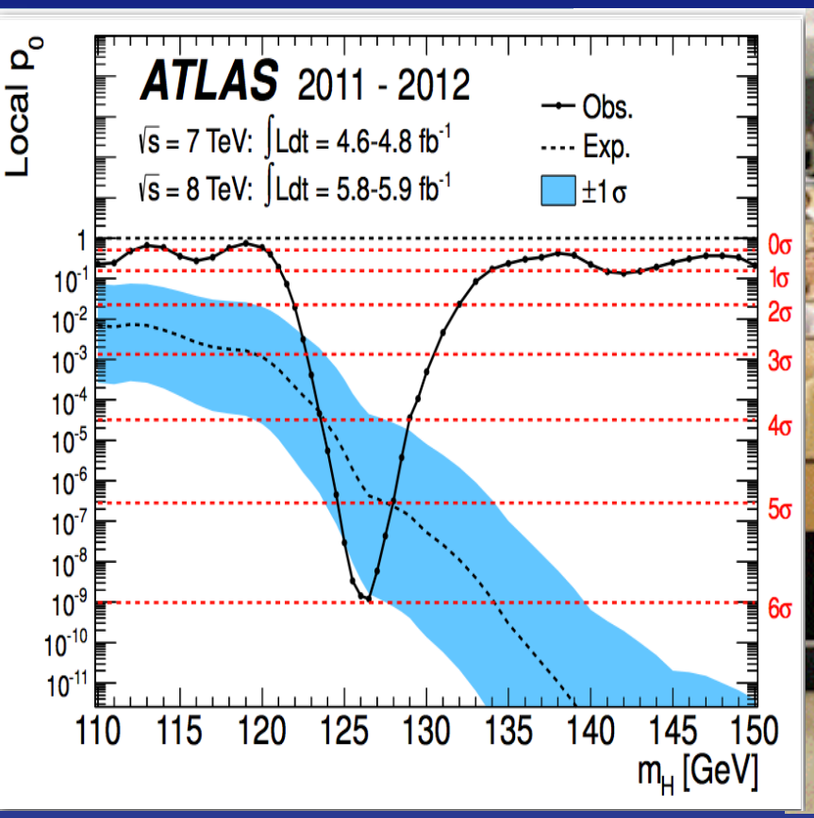
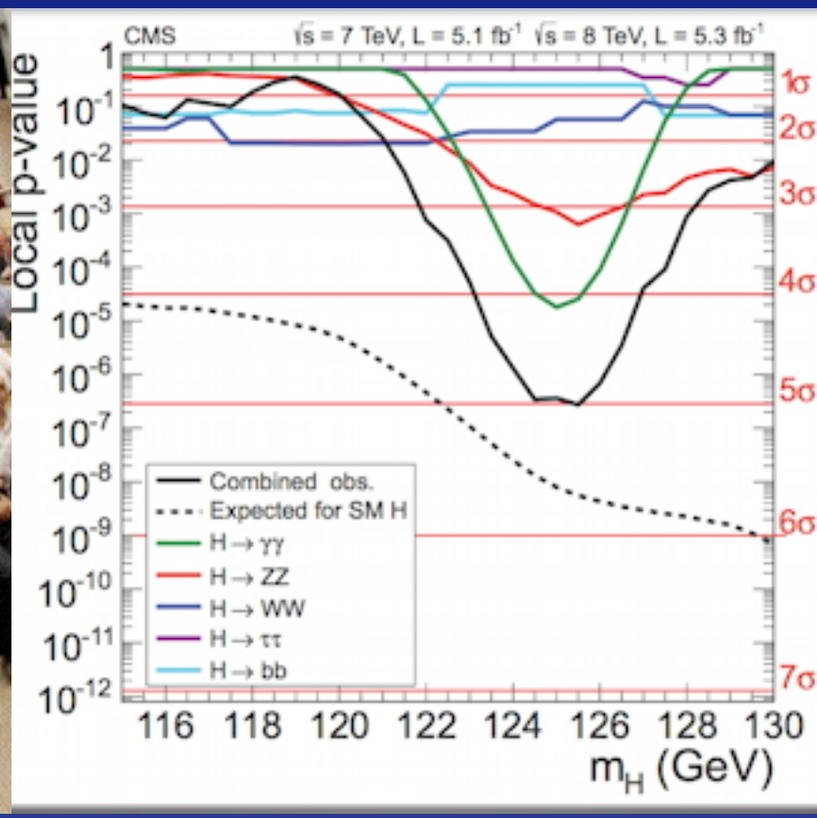
The Higgs Boson (?) Beyond the LHC: Theory

Chris Quigg

Fermi National Accelerator Laboratory

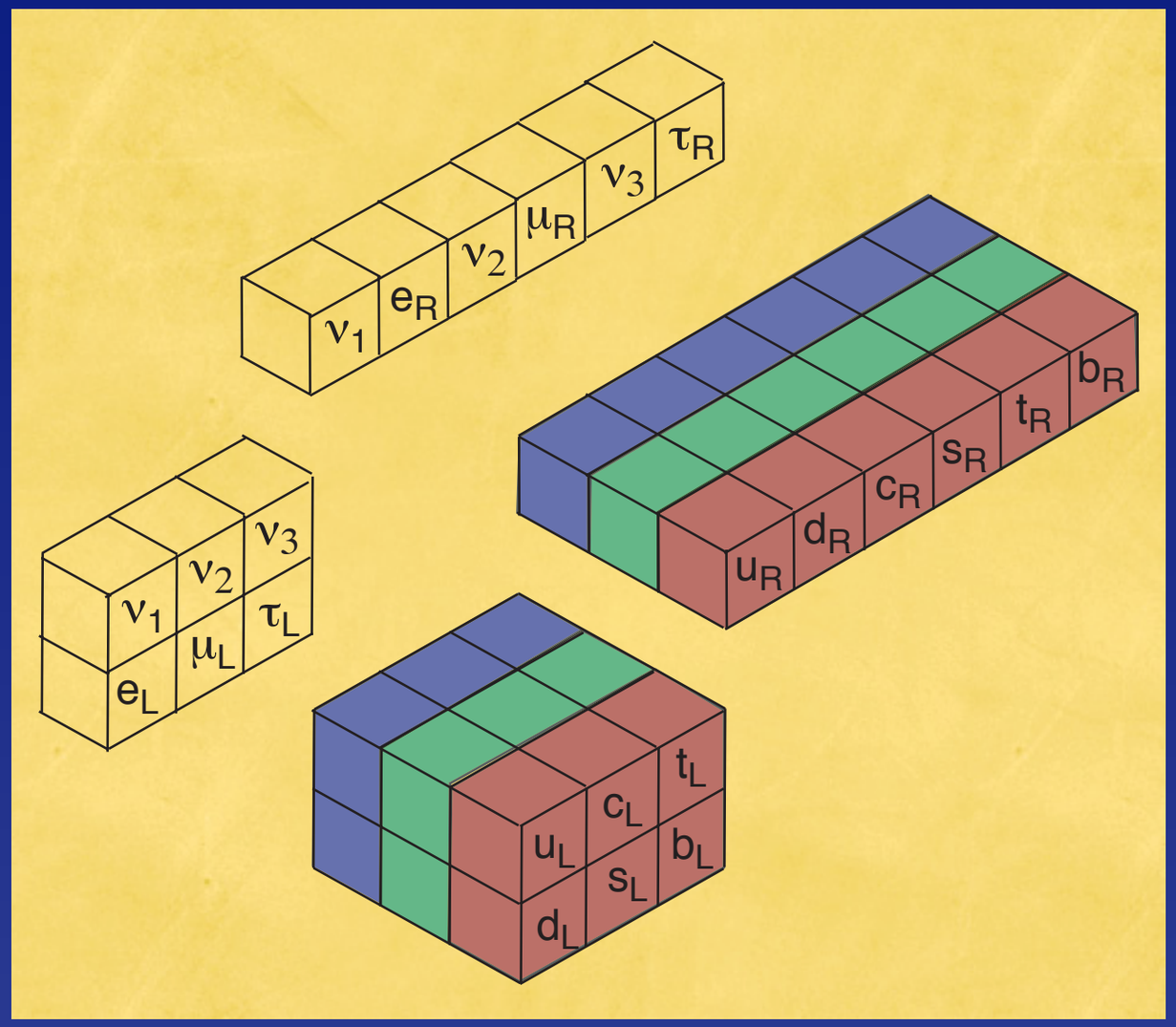




Higgs Factory 2012 · Fermilab · 14 November 2012

QCD + Electroweak Theory +

Pointlike ($r \leq 10^{-18}$ m) *quarks* and *leptons*



Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries

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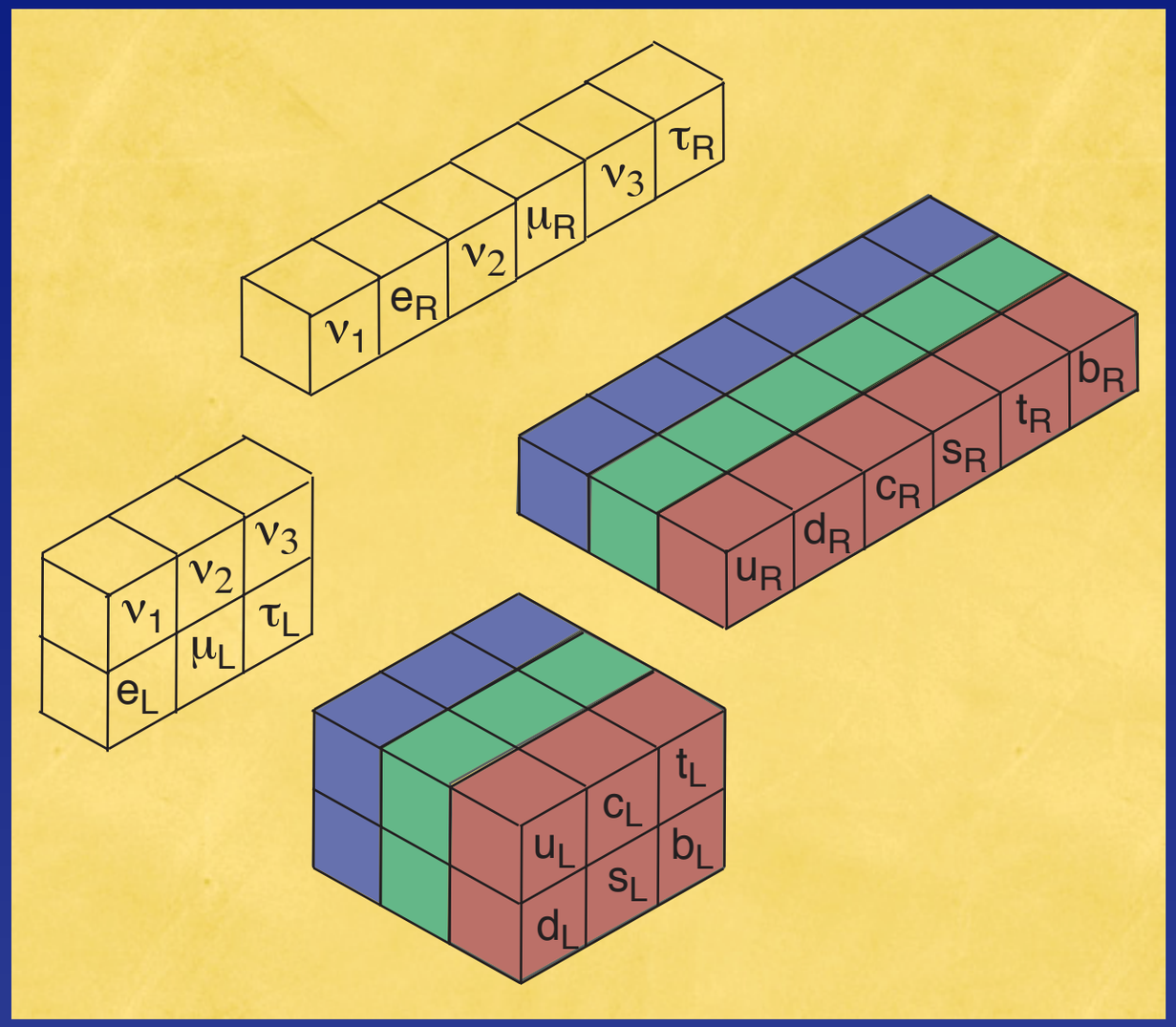


