High energy physics after three years of LHC data: status and prospects

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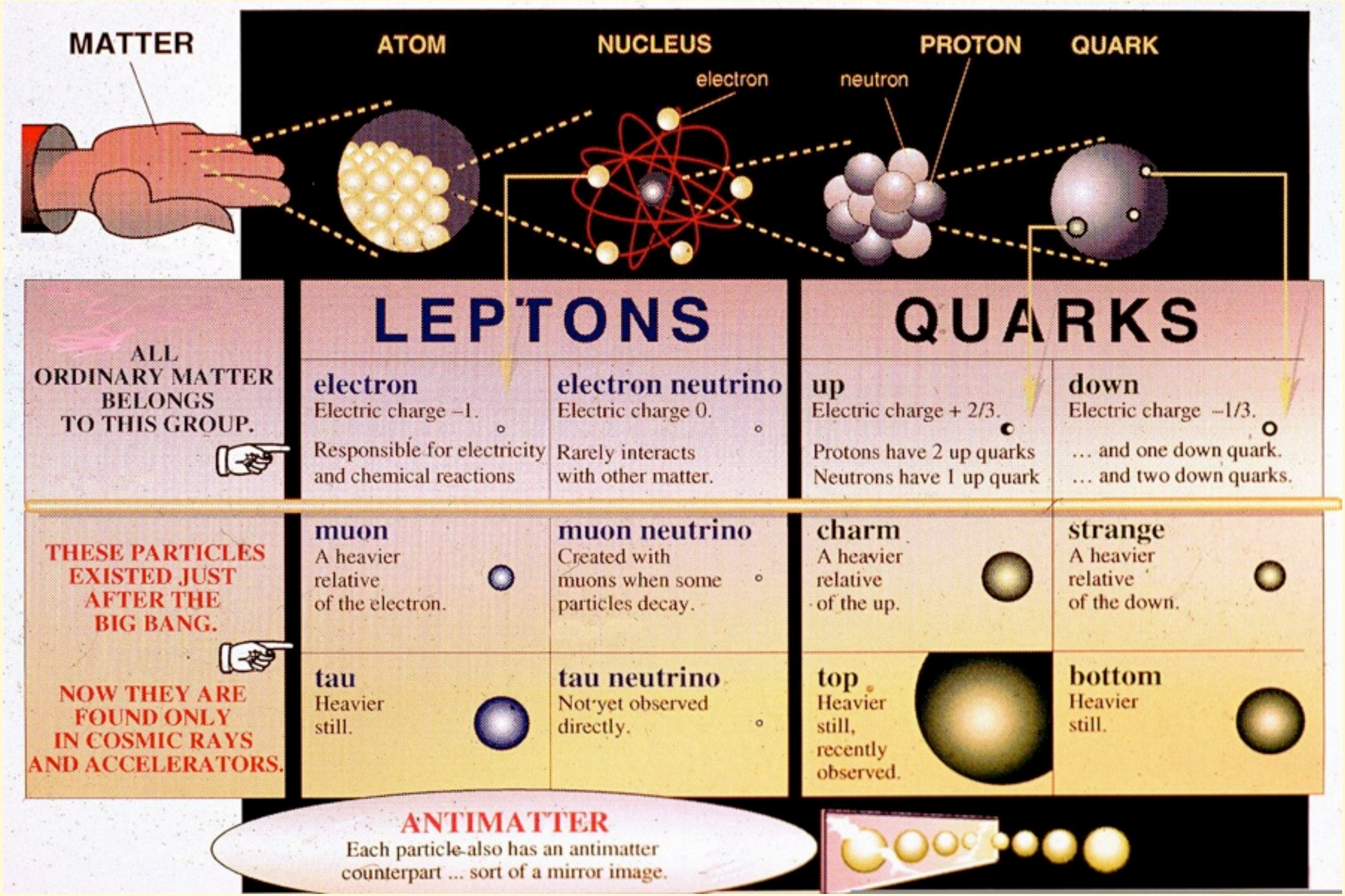
The Standard Model



Status of the Standard Model

- **< 1973: theoretical foundations of the SM**
  - renormalizability of SU(2)xU(1) with Higgs mechanism for EWSB
  - asymptotic freedom, QCD as gauge theory of strong interactions
  - KM description of CP violation
- **Followed by 40 years of consolidation:**
  - **experimental** verification, via **discovery** of
    - **Fermions**: charm, tau, bottom, top (all discovered in the USA)
    - **Bosons**: gluon, W and Z, **Higgs** (all discovered in Europe)
  - **technical theoretical advances** (higher-order calculations, lattice QCD, ...)
  - **experimental** consolidation, via **measurement** of
    - EW radiative corrections
    - running of α_S
    - CKM parameters
- **Remains to be verified:**
  - **mechanism at the origin of particles' masses: is the Higgs boson dynamics what prescribed by the SM, or are there other phenomena at work?**

On particles' masses

For a composite system the mass is obtained by solving the dynamics of the bound state ⇒ $\mathbf{m=\langle E\rangle/c^2}$ with $\mathbf{\langle E\rangle=\langle T+U\rangle}$

Example: the proton mass. Dynamics of quarks and gluons inside the proton (they have negligible masses) ⇒ m_p = 938 MeV

But what about elementary particles? Elementary ⇒ no internal dynamics

Need to develop a new framework within which to understand the origin and value of, for example, the electron mass

However:

- Why do we need a mechanism to accommodate the masses of elementary particles?
- How about just assigning mass values as parameters?

In other words:
WHY are particle physicists so *obsessed* with the problem of particles' masses?

Electroweak symmetry breaking and the Higgs boson

Two problems

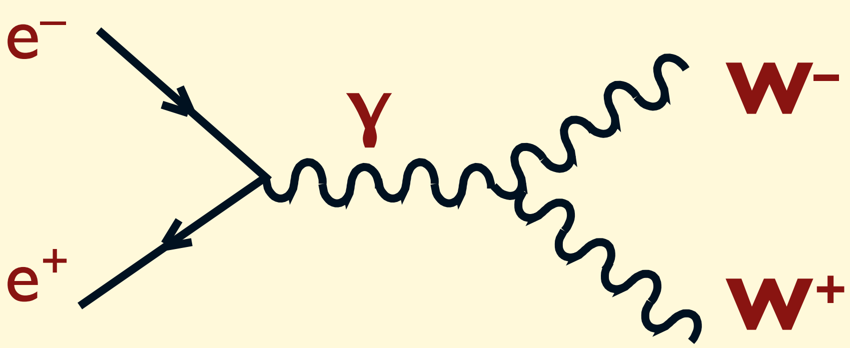
- The mass of vector bosons responsible for weak interactions
- The mass of quarks and leptons

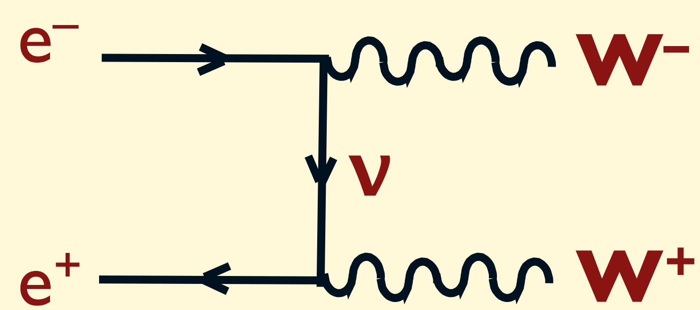
If vector bosons had a canonical mass term in the Lagrangian,

$$\sum_{pol} \epsilon_\mu \epsilon^*_\nu = -g_{\mu\nu} + \frac{k_\mu k_\nu}{M^2}$$

$k_\mu = (E\,,\mathbf{k})$

As a result, the naive couplings embodied in Fermi's theory:



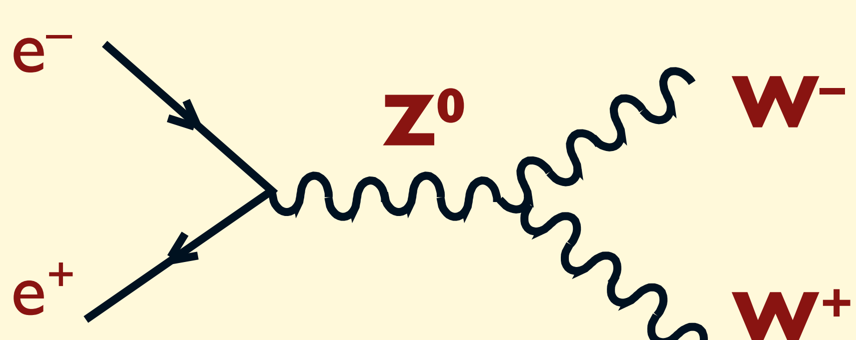


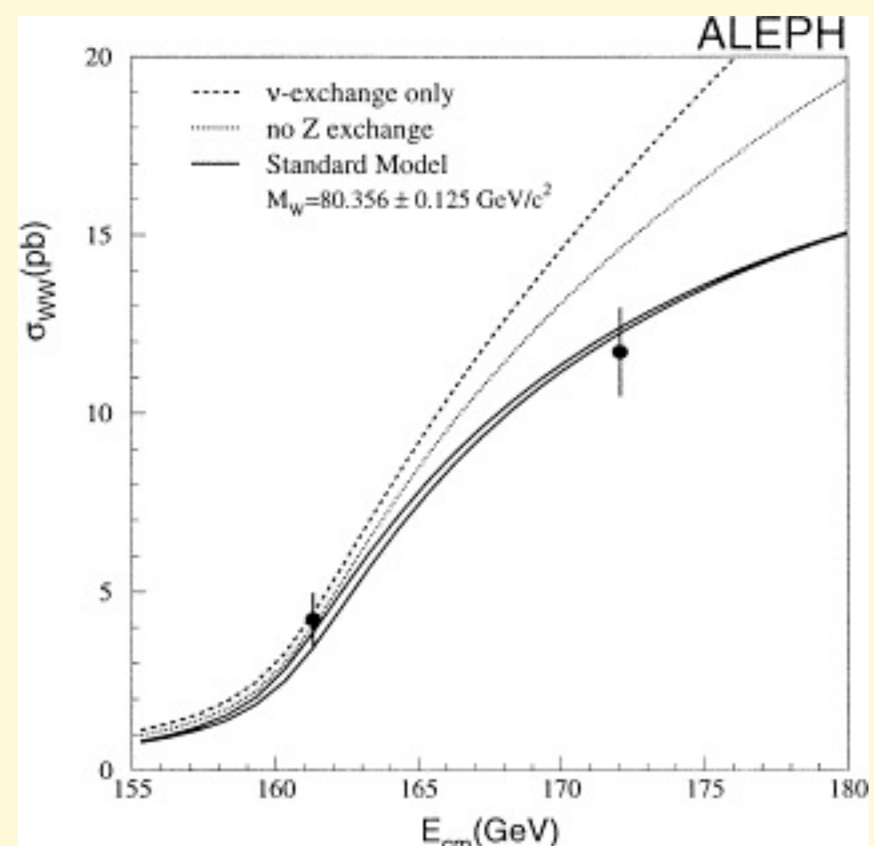
would lead, at high energy, $k_\mu \to \infty$, to:

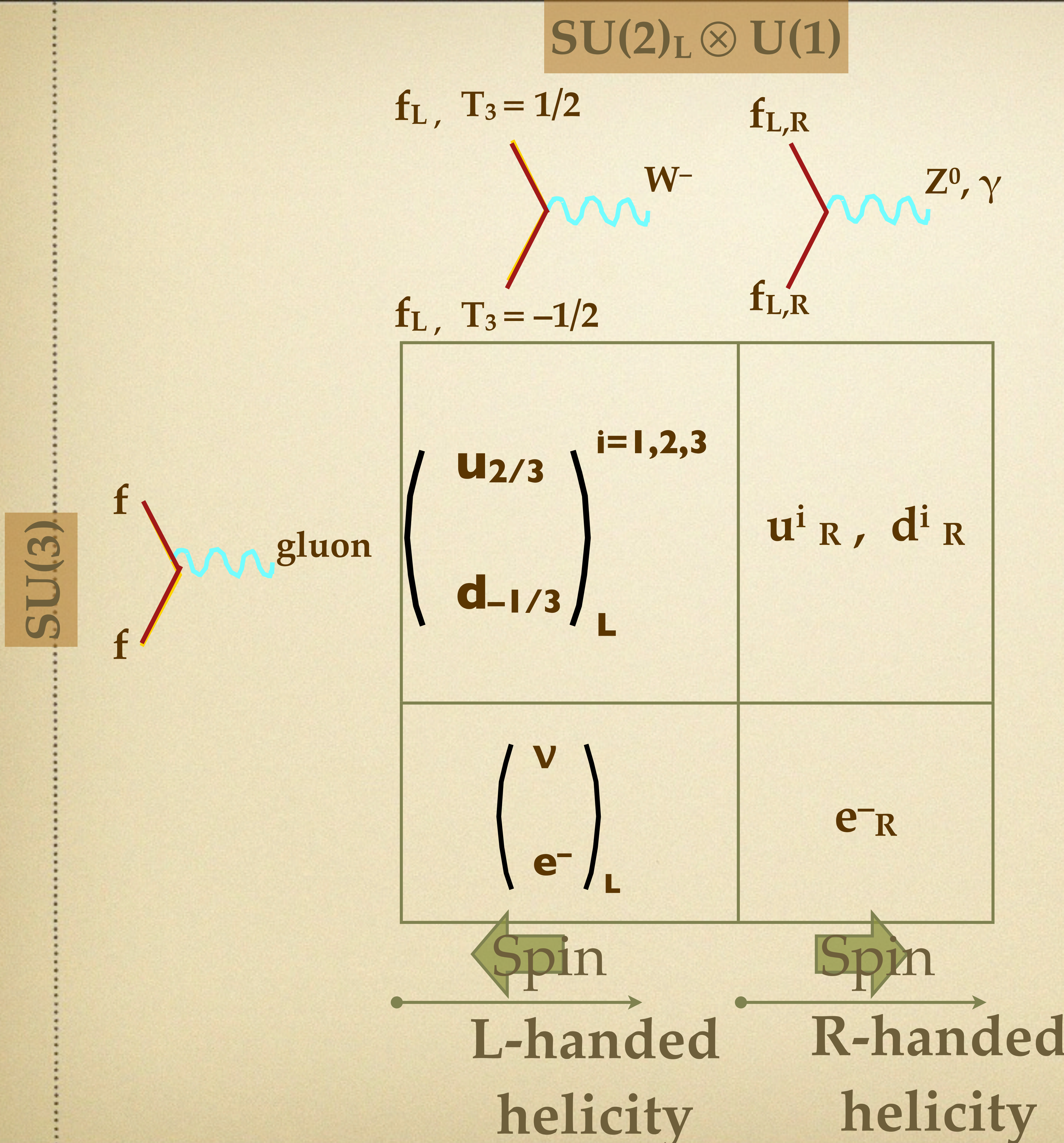
$$\sigma(e^+e^- \to W^+W^-) \propto \frac{E^2}{M^4}$$

which violates unitarity.

