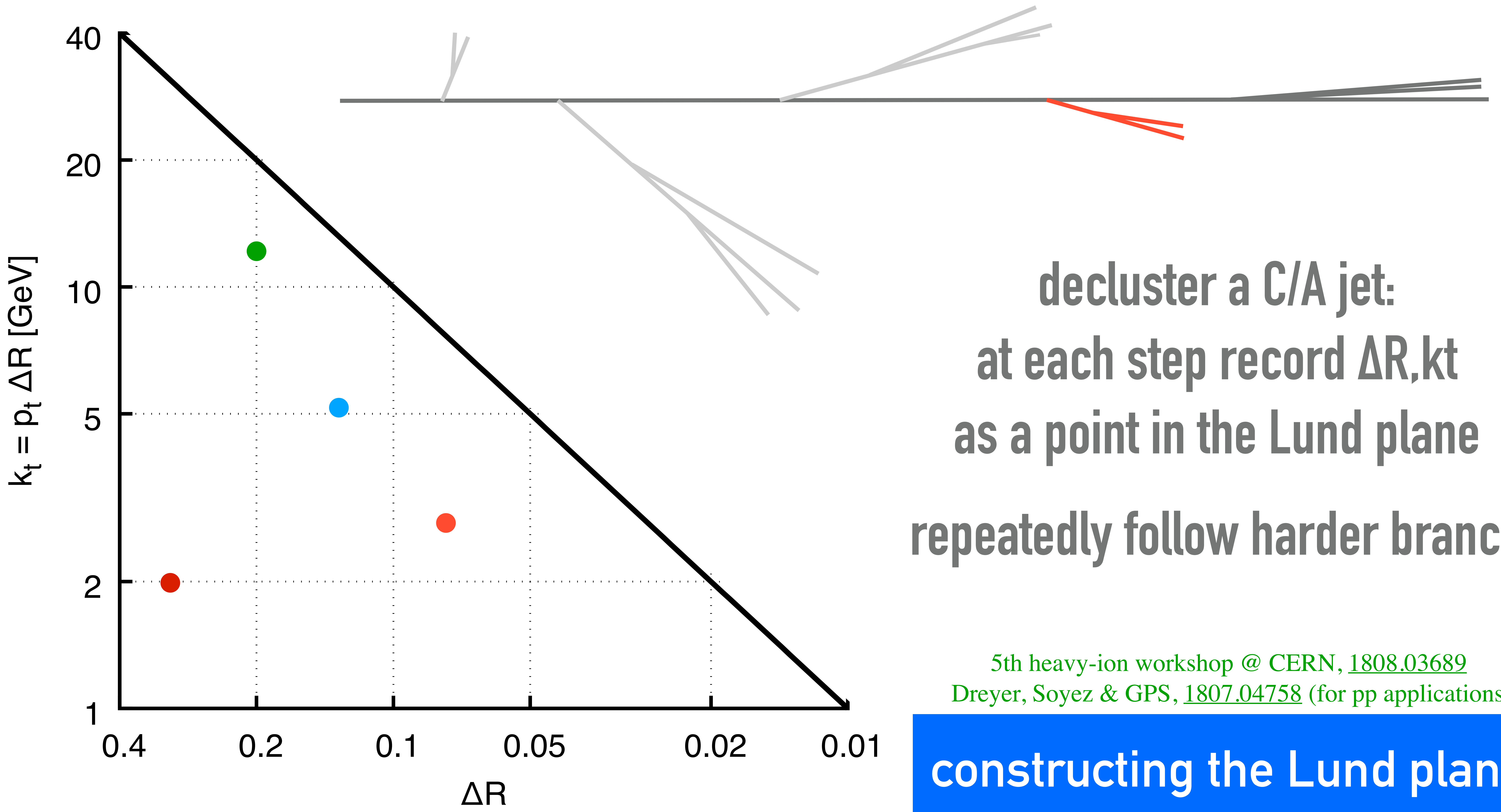

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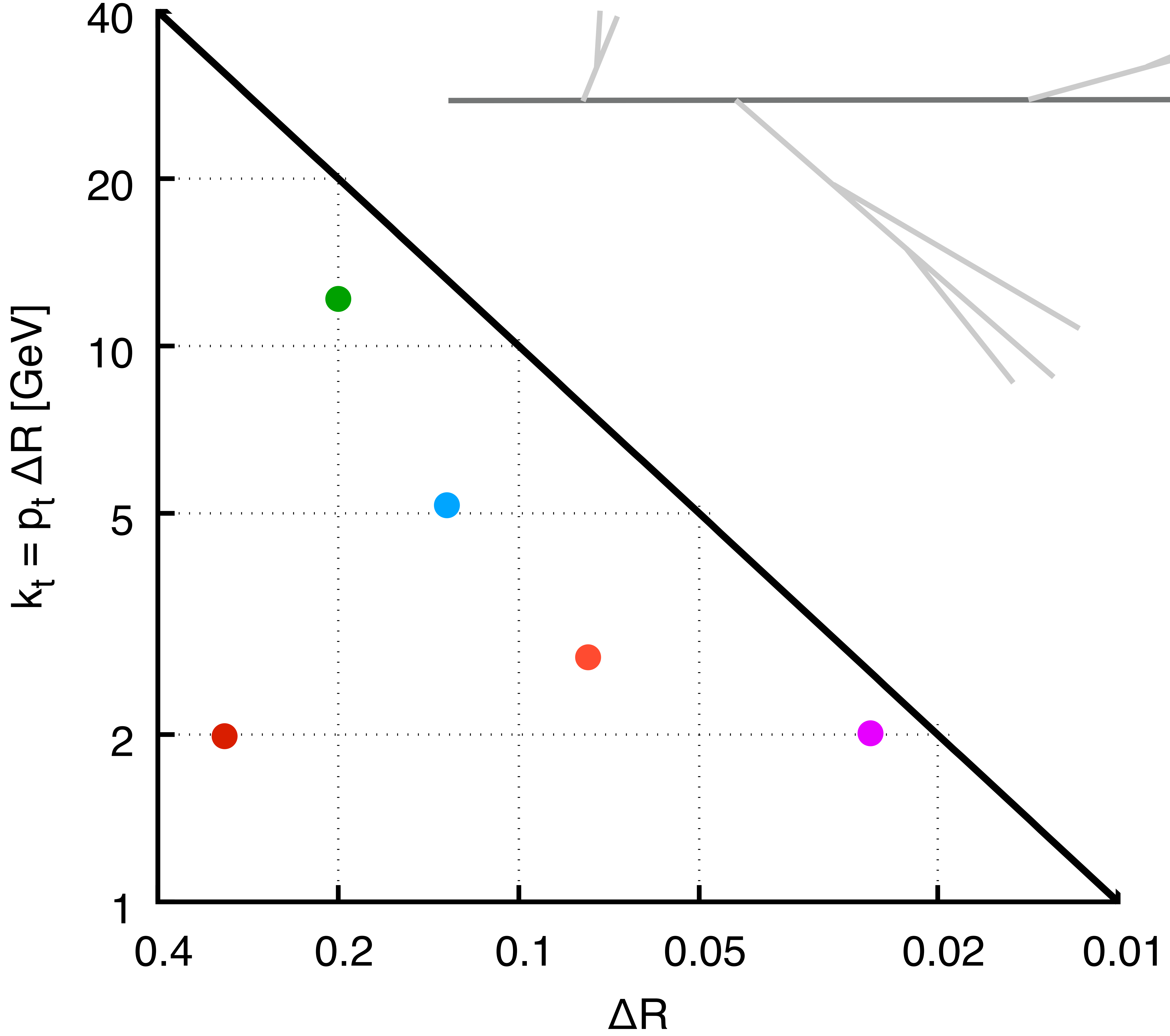

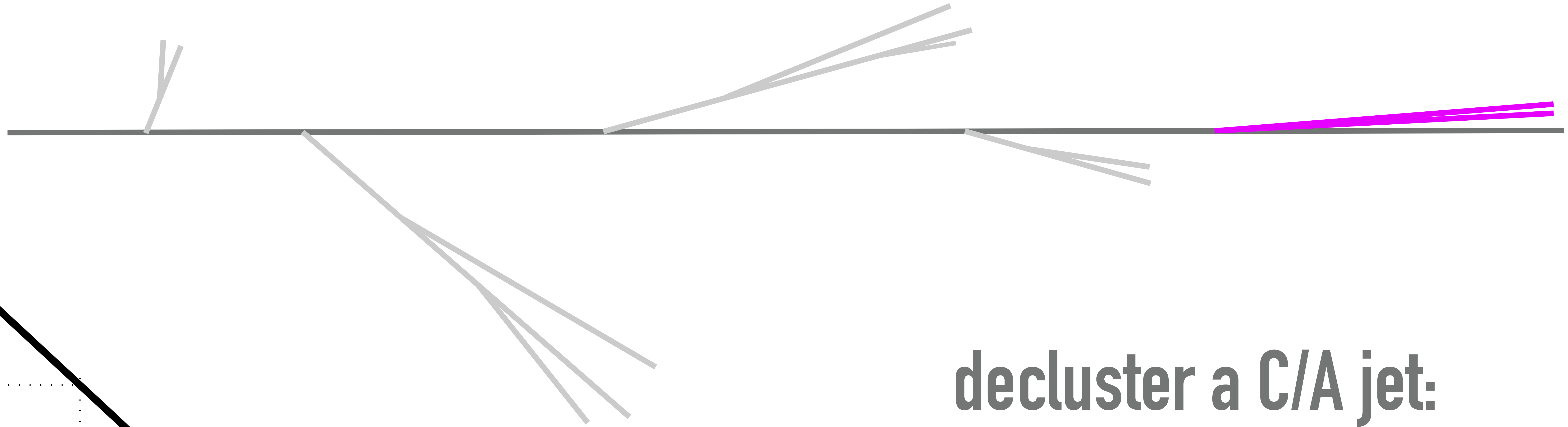

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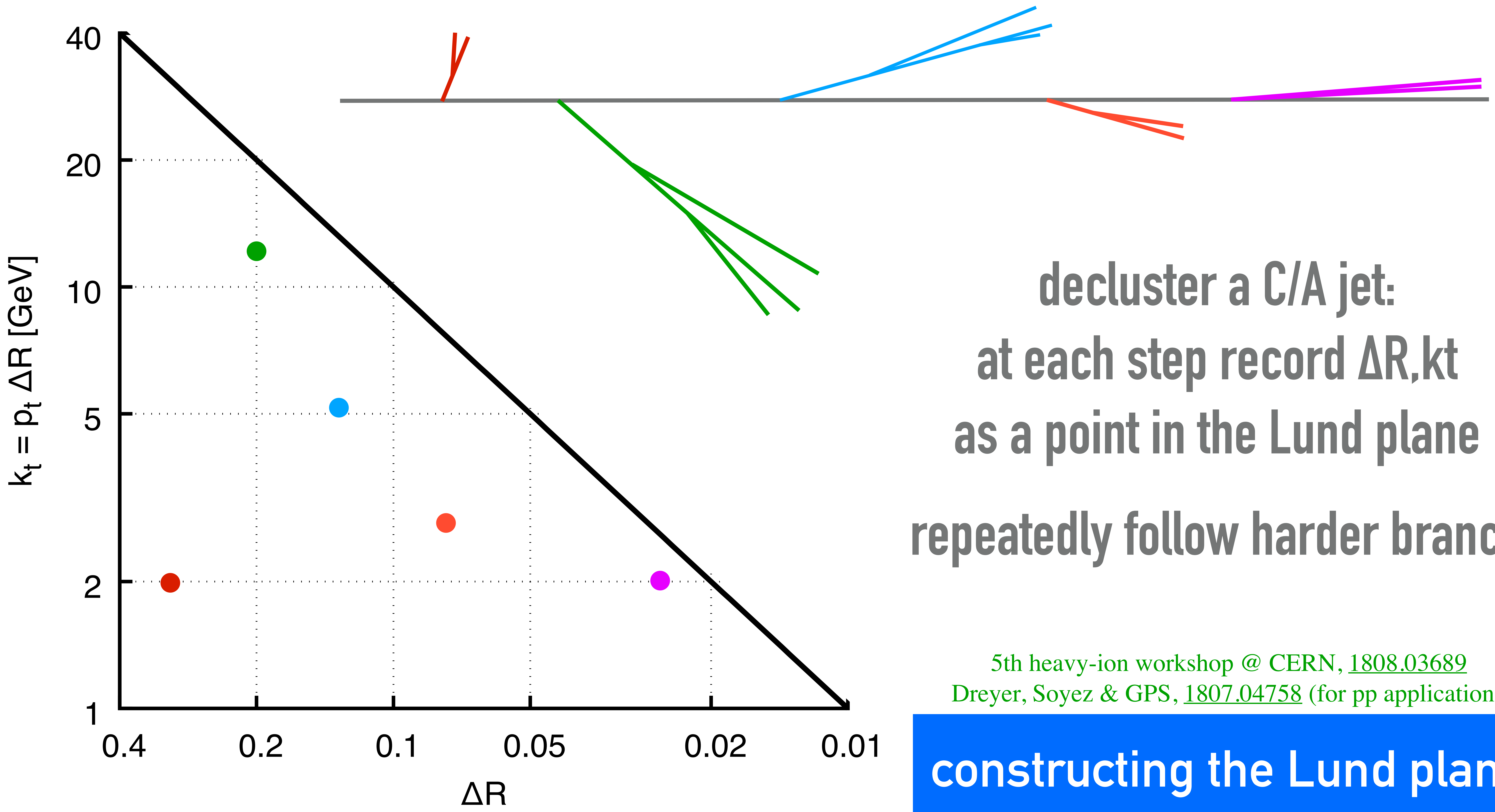

