Higgs and Beyond at Colliders

Gavin P. Salam, CERN (→ Oxford)

Rudolf Peierls Symposium
Oxford 5 & 6 July, 2018

image: http://www.peterbrett.com/media/3053/pba_website_project_beecroft_banner01_2018.jpg

“big unanswered questions”

about fundamental particles & their interactions

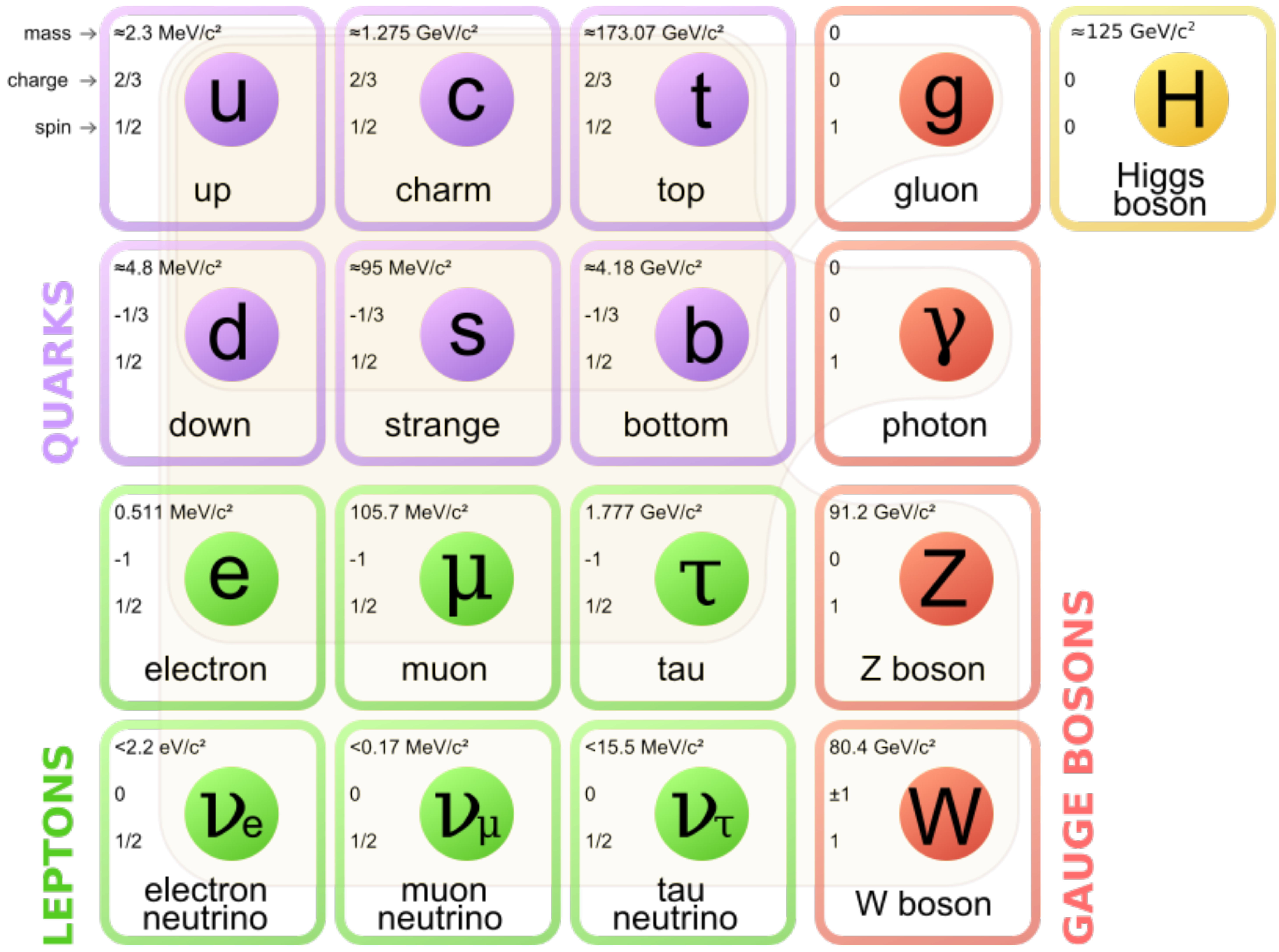
(dark matter, matter-antimatter asymmetry, nature of dark energy, hierarchy of scales…)

v.

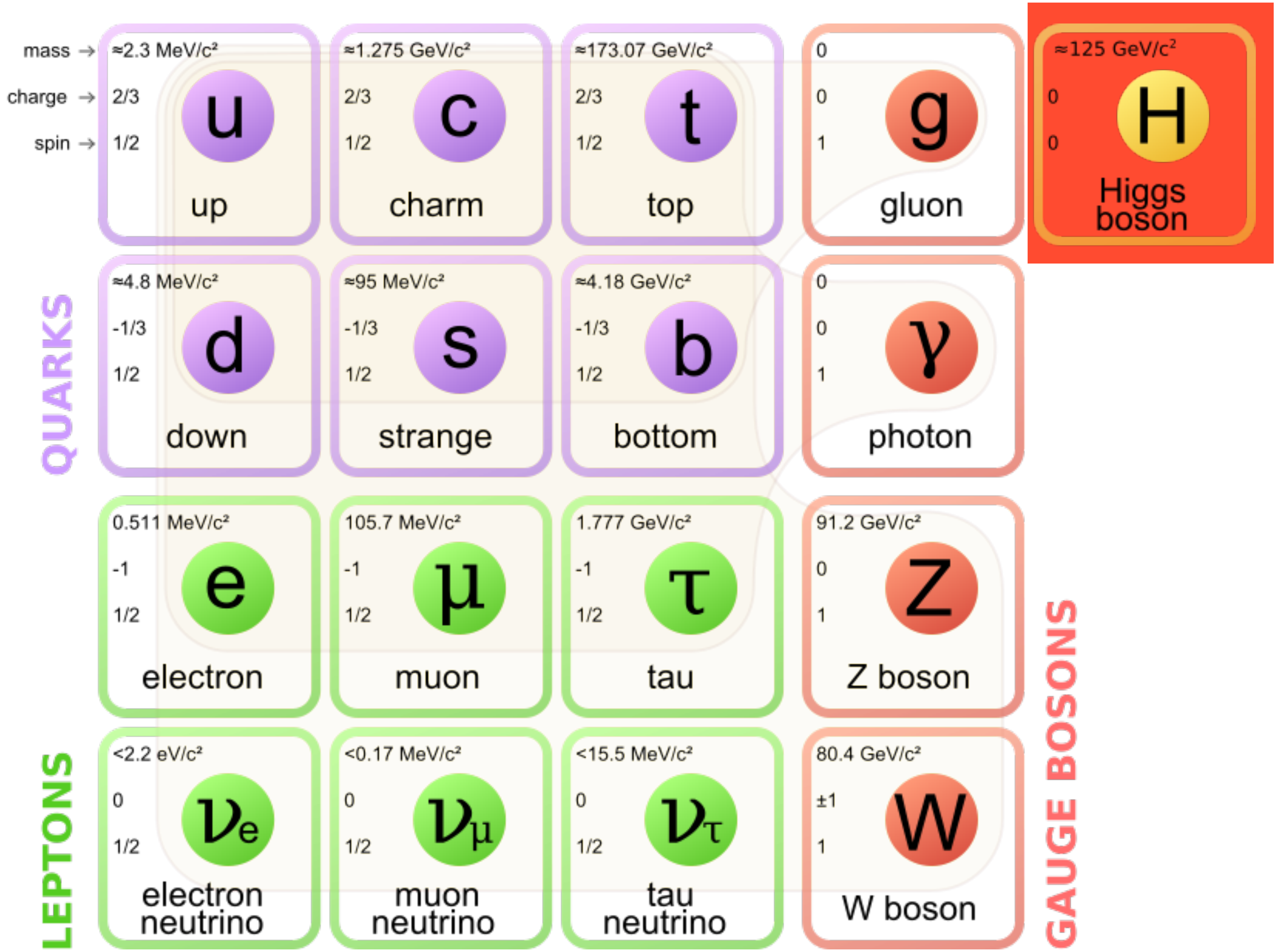
“big answerable questions”

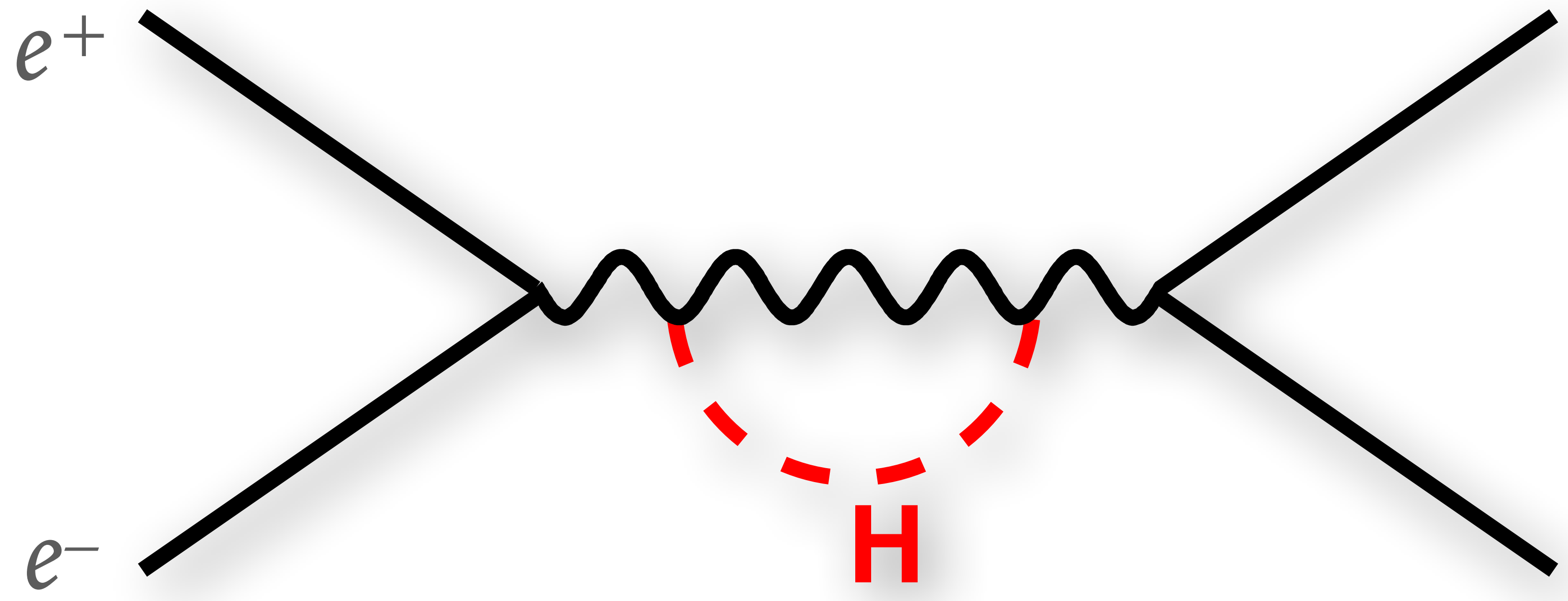
and how we go about answering them

The Higgs boson



The Higgs boson

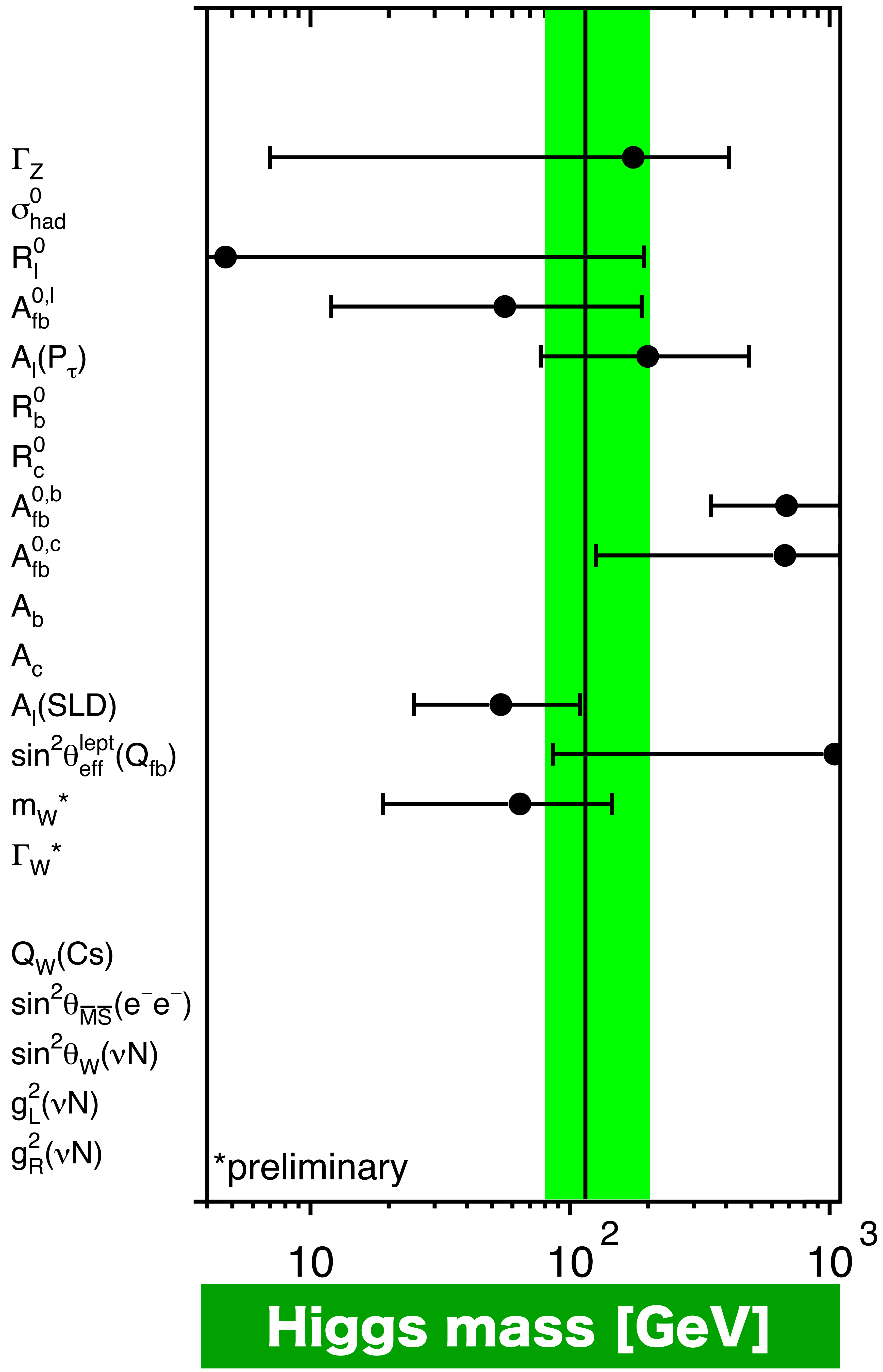




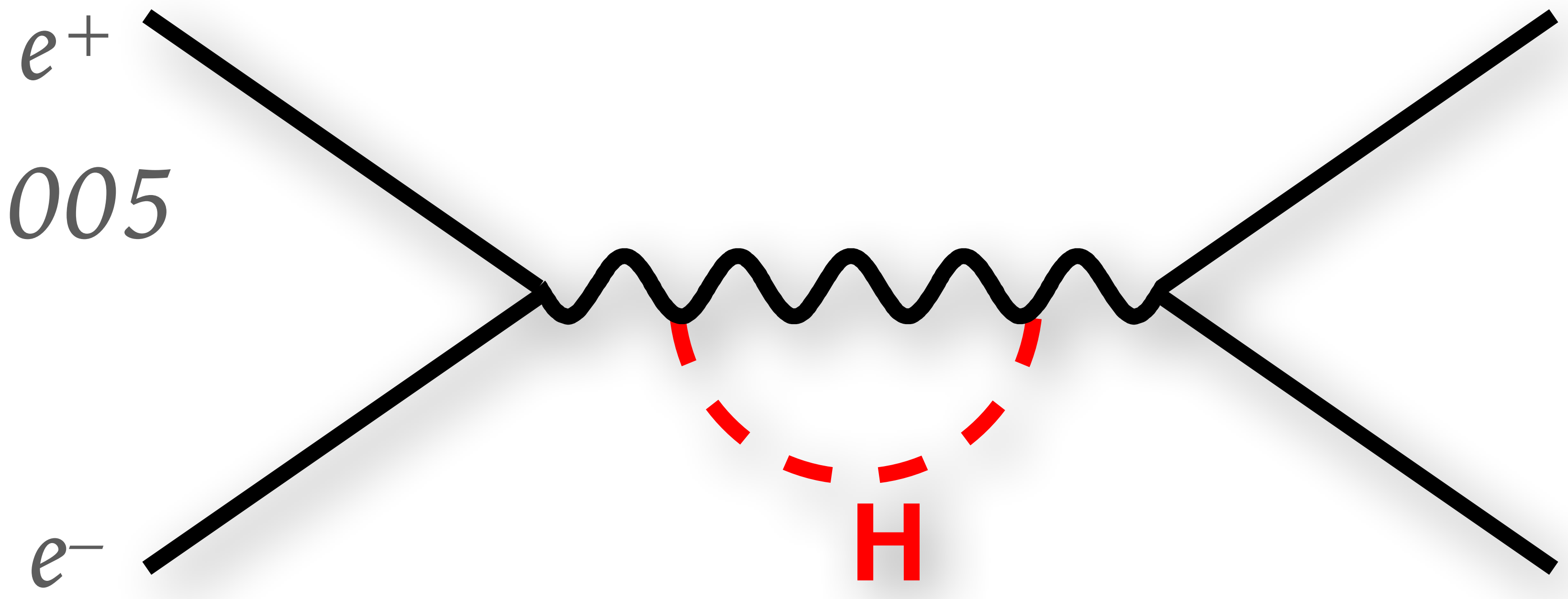
Higgs boson existence long known to be consistent with older e^+e^- collider data (cf. LEP, 1989–2000 + SLD).

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

Could be interpreted as a weak Higgs mass constraint.



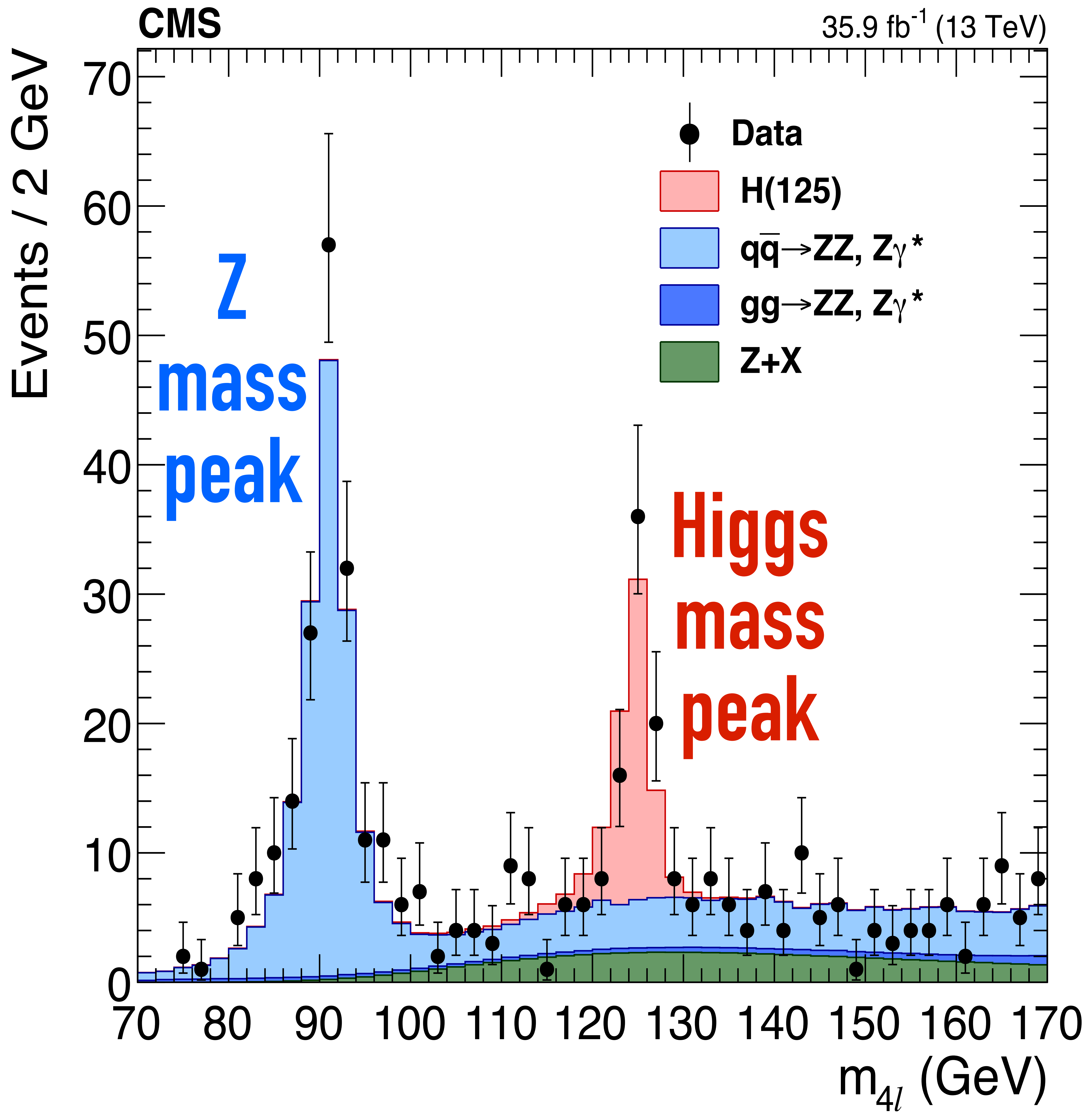
LEP electroweak working group, 2005
hep-ex/0509008



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.

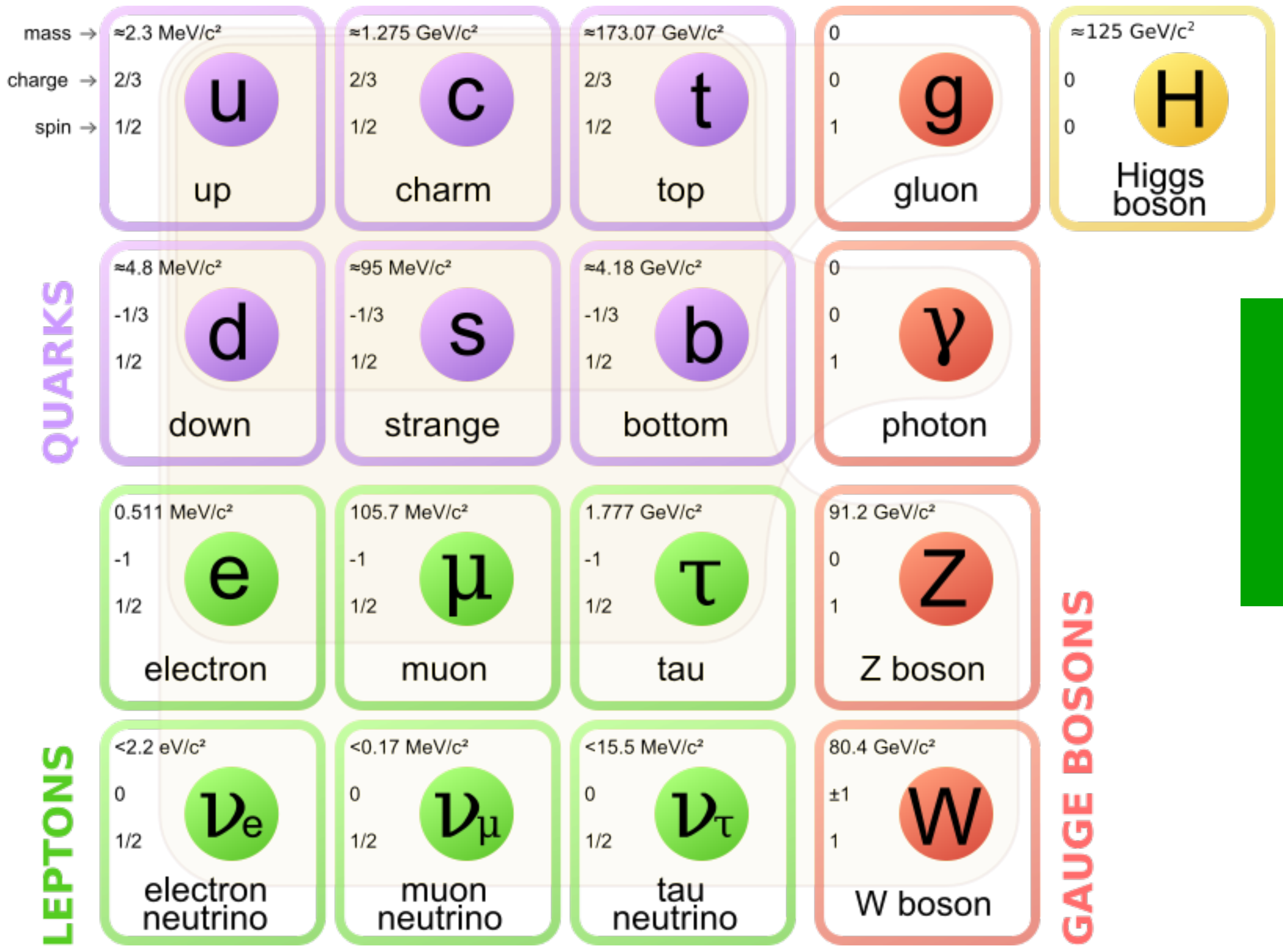


ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC):

2012 discovery of a Higgs-like boson

plot shows more recent data

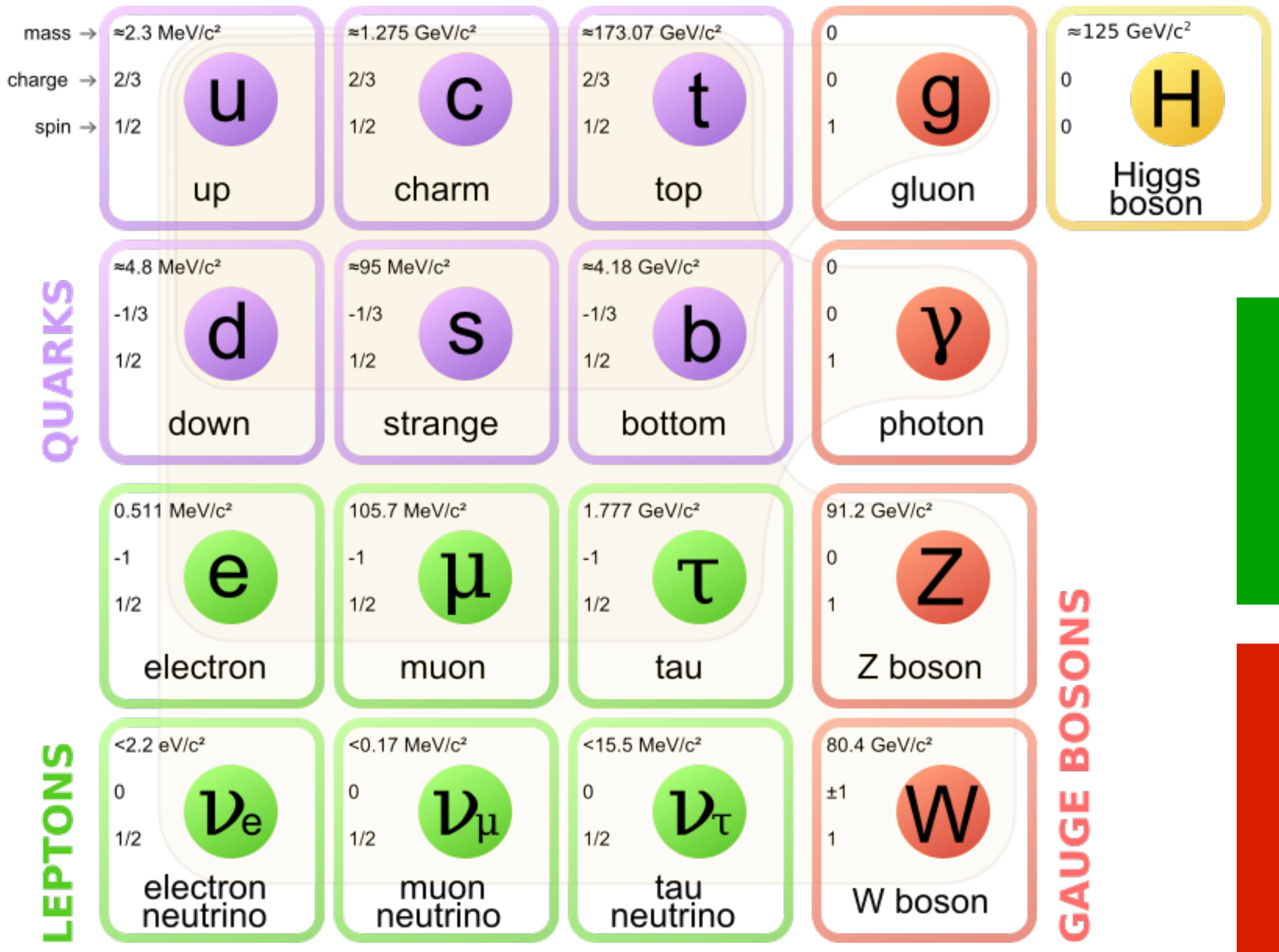
The Higgs boson



Success!

The Standard Model is complete

The Higgs boson



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

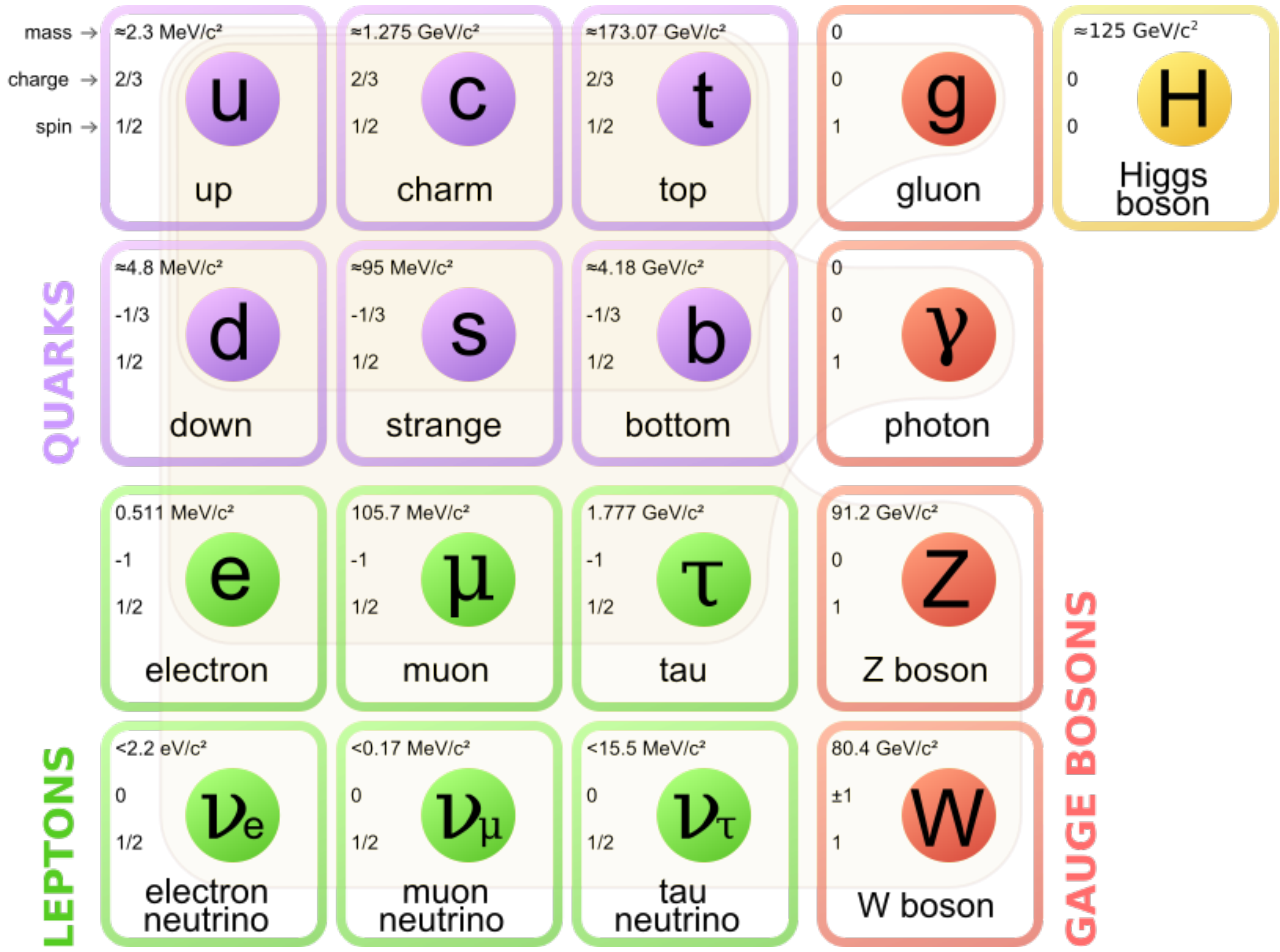
[…]

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

[…]

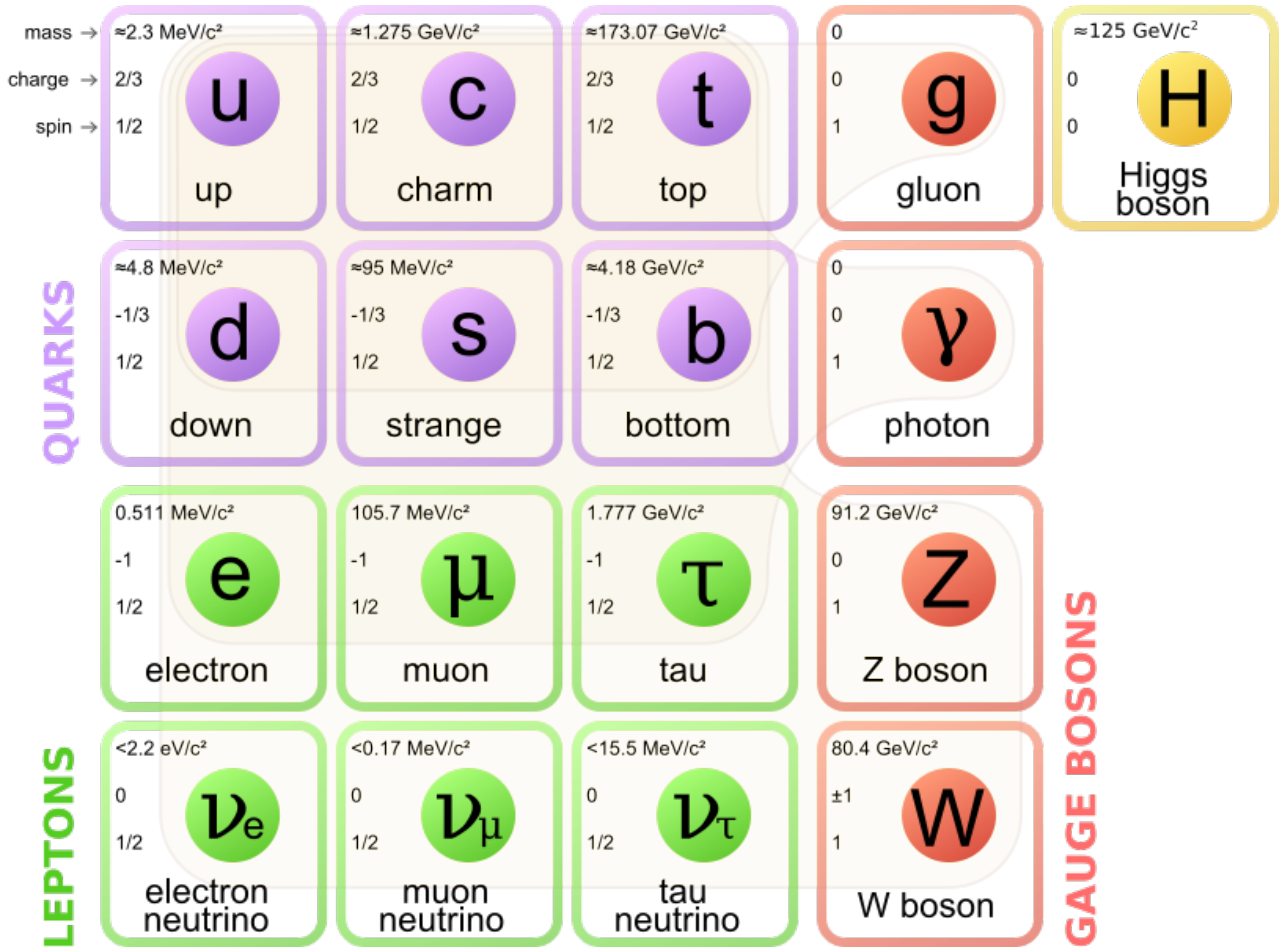
https://www.nytimes.com/2017/06/19/science/cern-large-hadron-collider-higgs-physics.html

what is the Standard Model?

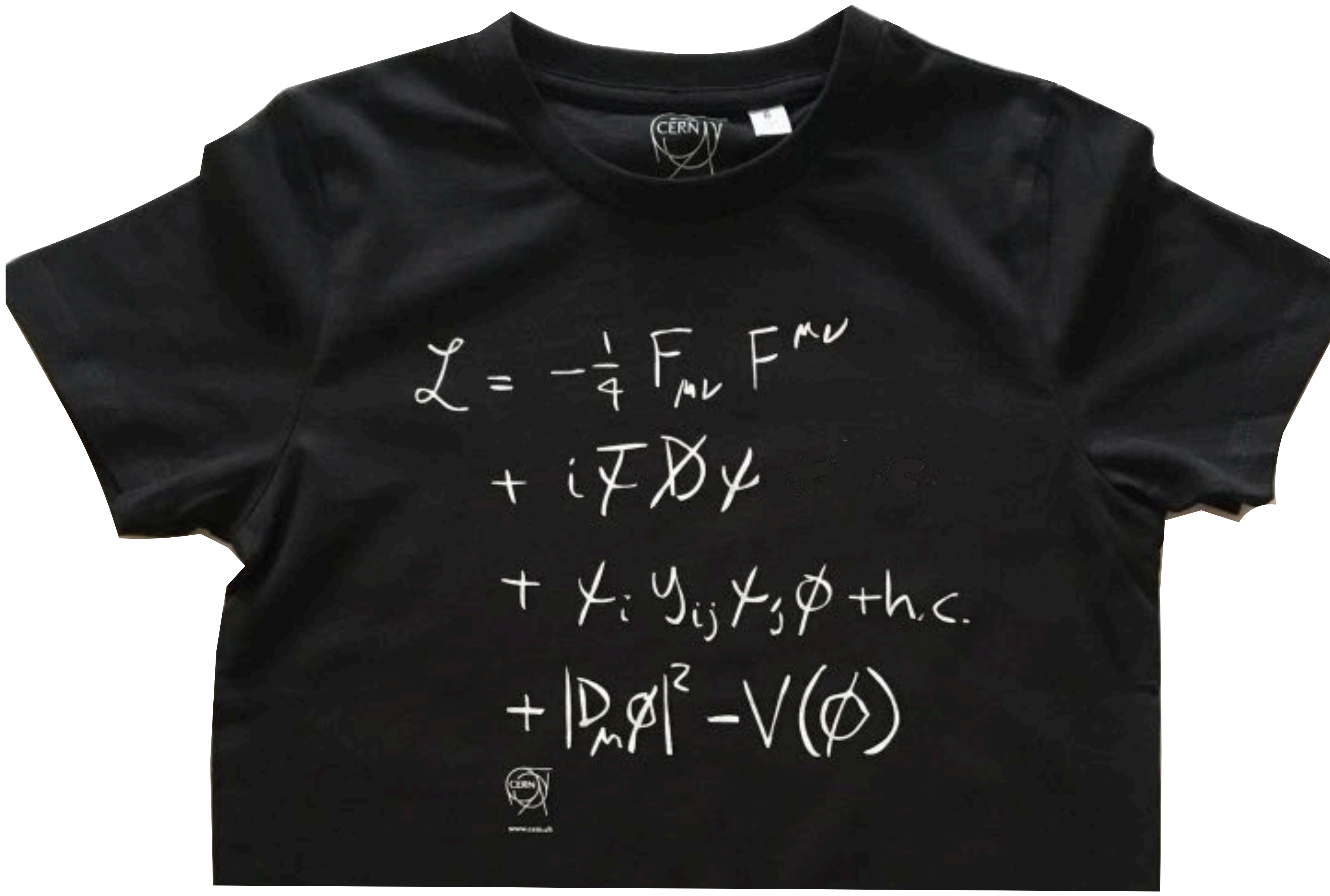


particles

what is the Standard Model?

