Hot TOPics

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MANCHESTER 1824

European Research Council
Established by the European Commission

Structure

- Introduction
- Angular Distributions
- Colour Flow
- Summary

Introduction

The Top Quark

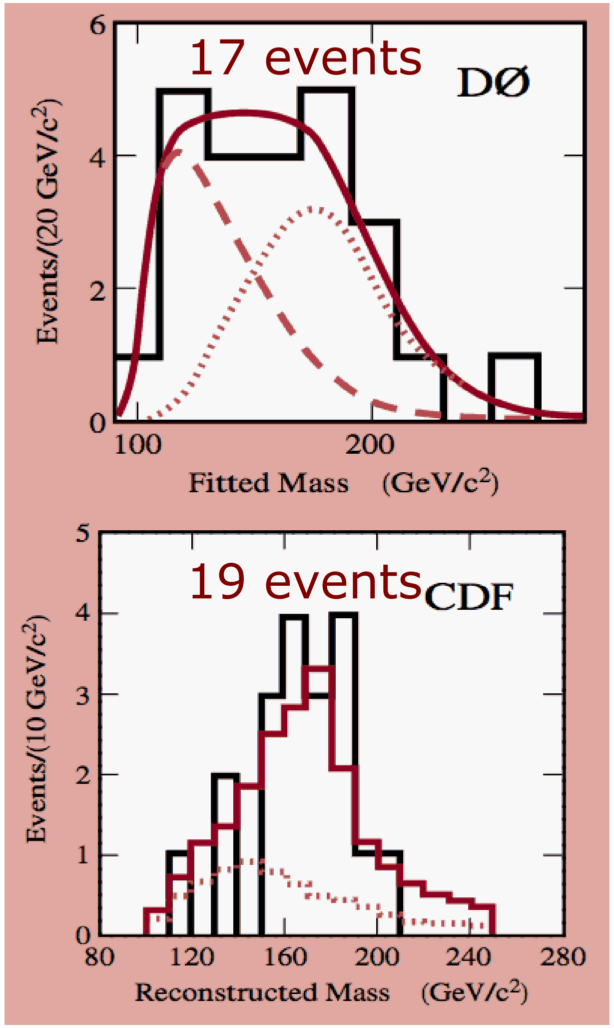
- Heaviest known elementary particle:

  m_t~173GeV

- Standard Model:
  - Single or pair production
  - Electric charge +2/3 e
  - Short lifetime 0.5x10^{-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

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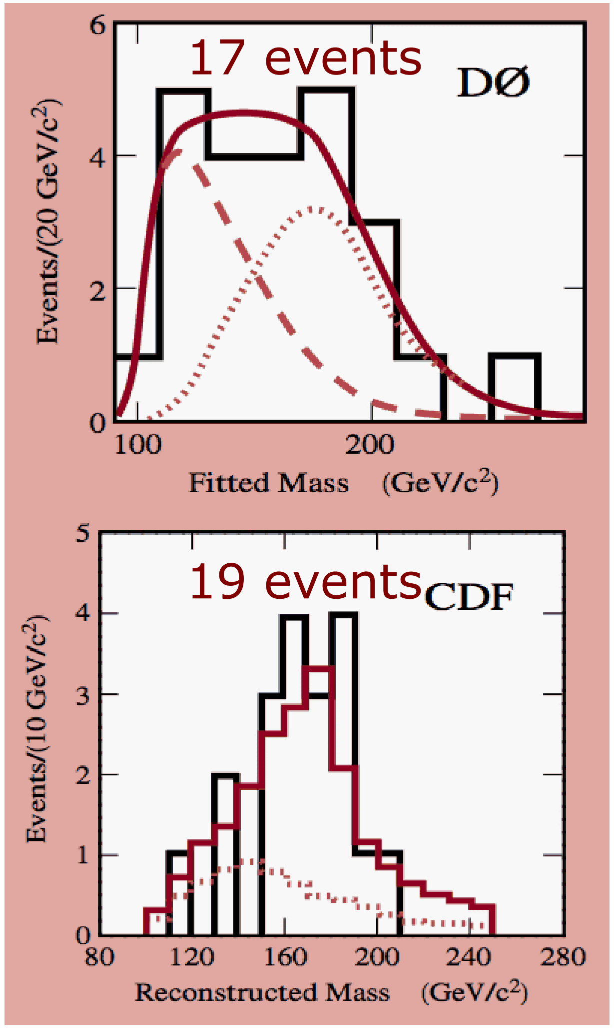
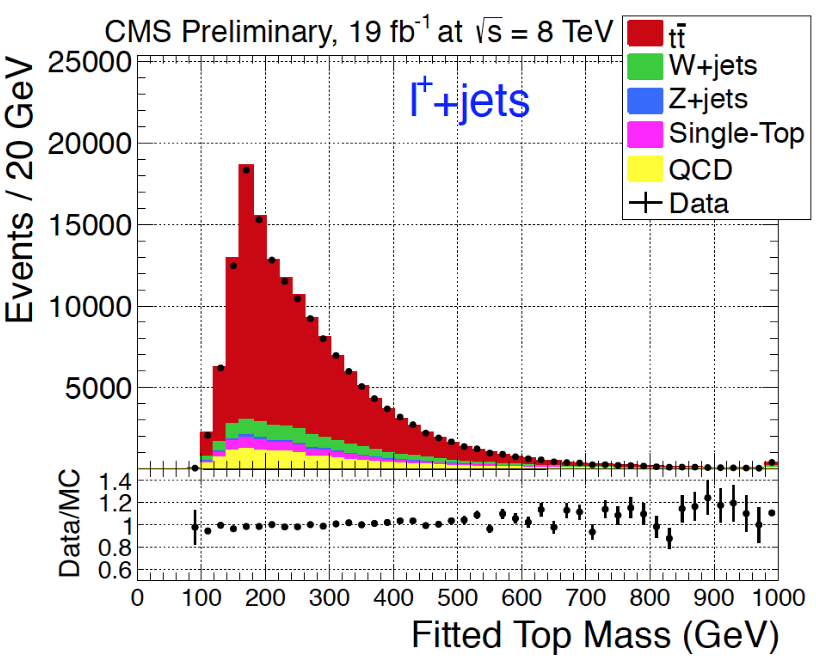
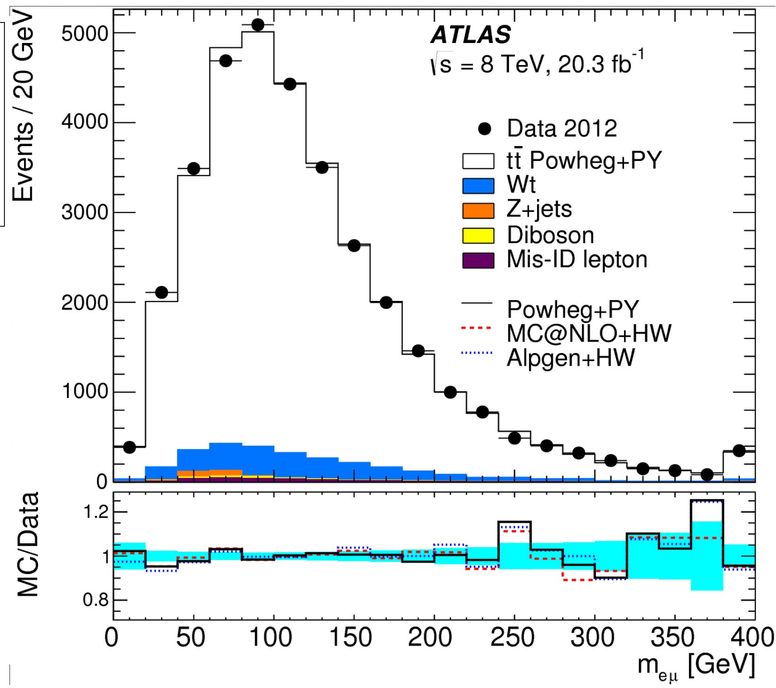


Situation today:

LHC → top quark factory!

- Many precision measurements possible!

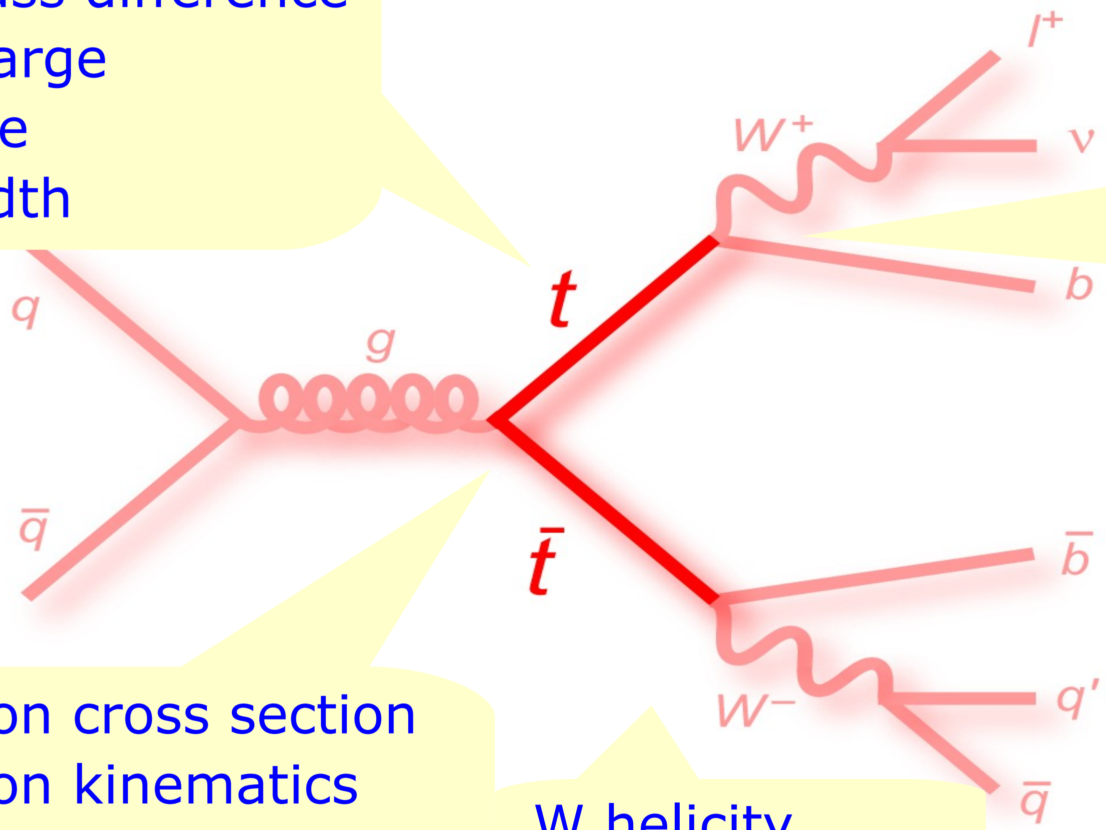




Top Studies: Overview

- 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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$|V_{tb}|$
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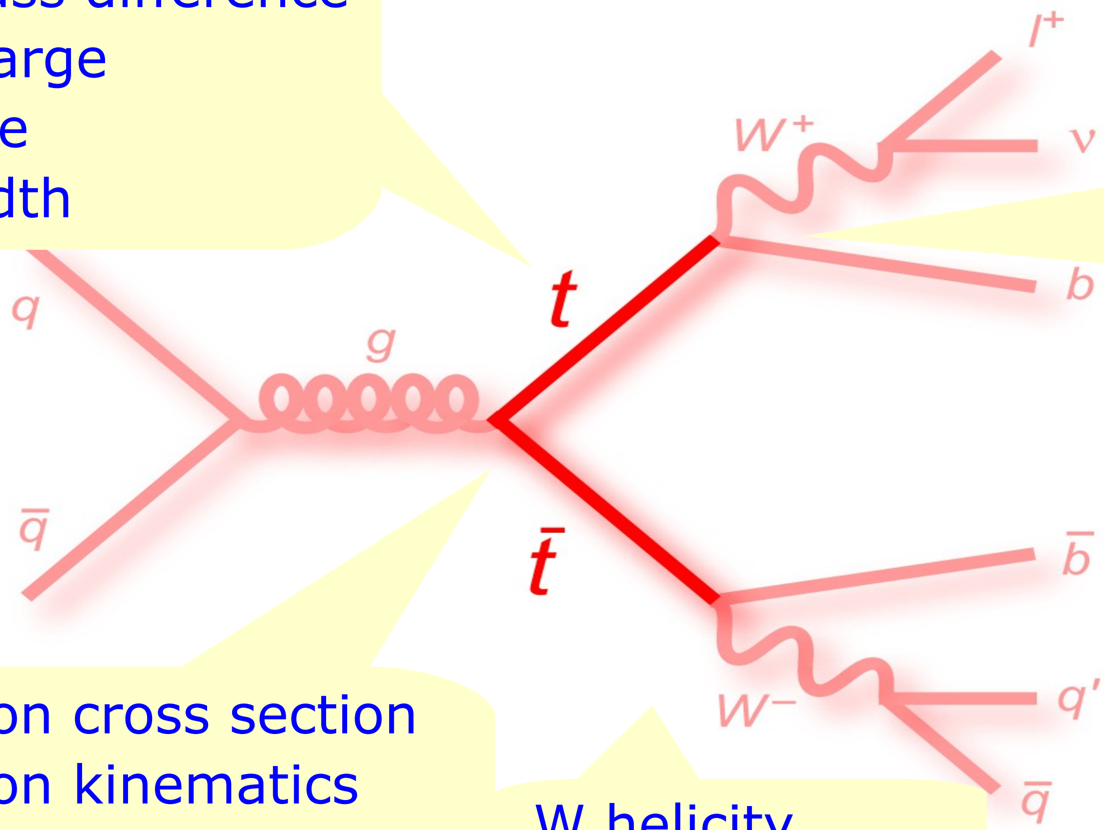

Spin correlation
Charge asymmetry
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Production kinematics
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W helicity

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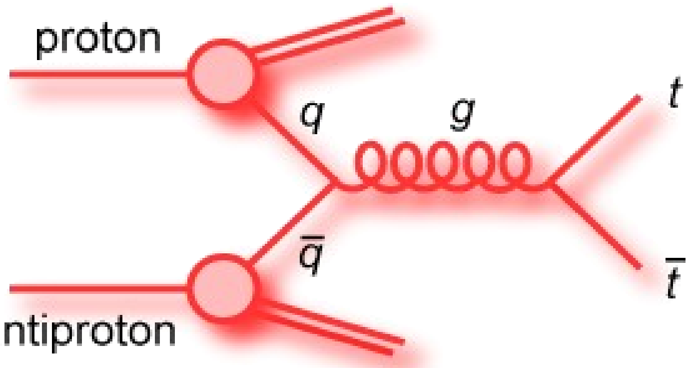
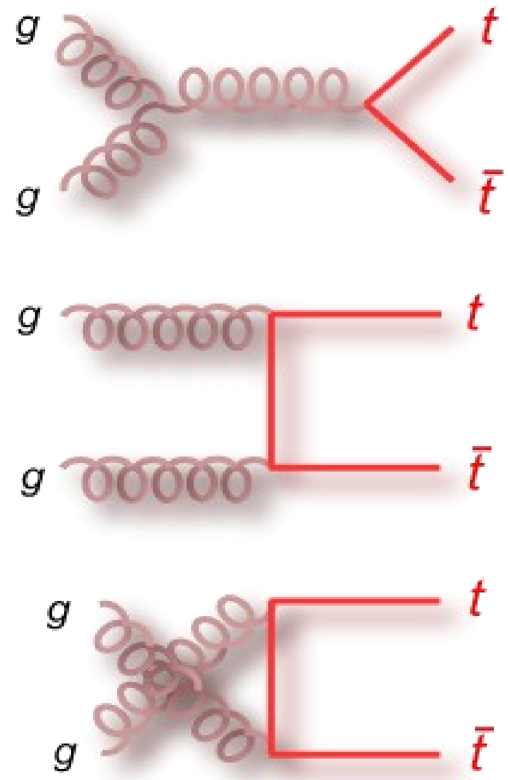
Top Quark Pair Production

