Testing the Standard Model of Elementary Particle Physics II

5th lecture

Dr. Dominik Duda

10th June 2021

4.4 The Top quark

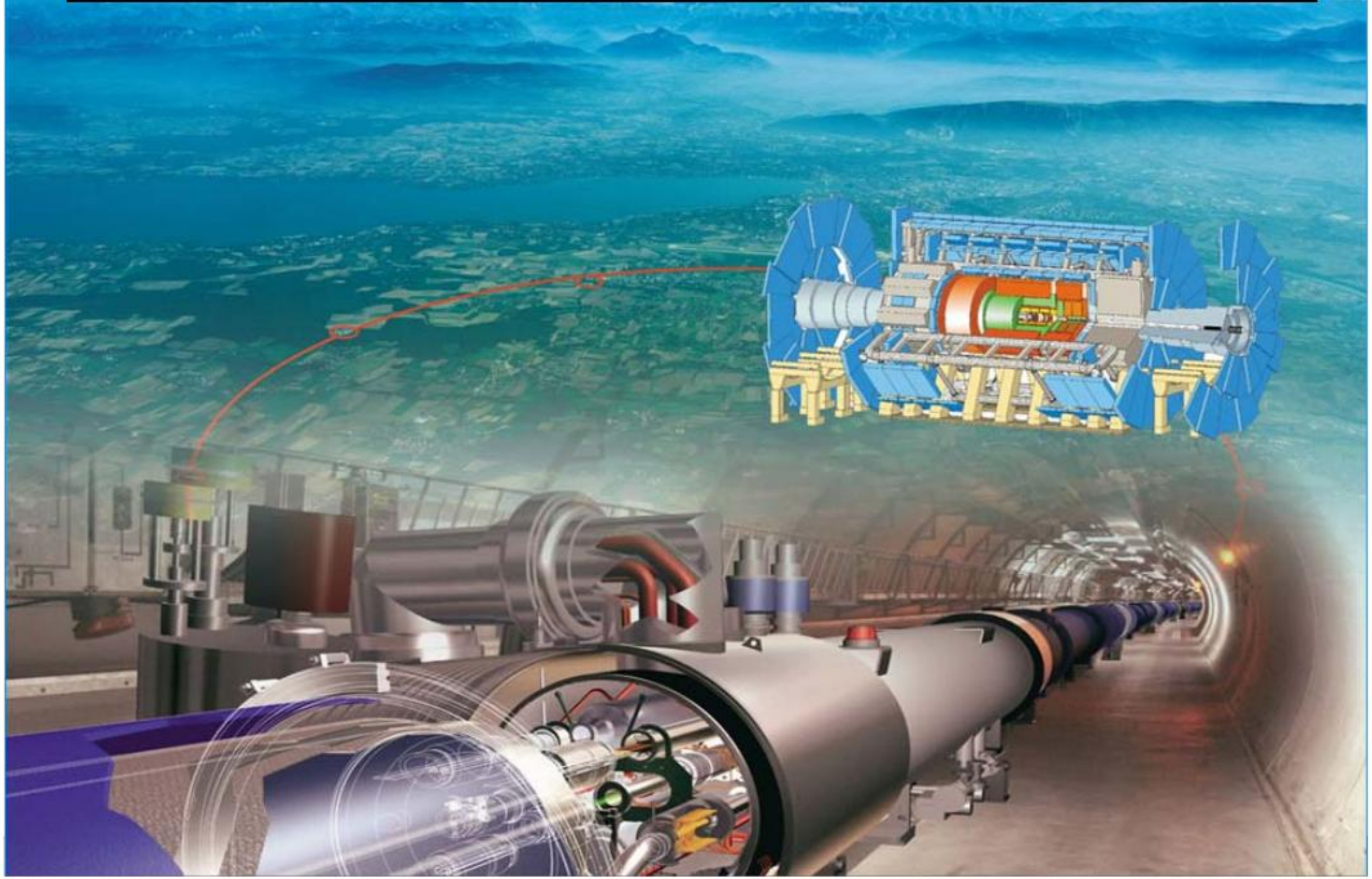


Table of content

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:**

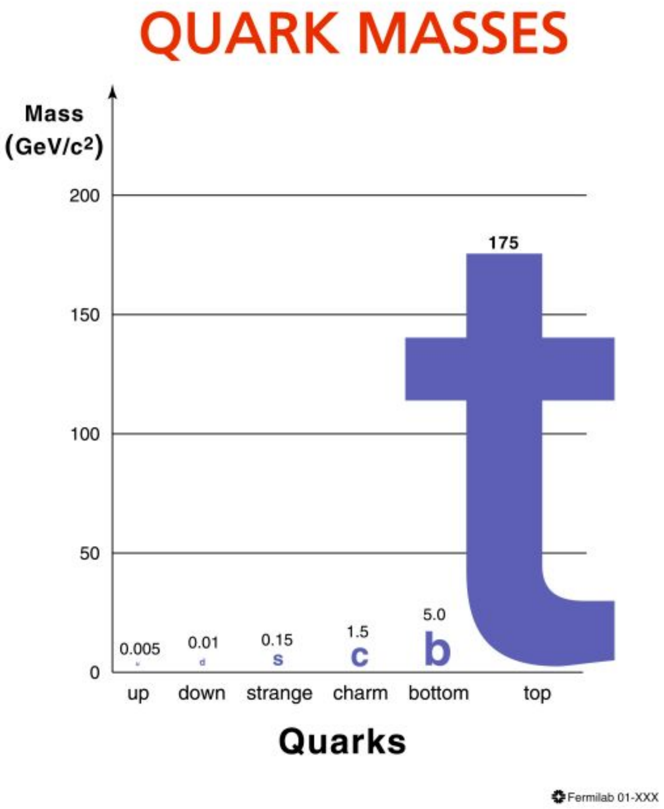
$$\tau_{\text{top}} \propto \left(\frac{M_W}{M_{\text{top}}}\right)^3$$

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

→ Top quark decays as a quasi free particle

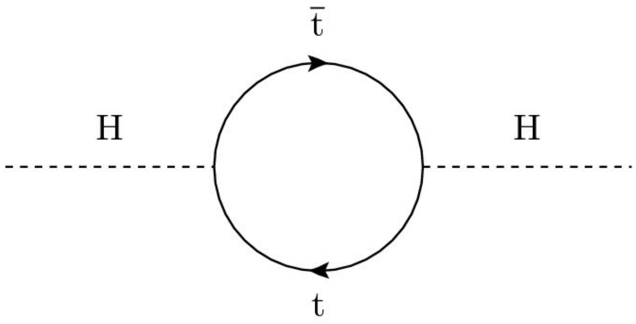
→ Spin information and polarisation are accessible

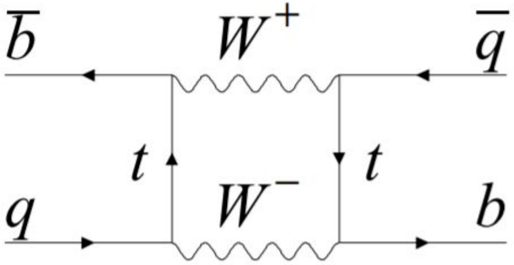
since spin decorrelation time (~10^{-21} s) is much larger than the hadronisation time (~10^{-23} s)

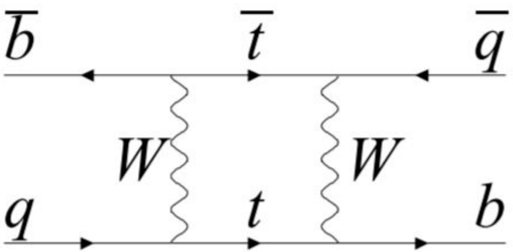


Top-quarks in loops

- Due to loop contributions, several observables and/or processes depend (strongly) on the top quark mass:
  - **Higgs propagator**
  - **B-hadron mixing**







→ Precise knowledge of top quark mass is crucial for theory/experiment

The running of the Higgs self-coupling

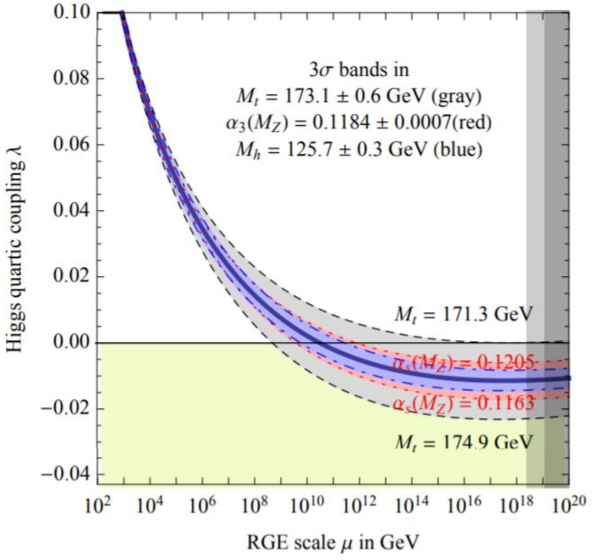
- The Higgs self-coupling λ is not a constant.

$$V(\phi) = \frac{1}{2}\mu^2\phi^\dagger\phi + \frac{1}{4}\lambda\left(\phi^\dagger\phi\right)^2$$

$$\lambda = \lambda(q^2)$$

- Loop corrections $\longrightarrow$ dependence on momentum scale μ
  - Main contributions from top-quark
- Condition for absolute stability of the potential: $\lambda(q^2)$ > 0

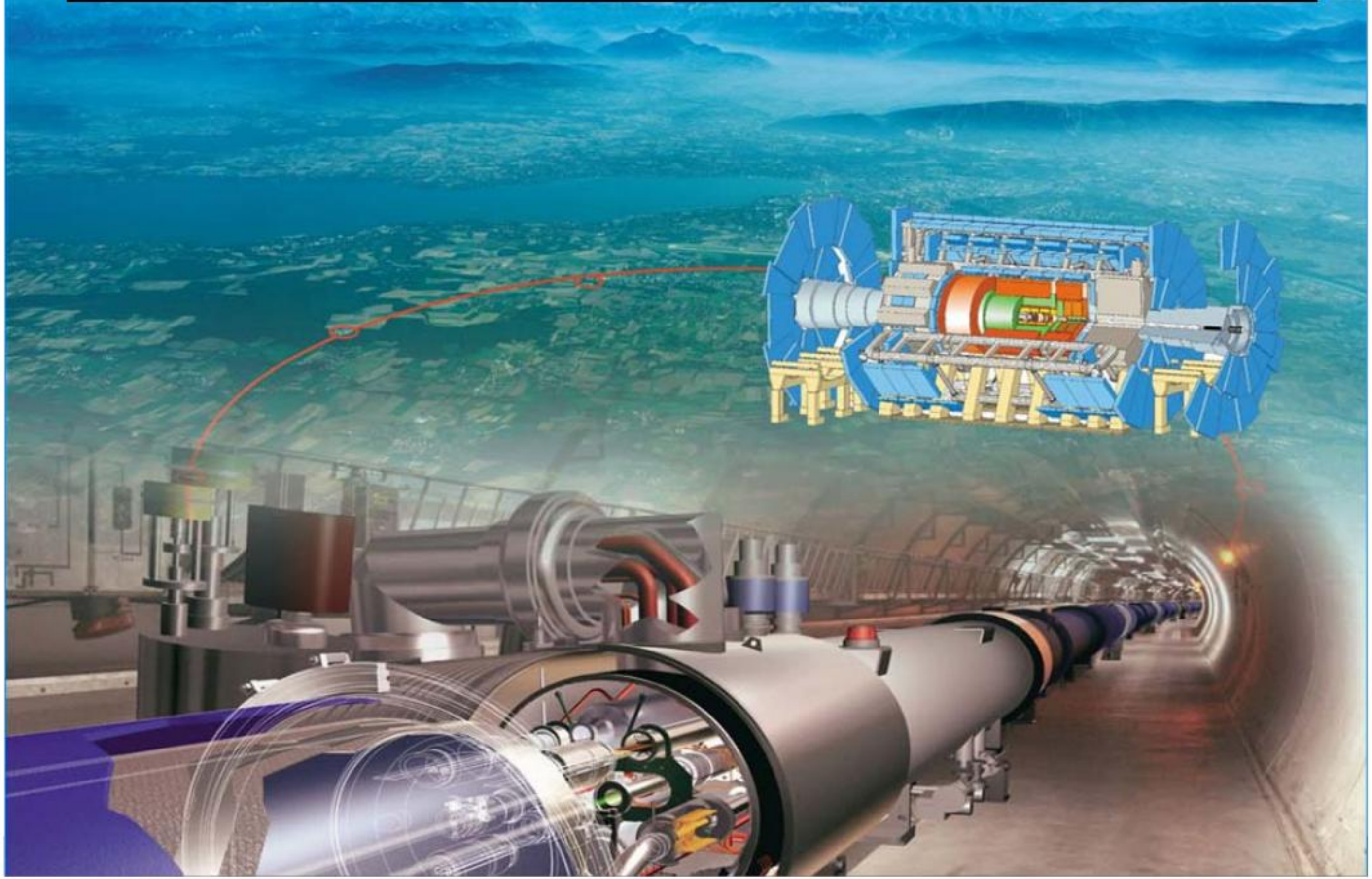
$$M_H \geqslant 129.2 + 1.8 \times \left(\frac{m_t^{\rm pole} - 173.2\,\mathrm{GeV}}{0.9\,\mathrm{GeV}}\right) - 0.5 \times \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0\,\mathrm{GeV}$$



Renormalization group running of the Higgs self-coupling λ, and its dependence on the top and Higgs masses, and the strong coupling constant α_S (m_Z).

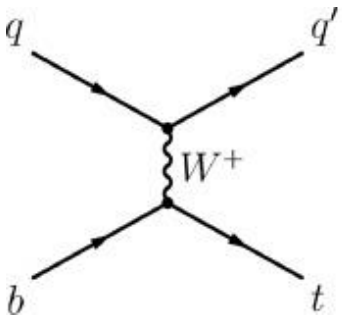
From: https://arxiv.org/pdf/1205.6497.pdf

4.4.1 Top quark properties

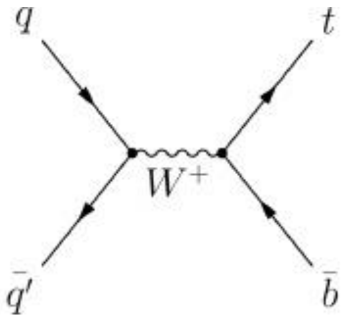


Top quark production

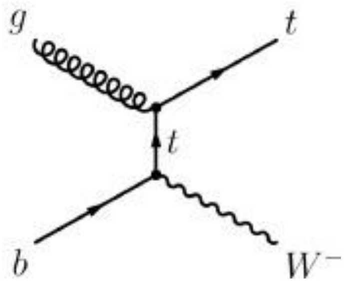
- Single top quarks:



t-channel



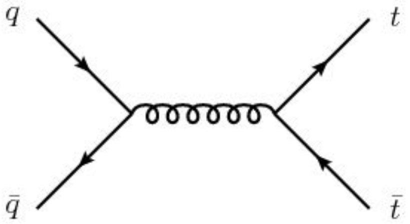
s-channel



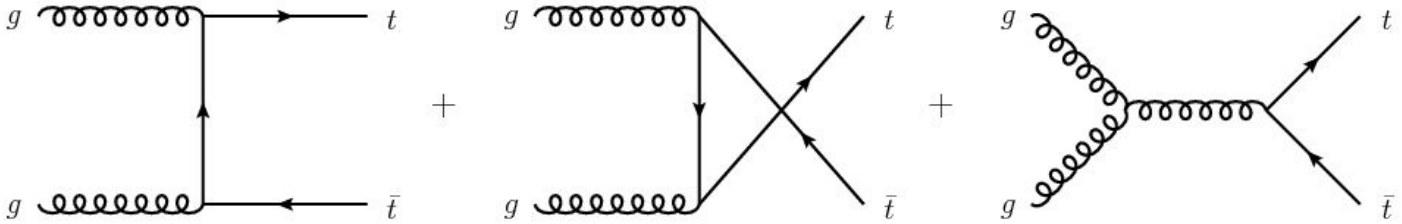
Wt-channel

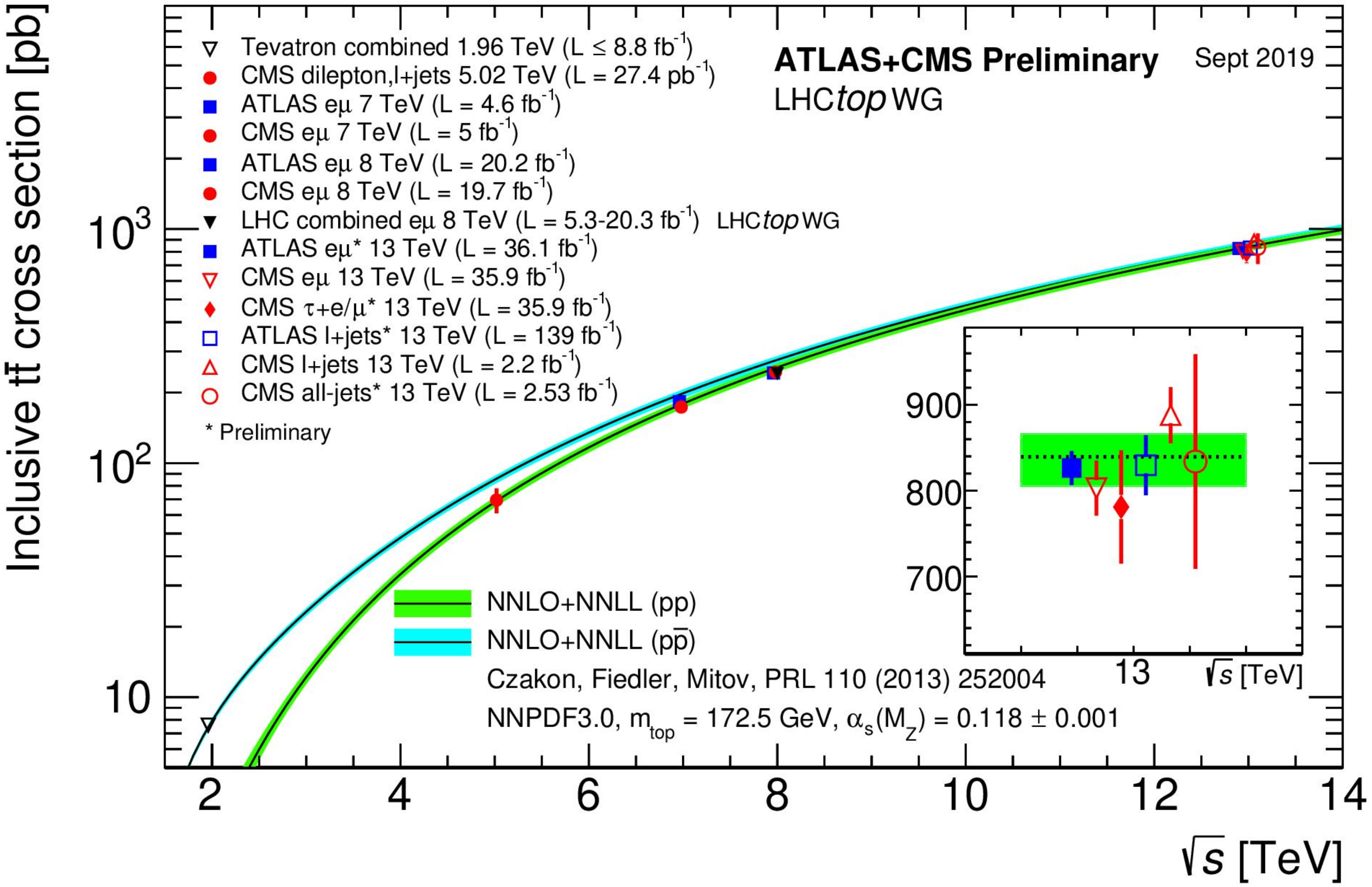
- Top quark pairs:

