# Testing the Standard Model of Elementary Particle Physics II

## 8th lecture

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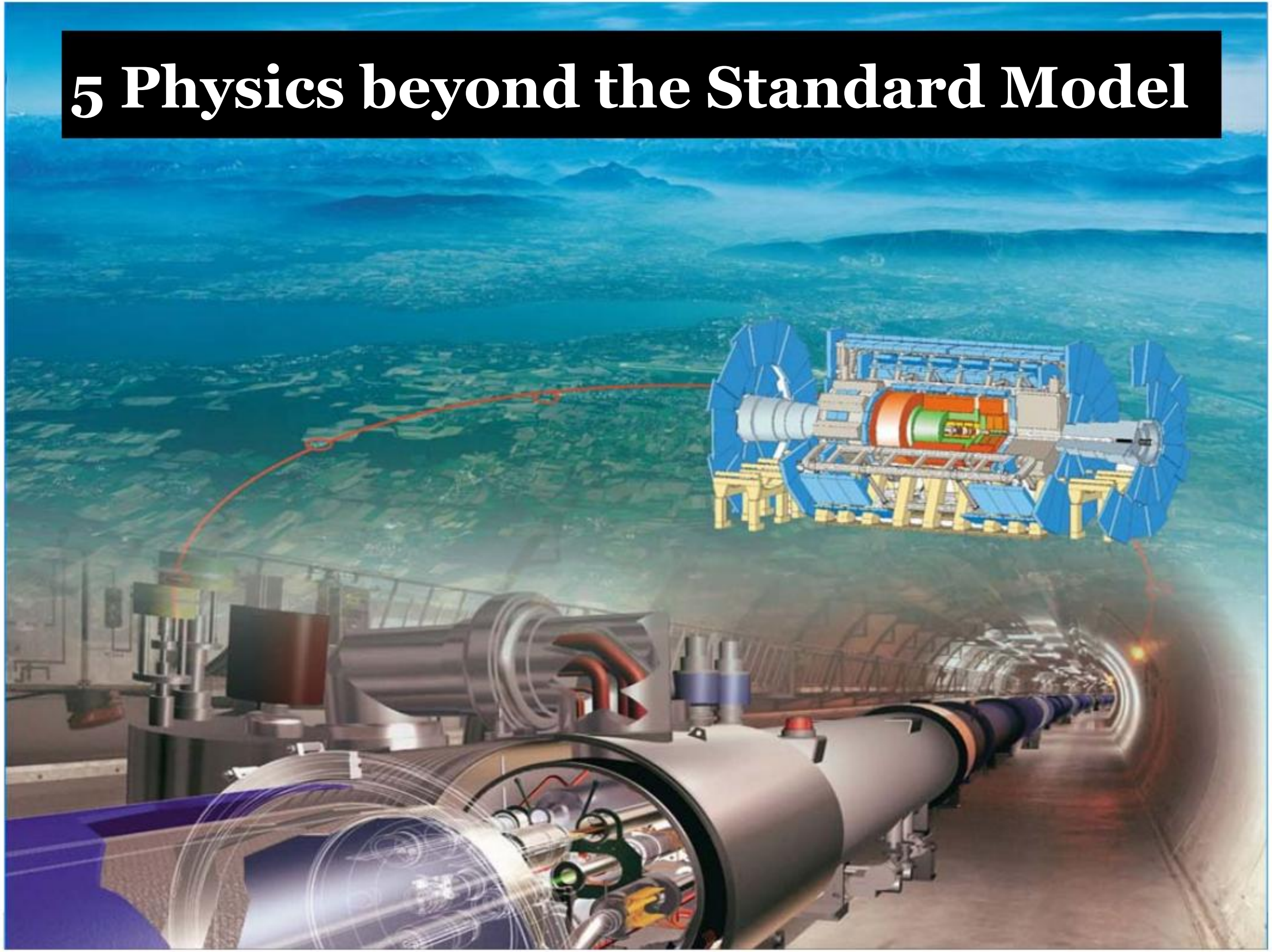
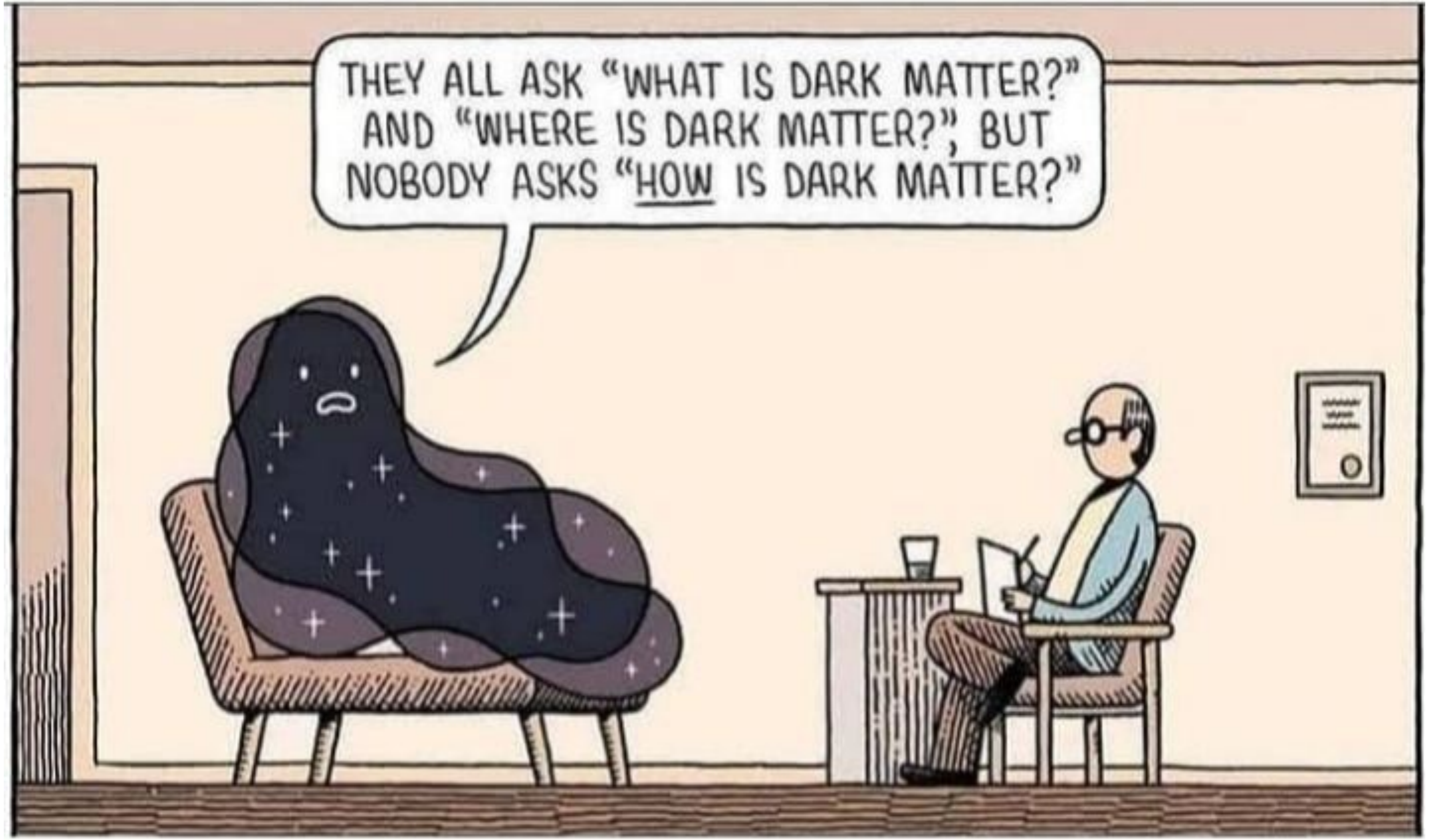
15th Juli 2021

# 5 Physics beyond the Standard Model




THEY ALL ASK "WHAT IS DARK MATTER?" AND "WHERE IS DARK MATTER?", BUT NOBODY ASKS "HOW IS DARK MATTER?"

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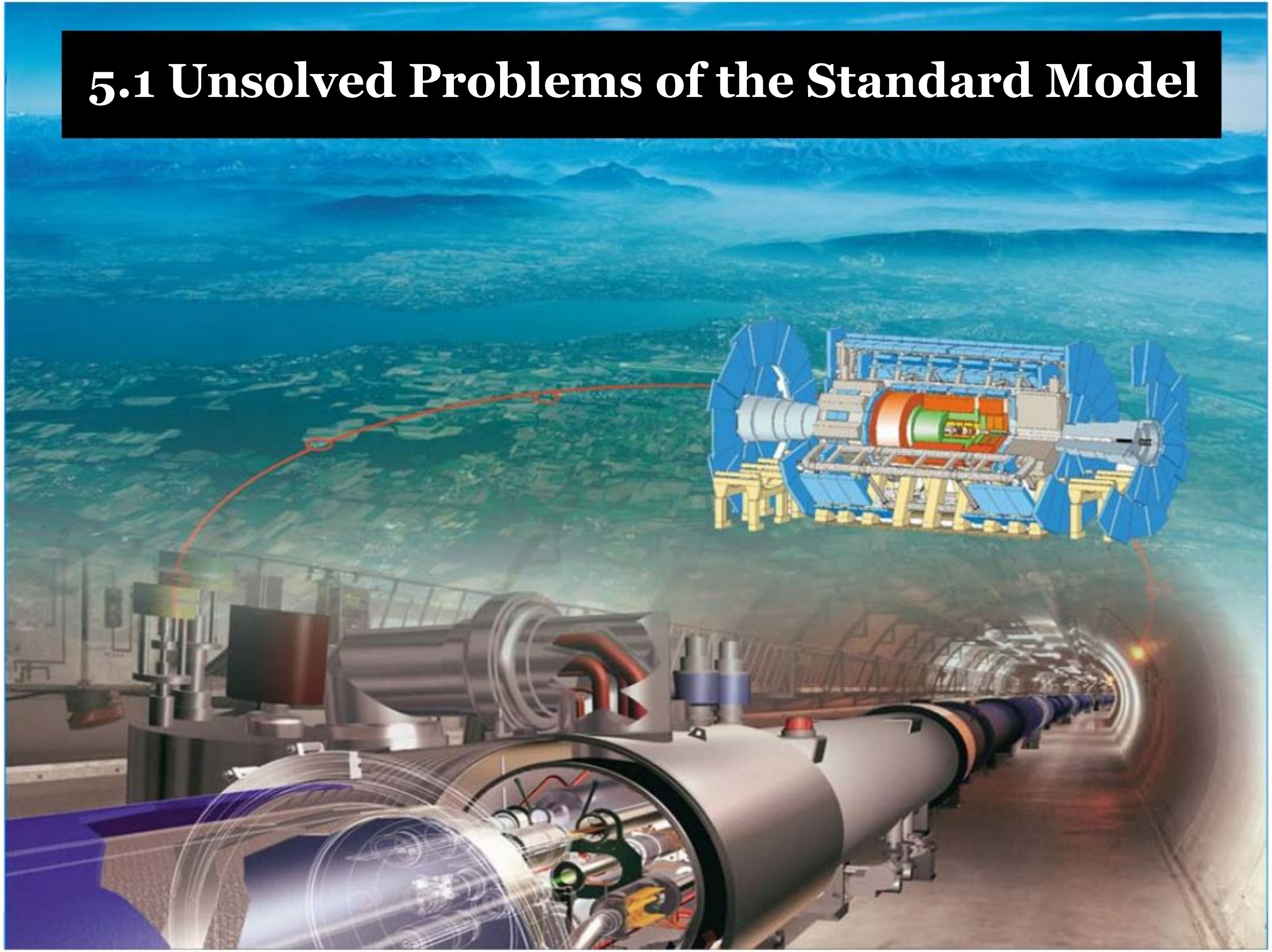
- Newest results on searches and measurements can be found:
  - For ATLAS: here
  - For CMS: here

# 5.1 Unsolved Problems of the Standard Model



# Unsolved Problems of the Standard Model

1. The naturalness problem

2. The origin of EW and QCD energy scales

3. Why are there only 3 generation of quarks and leptons ?

4. Quantization of electric charge
   - $Q_e = -Q_p$ measured with a precision of $10^{-21}$
   - Why is $Q_d = \frac{1}{3} Q_e$ and $Q_\nu + Q_e + 3Q_u + 3Q_d = 0$ ?

