Higgs and Beyond at Colliders

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European Research Council
Established by the European Commission
THE ROYAL SOCIETY

Oxford Department of Physics Colloquium
16 November 2018

“big unanswered questions”

about fundamental particles & their interactions

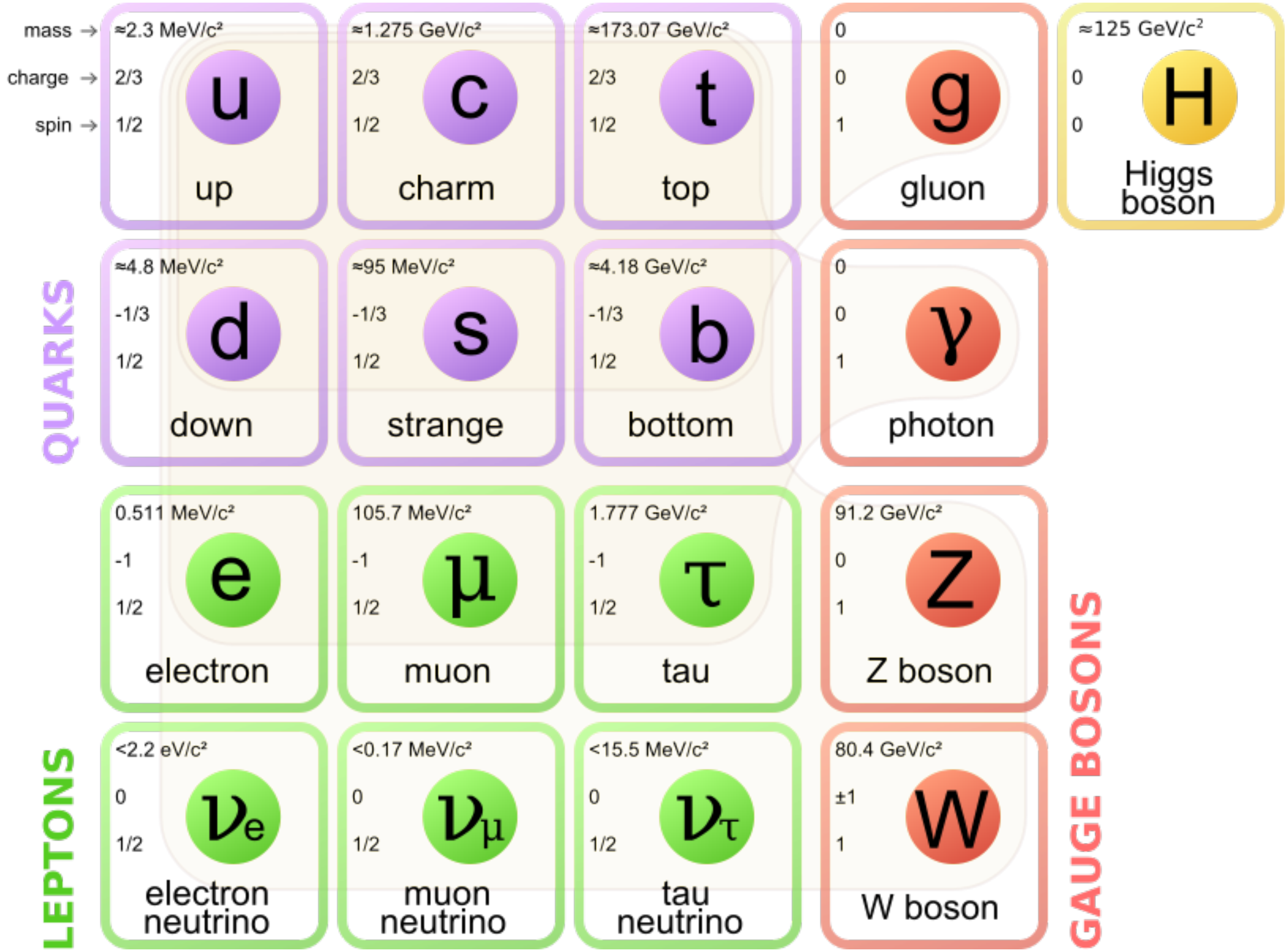
(dark matter, matter-antimatter asymmetry, nature of dark energy, hierarchy of scales…)

v.

“big answerable questions”

and how we go about answering them

The Higgs boson



≈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	0 0 1 g gluon	≈125 GeV/c² 0 0 H Higgs boson
≈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 0 1 γ photon	
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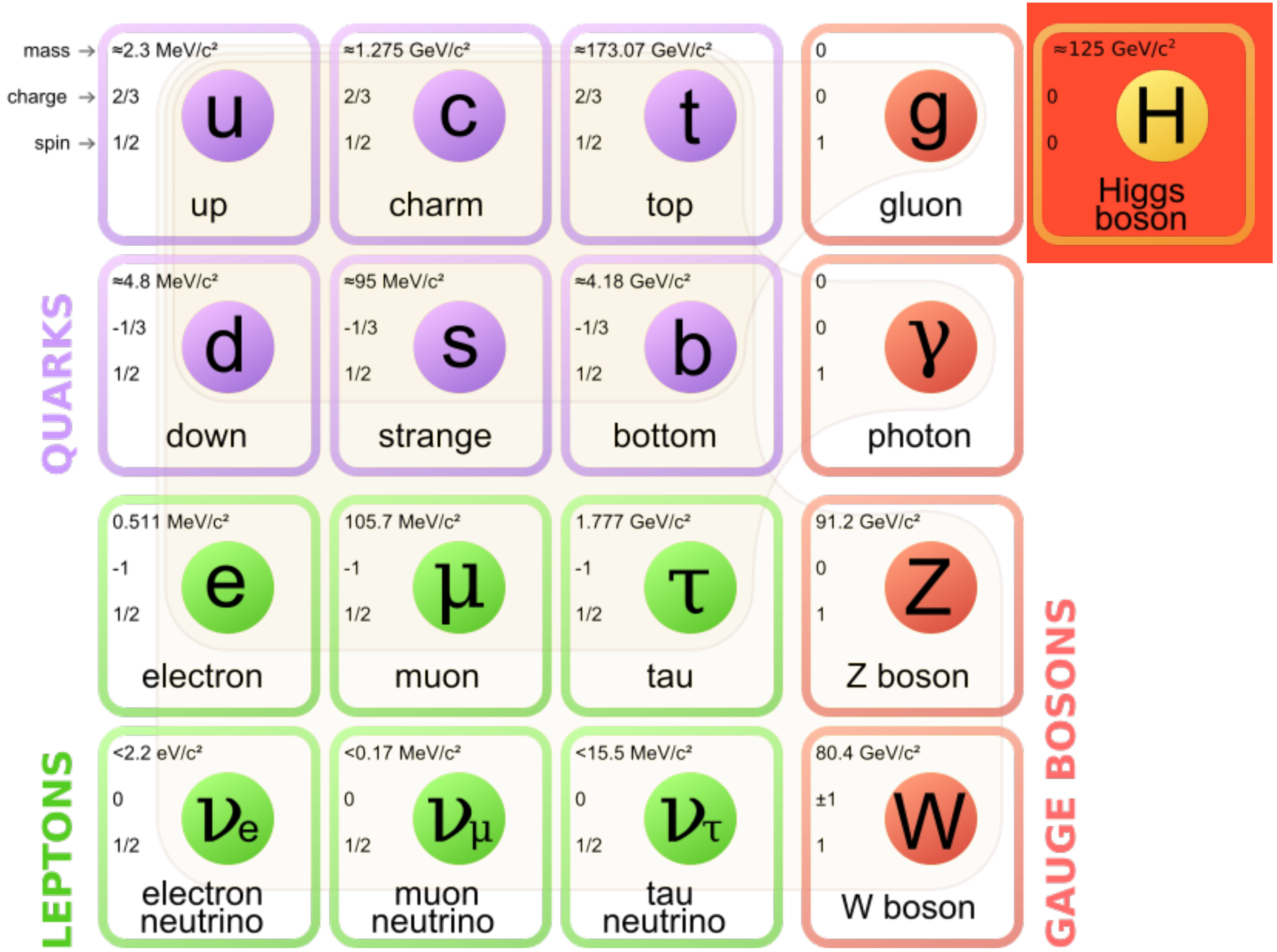
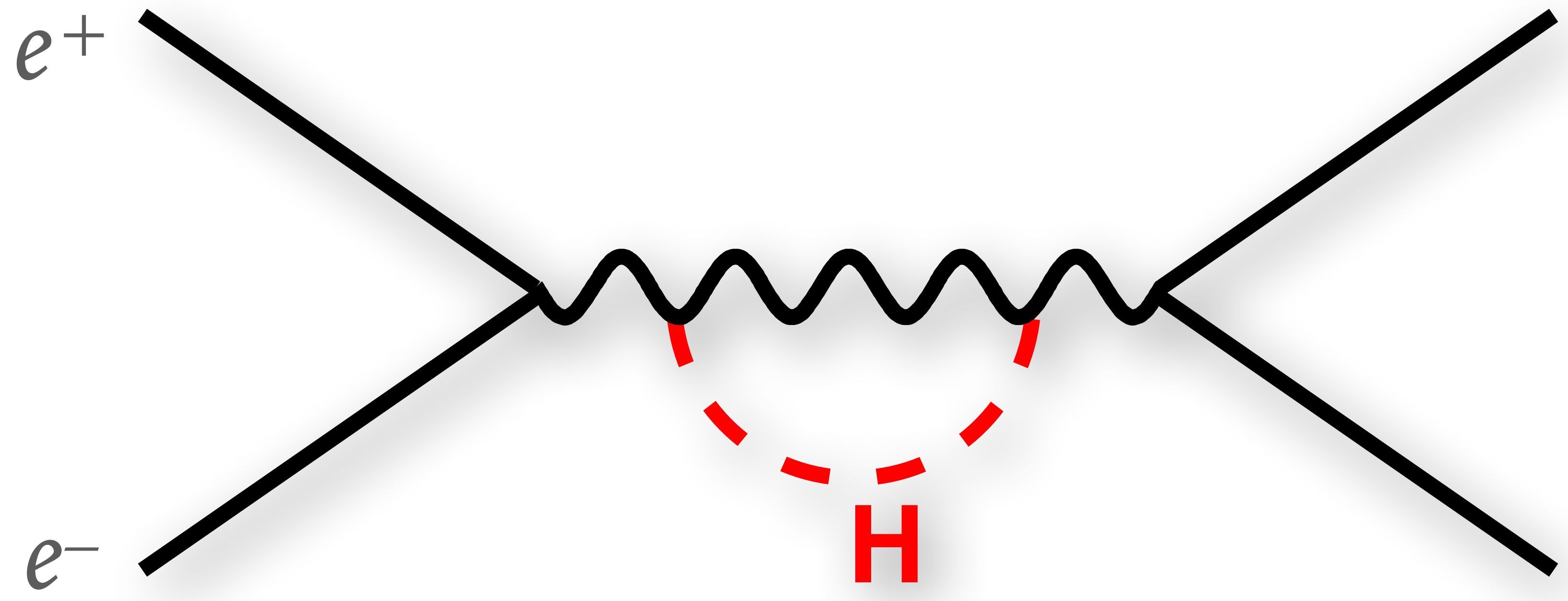
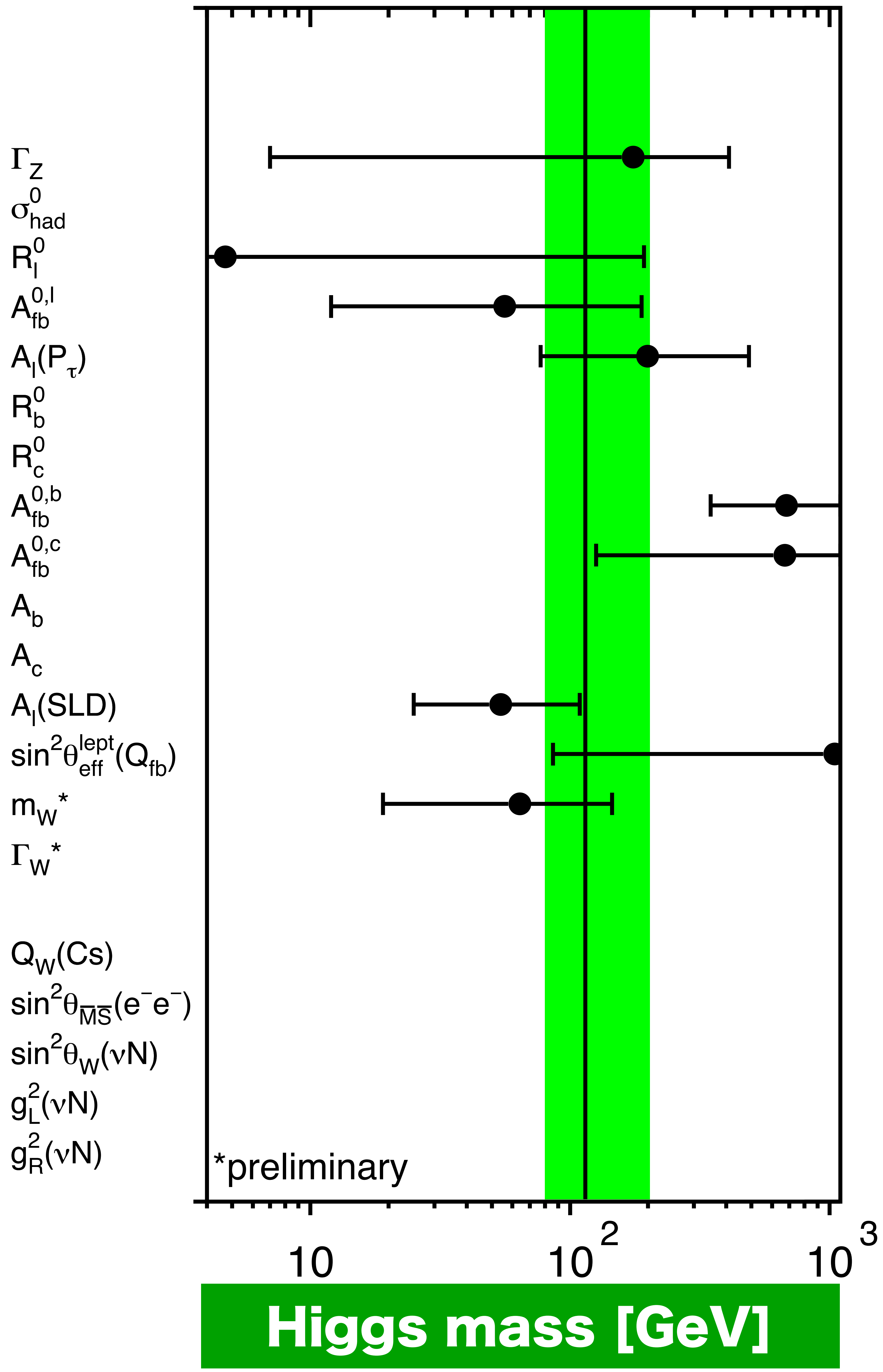




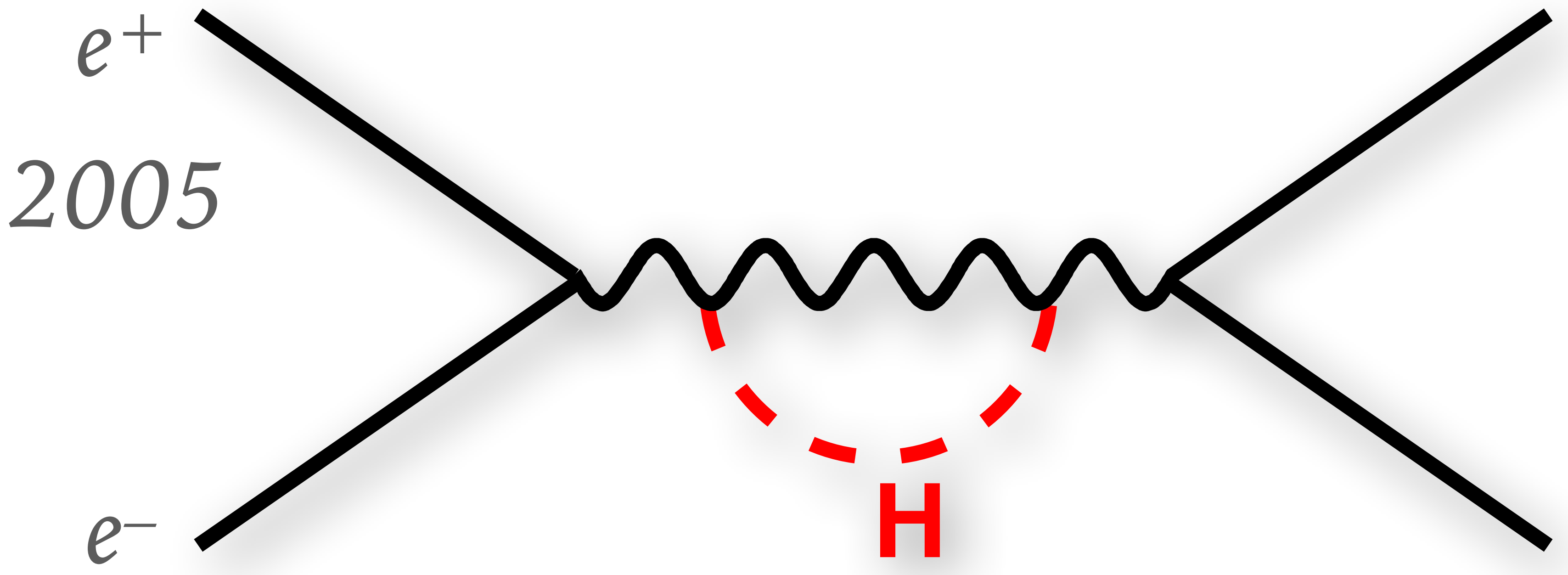
Higgs boson existence long known to be consistent with older e^+e^- collider data (cf. LEP, 1989–2000 + SLD).

Tested through the small effect of virtual Higgs bosons on high-precision *(per-mil)* measurements.

Could be interpreted as a weak Higgs mass constraint.



LEP electroweak working group, 2005
hep-ex/0509008



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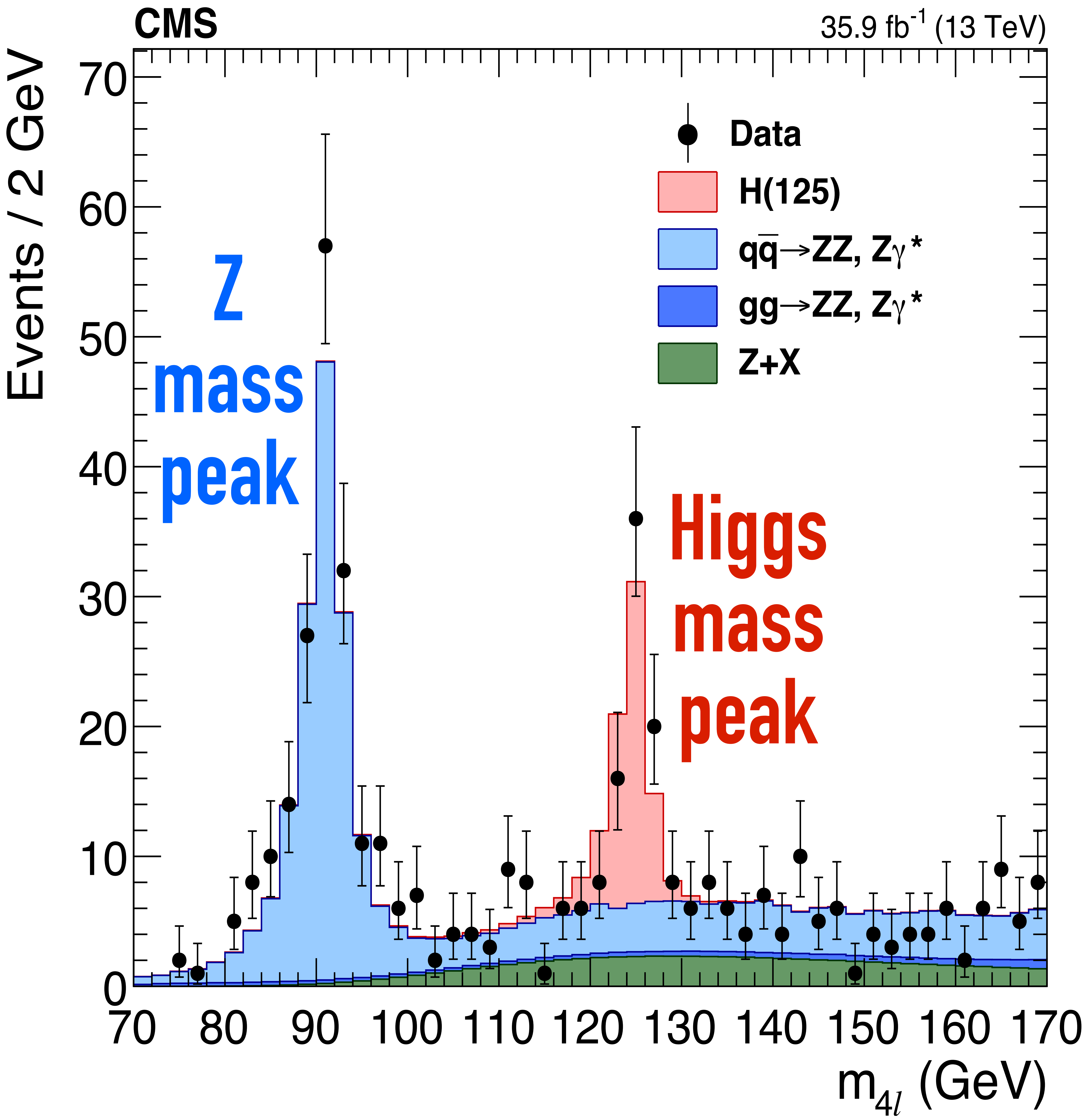
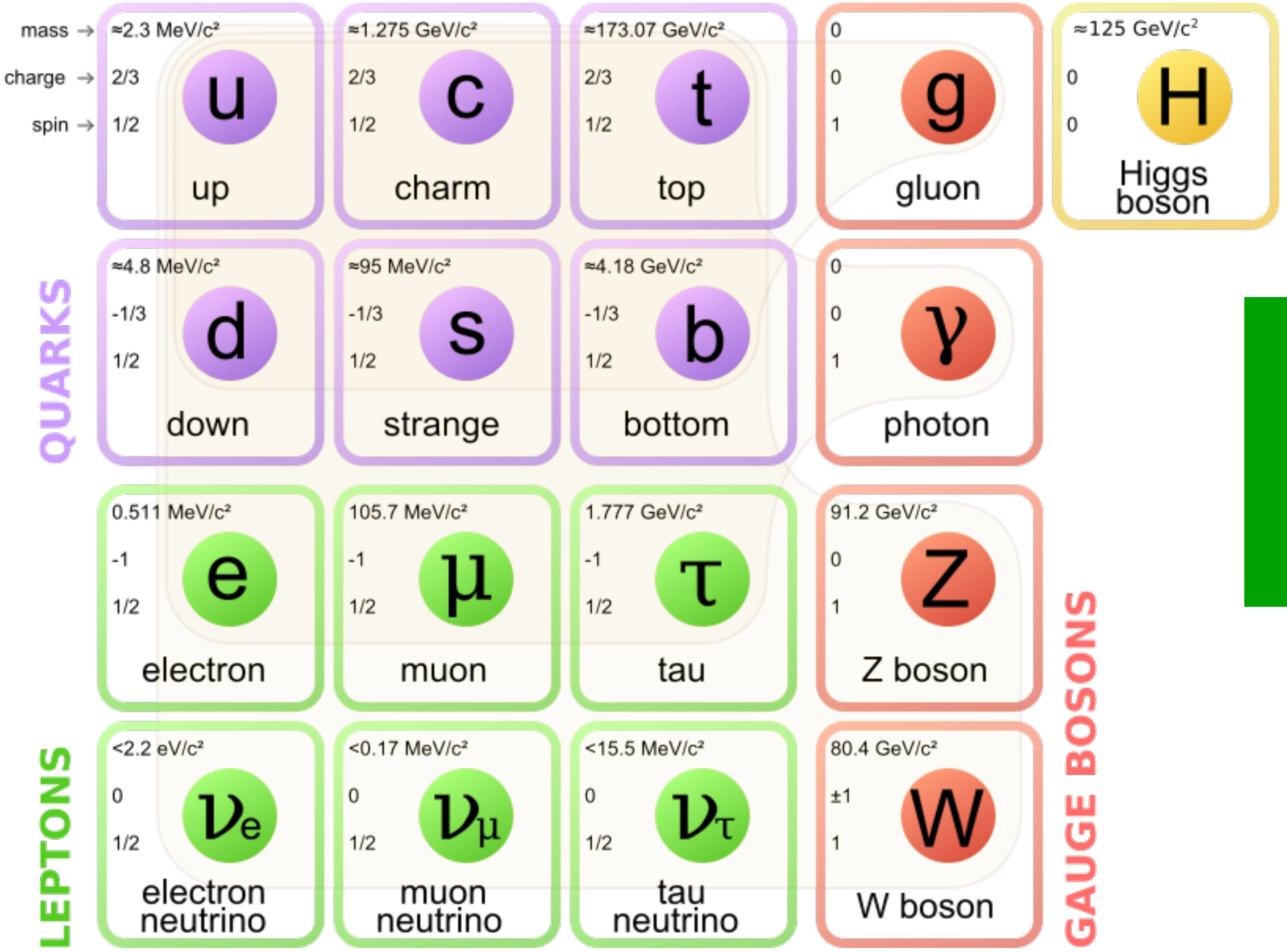


ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC):

2012 discovery of a Higgs-like boson

plot shows more recent data

The Higgs boson



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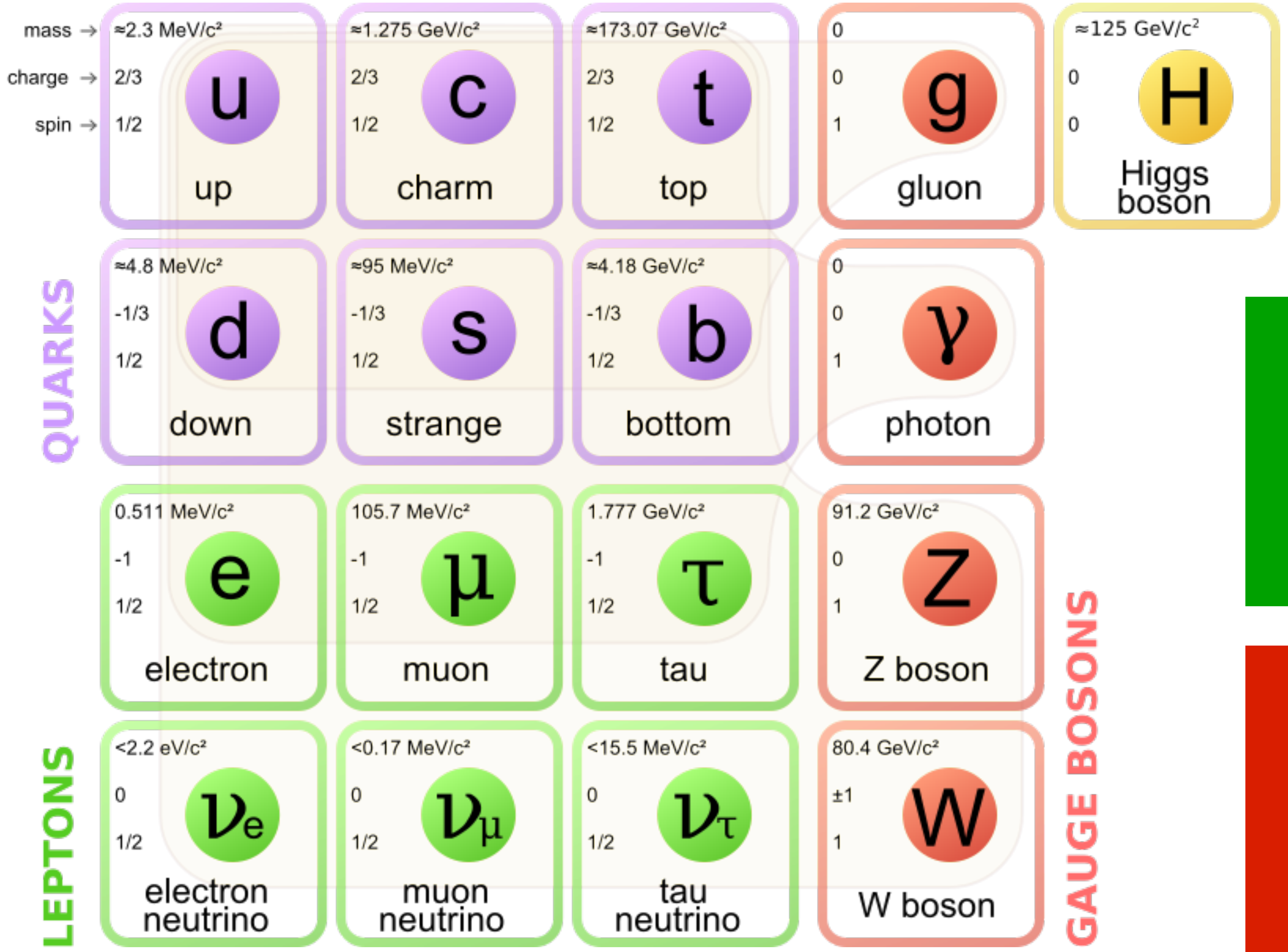
Success!

“The Standard Model is complete”

The Higgs boson



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Success!

“The Standard Model is complete”

Crisis!

No supersymmetry, no extra dimensions, there’s nothing left for us to do . . .

The New York Times

By **DENNIS OVERBYE** JUNE 19, 2017

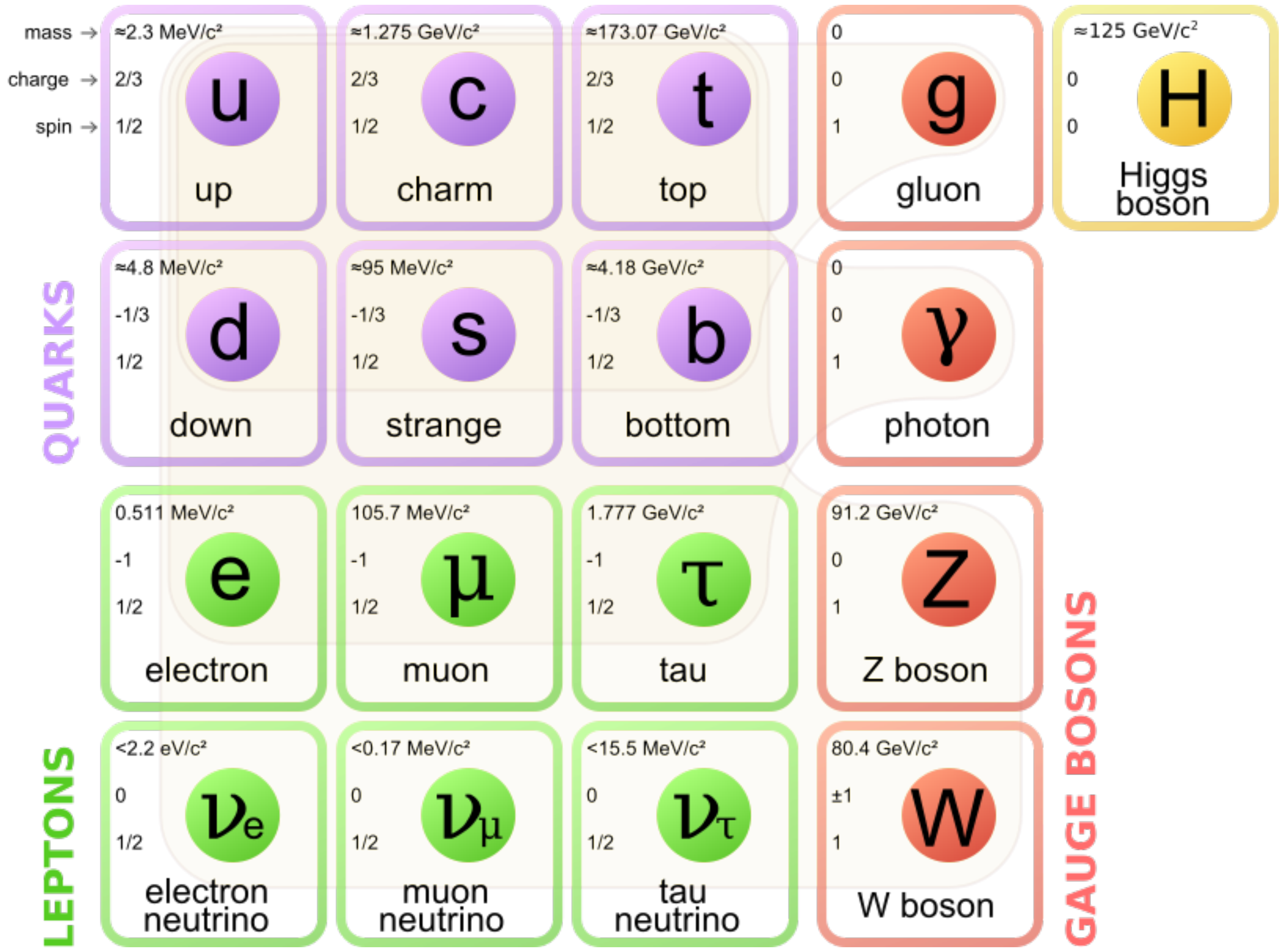
[…]

What if there is nothing new to discover? ***That prospect is now a cloud hanging over the physics community.***

[…]

https://www.nytimes.com/2017/06/19/science/cern-large-hadron-collider-higgs-physics.html

what is the Standard Model?



particles

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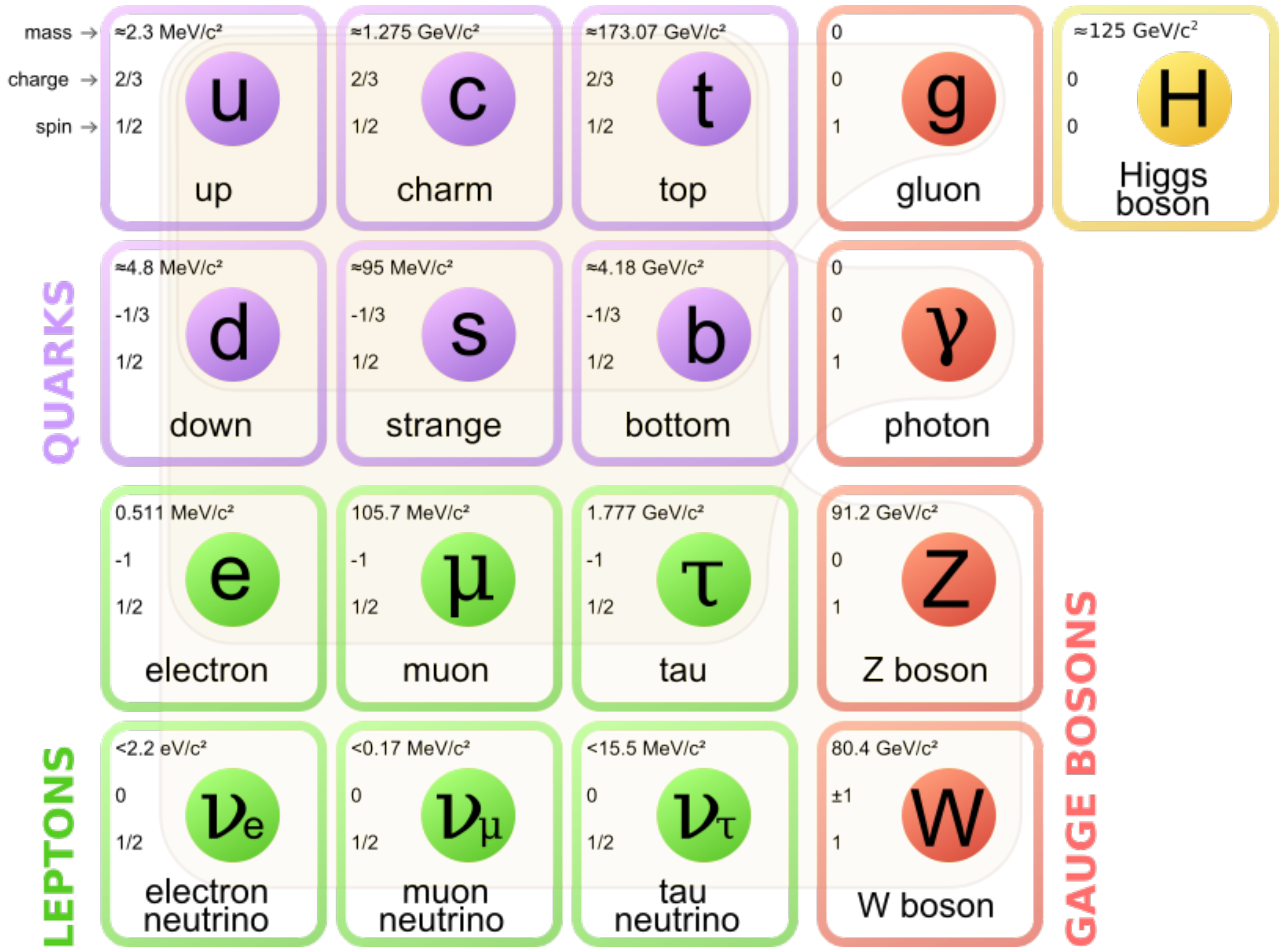

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particles

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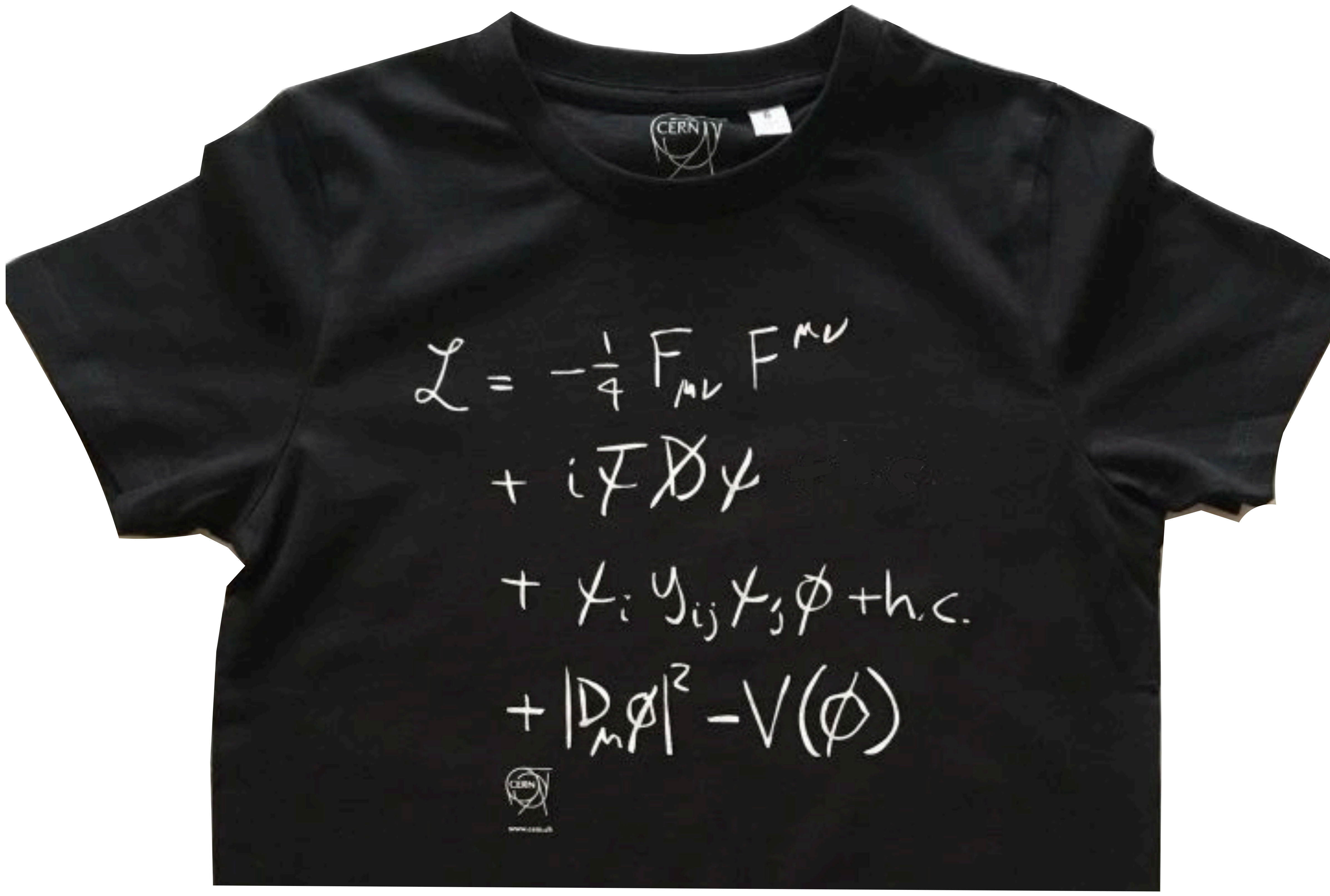
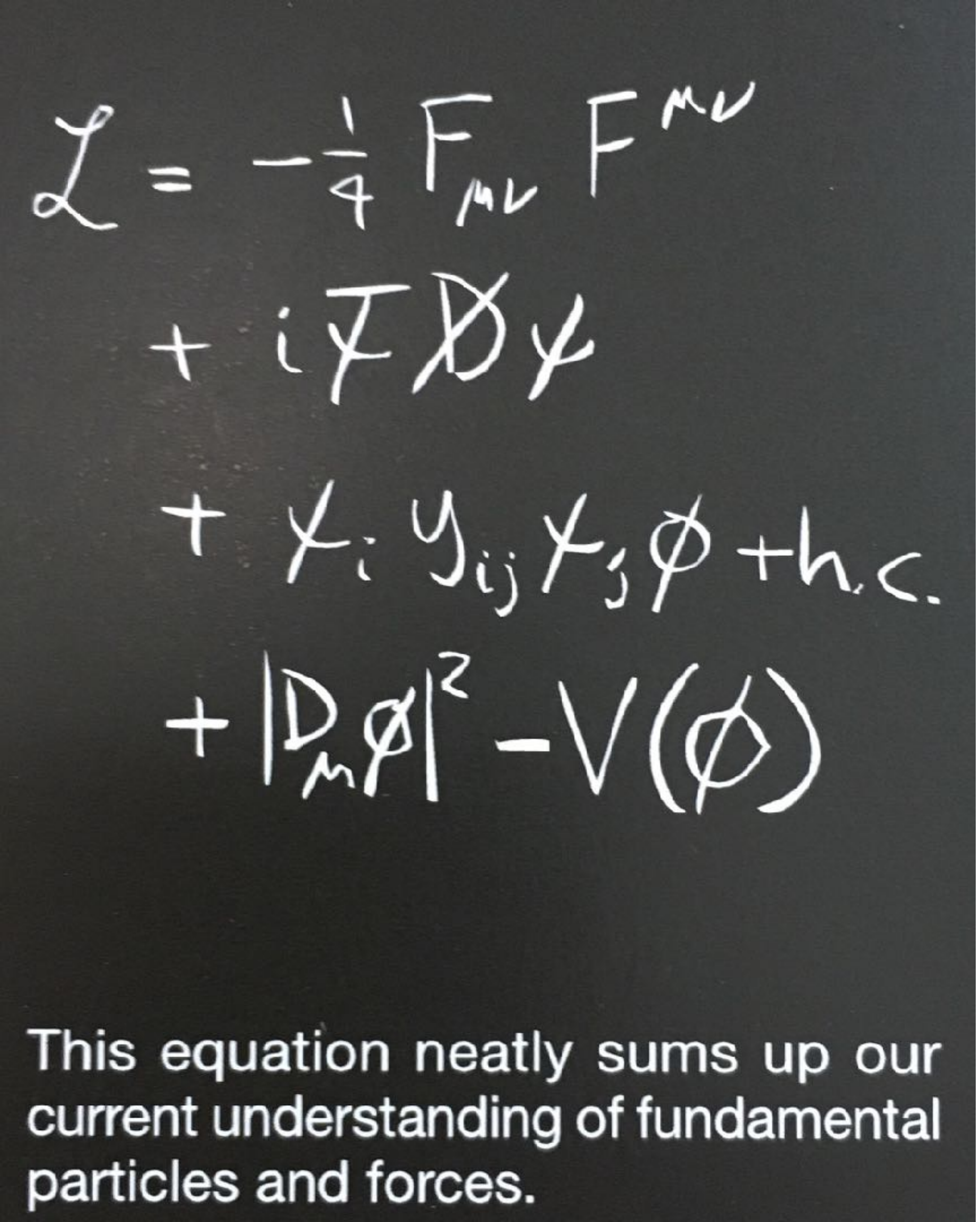


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

interactions

STANDARD MODEL — KNOWABLE UNKNOWNS



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

This is what you get when you buy one of those famous CERN T-shirts

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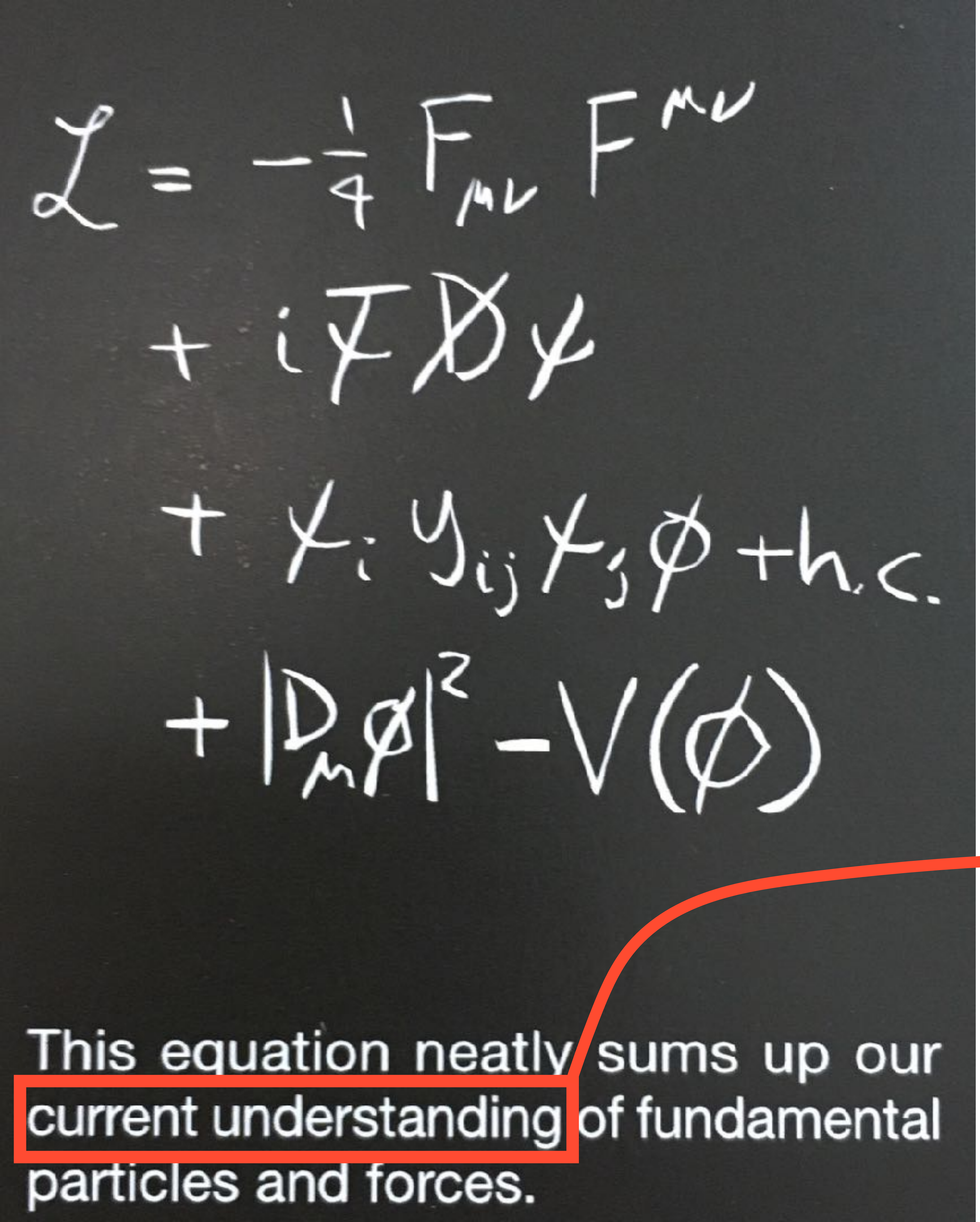

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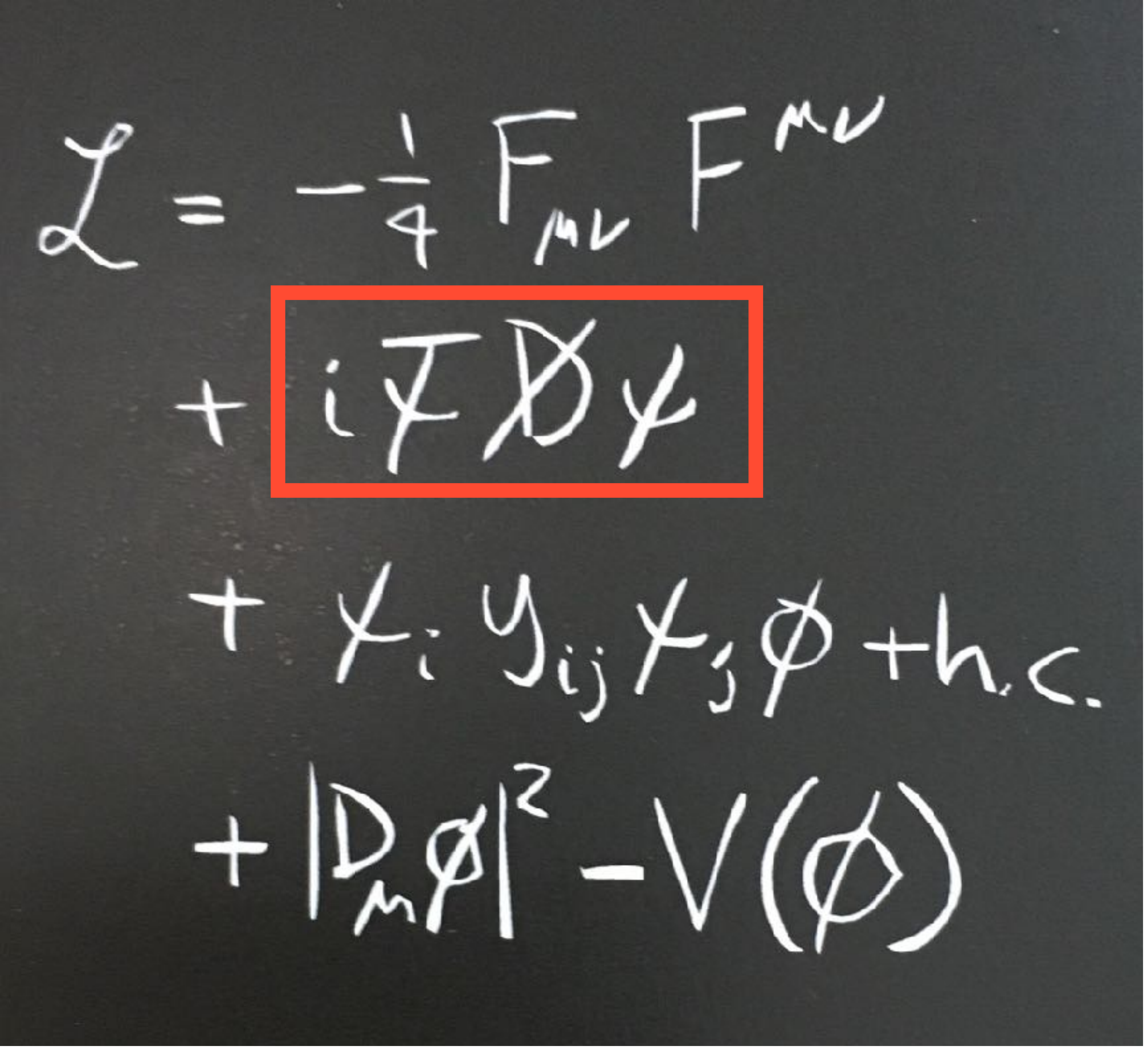
“understanding” = knowledge ?

“understanding” = assumption ?



