Nikhef

ATLAS EXPERIMENT

Matter Extensions

BND School 2025

Flavia de Almeida Dias

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University of Amsterdam
Institute of Physics

Matter Particles

- Fundamental matter: point-like spin- $^1/_2$ fermions

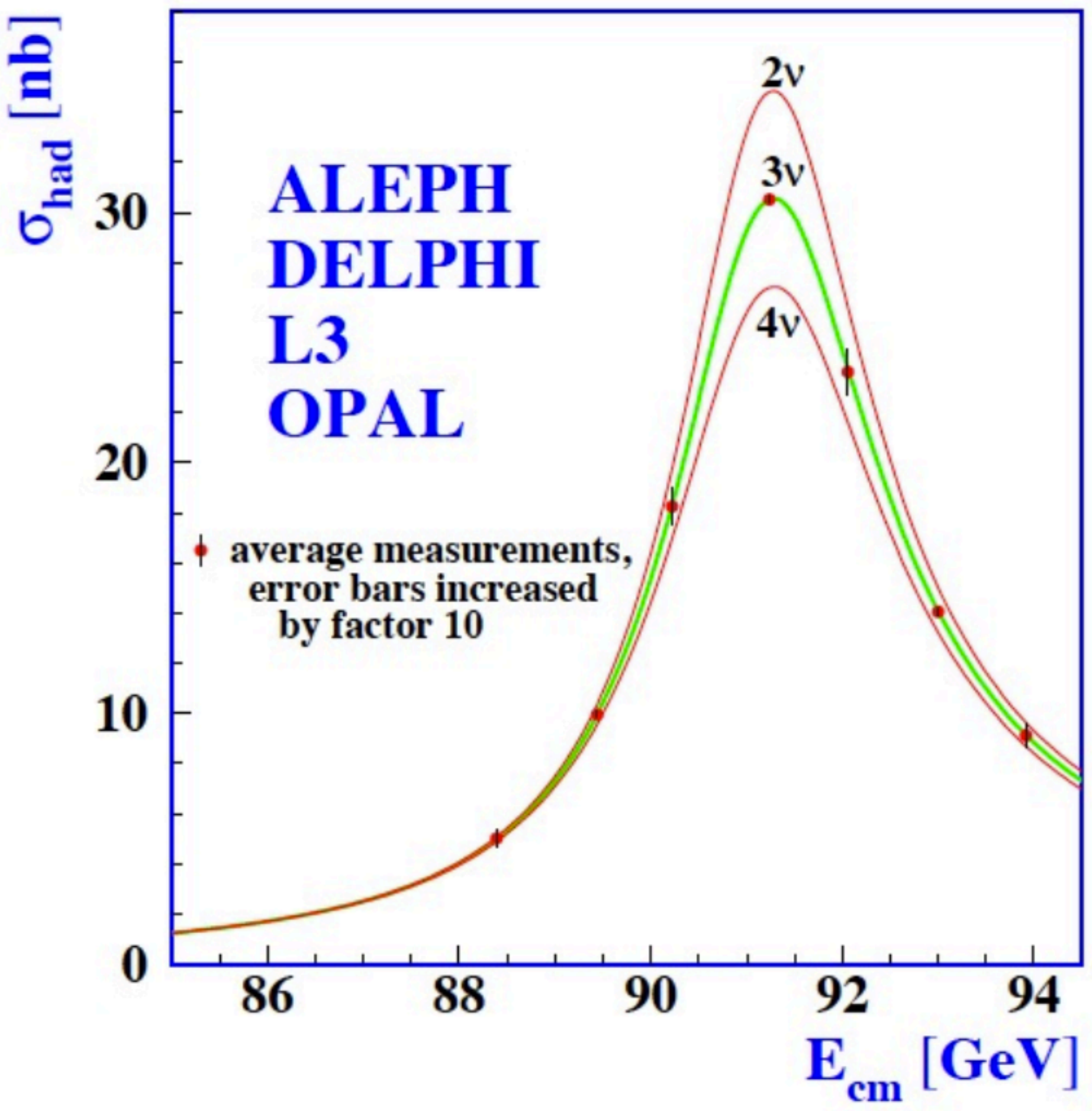
	LEPTONS			QUARKS		
		q	m/GeV		q	m/GeV
First Generation	e^-	–1	0.0005	d	–1/3	0.3
	ν_1	0	≈0	u	+2/3	0.3
Second Generation	μ^-	–1	0.106	s	–1/3	0.5
	ν_2	0	≈0	c	+2/3	1.5
Third Generation	τ^-	–1	1.77	b	–1/3	4.5
	ν_3	0	≈0	t	+2/3	173

The masses quoted for the quarks are the “constituent masses”, i.e. the effective masses for quarks confined in a bound state

➡ Is this all there is?
What if there are more matter particles?

Can we have more neutrinos?

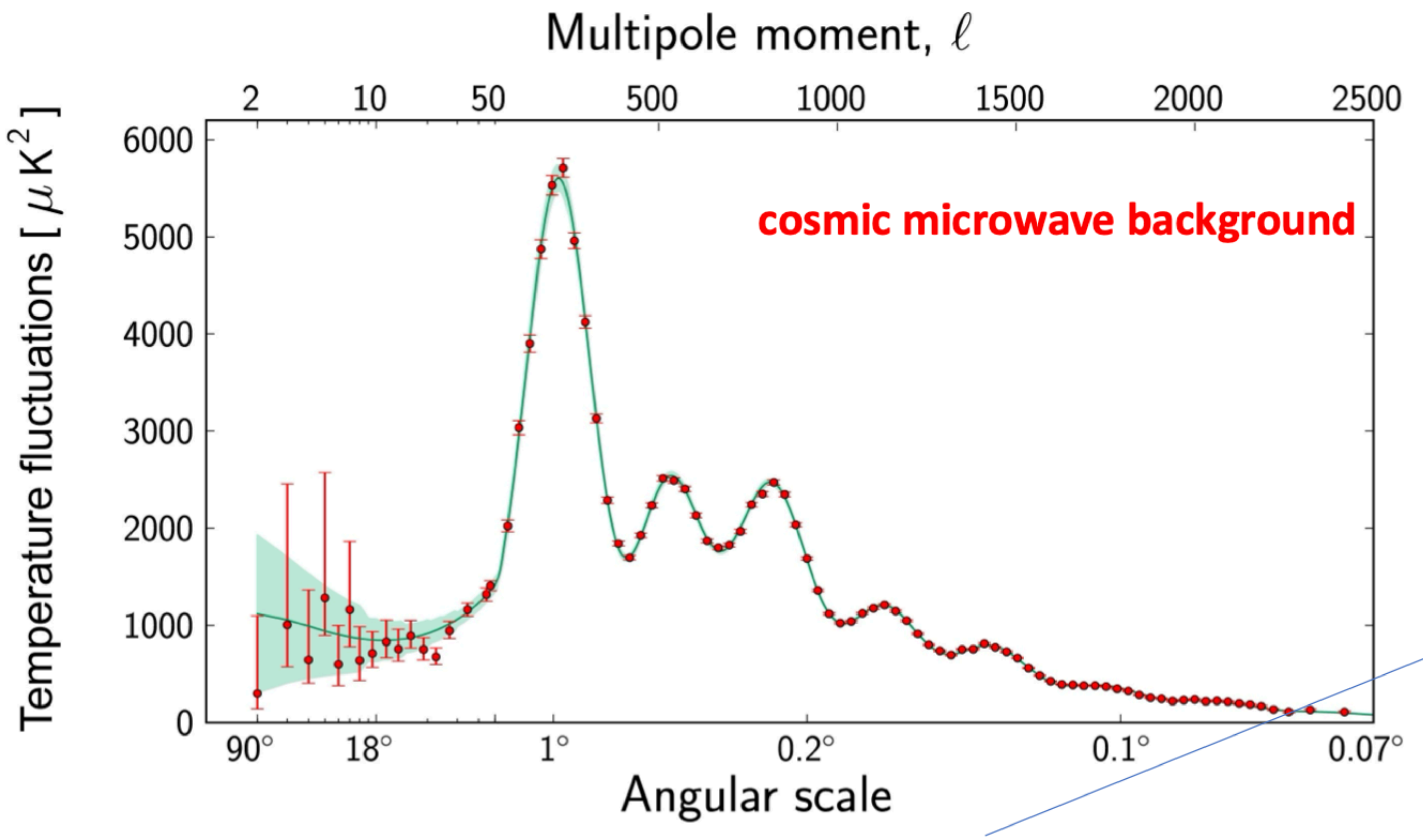
- From LEP experiment
  - New neutrino:
    - ➡ Does nor couple to Z OR
    - ➡ Is heavier than $^1/_2\, m_Z$



