Hot TOPics

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European Research Council

Established by the European Commission

Structure

- Introduction
- Colour Flow
- Angular Distributions
- The Top and The Higgs
- Summary

Introduction

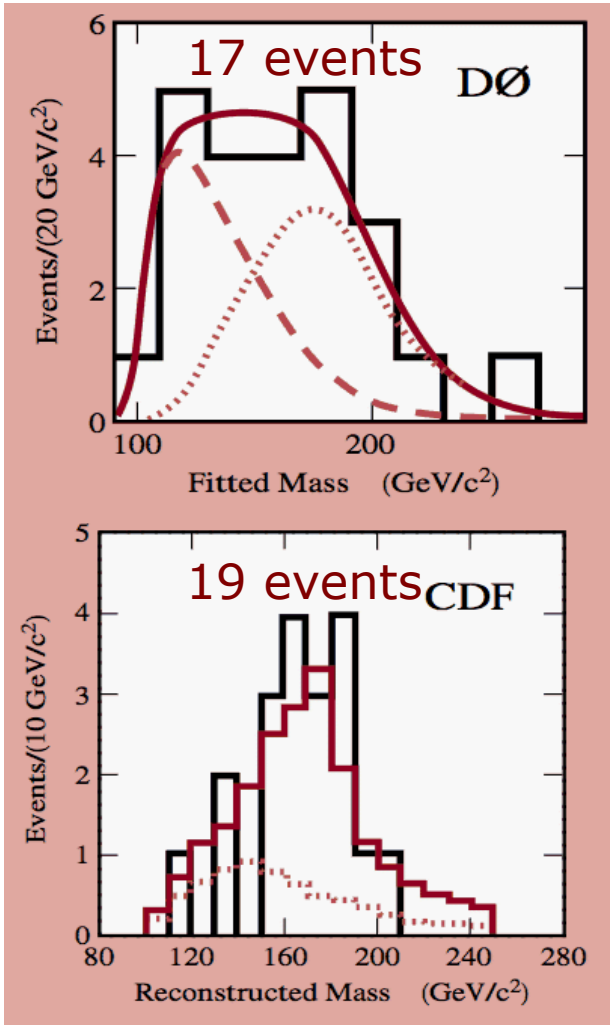
The Top Quark

- Heaviest known elementary particle:
  $m_t \sim 173\text{GeV}$

- Standard Model:
  - Single or pair production
  - Electric charge +2/3 e
  - Short lifetime 0.5×10^{-24}s
    - Bare quark - no hadronisation
  - ~100% decay into Wb
  - Large coupling to SM Higgs boson

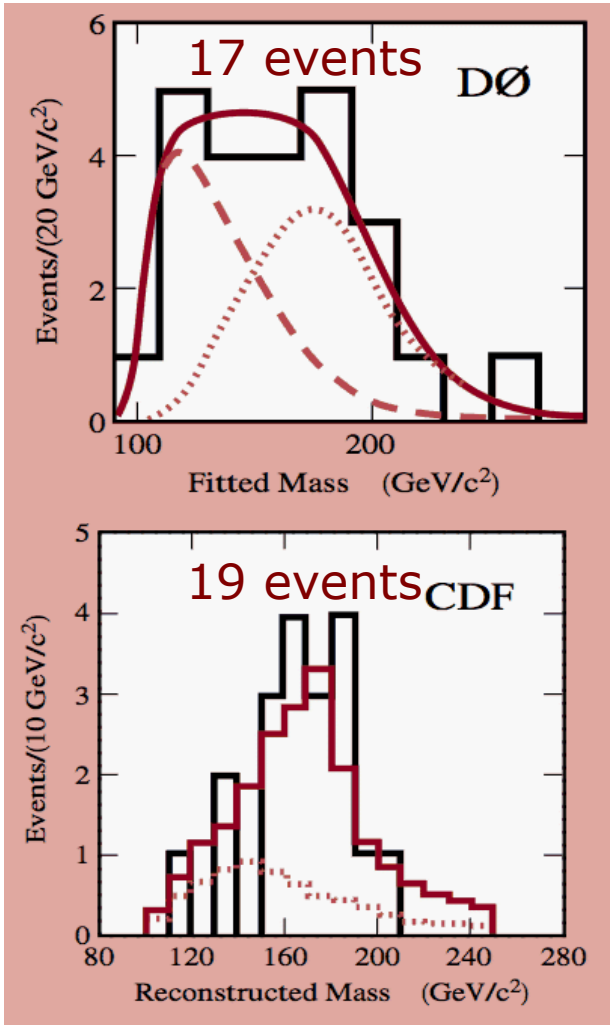
Top: From Discovery…

Discovered in 1995 by CDF and DØ at Fermilab (with few events)



...to Precision

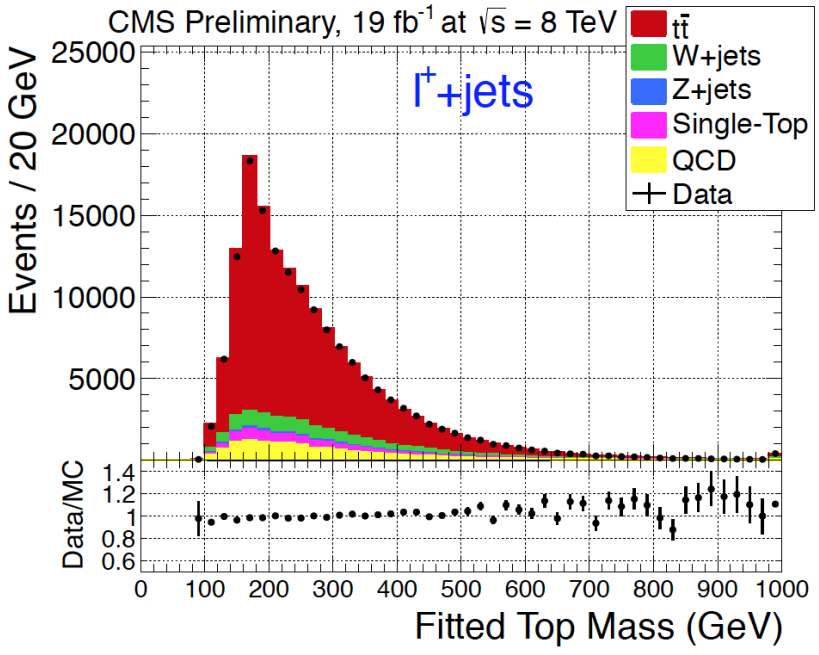
Discovered in 1995 by CDF and DØ at Fermilab (with few events)

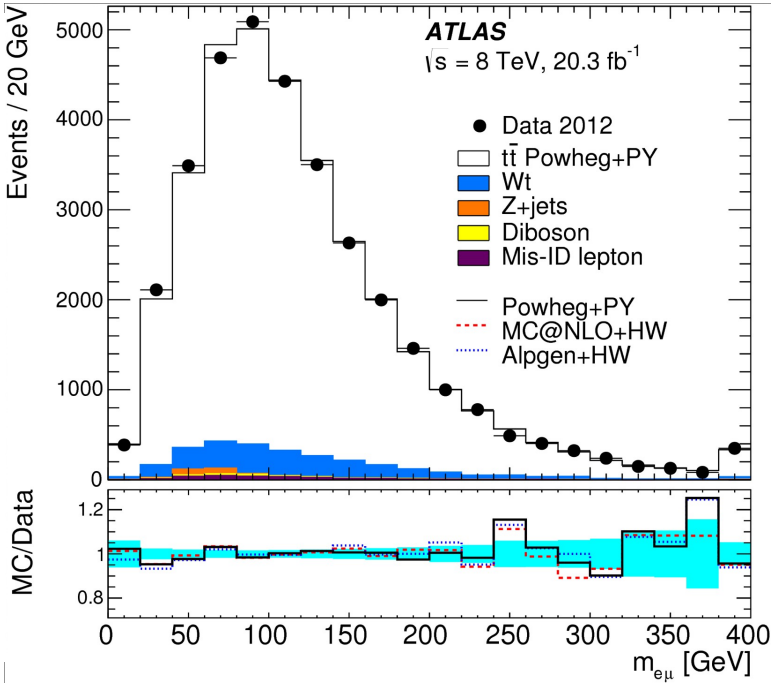


Situation today:

LHC → top quark factory!

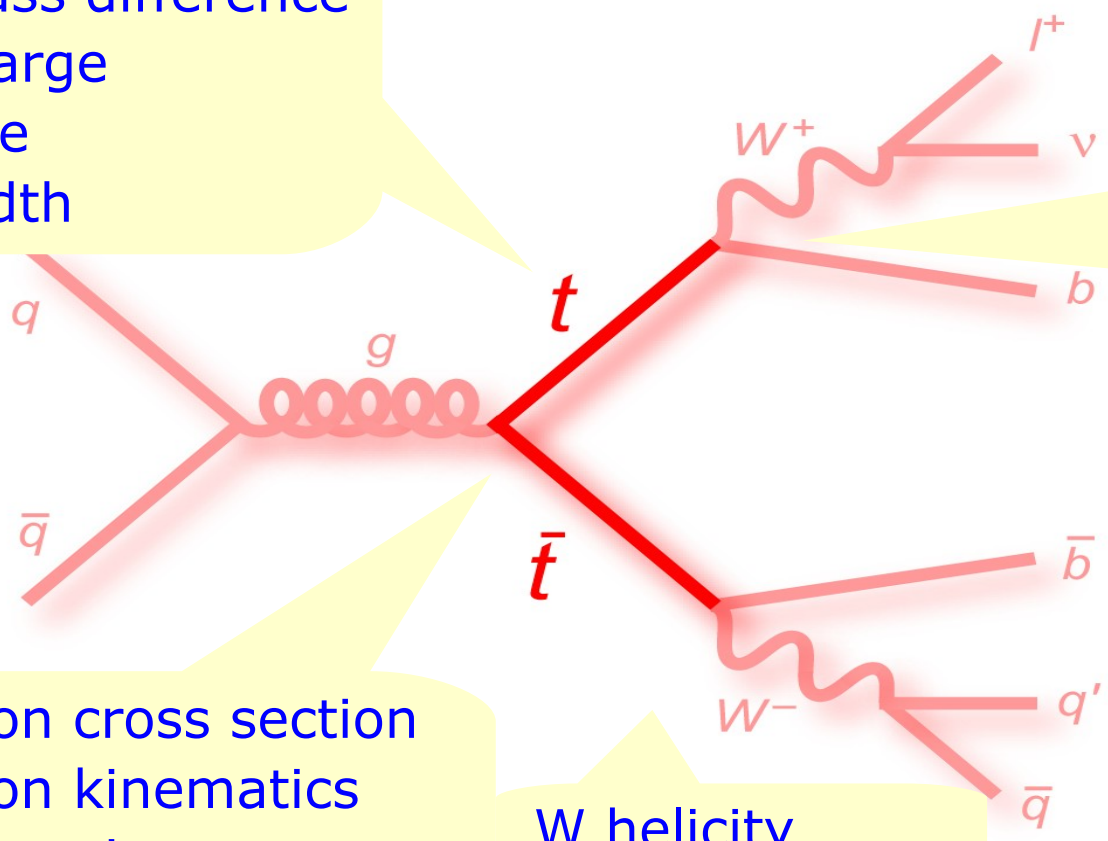
- Many precision measurements possible!





Top Studies: Overview

Top mass
Top mass difference
Top charge
Lifetime
Top width



Branching ratios
$|V_{tb}|$
Anomalous coupling
New/Rare decays

Production cross section
Production kinematics
Production via resonance
New particles

W helicity

Spin correlation
Charge asymmetry
Color Flow

s-, t- and Wt-channel production, properties and searches in single top events

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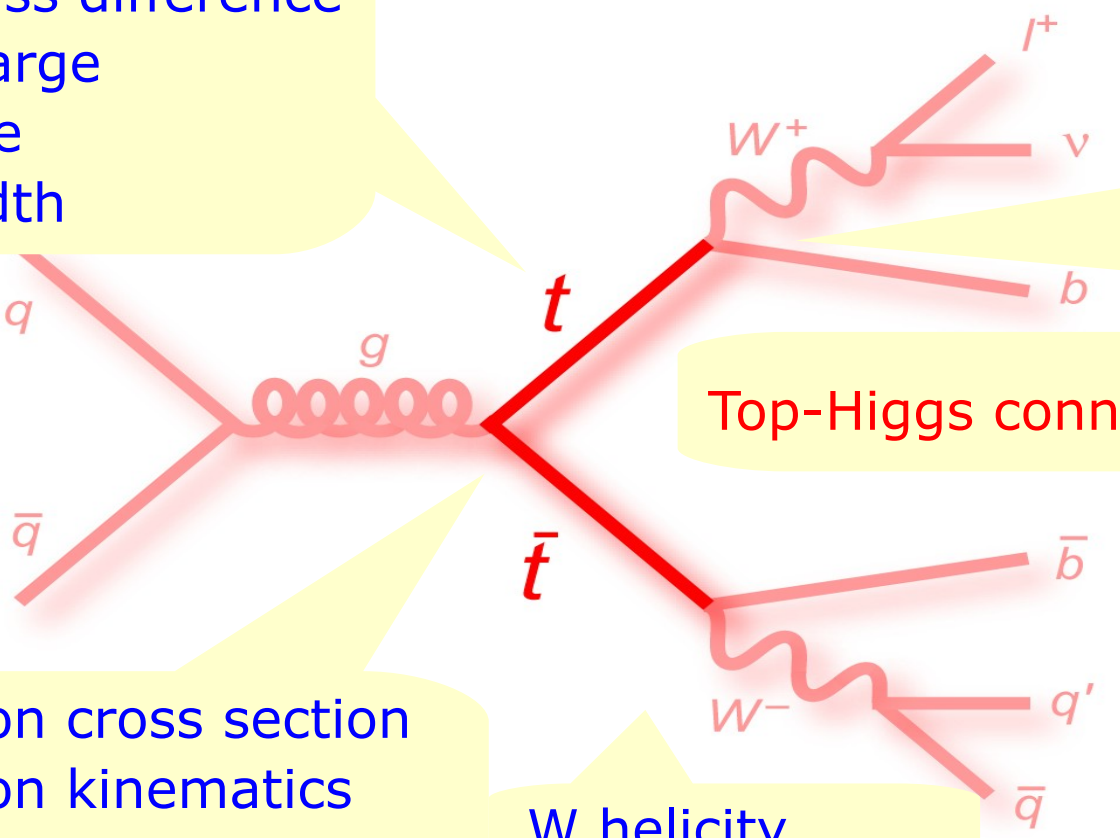


Top-Higgs connection

Spin correlation
Charge asymmetry
Color Flow

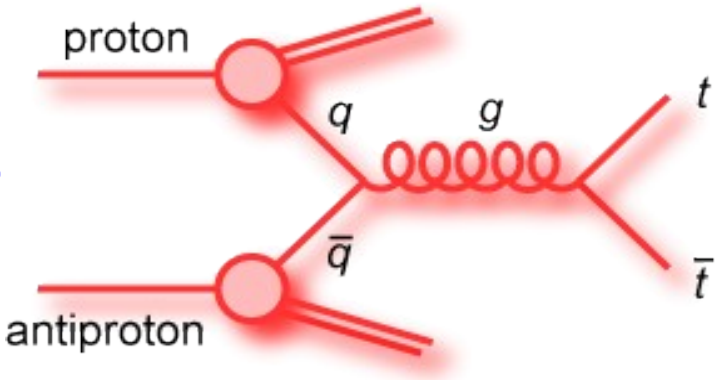
Production cross section
Production kinematics
Production via resonance
New particles

W helicity

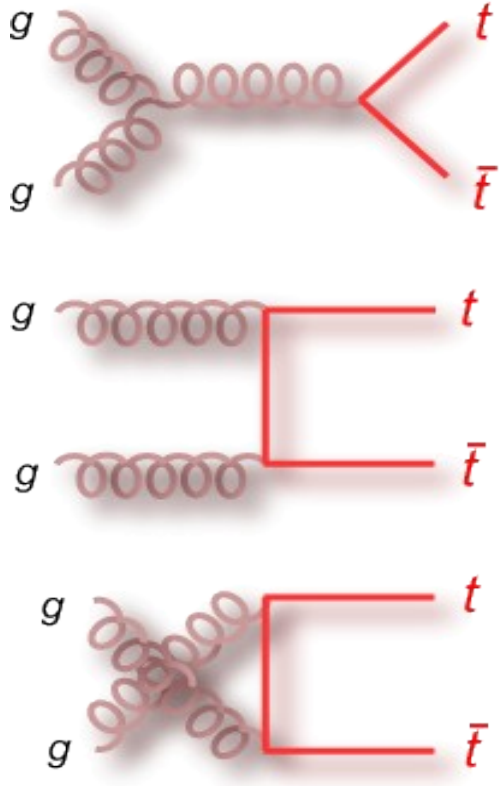
s-, t- and Wt-channel production, properties and searches in single top events

