Hot TOP(phys)ics

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MANCHESTER 1824

European Research Council

Established by the European Commission

Structure

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

Introduction

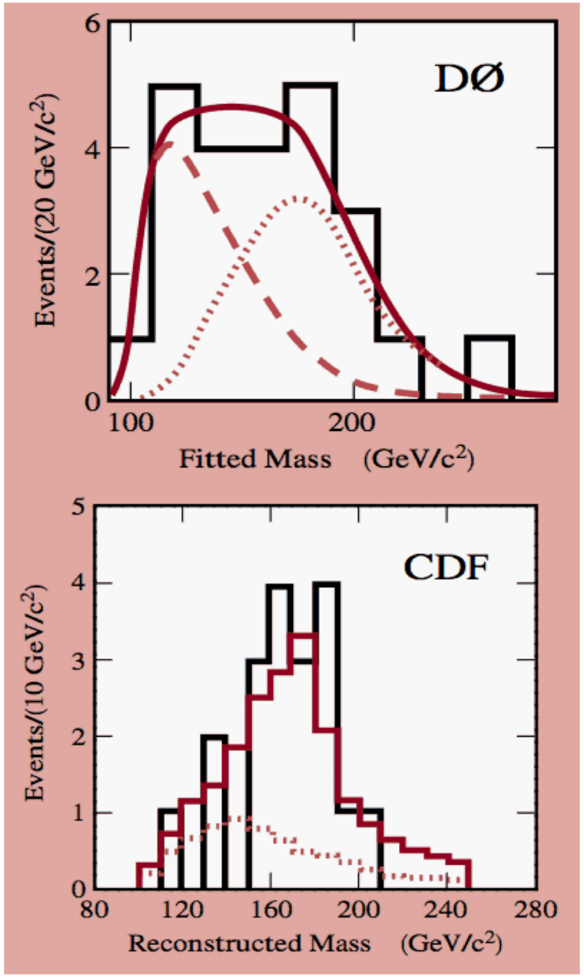
The Top Quark

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

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

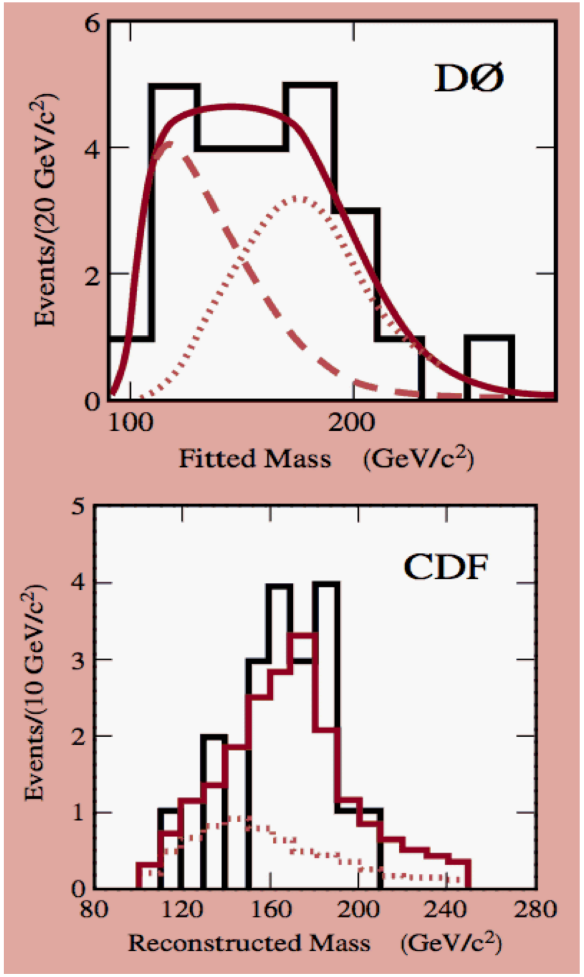
Top: From Discovery…

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



...to Precision

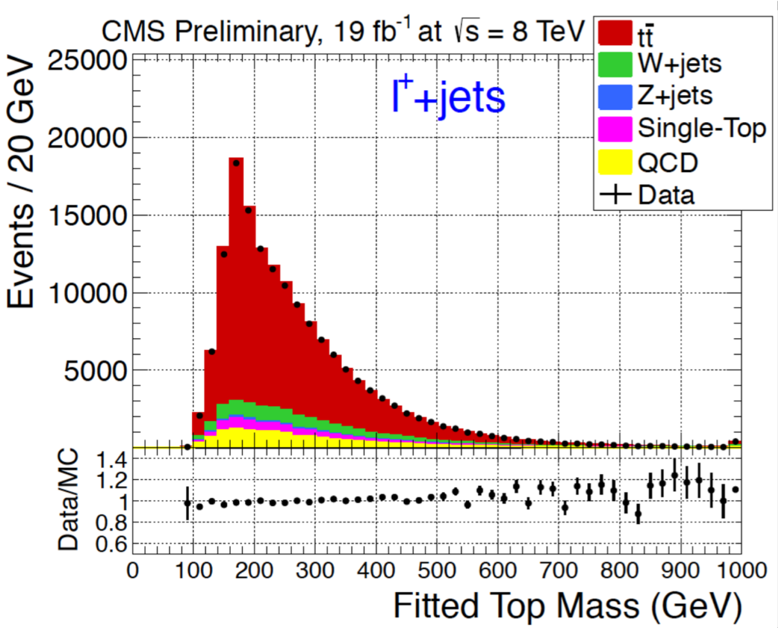
- Discovered in 1995 by CDF and DØ at Fermilab (with few events)

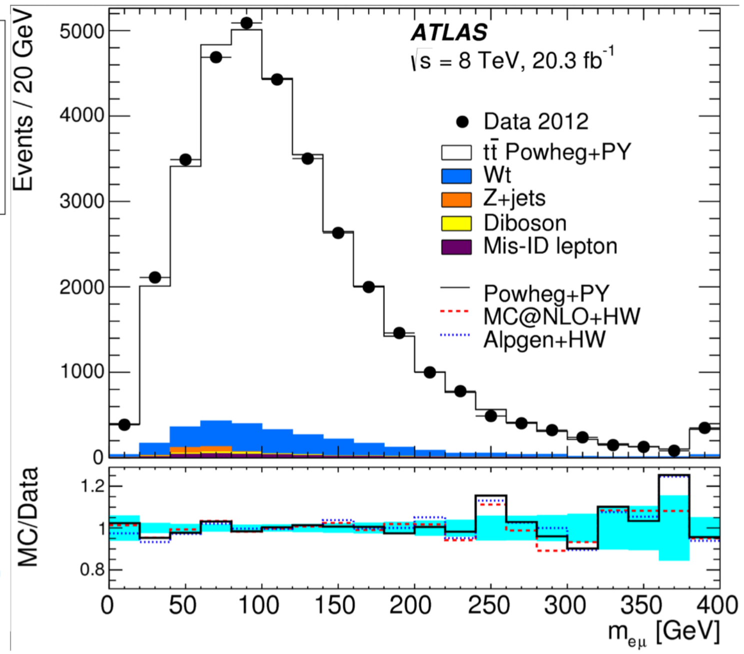


Situation today:

LHC → top quark factory!

Many precision measurements possible!

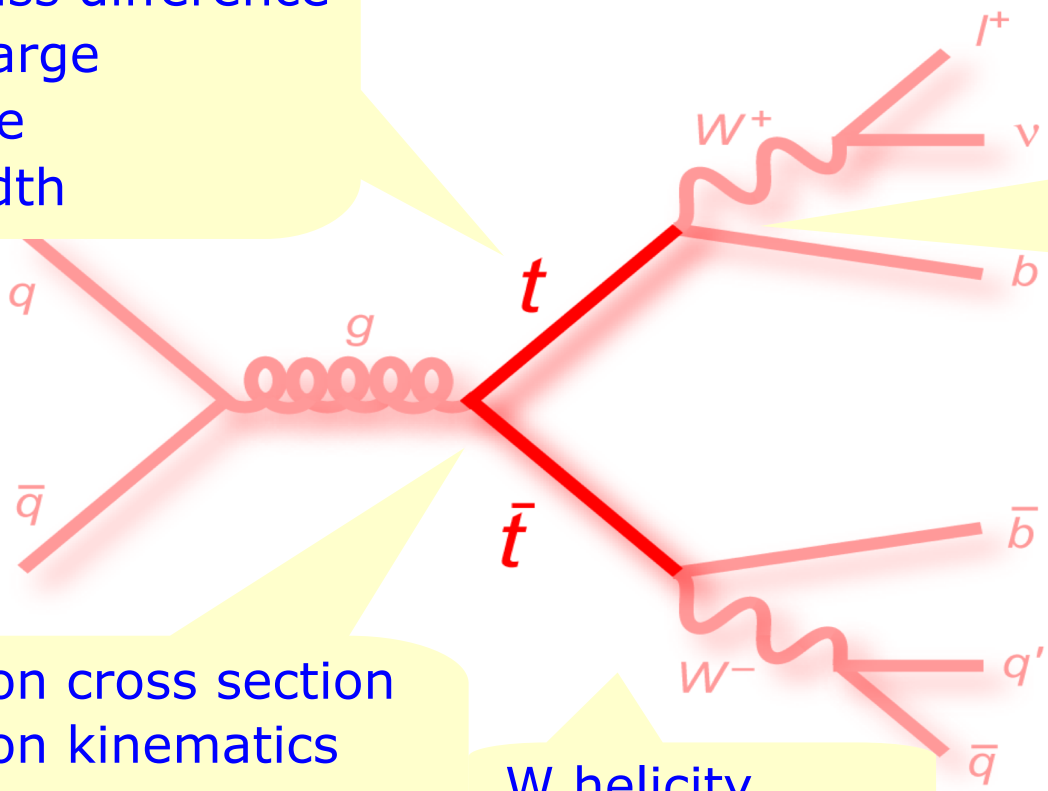




Top Studies: Overview

Top mass
Top mass difference
Top charge
Lifetime
Top width

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



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

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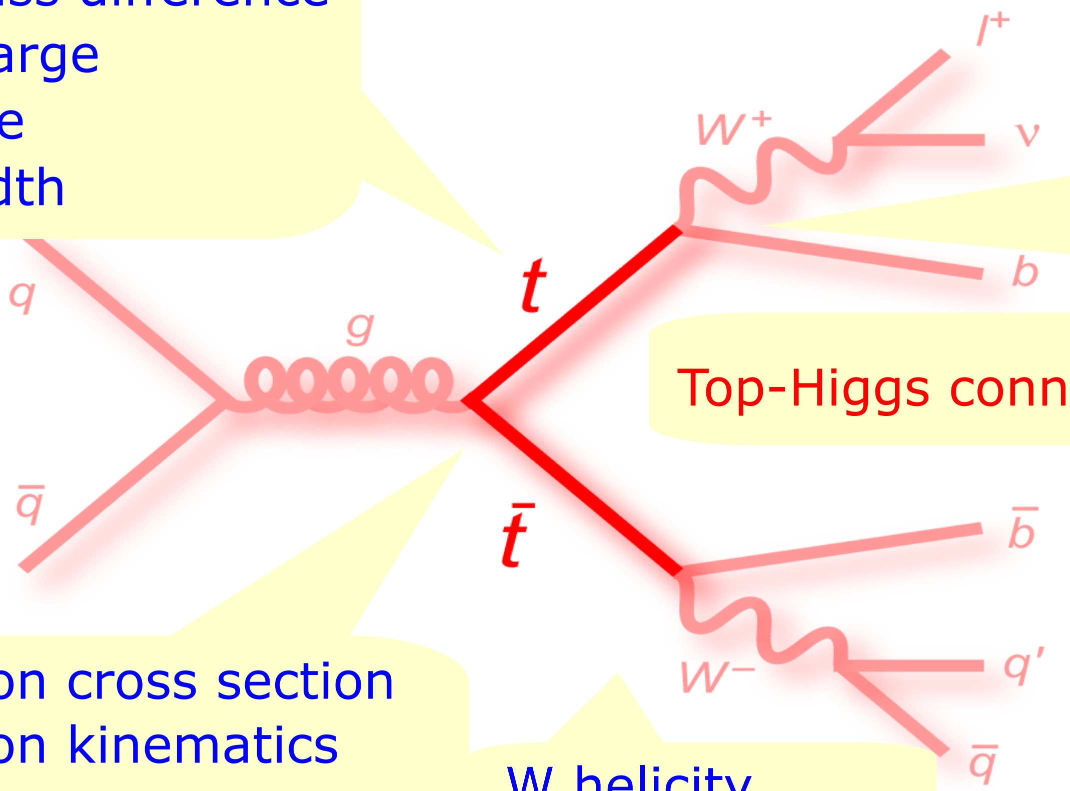

Top-Higgs connection

Spin correlation
Charge asymmetry
Color Flow

Production cross section
Production kinematics
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New particles

W helicity

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

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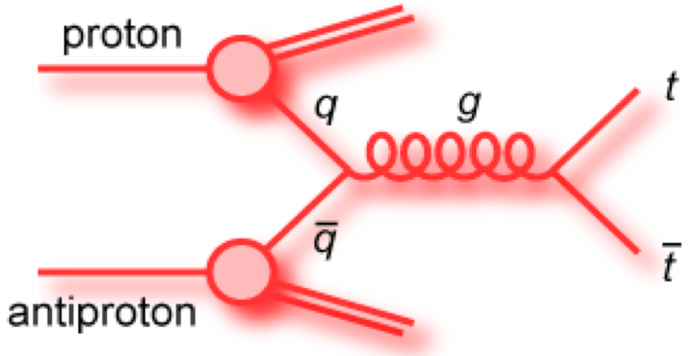
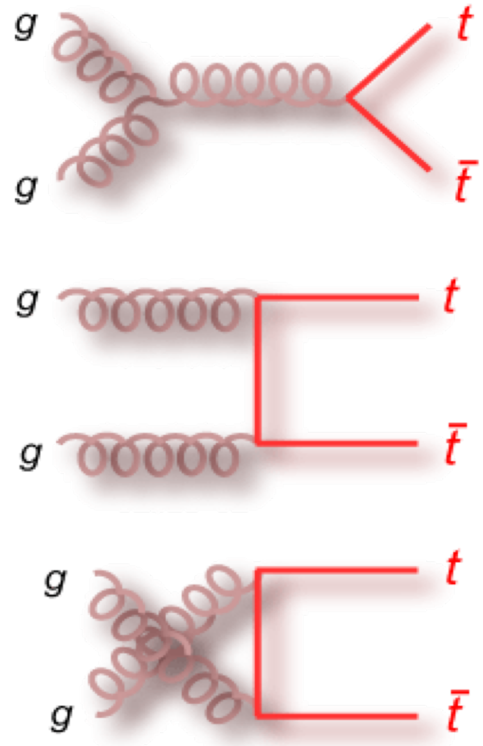
Top Quark Pair Production

At the Tevatron:



85% + 15%



At LHC:

14 TeV: 10% + 90%

7 TeV: 30% + 70%

Top Quark Pair Production

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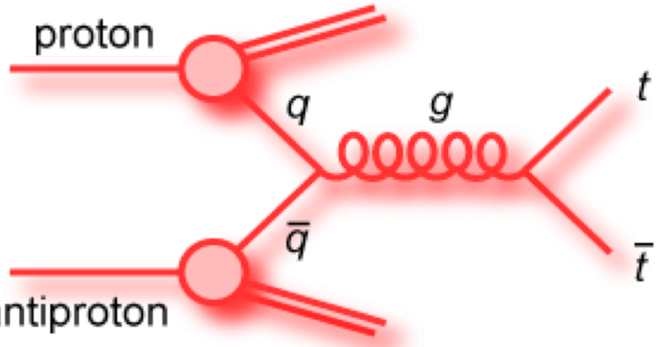
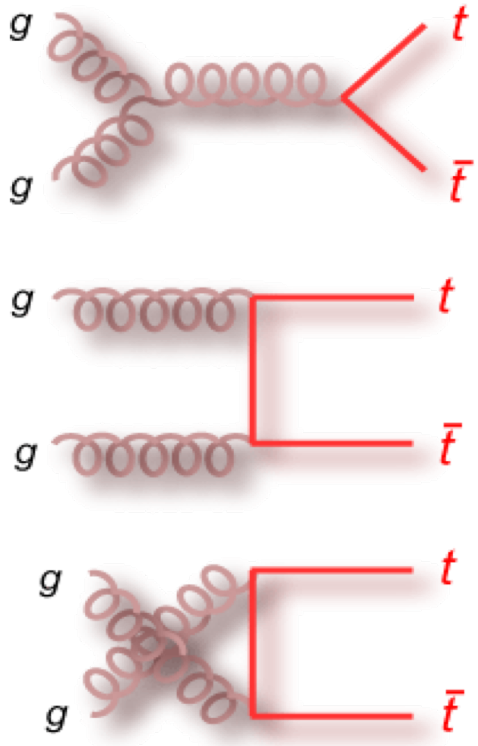
85%



+ 15%



At LHC:

14 TeV: 10% + 90%

7 TeV: 30% + 70%

Cross Sections:

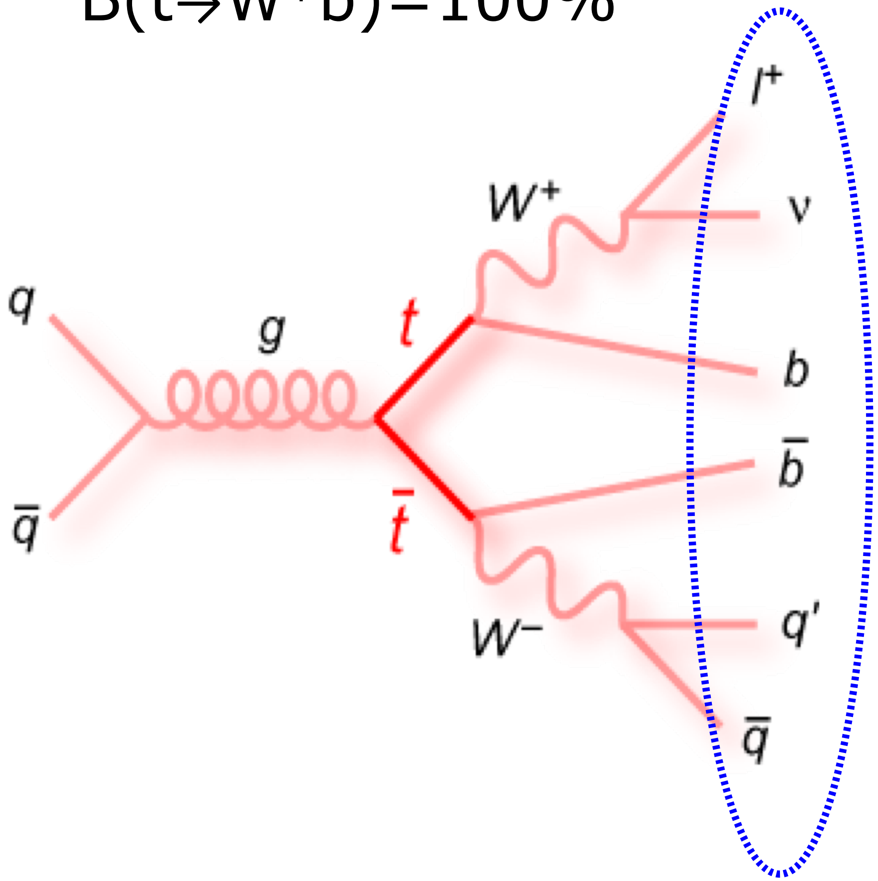
Collider	Cross section [pb]
Tevatron (1.96 TeV)	$7.35^{+0.23}_{-0.27}$
LHC (7 TeV)	$177.3^{+10.1}_{-10.8}$
LHC (8 TeV)	$252.9^{+13.3}_{-14.5}$
LHC (13 TeV)	$831.8^{+40.3}_{-45.6}$

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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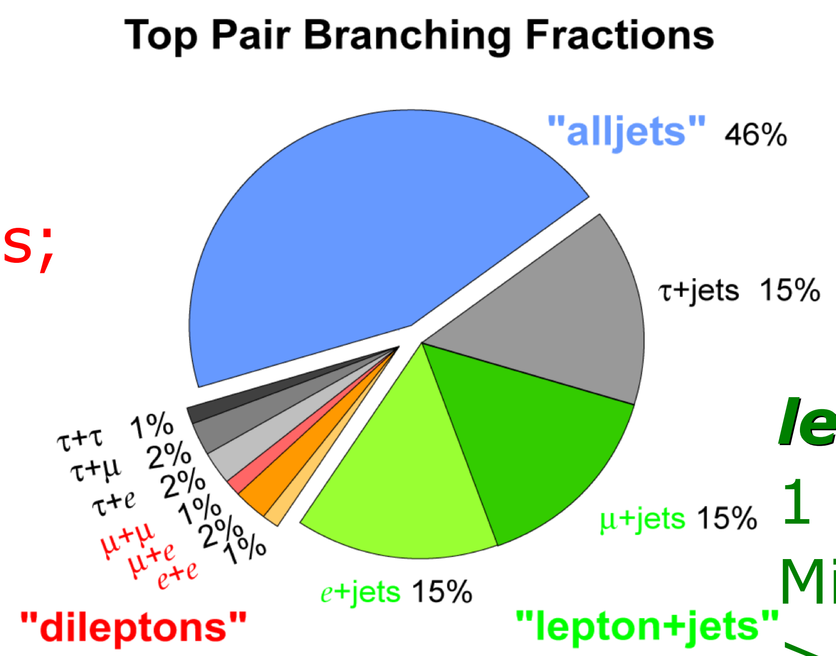
all-hadronic:
≥6 jets (2 b-jets)

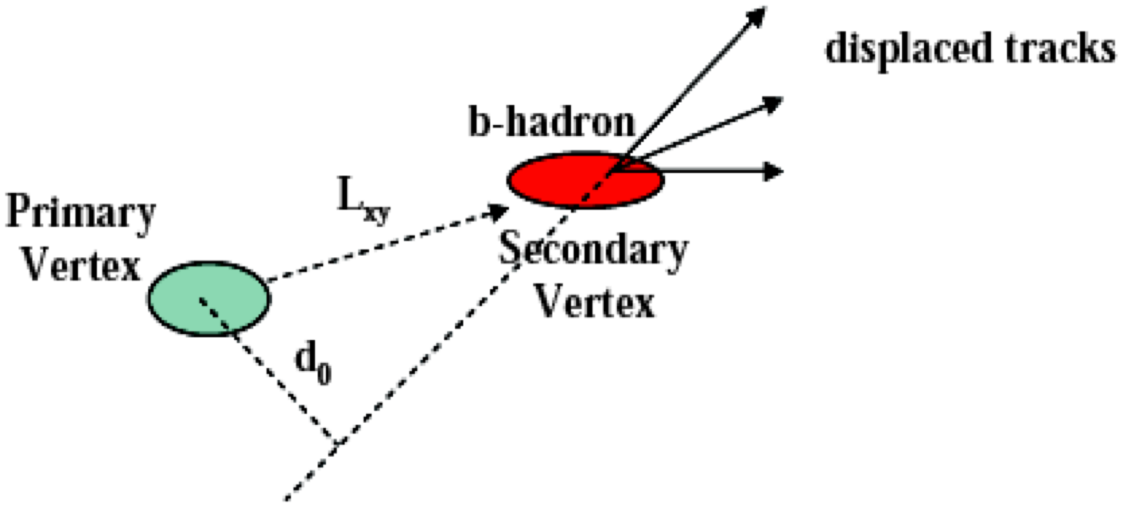
dilepton:
2 isolated leptons;
High missing E_T from neutrinos;
2 b-jets

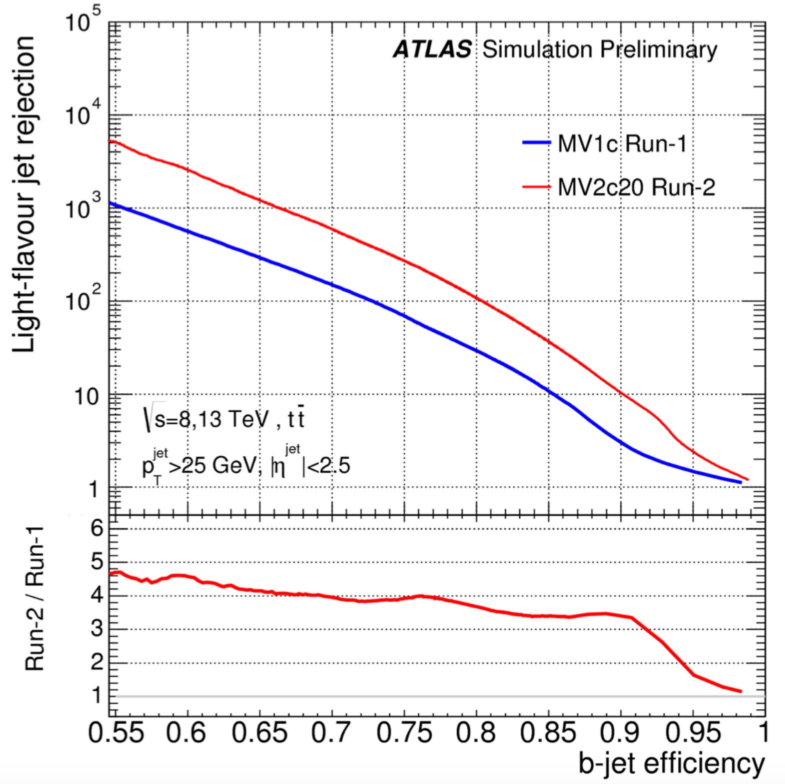


lepton+jets:
1 isolated lepton;
Missing E_T from neutrino;
≥4 jets (2 b-jets)

Ideontification 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





ATLAS-PHYS-PUB-2015-022

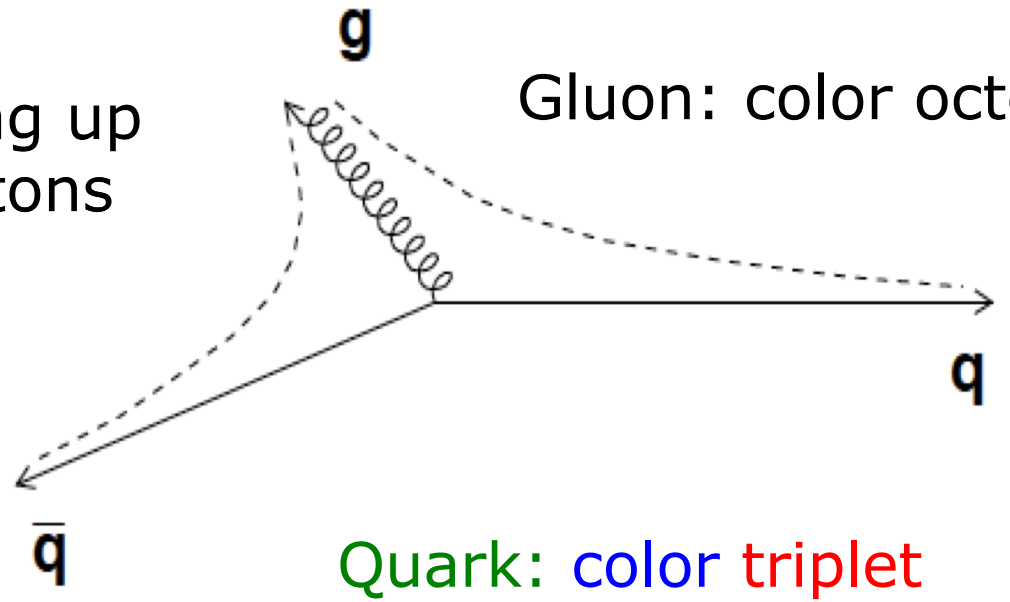
Top Events as a Laboratory

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

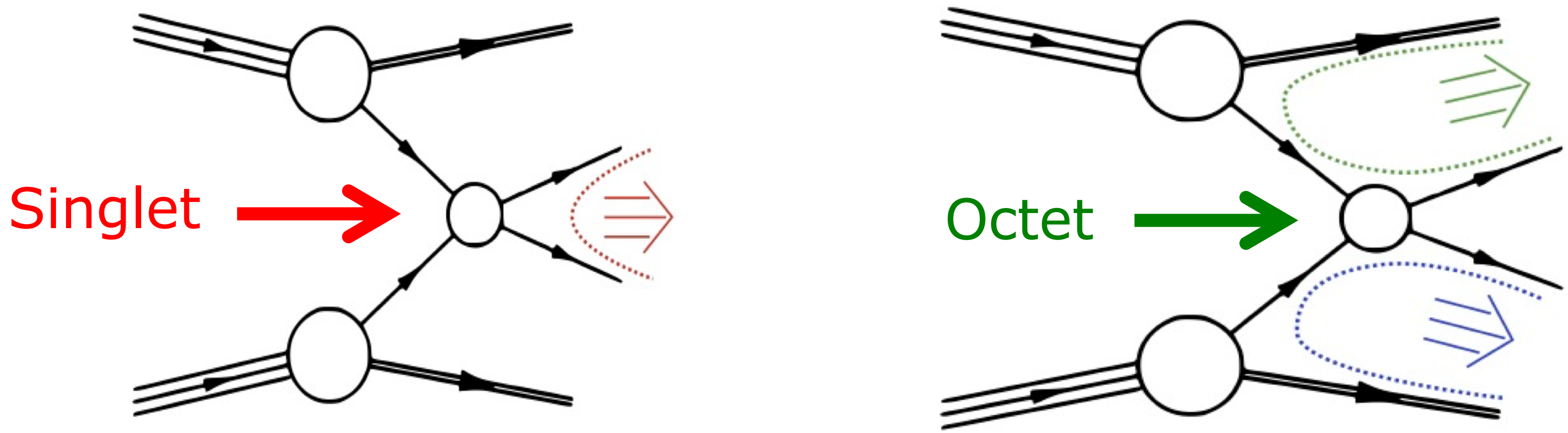


Gluon: color octet

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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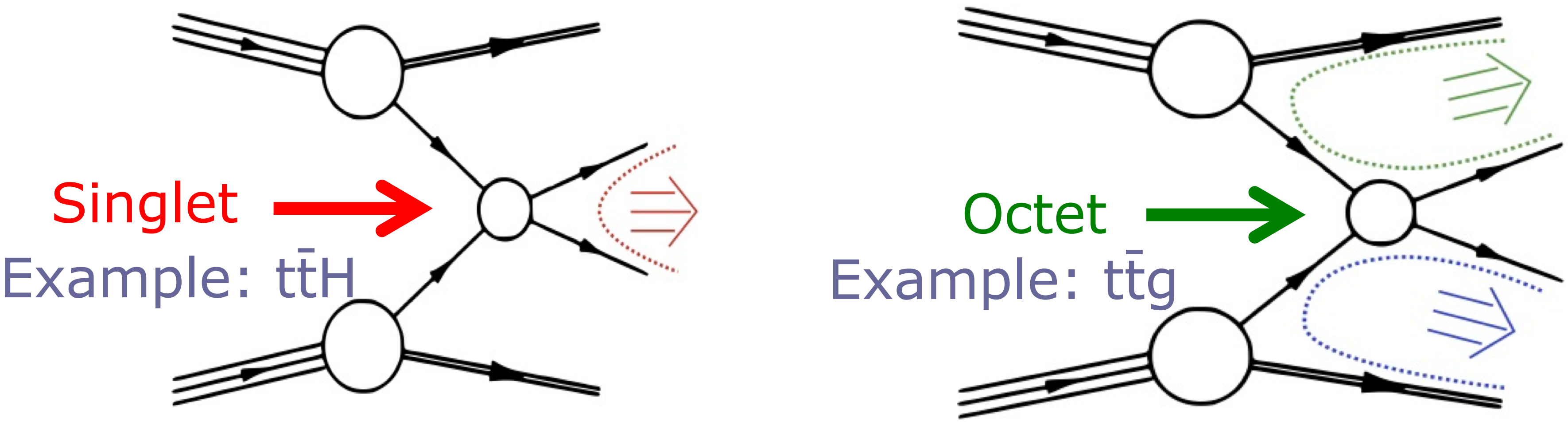