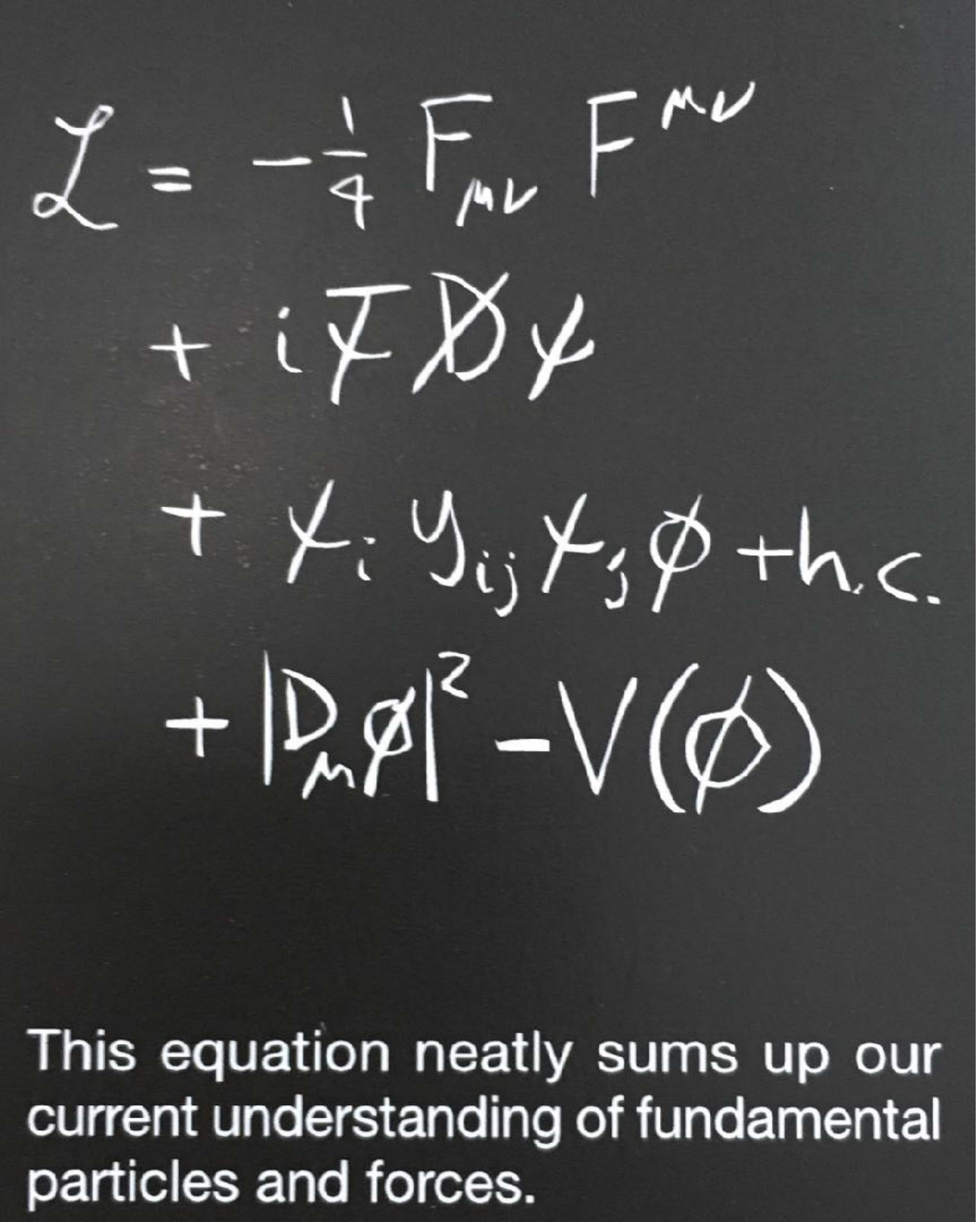


particles

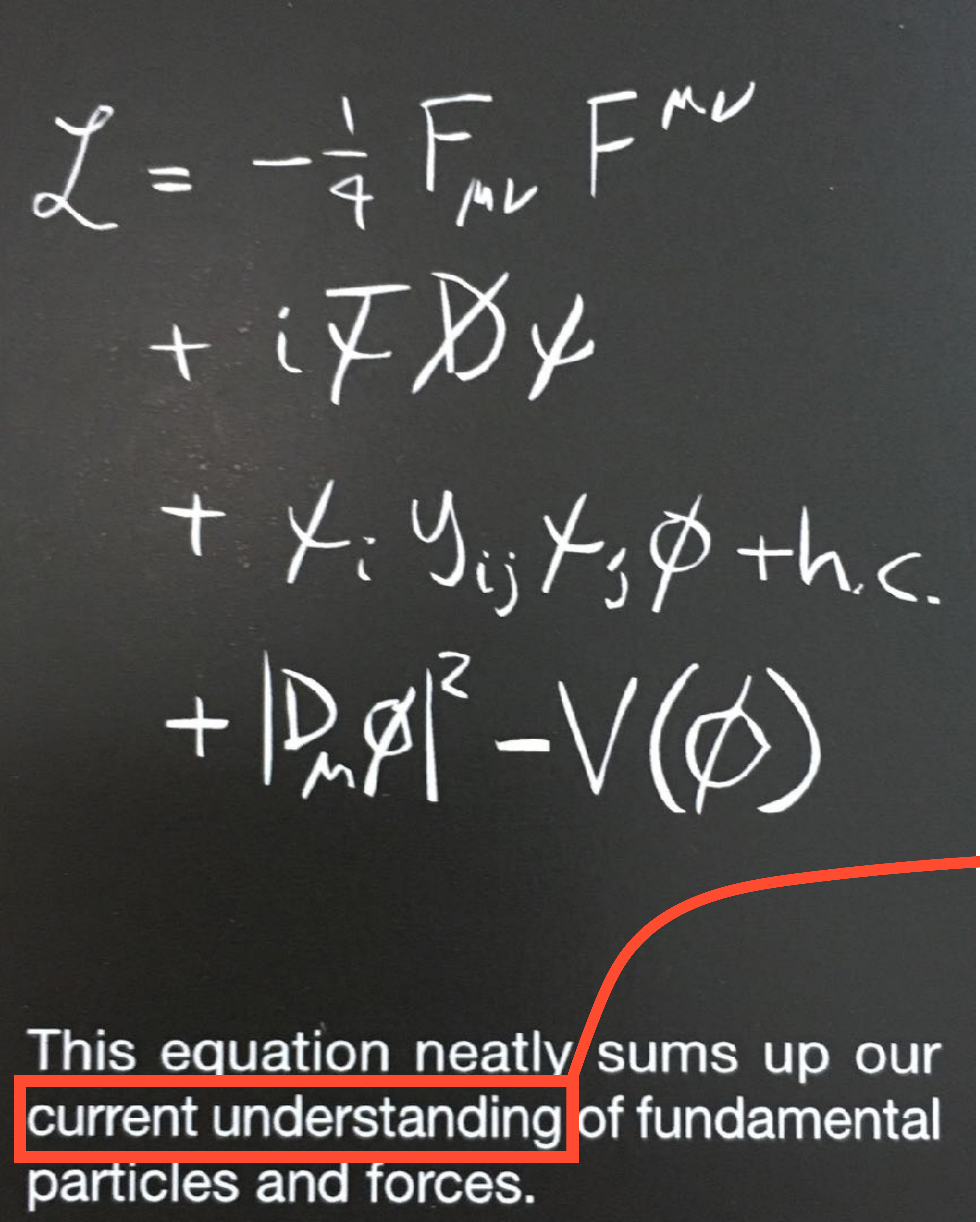


interactions

STANDARD MODEL —— KNOWABLE UNKNOWNS



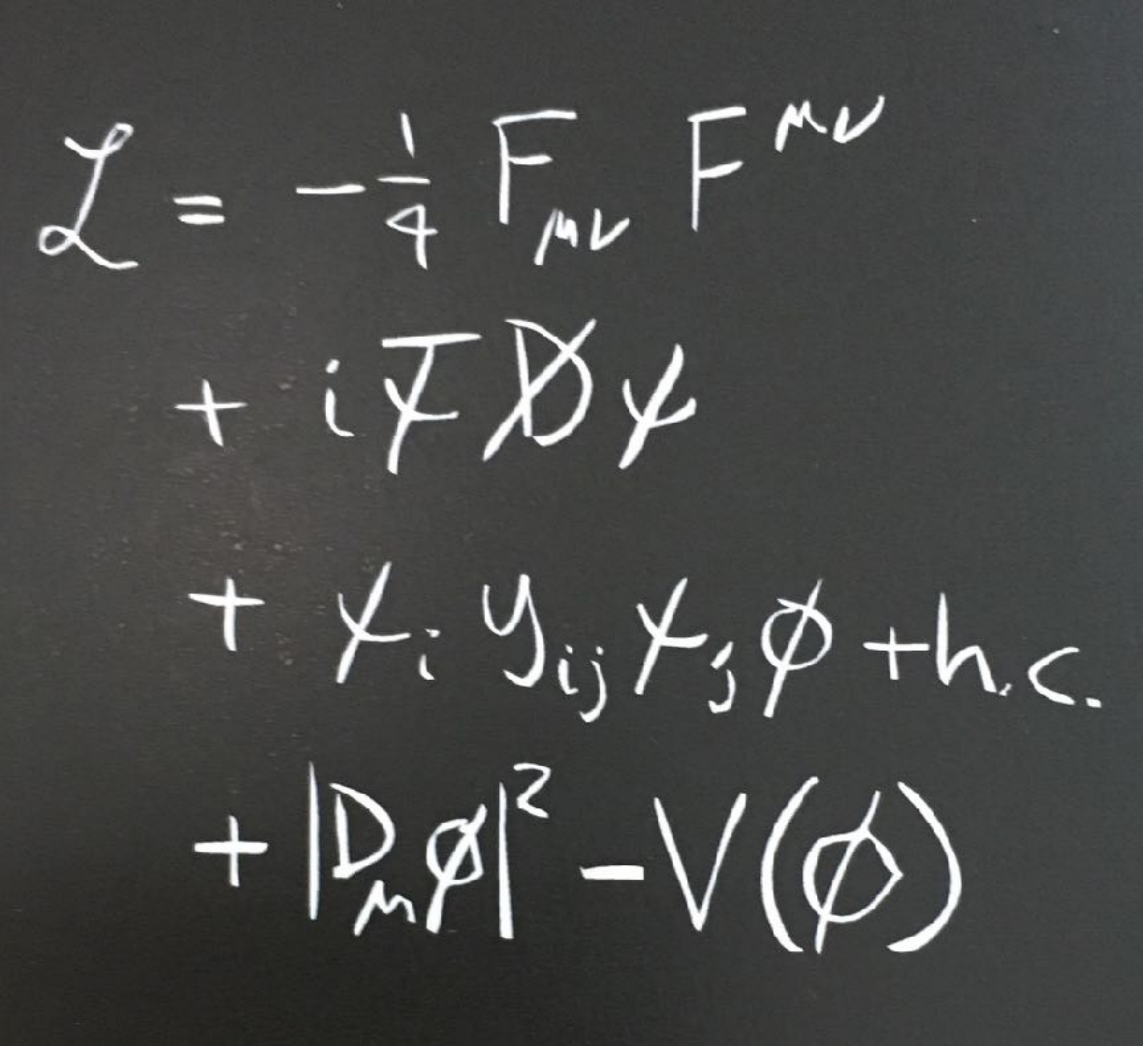
This is what you get when you buy one of those famous CERN T-shirts



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

"understanding" = knowledge ?

"understanding" = assumption ?



NOTATION

A_μ : gauge field

ψ : fermion field

ϕ : Higgs field

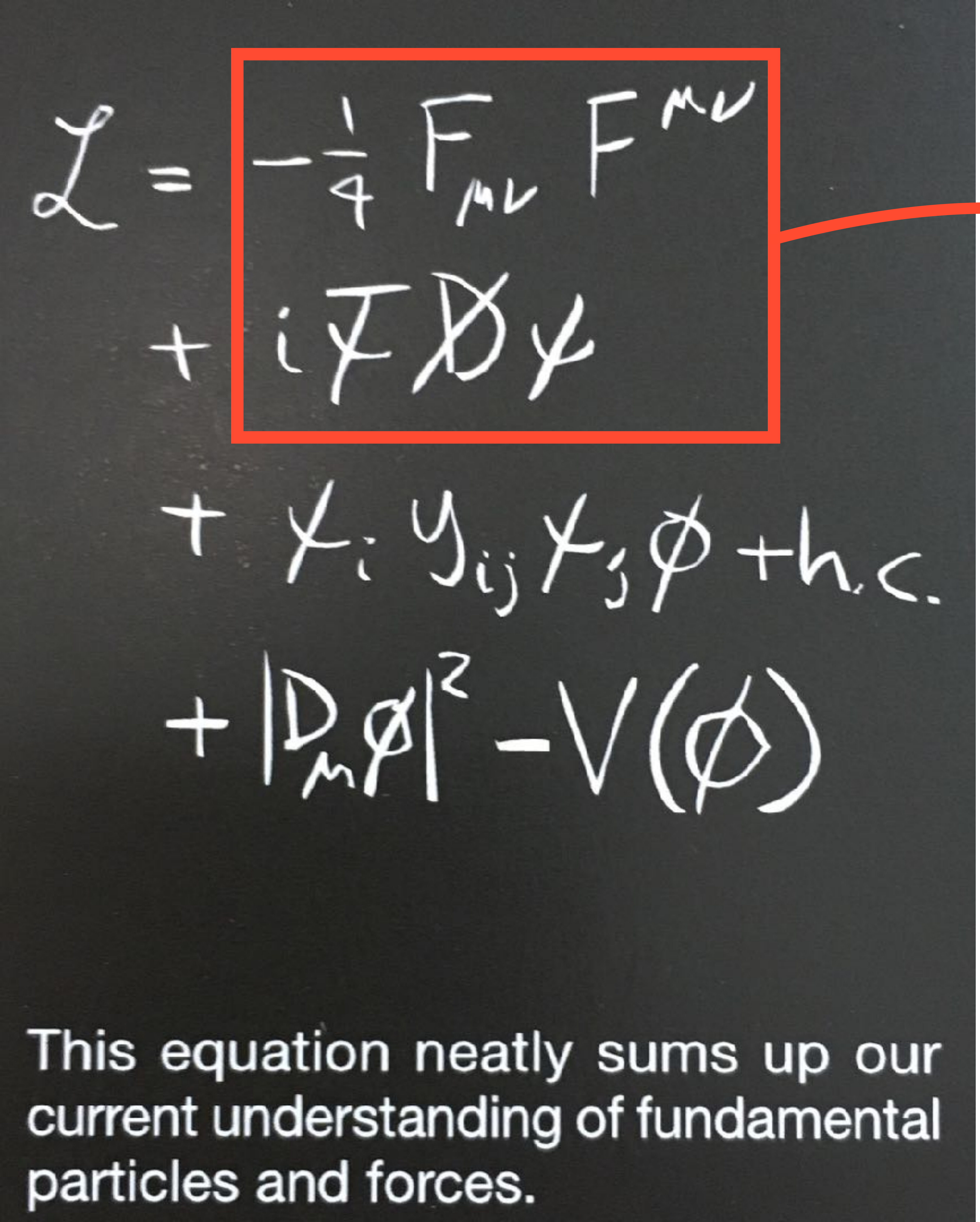
$= \phi_0(\text{VEV}) + H(\text{Higgs})$

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

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

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



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.)

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

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

Gauge part

e.g. $qq\gamma$, qqZ, qqg, $e\nu W$, ggg, interactions — well established in ep, e^+e^-, pp collisions, etc.

≡ KNOWLEDGE

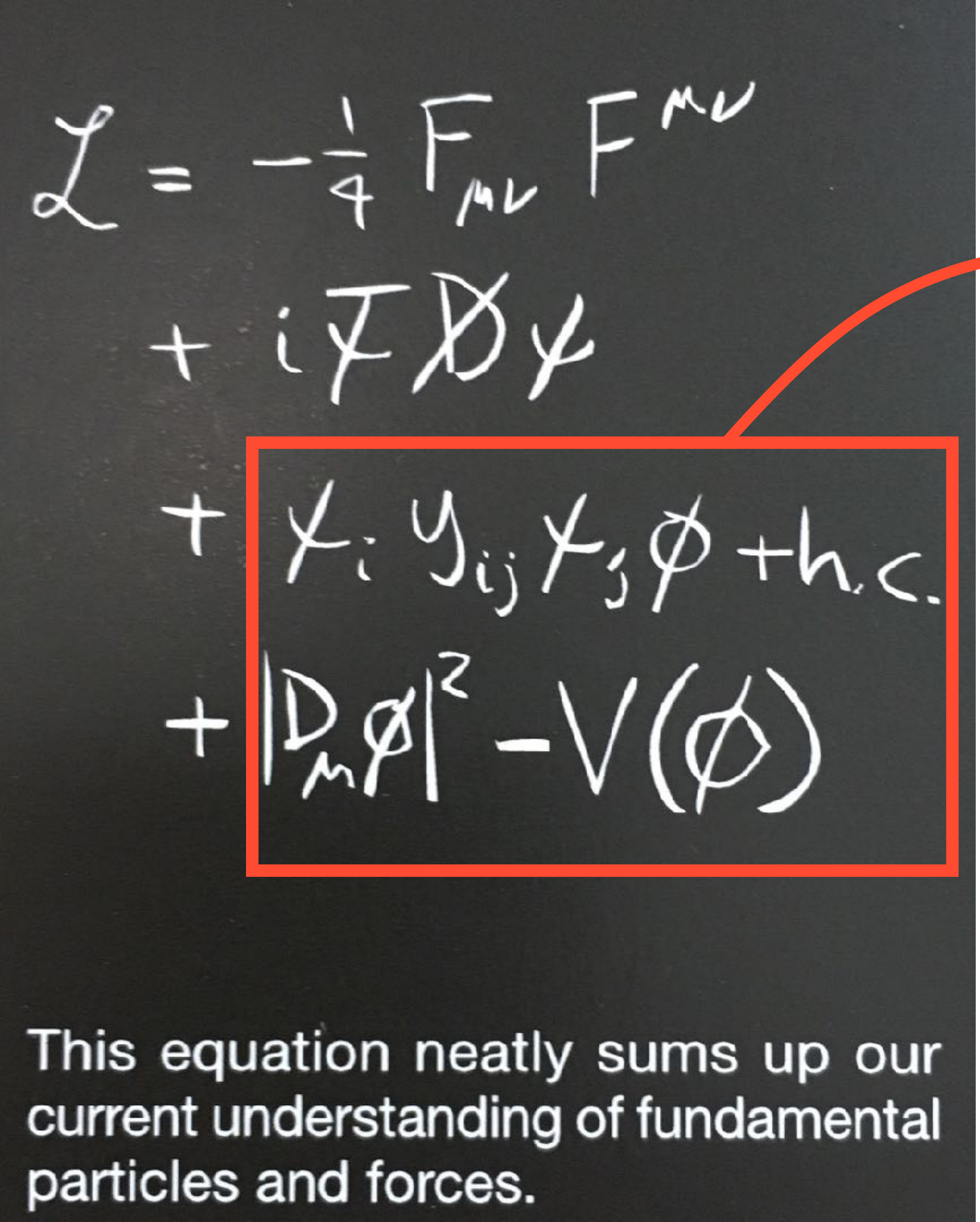
(also being studied at LHC — e.g. jets, DY/Z/W, V+jets, ttbar, etc.)

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

what terms are there in the Higgs sector?

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

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

$$\boxed{|D_\mu \phi|^2}$$

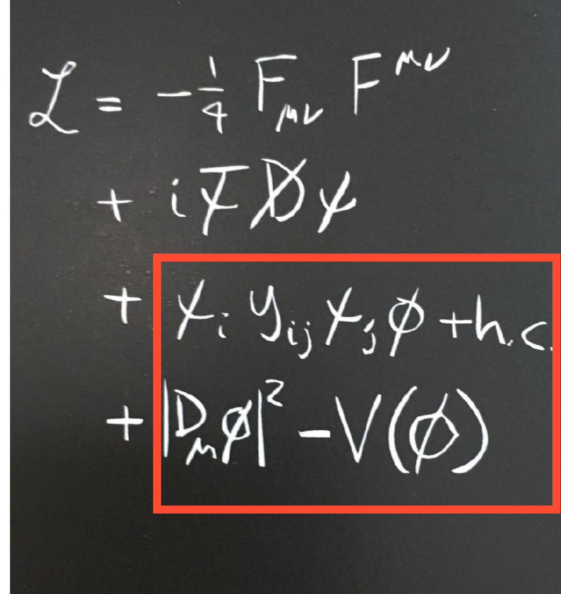
(HWW, HZZ): A gauge interaction, with scalars rather than fermions; much like other gauge interactions; indirectly probed in LEP EW precision tests

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

(Hbb, Htt, etc.): not a gauge interaction, and unlike anything we had probed before ($m \sim y$)

$$V(\phi)$$

($-\mu^2\varphi^2 + \lambda\varphi^4$, HHH) the keystone of the Higgs mechanism and Standard Model, familiar as QFT toy model, never probed in nature



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

what terms are there in the Higgs sector?

$|D_\mu \phi|^2$

(HWW, HZZ): A gauge interaction, with scalars rather than fermions; much like other gauge interactions; indirectly probed in LEP EW precision tests

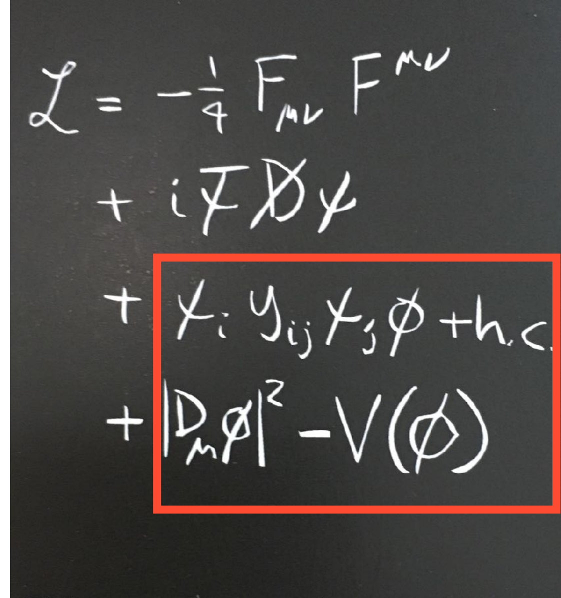
$\boxed{\psi_i y_{ij} \psi_j \phi}$

(Hbb, Htt, etc.): not a gauge interaction, and unlike anything we had probed before ($m \sim y$)

$V(\phi)$

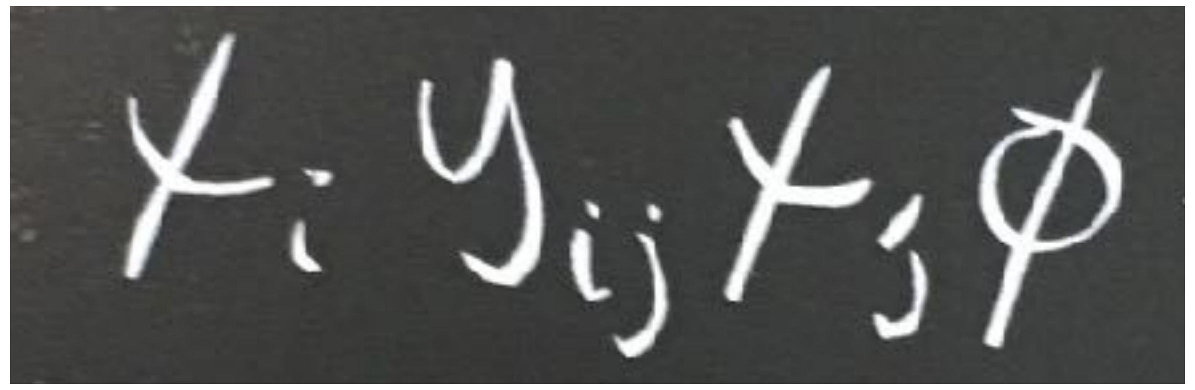
($-\mu^2\varphi^2 + \lambda\varphi^4$, HHH) the keystone of the Higgs mechanism and Standard Model, familiar as QFT toy model, never probed in nature

what terms are there in the Higgs sector?

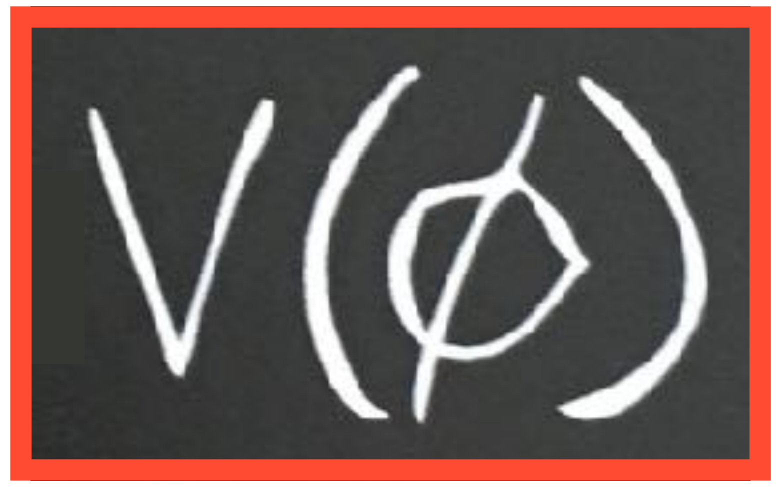


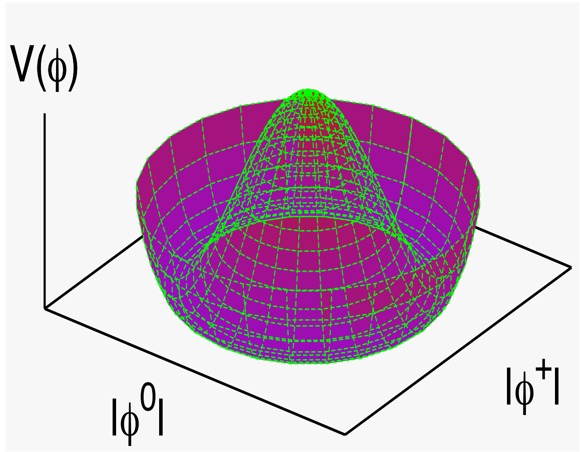
This equation neatly sums up our current understanding of fundamental particles and forces.

(HWW, HZZ): A gauge interaction, with scalars rather than fermions; much like other gauge interactions; indirectly probed in LEP EW precision tests



(Hbb, Htt, etc.): not a gauge interaction, and unlike anything we had probed before ($m \sim y$)





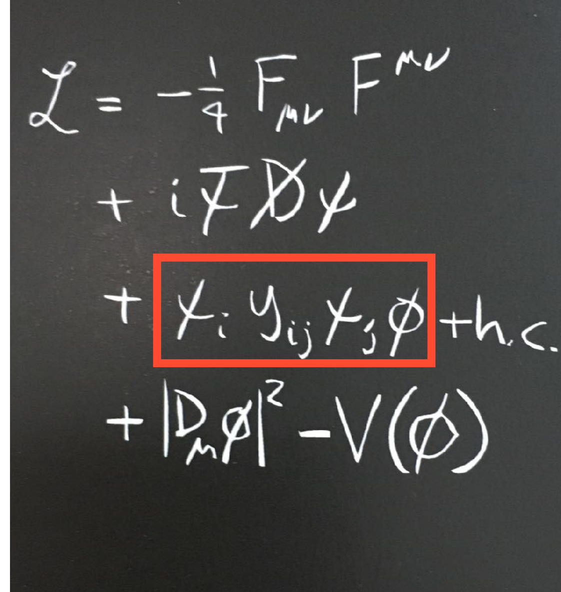
($-\mu^2\varphi^2 + \lambda\varphi^4$, HHH) the keystone of the Higgs mechanism and Standard Model, familiar as QFT toy model, never probed in nature

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**

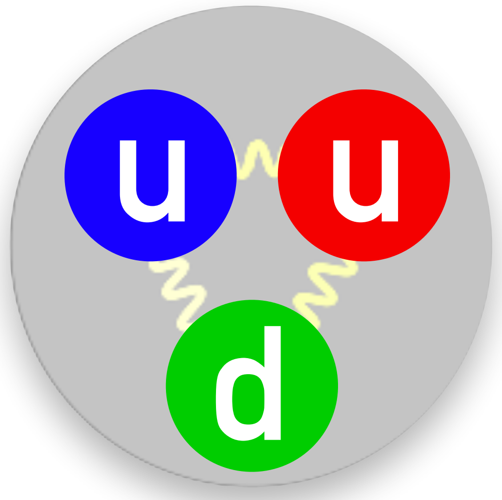


This equation neatly sums up our current understanding of fundamental particles and forces.

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

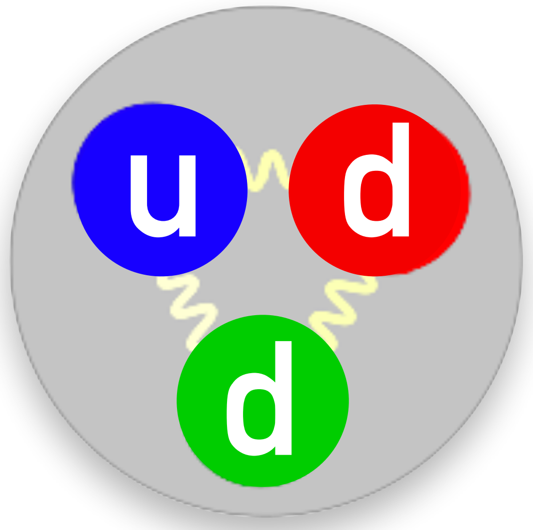
proton (up+up+down): 2.2 + 2.2 + 4.7 + … = 938.3 MeV
neutron (up+down+down): 2.2 + 4.7 + 4.7 + … = 939.6 MeV

proton
mass = 938.3MeV



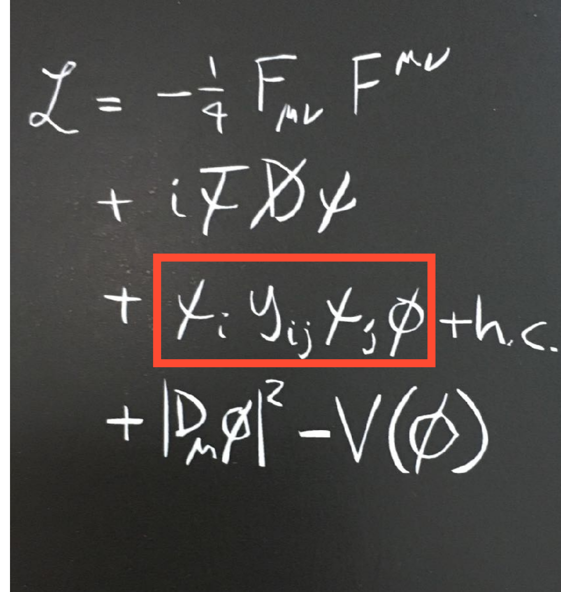
So protons are **lighter** than neutrons,
→ protons are stable.

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**



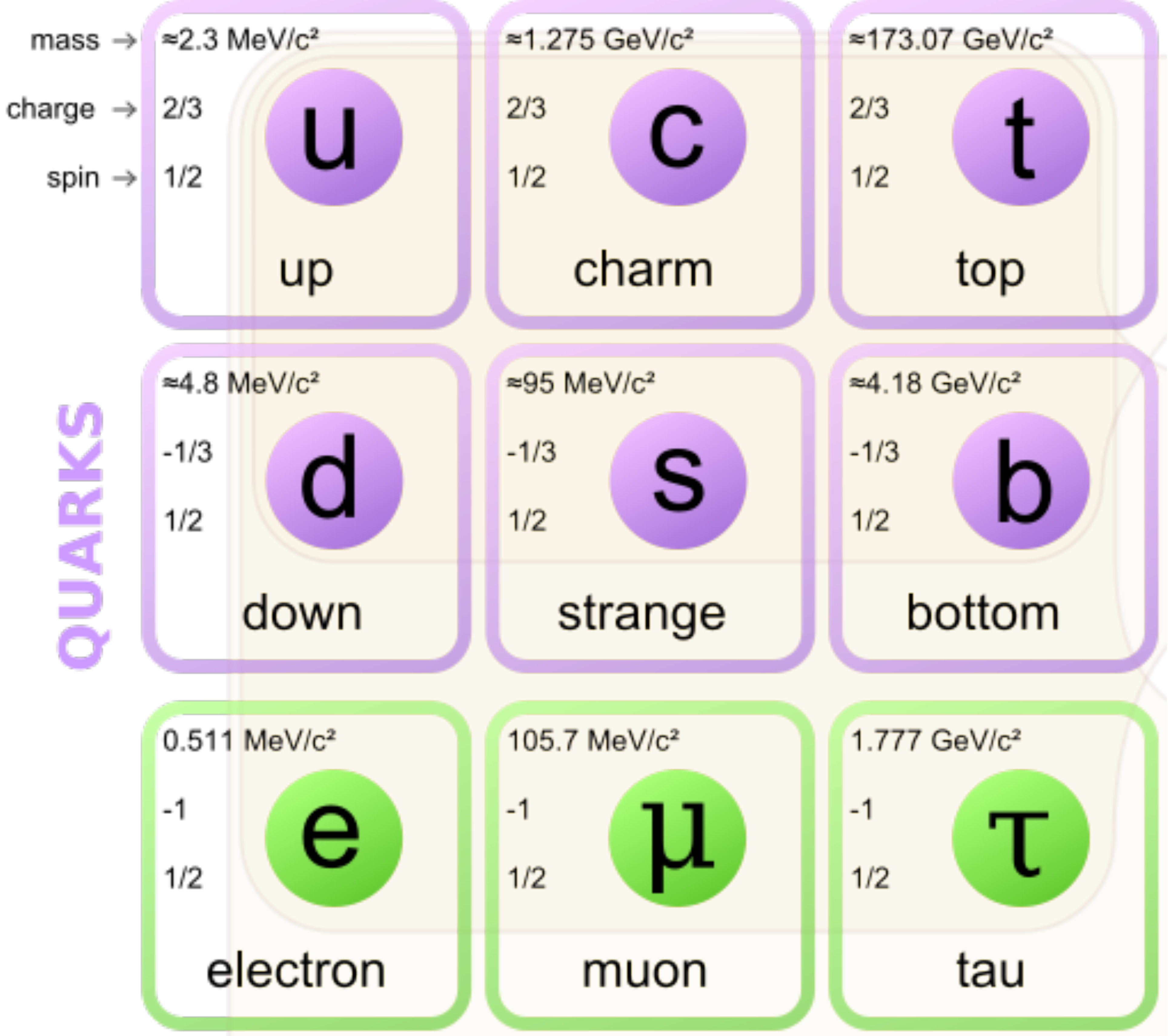
This equation neatly sums up our current understanding of fundamental particles and forces.

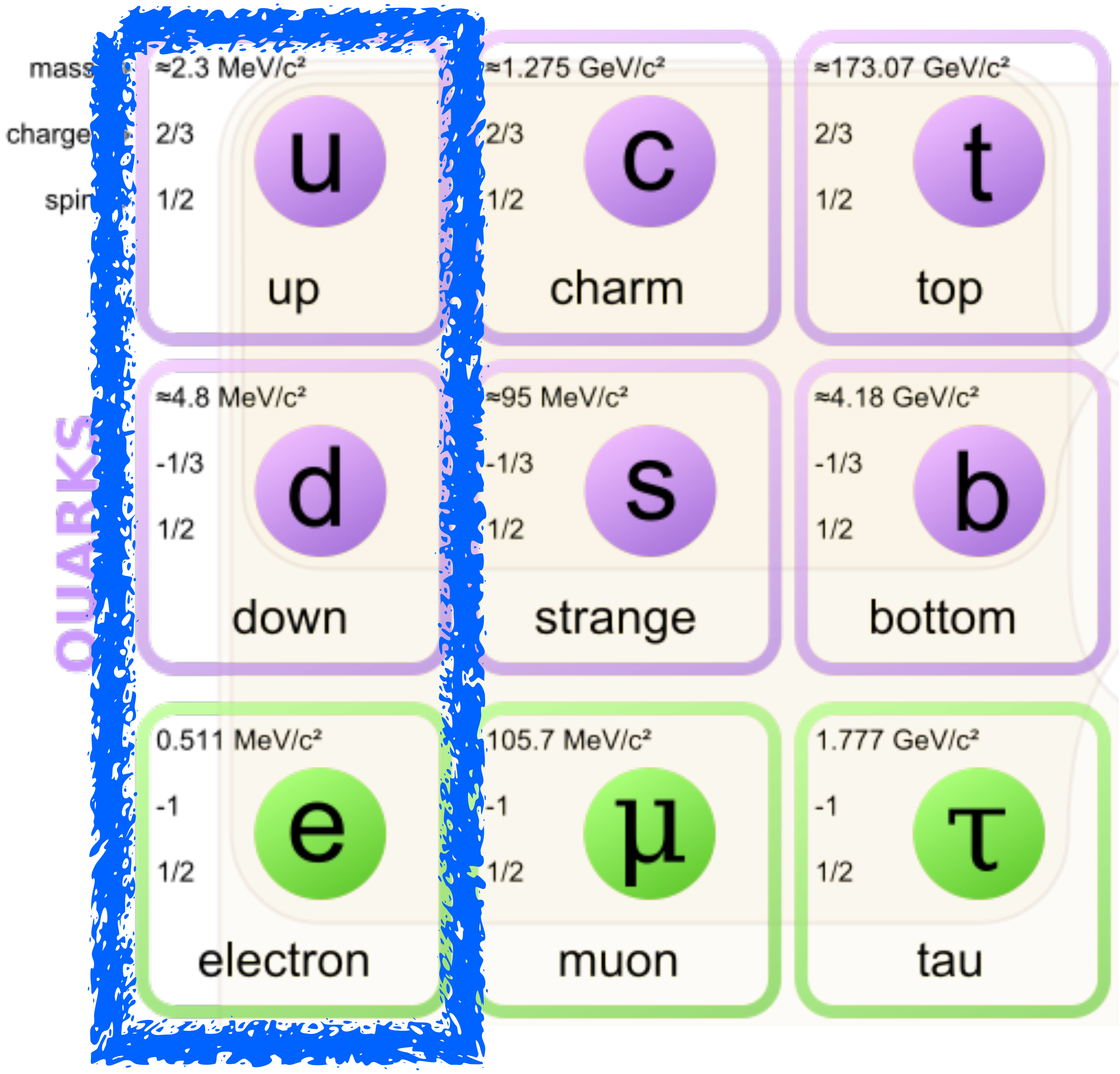
Bohr radius

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

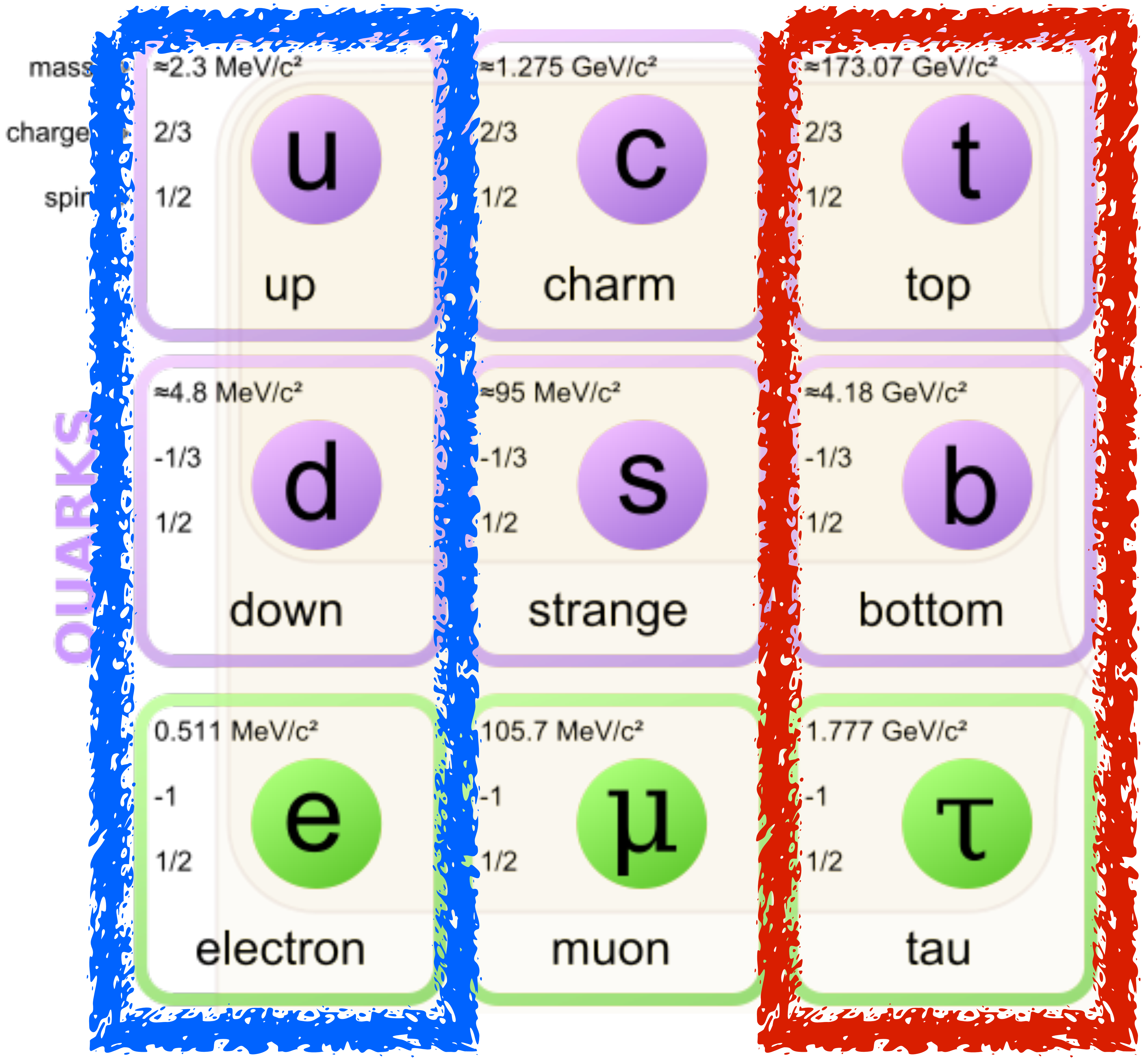
electron mass determines size of all atoms