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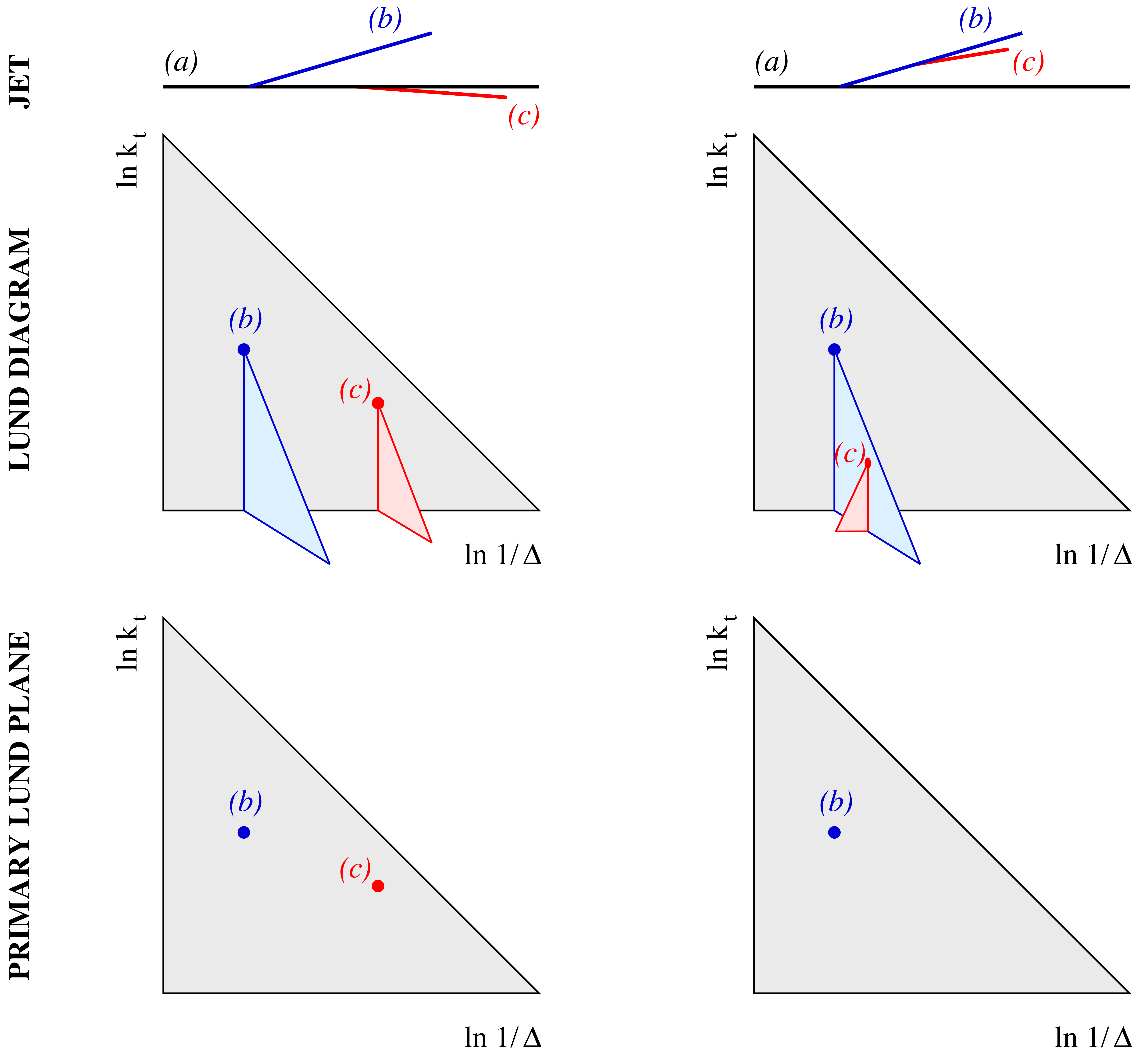
JET
LUND DIAGRAM
PRIMARY LUND PLANE
(a)
(b)
(c)
ln k_t
ln 1/Δ
(a)
(b)
(c)
ln k_t
ln 1/Δ
(b)
(c)
ln k_t
ln 1/Δ
(b)
(c)
ln k_t
ln 1/Δ
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(c)
ln k_t
ln 1/Δ
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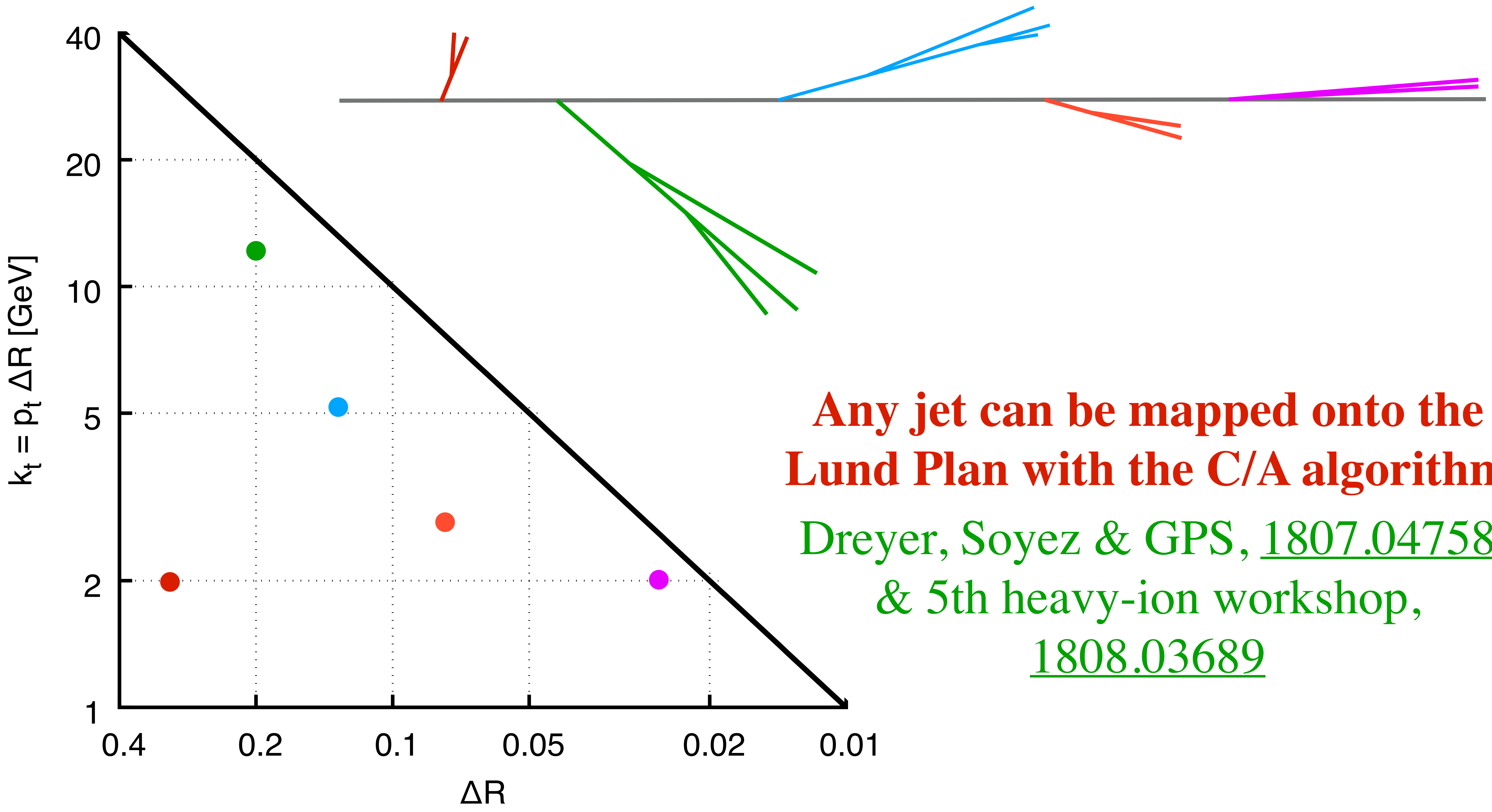
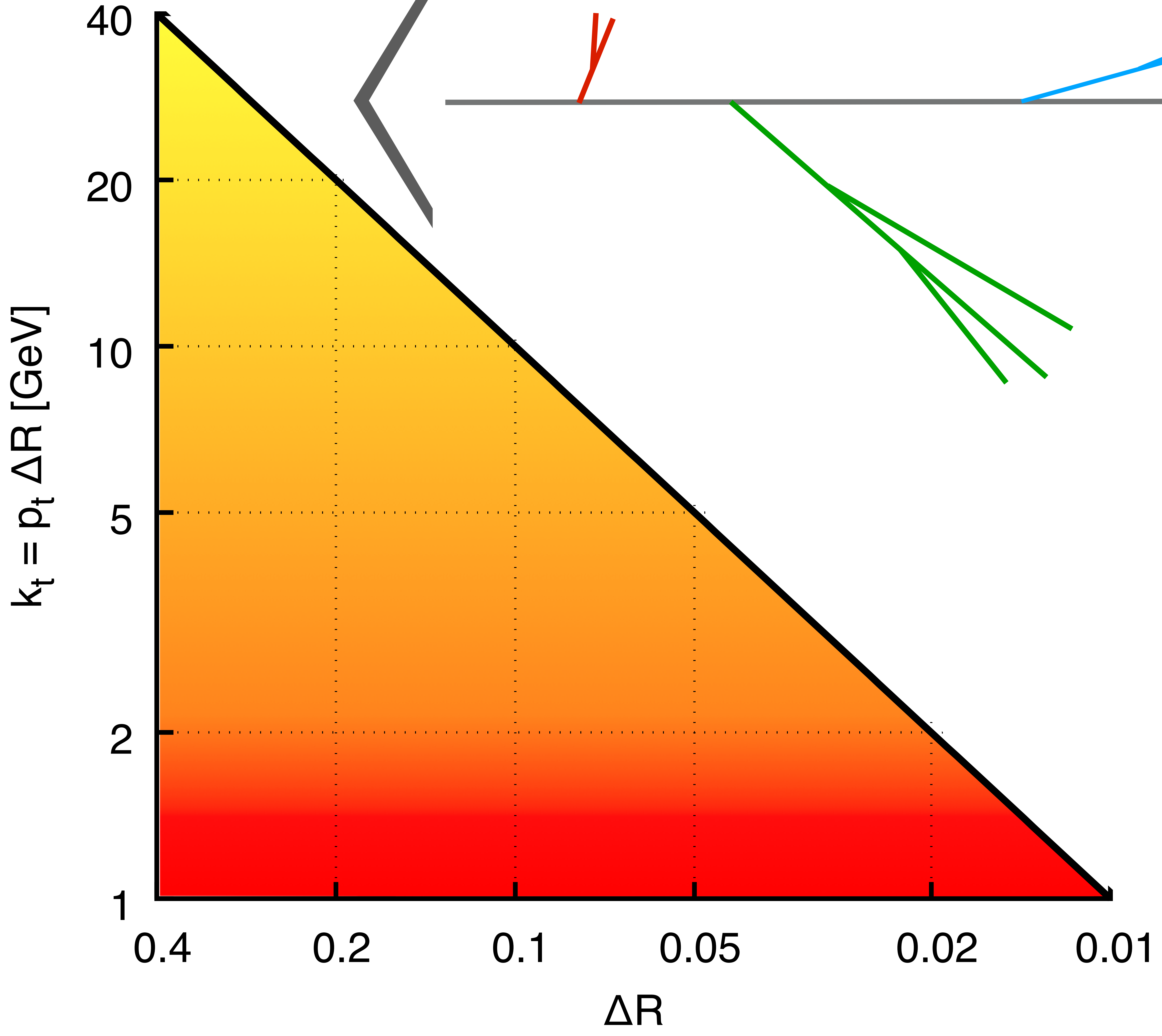
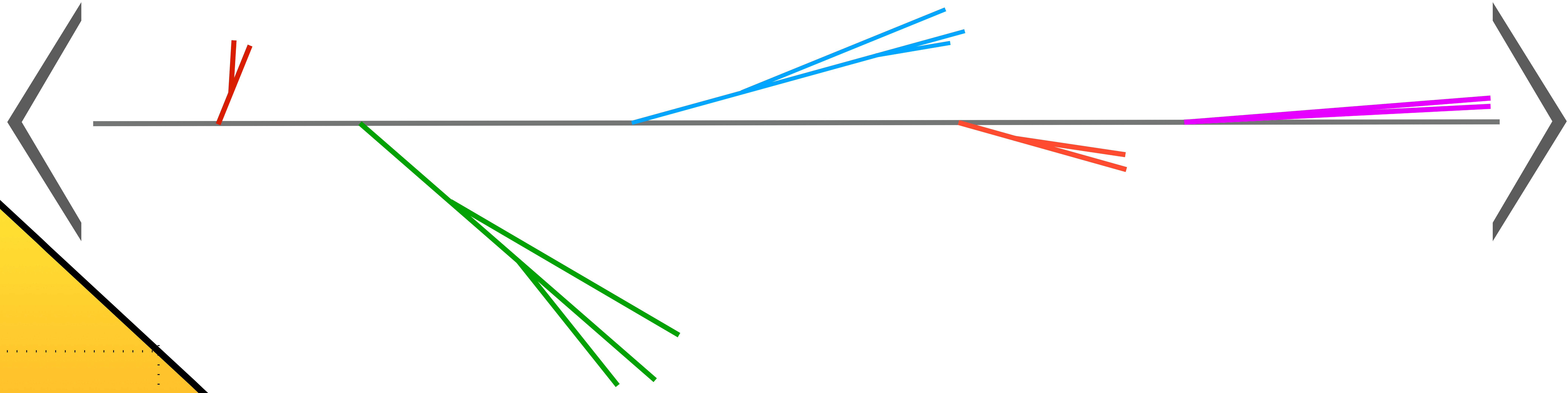
ln k_t
ln 1/Δ



