

Top Quark Phenomenology

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Top Quark Properties

- ▶ One of six possible quarks in Standard Model (SM)
- ▶ 3rd generation of quarks
 - ▶ Doublet with b quark
- ▶ Fermion - spin $\frac{1}{2}$
- ▶ Mass of 173.0 ± 0.4 GeV
 - ▶ ~mass of Tungsten atom (171.25 GeV)!
- ▶ Charge of $+2/3$

Three Generations of Matter (Fermions)

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	u up	c charm	t top	γ photon
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Quarks	d down	s strange	b bottom	g gluon
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z⁰ Z boson
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	± 1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Leptons	e electron	μ muon	τ tau	W[±] W boson

Gauge Bosons

Top Quark Proposal

- ▶ Existence first proposed by Kobayashi and Maskawa
 - ▶ Study of CP violation in weak interaction
- ▶ Discovery of τ lepton and third generation of leptons gave credence
- ▶ Constrain due to axial anomaly diagram

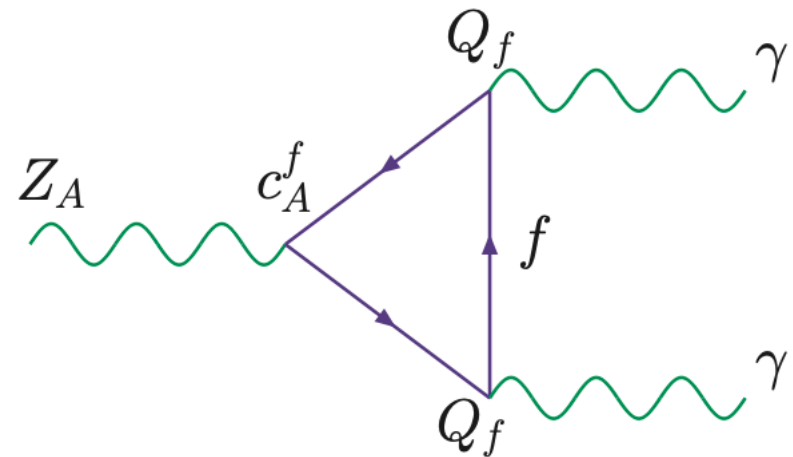
Top Quark Guaranteed

► Sum over fermions

► $\propto C_A^f Q_f^2, C_A^f = T_3$

$$\sum_{N_{families}} -\frac{1}{2}(-1)^2 + \frac{1}{2}N_c \left(\frac{2}{3}\right)^2 - \frac{1}{2}N_c \left(-\frac{1}{3}\right)^2$$

- First term from leptons
- Second from up type quarks (u, c, t)
- Third from down type quarks (d, s, b)



Top Quark Discovery

- ▶ Search lasted two decades!
 - ▶ High mass of top quarks
- ▶ Discovered by CDF and D ϕ collaboration at Tevatron in 1995