$$N_\nu = 2.9963 \pm 0.0074$$

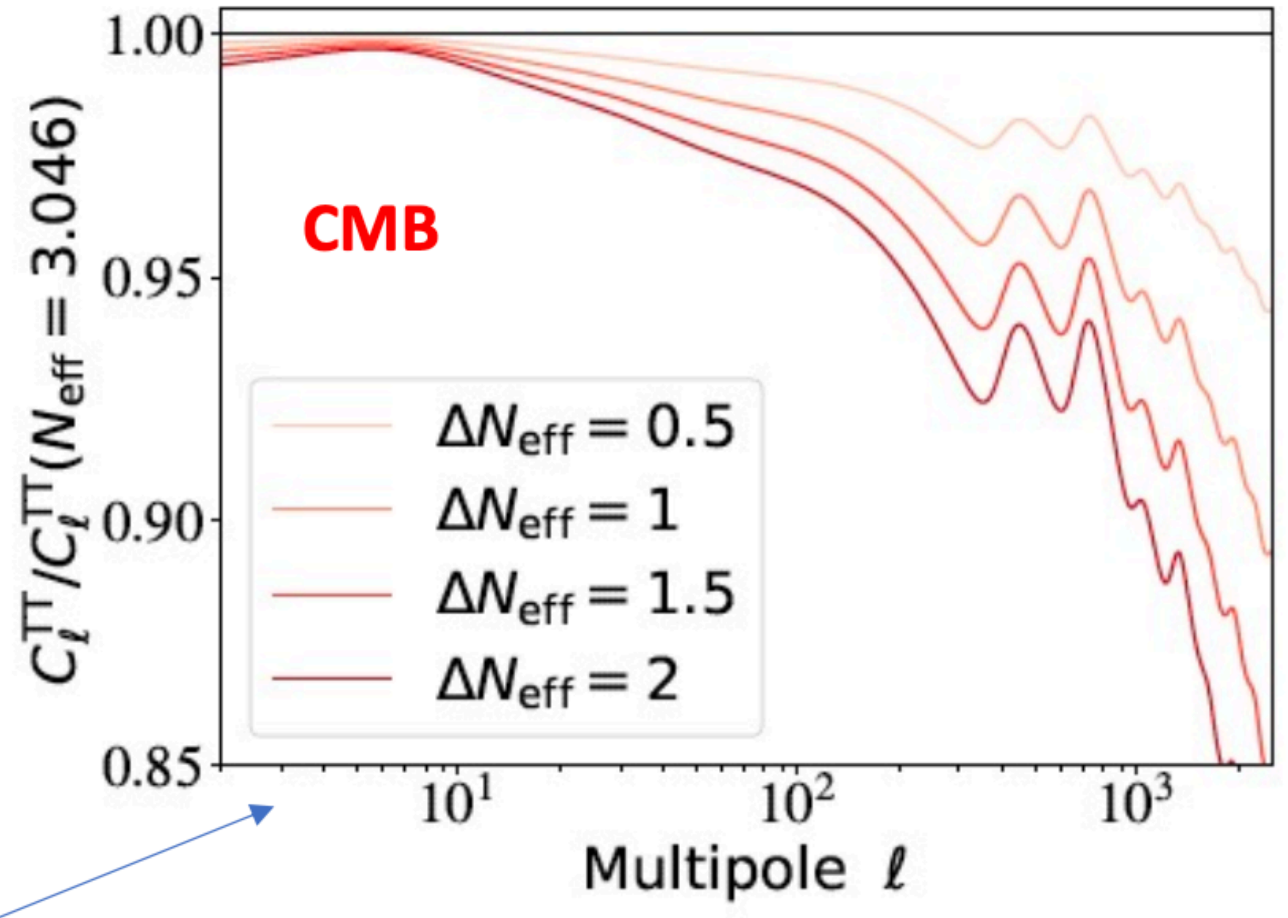
Cosmological constraints

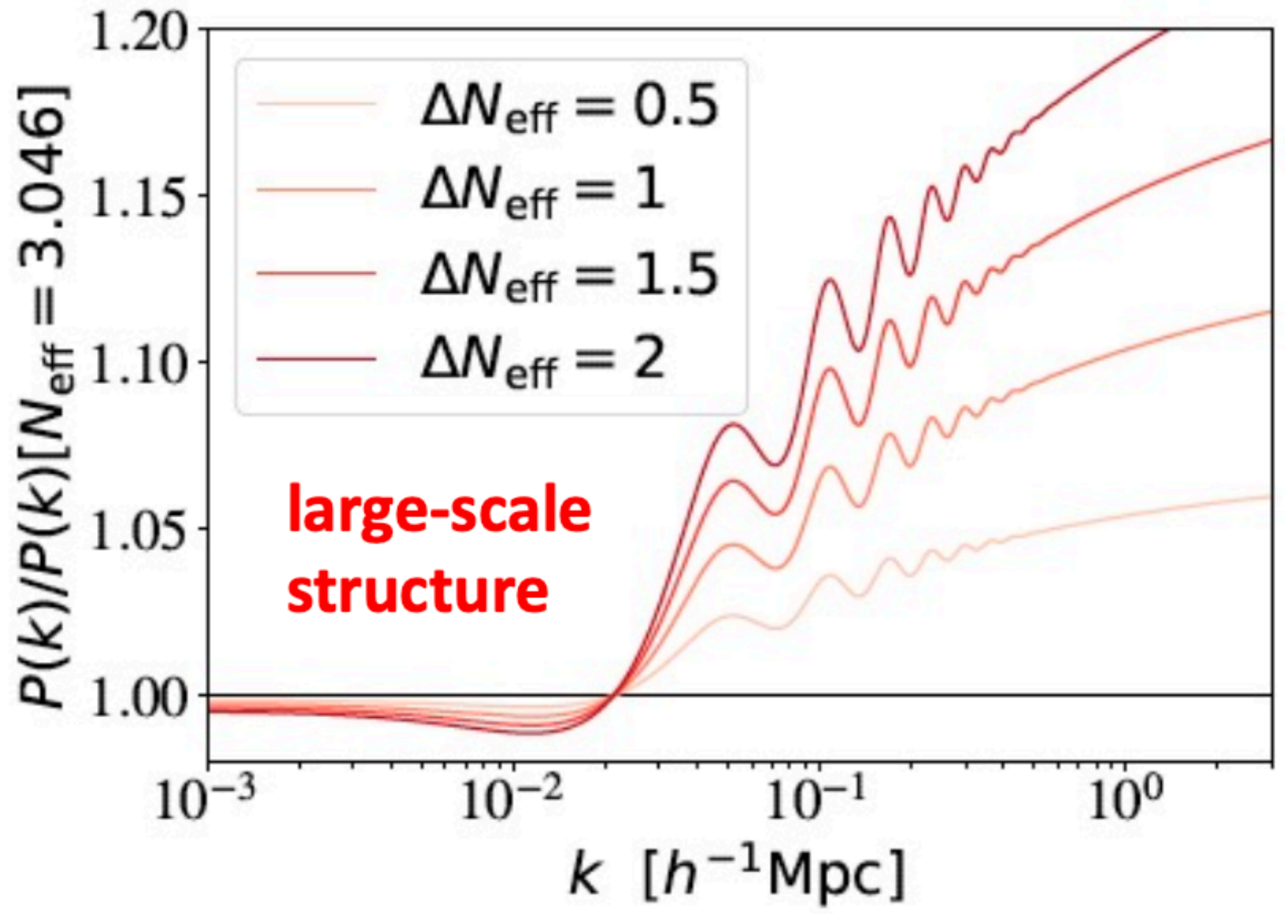
- Neutrinos contribute to the radiation energy density of the universe (~Nν)



Power spectrum (angular correlations between temperature fluctuations) is sensitive to N_{eff}

But also the large-scale density fluctuations of matter in the universe is.





Data prefer Nν = 3

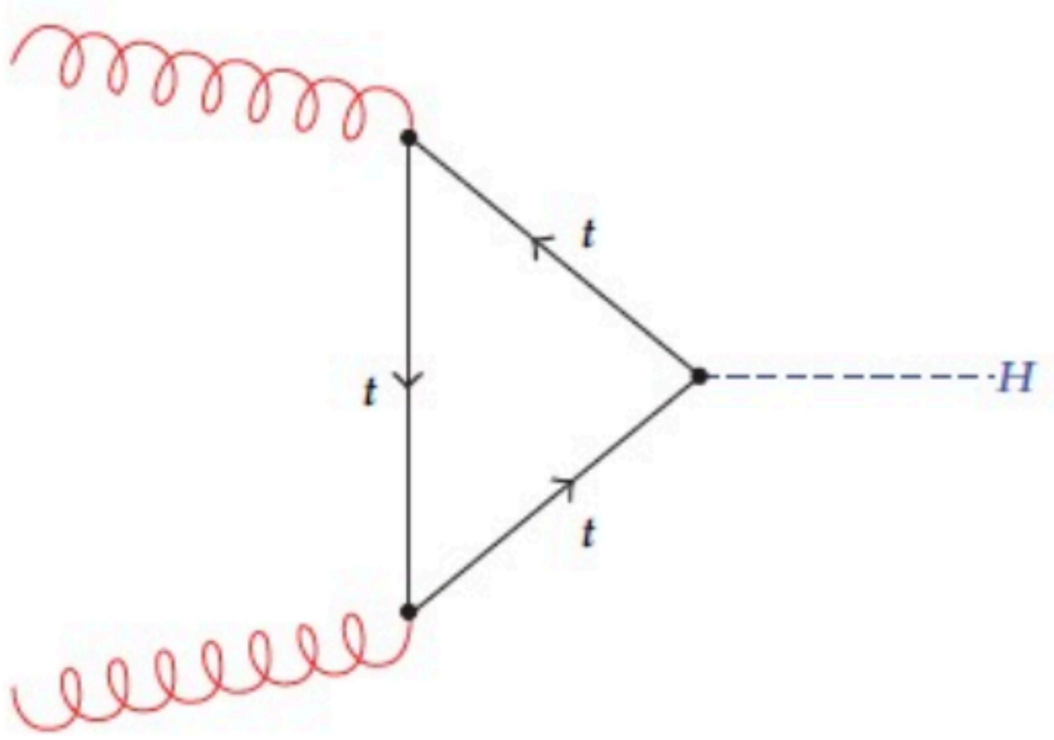
Valid for light (ultra-relativistic) neutrinos

We could still have heavy, sterile neutrinos

Can we have more quarks?

- Chiral quarks (like the SM ones): involved in Higgs production

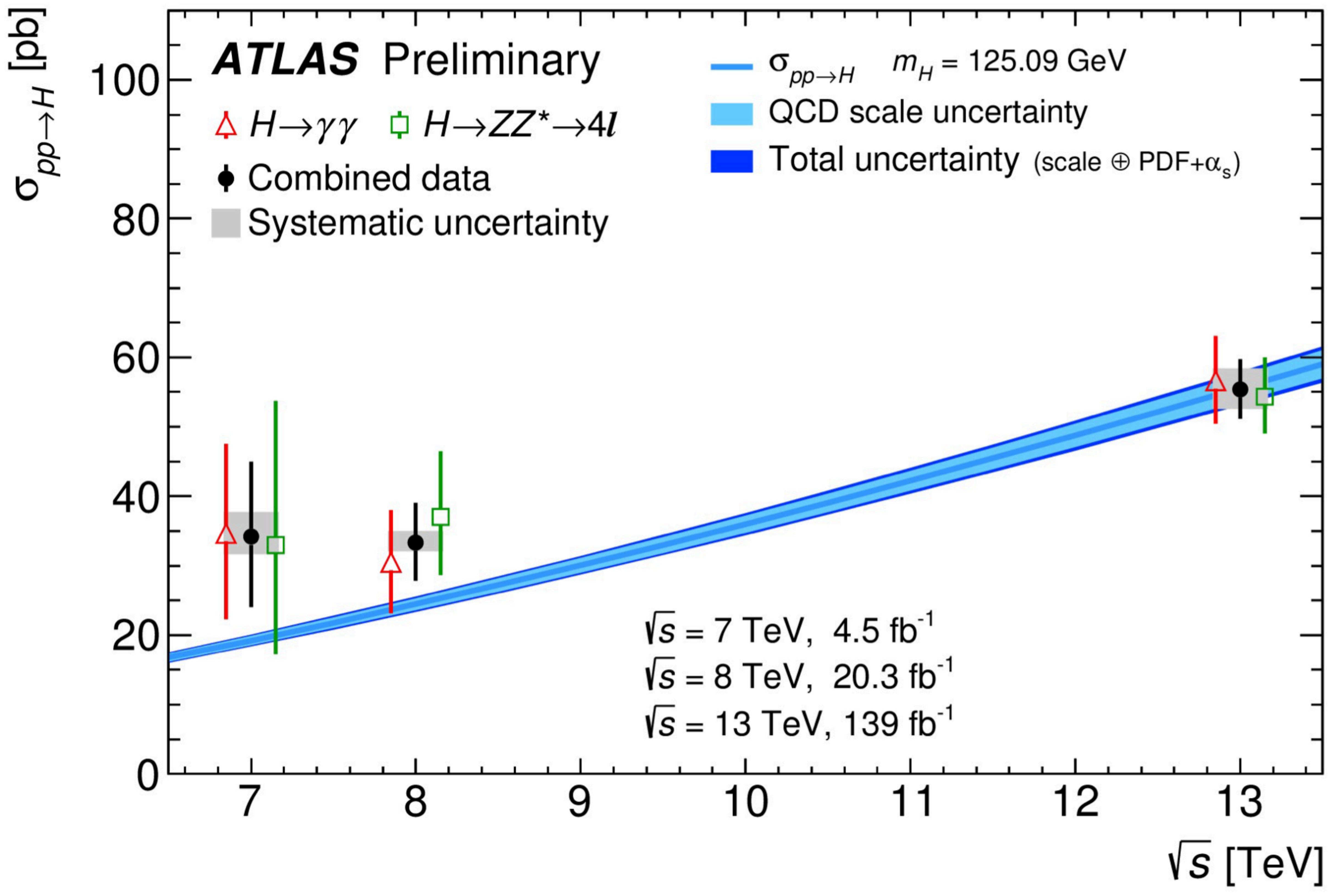
Dominant Higgs production mechanism at LHC: gluon-gluon fusion

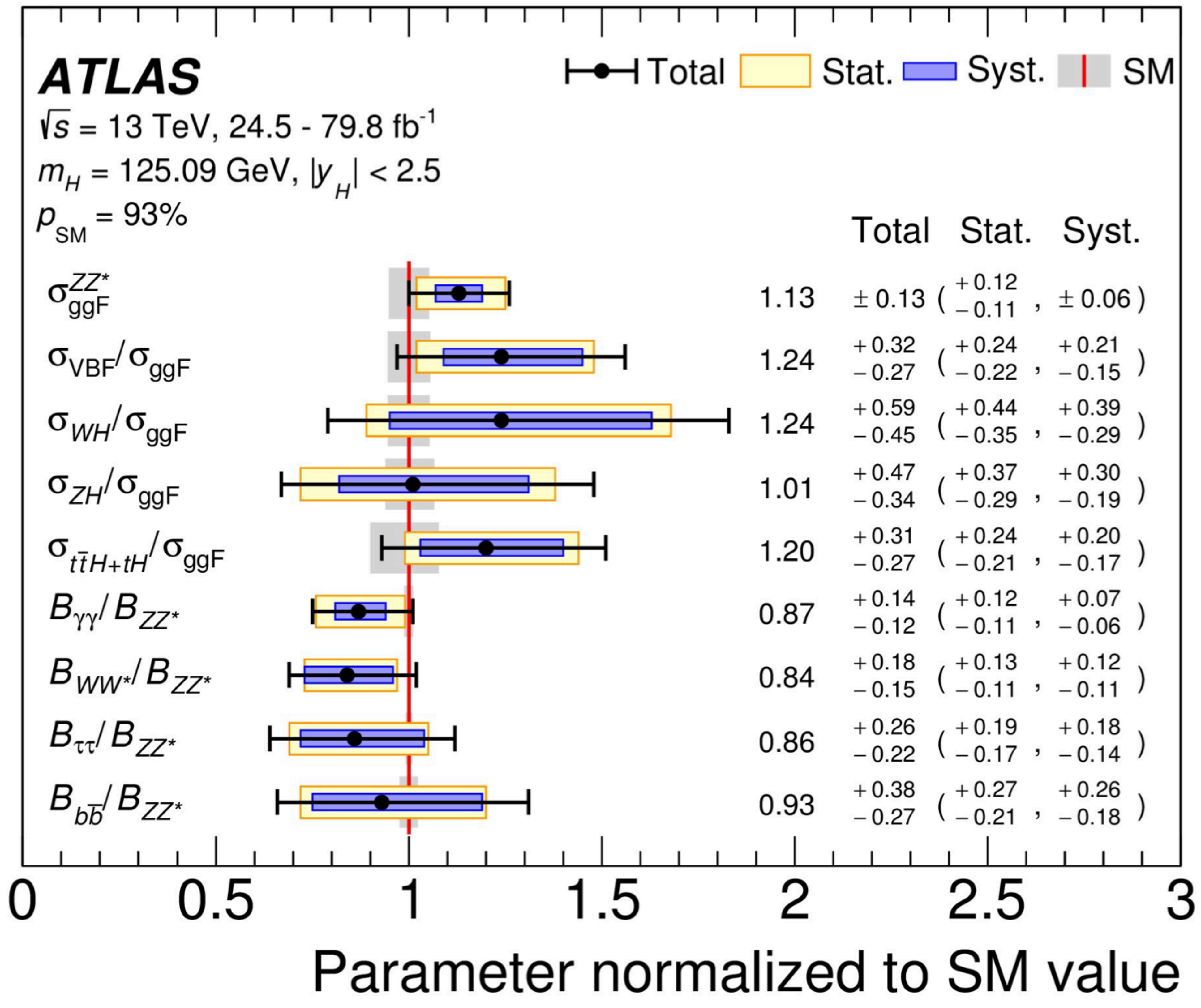


gluon couples to Higgs via a loop
all quarks run in the loop
cross-section turns out to be dominated by heaviest quarks