Top Quark Pair Production

At the Tevatron:



85%



+ 15%

At LHC:

14 TeV: 10% + 90%

7 TeV: 30% + 70%

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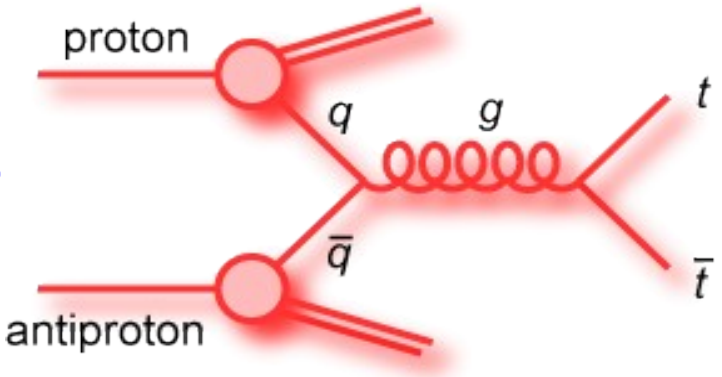

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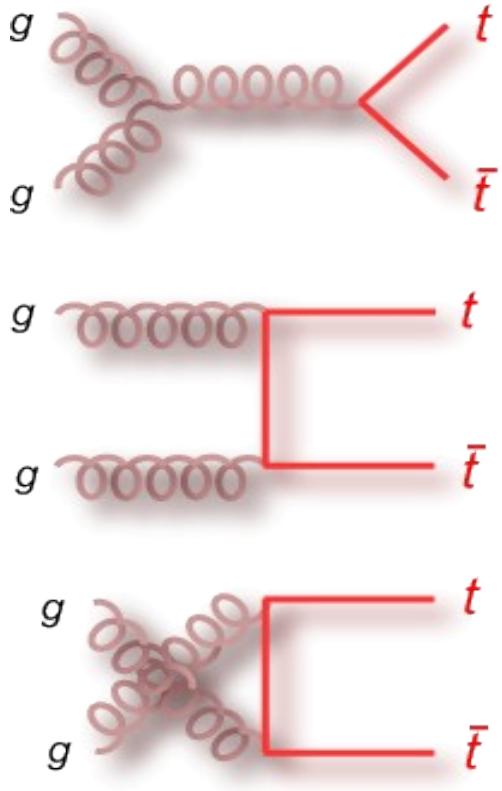

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At LHC:

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Cross Sections:

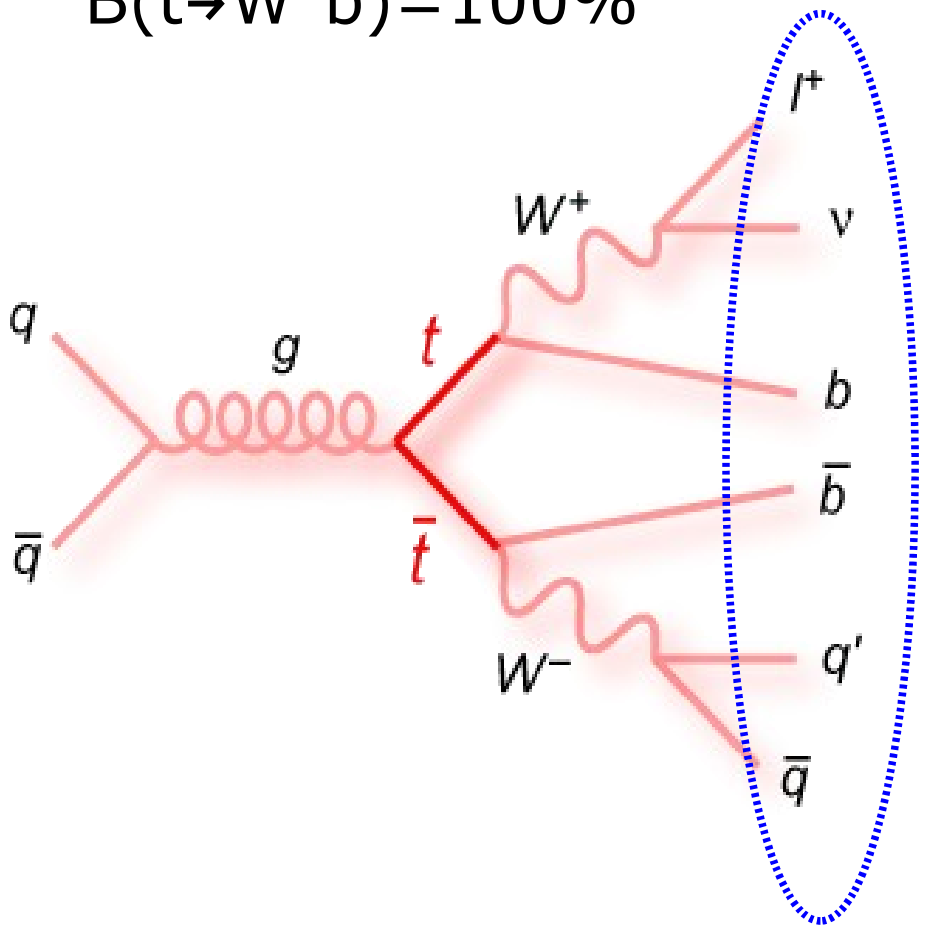
Collider	Cross section [pb]
Tevatron (1.96 TeV)	$7.35^{+0.23}_{-0.27}$
LHC (7 TeV)	$177.3^{+10.1}_{-10.8}$
LHC (8 TeV)	$252.9^{+13.3}_{-14.5}$
LHC (13 TeV)	$831.8^{+40.3}_{-45.6}$

M. Czakon et al. arXiv:1112.5675

Final States in $t\bar{t}$

$t\bar{t} \rightarrow W^+bW^-\bar{b}$: Final states are classified according to W decay

$B(t \rightarrow W^+b) = 100\%$



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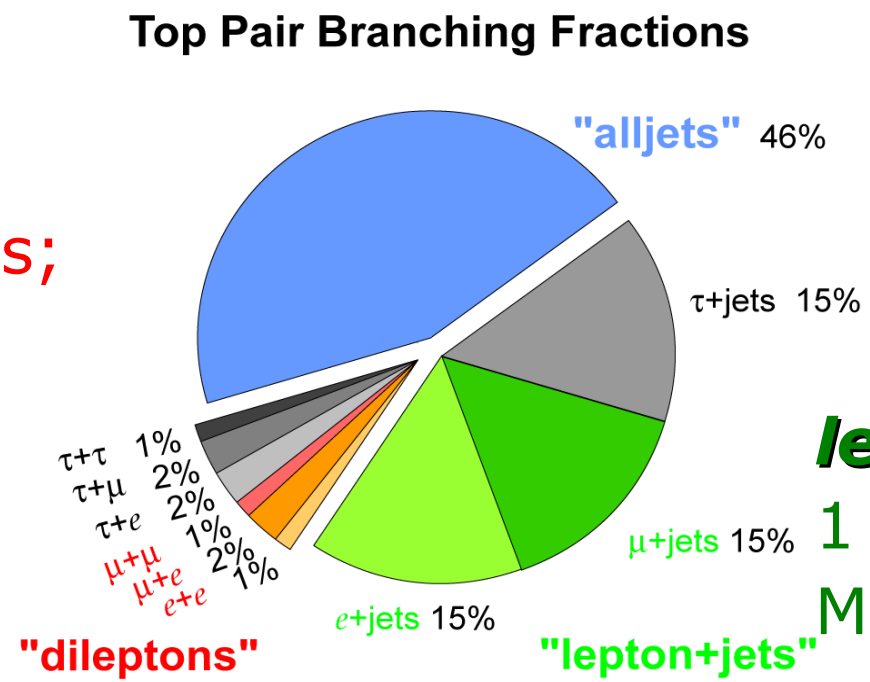
all-hadronic:
≥6 jets (2 b-jets)

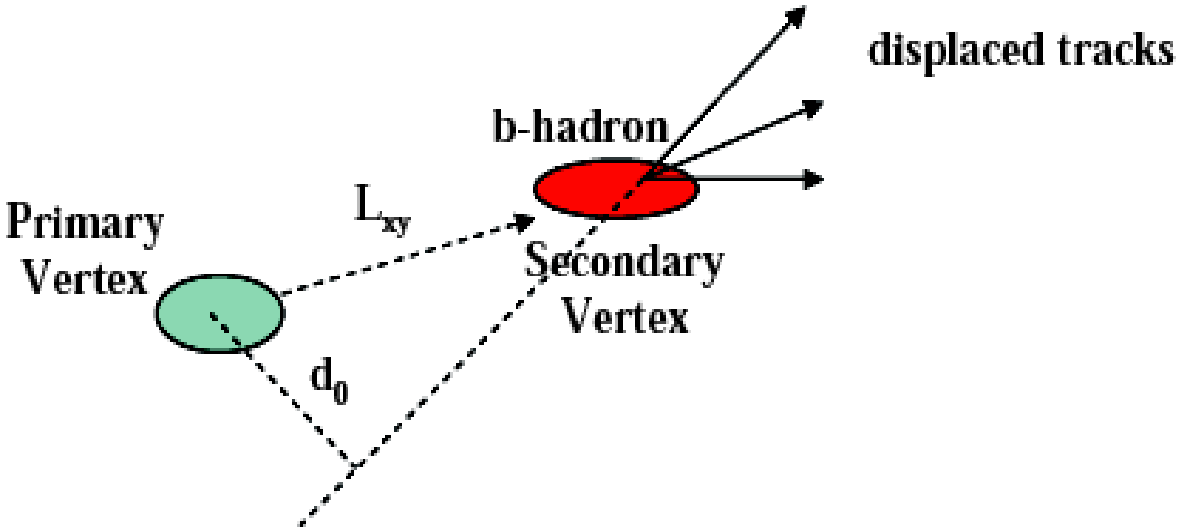


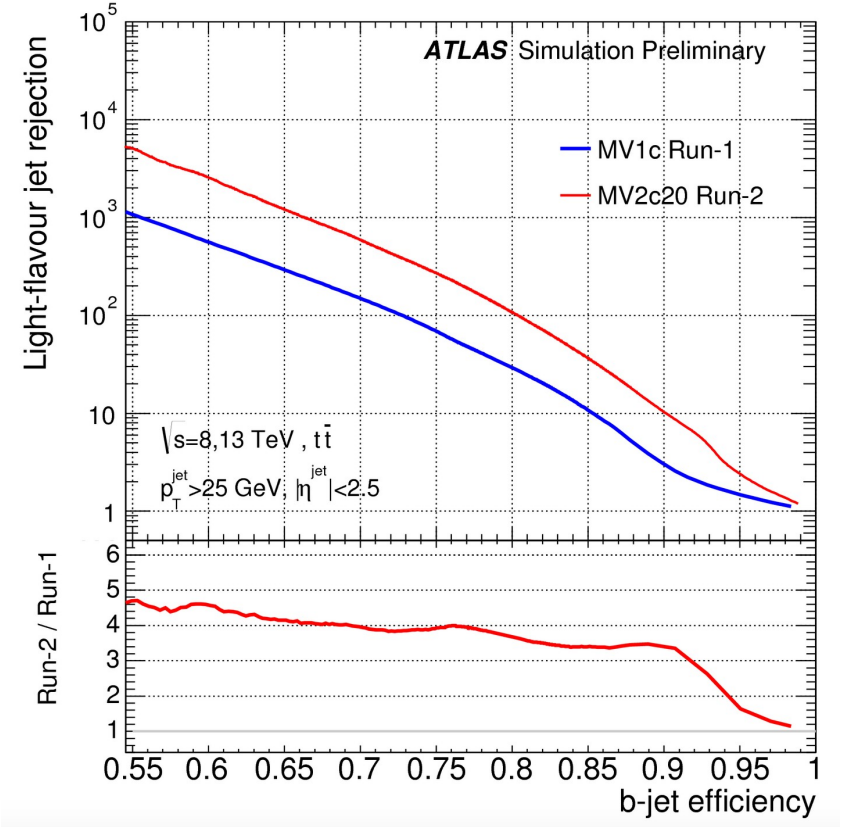
dilepton:
2 isolated leptons;
High missing E_T from neutrinos;
2 b-jets

lepton+jets:
1 isolated lepton;
Missing E_T from neutrino;
≥4 jets (2 b-jets)

Identification of b-Jets

- Important tool to increase $t\bar{t}$ purity
- b-hadron: travels some millimeters before it decays
- Neural Network (MV1)
  combines properties of displaced tracks and displaced vertices





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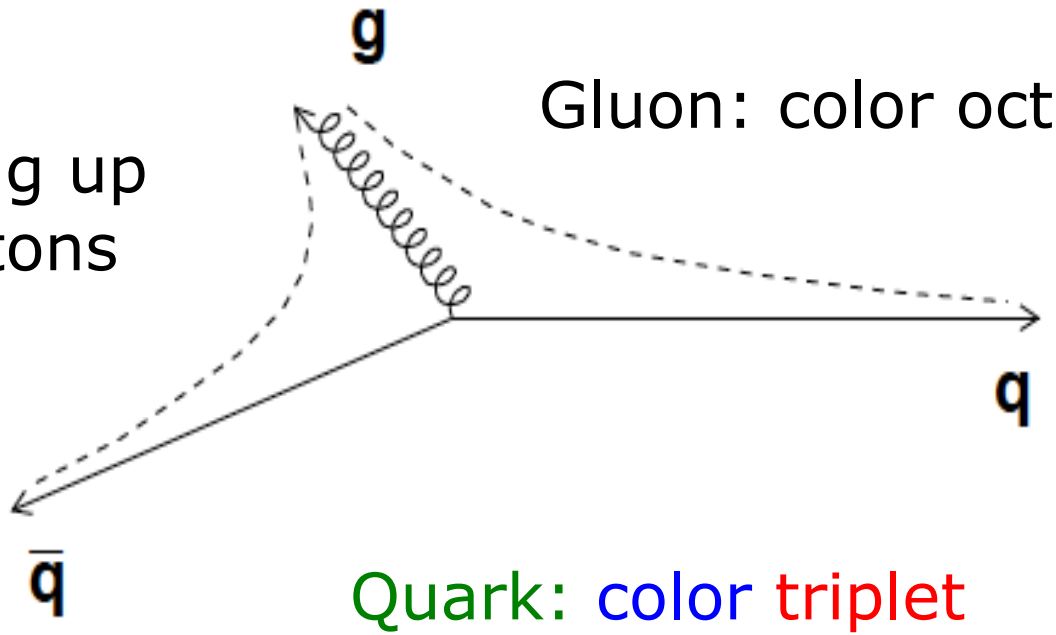
Top Events as a Laboratory

Introduction to Colour Connection and Hadronization

- Quarks carry QCD color charge
  - But only colour singlets can be observed
    - For example W, Z, or bound states like hadrons
- Partons carrying color are color connected to partons with anti-colour
- Hadronization: Particles building up between colour-connected partons

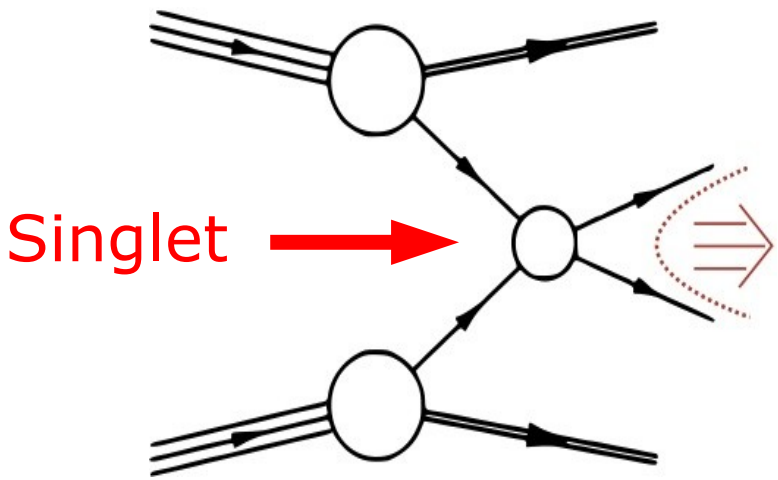


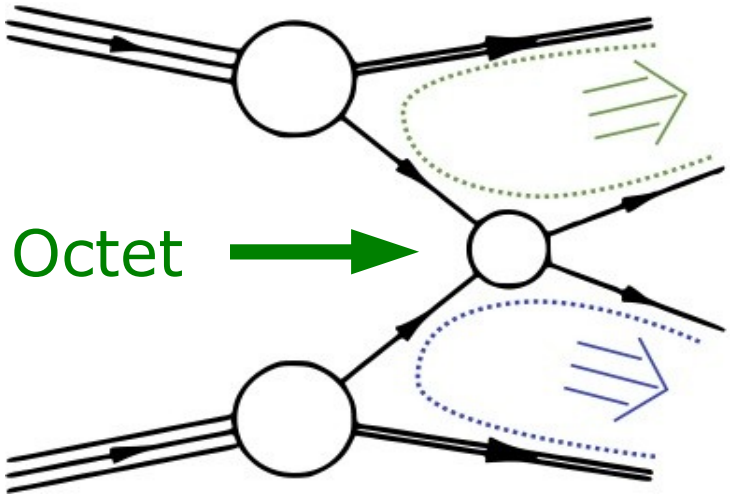
Gluon: color octet

Quark: color triplet

Color Flow between Jets

- Jets carry color, and are thus color connected to each other
  - Pairing of connection depends on nature of decaying particles





- Particles created during hadronization should be concentrated along angular region spanned by the color connected partons
  - Transverse jet profiles should not be round
  - Shape influenced by direction of color flow!