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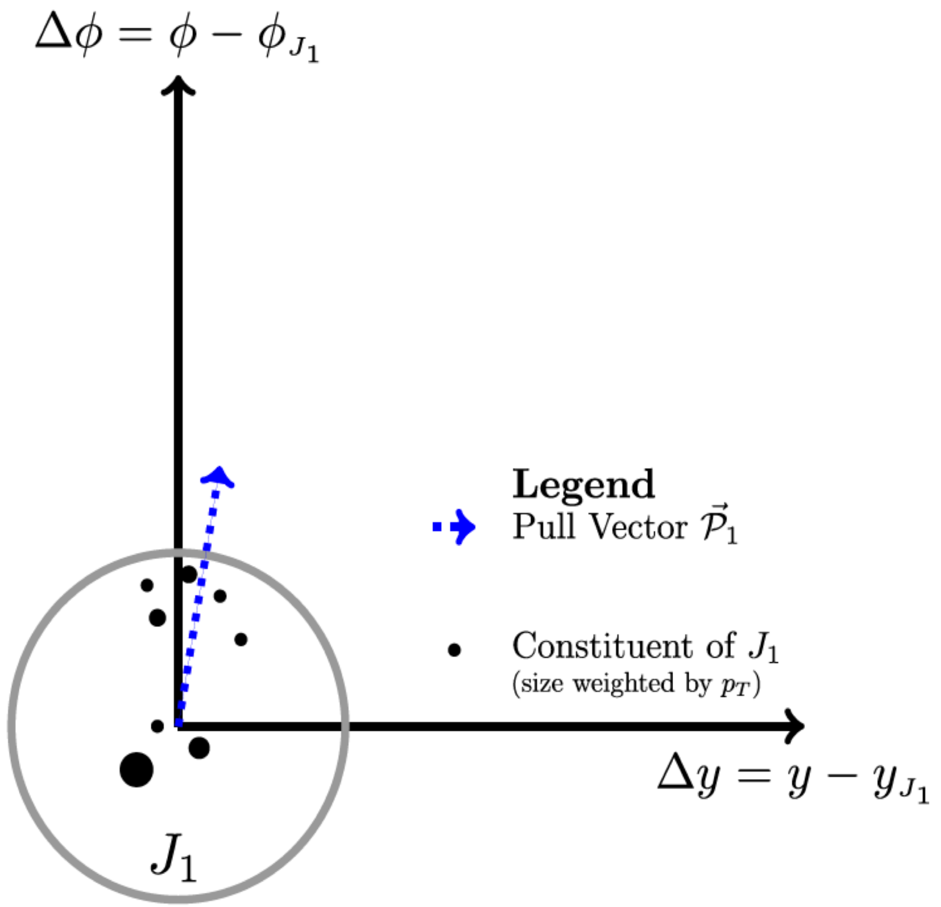
Color Flow Observable

- 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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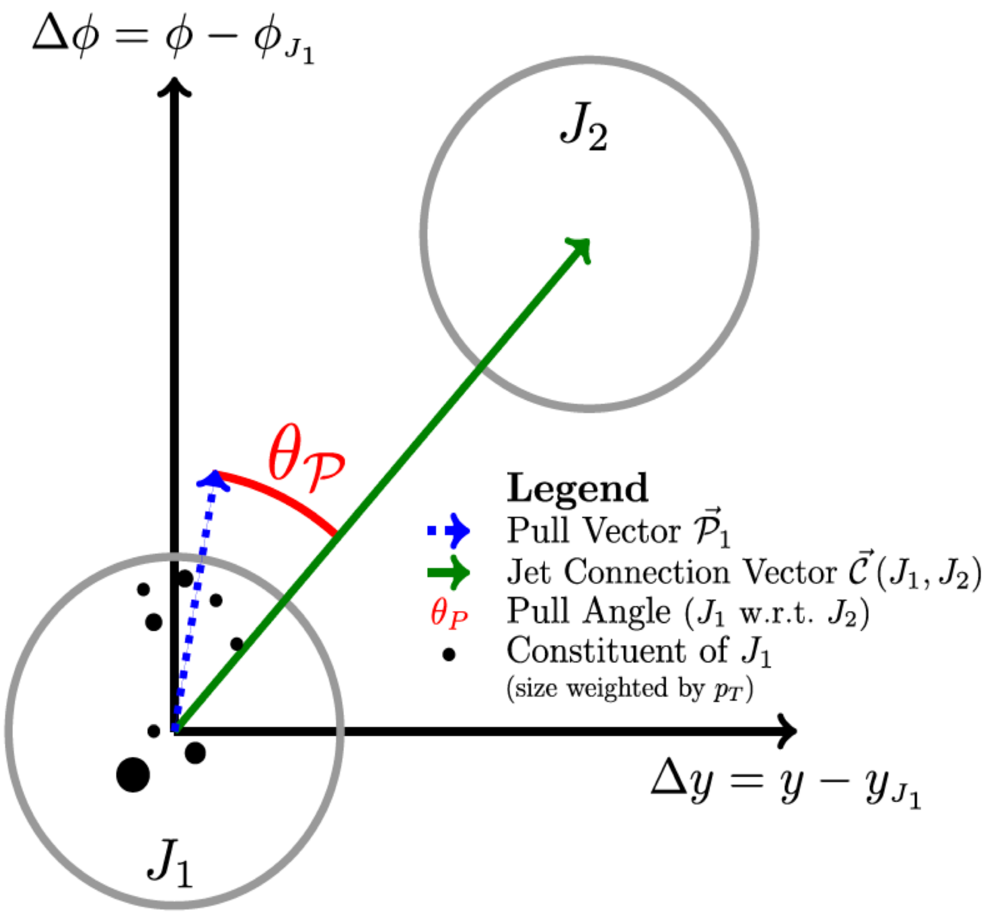
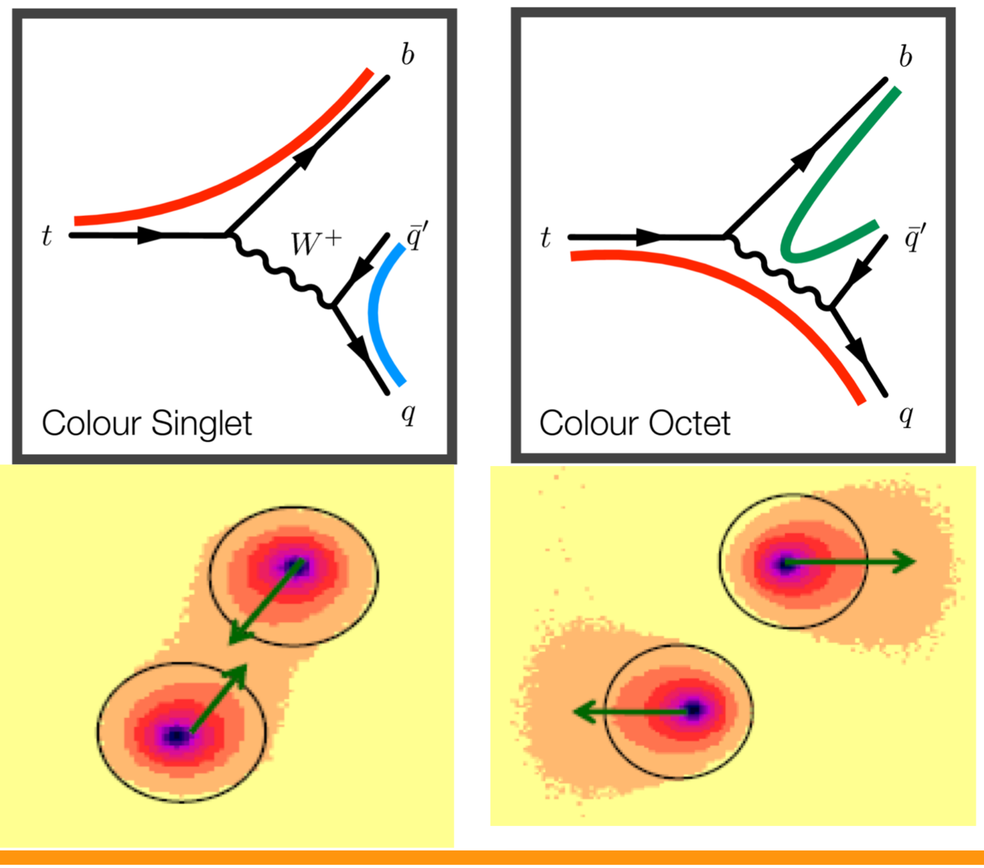


Gallicchio, Schwartz, PRL 105, 022001 (2010)

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)

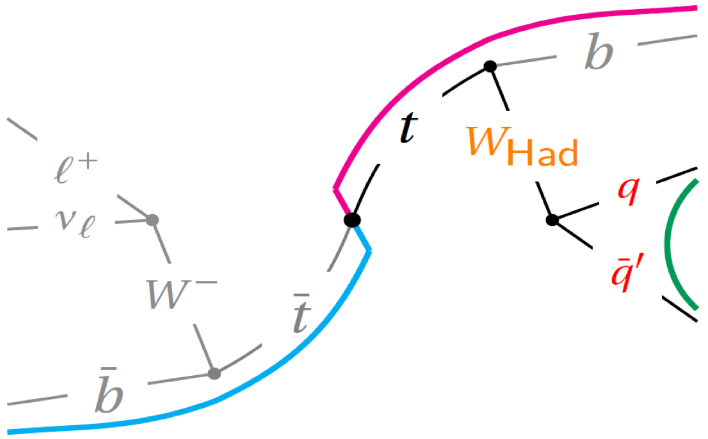


Jet pull: vectorial sum of components within each jet
→ jet pull angle: angle wrt. connection line of pair of jets

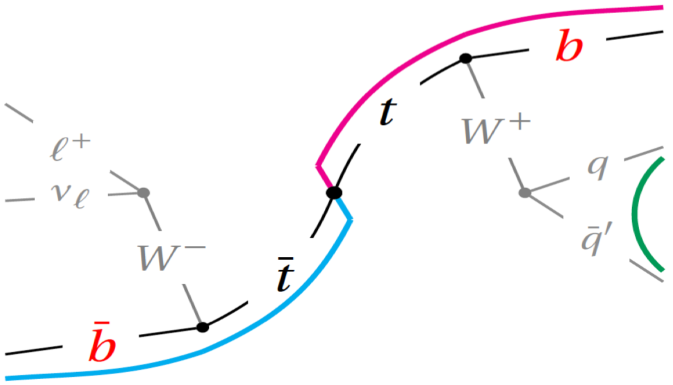
Colour Flow in Top

- 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



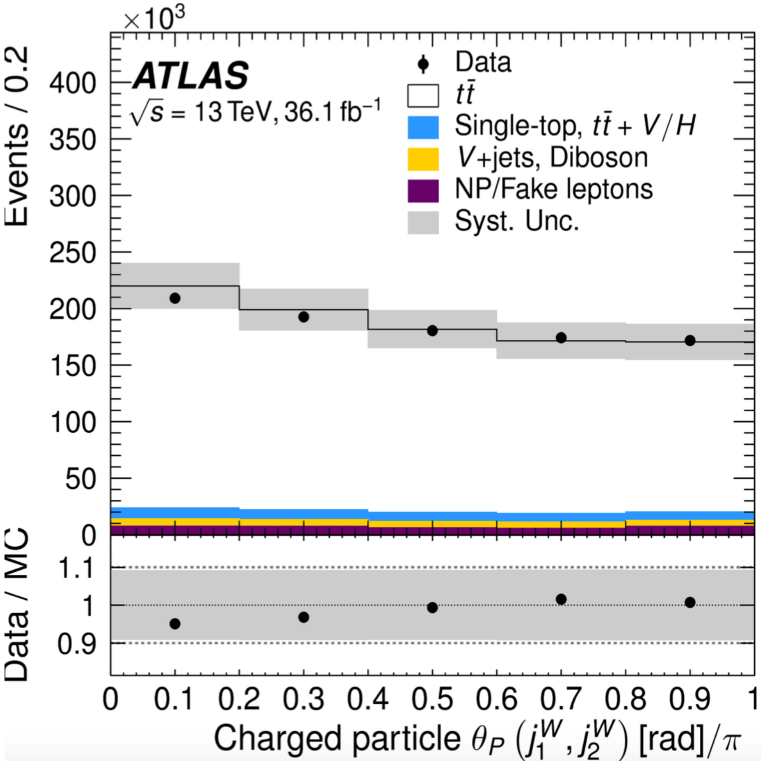
- Two b-tagged jets
  - Relative jet pull angle