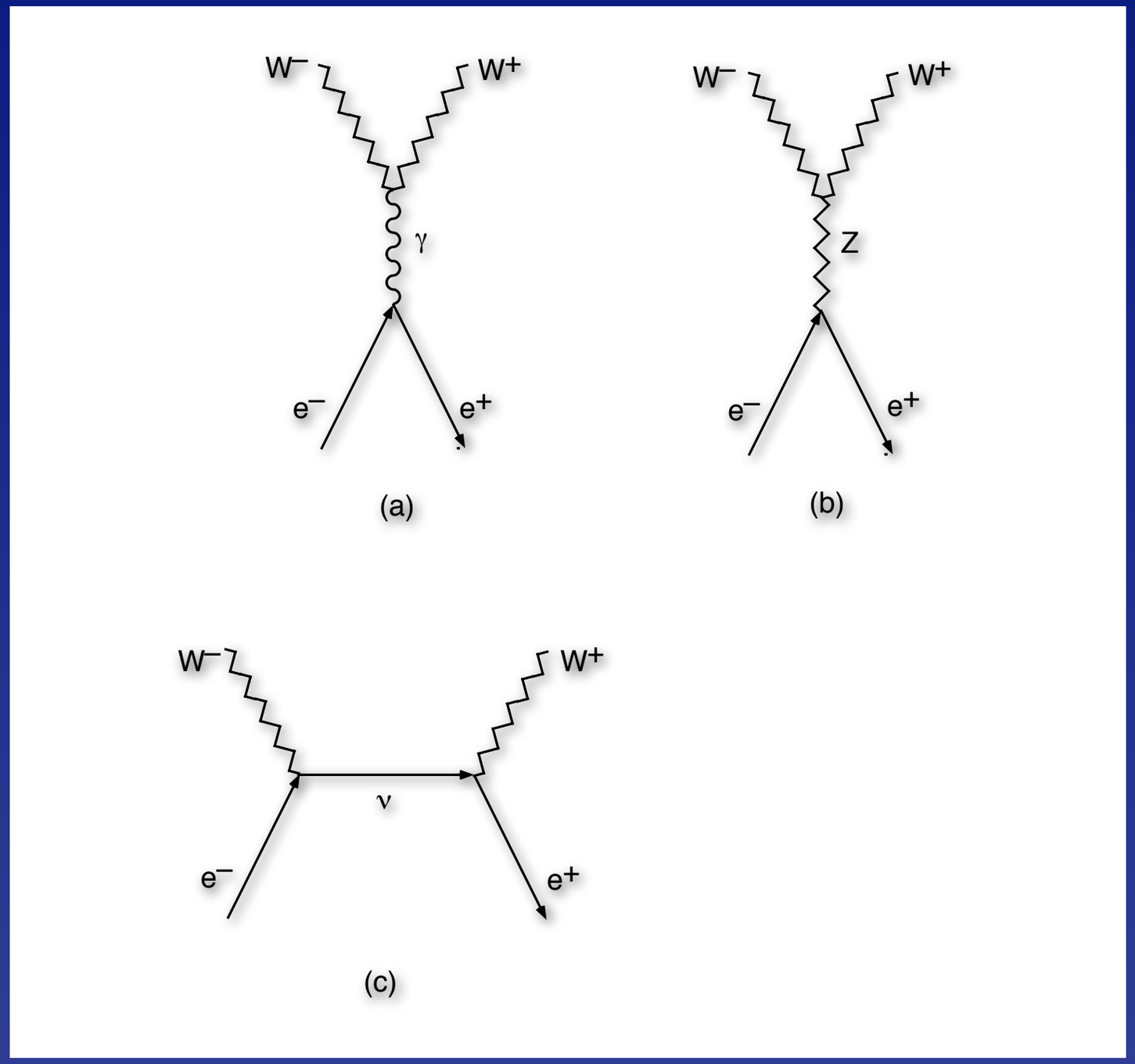
Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries → $U(1)_{EM}$

A hitherto unknown agent hides the electroweak symmetry

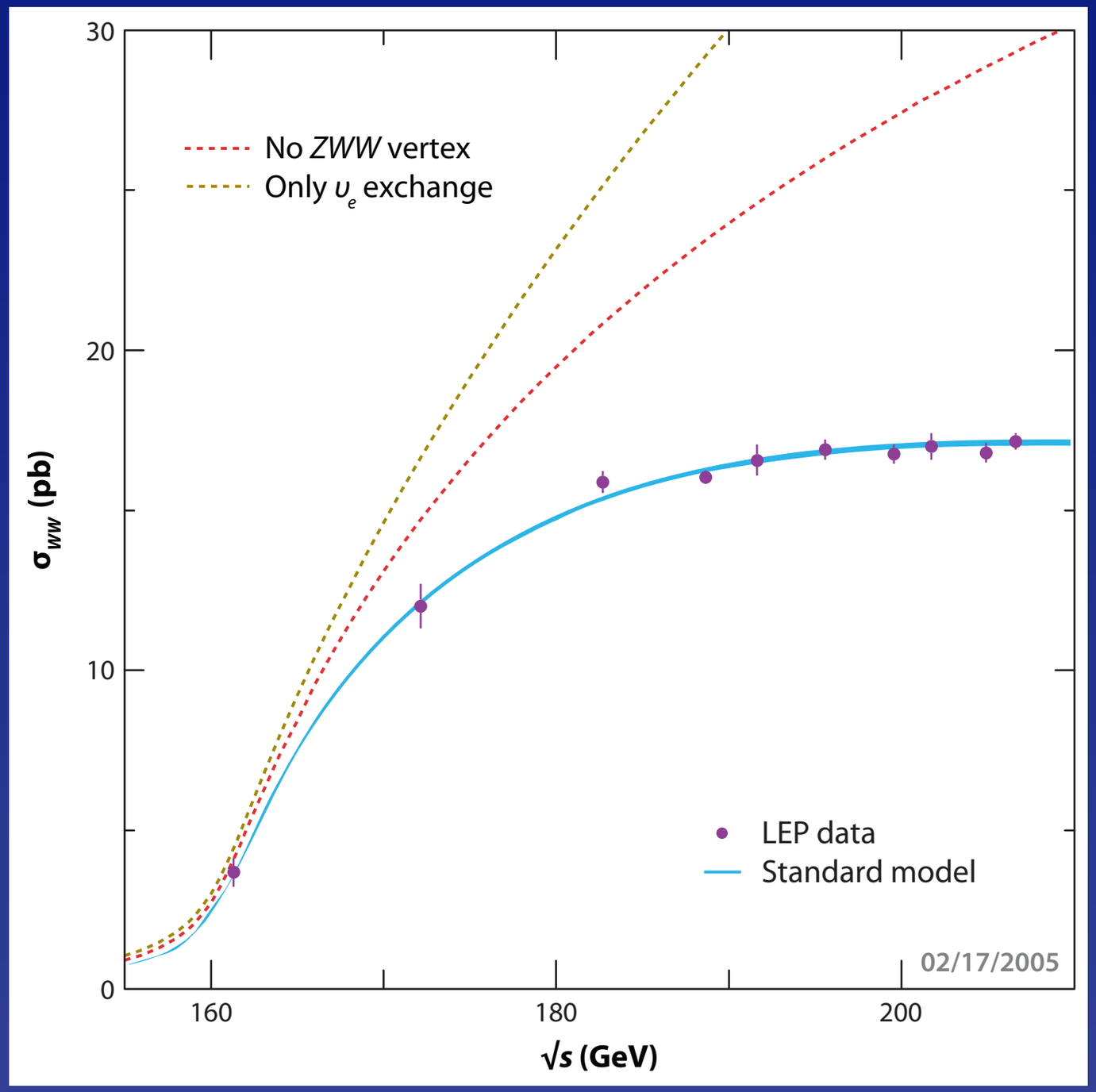
- ✳ A force of a new character, based on interactions of an elementary scalar
- ✳ A new gauge force, perhaps acting on undiscovered constituents
- ✳ A residual force that emerges from strong dynamics among electroweak gauge bosons
- ✳ An echo of extra spacetime dimensions

Gauge symmetry (group-theory structure) tested in

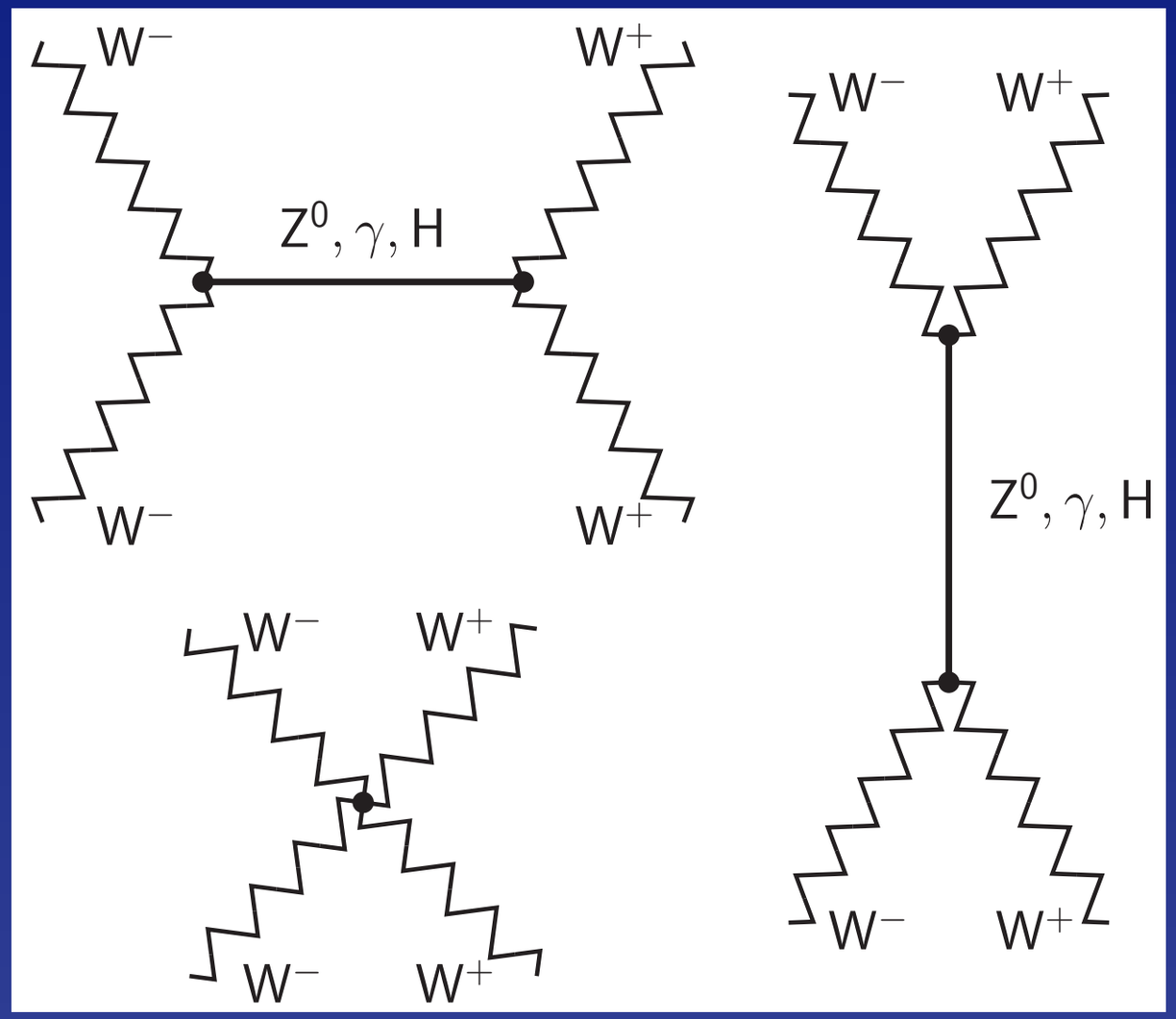
$$e^+e^- \to W^+W^-$$



Electroweak symmetry validated at LEP



Standard-model Higgs boson hides electroweak symmetry, gives masses to $W^{\pm}$ and Z^0, ensures good high-energy behavior.



Something must do this job

Origin of fermion mass?

By decree, Weinberg & Salam add interactions between fermions and scalars that give rise to quark and lepton masses.

$$\zeta_e \left[(\overline{e_{\mathsf{L}}} \Phi) e_{\mathsf{R}} + \overline{e_{\mathsf{R}}} (\Phi^\dagger e_{\mathsf{L}}) \right] \rightsquigarrow m_e = \zeta_e v / \sqrt{2}$$

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picked to give right mass, not predicted