At the Tevatron:

85%



+ 15%



At LHC:

14 TeV:	10%	+ 90%
7 TeV:	30%	+ 70%

Top Quark Pair Production

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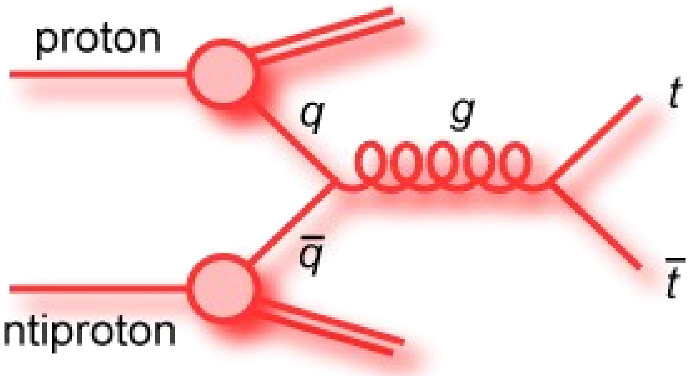

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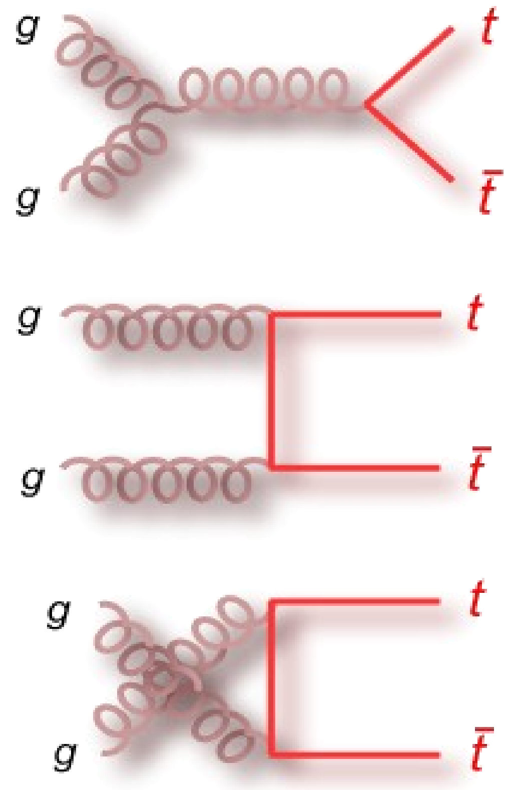


At LHC:

14 TeV: 10% + 90%

7 TeV: 30% + 70%

Cross Sections:

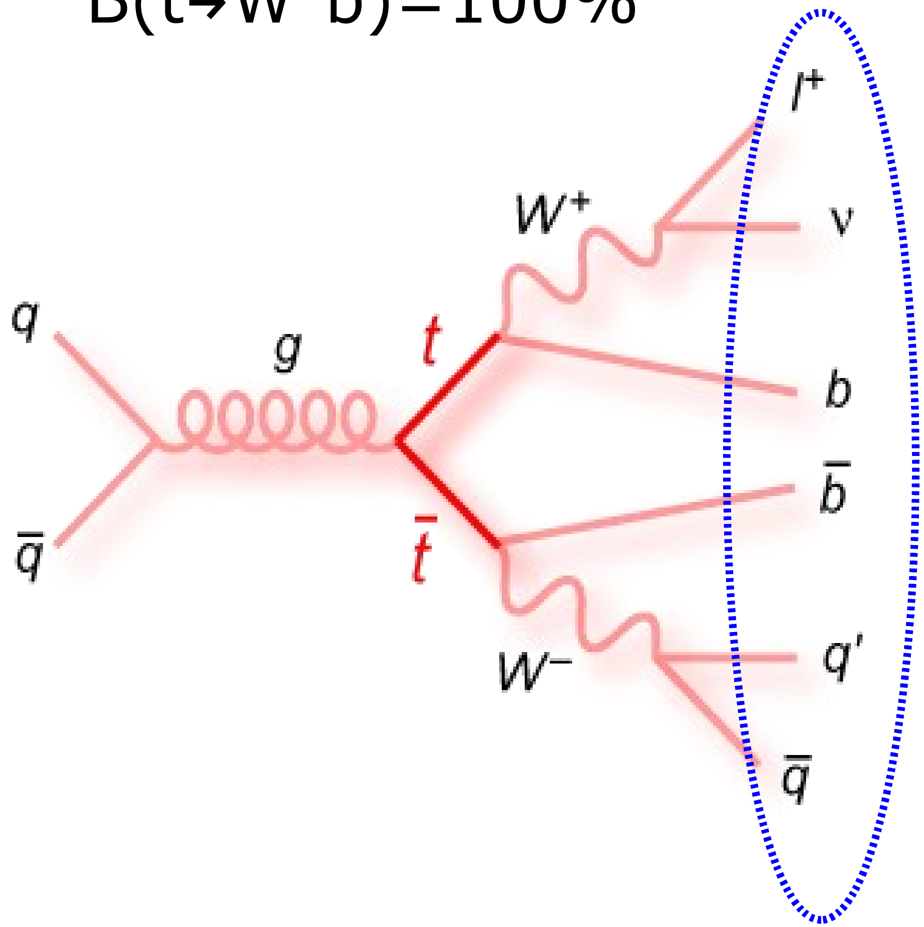
Collider	Cross section [pb]
Tevatron (1.96 TeV)	$7.35^{+0.23}_{-0.27}$
LHC (7 TeV)	$177.3^{+10.1}_{-10.8}$
LHC (8 TeV)	$252.9^{+13.3}_{-14.5}$
LHC (13 TeV)	$831.8^{+40.3}_{-45.6}$

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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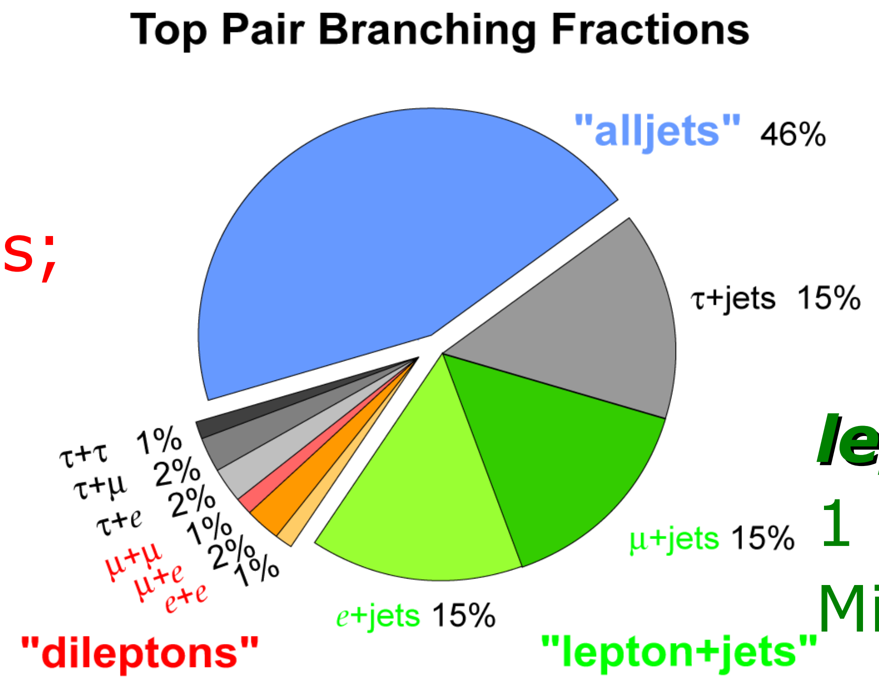
all-hadronic:
≥6 jets (2 b-jets)

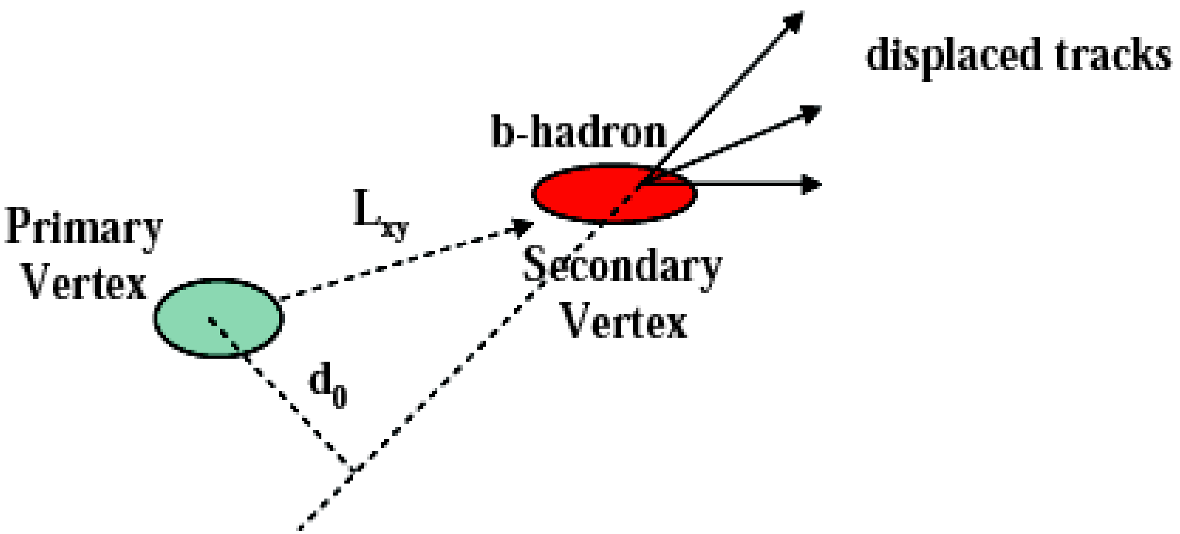
dilepton:
2 isolated leptons;
High missing E_T from neutrinos;
2 b-jets

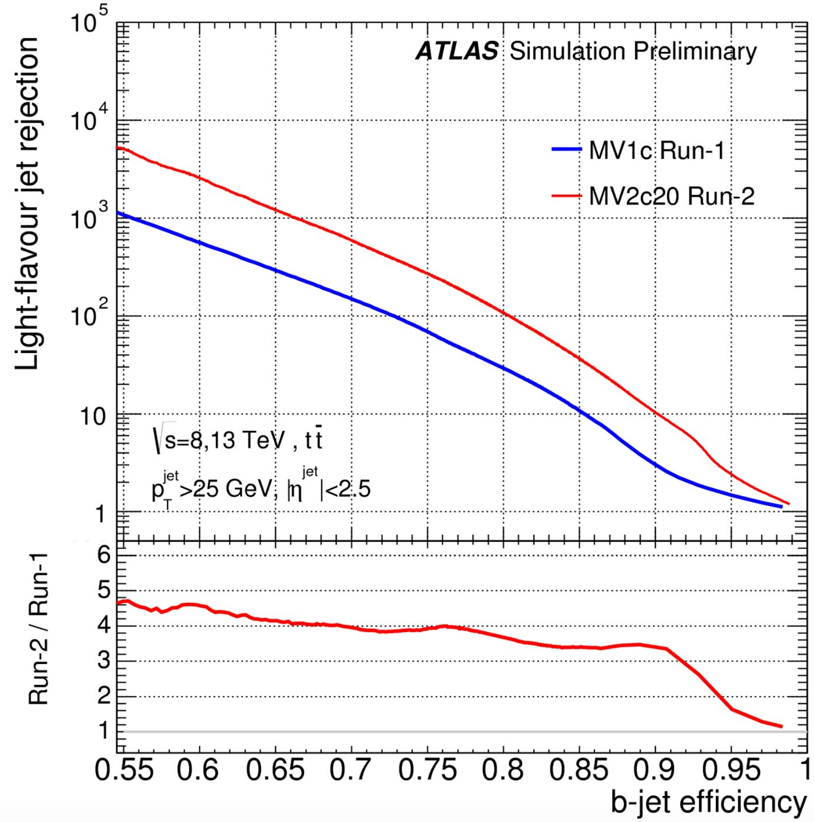


lepton+jets:
1 isolated lepton;
Missing E_T from neutrino;
≥4 jets (2 b-jets)