it sets energy levels of all chemical reactions


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

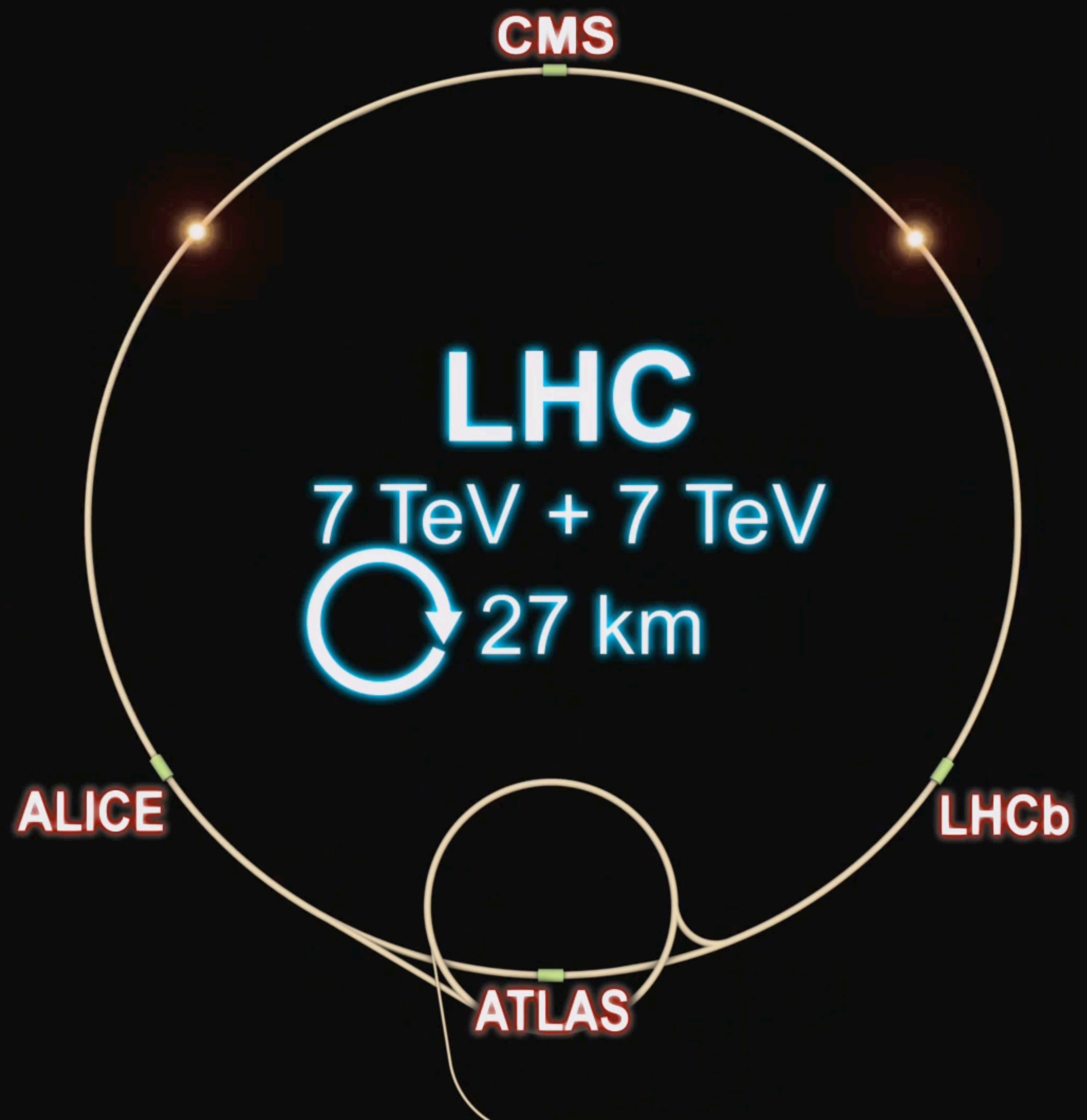


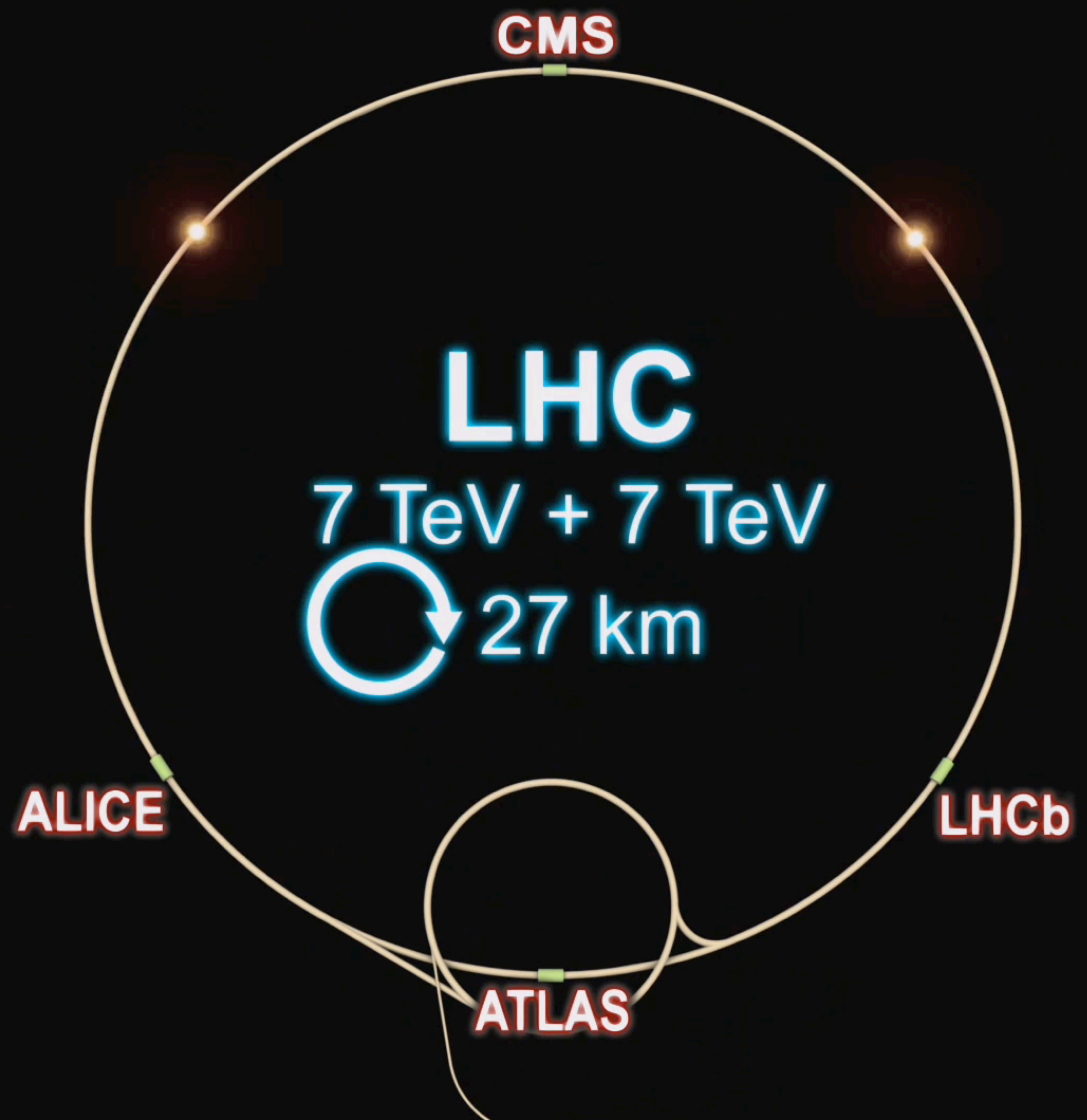
1st generation (us) has low mass because of weak interactions with Higgs field (and so with Higgs bosons): **too weak to test today**

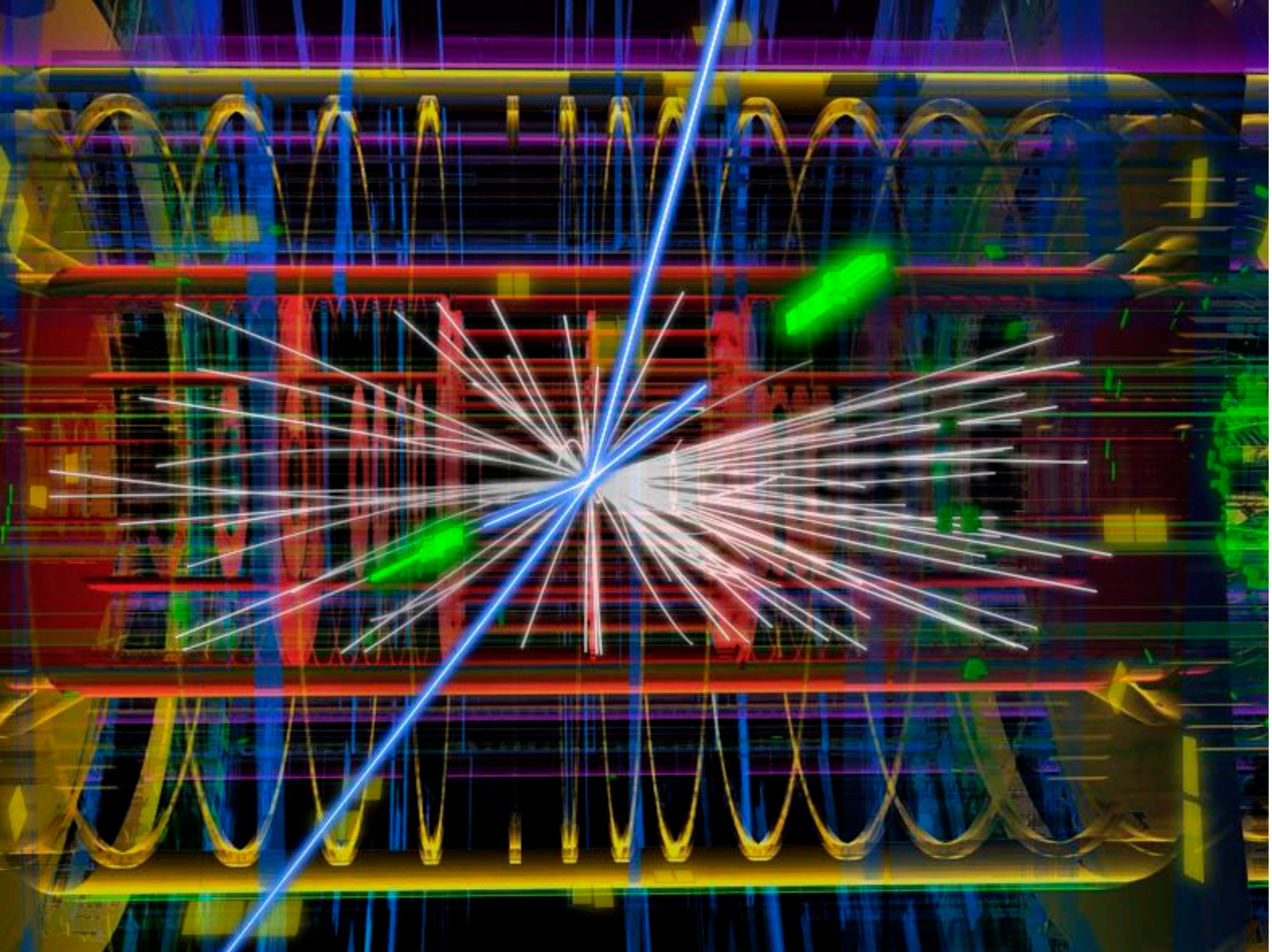


1st generation (us) has low mass because of weak interactions with Higgs field (and so with Higgs bosons): **too weak to test today**

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


CMS
LHC
7 TeV + 7 TeV
27 km
ALICE
LHCb
ATLAS


CMS
LHC
7 TeV + 7 TeV
27 km
ALICE
LHCb
ATLAS



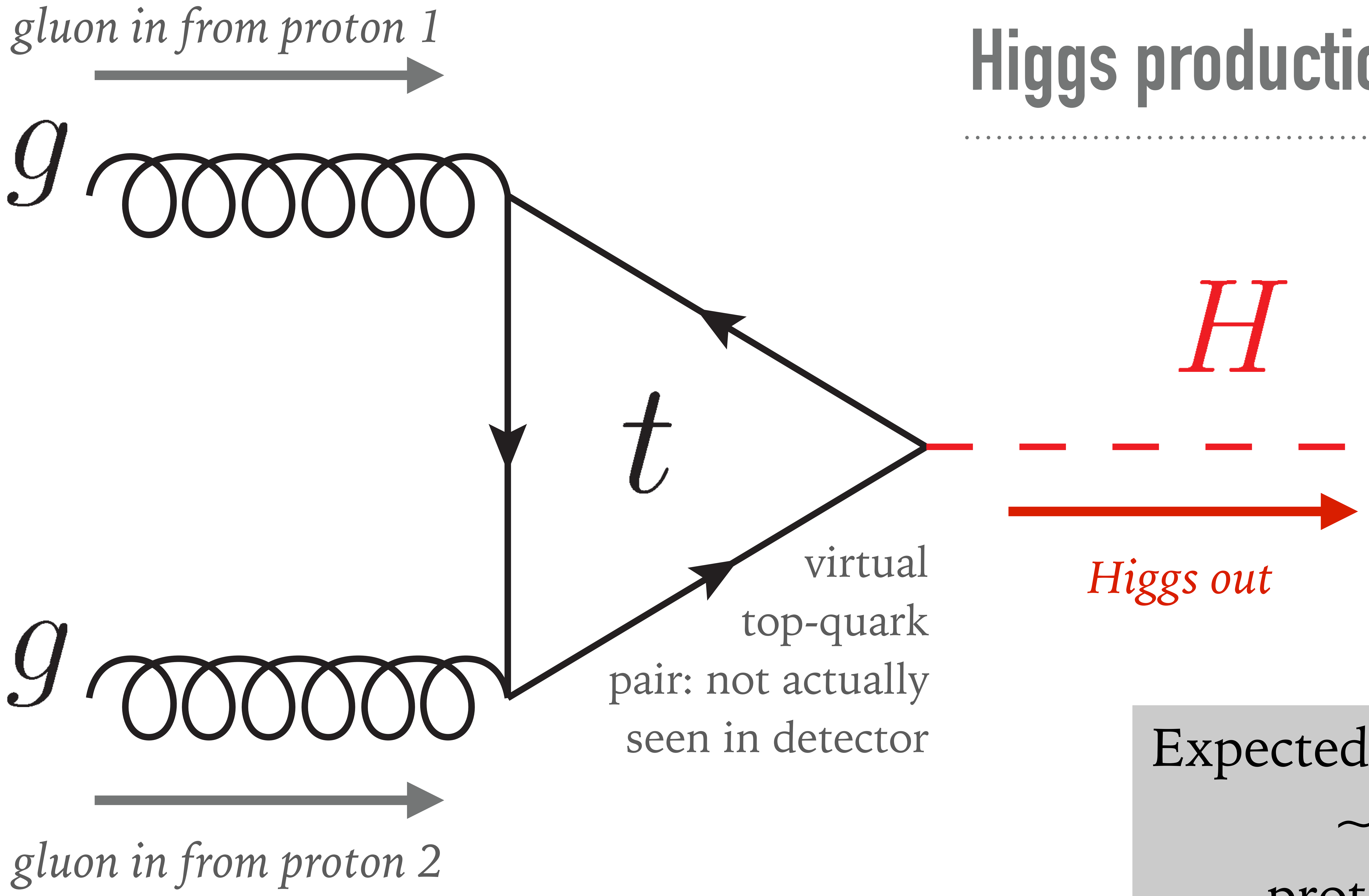
ATLAS & CMS
@LHC

~up to 2 billion collisions/second

(+ lower rates at LHCb and ALICE)

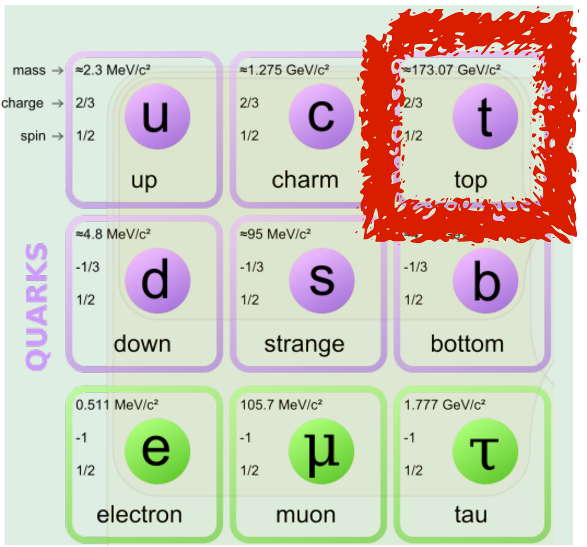
what underlying processes tell us about Yukawa interactions?

Higgs production: the dominant channel

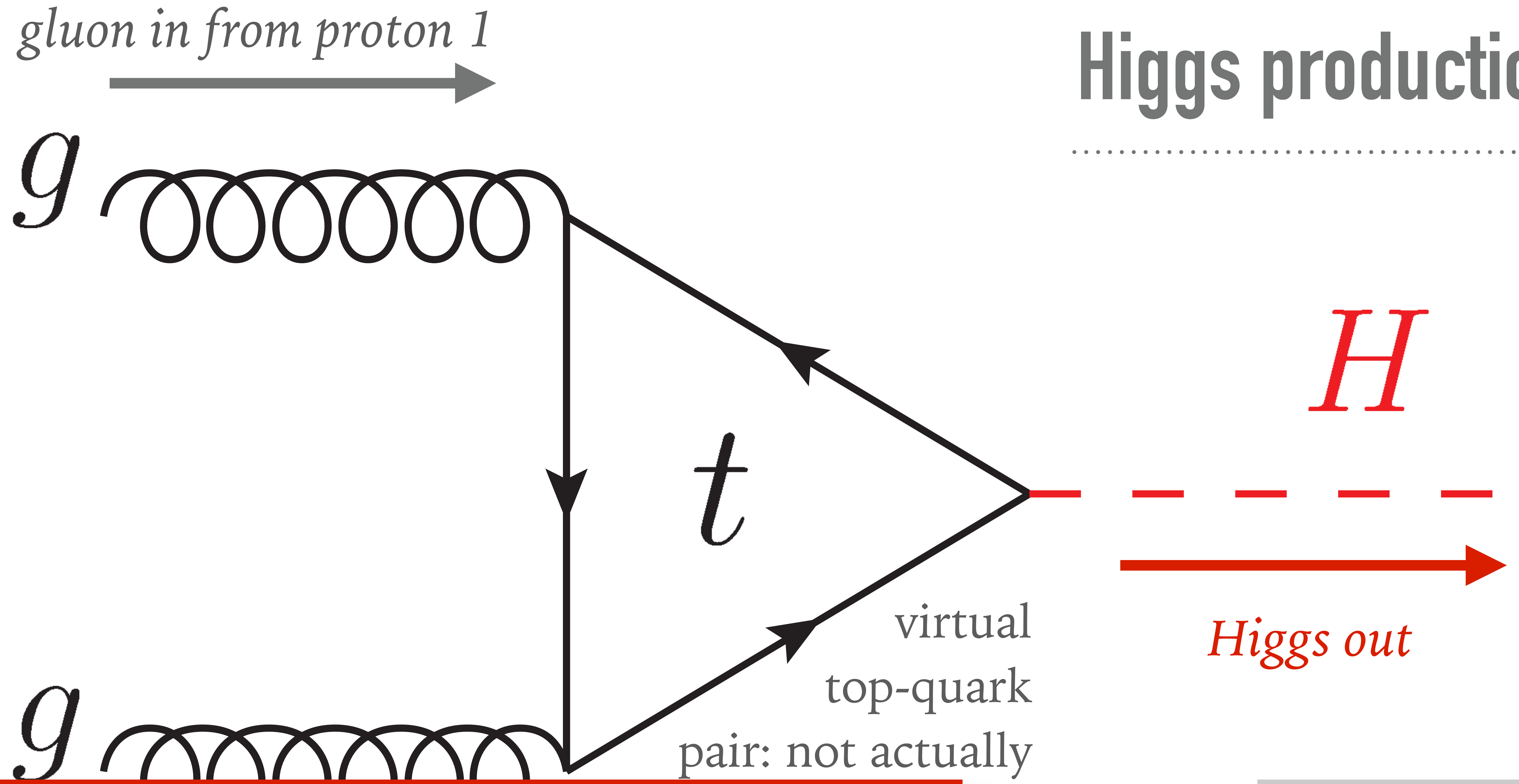


Expected to happen once for every ~2 billion inelastic proton–proton collisions

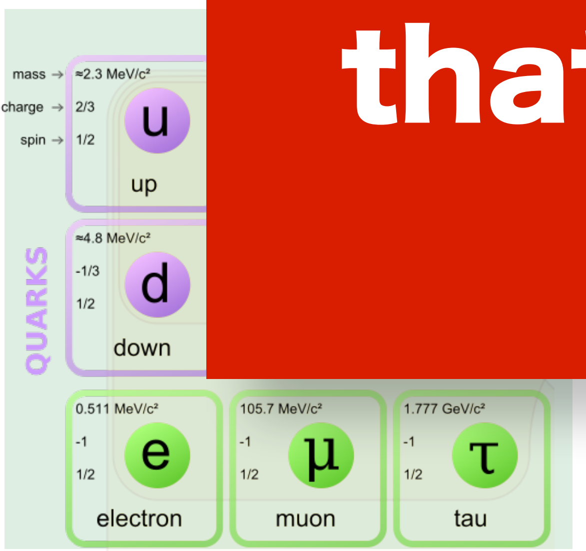
LHC data consistent with that already at discovery in 2012



Higgs production: the dominant channel



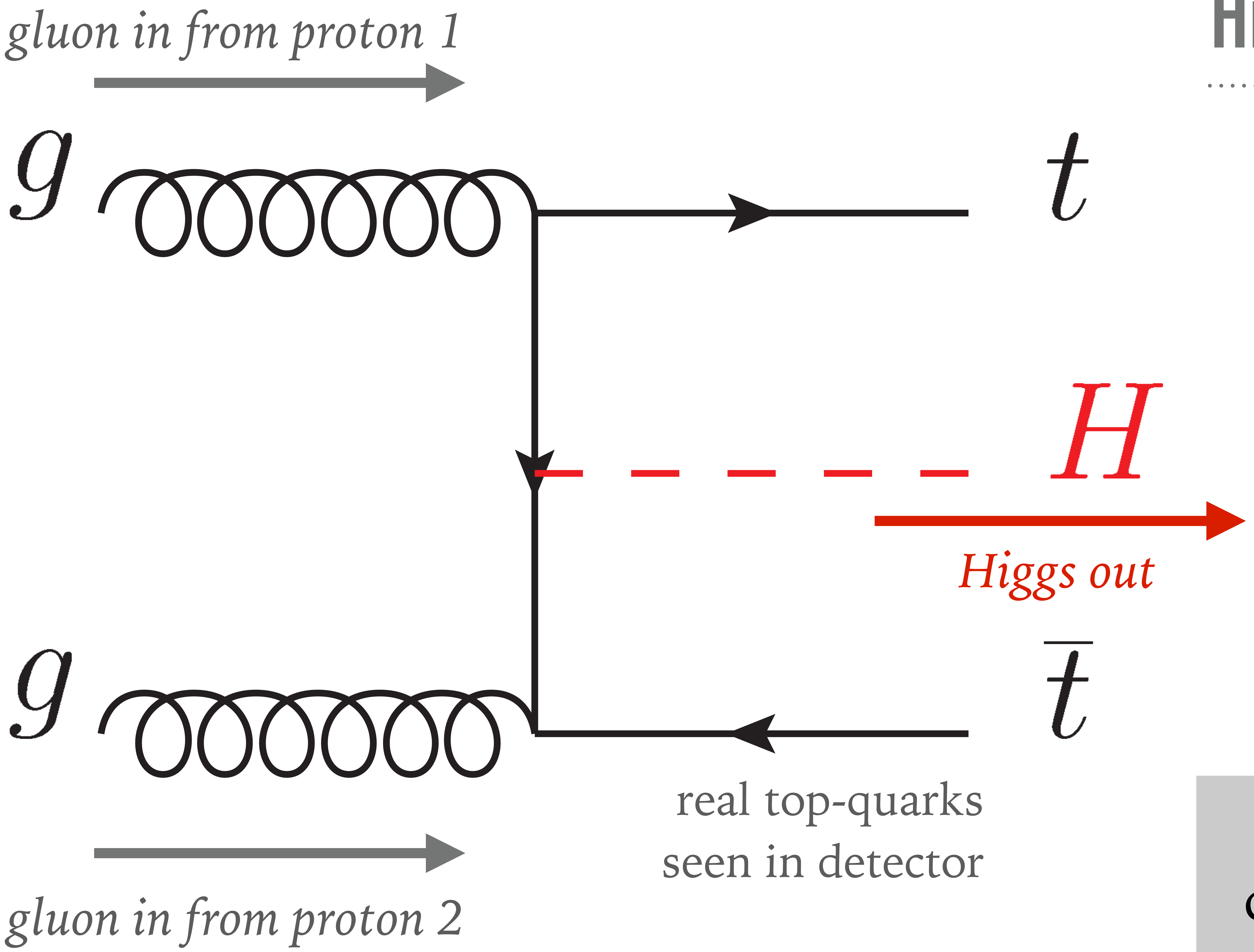
but how can you be sure the Higgs is really being radiated off a top-quark, i.e. that you're really seeing a Yukawa coupling?



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

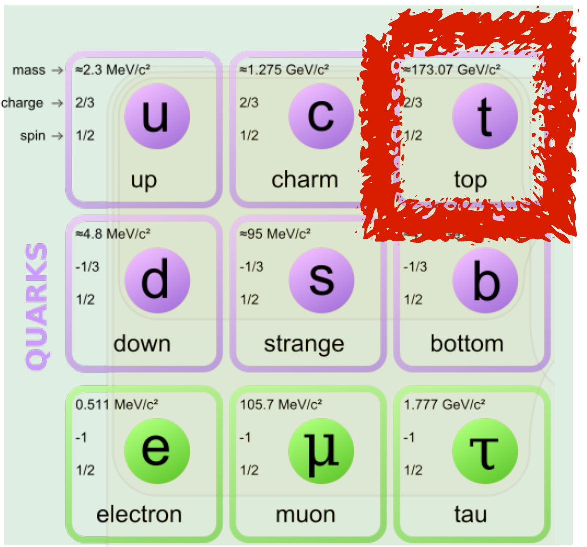
LHC data consistent with that already at discovery in 2012

Higgs production: the ttH channel



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

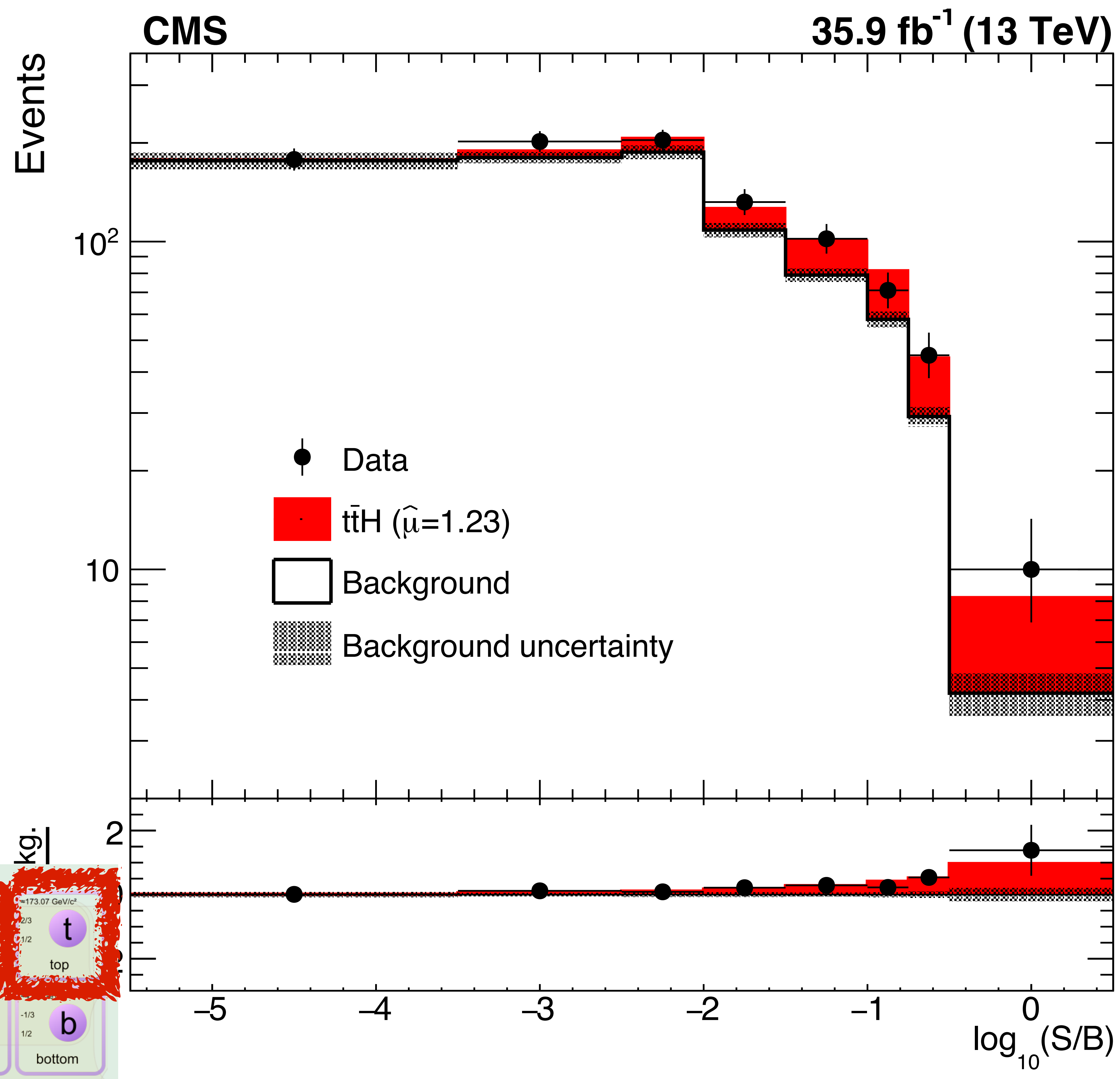
(rather than 1 Higgs for every 2 billion pp collisions)

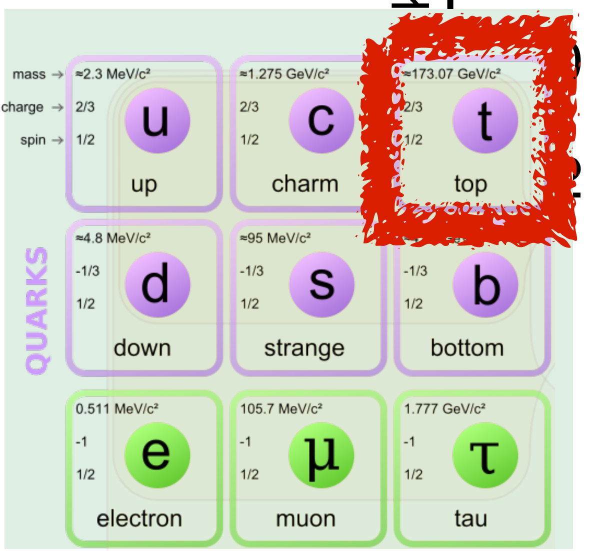


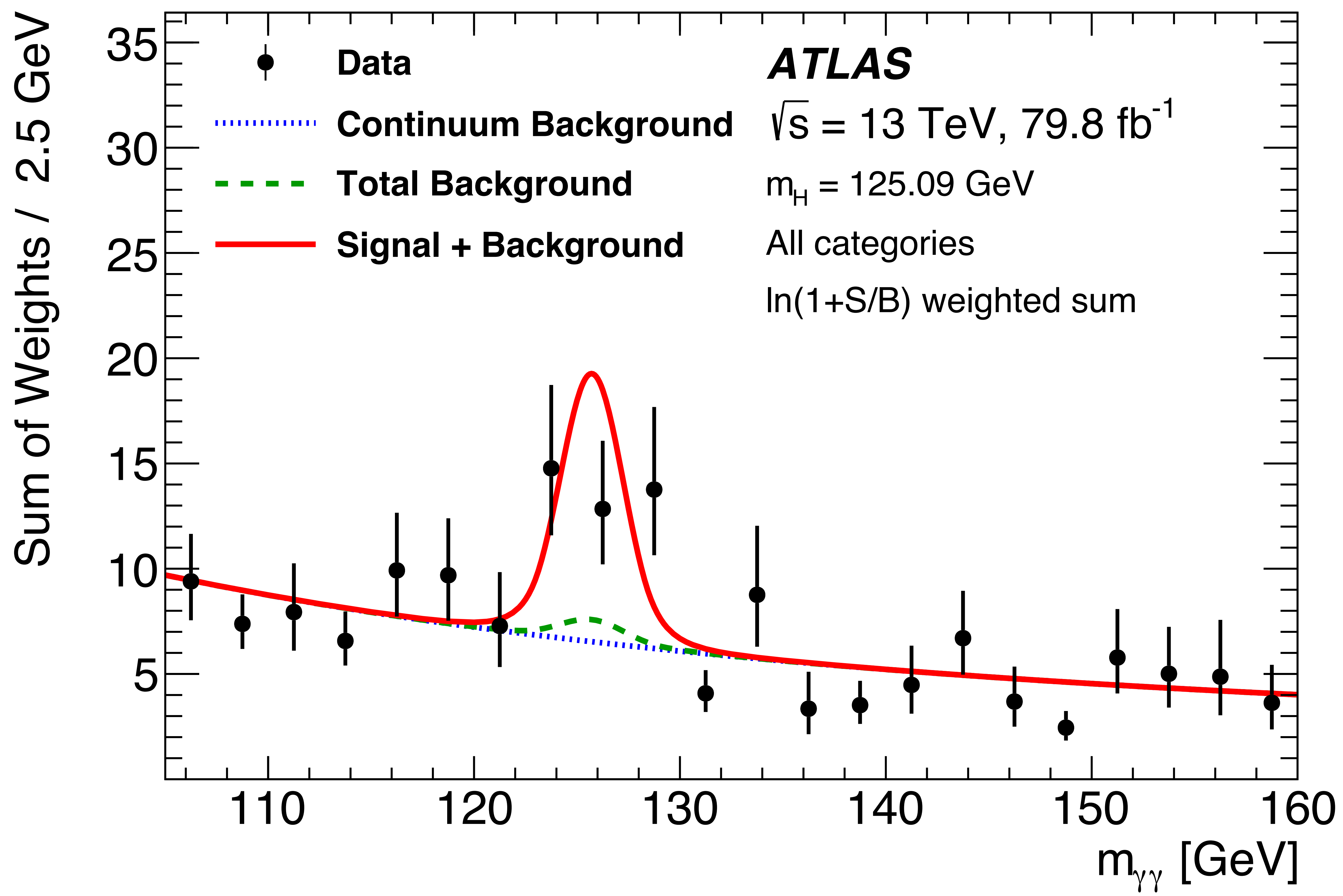
the news of the past months: ATLAS & CMS see events with top-quarks & Higgs simultaneously

CMS > 5-sigma ttH

ATLAS > 5-sigma ttH



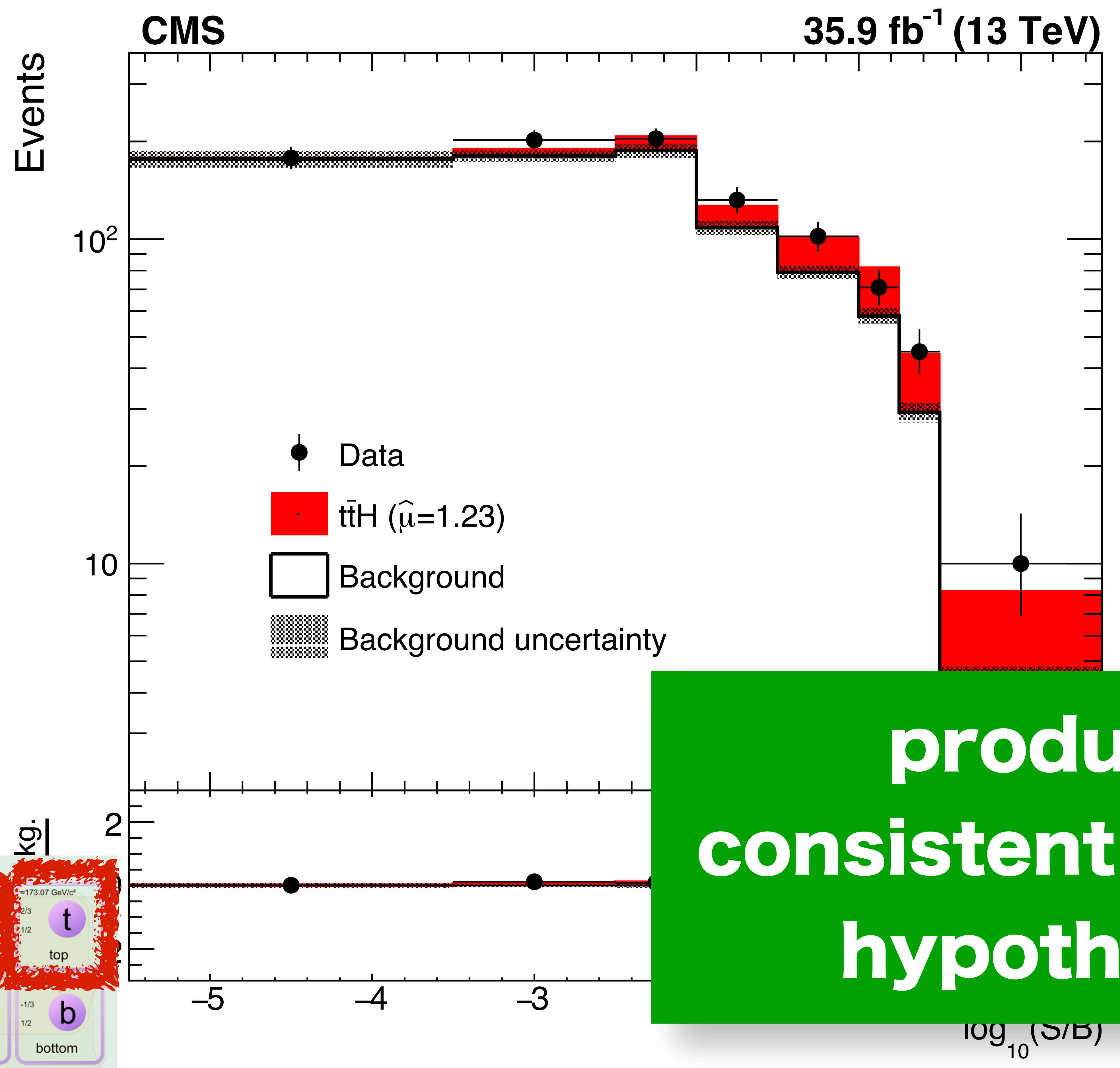


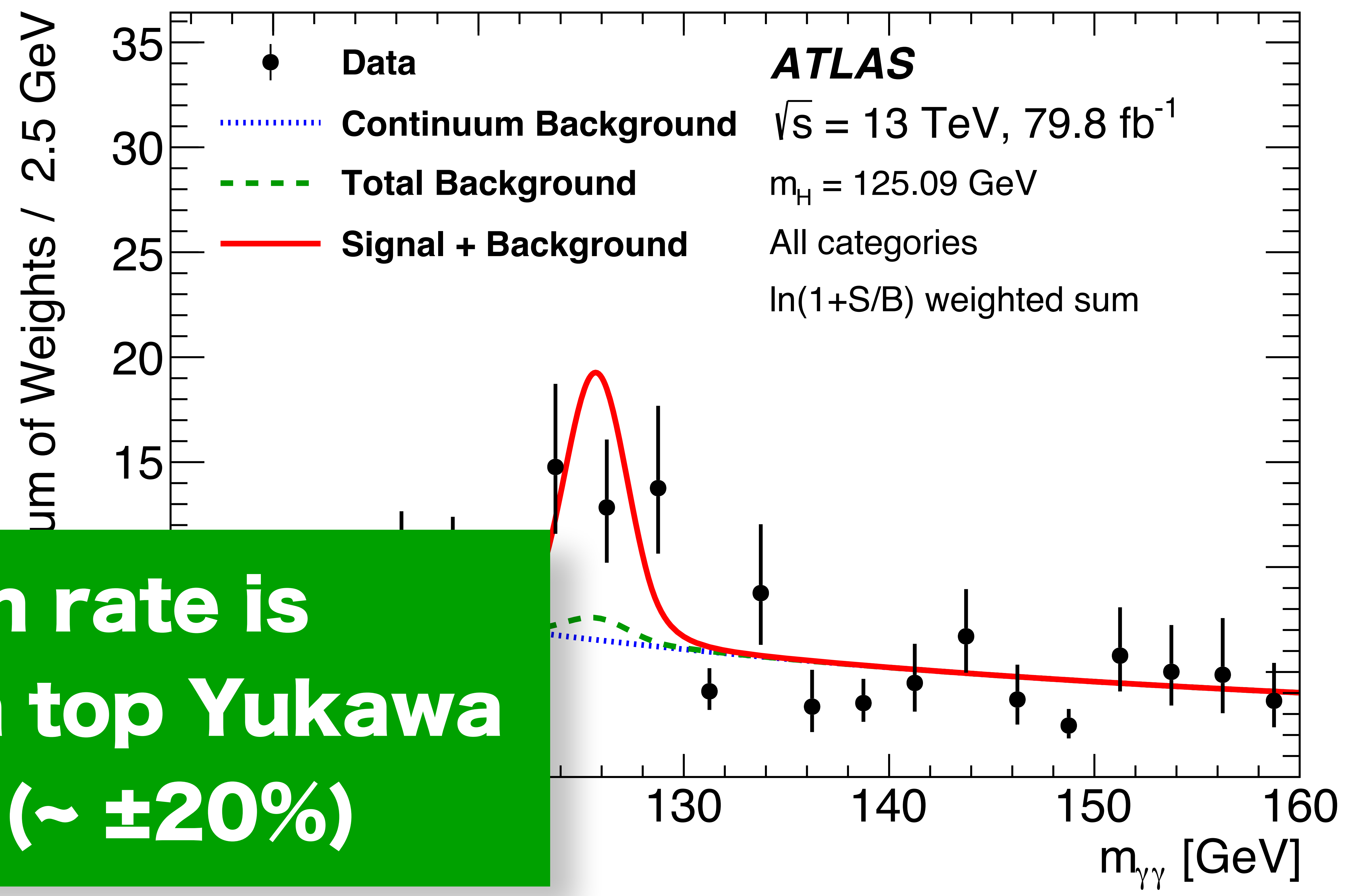


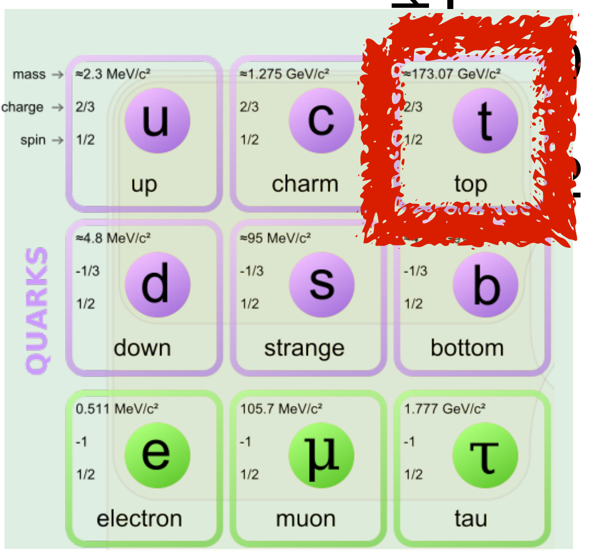
the news of the past months: ATLAS & CMS see events with top-quarks & Higgs simultaneously

CMS > 5-sigma ttH

ATLAS > 5-sigma ttH

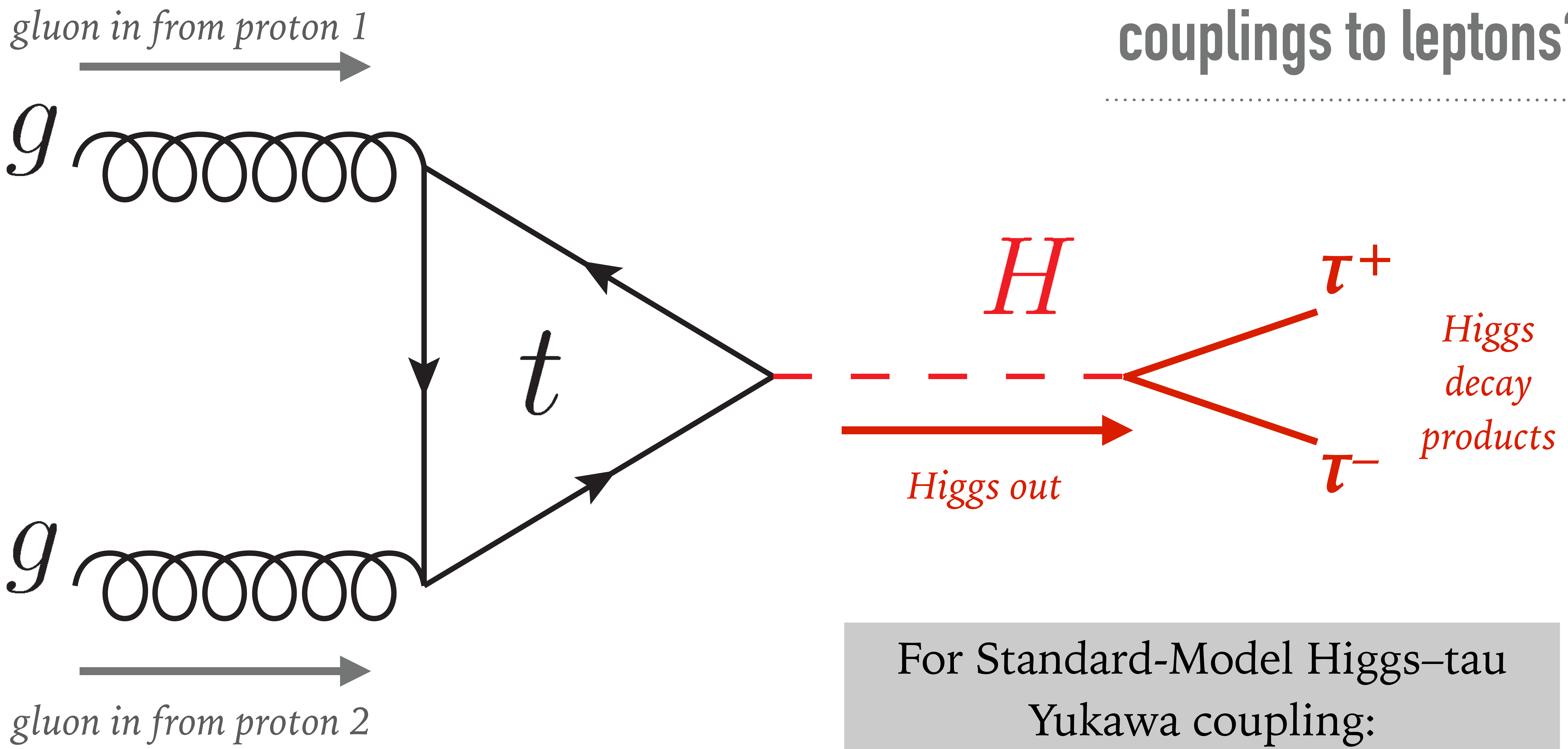






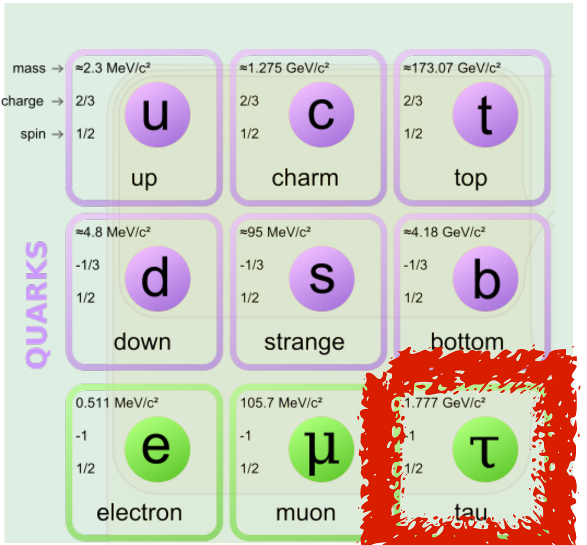
production rate is consistent with top Yukawa hypothesis (~ ±20%)

couplings to leptons?



