Standard Model and Beyond

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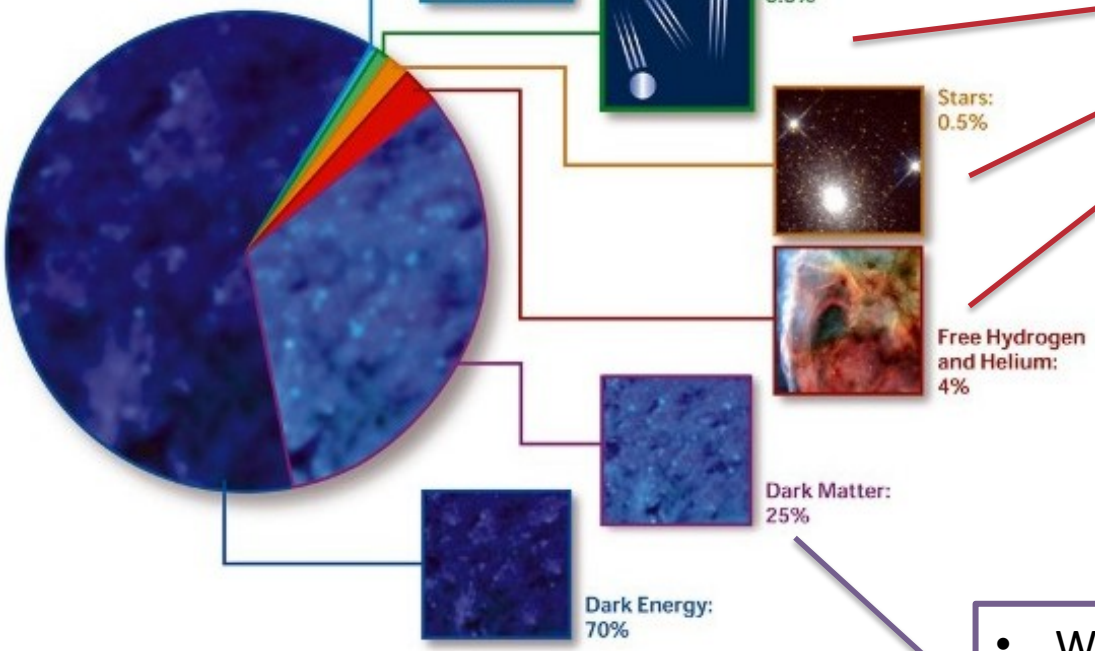
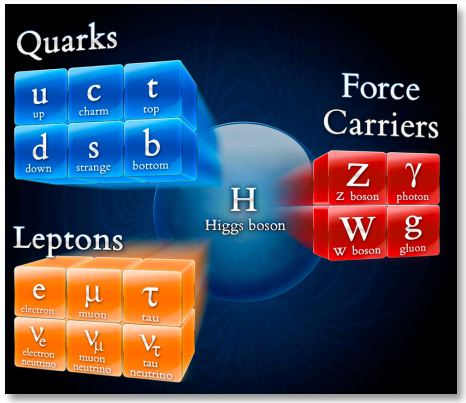
7/8/15, CERN, Geneva

Composition of the Universe





- Explains the ordinary matter quite accurately
- Not a finished story, there are several open questions and limitation

- Responsible for the accelerating expansion of the Universe

- Weekly interacting massive particles
- Searches with many experiments: ArDM, CDMS, IceCube, LHC…

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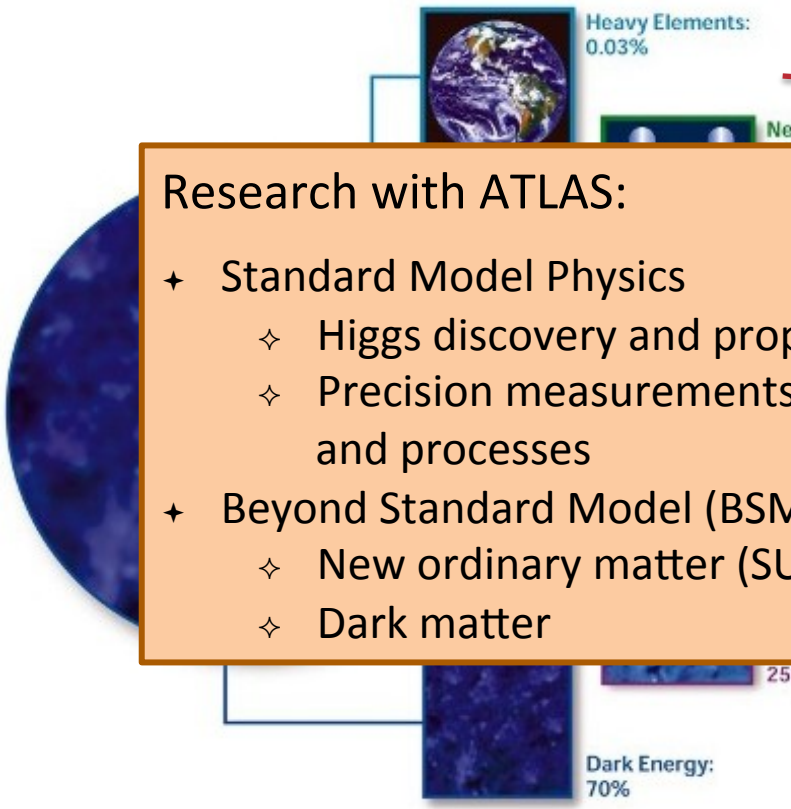

Research with ATLAS:

- Standard Model Physics
  - Higgs discovery and properties measurement
  - Precision measurements of known particles and processes
- Beyond Standard Model (BSM) physics searches
  - New ordinary matter (SUSY, exotic particles…)
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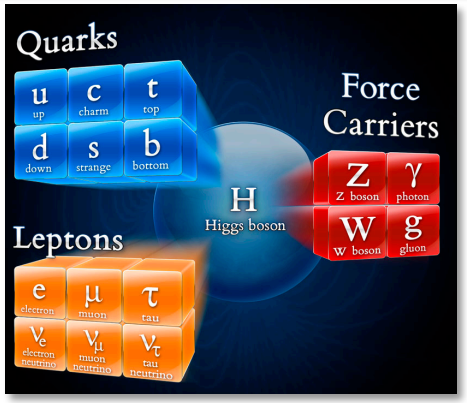

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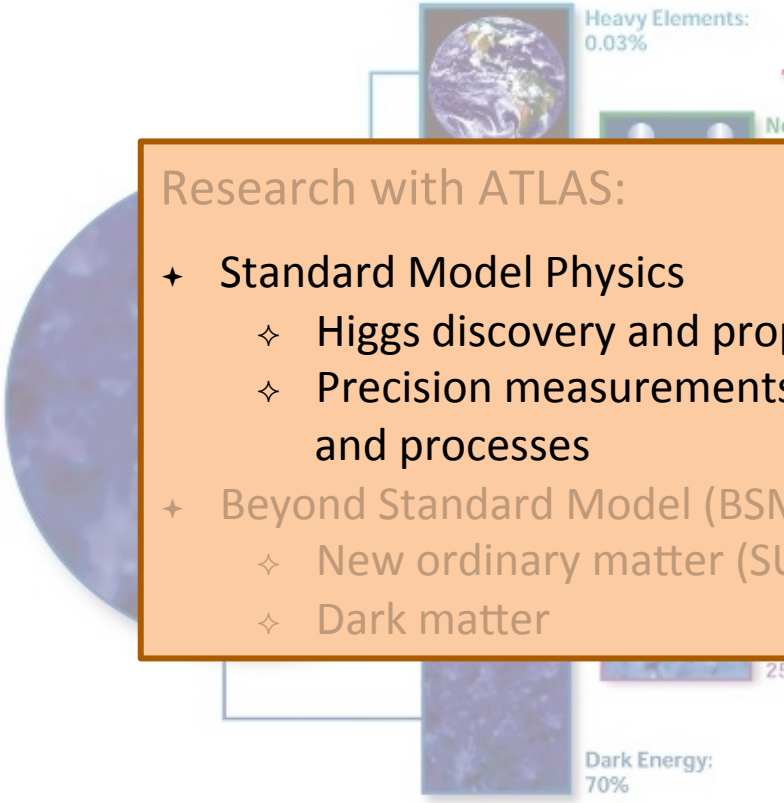

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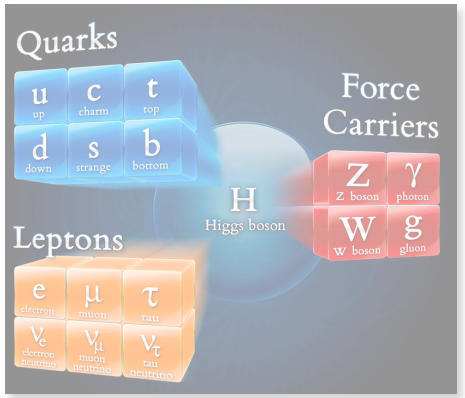

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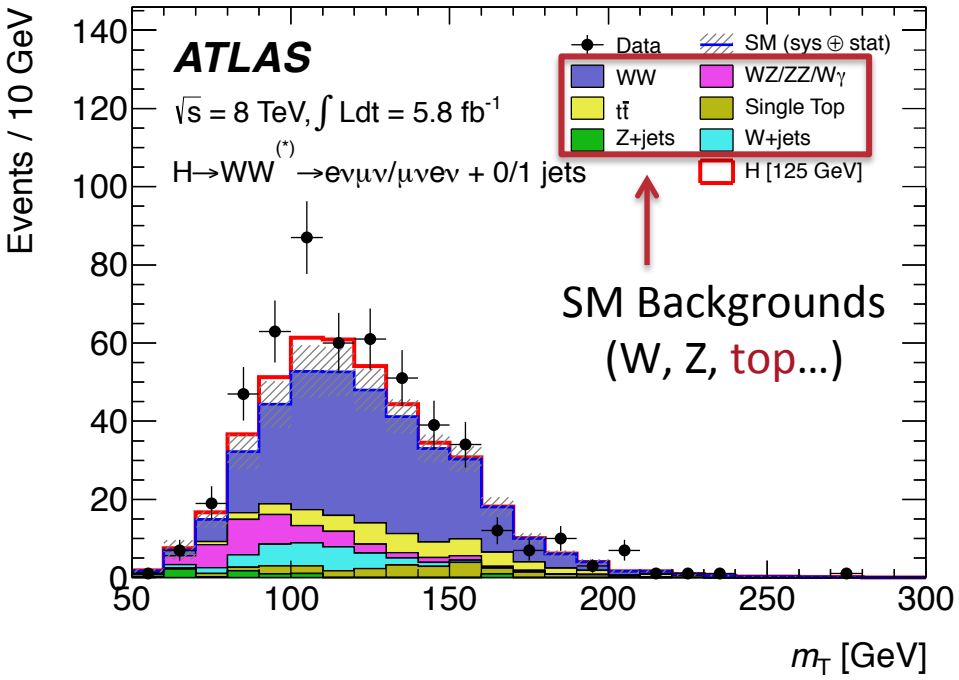
How do we search for new physics?

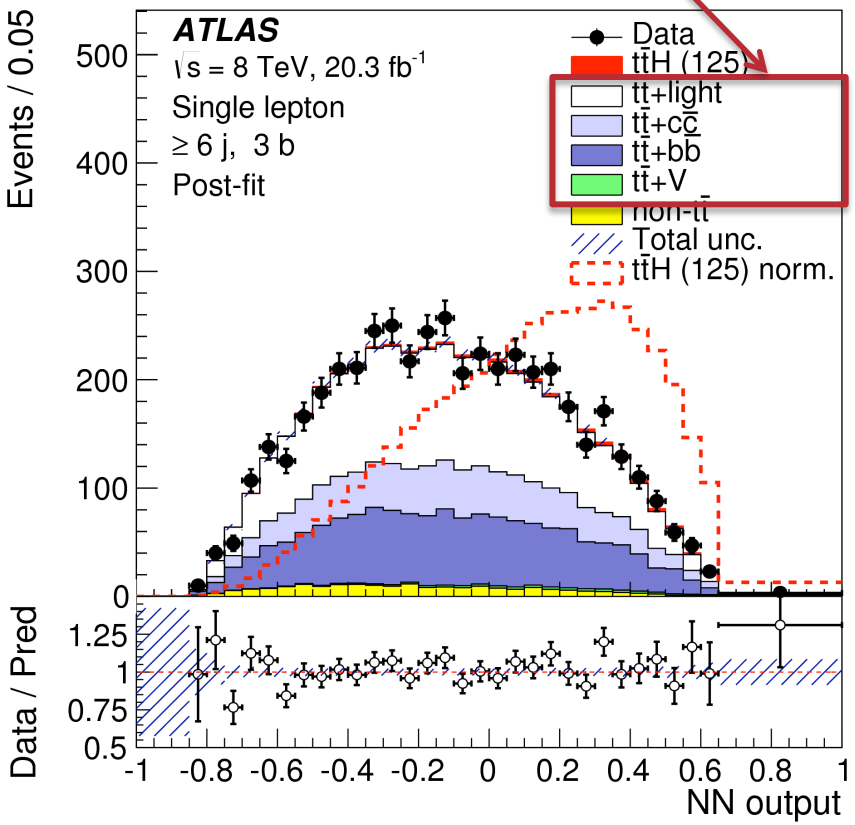


SM Backgrounds (W, Z, top…)

Each component of the SM backgrounds must be well estimated

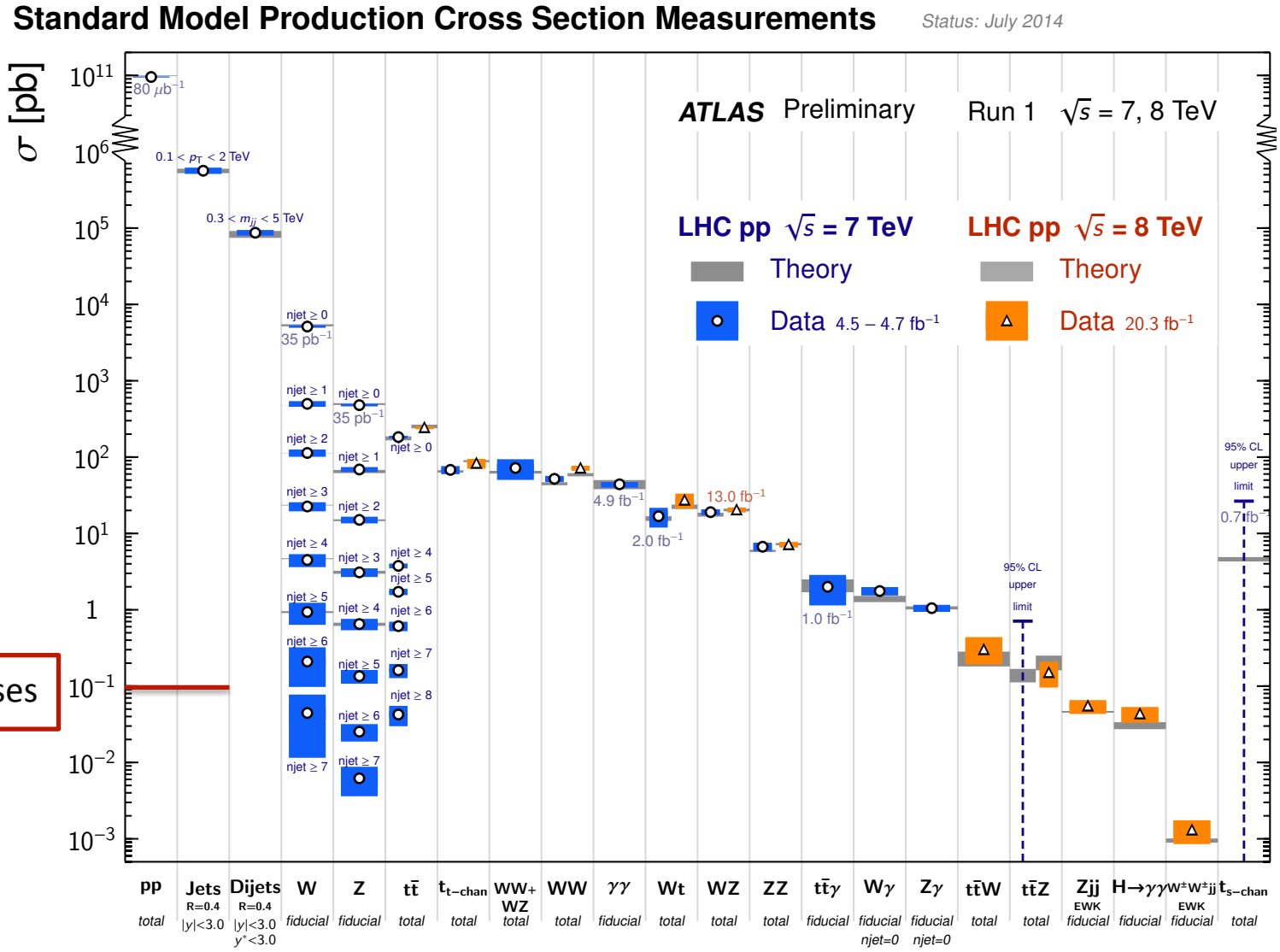
- Accurate modeling
  - Good knowledge of the processes involved (masses, couplings…)
- As low as possible uncertainties

Processes involving the top quark make major backgrounds in numerous searches -> their understanding is crucial