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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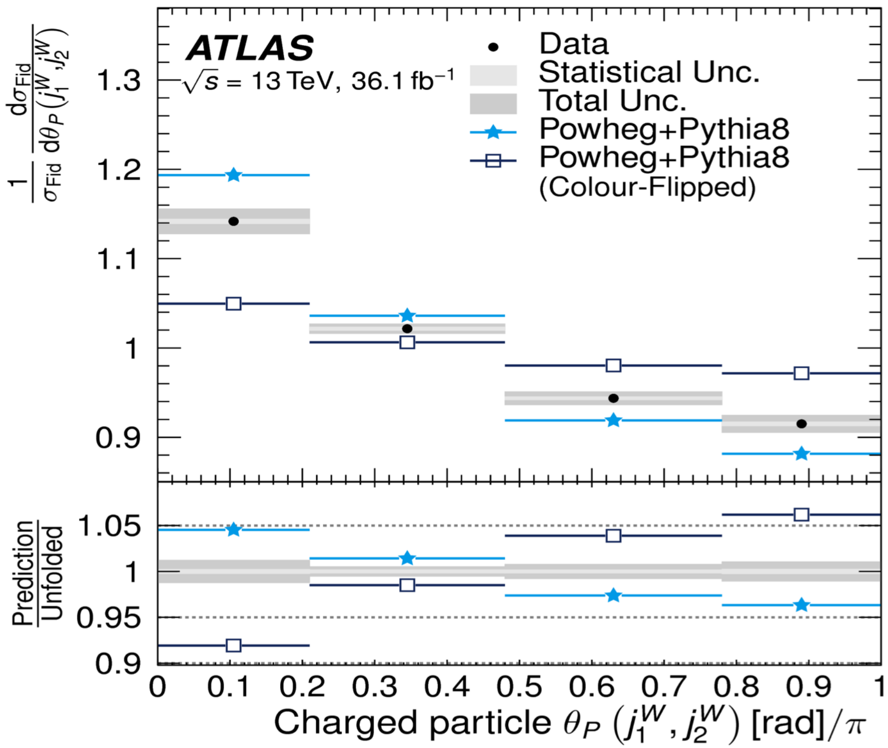
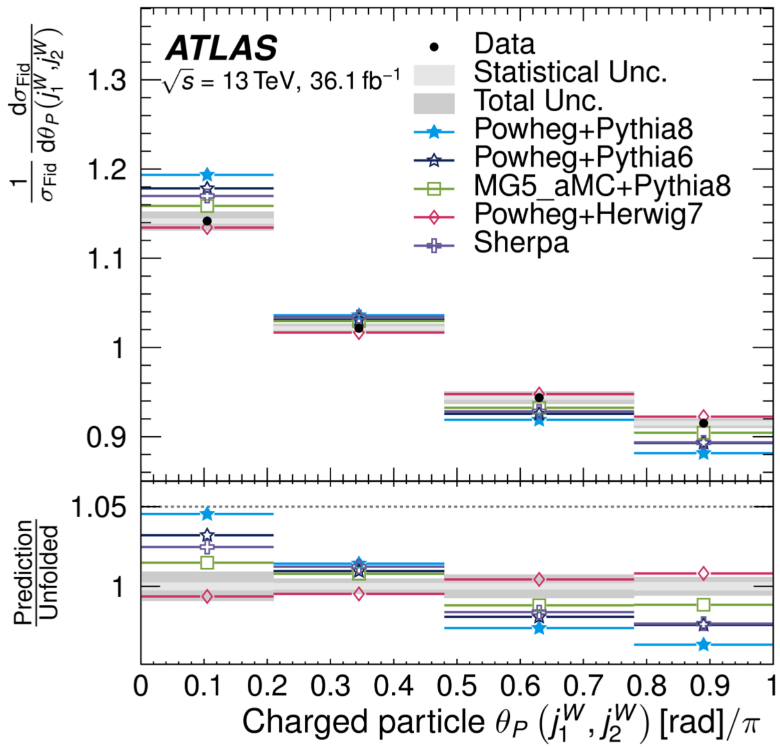
Results for W Daughters

- 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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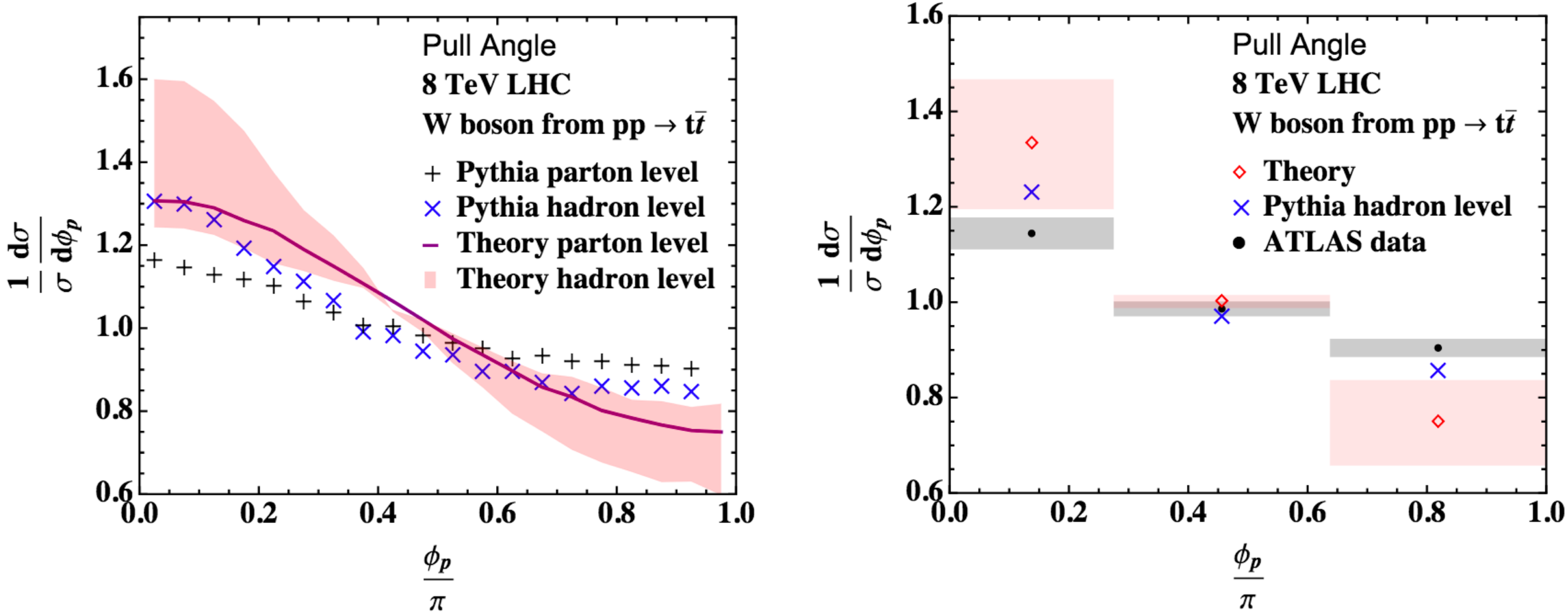
Theory

- Recent theory paper on theory prediction for Pull Angle
  - Inspired by our analyses



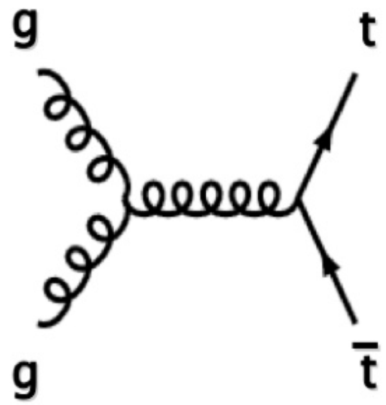
- First theoretical predictions of pull

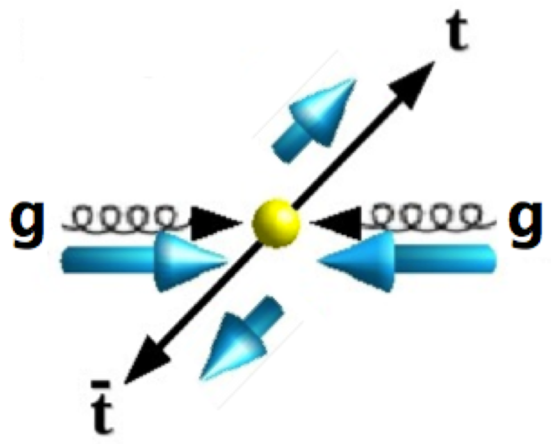
arXiv:1903.02275

Angular Distributions

Spin Correlations

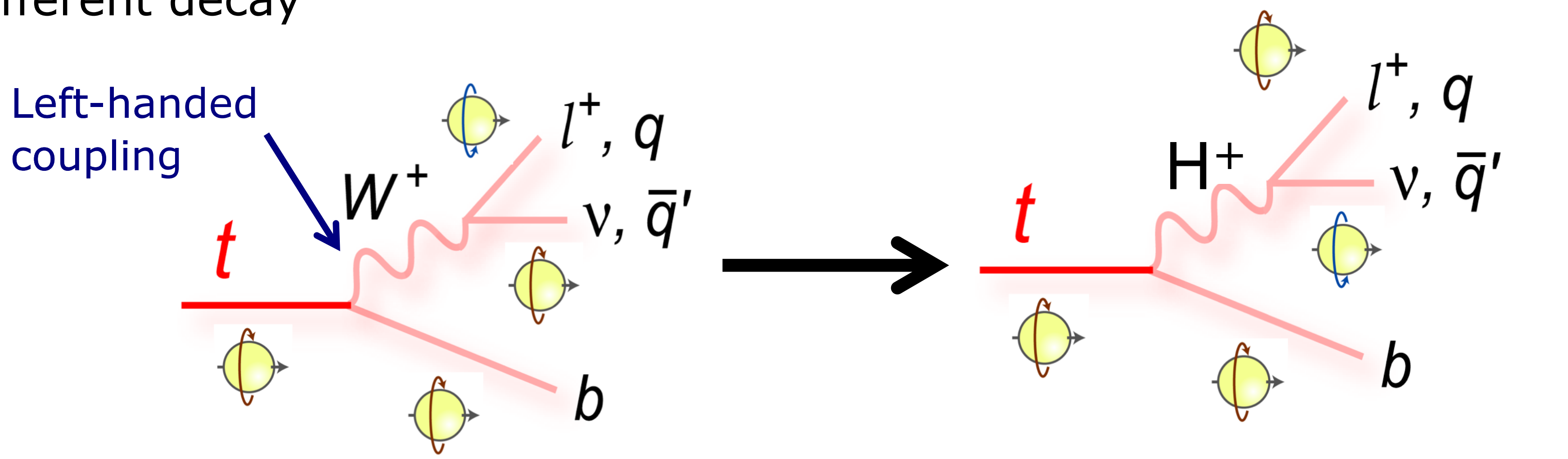
- Top quarks: decay before fragmentation
  - Spin information preserved in decay products
- Hadron colliders: top quarks produced unpolarized, but
  - New physics could induce polarization
    - For example: new physics can cause forward-backward asymmetry → more left-handed top quarks
  - Correlation between top and antitop quark can be measured



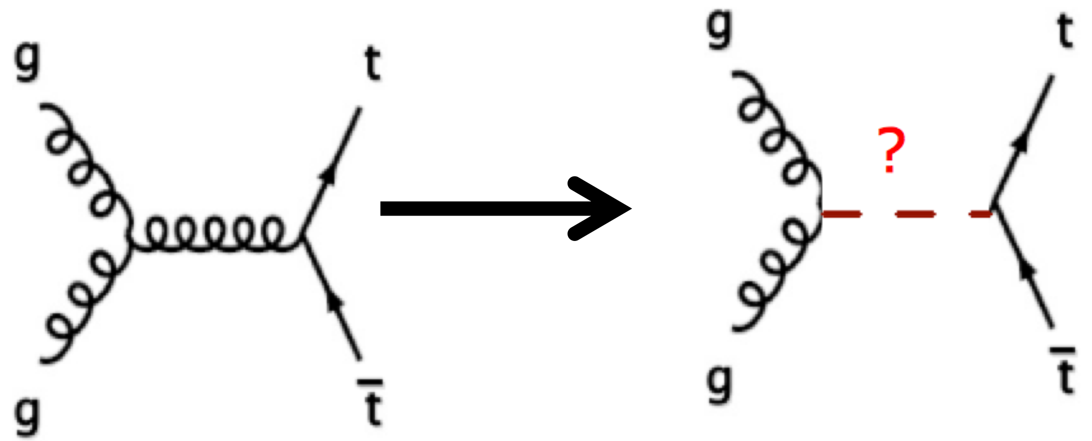


Spin Corrleations

- Measured spin correlation can change
  - Due to different decay



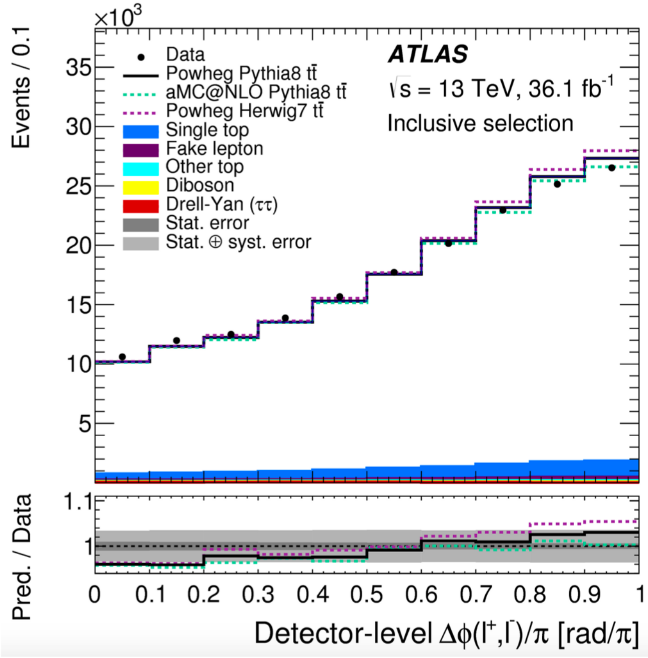
  - Due to different production



- Spin correlation: test full chain from production to decay

Analysis Strategy

- Highest spin analyzing power: leptons form top decay
  - Use dileptonic $t\bar{t}$ events
    - Very clean samples
- Use Δφ between both leptons
  - No kinematic event reconstruction required
- Full $t\bar{t}$ event reconstruction for $m_{t\bar{t}}$
  - For example neutrino weighting in ATLAS
    - Uses known top and W boson mass as constraints to explore missing neutrino information

