Testing the Standard Model of Elementary Particle Physics I

Physics at the LHC

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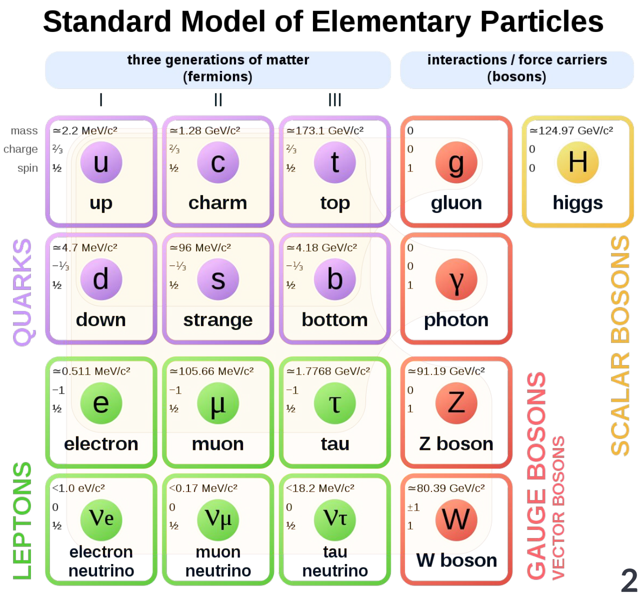
Standard Model of particle physics in a nutshell

- 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: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

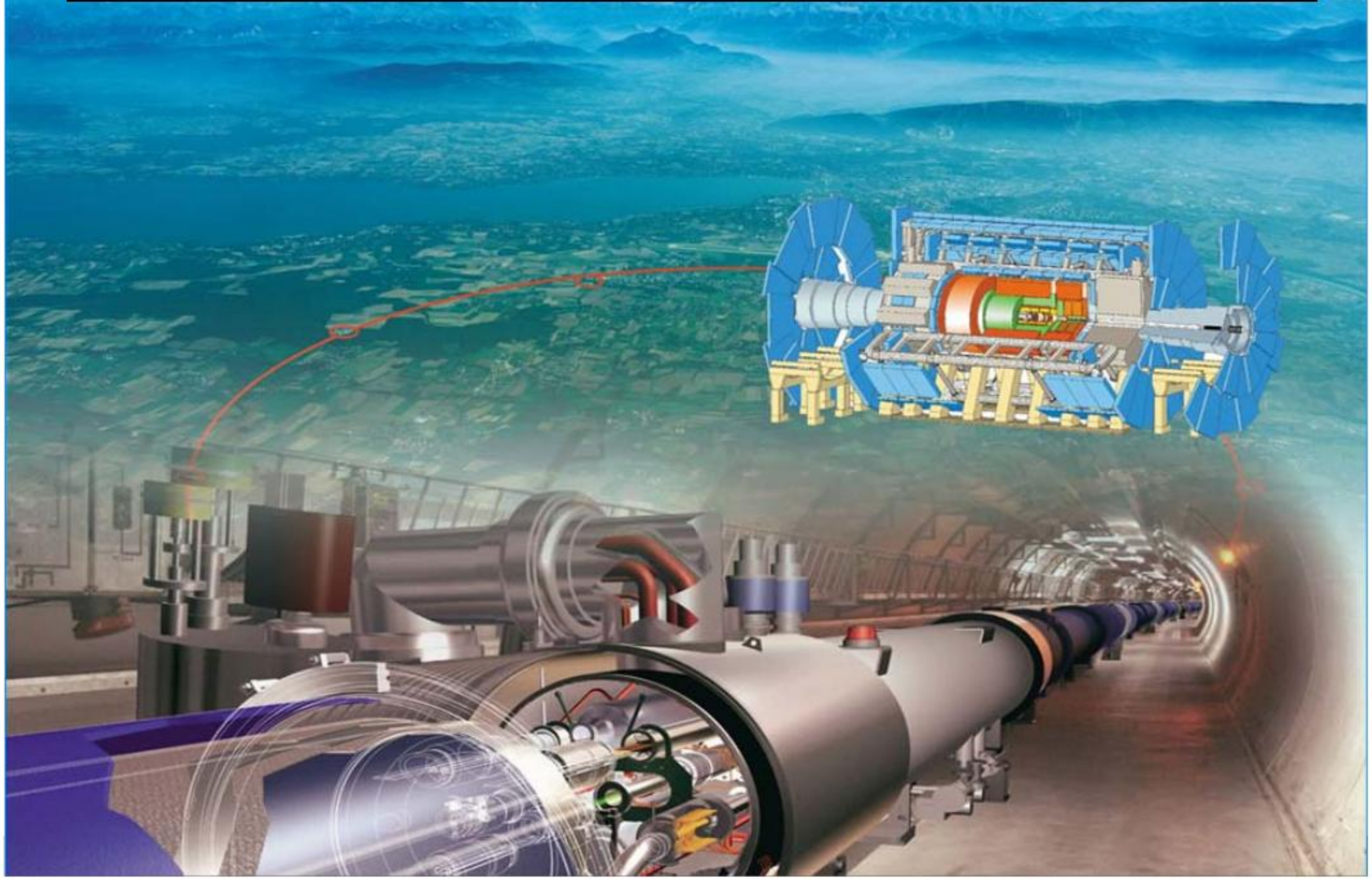
However, the Standard Model leaves some questions unanswered



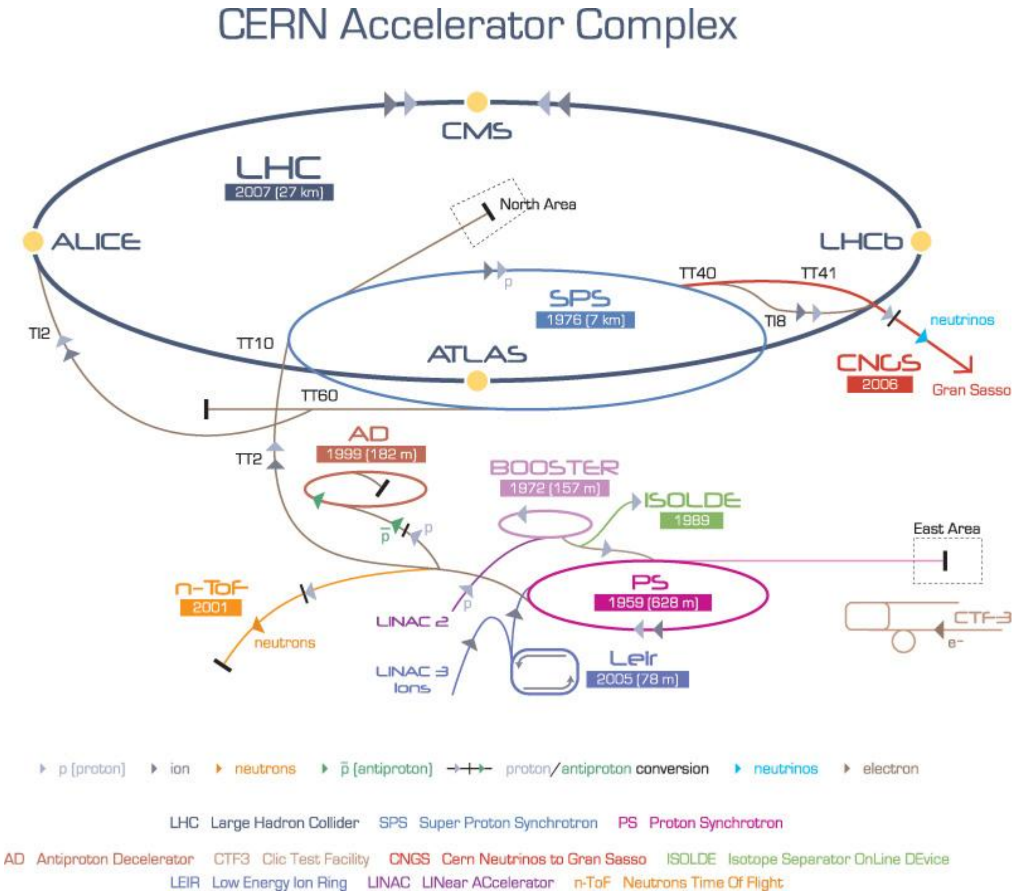
Physics at the LHC

- Use LHC and its experiments to find answers to these open questions
- Today’s lecture will highlight a few aspects of the physics programme of the LHC experiments
- **Content:**
    - Experimental setup
    - W & Z boson studies
    - Higgs boson studies
    - Top quark studies
    - Flavour-physics
    - Direct searches for new physics

Experimental setup



The Large Hadron Collider



- Instantaneous luminosity

$$\mathcal{L} = fn\frac{N_1 N_2}{A}$$

N_1, N_2 = Number of hadrons per bunch

n = Number of bunches per beam

f = Resolution frequency

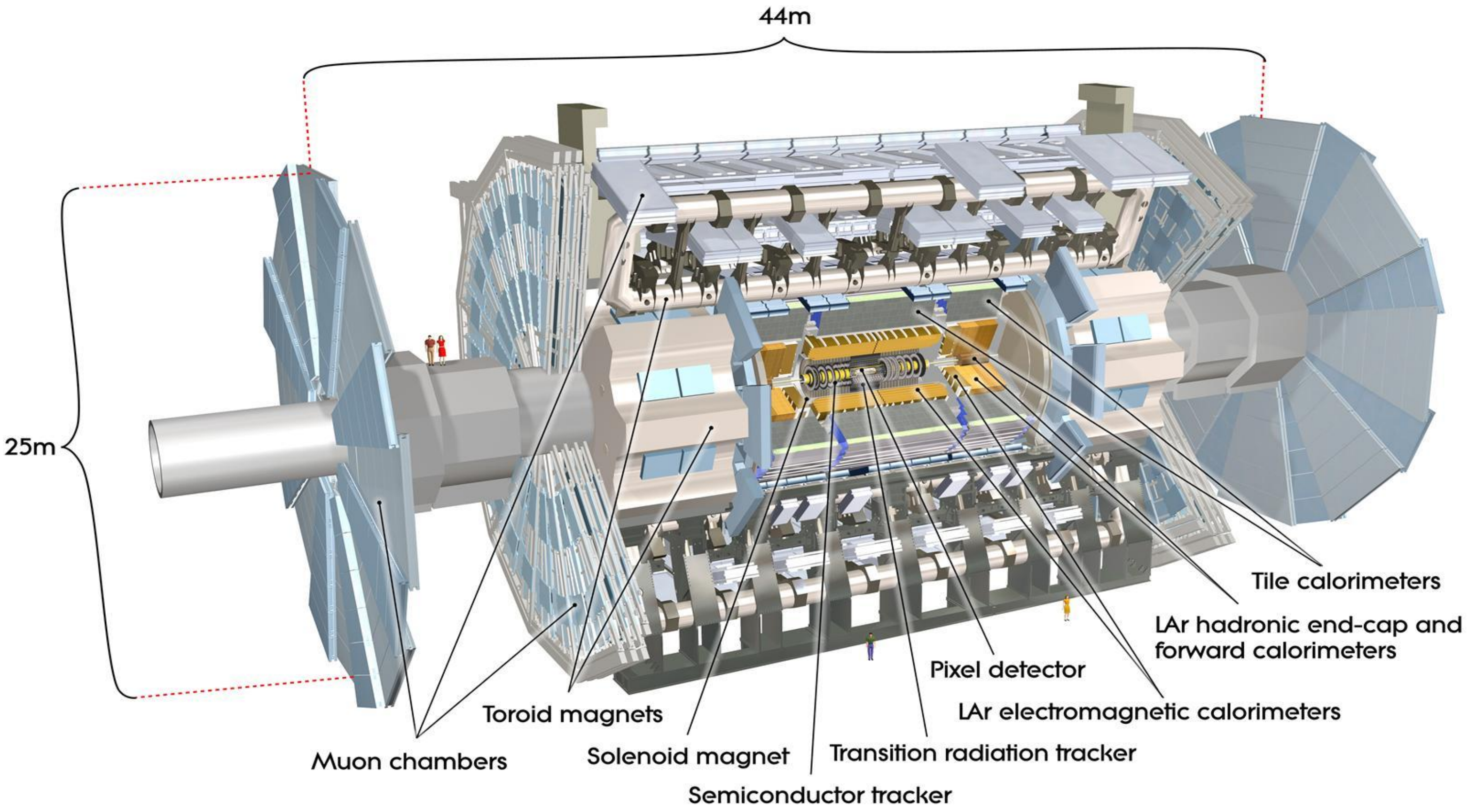
A = Beam cross section

- Integrated luminosity

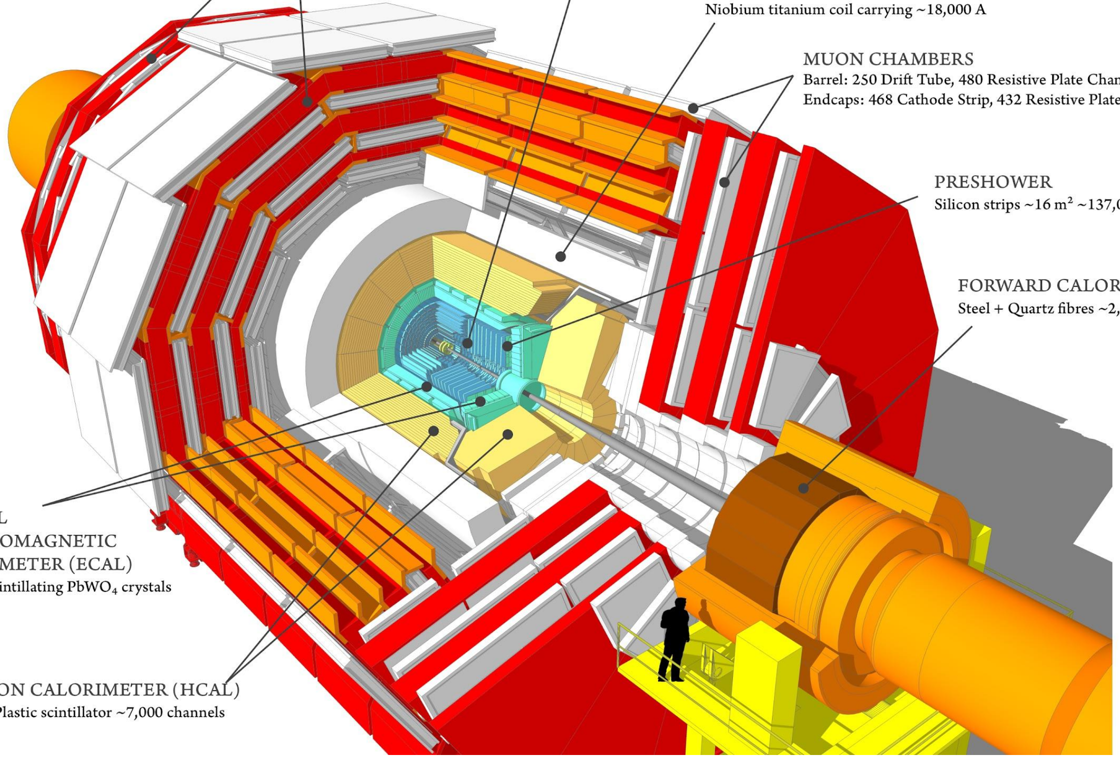
$$L = \int \mathcal{L} dt$$

- CoM energy: $\sqrt{s}$

The ATLAS Detector



The CMS Detector



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm^2) ~1 m^2 ~66M channels
Microstrips (80–180 μm) ~200 m^2 ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

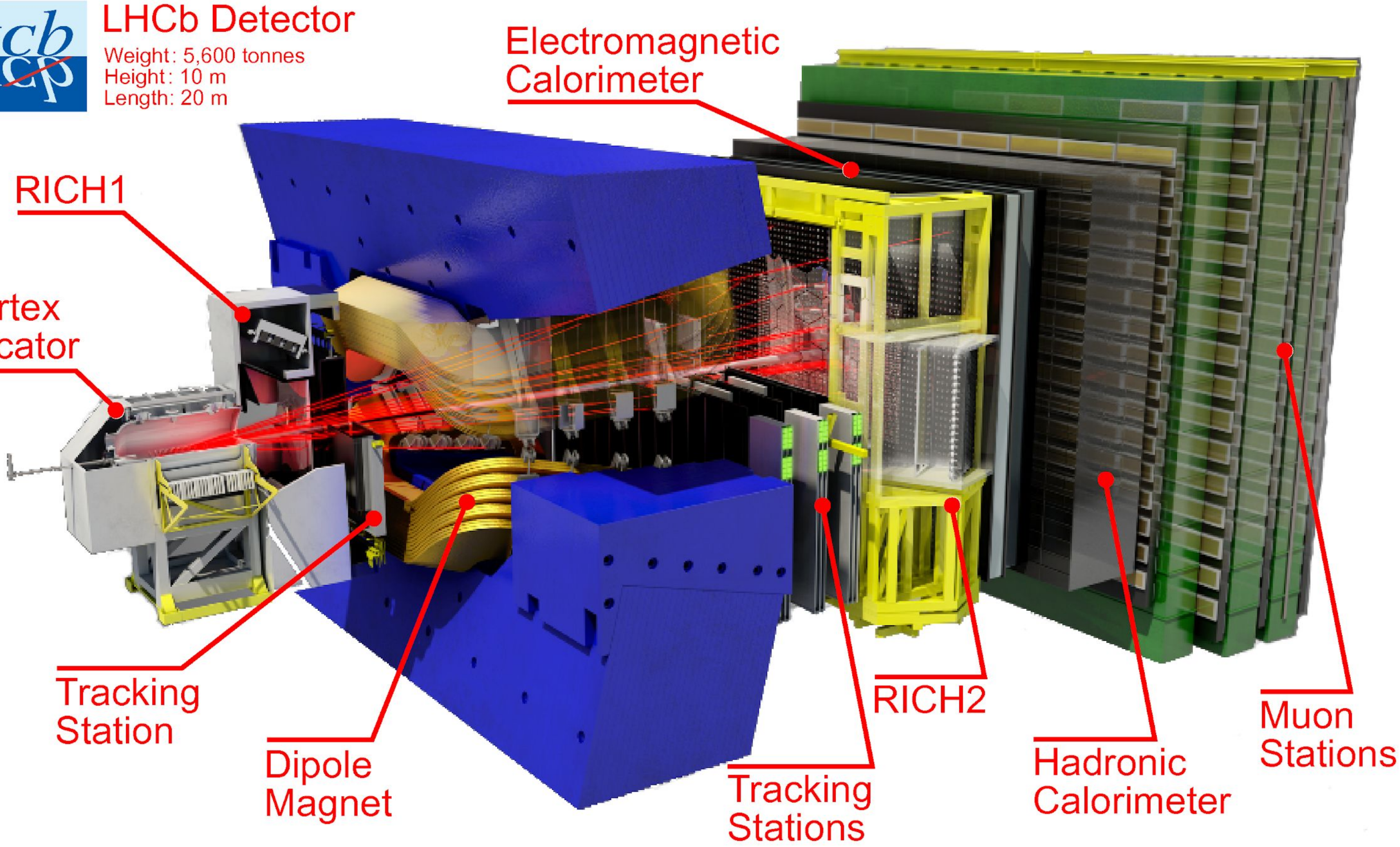
PRESHOWER
Silicon strips ~16 m^2 ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

