Testing the Standard Model of Elementary Particle Physics II

1st lecture

Dr. Dominik Duda

15th April 2021

Introduction

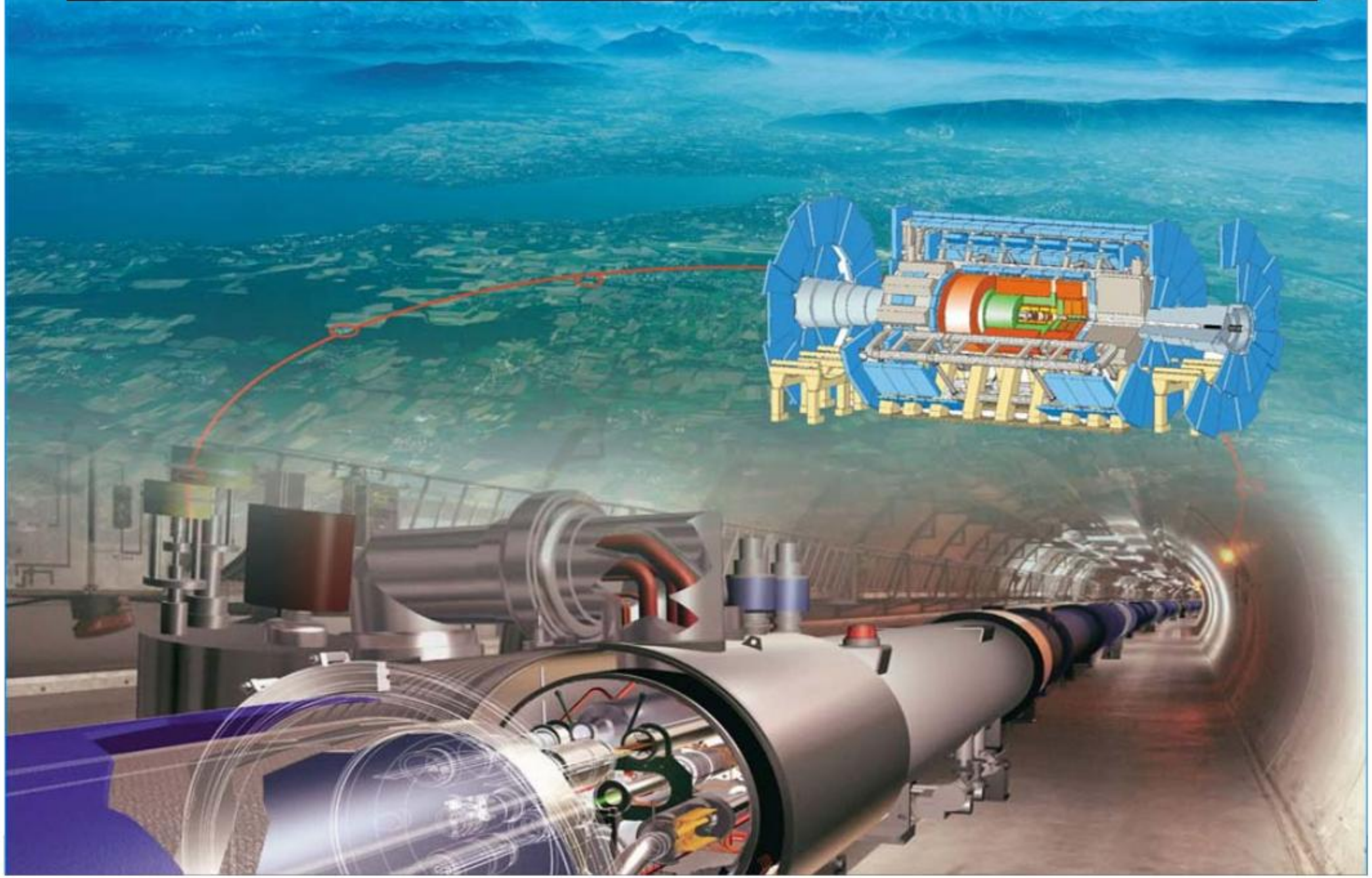


Table of content

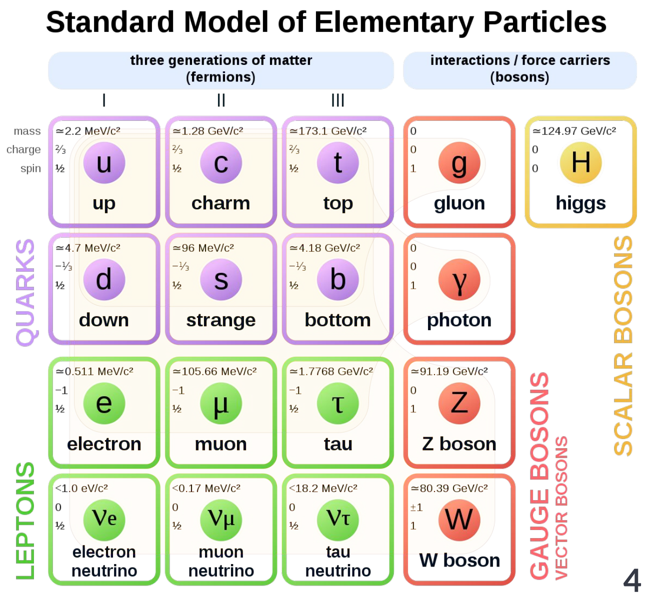
- This first lecture aims to give an overview of the various topics that we will discuss during this semester
  - So we will not go into too much detail on the various topics
    - Will be more detailed starting from next week

- **Introduction to Testing the Standard Model of Elementary Particle Physics II**
  - (Precision) Measurements
    - Electroweak Interaction (LEP)
    - Higgs and top quark properties (LHC)
    - B-hadron properties
    - Neutrino masses
  - Unsolved problems of the Standard Model
    - Examples of BSM theories
  - Searches for new physics
  - Machine learning in High Energy Physics

Standard Model of particle physics in a nutshell

- The Standard Model (SM) describes the elementary constituents of nature, and the fundamental forces with which those particles interact with each other
- Over time and through many experiments, the Standard Model has become one of the most extensively tested theories in physics
- After the discovery of the Higgs boson in 2012, the particle content of the SM is finally complete

- **Principles of the Standard Model:**
  - Unitarity (probabilities are limited to unity)
  - Renormalizability (ensures finite predictions)
  - Gauge principle (introduction of interactions)
    - **Symmetries:**
      - Lorentz (and Poincaré) symmetry
      - CPT symmetry
      - Three gauge symmetries: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

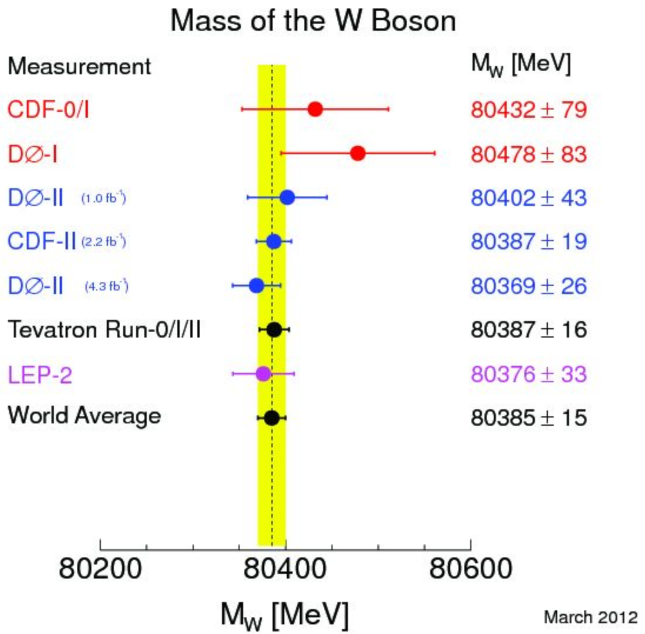


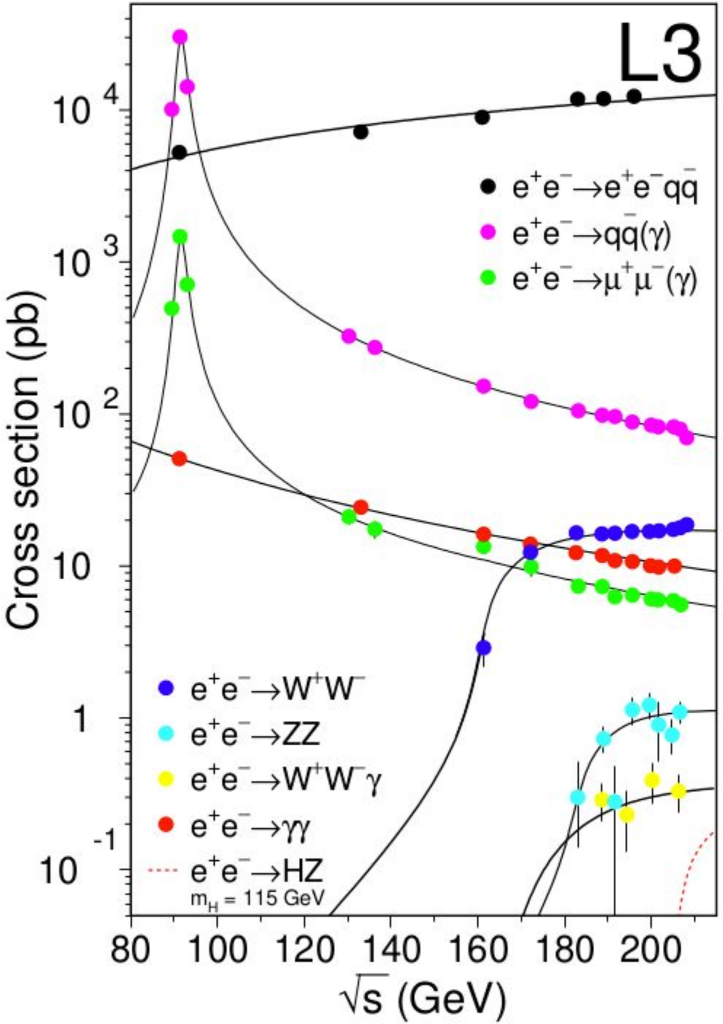
However, the Standard Model leaves some questions unanswered

(Precision) measurements

(Precision) measurements

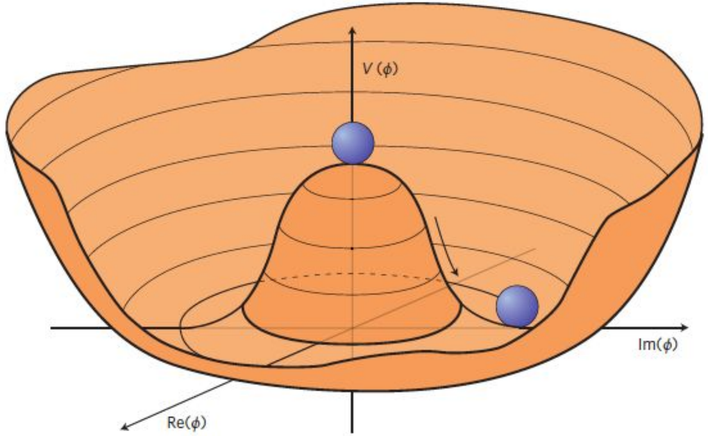
High precision measurements of W and Z boson properties at LEP



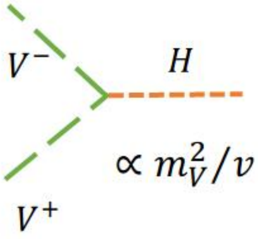


The Higgs boson: Last puzzle piece of the SM

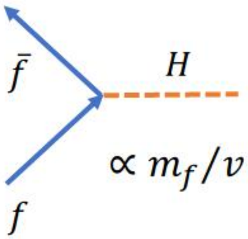
- Particles acquire mass via coupling to Higgs field (spontaneous symmetry breaking)
    - Postulated in 1964
    - Higgs boson (excitation of the Higgs field) was finally discovered in 2012
    - Spin: 0



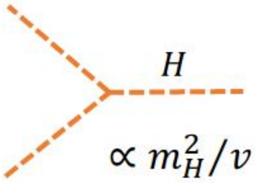
Gauge coupling:



Yukawa coupling:



Self coupling:



- **Higgs-potential**:

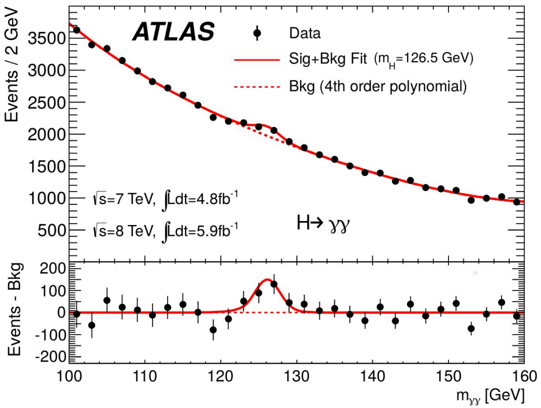
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

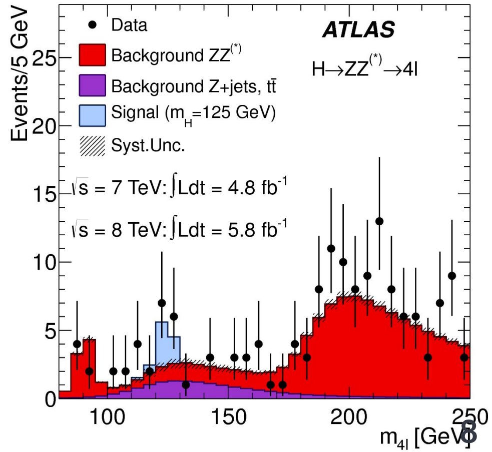
- **Vacuum expectation value**

$$v = \frac{\mu}{\sqrt{\lambda}}$$

(Precision) measurements of Higgs boson properties

- So far all measurements of the Higgs boson properties are consistent with the SM
  - Spin and CP state of the Higgs-boson are determined probing angular distribution of decay products
    - ATLAS data hints very strongly to a Spin^{CP} state of 0^+
    - Alternative models are rejected with a CL of more than 99.9%
- Higgs-boson mass measured by ATLAS and CMS:
  $m_H = 125.09 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{syst})$