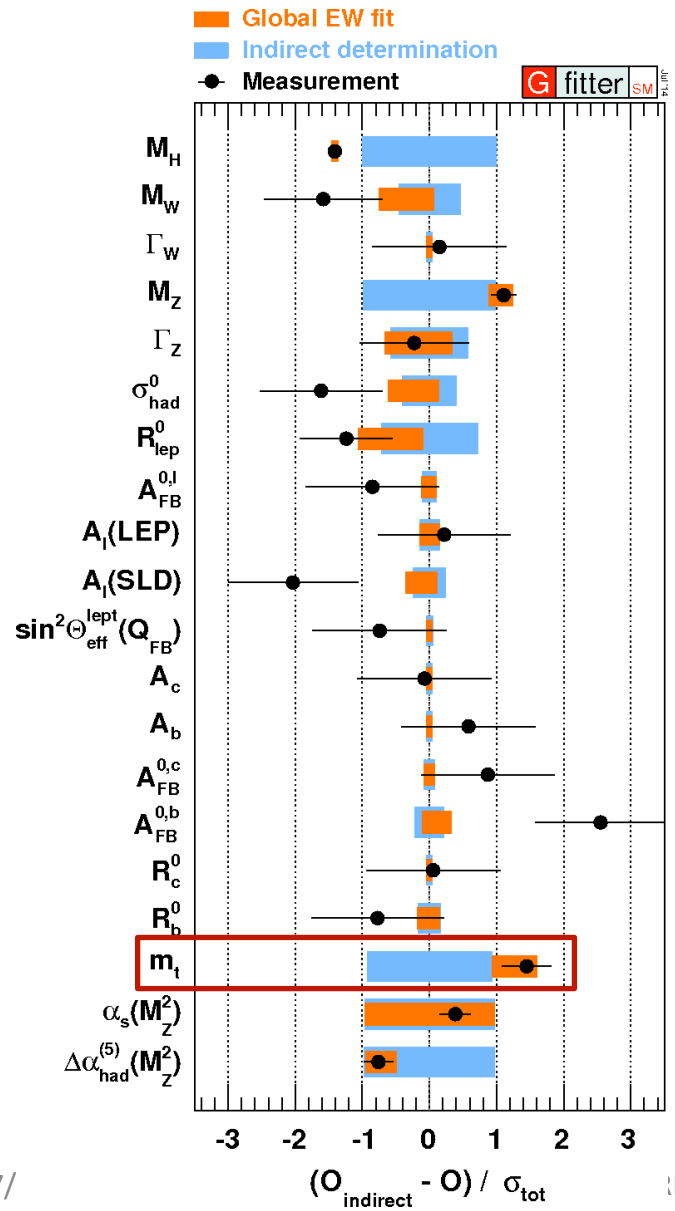


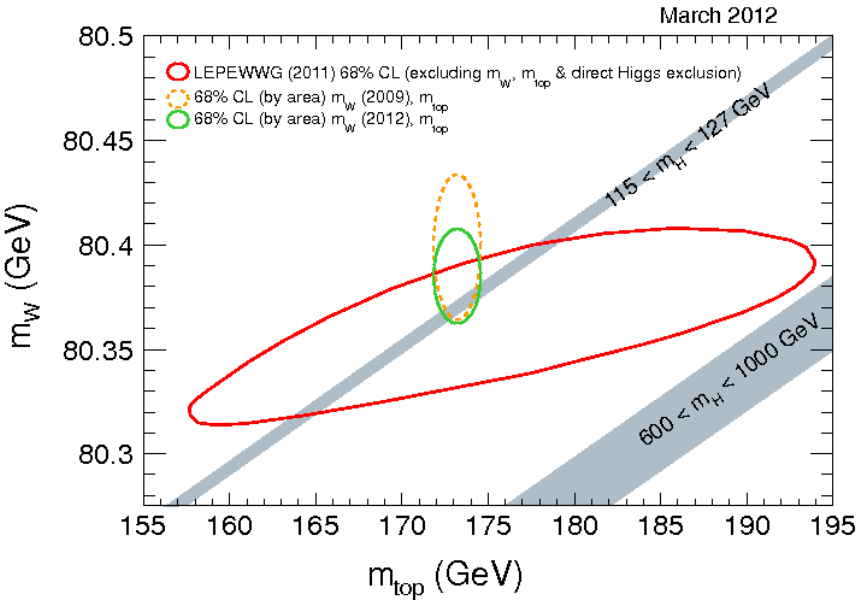
SM Backgrounds – Cross Sections

New Physics Processes

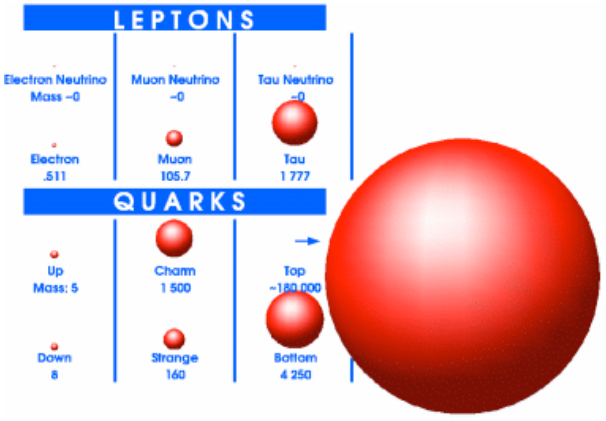


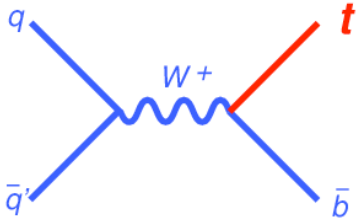
Global Fit of SM Parameters

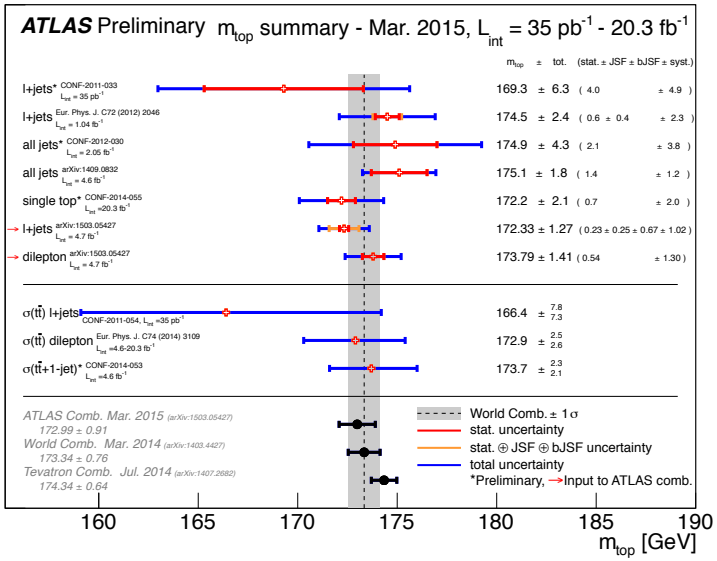


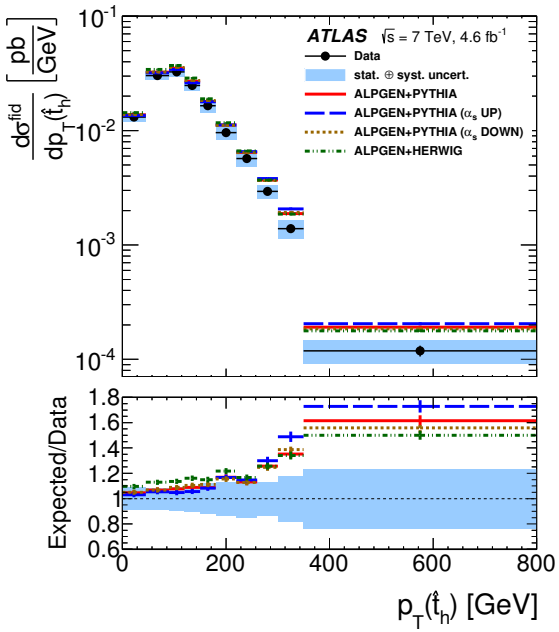


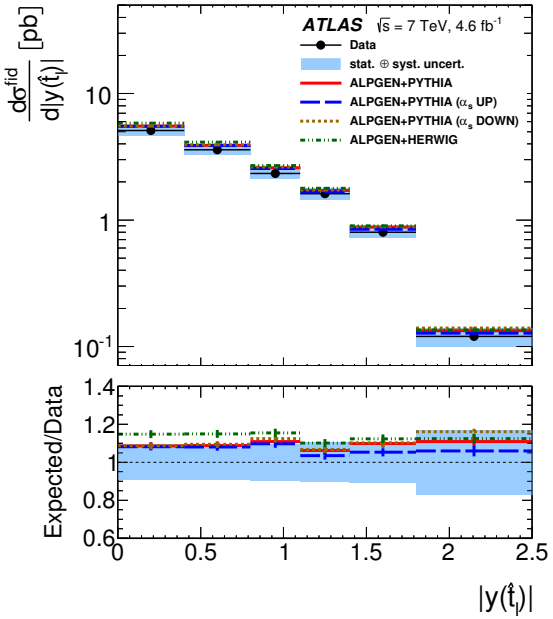
Top Quark Physics Measurements











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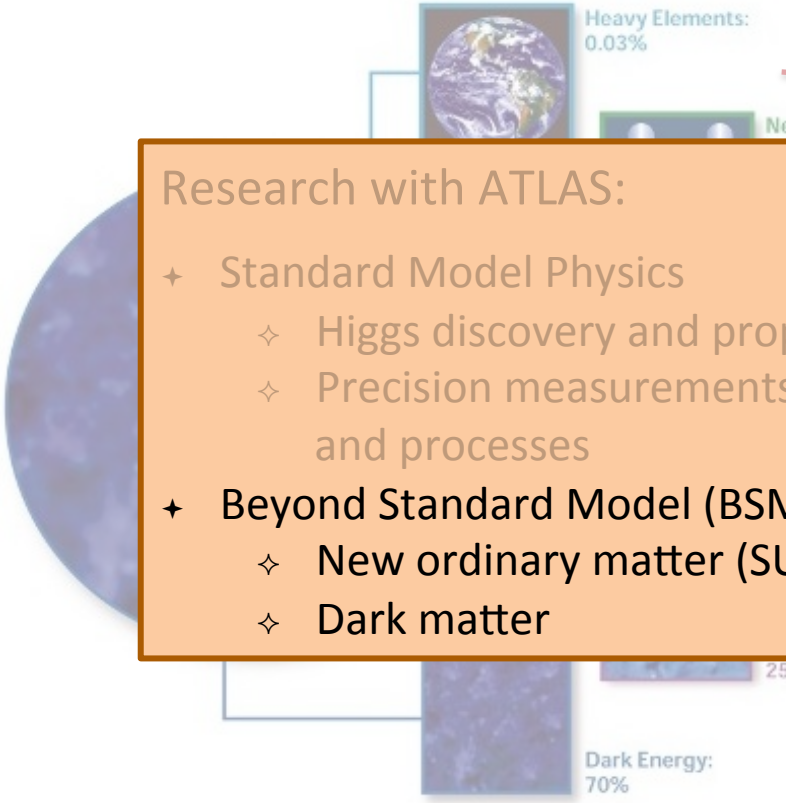

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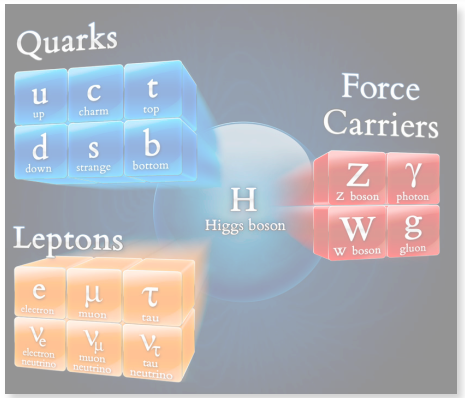

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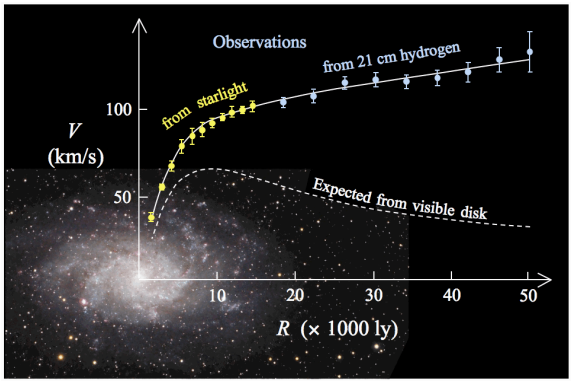
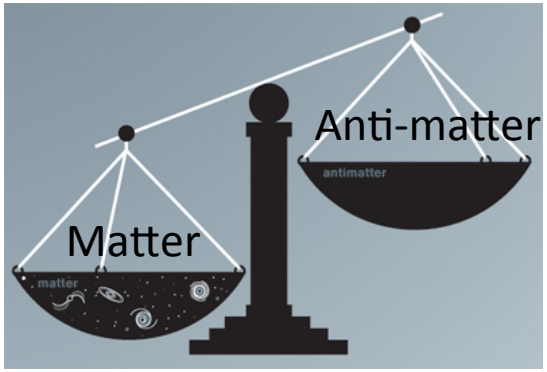
Limitations and Inconsistences of the Standard Model

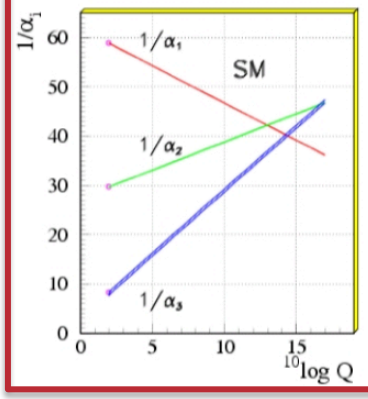
Dark matter

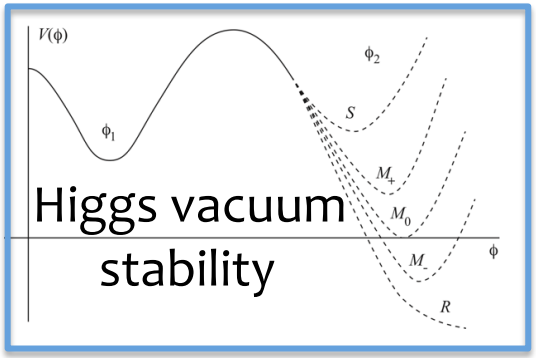


Baryon asymmetry of the Universe

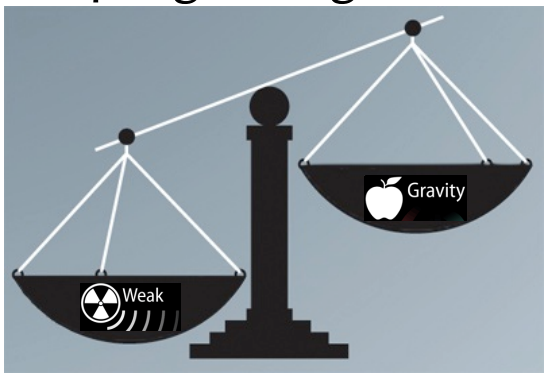


Grand Unification

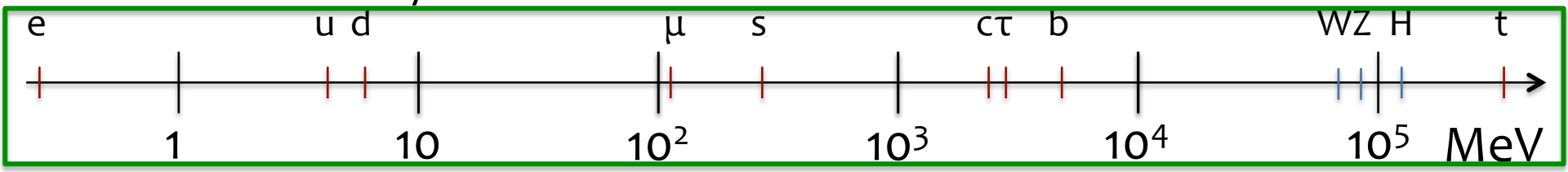




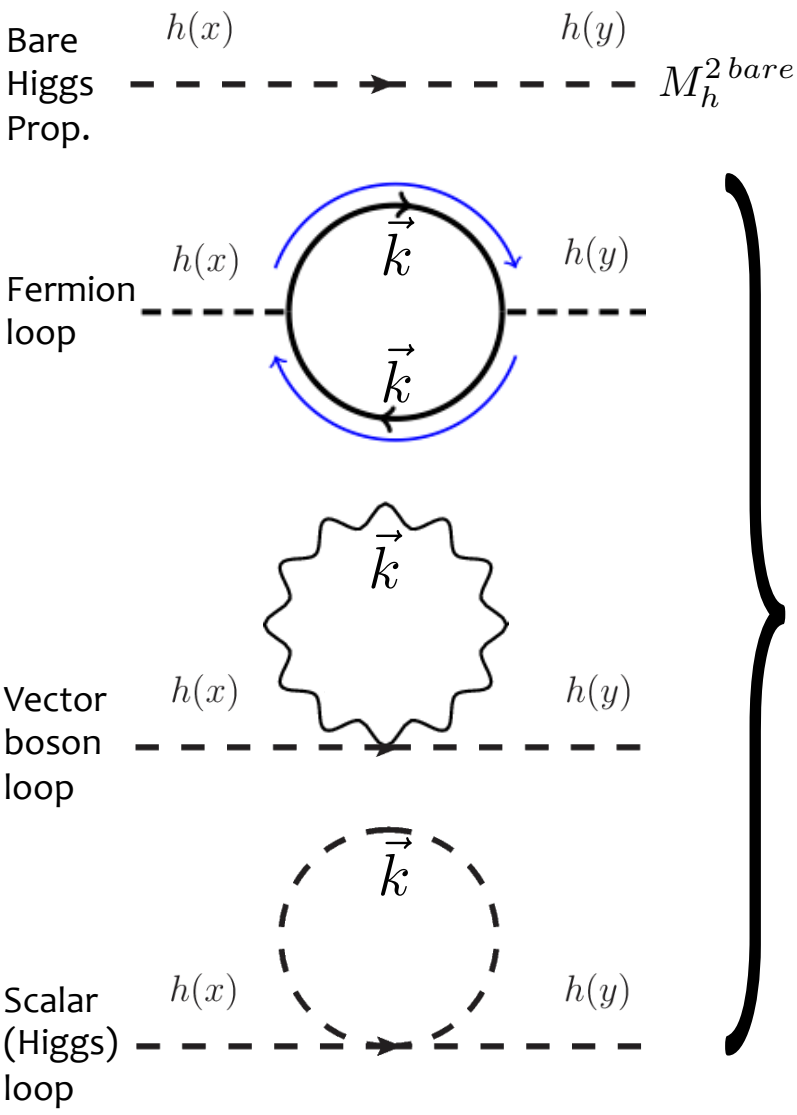
Coupling strength hierarchy



Particle mass hierarchy



Higgs Mass Problem – Quadratic Divergences



$$\sim \mathcal{C}\int \frac{d^4k}{k^2} \rightarrow \mathcal{C}\int_p^{\Lambda} \frac{d^4k}{k^2} \rightarrow \frac{\mathcal{C}}{16\pi^2}\Lambda^2$$

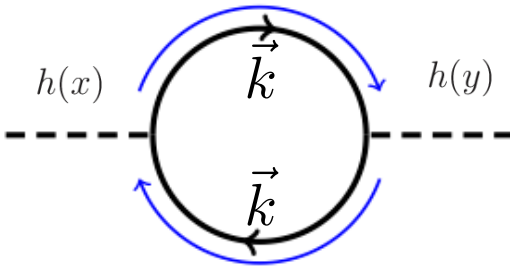
$\Lambda \rightarrow$ Cutoff scale up to which the SM is valid ⇒ at which new physics enters

Higgs Mass Problem – Quadratic Divergences

Bare Higgs Prop.

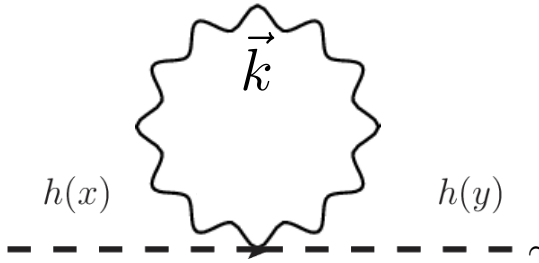
$$M_h^{2\,bare}$$

Fermion loop



$$\sim -\frac{3y_t^2}{8}\Lambda^2 = -\frac{3m_t^2}{4v^2}\Lambda^2$$

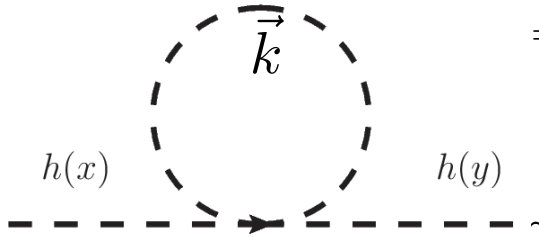
Vector boson loop



$$\sim \frac{9g^2 + 3g'^2}{64}\Lambda^2$$

$$= \frac{3(M_Z^2 + 2M_W^2)}{16v^2}\Lambda^2$$

Scalar (Higgs) loop



$$\sim \frac{\lambda^2}{16}\Lambda^2 = \frac{3M_h^2}{16v^2}\Lambda^2$$

Higgs Mass Problem – Quadratic Divergences

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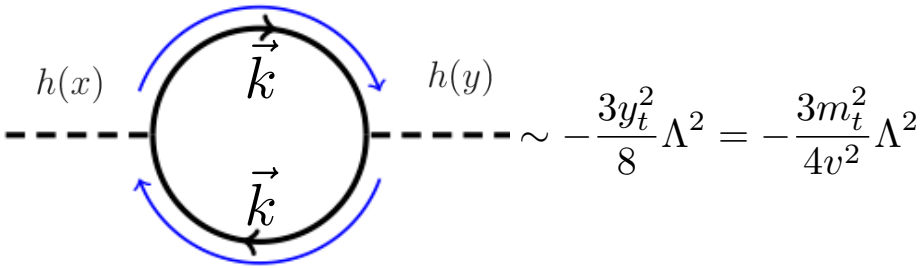

$$\Lambda^2 = ?$$

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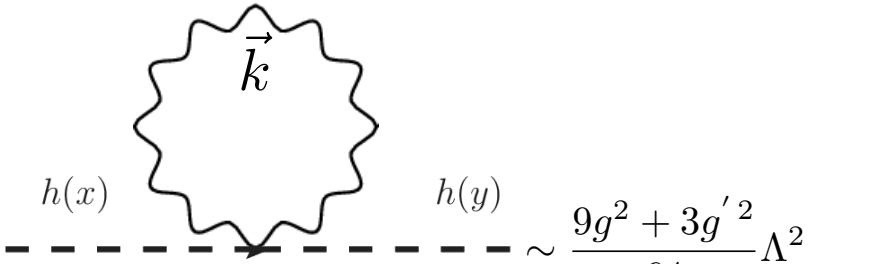

$$= \frac{3(M_Z^2 + 2M_W^2)}{16v^2}\Lambda^2$$

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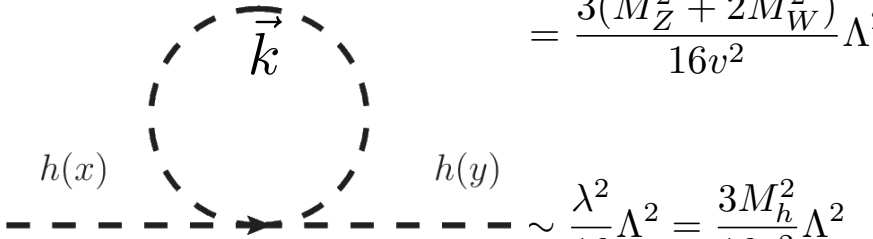
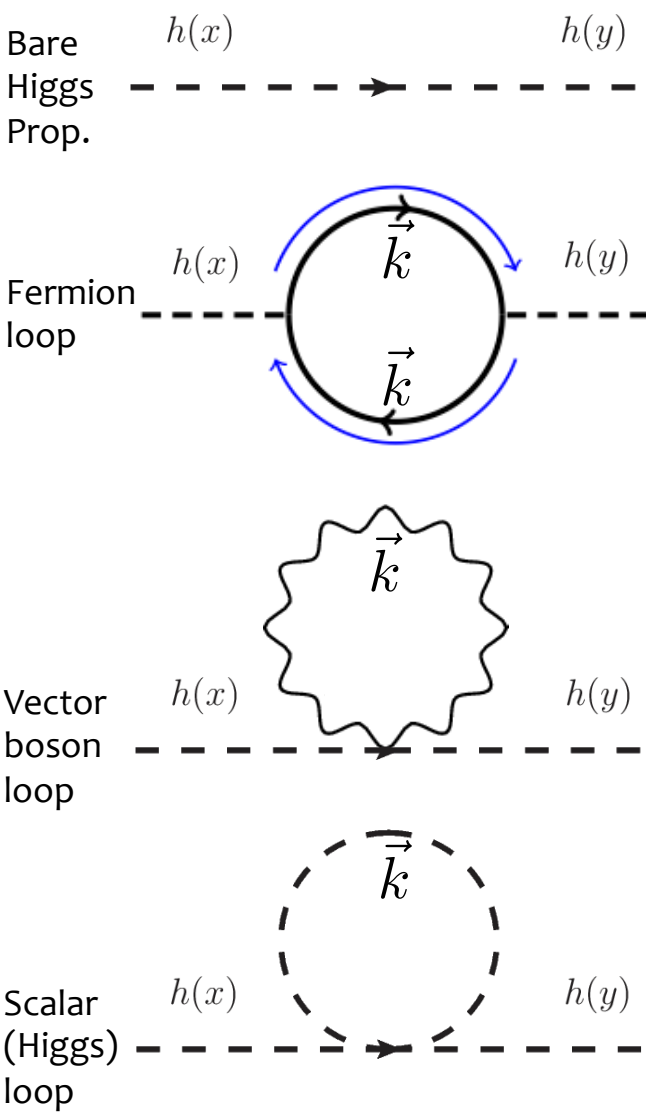
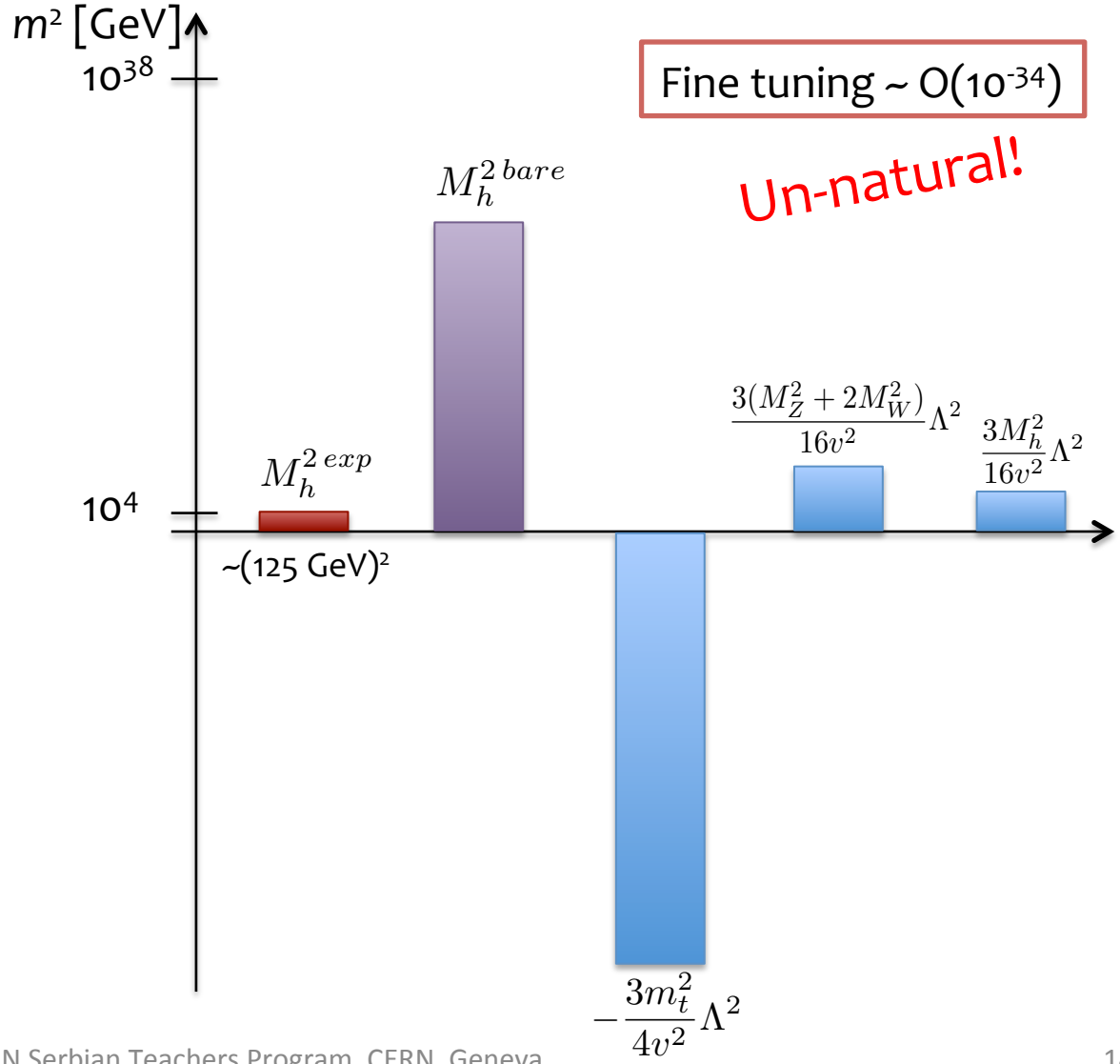


- Planck scale ~10^{19} GeV ?
  - Quantum gravity
- GUT scale ~10^{15} GeV ?
  - Grand unification (elw+strong)
- Other BSM physics?