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NOTATION

A_μ : gauge field *photons, gluons, W,Z*

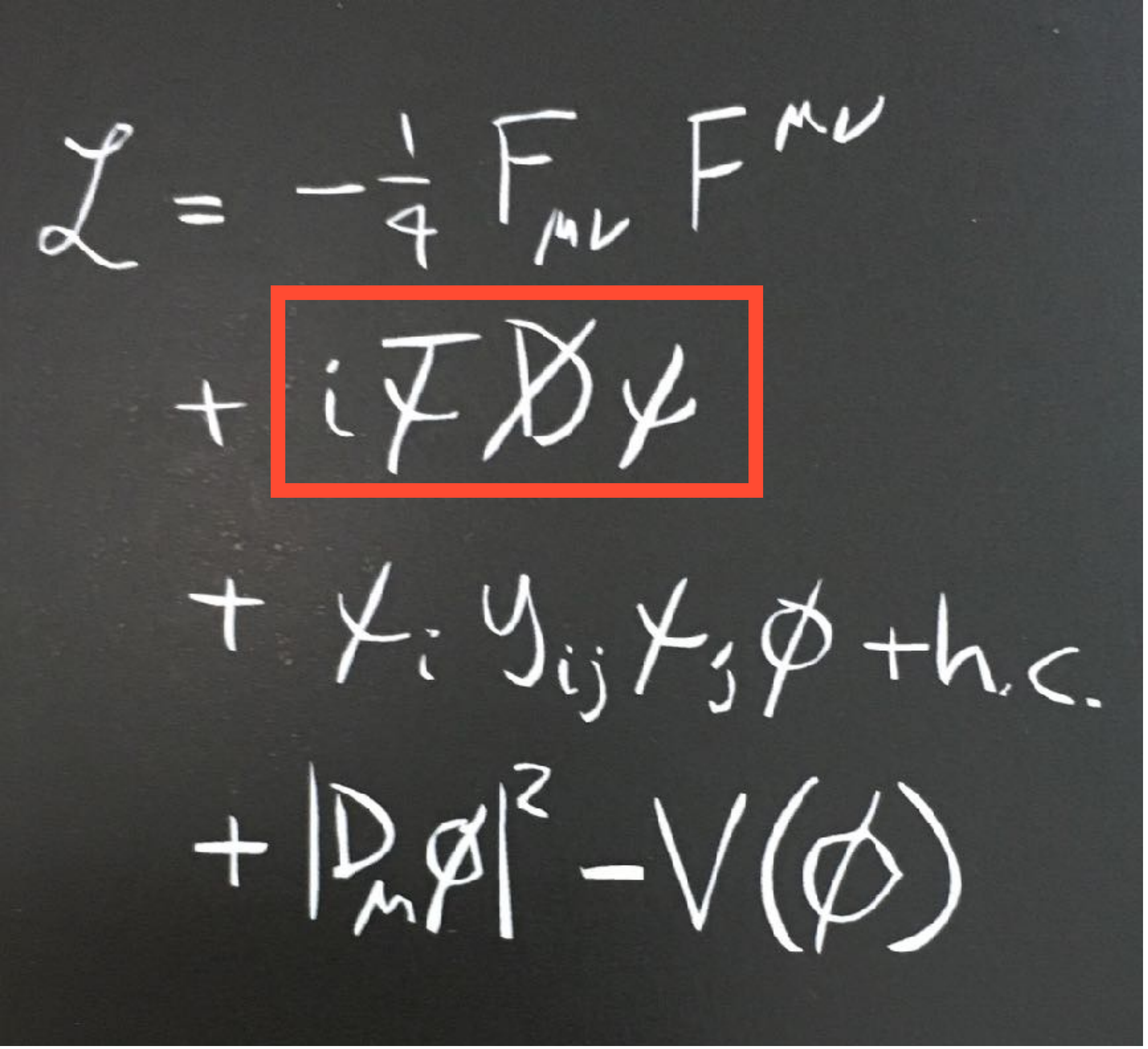
ψ : fermion field *quarks & leptons*

ϕ : Higgs field

$= \phi_0(\text{VEV}) + H(\text{Higgs})$

$$D_\mu = \partial_\mu + ieA_\mu \text{ etc.}$$

$$F_{\mu\nu} \sim [D_\mu, D_\nu]$$



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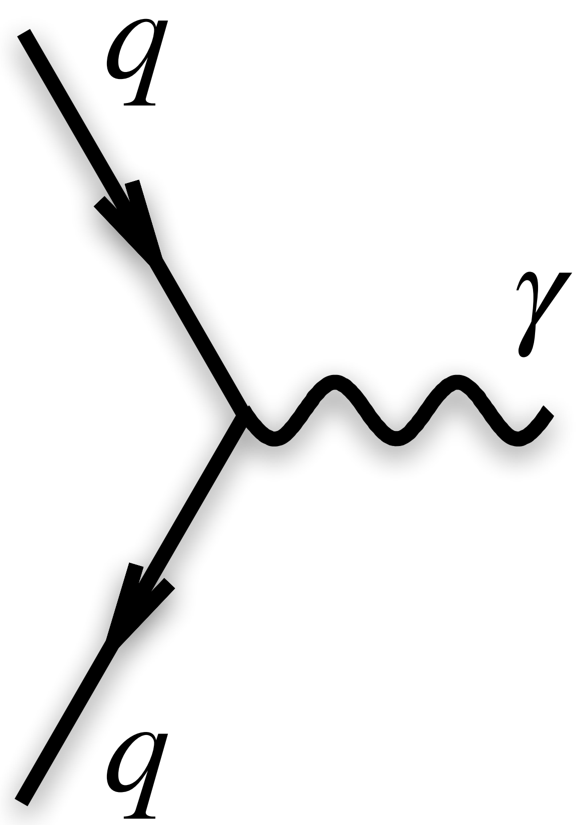
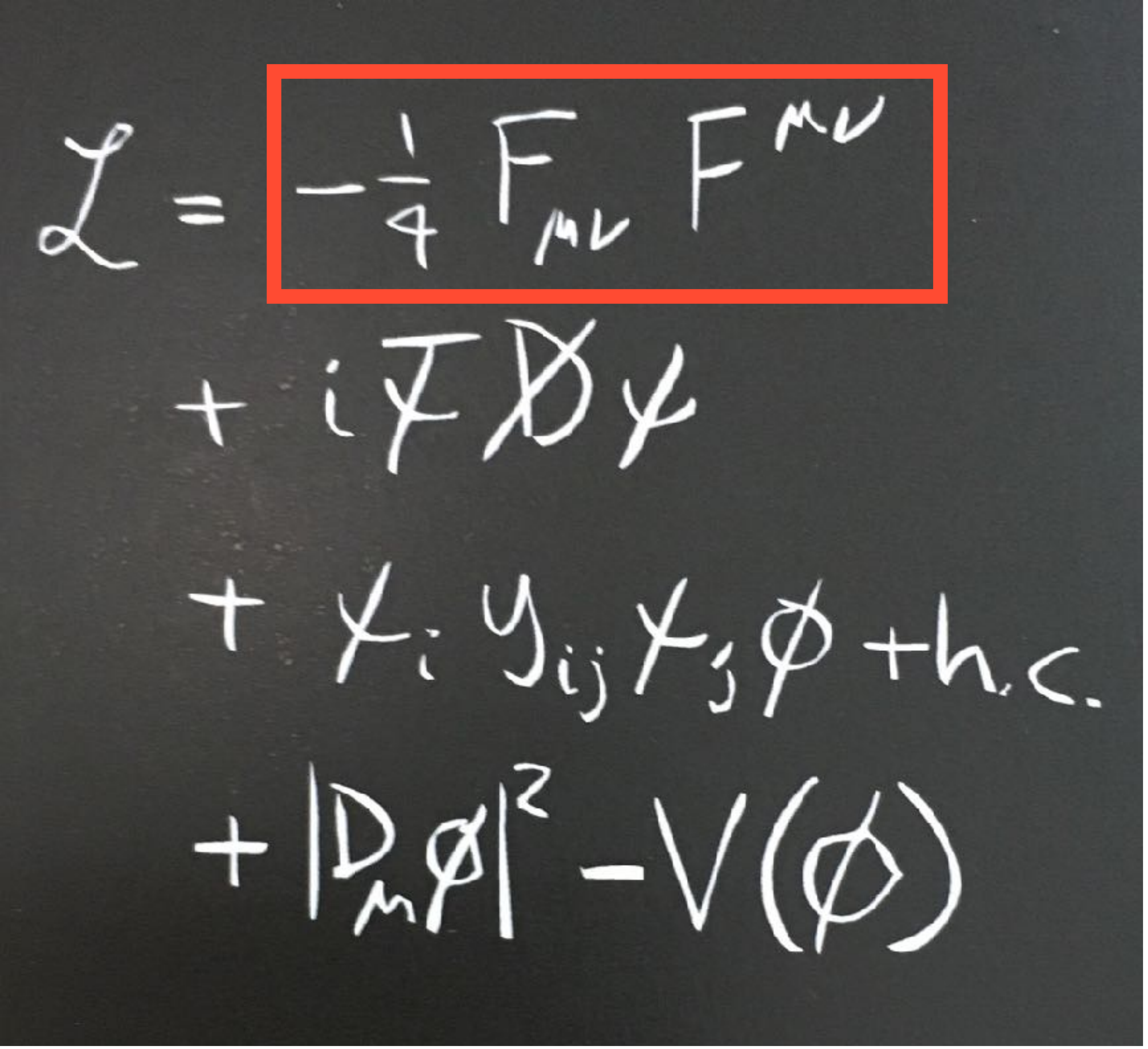
e.g. $\bar{\psi}D\psi \to \psi A_\mu \psi \to$ fermion-fermion-gauge vertex

i.e. terms of $\mathcal{L}$ map to particle interactions





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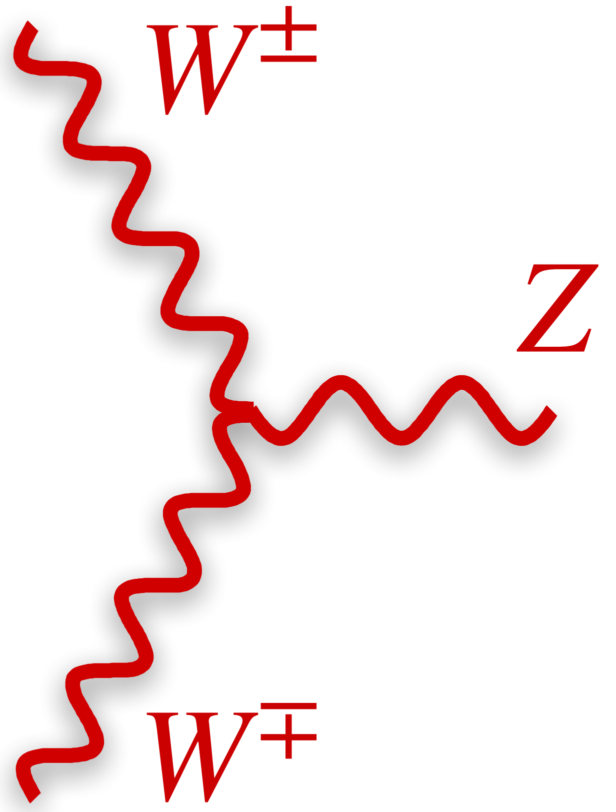

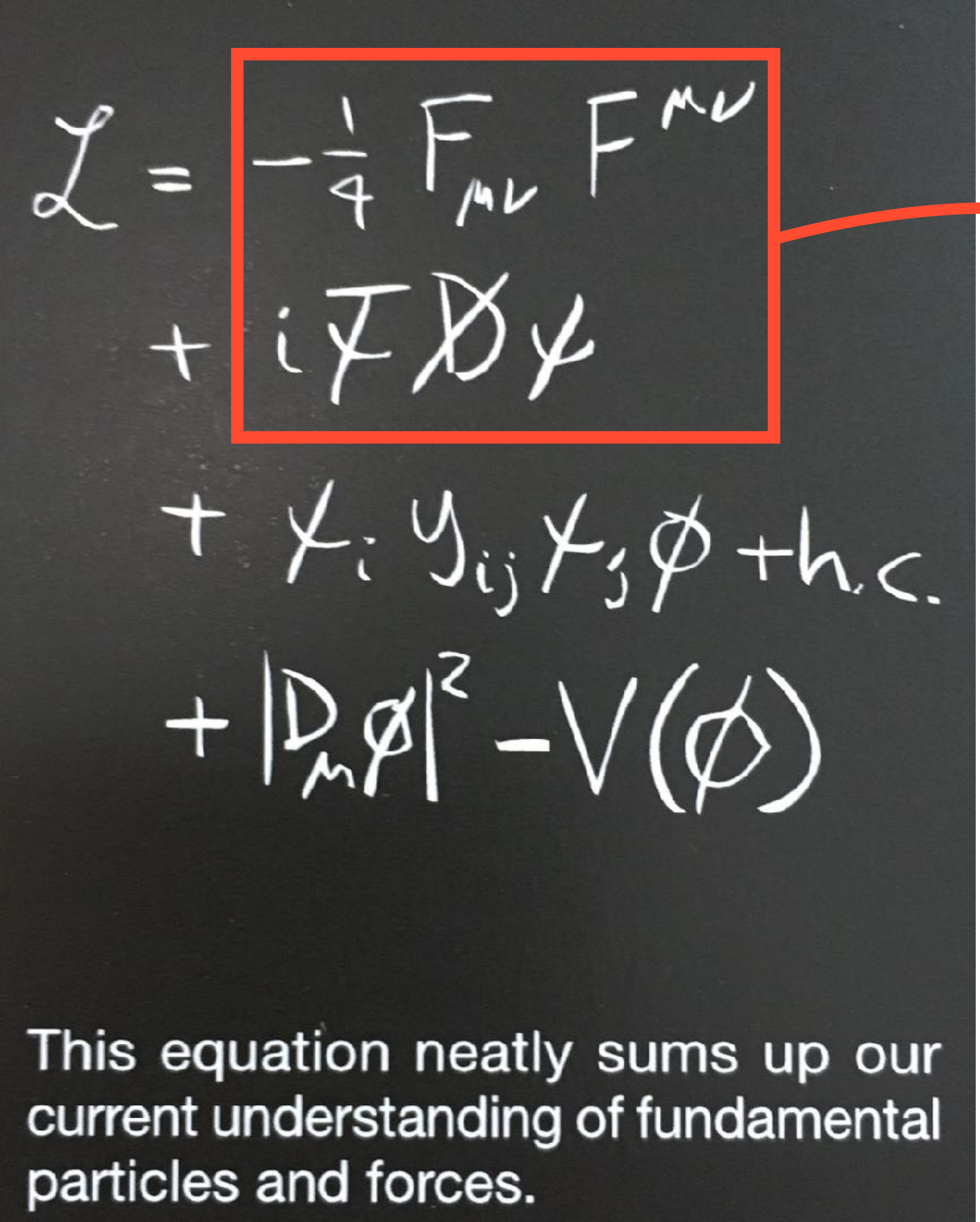

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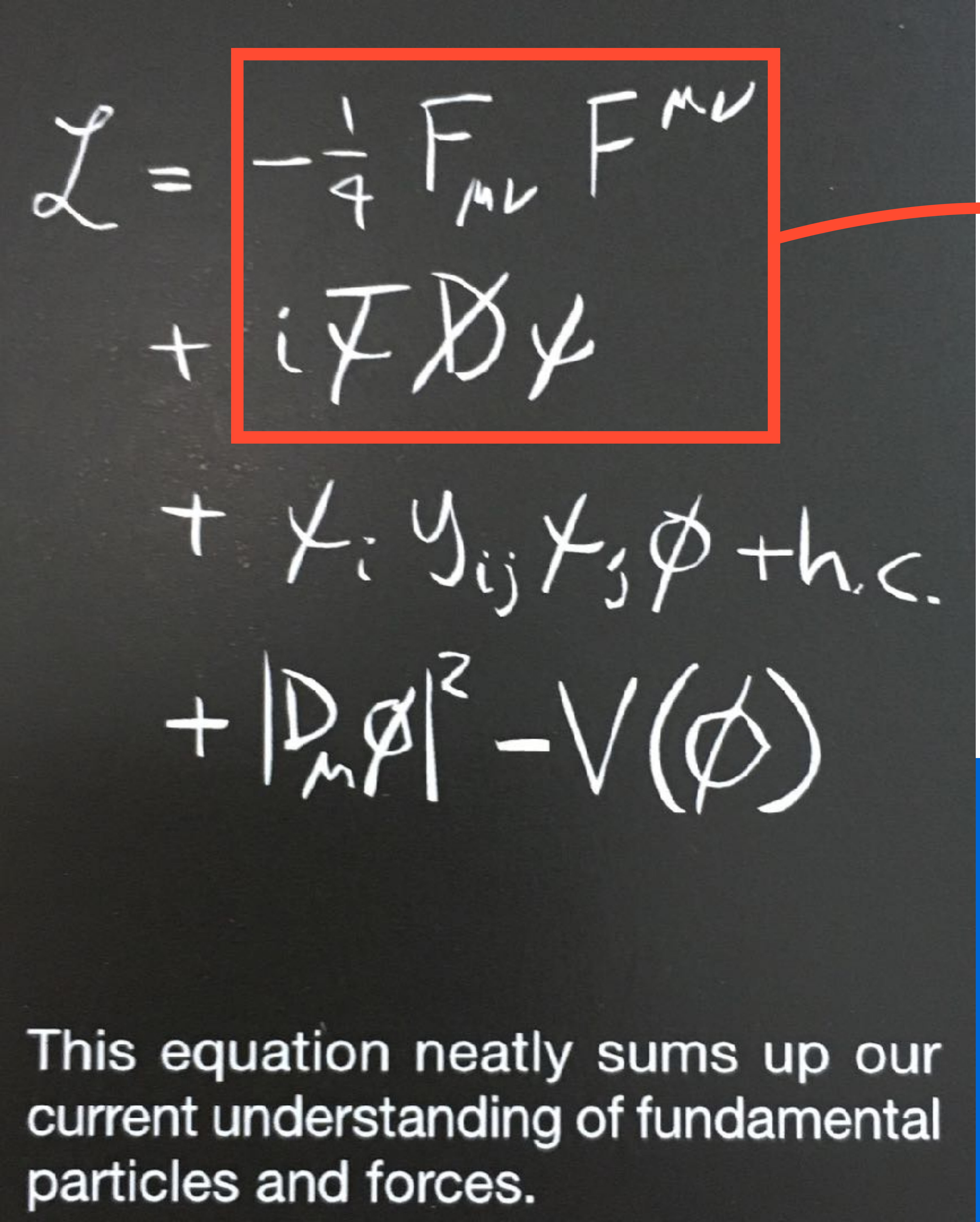
This equation neatly sums up our current understanding of fundamental particles and forces.

GAUGE PART

e.g. qqγ, qqZ, qqg, eνW, ggg, interactions — well established in ep, e^+e^-, pp collisions, etc.

≡ **KNOWLEDGE**

(also being studied at LHC — e.g. jets, DY/Z/W, V+jets, ttbar, etc.)



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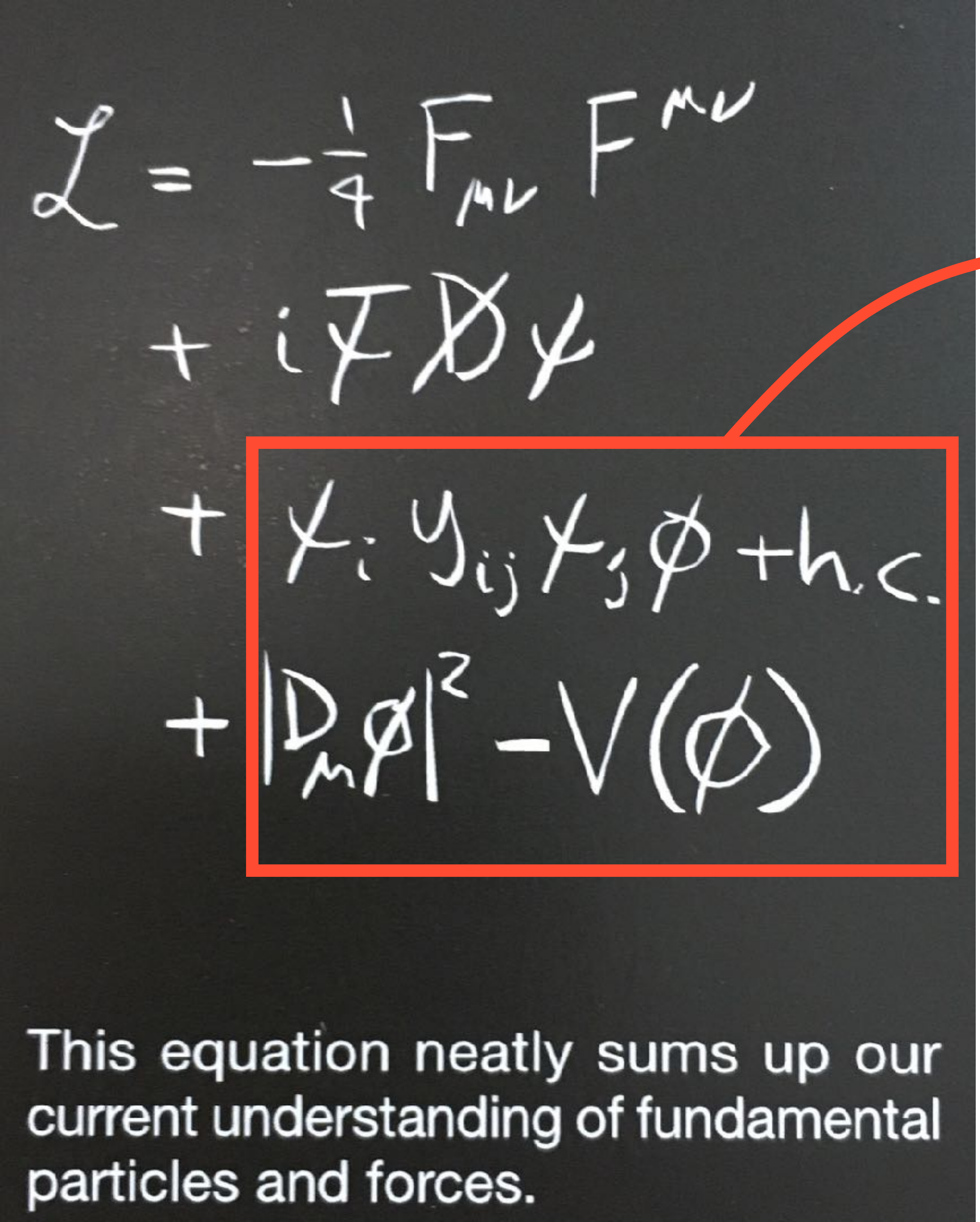
(also being studied at LHC — e.g. jets, DY/Z/W, V+jets, ttbar, etc.)

Many SM studies probe this part.

In some respects dates back to 1860's, i.e. **Maxwell's equations.**

If you test another corner of this (as one should), don't be surprised if it works

Higgs sector



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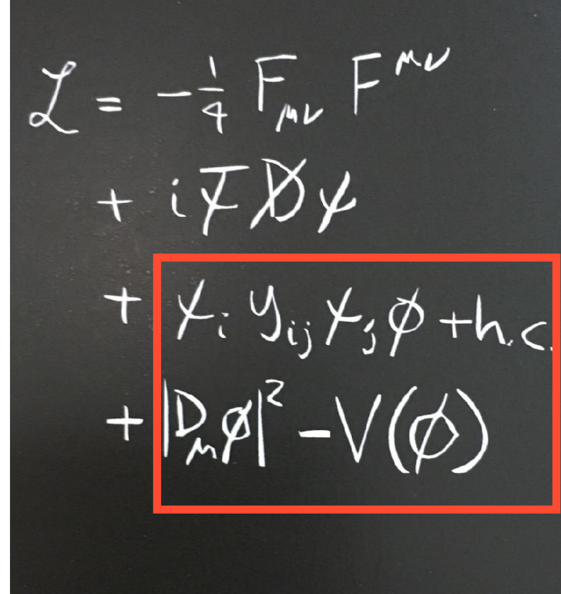
until 6 years ago none of these terms had ever been directly observed.

what terms are there in the Higgs sector?
1. Potential



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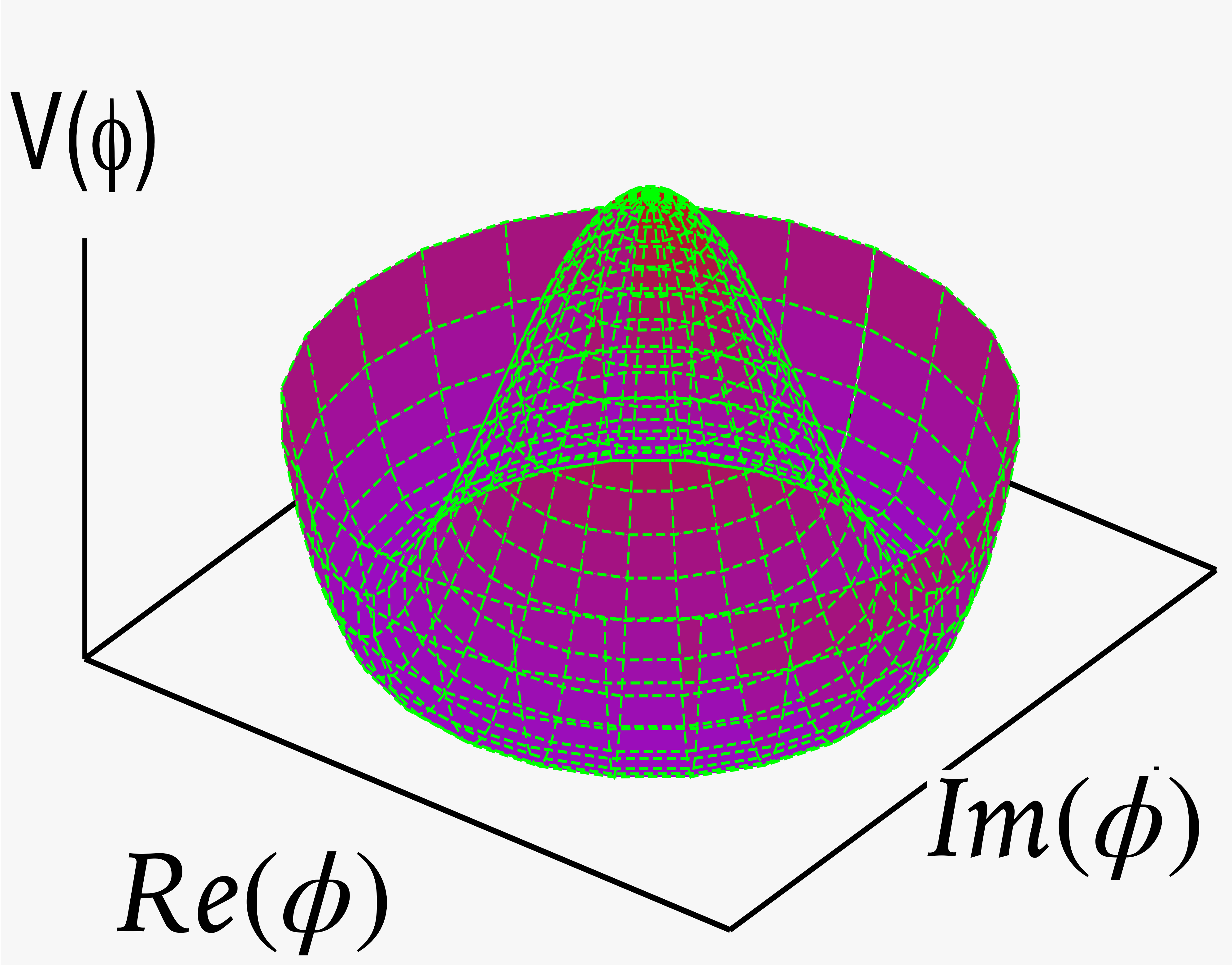

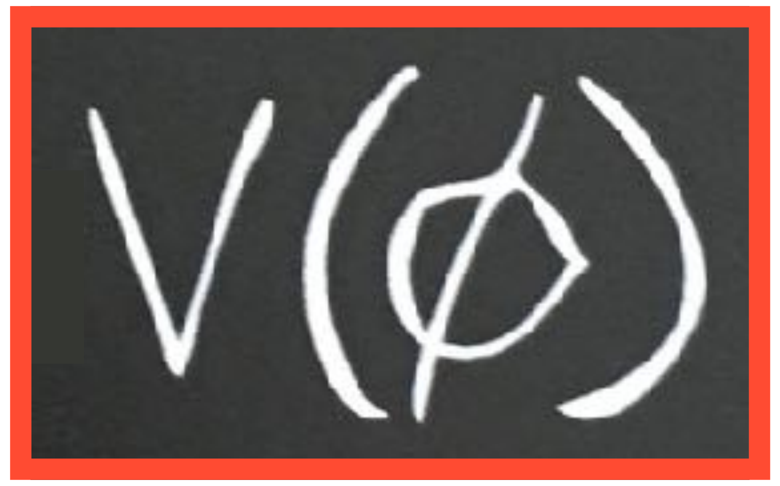

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

- φ is a complex doublet
- V(φ) has minimum at $\varphi = \varphi_0 = \frac{\mu}{\sqrt{2\lambda}}$
- Excitations of the φ field around φ_0 are Higgs bosons ($\varphi = \varphi_0 + H$)

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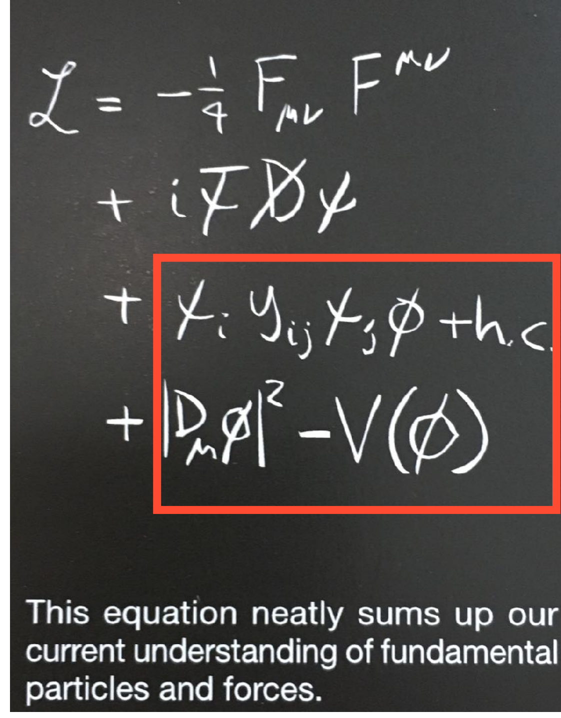
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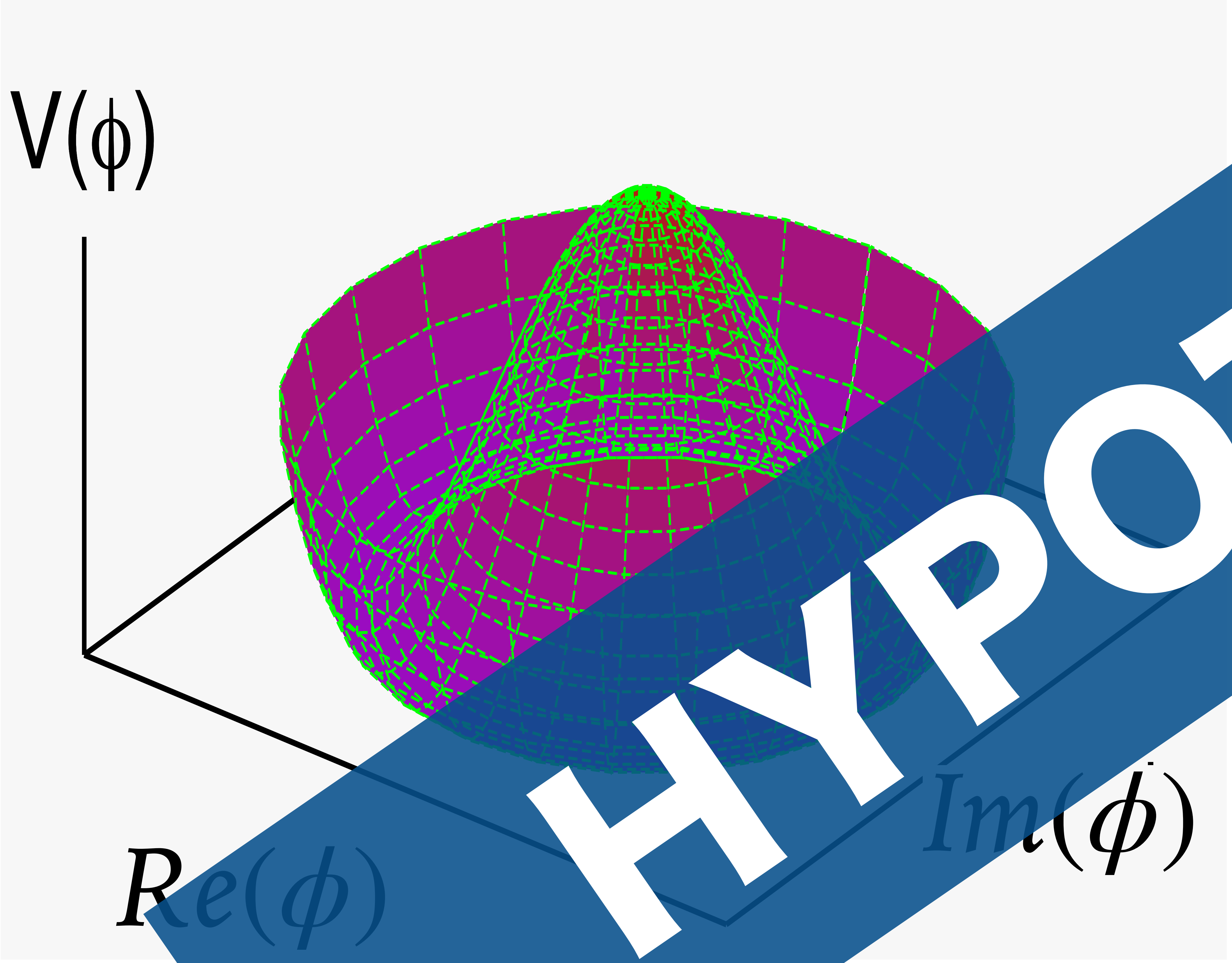

HYPOTHESIS

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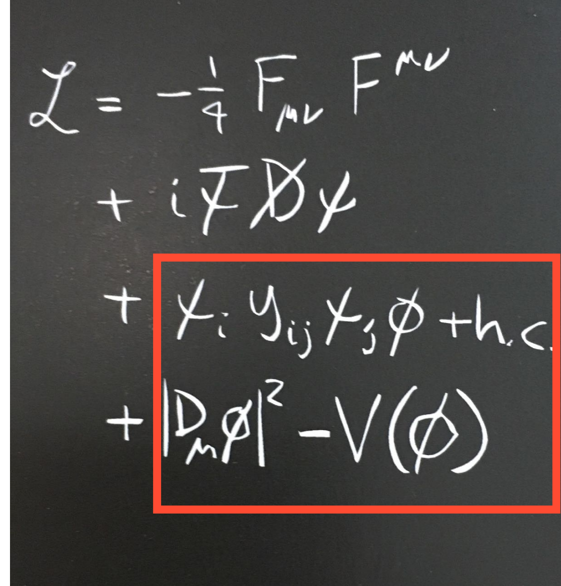
2. Gauge–Higgs term



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$$|D_\mu \phi|^2$$

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

Z-boson mass term

ZZH interaction term

$$D_\mu \sim \partial_\nu + ieZ_\mu + \ldots$$
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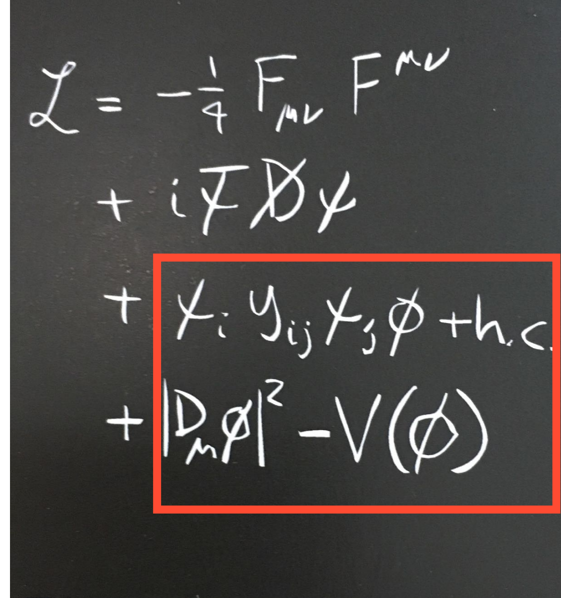

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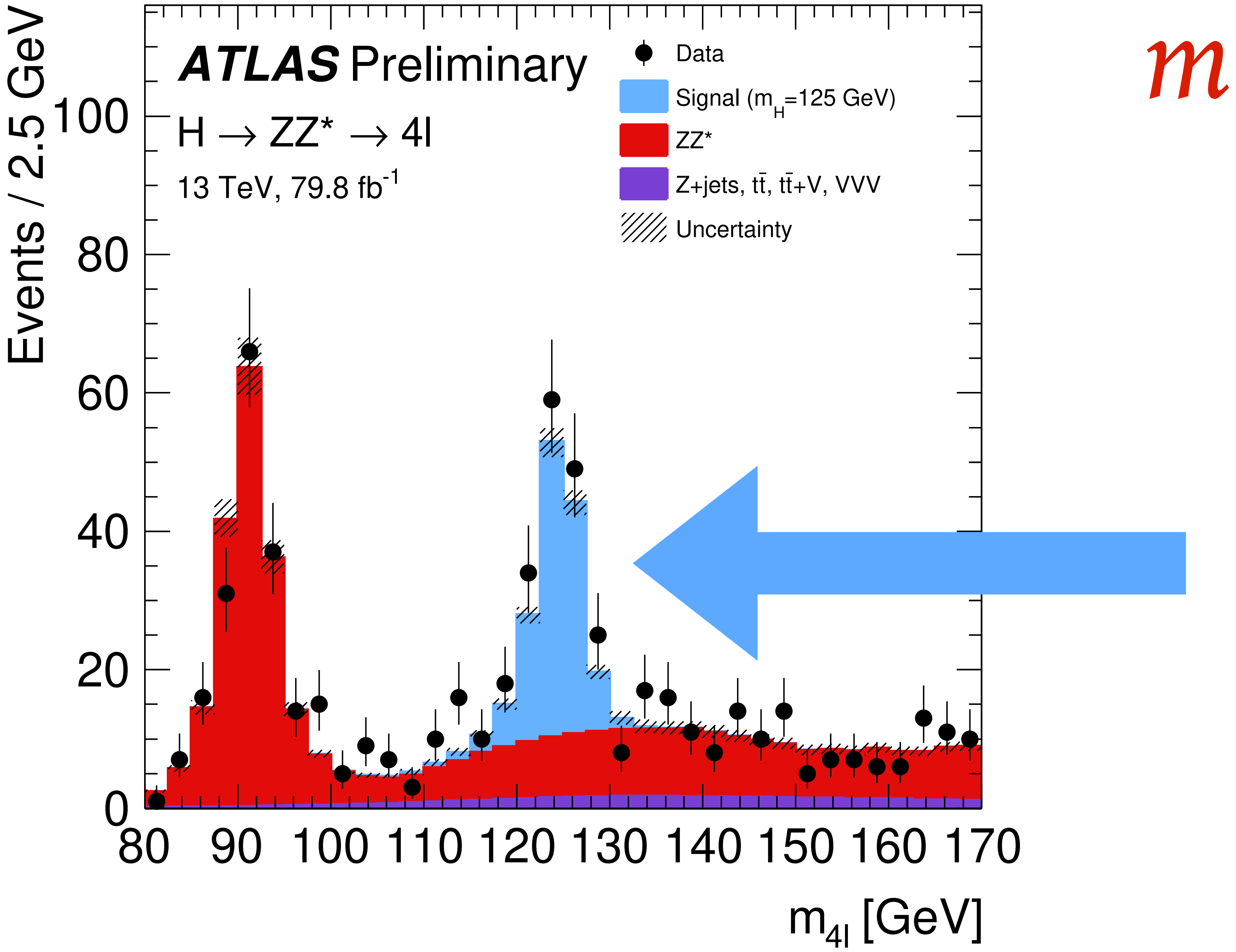

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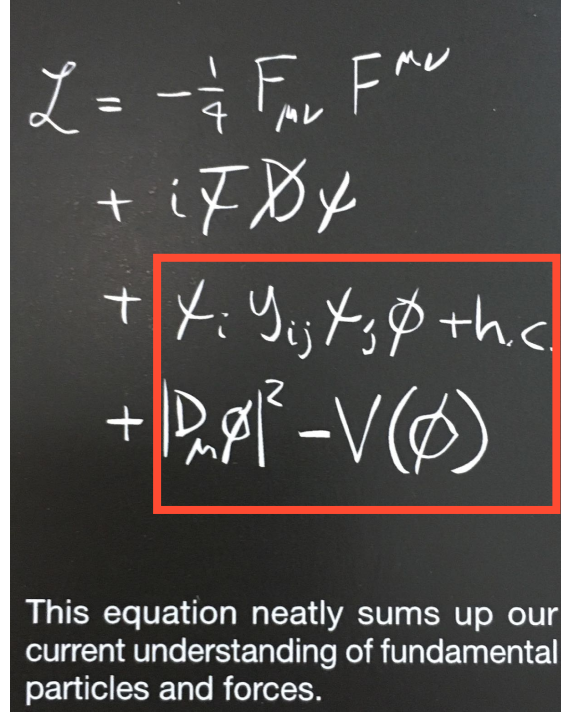
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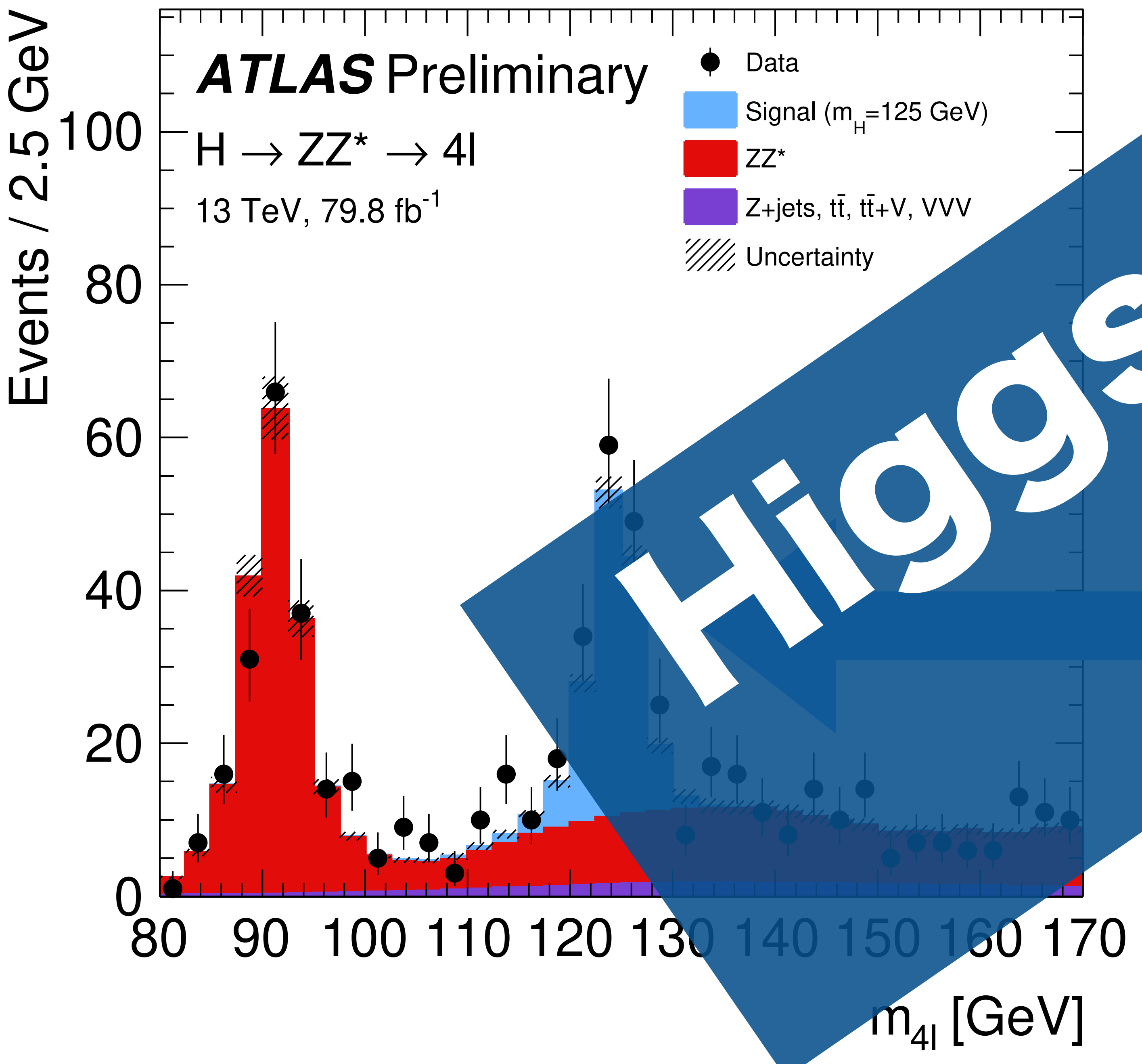
Higgs (BEH) mechanism for vector boson mass



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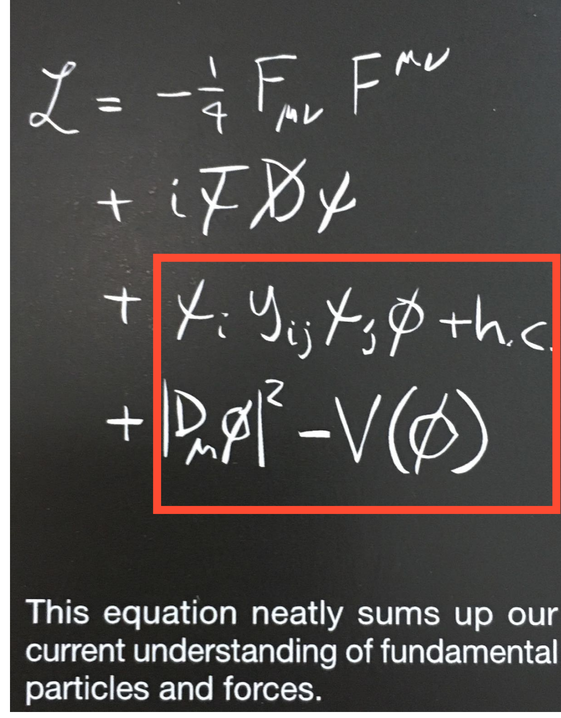
3. Fermion–Higgs (Yukawa) term



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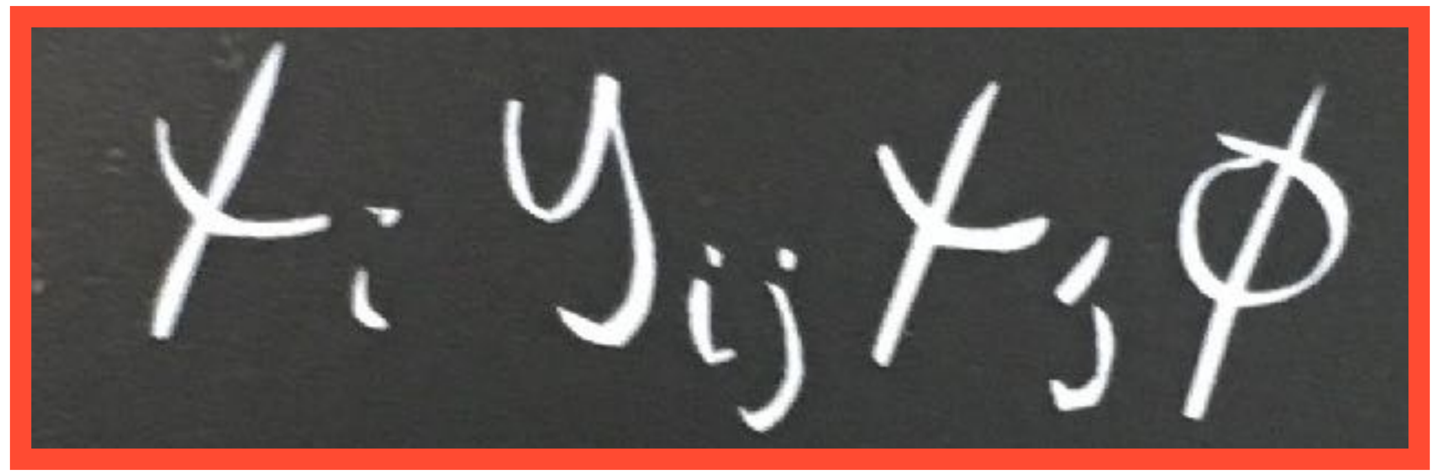


$$\psi_i y_{ij} \psi_j \phi$$

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

fermion mass term

$m_i = y_{ii}\phi_0$

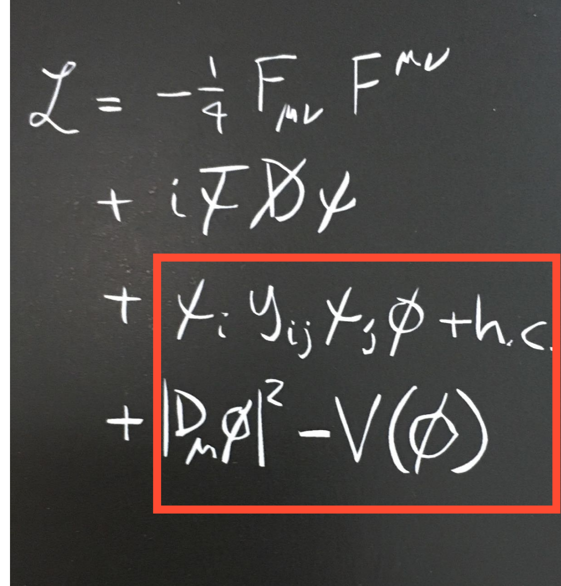
fermion-fermion-Higgs interaction term;

coupling $\sim y_{ii}$

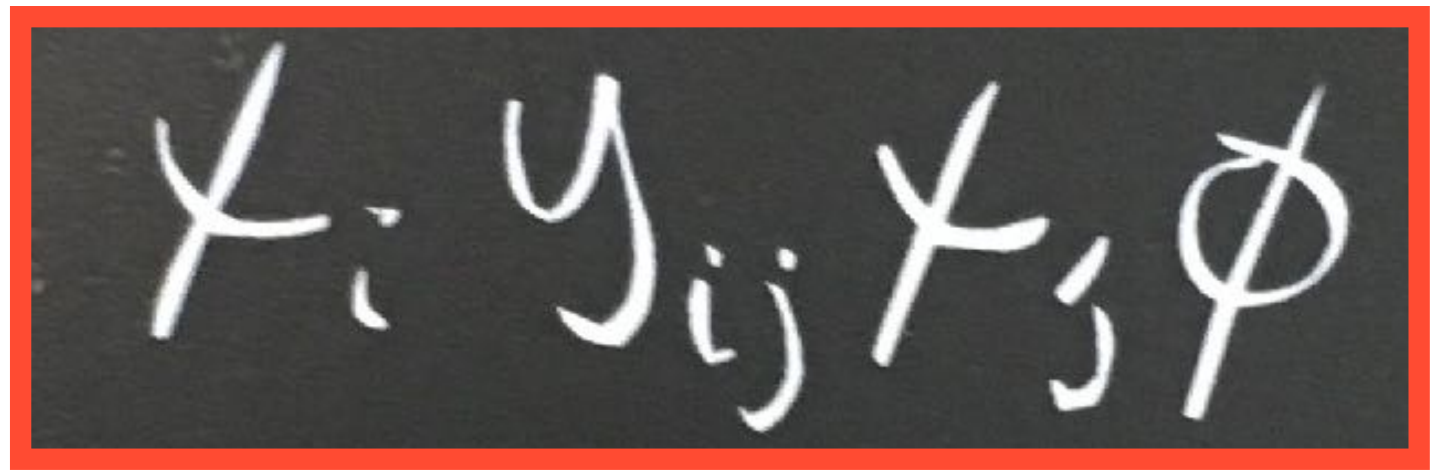
i	y_i	i	y_i
u	$2 \cdot 10^{-5}$	d	$3 \cdot 10^{-5}$
c	$8 \cdot 10^{-3}$	s	$6 \cdot 10^{-4}$
b	$3 \cdot 10^{-2}$	t	1
ν_e	$\sim 10^{-13}$?	e	$3 \cdot 10^{-6}$
ν_μ		μ	$6 \cdot 10^{-4}$
ν_τ		τ	$1 \cdot 10^{-4}$

$$\phi = \phi_0 + H$$

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



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



$$\to y_{ij}\phi_0\psi_i\psi_j \qquad y_{ij} H \psi_i \psi_j$$

fermion mass term

$m_i = y_{ii}\phi_0$

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

$$\phi = \phi_0 + H$$

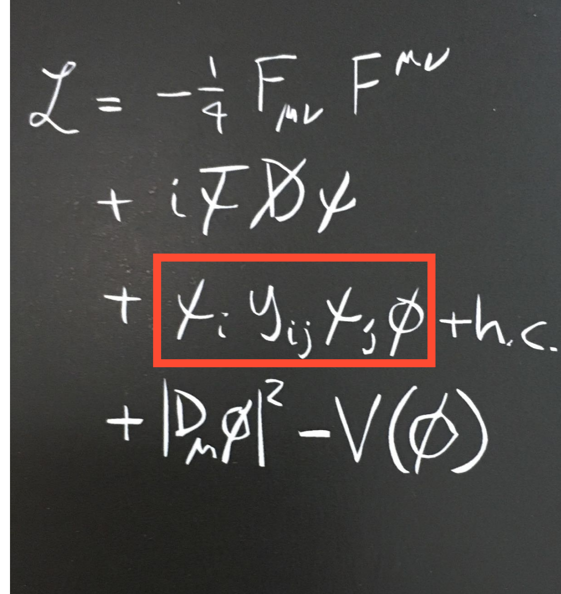
concentrate on
Yukawa interaction hypothesis

Yukawa couplings ~ fermion mass

first fundamental interaction that we probe at the quantum level where interaction strength is **not quantised**
(i.e. no underlying unit of 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.

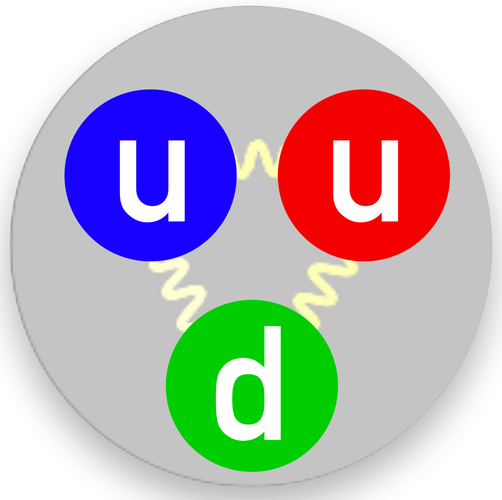
Up quarks (mass ~ 2.2 MeV) are lighter than
down quarks (mass ~ 4.7 MeV)

proton (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

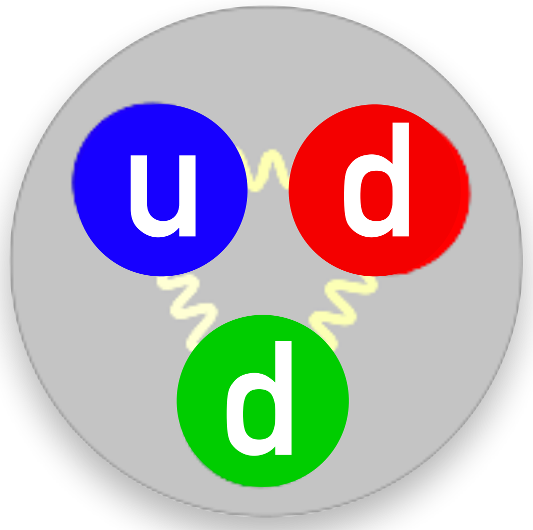
So protons are **lighter** than neutrons,
→ protons are stable.

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

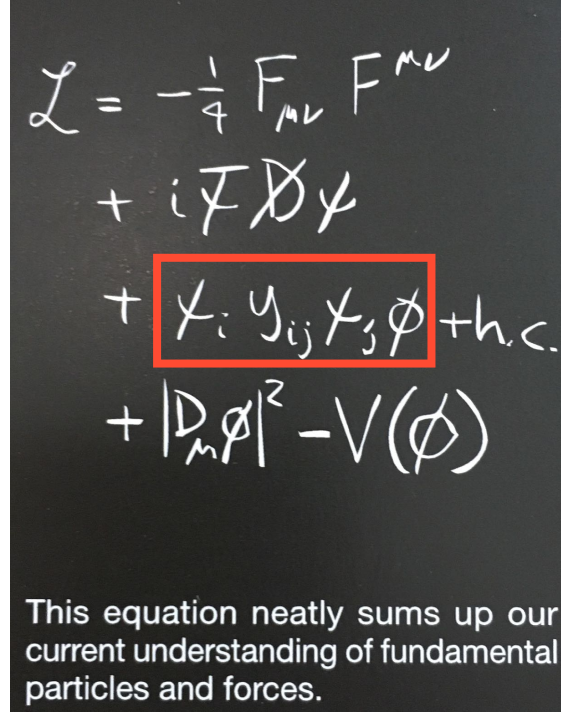
proton
mass = 938.3MeV



neutron
mass = 939.6MeV



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



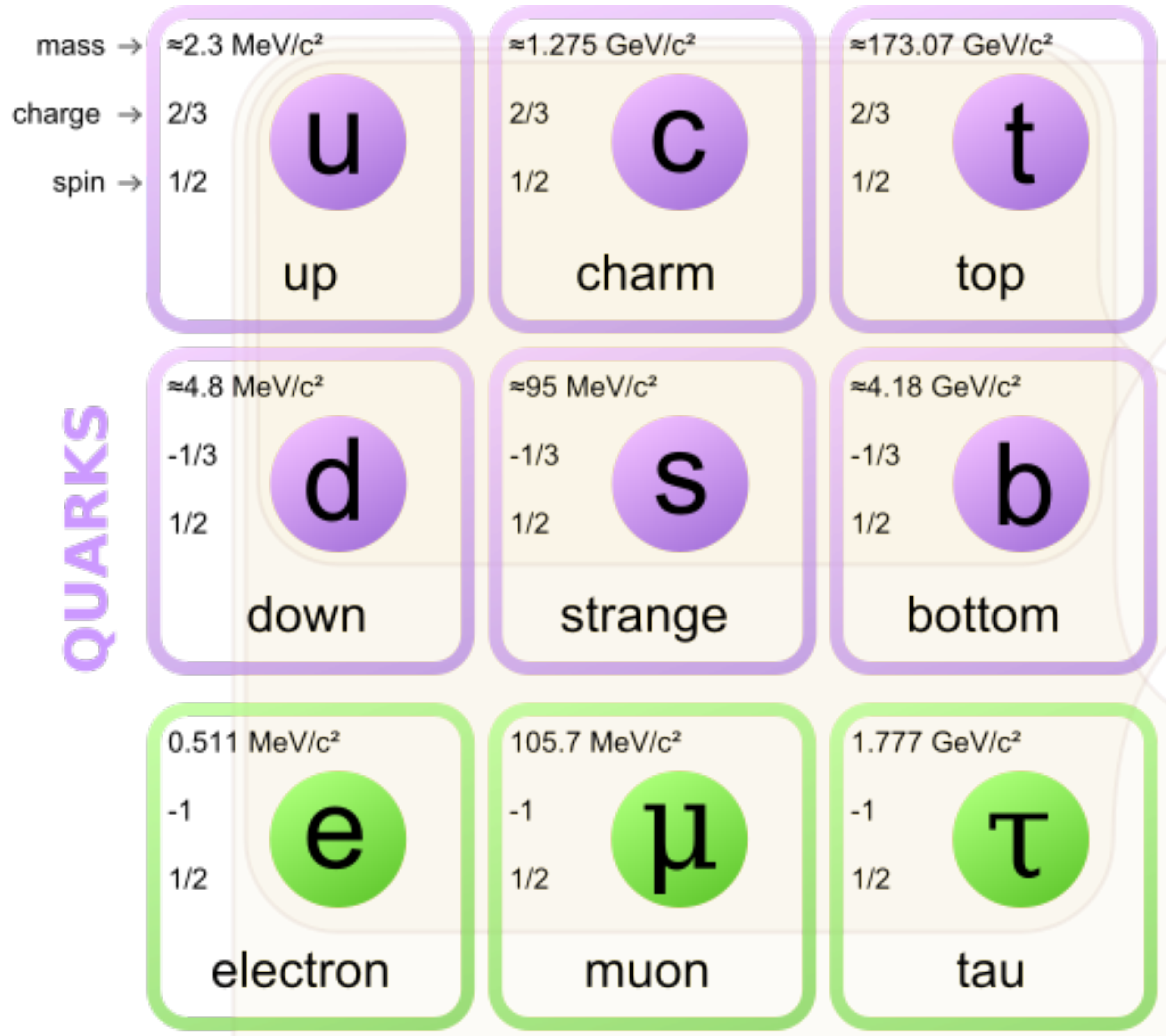
This equation neatly sums up our current understanding of fundamental particles and forces.