(Precision) measurements of Higgs boson properties

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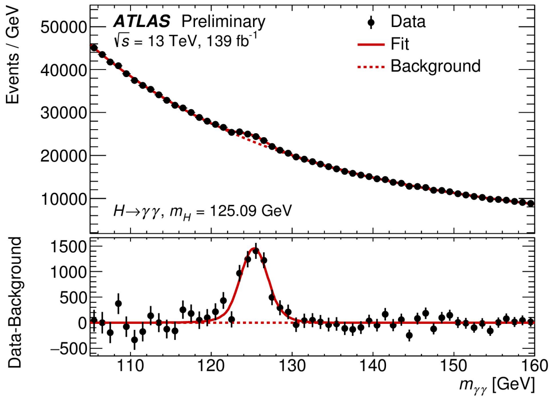
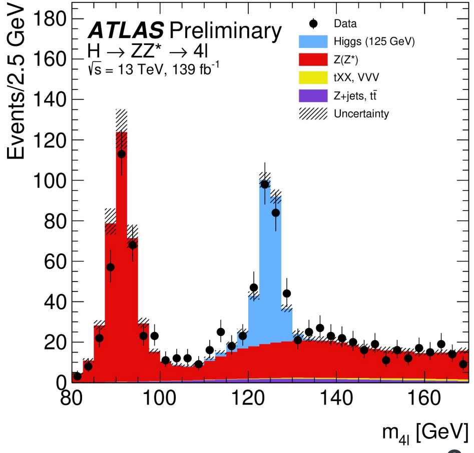
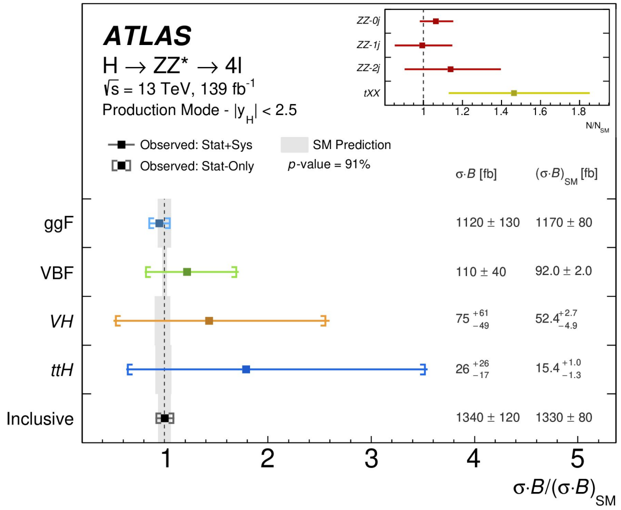
- Higgs-boson mass measured by ATLAS and CMS: m_H = 125.09 ± 0.21(stat) ± 0.11(syst)
- **With the large statistics of the full Run-II data set, we can probe differential distributions with high precision**
  - Makes the Higgs boson to a tool to search for new physics

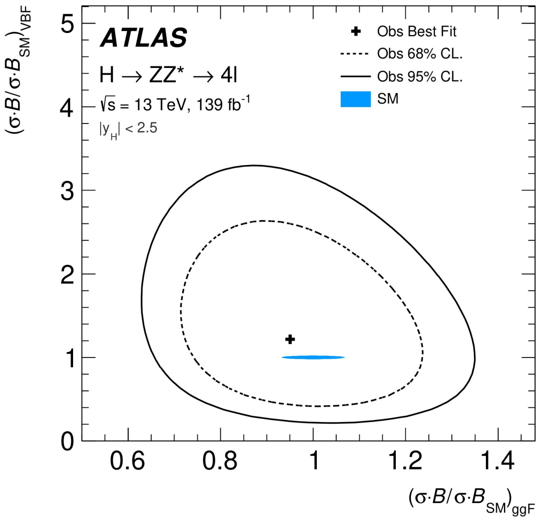


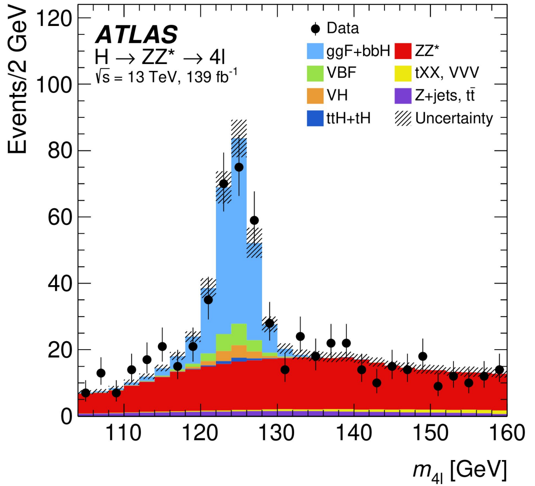


H → ZZ* → ℓℓℓℓ

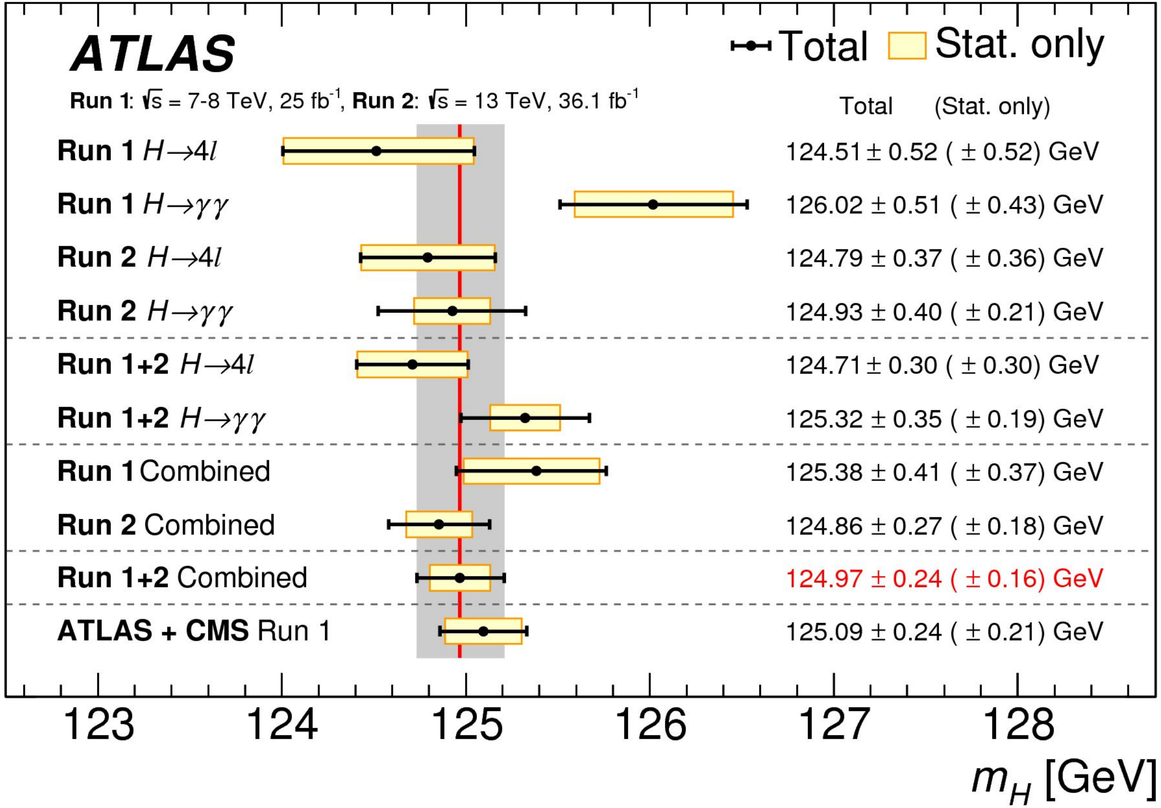
- H→ ZZ* → ℓℓℓℓ events provide a clean signature in the detector and thus have relative low background contributions
  - **Good channel to measure properties of the Higgs boson precisely**
  - Analyses are based on finding two pairs of isolated leptons with same flavor and opposite electric charges



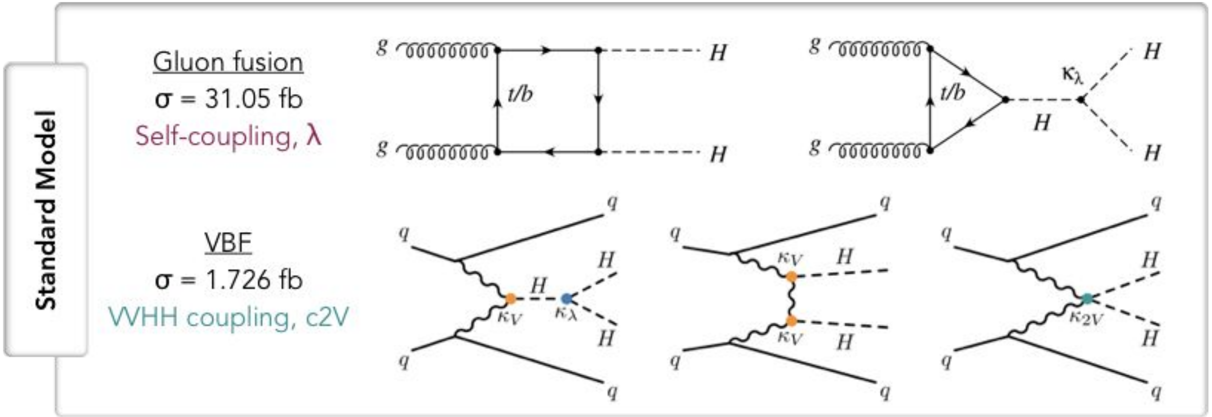


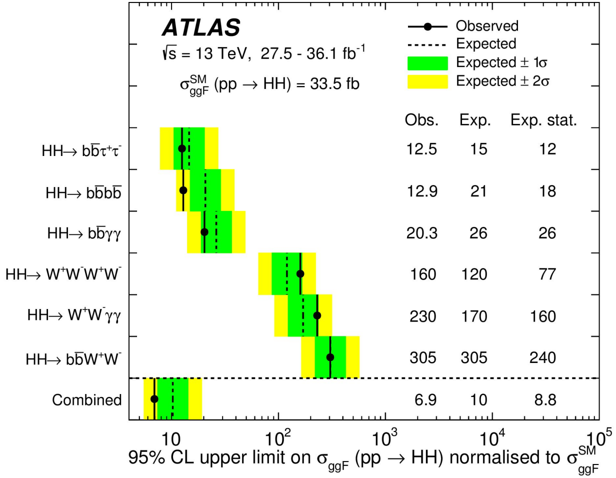


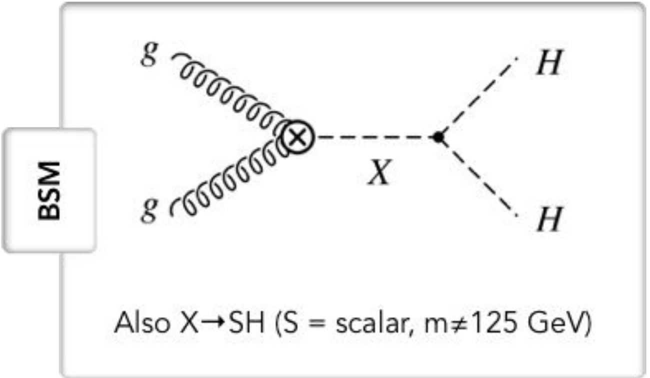
Higgs boson mass



Di-Higgs boson production at the LHC







- Probing the Di-Higgs production modes will further our understanding of the SM
  - Parameter of interests:
    - **Self-coupling κ_λ**
    - **Quartic VVHH coupling κ_{2V}**
  - Probing the self-coupling of the Higgs boson allows us to verify the form of the Higgs potential
  - **Sensitive to contribution from BSM physics**

The top quark

- Predicted in 1973 by Kobayashi and Maskawa
- Weak-isospin partner of the b-quark.
- Charge: +2/3 e
- Spin: 1⁄2
- The by far heaviest elementary particle:
    - **m_t = 172.7 ± 0.5 GeV**
- **Coupling to the Higgs boson: $y_t \approx 1$**
- **No bound states:**

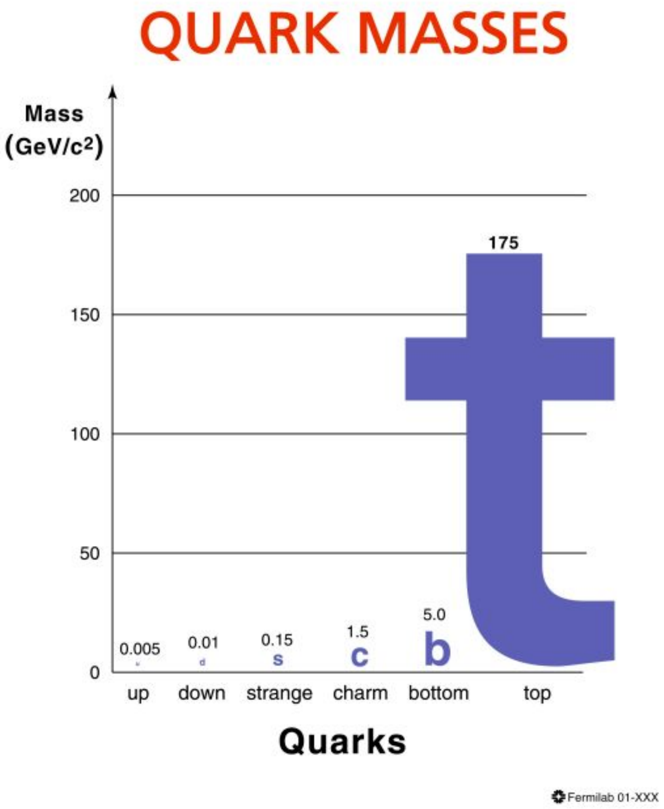
$$\tau_{\text{top}} \propto \left(\frac{M_W}{M_{\text{top}}}\right)^3$$