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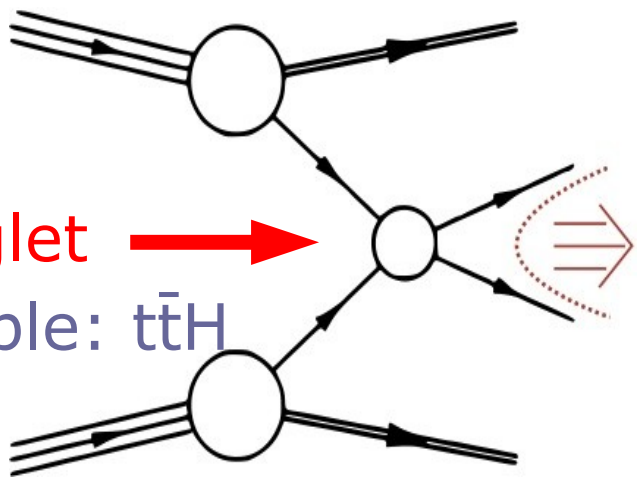

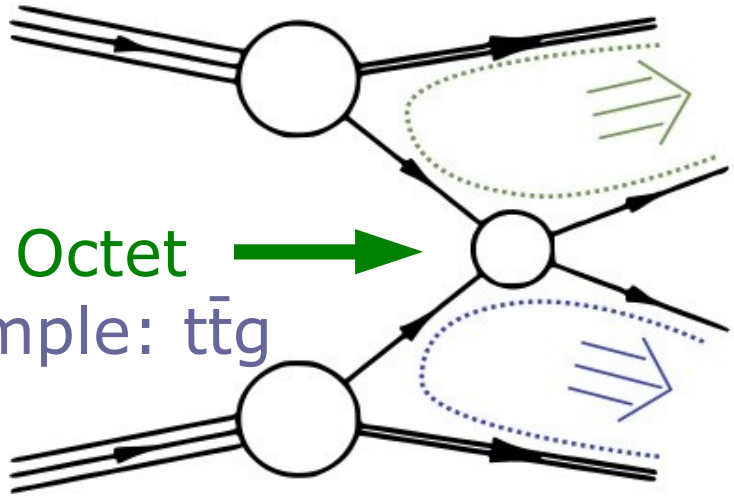

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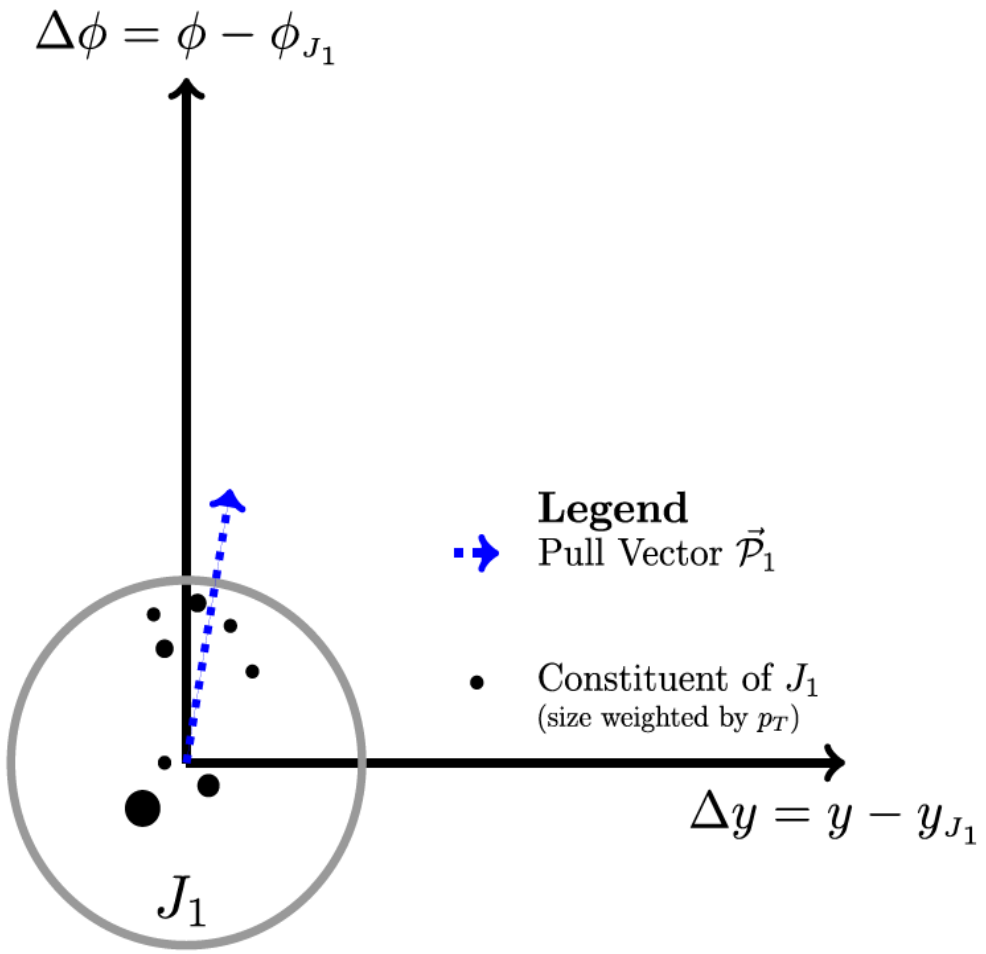
Color Flow Observable

Construct a local observable, constructed from particles within a chosen jet cone: Jet pull

- Pick a pair of jets in the event
- Build vectorial sum of jet components:

$$\vec{p} = \sum_i \frac{E_T^i |r_i|}{E_T^{jet}} \vec{r}_i$$

  - $\vec{r}_i$: position of jet component i relative to center of jet
  - E_T^i: transverse energy of component i
  - E_T^{Jet}: transverse energy of jet



Gallicchio, Schwartz, PRL 105, 022001 (2010)

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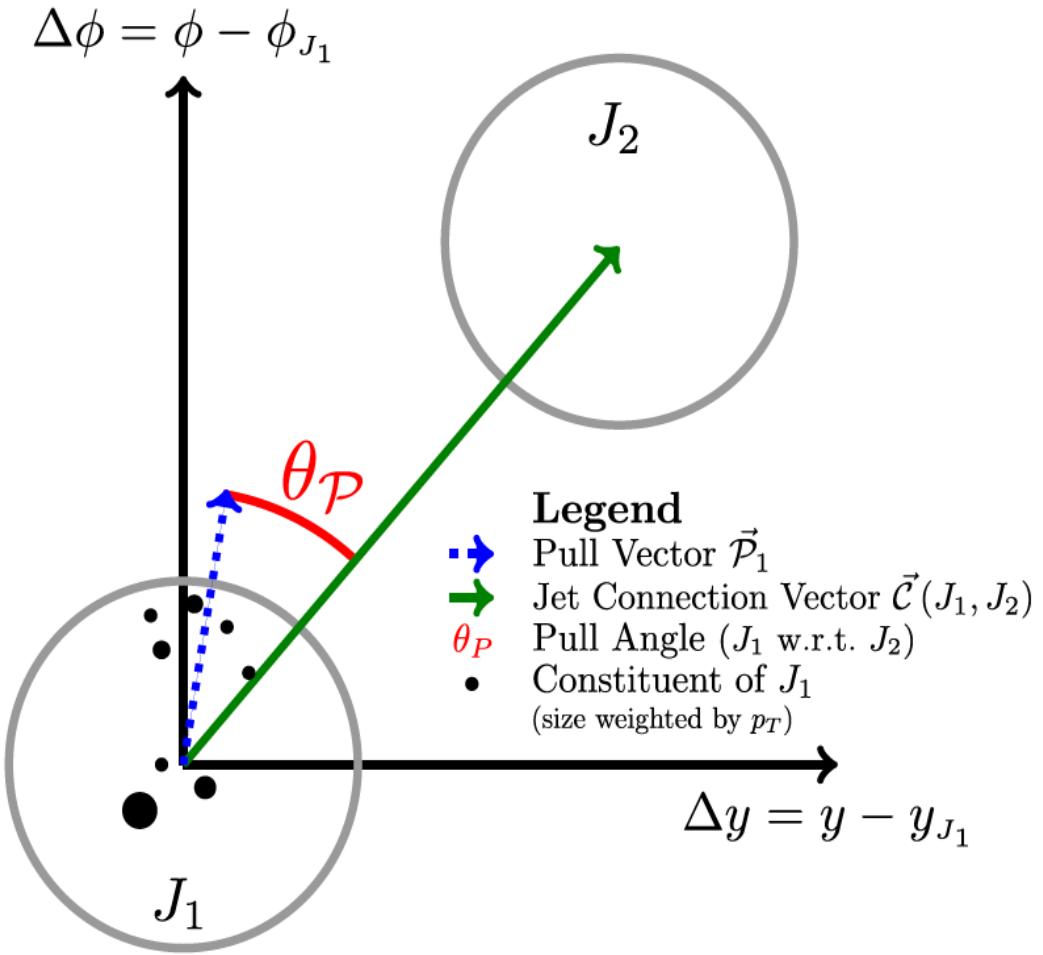
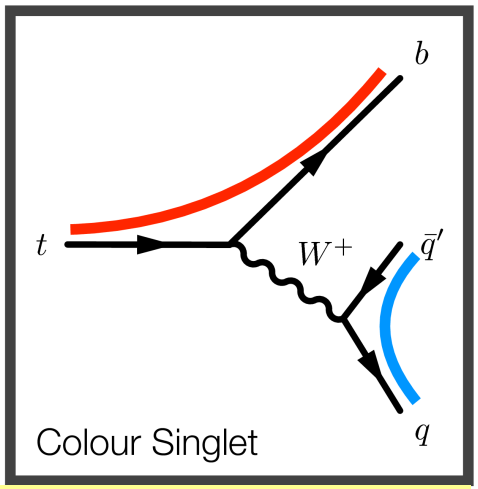


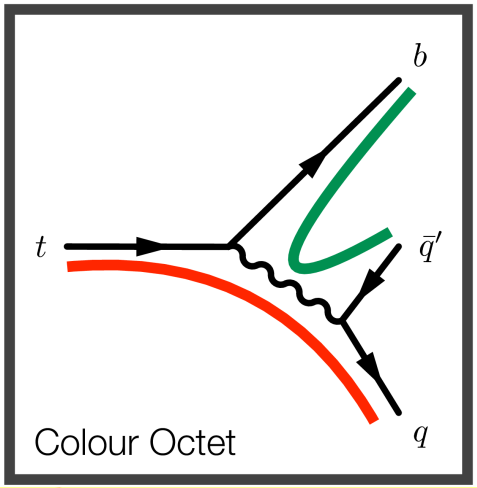
Gallicchio, Schwartz, PRL 105, 022001 (2010)

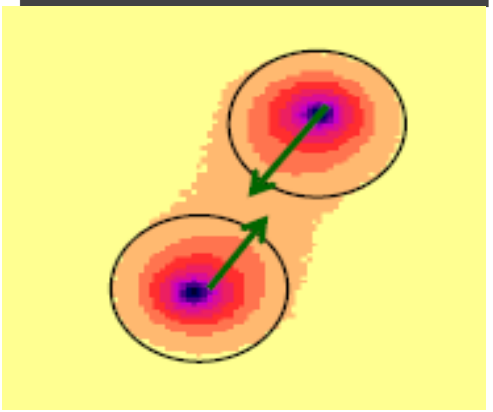
Colour Flow in Top

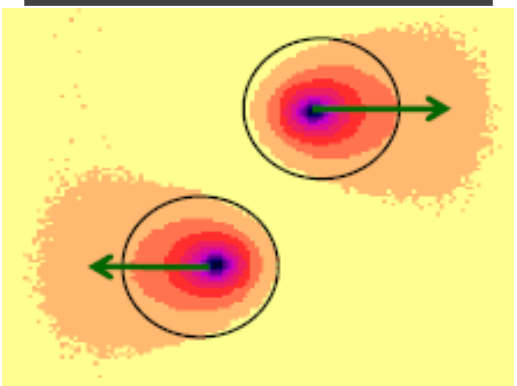
- Top events as laboratory to test new tools
- Jets carry color, and are thus color connected to each other
  - Pairing of connection depends on nature of decaying particles

Gallichio, Schwartz,
PRL 105, 022001 (2010)







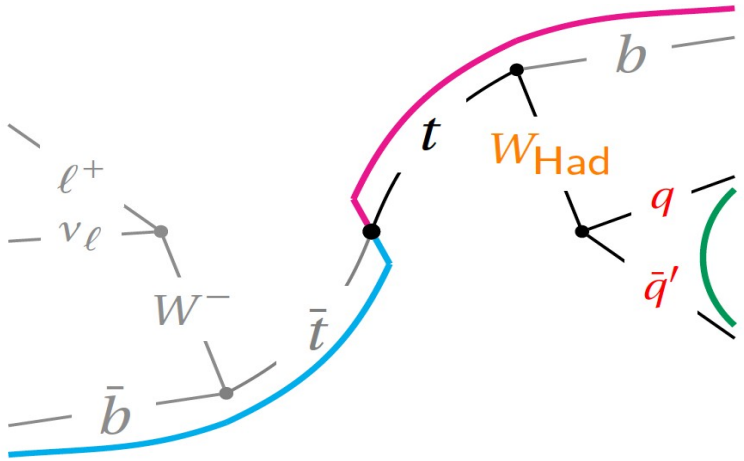


Jet pull: vectorial sum of components within each jet → jet pull angle: angle wrt. connection line of pair of jets

Colour Flow in Top

- Consider 4 variables in semileptonic $t\bar{t}$ events (>1 b-tagged jet)

- Two non-b-tagged jets:
  - Relative jet pull angles
  - Jet pull magnitude



- Two b-tagged jets
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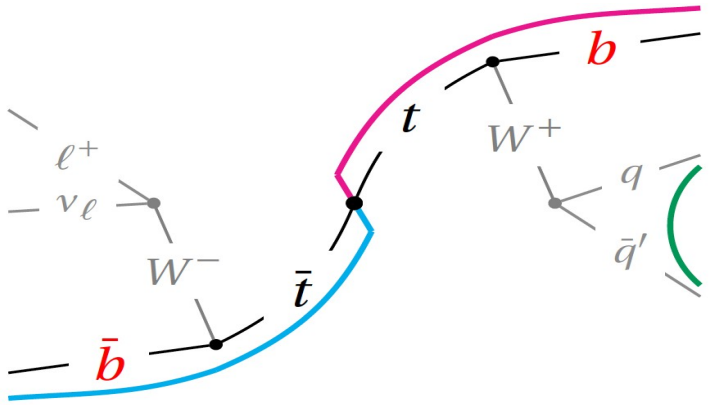
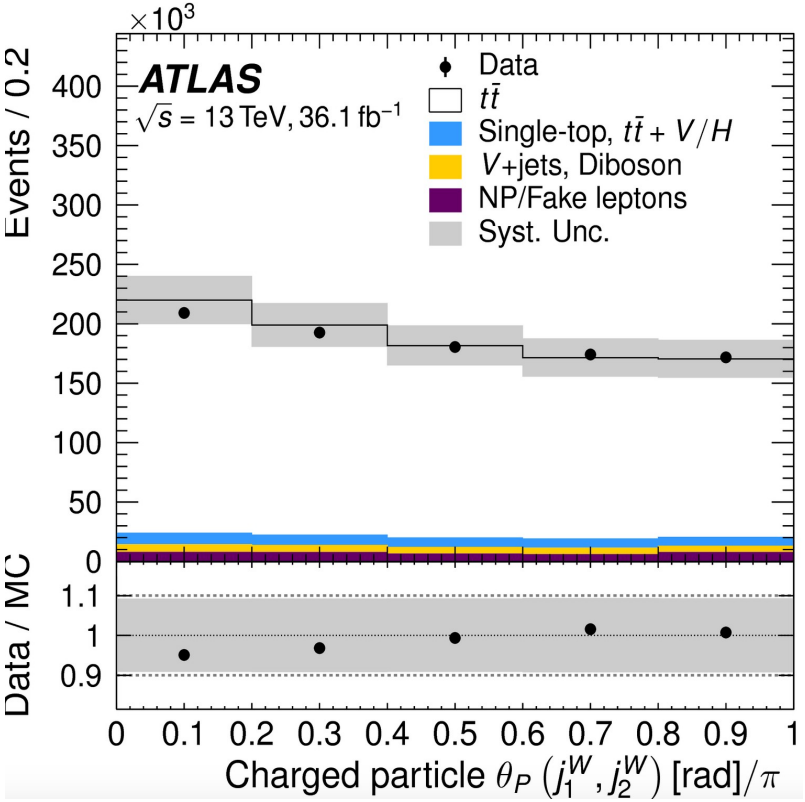


