Higgs and the new fundamental interactions

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European Research Council
Established by the European Commission
THE ROYAL SOCIETY

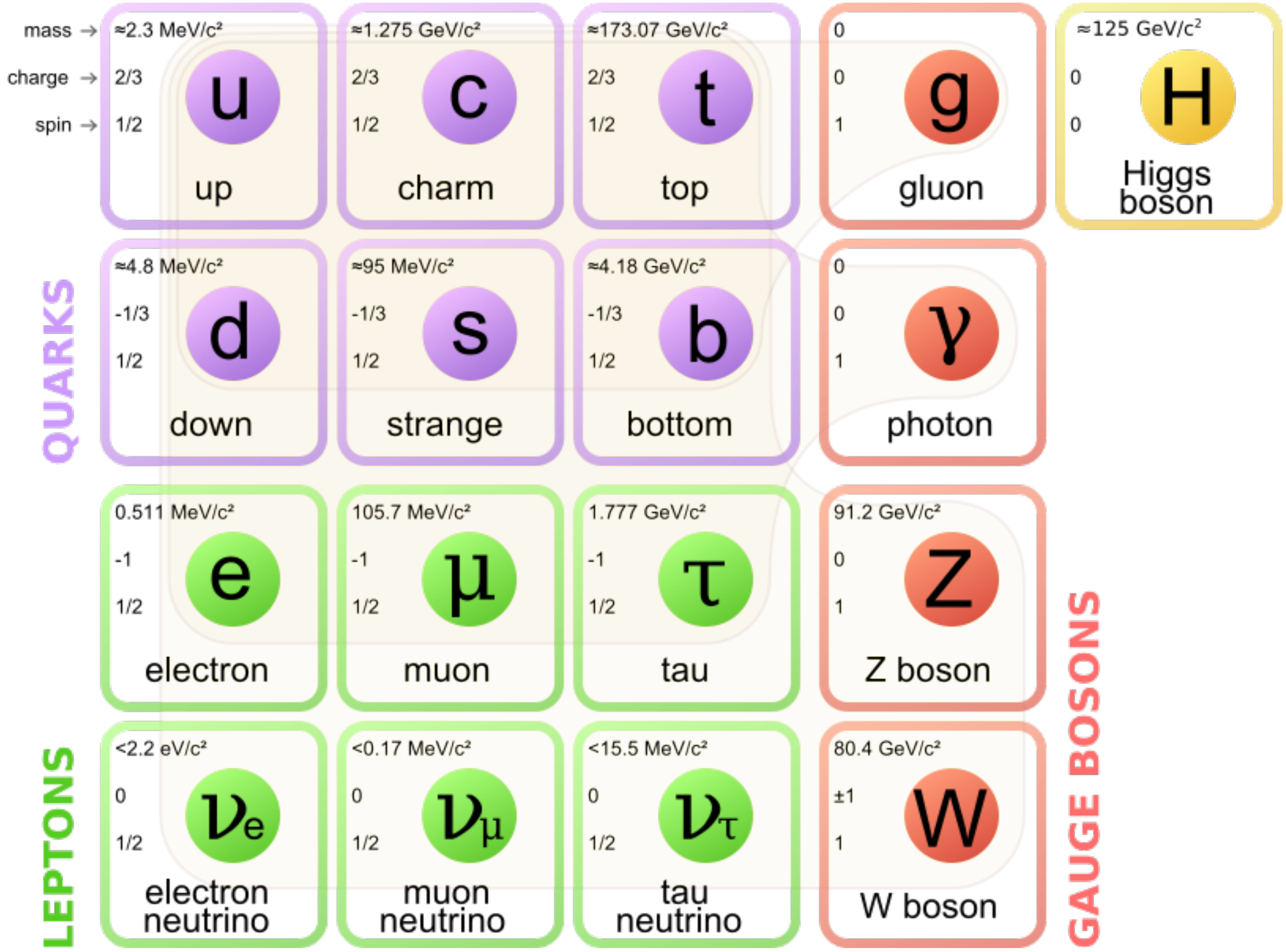
RAL particle physics department seminar
5 August 2020

“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



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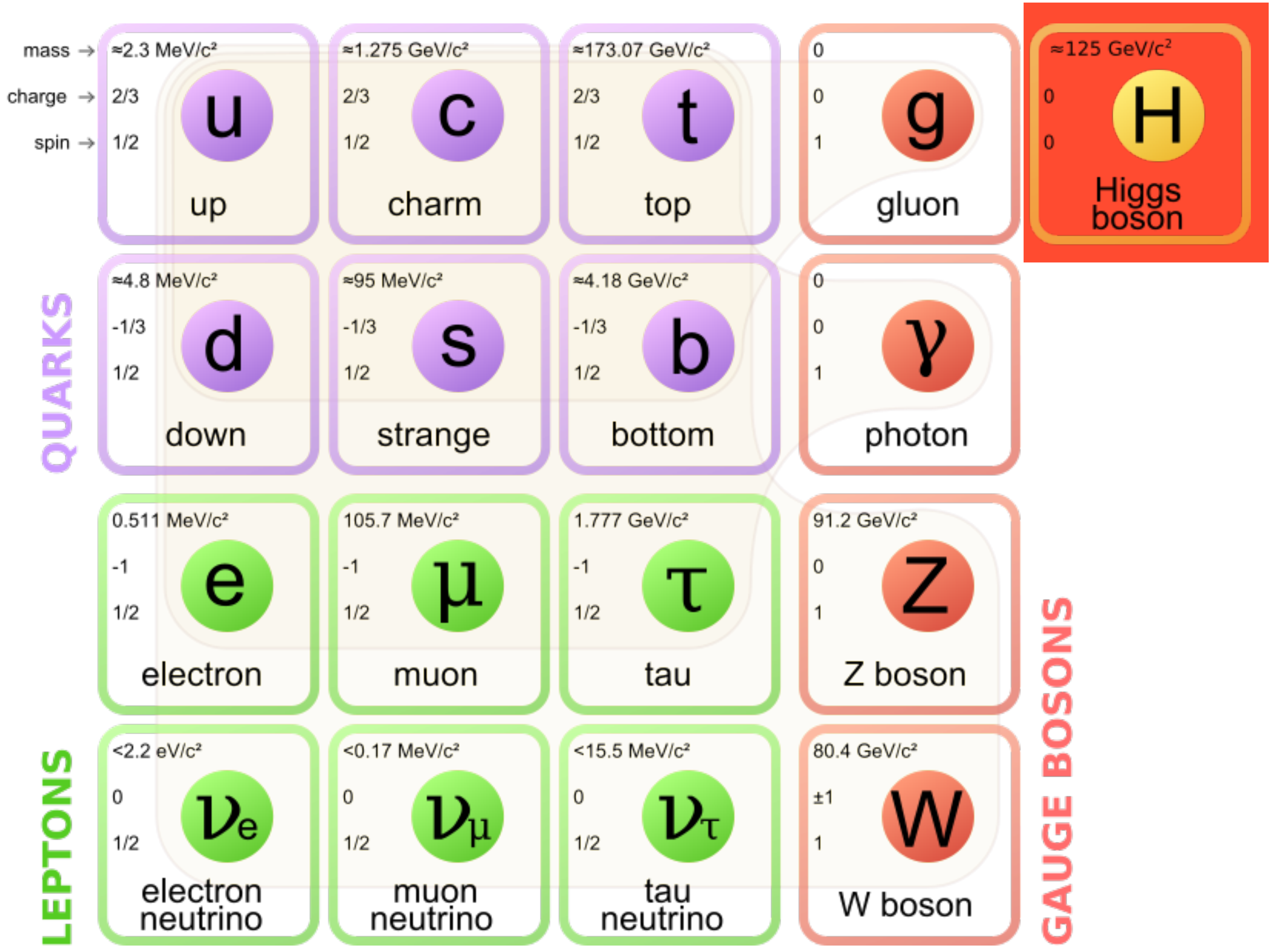
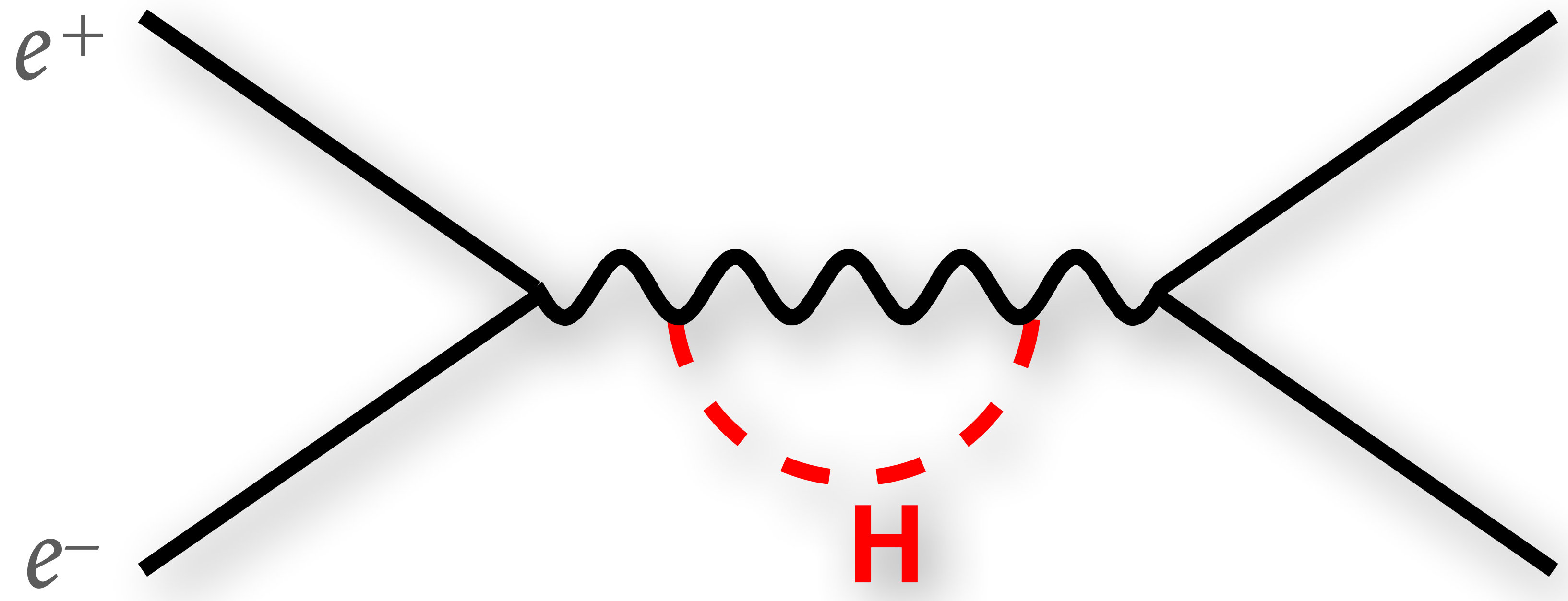
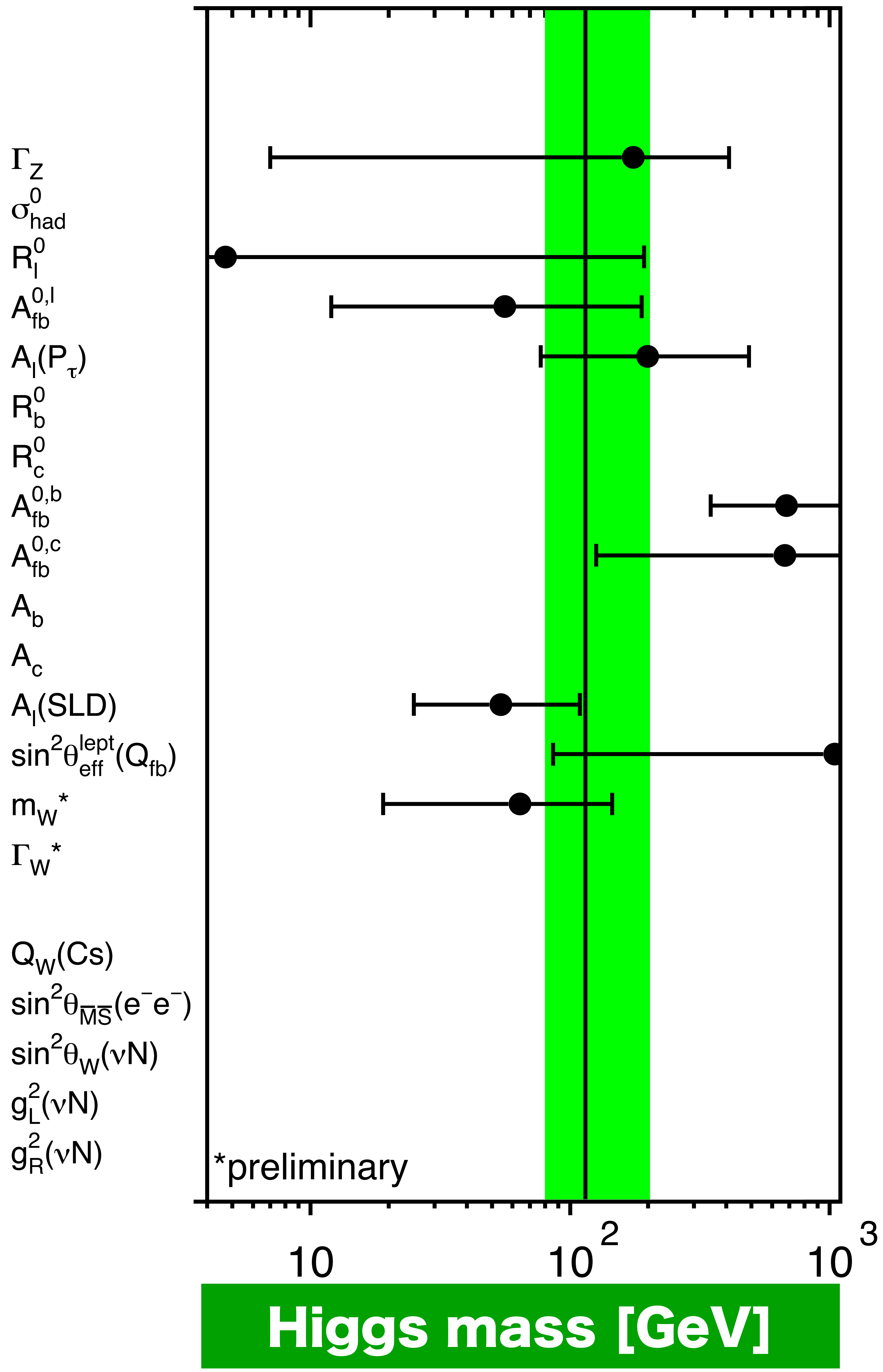




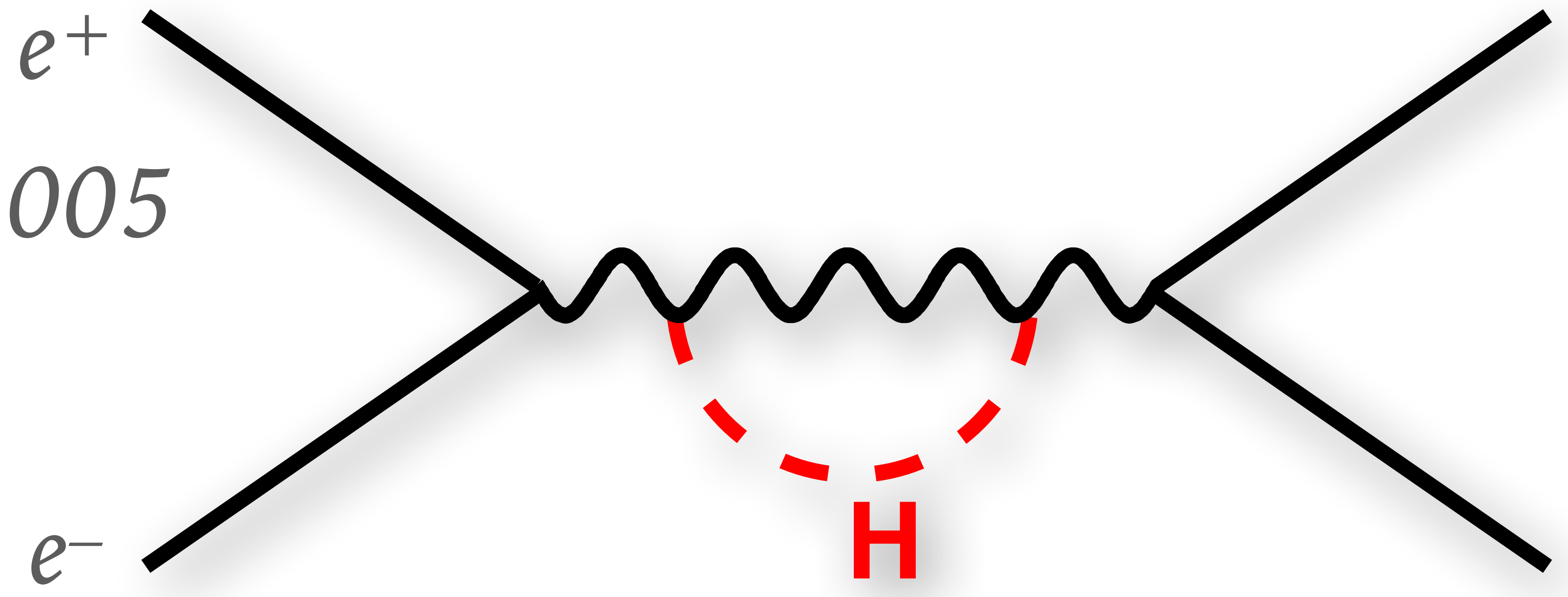
Higgs boson existence long known to be consistent with older e^+e^- collider data (cf. LEP, 1989–2000 + SLD).

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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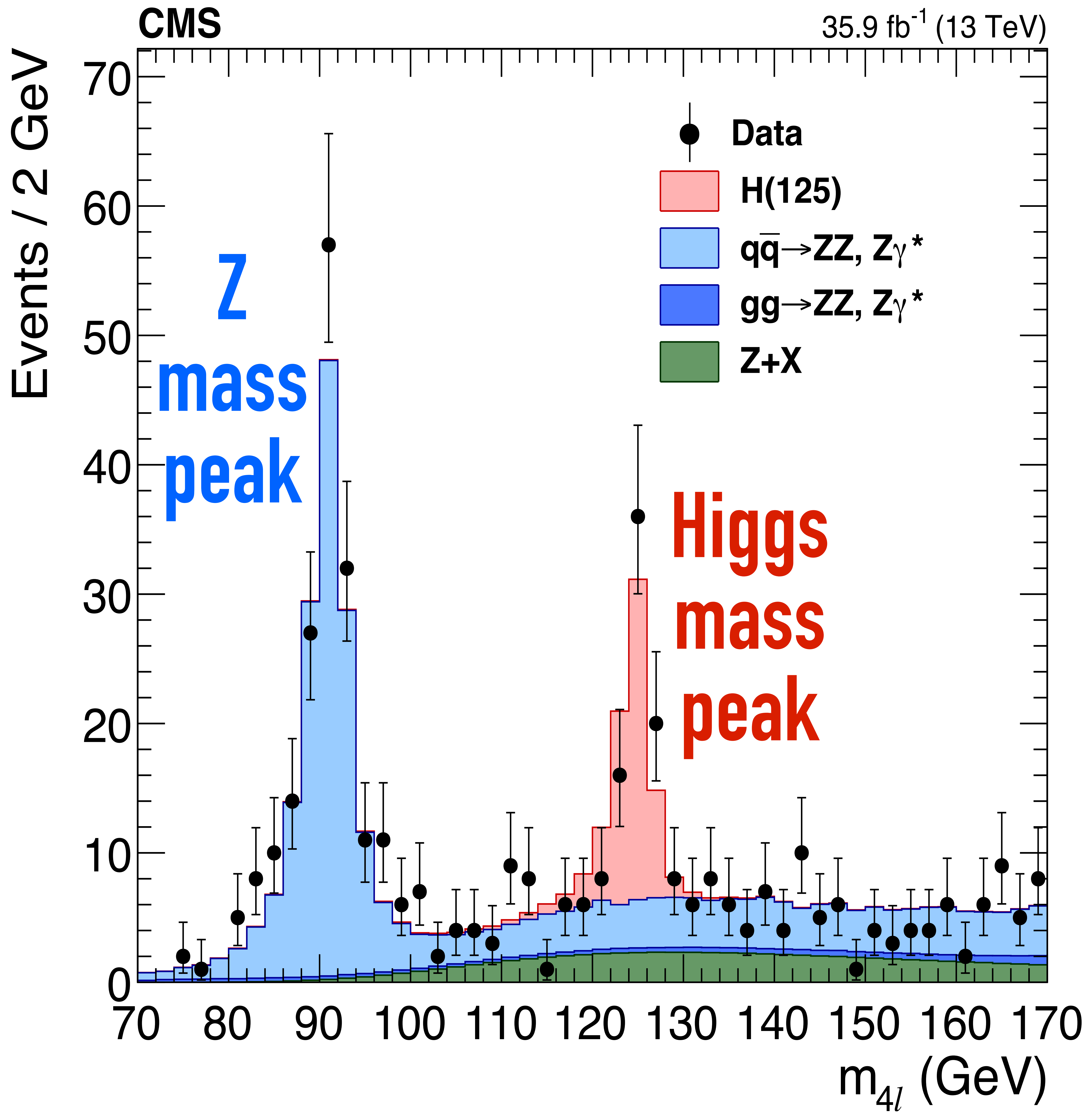
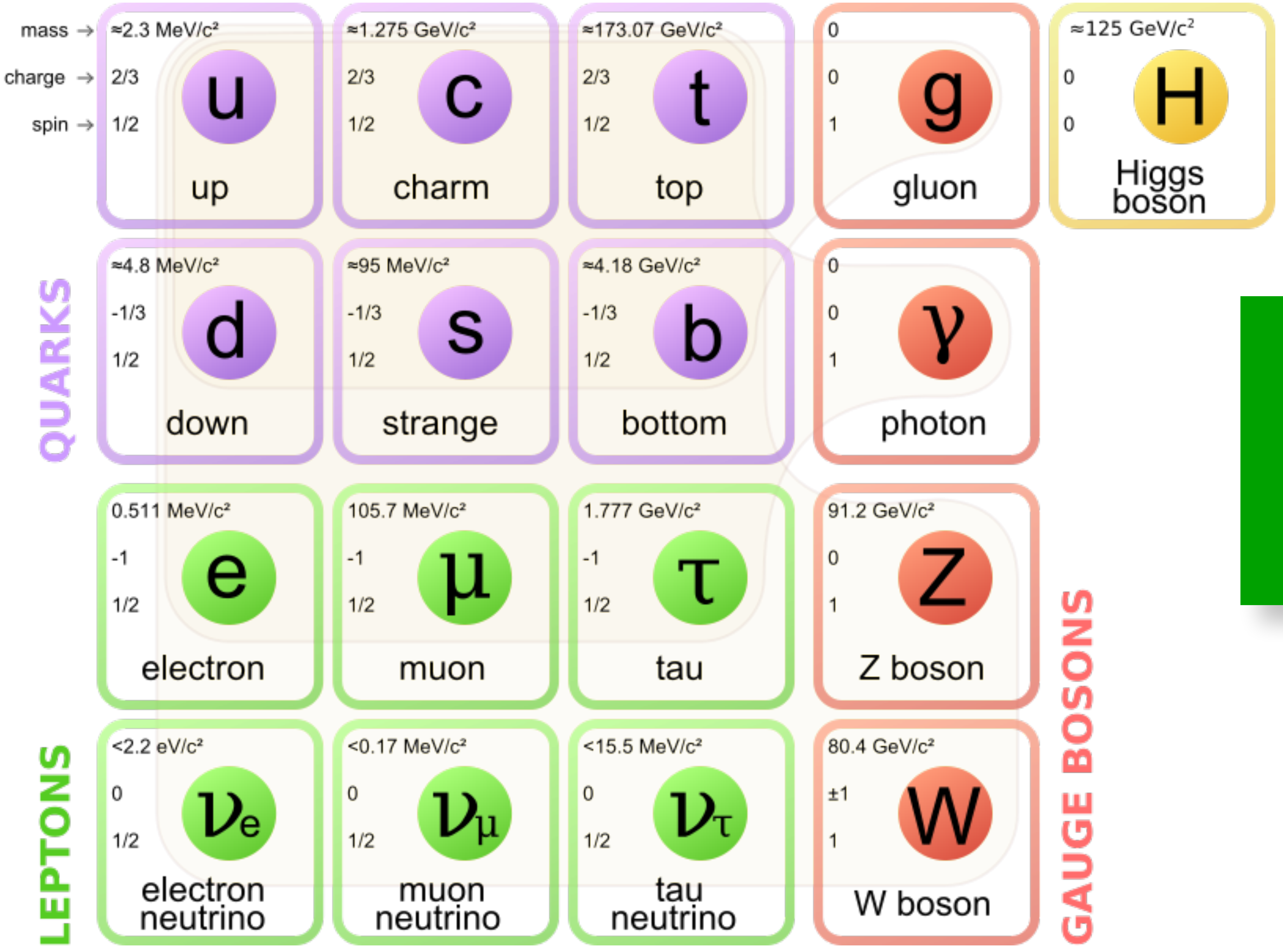


ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC):

2012 discovery of a Higgs-like boson

plot shows more recent data

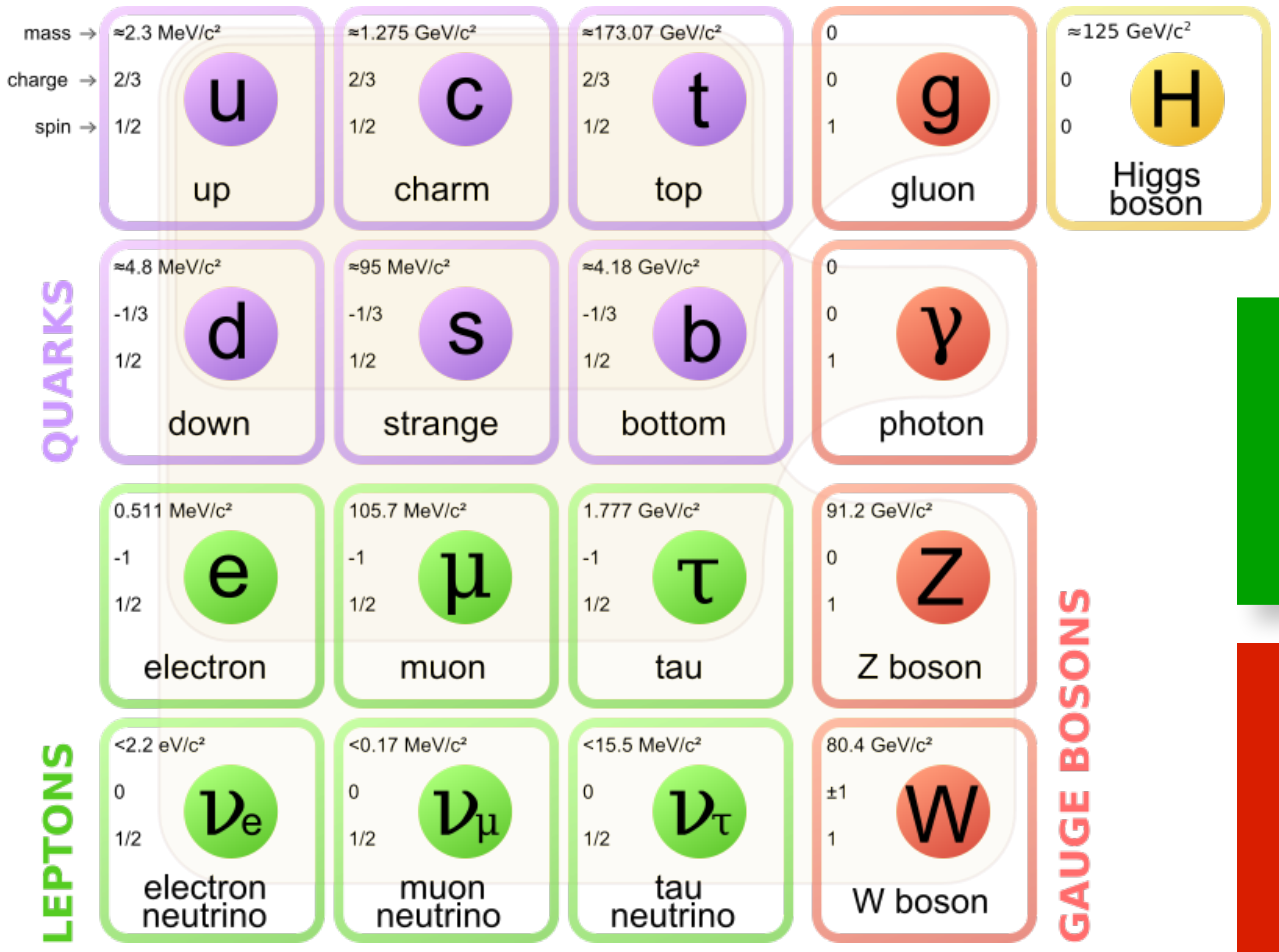
The Higgs boson (2012)



Success!

"The Standard Model is complete"

The Higgs boson (2012)



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

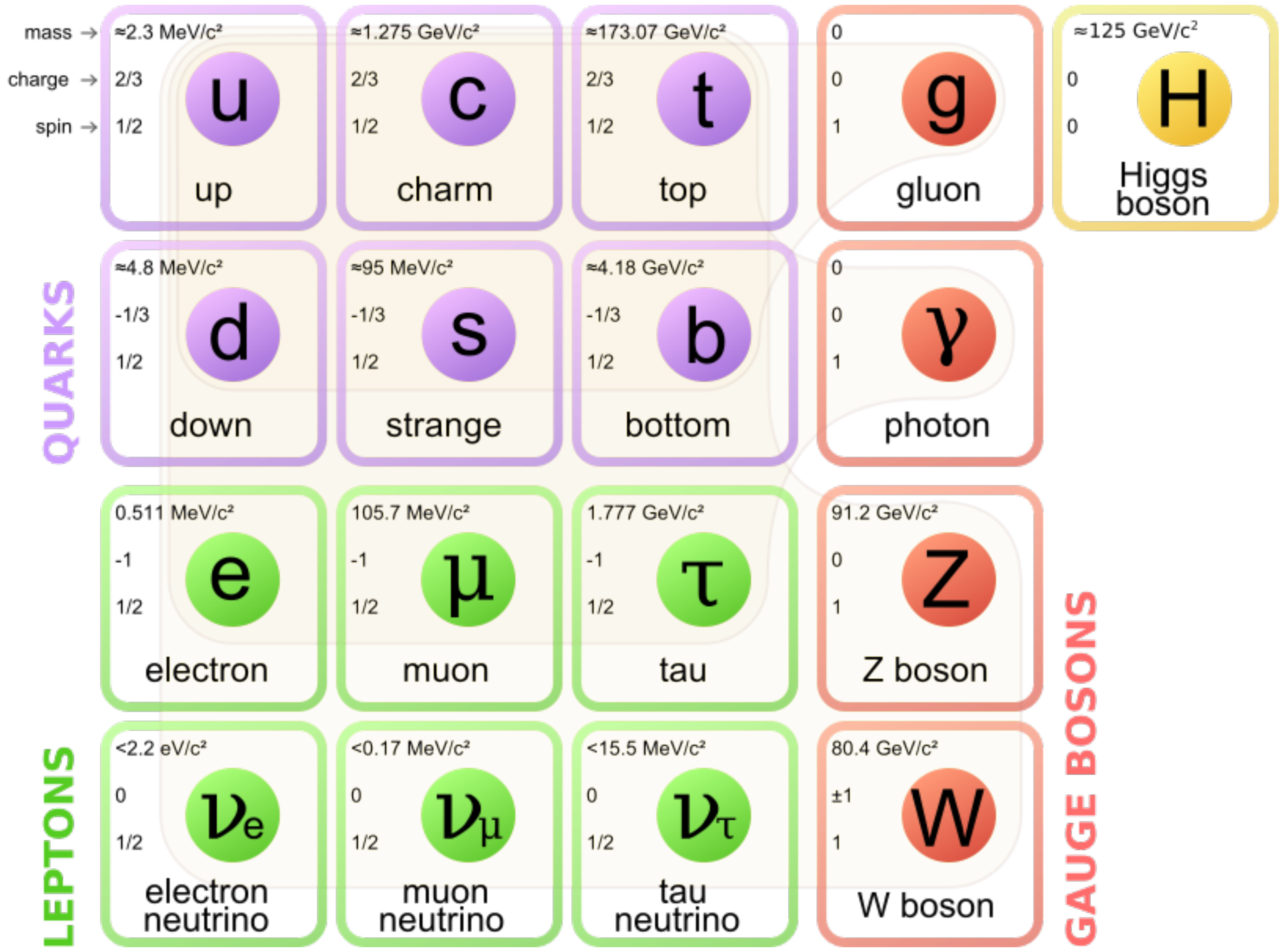
[…]

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

[…]

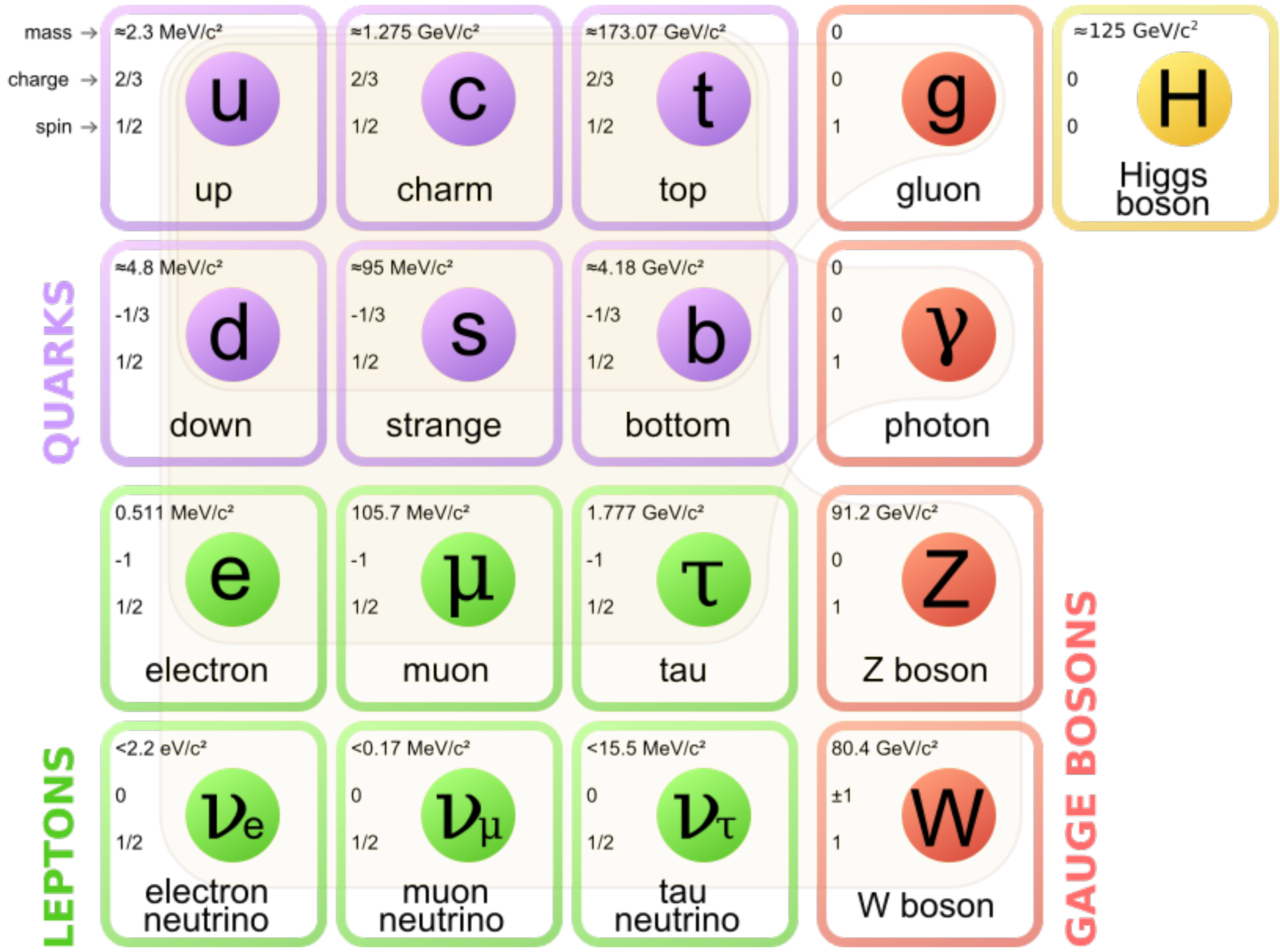
https://www.nytimes.com/2017/06/19/science/cern-large-hadron-collider-higgs-physics.html

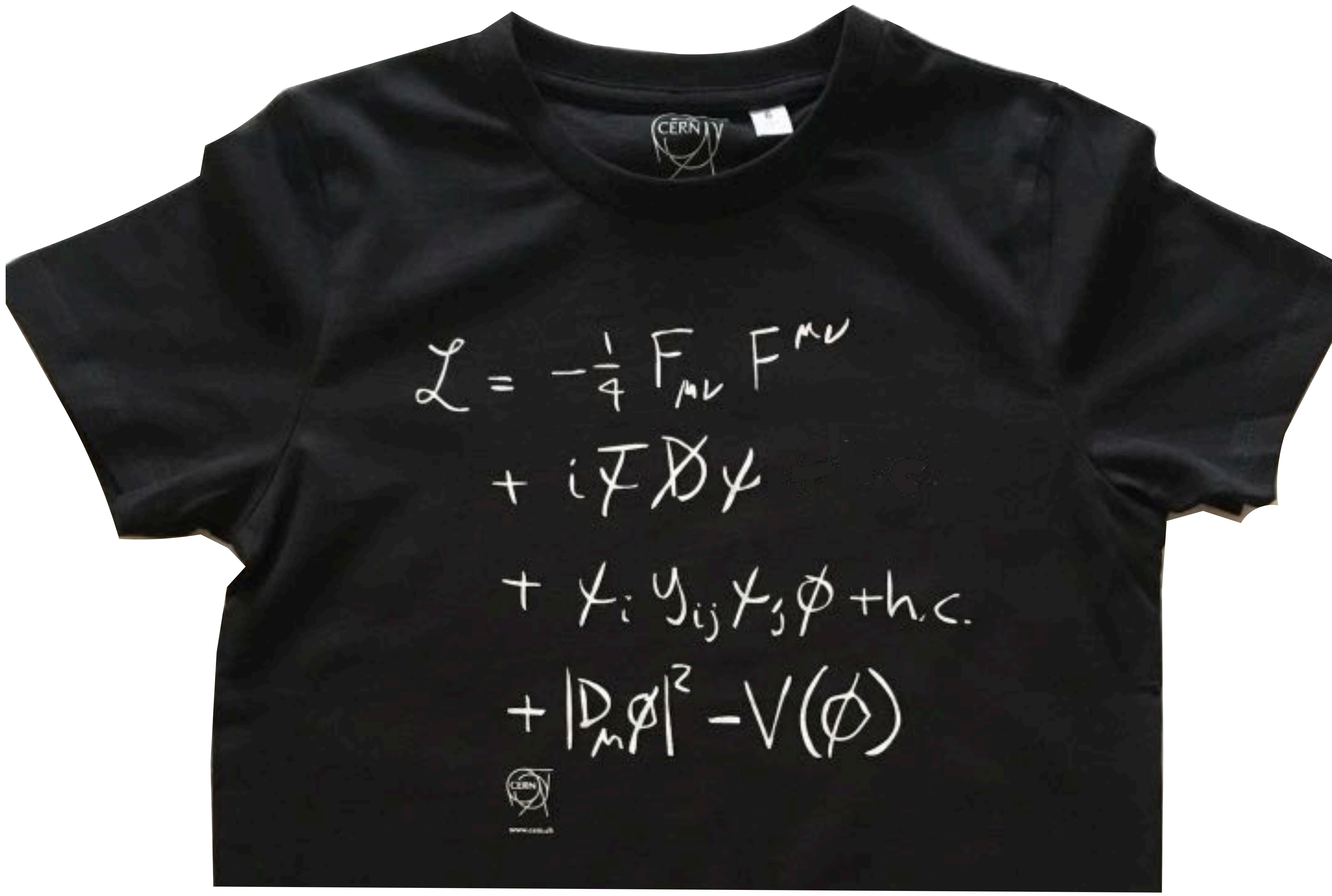
what is the Standard Model?



particles

what is the Standard Model?





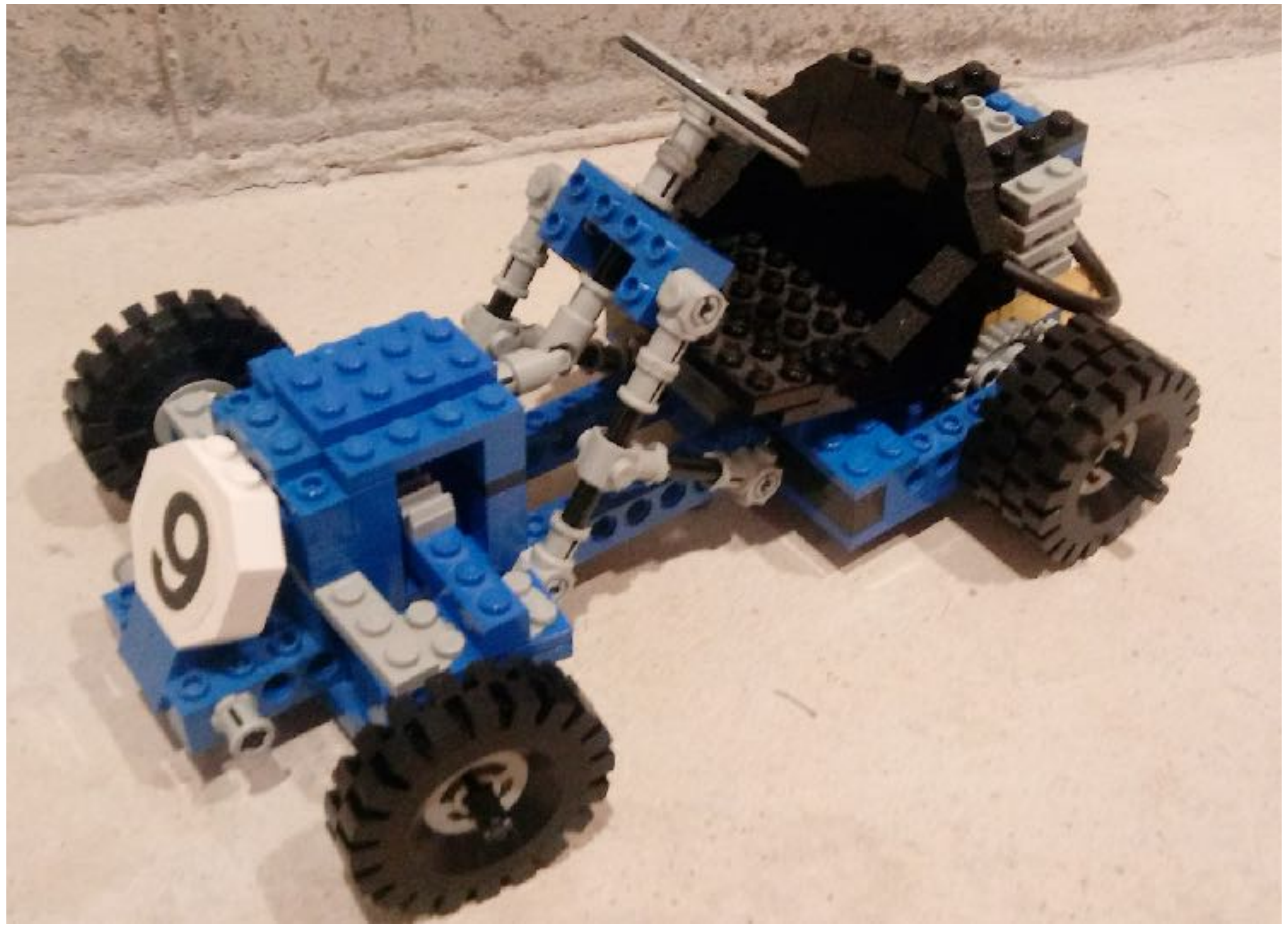
particles

interactions

particles

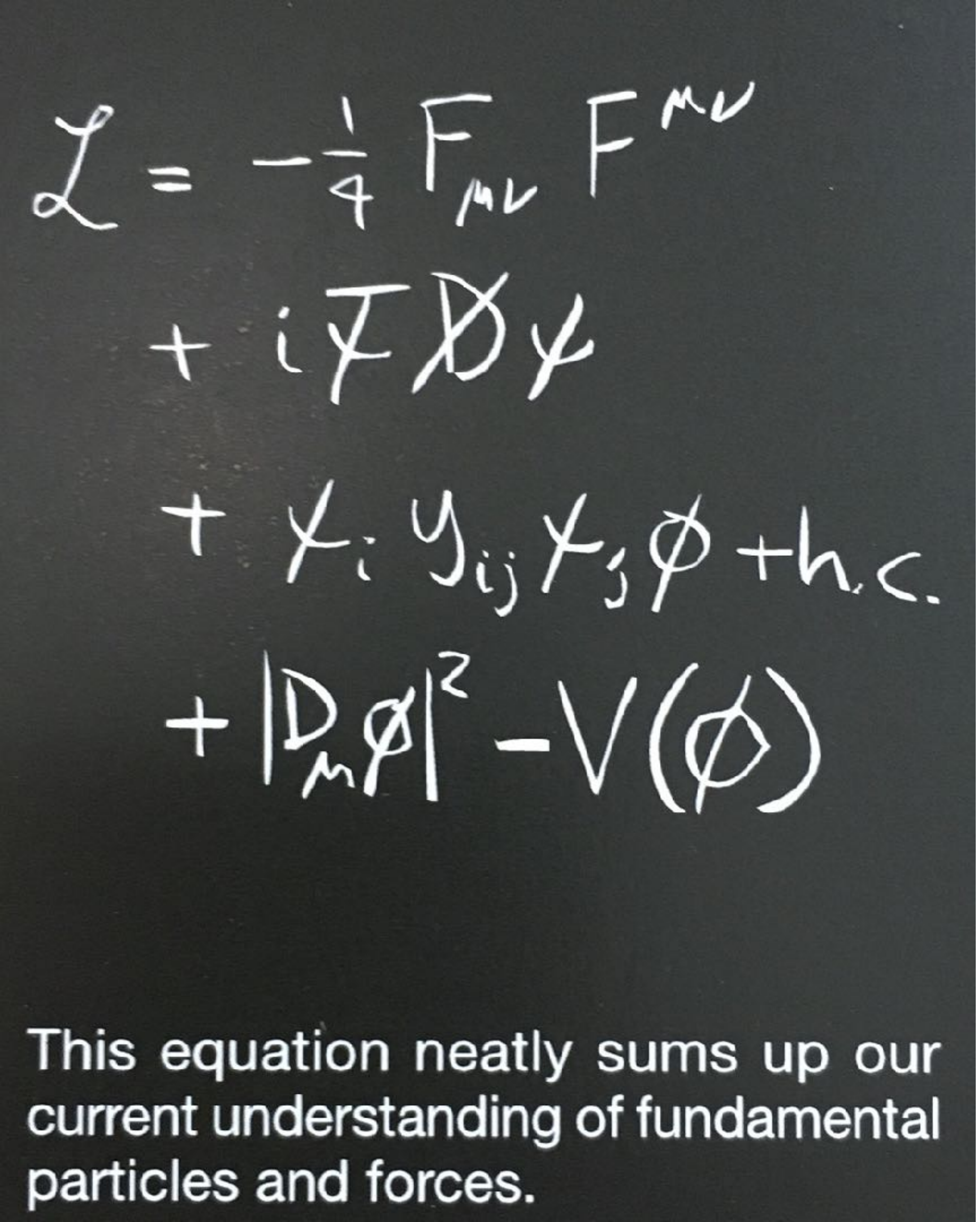
https://www.piqsels.com/en/public-domain-photo-fqrgz

particles + interactions

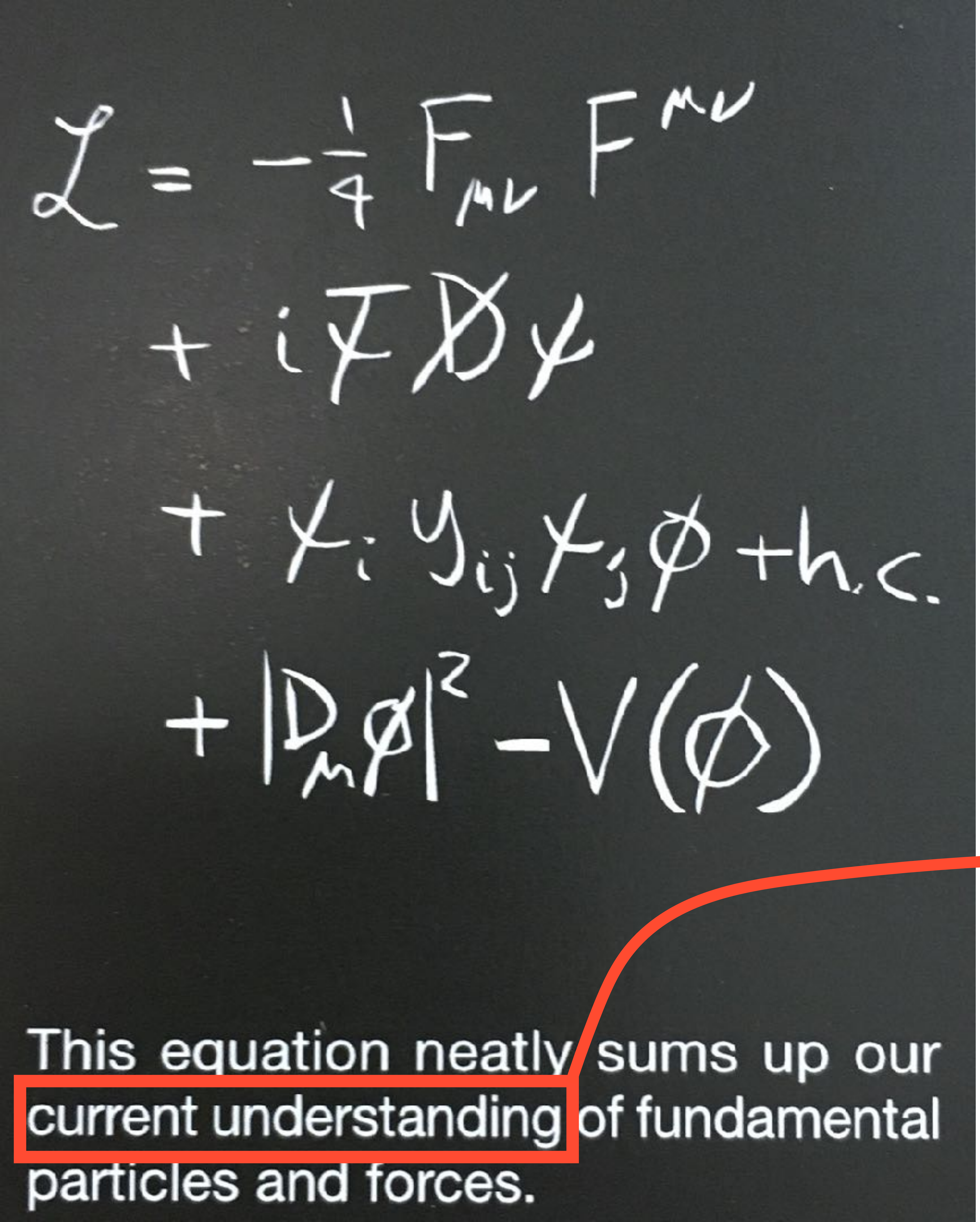


https://commons.wikimedia.org/wiki/File:LEGO_Expert_Builder_948_Go-Kart.jpg, CC-BY-SA-4.0

Standard Model — knowable unknowns



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

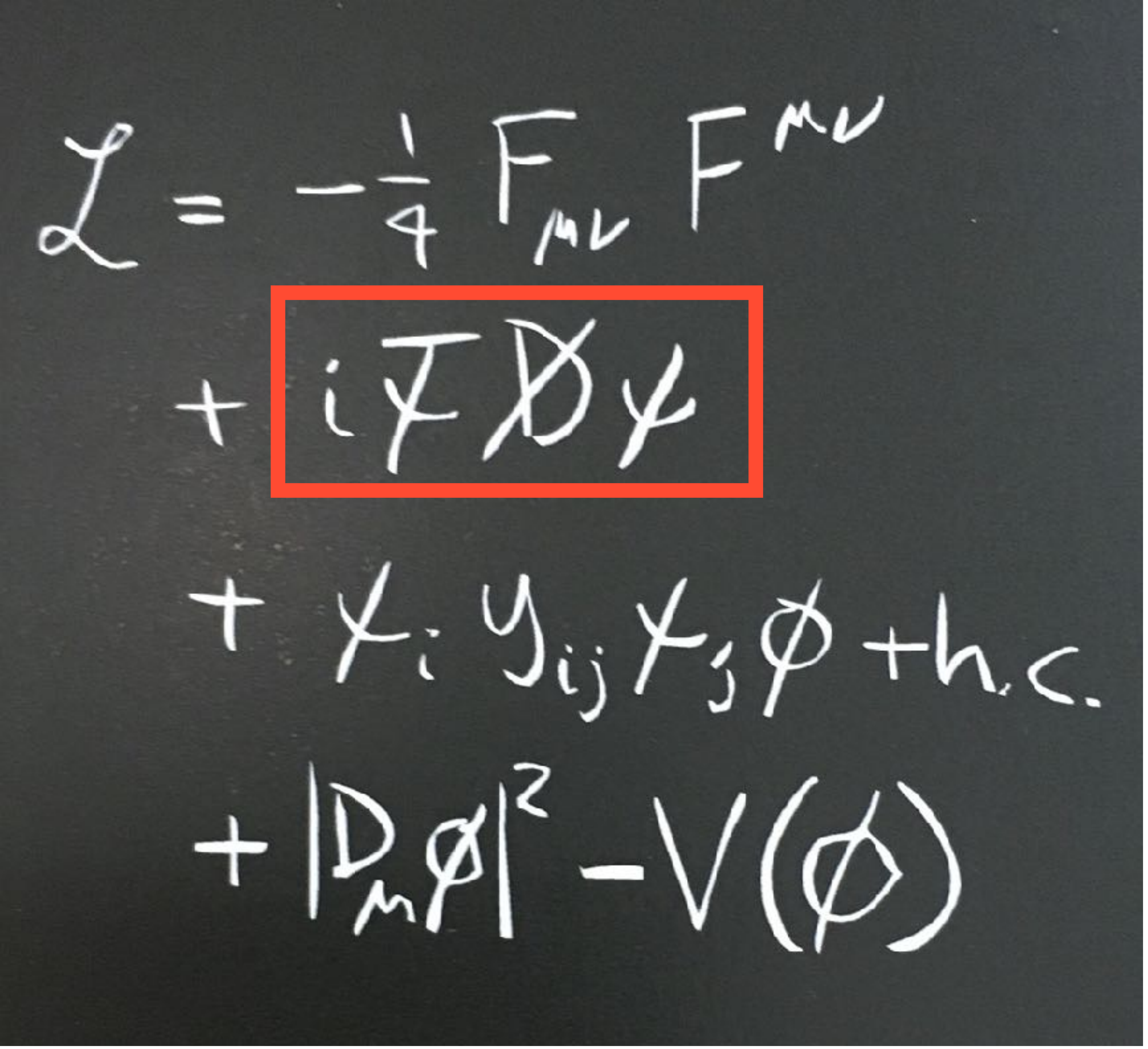


This is what you get when you buy one of those famous CERN T-shirts

“understanding” = knowledge ?

“understanding” = assumption ?