$$\tau_{\text{top}} \approx 4.7 \cdot 10^{-25}\ \text{s}$$

→ **Top quark decays as a quasi free particle**

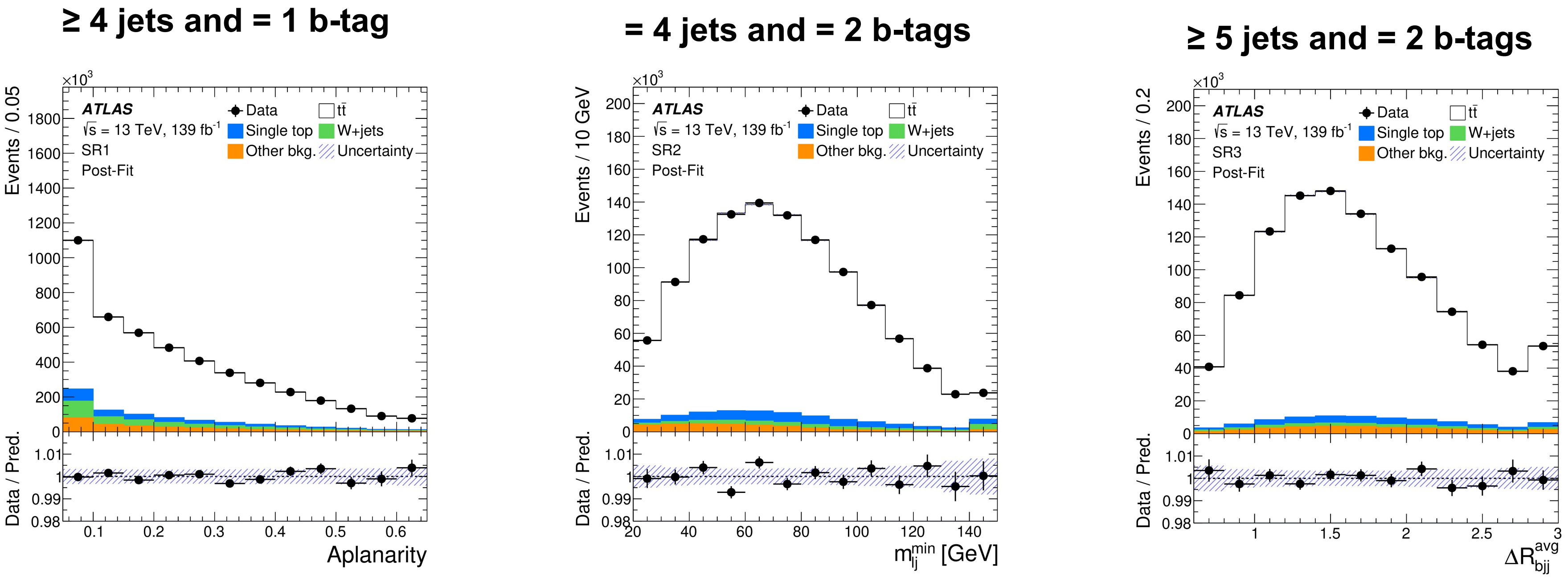
→ **Spin information and polarisation are accessible**

since spin decorrelation time (~10^{-21} s) is much larger than the hadronisation time (~10^{-23} s)



Production cross section measurement (ℓ+jets)

- Cross section is extracted via a simultaneous profile-likelihood fit of the sum of signal and background distributions to data in three regions.
  - Each region exploits a different fit variable.



Taken from: [Phys. Lett. B 810 (2020) 135797]()

Measurement:

$$\sigma(t\bar{t}) = 830.4 \ \pm 0.4\,(\mathrm{stat.}) \ {}^{+38.2}_{-37.0}\,(\mathrm{syst.})$$

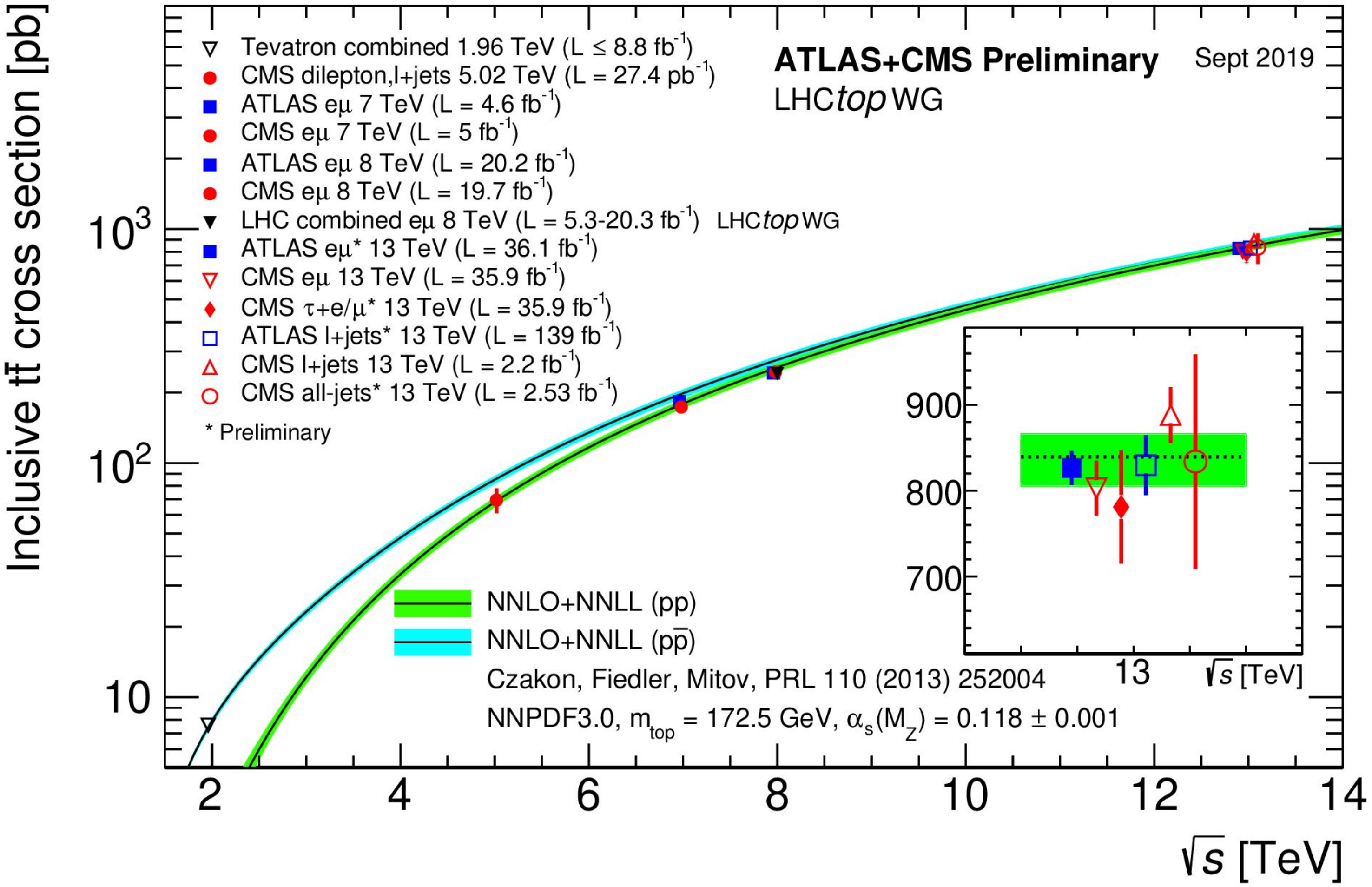
Theory prediction:

$$\sigma(t\bar{t}) = 832 \ {}^{+20}_{-29}\,(\mathrm{scale}) \ \pm 35\,(\mathrm{PDF} + \alpha_s)$$

Dominant uncertainties are due to the modelling of the top quark pair production process

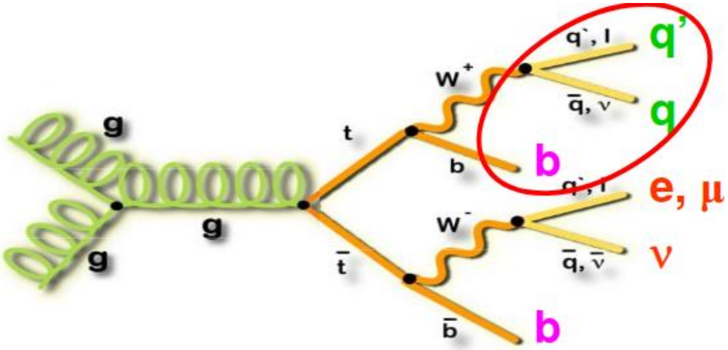
Category	$\frac{\Delta\sigma_{\mathrm{fid}}}{\sigma_{\mathrm{fid}}}$ [%]	$\frac{\Delta\sigma_{\mathrm{inc}}}{\sigma_{\mathrm{inc}}}$ [%]
Signal modelling		
$t\bar{t}$ shower/hadronisation	±2.8	±2.9
$t\bar{t}$ scale variations	±1.4	±2.0
Top p_{T} NNLO reweighting	±0.4	±1.1
$t\bar{t}$ h_{damp}	±1.5	±1.4
$t\bar{t}$ PDF	±1.4	±1.5
Background modelling		
MC background modelling	±1.8	±2.0
Multijet background	±0.8	±0.6
Detector modelling		
Jet reconstruction	±2.5	±2.6
Luminosity	±1.7	±1.7
Flavour tagging	±1.2	±1.3
$E_{\mathrm{T}}^{\mathrm{miss}}$ + pile-up	±0.3	±0.3
Muon reconstruction	±0.6	±0.5
Electron reconstruction	±0.7	±0.6
Simulation stat. uncertainty	±0.6	±0.7
Total systematic uncertainty	±4.3	±4.6
Data statistical uncertainty	±0.05	±0.05
Total uncertainty	±4.3	±4.6

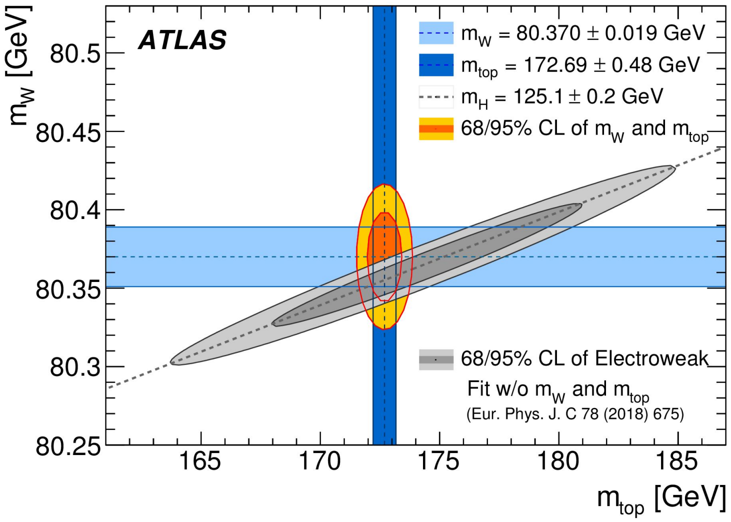
Taken from: [Phys. Lett. B 810 (2020) 135797]()

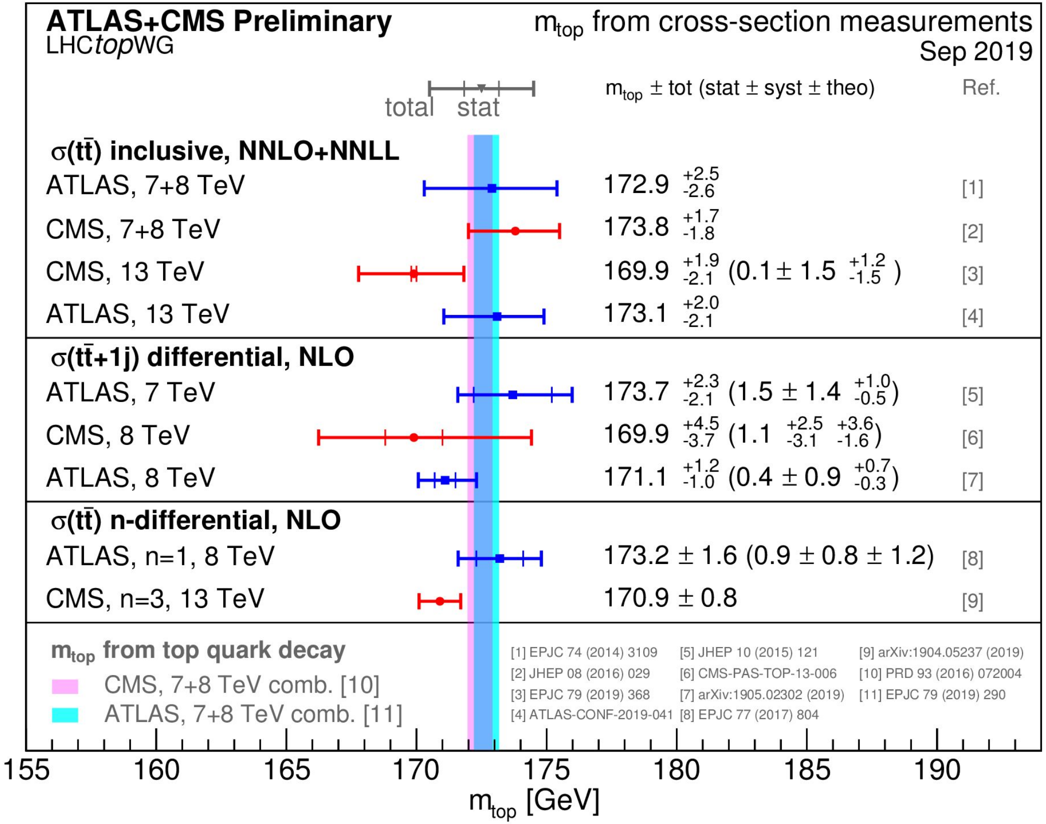


ATLAS+CMS Preliminary
Sept 2019
LHCtopWG
Inclusive tt̄ cross section [pb]
Tevatron combined 1.96 TeV (L ≤ 8.8 fb^{-1})
CMS dilepton,l+jets 5.02 TeV (L = 27.4 pb^{-1})
ATLAS eμ 7 TeV (L = 4.6 fb^{-1})
CMS eμ 7 TeV (L = 5 fb^{-1})
ATLAS eμ 8 TeV (L = 20.2 fb^{-1})
CMS eμ 8 TeV (L = 19.7 fb^{-1})
LHC combined eμ 8 TeV (L = 5.3-20.3 fb^{-1}) LHCtopWG
ATLAS eμ* 13 TeV (L = 36.1 fb^{-1})
CMS eμ 13 TeV (L = 35.9 fb^{-1})
CMS τ+e/μ* 13 TeV (L = 35.9 fb^{-1})
ATLAS l+jets* 13 TeV (L = 139 fb^{-1})
CMS l+jets 13 TeV (L = 2.2 fb^{-1})
CMS all-jets* 13 TeV (L = 2.53 fb^{-1})
* Preliminary
NNLO+NNLL (pp)
NNLO+NNLL (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
NNPDF3.0, m_{top} = 172.5 GeV, $\alpha_s(M_Z)$ = 0.118 ± 0.001
$\sqrt{s}$ [TeV]

