The Higgs Boson

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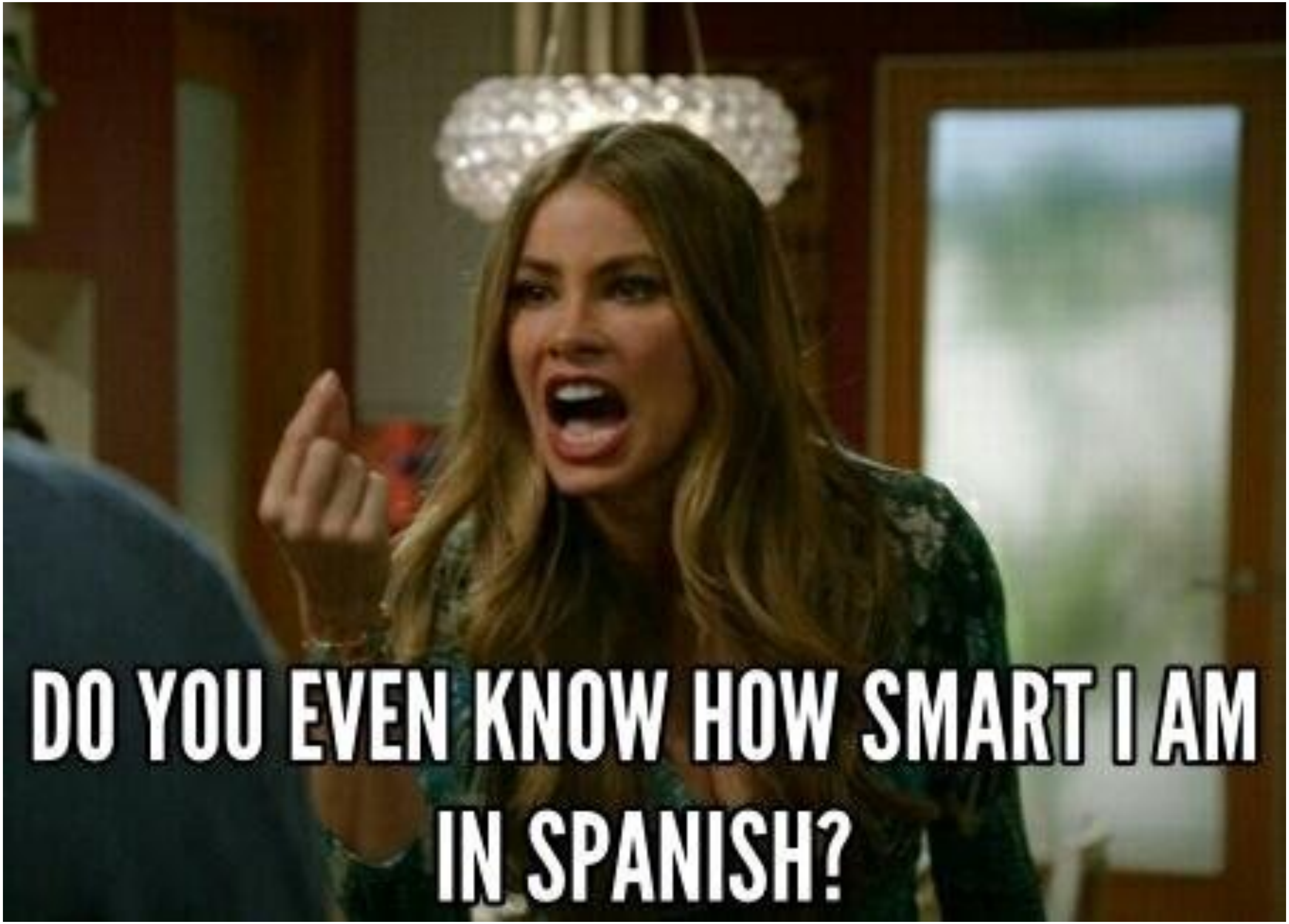
The Higgs Boson

Theoretical Introduction

Search and Discovery

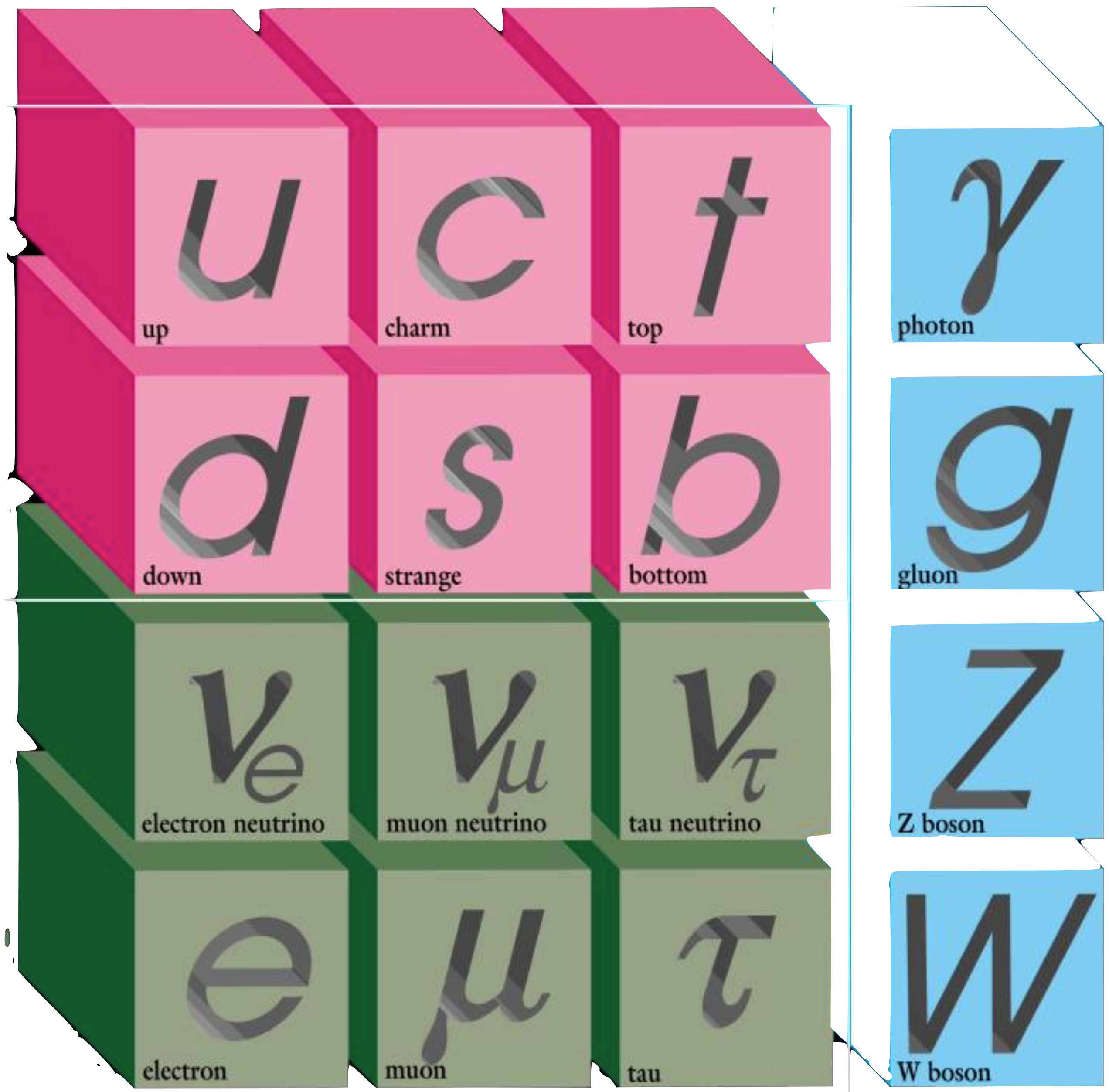
Properties

Future(s)


DO YOU EVEN KNOW HOW SMART I AM
IN SPANISH?

Theoretical Introduction

Standard Model Strong + Weak + EM interactions



'matter' + gauge bosons

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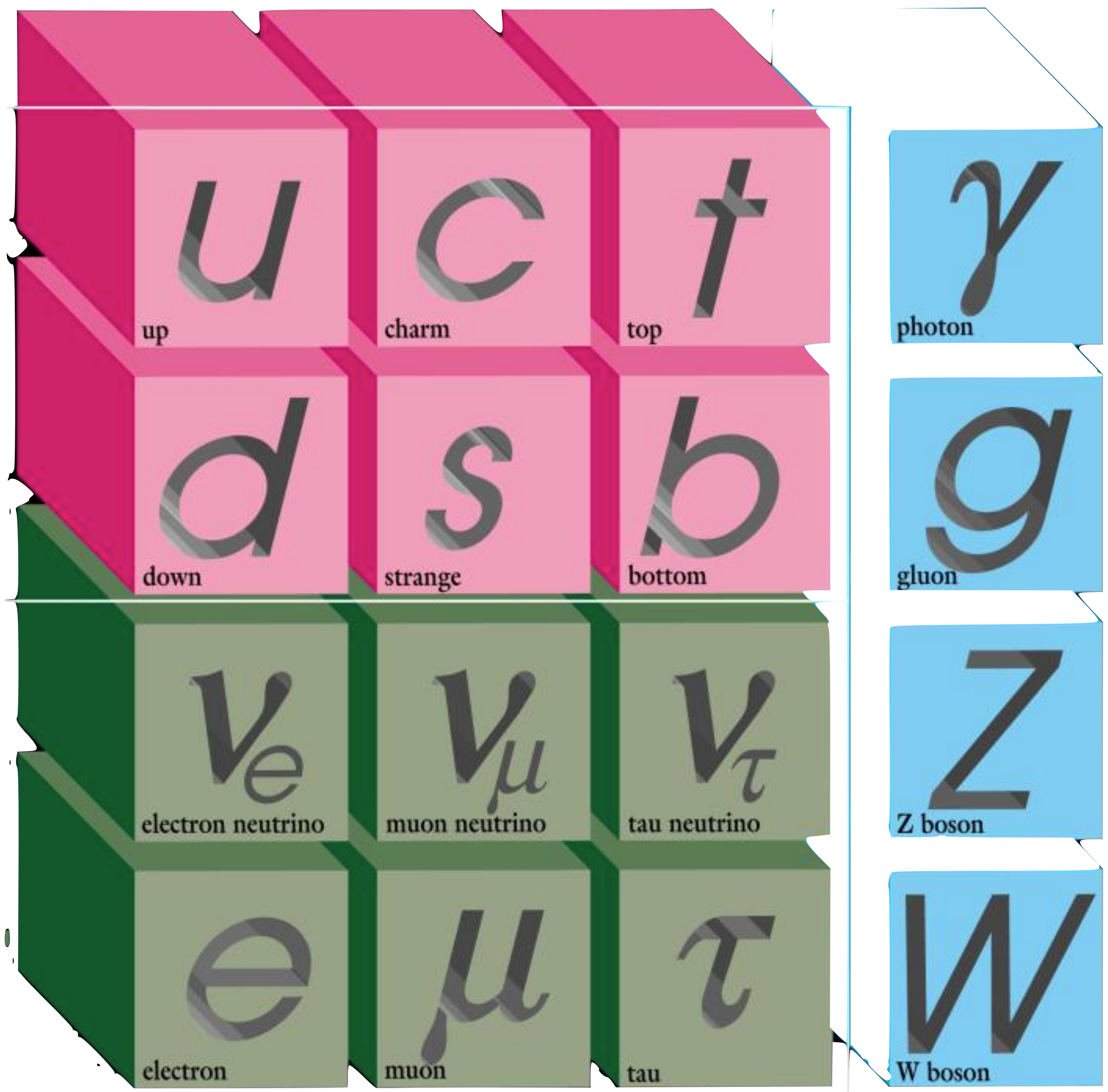

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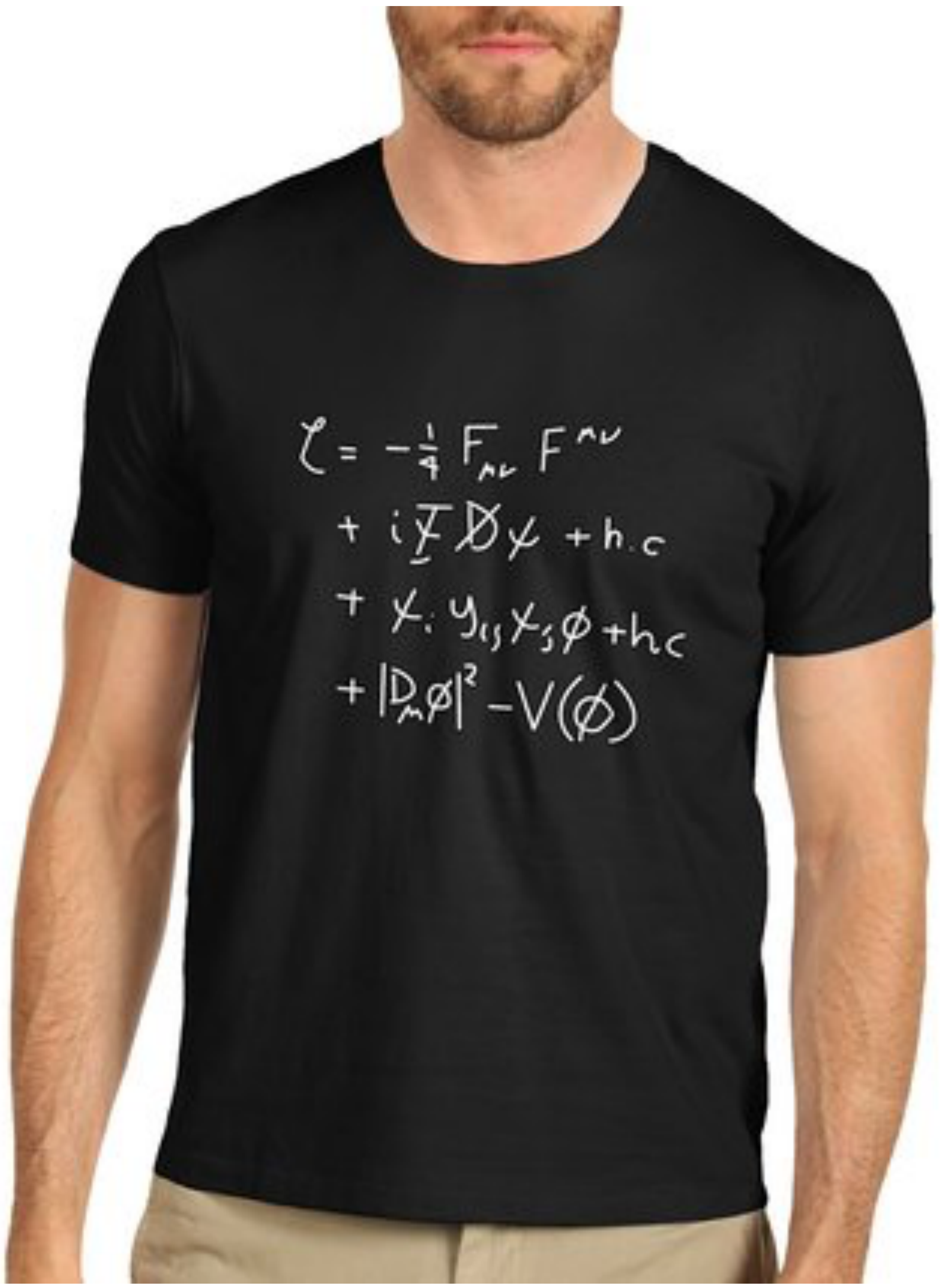

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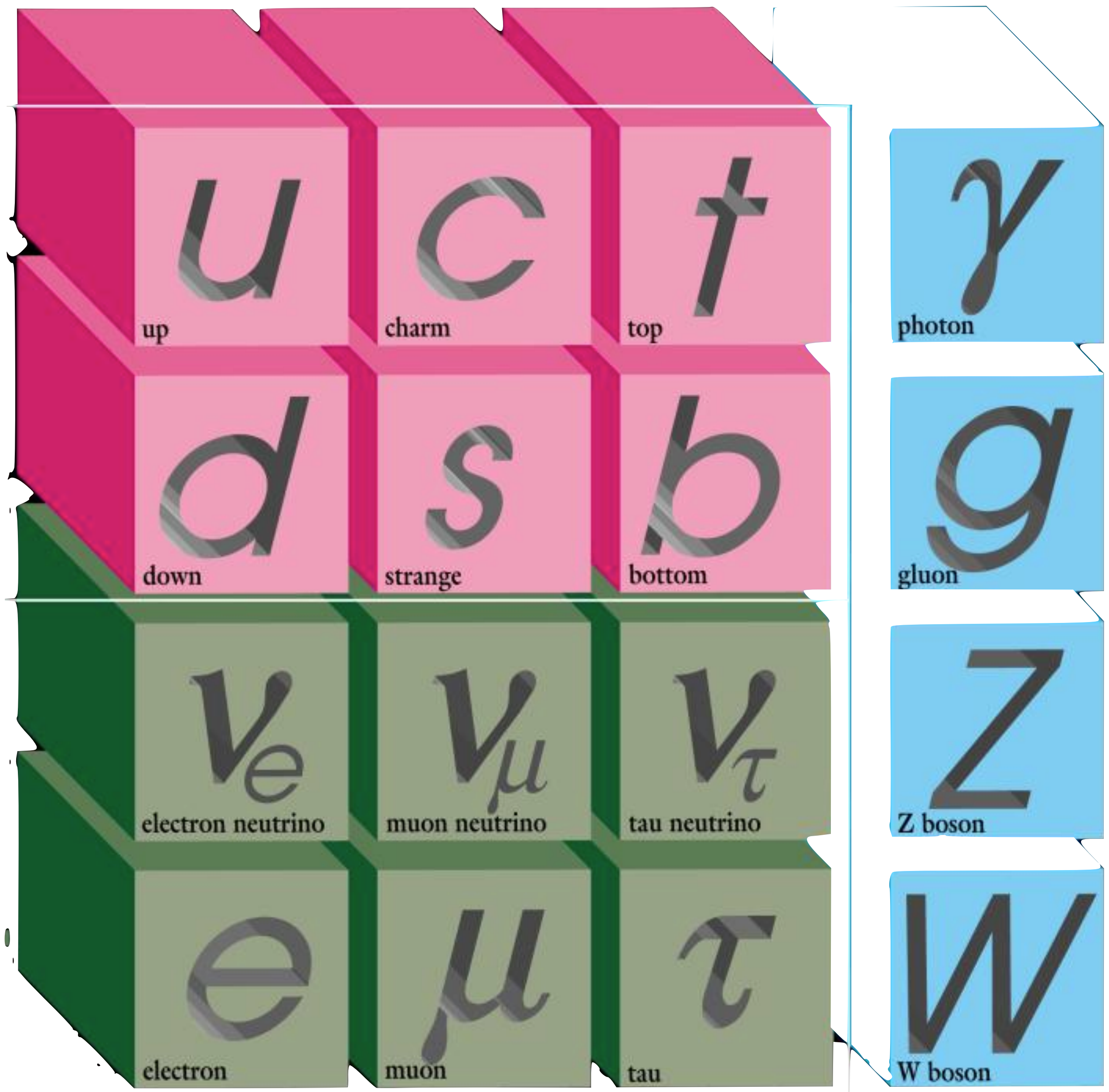

‘matter’ + gauge bosons

Standard Model from Gauge Principle

✓ Each particle represented by a field $< \psi > = < A^\mu > = 0$

ψ Fermion (spin 1/2) A^μ Boson (spin 1)

✓ Recognize symmetry of Nature $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

✓ Impose symmetry in local form (introduce gauge fields, just try U(1))

$$\psi(x) \to e^{i\alpha(x)}\psi(x) \qquad A^\mu(x) \to A^\mu(x) + \partial^\mu \alpha(x)$$

✓ Minimal coupling between matter and gauge fields

$$\mathcal{L}_{matter}(\psi, \partial_\mu \psi) \to \mathcal{L}_{matter}(\psi, D_\mu \psi) \qquad D_\mu = \partial_\mu - igA_\mu^a(x)T^a$$

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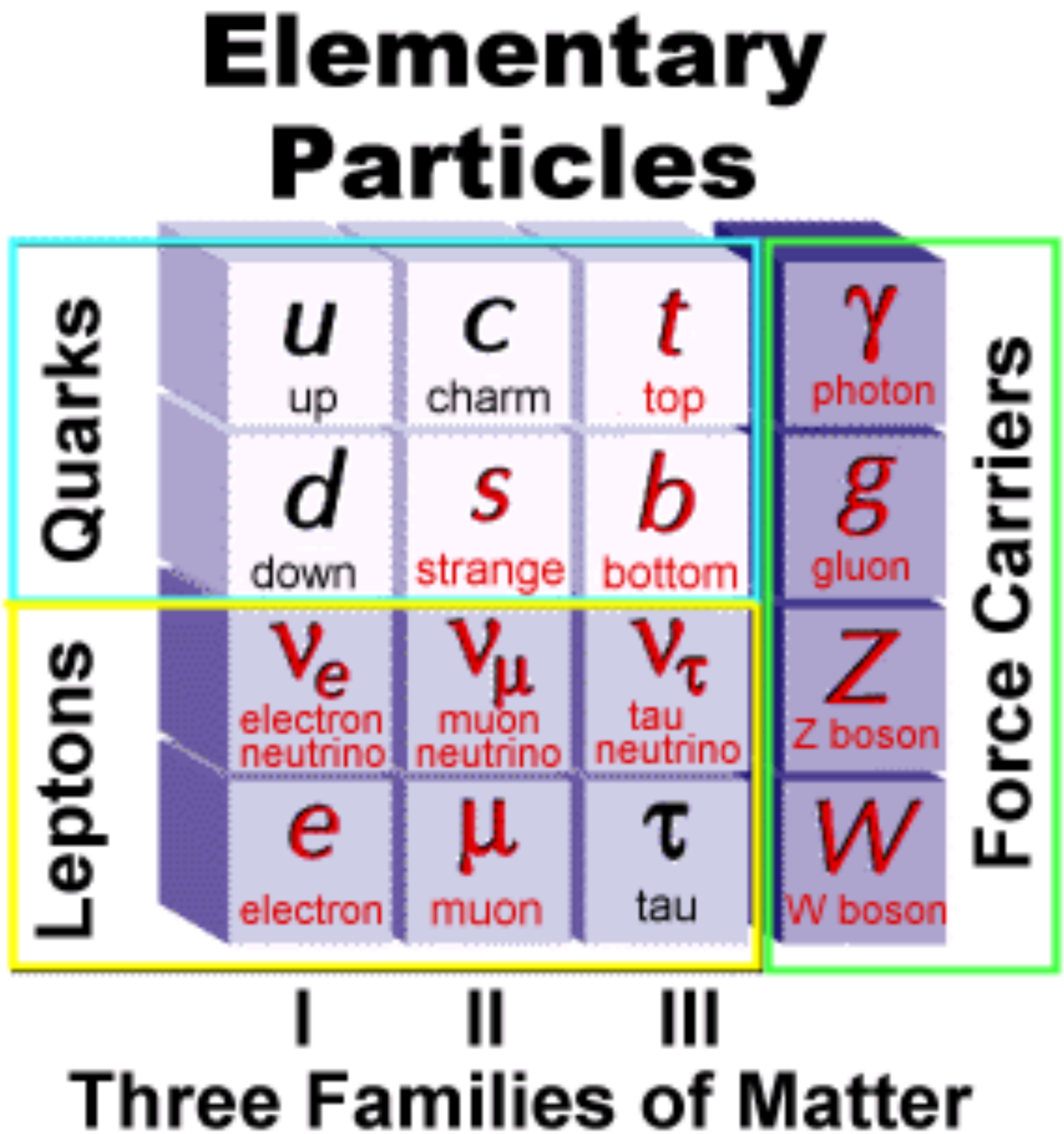
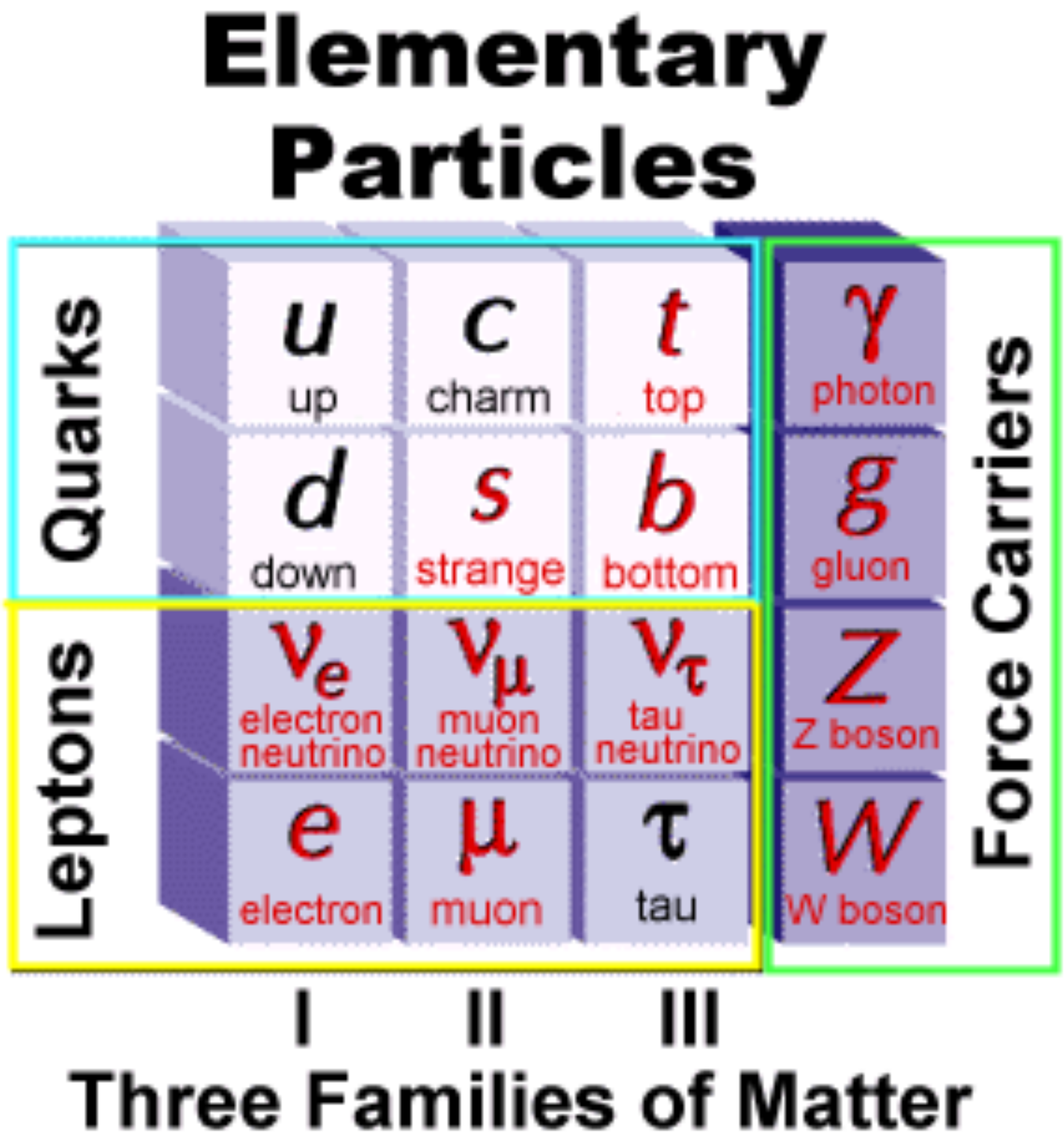