Analysis

- Correct distributions for detector effects
- 13 TeV analysis: use only track-jets
  - Have shown to have better resolution than calorimeter jets in 8 TeV analysis PLB 750, 475-493 (2015)



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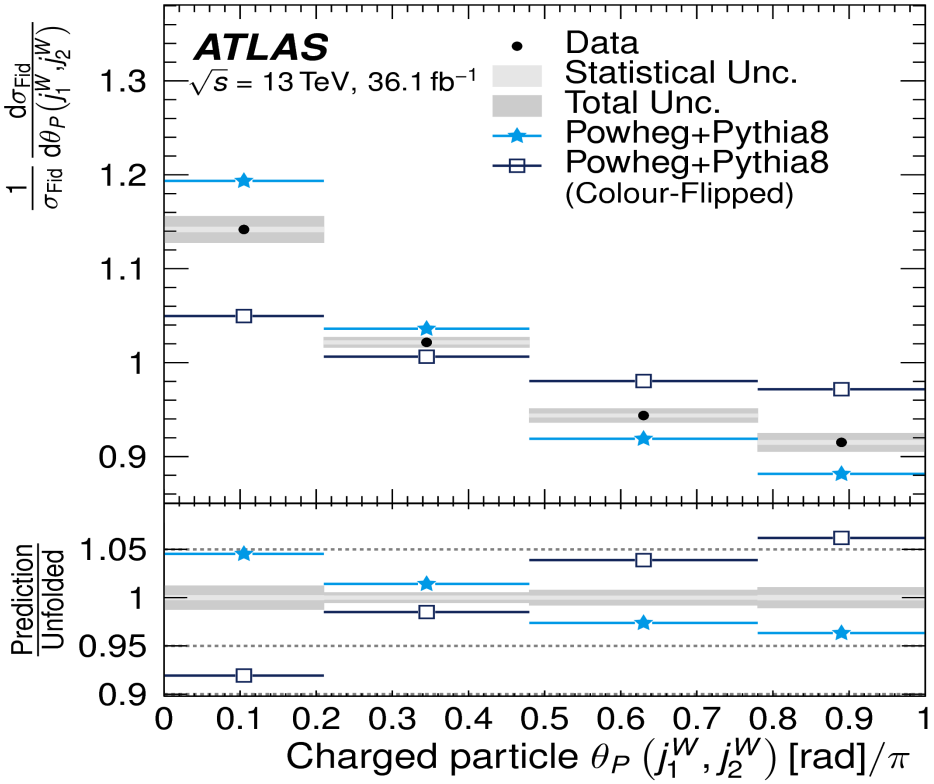
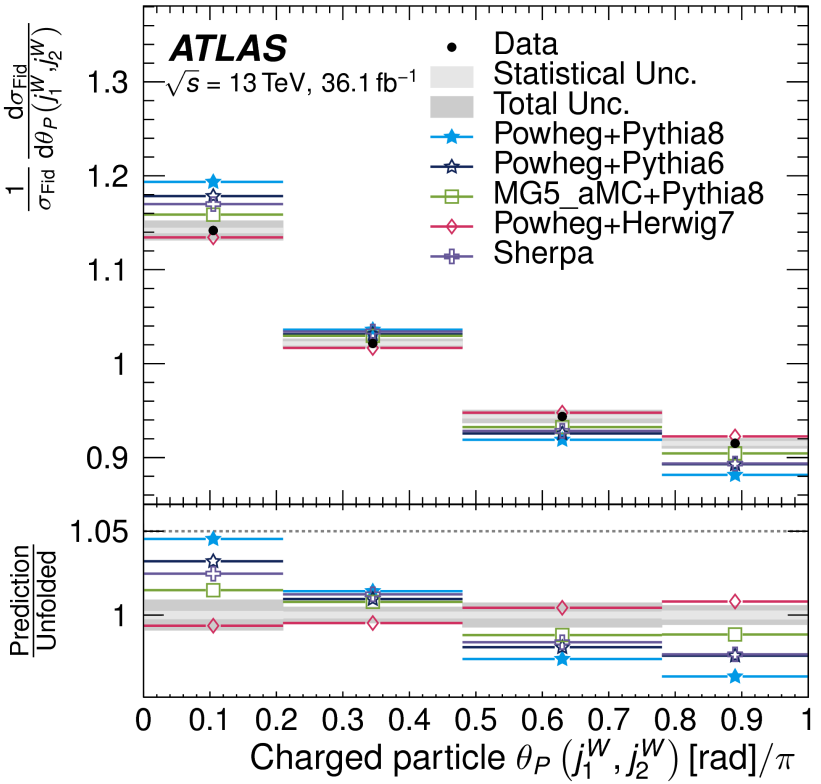
Results for W daughters

- Correction to stable particle-level (iterative Bayesian unfolding)





- Colour-flipped model disfavoured by the data
  (for this distribution χ^2/NDF: 45.3/3; SM Powheg+Pythia8: 17.1/3)
- MC modeling has room for improvement

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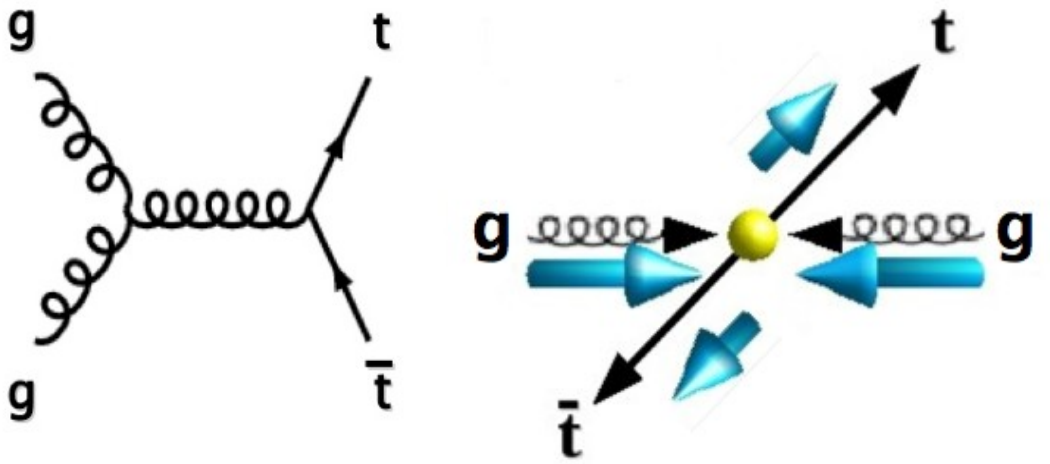
Angular Distributions

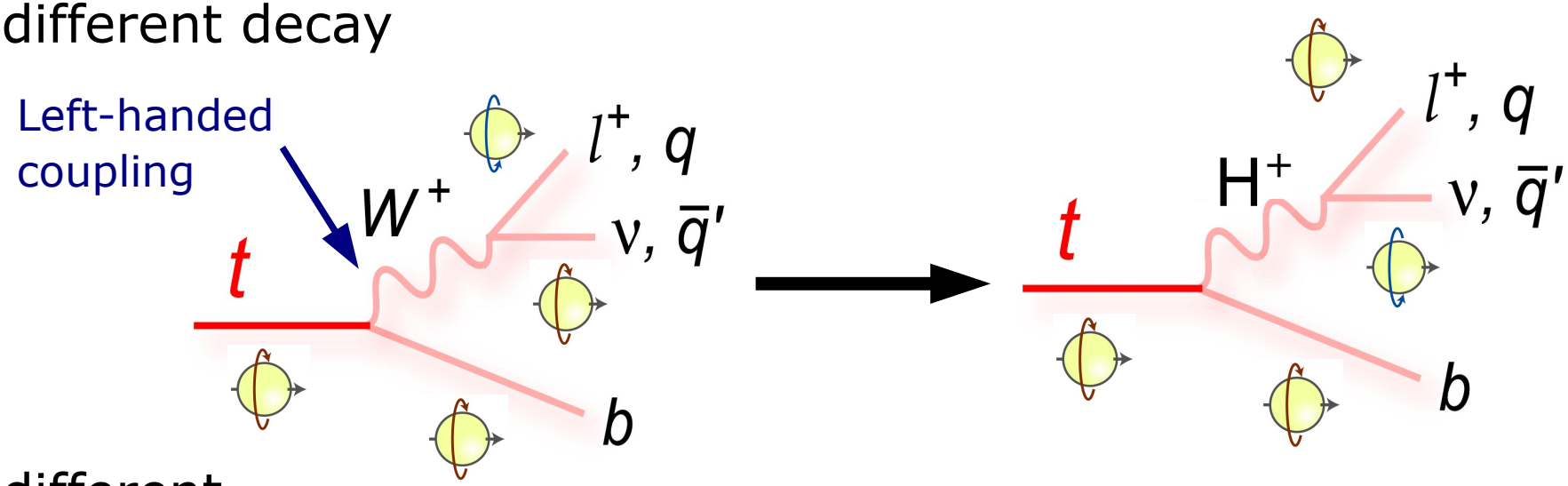
Spin Correlations

- Top quarks decay before fragmentation
  - Spin information is preserved
- Hadron colliders: top quarks produced un-polarized, but
  - New physics (NP) could induce polarization
    - e. g. NP causing forward-backward $t\bar{t}$ asymmetry → more left-handed tops
  - Correlation between top and antitop spin can be extracted

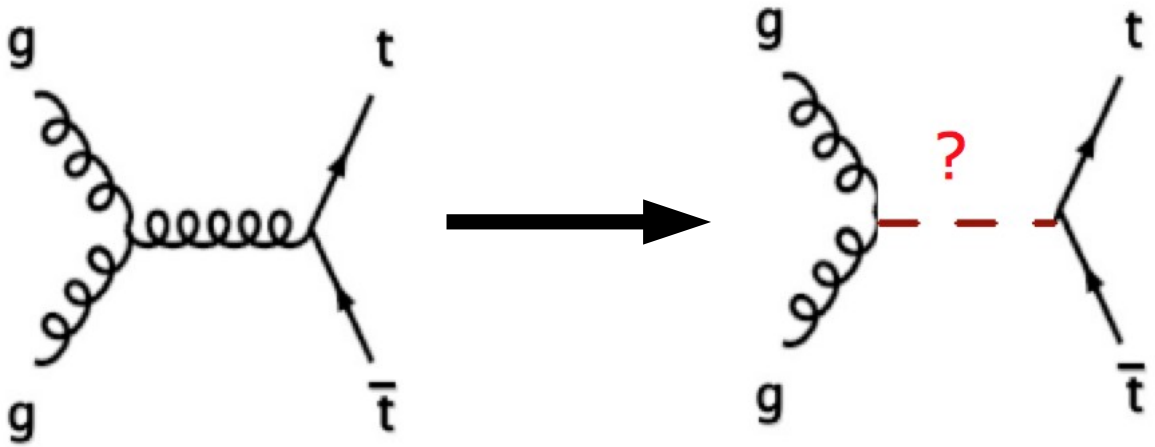


Spin Correlations

- Measured spin correlation can change
  - Due to different decay



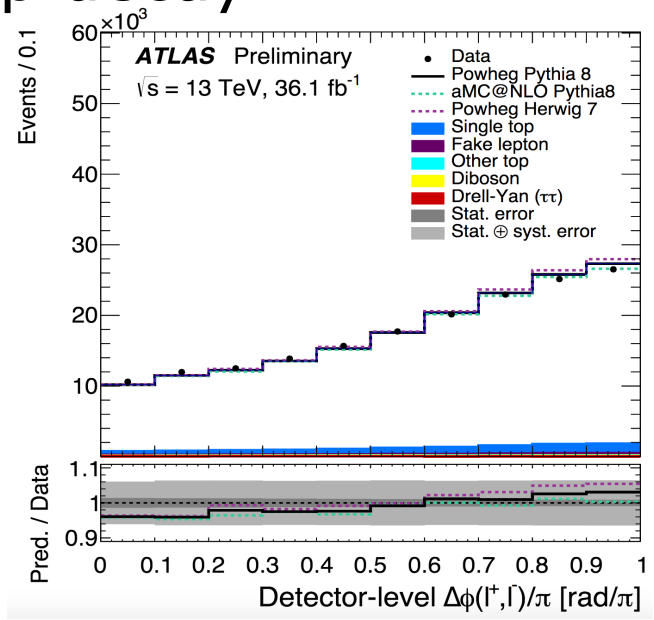
  - Due to different production



- Spin correlation: test the full chain form production to decay!

Analysis Strategy

- Highest spin analysing power: leptons from top decay
  → use dileptonic $t\bar{t}$ events ($e\mu$)
  - Very clean samples



- Use $\Delta\phi$ between both leptons
  → no kinematic event reconstruction required

- Full $t\bar{t}$ event reconstruction for $m_{t\bar{t}}$
  → use of neutrino weighting for full reconstruction
  - Uses known top and W boson mass as constraints to explore missing neutrino information

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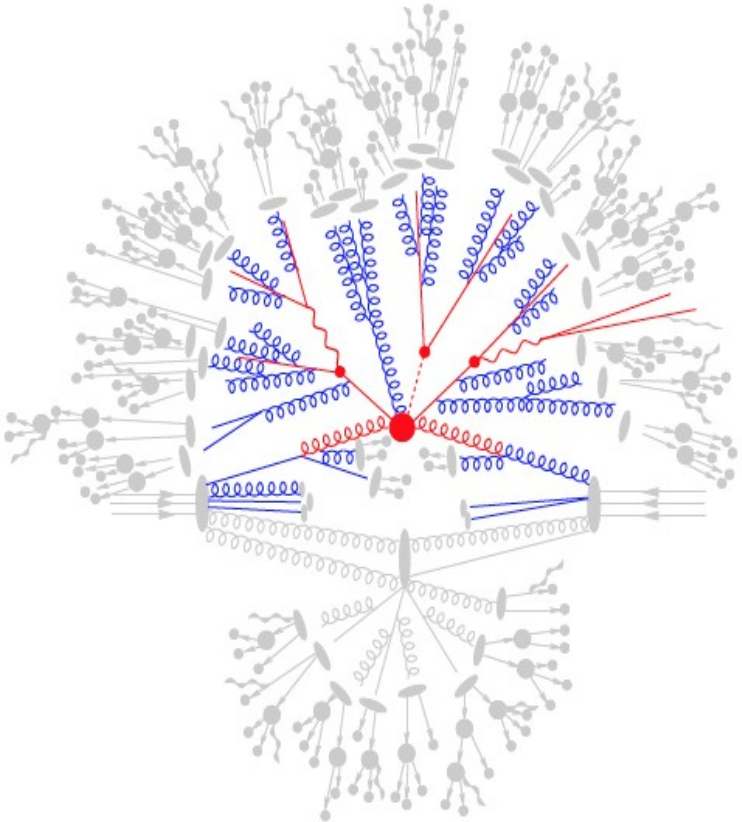
Analysis Strategy

- Unfolded differential measurements:
  - Parton-level
    - Inclusive and in bins of $m_{t\bar{t}}$
  - Particle level