Top quark mass







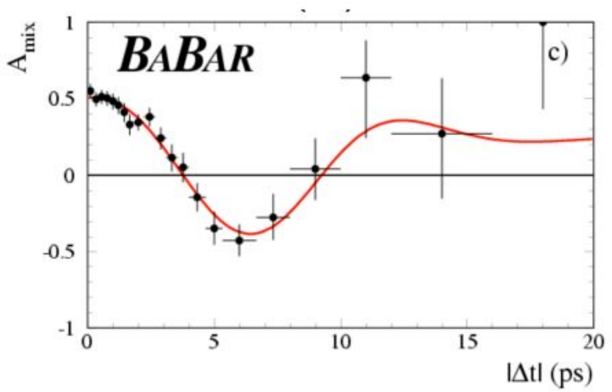
B-Hadron decays and CP Violation

- For quarks, the weak SU(2) eigenstates are different from the mass eigenstates
  - Mixing is described by CKM matrix
    - 3 real parameters
    - 1 complex (CP violating phase)

$$V_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -s_{23}c_{12} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$B_d^0 \bar{B}_d^0$ oscillation

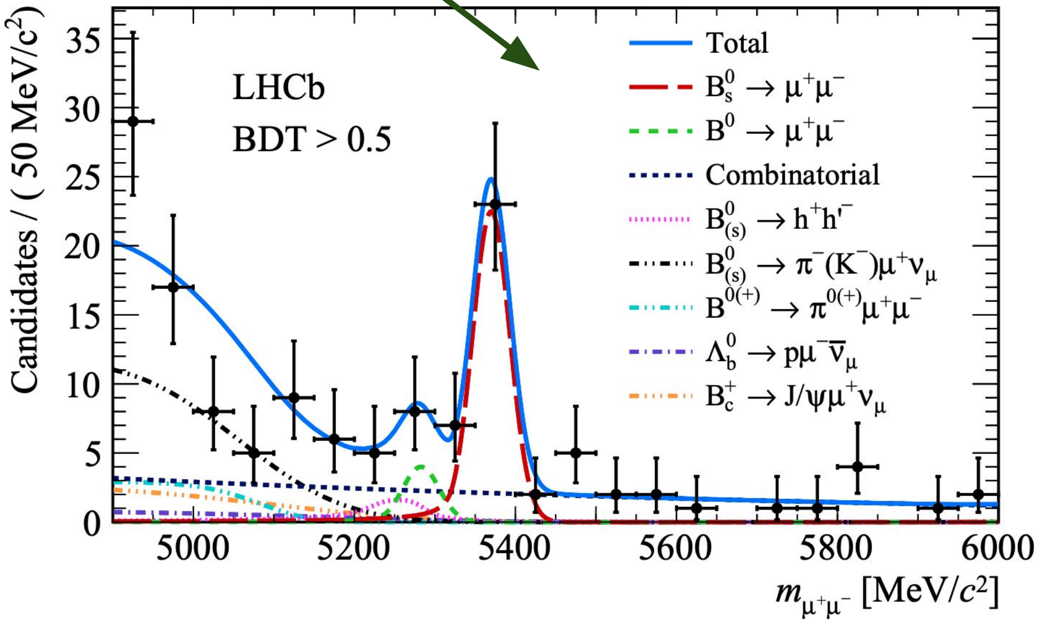


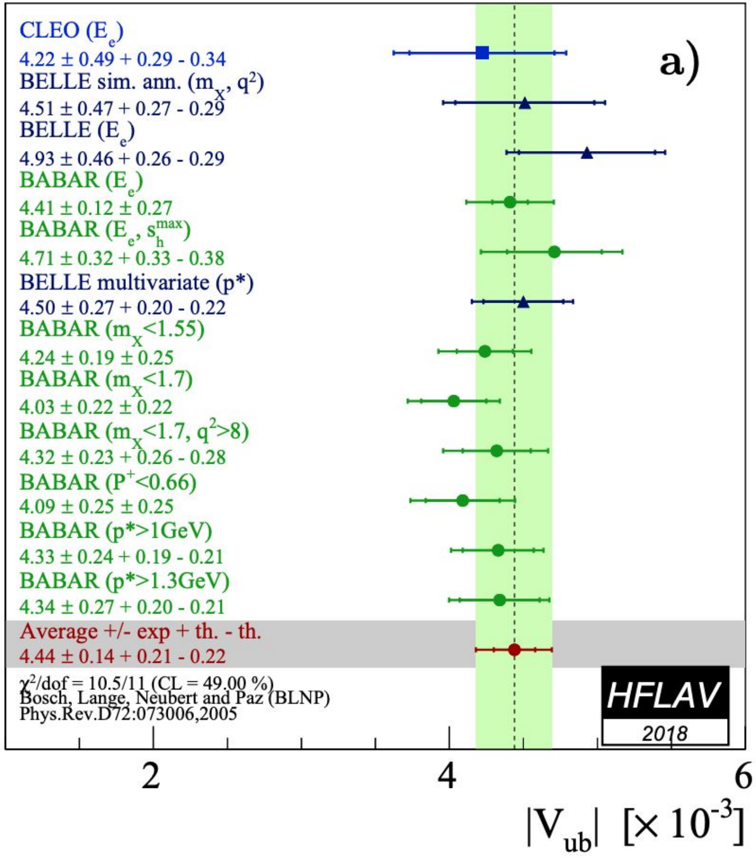
Searches for CP violation in e.g. kaon and B-meson mixing

B-Hadron decays and CP Violation

Precise measurement of CKM matrix elements

Rare decays





Neutrino masses and oszillation

- **In the Standard Model, neutrinos are massless**
  - Only left-handed neutrinos (and right handed anti-neutrinos)
  - Right-handed neutrinos do not participate in the weak interaction

- **Neutrino oscillation:**
  - First observed in 1998
  - Implíes that neutrino must have nonzero mass
  - As well as violation of lepton flavour conservation, as for quarks

	Mass	m measurements	Discovery
ν_e	< 2 eV	Mainz / Troitsk	Cowan, Reines 1956 (inverse β decay)
ν_μ	< 190 keV	PSI Zürich	Ledermann, Schwartz, Steinberger 1962
ν_τ	< 18.2 MeV	ALEPH (LEP)	DONUT Experiment (FNAL) 2001

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 $Q_d = ⅓\, Q_e$ 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**

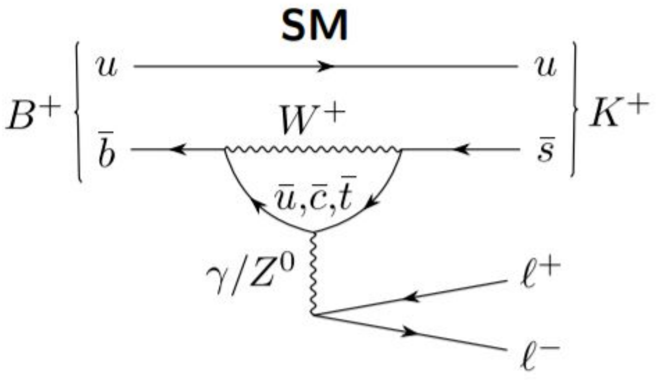
    → **String theories**

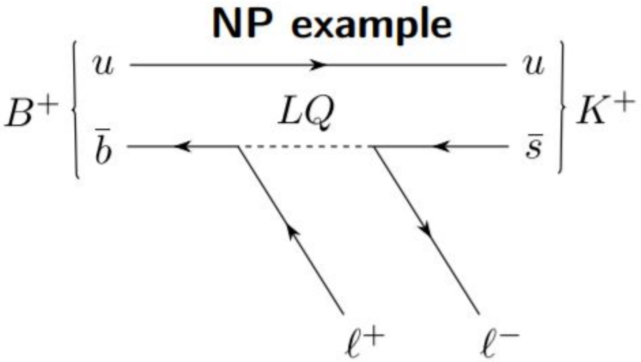
Lepton Flavour Universality tests

- 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:

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

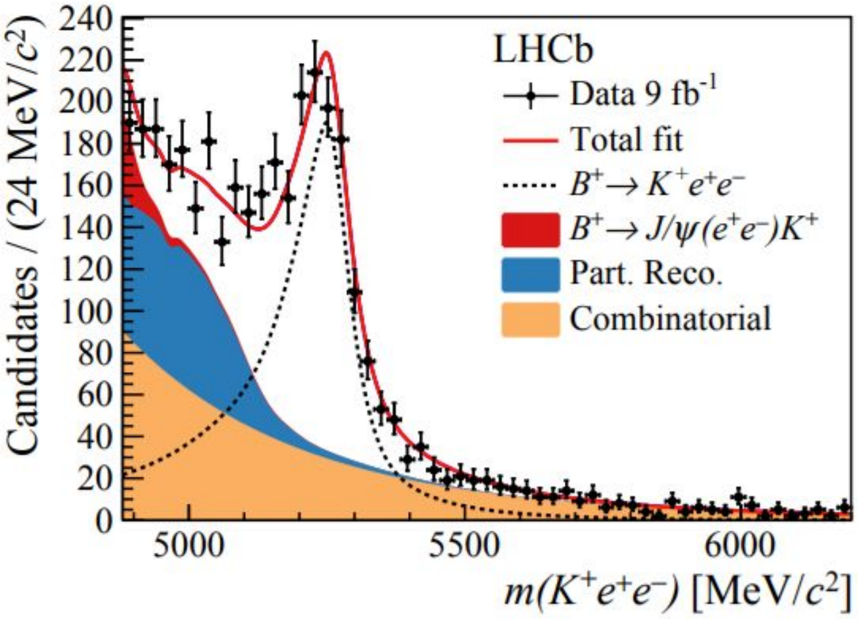
→ Any significant deviation would be a smoking gun for New Physics.

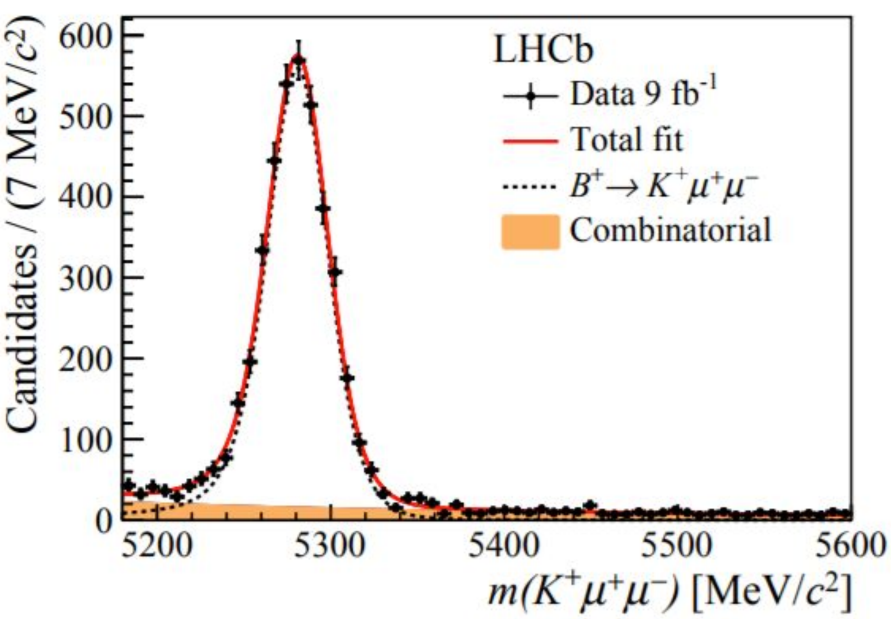




Taken from: https://indico.cern.ch/event/976688/attachments/2213706/3748404/RK_CernSeminar_Tue23rdMar2021.pdf

Lepton Flavour Universality tests



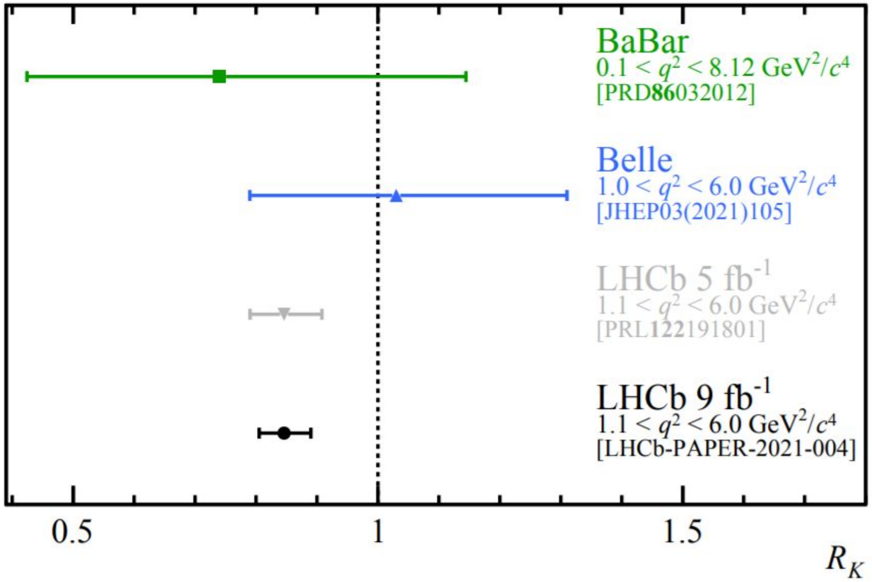


Measurement is based on study of invariant $K^+\ell\ell$ distribution and relies on excellent knowledge of electron/muon reconstruction efficiencies