Bohr radius

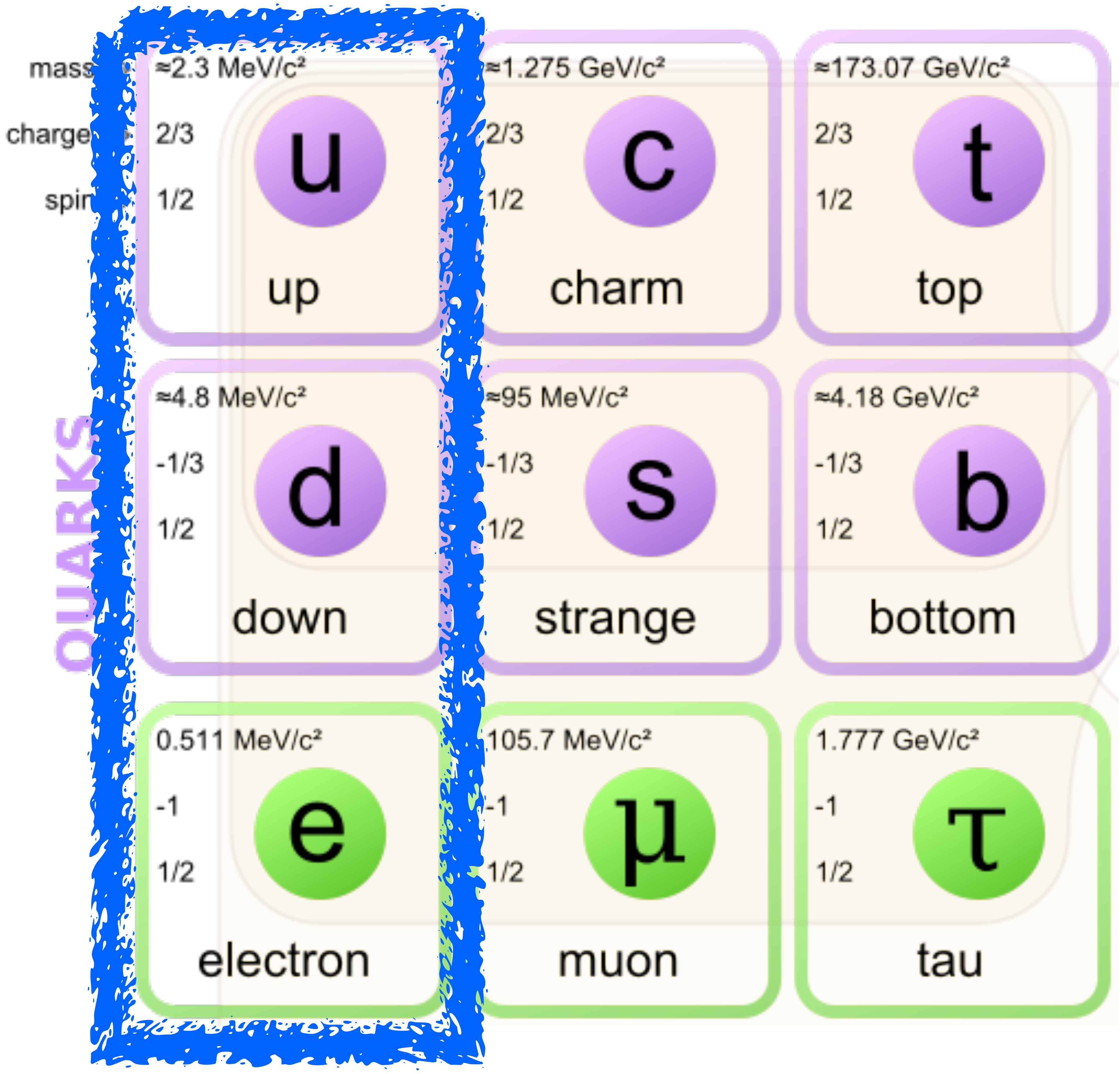
$$a_0 = \frac{4\pi\varepsilon_0 \hbar^2}{m_e e^2} = \frac{\hbar}{m_e\, c\, \alpha}$$

electron mass determines size of all atoms

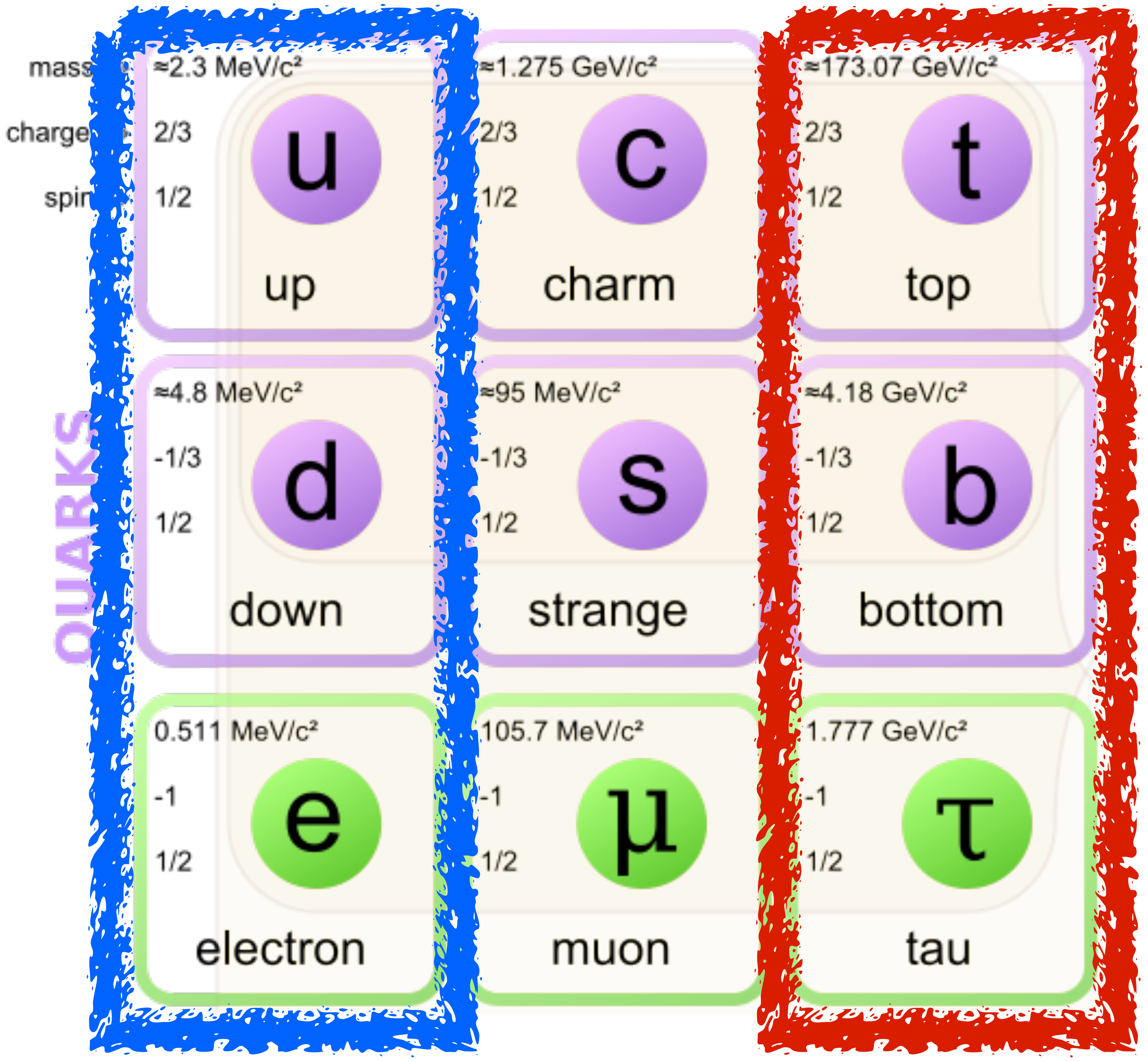
it sets energy levels of all chemical reactions



≈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

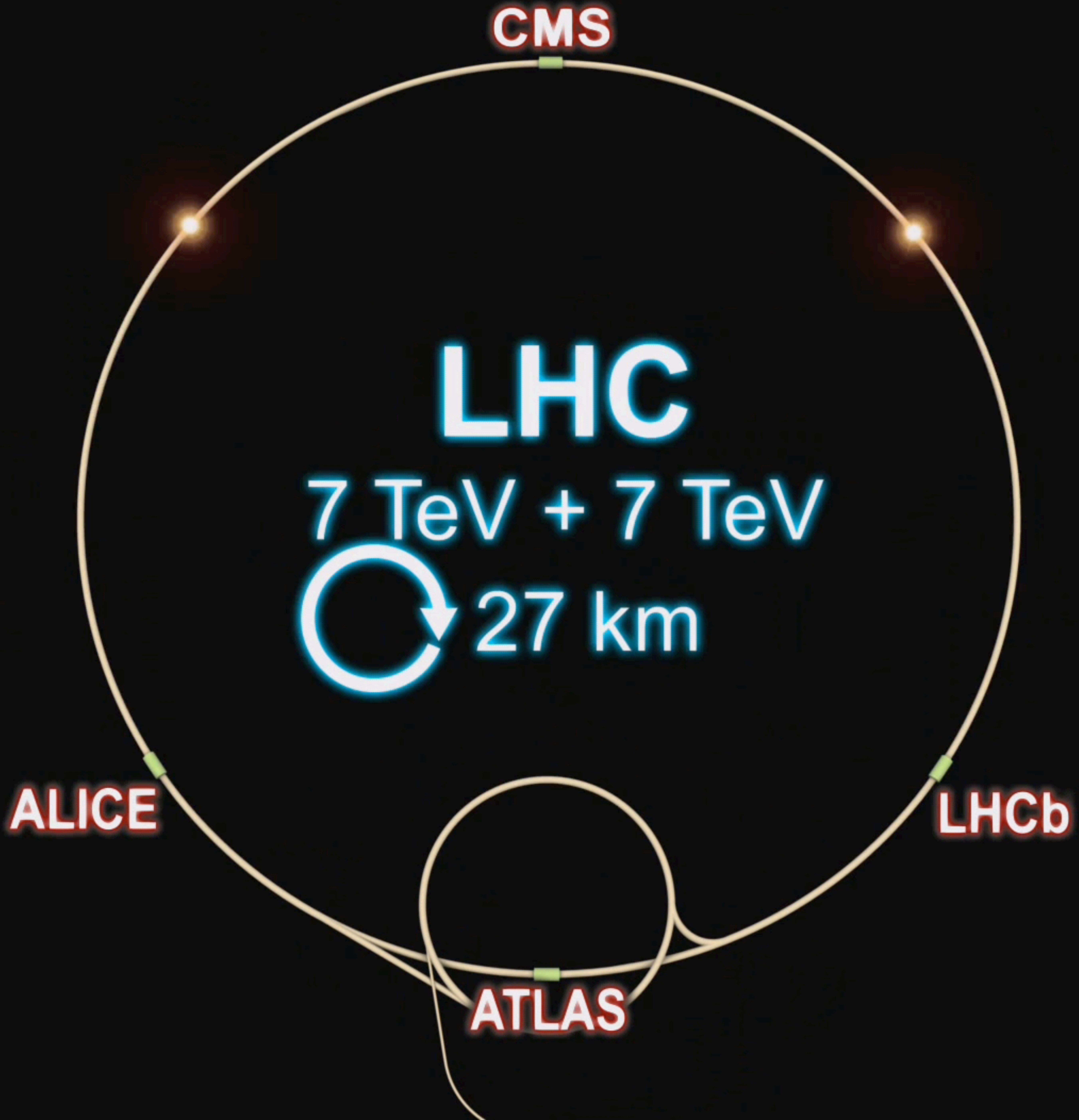


1st generation (us) has low mass because of weak interactions with Higgs field (and so with Higgs bosons): **too weak to test today**



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

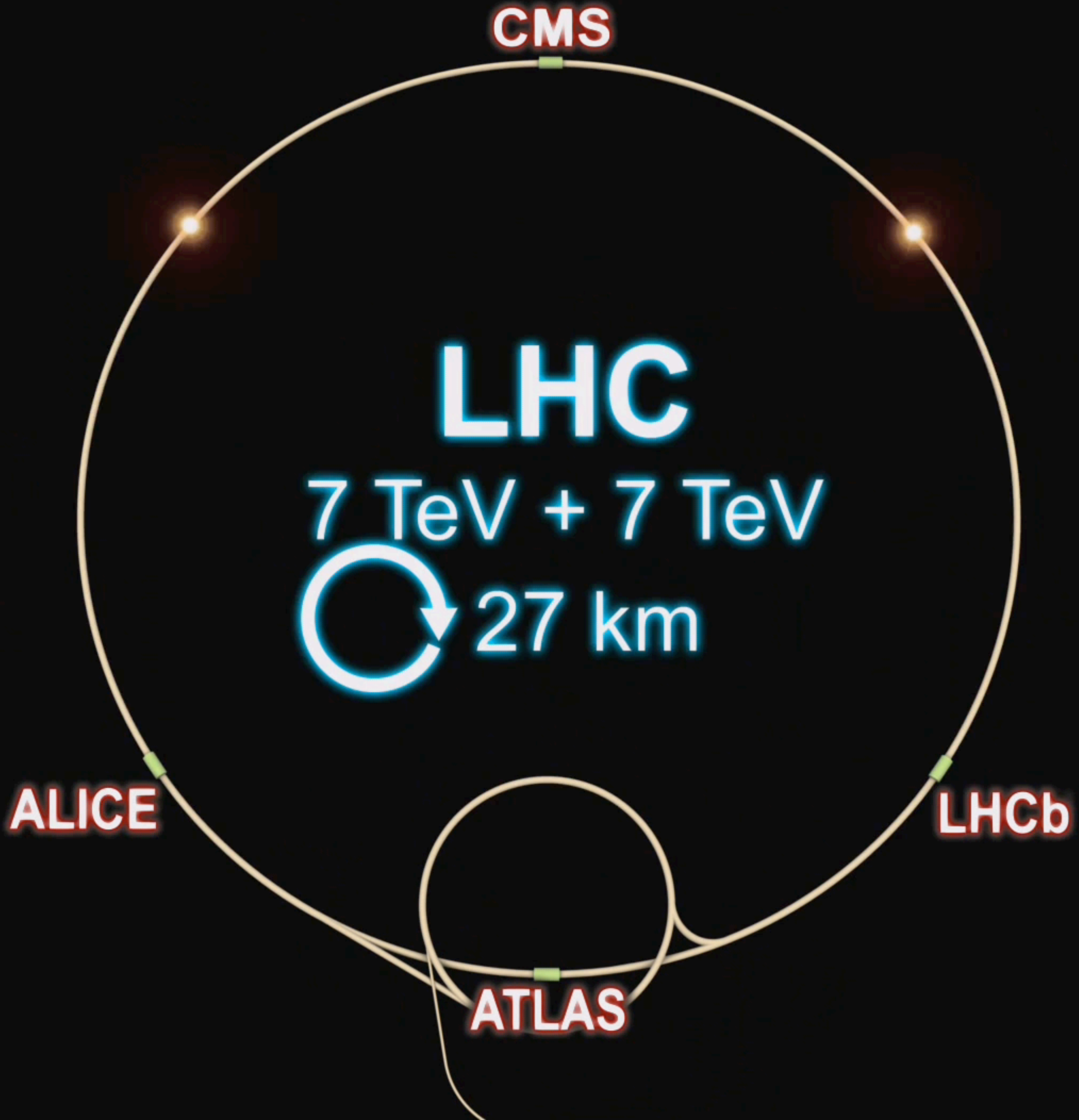
3rd generation (us) has high mass because of strong interactions with Higgs field (and so with Higgs bosons): can potentially be tested



LHC

7 TeV + 7 TeV

27 km



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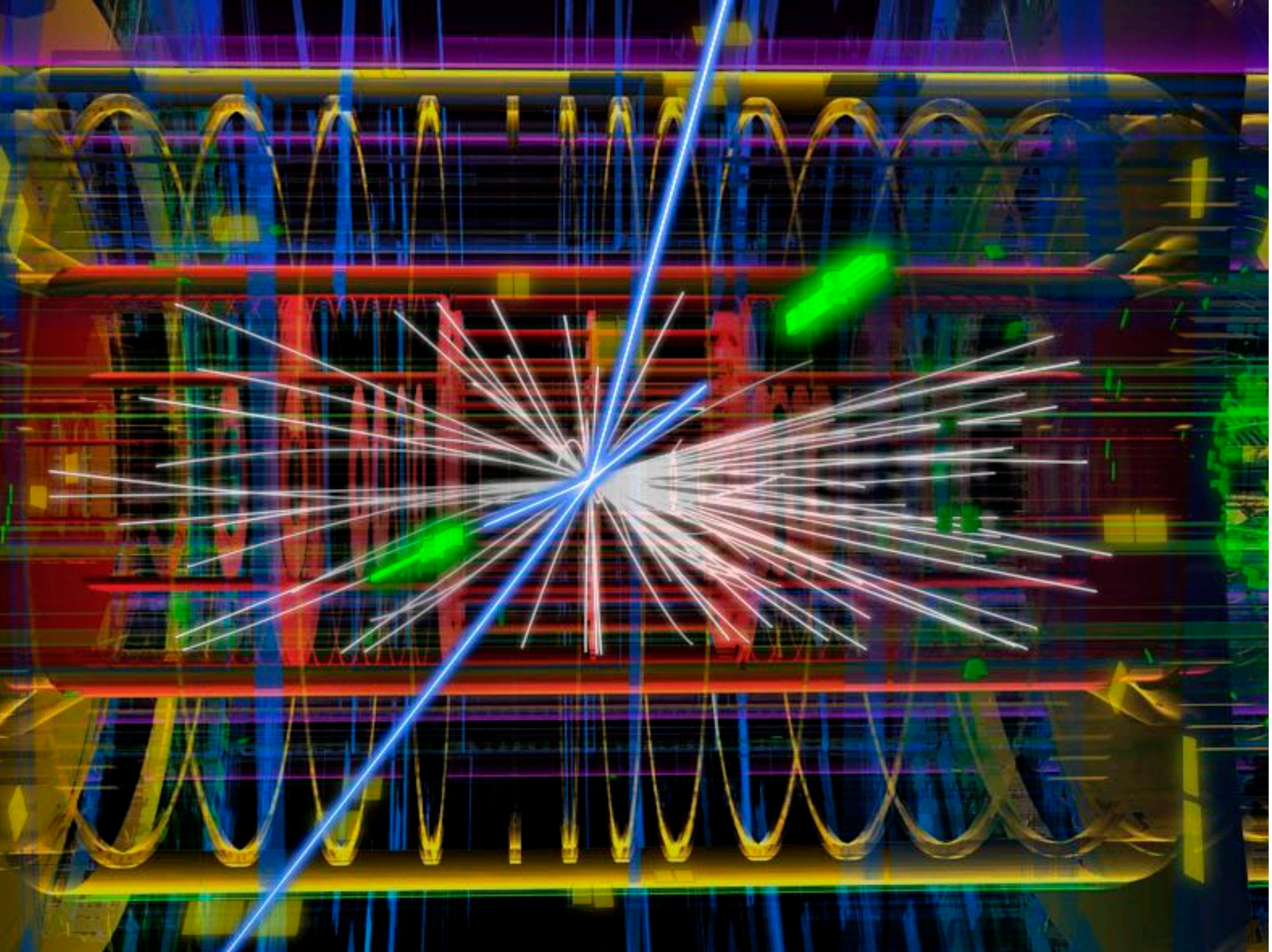


ATLAS & CMS @LHC

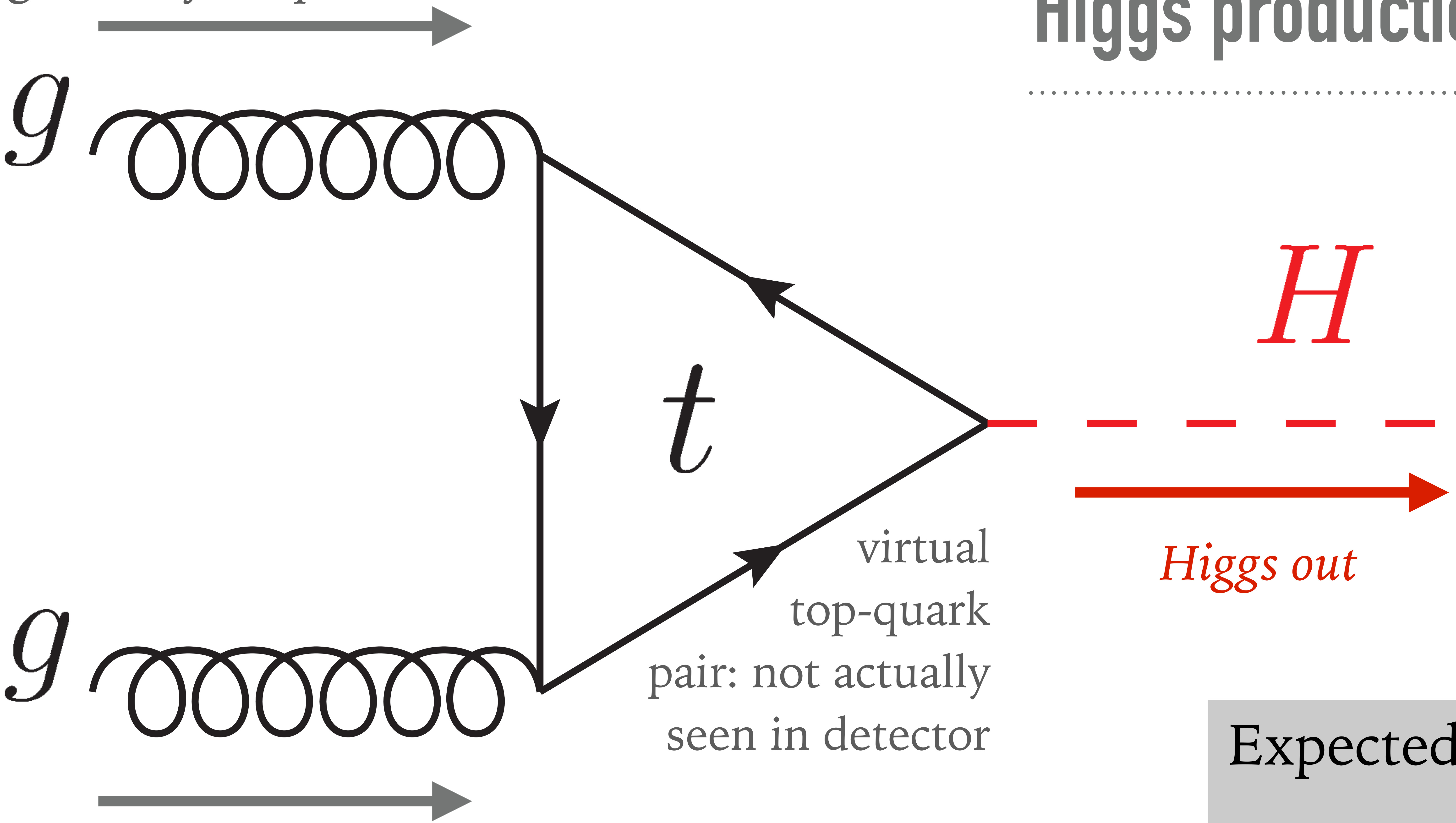
~up to 2 billion collisions/second

(+ lower rates at LHCb and ALICE)

what underlying processes tell us about Yukawa interactions?

Higgs production: the dominant channel

gluon in from proton 1



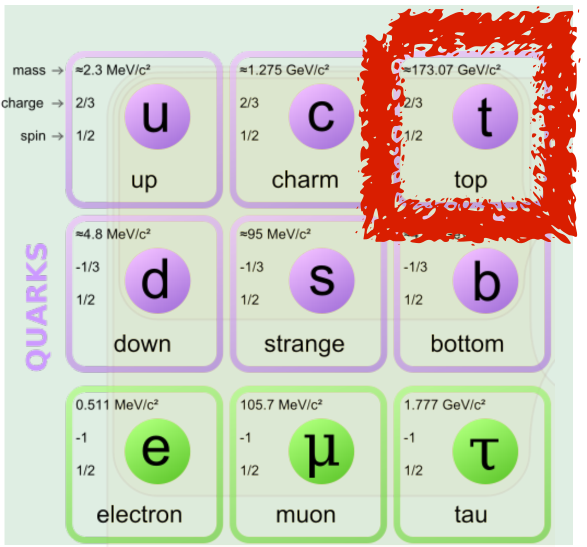
virtual
top-quark
pair: not actually
seen in detector

Higgs out

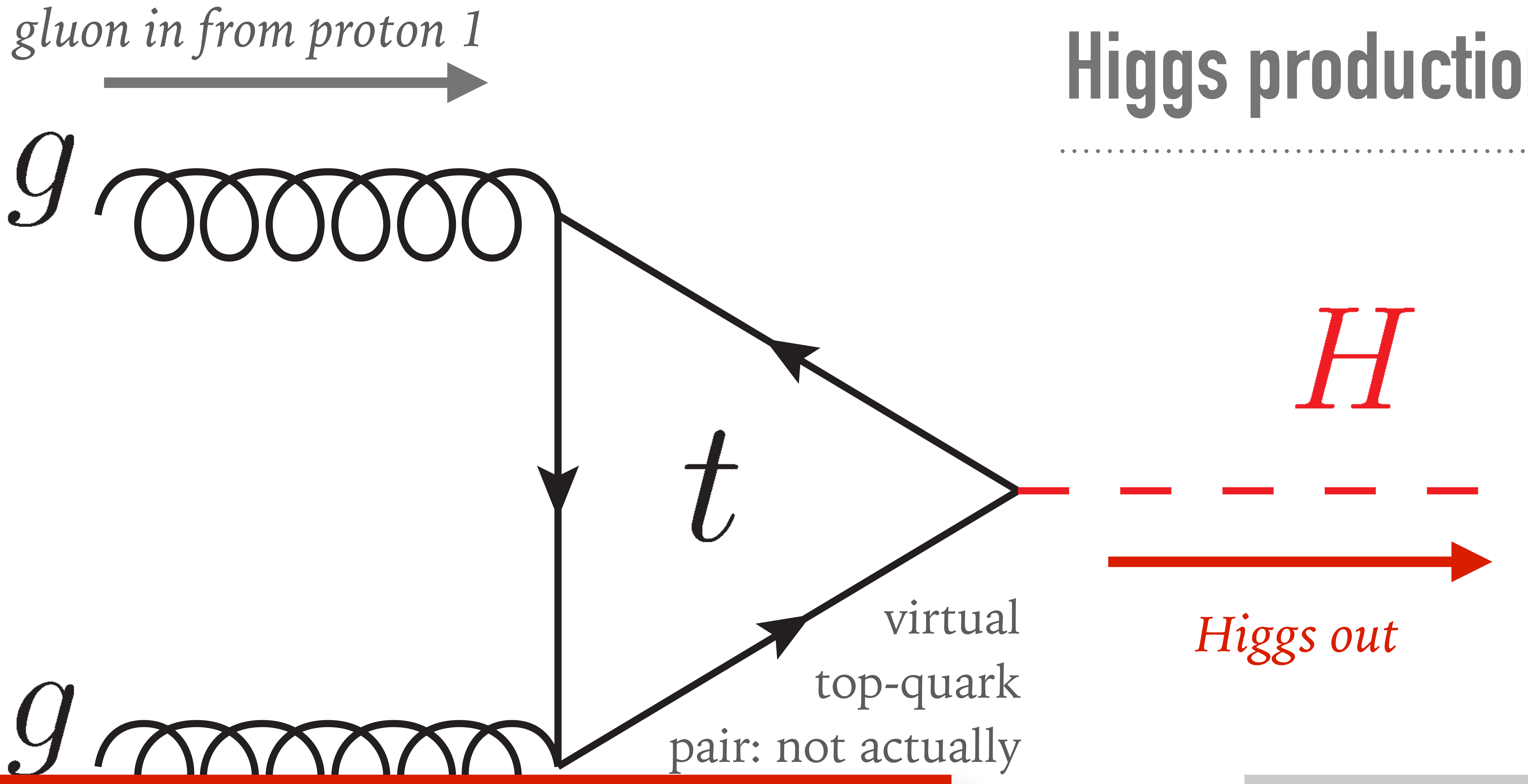
gluon in from proton 2

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

LHC data consistent with that already at discovery in 2012



Higgs production: the dominant channel



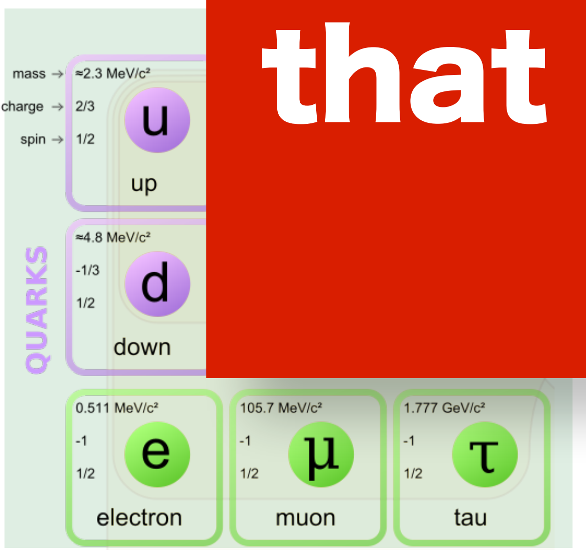
virtual top-quark pair: not actually

ctor

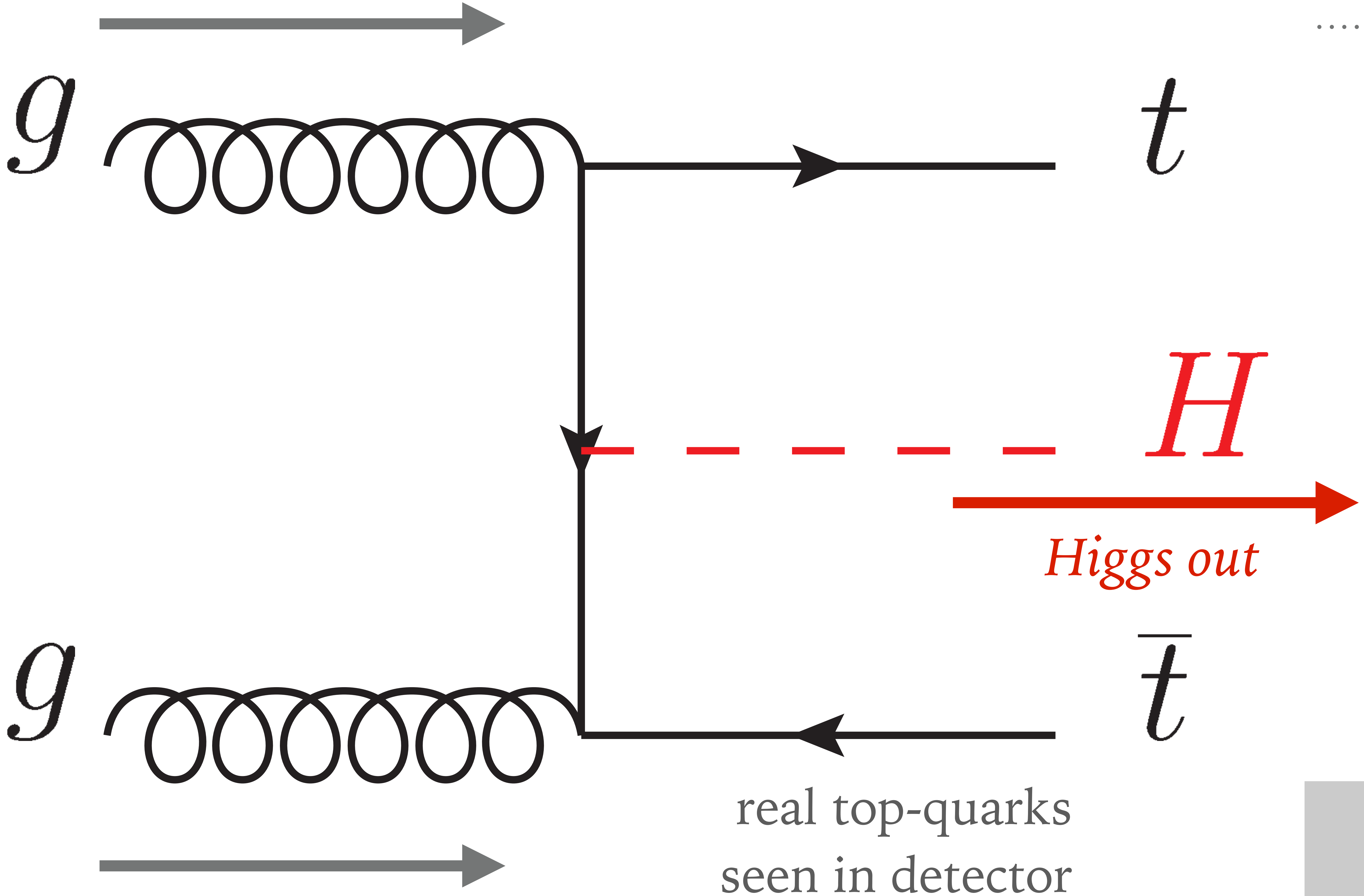
but how can you be sure the Higgs is really being radiated off a top-quark, i.e. that you're actually seeing a Yukawa coupling?

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

LHC data consistent with that already at discovery in 2012



Higgs production: the ttH channel



gluon in from proton 1

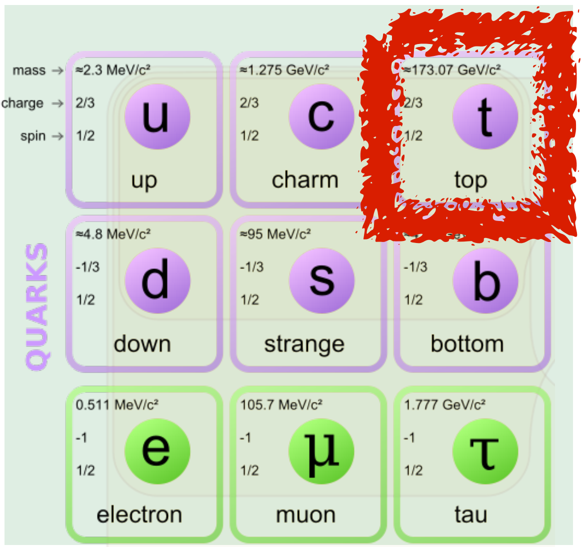
Higgs out

real top-quarks seen in detector

gluon in from proton 2

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

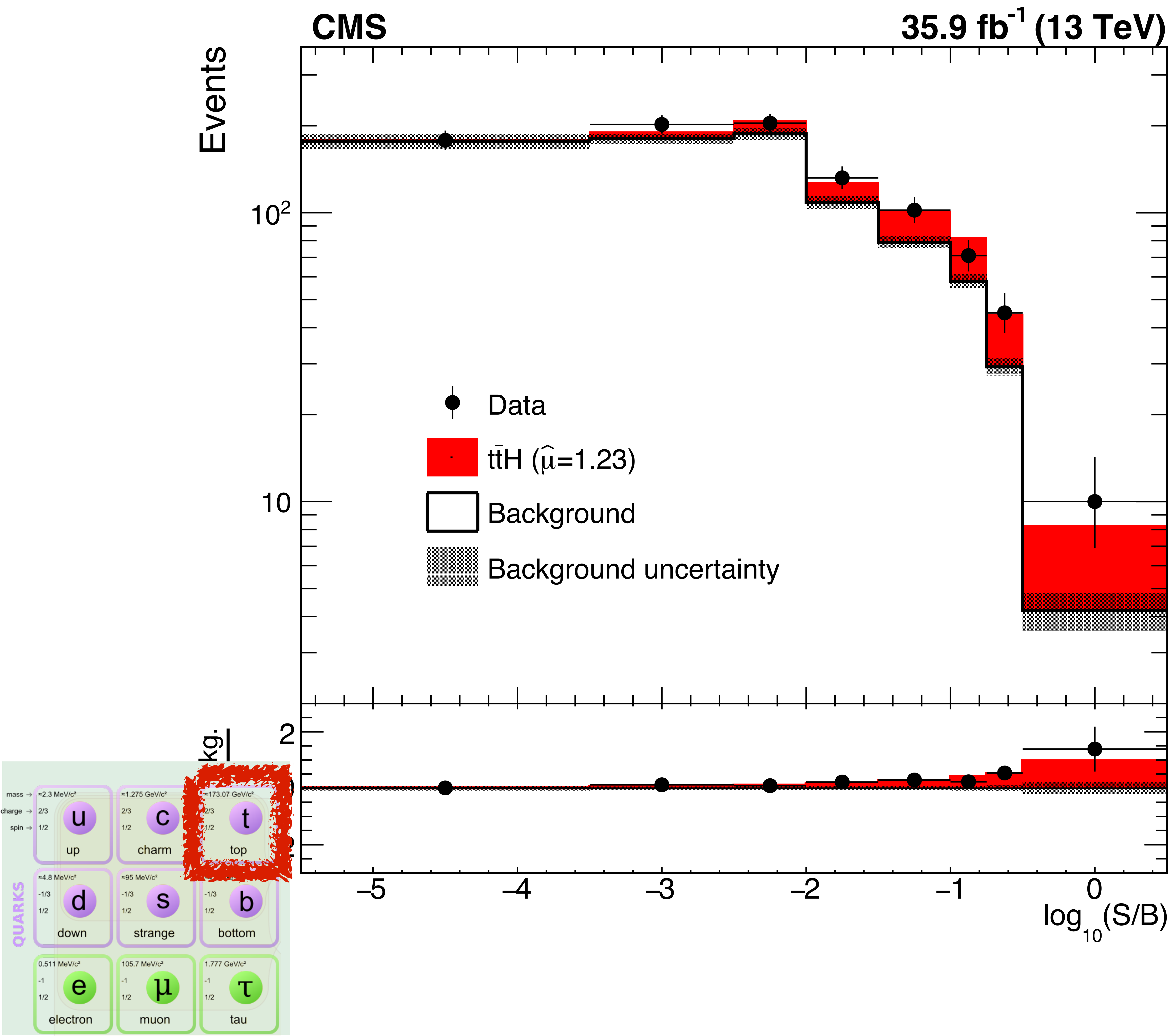
(rather than 1 Higgs for every 2 billion pp collisions)

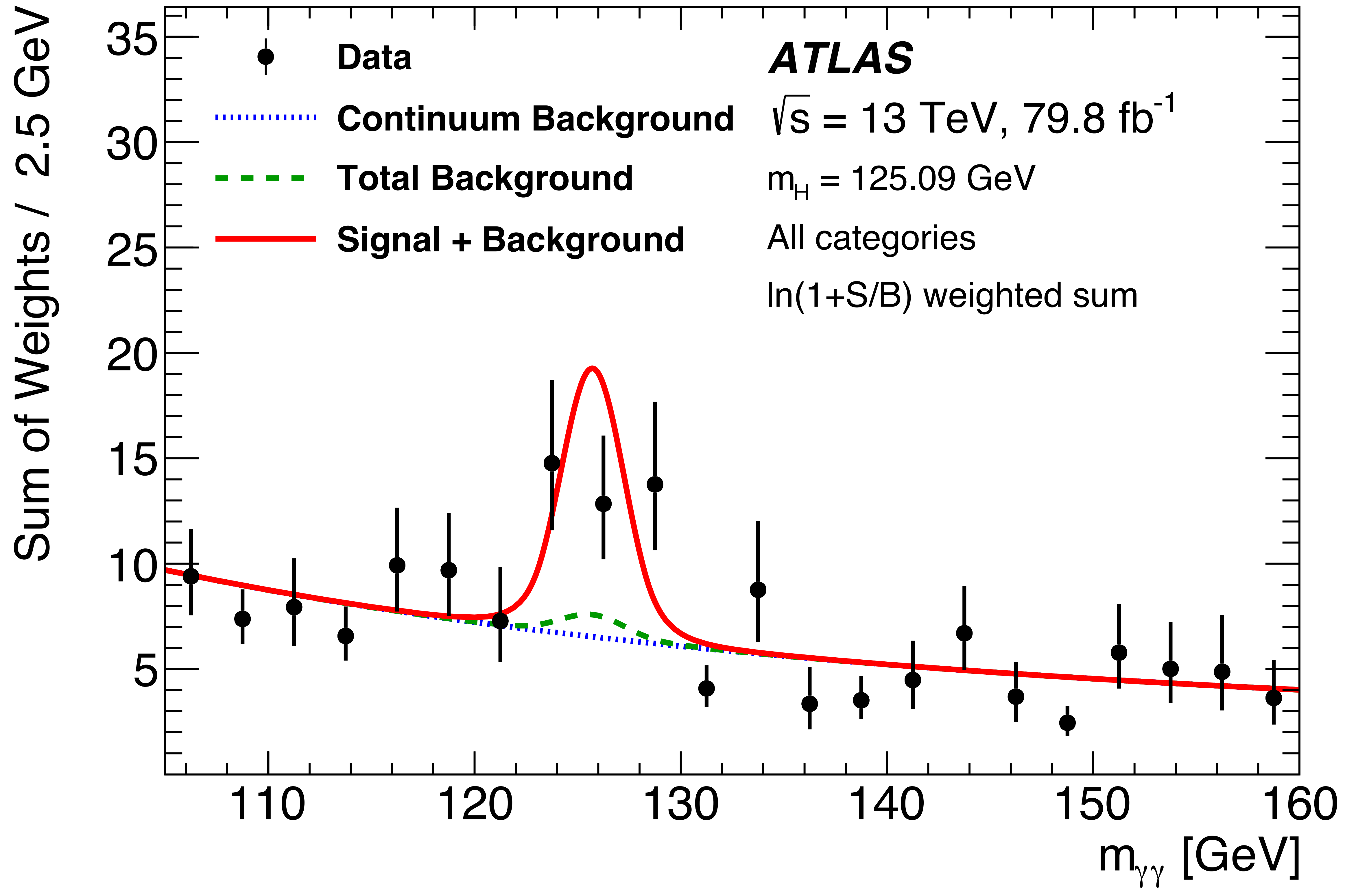


the news of the past months: ATLAS & CMS see events with top-quarks & Higgs simultaneously

CMS > 5-sigma ttH

ATLAS > 5-sigma ttH





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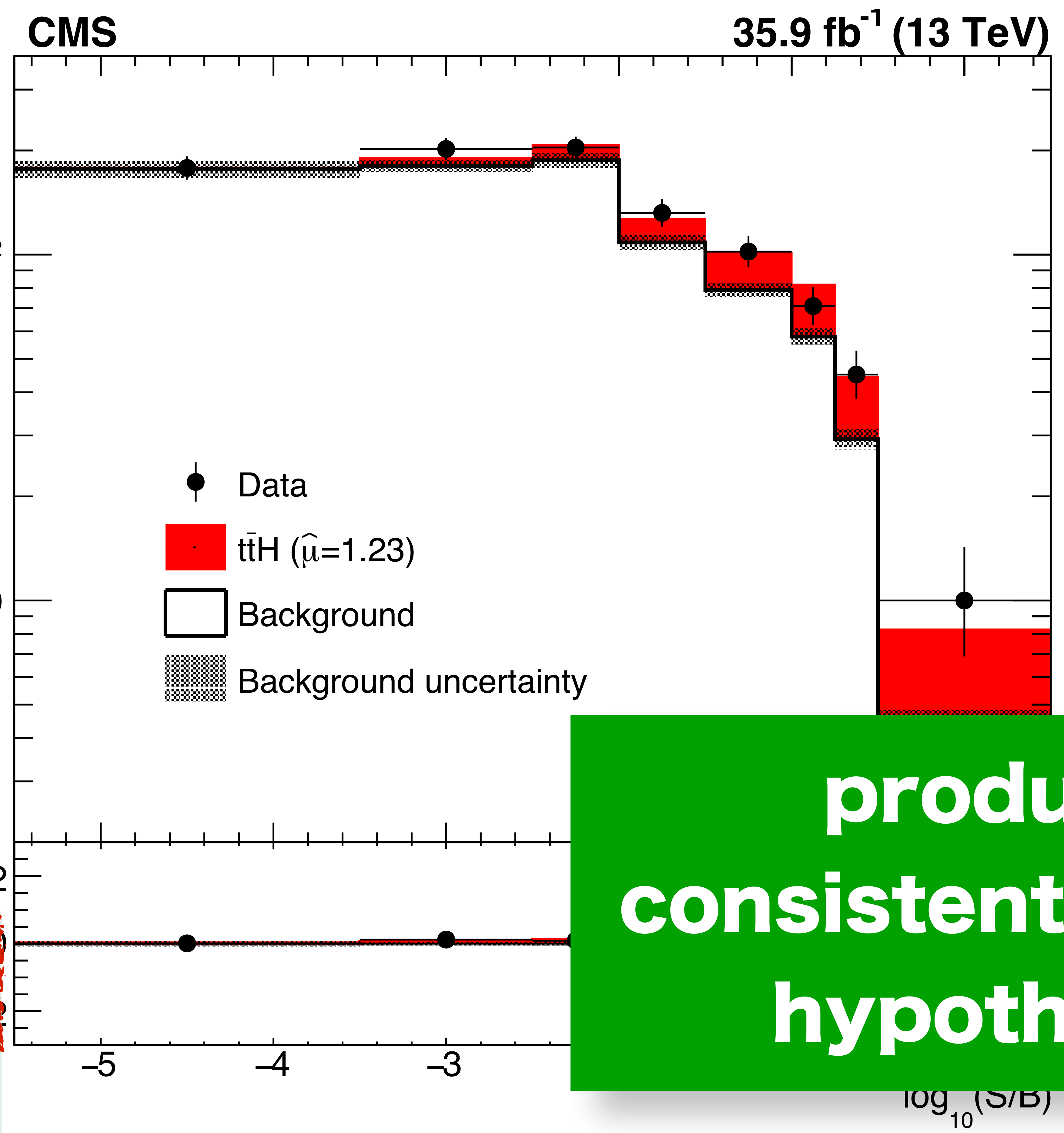
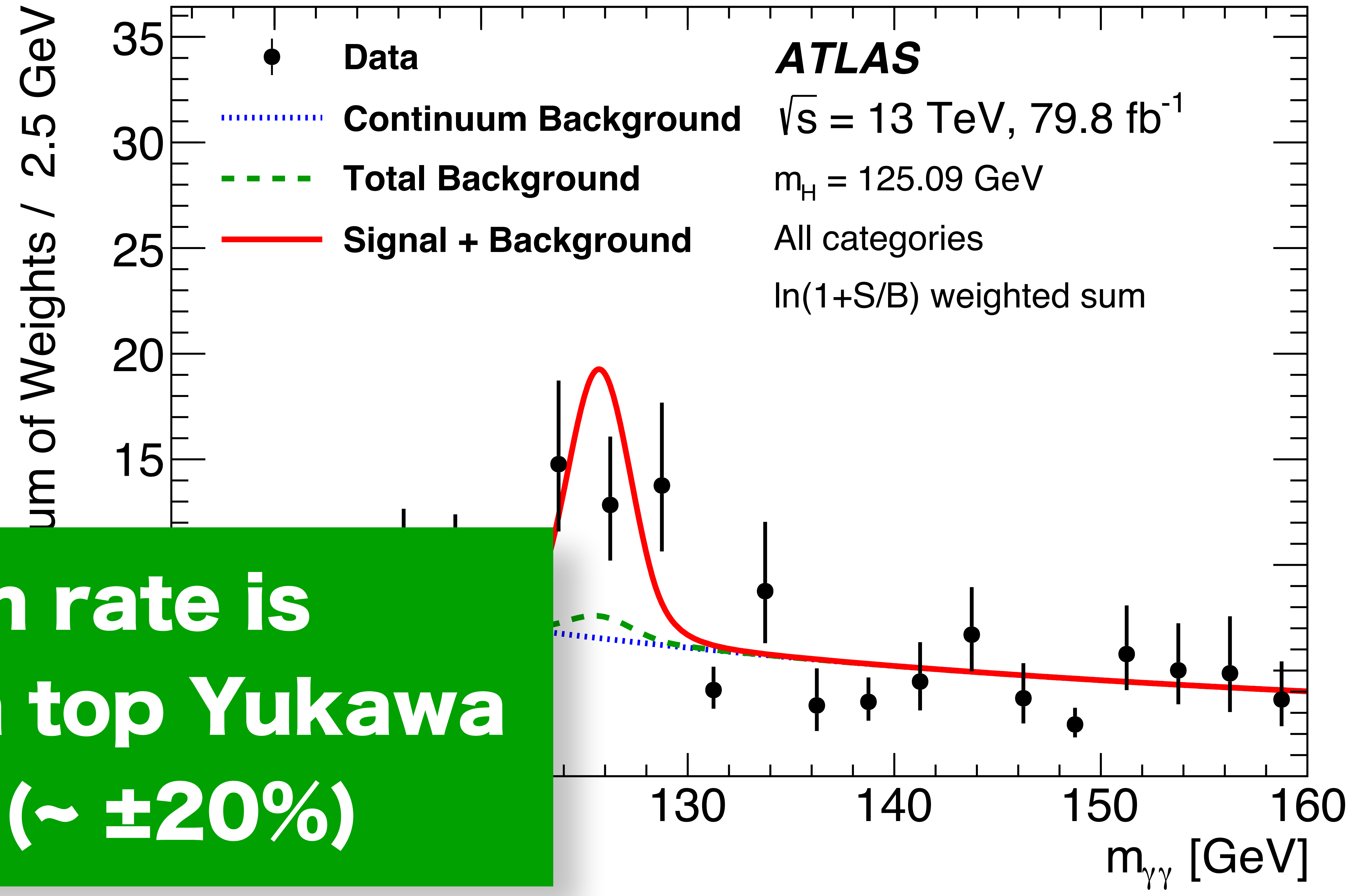
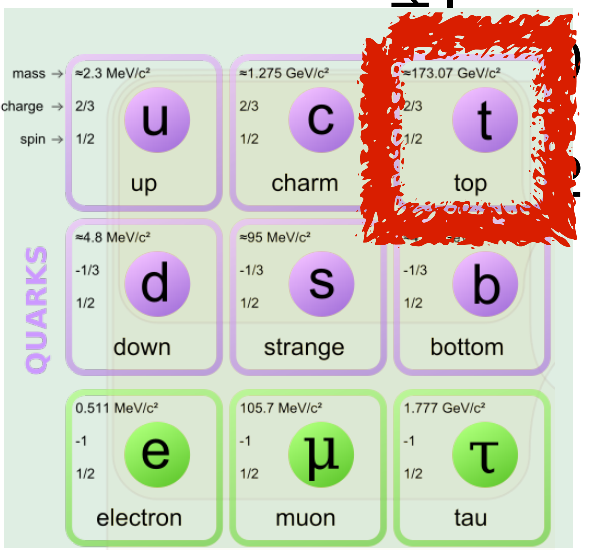
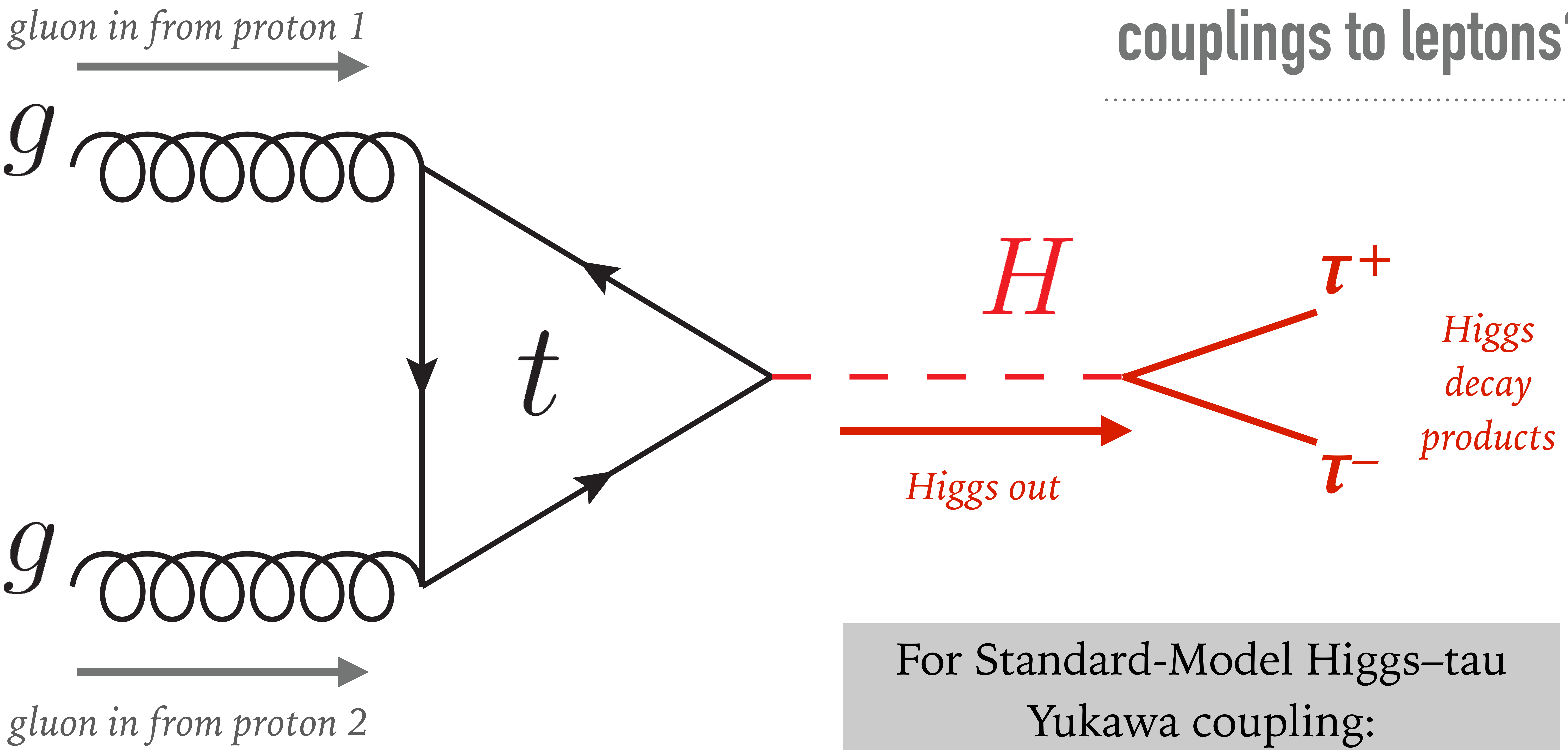




production rate is consistent with top Yukawa hypothesis (~ ±20%)

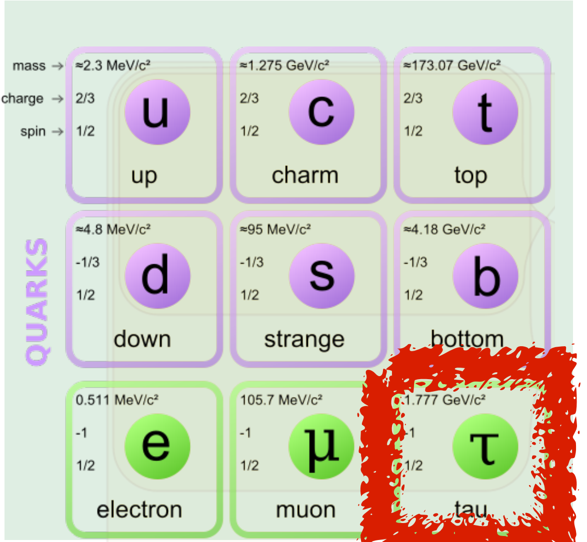


couplings to leptons?



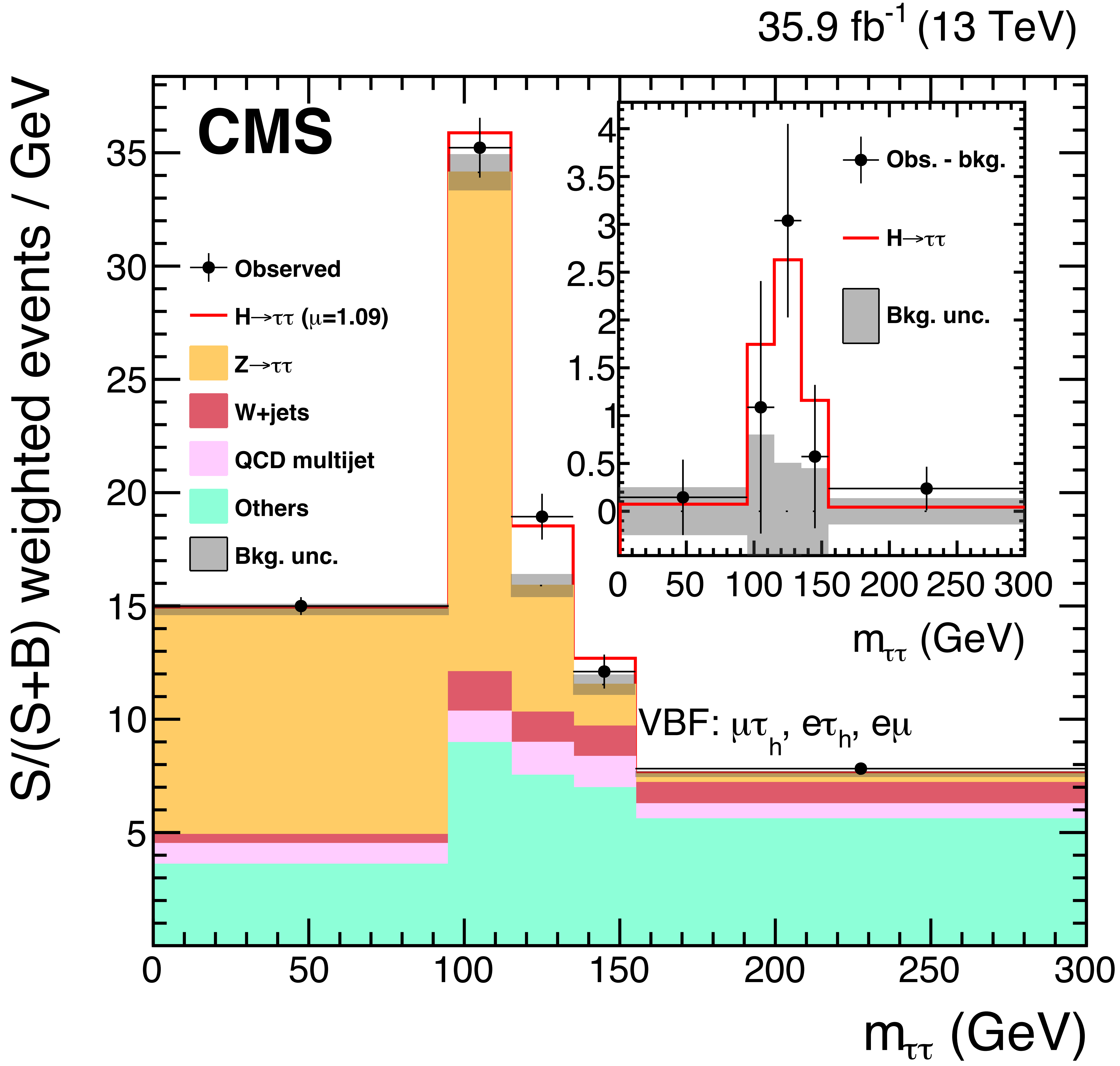
For Standard-Model Higgs–tau Yukawa coupling:

∼ 1 in every 16 Higgs bosons decays to $\tau^+\tau^-$

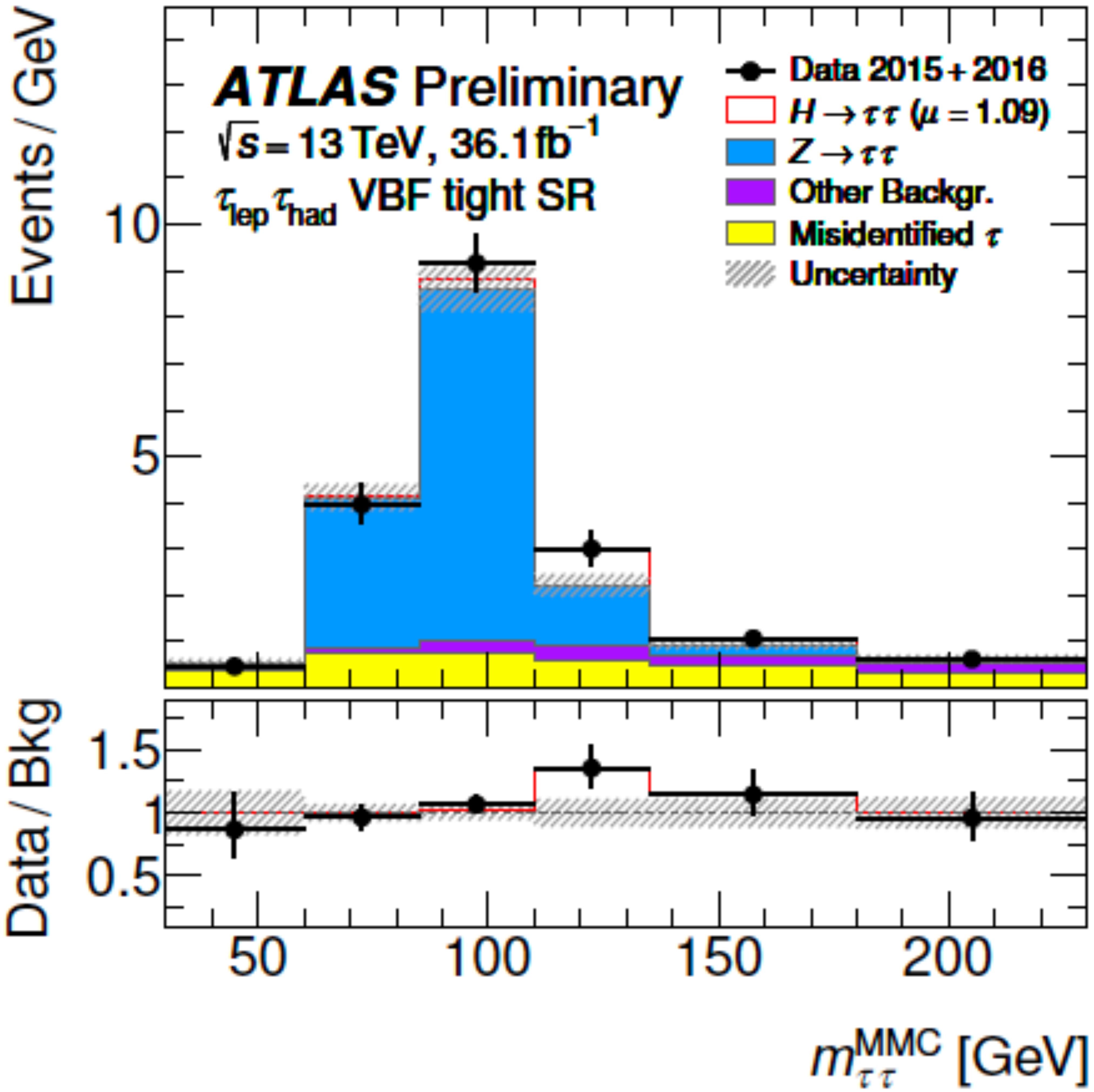


observation of H → ττ

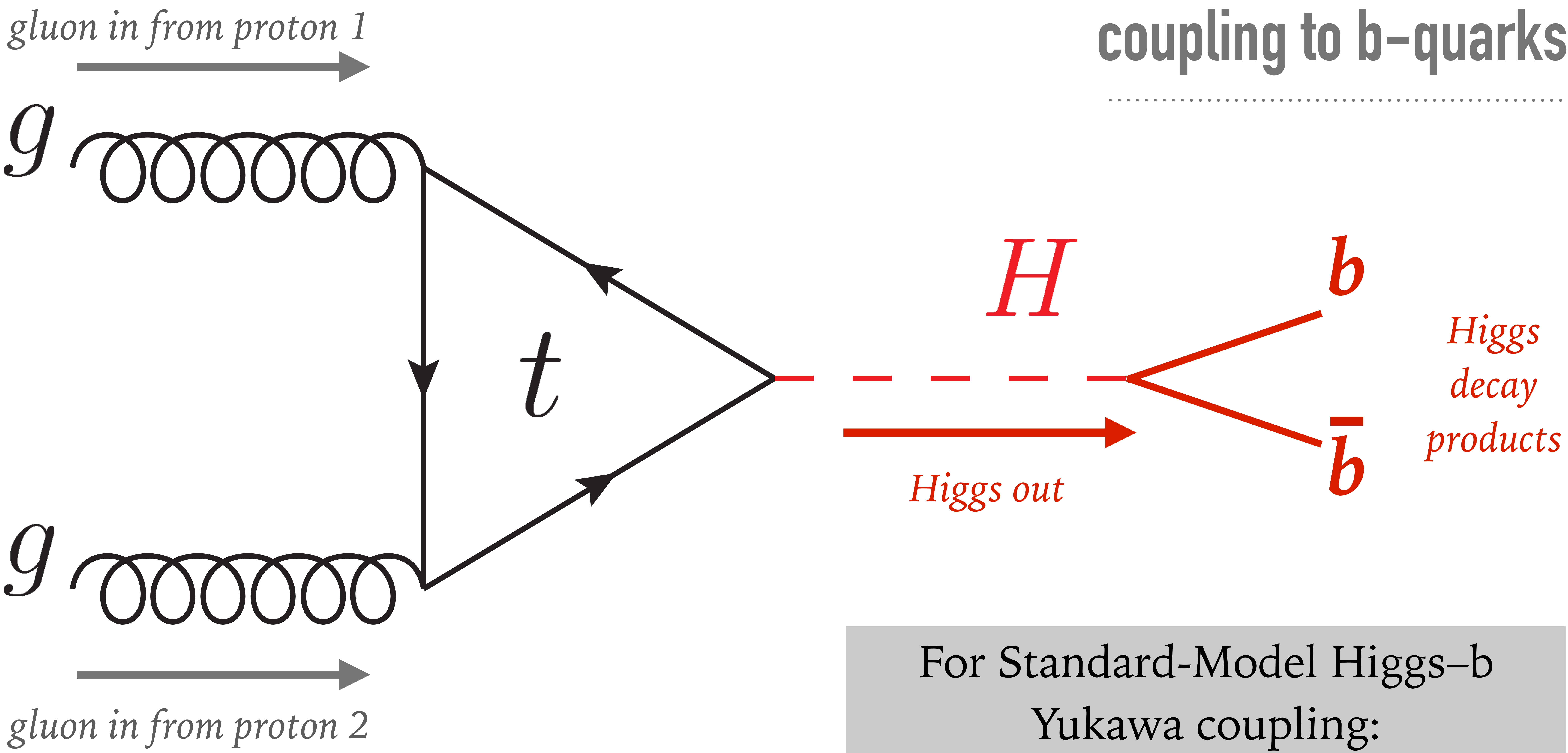
18 months ago: CMS >5-sigma H → $\tau\tau$

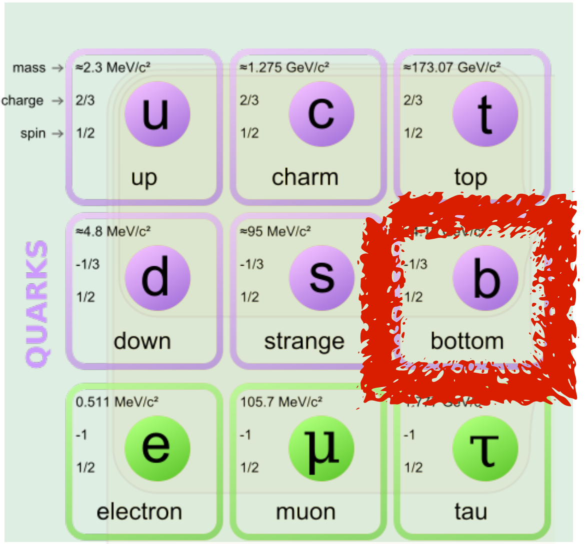


6 months ago: ATLAS >5-sigma H → $\tau\tau$



coupling to b-quarks?