(actually trade-off between $1/q^2$ and coupling to the Higgs)

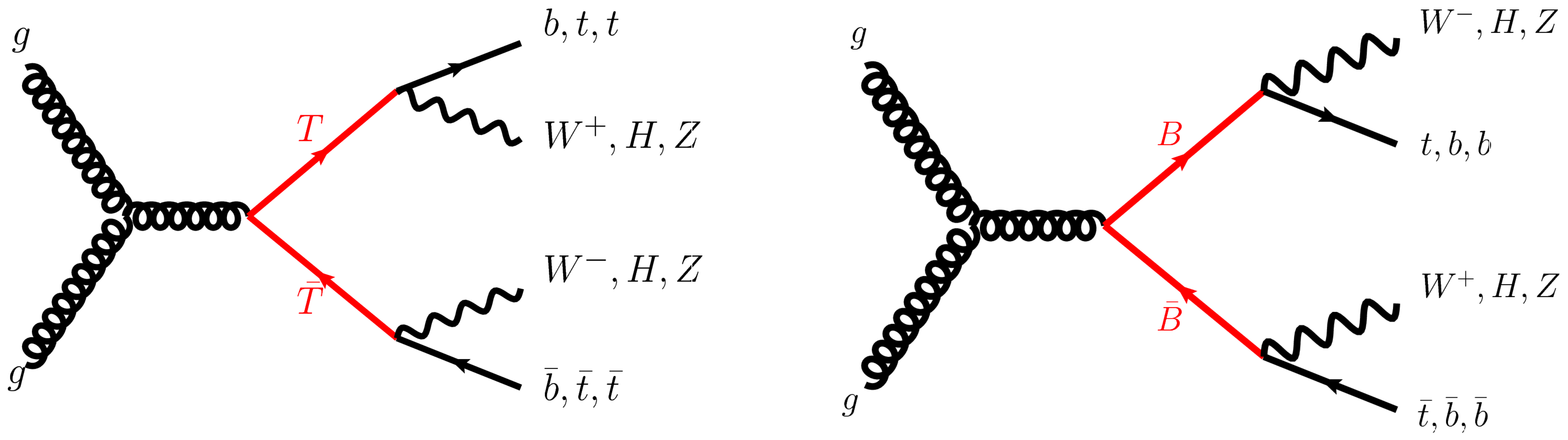
- Higgs data forbids new chiral quarks as the SM quarks

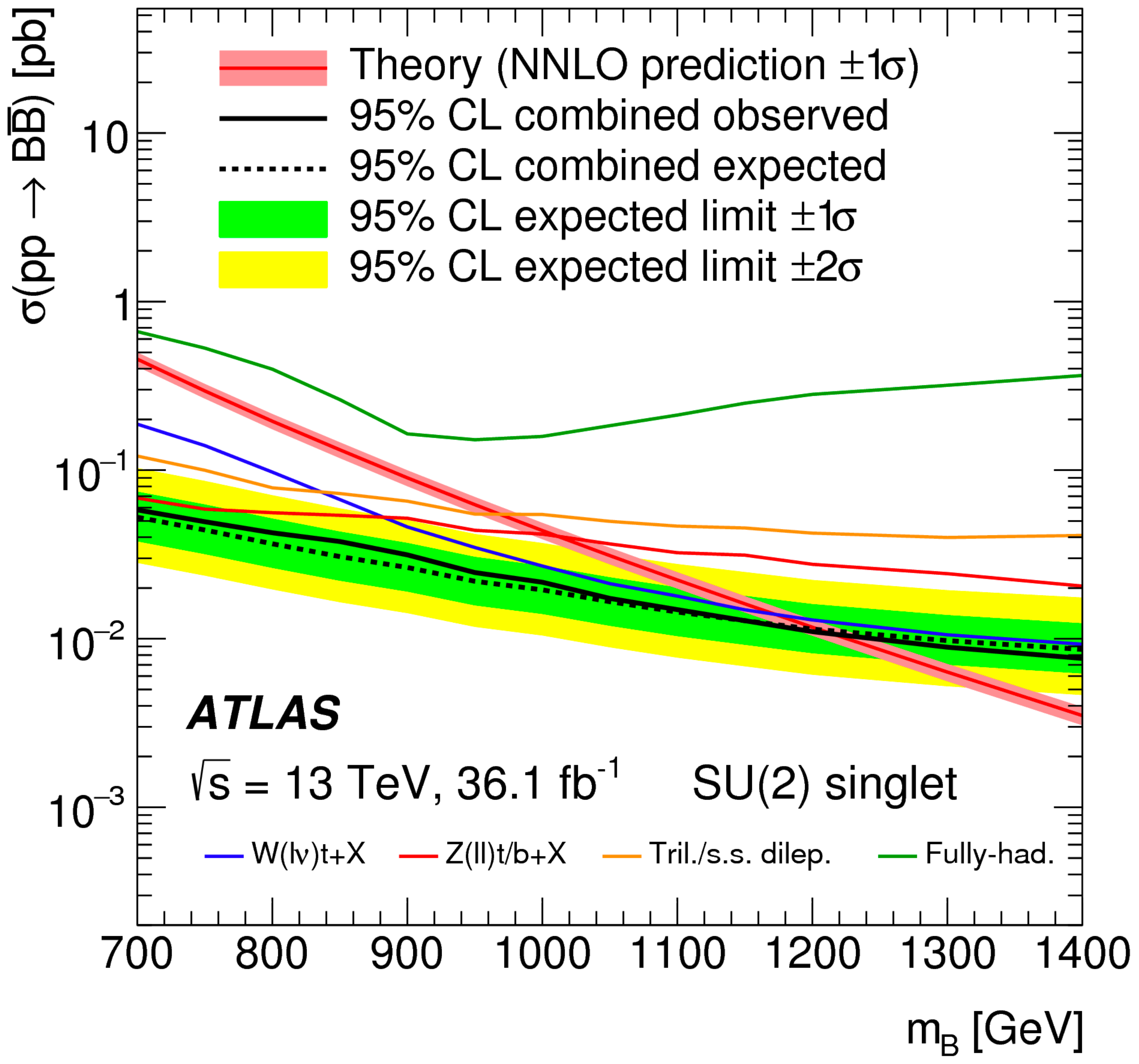




Can we have different quarks?

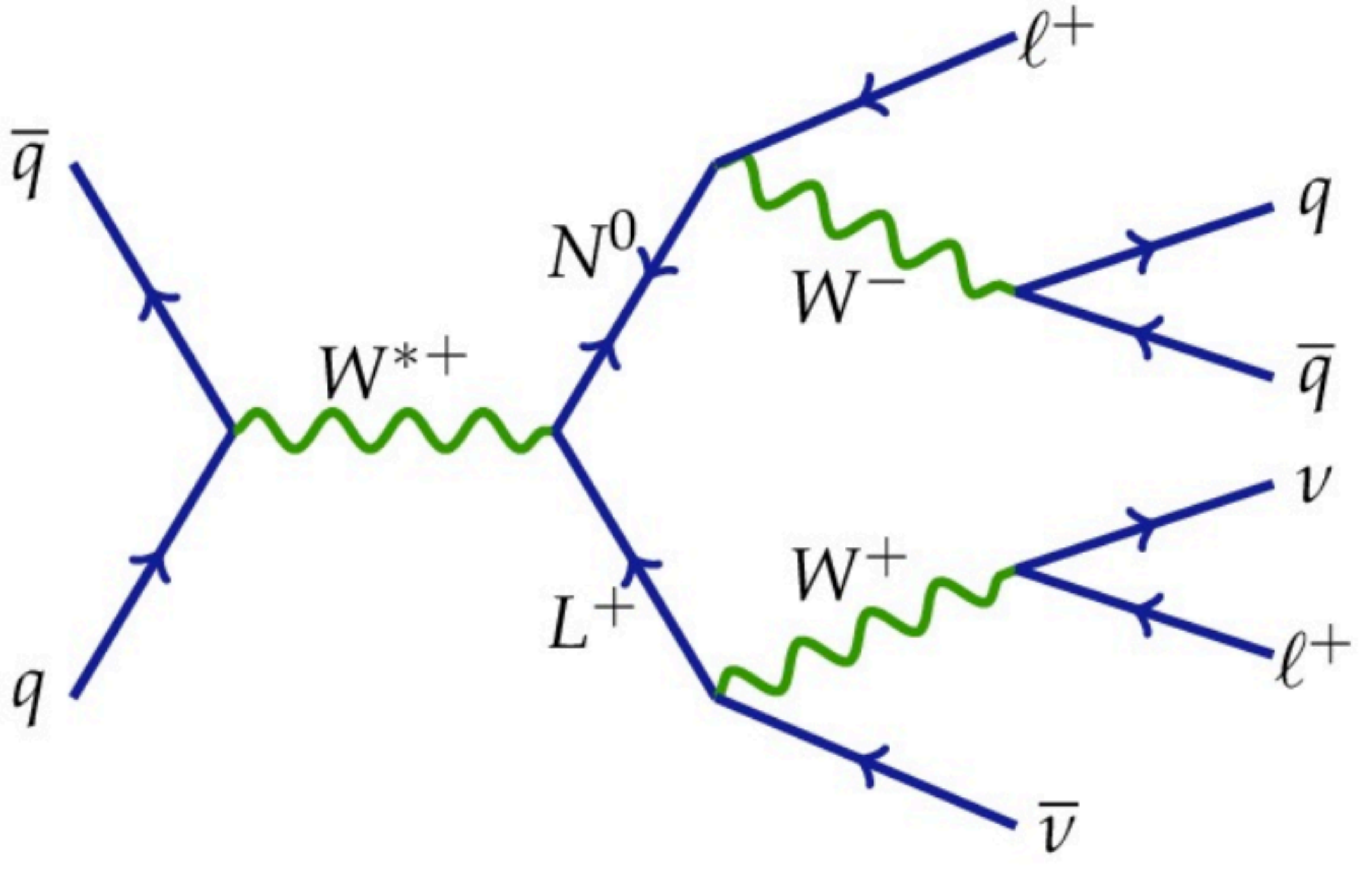
- Vector-like quarks (VLQ):
  - ➡ Right and left-handed are the same (no Higgs for mass)
  - ➡ Same $SU(3)_C$ gauge structure as SM.
    - ➡ Top-like VLQ: T′ → Ht, Zt, Wb
    - ➡ Bottom-like VLQ: B′ → Hb, Zb, Wt