With the particle content of SM before July 4 2012 : all massless

Solution: **Spontaneous Symmetry Breaking**

Keep symmetry at the Lagrangian level
Break symmetry at the level of the ground state



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Higgs; Brout-**Englert**; Guralnik–Hagen–Kibble (~1964) **Nobel 2013**

Spontaneous Symmetry Breaking

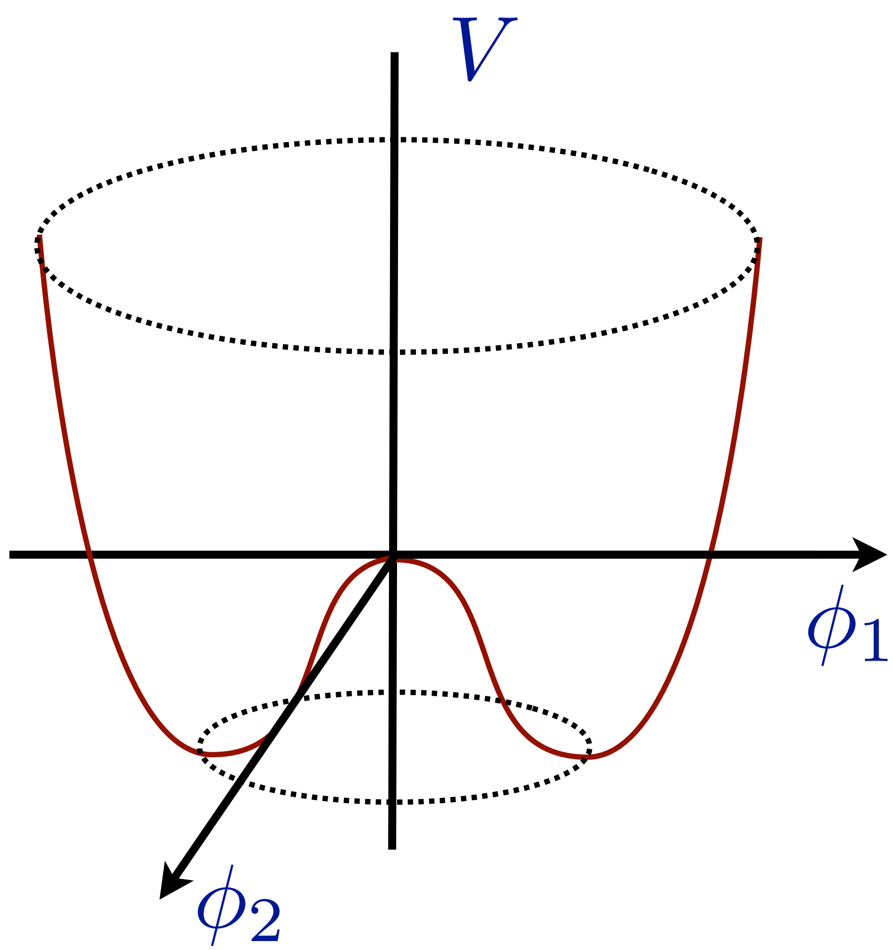
U(1) example: Introduce a complex scalar field $\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\,\phi_2)$

gauge coupling

$$\mathcal{L}_\phi = |D_\mu \phi|^2 - V(\phi)$$

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 \qquad \lambda > 0$$

$$\phi(x) \to \phi'(x) = e^{-i\alpha(x)}\phi(x)$$



If $\mu^2 < 0$

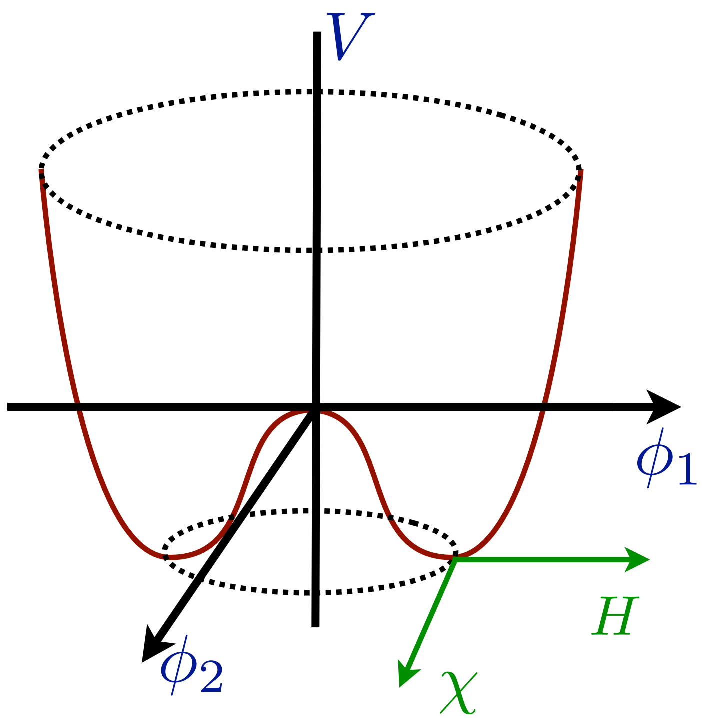
infinite vacuums

not gauge invariant

$$|\langle \phi \rangle|^2 = \frac{-\mu^2}{2\lambda} \equiv v^2$$


AFA
10

Spontaneous Symmetry Breaking



$$\phi(x) \equiv \frac{1}{\sqrt{2}} e^{i\frac{\chi(x)}{v}} (v + H(x))$$

moves between vev's
VEV not gauge invariant

perturbation away from minimum

$\chi(x)$ field can be rotated away by gauge transformation (unitary gauge)

scalar boson mass term

$m_H^2 = -2\mu^2$

interactions

$$|D_\mu \phi|^2 = \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}(-2\mu^2 H^2) + \frac{q^2 v^2}{2} A_\mu A^\mu + \frac{q^2}{2} A_\mu A^\mu H^2 + v q^2 A_\mu A^\mu H$$

$m_A = qv$ Gauge boson mass term

Degree of freedom "eaten" to provide longitudinal polarization

Two parameters in the potential $\mu\,,\,\lambda$ → $m_H\,,\,m_A$

Spontaneous Symmetry Breaking $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

The SM example: Introduce a doublet of complex scalar fields

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad V\left(\Phi^\dagger \Phi\right) = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2}\right)^2$$

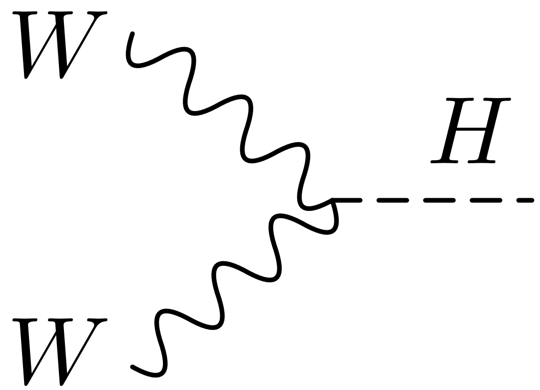
Transforms as (1,2,1/2) under $SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$

$$<\Phi> = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$ vacuum state neutral

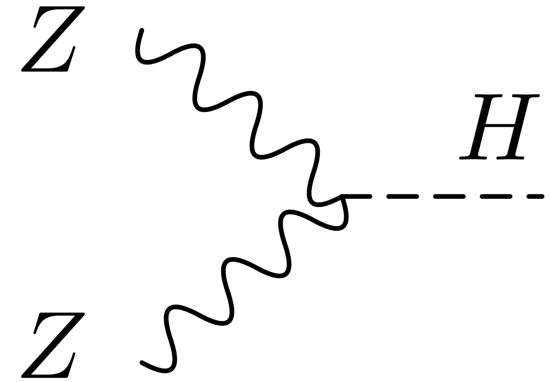
- Photon remains massless
- W and Z acquire masses $m_W^2 = \frac{g^2 v^2}{4} \qquad m_Z^2 = \frac{(g^2 + g'^2)v^2}{4} = \frac{m_W^2}{\cos^2 \theta_W}$
- **vev** known $v = \sqrt{\frac{1}{\sqrt{2} G_F}} \approx 246.22\,\mathrm{GeV}$

Interactions with Higgs Boson

WWH and ZZH couplings



$$2i\frac{m_W^2}{v}g^{\mu\nu}$$



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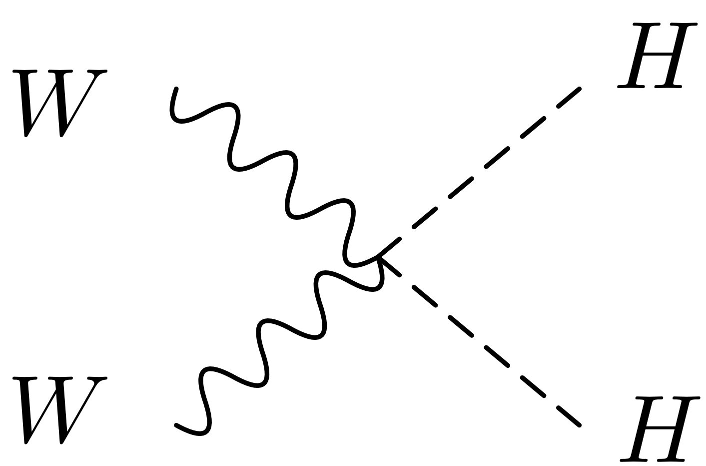
WWHH and ZZHH couplings



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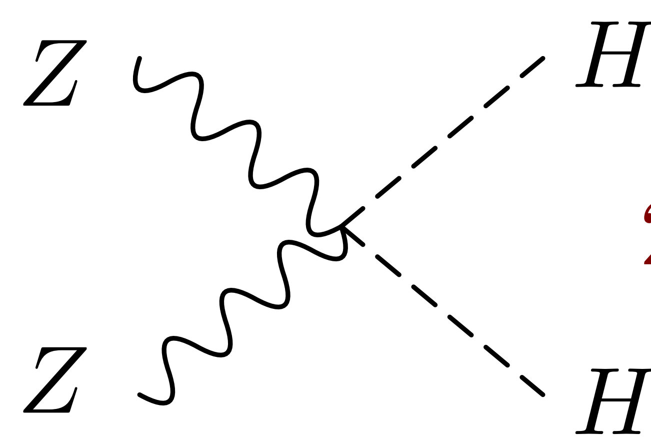


$$2i\frac{m_Z^2}{v^2}g^{\mu\nu}$$

Fermion Masses

$$\mathcal{L}_{mass}^{fermion} = -m_f \bar{\psi}\psi = -m_f \left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L\right)$$

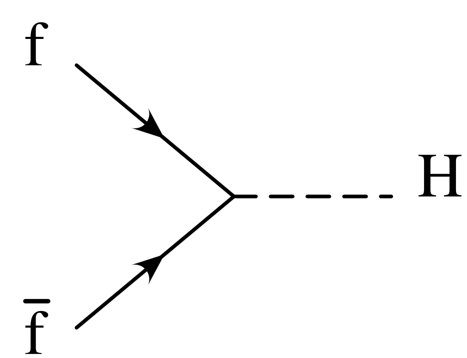
Generate Fermion masses through Yukawa interactions

$$\mathcal{L}_{Yukawa} = -\lambda_d \bar{Q}_L \Phi d_R - \lambda_u \bar{Q}_L (i\sigma_2 \Phi^*) u_R - \lambda_e \bar{L}_L \Phi e_R + \mathrm{h.c.}$$

Fermion mass

$$m_d = \lambda_d \frac{v}{\sqrt{2}}$$

Fermion-Higgs interaction



$$-i\frac{m_f}{v}$$

All interactions with Higgs boson proportional to particle mass

Back to Higgs potential

$$V\left(\Phi^\dagger\Phi\right) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2$$

Expanding the potential around the vacuum

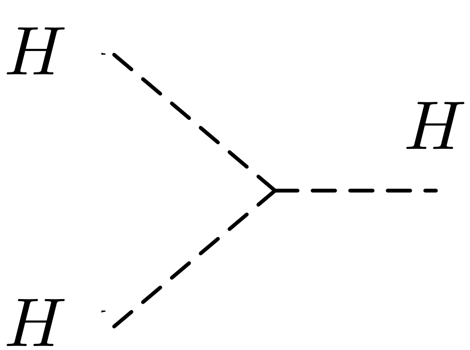
$$\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

results in

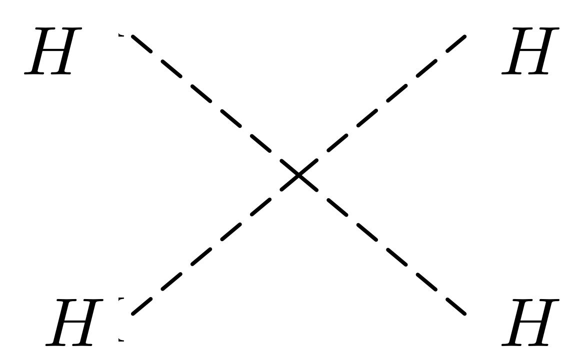
$$V = \frac{\lambda}{4}\left(2vH + H^2\right)^2 = \frac{1}{2}(2\lambda v^2)H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4$$

Higgs boson mass $m_H^2 = 2\lambda v^2$ can not be predicted (*only unknown*)

Cubic and Quartic self-couplings



$$-3i\frac{m_H^2}{v}$$



$$-3i\frac{m_H^2}{v^2}$$

Search and Discovery

Higgs search was never easy….

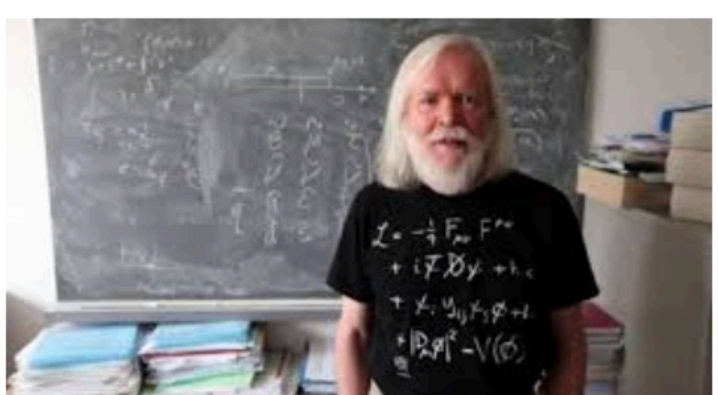
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

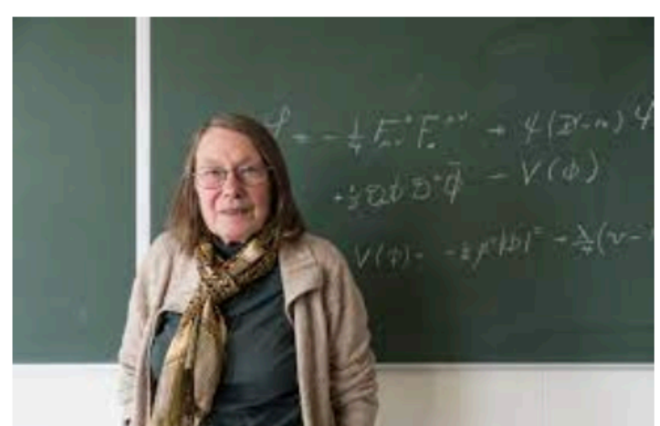
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

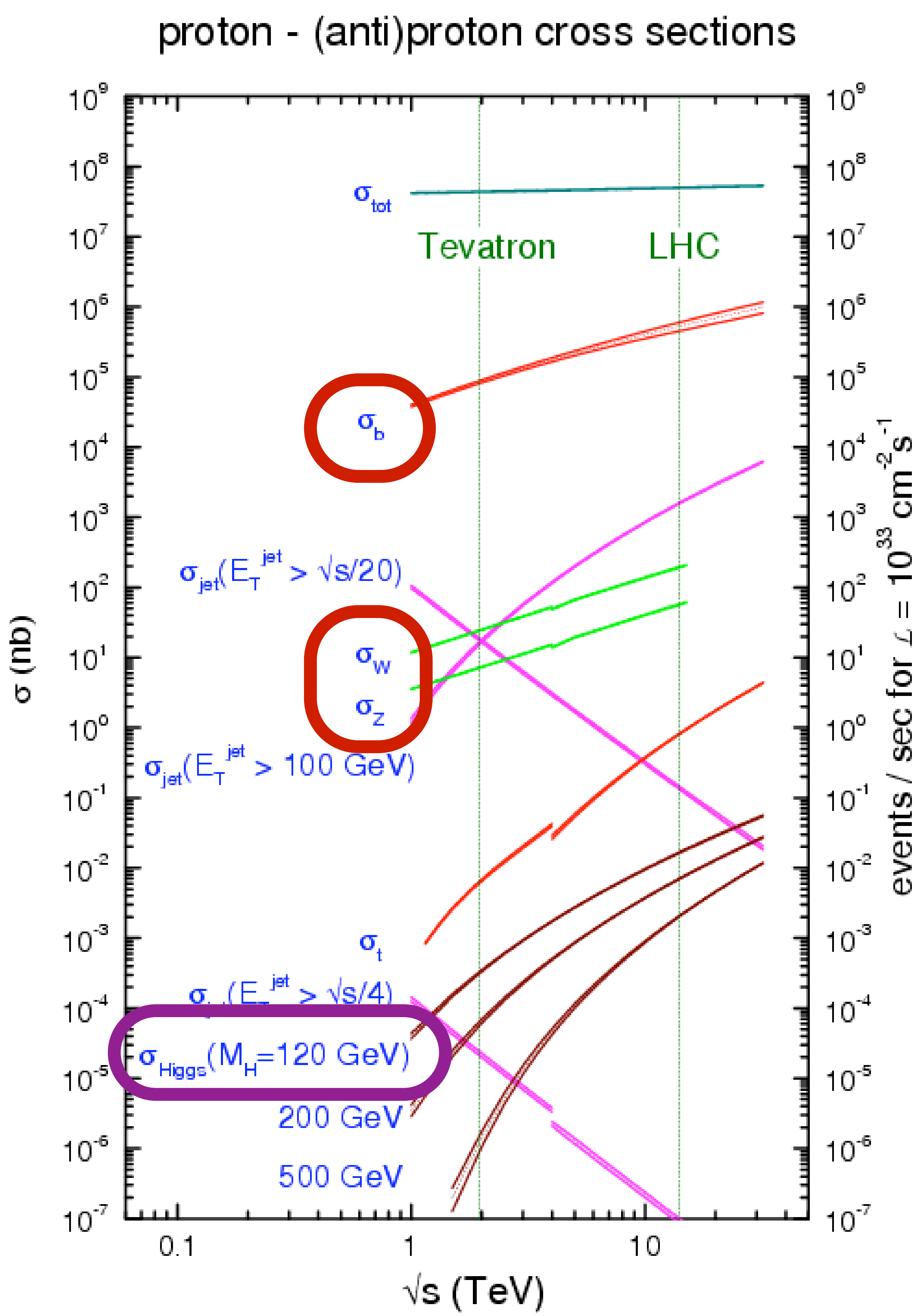
A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.





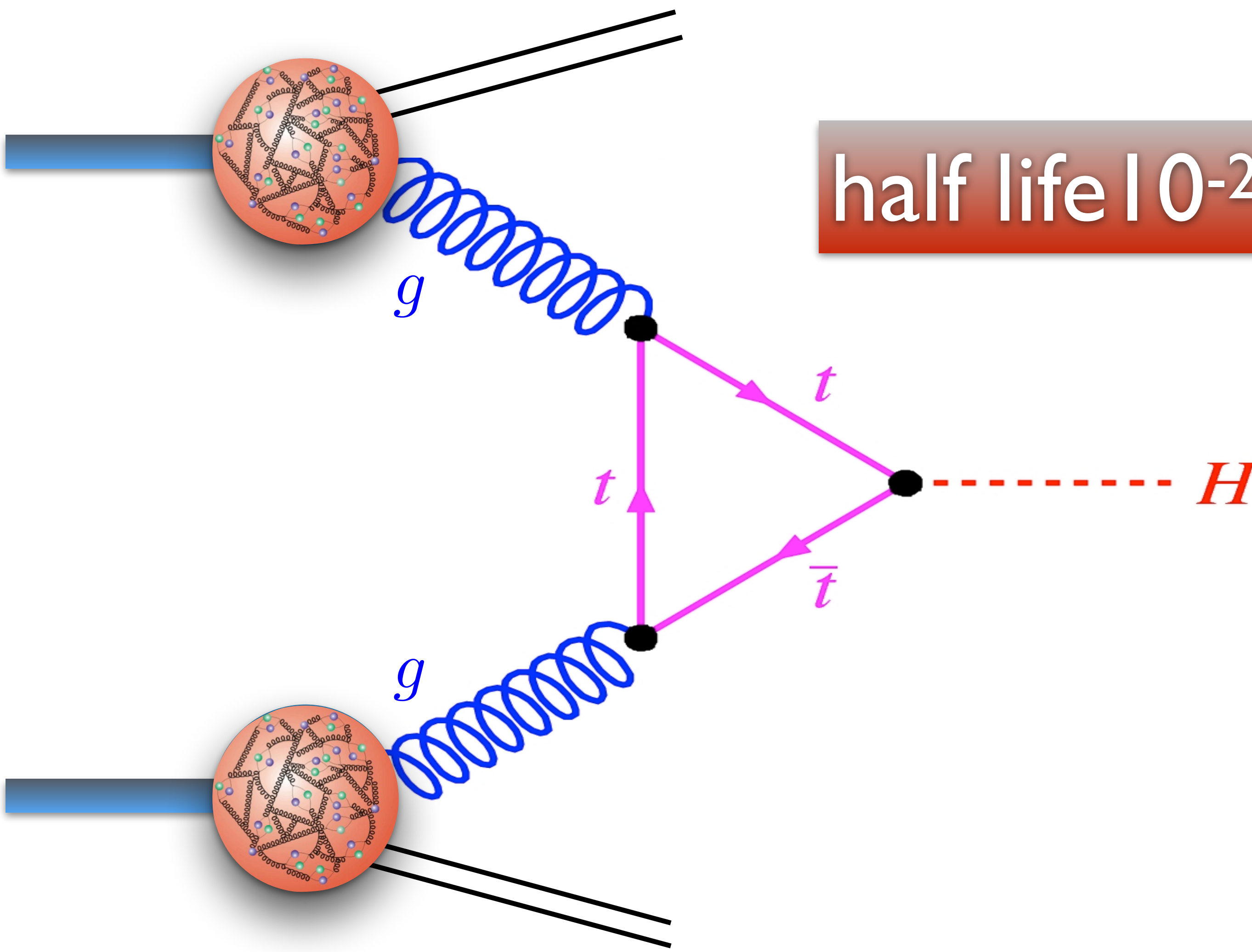
Particle production at hadronic colliders



- 1 Higgs in 10^{12} !