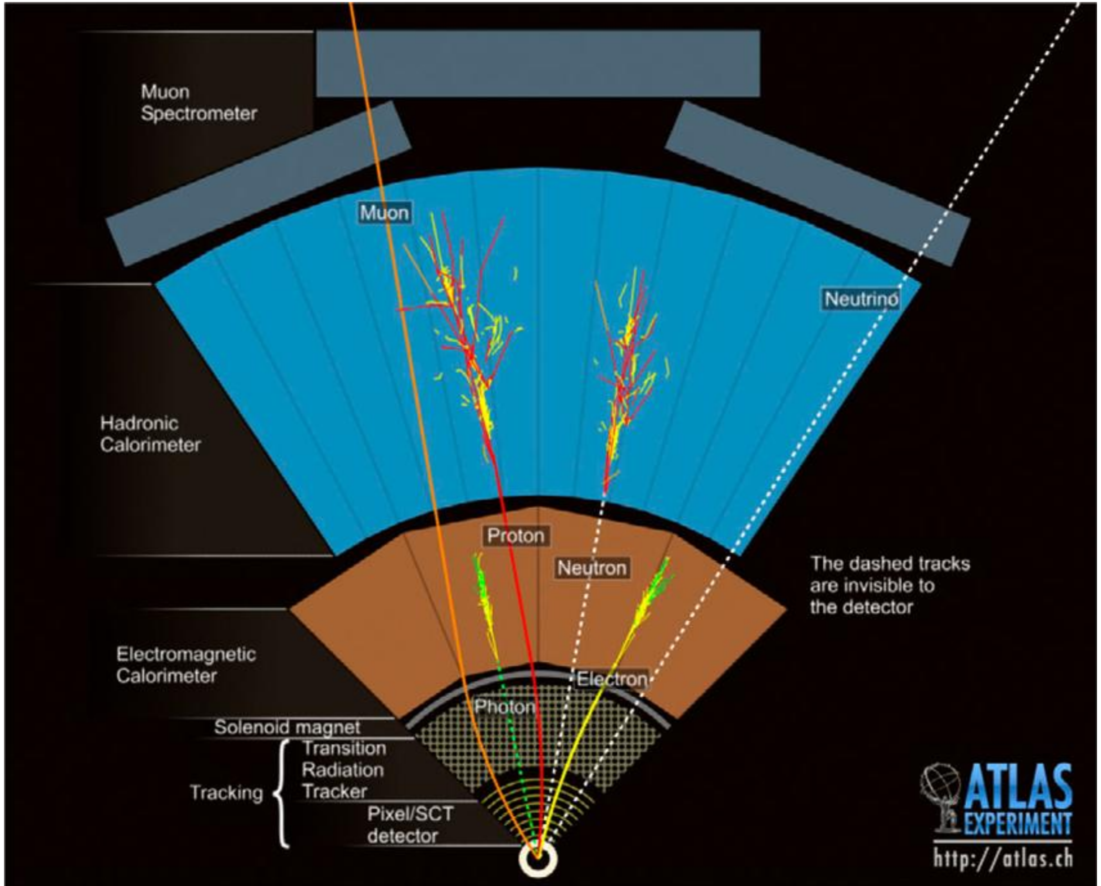
The LHCb Detector



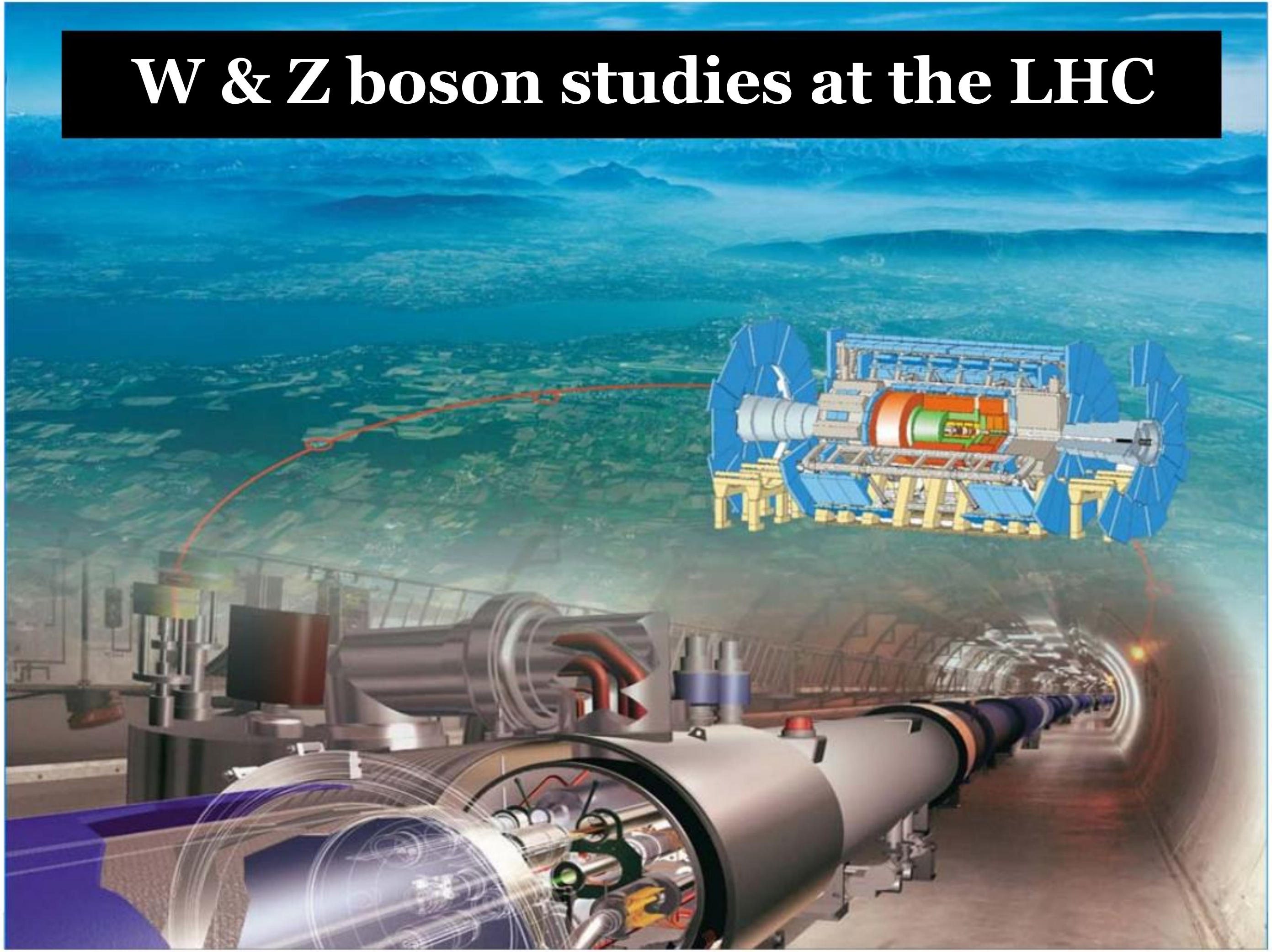
Particle identification

- **Hadronic particle shower**
  - Cone shaped jets build from calorimeter clusters or tracks
- **Muons**
  - Combined tracks from Inner Detector and Spectrometer
- **Electrons**
  - Inner Detector (ID) track
  - Energy clusters in calorimeter system
- **Taus**
  - Jets with either 1 or 3 ID tracks
- **Neutrinos**
  - Pass through the detector without leaving any trace.
  - Estimated from energy balance:

$$E_{\mathrm{X,Y}}^{\mathrm{mis}} = -\sum E_{\mathrm{X,Y}}^{\mathrm{obj.}} + E_{\mathrm{X,Y}}^{\mathrm{soft}}$$



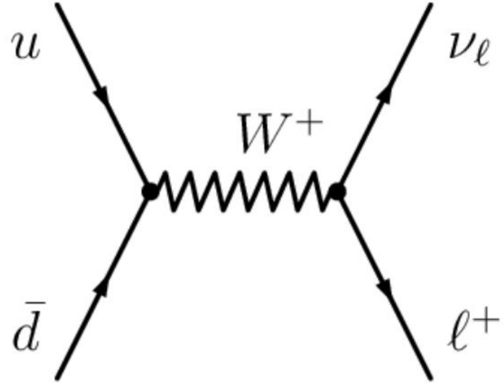
The dashed tracks are invisible to the detector

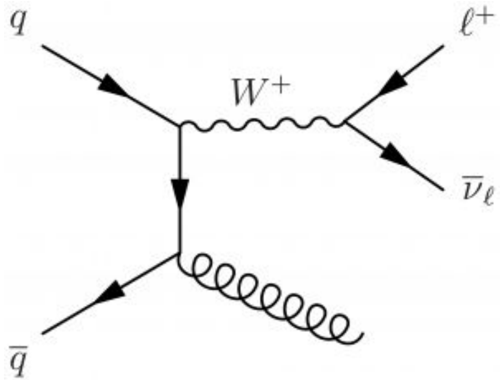


W & Z boson studies at the LHC

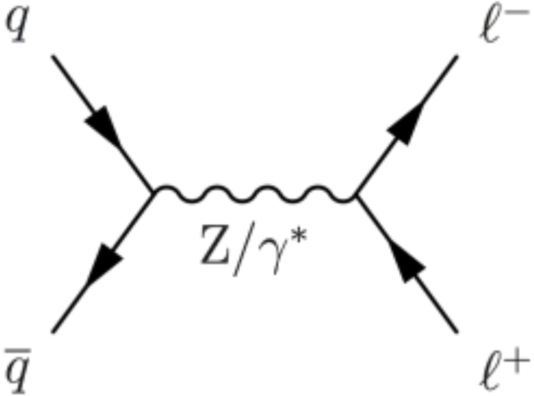
W/Z + jets production at the LHC

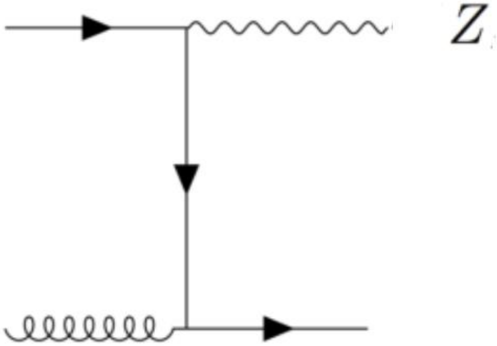
W + jets





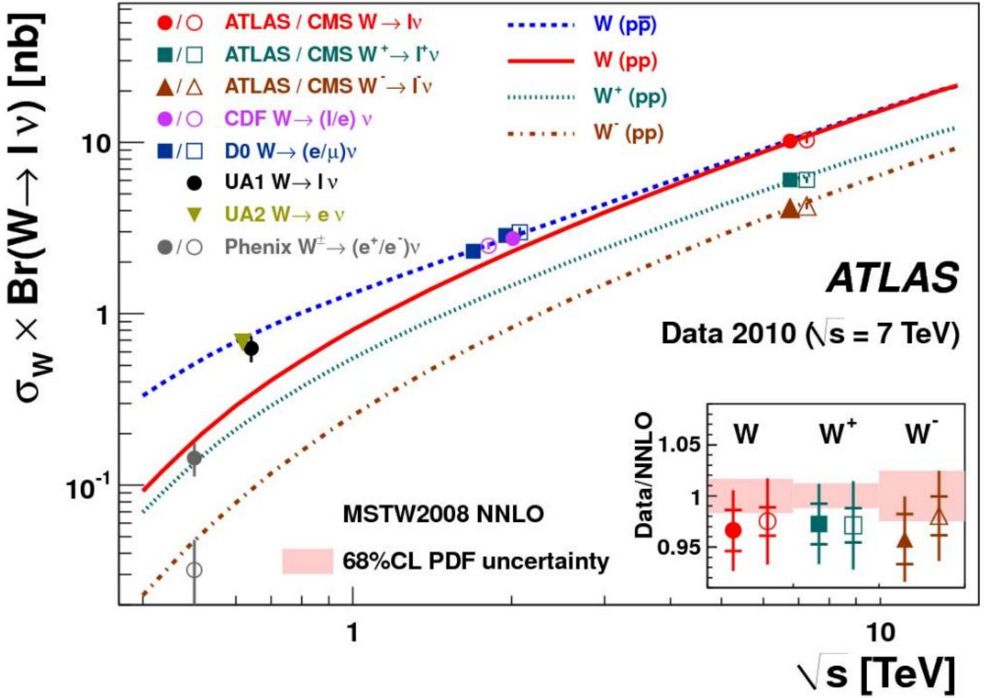
Z + jets

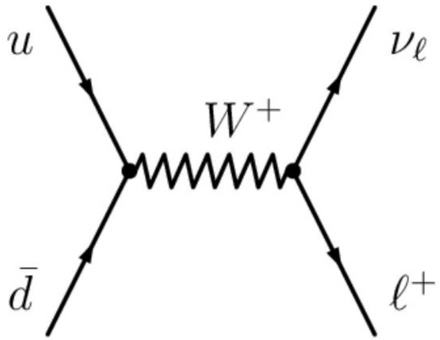


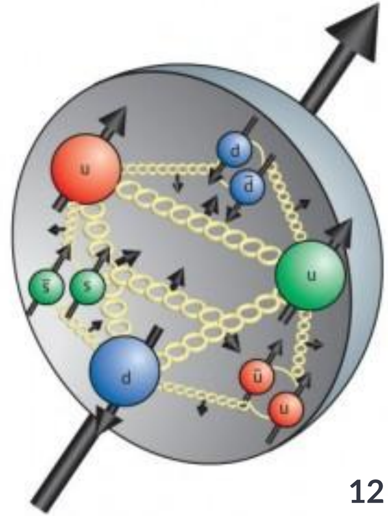


Charge asymmetry in W boson production

- **Parton distribution functions (PDFs) of u and d quarks in the proton differ** (mainly due to the fact that protons contain two valence u quarks and one valence d quark)

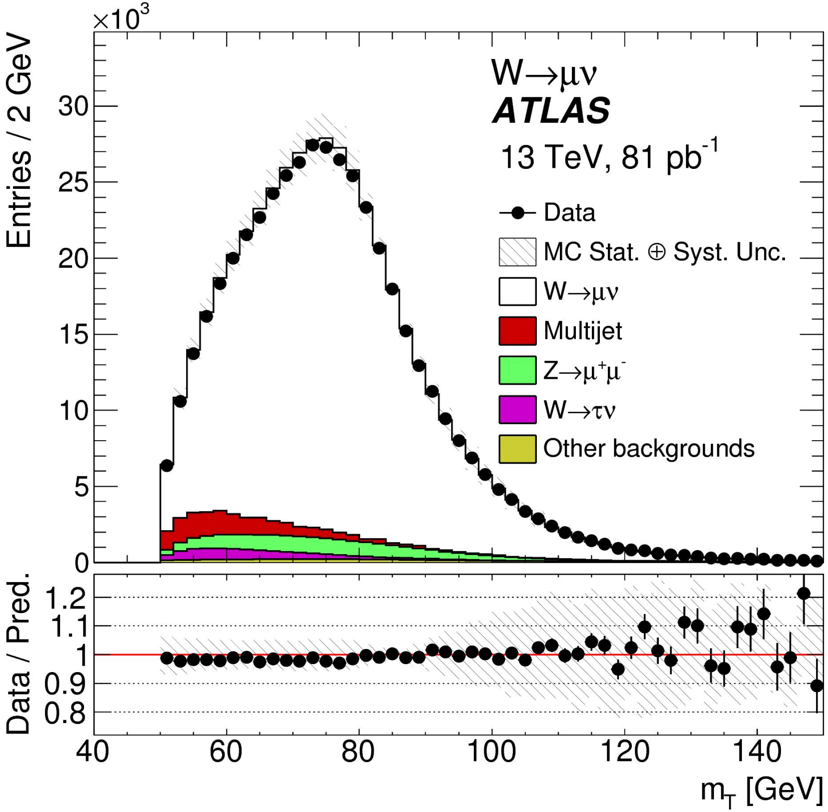




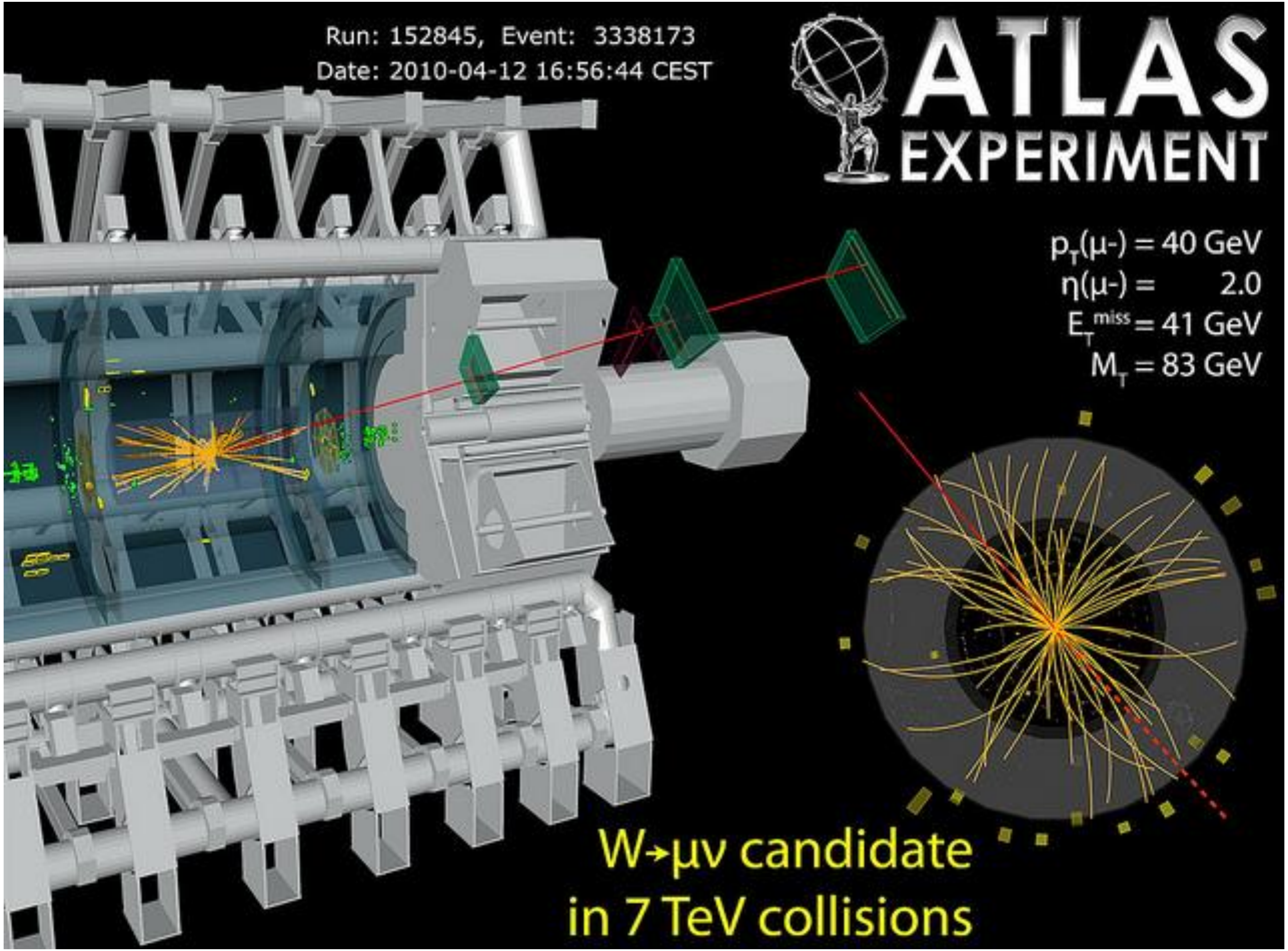


W boson production

- W boson candidate events are selected by requiring:
  - Exactly one identified electron or muon
  - MET > 25 GeV
  - m_T > 50 GeV
- Roughly 20% of all selected events stemm from background processes:
  - Most dominant contributions:
    - Multijets (10%)
    - $Z \rightarrow \ell\ell$ (5%)

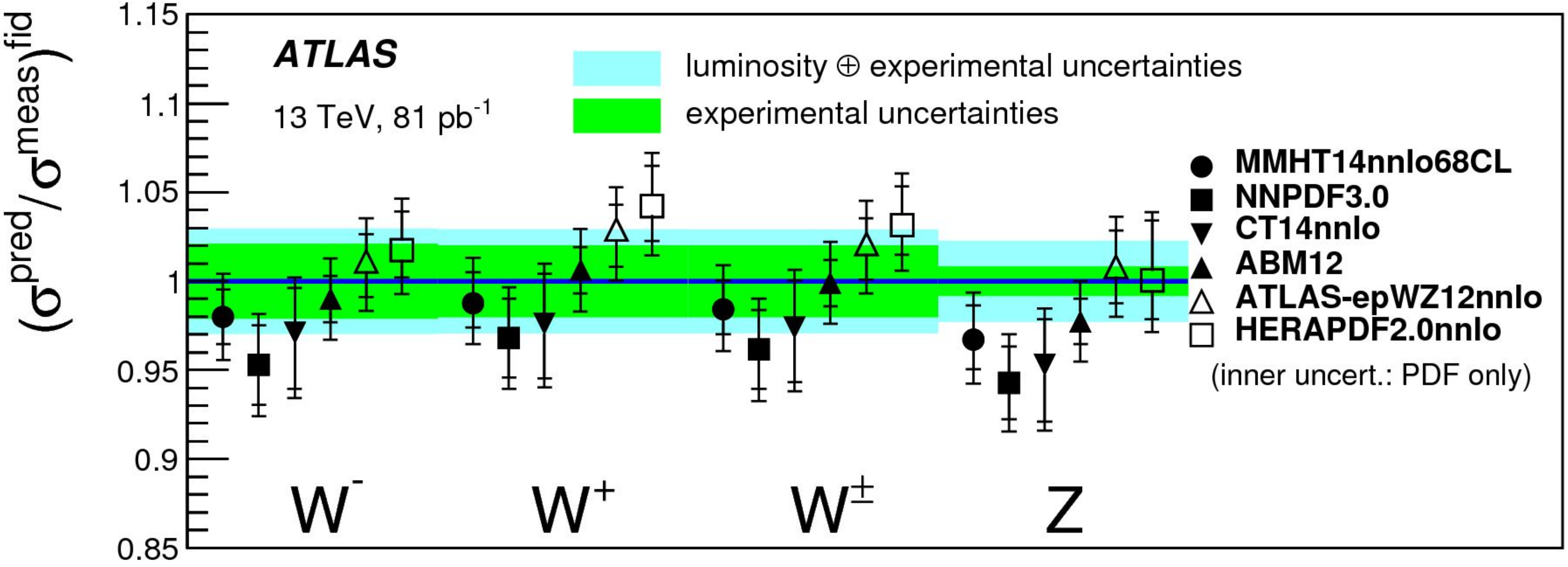


From: https://arxiv.org/abs/1603.09222


Run: 152845, Event: 3338173
Date: 2010-04-12 16:56:44 CEST
ATLAS EXPERIMENT
$p_T(\mu-) = 40$ GeV
$\eta(\mu-) = 2.0$
$E_T^{miss} = 41$ GeV
$M_T = 83$ GeV
W→μν candidate
in 7 TeV collisions