   → **Unification of gauge couplings: GUTs**

5. Why are the neutrino masses so small ?

   → **Unification of gauge couplings: GUTs**

# Unsolved Problems of the Standard Model

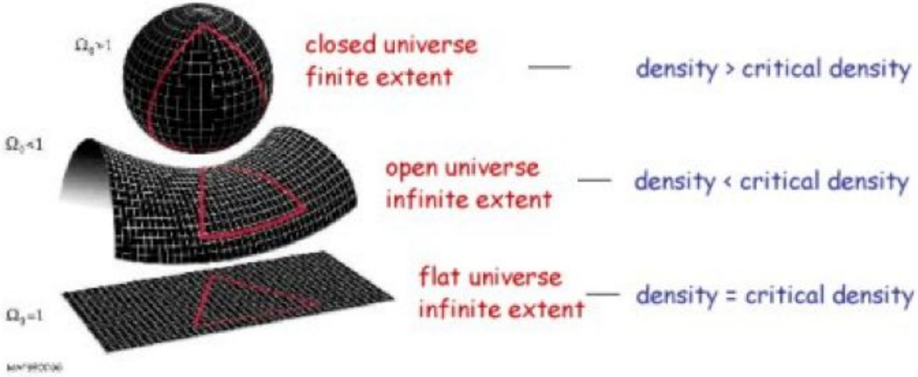
6. **Source of CP violation (responsible for the excess of matter over anti-matter in the universe)**
   - **absence of strong CP violation in the QCD sector ?**
7. **Is the Higgs boson an elementary particle ?**
   - Mechanism to dynamically break the electroweak gauge symmetry
     - Introduce substructure of the Higgs boson and a new strong interaction (analogous to cooper pairs, “Higgs field”, in superconductor)
8. **Why is the measured value of the muon's anomalous magnetic dipole moment ("muon g−2") significantly different from the theoretically predicted value ?**
9. **Recently emerging indications of lepton flavour universality violations**
10. **Origin of dark matter and dark energy**
11. **Common quantum field theory including gravity**

   → **String theories**

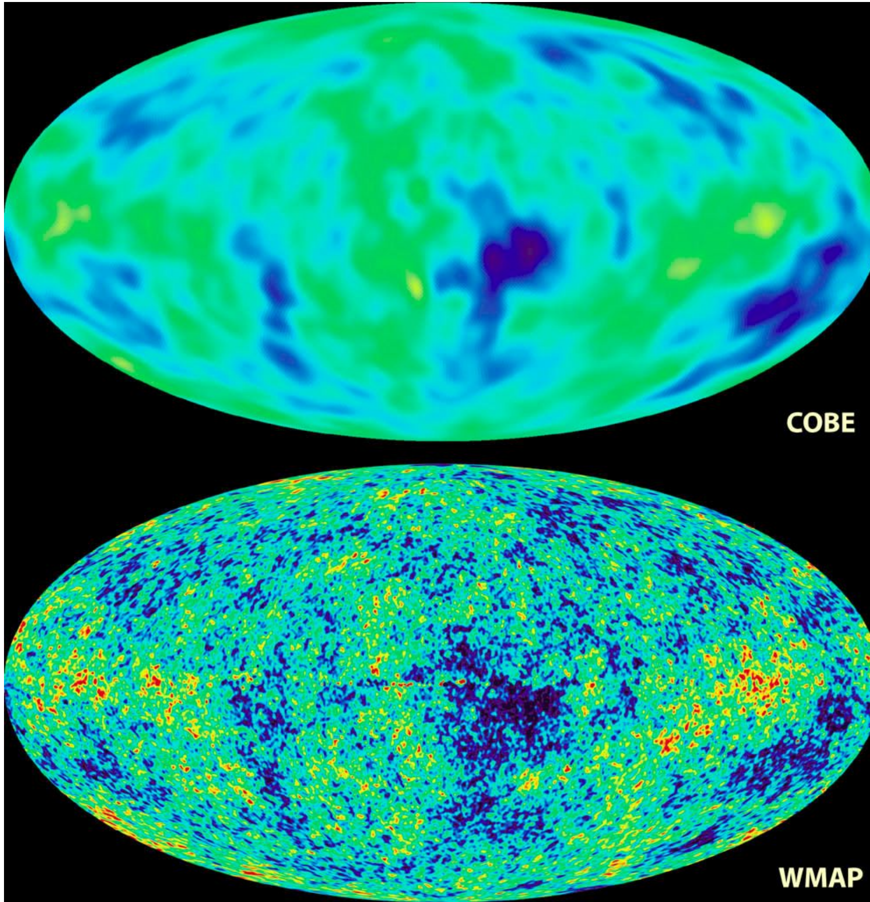
# Content of the universe

$\Omega$ = energy density / critical density

- **Isotropy of cosmic microwave background**
  - Measured by COBE, WMAP, satellites)
    $\Rightarrow$ inflation of early universe (phase of exponential expansion) $\Rightarrow \Omega_{total} = 1$
    - flat universe



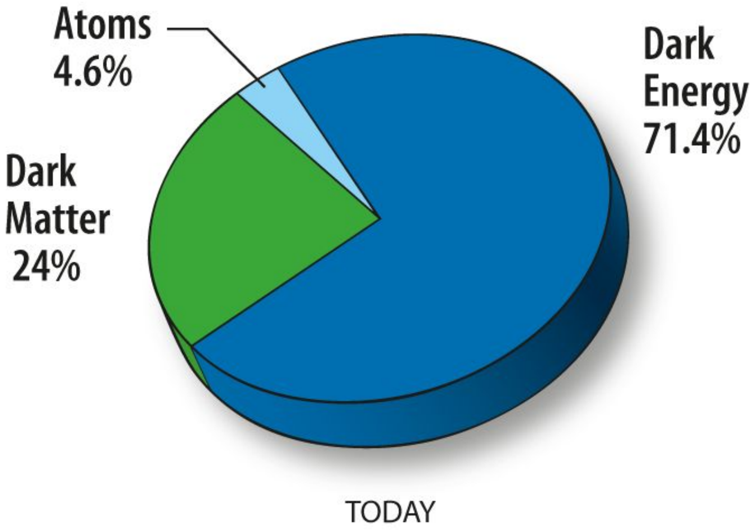

http://map.gsfc.nasa.gov/media/



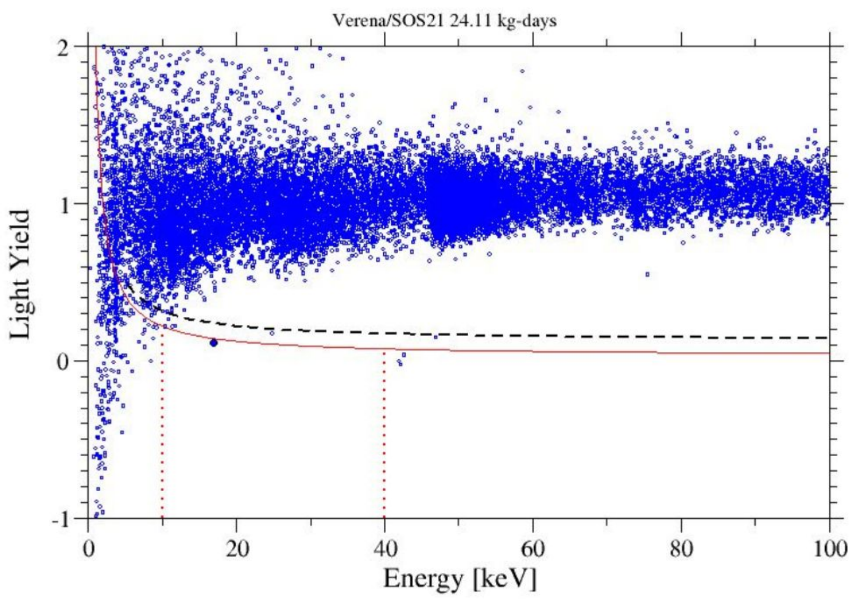
# Content of the universe

- **Matter density $\Omega_M \approx 30\%$ (measured via: Rotation curves of galaxies, gravitational lens)**
    - Baryonic matter (atoms): $\Omega_B \approx 4\%$ (nucleosynthesis).
    - Visible matter (stars): $\Omega_{lum} \approx 0.6\%$.
    - Dark matter: $\Omega_{DM} \approx 24\%$ (massive neutrinos, Axions or SUSY particles ?)

- **Dark Energy: $\Omega_\Lambda \approx 71\%$**
    - Corresponds to a positive cosmological constant (“antigravity”), used in general relativity to explain the (observed) accelerated expansion of the universe (i.e. redshift of supernovae).



# Content of the universe

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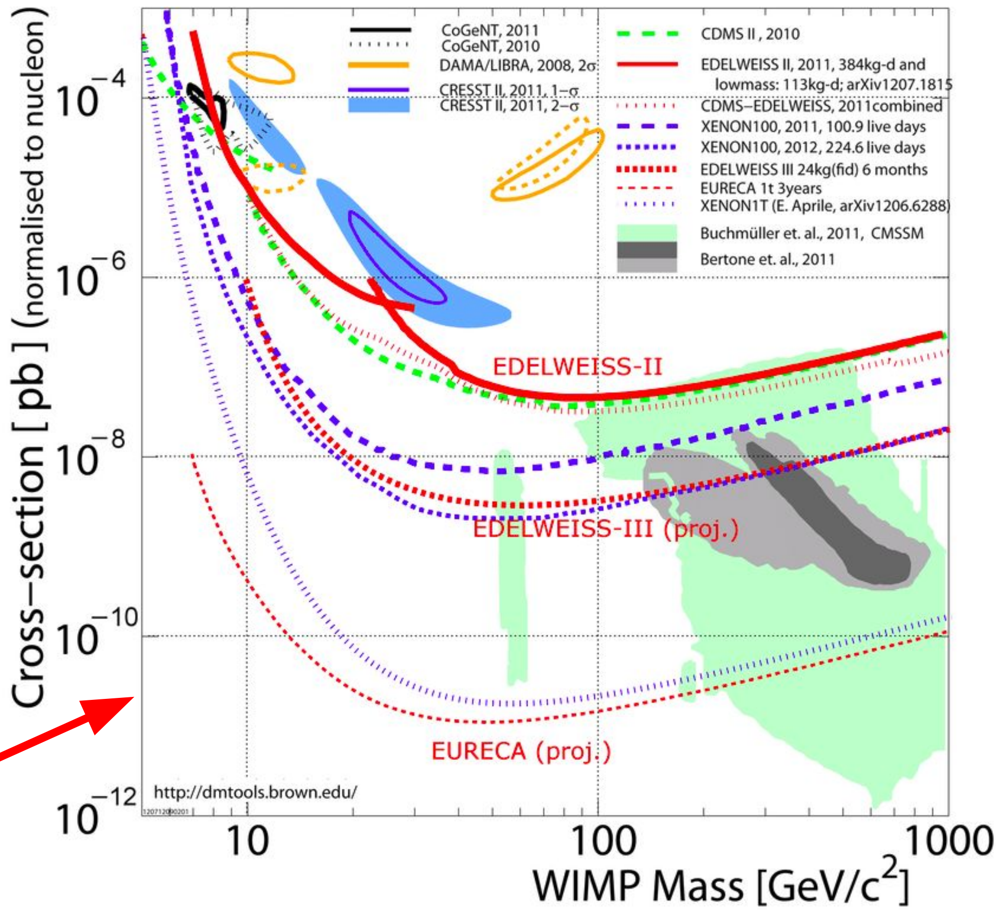



**Cross section for WIMP-nucleon interaction**

# Grand unification

- Unification of the three gauge interactions of the Standard Model (following the successful electroweak unification predicted in the 1960s)
    - Embedding the single gauge groups of the SM in a simple larger gauge group G with a single couplings constant (**Grand Unified Theories = GUTs**)

$$G \supset SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

- The Standard Model could be understood as an effective Theory at low energies (as the grand unified gauge symmetry is broken)

$$G \xrightarrow{M_{GUT}} SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \xrightarrow{M_{EW}} SU(3)_C \otimes SU(2)_L \otimes U(1)_Q$$

- Interactions become equally strong at the **Grand unification scale $M_{GUT} \approx 10^{15}$ GeV**
    - Compared to the scale of the electroweak symmetry breaking **$M_{EW} \approx v/\sqrt{2} \approx M_W$**