Any jet can be mapped onto the Lund Plan with the C/A algorithm

Dreyer, Soyez & GPS, 1807.04758 & 5th heavy-ion workshop, 1808.03689 *jet with R = 0.4, p_t = 200 GeV*



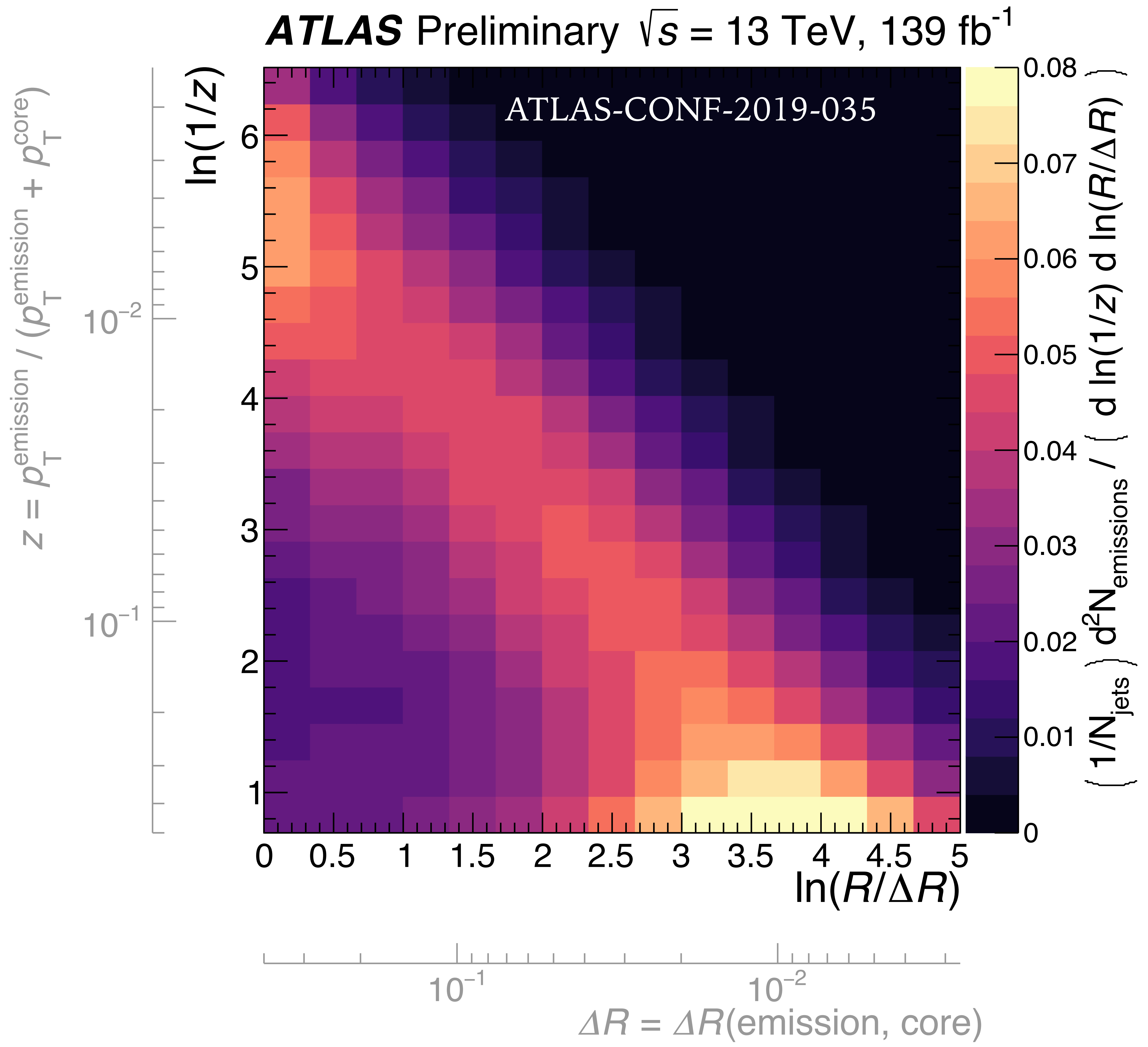


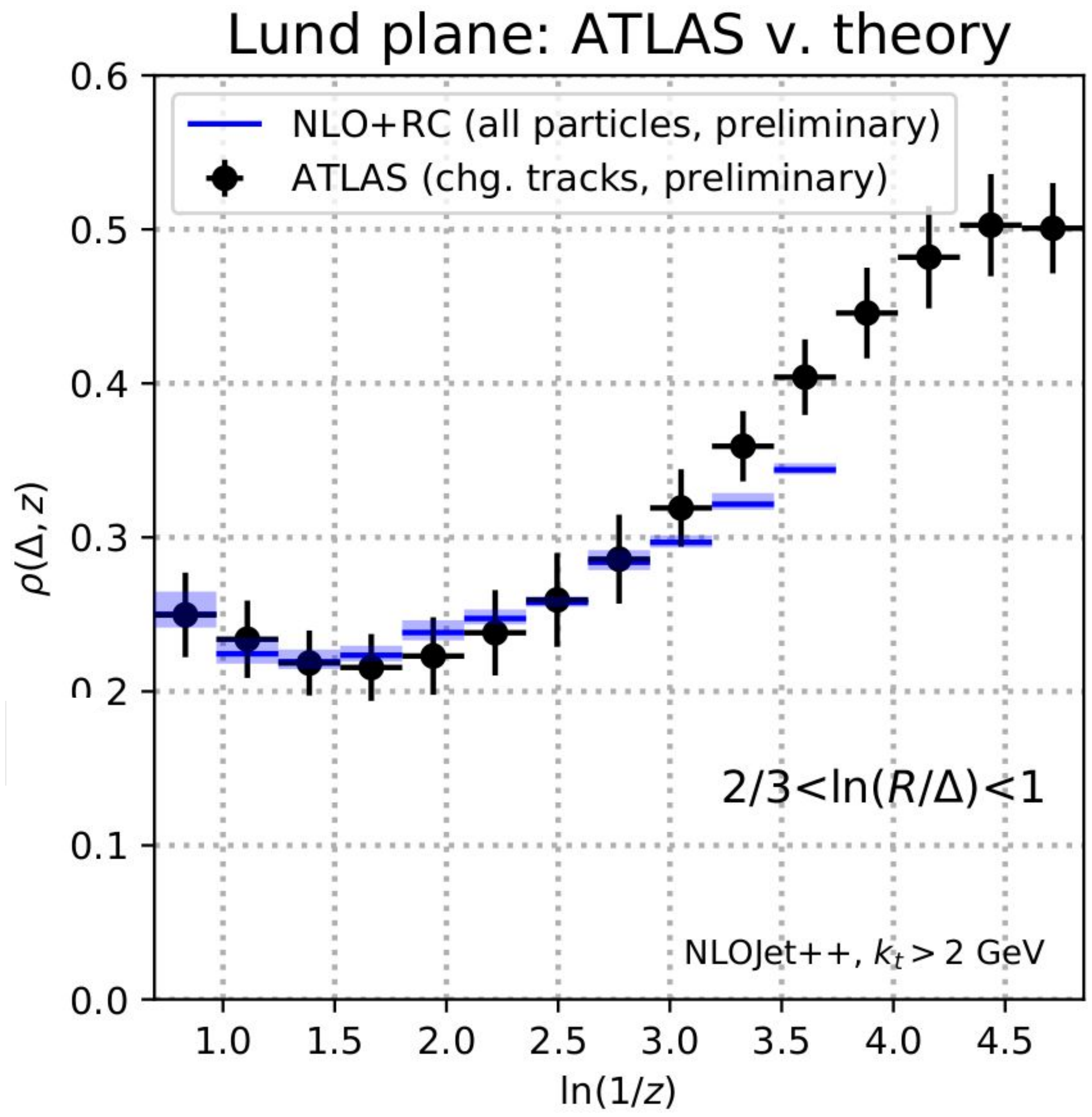
average over many jets:

Lund plane density

jet with R= 0.4, p_t = 200 GeV
40
20
10
5
2
1
$k_t = p_t\, \Delta R$ [GeV]
weak
coupling
(calculable)
strong coupling
(non-perturbative) region
0.4
0.2
0.1
0.05
0.02
0.01
ΔR
average over many jets:
Lund plane density