fermion mass implies physics beyond standard model

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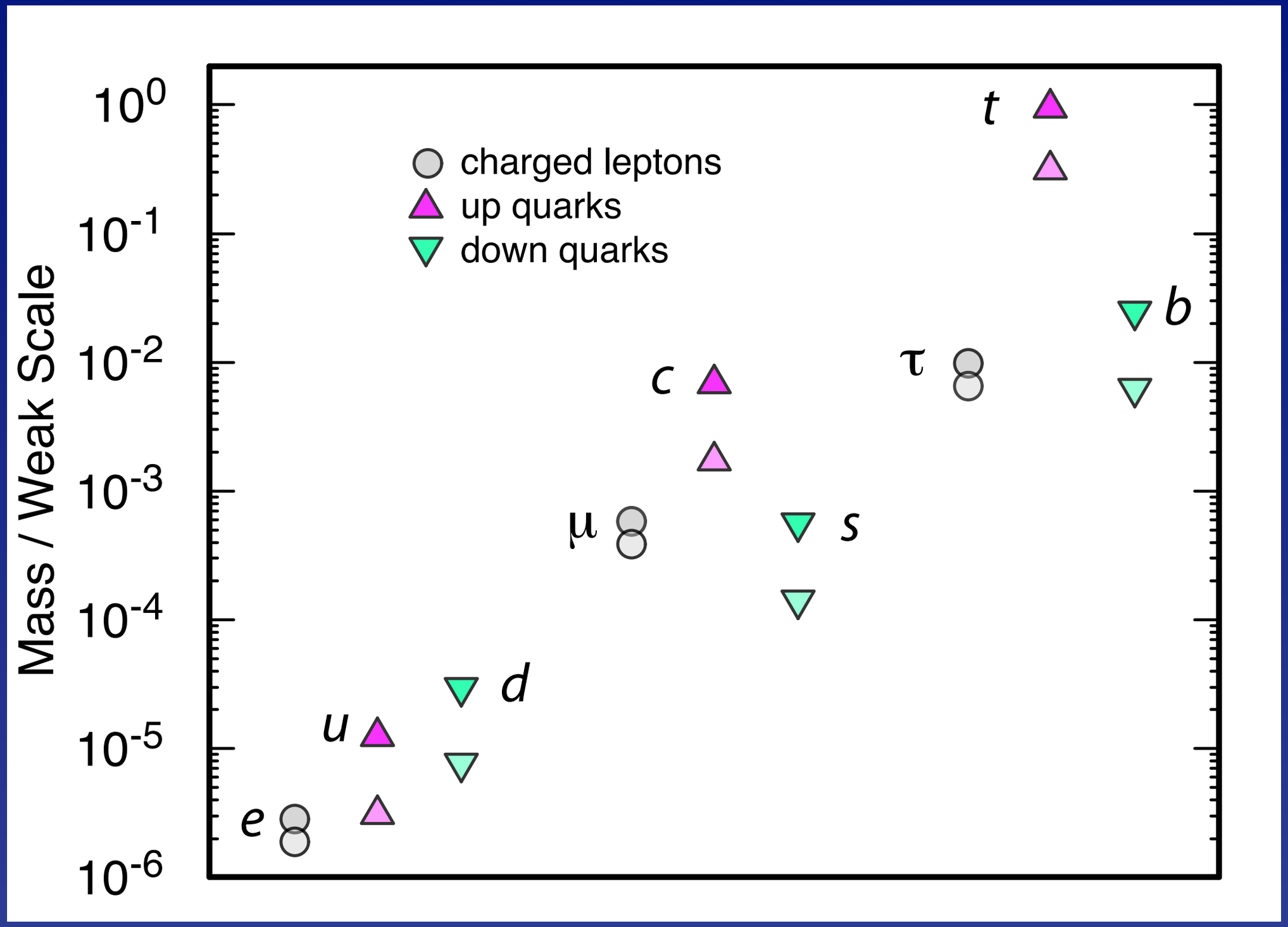
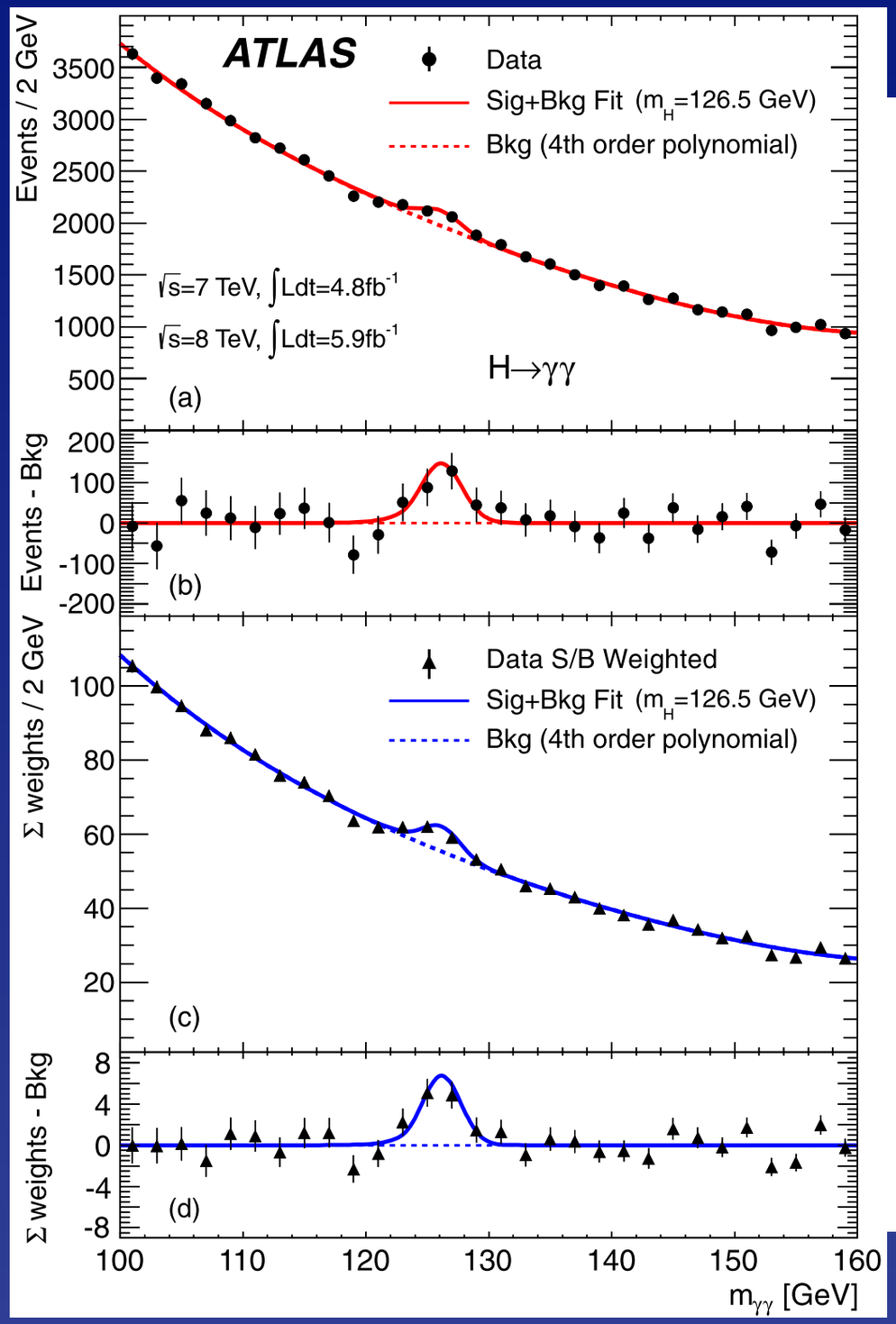
Highly economical, but is it true?