    Inclusive and in bins of $m_{t\bar{t}}$



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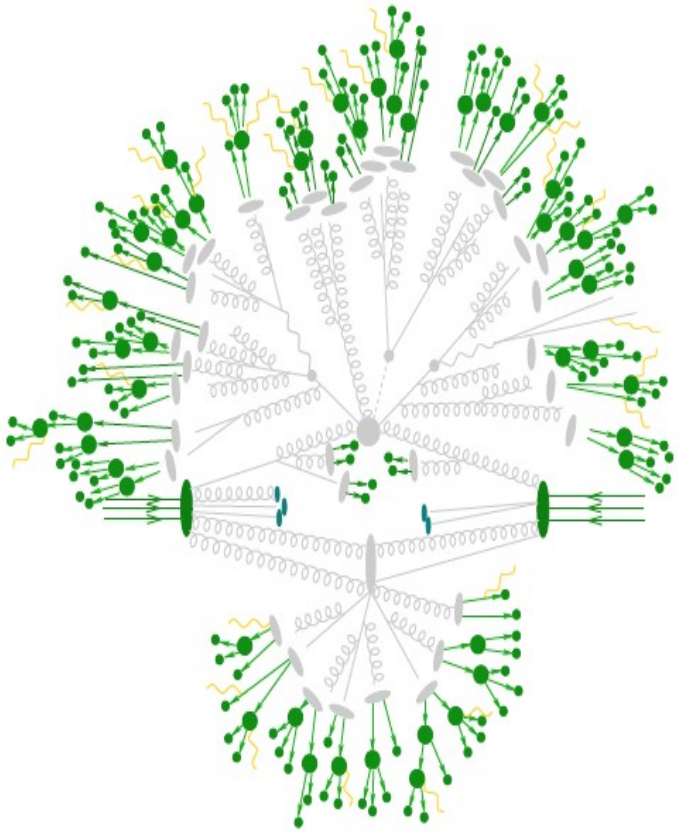
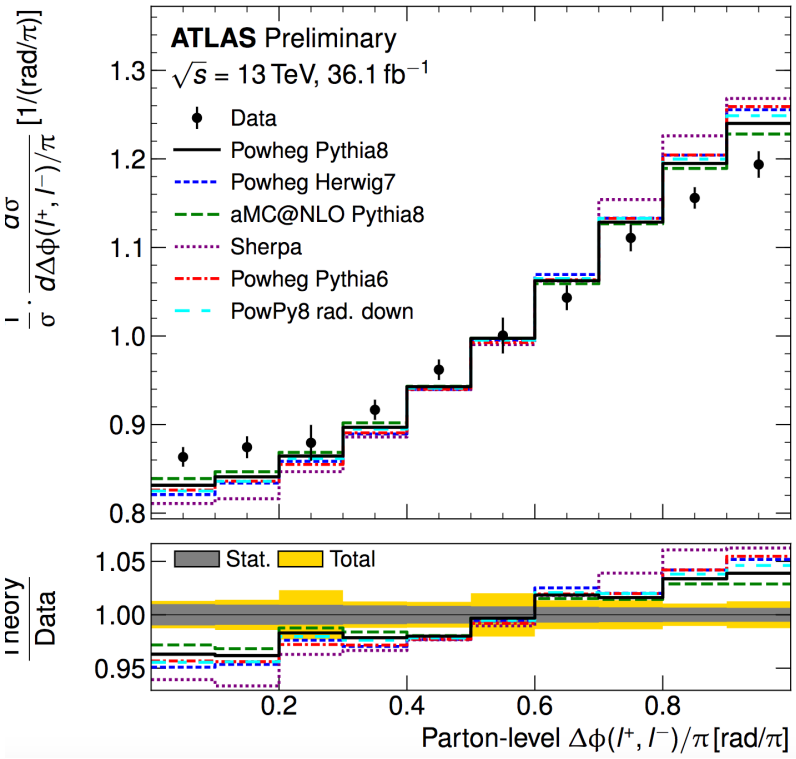


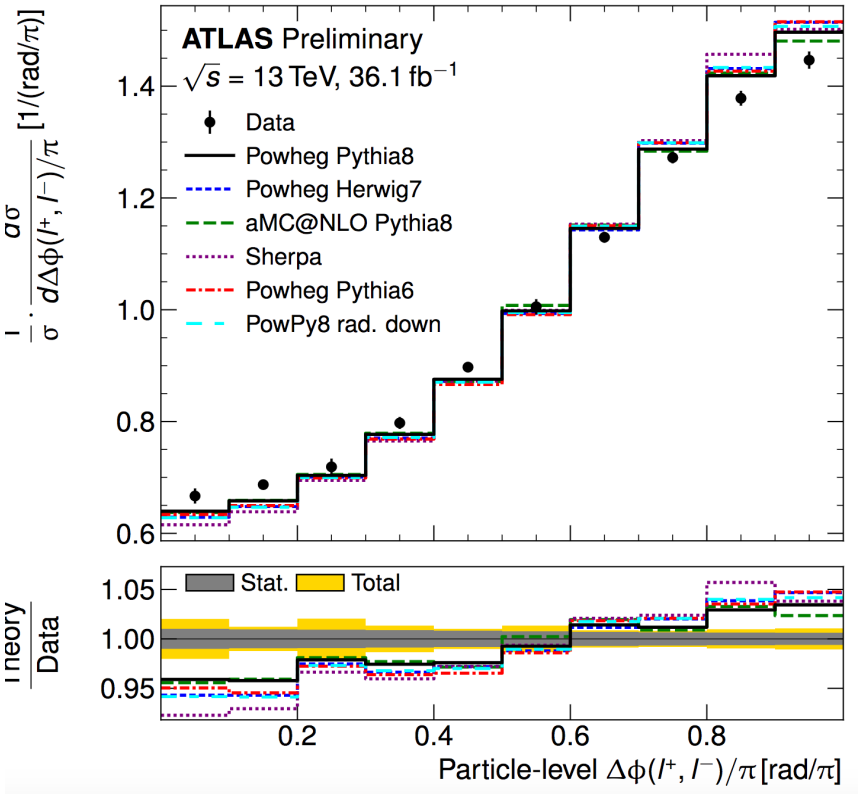
Unfolded distributions

- Unfolded distributions compared to different MC predictions

Parton



Particle



- Data shows shallower slope than prediction

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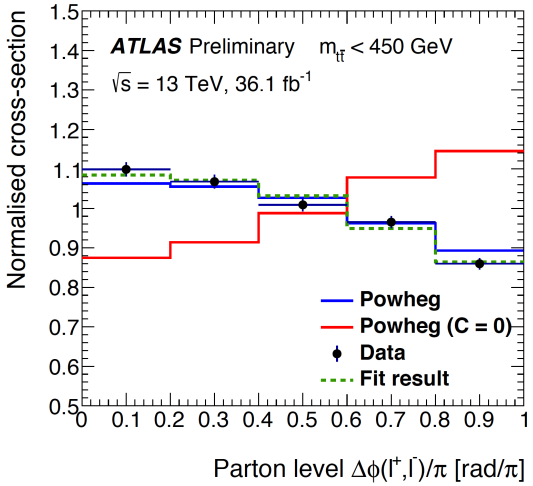
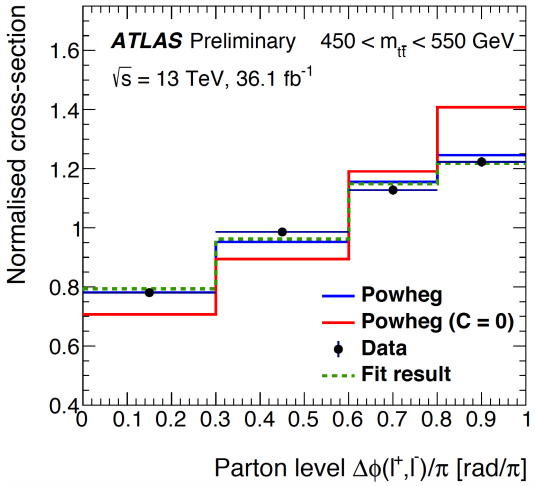
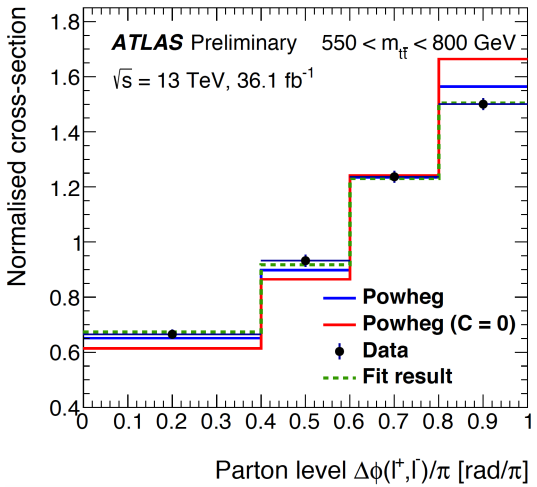
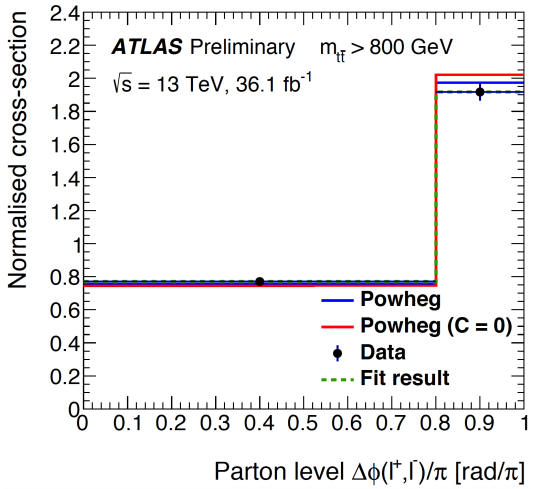
Template fit

- Fitting spin and no-spin hypotheses to parton-level distributions









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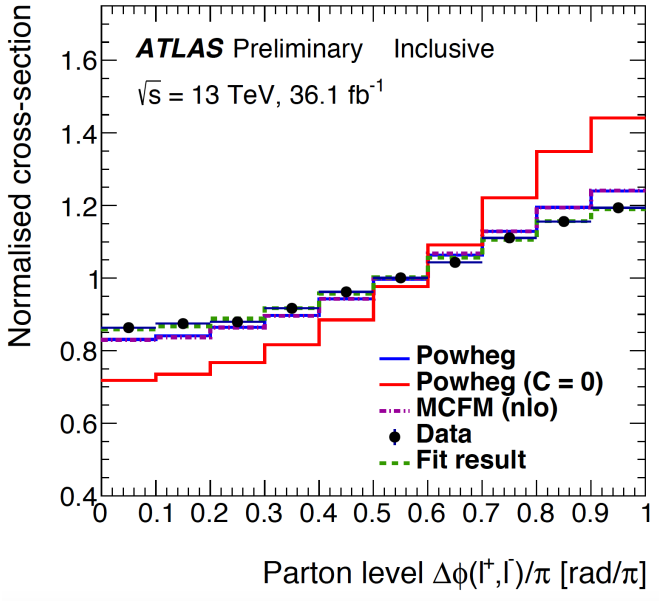
Template fit

- Fitting spin and no-spin hypotheses to parton-level distributions

Region	f_{SM}	Significance (incl. theory uncertainties)
$m_{t\bar{t}} < 450$ GeV	$1.11 \pm 0.04 \pm 0.13$	0.85 (0.84)
$450 < m_{t\bar{t}} < 550$ GeV	$1.17 \pm 0.09 \pm 0.14$	1.00 (0.91)
$550 < m_{t\bar{t}} < 800$ GeV	$1.60 \pm 0.24 \pm 0.35$	1.43 (1.37)
$m_{t\bar{t}} > 800$ GeV	$2.2 \pm 1.8 \pm 2.3$	0.41 (0.40)
inclusive	$1.250 \pm 0.026 \pm 0.063$	3.70 (3.20)



- Spin correlations higher than SM prediction by 3.7σ
  (3.2σ including theory uncertainty)

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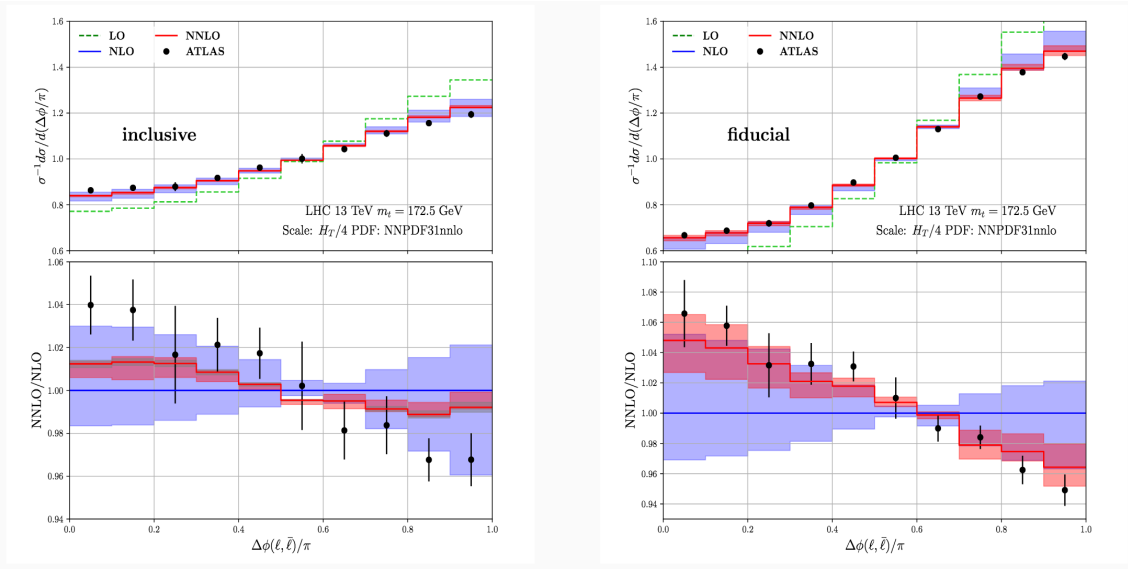
Spin: Quo Vadis?

- Many developments going on
  - Higher-Order calculations?
    (figure from Rene Poncelet's
    talk at TopLHCWG meeting 21.11.)
  - New Physics?



- Both communities working on understanding effect
  → need to measure more variables (e.g. full spin density matrix)

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left(1 \pm (\alpha P)_1 \cos\theta_1 \pm (\alpha P)_2 \cos\theta_2 - C\cos\theta_1\cos\theta_2\right)$$

α_i: spin analyzing power of decay product i;

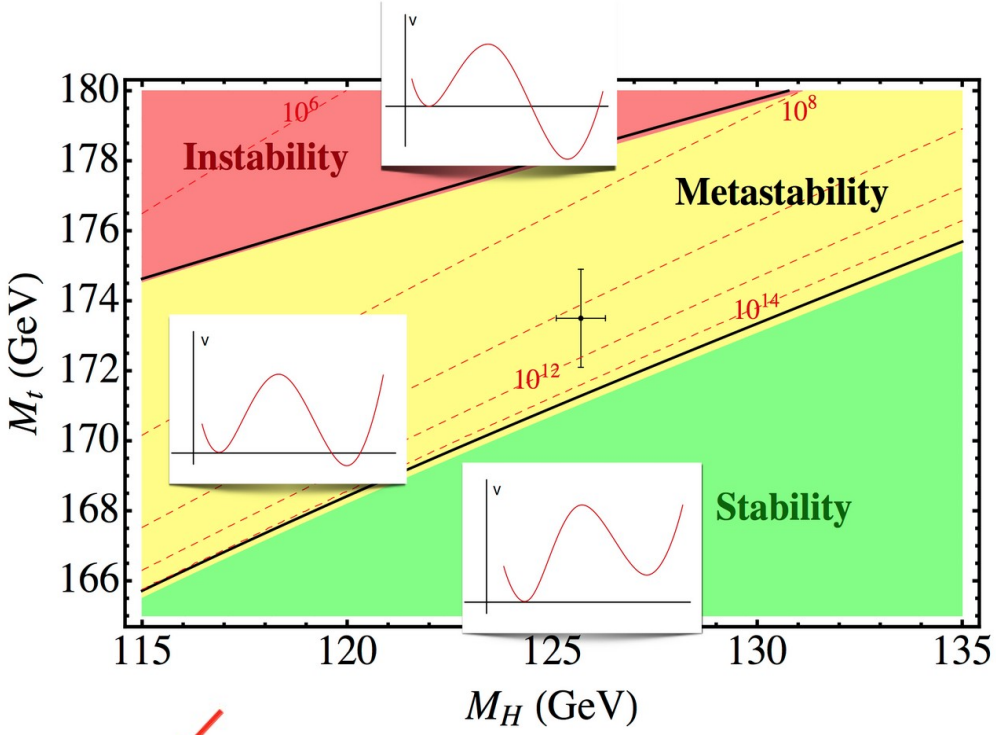
θ_i: direction of daughter wrt. chosen axis