Notation



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

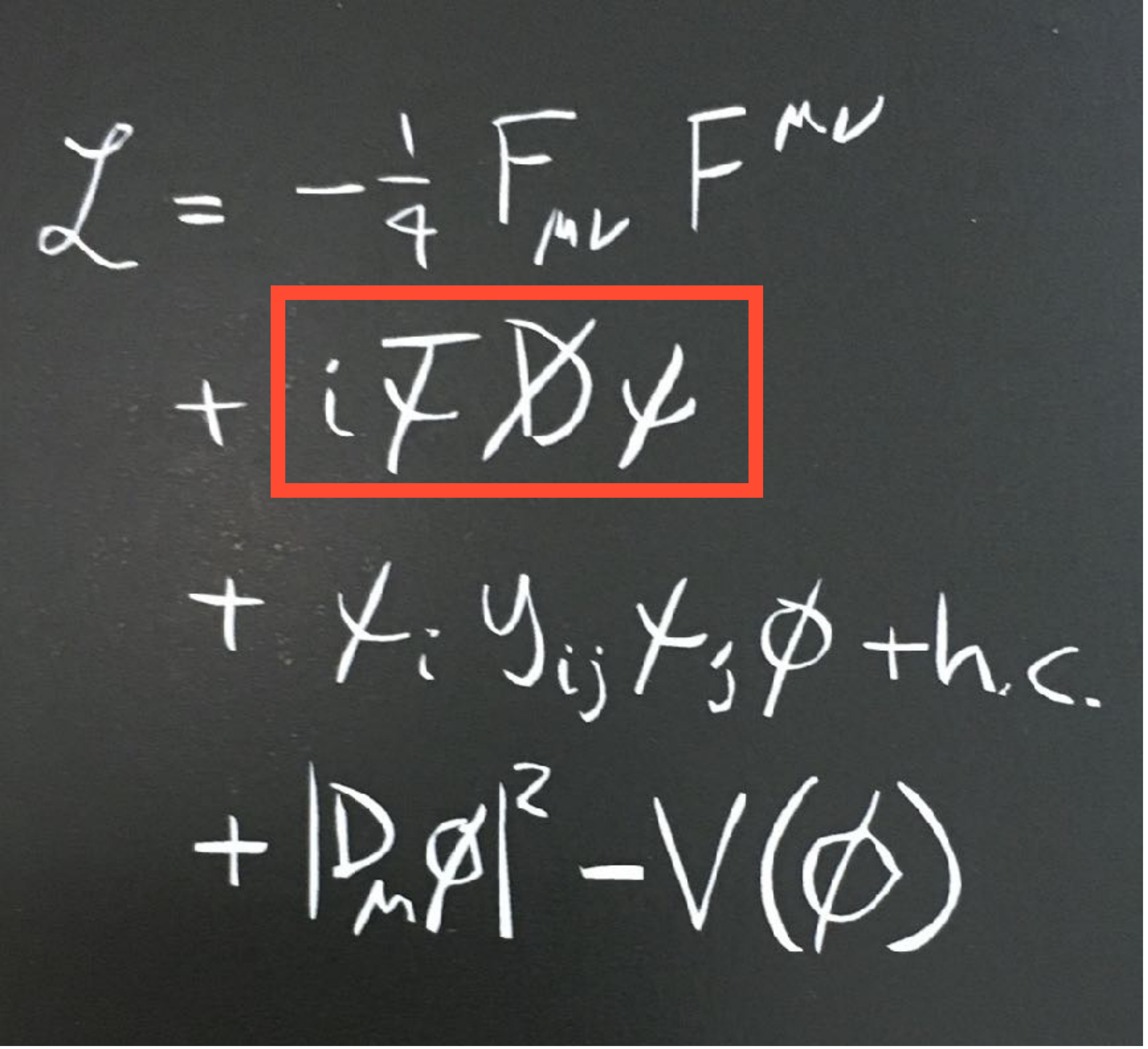
ψ : fermion field — *quarks & leptons*

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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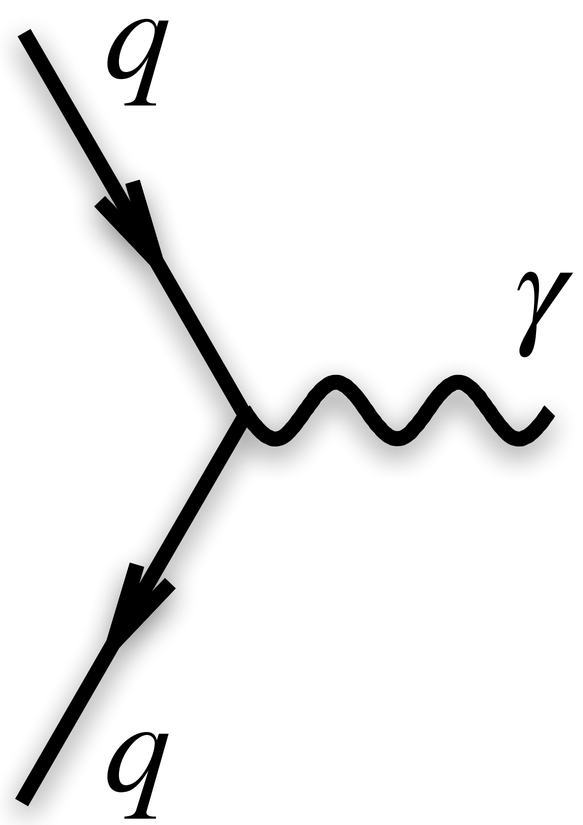
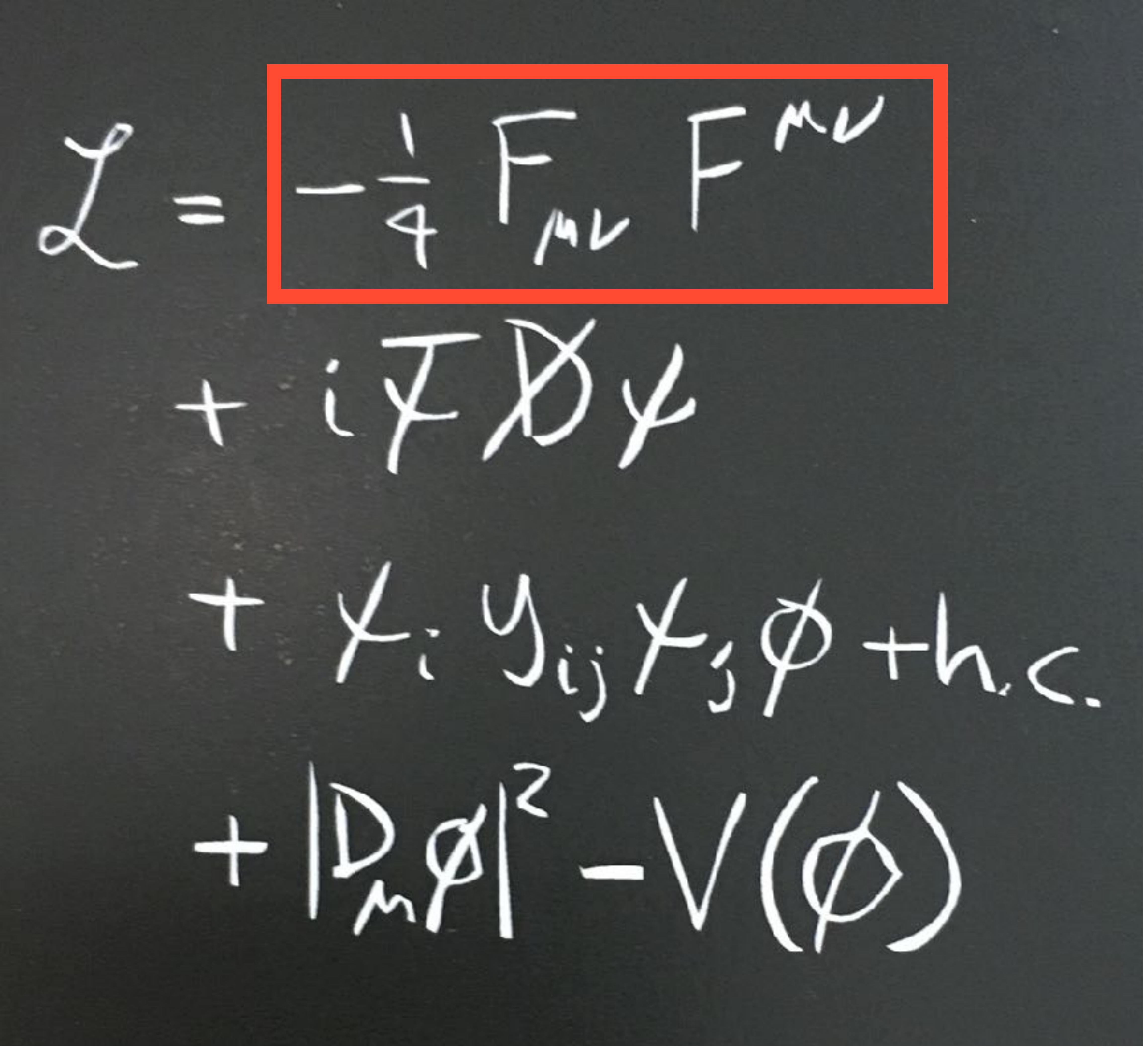


e.g. $\bar{\psi} D \psi \rightarrow \psi A_\mu \psi \rightarrow$ fermion-fermion-gauge vertex

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



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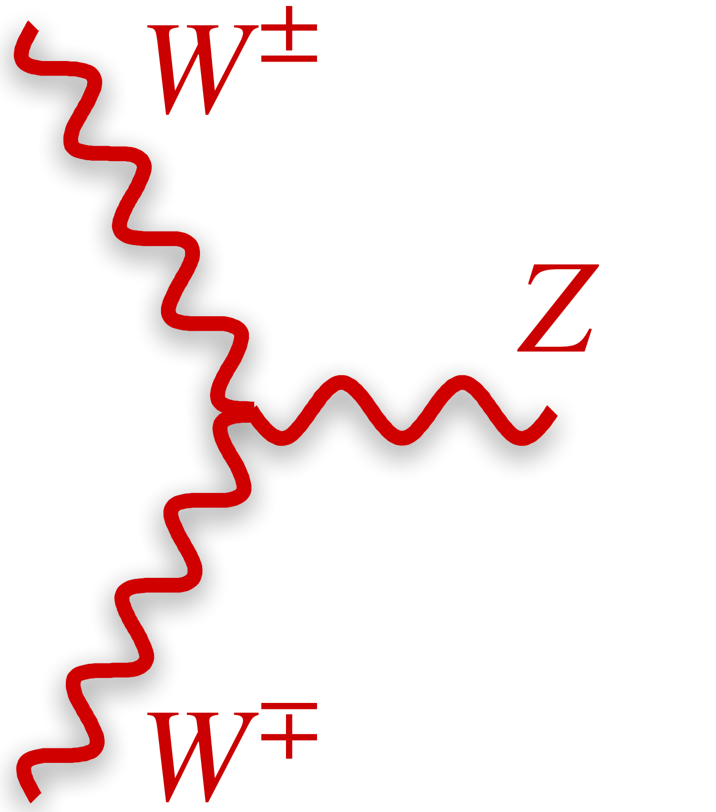
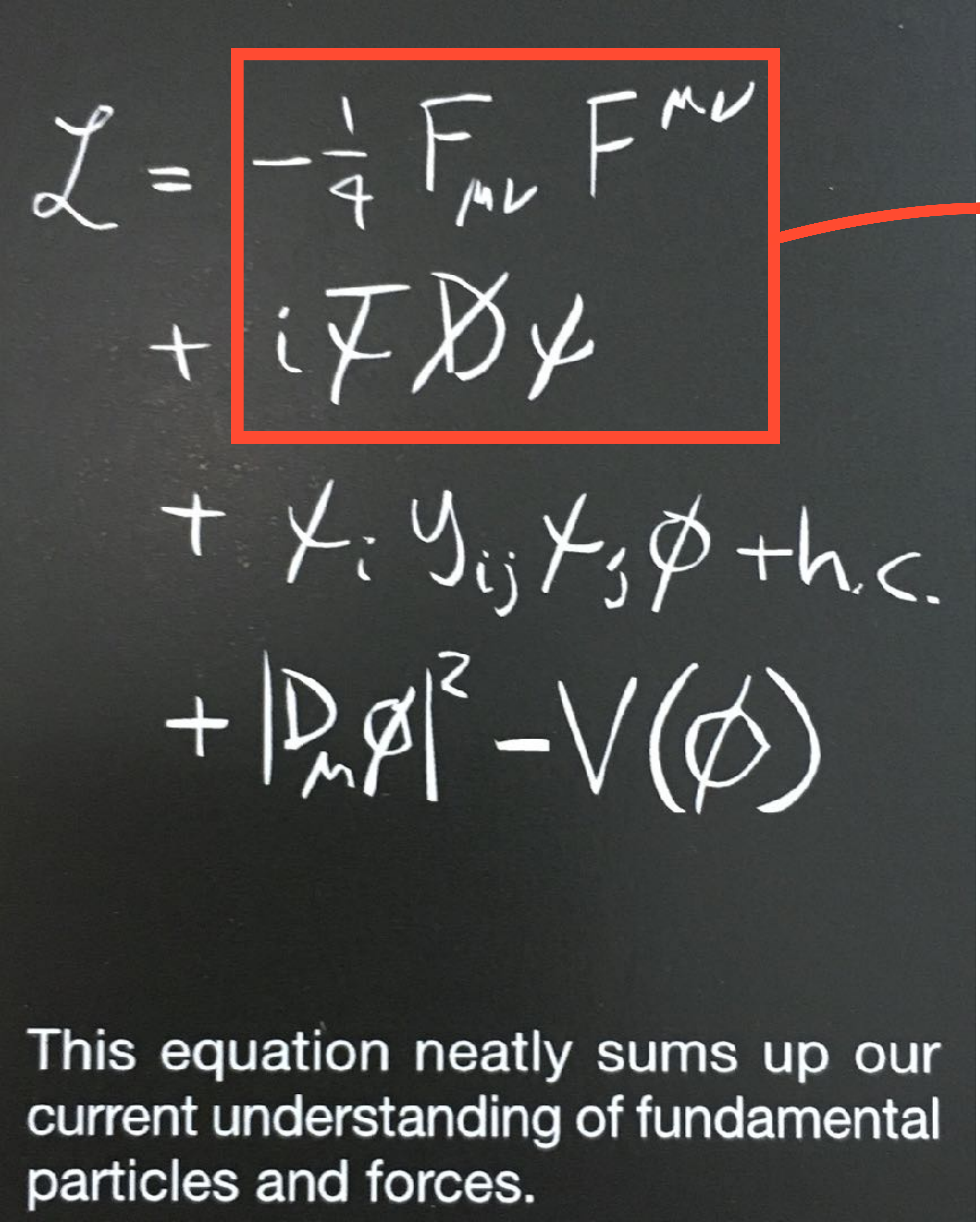


e.g. $F_{\mu\nu}F^{\mu\nu} \rightarrow A_\mu A_\nu \partial_\mu A_\nu \rightarrow$ triple-gauge vertex

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

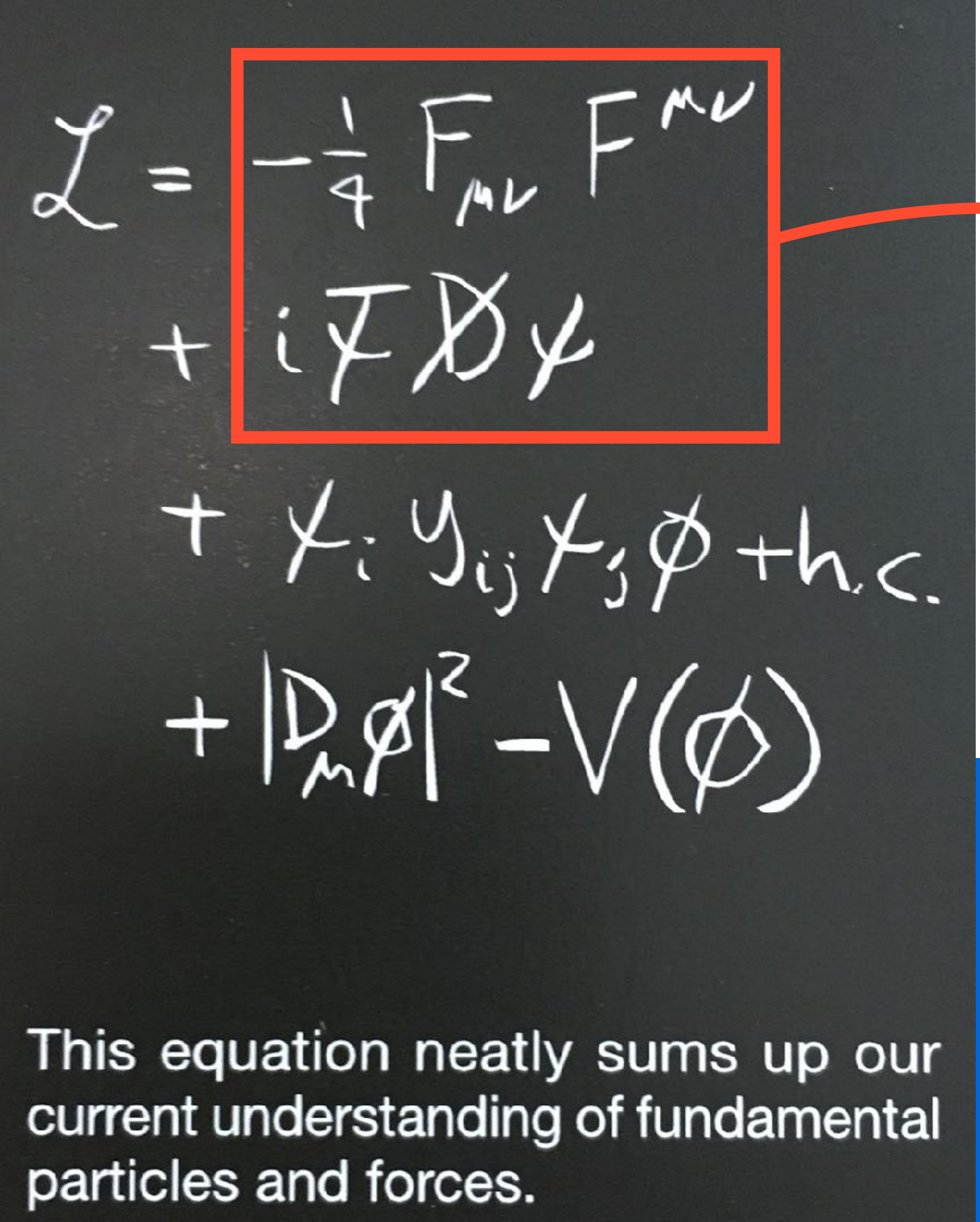


Gauge part

e.g. $qq\gamma$, qqZ, qqg, $e\nu W$, 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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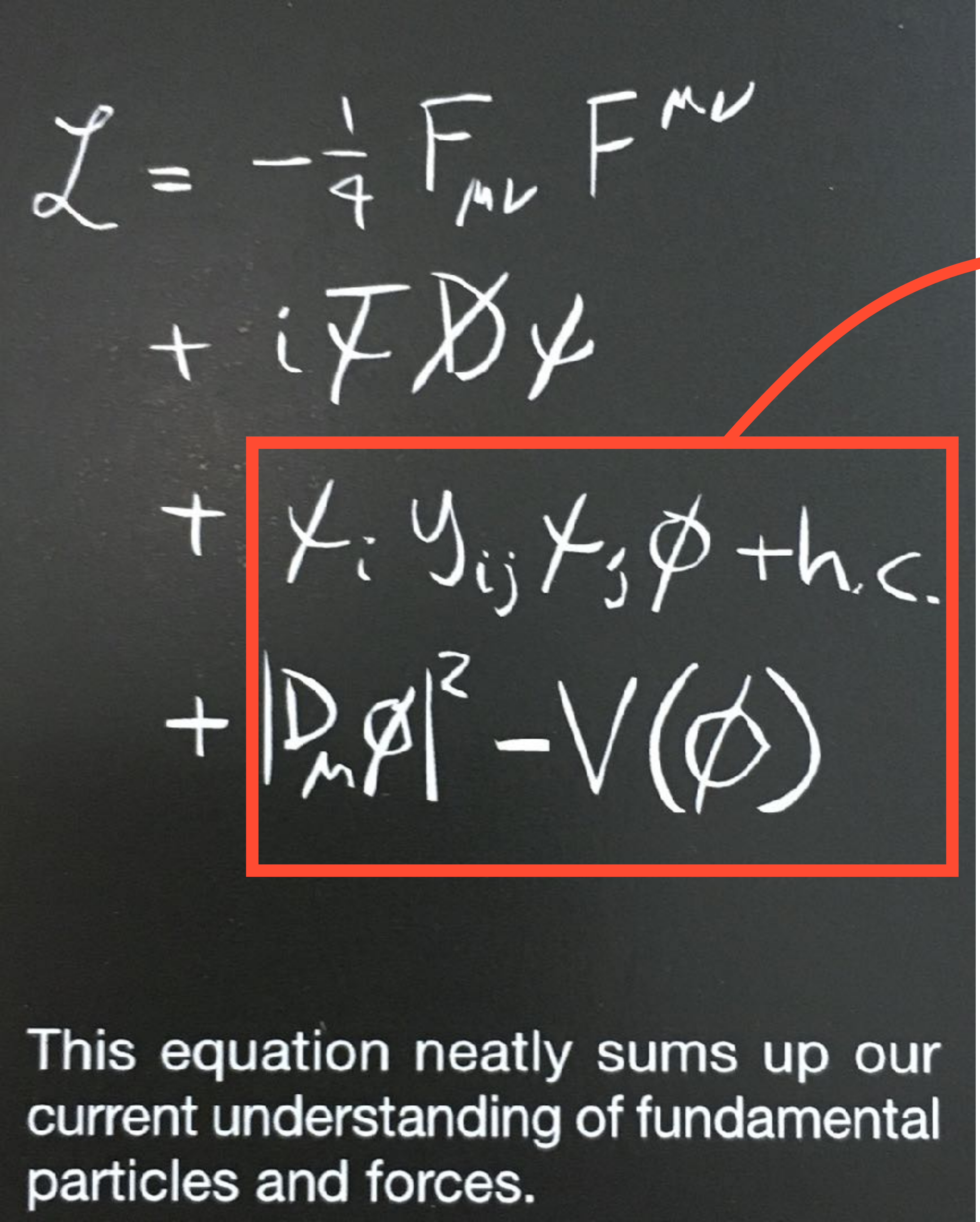
Many SM studies probe this part.

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

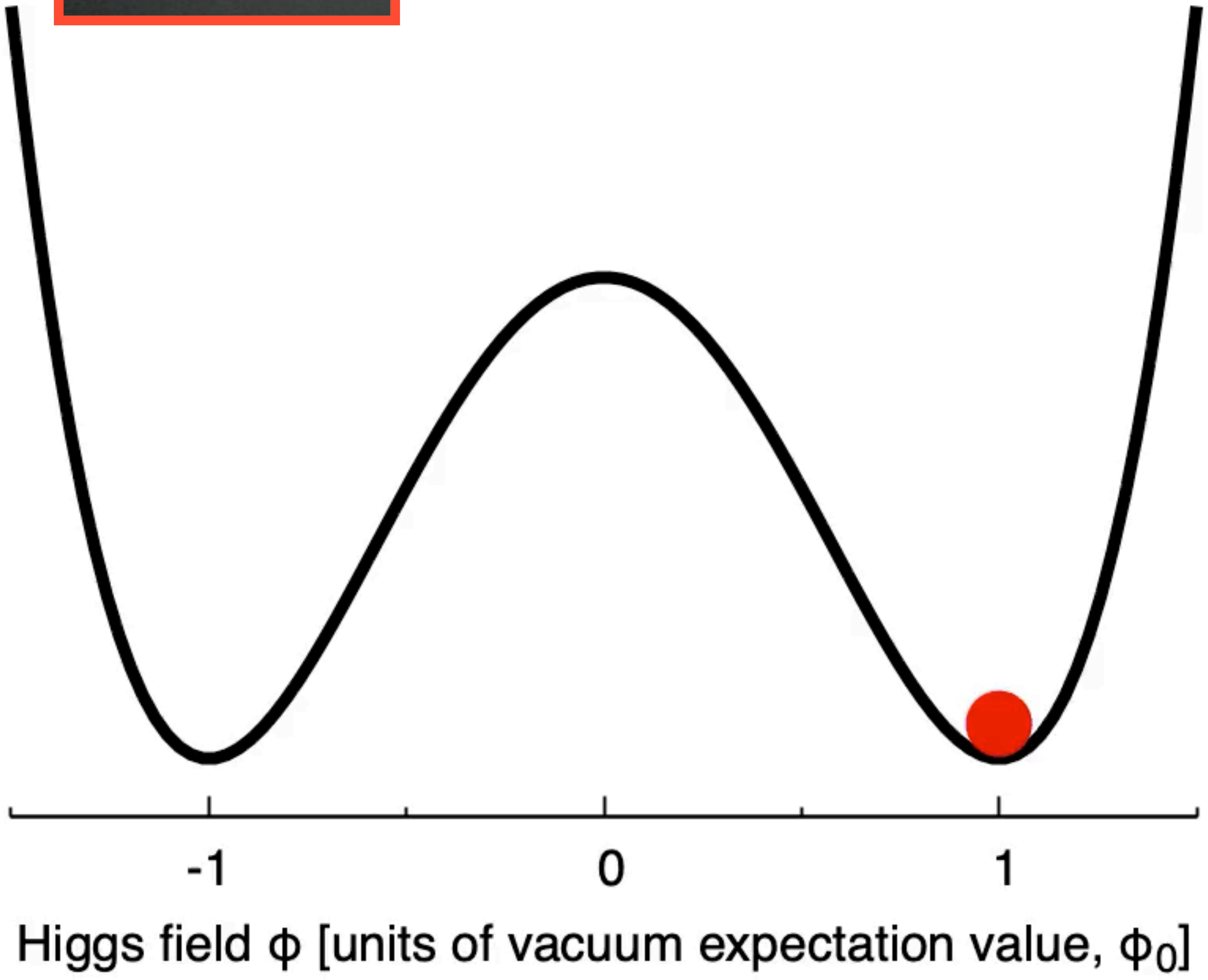
If you test another corner of this (as one should), don't be surprised if it works



Higgs sector

until 8 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)

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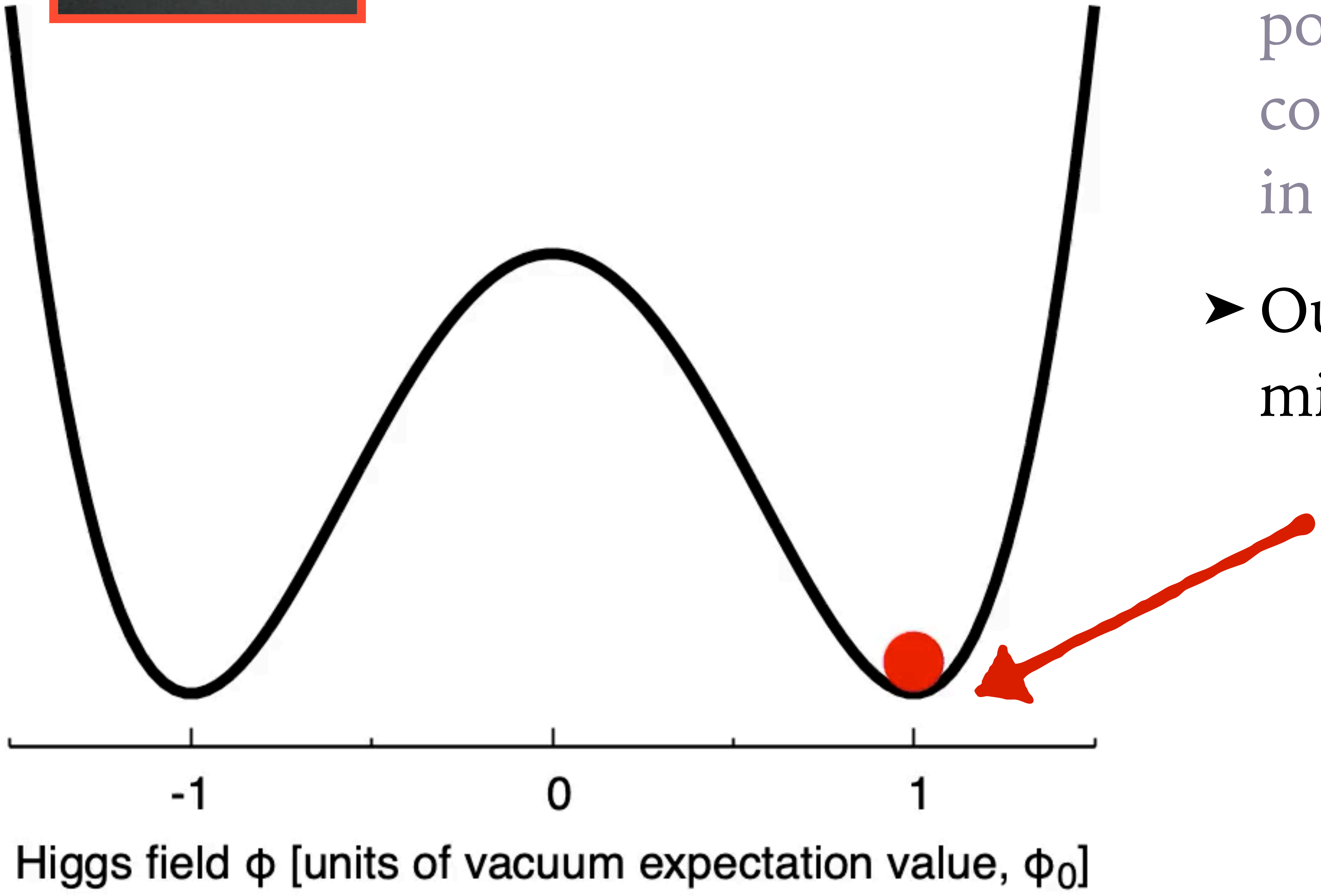
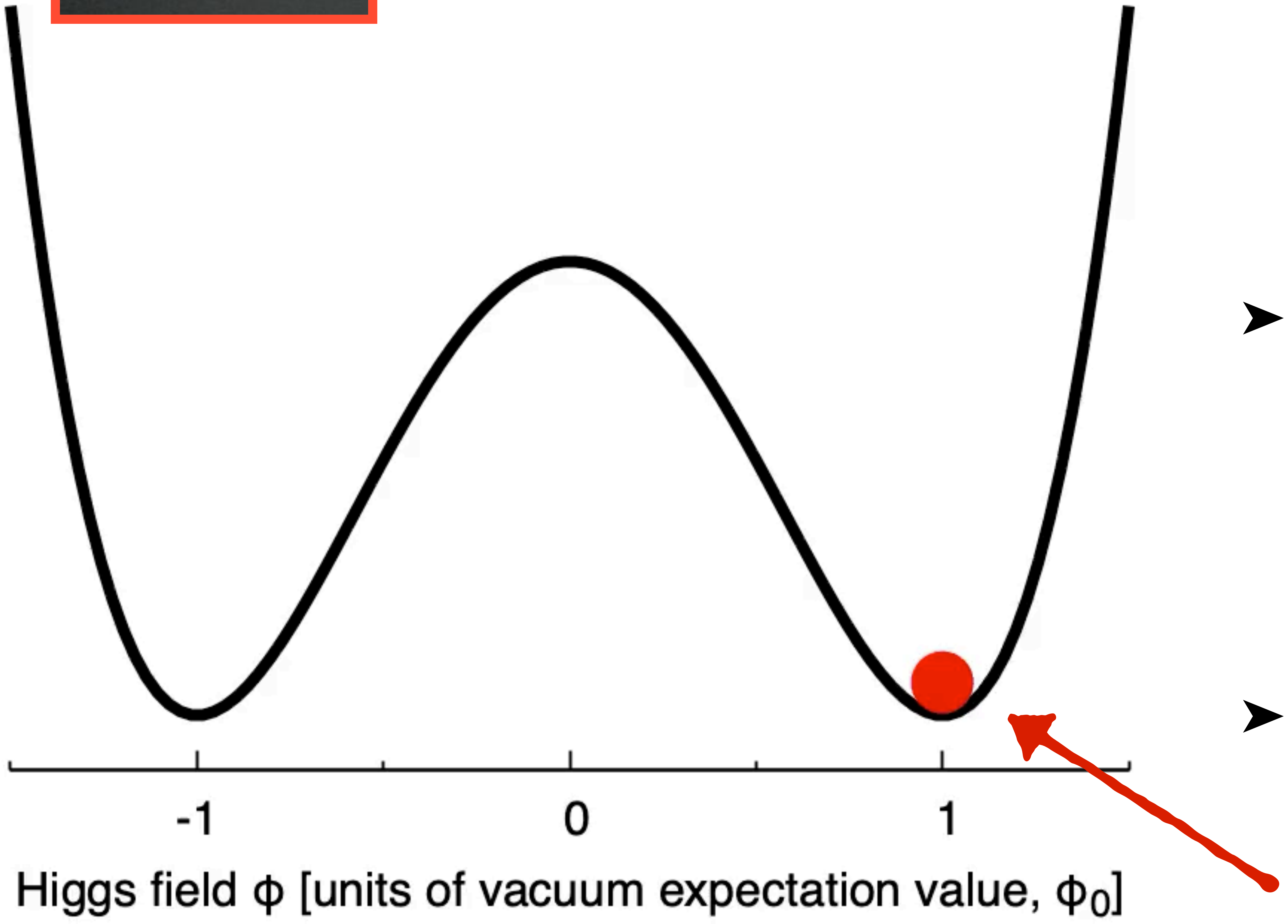


- φ is a field at every point in space (plot shows potential vs. 1 of 4 components, at 1 point in space)
- Our universe sits at minimum of V(φ), at

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

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



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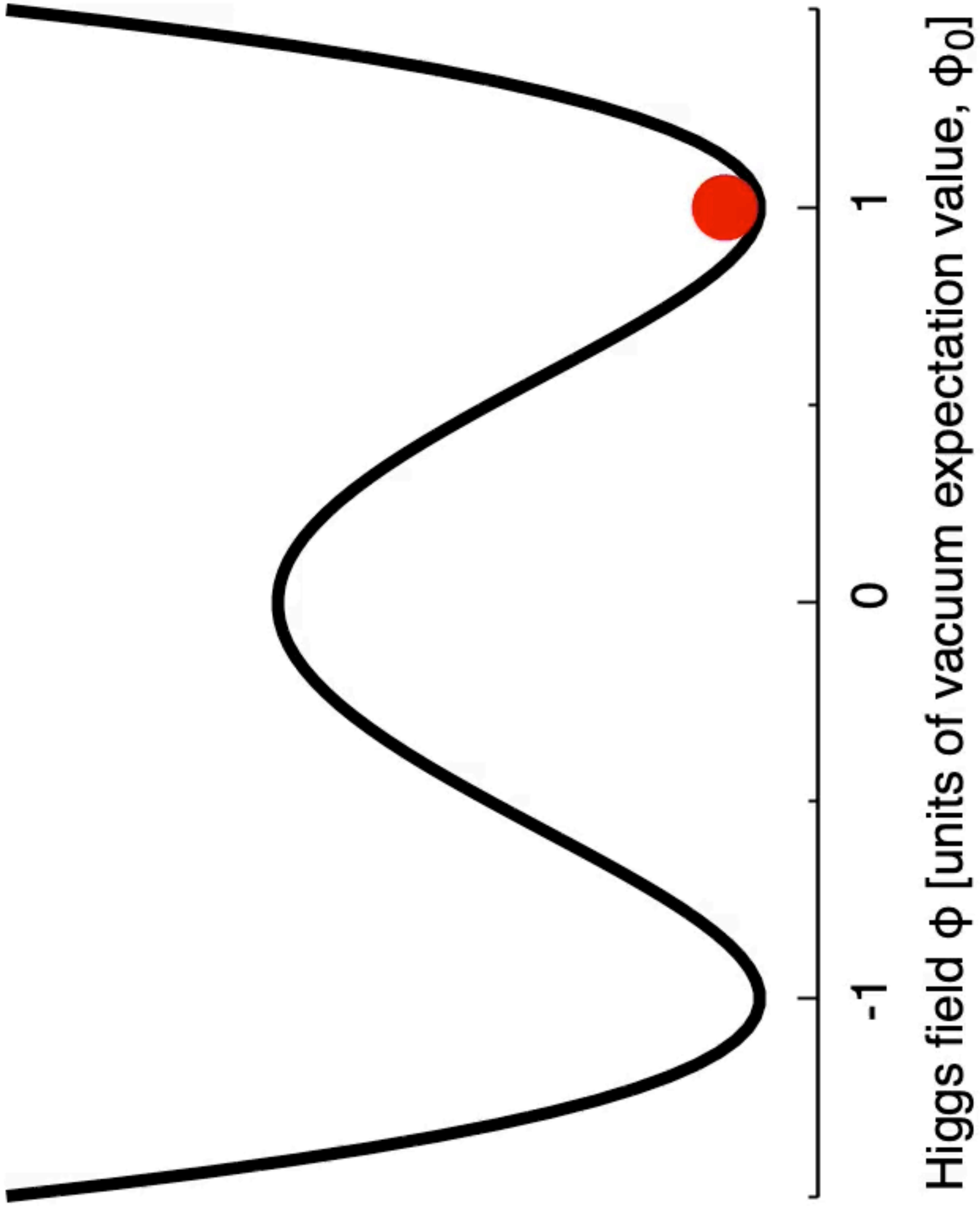
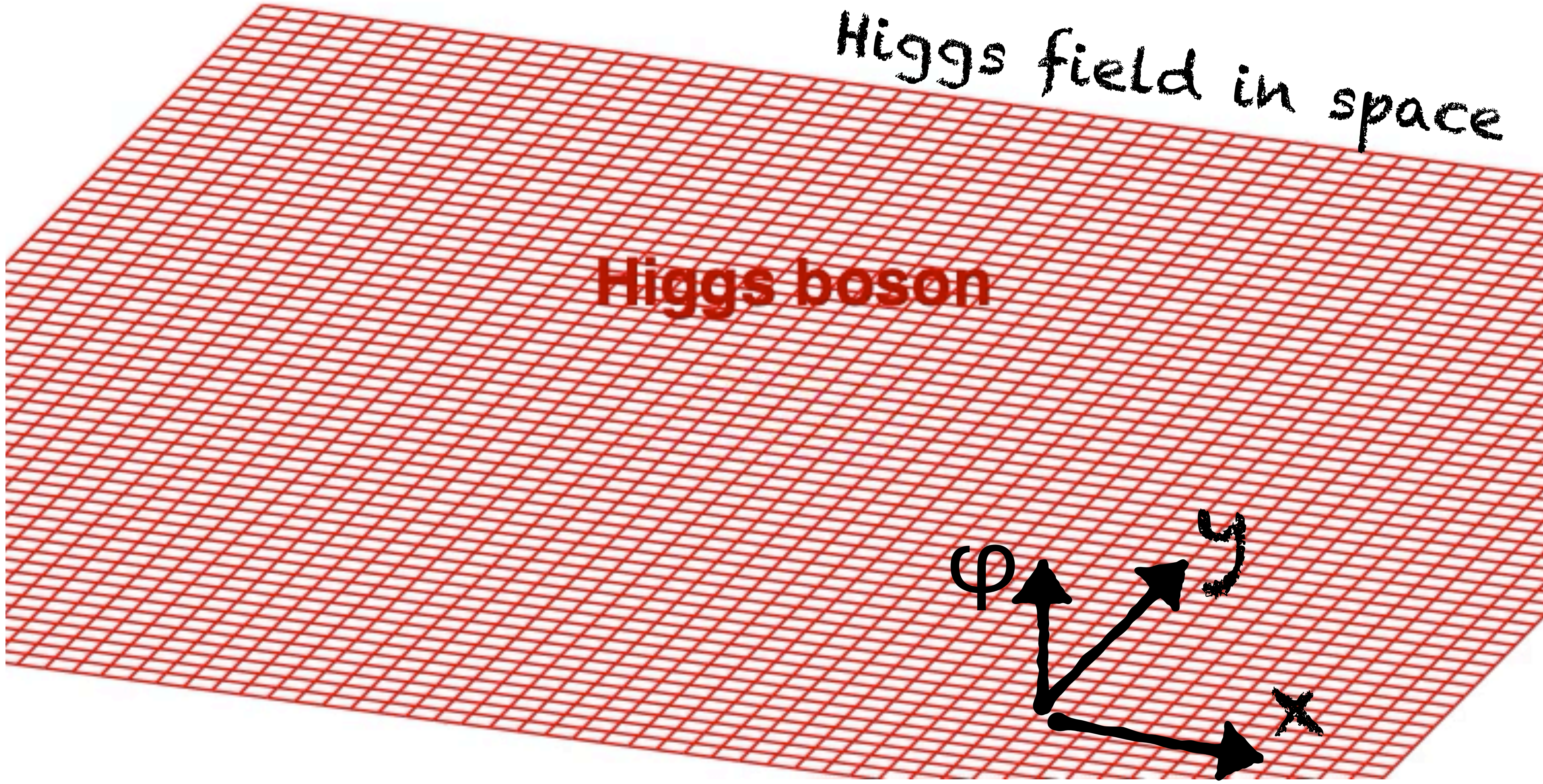
- Excitation of the φ field around φ_0 is a Higgs boson ($\varphi = \varphi_0 + H$)

$$\varphi = \varphi_0 + H$$



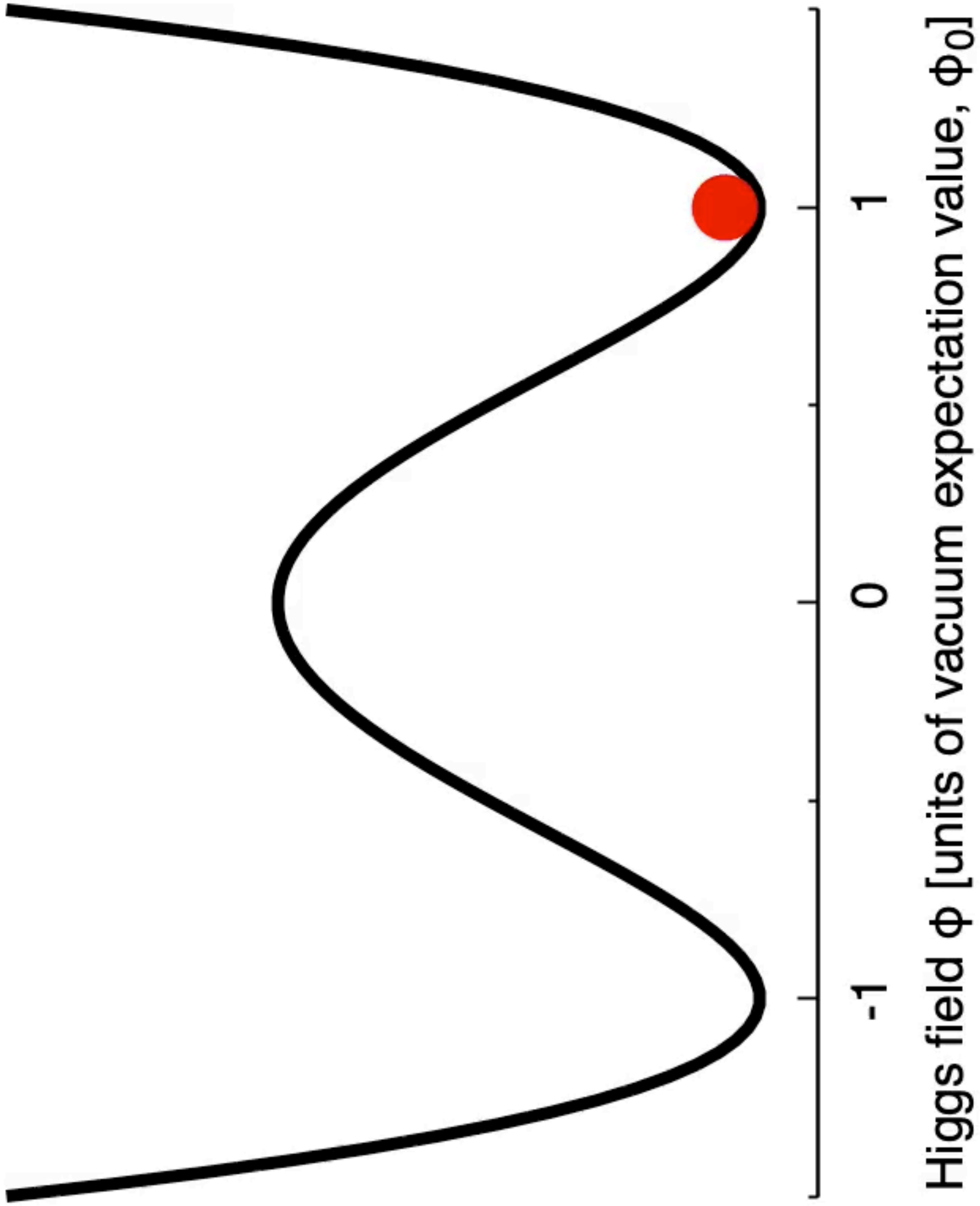


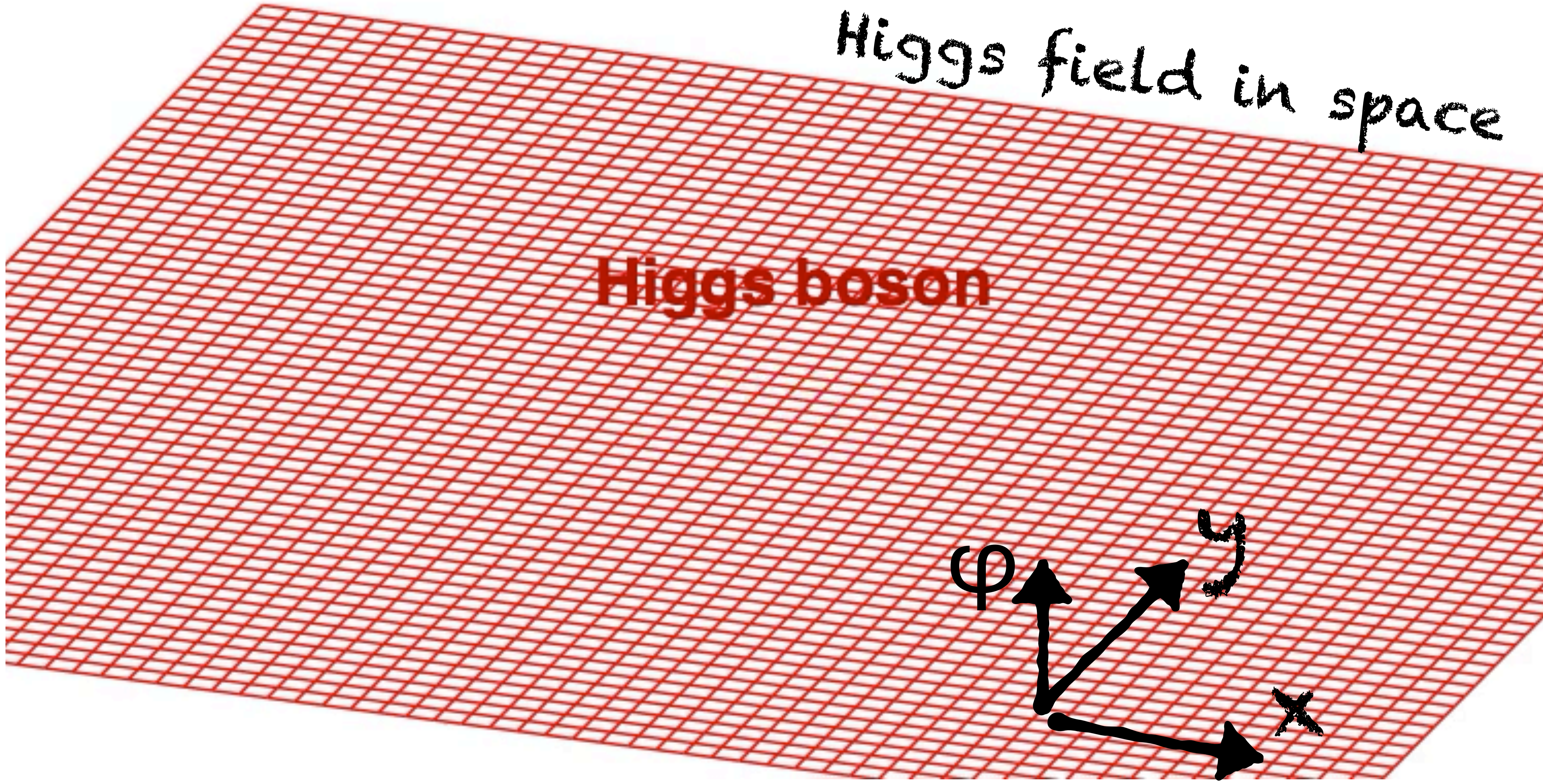
Higgs field can be different at each point in space

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

these and subsequent animations: https://cern.ch/gsalam/higgs

$$\varphi = \varphi_0 + H$$





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$$\varphi = \varphi_0 + H$$

established

(2012 Higgs boson discovery)

$$\varphi = \varphi_0 + H$$

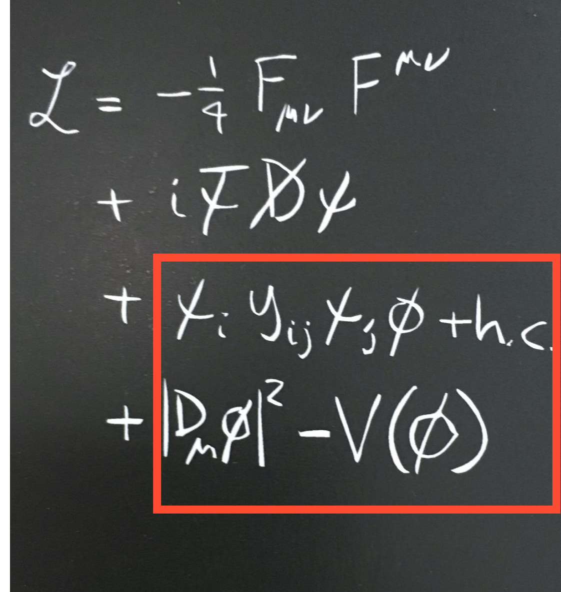
established

(2012 Higgs boson discovery)

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

hypothesis

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



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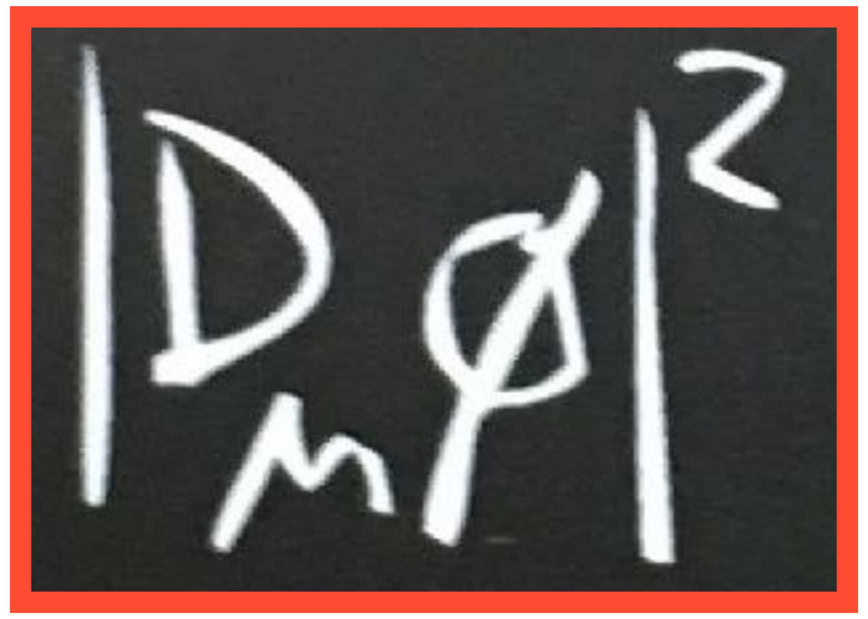


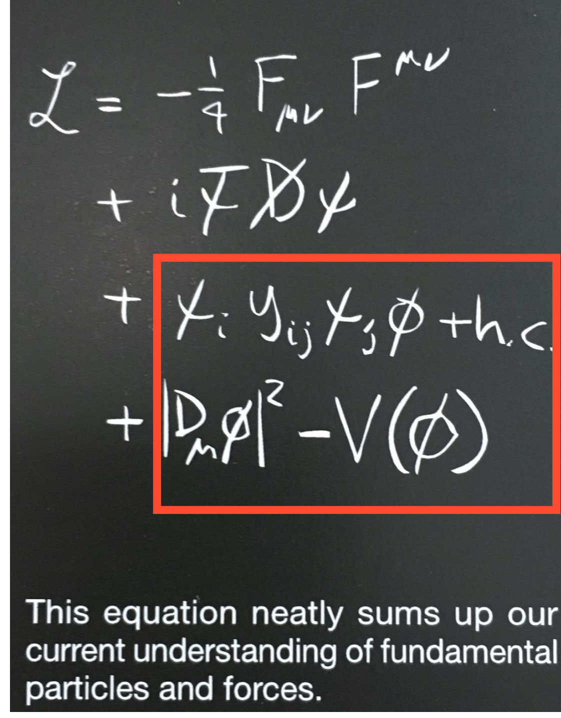
$$\rightarrow g^2\phi_0^2 Z_\mu Z^\mu + 2g^2\phi_0 H Z_\mu Z^\mu + \ldots$$

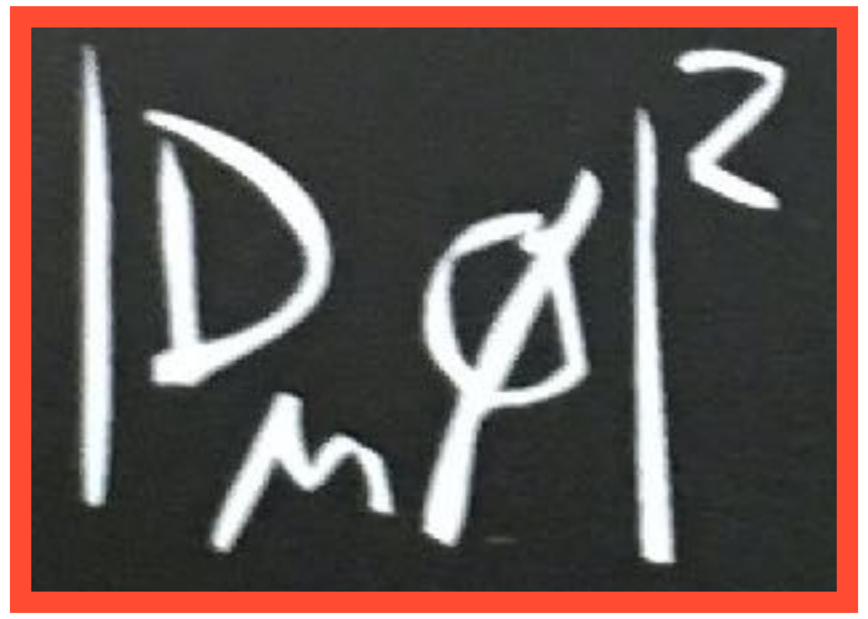
Z-boson mass term

ZZH interaction term

$$\left[\begin{array}{l}(D_\mu)^2 \sim (\partial_\mu + igZ_\mu + \ldots)^2 \sim g^2 Z_\mu Z^\mu + \cdots \\ (\phi)^2 = (\phi_0 + H)^2 = \phi_0^2 + 2\phi_0 H + H^2\end{array}\right]$$

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





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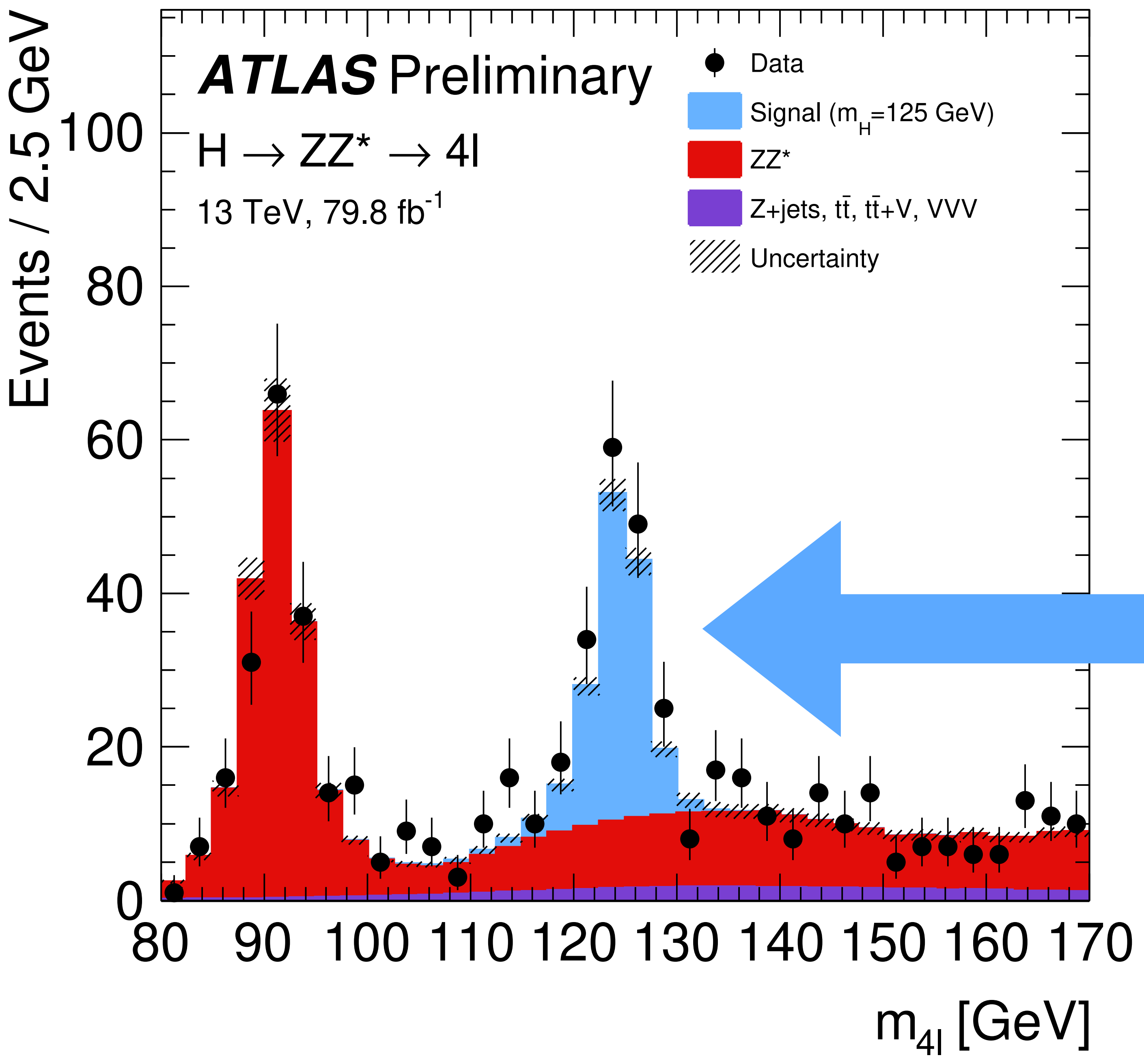
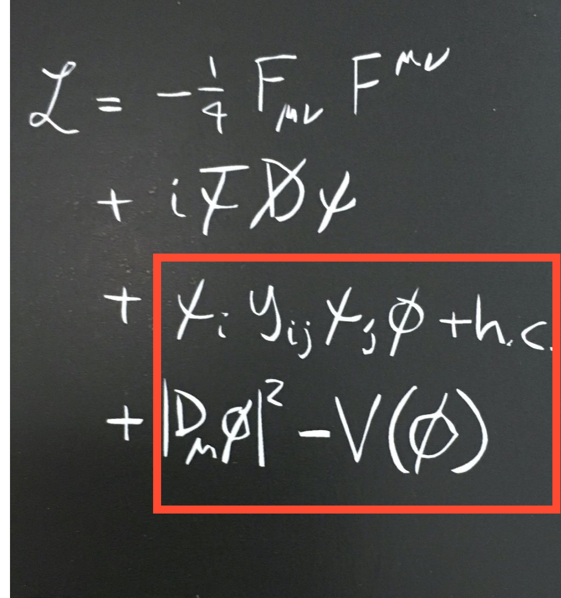


H → ZZ*

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

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



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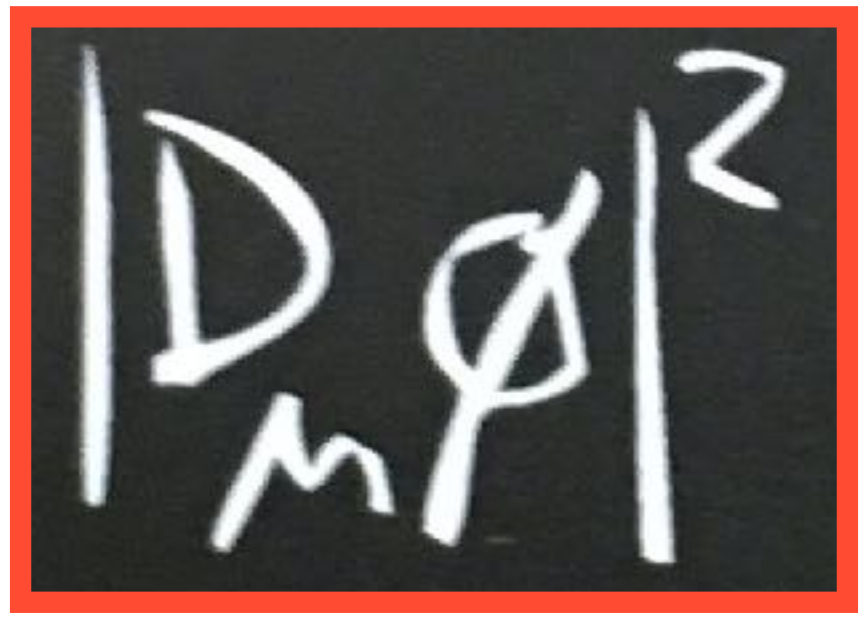
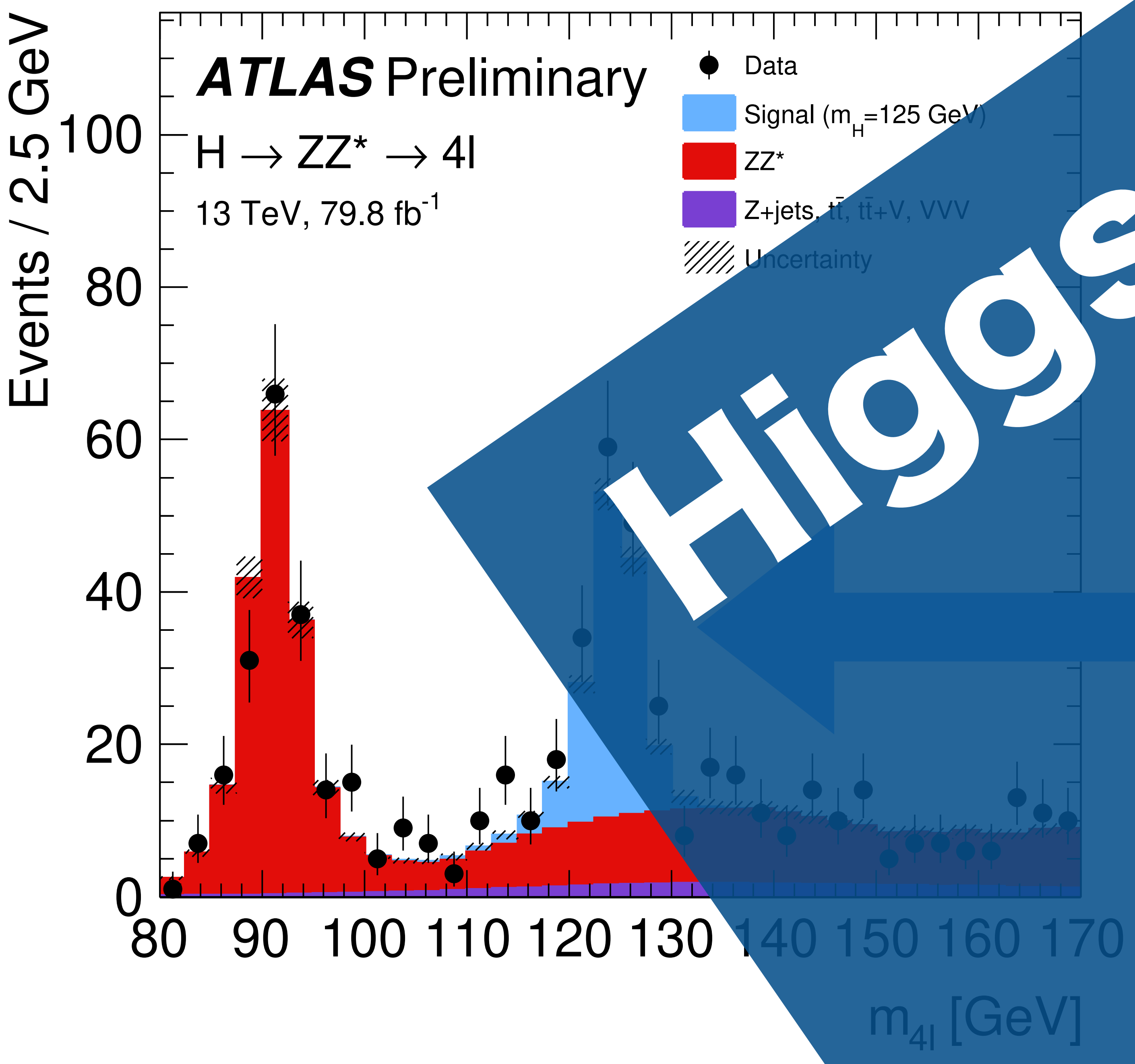


$$\rightarrow g^2 \phi_0^2 Z_\mu Z^\mu + 2 g^2 \phi_0 H Z_\mu Z^\mu + \ldots$$

Z boson mass term

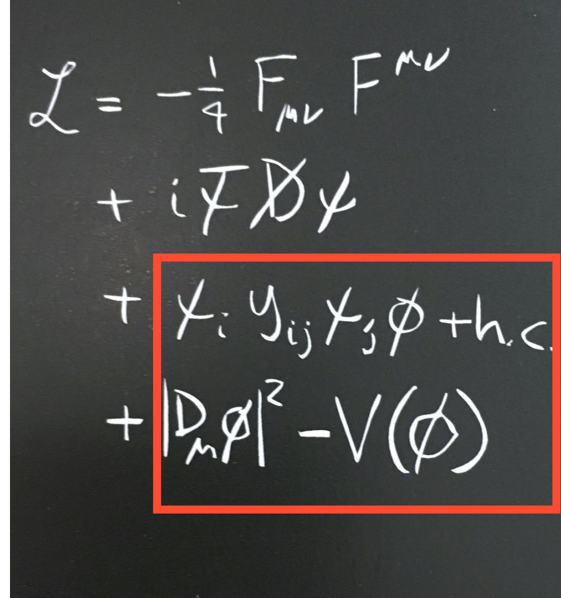
ZZH interaction term

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



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

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



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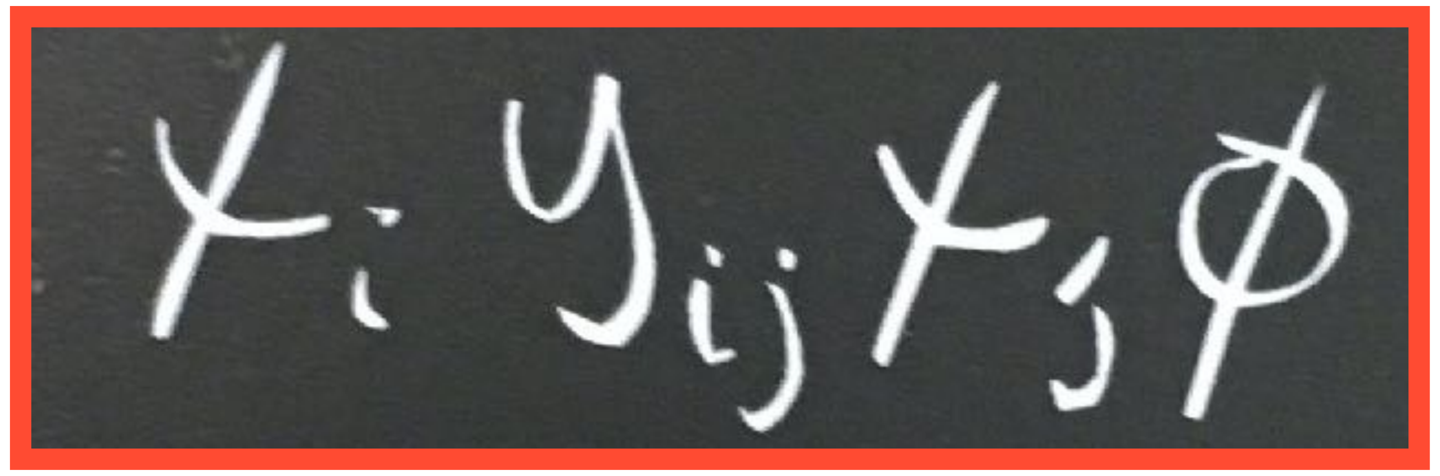

$$\rightarrow y_{ij} \phi_0 \psi_i \psi_j + y_{ij} H \psi_i \psi_j$$

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	$\sim 10^{-13}$?	μ	$6 \cdot 10^{-4}$
ν_τ	$\sim 10^{-13}$?	τ	$1 \cdot 10^{-4}$

$$\phi = \phi_0 + H$$

what terms are there in the Higgs sector?
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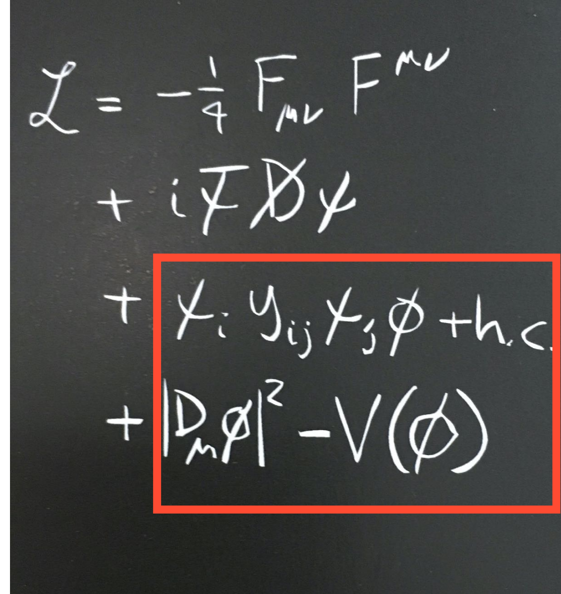

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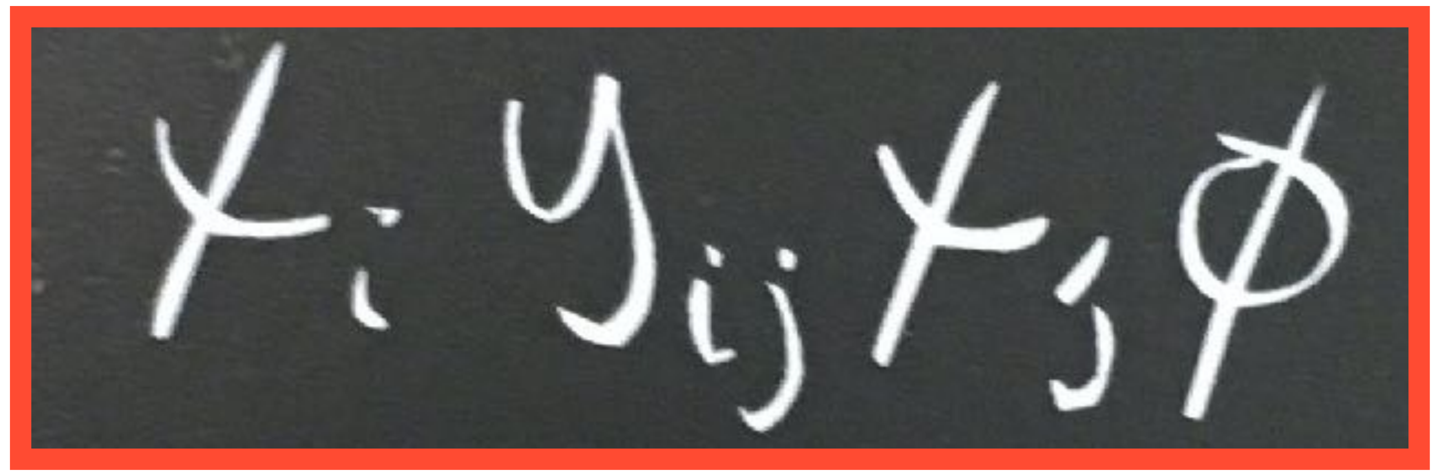

$\rightarrow y_{ii}\phi_0\psi_i\psi_i + y_{ij} H \psi_i \psi_j$

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	$2\cdot10^{-5}$	d	$3\cdot10^{-5}$
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b	$3\cdot10^{-2}$	t	1
ν_e	$\sim 10^{-13}$?	e	$3\cdot10^{-6}$
ν_μ		μ	$6\cdot10^{-4}$
ν_τ		τ	$1\cdot10^{-4}$

$\phi = \phi_0 + H$

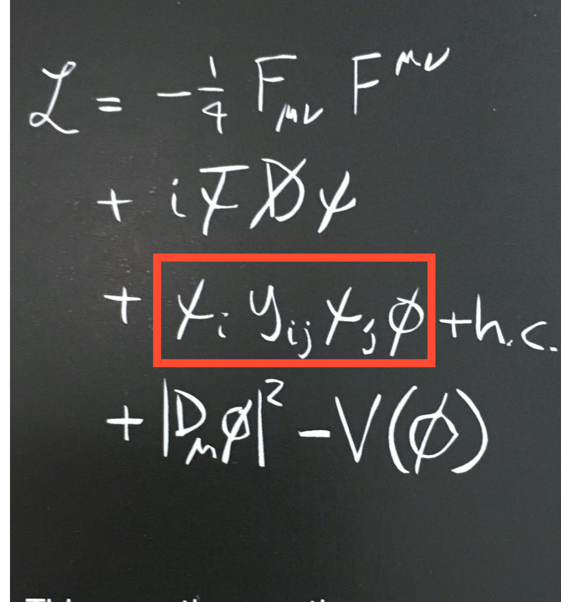
concentrate on Yukawa interaction hypothesis

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

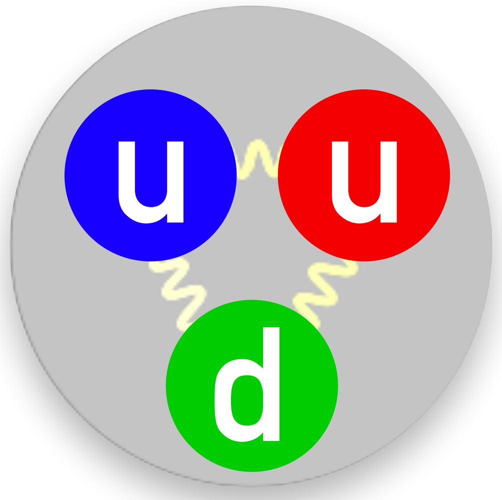


This equation neatly sums up our current understanding of fundamental particles and forces.