The only way to restore unitarity (at all perturbative orders) is to introduce a gauge symmetry that, among other things, requires a new particle, and well determined couplings:

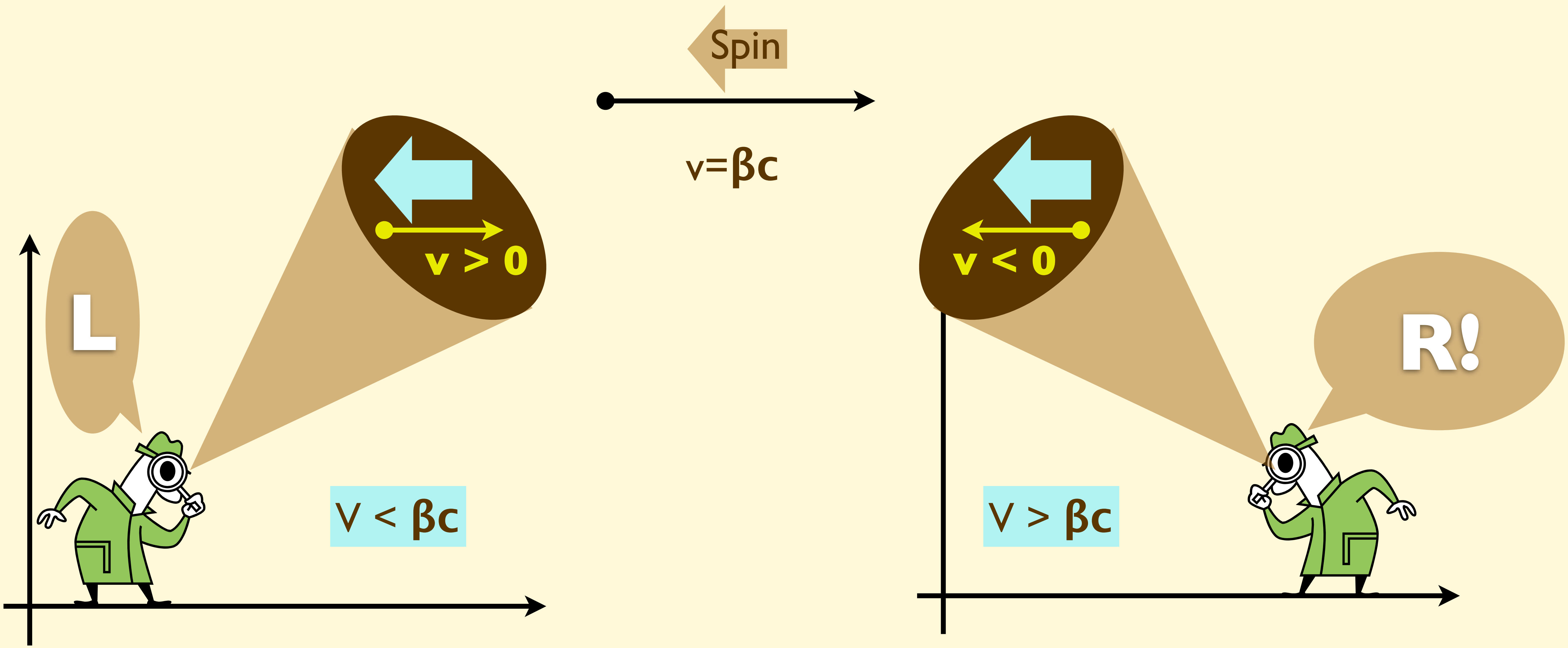






+ 2 more "families" differing from the 1st one only in the mass of their elements

Parity asymmetry and mass



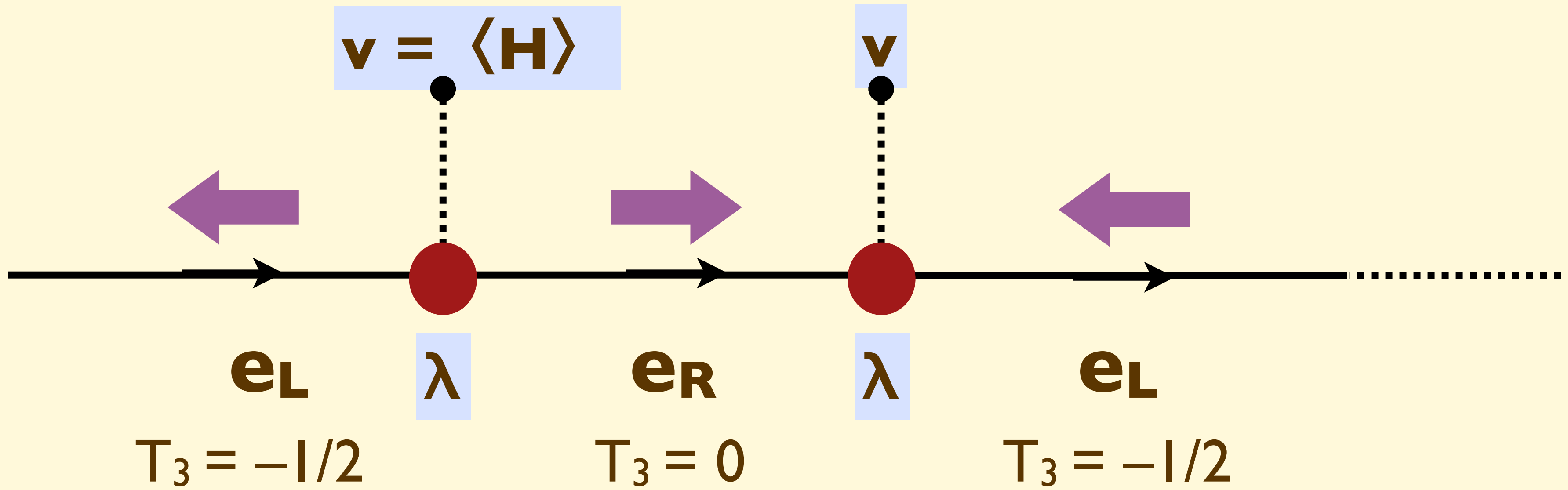
Helicity does not commute with Hamiltonian, so it cannot be conserved for a massive particle

Since helicity is directly connected with the weak charge, the weak charge of a massive particle is not observable, and cannot be conserved.

The symmetry associated with the conservation of the weak charge must therefore be broken for leptons and quarks to have a mass

Higgs mechanism

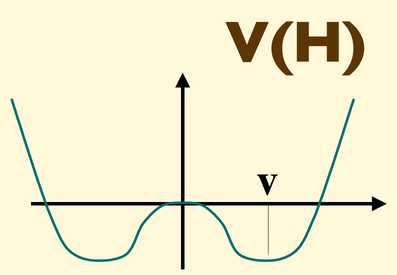
Evolution of a massive particle:



The transition between L and R states, and the absorption of the changes in weak charge, are ensured by the interaction with a background scalar field, **H**. Its "vacuum density" provides an infinite reservoir of weak charge.

The number "**v**" is the expectation value of the so-called **Higgs field**.
The quantity "**λ**" is characteristic of the particle interacting with the Higgs field.
It can easily be shown that **this interaction leads to a mass** $\mathbf{m \propto \lambda v}$

Why should the field H develop a non-zero background value?



What assigns to the various fermions the value of λ corresponding to their mass? Why λ[muon]≠ λ[electron]?

Particle masses play a crucial role in determining the nature of the universe as we know it:

m[electron] determines the "size of things"

m[electron] vs m[down]–m[up] determines the rates of both fission and fusion processes, defining the lifetime of stars, as well as abundance of primordial elements in the early universe

Intriguing questions arise from the spectrum of and mixings among different flavours

Since m[top]~170 GeV, λ[top]=1: **coincidence**?

In several theories beyond the SM, m[top]≈170 GeV is required for a dynamical breaking of the EW symmetry: **message**?

It turns out that $m[H]^2$ = m[top] x m[Z]: **coincidence**?

The precise identification of the cause of electroweak symmetry breaking phenomenon, of its dynamics and of the origin of the flavour structure, are therefore crucial goals for the progress of our understanding of Nature

Nevertheless ....

Note on "the mass of the Universe"

- proton's mass arises from QCD dynamics, not from the mass of its constituent quarks. Half of it is kinetic energy of the tightly bound relativisitic quarks, the other half is binding energy ($M=Ec^2$, $E=K+U$, virial theorem....)

- the mass of particles composing Dark Matter does not need to arise from the coupling with the Higgs. E.g. in Supersymmetry models it could mostly come from the breaking of supersymmetry, nothing to do with the Higgs or EWSB

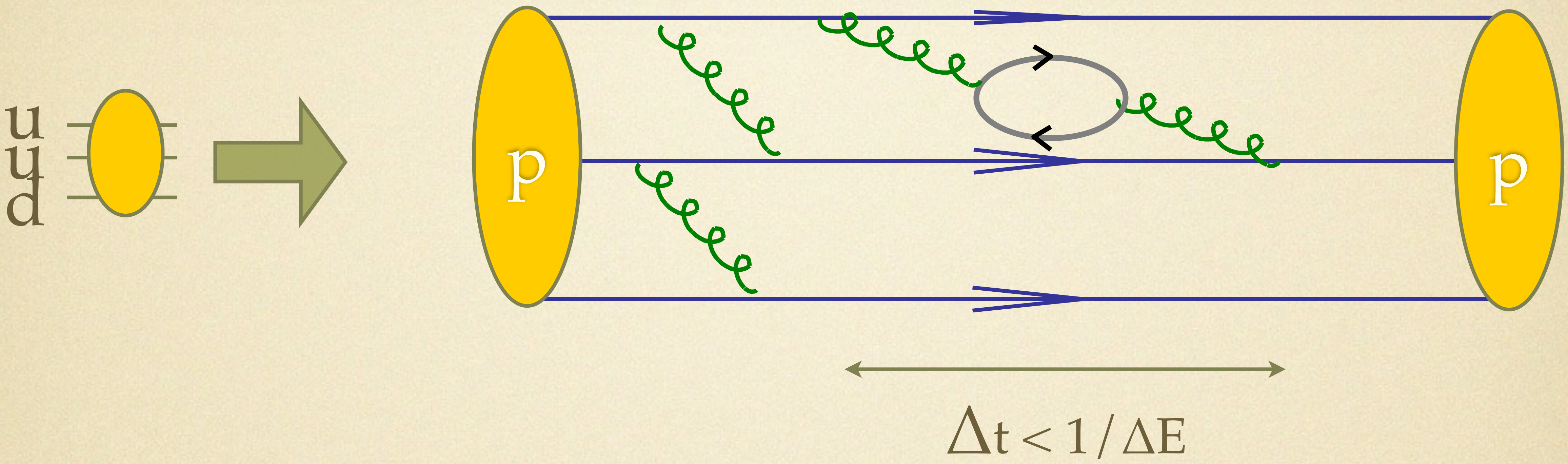
Detecting the Higgs boson

Like any other medium, the Higgs continuum background can be perturbed. Similarly to what happens if we bang on a table, creating sound waves, if we “bang” on the Higgs background (something achieved by concentrating a lot of energy in a small volume) we can stimulate “Higgs waves”. These waves manifest themselves as particles* , the so-called Higgs bosons

What is required is that the energy available be larger than the Higgs mass ⇒ LHC !!!

* Higgs particles are thus a bit like phonons ...

The structure of the proton



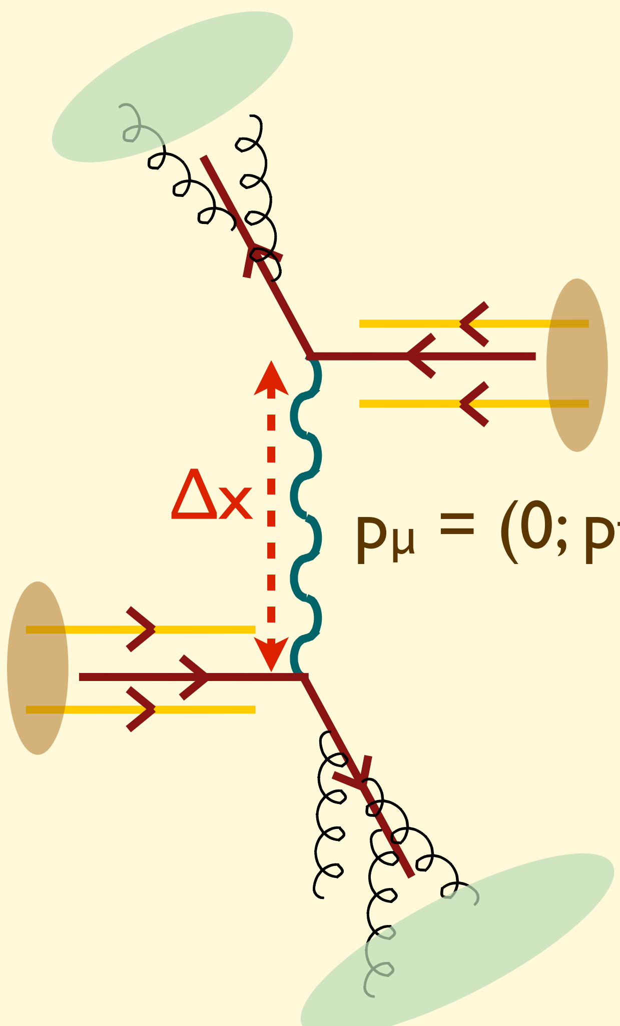
Inside the proton we can find, in addition to the component **uud** quarks, also **gluons** as well as **quark-antiquark** pairs

If we probe the proton at energies high enough, we take a picture of the proton with a very sharp time resolution, and we can "detect" the presence of these additional components. In particular, the gluons and antiquarks present inside will participate in the reactions involving proton.

Notice that, if Δt is small enough, even pairs of quark-antiquark belonging to the heavier generations (e.g. s-sbar, c-cbar) can appear!! The proton can contain quarks heavier than itself!!

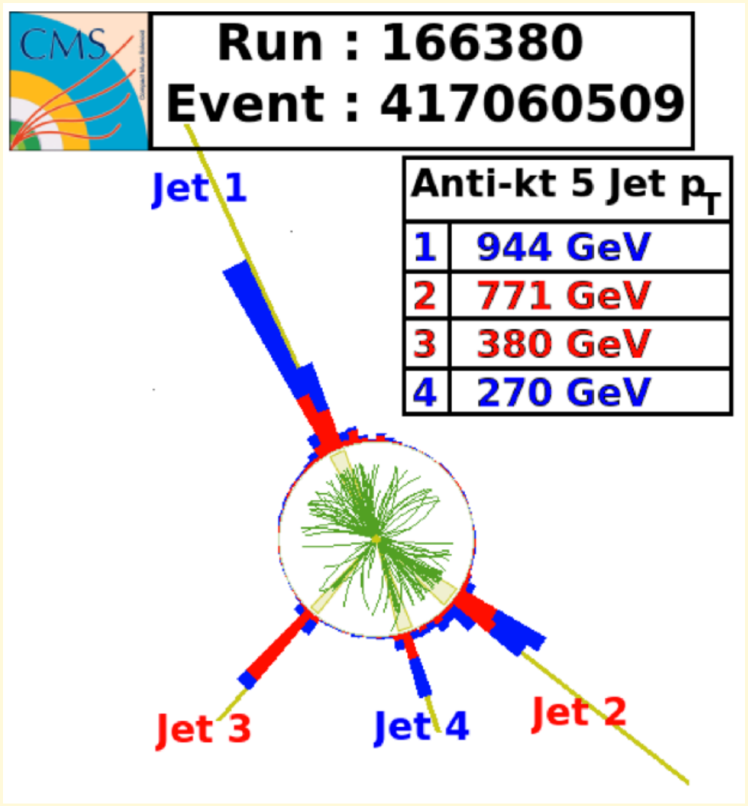
Jets

- Jet: focused stream of particles resulting from the evolution of a single accelerated quark or gluon
- Jet are used as probes of the quark structure (possible substructure implies departures from point-like behaviour of cross-section), or as probes of new particles (peaks in the invariant mass distribution of jet pairs)



$p_\mu = (0; p_T, 0, 0) \Rightarrow p^2 = -p_T^2$

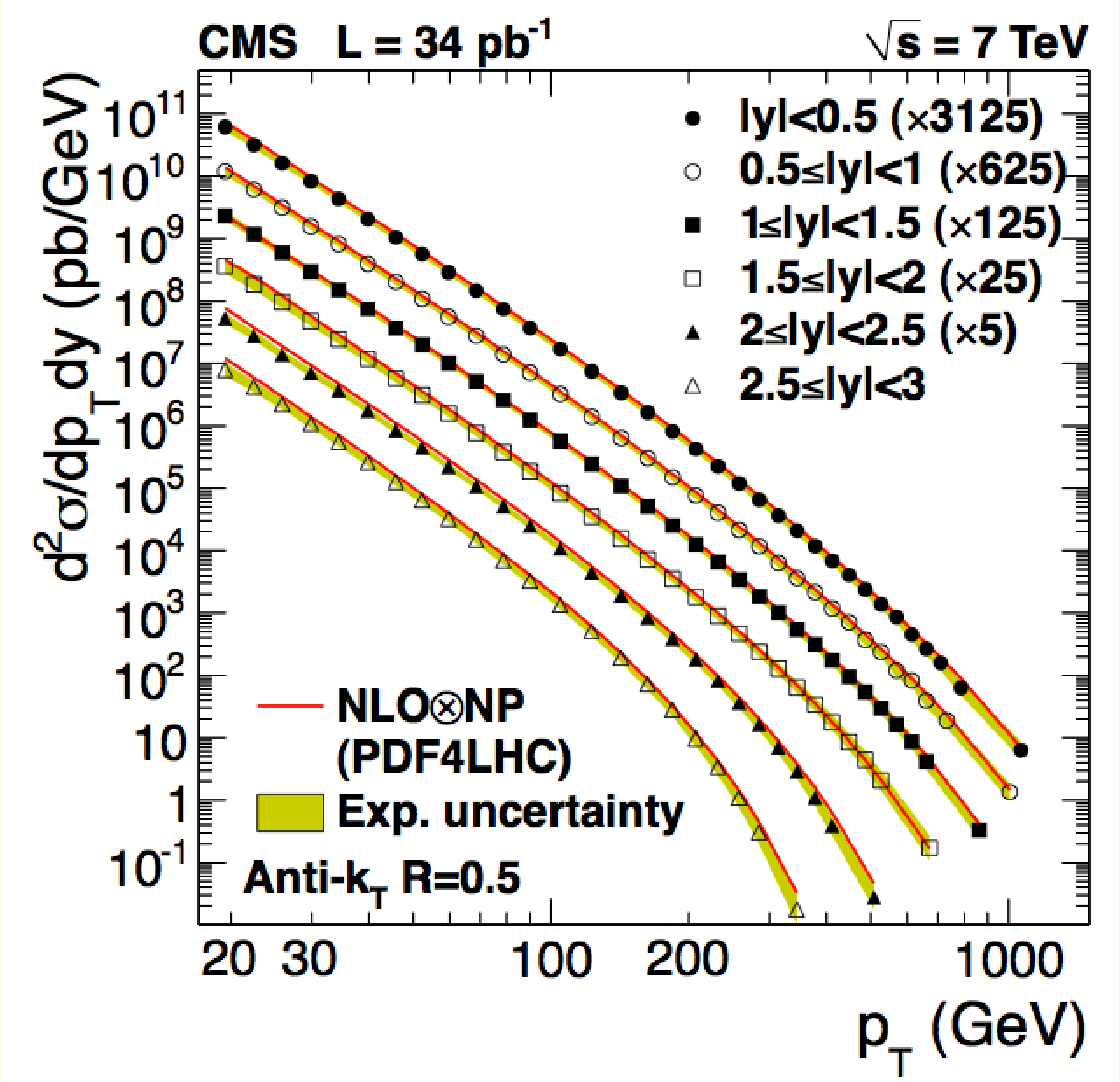
In QM terms, $\Delta E = p_T$, and thus $\Delta t < 1/p_T$, and $\Delta x < 1/p_T$