W/Z production cross sections

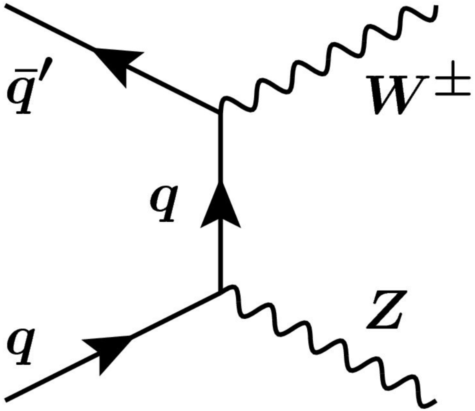
From: https://arxiv.org/abs/1603.09222

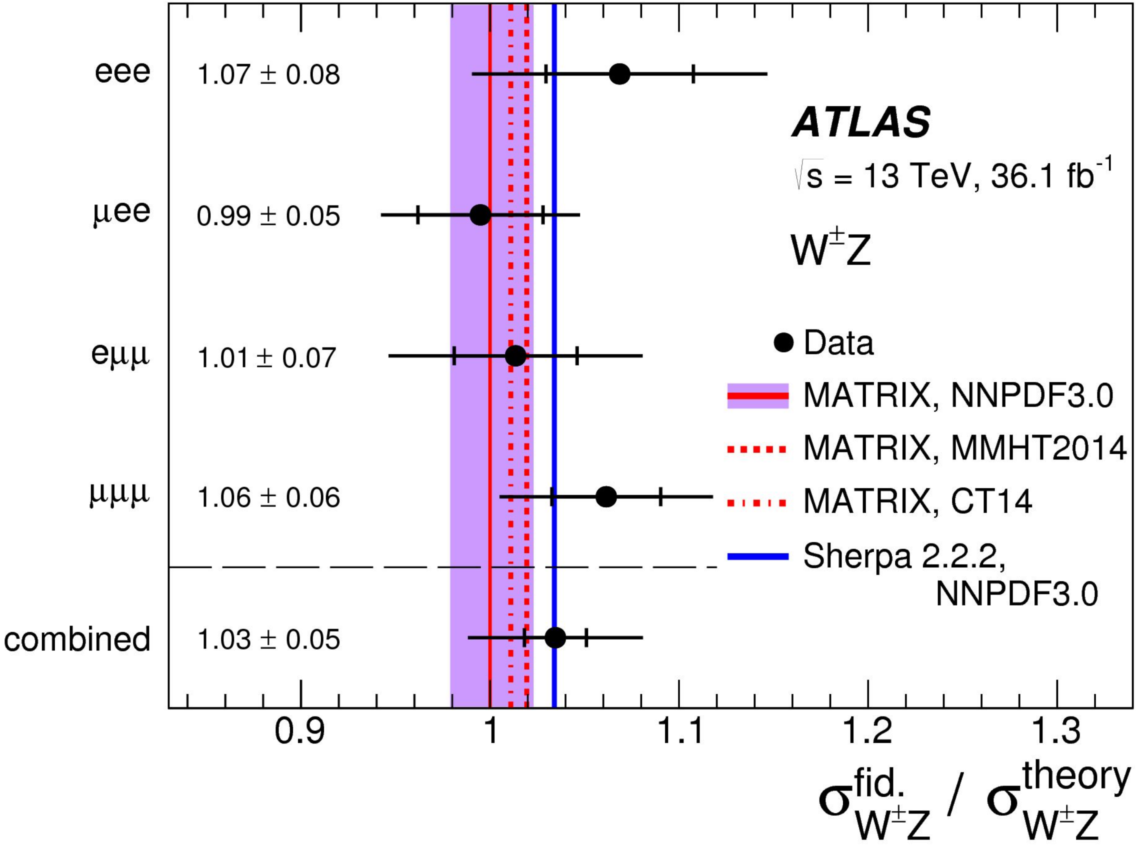


W & Z boson production cross section measurements are sensitive to the PDF sets

→ Can constrain them

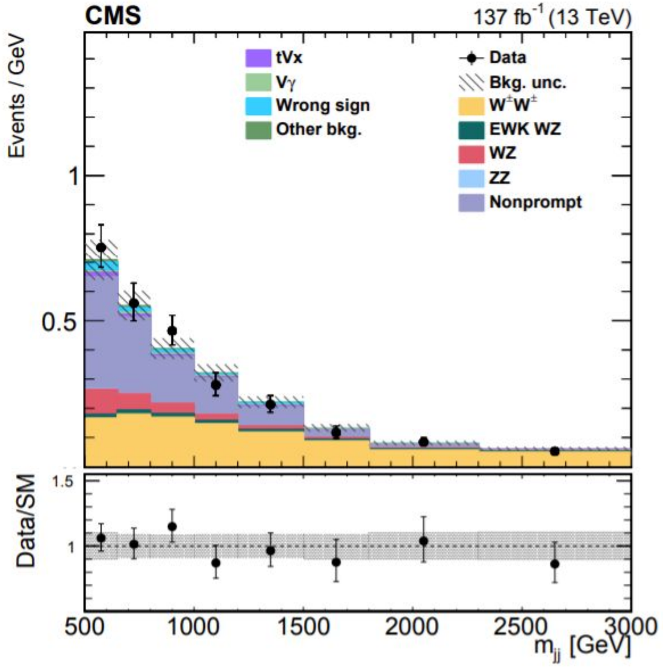
WZ production cross section measurements

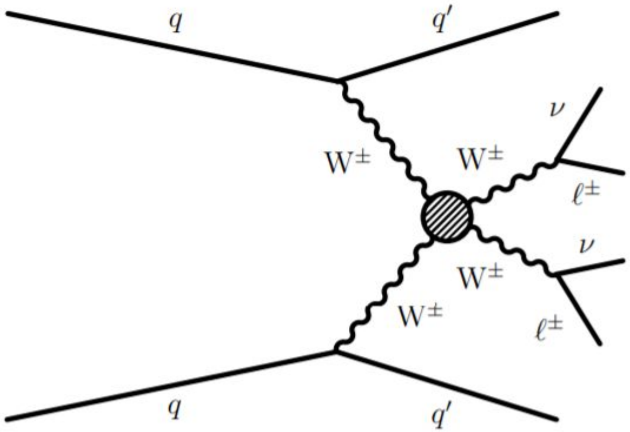




Same-sign WW boson pair production

- Insights into the mechanism of electroweak (EW) symmetry breaking can be achieved via vector boson scattering (VBS) processes
    - Via studies of vector boson self interaction
- Sensitive to anomalous quartic gauge couplings (aQGC)
- Same-sign $W^{\pm}W^{\pm}$ channel is promising due to small background yields from SM processes

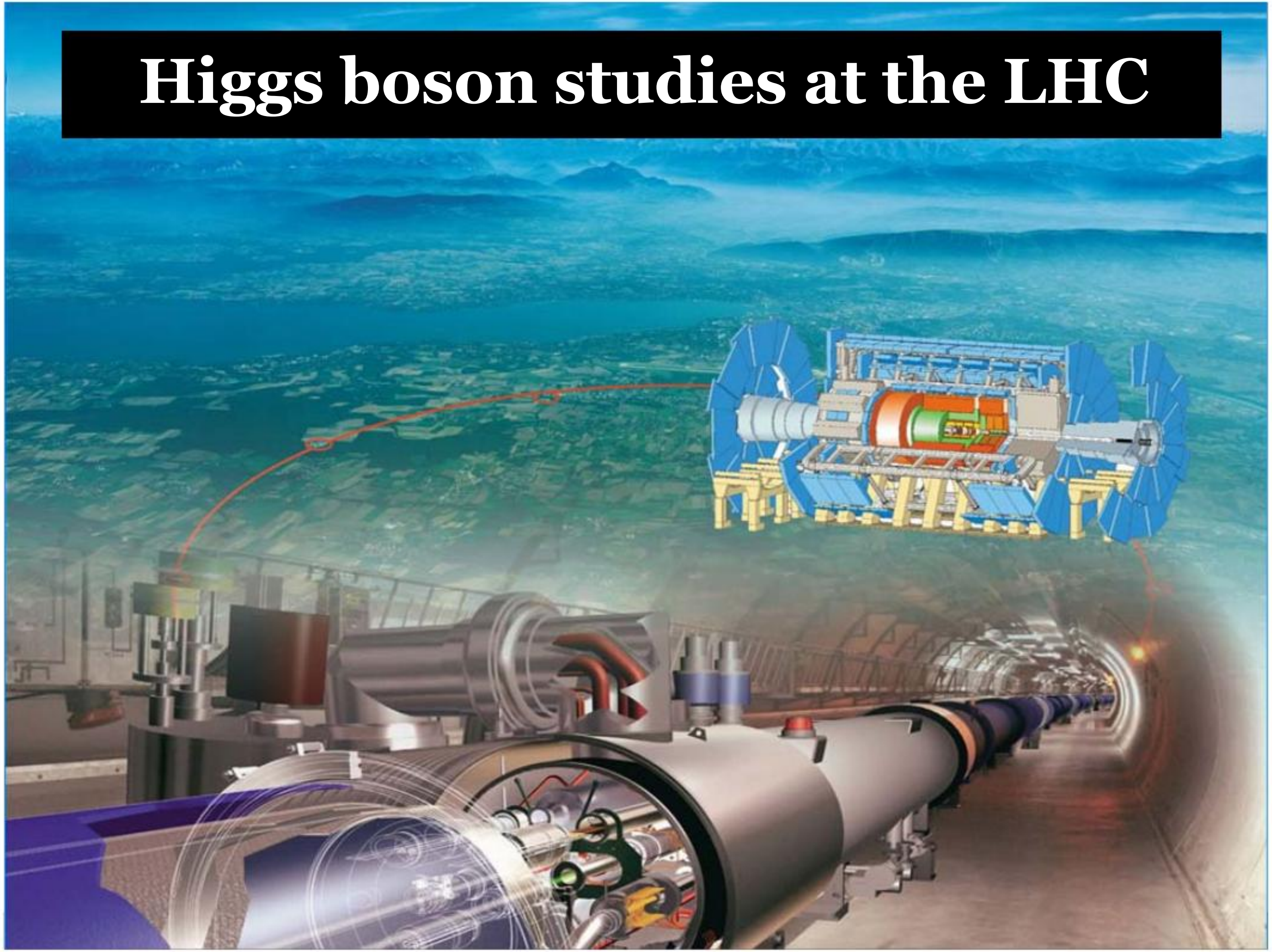




σ BR($W^{\pm}W^{\pm} \rightarrow \ell^{\pm}\ell^{\pm}$) = 3.98 ± 0.37 (stat) ± 0.25 (syst) fb

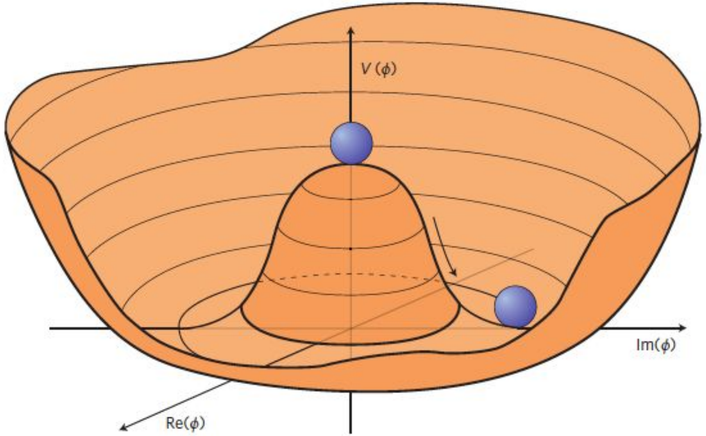
From https://arxiv.org/pdf/2005.01173.pdf

Higgs boson studies at the LHC

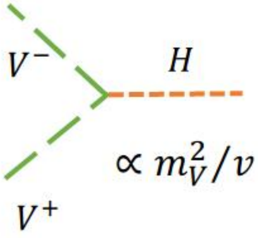


The Higgs boson: Last puzzle piece of the SM

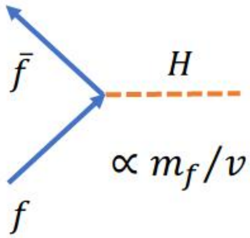
- Particles acquire mass via coupling to Higgs field (spontaneous symmetry breaking)
    - Postulated in 1964
    - Higgs boson (excitation of the Higgs field) was finally discovered in 2012
    - Spin: 0



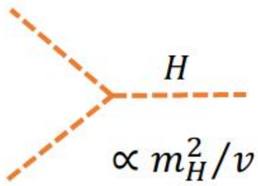
Gauge coupling:



Yukawa coupling:



Self coupling:



- **Higgs-potential**:

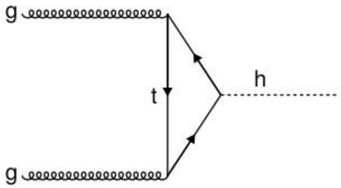
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

- **Vacuum expectation value**

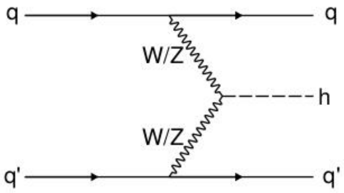
$$v = \frac{\mu}{\sqrt{\lambda}}$$

Higgs boson production at the LHC

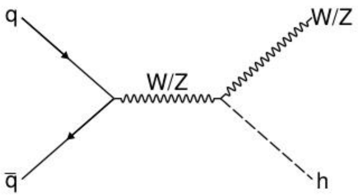
Gluon fusion (86%)



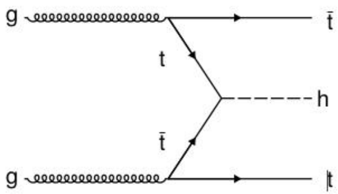
Vector boson fusion (7%)

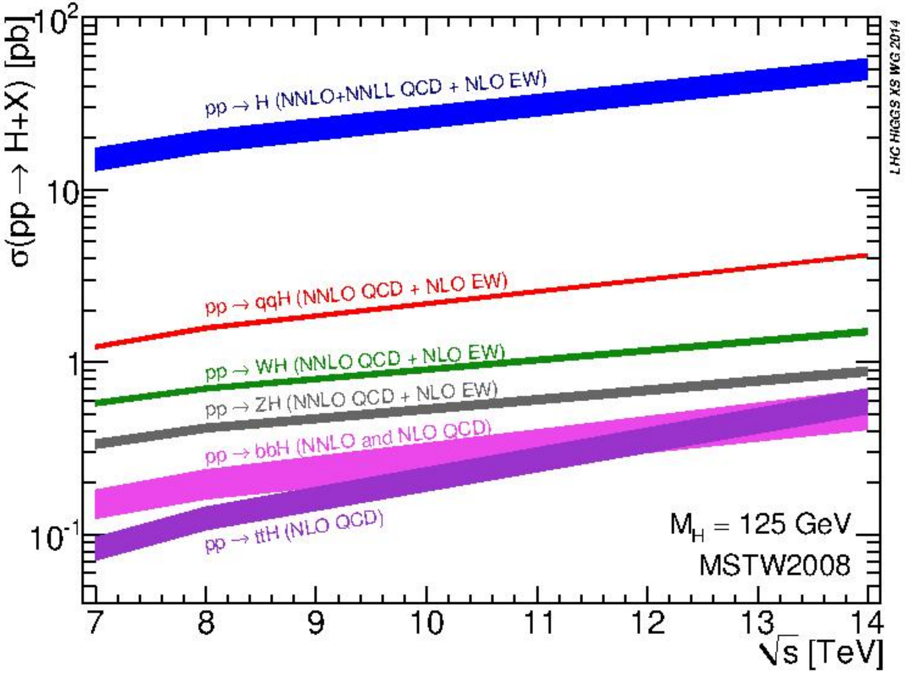


Higgs Strahlung (5%)



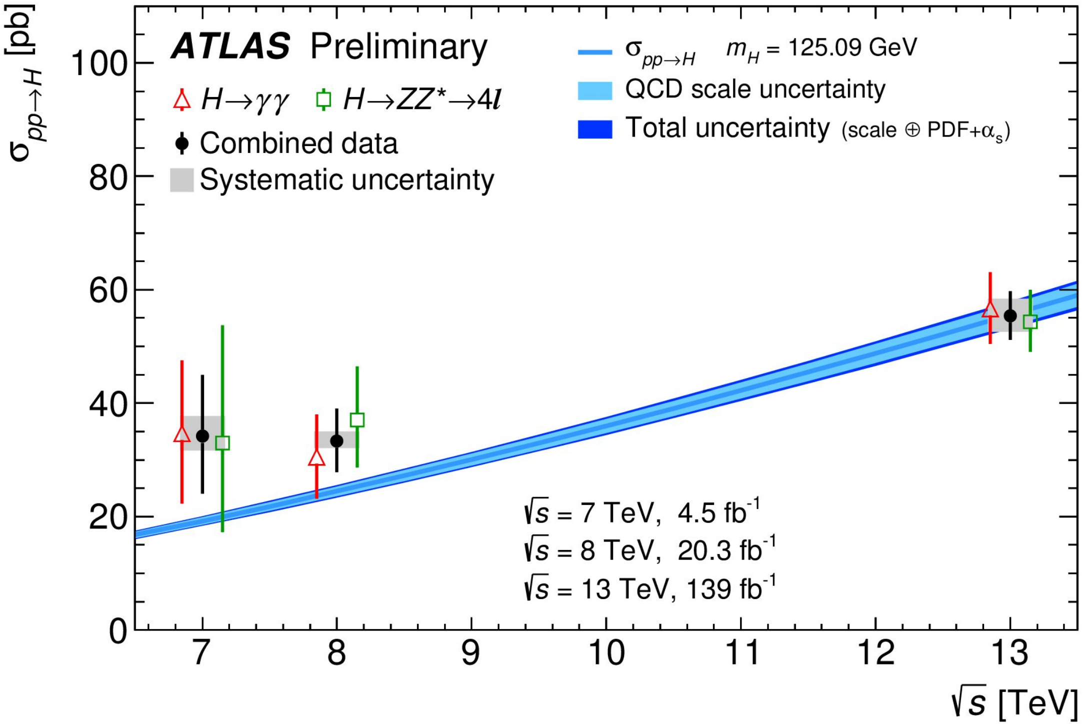
***ttH* production (0.8%)**

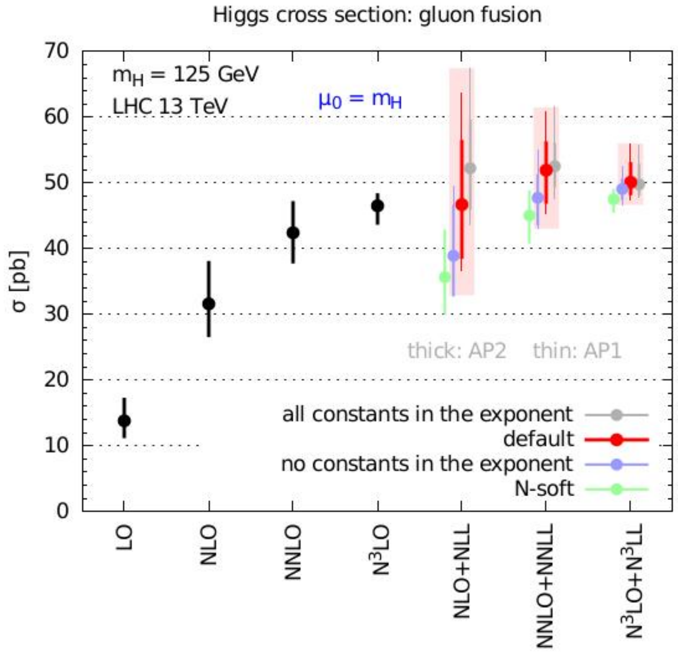




- All main production modes are probed at the LHC

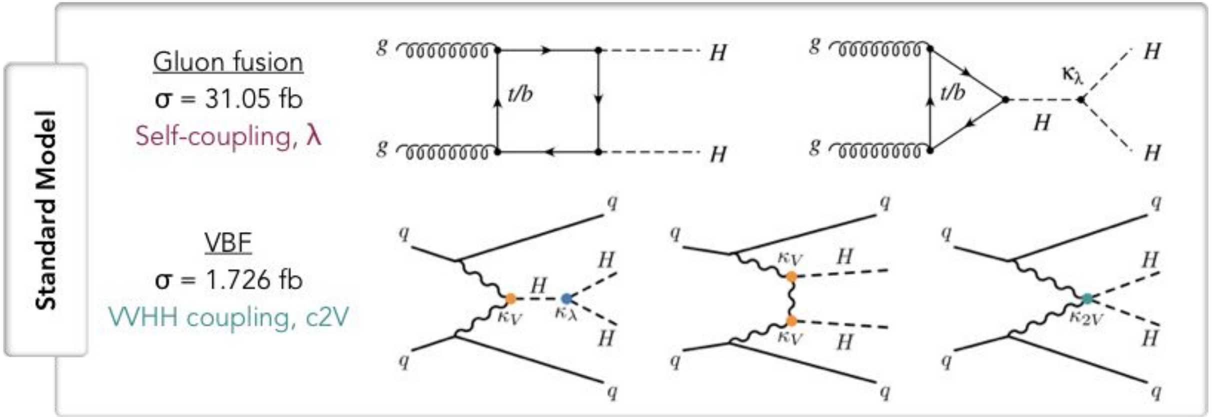
Interplay between theory and experiment





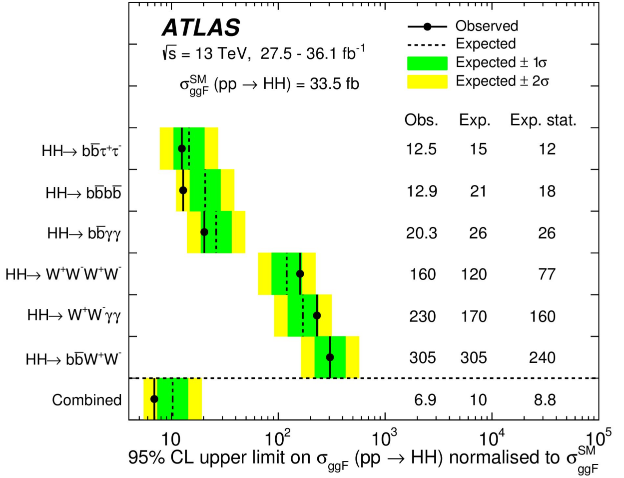
- **Experimental results depend strongly on the precision of theoretical predictions !!!**