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

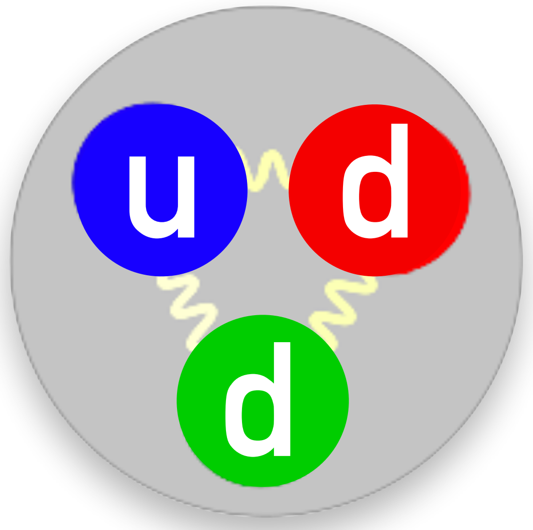
proton (up+up+down): 2.2 + 2.2 + 4.7 + … = 938.3 MeV
neutron (up+down+down): 2.2 + 4.7 + 4.7 + … = 939.6 MeV

proton
mass = 938.3MeV



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

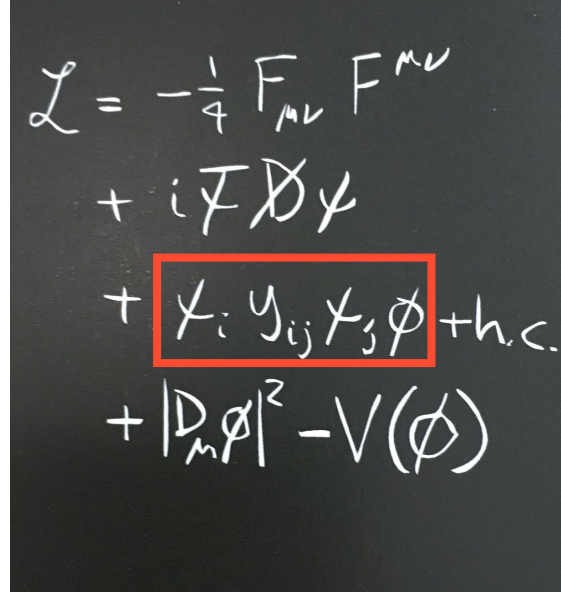
neutron
mass = 939.6MeV



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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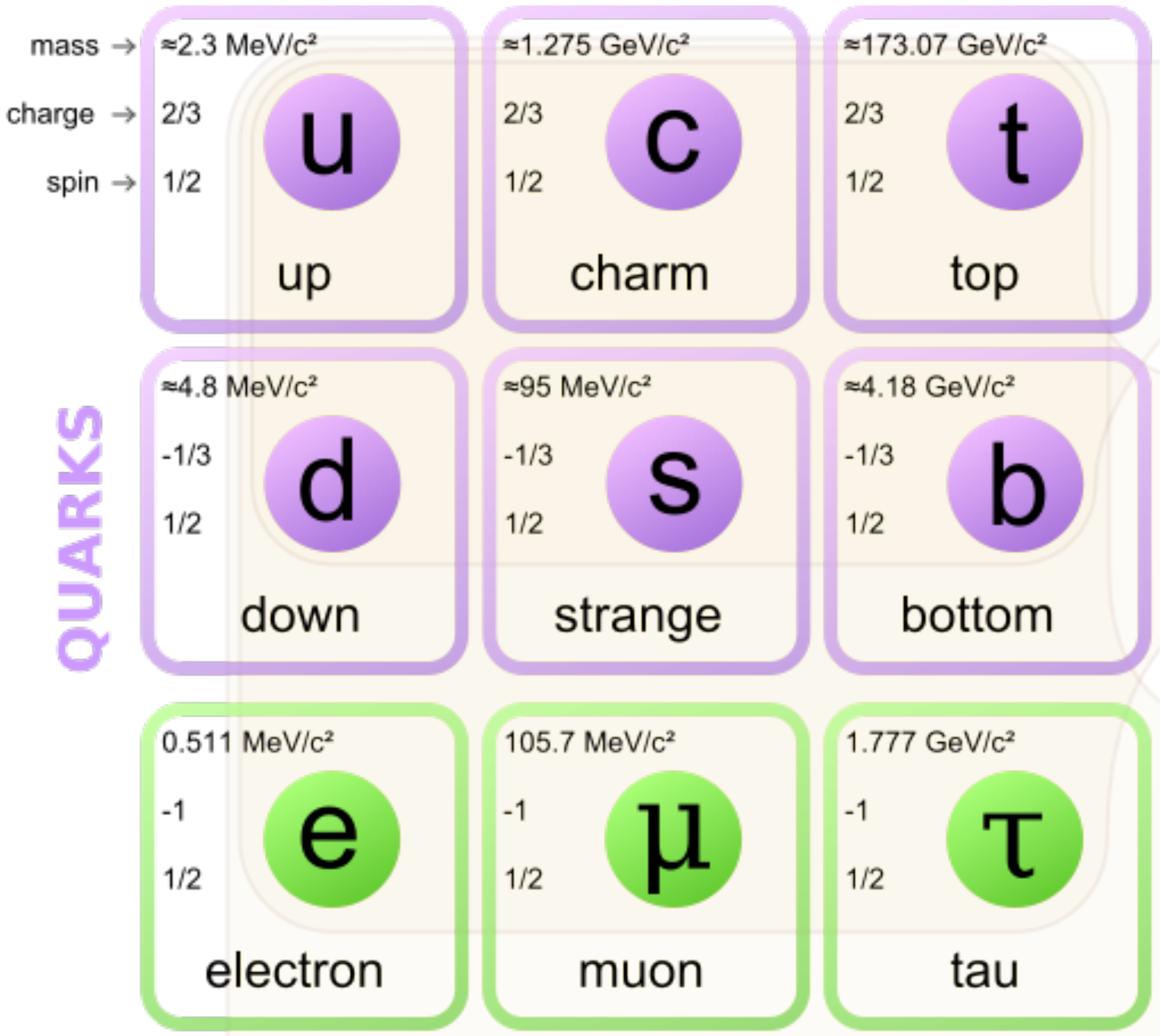
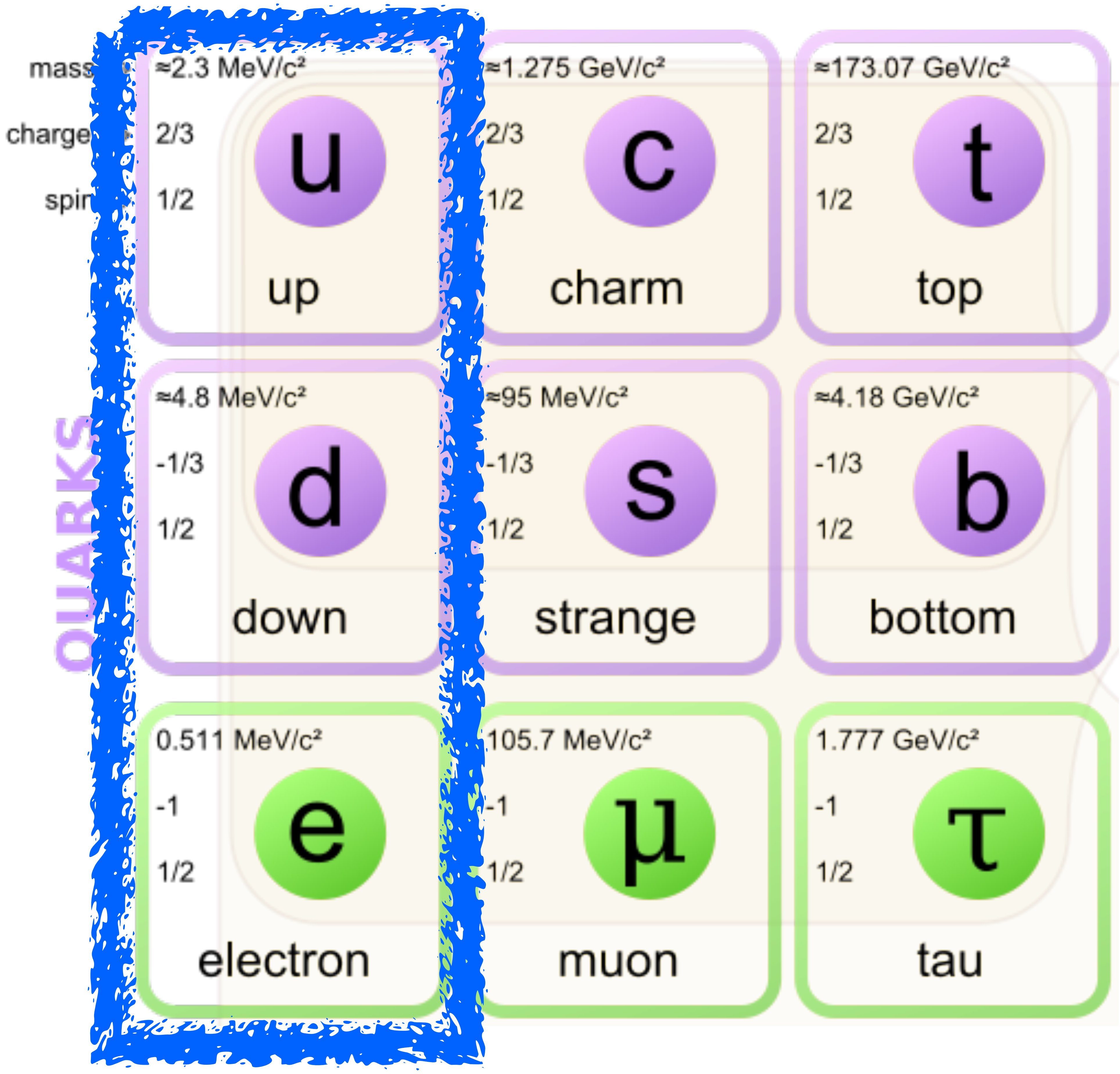
Bohr radius

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

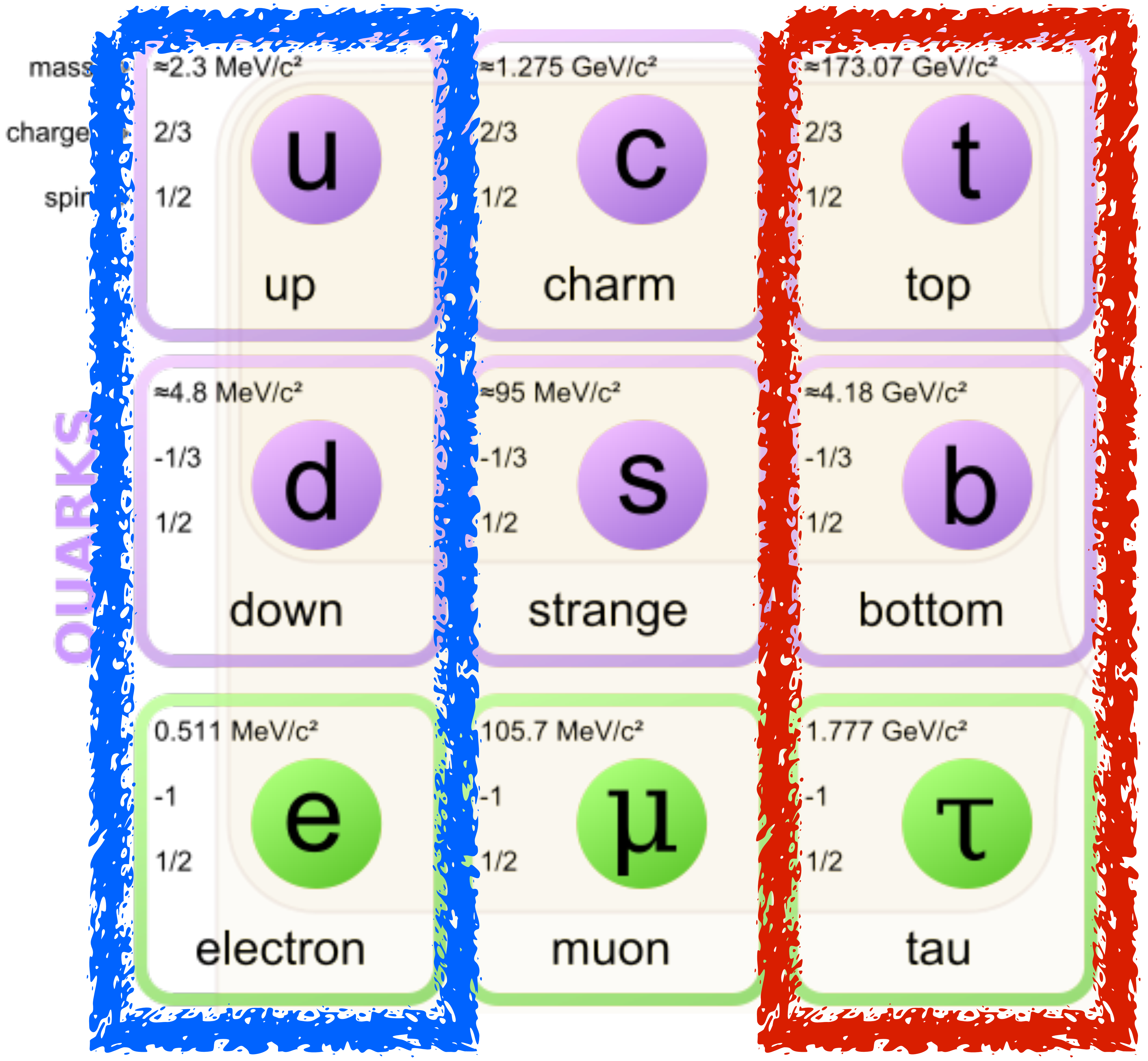
electron mass determines size of all atoms

it sets energy levels of all chemical reactions


mass →
charge →
spin →
≈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
QUARKS
≈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**

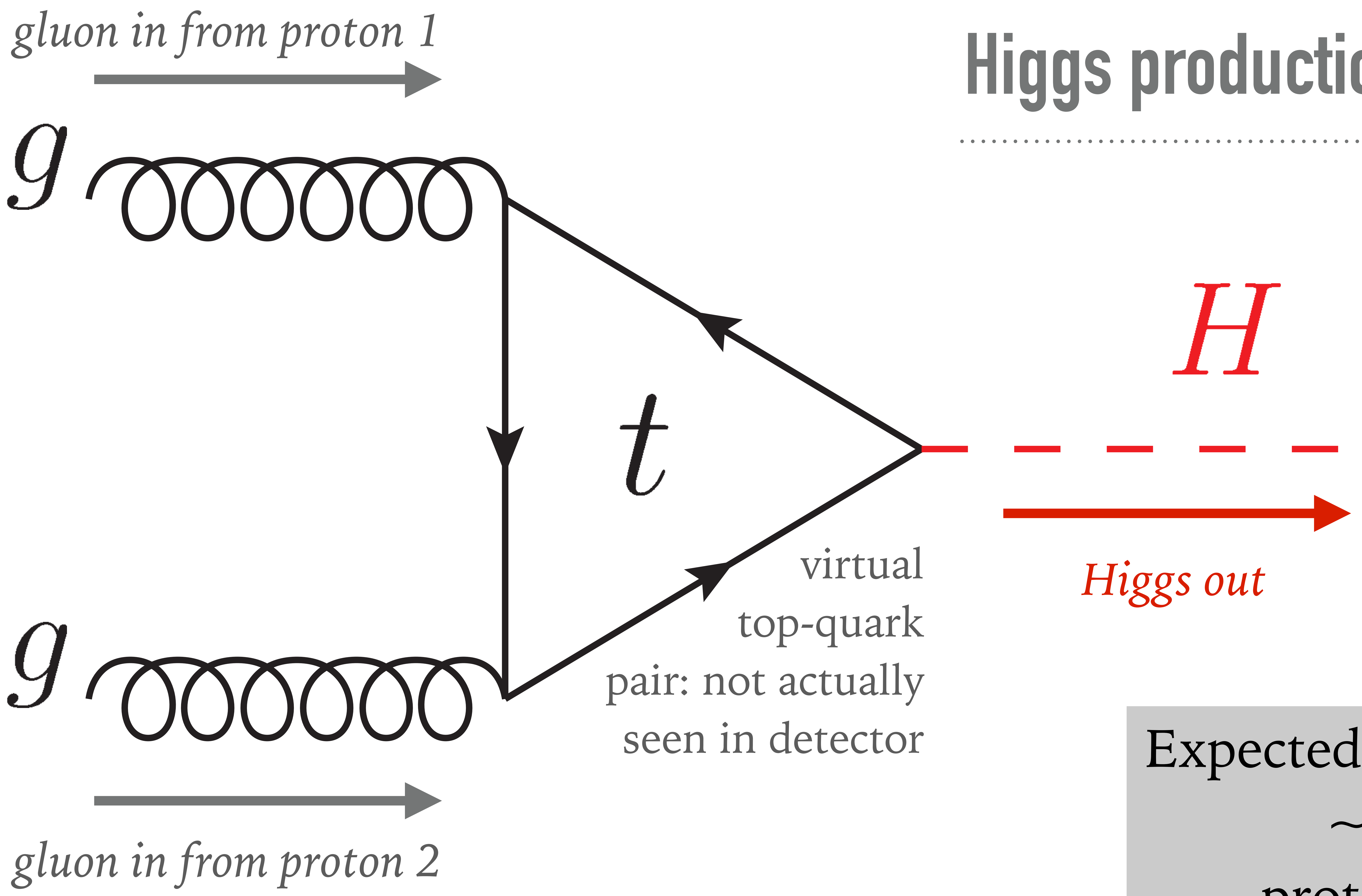


1st generation (us) has low mass because of weak interactions with Higgs field (and so with Higgs bosons): **too weak to test today**

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

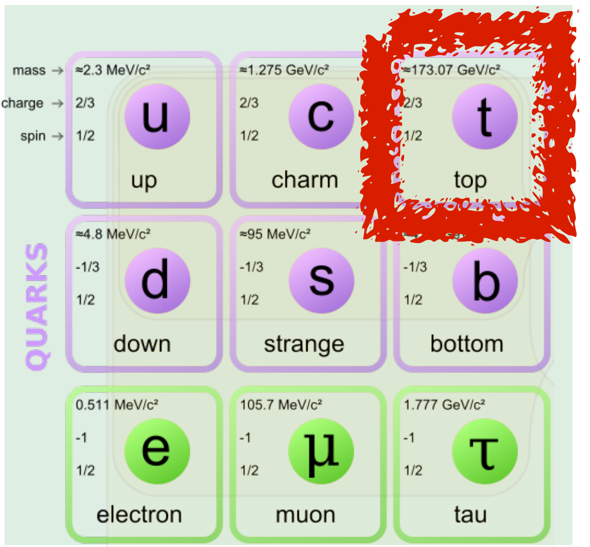
what underlying processes tell us about Yukawa interactions?

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
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Higgs field in space

g
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y
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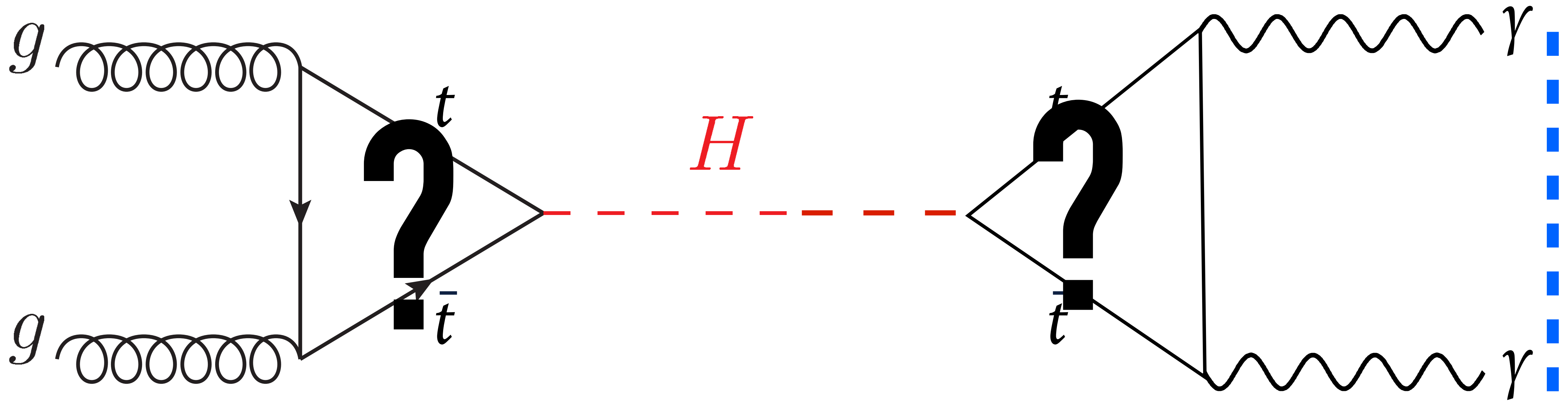
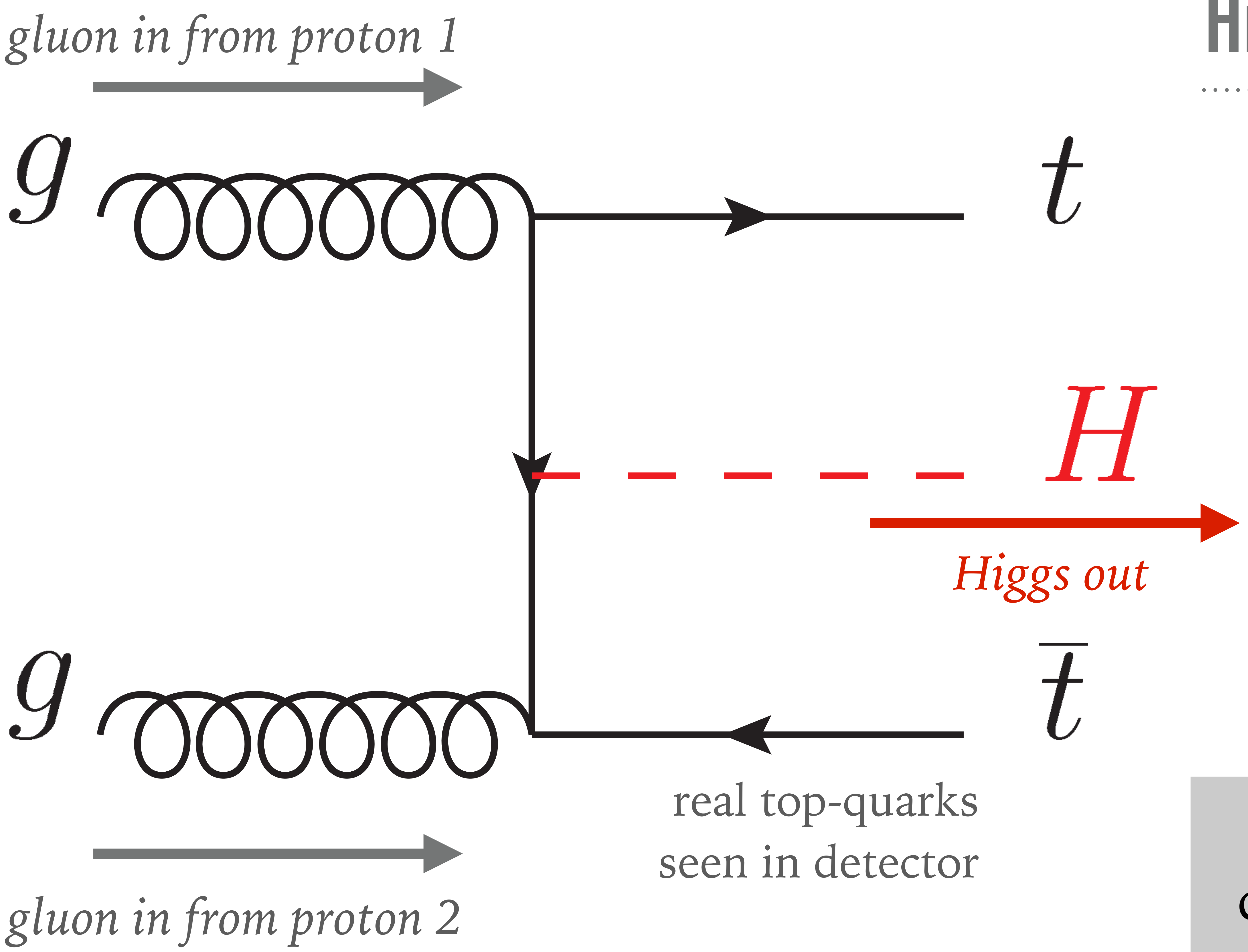
Higgs field in space

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?

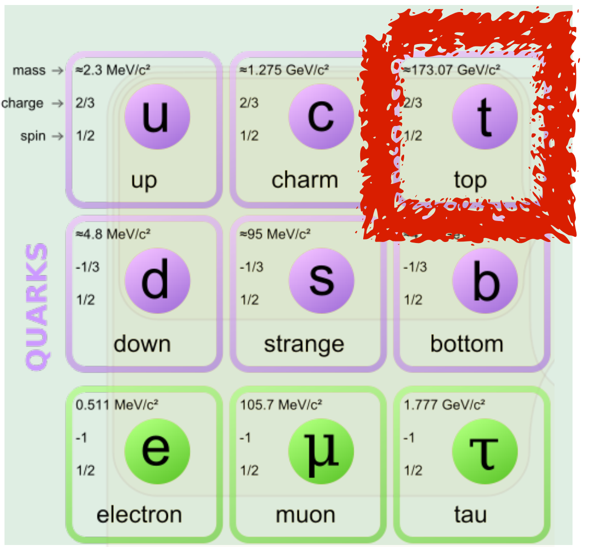


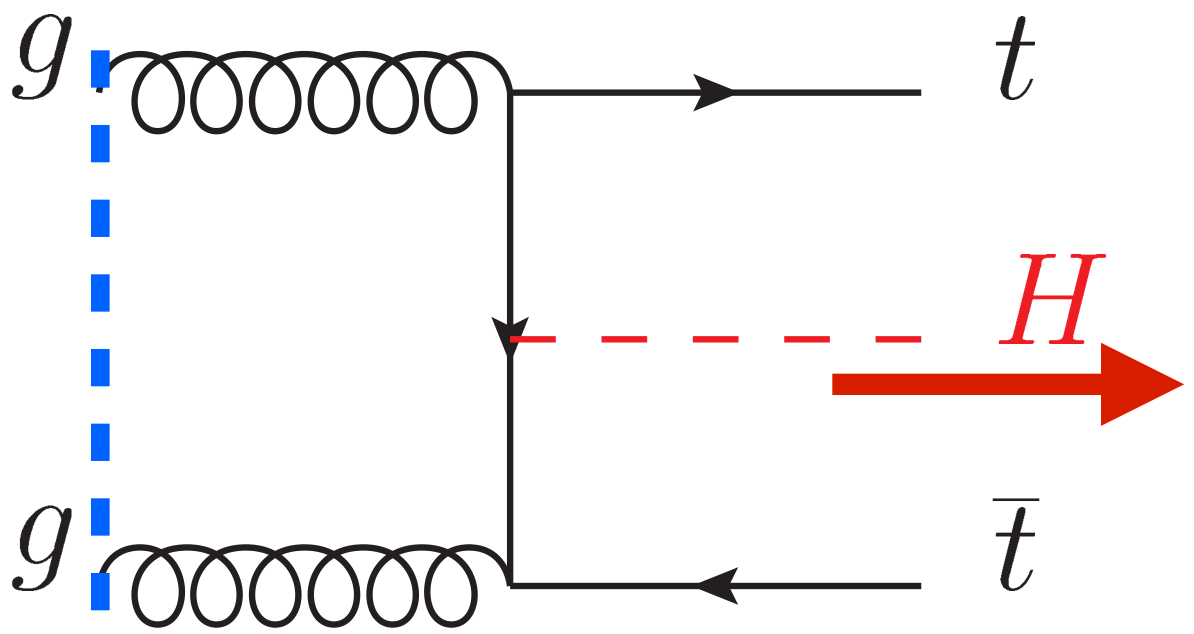
Higgs production: the ttH channel



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)

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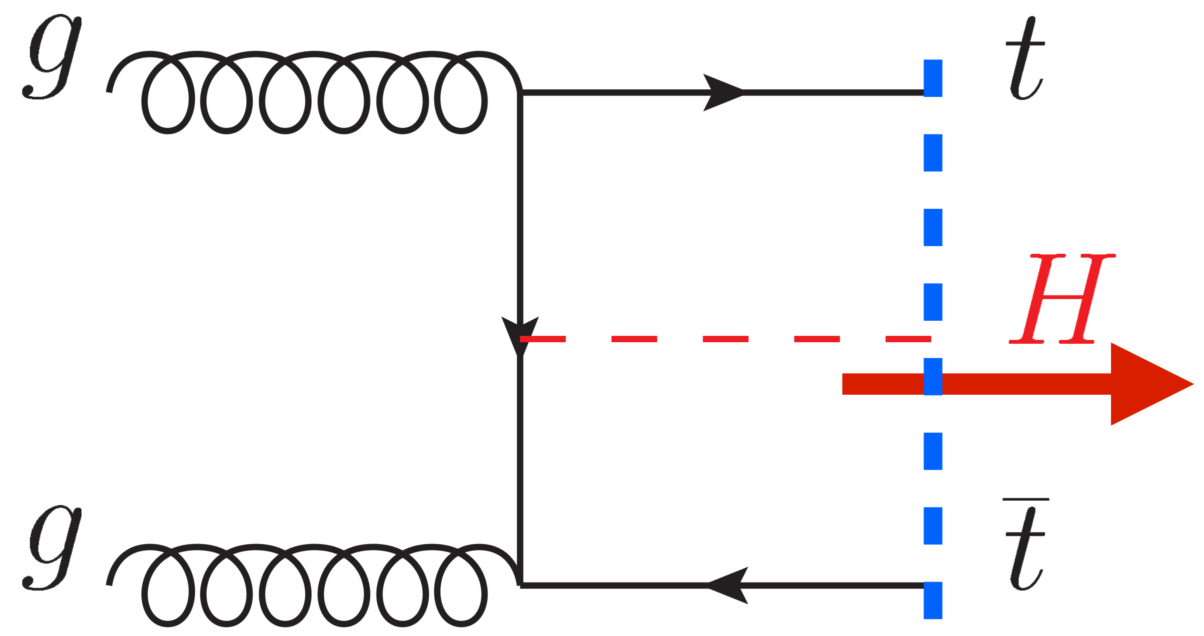
Higgs field in space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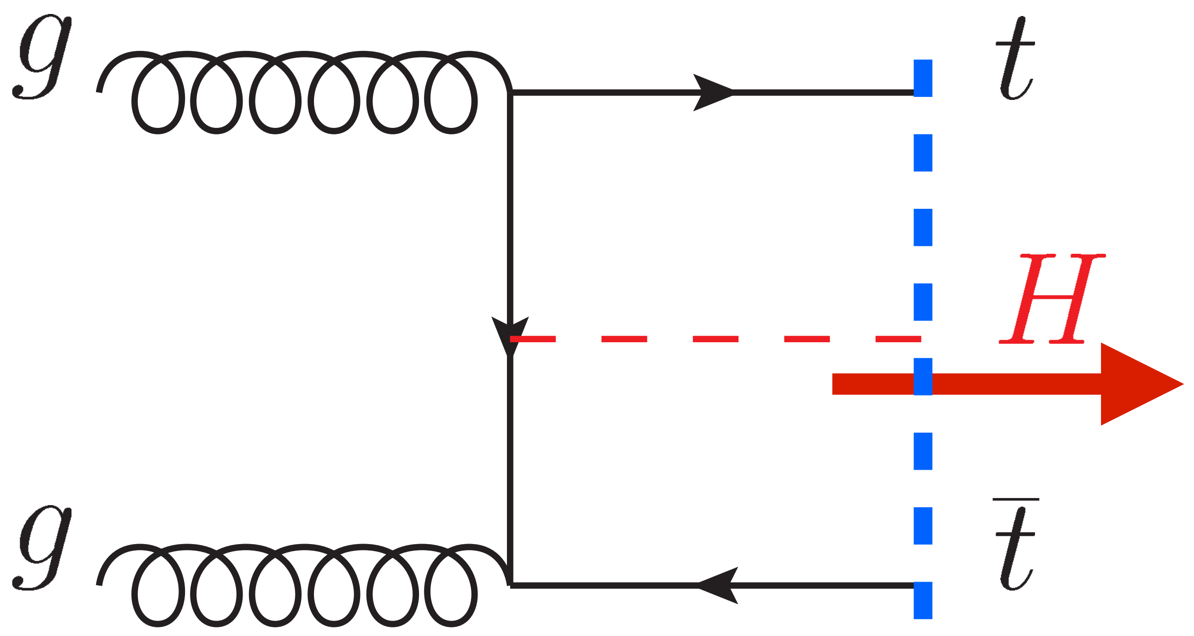
Higgs field in space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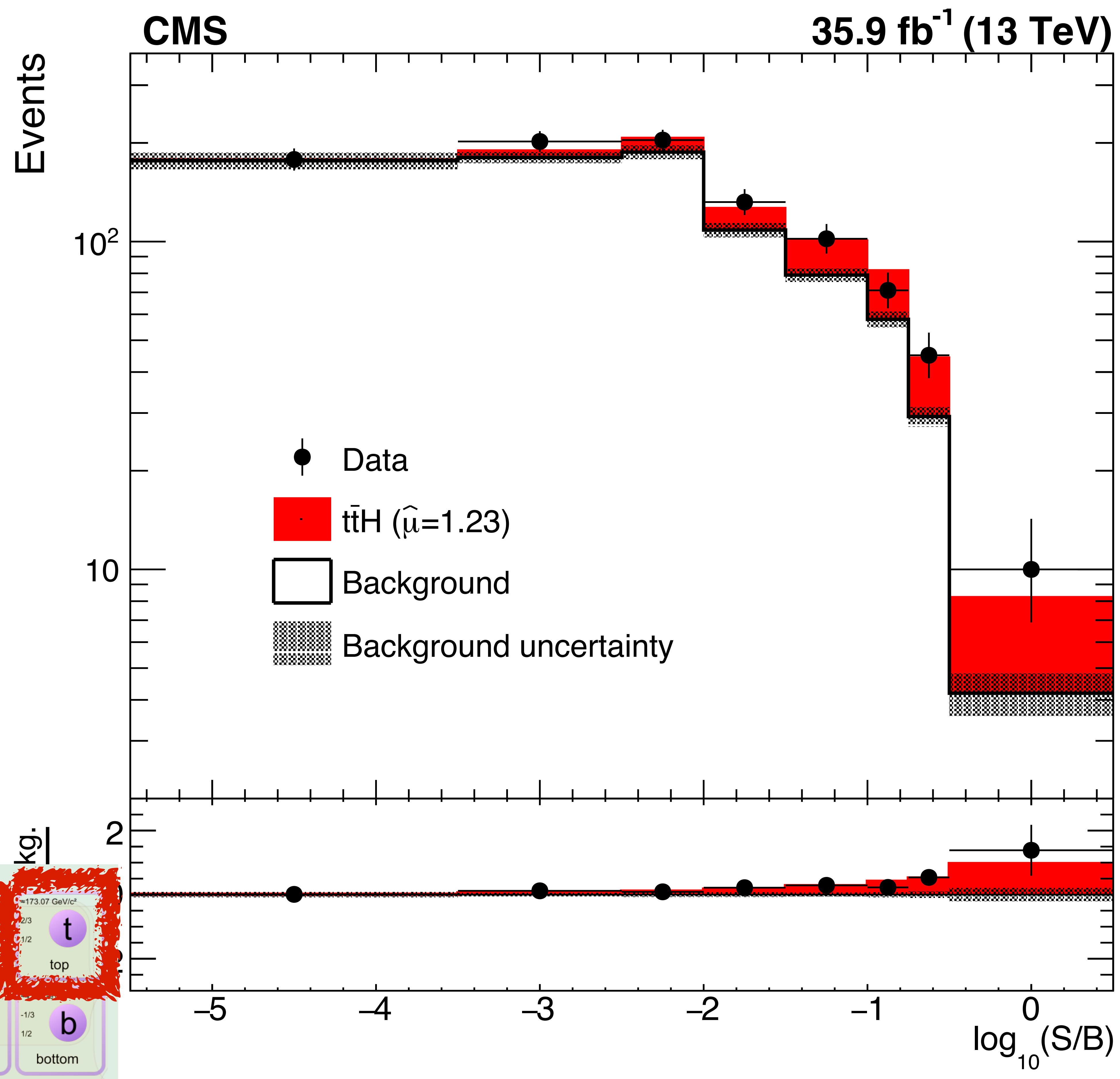
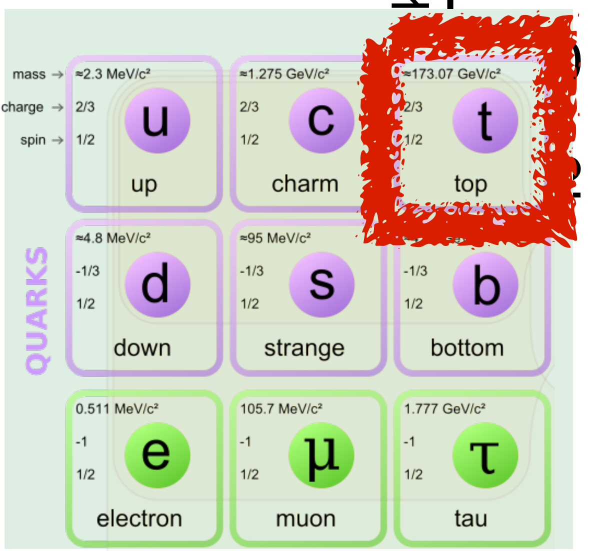
Higgs field in space

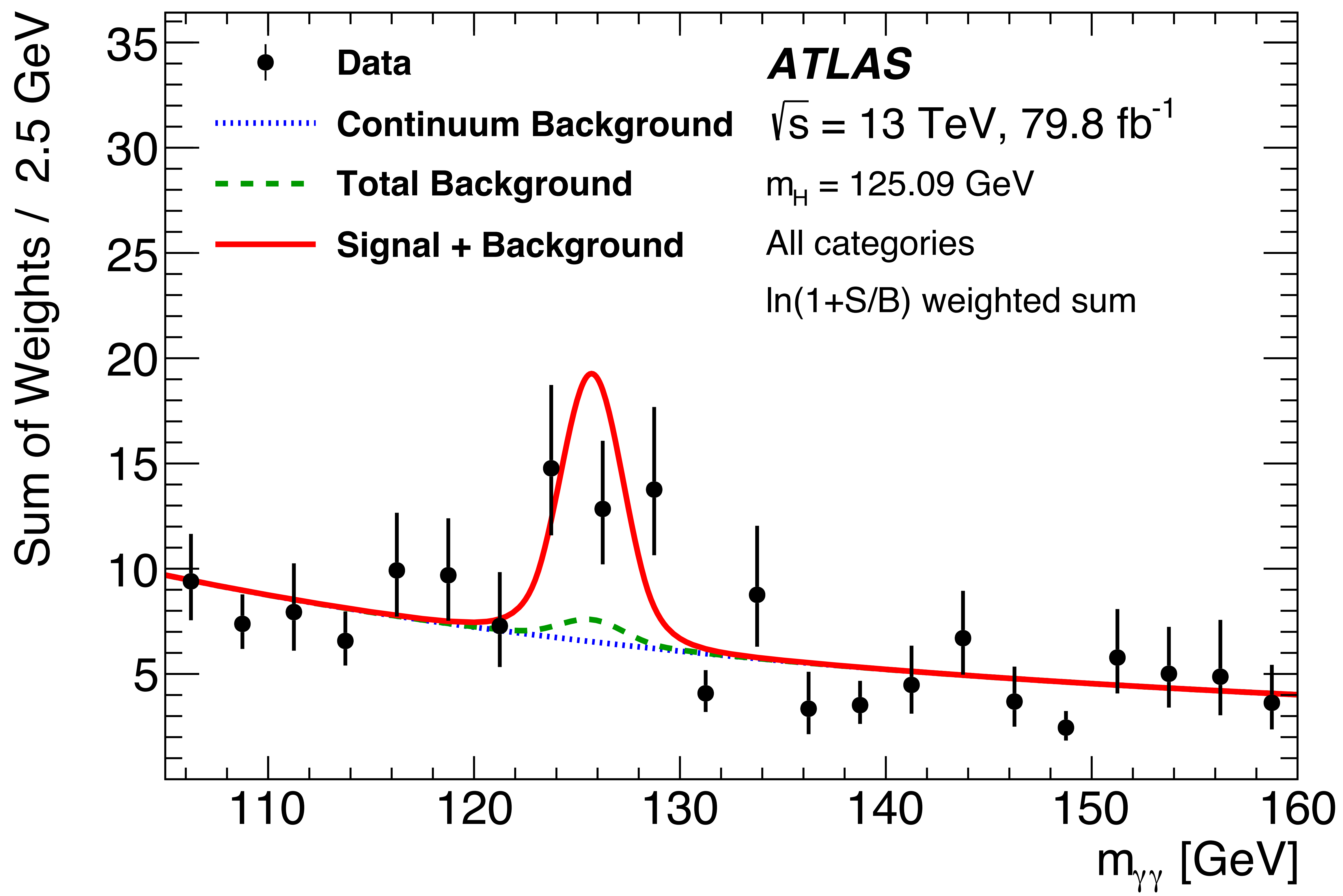
major news of 2018: ATLAS & CMS see events with top-quarks & Higgs simultaneously

CMS > 5-sigma ttH

ATLAS > 5-sigma ttH







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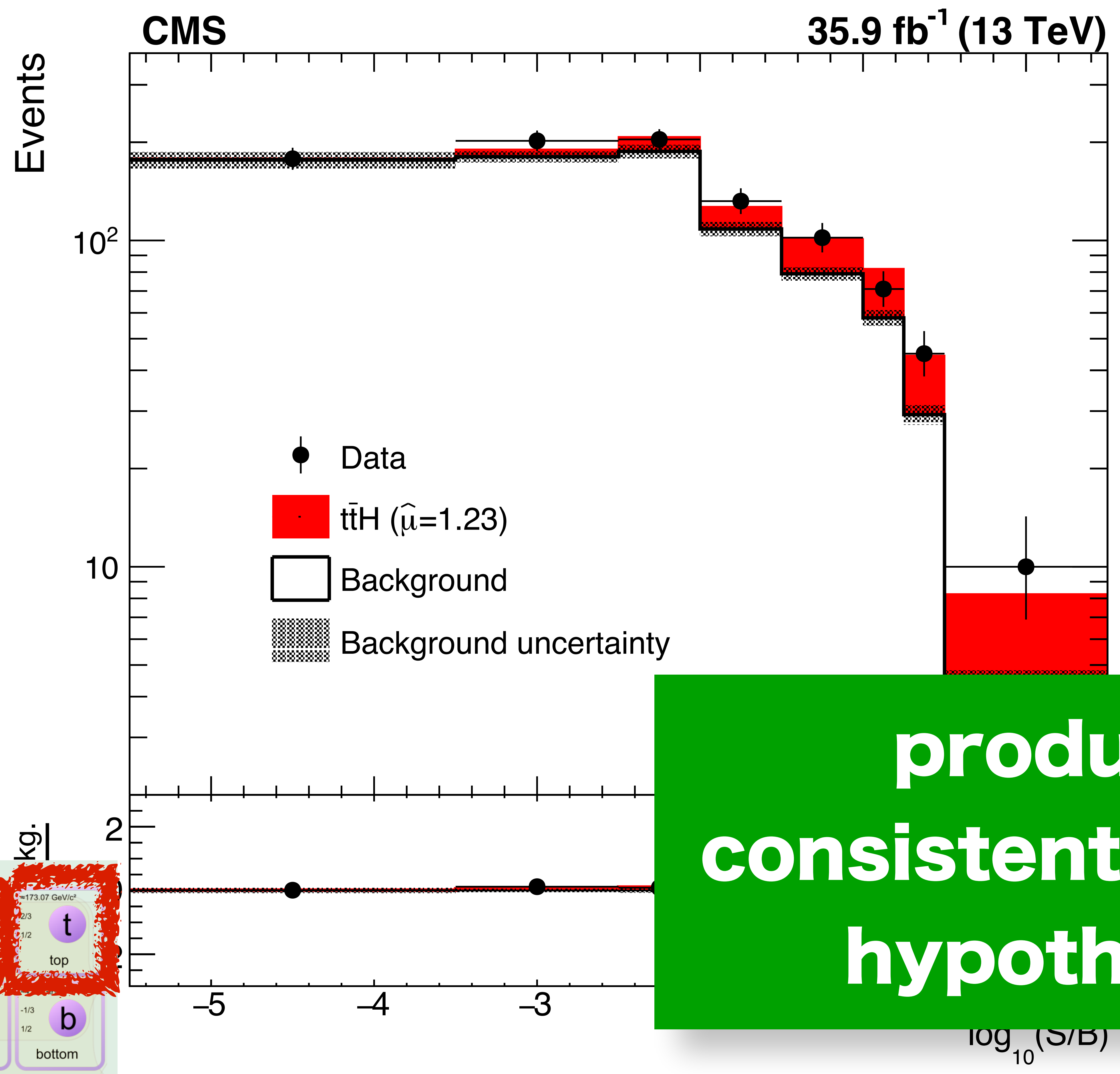
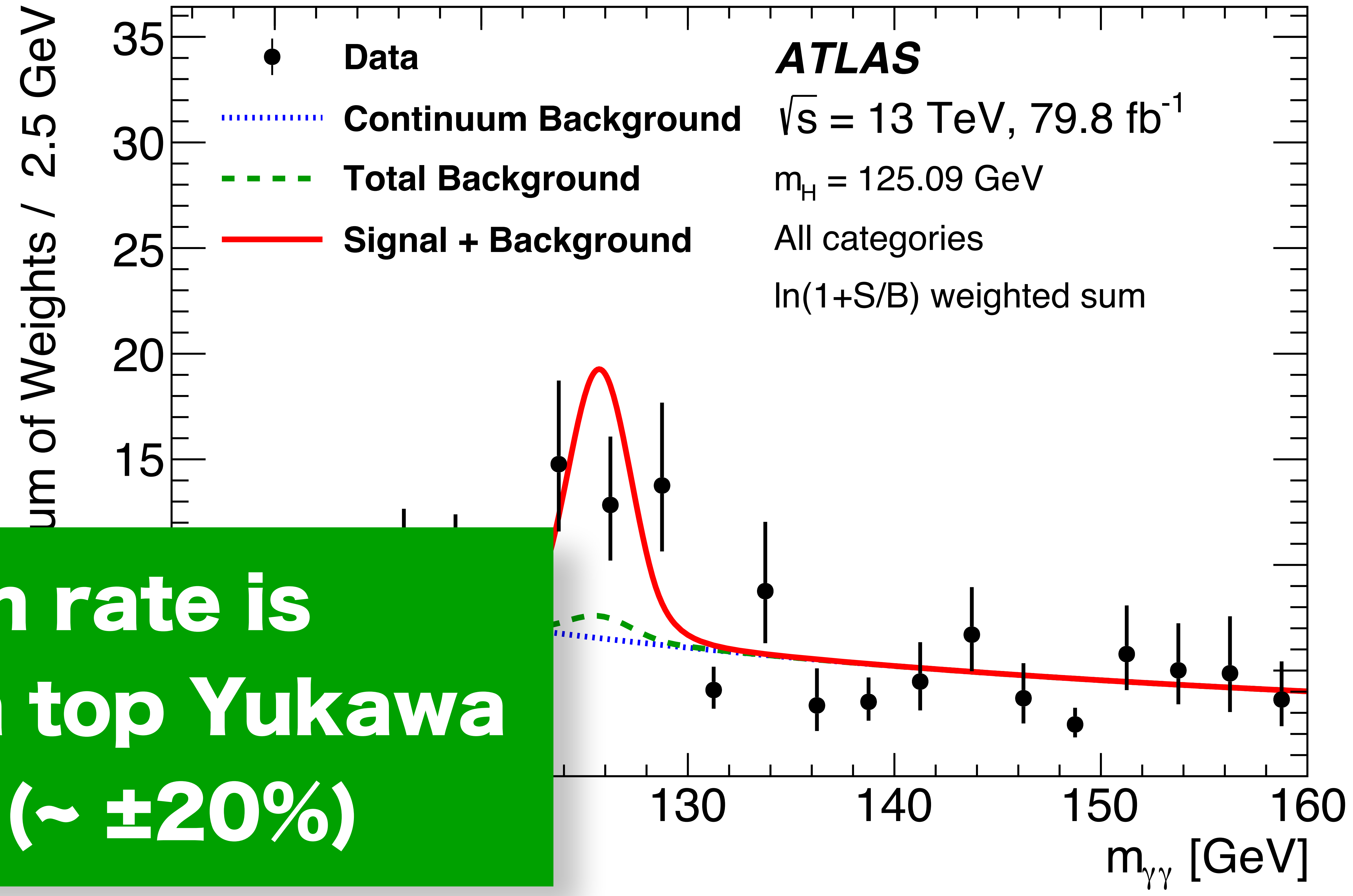
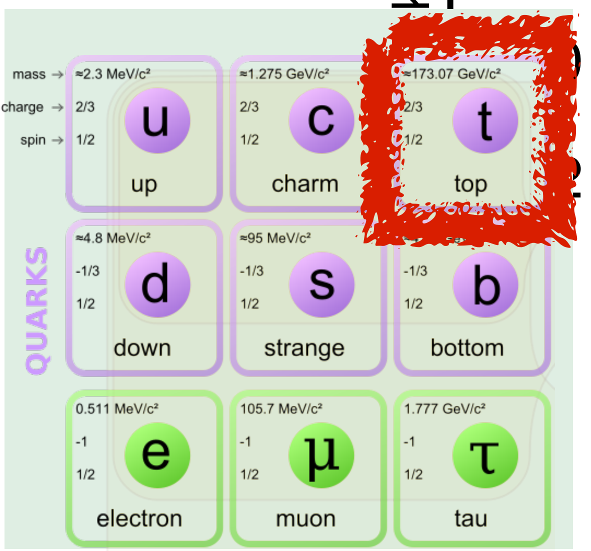


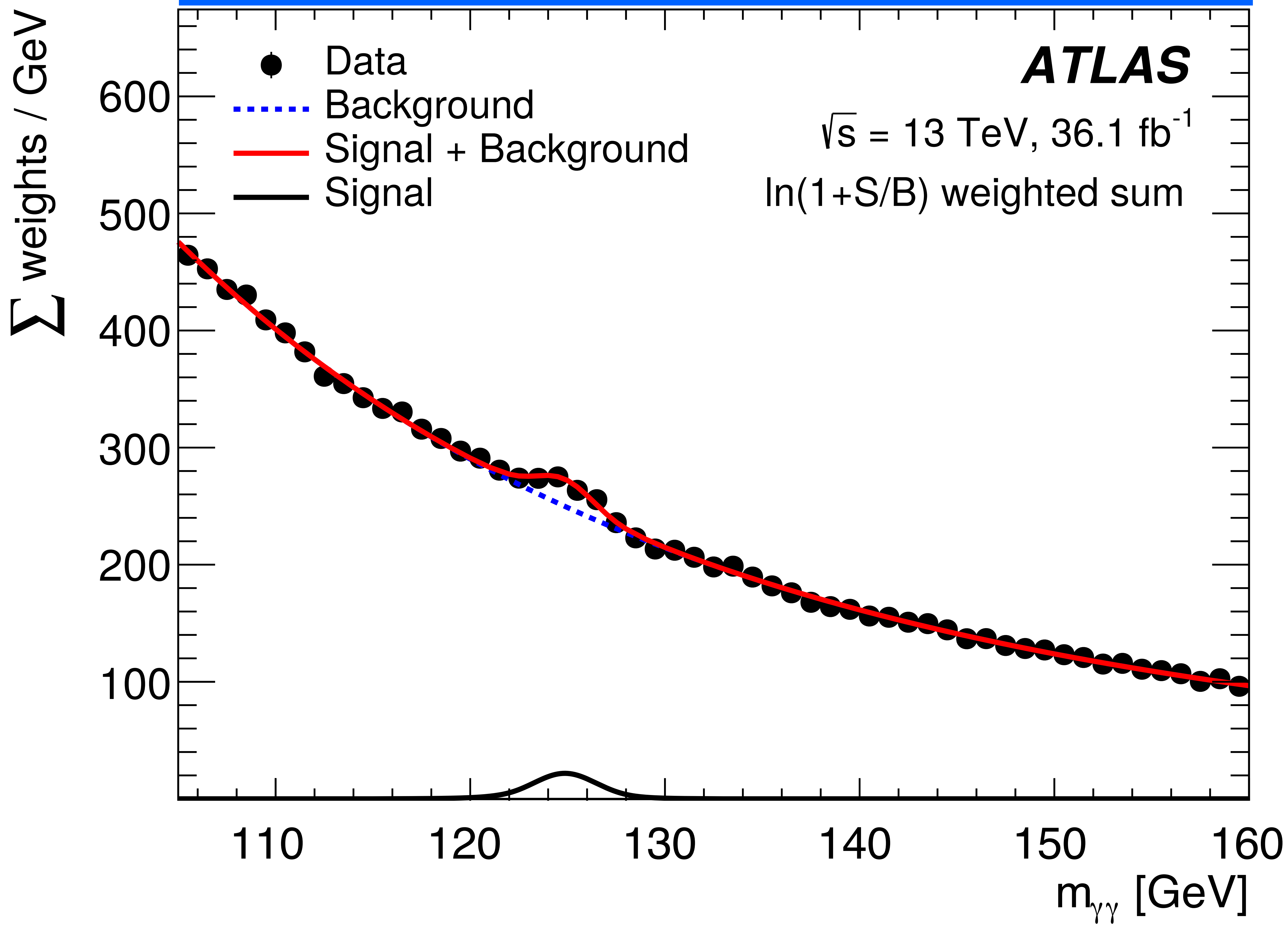




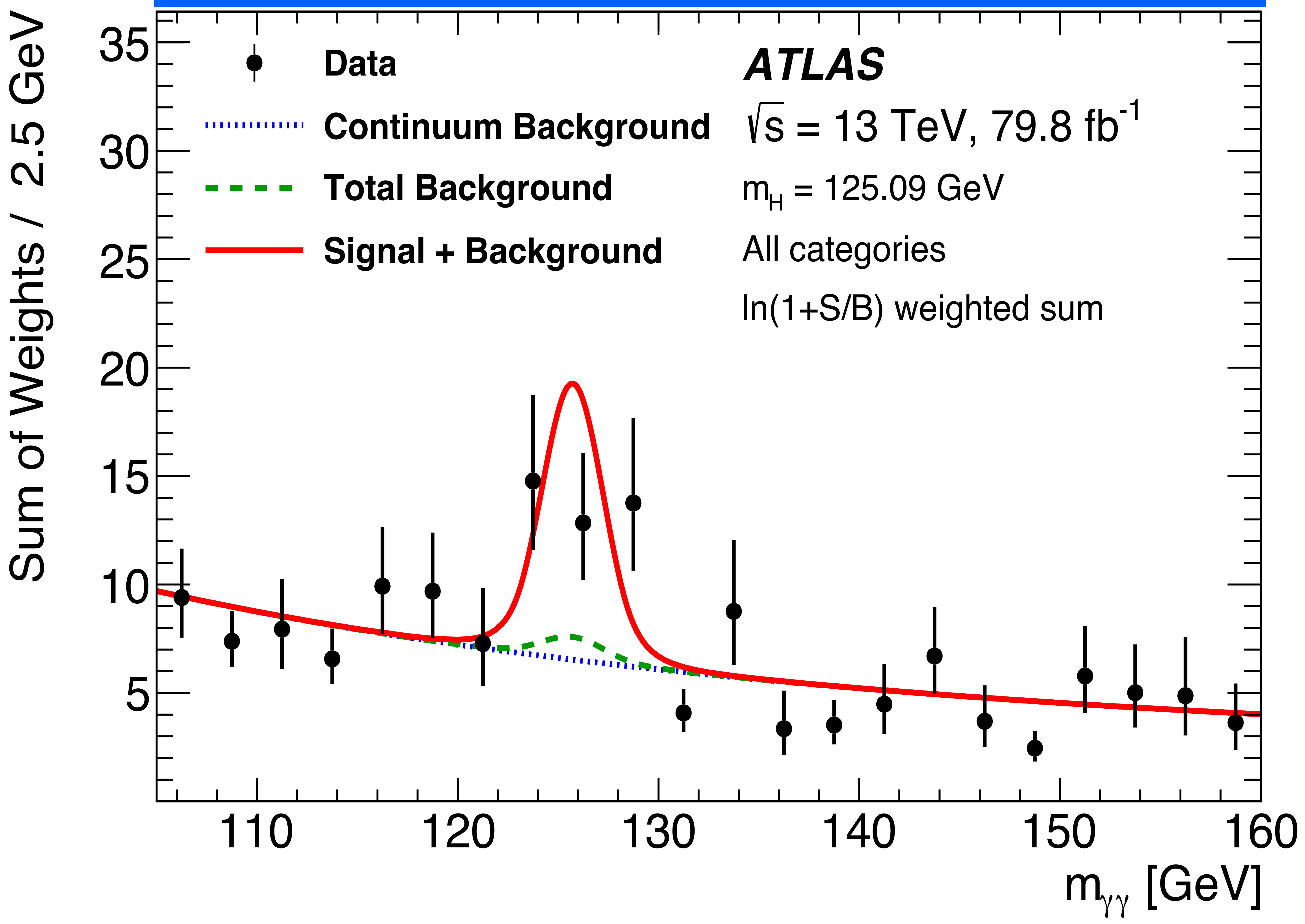
production rate is consistent with top Yukawa hypothesis (~ ±20%)

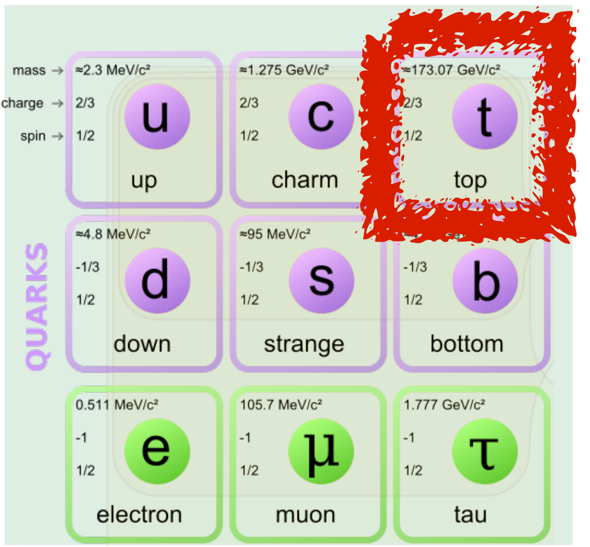
major news of 2018: ATLAS & CMS see events with top-quarks & Higgs simultaneously

$H \to \gamma\gamma$ across all events



in events with top quarks



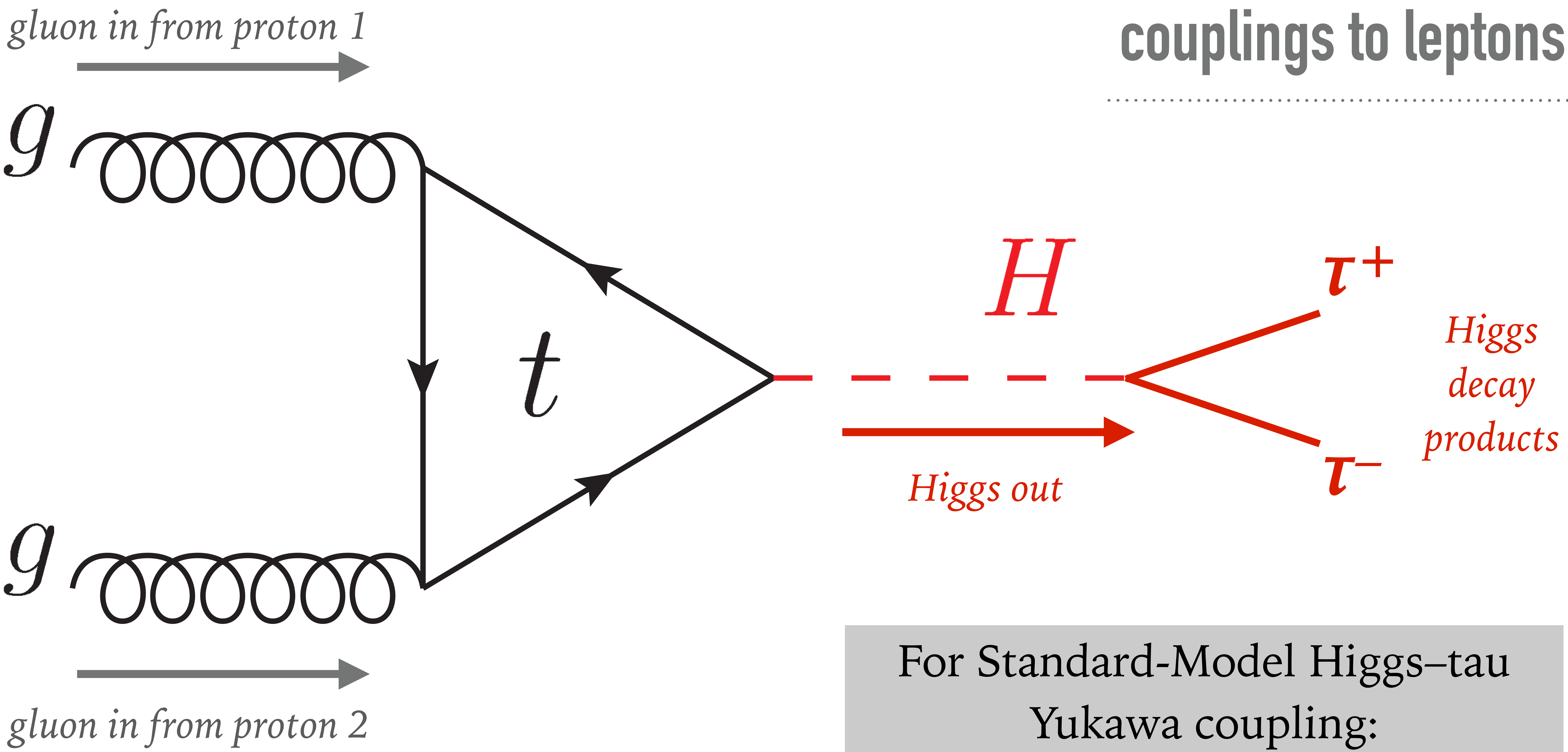


enhanced fraction of Higgs bosons in events with top quarks

→ direct observation of Higgs interaction with tops

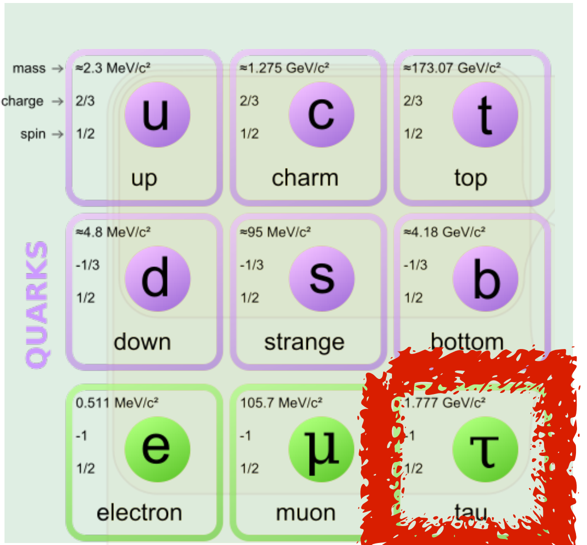
(consistent with SM to c. ±20%)

couplings to leptons?