Higgs Mass Problem – Fine Tuning

Assume Planck scale: $\Lambda^2 \sim 10^{38}$

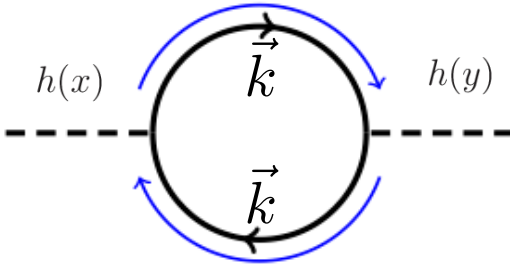




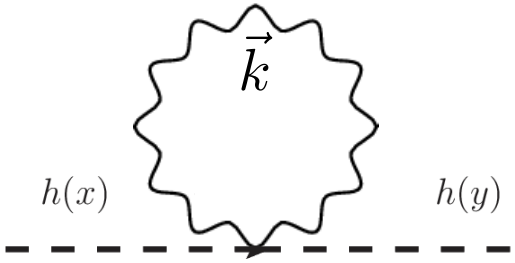
Higgs Mass Problem Solutions – Supersymmetry

Bare Higgs Prop.

Fermion loop



Vector boson loop



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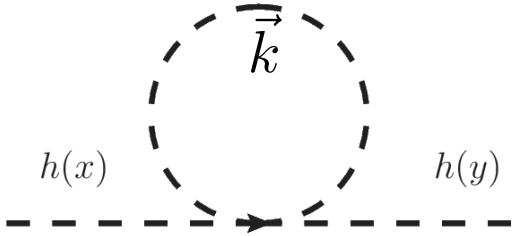


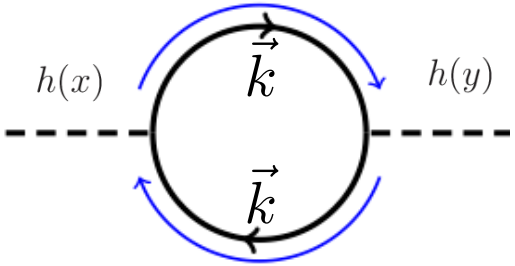
- Fermionic loops: "-" sign
- Bosonic loops: "+" sign

⇒ Introduce a fermion-boson symmetry!

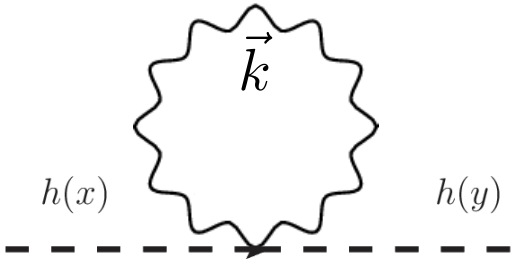
Higgs Mass Problem Solutions – Supersymmetry

Bare Higgs Prop.

Fermion loop



Vector boson loop



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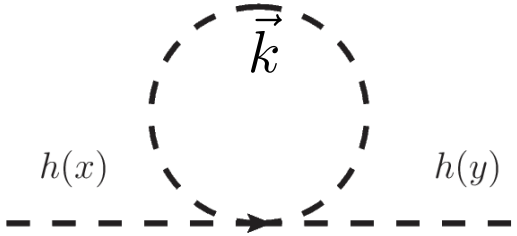

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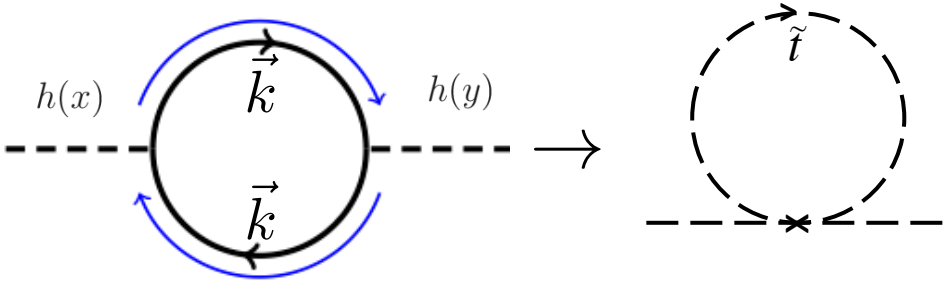
⇓

Supersymmetry

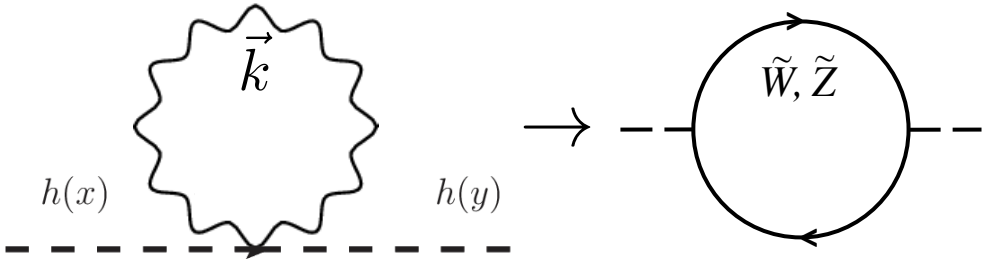
Higgs Mass Problem Solutions – Supersymmetry

Bare Higgs Prop.

Fermion loop



Vector boson loop



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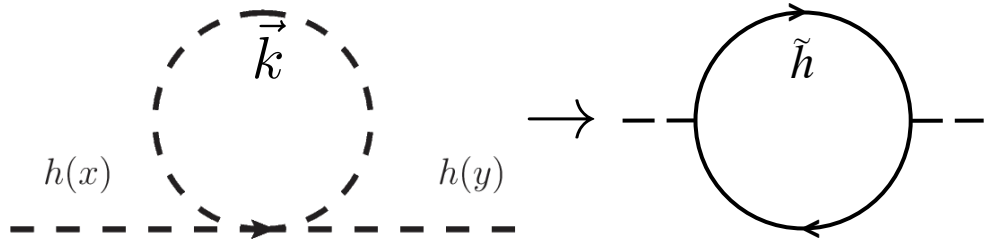
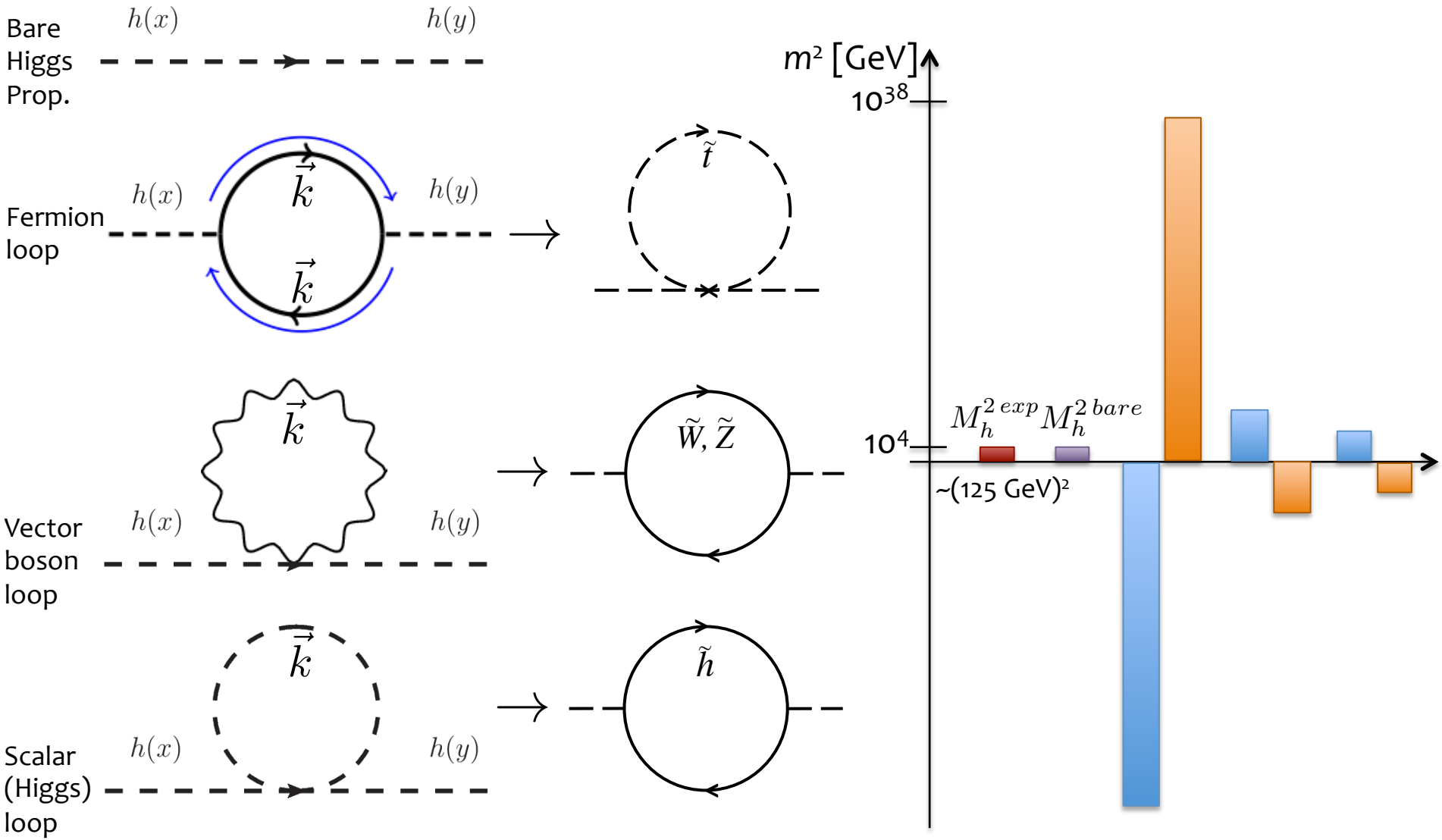


Higgs Mass Problem Solutions – Supersymmetry



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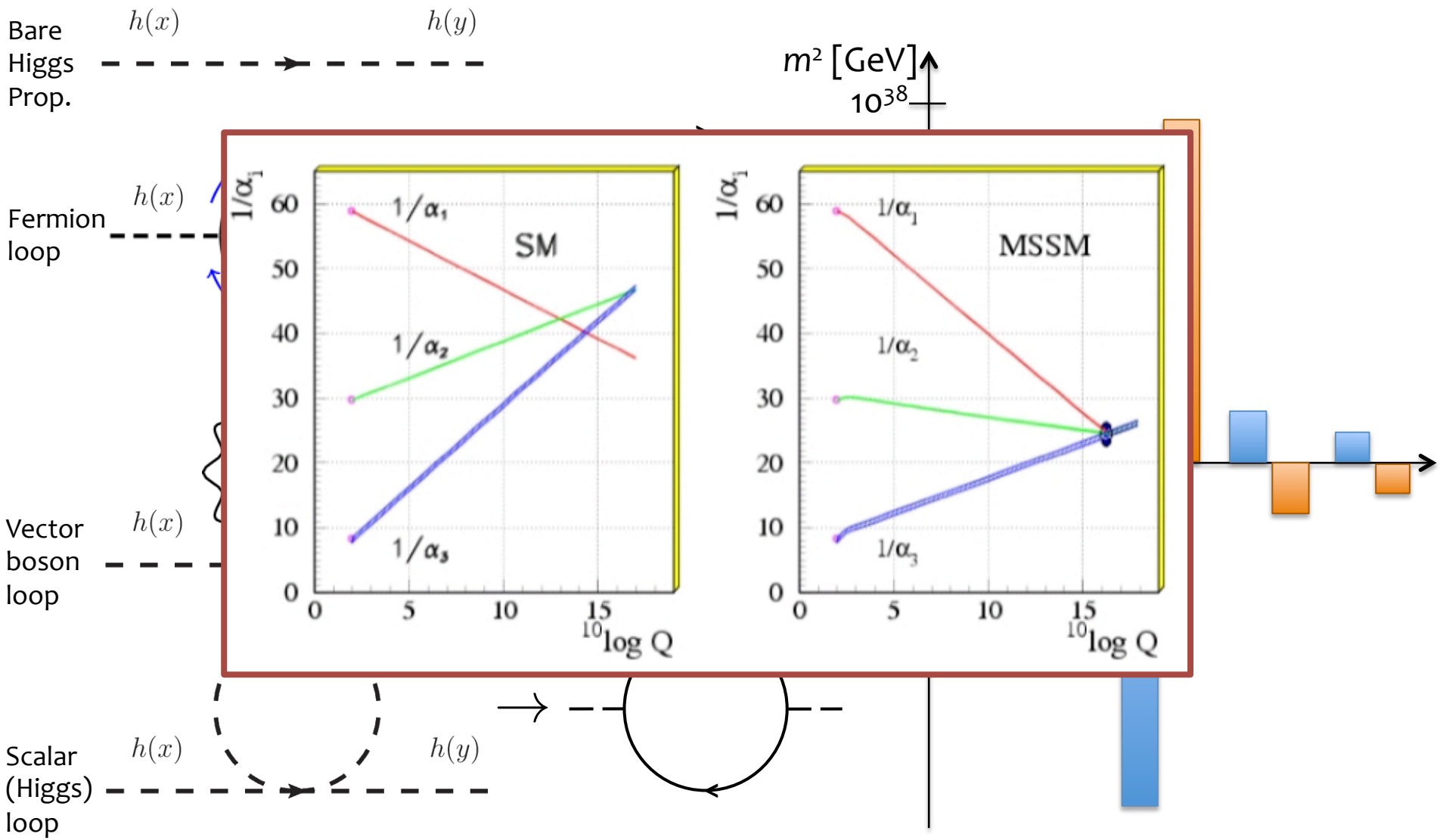

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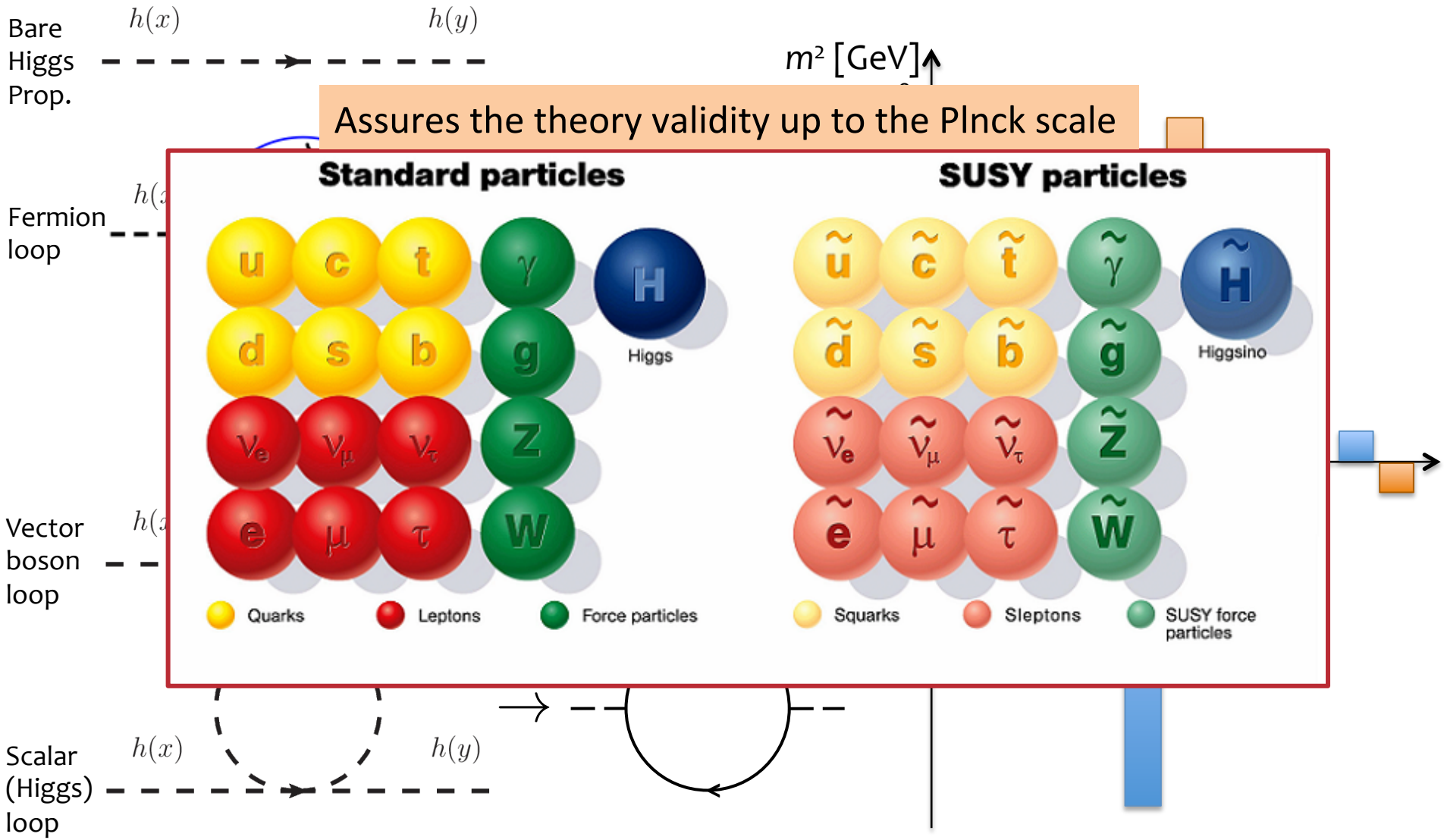
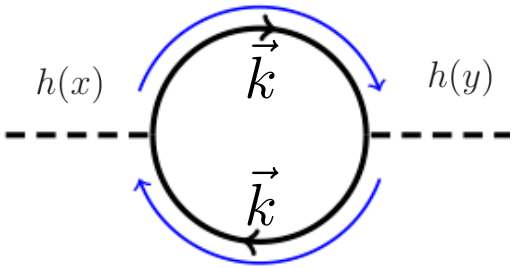


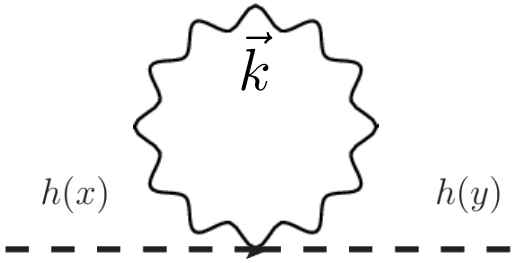
Higgs Mass Problem Solutions – Exotics

Bare Higgs Prop.