Di-Higgs boson production at the LHC

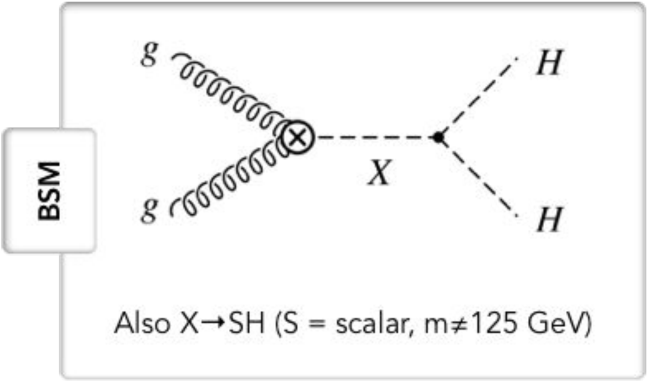


Gluon fusion
σ = 31.05 fb
Self-coupling, λ

VBF
σ = 1.726 fb
VVHH coupling, c2V



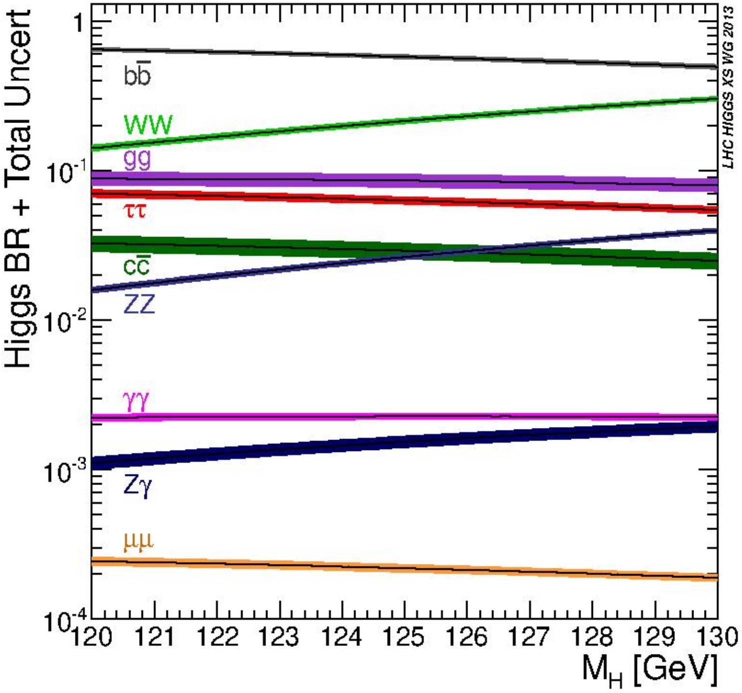
	Obs.	Exp.	Exp. stat.
HH→ $b\bar{b}\tau^+\tau^-$	12.5	15	12
HH→ $b\bar{b}b\bar{b}$	12.9	21	18
HH→ $b\bar{b}\gamma\gamma$	20.3	26	26
HH→ $W^+W^-W^+W^-$	160	120	77
HH→ $W^+W^-\gamma\gamma$	230	170	160
HH→ $b\bar{b}W^+W^-$	305	305	240
Combined	6.9	10	8.8

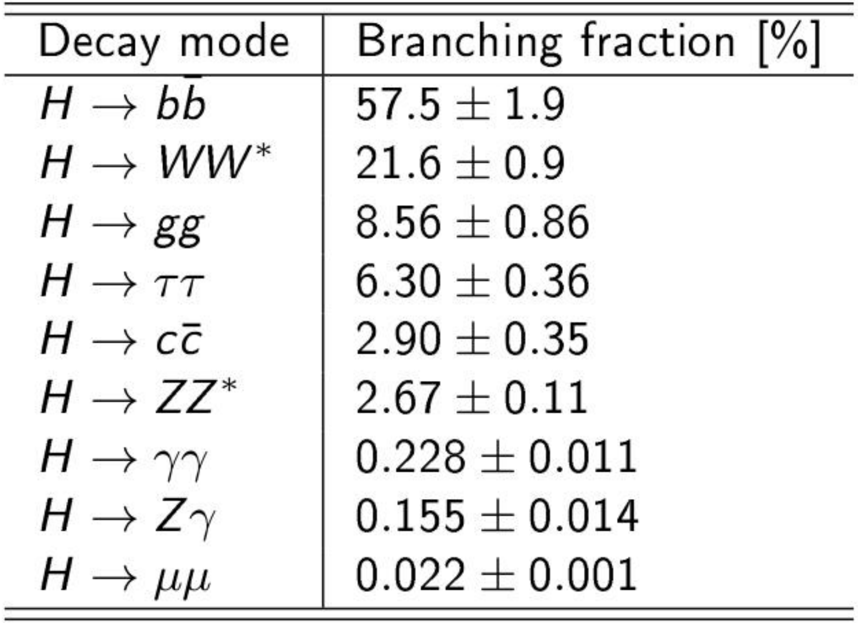


Also X→SH (S = scalar, m≠125 GeV)

- 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**

Higgs boson decay



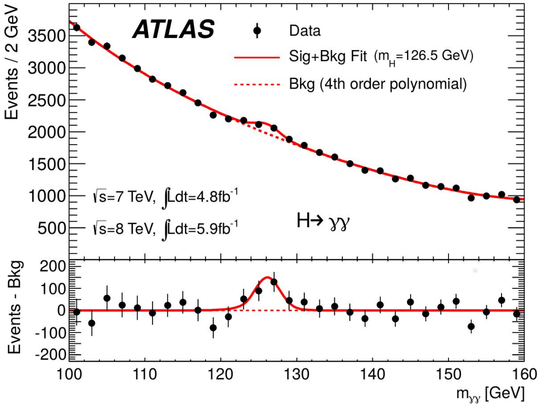


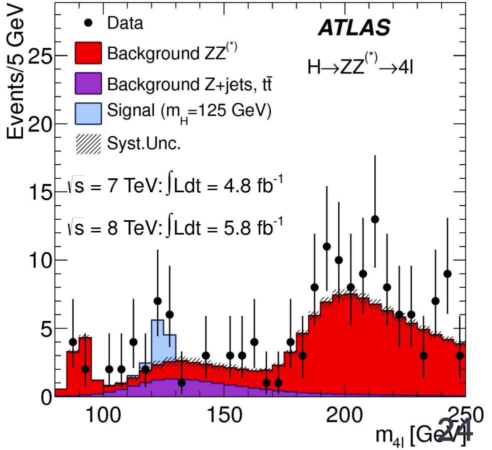
Decay mode	Branching fraction [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW^*$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ^*$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

- **Some channels with low BRs have a clean signature in the detector**
  - e.g. H → ZZ and H → yy

(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 ± 0.21(stat) ± 0.11(syst) GeV





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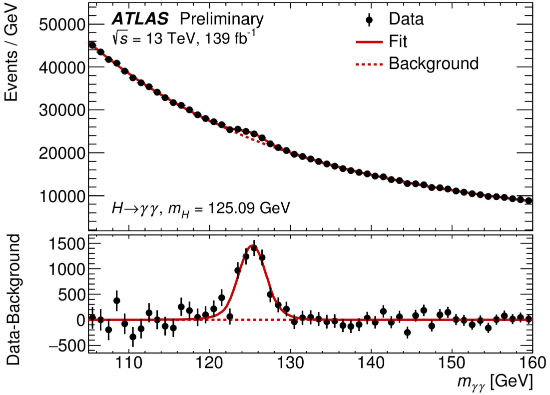
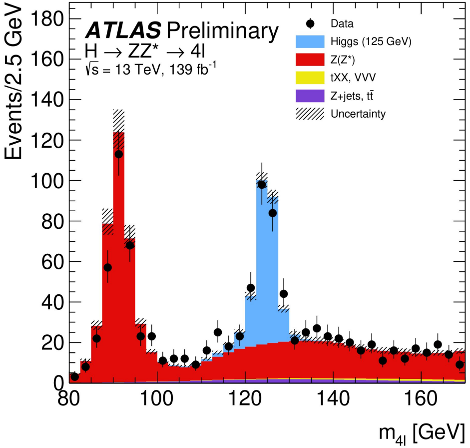
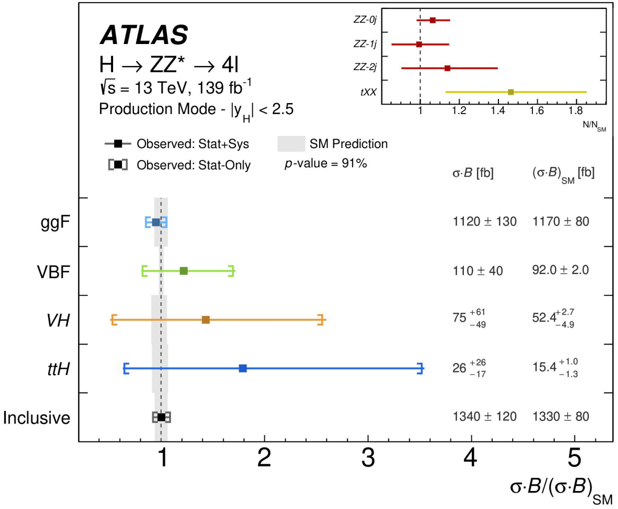
- Higgs-boson mass measured by ATLAS and CMS: m_H = 125.09 ± 0.21(stat) ± 0.11(syst) GeV
- **With the large statistics of the full Run-II data set, we can probe differential distributions with high precision**
    - Makes the Higgs boson to a tool to search for new physics

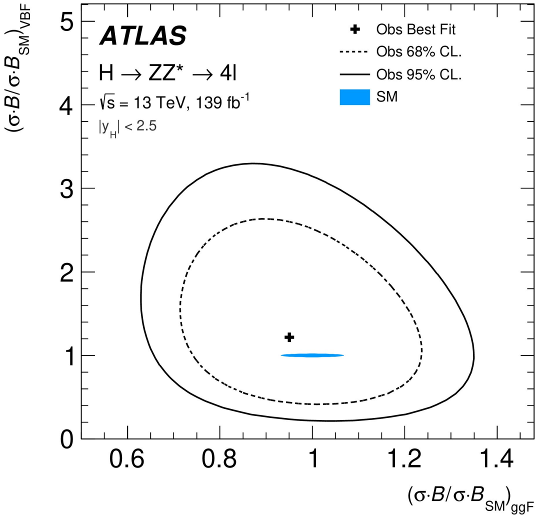


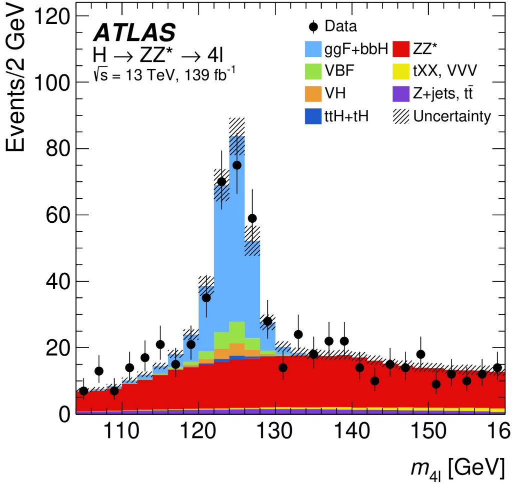


H → ZZ* → ℓℓℓℓ

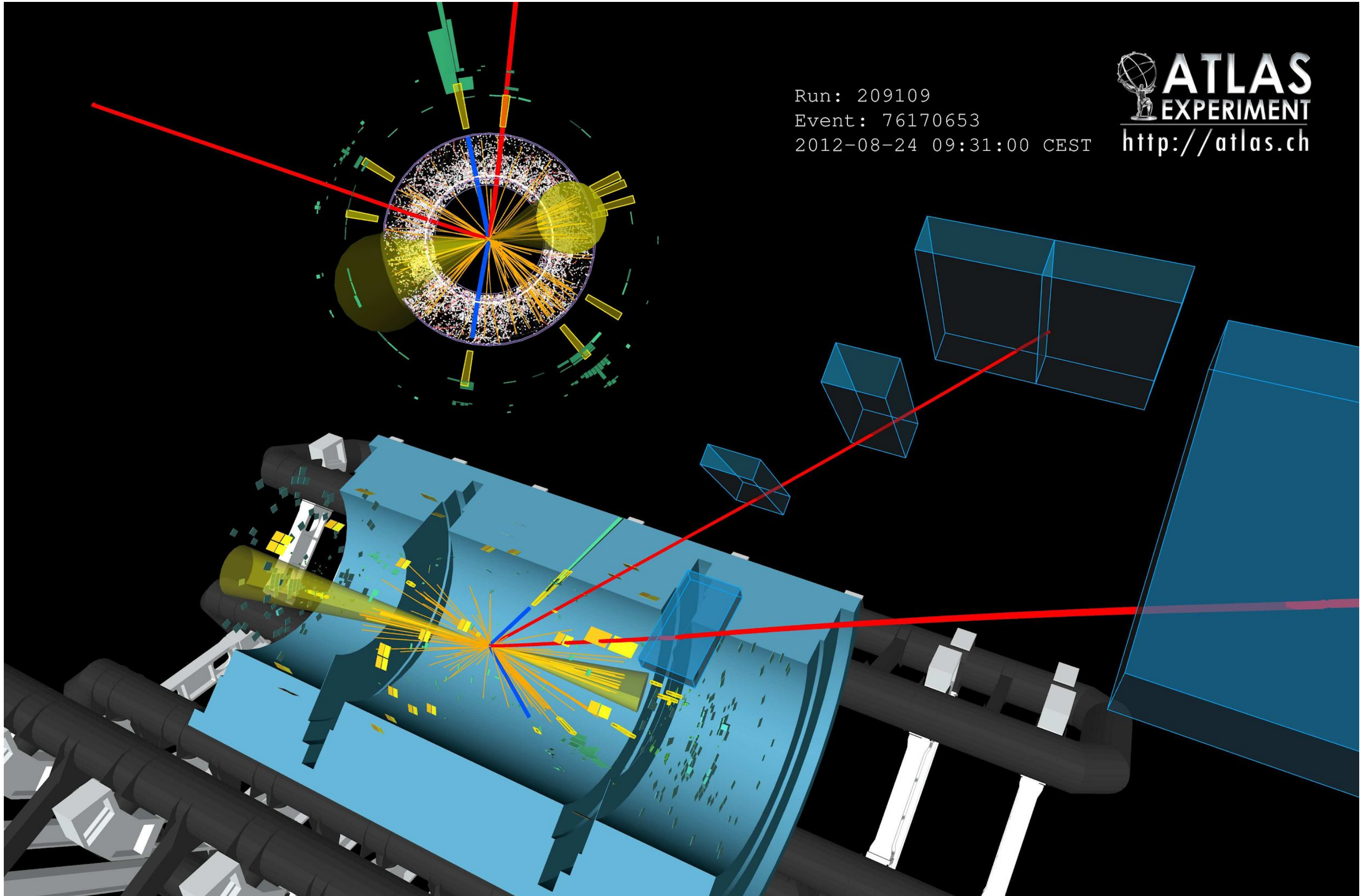
- H→ ZZ* → ℓℓℓℓ events provide a clean signature in the detector and thus have relative low background contributions
  - **Good channel to measure properties of the Higgs boson precisely**
  - Analyses are based on finding two pairs of isolated leptons with same flavor and opposite electric charges





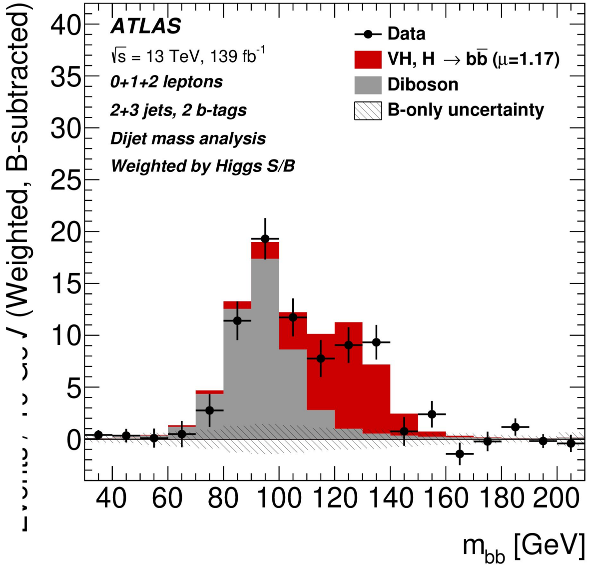


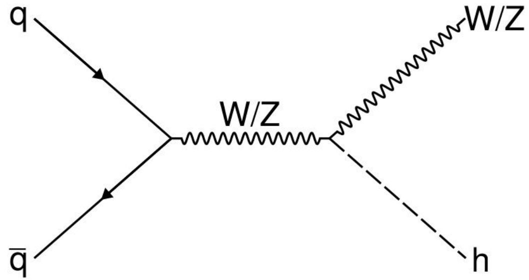
$\mathbf{H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell}$

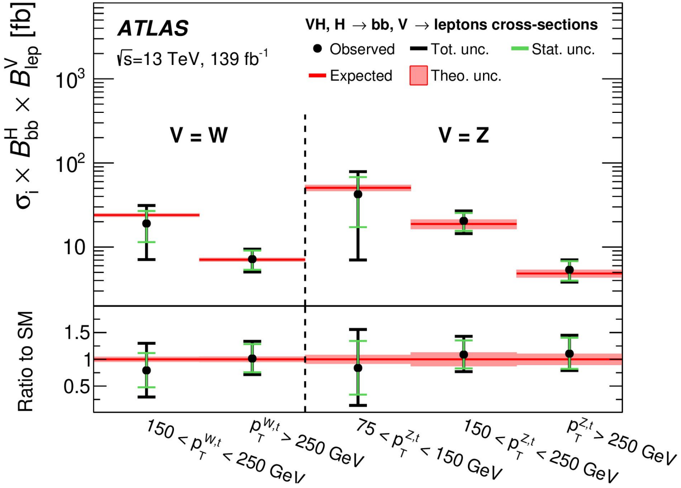


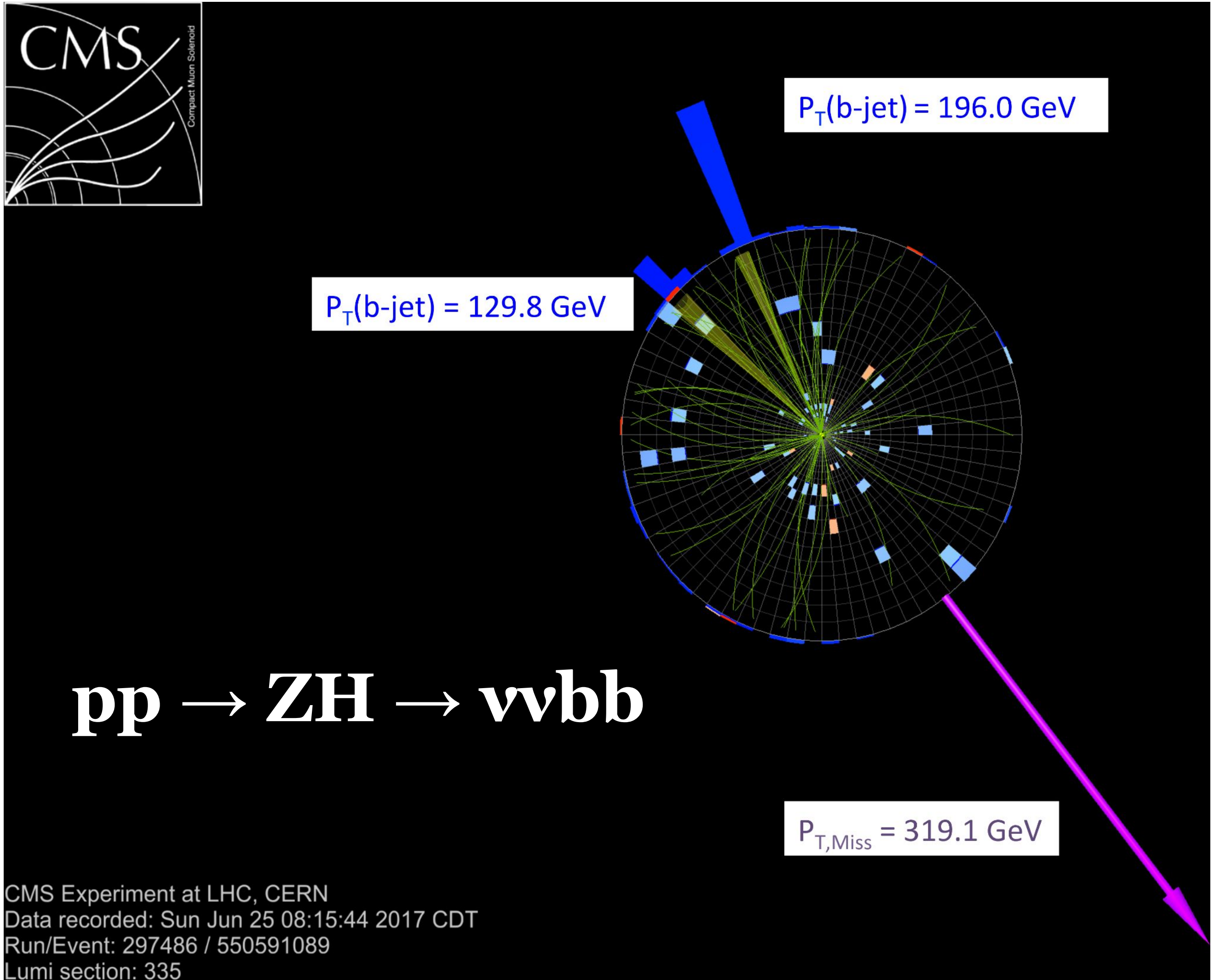
VH H → bb

- ggF H → bb has a large σ × BR, but can not be separated from huge dijet backgrounds and is difficult to trigger
    - ○ **Instead, probe H→ bb in Higgs-Strahlungs events (bb-pair is produced in addition to charged leptons)**
- **Observation of H → bb decays and VH production mode in 2018**