# The SU(5) Model

- The smallest (simple) Lie group that contains all gauge groups of the Standard Model is a **SU(5)**
  - with $n^2 - 1 = 24$ generators $T^a$ and 24 gauge fields $V_\mu{}^a(x)$ (a = 1,...,24)
    - Only 12 out of these 24 gauge fields are already contained in the SM
      - (8 Gluonen, $W^+$, $W^-$, $Z^0$, γ):

$$\mathcal{L}_{SU(5)} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a} + \overline{\psi} i \gamma^\mu D_\mu \psi_f$$

$$D_\mu = \partial_\mu - i g_5 T^a V^a_\mu$$

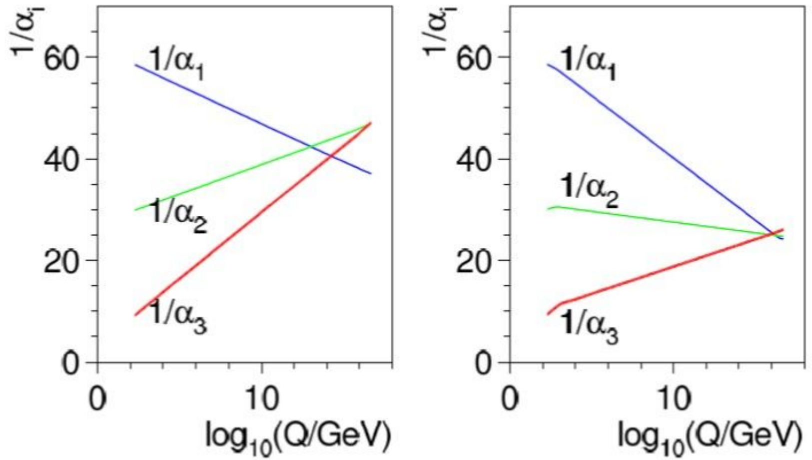
- Fundamental representation has the dimension n=5
  - Leptons and quarks are unified within common multi-pletts

# Supersymmetry (SUSY)

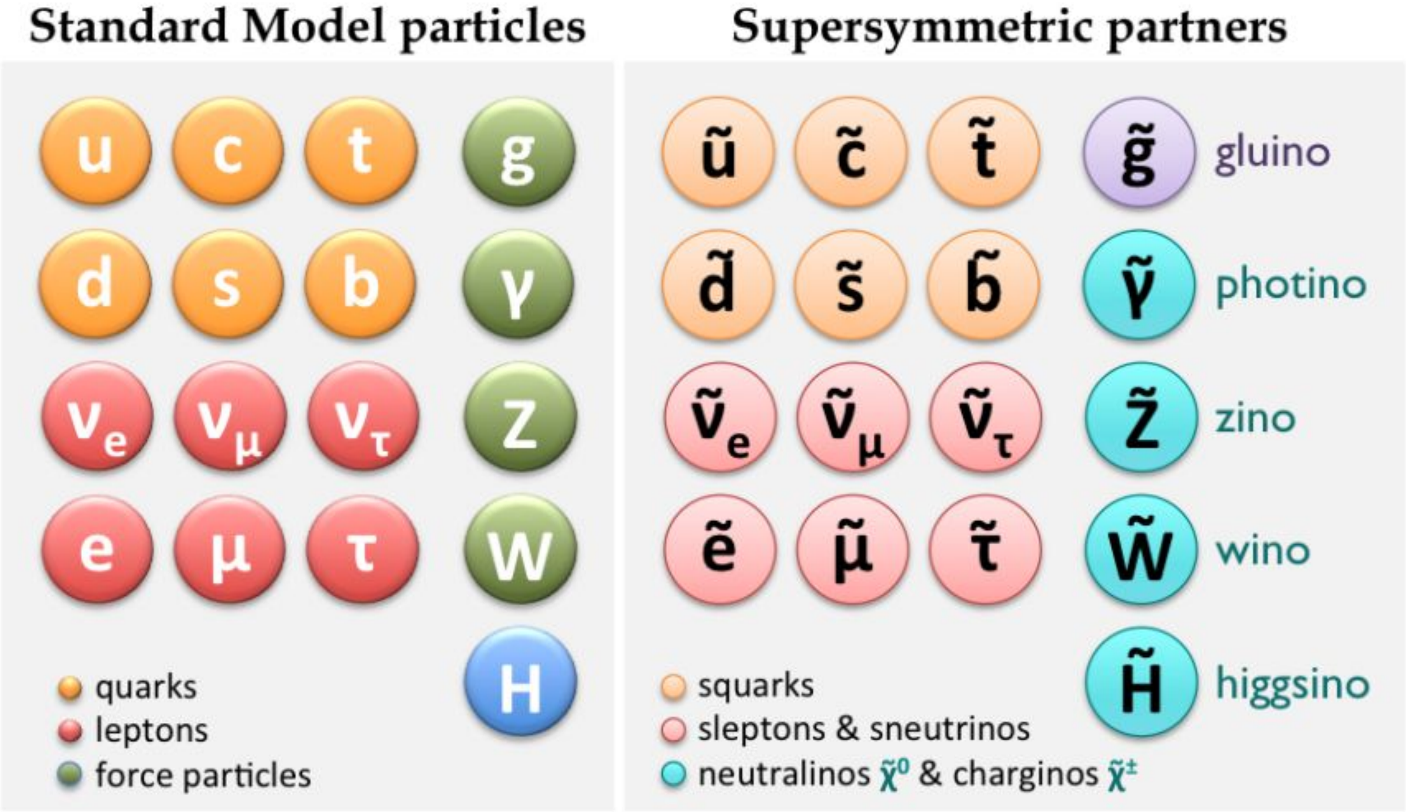
- **SUSY in a Nutshell:**
  - **Symmetry between fermions and bosons**
    - Each SM particle has a (heavy) SUSY partner particle
  - **Lightest SUSY particle (if neutral and stable) is Dark Matter candidate**
  - Extension of scalar sector:
    - 3 neutral and 2 charged Higgs-Bosons within the minimal supersymmetric extension of the SM (MSSM)
  - Predicts unification of gauge couplings
  - Local SUSY describes Gravitation
  - **Introduces R-parity:**

$$P_R = (-1)^{3B+L+2s}$$

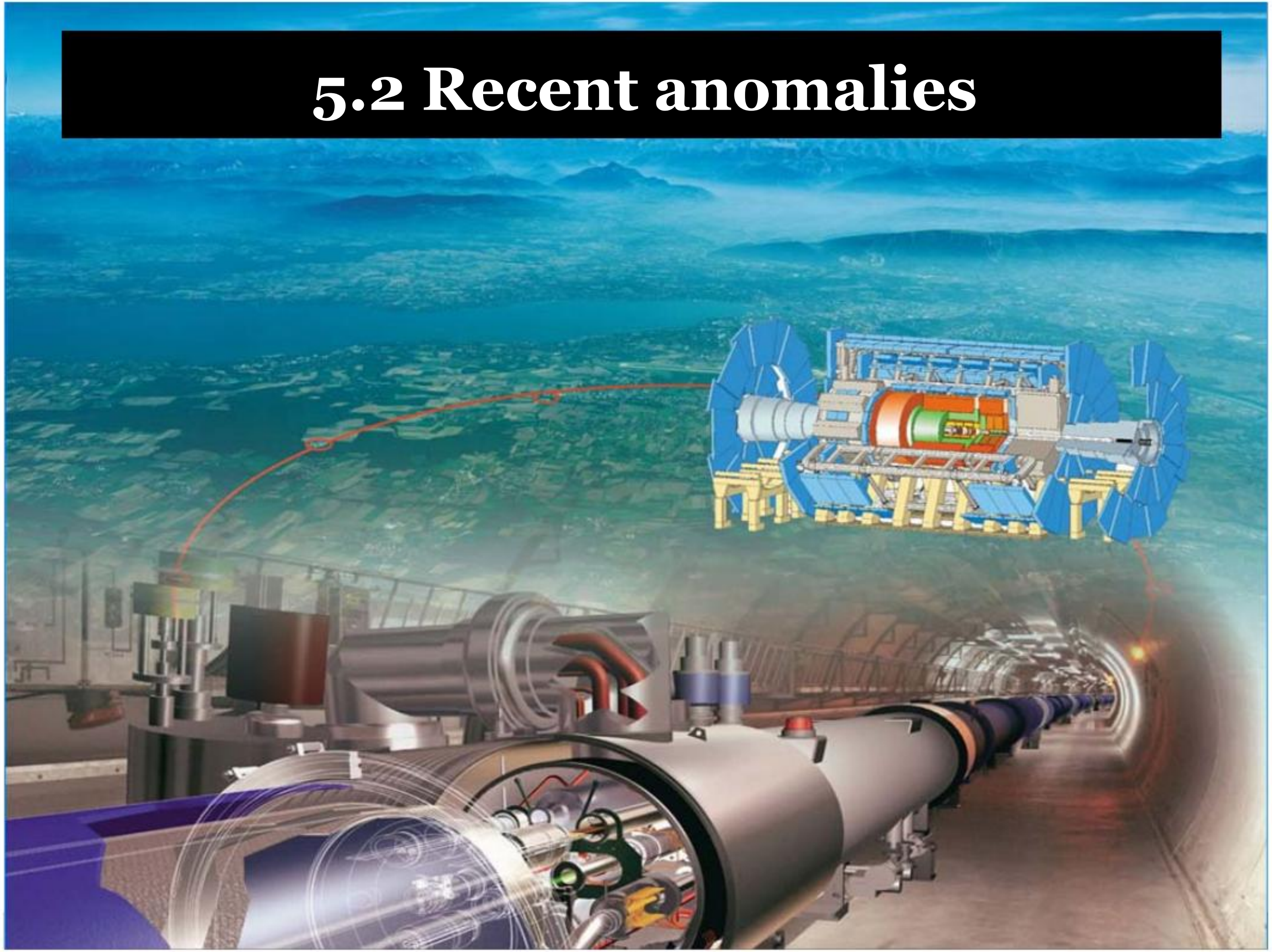
**conserved in many SUSY scenarios**



# Supersymmetry (SUSY)



# 5.2 Recent anomalies

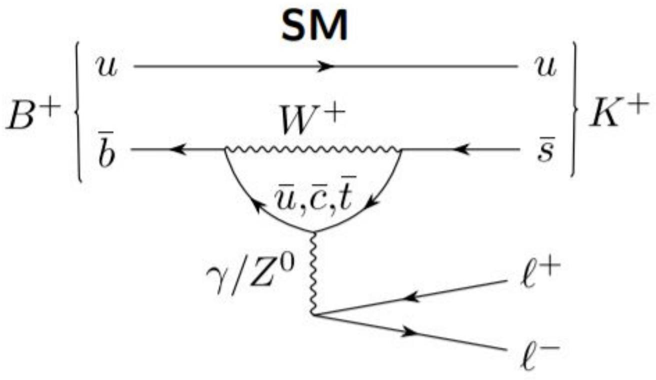


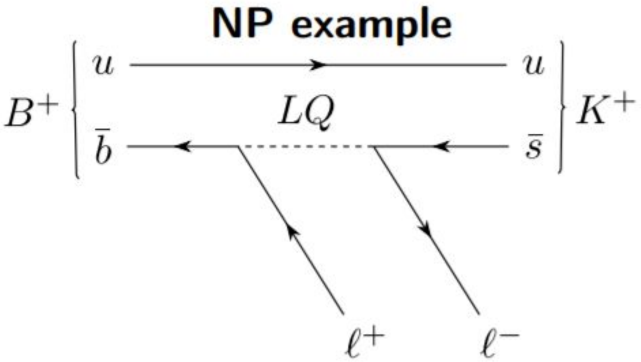
# Lepton Flavour Universality tests

- In the SM couplings of gauge bosons to leptons are independent of lepton flavour
  - Branching fractions differ only by phase space and helicity-suppressed contributions
- LHCb is performing LFU tests in B hadron decays:

$$R_{K^{(*)}} = \frac{\mathcal{B}\left(B \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(B \to K^{(*)}e^+e^-\right)} \overset{\text{SM}}{\cong} 1$$

**→ Any significant deviation would be a smoking gun for New Physics.**

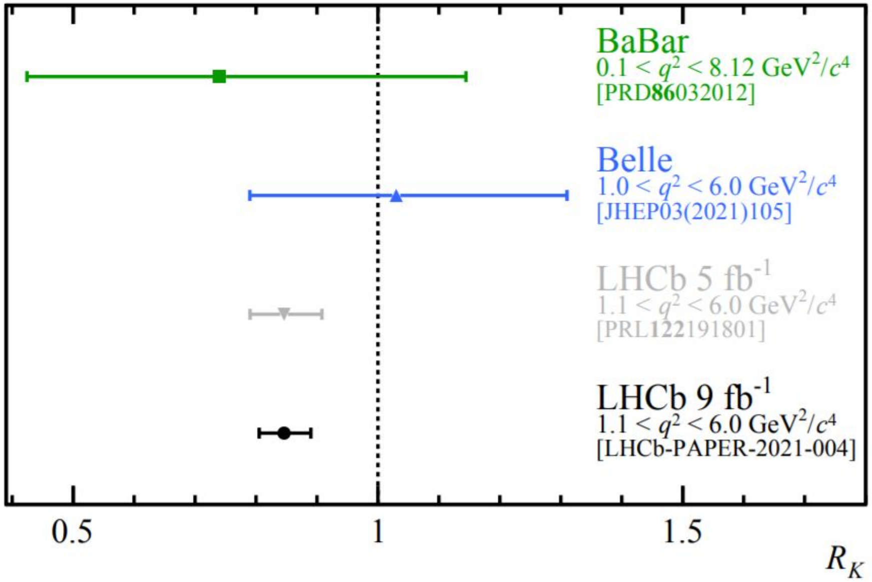



Taken from: https://indico.cern.ch/event/976688/attachments/2213706/3748404/RK_CernSeminar_Tue23rdMar2021.pdf