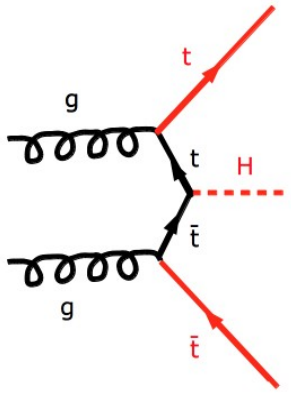
- P: polarization
- C: spin correlation

The Top and The Higgs

The Top and The Higgs

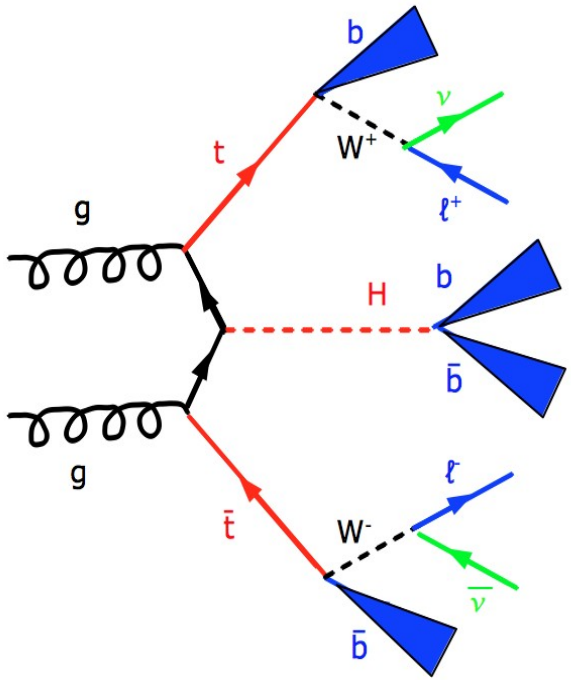
- Top and Higgs: Heaviest known elementary fermion and boson!
  - Top-Higgs Yukawa coupling: predicted to be ~1 in the SM
    → special role of top quark in electroweak symmetry breaking?
    → window to new physics?
    → metastable universe?
- Measuring top-Higgs Yukawa coupling directly: important! (indirectly: in H→$\gamma\gamma$ and gg→H)
  - Main channel: $t\bar{t}H$





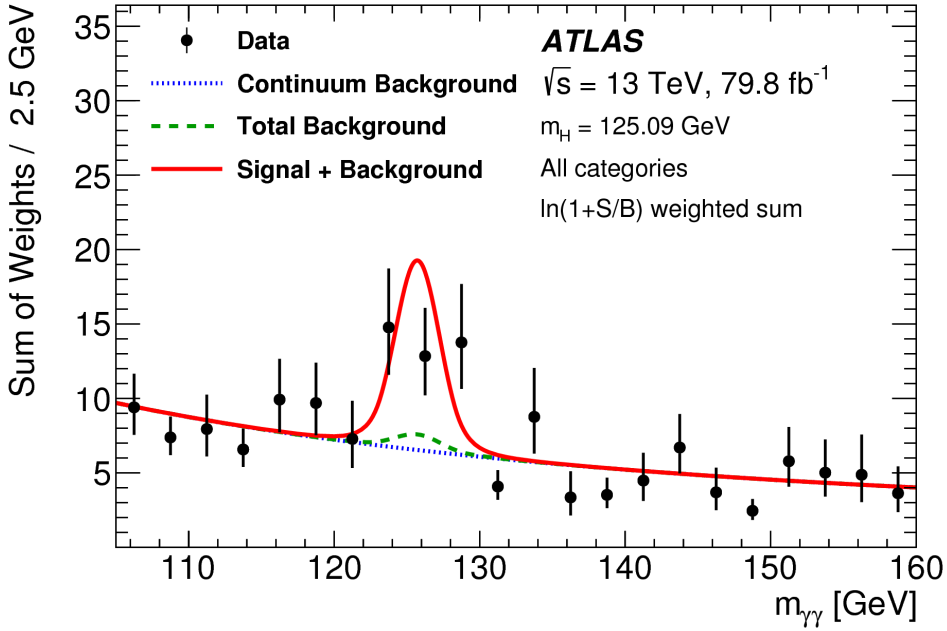
The Top and The Higgs

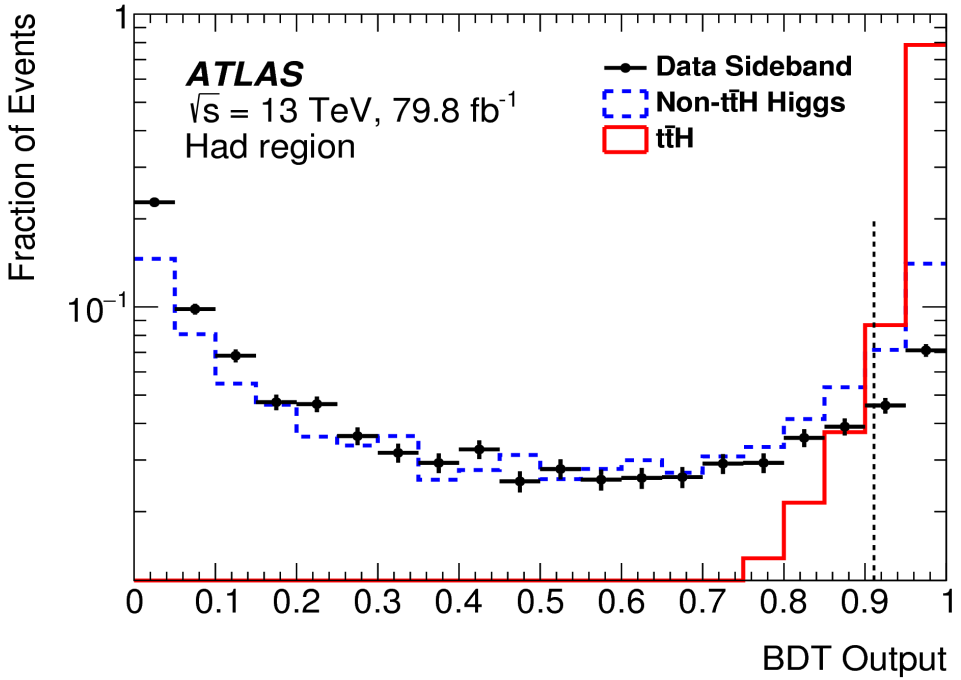
- This year: First observation of ttH!
  (first by CMS, then ATLAS; similar strategies, concentrating on ATLAS here)
  - Combination of multiple channels:
    - Higgs decay to $b\bar{b}$, WW*, $\tau^+\tau^-$, $\gamma\gamma$, ZZ*
    - Hadronic and/or leptonic top decays used



Diphoton Channel

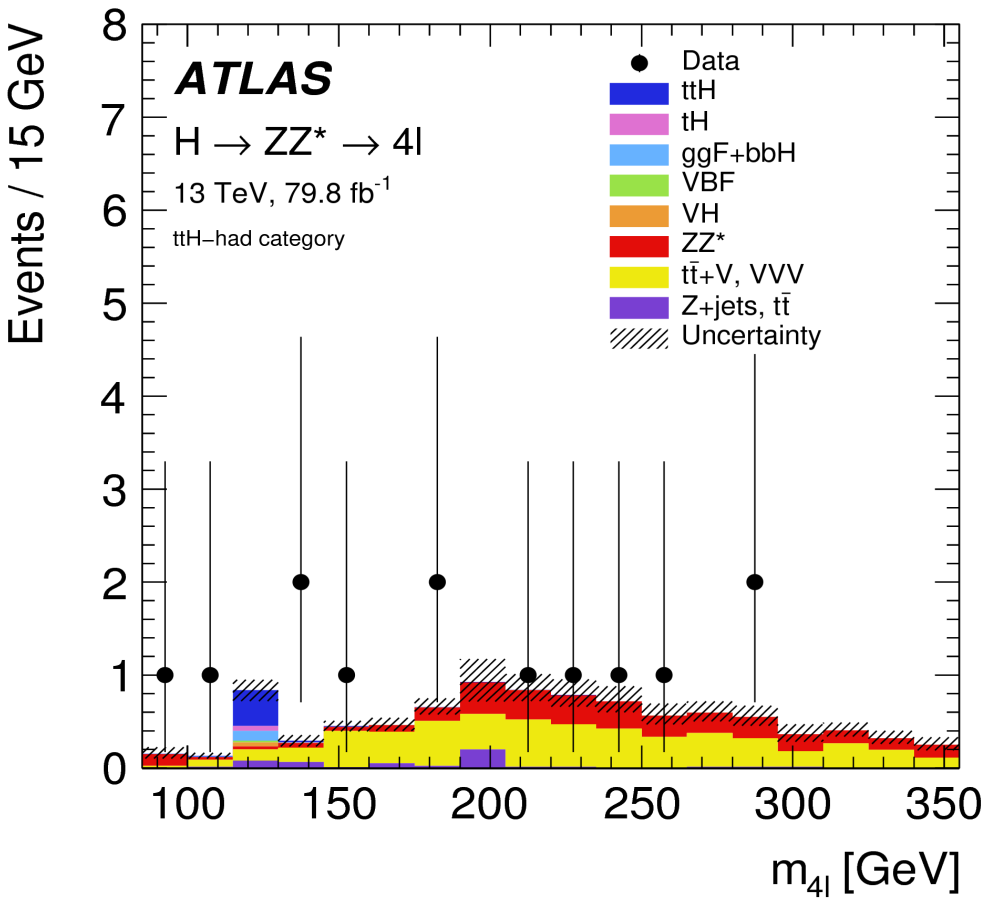
- Define two regions: hadronic top decays or events with at least one charged lepton
  - $m_{\gamma\gamma}$: has to be between 105 and 160GeV
- For each region: train BDTs





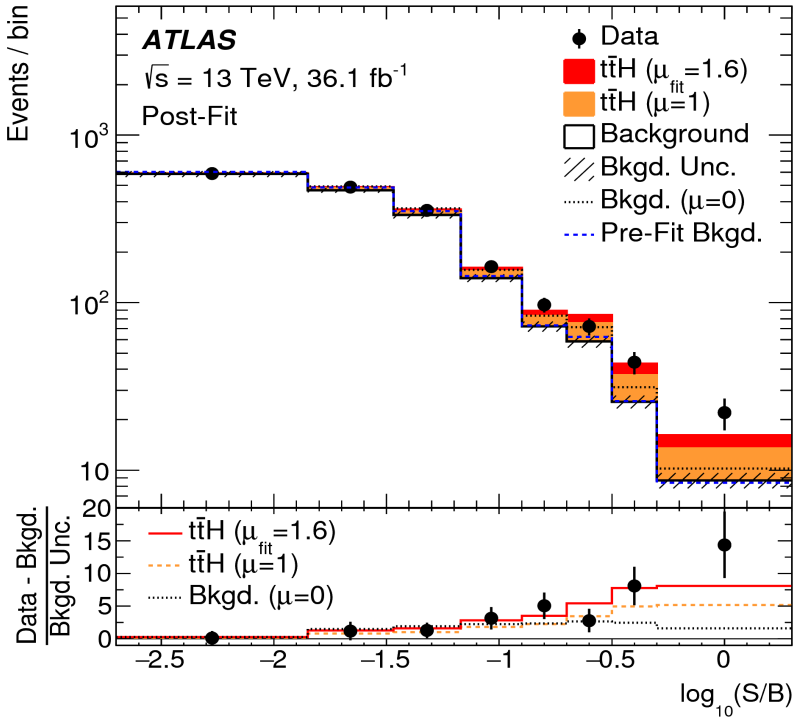
ZZ Channel

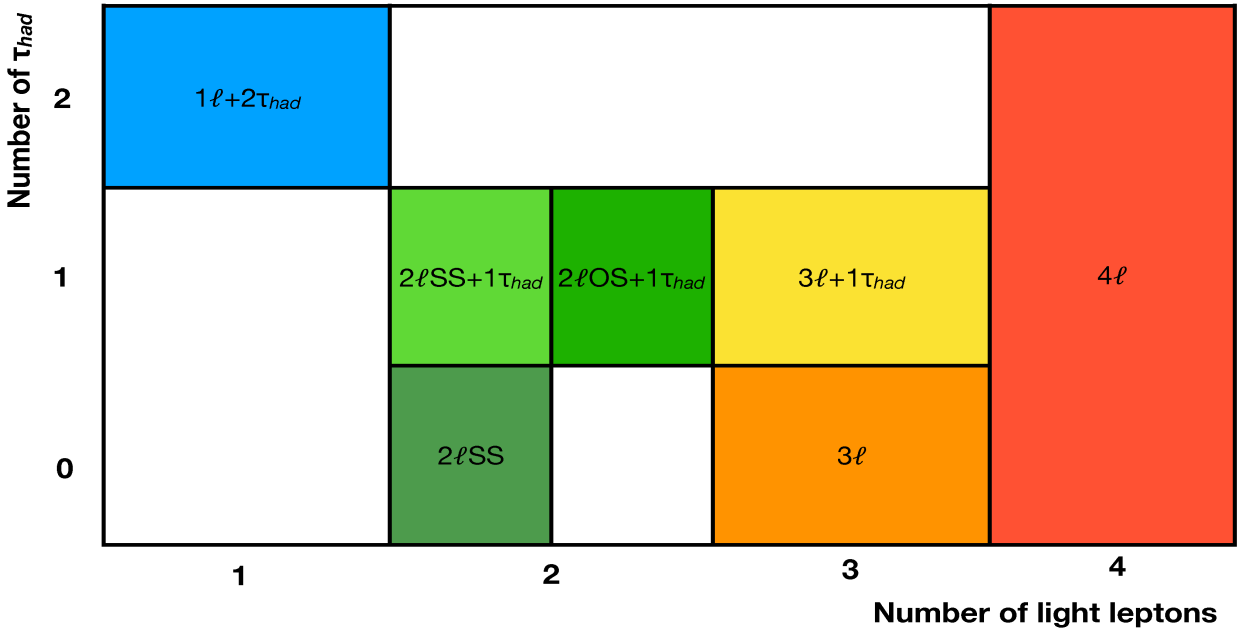
- Use events with at least 4 isolated charged leptons
  - Two regions: hadronic (both tops decay hadronically) and leptonic (at least one top decays leptonically)
  - BDT used on hadronic region



Multilepton Channel

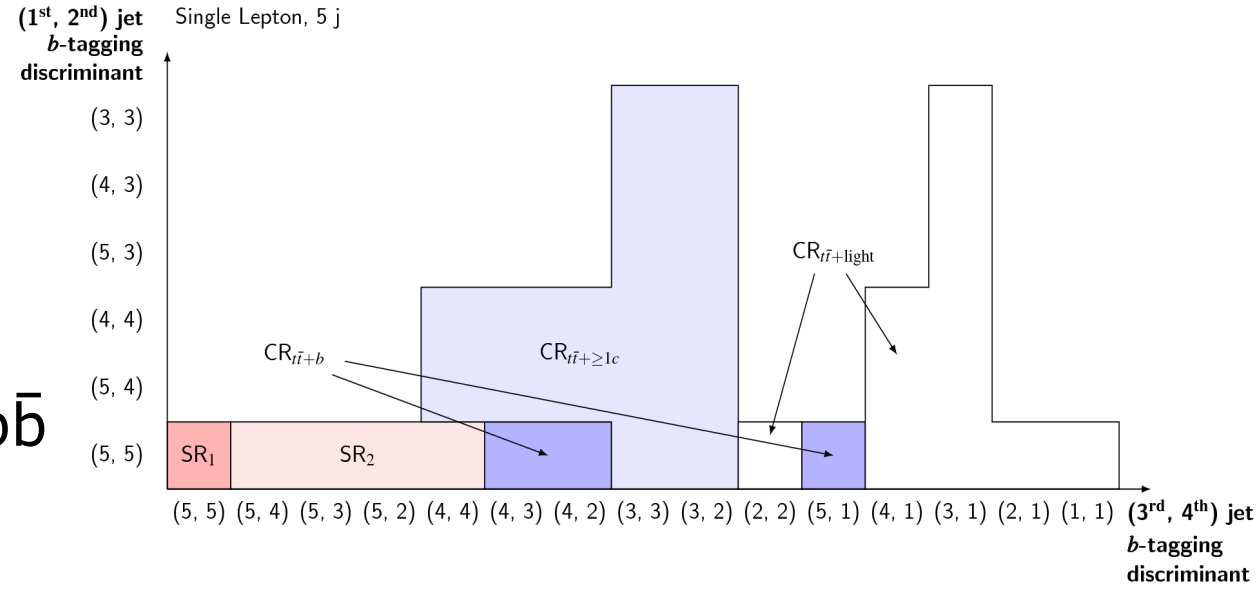
- Includes H→WW (&ZZ) and H→$\tau\tau$ decays
- Many channels considered
  - Some use BDTs