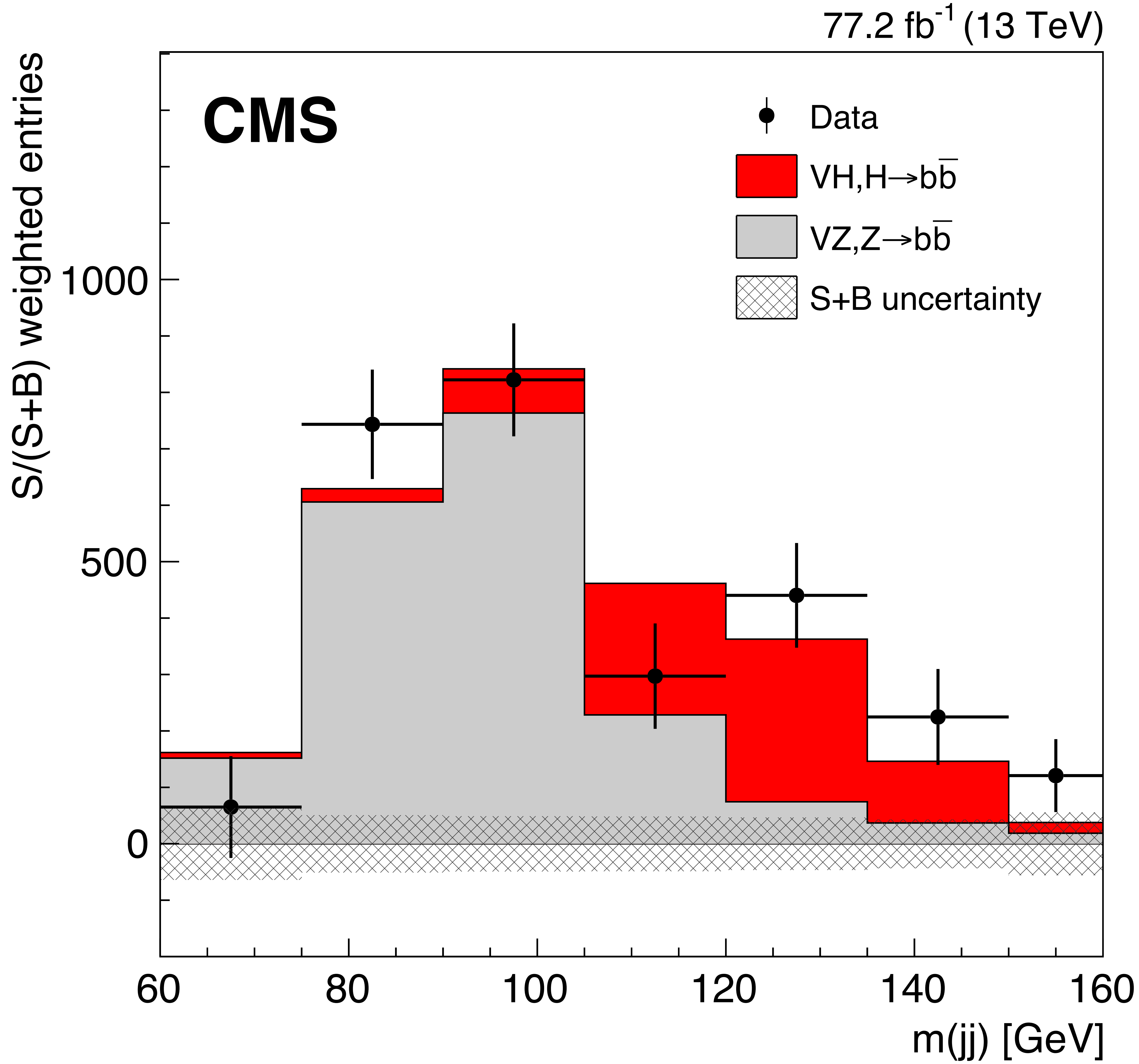


For Standard-Model Higgs–b Yukawa coupling:

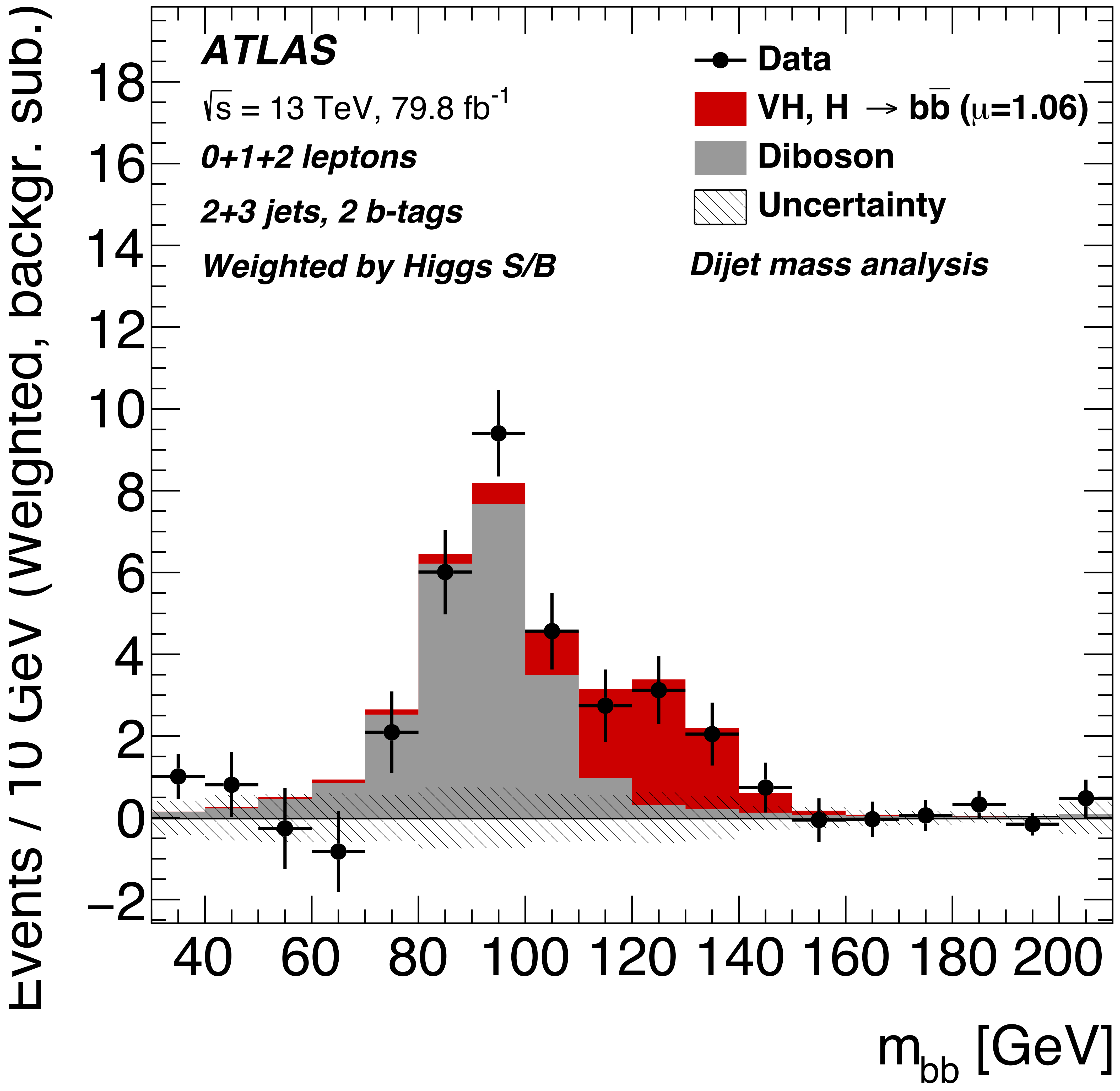
~ 58% of Higgs bosons should decay to bb

three months ago, observation of H → bb

CMS >5-sigma H → bb



ATLAS > 5-sigma H → bb



Analysis includes key idea from Butterworth, Davison, Rubin, GPS (PRL 100 (2008) 242001)

what could one be saying about it?

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 not merely because they had never before been directly observed, but also because they are **hypothesized to be responsible for the stability of hydrogen,** and for determining the size of atoms and the energy scales of chemical reactions.

Establishing the pattern of Yukawa couplings across the full remaining set of quarks and charged leptons is one of the major challenges for particle physics today.

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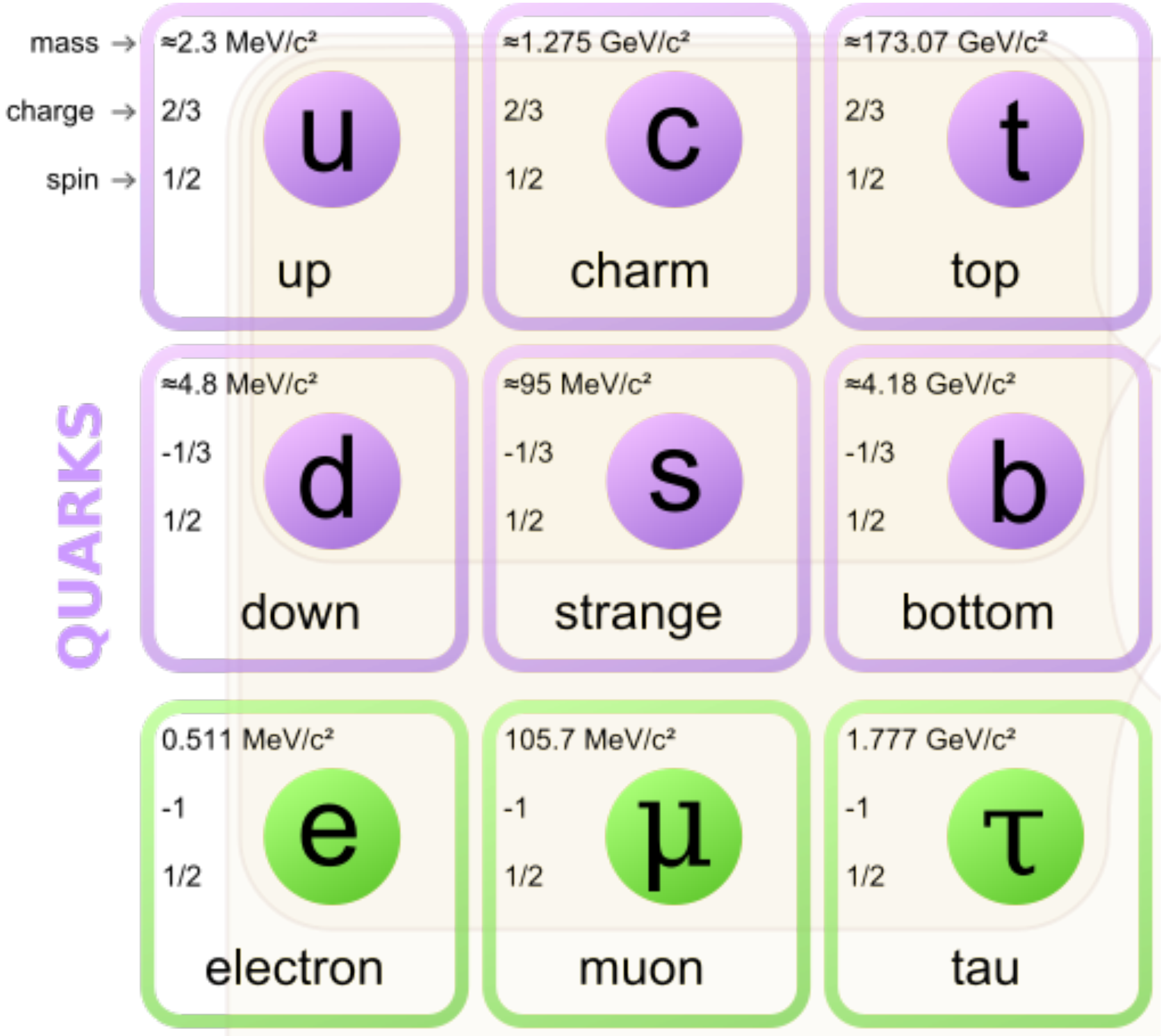
Is this any less important than the discovery of the Higgs boson itself?

My opinion: no, because fundamental interactions are as important as fundamental particles

Yukawas


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
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1.777 GeV/c²
-1
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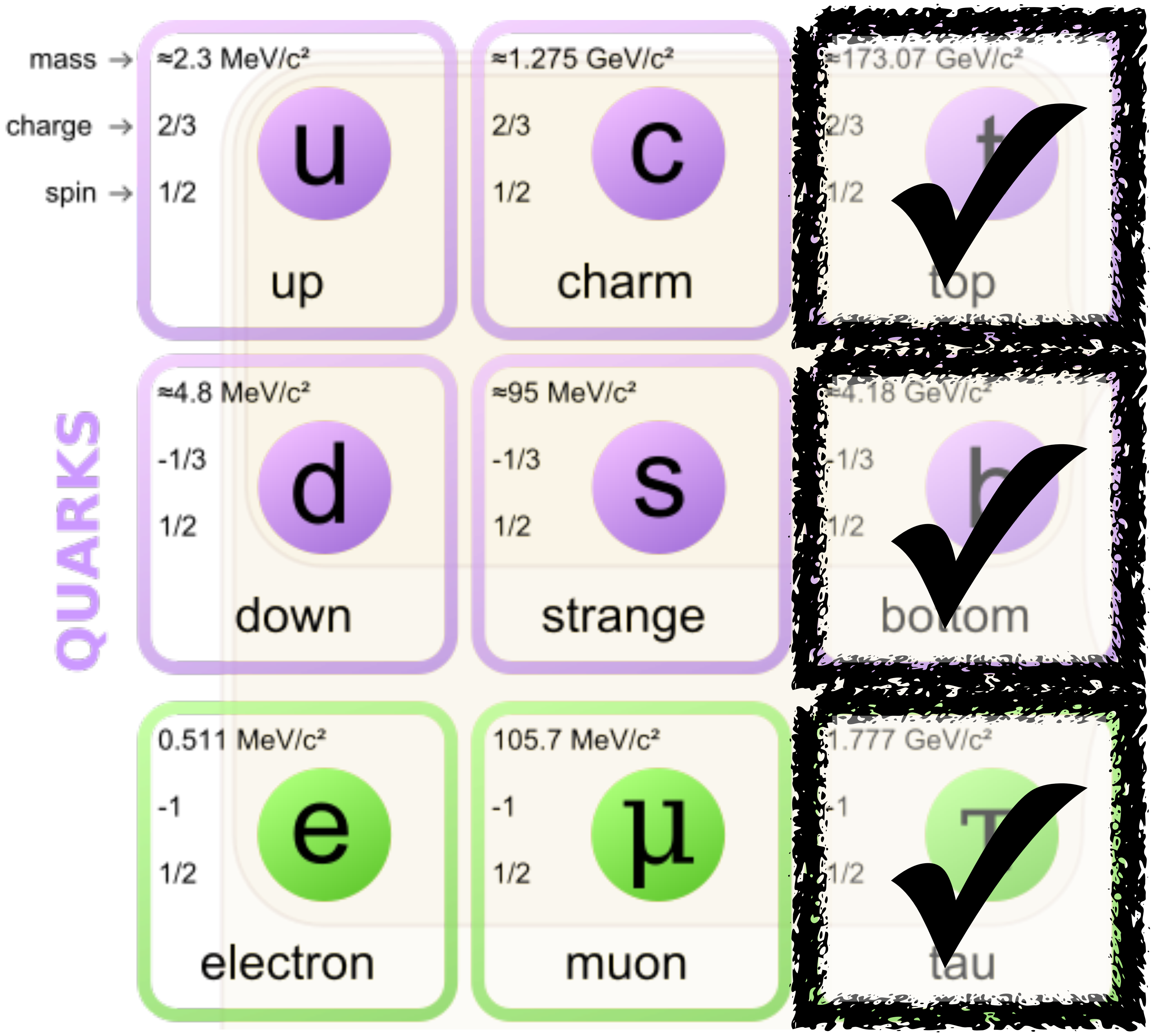
τ
tau

Yukawas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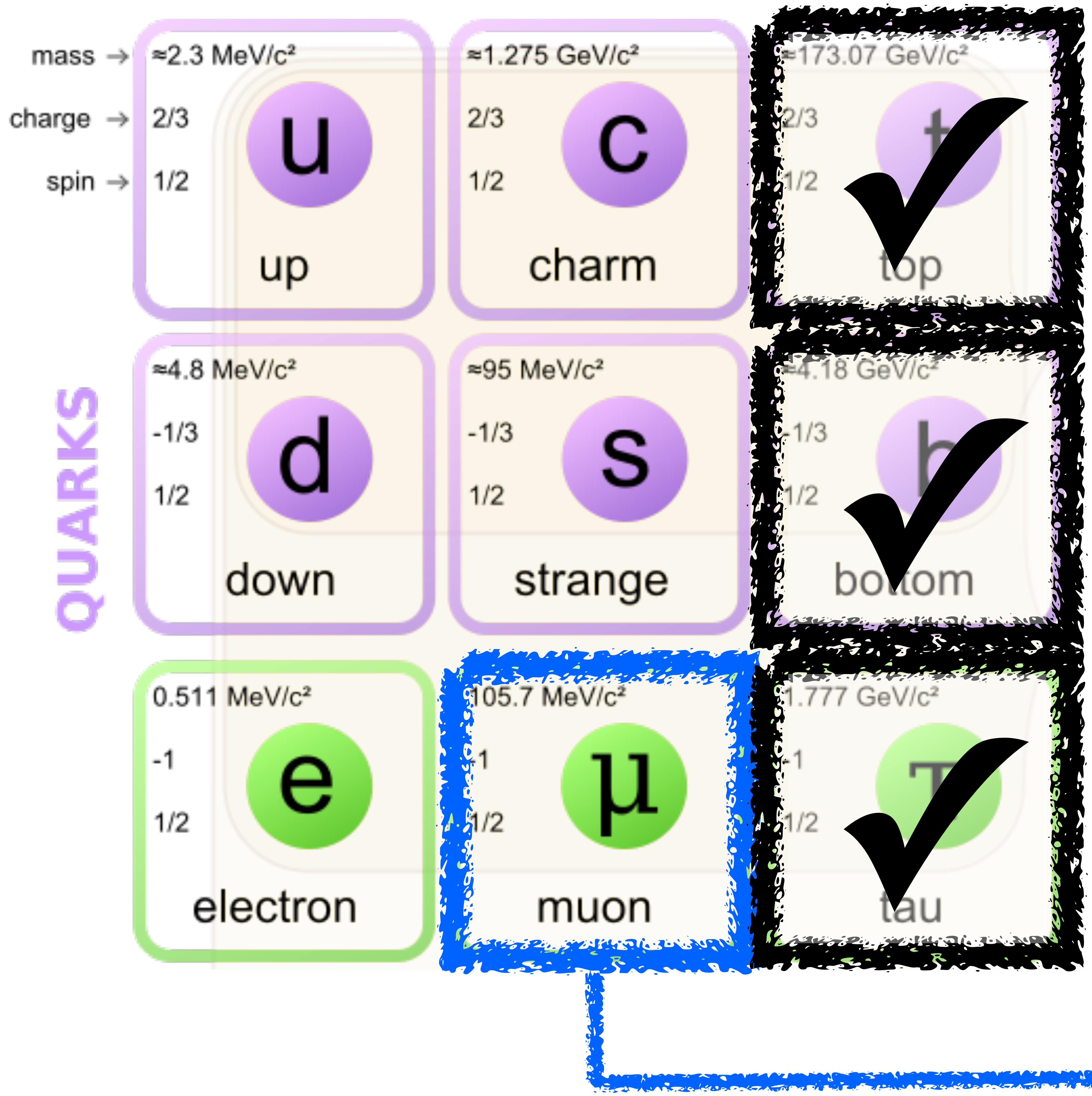
Yukawas



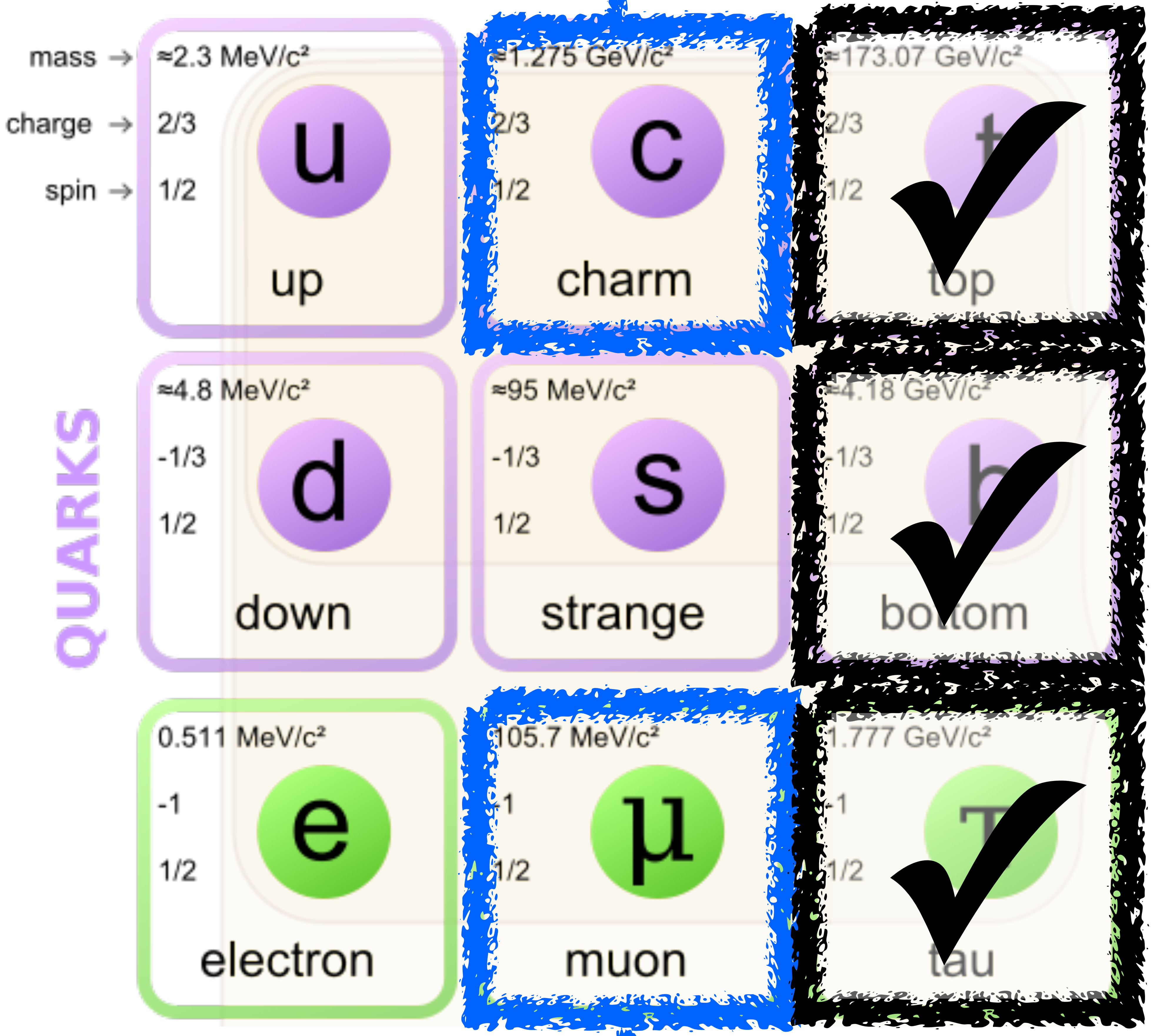
today: no evidence yet
(1 in 4570 decays)

observable at the LHC
within about 10 years.

Yukawas

today: no evidence yet
(1 in 35 decays)

needs a lepton
collider



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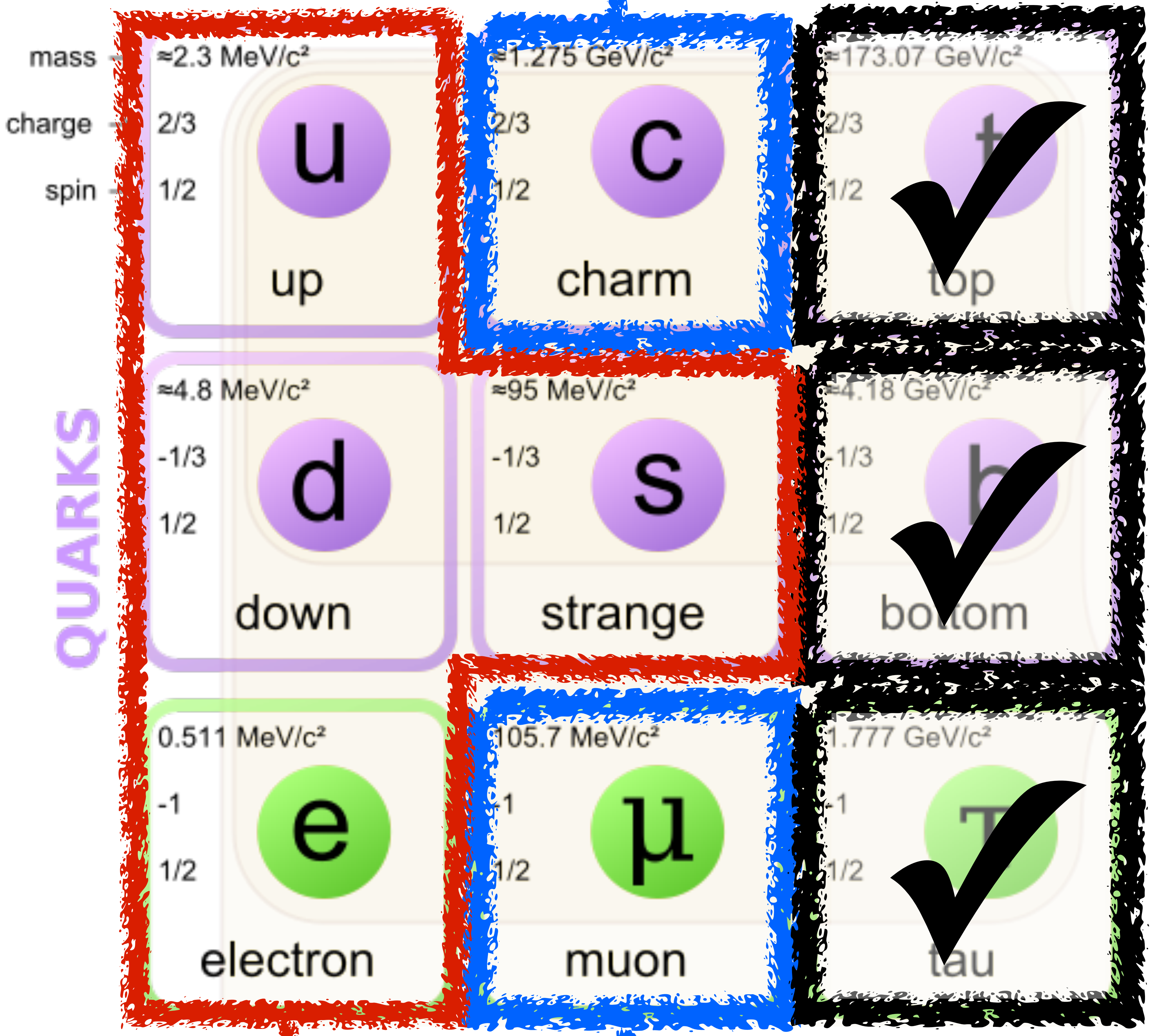

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no clear route to
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couplings at 5σ

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within about 10 years.

Yukawas

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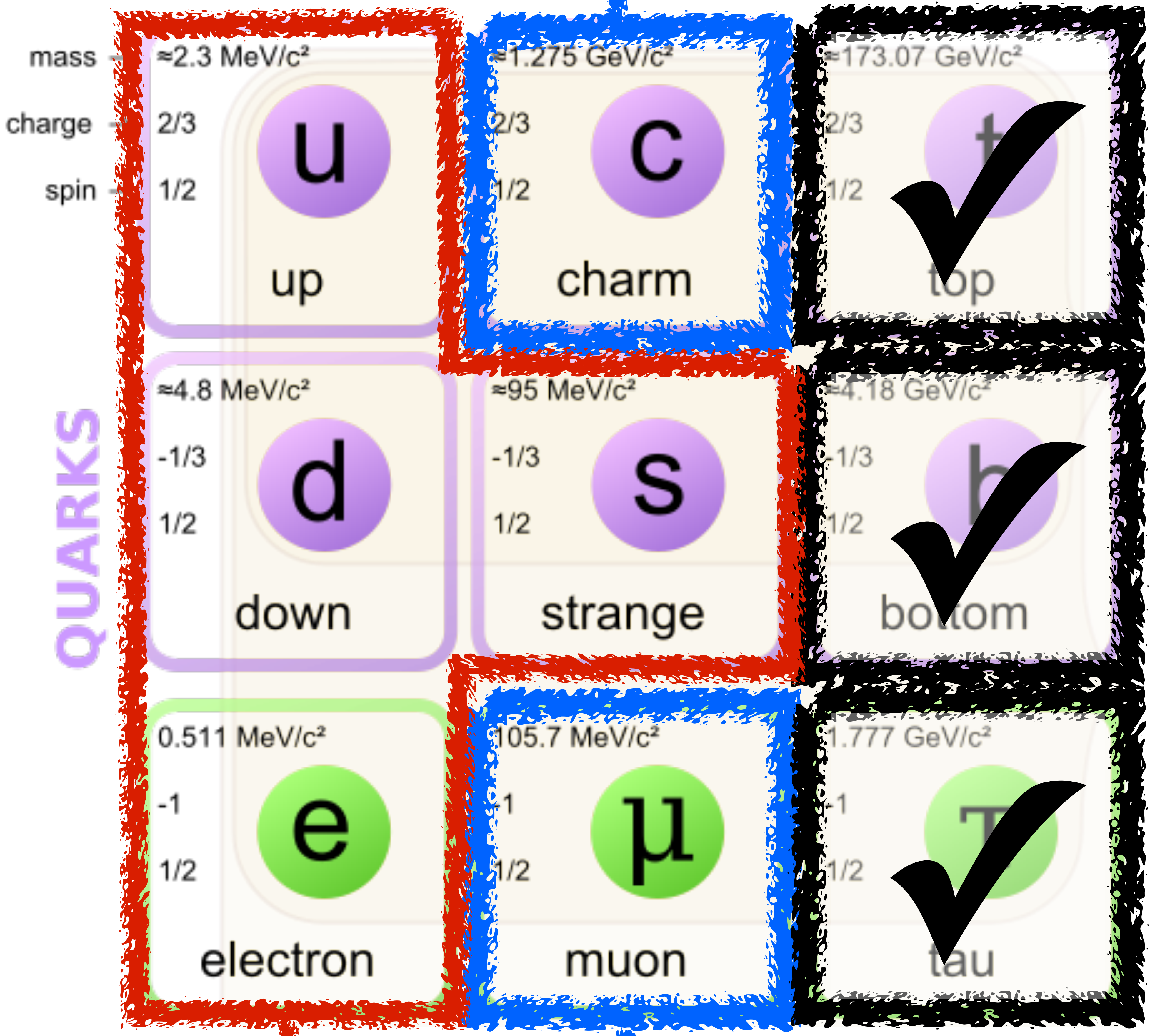
overall normalisation
(related to Higgs width):

needs a lepton collider



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2nd & 1st generation Yukawas

- the hierarchy of masses between generations remains a mystery (even if it's one that some people consign to the "hopeless" category)
- Does not necessarily come from hierarchy of dimensionless Yukawa coefficients
- E.g. the Giudice-Lebedev mechanism (and follow-up work)

0804.1753

$$-\mathcal{L}_Y = Y_{ij}(\phi)\bar{\psi}_i\psi_j\phi + \text{h.c.} \qquad Y_{ij}(\phi) = c_{ij}\left(\frac{\phi^\dagger\phi}{M^2}\right)^{n_{ij}}$$

- smallness of certain masses is consequence of vev^2/M^2 suppression, not small c_{ij}
- measured Hqq interaction larger by factor $(2n_{ij} + 1)$
- cf. also various more recent discussions, e.g. by Bauer, Carena, Carmona

1801.00363

Bottom-Yukawa coupling

How?

- Look for Higgs decays into t
- Huge background from jet e additional objects to tag: **VB**
- Complex final states ⟹ **mul** jets to objects and to disting

Greatest challenges

- Good **flavour tagging** perfo
- Large backgrounds from ***tt*** a

Grefe

C. Grefe - Higgs

Search for $H \rightarrow \mu\mu$

Phys. Rev. Lett. 119 (20

CMS-PAS-

- Loose event selection **requiring two isolated OS muons** and veto *b*-jets
- Large background from Drell-Yan and smaller background from top quarks
- Signal and background described by analytical functions; fit to di-muon mass distribution in all signal regions

- Use **BDT to select events in 2 VBF** categories (m_{jj}, $p_T^{\mu\mu}$, $|\Delta\eta_{jj}|$, ΔR_{jj}, etc.)

ATLAS

- All other events categorised in 6 *ggF* categories based on $p_T^{\mu\mu}$ and $|\Delta\eta_{\mu}|$

- Separate signal from background using BDT ($p_T^{\mu\mu}$, $\eta_{\mu\mu}$, m_{jj}, $|\Delta\eta_{jj}|$, N$_{b\text{-jets}}$ etc.)

CMS

- De sc

Grefe

C. Grefe - Higgs couplings to ferm

---

so much more to do with the Higgs sector

[LHCP conf. 2018]

EFT approach

Well-defined theoretical approach
Assumes New Physics states are heavy
Write Effective Lagrangian with only light (SM) particles
BSM effects can be incorporated as a momentum expansion

dimension-6 dimension-8

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4}\mathcal{O}_i^{d=8} + \ldots$$

BSM effects SM particles

example:

2HDM

$$\frac{ig}{2m_W^2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu}$$

$$\text{where } \bar{c}_W = \frac{m_W^2\,(2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2}$$

Sanz

Light quark Yukawas (2)

New idea: Using kinematic distributions i.e. the Higgs pT

κ_c
LHC Run I: $[-16, 18]$
LHC Run II: $[-1.4, 3.8]$
$\boxed{\text{HL-LHC: } [-0.6, 3.0]}$

1st generation
To be fully explored

Inclusive Higgs decays i.e VH + flavour tagging (limited by c-tagging)
(for evidence of bottom couplings: ATLAS: arXiv:1708.03299 and CMS: arXiv:1708.04188)
$ZH(H \to c\bar{c})$ gives a limit of 110 x SM expectation (ATLAS-CONF-2017-078)

Vryonidou

LHCP2018

13

The Higgs potential

Higgs potential: $\boxed{V(H) = \frac{1}{2}M_H^2H^2 + \lambda_{HHH}vH^3 + \frac{1}{4}\lambda_{HHHH}H^4}$

Fixed values in the SM: $\boxed{\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}}$

Measuring λ$_{HHH}$ and λ$_{HHHH}$ tests the SM

What can measuring λ$_{HHH}$ tell us?

Electroweak baryogenesis requires a first order strong EWPT ➡ $\boxed{\frac{\phi_c}{T_c} \gtrsim 1}$

$\lambda_{H^3}/\lambda_{H^3,SM} < 1.5 : \phi_c/T_c < 1$
EW baryogenesis is disfavoured
$\lambda_{H^3}/\lambda_{H^3,SM} > 2 : \phi_c/T_c > 1$
EW baryogenesis is favoured

Reichert et al: arXiv:1711.00019

Vryonidou

LHCP2018

20

A cosmological Higgs

HIGGS

Dark Matter
Higgs portal
Higgs DM mediator

UV sensitivity
Naturalness
heavy new physics
Relaxation

Inflation
Higgs inflation
Inflaton vs Higgs

Phase transitions
Baryogenesis
gravitational waves

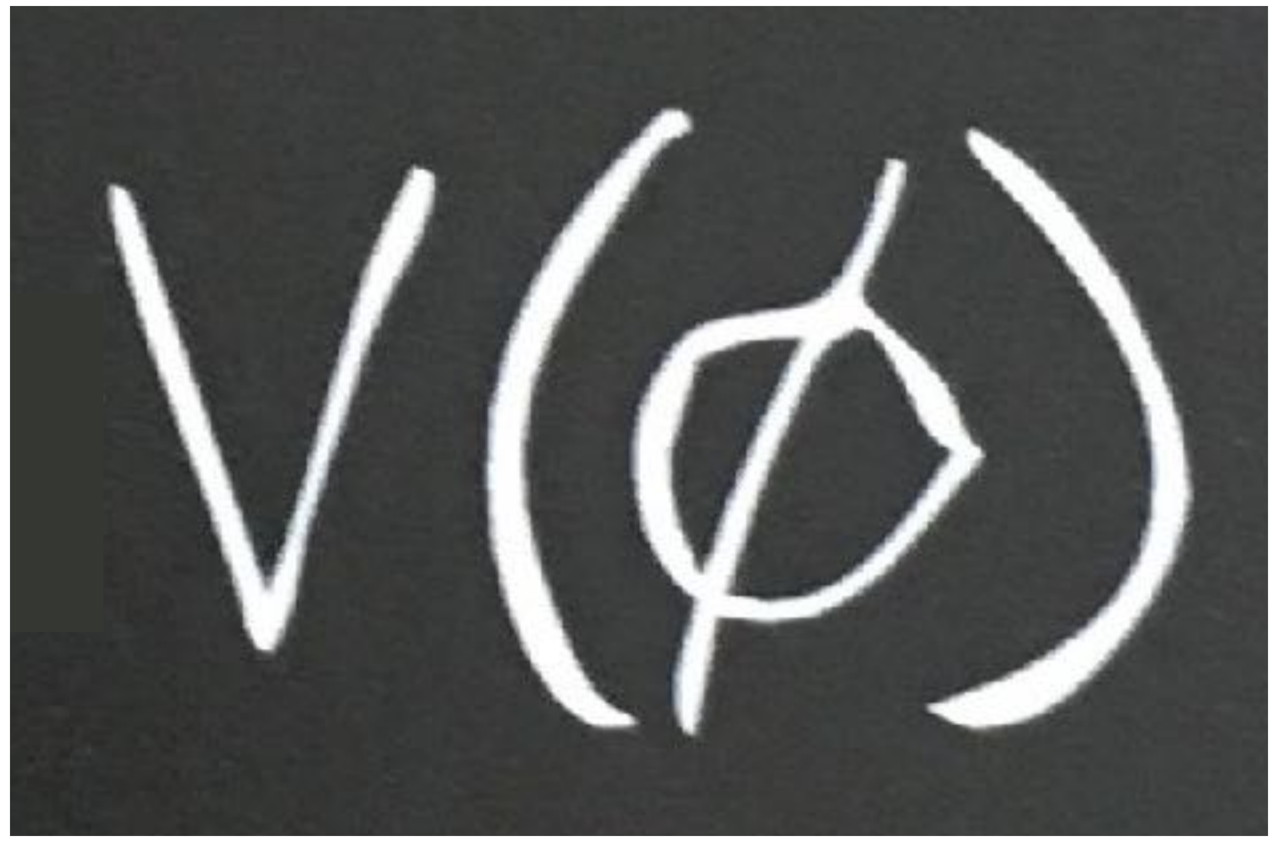
Fate of the Universe
Stability

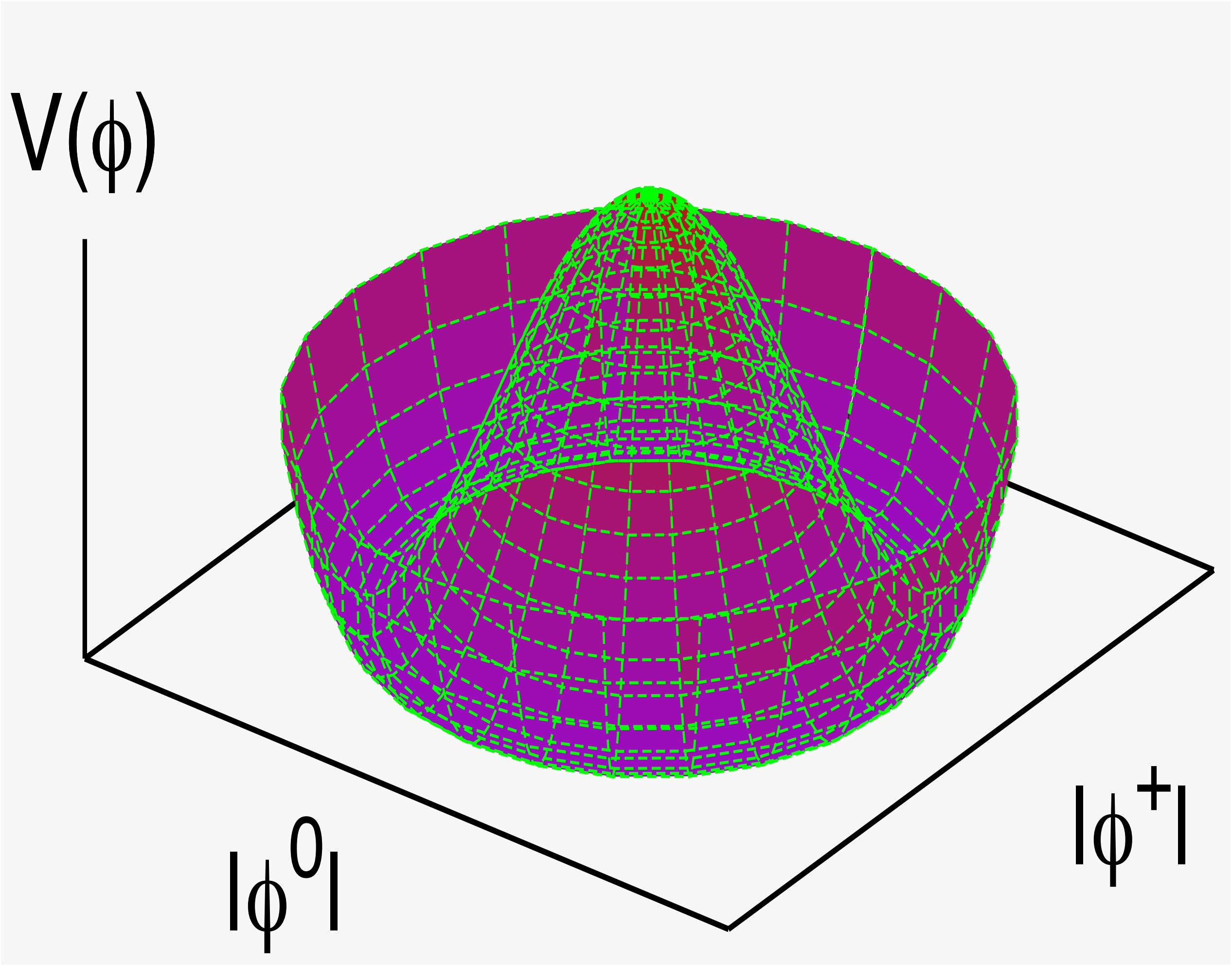
The LHC provides the most precise, controlled way of studying the Higgs and direct access to TeV scales
Exploiting complementarity with cosmo/astro probes

Similar story for Axions and ALPs, scalars are versatile

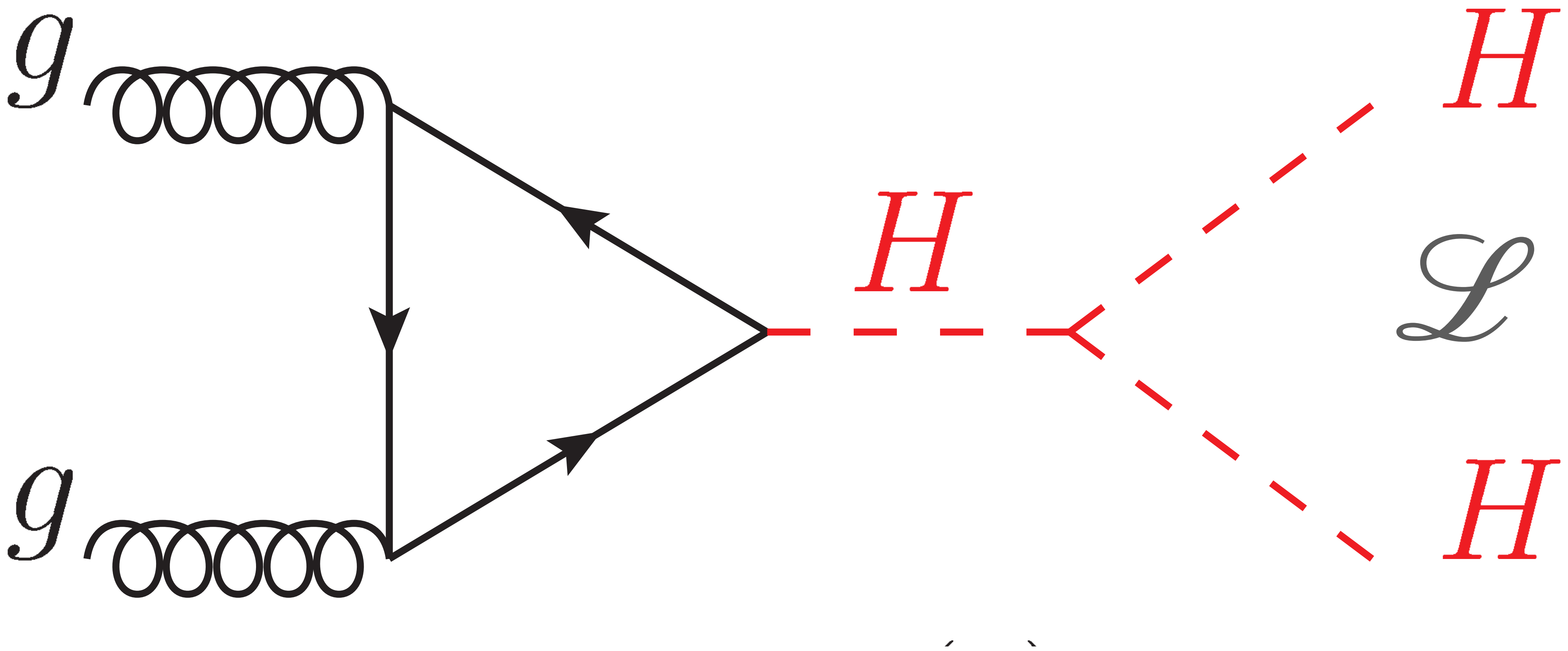
Sanz

$V(\Phi) = m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$?





- keystone of standard model
- so far φ^4 only ever seen in textbooks!
- can be tested through triple-Higgs interaction



$$\mathscr{L} = \frac{m_H^2}{2v} H^3 + \cdots$$

- **best route: a higher-energy pp collider**

(at LHC, Higgs pair produced only in ~ 1 in 3 trillion collisions

for much of Higgs sector, we know what to do to get answers.
What about other "big" questions

Nature of dark matter (& dark energy)

Fine-tuning (e.g. supersymmetry and similar)

Matter-antimatter asymmetry of the universe

[…]

> Finding dark matter and studying it will be the biggest challenge for the Large Hadron Collider’s second run

-a large LHC experiment’s spokesperson [2015]

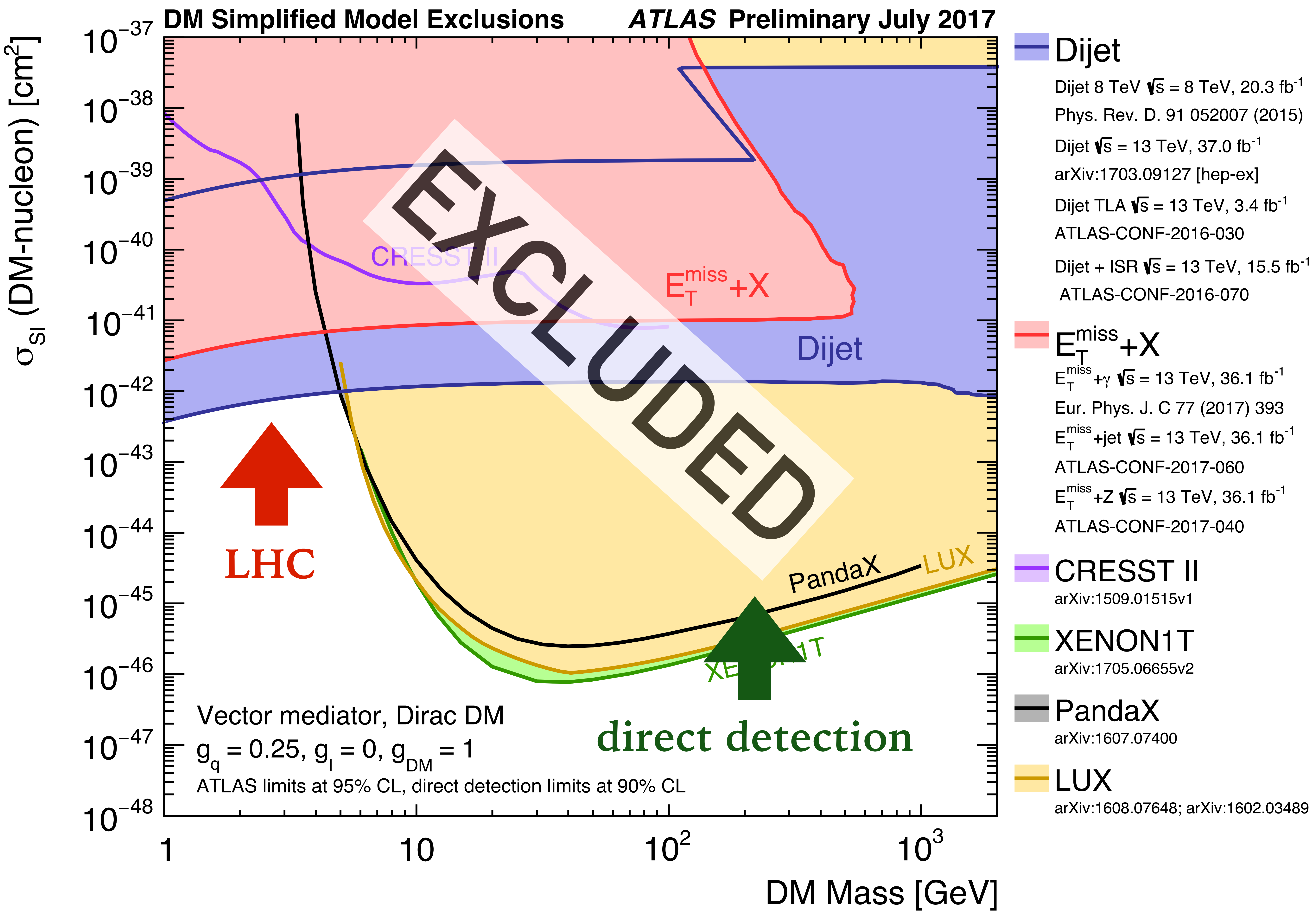
https://www.pbs.org/newshour/science/large-hadron-collider-gears-find-dark-matter-new-particles-second-run

Looking beyond the SM: searches for dark matter at LHC & elsewhere

Classic dark-matter candidate: a weakly-interacting massive particle (**WIMP**, e.g. from supersymmetry).

Masses ~ GeV upwards

(search interpretations strongly model dependent)



musn't be (too) disappointed at lack of dark matter signal at LHC

Evidence for dark matter exists since the 1930s.

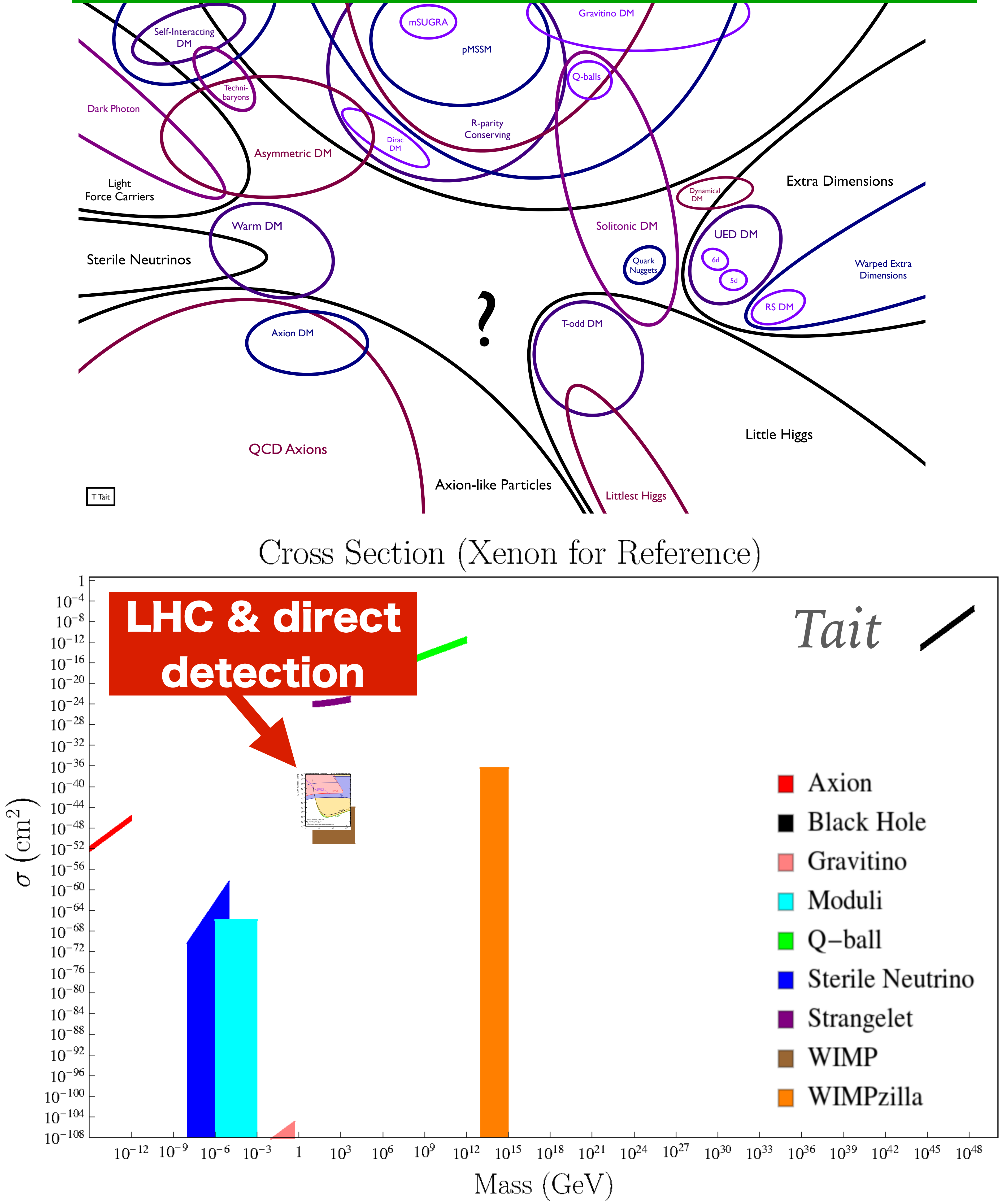
Today we know that

- **there are many possible models**
- **the range of parameters they span is large**

We must deploy full ingenuity in searching for dark matter, including at LHC.

But must also recognise that it has remained elusive for 80–90 years, and chances of finding it in any given year are small!