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

Lepton Flavour Universality tests

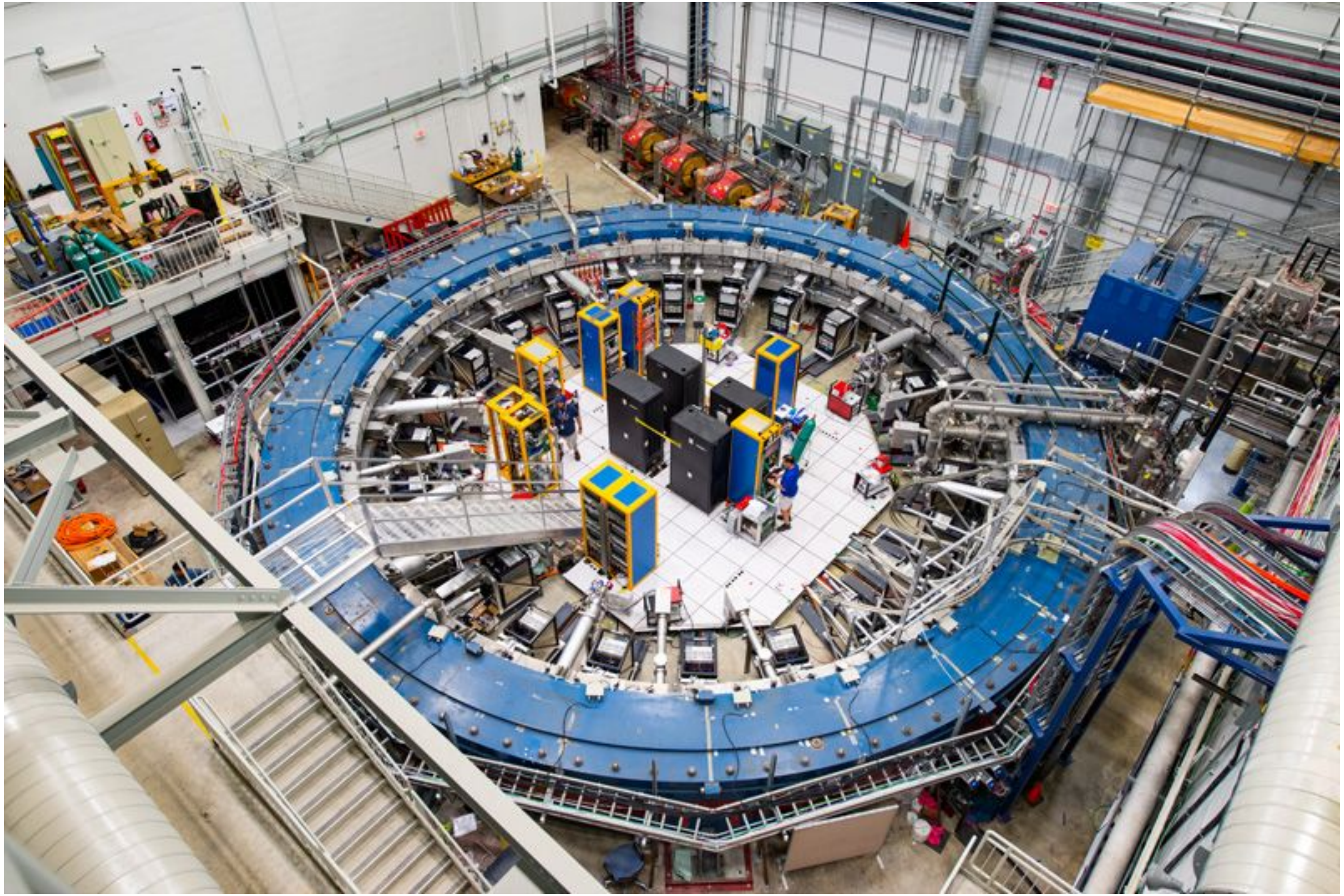
Newest results from LHCb



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

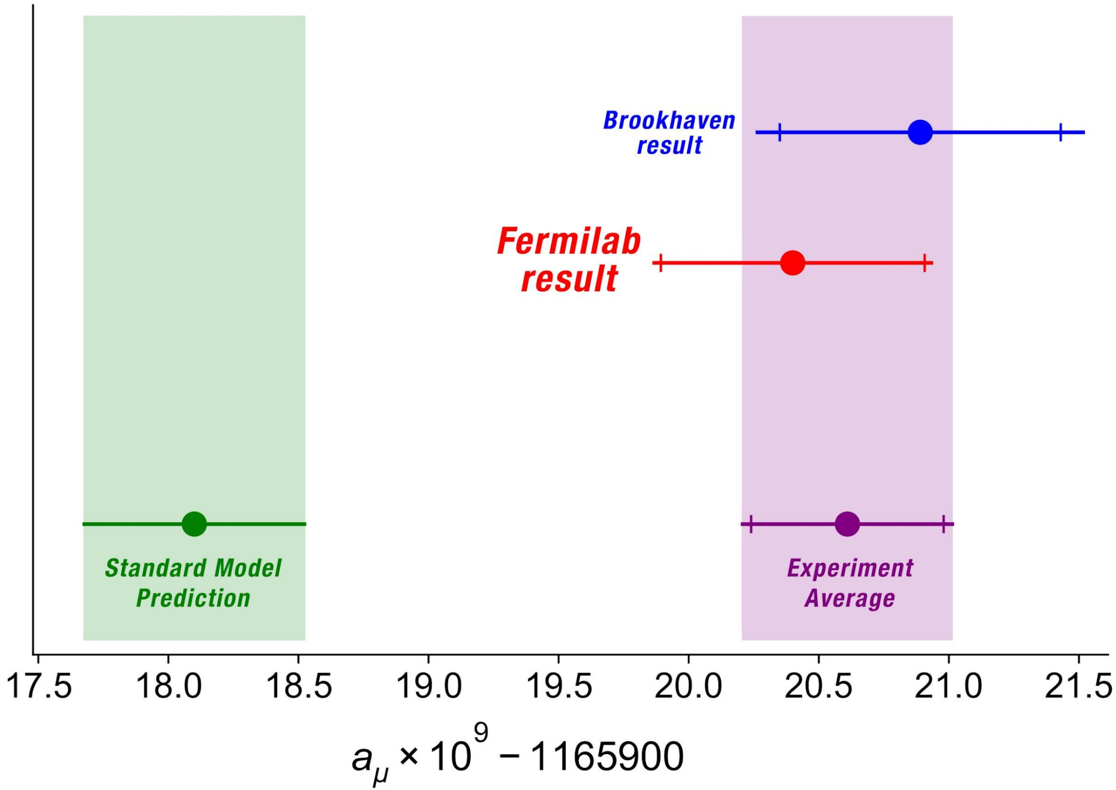
→ **Evidence of LFU violation at 3.1σ**

g - 2 experiment



g - 2 experiment

First results from g-2 experiment



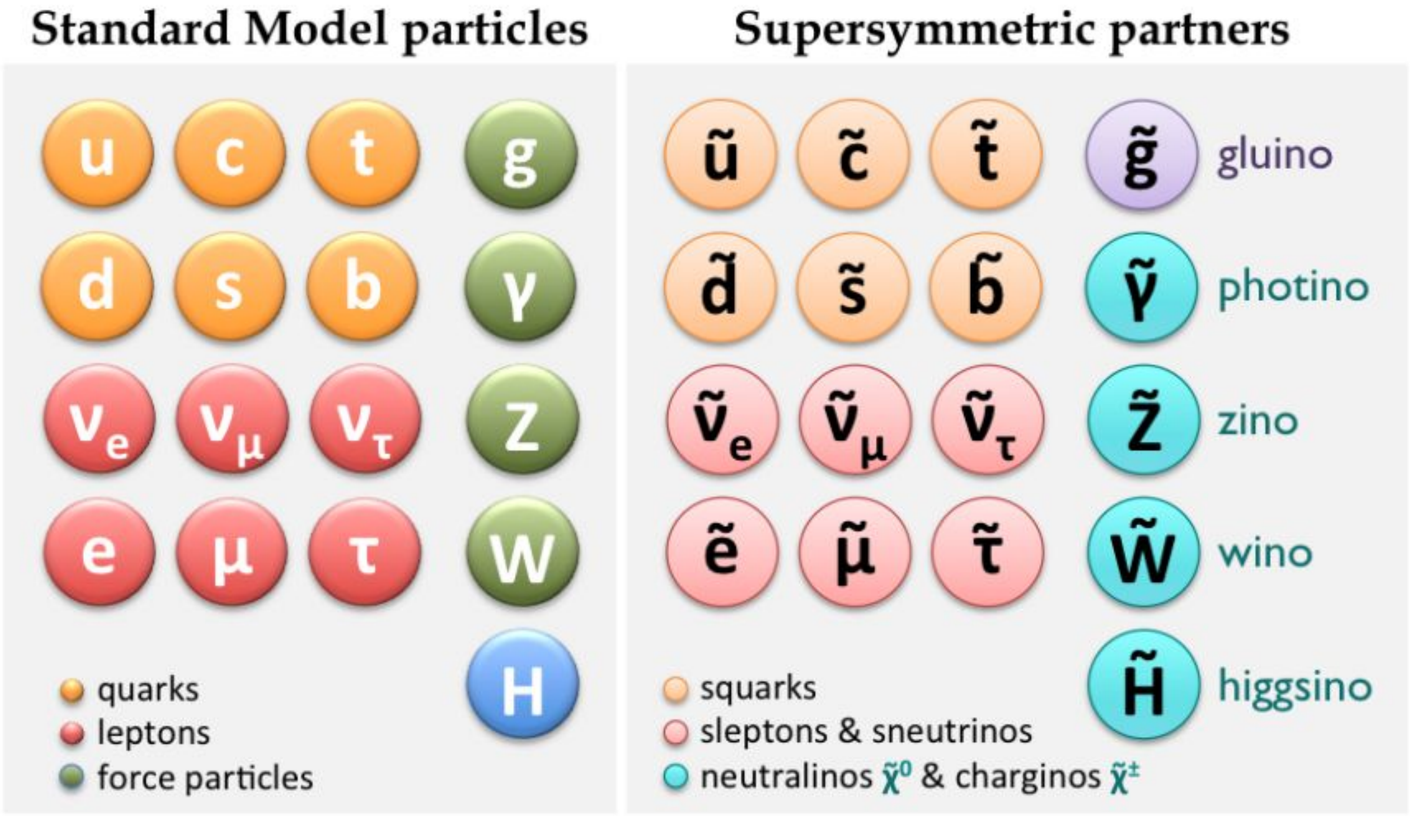
The combined results from Fermilab and Brookhaven show a difference with the theory predictions at a significance of 4.2σ

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]

Searches for new physics

Supersymmetry (SUSY)