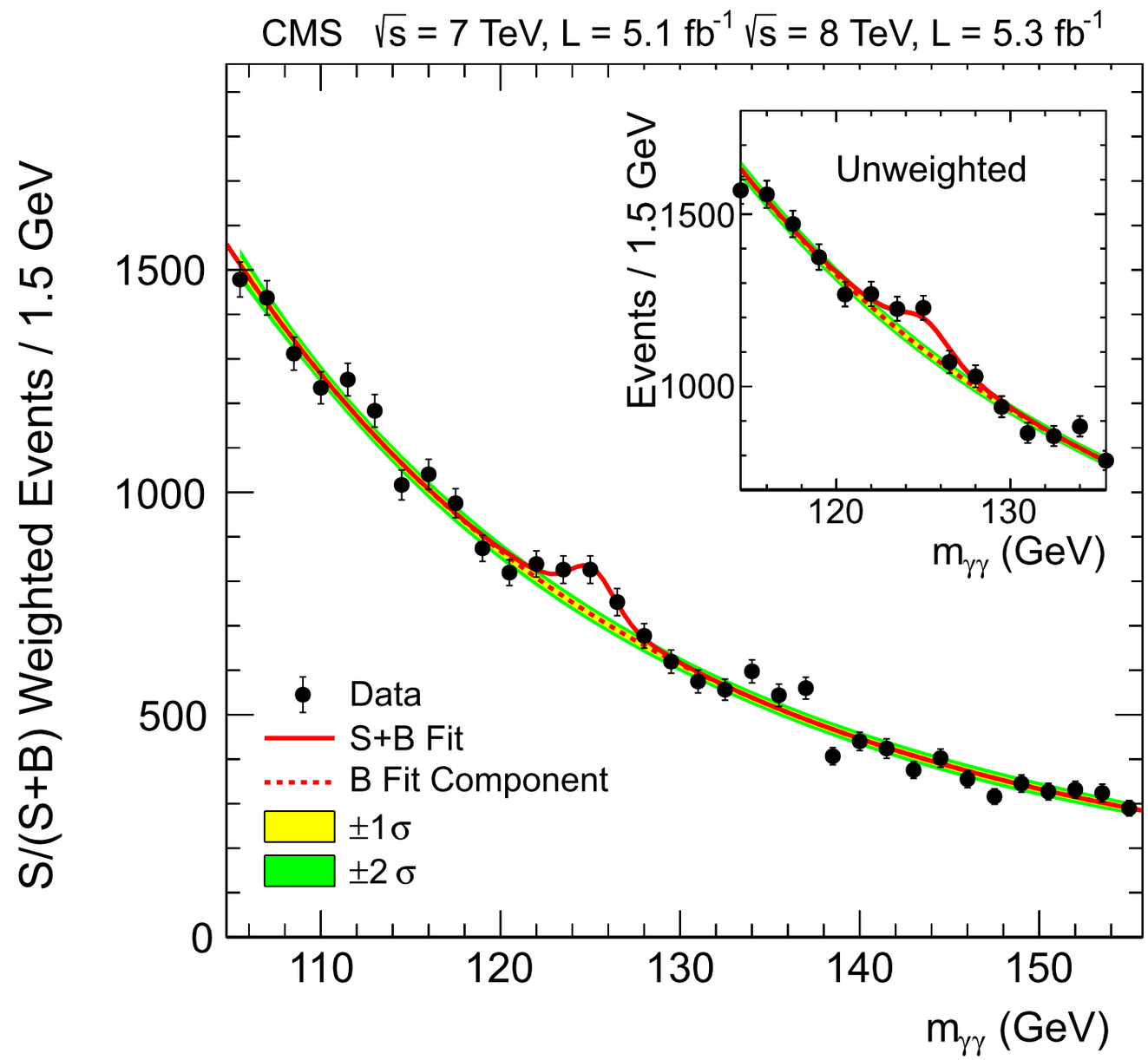
Fermion Masses



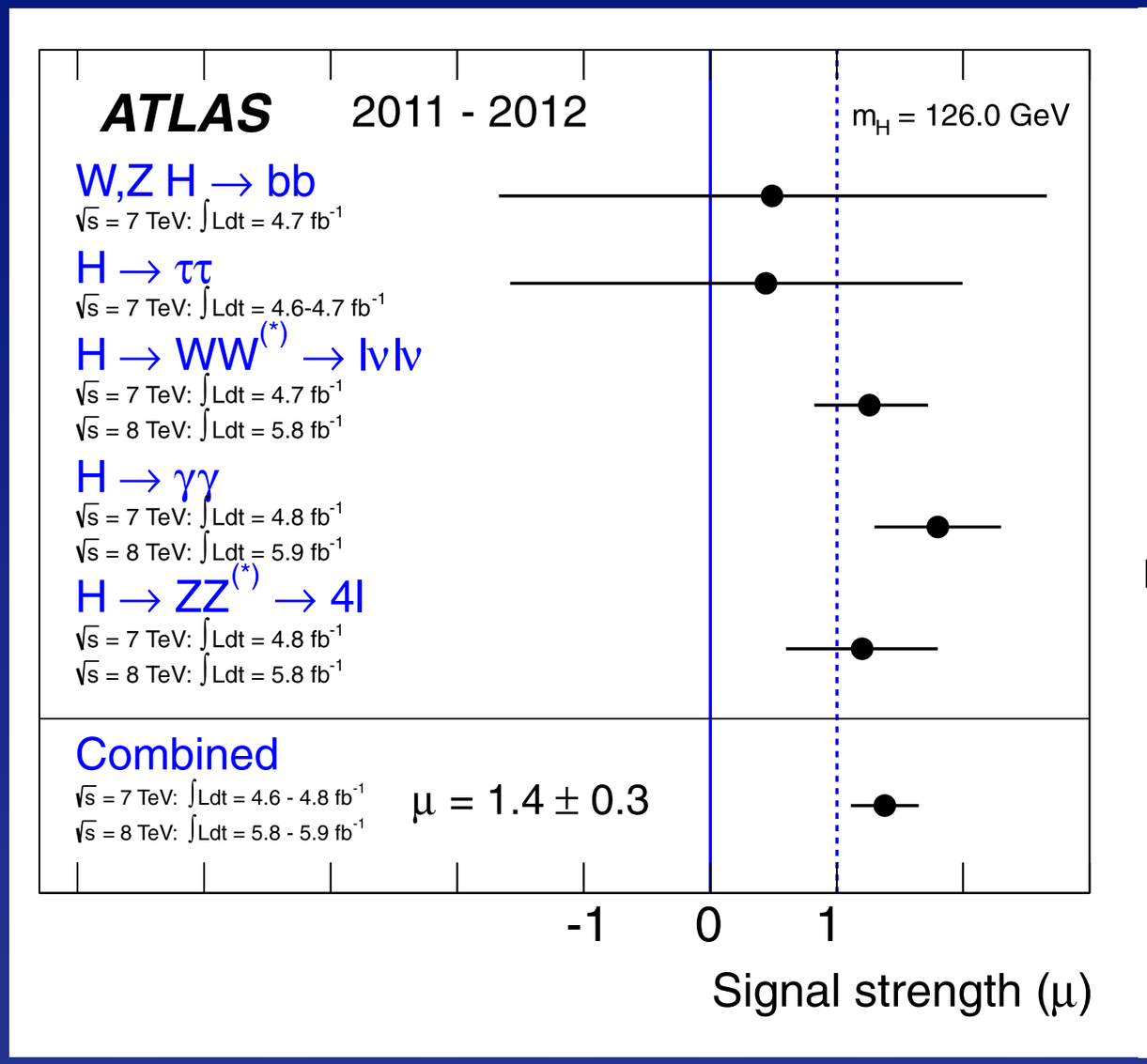
Running mass $m(m)$ … $m(U)$

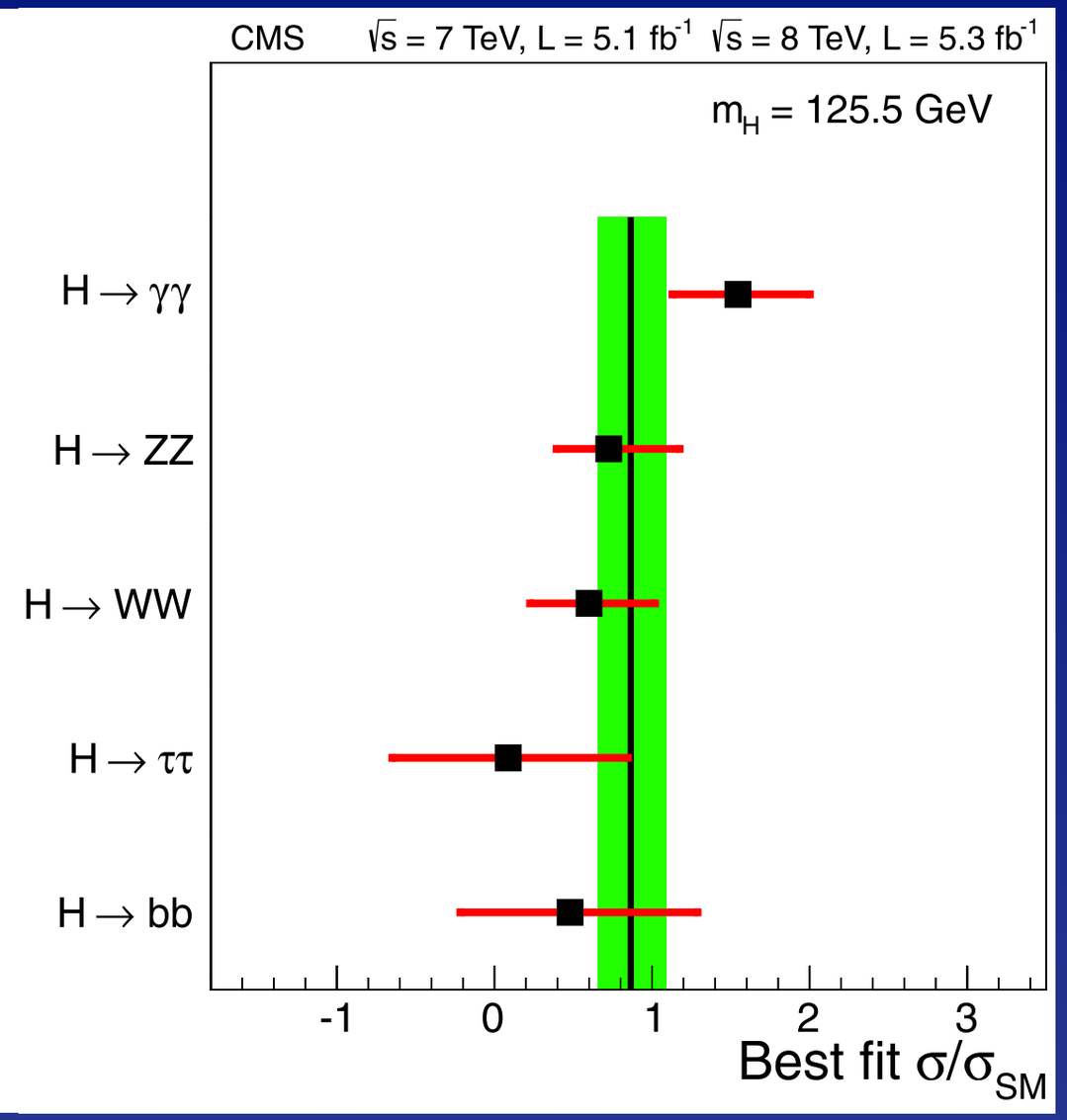
Summer 2012 Discovery Evidence …



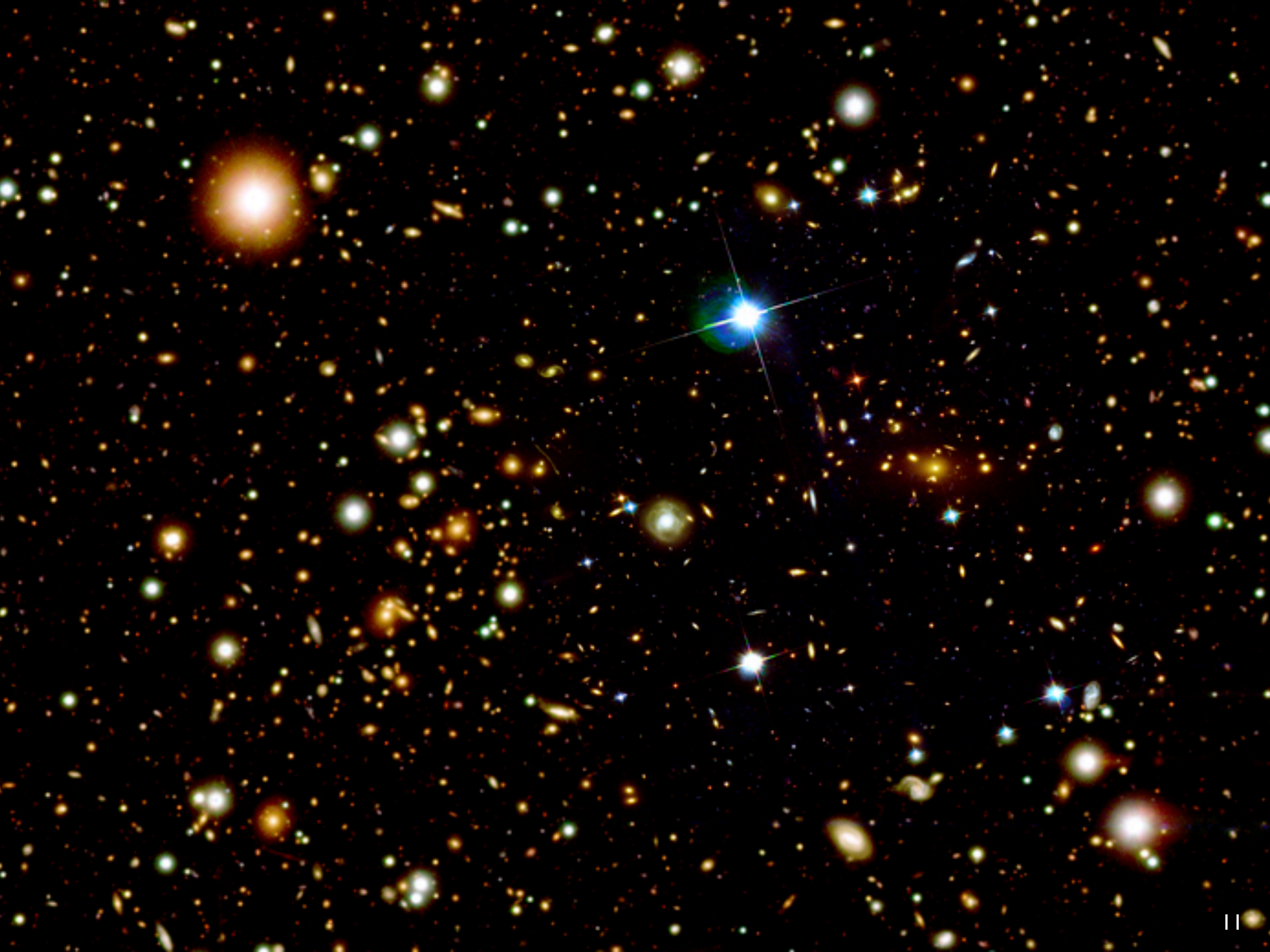


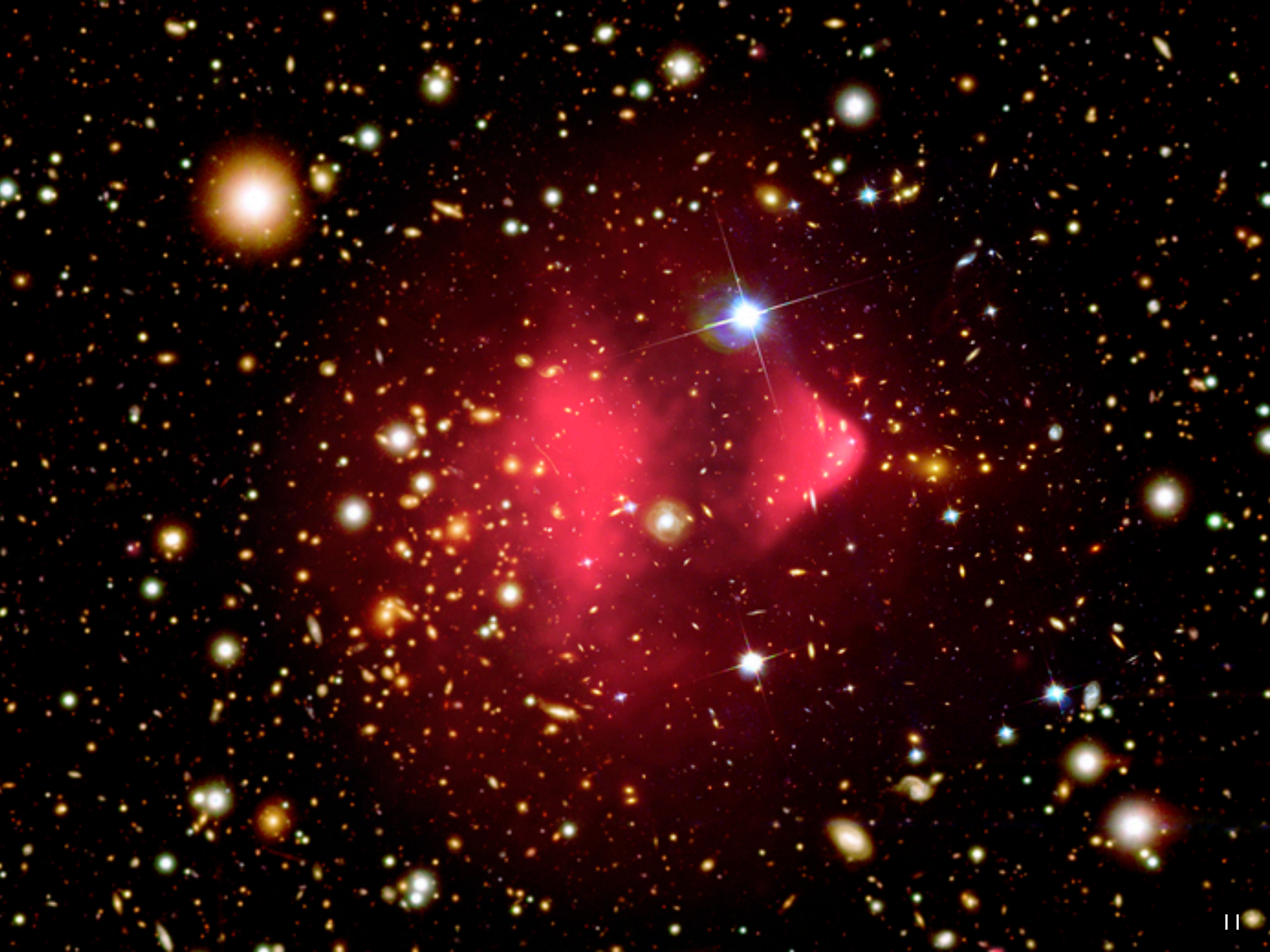
Known before today …

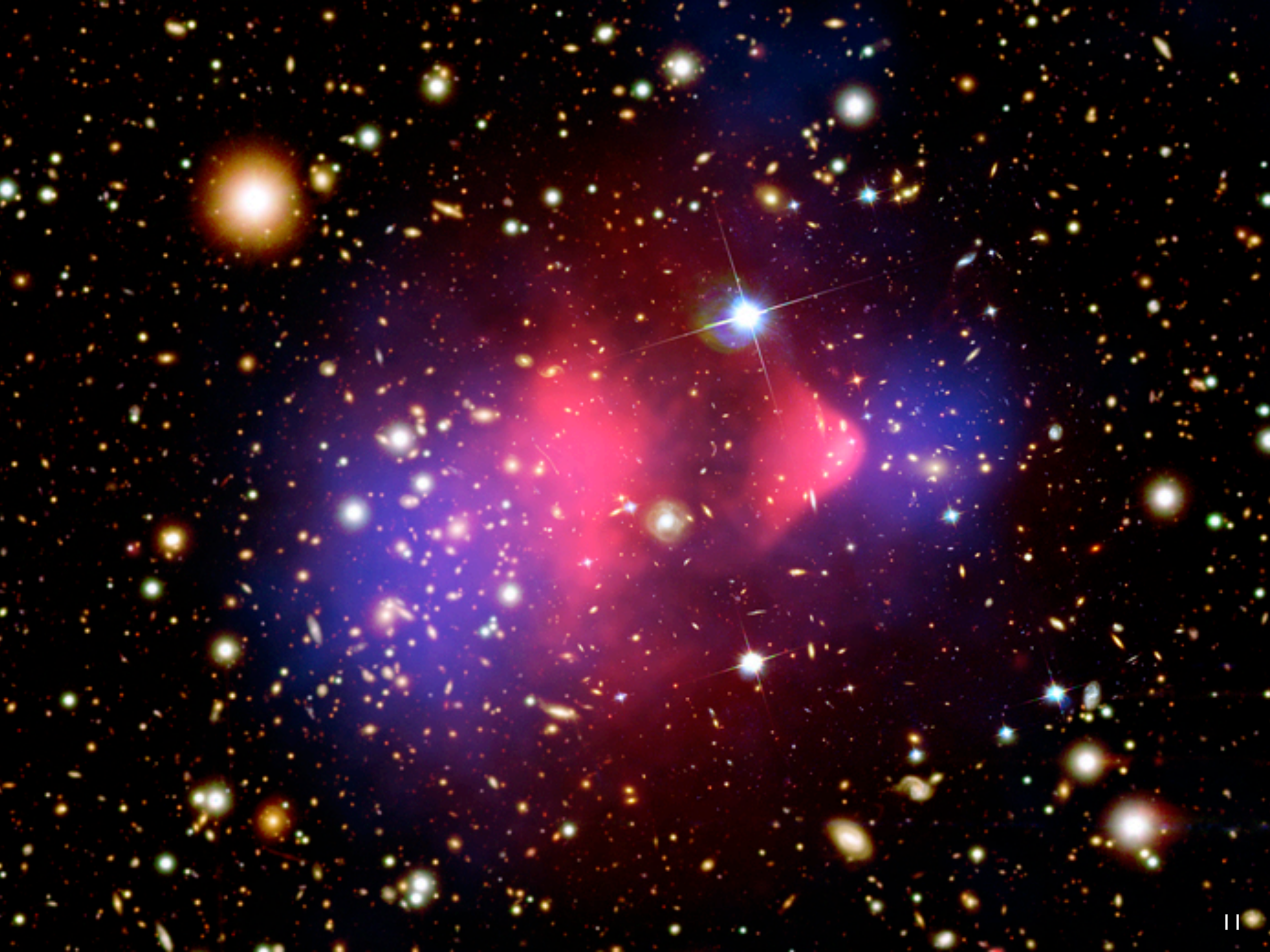




+ Tevatron evidence for $b\bar{b}$

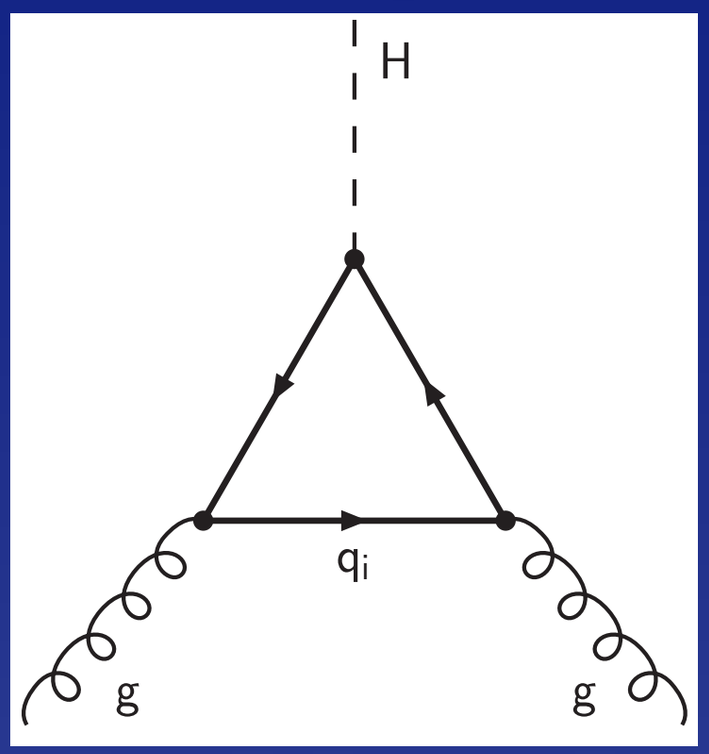


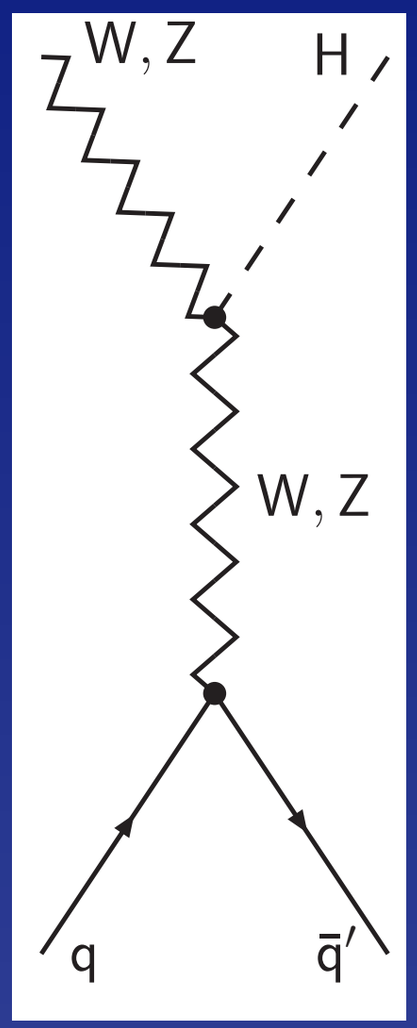


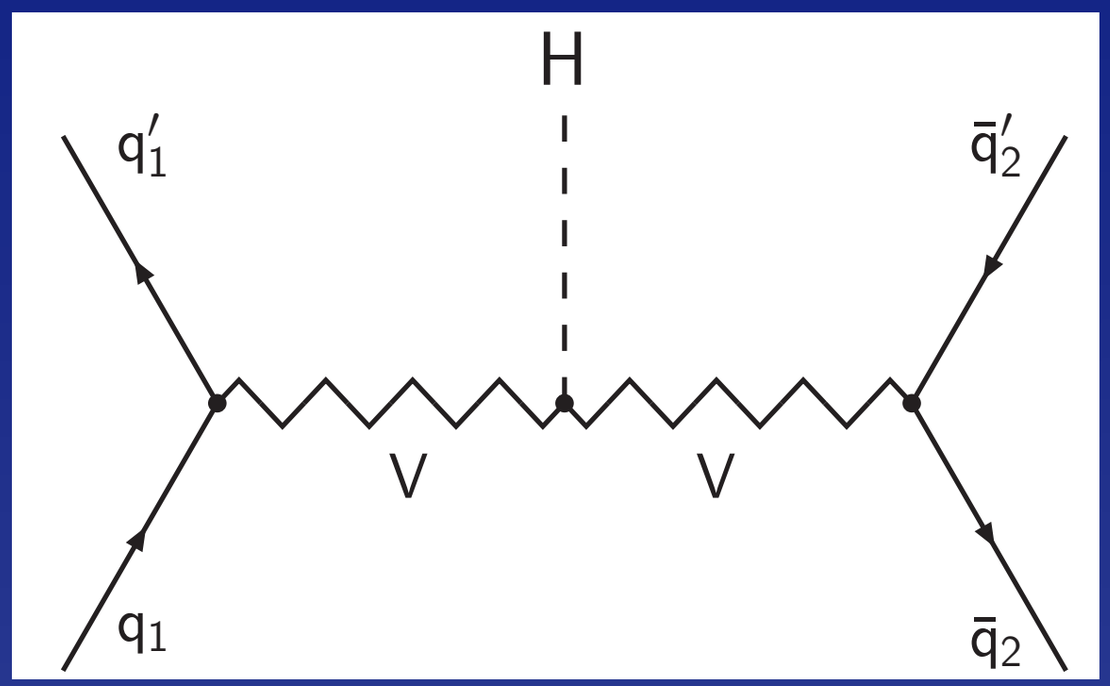


LHC affords multiple looks at the new boson

3 production mechanisms, ≥ 5 decay channels

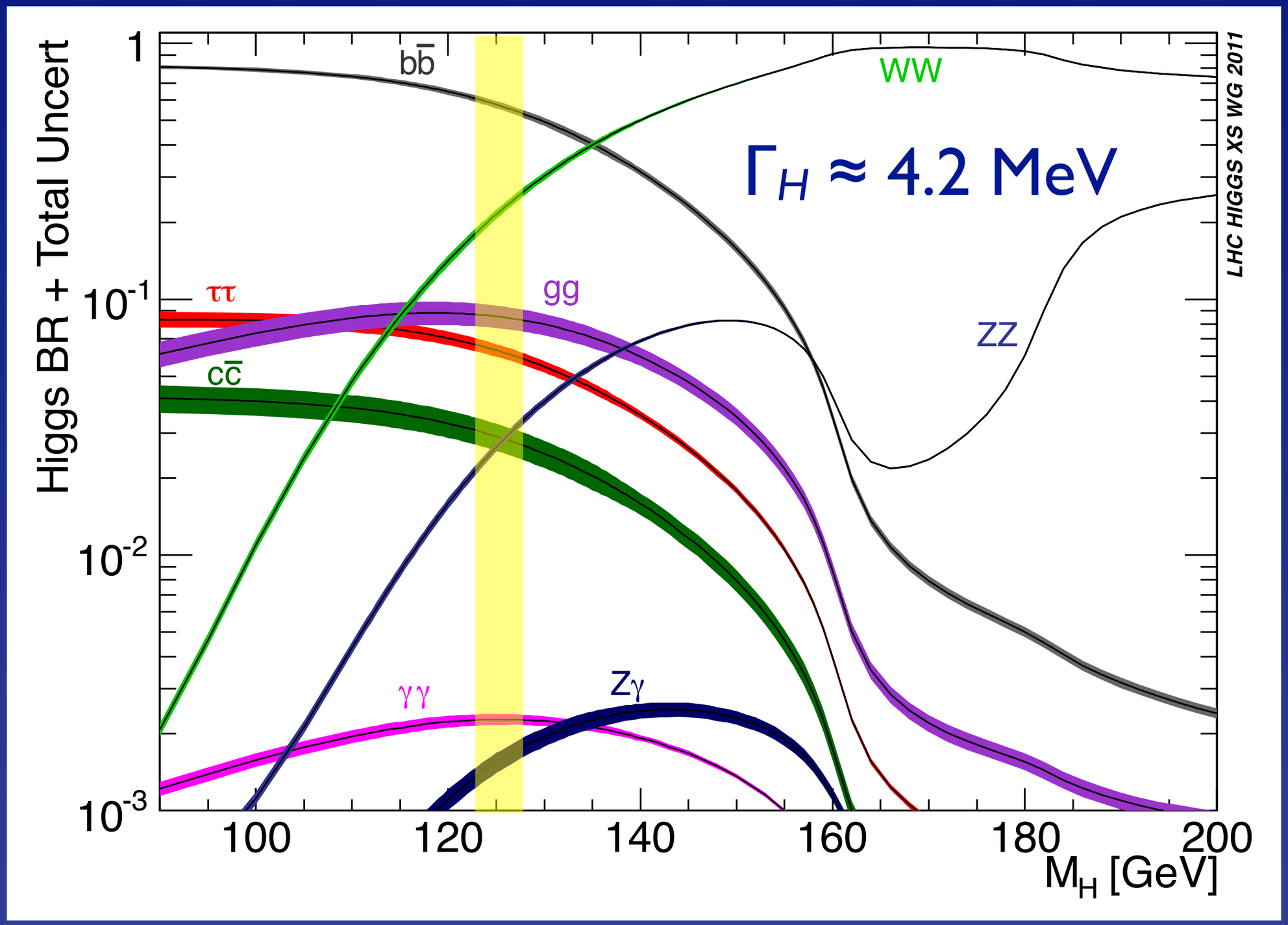






$\gamma\gamma$, *ZZ**, *WW**, *b* pairs, $\tau^+\tau^-$

Standard-Model Higgs-Boson Branching Fractions



SM

H → 2 fermions												
MH [GeV]	H → bb			H → τ τ			H → μ μ			H → cc		
125.5	5.69E−01	+3.3	−3.3	6.24E−02	+5.7	−5.6	2.17E−04	+6.0	−5.8	2.87E−02	+12.2	−12.2
126.0	5.61E−01	+3.3	−3.4	6.15E−02	+5.6	−5.6	2.14E−04	+5.9	−5.8	2.83E−02	+12.2	−12.2
126.5	5.53E−01	+3.4	−3.4	6.08E−02	+5.6	−5.5	2.11E−04	+5.9	−5.7	2.79E−02	+12.2	−12.2

H → gauge bosons																		
MH [GeV]	H → gg			H → γ γ			H → Z γ			H → WW			H → ZZ			Total Width Γ H [GeV]		
125.5	8.52E−02	+10.2	−9.9	2.28E−03	+4.9	−4.8	1.58E−03	+8.9	−8.8	2.23E−01	+4.2	−4.1	2.76E−02	+4.3	−4.1	4.14E−03	+3.9	−3.9