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



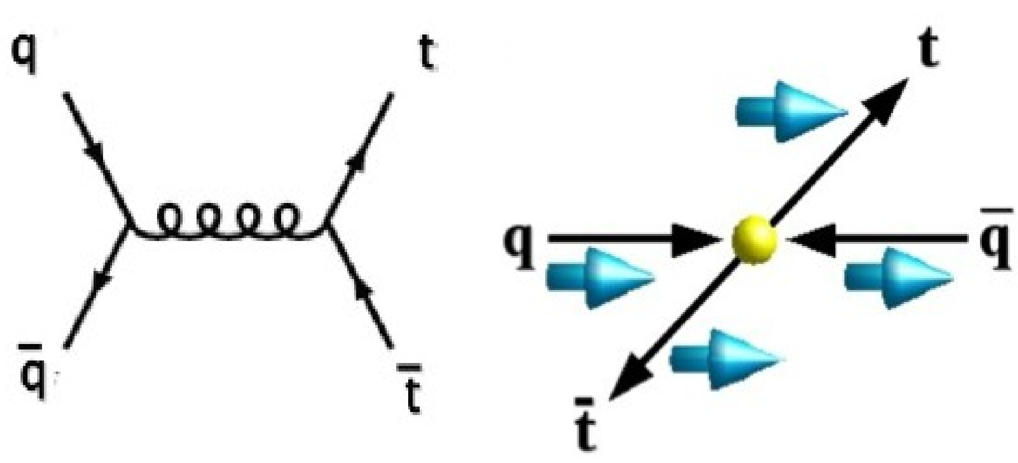


ATLAS-PHYS-PUB-2015-022

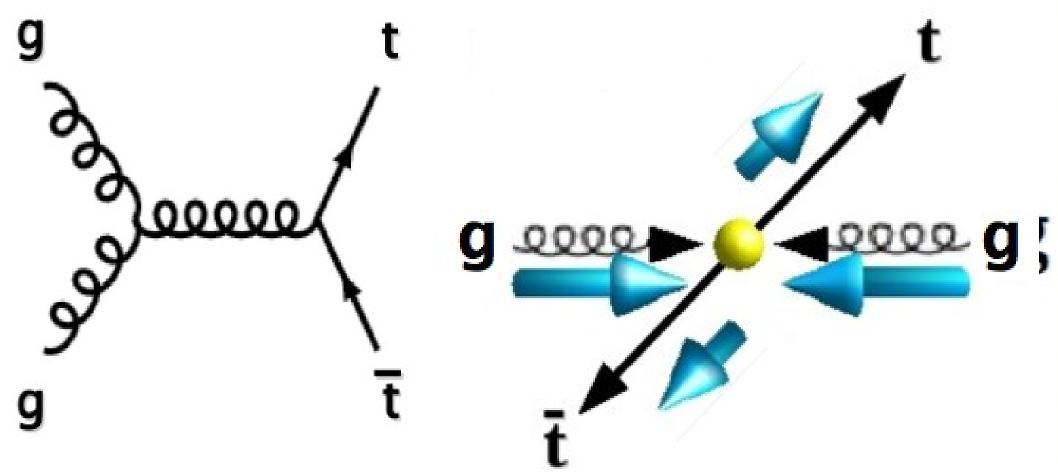
Angular Distributions

Spin Correlations & Polarization

- 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



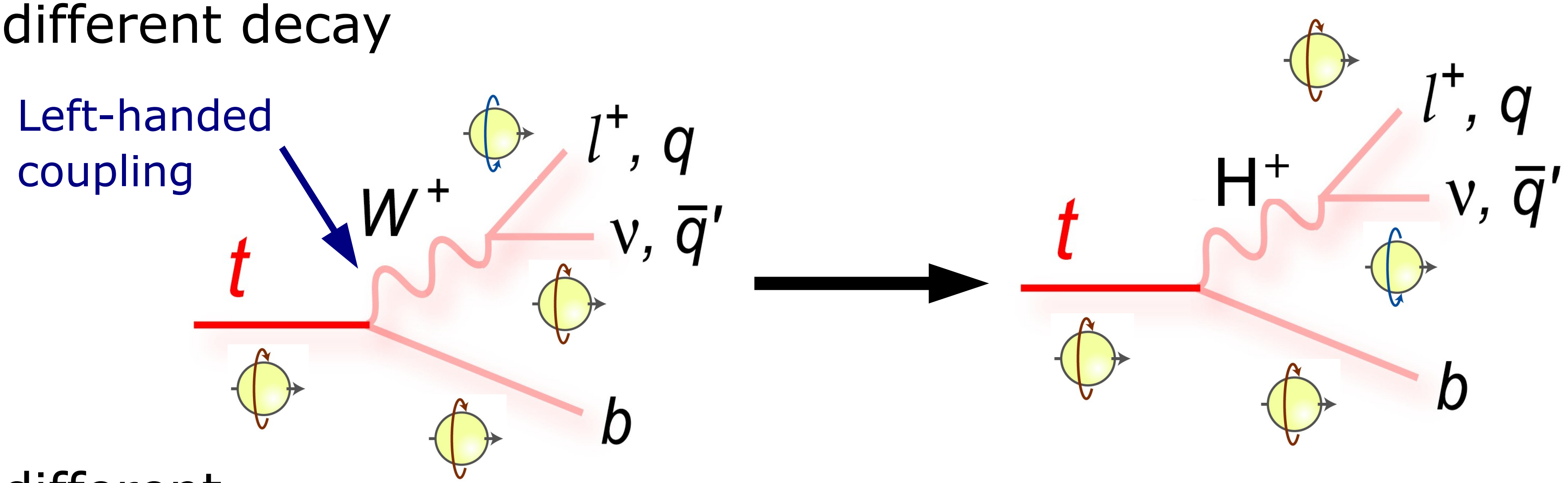
Dominant spin correlation at Tevatron



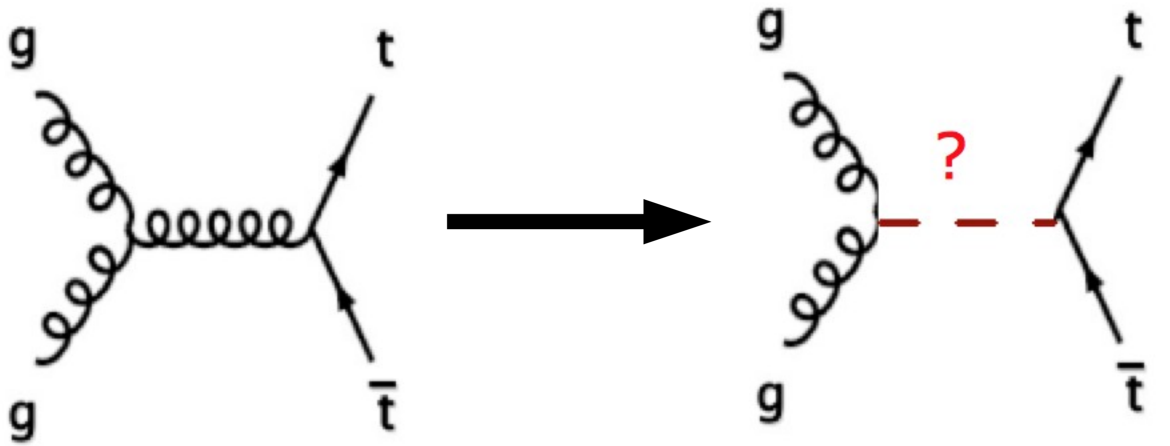
Dominant spin correlation at LHC

Spin Correlations & Polarization

- Measured spin correlation can change
  - Due to different decay



  - Due to different production



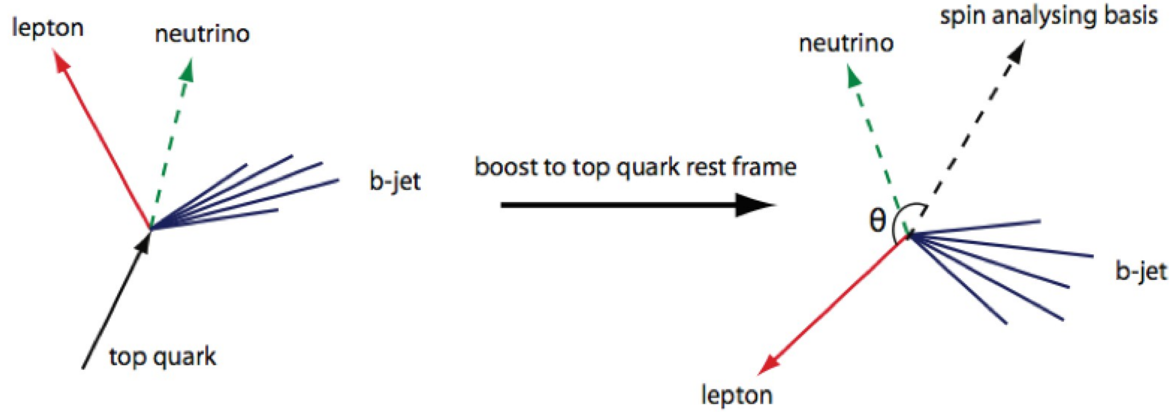
- Spin correlation: test the full chain form production to decay!

Spin Correlation & Polarization

- Doubly differential cross section:

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

  - α_i: spin analyzing power of decay product i; θ_i: direction of daughter wrt. chosen axis
  - P: polarization
  - C spin correlation;



Spin Correlation & Polarization

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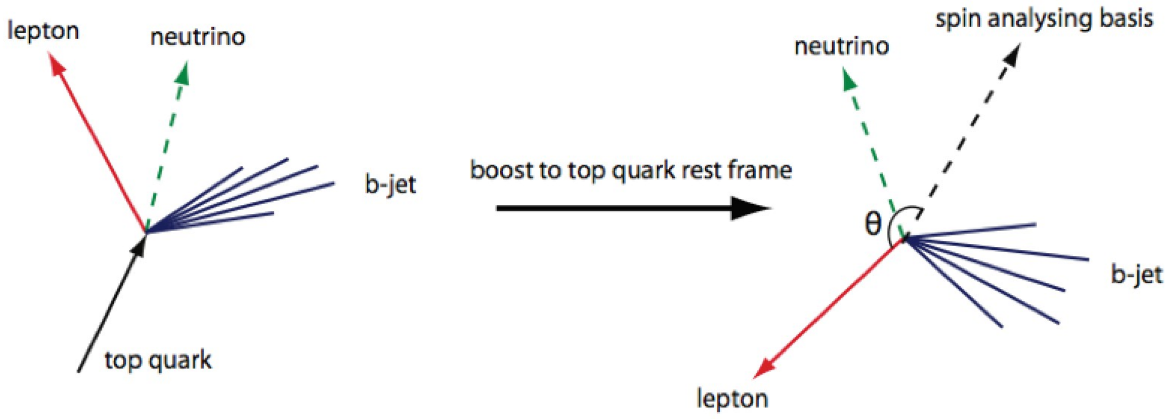
  - P: polarization
  - C spin correlation; C= $A\alpha_1\alpha_2$



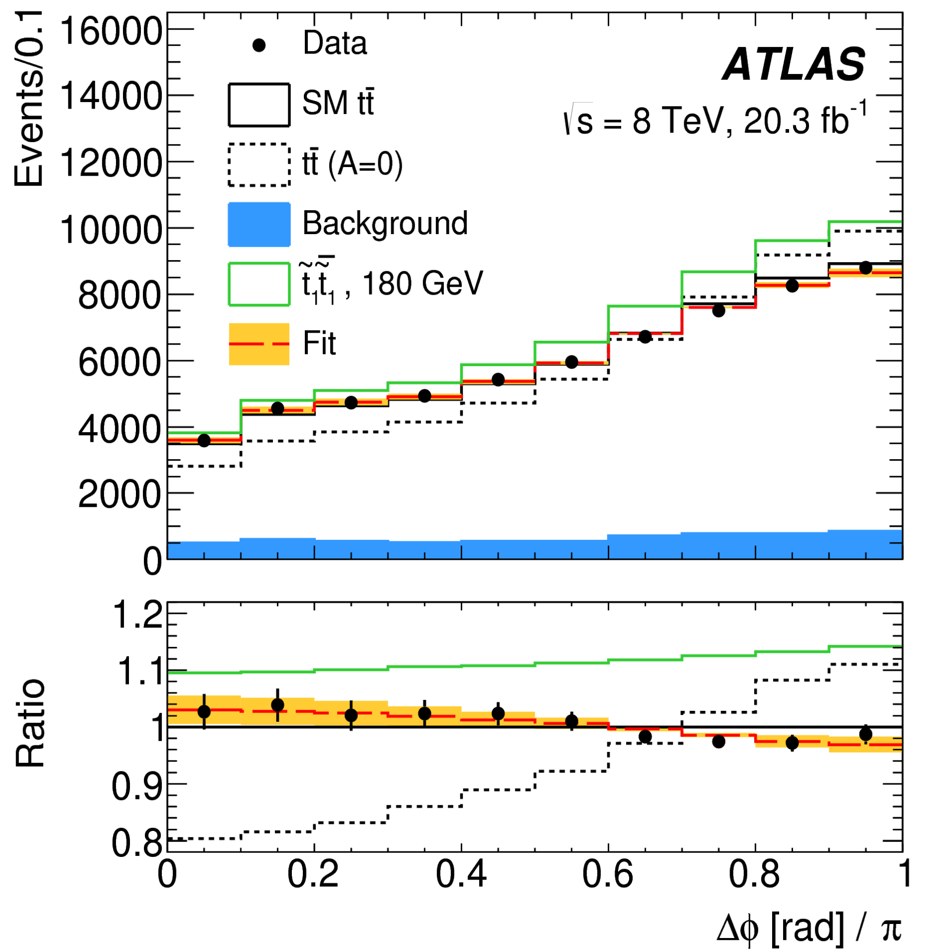
	b	lepton	d	u
$\alpha_{i/j}$ (LO)	-0.41	1.00	1.00	-0.31
$\alpha_{i/j}$ (NLO)	-0.39	0.998	0.93	-0.31

$$A=\frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)}$$

Spin Correlations: Stop

- Simple azimuthal angle: $\Delta\varphi = |\varphi_1 - \varphi_2|$
  - No kinematic reconstruction needed!
- Extract spin correlation using MC with SM spin correlation, and without spin correlation
  - Extract f_{SM} with template fit to different observables
- Result:

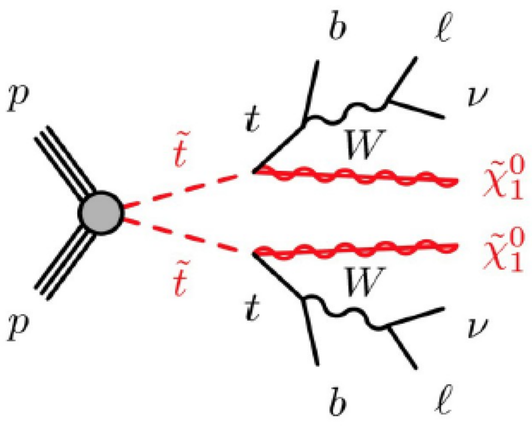
$$f_{SM} = 1.20 \pm 0.14\,(stat + syst)$$

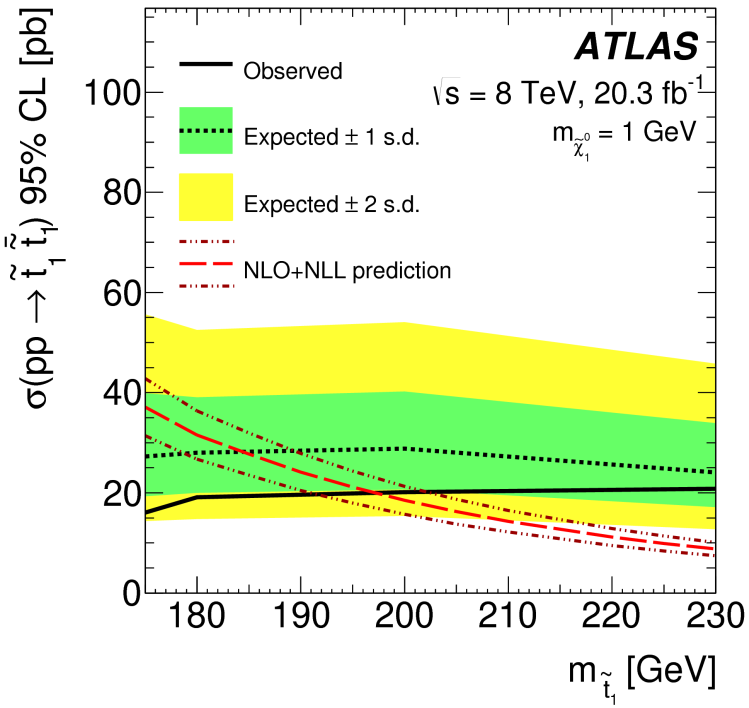


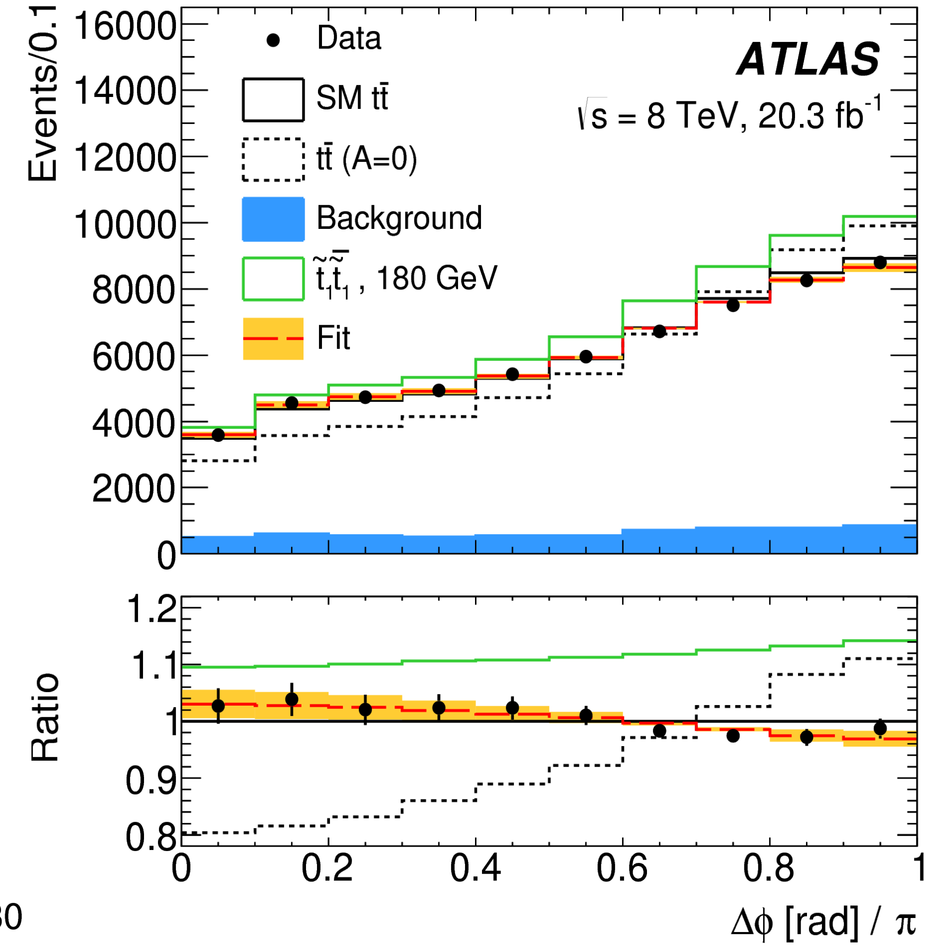
Phys. Rev. Lett. 114, 142001 (2015)