The most energetic jets observed at the LHC have $p_T \sim 2$ TeV

$\Rightarrow \Delta x \sim 10^{-4}$ of $R_{proton} \sim 10^{-17}$ cm ~ 1 nÅ ~ 10^{18} GHz

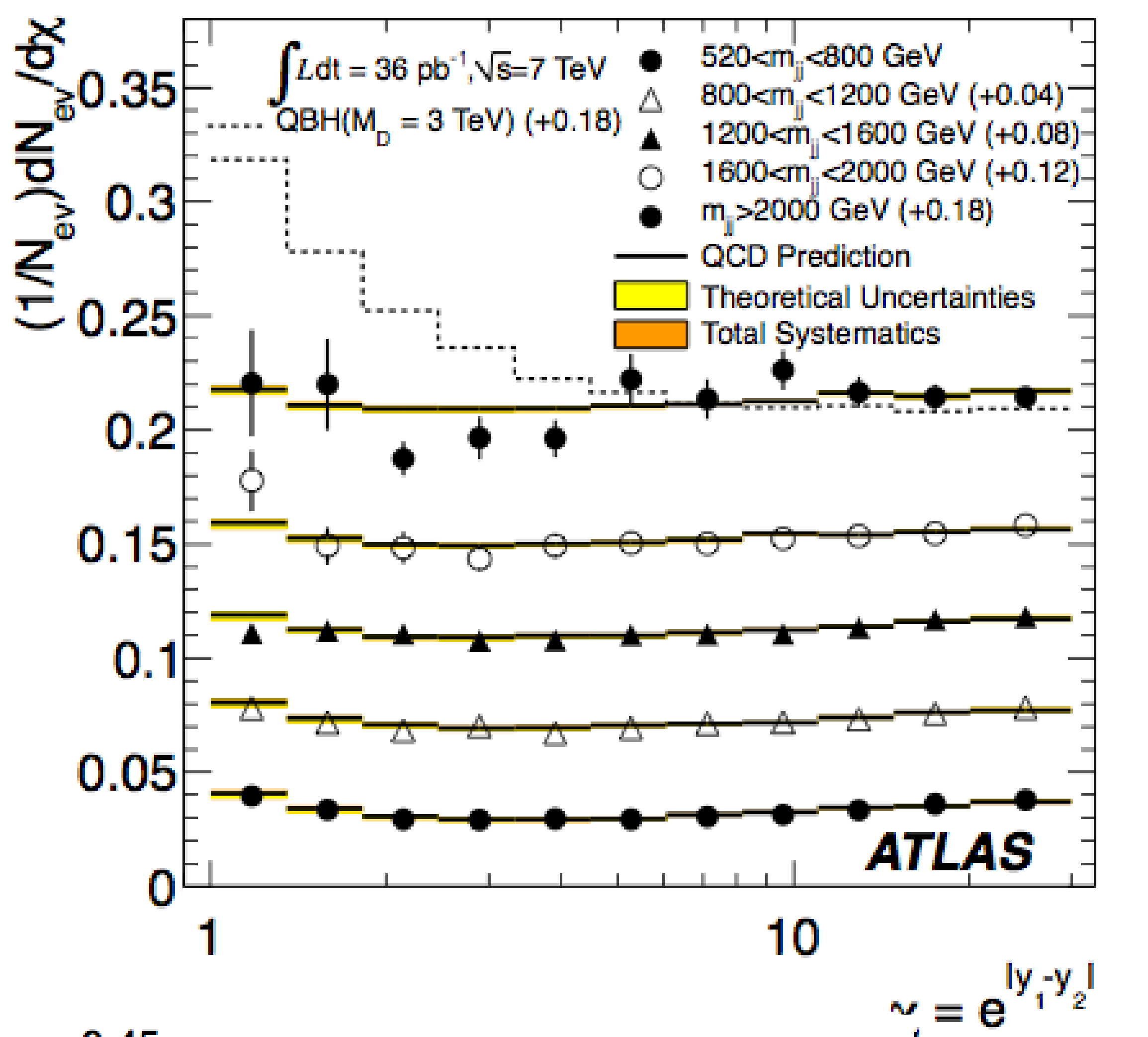
Jet cross section

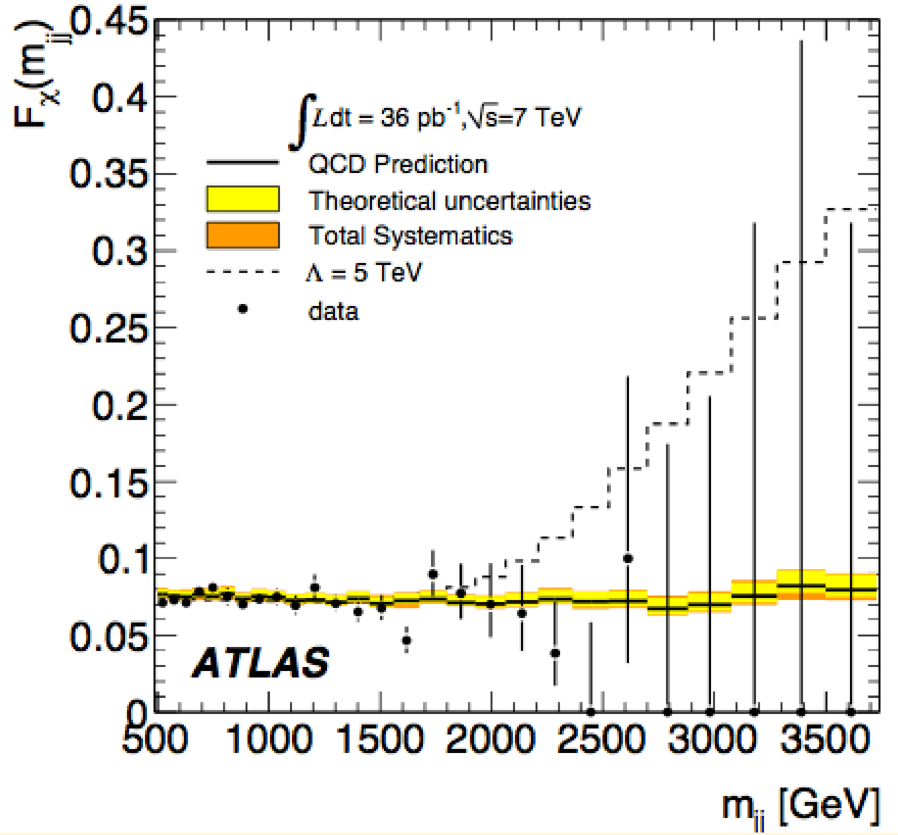


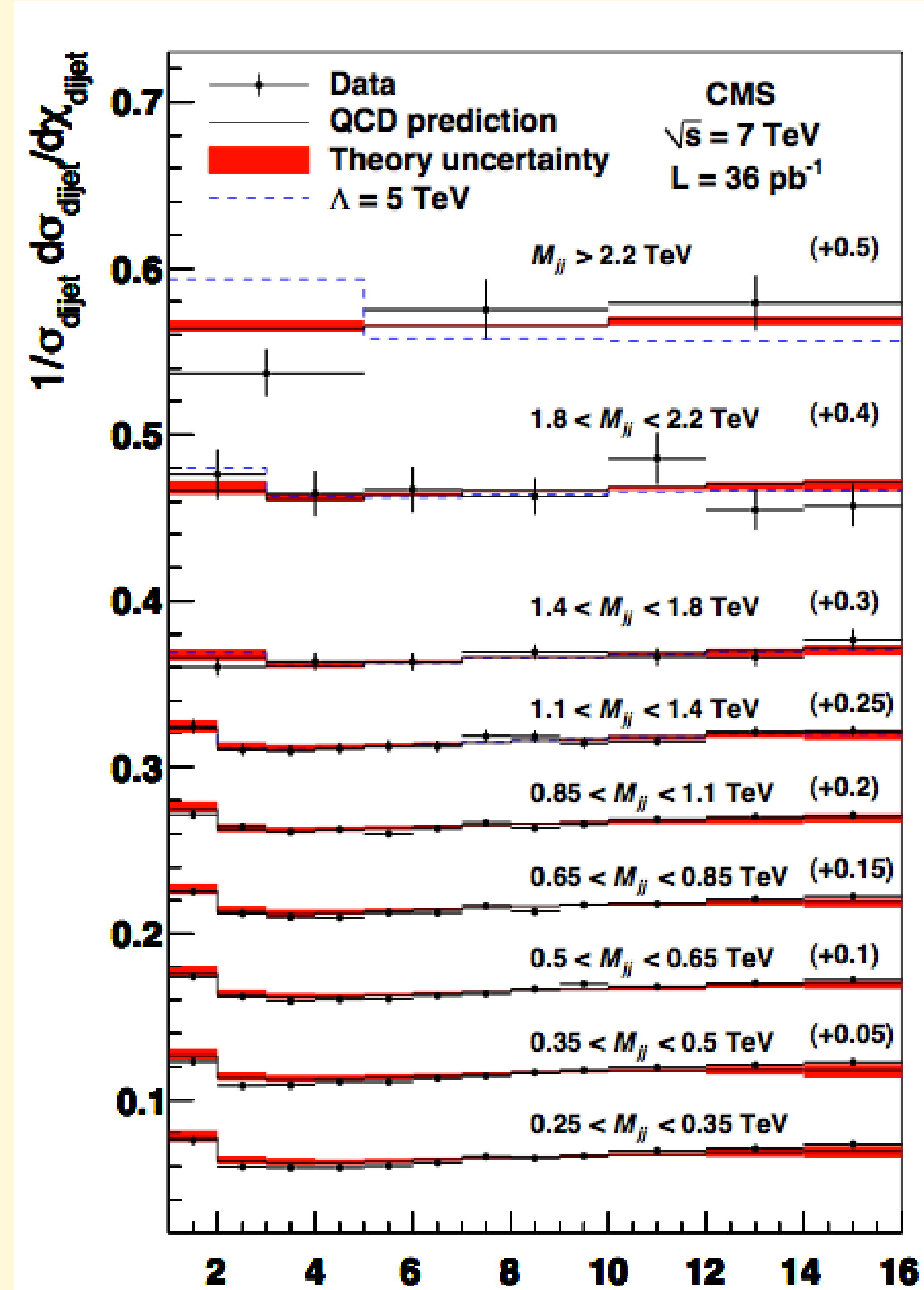
Rates span 10 orders of magnitude!

Constraints on quark contact interactions

$$\chi = \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$







Exclude quark contact interactions with scale < 5 TeV @ 95% CL

Quarks appear pointlike even at the distances probed by the LHC

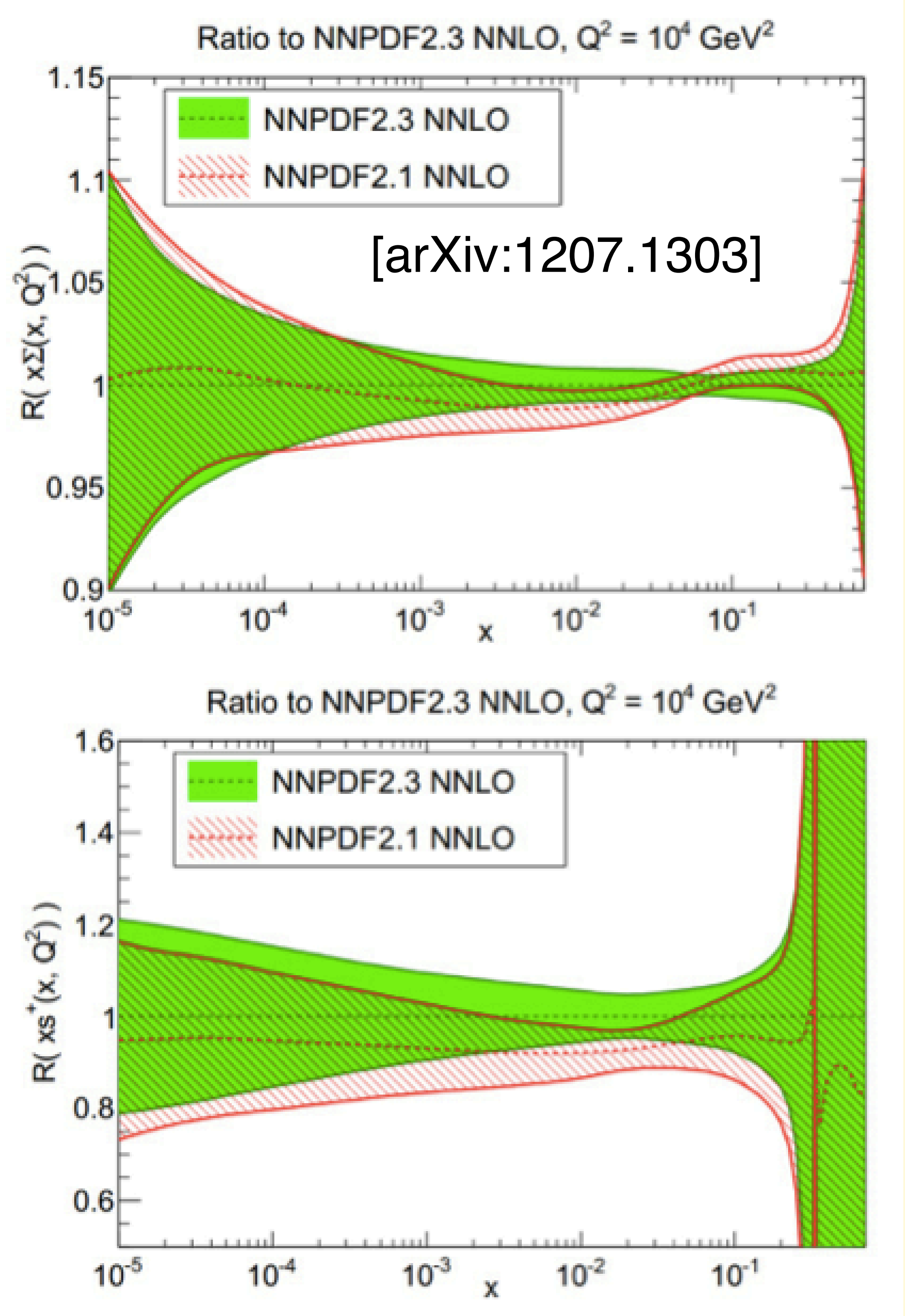
A vast programme of SM measurements is being carried out at the LHC

- Cross sections for QCD and EW processes, testing difficult-to-compute dynamics with high precision
  - multijets, top quarks
  - Drell Yan
  - associated production of W/Z and jets
- Precision measurements of SM parameters
  - m(top), m(W), PDFs
- Flavour physics (b rare decays, CP violation, ...)
- Total, elastic cross sections and diffractive phenomena
- Forward physics, connection to cosmic rays

Using LHC data to improve PDFs

NNPDF2.3: First publicly available PDF set that includes LHC data in the fit.
Global fit, includes all relevant LHC data that were available with full covariance matrix

- ATLAS Inclusive Jets, 36pb^{-1}
- ATLAS W/Z lepton rapidity distributions, 36pb^{-1}
- CMS W lepton asymmetry, 840pb^{-1}
- LHCb W rapidity distributions, 36pb^{-1}