126.0	8.48E−02	+10.1	−9.9	2.28E−03	+4.9	−4.8	1.62E−03	+8.9	−8.8	2.31E−01	+4.1	−4.1	2.89E−02	+4.2	−4.0	4.21E−03	+3.9	−3.8
126.5	8.42E−02	+10.1	−9.8	2.28E−03	+4.8	−4.7	1.66E−03	+8.8	−8.7	2.39E−01	+4.1	−4.0	3.02E−02	+4.1	−4.0	4.29E−03	+3.8	−3.8

H → 4 fermions									
MH [GeV]	H → l+l−l+l− l=e, μ , τ	H → l+l−l+l− l=e, μ	H → e+e−e+e−	H → e+e− μ + μ -	H → l+ l− ν , ν , l = e, μ or τ ν = any	H → l+ l− ν , ν , l = e or μ ν = any	H → e+ ν e− ν H → e+ ν μ− ν		ΔBR (%)
125.5	2.89E−04	1.30E−04	3.42E−05	6.21E−05	2.43E−02	1.10E−02	2.62E−03	2.62E−03	4.2
126.0	3.02E−04	1.36E−04	3.56E−05	6.49E−05	2.53E−02	1.14E−02	2.72E−03	2.72E−03	4.1
126.5	3.15E−04	1.42E−04	3.72E−05	6.78E−05	2.62E−02	1.18E−02	2.83E−03	2.82E−03	4.1

H → 4 fermions							
MH [GeV]	H → l+ l− q q l = e, μ or τ q = udcsb	H → l+ l− q q l = e or μ q = udcsb	H → l+ ν , q q (* l = e or μ q = udcsb	H → ν , ν , q q ν = any q = udcsb	H → qqqq q = udcsb	H → ffff f = any type of fermion	ΔBR (%)
125.5	3.87E−03	2.58E−03	3.26E−02	7.73E−03	1.14E−01	2.49E−01	4.2
126.0	4.05E−03	2.70E−03	3.38E−02	8.08E−03	1.18E−01	2.59E−01	4.1
126.5	4.23E−03	2.82E−03	3.51E−02	8.44E−03	1.23E−01	2.68E−01	4.1

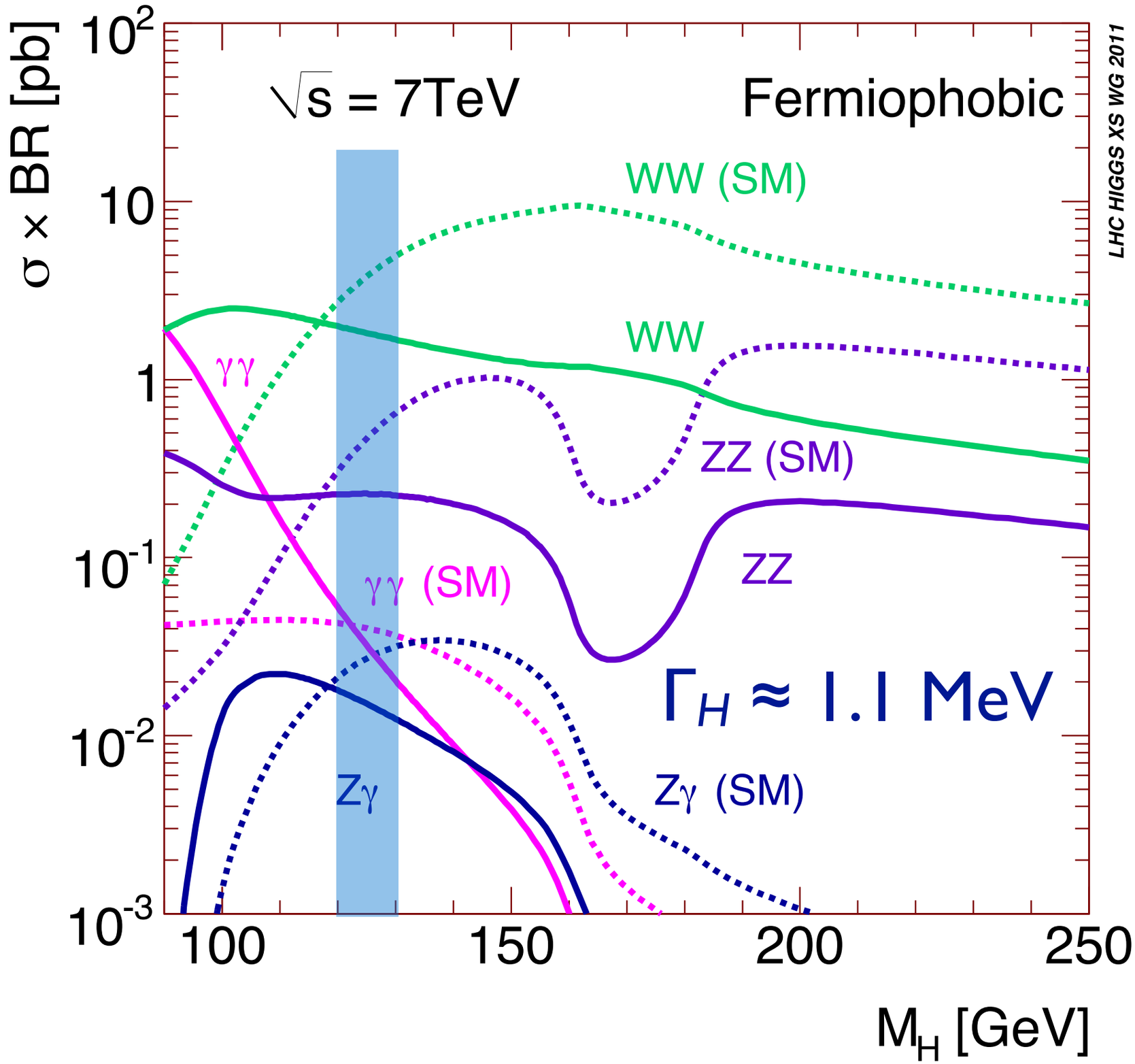
Fully accounts for EWSB (W, Z couplings)?