Spin Correlations: Stop

- Test also stop pair production
  - For $m_{stop} \sim m_{top}$
  - Looks like no-correlation $t\bar{t}$







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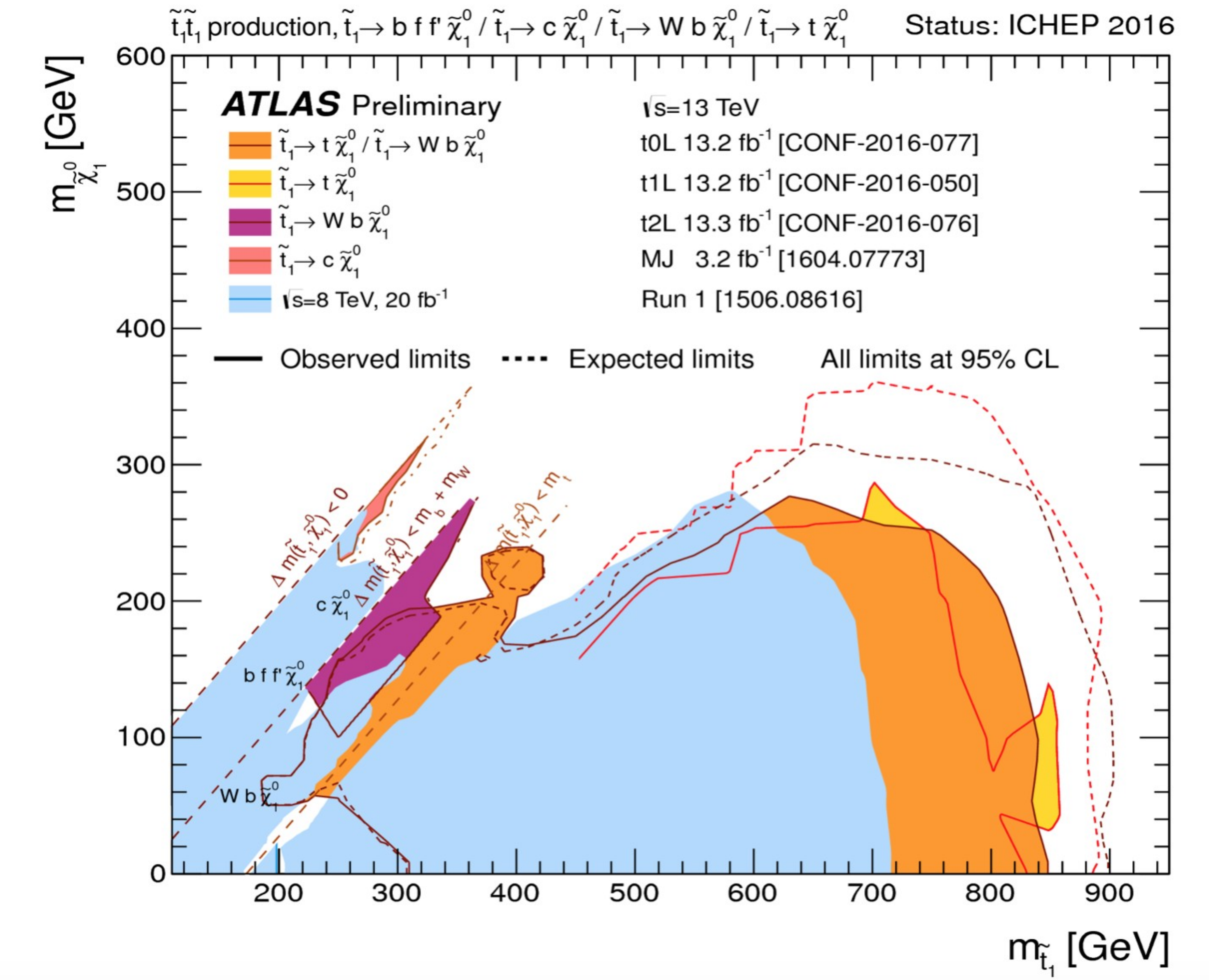
Spin Correlations: Stop



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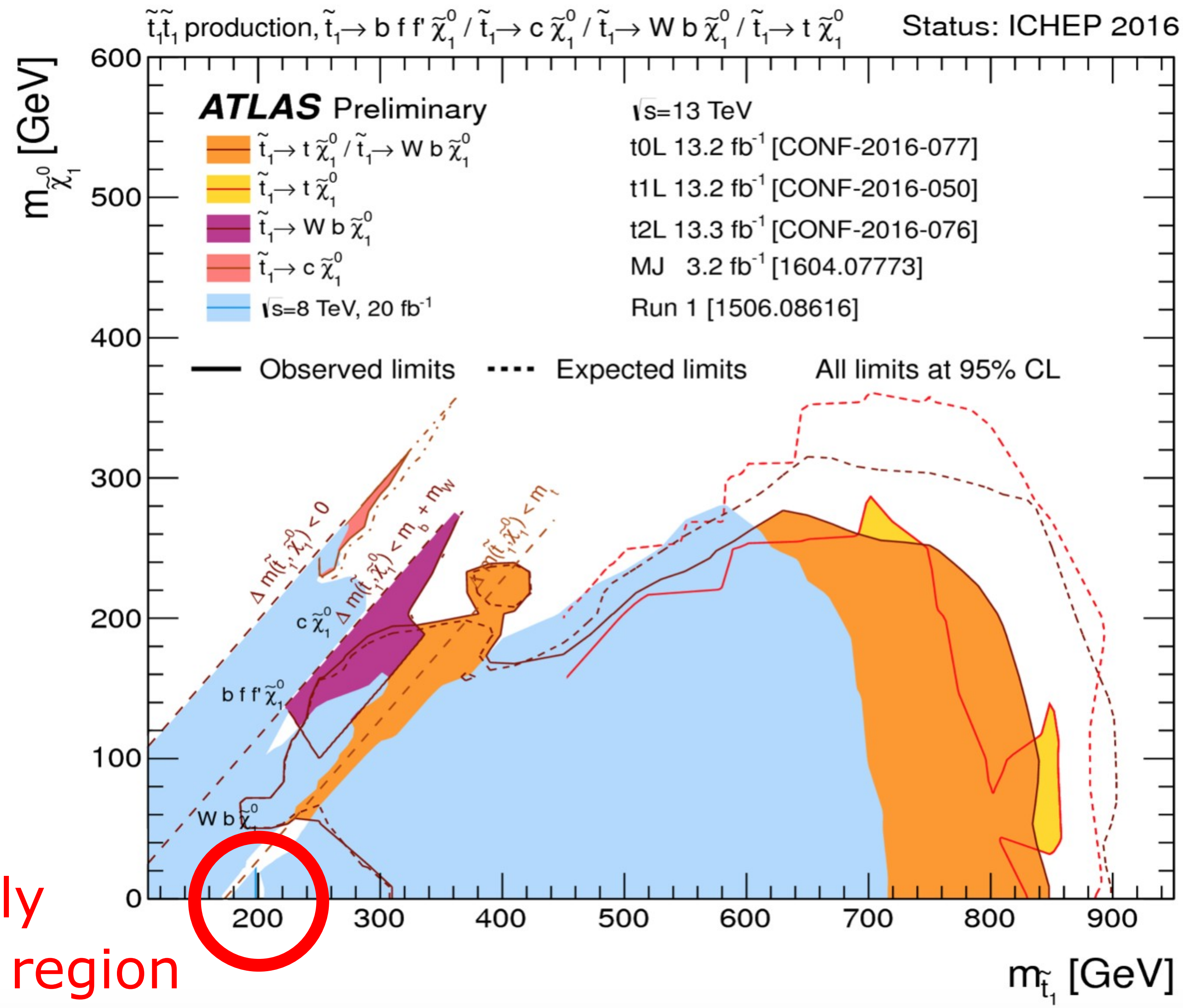
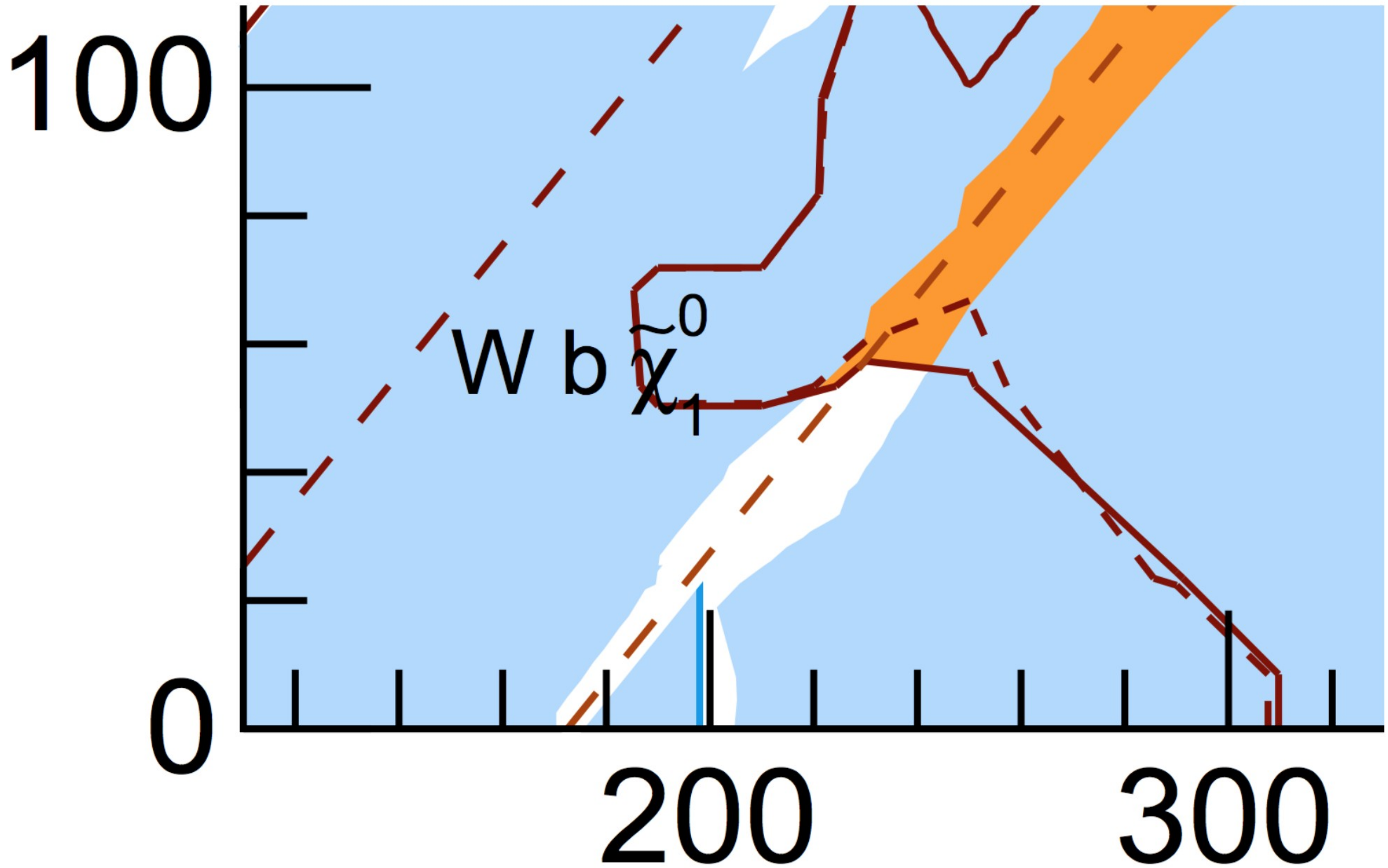


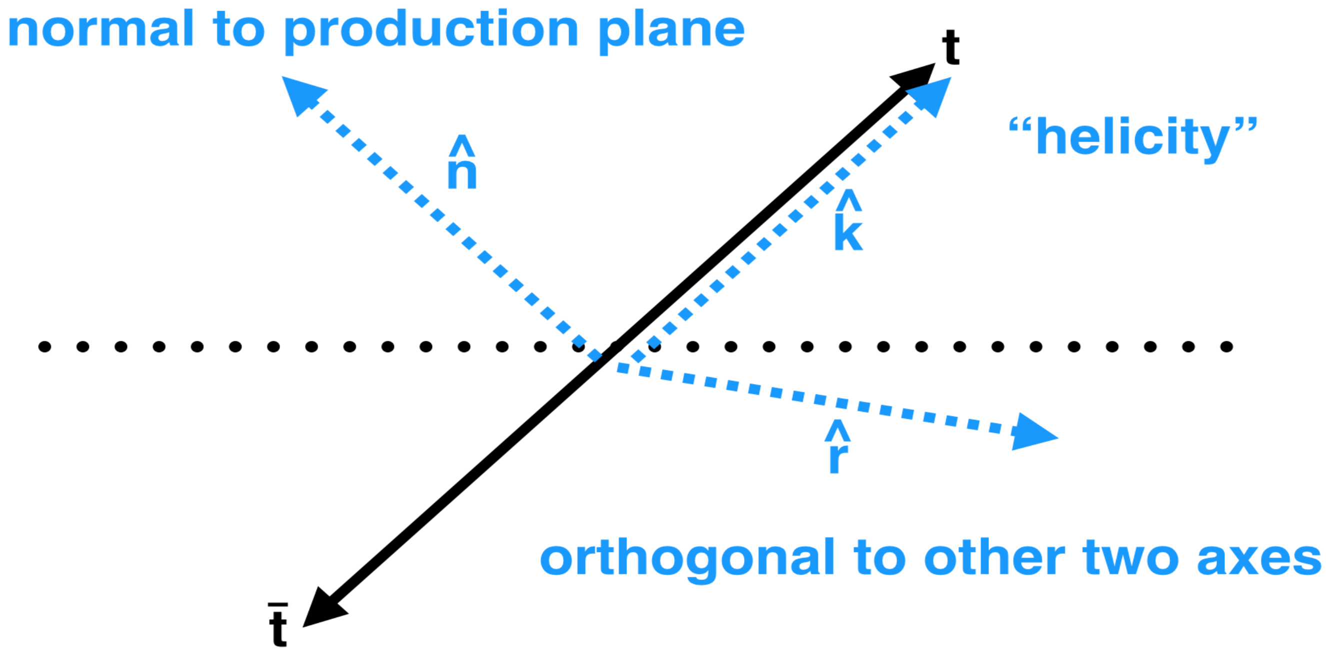
Kinematically challenging region

Spin Correlations: Stop



Spin Density Matrix

- Many more spin correlation and polarization results by Tevatron experiments, ATLAS and CMS
  - Issue: no 1-to-1 correspondence to spin density matrix
- Construct system of orthogonal axes → extract polarization, spin correlations and cross correlations