# Lepton Flavour Universality tests

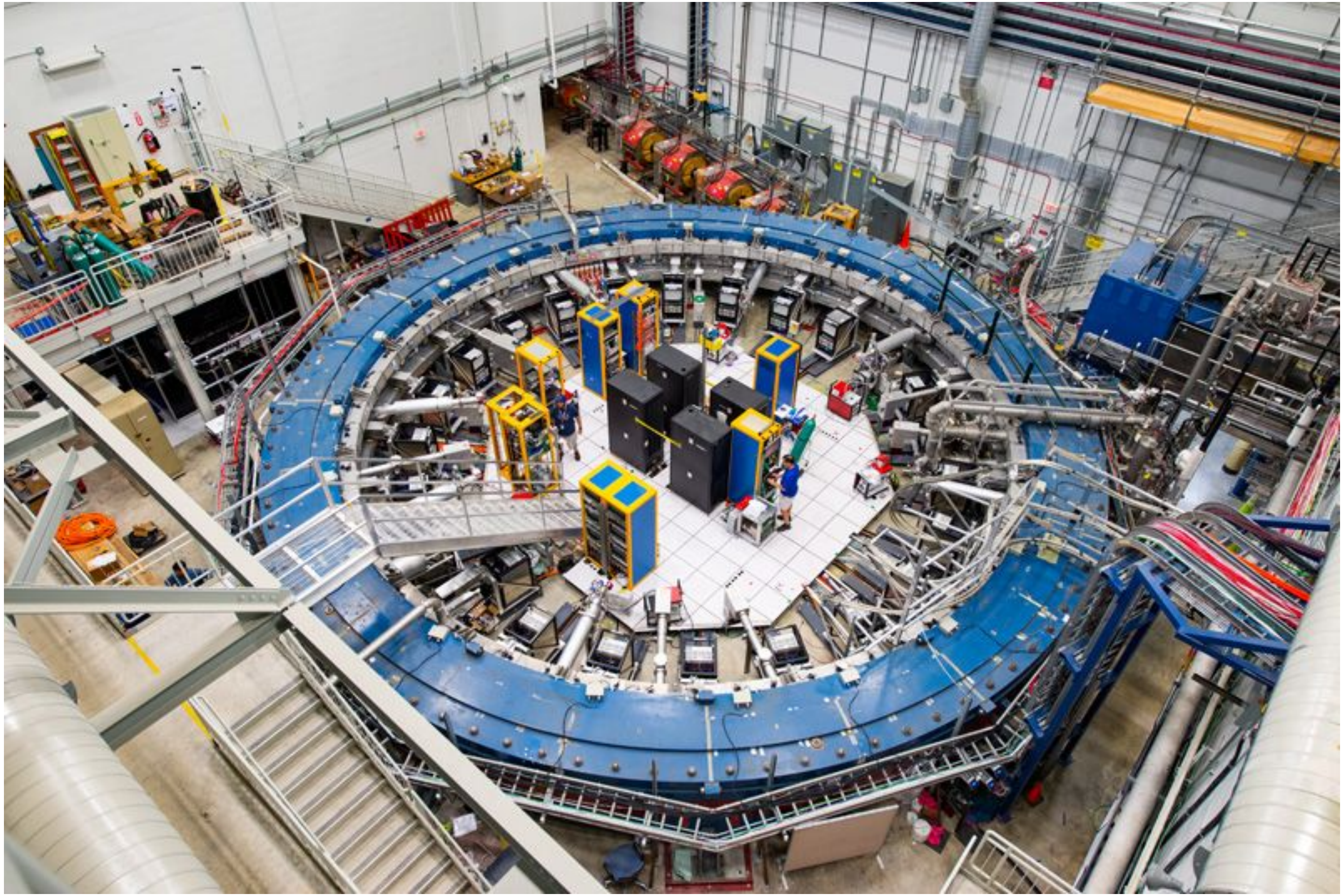
**Newest results from LHCb**




$$R_K = 0.846\ ^{+0.042}_{-0.039}\ (\mathrm{stat})\ ^{+0.013}_{-0.012}\ (\mathrm{syst})$$

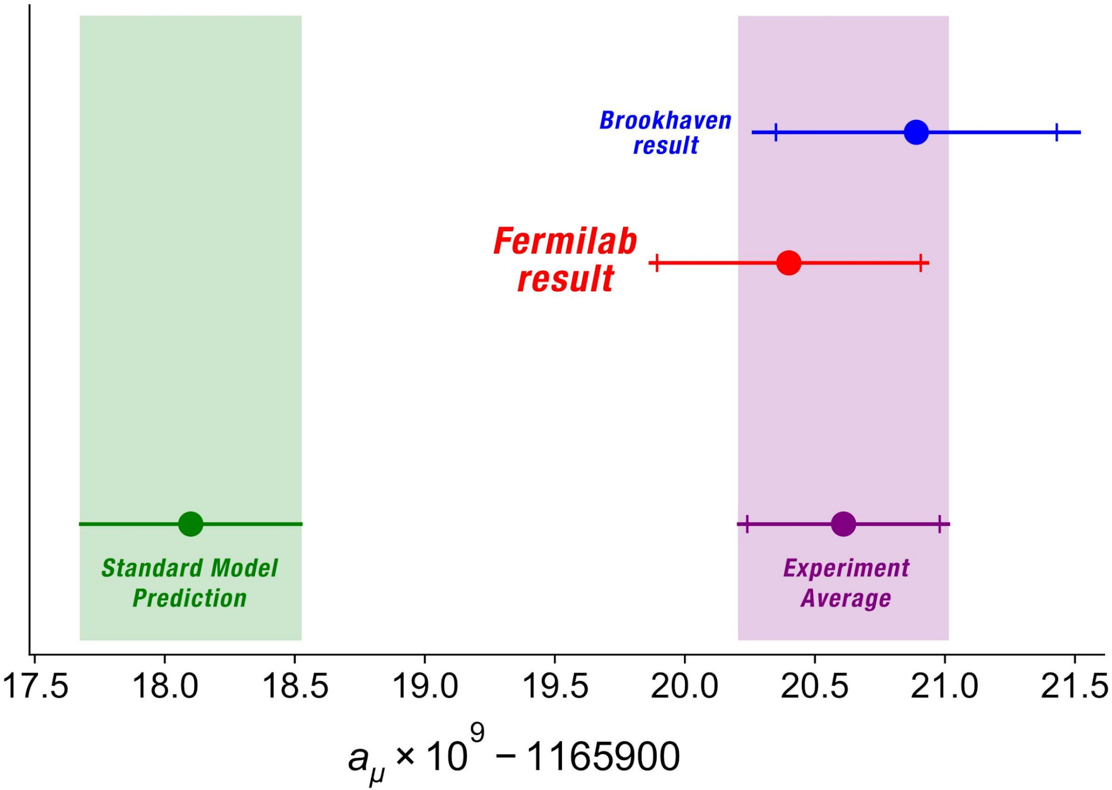
→ **Evidence of LFU violation at 3.1σ**

# g - 2 experiment



# g - 2 experiment

## First results from g-2 experiment



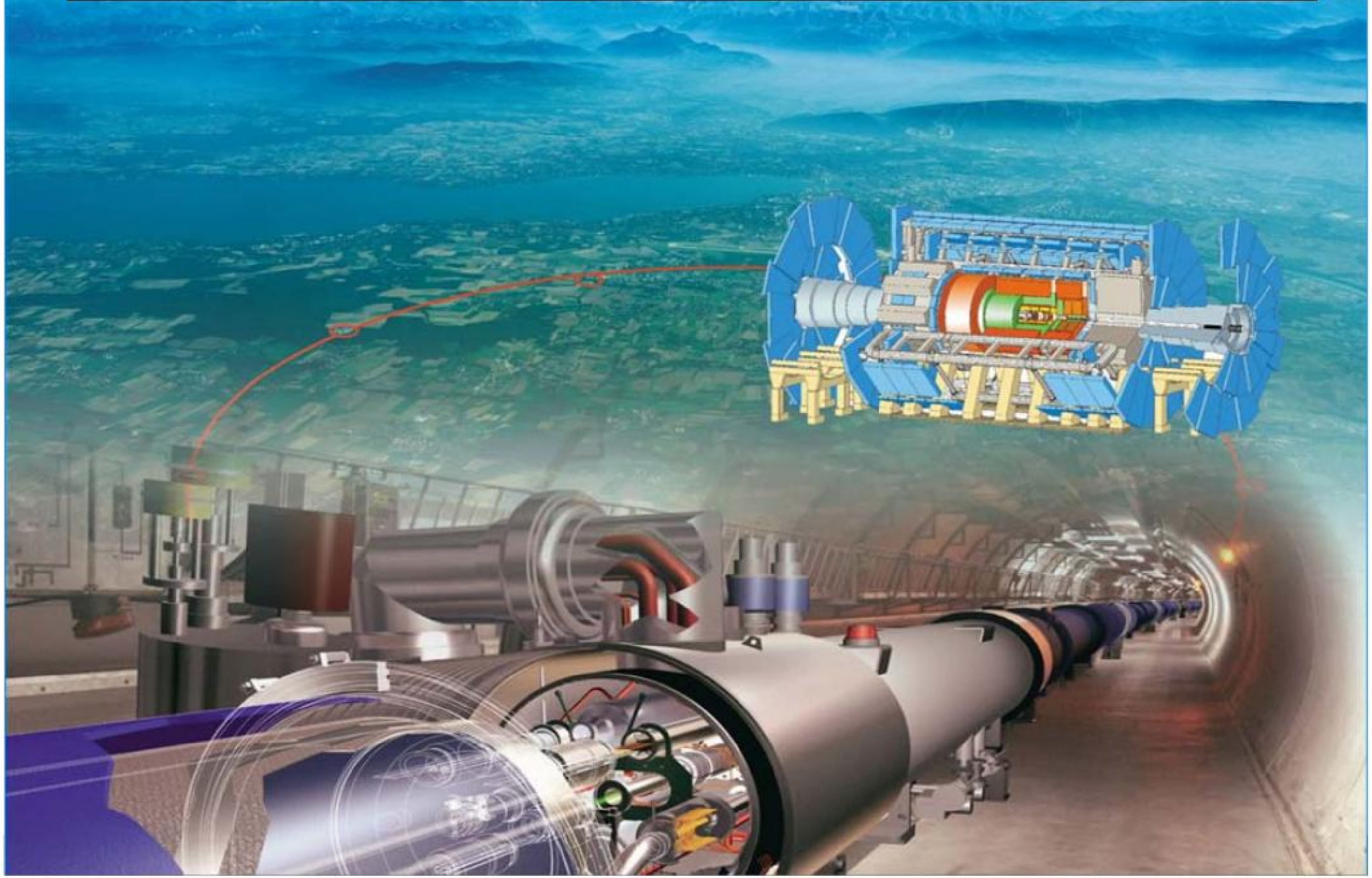

**The combined results from Fermilab and Brookhaven show a difference with the theory predictions at a significance of 4.2σ**

# 5.3 Direct searches for new physics

# Direct Searches for new physics at the LHC

- **Broad range of searches for BSM physics at ATLAS/CMS**
  - Supersymmetry
  - Excited leptons **[1]**
  - Leptoquarks [2]
  - Dark matter (e.g. invisible Higgs) **[3]**
  - Vector-like quarks [4]
  - Highly ionizing particles (i.e. **monopoles**) [5]
  - Heavy neutrinos [6]
  - Lepton-flavour violation [7]
  - Extended Higgs sector
    - The **Two Higgs Doublet Model (2HDM)** [8]
    - **Singlet extensions** [9], [10]
    - **Scalar triplet Models** [11], [12]
    - **Composite Higgs**
  - Technicolour (dynamically breaking of EW symmetry) [13]