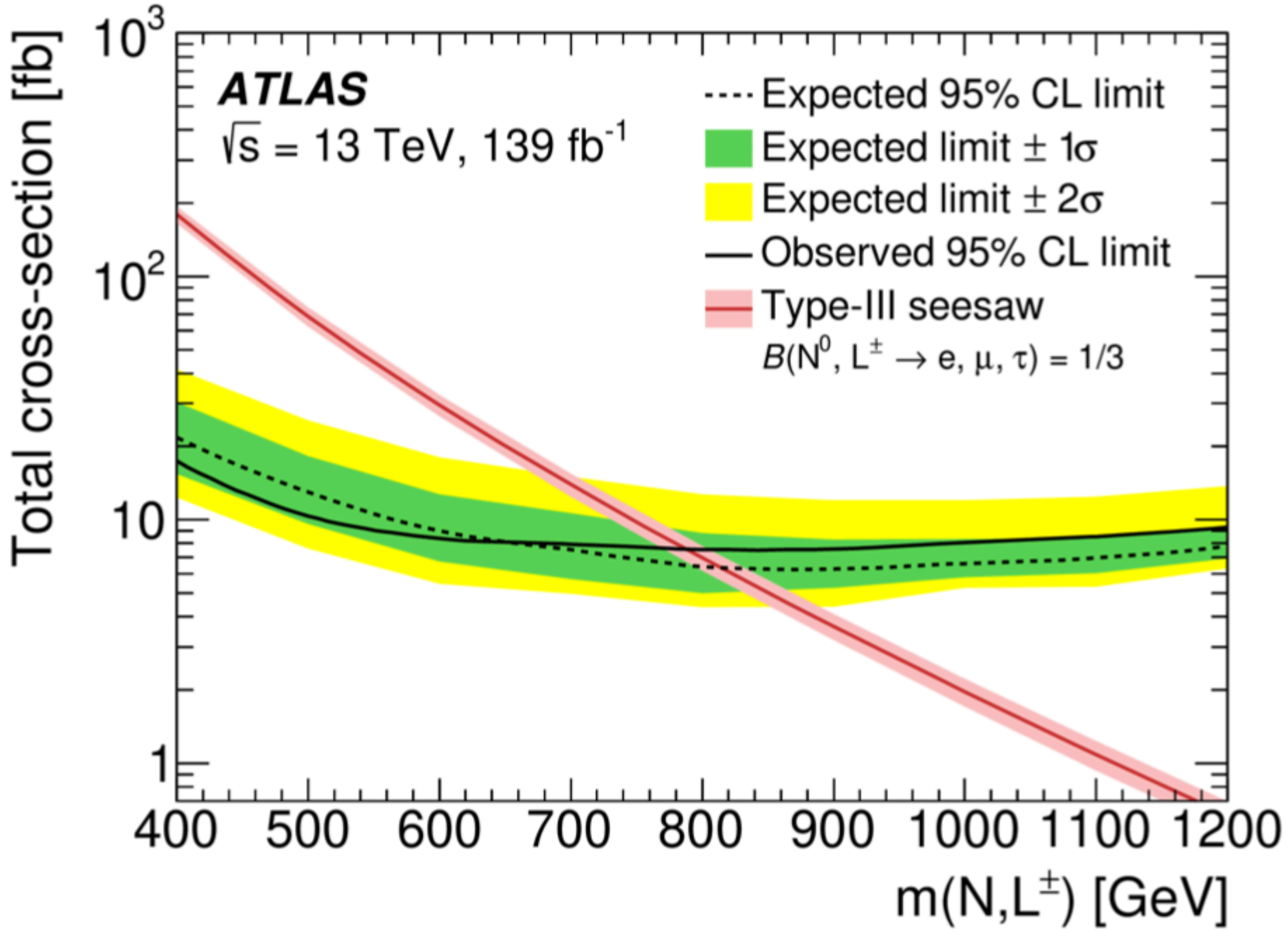




Can we have heavy charged leptons?

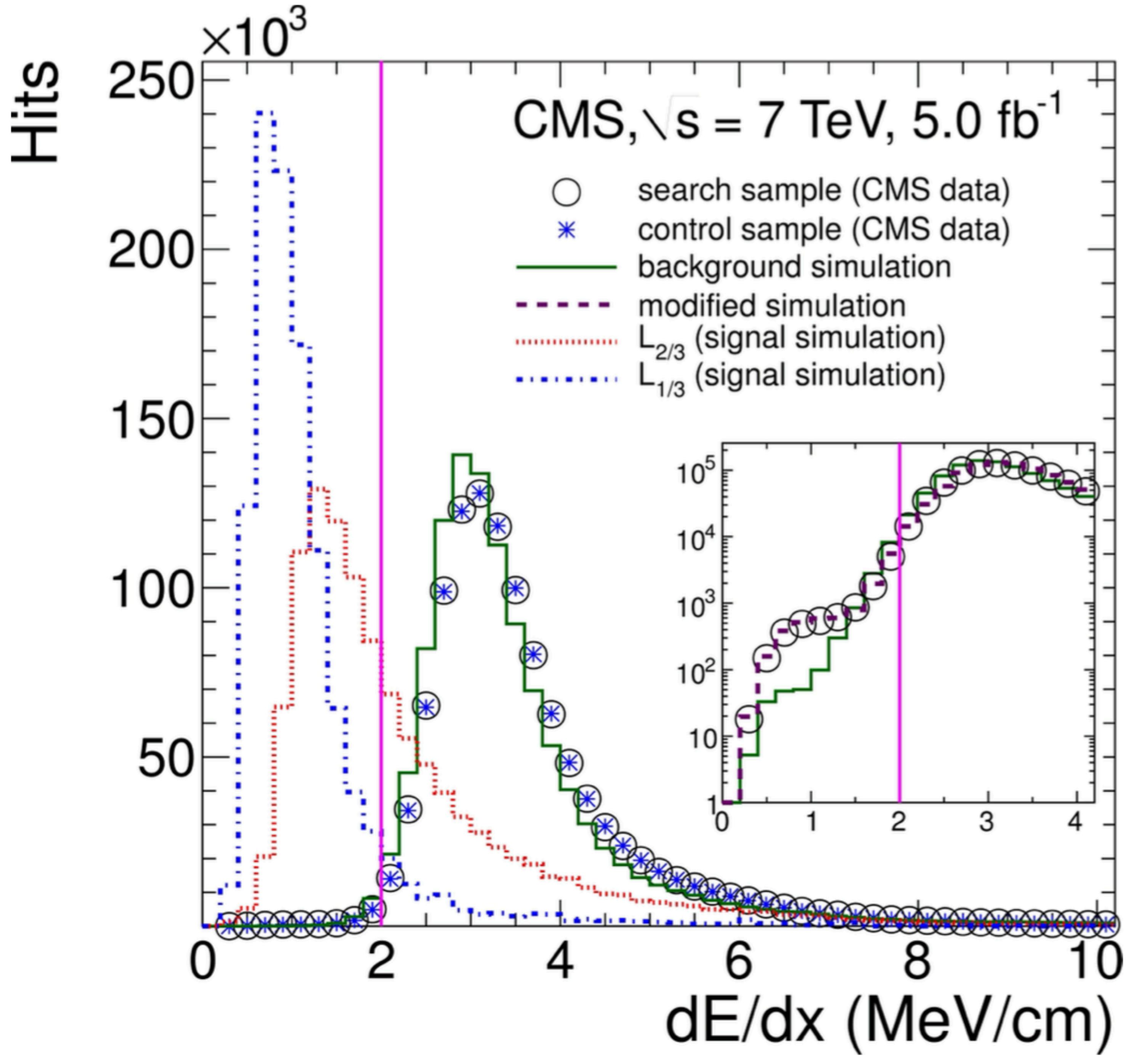
- $L^{\pm} \to \nu W$: LEP exclusion at ~100 GeV
- Models to give neutrino masses (see-saw) could have a triplet: $L^{\pm}$, N^0





Can we have particles with fractional charges?

- "Free" quarks
  - ➡ Particles with fractional charge which are not confined by the strong force
  - ➡ Ionisation properties ~charge



Millikan Oil Drop Experiment

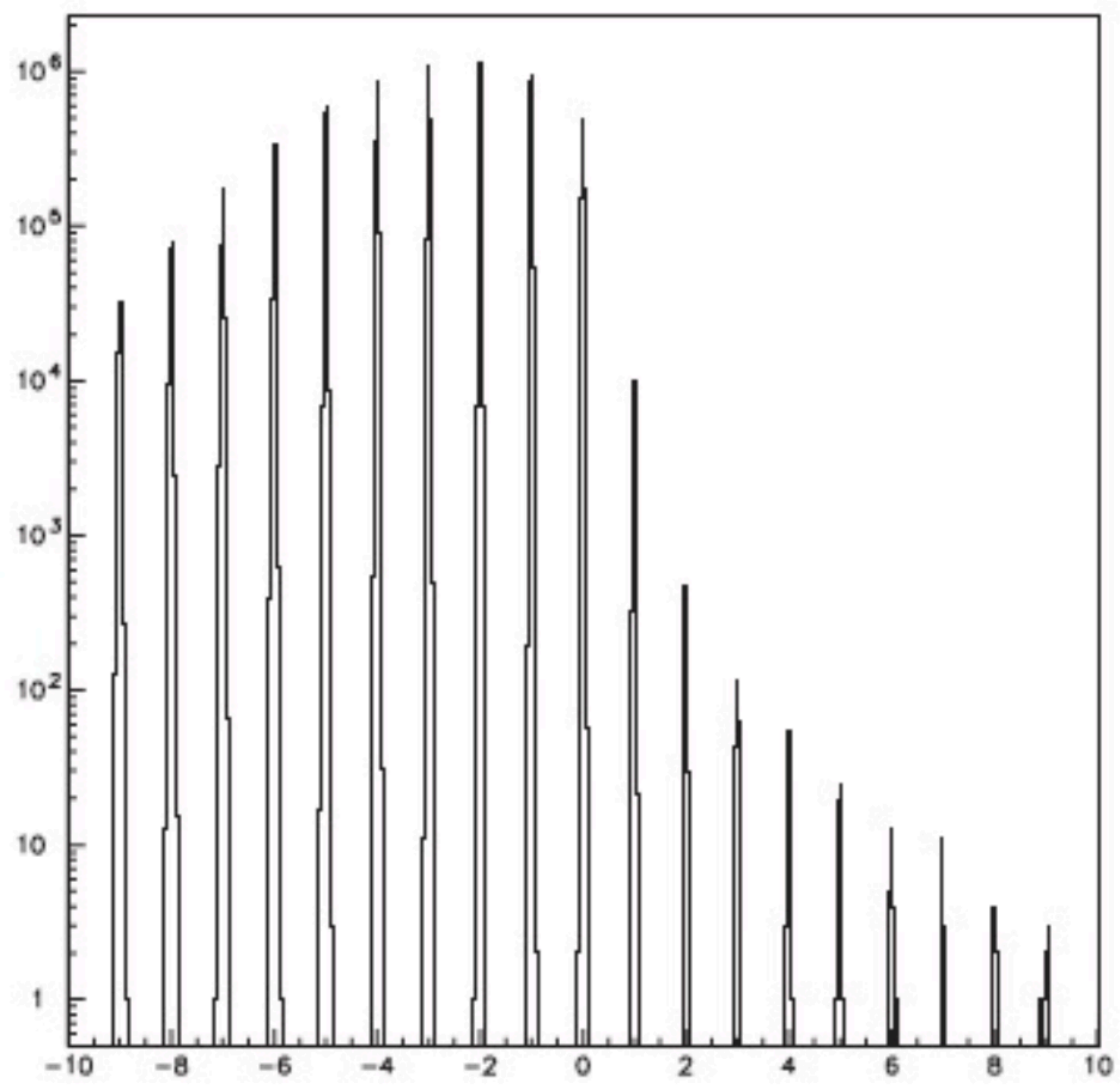
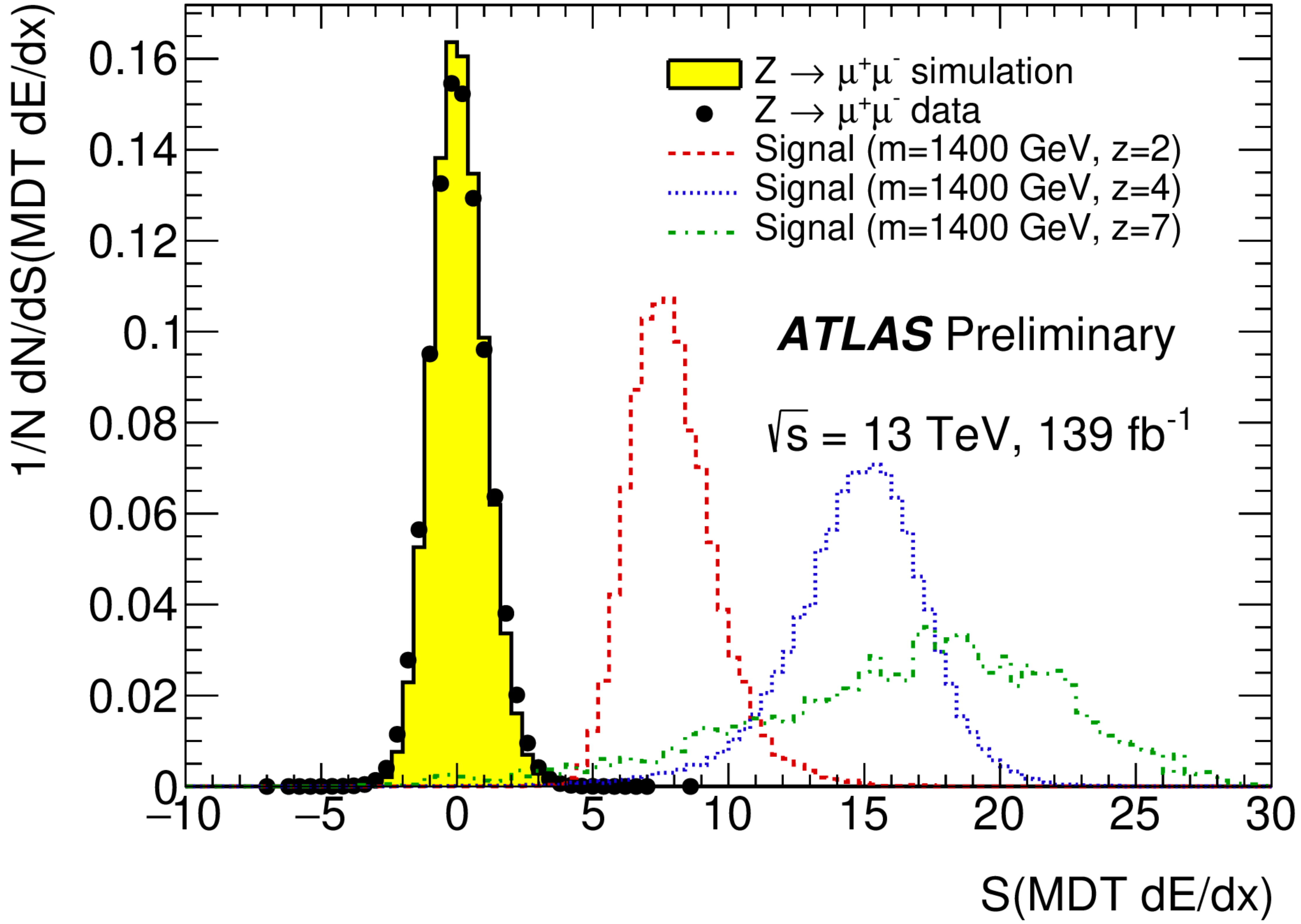
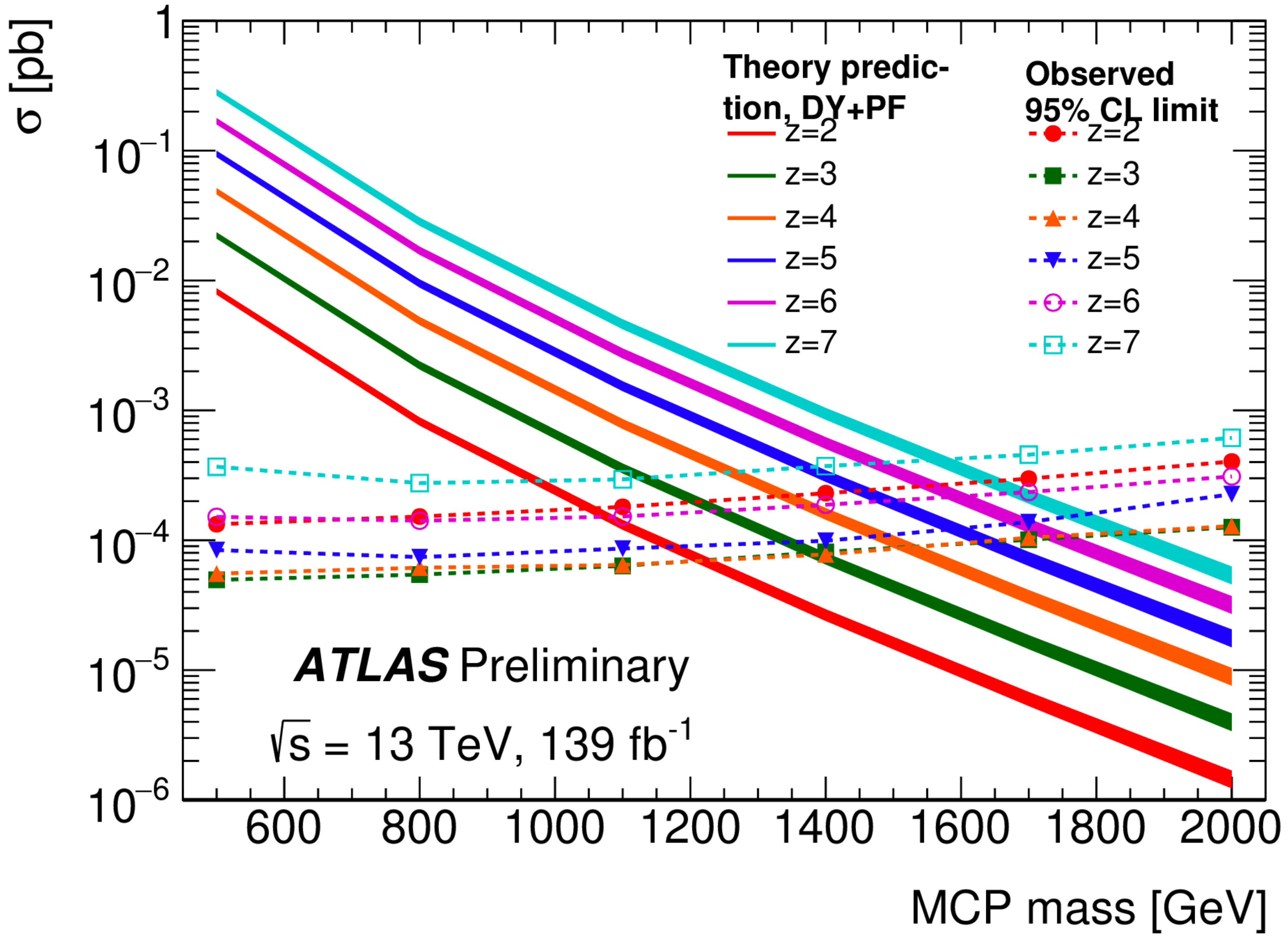