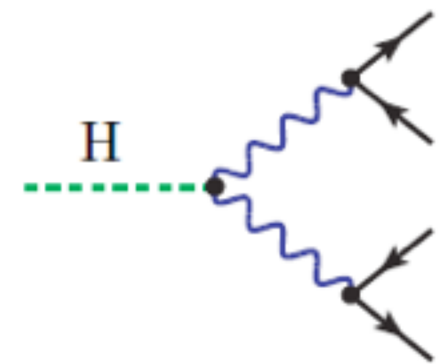
Higgs in hadronic colliders

Production

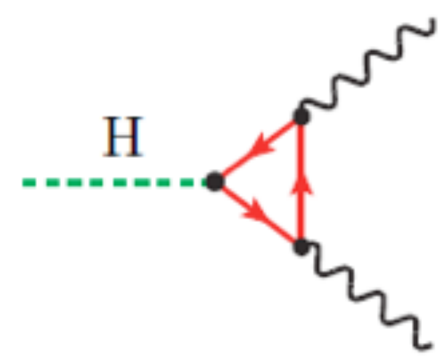


half life 10^{-22} s

Decay

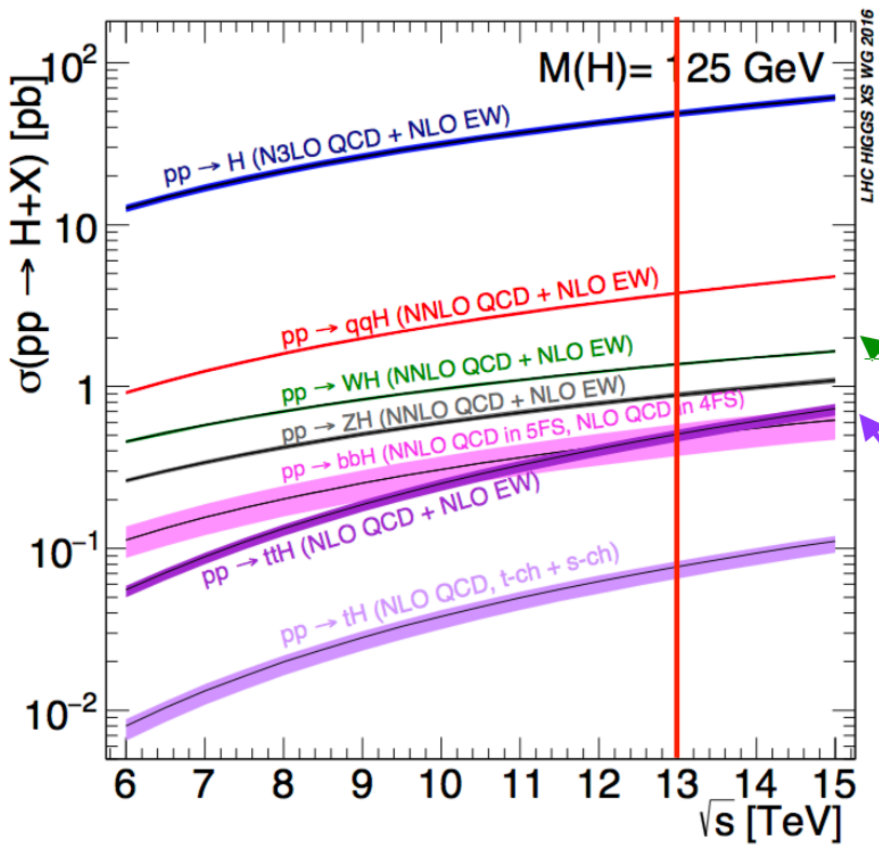


4 leptons
21%

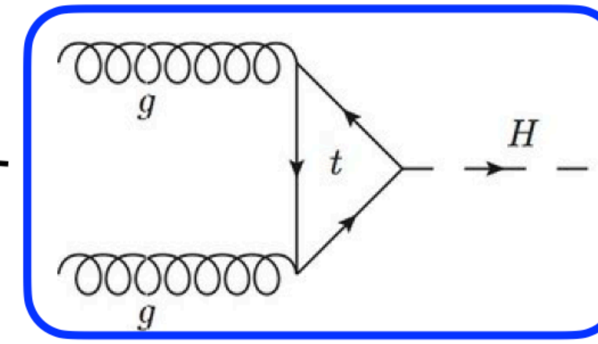


2 photons
0.2%

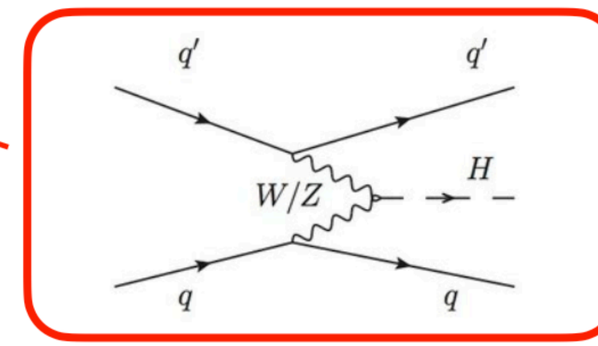
Higgs in hadronic colliders (all channels)



$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125$ GeV					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$16.9^{+5\%}_{-5\%}$	$1.24^{+2\%}_{-2\%}$	$0.58^{+3\%}_{-3\%}$	$0.34^{+4\%}_{-4\%}$	$0.09^{+8\%}_{-14\%}$	19.1
8	$21.4^{+5\%}_{-5\%}$	$1.60^{+2\%}_{-2\%}$	$0.70^{+3\%}_{-3\%}$	$0.42^{+5\%}_{-5\%}$	$0.13^{+8\%}_{-13\%}$	24.2
13	$48.6^{+5\%}_{-5\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.50^{+9\%}_{-13\%}$	55.1
14	$54.7^{+5\%}_{-5\%}$	$4.28^{+2\%}_{-2\%}$	$1.51^{+2\%}_{-2\%}$	$0.99^{+5\%}_{-5\%}$	$0.60^{+9\%}_{-13\%}$	62.1



N^{3}LO



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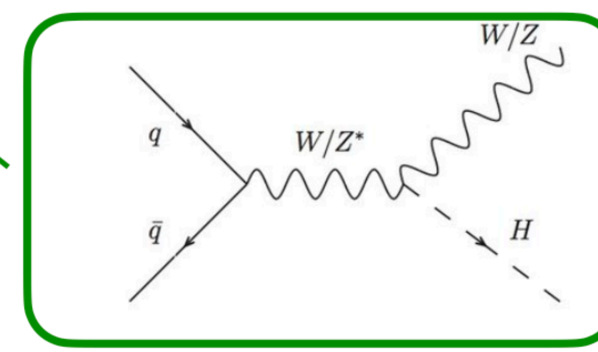
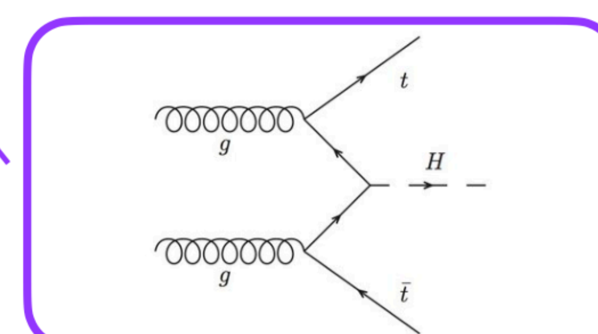


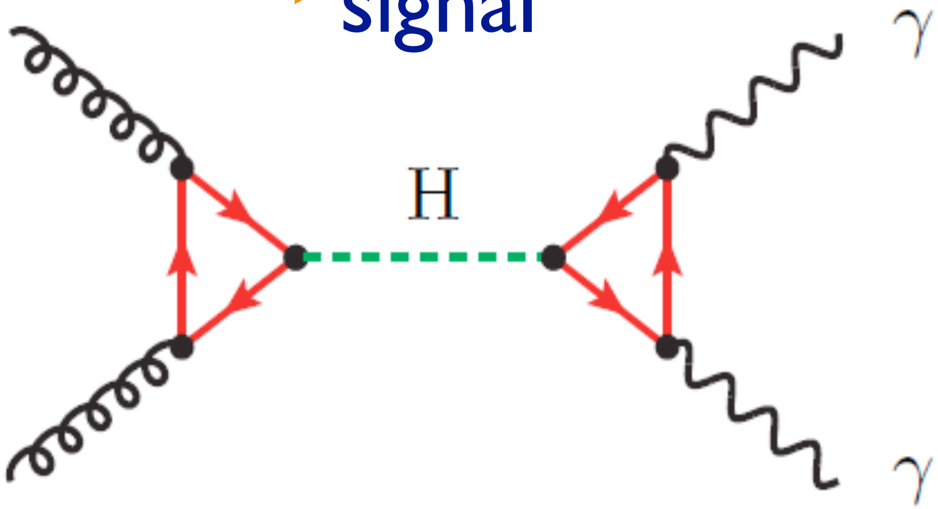
NNLO



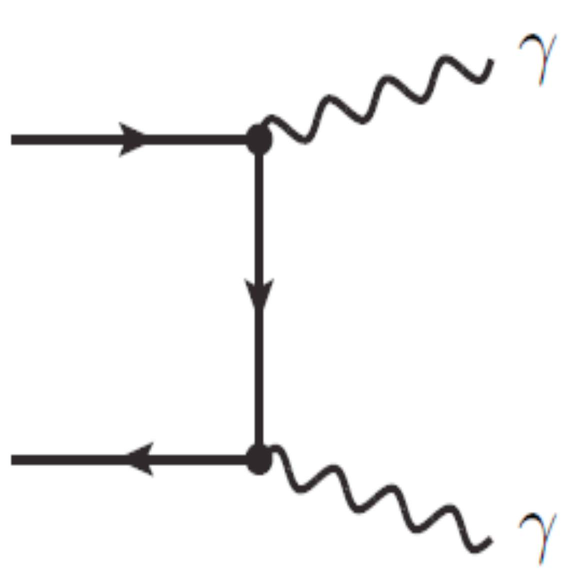
NLO + approx NNLO

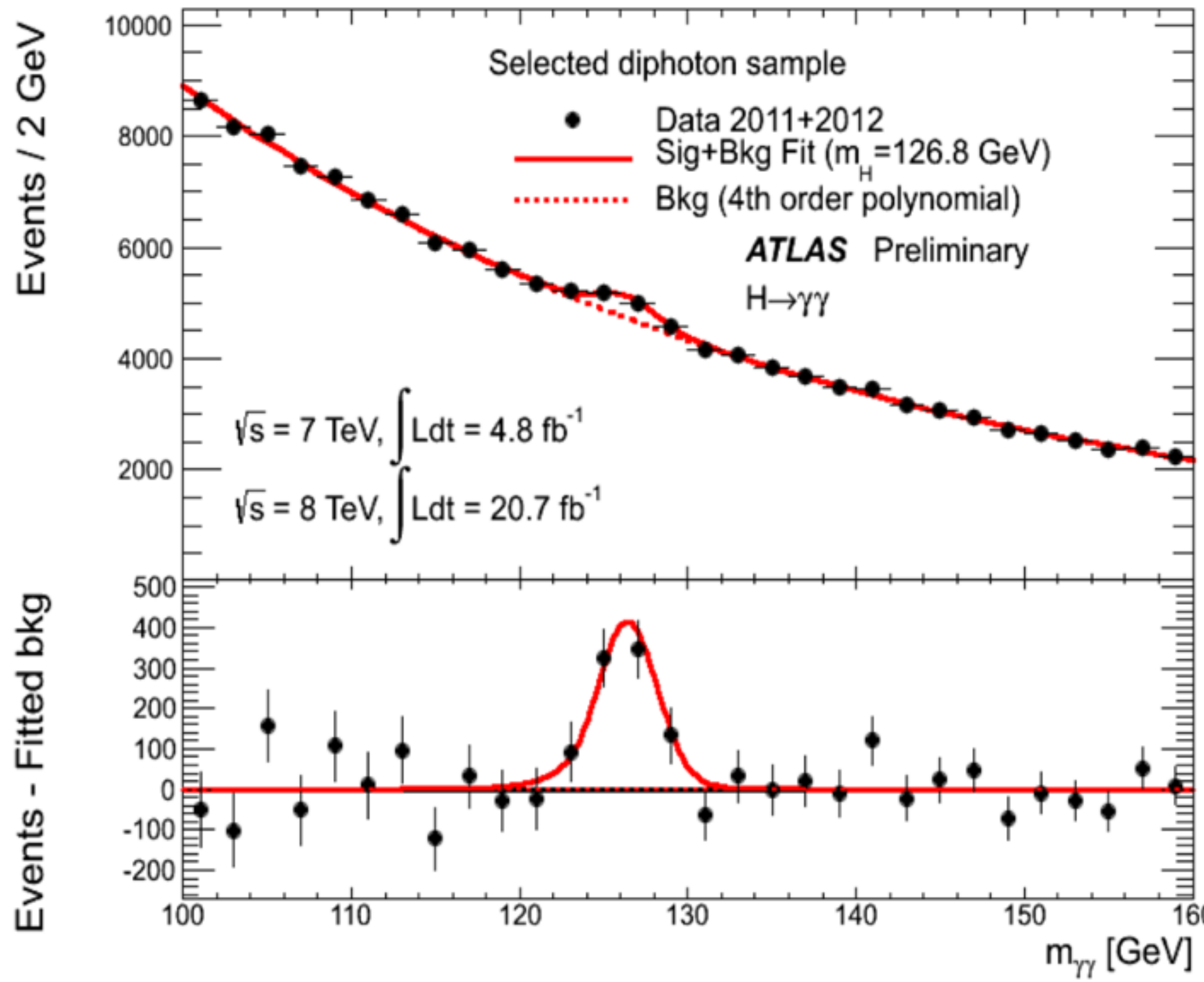
HIGGS boson discovery at the LHC

- signal



- background

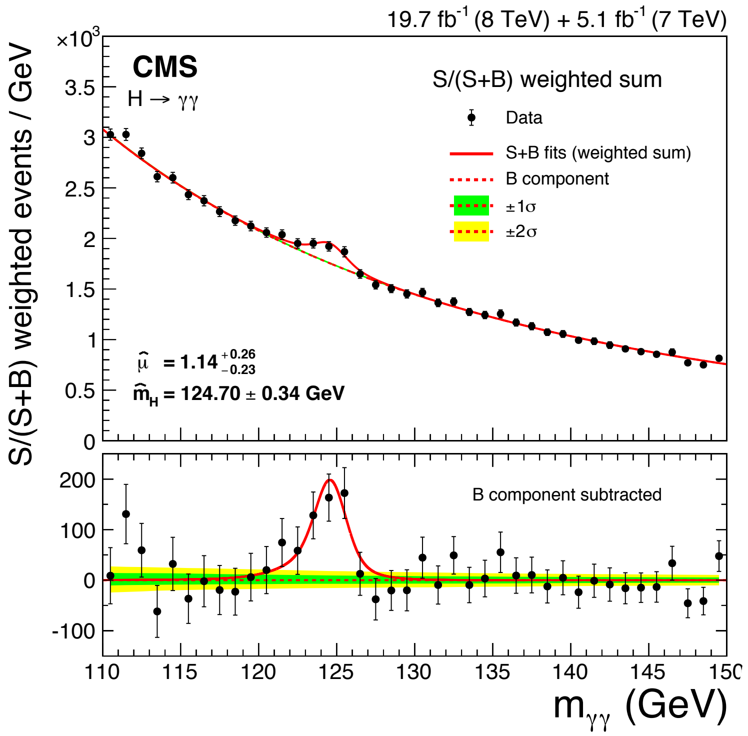


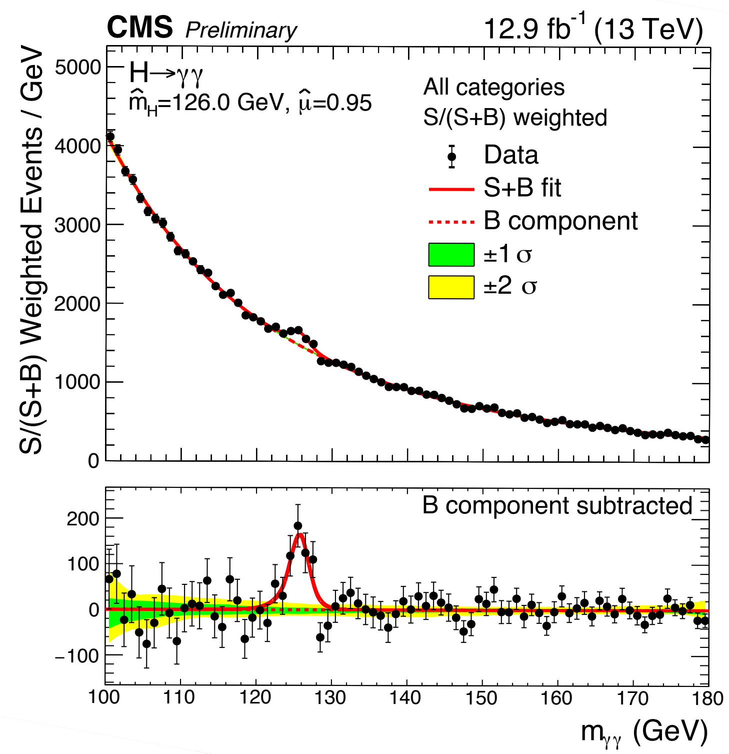


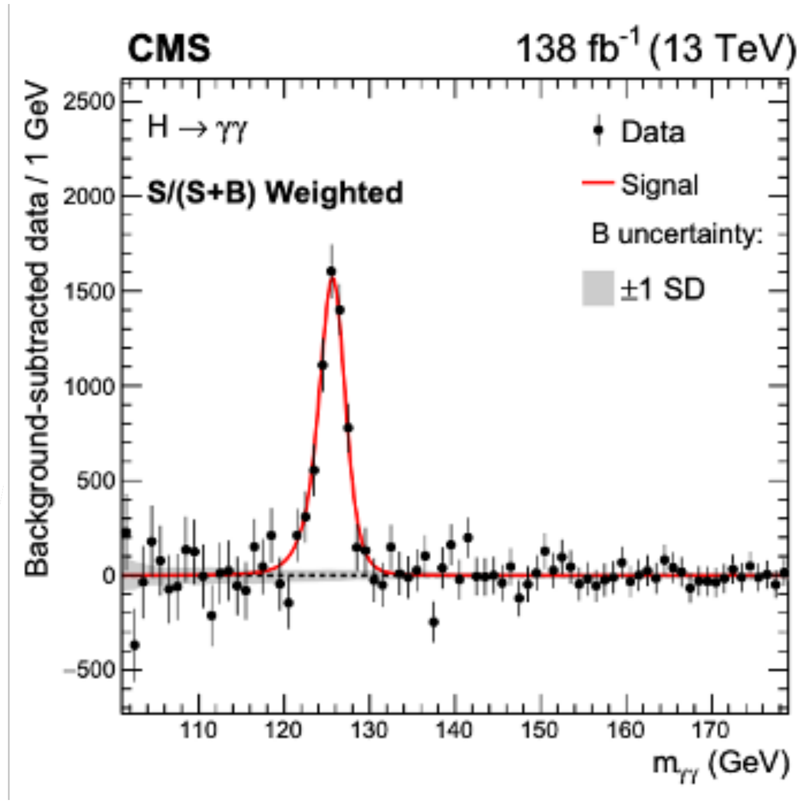
$$(p_{\gamma_1} + p_{\gamma_2})^2 = m_{\gamma\gamma}^2$$

Properties

Higgs discovered, re-discovered and re-re-discovered

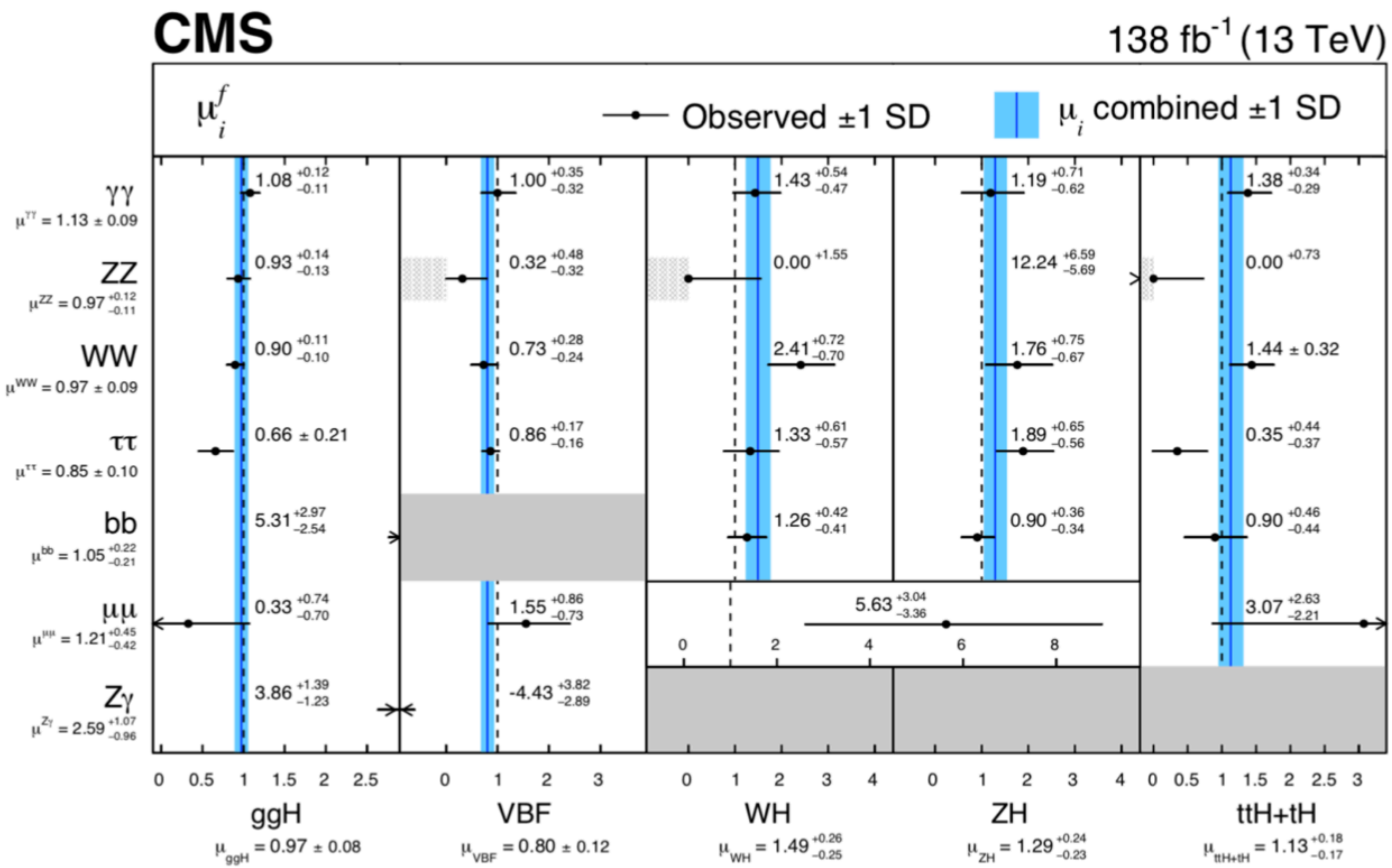






today: 30 x Higgs

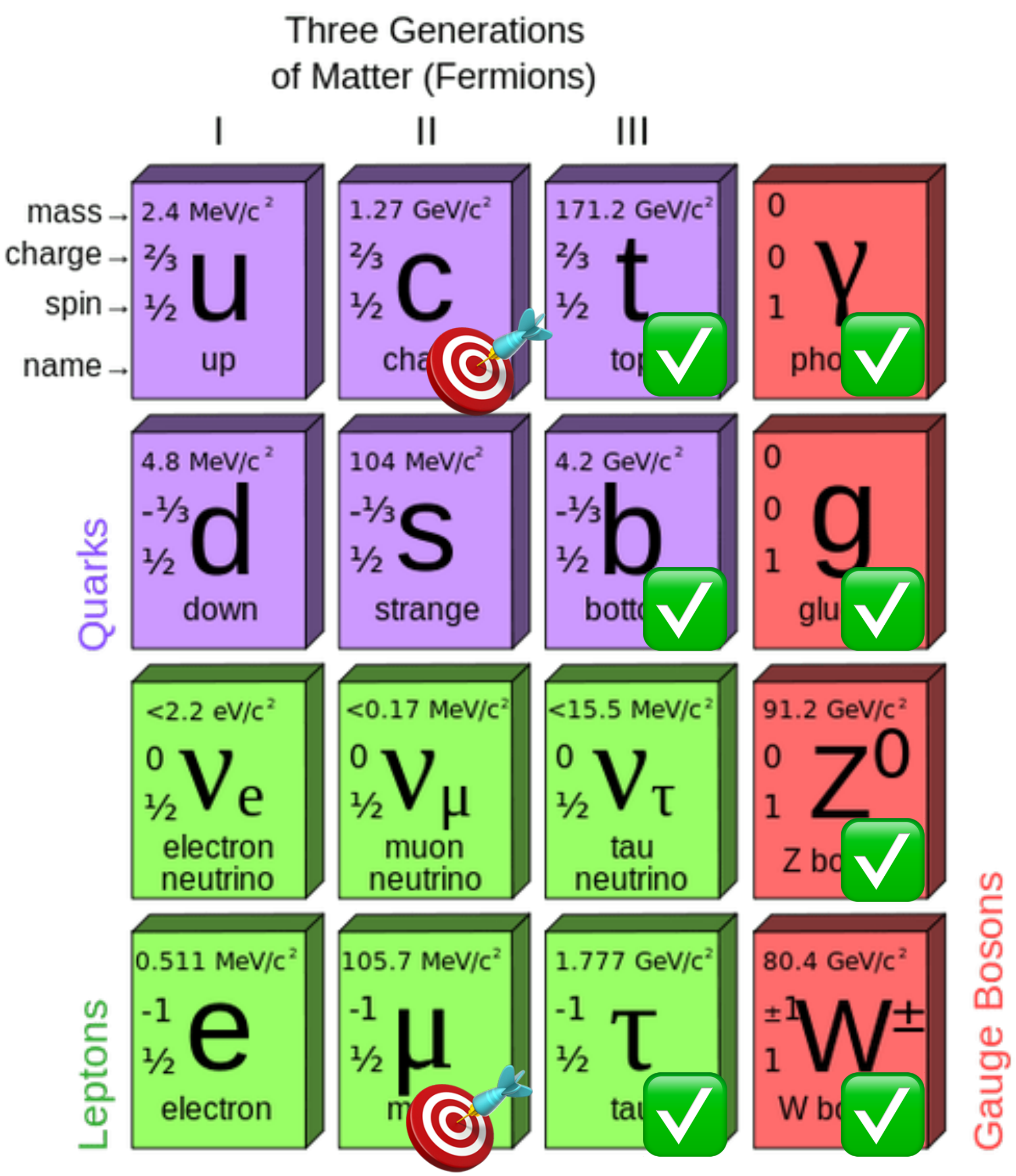
- Mass uncertainty (125 GeV) ~ 0.2% !
- Signal strength
  - ATLAS $\mu = 1.05 \pm 0.04$ (th) $\pm\, 0.03$ (exp) $\pm\, 0.03$ (stat)
  - CMS $\mu = 1.002 \pm 0.036$ (th) $\pm\, 0.033$ (exp) $\pm\, 0.029$ (stat)
- Cross sections in agreement with SM
- Electric charge = 0
- Spin = 0