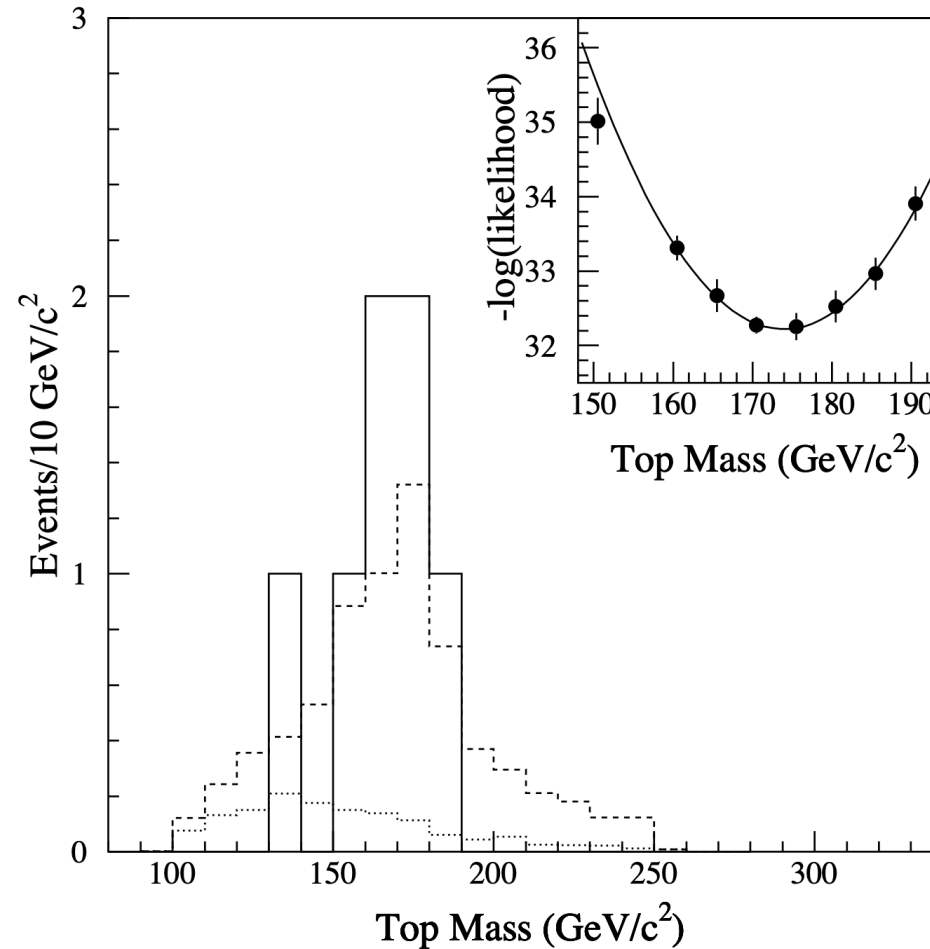
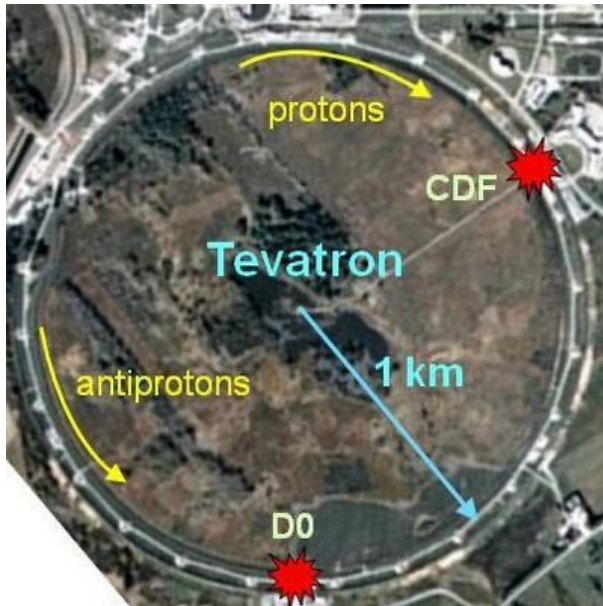
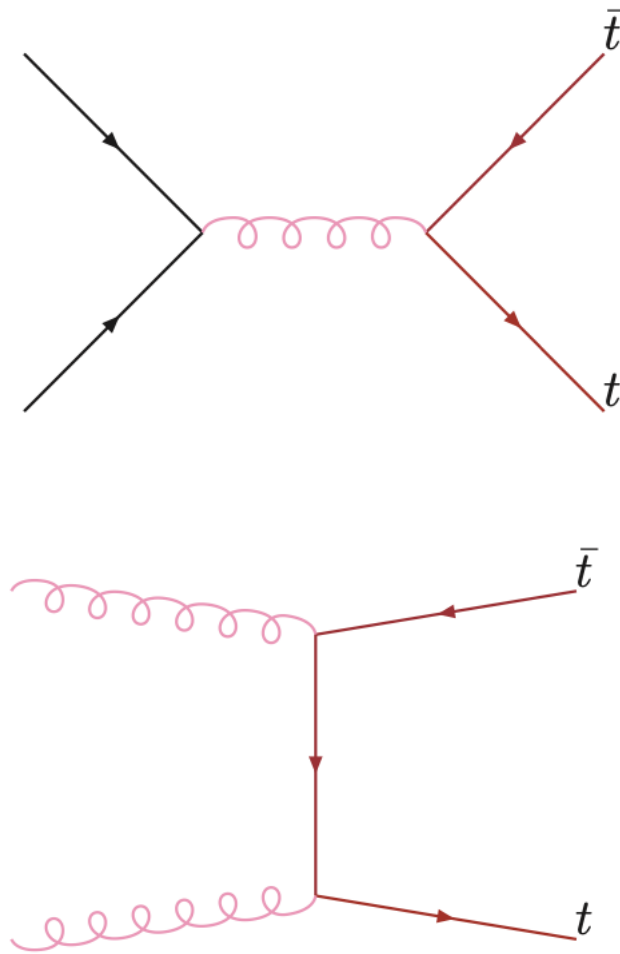


Figure 2: Top mass distribution for the data (solid histogram), the W +jets background (dots), and the sum of background + Monte Carlo $t\bar{t}$ for $M_{top} = 175 \text{ GeV}/c^2$ (dashed). The background distribution has been normalized to the 1.4 background events expected in the mass-fit sample. The inset shows the likelihood fit used to determine the top mass.