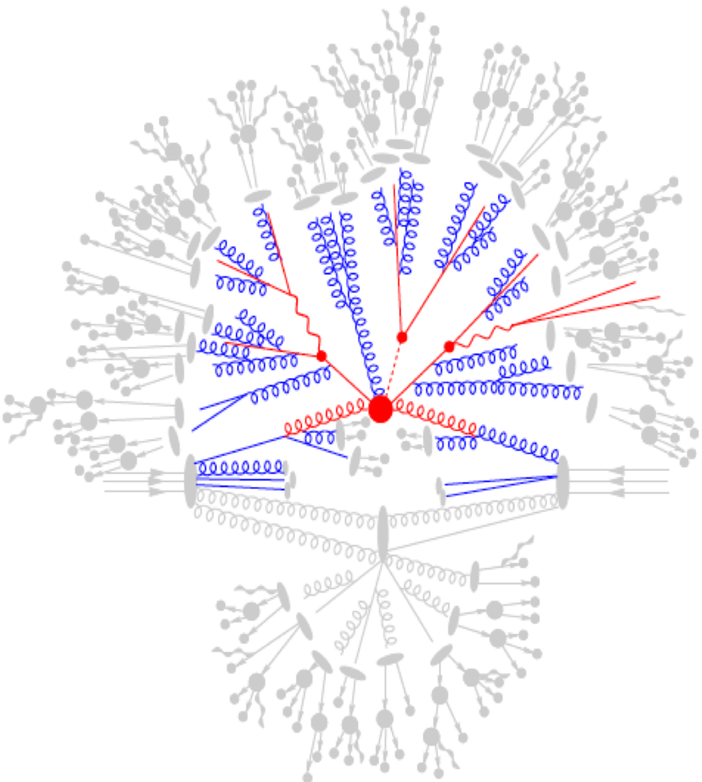


arxiv:1903.07570

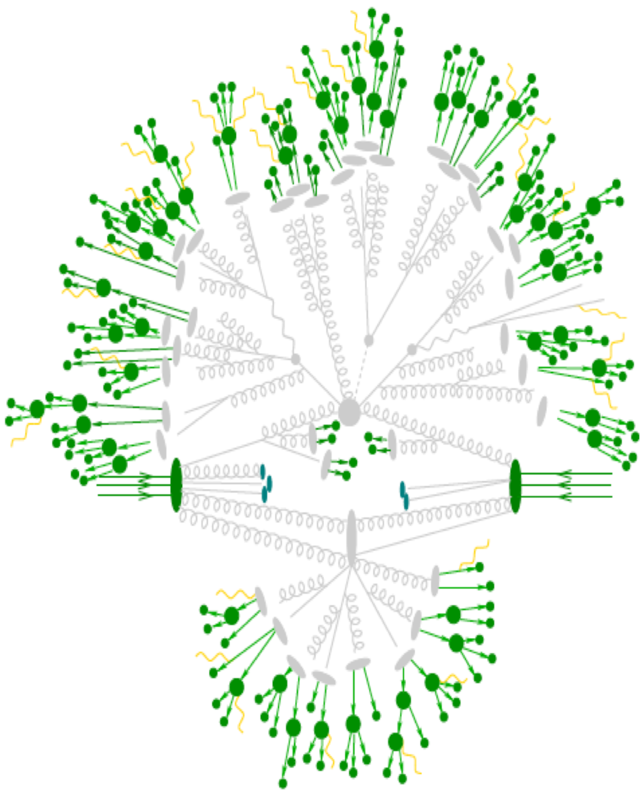
Analysis Strategy

- Unfolded differential measurements:

Parton-level

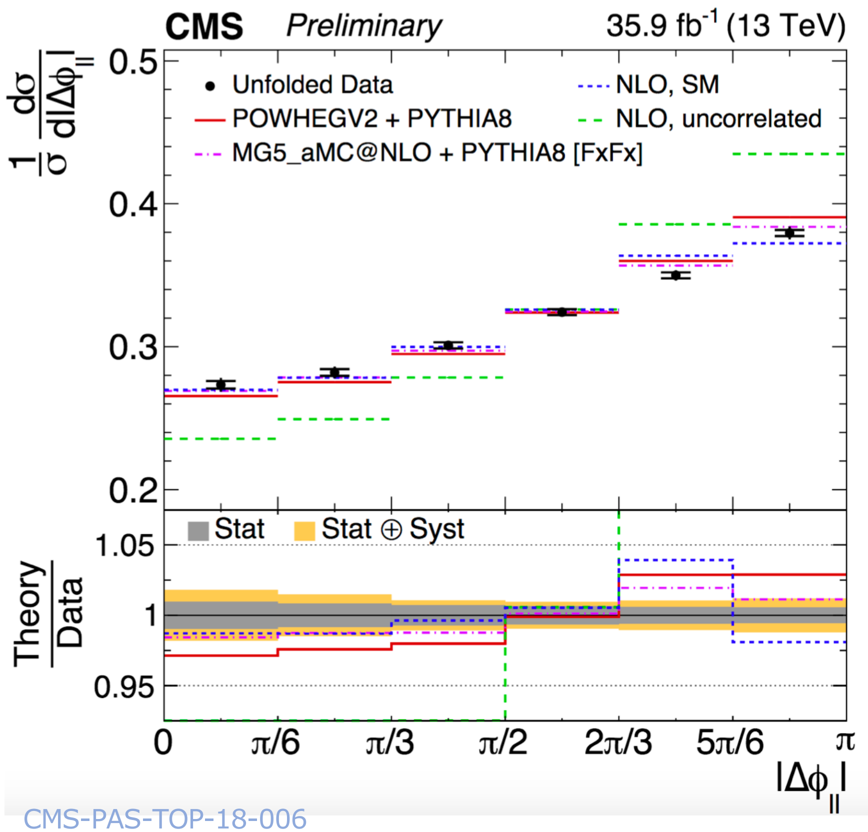


Particle level

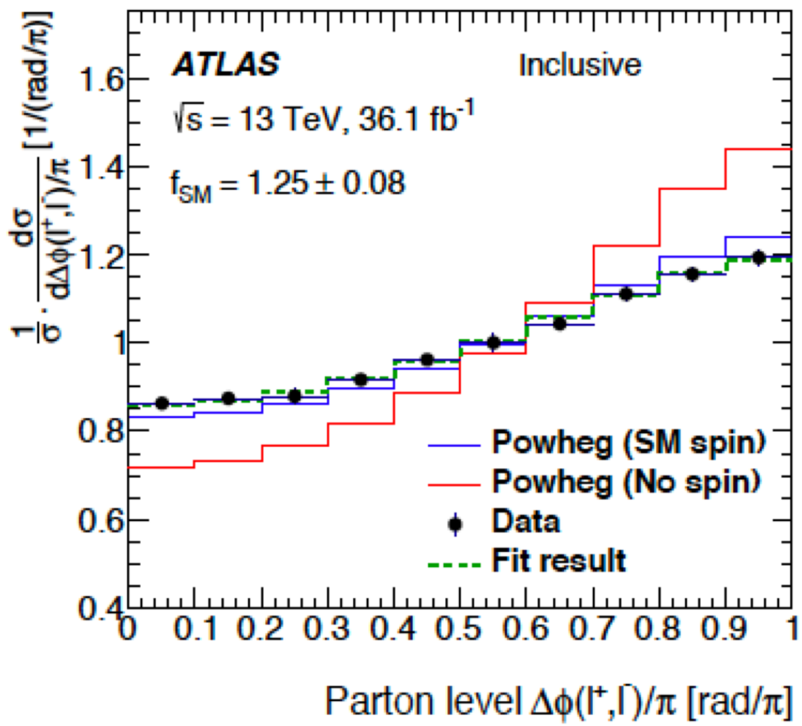


Measured Distributions

- Both ATLAS & CMS: fitted spin correlation higher than expected
  - ATLAS: 3.2σ from SM prediction of Powheg MC



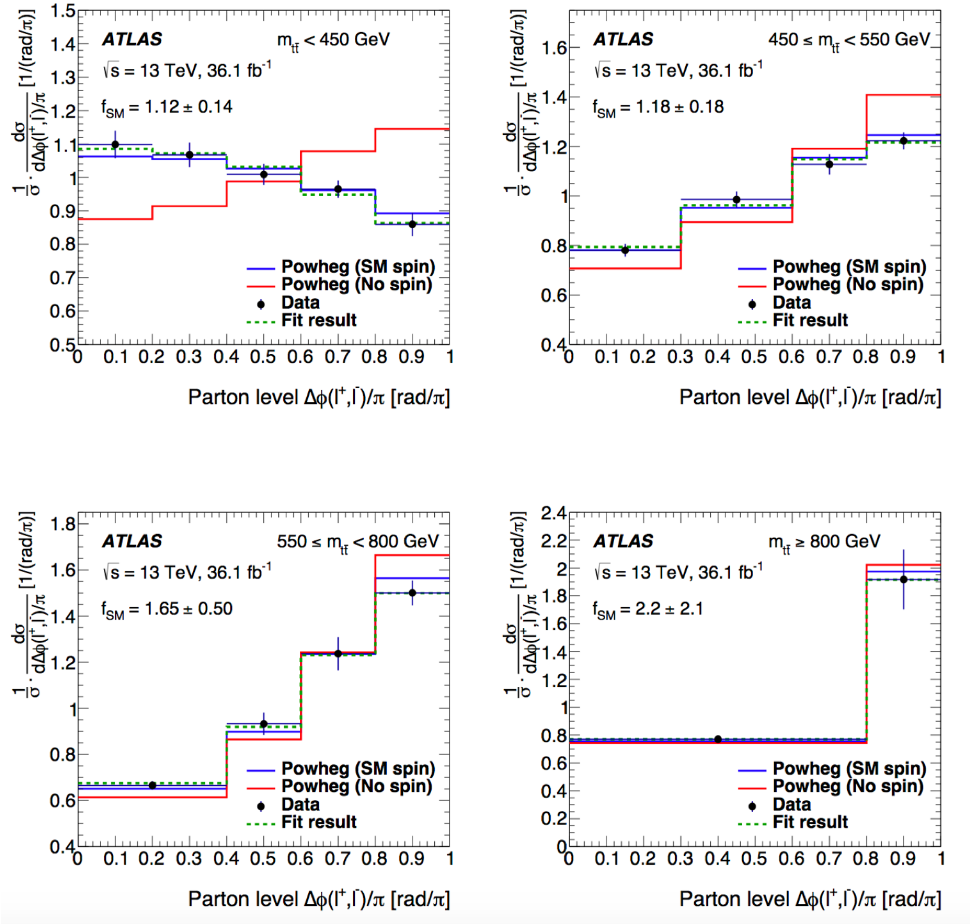
CMS-PAS-TOP-18-006



arxiv:1903.07570

Template Fit

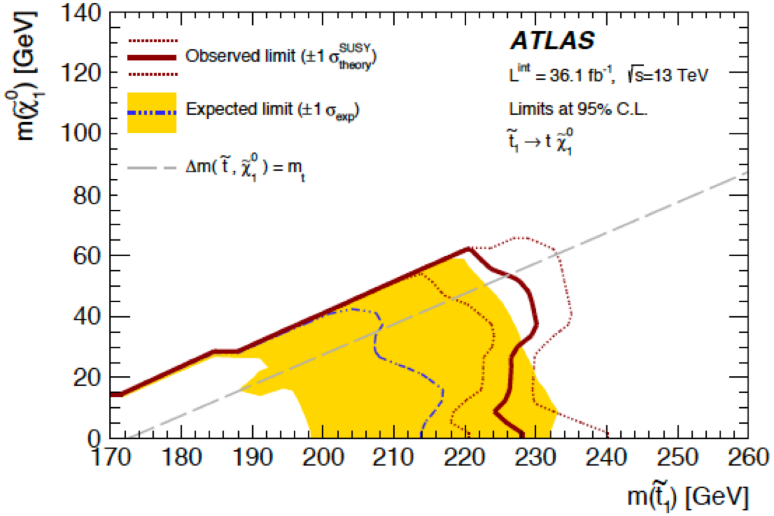
- Fitting spin and no-spin hypotheses to parton-level distributions

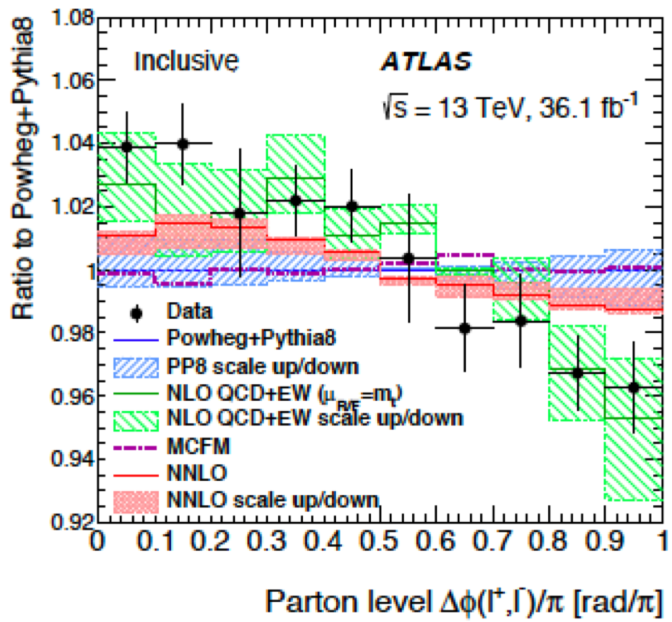


arxiv:1903.07570

More measured distributions

- Result caused interest in field → new theory predictions
- NLO+EW agrees better with measurement, NNLO (but no EW corrections) worse again
  - NLO+EW: large scale uncertainties
  - Still open riddle what's exactly going on!
  - Need more calculations/measurements?
- Interpretations done in terms of EFT and SuSy models





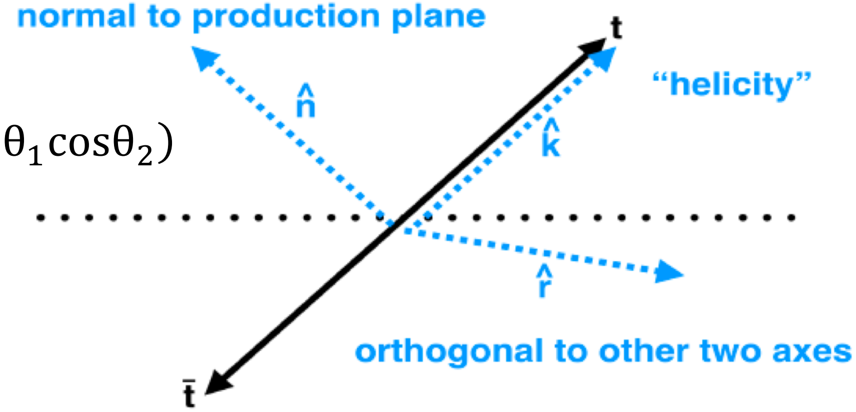
arxiv:1903.07570

Other Measurements

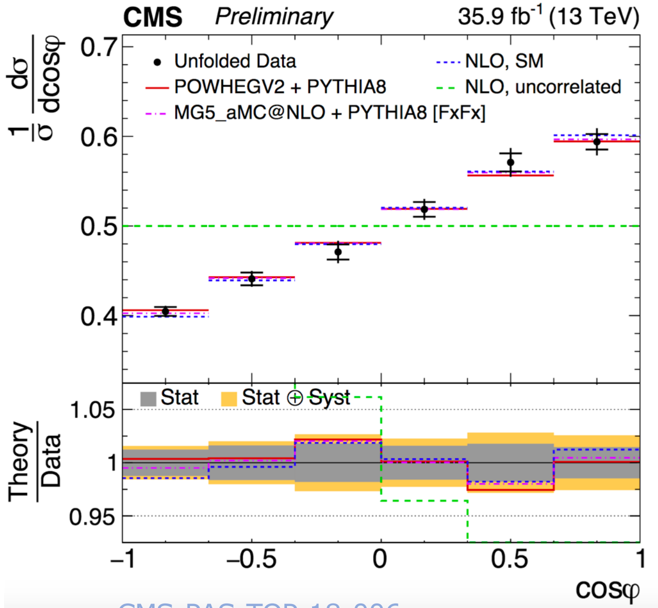
- Double differential cross section:

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

  - α: spin analyzing power of decay product
  - θ: direction of daughter particle wrt. chosen quantization axis
  - P: polarization and C: spin correlations