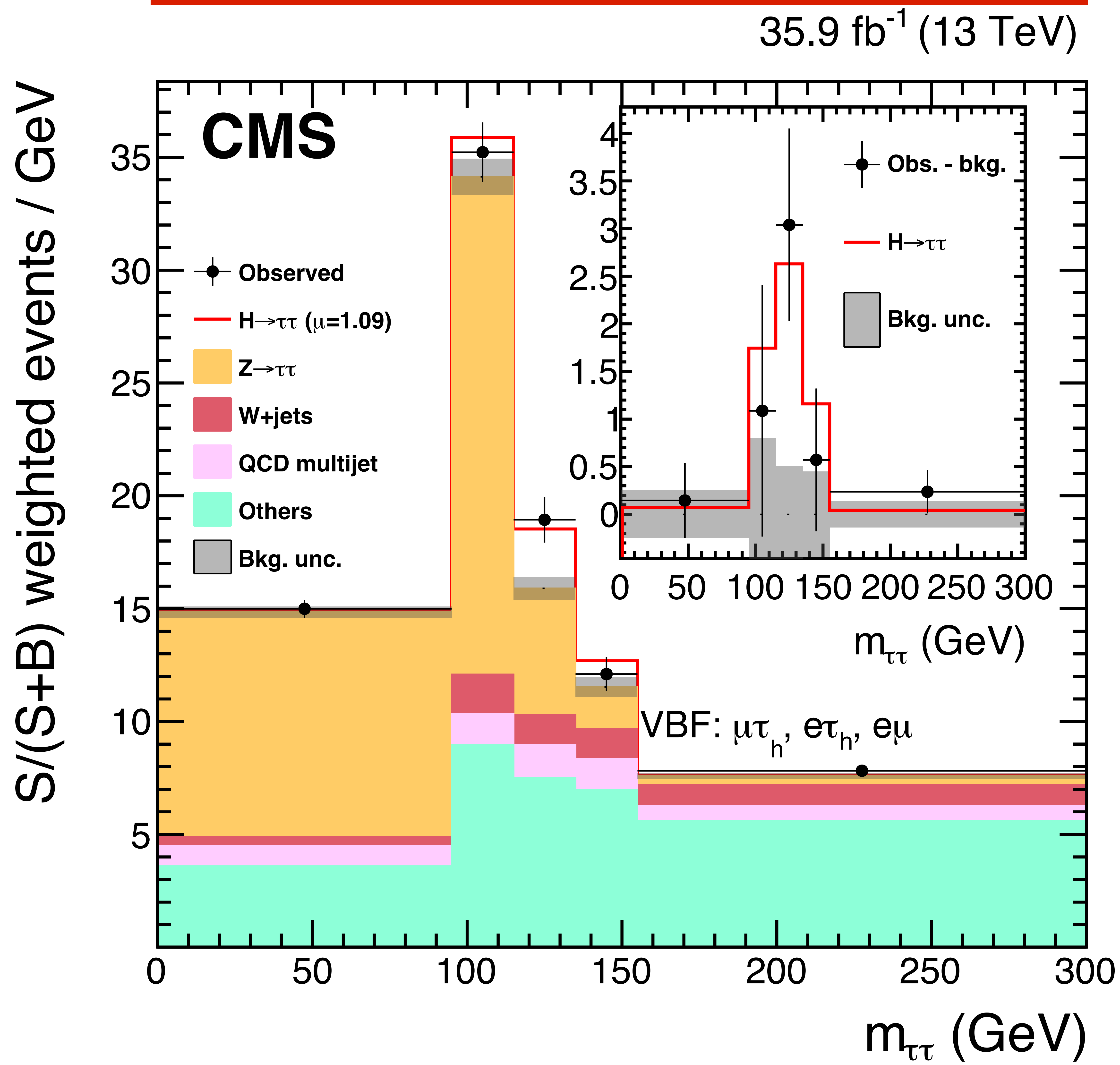
For Standard-Model Higgs–tau Yukawa coupling:

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

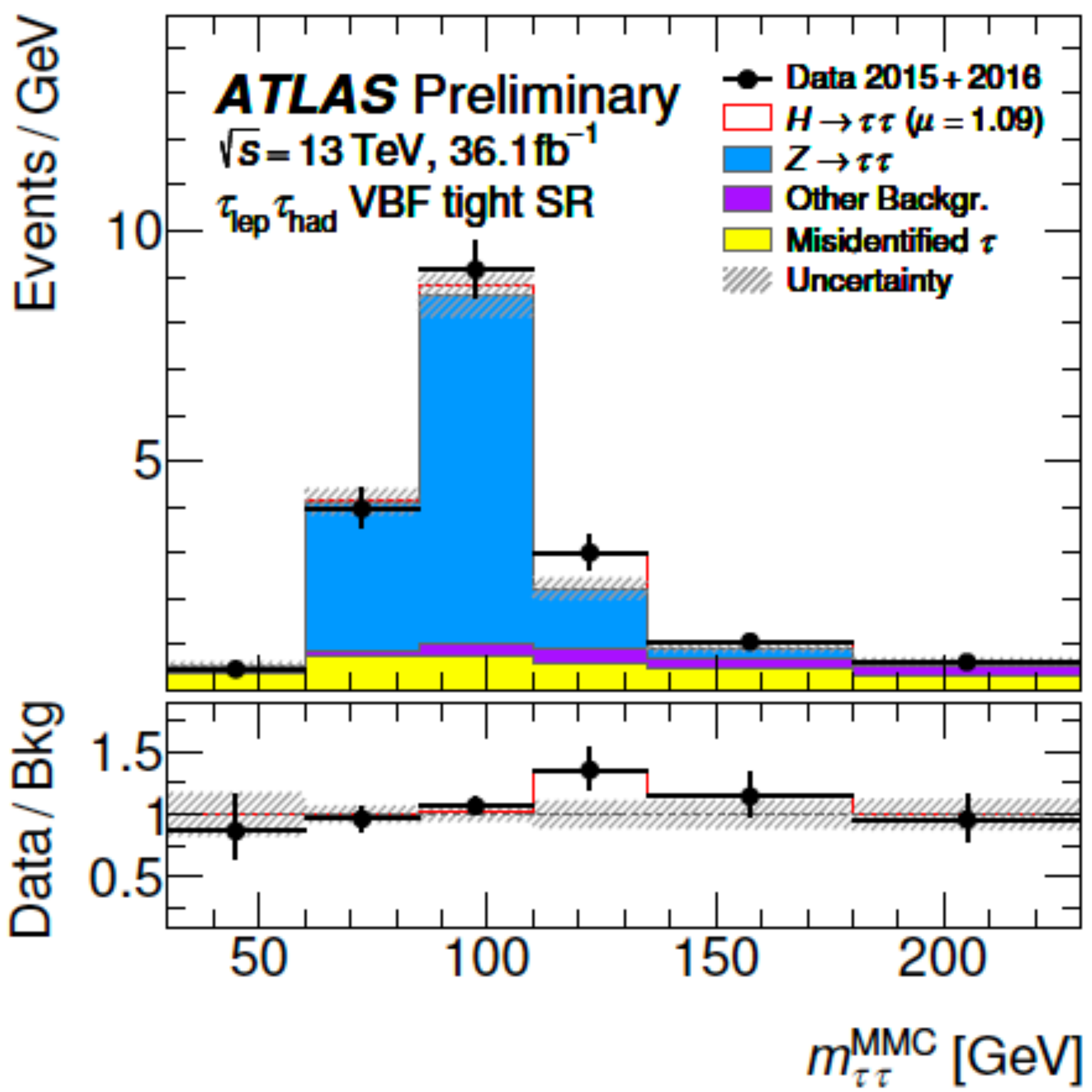


observation of H → ττ

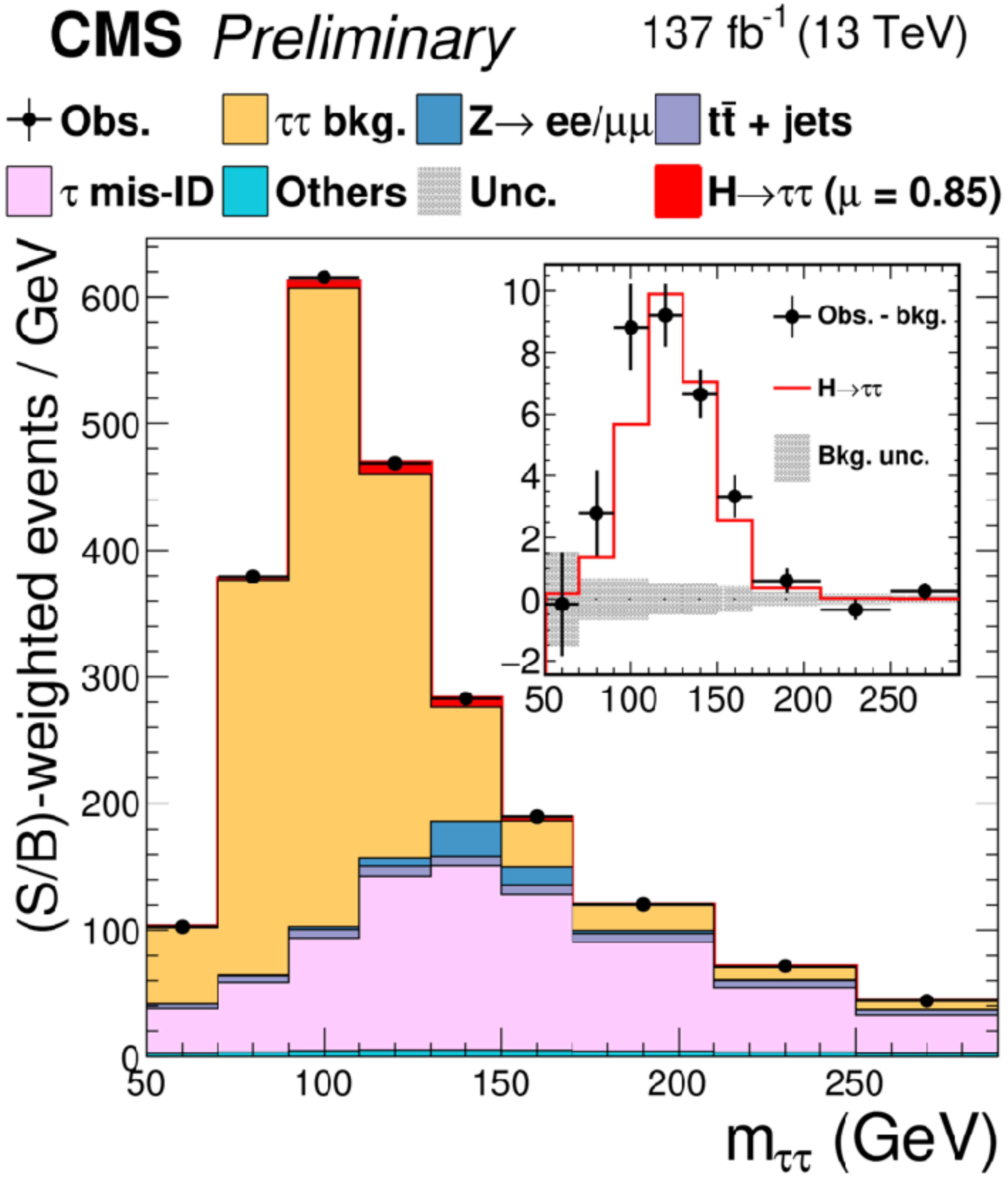
~3 years ago:
CMS >5-sigma H → τ τ



2 years ago:
ATLAS >5-sigma H → τ τ

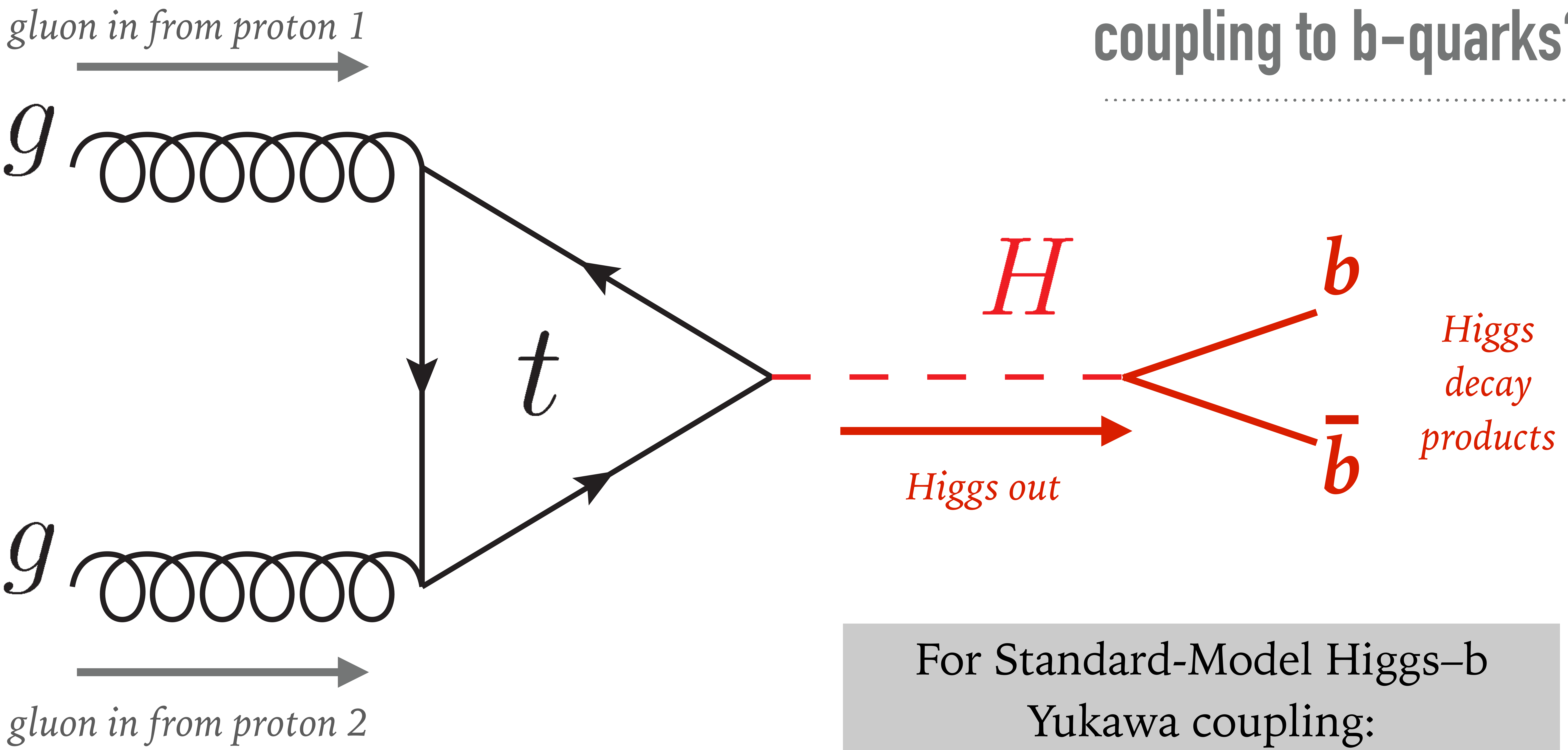


updated H→ ττ



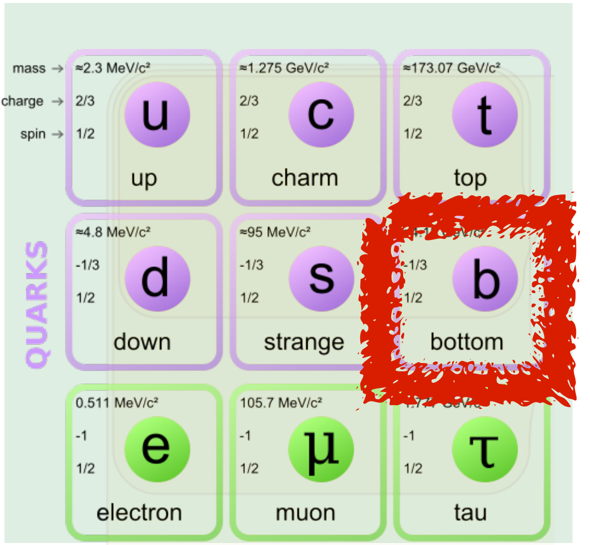
CMS Preliminary
137 fb-1 (13 TeV)
Obs.
ττ bkg.
Z→ ee/μμ
tt̄ + jets
τ mis-ID
Others
Unc.
H→ττ (μ = 0.85)
(S/B)-weighted events / GeV
0
100
200
300
400
500
600
50
100
150
200
250
mττ (GeV)
Obs. - bkg.
H→ττ
Bkg. unc.
−2
0
2
4
6
8
10
50
100
150
200
250

coupling to b-quarks?



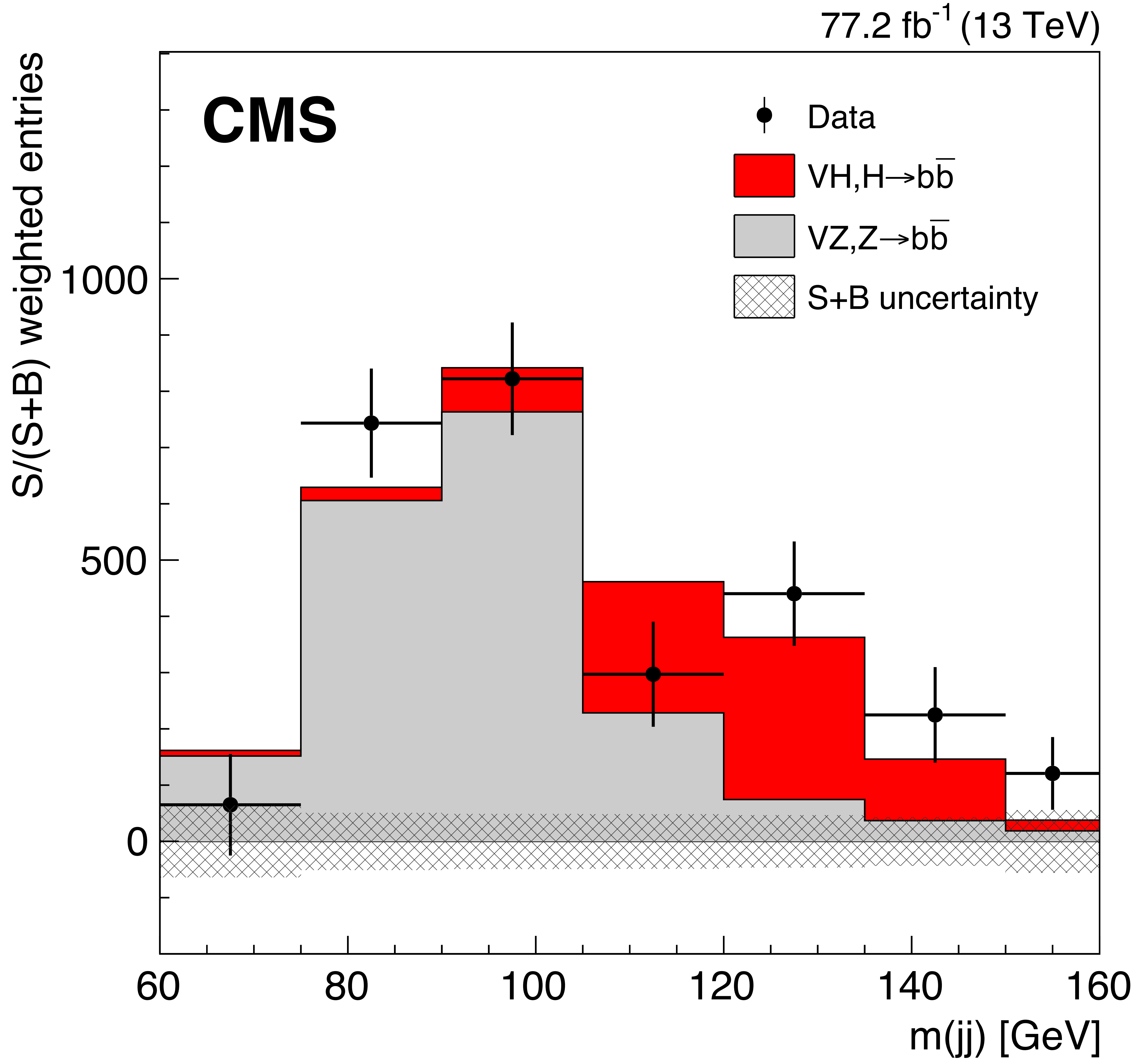
For Standard-Model Higgs–b Yukawa coupling:

~ 58% of Higgs bosons should decay to bb

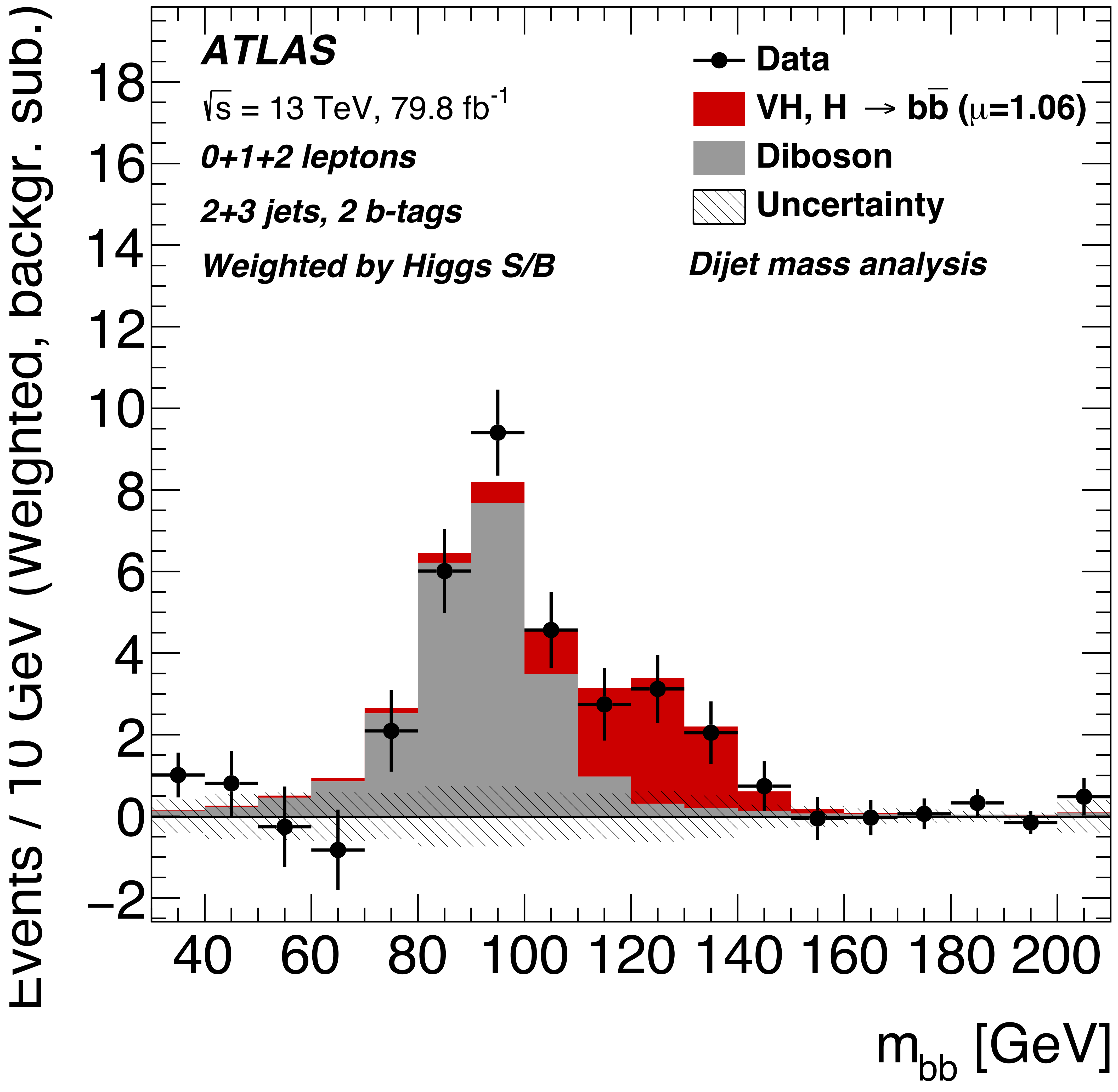


2 years ago, observation of H → bb

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 because they are:
(1) **qualitatively unlike any quantum interaction probed before** (effective charge not quantised),
(2) **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

what could one be saying about it?

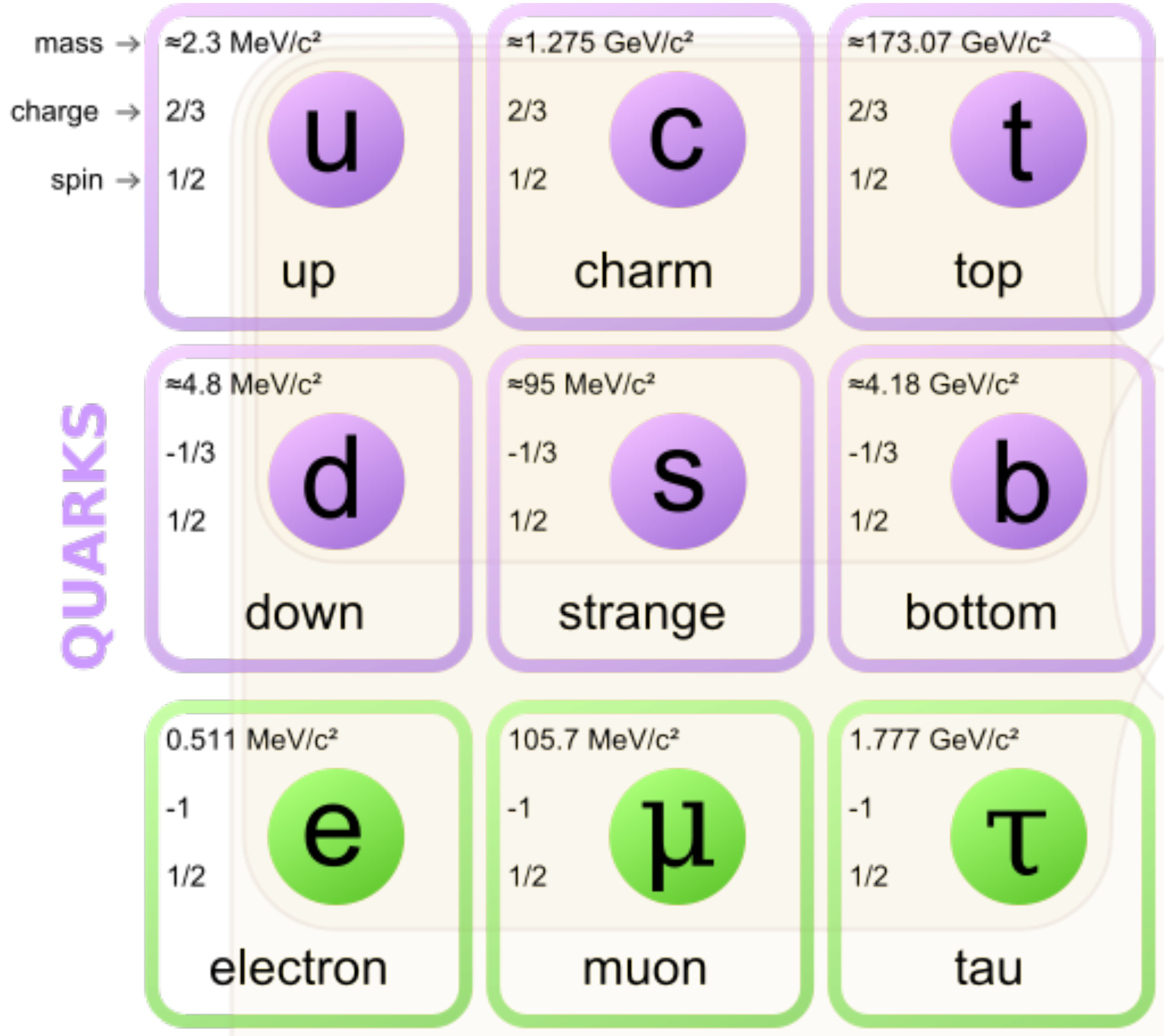
This is a **fifth force, the "Higgs force"**

(up to you to decide whether you prefer to talk about new interactions or new force)

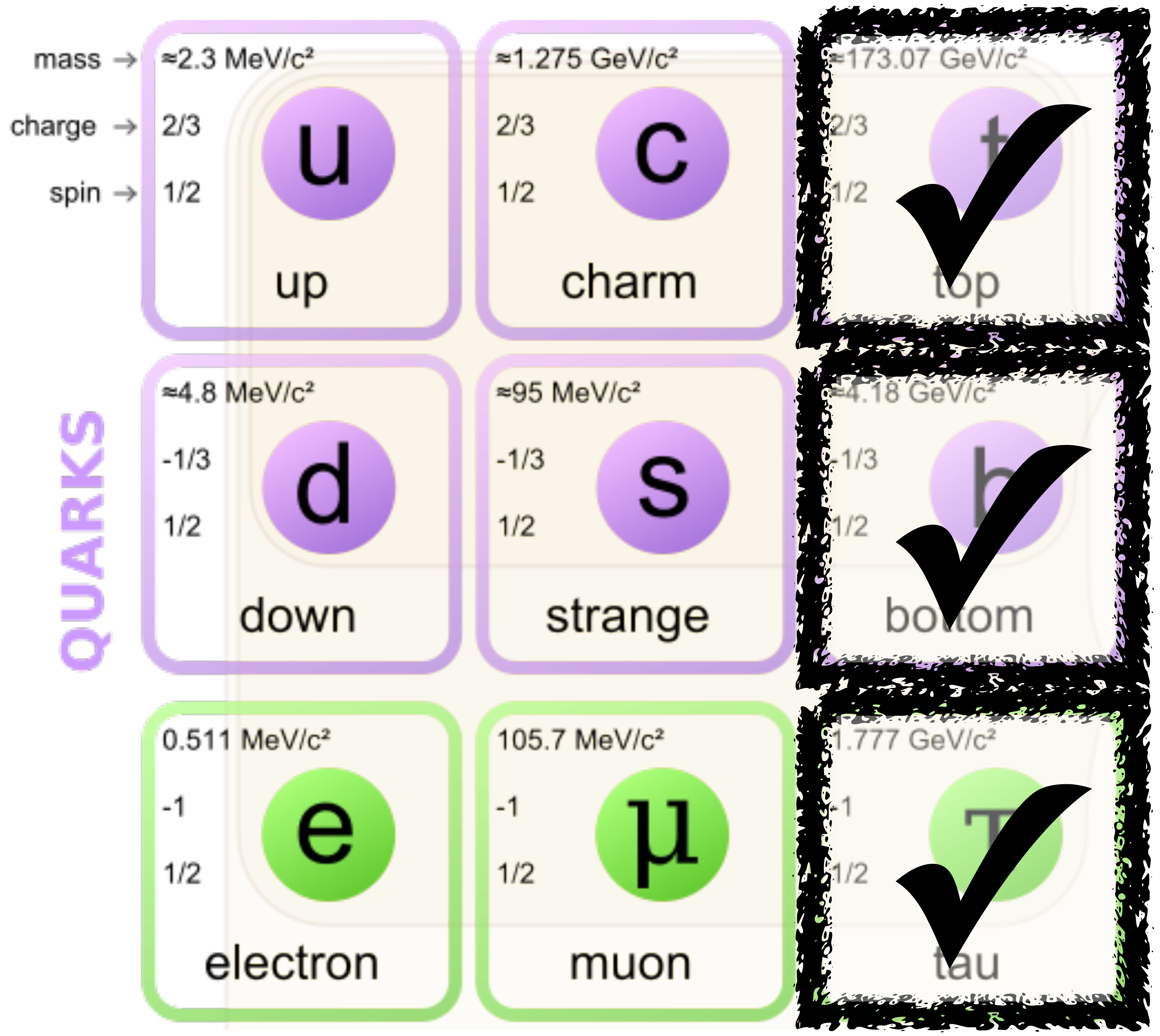
Is this any less important than the discovery of the Higgs boson itself?

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
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

Yukawas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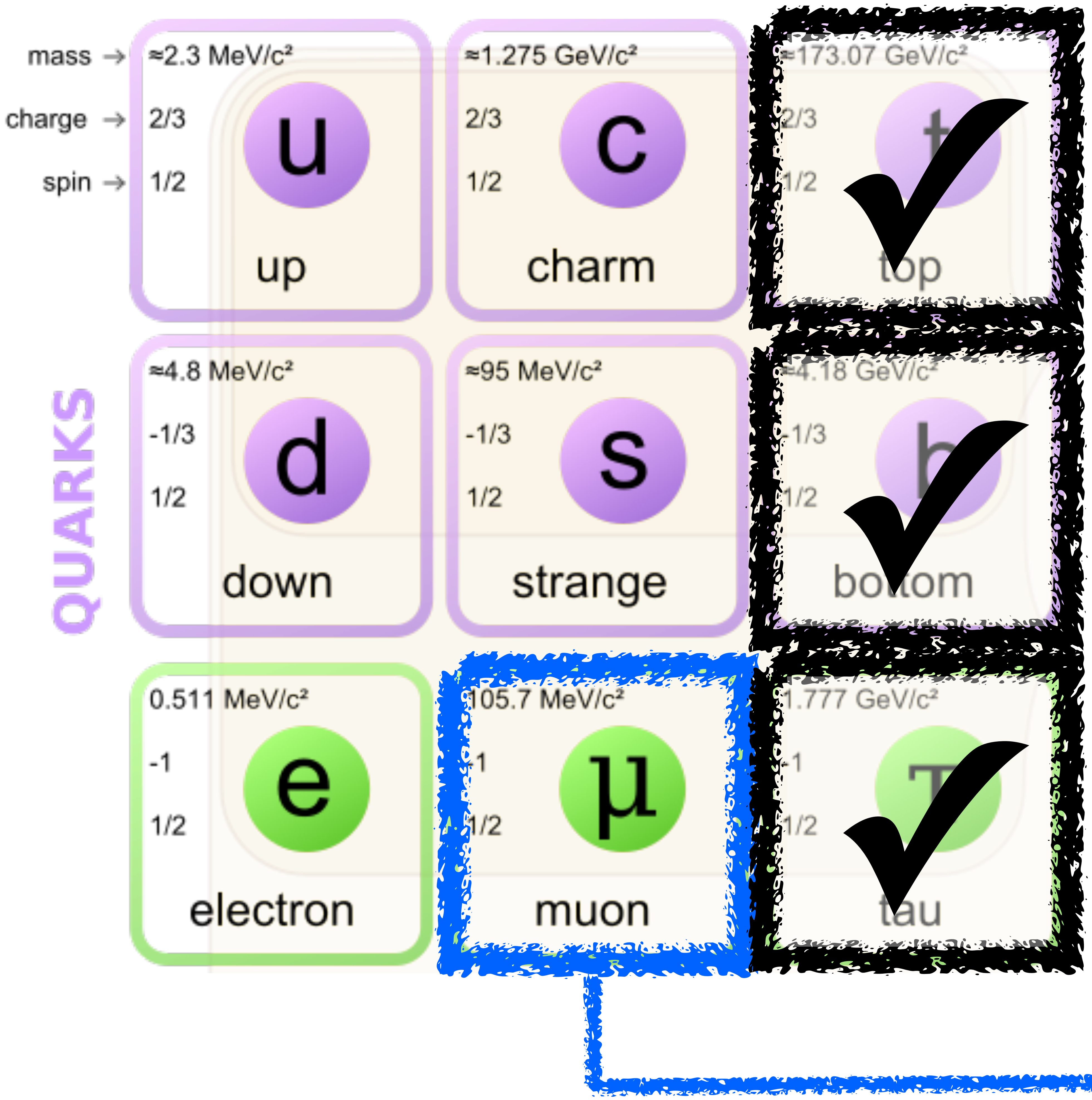
1.777 GeV/c²
-1
1/2
tau

Yukawas



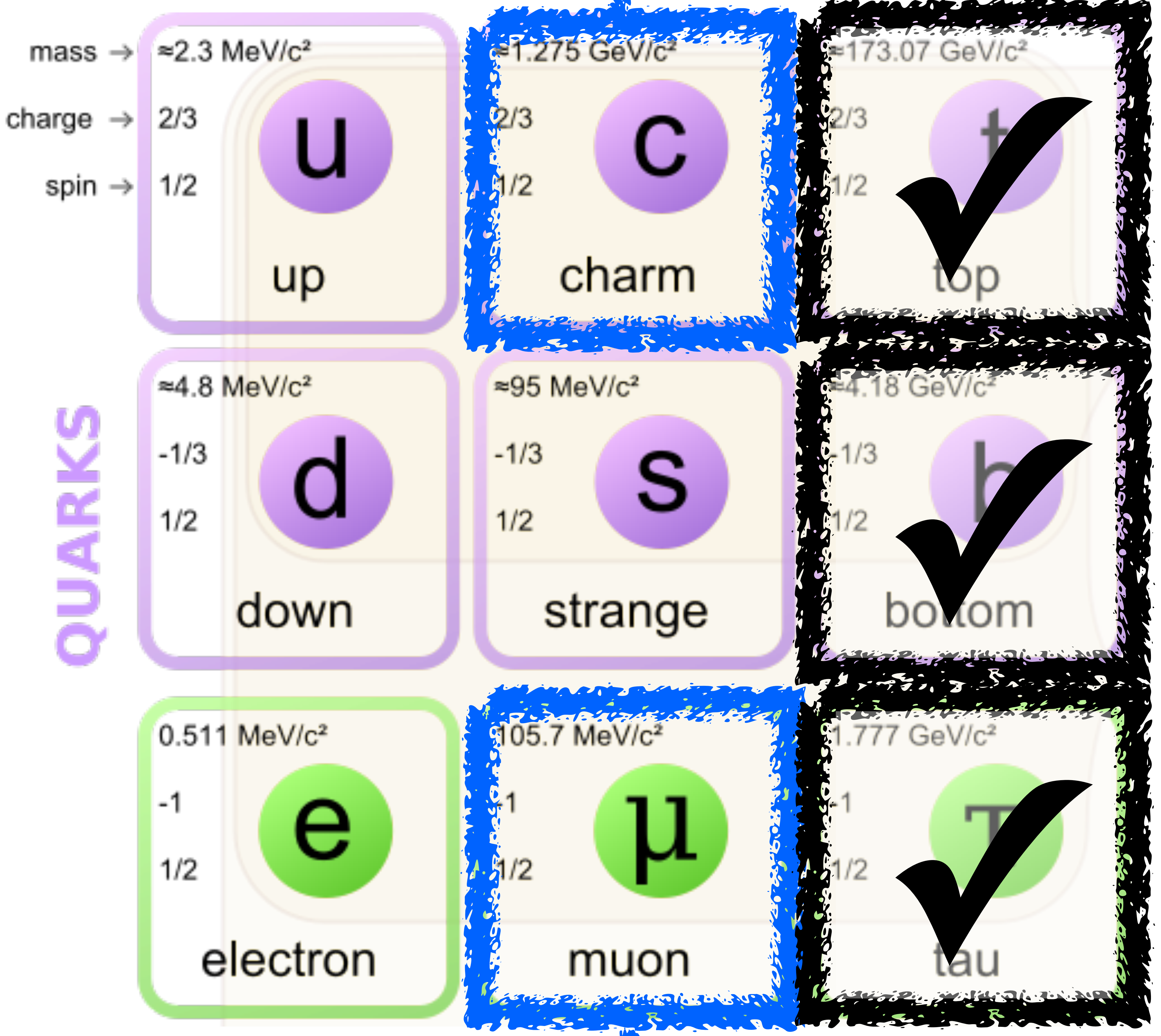
today: first evidence
(1 in 4570 decays)

expect 5σ at HL-LHC,
within about 8 years.

Yukawas

today: no evidence yet
(1 in 35 decays)

needs an e⁺e⁻
or ep collider?



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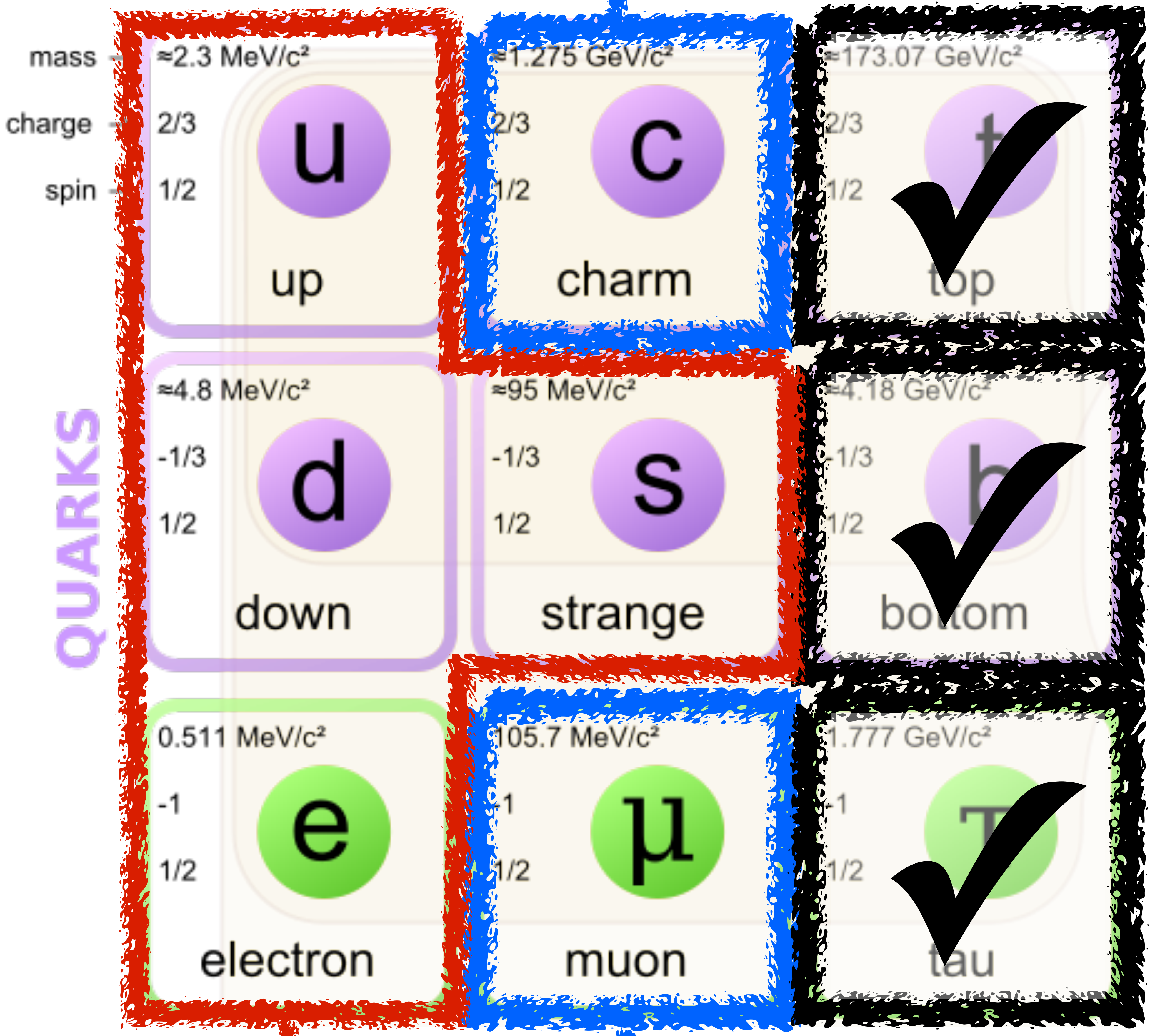

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(1 in 4000 decays)
no clear route to
establishing SM
couplings at 5σ

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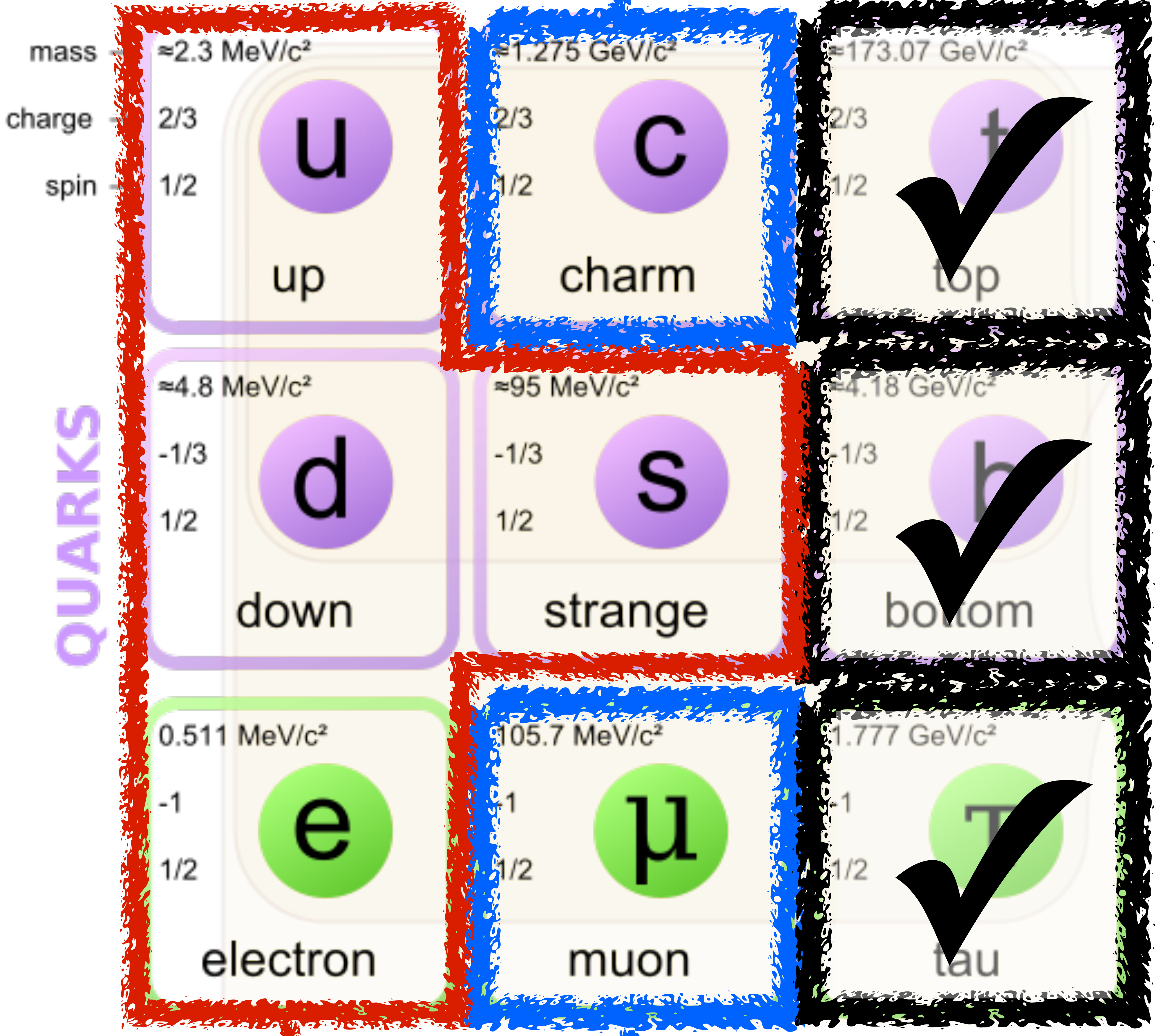
expect 5σ at HL-LHC,
within about 8 years.

Yukawas

today: no evidence yet
(1 in 35 decays)
needs an e^+e^-
or ep collider?

overall normalisation
(related to Higgs width):
needs an e^+e^- collider



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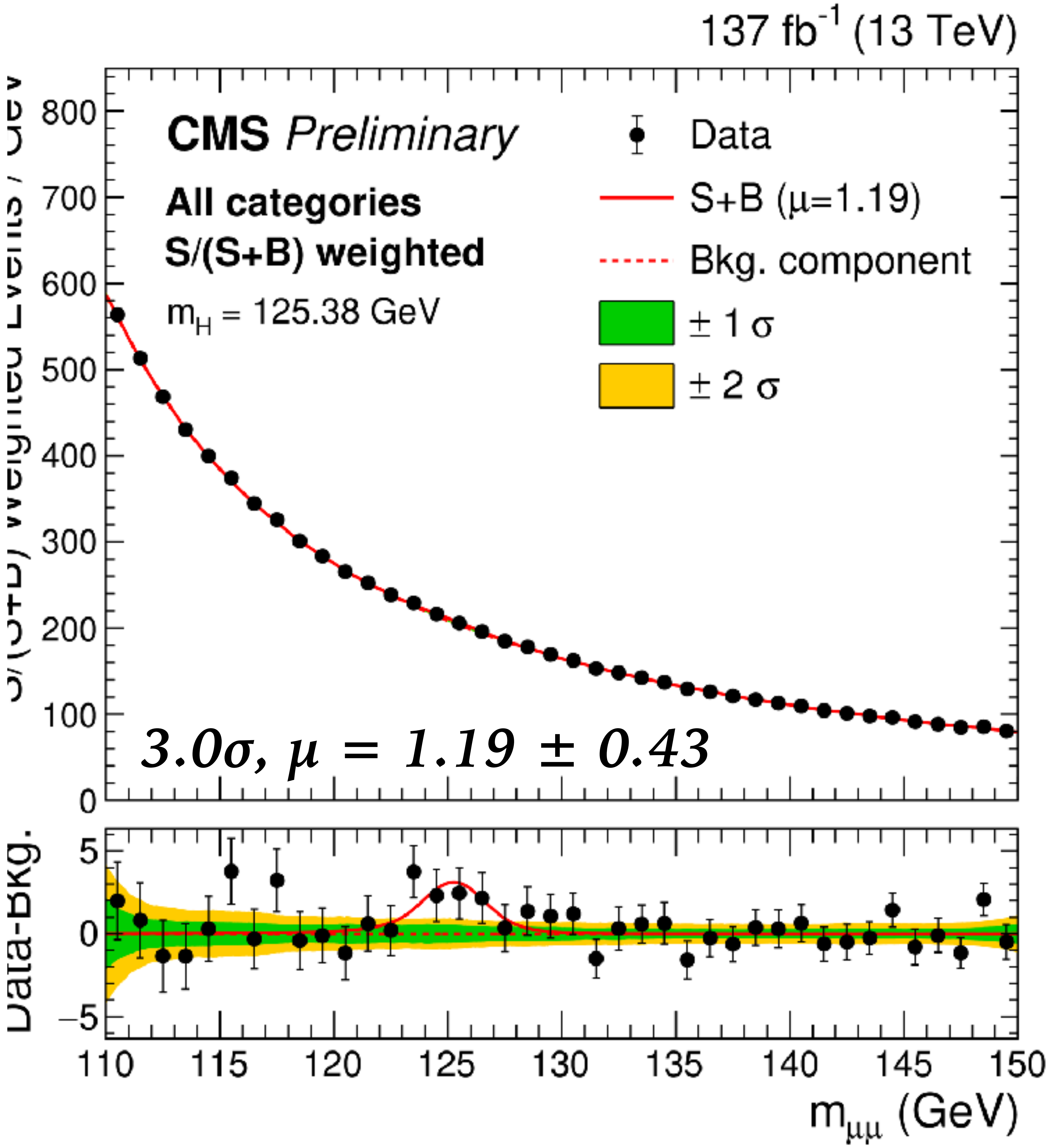
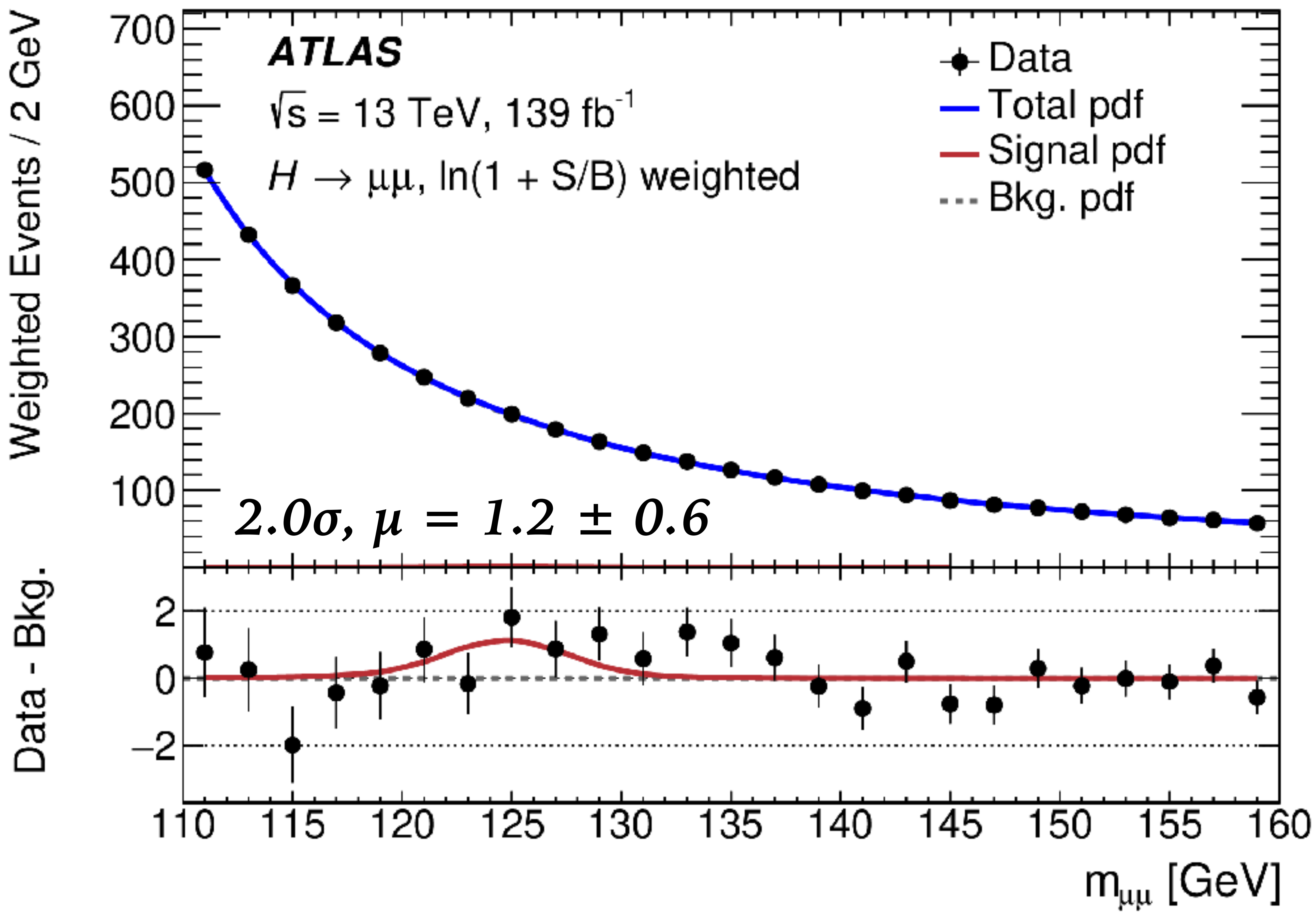
H → μμ (new as of summer 2020)





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

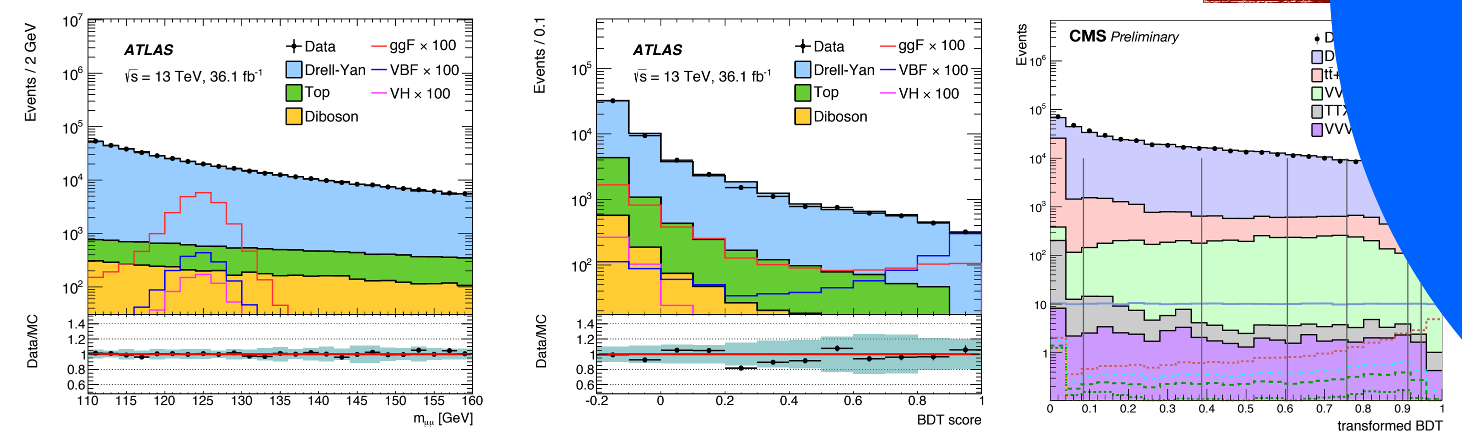
- Good **flavour tagging** perfo
- Large backgrounds from ***tt*** a

Grefe — C. Grefe - Higgs

Search for $H \to \mu\mu$

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

ATLAS
- Use **BDT to select events in 2 VBF** categories (m_{jj}, $p_T^{\mu\mu}$, $|\Delta\eta_{jj}|$, ΔR_{jj}, etc.)
- All other events categorised in 6 *ggF* categories based on $p_T^{\mu\mu}$ and $|\Delta\eta_{\mu}|$

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

Grefe — C. Grefe - Higgs couplings to ferm

so much more to do with the Higgs sector

[LHCP conf. 2018]

EFT approach

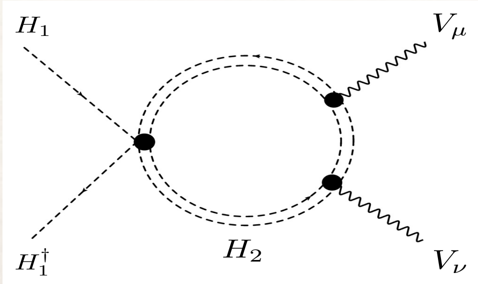
Well-defined theoretical approach
Assumes New Physics states are heavy
Write Effective Lagrangian with only light (SM) particles
BSM effects can be incorporated as a momentum expansion

dimension-6 dimension-8

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

BSM effects SM particles

example: 2HDM



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

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

Sanz

The Higgs potential

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

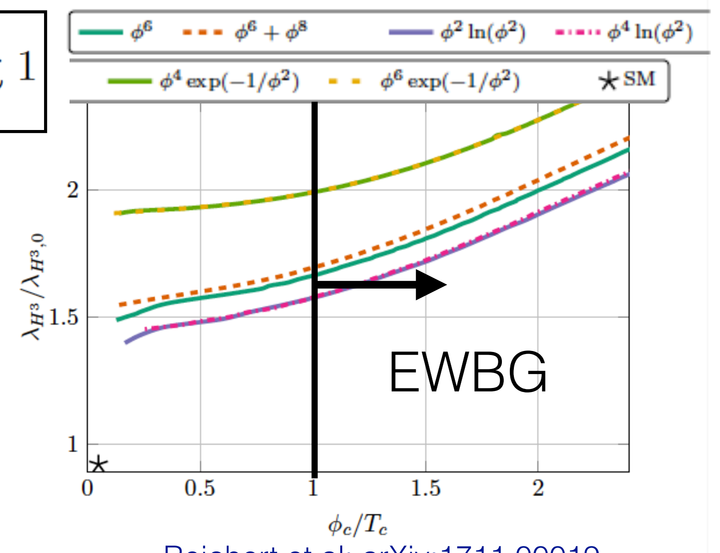
Fixed values in the SM: $\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}$

Measuring λ_{HHH} and λ_{HHHH} tests the SM

What can measuring λ_{HHH} tell us?