Top Quark, Pair Production

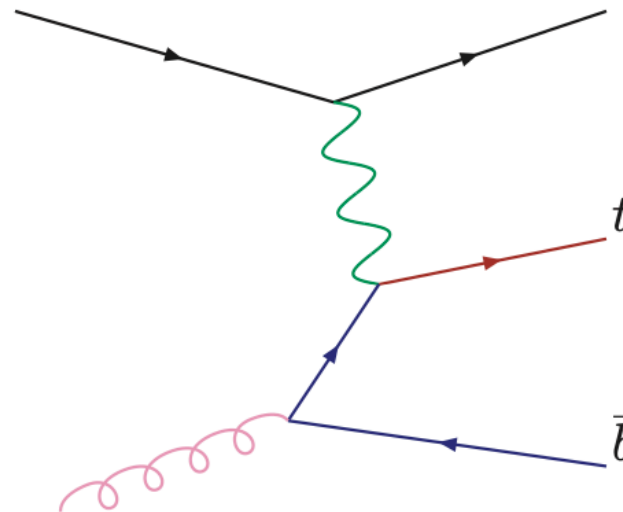
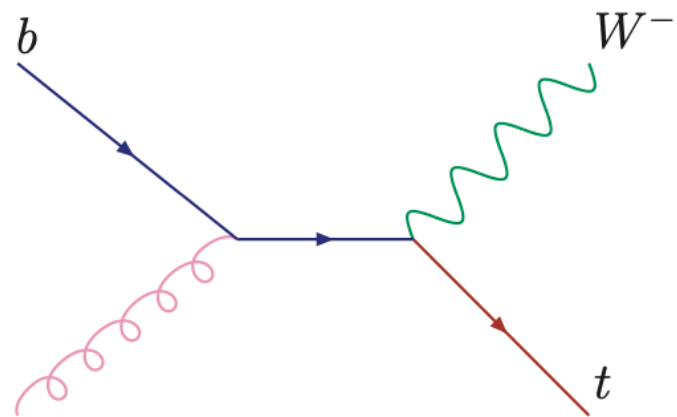
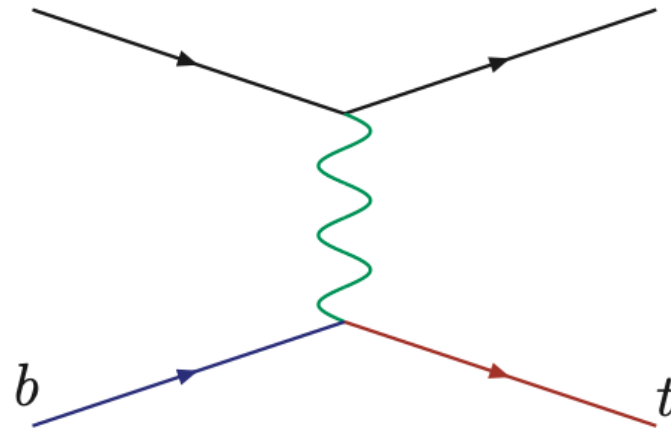
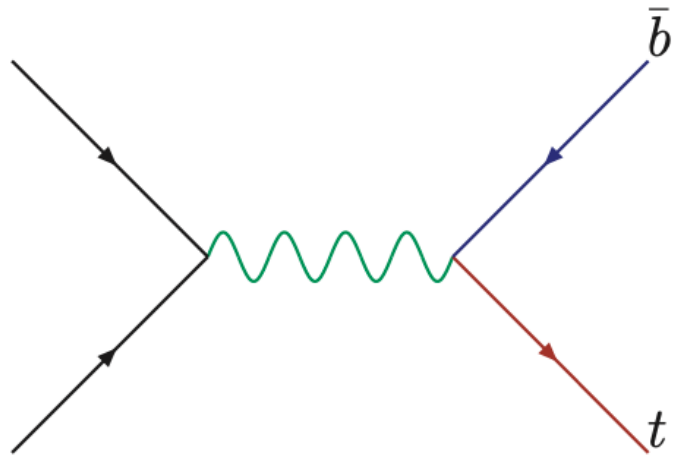
- ▶ At LO, two Feynman diagrams contribute
 - ▶ Quark anti-quark annihilation
 - ▶ Gluon gluon fusion (GGF)
- ▶ At Tevatron, ~85% quark anti-quark annihilation
 - ▶ $p\bar{p}$ collider
- ▶ At LHC, ~99% GGF



Top Quark, Single Production

- ▶ Single top production mediated by flavor changing using W boson
- ▶ Proportional to $|V_{tb}|^2$ in CKM matrix
- ▶ At LO, four Feynman diagrams contribute
 - ▶ s-channel
 - ▶ Two t-channel
 - ▶ Wt Associated production