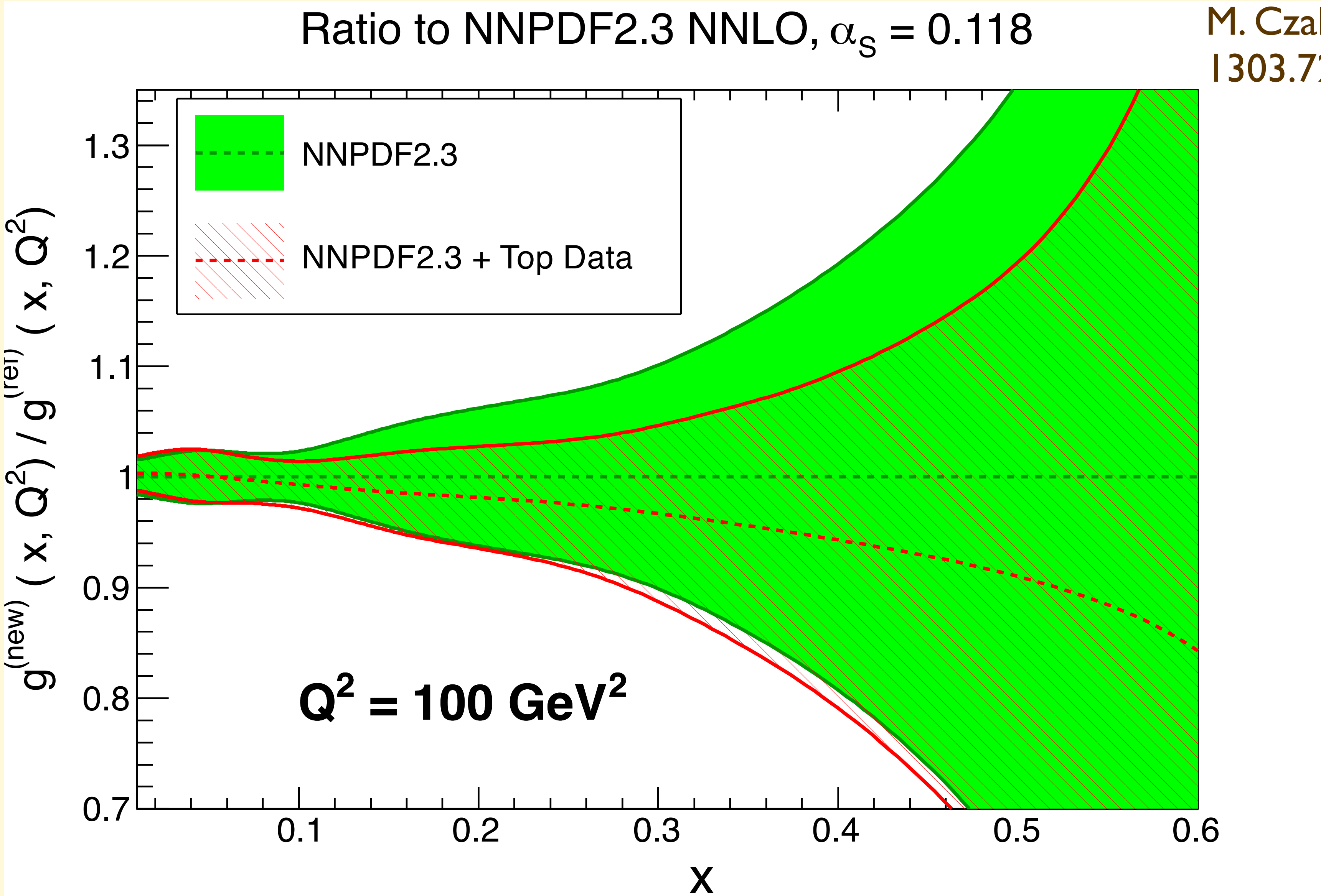


Impact of LHC data:

- Moderate effect from LHC data, generally less than half a sigma in central values.
- Largest impact is for Singlet and strange distributions.
- Expect more substantial improvements with 2011 and 2012 data.

Further progress from more data, and more accurate (NNLO) theory for a variety of processes probing different flavours and ranges of x and Q.

Constraining the gluon PDF with LHC σ(tt)



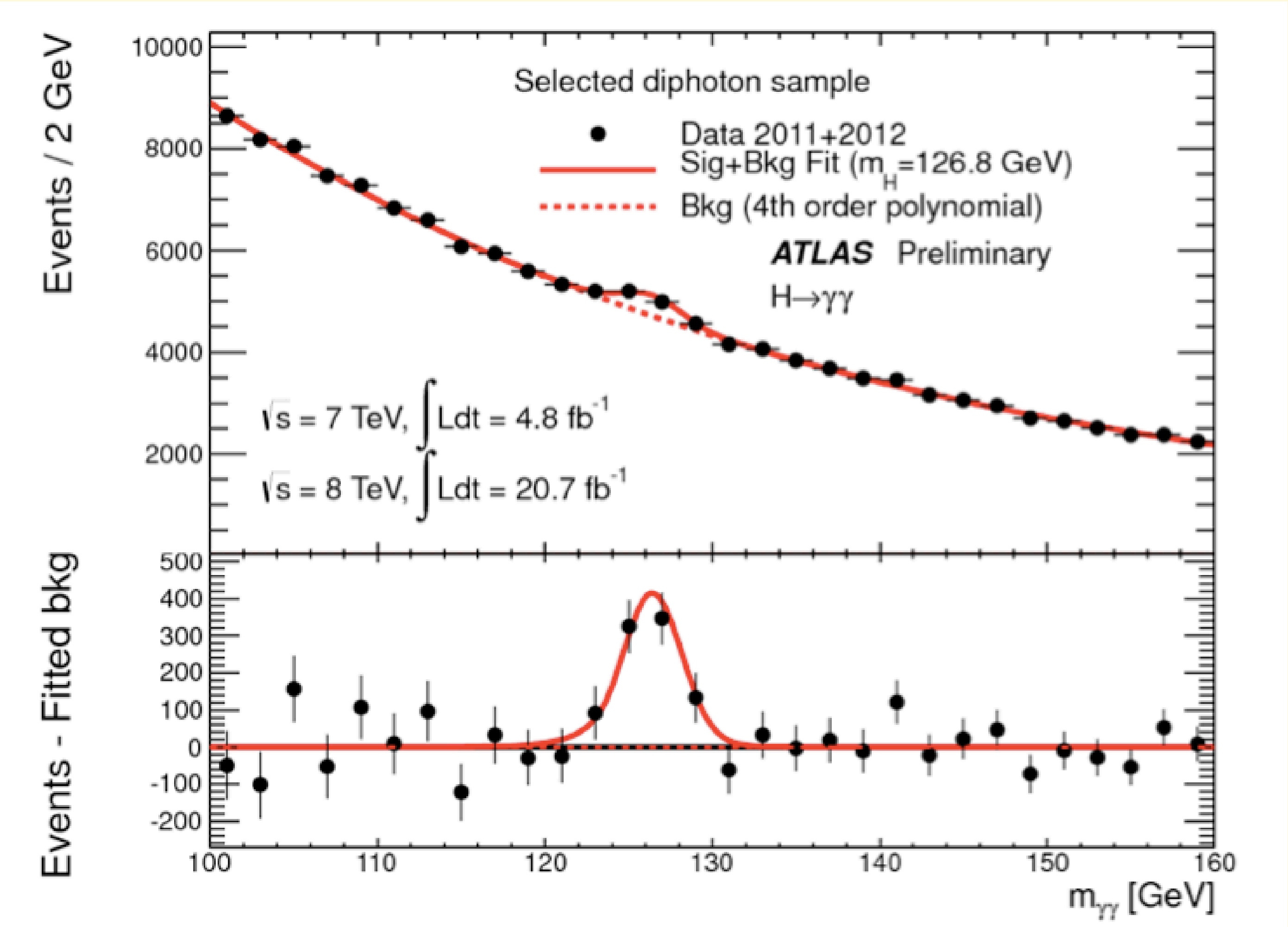
M. Czakon et al, arXiv: 1303.7215

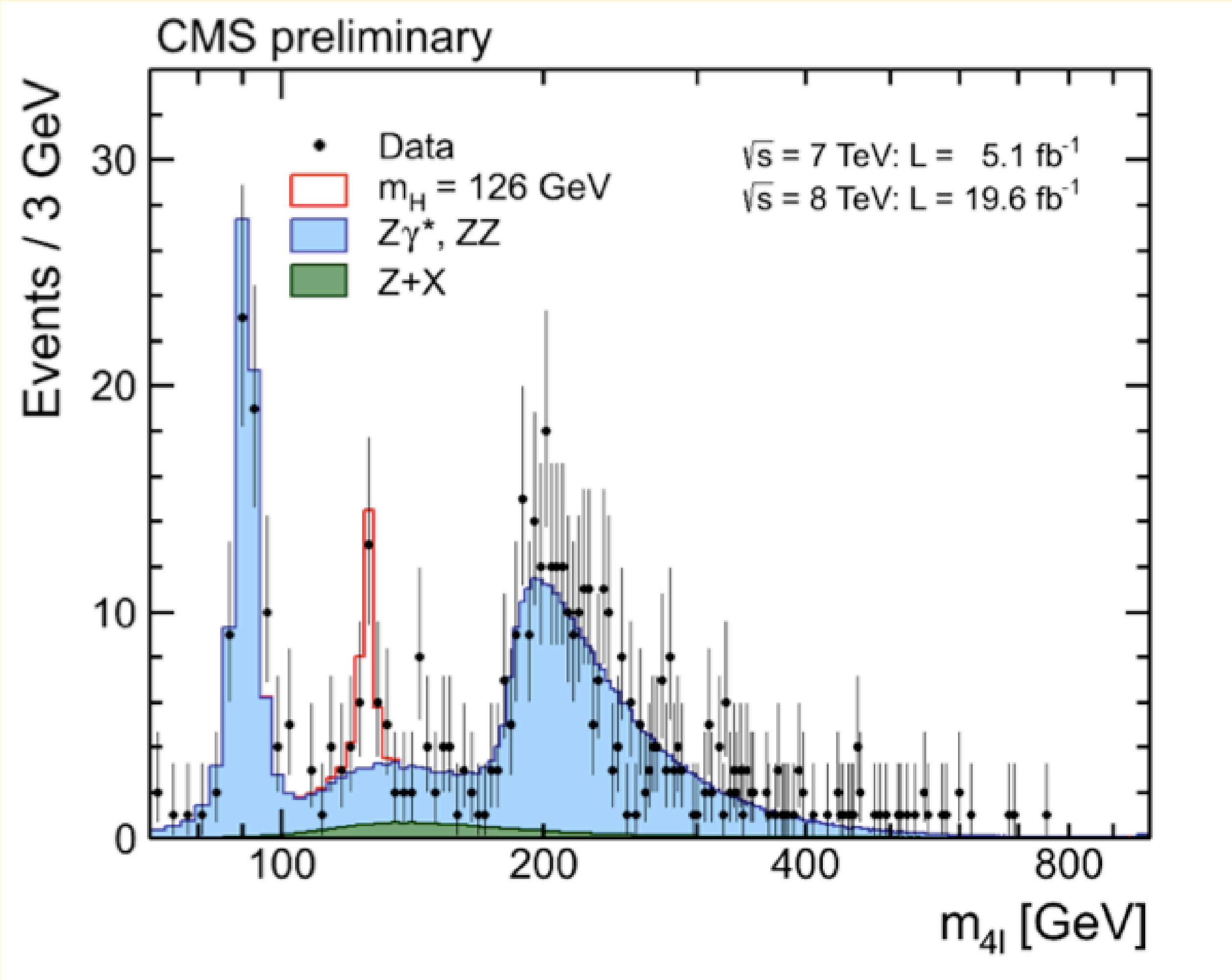
Collider	Ref	Ref+TeV	Ref +TeV+LHC7	Ref+TeV+LHC7+8
Tevatron	7.26 ± 0.12	-	-	-
LHC 7 TeV	172.5 ± 5.2	172.7 ± 5.1	-	-
LHC 8 TeV	247.8 ± 6.6	248.0 ± 6.5	245.0 ± 4.6	-
LHC 14 TeV	976.5 ± 16.4	976.2 ± 16.3	969.8 ± 12.0	969.6 ± 11.6

x-range relevant for gg→H is smaller. Direct probe: $d\sigma/dp_T$ (Z), to be calculated at NNLO

Current status of the Higgs studies at the LHC

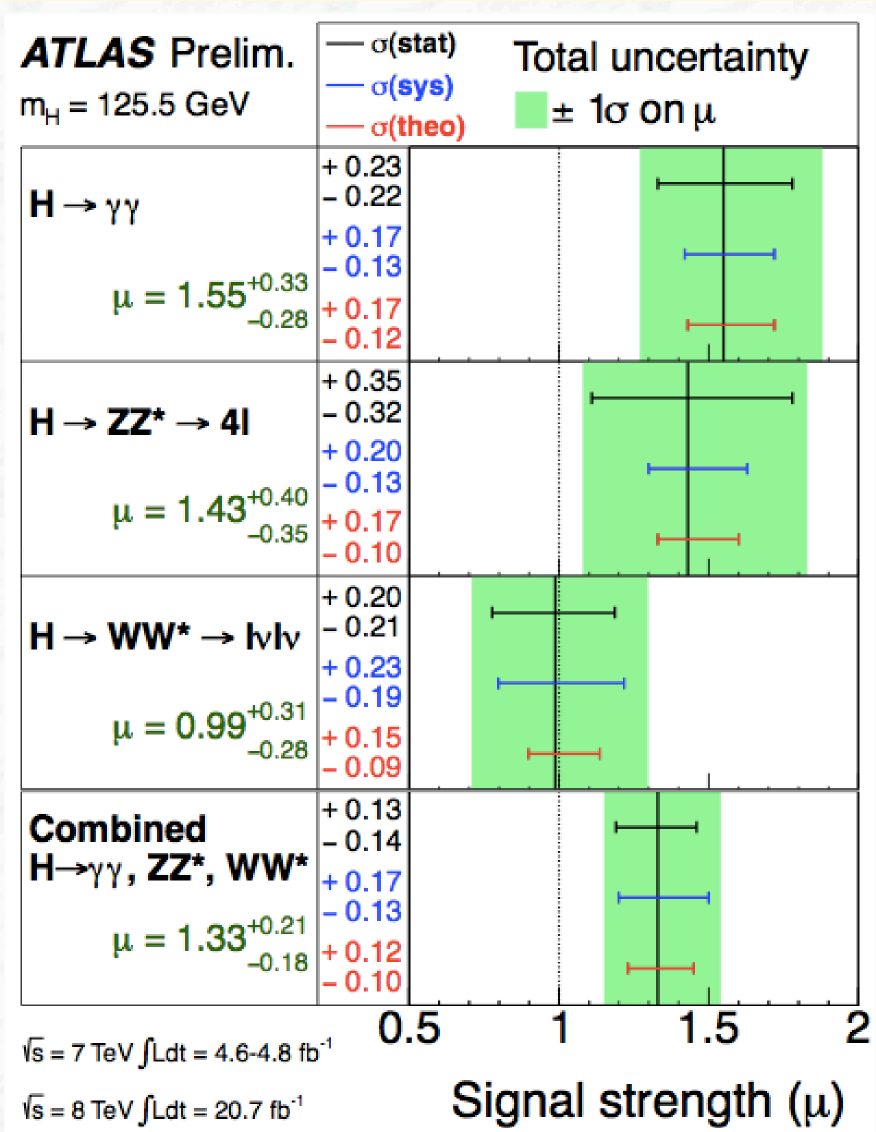
1: The Higgs signal has been detected through sharp mass peaks in several channels