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

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

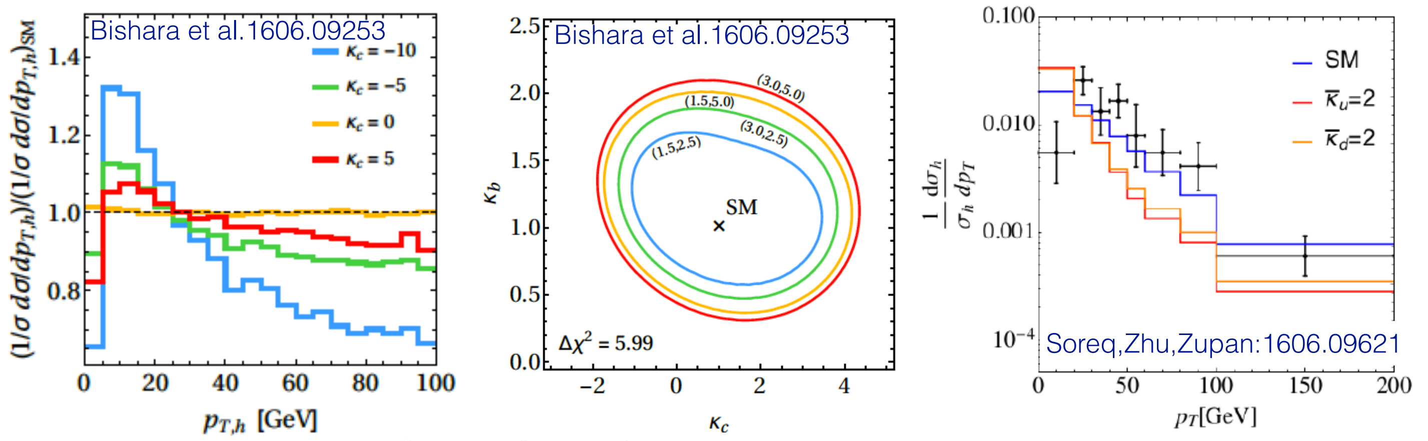


Reichert et al: arXiv:1711.00019

Vryonidou LHCP2018 20

Light quark Yukawas (2)

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



κ_c LHC Run I: $[-16, 18]$
LHC Run II: $[-1.4, 3.8]$
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

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

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

dark matter

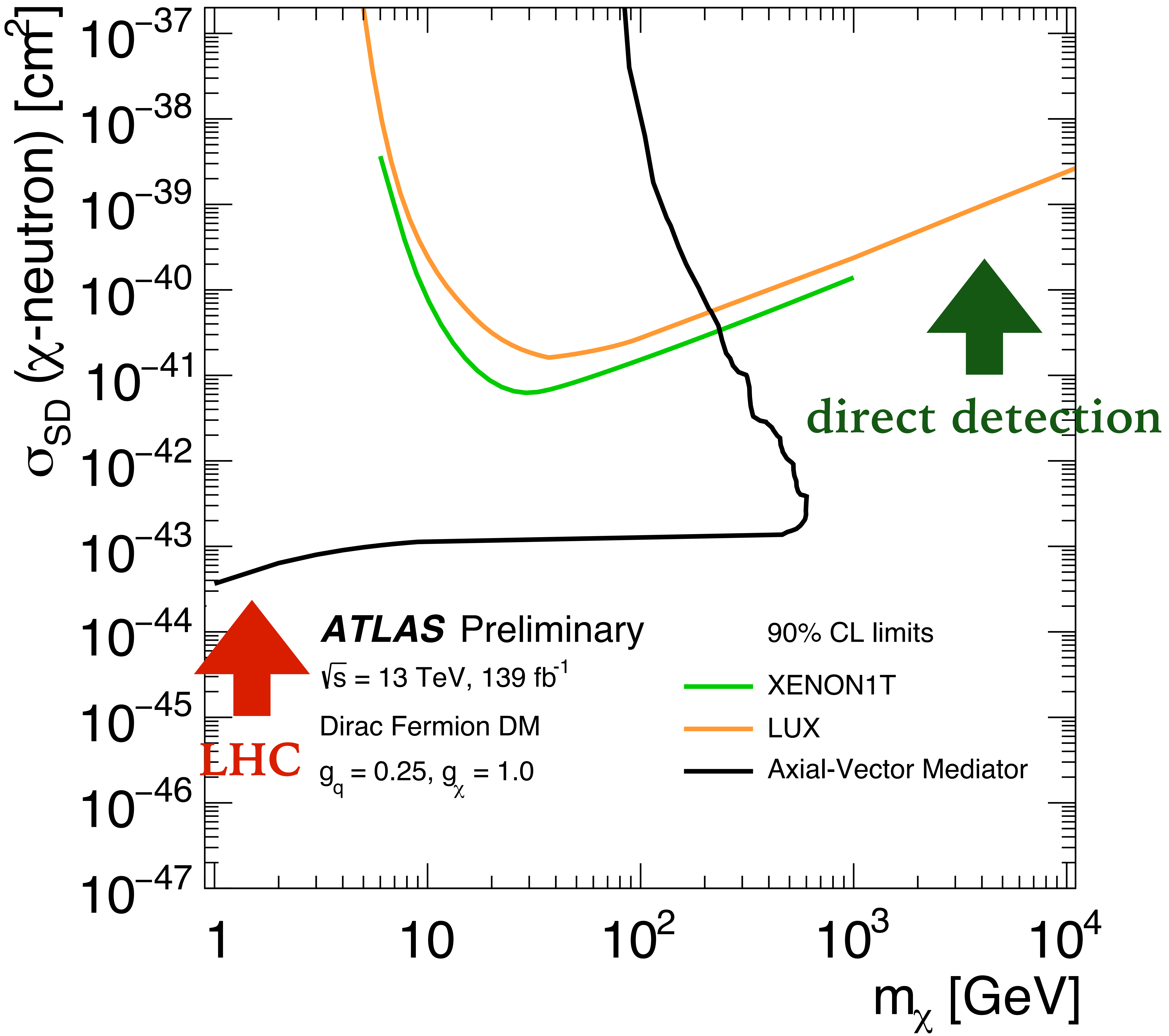

Observations
from starlight
Observations from
21 cm hydrogen
100
50
Velocity
(km s^{-1})
Expected from
the visible disk
Rotation curve of spiral galaxy Messier 33
10,000
20,000
30,000
40,000
Distance (light years)

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

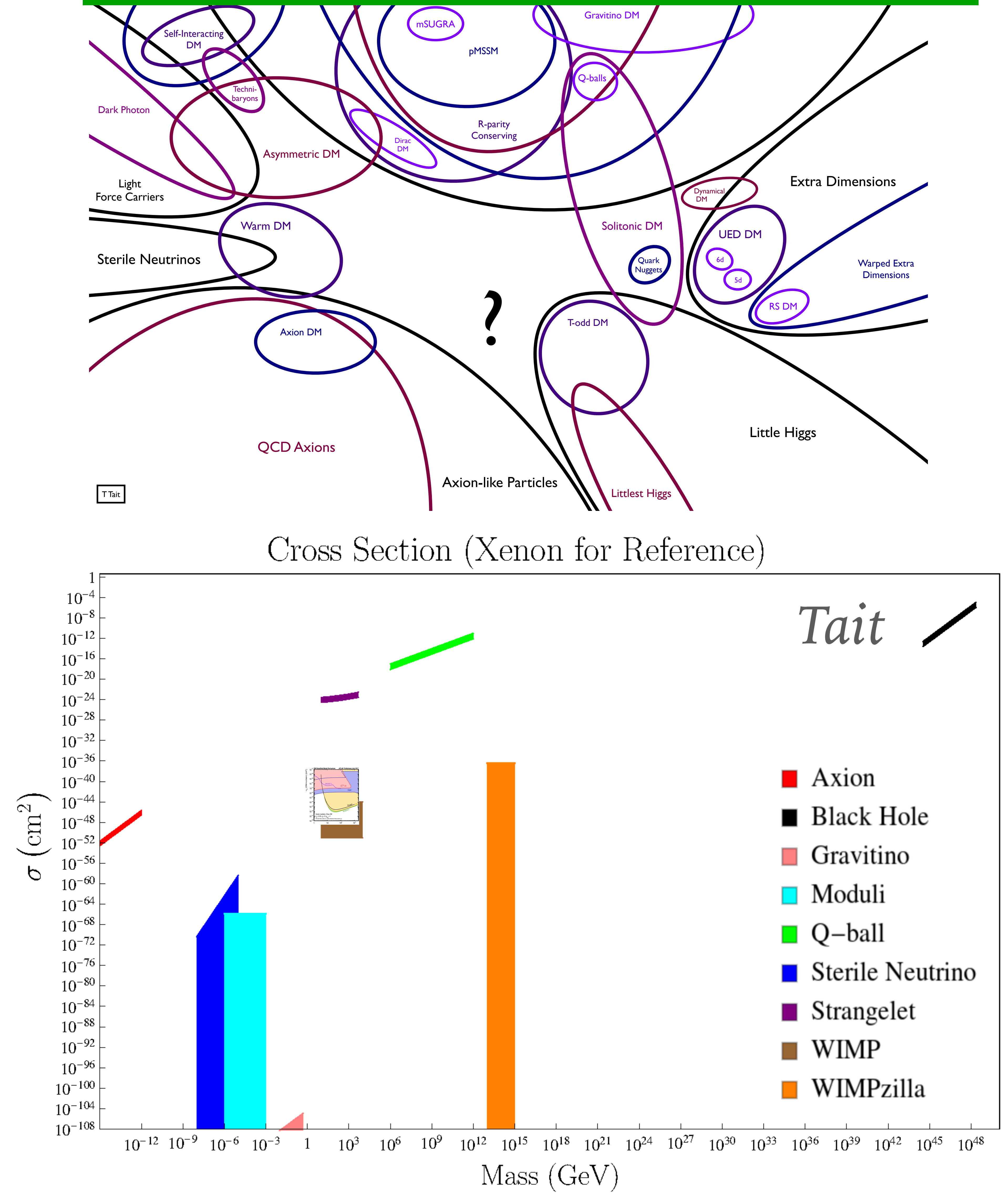


Figure 1. *Graphical representation of the (incomplete) landscape of candidates. Above, the landscape of dark matter candidates due to T. Tait. Below, the range of dark matter candidates' masses and interaction cross sections with a nucleus of Xe (for illustrative purposes) compiled by L. Pearce. Dark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

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

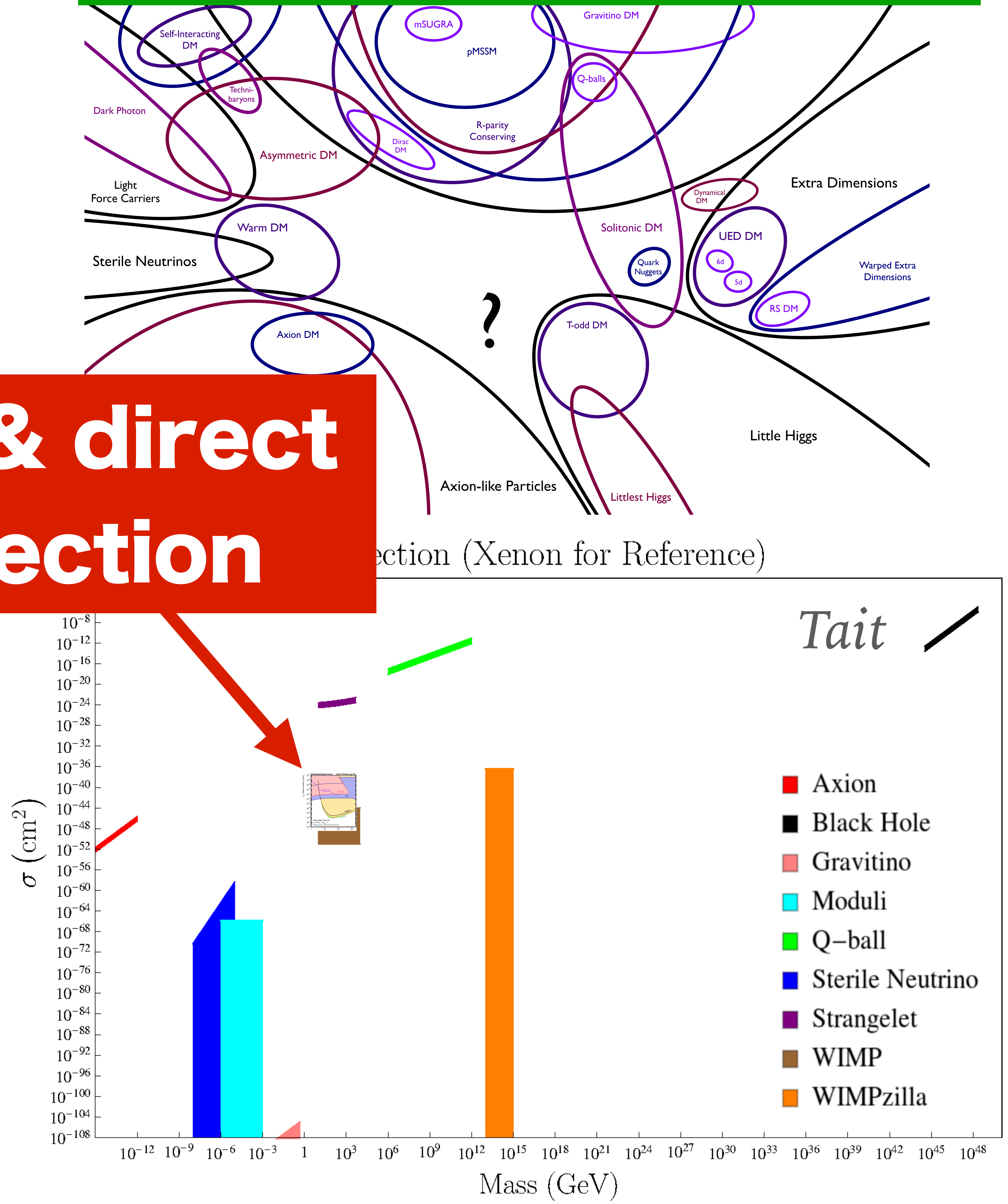
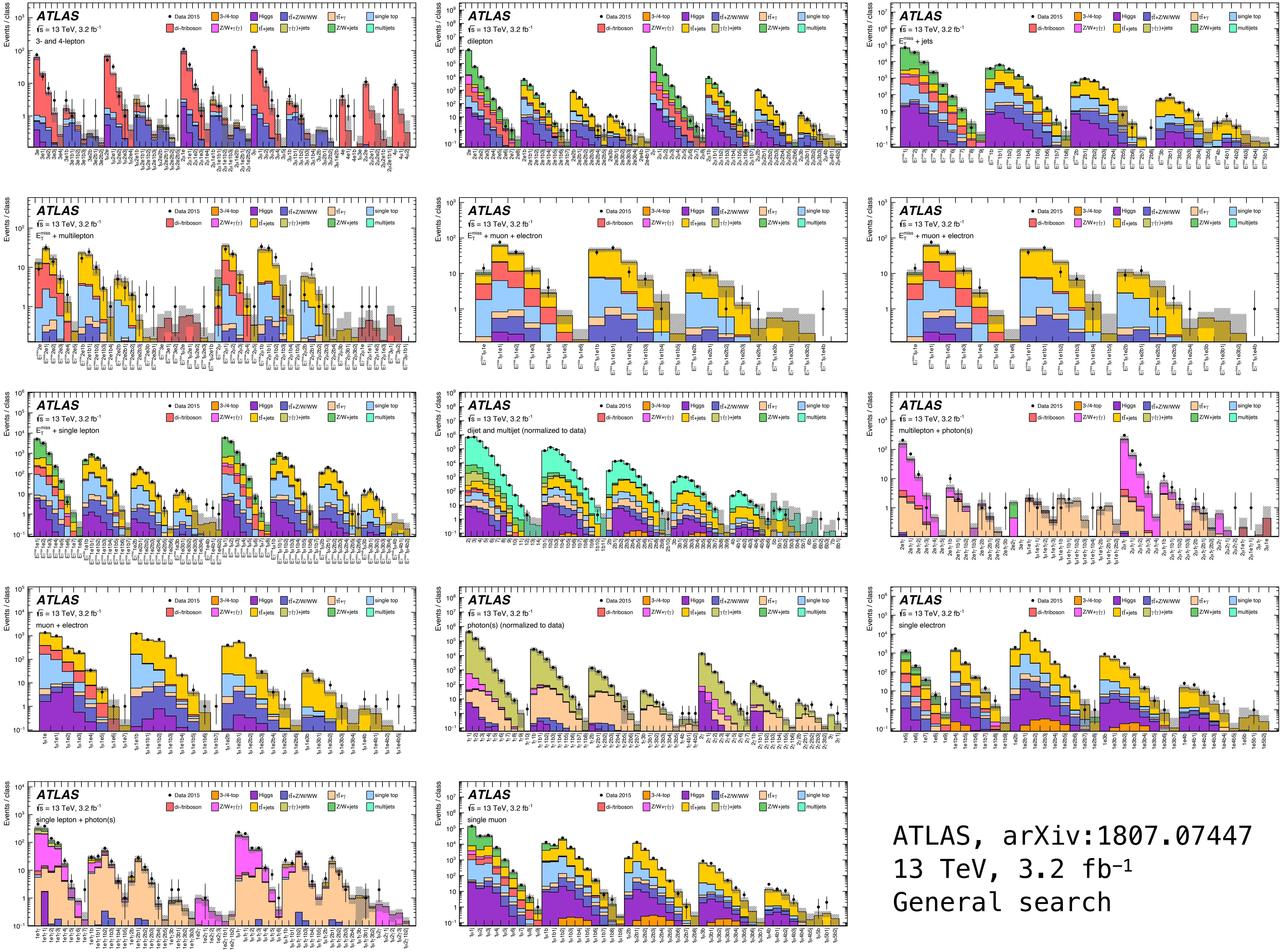


Figure 1. *Graphical representation of the (incomplete) landscape of candidates. Above, the landscape of dark matter candidates due to T. Tait. Below, the range of dark matter candidates' masses and interaction cross sections with a nucleus of Xe (for illustrative purposes) compiled by L. Pearce. Dark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

LHC searches are broad-band (here, a "general search" with 704 event classes, 10^5 bins)



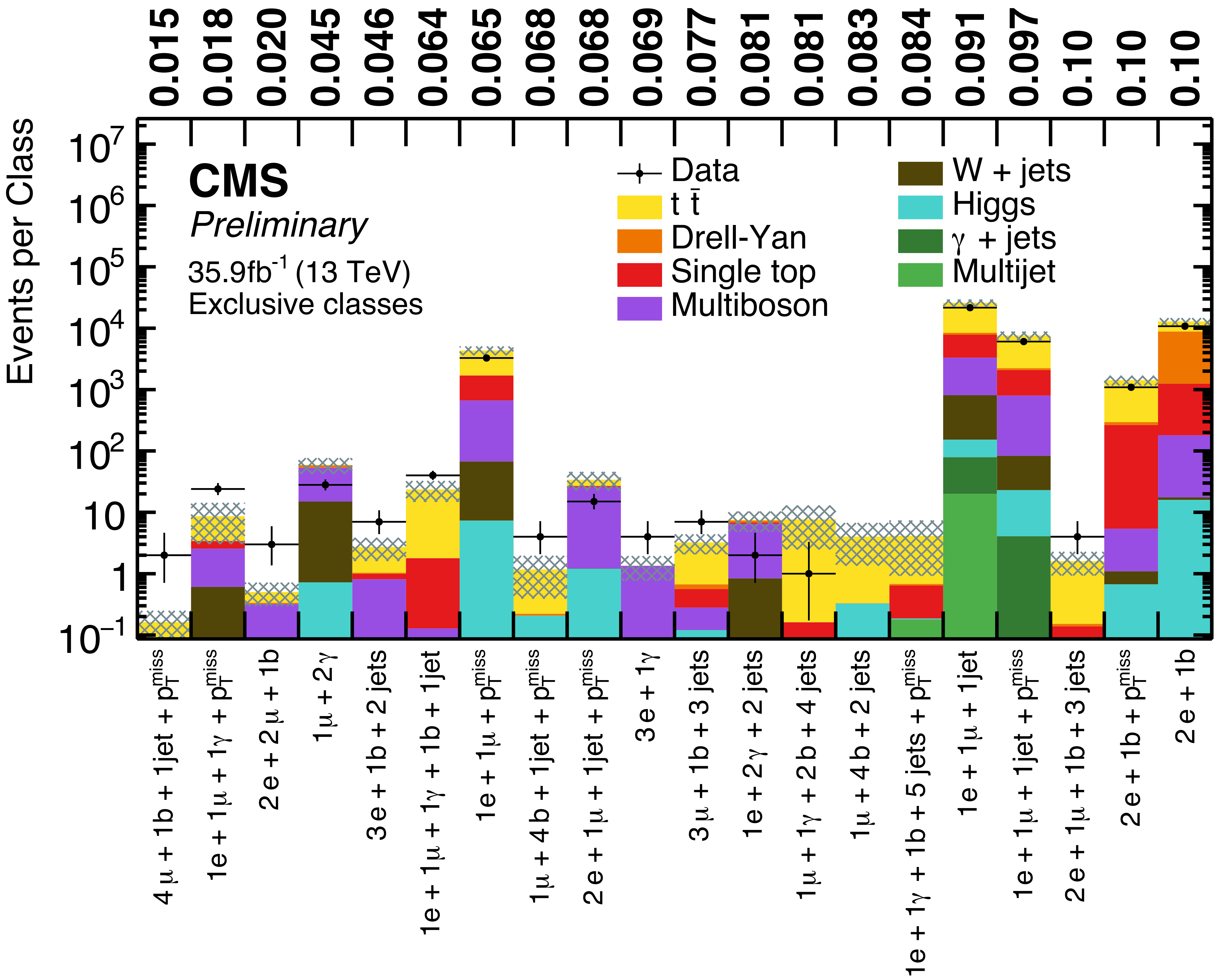
ATLAS, arXiv:1807.07447
13 TeV, 3.2 fb⁻¹
General search

LHC experiments explore vast array of signatures across broad phase-space.

This search is especially reliant on theory predictions, because it's so general.

(Other searches often have a mix of theory and "data-driven" background estimates)

CMS: 498 exclusive event classes and 571 (530) inclusive (jet-inclusive) event classes



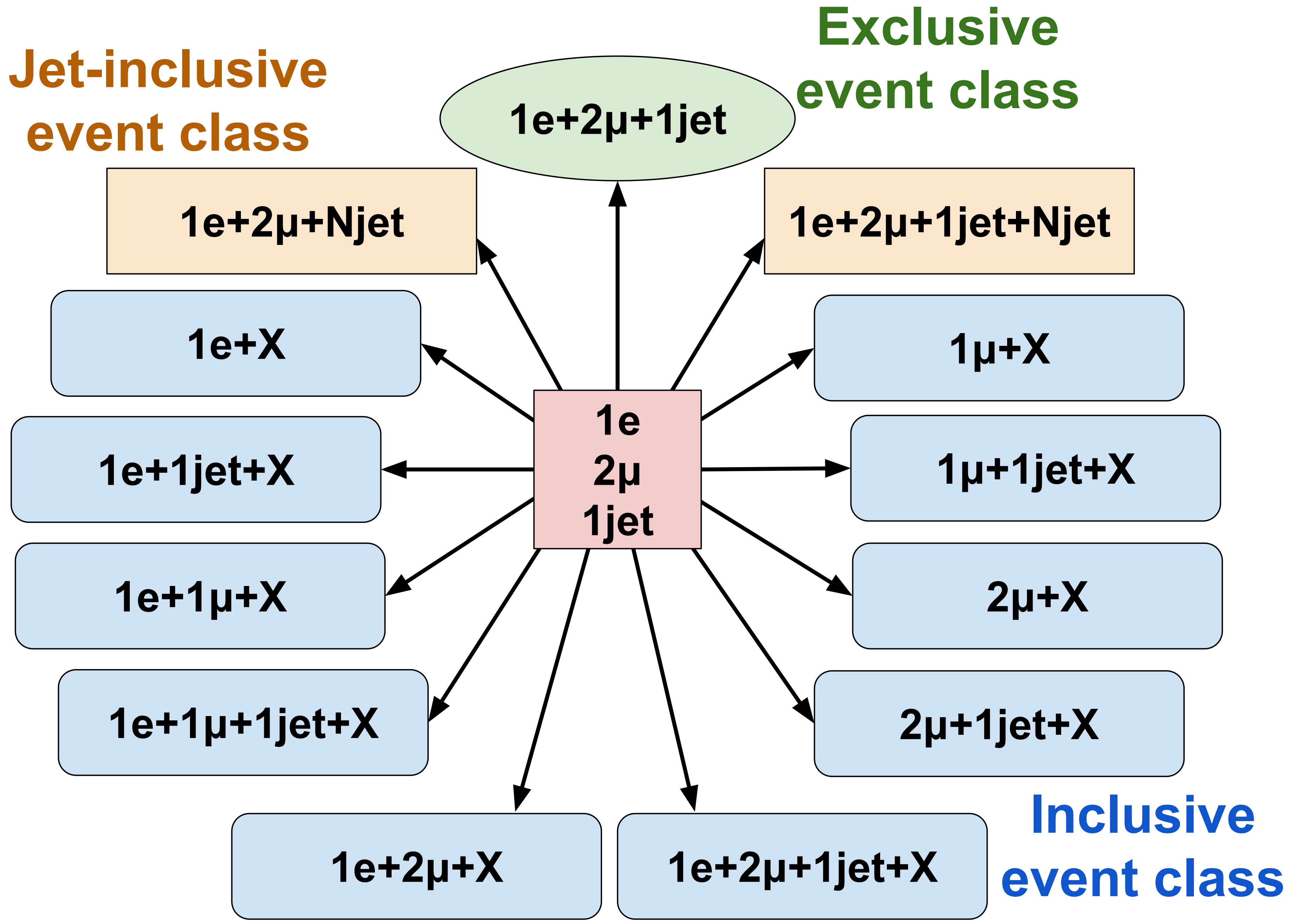


Figure 8: Most significant exclusive event classes, where the significance of an event class is calculated in a single aggregated bin. The values at the top indicate the observed p-value for each event class.

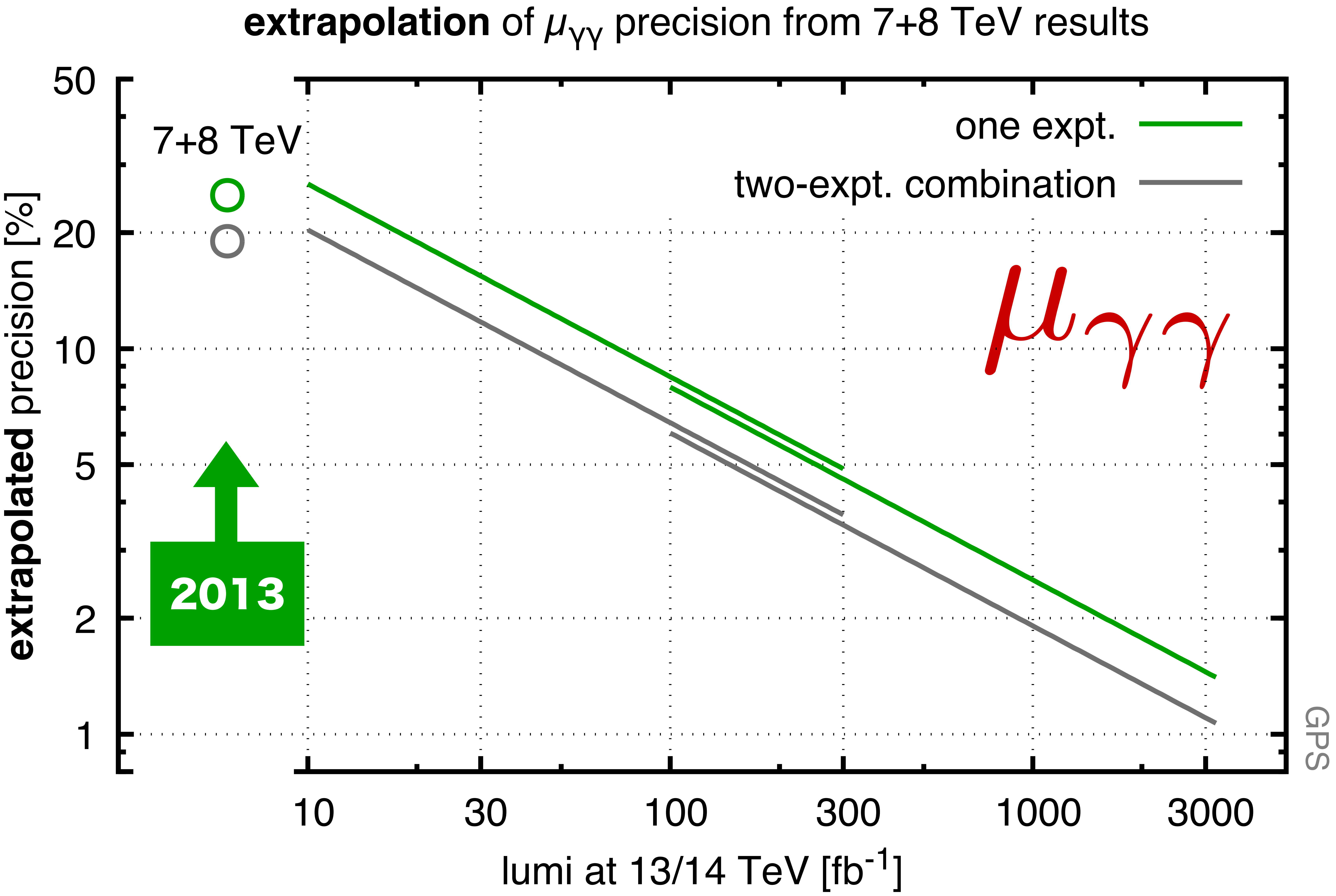
CMS, PAS-EXO-19-008
13 TeV, 35.9 fb^{-1}
MUSiC General search

future progress?

(1) approved plans

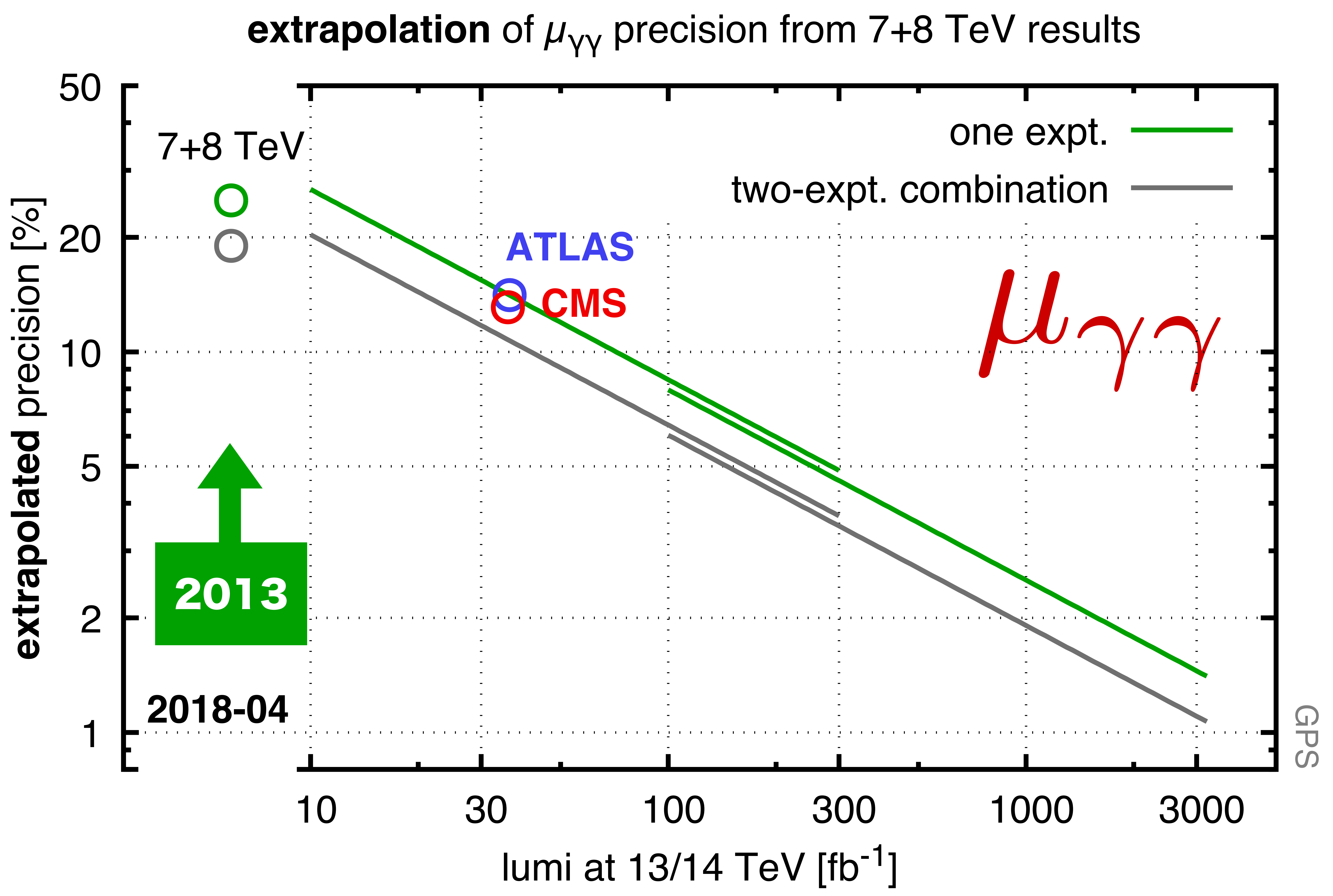
LHC will collect ~40 times more data than used for the plots shown so far, though at mostly similar energy (13–14 TeV)

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



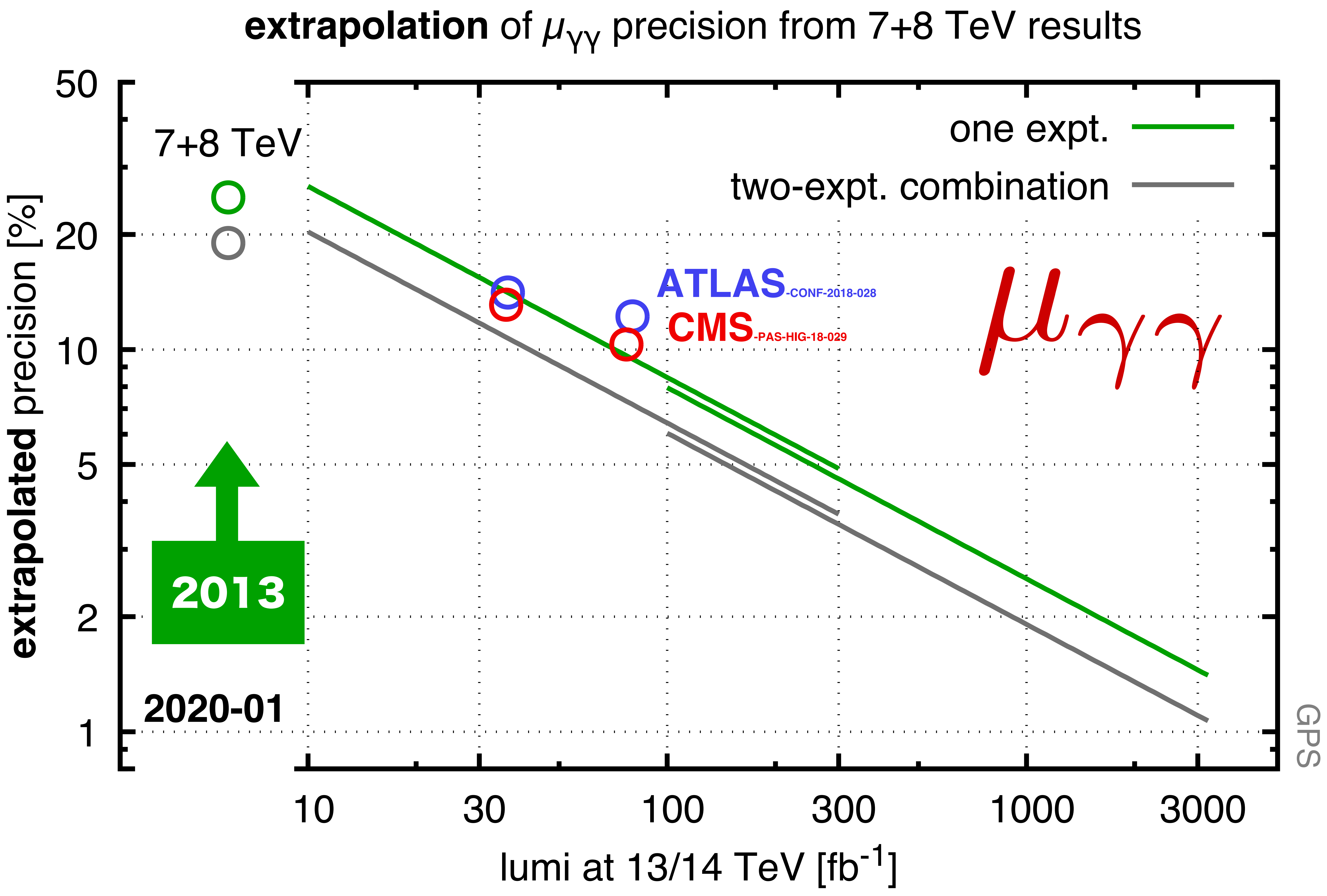
1 fb^{-1} = 10^{14} collisions

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



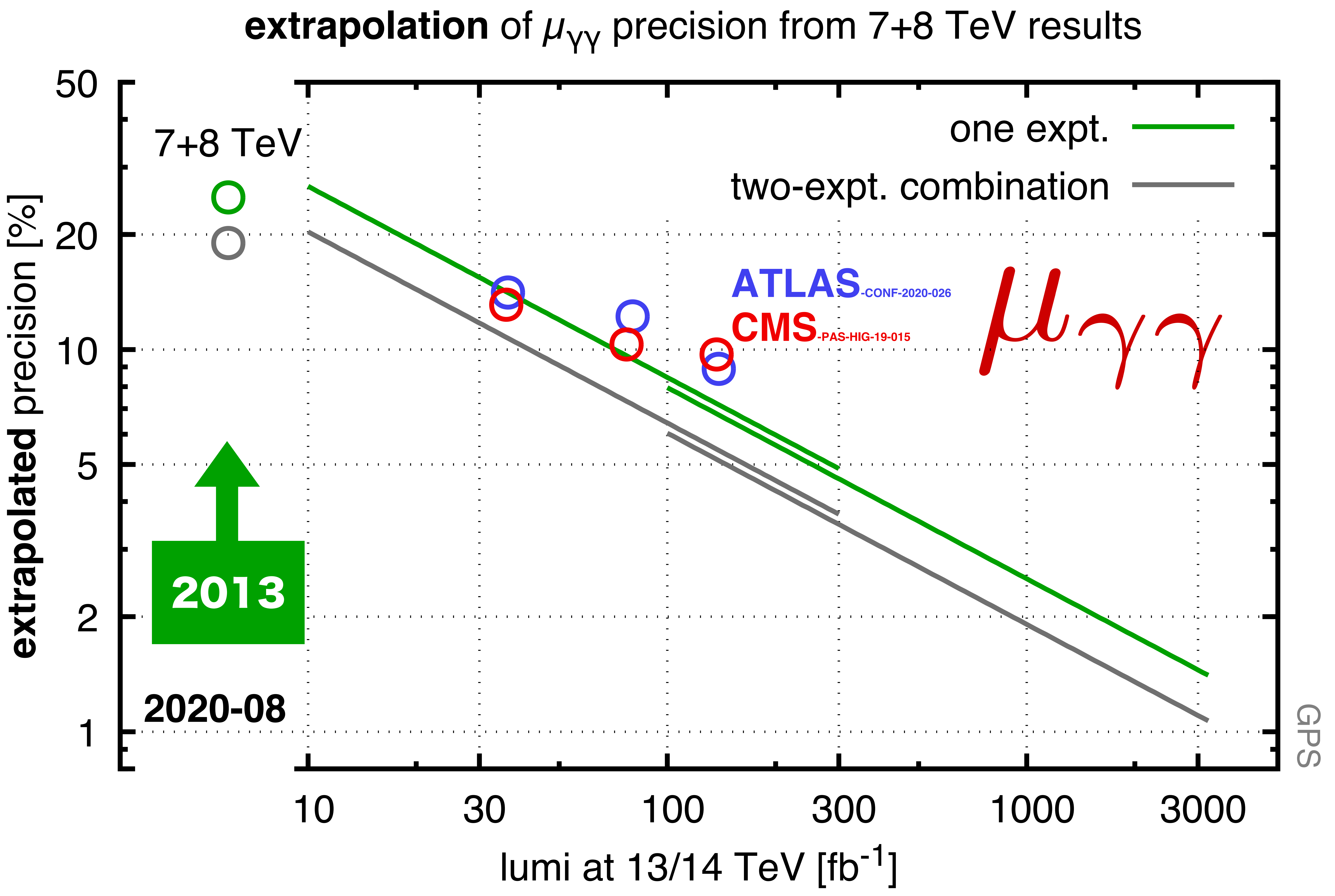
1 fb^{-1} = 10^{14} collisions

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



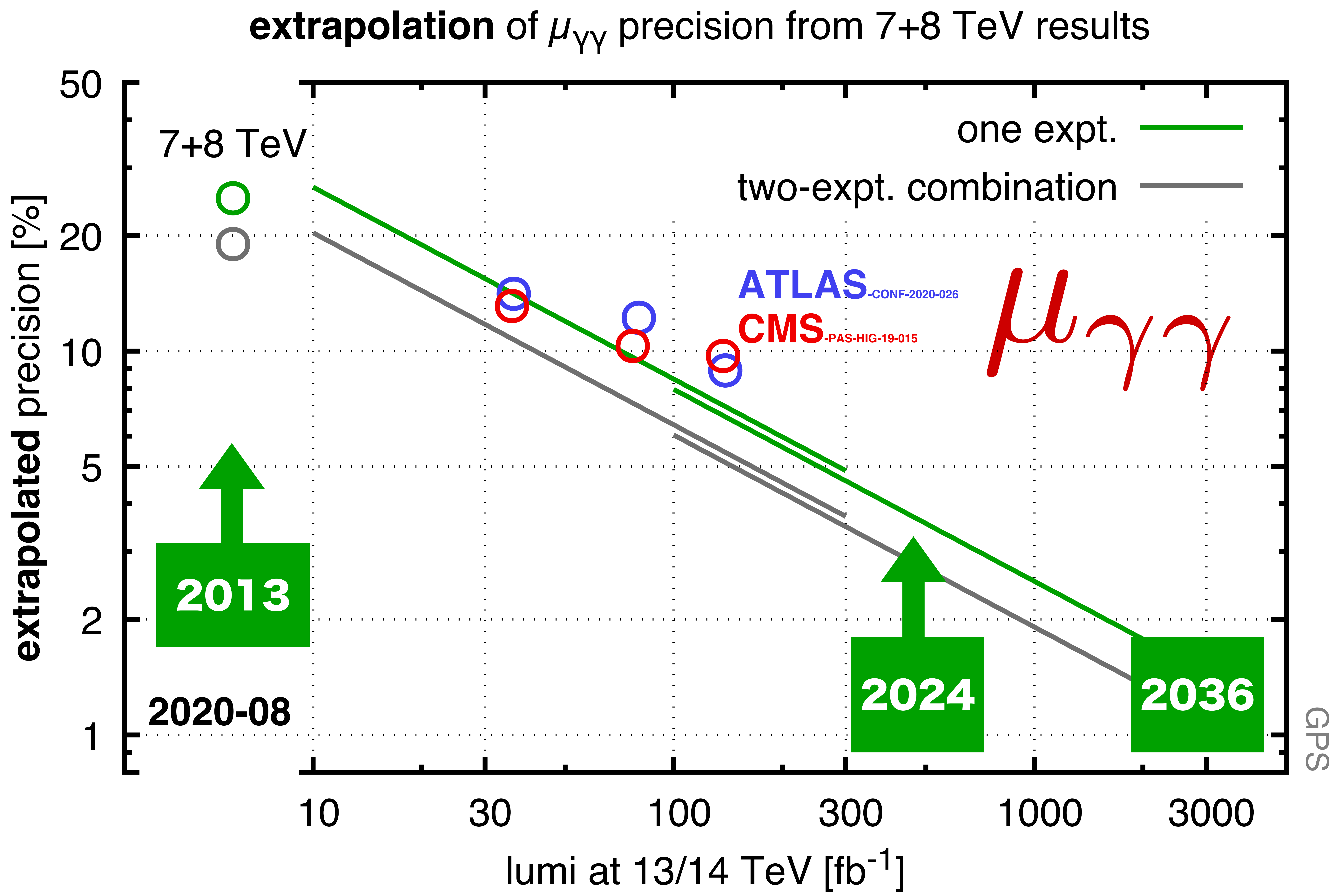
1 fb^{-1} = 10^{14} collisions

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



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

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

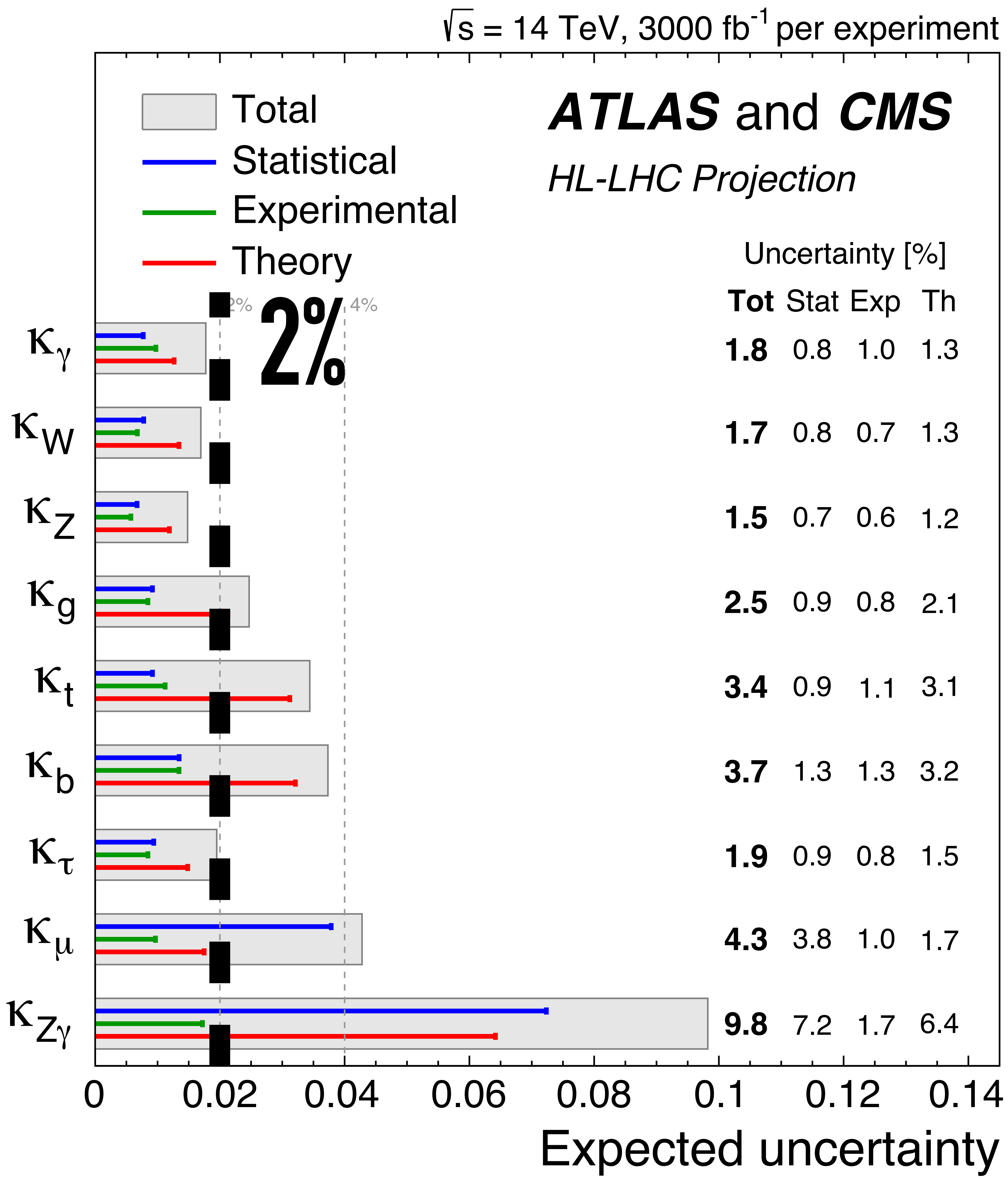


The LHC has the statistical potential to take Higgs physics from "observation" to 1–2% precision

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

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

HL-LHC official Higgs coupling projections (by 2036)

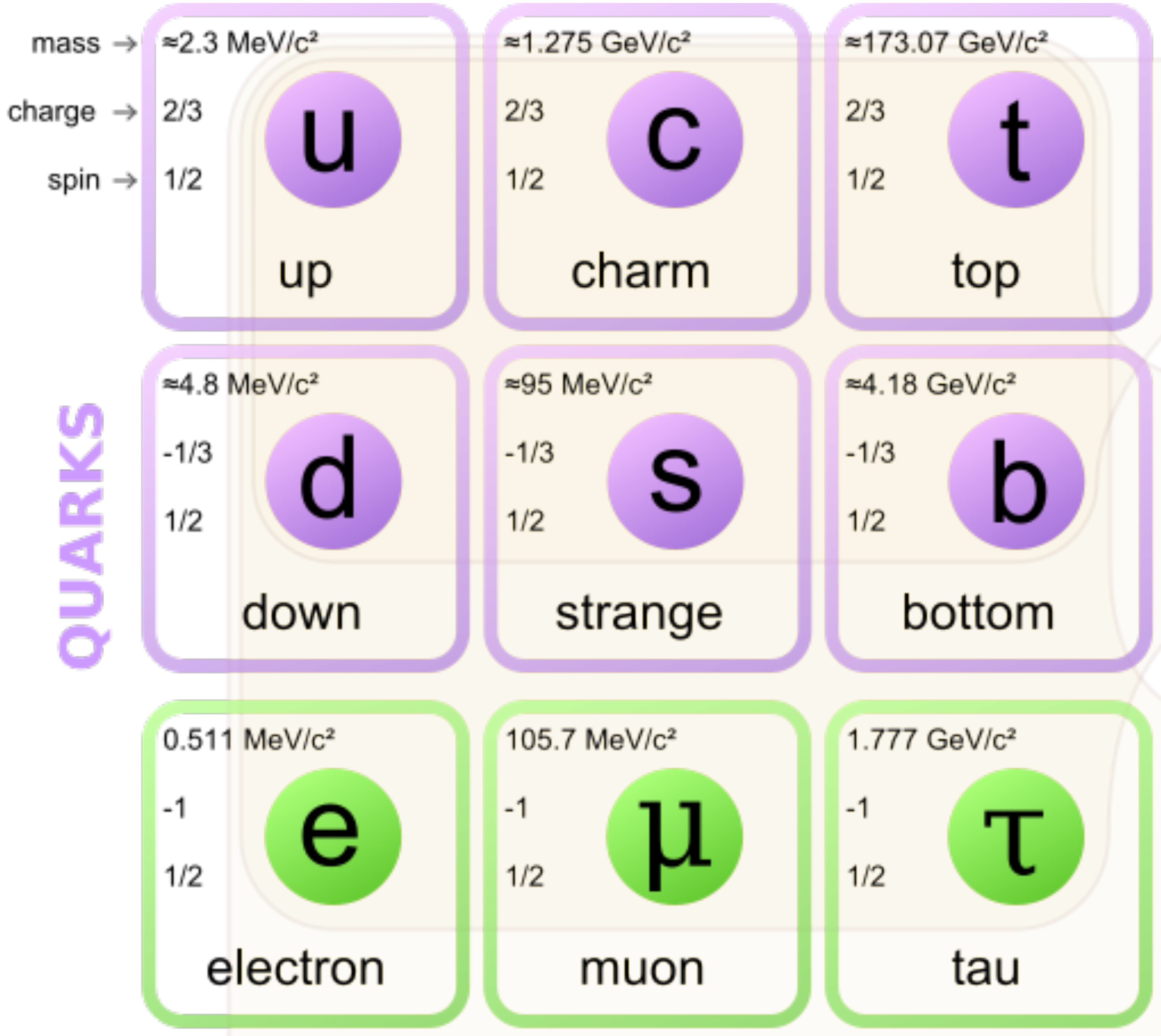


Right now, Higgs coupling precisions are in the 10-20% range.

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

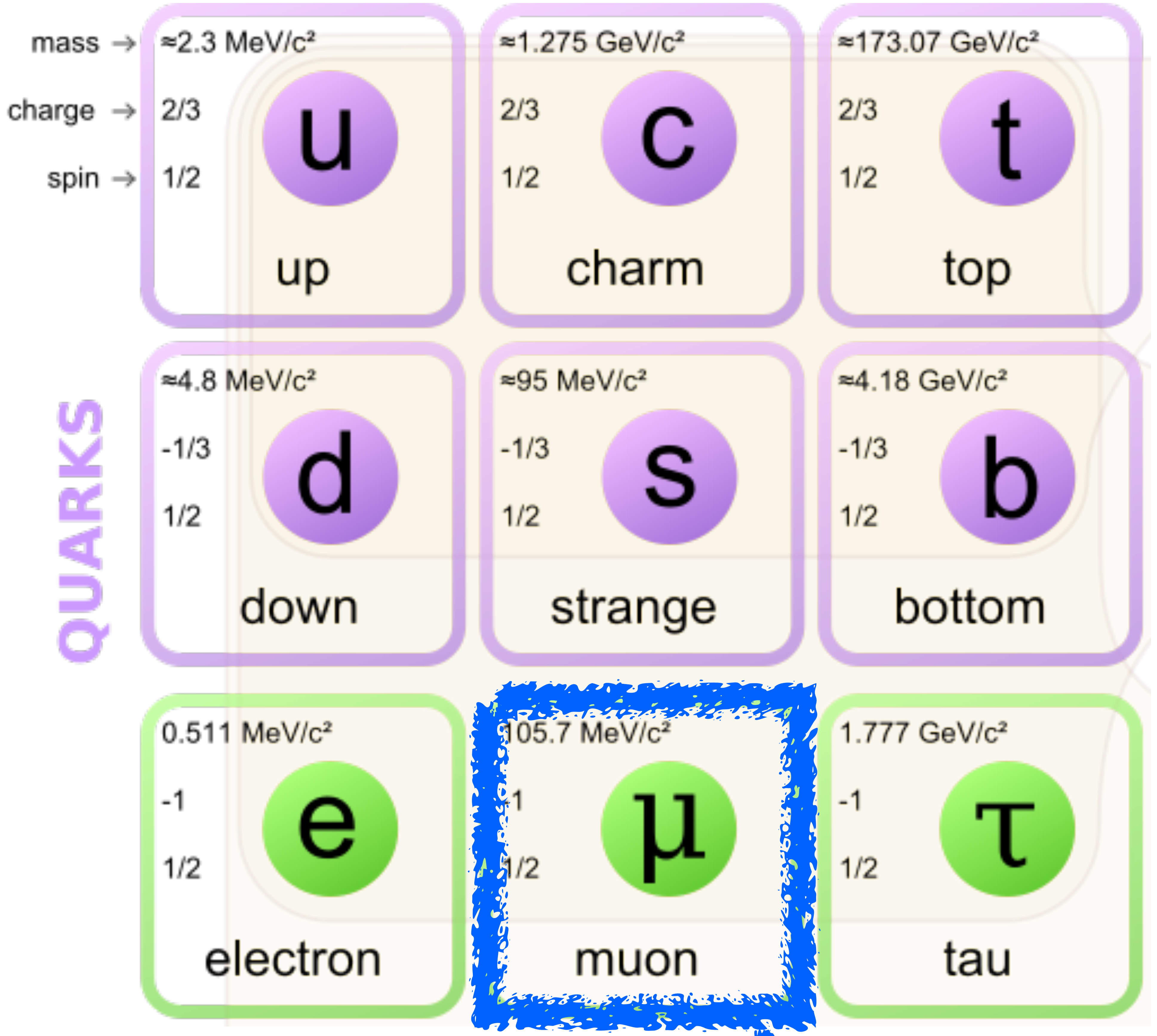
HL-LHC can deliver 1–2% for a range of couplings

2nd-generation Yukawas at HL-LHC (H → μμ)

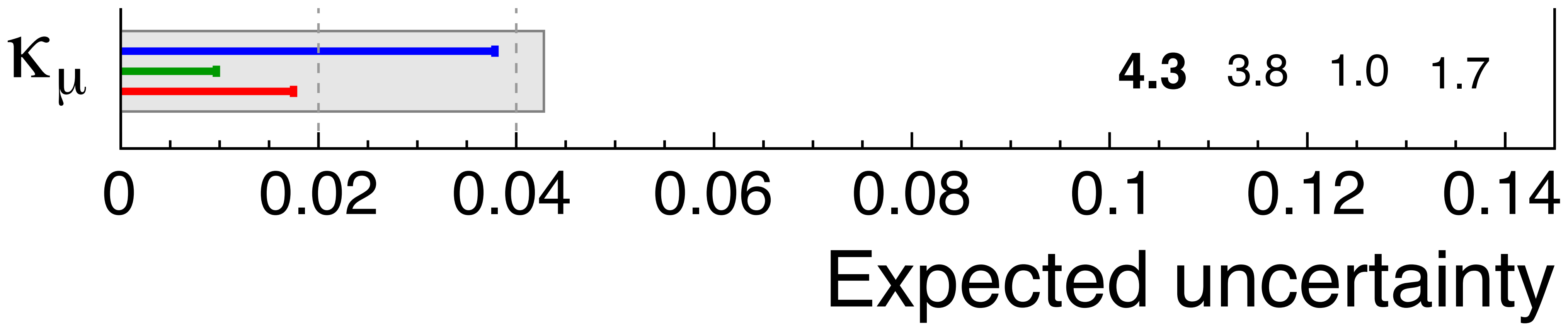


i	y_i	i	y_i
u	$2 \cdot 10^{-5}$	d	$3 \cdot 10^{-5}$
c	$8 \cdot 10^{-3}$	s	$6 \cdot 10^{-4}$
b	$3 \cdot 10^{-2}$	t	1
ν_e	$\sim 10^{-13}$	e	$3 \cdot 10^{-6}$
ν_μ		μ	$6 \cdot 10^{-4}$
ν_τ		τ	$1 \cdot 10^{-4}$

2nd-generation Yukawas at HL-LHC (H ⟶ μμ)



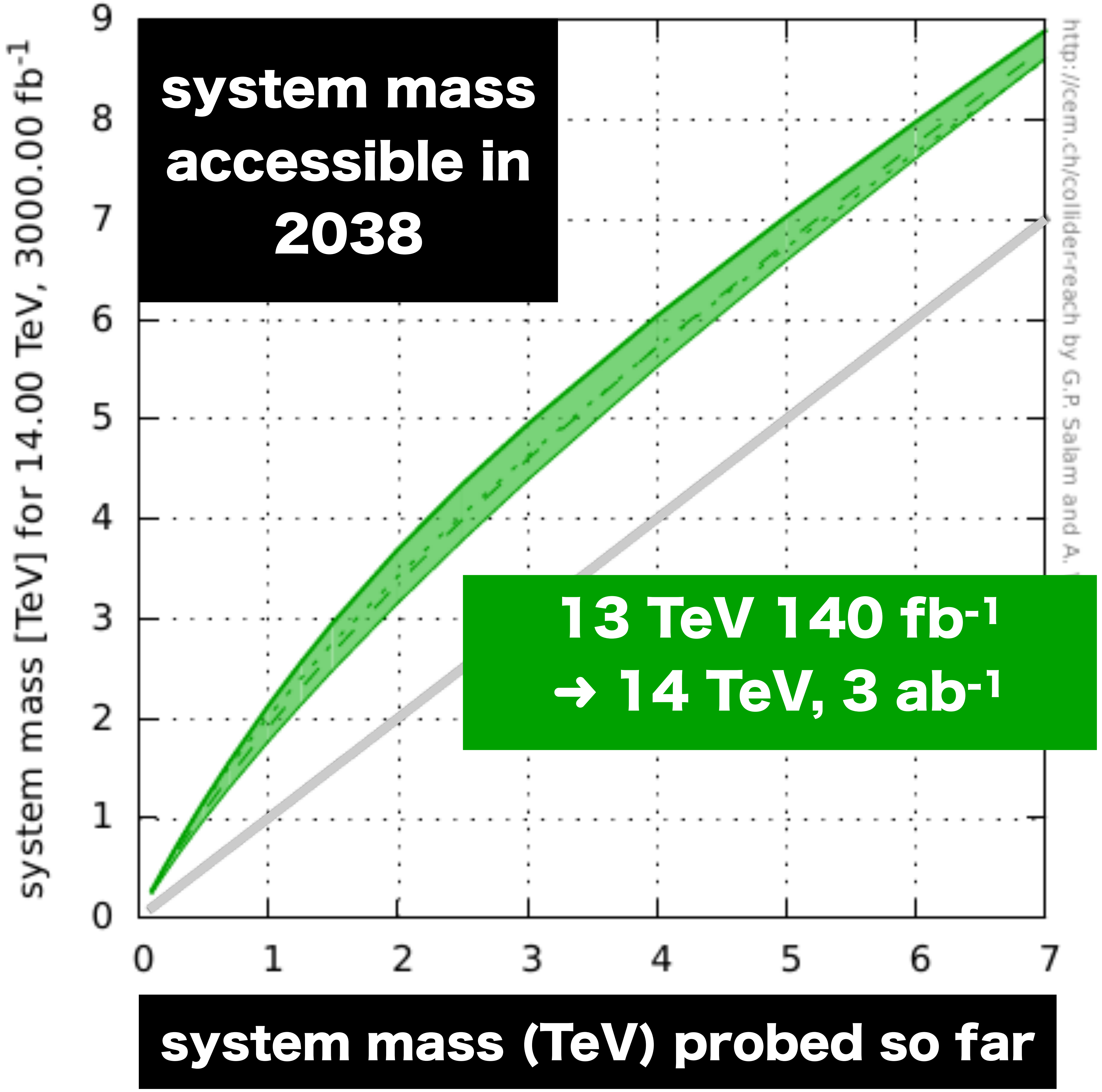
i	y_i	i	y_i
u	$2 \cdot 10^{-5}$	d	$3 \cdot 10^{-5}$
c	$8 \cdot 10^{-3}$	s	$6 \cdot 10^{-4}$
b	$3 \cdot 10^{-2}$	t	1
ν_e	$\sim 10^{-13}$	e	$3 \cdot 10^{-6}$
ν_μ		μ	$6 \cdot 10^{-4}$
ν_τ		τ	$1 \cdot 10$



today: first evidence
(1 in 4570 decays)

expect 5σ at HL-LHC, within about 8 years.

LHC direct search prospects (e.g. SUSY, Z', etc.)