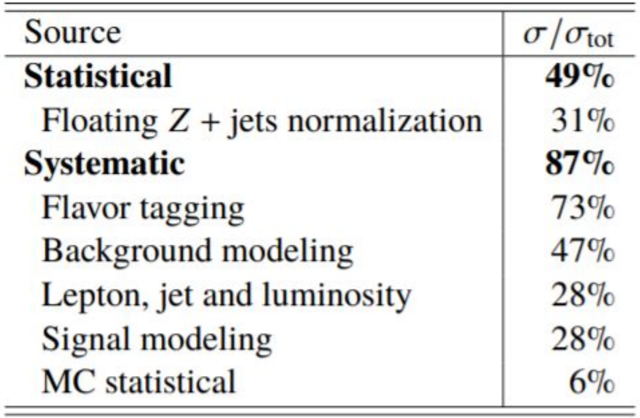


pp → ZH → vvbb

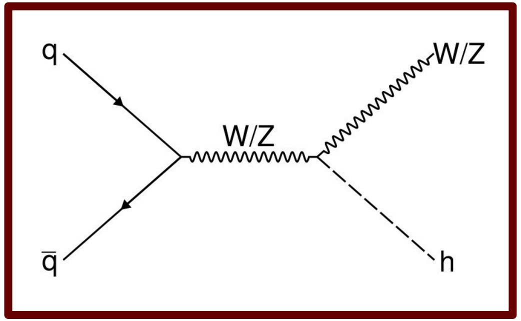
CMS Experiment at LHC, CERN
Data recorded: Sun Jun 25 08:15:44 2017 CDT
Run/Event: 297486 / 550591089
Lumi section: 335

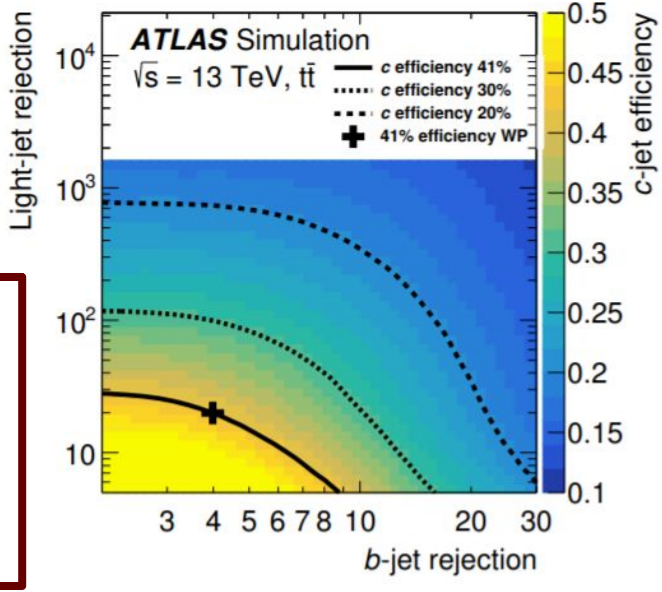
VH H → cc

- Study of Yukawa coupling of the Higgs boson to 2nd generation quarks is challenging at hadron colliders, due to small branching fractions and large backgrounds
- **Charm tagging is crucial for eventual H → cc observation**
- Upper limit on σ(pp → ZH)×B(H → cc) at the 95% CL:
  - **Observed:** 2.7 pb (104 times the SM predictions)
  - **Expected:** 3.9 +2.1/−1.1 pb



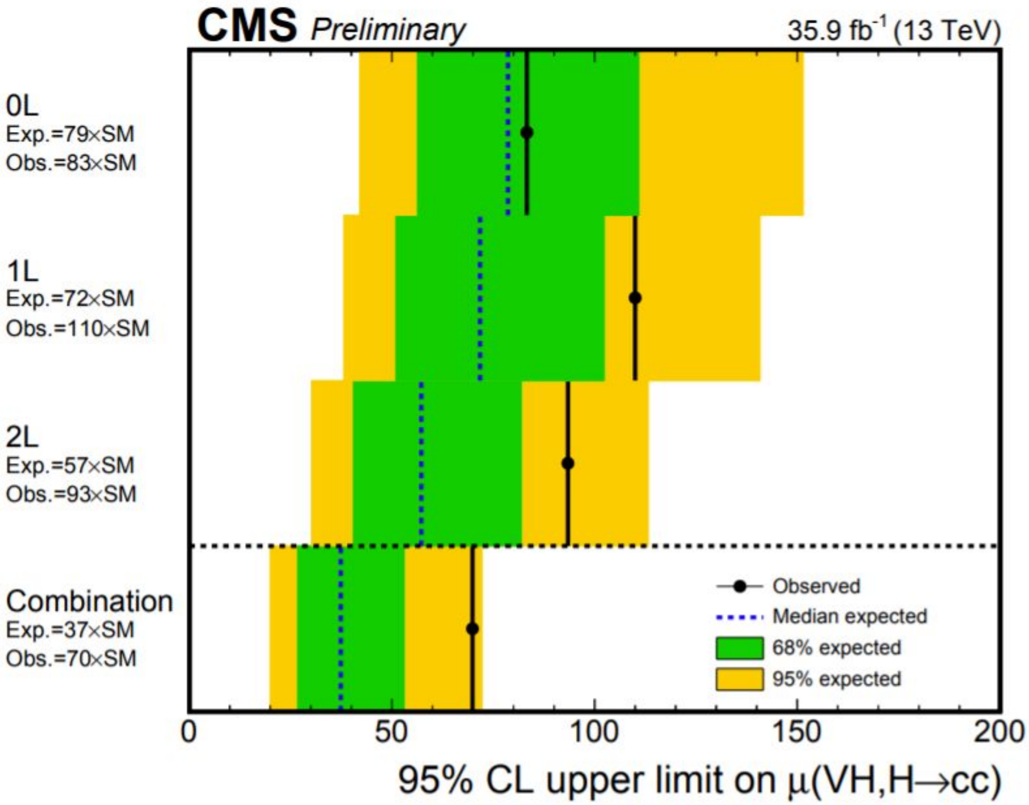
Source	$\sigma/\sigma_{\text{tot}}$
Statistical	**49%**
Floating Z + jets normalization	31%
Systematic	**87%**
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%

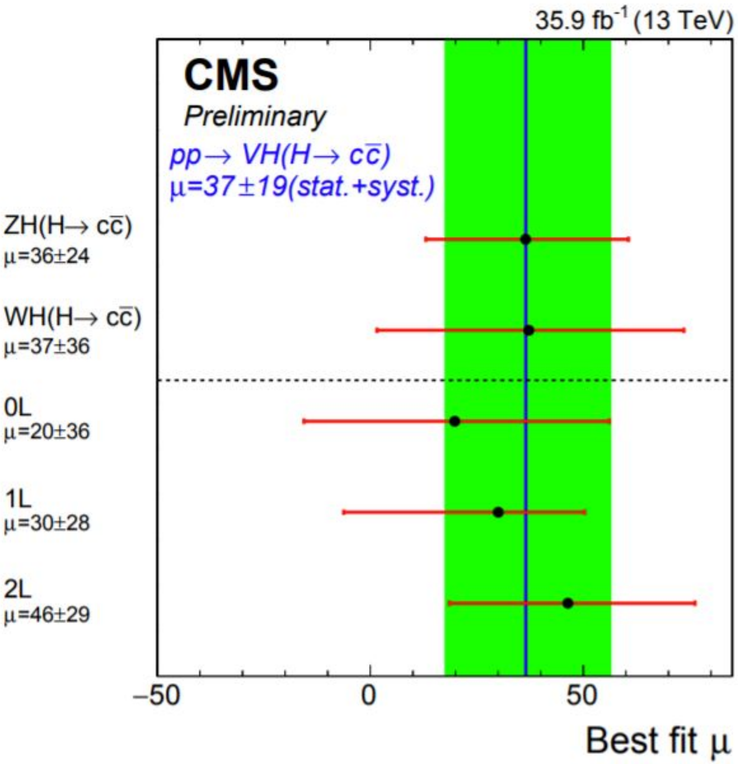




Taken from https://arxiv.org/pdf/1802.04329.pdf

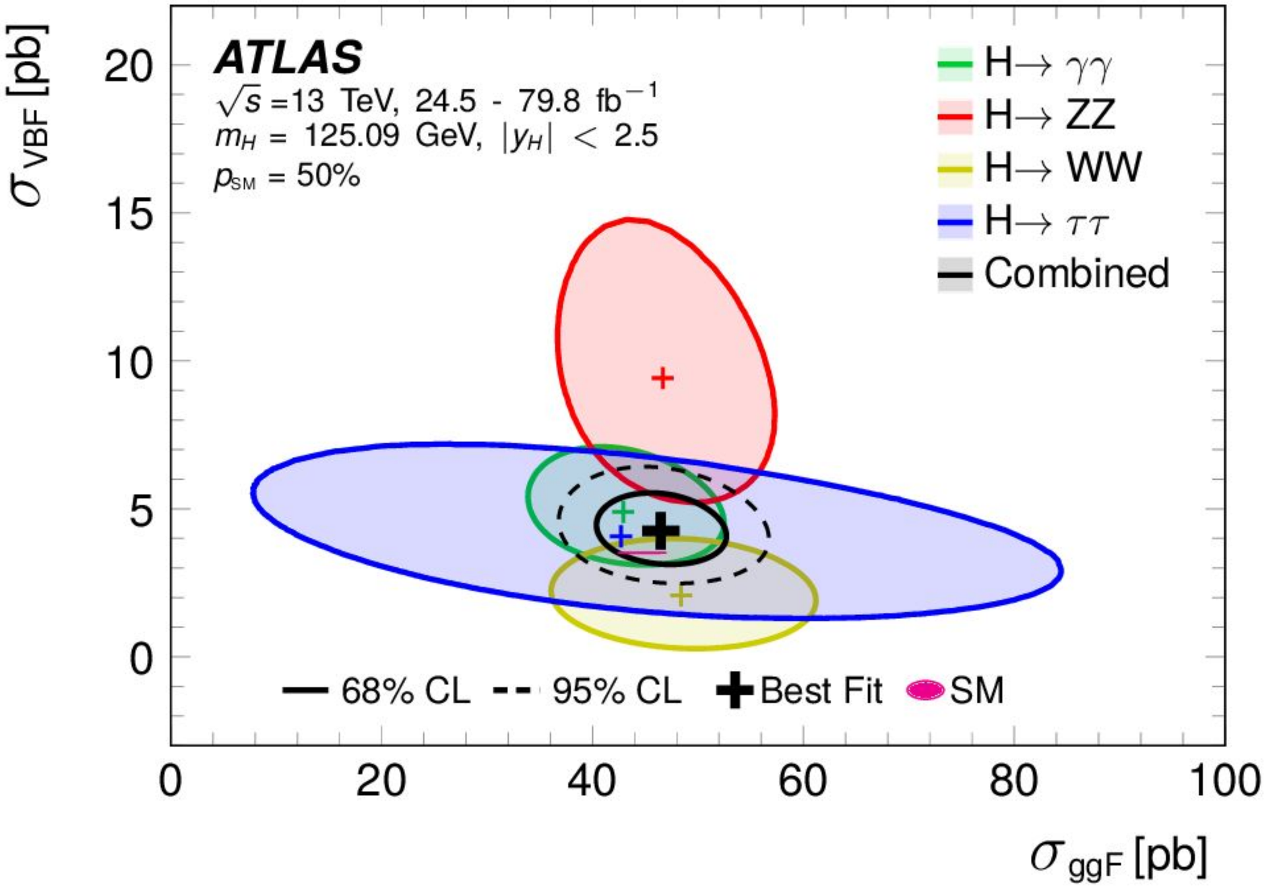
VH H → cc



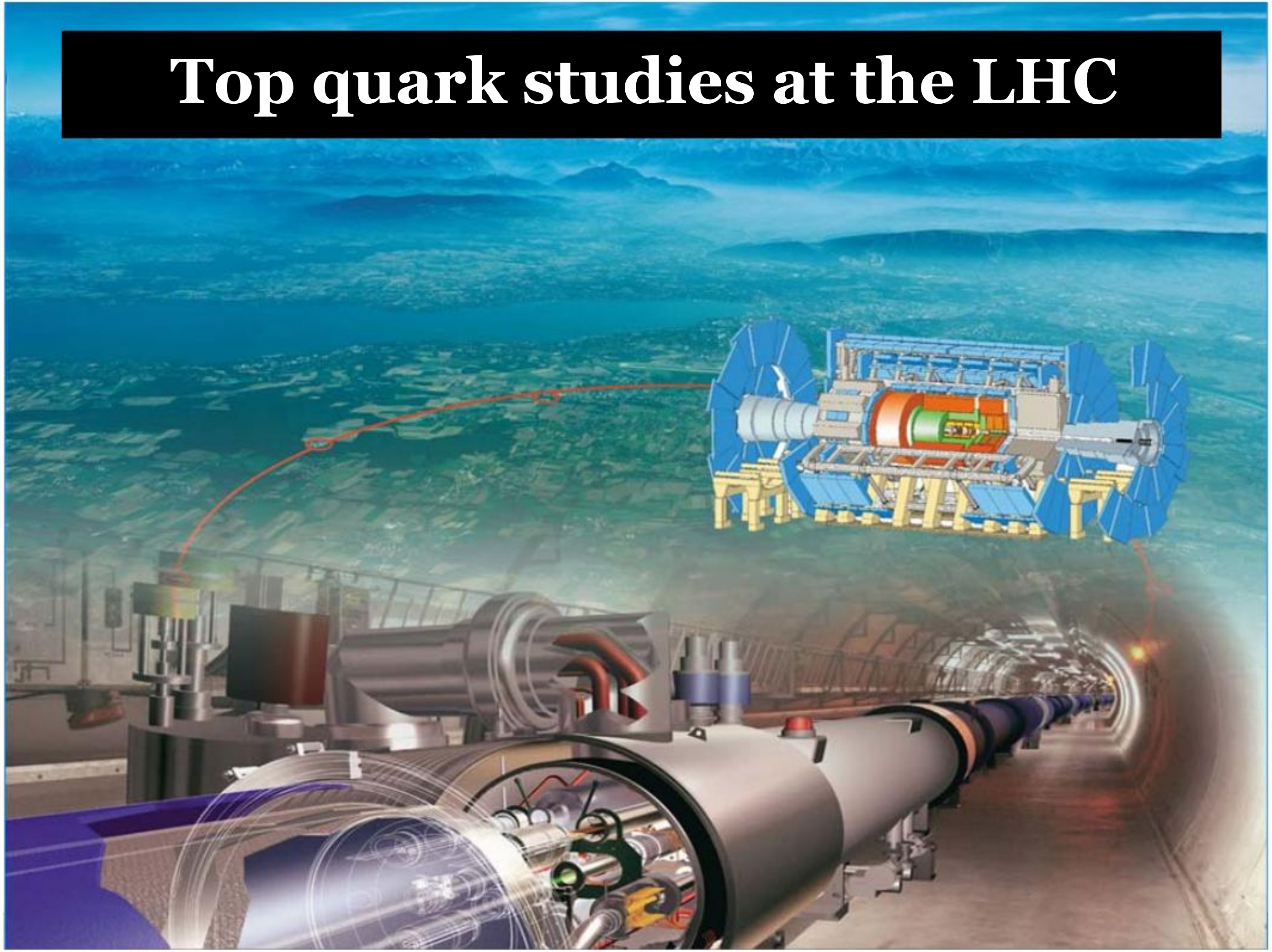


Taken from https://inspirehep.net/files/8f40463278676edecdd49e0d89fb861e

Combinations



Top quark studies at the LHC



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:
  - **$m_t = 172.7 \pm 0.5$ GeV**
- **Coupling to the Higgs boson: $y_t \approx 1$**
- **No bound states:**

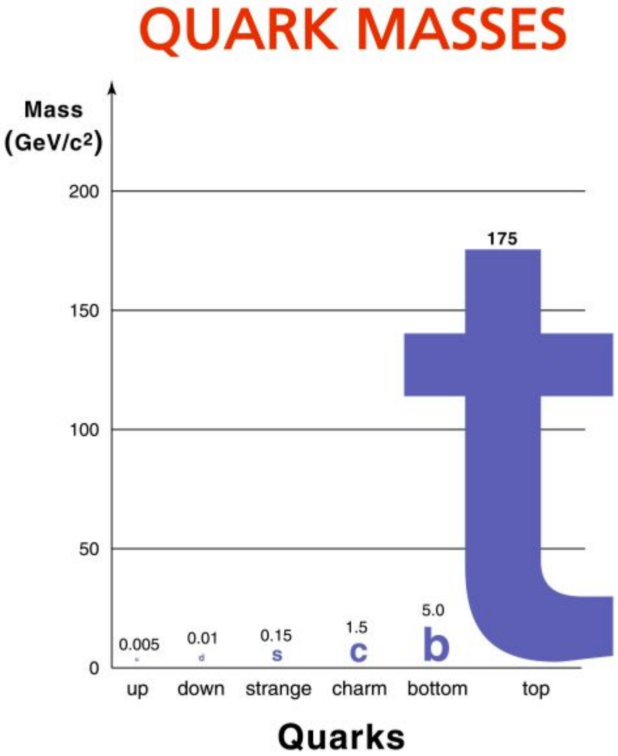
$$\tau_{\text{top}} \propto \left(\frac{M_W}{M_{\text{top}}}\right)^3$$

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

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

→ **Spin information and polarisation are accessible**

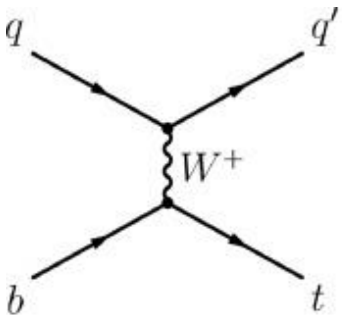
since spin decorrelation time (~10^{-21} s) is much larger than the hadronisation time (~10^{-23} s)