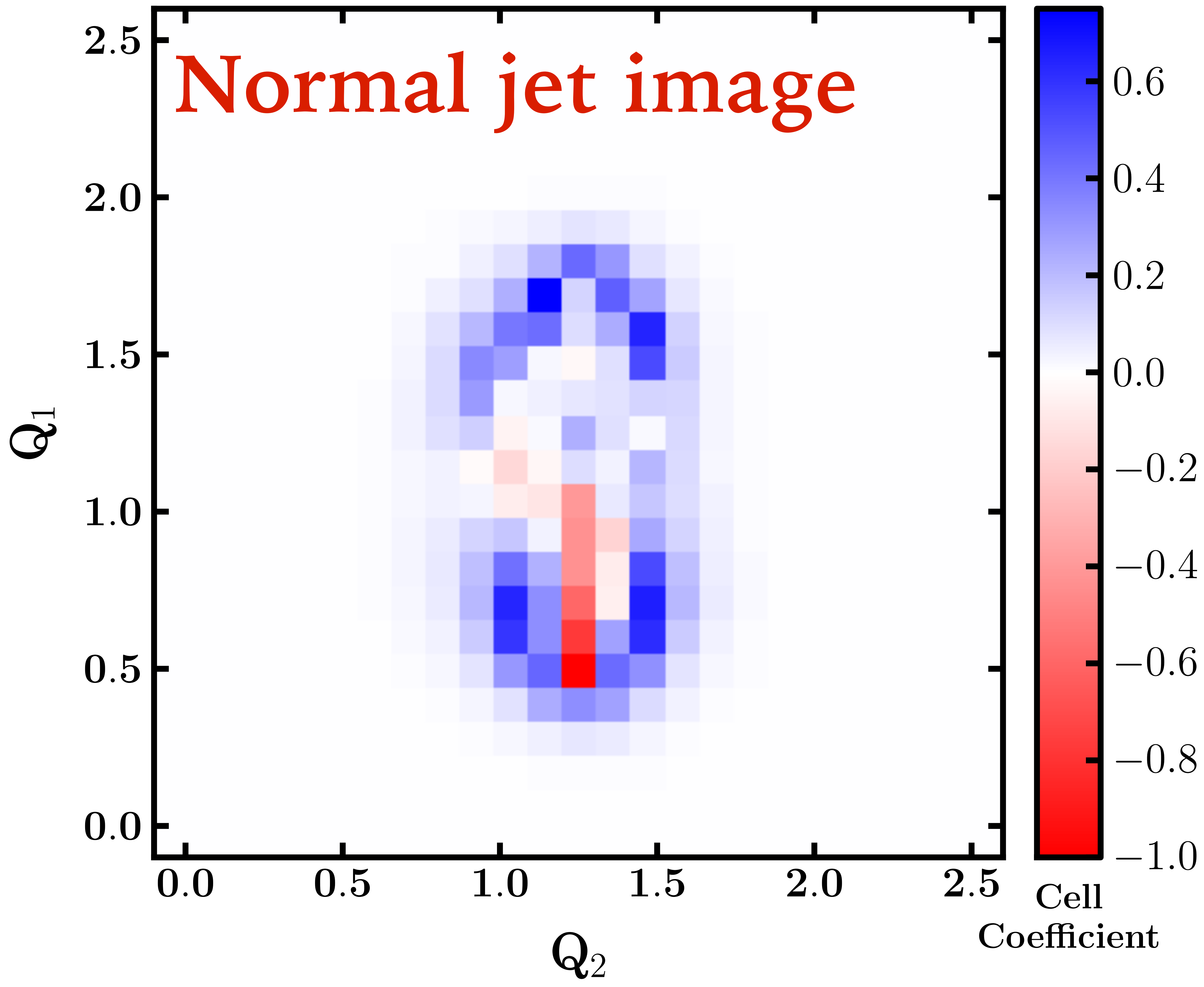
Lund plane measurement



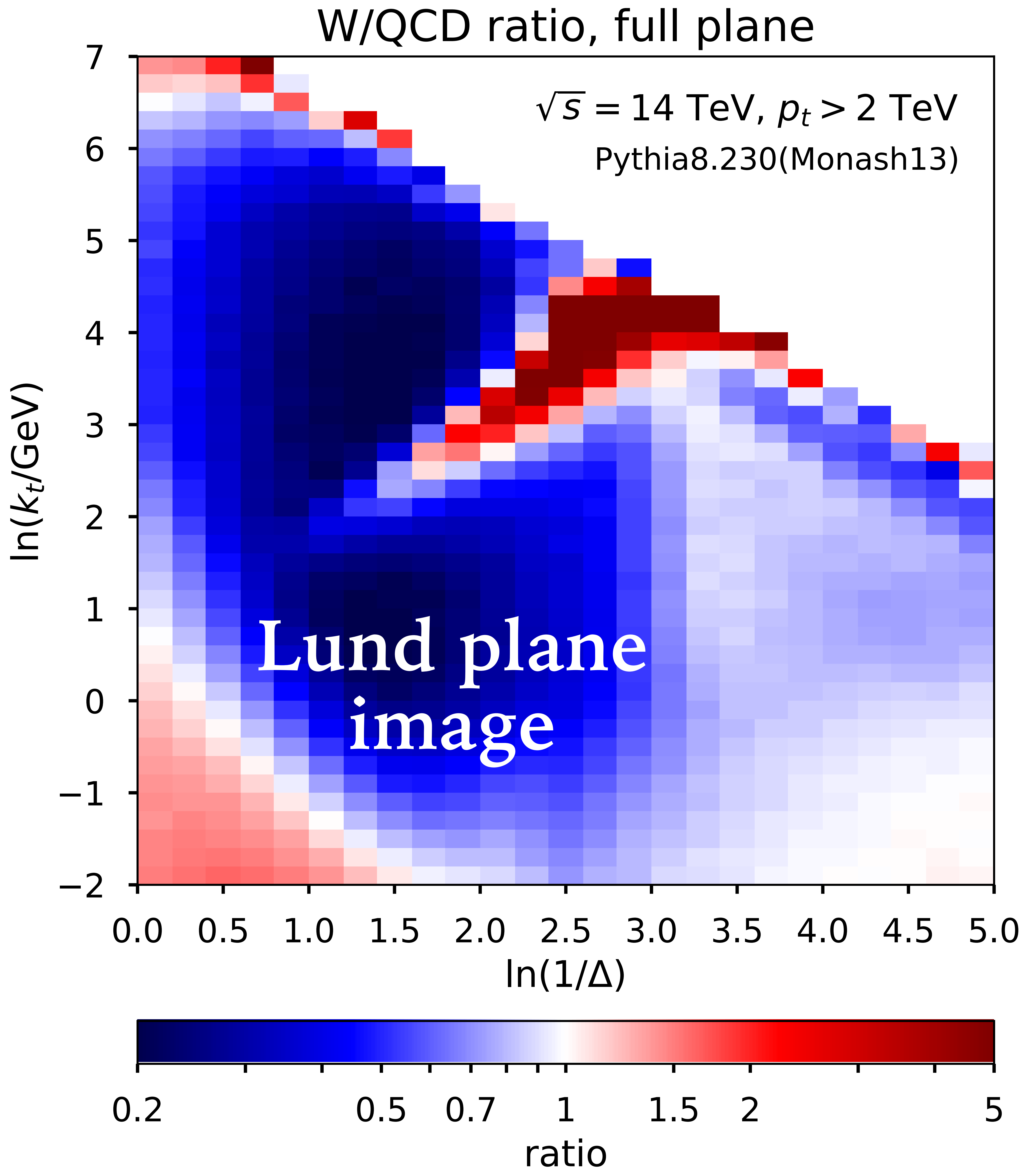


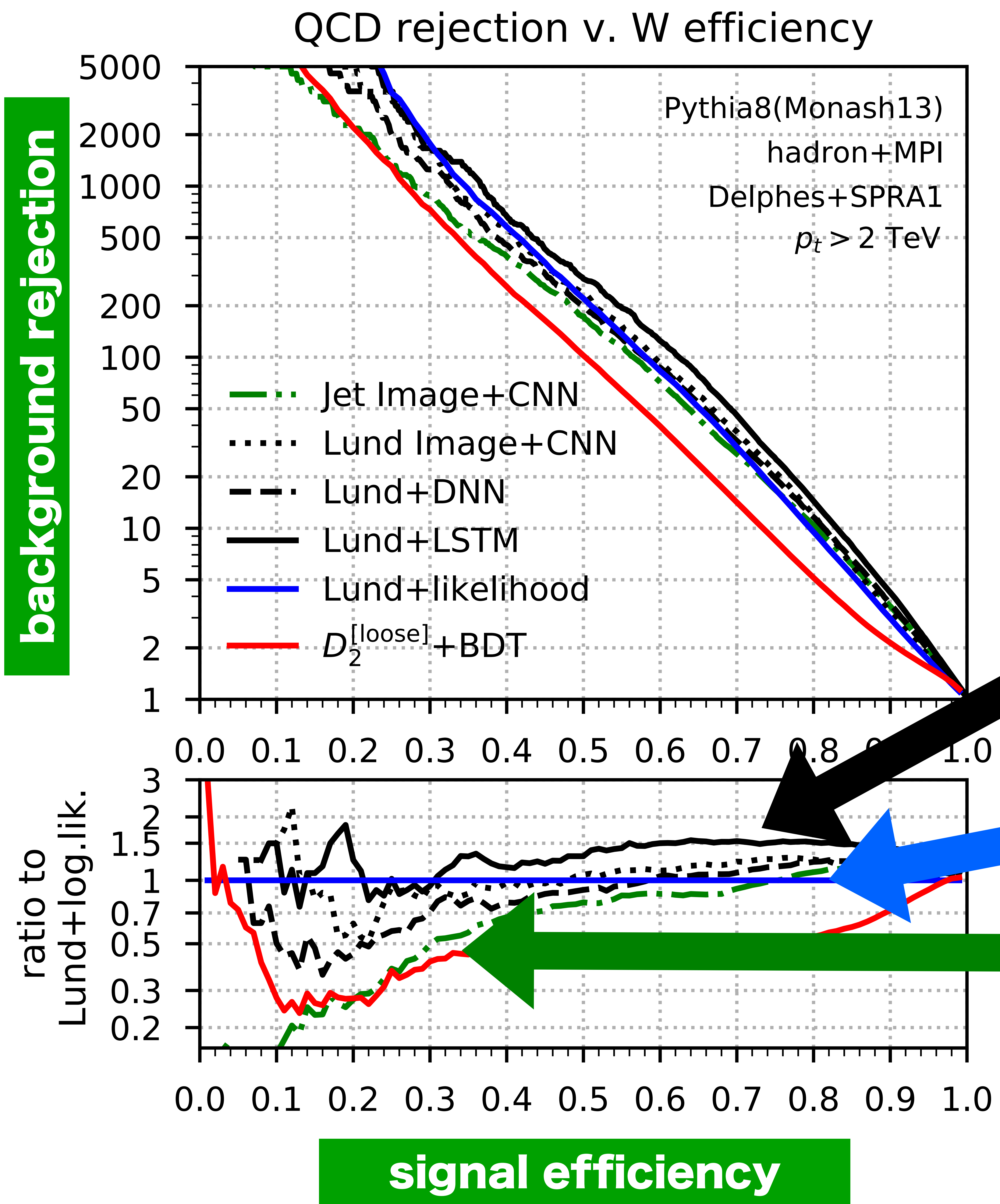
Dreyer & Soyez prelim @Boost 2019

W-boson (~H-boson) v. normal jets



Cogan, Kagan, Strauss, Schwartzman, 1407.5674





Performance:
background rejection v. signal efficiency

Lund + machine-learning (LSTM)
up to twice the bkgd rejection compared to non-Lund methods

Lund info without machine learning

Jet image + CNN

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

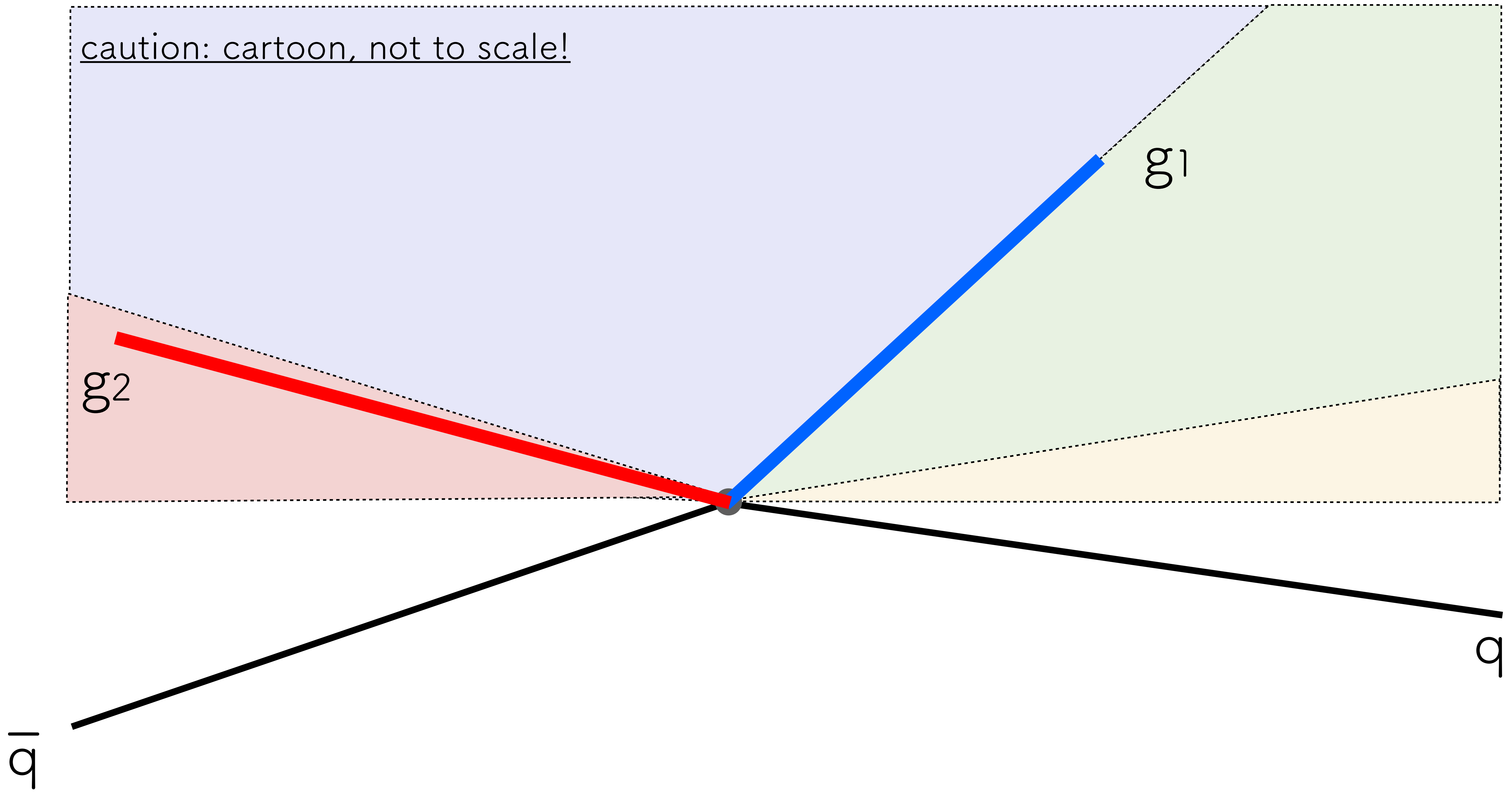
“

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

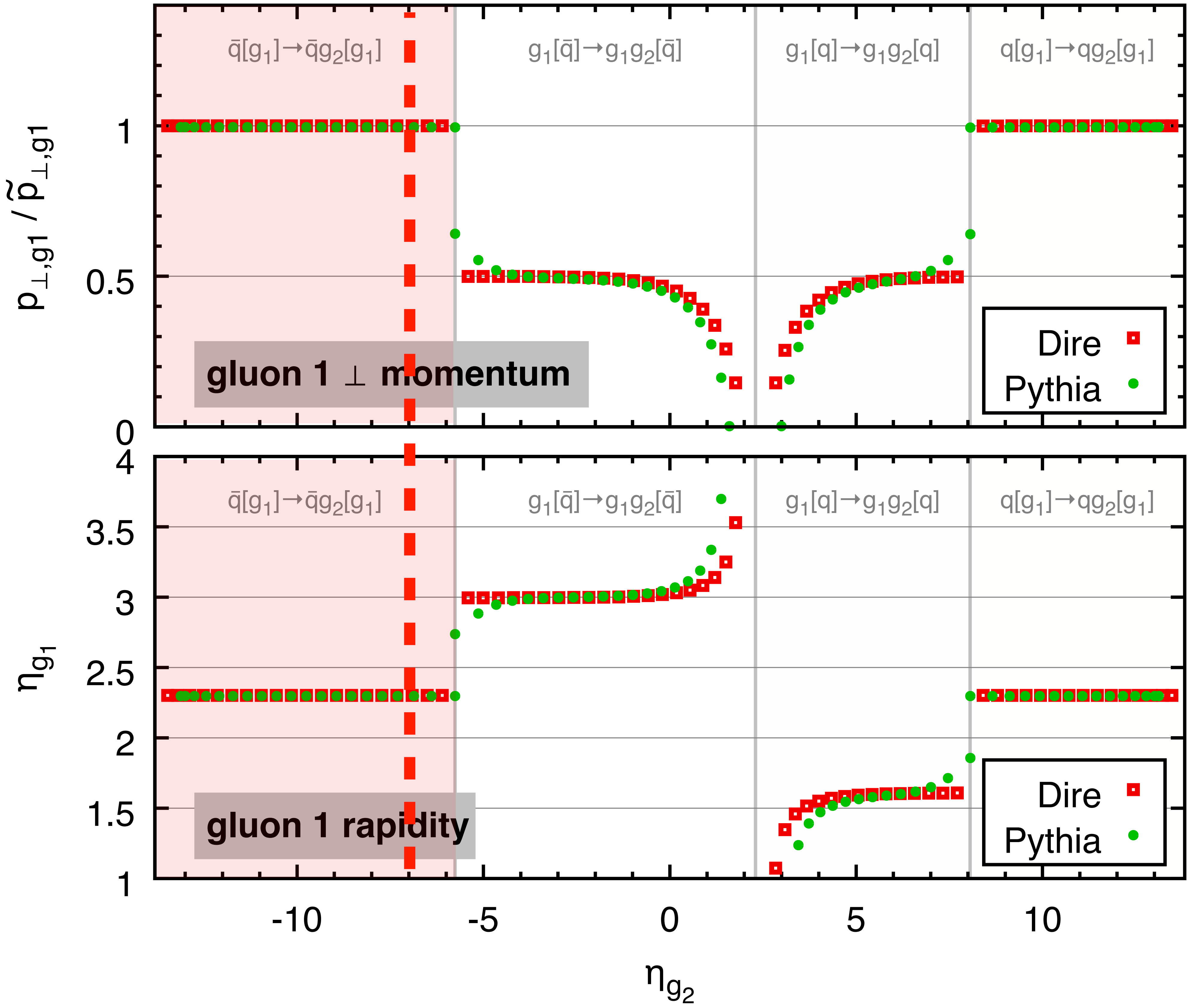
- Harry Markowitz (1990 Nobel Prize in Economics)