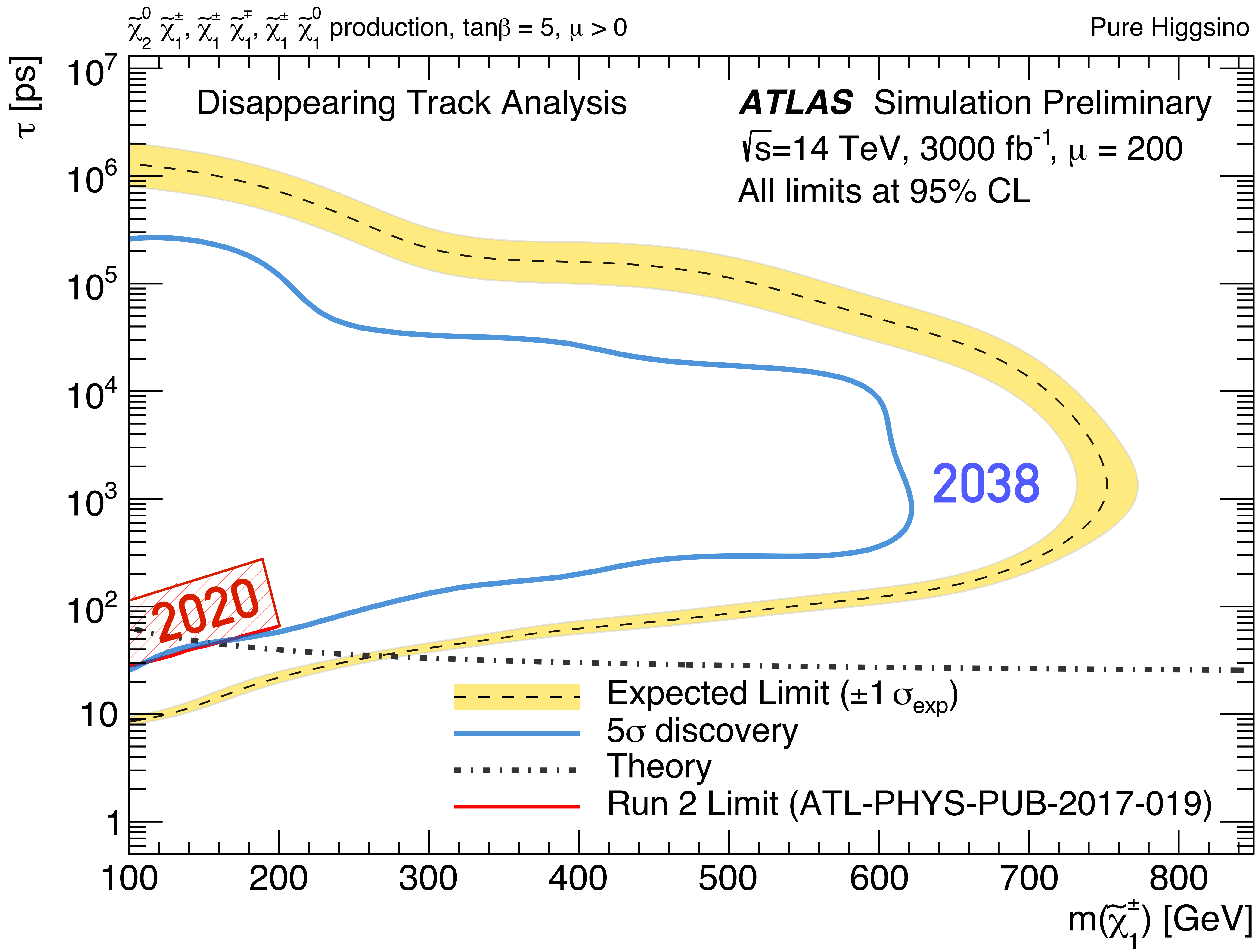


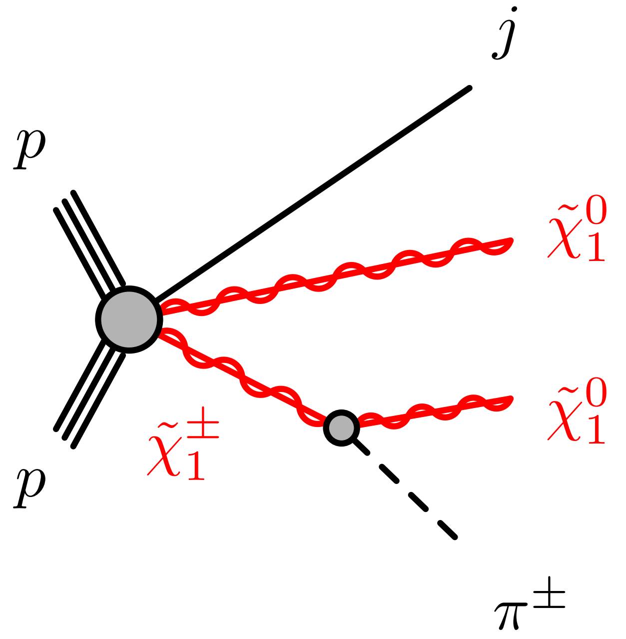
- Roughly 1.5 – 2 TeV increase in mass reach over next 18 years
- Proportionally more significant for searches at lower end of mass scale

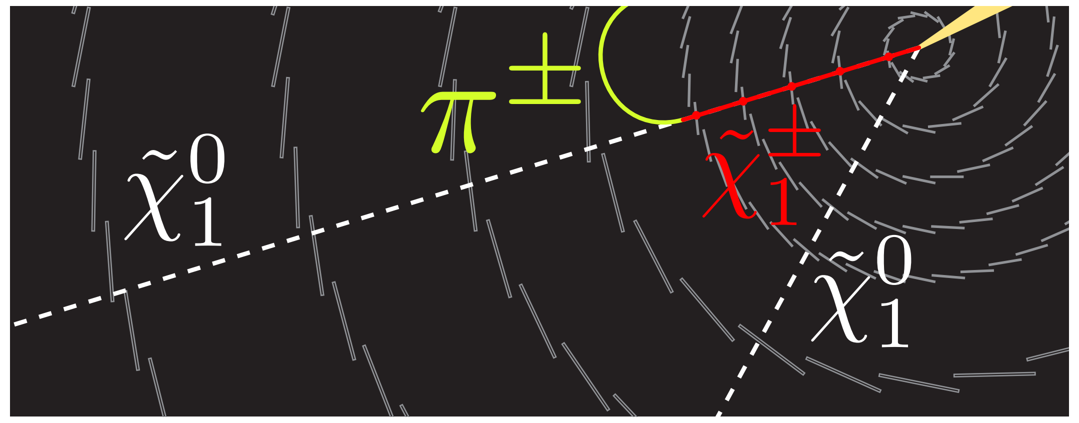

Sequential SM Z' exclusion reach
long-term pp(bar) view:
phases of fast, then slow energy frontier increase are normal
100 TeV pp, 30ab-1, from 2043
100 TeV pp
30ab-1 from 2063
40 TeV pp
12ab-1 from 2043
14 TeV pp, 3ab-1
13 TeV pp
8 TeV pp
7 TeV pp
1.96 TeV pp̄
1.80 TeV pp̄
0.63 TeV pp̄
Z'SSM limit [TeV]
year in which data recorded
Z' → l+l-
points: UA1/CDF/D0/ATLAS/CMS
lines: collider-reach extrapolation
year adjusted when only one lepton channel used
GPS + AW 2019 (with http://cern.ch/collider-reach)
100
70
50
30
20
10
7
5
3
2
1
0.7
0.5
0.3
0.2
0.1
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090


Sequential SM Z' exclusion reach
long-term pp(bar) view:
phases of fast, then slow energy
frontier increase are normal
average increase in reach
roughly × 2 / decade
100 TeV pp, 30ab-1, from 2043
100 TeV pp
30ab-1 from 2063
40 TeV pp
12ab-1 from 2043
14 TeV pp, 3ab-1
13 TeV pp
8 TeV pp
7 TeV pp
1.96 TeV pp̄
1.80 TeV pp̄
0.63 TeV pp̄
year adjusted when only one lepton channel used
GPS + AW 2019 (with http://cern.ch/collider-reach)
Z'SSM limit [TeV]
year in which data recorded
100
70
50
30
20
10
7
5
3
2
1
0.7
0.5
0.3
0.2
0.1
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090

electroweak SUSY partners: projections

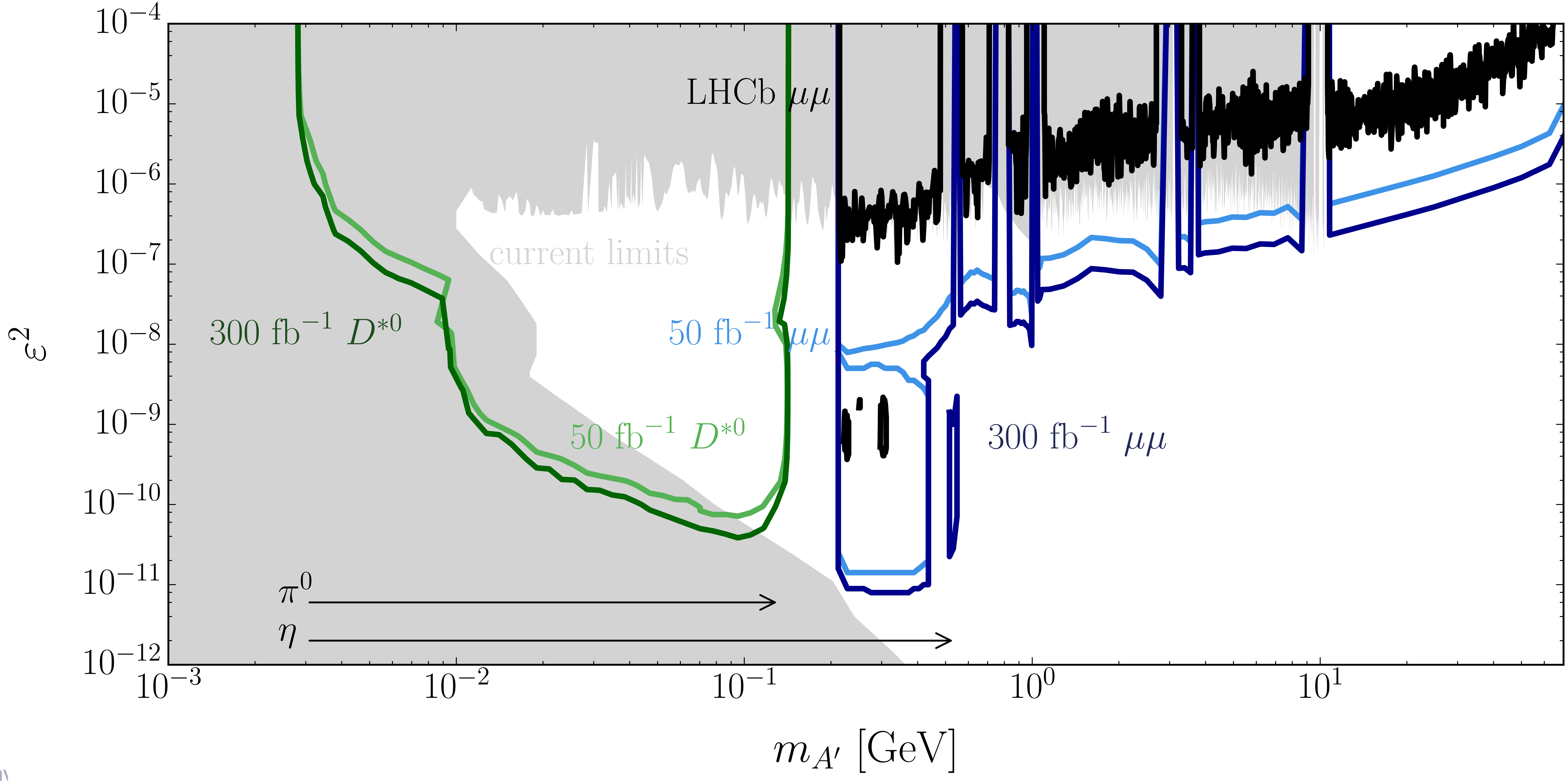




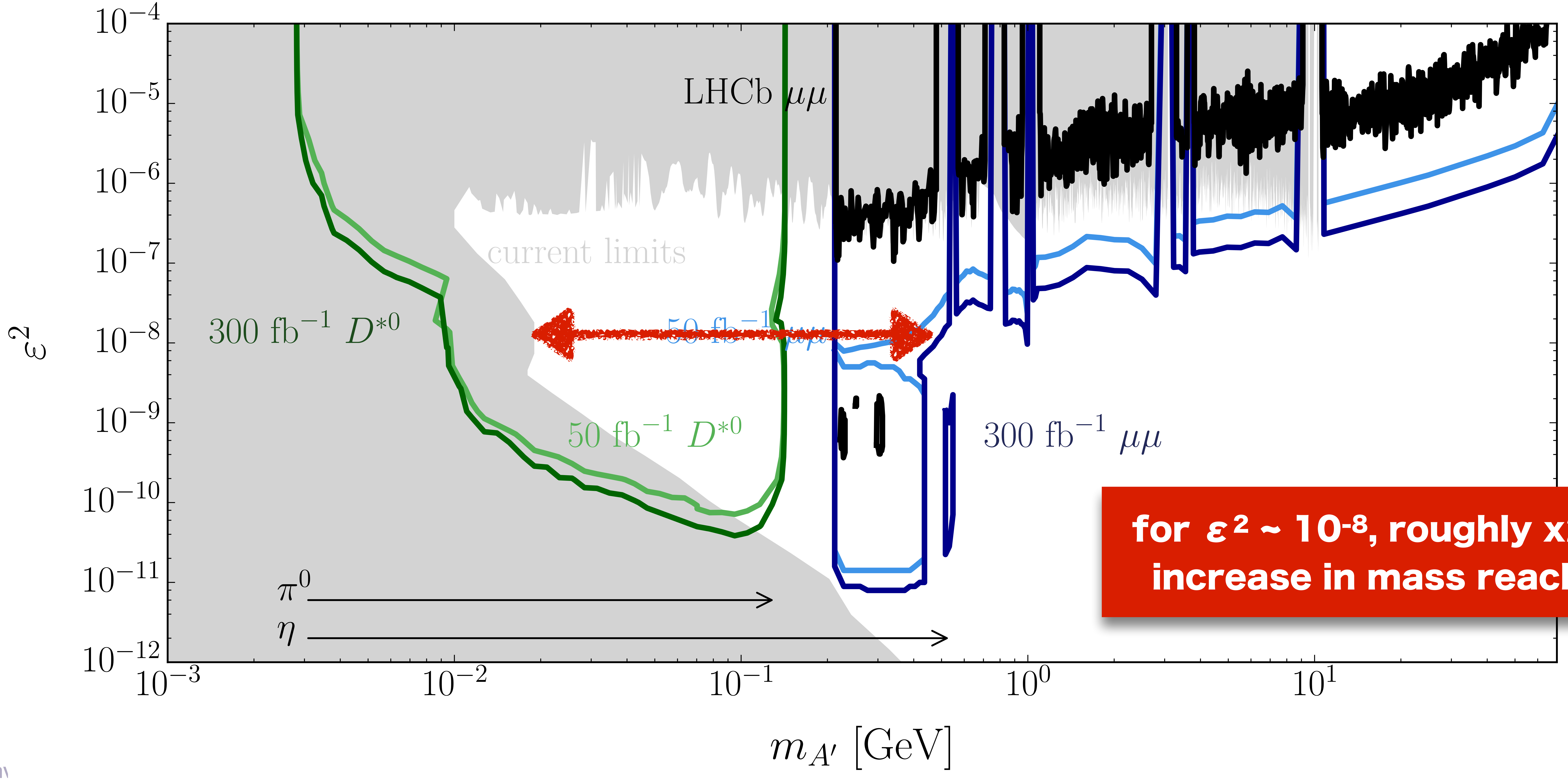


LHC lumi increase & detector upgrades bring unprecedented reach for processes with small cross sections (& sometimes weird signatures — here, disappearing tracks)

extreme lower end: A′ searches at LHCb

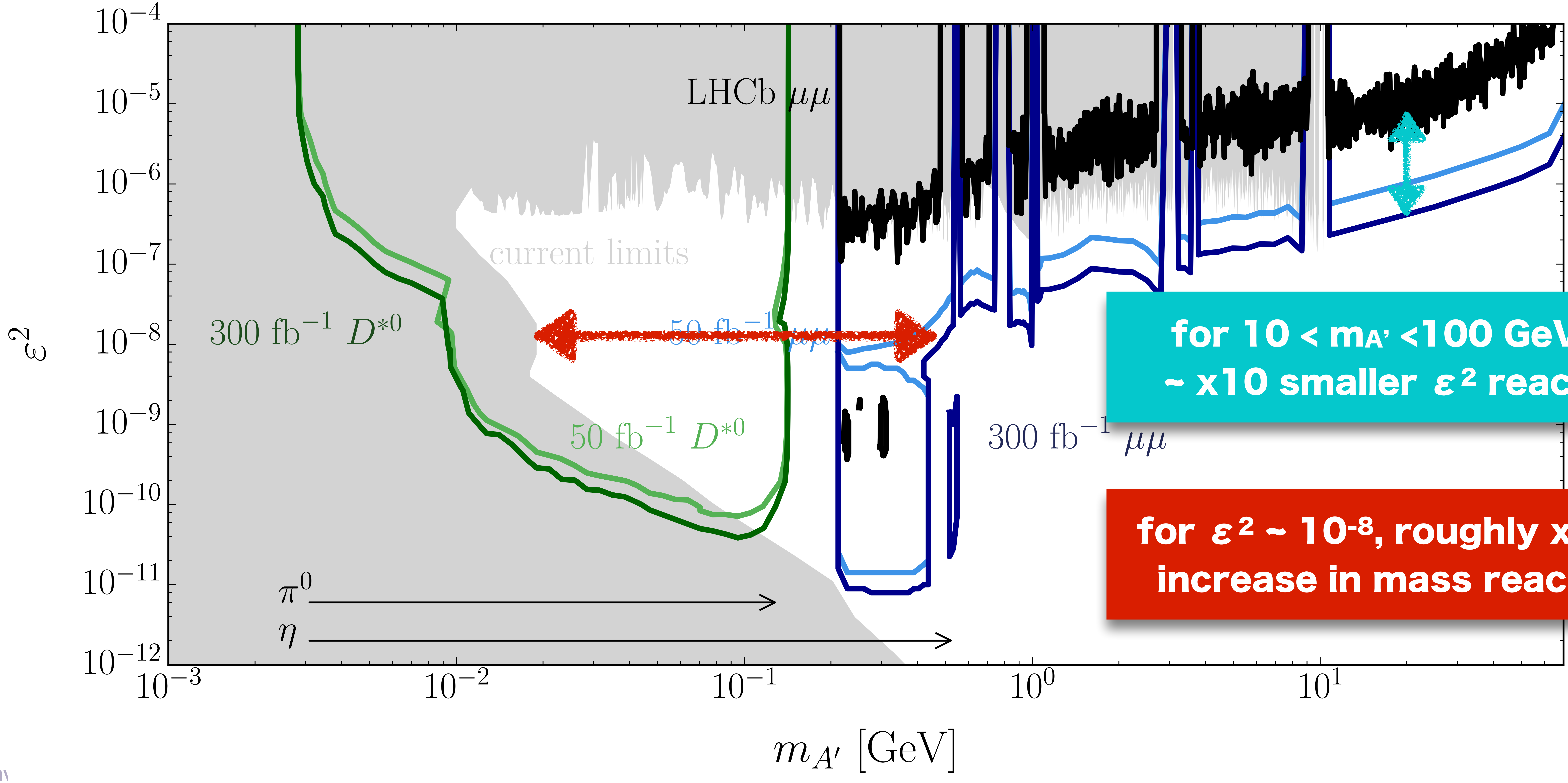


extreme lower end: A′ searches at LHCb



for $\varepsilon^2 \sim 10^{-8}$, roughly x20 increase in mass reach!

extreme lower end: A′ searches at LHCb



for 10 < $m_{A'}$ <100 GeV, ~ x10 smaller ε^2 reach

for ε^2 ~ 10^{-8}, roughly x20 increase in mass reach!

the methods we rely on

QCD, QCD, QCD, QCD, EW
(plus modelling)

Calculations used in 1807.07447 (ATLAS general search)

Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
$W\ (\to \ell\nu)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z\ (\to \ell^+\ell^-)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z\,/\,W\ (\to q\bar{q})$ + jets	Sherpa 2.1.1	1,2,3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z\,/\,W + \gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
$Z\,/\,W + \gamma\gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
γ + jets	Sherpa 2.1.1	0,1,2,3,4j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma$ + jets	Sherpa 2.1.1	0,1,2j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	Pythia 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	Powheg-Box v2	NLO	Pythia 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + WW$	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + \gamma$	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
$t\bar{t} + b\bar{b}$	Sherpa 2.2.0	NLO	Sherpa 2.2.0	NLO	NLO CT10f4	Sherpa default
Single-top (t-channel)	Powheg-Box v1	NLO	Pythia 6.428	app. NNLO	NLO CT10f4	Perugia 2012
Single-top (s- and Wt-channel)	Powheg-Box v2	NLO	Pythia 6.428	app. NNLO	NLO CT10	Perugia 2012
tZ	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
3-top	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
4-top	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
WW	Sherpa 2.1.1	0j@NLO + 1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
WZ	Sherpa 2.1.1	0j@NLO + 1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
ZZ	Sherpa 2.1.1	0,1j@NLO + 2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
Multijets	Pythia 8.186	LO	Pythia 8.186	data	NNPDF2.3LO	A14
Higgs (ggF/VBF)	Powheg-Box v2	NLO	Pythia 8.186	NNLO	NLO CT10	AZNLO
Higgs ($t\bar{t}H$)	MG5_aMC@NLO 2.2.2	NLO	Herwig++	NNLO	NLO CT10	UEEE5
Higgs (W/ZH)	Pythia 8.186	LO	Pythia 8.186	NNLO	NNPDF2.3LO	A14

Calculations used in 1807.07447 (ATLAS general search)

Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
$W\ (\to \ell\nu)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z\ (\to \ell^+\ell^-)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z\,/\,W\ (\to q\bar{q})$ + jets	Sherpa 2.1.1	1,2,3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z\,/\,W + \gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
$Z\,/\,W + \gamma\gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
γ + jets	Sherpa 2.1.1	0,1,2,3,4j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma$ + jets	Sherpa 2.1.1	0,1,2j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	Pythia 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	Powheg-Box v2	NLO	Pythia 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + WW$	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + \gamma$	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
$t\bar{t} + b\bar{b}$	Sherpa 2.2.0	NLO	Sherpa 2.2.0	NLO	NLO CT10f4	Sherpa default
Single-top (t-channel)	Powheg-Box v1	NLO	Pythia 6.428	app. NNLO	NLO CT10f4	Perugia 2012
Single-top (s- and Wt-channel)	Powheg-Box v2	NLO	Pythia 6.428	app. NNLO	NLO CT10	Perugia 2012
tZ	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
3-top	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
4-top	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
WW	Sherpa 2.1.1	0j@NLO + 1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
WZ	Sherpa 2.1.1	0j@NLO + 1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
ZZ	Sherpa 2.1.1	0,1j@NLO + 2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
Multijets	Pythia 8.186	LO	Pythia 8.186	data	NNPDF2.3LO	A14
Higgs (ggF/VBF)	Powheg-Box v2	NLO	Pythia 8.186	NNLO	NLO CT10	AZNLO
Higgs ($t\bar{t}H$)	MG5_aMC@NLO 2.2.2	NLO	Herwig++	NNLO	NLO CT10	UEEE5
Higgs (W/ZH)	Pythia 8.186	LO	Pythia 8.186	NNLO	NNPDF2.3LO	A14

Calculations used in 1807.07447 (ATLAS general search)

Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
$W (\to \ell\nu)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z (\to \ell^+\ell^-)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W (\to q\bar{q})$ + jets	Sherpa 2.1.1	1,2,3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W + \gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
$Z / W + \gamma\gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
γ + jets	Sherpa 2.1.1	0,1,2,3,4j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma$ + jets	Sherpa 2.1.1	0,1,2j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	Pythia 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	Powheg-Box v2	NLO	Pythia 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14

theory (hadron-level + detector sim) compared to data

Calculations used in 1807.07447 (ATLAS general search)

Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
$W (\to \ell\nu)$ + jets	SHERPA 2.1.1	0,1,2j@NLO + 3,4j@LO	SHERPA 2.1.1	NNLO	NLO CT10	SHERPA default
$Z (\to \ell^+\ell^-)$ + jets	SHERPA 2.1.1	0,1,2j@NLO + 3,4j@LO	SHERPA 2.1.1	NNLO	NLO CT10	SHERPA default
$Z / W (\to q\bar{q})$ + jets	SHERPA 2.1.1	1,2,3,4j@LO	SHERPA 2.1.1	NNLO	NLO CT10	SHERPA default
$Z / W + \gamma$	SHERPA 2.1.1	0,1,2,3j@LO	SHERPA 2.1.1	NLO	NLO CT10	SHERPA default
$Z / W + \gamma\gamma$	SHERPA 2.1.1	0,1,2,3j@LO	SHERPA 2.1.1	NLO	NLO CT10	SHERPA default
γ + jets	SHERPA 2.1.1	0,1,2,3,4j@LO	SHERPA 2.1.1	data	NLO CT10	SHERPA default
$\gamma\gamma$ + jets	SHERPA 2.1.1	0,1,2j@LO	SHERPA 2.1.1	data	NLO CT10	SHERPA default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	PYTHIA 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	POWHEG-BOX v2	NLO	PYTHIA 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	PYTHIA 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	PYTHIA 8.186	NLO	NNPDF2.3LO	A14

The sets of amplitudes being used at the hard scale

theory (hadron-level + detector sim) compared to data

Calculations used in 1807.07447 (ATLAS general search)

Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
$W(\to \ell\nu)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z(\to \ell^+\ell^-)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z\,/\,W(\to q\bar{q})$ + jets	Sherpa 2.1.1	1,2,3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z\,/\,W + \gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
$Z\,/\,W + \gamma\gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
γ + jets	Sherpa 2.1.1	0,1,2,3,4j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma$ + jets	Sherpa 2.1.1	0,1,2j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	Pythia 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	Powheg-Box v2	NLO	Pythia 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14

the parton shower (from hard scale down to GeV scale)

The sets of amplitudes being used at the hard scale

theory (hadron-level + detector sim) compared to data

Calculations used in 1807.07447 (ATLAS general search)

Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
$W (\to \ell\nu)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z (\to \ell^+\ell^-)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W (\to q\bar{q})$ + jets	Sherpa 2.1.1	1,2,3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W + \gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
$Z / W + \gamma\gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
γ + jets	Sherpa 2.1.1	0,1,2,3,4j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma$ + jets	Sherpa 2.1.1	0,1,2j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	Pythia 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	Powheg-Box v2	NLO	Pythia 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14

The matching between amplitudes and parton shower

the parton shower (from hard scale down to GeV scale)

The sets of amplitudes being used at the hard scale

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Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
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$Z (\to \ell^+\ell^-)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W (\to q\bar{q})$ + jets	Sherpa 2.1.1	1,2,3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W + \gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
$Z / W + \gamma\gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
γ + jets	Sherpa 2.1.1	0,1,2,3,4j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma$ + jets	Sherpa 2.1.1	0,1,2j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	Pythia 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	Powheg-Box v2	NLO	Pythia 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14

The matching between amplitudes and parton shower

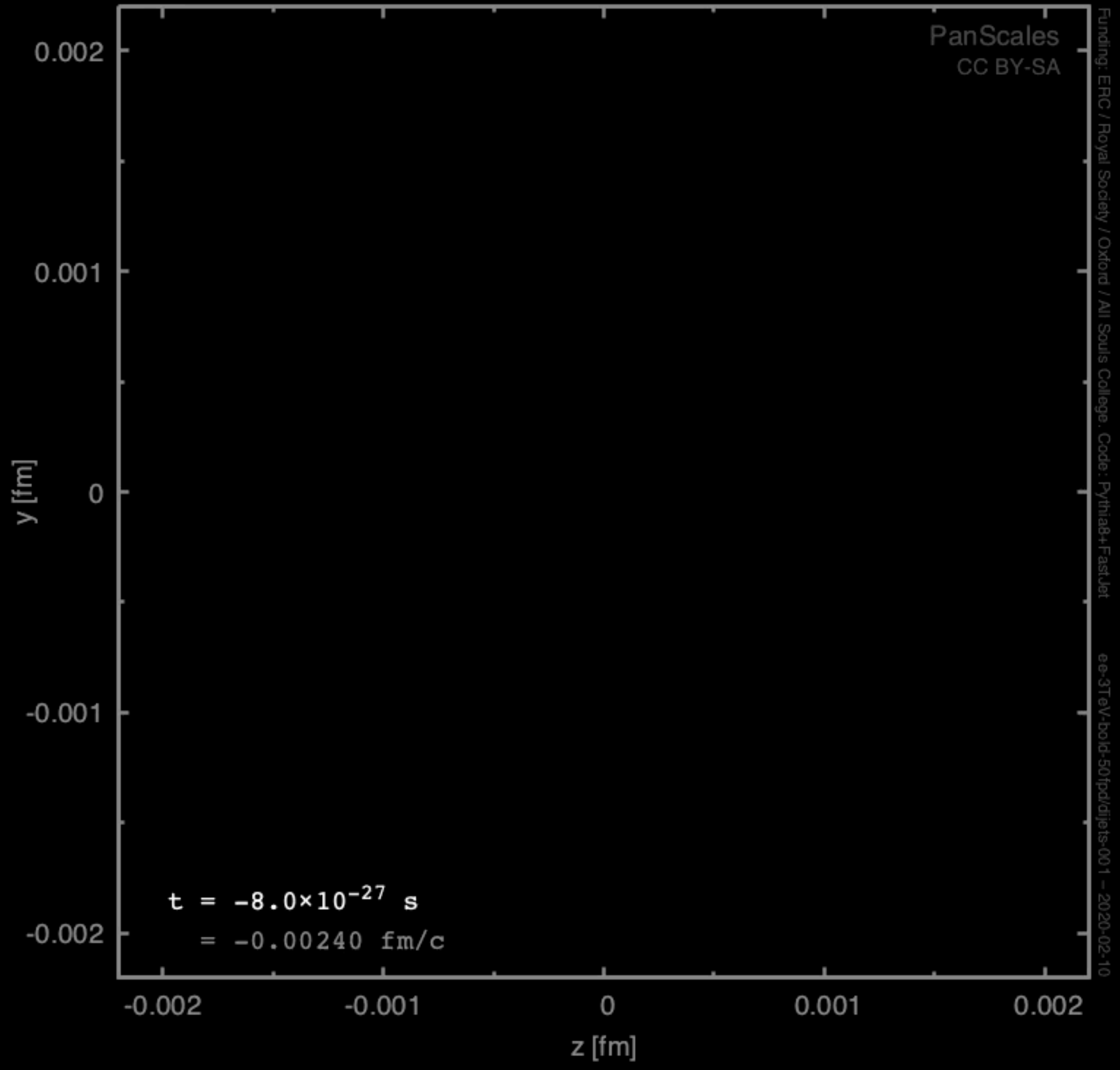
the parton shower (from hard scale down to GeV scale)

The sets of amplitudes being used at the hard scale

non-perturbative physics:

proton structure (PDFs) and hadronisation models etc.

theory (hadron-level + detector sim) compared to data

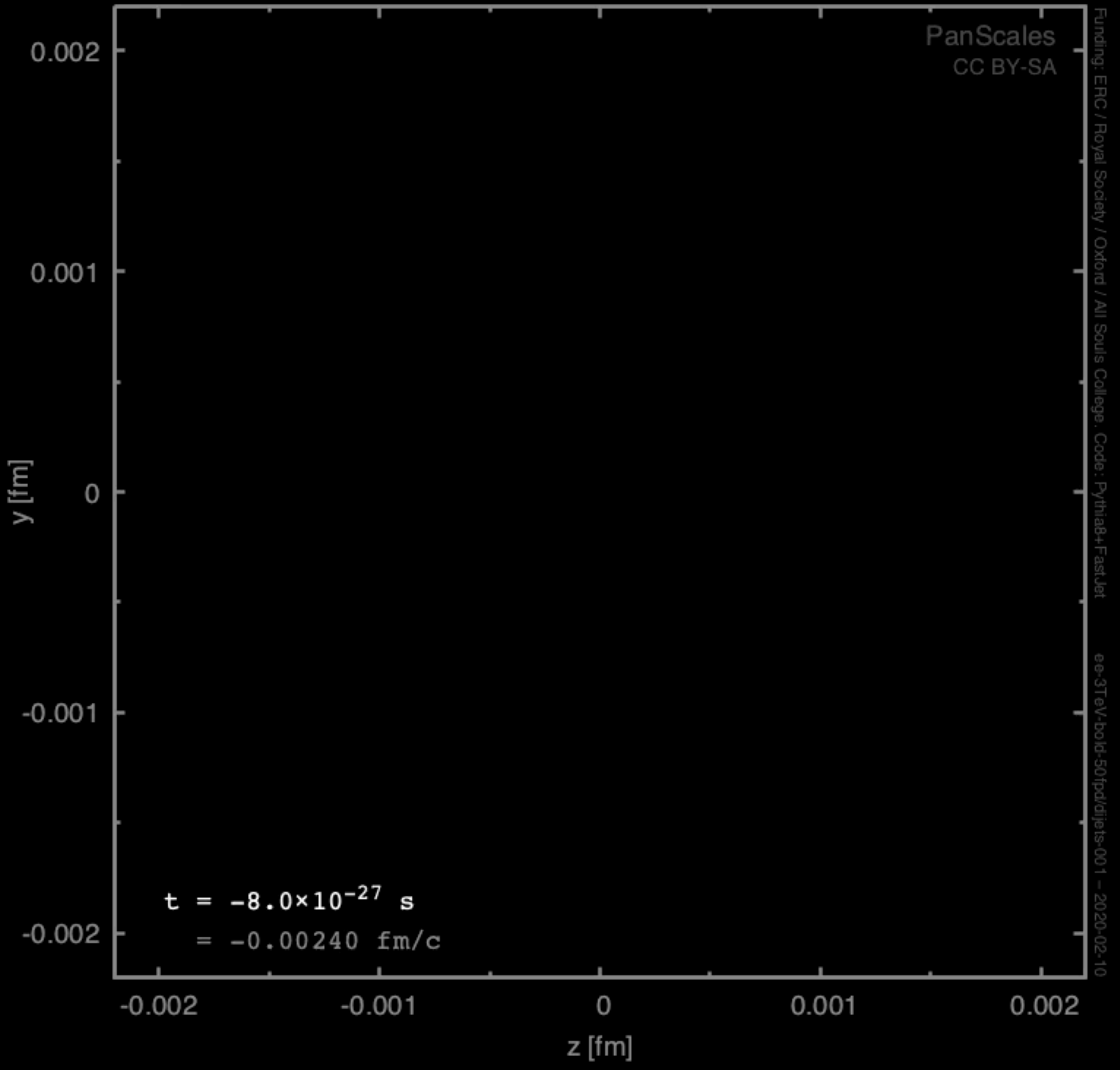


incoming beam particle

intermediate particle

final particle

Event evolution spans 7 orders of magnitude in space-time



incoming beam particle

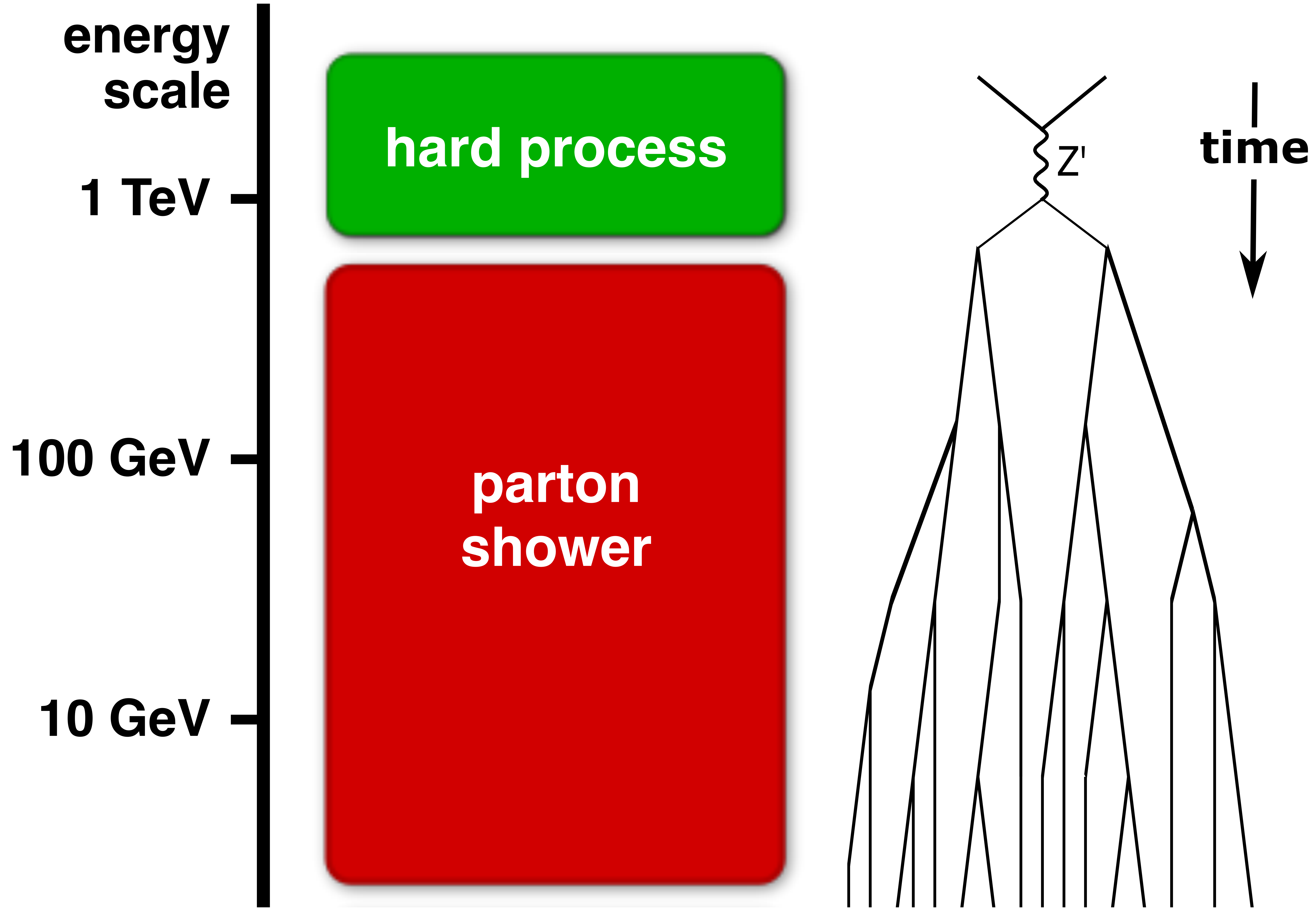
intermediate particle

final particle

Event evolution spans 7 orders of magnitude in space-time

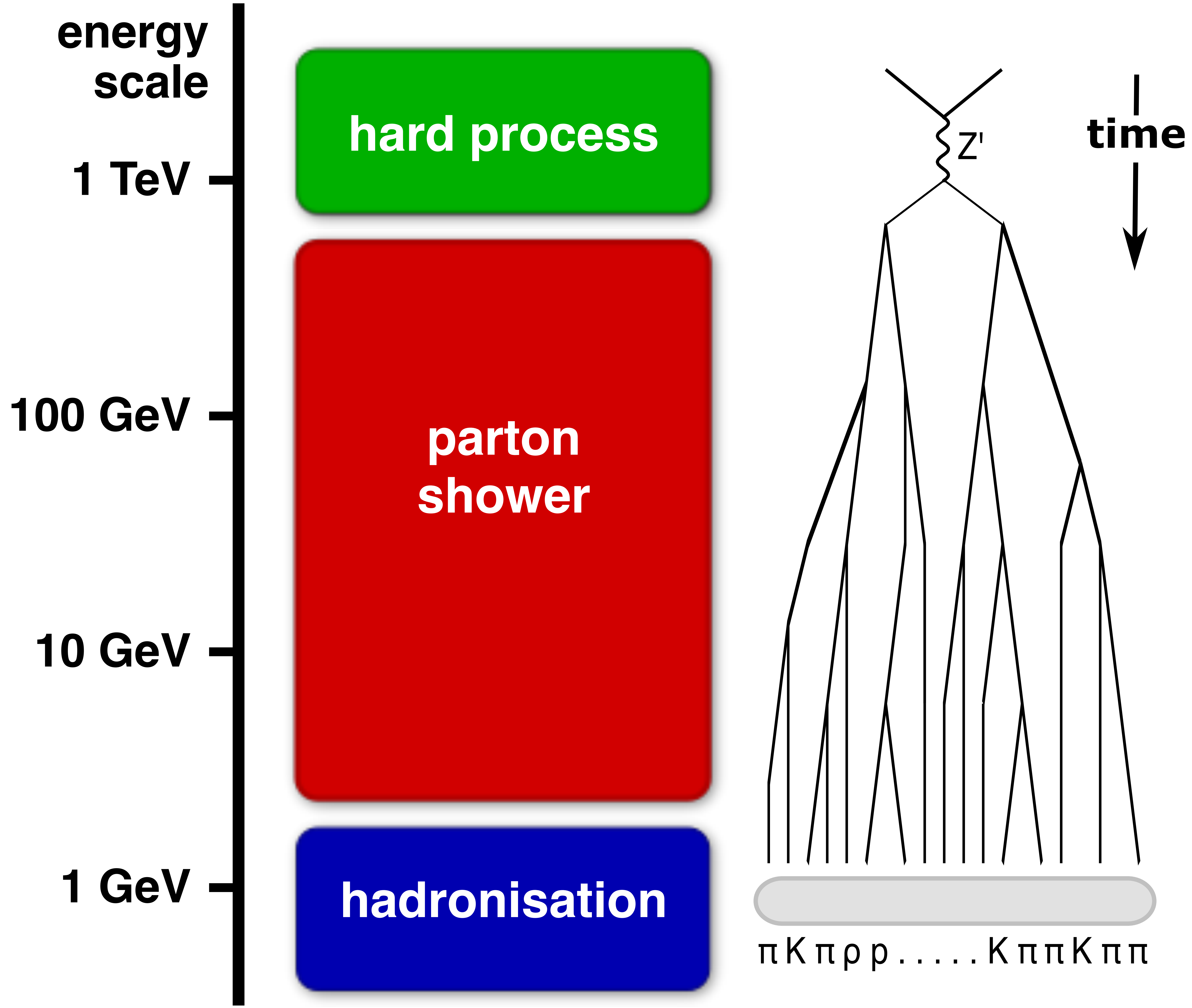
Amplitudes are most critical here

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



Amplitudes are most critical here

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



Amplitudes are most critical here

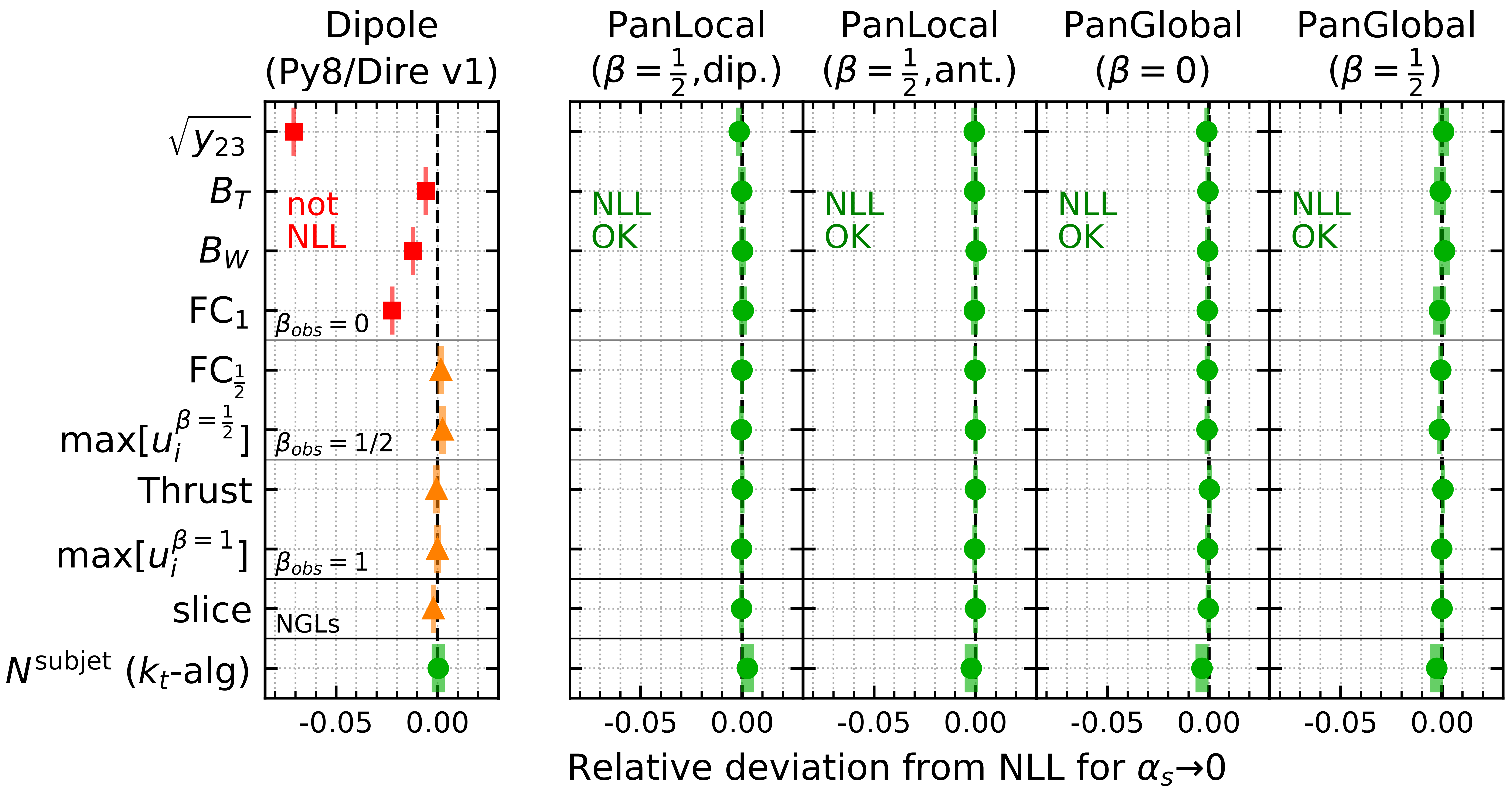
schematic view of key components of QCD predictions and Monte Carlo event simulation

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

standard parton showers

new "PanScales" parton showers, designed specifically to achieve NLL accuracy

Dasgupta, Dreyer, Hamilton, Monni GPS, Soyez, 2002.11114 (PRL)



"PanScales" family reproduces squared matrix element for arbitrary n, in limit where each & every pair of particles is well separated in logarithm of angle, energy or transverse momentum
(modulo spin correlations, work ongoing)

first time comprehensive accuracy tests achieved for parton showers — sets baseline for future work & demonstrates that it is possible to achieve NLL accuracy from simple iterated 2→3 splitting

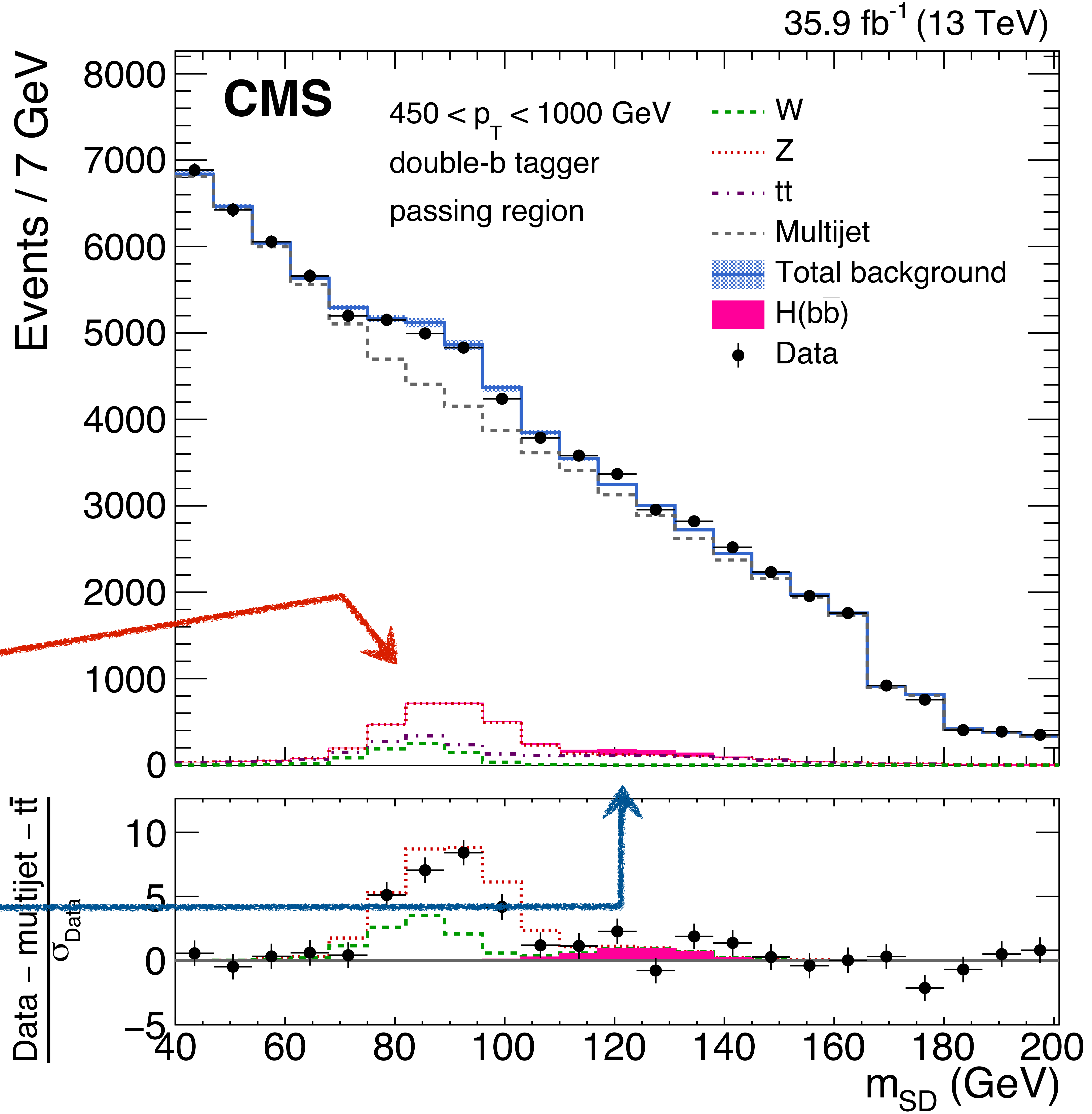
high p_T Higgs & [SD] jet mass

We wouldn't trust electromagnetism if we'd only tested at one length/momentum scale.

New Higgs interactions need testing at both low and (here) **high momenta.**

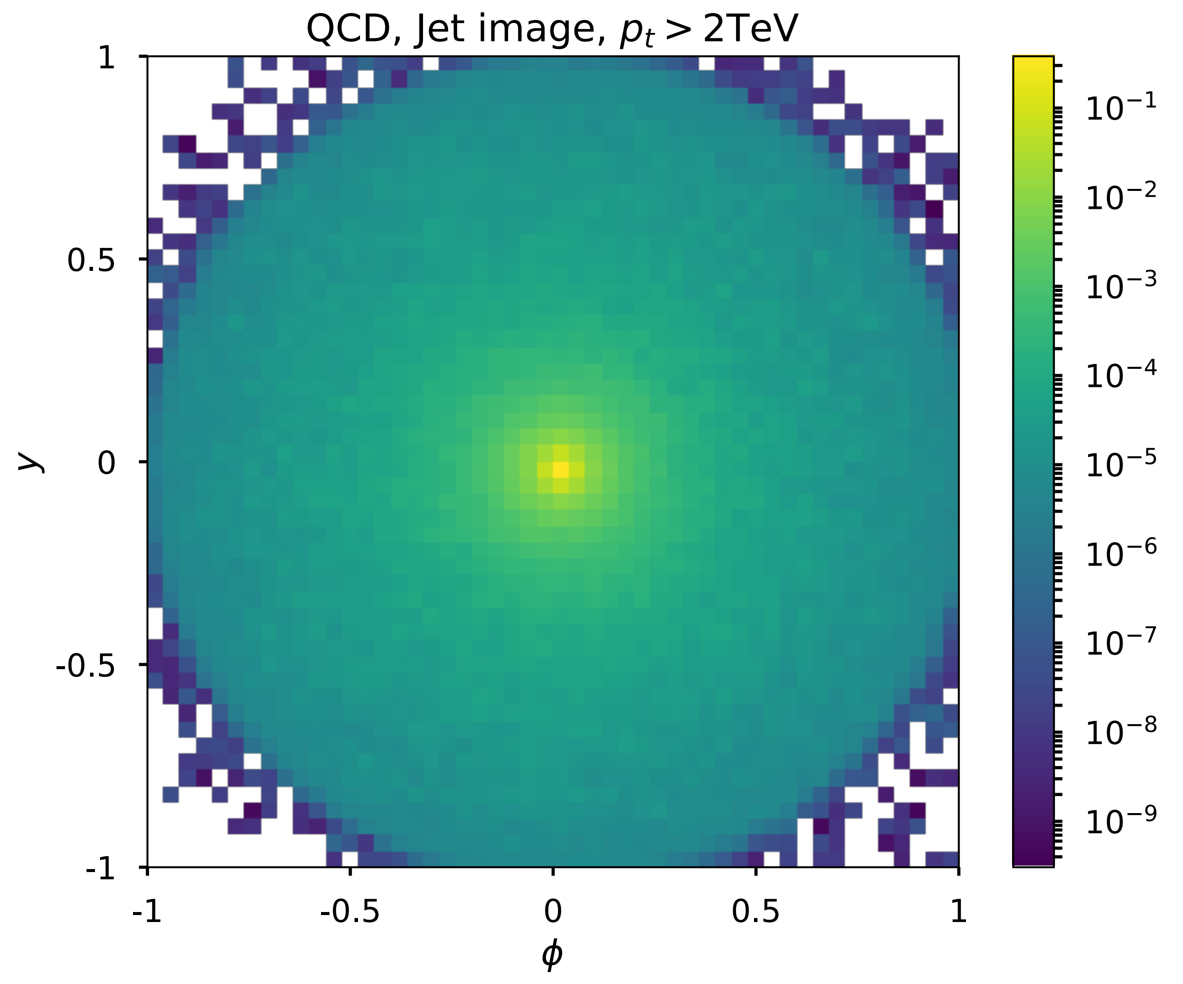
high-p_T Z → bb (5σ)

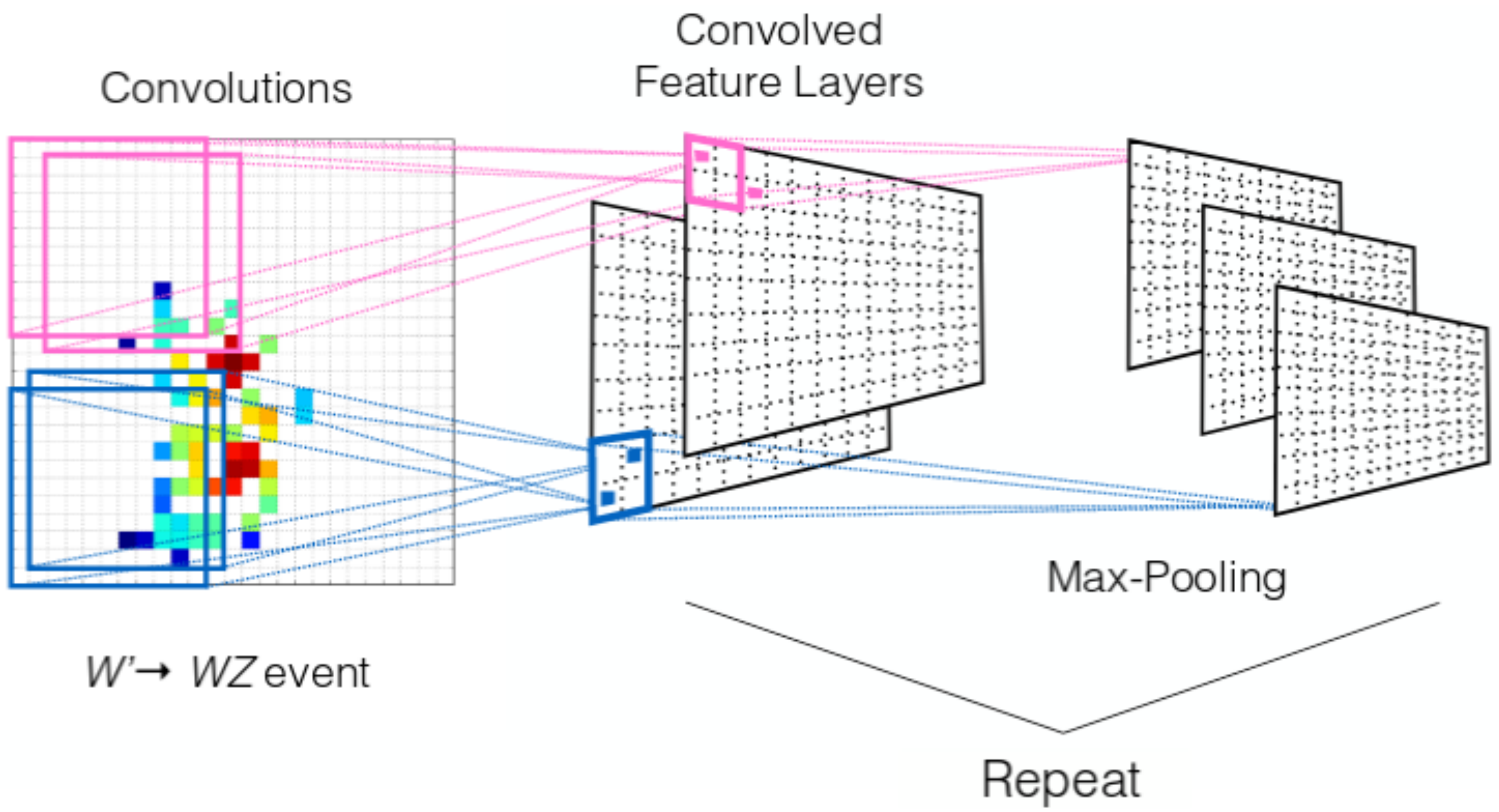
high-p_T H → bb (~ 1σ)



Convolutional neural networks and jet images

- Project a jet onto a fixed $n \times n$ pixel image in rapidity-azimuth, where each pixel intensity corresponds to the momentum of particles in that cell.
- Can be used as input for classification methods used in computer vision, such as deep convolutional neural networks.





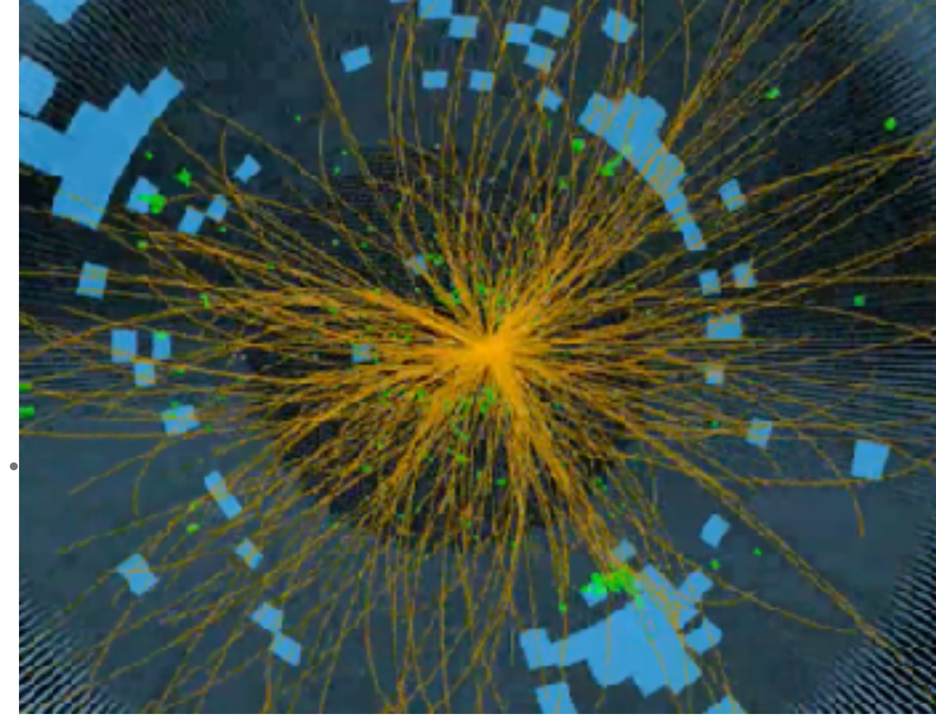
powerful

but black box

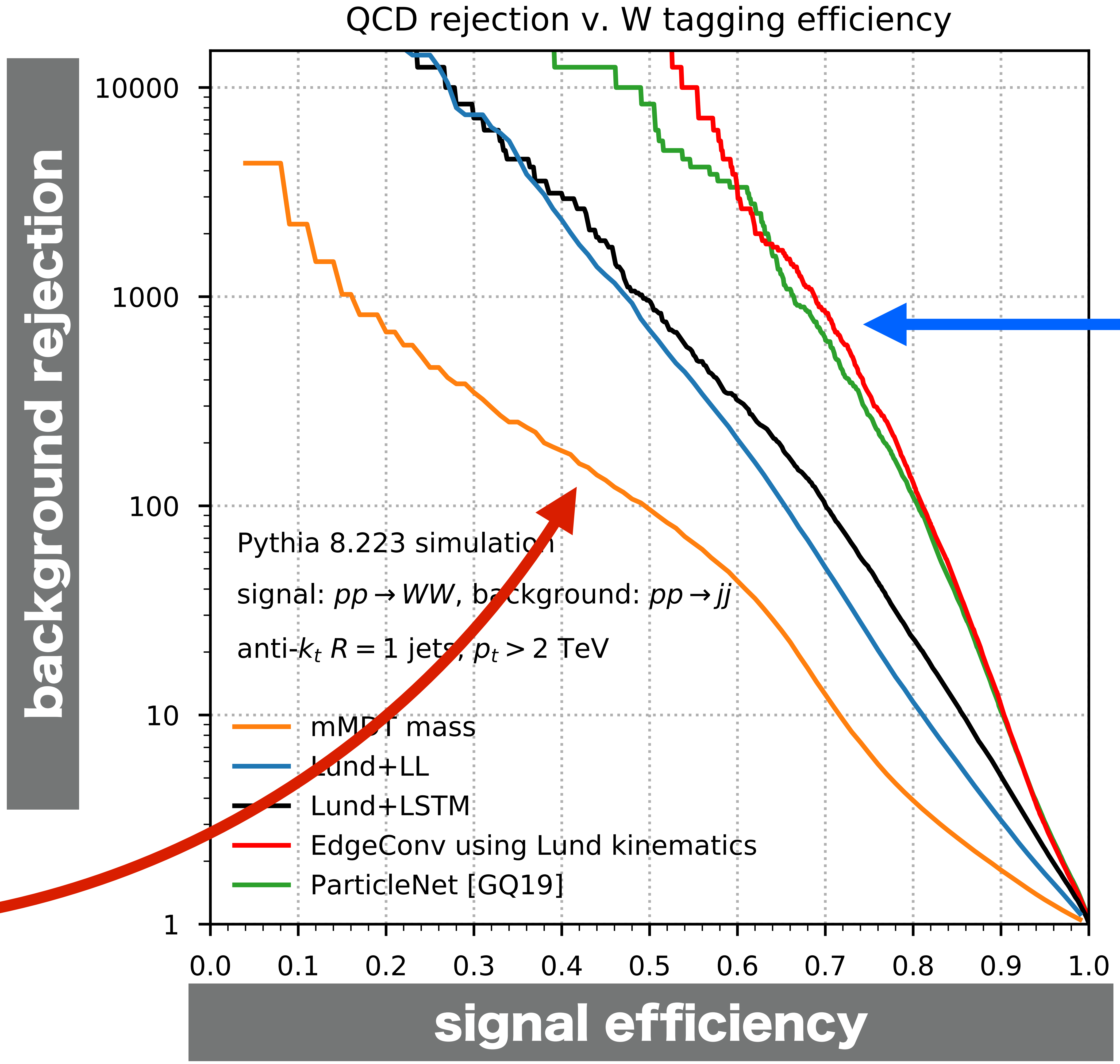
[Cogan, Kagan, Strauss, Schwartzman JHEP 1502 (2015) 118]

[de Oliveira, Kagan, Mackey, Nachman, Schwartzman JHEP 1607 (2016) 069]

using full event information for H/etc. boson tagging



Dreyer 2020 (work in progress)



QCD rejection with use of full jet substructure (2019 tools)

100x better

QCD rejection with just jet mass (SD/mMDT) i.e. 2008 tools & their 2013/14 descendants

First started to be exploited by Thaler & Van Tilburg with "N-subjettiness" (2010/11)

future progress?

(2) proposed future colliders

e^+e^-: ILC, CLIC, CepC, FCC-ee [LEP3]

pp: CppC, HE-LHC, FCC-hh

ep: LHeC, FCC-eh, ***EIC***

[$\mu\mu$?]

Improvements w.r.t. HL-LHC

M. Cepeda

Kappa-framework

	LHeC *	HE-LHC *	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
κ_W *	5.7	2.1	1.5	5.9	2.3	4.2	4.5	1.8	1.8	4.1	8.5
κ_Z *	1.9	1.9	4.5	5.7	3.0	3.3	3.3	7.2	6.8	7.6	7.6
κ_g	1.4	2.0	1.6	2.6	1.5	2.0	2.6	2.0	1.8	2.5	4.2
κ_γ	1.1	2.1	1.3	1.4	1.1	1.3	1.5	1.4	1.3	1.4	4.7
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	1.7	1.0	1.2	1.0	1.5	1.5	1.1	1.1	1.1	2.9
κ_b	2.2	1.9	2.2	4.6	2.2	4.3	4.9	2.8	2.6	4.1	5.4
κ_μ	1.0	2.6	1.0	1.1	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.2	1.8	1.5	2.5	1.1	1.6	2.0	1.7	1.6	2.4	3.3
Br_{inv}	1.7	1.3	7.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.2	1.9	2.3	2.9	1.5	1.7	1.7	3.7	3.4	4.1	4.1
Br_{unt} **			⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HL-LHC

EFT-framework

prel.

	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g^{eff}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	3.1	3.1	≥ 10
$g^{eff}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.1	2.3	3.0	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.7	2.0	2.8	1.7	2.3	2.9	2.8	2.3	2.7	4.5
g^{eff}_{Htt}	1.1	1.7	1.1	1.2	1.1	1.4	1.4	1.1	1.1	1.1	1.8
g^{eff}_{Hcc}	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{eff}_{Hbb}	2.7	1.5	6.1	9.8	5.1	≥ 10	≥ 10	7.6	7.3	9.1	≥ 10
$g^{eff}_{H\tau\tau}$	1.6	1.3	4.1	5.8	2.7	3.8	4.8	5.0	5.0	6.1	7.8
$g^{eff}_{H\mu\mu}$	1.2	1.8	1.3	1.4	1.3	1.4	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.4	6.7	≥ 10	≥ 10	≥ 10	≥ 10	7.3	7.8	≥ 10	≥ 10
$\delta \kappa_\gamma[\times 10^2]$	1.3	1.2	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.0	≥ 10	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

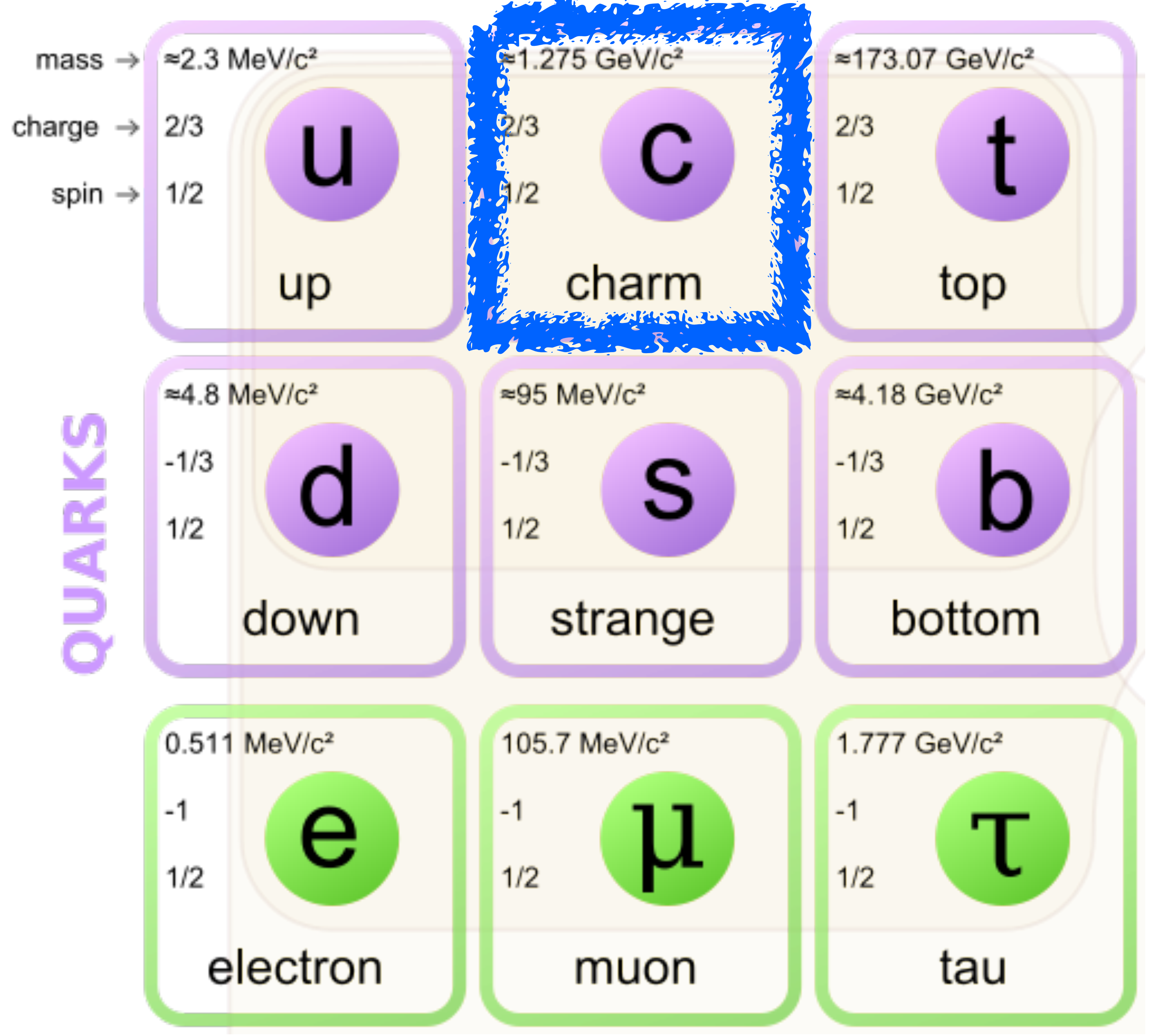
SMEFT ND (⋆) not measured in HL-LHC

e+e− & eh colliders: Higgs-charm (2nd generation) coupling

today: no evidence yet

(1 in 35 decays)

needs an e+e− or ep collider



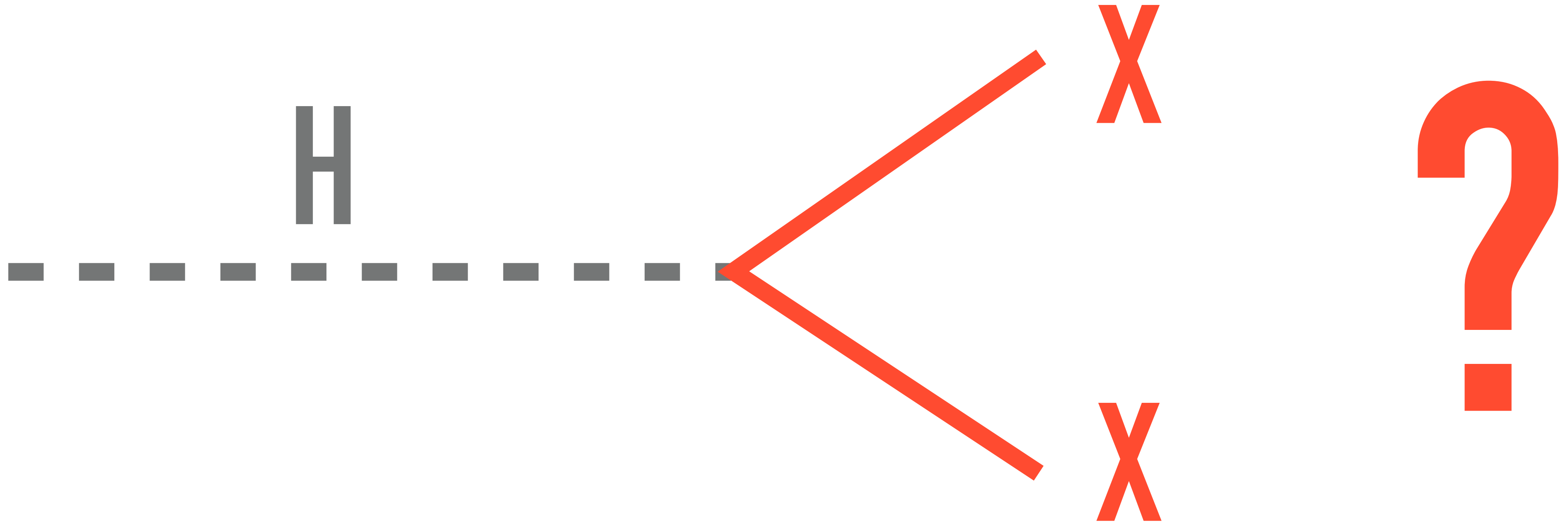
Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	2	0.5	5 @ 240 GeV	+1.5 @ 365 GeV	+ HL-LHC	2
Years	25	15	7	3	+4	—	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.8	6.3	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.35	0.80	0.2	**0.17**	0.16	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.7	1.3	1.3	**0.43**	0.40	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.8	2.8	1.3	**0.61**	0.55	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	6.8	1.7	**1.21**	1.18	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	2.2	5.8	1.6	**1.01**	0.83	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7	1.9	4.2	1.4	**0.74**	0.64	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	13	n.a.	10.1	**9.0**	3.9	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	6.4	n.a.	4.8	**3.9**	1.1	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	–	–	–	2.4	1.7
BR_{EXO} (%)	SM	< 1.8	< 3.0	< 1.2	< 1.0	< 1.0	n.a.

e^+e^- colliders: total Higgs width (≡ lifetime)

All current fits need to make assumptions about the total Higgs width (sum over all decay channels, whether observed or not).