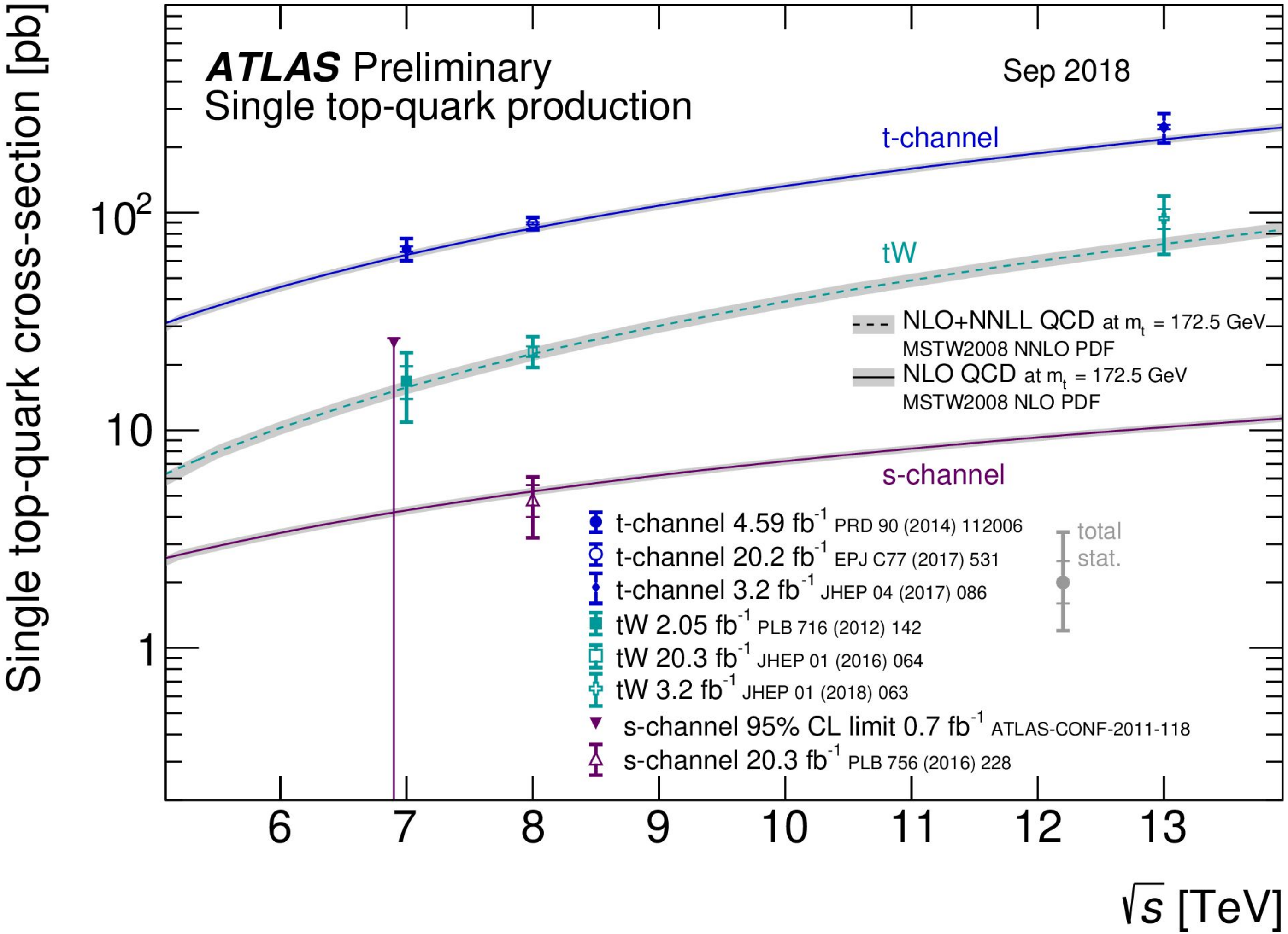
15%



85%




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
Sept 2019
LHC*top*WG
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
Inclusive $t\bar{t}$ cross section [pb]
$\sqrt{s}$ [TeV]



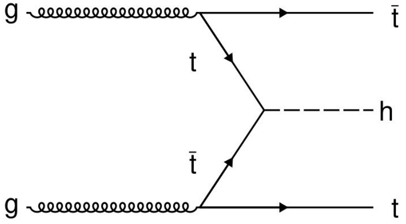
ATLAS Preliminary
Single top-quark production
Sep 2018
t-channel
tW
s-channel
NLO+NNLL QCD at m_t = 172.5 GeV
MSTW2008 NNLO PDF
NLO QCD at m_t = 172.5 GeV
MSTW2008 NLO PDF
t-channel 4.59 fb^{-1} PRD 90 (2014) 112006
t-channel 20.2 fb^{-1} EPJ C77 (2017) 531
t-channel 3.2 fb^{-1} JHEP 04 (2017) 086
tW 2.05 fb^{-1} PLB 716 (2012) 142
tW 20.3 fb^{-1} JHEP 01 (2016) 064
tW 3.2 fb^{-1} JHEP 01 (2018) 063
s-channel 95% CL limit 0.7 fb^{-1} ATLAS-CONF-2011-118
s-channel 20.3 fb^{-1} PLB 756 (2016) 228
total
stat.
Single top-quark cross-section [pb]
$\sqrt{s}$ [TeV]

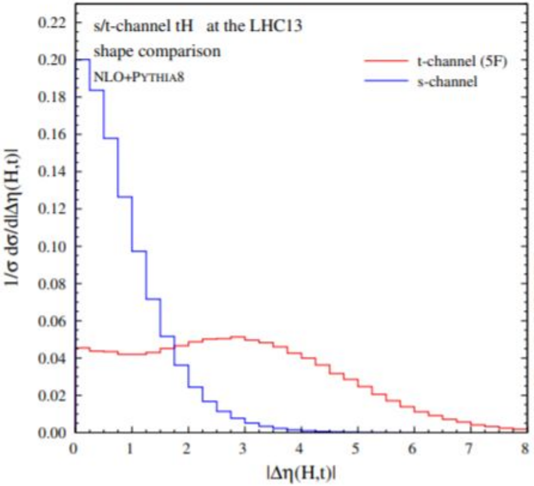
Production of top quarks + Higgs

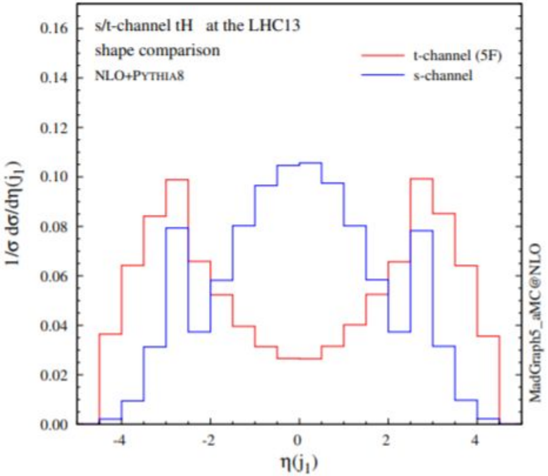
σ_{ttH} = 0.5085 pb (+10.5% / -12.8%)

$\sigma_{t\text{-}chan}$ = 0.07154 pb (+7.3% / -2.1%)

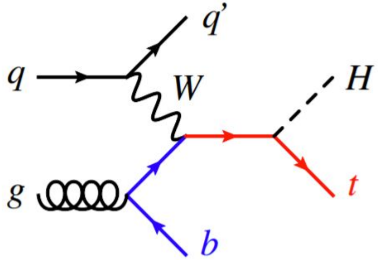
$\sigma_{s\text{-}chan}$ = 0.002812 pb (+2.2% / -1.9%)



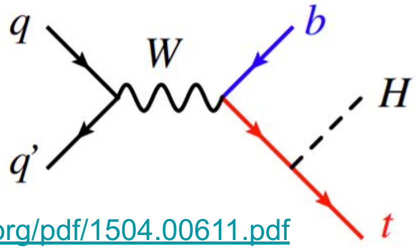




t-channel production:



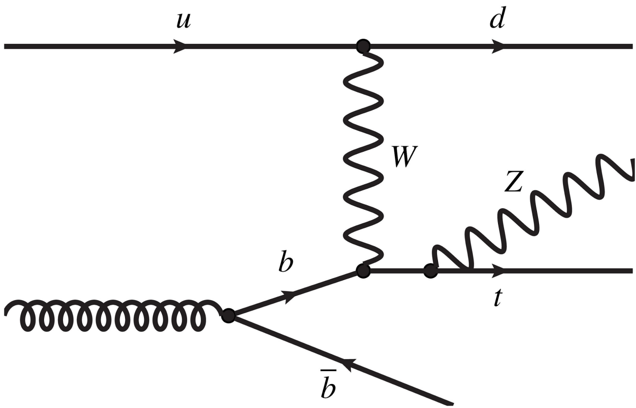
s-channel production:

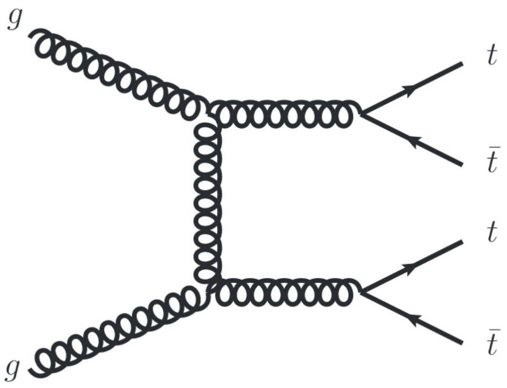


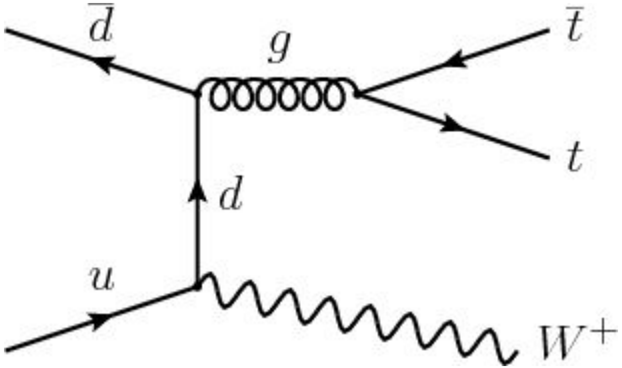
From: https://arxiv.org/pdf/1504.00611.pdf

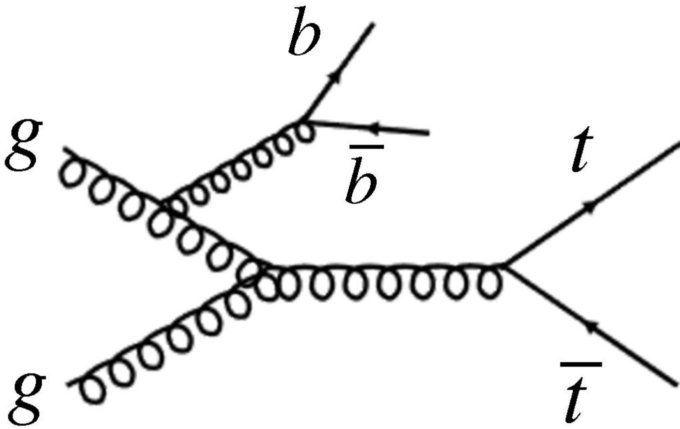
Production of top + X

- Rare processes (observed for the first time at the LHC):
  - Single top quark + Z boson
  - Top quark pairs + W/Z boson
  - Top quark pairs + bb
  - Four top quarks









Top quark decays

- **CKM matrix elements describe transition from one quark flavour to another:**
  - I.e. V_{ij} measures the coupling of quark i to quark j:
  - The CKM matrix is given via:

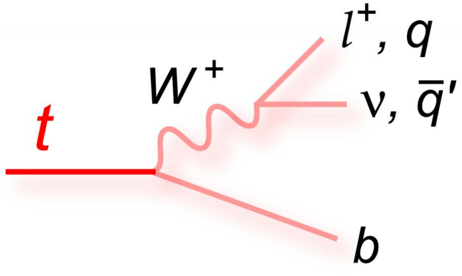
$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{tc} & V_{tb} \end{pmatrix}$$

  - The magnitudes of the matrix elements are:

$$\begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

- Top quark decays almost exclusively via $t \rightarrow bW$

$$|V_{tb}| \approx 1$$



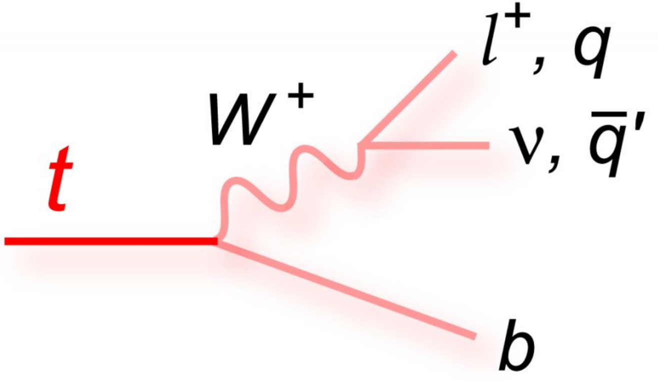
Latest measurements of CKM matrix elements taken from: https://pdg.lbl.gov/2019/reviews/rpp2019-rev-ckm-matrix.pdf

Top quark decays

- Decays via the weak interaction
- Involves left-handed chiral fermion fields

$$\psi_L = \frac{1}{2}(1 - \gamma_5)\,\psi$$

- Since $|V_{tb}| \approx 1$ thus $\mathcal{B}(t \to Wb) \approx 1$

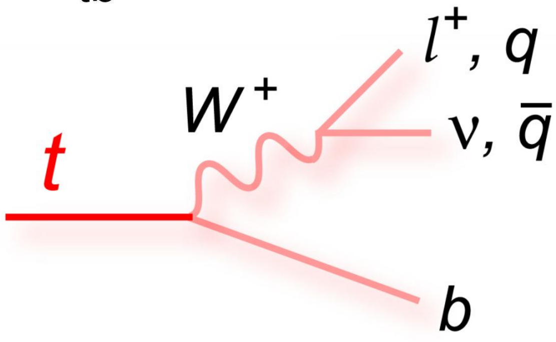


$$\boxed{< |\mathcal{M}|^2 > = \frac{g_W^2\, c^2}{4\, m_W^2}\,(m_t^2 - m_W^2)\,(m_t^2 + 2m_W^2)}$$

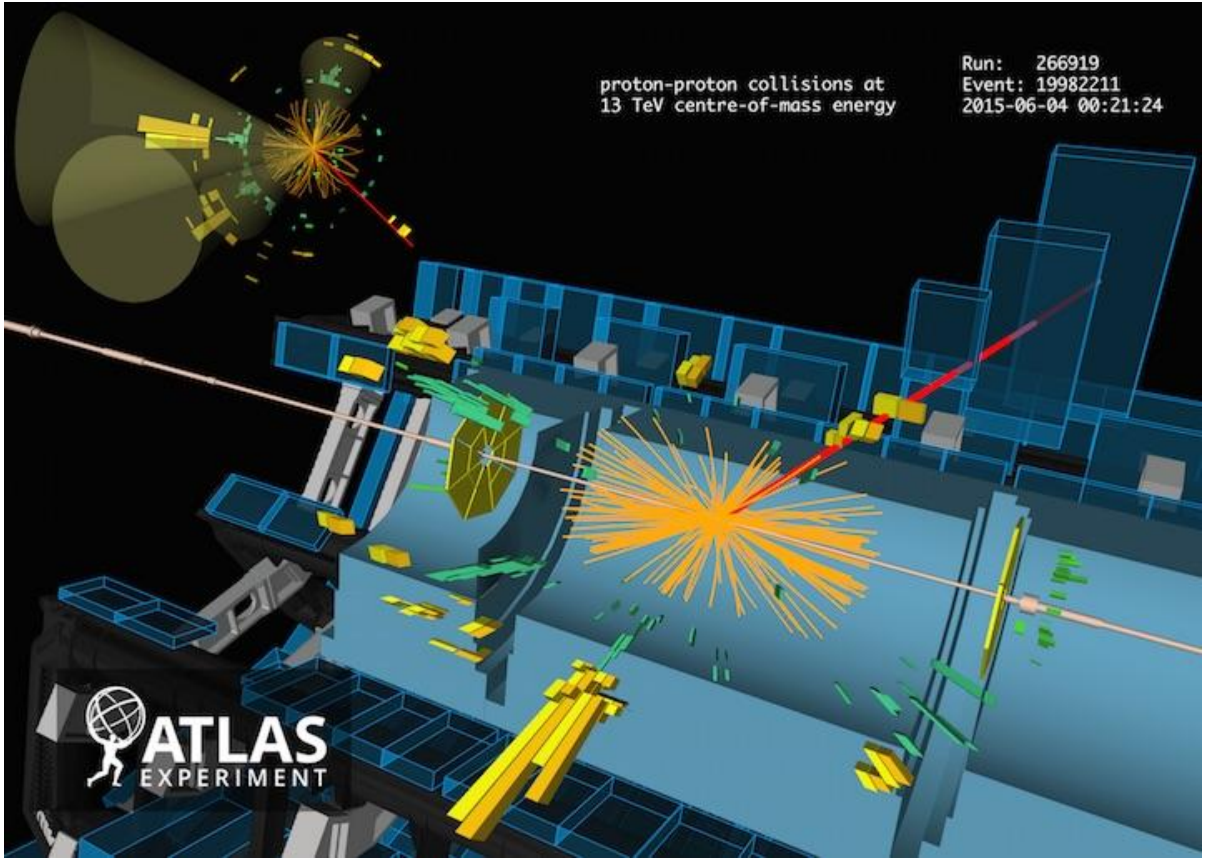
Top quark decays

- Top quark decays almost exclusively via $t \to bW$

$$|V_{tb}| \approx 1$$

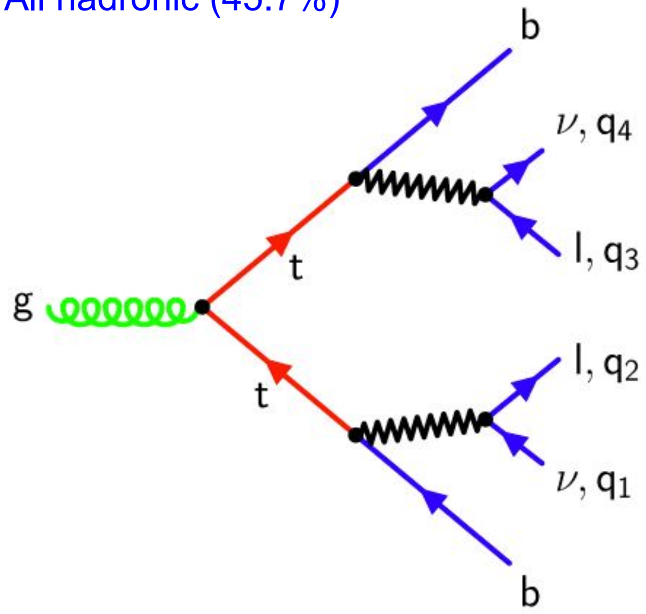


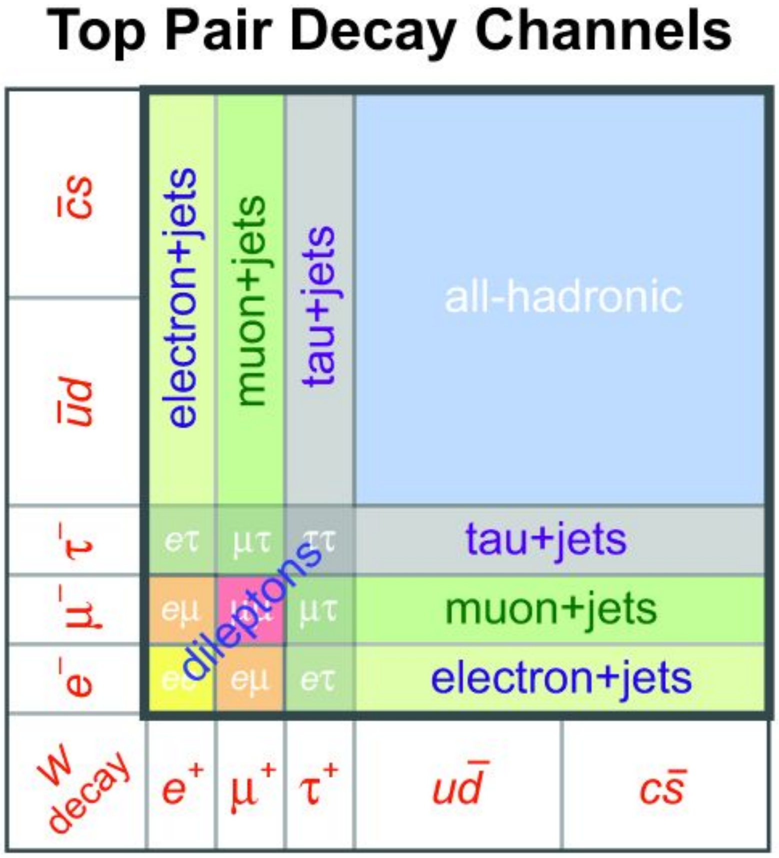
- Top quark decays are characterised by high p_T leptons, jets and missing transverse momentum