Couples to fermions?

Top from production,

need direct observation for b, τ

Distinguishing SM, bosogamous Higgs bosons



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Accounts for fermion masses?

Fermion couplings $\propto$ masses?

Are there others?

Quantum numbers?

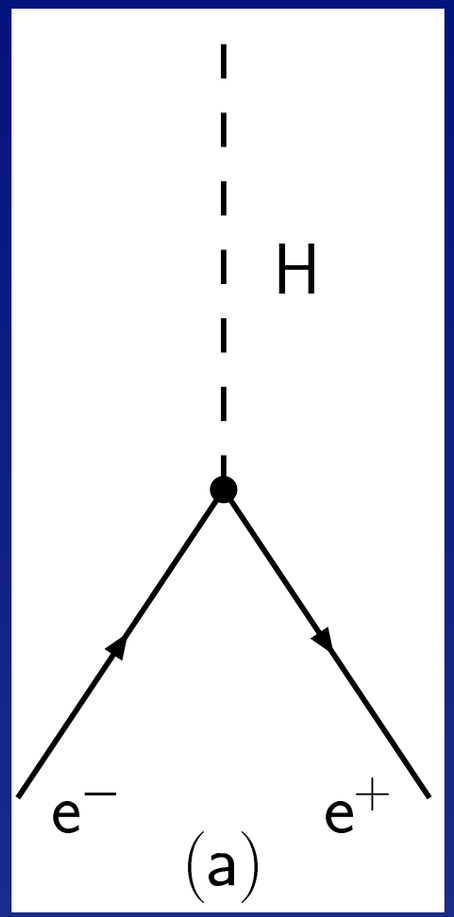
SM branching fractions to gauge bosons?

Decays to new particles?

All production modes as expected?

Implications of $M_H \approx 126$ GeV?

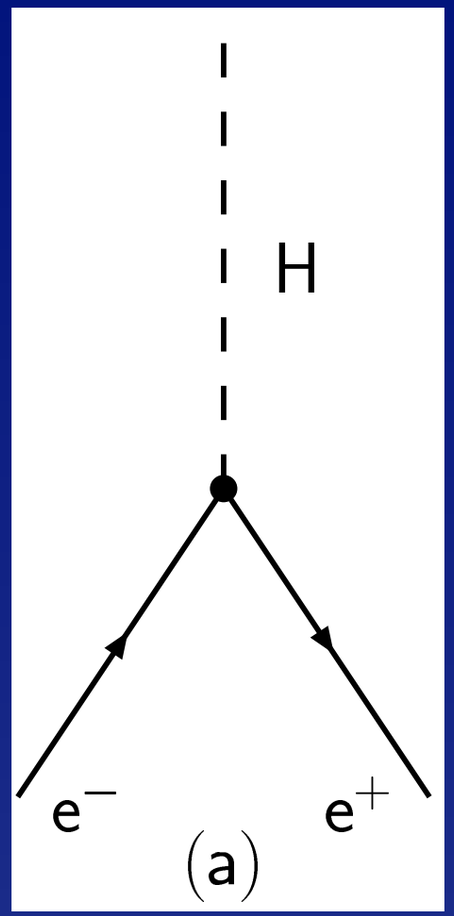
Any sign of new strong dynamics?



s-channel formation?

$$\sigma_{\rm peak}(e^+e^- \to H) = \frac{4\pi}{M_H^2} \cdot \frac{\Gamma(H \to e^+e^-)}{\Gamma(H \to \text{all})}$$

$$= 4.89 \times 10^{-31}\ \text{cm}^2 \left[\frac{100\ \text{GeV}}{M_H}\right]^2 \cdot \frac{\Gamma(H \to e^+e^-)}{\Gamma(H \to \text{all})}$$



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$$\approx 1.5 \times 10^{-39}\ {\rm cm}^2$$

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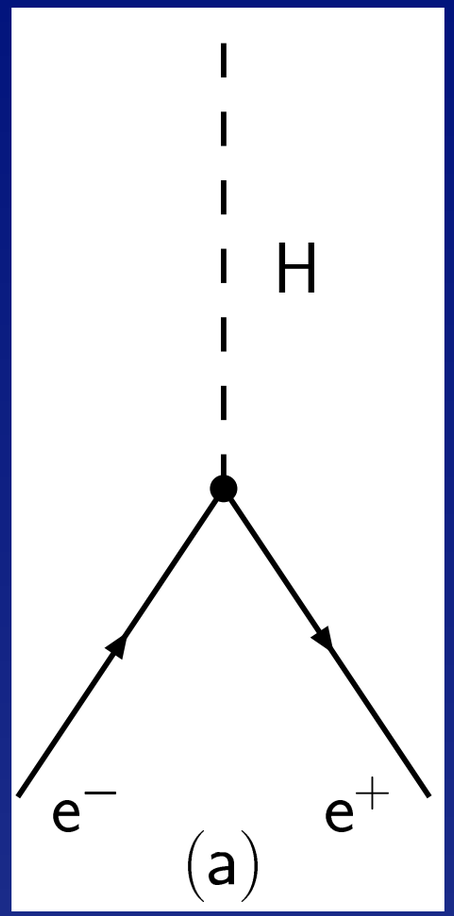

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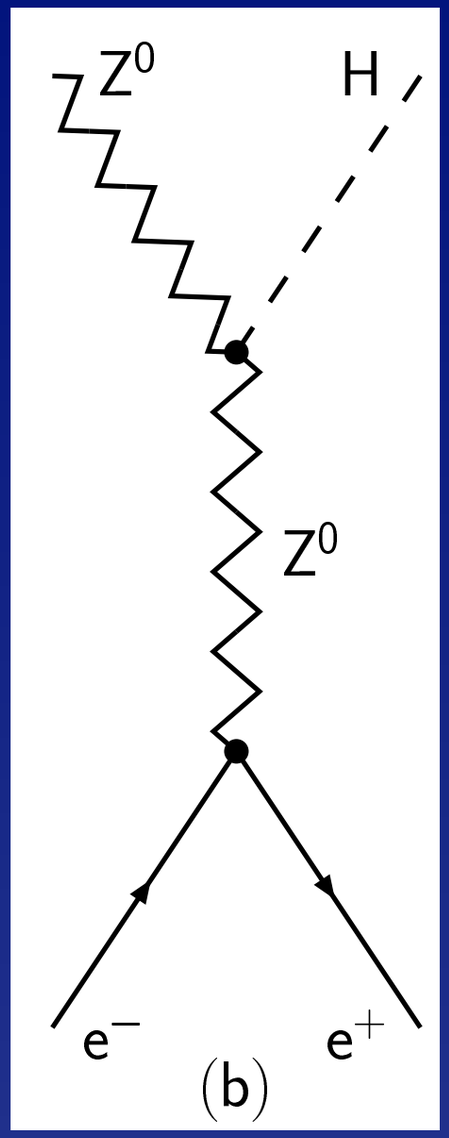
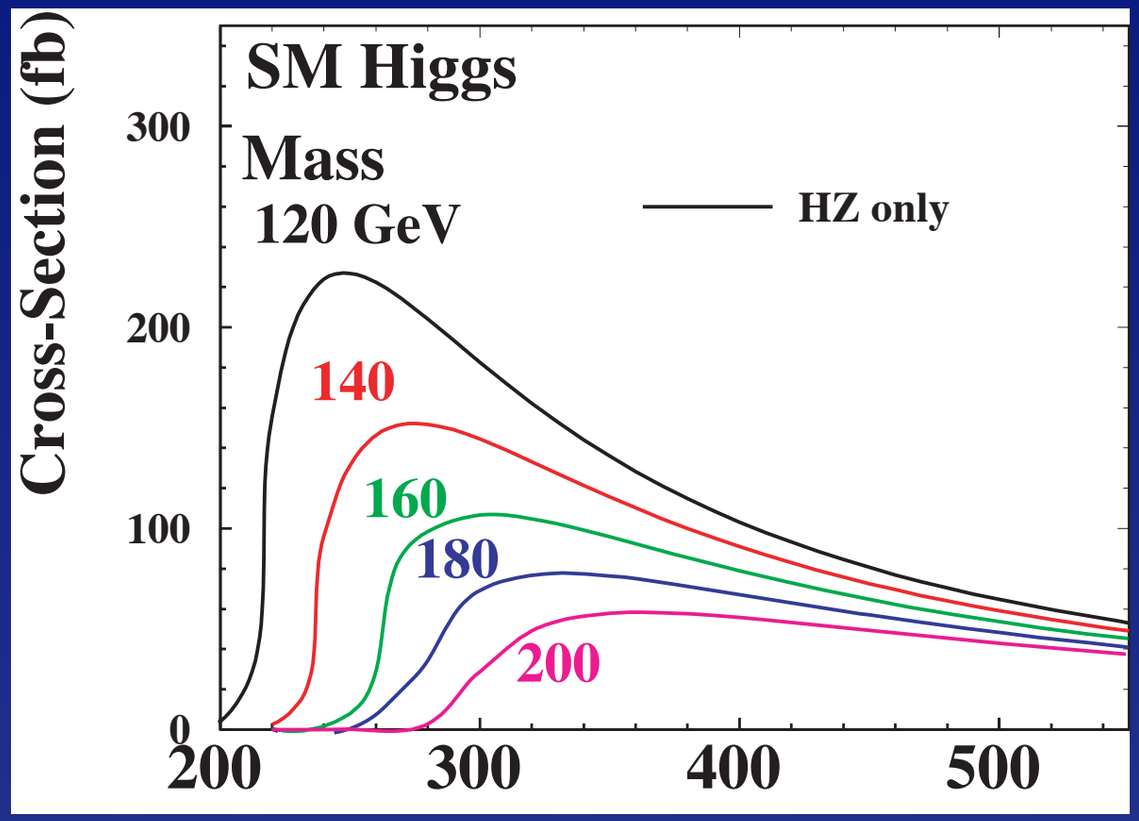
$$\approx 1.5 \times 10^{-39}\ {\rm cm}^2$$