[via S Gukov]

Two emissions in dipole showers (Dire / Pythia8)



impact of gluon-2 emission on gluon-1 momentum



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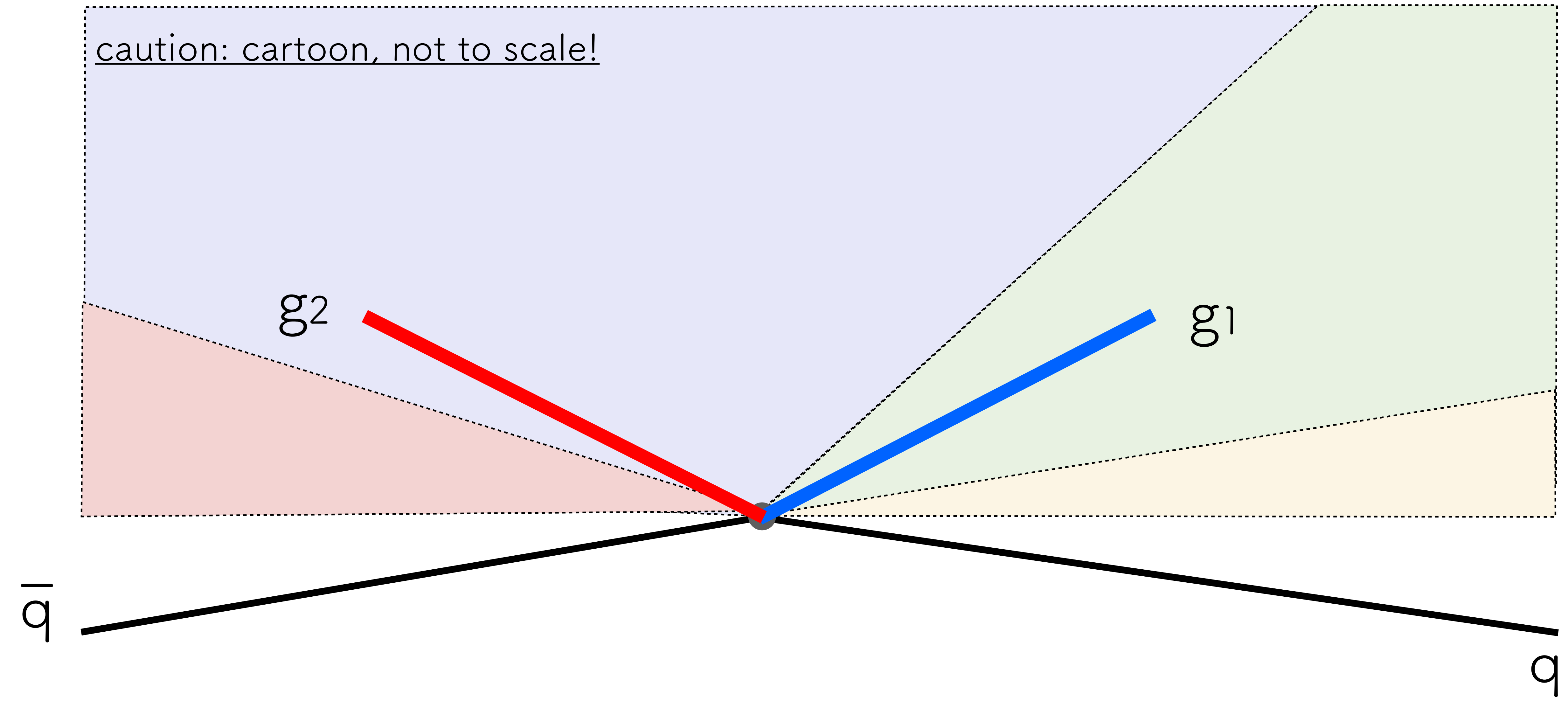

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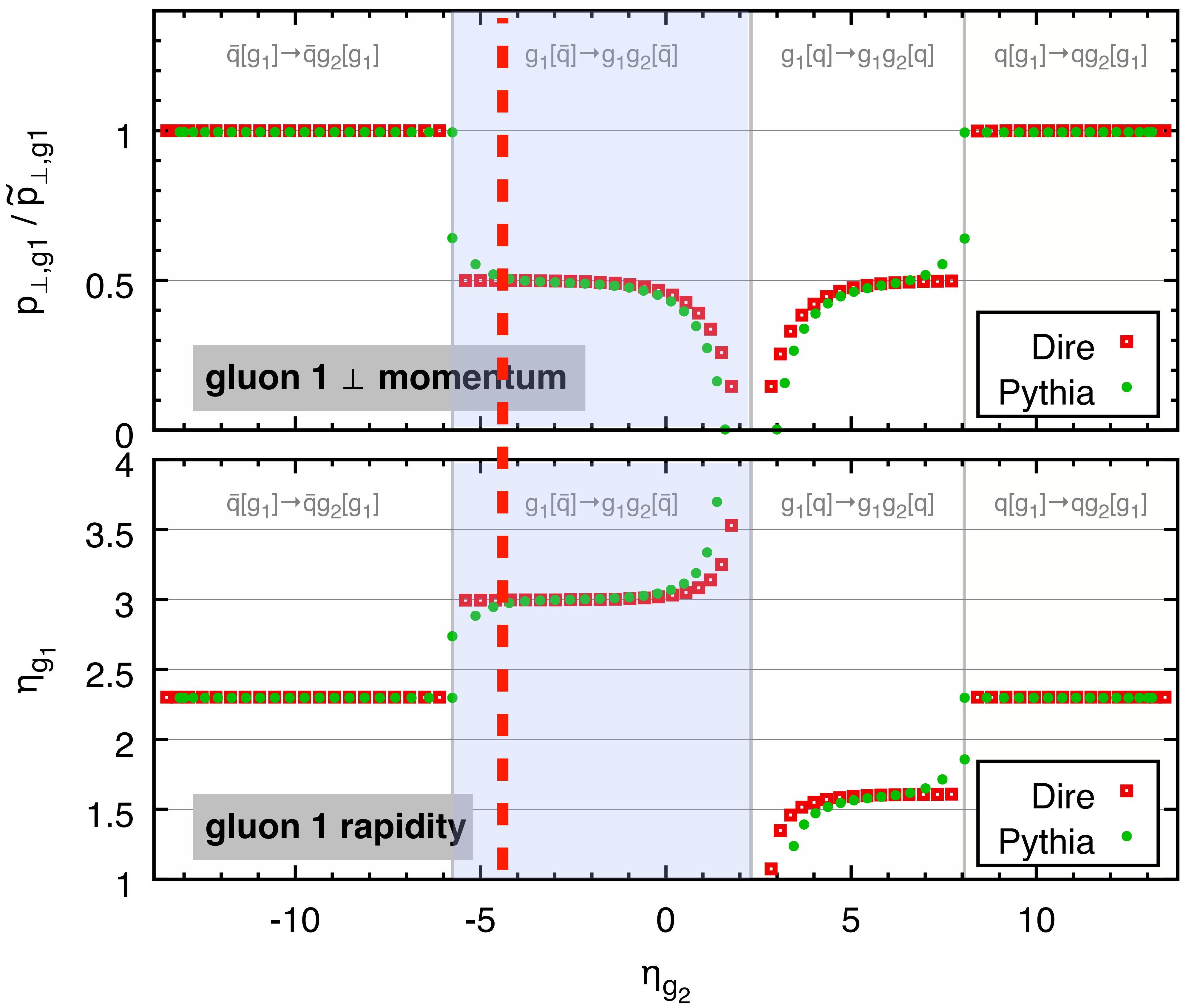

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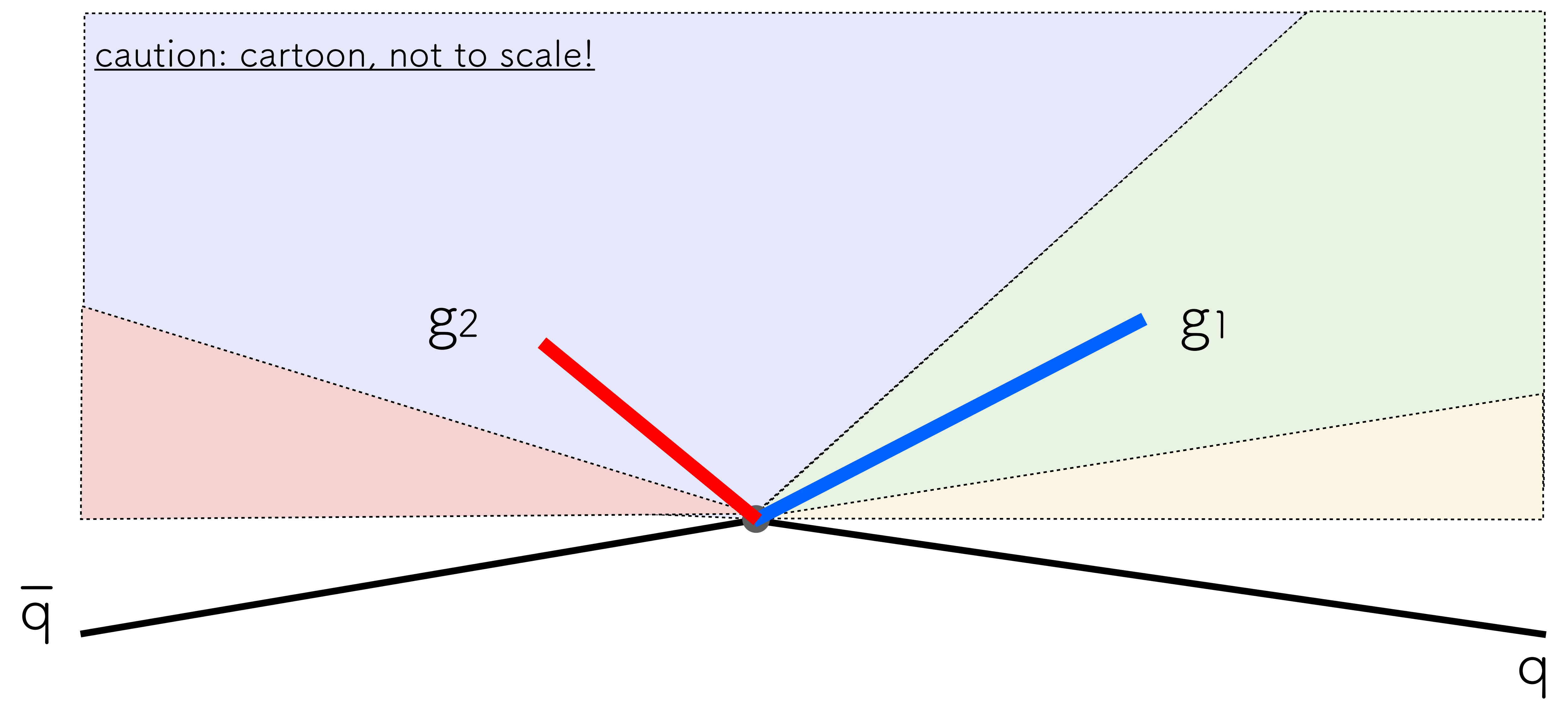