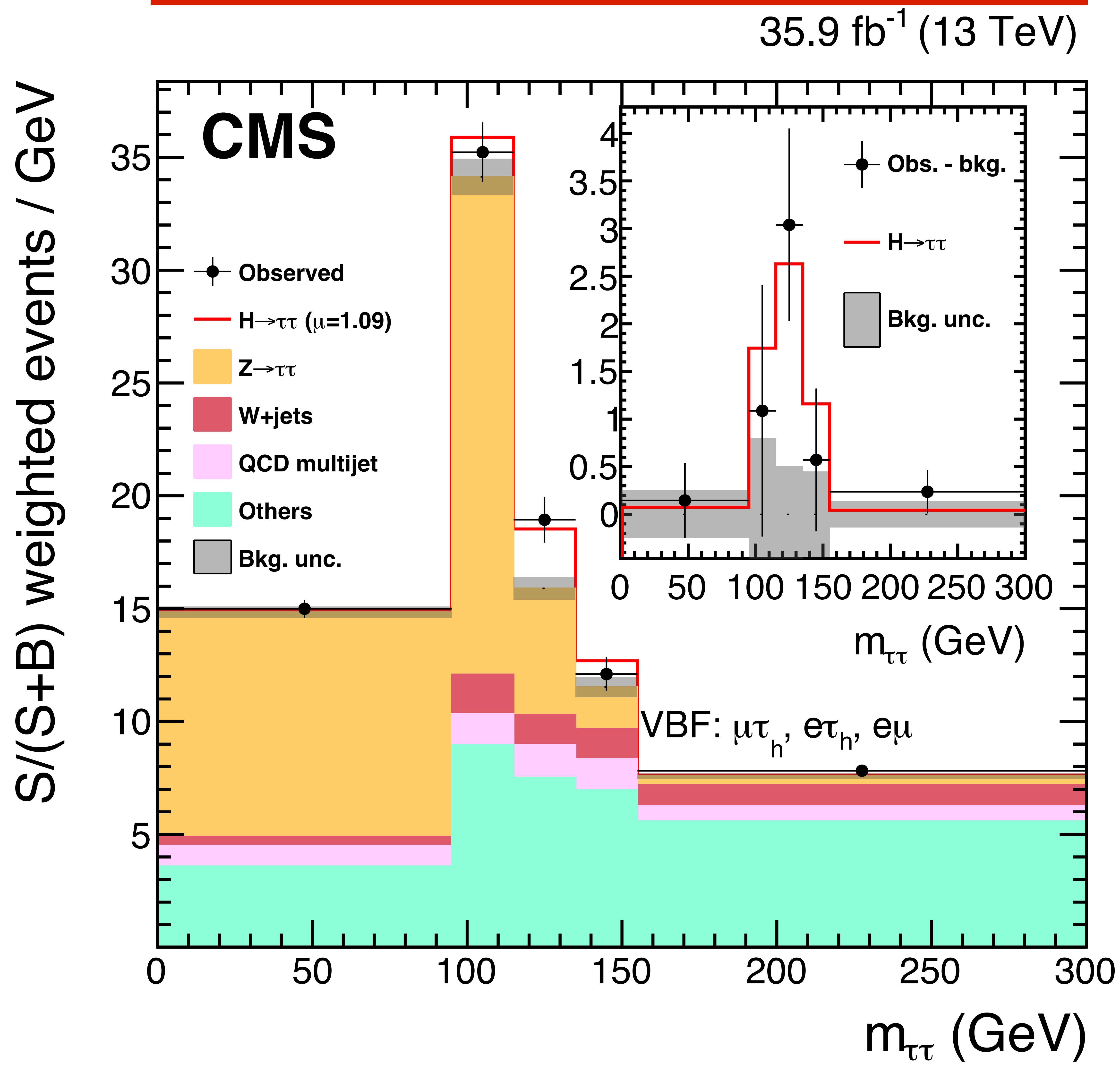
For Standard-Model Higgs–tau Yukawa coupling:

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

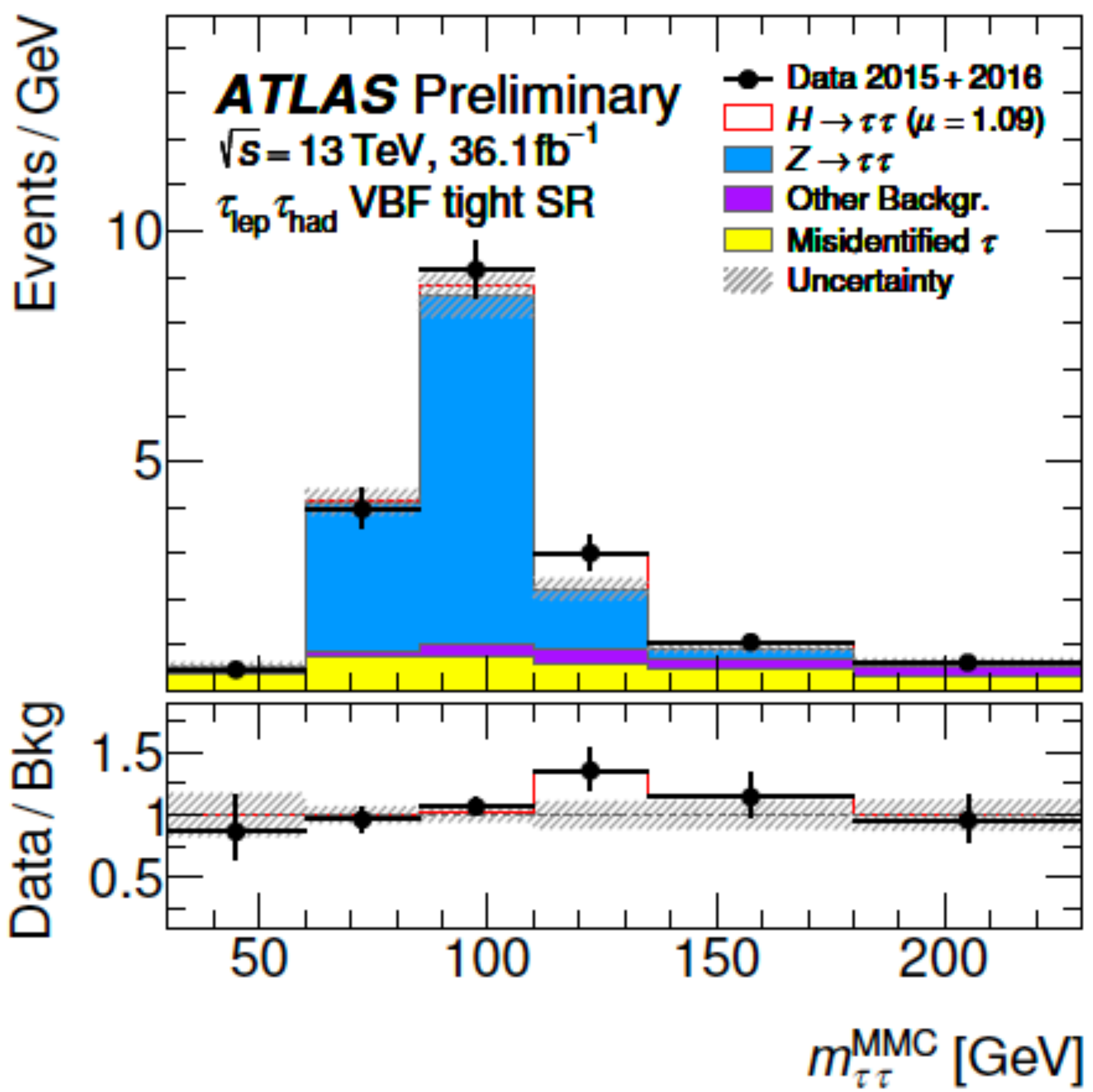


observation of H → ττ

a year ago:
CMS >5-sigma H → τ τ



a few weeks ago:
ATLAS >5-sigma H → τ τ



what could one be saying about it?

The >5σ observations of ttH and H → ττ, 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.

what could one be saying about it?

The >5σ observations of ttH and H → ττ, 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.

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

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

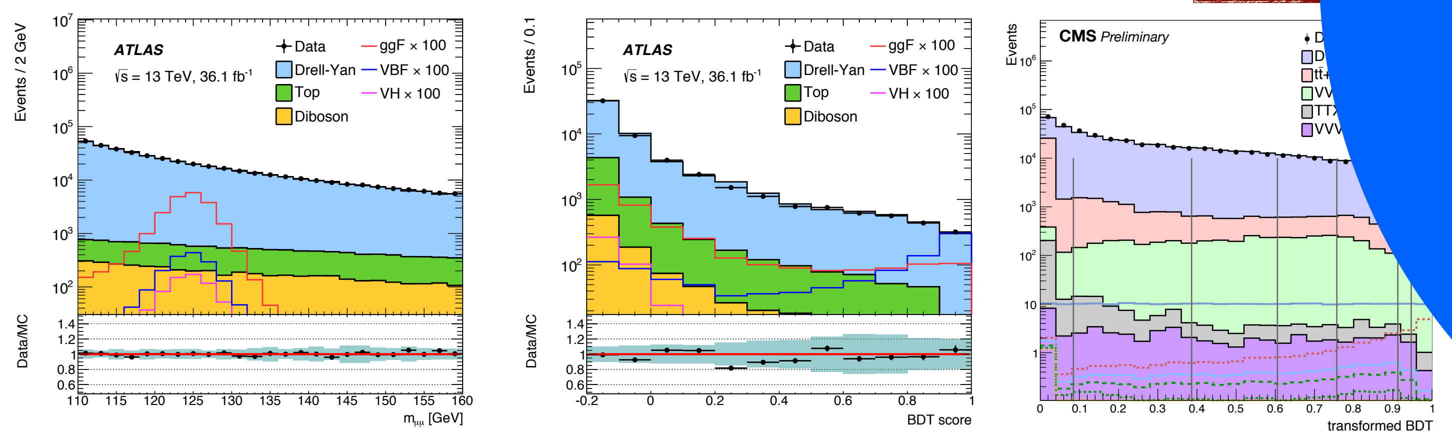
Grefe C. Grefe - Higgs

Search for $H \to \mu\mu$

ATLAS CMS

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

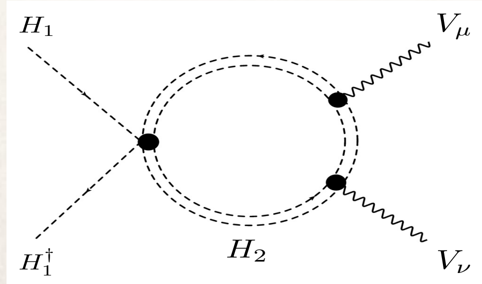
Well-defined theoretical approach
Assumes New Physics states are heavy
Write Effective Lagrangian with only light (SM) particles
BSM effects can be incorporated as a momentum expansion

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



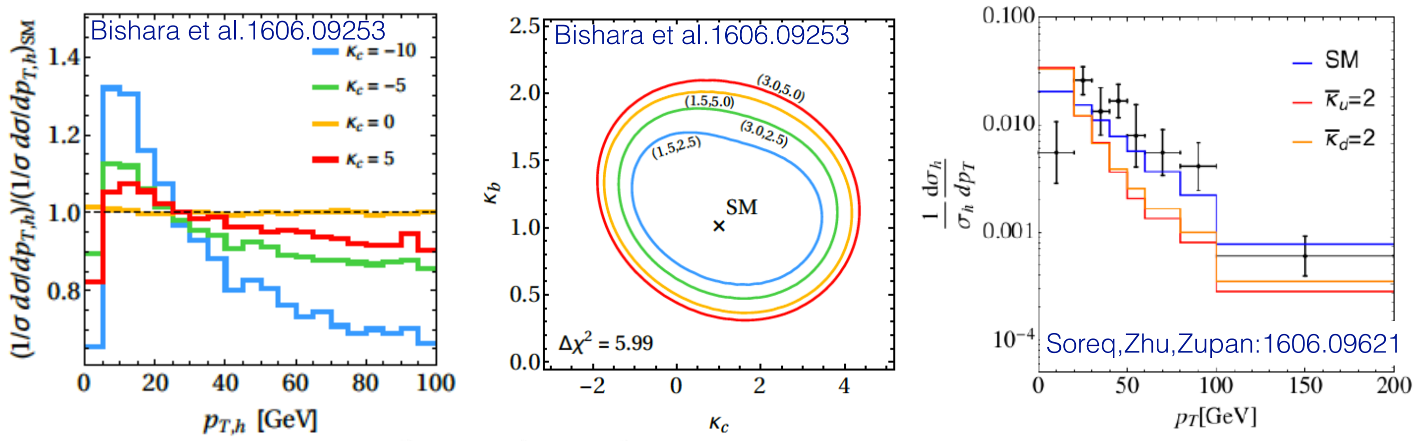
$$\frac{ig}{2m_W^2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu}$$

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

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: $[-1.4, 3.8]$
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: $V(H) = \frac{1}{2}M_H^2H^2 + \lambda_{HHH}vH^3 + \frac{1}{4}\lambda_{HHHH}H^4$

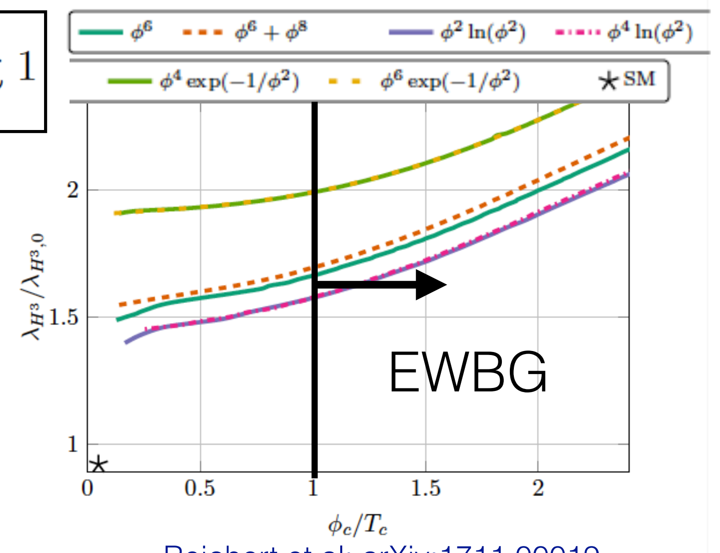
Fixed values in the SM: $\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}$

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

A cosmological Higgs

HIGGS

Dark Matter
Higgs portal
Higgs DM mediator

UV sensitivity
Naturalness
heavy new physics
Relaxation

Inflation
Higgs inflation
Inflaton vs Higgs

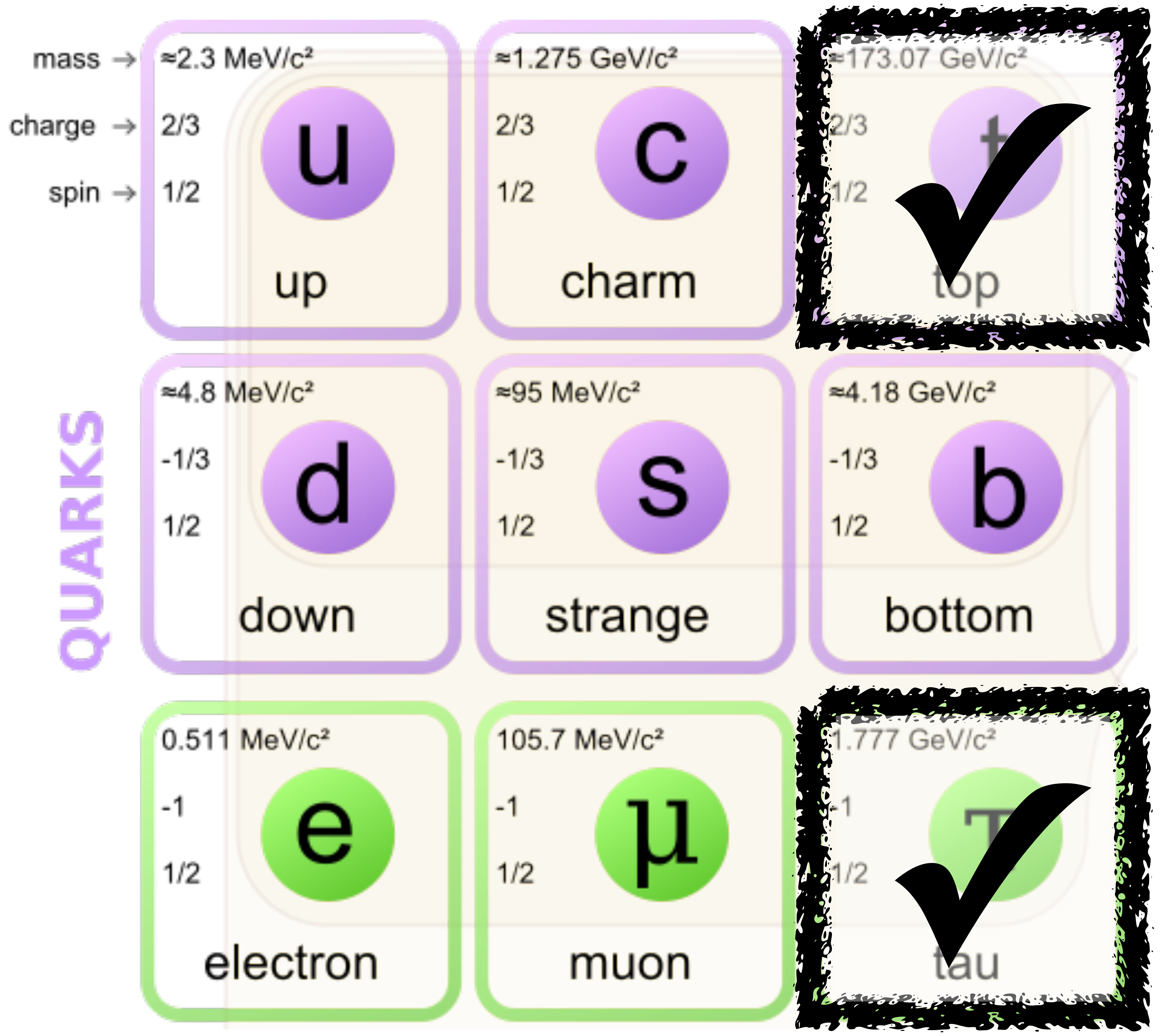
Phase transitions
Baryogenesis
gravitational waves

Fate of the Universe
Stability

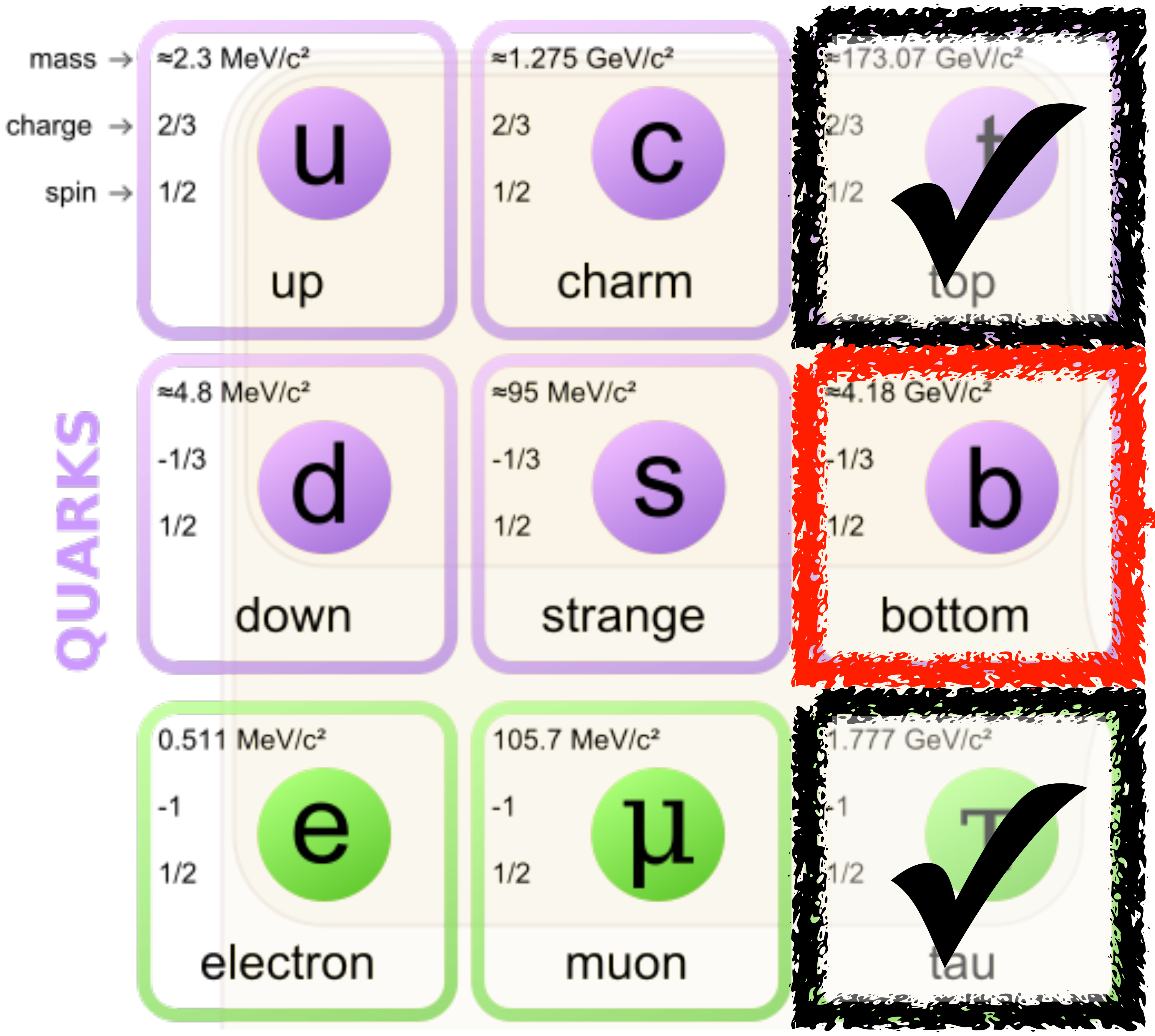
The LHC provides the most precise, controlled way of studying the Higgs and direct access to TeV scales
Exploiting complementarity with cosmo/astro probes

Similar story for Axions and ALPs, scalars are versatile

Sanz

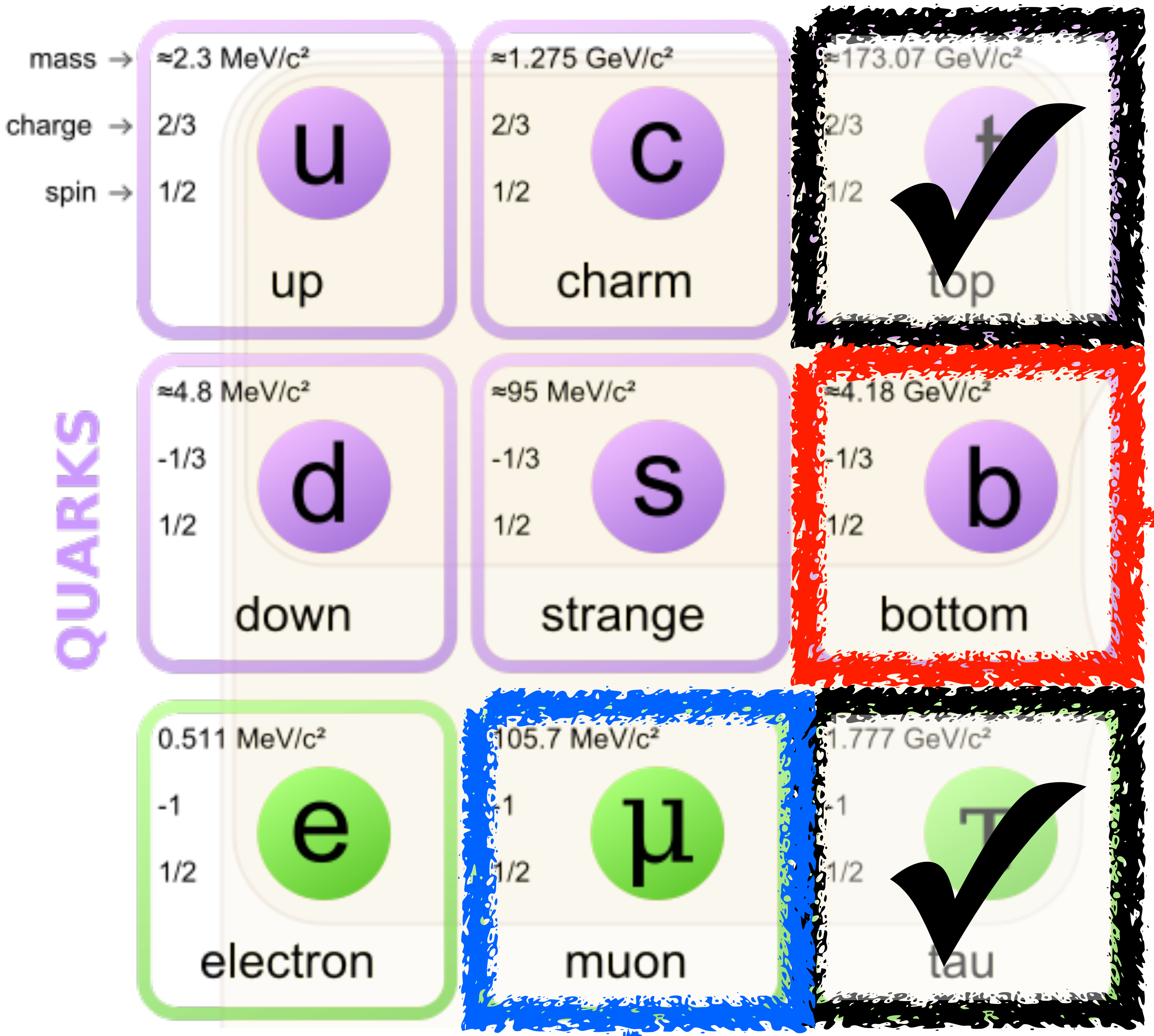


mass →
charge →
spin →
QUARKS
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau



today: indirect + direct evidence

SM value can be directly observed within next year or two



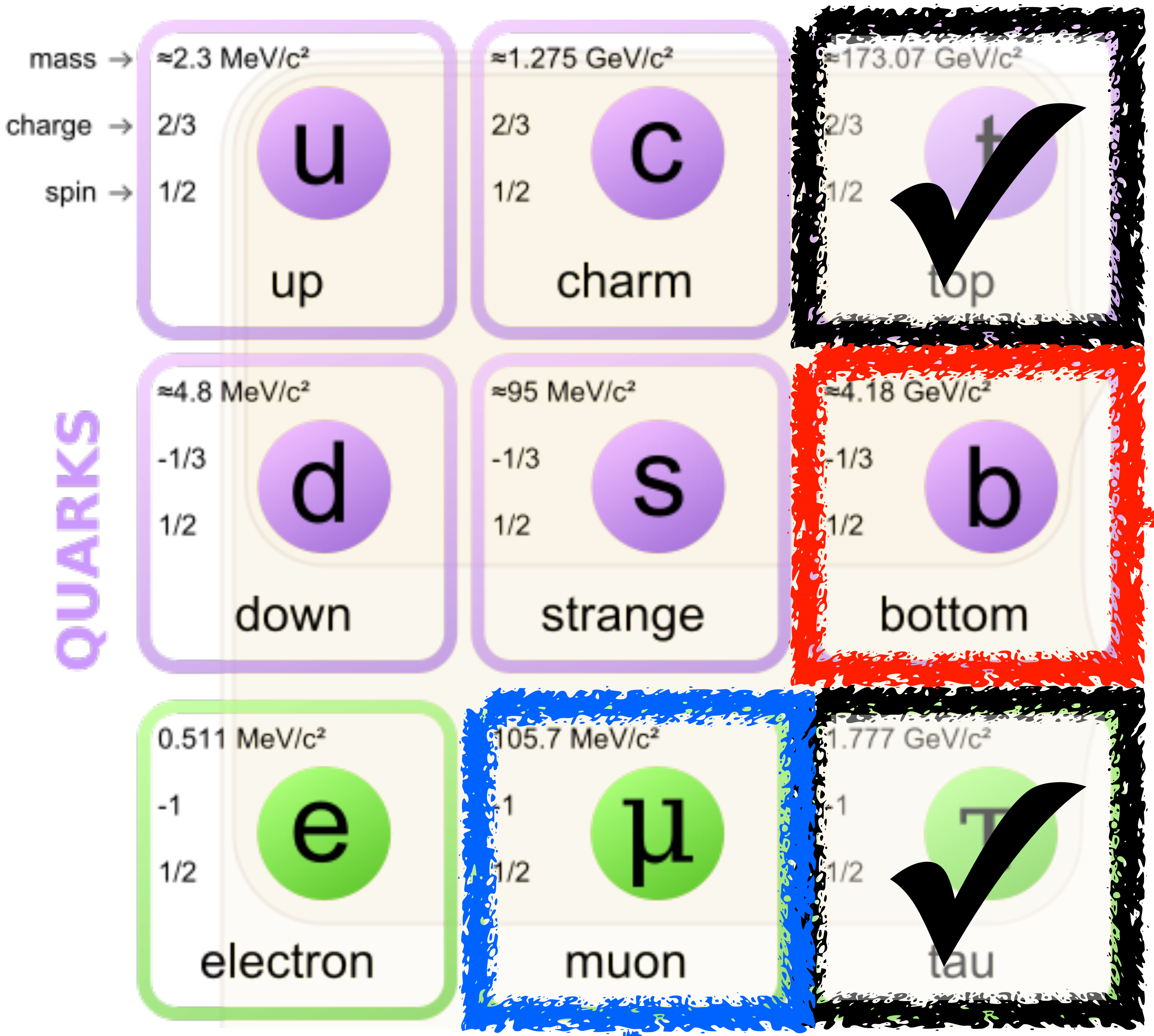
today: indirect + direct evidence

SM value can be directly observed within next year or two

today: no evidence yet

(1 in 4570 decays)

observable at the LHC within about 10 years.



overall normalisation
(related to Higgs width)

today: indirect + direct evidence

SM value can be directly observed within next year or two

today: no evidence yet
(1 in 4570 decays)

observable at the LHC within about 10 years.

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

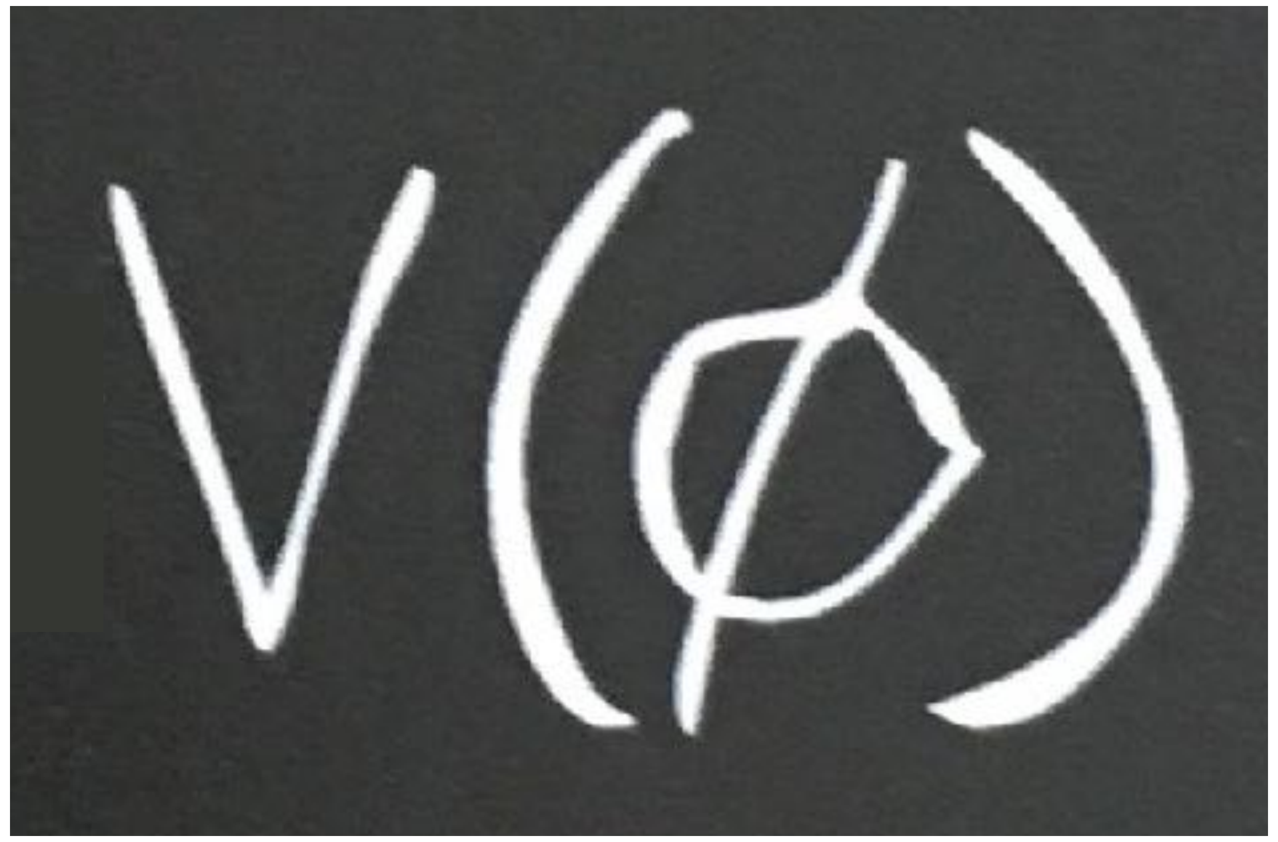
$$-\mathcal{L}_Y = Y_{ij}(\phi)\bar{\psi}_i\psi_j\phi + \text{h.c.} \qquad\qquad Y_{ij}(\phi) = c_{ij}\left(\frac{\phi^\dagger\phi}{M^2}\right)^{n_{ij}}$$

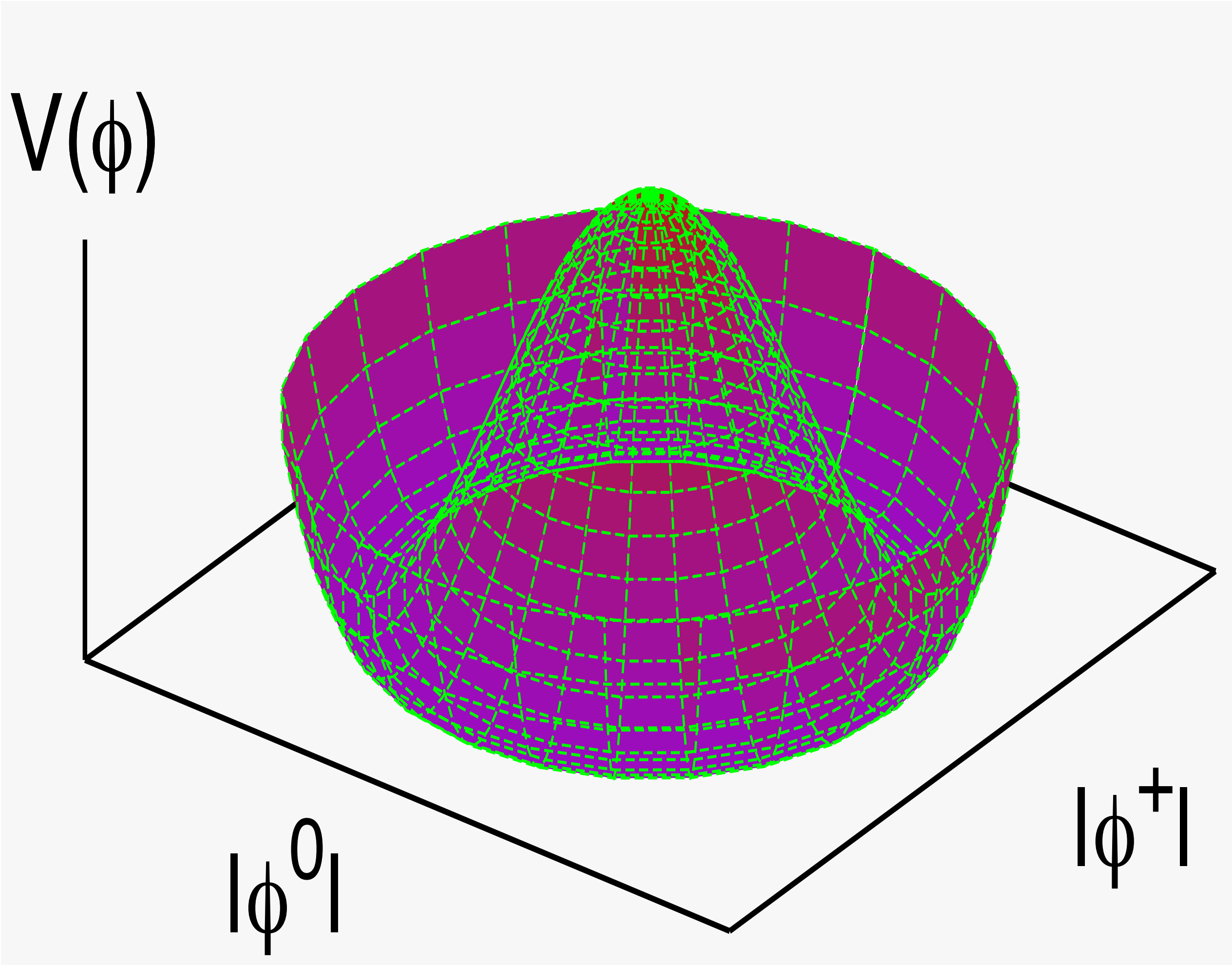
- smallness of certain masses is consequence of vev^2/M^2 suppression, not small c_{ij}
- measured Hqq interaction larger by factor $(2n_{ij} + 1)$
- cf. also various more recent discussions, e.g. by Bauer, Carena, Carmona