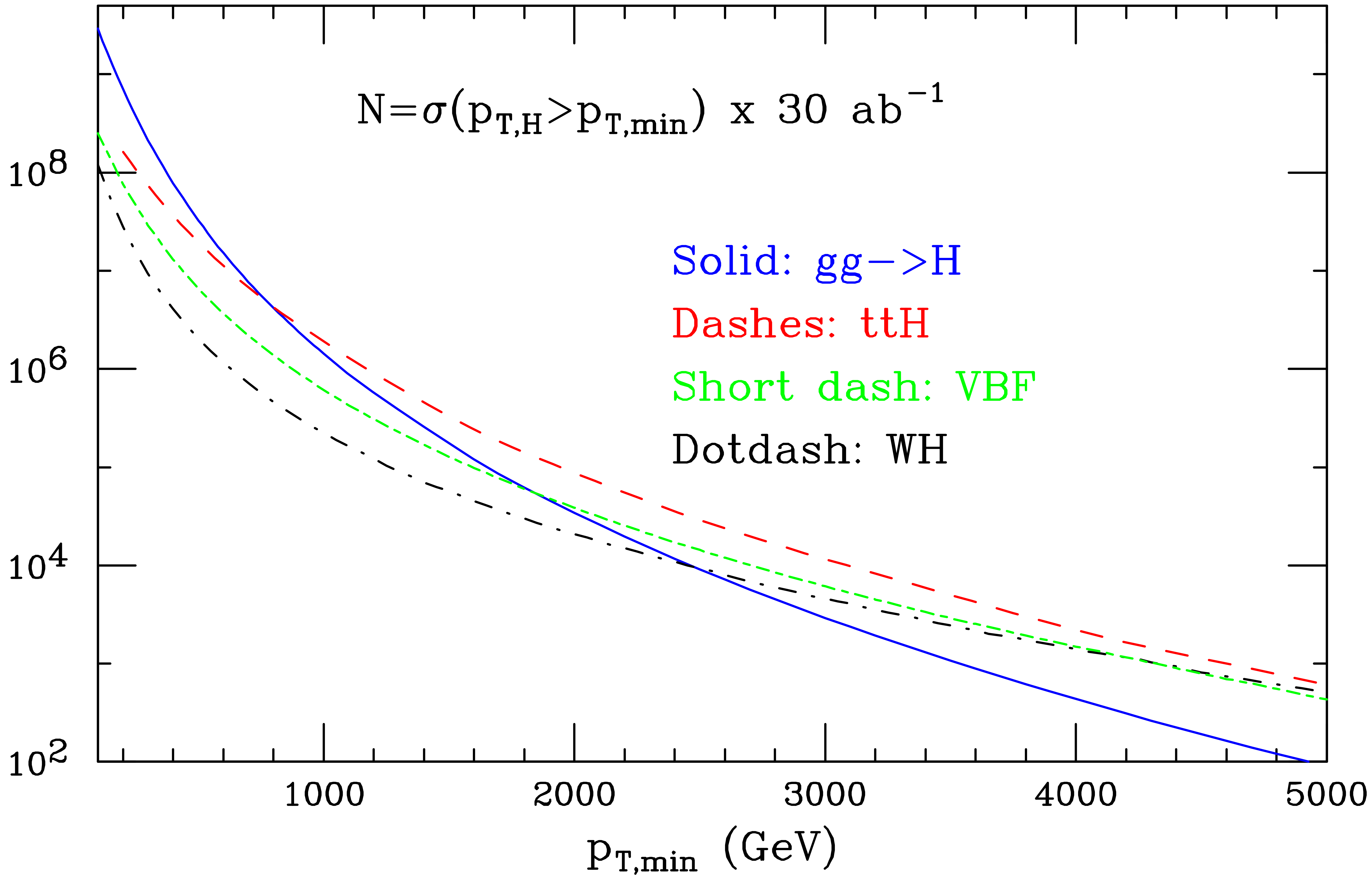
Only e^+e^- colliders can measure this directly.

$$\Gamma_H = \sum_X$$



Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	2	0.5	5 @ 240 GeV	+1.5 @ 365 GeV	+ HL-LHC	2
Years	25	15	7	3	+4	—	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.8	6.3	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.35	0.80	0.2	**0.17**	0.16	0.43

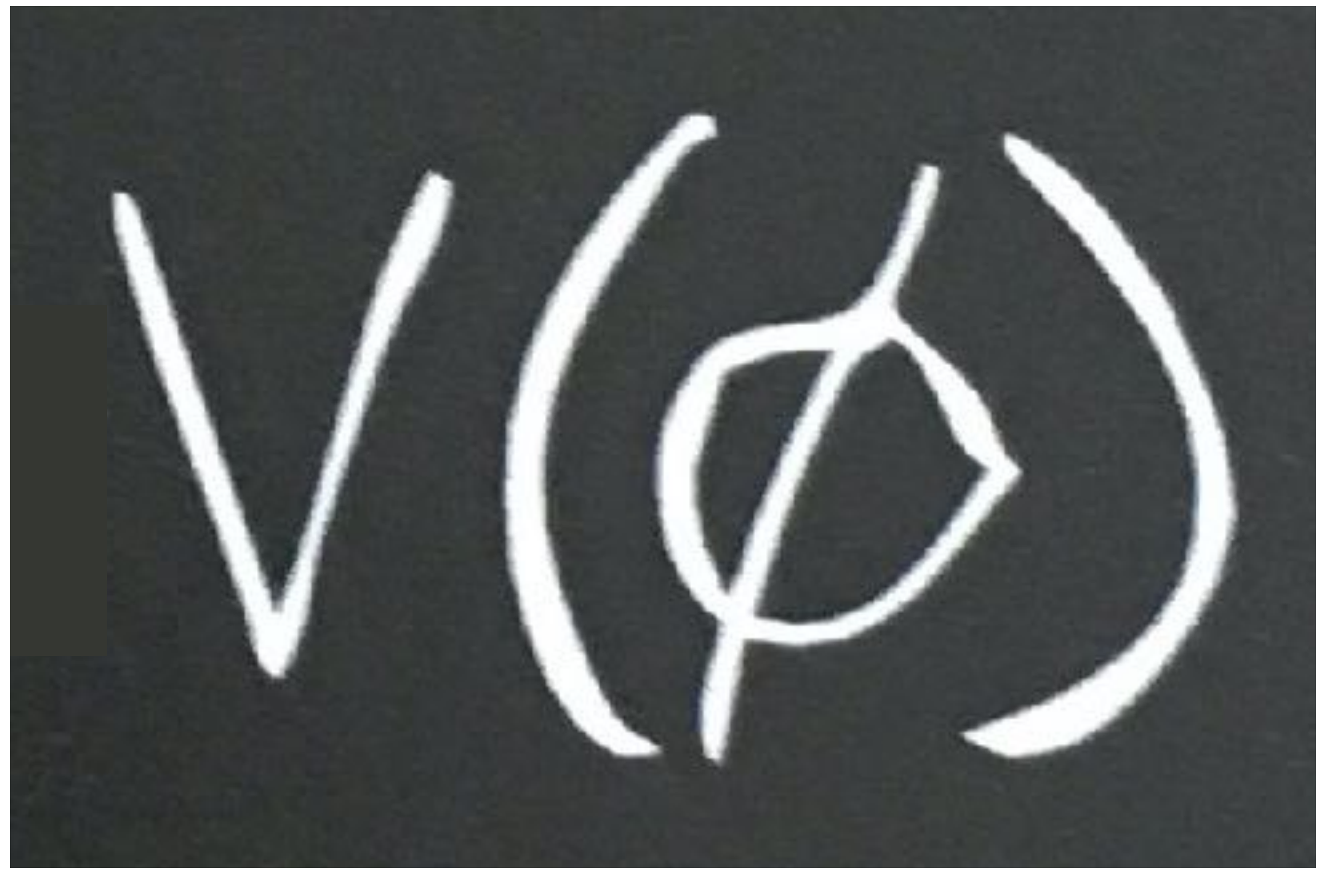
is Higgs interaction pointlike?

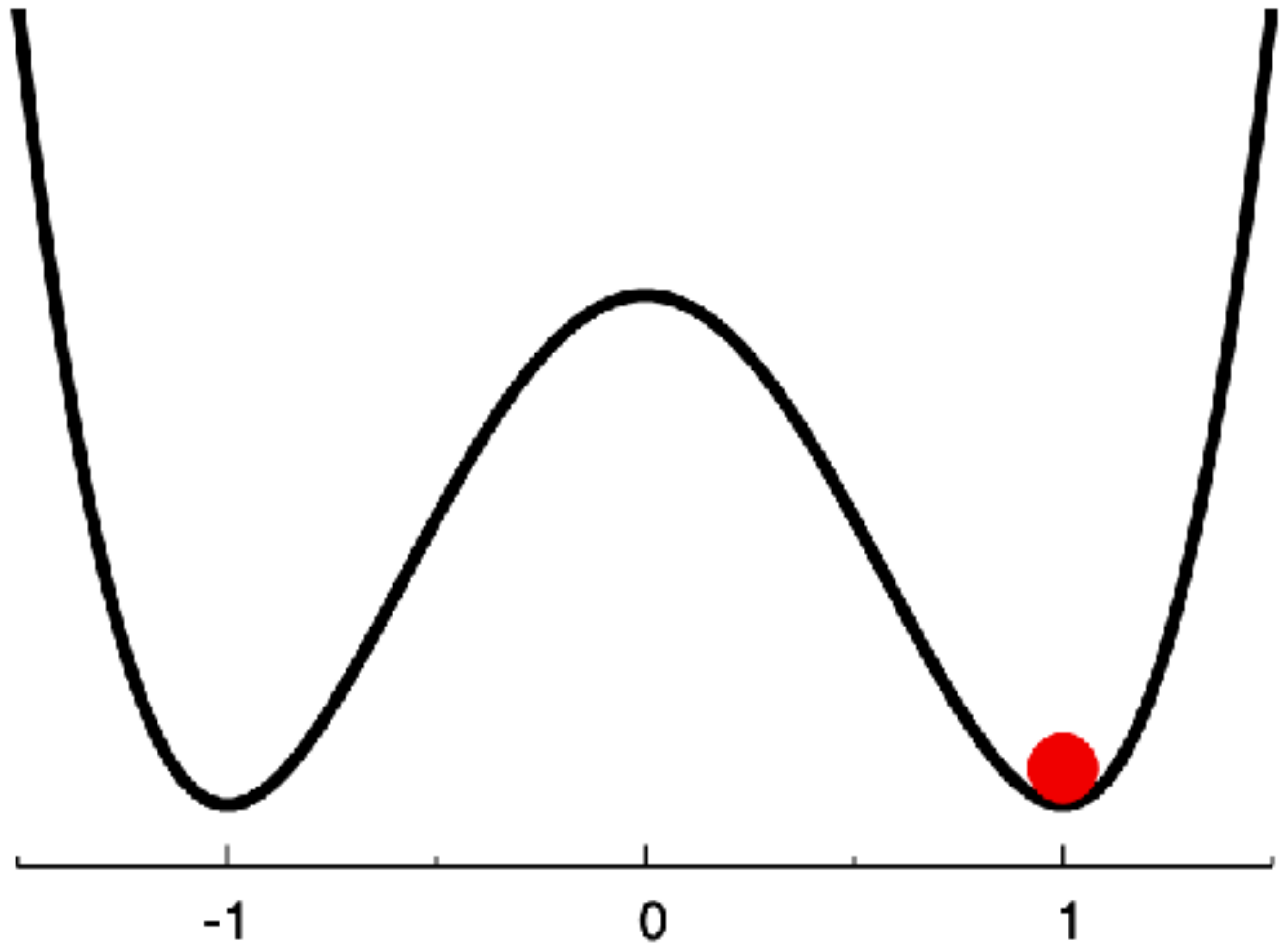


study in events with large momentum transfers

high-p_T or offshell Higgs

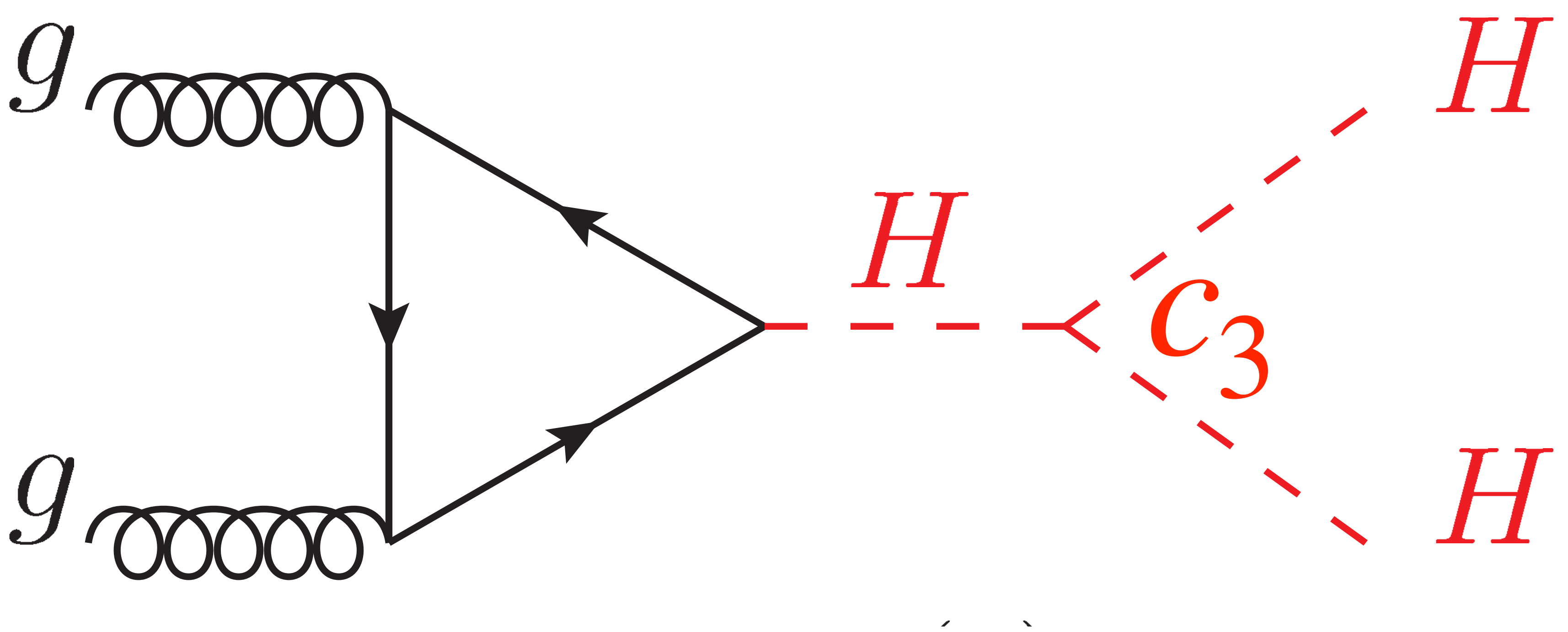
$$V(\Phi) = m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 \quad ?$$





- **The Higgs potential holds together the rest of the standard model (keystone)**
- so far (as a fundamental potential) only ever seen in textbooks!
- $-\varphi^2 + \varphi^4$ implies specific Taylor expansion around $\varphi = \varphi_0$:

$$V(\phi_0 + H) = V_0 + \frac{1}{2}m_H^2 H^2 + c_3 H^3 + \cdots$$



g
g
H
c_3
H
H
luon
gluo
φ
y
x
Higgs field in space


g
g
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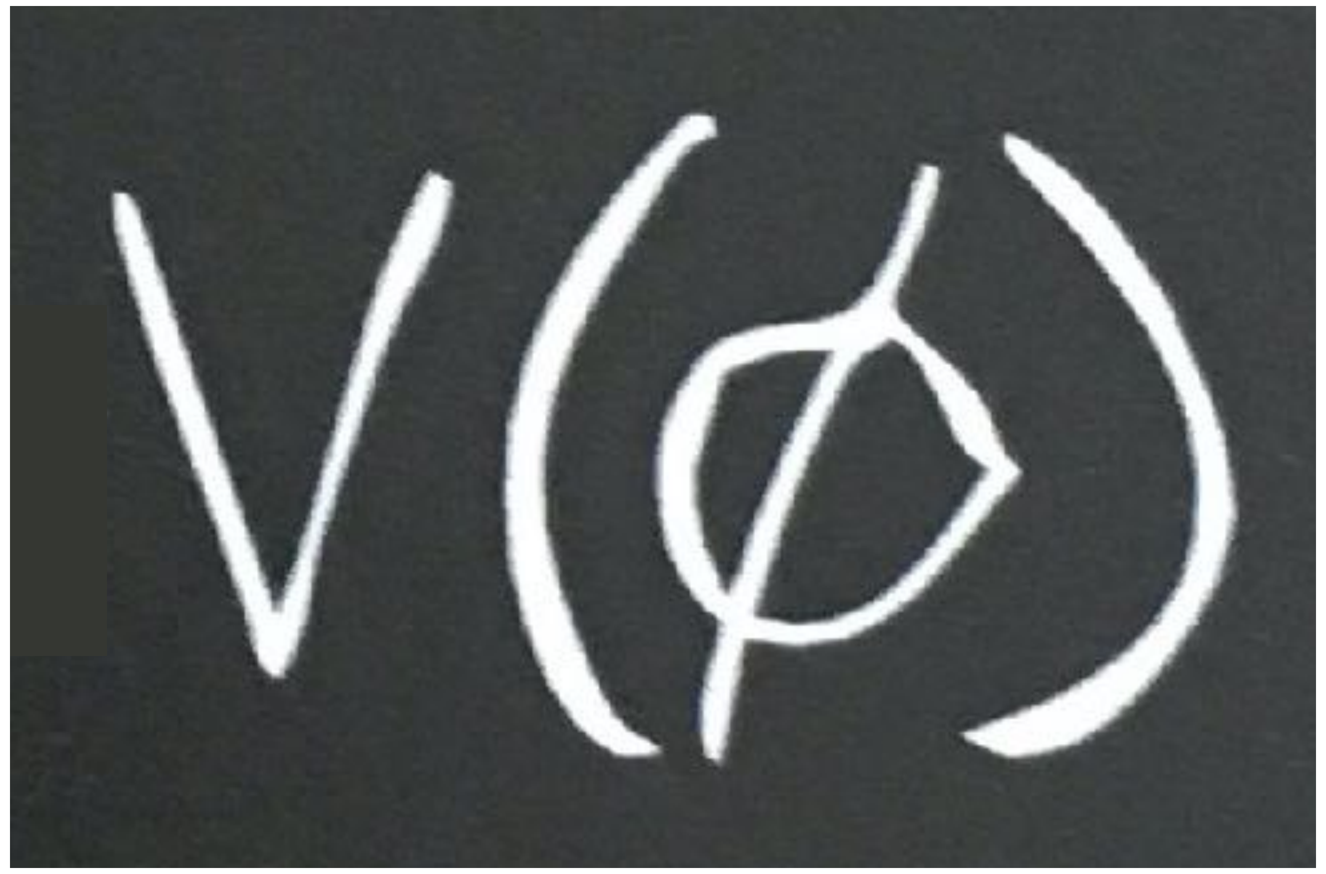
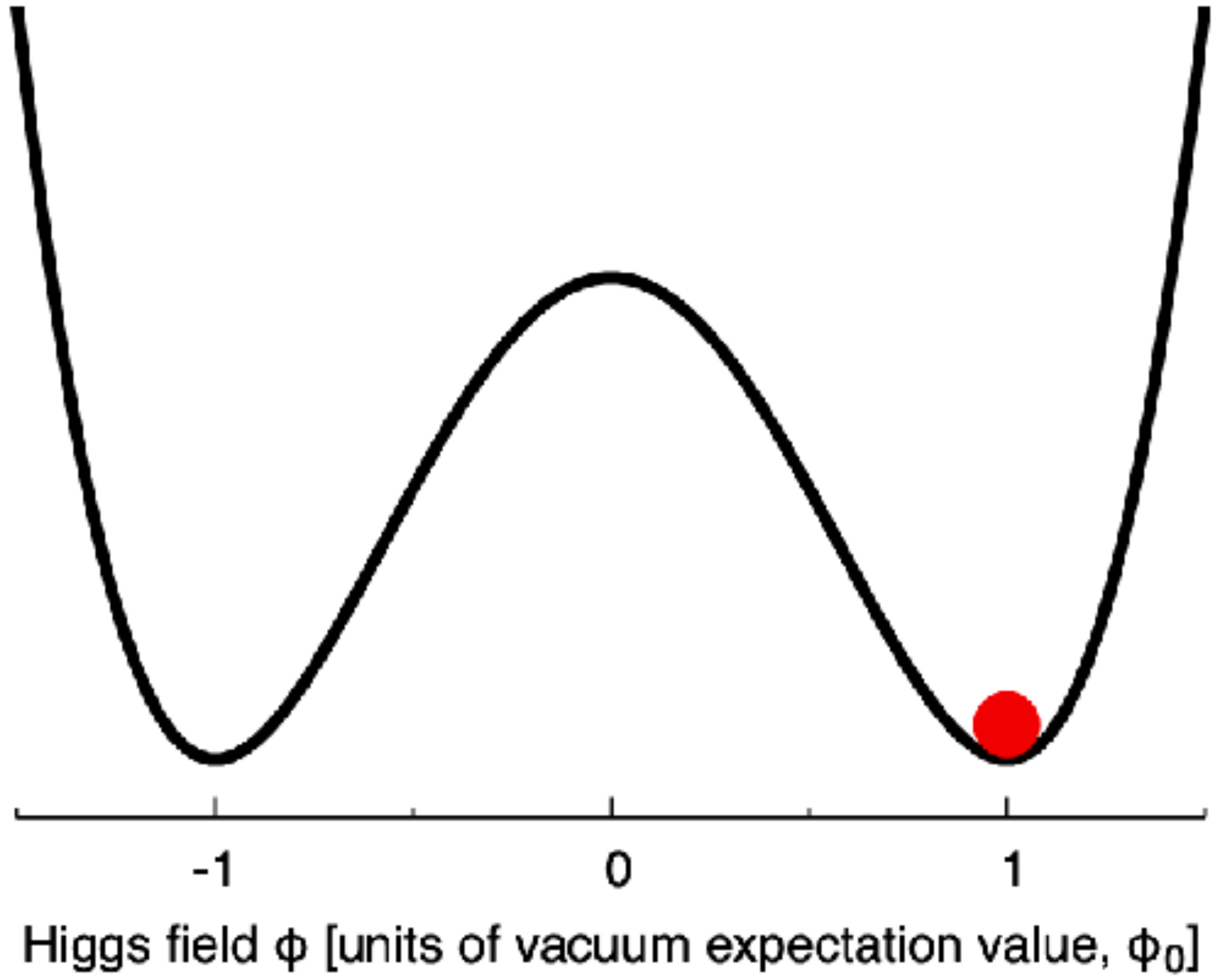
luon
gluo
φ
y
x
Higgs field in space

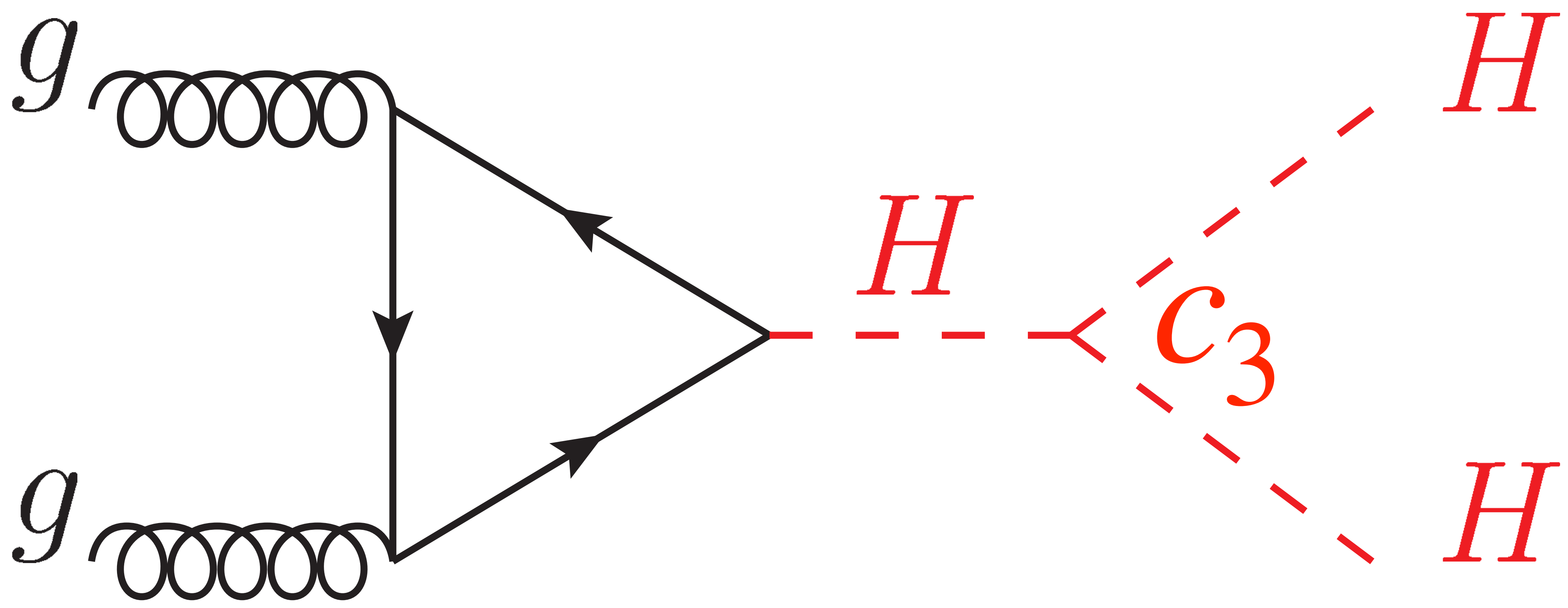
g
g
H
c3
H
H
luon
gluo
φ
y
x
Higgs field in space

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

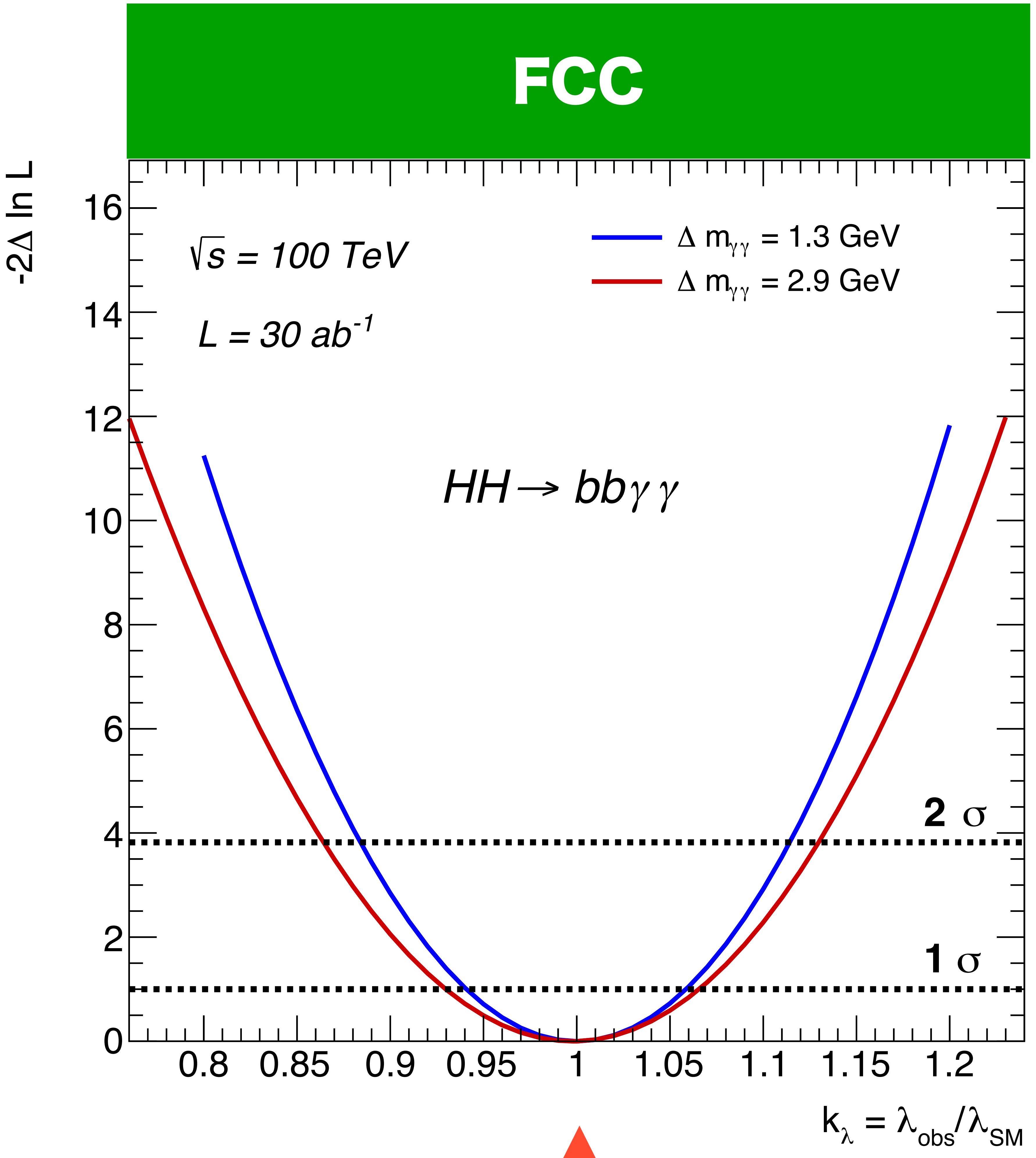


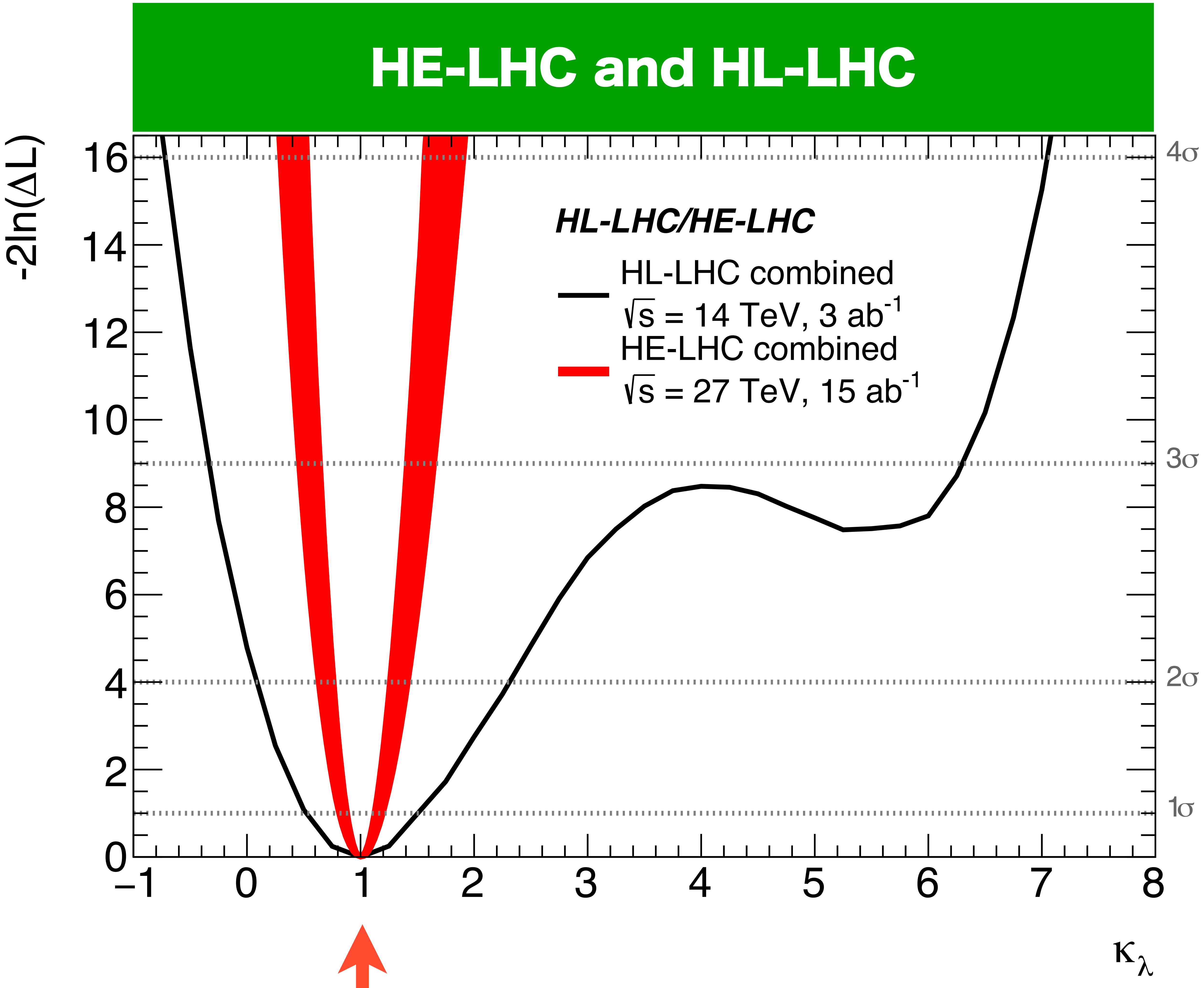
FCC-hh channel	$b\bar{b}\gamma\gamma$	$b\bar{b}ZZ^*[\to 4\ell]$
c_3 precision	6.5%	14%





FCC triple Higgs v. LHC and HE-LHC





note different scales

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

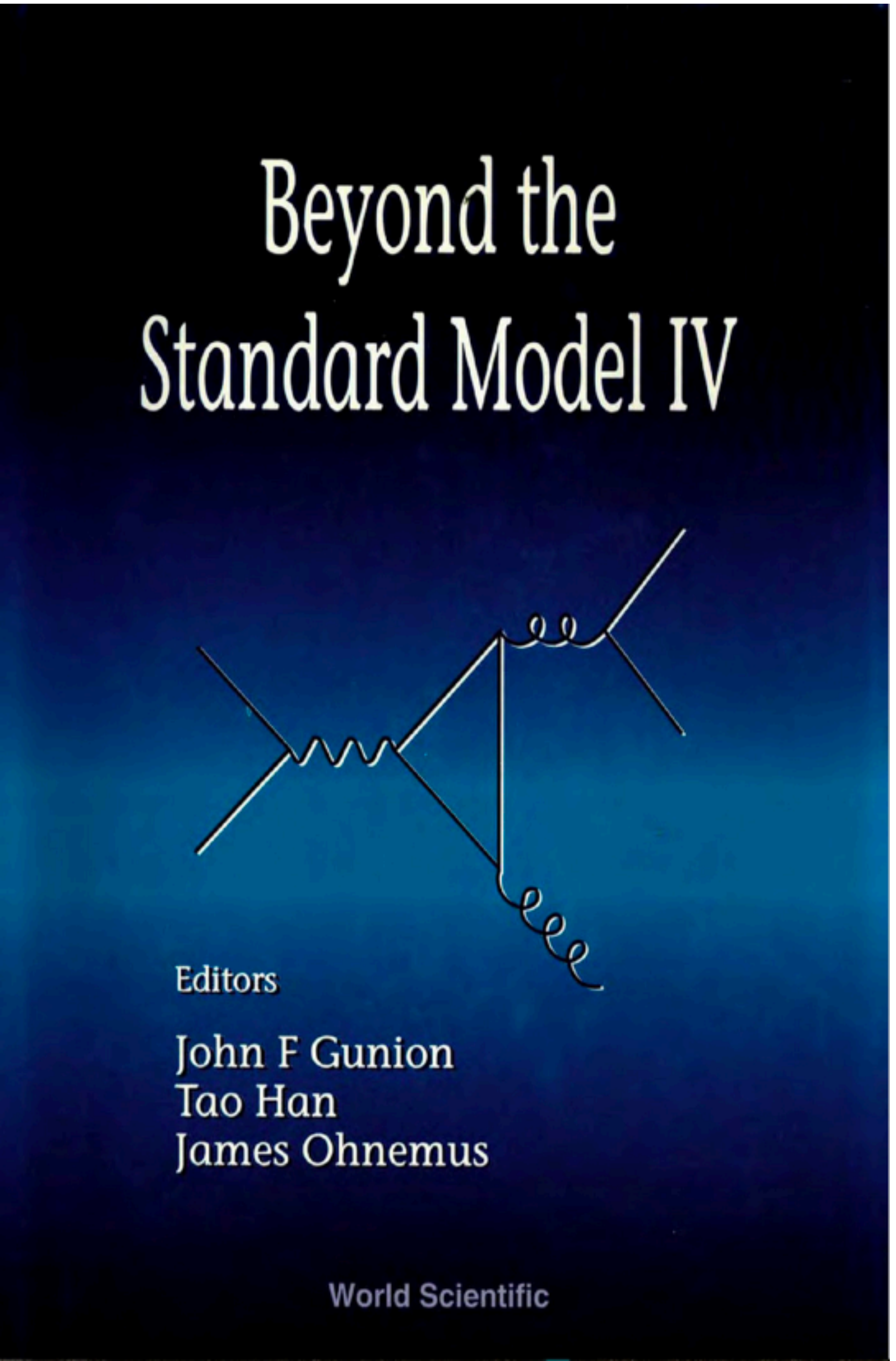
I disagree.

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 […]”

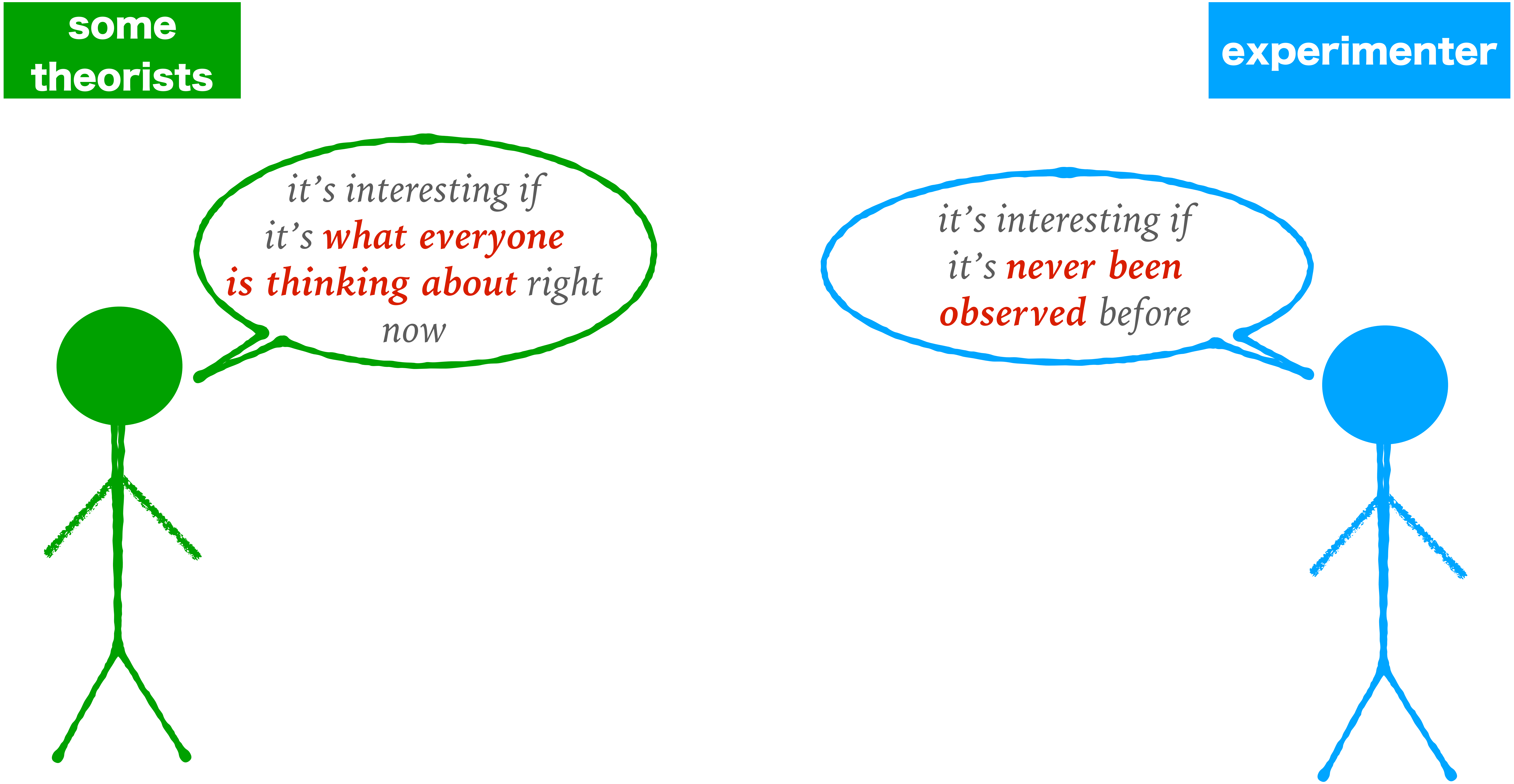
it would be so much more exciting if we'd discovered new physics, right?



not everyone would agree

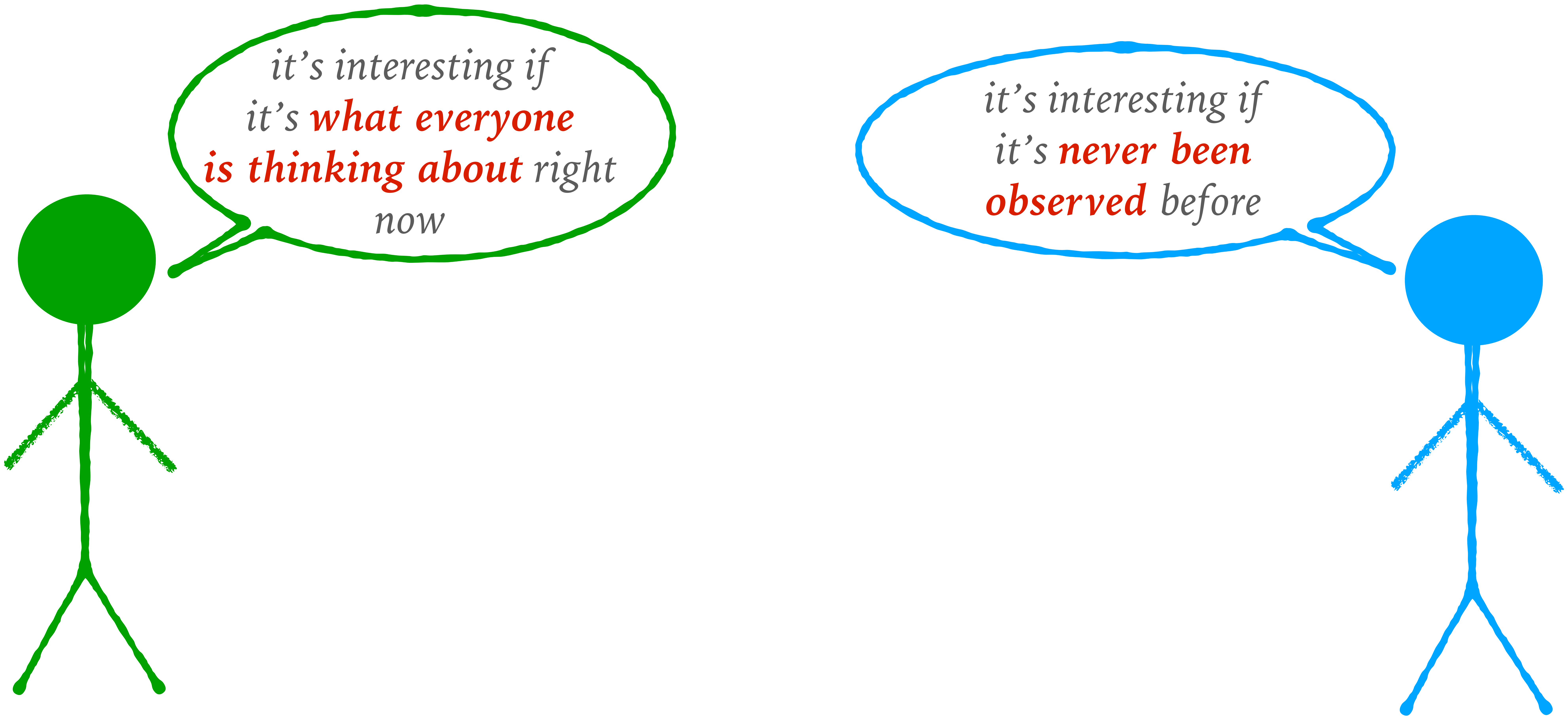
Back in 1995:

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.


some theorists
it's interesting if it's what everyone is thinking about right now
experimenter
it's interesting if it's never been observed before

some theorists

experimenter



both have a point

(don’t let one side dampen the other side’s interest)

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 (today's ~10% doesn't even get close to seeing quantum effects)

Preamble

Nature hides the secrets of the fundamental physical laws in the tiniest nooks of space and time. By developing technologies to probe ever-higher energy and thus smaller distance scales, particle physics has made discoveries that have transformed the scientific understanding of the world. Nevertheless, many of the mysteries about the universe, such as the nature of dark matter, and the preponderance of matter over antimatter, are still to be explored.

This 2020 update of the European Strategy for Particle Physics proposes a vision for both the near-term and the long-term future. It aims to significantly extend knowledge beyond the current limits, to drive innovative technological development, and to maintain Europe's leading role in particle physics, within the global context. The 2013 update came shortly after the monumental discovery of the Higgs boson, which was a turning point for research in particle physics. The Large Hadron Collider (LHC) has established the crucial role of the Higgs boson in the acquisition of mass by the fundamental particles, but the observed pattern of masses remains an enigma. The Higgs boson is a unique particle that raises profound questions about the fundamental laws of nature. It also provides a powerful experimental tool to study these questions.

In the coming decade, the LHC, including its high-luminosity upgrade, will remain the world's primary tool for exploring the high-energy frontier. Given the unique nature of the Higgs boson, there are compelling scientific arguments for a new electron-positron collider operating as a "Higgs factory". Such a collider would produce copious Higgs bosons in a very clean environment, would make dramatic progress in mapping the diverse interactions of the Higgs boson with other particles and would form an essential part of a research programme that includes exploration of the flavour puzzle and the neutrino sector.

The exploration of significantly higher energies than the LHC will make it possible to study the production of Higgs boson pairs and thus to explore the particle's interaction with itself, which is key to understanding the fabric of the universe. Further, through the exploration of a new realm of energies, discoveries will be made and the answers to existing mysteries, such as the nature of dark matter, may be found. The particle physics community is ready to take the next step towards even higher energies and smaller scales. The vision is to prepare a Higgs factory, followed by a future hadron collider with sensitivity to energy scales an order of magnitude higher than those of the LHC, while addressing the associated technical and environmental challenges.

This Strategy presents exciting and ambitious scientific goals that will drive technological and scientific exploration into new and uncharted territory for the benefit of the field and of society.

meanwhile, the search for new physics continues

a unique feature of the energy-frontier searches at colliders is how broadly they search ($\sim$ 1000 channels)

(And while the search continues we may find 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

BACKUP

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

thanks to U. Haisch for a crash course on the models — any naivety is mine, not his

FCC

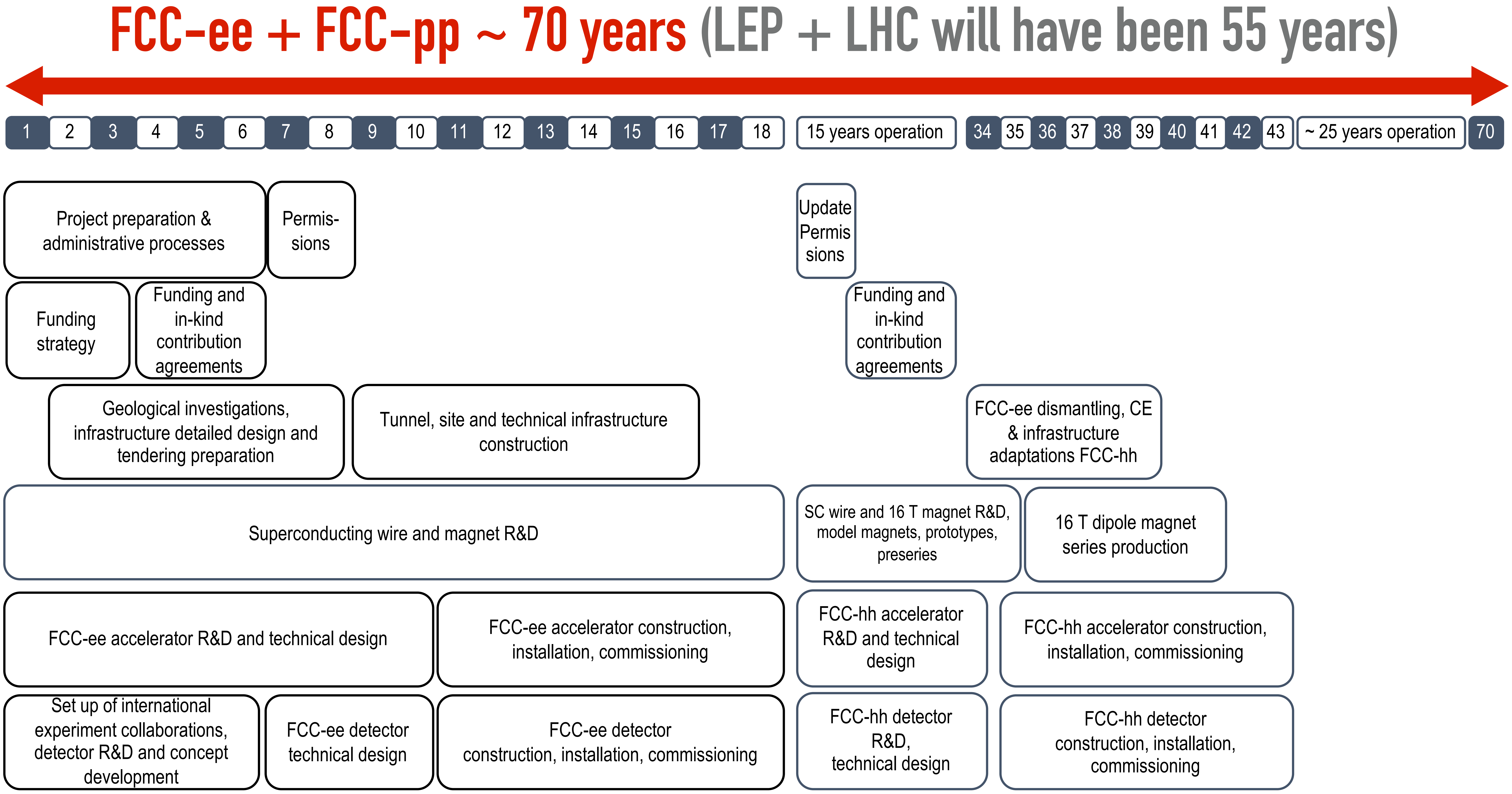


Figure 9: Overview of implementation timeline for the integral FCC program, starting in 2020. Numbers in the top row indicate the year. Physics operation for FCC-ee would start towards the end-2030s; physics operation for FCC-hh would start in the mid-2060s.

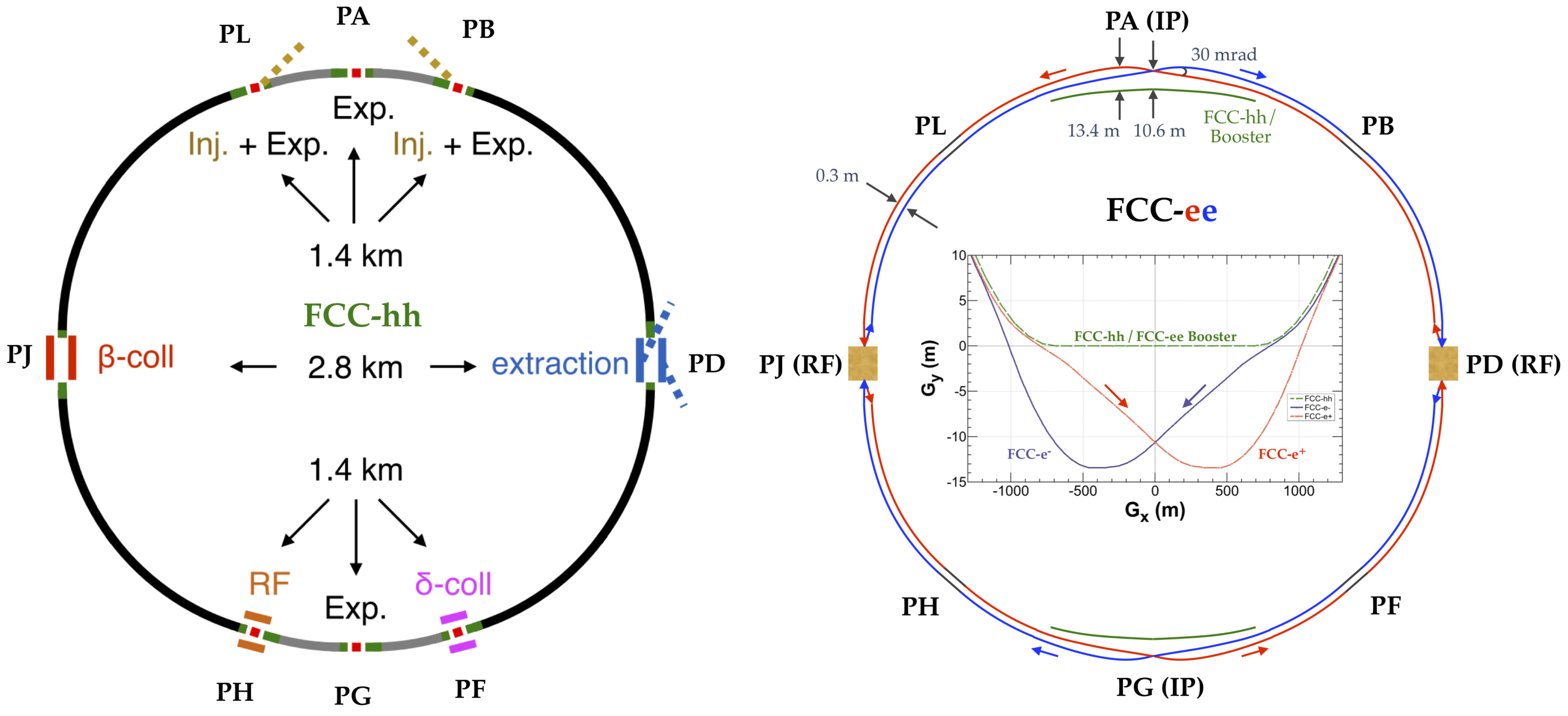


Figure 2.1: The layouts of FCC-hh (left), FCC-ee (right), and a zoom in on the trajectories across interaction point G (right middle). The FCC-ee rings are placed 1 m outside the FCC-hh footprint in the arc. The e^+ and e^- rings are separated by 30 cm horizontally in the arc. The main booster follows the footprint of the FCC-hh. The interaction points are shifted by 10.6 m towards the outside of FCC-hh. The beams coming toward the IP are straighter than the outgoing ones in order to reduce the synchrotron radiation at the IP.

Table 5: Summary of capital cost to implement the integral FCC programme (FCC-ee followed by FCC-hh).