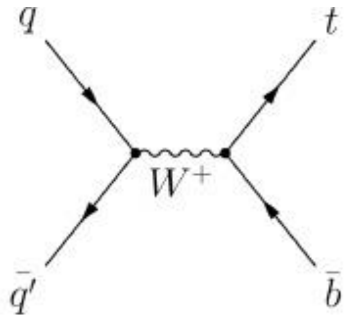
Fermilab 01-XXX

Top quark production at the LHC

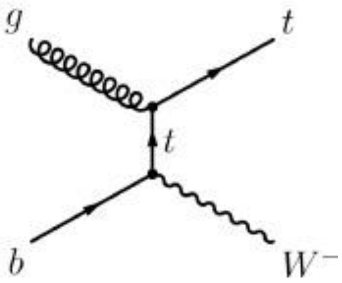
- Single top quarks:



t-channel

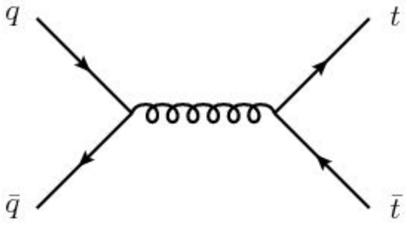


s-channel

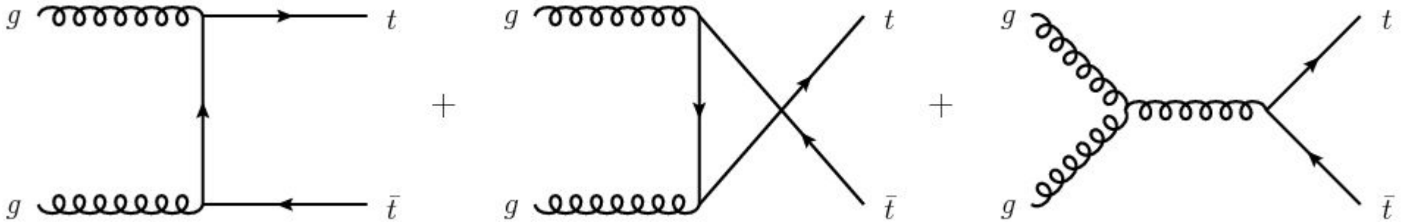


Wt-channel

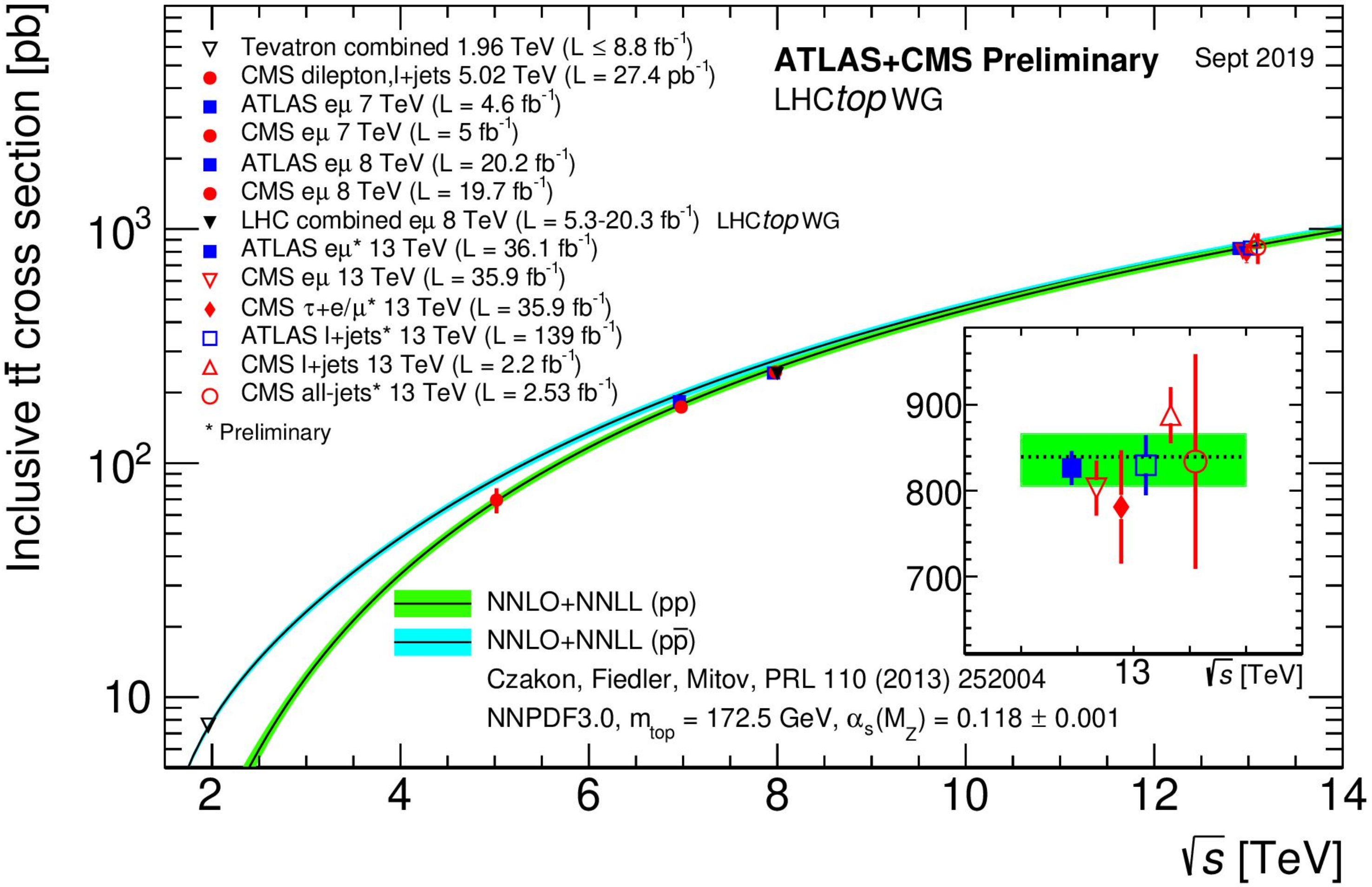
- Top quark pairs:



15%

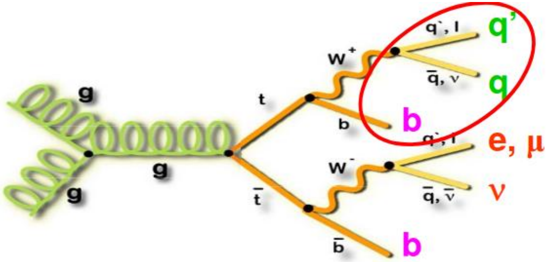


85%

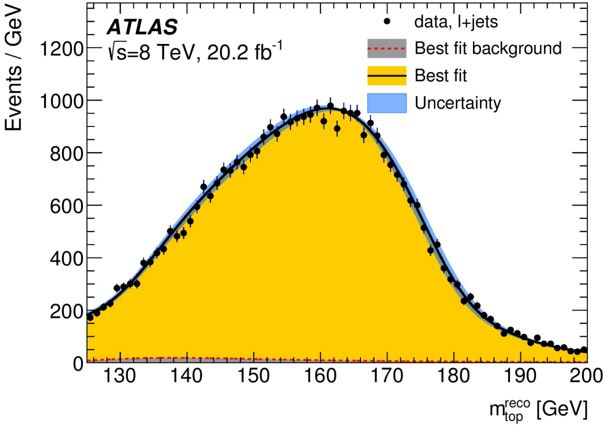

Inclusive tt̄ cross section [pb]
10^3
10^2
10
2
4
6
8
10
12
14
√s [TeV]
▽ Tevatron combined 1.96 TeV (L ≤ 8.8 fb^{-1})
● CMS dilepton,l+jets 5.02 TeV (L = 27.4 pb^{-1})
■ ATLAS eμ 7 TeV (L = 4.6 fb^{-1})
● CMS eμ 7 TeV (L = 5 fb^{-1})
■ ATLAS eμ 8 TeV (L = 20.2 fb^{-1})
● CMS eμ 8 TeV (L = 19.7 fb^{-1})
▼ LHC combined eμ 8 TeV (L = 5.3-20.3 fb^{-1}) LHC*top*WG
■ 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
ATLAS+CMS Preliminary
LHC*top*WG
Sept 2019
🟩 NNLO+NNLL (pp)
🟦 NNLO+NNLL (p$\bar{p}$)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
NNPDF3.0, m_{top} = 172.5 GeV, $\alpha_s(M_Z)$ = 0.118 ± 0.001
900
800
700
13
√s [TeV]

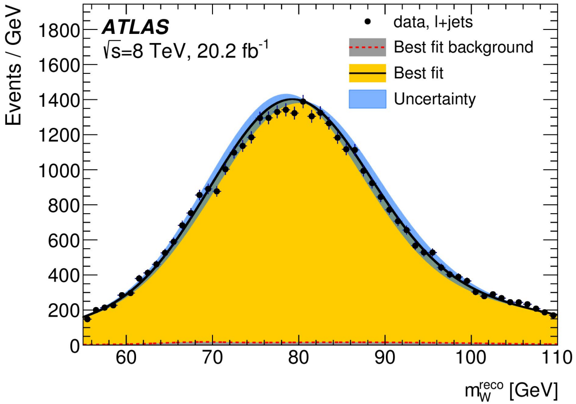
Top-quark mass measurements

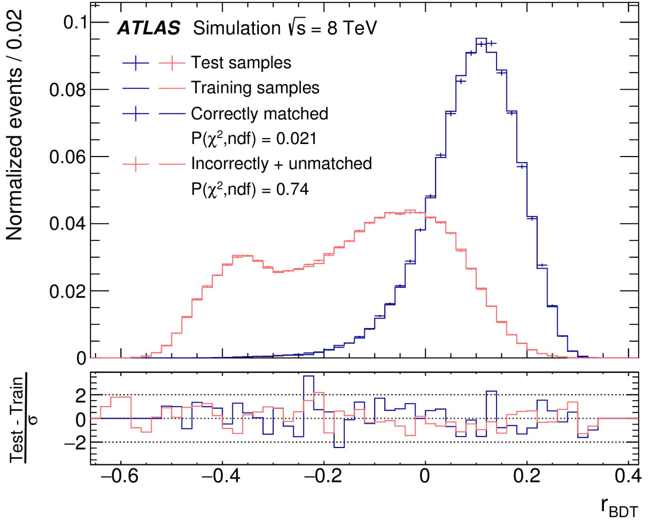
- Measurement of the top quark mass in the lepton+jets channel:
  - Exploiting a three-dimensional template technique
    - Fitting m_{top}, m_W, R_{bq} (heavy to light-flavour momentum ratio)
  - Use likelihood approach to reconstruct events
    - Reject combinatorial background using a BDT
  - Fit yields:



$$m_{\text{top}} = 172.08 \pm 0.39\,(\text{stat}) \pm 0.82\,(\text{syst})\ \text{GeV}$$





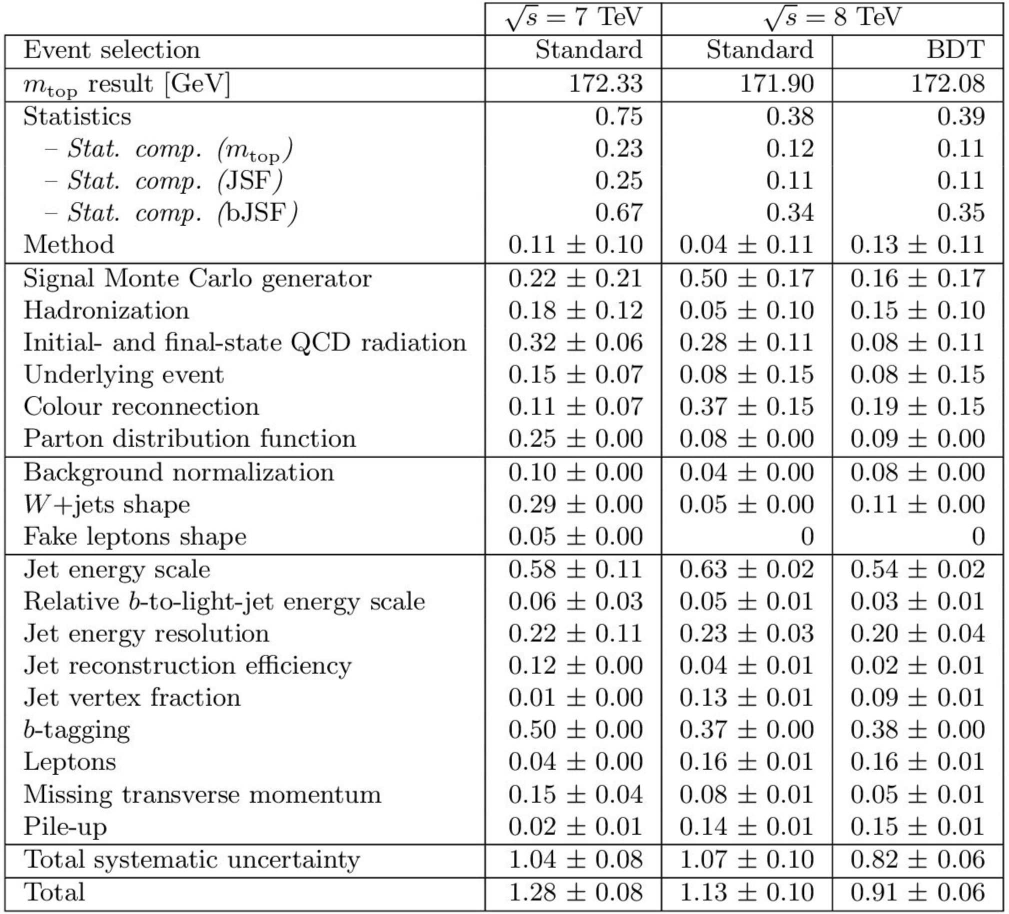


Top-quark mass measurements

- Systematic uncertainties in m_{top} given together with the statistical and systematic uncertainties in GeV
  - For the standard and BDT selections.
  - For comparison, results corresponding to √s=7 TeV are also listed.

- Dominant uncertainties:
  - Jet energy scale
  - b-tagging

→ **top-quark mass can be measured with high precision**

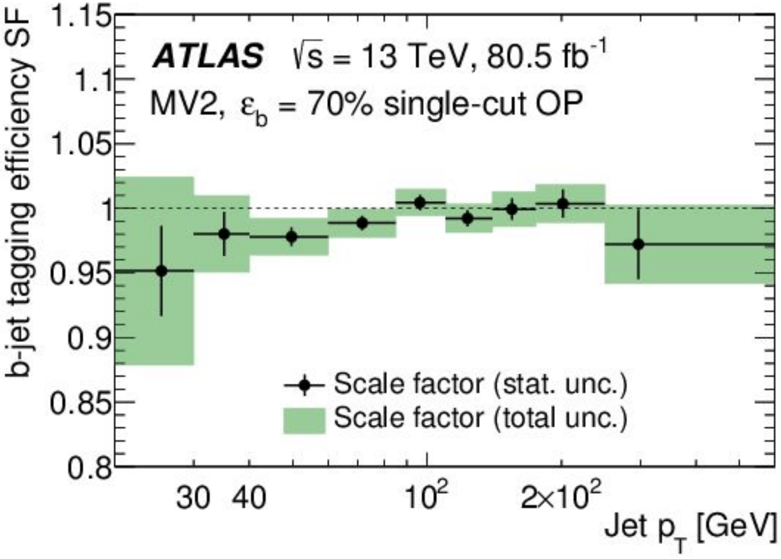


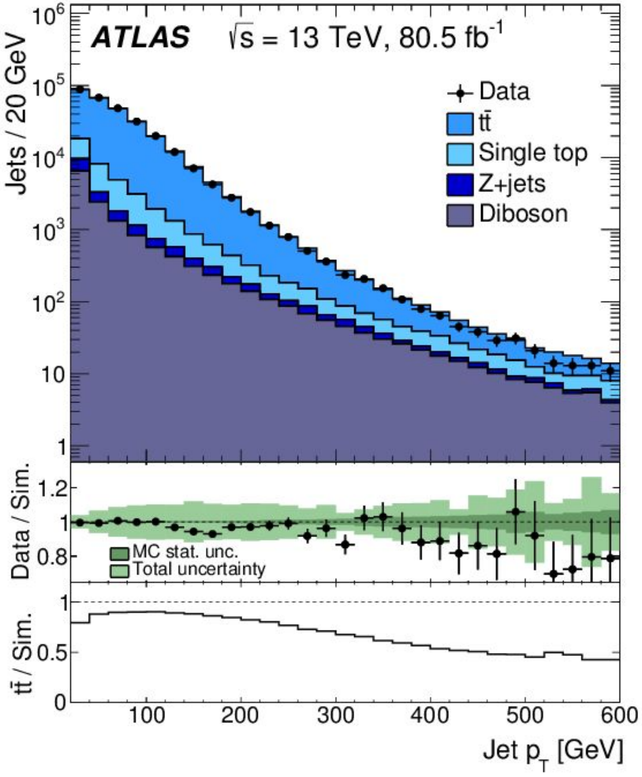
	$\sqrt{s}=7$ TeV	$\sqrt{s}=8$ TeV	
Event selection	Standard	Standard	BDT
m_{top} result [GeV]	172.33	171.90	172.08
Statistics	0.75	0.38	0.39
– *Stat. comp.* (m_{top})	0.23	0.12	0.11
– *Stat. comp.* (JSF)	0.25	0.11	0.11
– *Stat. comp.* (bJSF)	0.67	0.34	0.35
Method	0.11 ± 0.10	0.04 ± 0.11	0.13 ± 0.11
Signal Monte Carlo generator	0.22 ± 0.21	0.50 ± 0.17	0.16 ± 0.17
Hadronization	0.18 ± 0.12	0.05 ± 0.10	0.15 ± 0.10
Initial- and final-state QCD radiation	0.32 ± 0.06	0.28 ± 0.11	0.08 ± 0.11
Underlying event	0.15 ± 0.07	0.08 ± 0.15	0.08 ± 0.15
Colour reconnection	0.11 ± 0.07	0.37 ± 0.15	0.19 ± 0.15
Parton distribution function	0.25 ± 0.00	0.08 ± 0.00	0.09 ± 0.00
Background normalization	0.10 ± 0.00	0.04 ± 0.00	0.08 ± 0.00
W+jets shape	0.29 ± 0.00	0.05 ± 0.00	0.11 ± 0.00
Fake leptons shape	0.05 ± 0.00	0	0
Jet energy scale	0.58 ± 0.11	0.63 ± 0.02	0.54 ± 0.02
Relative b-to-light-jet energy scale	0.06 ± 0.03	0.05 ± 0.01	0.03 ± 0.01
Jet energy resolution	0.22 ± 0.11	0.23 ± 0.03	0.20 ± 0.04
Jet reconstruction efficiency	0.12 ± 0.00	0.04 ± 0.01	0.02 ± 0.01
Jet vertex fraction	0.01 ± 0.00	0.13 ± 0.01	0.09 ± 0.01
b-tagging	0.50 ± 0.00	0.37 ± 0.00	0.38 ± 0.00
Leptons	0.04 ± 0.00	0.16 ± 0.01	0.16 ± 0.01
Missing transverse momentum	0.15 ± 0.04	0.08 ± 0.01	0.05 ± 0.01
Pile-up	0.02 ± 0.01	0.14 ± 0.01	0.15 ± 0.01
Total systematic uncertainty	1.04 ± 0.08	1.07 ± 0.10	0.82 ± 0.06
Total	1.28 ± 0.08	1.13 ± 0.10	0.91 ± 0.06

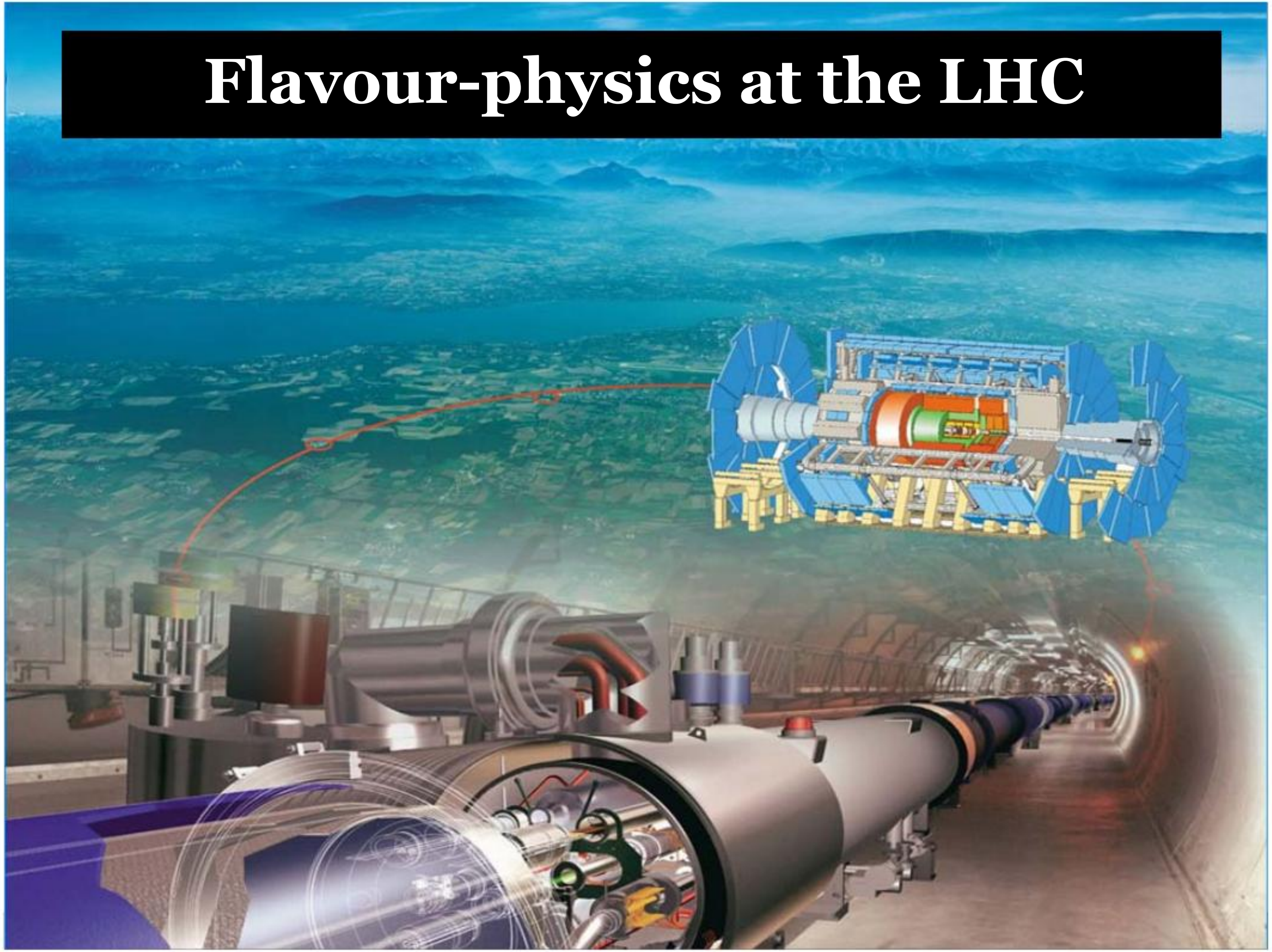
Taken from: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2017-03/