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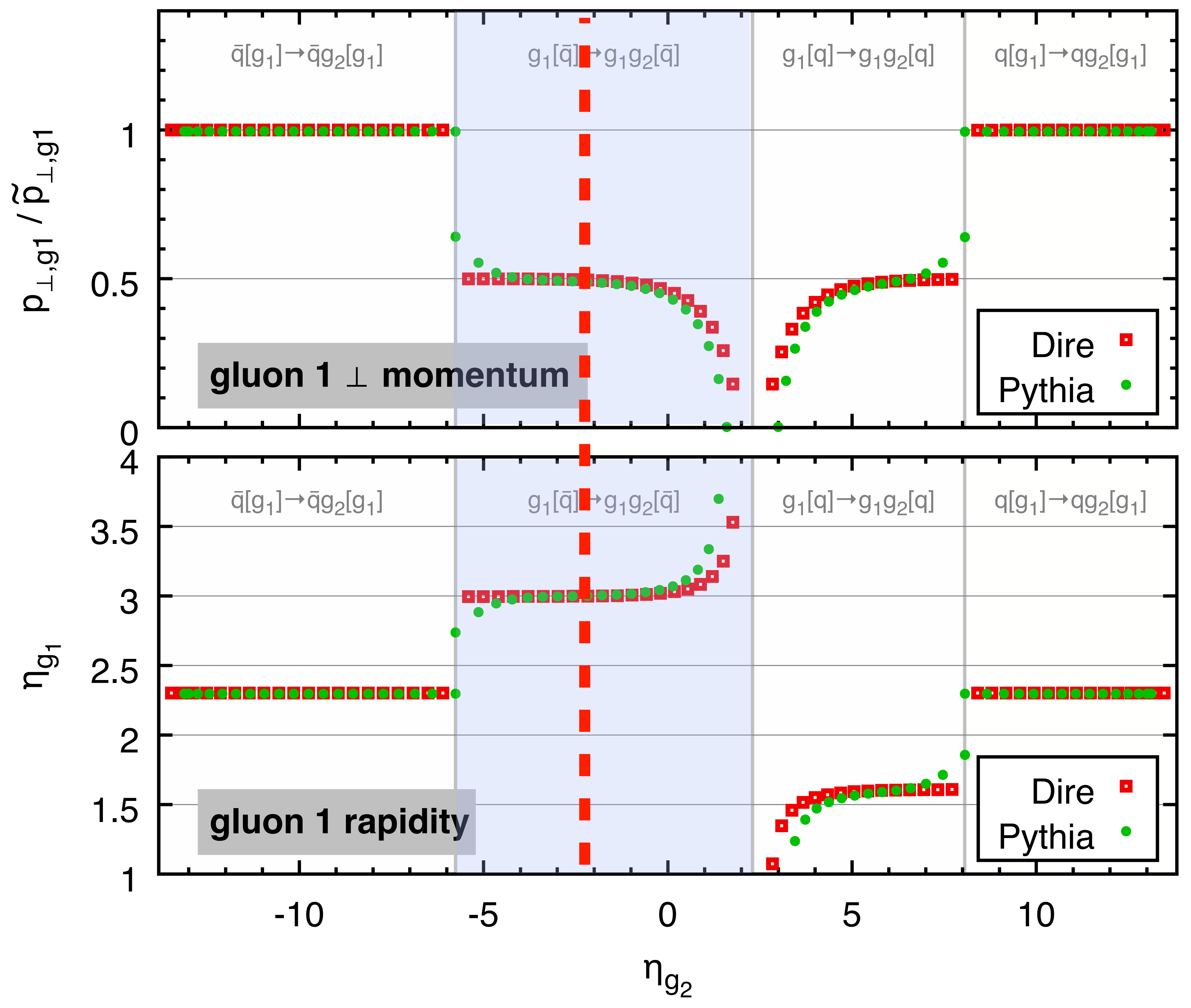

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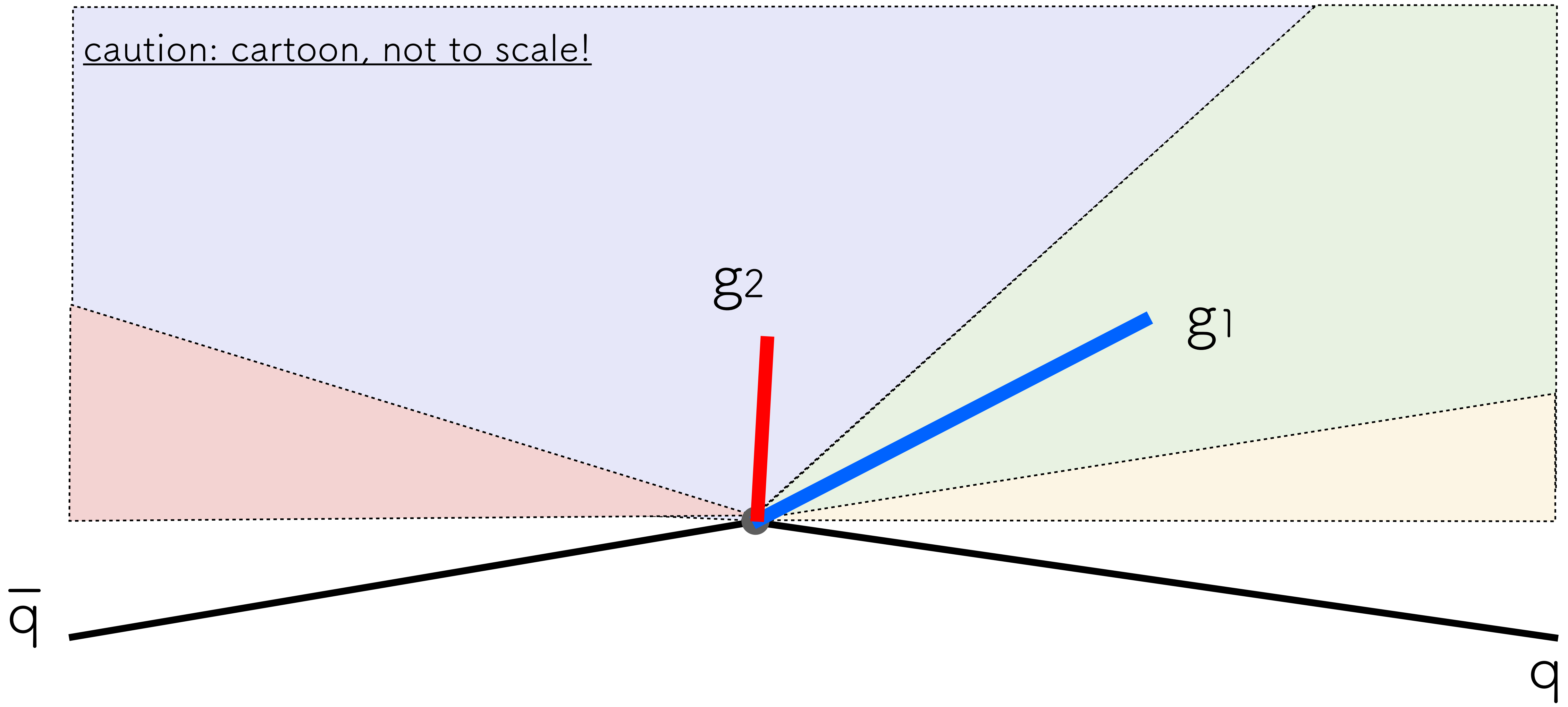

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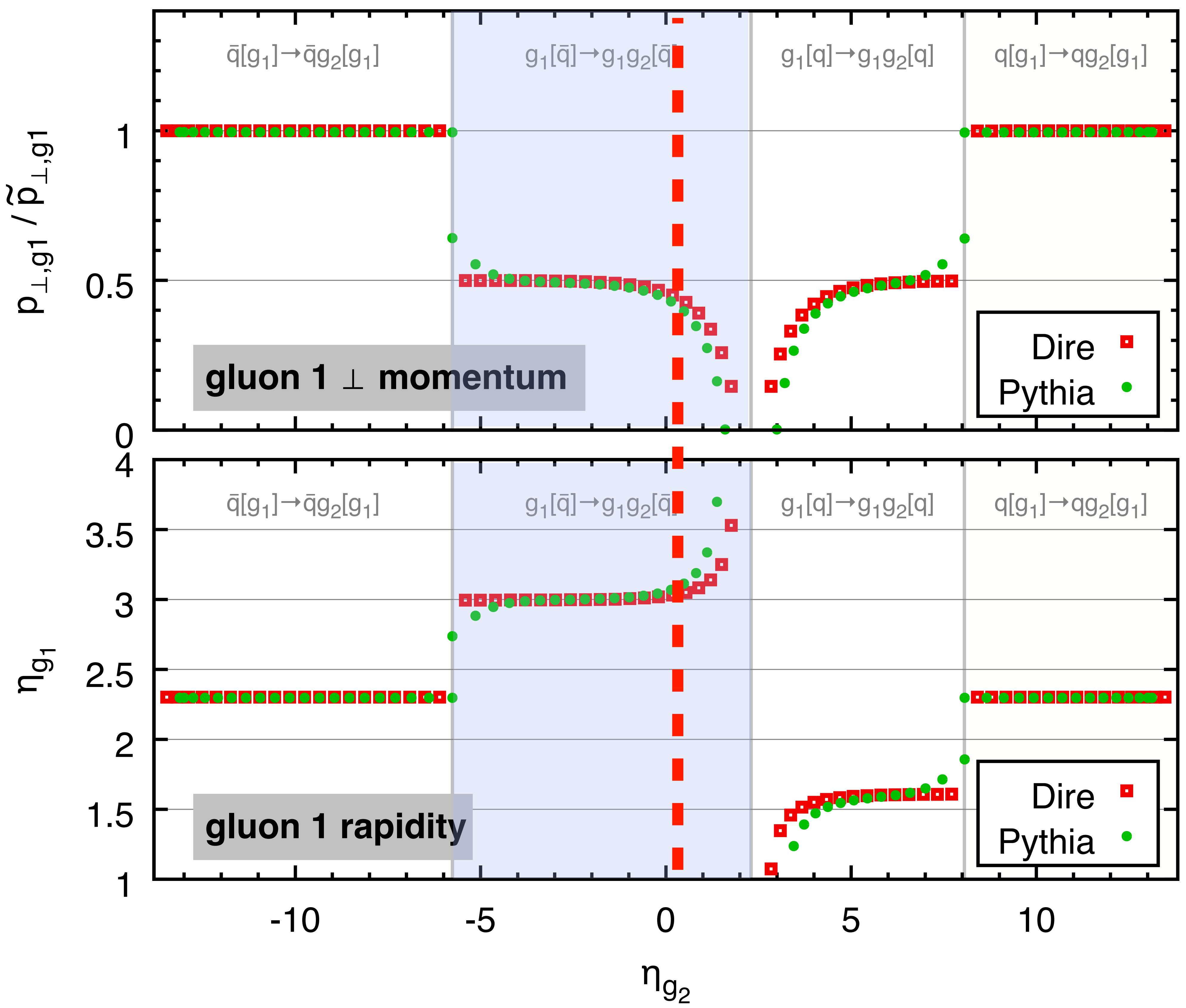

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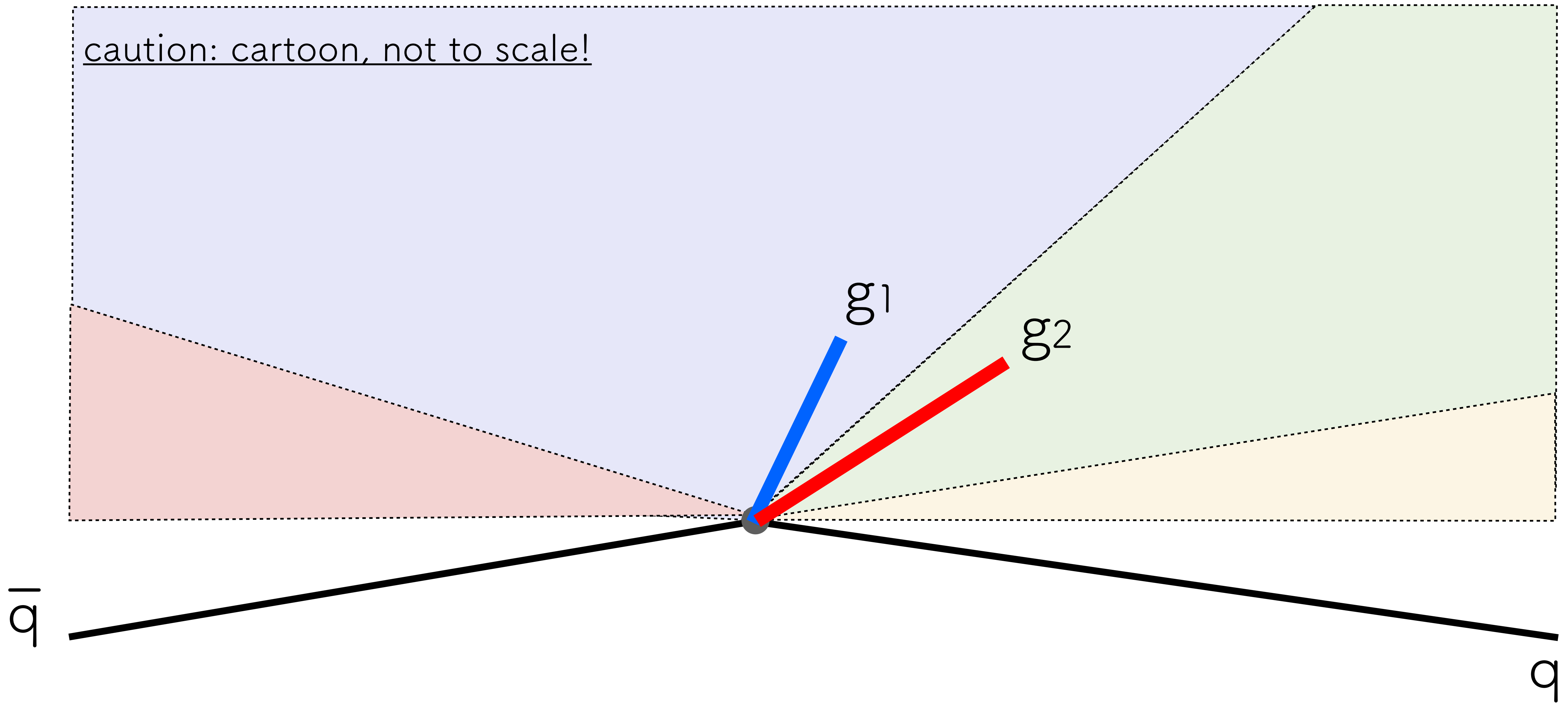