Fig. 2. The f charge distribution in 70.1 mg of silicone oil.

Can we have particles with charge >1?

- Multi-charged particles would also have a different ionisation behaviour

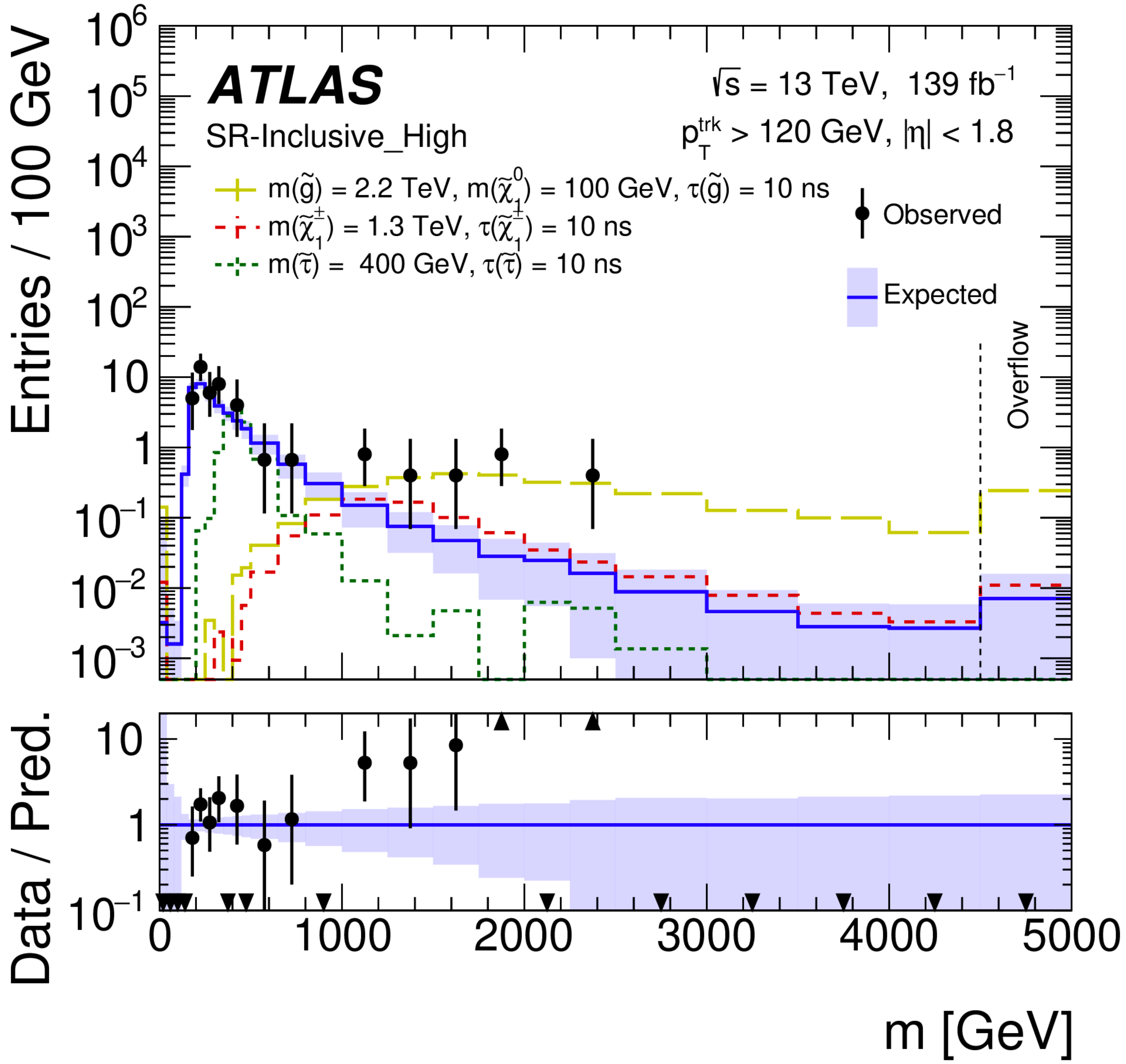




Selection	$N_{\text{data}}^{\text{A observed}}$	$N_{\text{data}}^{\text{B observed}}$	$N_{\text{data}}^{\text{C observed}}$	$N_{\text{data}}^{\text{D expected}}$	$N_{\text{data}}^{\text{D observed}}$
$z = 2$	24 294	4039	9	1.5 ± 0.5 (stat.) ± 0.5 (syst.)	4
$z > 2$	192 036 934	15 004	441	0.034 ± 0.002 (stat.) ± 0.004 (syst.)	0

SUSY dE/dX Excess

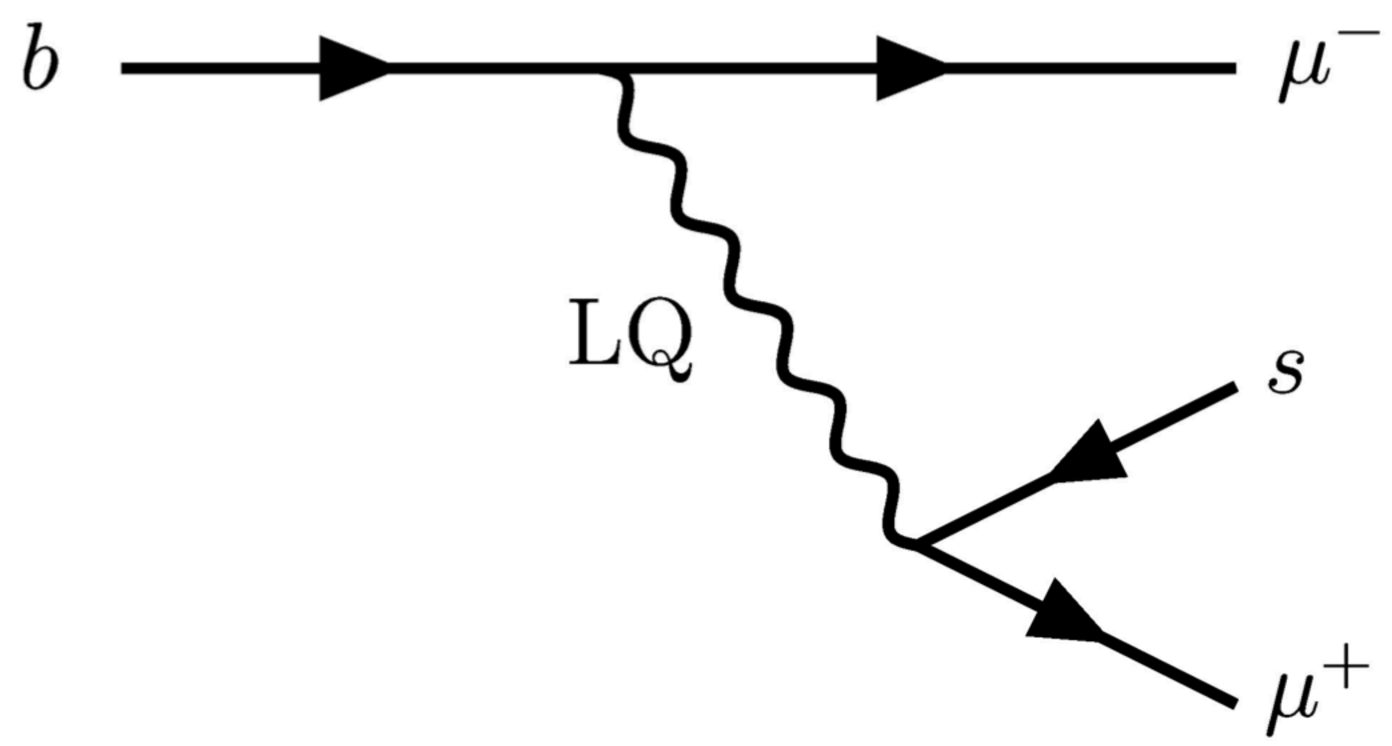
- Search for stable hypothetical massive, charged, long-lived particles