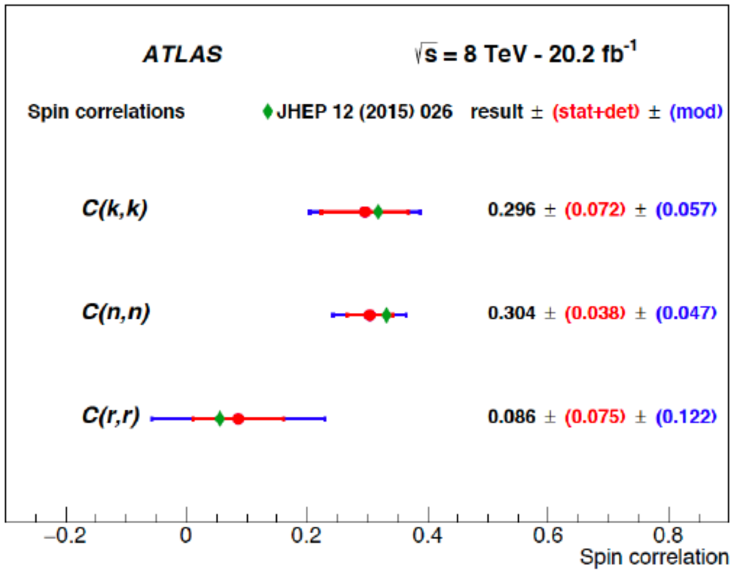
- More "direct" spin correlation measurement: Spin density matrix elements
  - Challenge: requires full event reconstruction
- ATLAS &CMS: Unfolded distributions extracted



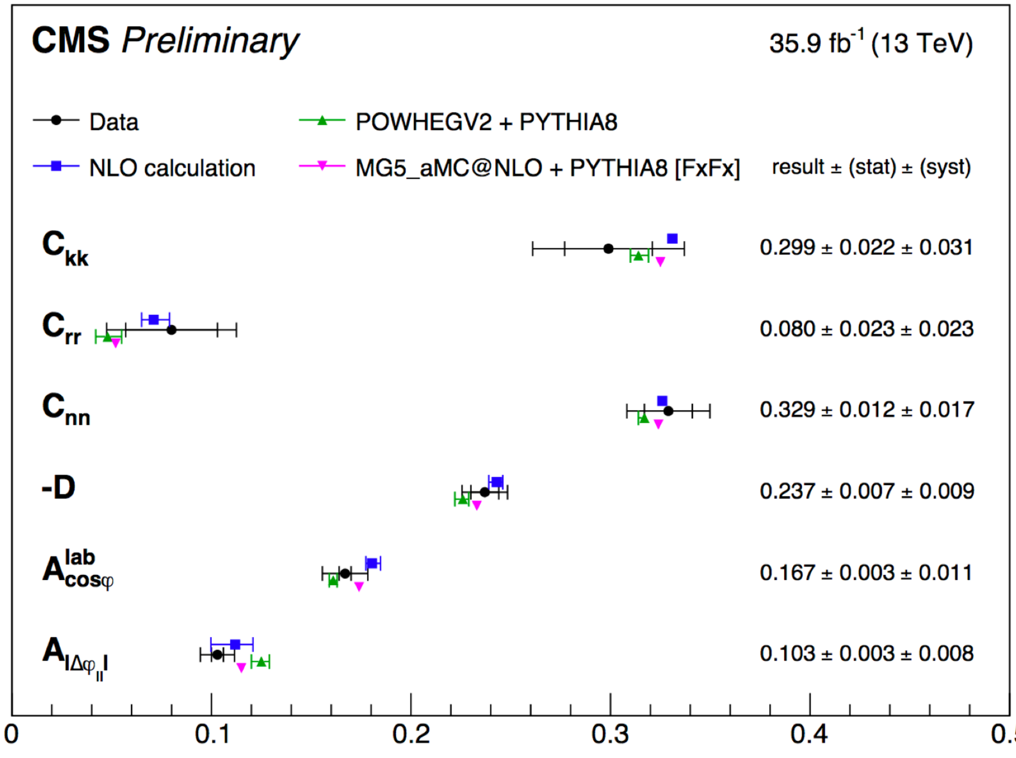
CMS-PAS-TOP-18-006

Other Spin Measurements

- All spin-density matrix elements measured
  - More to do to improve sensitivity



JHEP 03, 113 (2017)



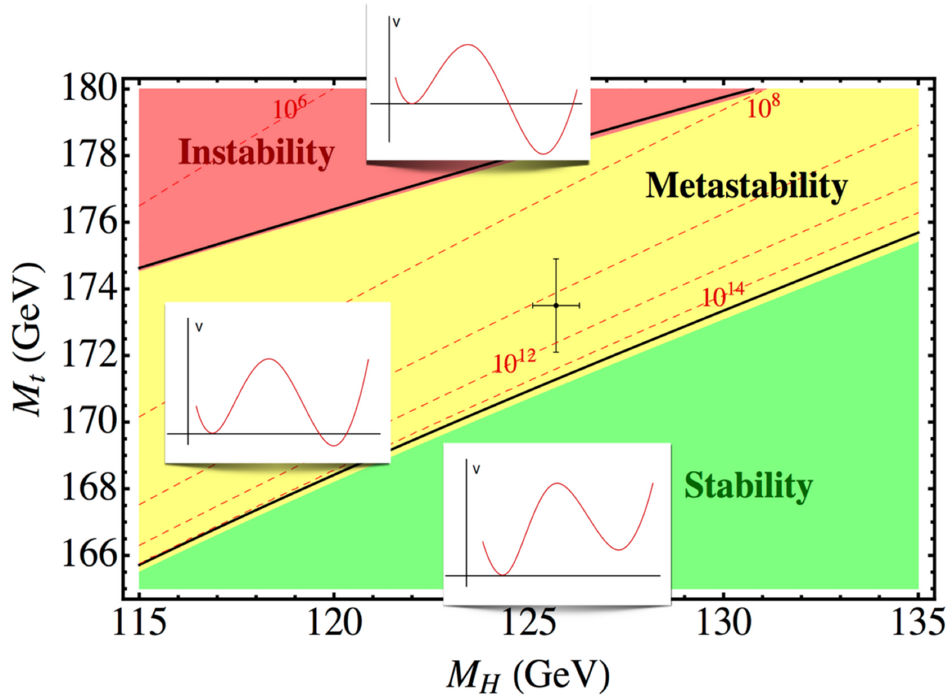
CMS-PAS-TOP-18-006

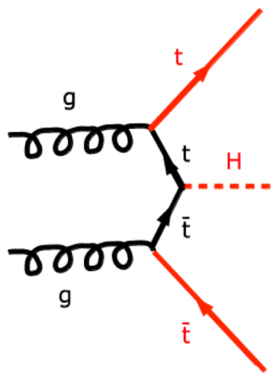
- Still more to do to understand the riddle of $t\bar{t}$ spin correlations!

The Top and The Higgs

The Top and The Higgs

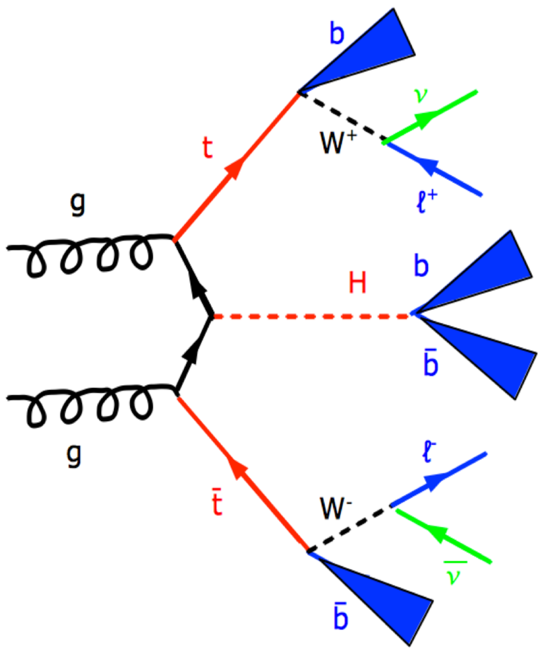
- Top and Higgs: Heaviest known elementary fermion and boson!
  - Top-Higgs Yukawa coupling: predicted to be ~1 in the SM
    → special role of top quark in electroweak symmetry breaking?
    → window to new physics?
    → metastable universe?
- Measuring top-Higgs Yukawa coupling directly: important!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





The Top and The Higgs

- Last 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



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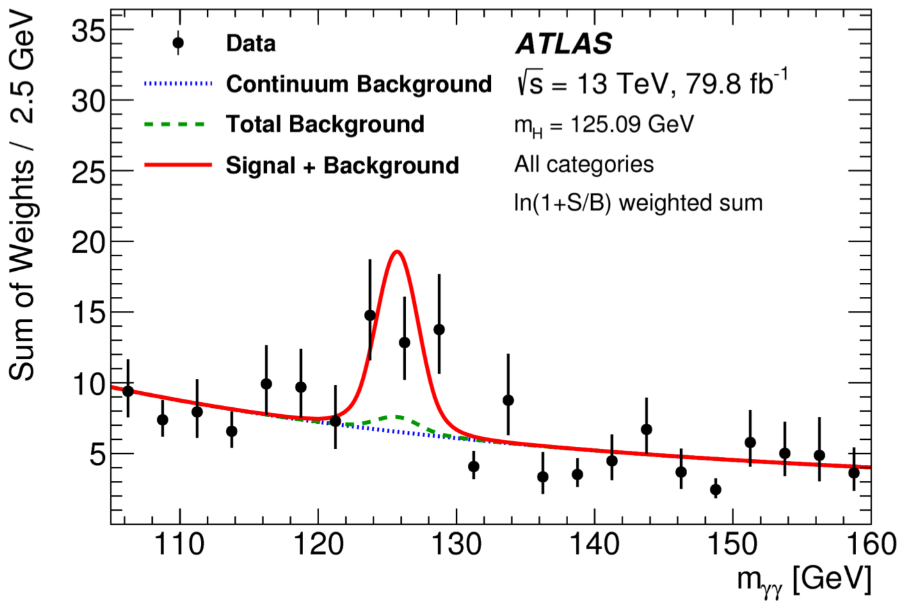
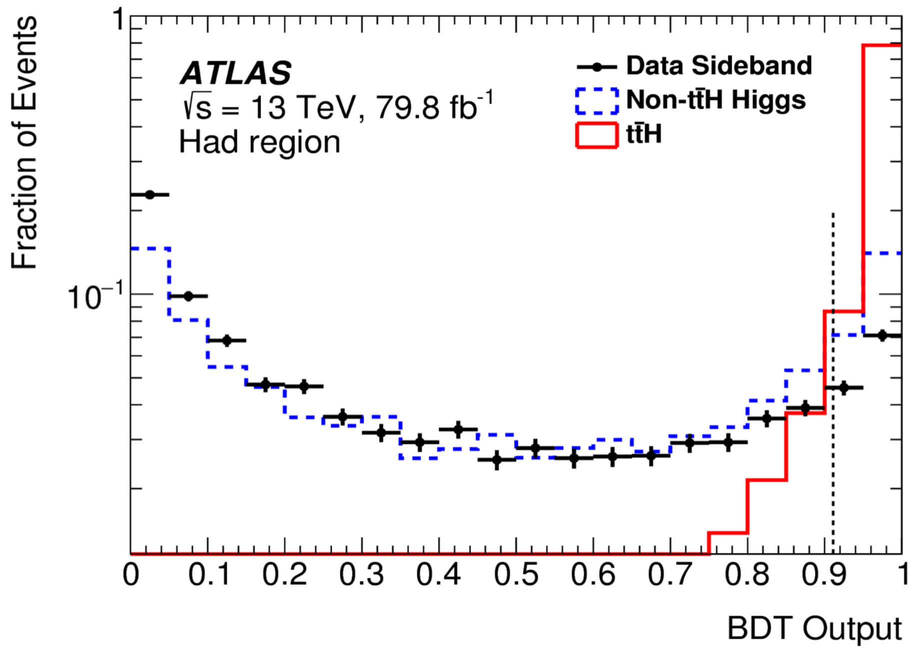
Diphoton Channel

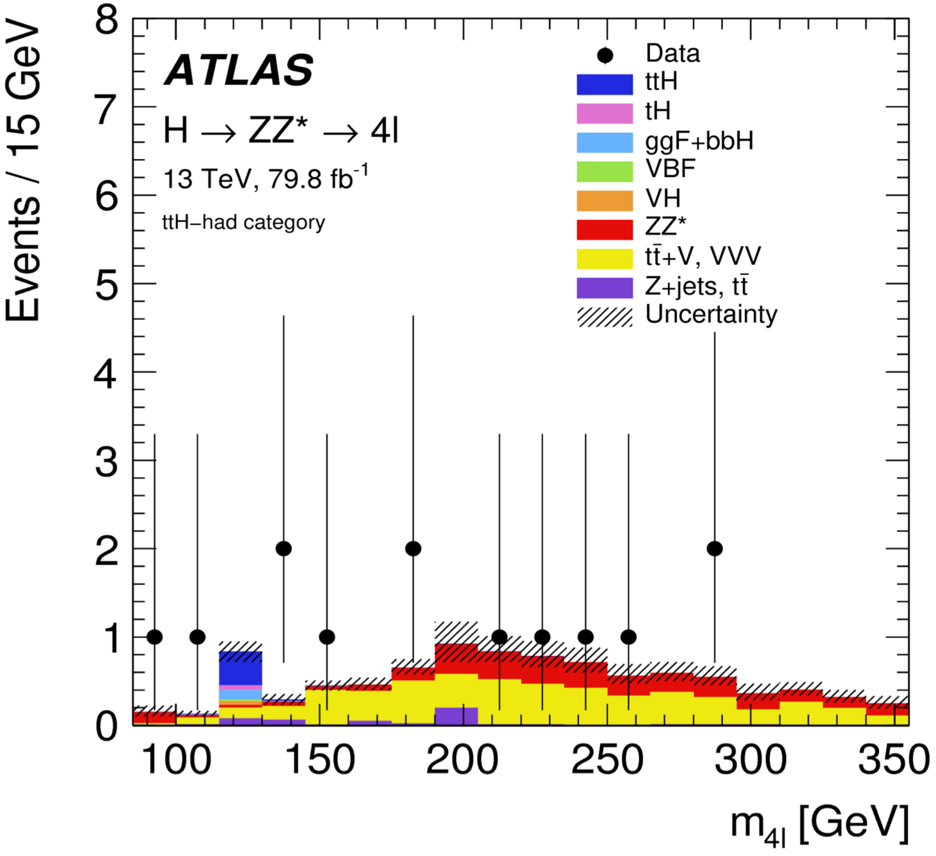
- Define two regions: hadronic top decays or events with at least one charged lepton
  - $m_{\gamma\gamma}$: has to be between 105 and 160GeV
- For each region: train BDTs