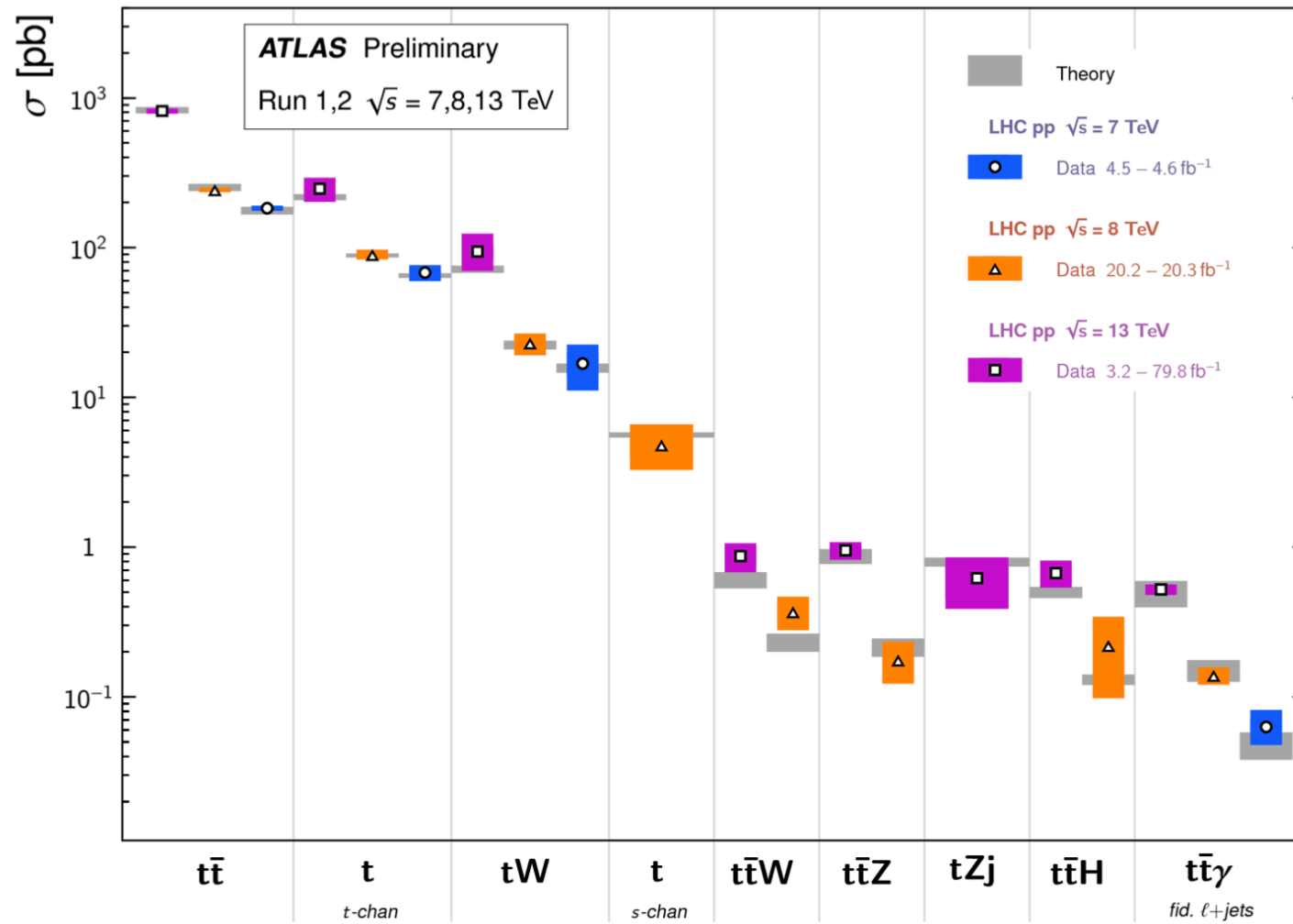
Single Production Diagrams



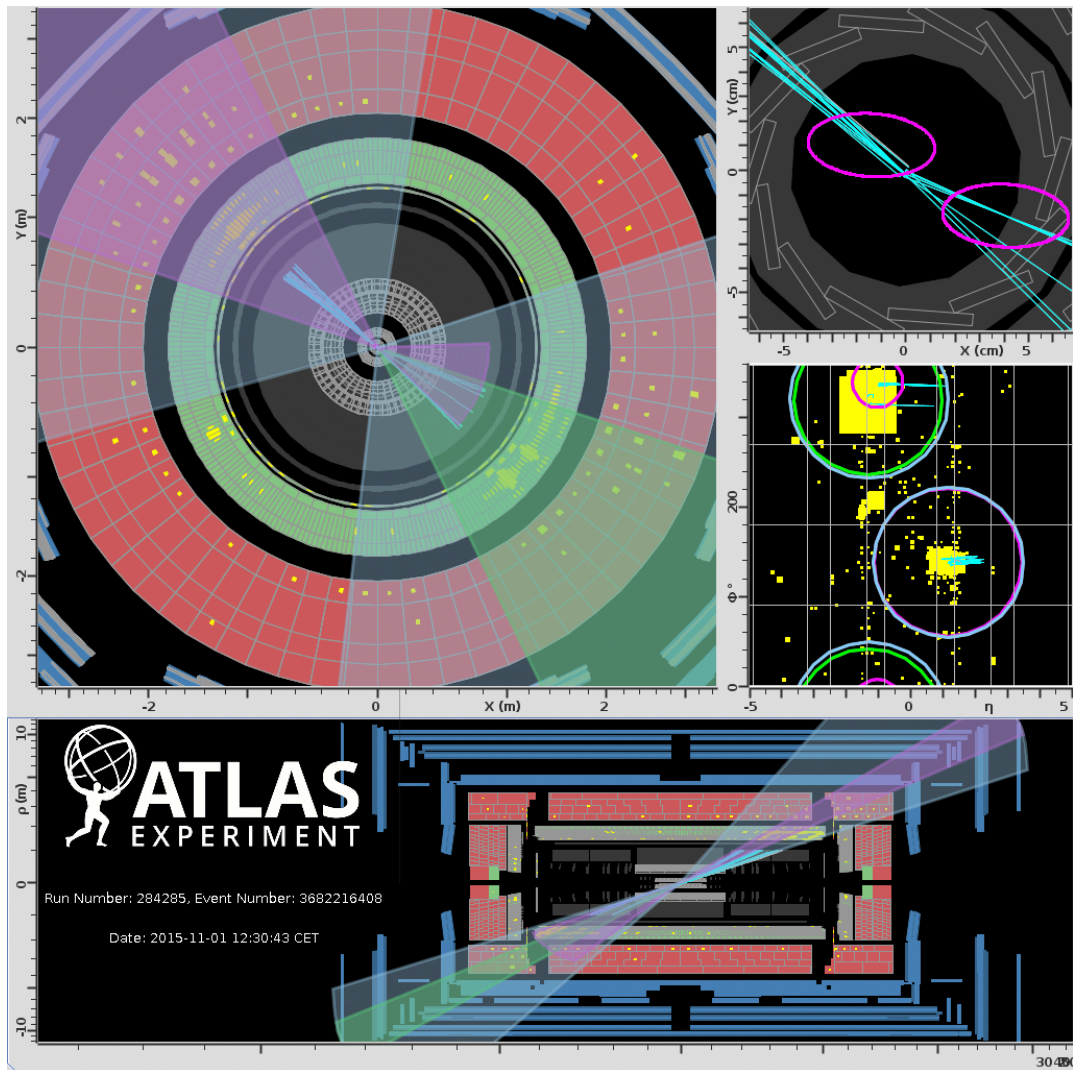
Top Quark At LHC

- ▶ $\sim 140 \text{ fb}^{-1}$ integrated luminosity
- ▶ $\sigma_{t\bar{t}} \sim 800 \text{ pb} \rightarrow N_{events} = \sigma \cdot L_{int} \sim 1.1 \cdot 10^8$
- ▶ 8 orders of magnitude higher than Tevatron
 - ▶ Allow for precision measurements in top sector

Top Quark At LHC

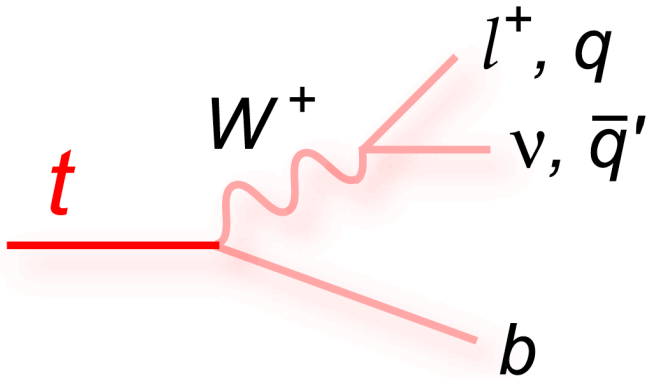


Top Pair Event



Top Quark Decay