Fermion loop



Vector boson loop



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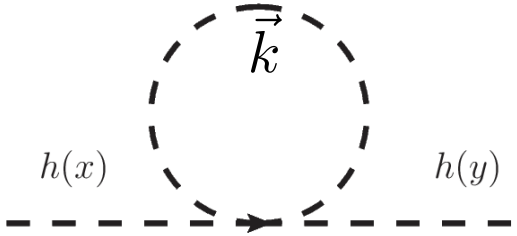
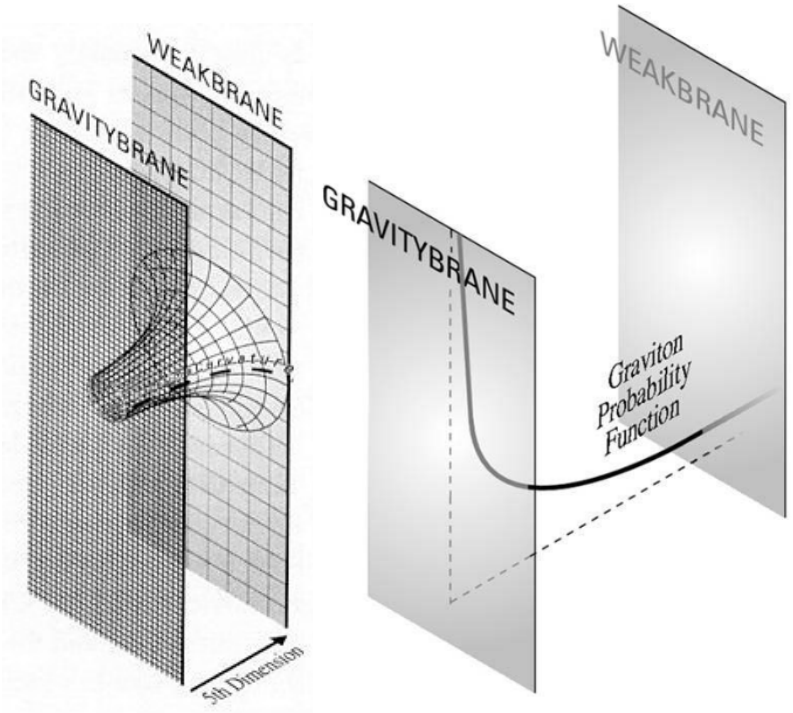


- Fine tuning to strong for $\Lambda^2 \sim 10^{38}$?

⇒ Bring the cutoff scale down to ~10 TeV by introducing new physics!

Higgs Mass Problem Solutions – Extra Dimensions



- ✧ Fine tuning to strong for $\Lambda^2 \sim 10^{38}$?

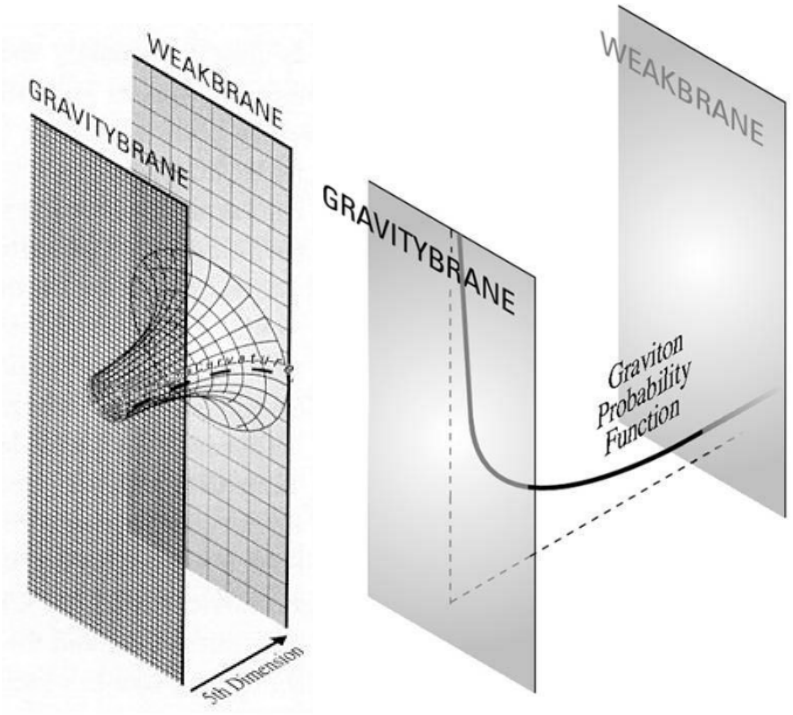
⇒ Bring the cutoff scale down to ~10 TeV by introducing new physics!

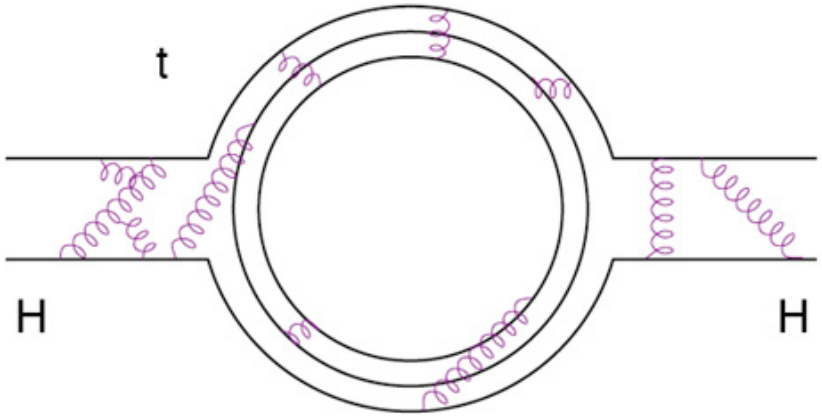
⇒ Warped extra dimensions

- ✦ SM confined in the weakbrane
- ✦ Gravity mainly contained in the gravity brane, gravitons propagate through the bulk into the weakbrane

⇒ Gravity very weak in the weakbrane

Higgs Mass Problem Solutions – Composite Higgs





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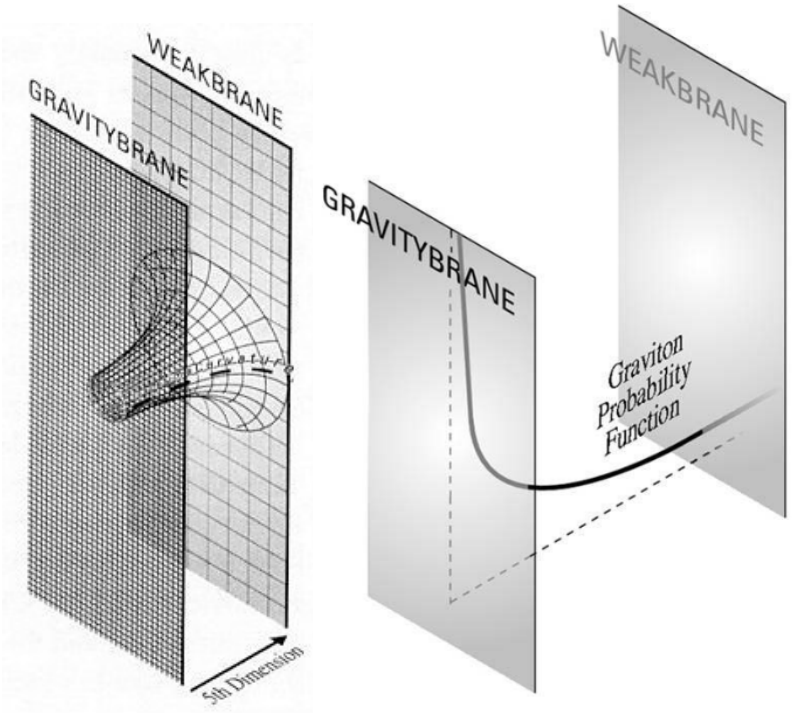
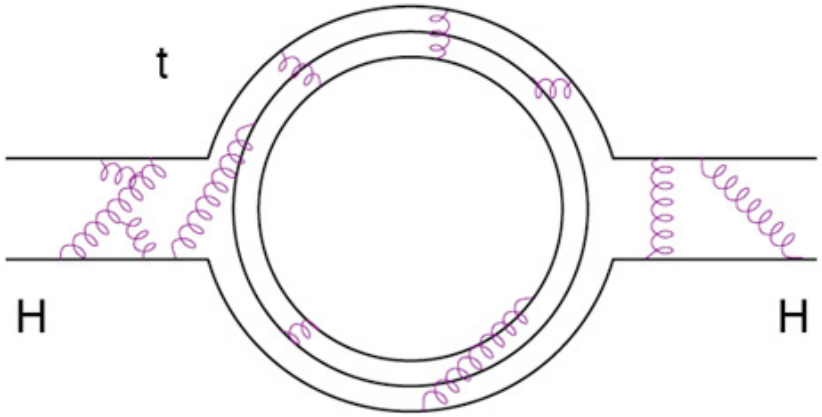
- ⇒ Composite / Little Higgs
  - ✦ Higgs is a bound state of a new strong interaction

Higgs Mass Problem Solutions – Vector-like Quarks





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  - ✦ Higgs is a bound state of a new strong interaction

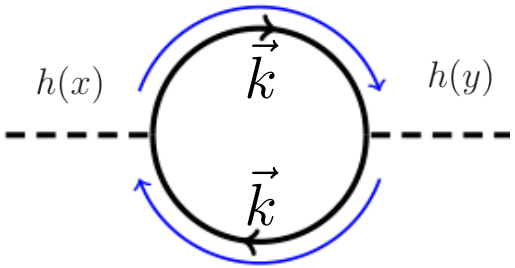
⇓

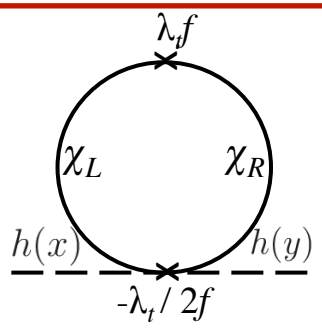
Vector-like quarks, ttbar resonances…

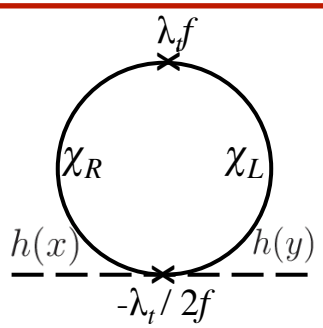
Higgs Mass Problem Solutions – Vector-like Quarks

Bare Higgs Prop.

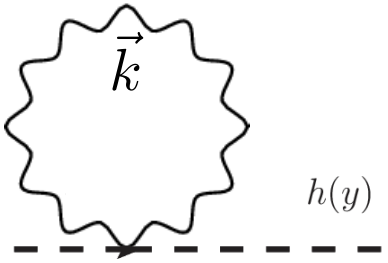
Fermion loop



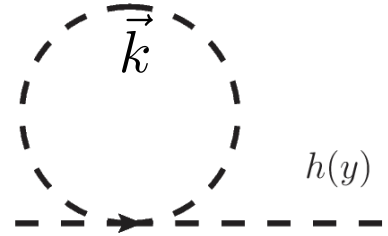




Vector boson loop



Scalar (Higgs) loop

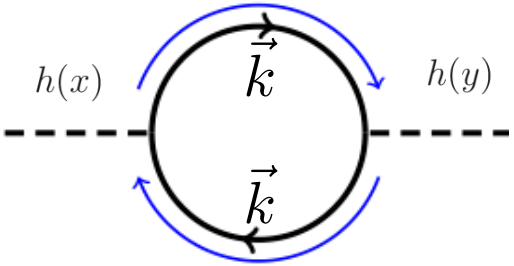


- Top loop canceled by the fermionic vector-like quark loops determined by:
  - the top Yukawa coupling λ_t
  - the compositeness scale f
- Analogously, bosonic contributions canceled by same-spin loops
- Cutoff scale ~ 10 TeV

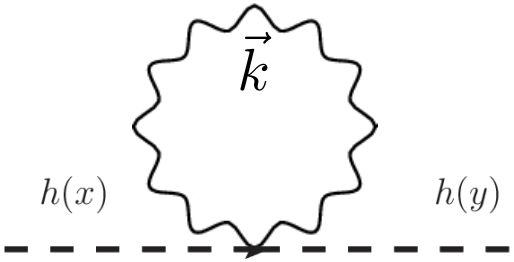
Higgs Mass Problem Solutions – Vector-like Quarks

Bare Higgs Prop.

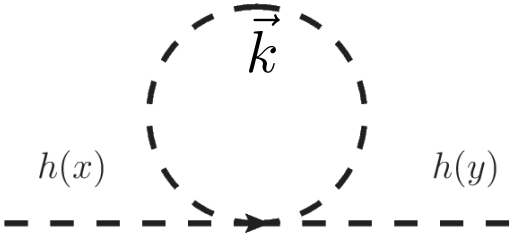
Fermion loop



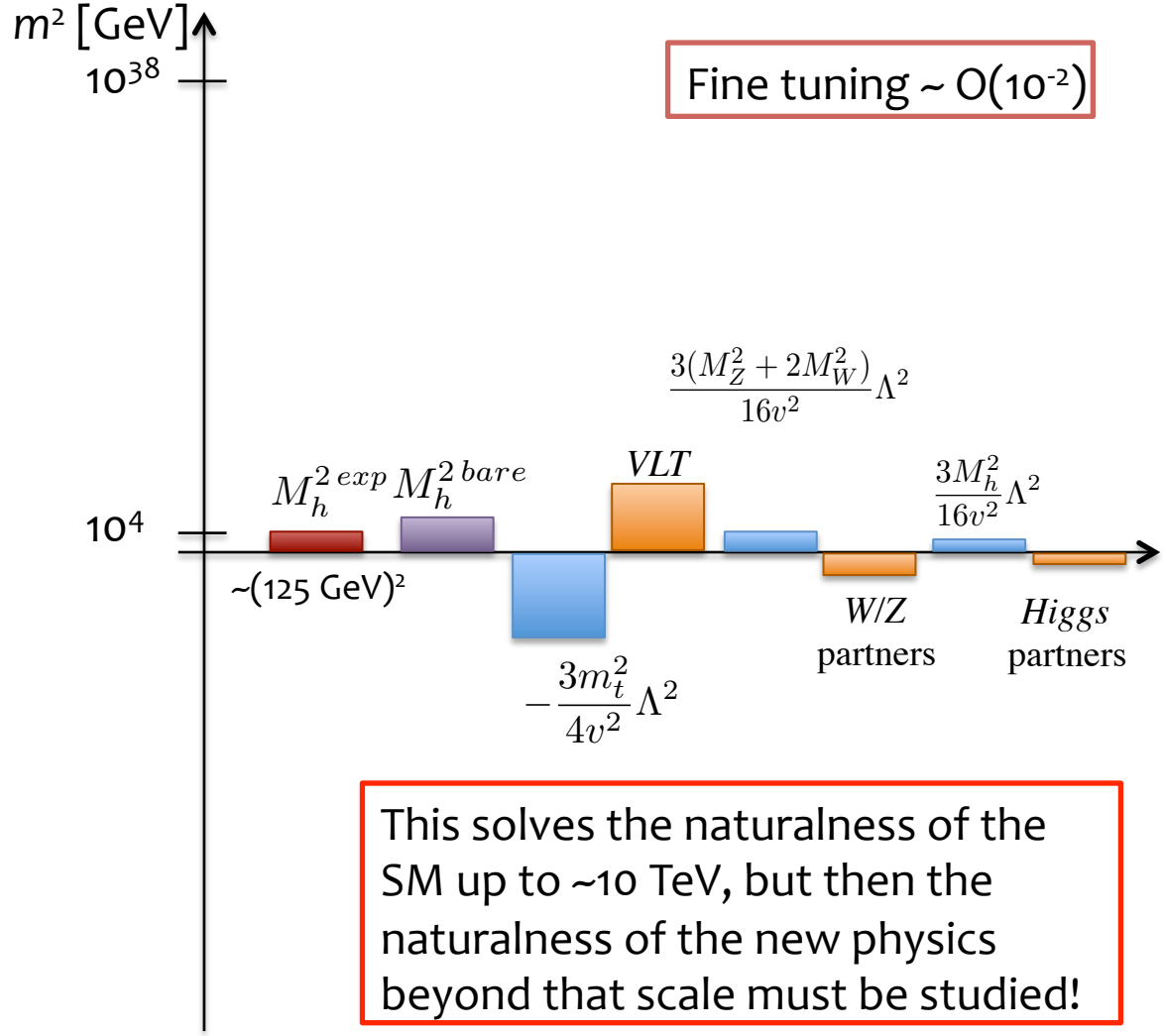
Vector boson loop



Scalar (Higgs) loop



Assume: $\Lambda^2 \sim (10^4\ \mathrm{GeV})^2$

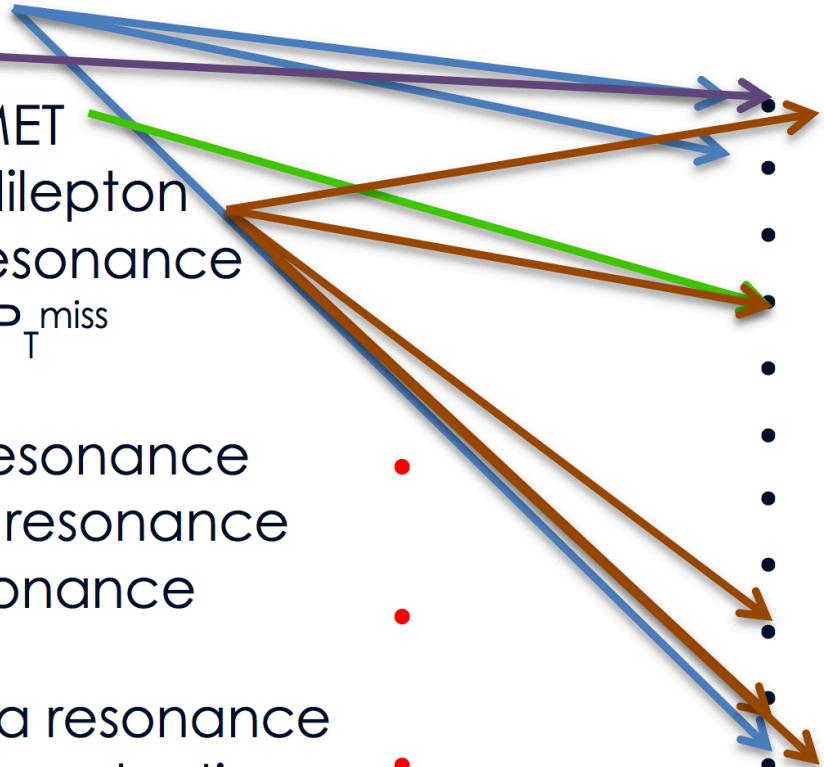


Fine tuning ~ O(10^{-2})

This solves the naturalness of the SM up to ~10 TeV, but then the naturalness of the new physics beyond that scale must be studied!

BSM Physics Searches

- 1-jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign dilepton
- Diphoton Resonance
- Diphoton + P_T^{miss}
- Multileptons
- Lepton-jet resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+gamma resonance
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet Resonance
- …

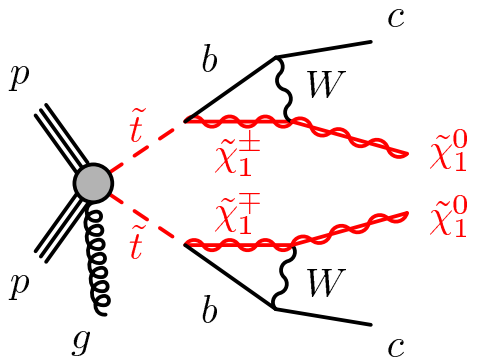


- Supersymmetry
- Extra-Dimmensions
- Technicolor
- Little Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositness
- 4^{th} generation (t', b')
- LRSM, heavy neutrino
- DM
- Quantum black holes
- Magnetic monopoles
- …

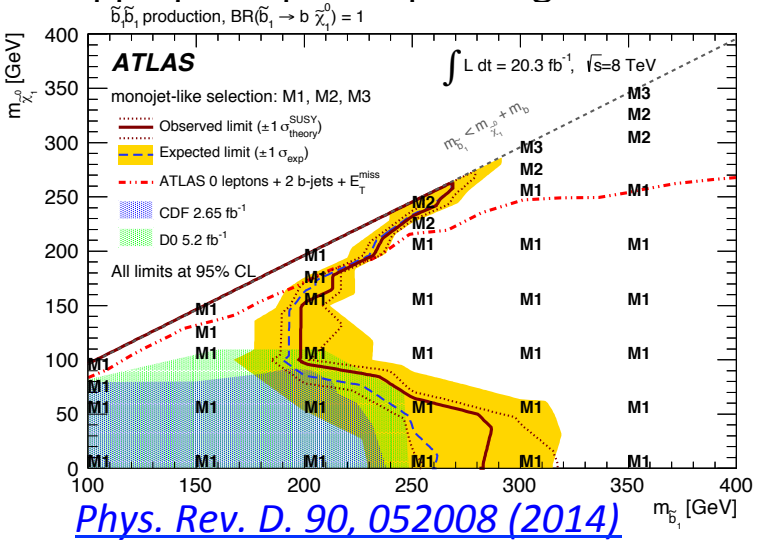
BSM Physics Searches

SUSY & VLQ

SUSY

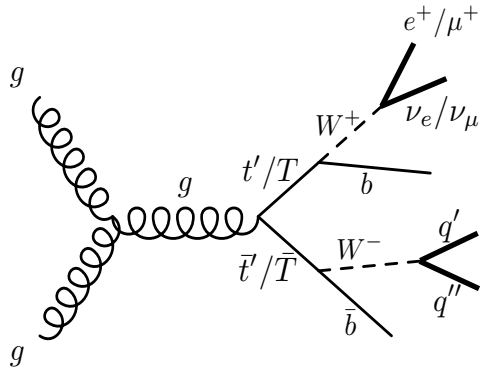


- SUSY models have many parameters
- SUSY particles are rather heavy and produce long decay chains
- In the absence of any evidence, exclusion limits are placed on appropriate phase space regions.

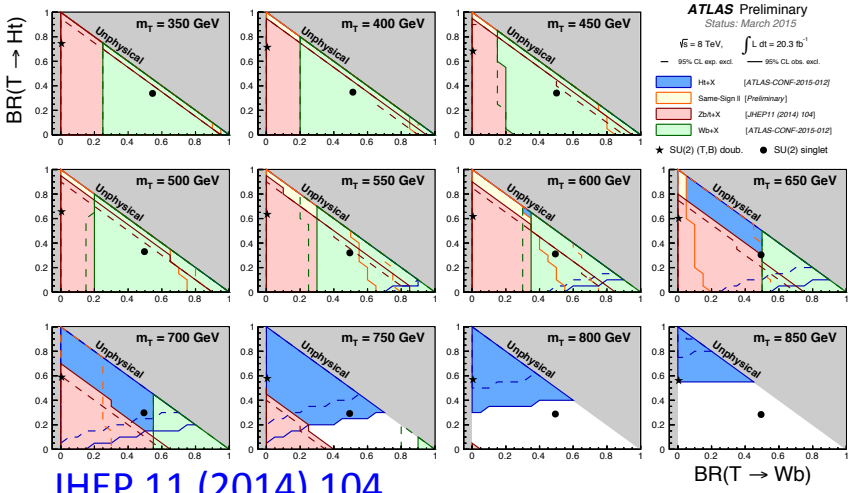


[Phys. Rev. D. 90, 052008 (2014)]

VLQ



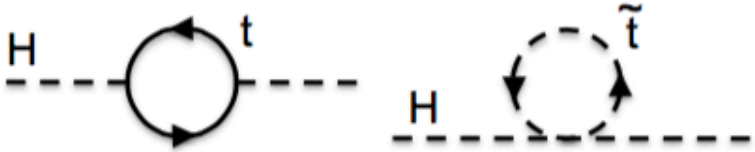
- Similar production as for the SM particles, but more decay modes. In the absence of any evidence, exclusion limits are placed on the VLQ masse.