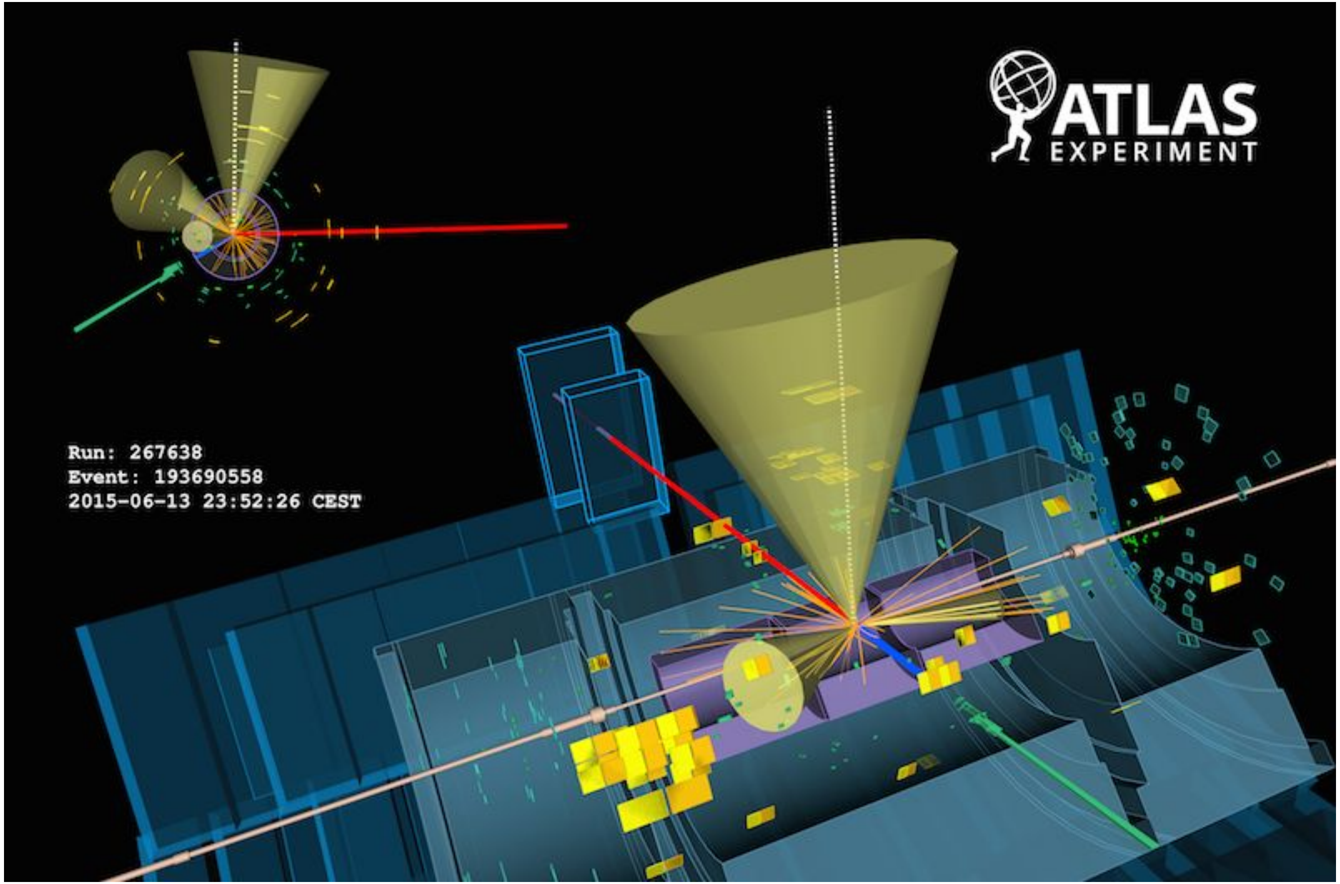
Top quark pair decays

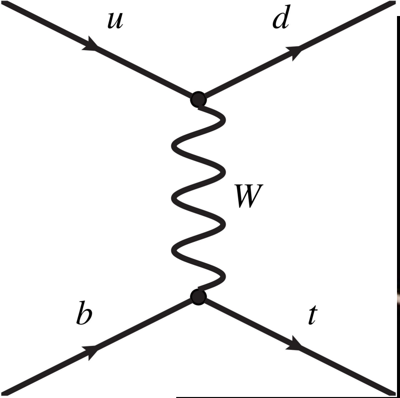
- Top quark pair decays are classified based on decay modes of the W bosons:
  - Dilepton (10.5%)
  - Lepton + jets (43.8%)
  - All hadronic (45.7%)

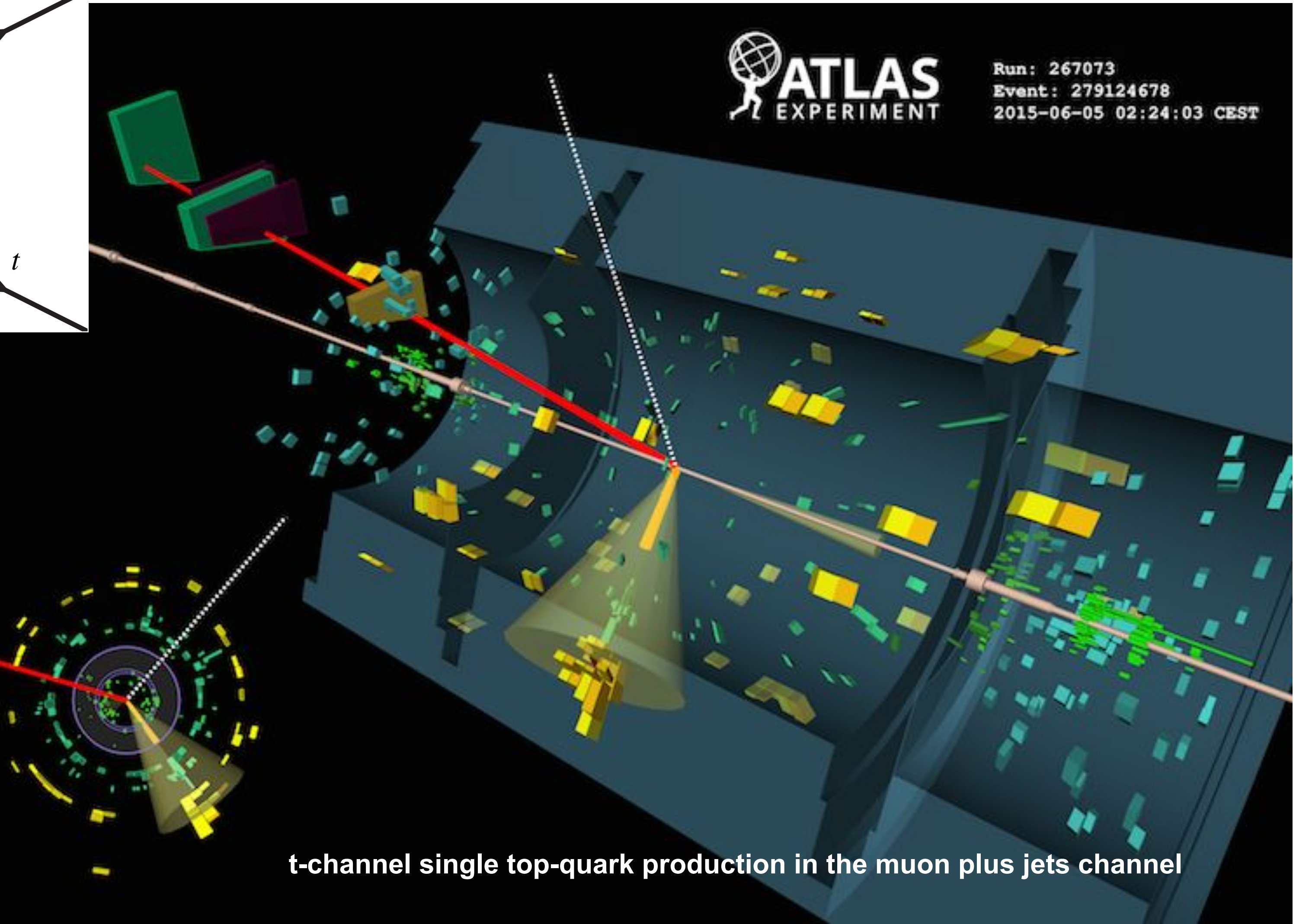




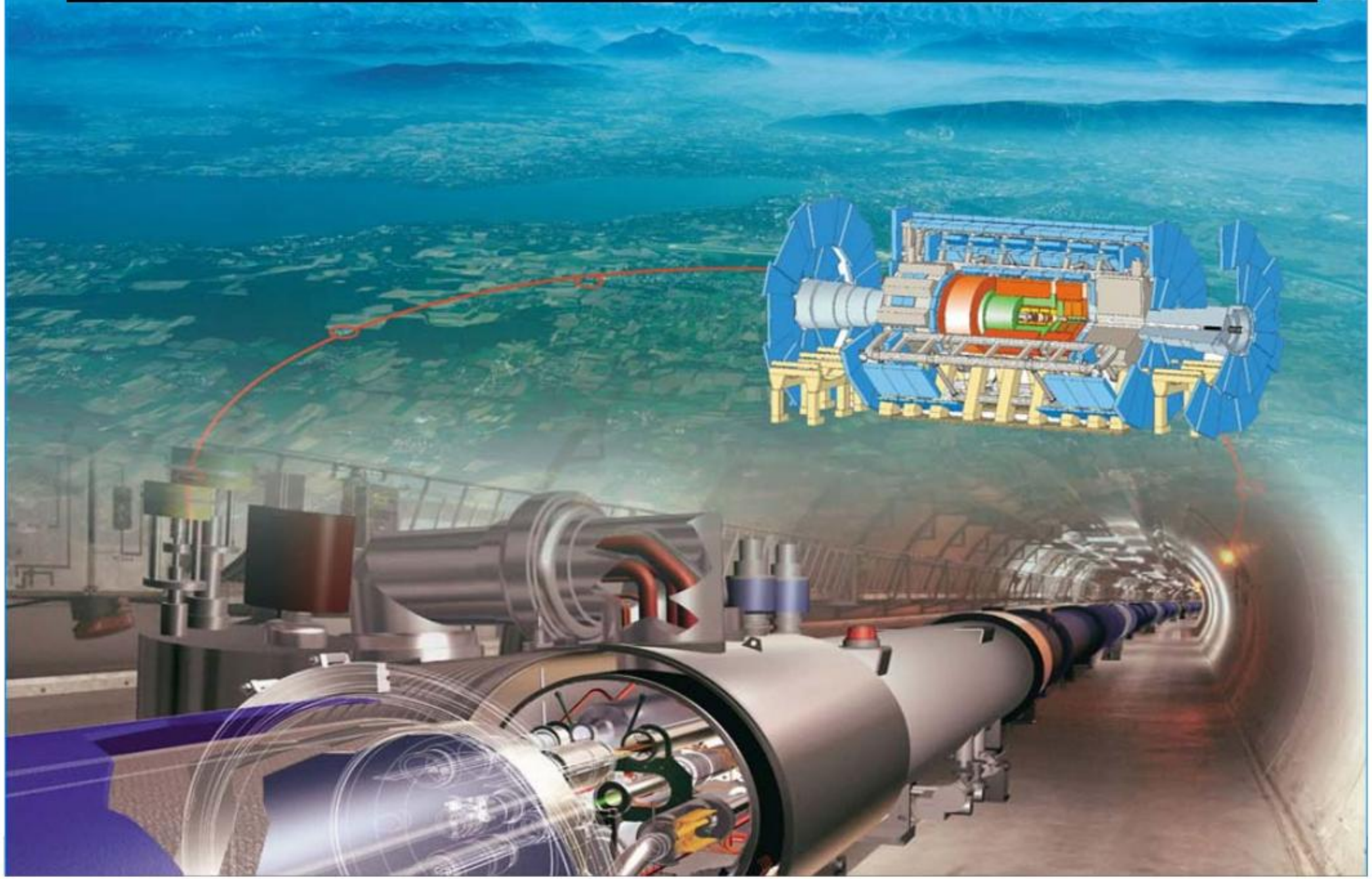
Top quark decay (dilepton)




u
d
W
b
t


ATLAS
EXPERIMENT
Run: 267073
Event: 279124678
2015-06-05 02:24:03 CEST
t-channel single top-quark production in the muon plus jets channel

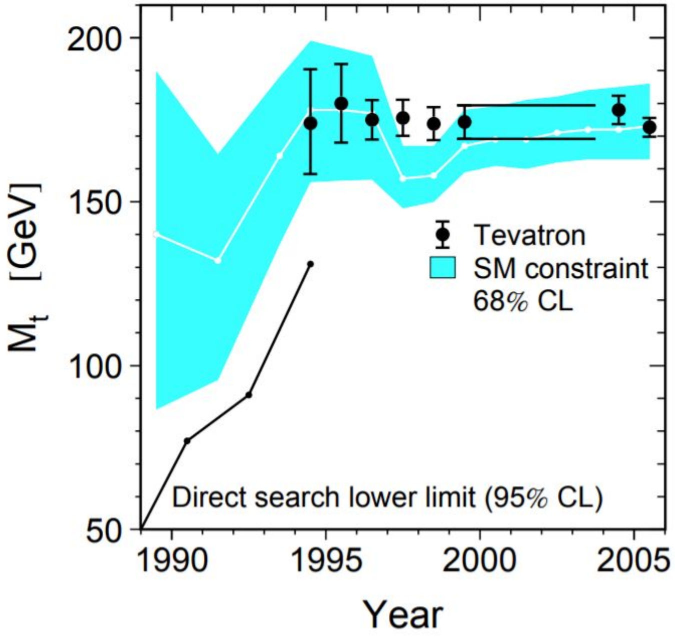
4.4.2 Top quark discovery



Top quark discovery

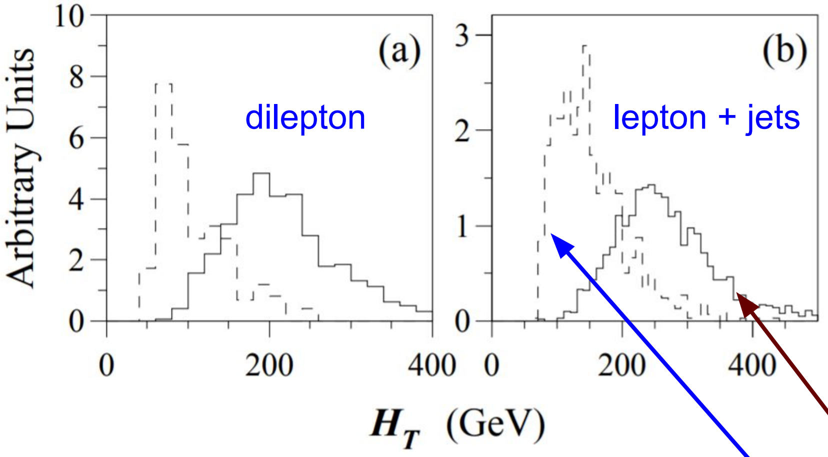
- The top quark was discovered in 1995 by the CDF and D0 experiments at the Tevatron.
    - Predicted in 1977 (directly after discovery of b-quark)

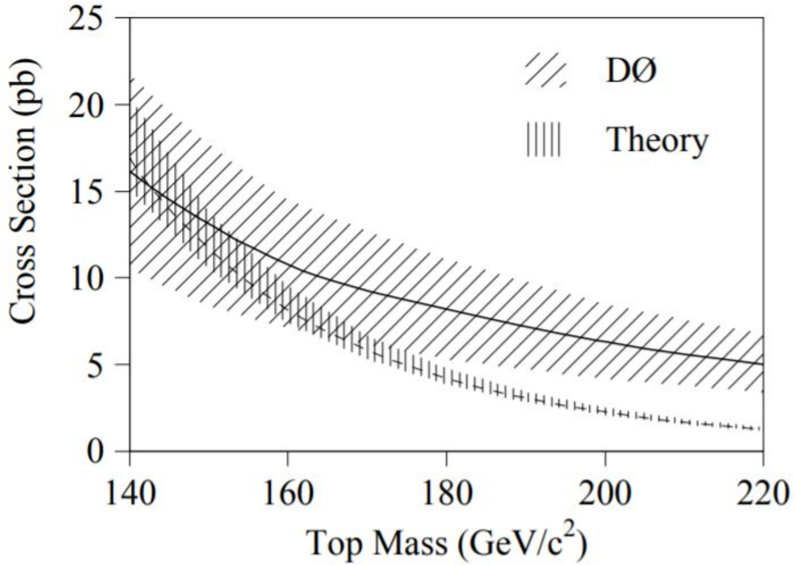
- Discovery was based on data from the 1992–93 (full Run Ia) and 1994–1995 (part of Run Ib) runs of the Tevatron collider
- The total integrated luminosities were $67pb^{-1}$ for CDF and between 44 and $56pb^{-1}$ (depending on the top decay mode) for D0
- Searches have been performed in dilepton and lepton + jets signatures