- ▶ $\Gamma_t \sim 1.5 \text{ GeV} \sim 5 \cdot 10^{-25} \text{ s}$ - order of magnitude higher than QCD hadronization scale ($\Lambda_{QCD} \sim 0.2 \text{ GeV} \sim 10^{-24} \text{ s}$)
 - ▶ Top quark decays faster than hadronization time scale - only bare quark decay
 - ▶ Also decays before spin decorrelation timescale (10^{-23} s)
- ▶ Top quark decays predominantly to $t \rightarrow W^+ b$

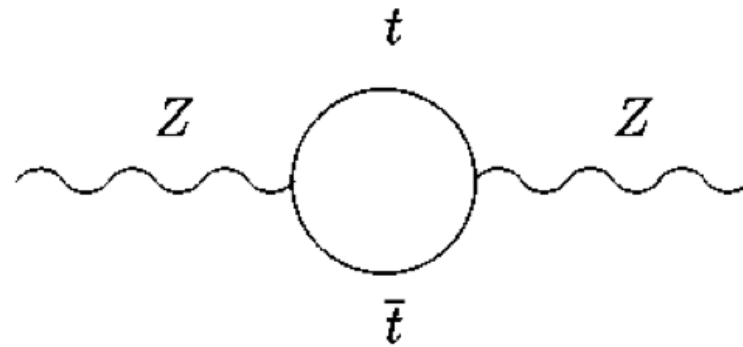
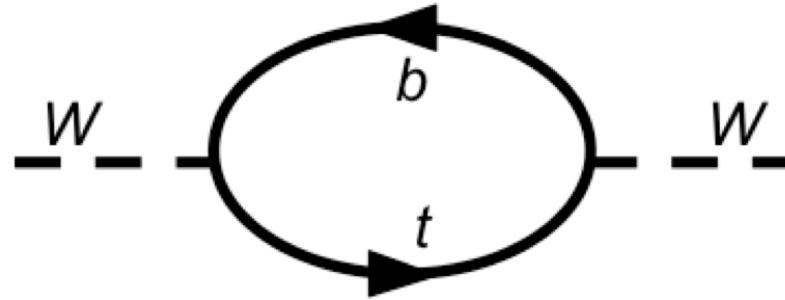