ATLAS SUSY Searches* - 95% CL Lower Limits

July 2020

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

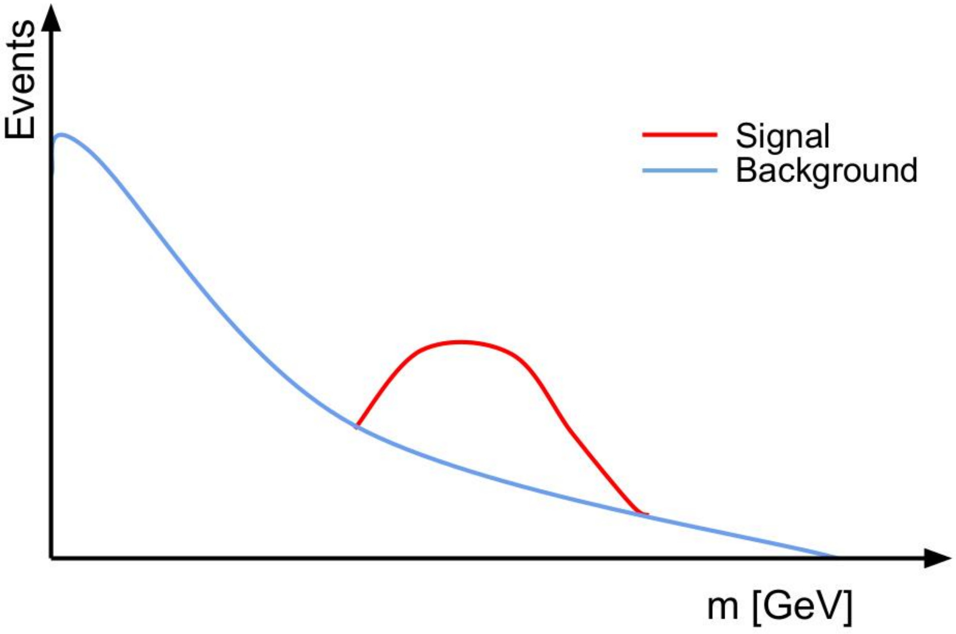
	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	$\tilde q\tilde q$, $\tilde q\to q\tilde\chi^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde q$ [10× Degen.] 1.9	m($\tilde\chi^0_1$)<400 GeV	ATLAS-CONF-2019-040
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde q$ [1×, 8× Degen.] 0.43 0.71	m($\tilde q$)-m($\tilde\chi^0_1$)=5 GeV	1711.03301
	$\tilde g\tilde g$, $\tilde g\to q\bar q\tilde\chi^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde g$ 2.35	m($\tilde\chi^0_1$)=0 GeV	ATLAS-CONF-2019-040
						$\tilde g$ Forbidden 1.15-1.95	m($\tilde\chi^0_1$)=1000 GeV	ATLAS-CONF-2019-040
	$\tilde g\tilde g$, $\tilde g\to q\bar qW\tilde\chi^0_1$	1 e,μ	2-6 jets		139	$\tilde g$ 2.2	m($\tilde\chi^0_1$)<600 GeV	ATLAS-CONF-2020-047
	$\tilde g\tilde g$, $\tilde g\to q\bar q(\ell\ell)\tilde\chi^0_1$	$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	36.1	$\tilde g$ 1.2	m($\tilde g$)-m($\tilde\chi^0_1$)=50 GeV	1805.11381
	$\tilde g\tilde g$, $\tilde g\to qqWZ\tilde\chi^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	139	$\tilde g$ 1.97	m($\tilde\chi^0_1$) <600 GeV	ATLAS-CONF-2020-002
		SS e,μ	6 jets		139	$\tilde g$ 1.15	m($\tilde g$)-m($\tilde\chi^0_1$)=200 GeV	1909.08457
	$\tilde g\tilde g$, $\tilde g\to t\bar t\tilde\chi^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde g$ 2.25	m($\tilde\chi^0_1$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde g$ 1.25	m($\tilde g$)-m($\tilde\chi^0_1$)=300 GeV	1909.08457
3rd gen. squarks direct production	$\tilde b_1\tilde b_1$, $\tilde b_1\to b\tilde\chi^0_1/t\tilde\chi^\pm_1$		Multiple		36.1	$\tilde b_1$ Forbidden 0.9	m($\tilde\chi^0_1$)=300 GeV, BR($b\tilde\chi^0_1$)=1	1708.09266, 1711.03301
			Multiple		139	$\tilde b_1$ Forbidden 0.74	m($\tilde\chi^0_1$)=200 GeV, m($\tilde\chi^\pm_1$)=300 GeV, BR($t\tilde\chi^\pm_1$)=1	1909.08457
	$\tilde b_1\tilde b_1$, $\tilde b_1\to b\tilde\chi^0_2\to bh\tilde\chi^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde b_1$ Forbidden 0.23-1.35	$\Delta m(\tilde\chi^0_2,\tilde\chi^0_1)$=130 GeV, m($\tilde\chi^0_1$)=100 GeV	1908.03122
		2 τ	2 b	$E_T^{\rm miss}$	139	$\tilde b_1$ 0.13-0.85	$\Delta m(\tilde\chi^0_2,\tilde\chi^0_1)$=130 GeV, m($\tilde\chi^0_1$)=0 GeV	ATLAS-CONF-2020-031
	$\tilde t_1\tilde t_1$, $\tilde t_1\to t\tilde\chi^0_1$	0-1 e,μ	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde t_1$ 1.25	m($\tilde\chi^0_1$)=1 GeV	ATLAS-CONF-2020-003, 2004.14060
	$\tilde t_1\tilde t_1$, $\tilde t_1\to Wb\tilde\chi^0_1$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	139	$\tilde t_1$ 0.44-0.59	m($\tilde\chi^0_1$)=400 GeV	ATLAS-CONF-2019-017
	$\tilde t_1\tilde t_1$, $\tilde t_1\to\tilde\tau_1 b\nu$, $\tilde\tau_1\to\tau\tilde G$	1 τ + 1 e,μ,τ	2 jets/1 b	$E_T^{\rm miss}$	36.1	$\tilde t_1$ 1.16	m($\tilde\tau_1$)=800 GeV	1803.10178
	$\tilde t_1\tilde t_1$, $\tilde t_1\to c\tilde\chi^0_1$ / $\tilde c\tilde c$, $\tilde c\to c\tilde\chi^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde c$ 0.85	m($\tilde\chi^0_1$)=0 GeV	1805.01649
						$\tilde t_1$ 0.46	m($\tilde t_1$,$\tilde c$)-m($\tilde\chi^0_1$)=50 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	36.1	$\tilde t_1$ 0.43	m($\tilde t_1$,$\tilde c$)-m($\tilde\chi^0_1$)=5 GeV	1711.03301
	$\tilde t_1\tilde t_1$, $\tilde t_1\to t\tilde\chi^0_2$, $\tilde\chi^0_2\to Z/h\tilde\chi^0_1$	1-2 e,μ	1-4 b	$E_T^{\rm miss}$	139	$\tilde t_1$ 0.067-1.18	m($\tilde\chi^0_2$)=500 GeV	SUSY-2018-09
	$\tilde t_2\tilde t_2$, $\tilde t_2\to\tilde t_1 + Z$	3 e,μ	1 b	$E_T^{\rm miss}$	139	$\tilde t_2$ Forbidden 0.86	m($\tilde\chi^0_1$)=360 GeV, m($\tilde t_1$)-m($\tilde\chi^0_1$)= 40 GeV	SUSY-2018-09
EW direct	$\tilde\chi^\pm_1\tilde\chi^0_2$ via WZ	3 e,μ		$E_T^{\rm miss}$	139	$\tilde\chi^\pm_1/\tilde\chi^0_2$ 0.64	m($\tilde\chi^0_1$)=0	ATLAS-CONF-2020-015
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde\chi^\pm_1/\tilde\chi^0_2$ 0.205	m($\tilde\chi^\pm_1$)-m($\tilde\chi^0_1$)=5 GeV	1911.12606
	$\tilde\chi^\pm_1\tilde\chi^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde\chi^\pm_1$ 0.42	m($\tilde\chi^0_1$)=0	1908.08215
	$\tilde\chi^\pm_1\tilde\chi^0_2$ via Wh	0-1 e,μ	2 b/2 γ	$E_T^{\rm miss}$	139	$\tilde\chi^\pm_1/\tilde\chi^0_2$ Forbidden 0.74	m($\tilde\chi^0_1$)=70 GeV	2004.10894, 1909.09226
	$\tilde\chi^\pm_1\tilde\chi^\mp_1$ via $\tilde\ell_L/\tilde\nu$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde\chi^\pm_1$ 1.0	m($\tilde\ell,\tilde\nu$)=0.5(m($\tilde\chi^\pm_1$)+m($\tilde\chi^0_1$))	1908.08215
	$\tilde\tau\tilde\tau$, $\tilde\tau\to\tau\tilde\chi^0_1$	2 τ		$E_T^{\rm miss}$	139	$\tilde\tau$ [$\tilde\tau_L$, $\tilde\tau_{R,L}$] 0.16-0.3 0.12-0.39	m($\tilde\chi^0_1$)=0	1911.06660
	$\tilde\ell_{L,R}\tilde\ell_{L,R}$, $\tilde\ell\to\ell\tilde\chi^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde\ell$ 0.7	m($\tilde\chi^0_1$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde\ell$ 0.256	m($\tilde\ell$)-m($\tilde\chi^0_1$)=10 GeV	1911.12606
	$\tilde H\tilde H$, $\tilde H\to h\tilde G/Z\tilde G$	0 e,μ	$\geq$ 3 b	$E_T^{\rm miss}$	36.1	$\tilde H$ 0.13-0.23 0.29-0.88	BR($\tilde\chi^0_1\to h\tilde G$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde H$ 0.55	BR($\tilde\chi^0_1\to Z\tilde G$)=1	ATLAS-CONF-2020-040
Long-lived particles	Direct $\tilde\chi^+_1\tilde\chi^-_1$ prod., long-lived $\tilde\chi^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	$\tilde\chi^\pm_1$ 0.46	Pure Wino	1712.02118
						$\tilde\chi^\pm_1$ 0.15	Pure higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde g$ R-hadron		Multiple		36.1	$\tilde g$ 2.0		1902.01636,1808.04095
	Metastable $\tilde g$ R-hadron, $\tilde g\to qq\tilde\chi^0_1$		Multiple		36.1	$\tilde g$ [$\tau(\tilde g)$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde\chi^0_1$)=100 GeV	1710.04901,1808.04095
RPV	$\tilde\chi^\pm_1\tilde\chi^\mp_1/\tilde\chi^0_1$, $\tilde\chi^\pm_1\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde\chi^\pm_1/\tilde\chi^0_1$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05	Pure Wino	ATLAS-CONF-2020-009
	LFV $pp\to\tilde\nu_\tau + X$, $\tilde\nu_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	$\tilde\nu_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde\chi^\pm_1\tilde\chi^\mp_1/\tilde\chi^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde\chi^\pm_1/\tilde\chi^0_2$ [$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$] 0.82 1.33	m($\tilde\chi^0_1$)=100 GeV	1804.03602
	$\tilde g\tilde g$, $\tilde g\to qq\tilde\chi^0_1$, $\tilde\chi^0_1\to qqq$		4-5 large-R jets		36.1	$\tilde g$ [m($\tilde\chi^0_1$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde g$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde\chi^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde t\tilde t$, $\tilde t\to t\tilde\chi^0_1$, $\tilde\chi^0_1\to tbs$		Multiple		36.1	$\tilde t$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde\chi^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde t\tilde t$, $\tilde t\to b\tilde\chi^\pm_1$, $\tilde\chi^\pm_1\to bbs$		$\geq$ 4b		139	$\tilde t$ Forbidden 0.95	m($\tilde\chi^\pm_1$)=500 GeV	ATLAS-CONF-2020-016
	$\tilde t_1\tilde t_1$, $\tilde t_1\to bs$		2 jets + 2 b		36.7	$\tilde t_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde t_1\tilde t_1$, $\tilde t_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde t_1$ 0.4-1.45	BR($\tilde t_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde t_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde t_1\to q\mu$)=100%, cosθ_t=1	2003.11956

10^{-1} 1 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Direct Search for heavy Resonances

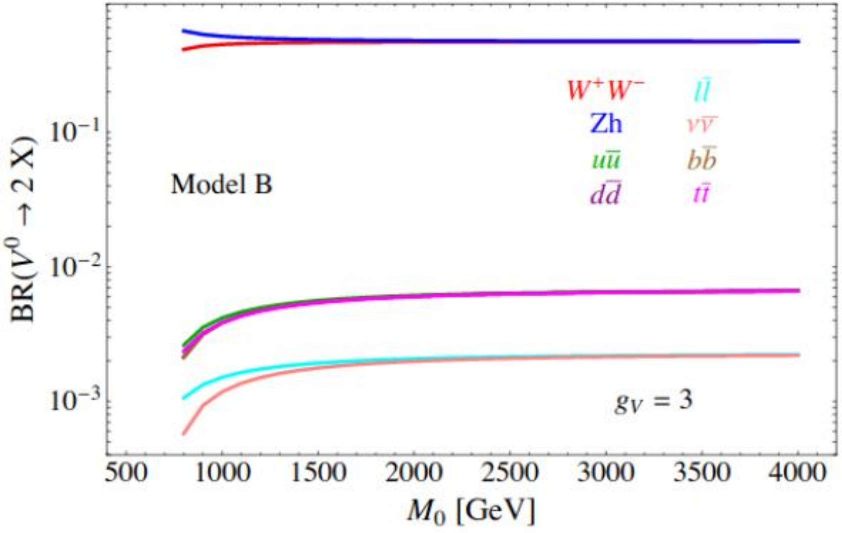
- Most searches for resonances in ATLAS and CMS follow the same principle:
    - Perform (quasi) **model-independent search for a bump in a smoothly falling mass spectrum**

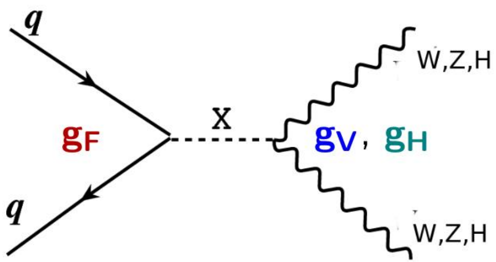


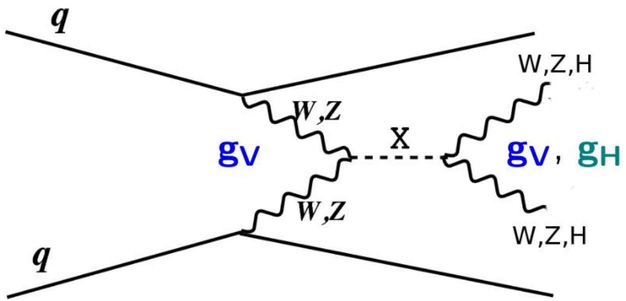
- **Interpretations in generic frameworks:**
    - Two Higgs Doublet Model (2HDM)
    - Higgs Triplet models
    - Heavy Vector Triplet (HVT) models
    - RS Extra-dimensional models

Heavy vector triplet (HVT) models

- **Heavy vector triplet** (HVT) as an example for a simplified model:
  - Simply introduces an additional SU(2) field to the SM
    - Results in a Z' and W'
    - Coupling to SM particles governed by model parameters g_V , g_F , g_H
  - Representative for:
    - Minimal Walking Technicolour
    - Little Higgs models
    - Composite Higgs models
    - Models with extra dimension



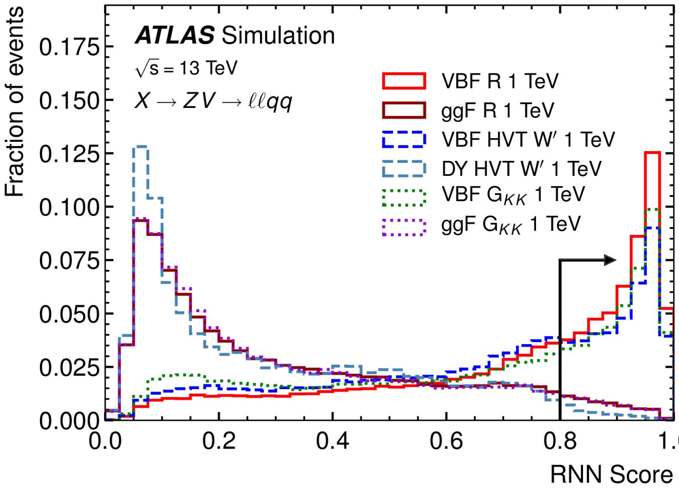


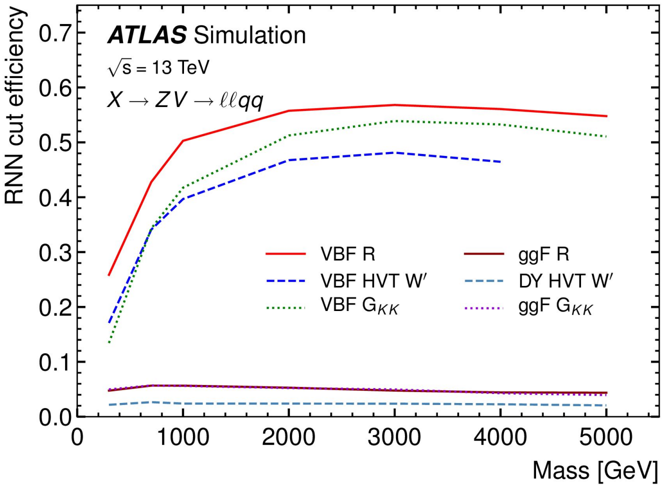


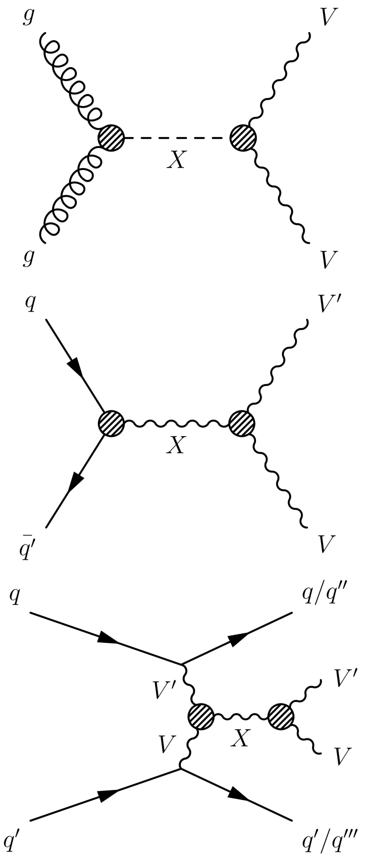
- **Model A:**
  - Prefer coupling to fermions
- **Model B:**
  - Prefer coupling to bosons
- **Model C:**
  - Fermiophobic