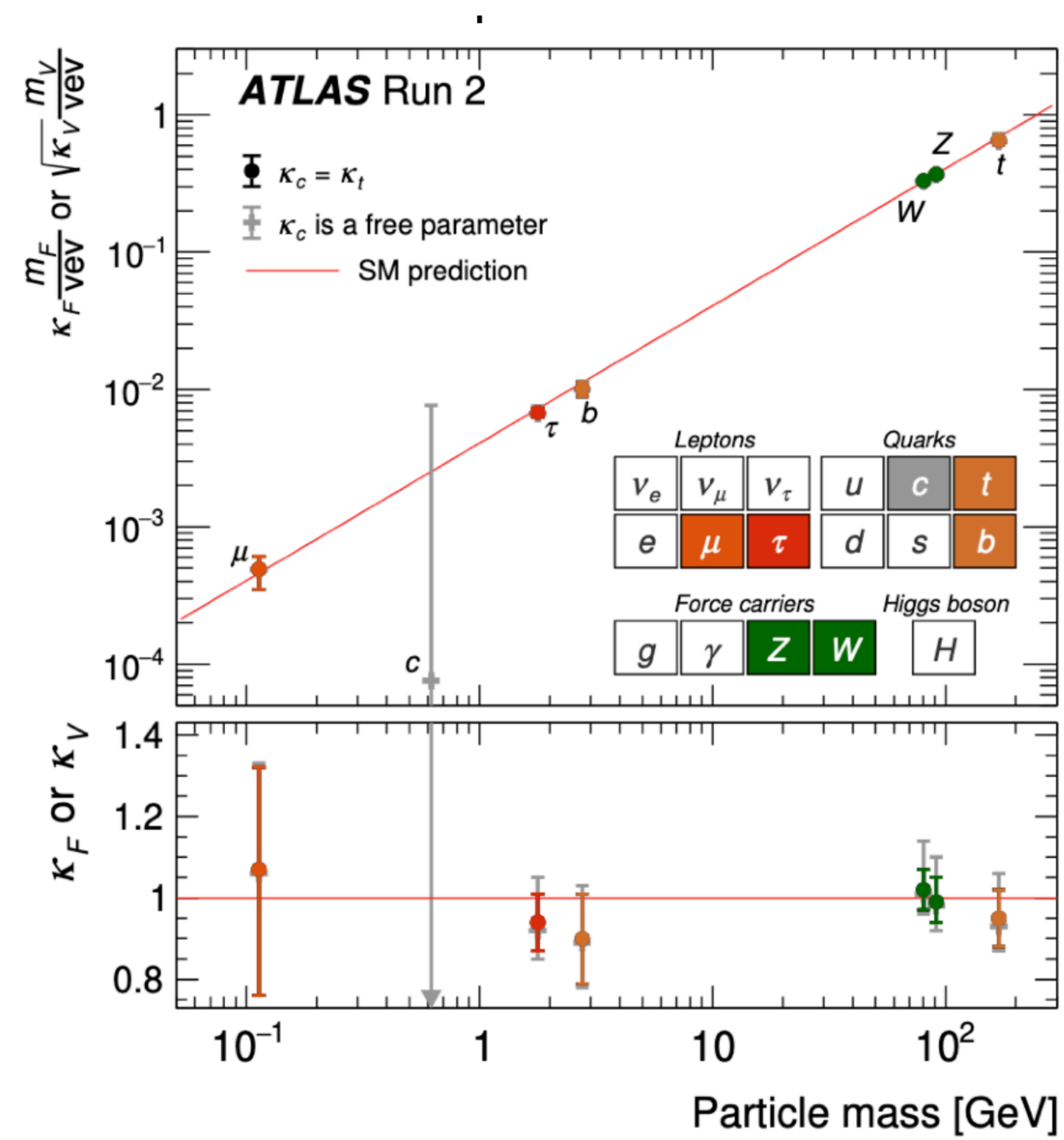


Overall signal strength normalised to SM expectation:
$\mu = 1.002 \pm 0.057$

Higgs couplings

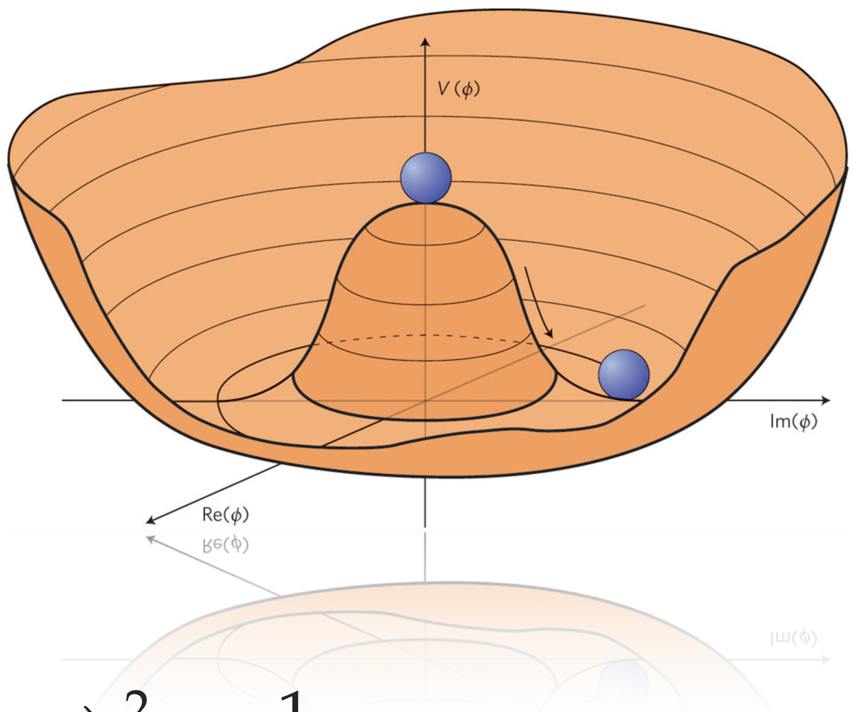
- Observation in all production channels, including $t\bar{t}H$!
- Observation of decay in $\gamma\gamma, WW, ZZ, b\bar{b}, \tau\bar{\tau}$
- Second generation more difficult but on the way to $c\bar{c}, \mu^+\mu^-$
- No measurement of HHH and HHHH couplings (see later)



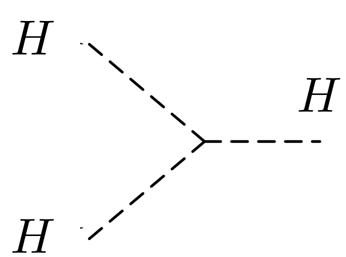


- **NO information about Higgs self-couplings**

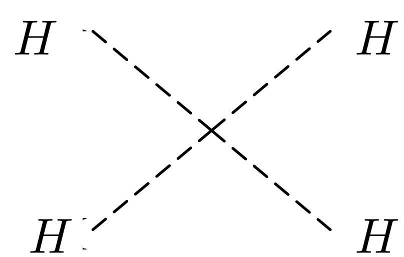
- Need to study multiple Higgs production
  to explore mechanism for Spontaneous Symmetry Breaking



$$V = \frac{\lambda}{4}\left(2vH + H^2\right)^2 = \frac{1}{2}(2\lambda v^2)H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4$$



$$-3i\frac{m_H^2}{v}$$

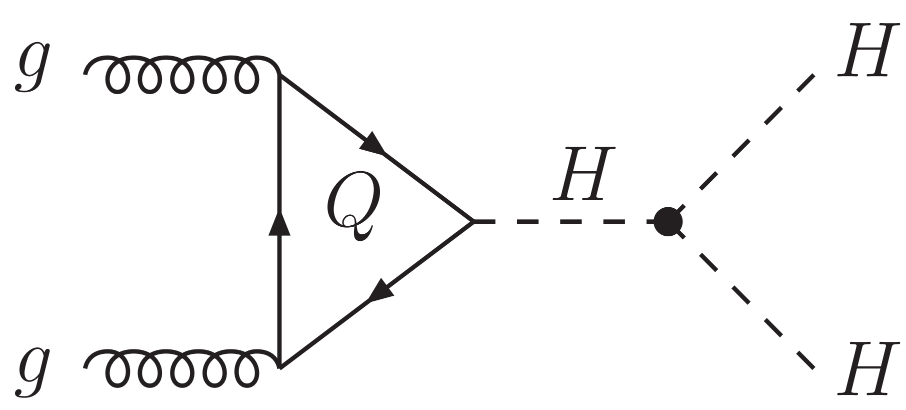


$$-3i\frac{m_H^2}{v^2}$$

Higgs pair production

- To measure 3H coupling one needs to look at 2H production

much smaller cross sections @ 14 TeV



~ 40 fb

difficult but **next discovery**?

HL-LHC 4000 fb^{-1} ~ 160.000 HH

- Production rate drops 3 orders of magnitude for each extra H

Experimental limit in self-coupling today ~ 5 x SM

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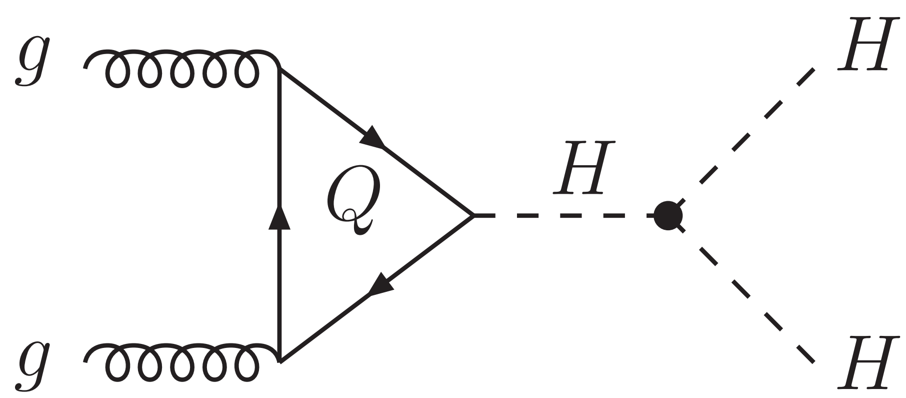

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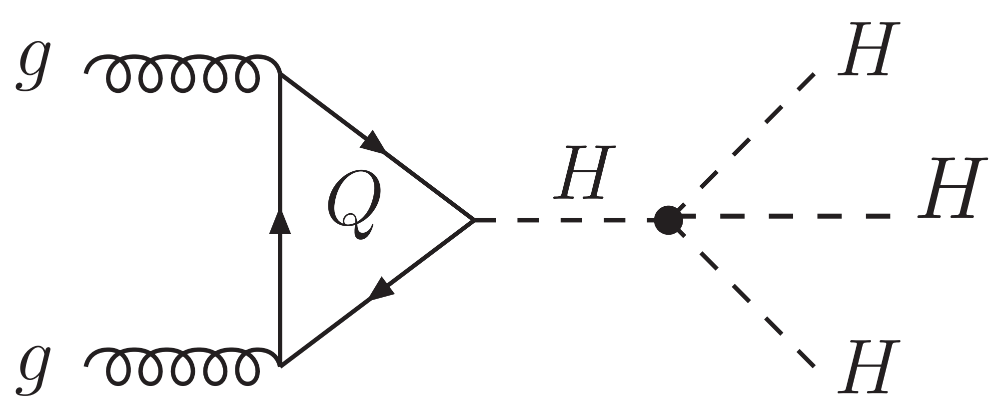
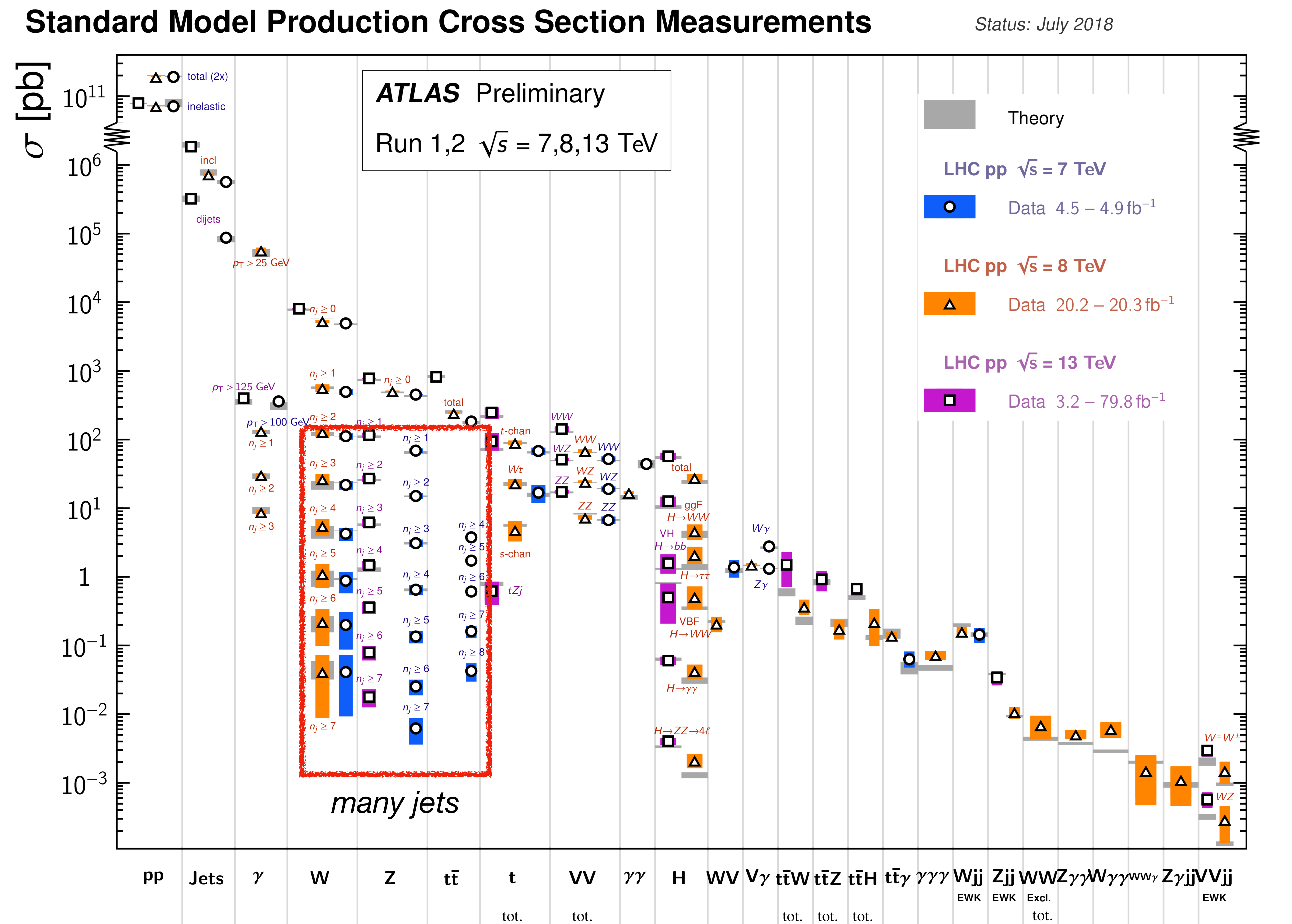


~ 0.05 fb impossible at LHC

- Production rate drops 3 orders of magnitude for each extra H

Experimental limit in self-coupling today ~ 5 x SM

Future 1



Standard Model Production Cross Section Measurements
Status: July 2018
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 79.8 fb⁻¹
σ [pb]
many jets
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
WV
Vγ
tt̄W
tt̄Z
tt̄H
tt̄γ
γγγ
Wjj EWK
Zjj EWK
WW Excl.
Zγγ
Wγγ
WWγ
Zγjj
VVjj EWK
tot.

Everything looks SM-like within (large) uncertainties

- There is plenty of room for discoveries yet

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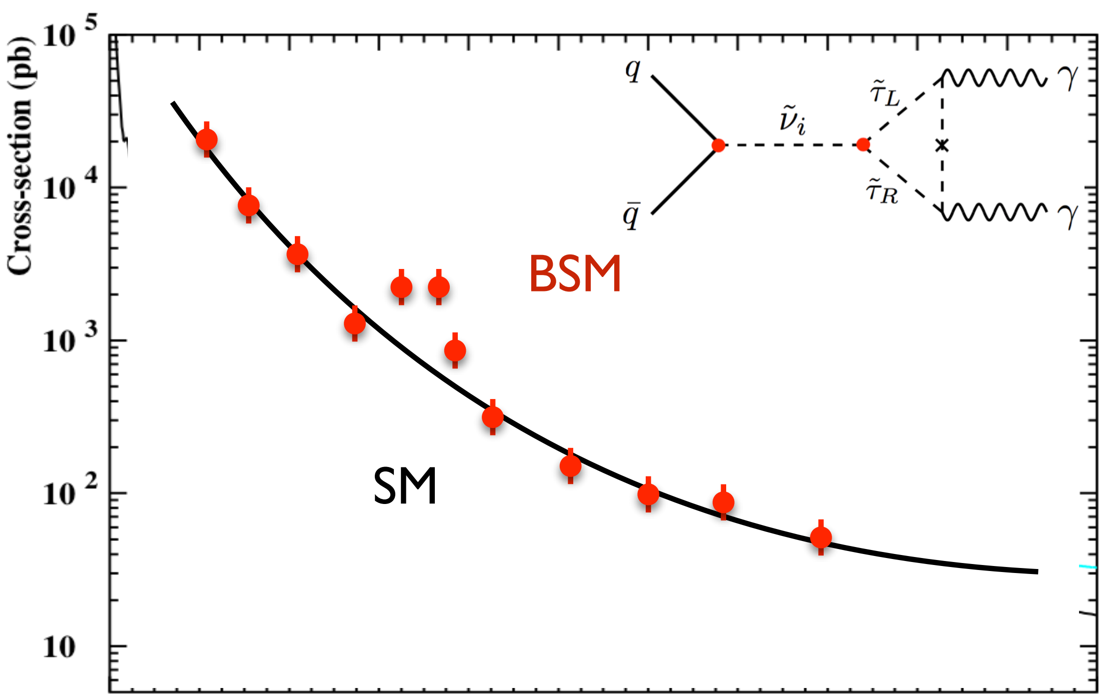
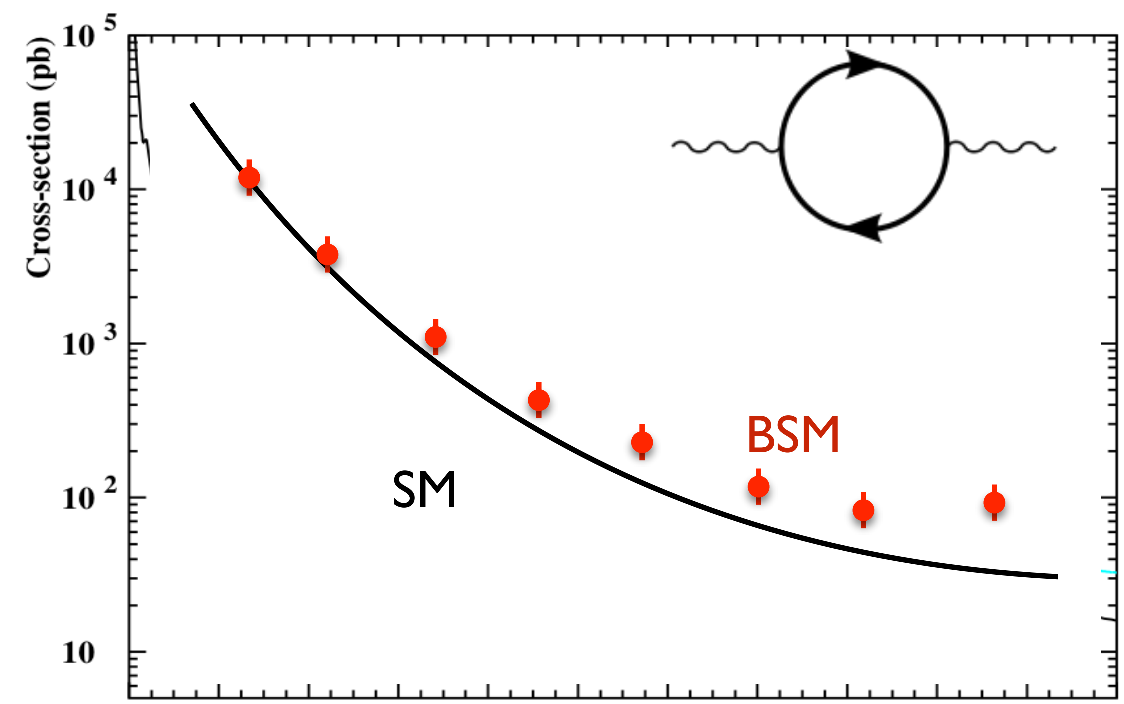


Search for new *states*
Resonances: "Descriptive TH"



Search for new *interactions*
Deviations: "Precision TH"
+ EFT description

- **Explore Higgs sector with precision**
  - less known (room for surprises!)
  - more sensitive (Portal) to new physics
  - *Potential* : look at multiple Higgs production