Top-quark pairs as standard candles

- Top-quark pair events (in particular dilepton decays) lead to a clear signatures in the detector
    - Purities of > 90% can easily be reached
- Use top-quark pair events to calibrate e.g. b-tagging or top/W tagging algorithms







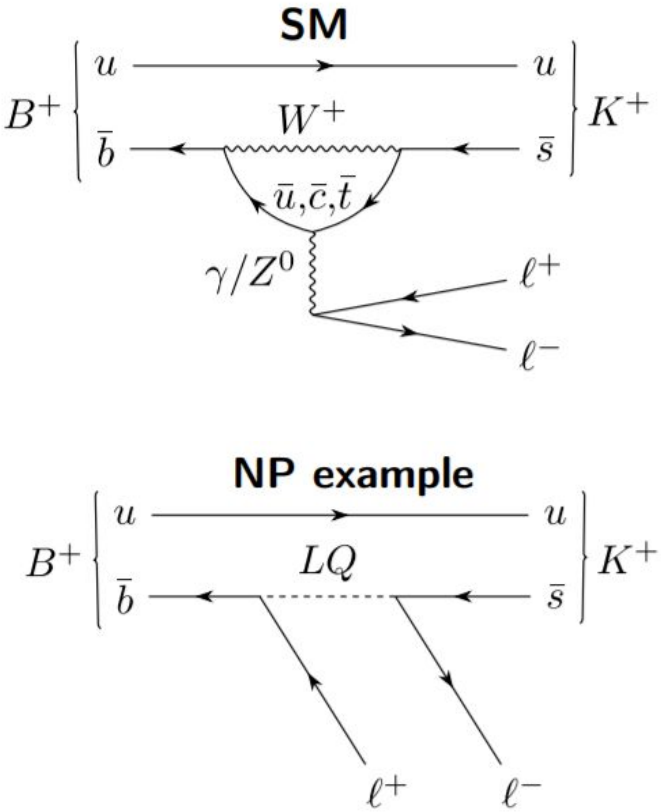
Flavour-physics at the LHC

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:

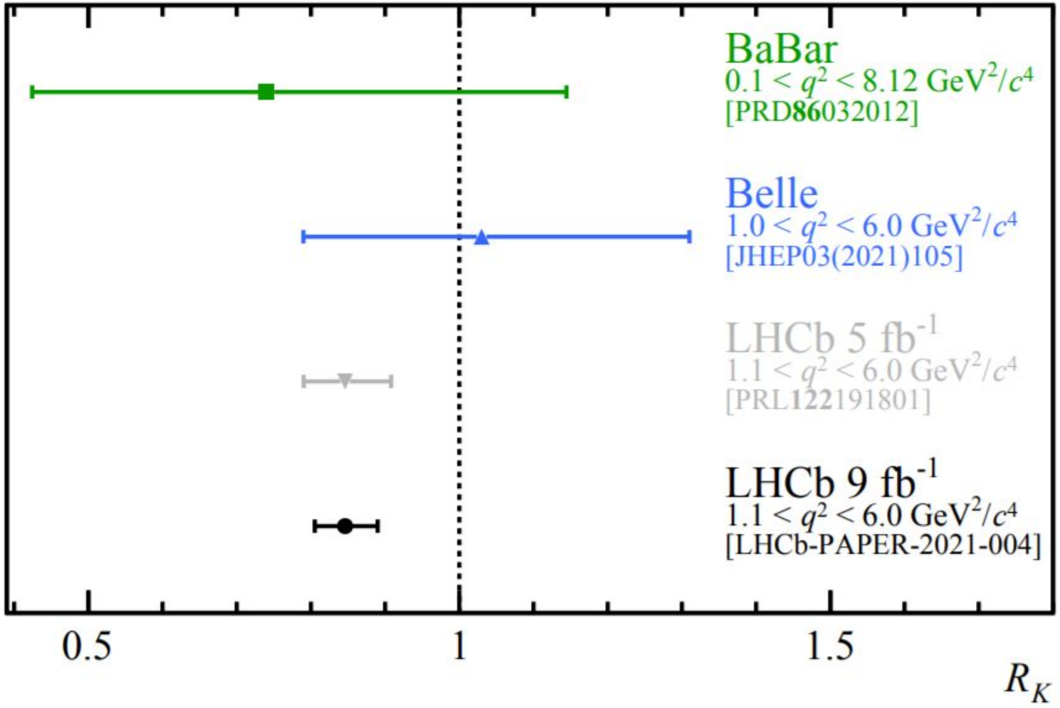
$$R_{K^{(*)}} = \frac{\mathcal{B}\left(B \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(B \to K^{(*)}e^+e^-\right)} \overset{\text{SM}}{\cong} 1$$

→ 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



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

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

Pentaquarks

Pentaquarks = hadrons composed of **four quarks and one antiquark**

Observation of pentaquark states by LHCb in 2015 and 2019

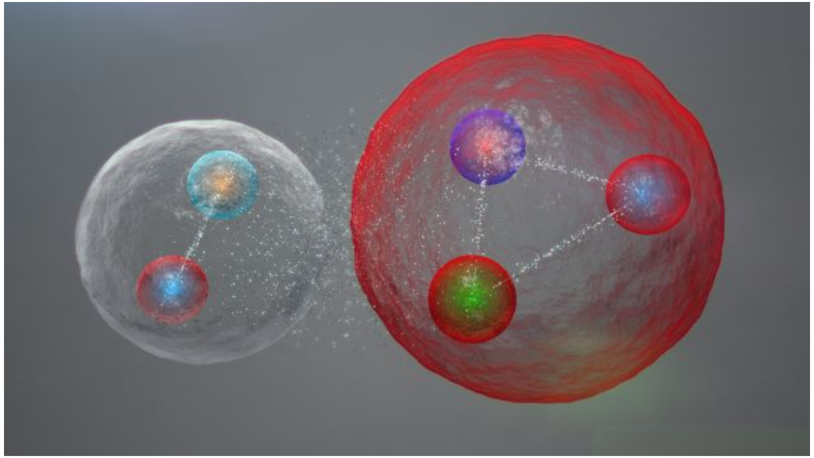
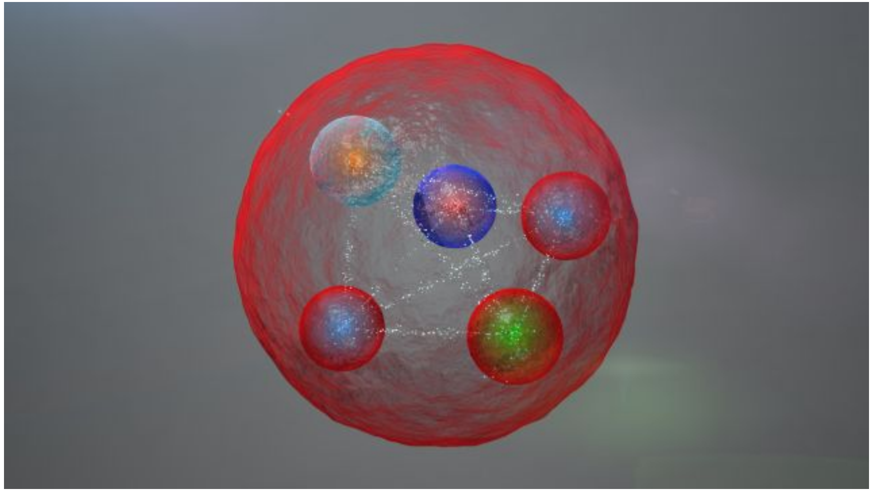


Illustration of the possible layout of the quarks in a pentaquark particle such as those discovered at LHCb. The five quarks might be assembled into a meson (one quark and one antiquark) and a baryon (three quarks), weakly bound together

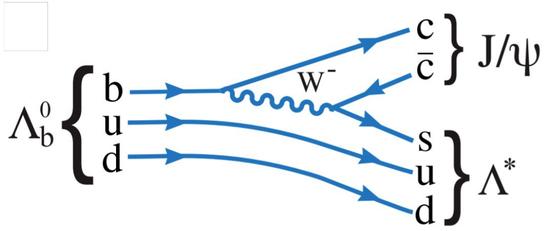


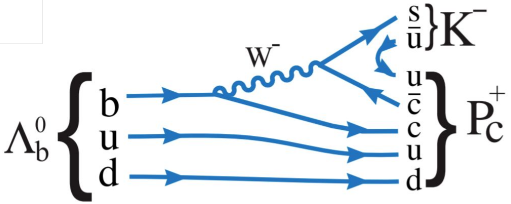
The five quarks might be tightly bonded

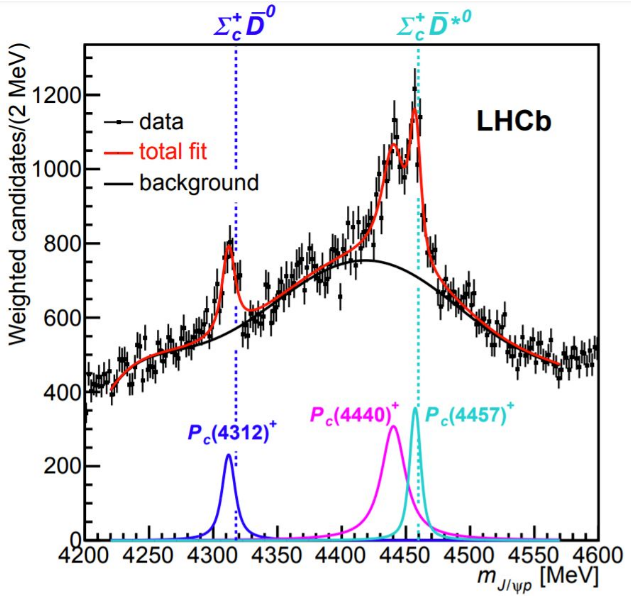
Taken from: https://home.cern/news/news/physics/lhcb-experiment-discovers-new-pentaquark

Pentaquarks

- The prospect of hadrons with more than the minimal quark content (qq or qqq) was proposed by Gell-Mann in 1964 [1] and Zweig [2]
  - Followed by a quantitative model for two quarks plus two antiquarks (Tetraquarks) [3].
  - The idea was expanded [4] to include hadrons composed of **four quarks plus one antiquark**
- Large yields of **$\Lambda^0_b \rightarrow J/\psi\ K^- p$** decays are available at LHCb
  - Expected to be dominated by **$\Lambda^* \rightarrow K^-\ p$**
  - It could also have exotic decays via: **$\Lambda_b^0 \rightarrow K^-\ P_C^+$**
- **P_C^+** mainly decays via: **$P_C^+ \rightarrow J/\psi\ p$**

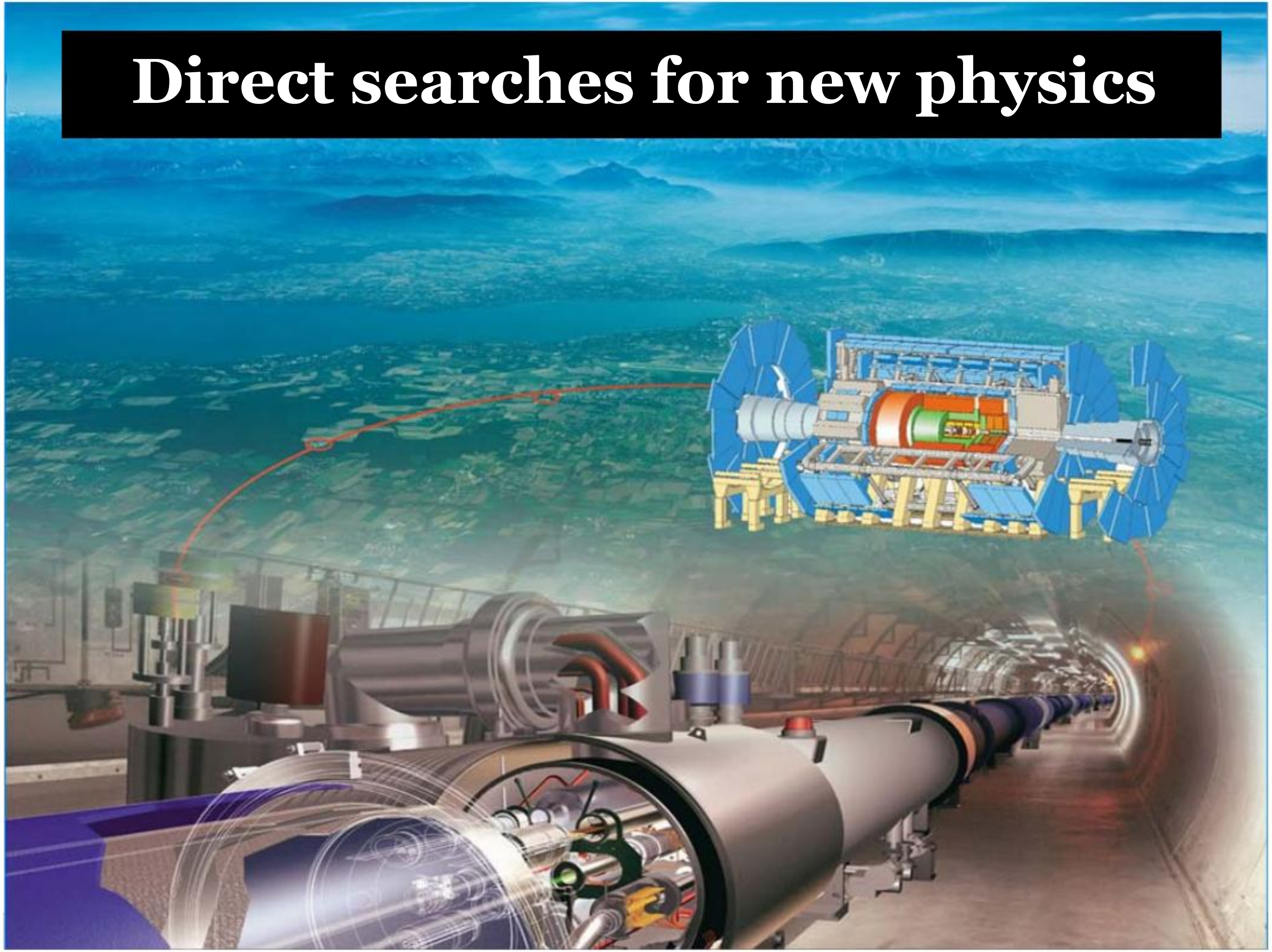




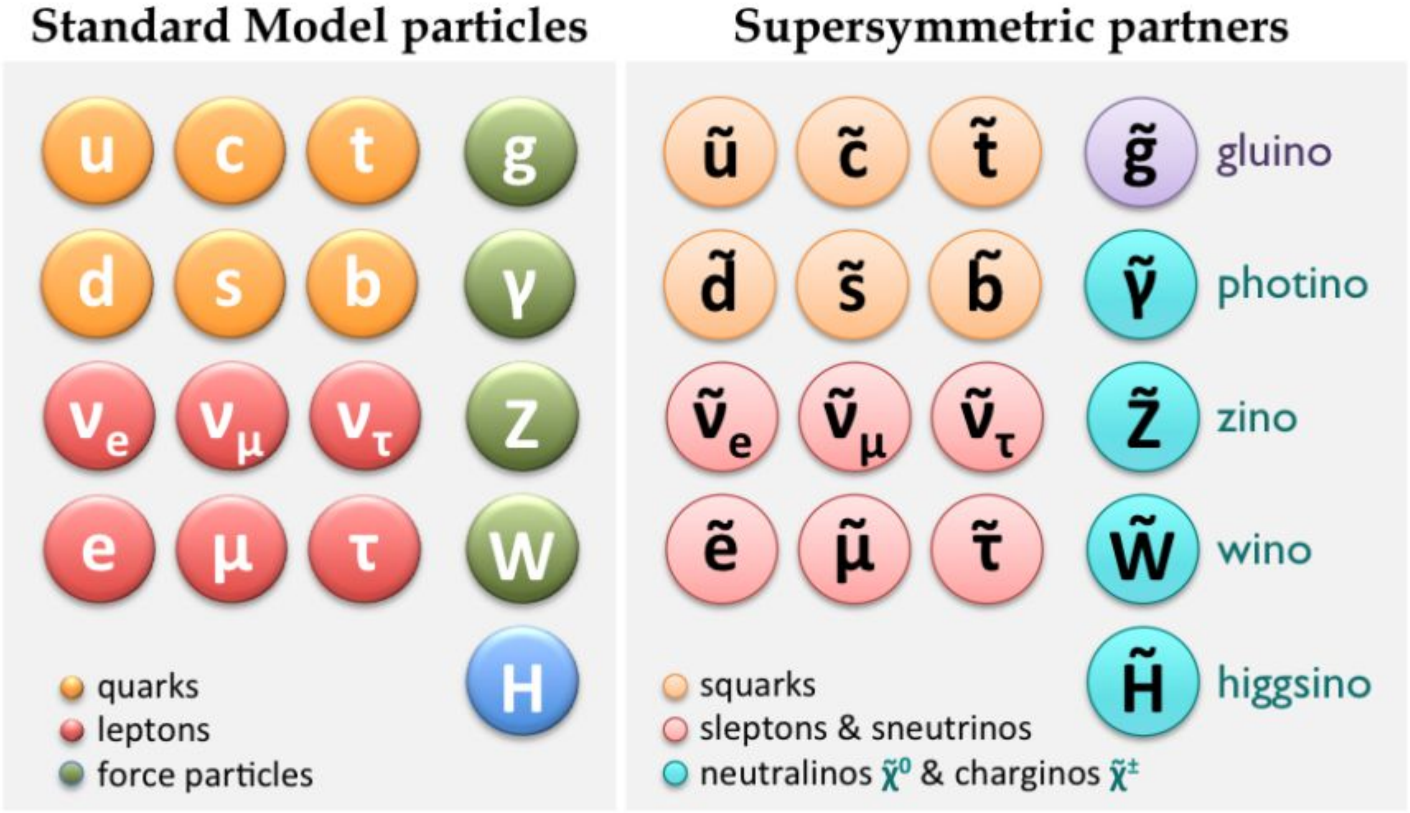


Taken from: https://arxiv.org/pdf/1507.03414.pdf

Direct searches for new physics

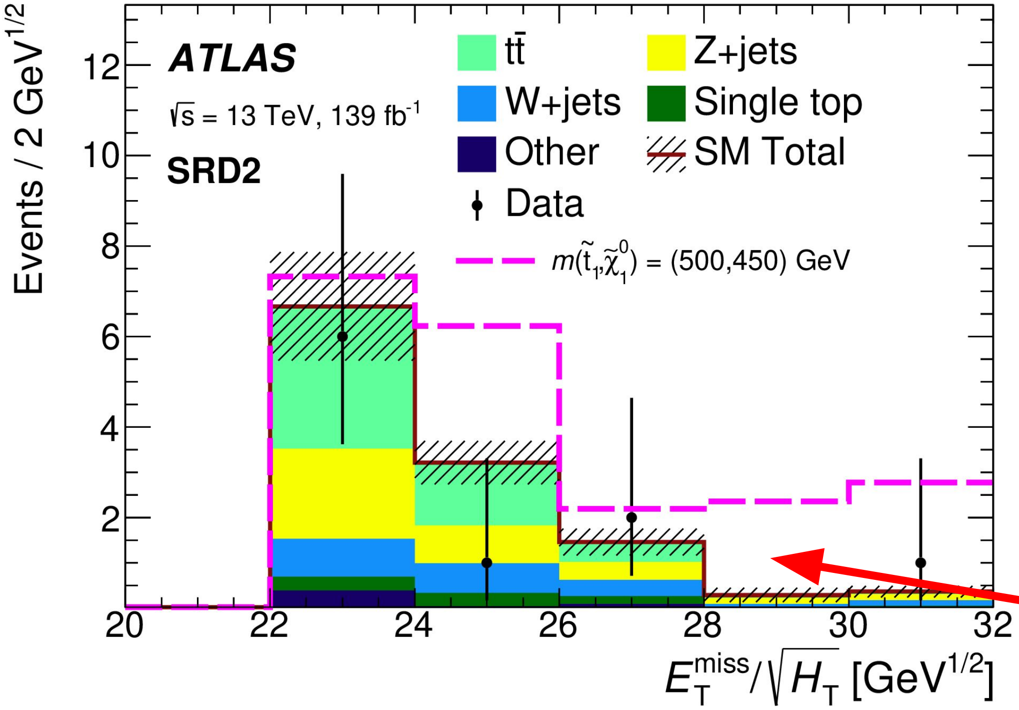


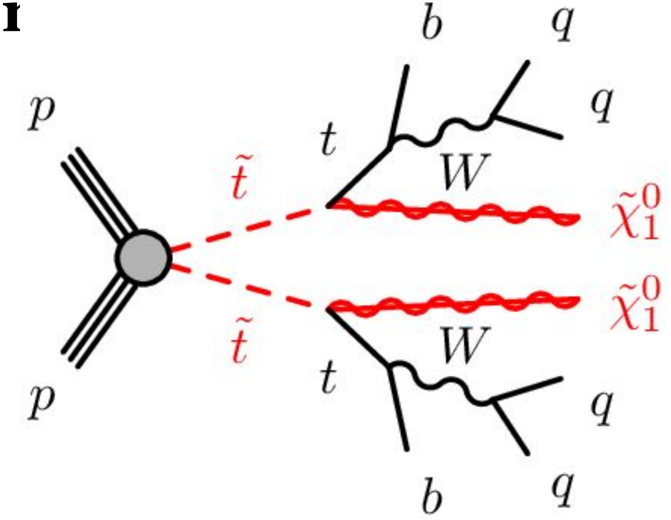
Supersymmetry (SUSY)