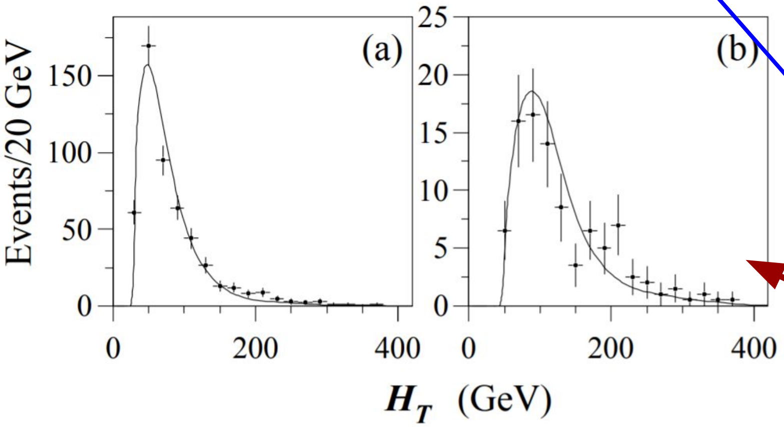


Top quark discovery

Taken from: https://arxiv.org/pdf/hep-ex/9503003.pdf





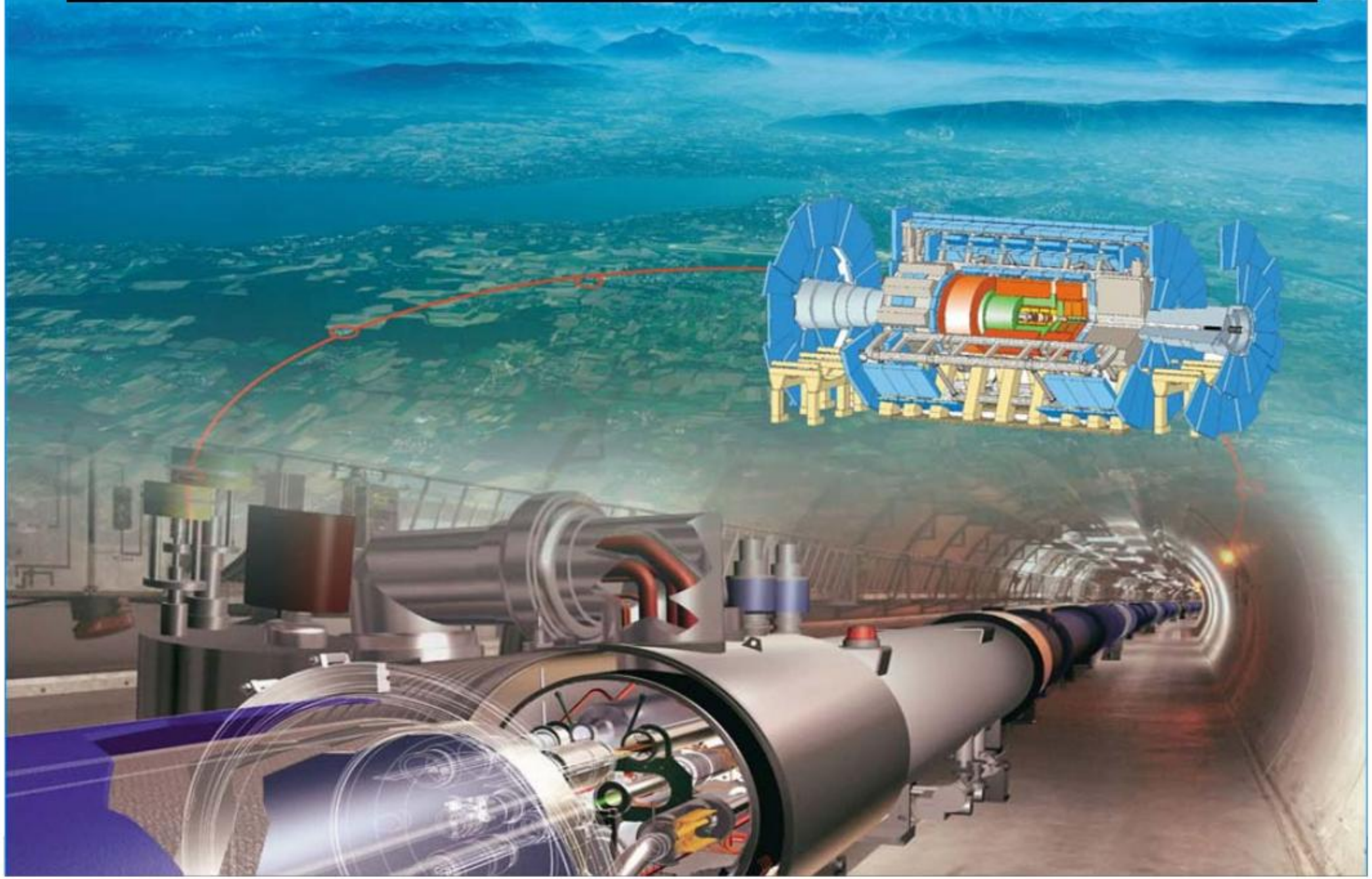


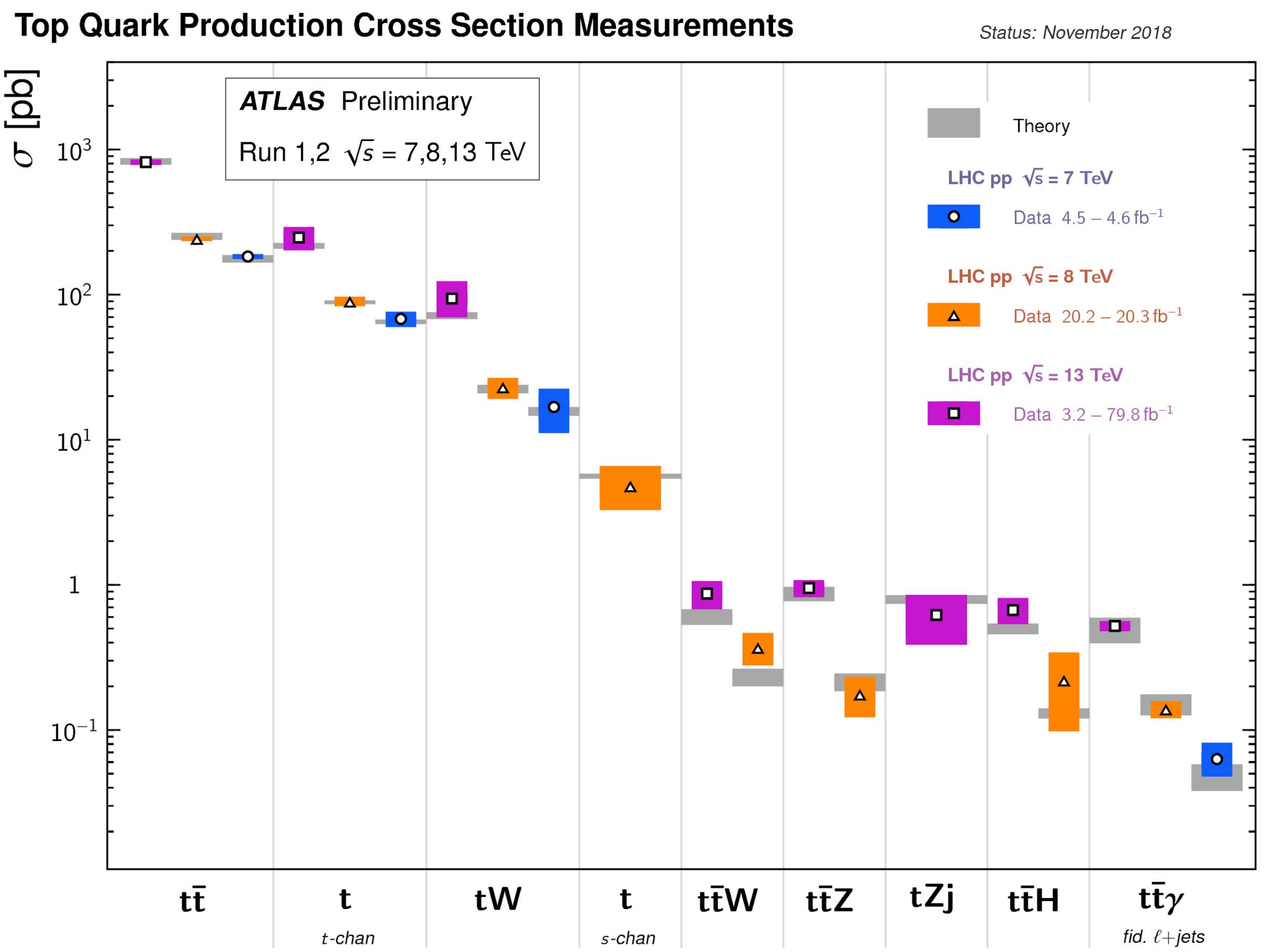
signal (m_{top} = 200GeV)

backgrounds

Observed H_T distributions (points) compared to the distributions expected from background

4.4.3 Measurement of top quark properties at the LHC



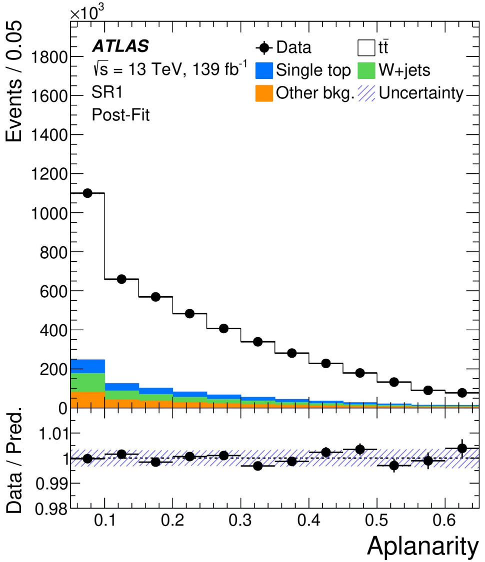


Top Quark Production Cross Section Measurements
Status: November 2018
ATLAS Preliminary
Run 1,2 $\sqrt{s}$ = 7,8,13 TeV
σ [pb]
10^3
10^2
10^1
1
10^{-1}
Theory
LHC pp $\sqrt{s}$ = 7 TeV
Data 4.5 – 4.6 fb^{-1}
LHC pp $\sqrt{s}$ = 8 TeV
Data 20.2 – 20.3 fb^{-1}
LHC pp $\sqrt{s}$ = 13 TeV
Data 3.2 – 79.8 fb^{-1}
$t\bar{t}$
t
t-chan
tW
t
s-chan
$t\bar{t}W$
$t\bar{t}Z$
tZj
$t\bar{t}H$
$t\bar{t}\gamma$
fid. ℓ+jets

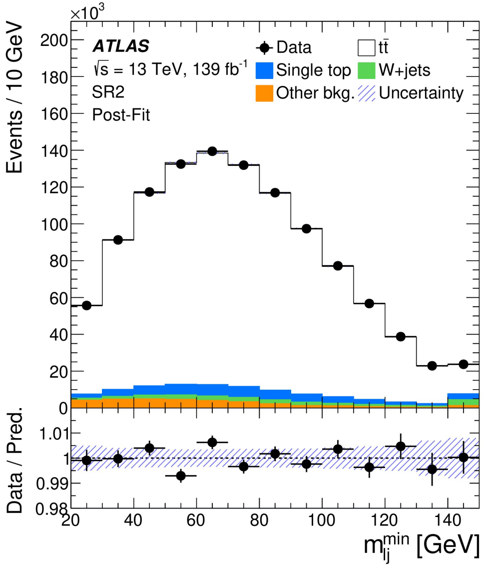
Production cross section measurement (ℓ+jets)

- 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.

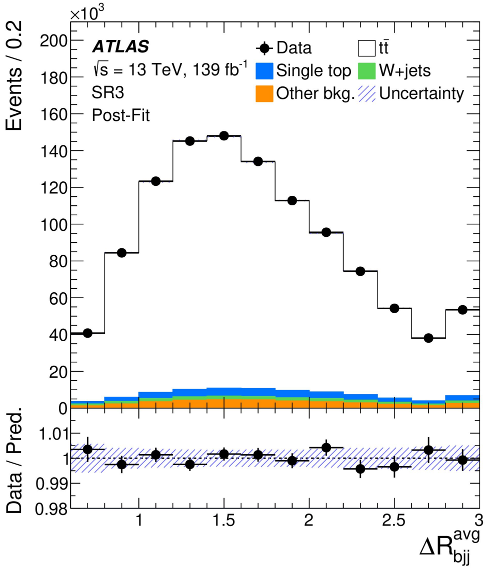
≥ 4 jets and = 1 b-tag



= 4 jets and = 2 b-tags



≥ 5 jets and = 2 b-tags



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

Measurement:

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

Theory prediction:

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

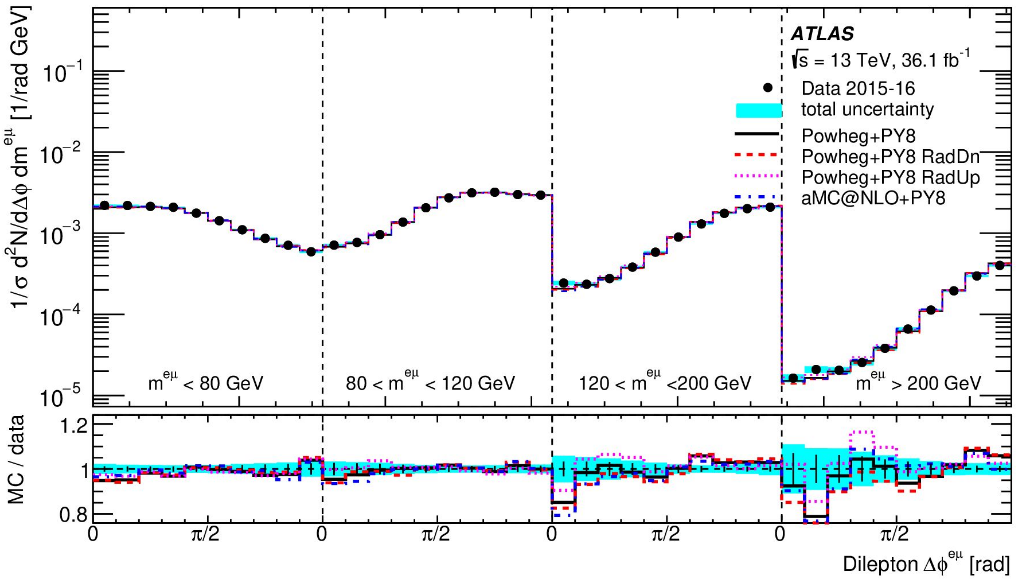
Dominant uncertainties are due to the modelling of the top quark pair production process

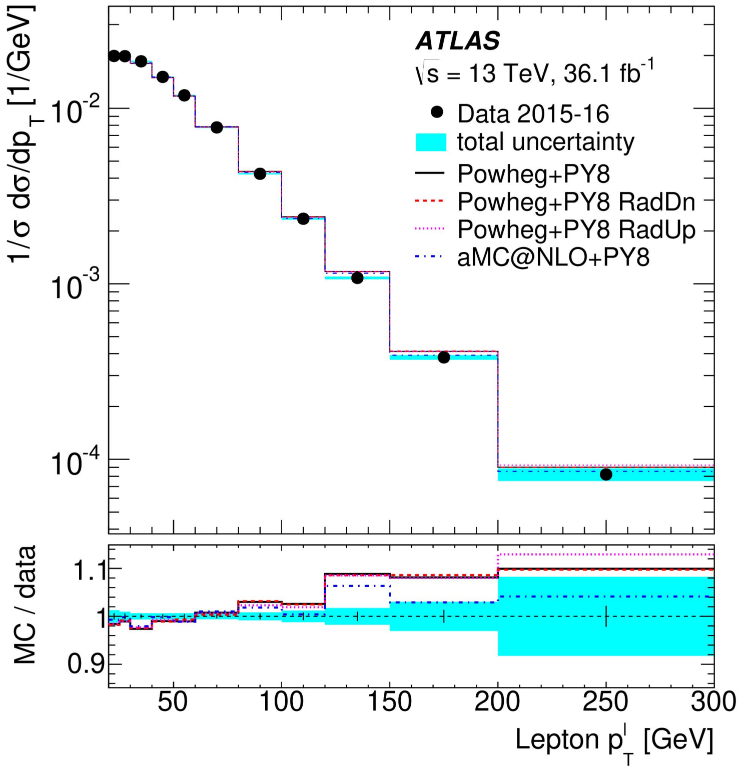
Category	$\frac{\Delta\sigma_{\text{fid}}}{\sigma_{\text{fid}}}$ [%]	$\frac{\Delta\sigma_{\text{inc}}}{\sigma_{\text{inc}}}$ [%]
Signal modelling		
$t\bar{t}$ shower/hadronisation	±2.8	±2.9
$t\bar{t}$ scale variations	±1.4	±2.0
Top p_T NNLO reweighting	±0.4	±1.1
$t\bar{t}$ h_{damp}	±1.5	±1.4
$t\bar{t}$ 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_T^{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]

Differential cross section measurements

Used to tune MC generator setups



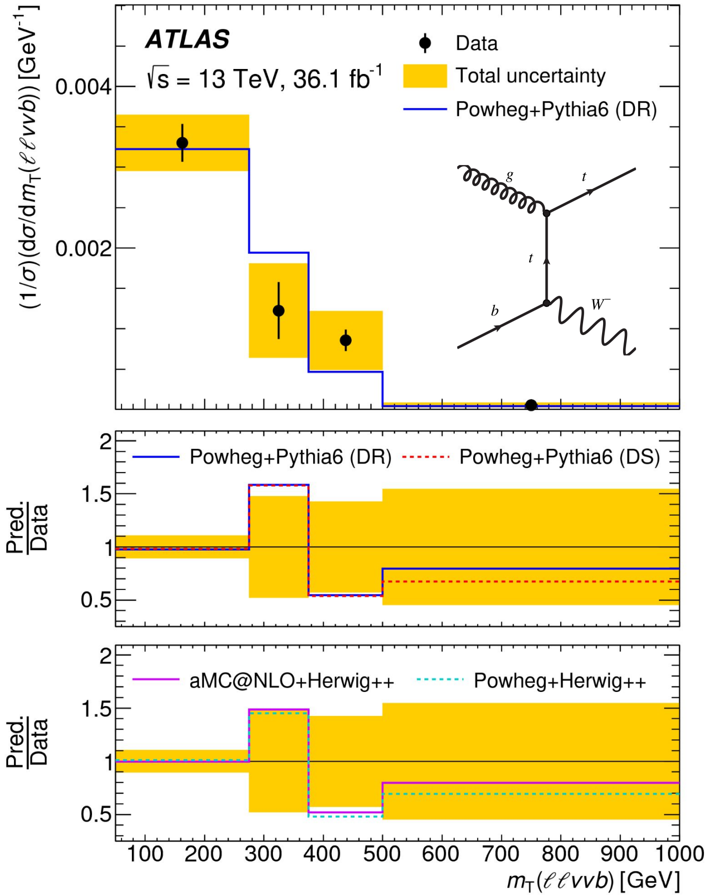


Some discrepancies for higher $m_{e\mu}$ and $|y^{e\mu}|$

Data are softer than predictions by MC generators.

Production cross section measurement (tW)

- Overlap between Wt and top-quark pair production at NLO (i.e. WbWb final state)
  - Overlap is removed with either of two commonly used approaches (https://arxiv.org/abs/0805.3067):
    - Diagram removal (DR)
    - Diagram subtraction (DS)
- Multivariate techniques are used to suppress the large backgrounds
  - top-quark pairs, V + jets, diboson
- Differential cross-sections have been measured as a function of characteristic observables
  - Measurements are compared to theory predictions

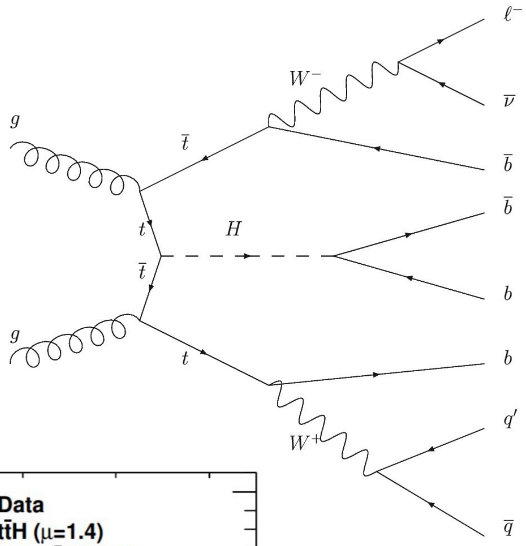


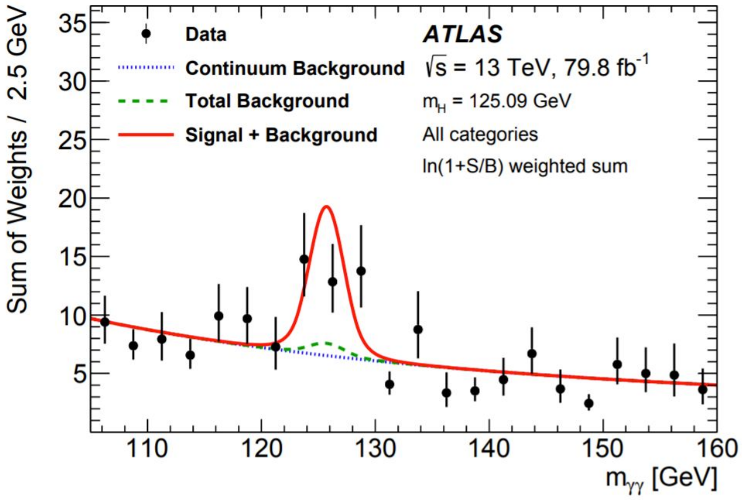
DR approach: NLO diagrams that overlap with top quark pair production are removed from the calculation of the tW amplitude
DS approach: A subtraction term is built into the amplitude to cancel out the top-quark pair contribution

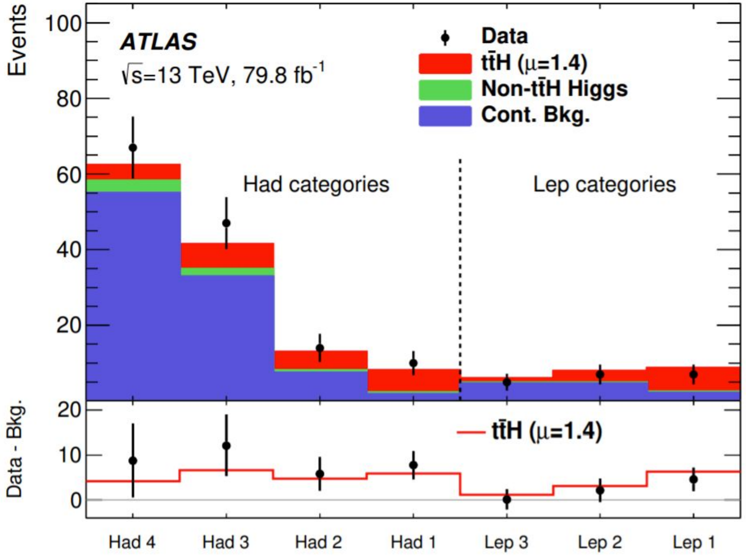
Taken from: https://arxiv.org/pdf/1712.01602.pdf

ttH

- Direct measurements of the top-quark Yukawa coupling in ttH events:
    - Observations of ttH (with H → bb, H → γγ and H → multi-leptons)
- Probe set of complex final states (have to deal with difficult background composition)
    - Use MVAs to reduce background contributions