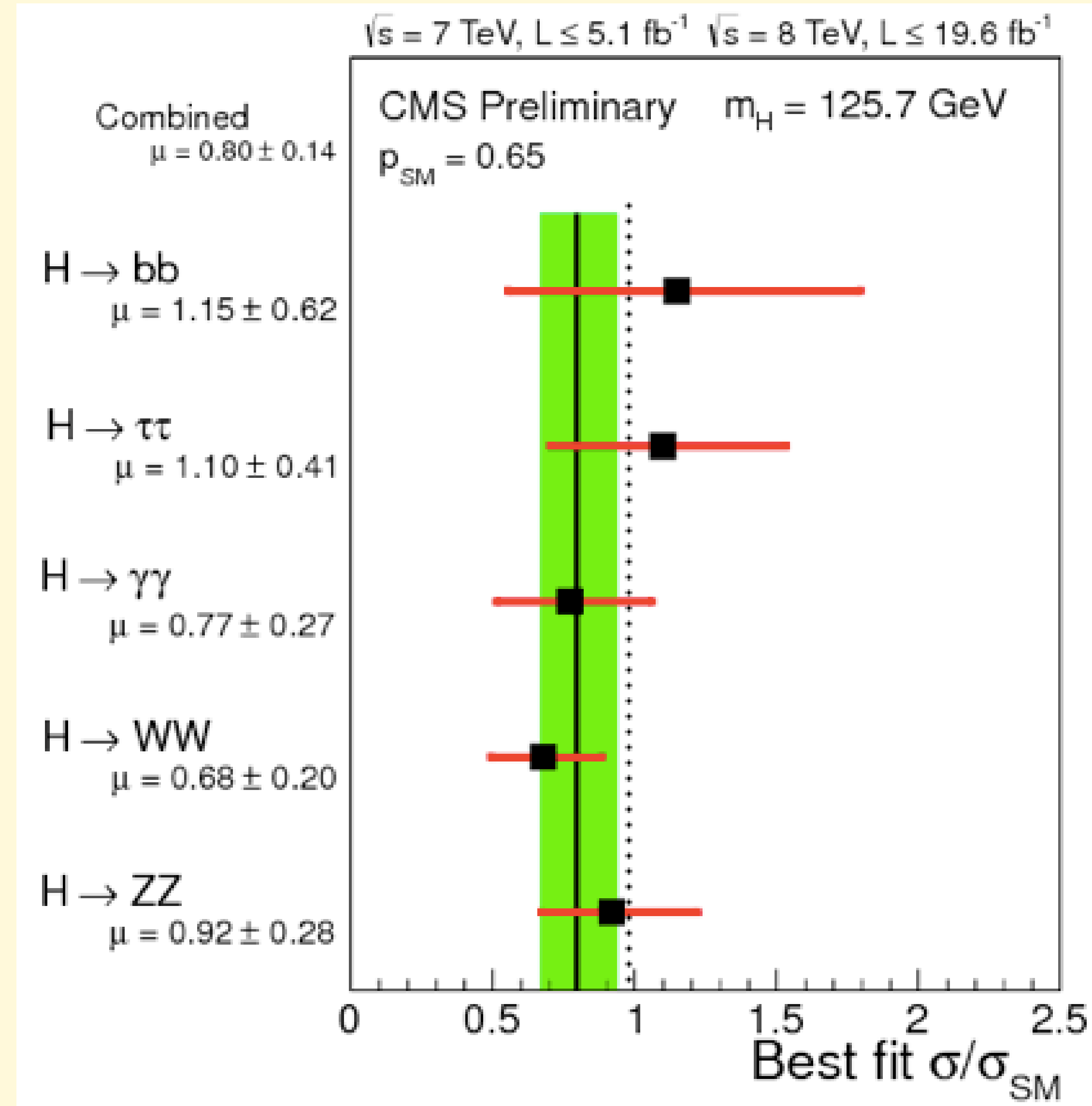




II: Its production and decay rates are consistent with the SM expectation

$\mu = (\sigma \cdot BR)_{exp} / (\sigma \cdot BR)_{SM}$





$\mu_{ATLAS} = 1.33 \pm 0.20$

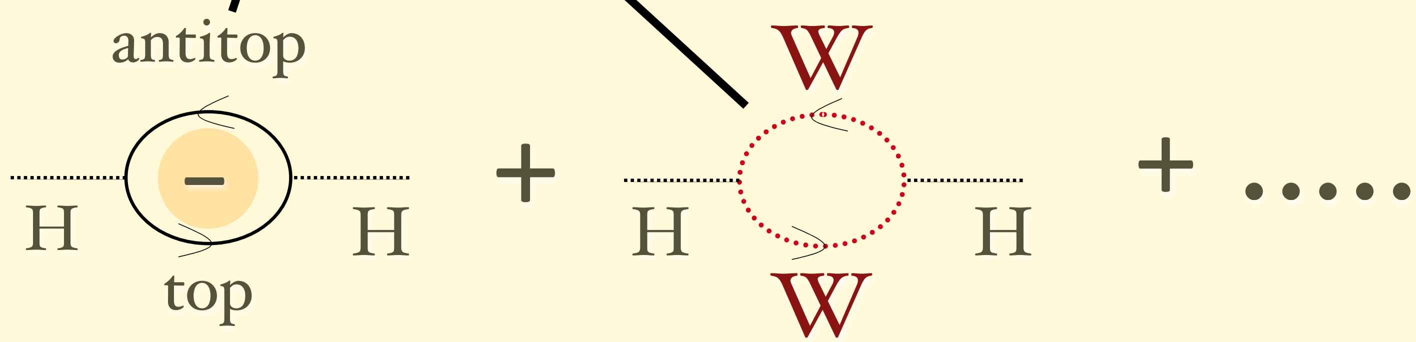
$\mu_{CMS} = 0.80 \pm 0.14$

III: None of its properties (spin, mass) nor any ancillary measurement show, as yet, any significant evidence of departures from the SM picture of EWSB

Seen the Higgs, what's next?

Calculating the radiative corrections to the Higgs mass in the SM poses an intriguing puzzle:

$$m_H^2 = m_0^2 - \frac{6G_F}{\sqrt{2}\pi^2}\left(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2\right)\Lambda^2 \sim m_0^2 - (115\text{GeV})^2\left(\frac{\Lambda}{400\text{GeV}}\right)^2$$



Λ= scale up to which only SM d.o.f. are present

renormalizability =>

$$m_H^2(v) \sim m_H^2(\Lambda) - (\Lambda^2 - v^2) \quad , \quad v = \langle H \rangle \sim 250\text{GeV}$$

Assuming Λ can extend up to the highest energy beyond which quantum gravity will enter the game, 10^{19} GeV, keeping m_H below 1 TeV requires a fine tuning among the different terms at a level of 10^{-34}:

$$\frac{m_H^2(\Lambda) - \Lambda^2}{\Lambda^2} \sim \frac{v^2}{\Lambda^2} = O(10^{-34}) \text{ if } \Lambda \sim M_{Planck}$$

extremely **unnatural** if it is to be an accident !!

hierarchy, or **fine tuning,** problem

The issue can be rephrased with the following example:

- Ask 10 of your friends to each give you an **irrational number**, **randomly** distributed between –1 and 1.

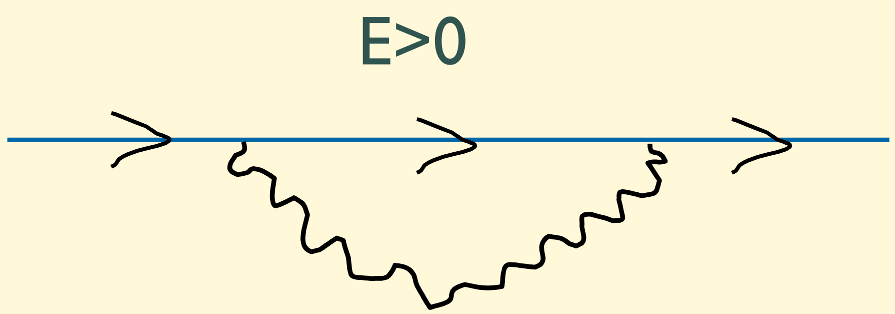
- **Sum the 10 numbers**

- **How would you feel** if the sum were smaller than 10^{-32} ?

Nothing wrong with it, it can happen, but **most likely** your friends agreed in advance on the numbers to give you, and forced the cancellation with a judicious choice.

Theorists feel the same about the Higgs mass .... the accurate cancellation between bare mass and rad corr's can't be an accident!

Electron self-energy, Lorentz invariance, the positron



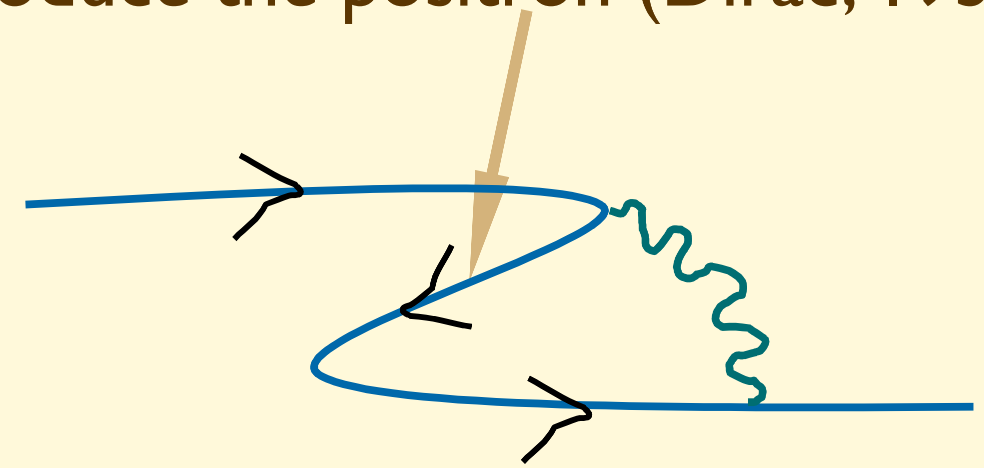
$$\Delta(mc^2)_{Coulomb} \sim \frac{e^2}{r}$$

Requiring:

$$\Delta m < m = 0.5 \text{ MeV}$$

$$\Lambda \equiv 1/r < 5 \text{ MeV}$$

Introduce the positron (Dirac, 1931)



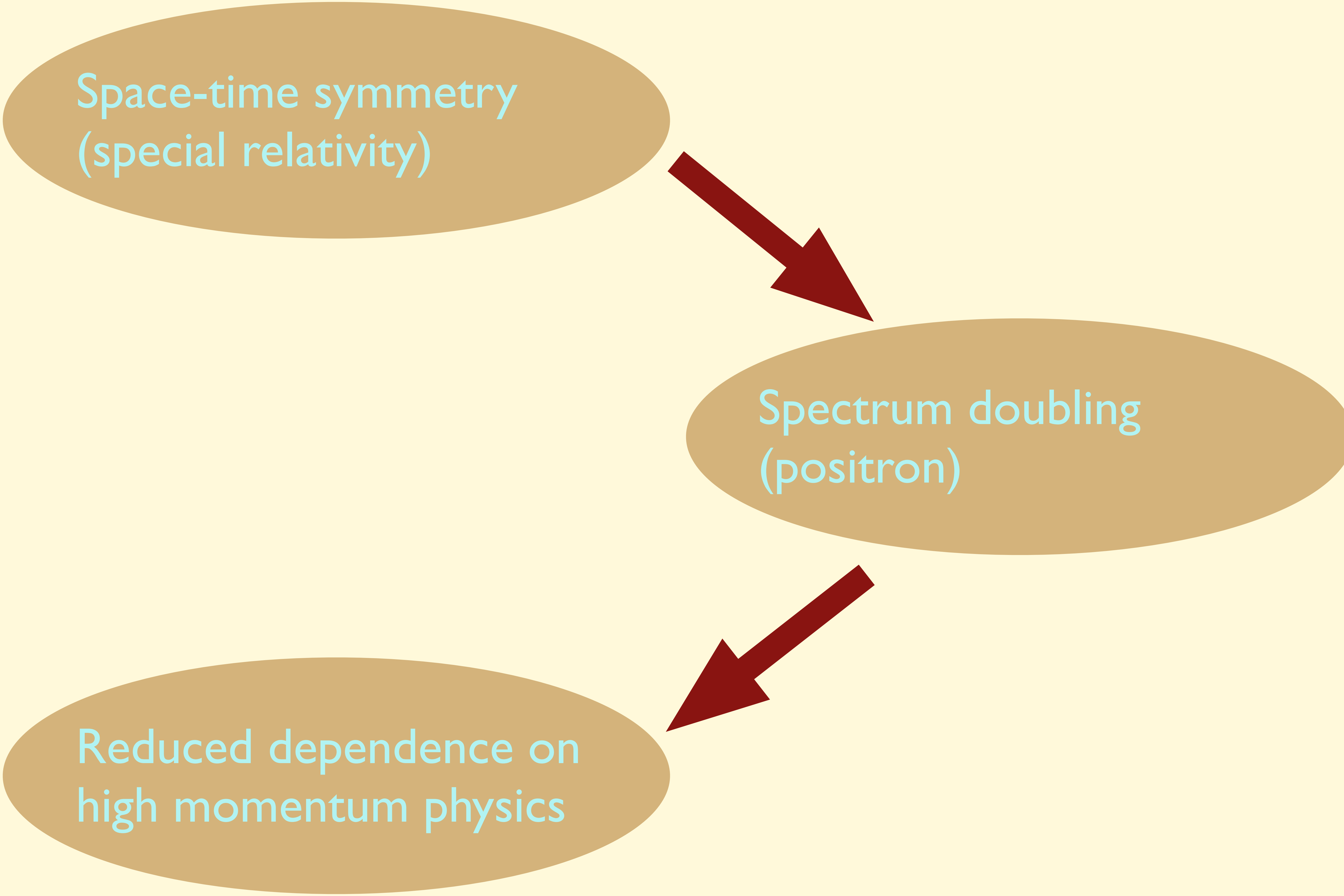
$$\Delta(m)_{E>0 \oplus E<0} \sim e^2 m \log(\Lambda/m)$$

which is a correction of only 10% even at scales of the order of the Plank mass:

$$\Delta(m)_{E>0 \oplus E<0} \sim 0.1\, m$$

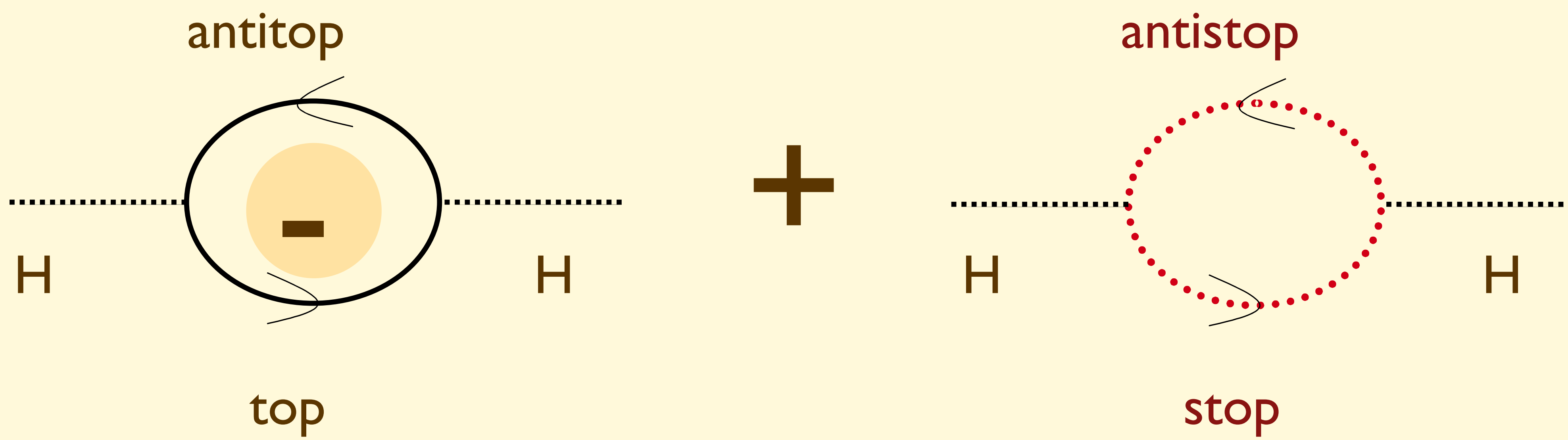
at

$$\Lambda = 10^{19} \text{ GeV}$$


Space-time symmetry
(special relativity)
Spectrum doubling
(positron)
Reduced dependence on
high momentum physics

We are therefore led to speculate the existence of **new phenomena at a scale of the order of the TeV**, to introduce new contributions to the Higgs self-energy equation, which cancel the quadratic growth with Λ in a natural **way**

Higgs self-energy, Susy fix

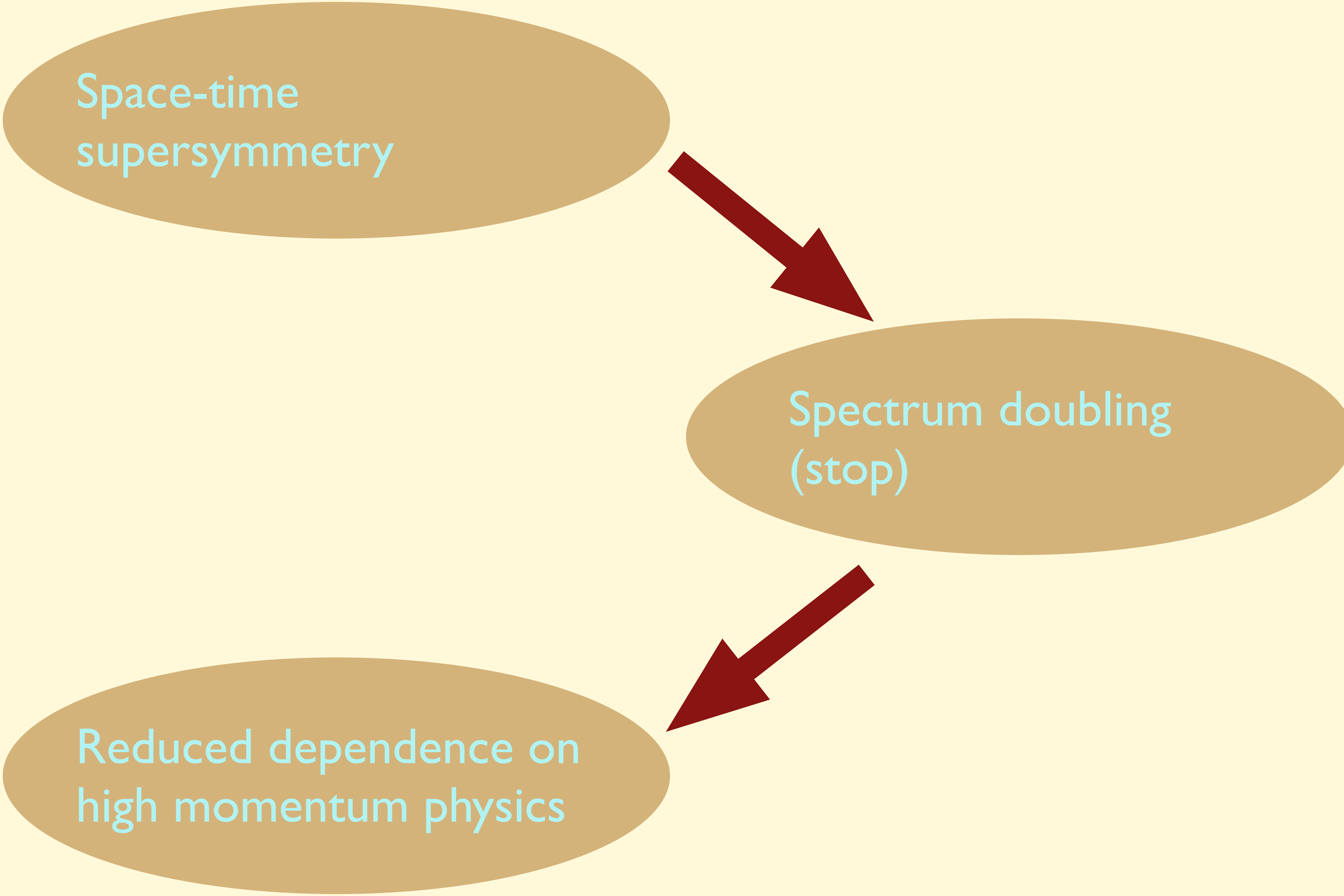


(I)

$$\Delta m_H^2 \propto G_F\, m_t^4 \log(m_t/m_{stop})$$

stability of the natural scale of the Higgs mass restored!

$$m_H \leq M_Z + \text{ radiative corrections } (\propto \log(m_t/m_{stop}) \leq 135 \text{ GeV}$$


Space-time supersymmetry
Spectrum doubling (stop)
Reduced dependence on high momentum physics

More in general ....