$$\approx 5 \times 10^{-9}$$

$$\sigma_{\rm peak}(\mu^+\mu^- \to H) \approx 6.4 \times 10^{-35}\ {\rm cm}^2$$

Higgsstrahlung

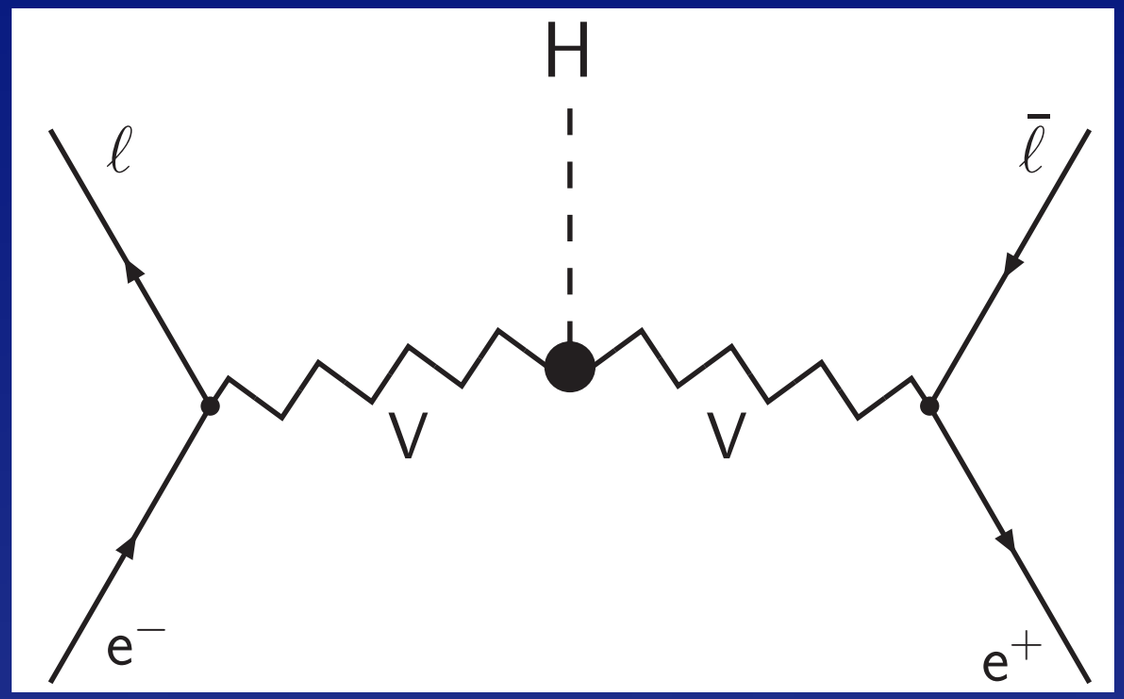


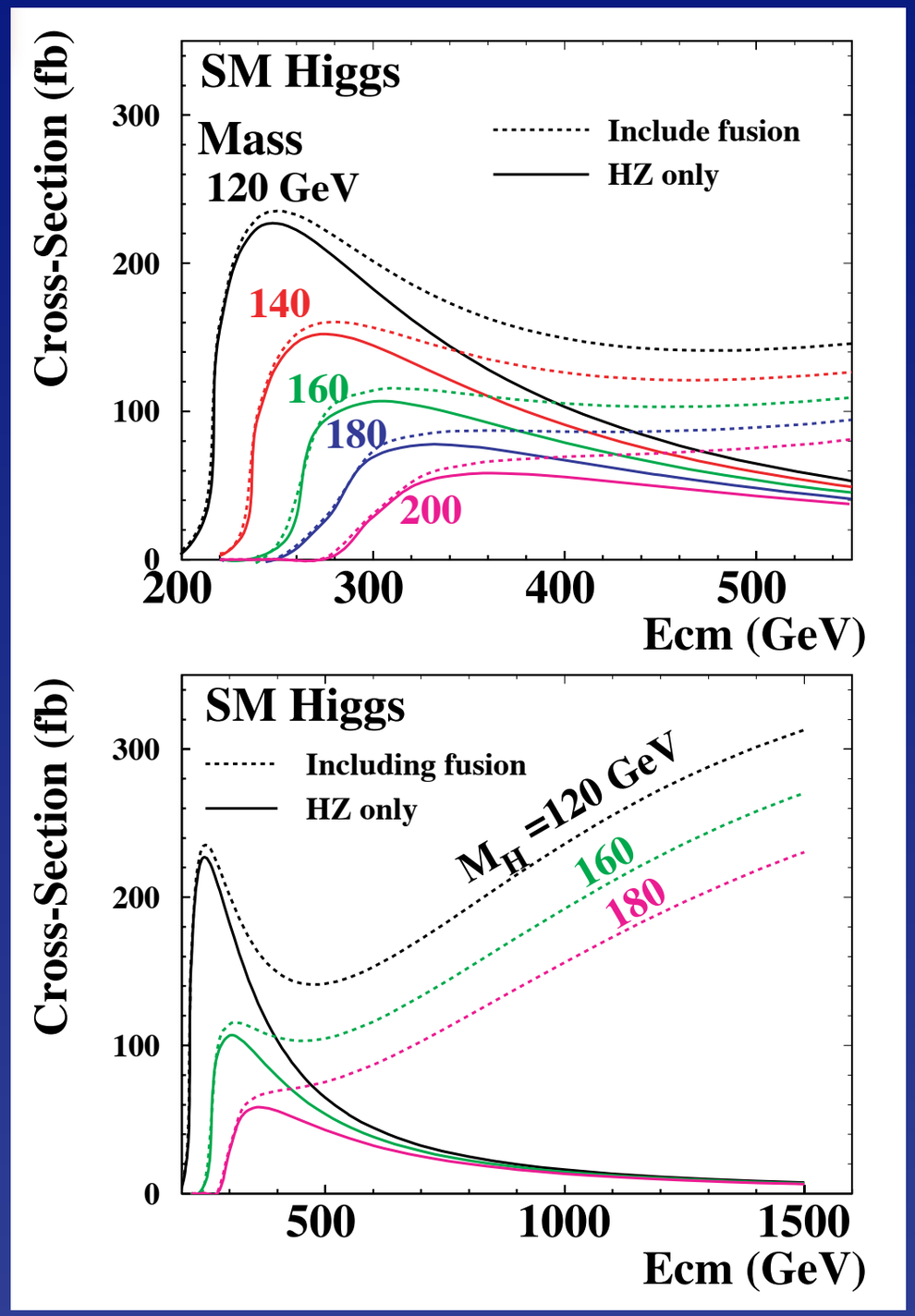


$$\sigma(e^+e^- \to HZ) = \frac{\pi\alpha^2}{24}\left(\frac{2K}{\sqrt{s}}\right)\frac{(K^2+3M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\frac{(1-4x_{\rm W}+8x_{\rm W}^2)}{x_{\rm W}^2(1-x_{\rm W})^2}$$

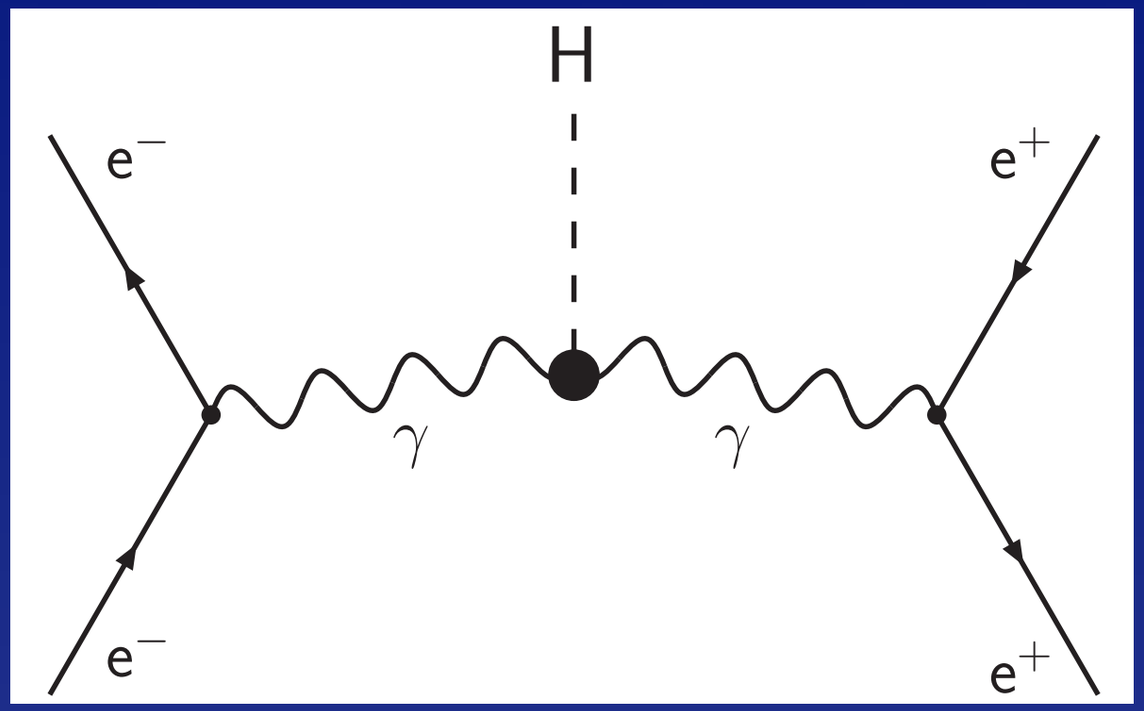
$$x_{\rm W} = \sin^2\theta_{\rm W}; \quad K = \text{c.m. momentum}$$

Vector Boson Fusion





Photon–Photon Collisions



$$\sigma(E) = 16\alpha^2 \frac{\Gamma(H^0 \to \gamma\gamma)}{M_H^3}(2J+1)\ln^2\left(\frac{E}{m_e}\right) f\left(\frac{M_H}{2E}\right)$$

↳ γγ Collider

Important measurements at any moment depend on what is already known

SM-like or very nonstandard

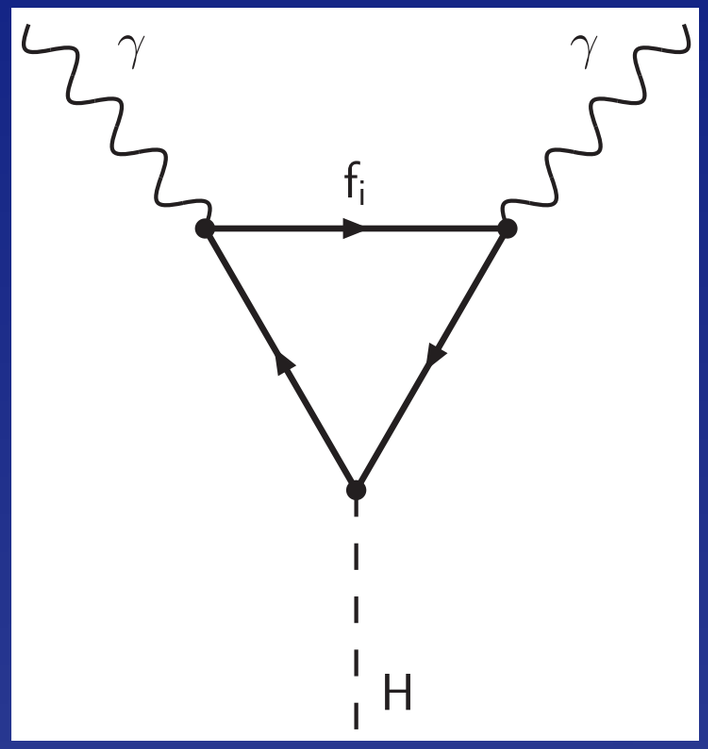
Discovery of another "Higgs-like object"

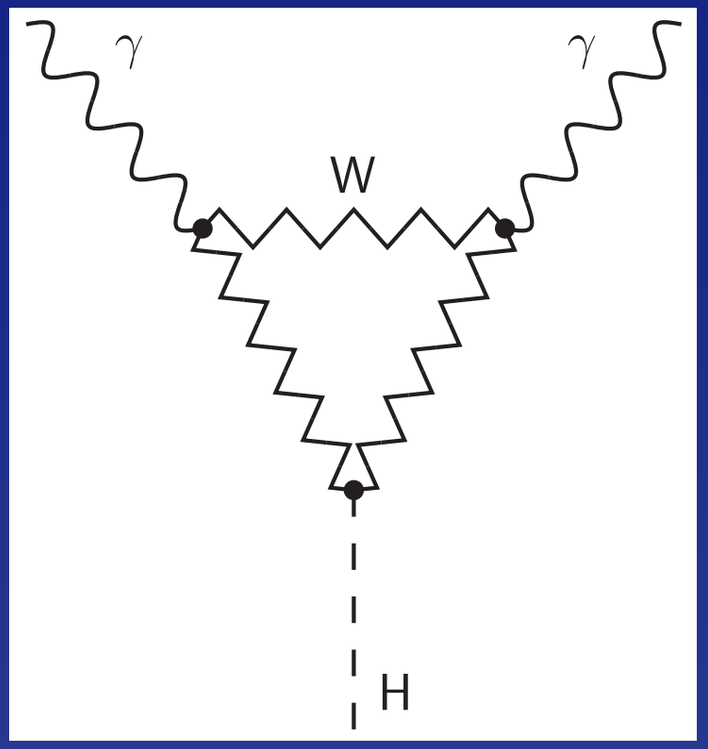
Direct evidence for or against new degrees of freedom

Examples of non-standard behavior

Spin ≠ 0

deviant γγ branching fraction





↳ New particles in loops (not too heavy)

Examples of non-standard behavior

Suppression of *WW*, *ZZ* modes
Acid test for low-scale technicolor:
Higgs impostor, η_T(126 GeV)
+ higher mass (180 GeV?) companion

Eichten, Lane, Martin arXiv:1210.5462

Not a favorable scenario for a Higgs factory!

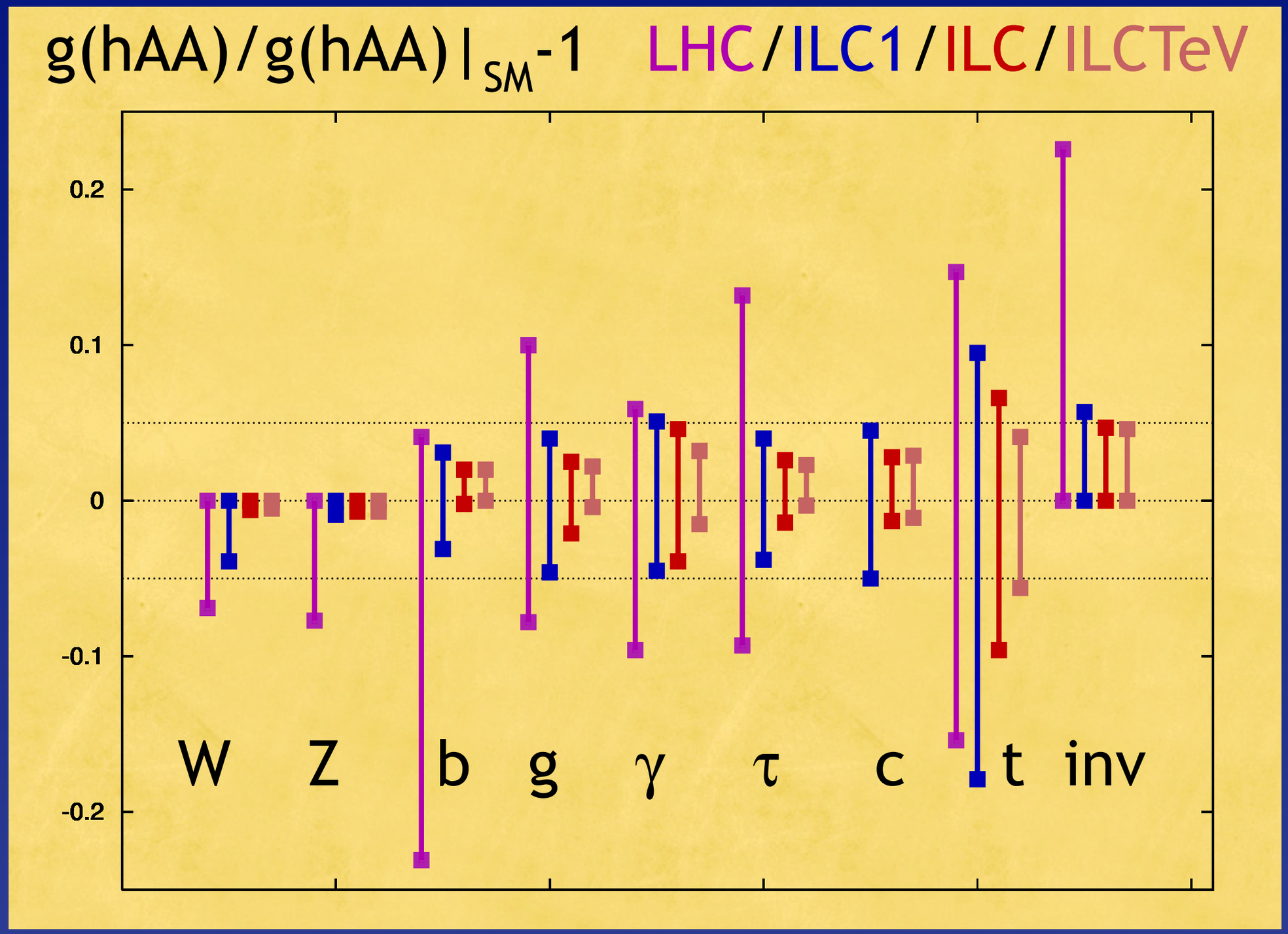
Examples of non-standard behavior

"Higgs" is not a simple Breit-Wigner,
or does not account for all of EWSB

Premium on measuring Γ_H
(perhaps 1 GeV),
seeking remaining contribution,
scanning spectral density