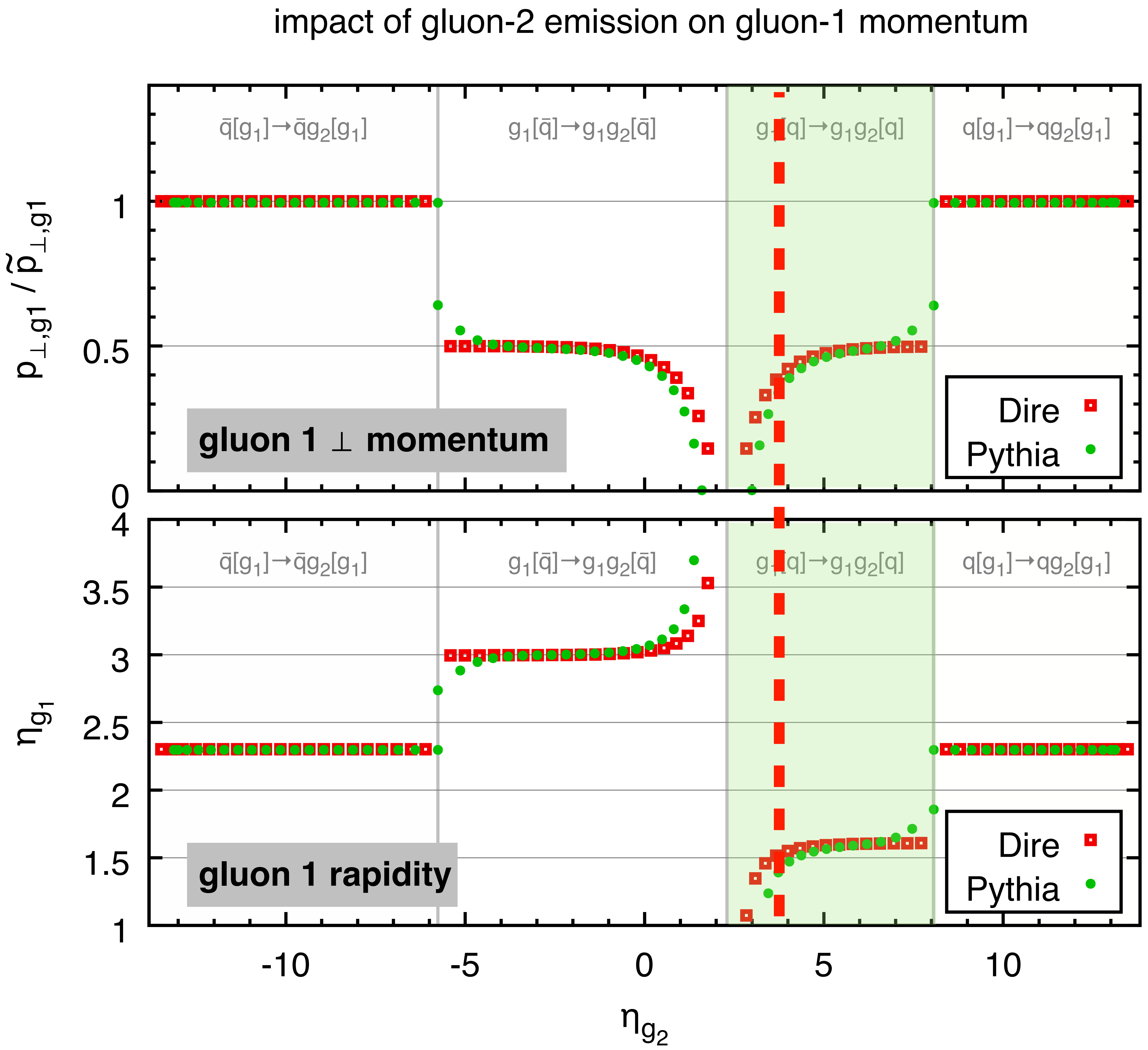

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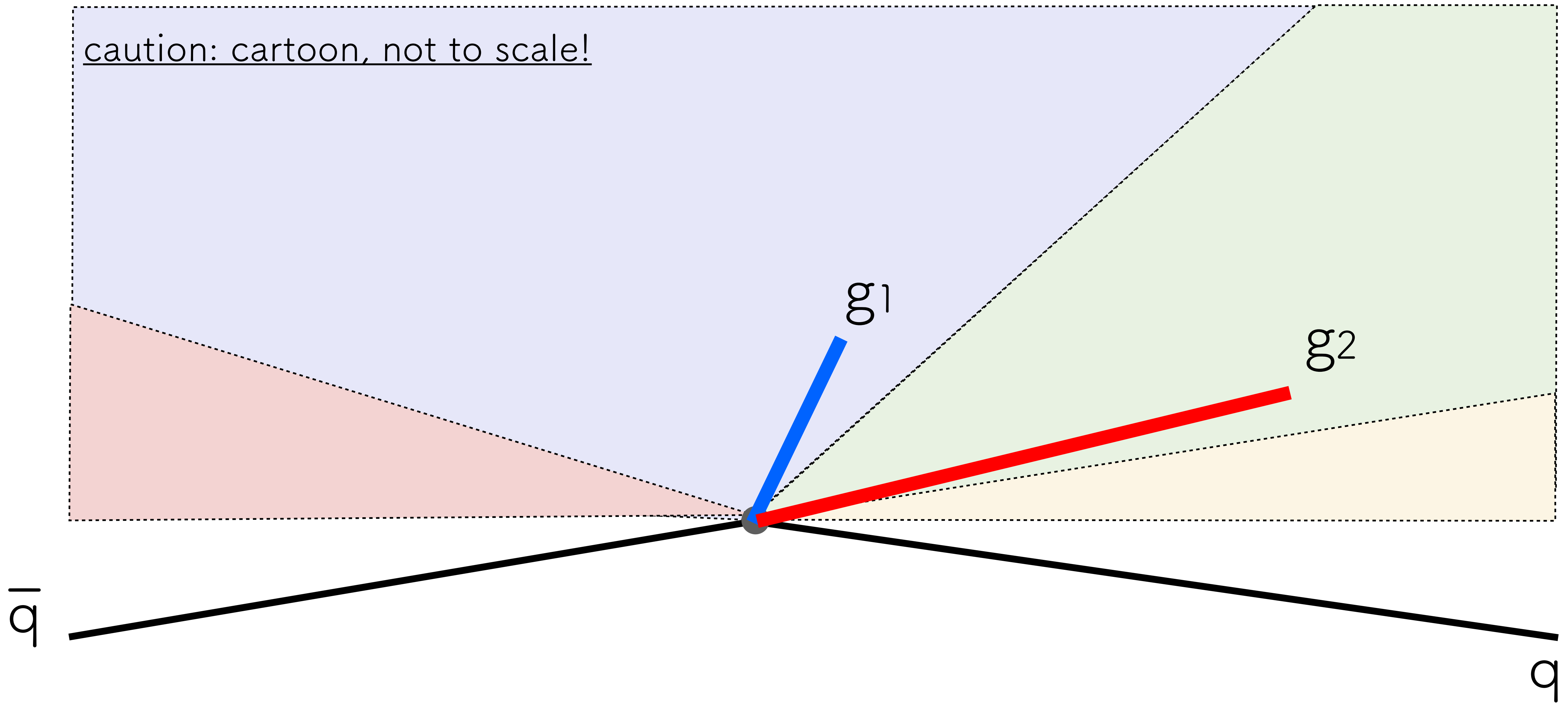

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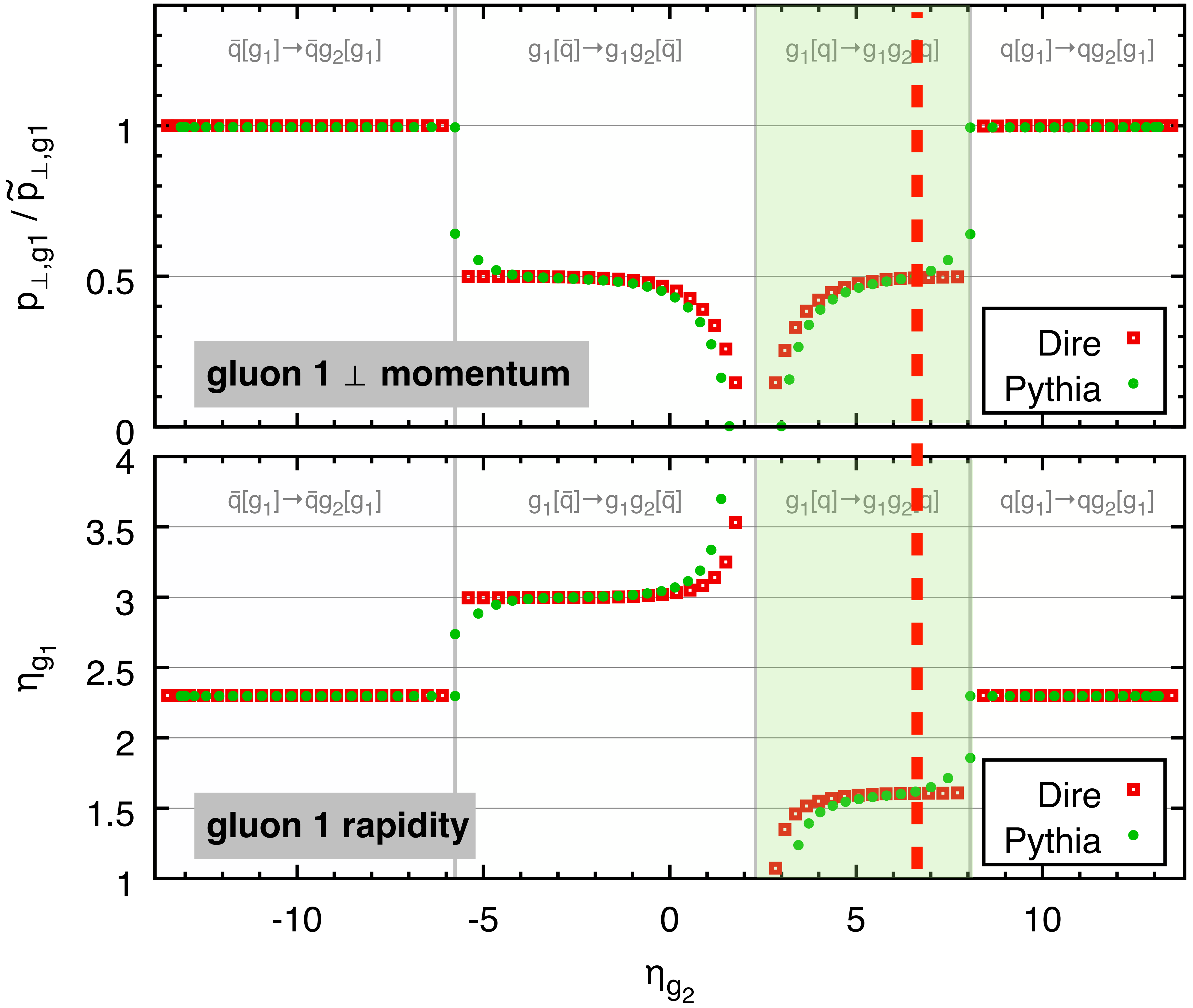