Tie the Higgs mass to some symmetry that protects it against quadratic divergencies

Supersymmetry

H (scalar) ↔ fermion

$$\delta m_e = \frac{\alpha_{em}}{3\pi} m_e \log \frac{\Lambda}{m_e}$$

Gauge symmetry

H (scalar) ↔ 5th component of a gauge bosons in 5 dimensions or more

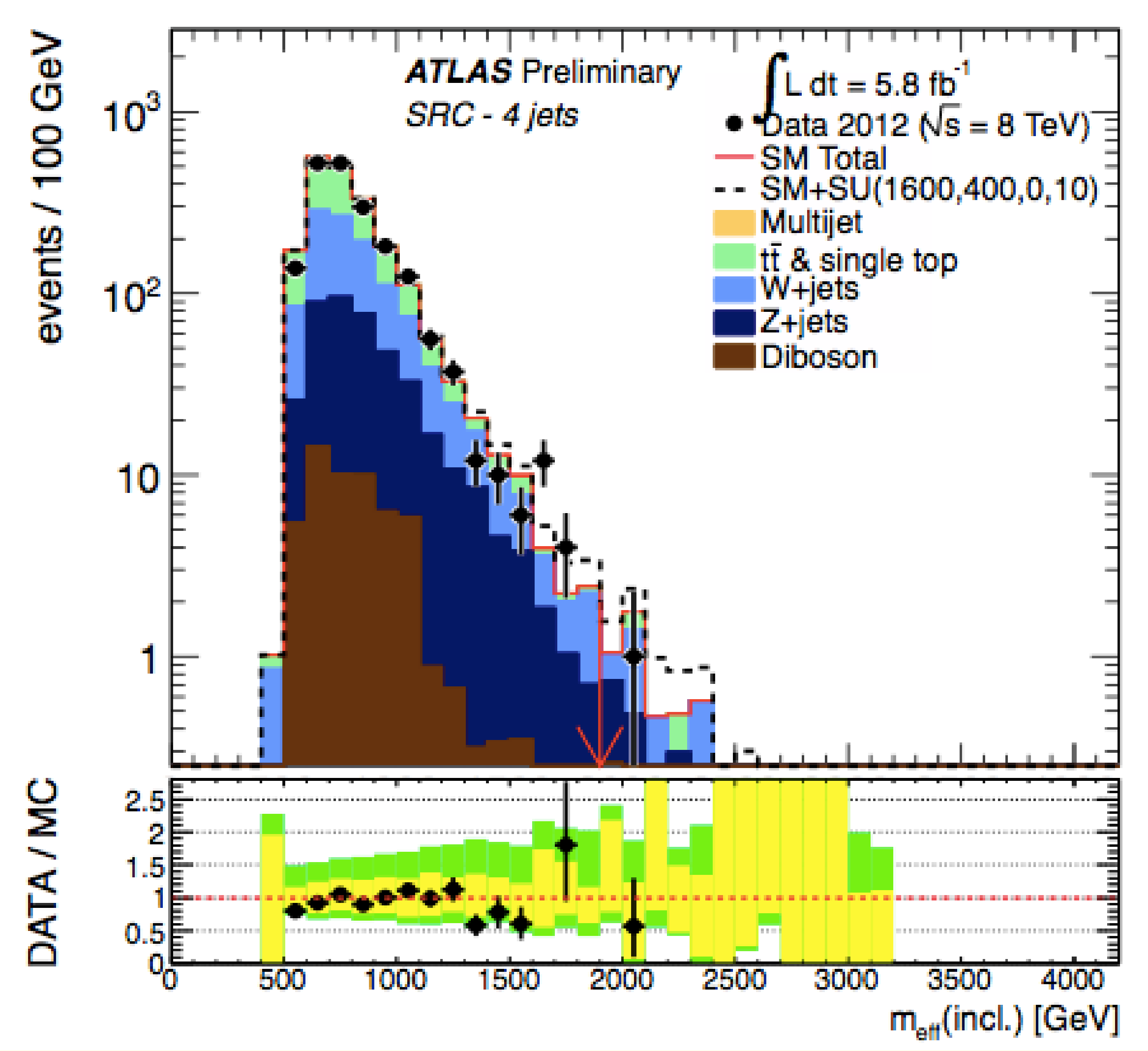
=> extra dimensional theories

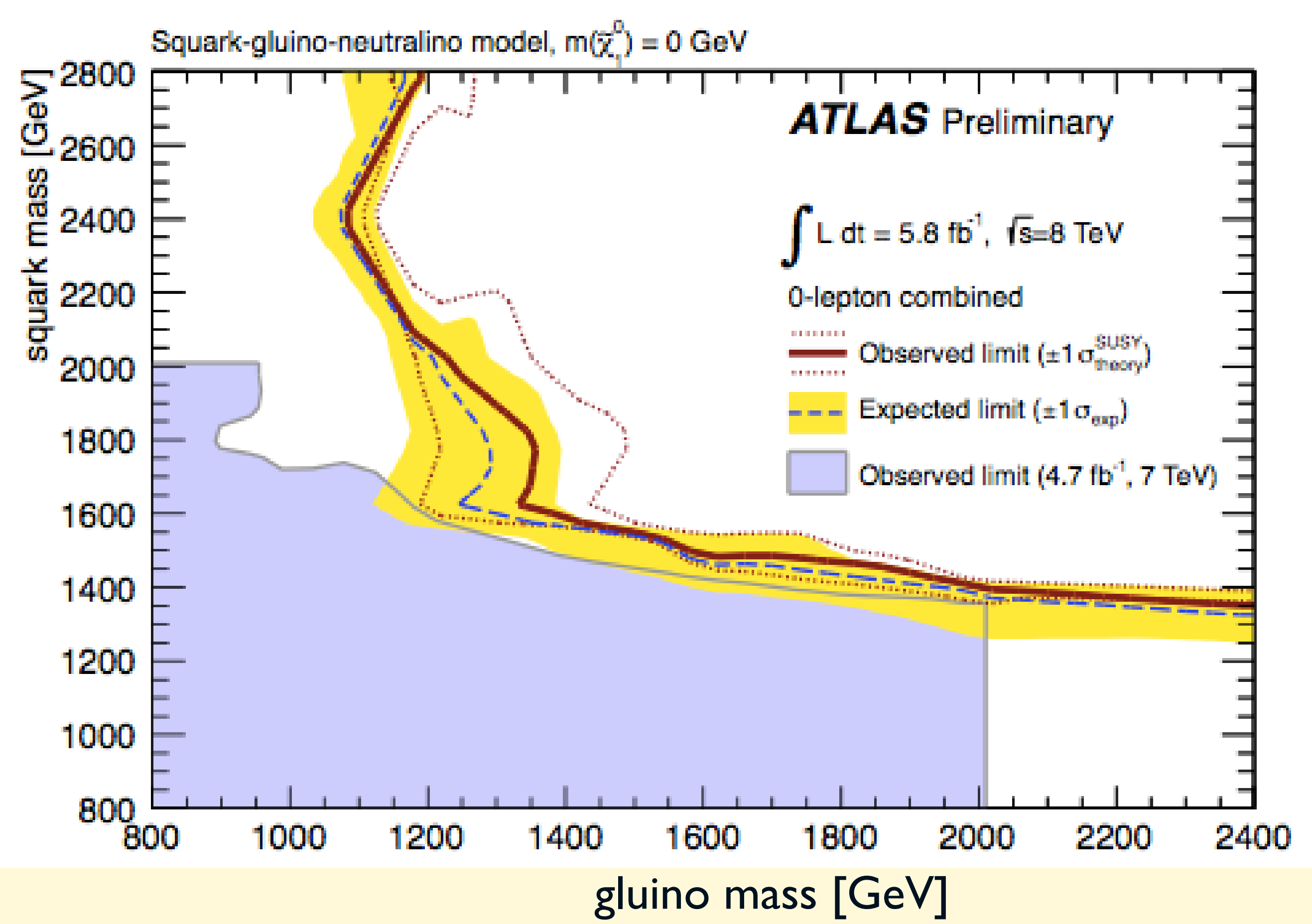
Global symmetry

H → H + a ⇒ L(H)=L(∂H)

=> Little Higgs theories, Technicolor
H=pseudo-goldstone boson

SUSY searches, example





m(gluino) ≳ 1100 GeV

m(squarks) ≳ 1400 GeV

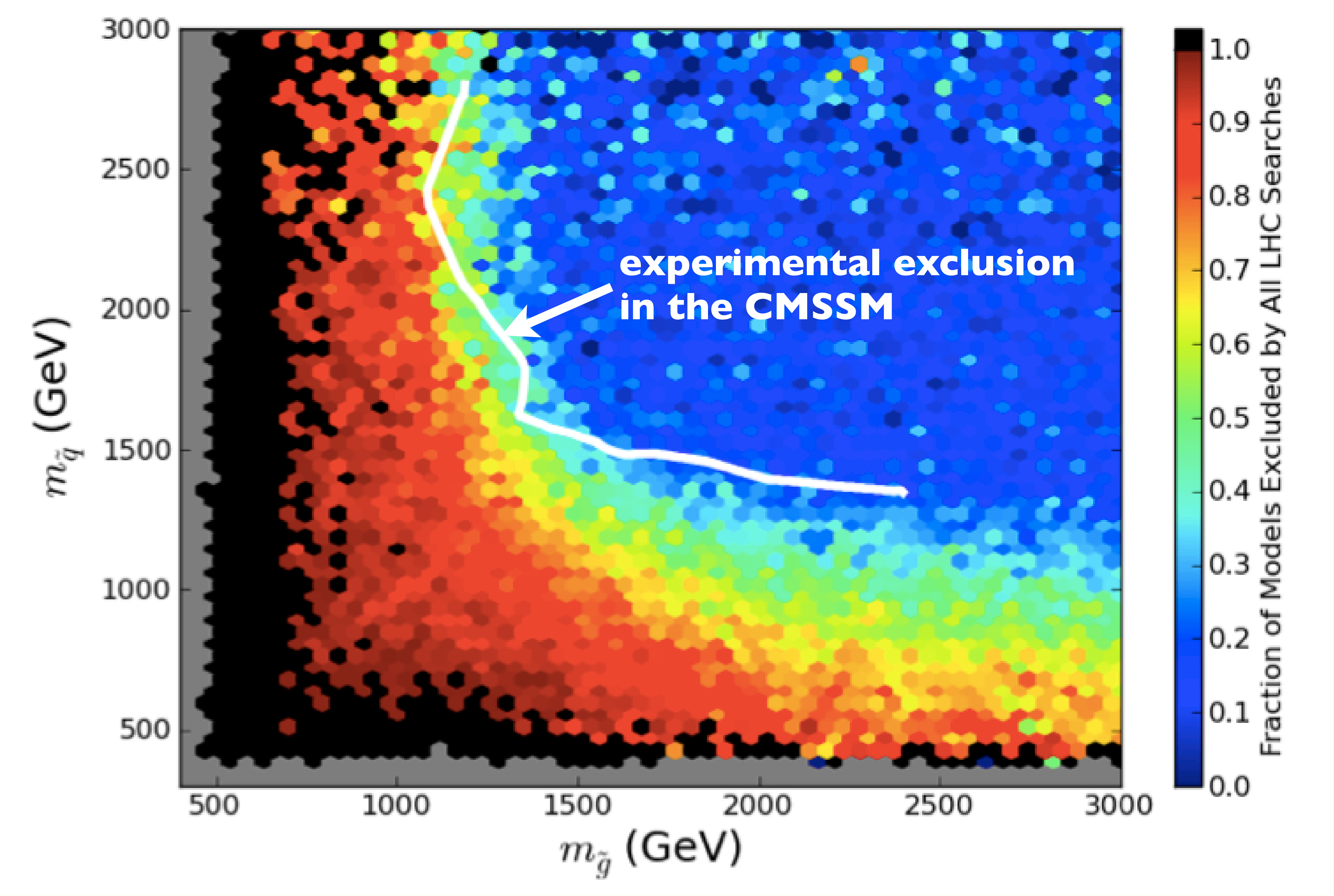
- **No search** of new particles at the LHC, whether related to the solution of the hierarchy problem or otherwise, **has led to positive results** so far.
- So, **where is everyone** ?
- In spite of the Higgs discovery, the origin of EW symmetry breaking remains therefore a huge mistery
  - The observation of the Higgs where the SM predicted it would be, its SM-like properties, and the lack, at the LHC, of BSM phenomena observed up to the TeV scale, make the hierarchy problem as puzzling as ever
- Lack of evidence for new physics from the LHC at the TeV scale raises an issue of **fine tuning**.
  - The higher the scale of the phenomena solving the hierarchy problem, the higher the degree of fine tuning required to keep the scale of weak interactions at ~100 GeV.
  - The solutions to the naturalness problem are themselves becoming "unnatural".