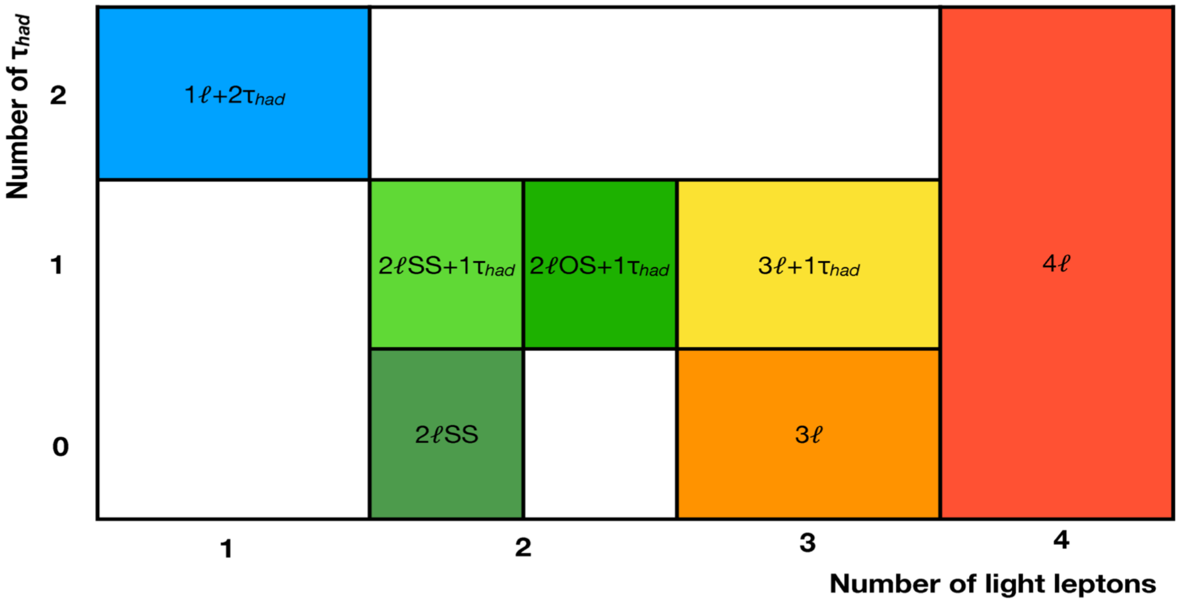
ZZ Channel

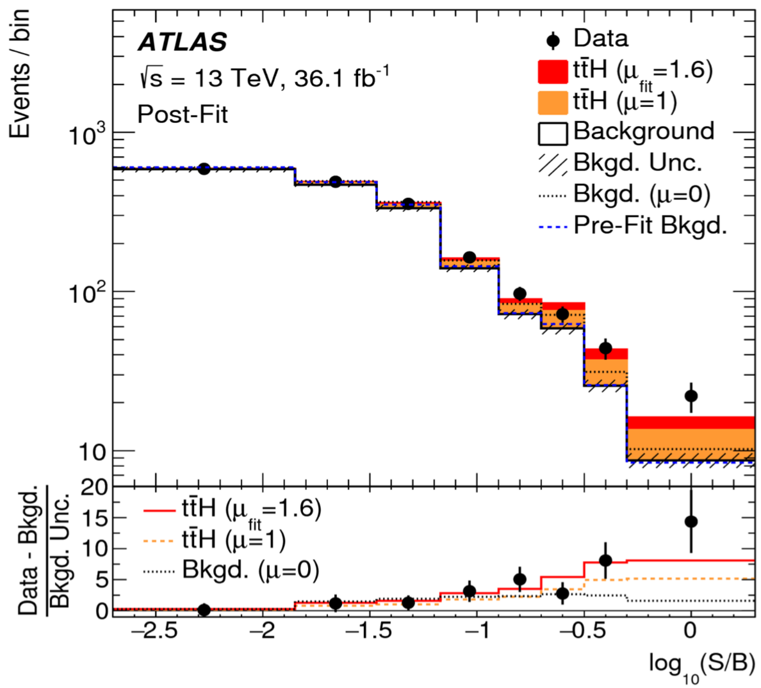
- Use events with at least 4 isolated charged leptons
  - Two regions: hadronic (both tops decay hadronically) and leptonic (at least one top decays leptonically)
  - BDT used on hadronic region



Multilepton Channel

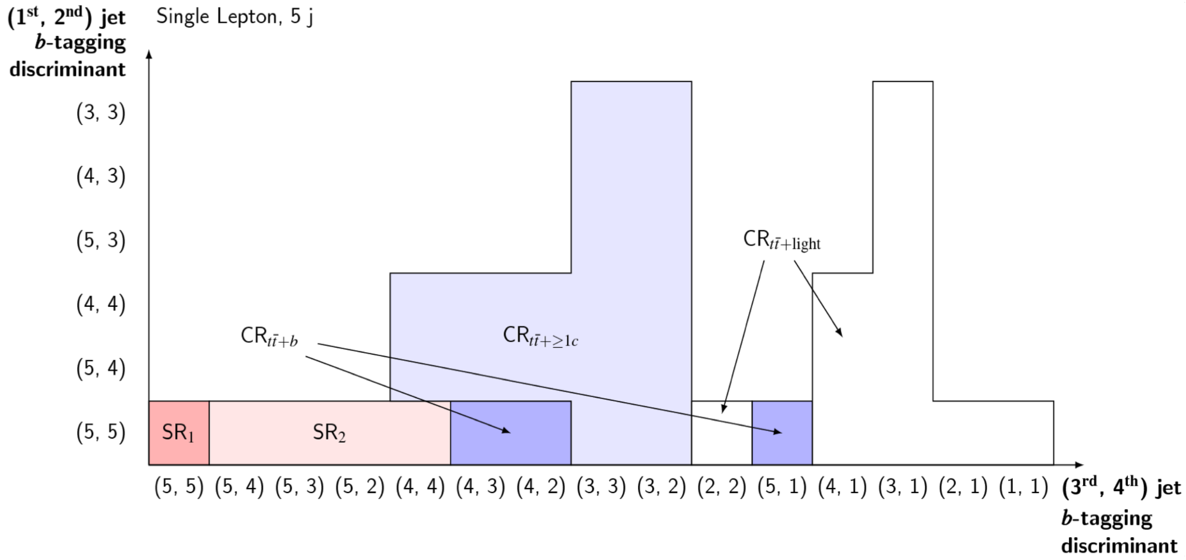
- Includes H→WW (&ZZ) and H→$\tau\tau$ decays
- Many channels considered
  - Some use BDTs

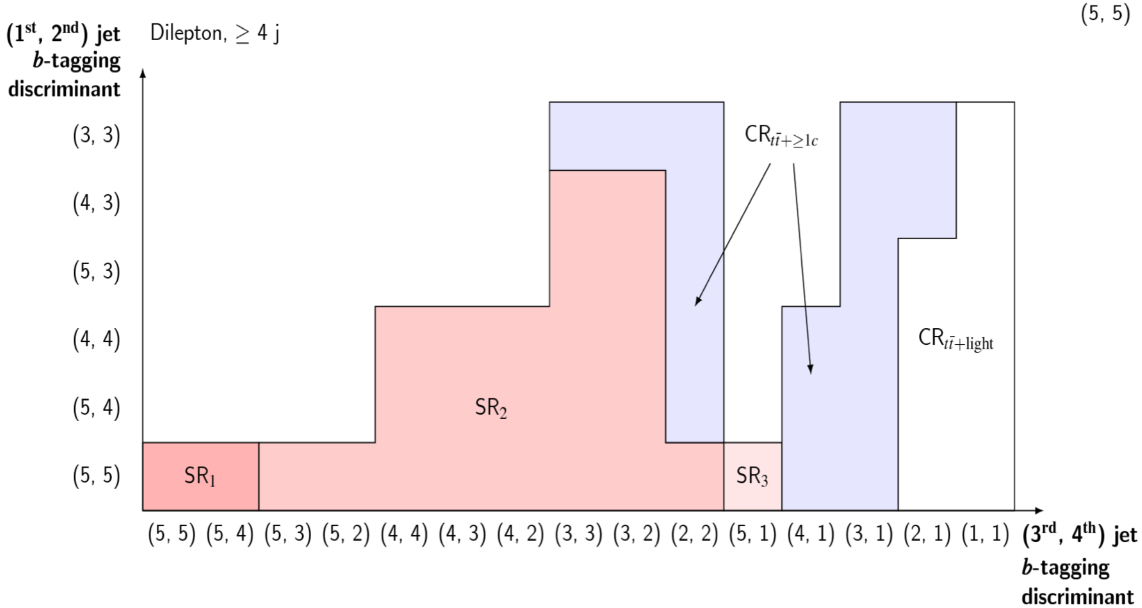




$H \rightarrow b\bar{b}$ Channel

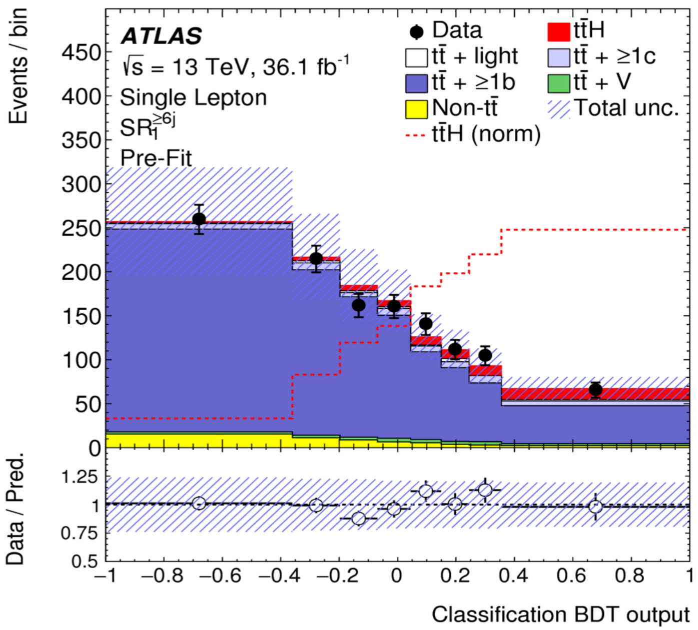
- Semileptonic and dileptonic channels considered
  - Separation in many different control and signal regions
- Very challenging analysis
  - Modeling of background $t\bar{t}b\bar{b}$

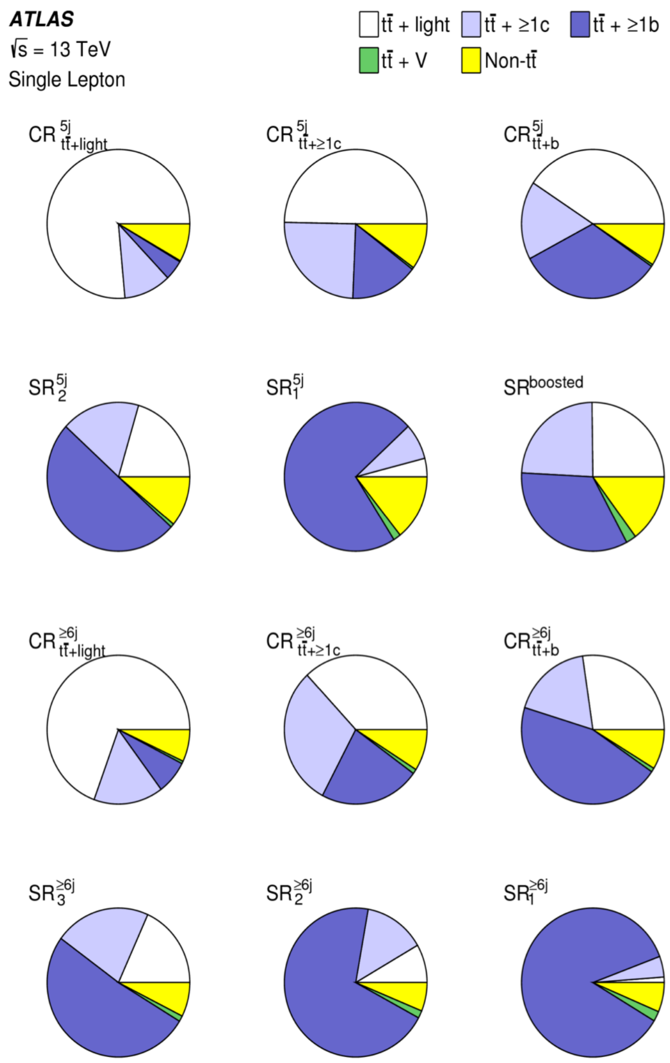




Semileptonic

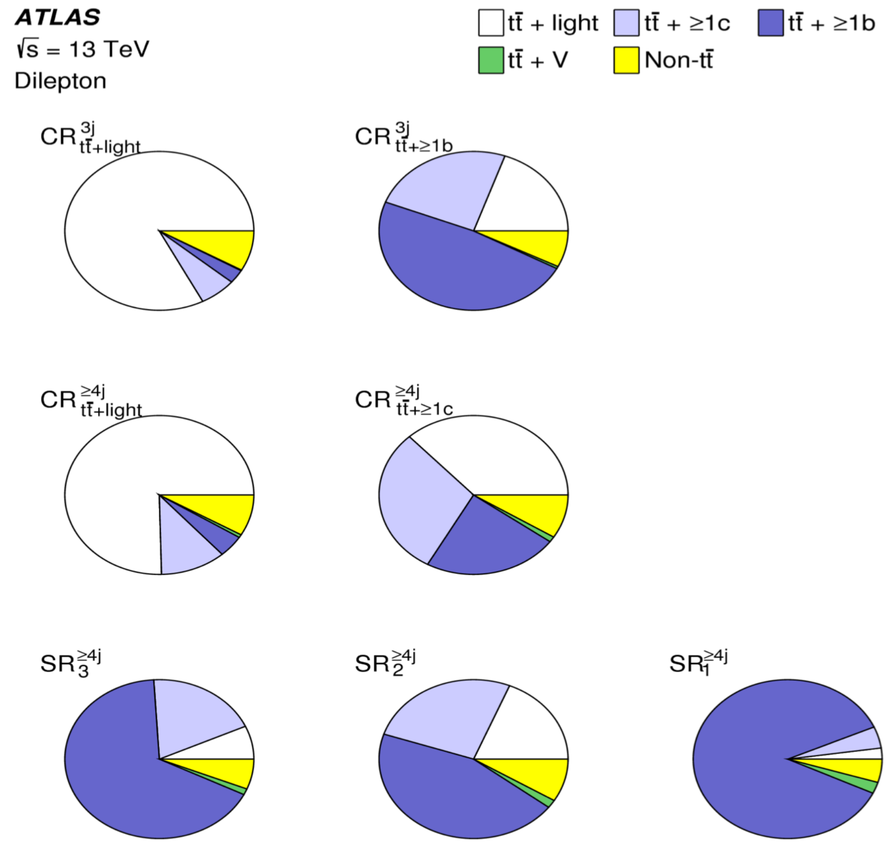
- BDTs used enhancing significance
  - Reconstruction of event done with "reconstruction BDT" → access to variables using full events
- Fits including control regions → improves control over backgrounds