1801.00363

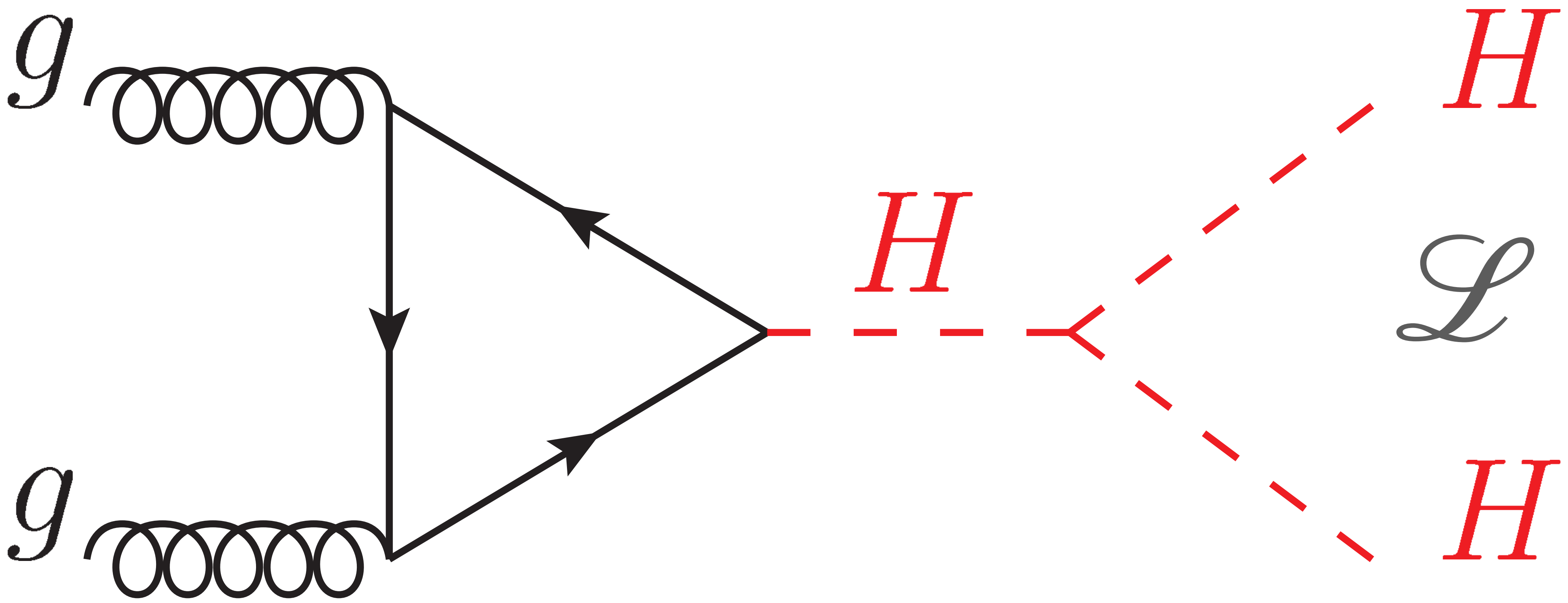
thanks to U. Haisch for a crash course on the models — any naivety is mine, not his

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





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



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

- **probably needs a bigger collider**

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]

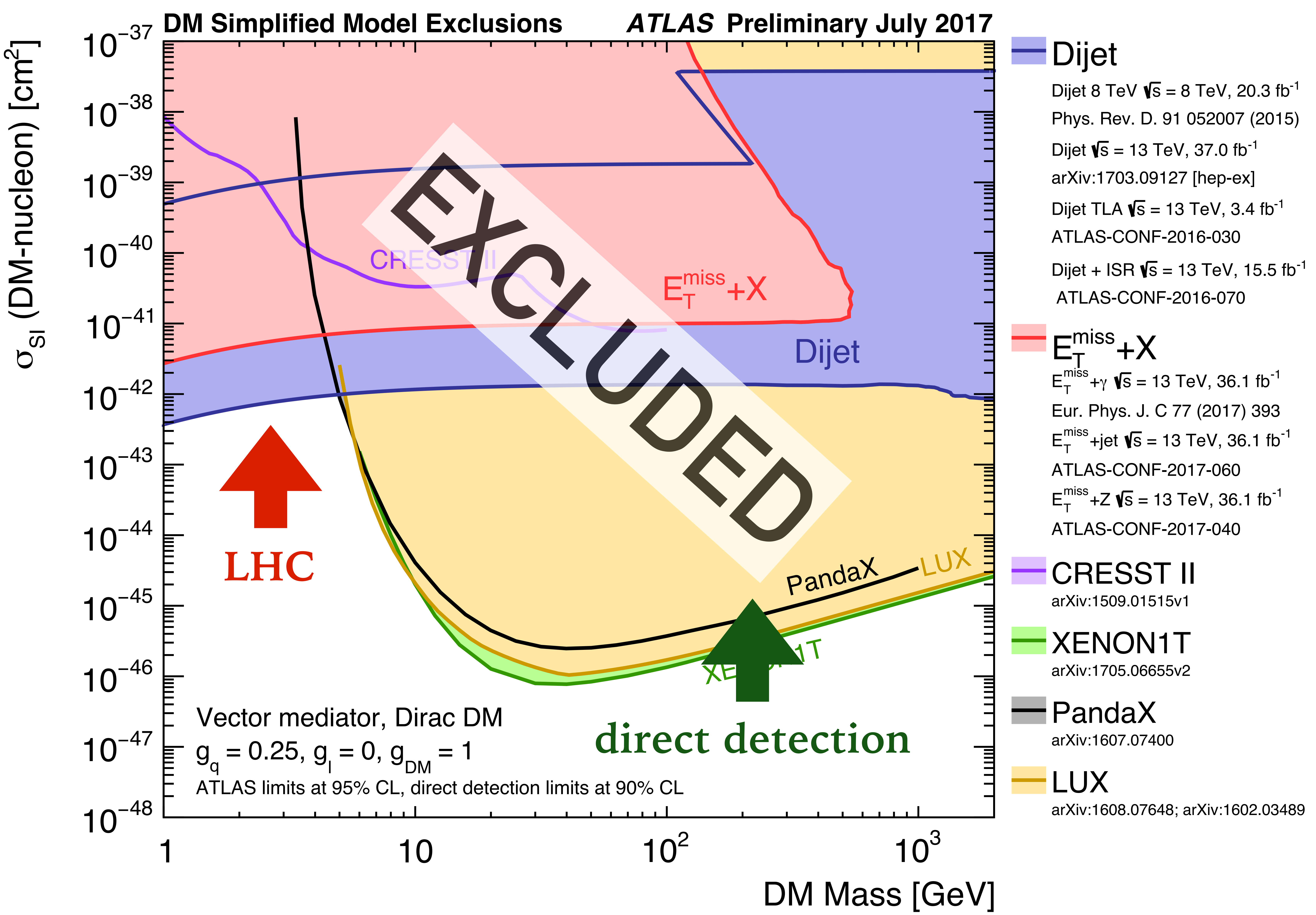
https://www.pbs.org/newshour/science/large-hadron-collider-gears-find-dark-matter-new-particles-second-run

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).

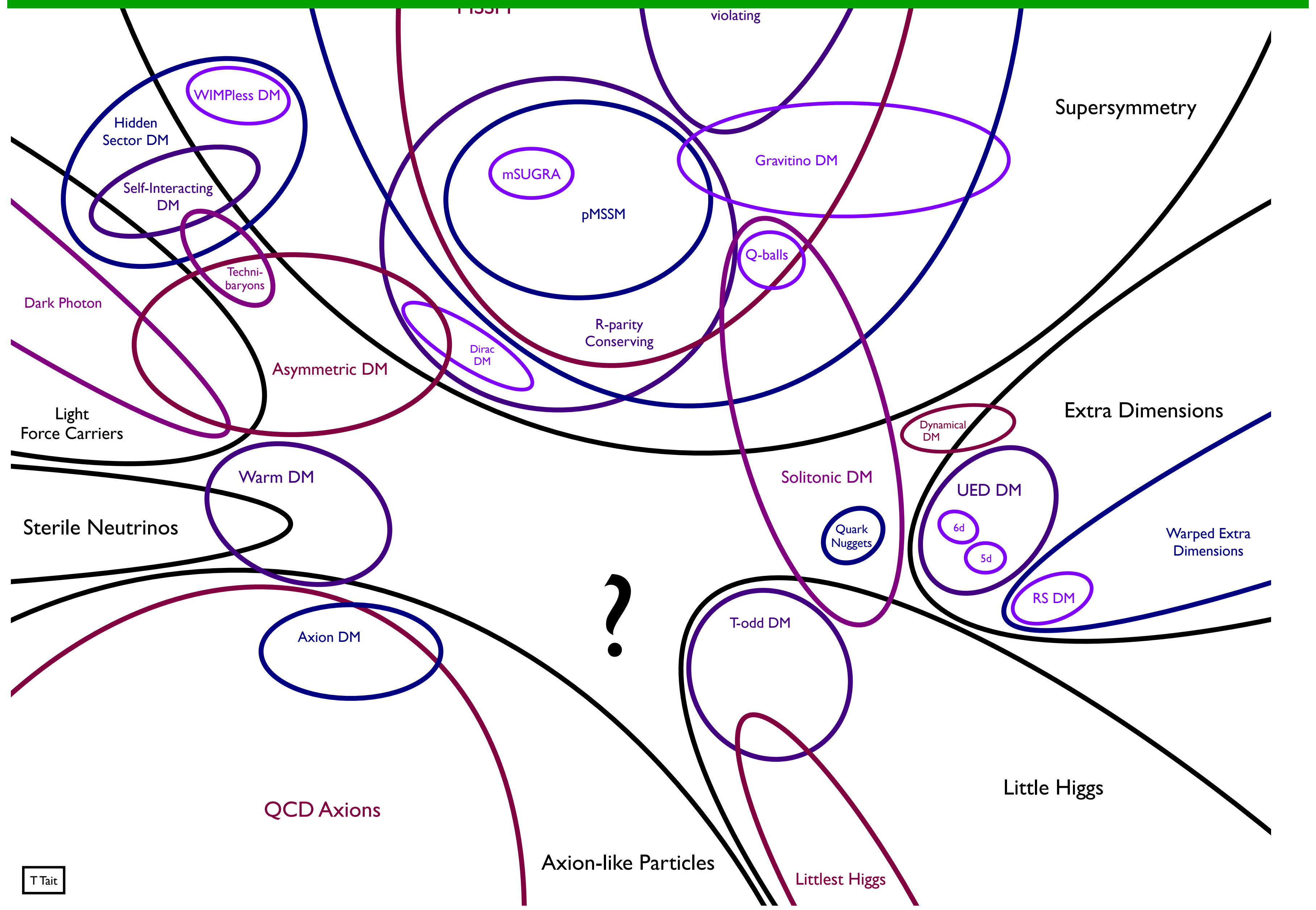
Masses ~ GeV upwards

(search interpretations strongly model dependent)

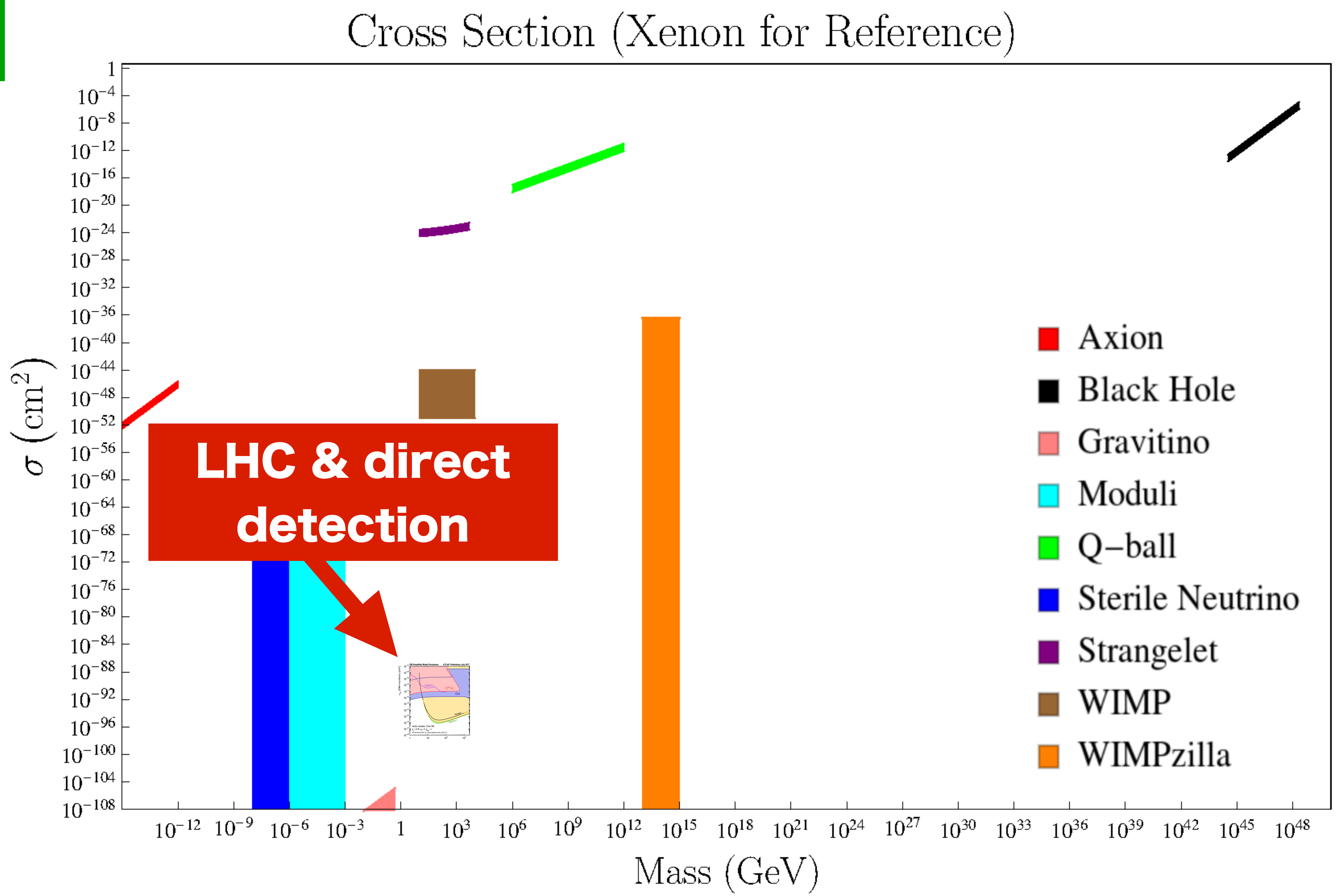


LHC searches only a subset of dark matter phase-space

Snowmass non-WIMP dark matter report, 1310.8642



Tim Tait



ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

ATLAS Preliminary

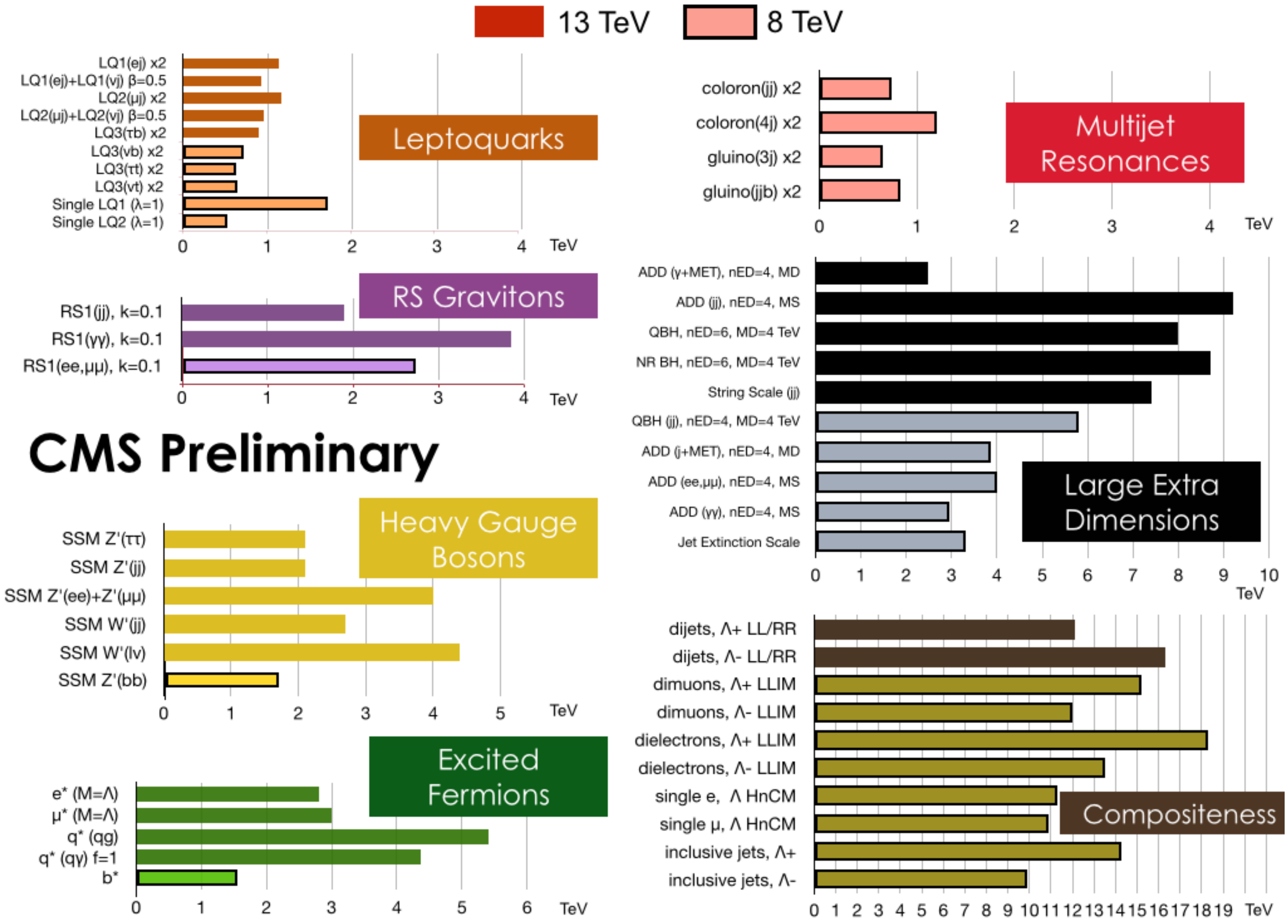
$\sqrt{s}$ = 7, 8, 13 TeV

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

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt\,[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde q\tilde q,\ \tilde q\to q\tilde\chi^0_1$	0	2-6 jets	Yes	36.1	$\tilde q$ 1.57 TeV	$m(\tilde\chi^0_1)$<200 GeV, m(1st gen. $\tilde q$)=m(2nd gen. $\tilde q$)	1712.02332
	$\tilde q\tilde q,\ \tilde q\to q\tilde\chi^0_1$ (compressed)	mono-jet	1-3 jets	Yes	36.1	$\tilde q$ 710 GeV	$m(\tilde q)-m(\tilde\chi^0_1)$<5 GeV	1711.03301
	$\tilde g\tilde g,\ \tilde g\to q\bar q\tilde\chi^0_1$	0	2-6 jets	Yes	36.1	$\tilde g$ 2.02 TeV	$m(\tilde\chi^0_1)$<200 GeV	1712.02332
	$\tilde g\tilde g,\ \tilde g\to qq\tilde\chi^\pm_1\to qqW^\pm\tilde\chi^0_1$	0	2-6 jets	Yes	36.1	$\tilde g$ 2.01 TeV	$m(\tilde\chi^0_1)$<200 GeV, $m(\tilde\chi^\pm)=0.5(m(\tilde\chi^0_1)+m(\tilde g))$	1712.02332
	$\tilde g\tilde g,\ \tilde g\to q\bar q(\ell\ell)\tilde\chi^0_1$	$ee,\mu\mu$	2 jets	Yes	14.7	$\tilde g$ 1.7 TeV	$m(\tilde\chi^0_1)$<300 GeV,	1611.05791
	$\tilde g\tilde g,\ \tilde g\to qq(\ell\ell/\nu\nu)\tilde\chi^0_1$	3 e,μ	4 jets	-	36.1	$\tilde g$ 1.87 TeV	$m(\tilde\chi^0_1)$=0 GeV	1706.03731
	$\tilde g\tilde g,\ \tilde g\to qqWZ\tilde\chi^0_1$	0	7-11 jets	Yes	36.1	$\tilde g$ 1.8 TeV	$m(\tilde\chi^0_1)$ <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	$m(\tilde\chi^0_1)$=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	$m(\tilde G)>1.8\times10^{-4}$ eV, $m(\tilde g)=m(\tilde q)$=1.5 TeV	1502.01518
3rd gen. $\tilde g$ med.	$\tilde g\tilde g,\ \tilde g\to b\bar b\tilde\chi^0_1$	0	3 b	Yes	36.1	$\tilde g$ 1.92 TeV	$m(\tilde\chi^0_1)$<600 GeV	1711.01901
	$\tilde g\tilde g,\ \tilde g\to t\bar t\tilde\chi^0_1$	0-1 e,μ	3 b	Yes	36.1	$\tilde g$ 1.97 TeV	$m(\tilde\chi^0_1)$<200 GeV	1711.01901
3rd gen. squarks direct production	$\tilde b_1\tilde b_1,\ \tilde b_1\to b\tilde\chi^0_1$	0	2 b	Yes	36.1	$\tilde b_1$ 950 GeV	$m(\tilde\chi^0_1)$<420 GeV	1708.09266
	$\tilde b_1\tilde b_1,\ \tilde b_1\to t\tilde\chi^\pm_1$	2 e,μ (SS)	1 b	Yes	36.1	$\tilde b_1$ 275-700 GeV	$m(\tilde\chi^0_1)$<200 GeV, $m(\tilde\chi^\pm_1)=m(\tilde\chi^0_1)$+100 GeV	1706.03731
	$\tilde t_1\tilde t_1,\ \tilde t_1\to b\tilde\chi^\pm_1$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde t_1$ 117-170 GeV, 200-720 GeV	$m(\tilde\chi^\pm_1)=2m(\tilde\chi^0_1)$, $m(\tilde\chi^0_1)$=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde t_1\tilde t_1,\ \tilde t_1\to Wb\tilde\chi^0_1$ or $t\tilde\chi^0_1$	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	$m(\tilde\chi^0_1)$=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde t_1\tilde t_1,\ \tilde t_1\to c\tilde\chi^0_1$	0	mono-jet	Yes	36.1	$\tilde t_1$ 90-430 GeV	$m(\tilde t_1)-m(\tilde\chi^0_1)$=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	$m(\tilde\chi^0_1)$>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	$m(\tilde\chi^0_1)$=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	$m(\tilde\chi^0_1)$=0 GeV	1706.03986
EW direct	$\tilde\ell_{L,R}\tilde\ell_{L,R},\ \tilde\ell\to\ell\tilde\chi^0_1$	2 e,μ	0	Yes	36.1	$\tilde\ell$ 90-500 GeV	$m(\tilde\chi^0_1)$=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	$\tilde\chi^\pm_1$ 750 GeV	$m(\tilde\chi^0_1)$=0, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi^\pm_1)+m(\tilde\chi^0_1))$	ATLAS-CONF-2017-039
	$\tilde\chi^\pm_1\tilde\chi^\mp_1/\tilde\chi^0_2,\ \tilde\chi^+_1\to\tilde\tau\nu(\tau\tilde\nu),\ \tilde\chi^0_2\to\tilde\tau\tau(\nu\tilde\nu)$	2 τ	-	Yes	36.1	$\tilde\chi^\pm_1$ 760 GeV	$m(\tilde\chi^0_1)$=0, $m(\tilde\tau,\tilde\nu)=0.5(m(\tilde\chi^\pm_1)+m(\tilde\chi^0_1))$	1708.07875
	$\tilde\chi^\pm_1\tilde\chi^0_2\to\tilde\ell_L\nu\tilde\ell_L\ell(\tilde\nu\nu),\ \ell\tilde\nu\tilde\ell_L\ell(\tilde\nu\nu)$	3 e,μ	0	Yes	36.1	$\tilde\chi^\pm_1,\tilde\chi^0_2$ 1.13 TeV	$m(\tilde\chi^\pm_1)=m(\tilde\chi^0_2)$, $m(\tilde\chi^0_1)$=0, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi^\pm_1)+m(\tilde\chi^0_1))$	ATLAS-CONF-2017-039
	$\tilde\chi^\pm_1\tilde\chi^0_2\to W\tilde\chi^0_1Z\tilde\chi^0_1$	2-3 e,μ	0-2 jets	Yes	36.1	$\tilde\chi^\pm_1,\tilde\chi^0_2$ 580 GeV	$m(\tilde\chi^\pm_1)=m(\tilde\chi^0_2)$, $m(\tilde\chi^0_1)$=0, $\tilde\ell$ decoupled	ATLAS-CONF-2017-039
	$\tilde\chi^\pm_1\tilde\chi^0_2\to W\tilde\chi^0_1h\tilde\chi^0_1,\ h\to b\bar b/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde\chi^\pm_1,\tilde\chi^0_2$ 270 GeV	$m(\tilde\chi^\pm_1)=m(\tilde\chi^0_2)$, $m(\tilde\chi^0_1)$=0, $\tilde\ell$ decoupled	1501.07110
	$\tilde\chi^0_2\tilde\chi^0_3,\ \tilde\chi^0_{2,3}\to\tilde\ell_R\ell$	4 e,μ	0	Yes	20.3	$\tilde\chi^0_{2,3}$ 635 GeV	$m(\tilde\chi^0_2)=m(\tilde\chi^0_3)$, $m(\tilde\chi^0_1)$=0, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi^0_2)+m(\tilde\chi^0_1))$	1405.5086
	GGM (wino NLSP) weak prod., $\tilde\chi^0_1\to\gamma\tilde G$	1 e,μ + γ	-	Yes	20.3	$\tilde W$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde\chi^0_1\to\gamma\tilde G$	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 $\tilde\chi^\pm_1$	Disapp. trk	1 jet	Yes	36.1	$\tilde\chi^\pm_1$ 460 GeV	$m(\tilde\chi^\pm_1)-m(\tilde\chi^0_1)$~160 MeV, $\tau(\tilde\chi^\pm_1)$=0.2 ns	1712.02118
	Direct $\tilde\chi^+_1\tilde\chi^-_1$ prod., long-lived $\tilde\chi^\pm_1$	dE/dx trk	-	Yes	18.4	$\tilde\chi^\pm_1$ 495 GeV	$m(\tilde\chi^\pm_1)-m(\tilde\chi^0_1)$~160 MeV, $\tau(\tilde\chi^\pm_1)$<15 ns	1506.05332
	Stable, stopped $\tilde g$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde g$ 850 GeV	$m(\tilde\chi^0_1)$=100 GeV, 10 μs<$\tau(\tilde g)$<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	$m(\tilde\chi^0_1)$=100 GeV, τ>10 ns	1604.04520
	Metastable $\tilde g$ R-hadron, $\tilde g\to qq\tilde\chi^0_1$	displ. vtx	-	Yes	32.8	$\tilde g$ 2.37 TeV	$\tau(\tilde g)$=0.17 ns, $m(\tilde\chi^0_1)$ = 100 GeV	1710.04901
	GMSB, stable $\tilde\tau$, $\tilde\chi^0_1\to\tilde\tau(\tilde e,\tilde\mu)+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde\chi^0_1$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde\chi^0_1\to\gamma\tilde G$, long-lived $\tilde\chi^0_1$	2 γ	-	Yes	20.3	$\tilde\chi^0_1$ 440 GeV	1<$\tau(\tilde\chi^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde g\tilde g,\ \tilde\chi^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde\chi^0_1$ 1.0 TeV	7 <$c\tau(\tilde\chi^0_1)$< 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
	$\tilde\chi^+_1\tilde\chi^-_1,\ \tilde\chi^+_1\to W\tilde\chi^0_1,\ \tilde\chi^0_1\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	$\tilde\chi^\pm_1$ 1.14 TeV	$m(\tilde\chi^0_1)$>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2)	ATLAS-CONF-2016-075
	$\tilde\chi^+_1\tilde\chi^-_1,\ \tilde\chi^+_1\to W\tilde\chi^0_1,\ \tilde\chi^0_1\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde\chi^\pm_1$ 450 GeV	$m(\tilde\chi^0_1)>0.2\times m(\tilde\chi^\pm_1)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde g\tilde g,\ \tilde g\to qq\tilde\chi^0_1,\ \tilde\chi^0_1\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde g$ 1.875 TeV	$m(\tilde\chi^0_1)$=1075 GeV	SUSY-2016-22
	$\tilde g\tilde g,\ \tilde g\to t\bar t\tilde\chi^0_1,\ \tilde\chi^0_1\to qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde g$ 2.1 TeV	$m(\tilde\chi^0_1)$= 1 TeV, $\lambda_{112}\neq0$	1704.08493
	$\tilde g\tilde g,\ \tilde g\to\tilde t_1t,\ \tilde t_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde g$ 1.65 TeV	$m(\tilde t_1)$= 1 TeV, $\lambda_{323}\neq0$	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, $\tilde c\to c\tilde\chi^0_1$	0	2 c	Yes	20.3	$\tilde c$ 510 GeV	$m(\tilde\chi^0_1)$<200 GeV	1501.01325

10^{-1} — 1 — Mass scale [TeV]

*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
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)
Leptoquarks
TeV
RS Gravitons
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
CMS Preliminary
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM Z'(bb)
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Multijet Resonances
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
Large Extra Dimensions
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-
Compositeness

flavour anomalies

the current place where there are hints of something happening

charged current

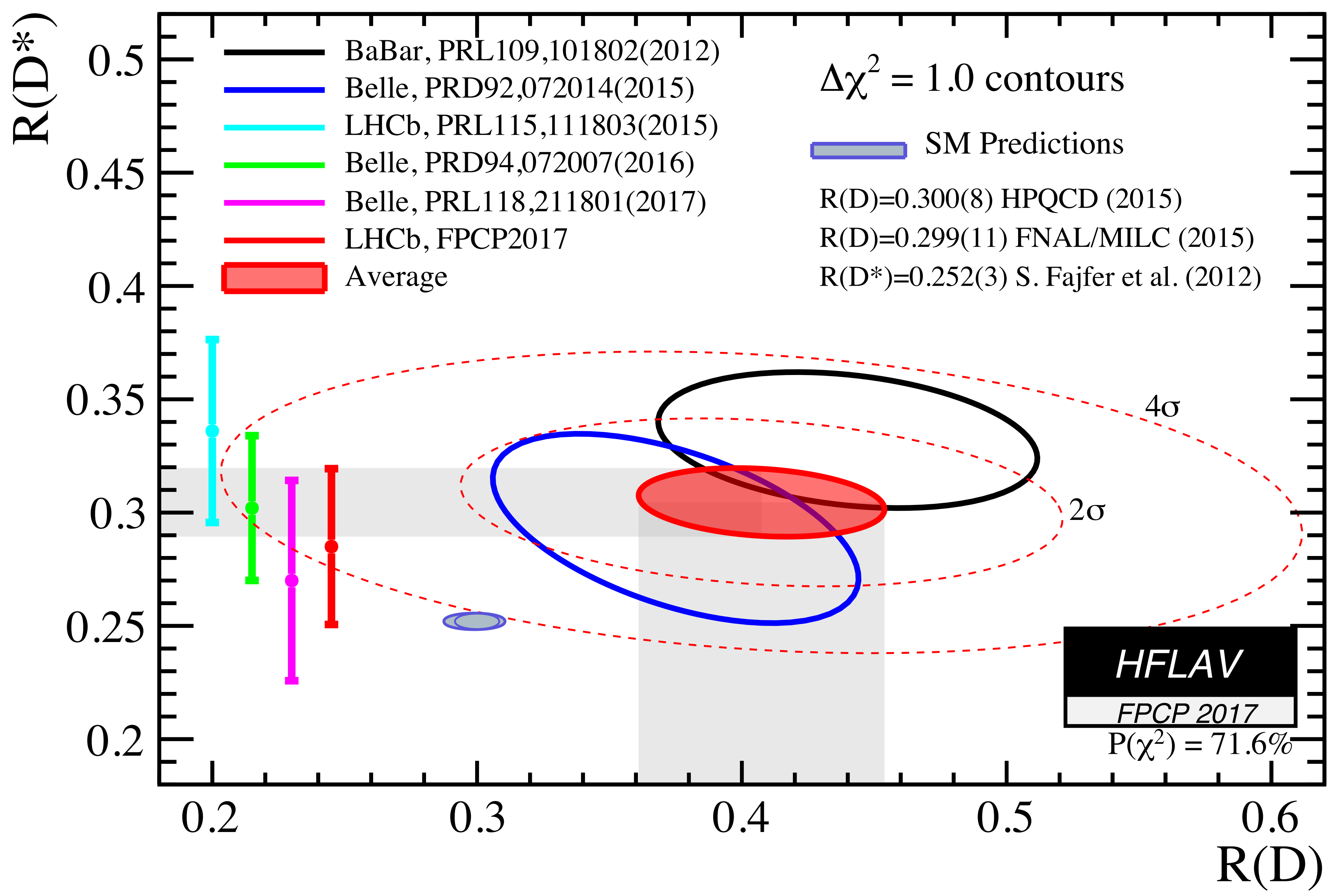
neutral current

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

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

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

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



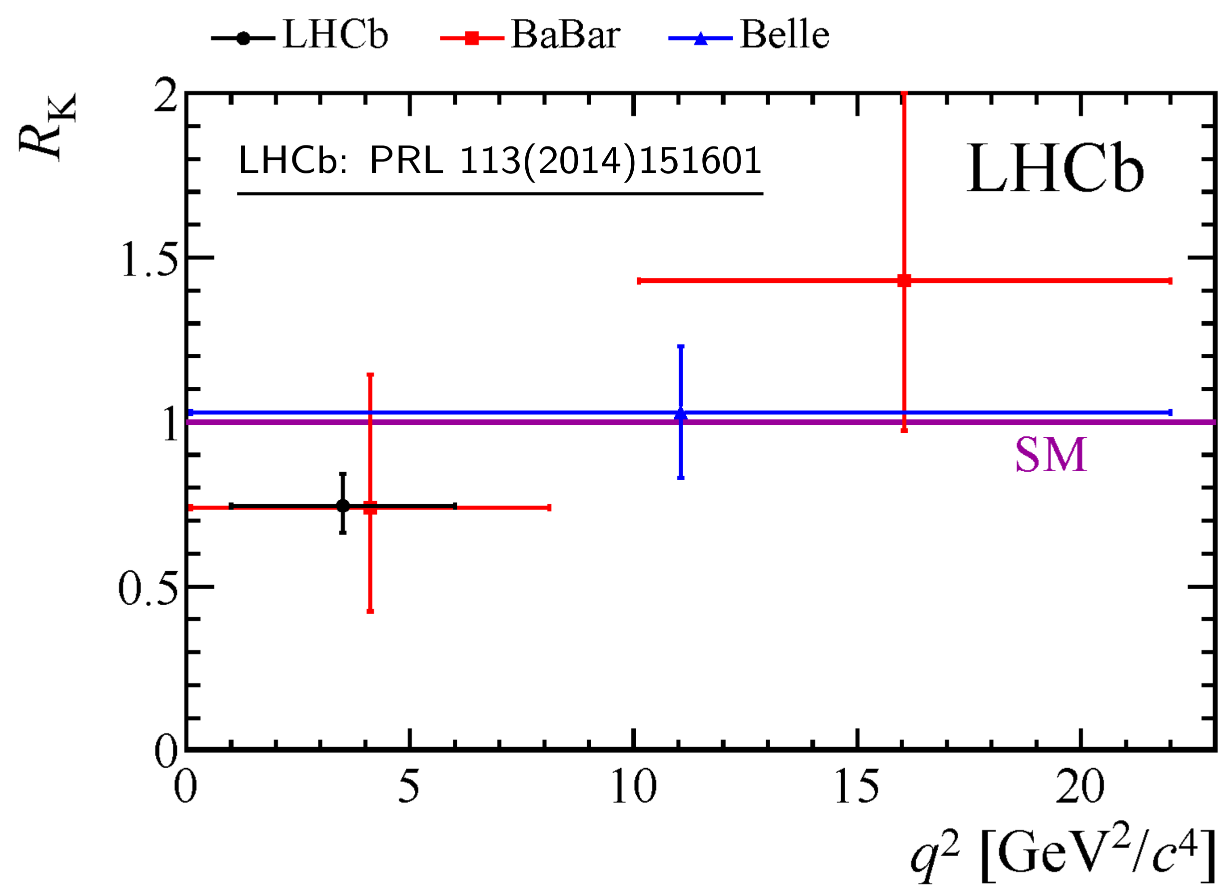
$\Rightarrow$ $R(D^*)$ and $R(D)$ average $\sim 4\ \sigma$ from SM

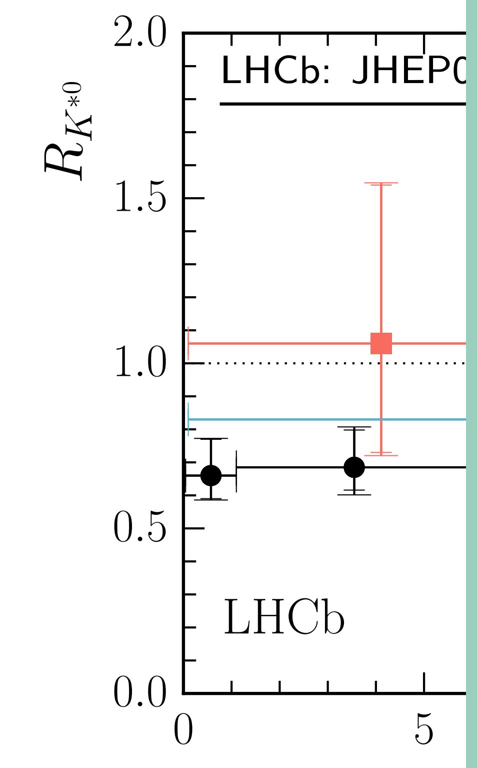
(latest SM computation: JHEP 11 (2017) 061)

$R(K)$ 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

flavor	generic	minimal
$R_{K^{(*)}}$ tree	30 TeV	6 TeV
$R_{K^{(*)}}$ loop	few TeV	0.5 TeV
$R_{D^{(*)}}$ tree	$\sim$ a TeV	0.3 TeV

Hiller @ LHCP'18

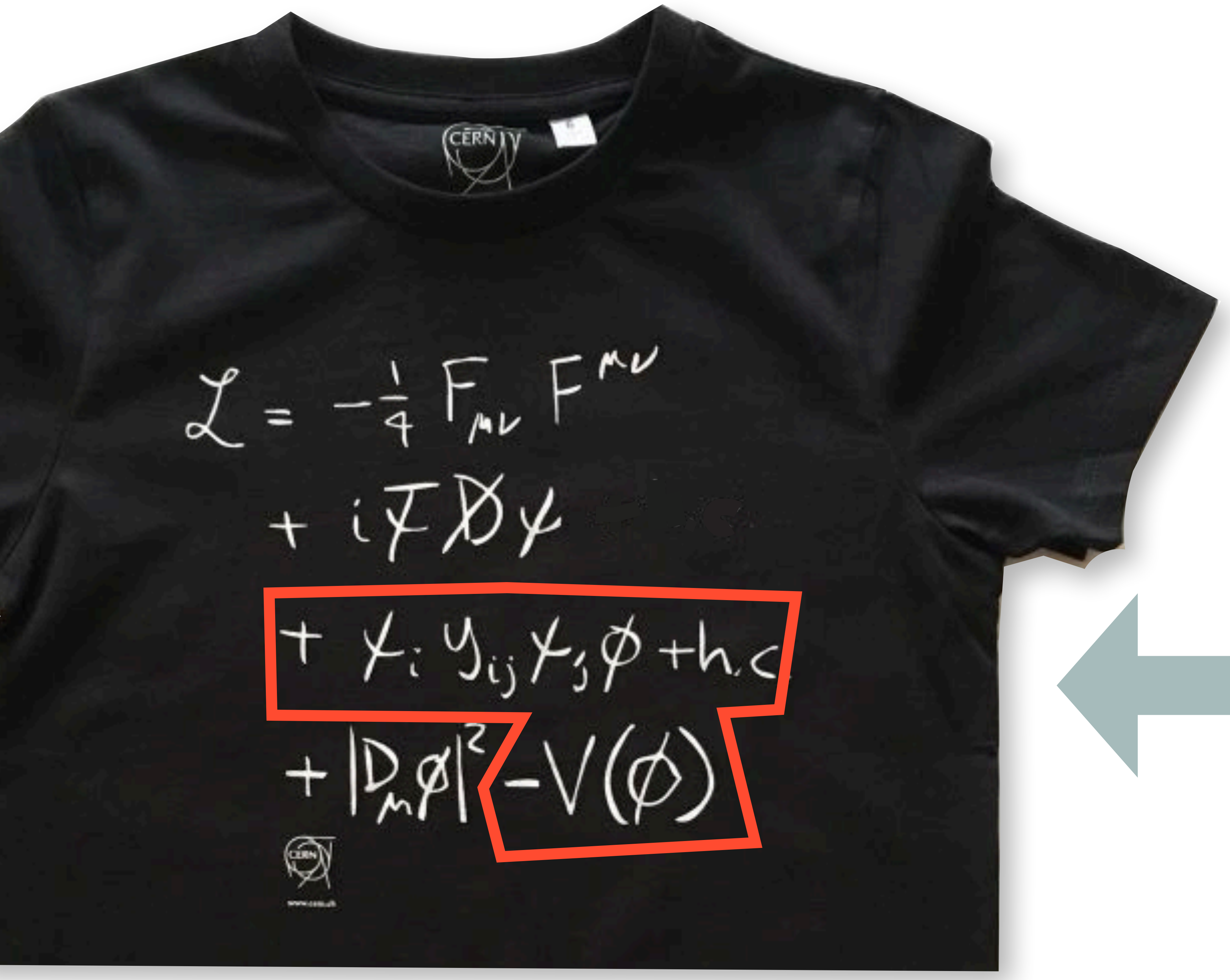
Linking the anomalies is intriuging however not straightforward, lower deviation in $R_{D^{(*)}}$, in particular R_{D^*} more "natural".