Ways out

- BSM particles are already being created at the LHC, but are hiding well:
  - compressed spectra: low MET, low ET, long lifetime heavy particles, ...
  - RPV
  - ....
- BSM is less "conventional": fine-tuning and/or direct search constraints less tight
  - NMSSM
  - non-degenerate squarks
  - ....
- Naturalness is an ill guided principle ⇒ Anthropic principle

Example of ways out: explore less constrained SUSY models

Fraction of excluded models in the pMSSM (19 parameters MSSM)

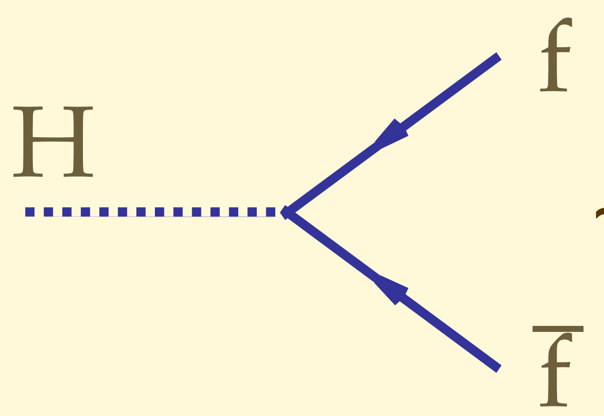


Rizzo et al, arXiv:1211.1981

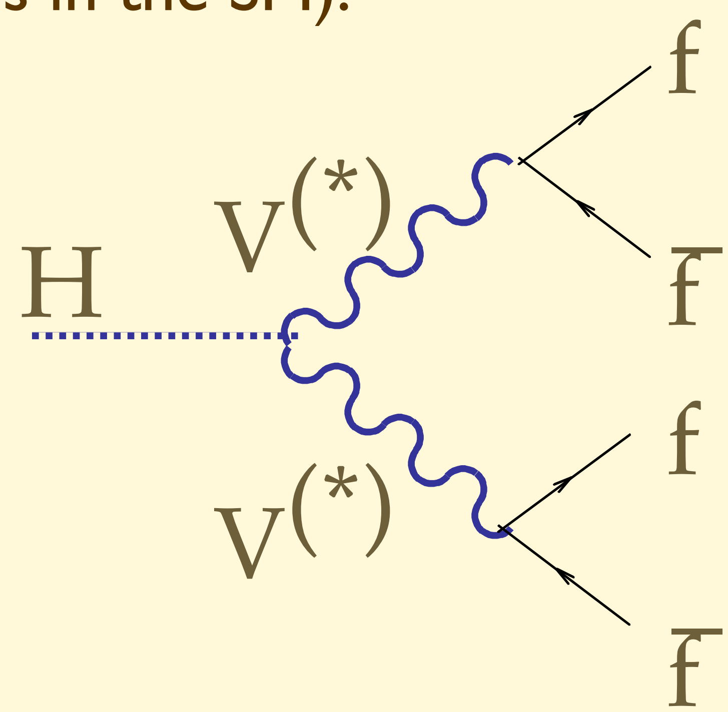
- Confidence in the appearance of new physics at the LHC at 14 TeV remains fully justified:
  - exploration of the "ways out" listed before (NMSSM, RPV, compressed spectra, push to higher mass all conventional searches, ...)
  - WIMP DM in the LHC range is still a sensible thing to expect: how far and how conclusively can one push its search ?
  - flavour physics remains alert for new phenomena (CPV, LFV, ...)
- Whether new particles can be seen or not at 14 TeV, the most concrete and urgent questions now are
  - up to which scale do Higgs interactions behave SM-like ?
  - are there any hints of natural solutions to the hierarchy problem?
- What is the need for precision measurements of the Higgs sector, what are the possible implications of these measurements, what do they probe, how do they bear on the naturalness problem ?

Higgs couplings

Tree level (proportional to particle's mass in the SM):



$\sim m_f / v$



$\sim m_V / v$

Modifications, possibly breaking the linear relation coupling-mass, are common in BSM models (although constrained, e.g., by EW precision tests, in addition today to direct BR measurements). For example:

SUSY:

hbb, hττ, hμμ $\propto \tan\beta$ δ(**hVV**)/**hVV** $\propto m^2(h)/m^2(H)$

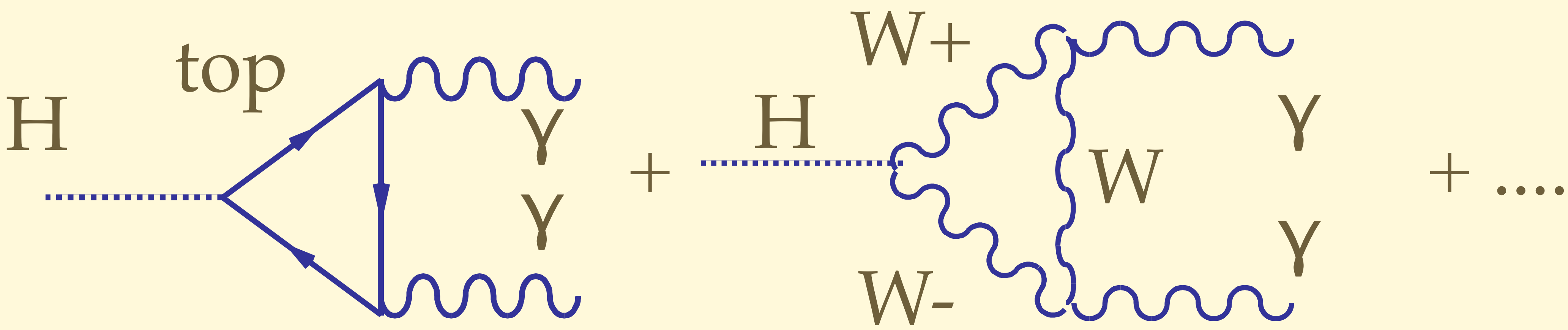
... more complex deviations in models with extended Higgs structures (e.g. NMSSM)

Composite Higgs models:

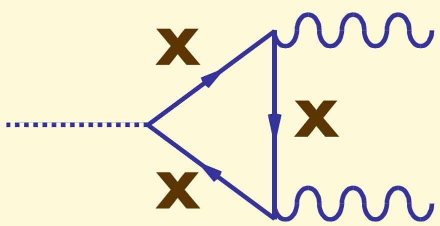
δ(**hVV**)/**hVV** $\propto \xi = v^2/f^2$, f being the "decay constant" of the strong interactions which the Higgs would be a pseudo goldstone boson of

Higgs couplings

Loop level (in the SM, proportional to mass of particles in the loop)



Modifications can arise both from modif's of the tree-level couplings, and from possible new states present in the loops.



Comments:

- Loop-induced couplings, which in the SM are fully determined by the tree-level ones, add important new information on the presence of BSM
- Cancellations of different contributions may take place. It is necessary to **resolve** what circulates in the loop, e.g. using different probes such as

$H \to Z\gamma$ vs $H \to \gamma\gamma$

- Precision measurements of super-rare decays like $H \to Z\gamma$ are therefore very important, although beyond the reach of either the nominal LHC, or LC, programmes

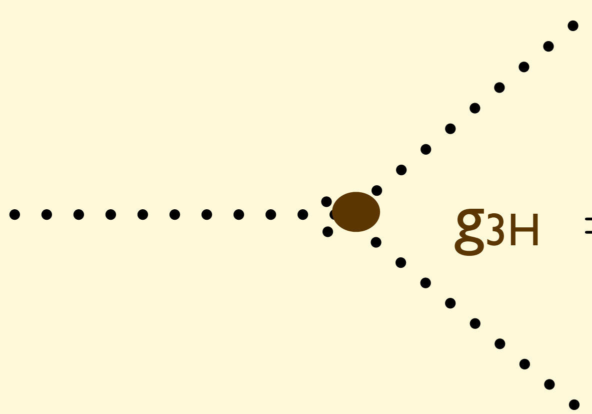
Higgs selfcouplings

The Higgs sector is defined in the SM by two parameters, **μ** and **λ**:

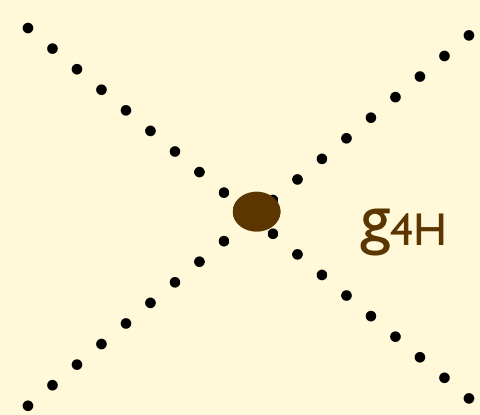
$$V_{SM}(H) = -\mu^2 \, |H|^2 + \lambda \, |H|^4$$

$$\frac{\partial V_{SM}(H)}{\partial H}|_{H=v} = 0 \quad \text{and} \quad m_H^2 = \frac{\partial^2 V_{SM}(H)}{\partial H \partial H^*}|_{H=v} \quad \Rightarrow \quad \begin{array}{ccc} \mu & = & m_H \\ \lambda & = & \frac{m_H^2}{2v^2} \end{array}$$

These relations uniquely determine the strength of Higgs selfcouplings in terms of m_H



$g_{3H} \Rightarrow 6\lambda \, v = \frac{3m_H^2}{v}$ ~O(m_{top})

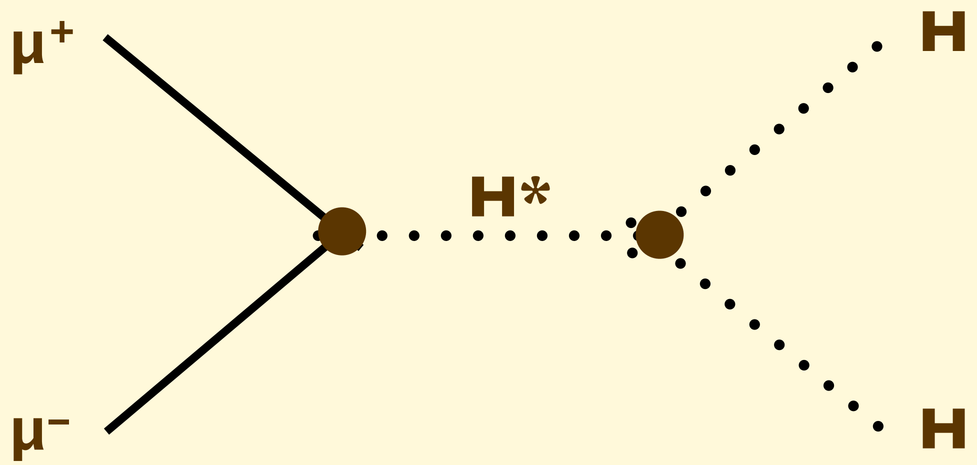


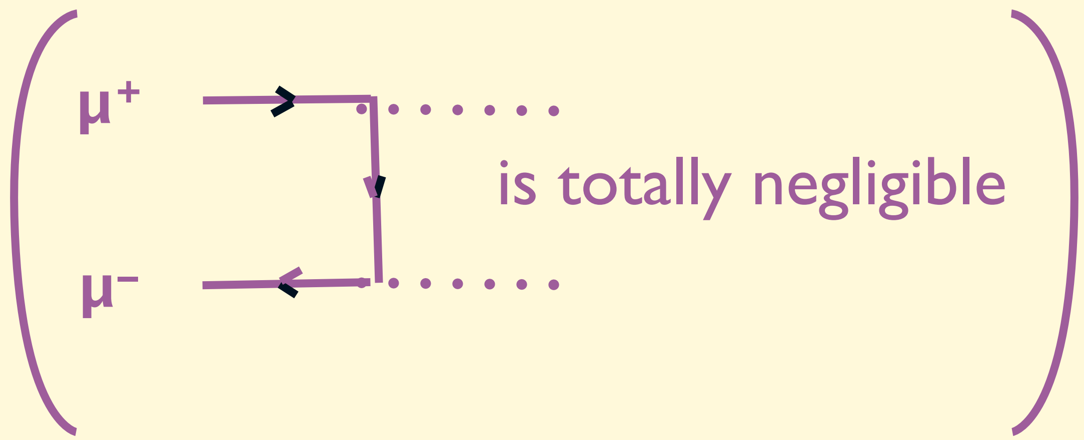
$g_{4H} \Rightarrow 6\lambda = \frac{3m_H^2}{v^2}$ ~O(1)

Testing these relations is therefore an important test of the SM nature of the Higgs mechanism

Higgs pair production

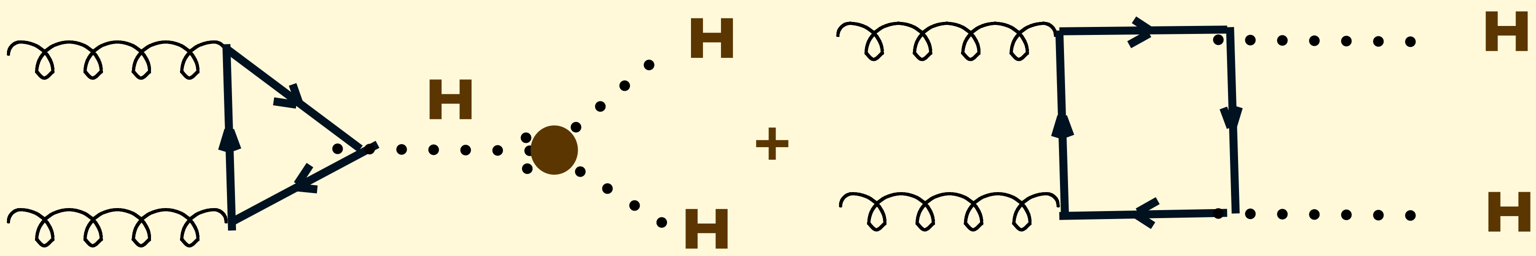
The only clean way to probe the triple H coupling is at a muon collider, at $\sqrt{S} > 2\, m_H$:



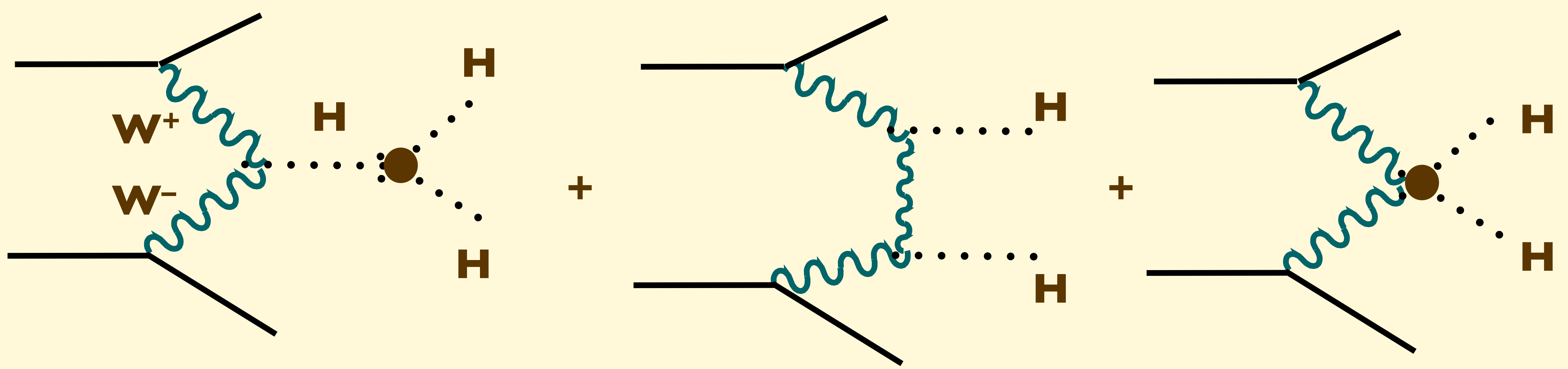


For HH production in hadronic collisions, the HHH coupling is always mixed with other processes:

gg fusion:



VBF:



In the SM this causes accidental cancellations among diagrams, small rates, and typically suppressed sensitivity to the HHH coupling

Recent assessments of Higgs measurement potential, at HL-LHC

CMS submission to Strategy Group,
https://indico.cern.ch/contributionDisplay.py?contribId=177&confId=175067

Coupling	Uncertainty (%)			
	$300\ \mathrm{fb}^{-1}$		$3000\ \mathrm{fb}^{-1}$	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Plus Hμμ coupling to better than 5% at $3000\mathrm{fb}^{-1}$

Scenario 1: same systematics as 2012 (TH and EXP)
Scenario 2: half the TH syst, and scale with 1/sqrt(L) the EXP syst

Note: assume no invisible Higgs decay contributing to the Higgs width

Note: results of scenario 2 @ 3000/fb are overall as powerful as LC@500GeV !!