[JHEP 11 (2014) 104]

3rd Generation SUSY Quarks

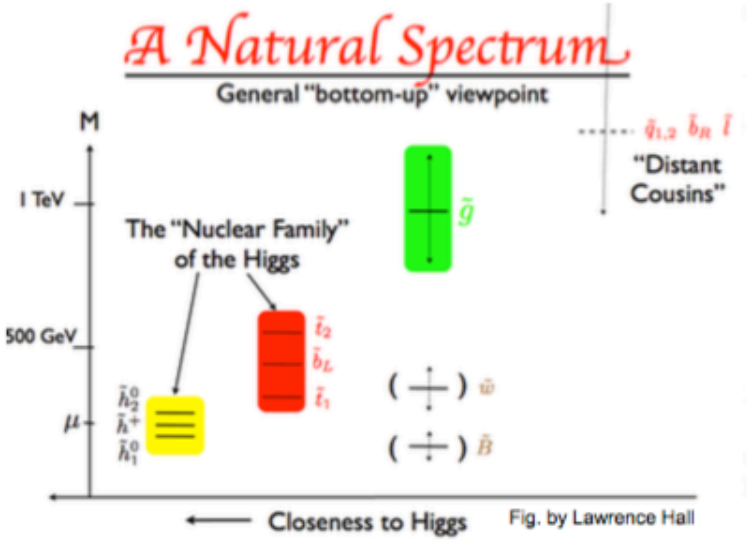
- **Bosonic (scalar) top / bottom partner particles are predicted by Supersymmetry (SUSY)**
- **Natural SUSY scenarios:**
  - Light stops & sbottoms (< 1 TeV)
  - Light gluinos (< 1-2 TeV)
  - Light higgsinos
  - → Low level of fine-tuning

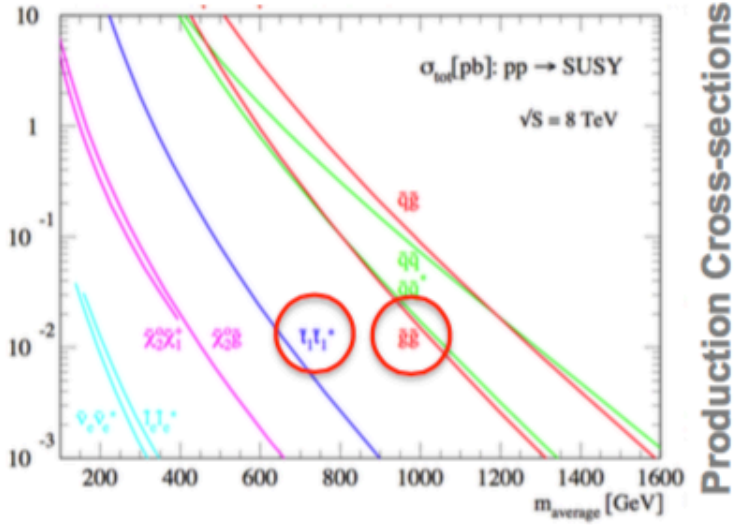


- **R-parity conservation:**
  - Pair production of 3rd generation squarks and stable lightest SUSY particle
    - → Natural candidate for dark matter

→ **Strong physics motivation for 3rd generation SUSY quarks**

→ **Production at the LHC:**
  - Direct & gluino-mediated

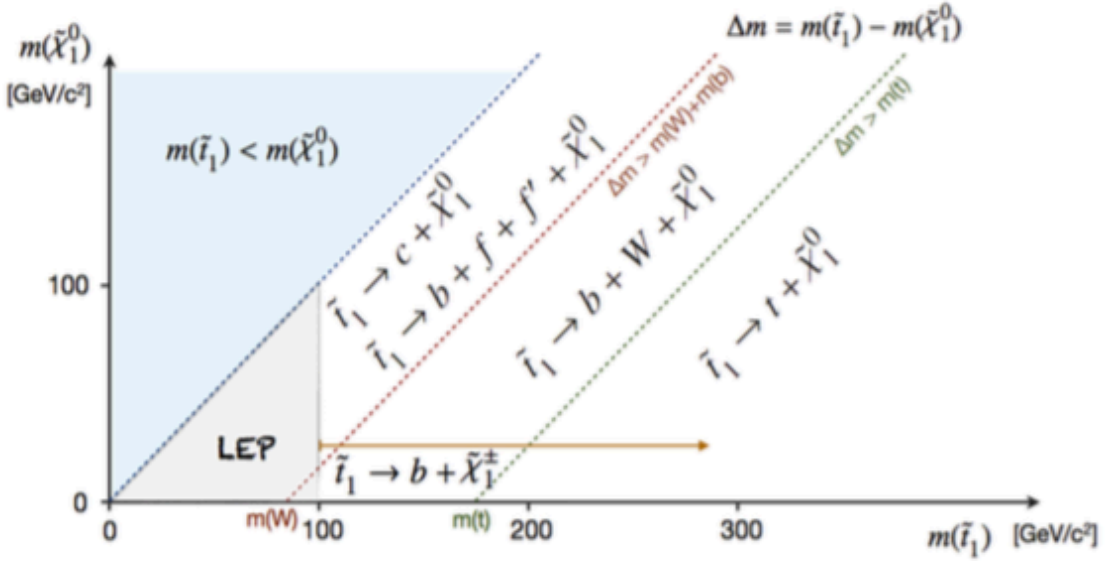


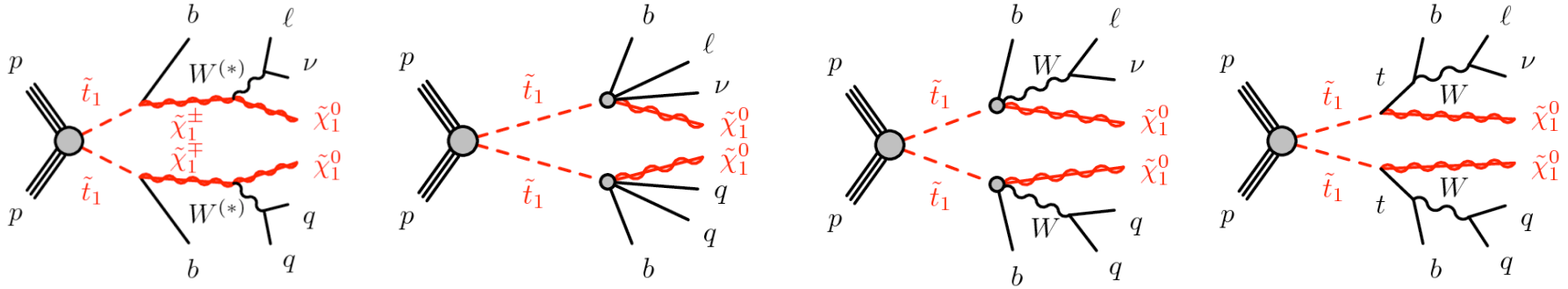


3rd Generation SUSY Quarks in ATLAS

Comprehensive set of 3rd generation searches in ATLAS:

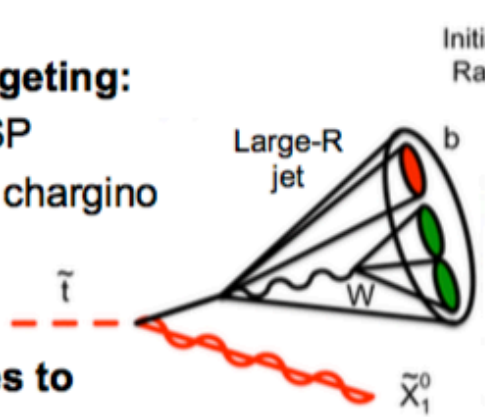
- Cover different production mechanisms & decays
- Target new regions of model phase space (compressed mass scenarios, boosted regime)
- Interpretation in terms of simplified models:
  - 100 % BR for a given decay
  - Mixed decay models

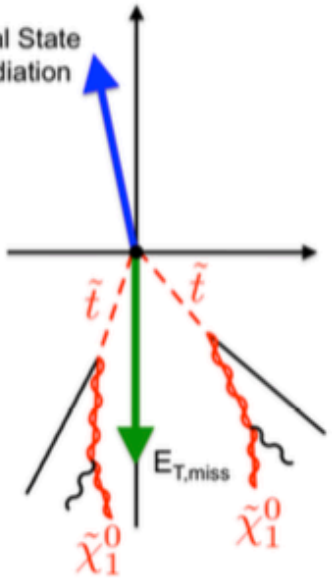




1-lepton Stop Searches

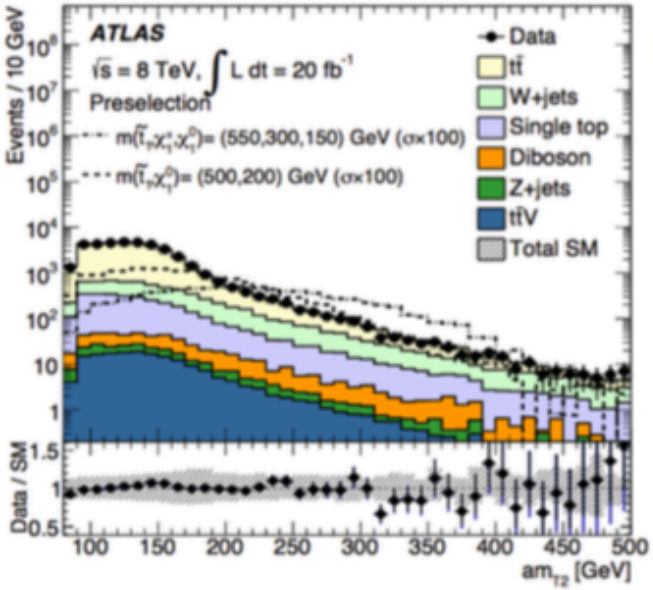
- **Versatile direct stop production search targeting:**
  - 2/3/4-body decay modes to neutralino-LSP
  - If chargino accessible: Stop → b quark + chargino decays





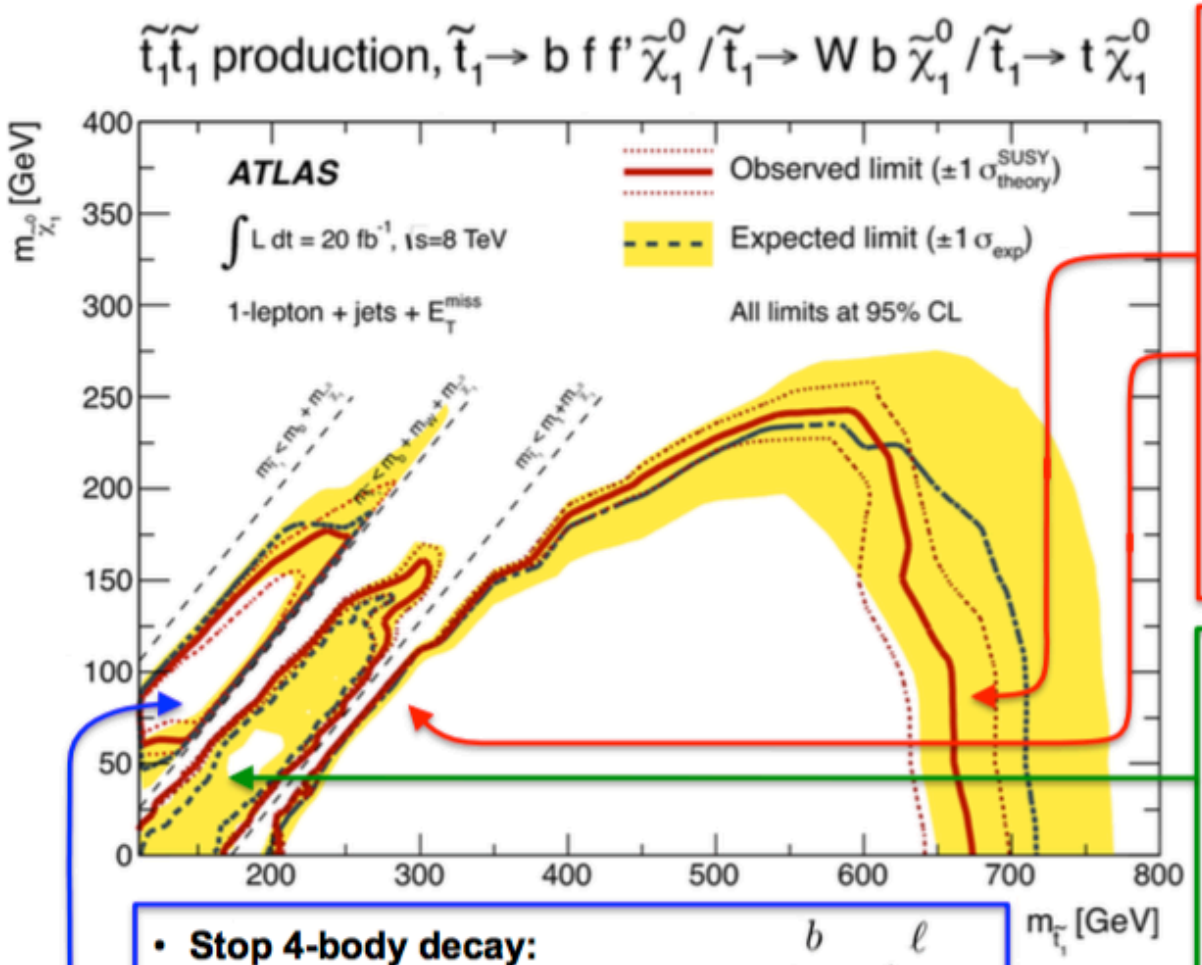
arXiv:1407.0583

- **Large spectrum of experimental techniques to maximally cover the model phase space:**
  - Large-R jets (enhance sensitivity in high-mass boosted regime)
  - Soft leptons & initial state radiation selections (enhance sensitivity in compressed mass regions)
  - Sophisticated discriminating variables (asymmetric m_{T2}, topness, hadronic top mass, …)
  - Hypothesis testing with shape fits

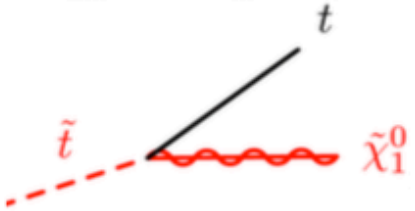


- **Dominant backgrounds:**
  - $t\bar{t}$, W+jets: Normalized in control regions and extrapolated to the signal regions

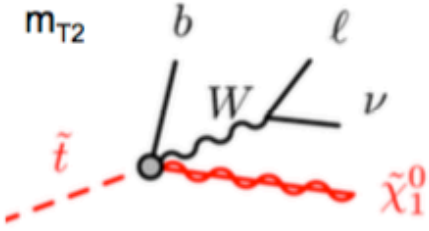
1-lepton Stop Searches: 2/3/4-body decays



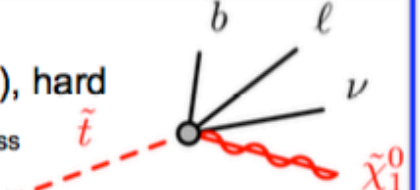
- **Stop → top + neutralino decay:**
  - 1 lepton, ≥ 4 jets, ≥ 1 b-jet, $E_{T,miss}$
  - Large-R jets (boosted regime)
  - Shape fit (diagonal),



- **Stop 3-body decay:**
  - 1 lepton, ≥ 4 jets, ≥ 1 b-jet, $E_{T,miss}$
  - Softer thresholds
  - 2-D shape fit in m_T and m_{T2}



- **Stop 4-body decay:**
  - 1 soft lepton (6/7 GeV), hard ISR jet, ≥ 1 b-jet, $E_{T,miss}$
  - Shape fit in lepton p_T



arXiv:1407.0583

Vector-Like Quarks (VLQs)

- What are vector-like quarks (VLQ)?
  - ψ_L and ψ_R transform in the same way under $SU(2)\times U(1)$
  - What does it practically mean? Chiral vs vector-like quarks?

Fermionic field:

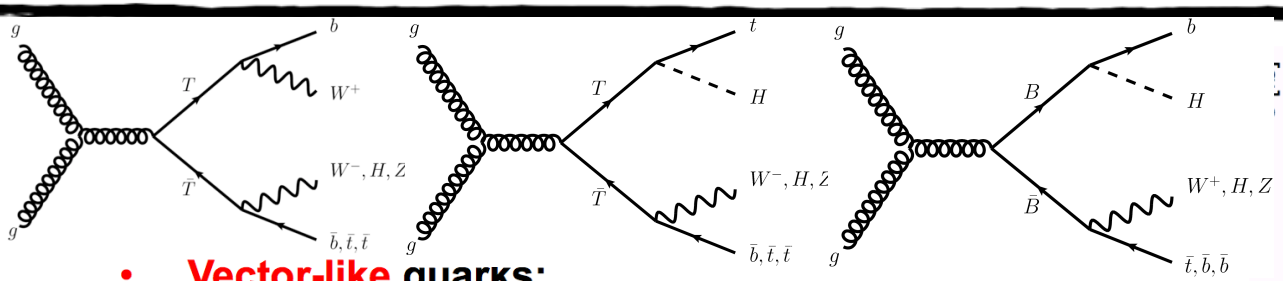
$$\psi = \begin{pmatrix} u \\ d \end{pmatrix} = \underbrace{\frac{1}{2}(1-\gamma^5)\psi}_{\psi_L} + \underbrace{\frac{1}{2}(1+\gamma^5)\psi}_{\psi_R}$$

Charged electro-weak current:

$$J^{\mu+} = J_L^{\mu+} + J_R^{\mu+} = \bar{u}_L\gamma^\mu d_L + \bar{u}_R\gamma^\mu d_R$$

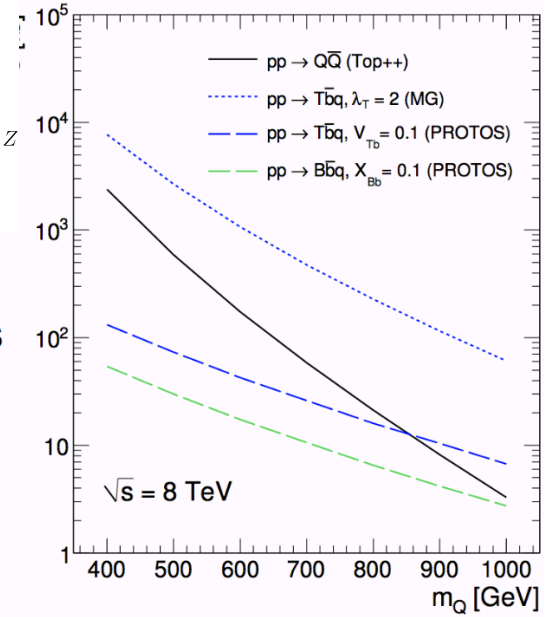
$$= \begin{cases} \bar{u}\gamma^\mu(1-\gamma^5)d + 0 & = \text{V - A} \quad \text{chiral quarks} \\ \bar{u}\gamma^\mu d & = \text{V} \quad \text{Vector-like quarks} \end{cases}$$

Vector-like Quarks (VLQs)

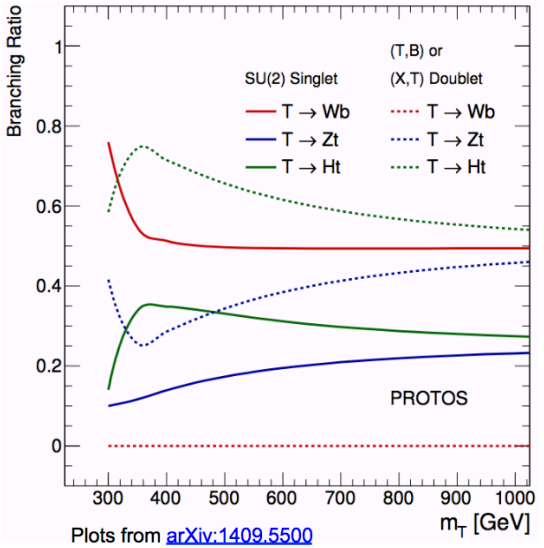


- **Vector-like quarks:**
  - Left- and right-handed components transform identically under electroweak symmetry transformations

    Singlets: $T_{L,R}$ $B_{L,R}$ *Doublets:* $\begin{pmatrix} X \\ T \end{pmatrix}_{L,R}$ $\begin{pmatrix} B \\ Y \end{pmatrix}_{L,R}$ $\begin{pmatrix} T \\ B \end{pmatrix}_{L,R}$
- **Pair production (strong interaction):**
  - Dominant in the sub-TeV range
  - Scales with heavy quark mass
- **Single production (electroweak interaction):**
  - Dominant at larger masses
  - Scales with heavy quark mass and couplings (model-dependent)
- **Decay:**
  - W/H/Z + SM quark
  - Preferential mixing with 3rd generation quarks assumed
  - Branching ratios (BRs) model-dependent



Production Cross-sections



T-quark Decay BRs

Plots from arXiv:1409.5500

VLQ Searches in ATLAS

arXiv:1409.5500

Common pre-selection:

- 2 leptons from Z decay
- ≥ 2 central jets
- p_T (Z) > 150 GeV

Di-lepton channel:

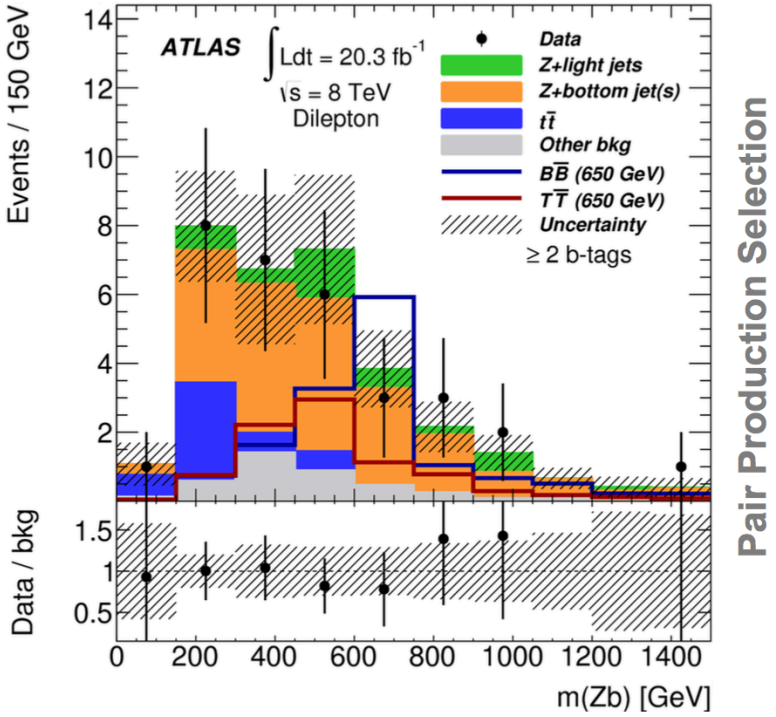
- == 2 leptons, ≥ 2 b-jets
- Single production: ≥ 1 forward jet
- Pair production: H_T (jets) ≥ 600 GeV

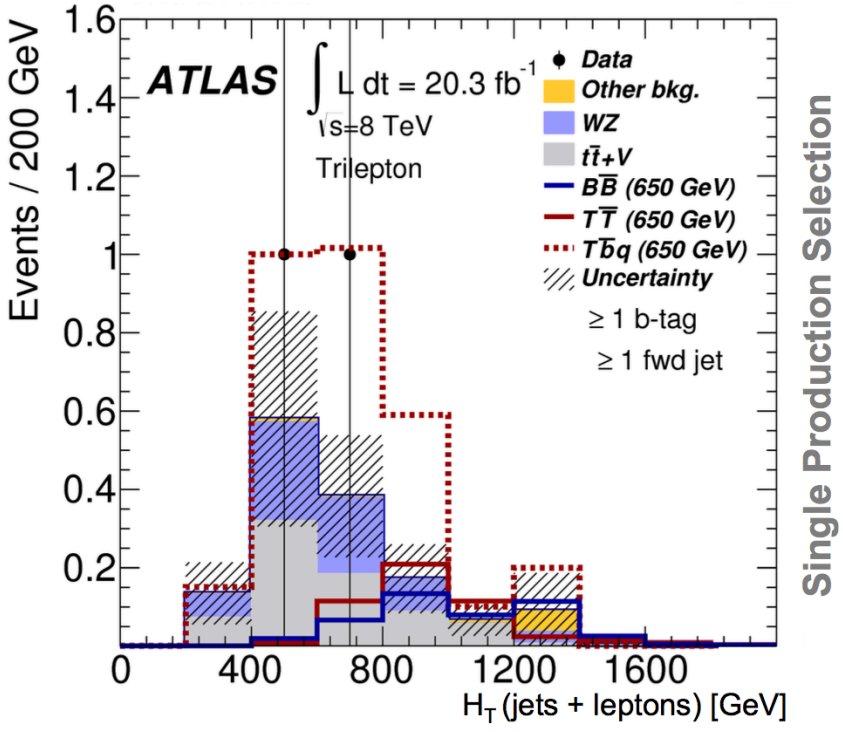
→ Final discriminant: m (Zb)

Tri-lepton channel:

- ≥ 3 leptons, ≥ 1 b-jets
- Single production: ≥ 1 forward jet
- Pair production: -

→ Final discriminant: H_T (jets + leptons)



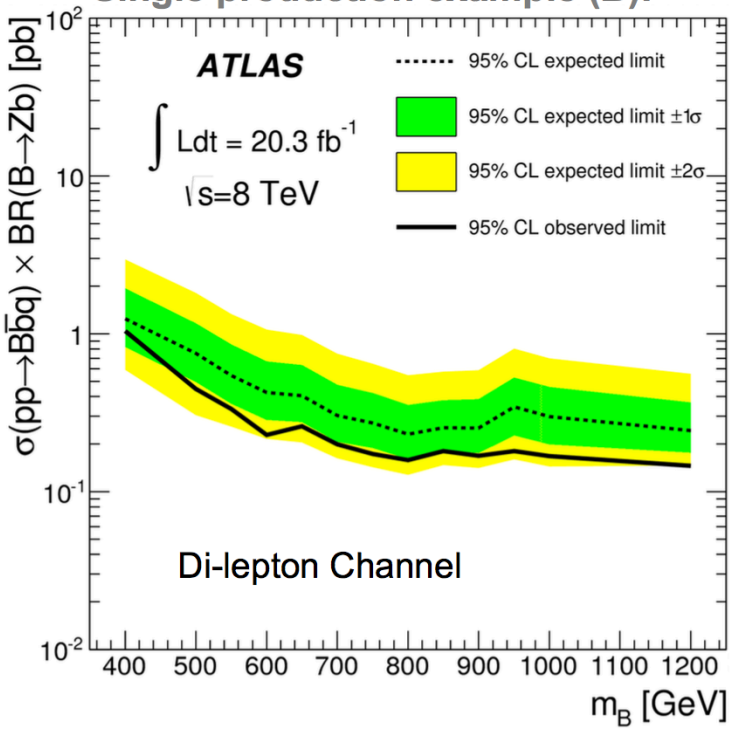


VLQ Results

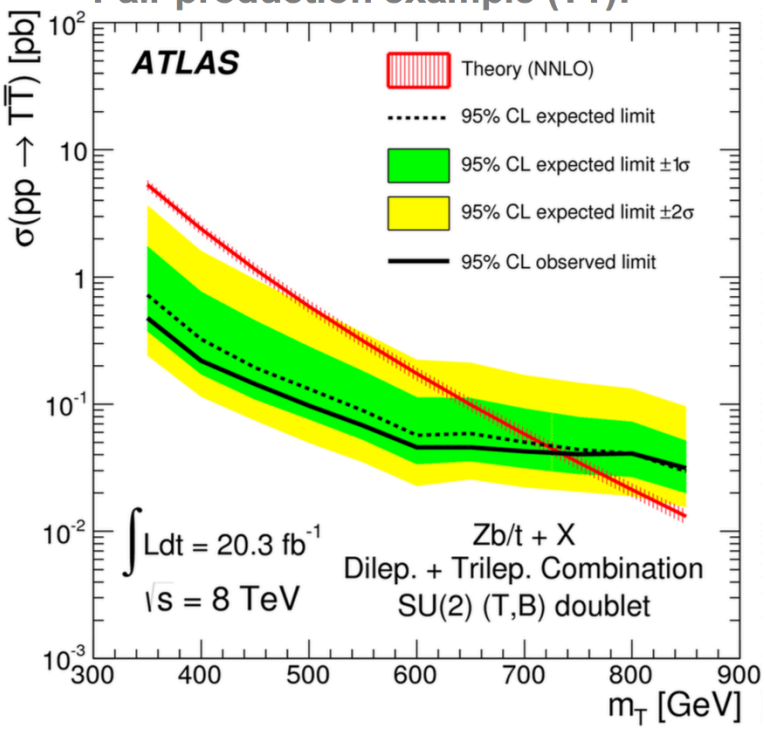
arXiv:1409.5500

- Data found to be consistent with SM expectation: Limits are derived for single / pair production VLQ models

Single production example (B):



Pair production example (TT):

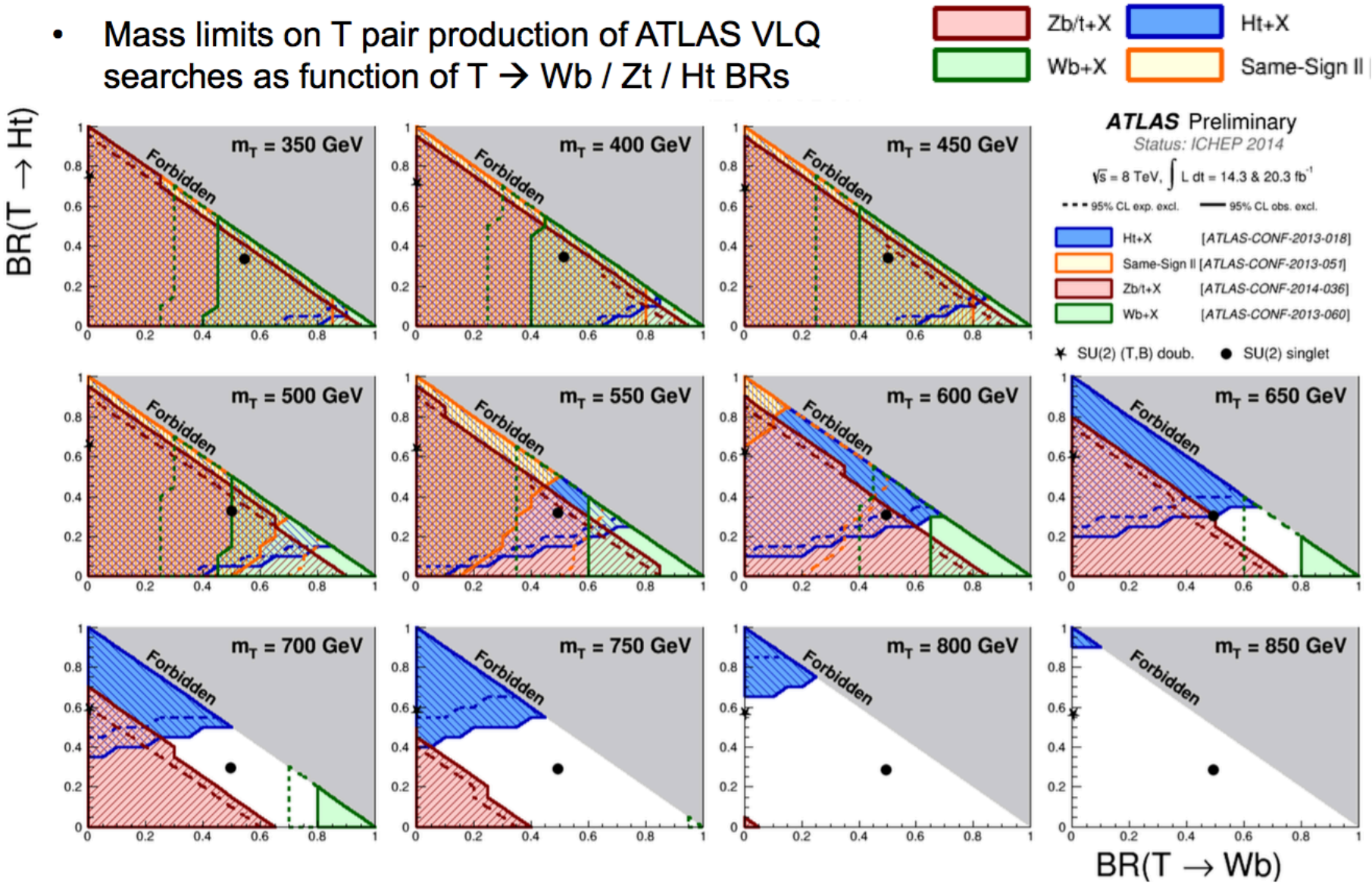


Mass limits for TT, BB pair production:

	Singlet mass limit [GeV]			Doublet mass limit [GeV]		
Hypothesis	Dilepton	Trilepton	Comb.	Dilepton	Trilepton	Comb.
$B\bar{B}$	690 (665)	610 (610)	685 (670)	765 (750)	540 (530)	755 (755)
$T\bar{T}$	620 (585)	620 (620)	655 (625)	705 (665)	700 (700)	735 (720)

Summary of Vector-like T Searches

- Mass limits on T pair production of ATLAS VLQ searches as function of T → Wb / Zt / Ht BRs



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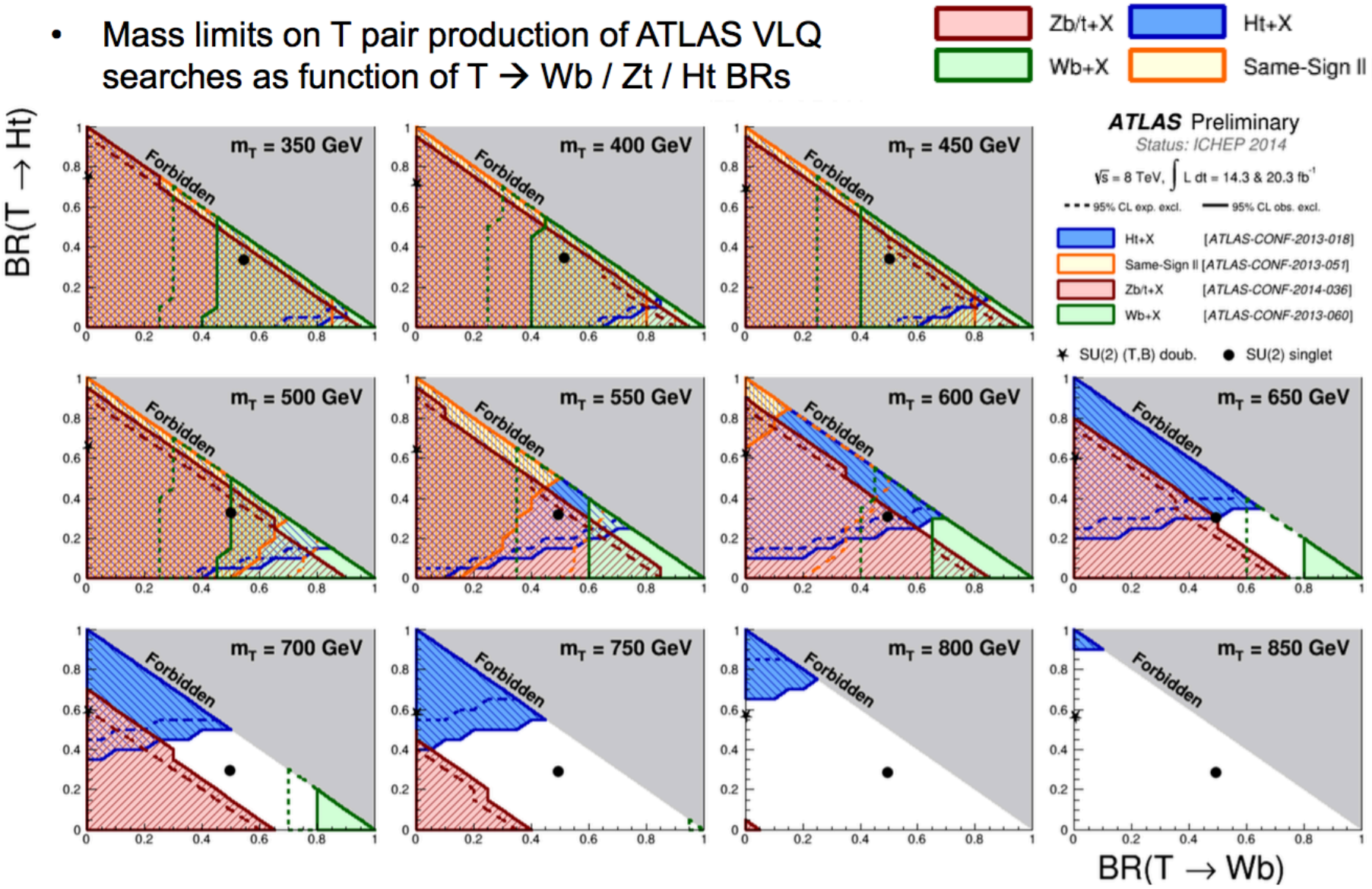
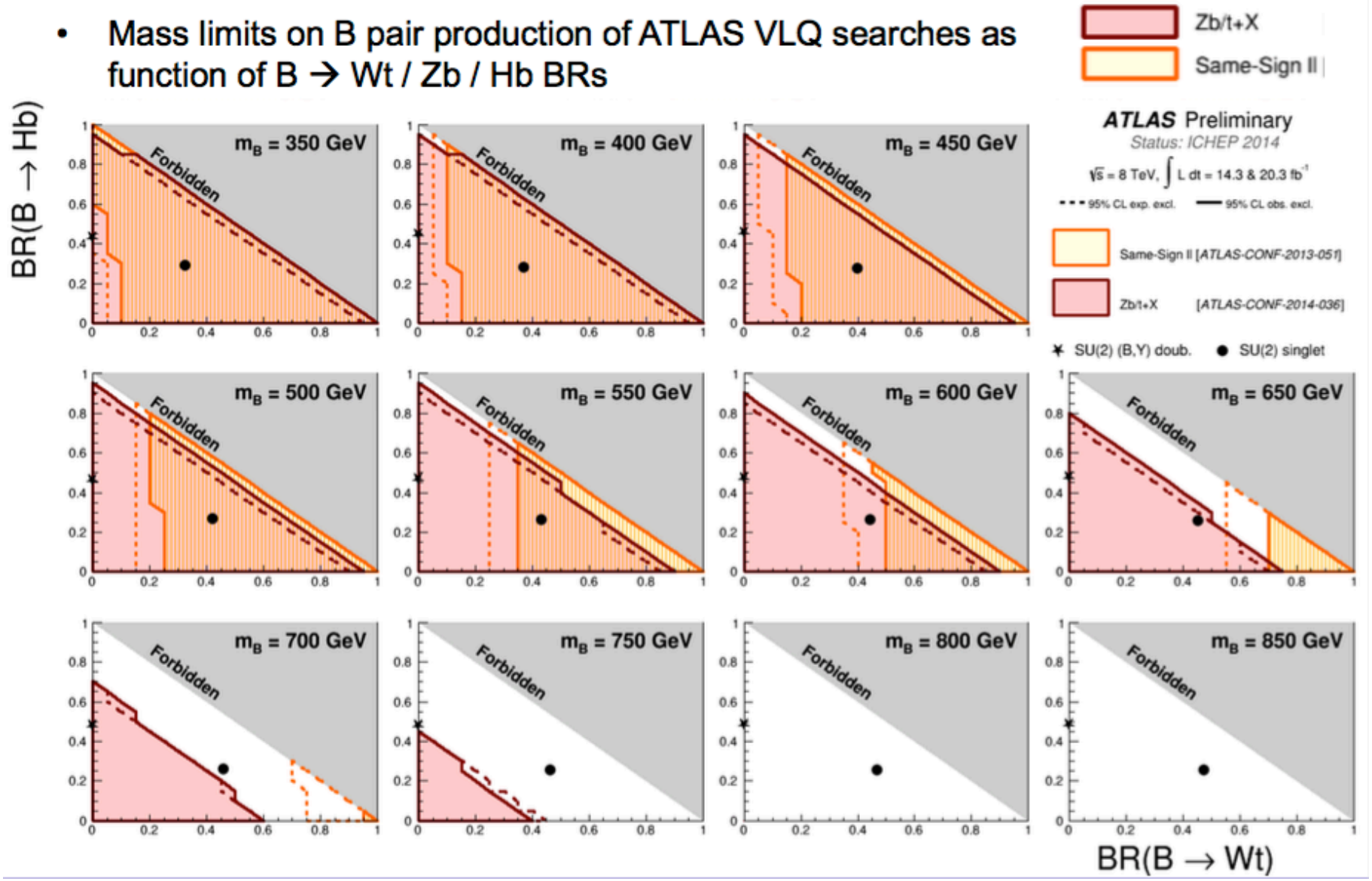


Summary of Vector-like T Searches

- Mass limits on B pair production of ATLAS VLQ searches as function of B → Wt / Zb / Hb BRs



Conclusion

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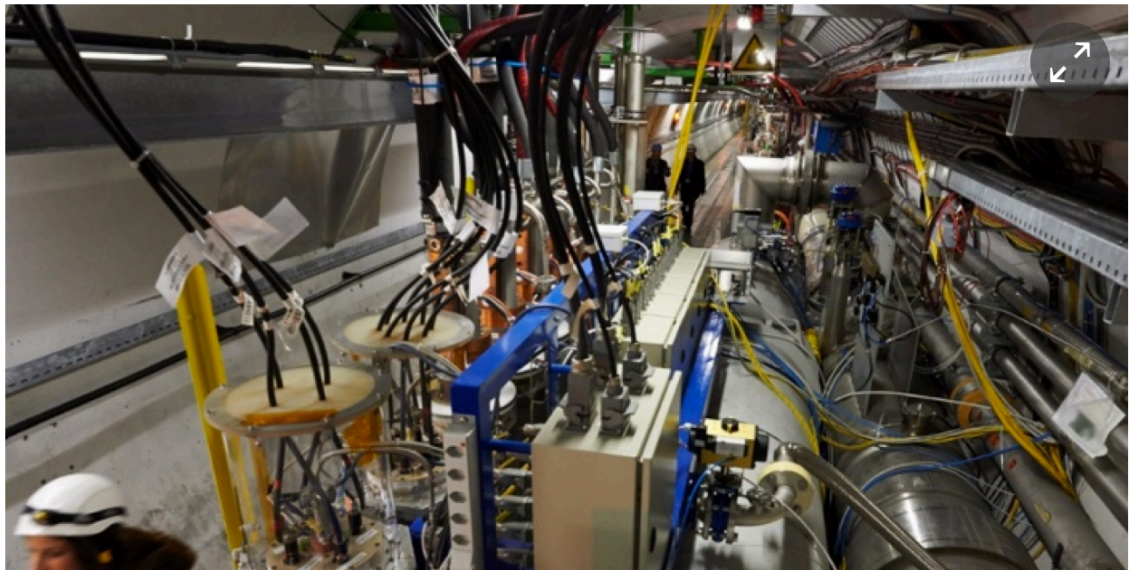
Cern restarts Large Hadron Collider with mission to make scientific history

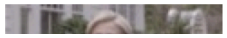
Physicists hope particle accelerator will explain dark matter, gravity and antimatter as it completes its test run following an upgrade