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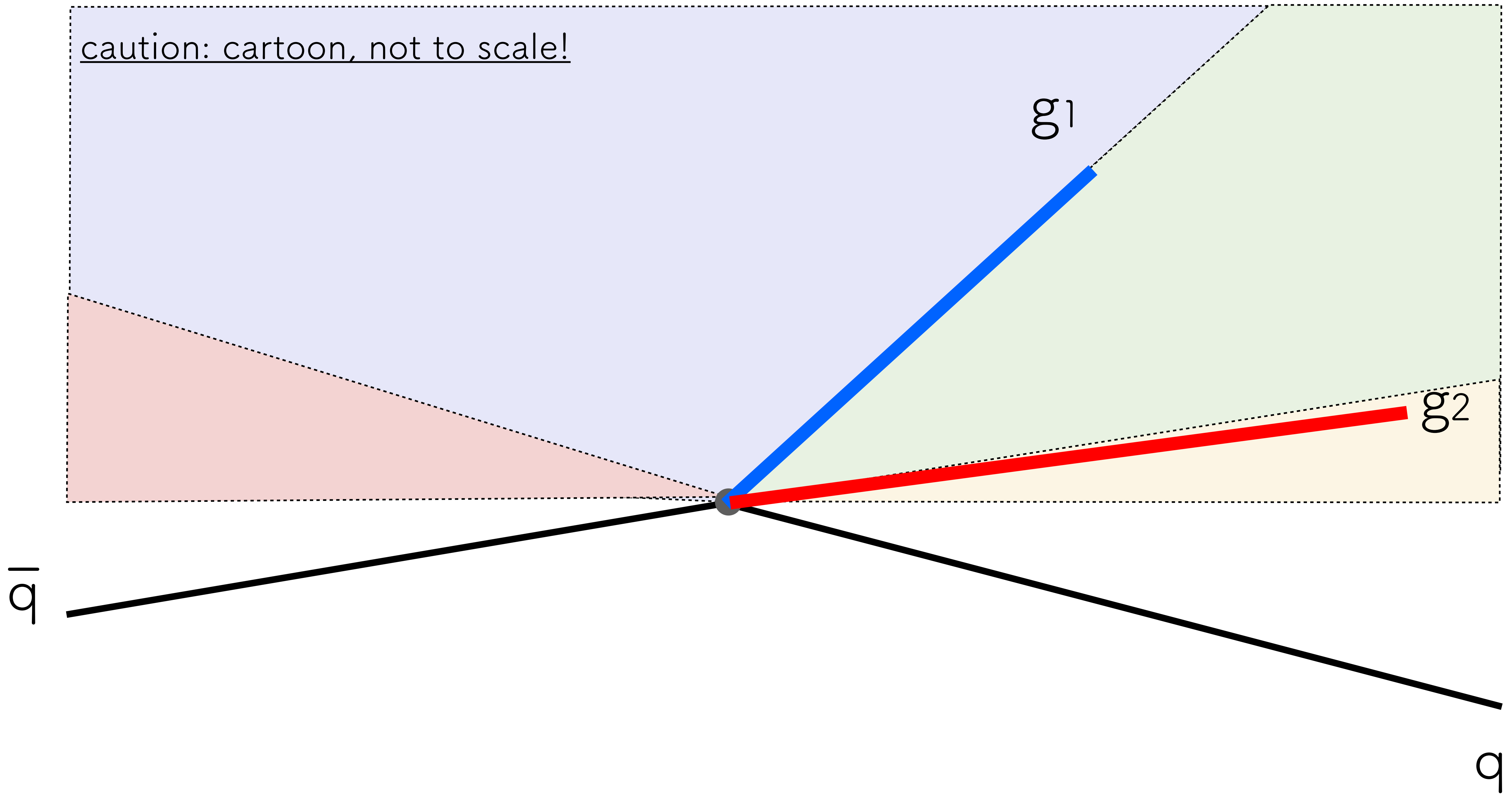

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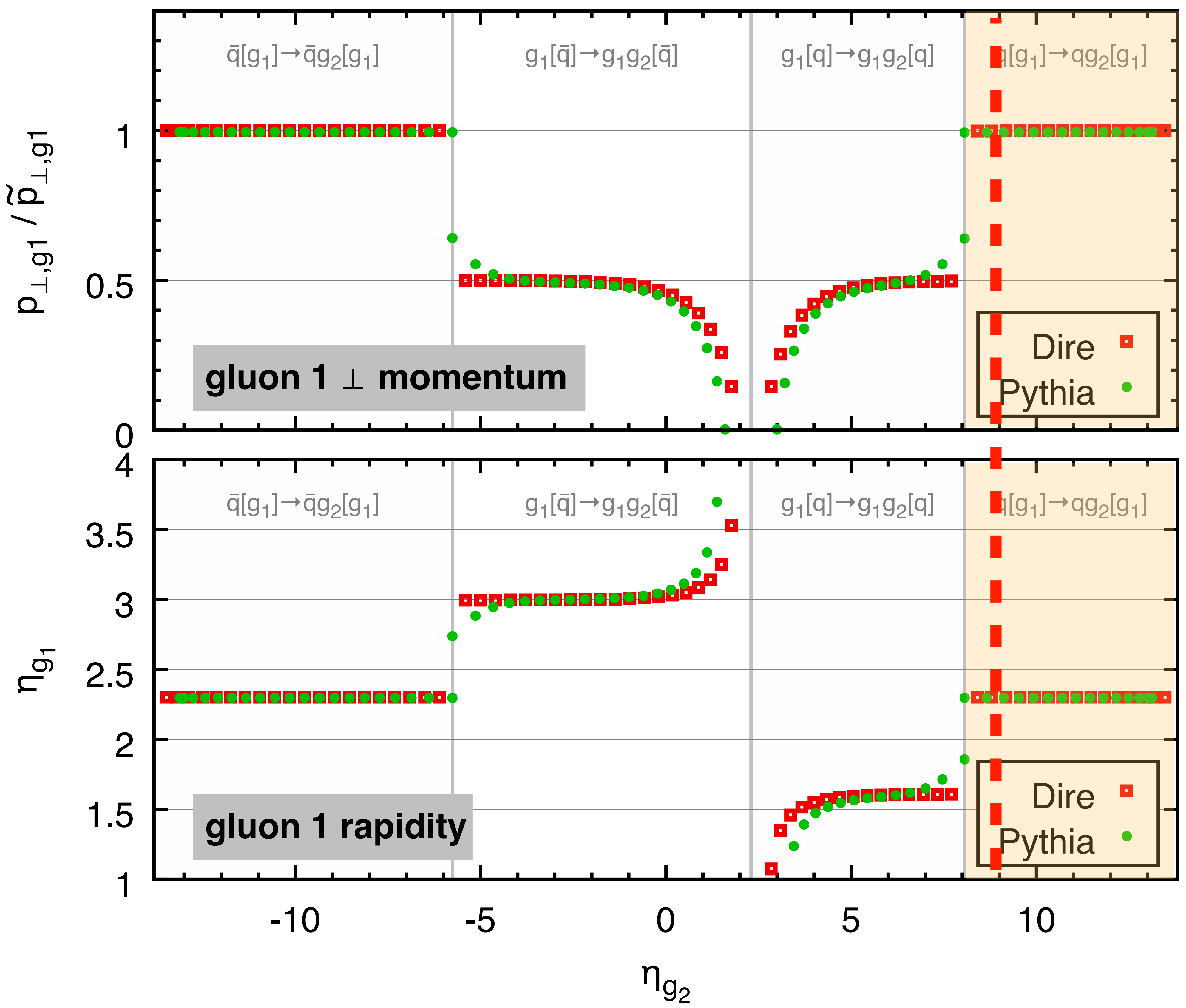

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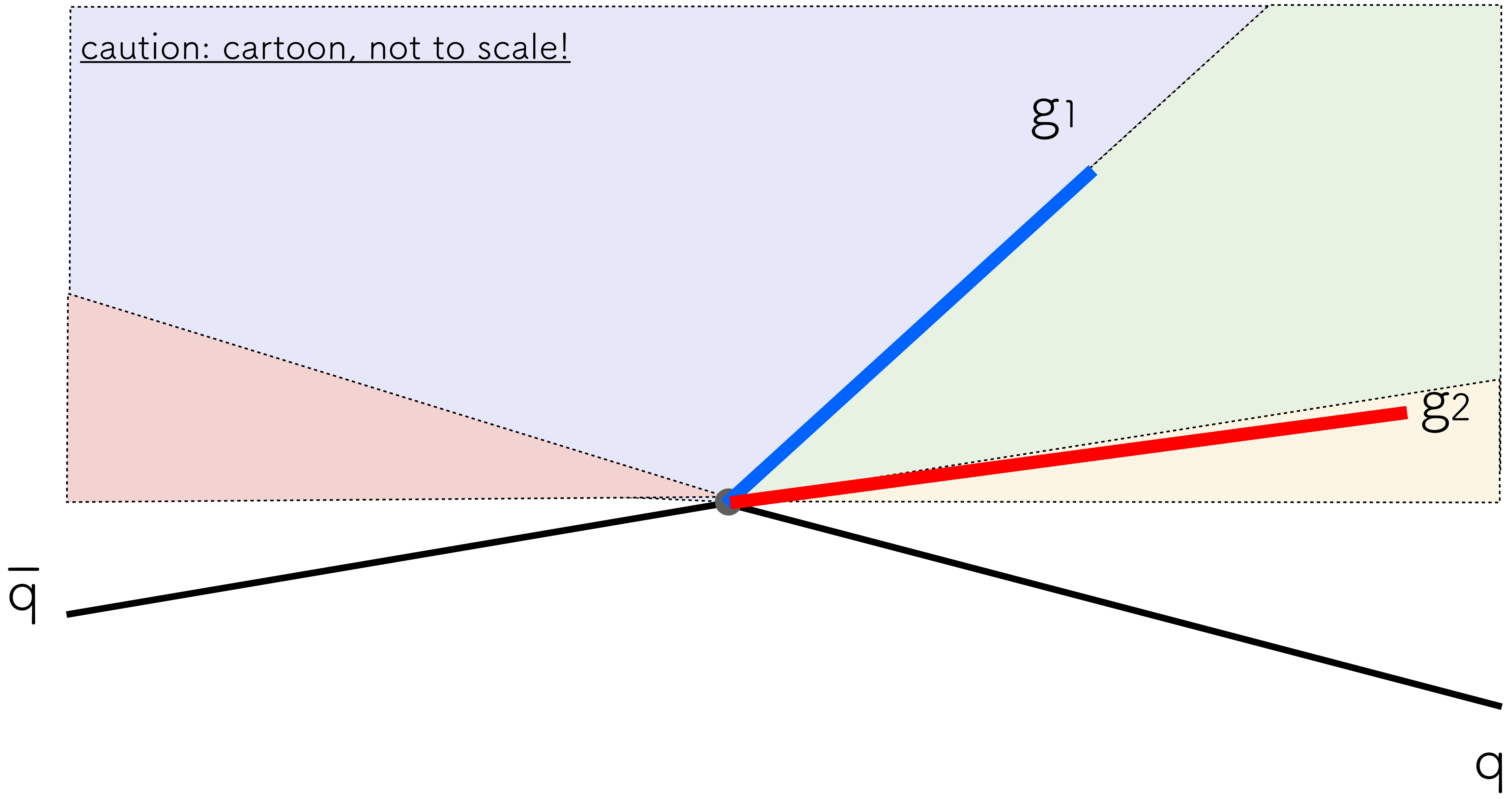

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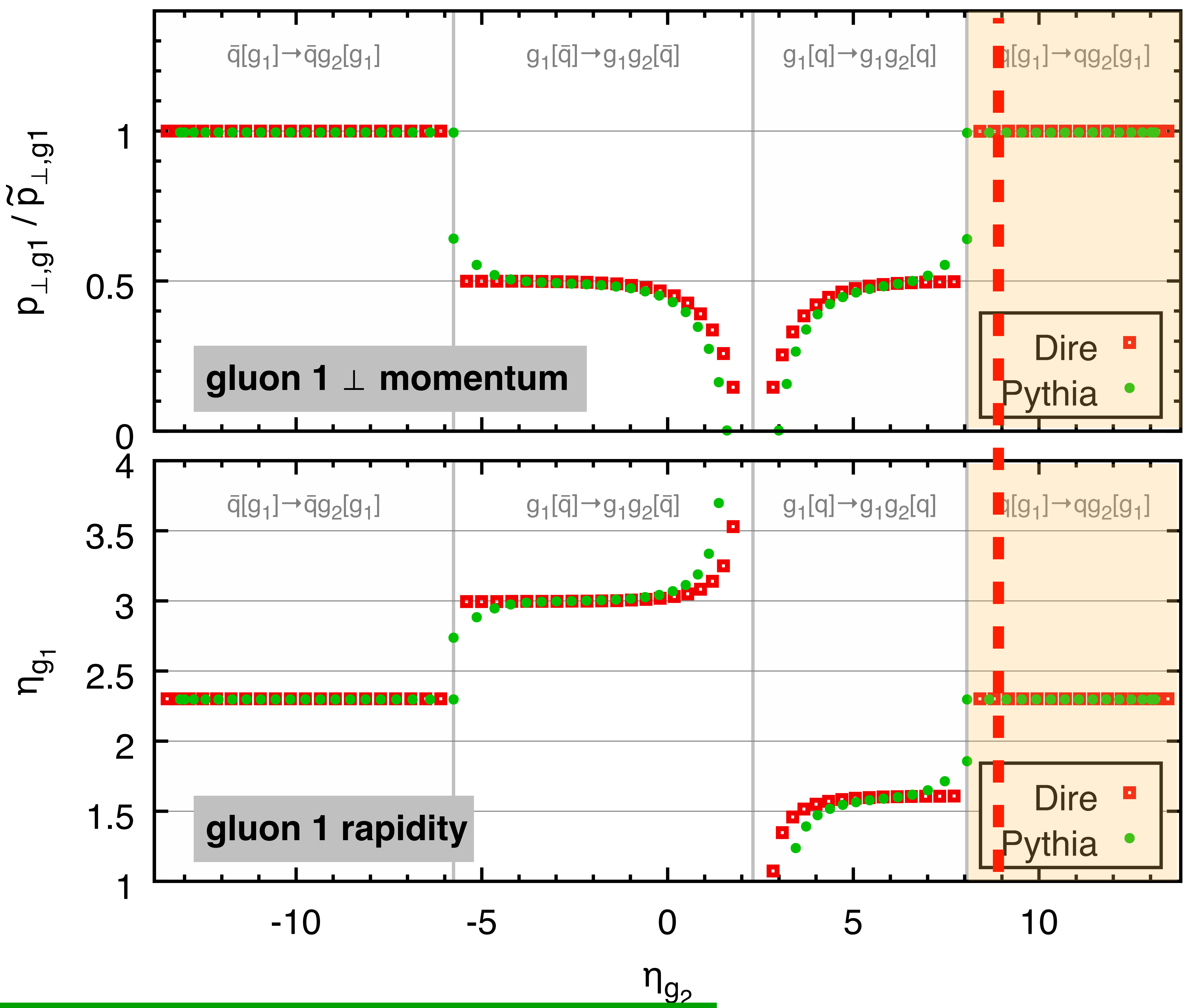

Key observation #1

highly non-trivial cross talk between emissions

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

in equations

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

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