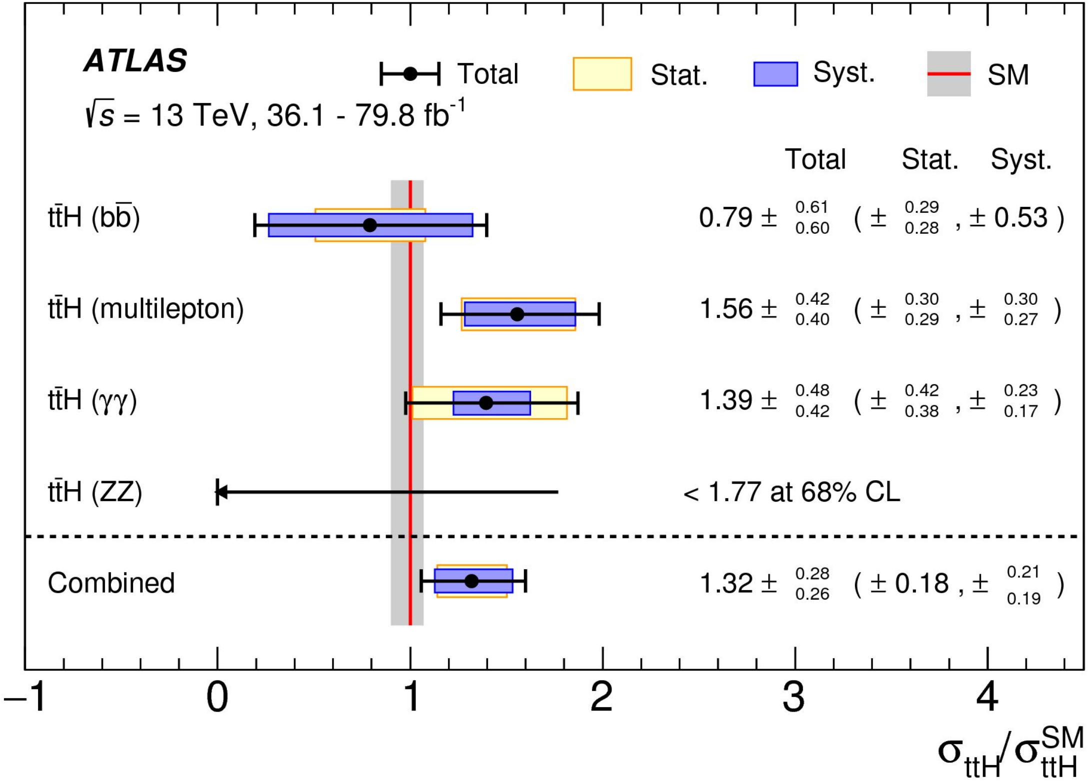


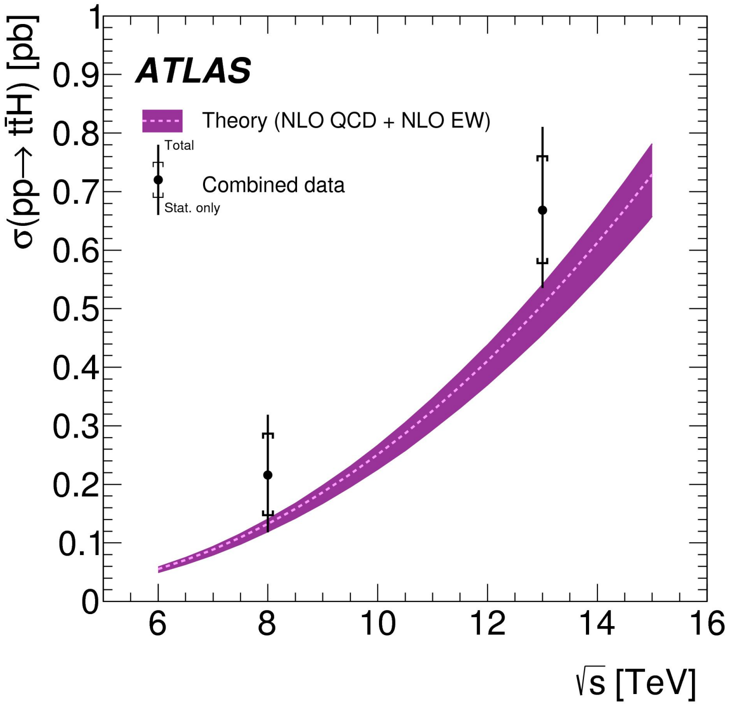




Taken from: https://arxiv.org/pdf/1806.00425.pdf

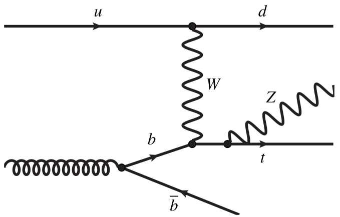
ttH



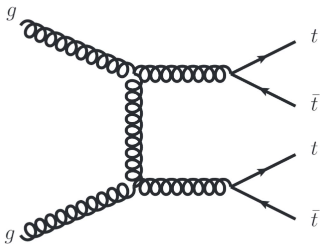


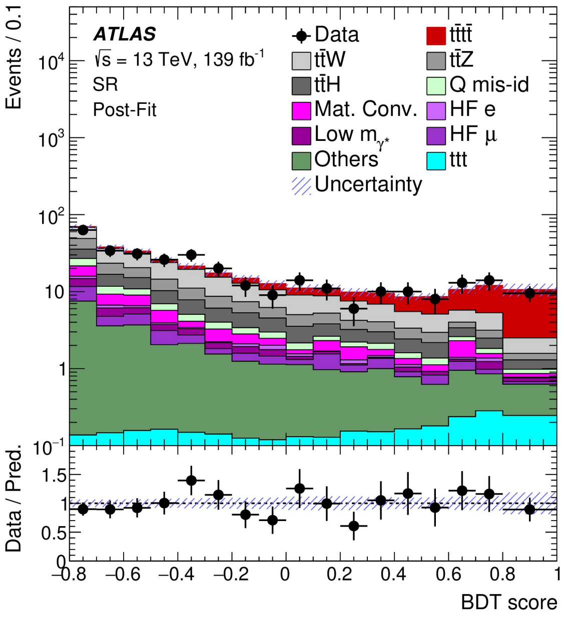
Taken from: https://arxiv.org/pdf/1806.00425.pdf

Production of top + X



- First observations of particularly rare top quark processes during Run II data taking
- First cross section measurements
- Use sophisticated MVAs to separate signals and bkgs.





$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 5(\text{stat})\,^{+5}_{-4}(\text{syst})\text{ fb} = 24\,^{+7}_{-6}\text{ fb}$$

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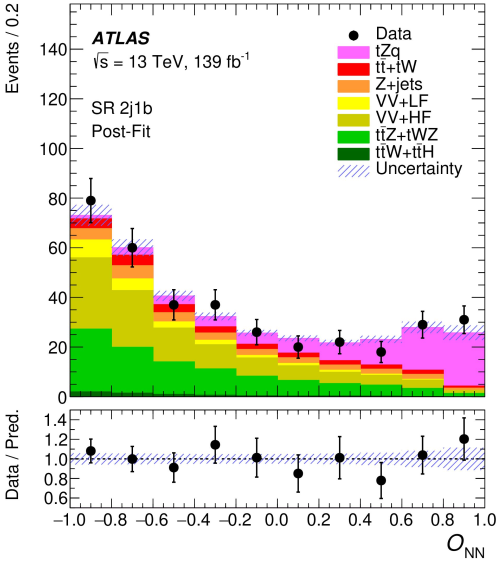

$$97 \pm 13\ (\text{stat.}) \pm 7\ (\text{syst.})\text{ fb}$$

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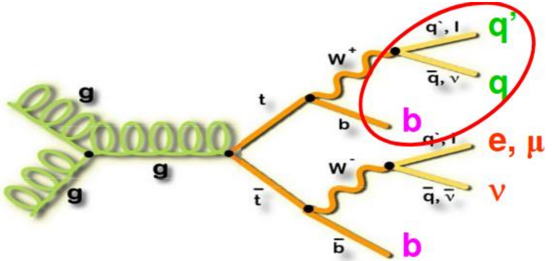
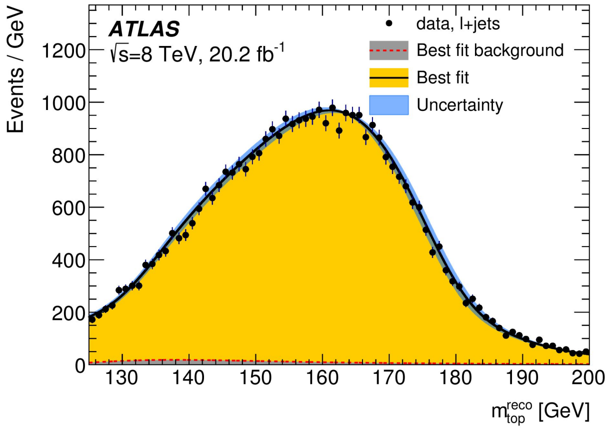
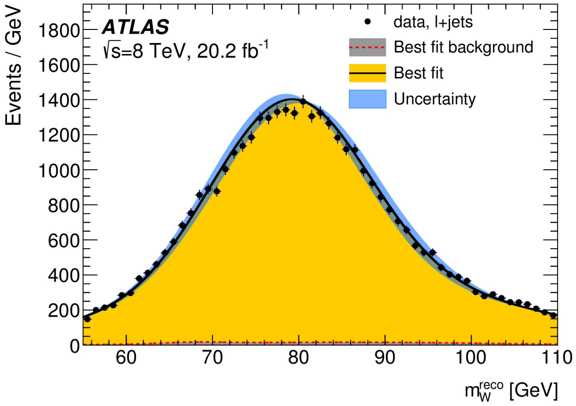
Top-quark mass measurements

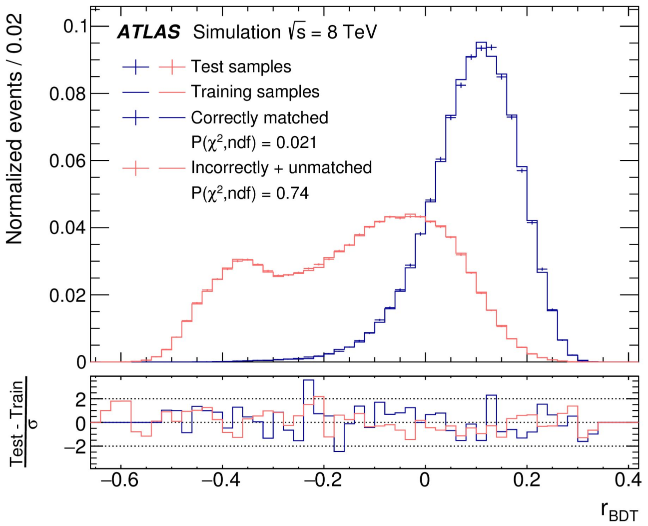
- Measurement of the top quark mass in the lepton+jets channel:
  - Exploiting a three-dimensional template technique
    - Fitting m_{top}, m_W, R_{bq} (heavy to light-flavour momentum ratio)
  - Use likelihood approach to reconstruct events
    - Reject combinatorial background using a BDT
  - Fit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



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







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

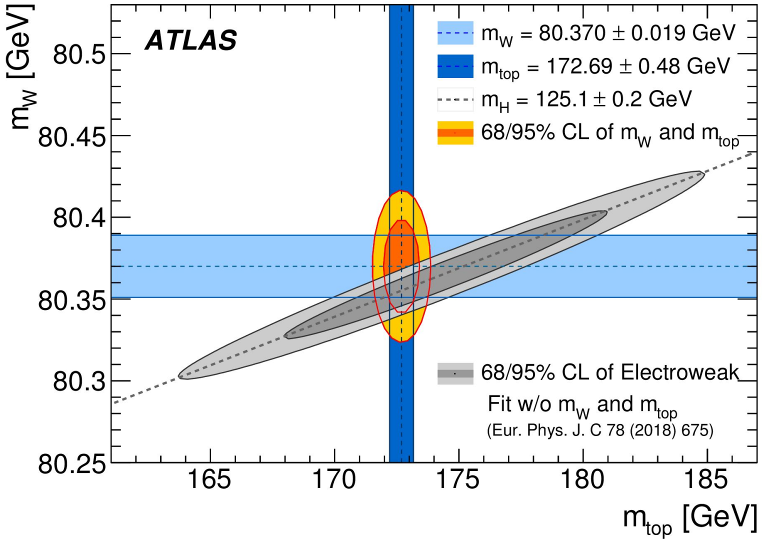
→ **top-quark mass can be measured with high precision**

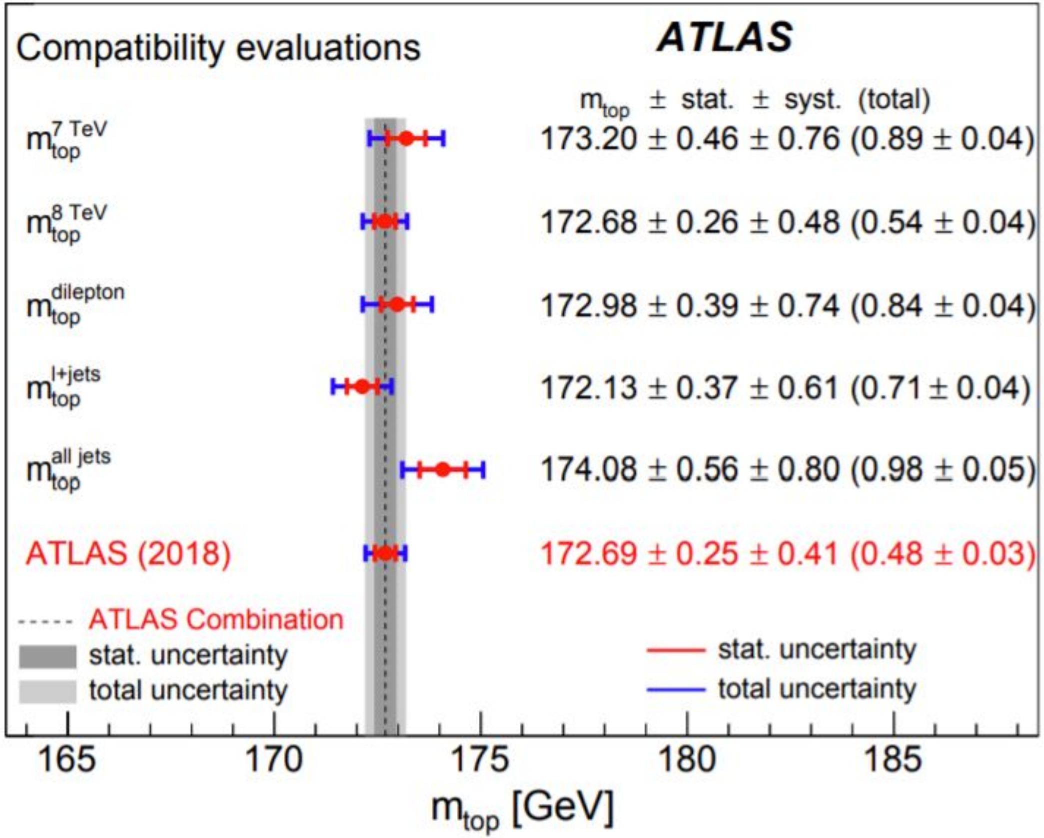
Taken from: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2017-03/

	$\sqrt{s} = 7$ 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

Top-quark mass measurement

- **Combination with previous measurements**

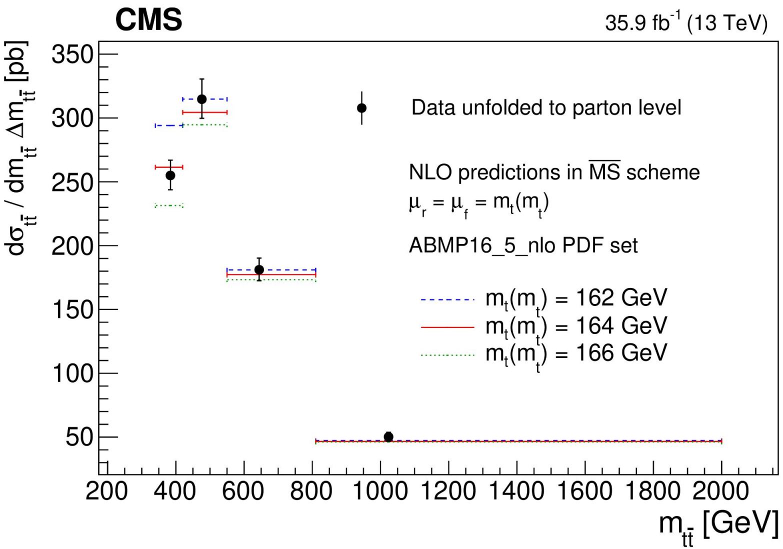




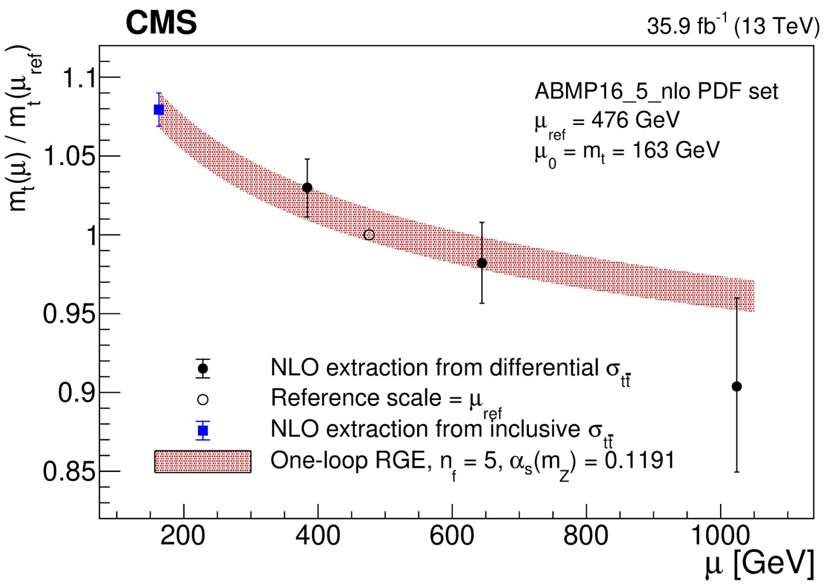
Running of the top quark mass

- SImilar to the strong coupling constant α_S, the quark masses are subject to renormalisation

- The running is extracted from a measurement of the differential top quark-antiquark cross section as a function of the invariant mass of the tt system



Taken from: https://arxiv.org/pdf/1909.09193.pdf

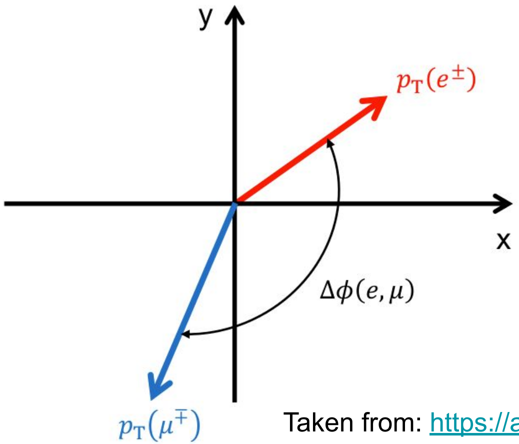


- The running mass $m_t(\mu)$, is extracted at one-loop precision as a function of m_{tt} by comparing fixed-order theoretical predictions at next-to-leading order to the measurements

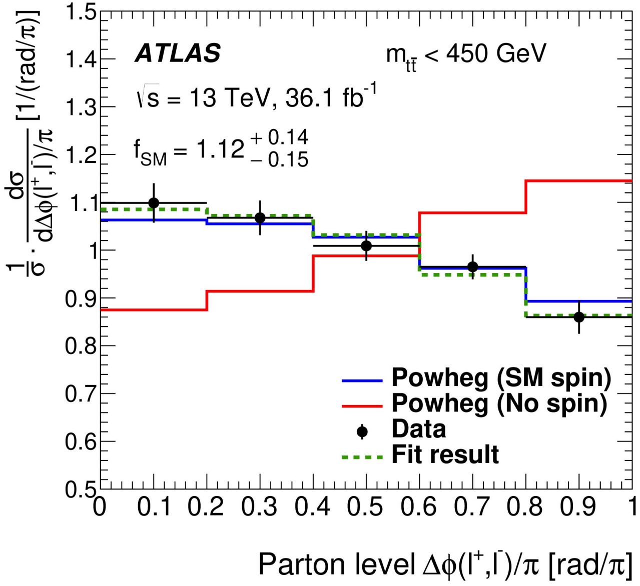
Spin correlation measurements

- The lifetime of the top quark is shorter than the timescale for hadronisation (~10^{-23} s) and is much shorter than the spin decorrelation time (~10^{-21} s)
  - The spin information of the top quark is transferred directly to its decay products.
    - Probe $\Delta\phi$ between electron and muon
  - Spins of the top and anti-top quarks should be correlated

- **Contributions from BSM physics can decrease the expected SM spin correlation**