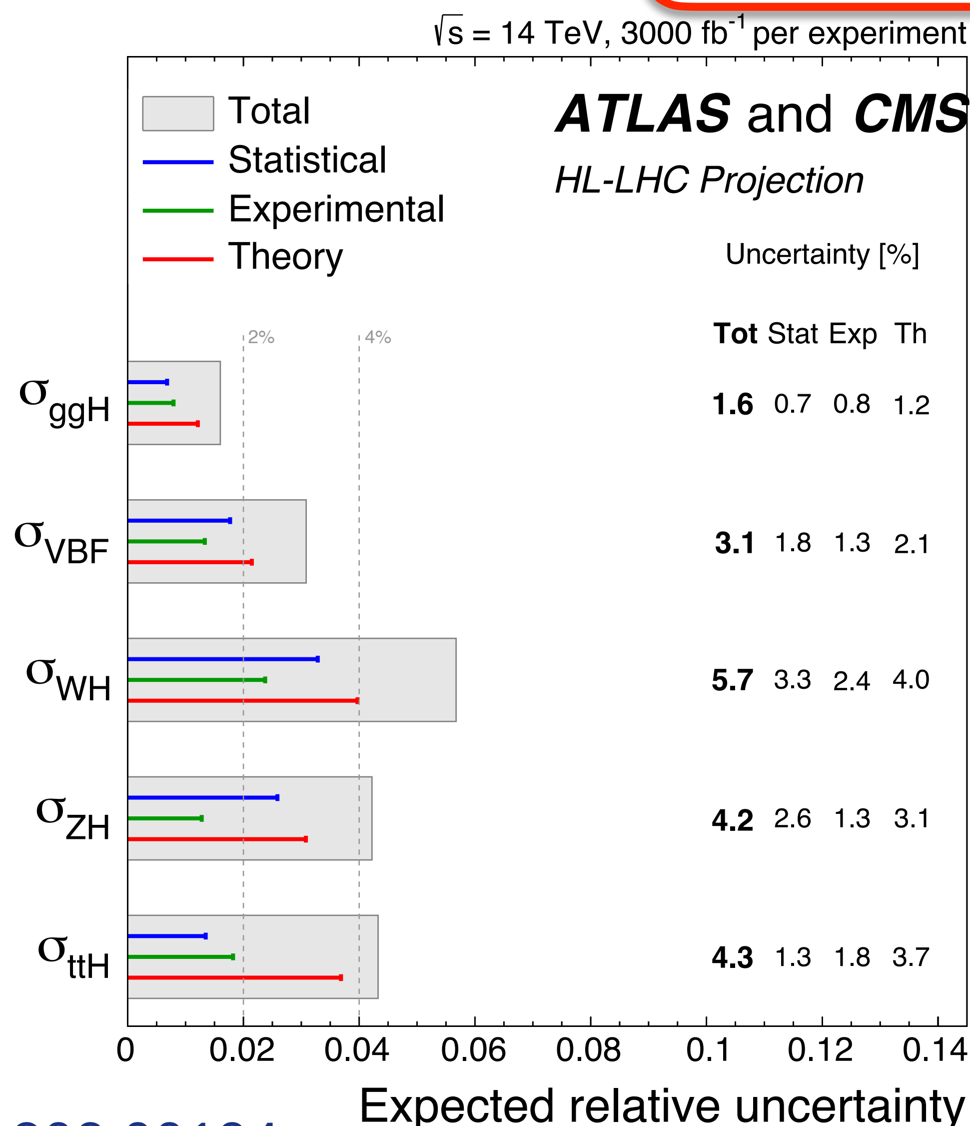
- **EXP and TH : (for Higgs) Precision is the name of the game**

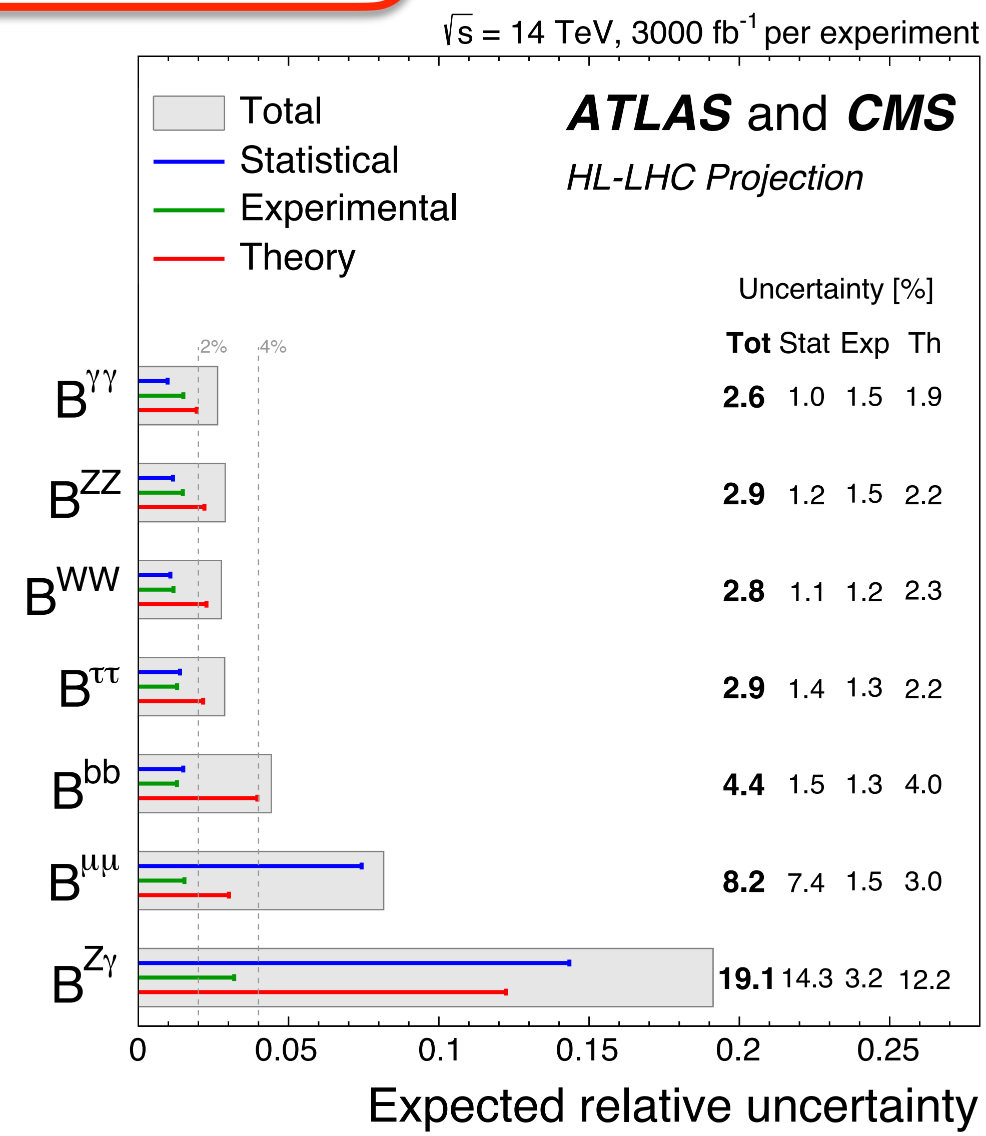
electron	(1897) Thompson
positron	(1932) Anderson
muon	(1937) Cosmic radiation-Cloud chamber
neutrino electron	(1956) Savannah River Plant
neutrino muon	(1962) BNL
u,d,s	(1969) SLAC
charm	(1974) SLAC-BNL
tau	(1975) SLAC-SPEAR-LBL
bottom	(1977) E288
gluon	(1979) DORIS/PETRA
W/Z	(1983) UA1
top	(1995) Tevatron
neutrino tau	(2000) DONUT
Higgs	(2012) LHC

One big discovery per experiment…

HL-LHC projections ~20 years from now!

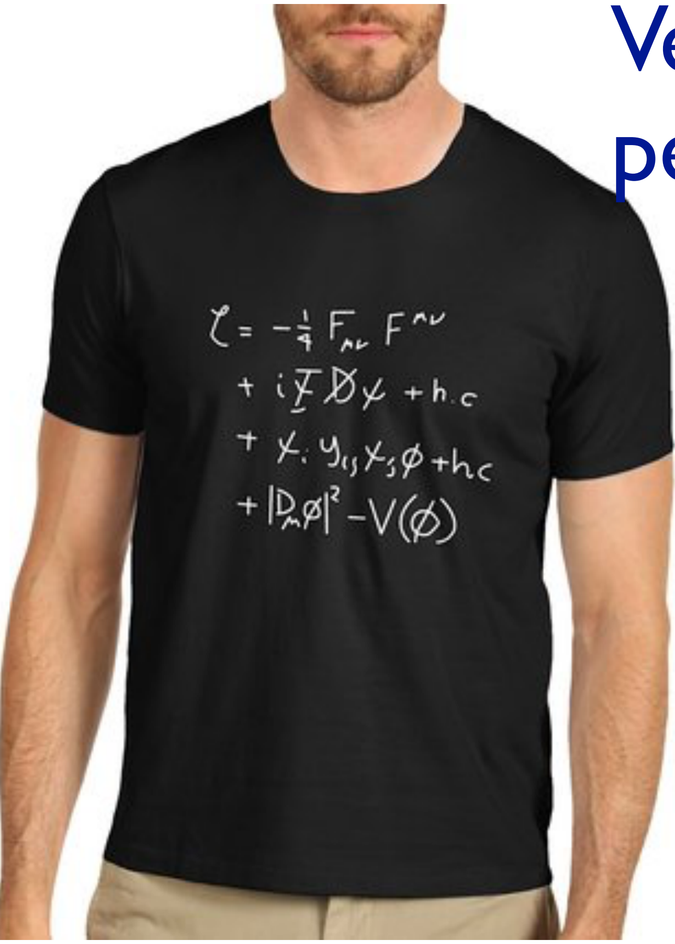
(S2) TH uncertainties scaled down by factor 2, EXP scaled according to $\sqrt{\mathcal{L}}$





1902.00134

- Theoretical uncertainties on SM predictions generally largest component
- Precision becomes critical
- TH: can we improve calculations? Where? How?



Very nice Lagrangian, but can not be solved analytically
perturbative expansion

Actual
Taylor expansion

Lies invented by mathematicians
to feel superior to physicists

$$f(x) = f(0) + f'(0)x + \frac{f''(0)}{2!}x^2 + \frac{f'''(0)}{3!}x^3 \ldots$$

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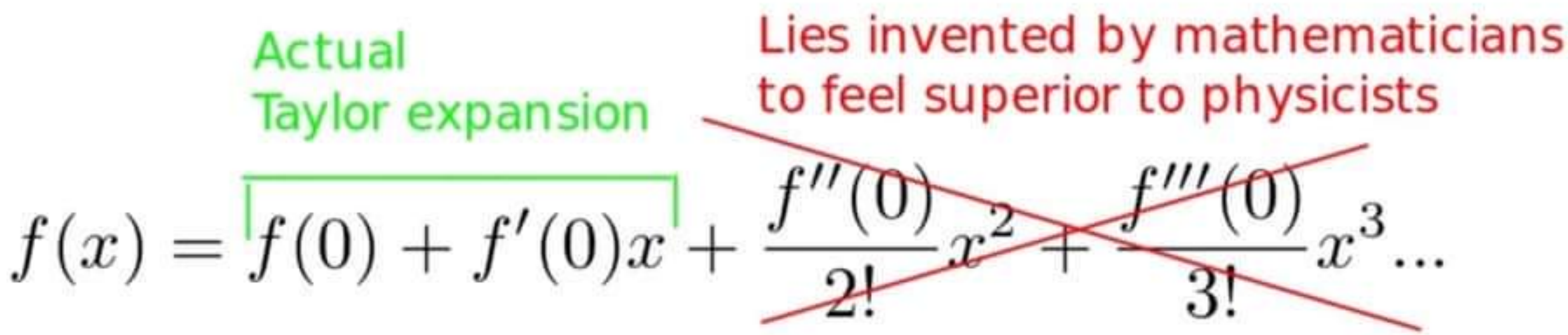
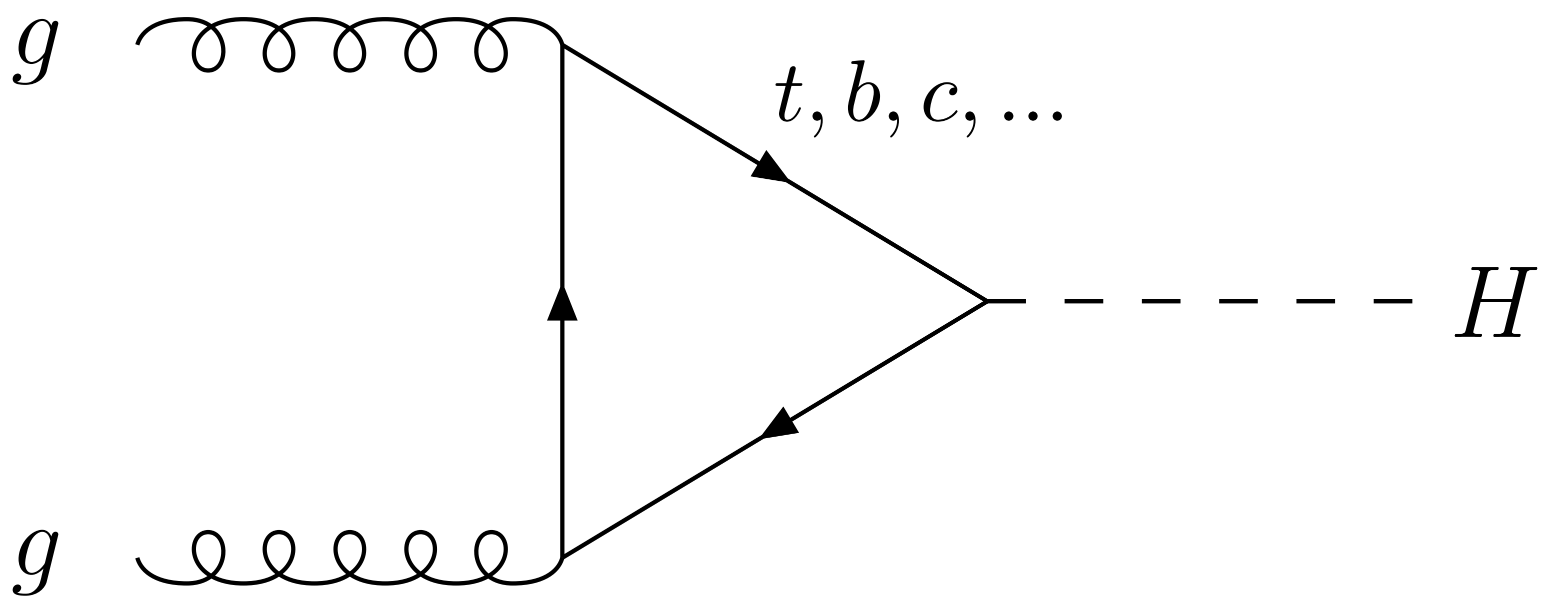


- Perturbative parameter $\alpha_s \sim 0.11$
- Strong coupling

QCD requires high orders…

- Perturbative expansion in QCD coupling $\alpha_s \sim 0.11$

$$C_0\alpha_s^0 + C_1\alpha_s^1 + C_2\alpha_s^2 + C_3\alpha_s^3 + ...$$



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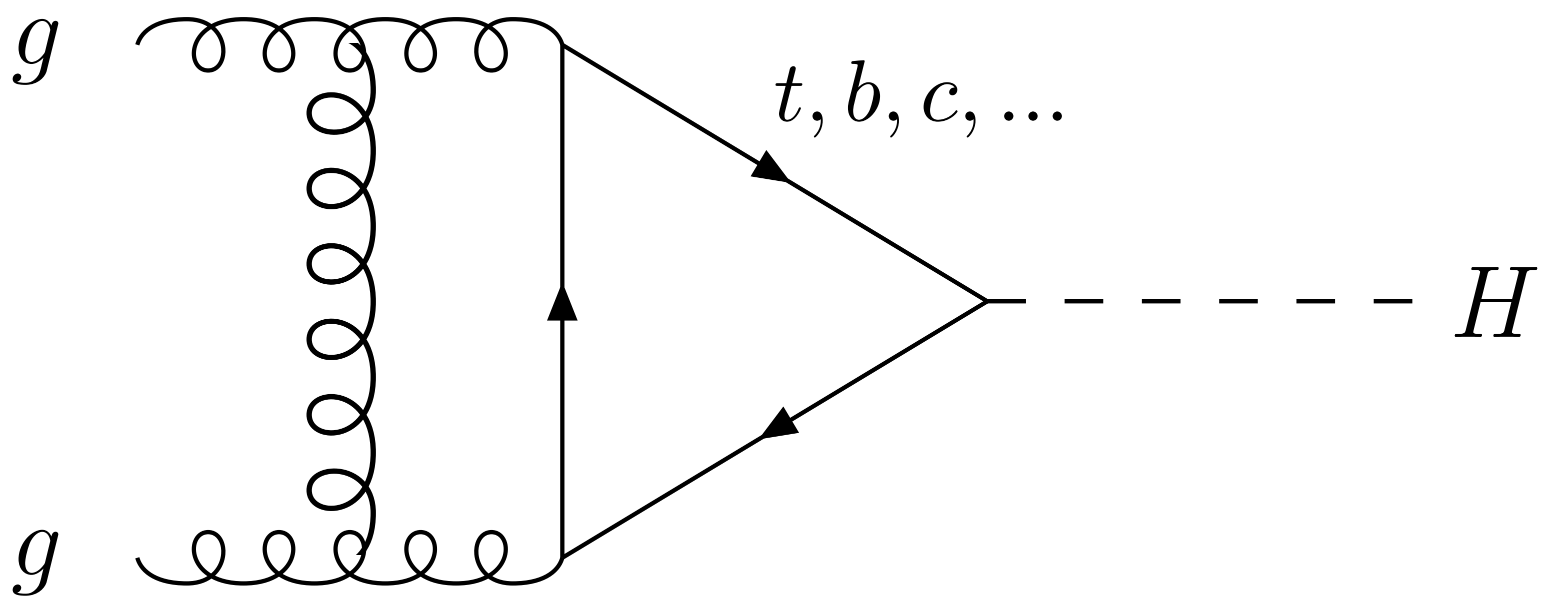

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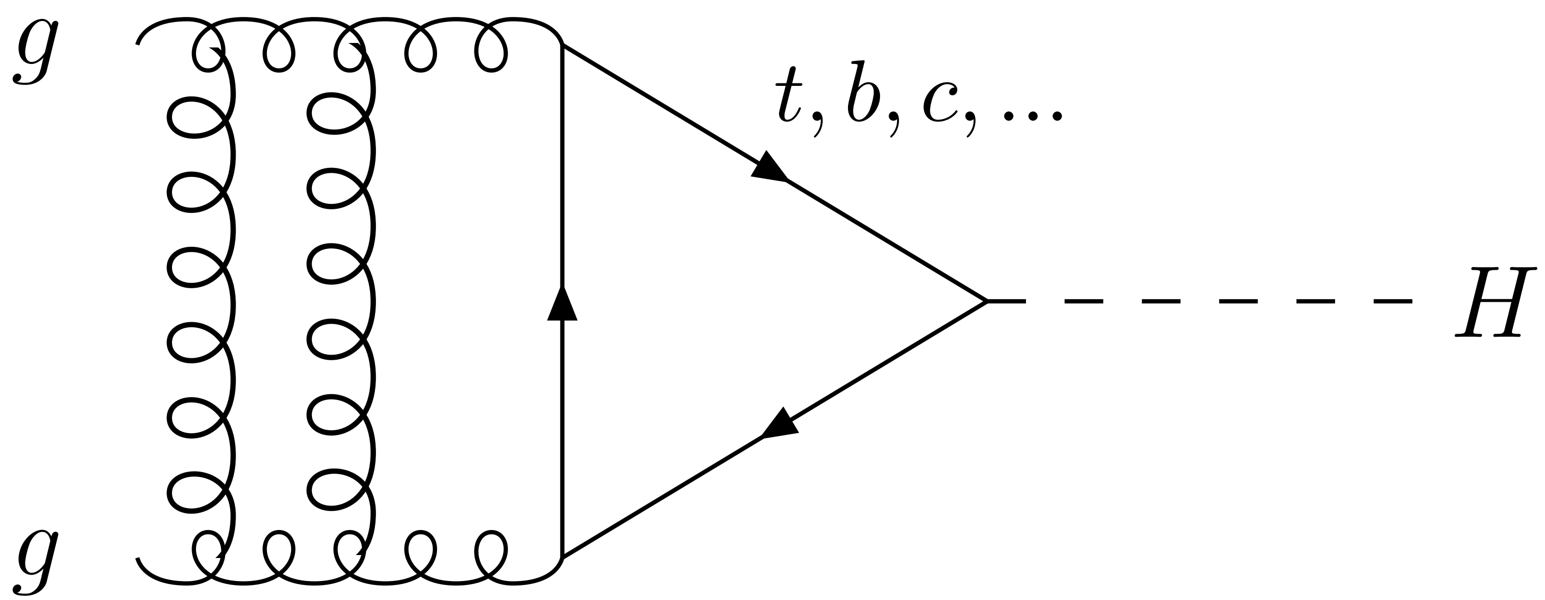