Search for semileptonic VV resonances:

- **Study of X → VV resonances in ννqq, ℓνqq and ℓℓqq final states**
  - Probe a variety of different production modes and spin hypotheses
    - gg → X (spin-0, spin-2)
    - qq → X (spin-1)
    - VBF X (spin-0, spin-1, spin-2)
  - Classify events into resolved and merged event categories
- **Use Recurrent Neural Network (RNN) to split signal regions into gg/qq-like and VBF-like**



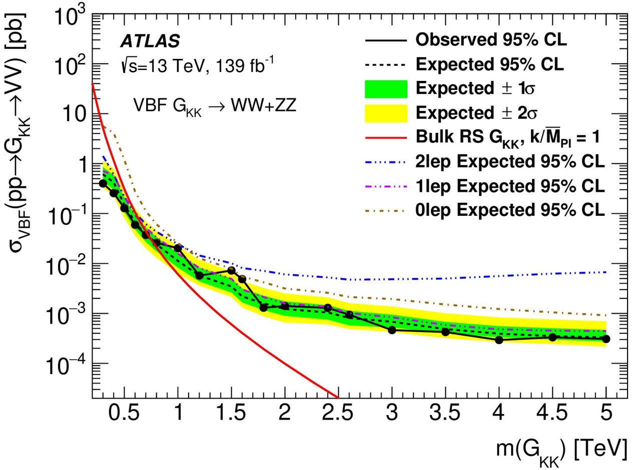


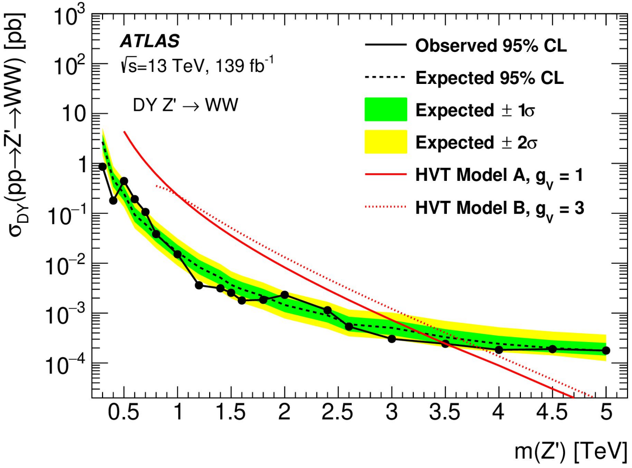


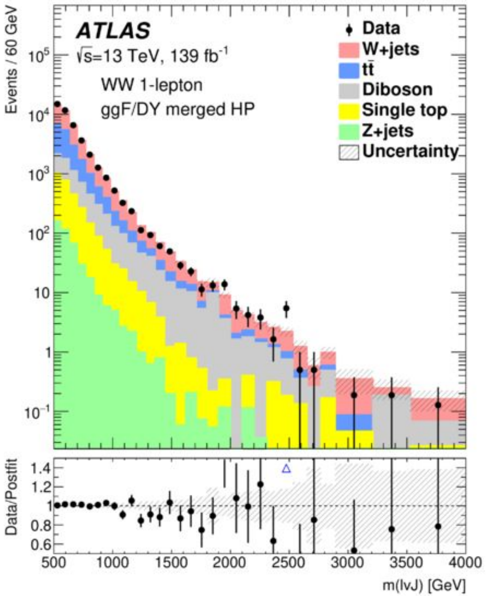
arXiv:2004.14636

Search for semileptonic VV resonances:

- Use m_T (in ννqq) and m_{VV} (in ℓνqq and ℓℓqq) distributions as input to likelihood (LLH) fit
- Exclude:
  - DY Z' with masses up to 3.5TeV (3.9TeV) for HVT Model A (Model B)
  - qq' W' with masses up to 3.9TeV (4.3TeV) for HVT Model A (Model B)
  - VBF RS Graviton with masses up to 0.8TeV
- Dominant uncertainties:
  - Data statistics (for m_X ~ 1 TeV)
  - Large-R jets (mass)
  - Background modelling







arXiv:2004.14636

Search for pseudo scalars in A → Zh decays:

- **Probe resolved and merged ννbb and ℓℓbb (ℓ = μ,e) final states**
- **Analysis strategy:**
  - Search for bumps in m_T or $m_{\ell\ell bb}$ spectra

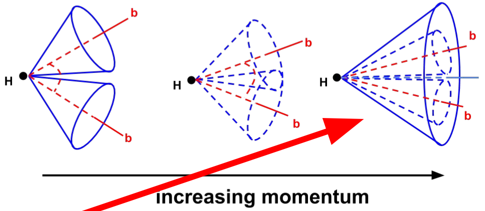
$$m_{\mathrm{T},Vh} = \sqrt{\left(E_{h,\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left(\vec{p}_{h,\mathrm{T}} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right)^2}$$

- **Dominant uncertainties:**
  - Modelling of backgrounds (top bkg. ME +PS)
  - Large-R jets (mass resolution)

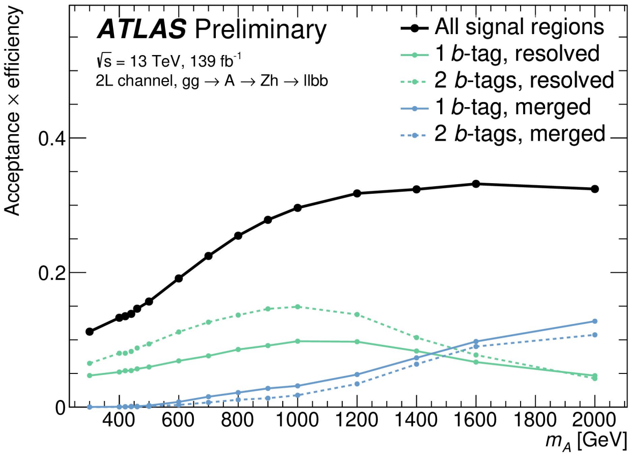
Resolved: use two small-R jets

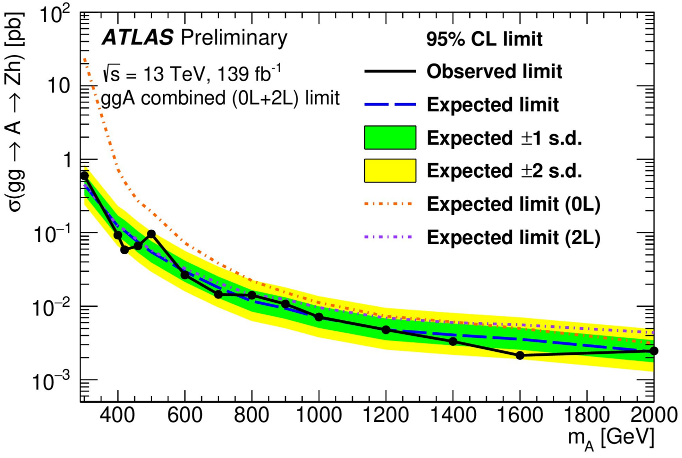
Merged: use a large-R jet to reconstruct Higgs bosons with around p_T > 250GeV

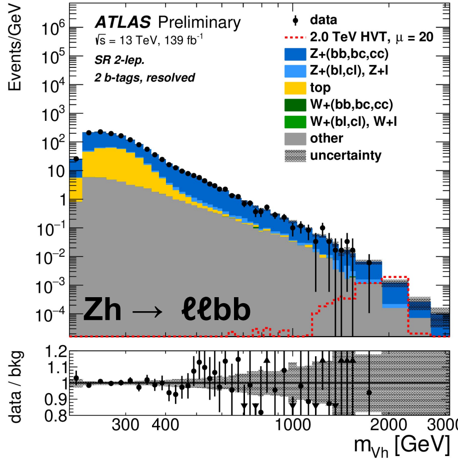
for m_h = 125 GeV



$$\Delta R \approx \frac{2m}{p_T}$$







ATLAS-CONF-2020-043

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WW \to qqqq$	$0\ e, \mu$	2 J	–	139	G_{KK} mass 1.6 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2019-003
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	139	W' mass 6.0 TeV		CERN-EP-2019-100
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WZ \to qqqq$ model B	$0\ e, \mu$	2 J	–	139	V' mass 3.6 TeV	$g_V = 3$	ATLAS-CONF-2019-003
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	$2\ \mu$	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η_{LL}^-		1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	Λ 40.0 TeV η_{LL}^-		1707.02424
	CI $tttt$	$\geq 1\ e, \mu$	≥ 1 b, ≥ 1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	$2\ \tau$	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(LQ_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/$\geq$3 e,μ	≥ 1 b, ≥ 1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	$0\ e,\mu$, $2\ \gamma$	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2019-007
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	$1\ e, \mu$	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q \rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1905.10130

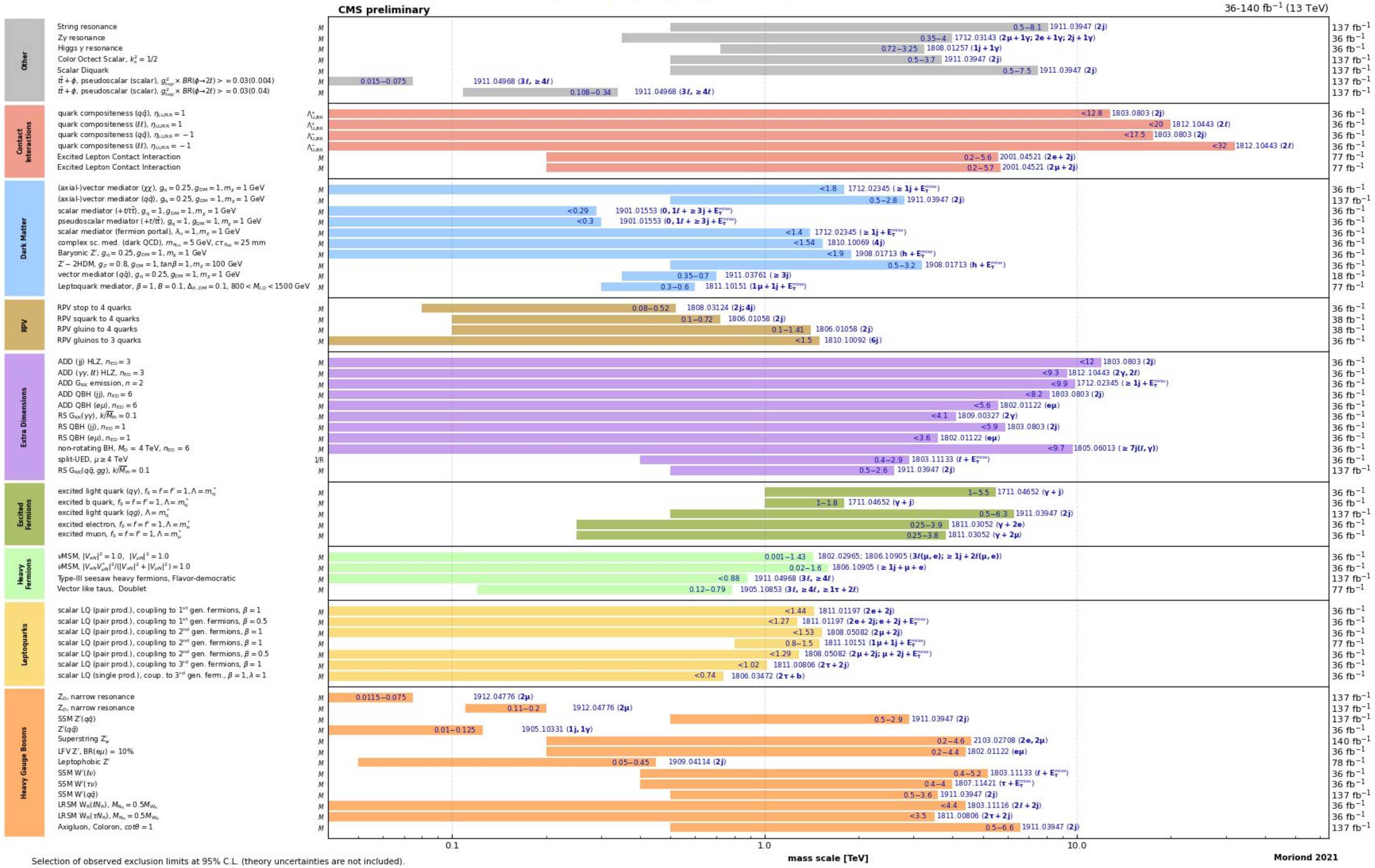
$\sqrt{s}$ = 8 TeV | $\sqrt{s}$ = 13 TeV partial data | $\sqrt{s}$ = 13 TeV full data

10^{-1} 1 10 **Mass scale [TeV]**

**Only a selection of the available mass limits on new states or phenomena is shown.*

†Small-radius (large-radius) jets are denoted by the letter j (J).