Most popular

Manchester United 4-2 Manchester City: five talking points

UK one of world's least religious countries, survey finds



Hillary Clinton: I'm

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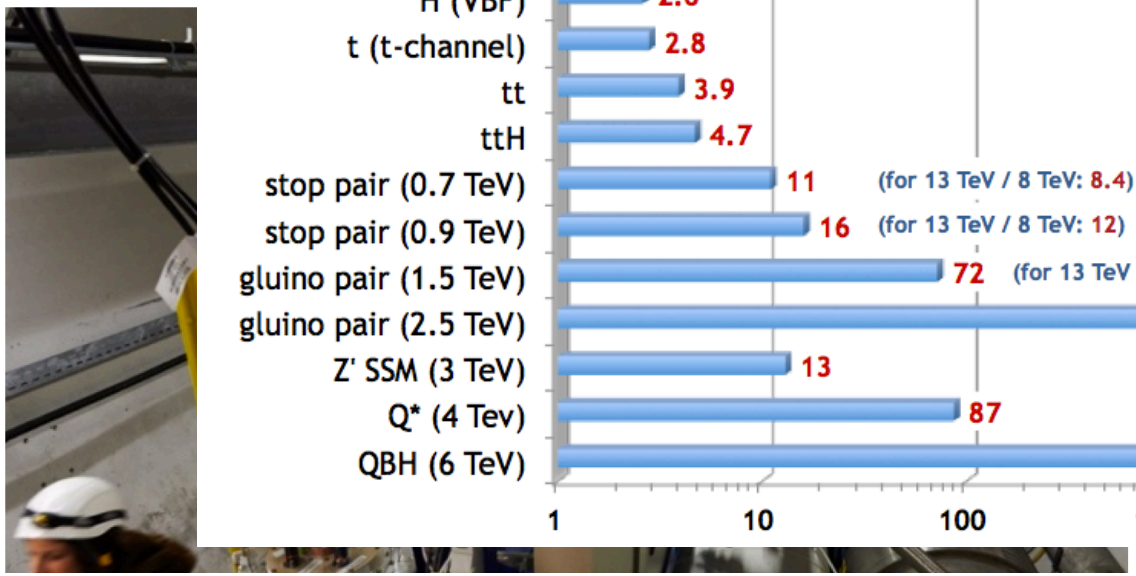

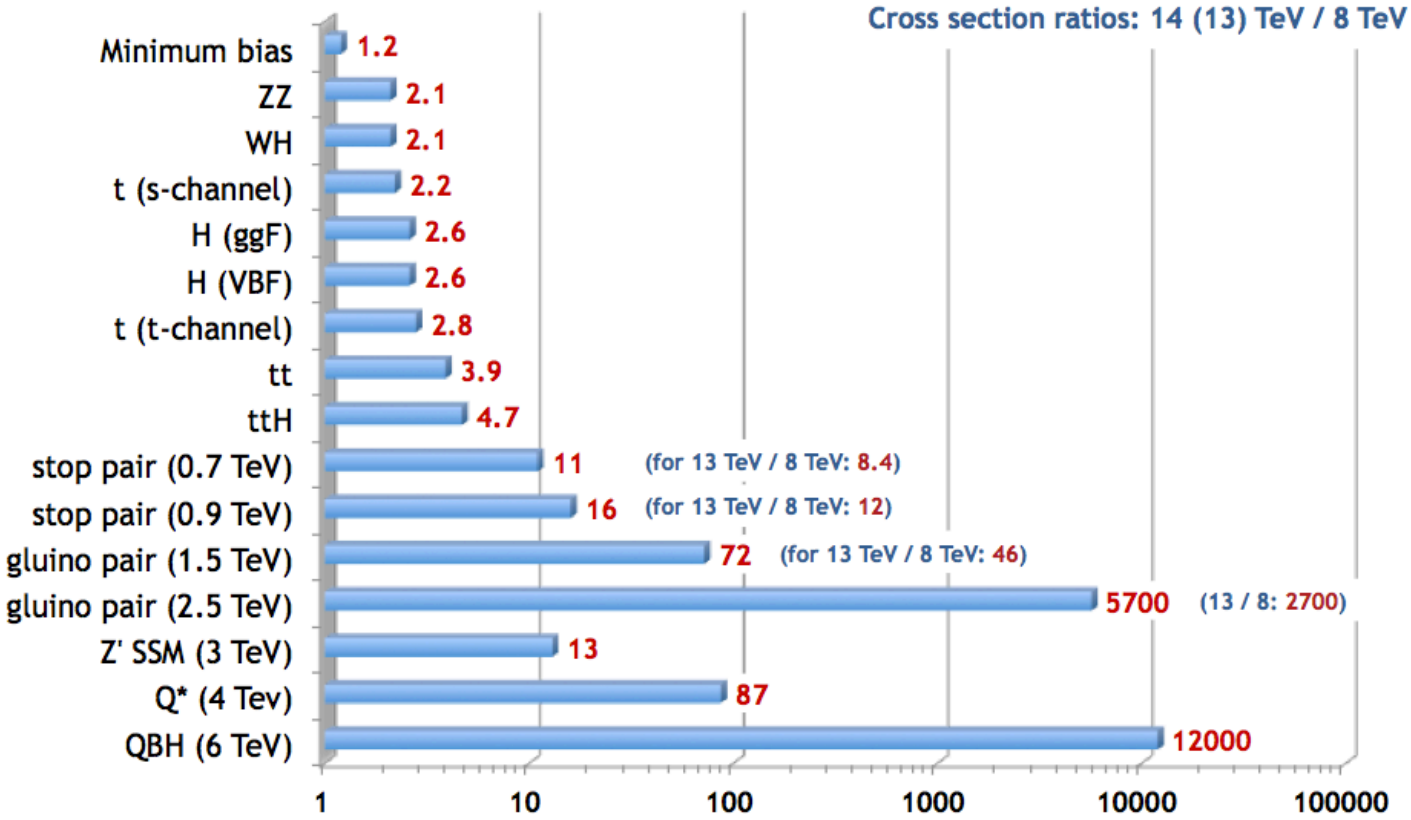

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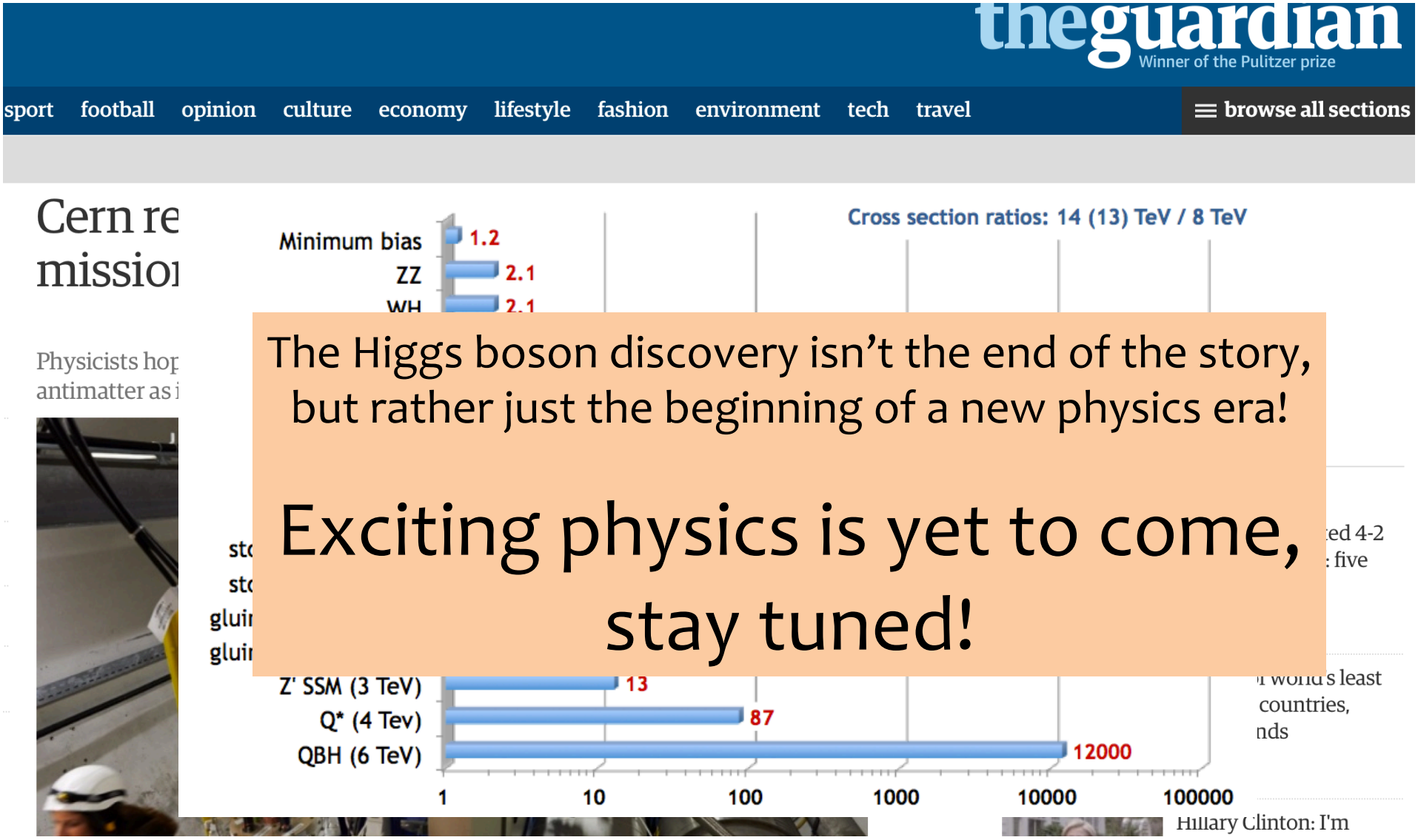


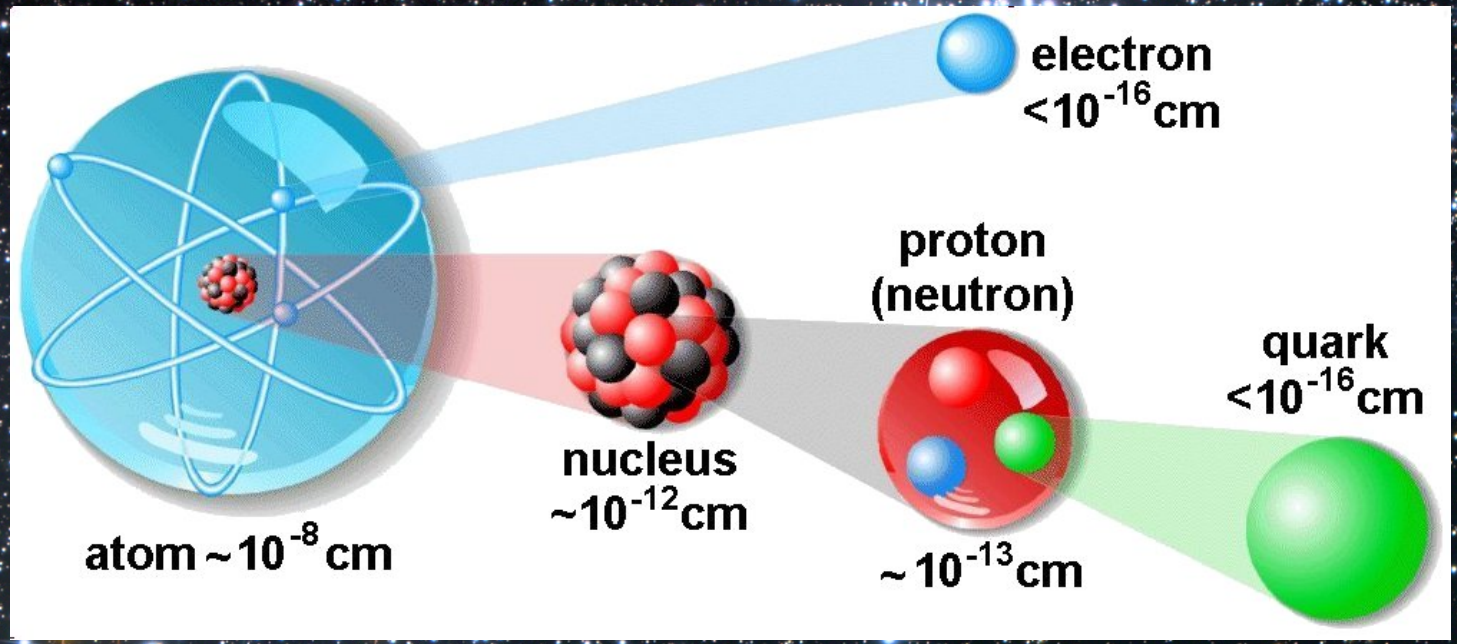
The Higgs boson discovery isn't the end of the story, but rather just the beginning of a new physics era!

Exciting physics is yet to come, stay tuned!

Backup

Composition of the Universe

Composition of the Universe



Standard Model of Particle Physics

- SM: relativistic quantum field theory in Lagrangian formalism

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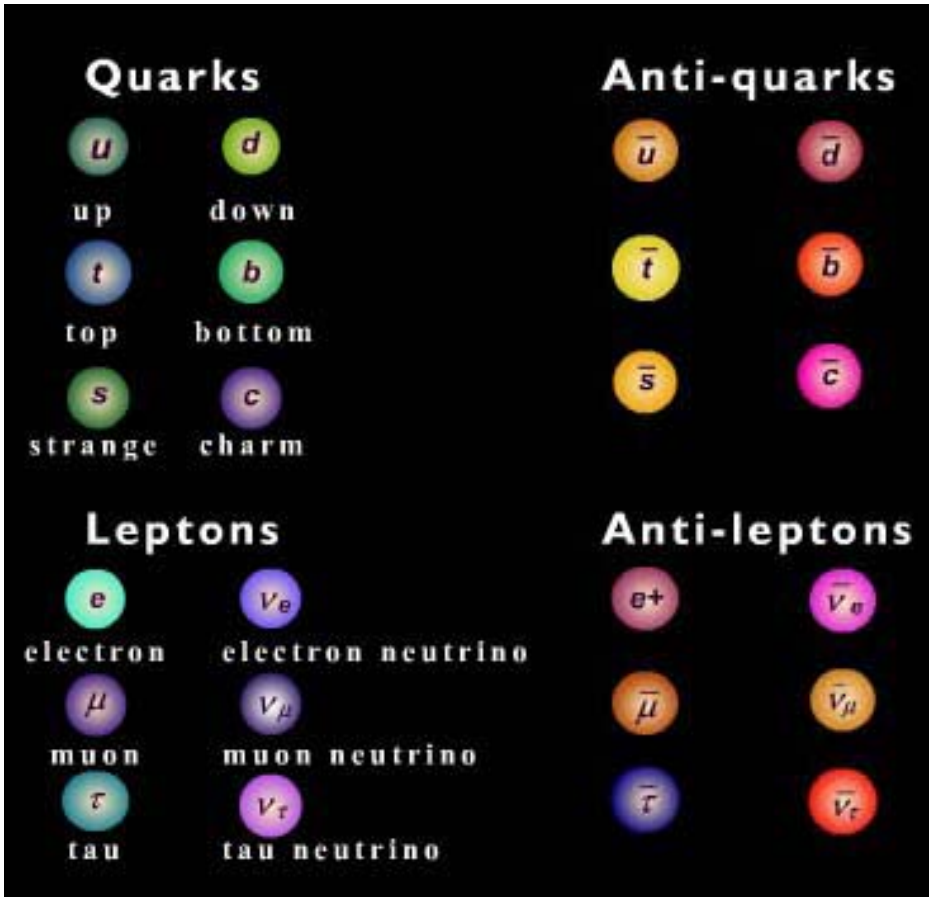
- Matter Particles: relat. quantum fields
  - spin-½ fermions

$$\mathcal{L} = \bar{\psi} i \gamma^\mu \partial_\mu \psi - m \bar{\psi} \psi$$



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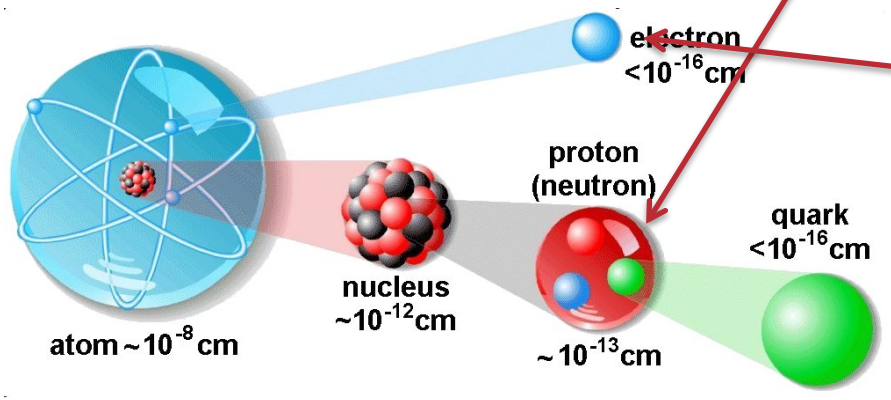

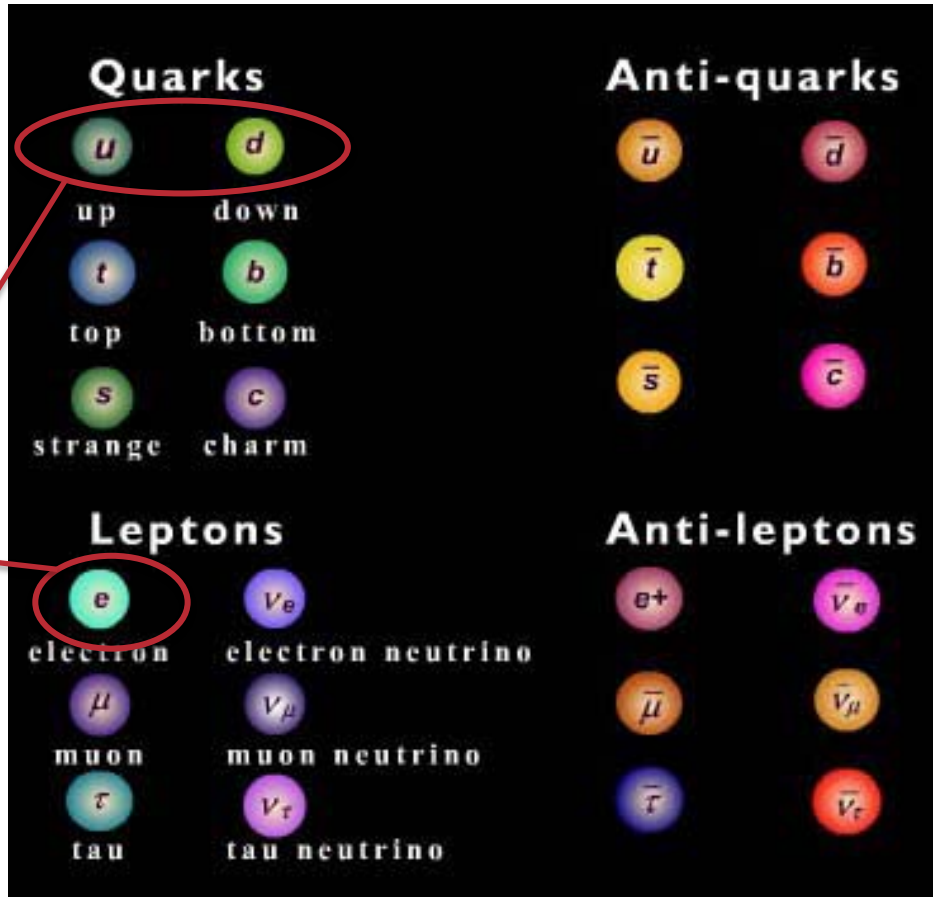

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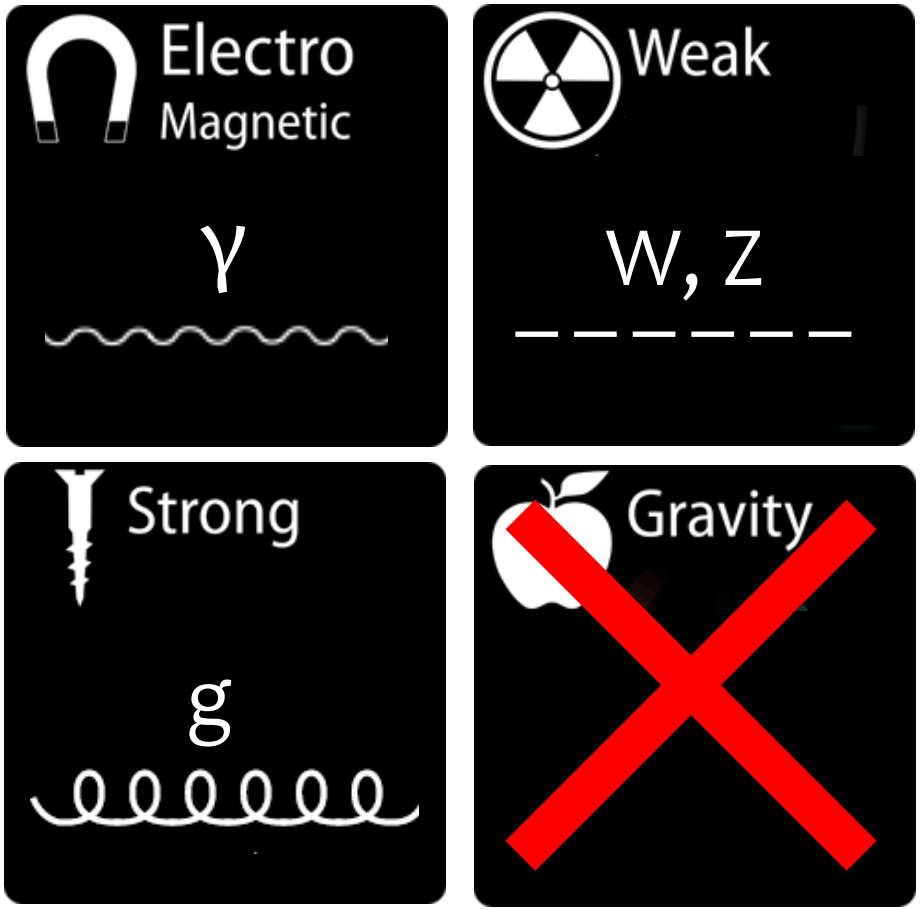