van der Bij, arXiv:1204.3435

An early attempt at a shopper's guide



M. Peskin, arXiv:1207.2516

Requirements for a shopper's guide

Clearly stated assumptions

Documented uncertainty estimates

Rich list of observables, including

$\Gamma(\mu\mu)$, M_H, ΔM_H, $\Delta\Gamma_H$, …

Rich list of possible machines

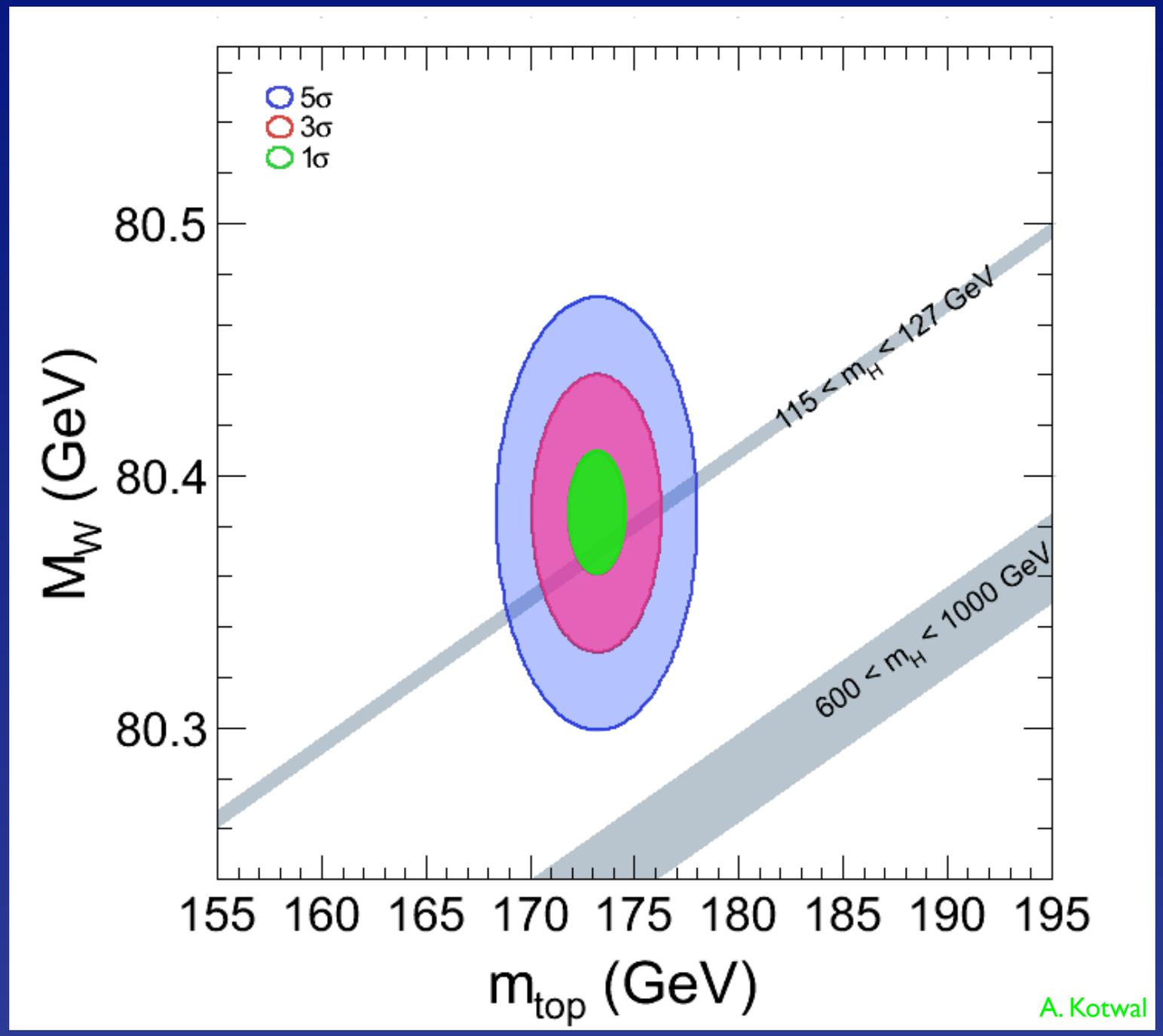
<u>A time dimension</u> (linear scale)

Specifying Physics Program & Requirements

Inspired by cta cherenkov telescope array

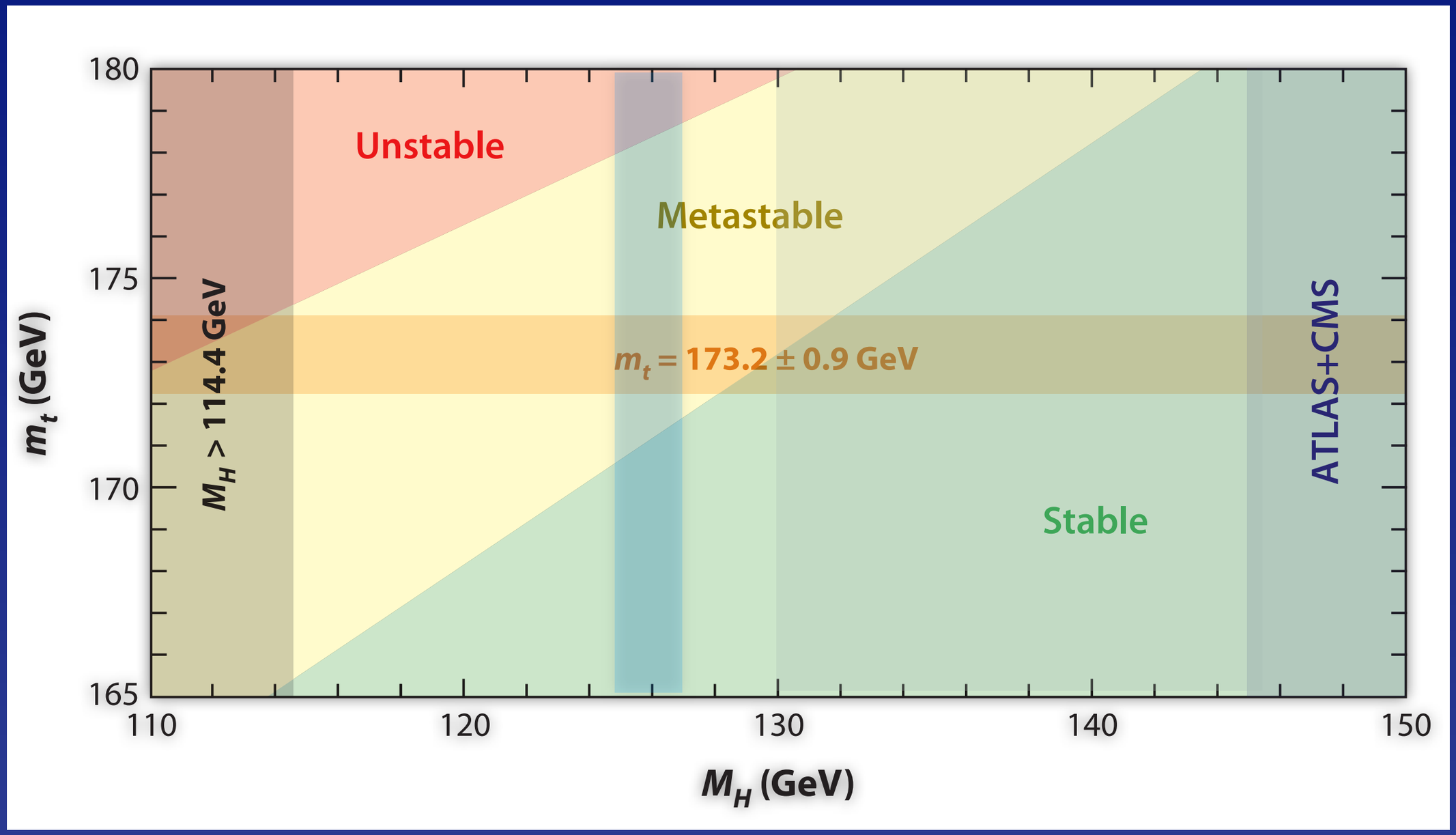
CTA Physics case: Driver	Sensitivity	Angular Resolution	Energy Resolution	Energy Threshold	Energy Range
HF Physics case: Driver	Integrated Luminosity (+ time)	Polarization	Energy Resolution	Energy Threshold	Energy Range

Collateral Measurements: M_W, m_t?



Will it be important to improve on Tevatron + LHC?

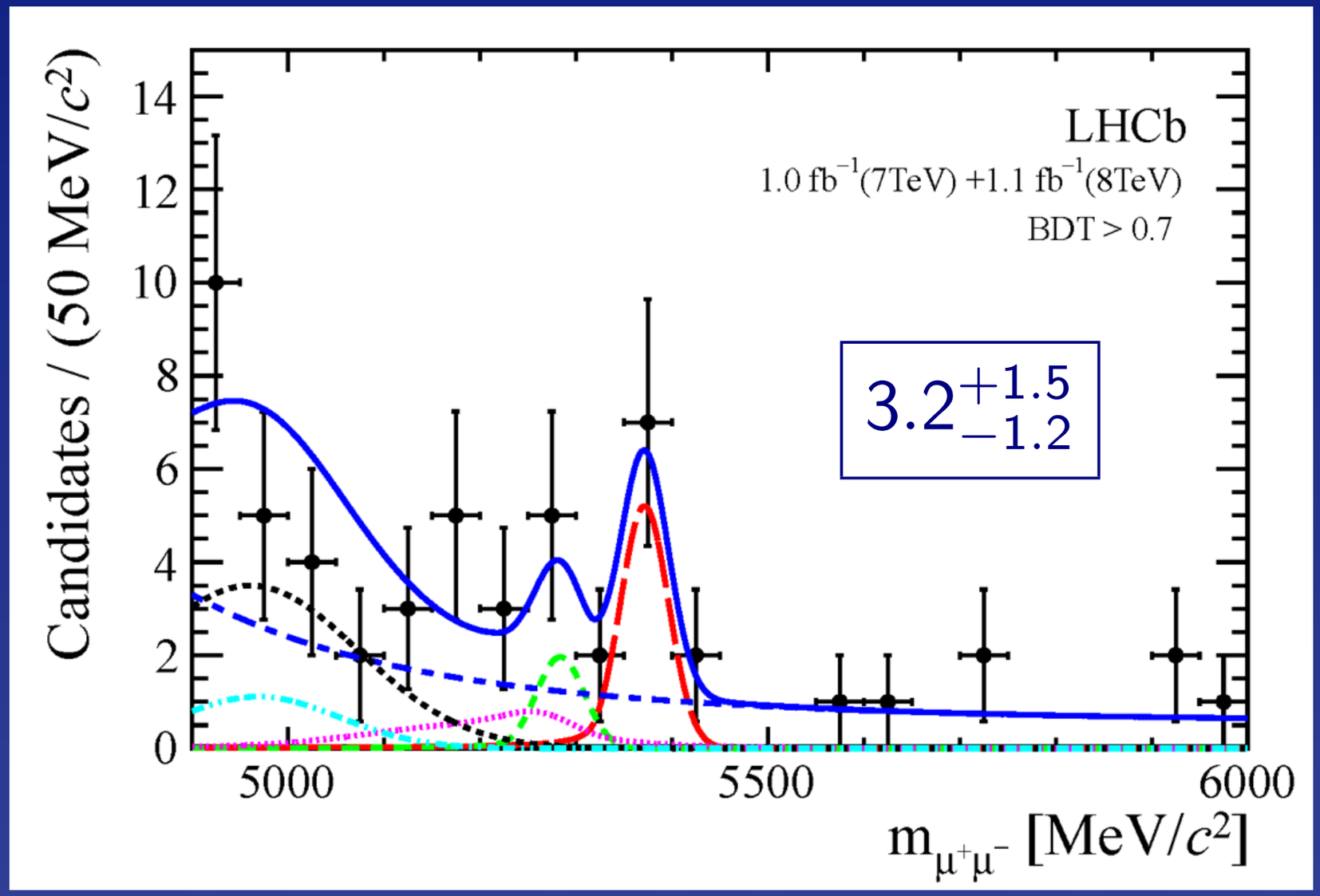
Might we live in a metastable vacuum?



We will learn from other quarters …

SM: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$

MSSM: $\mathrm{BR}(B_s \to \mu^+\mu^-) \propto \frac{m_b^2 m_t^2}{M_A^4} \tan^6\beta$



Stone, ICHEP 2012

As you elaborate machine concepts …

Important not to narrow the physics vision by pretending we know the answer

Couplings

Distributions

Mass / width

Searches in the Higgs sector

Searches beyond the Higgs sector

Other parameters: M_W, m_t

Back to Z^0?