# 5.3.1 Searches for Leptoquarks



# Leptoquarks

- Leptoquarks are hypothetical particles carrying both baryon number (B) and lepton number (L)
- The spin of a leptoquark state can be either 1 (vector leptoquark) or 0 (scalar leptoquark)
- Leptoquark states are expected to exist in various extensions of the SM
  - The Pati-Salam model [1] is an example predicting the existence of a leptoquark state
  - Scalar leptoquarks are expected to exist at the TeV scale in extended technicolor models
  - Leptoquark states exist in grand unification theories based on SU(5) or SO(10) groups
  - Scalar quarks in supersymmetric models with R-parity violation may also have leptoquark-type Yukawa couplings
  - Compositeness of quarks and leptons also provides examples of models which may have light leptoquark states
- Leptoquarks are an attractive explanation for violation of lepton flavor universalites

More information can be found via: https://pdg.lbl.gov/2021/reviews/rpp2020-rev-leptoquark-quantum-numbers.pdf

# Leptoquarks

**Possible leptoquarks and their quantum numbers**

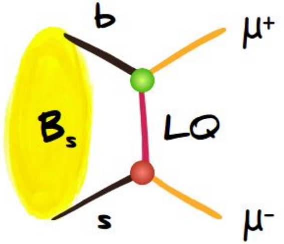
If leptoquark states are not required to couple directly with SM fermions, different assignments of quantum numbers become possible

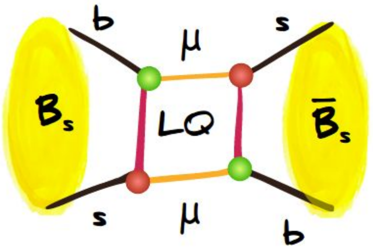
| Spin | $3B+L$ | $SU(3)_c$ | $SU(2)_W$ | $U(1)_Y$ | Allowed coupling |
|---|---|---|---|---|---|
| 0 | $-2$ | $\bar{3}$ | 1 | 1/3 | $\bar{q}^c_L \ell_L$ or $\bar{u}^c_R e_R$ |
| 0 | $-2$ | $\bar{3}$ | 1 | 4/3 | $\bar{d}^c_R e_R$ |
| 0 | $-2$ | $\bar{3}$ | 3 | 1/3 | $\bar{q}^c_L \ell_L$ |
| 1 | $-2$ | $\bar{3}$ | 2 | 5/6 | $\bar{q}^c_L \gamma^\mu e_R$ or $\bar{d}^c_R \gamma^\mu \ell_L$ |
| 1 | $-2$ | $\bar{3}$ | 2 | $-1/6$ | $\bar{u}^c_R \gamma^\mu \ell_L$ |
| 0 | 0 | 3 | 2 | 7/6 | $\bar{q}_L e_R$ or $\bar{u}_R \ell_L$ |
| 0 | 0 | 3 | 2 | 1/6 | $\bar{d}_R \ell_L$ |
| 1 | 0 | 3 | 1 | 2/3 | $\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$ |
| 1 | 0 | 3 | 1 | 5/3 | $\bar{u}_R \gamma^\mu e_R$ |
| 1 | 0 | 3 | 3 | 2/3 | $\bar{q}_L \gamma^\mu \ell_L$ |

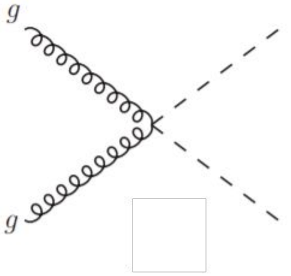
Taken from: https://pdg.lbl.gov/2021/reviews/rpp2020-rev-leptoquark-quantum-numbers.pdf

# Leptoquark production

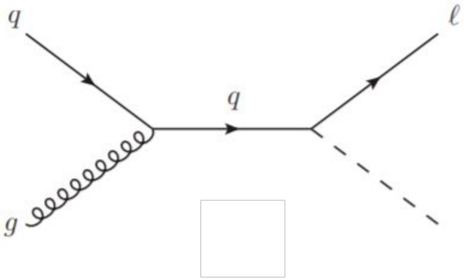
- At the LHC, Leptoquarks are dominantly produced in pairs or in association with a single lepton/quark
- Rare (**resonant**) s-channel production due to non-zero lepton parton distribution functions
- Potential contribution to flavour physics (via  loop-diagrams)
    - Significant enhancement of rates for rare decays



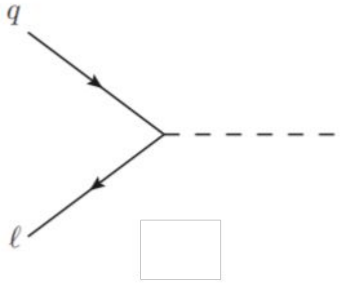




**pair production**

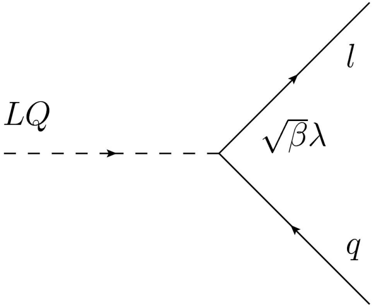


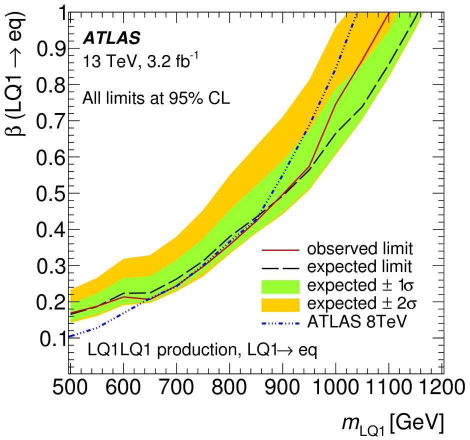

**single production**

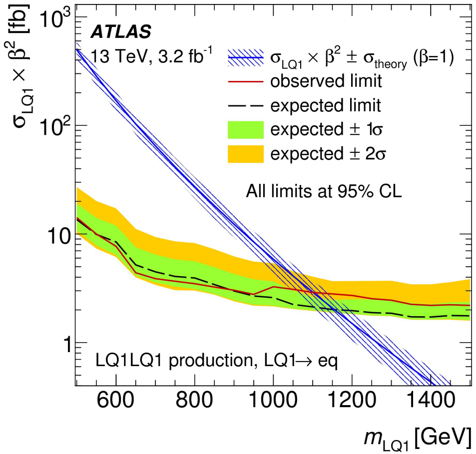



**s-channel**

# Leptoquark searches

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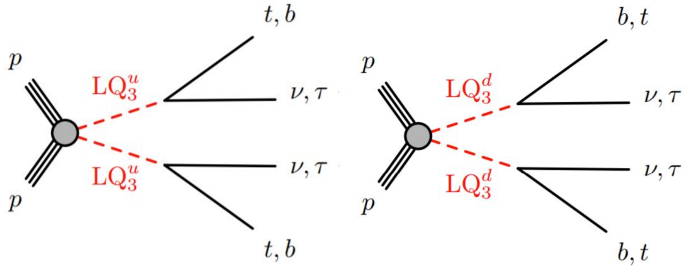
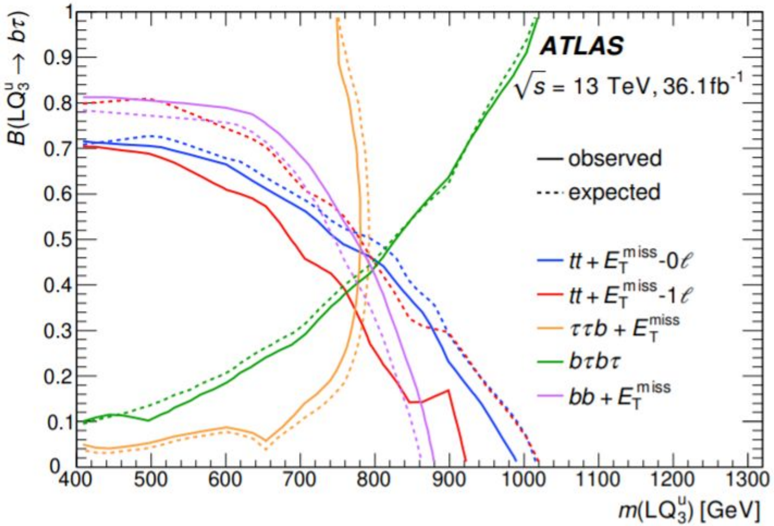
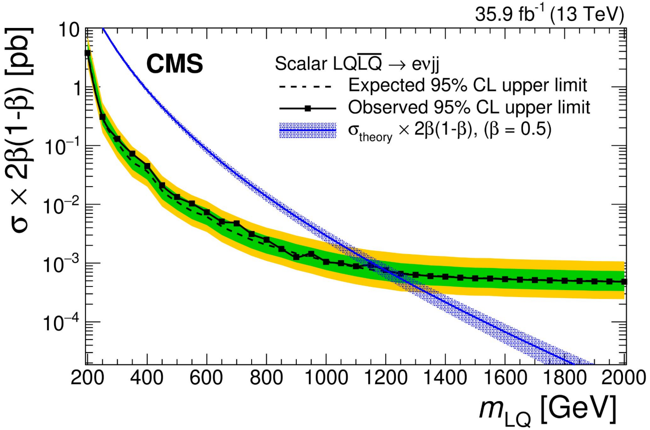
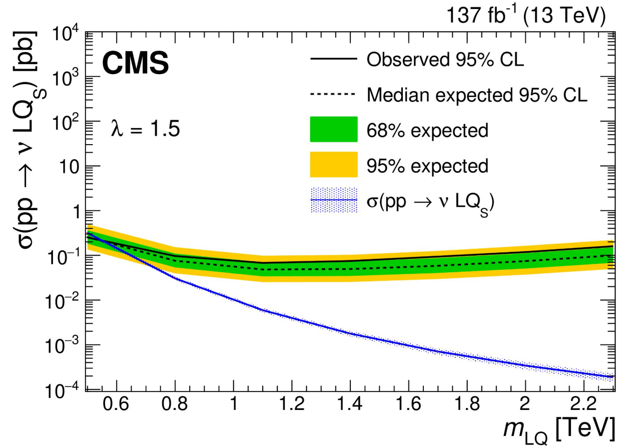