Domain	**Cost in MCHF**
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**

~35% of CERN budget (1.17BCHF) integrated over 70 years

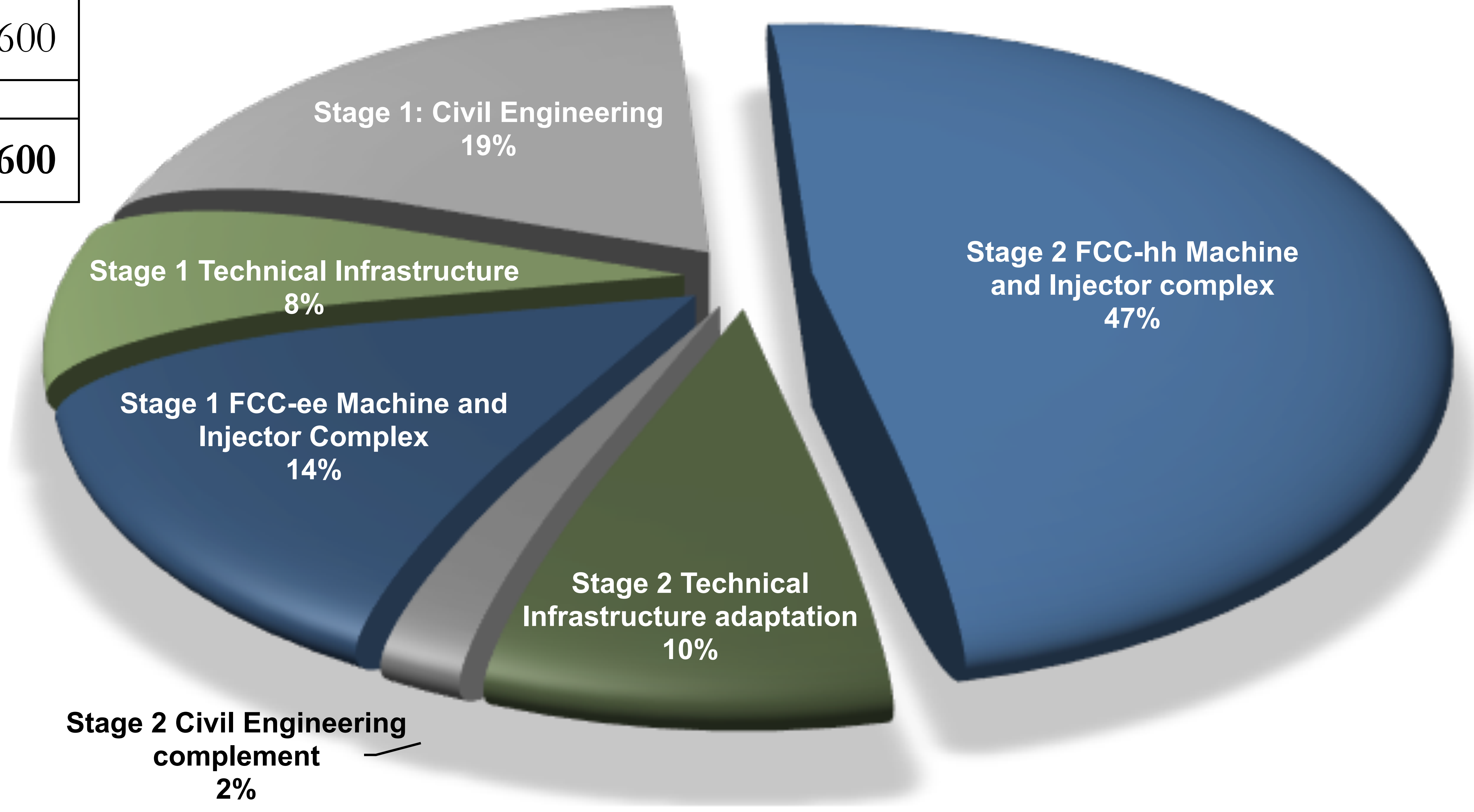


Figure 10: FCC-hh capital cost per domain for the integral FCC project.

budgets in perspective

Total capital costs for FCC-ee + FCC-hh (for a 70-year programme):

Current CERN budget

- ~ 1B€ budget / year
- ~14k international scientists use CERN's facilities ("associated members of the personnel", https://cds.cern.ch/record/2317058/files/CERN-HR-STAFF-STAT-2017-RESTR.pdf)
- ~70k€ / scientist
- [NB: figures from Wikipedia suggest DESY cost per external scientist is similar]

LEP + LHC timeline

- 1981: LEP approved
- 1983: construction started
- 1989 – 2000: LEP operation
- 2001 – 2009: LHC construction
- 2009 – 2036: LHC operation (+regular upgrades)

- **TOTAL: 55 years**

FCC physics CDR, table of contents

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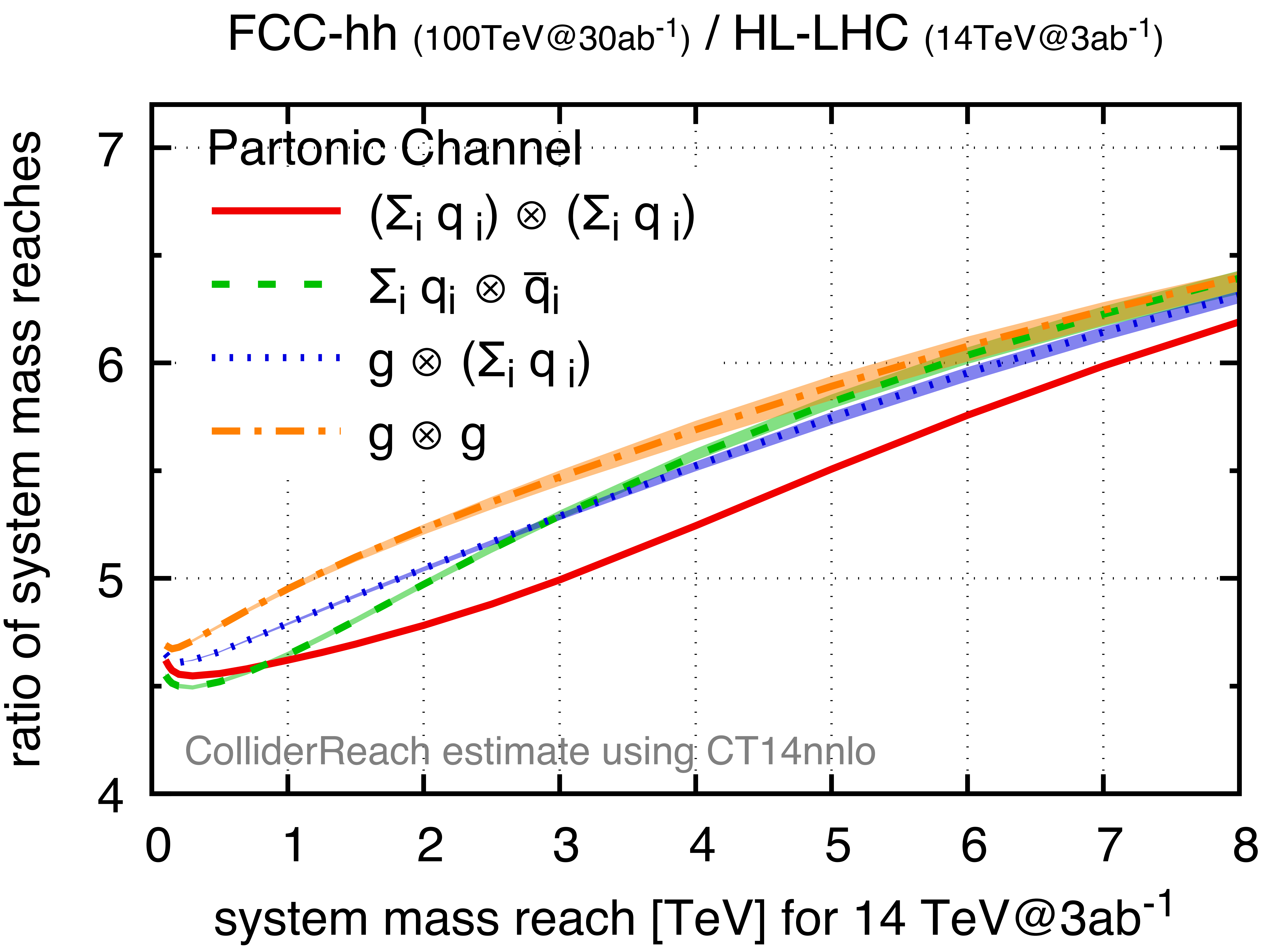
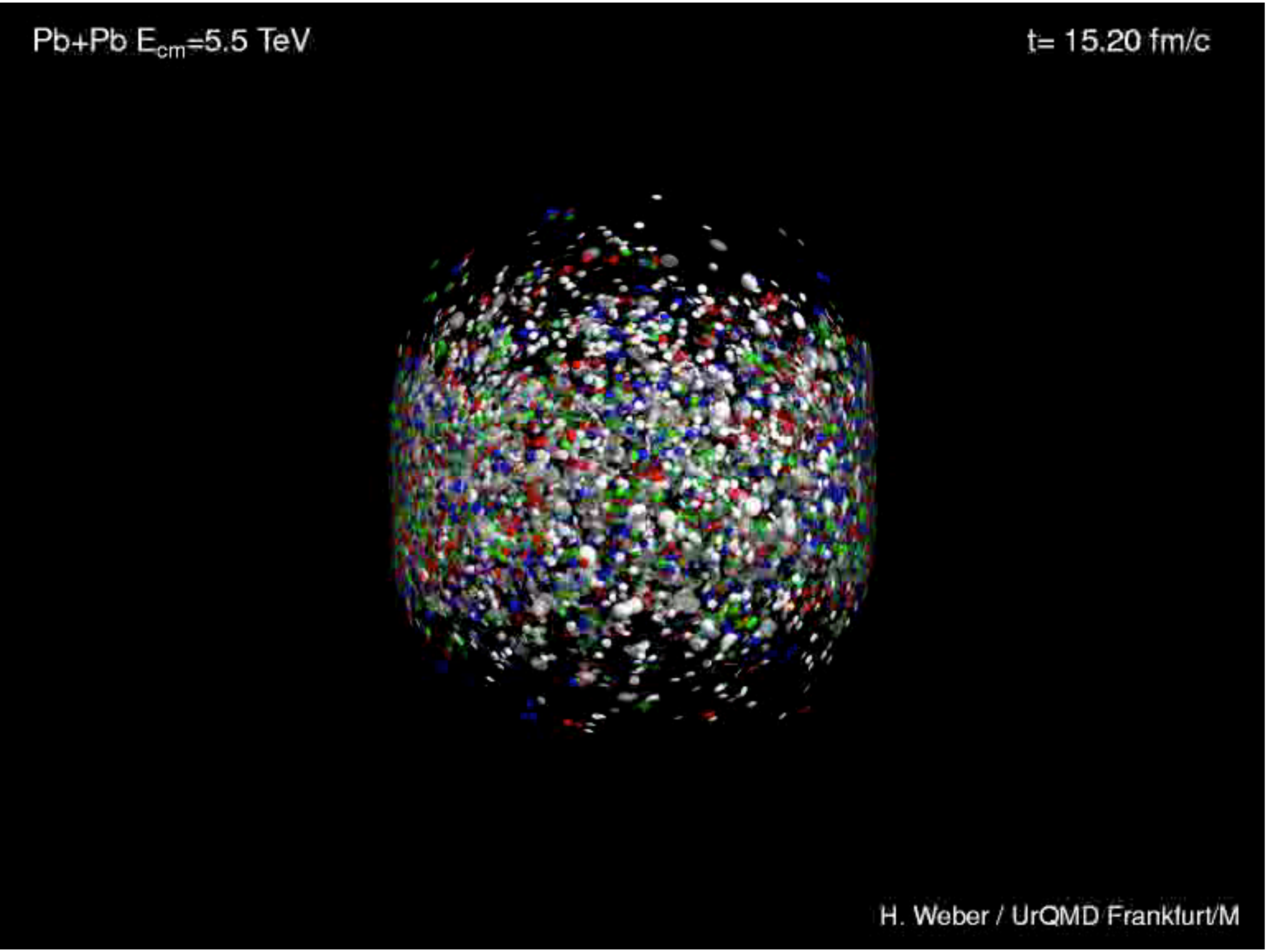

FCC-hh (100TeV@30ab-1) / HL-LHC (14TeV@3ab-1)
Partonic Channel
(Σi q i) ⊗ (Σi q i)
Σi qi ⊗ q̄i
g ⊗ (Σi q i)
g ⊗ g
ColliderReach estimate using CT14nnlo
ratio of system mass reaches
system mass reach [TeV] for 14 TeV@3ab-1
7
6
5
4
0
1
2
3
4
5
6
7
8

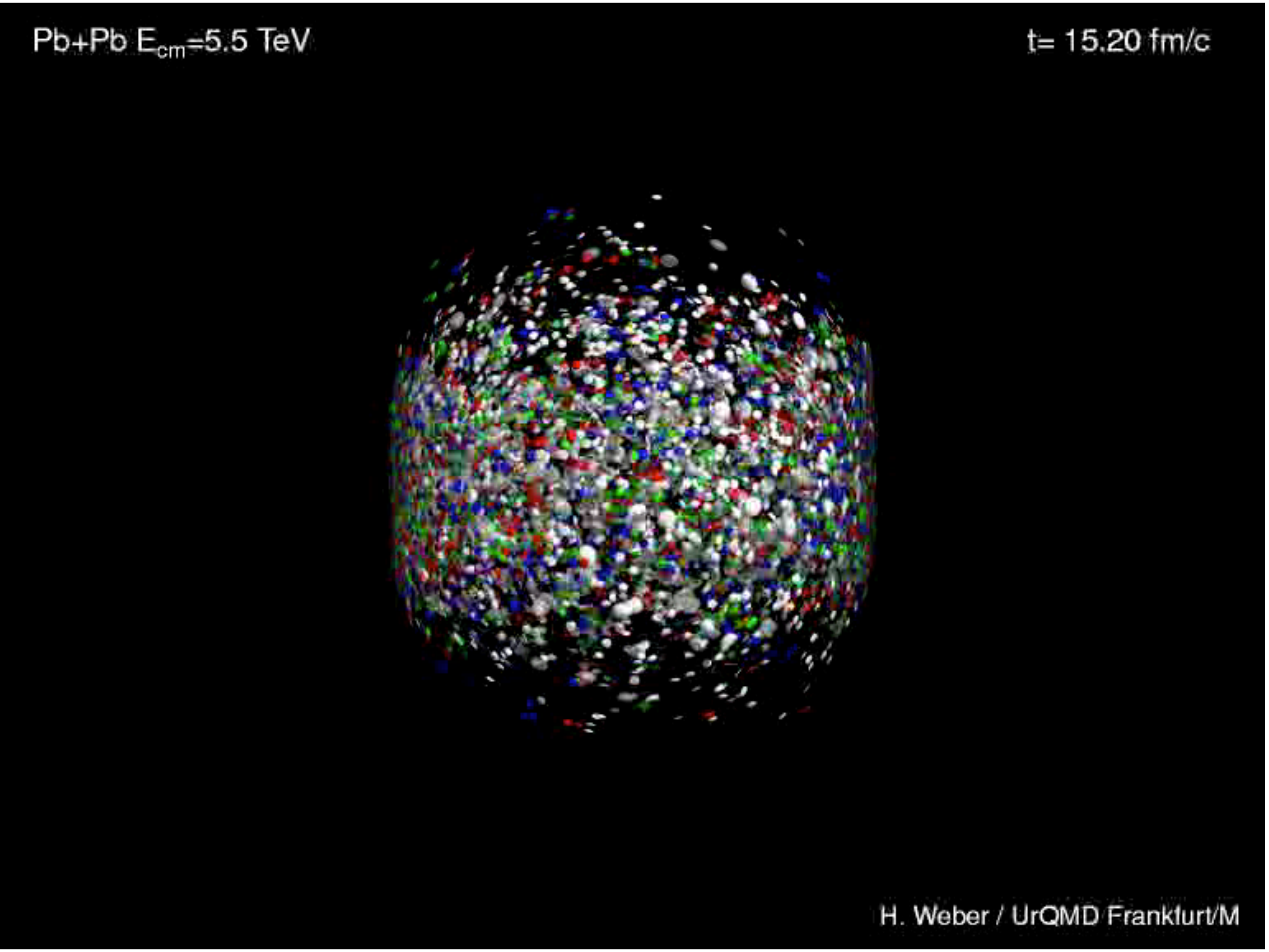
heavy-ion collisions

the highest-temperature plasmas in the laboratory

Flörchinger @ LHCP'18: "Little bangs in the laboratory"



Hot (5×10^{12}K), dense system, which evolves on timescales
~0.3 – 10 fm/c
~1 – 30 × 10^{-24} s

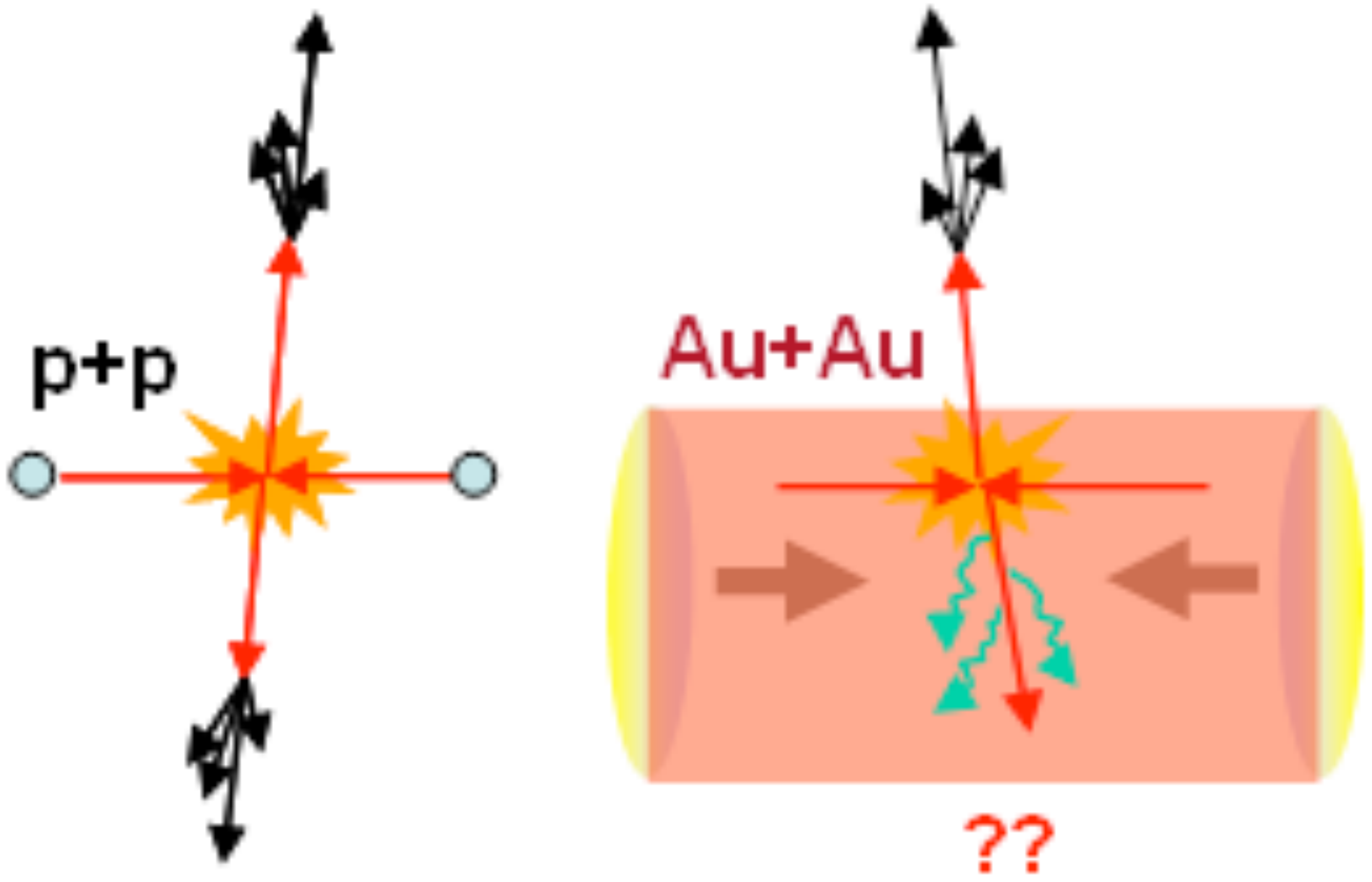


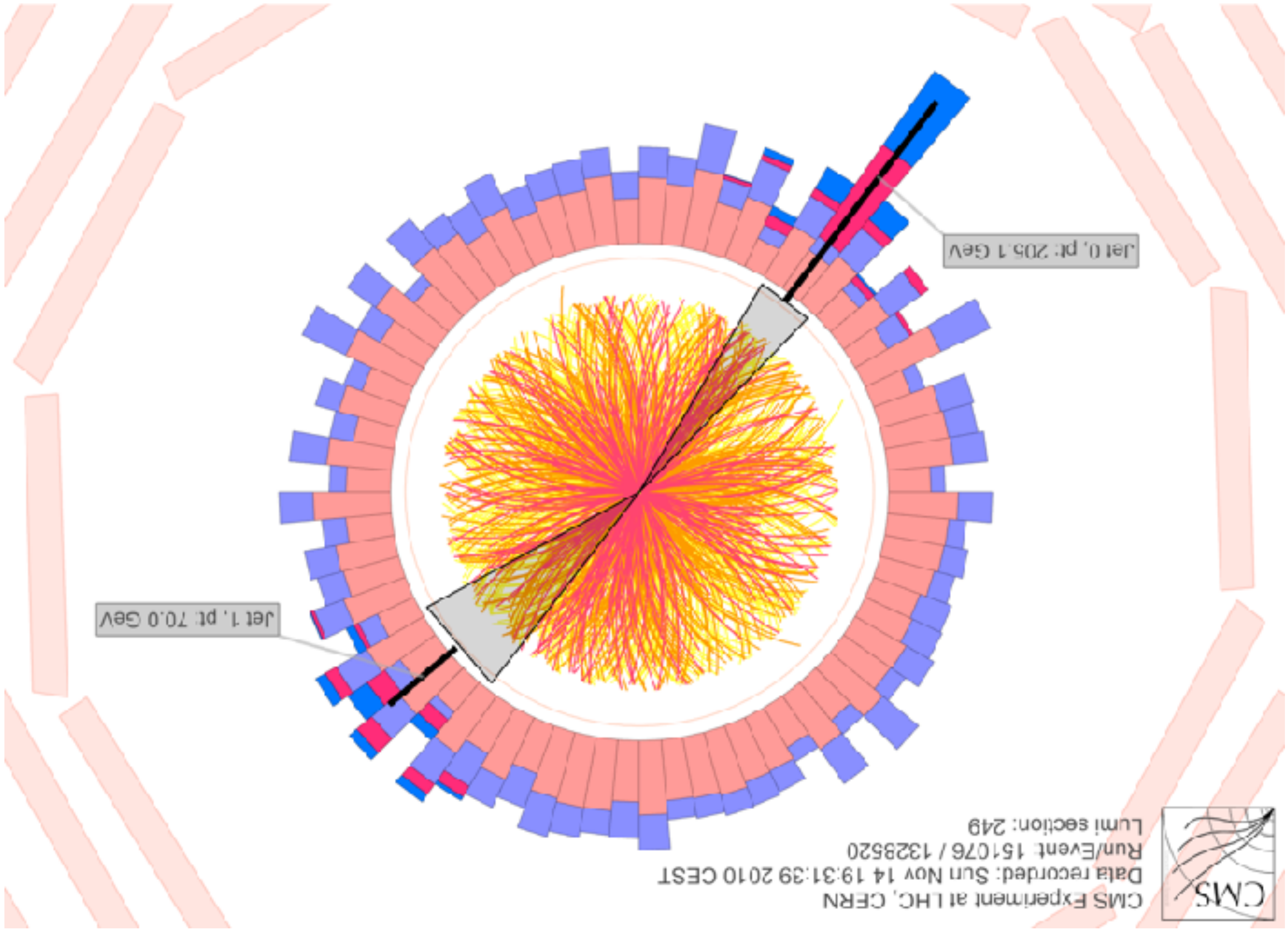
Hot (5×10^{12}K), dense system, which evolves on timescales
$\sim 0.3 - 10$ fm/c
$\sim 1 - 30 \times 10^{-24}$ s

a key probe of the medium: jet quenching

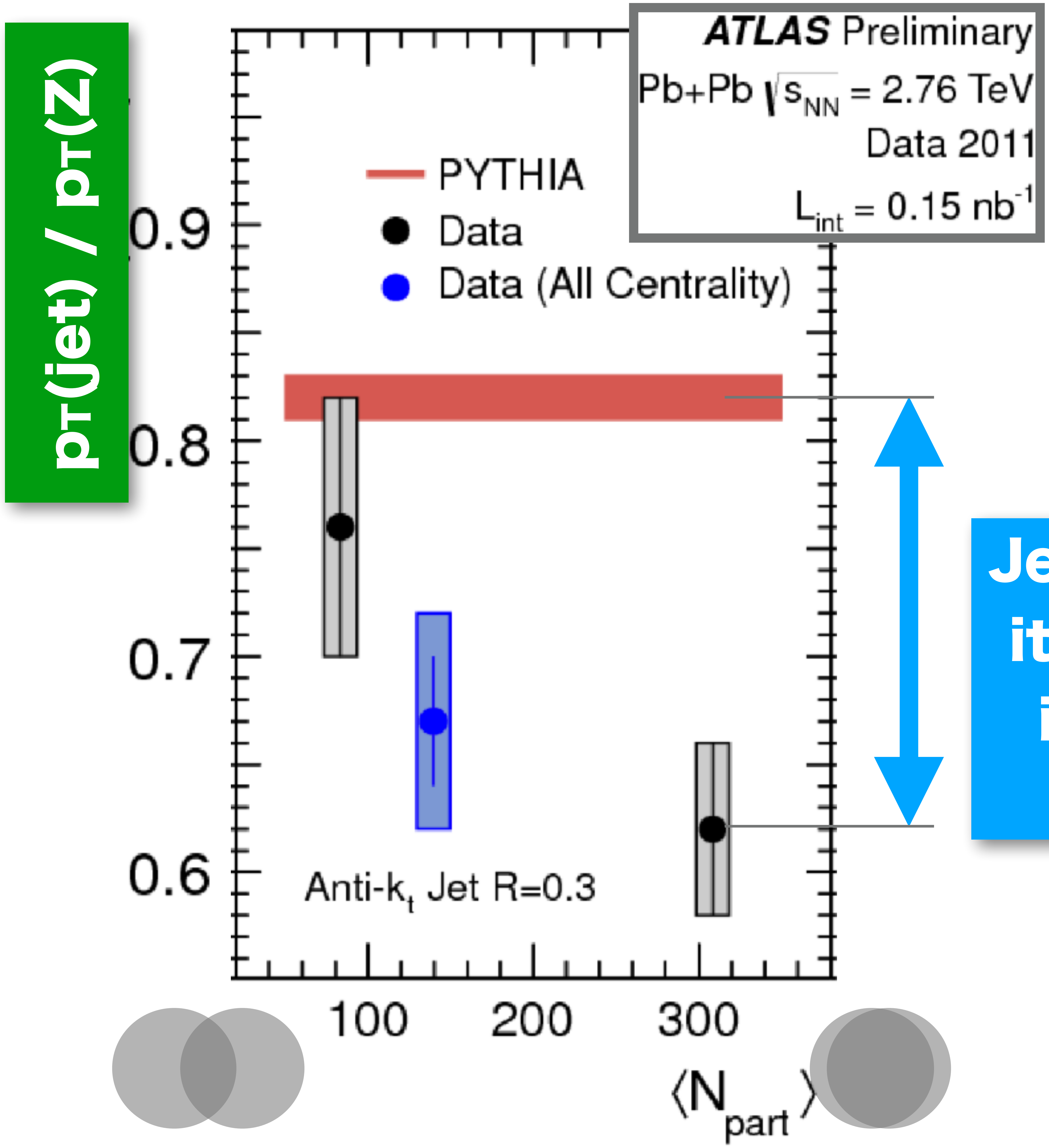
As a parton goes through the quark-gluon plasma, it loses energy.

Amount (and pattern) of energy loss tells you about the medium.
Interpretation of existing data is still an open topic.

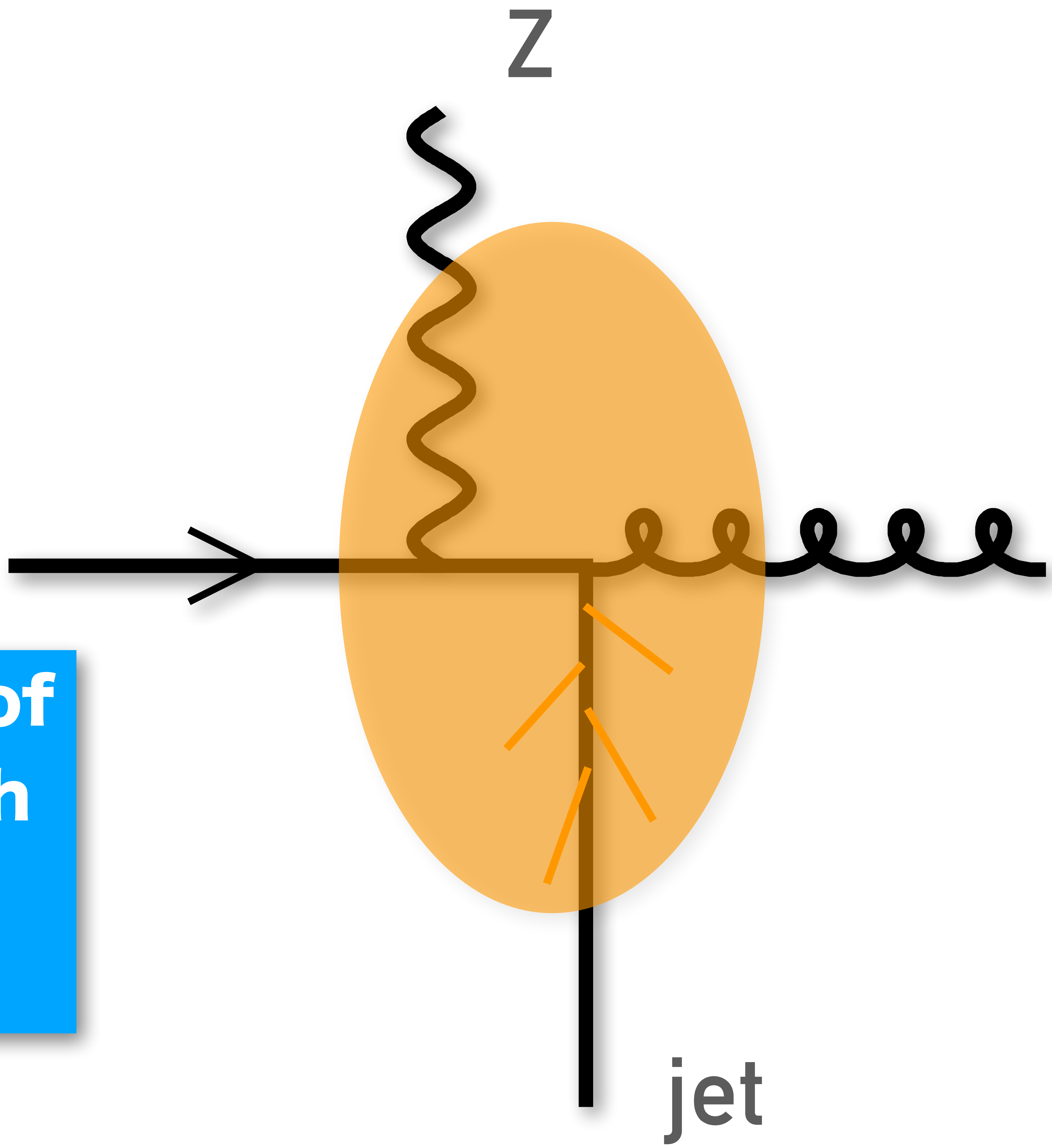




magnitude of effects? Look at jet recoiling against a Z boson



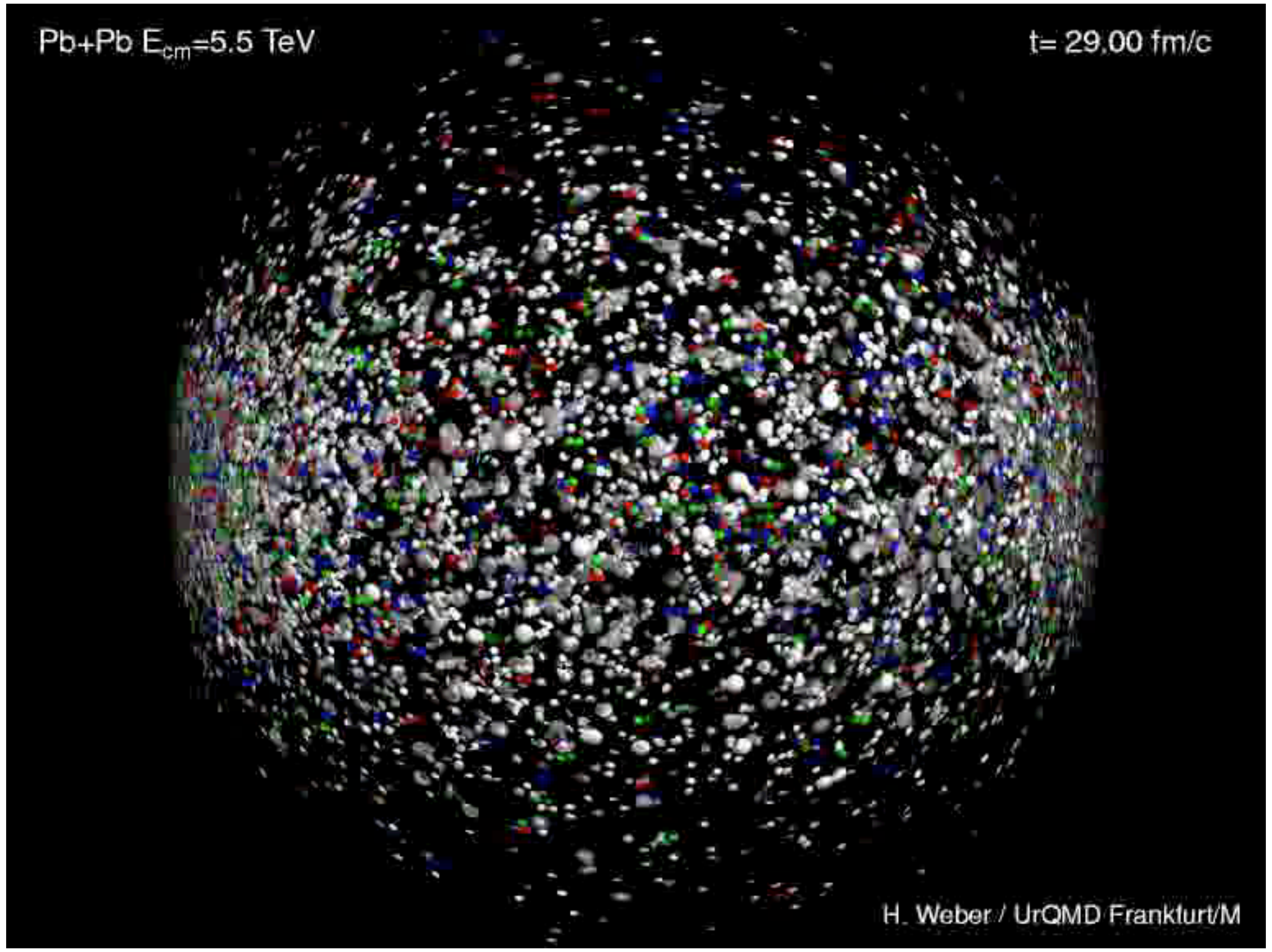
Jet loses 10-20% of its energy through interactions with the medium

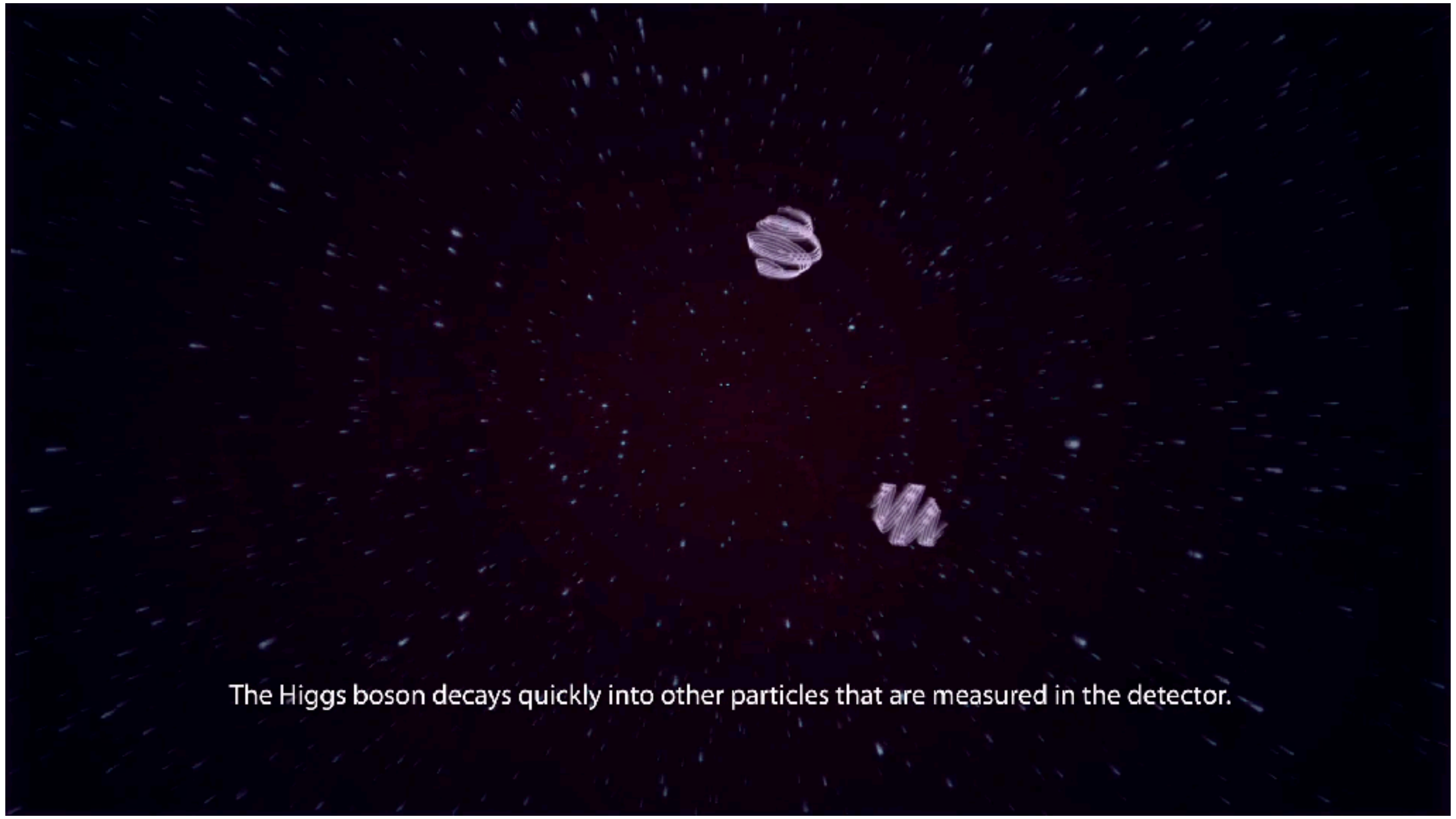


putting together heavy-ion physics and particle physics?

heavy Standard Model particles as time-delayed probes

Apolinário, Milhano, GPS & Salgado, PRL 2018





Hot (~5 ×10^{12}K), dense system, on timescales ~ 0.3 – 10 fm/c ~1 – 30 × 10^{-24} s

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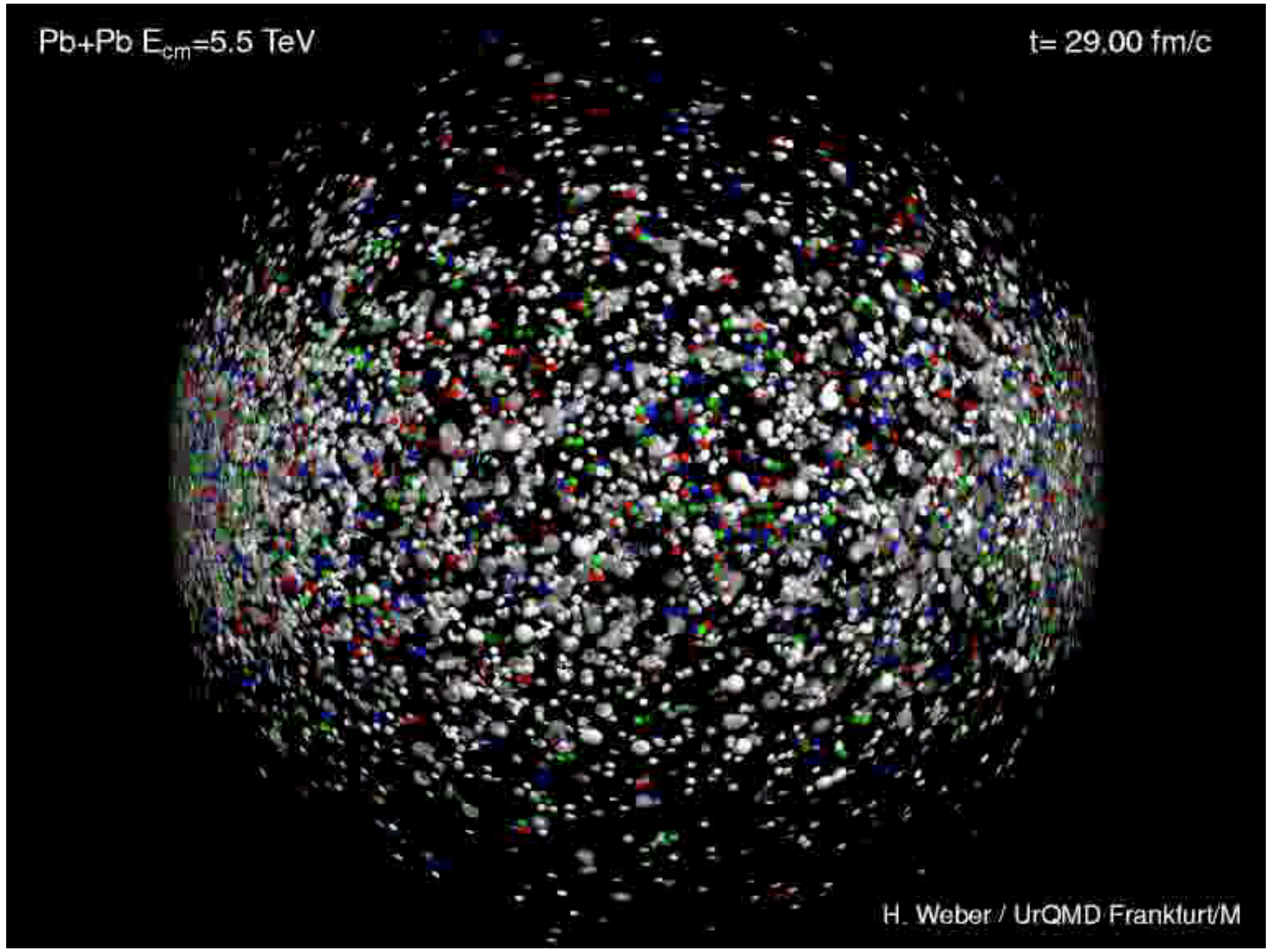

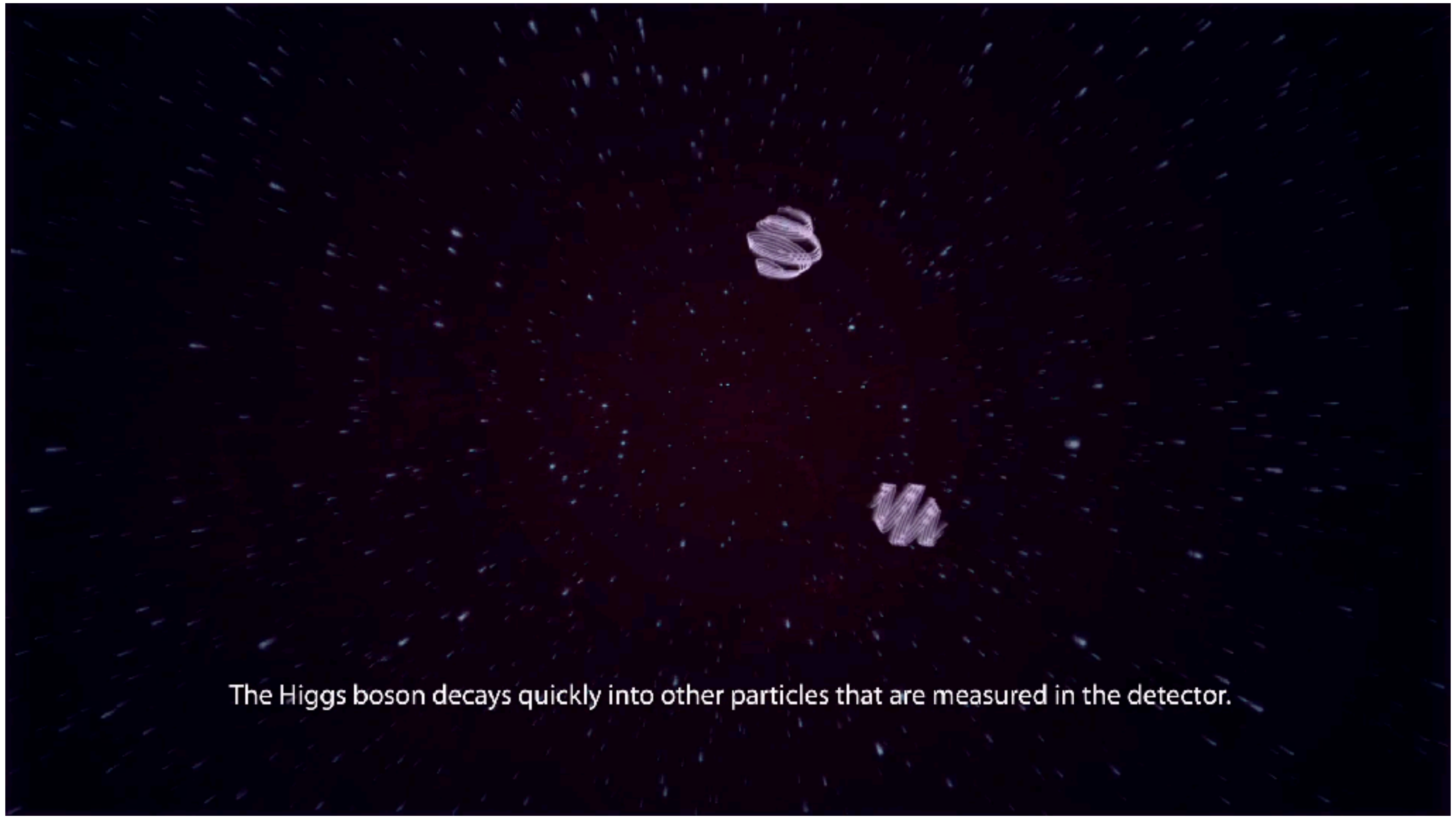

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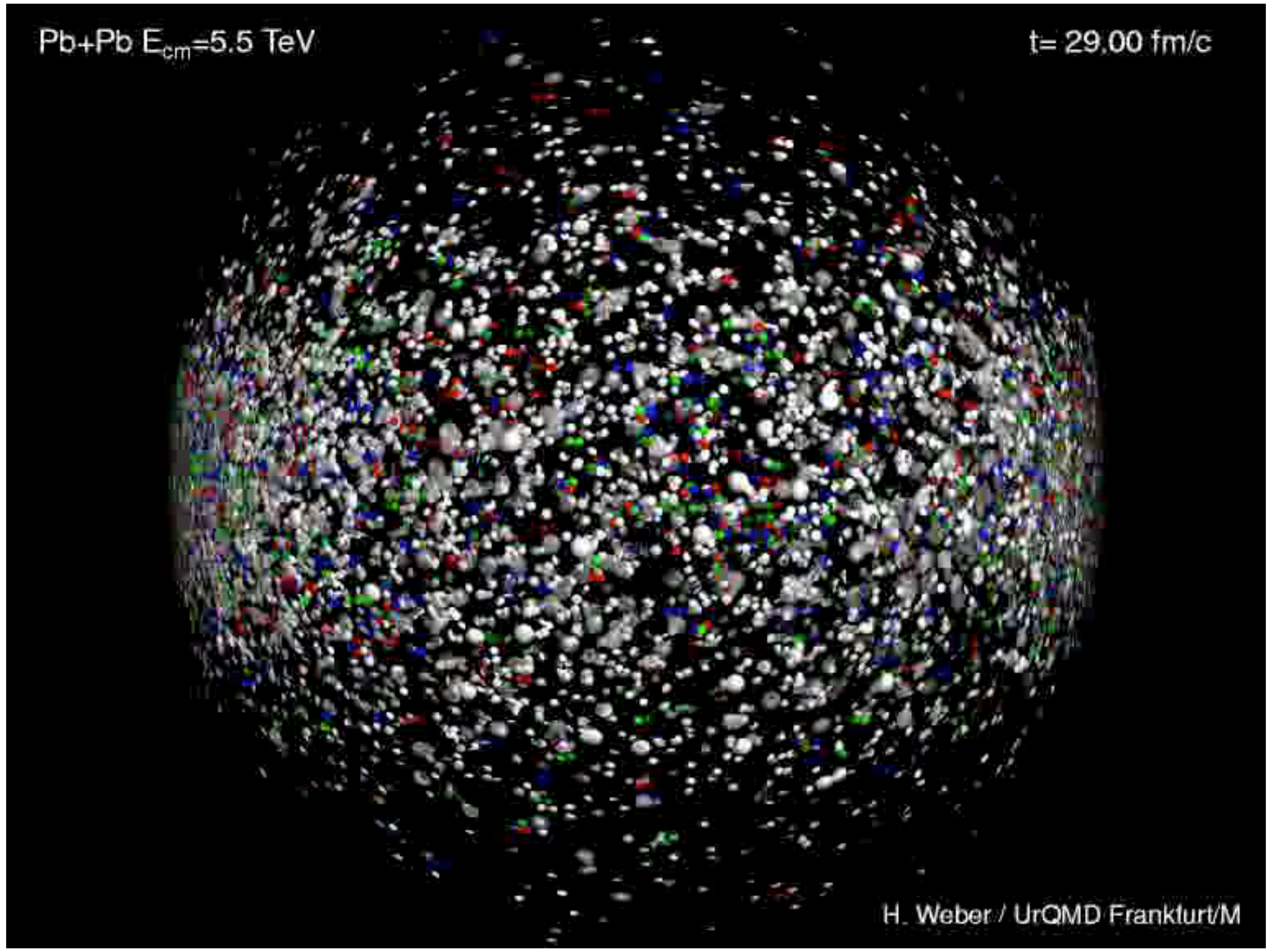
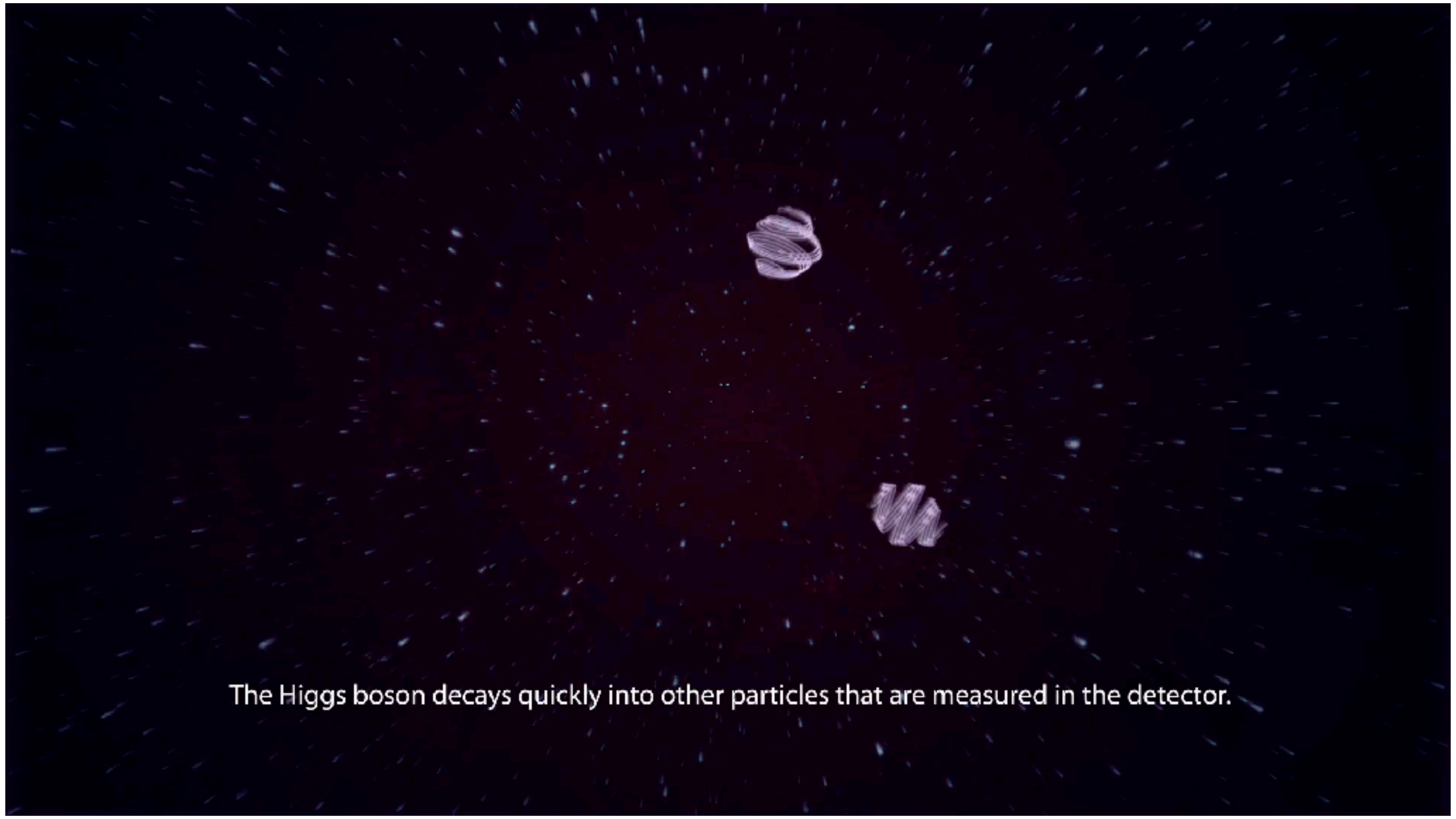
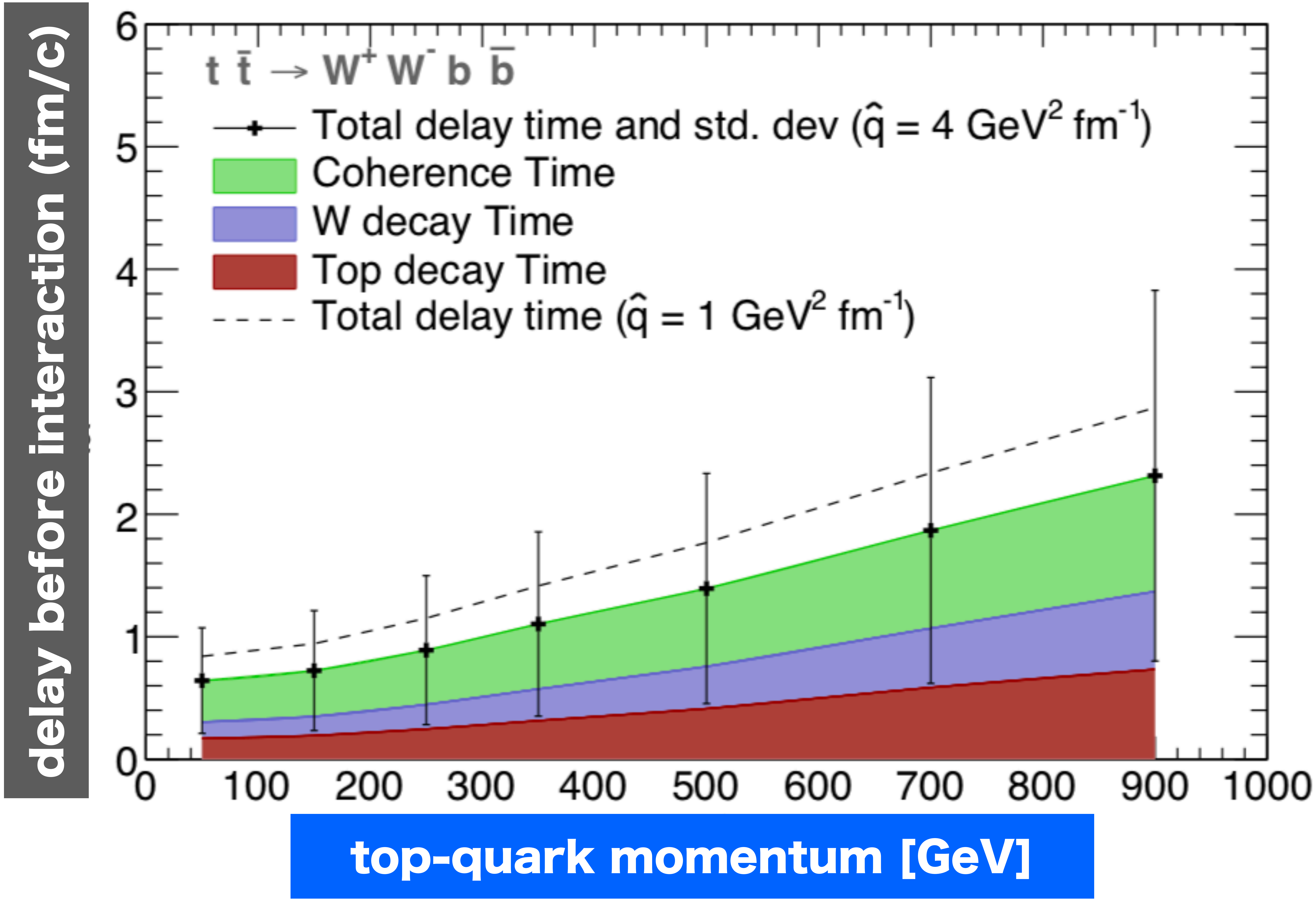




Hot ($\sim 5 \times 10^{12}$K), dense system, on timescales ~ 0.3 – 10 fm/c ~1 – 30 × 10^{-24} s

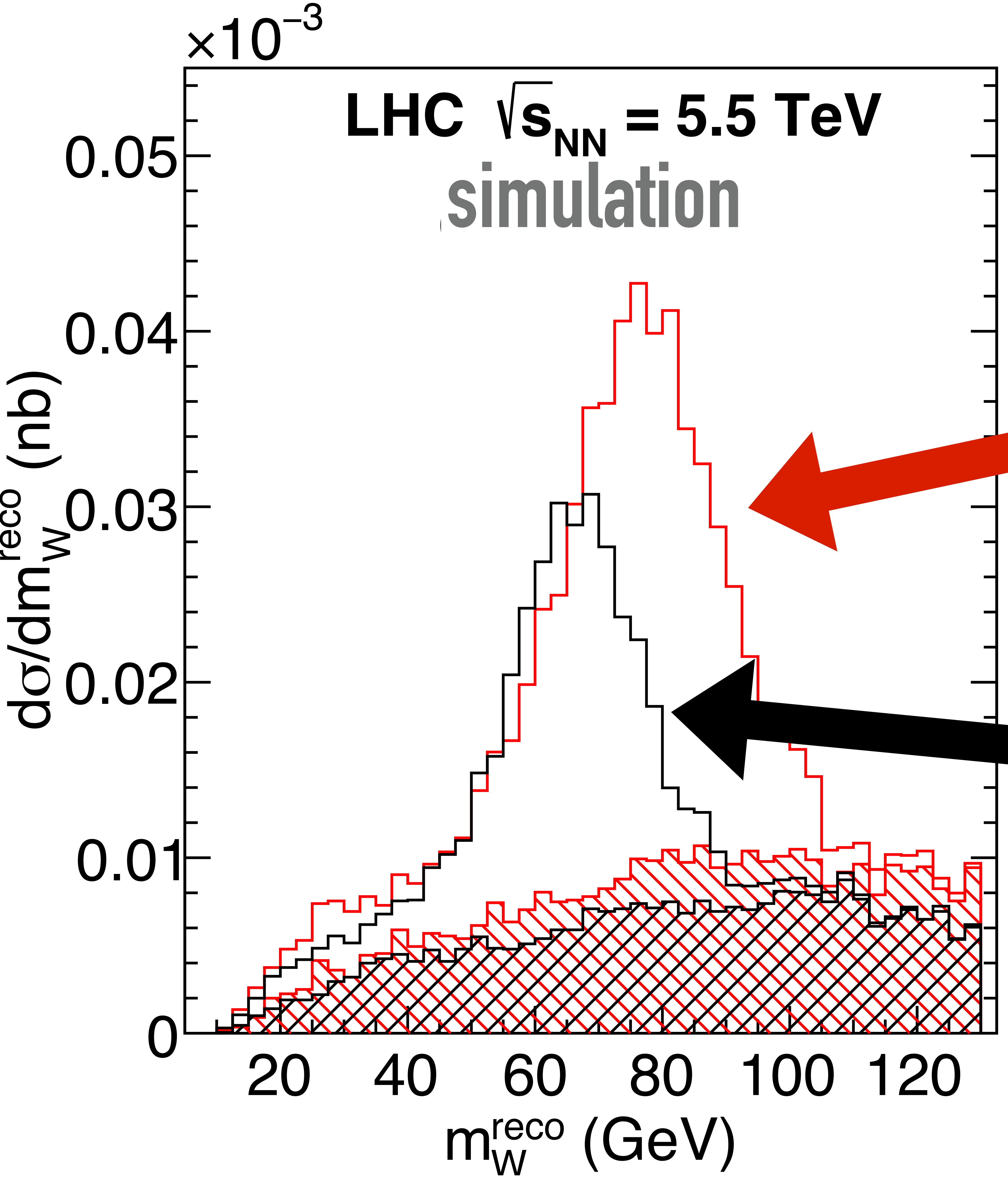
top quark lifetime: ~0.25 fm/c
W boson lifetime: ~0.1 fm/c
Higgs boson lifetime: ~50 fm/c

Concentrate on top quarks: easy to detect, even with hadronic decay products



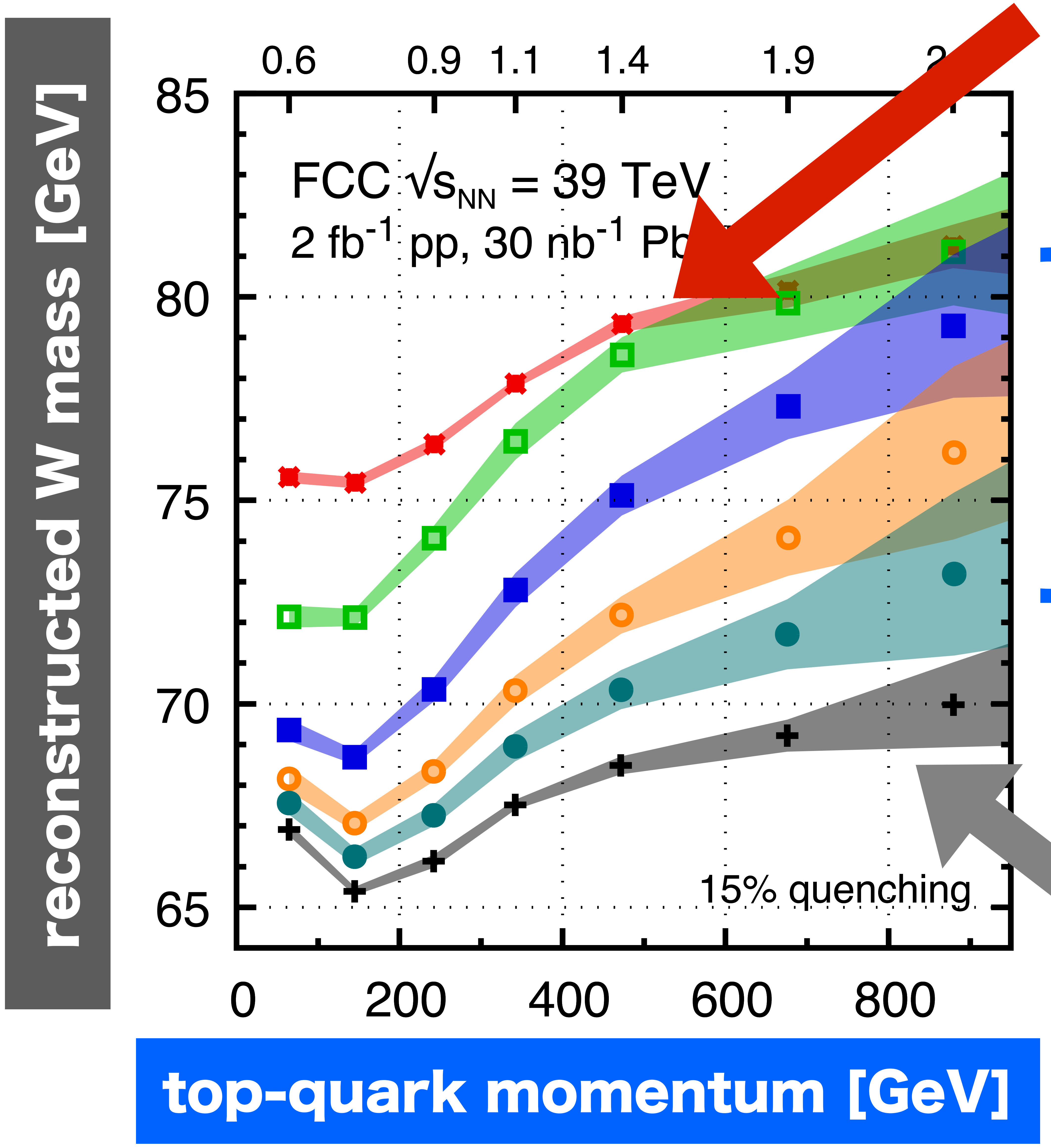
top-quark decay products ***start interacting*** *with the medium* ***after a delay***

delay can be tuned by selecting top-quark momentum (Lorentz dilation) examine reconstructed mass of top → W → jets



W in vacuum ("unquenched")

W decay products travel through full quark–gluon plasma ("quenched")



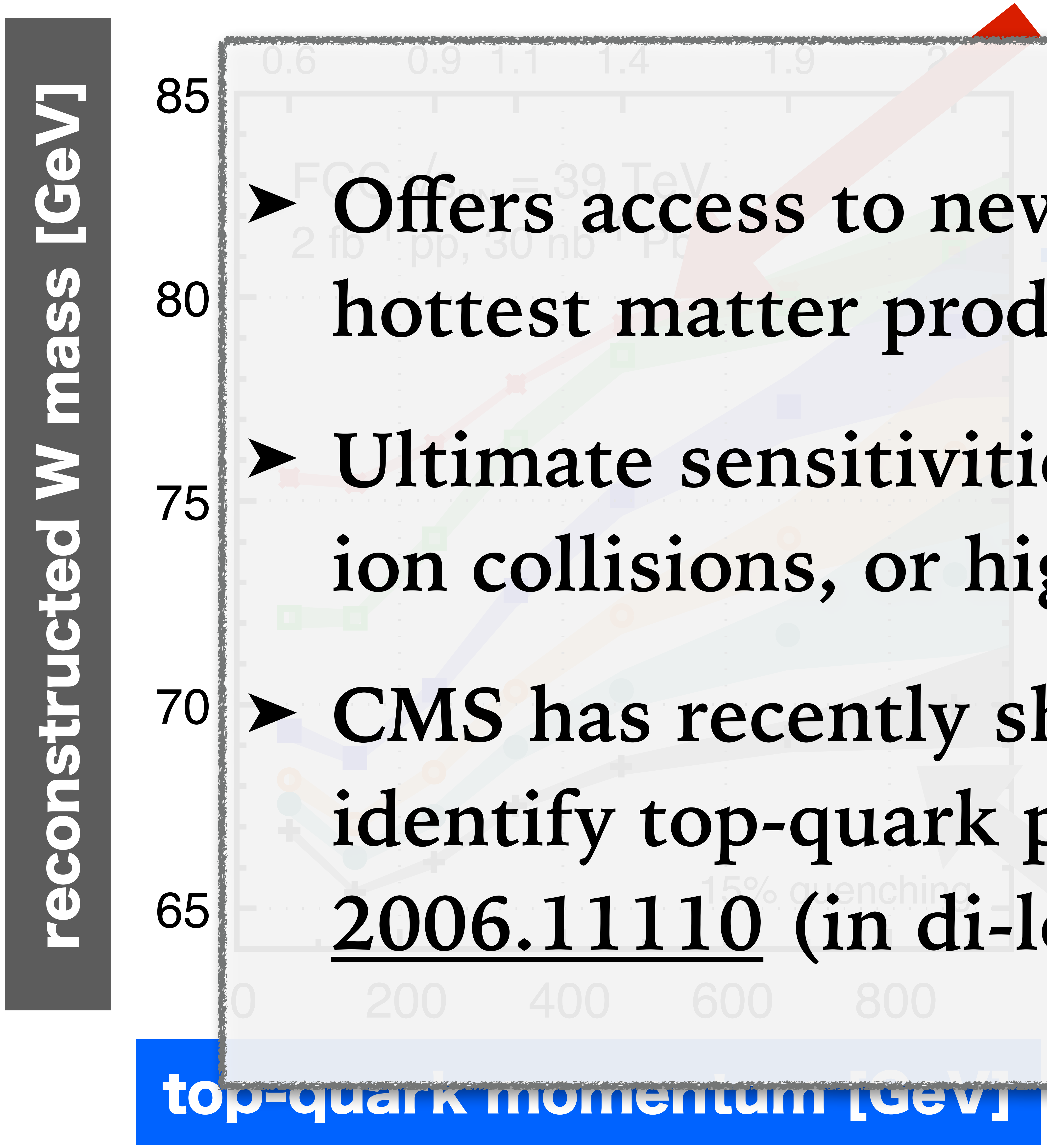
W in vacuum (“unquenched”)

different characteristic medium lifetimes

τ_m= 1.0 fm/c
τ_m= 5 fm/c
τ_m= 2.5 fm/c
τ_m= 10 fm/c

W decay products travel through full quark–gluon plasma (“quenched”)

W in vacuum (“unquenched”)



- ➤ Offers access to new dimension, time, in study of hottest matter produced on earth.
- ➤ Ultimate sensitivities need large numbers of heavy-ion collisions, or higher collider energies.
- ➤ CMS has recently shown evidence (3.8σ) they can identify top-quark production in AA collisions, 2006.11110 (in di-lepton channel)

CMS ttbar in nucleus-nucleus collisions (2006.11110)