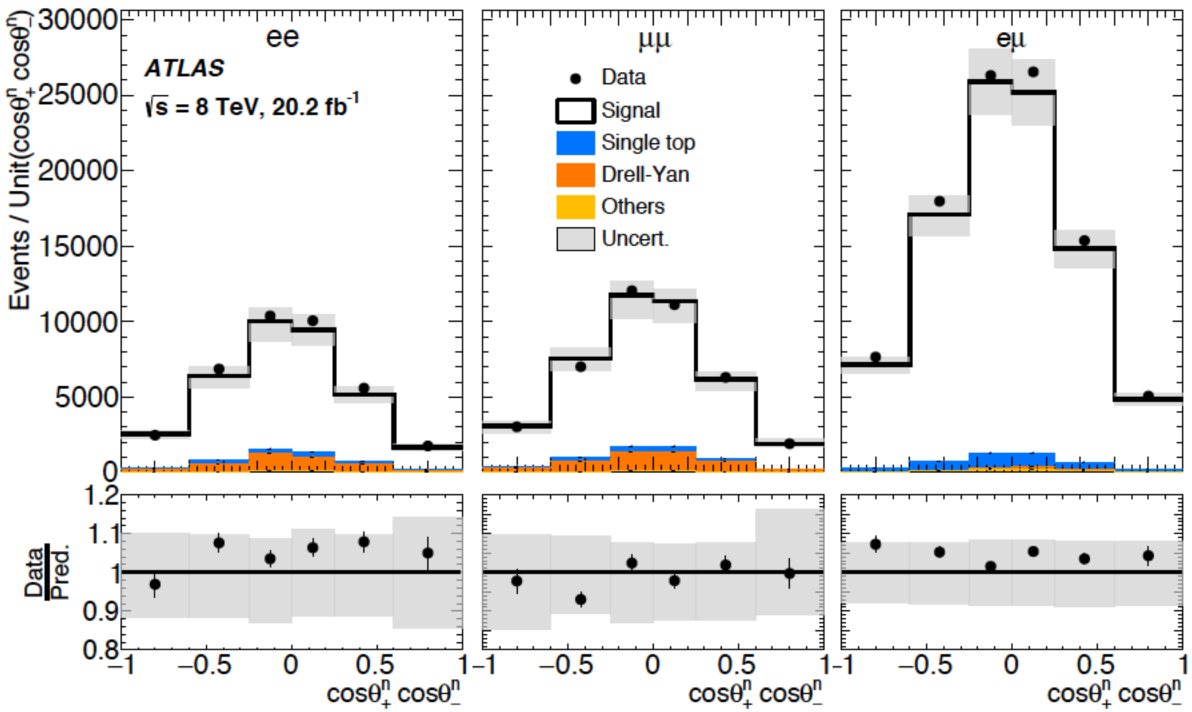


Spin Density Matrix

	Expectation values	NLO predictions	Observables
polarization	B_+^k	0.0030 ± 0.0010	$\cos\theta_+^k$
	B_-^k	0.0034 ± 0.0010	$\cos\theta_-^k$
	B_+^n	0.0035 ± 0.0004	$\cos\theta_+^n$
	B_-^n	0.0035 ± 0.0004	$\cos\theta_-^n$
	B_+^r	0.0013 ± 0.0010	$\cos\theta_+^r$
	B_-^r	0.0015 ± 0.0010	$\cos\theta_-^r$
Spin correlation	$C(k,k)$	0.318 ± 0.003	$\cos\theta_+^k \cos\theta_-^k$
	$C(n,n)$	0.332 ± 0.002	$\cos\theta_+^n \cos\theta_-^n$
	$C(r,r)$	0.055 ± 0.009	$\cos\theta_+^r \cos\theta_-^r$
Cross correlations	$C(n,k) + C(k,n)$	0.0023	$\cos\theta_+^n \cos\theta_-^k + \cos\theta_+^k \cos\theta_-^n$
	$C(n,k) - C(k,n)$	0	$\cos\theta_+^n \cos\theta_-^k - \cos\theta_+^k \cos\theta_-^n$
	$C(n,r) + C(r,n)$	0.0010	$\cos\theta_+^n \cos\theta_-^r + \cos\theta_+^r \cos\theta_-^n$
	$C(n,r) - C(r,n)$	0	$\cos\theta_+^n \cos\theta_-^r - \cos\theta_+^r \cos\theta_-^n$
	$C(r,k) + C(k,r)$	-0.226 ± 0.004	$\cos\theta_+^r \cos\theta_-^k + \cos\theta_+^k \cos\theta_-^r$
	$C(r,k) - C(k,r)$	0	$\cos\theta_+^r \cos\theta_-^k - \cos\theta_+^k \cos\theta_-^r$

Spin Density Matrix

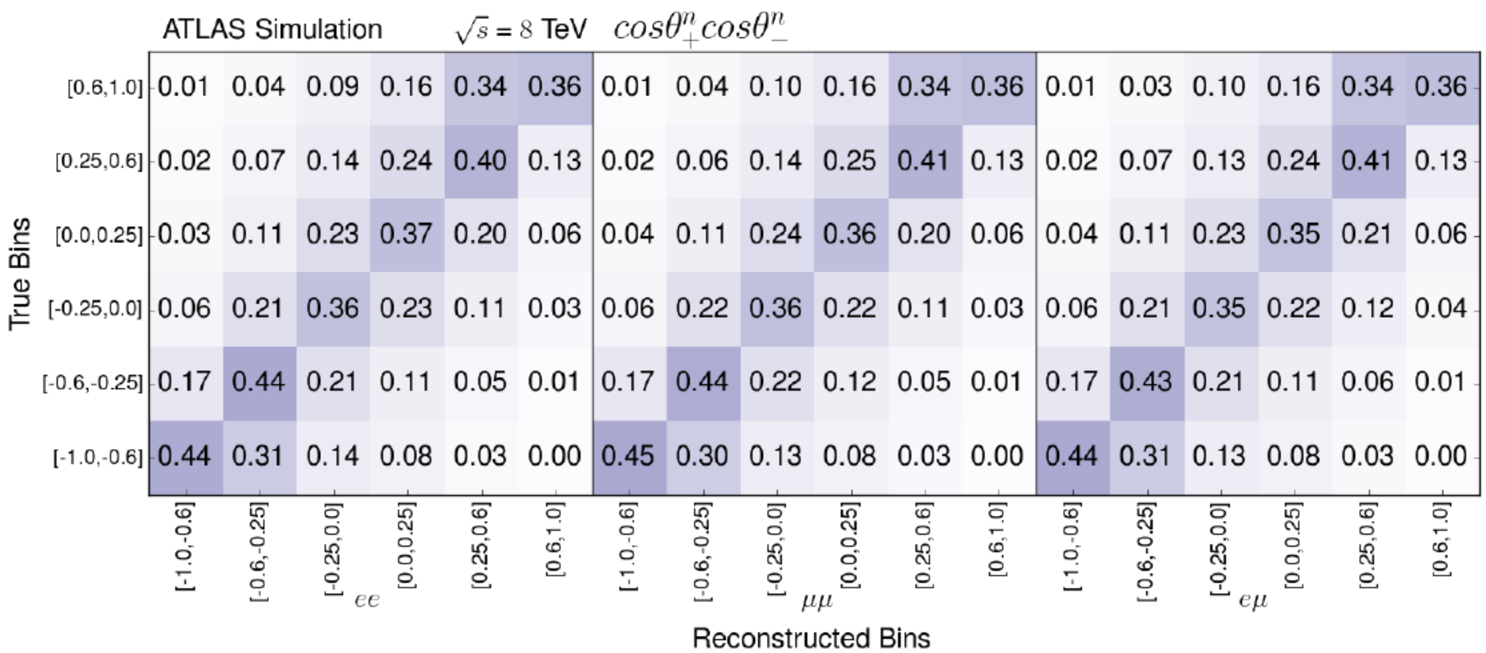
- Analysis in dilepton final state
- Unfolding to particle and parton level



JHEP 03 (2017) 113

Spin Density Matrix

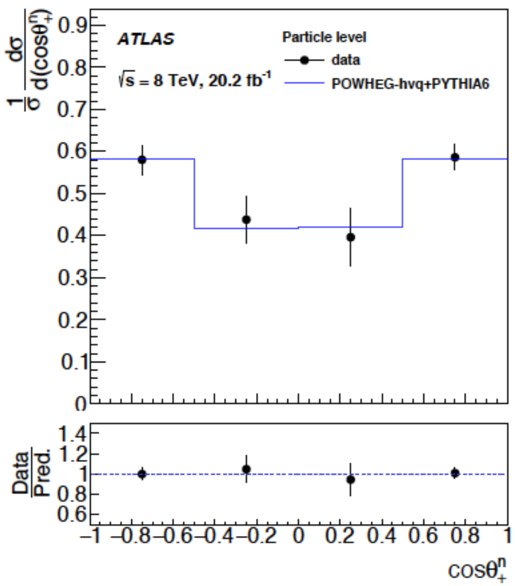
- Unfolding using fully bayesian unfolding
- Example response matrix for unfolding to parton level
  - Bin optimization taking into account expected statistical uncertainty and bias

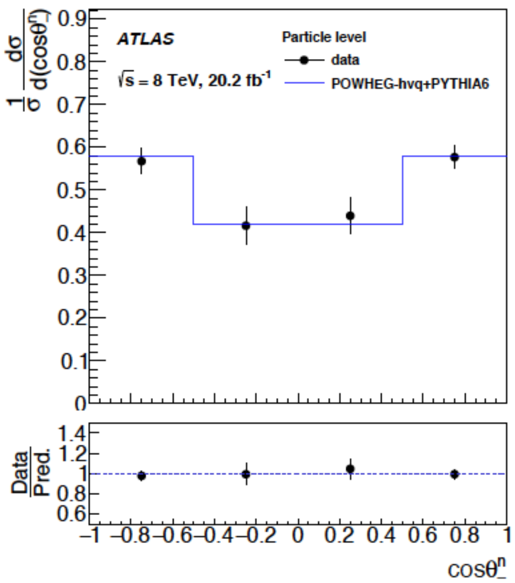


Spin Density Matrix

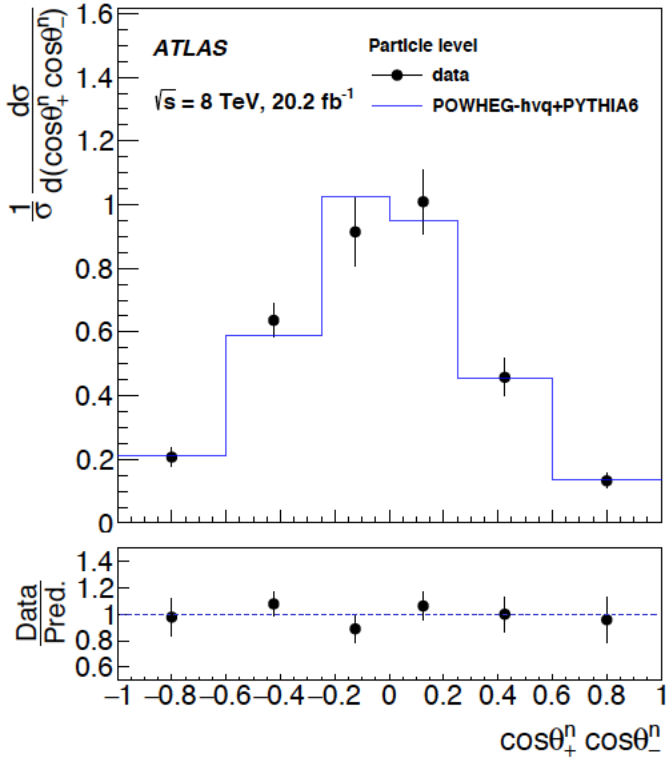
- Particle level:

Transverse polarization

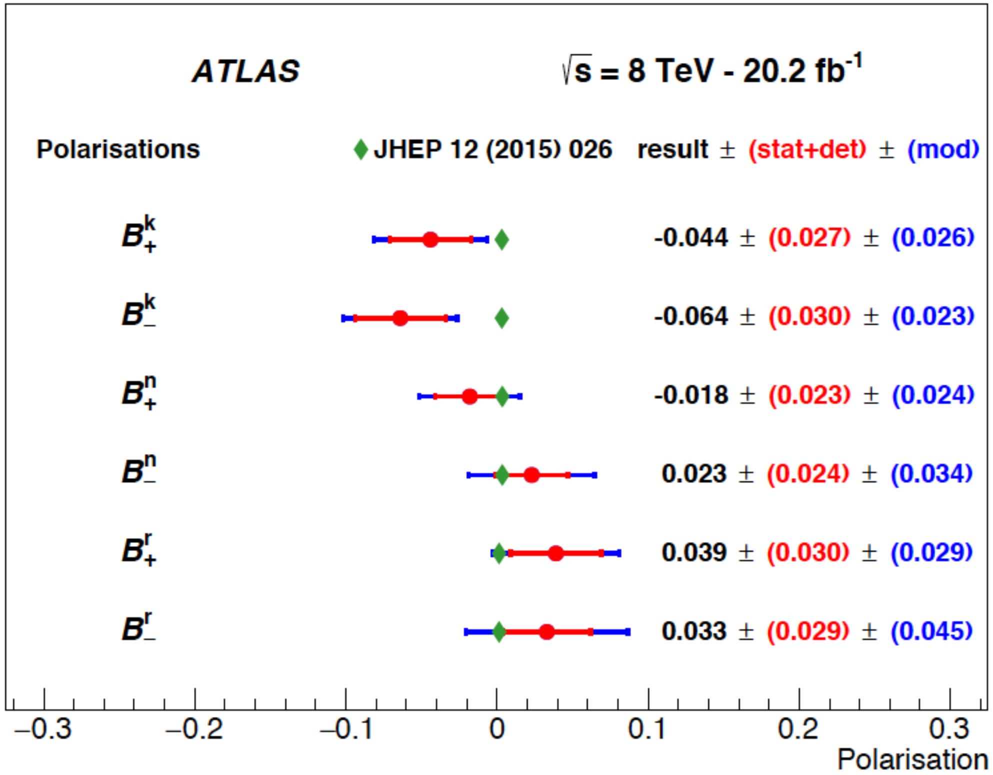


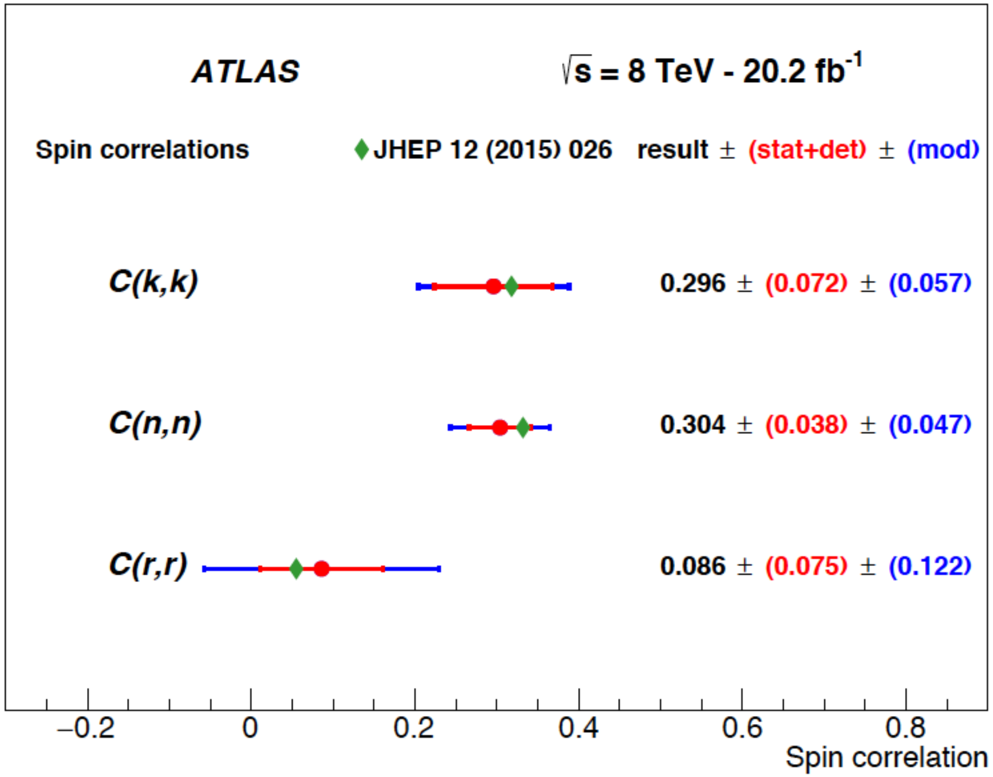


Transverse spin correlations



Spin Density Matrix





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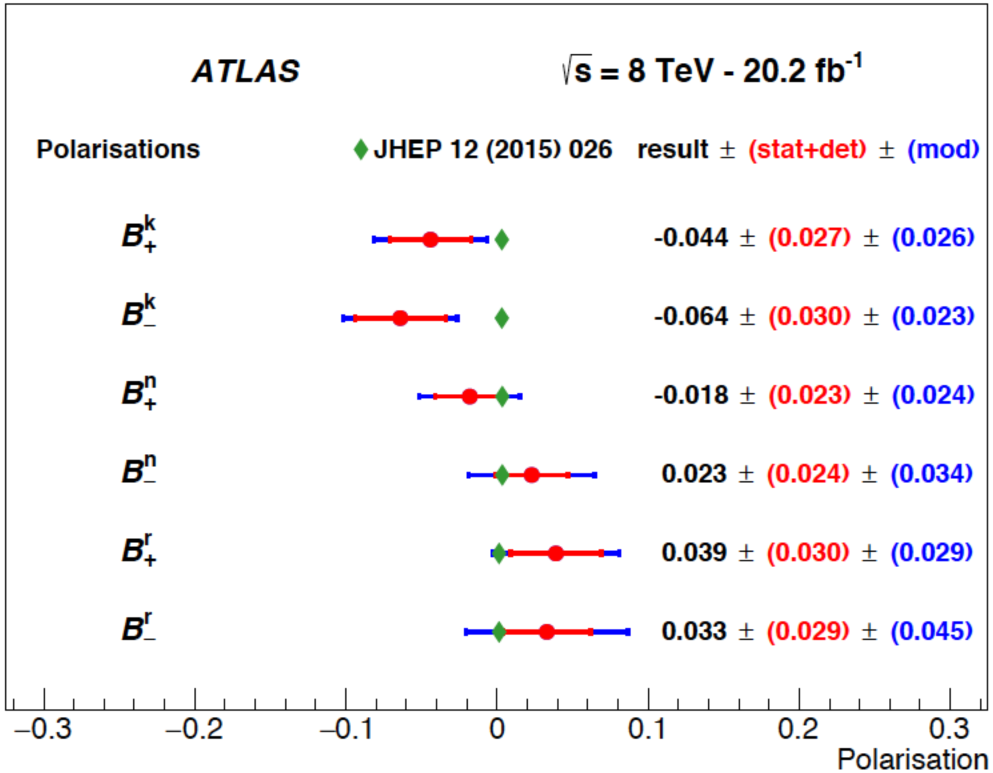
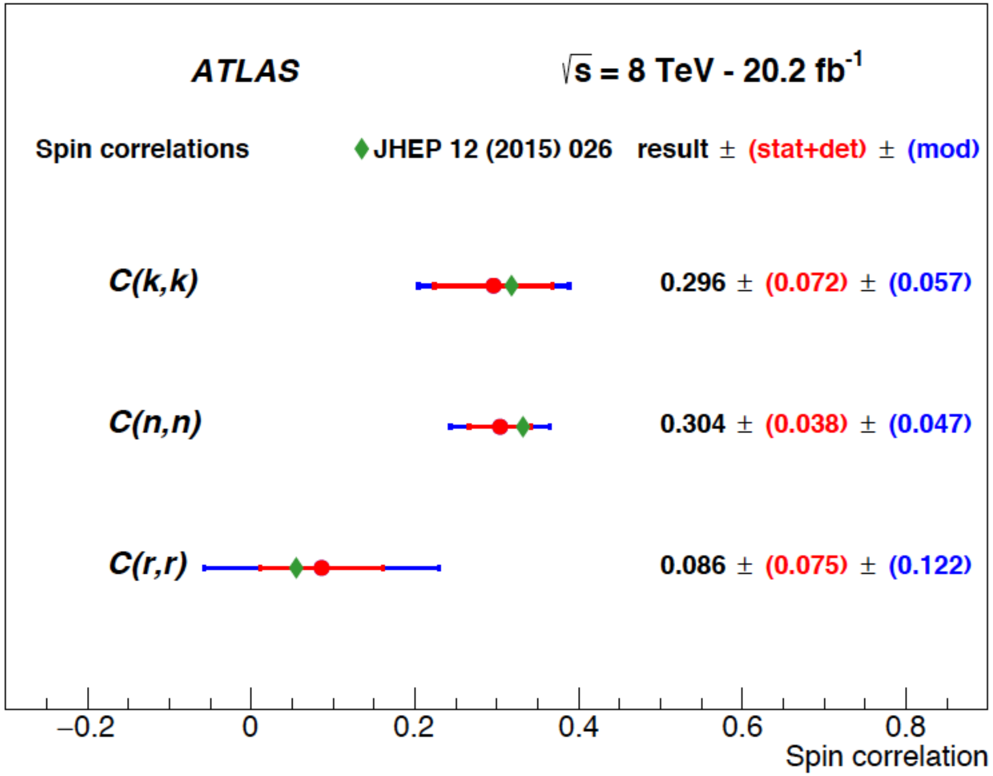
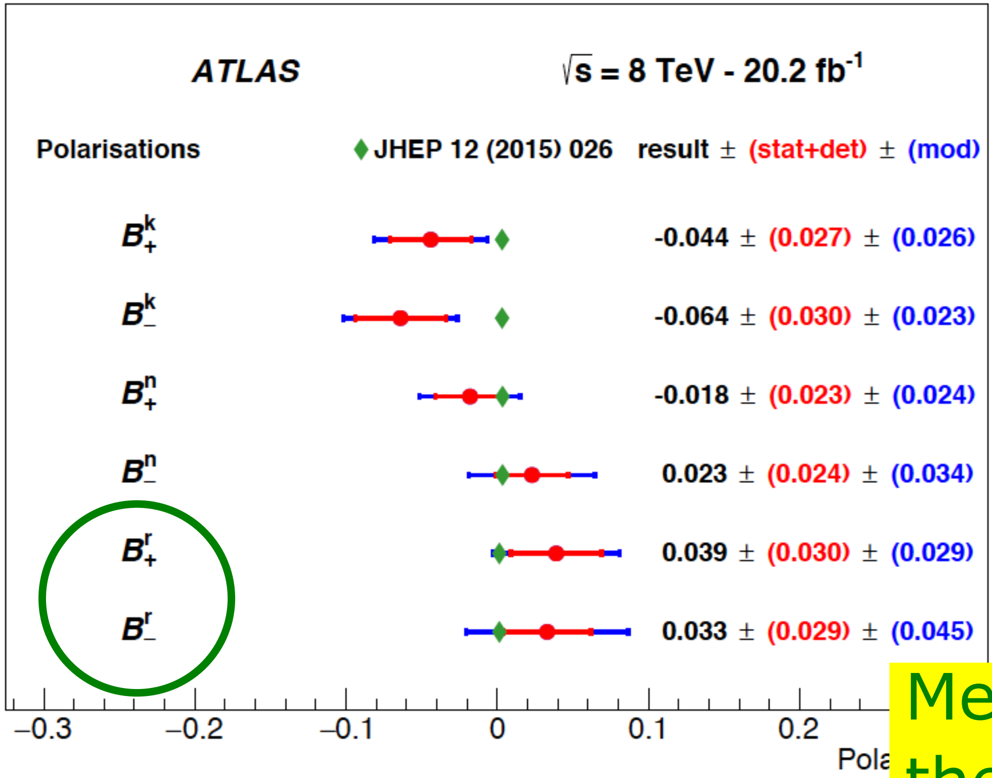
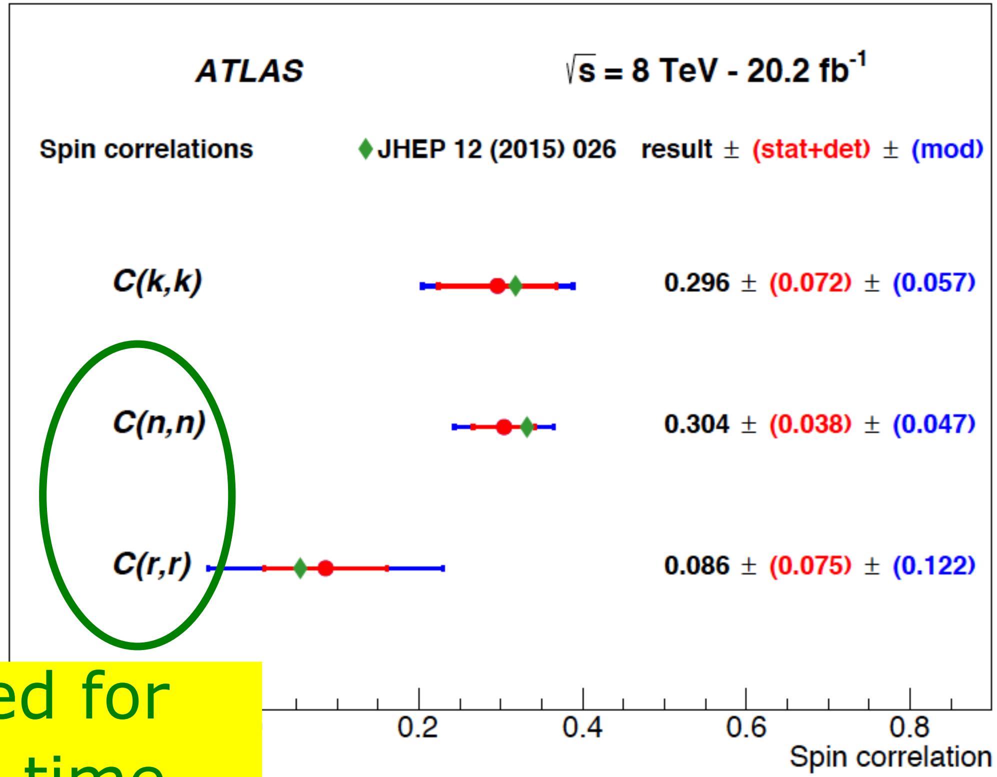




Experiment	$\sqrt{s}$	Method	B_+^k	B_-^k	$C(k,k)$	B_+^n	B_-^n
ATLAS	8 TeV	Unfolding	-0.044 ± 0.038	-0.064 ± 0.040	0.296 ± 0.093	-0.018 ± 0.034	0.023 ± 0.042
CMS [16]	8 TeV	Unfolding	-0.022 ± 0.058		0.278 ± 0.084	-	-
ATLAS [11]	7 TeV	Template fit	-0.035 ± 0.040		-	-	-
ATLAS [10]	7 TeV	Template fit	-	-	0.23 ± 0.09	-	-
ATLAS [12]	7 TeV	Unfolding	-	-	0.315 ± 0.078	-	-
D0 [17]	1.96 TeV	Template fit	-0.102 ± 0.061		-	0.040 ± 0.034	

Spin Density Matrix





Measured for the first time

Experiment	$\sqrt{s}$	Method	B^k_+	B^k_-	$C(k,k)$	B^n_+	B^n_-
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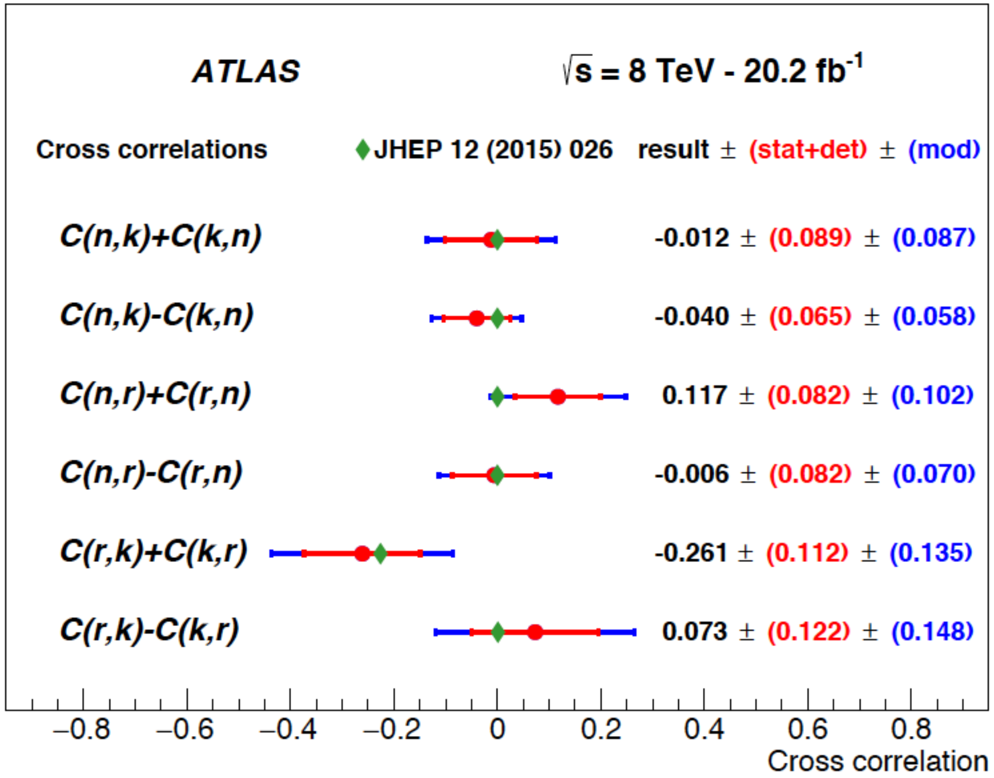
Spin Density Matrix

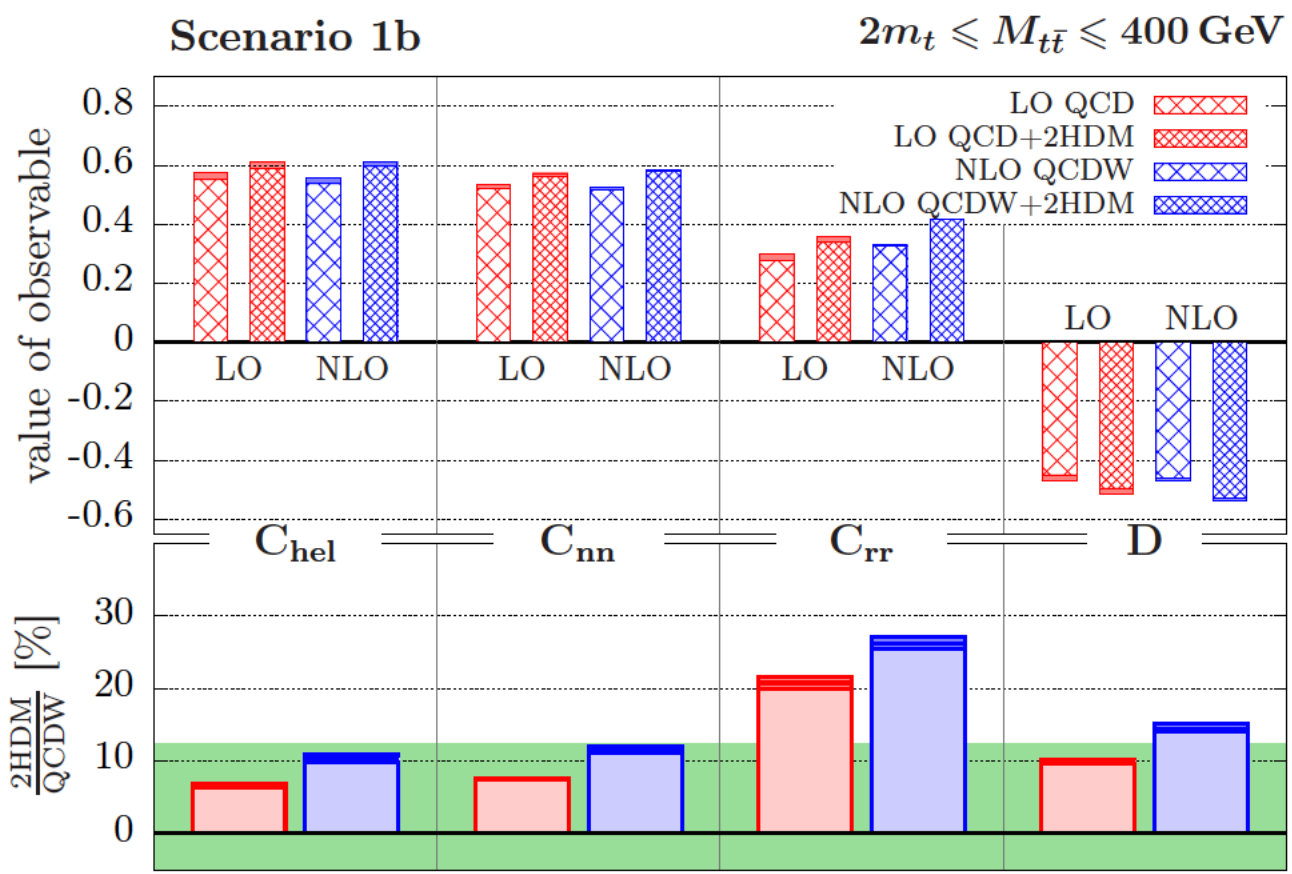
- Cross correlations measured for the first time