- In general the main observable generating tensions is $R(D^{(*)})$, with EW precision tests and B_s-mixing.
- Still work has to be done to find a completely satisfying NP model for the B-anomalies.

Marzocca @ LHCP '18

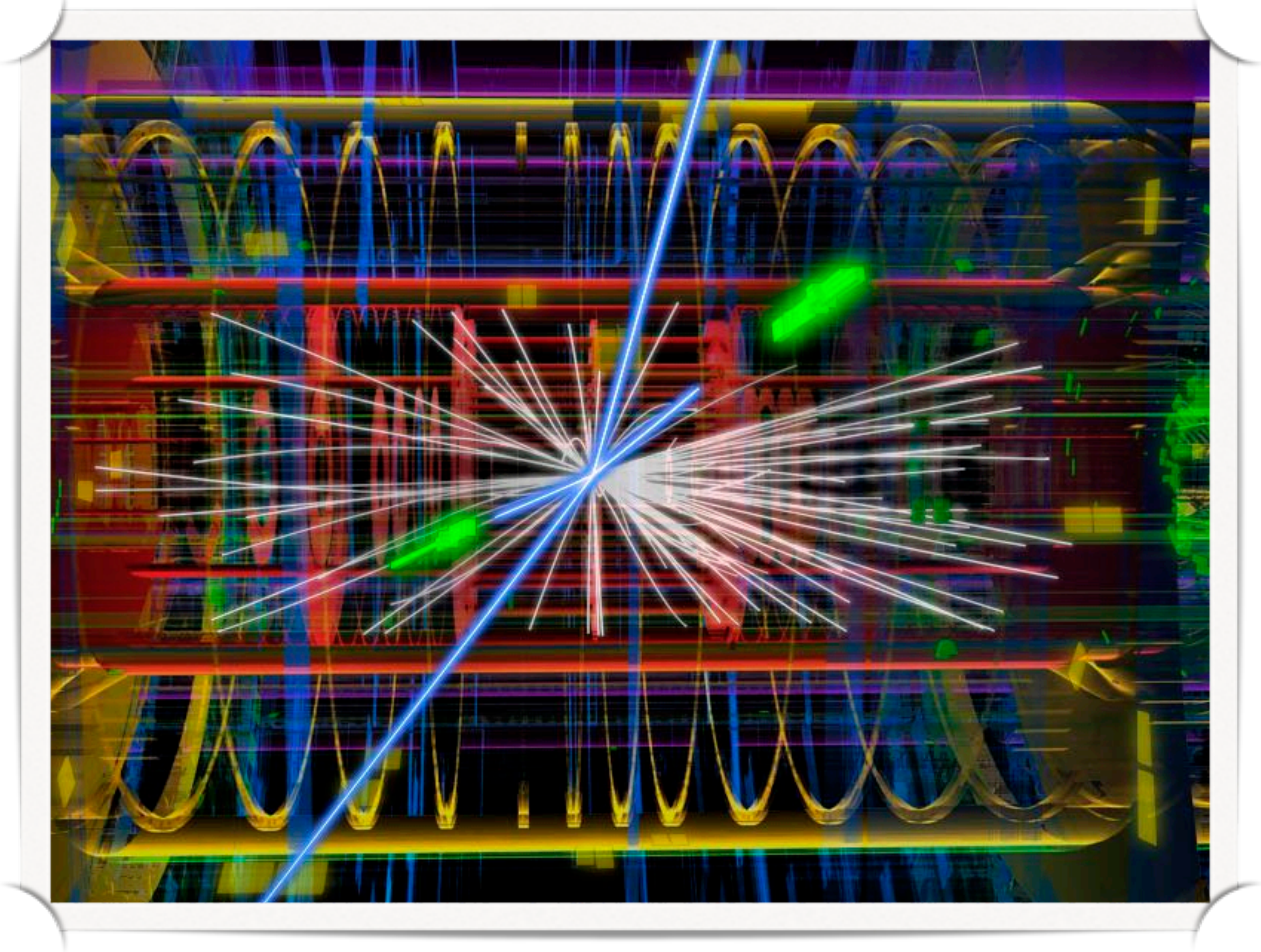
how is all of this made quantitative?

UNDERLYING
THEORY



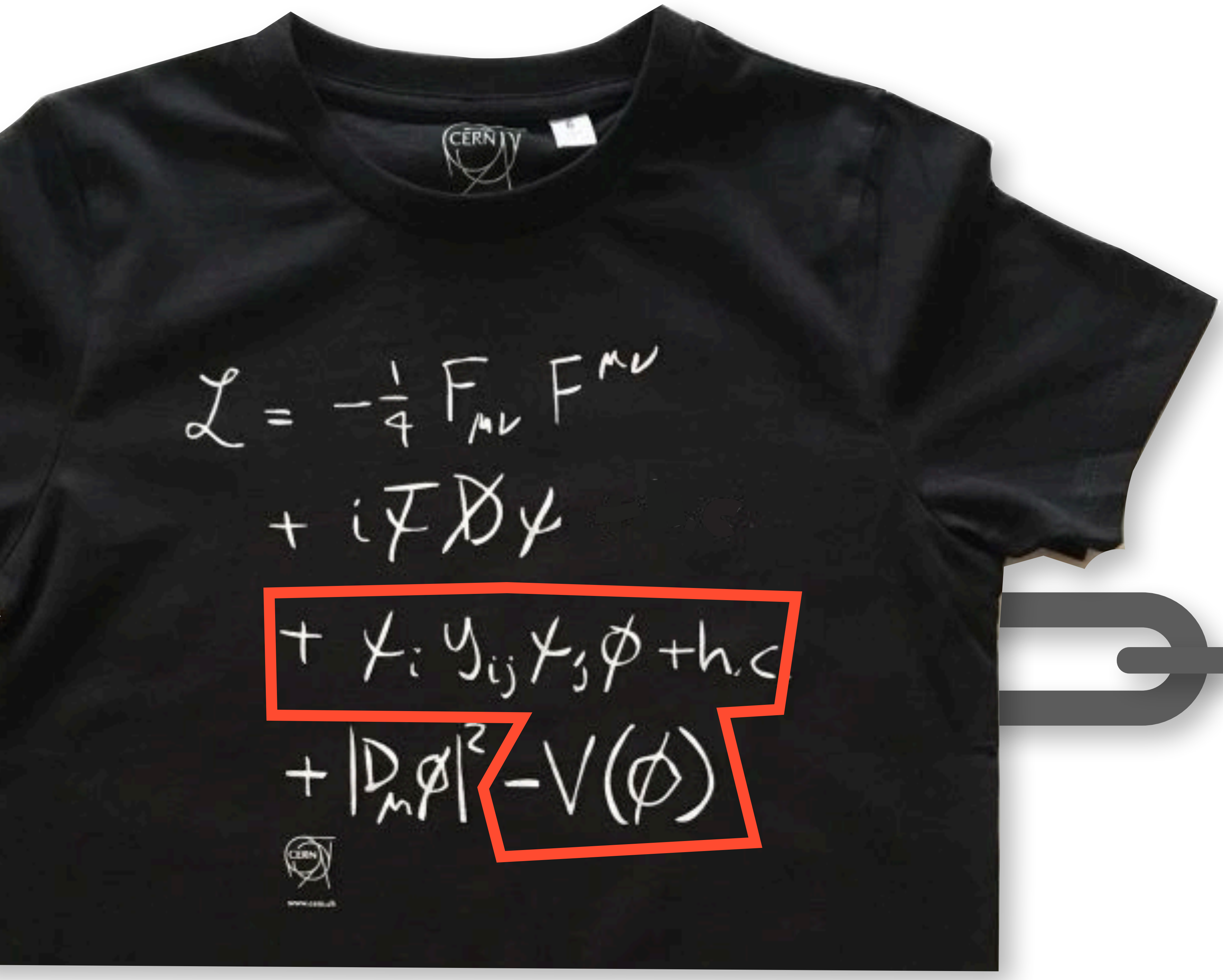
how do you make quantitative connection?

EXPERIMENTAL
DATA

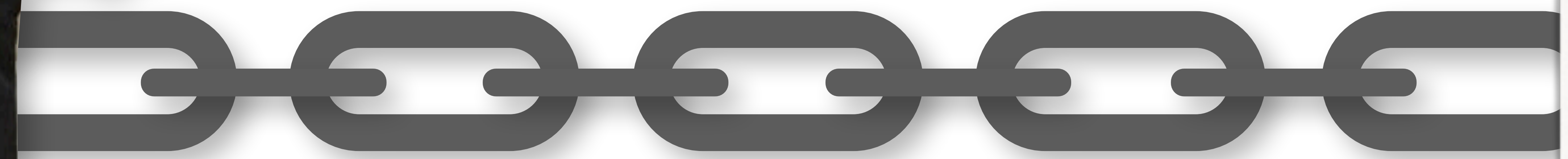


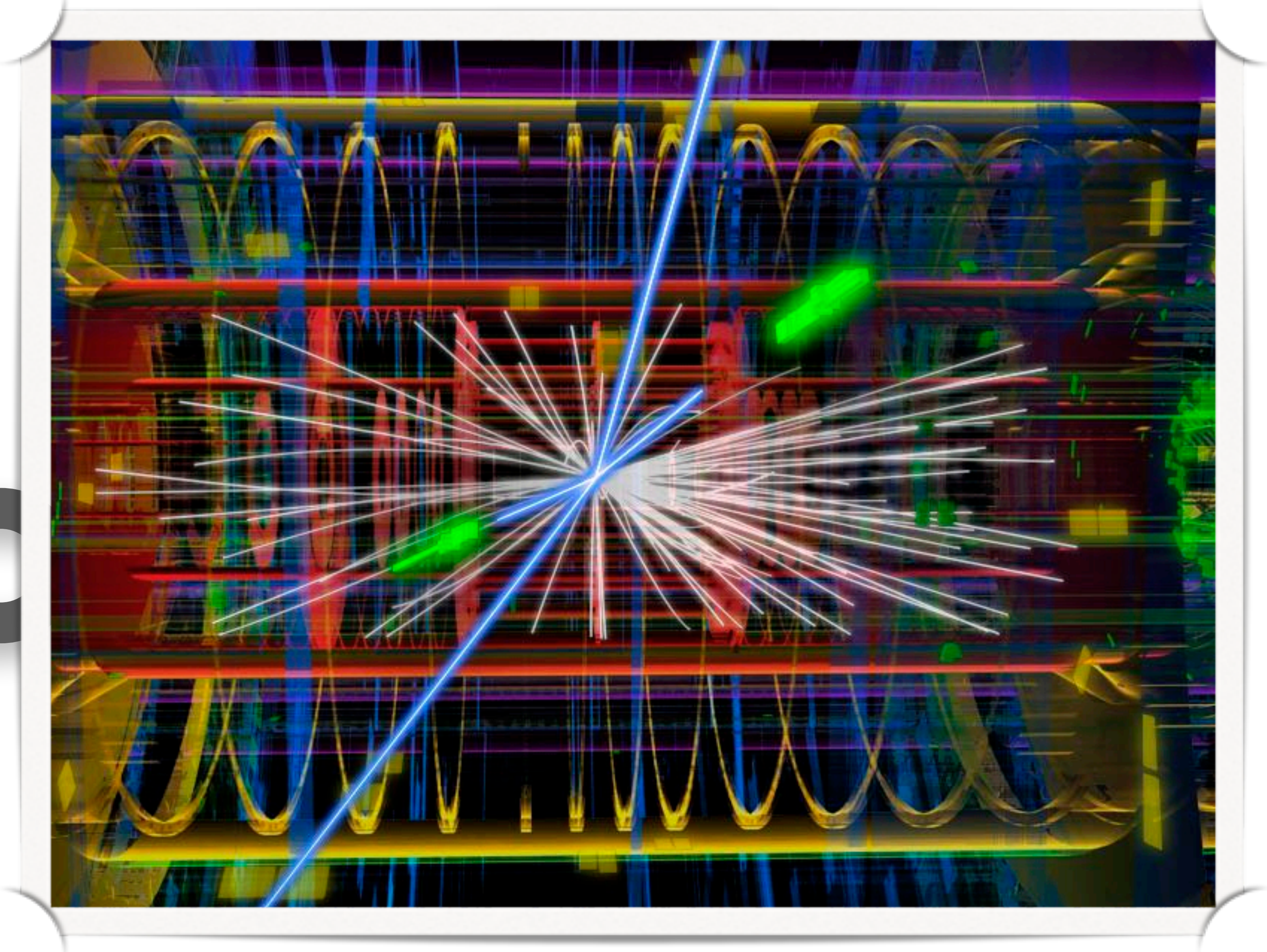
UNDERLYING THEORY

EXPERIMENTAL DATA



how do you make quantitative connection?





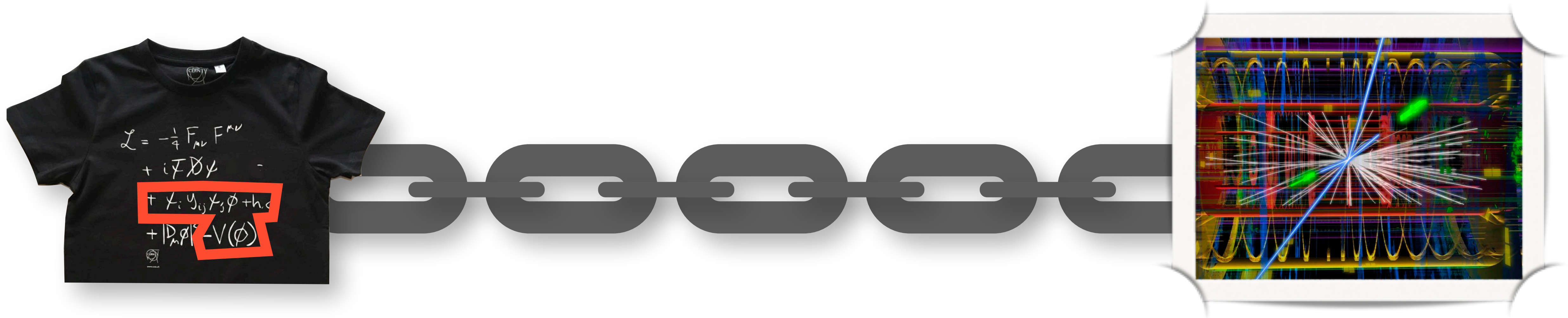
through a chain of experimental and theoretical links

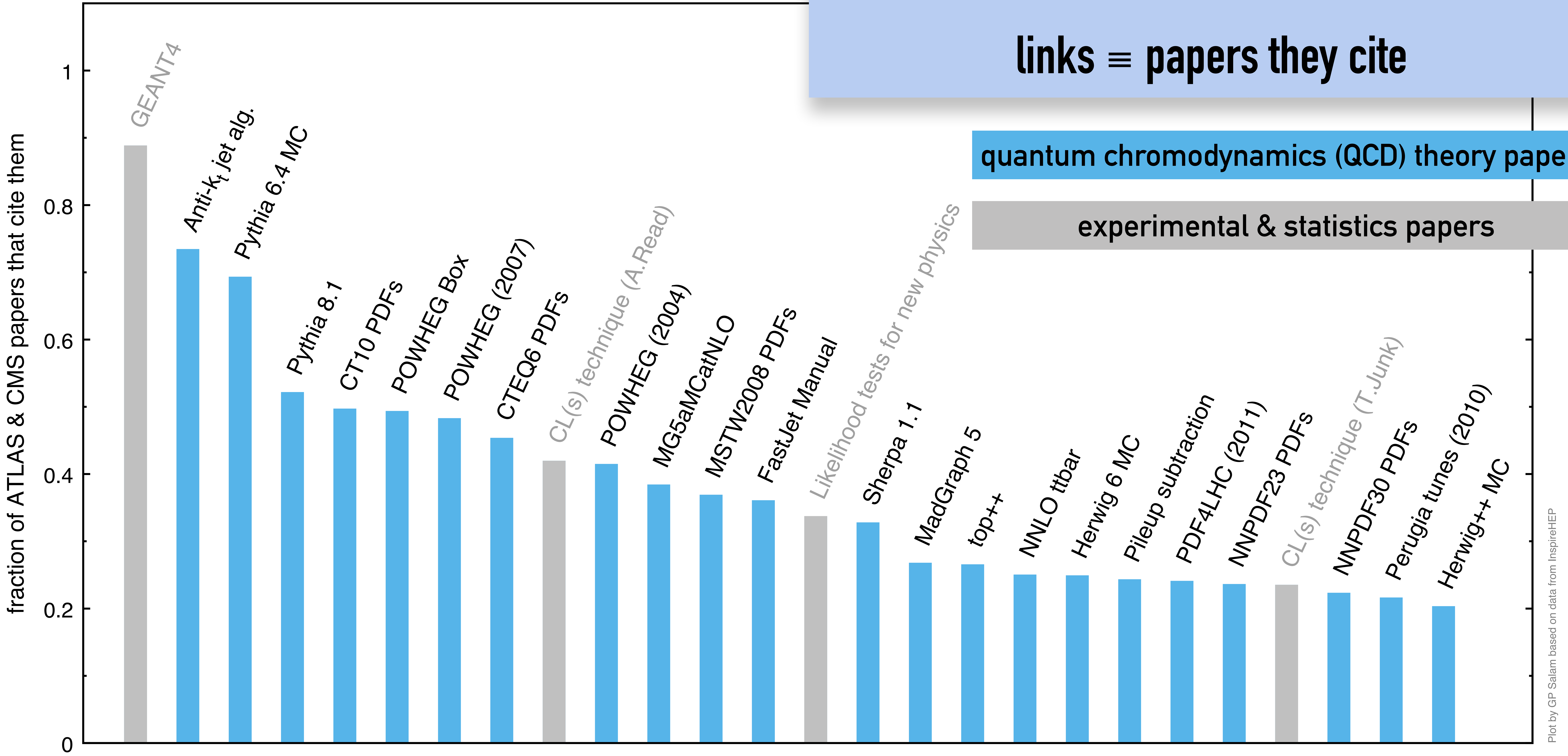
[in particular Quantum Chromodynamics (QCD)]

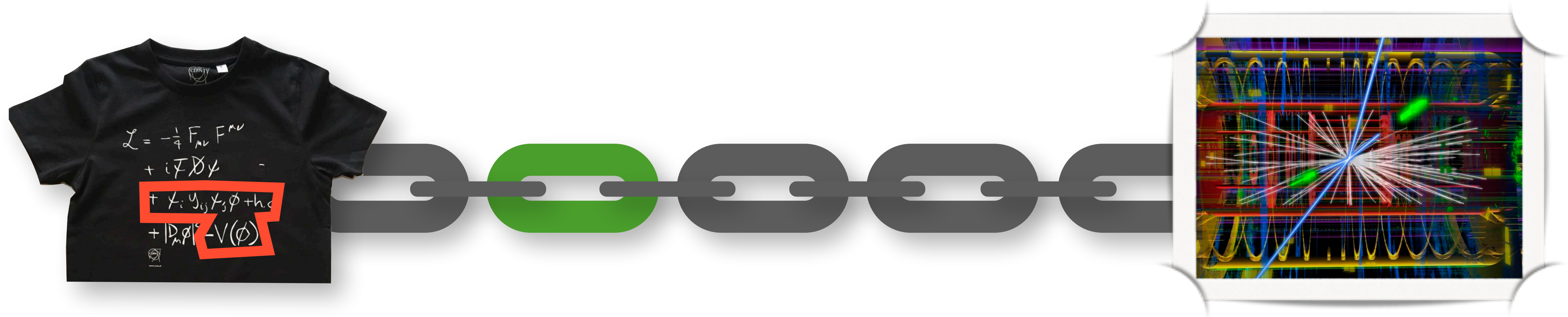
What are the links?

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

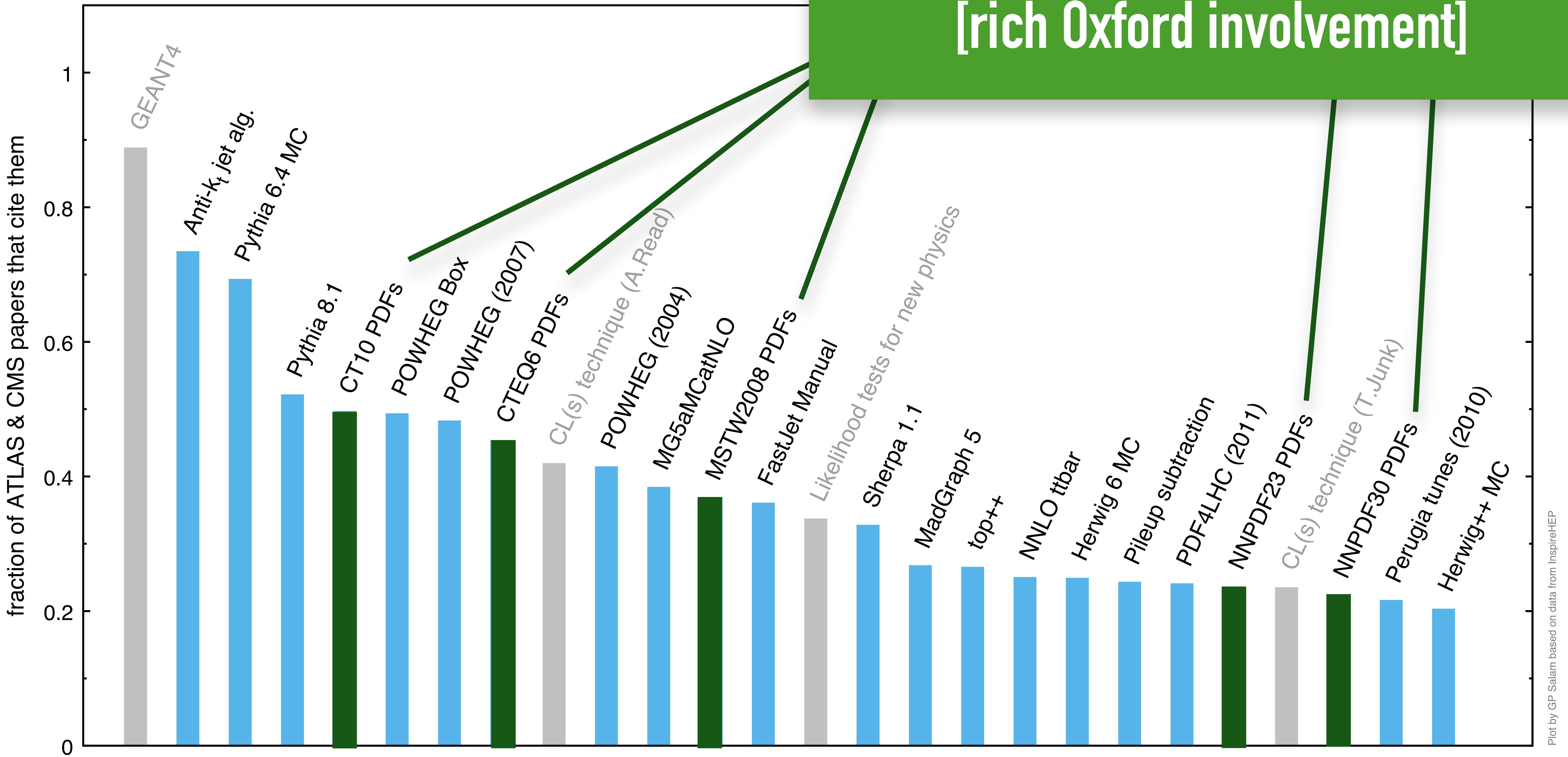
links ≡ papers they cite

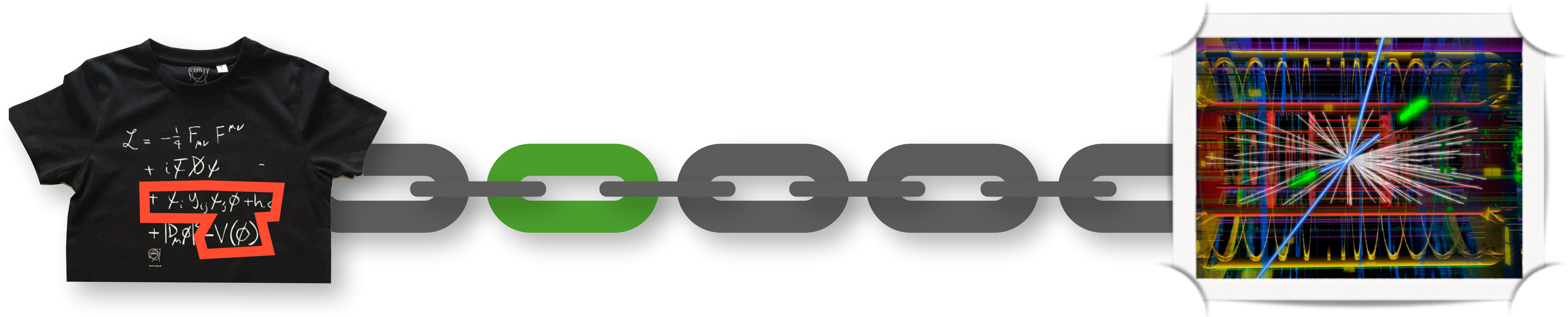




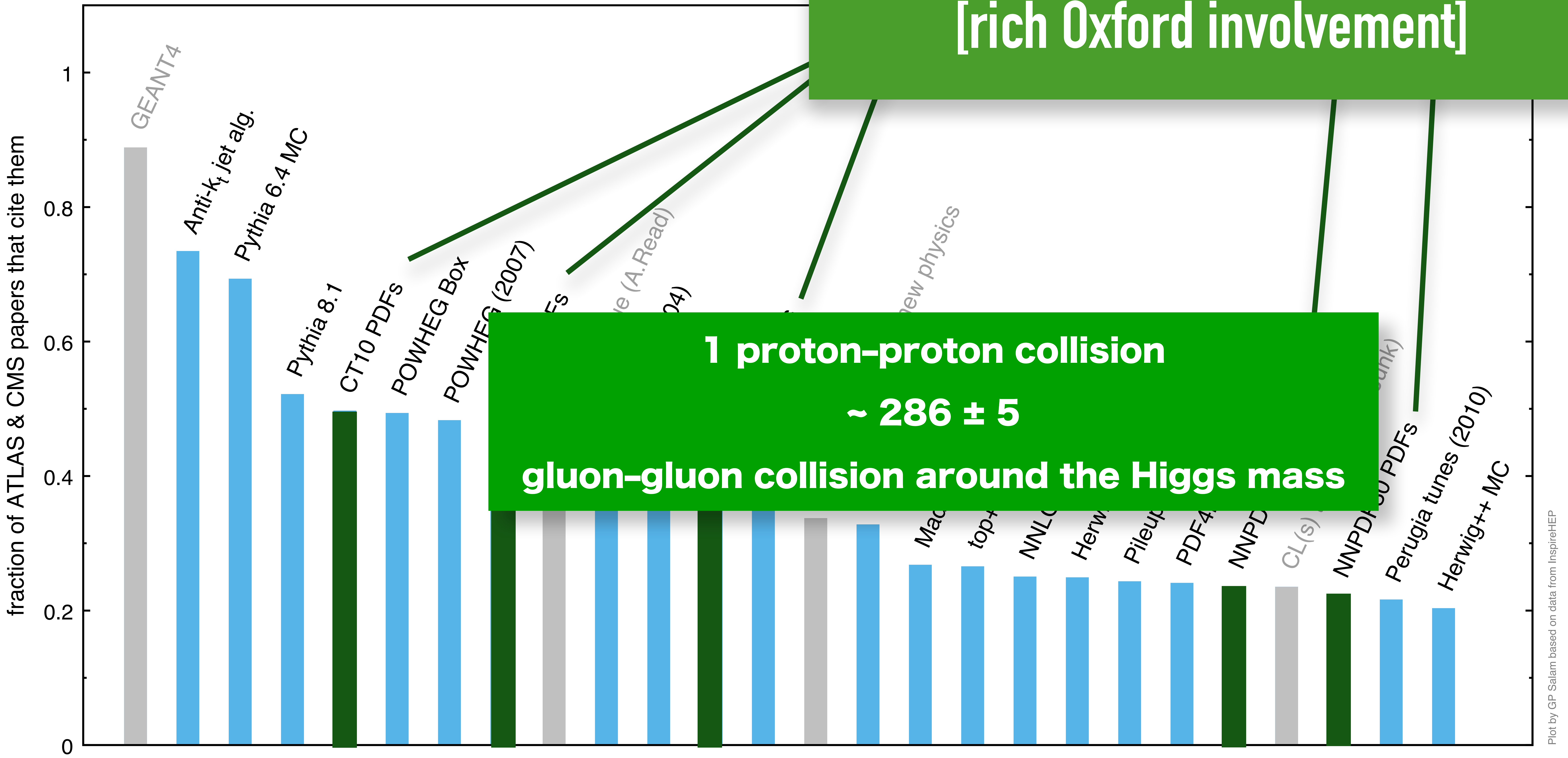


knowing what goes into a collision i.e. proton structure [rich Oxford involvement]

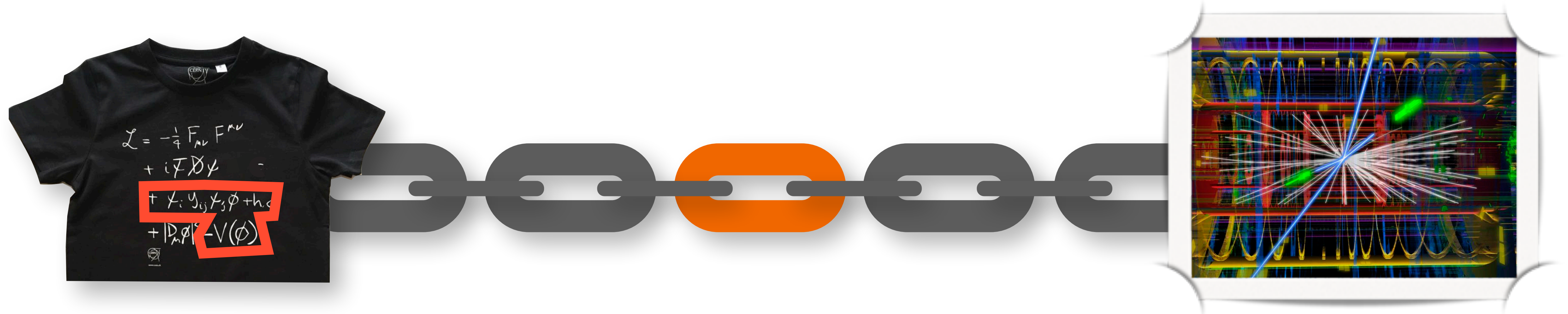




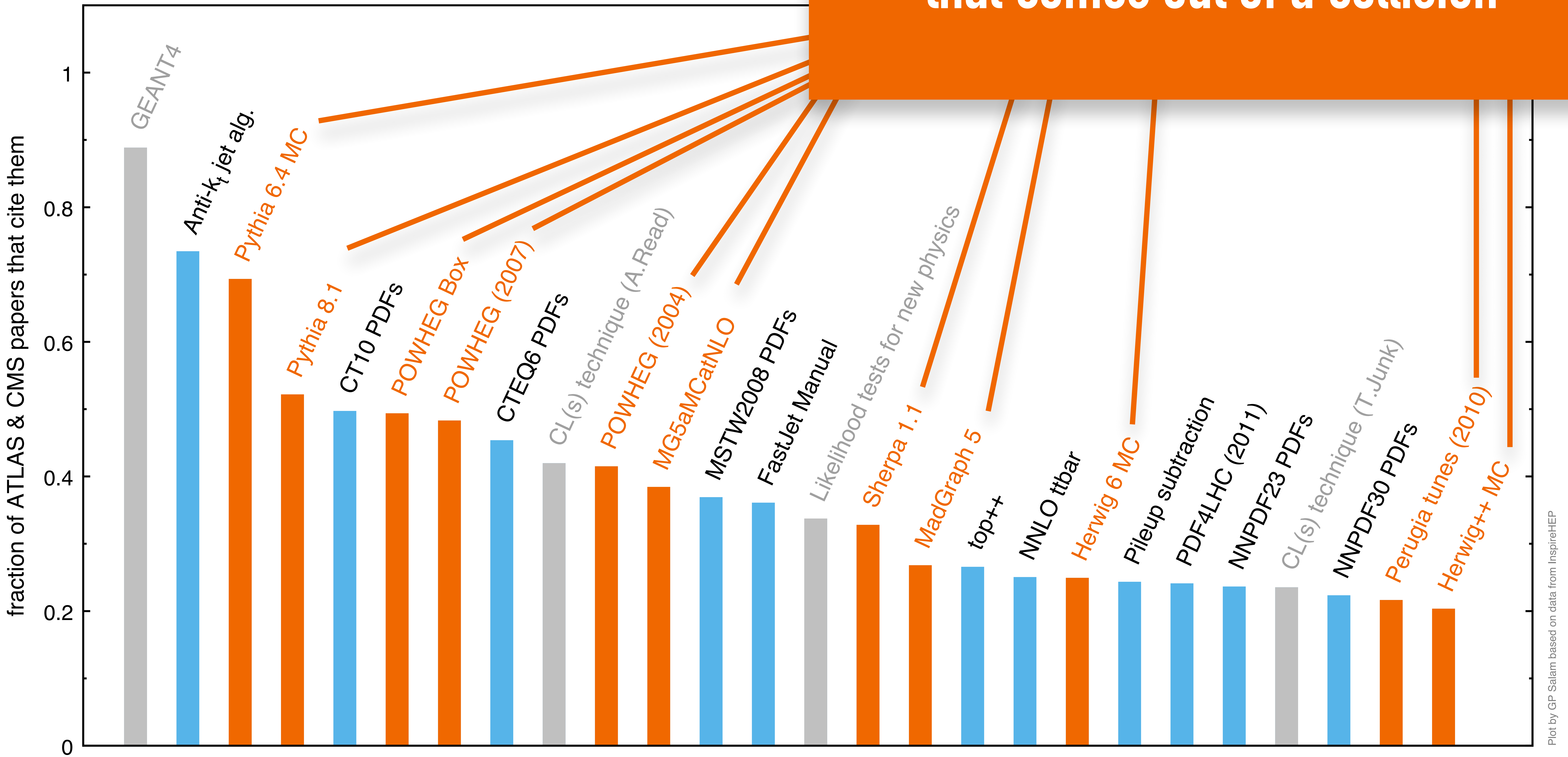
knowing what goes into a collision
i.e. proton structure
[rich Oxford involvement]

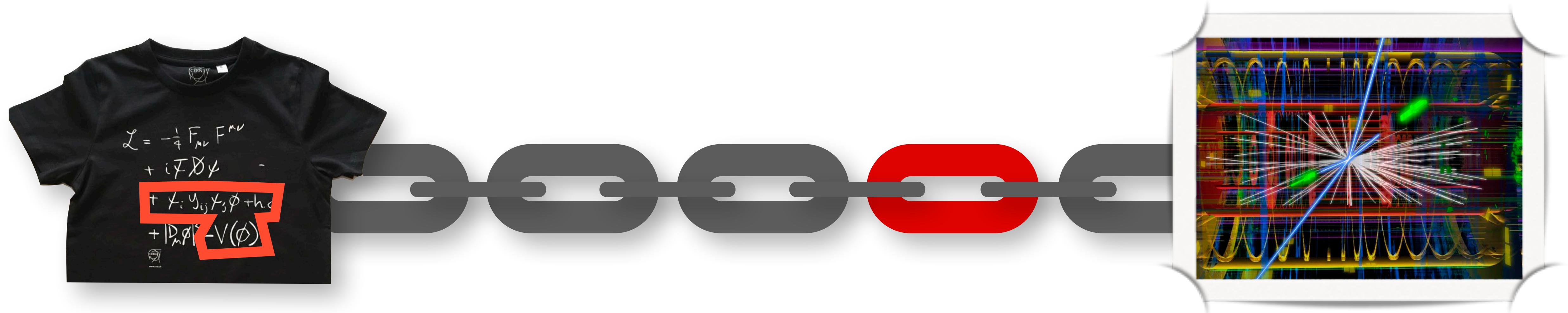


1 proton-proton collision
~ 286 ± 5
gluon-gluon collision around the Higgs mass

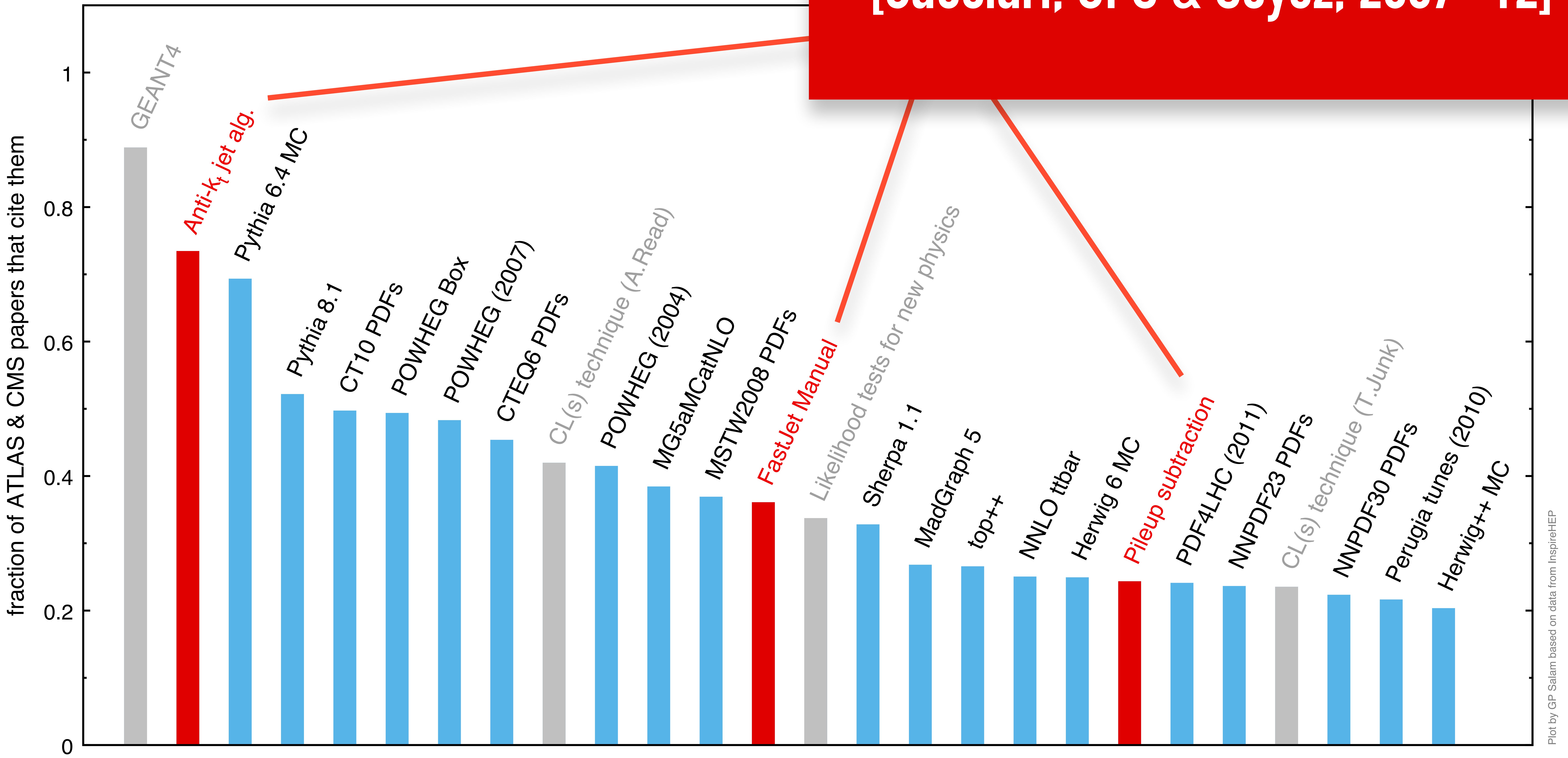


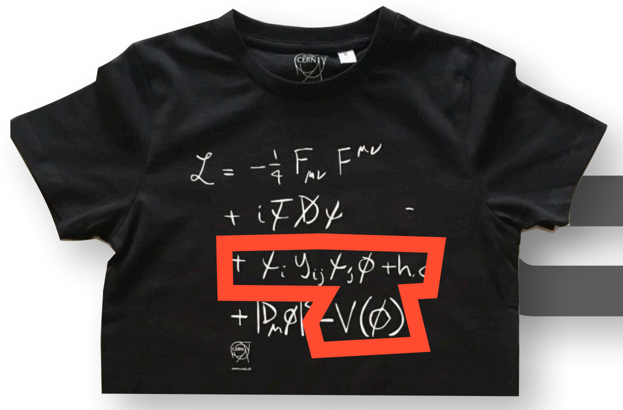
predicting full particle structure that comes out of a collision