Search for Supersymmetry (SUSY)

- **Search for stop quark pair productio**



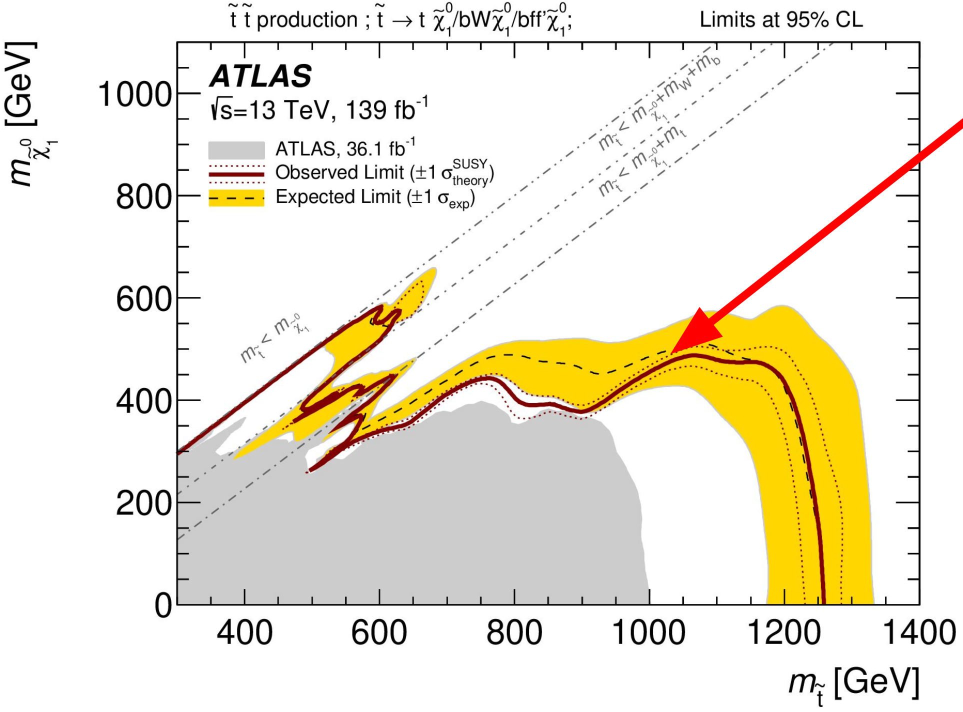


- **Search for multi-jet final state incl. large amount of missing E_T**

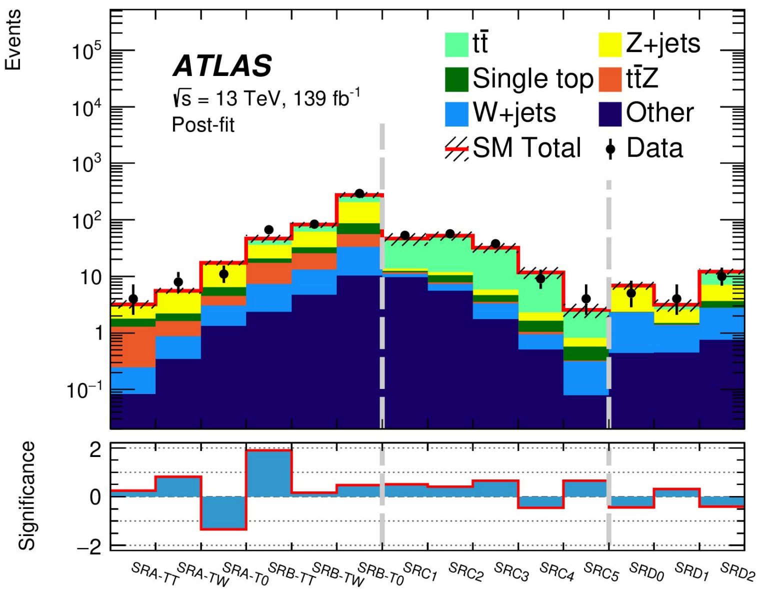
Probe phase space regions sensitive to contributions from SUSY signal

Search for Supersymmetry (SUSY)

- **Search for stop quark pair production**



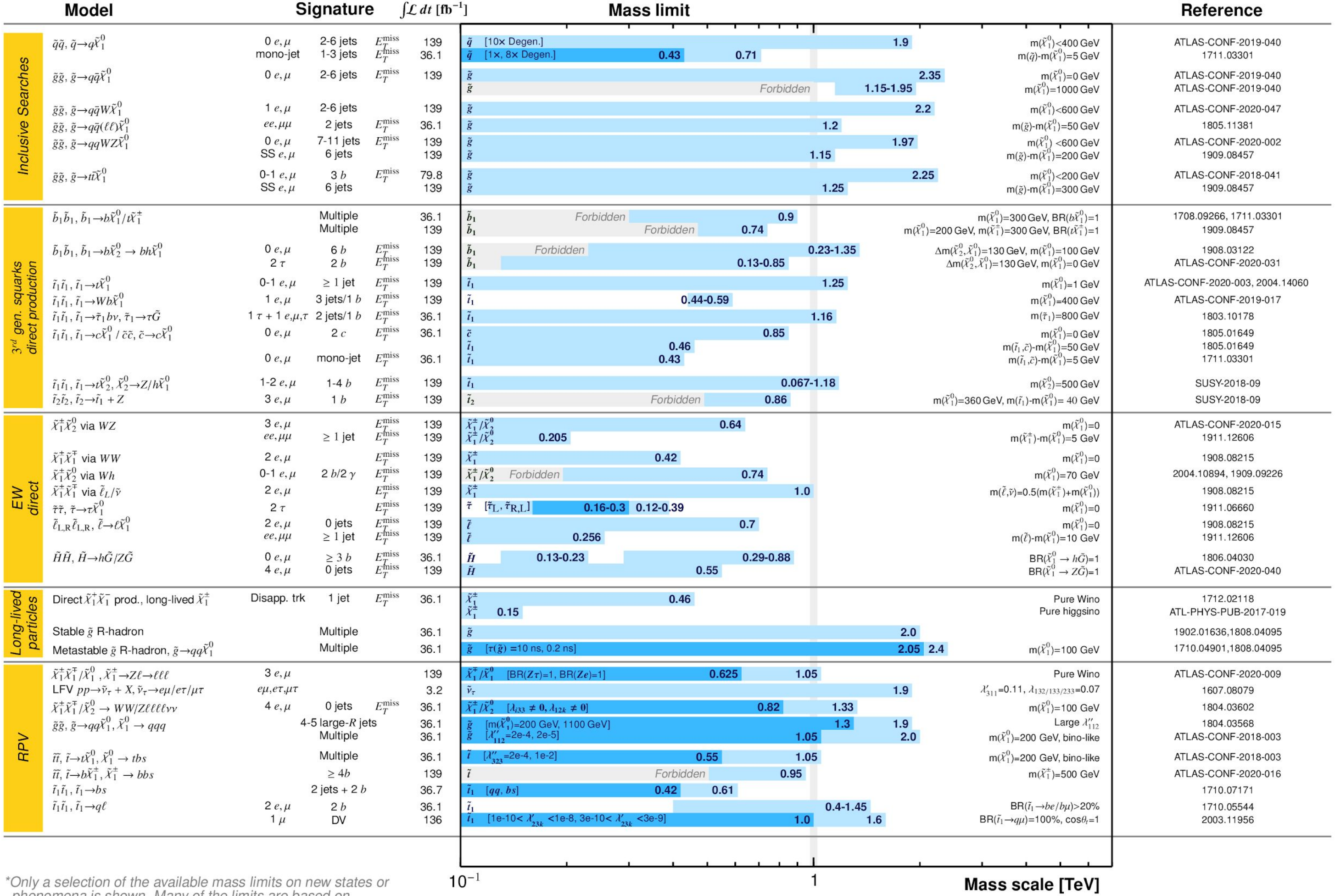
Exclude stop masses up to ~ 1300 GeV for neutralino masses below 400 GeV



ATLAS SUSY Searches* - 95% CL Lower Limits

July 2020

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV

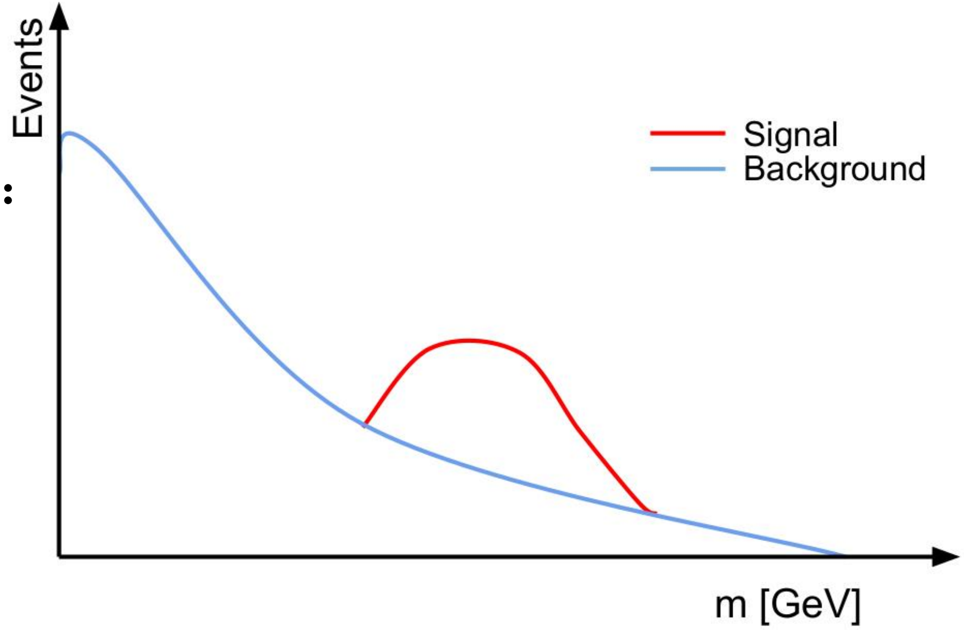


	Model	Signature			$\int \mathcal{L}\,dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{q}$	[10× Degen.] 1.9	m($\tilde{\chi}^0_1$)<400 GeV	ATLAS-CONF-2019-040
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$	[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
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	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
3^{rd} 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	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=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	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=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	$\tilde{\tau}$	[$\tilde{\tau}_{\rm L}$, $\tilde{\tau}_{\rm R,L}$] 0.16-0.3 0.12-0.39	m($\tilde{\chi}^0_1$)=0	1911.06660
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	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	$\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$	[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

*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

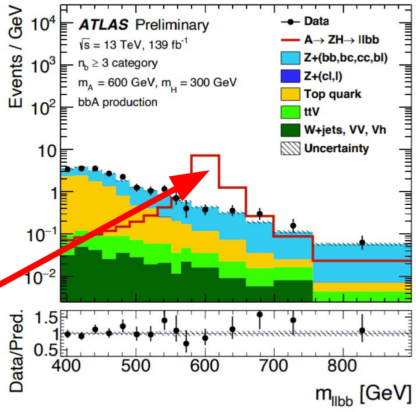
- Most searches for resonances in ATLAS and CMS follow the same principle:
  - Perform (quasi) **model-independent search for a bump in a smoothly falling mass spectrum**

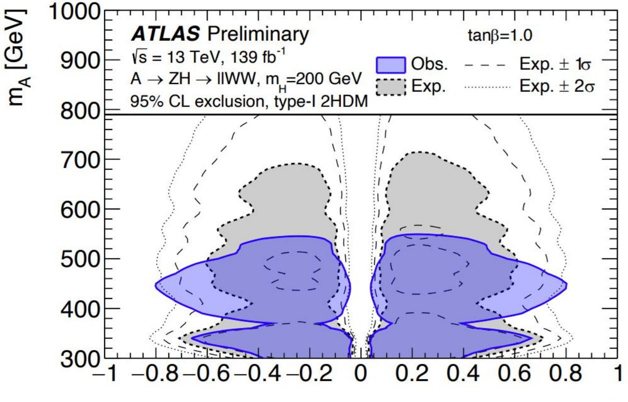


- **Interpretations in generic frameworks:**
  - Two Higgs Doublet Model (2HDM)
  - Higgs Triplet models
  - Heavy Vector Triplet (HVT) models
  - RS Extra-dimensional models

Direct Search for heavy Resonances

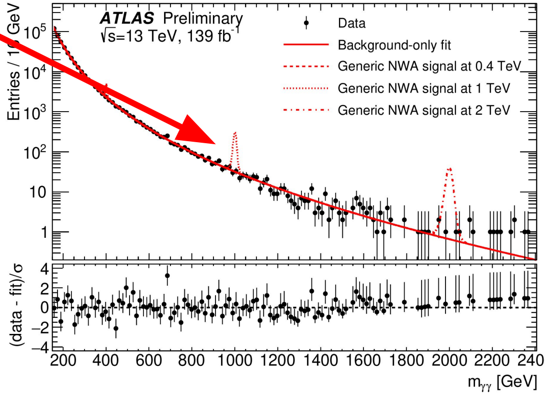
Probe observables sensitive to contribution from signal process

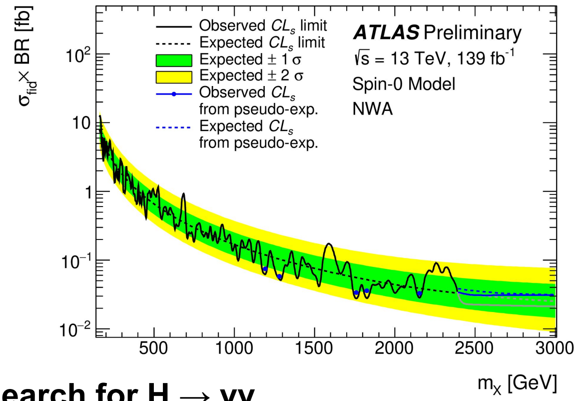




Search for A → ZH → ℓℓbb

cos(β-α)



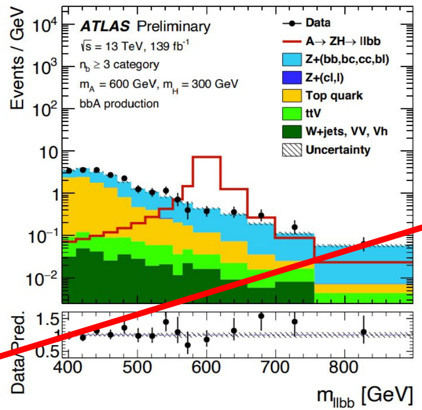


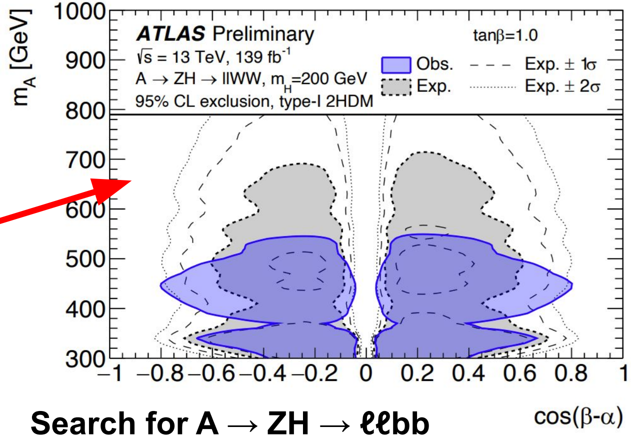
Search for H → γγ

Direct Search for heavy Resonances

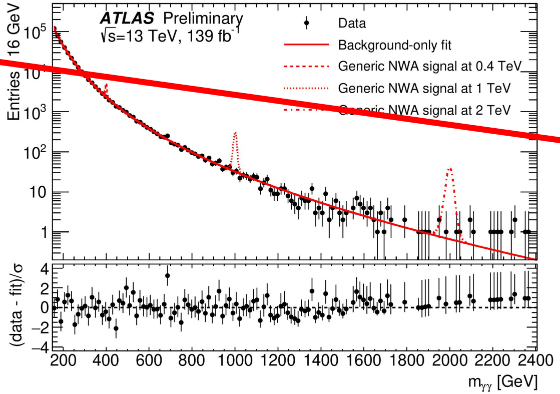
In the absence of a signal:

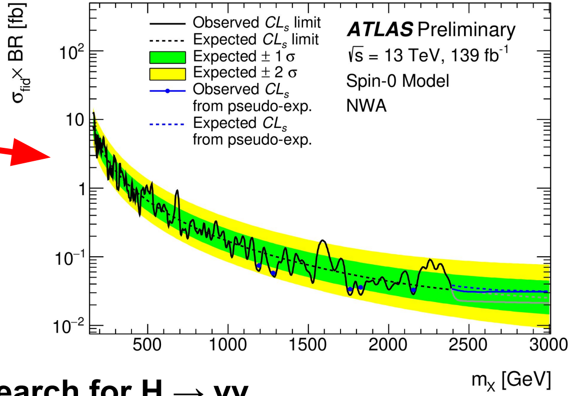
- Derive model dependent exclusion contours
- Set “model independent” limits on the production cross section times branching ratio





Search for A → ZH → ℓℓbb





Search for H → γγ

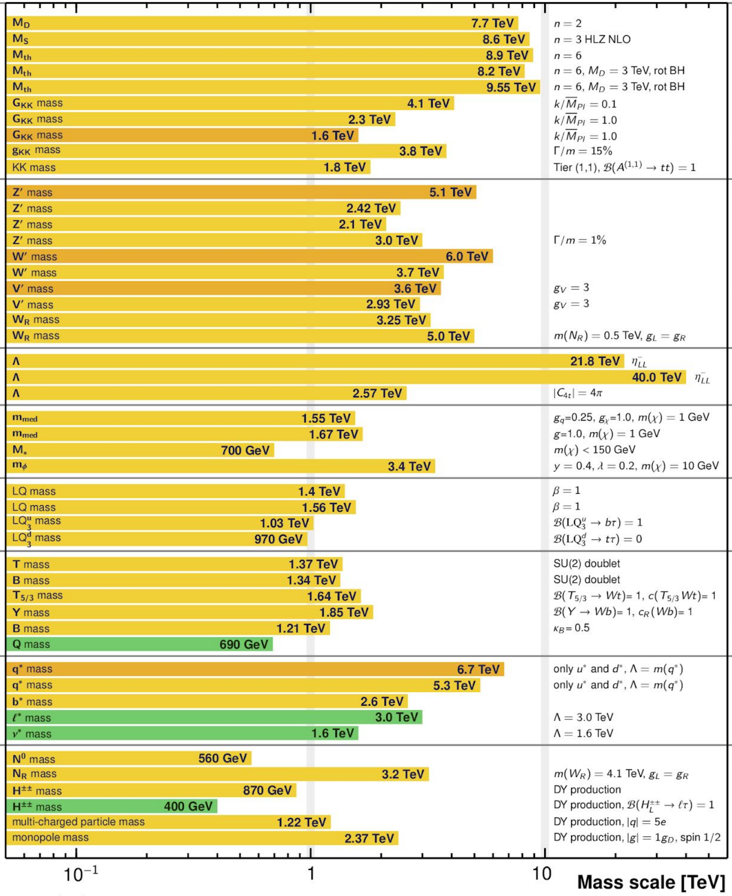
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 139)\ \text{fb}^{-1}$

$\sqrt{s} = 8,\ 13$ TeV



	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	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	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass	970 GeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 0$	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 $T_{5/3} T_{5/3} \vert T_{5/3} \to Wt + X$	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,μ, 2 γ	≥ 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, $\lvert g \rvert = 1 g_D$, spin 1/2	1905.10130

🟩 $\sqrt{s} = 8$ TeV

🟨 $\sqrt{s} = 13$ TeV partial data

🟧 $\sqrt{s} = 13$ TeV full data

*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).

Concluding remarks

- The standard Model of particle physics leaves some questions unanswered
    - Use LHC experiments to find answer to these questions

- LHC experiments have a diverse physics programme
    - SM high precision measurements (W, Z, top-quark)
    - Higgs boson property measurements
    - Searches for BSM physics (SUSY, heavy vector bosons, exrta-dimensions, ...)
    - Flavour-physics
    - ....

- New round of data-taking with increased center-of-mass energy to be started.
    - Exciting times ahead of us !!!