Taken from: https://arxiv.org/pdf/1902.08103.pdf

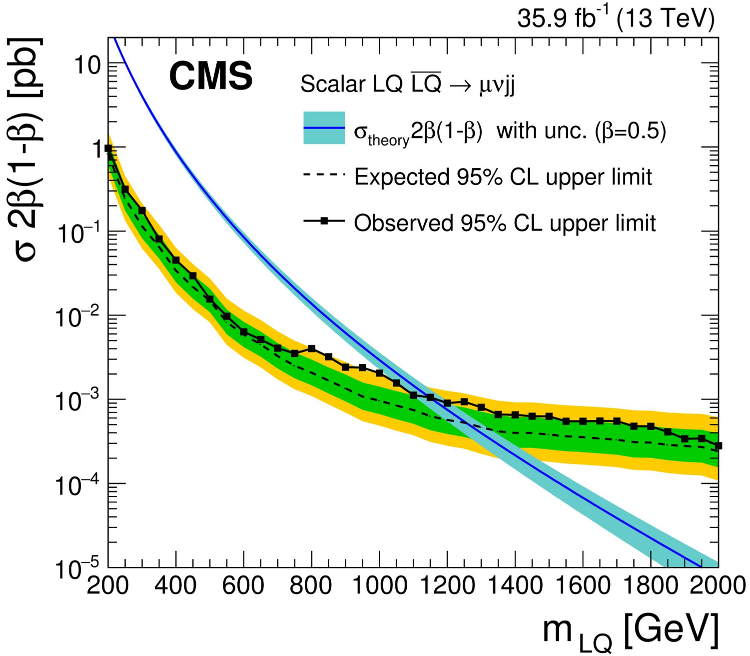


# Leptoquark searches

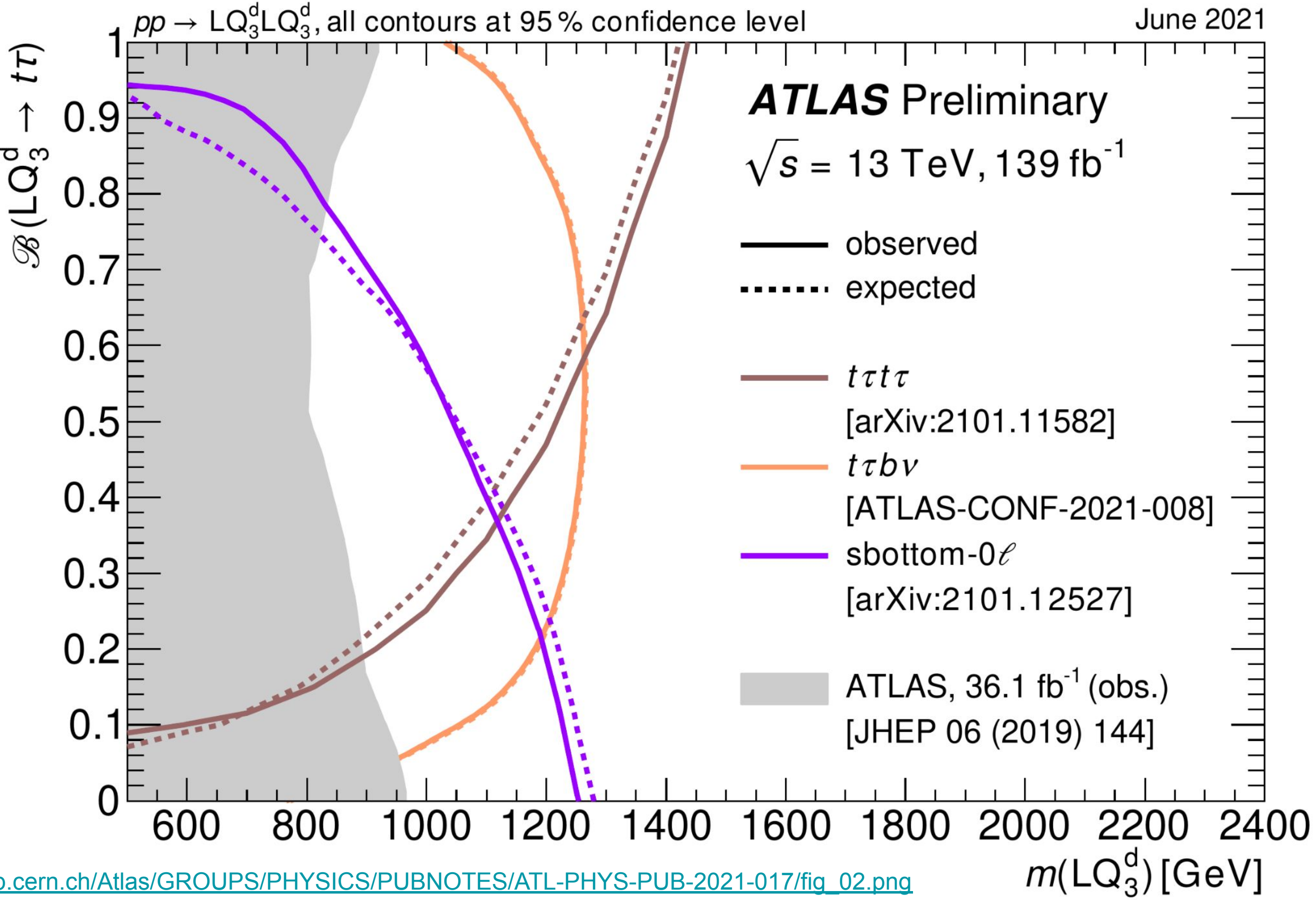



**Limits on single and double production of 1st, 2nd and 3rd generation LQs**



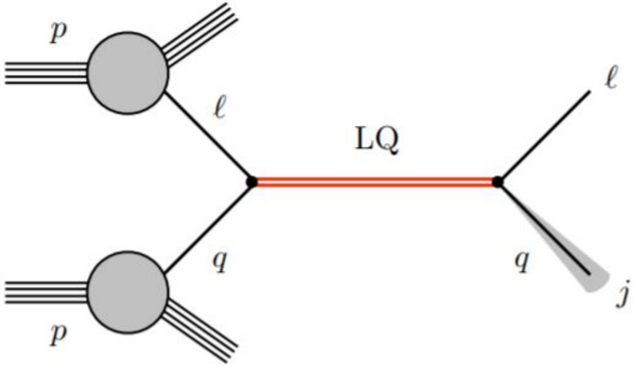
# Leptoquark searches

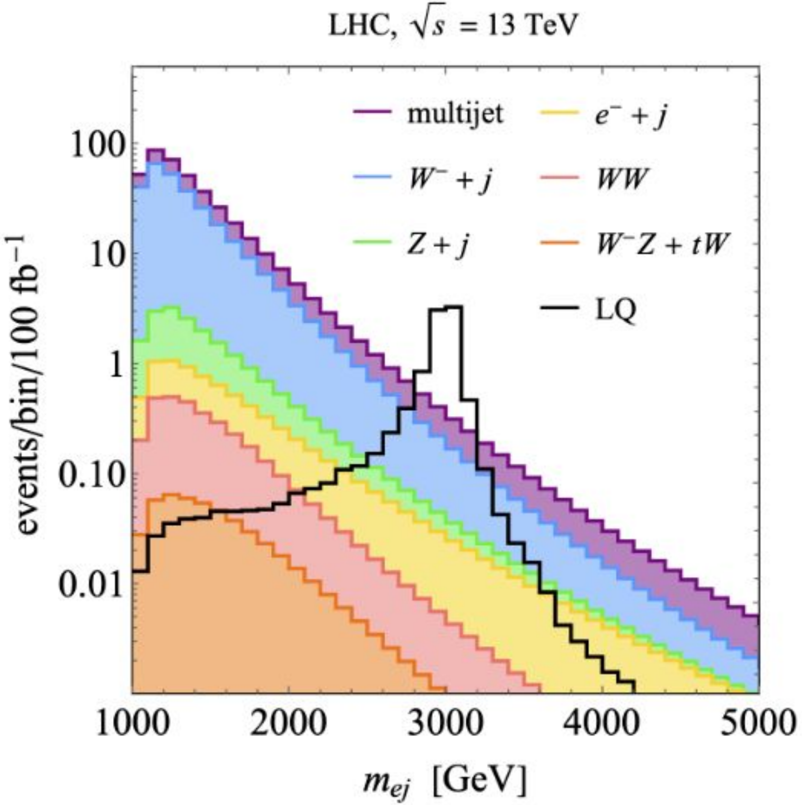



Taken from: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-017/fig_02.png

# Future Leptoquark searches

- Non-zero lepton parton distribution functions allow for resonant LQ production @LHC
- **Search for lepton + jet final state**




Taken from [here]() and [here]()

# 5.3.2 Searches for an extended scalar sector

# 2-Higgs Doublet Model (2HDM)

- The 2-Higgs Doublet Model (2HDM) with 2 complex Higgs doublets is (together with the singlet extension) the simplest possible extension
  - **Motivated by e.g. supersymmetric model**
  - **Introduces additional sources for explicit or spontaneous CP violation**

- The scalar potential of the two Higgs doublets $\Phi_1$ and $\Phi_2$ can have CP-conserving, CP-violating or charge-violating minima
- Assuming **CP conservation,** the most general scalar potential for two doublets $\Phi_1$ and $\Phi_2$ with hypercharge +1 is given via:

$$
\begin{aligned}
V \;=\;& m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 \\
& + \lambda_3\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2 + \lambda_4\Phi_1^\dagger\Phi_2\Phi_2^\dagger\Phi_1 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Phi_2^\dagger\Phi_1\right)^2\right]
\end{aligned}
$$

# 2-Higgs Doublet Model (2HDM)

- In the minimum of the Higgs potential, the real components of the Higgs doublets have the **VEVs:**

$$\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix} \qquad \text{and} \qquad \langle\Phi_2\rangle = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

- The two complex Higgs doublets contain **eight real fields**,

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ \frac{v_a+\rho_a+i\eta_a}{\sqrt{2}} \end{pmatrix} , \qquad a = 1, 2$$

- Three out of them provide the longitudinal degrees of freedom for the massive W and Z bosons.
- After EWSB we are hence left with five Higgs fields.
  - Assuming CP conservation: h, H (two neutral scalars), A (one neutral pseudoscalar), and $H^+$, $H^-$ (two charged Higgs bosons).

# 2-Higgs Doublet Model (2HDM)

- **In order to reproduce the W and Z boson masses as in the SM we have to set:**

$$v_1^2 + v_2^2 = v \qquad \text{with} \qquad v^2 = \frac{1}{\sqrt{2}G_F} \approx 246^2\ (\mathrm{GeV})^2$$

- Important model parameters are the **mixing angle α and the ratio of VEVs:**

$$\tan\beta = \frac{v_2}{v_1}$$

- **The CP-even mass eigenstates h and H are defined via**

$$\begin{aligned} H &= \rho_1 \cos\alpha + \rho_2 \sin\alpha \\ h &= -\rho_1 \sin\alpha + \rho_2 \cos\alpha \end{aligned}$$

- **The SM Higgs boson can be reproduced via:**

$$\begin{aligned} H^{\mathrm{SM}} &= \rho_1 \cos\beta + \rho_2 \sin\beta \\ &= H\cos(\alpha-\beta) - h\sin(\alpha-\beta) \end{aligned}$$

# 2-Higgs Doublet Model (2HDM)

- Distinguish several 2HDM scenarios:
  - **Type I 2HDM:** All quarks couple to just one of the Higgs doublets (conventionally chosen to be $\Phi_2$)
  - **Type II 2HDM:** The Q = 2/3 right-handed (RH) quarks couple to one Higgs doublet (conventionally chosen to be $\Phi_2$) and the Q = −1/3 RH quarks couple to the other ($\Phi_1$)
  - **Lepton-specific model:** The RH quarks all couple to $\Phi_2$ and the RH leptons couple to $\Phi_1$
  - **Flipped model:** The RH up-type quarks couple to $\Phi_2$ , the RH down-type quarks couple to $\Phi_1$ , as in type II, but now the RH leptons couple to $\Phi_2$

# 2-Higgs Doublet Model (2HDM)

- **Yukawa-coupling:**

$$\begin{aligned}\mathcal{L}^{\text{2HDM}}_{\text{Yukawa}} &= -\sum_{f=u,d,l}\frac{m_f}{v}\left(\xi_h^f\bar{f}fh+\xi_H^f\bar{f}fH-i\xi_A\bar{f}\gamma_5 fA\right)\\ &\quad -\left\{\frac{\sqrt{2}V_{ud}}{v}\bar{u}(m_u\xi_A^u P_L+m_d\xi_A^d P_R)dH^+ +\frac{\sqrt{2}m_l\xi_A^l}{v}\bar{\nu}_L l_R H^+ + h.c.\right\}\end{aligned}$$

- **Couplings to vector-bosons:**

$$\begin{aligned} g_{hWW} &= \sin(\beta-\alpha)g_{H^{\text{SM}}WW}\\ g_{HWW} &= \cos(\beta-\alpha)g_{H^{\text{SM}}WW}\\ g_{AWW} &= g_{AZZ}=0\end{aligned}$$

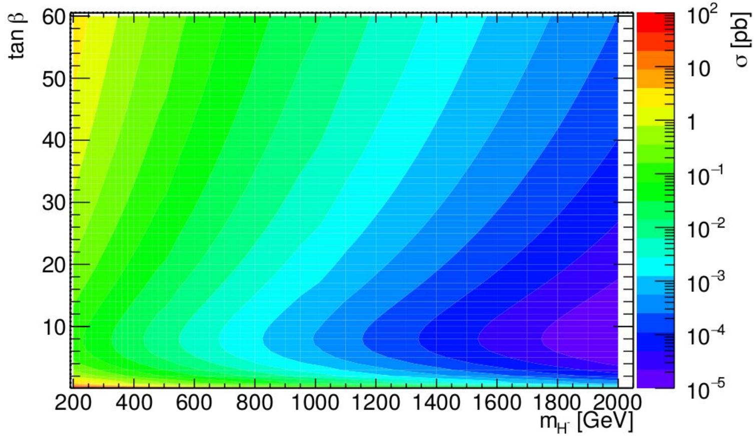
$$g_{hZZ}=\sin(\beta-\alpha)g_{H^{\text{SM}}ZZ}$$

$$g_{HZZ}=\cos(\beta-\alpha)g_{H^{\text{SM}}ZZ}$$

| | Type I | Type II | Lepton-specific | Flipped |
|---|---|---|---|---|
| $\xi_h^u$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ |
| $\xi_h^d$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ |
| $\xi_h^l$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\sin\beta$ |
| $\xi_H^u$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ |
| $\xi_H^d$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ |
| $\xi_H^l$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ | $\cos\alpha/\cos\beta$ | $\sin\alpha/\sin\beta$ |
| $\xi_A^u$ | $\cot\beta$ | $\cot\beta$ | $\cot\beta$ | $\cot\beta$ |
| $\xi_A^d$ | $-\cot\beta$ | $\tan\beta$ | $-\cot\beta$ | $\tan\beta$ |
| $\xi_A^l$ | $-\cot\beta$ | $\tan\beta$ | $\tan\beta$ | $-\cot\beta$ |