Top Quark Final States

- ▶ Top quark final states depend on W decays
- ▶ $W^\pm \rightarrow q\bar{q} \sim 46\%$
 - ▶ All hadronic channel
- ▶ One W decays hadronically, the other $W \rightarrow l + \nu \sim 44\%$
 - ▶ l+jets channel
- ▶ $W^+bW^-\bar{b} \rightarrow l^+\nu + l^-\bar{\nu} \sim 10\%$
 - ▶ Dilepton channel

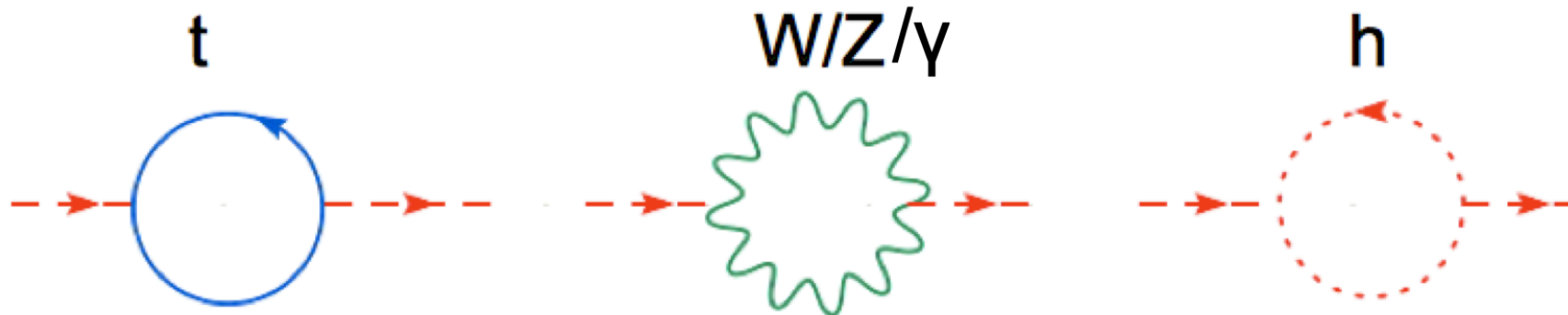
Top Quark and Electroweak Sector

- ▶ Single top produced via W boson flavor changing current
- ▶ Decays predominantly to W boson
- ▶ LO radiative correction to Z and W boson mass
 - ▶ $m_Z, m_W \propto m_t^2$



Top Quark And Higgs Sector

- ▶ Highest mass → highest Yukawa coupling to Higgs boson
 - ▶ $y_t = \frac{m_t\sqrt{2}}{v} \sim 1$
- ▶ Predominantly top quark involved in Higgs production via GGF
- ▶ Plays a major role in Higgs naturalness problem
 - ▶ $\delta m_H^2 \propto \Lambda_{SM}^2 (-4m_t^2 + 2m_W^2 + m_Z^2 + m_H^2)$
 - ▶ Largest contribution from high mass of top quark