3.3σ excess in region optimised for 1.4 TeV mass hypothesis

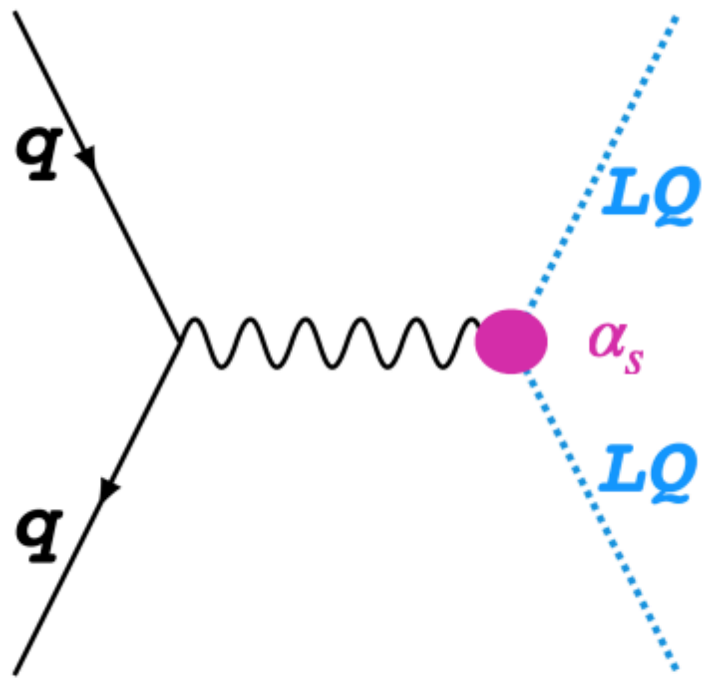
Leptoquarks

- Particle carrying both baryon and lepton numbers



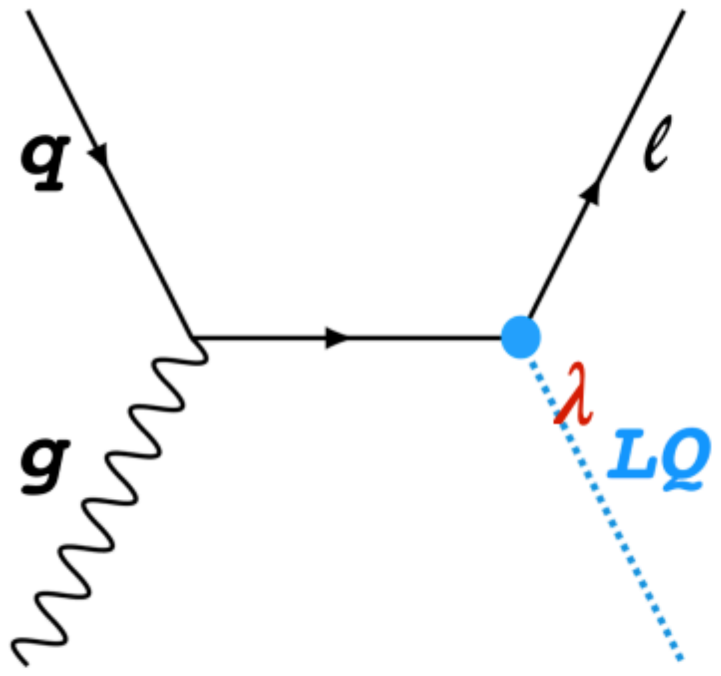
- Can be scalar (spin-0) or vector (spin-1)
- SU(3) triplets or SU(2) singlets, doublets, triplets

- Many degrees of freedom
  - Mass, electrical charge, scalar/vector type, Yukawa couplings (λ)
  - Produced in pairs, singly, off-shell, s/t-channel
  - β parameter: branching fraction of LQ into charge lepton (β=1) or neutrino (β=0)