# 2-Higgs Doublet Model (2HDM)

arXiv:1610.07922

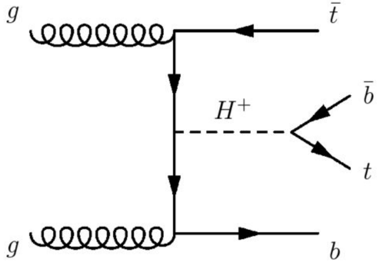


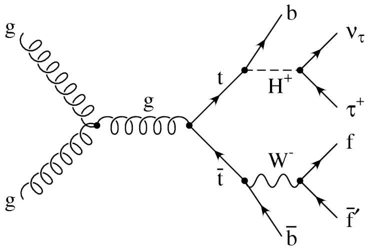

- **Charged Higgs boson**
  - Dominant production modes:
    - $t \rightarrow bH$ ($m_H < m_t$)
    - $pp \rightarrow tbH^+$ ($m_H > m_t$)

- **Yukawa couplings of charged Higgs:**

$$\mathcal{L}_{H^\pm} = -H^+ \left( \frac{\sqrt{2}\, V_{ud}}{v}\, \bar{u}\, (m_u X P_L + m_d Y P_R)\, d + \frac{\sqrt{2}\, m_\ell}{v}\, Z \bar{\nu}_L \ell_R \right) + \text{H.c.}$$

| | Type I | Type II | Lepton-specific | Flipped |
|---|---|---|---|---|
| $X$ | $\cot\beta$ | $\cot\beta$ | $\cot\beta$ | $\cot\beta$ |
| $Y$ | $\cot\beta$ | $-\tan\beta$ | $\cot\beta$ | $-\tan\beta$ |
| $Z$ | $\cot\beta$ | $-\tan\beta$ | $-\tan\beta$ | $\cot\beta$ |

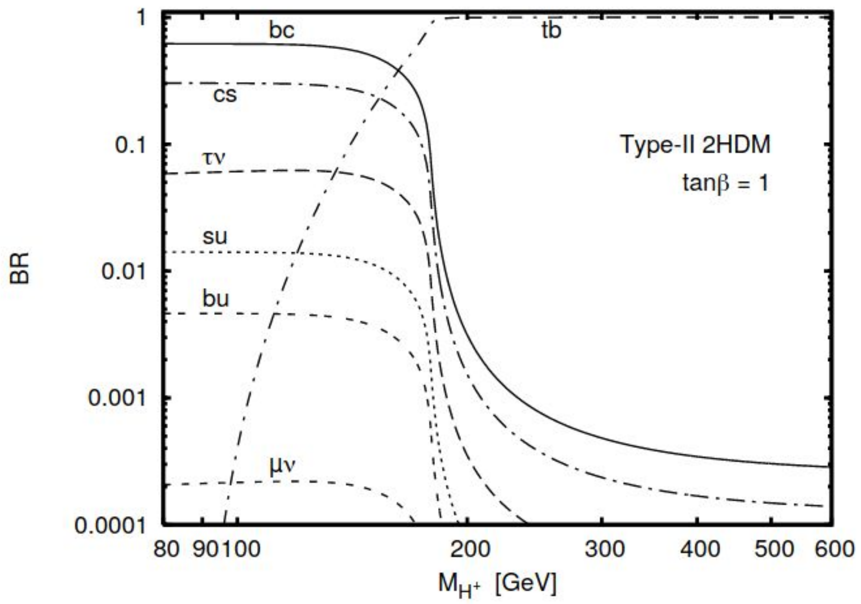


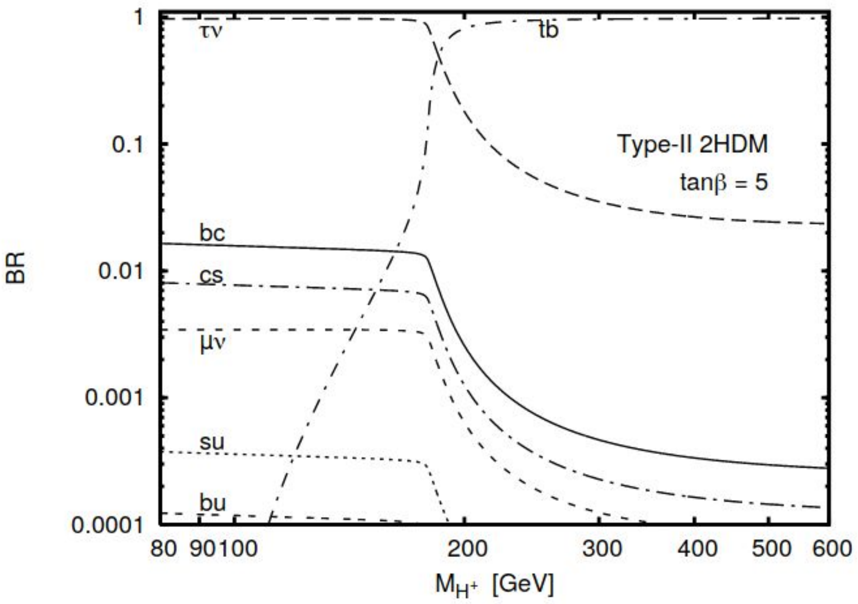



# 2-Higgs Doublet Model (2HDM)

- **Charged Higgs boson decays**
  - In alignment limit cos(β - α) → 0, the $H^+$ decays dominantly via $H^+ \to tb$ (for $m_H > m_t$)
    - For light charged Higgs bosons, the decay $H^+ \to \tau\nu$ or $H^+ \to bc$ dominate

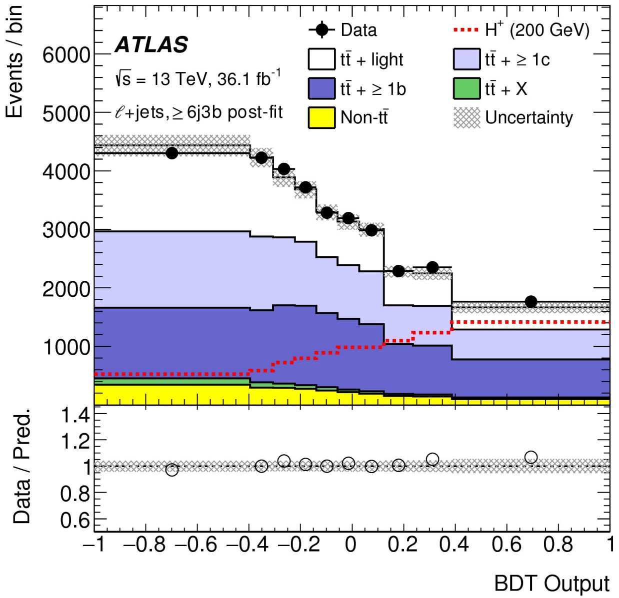
https://arxiv.org/pdf/1106.0034.pdf

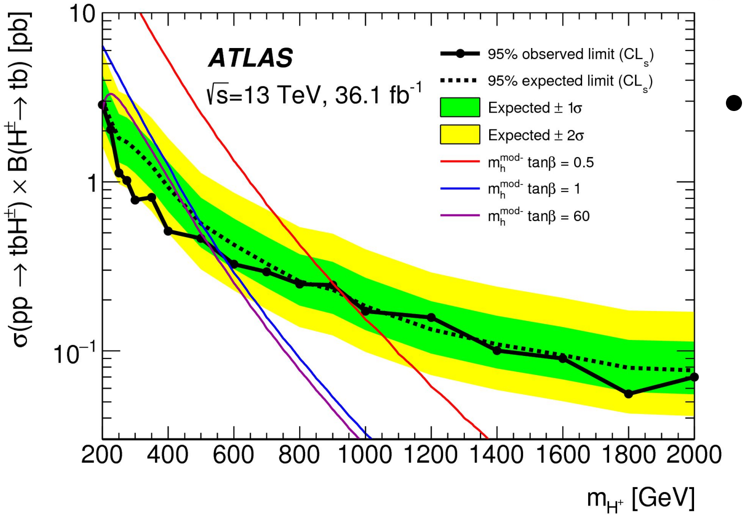


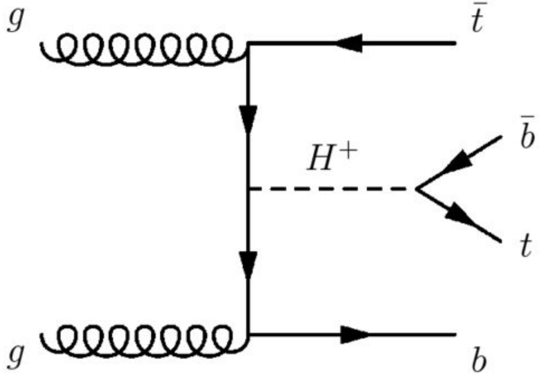



# Direct searches for an extended Higgs sector

- **Search for a charged Higgs boson**
  - Predicted by e.g. models containing 2HDMs
  - Analysis is based on modern machine learning techniques



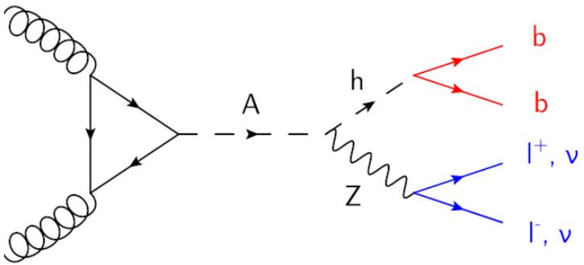



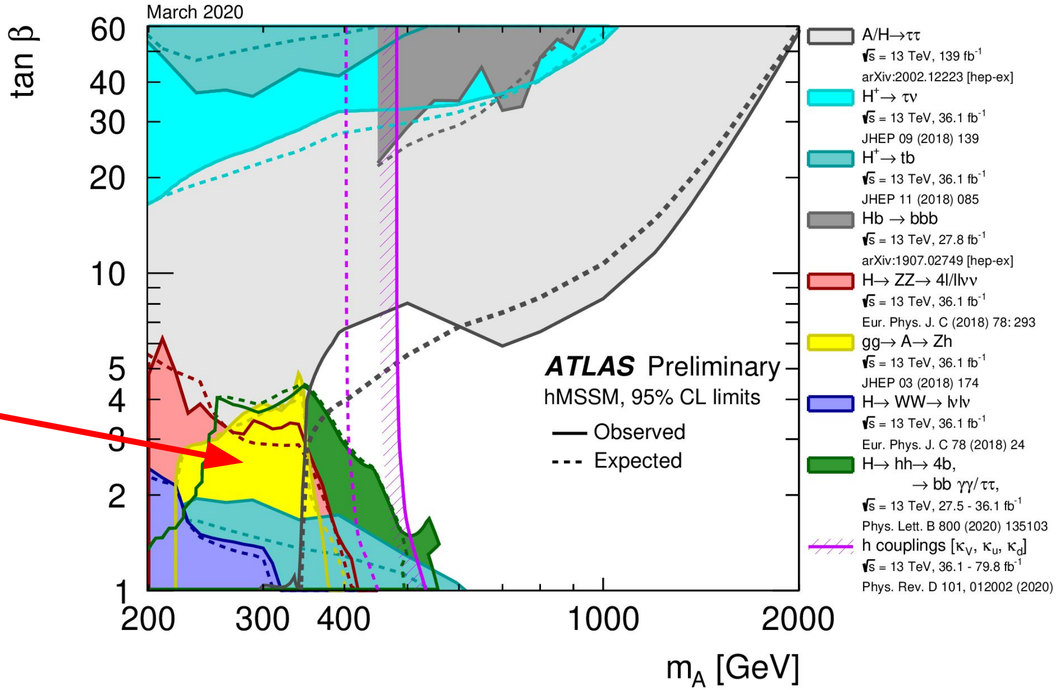




- Dominant for $m_{H+}$ > 180GeV at alignment limit

# 2-Higgs Doublet Model (2HDM)

- **Interpretations**
  - **Combine**
    - Already exclude large region of model parameter space