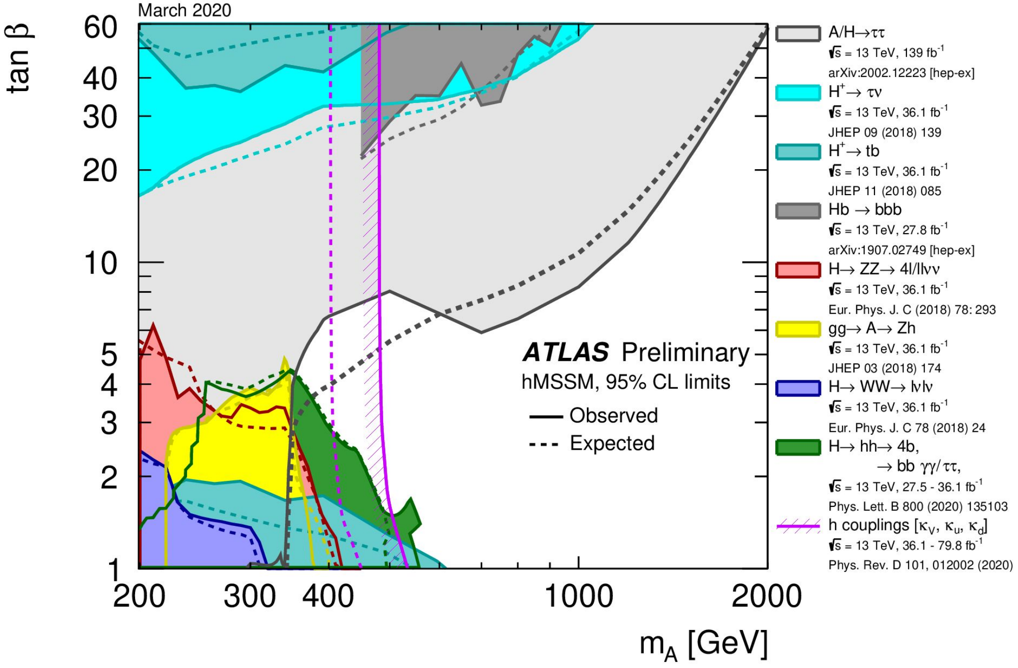
Overview of CMS EXO results

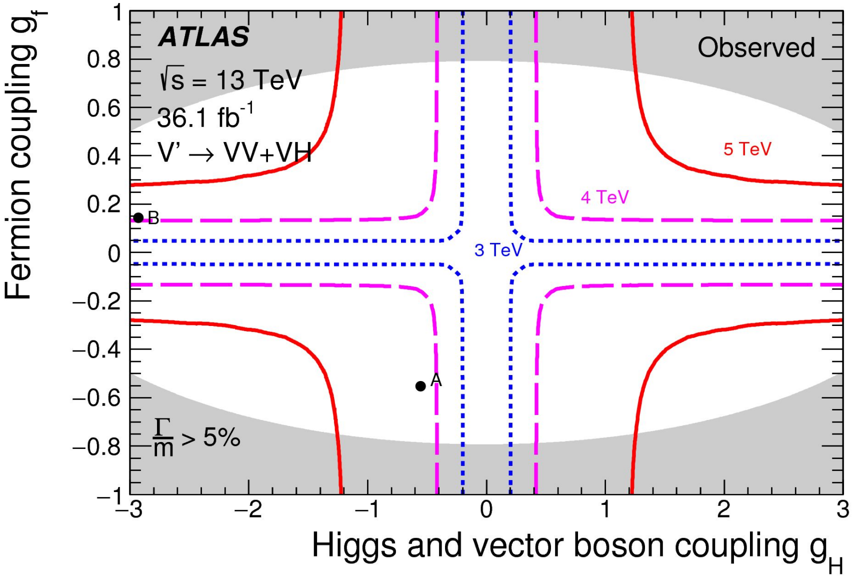


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Exclusion limits are not only set on particle masses, but also on model parameters

2HDM

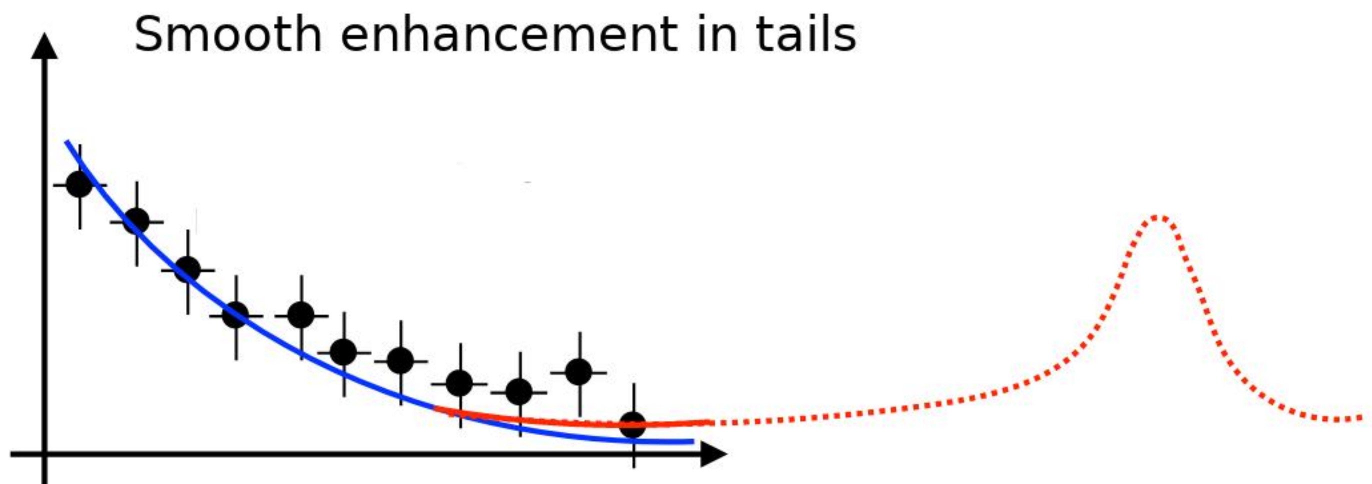




HVT

Effective field theories

- So far no hints for new physics in direct searches
- What if scale of new physics is outside the reach of the LHC?
  - **Search for smooth enhancements in the tails of our observables**
    - E.g. from resonances with masses beyond our reach
  - **Probing for shape modifications of our observables**
    - E.g. from anomalous couplings
- **Effective field theories (EFT) allow for model independent approaches to search for such new physics effects**

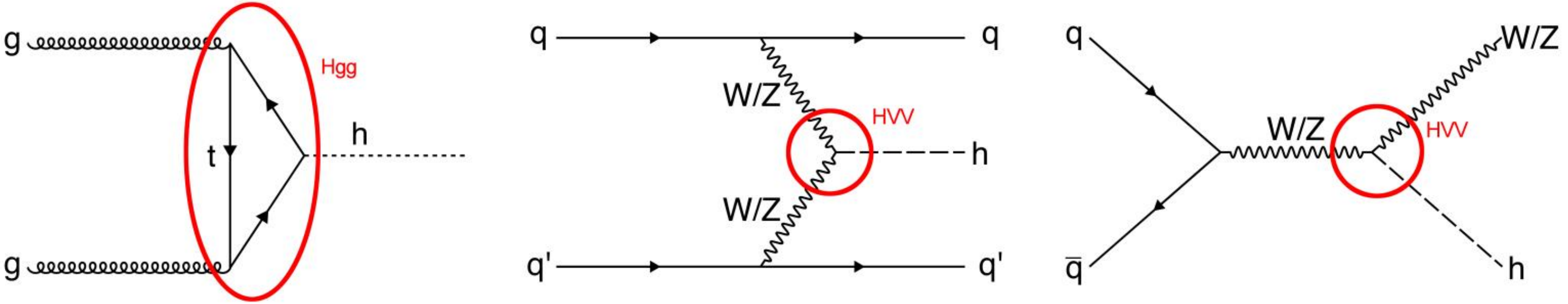


Effective field theory (EFT)

- **In EFTs, Lagrangian of the Standard Model of particle physics is supplemented with additional BSM terms:**

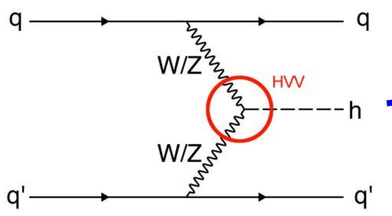
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda}\mathcal{O}_i$$

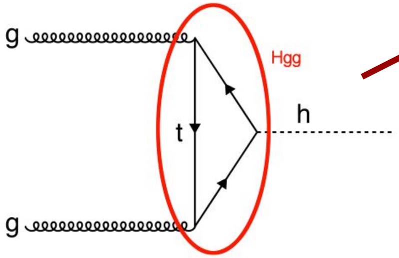
- $\mathcal{O}_i$ are higher dimension operators
- c_i are the so-called Wilson coefficients
  - Specify the strength of a new CP-even (or CP-odd) interaction (i.e. they describe deviation from SM)
- Λ is mass scale for new particle

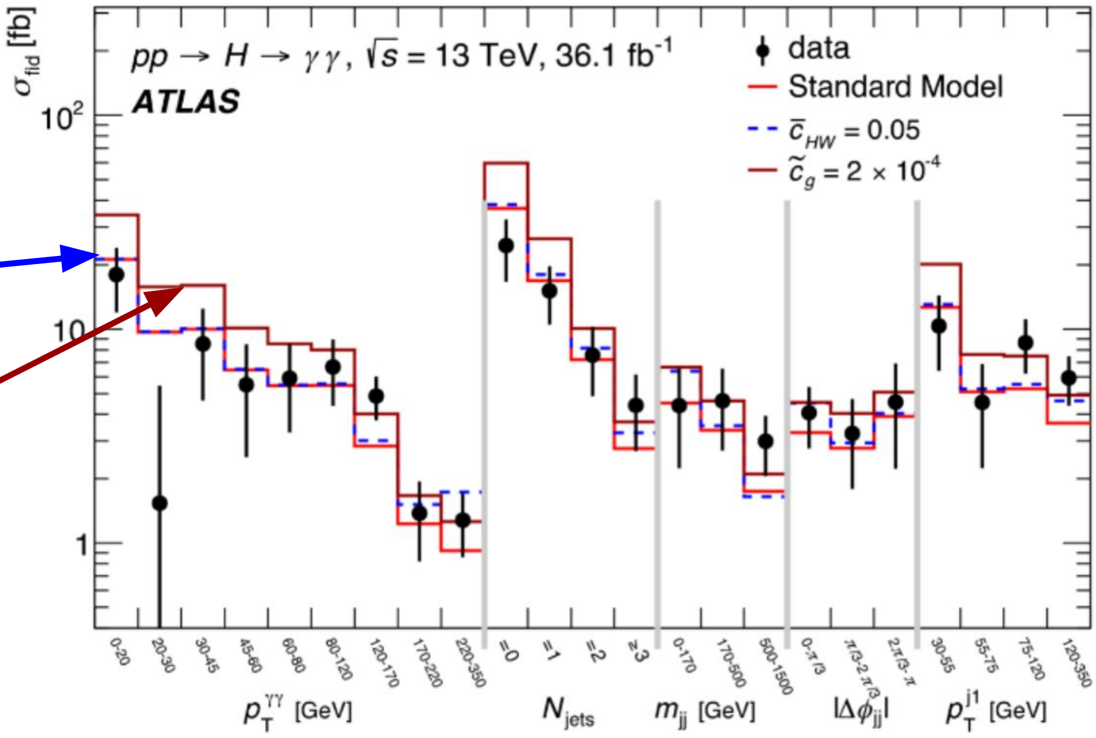


Effective field theory (EFT)

BSM physics contributions to the Higgs boson production process can modulate certain kinematical observables





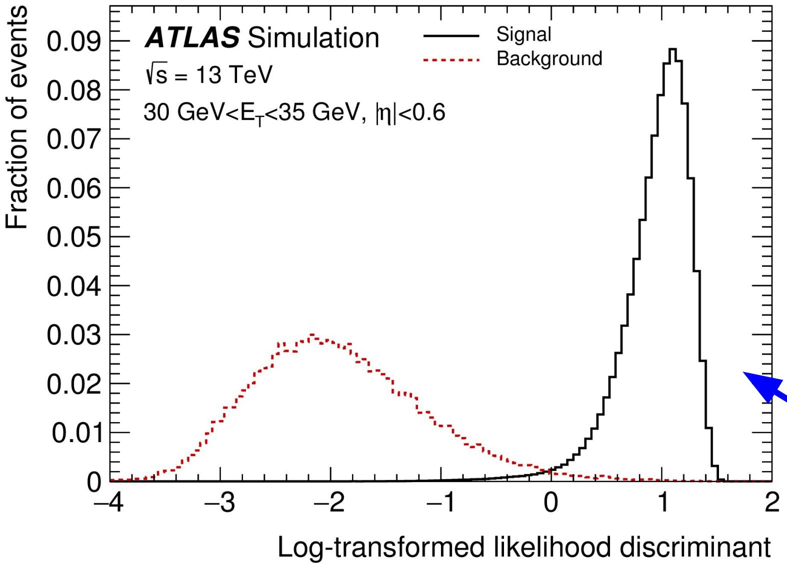


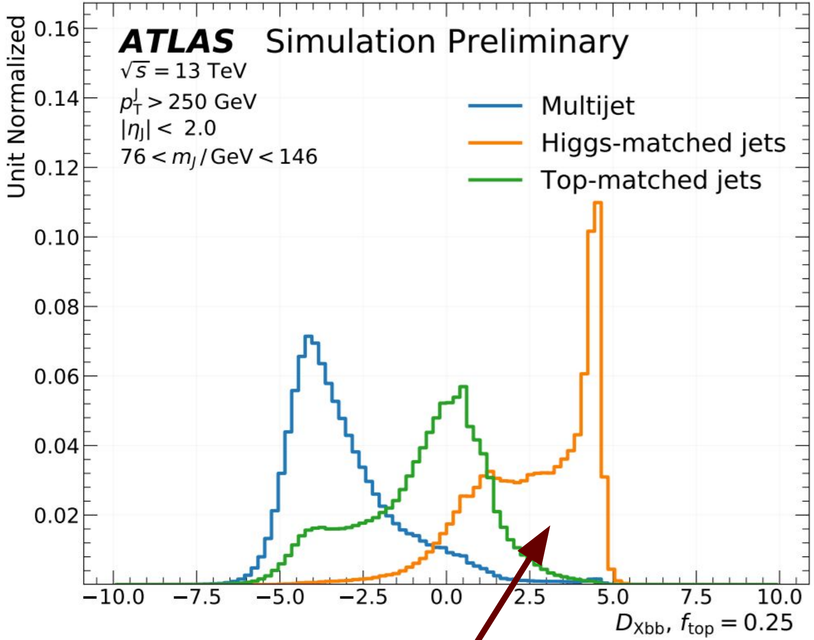
Perform hypothesis tests to determine whether data fits better to SM predictions or BSM hypotheses

Machine learning in HEP

Machine learning in HEP

MVAs are widely used in the ATLAS/CMS object reconstruction/identification





Boosted Higgs identification algorithm

Electron identification algorithm

Machine learning in HEP

MVAs are also applied at the event level to separate between signal and background processes