- Overall agreement with the SM
- Sensitive to different NP effects (e.g. CP-violating effects)

Spin Correlations & 2HDM

- Spin observables can be used to search for heavy Higgs bosons (for example)



arxiv:1702.06063

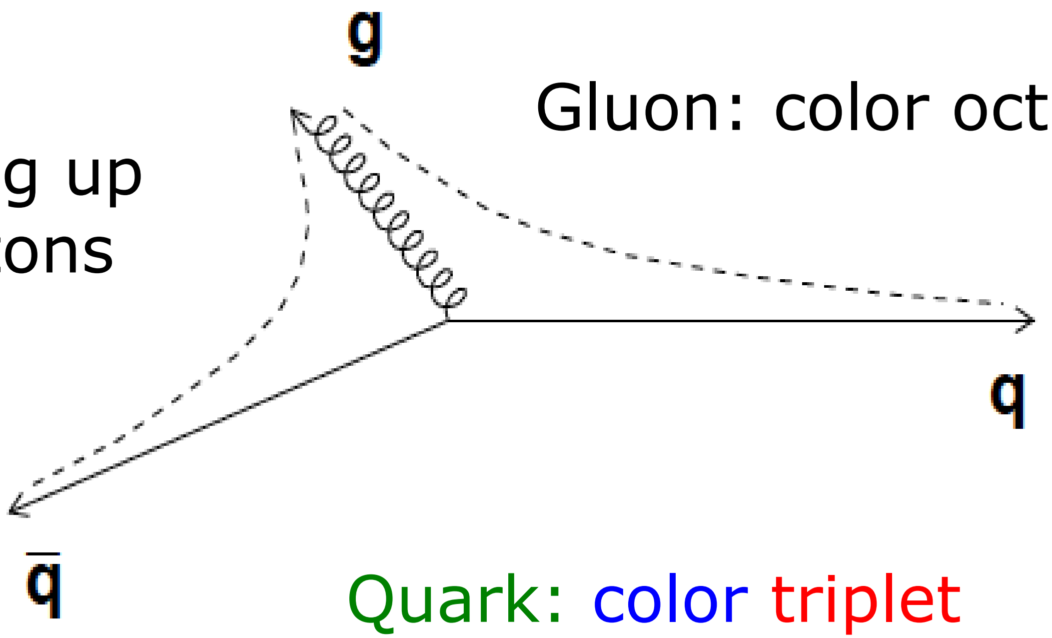
Top Events as a Laboratory

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

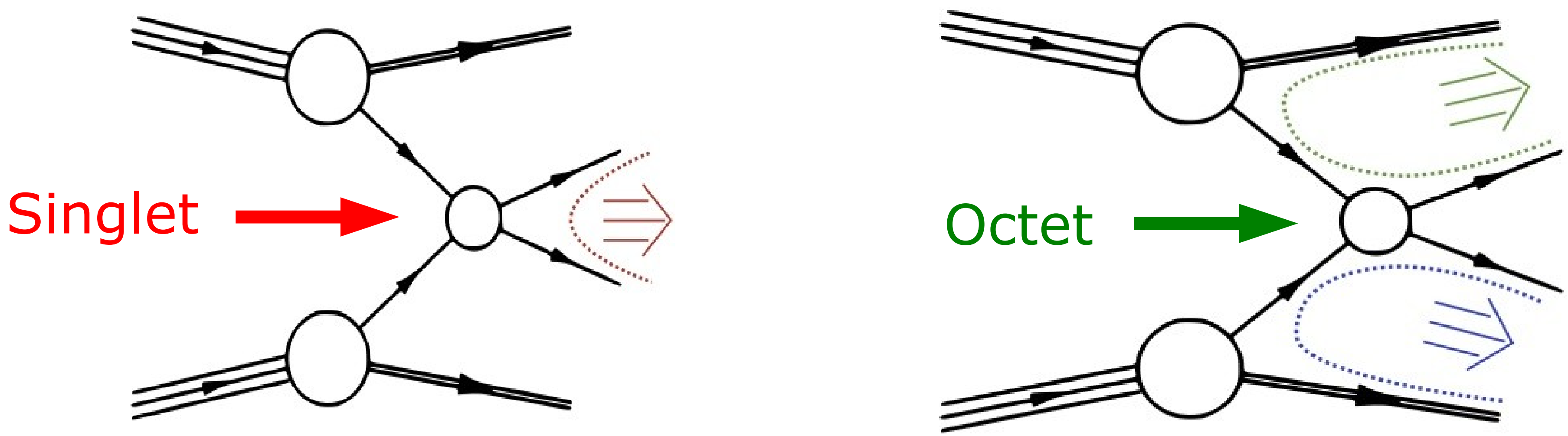


Gluon: color octet

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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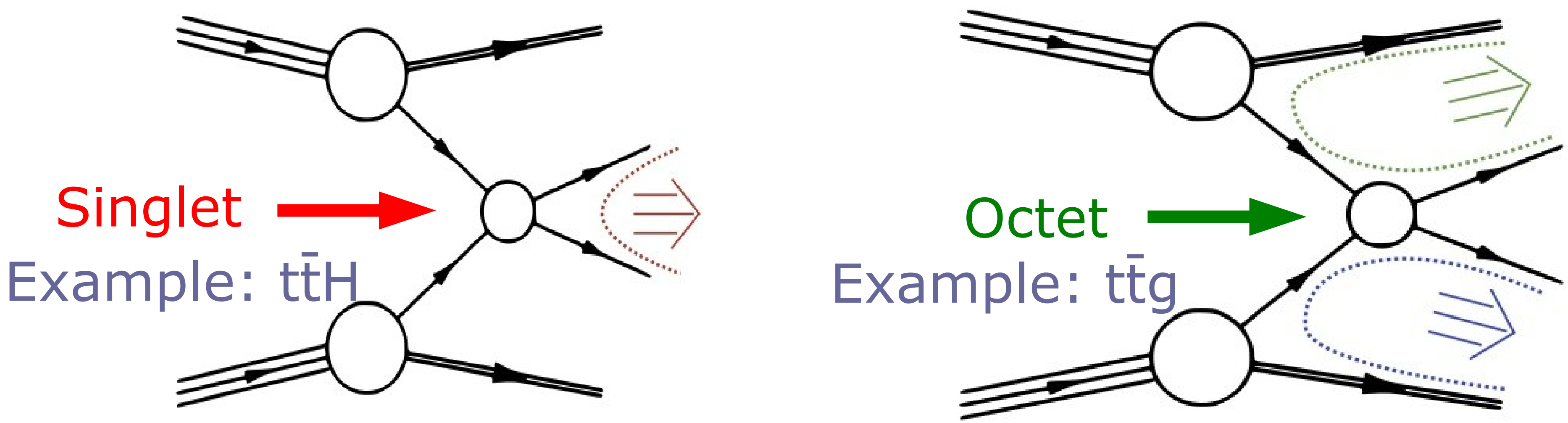

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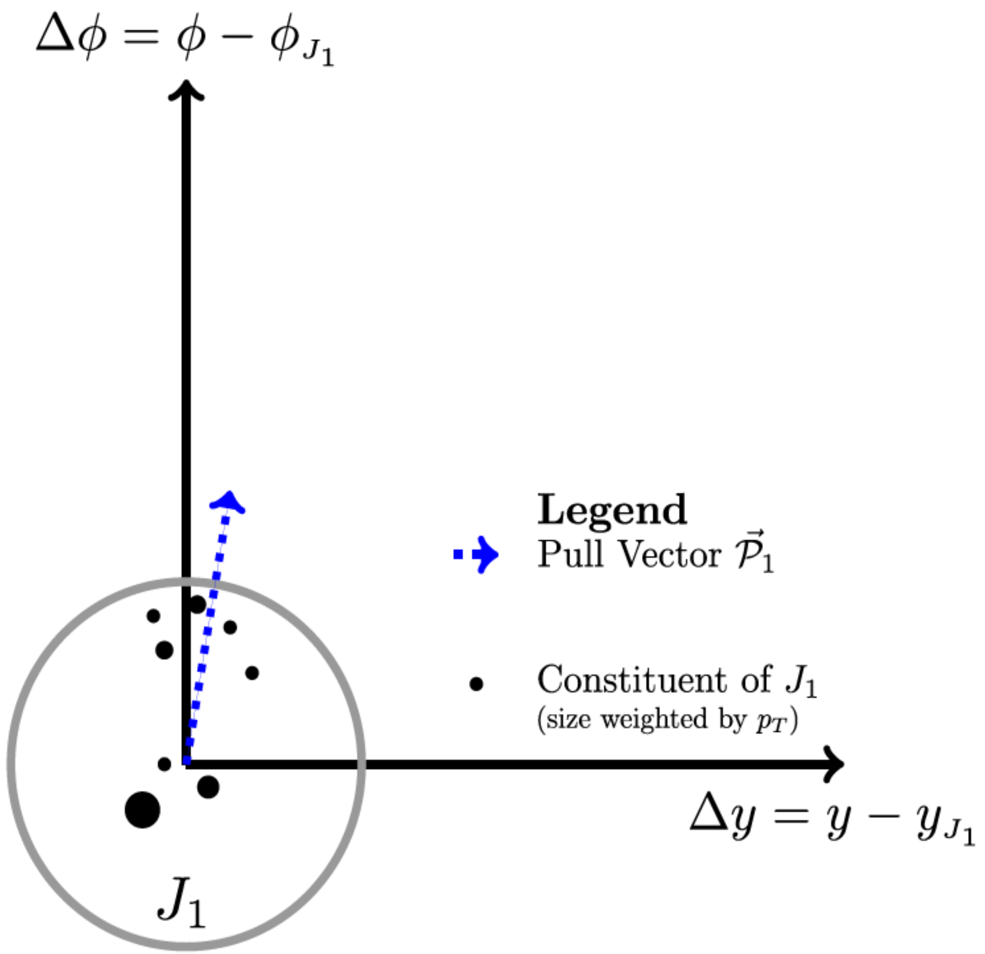
Color Flow Observable

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)

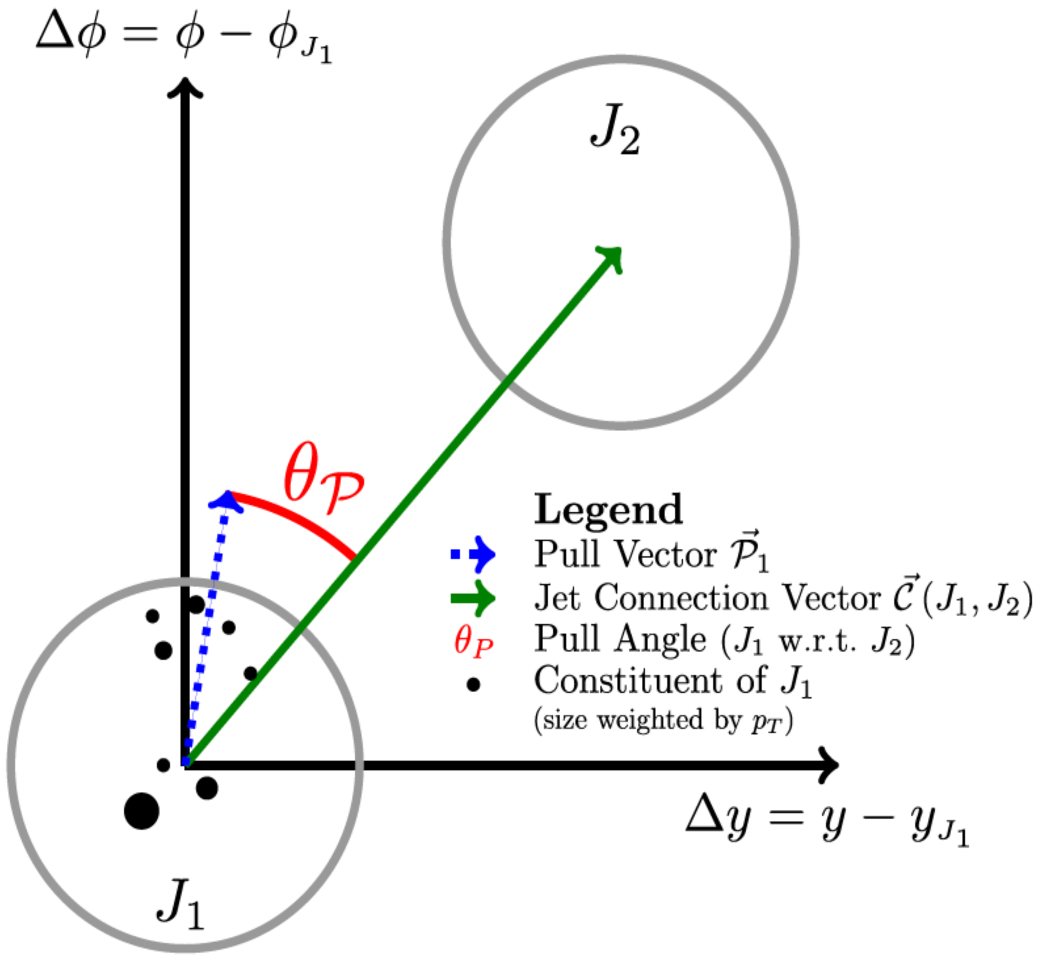
Color Flow Observable

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:

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

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

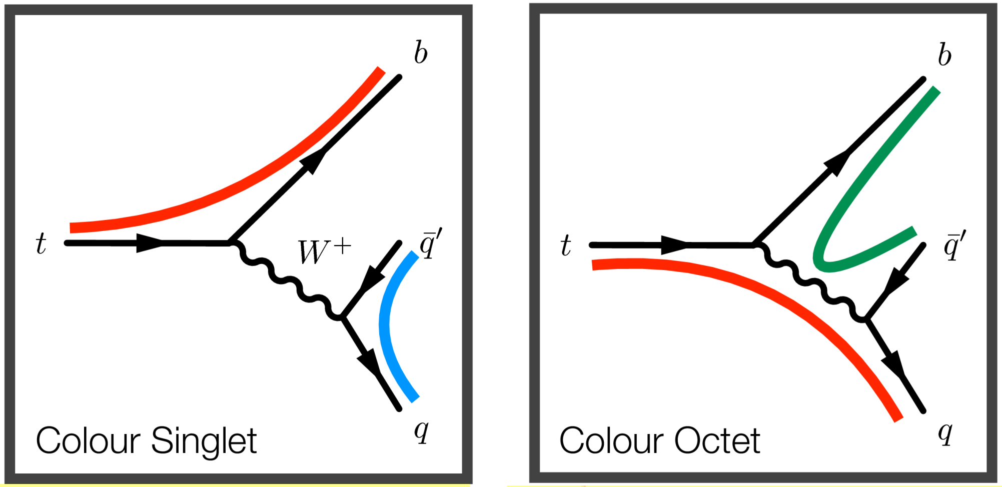


Gallicchio, Schwartz, PRL 105, 022001 (2010)