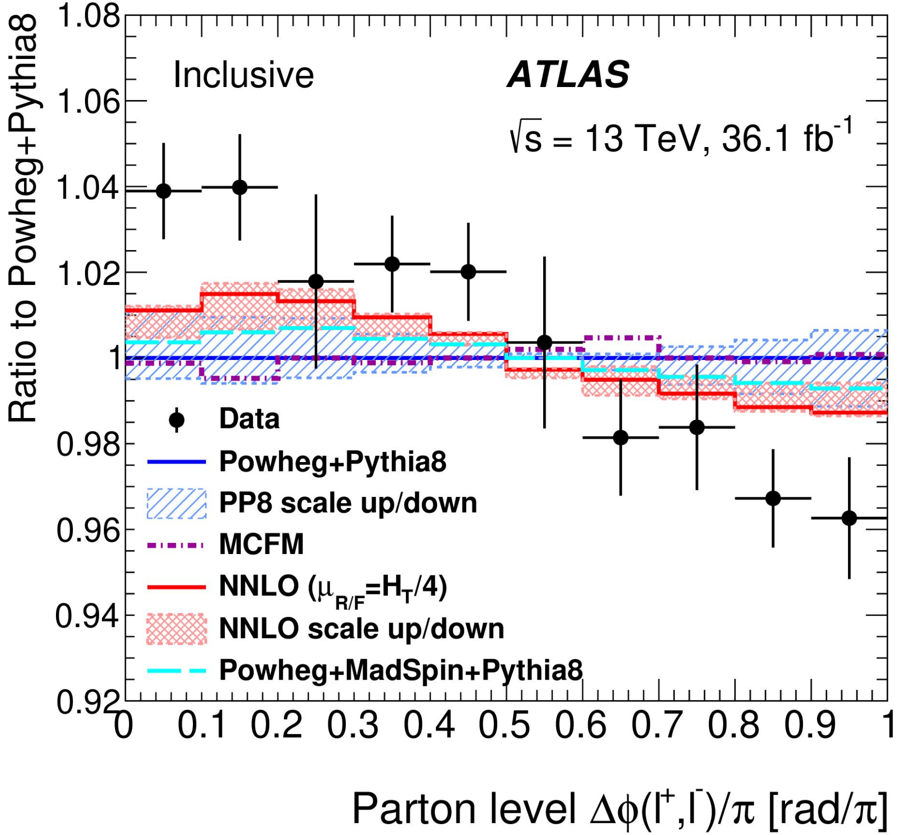


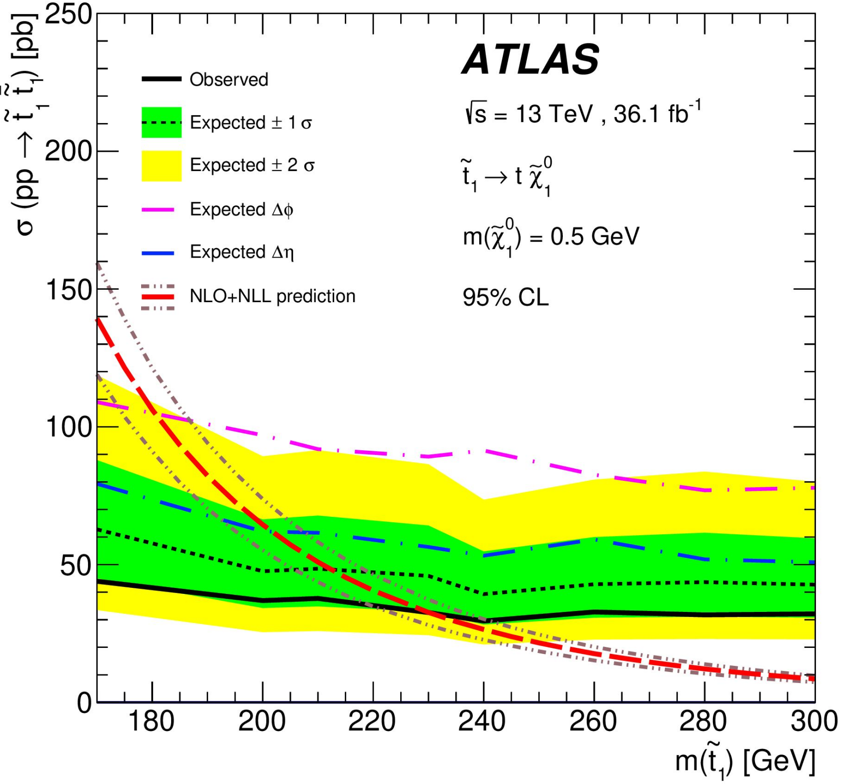
- Examples:
  - Supersymmetric top squarks



Taken from: https://arxiv.org/pdf/1903.07570.pdf

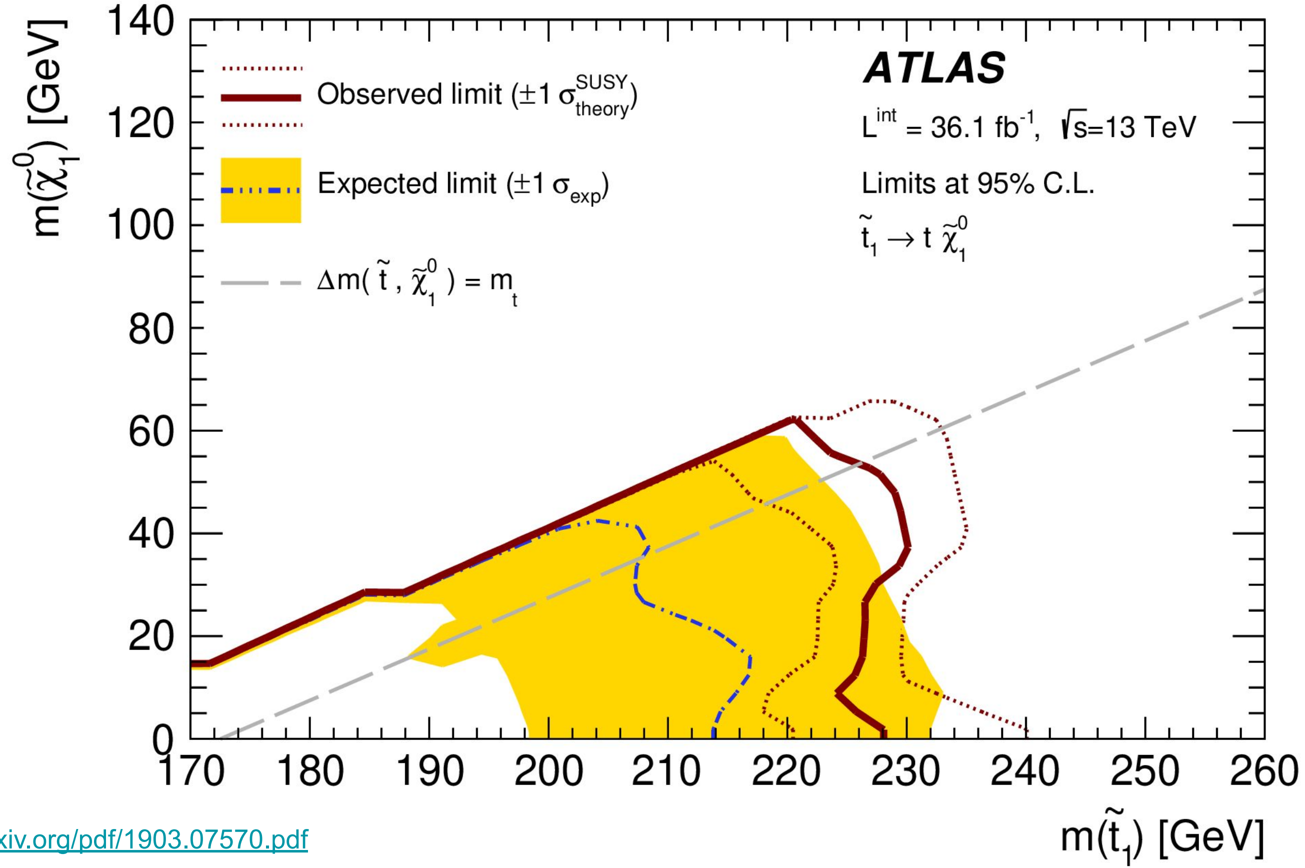
Spin correlation measurements





Taken from: https://arxiv.org/pdf/1903.07570.pdf

Spin correlation measurements



Taken from: https://arxiv.org/pdf/1903.07570.pdf

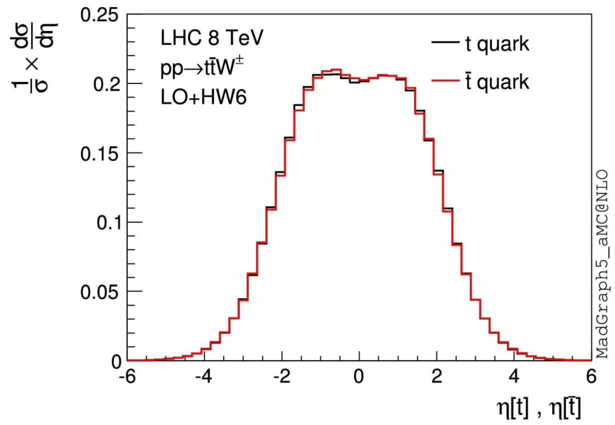
Charge asymmetry in top quark pair production

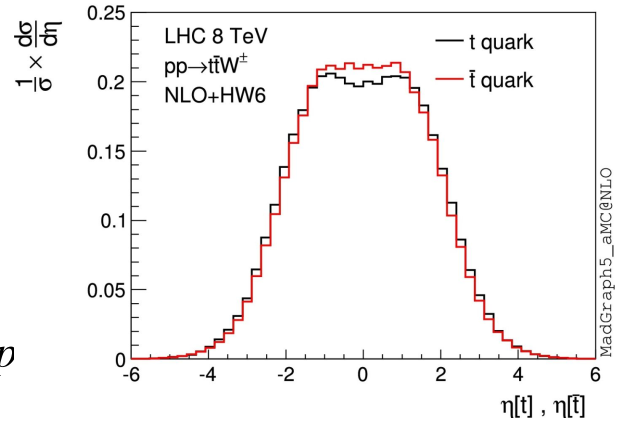
- Top-quarks are produced slightly more forward than top-antiquarks.
  → central-forward asymmetry
- Asymmetry can be quantified via:

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

with: $\Delta|y| = |y_t| - |y_{\bar{t}}|$

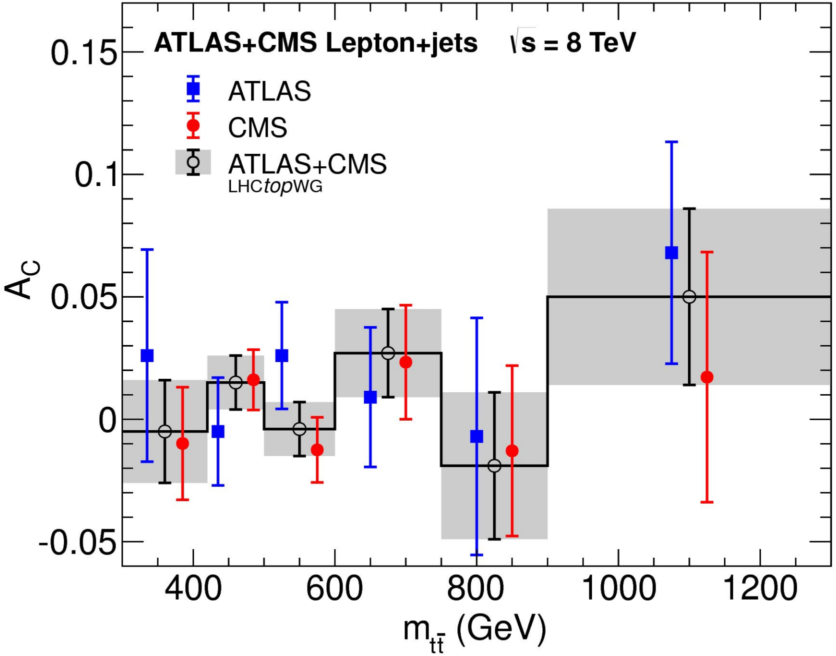
- SM effect is quite small (~1%)
  - New physics contributions could significantly enhance the asymmetry
- Tevatron observed large forward-backward asymmetries ($p\bar{p}$ initial state), but tensions have eased in the meanwhile.

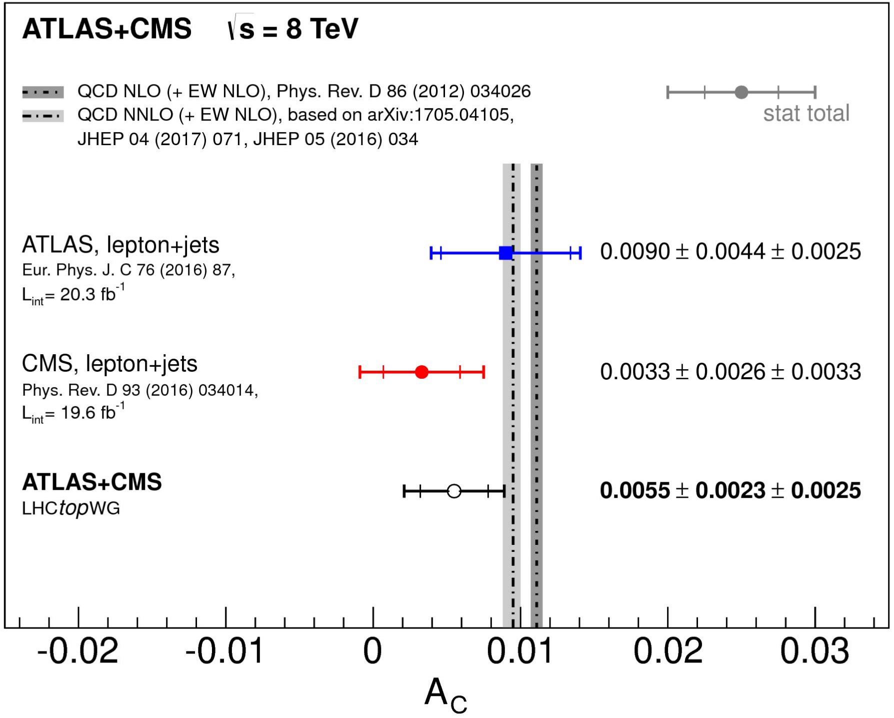




Charge asymmetry in top quark pair production

- Probe asymmetry in different invariant mass intervals
  → More sensitive to new physics

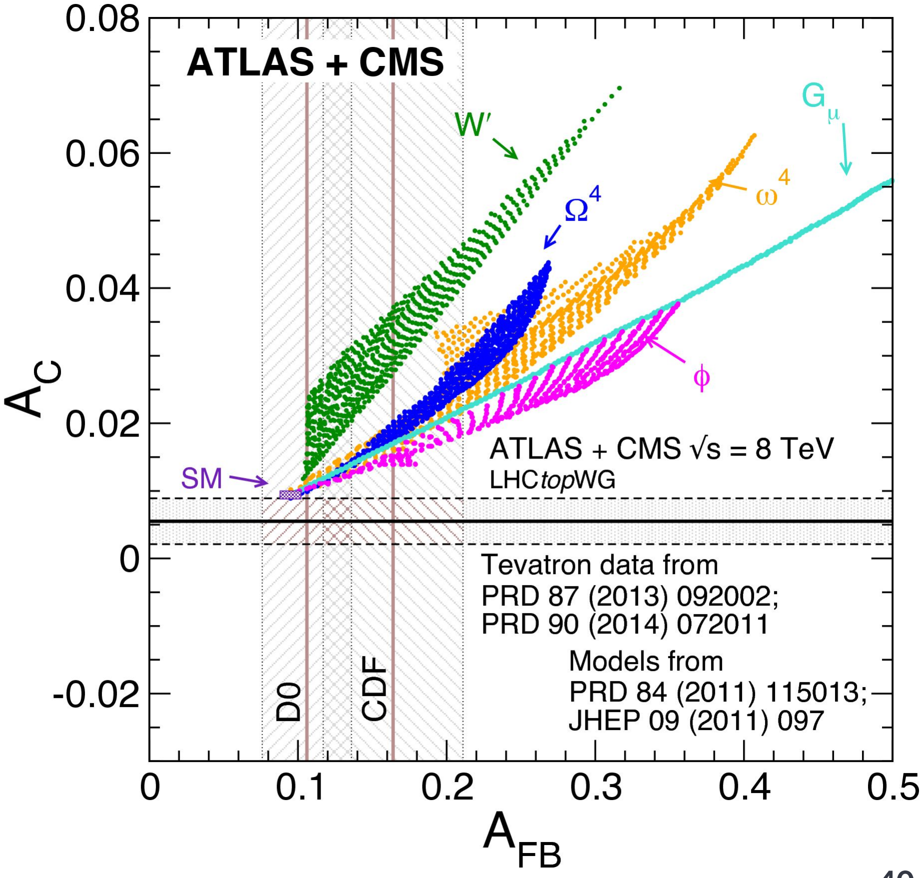




Charge asymmetry in top quark pair production

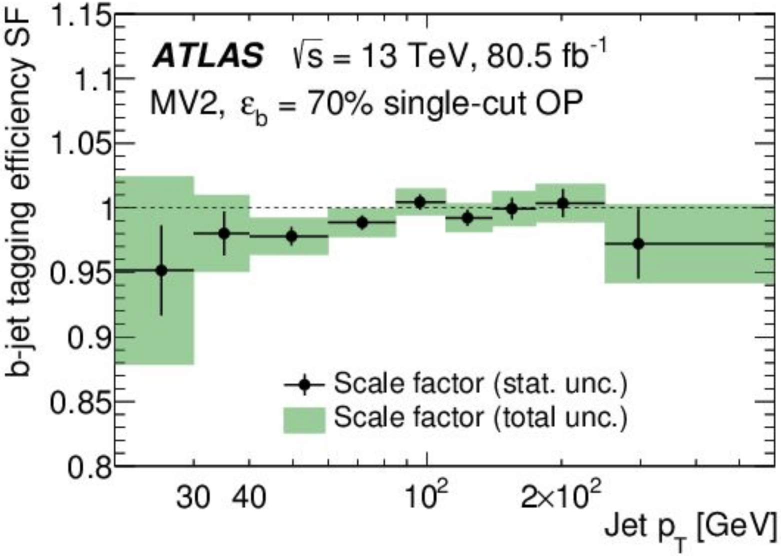
- Comparison of LHC and Tevatron measurements with SM and various BSM theories

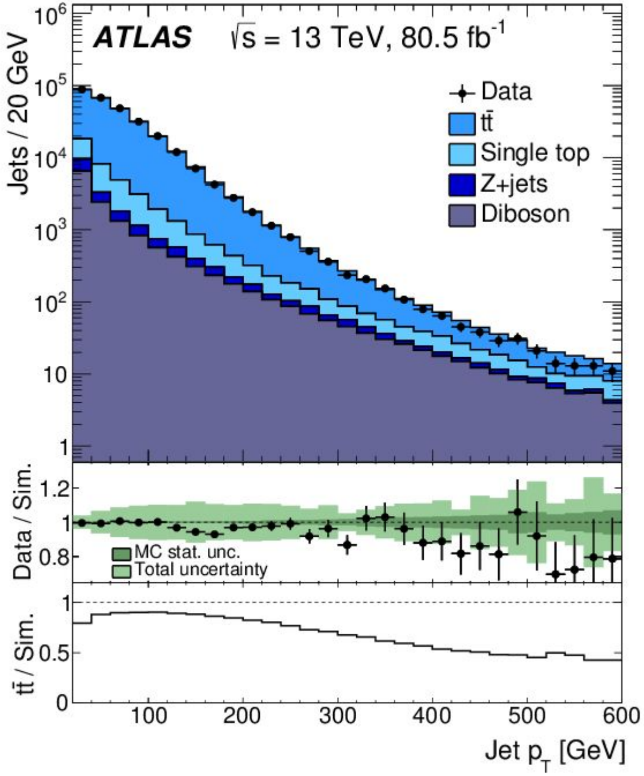
- **Tested for:**
  - W’ boson
  - Heavy axi-gluon G_μ
  - Scalar isodoublet ϕ
  - Colour triplet scalar ω^4
  - Colour sextet scalar Ω^4