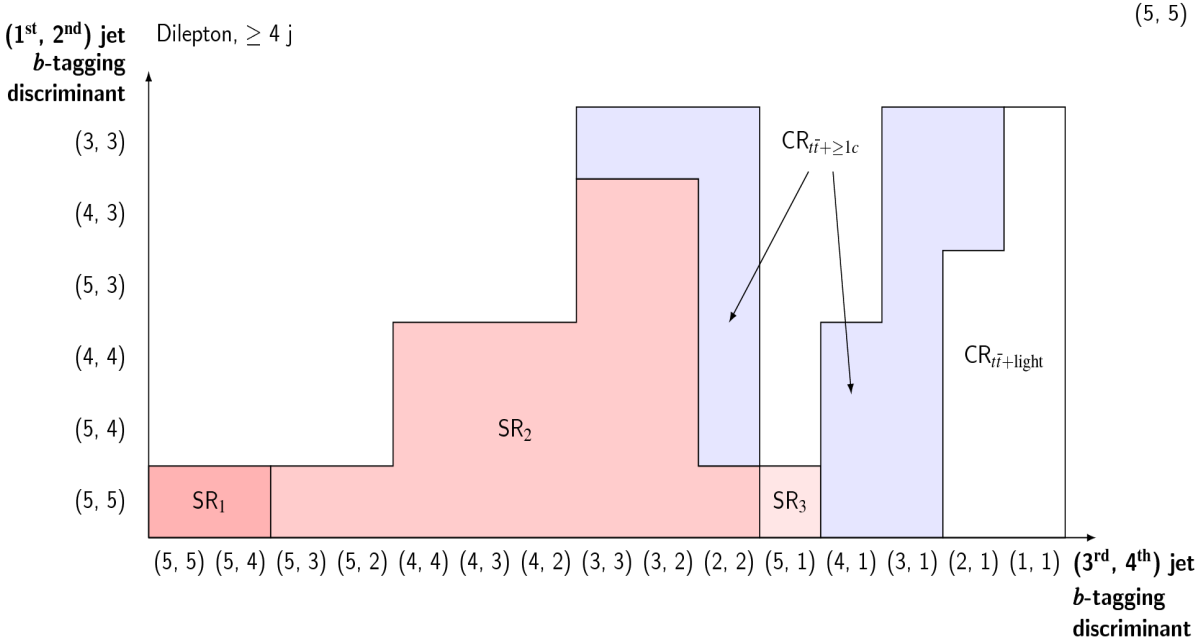




H → bb̄ Channel

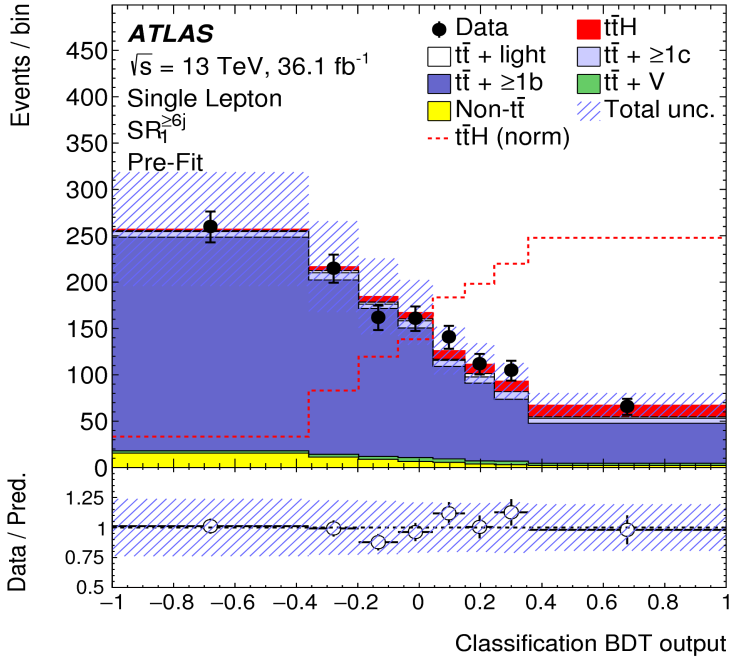
- Semileptonic and dileptonic channels considered
  - Separation in many different control and signal regions
- Very challenging analysis
  - Modeling of background tt̄bb̄

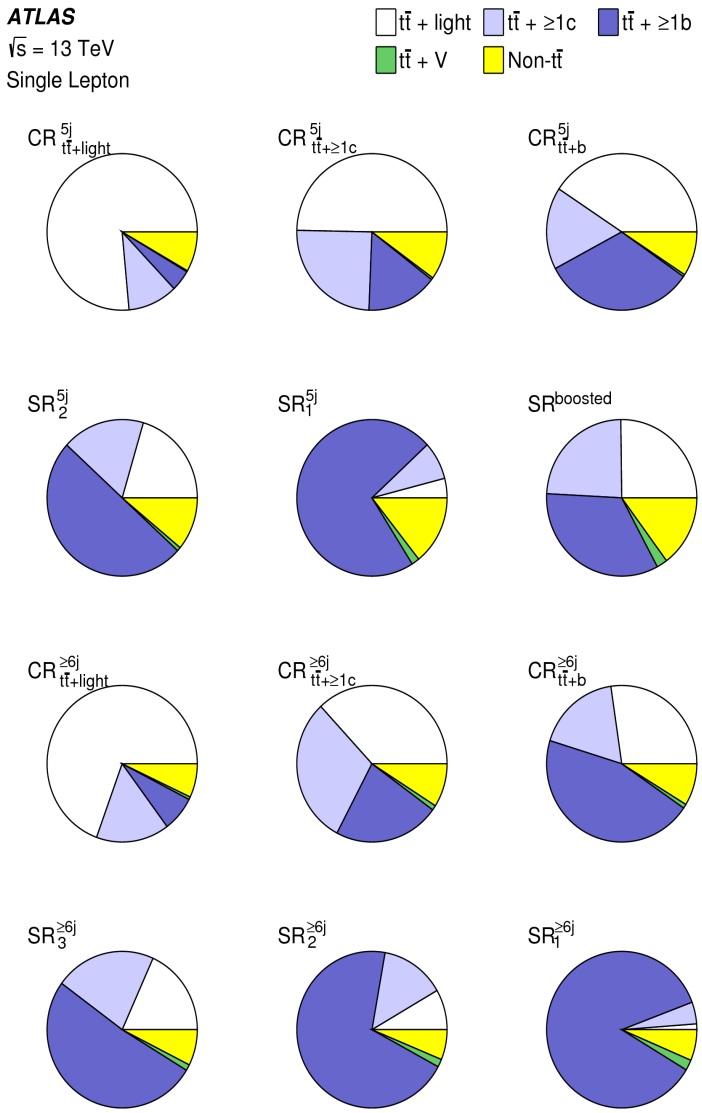




Semileptonic

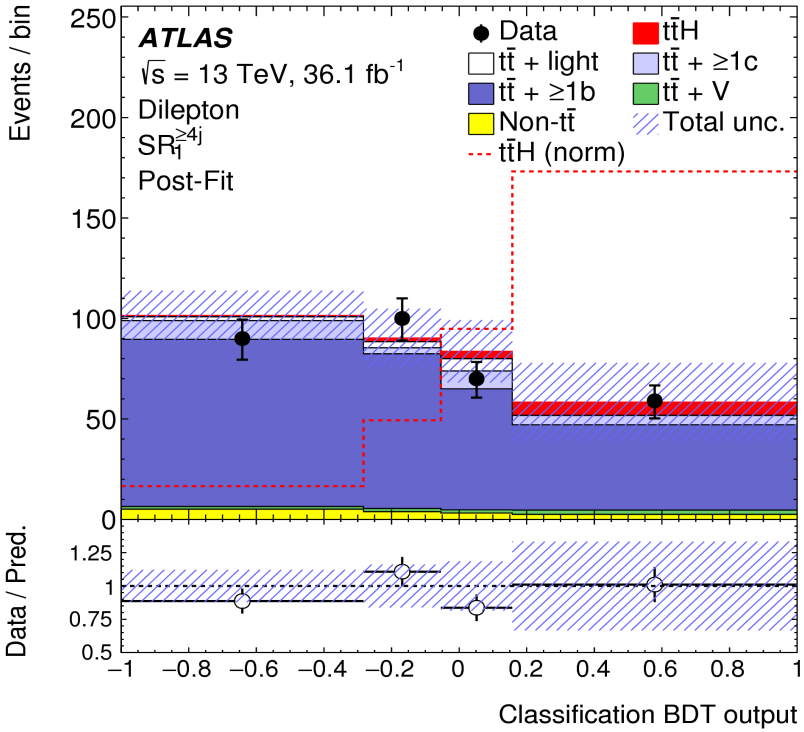
- BDTs used enhancing significance
  - Reconstruction of event done with "reconstruction BDT"
    → access to variables using full events
- Fits including control regions
  → improves control over backgrounds

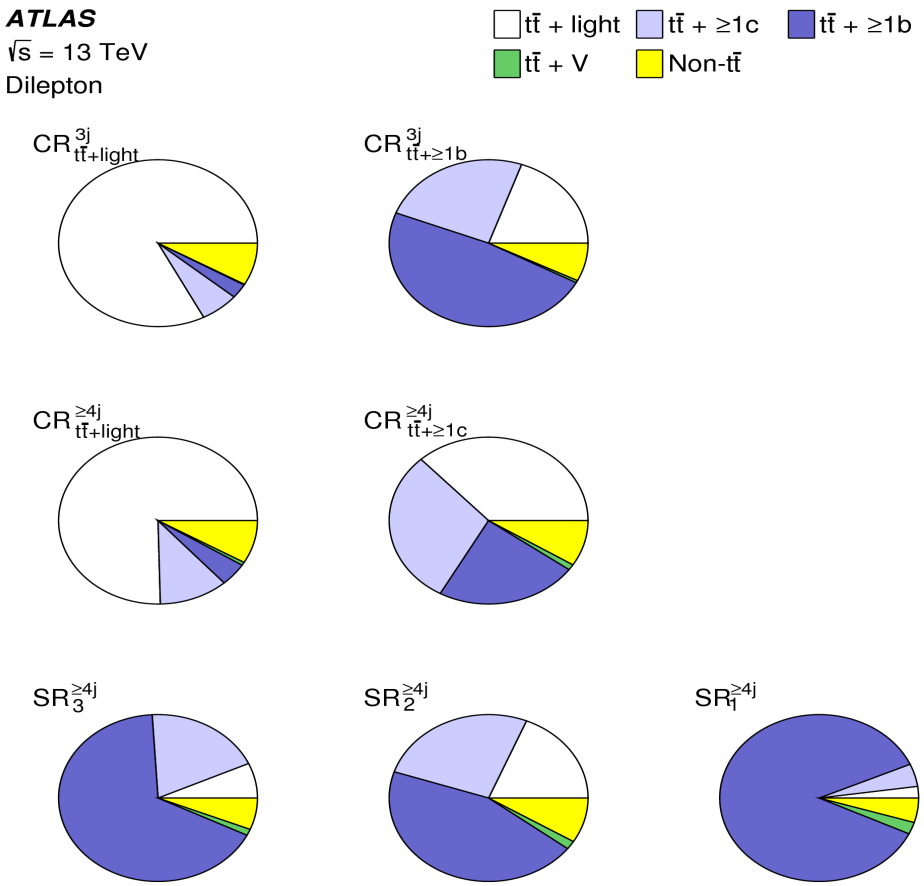




Dileptonic

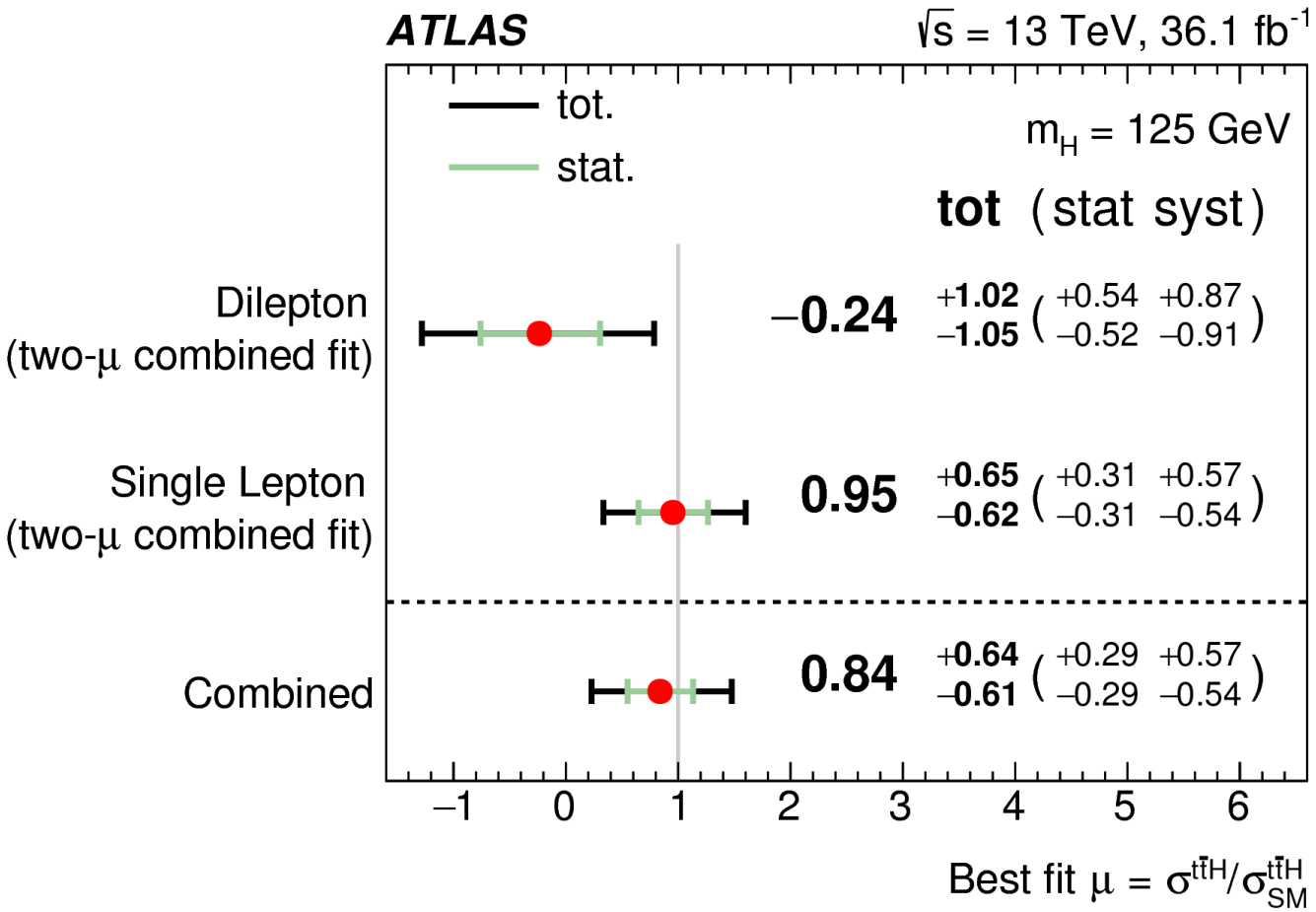
- Similar strategy as in semileptonic channel
  - Reconstruction of full event information more challenging due to two neutrinos





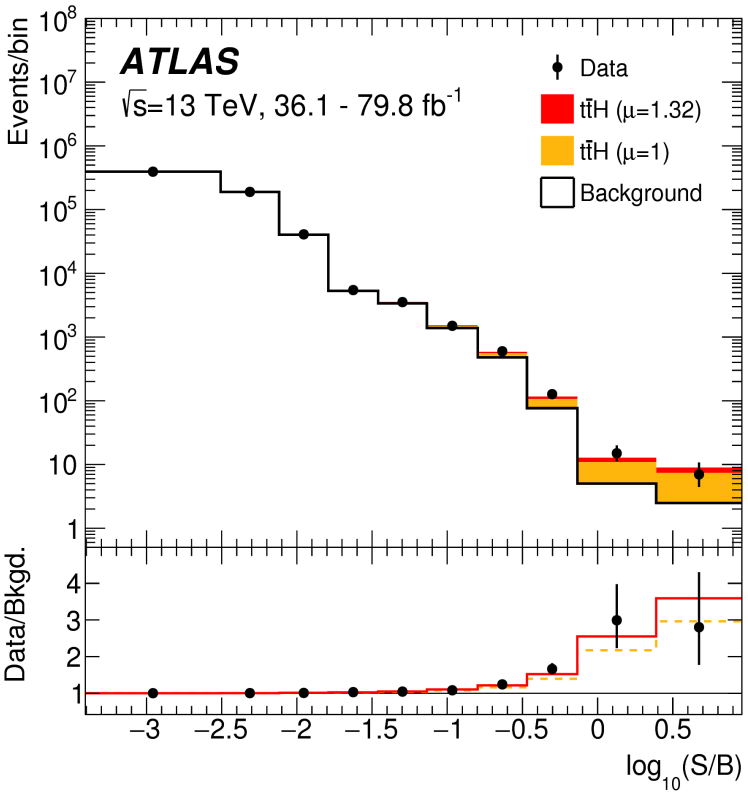
$t\bar{t}H$, $H \rightarrow b\bar{b}$ Results