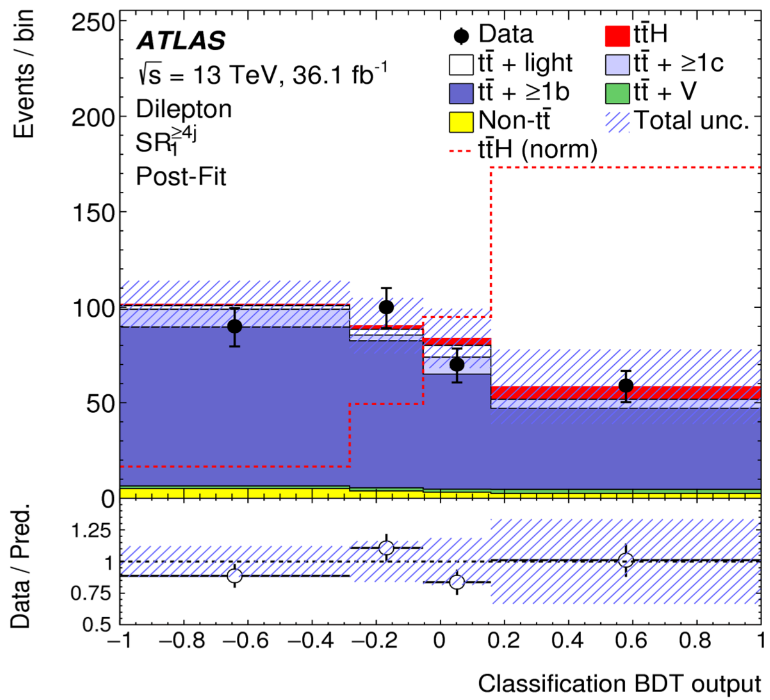




Dileptonic

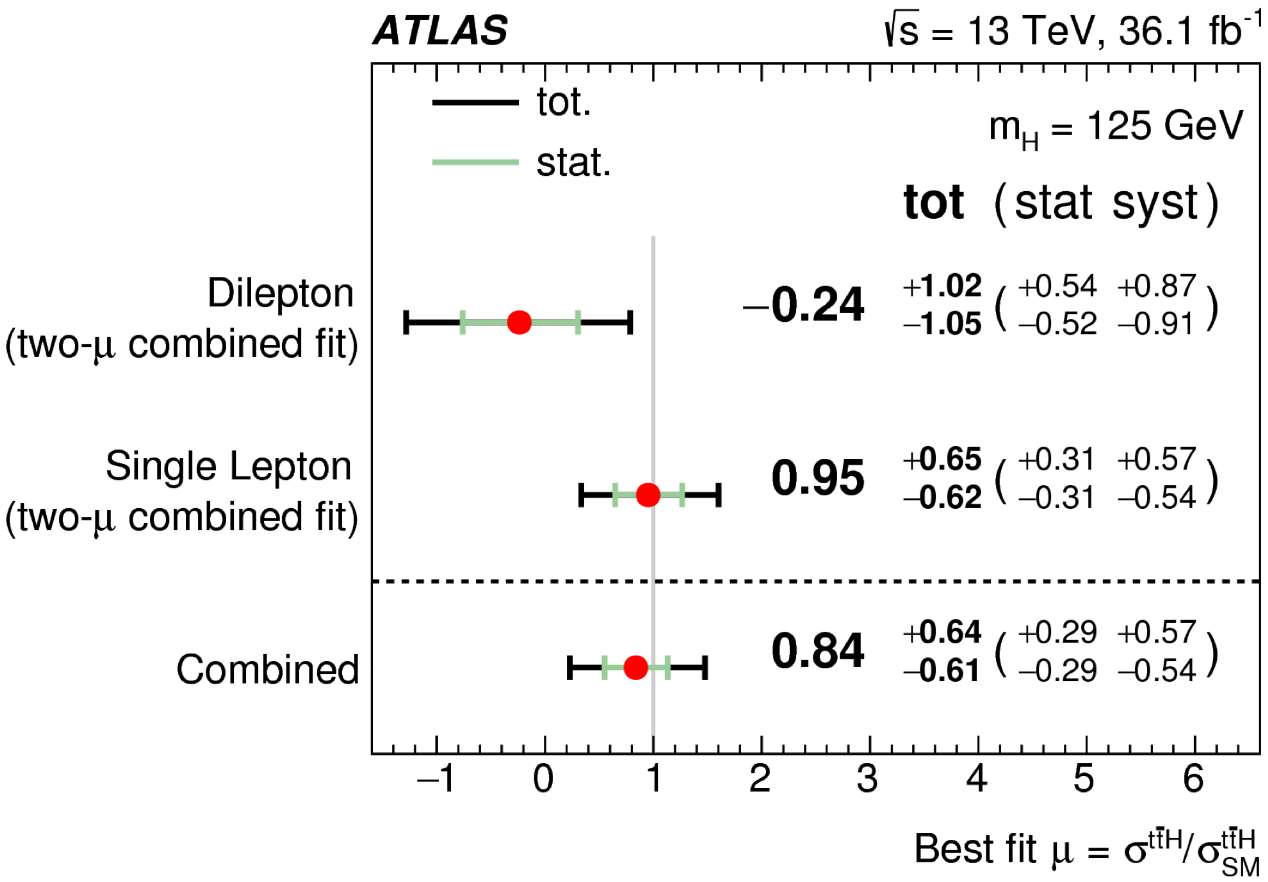
- Similar strategy as in semileptonic channel
  - Reconstruction of full event information more challenging due to two neutrinos





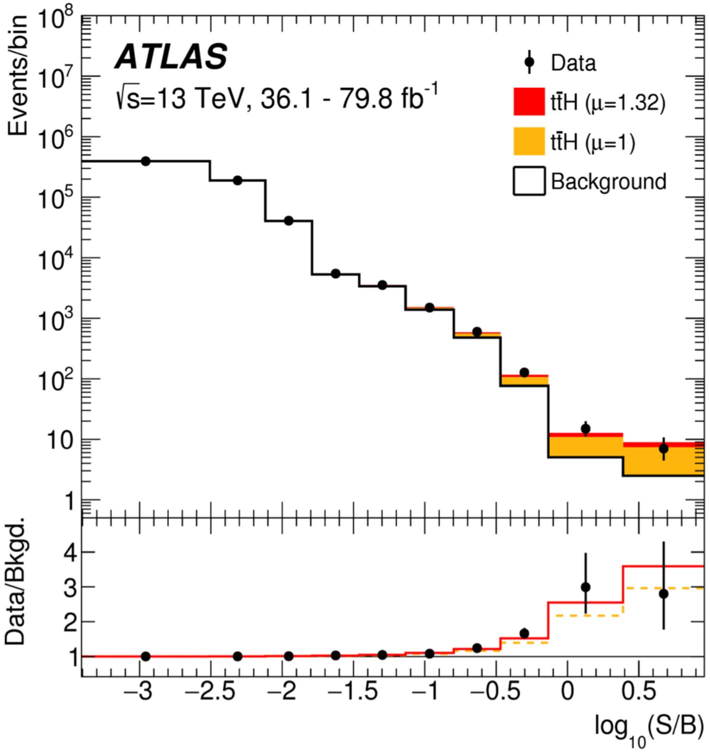
$t\bar{t}H$, $H\rightarrow b\bar{b}$ Results

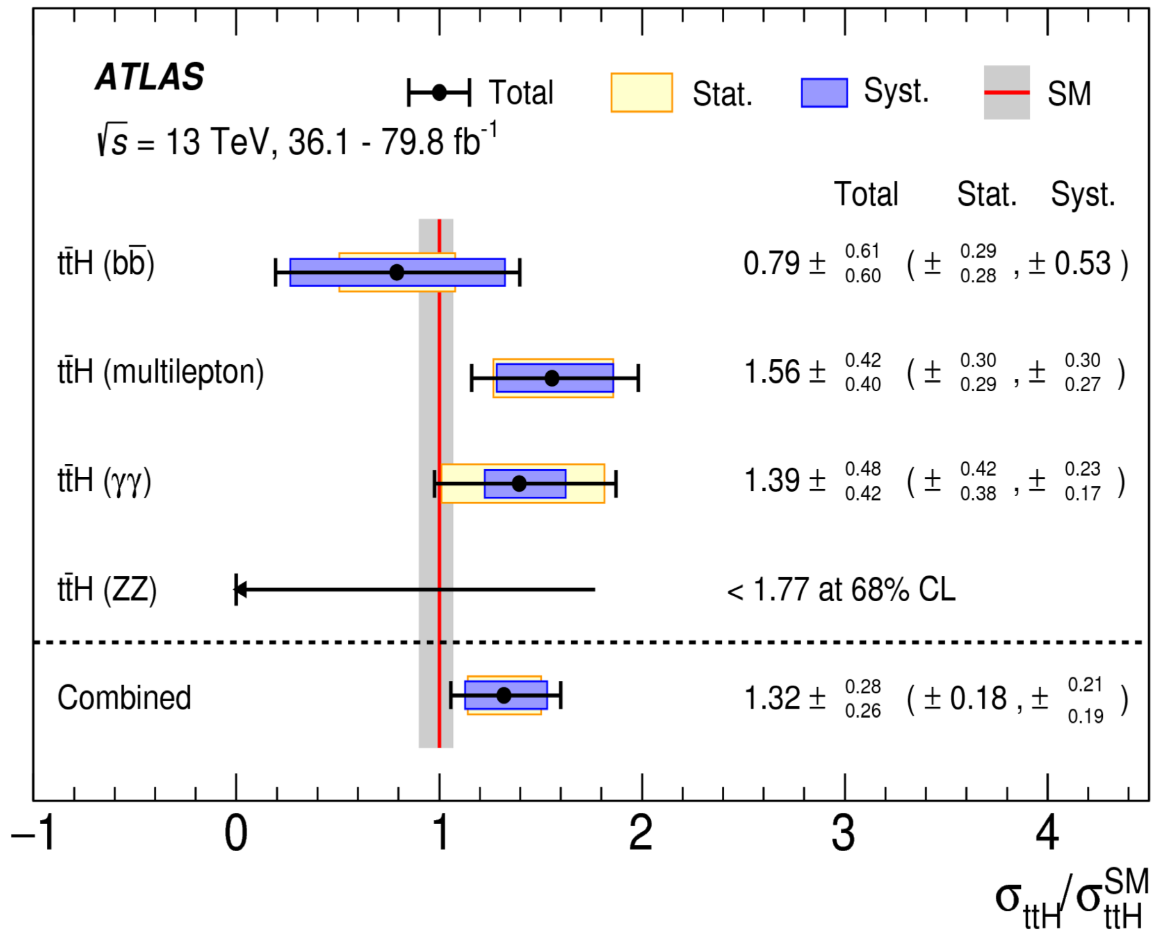
- Results already dominated by systematic uncertainties
  → background modeling of $t\bar{t}b\bar{b}$ a main factor



Combination

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





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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

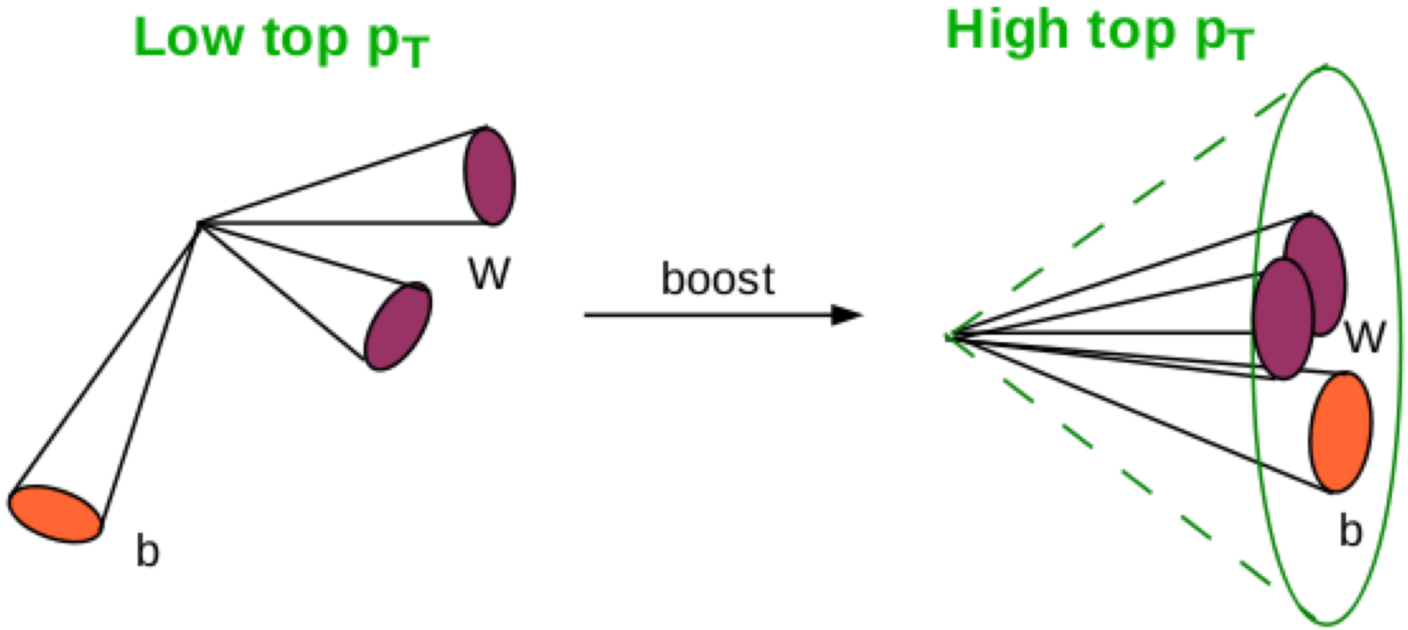
    → still an open riddle where the deviation from prediction comes from
  - Top-Higgs: observation of ttH
    → new era of exploring the connection between heaviest elementary particles
- Everything compatible with SM so far
- Tops were, are and stay awesome
  → much to learn about the SM and beyond

Backup

Boosting algorithms

Boosting algorithms important

- Higher collision energy → more events can be boosted
- Production of heavy particles → decay products can be boosted → results in boosted regimes



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

Spin Correlations: Systematics

Table 5: Summary table of the effect of experimental systematic uncertainties on the f_{SM} extraction. Uncertainties which are smaller than the precision shown are included in the totals and the f_{SM} significance calculations.

		$m_{t\bar{t}}$ range [GeV]			
Systematic	Inclusive	$m_{t\bar{t}} < 450$	$450 \leq m_{t\bar{t}} < 550$	$550 \leq m_{t\bar{t}} < 800$	$m_{t\bar{t}} \geq 800$
Matrix element	± 0.006	± 0.11	± 0.064	± 0.01	± 0.3
Parton shower and hadronisation	± 0.010	± 0.02	± 0.005	± 0.01	± 1.4
Radiation and scale settings	± 0.055	± 0.05	± 0.061	± 0.23	< 0.1
PDF	± 0.002	< 0.01	± 0.003	± 0.01	< 0.1
Background modelling	± 0.009	± 0.01	$^{+0.014}_{-0.015}$	± 0.01	± 0.1
Lepton ID and reconstruction	± 0.008	± 0.01	$^{+0.030}_{-0.036}$	$^{+0.03}_{-0.10}$	$^{+0.5}_{-0.2}$
b-tagging	$^{+0.004}_{-0.003}$	± 0.01	± 0.025	$^{+0.04}_{-0.02}$	$^{+0.1}_{-0.2}$
Jet ID and reconstruction	$^{+0.014}_{-0.017}$	$^{+0.02}_{-0.05}$	$^{+0.076}_{-0.093}$	$^{+0.17}_{-0.26}$	$^{+1.7}_{-0.6}$
E_T^{miss} reconstruction	< 0.001	$^{+0.01}_{-0.02}$	$^{+0.042}_{-0.034}$	$^{+0.12}_{-0.14}$	$^{+0.9}_{-0.7}$
Pile-up effects	$^{+0.013}_{-0.010}$	< 0.01	$^{+0.015}_{-0.019}$	$^{+0.07}_{-0.04}$	$^{+0.2}_{-0.4}$
Luminosity	± 0.001	< 0.01	$^{+0.002}_{-0.000}$	< 0.01	< 0.1
MC statistical uncertainty	± 0.005	< 0.01	± 0.007	± 0.03	± 0.05
Total systematics	± 0.061	$^{+0.12}_{-0.13}$	$^{+0.13}_{-0.14}$	$^{+0.31}_{-0.41}$	$^{+2.5}_{-1.7}$