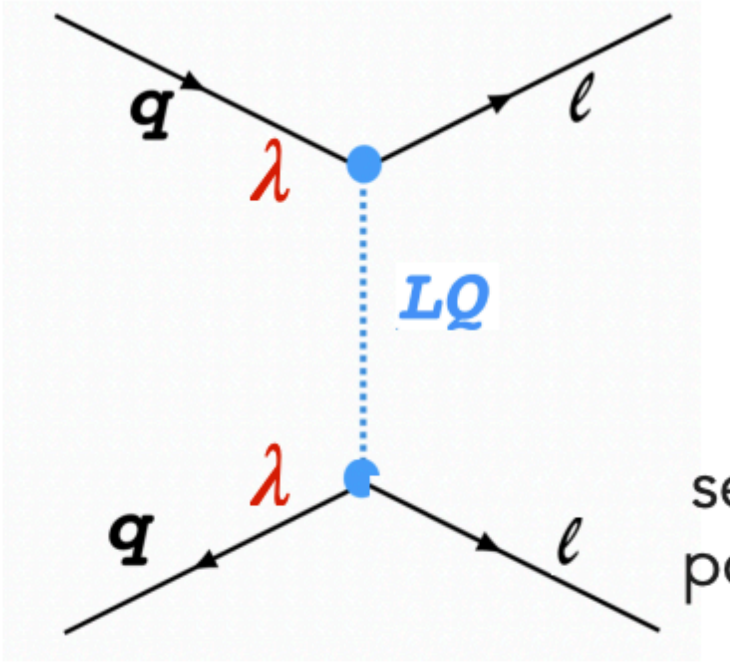
Pair production

QCD driven process
cross section depends on the mass



Single production

cross section ∝ λ^2
sensitive to higher m_{LQ} for sufficiently high λ

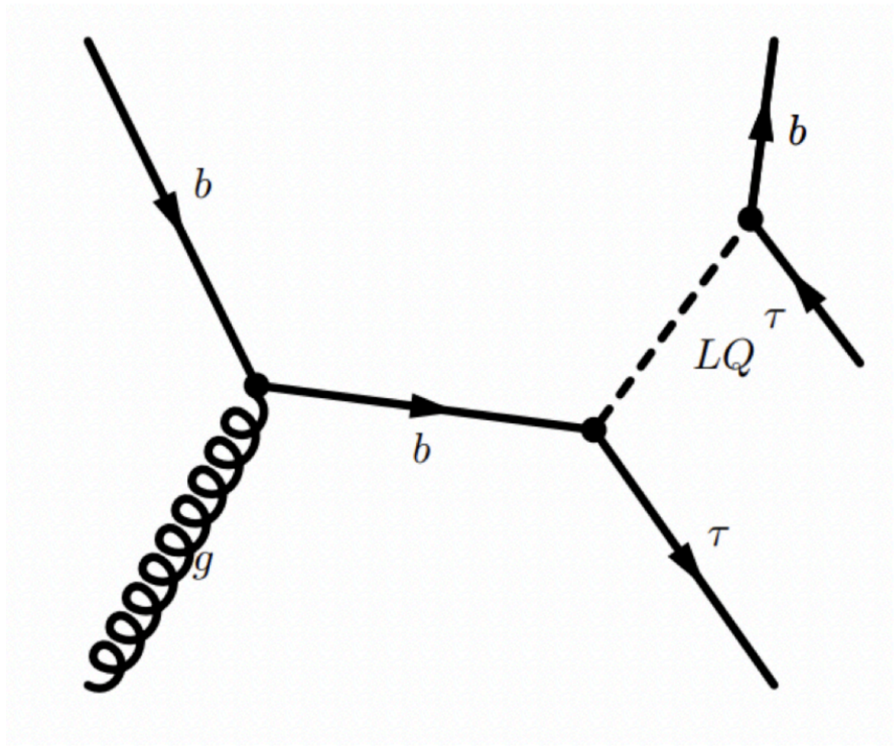


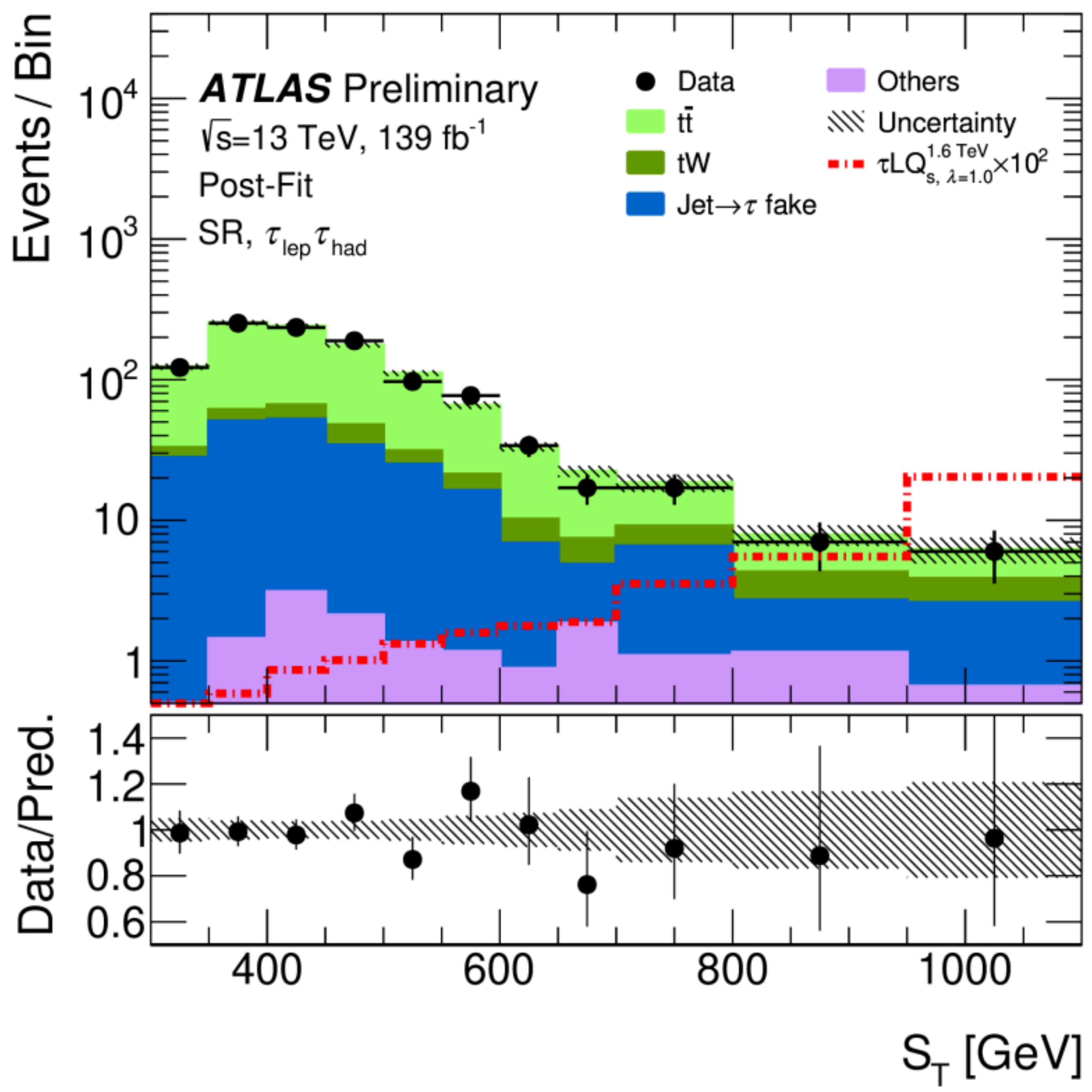
Off-shell production

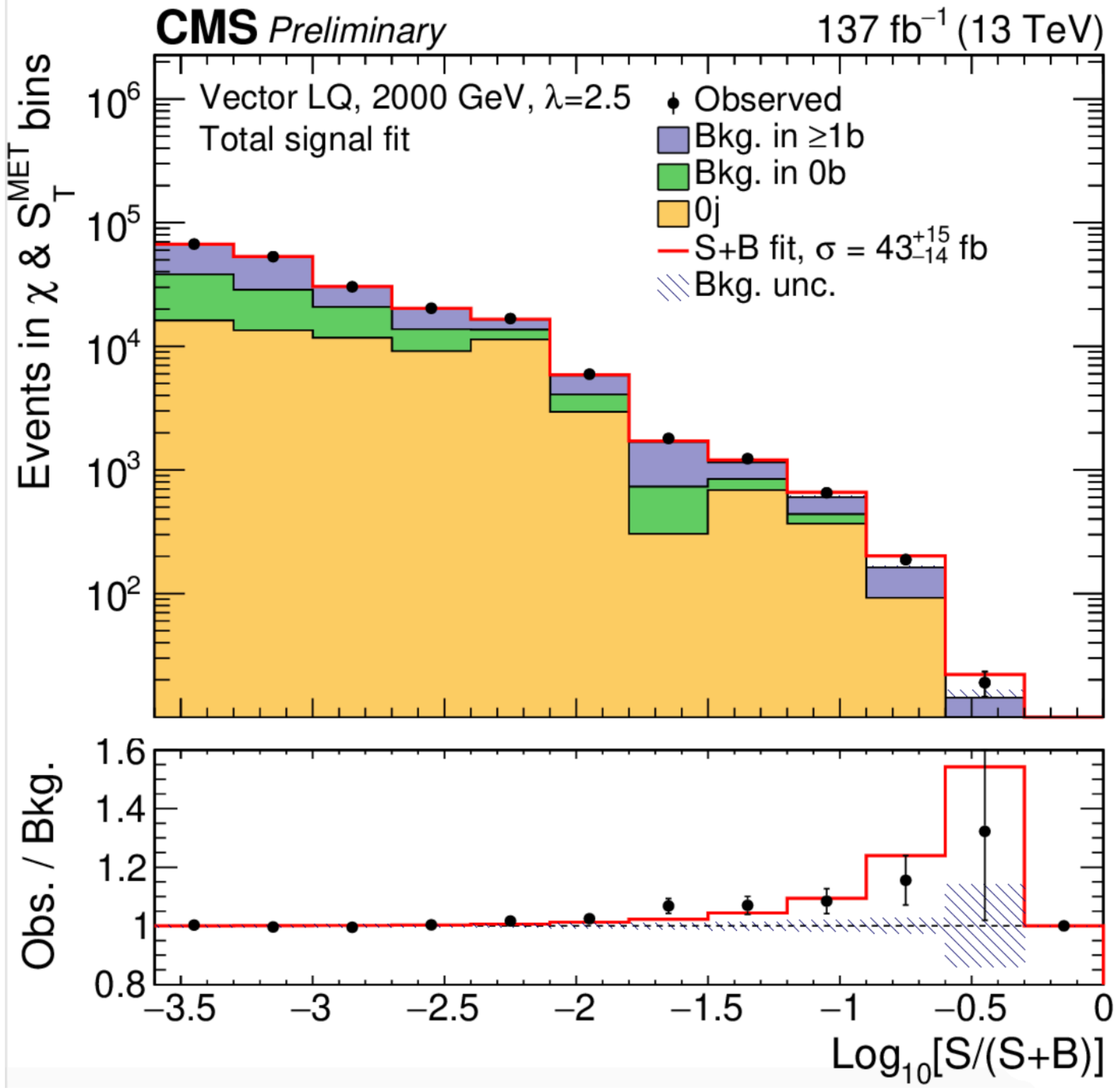
cross section ∝ λ^4
non-resonant
sensitive to very high masses
possible interference with SM

Leptoquark Searches at the LHC

- Broad program searching in single or double production

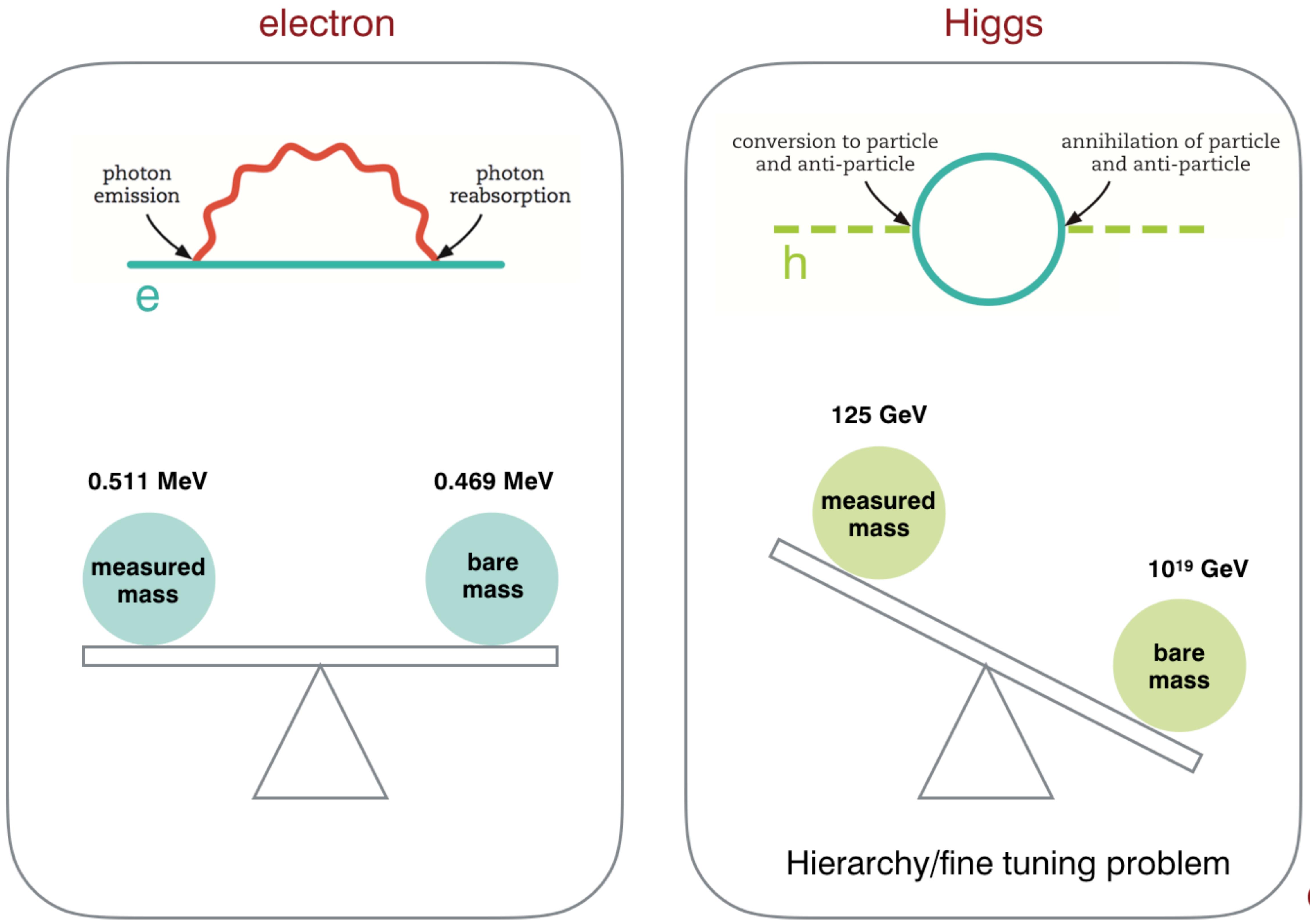






Can we have more Higgs bosons?

- Higgs boson is unique:
  - ➡ Only fundamental scalar in the Standard Model
  - ➡ Hierarchy problem and the Higgs mass

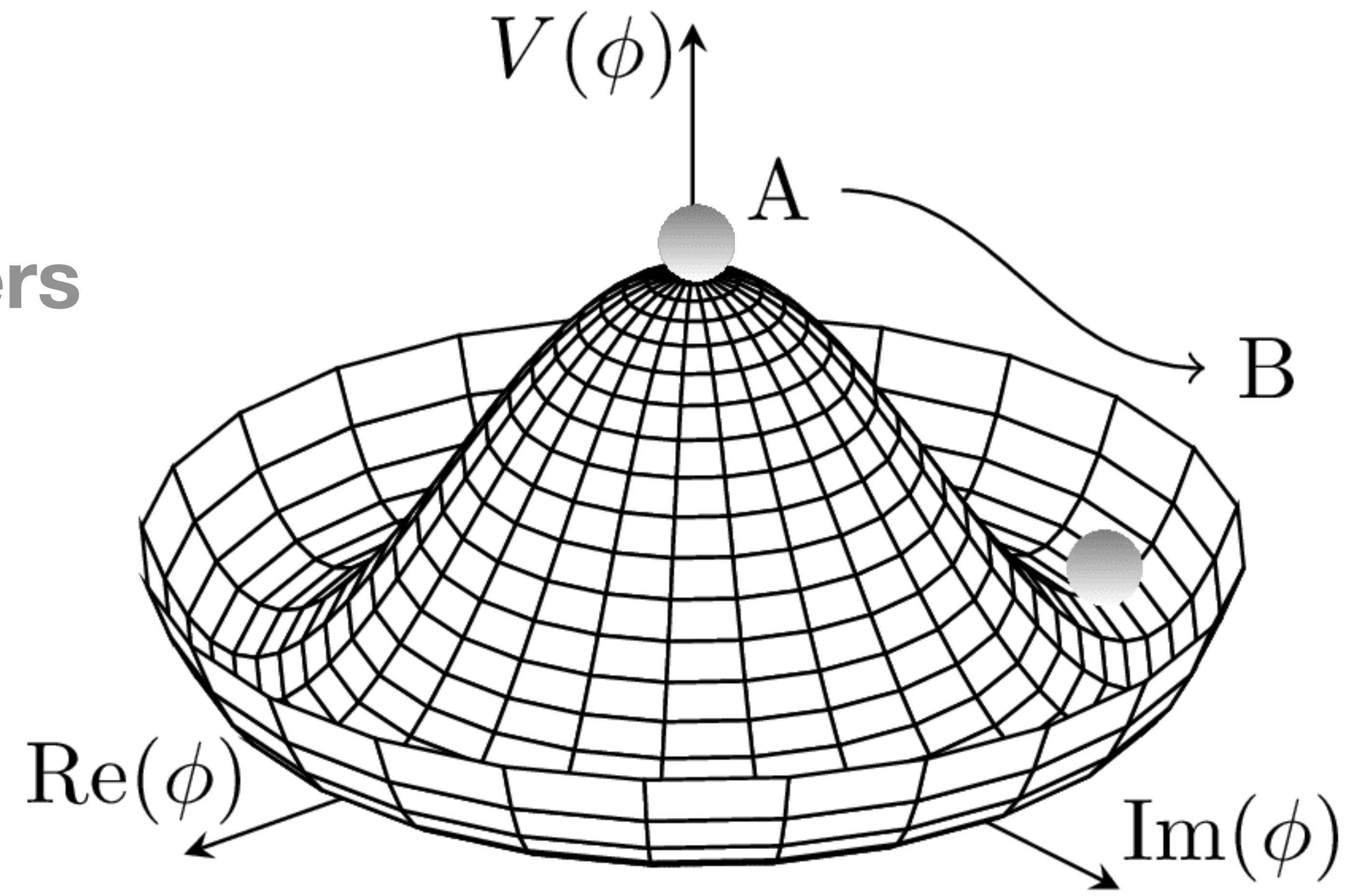


Standard Model Higgs Mechanism

One scalar SU(2)$_L$ doublet with hypercharge $Y = +1$:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Complex numbers
4 degrees of freedom



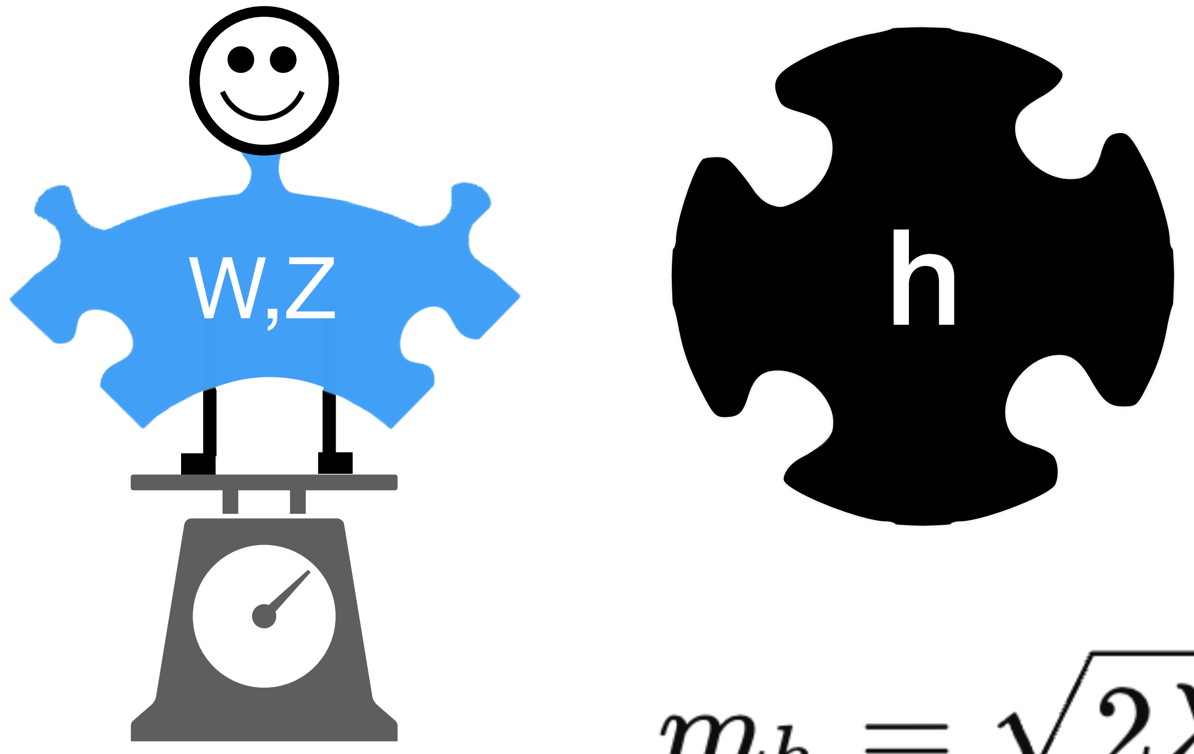
Scalar potential:

$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

CP-even Higgs boson: h

Spontaneous symmetry breaking:

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v \approx 246\,\mathrm{GeV}$$



$$m_h = \sqrt{2\lambda}v$$

Two Higgs Doublet Models (2HDM)

two scalar SU(2)$_L$ doublets. $Y = +1$

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \phi_i^0 \end{pmatrix}, \quad i = 1, 2$$

Complex numbers
8 degrees of
freedom

The **most general, renormalizable, gauge-invariant scalar potential** involving Φ_1 and Φ_2 is:

$$\begin{aligned} V(\Phi_1, \Phi_2) = & m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] \\ & + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 \\ & + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \left[\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 |\Phi_1|^2 (\Phi_1^\dagger \Phi_2) + \lambda_7 |\Phi_2|^2 (\Phi_1^\dagger \Phi_2) + \text{h.c.} \right] \end{aligned}$$

😳

14 parameters:
6 coeffs. $\in \mathbb{R}$
4 coeffs. $\in \mathbb{C}$

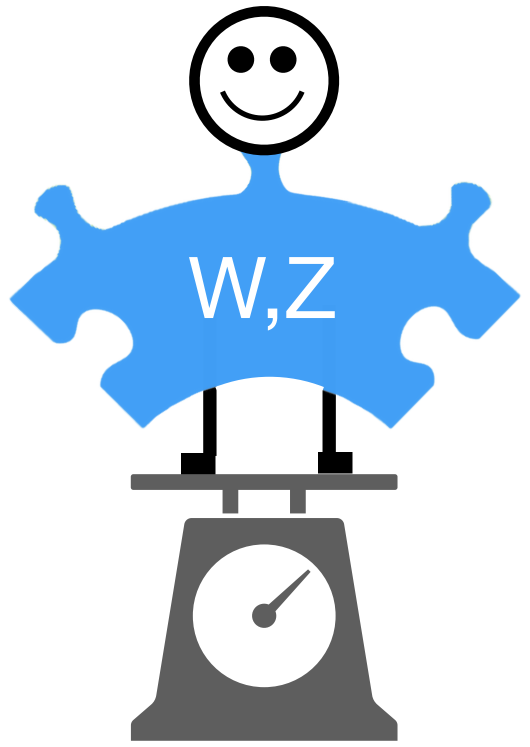
Two Higgs Doublet Models (2HDM)

two scalar SU(2)$_L$ doublets $Y = +1$

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \phi_i^0 \end{pmatrix}, \quad i = 1, 2$$

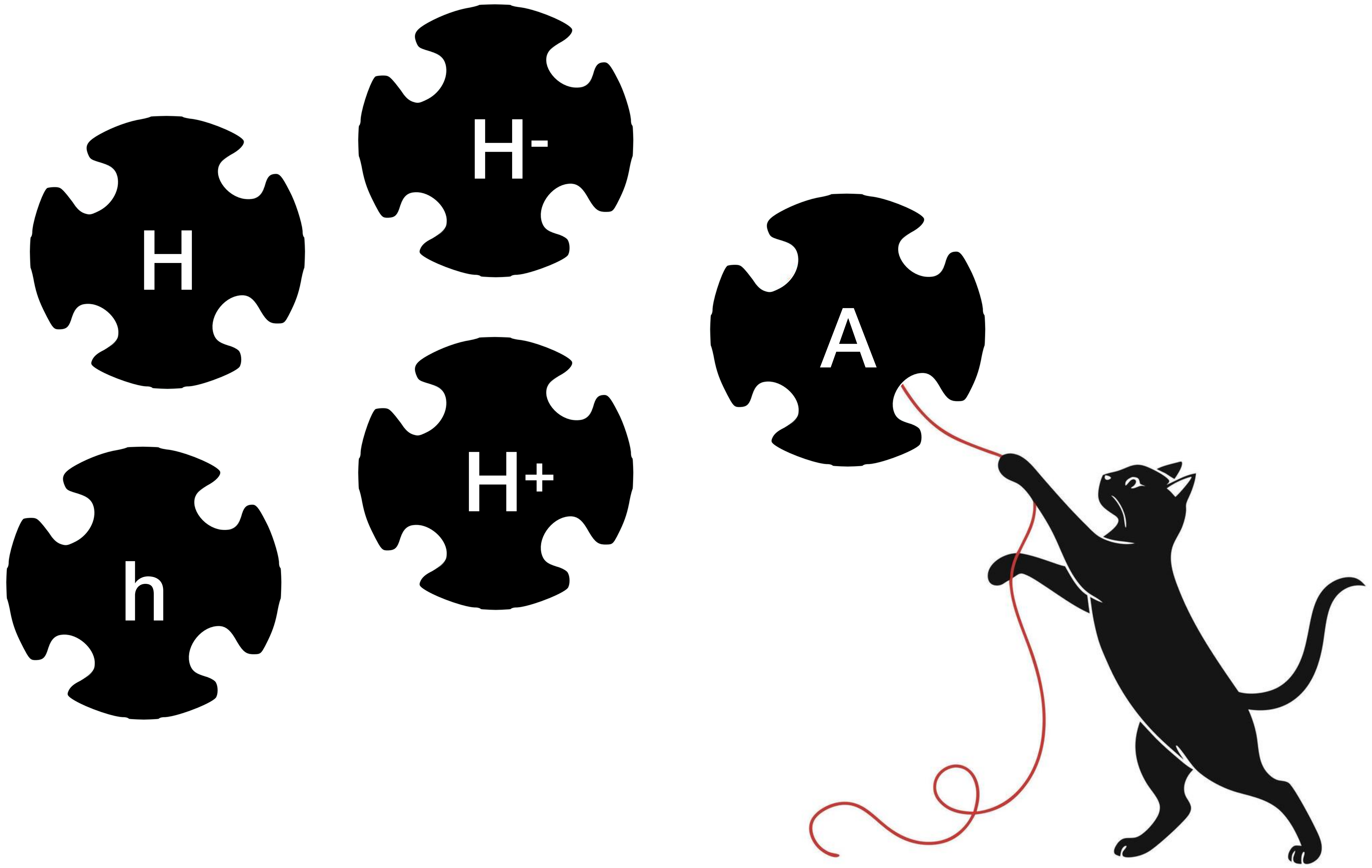
Complex numbers 8 degrees of freedom

8 - 3 = 5



Leads to **five Higgs particles:**

- **CP-even:** h (SM-like), H
- **CP-odd:** A
- **Charged:** $H^{\pm}$



Two Higgs Doublet Models (2HDM)

Key Parameters

- $\tan\beta = \frac{v_2}{v_1}$: Ratio of VEVs
- α: Mixing angle of CP-even Higgs
- Masses: $m_h, m_H, m_A, m_{H^\pm}$
- Z_2 symmetry types to avoid FCNCs:

Type-I

- $\Phi_1 \rightarrow -\Phi_1$
  - ➡ All quarks couple to just one of the Higgs doublets (Φ_2)

Type-II

- $\Phi_1 \rightarrow -\Phi_1$; $d^i_R \rightarrow -d^i_R$
  - ➡ Q = $^2/_3$ right-handed quarks couples to Φ_2 and Q = - $^1/_3$ right-handed quarks to Φ_1

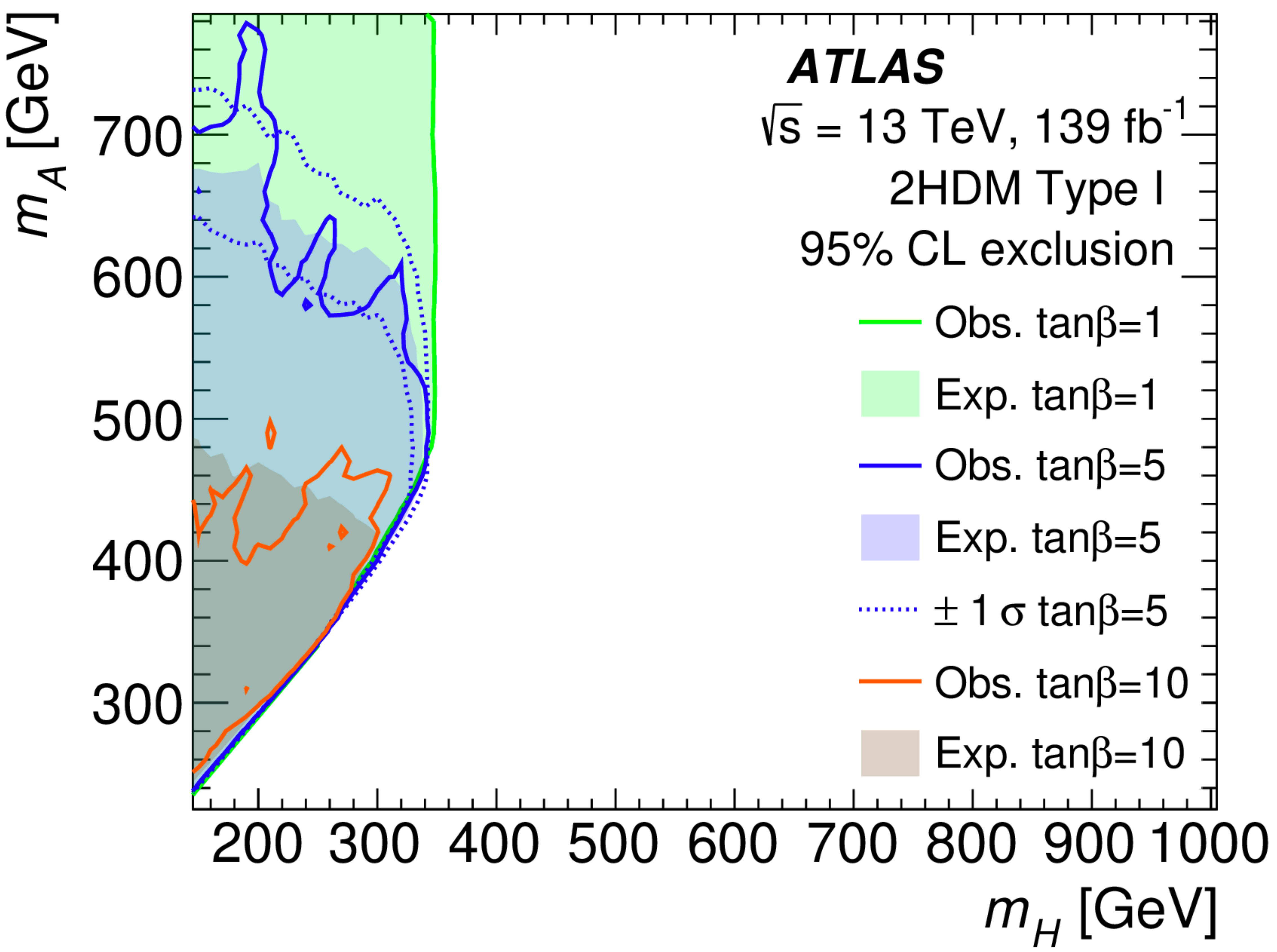
- **New resonances**:
  - $H/A \rightarrow \tau^+\tau^-, ZZ, Zh, hh$
  - $H^\pm \rightarrow \tau\nu, tb$
- **Modified Higgs couplings**:
  - Deviations in SM h production/decay rates

Do you know a famous 2HDM-type theory?

2HDM Searches at the LHC

- Neutral pseudo-scalar A:
  - ➡A→ZH, A→Zh, bbA(A→μ+μ-), bbA(A→τ+τ-)
- Neutral heavy scalar H:
  - ➡H→ZZ, H→hh, H→ZA, H→H±W∓→hW±W∓ (h→bb)
- Either A/H:
  - ➡A/H→tt, A/H+b+X→bb, A/H→γγ
- H±:
  - ➡H±→τν, H±→tb, H±→WZ, t→bH±(H±→cb), t→bH±(H±→cs)

- A→ZH (H→bb), EW cosmology benchmark



Summary

- We have looked into the Standard Model particle content and tried to extend it to include more particles in a similar way to the current ones
  - ➡ Lots of theoretical possibilities
  - ➡ All of them are being searched for extensively!
  - ➡ Unfortunately, we have not found any of them yet ☹️
  - ➡ There are some hints out there: ~~b-anomalies~~, dE/dx…