Snowmass non-WIMP dark matter report, 1310.8642



LHC & direct detection

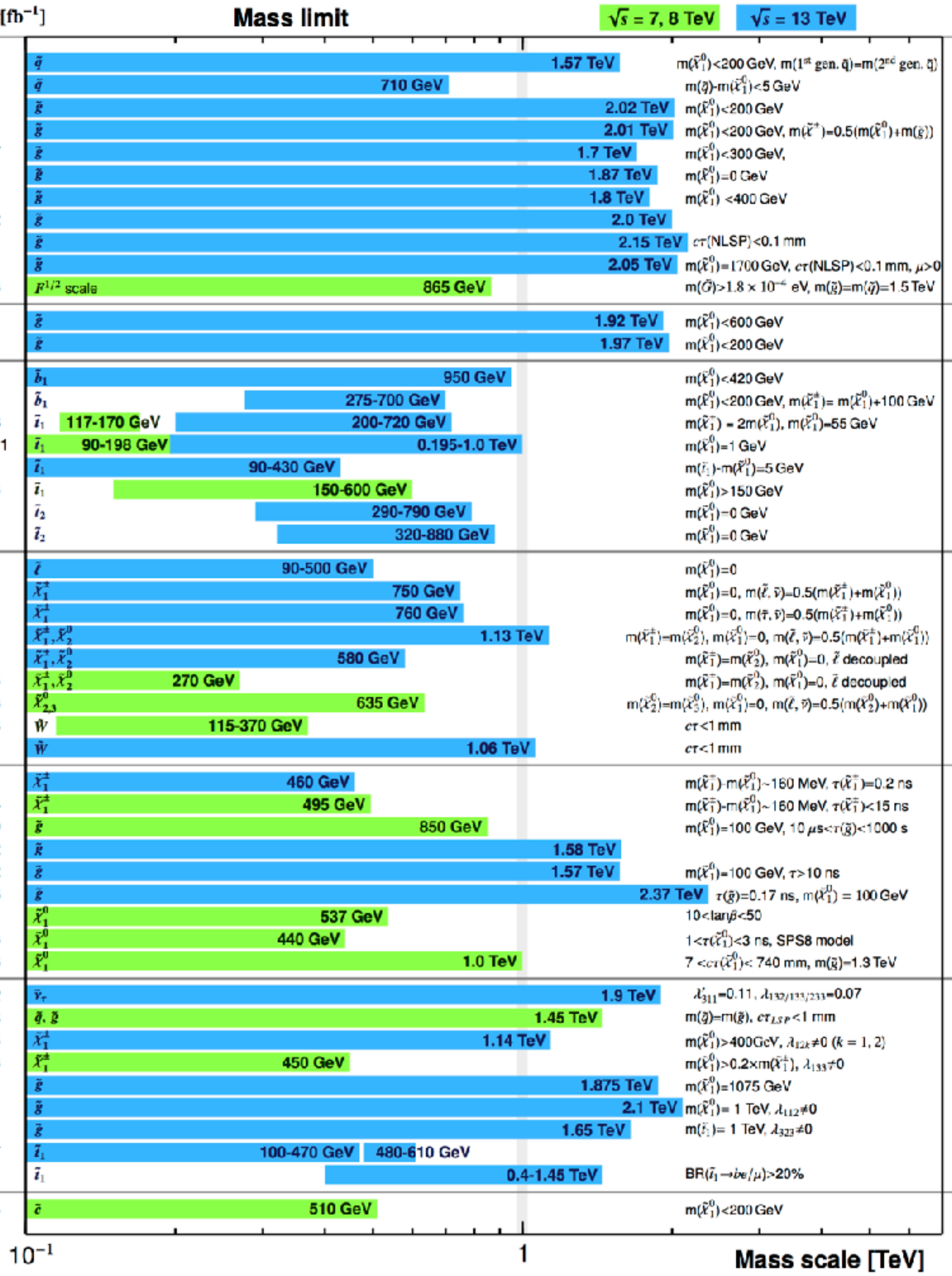
Figure 1. *Graphical representation of the (incomplete) landscape of candidates. Above, the landscape of dark matter candidates due to T. Tait. Below, the range of dark matter candidates' masses and interaction cross sections with a nucleus of Xe (for illustrative purposes) compiled by L. Pearce. Dark matter candidates have an enormous range of masses and interaction cross sections.*

ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

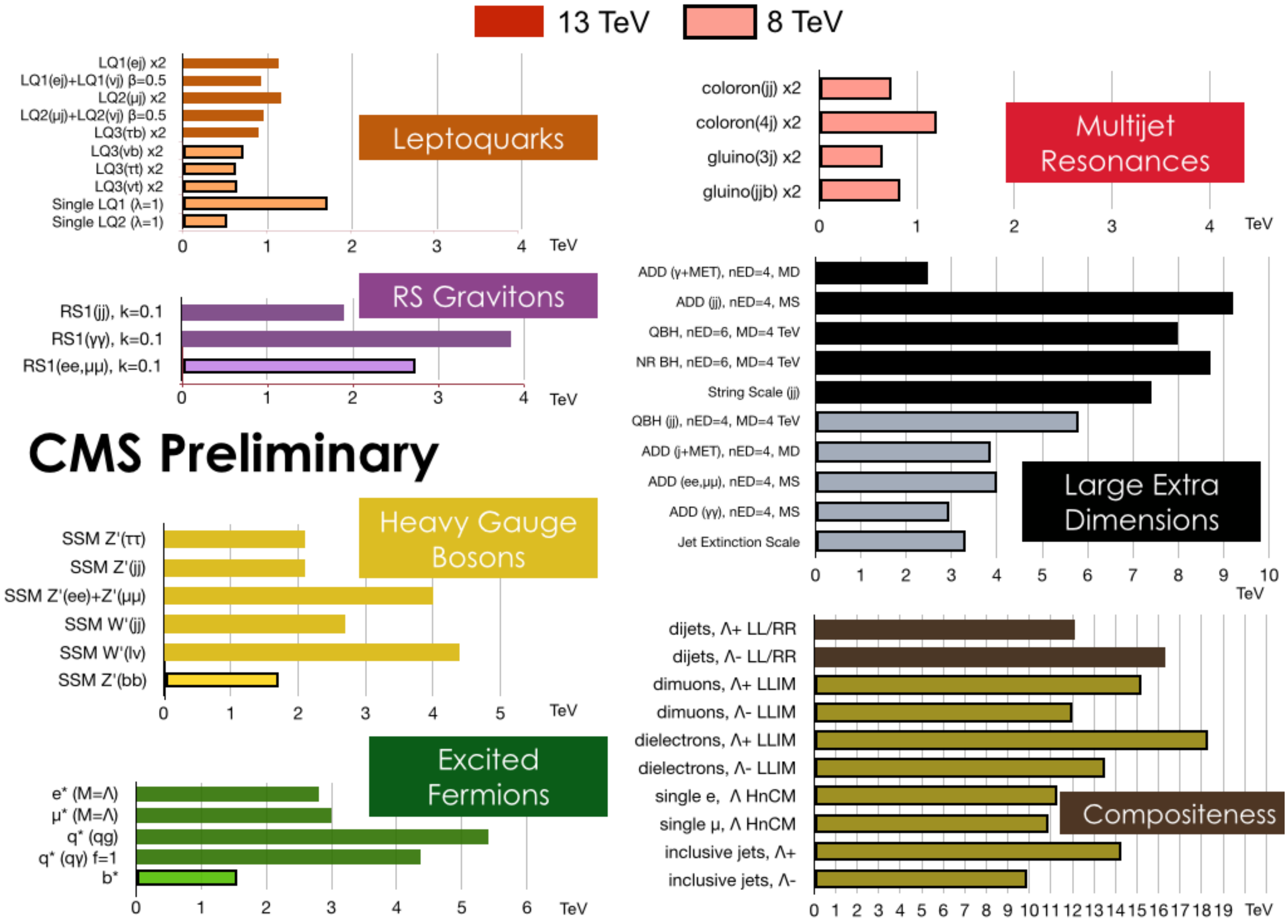
ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV



	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$	🟦 1.57 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1712.02332
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$	🟦 710 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	🟦 2.02 TeV	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	🟦 2.01 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	Yes	14.7	$\tilde{g}$	🟦 1.7 TeV	m($\tilde{\chi}_1^0$)<300 GeV,	1611.05791
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	$\tilde{g}$	🟦 1.87 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$	🟦 1.8 TeV	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$	🟦 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	36.1	$\tilde{g}$	🟦 2.15 TeV	$c\tau$(NLSP)<0.1 mm	ATLAS-CONF-2017-080
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	$\tilde{g}$	🟦 2.05 TeV	m($\tilde{\chi}_1^0$)=1700 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2017-080
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	🟩 865 GeV	m($\tilde{G}$)>1.8 × 10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$	🟦 1.92 TeV	m($\tilde{\chi}_1^0$)<600 GeV	1711.01901
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$	🟦 1.97 TeV	m($\tilde{\chi}_1^0$)<200 GeV	1711.01901
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	$\tilde{b}_1$	🟦 950 GeV	m($\tilde{\chi}_1^0$)<420 GeV	1708.09266
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e, μ (SS)	1 b	Yes	36.1	$\tilde{b}_1$	🟦 275-700 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)= m($\tilde{\chi}_1^0$)+100 GeV	1706.03731
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^\pm$	0-2 e, μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$	🟩 117-170 GeV 🟦 200-720 GeV	m($\tilde{\chi}_1^\pm$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$	🟩 90-198 GeV 🟦 0.195-1.0 TeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	36.1	$\tilde{t}_1$	🟦 90-430 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	🟩 150-600 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1	$\tilde{t}_2$	🟦 290-790 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$	🟦 320-880 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03986
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	$\tilde{\ell}$	🟦 90-500 GeV	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^\pm$	🟦 750 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^\pm$	🟦 760 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	36.1	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	🟦 1.13 TeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	🟦 580 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	🟩 270 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	🟩 635 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	$\tilde{W}$	🟩 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	2 γ	-	Yes	36.1	$\tilde{W}$	🟦 1.06 TeV	$c\tau$<1 mm	ATLAS-CONF-2017-080
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$	🟦 460 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^\pm$)=0.2 ns	1712.02118
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$	🟩 495 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^\pm$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	🟩 850 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$	🟦 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$	🟦 1.57 TeV	m($\tilde{\chi}_1^0$)=100 GeV, τ>10 ns	1604.04520
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$	displ. vtx	-	Yes	32.8	$\tilde{g}$	🟦 2.37 TeV	τ($\tilde{g}$)=0.17 ns, m($\tilde{\chi}_1^0$) = 100 GeV	1710.04901
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	🟩 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	🟩 440 GeV	1<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	🟩 1.0 TeV	7 <$c\tau$($\tilde{\chi}_1^0$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	🟦 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	🟩 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^\pm$	🟦 1.14 TeV	m($\tilde{\chi}_1^0$)>400GeV, $\lambda_{12k}\neq 0$ (k = 1, 2)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$	🟩 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{133}\neq 0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$	🟦 1.875 TeV	m($\tilde{\chi}_1^0$)=1075 GeV	SUSY-2016-22
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	🟦 2.1 TeV	m($\tilde{\chi}_1^0$)= 1 TeV, $\lambda_{112}\neq 0$	1704.08493
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	🟦 1.65 TeV	m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq 0$	1704.08493
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$	🟦 100-470 GeV 🟦 480-610 GeV		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e, μ	2 b	-	36.1	$\tilde{t}_1$	🟦 0.4-1.45 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	1710.05544
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$	🟩 510 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

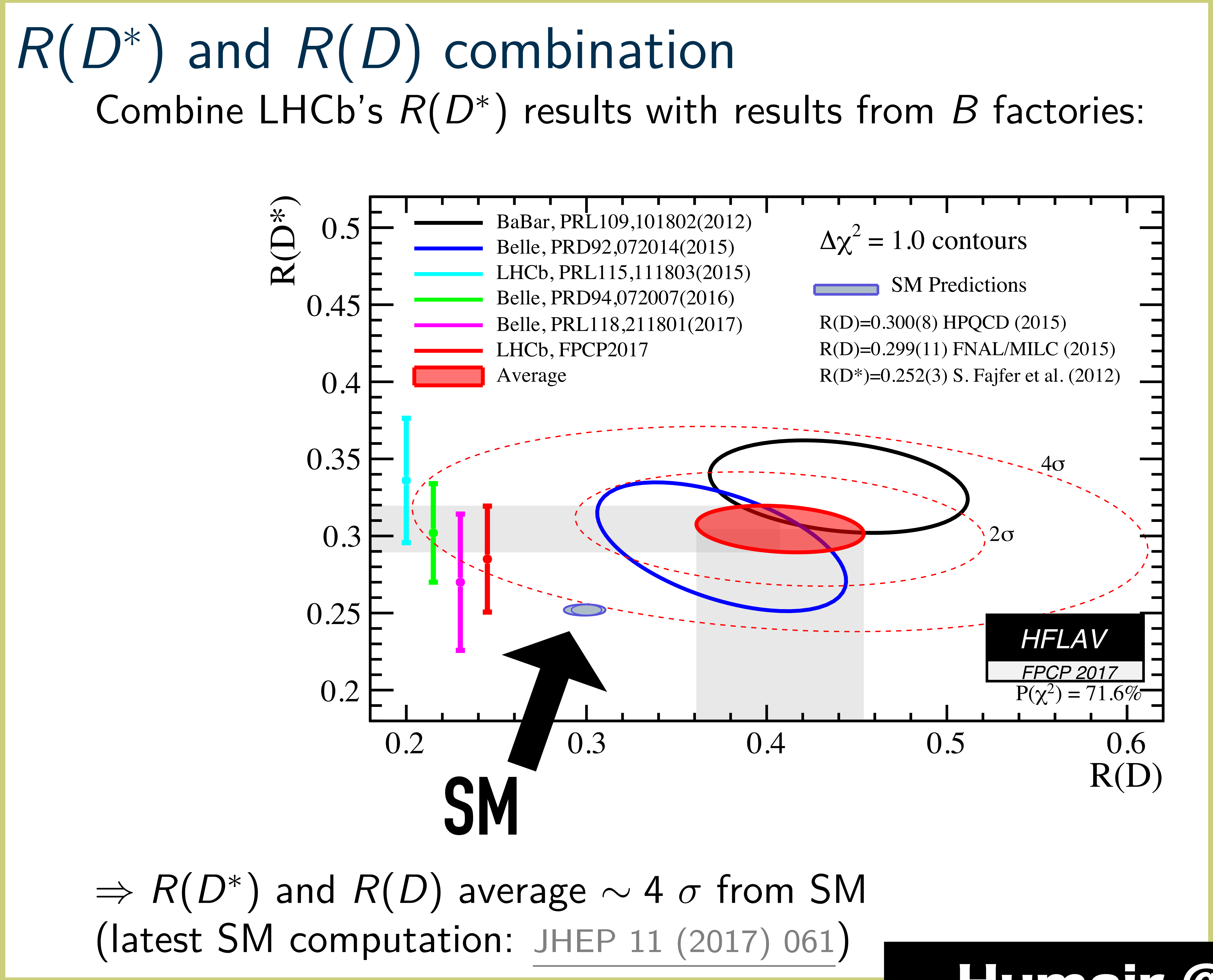

13 TeV
8 TeV
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj) β=0.5
LQ2(μj) x2
LQ2(μj)+LQ2(νj) β=0.5
LQ3(τb) x2
LQ3(νb) x2
LQ3(τt) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
0 1 2 3 4 TeV
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
0 1 2 3 4 TeV
RS Gravitons
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
0 1 2 3 4 TeV
CMS Preliminary
Large Extra Dimensions
ADD (γ+MET), nED=4, MD
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
String Scale (jj)
QBH (jj), nED=4, MD=4 TeV
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
Jet Extinction Scale
0 1 2 3 4 5 6 7 8 9 10 TeV
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM Z'(bb)
0 1 2 3 4 5 TeV
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 TeV
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
0 1 2 3 4 5 6 TeV

anomalies

the current place where there are hints of something happening

charged current

$$R(D^*) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$



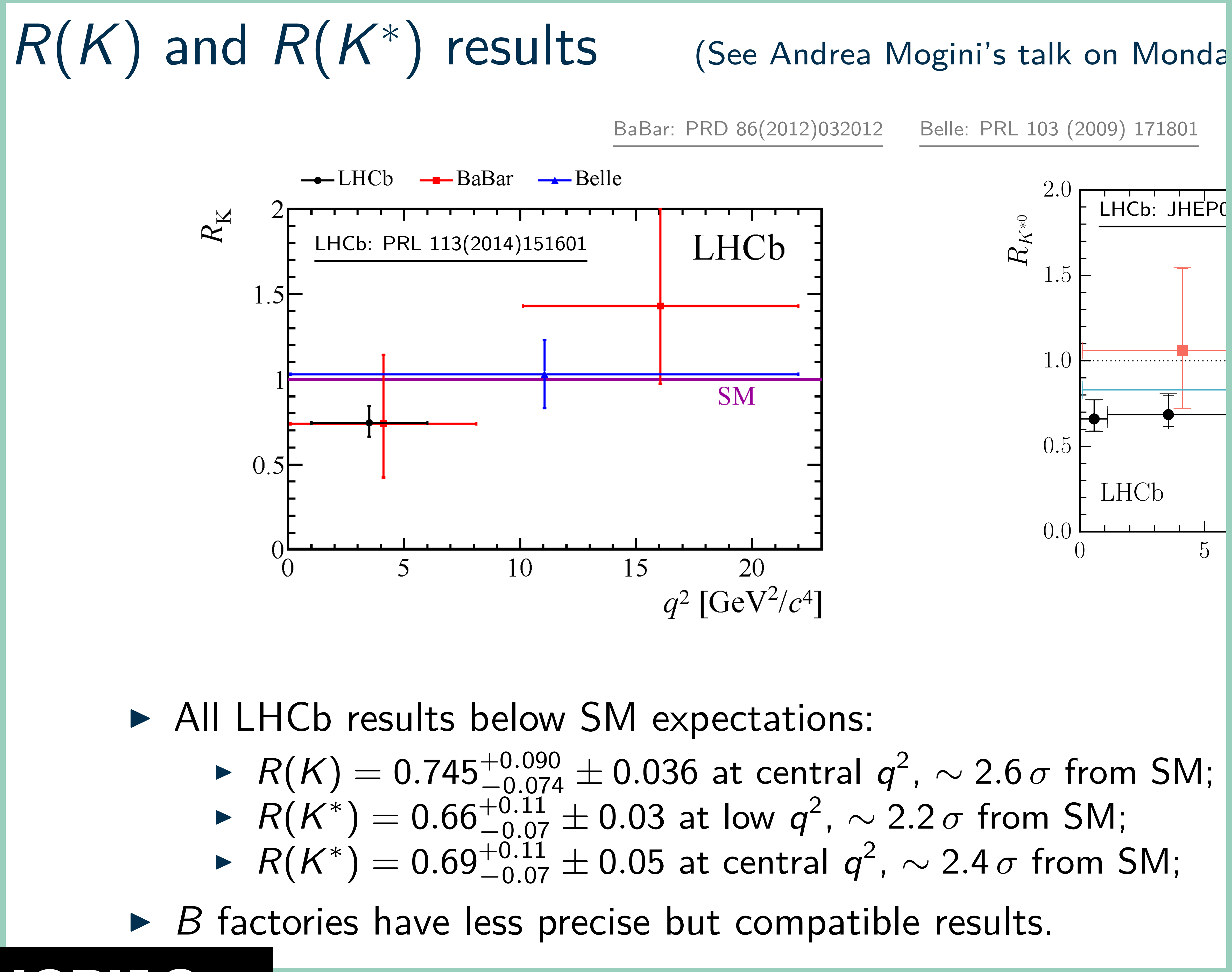
$R(D^*)$ and $R(D)$ combination

Combine LHCb's $R(D^*)$ results with results from B factories:

⇒ $R(D^*)$ and $R(D)$ average $\sim 4\ \sigma$ from SM
(latest SM computation: JHEP 11 (2017) 061)

neutral current

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$



$R(K)$ and $R(K^*)$ results

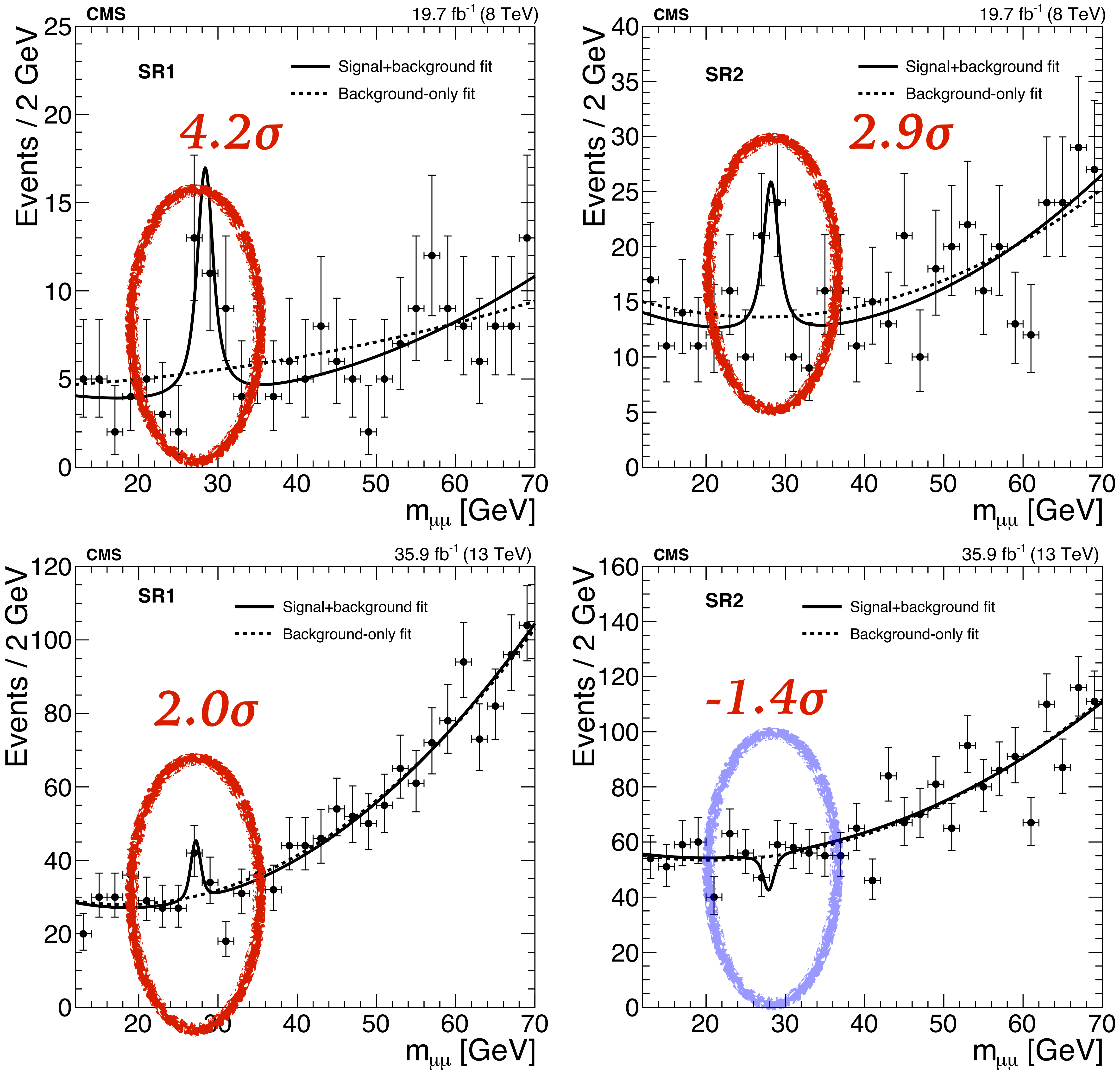
(See Andrea Mogini's talk on Monda

BaBar: PRD 86(2012)032012 Belle: PRL 103 (2009) 171801

- All LHCb results below SM expectations:
  - $R(K) = 0.745^{+0.090}_{-0.074} \pm 0.036$ at central q^2, $\sim 2.6\,\sigma$ from SM;
  - $R(K^*) = 0.66^{+0.11}_{-0.07} \pm 0.03$ at low q^2, $\sim 2.2\,\sigma$ from SM;
  - $R(K^*) = 0.69^{+0.11}_{-0.07} \pm 0.05$ at central q^2, $\sim 2.4\,\sigma$ from SM;
- *B* factories have less precise but compatible results.

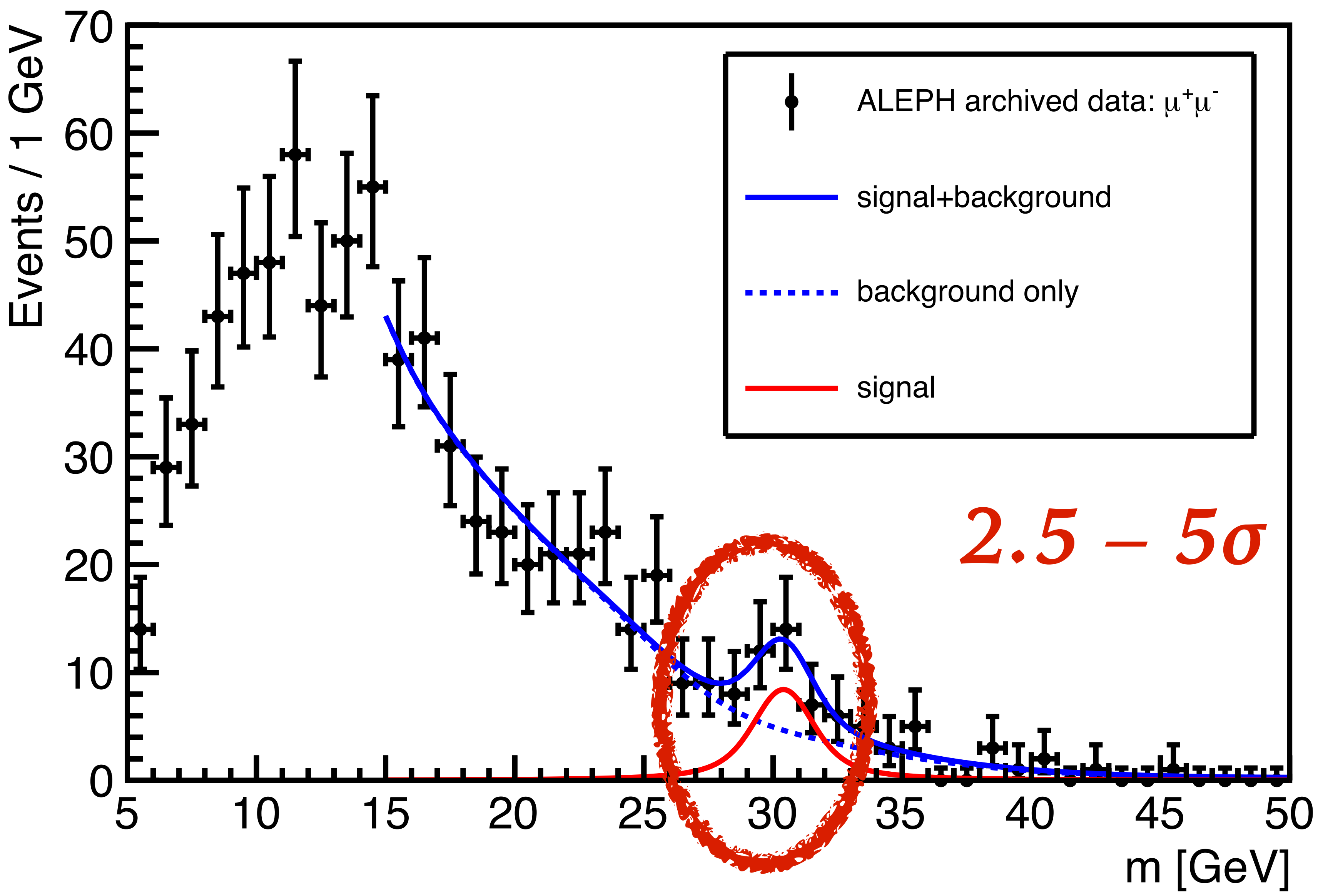
Humair @ LHCP'18

CMS pp → b j $\mu^+\mu^-$ + X



https://arxiv.org/abs/1808.01890

ALEPH e^+e^- → b b $\mu^+\mu^-$ + X



https://arxiv.org/abs/1610.06536

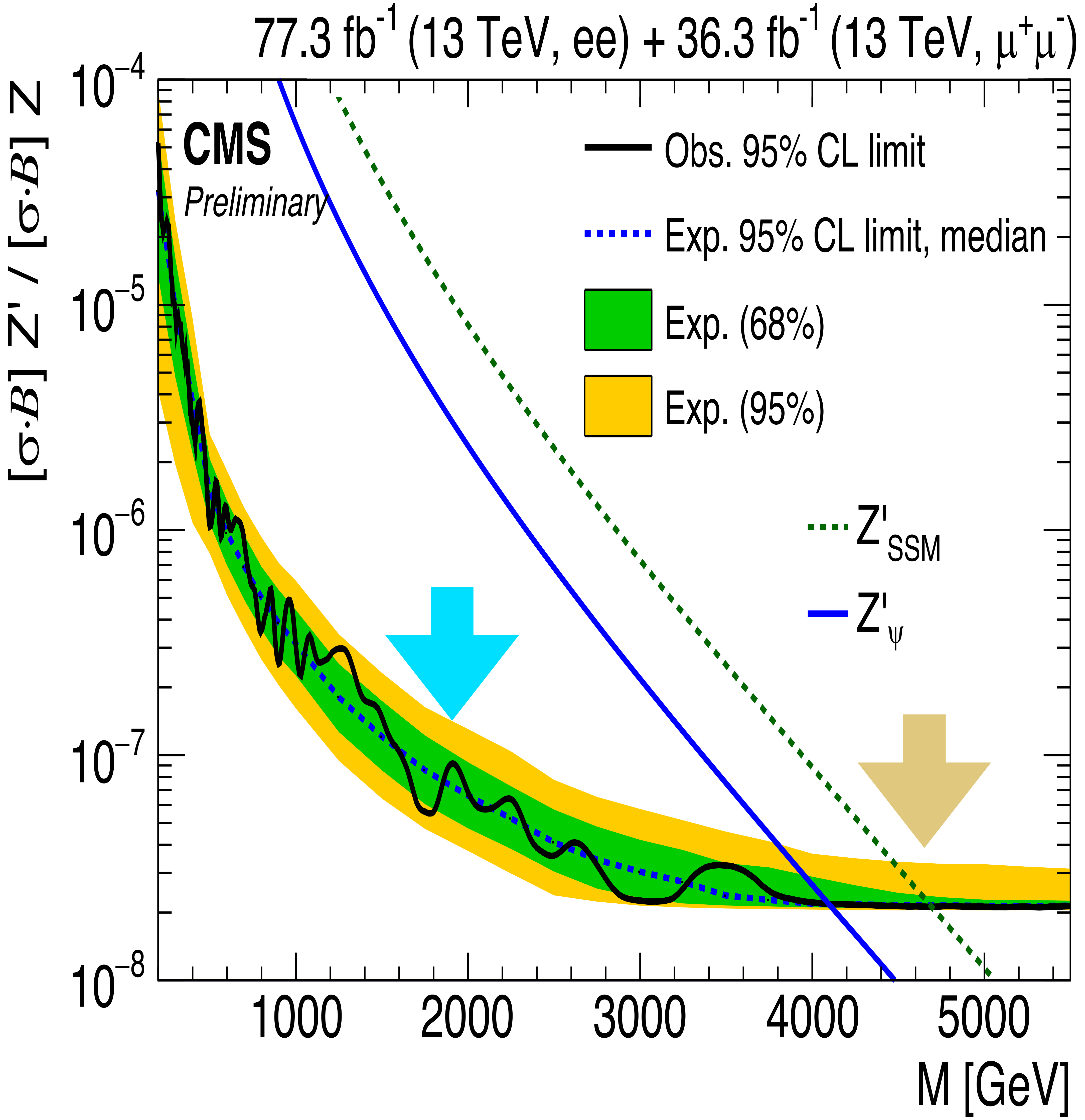
and various non-collider anomalies

- DAMA
- Miniboone & LSND
- $g_\mu - 2$
- ^{8}Be 16.7 MeV e^+e^- peak

future progress?

LHC will collect ~40 times more data than used for the plots shown so far, though at mostly similar energy (13–14 TeV)

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

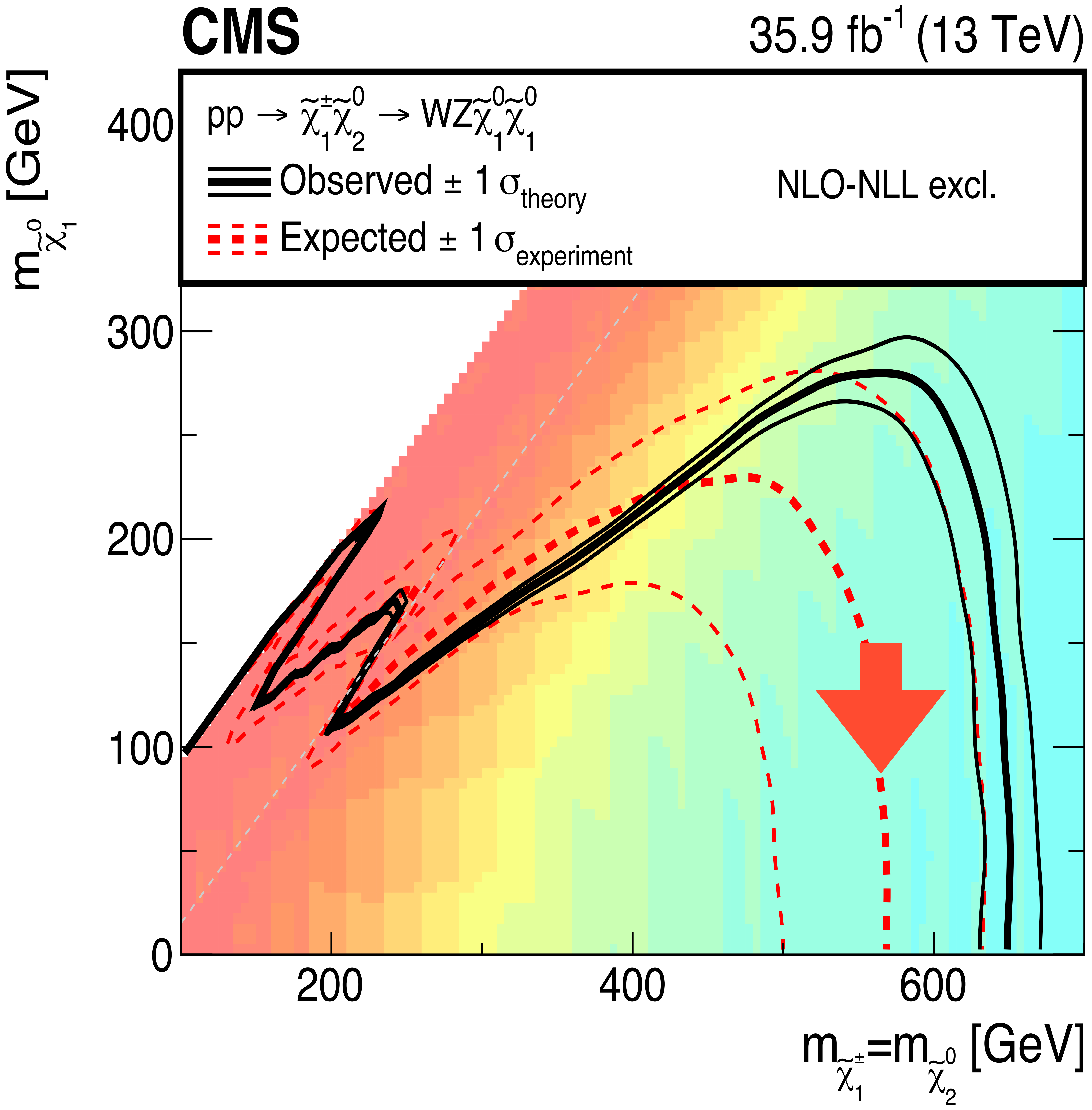


- Suppose we had a choice between
  - HL-LHC (14 TeV, 3ab^{-1})
  - or going to higher c.o.m. energy but limited to 80fb^{-1}.
- How much energy would we need to equal the HL-LHC?

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

estimated with http://collider-reach.cern.ch , Weiler & GPS

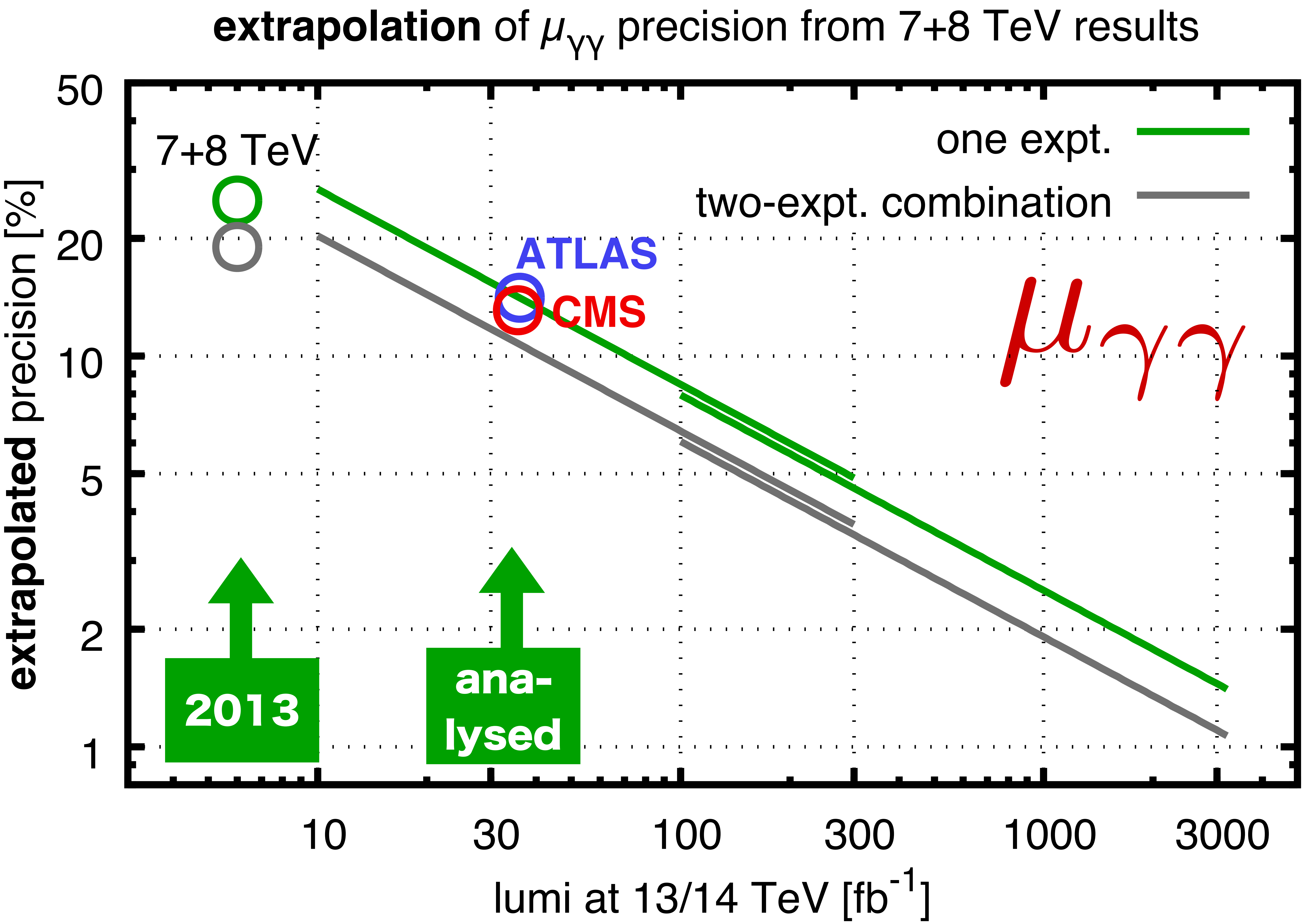
The path forward: collect 20–30x more collisions by ~2035



- 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?

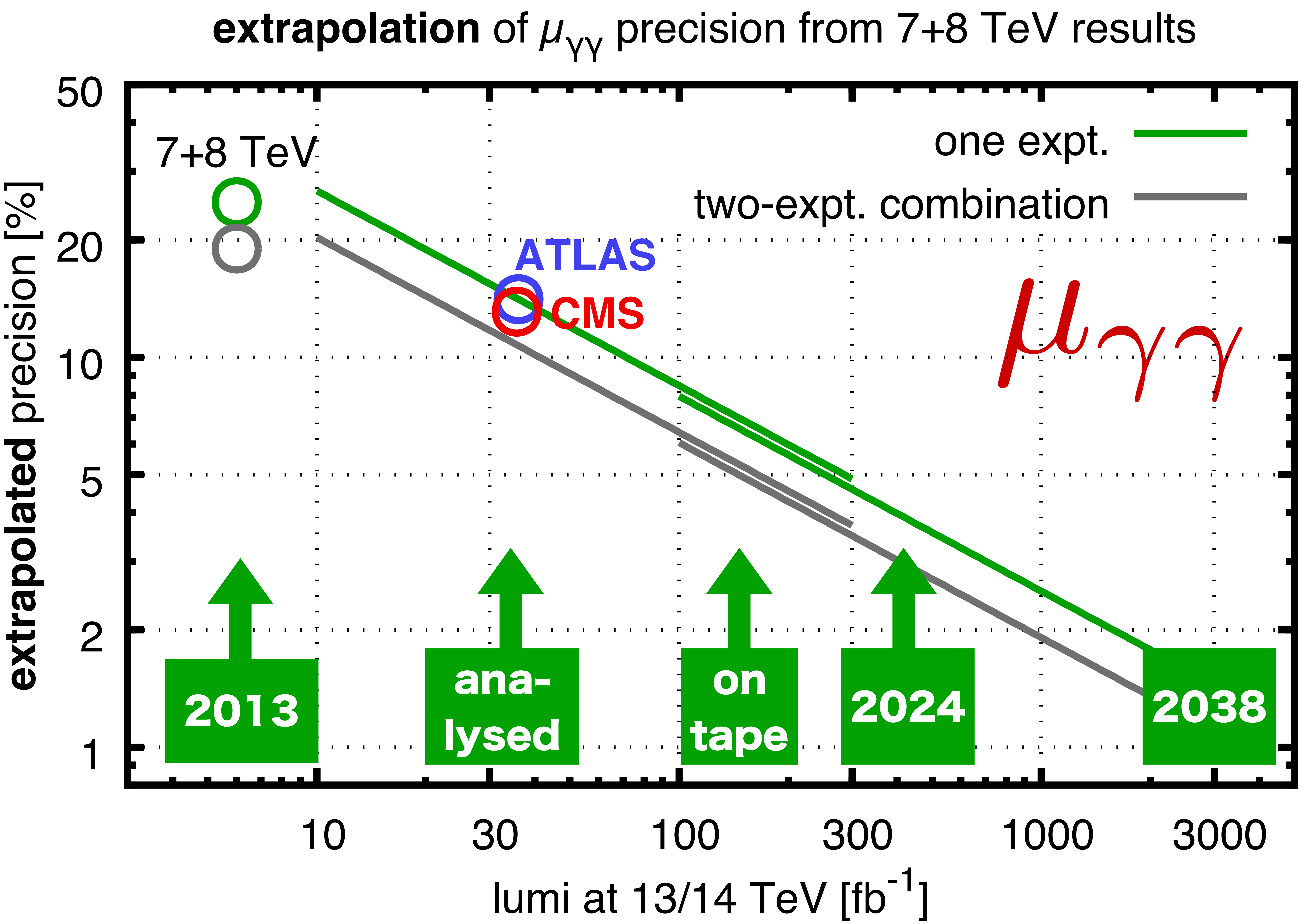
today's reach (13 TeV, 80fb^{-1})	HL-LHC reach (14 TeV 3ab^{-1})	energy needed for same reach with 80fb^{-1}
4.7 TeV SSM Z'	6.7 TeV	20 TeV
2 TeV weakly coupled Z'	3.7 TeV	37 TeV
680 GeV chargino	1.4 TeV	54 TeV

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



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

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



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

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

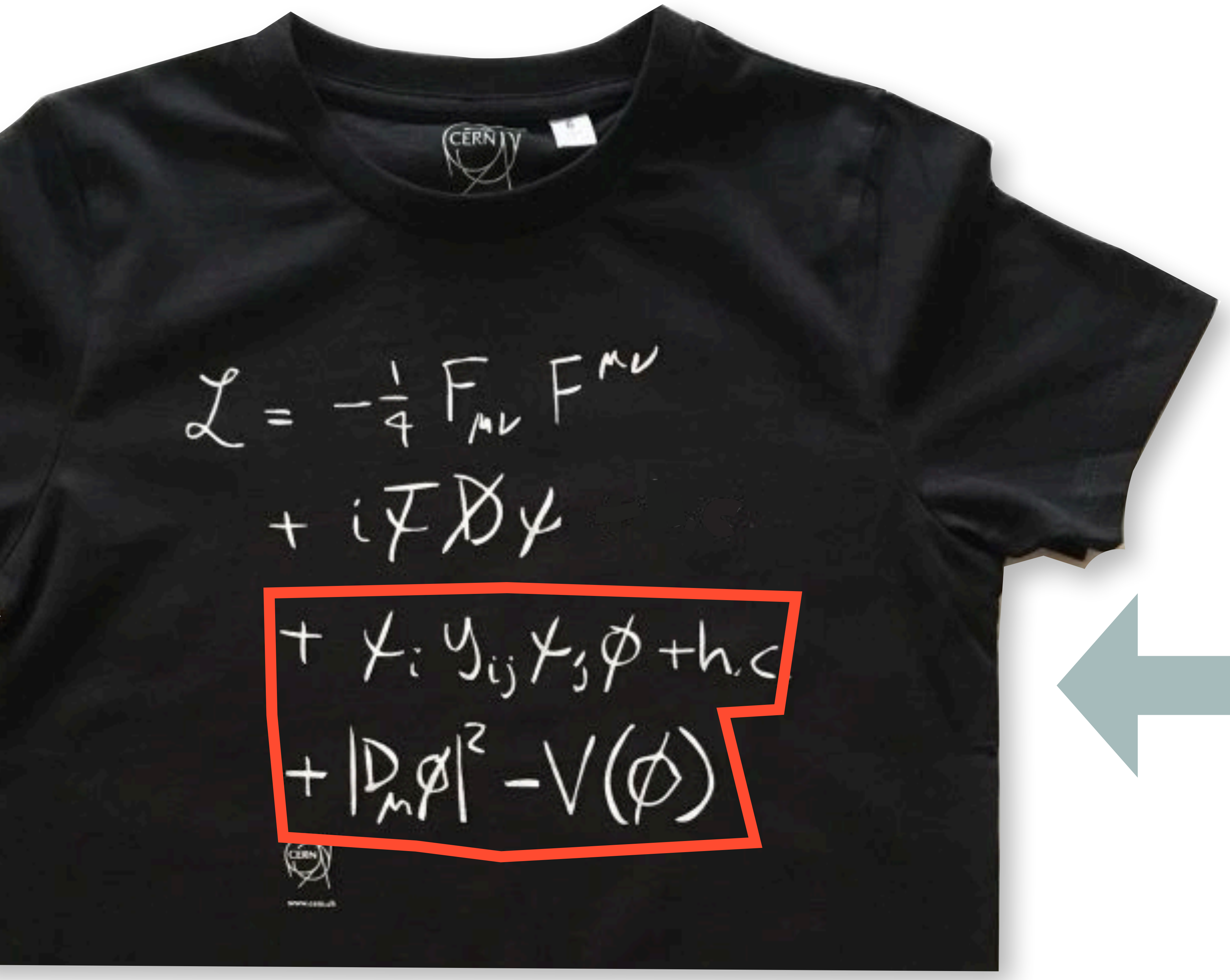
1 fb^{-1} = 10^{14} collisions

how is all of this made quantitative?

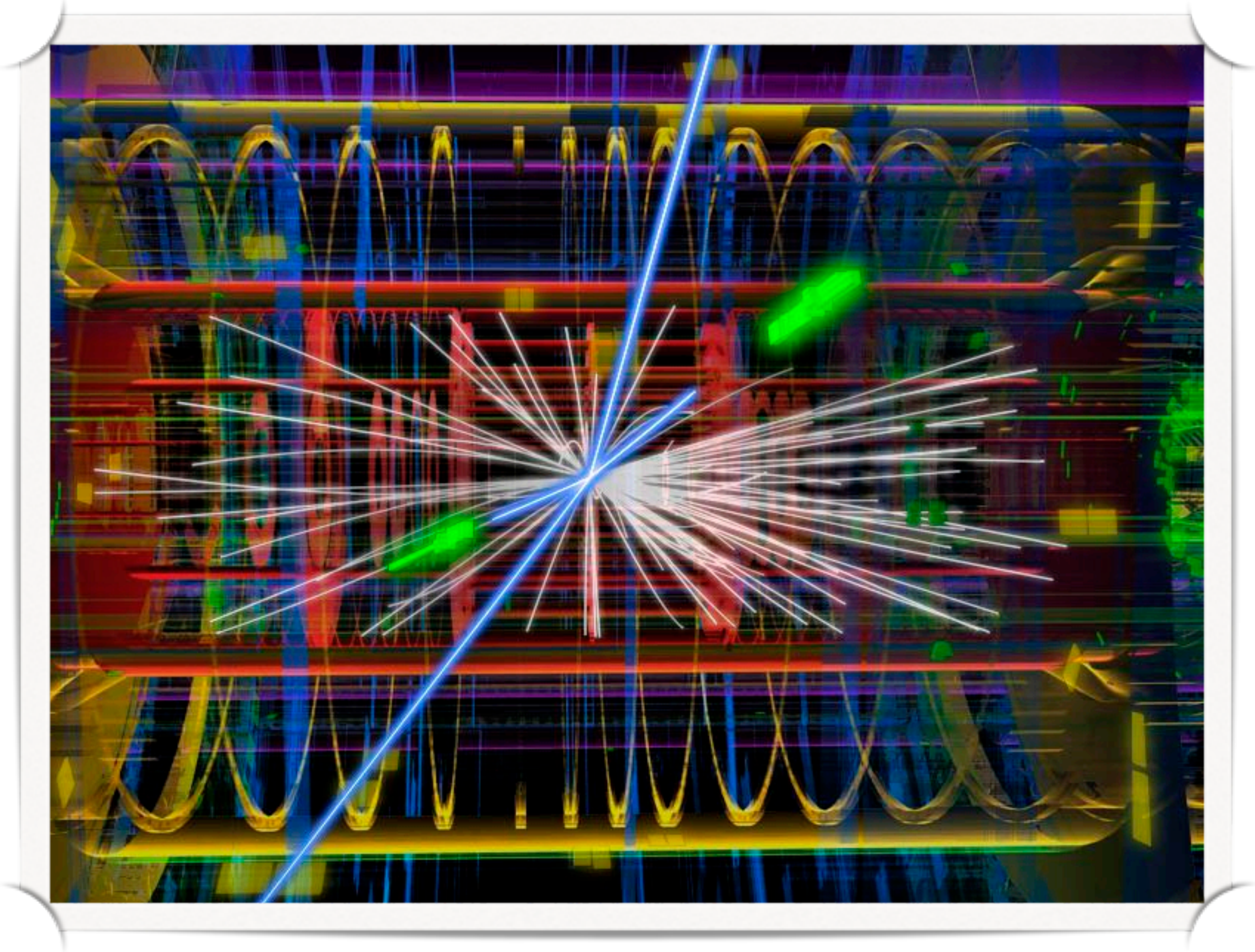
whether new-physics searches, Higgs physics, or other SM studies

UNDERLYING
THEORY

EXPERIMENTAL
DATA



how do you make quantitative connection?



UNDERLYING THEORY

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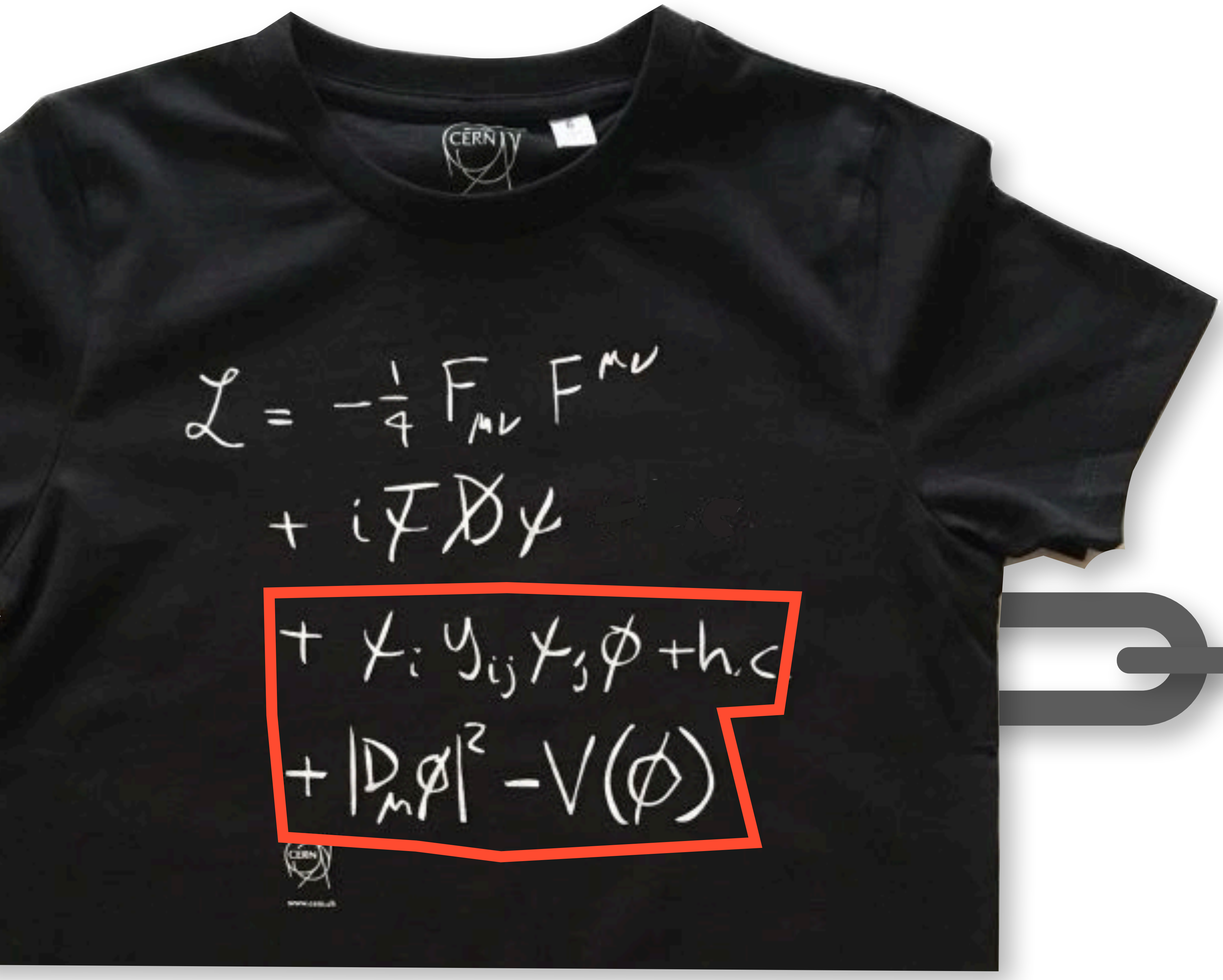

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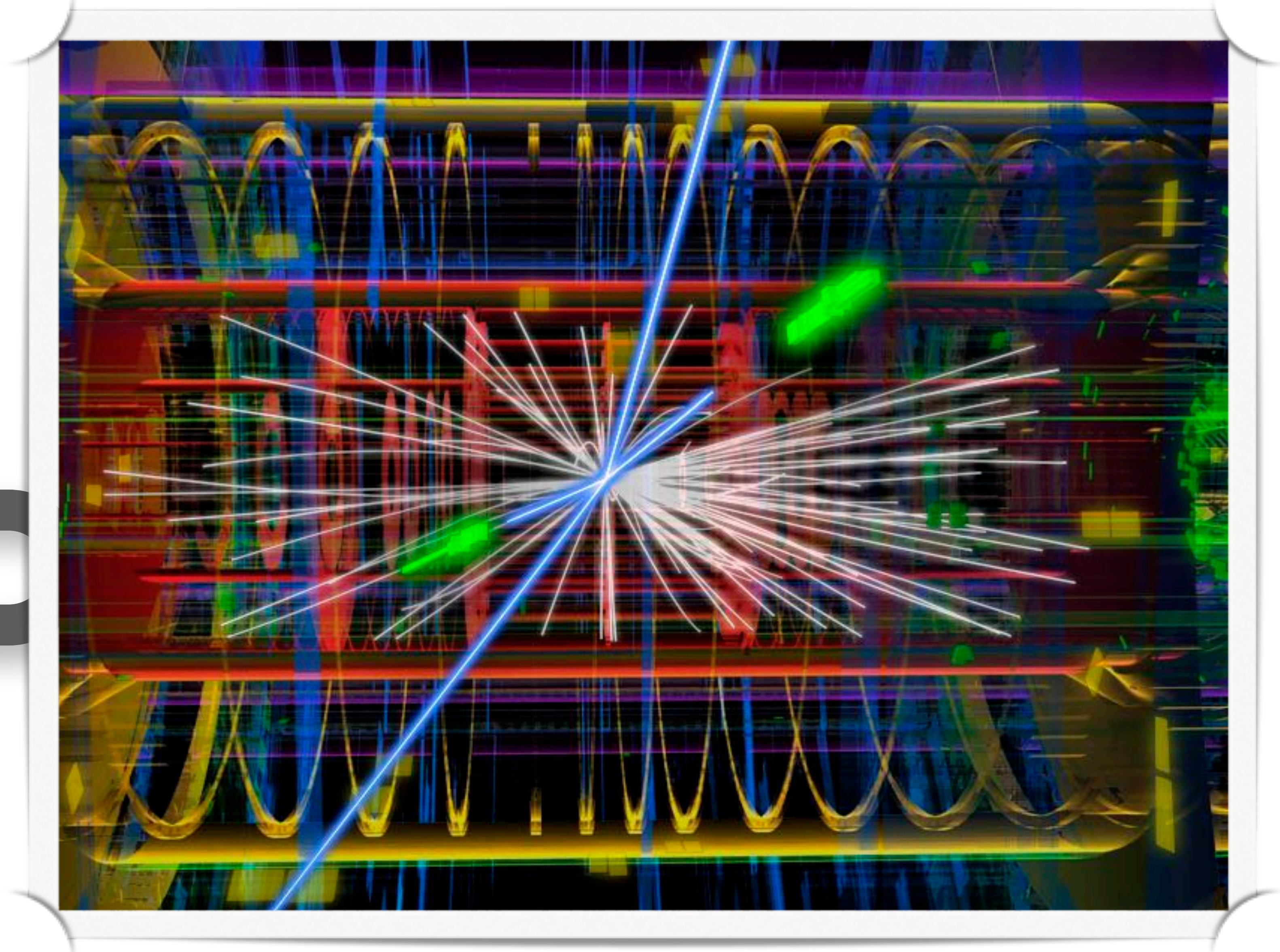


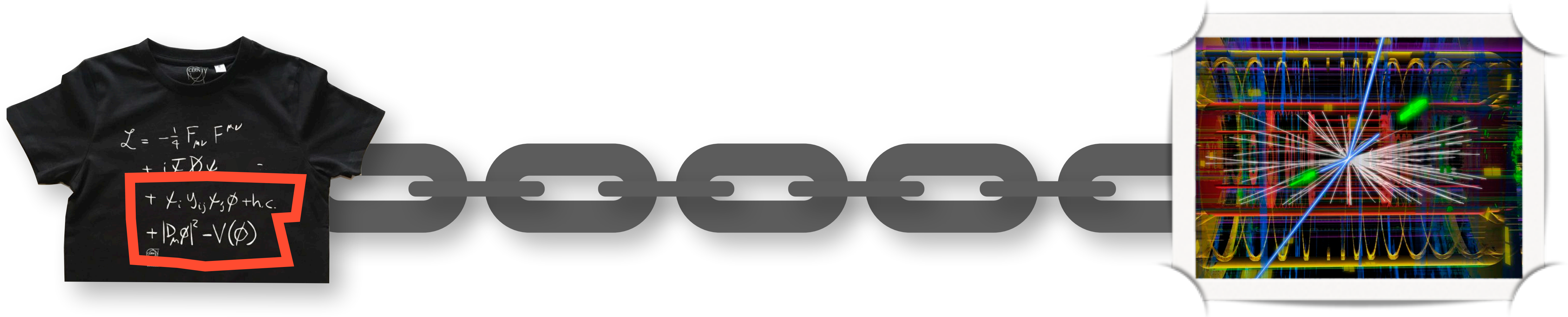
through a chain of experimental and theoretical links

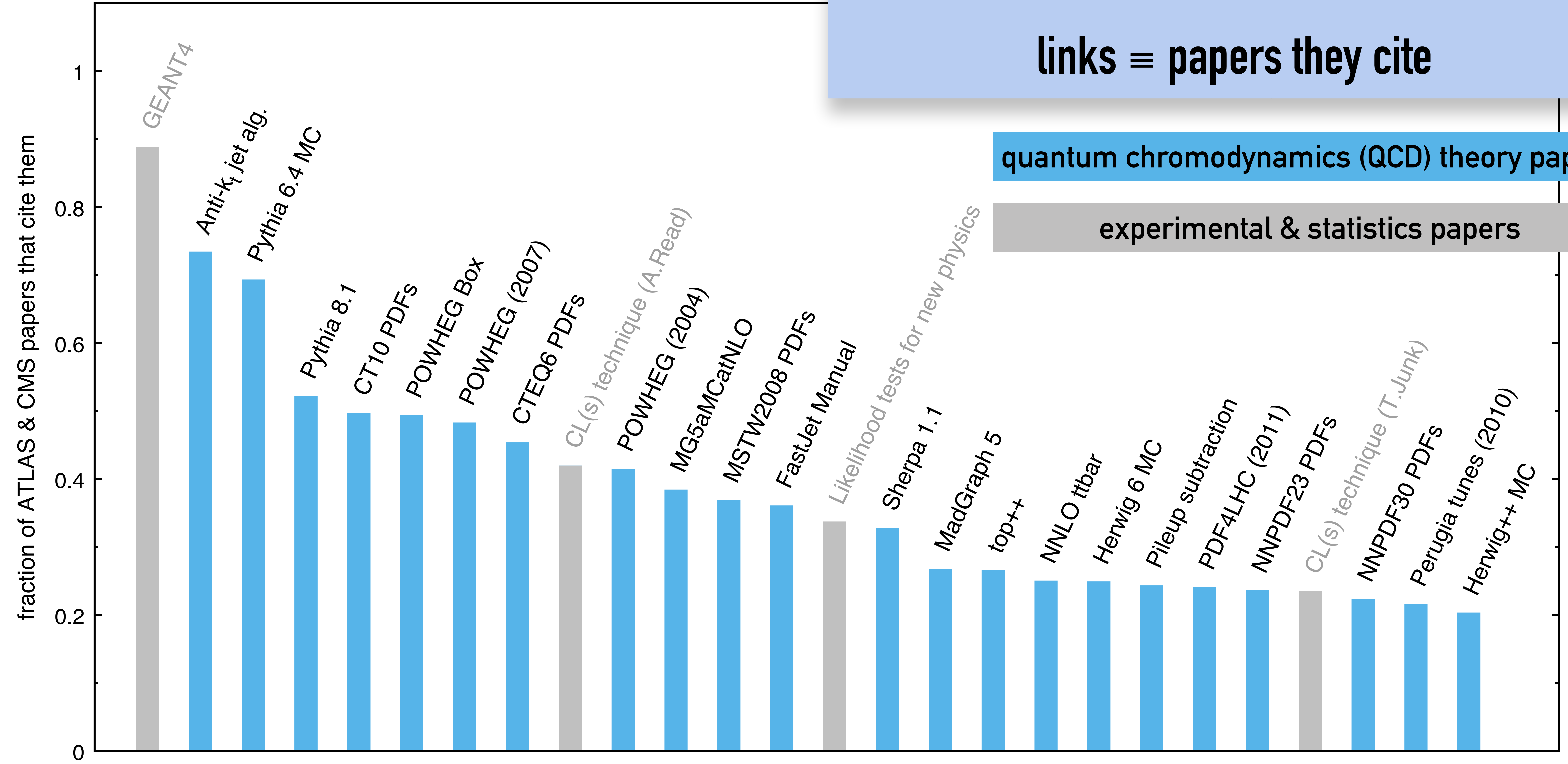
[in particular Quantum Chromodynamics (QCD)]

What are the links?