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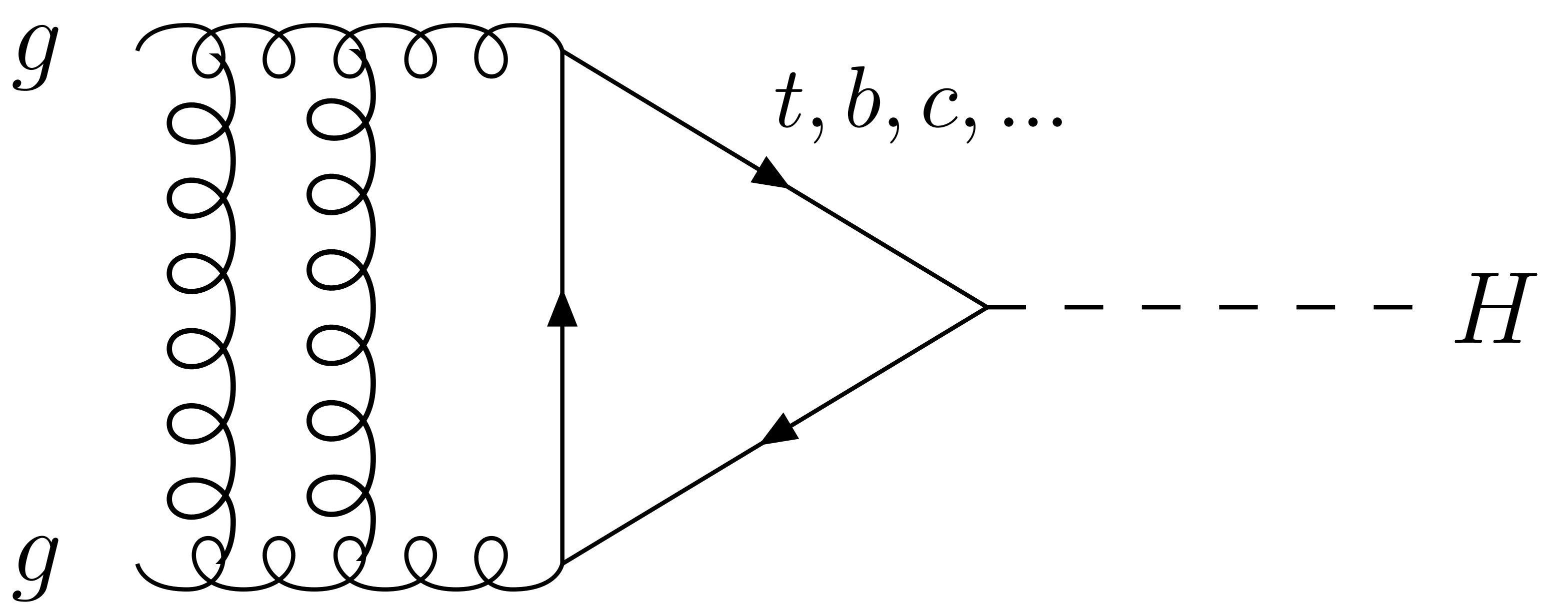
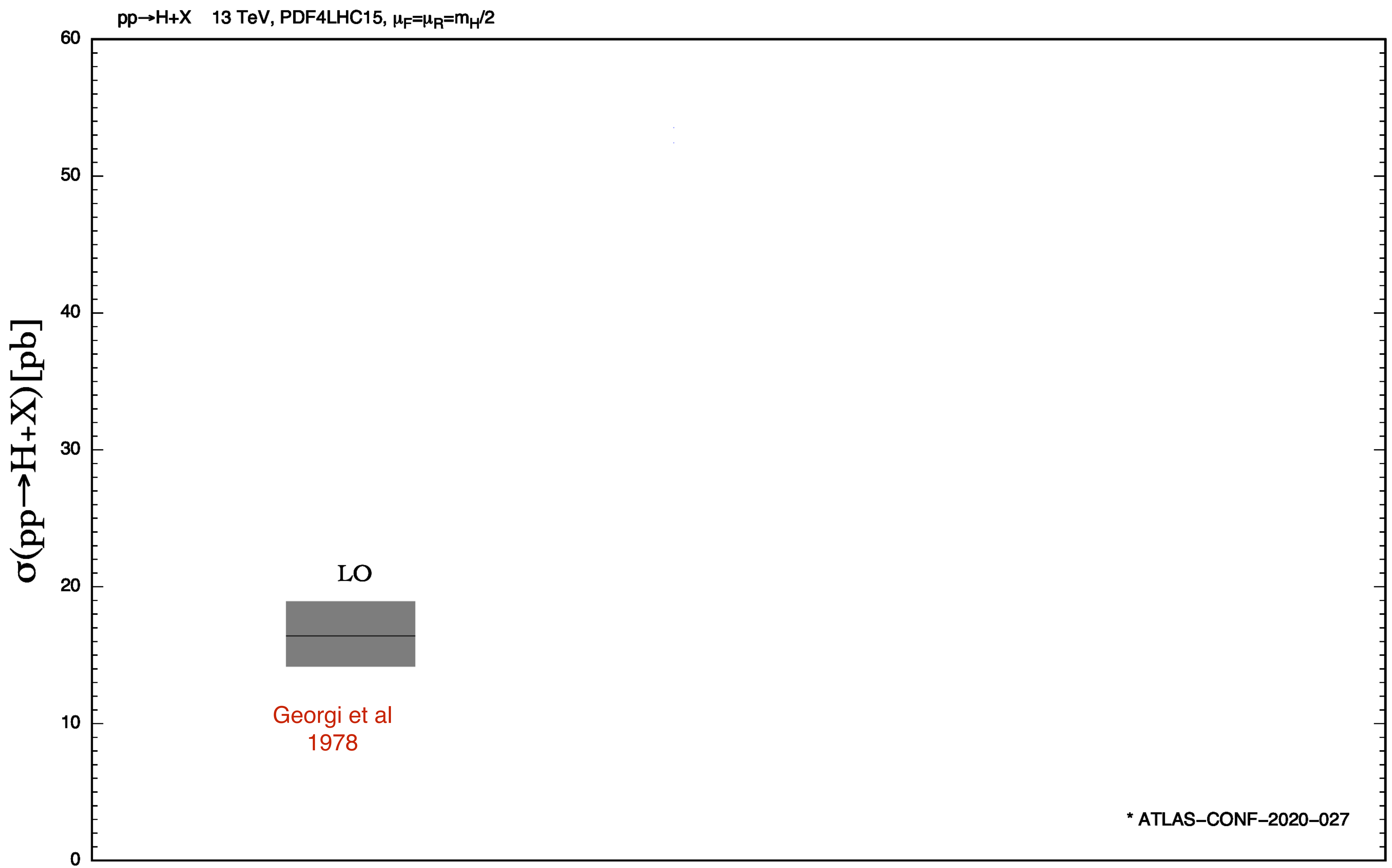
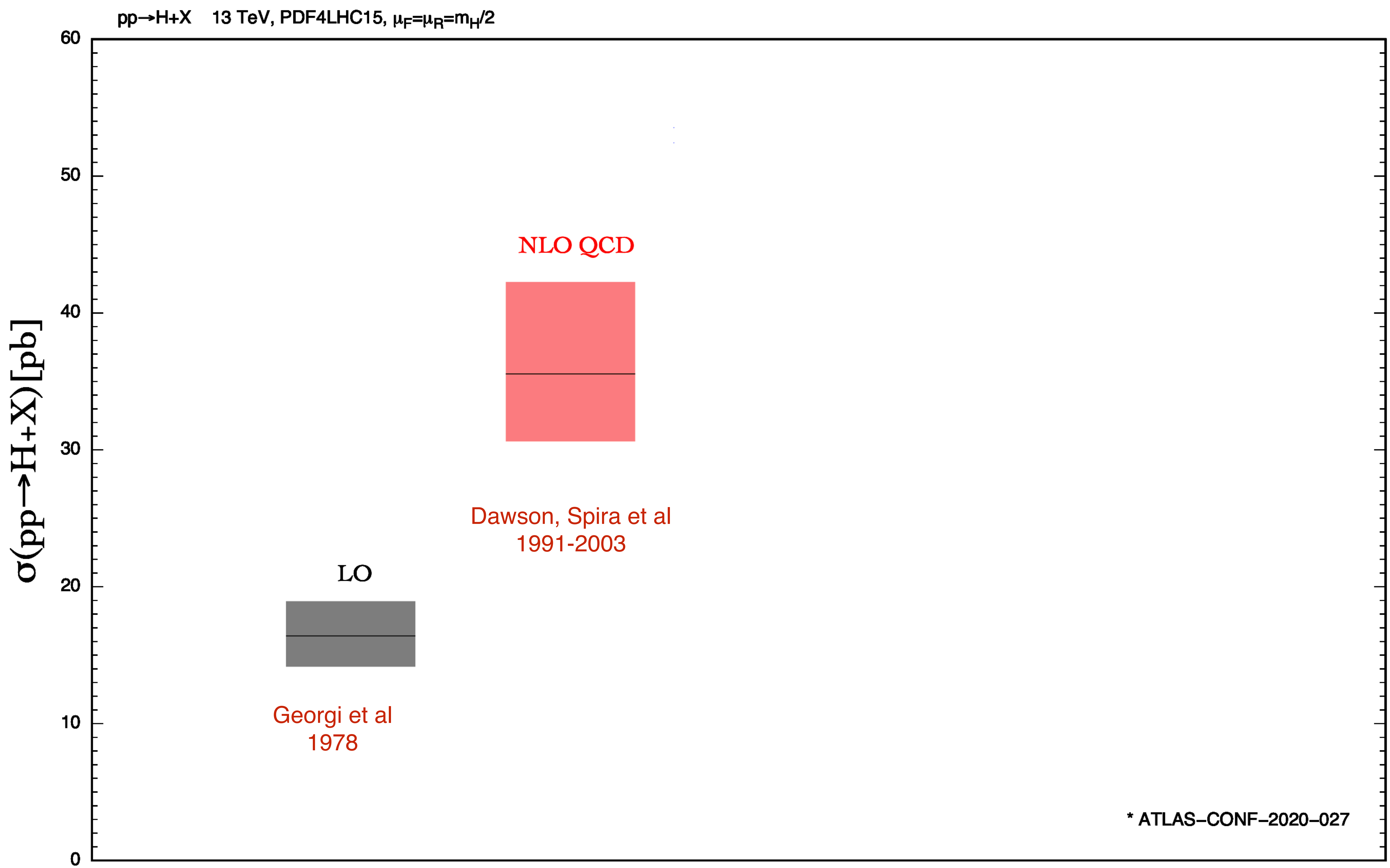


$$\sigma = \sigma^{(0)}(1 + 0.89 + 0.55 + 0.3 + \ldots)$$

$$\alpha_s^0 + \alpha_s^1 + \alpha_s^2 + \alpha_s^3$$

Very slow convergence (and millions of integrals needed…)


pp→H+X 13 TeV, PDF4LHC15, μF=μR=mH/2
σ(pp→H+X) [pb]
60
50
40
30
20
10
0
LO
Georgi et al
1978
* ATLAS-CONF-2020-027



pp→H+X 13 TeV, PDF4LHC15, μF=μR=mH/2
σ(pp→H+X) [pb]
60
50
40
30
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NLO QCD
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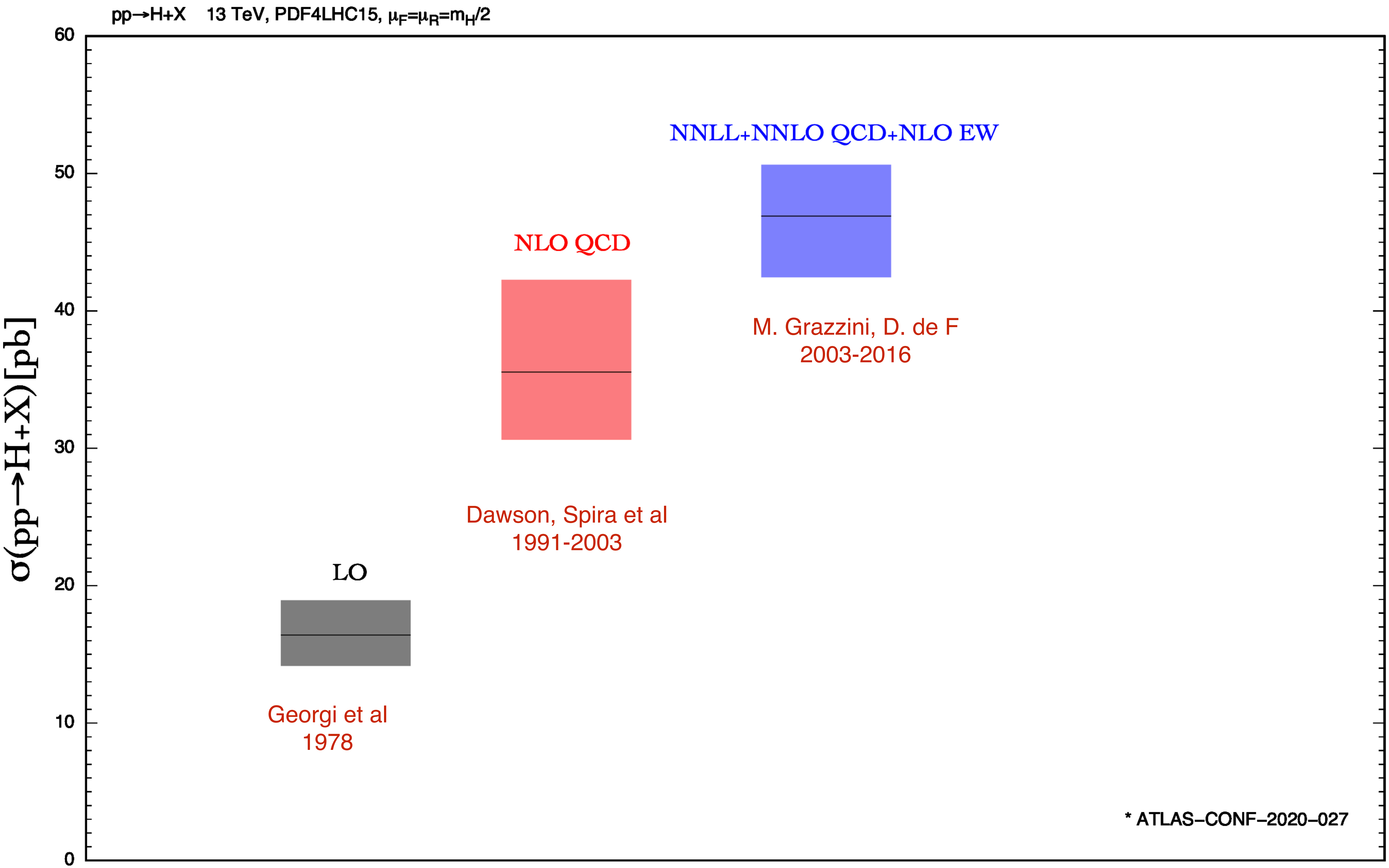

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M. Grazzini, D. de F
2003-2016
Dawson, Spira et al
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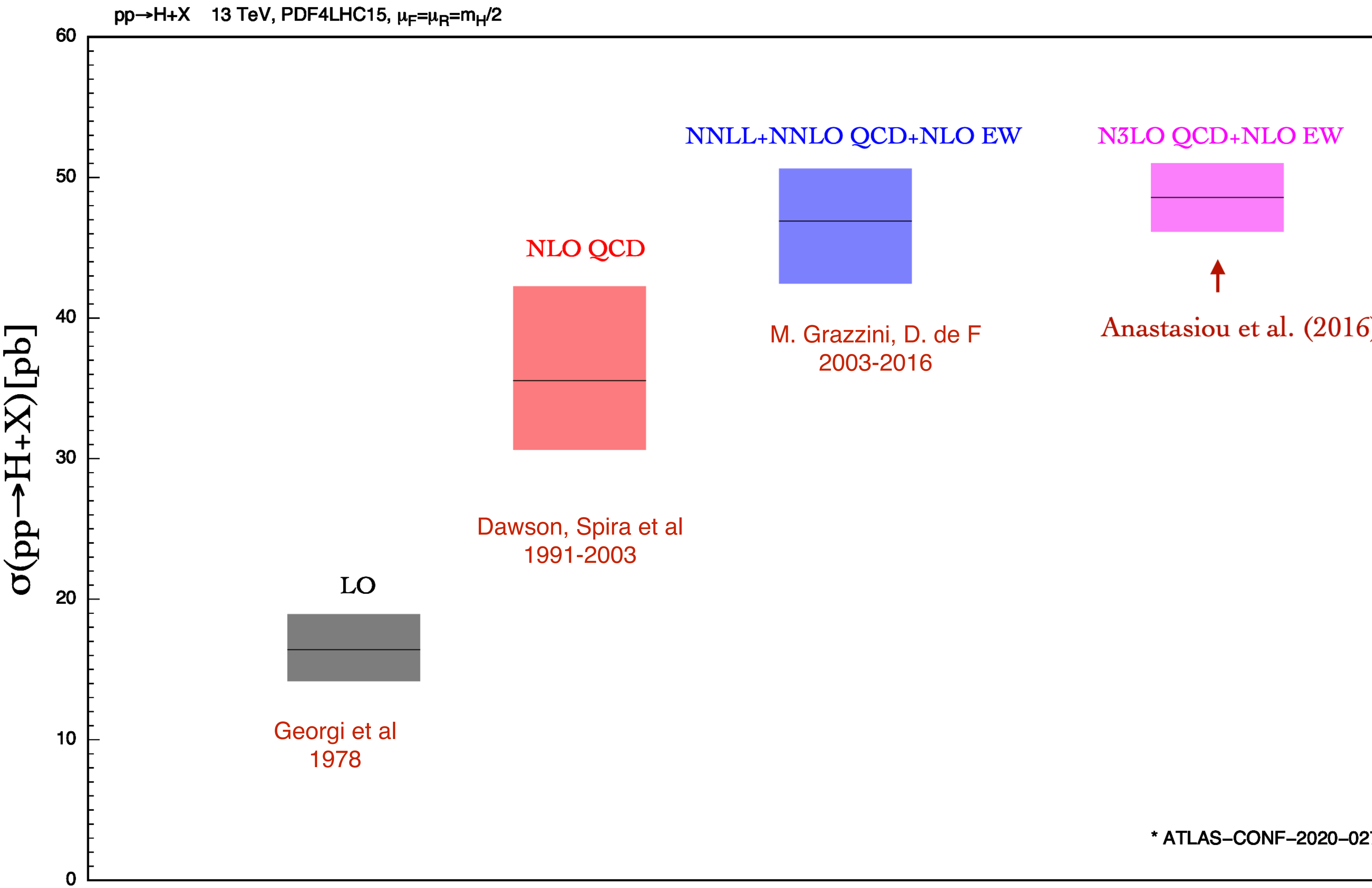

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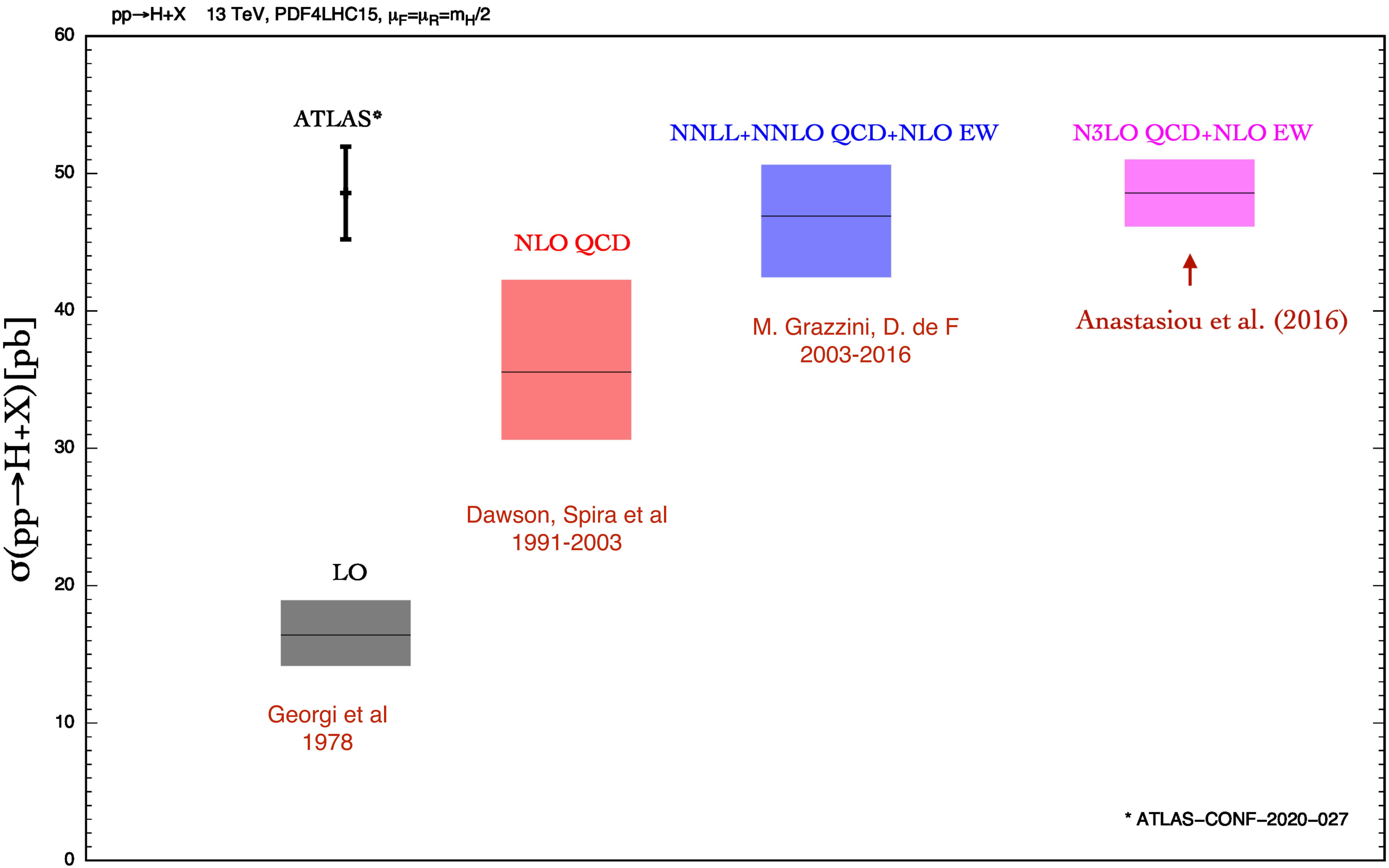

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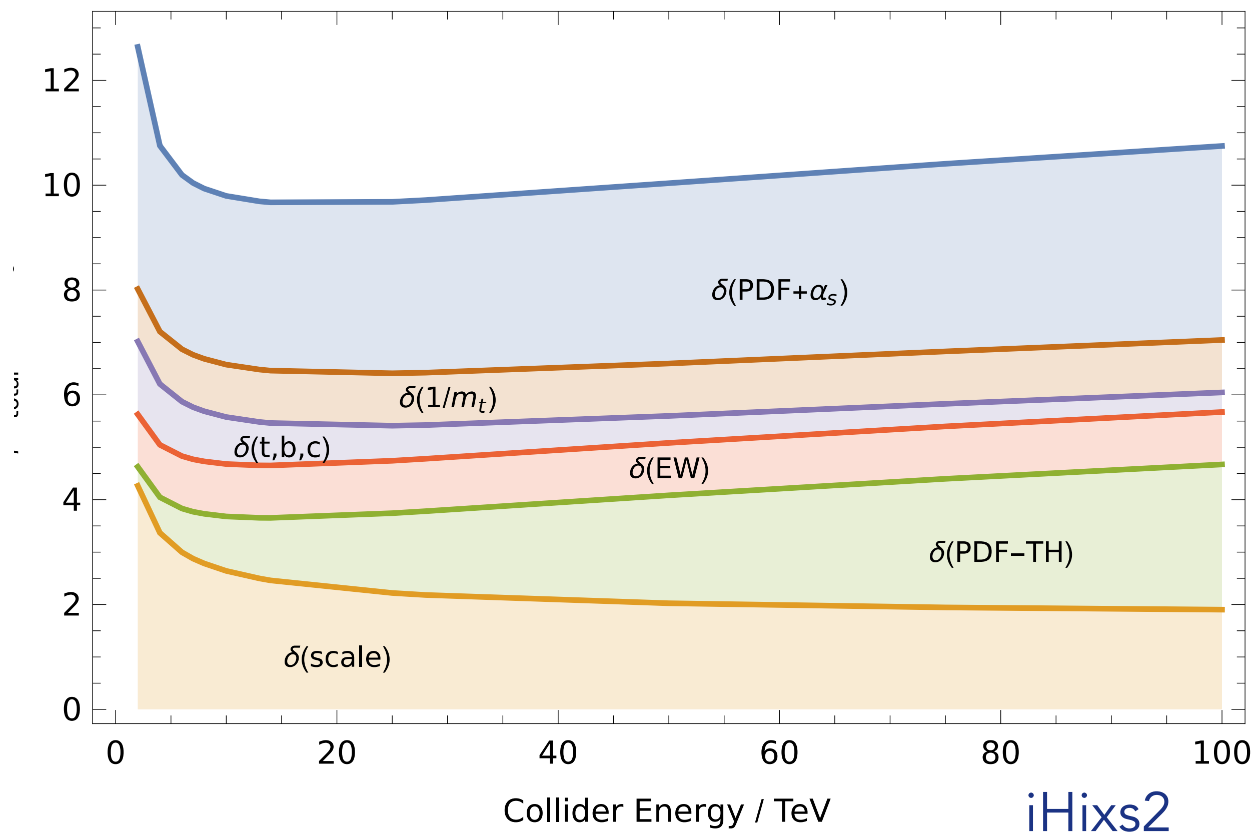
Improved Higgs Cross-section @ LHC

✓at 13 TeV   Higgs Cross-Section WG

$$
\begin{aligned}
\sigma_{PP\to H+X} &= 16.00\text{ pb} \quad (+32.87\%) \quad \text{LO, rEFT}\\
&+ 20.84\text{ pb} \quad (+42.82\%) \quad \text{NLO, rEFT}\\
&+ 9.56\text{ pb} \quad (+19.64\%) \quad \text{NNLO, rEFT}\\
&+ 1.62\text{ pb} \quad (+3.32\%) \quad \text{N}^3\text{LO, rEFT}\\
&- 2.07\text{ pb} \quad (-4.25\%) \quad \text{(t,b,c) corr. to exact NLO}\\
&+ 0.34\text{ pb} \quad (+0.70\%) \quad 1/m_t \text{ corr. to NNLO}\\
&+ 2.37\text{ pb} \quad (+4.87\%) \quad \text{EWK corr.}\\
&= 48.67\text{ pb}\,.
\end{aligned}
$$

$$
\begin{aligned}
\delta(\text{theory}) &= {}^{+0.13pb}_{-1.20pb} \quad \left({}^{+0.28\%}_{-2.50\%}\right) \quad \delta(\text{scale})\\
&+ \pm 0.56pb \quad (\pm 1.16\%) \quad \delta(\text{PDF-TH})\\
&+ \pm 0.49pb \quad (\pm 1.00\%) \quad \delta(\text{EWK})\\
&+ \pm 0.41pb \quad (\pm 0.85\%) \quad \delta(\text{t,b,c})\\
&+ \pm 0.49pb \quad (\pm 1.00\%) \quad \delta(1/m_t)\\
&= {}^{+2.08pb}_{-3.16pb} \quad \left({}^{+4.28\%}_{-6.5\%}\right),\\
\delta(\text{PDF}) &= \pm 0.89\text{pb} \quad (\pm 1.85\%),\\
\delta(\alpha_S) &= {}^{+1.25pb}_{-1.26pb} \quad \left({}^{+2.59\%}_{-2.62\%}\right).
\end{aligned}
$$

- uncertainties



- Great improvement over the last years
- Without QCD corrections : fail by more than a factor of 2
- Need to attack in many fronts to further improve: pdf, top mass, EW