Example: precision Higgs physics

Theoretical uncertainties on production rates (Higgs XS WG, arXiv:1101.0593)

14 TeV	δ(pert. theory)	δ(PDF, α_S)
$gg \to H$	± 10 %	± 7%
VBF ($WW \to H$)	± 1 %	± 2%
$qq \to WH$	± 0.5 %	± 4%
$(qq,gg) \to ZH$	± 2 %	± 4%
$(qq,gg) \to ttH$	± 8 %	± 9%

Improve with higher-loop calculations:
gg->H @ NNNLO
ttH @ NNLO

Improve with dedicated QCD measurements, and appropriate calculations

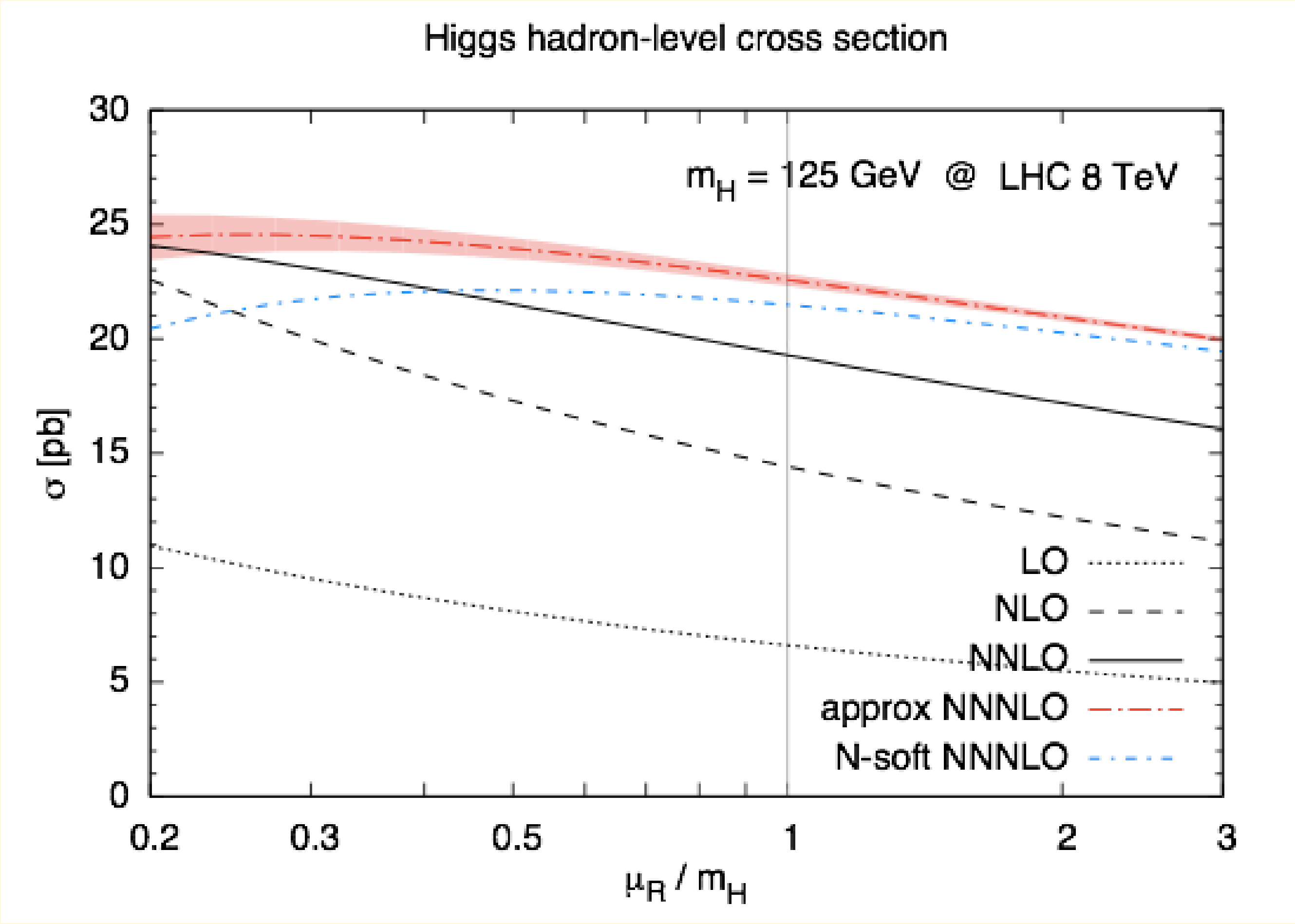
Ongoing theoretical progress for σ(gg→H)

- First steps towards the cross section at NNNLO: triple soft limits, O(ϵ) expansion of NNLO, ...

Anastasiou, Buehler, Duhr, Herzog, arXiv:1208.3130
Anastasiou, Duhr, Dulat, Mistlberger, arXiv:1302.4379
Hoschele, Hoff, Pak, Steinhauser, Ueda, arXiv:1211.6559

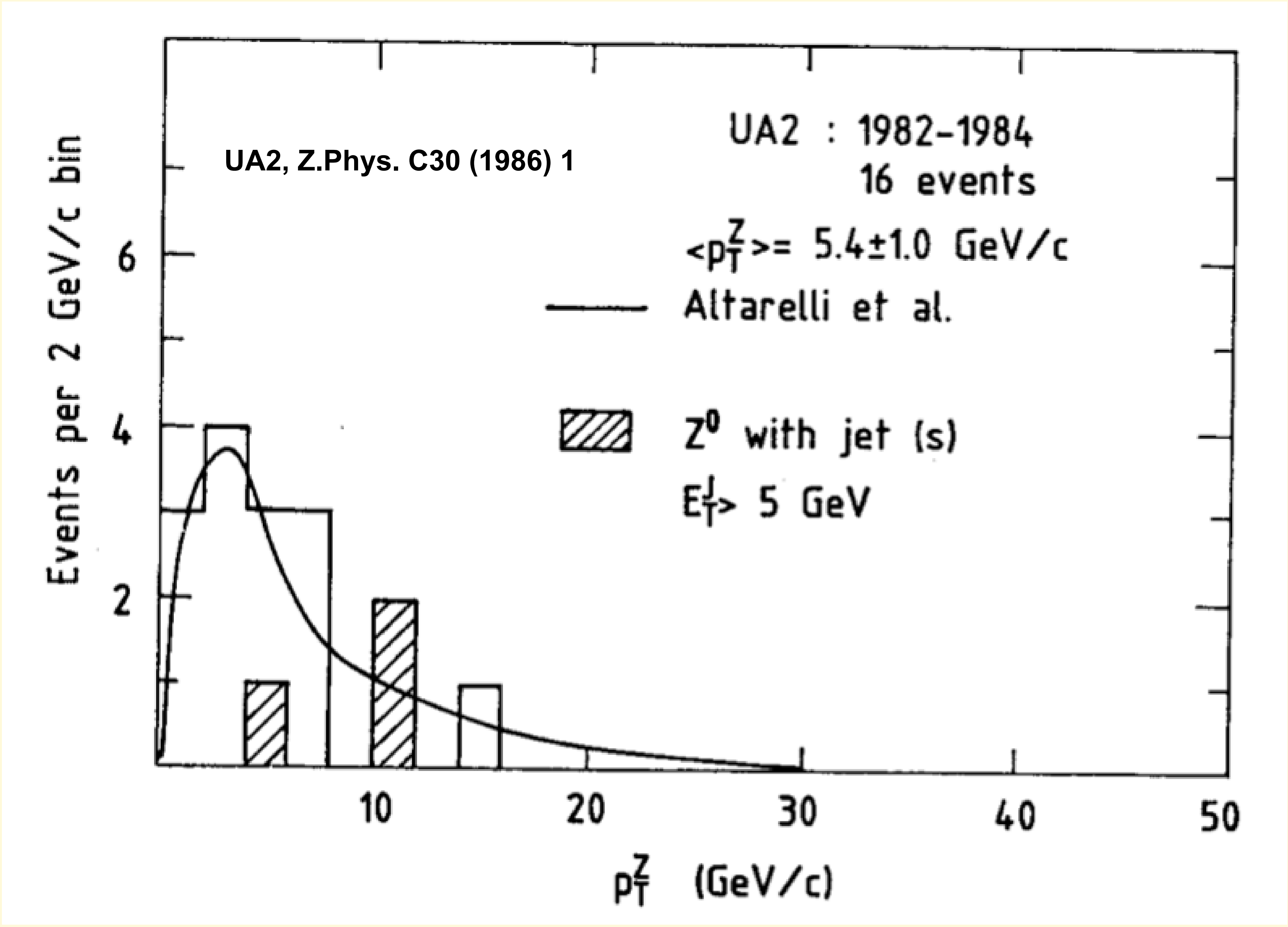
- Approximate NNNLO from structure of leading large-x and small-x logs

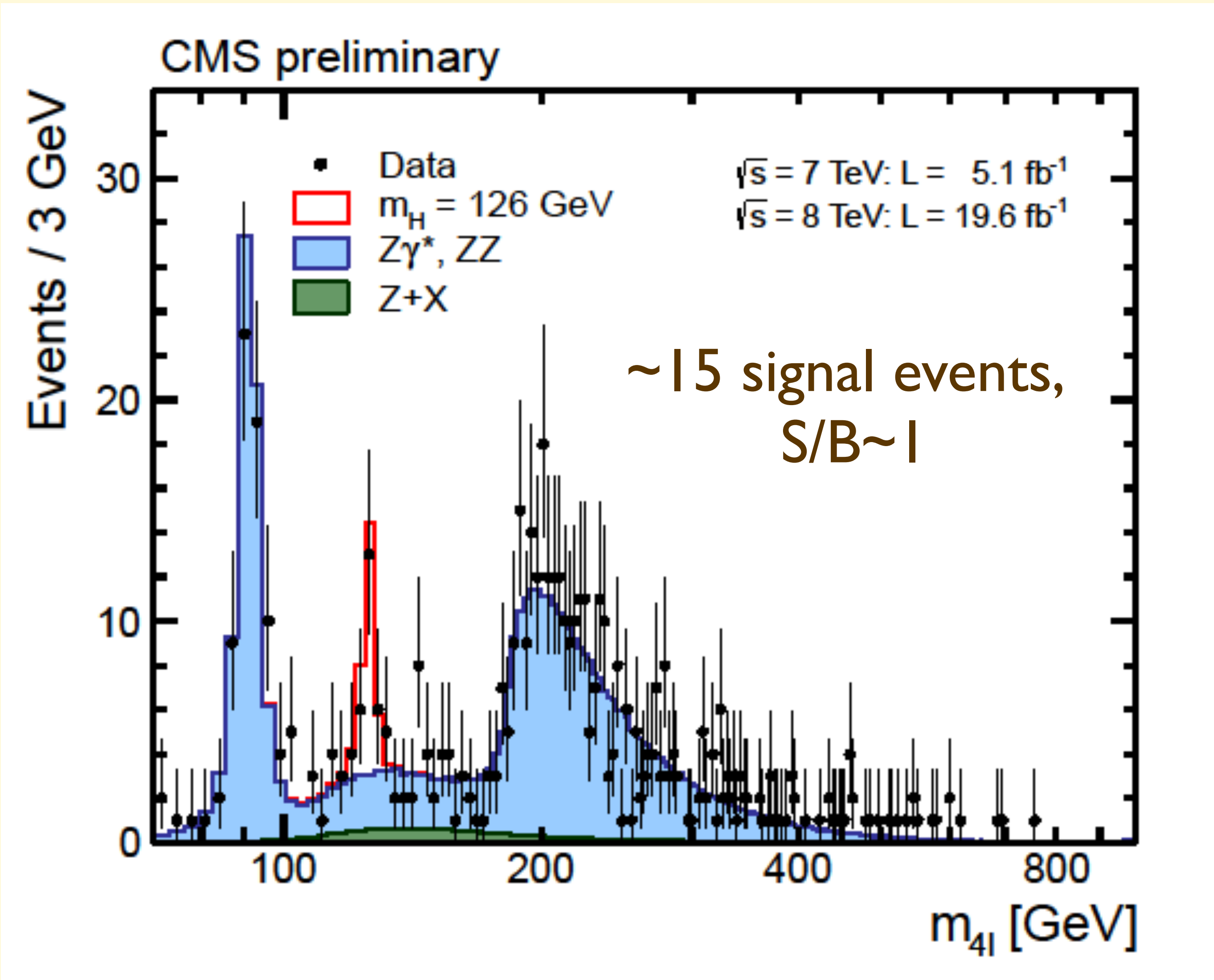
R. Ball etal, arXiv:1303.3590

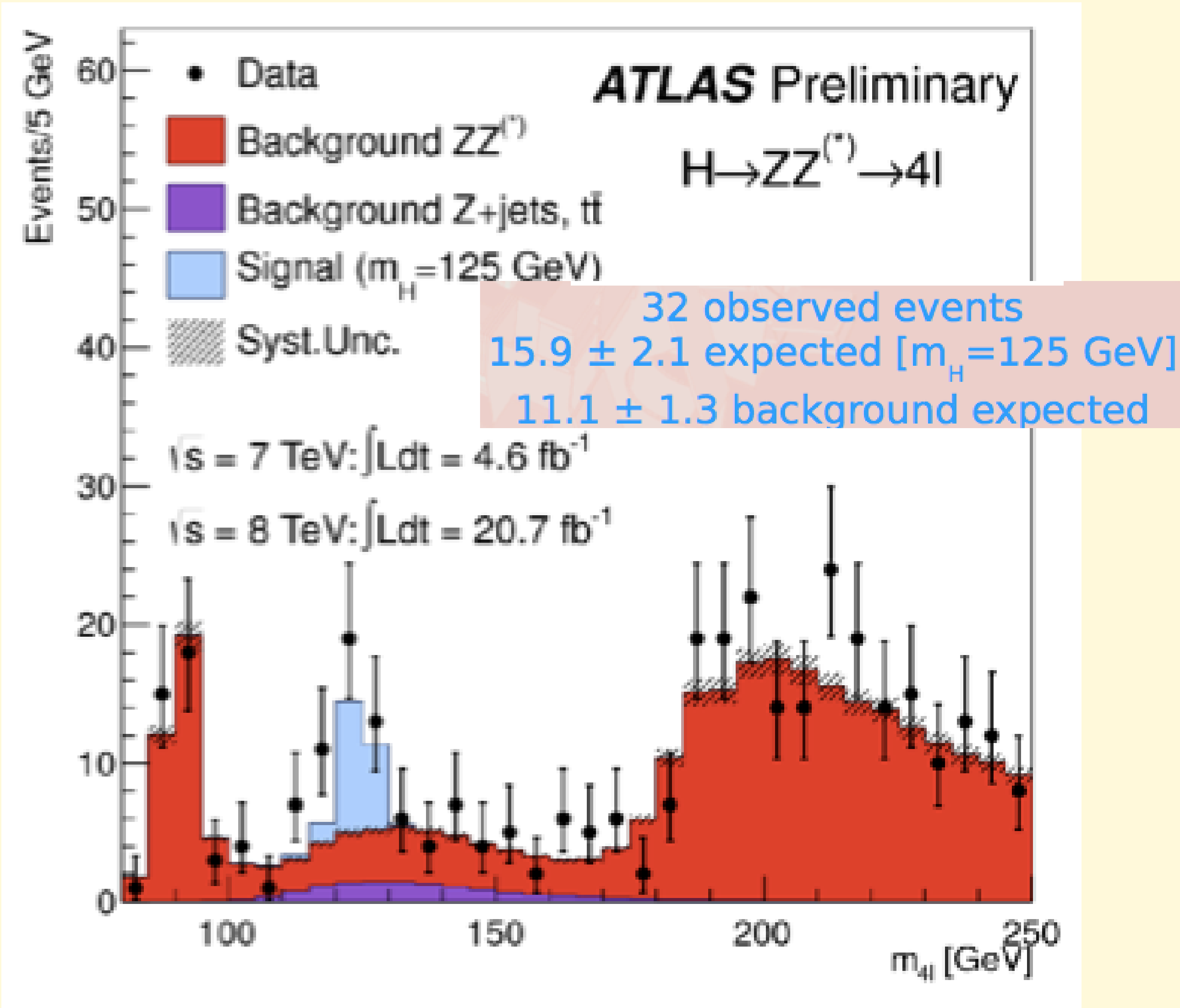


Towards experimental constraints on Higgs production dynamics ....

To put it in perspective, the study of W/Z production properties started like this ....., from a score of events:







There is enough to start plotting pt(H), N_{jet} distribution in H production, etc.

Concluding remarks

- **LHC measurements moved to a new phase of quantitative and precision level**
  - proton structure (cross sections, PDFs)
  - final state dynamics
  - extreme kinematical configurations
  - EW and flavour sector parameters
- **It's a great reward for theorists to see the fruits of years of work developing tools**
  - theory/data agreement beyond expectations and hopes
  - thanks to the expt's for the thorough and incisive tests of theory
  - still, interesting open issues and problems to keep the challenge up
- **The Higgs is there ... but where is everyone else ??**

Concluding remarks

- The key outcome of the Higgs observation and other LHC findings is a confirmation of the relevance of the hierarchy problem. The future of accelerator physics should be tailored to address this question.
- Obvious priorities include:
  - Precision studies of Higgs properties:
    - H decay branching ratios, very rare H decay modes, including flavour violating ones
    - H production and interactions at large Q^2
  - Dig deeper in the search of well-hidden BSM processes, and extend mass reach going to higher energy
- The fact that no BSM has been seen as yet implies that, if anything will be seen, it will take a lot of luminosity and/or energy to study it in detail!
- The same is true for a complete study of the EWSB sector.

Concluding remarks

- The difficulty and timescales of necessary theoretical calculations match the challenge of building the experiments, and of doing precise measurements. It will be a tough ride for the whole community, mitigated only by the occasional excitement of a fresh discovery.
- It took 40 years to wrap up the SM, it may take longer to tackle the next layer. The future plan must ensure a continued interest and excitement, justified by new and challenging measurements, to fill possibly long discover-less periods!
- Experimentalists often want from theorists a good physics case to justify some future facility. We can give many physics cases: whether they're good, it's a different story. So far theorists have been mostly right with the SM (mtop, CKM and CPV, mHiggs), but mostly wrong with BSM, which is where we are moving towards now. Expts should take the lead again, and revamp the excitement of the exploration of the unknown, motivated by the pleasure of meeting tough technological challenges, making exciting and unique measurements, and pushing the frontier of knowledge.
- In my view, the current theoretical perspective justifies a call for a fast track approach to (a hadron collider at) the highest possible energy, with an interim filled by the fullest exploitation of the LHC, pushing further the discovery reach and the precision measurements, and possibly by a Japanese e^+e^- Higgs factory