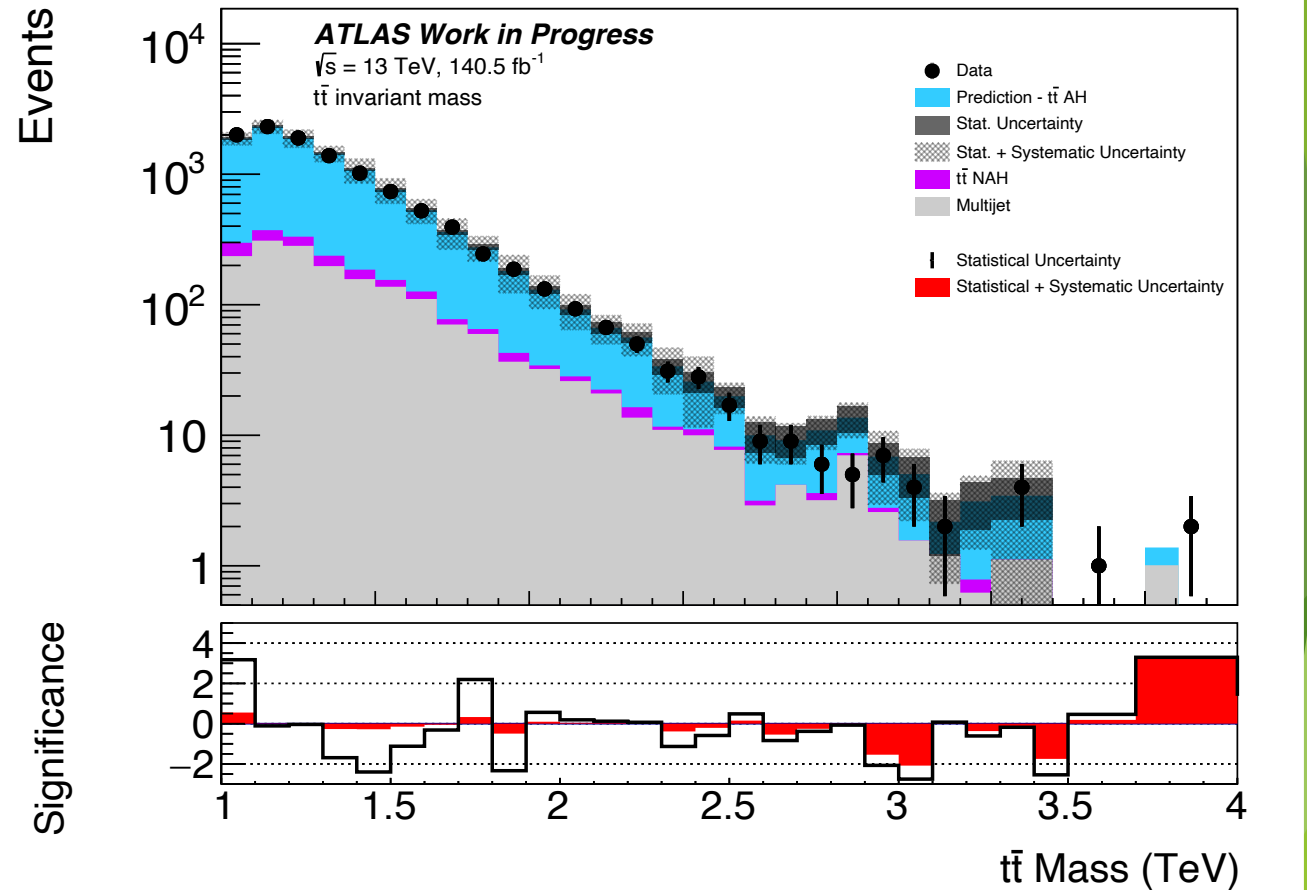


Top Quark And BSM

- ▶ High top quark mass connects to many BSM theories
- ▶ Large Higgs corrections from top quark imply a connection with electroweak symmetry breaking
 - ▶ New models such as topcolor and topcolor assisted technicolor
- ▶ Topcolor: High top quark mass arises from $t\bar{t}$ condensate formed via new strong gauge force
- ▶ Topcolor assisted technicolor: Predicts existence of heavy Z' boson

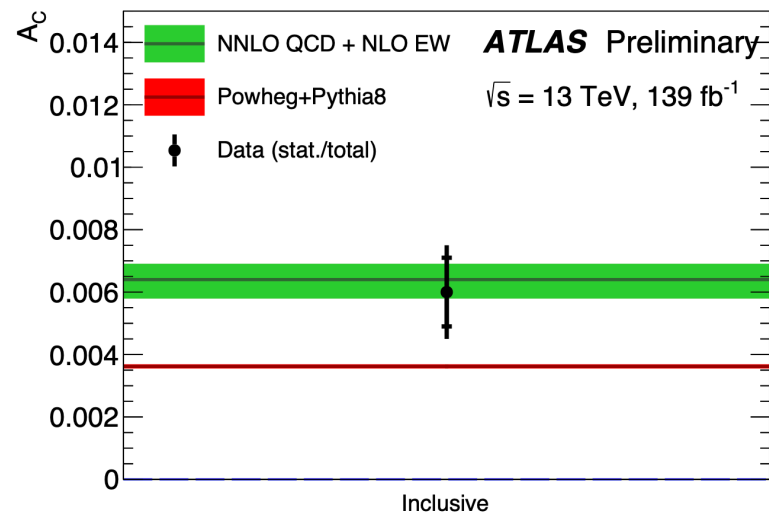
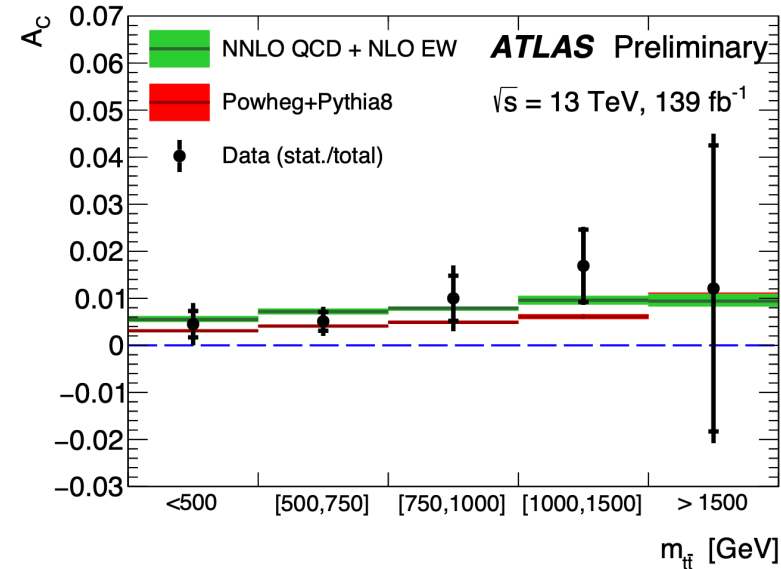
Top Quark And Z'