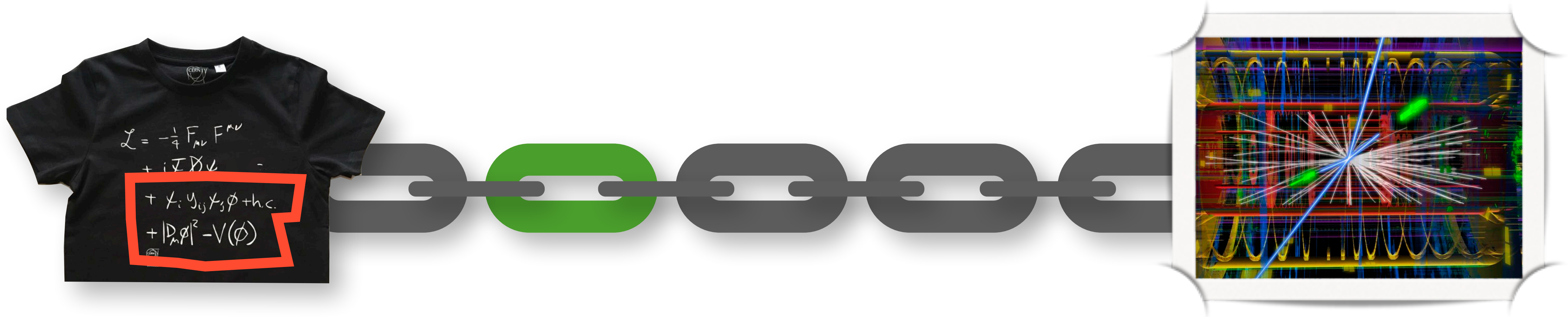
ATLAS and CMS (big LHC expts.) have written 850 articles since 2014

links ≡ papers they cite

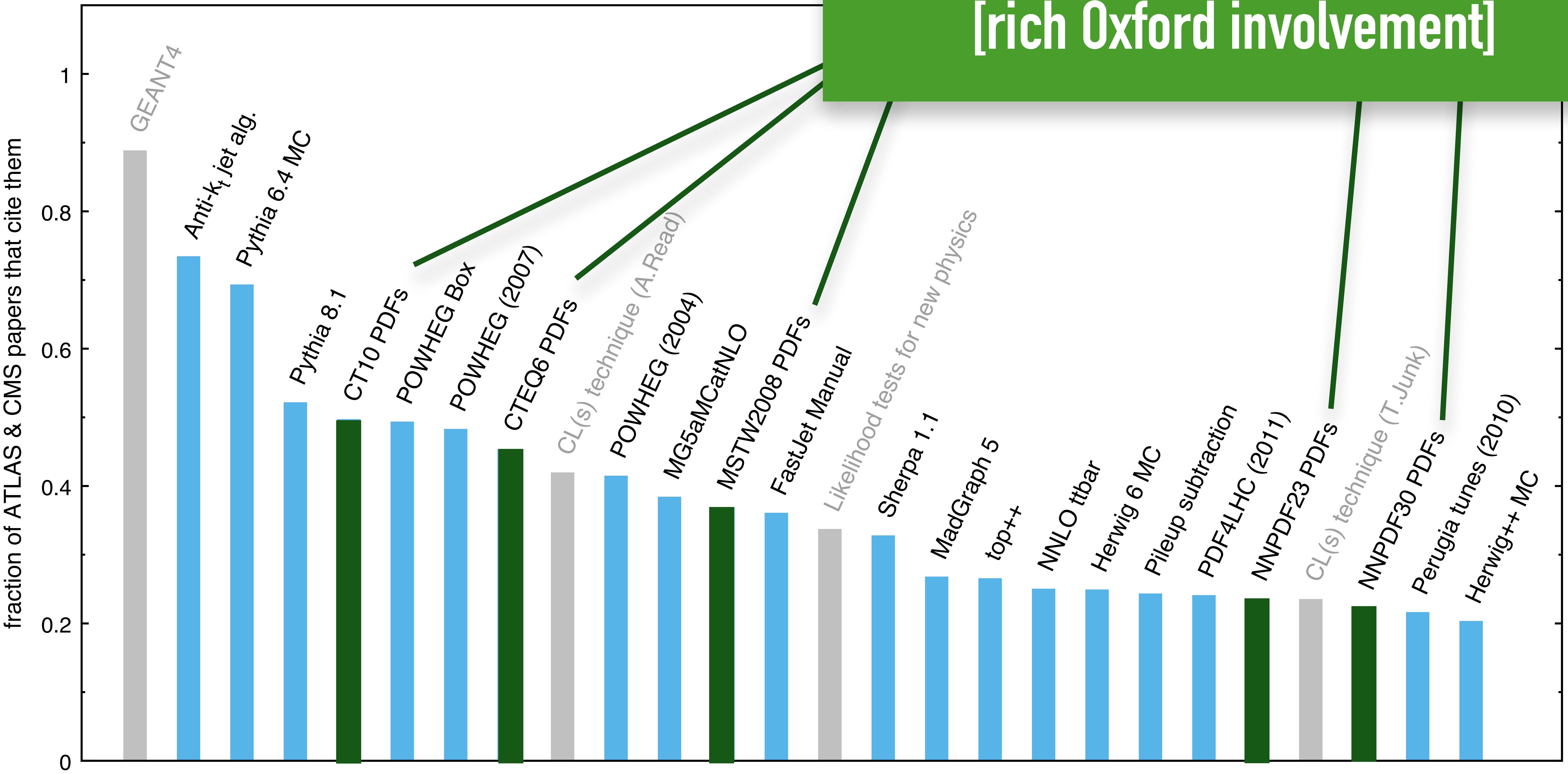




Plot by GP Salam based on data from InspireHEP



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



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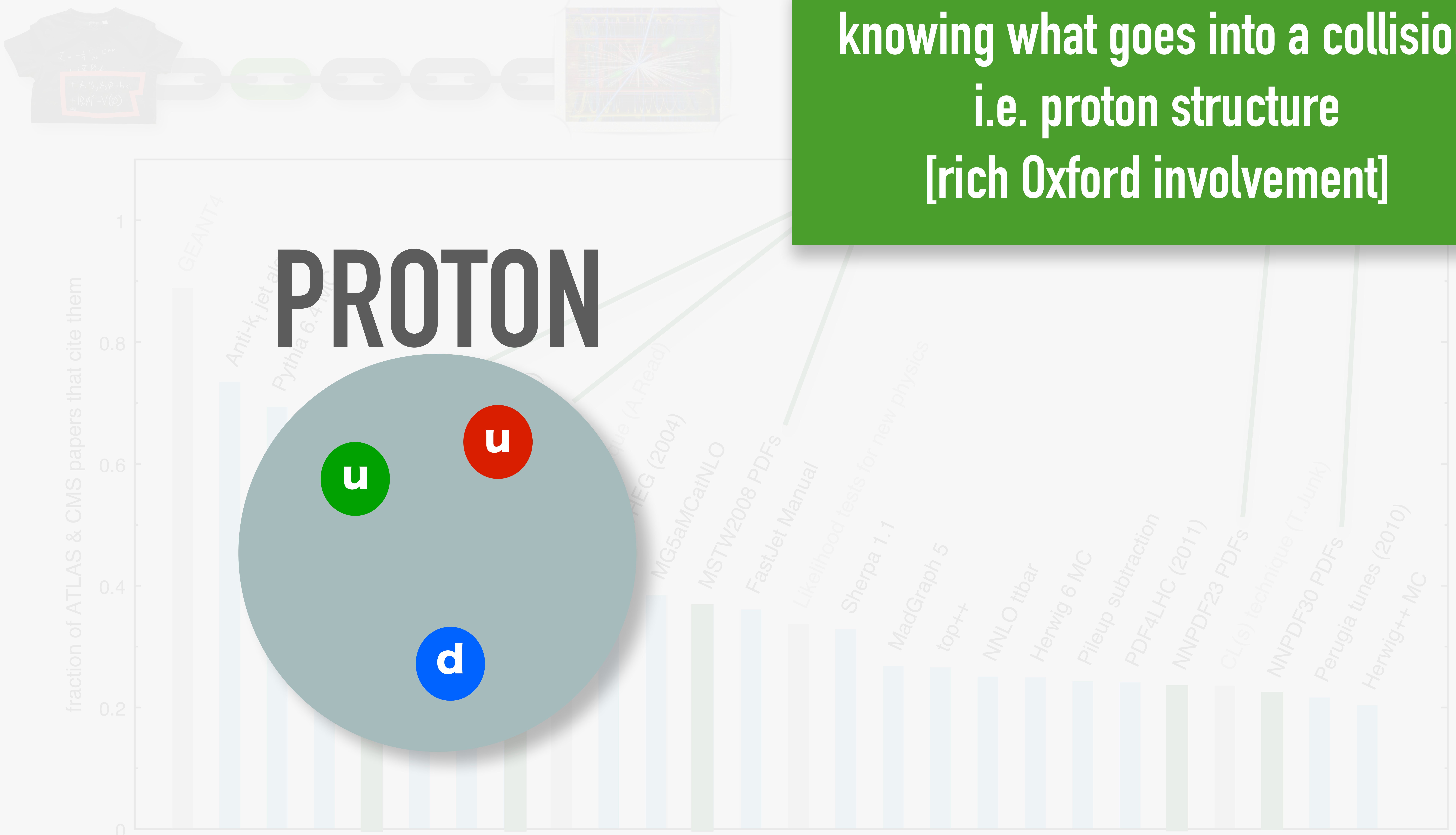
PROTON



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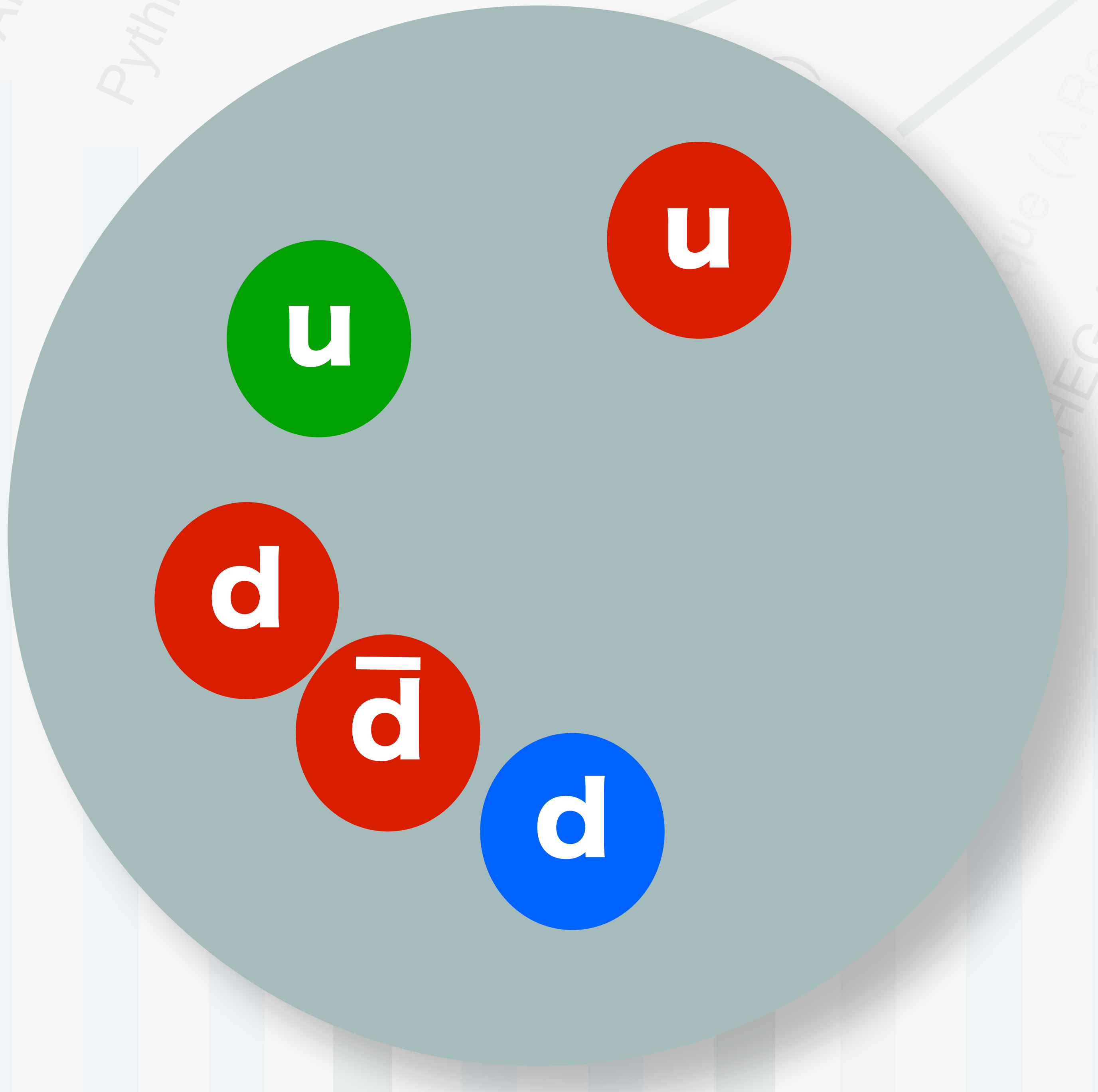

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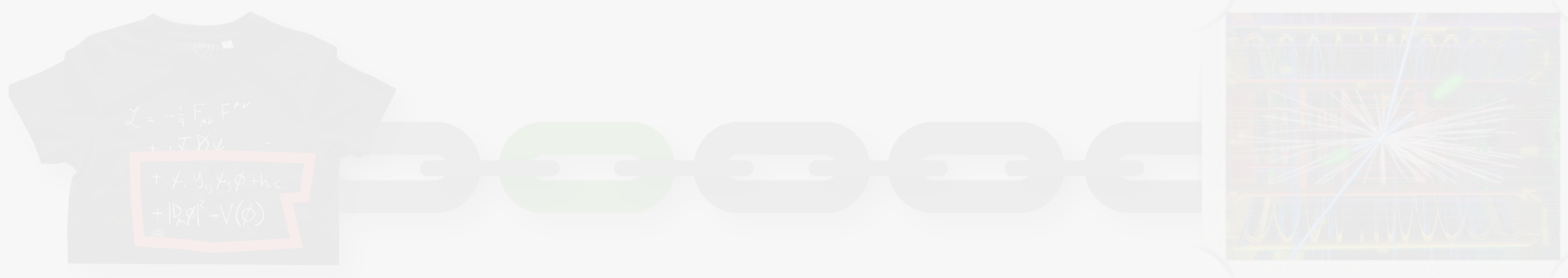

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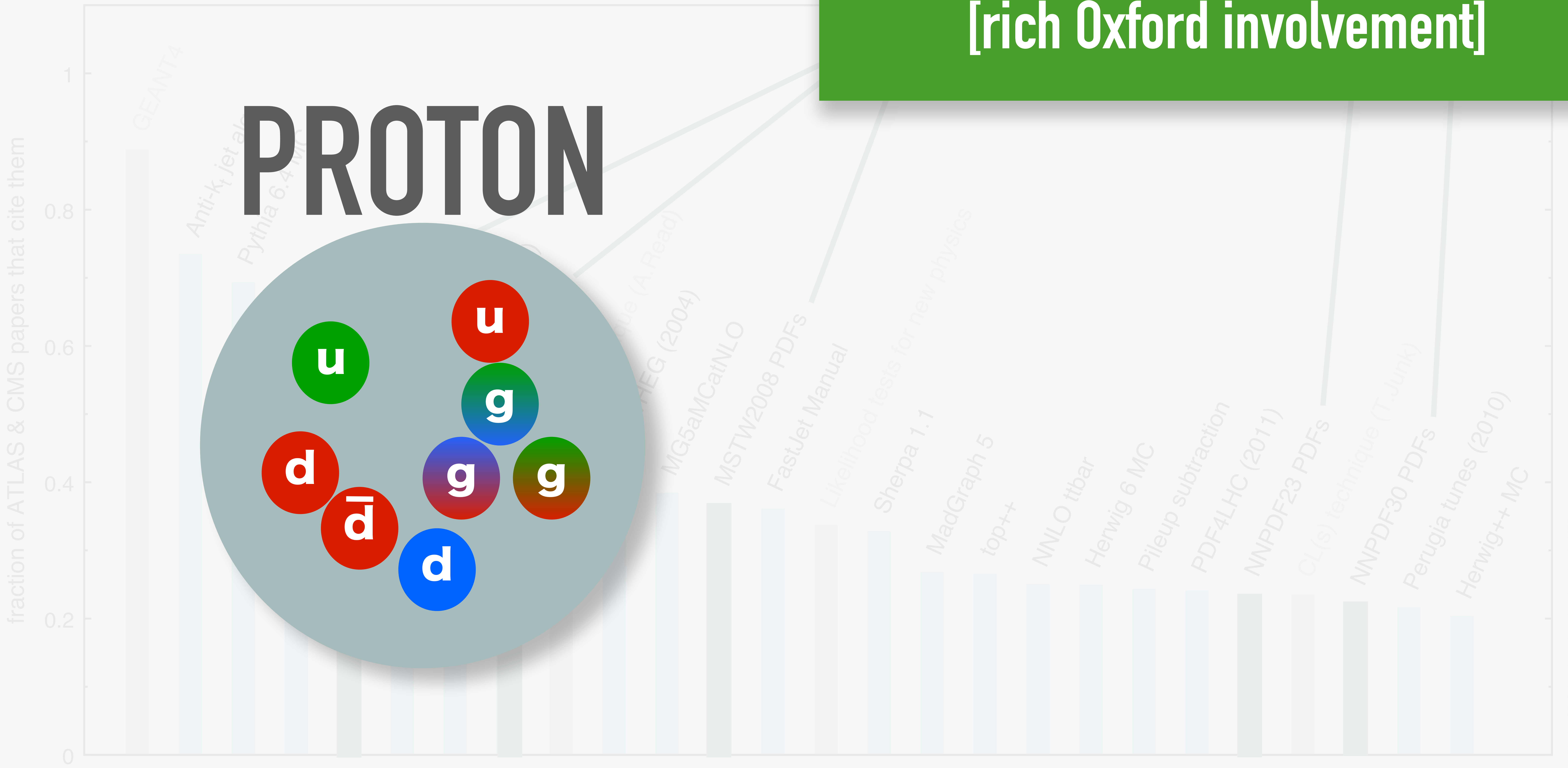

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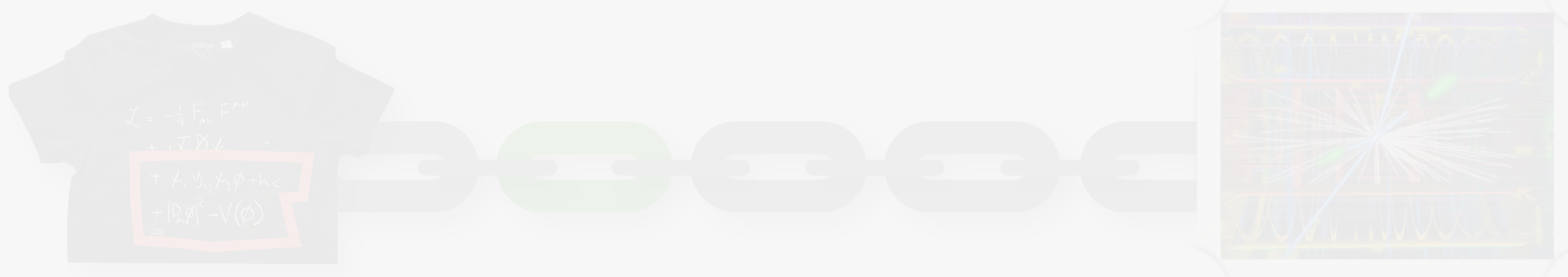

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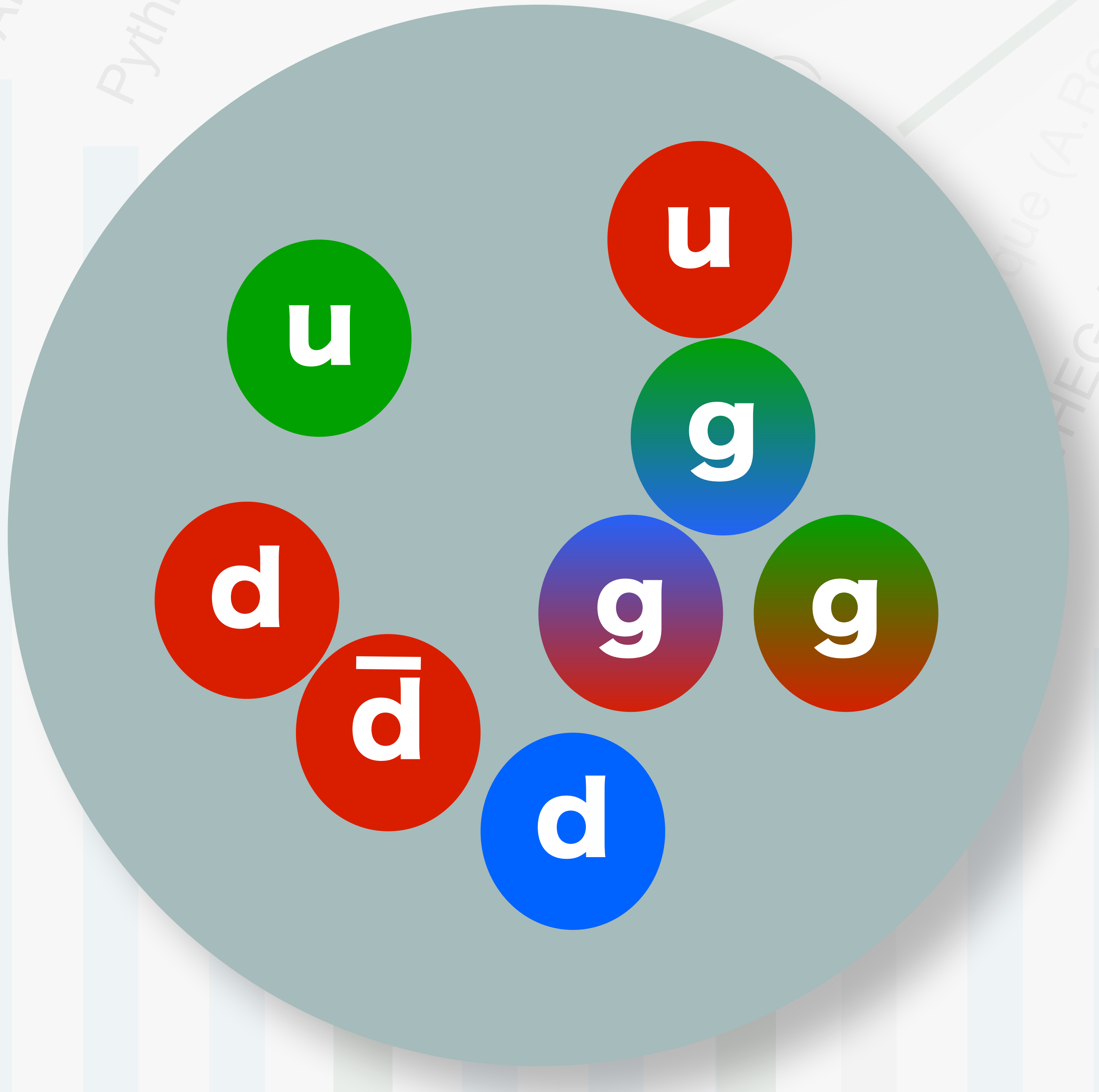


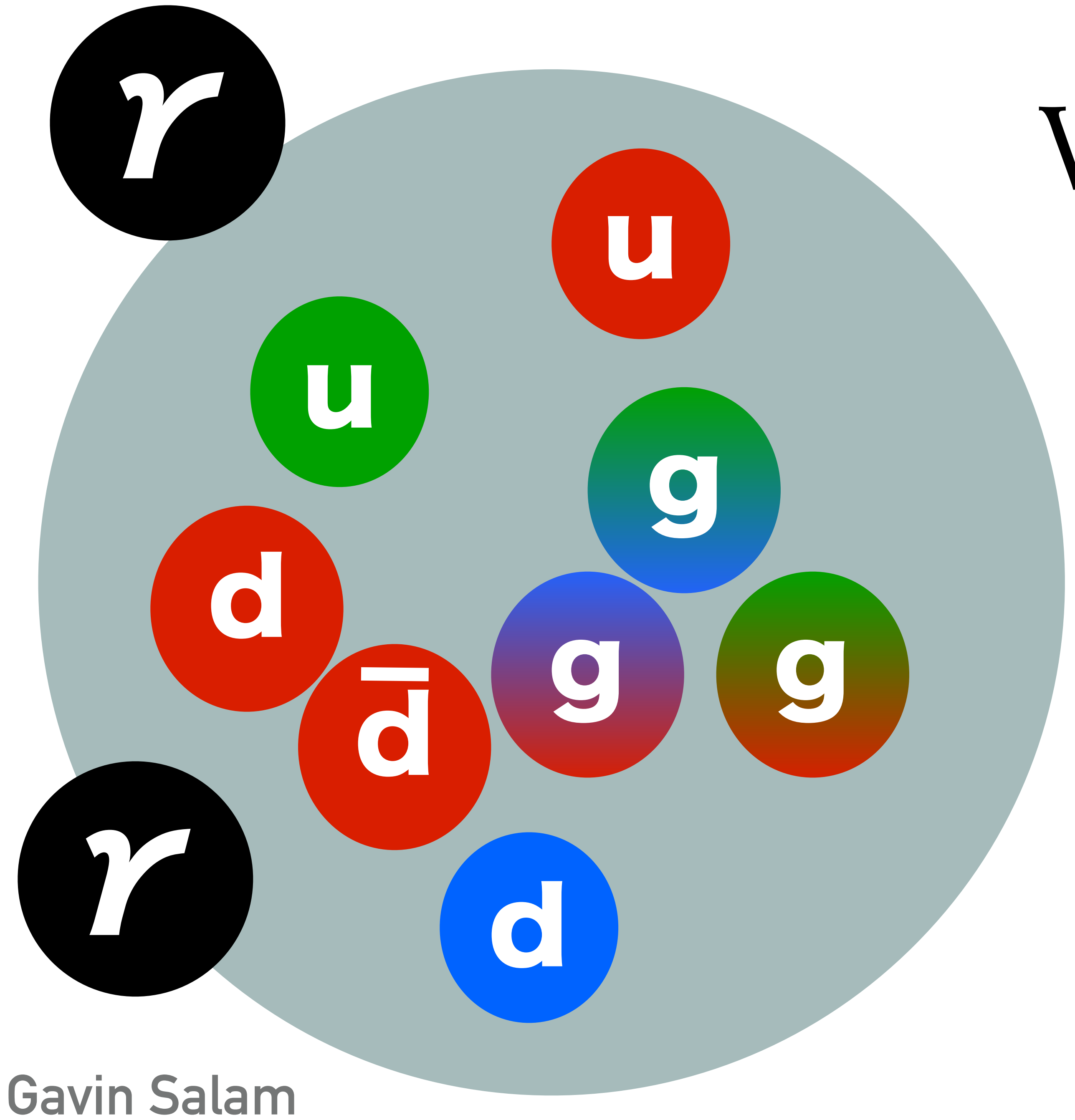
1 proton-proton collision

~ 286 ± 5 gluon-gluon collisions around the Higgs mass

how many photons accompany each proton?

A fast-moving proton comes with a cloud of photons. How many?

Number of photons accompanying an **electron** understood since 1934 (Fermi-Weizsäcker-Williams).



Was largest uncertainty on HW± production at LHC

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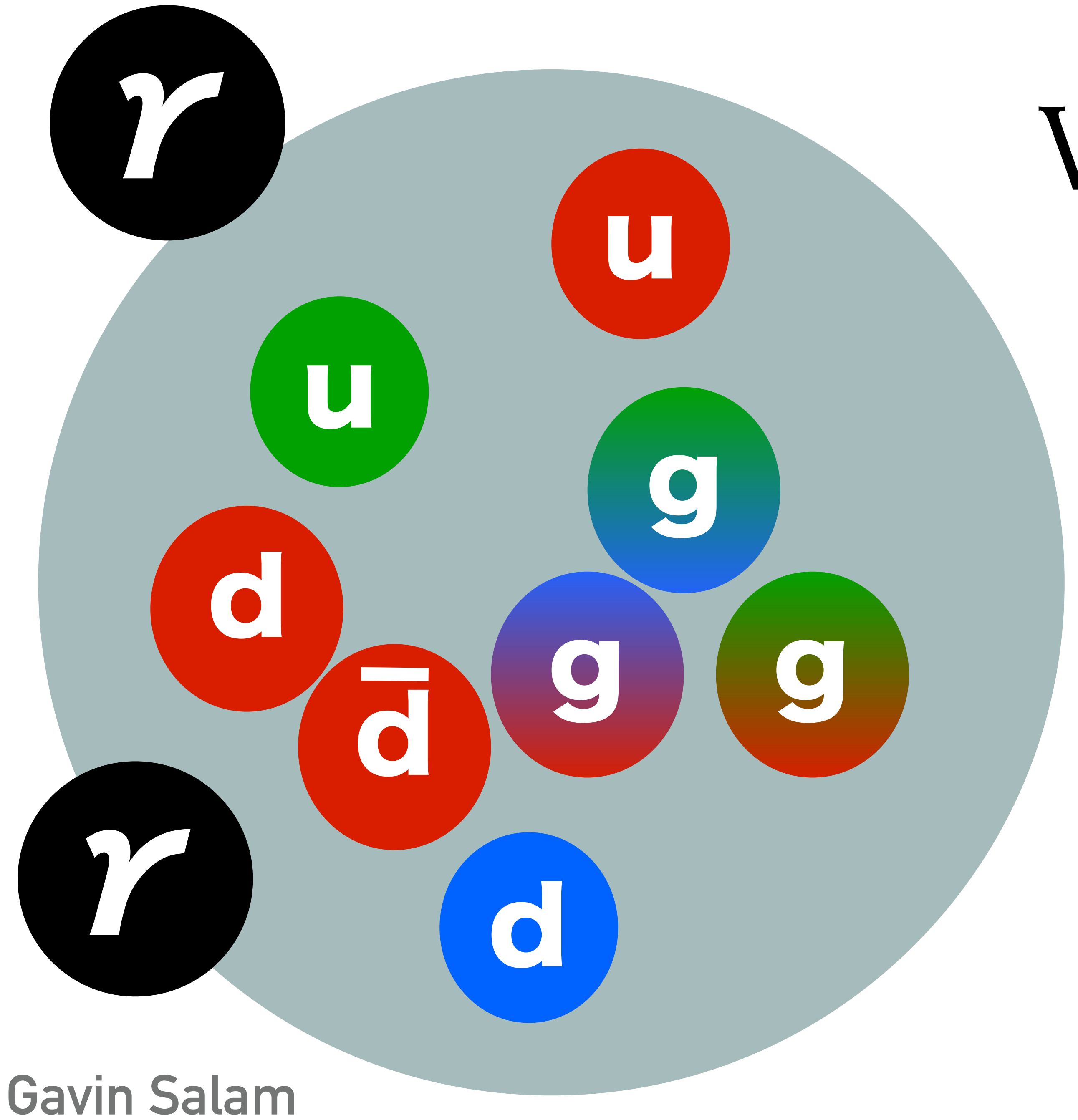

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Solved for proton 2 years ago

[Manohar, Nason, GPS & Zanderighi, Phys.Rev.Lett. 117 (2016) 242002+ JHEP 1712 (2017) 046]

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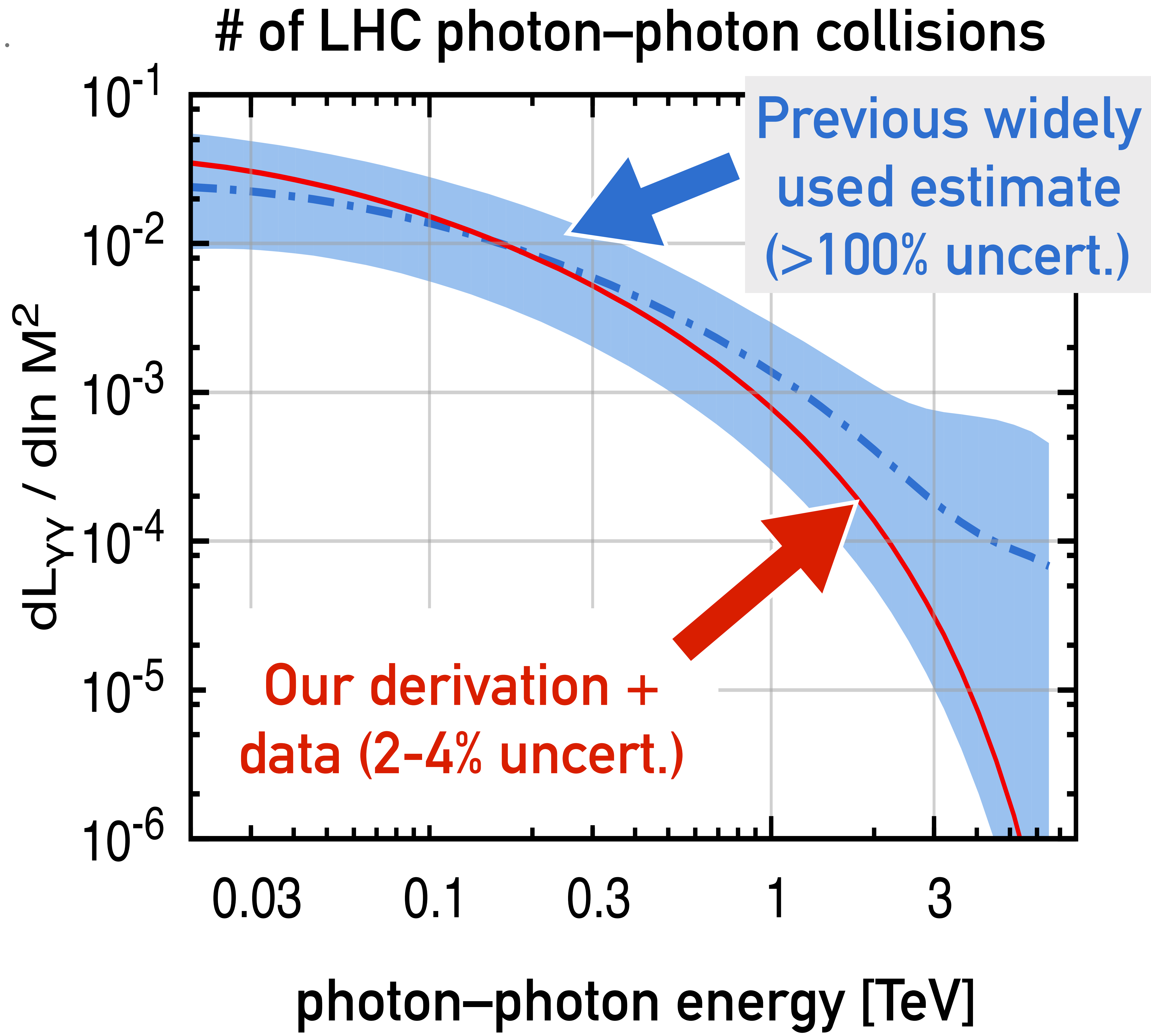
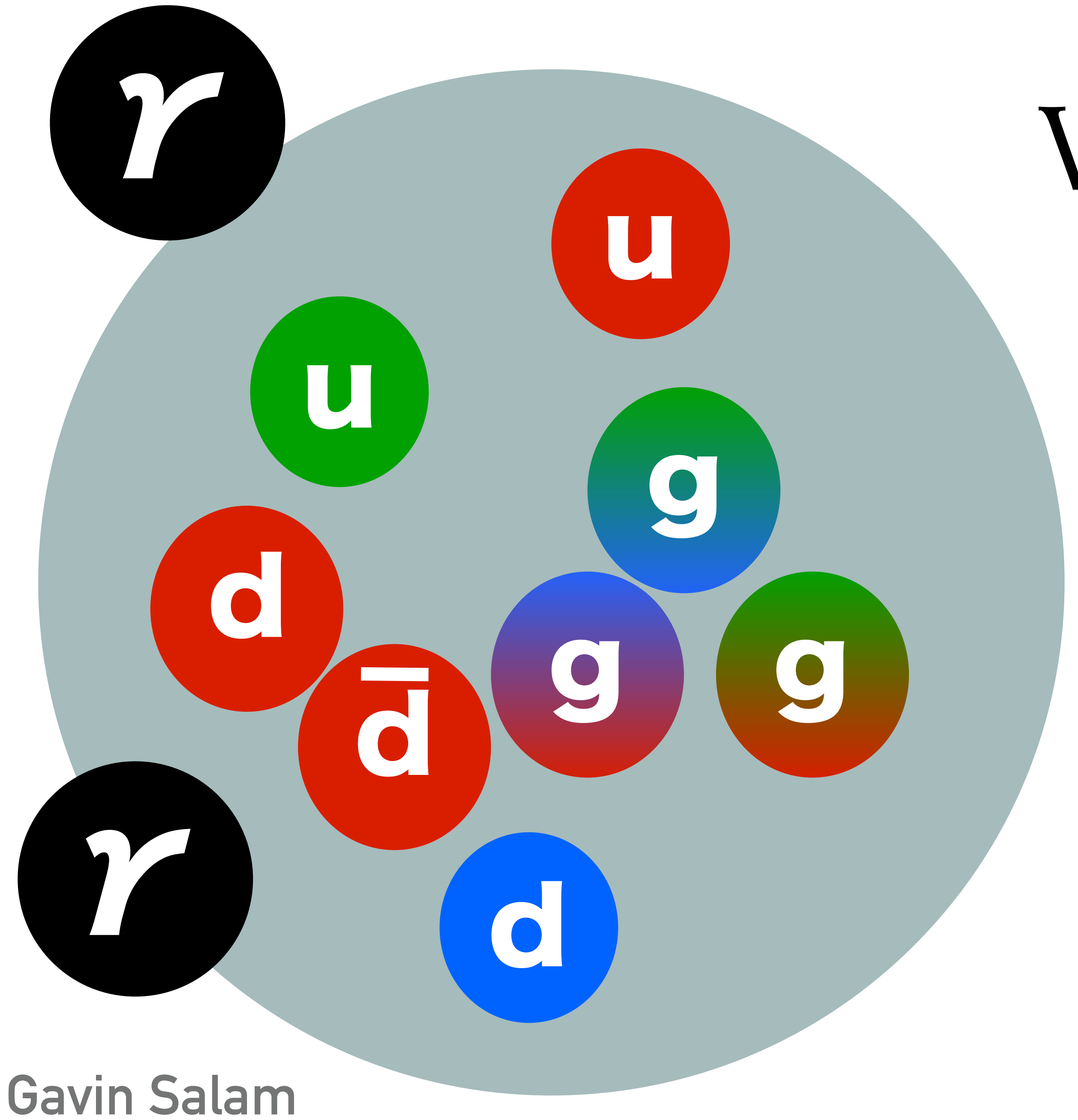


Previous widely used estimate (>100% uncert.)

Our derivation + data (2-4% uncert.)



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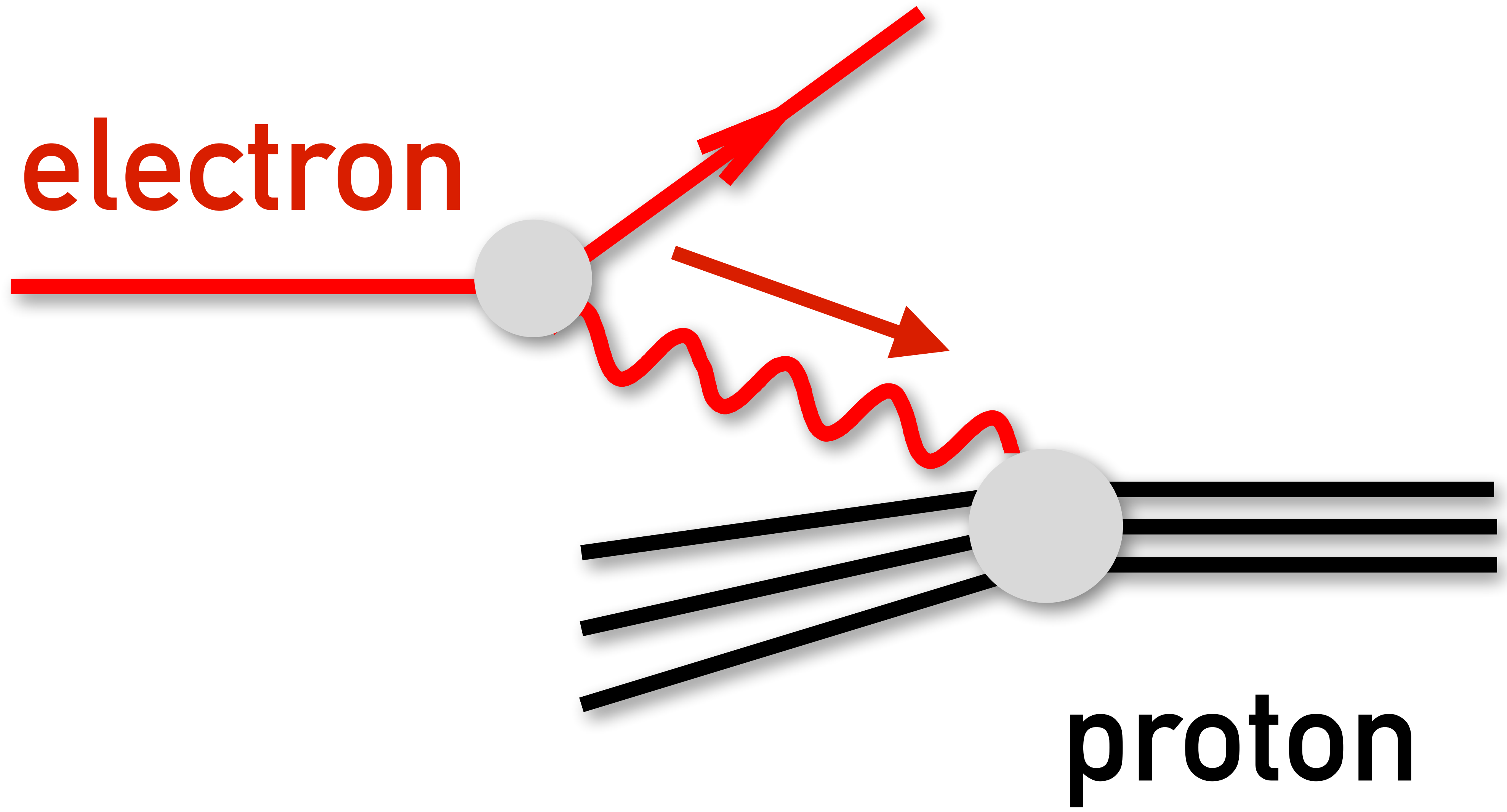
electron–proton scattering

- Experiments have been going on for decades
- Usually seen as photons from electron probing proton structure



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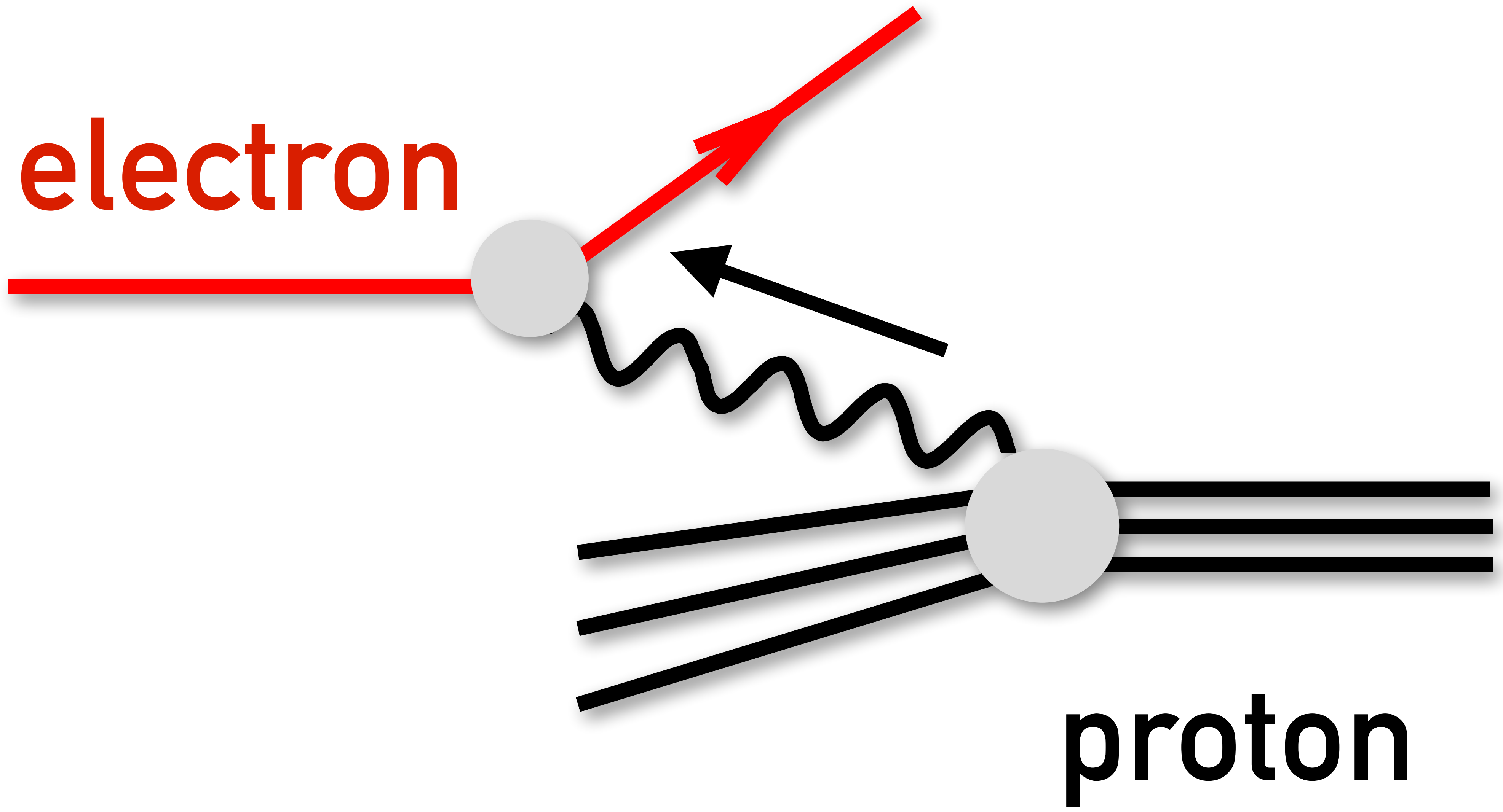

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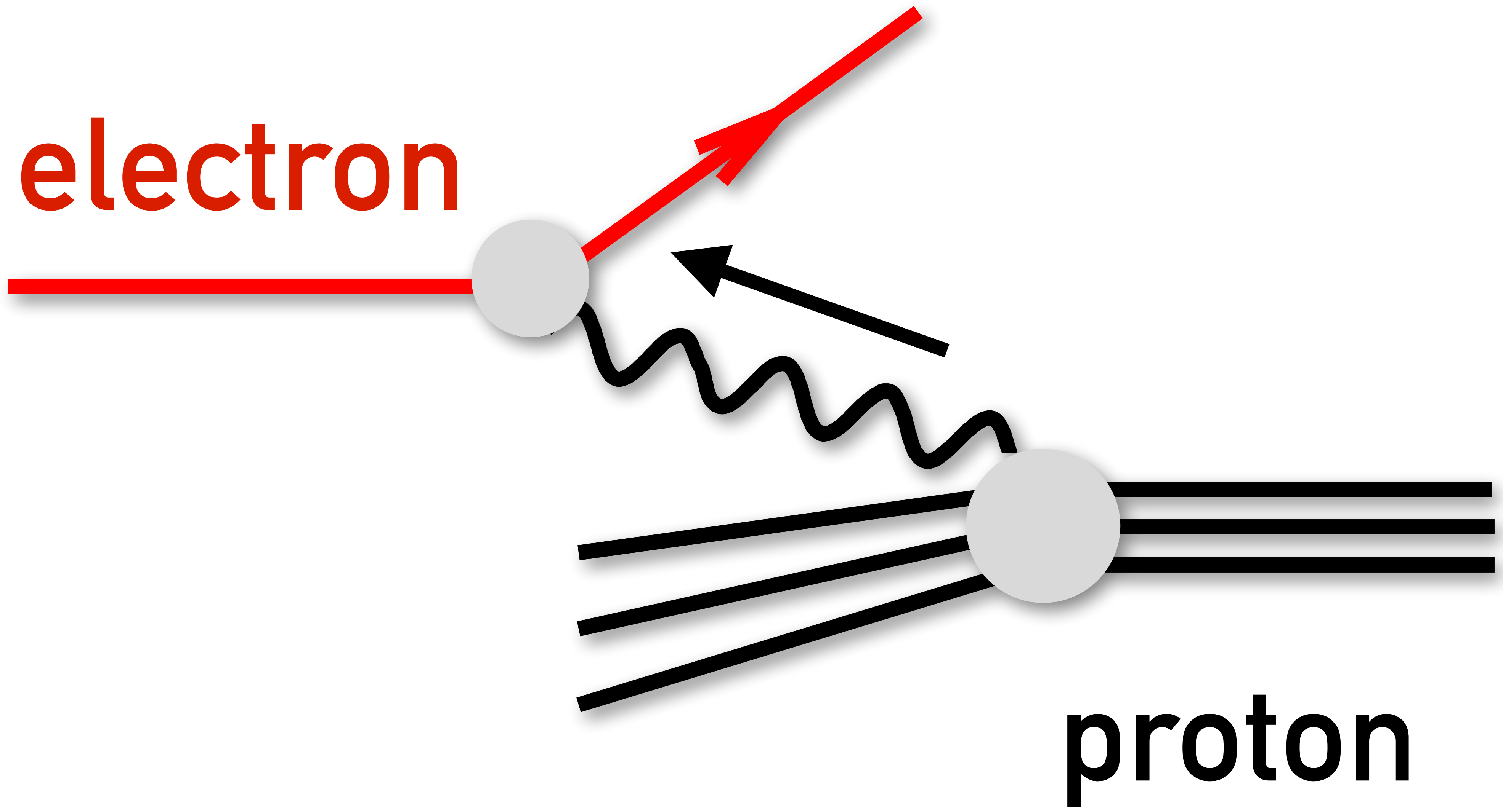
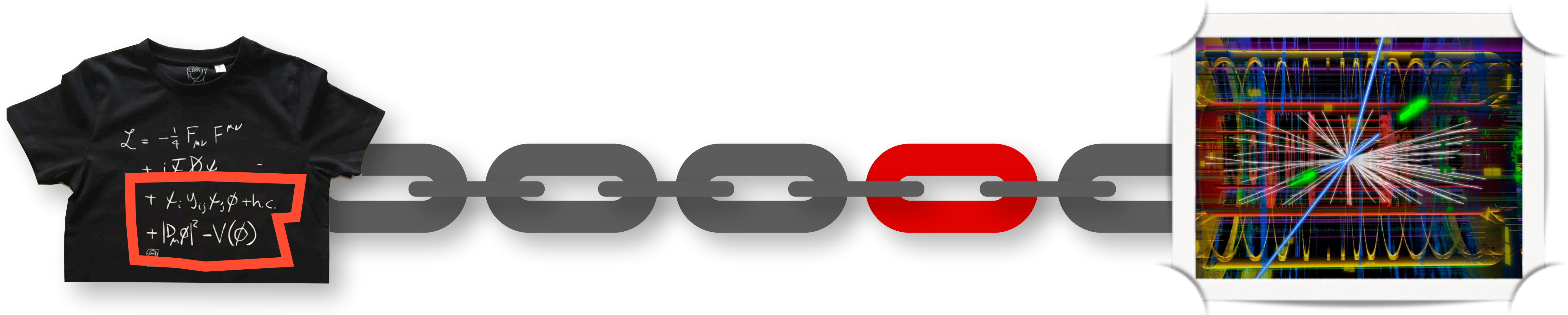
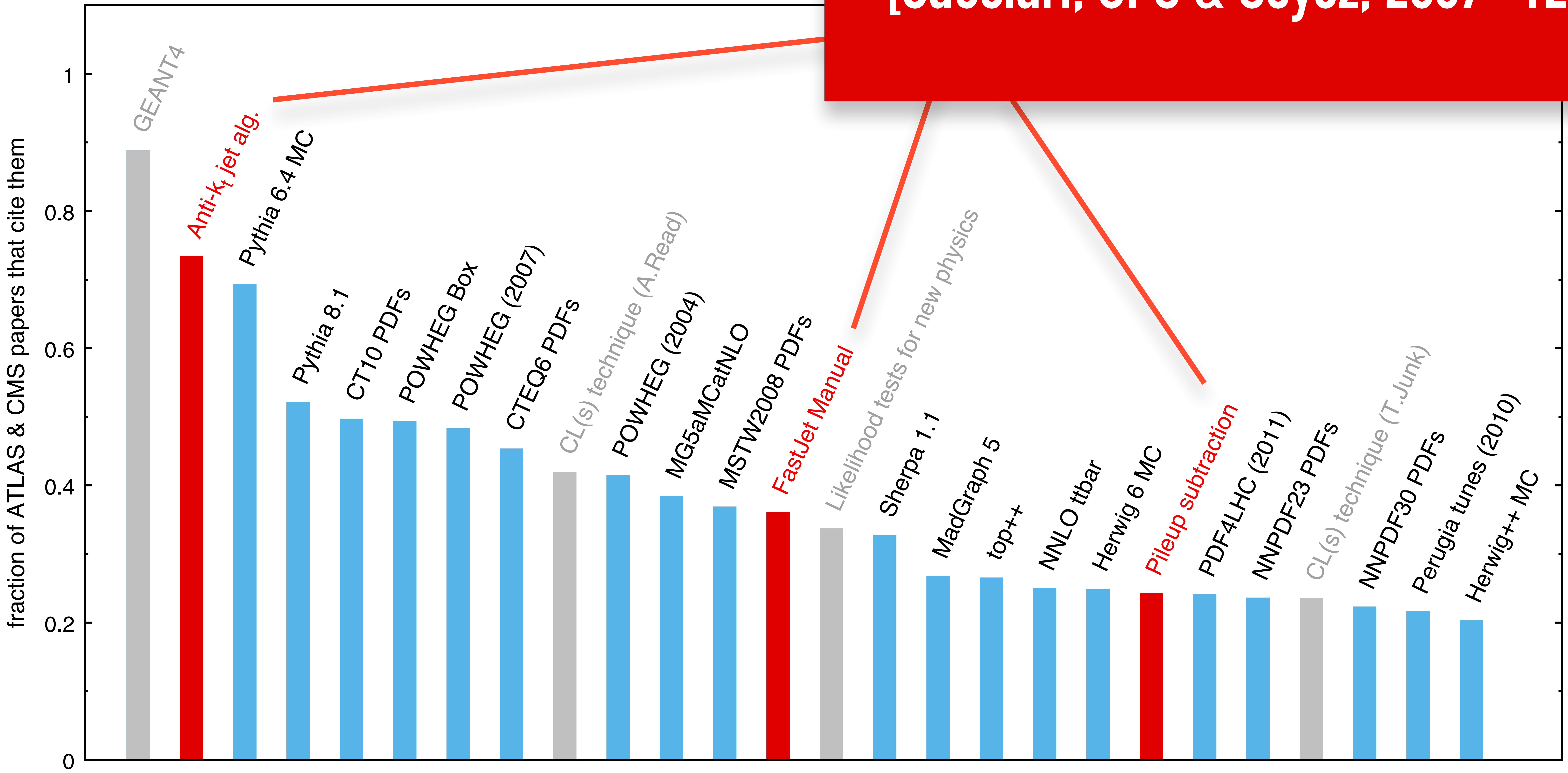


- Eveything about electron–proton interaction encoded in two well measured "structure functions" $F_2(x,Q^2)$ & $F_L(x,Q^2)$

$$\frac{d\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left(\left(1 - y + \frac{y^2}{2}\left(1 + 2x^2\frac{m_p^2}{Q^2}\right)\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right)$$

organising event information ("jets")
[Cacciari, GPS & Soyez, 2007–12]





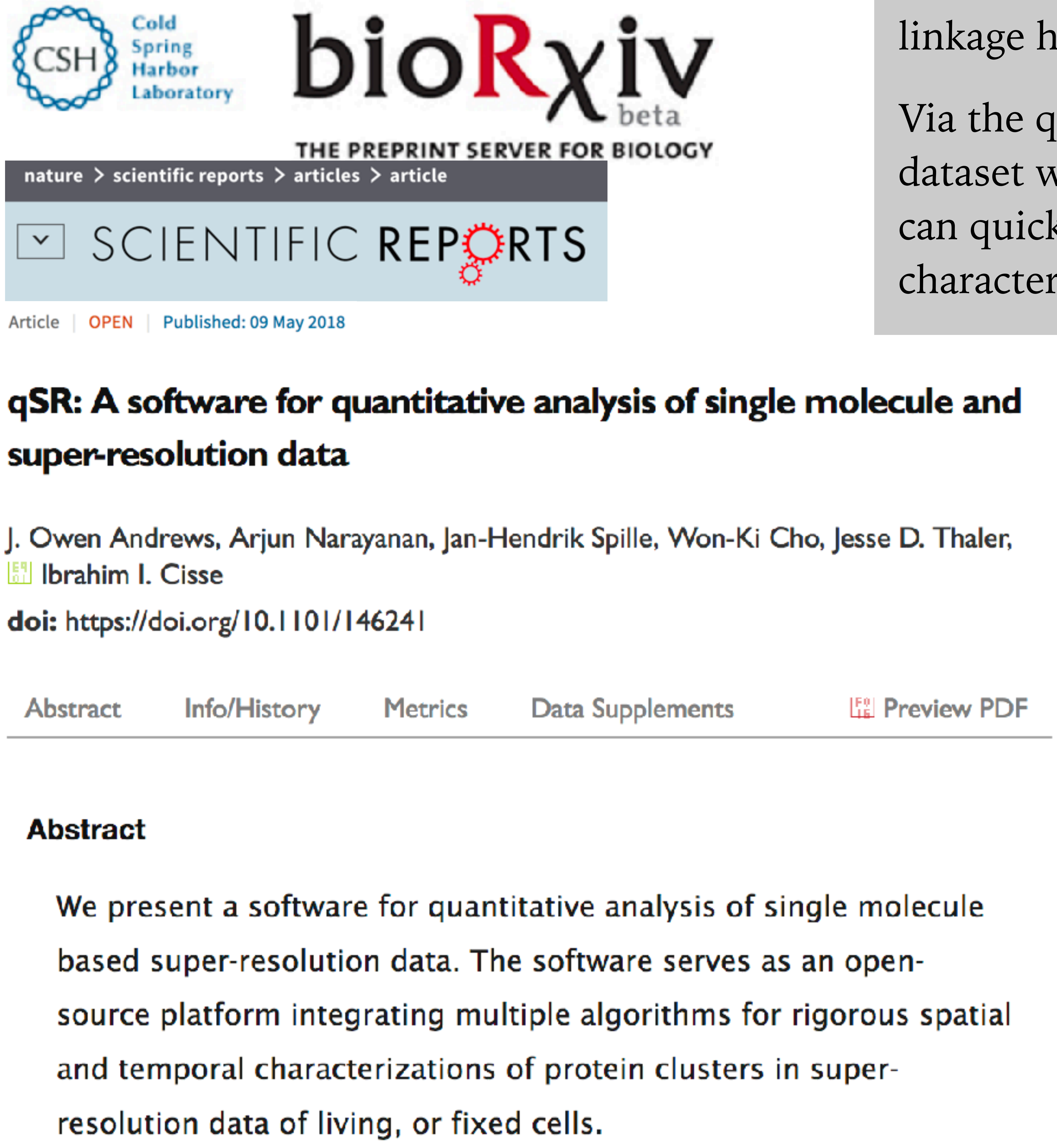
Plot by GP Salam based on data from InspireHEP

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
Y

Anti-k_t algorithm, Cacciari, GPS & Soyez, 2008 (solved a 30-year old problem, first addressed by Sterman & Weinberg)

FastJet program, Cacciari, GPS & Soyez, 2005 – 18
FastJet contrib, $\sim$ 20 contributors, 2013 – 18



nature > scientific reports > articles > article

SCIENTIFIC REPORTS

Article | OPEN | Published: 09 May 2018

qSR: A software for quantitative analysis of single molecule and super-resolution data

J. Owen Andrews, Arjun Narayanan, Jan-Hendrik Spille, Won-Ki Cho, Jesse D. Thaler, Ibrahim I. Cisse

doi: https://doi.org/10.1101/146241

Abstract | Info/History | Metrics | Data Supplements | Preview PDF

Abstract

We present a software for quantitative analysis of single molecule based super-resolution data. The software serves as an open-source platform integrating multiple algorithms for rigorous spatial and temporal characterizations of protein clusters in super-resolution data of living, or fixed cells.