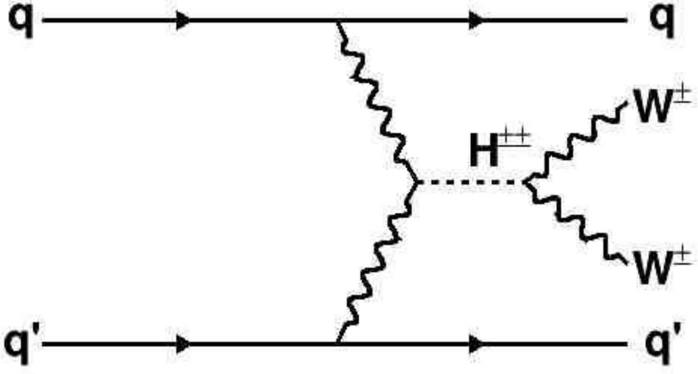


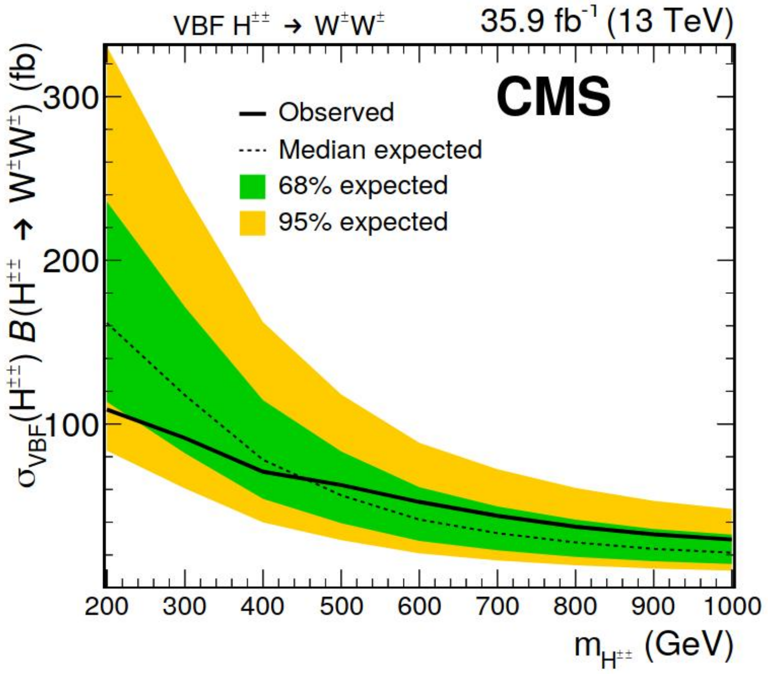



# Direct searches for an extended Higgs sector

- **Search for doubly-charged Higgs bosons**
  - Predicted in models that contains a Higgs triplet.
    - Leading to same-sign dilepton events

**$pp \rightarrow H^{++}\, jj \rightarrow W^{+}\, W^{+}\, jj$**
**(VBF)**

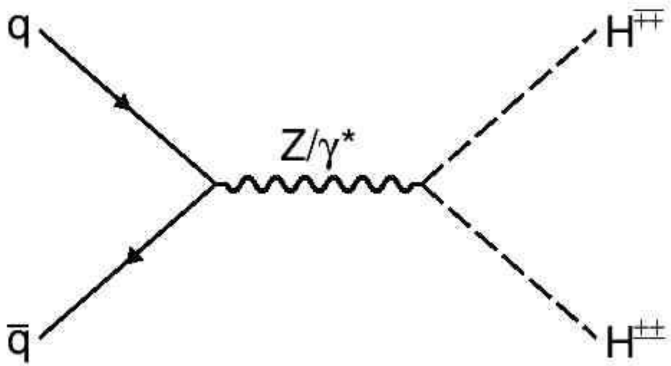


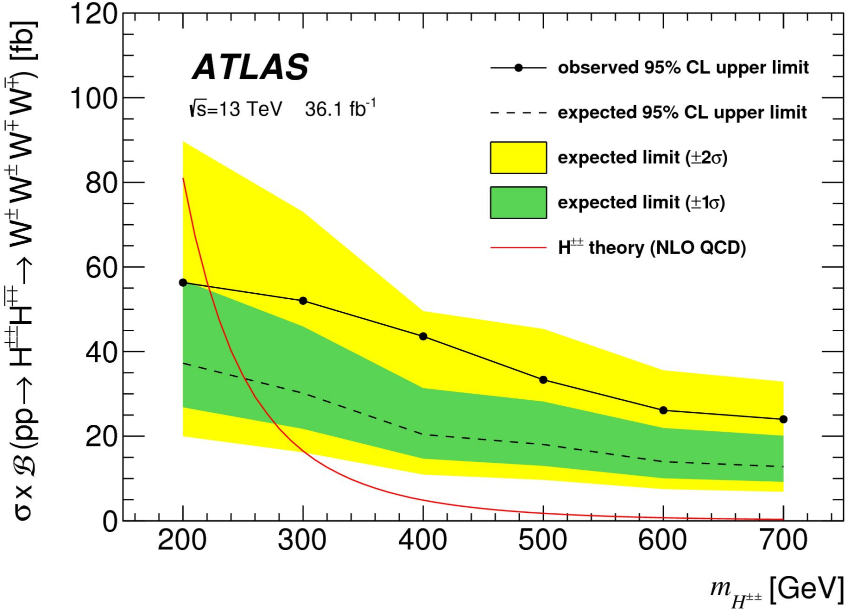



# Direct searches for an extended Higgs sector

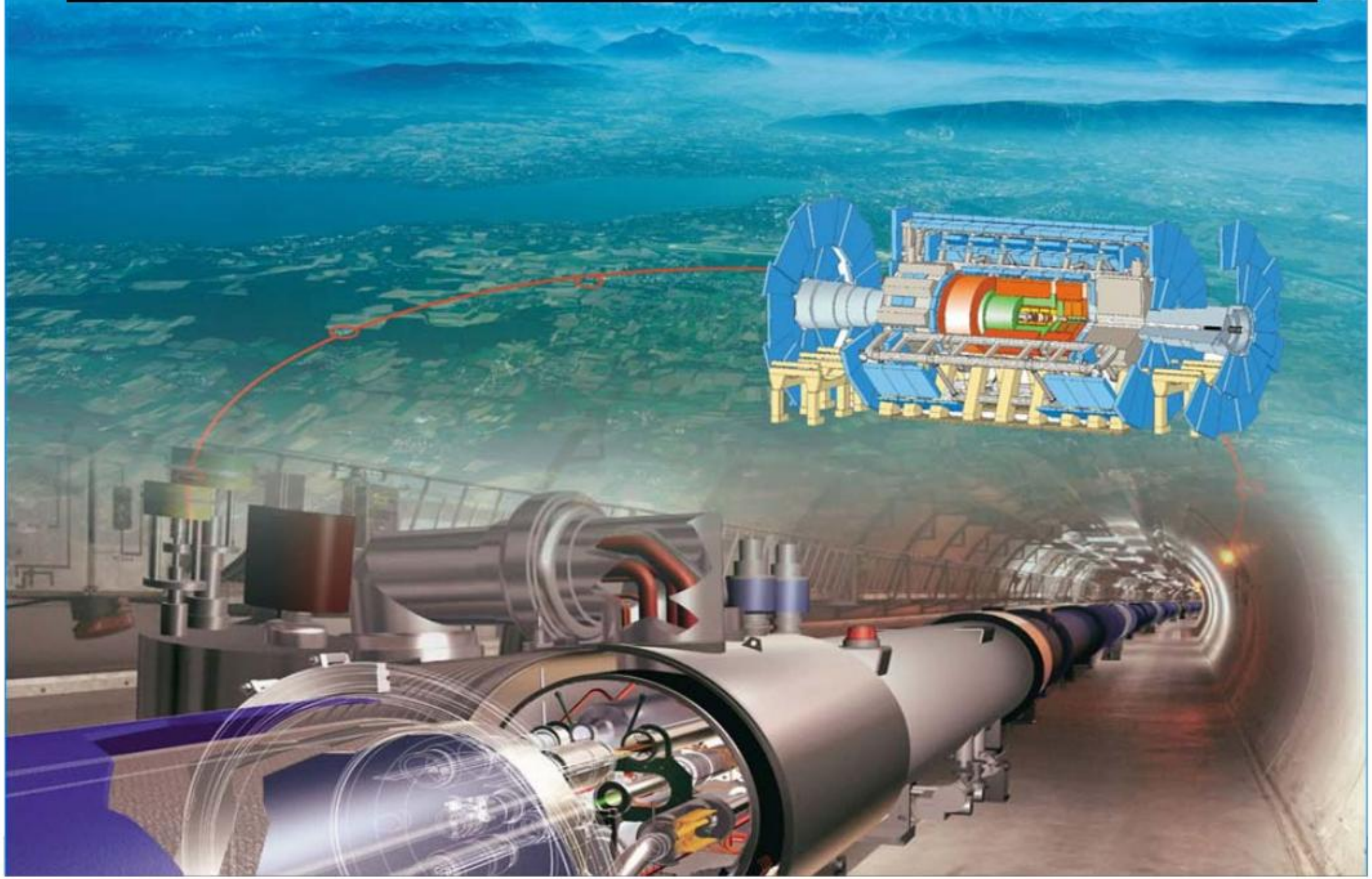
- **Search for doubly-charged Higgs bosons**
  - Predicted in models that contains a Higgs triplet.
    - Leading to final states with 4 leptons

**$pp \rightarrow H^{++}\, H^{--} \rightarrow W^{+}\, W^{+}\, W^{-}\, W^{-}$**



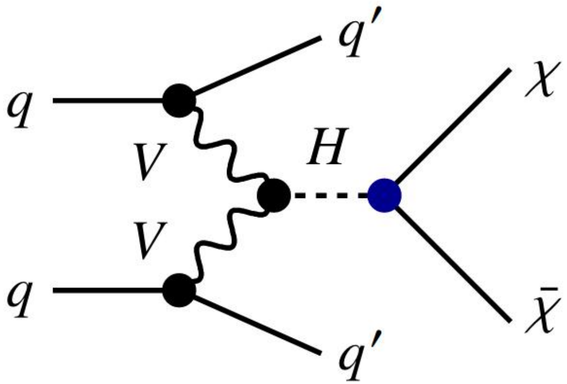



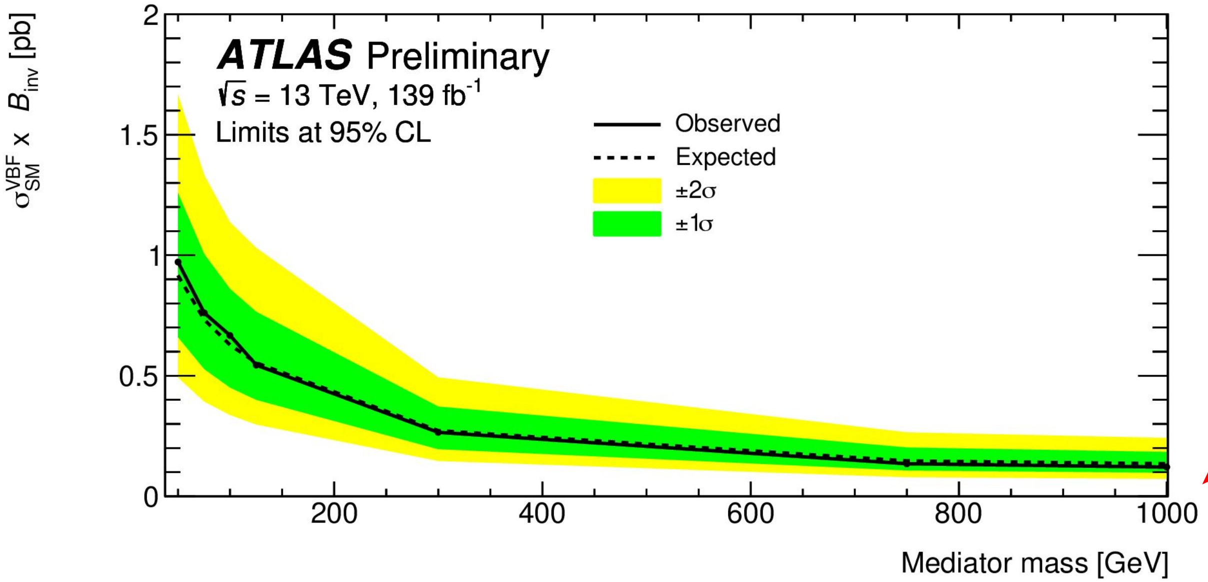
# Searches for other BSM models



# Direct Search for Dark Matter

- Search for **invisible Higgs boson decays [1]**
  - **Motivated by e.g. Higgs-portal models,** which allow BR ~10% for invisible Higgs boson decays
    - **SM predicts BR(H→ νν) = 0.12%**
    - **Decays into WIMPs could explain the**




- **Not necessarily the $m_H$=125 GeV Higgs boson of the SM**

# Direct Search for excited electrons

- **Excited leptons appear in composite models [1]**
  - Introduce new constituent particles called **presons**
    - Binding at high energy scales to form the SM fermions and their excited states
  - Explain the existence of the three generations of quarks and leptons