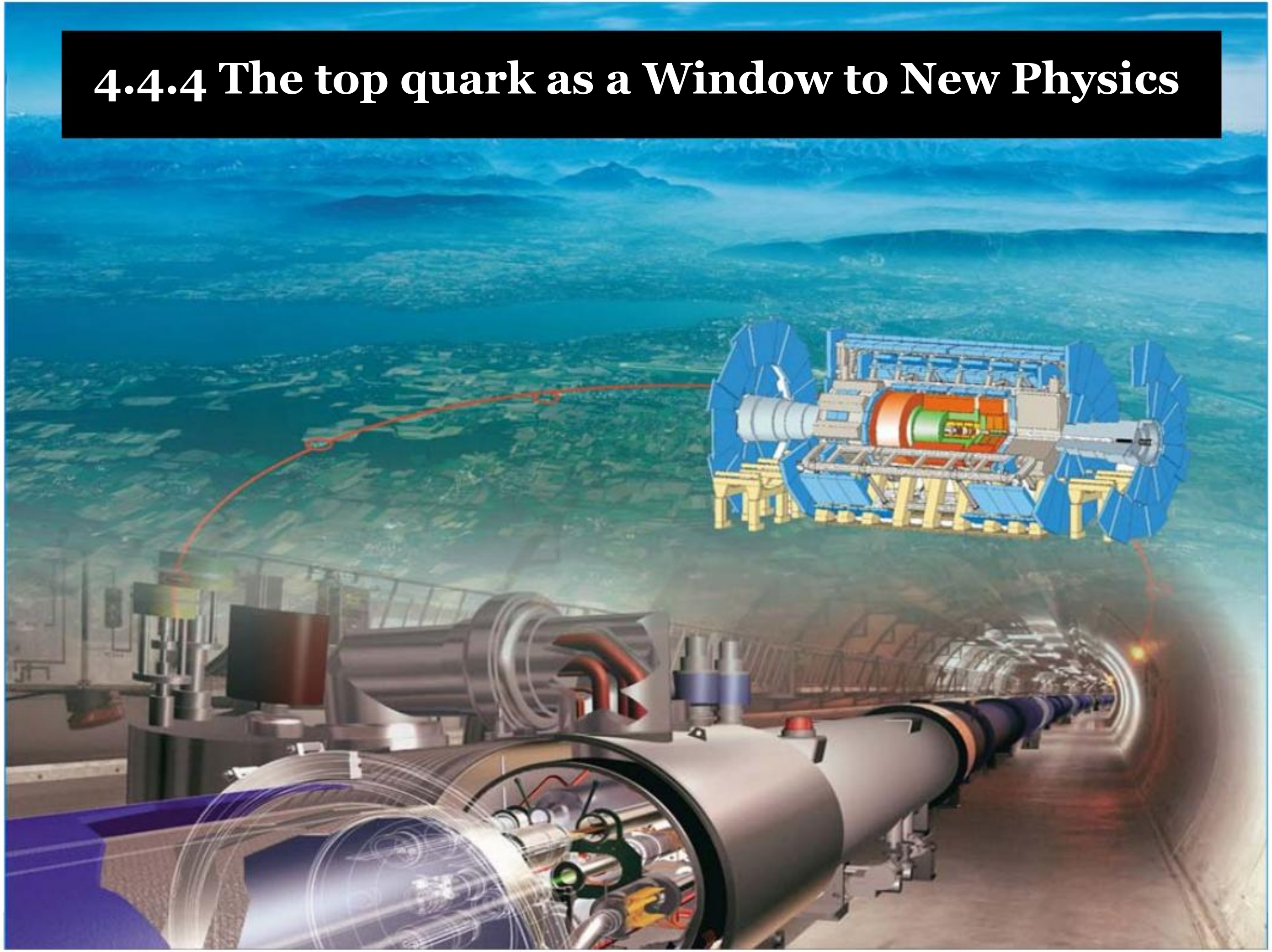
Top-quark pairs as standard candles

- 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



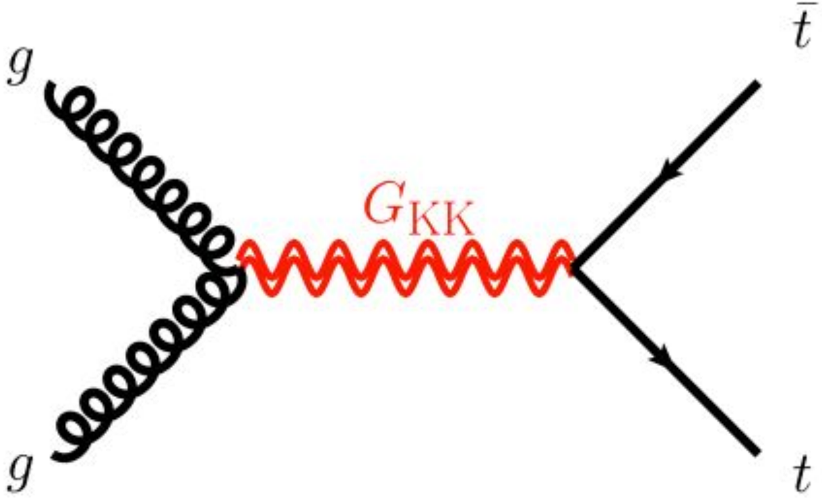


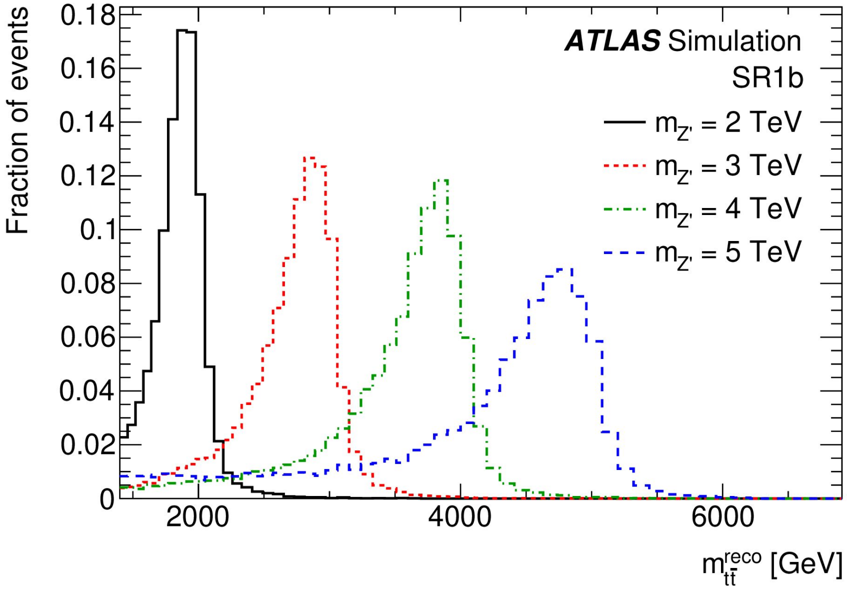
4.4.4 The top quark as a Window to New Physics



Top-Antitop Resonances

- Searches for:
  - (Pseudo) scalars (2HDM)
  - Z' (technicolour model)
  - G_{KK} (warped extra dimensions)
- Performed in semileptonic or fully hadronic final states





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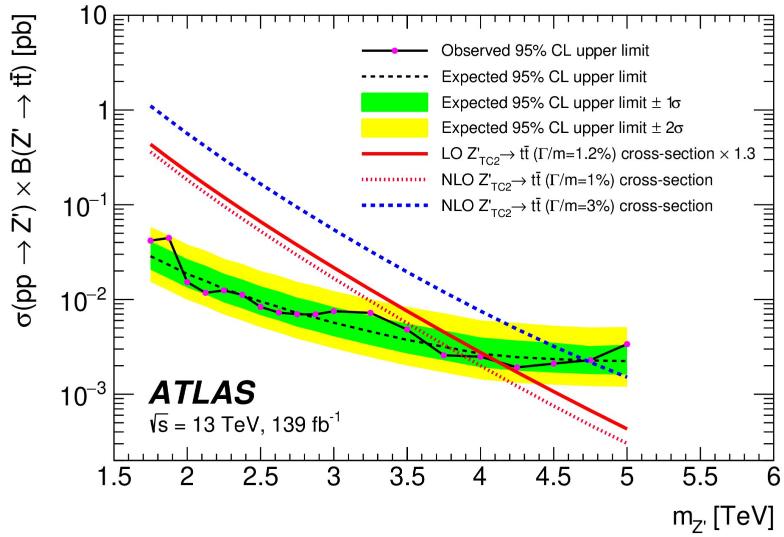
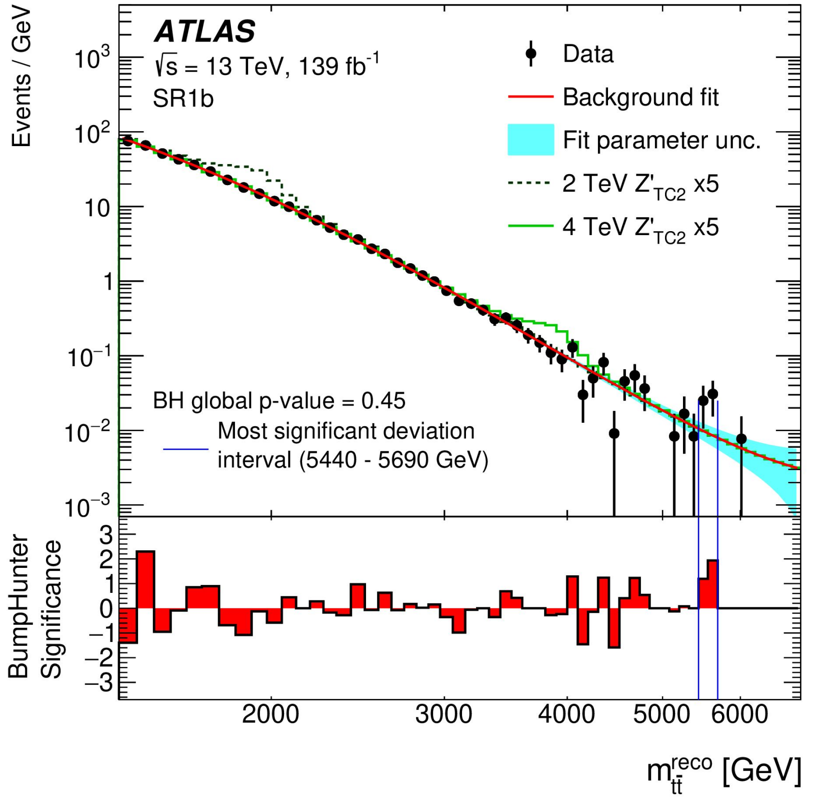
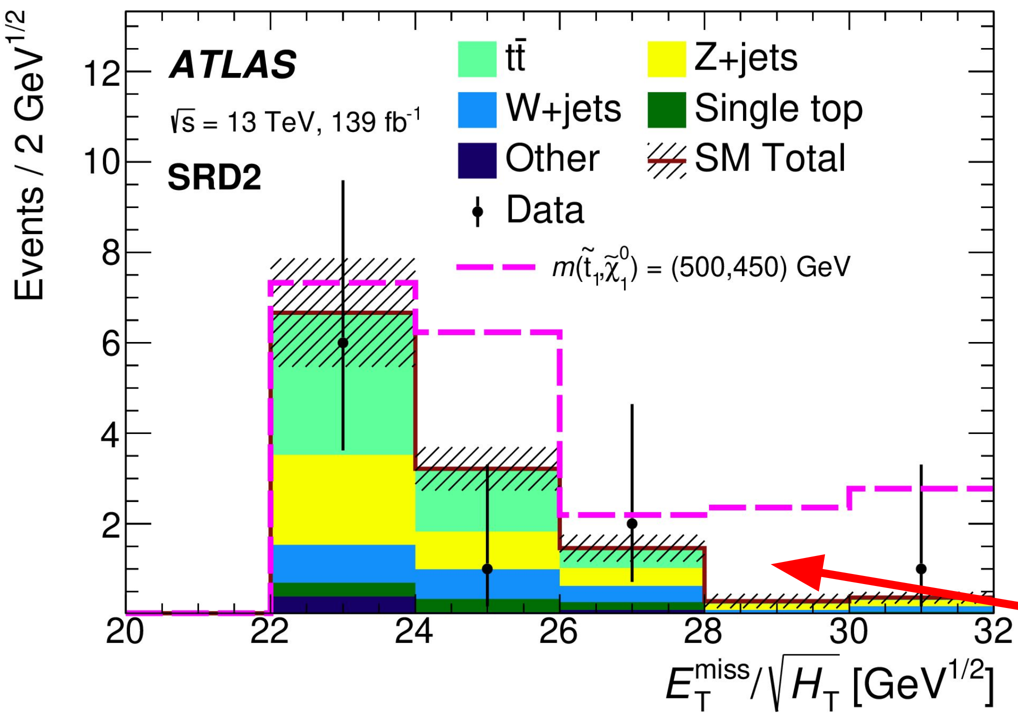
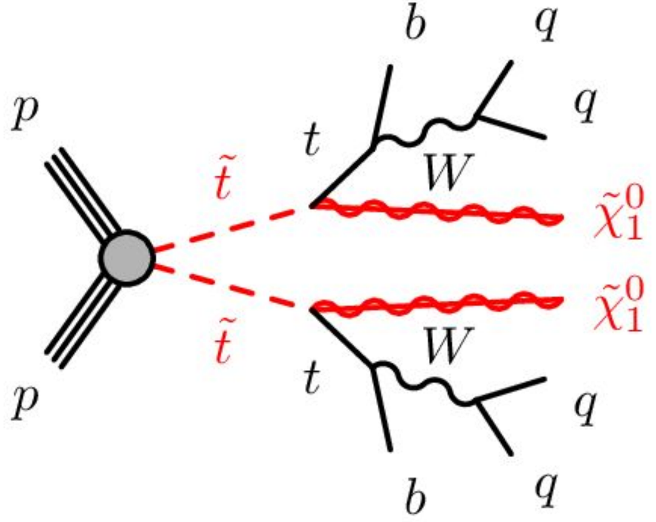




Search for Supersymmetric particles

- **Search for stop quark pair production**





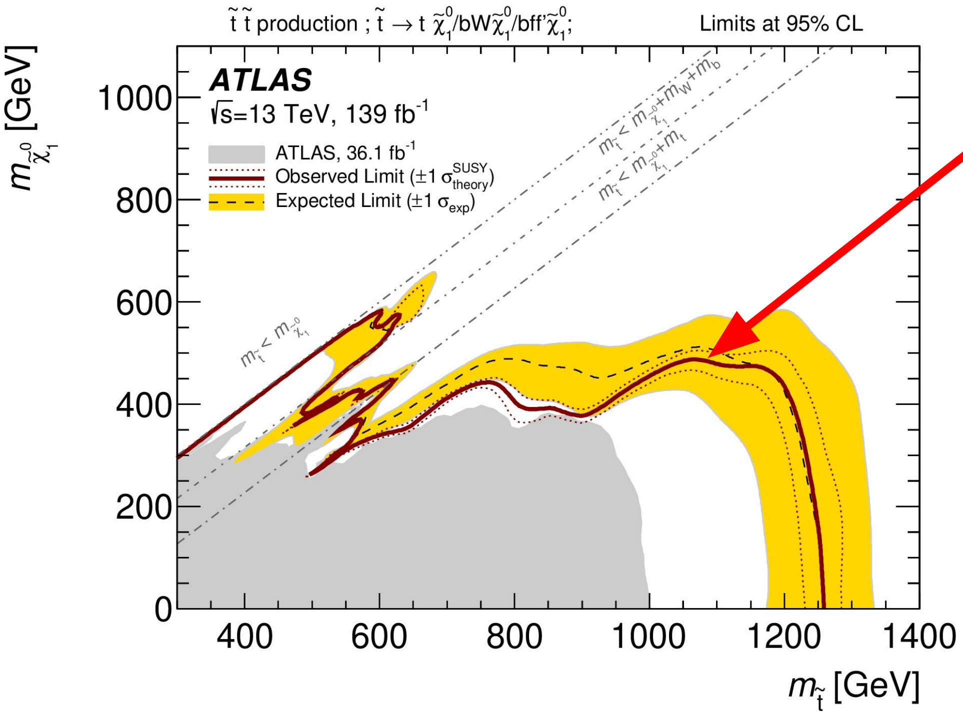
- **Search for multi-jet final state incl. large amount of missing E_T**

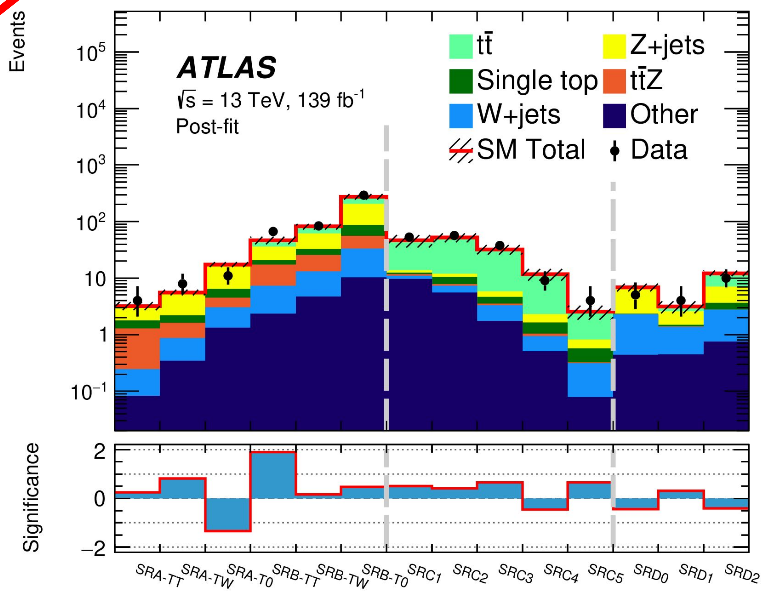
Probe phase space regions sensitive to contributions from SUSY signal

Search for Supersymmetric particles

- **Search for stop quark pair production**

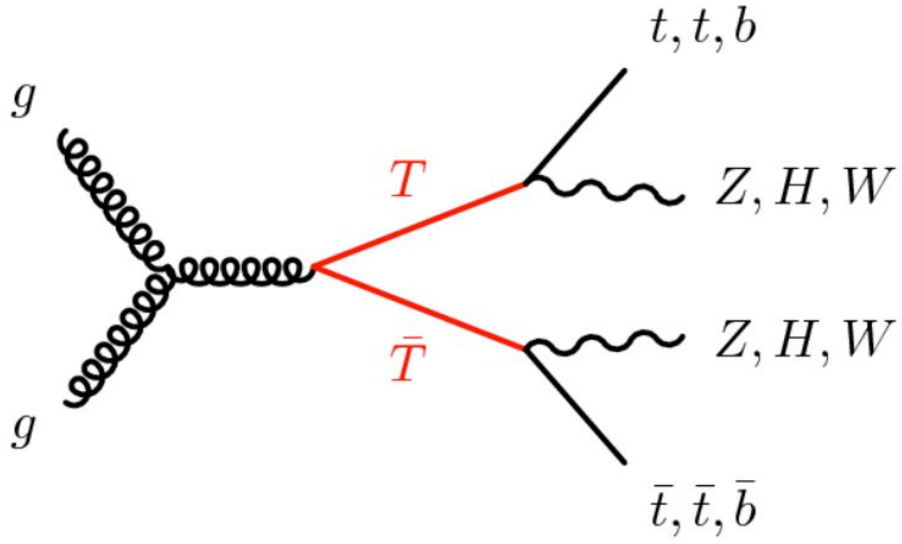
Exclude stop masses up to ~ 1300 GeV for neutralino masses below 400 GeV





Searches for vector-like top quarks

- Search for pair production of vector-like top quark partners (T)



- T quarks have spin ½
- Left-handed and right-handed states have the same electroweak coupling = no need to consider chiral states
- Avoids exclusion of a simple sequential 4th generation as obtained from Higgs production cross sections at the LHC.
- Contributions by T quarks dampen large quadratic corrections to the Higgs boson mass (propagator).
  → **Solution to the naturalness problem**
- Occur in Little Higgs or Composite Higgs models.