- ▶ Heavy Z' boson expected to decay into highly boosted $t\bar{t}$ pairs
- ▶ Simple search for excess $t\bar{t}$ events in invariant mass distribution of $t\bar{t}$ system



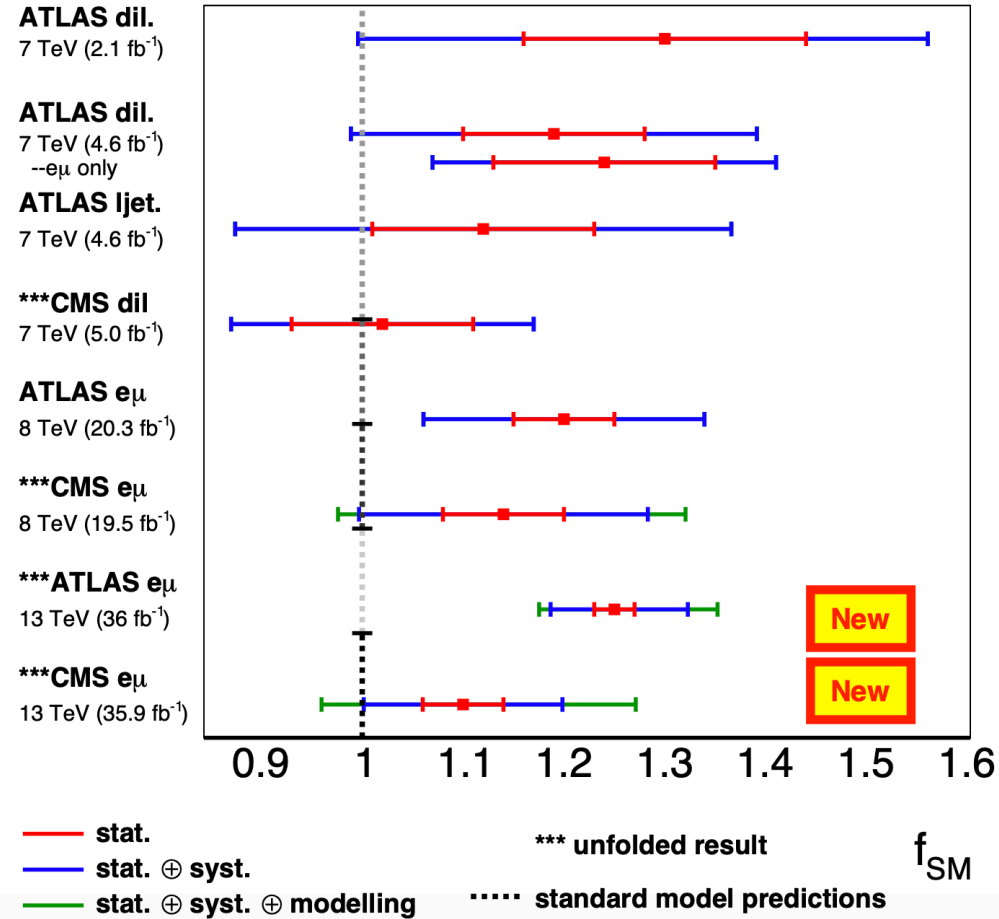
Top Quark Charge Asymmetry

- ▶ Higher order corrections to top pair production lead to charge asymmetry
 - ▶ Only exists in $q\bar{q}$ annihilation - ~10% at LHC!
 - ▶ Symmetric to all orders for GGF
- ▶ Top quarks are produced with higher rapidity than anti-top
- ▶ Measured to be $0.6 \pm 0.15\%$
 - ▶ Agrees with NNLO QCD + NLO EW Monte Carlo predictions



Top Quark Spin Correlations

- ▶ Top quark pairs produced via QCD are not polarized
 - ▶ Spin between top and anti-top correlated
- ▶ Top quarks decay before spin decorrelation occurs



Questions