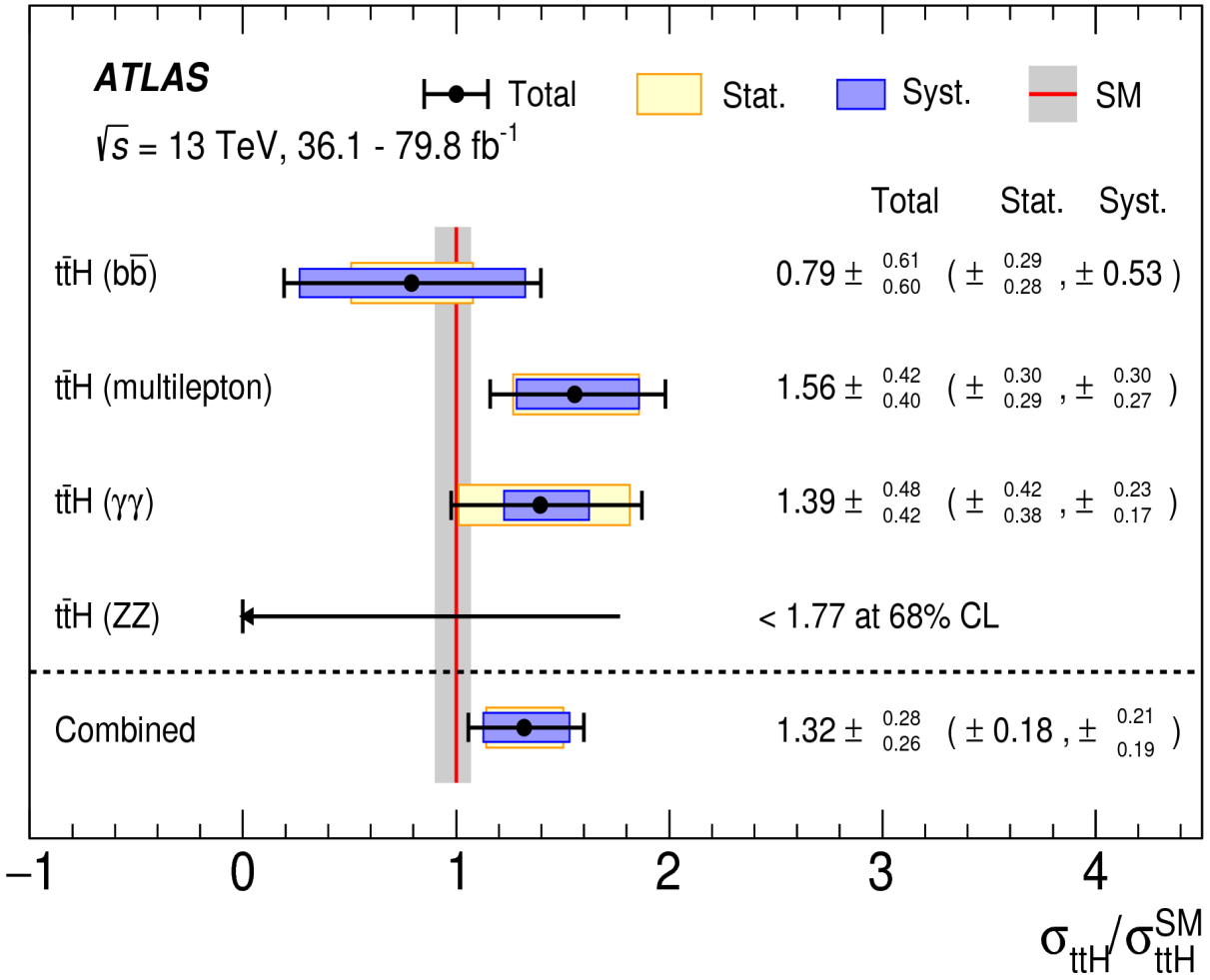
- Results already dominated by systematic uncertainties
  → background modeling of $t\bar{t}b\bar{b}$ a main factor



Combination

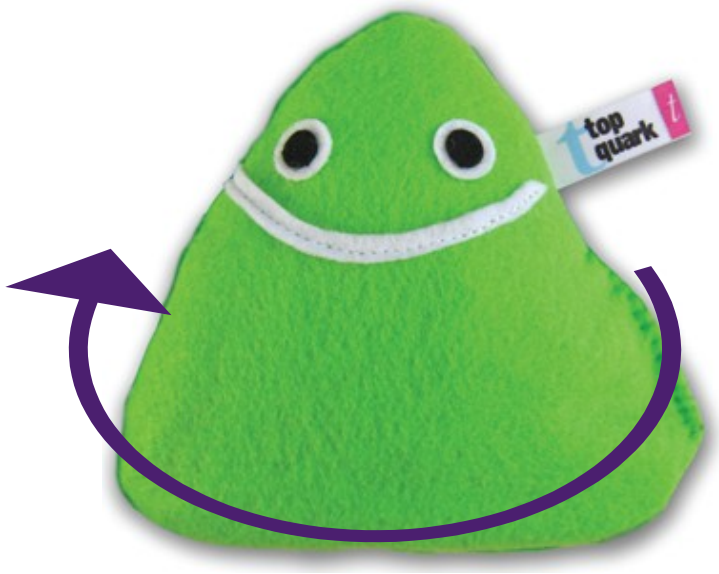
- Combination of all channels: Observation of $t\bar{t}H$!
  - Observed significance of 5.8σ





Summary

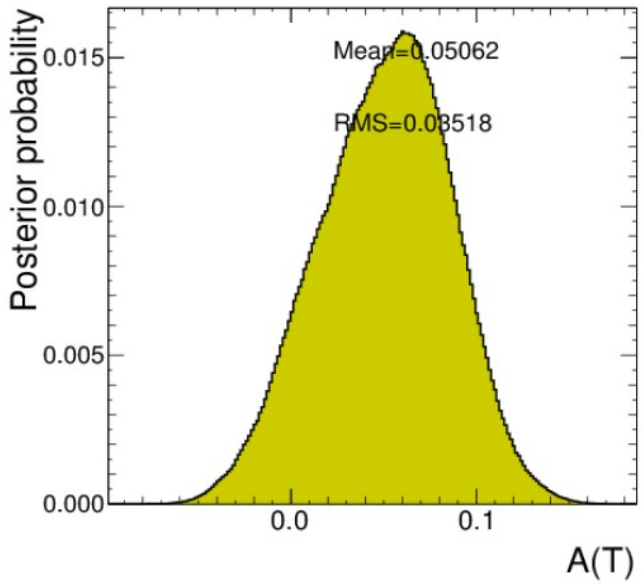
- Top Quark Physics: Probing the heaviest known elementary particle!
  - Jet pull: accessing colour-flow information between jets
    → information on QCD colour-nature of mother particle
  - Precision measurement of spin correlations
    - probing the full top production and decay chain ever more precise
  - Top-Higgs: observation of $t\bar{t}H$
    → new era of exploring the connection between heaviest elementary particles
- Everything compatible with SM so far
- Tops were, are and stay awesome
  → much to learn about the SM and beyond



BACKUP

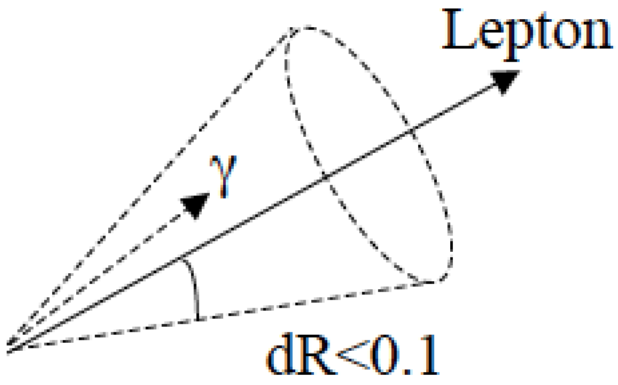
FBU

- FBU principle: apply Bayes theorem and give posterior probability for different possible spectra
- Elements needed:
  - input: $\Delta|y|$ distribution in background subtracted data
  - efficiency and response matrix taken from the signal sample (Powheg)
  - output: posterior distribution for the asymmetry
- We take the mean as central value and the smallest interval covering 68% of the integral as the uncertainty.



Differential

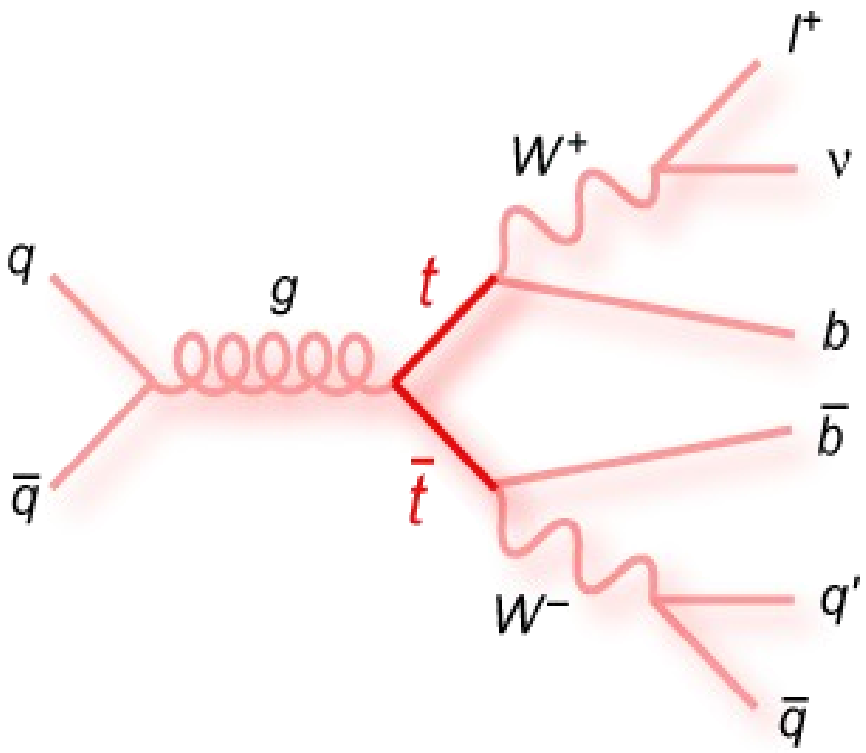
- Define "pseudo-tops" on particle level
  - In fiducial region
  - Easy to reproduce for theorists!



- Pseudo-top:
  - Use particles with mean lifetime > $3*10^{-11}$s
  - Leptons: use "dressed lepton":
    leptons are used together with photons in their vicinity
  - Jets: anti-k_T with R=0.4 applied on stable particles (not leptons or neutrinos)
    - Presence of b-hadron with p_T>5GeV: jet is taken as a b-jet

Differential

- l+jets channel: selection



Exactly 1 lepton (e or μ)

e: p_T>25GeV, $|\eta|$<2.47 & !(1.37<$|\eta|$<1.52)

μ: p_T>25GeV, $|\eta|$<2.5

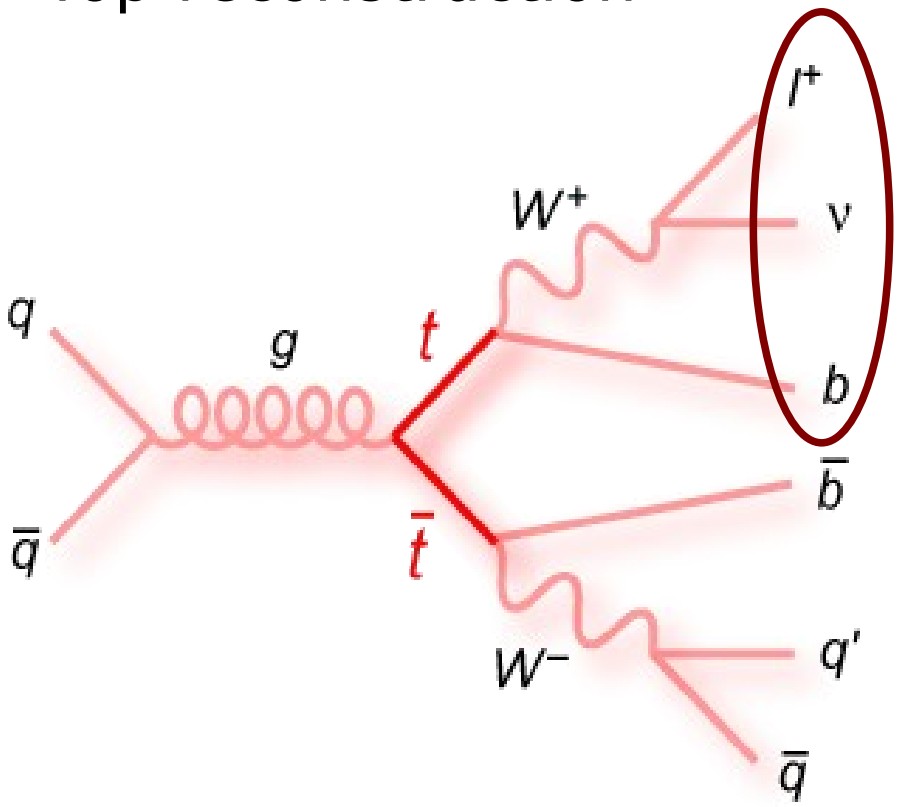
Missing p_T for neutrino ($\not{E}_T$): >30GeV

≥4 jets with p_T>25GeV; $|\eta|$<2.5

≥2 jets b-tagged

Differential

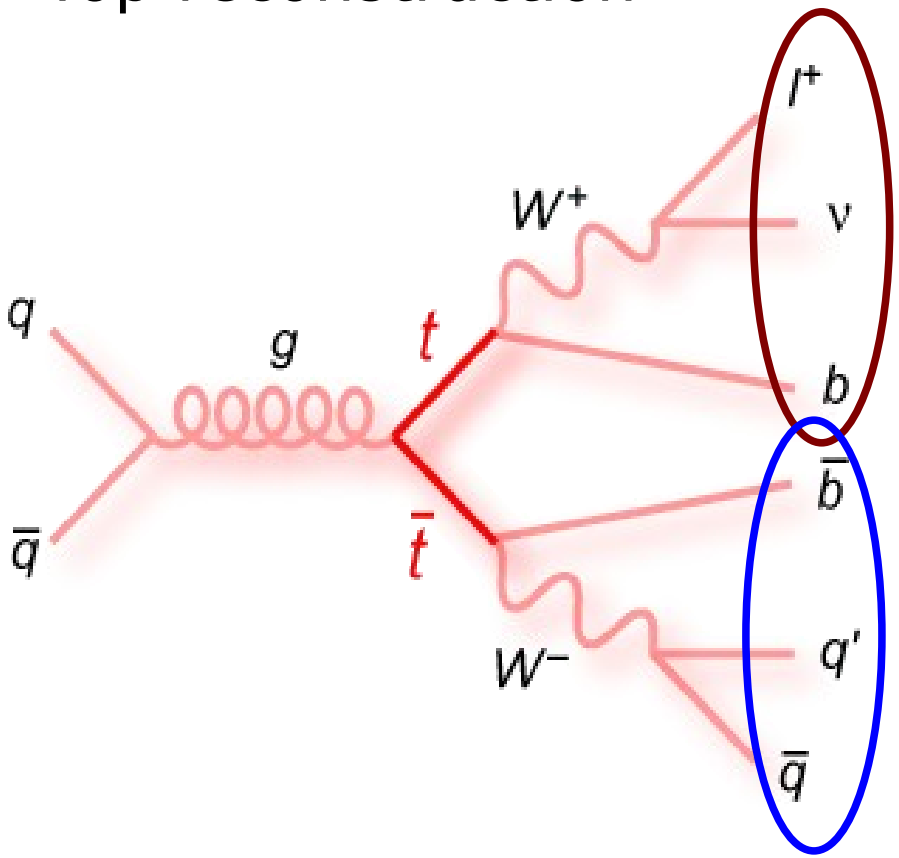
- Top reconstruction



Leptonic pseudo-top:
- construct leptonically decaying W from lepton and E_T^{miss}
- b-jet with smallest ΔR to lepton

Differential

- Top reconstruction



Leptonic pseudo-top:
- construct leptonically decaying W from lepton and E_T^{miss}
- b-jet with smallest ΔR to lepton

Hadronic pseudo-top:
- construct W from remaining two highest-p_T jets
- use remaining b-jet

Colour Flow: Systematics

$\Delta\theta_P\left(j_1^W, j_2^W\right)$ [%]	$\theta_P\left(j_1^W, j_2^W\right)$			
	0.0 – 0.21	0.21 – 0.48	0.48 – 0.78	0.78 – 1.0
Hadronisation	0.63	0.22	0.27	0.09
Generator	0.37	0.24	0.50	0.06
Colour Reconnection	0.11	0.26	0.03	0.53
b-Tagging	0.35	0.12	0.20	0.31
Non-Closure	0.25	0.07	0.08	0.30
ISR / FSR	0.32	0.12	0.15	0.01
Other	0.25	0.20	0.11	0.18
JER	0.12	0.13	0.21	0.03
JES	0.13	0.06	0.13	0.07
Tracks	0.09	0.04	0.05	0.07
Syst.	0.97	0.52	0.68	0.72
Stat.	0.22	0.18	0.17	0.26
Total	0.99	0.55	0.71	0.76