Searches for vector-like top quarks

- **Basic event selection:**
  - MET > 300 GeV
  - exactly 1 charged lepton
  - ≥ 4 jets with
- **Probe MET spectrum**

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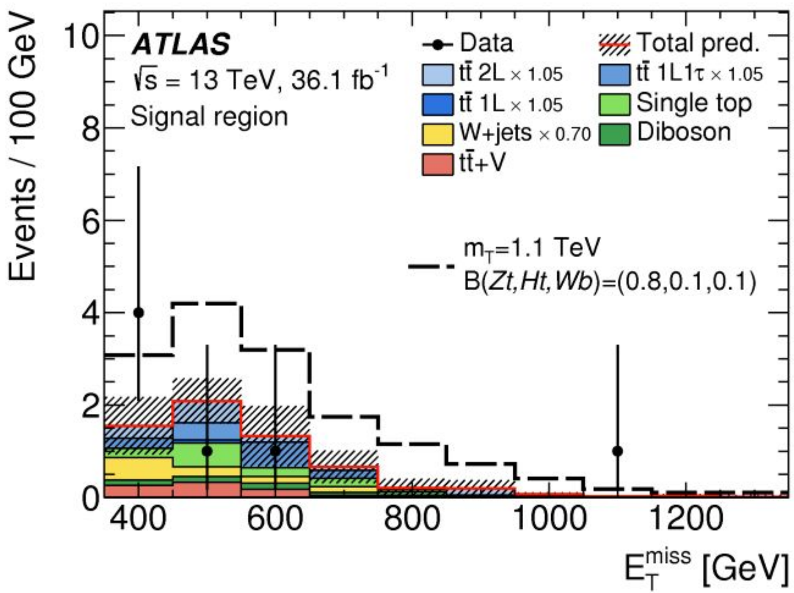
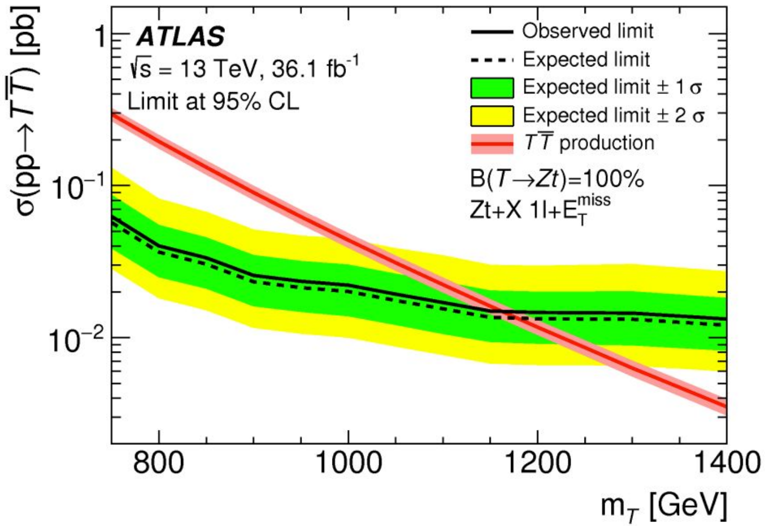
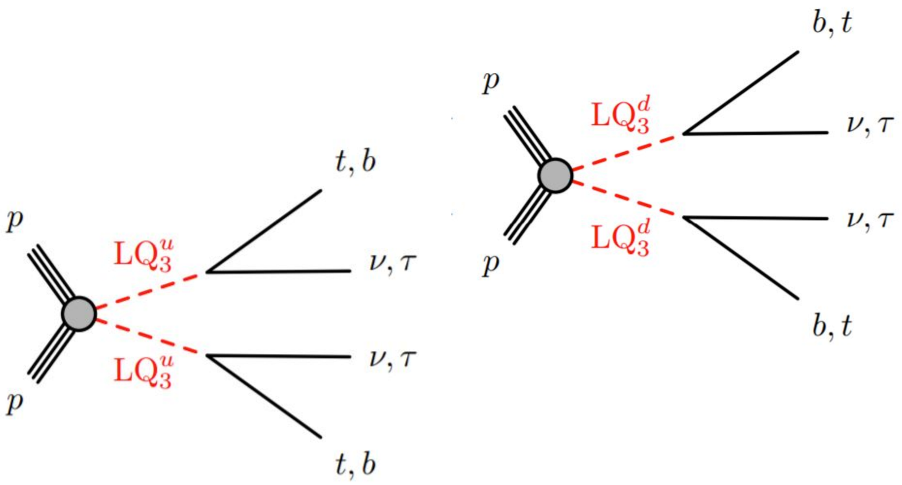


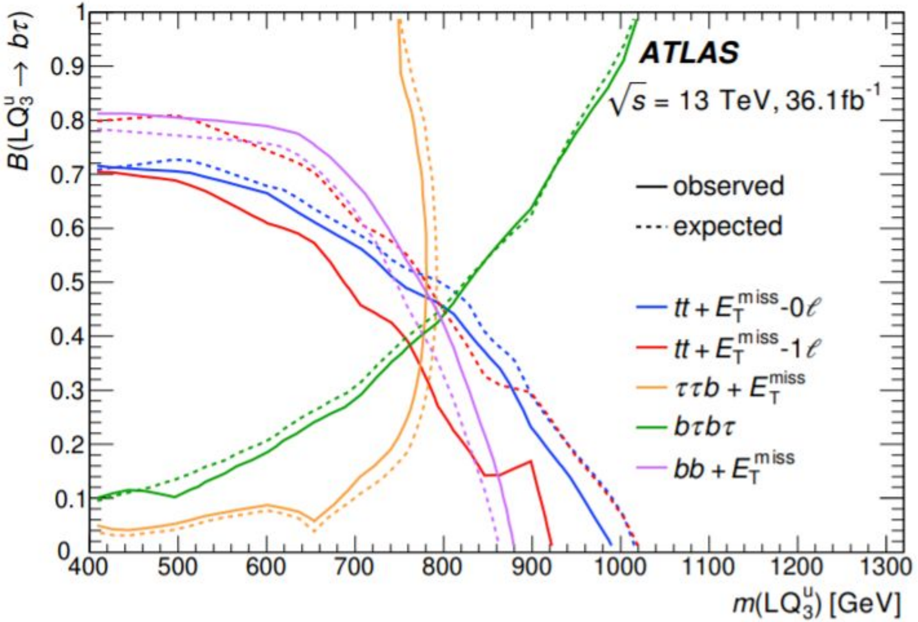


- T quarks with m_T < 1.16 TeV are excluded if BR(T → Zt) = 100% is assumed.

Searches for third-generation scalar leptoquarks

- Leptoquarks (LQs) are predicted by many extensions of the SM and provide a connection between the quark and lepton sectors
- LQs are bosons carrying colour and fractional electrical charge
- Leptoquarks can be scalar or vector bosons and can be produced singly or in pairs in proton–proton collisions

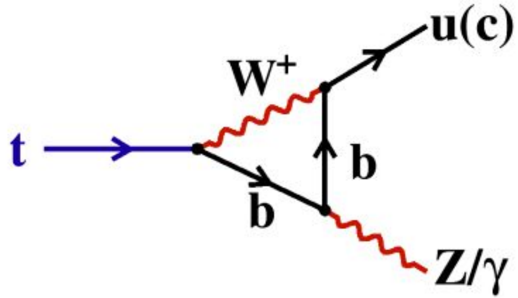




Taken from: https://arxiv.org/pdf/1902.08103.pdf

Exotic/Rare Top quark decays

- **Decays via flavour-changing neutral currents (FCNC):**
  - Do not exist at tree (Born) level in the SM
  - Very strongly suppressed at next-to-leading order (loop level): GIM mechanism = CKM unitarity
  - Suppression is lifted by non-degenerate quark masses.
  - Branching ratios are extremely small.



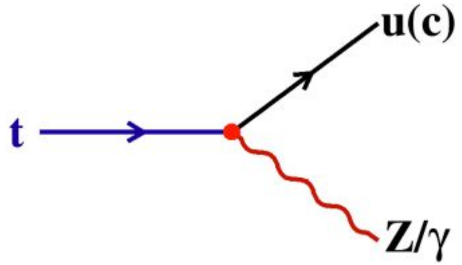
	$Br(t \to q\gamma)$	$Br(t \to qZ)$	$Br(t \to qg)$
$q = u$	3.7×10^{-16}	8×10^{-17}	3.7×10^{-14}
$q = c$	4.6×10^{-14}	1×10^{-14}	4.6×10^{-12}

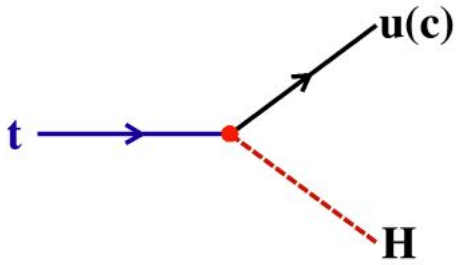
Exotic/Rare Top quark decays

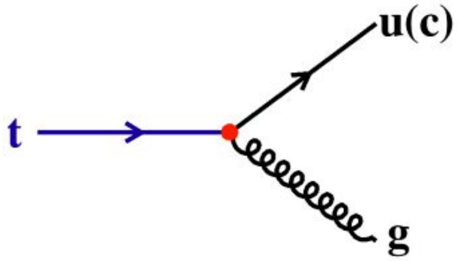
Predicted Branching ratios of top-quark decays in SM and BSM theories:

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\lesssim 10^{-6}$	$\lesssim 10^{-10}$	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	$\lesssim 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\lesssim 10^{-4}$	$\lesssim 10^{-8}$	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	$\lesssim 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\lesssim 10^{-7}$	$\lesssim 10^{-9}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$	$\lesssim 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\lesssim 10^{-5}$	$\lesssim 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\lesssim 10^{-5}$	$\lesssim 10^{-5}$	$\lesssim 10^{-9}$	$\lesssim 10^{-4}$

From: https://arxiv.org/pdf/1311.2028.pdf (Snowmass Workshop 2013)





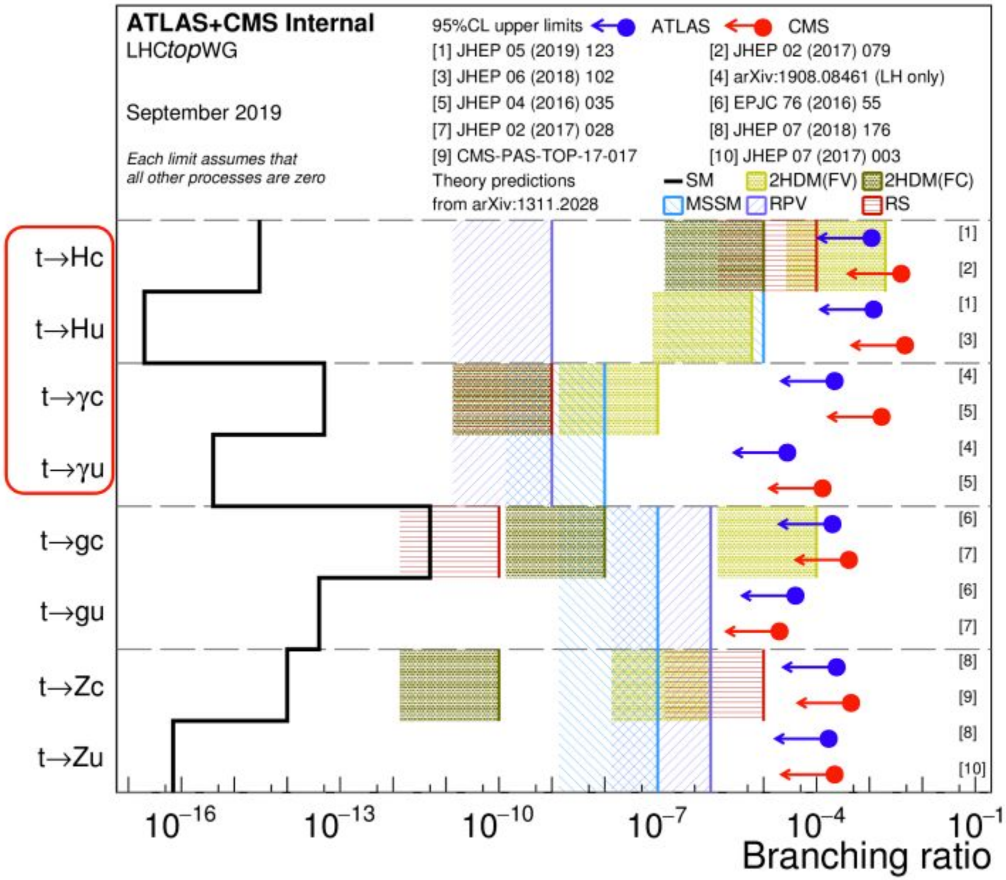


Strong enhancement!

Any FCNC signal would be evidence for BSM physics!

Exotic/Rare Top quark decays

Latest limits on FCNC top quark decays from ATLAS and CMS



Exotic/Rare Top quark decays

- Search for flavour-changing neutral current top quark decays $t \to Hq$

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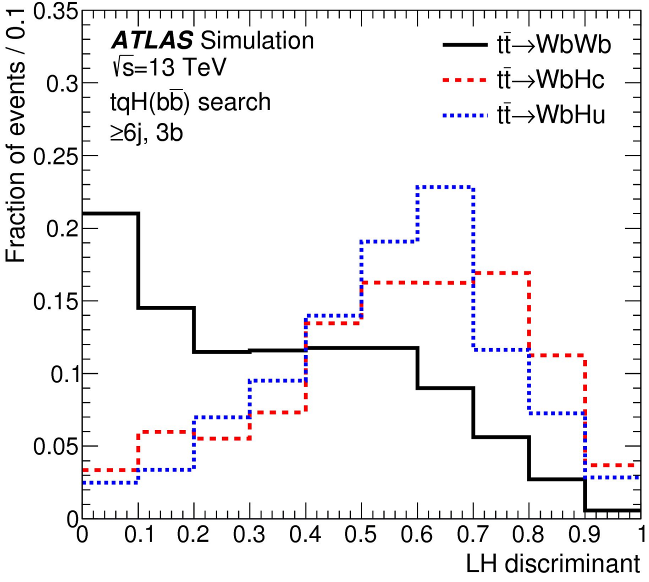
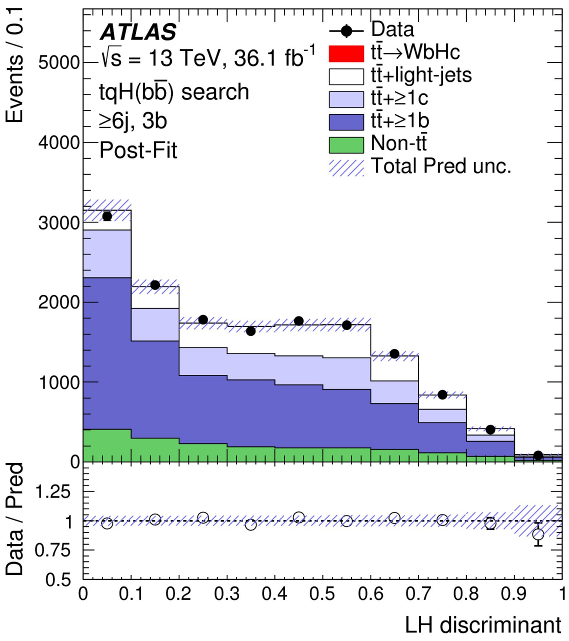
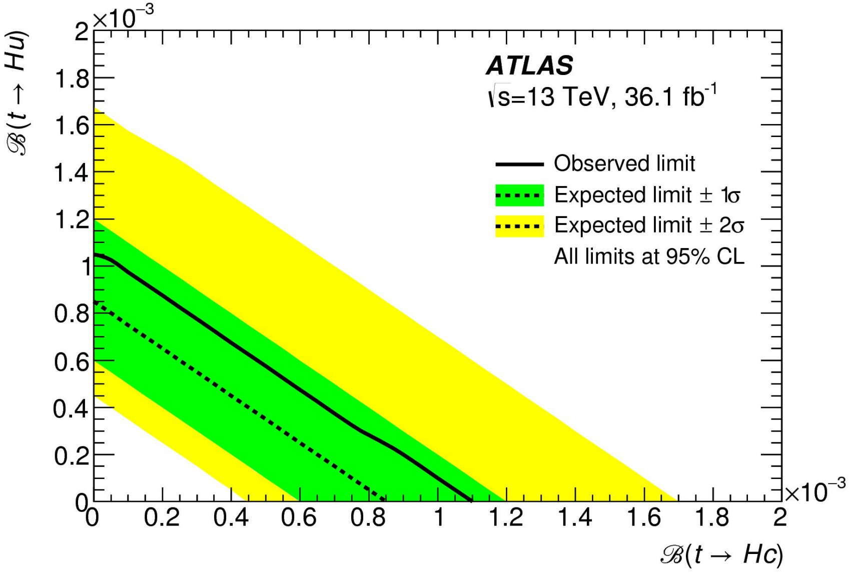


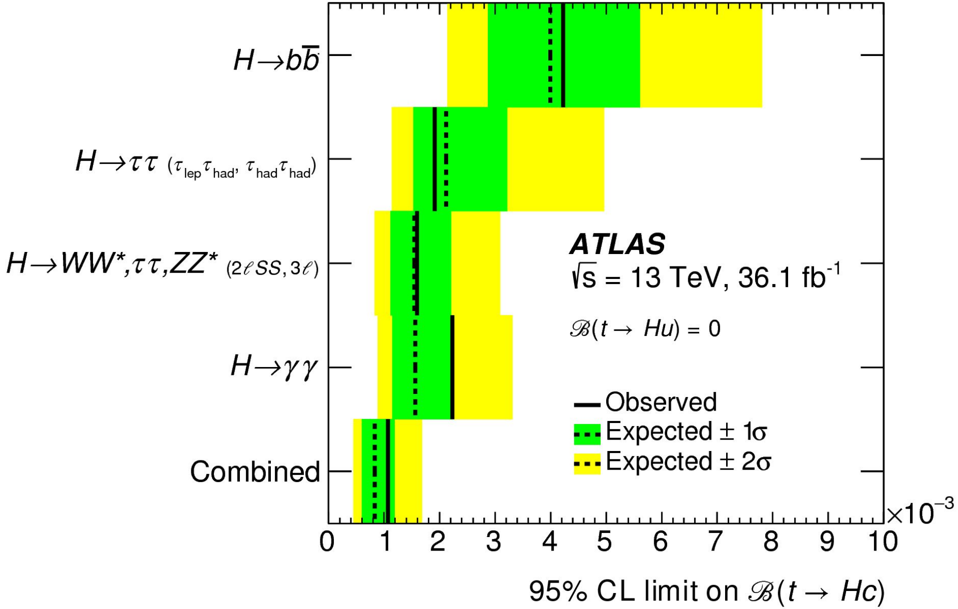


Combine kinematic variables within a likelihood ratio:

$$L(\vec{x}) = \frac{p_{\mathrm{sig}}(\vec{x})}{p_{\mathrm{sig}}(\vec{x}) + p_{\mathrm{bkg}}(\vec{x})}$$

Exotic/Rare Top quark decays



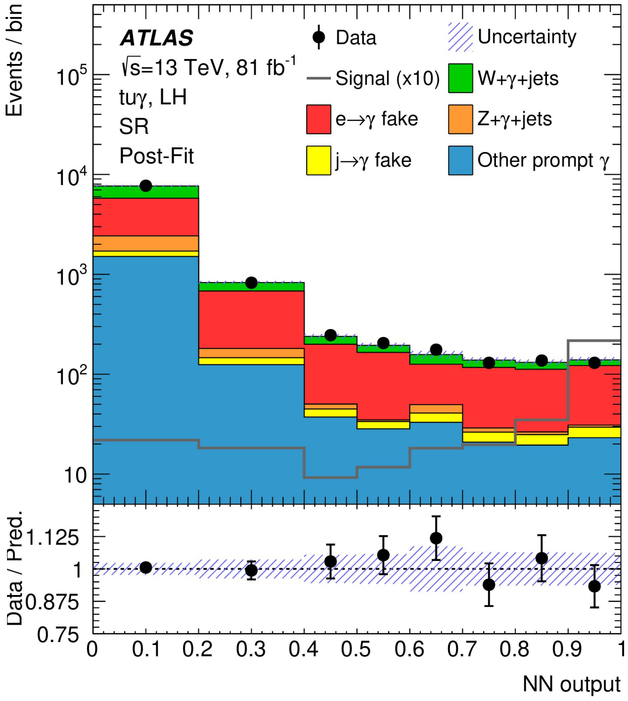


$$\mathcal{B}(t \to uH) < 1.2 \cdot 10^{-3}$$

$$\mathcal{B}(t \to cH) < 1.1 \cdot 10^{-3}$$

Search for FCNC in single top events

- Flavour-changing neutral currents (FCNCs) are forbidden at tree level in the SM
  - Strongly suppressed at higher orders.
- Several extensions to the SM predict processes involving FCNCs (e.g. top-quark decays via FCNC)
  - Examples:
    - R-parity-violating supersymmetric models
    - Two Higgs doublet Models



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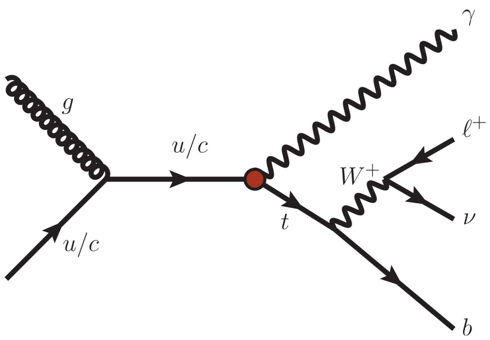
Limits:

	Vertex	Coupling	Obs:	Exp:
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	LH	36	52^{+21}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	RH	78	75^{+31}_{-21}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	LH	40	49^{+20}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	RH	33	52^{+22}_{-14}



Left-handed (LH) and right-handed (RH) couplings result in different kinematic properties of the top-quark decay products,