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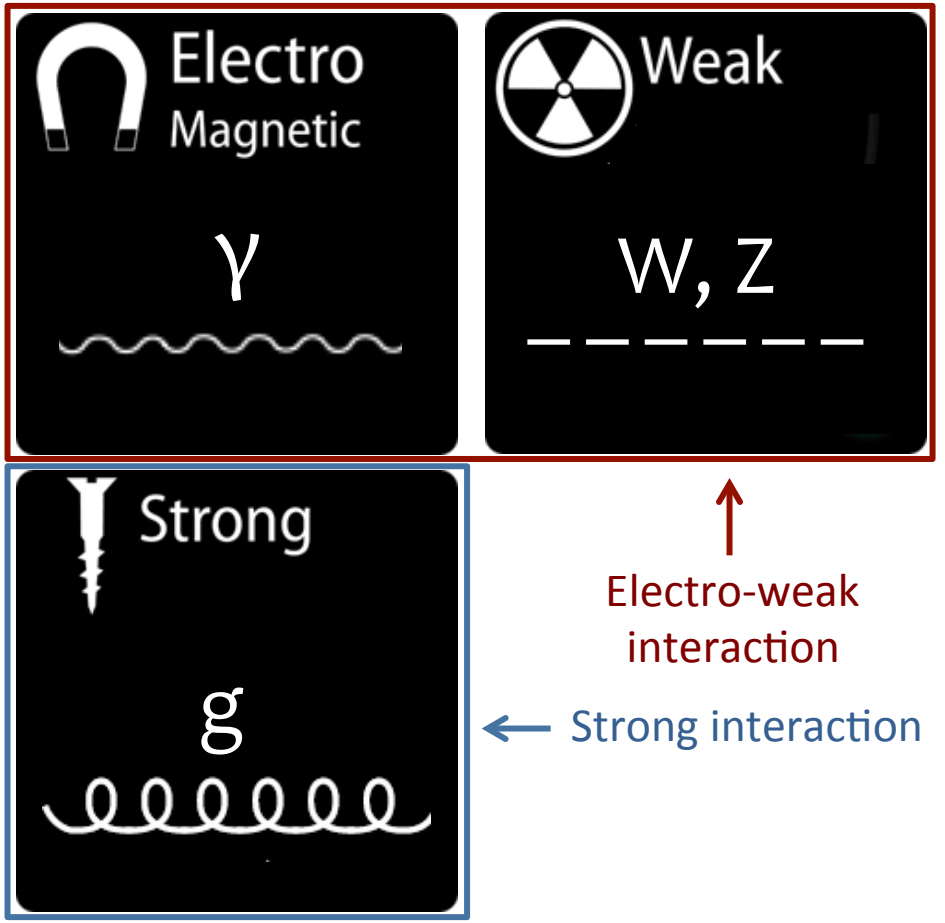
Noether theoreme:

Every symmetry of a physical system comes with an associated conserved quantity (and vice versa)



$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

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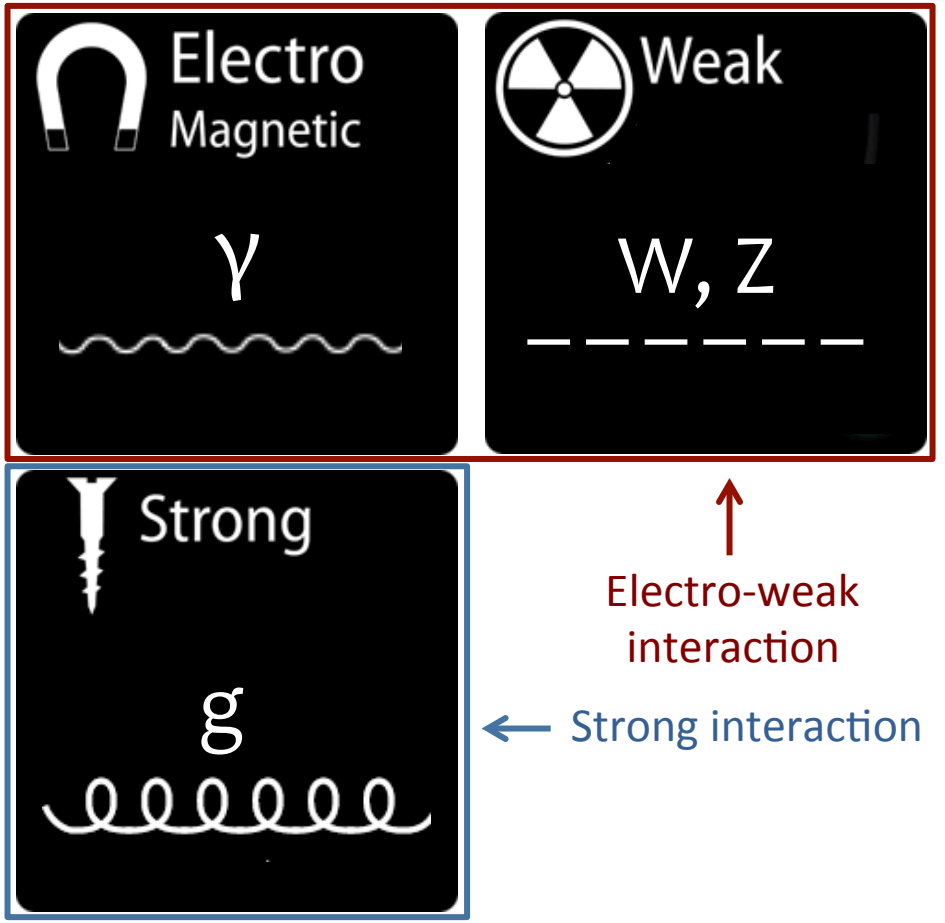
$$\mathcal{L} = \bar{\psi}\left(i\gamma^\mu \partial_\mu - m\right)\psi + g\bar{\psi}\gamma^\mu A^a_\mu \psi - \frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu}$$



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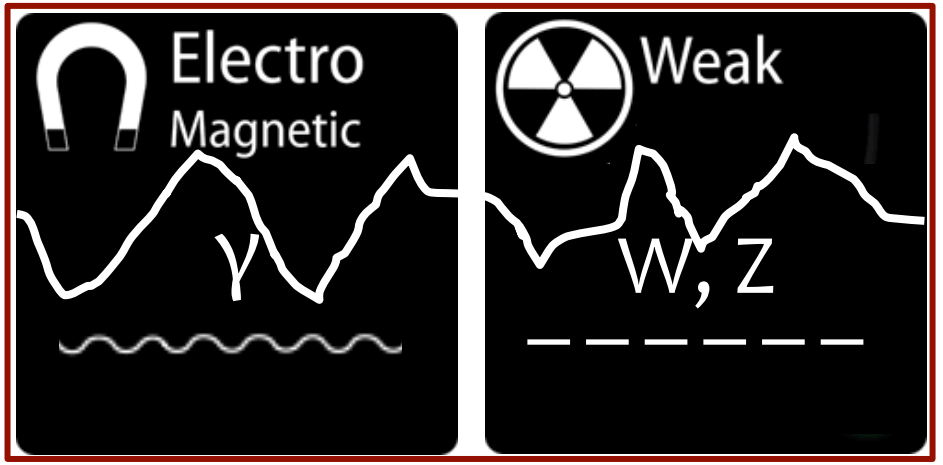

$$SU(2)_L \times U(1)_Y \longrightarrow U(1)_{em}$$

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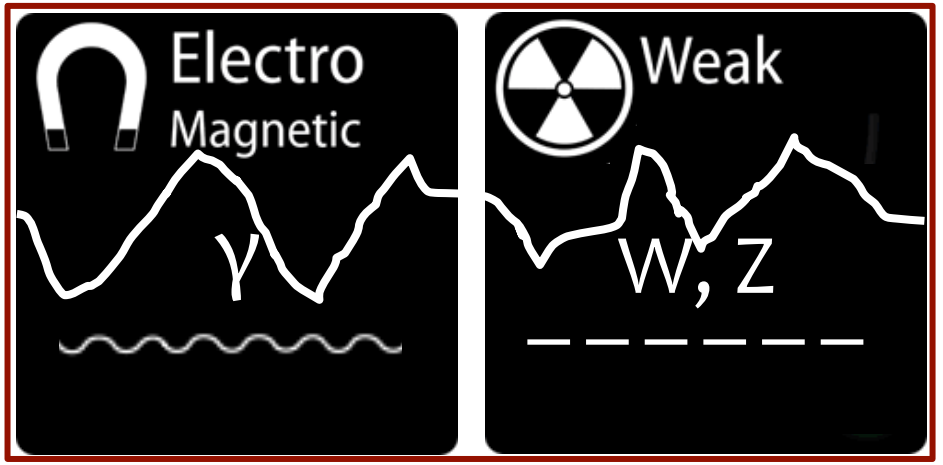

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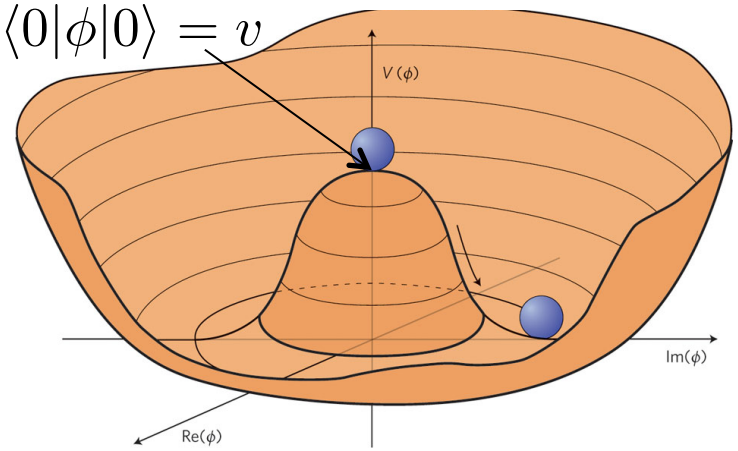

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2$$

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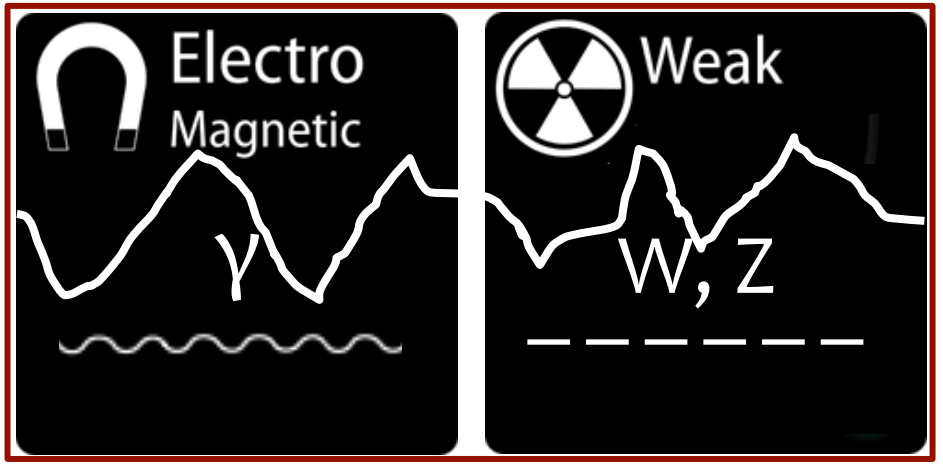

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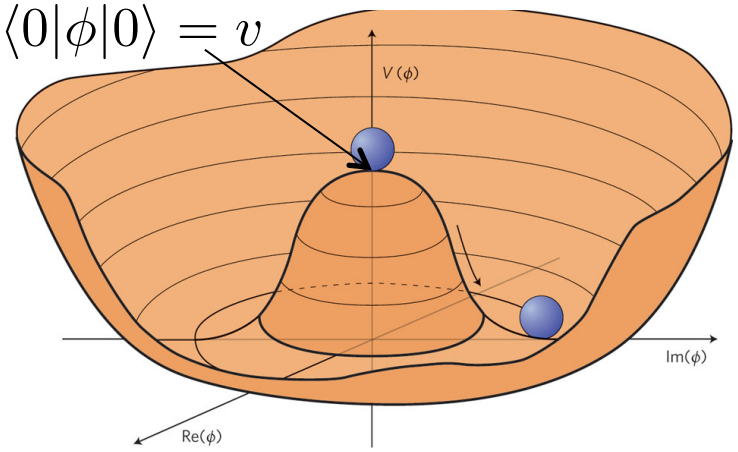

$$m_W = \frac{gv}{2},\ m_\psi = y_\psi v/\sqrt{2}$$

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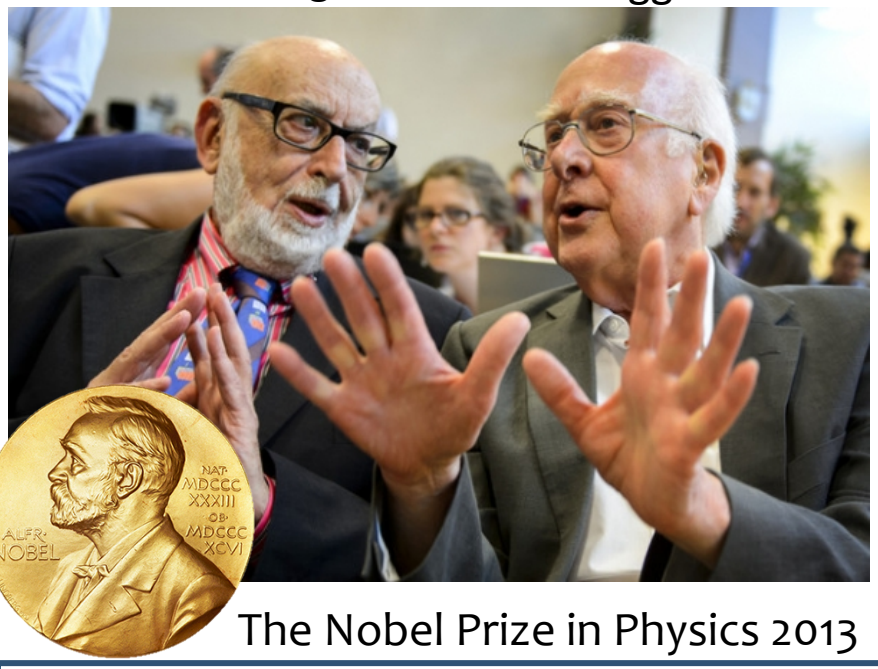
  - "Sombrero"-shaped potential with a non-zero vacuum expectation value v
  - Interaction with this field generates masses of all massive particles
  - Manifestation of the Higgs field is the spin-0 Higgs boson. A candidate of the Higgs boson has been discovered at CERN in 2012

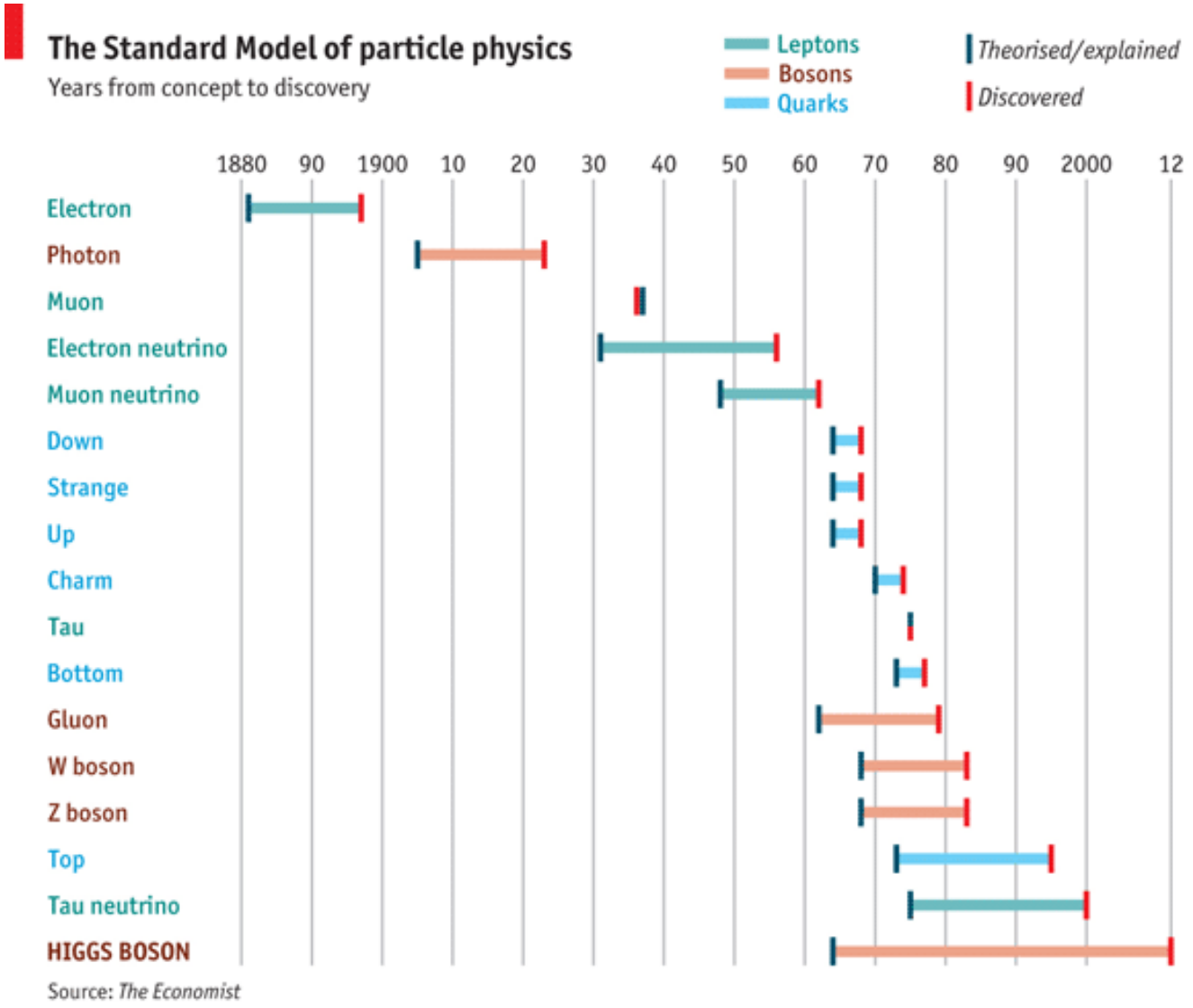
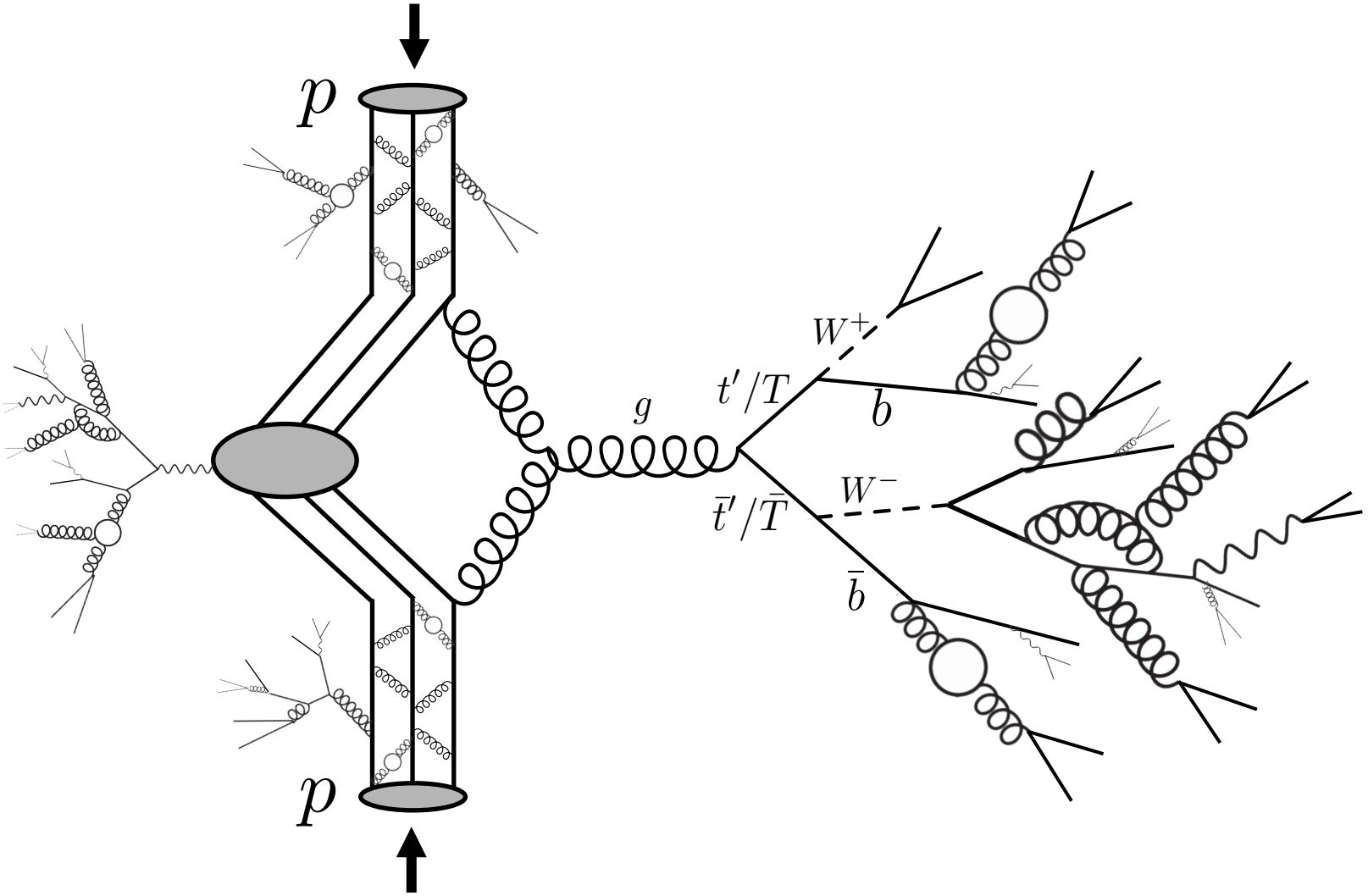
F. Englert P. Higgs



The Nobel Prize in Physics 2013

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Standard Model through Decades



Final States