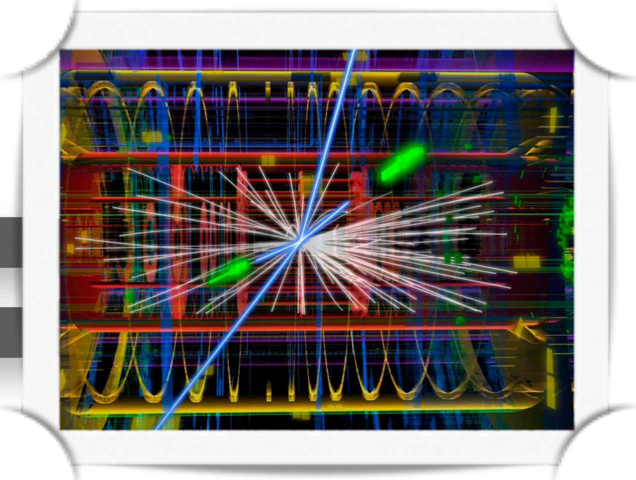




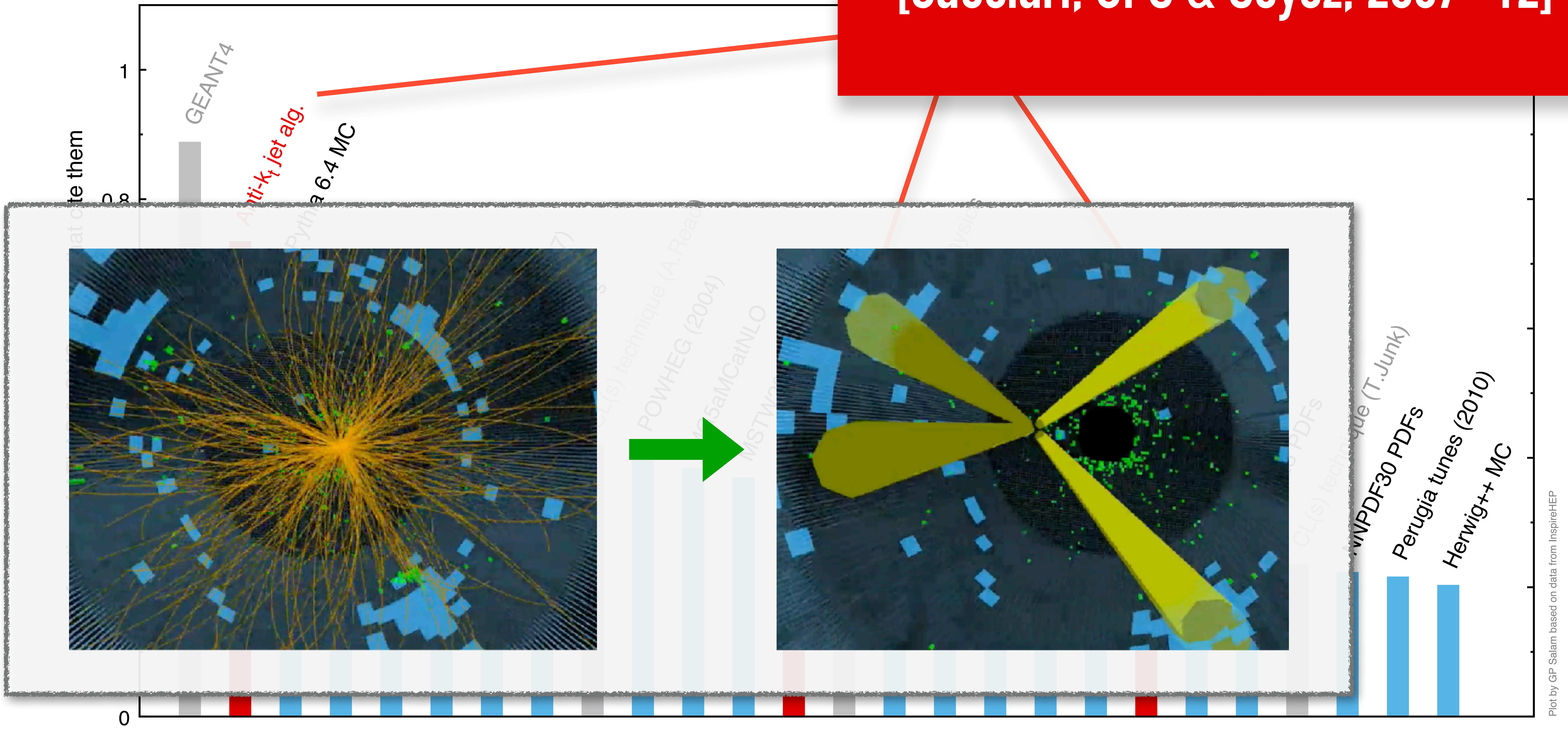
organising event information ("jets") [Cacciari, GPS & Soyez, 2007—12]







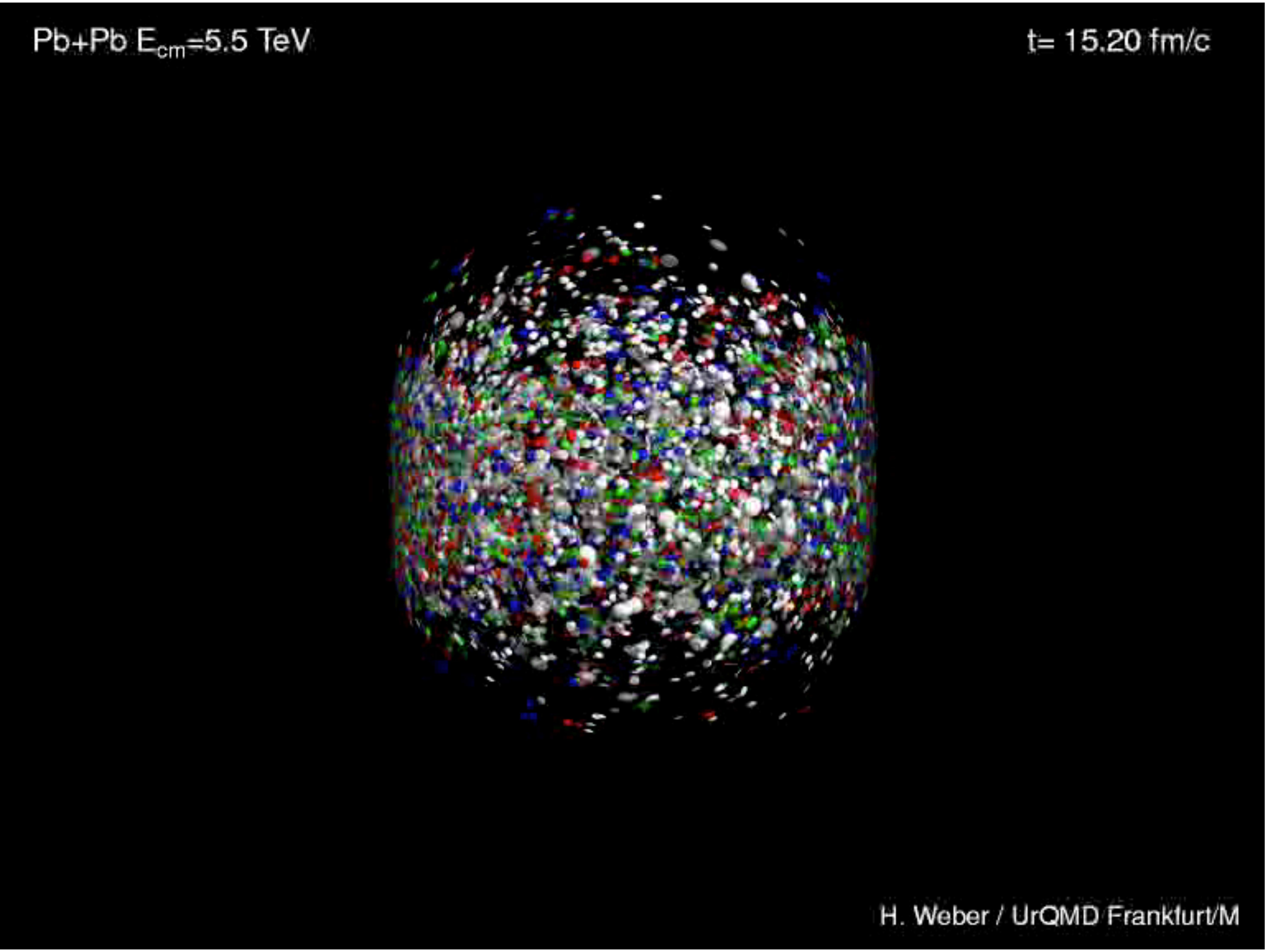
organising event information ("jets") [Cacciari, GPS & Soyez, 2007–12]



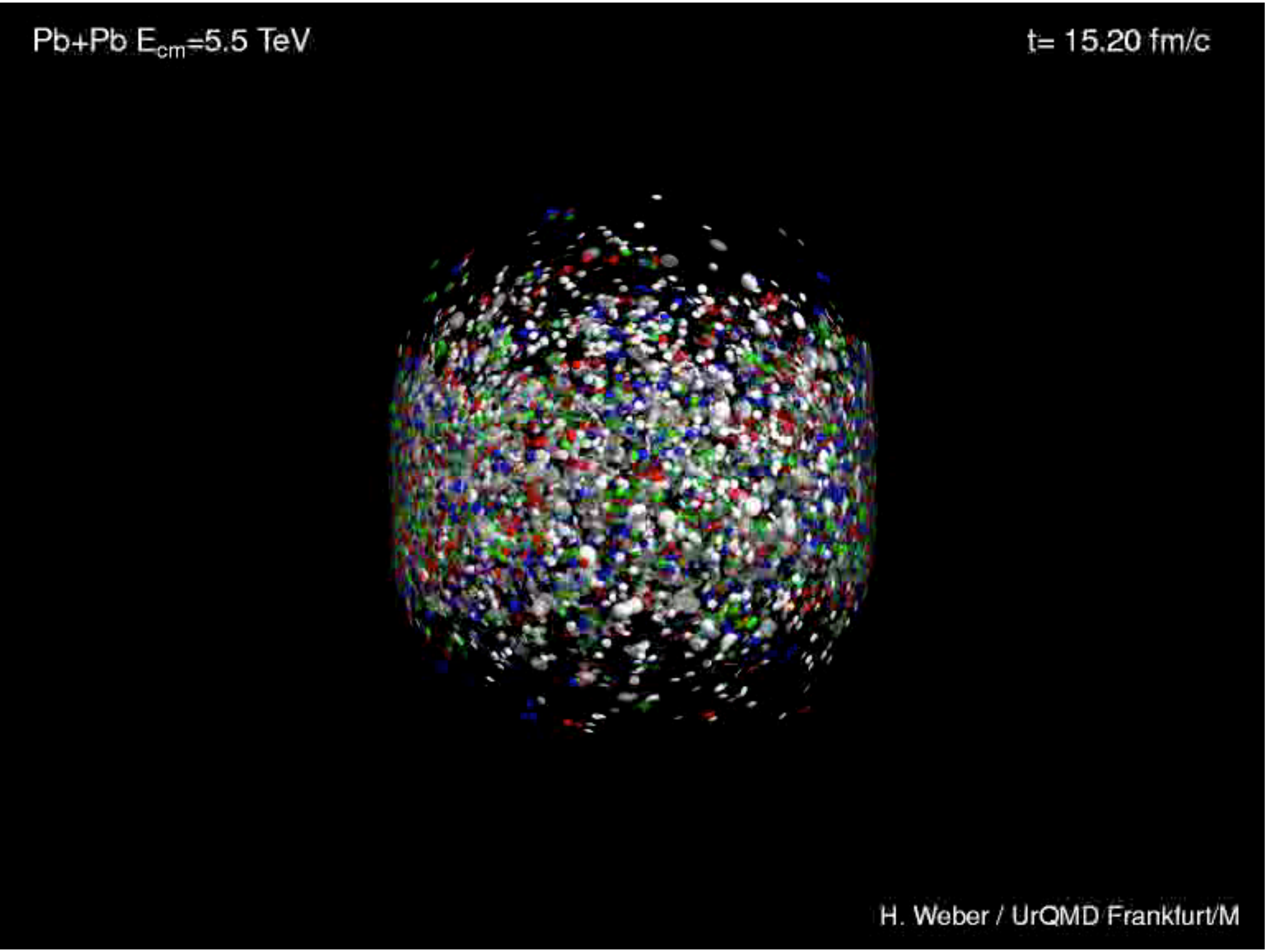
heavy-ion collisions

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
$\sim 0.3 - 10$ fm/c
$\sim 1 - 30 \times 10^{-24}$ s



Hot (5×10^{12}K), dense system, which evolves on timescales

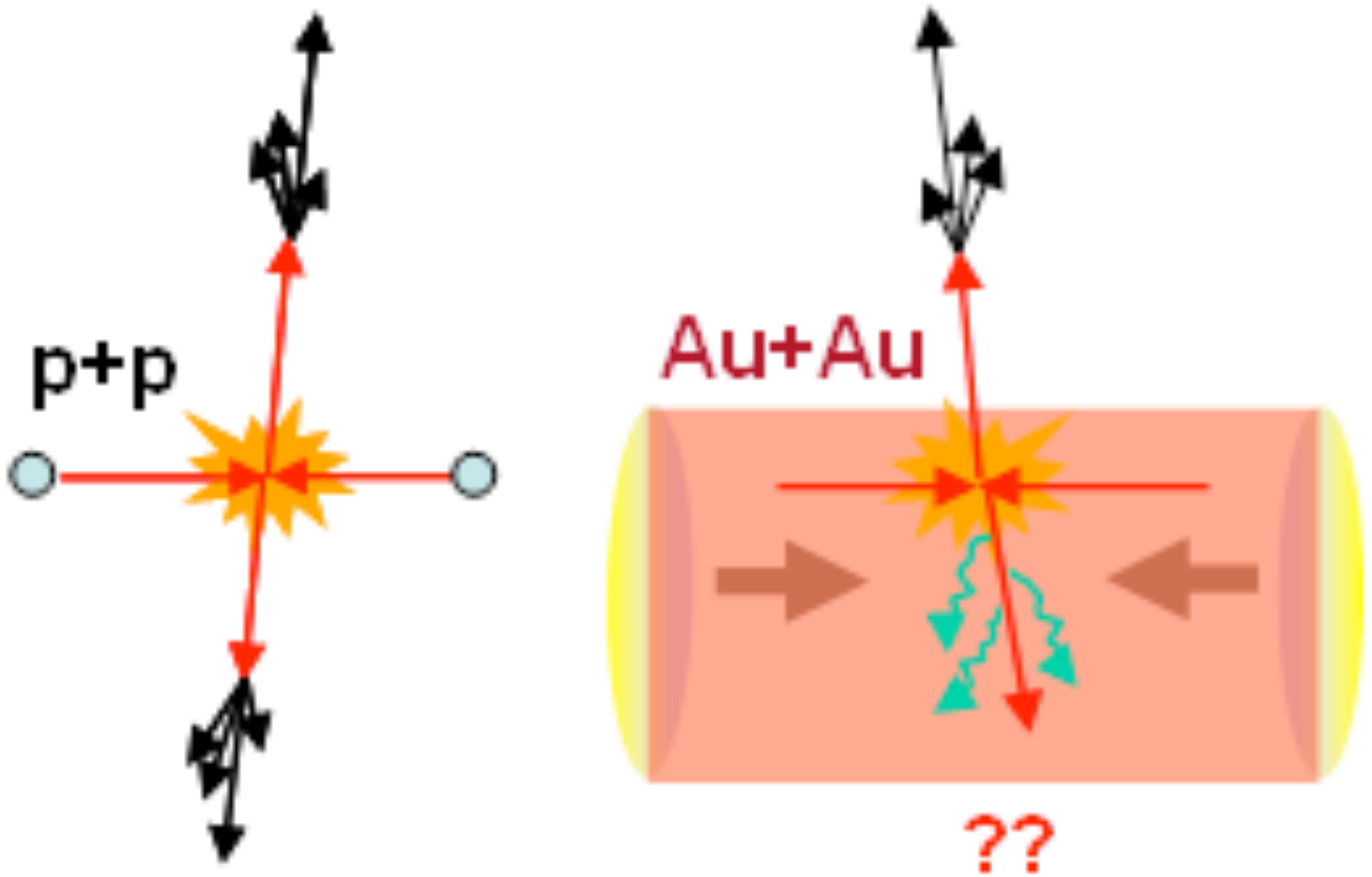
$\sim$0.3 – 10 fm/c

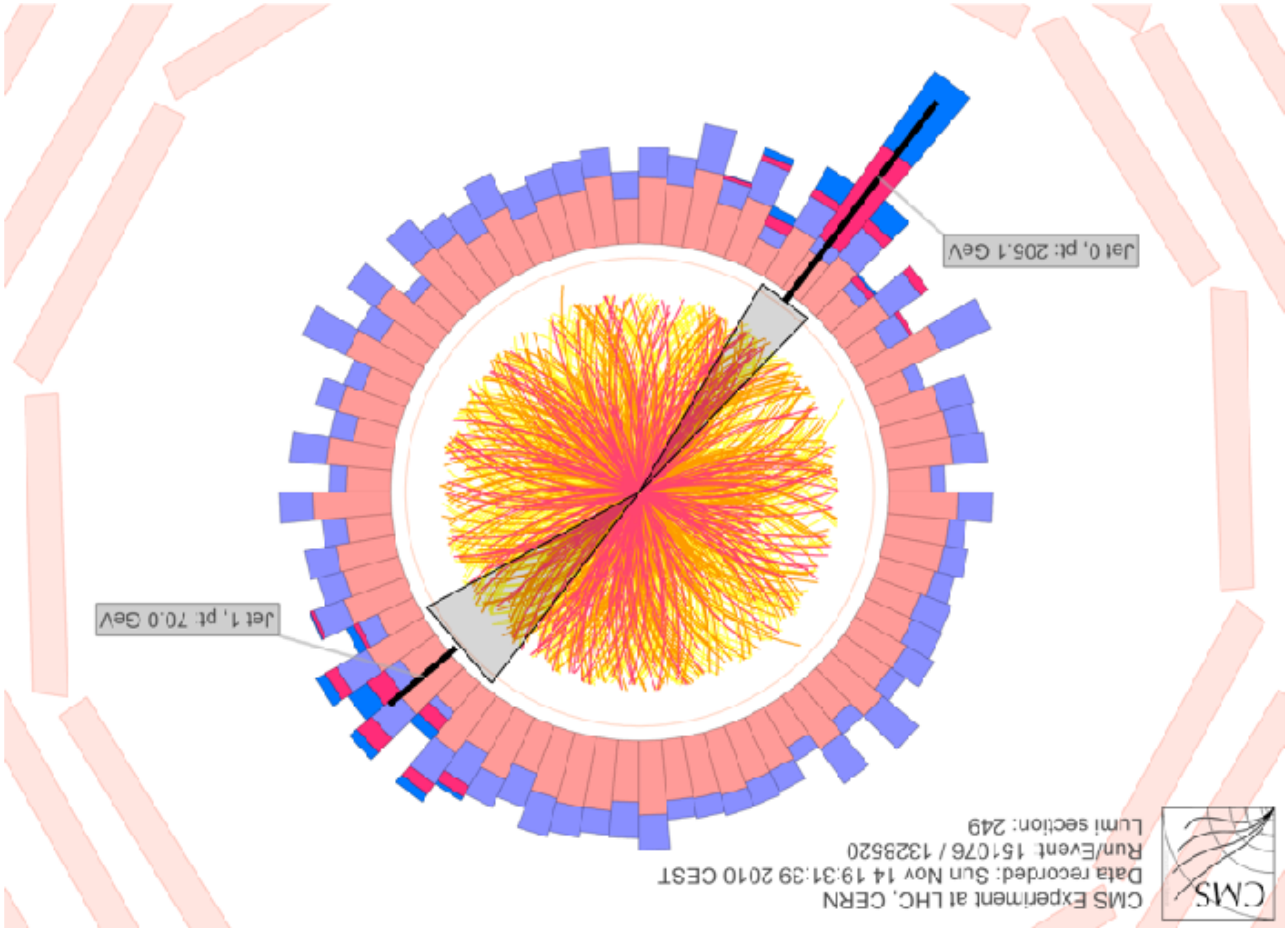
$\sim 1 - 30 \times 10^{-24}$ s

a key probe of the medium: jet quenching

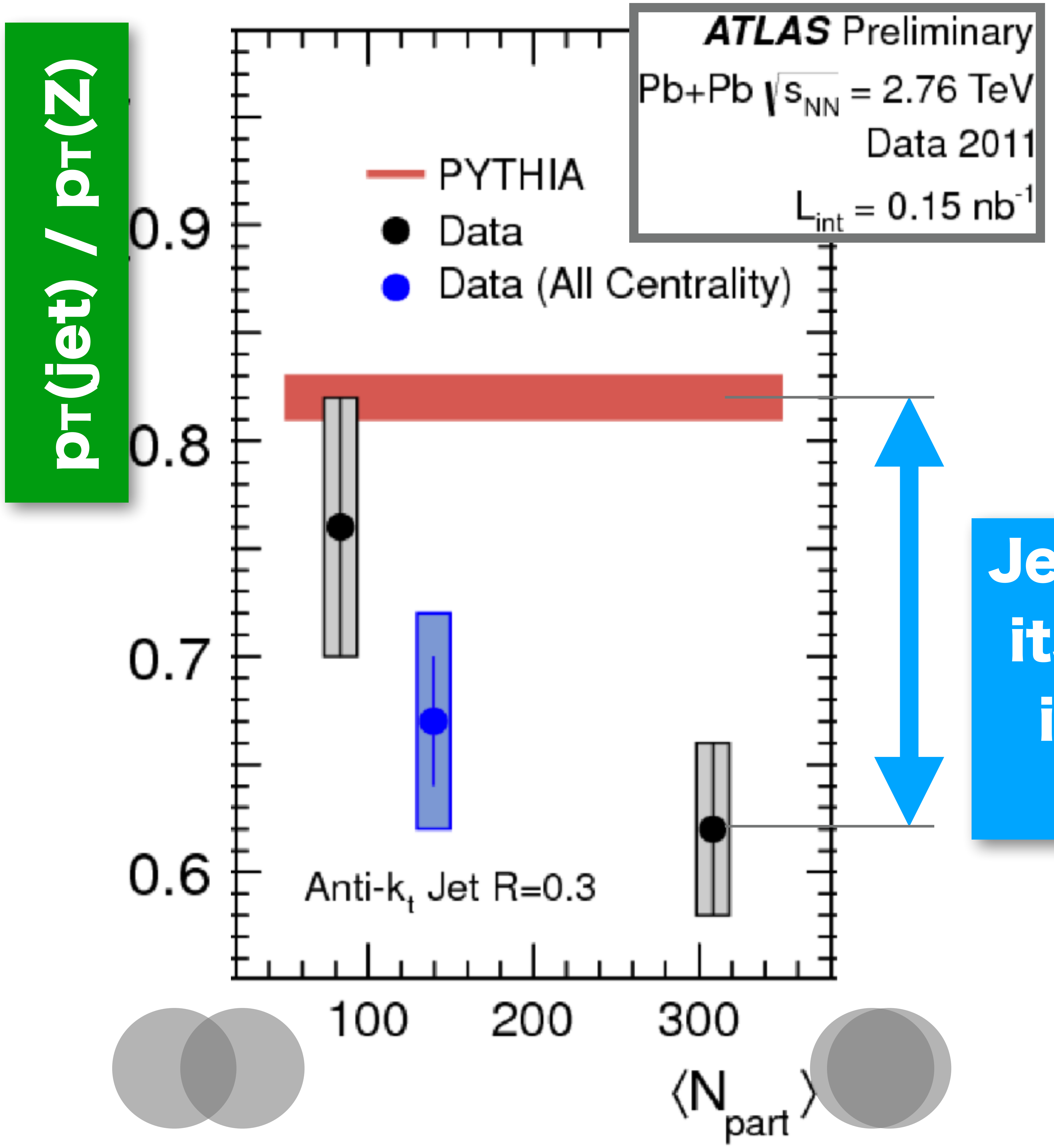
As a parton goes through the quark-gluon plasma, it loses energy.

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

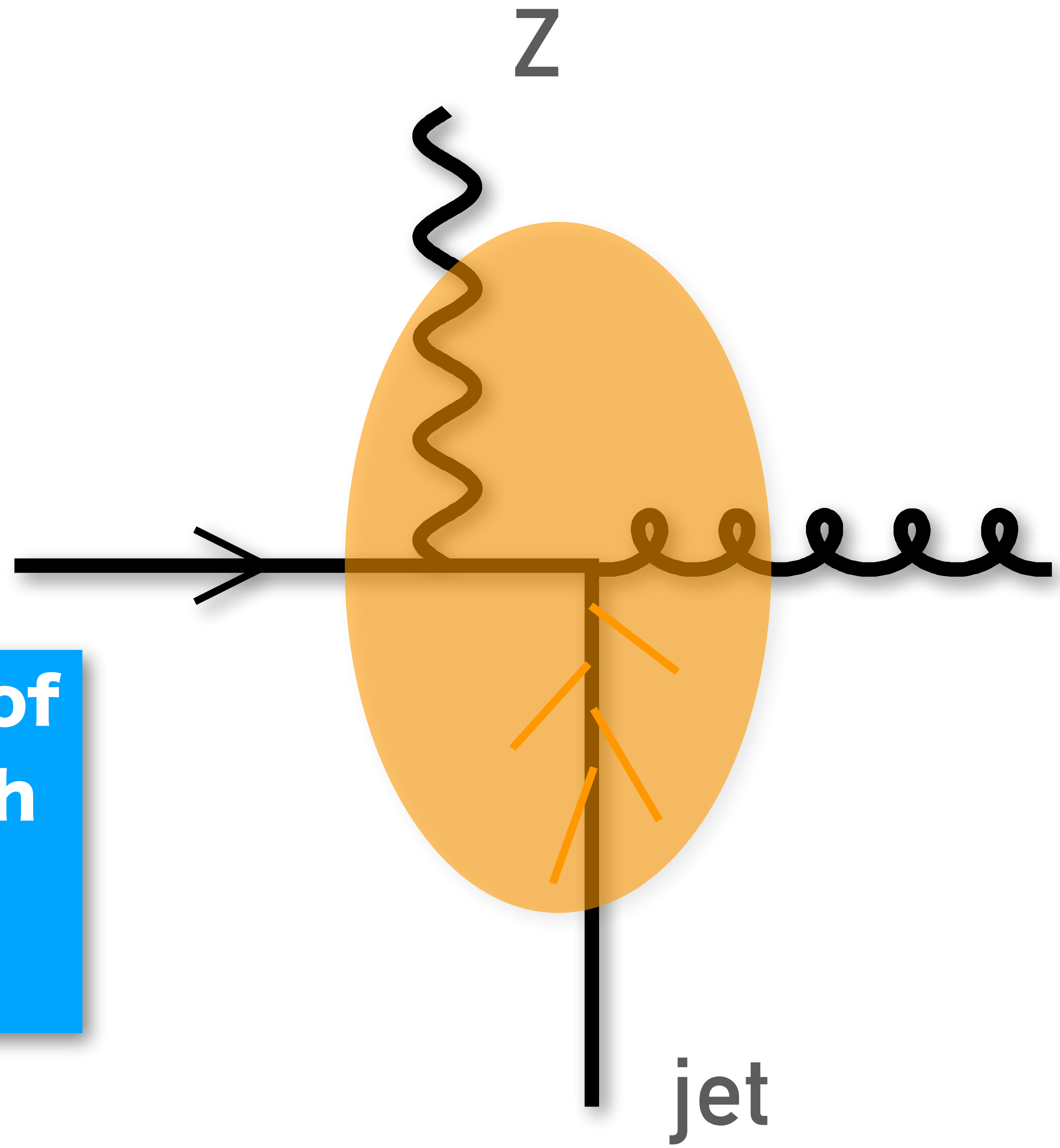




magnitude of effects? Look at jet recoiling against a Z boson



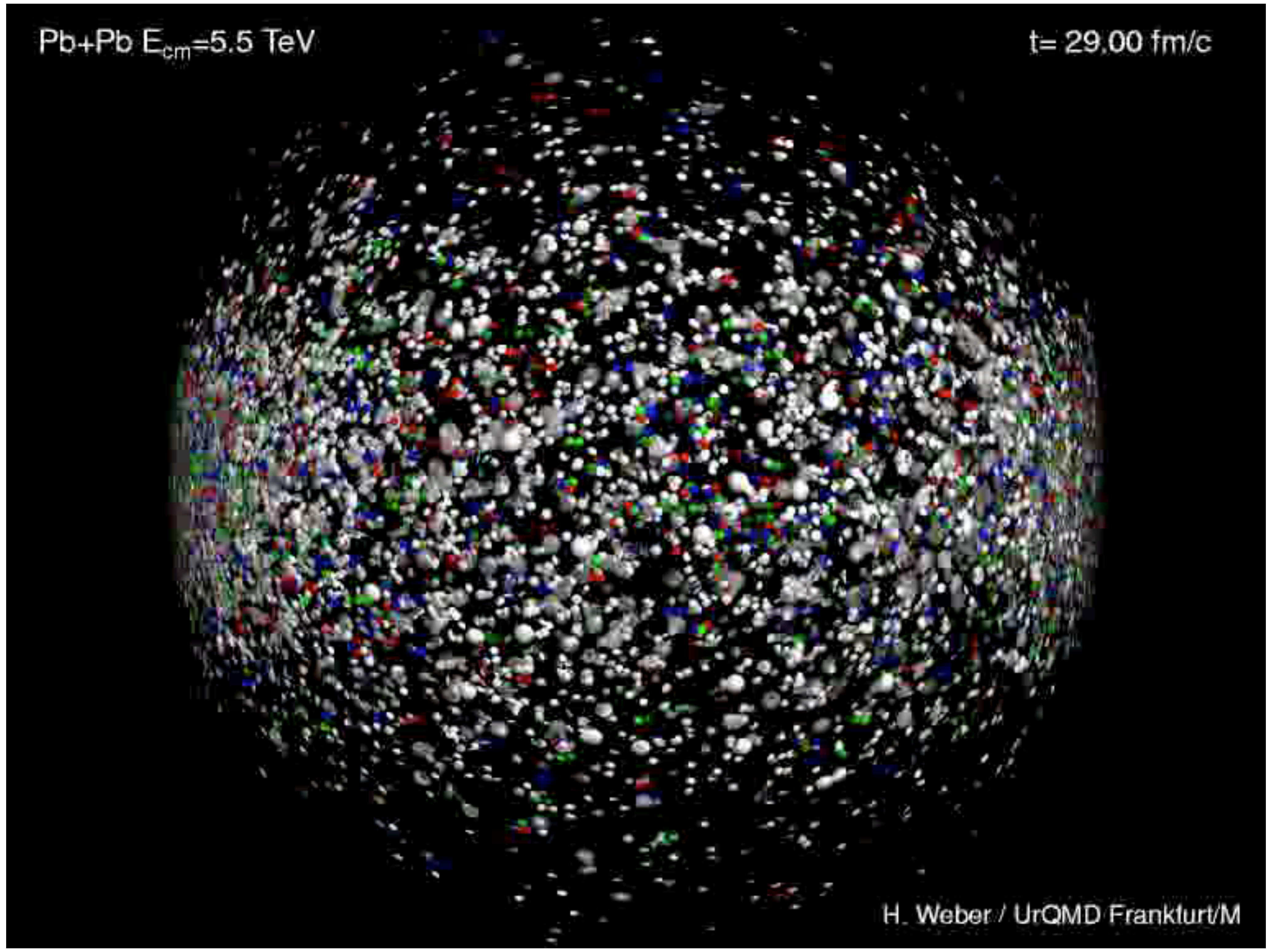
Jet loses 10-20% of its energy through interactions with the medium

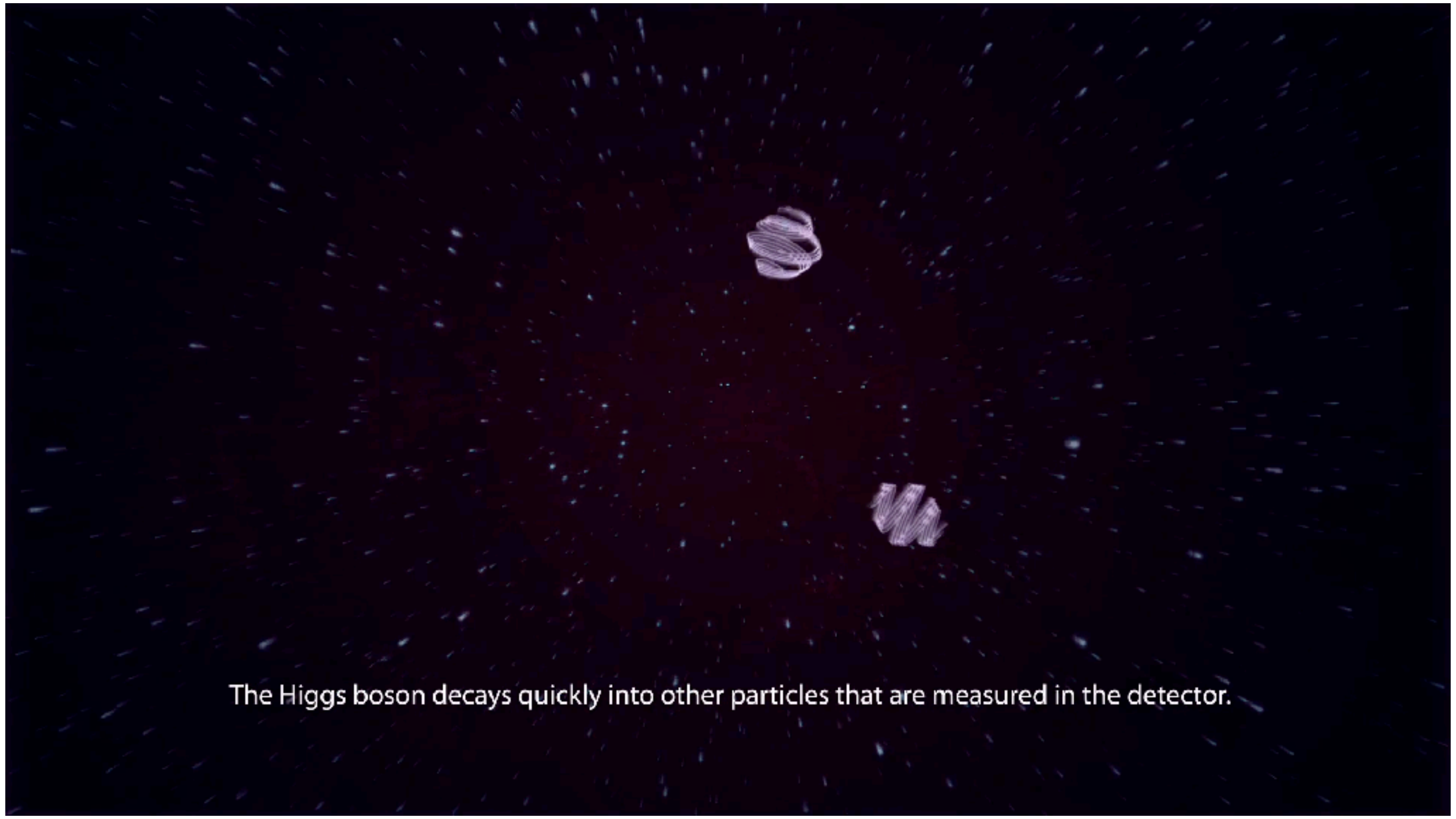


putting together heavy-ion physics and particle physics?

heavy Standard Model particles as time-delayed probes

Apolonario, Milhano, GPS & Salgado, PRL 2018



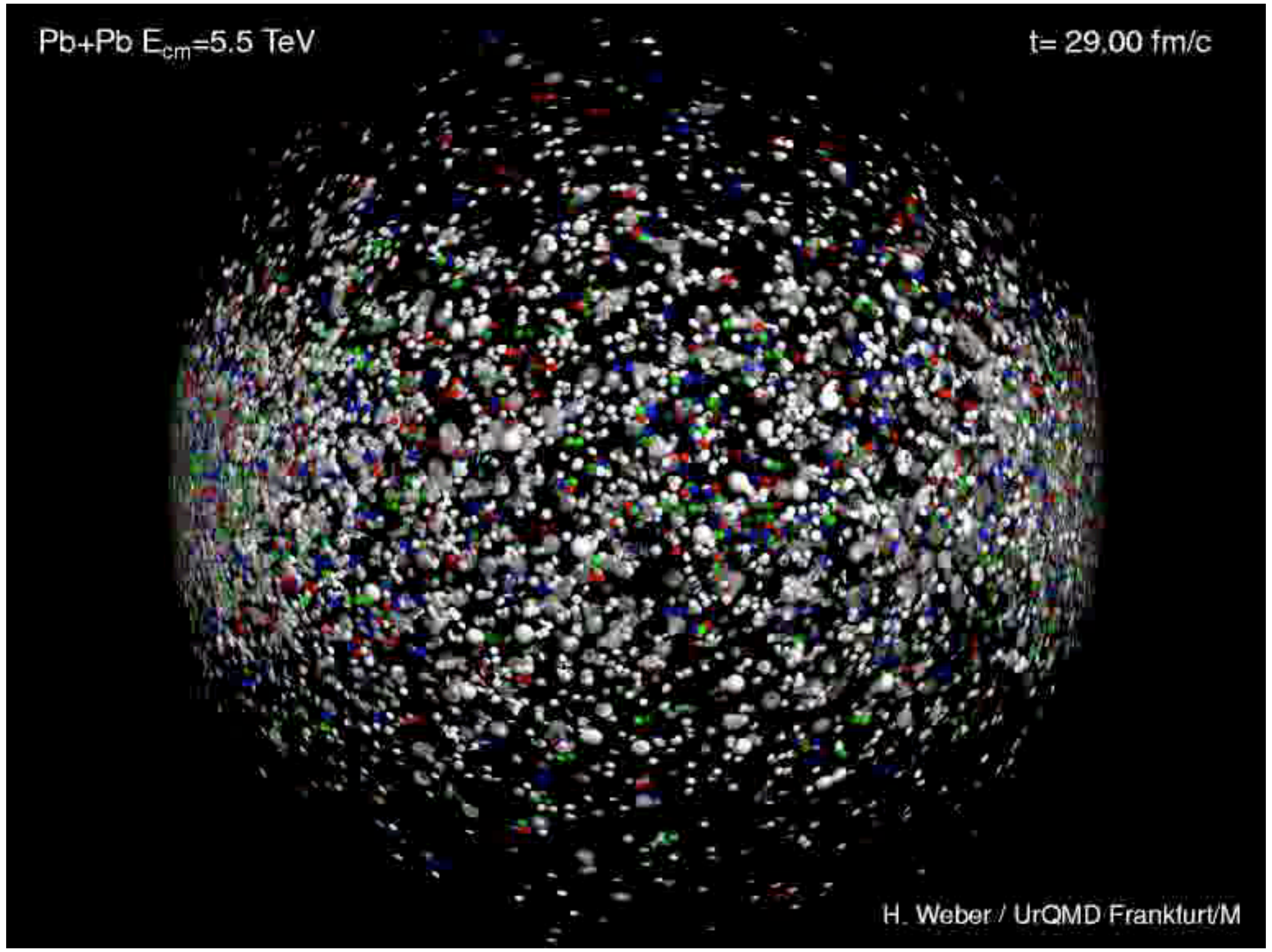


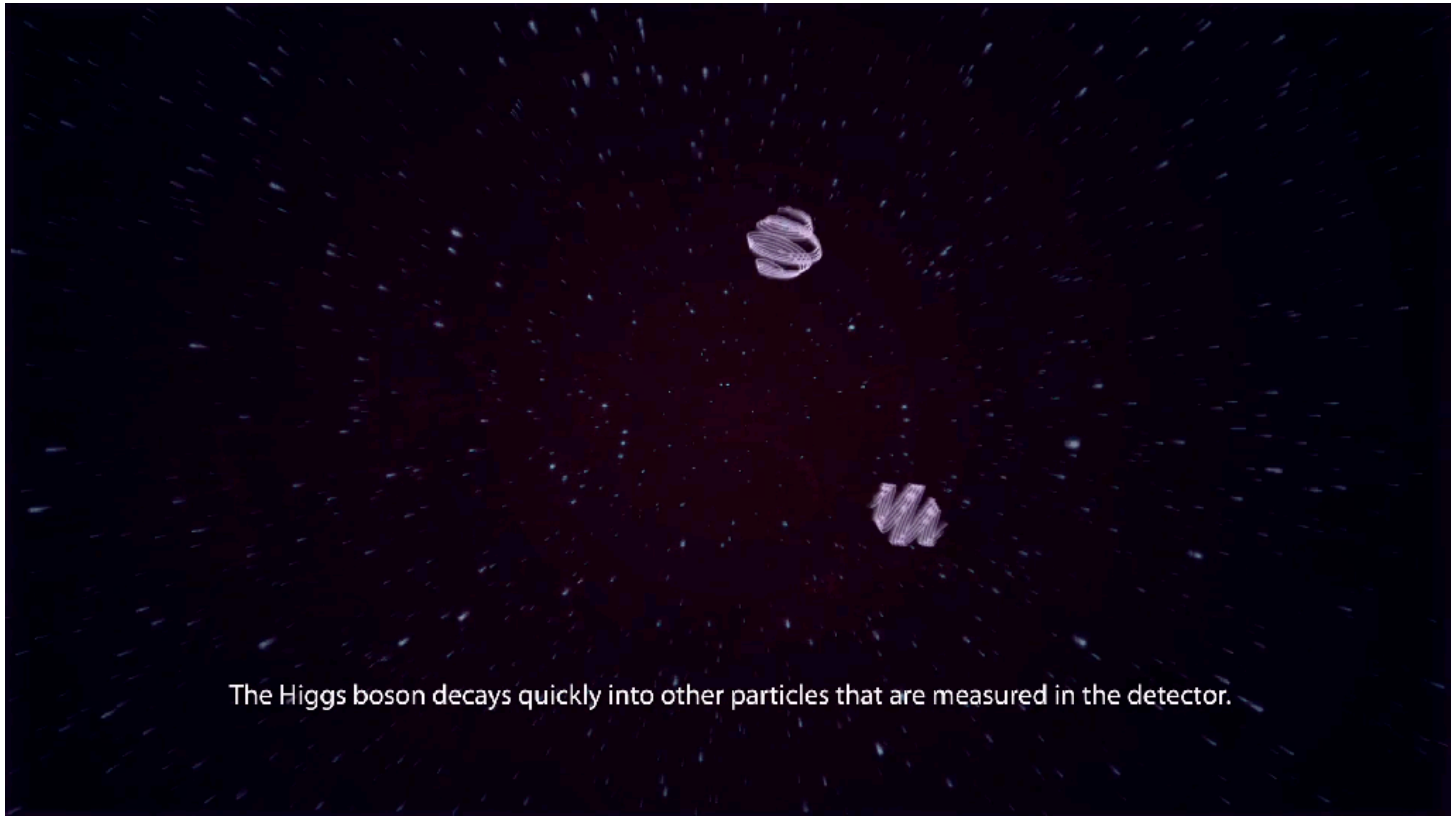
Hot (~5 ×10^{12}K), dense system, on timescales ~ 0.3 – 10 fm/c ~1 – 30 × 10^{-24} s

putting together heavy-ion physics and particle physics?