For identifying spatial clusters, we have implemented both centroid-linkage hierarchical clustering using FastJet […]

Via the qSR software, FastJet can analyze a typical super-resolution dataset within a few seconds. By storing the full tree structure, the user can quickly re-cluster data and compare the resulting clusters at varying characteristic sizes.

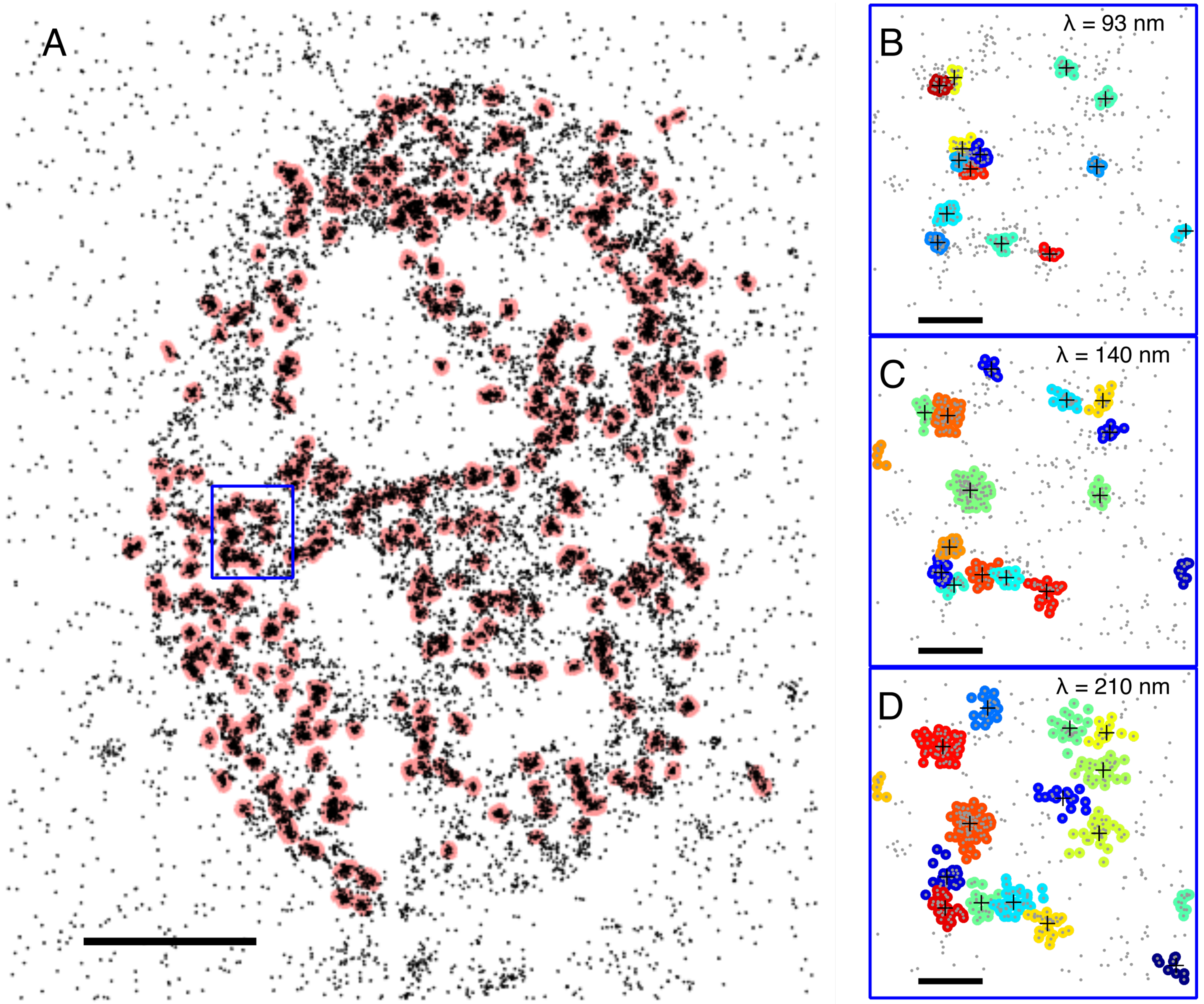
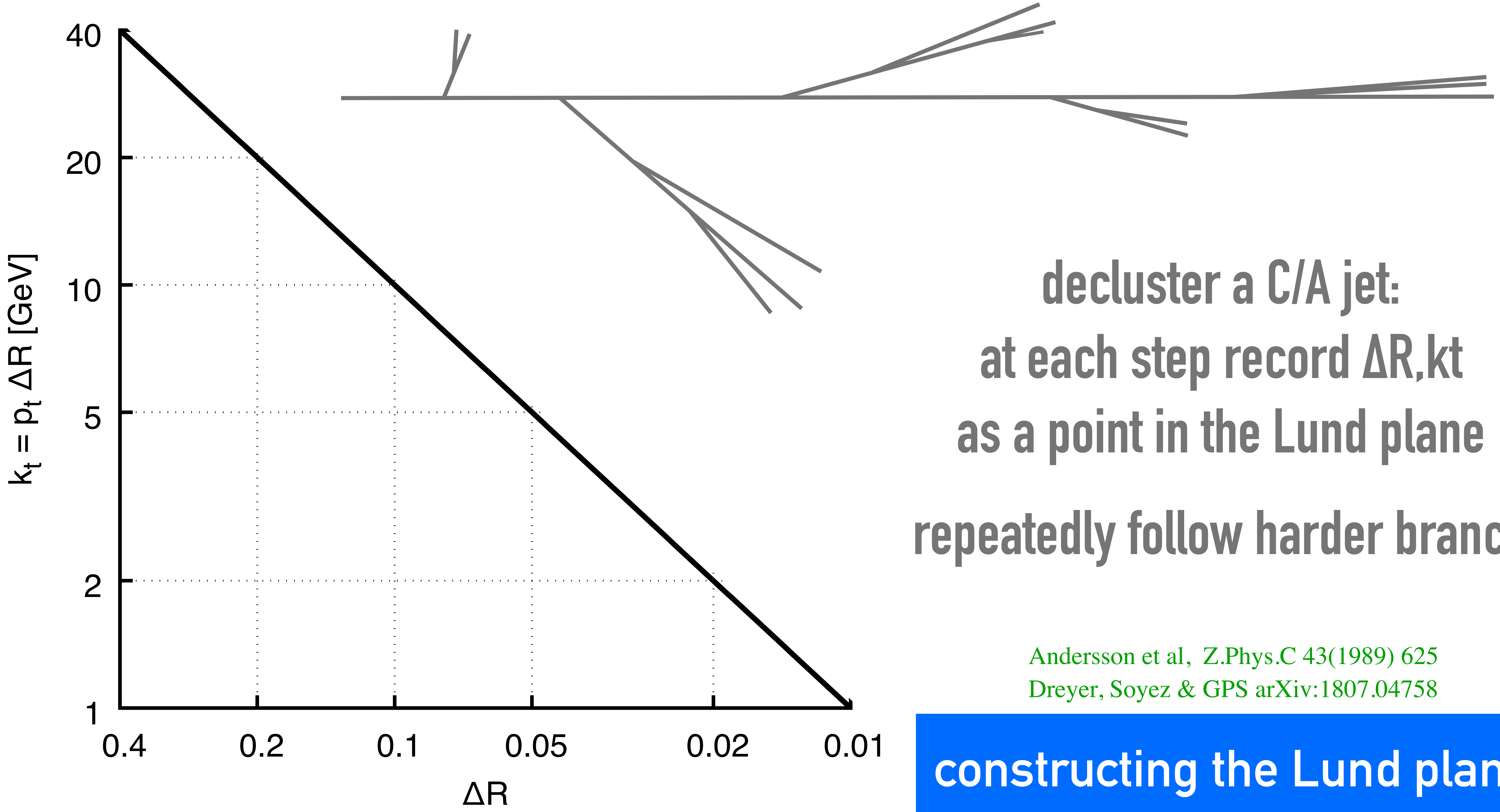


Figure S6: FastJet hierarchical clustering. (A) FastJet clusters found with a length scale of 140nm. (B-D) Zoomed in view of the region in the blue box from A. The clusters were generated by cutting the tree with a length scale of 93 nm, 140 nm, and 210 nm respectively. The black + signs mark the centroids of each cluster. Scale Bars – A: 5 μm B - D: 500 nm

constructing the Lund plane

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



decluster a C/A jet:

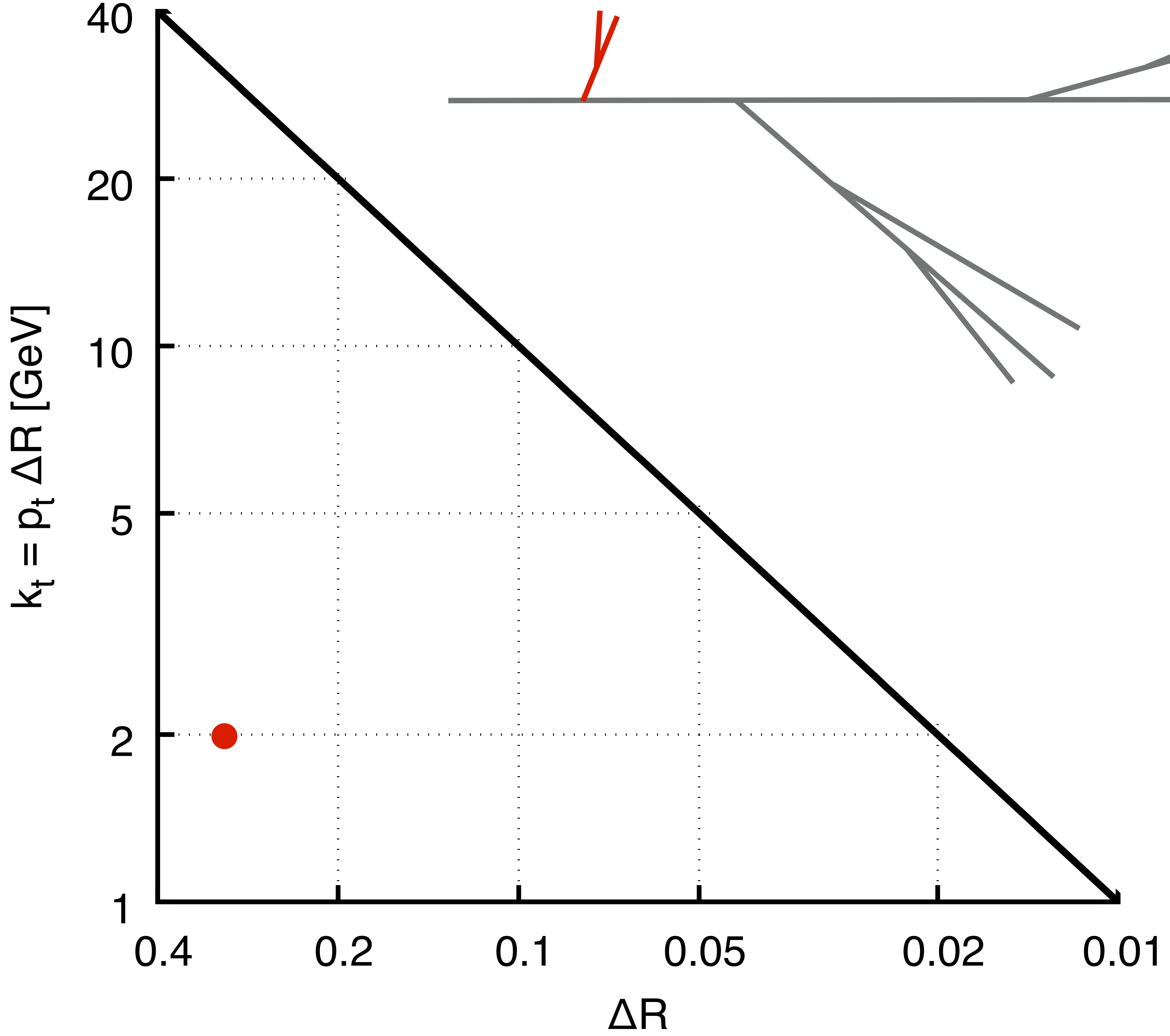
at each step record ΔR,kt

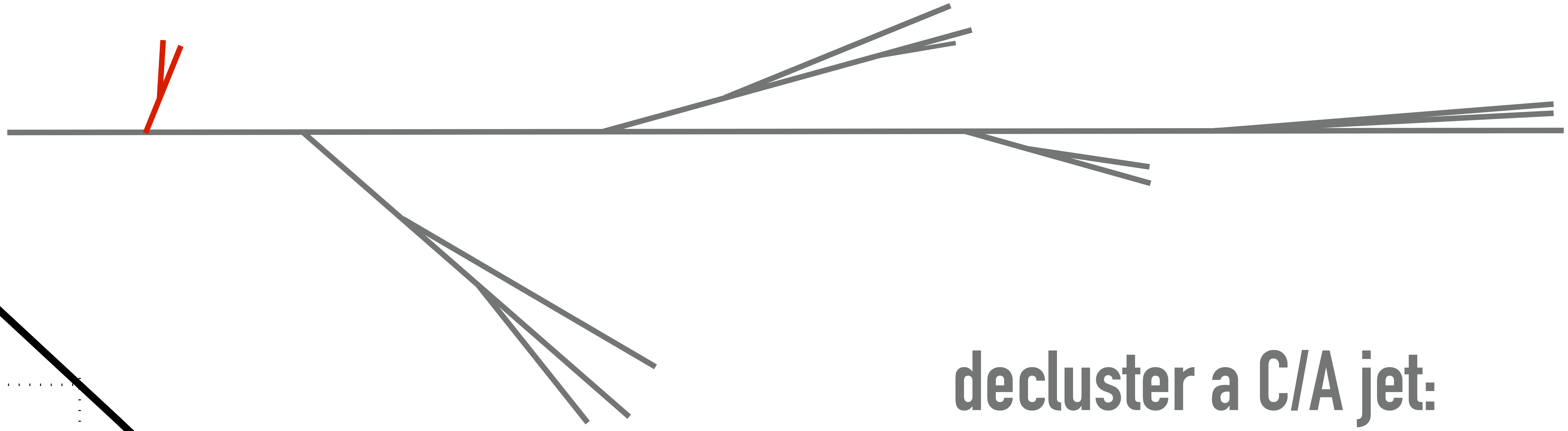
as a point in the Lund plane

repeatedly follow harder branch

Andersson et al, Z.Phys.C 43(1989) 625

Dreyer, Soyez & GPS arXiv:1807.04758





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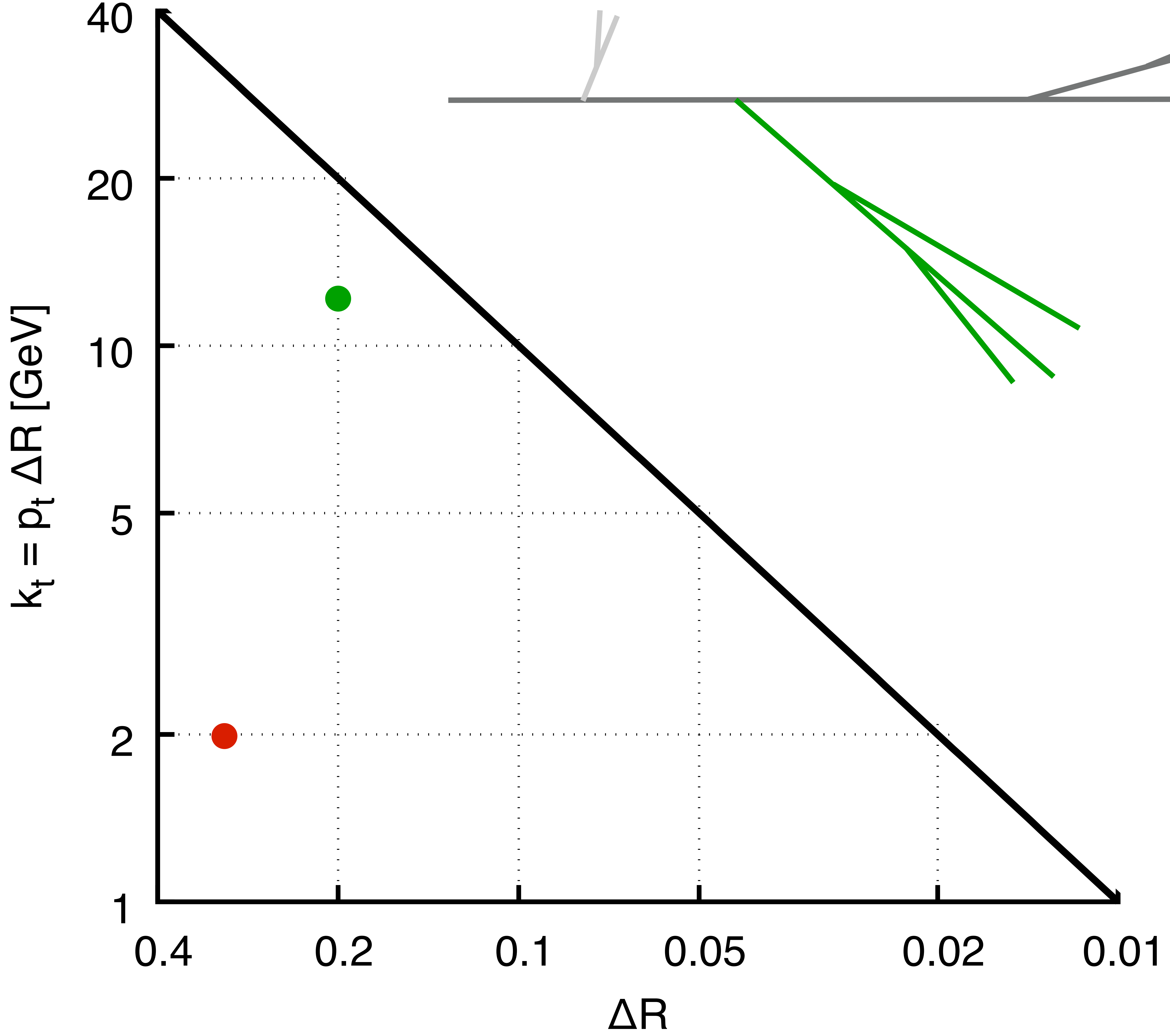

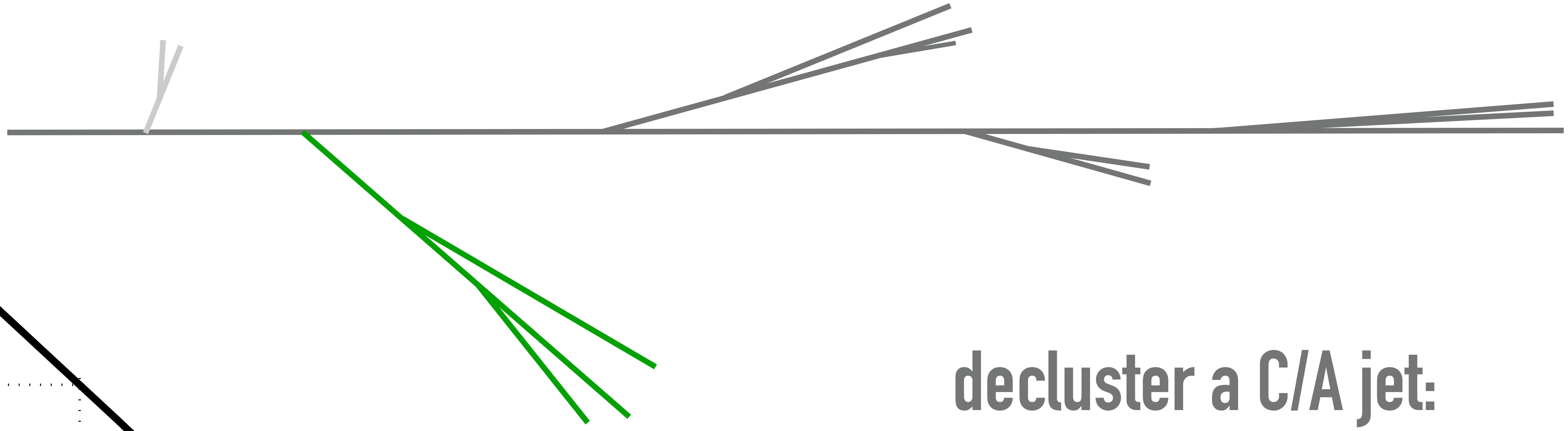

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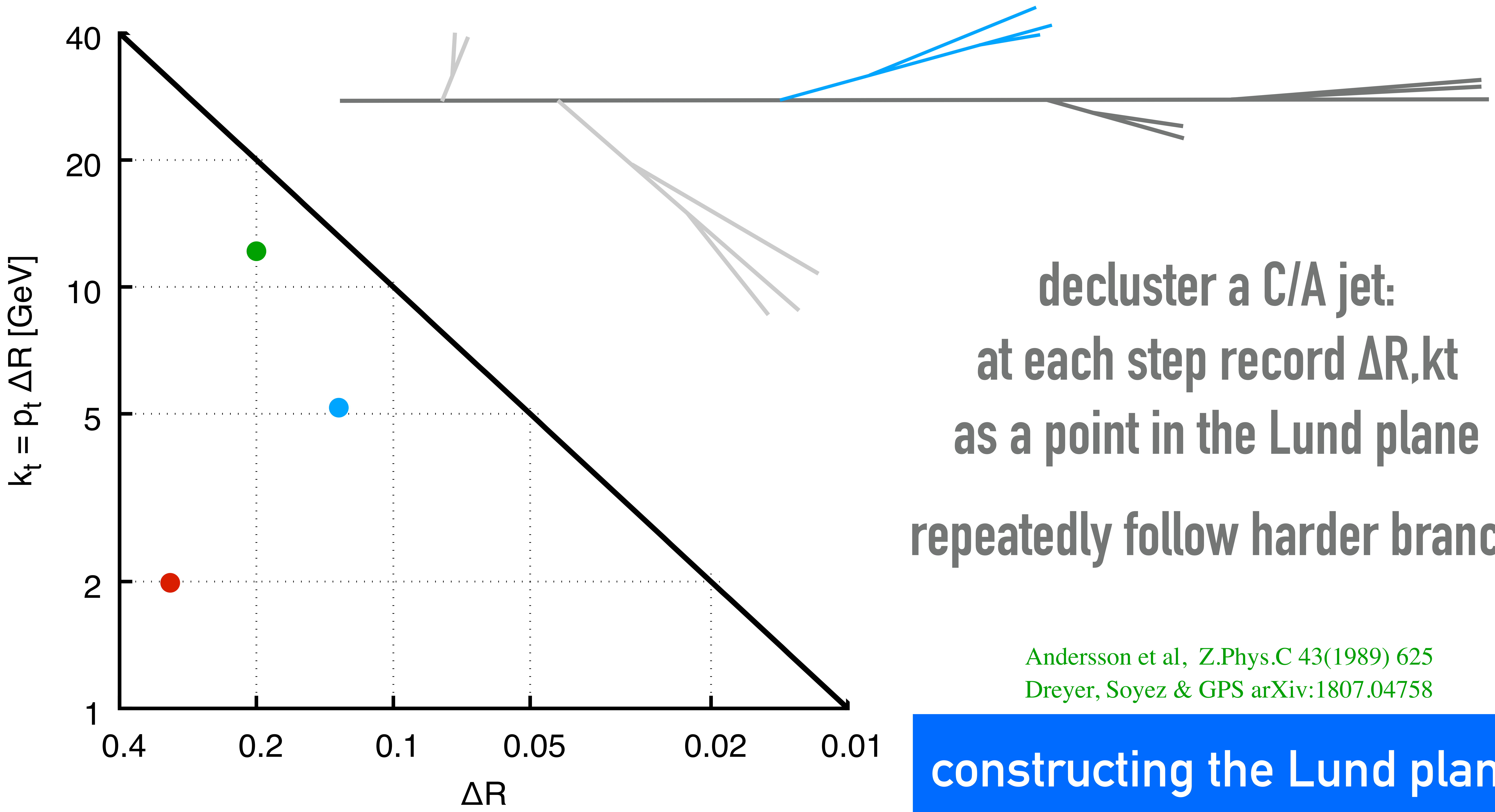

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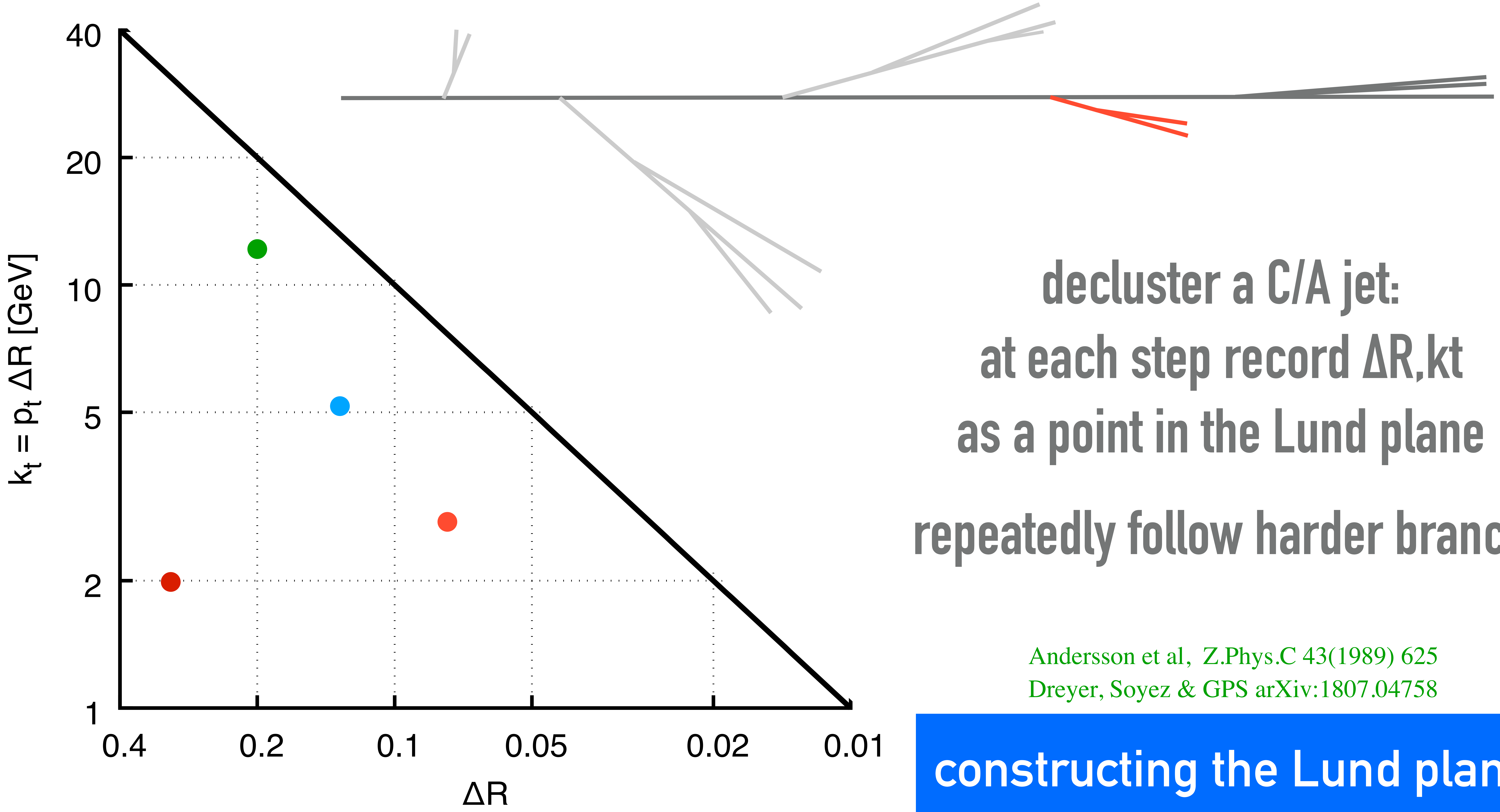

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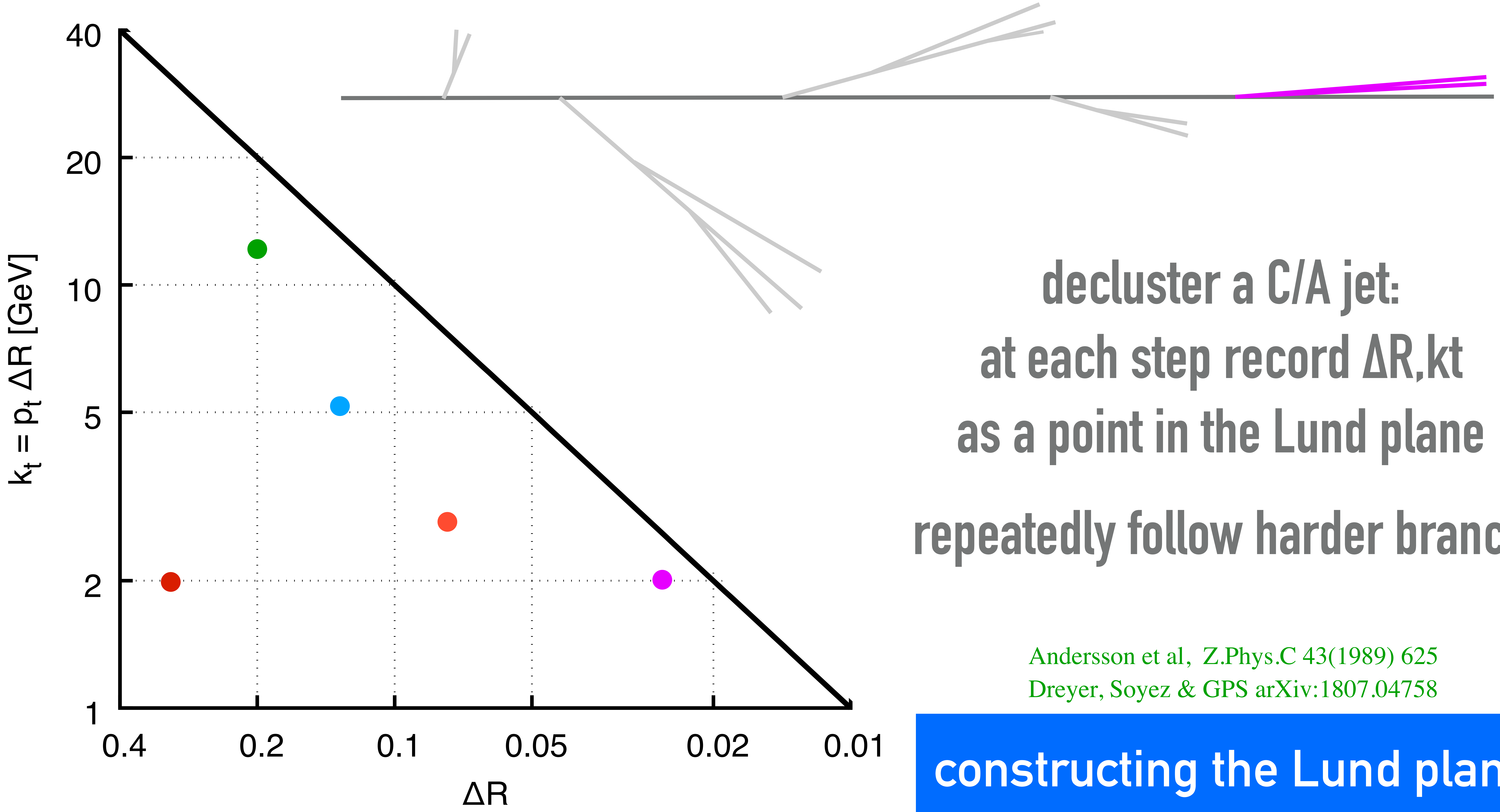

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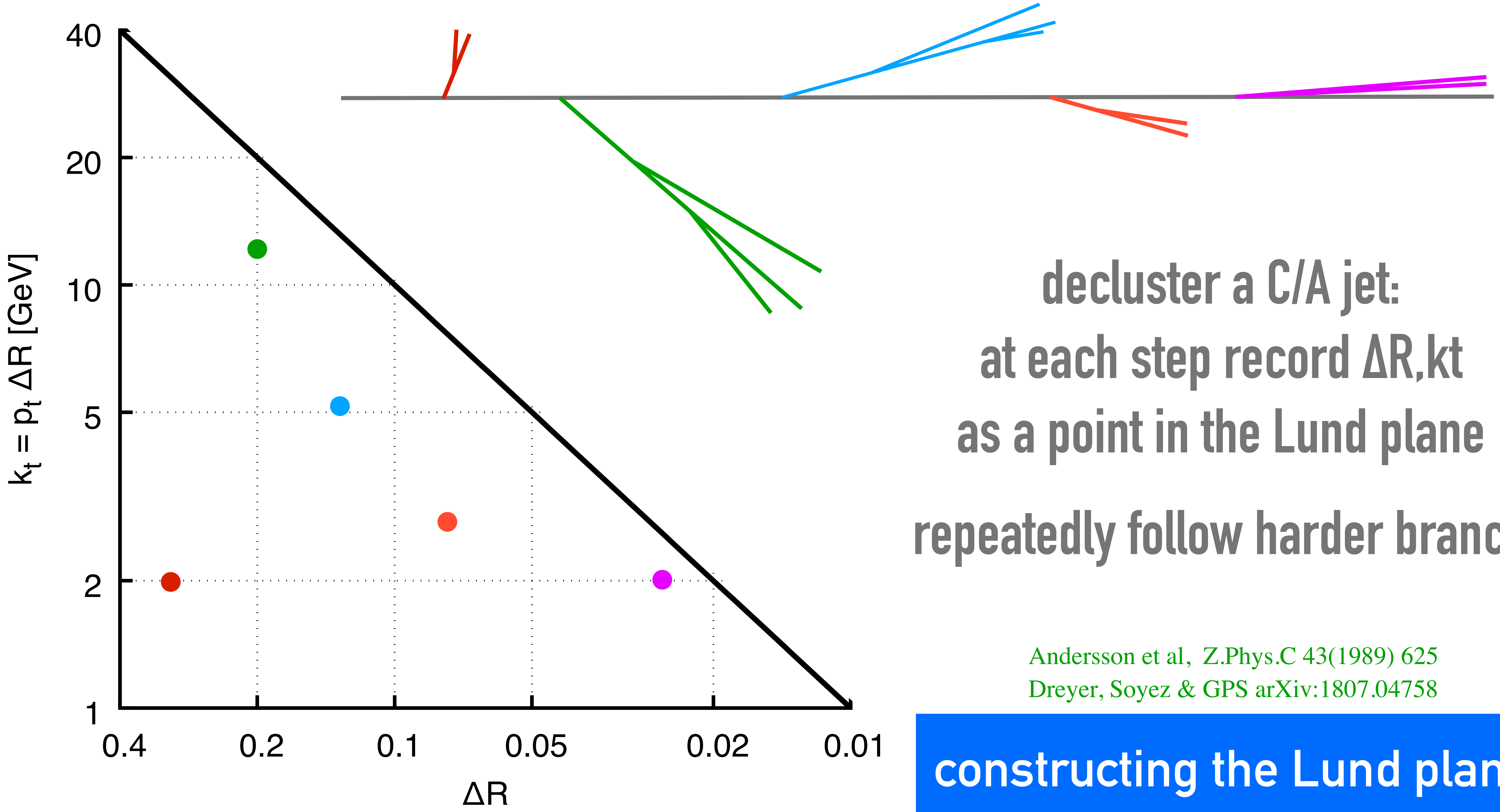

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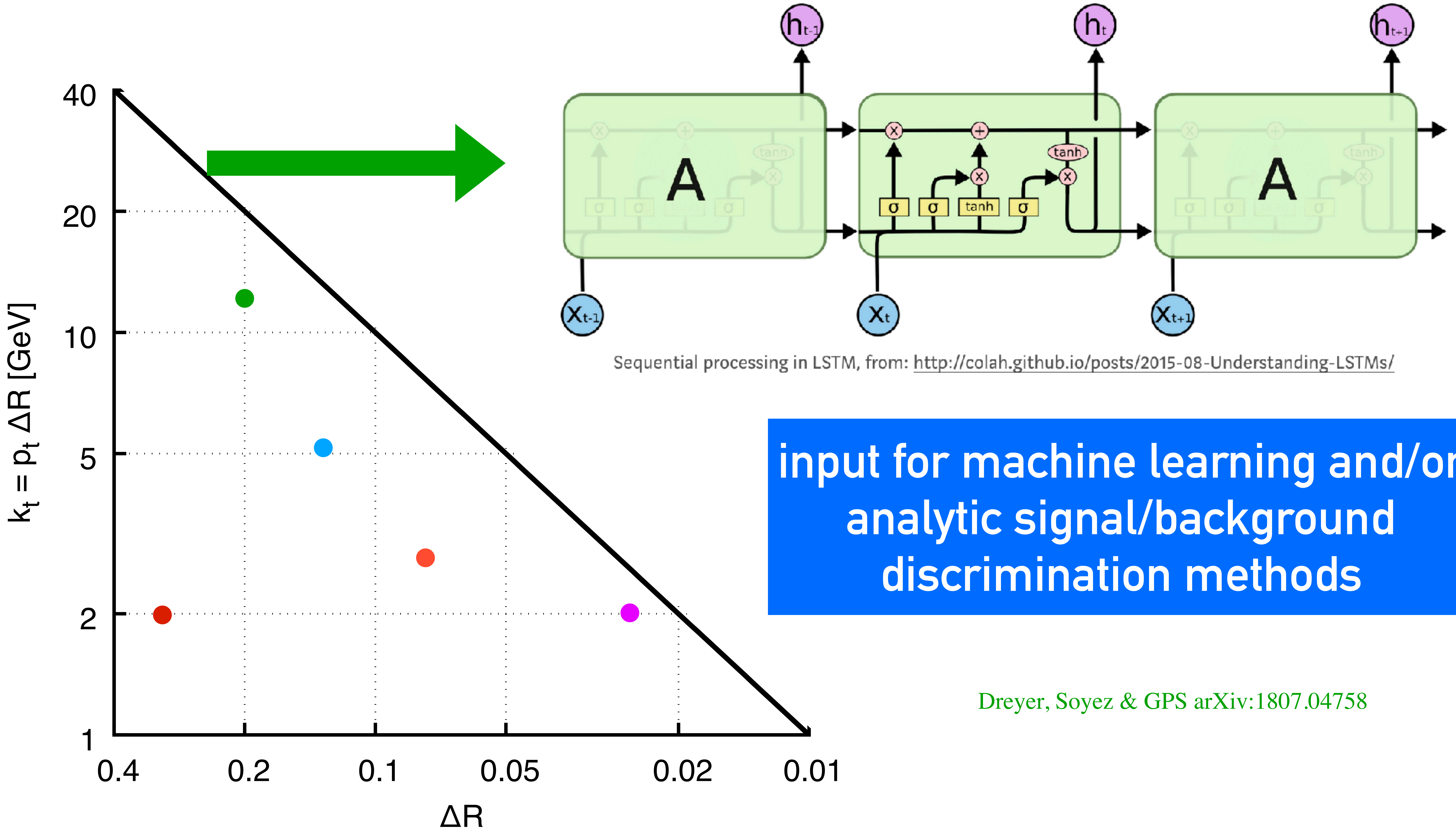
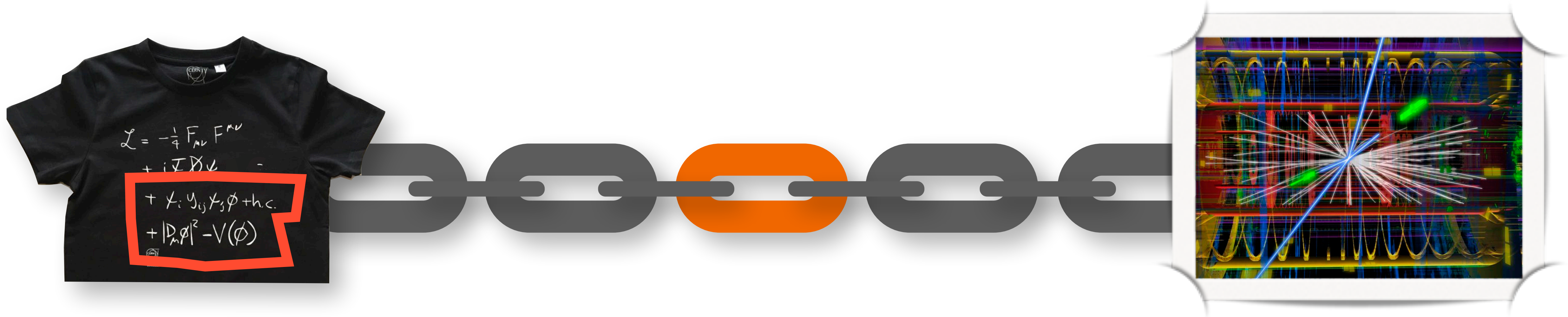


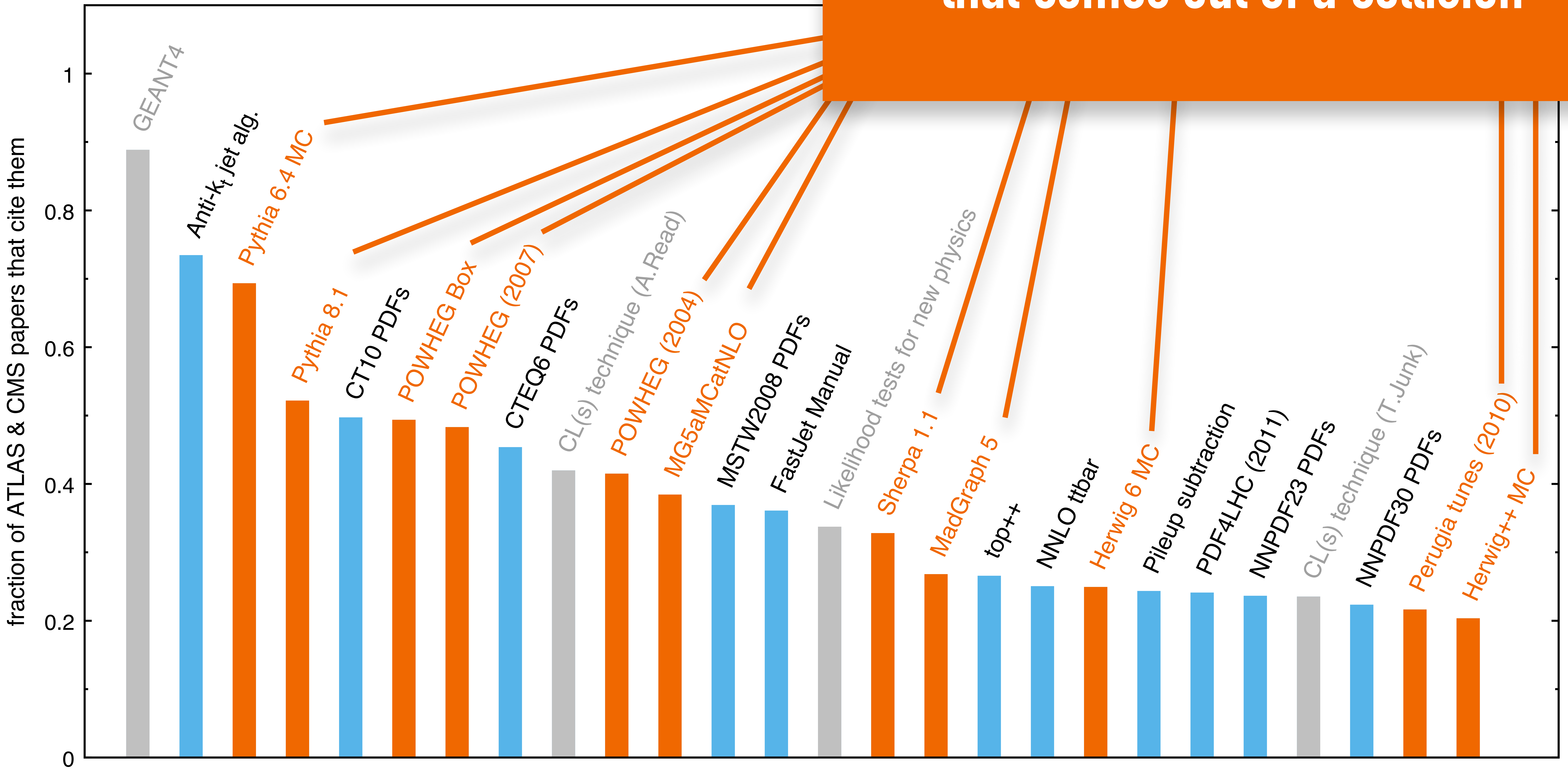
Sequential processing in LSTM, from: http://colah.github.io/posts/2015-08-Understanding-LSTMs/

input for machine learning and/or analytic signal/background discrimination methods

Dreyer, Soyez & GPS arXiv:1807.04758

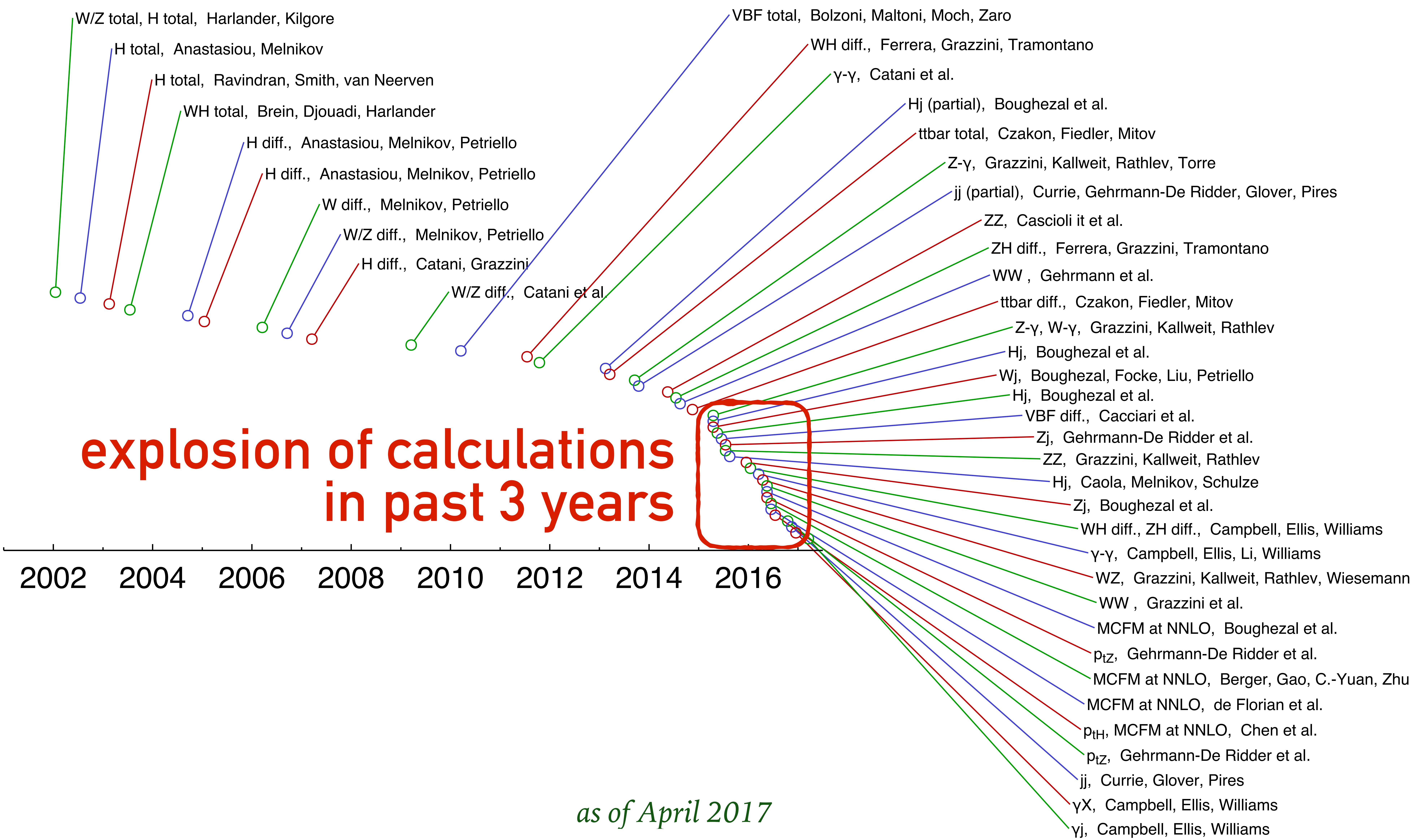
predicting full particle structure that comes out of a collision





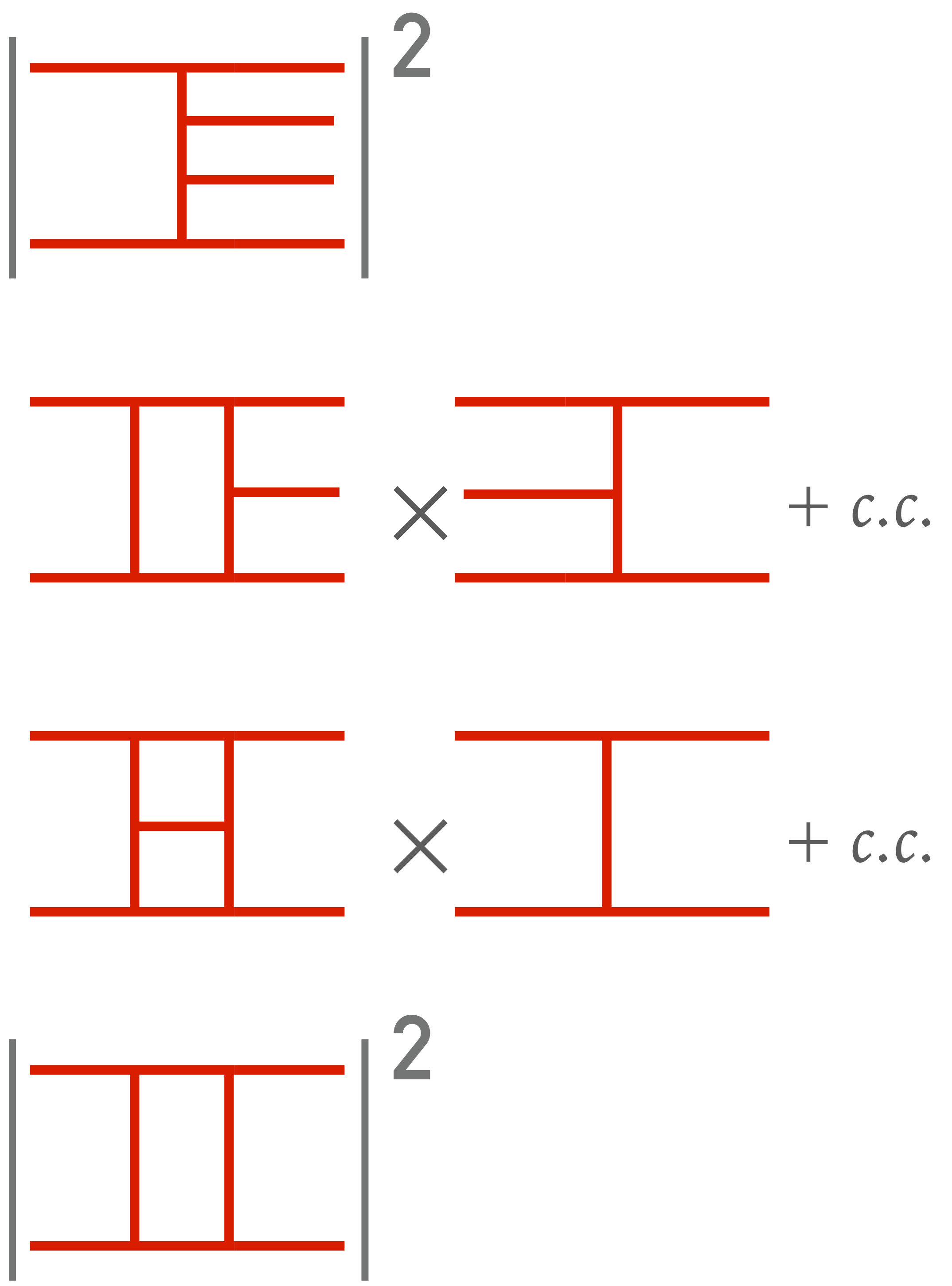
Plot by GP Salam based on data from InspireHEP

Calculations to 3rd order (NNLO) in perturbation theory strong coupling constant (α_s)