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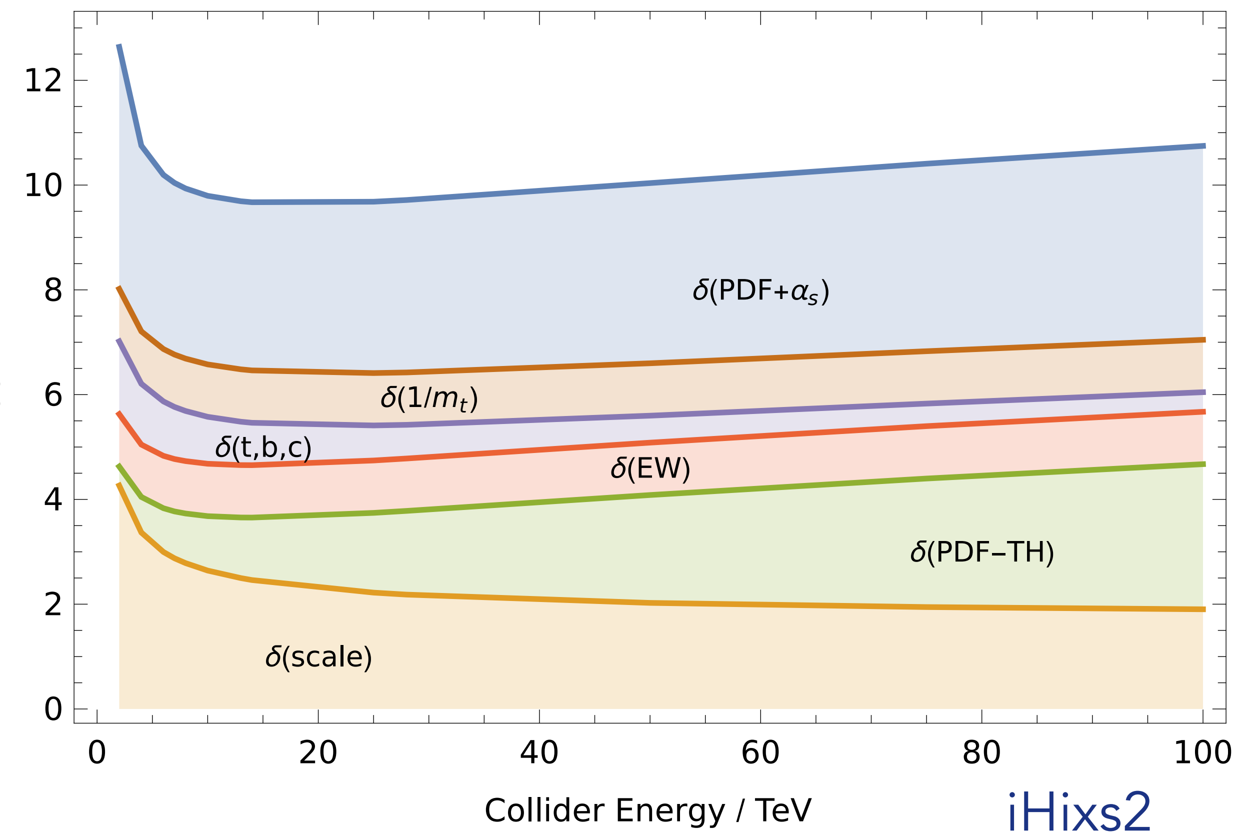
- uncertainties



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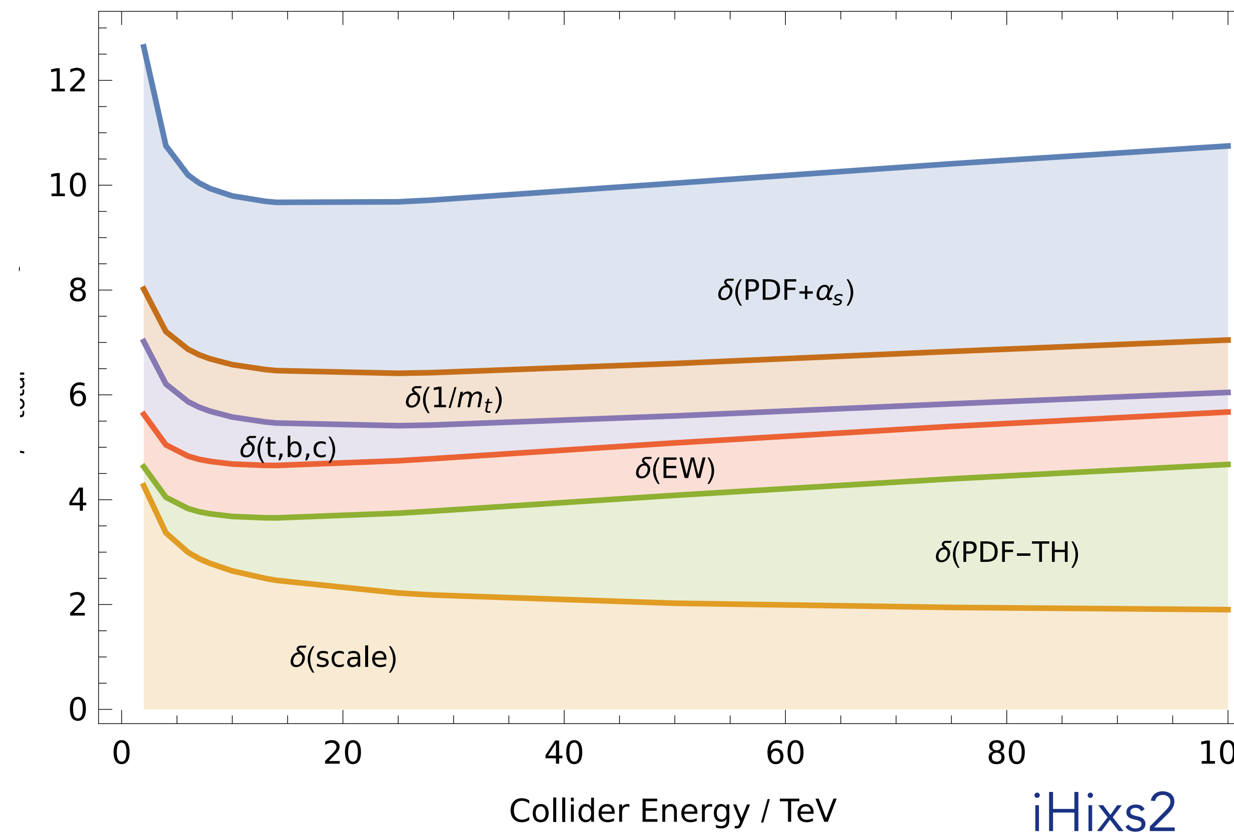
- uncertainties



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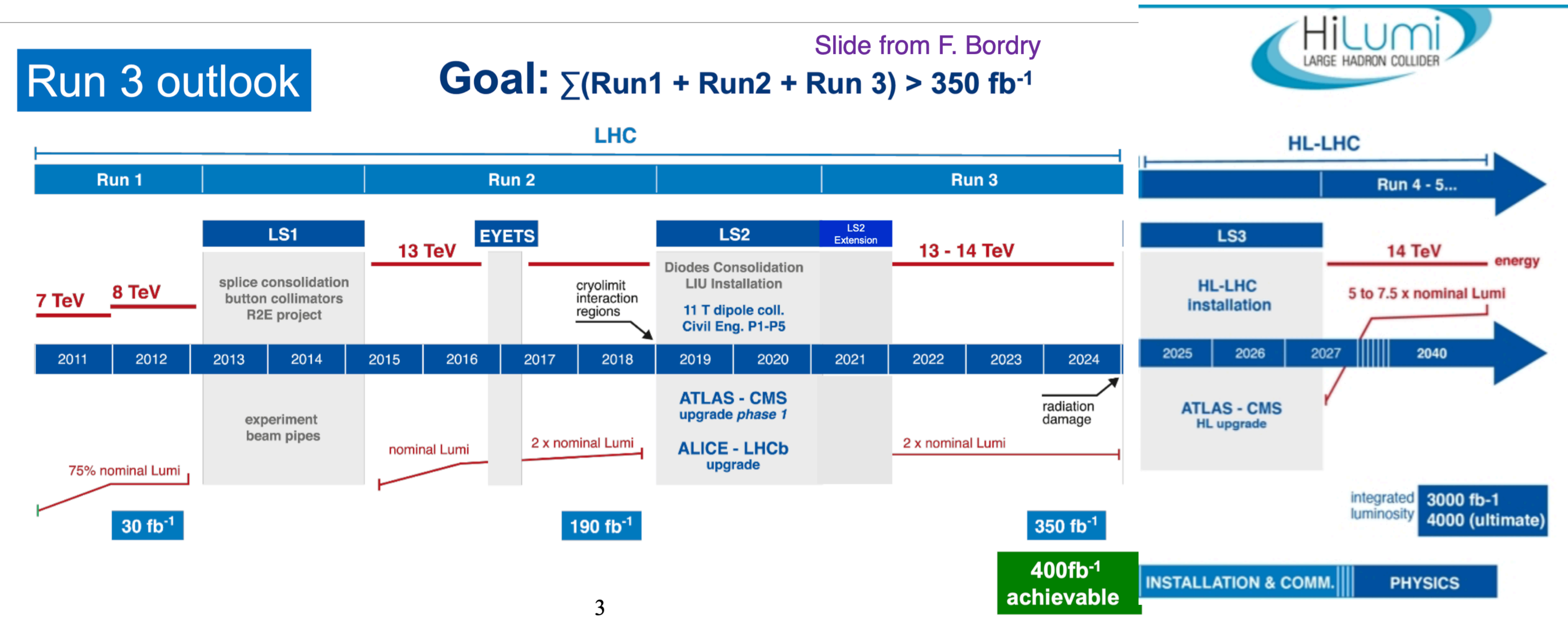
TH : precision calculations

- QCD at high orders NNLO or more
- EW corrections
- Resummation
- MonteCarlos matched to fixed order calculations

Future 2

Next years (>20x number of events

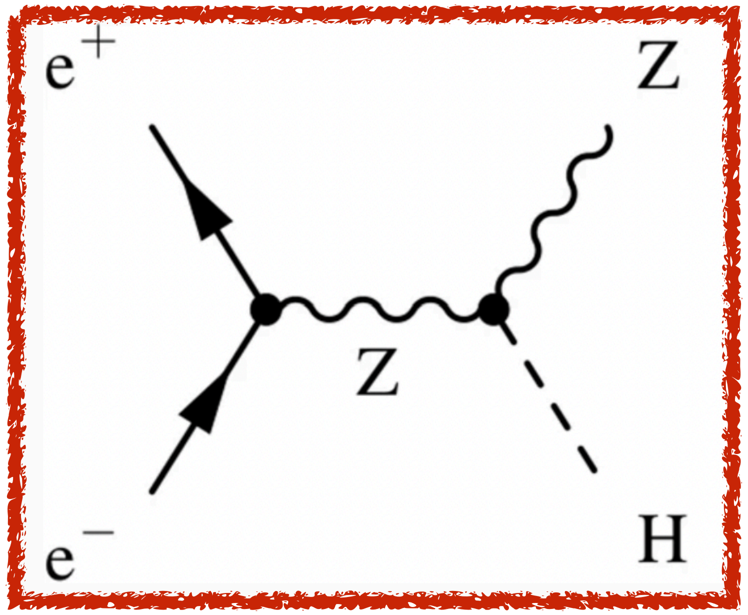
Discovery and **precision**

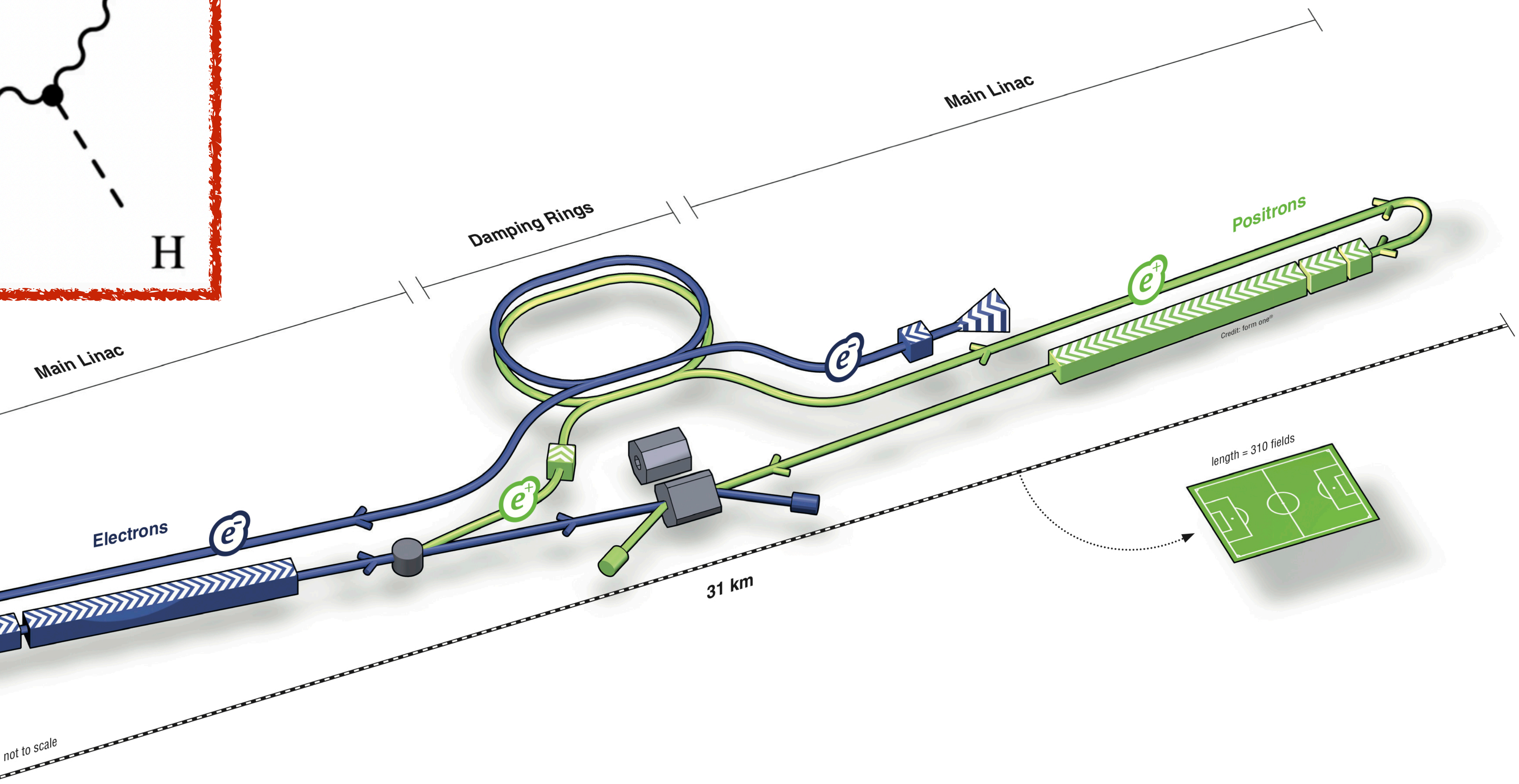


- Approved >2040?

International Linear Collider (e+e-)

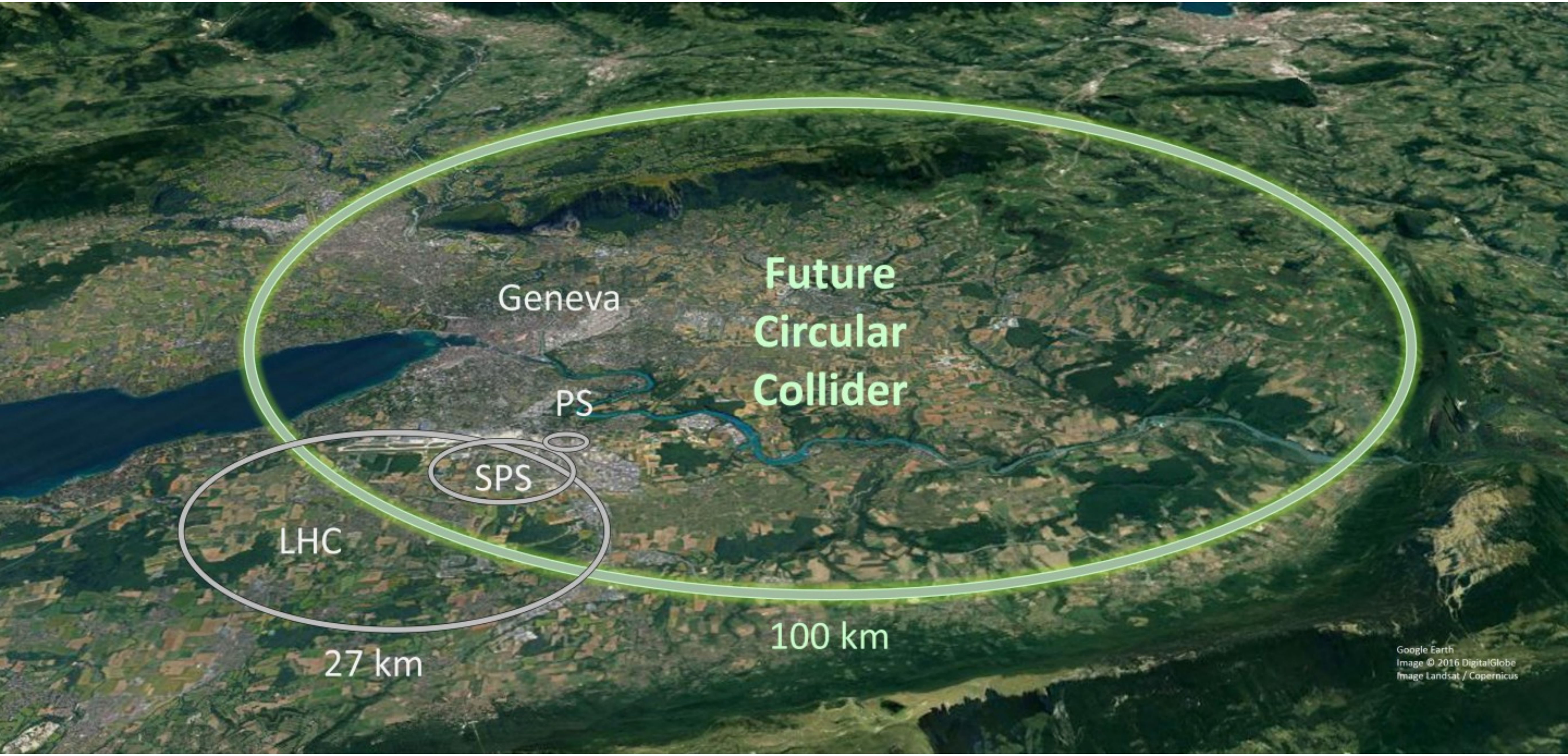
~250 GeV : Higgs Factory (precision)



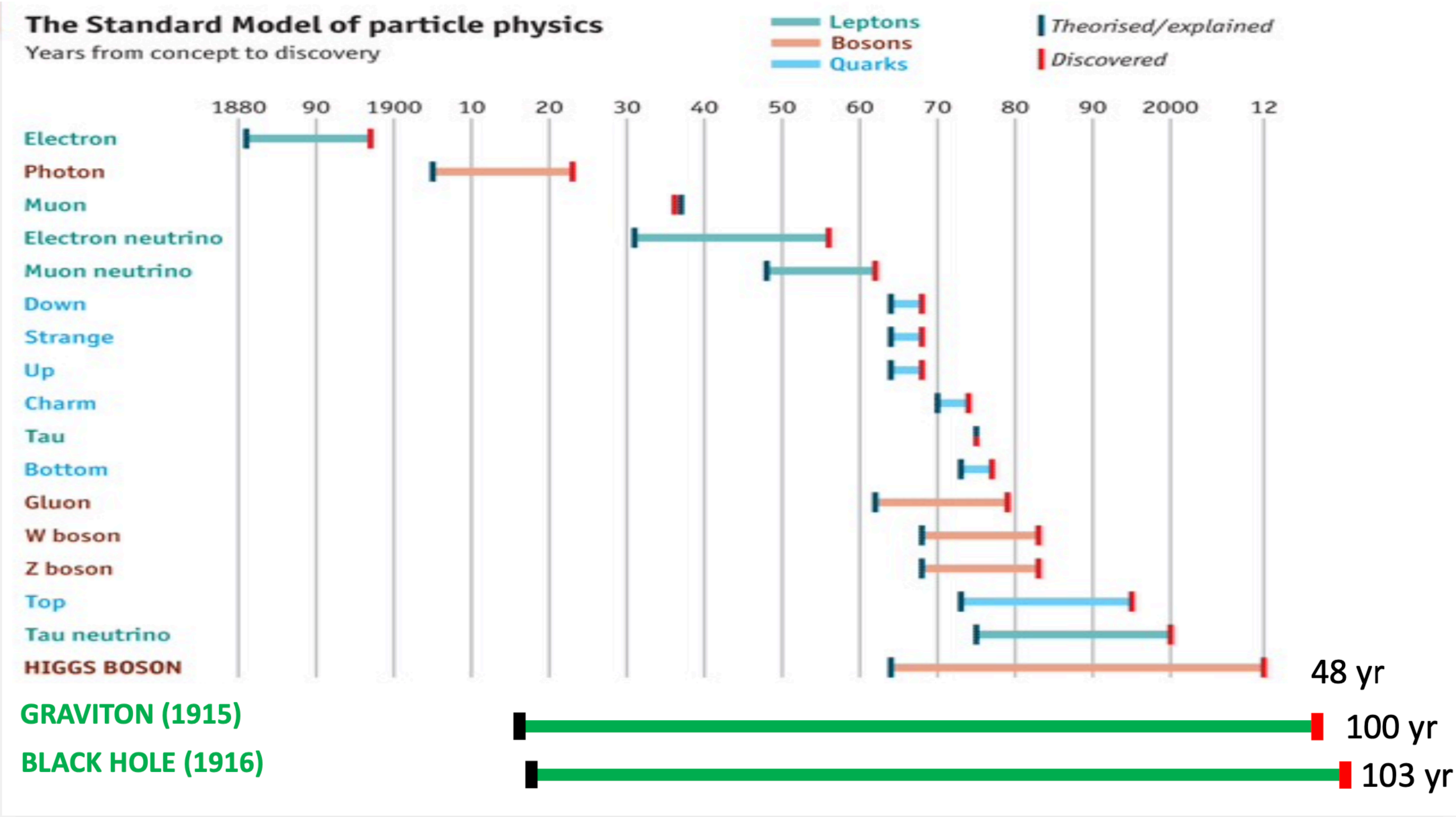


- Technology available, ready to build (lack of funds and site...)