heavy Standard Model particles as time-delayed probes

Apolonario, Milhano, GPS & Salgado, PRL 2018



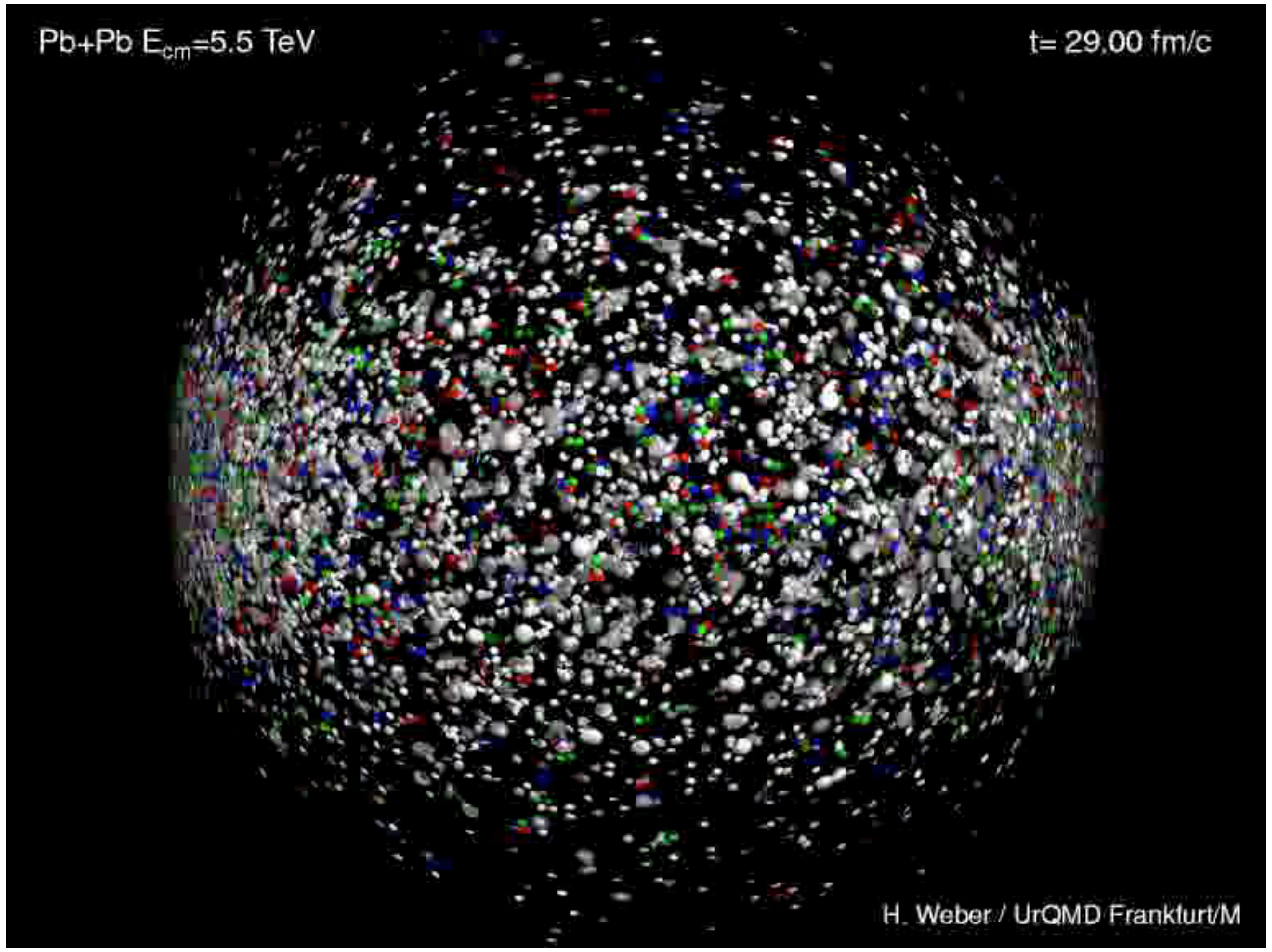


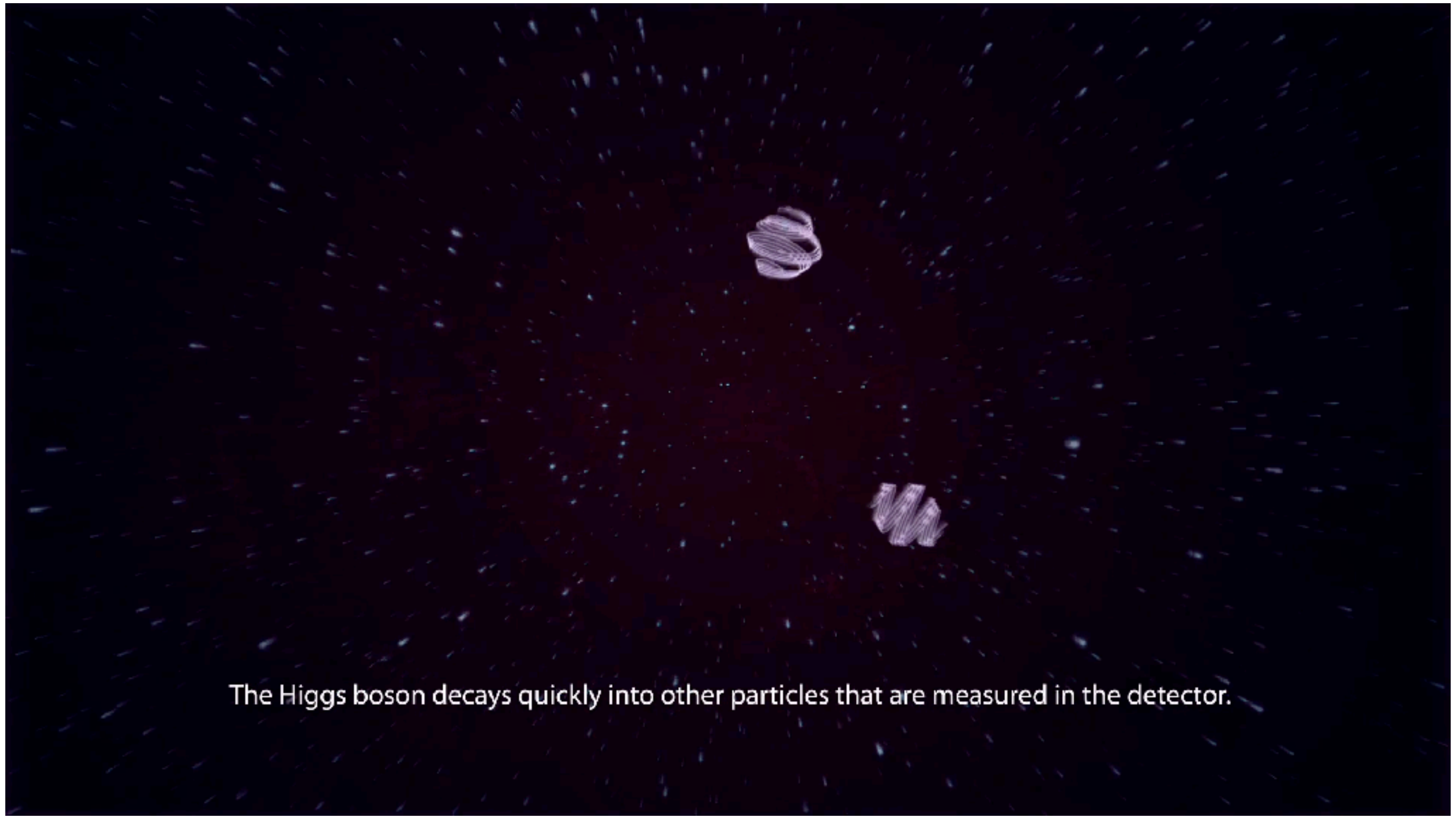
Hot (~5 ×10^{12}K), dense system, on timescales ~ 0.3 – 10 fm/c ~1 – 30 × 10^{-24} s

putting together heavy-ion physics and particle physics?

heavy Standard Model particles as time-delayed probes

Apolonario, Milhano, GPS & Salgado, PRL 2018

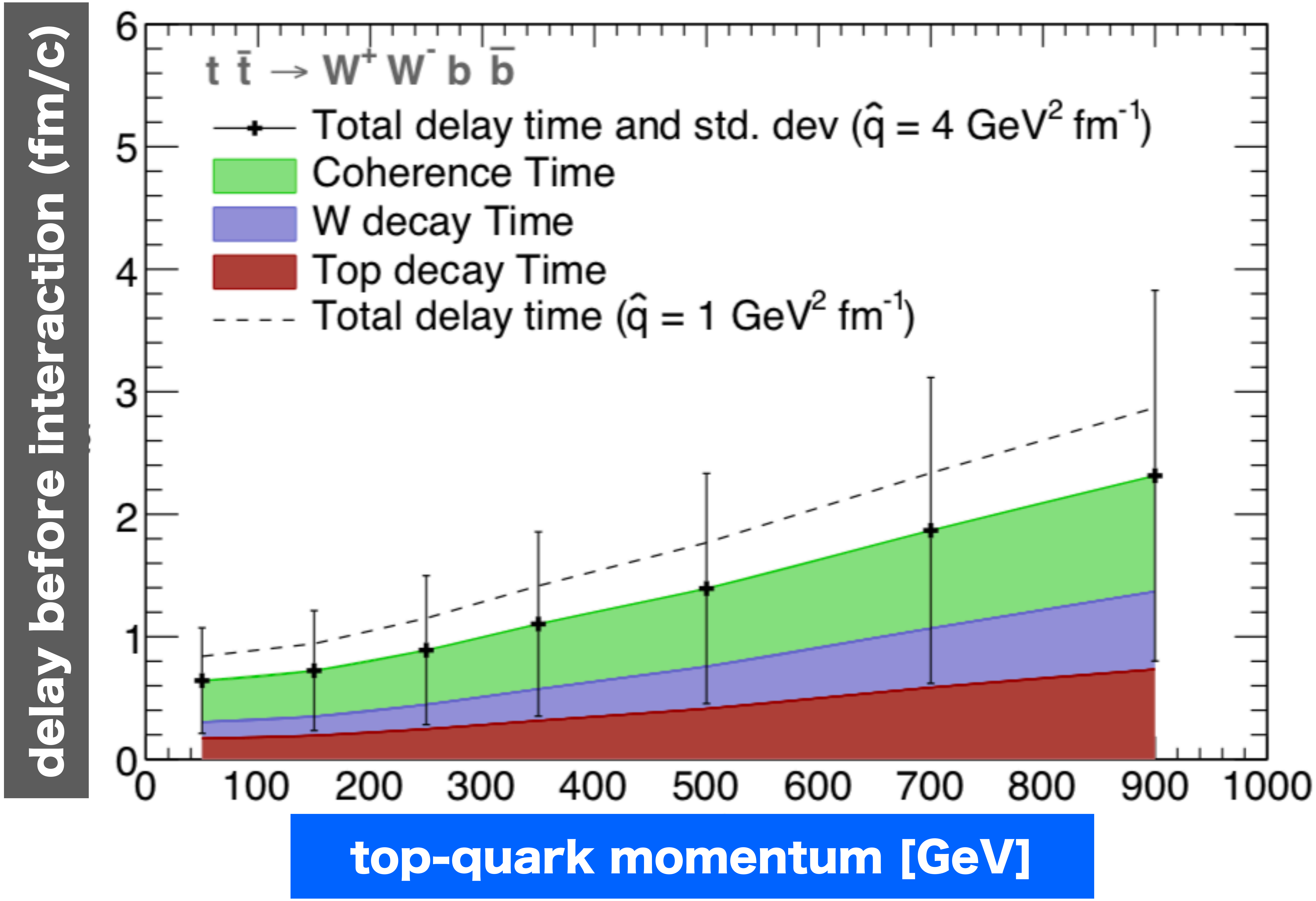




Hot (~5 ×10^12^K), dense system, on timescales ~ 0.3 – 10 fm/c ~1 – 30 × 10^-24^ s

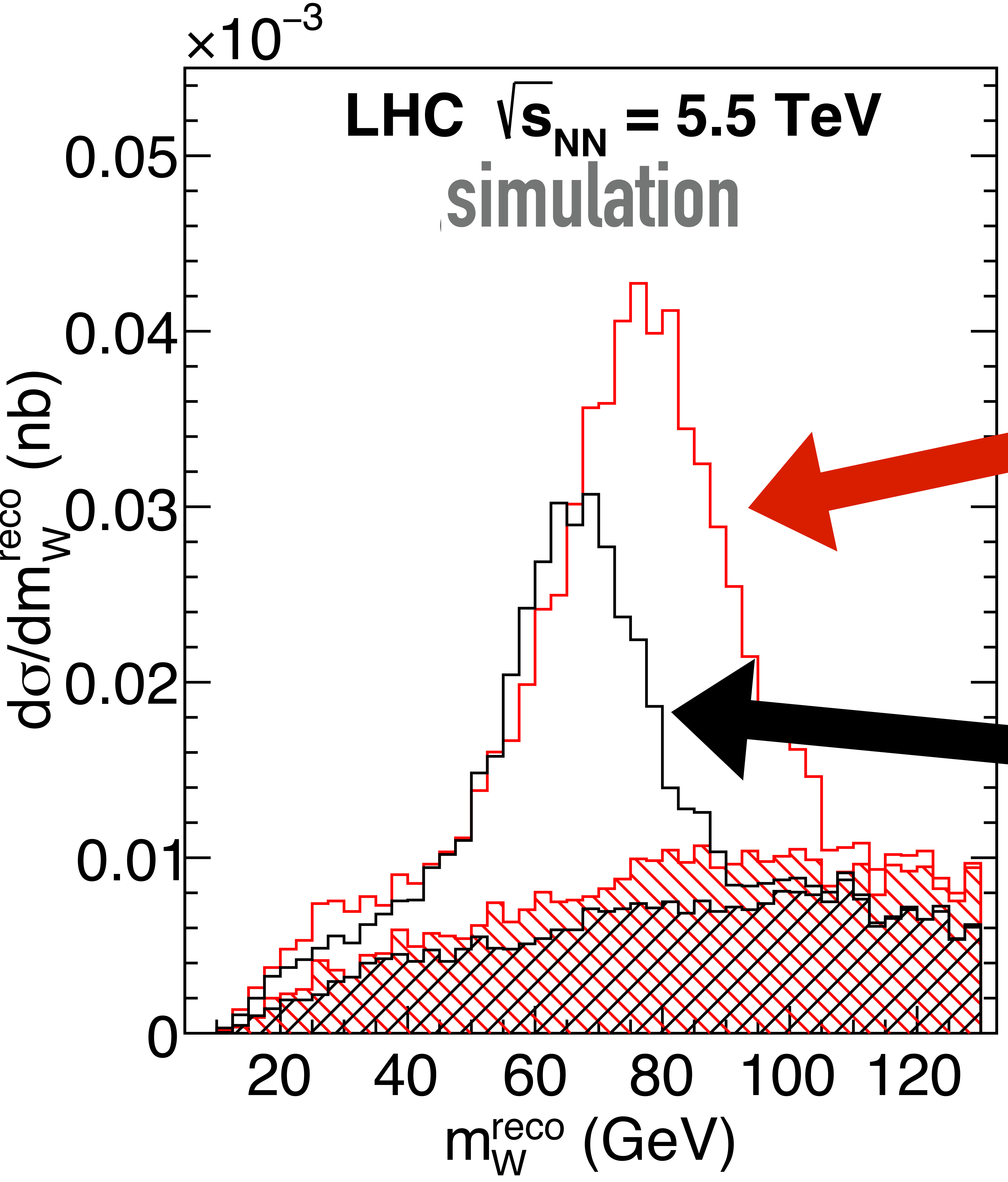
top quark lifetime: ~0.25 fm/c
W boson lifetime: ~0.1 fm/c
Higgs boson lifetime: ~50 fm/c

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



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

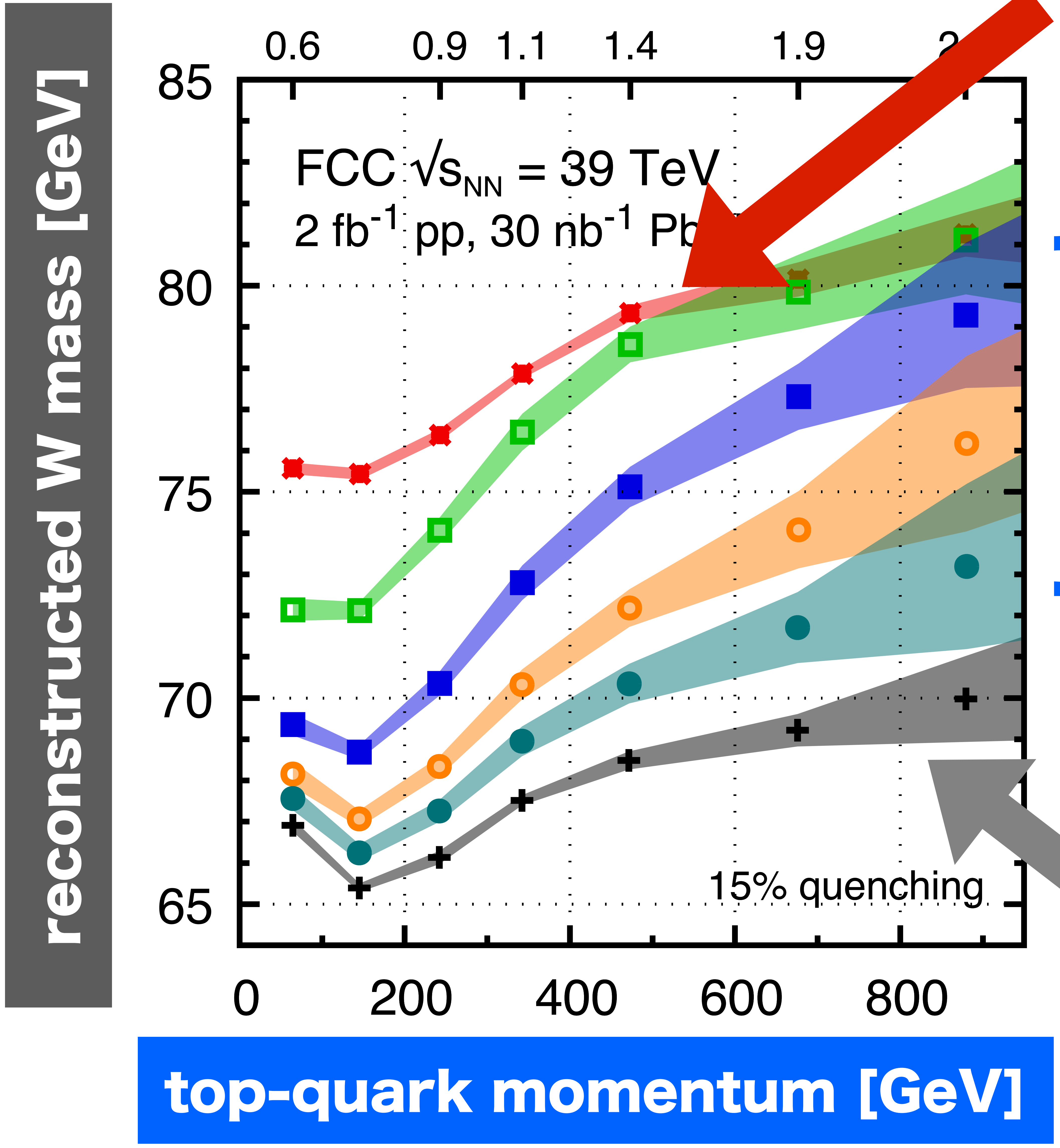
delay can be tuned by selecting top-quark momentum (Lorentz dilation) examine reconstructed mass of top → W → jets



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= 2.5 fm/c
τ_m= 5 fm/c
τ_m= 10 fm/c

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

W in vacuum ("unquenched")

reconstructed W mass [GeV]

- 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.
- Other groups examining potential of using Higgs as a probe

(Berger, Gao, Jueid, Zhang 1804.06858, d'Enterria et al)

top-quark momentum [GeV]

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

conclusions

"

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

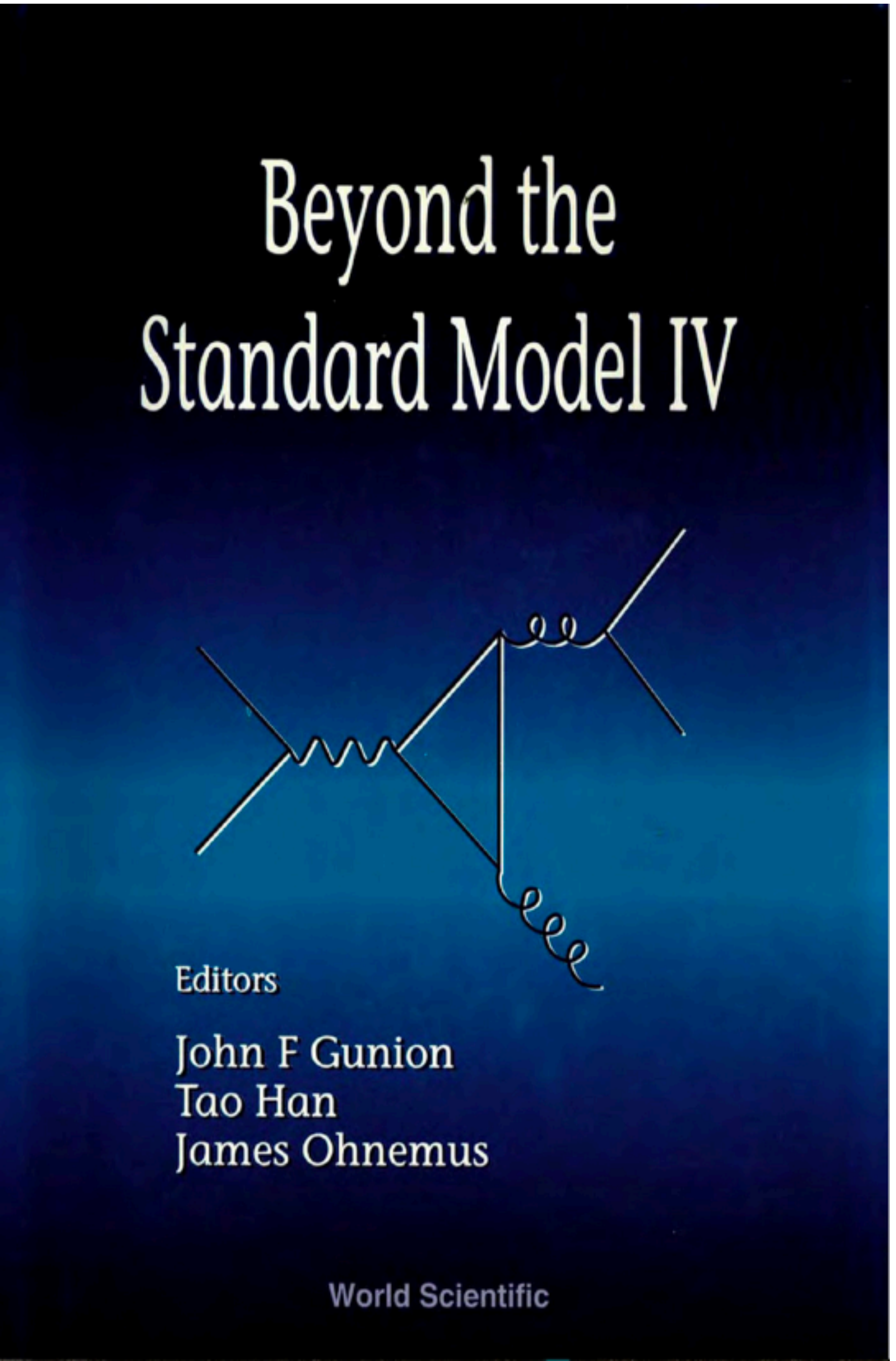
I disagree.

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

2 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.

one musn't underestimate our ignorance about the Higgs sector nor the value of exploring and establishing it

e.g. accessing the triple-Higgs coupling,
to establish to the Higgs-field potential, keystone of SM

meanwhile, the search for new physics continues

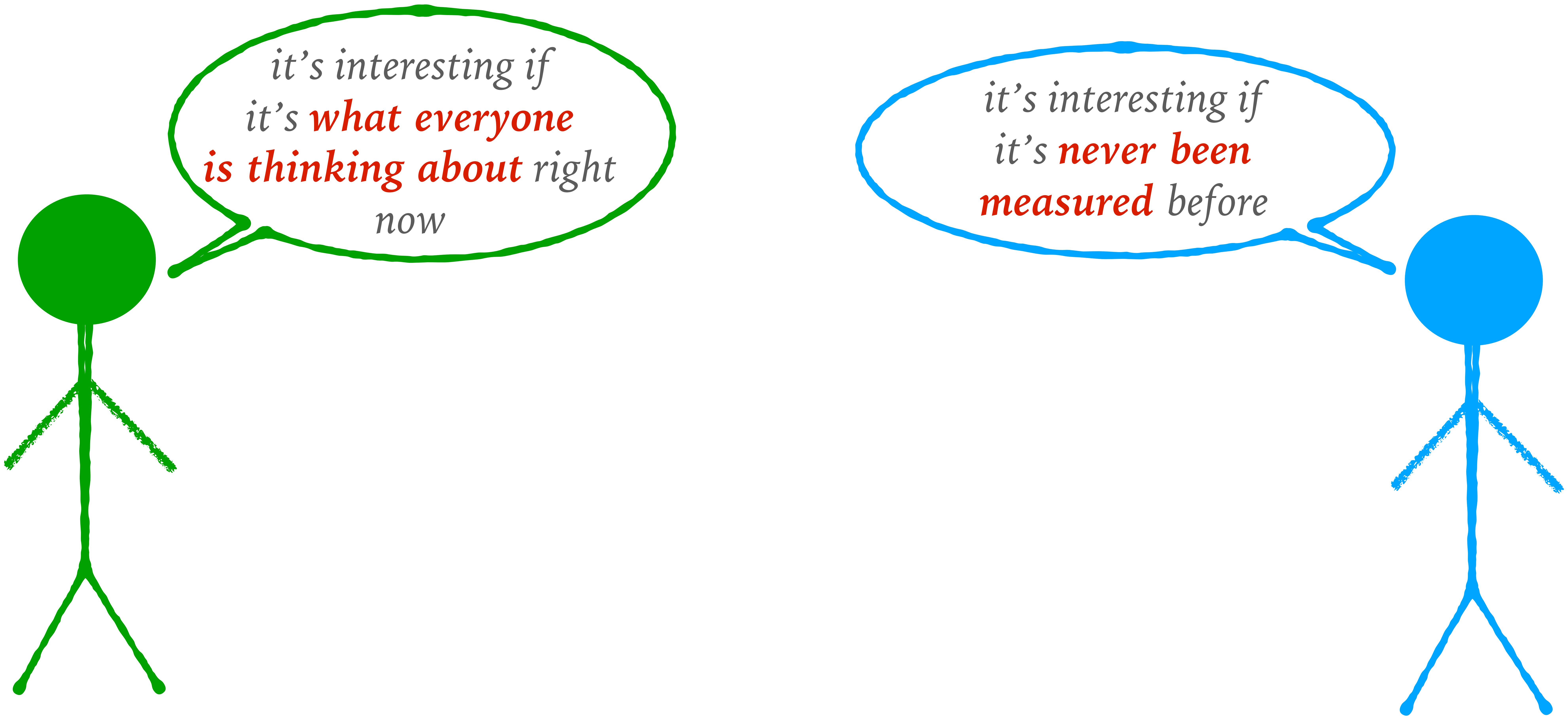
with much scope for inventing ingenious search techniques, identifying novel models that could be probed

And finding other things to do with the particles we have

BACKUP

some theorists

experimenter



both have a point
(don't let one side dampen the other side's interest)

I think Nature is smarter than physicists. We should have the courage to say: "Let Nature tell us what is going on."

-Carlo Rubbia [2008]

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

EFT (expressive formulation of constraints) or not?

- If you've observed a given channel, and it agrees roughly ($\pm 30\%$) with SM, then go to EFT
- if you've not observed it, e.g. charm Yukawa, Higgs self coupling, then use of EFT is more debatable

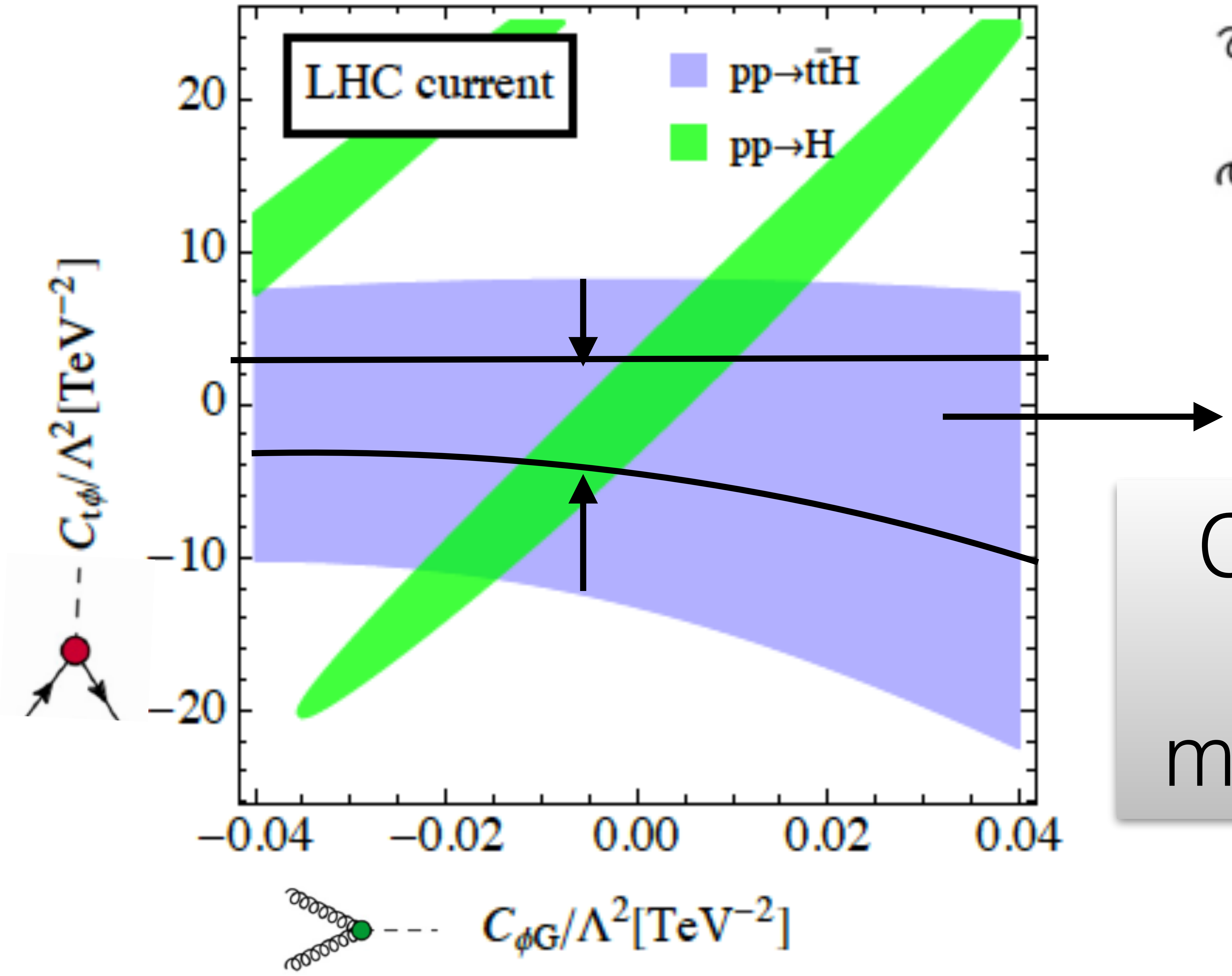
establish SM first

then use (lack of) any deviations to (constrain) characterise new physics

dimension-6 dimension-8

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

BSM effects SM particles



impact of recent ttH observation

Current limits using LHC measurements

Vryonidou

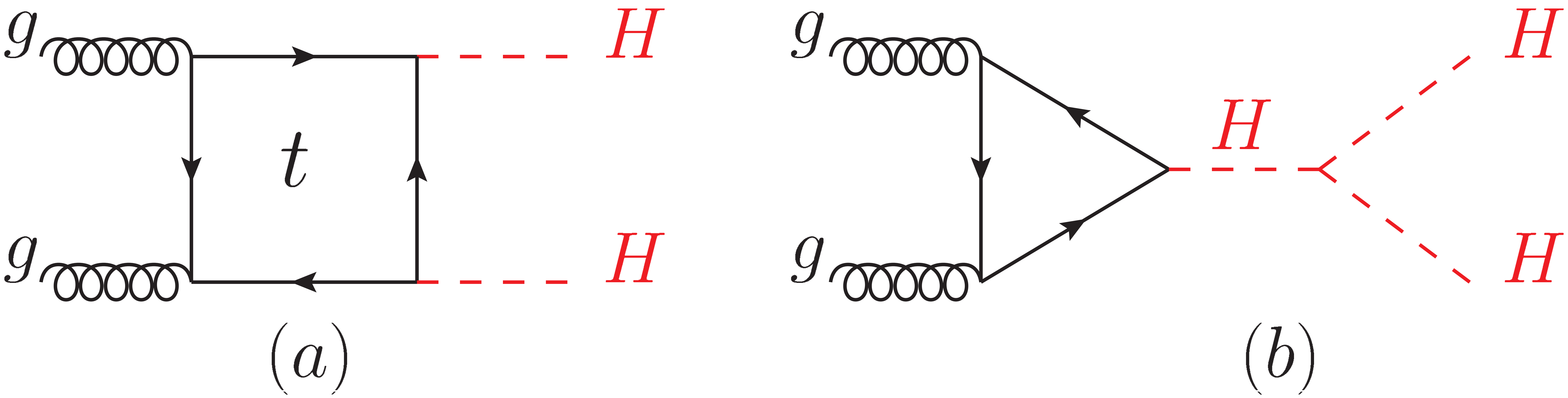
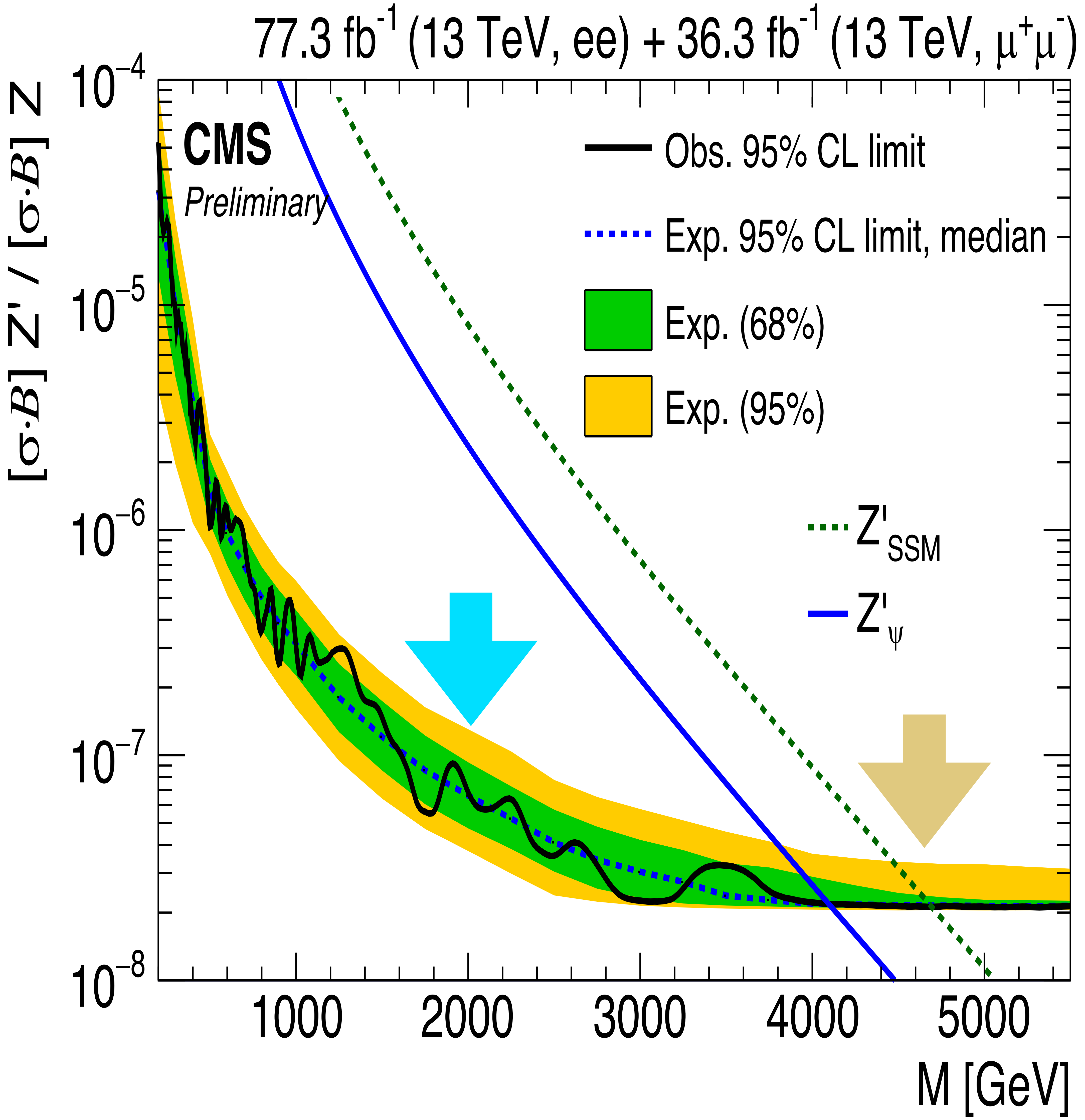


Figure 11.5: Feynman diagrams contributing to Higgs boson pair production through (a) a top- and b-quark loop and (b) through the self couplings of the Higgs boson.

don't underestimate the value of luminosity

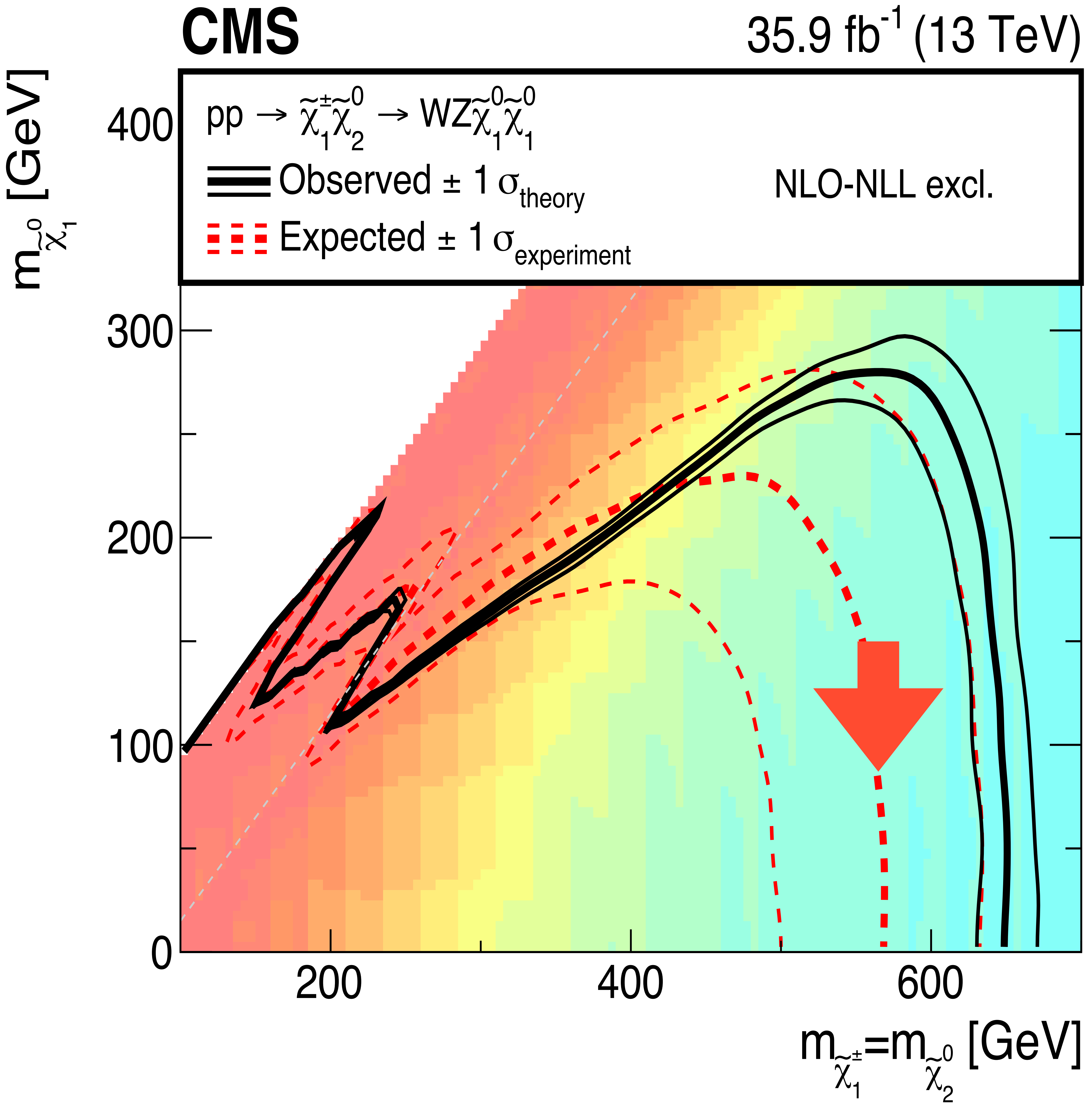


- Suppose we had a choice between
  - HL-LHC (14 TeV, $3ab^{-1}$)
  - or going to higher c.o.m. energy but limited to $80fb^{-1}$.
- How much energy would we need to equal the HL-LHC?

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

don't underestimate the value of luminosity



- 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