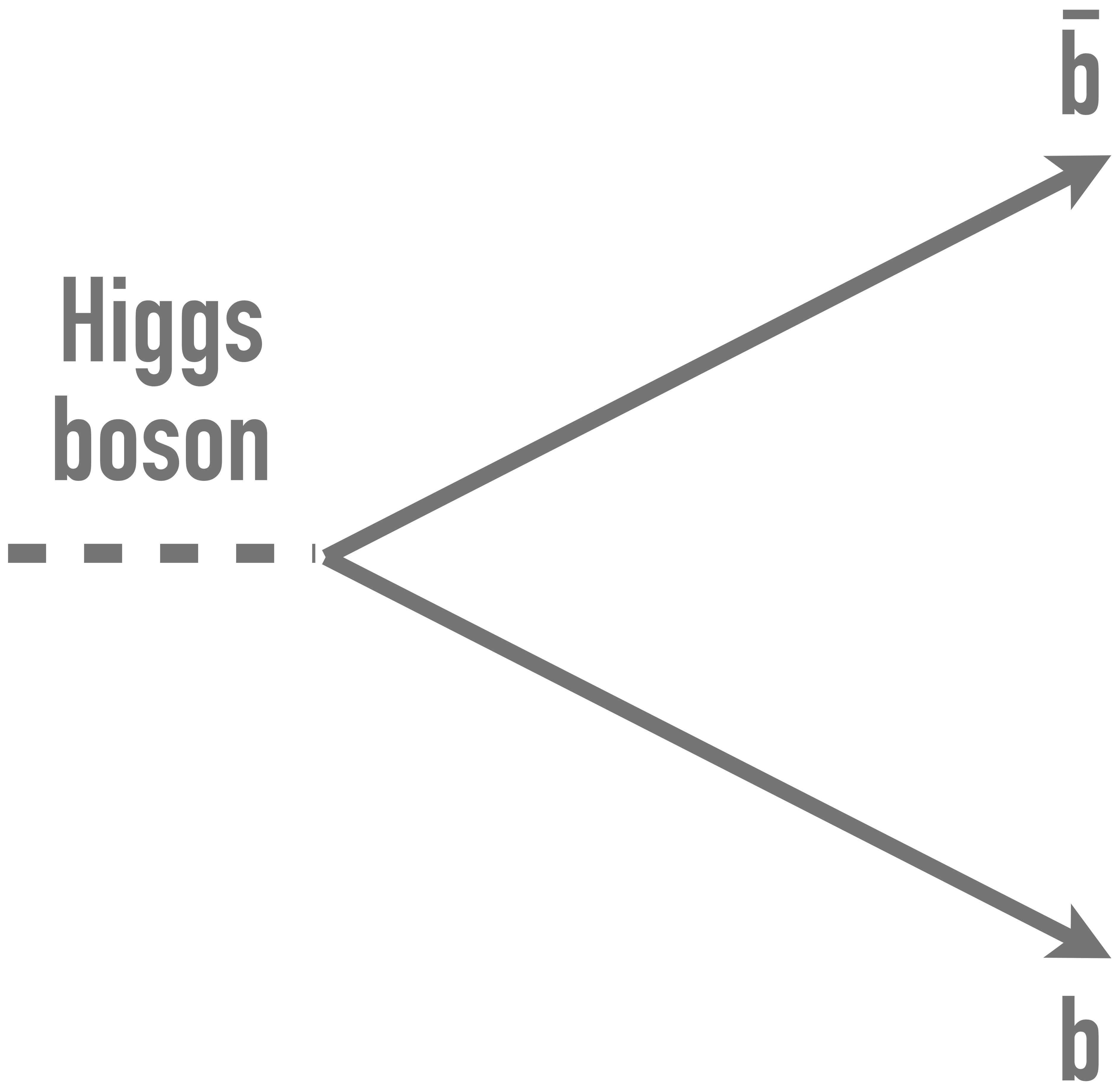


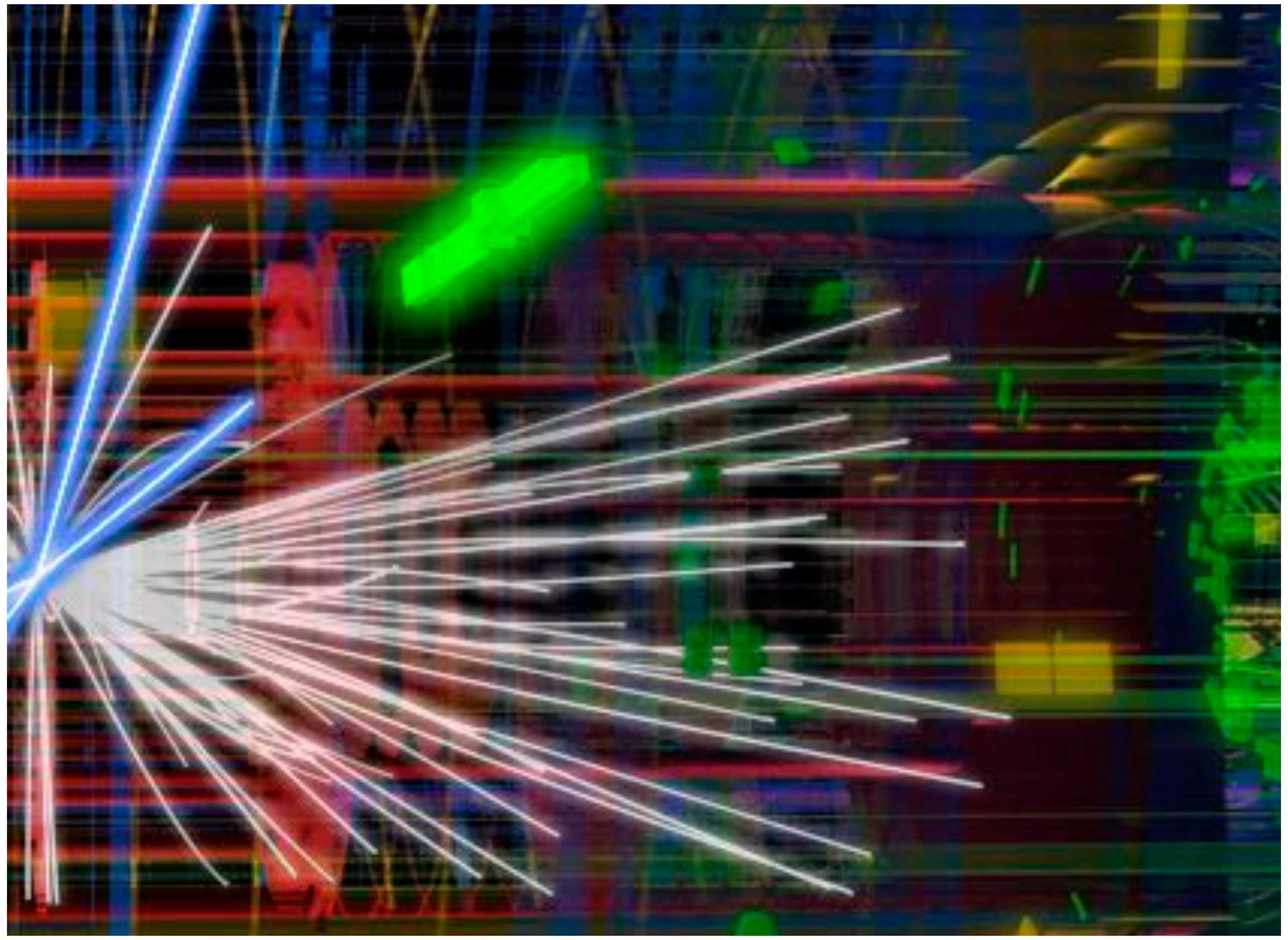
explosion of calculations in past 3 years

as of April 2017



QCD Parton Shower [parton = quark or gluon]





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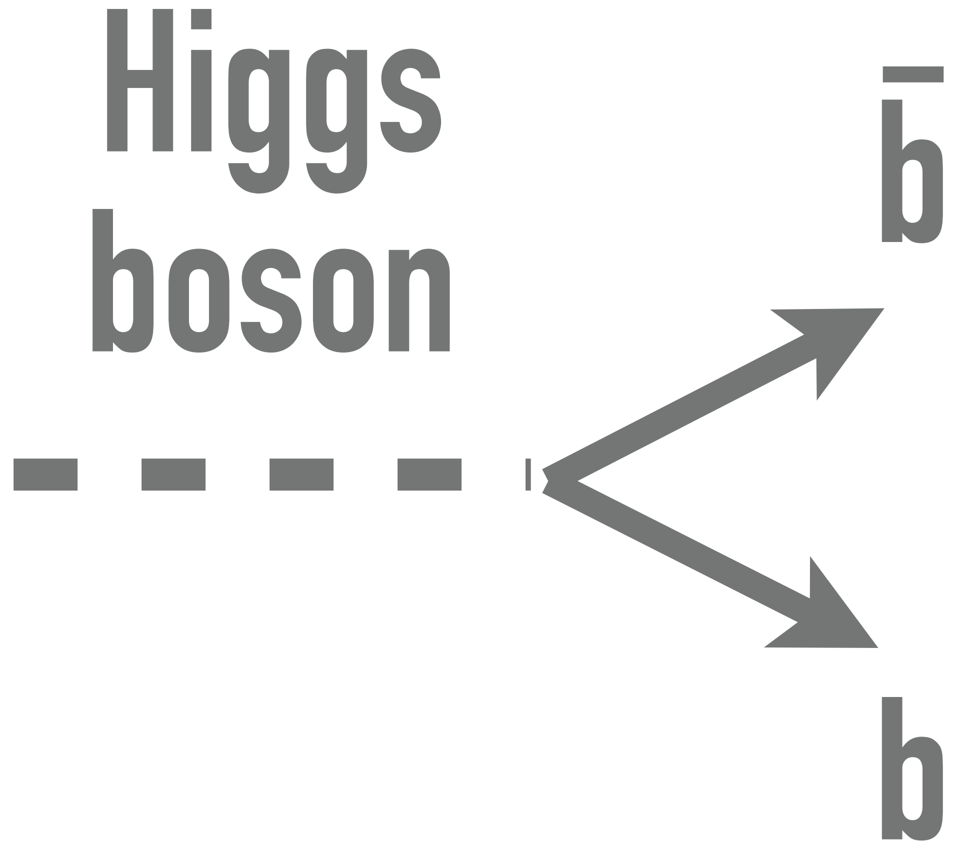

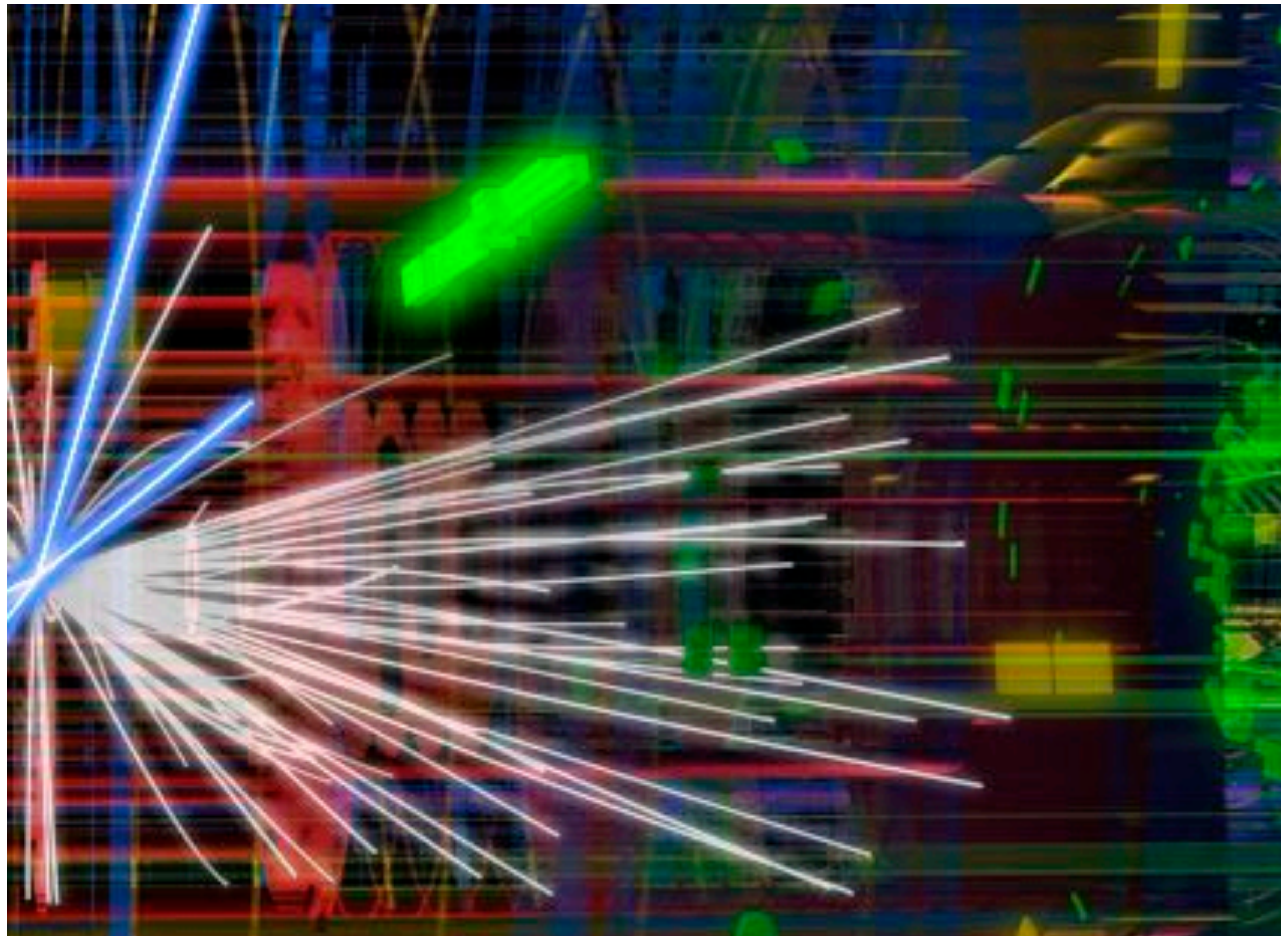

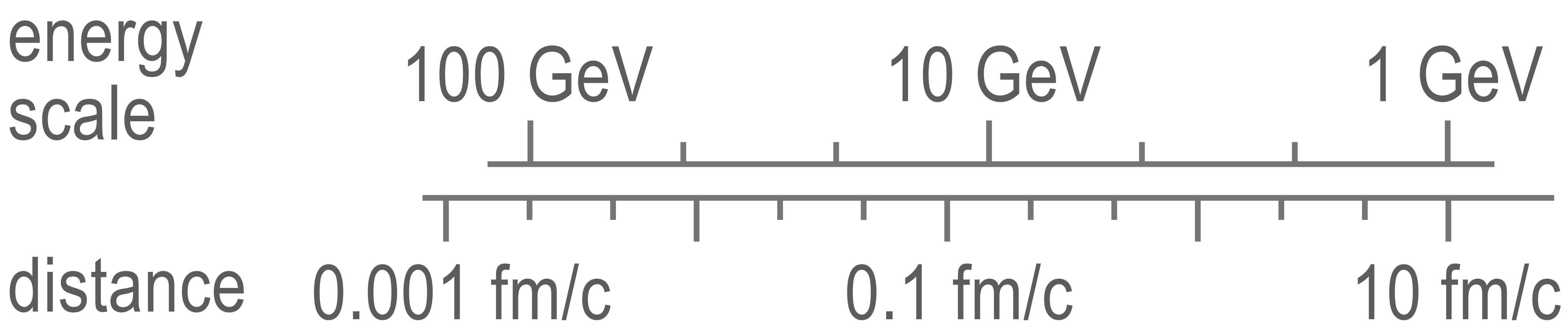

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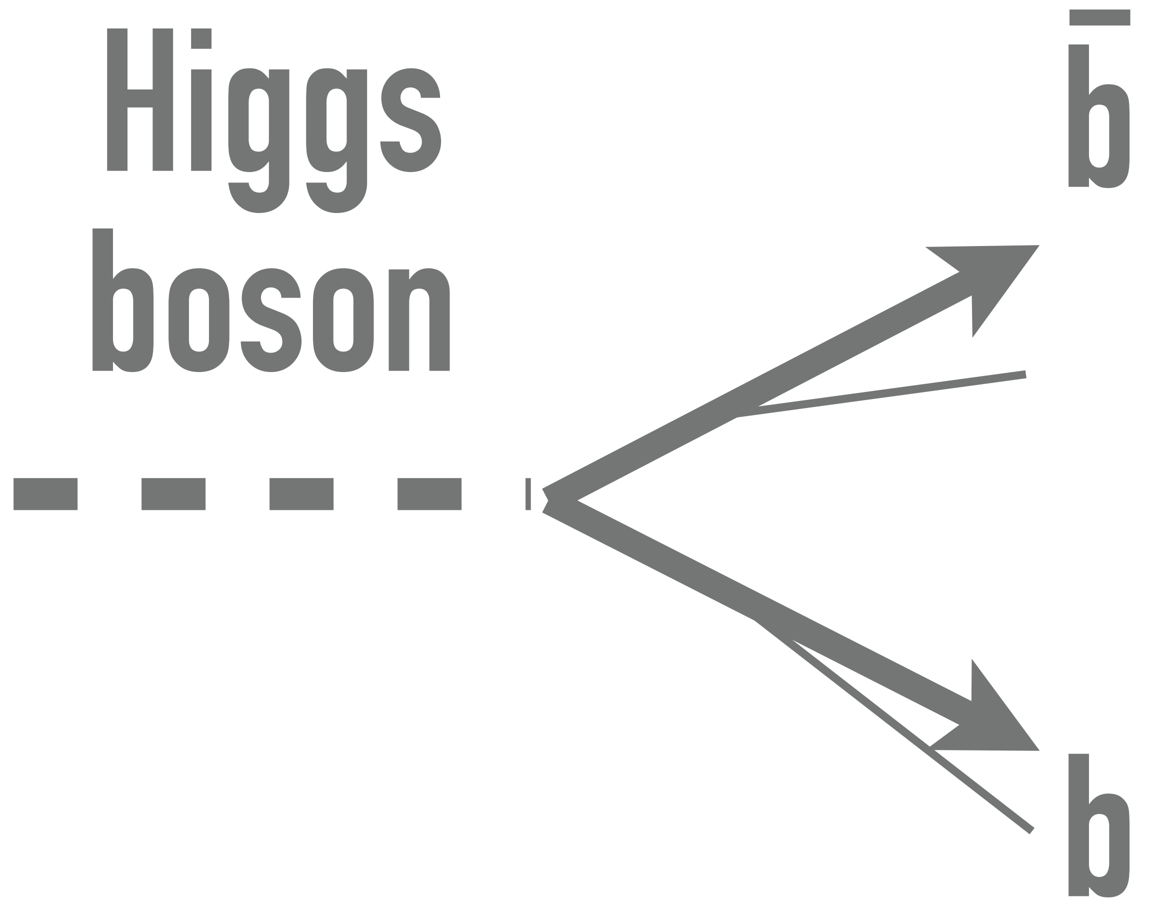

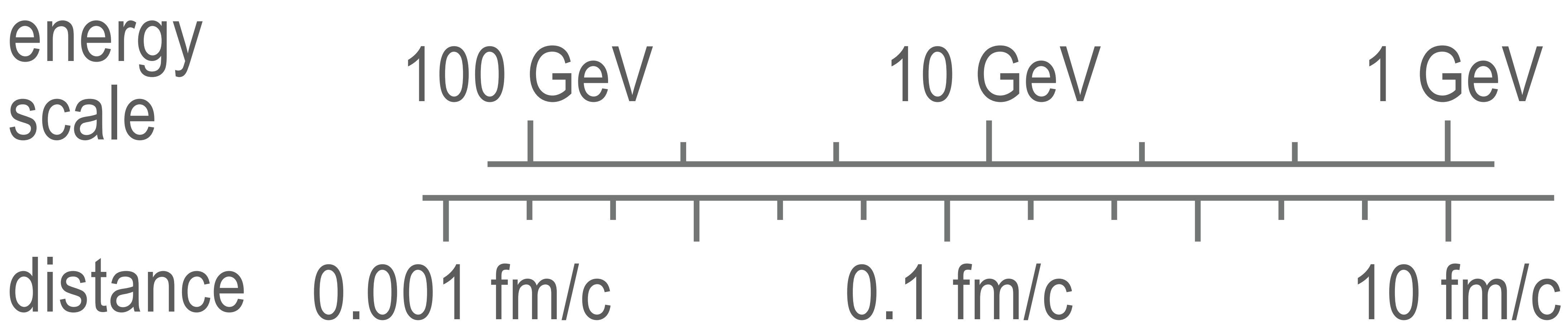

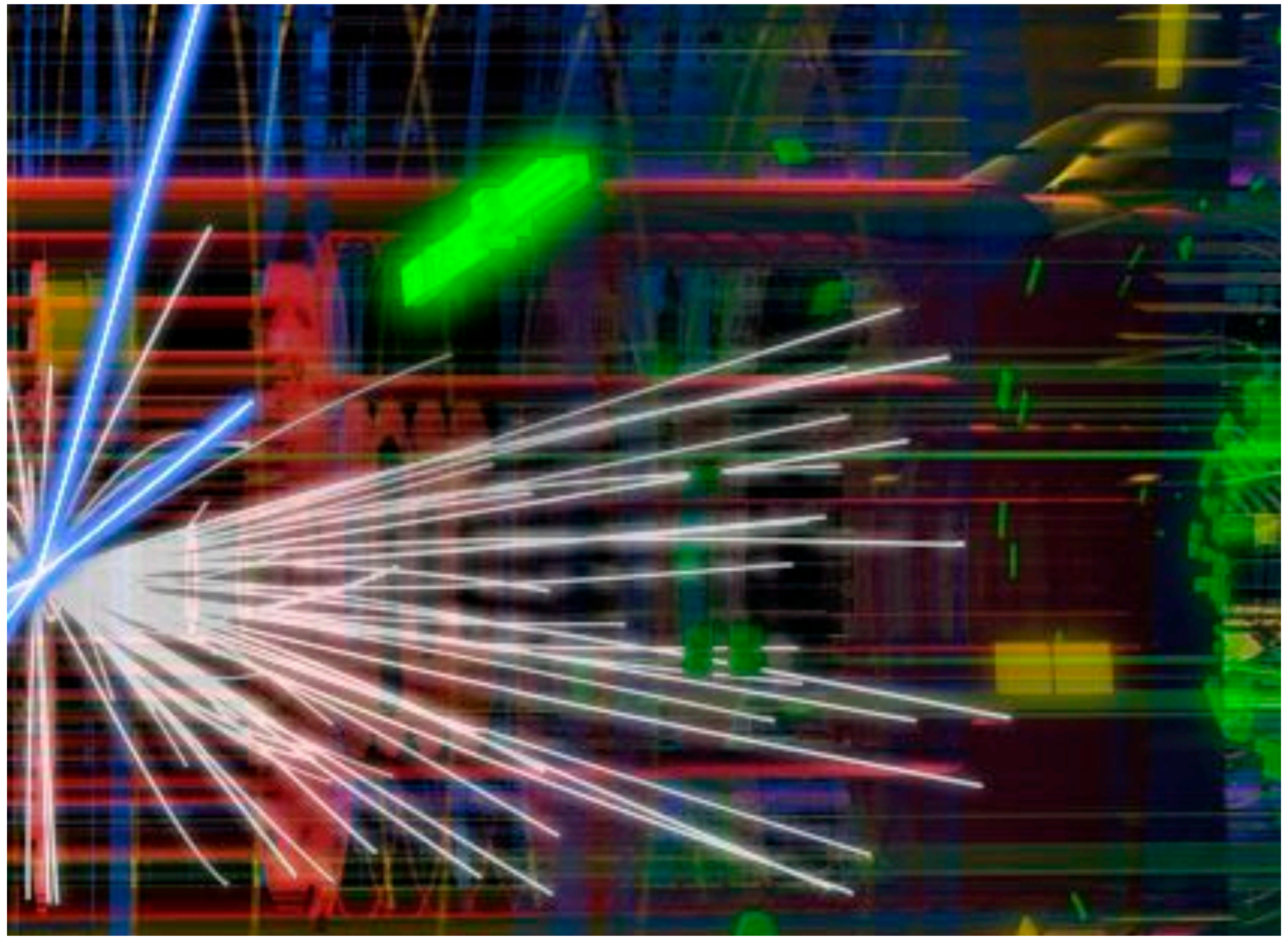

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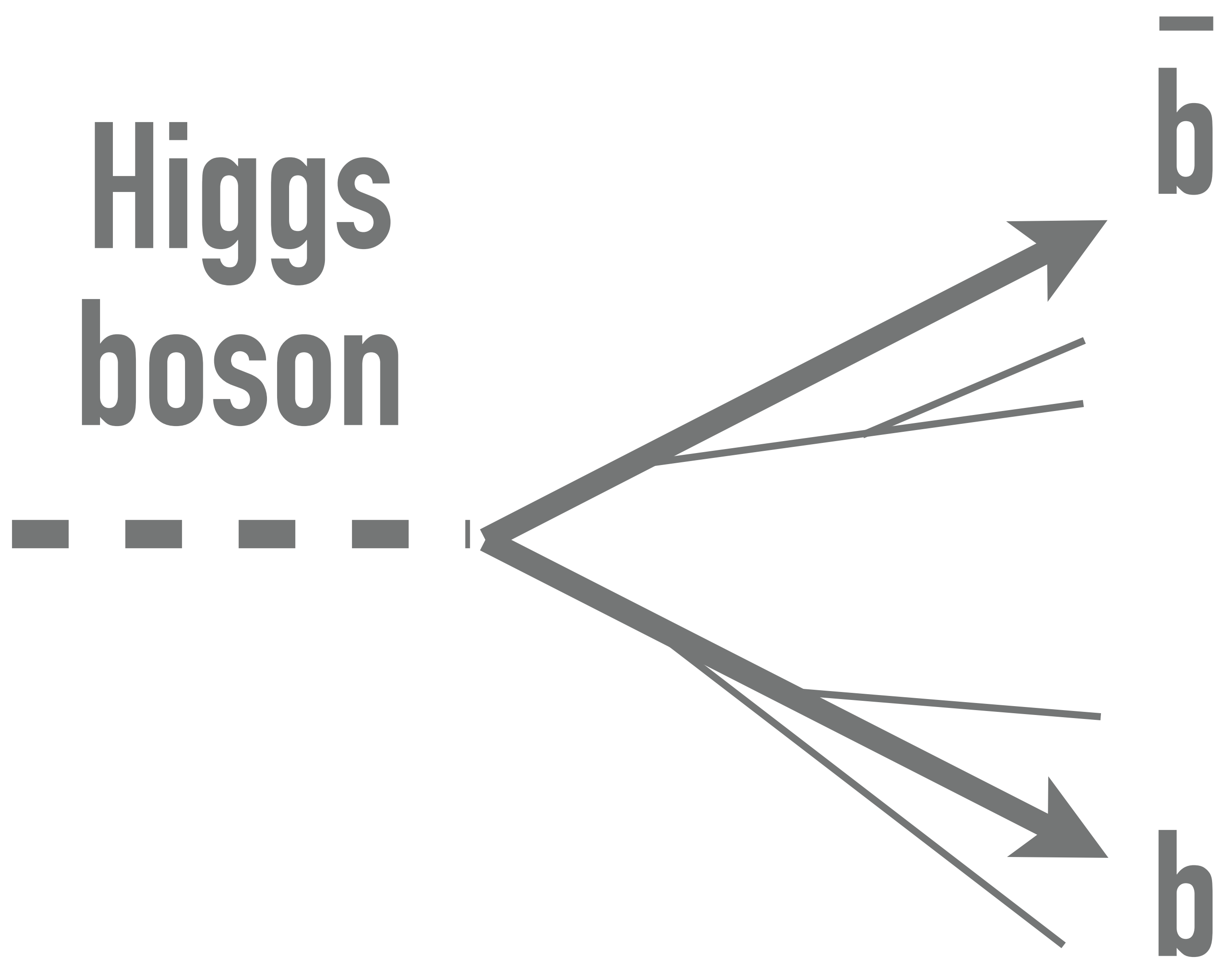
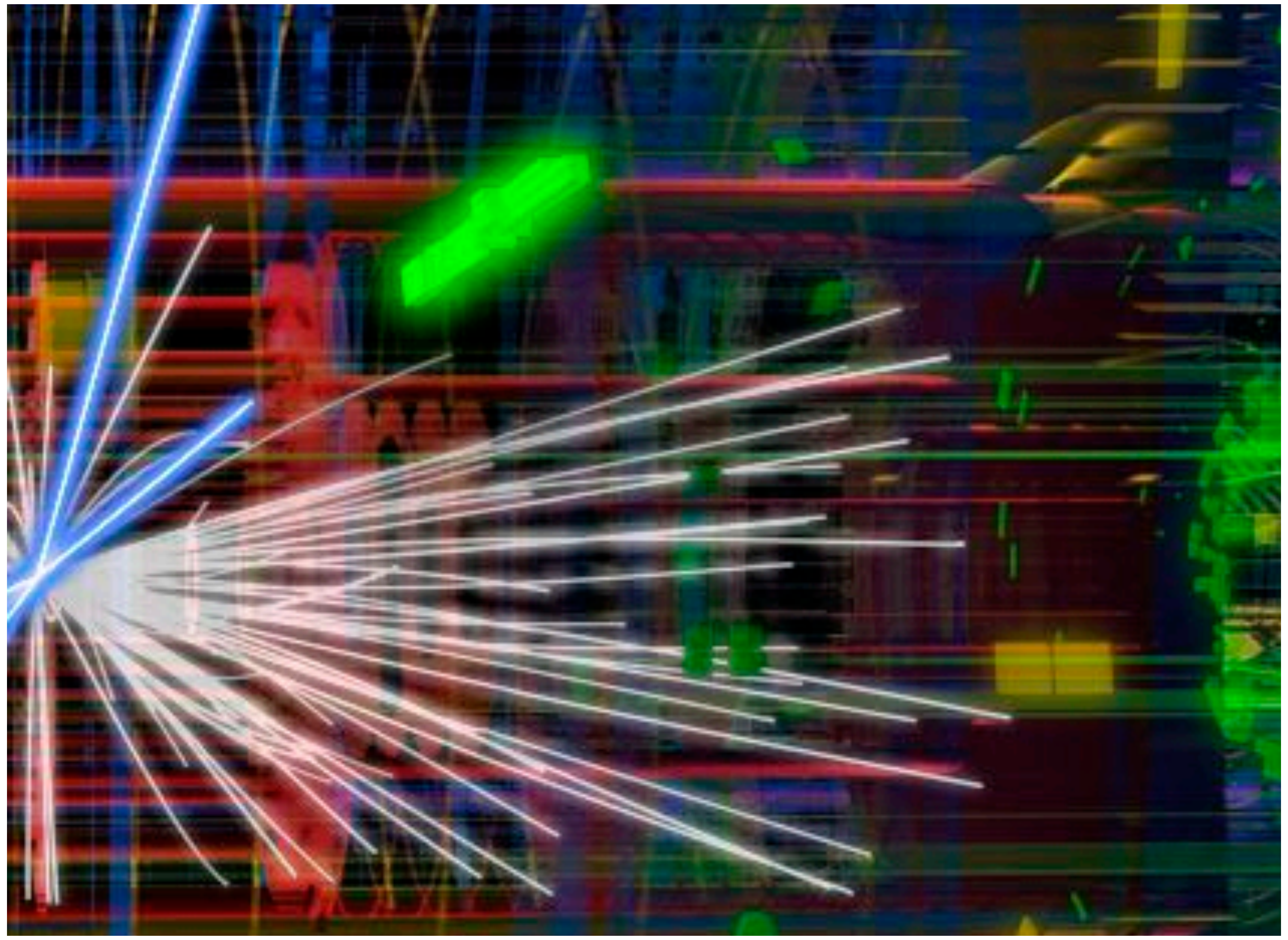
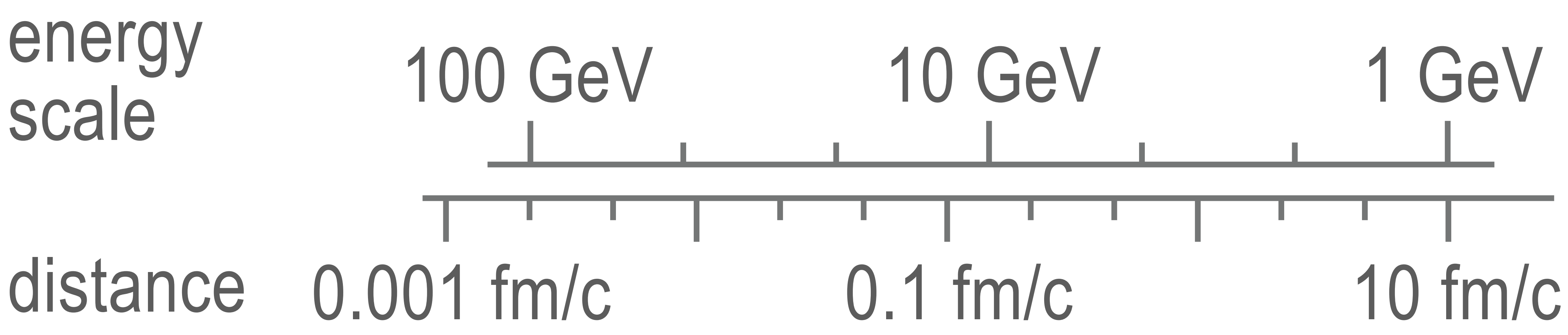
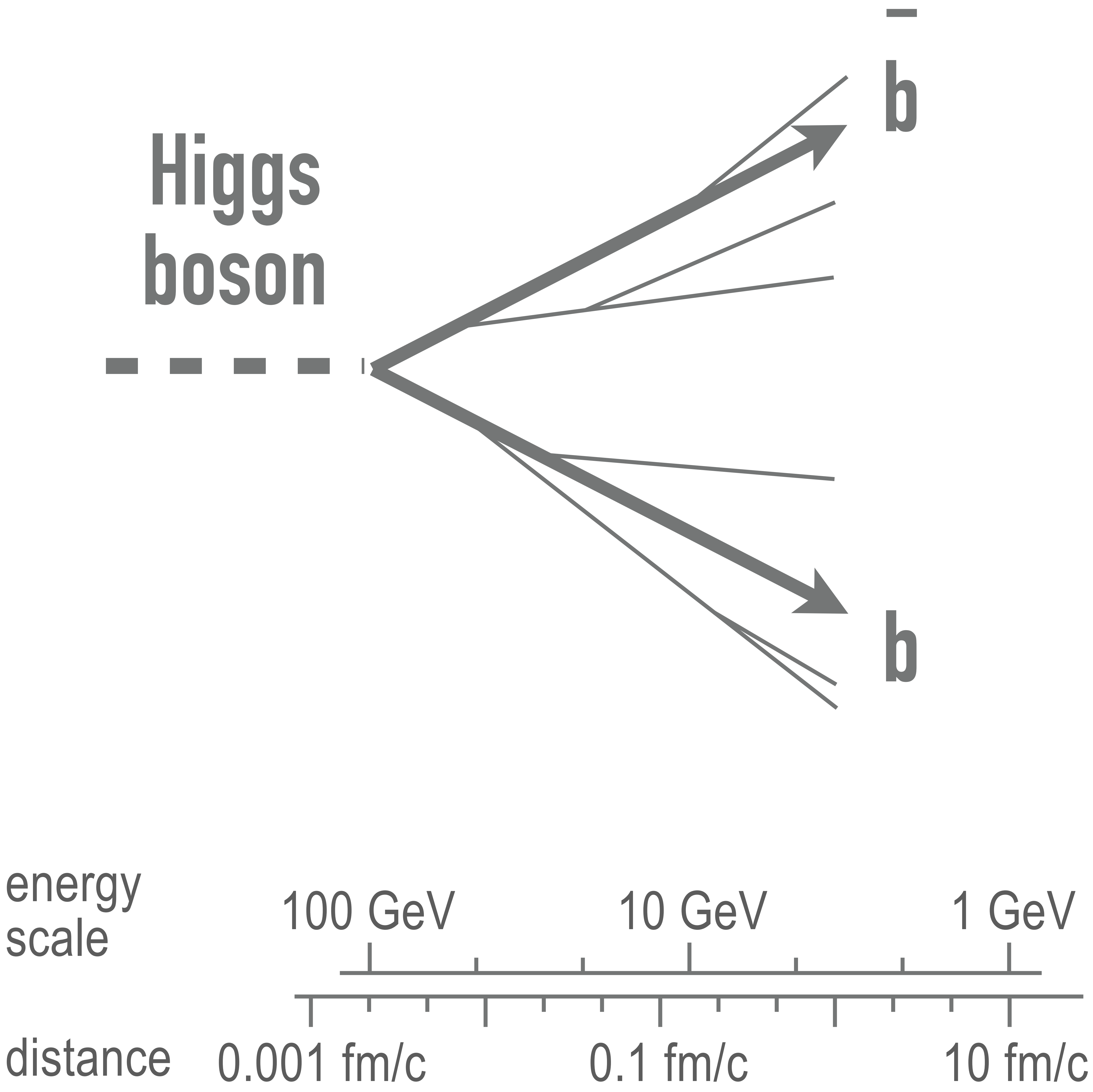
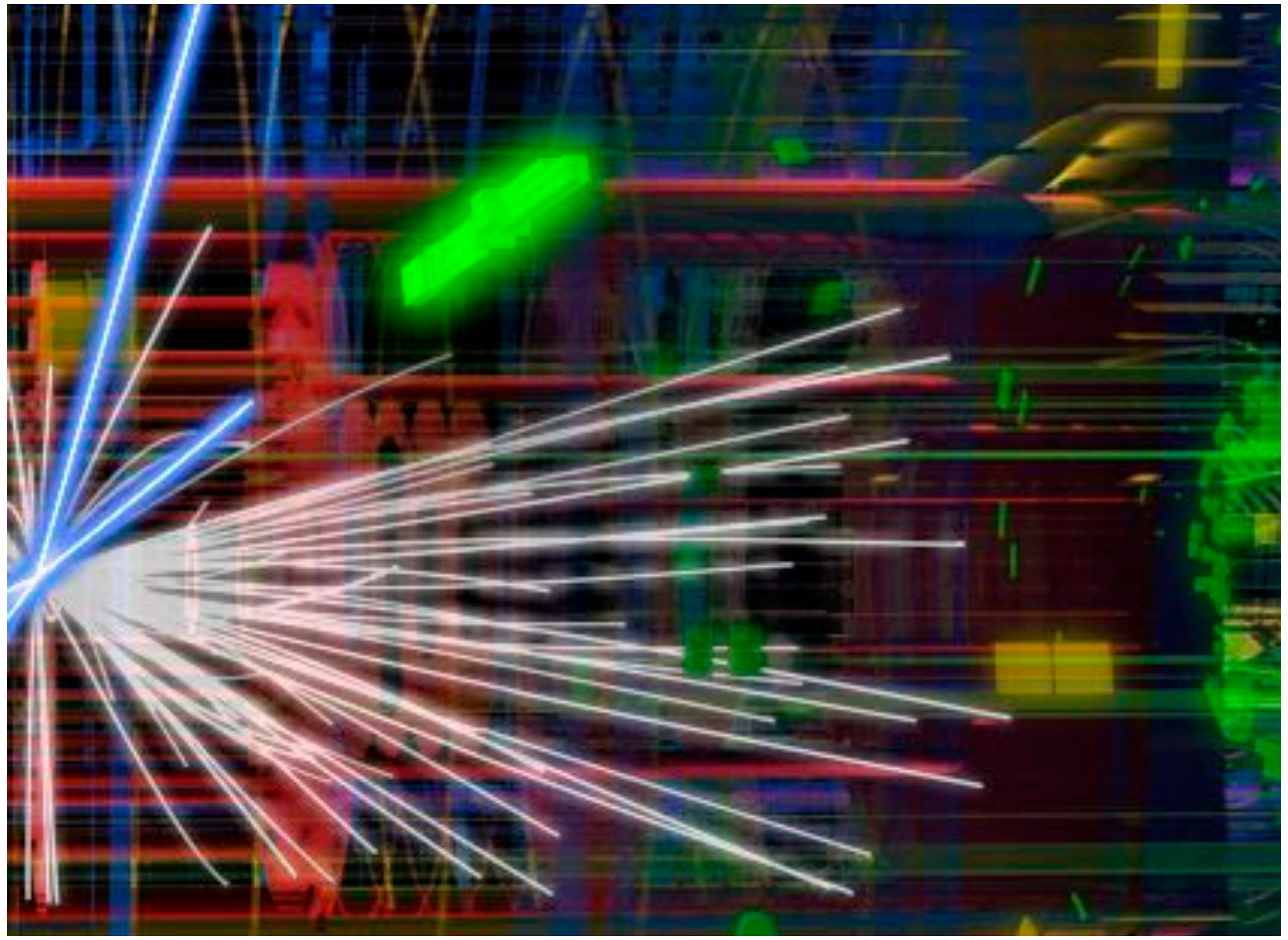






QCD Parton Shower [parton = quark or gluon]





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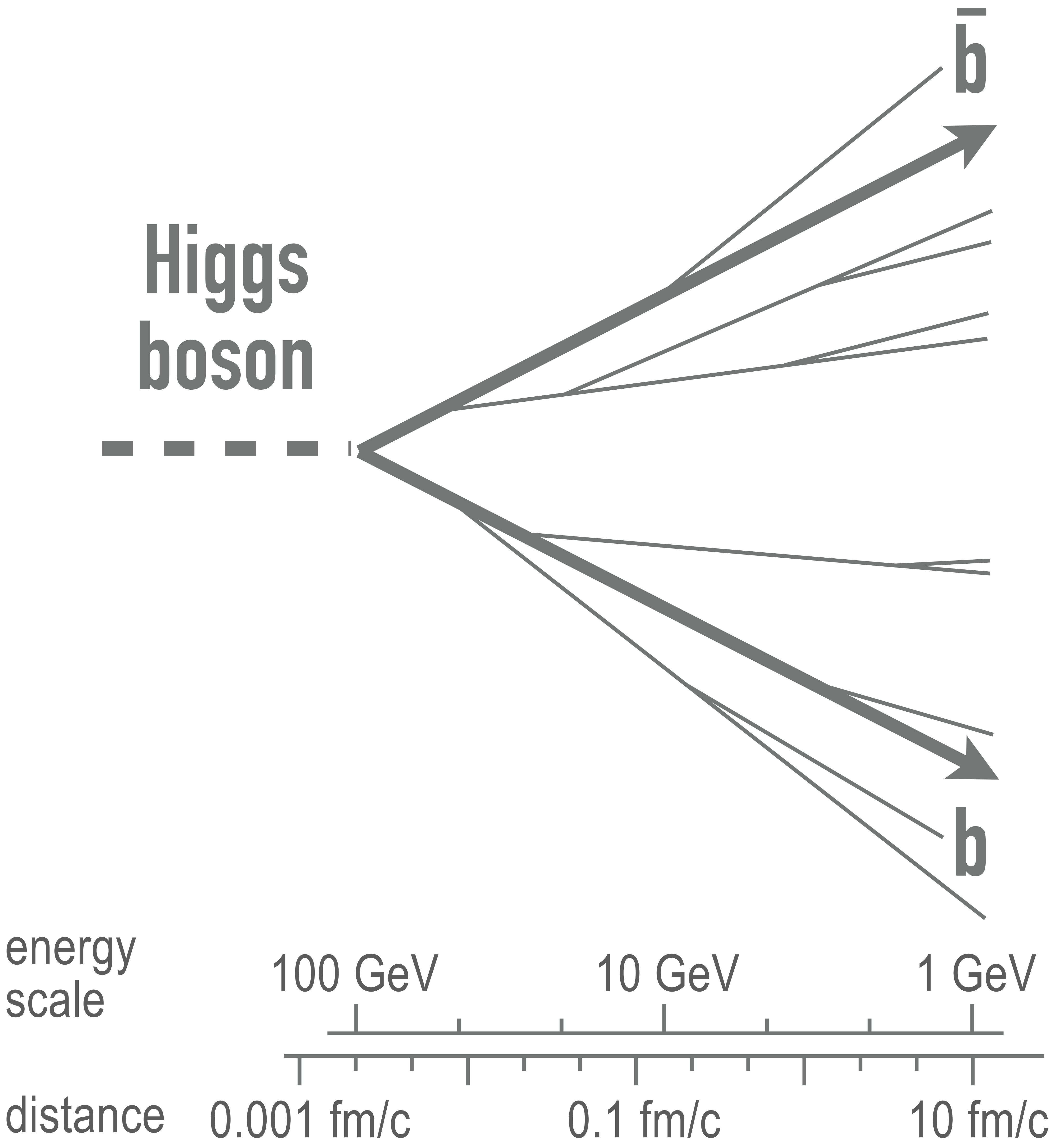
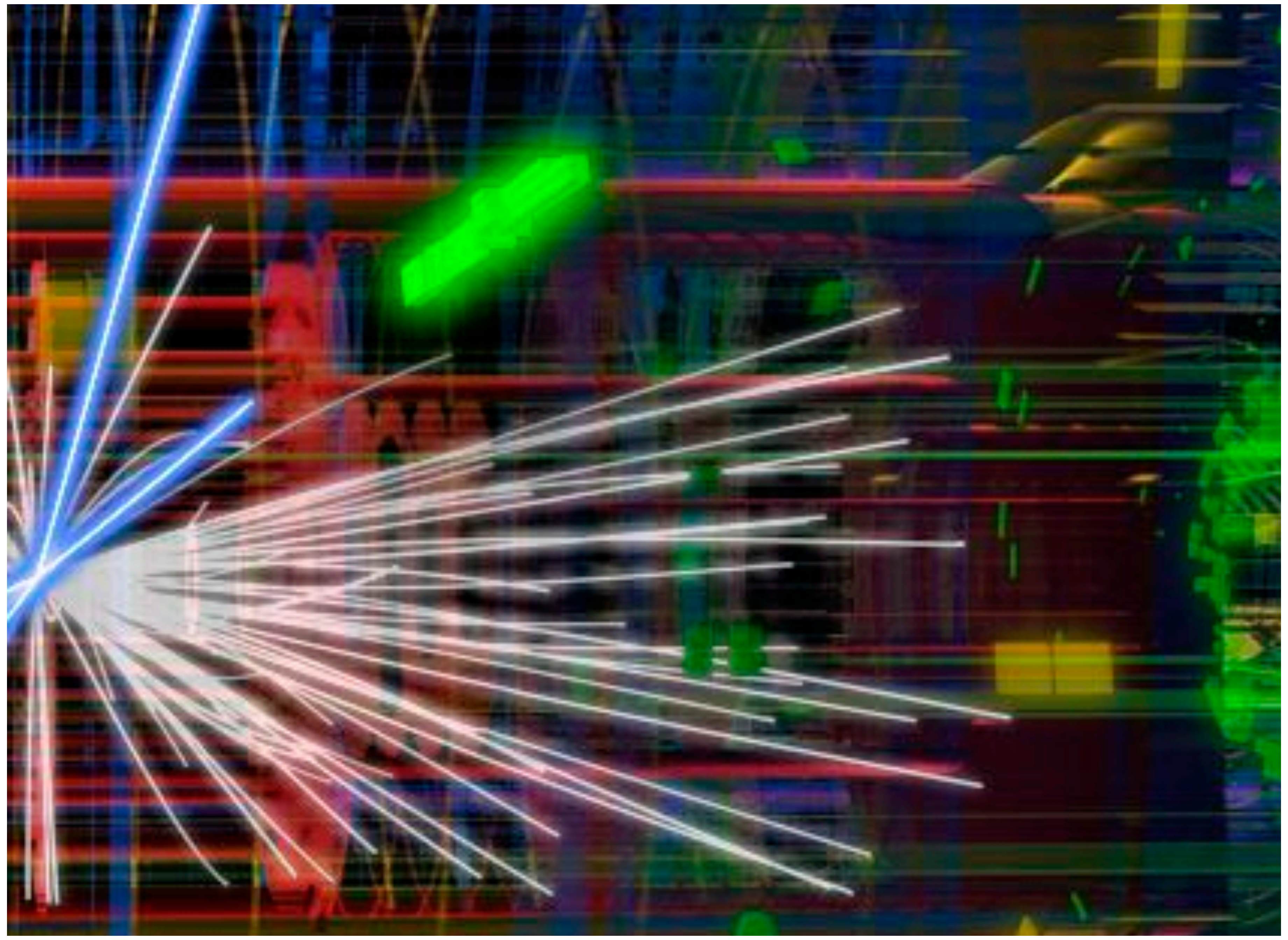
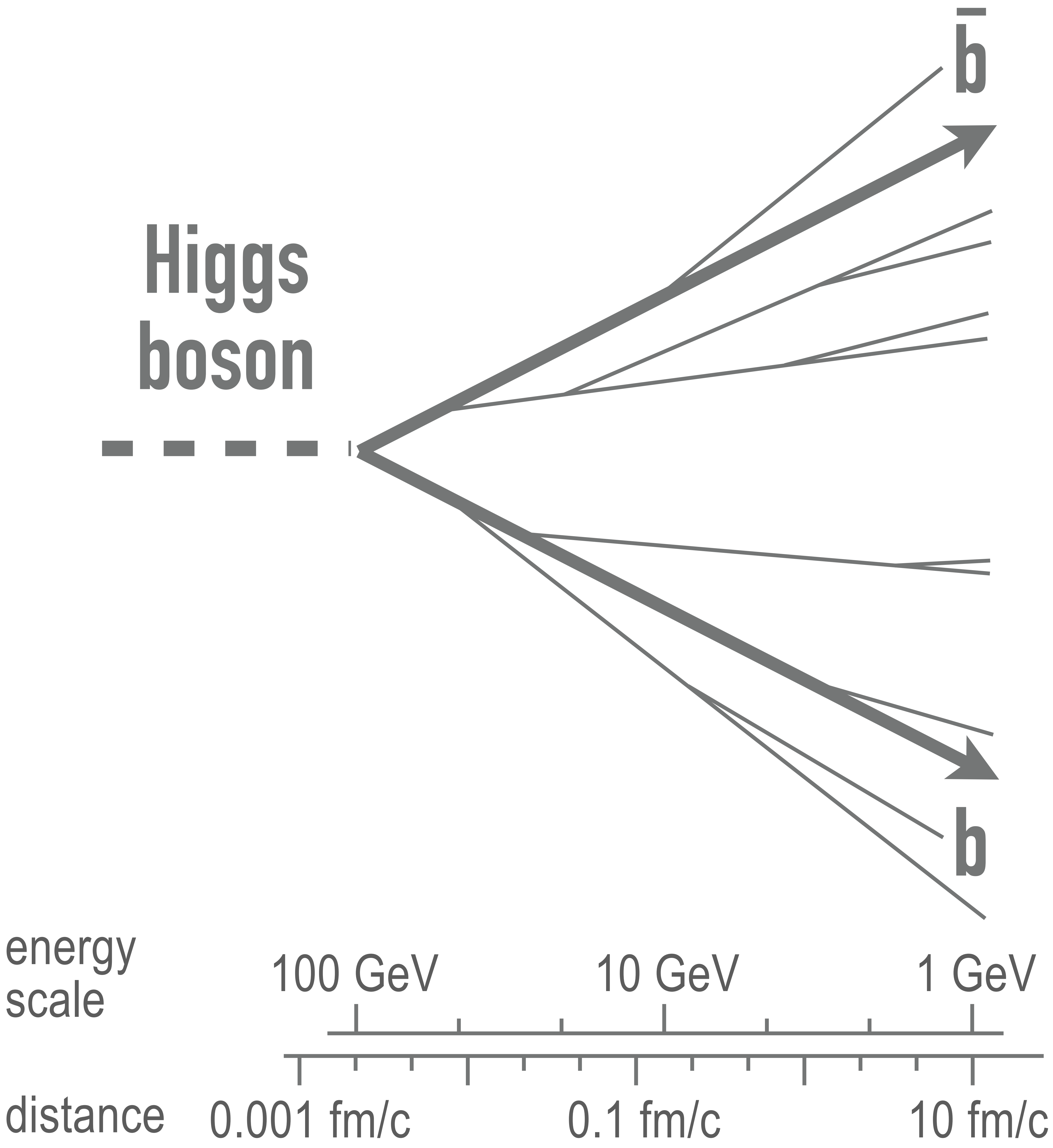




QCD Parton Shower [parton = quark or gluon]

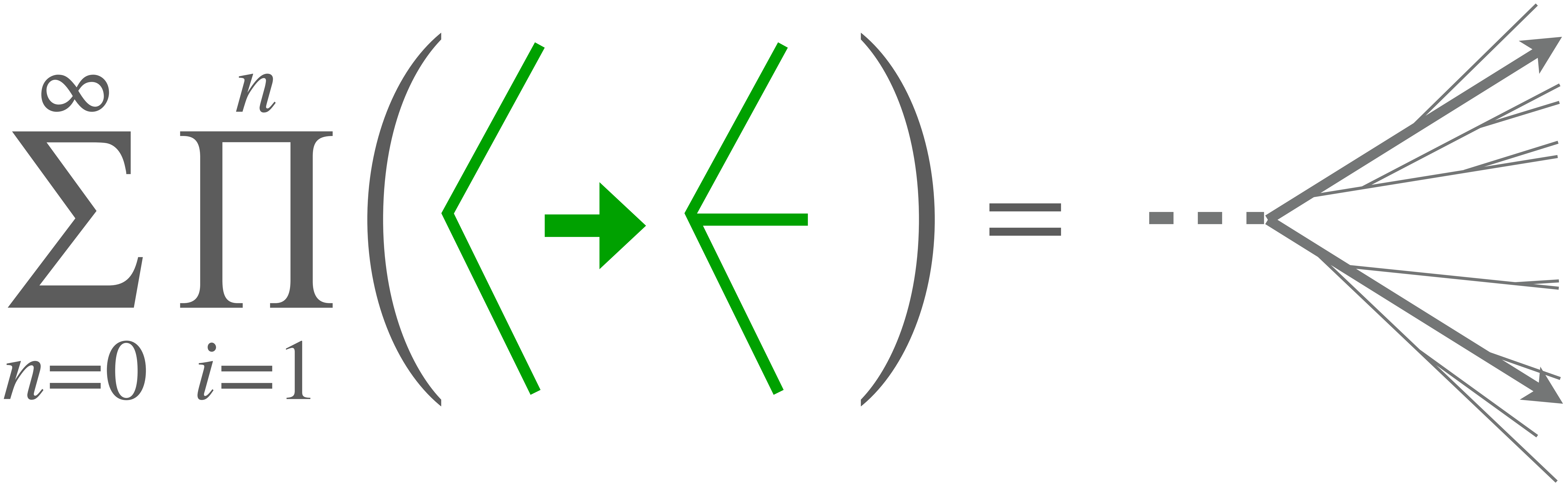


Pattern of branching usually simulated with a **Monte Carlo Parton Shower algorithm**

Experiments **always compare data to Monte Carlo simulations** to establish fundamental hypotheses

Little is known about their robustness & accuracy of multi-scale properties of these simulations:
a weak link in the chain

Parton shower = iteration of 2→3 (or 1→2) splitting kernel



- in what sense should the distribution of final n-particle states be correctly described?
- can it even be correctly described, and with what constraints on the splitting kernels?

Dasgupta, Dreyer, Hamilton, Monni & GPS, JHEP 1809 (2018) 033

and topic of “PanScales” ERC project

closing

> I personally expect supersymmetry to be discovered at the LHC

-a Nobel prize-winning theorist [2008]

http://cerncourier.com/cws/article/cern/35456

The New York Times

Opinion

GRAY MATTER

A Crisis at the Edge of Physics

By Adam Frank and Marcelo Gleiser

June 5, 2015

“the standard model, despite the glory of its vindication, is also a dead end. It offers no path forward […]”

The New York Times

Opinion

GRAY MATTER

A Crisis at the Edge of Physics

By Adam Frank and Marcelo Gleiser

June 5, 2015

I disagree.

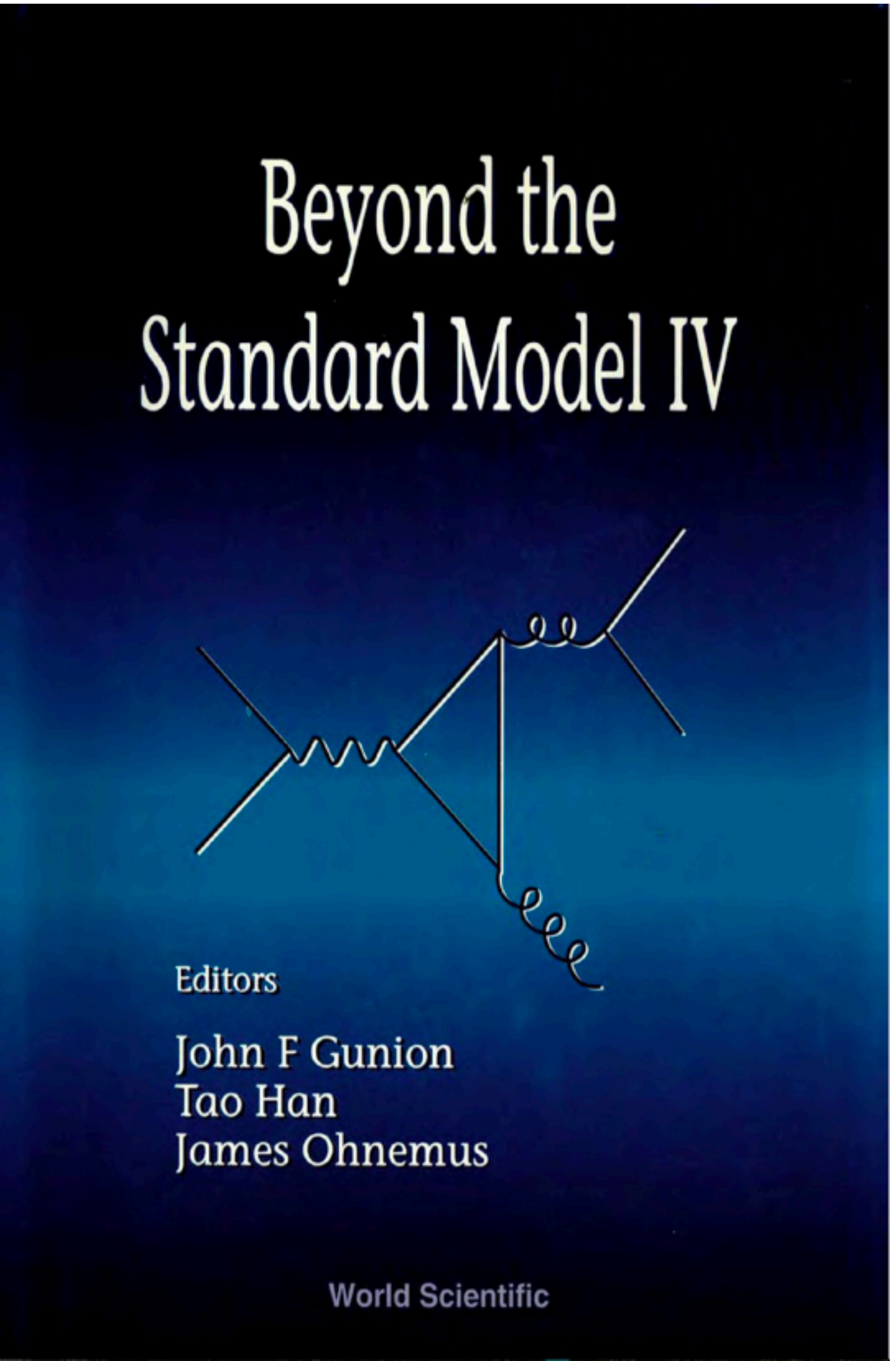
Because the non-gauge part of the standard model is far from being fullly explored.

3 Yukawas out of 9

We know nothing about the self coupling

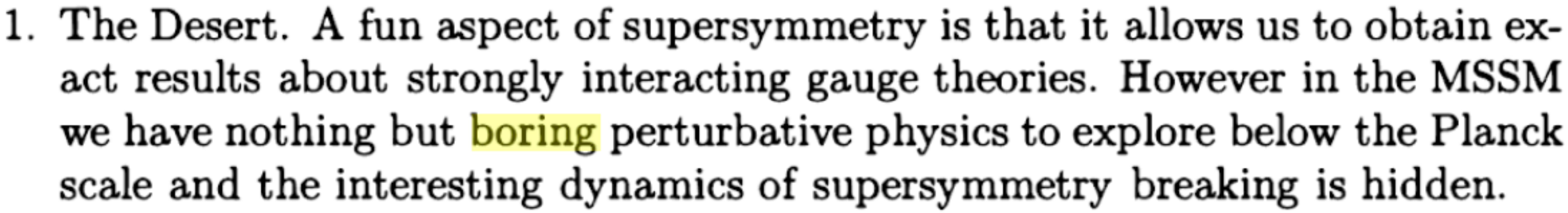
“the standard model, despite the glory of its vindication, is also a dead end. It offers no path forward […]”

it would be so much more exciting if we'd discovered new physics, right?



not everyone would agree

Back in 1995:



1. The Desert. A fun aspect of supersymmetry is that it allows us to obtain exact results about strongly interacting gauge theories. However in the MSSM we have nothing but boring perturbative physics to explore below the Planck scale and the interesting dynamics of supersymmetry breaking is hidden.

we must not underestimate our ignorance about the Higgs sector, nor the value of exploring and establishing it

e.g. accessing Yukawa couplings beyond the 3rd generation,

the triple-Higgs coupling → Higgs-field potential, SM keystone,

& the pathway from discovery to precision

meanwhile, the search for new physics continues

with much scope for inventing ingenious search techniques, identifying novel models that could be probed

(And finding other things to do with the particles we have)

searches, Higgs & other SM physics share in common

the need to think about how we relate the
underlying Lagrangian of particle physics
with observations of $\sim 10^{16}$ *high-energy proton collisions*