FCC pp collider (y e+e-)
~ 100 TeV (descubrimiento)

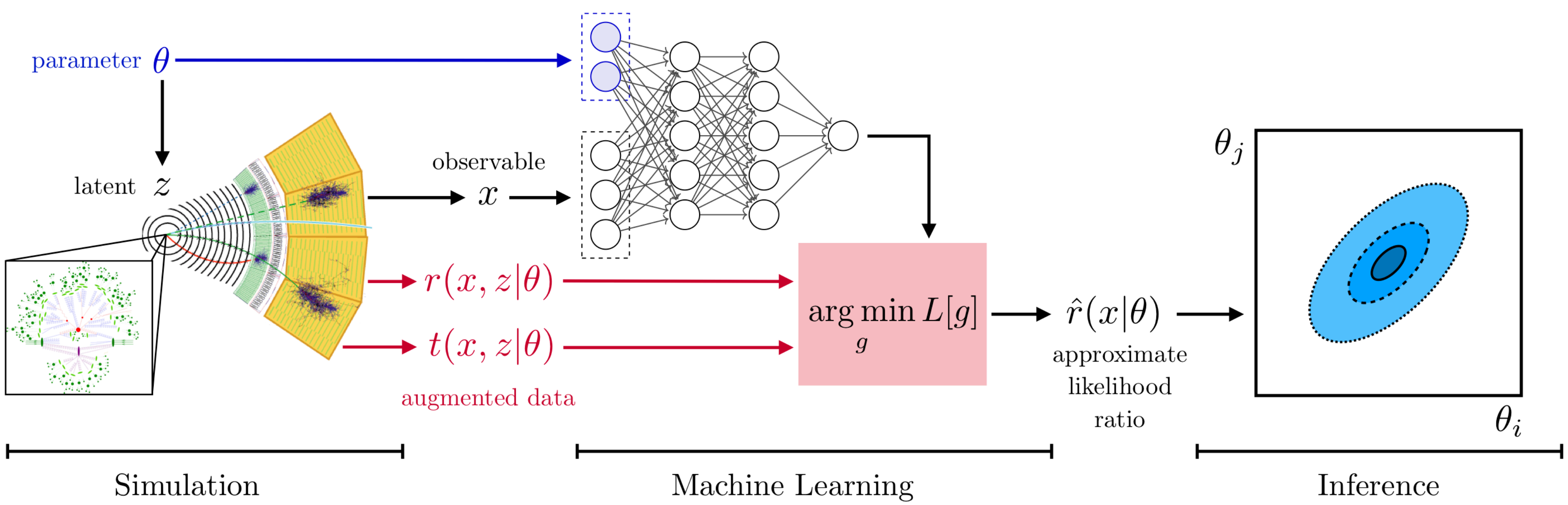


For a long time search was guided by Theoretical expectations

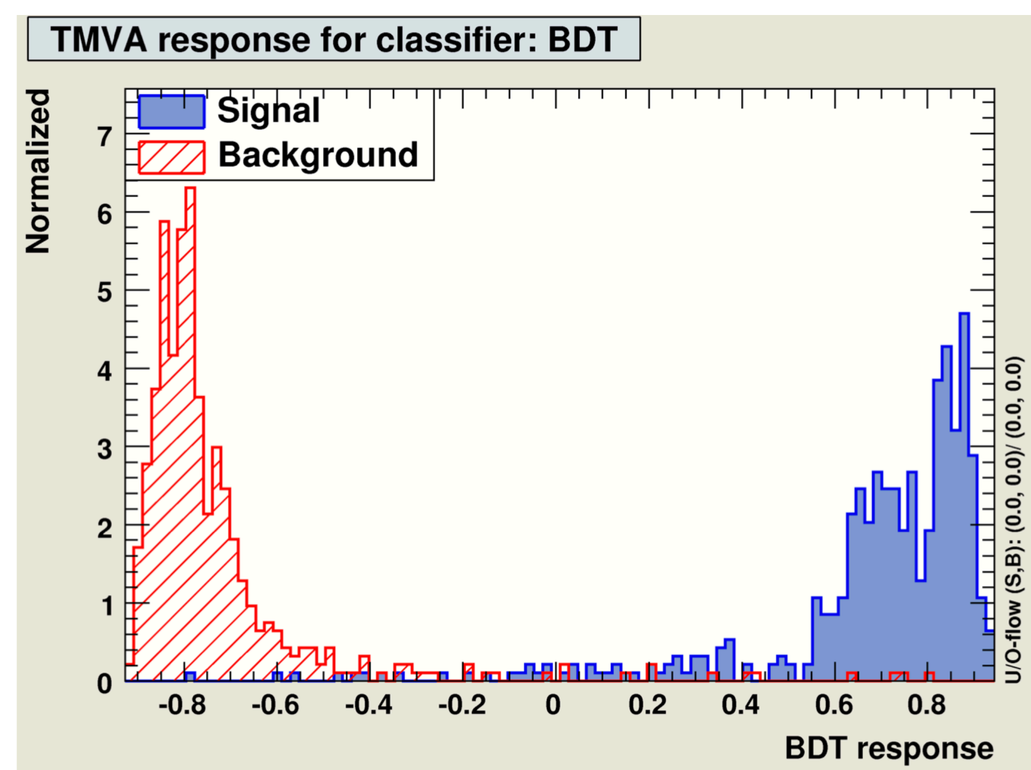


Now is experimentally-driven

- new methods for discovering new physics based on data rather than theory: machine learning



- Search for variables that maximize signal vs background
- Search for "anomalies" and new physics without theoretical bias



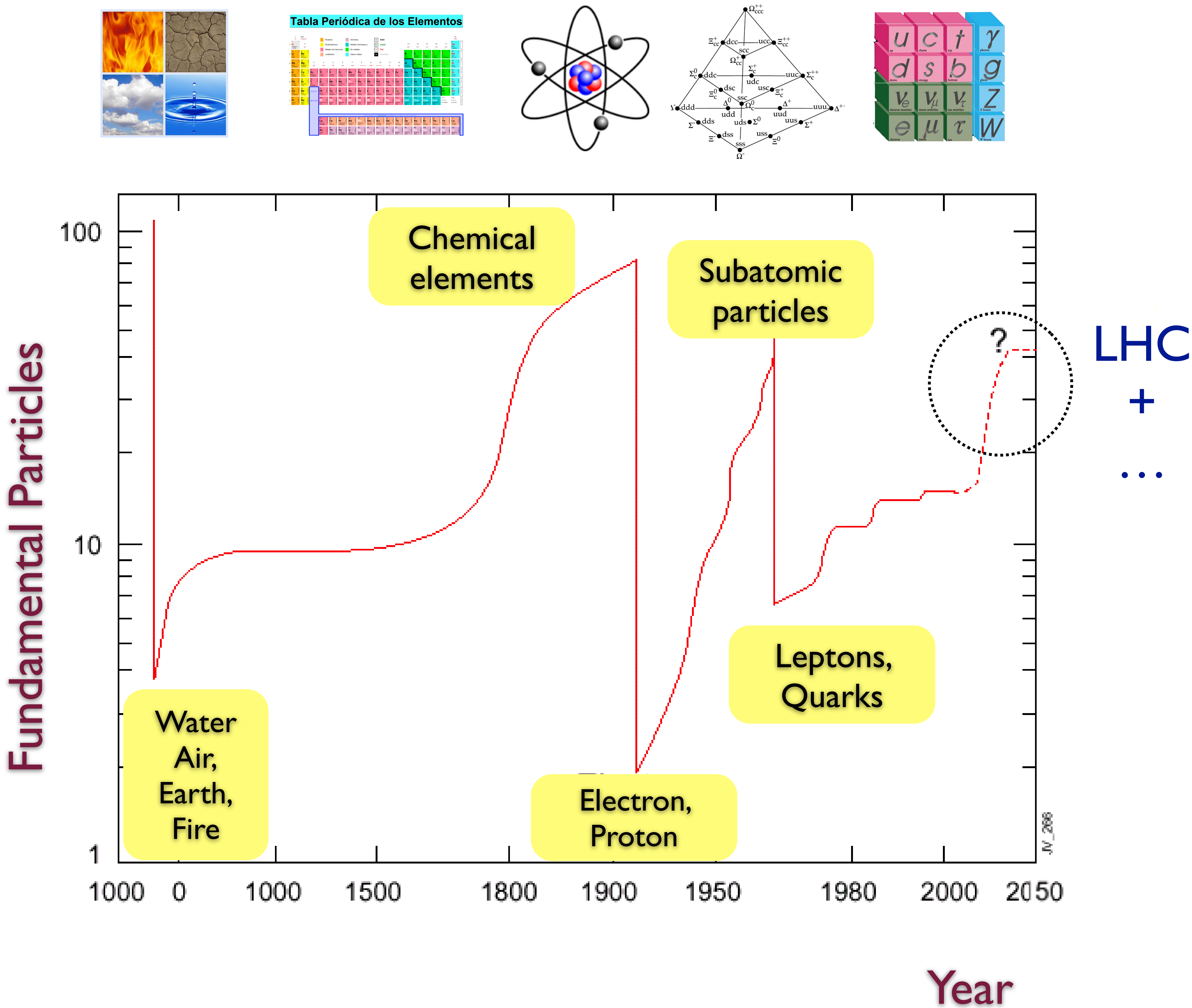


Tabla Periódica de los Elementos
u c t γ
d s b g
ν_e ν_μ ν_τ Z
e μ τ W
Fundamental Particles
100
10
1
Chemical elements
Subatomic particles
Water Air, Earth, Fire
Electron, Proton
Leptons, Quarks
?
LHC
+
...
1000
0
1000
1500
1800
1900
1950
1980
2000
2050
Year

¡Gracias!

Physics

History

Aristotle said a bunch of stuff that was wrong. Galileo and Newton fixed things up. Then Einstein broke everything again. Now, we've basically got it all worked out, except for small stuff, big stuff, hot stuff, cold stuff, fast stuff, heavy stuff, dark stuff, turbulence and the concept of time.

Summary

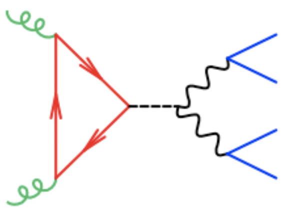
- A Higgs boson was found at the LHC
- Consistent with SM Higgs (large uncertainties yet)
- Great TH work to match EXP precision
    - High order corrections
- Can still expect surprises at the LHC
- Need to analyze Higgs sector with detail
- **PRECISION** for the next decades
- Studies underway for new colliders

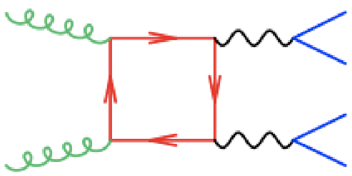
Off-shell effects and interference

signal | background

$$\mathcal{A}_{ij\to X} = \mathcal{A}_{ij\to H}\;\Delta_{\mathrm{H}}\;\mathcal{A}_{H\to X} + \mathcal{A}_{continuum}$$

Propagator





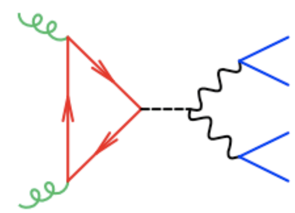
$$\Delta_H^2(q^2) \sim \frac{1}{(q^2 - M_H^2)^2 + \Gamma_H^2 M_H^2} \sim \frac{\pi}{M_H \Gamma_H}\delta(q^2 - M_H^2) + \mathcal{O}\left(\frac{\Gamma_H}{M_H}\right)$$ ZWA

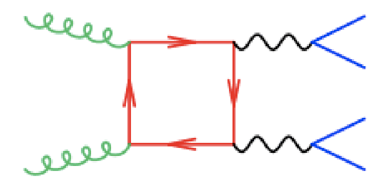
Off-shell effects and interference

signal | background

$$\mathcal{A}_{ij\to X} = \quad \mathcal{A}_{ij\to H} \quad \Delta_{\rm H} \quad \mathcal{A}_{H\to X} \quad + \mathcal{A}_{continuum}$$

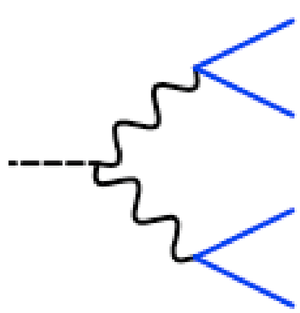
Propagator





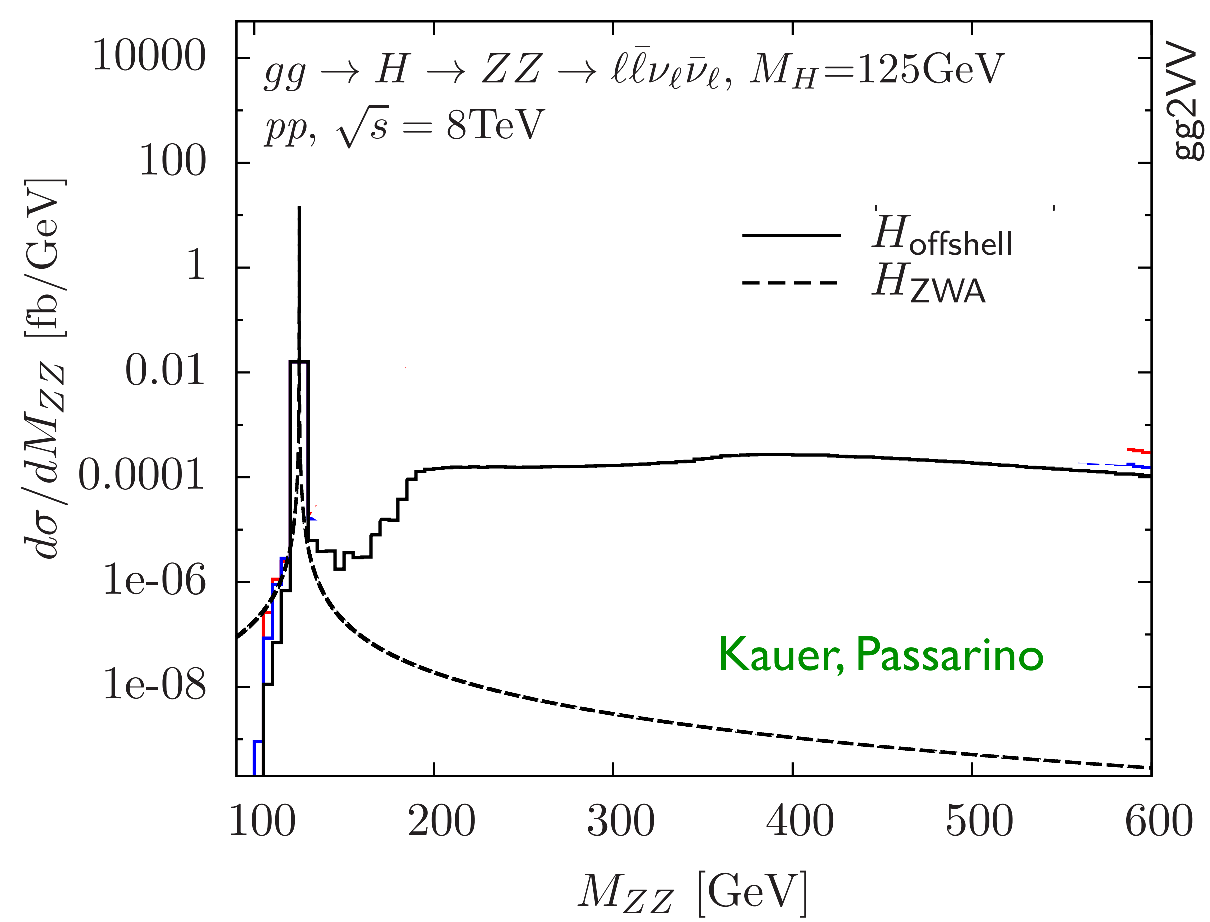
$$\Delta_H^2(q^2) \sim \frac{1}{(q^2 - M_H^2)^2 + \Gamma_H^2 M_H^2} \sim \frac{\pi}{M_H \Gamma_H} \delta(q^2 - M_H^2) + \mathcal{O}\left(\frac{\Gamma_H}{M_H}\right)$$ ZWA

But above threshold decay amplitude compensates $1/(q^2)^2$

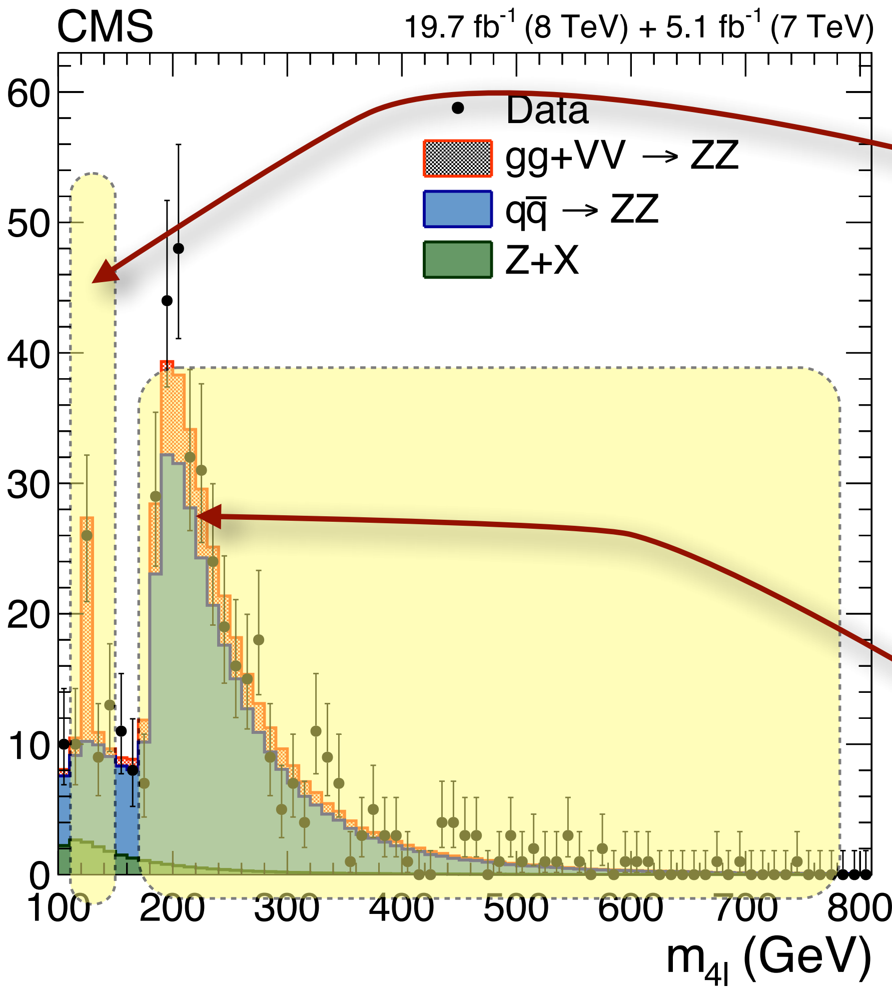


$$|\mathcal{A}_{H\to VV}|^2 \sim (q^2)^2$$

- Sizeable contribution from off-shell
- Enhances effect of interference



Width measurement from off-shell $gg \to H \to VV$



$$\sigma^{\text{on}} \quad \int_{M_H^2-\Delta^2}^{M_H^2+\Delta^2} dq^2 \frac{|A_{gg\to H\to VV}|^2}{(q^2-M_H^2)+\Gamma_H^2 M_H^2} \sim \frac{g_{ggH}^2(M_H^2)\, g_{HVV}^2(M_H^2)}{\Gamma_H}$$

SM assumptions on couplings (running)

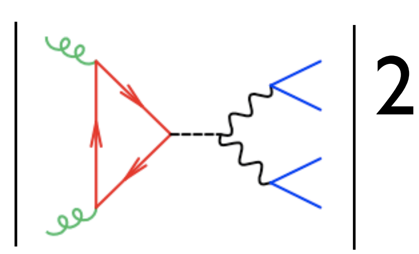
$$g = \xi\, g^{SM}$$
$$\Gamma_H = \xi^4\, \Gamma_H^{SM}$$

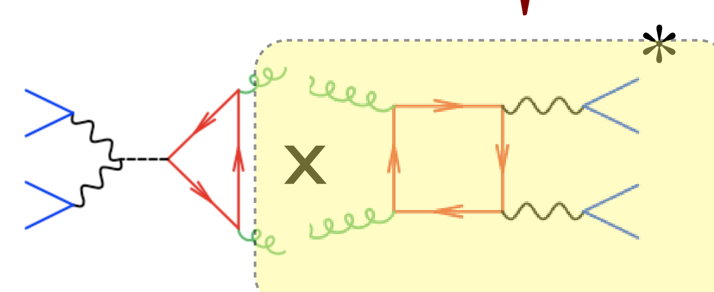
$$\sigma^{\text{off}} \int_{q^2 \gg M_H^2} dq^2 \frac{|A_{gg\to H\to VV}|^2}{(q^2-M_H^2)+\Gamma_H^2 M_H^2} \sim \int dq^2 g_{ggH}^2(q^2)\, g_{HVV}^2(q^2)$$

$$\sigma^{\text{exp}} = \sigma^{\text{back}} + \sigma^{\text{on}} + \sigma^{\text{off}} \times \frac{\Gamma_H}{\Gamma_H^{SM}} + \sigma^{\text{int}} \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

CMS

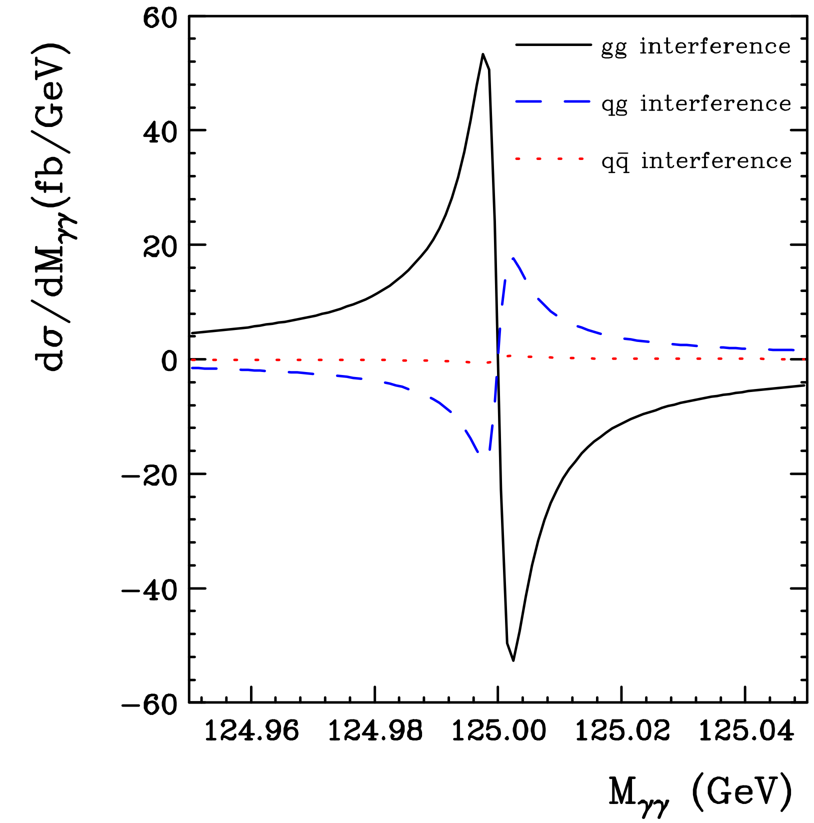
$3.2^{+2.8}_{-2.2}$ MeV





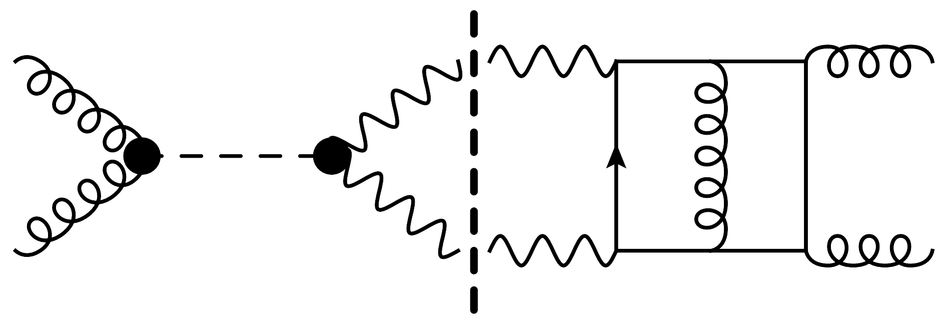
need precision on $gg \to VV$ NNLO for background but sizeable

Width from interference $H \to \gamma\gamma$



- In diphoton channel, interference small for total cross section but asymmetry produces shift in invariant mass : enhanced by detector resolution

Dicus, Willenbrock (1986)
Dixon, Siu (2003)
Martin (2012,2013)
deF et al (2013)
Dixon, Li (2013)

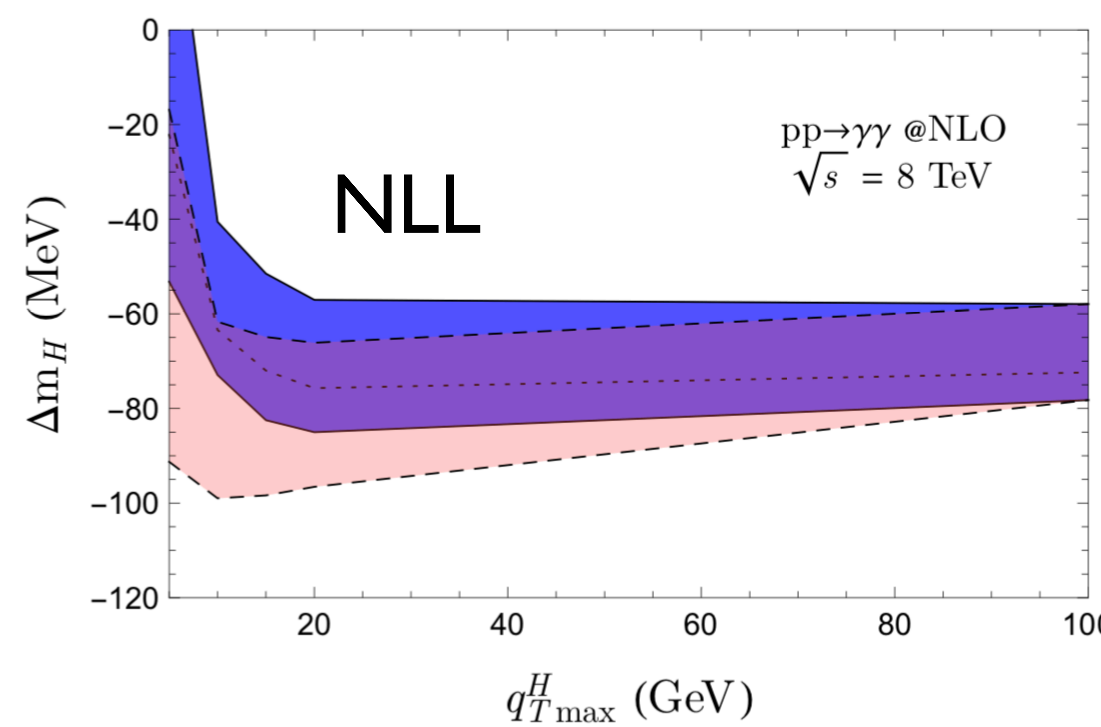


Known to $\mathcal{O}(\alpha_s^3)$

- Look at $\Delta M_{\mathrm{H}} = M_{\mathrm{H}}^{\gamma\gamma} - M_{\mathrm{H}}^{\mathrm{ZZ}}$

  or precise mass measurements in different H q_T bins in $\gamma\gamma$

  Cieri, Coradeschi, deF, Fidanza (2017)



Campbell, Carena, Harnik, Liu (2017)

- Search for -2% effect of interference in cross section
- All effects might be enhanced by BSM