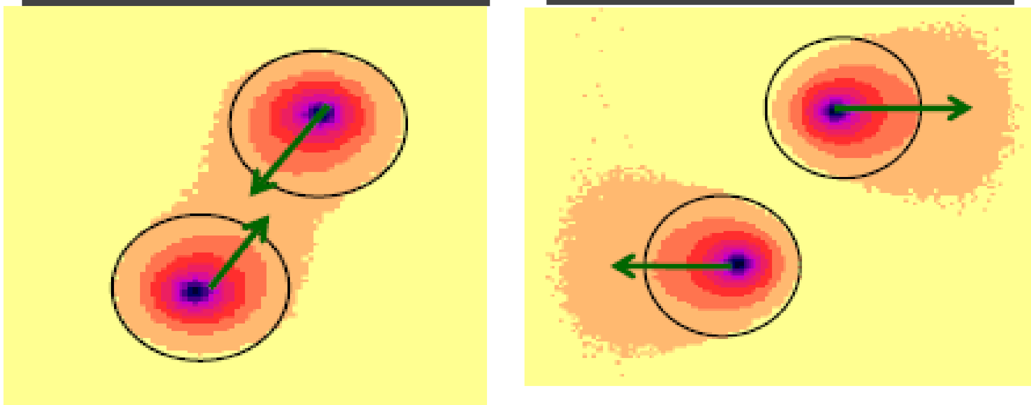
Colour Flow in Top

- 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)



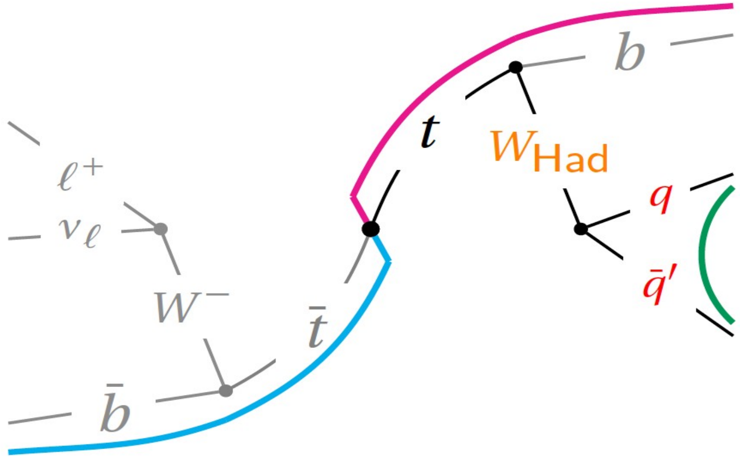
Jet pull: vectorial sum of components within each jet $\rightarrow$ jet pull angle: angle wrt. connection line of pair of jets



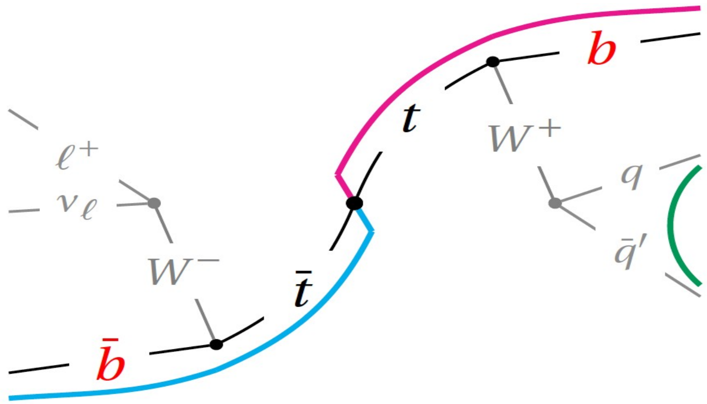
Colour Flow in Top

- 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

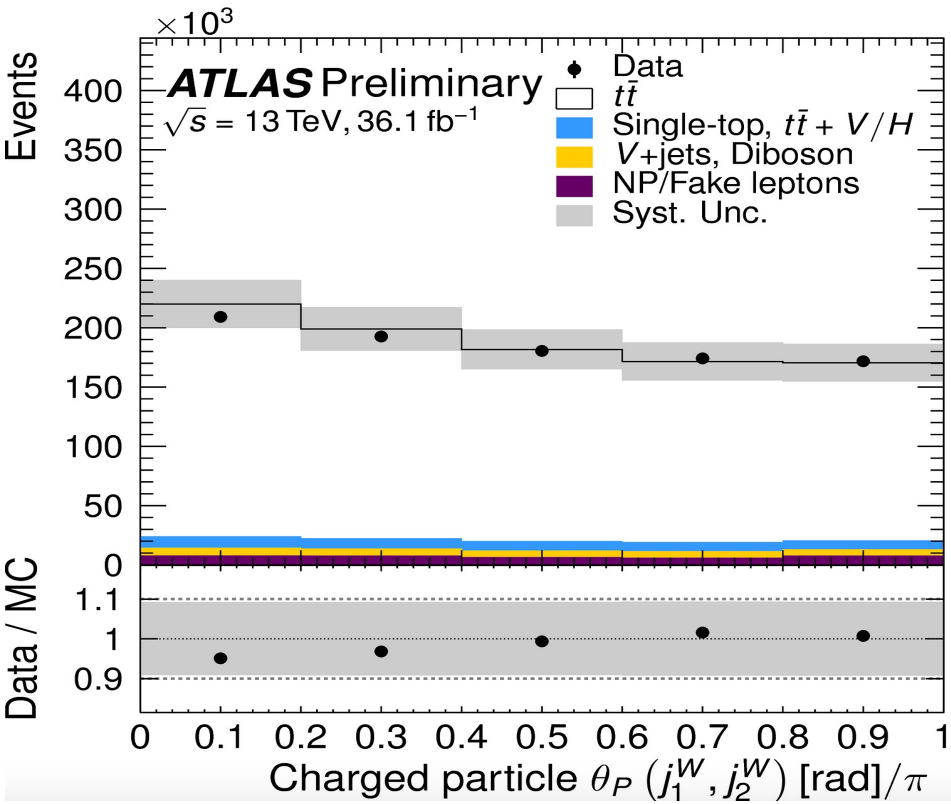


- Two b-tagged jets
  - Relative jet pull angle



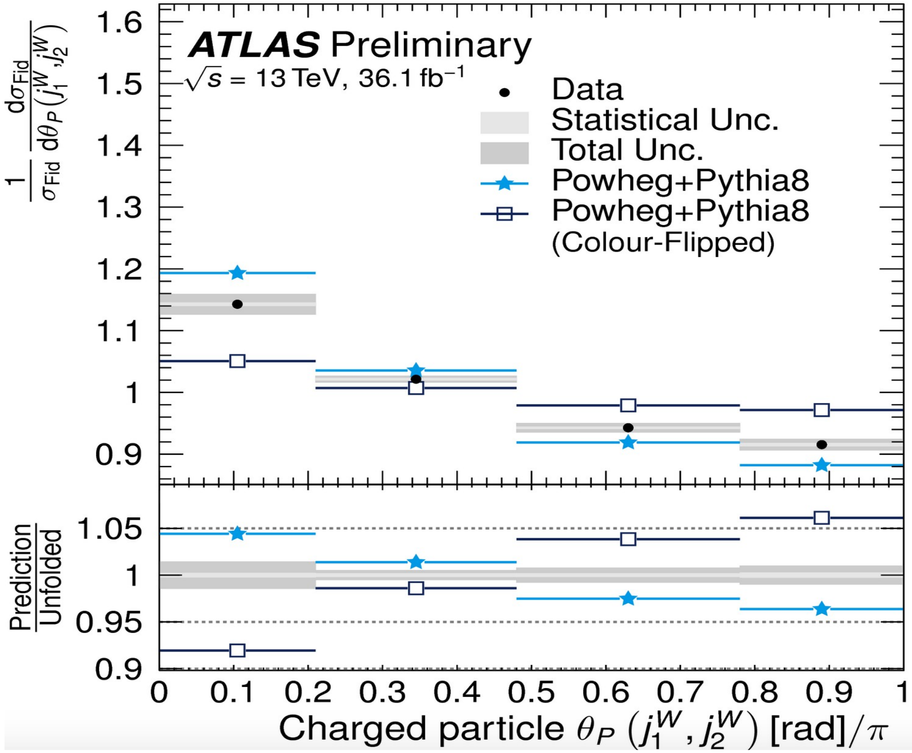
Analysis

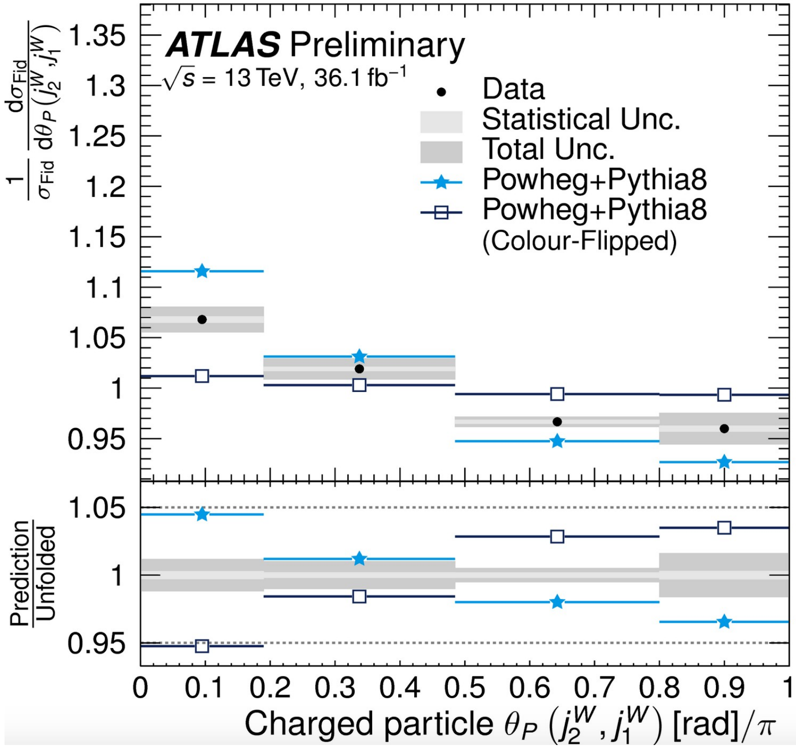
- Correct distributions for detector effects
- 13 TeV analysis: use only track-jets
  - Have shown to have better resolution than calorimeter jets in 8 TeV analysis PLB 750, 475-493 (2015)



Results for W daughters

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





- Relative jet pull angles for jets from W boson

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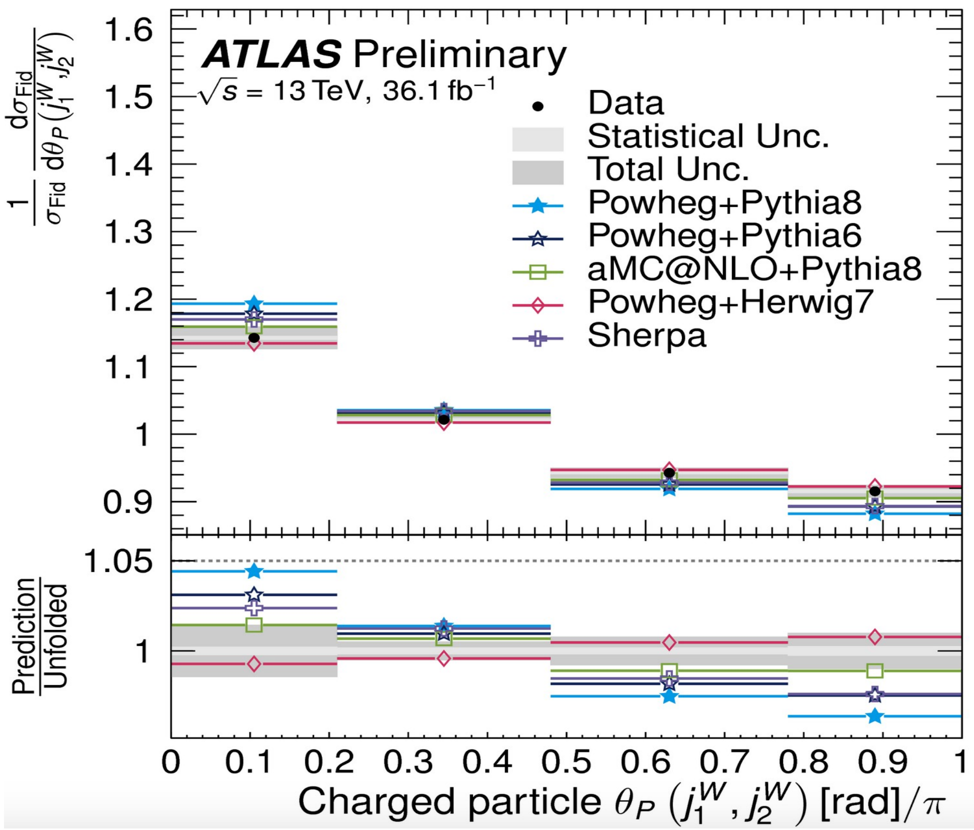
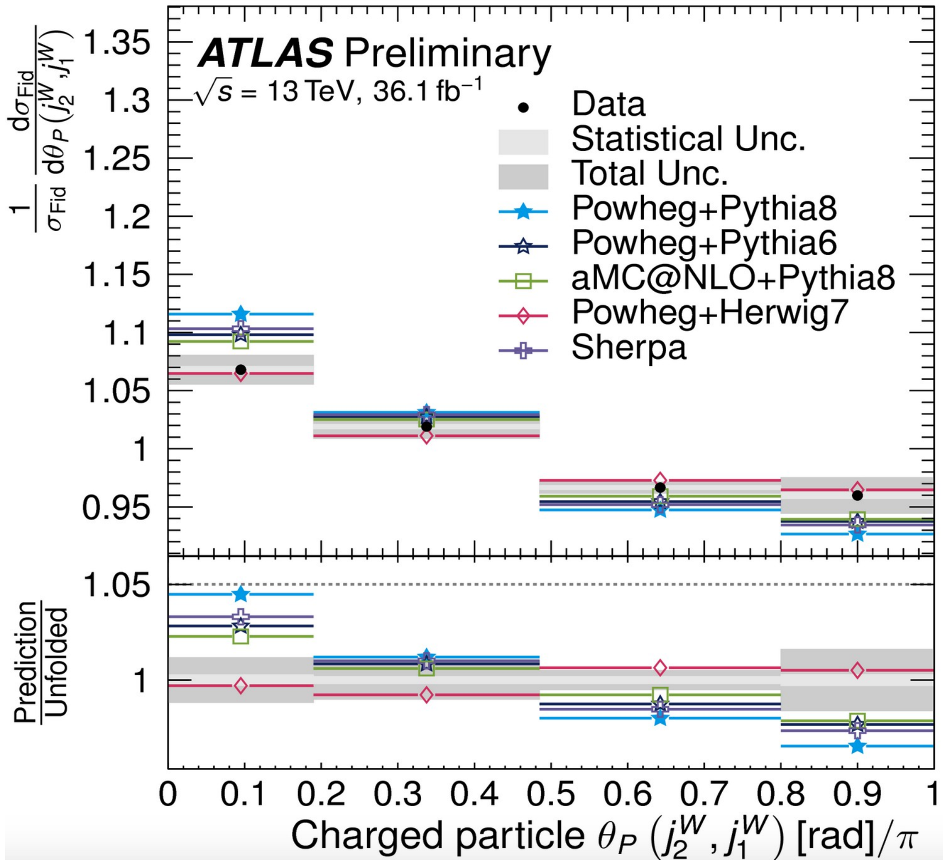
- Colour-flipped model disfavoured by the data

Results for W daughters

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

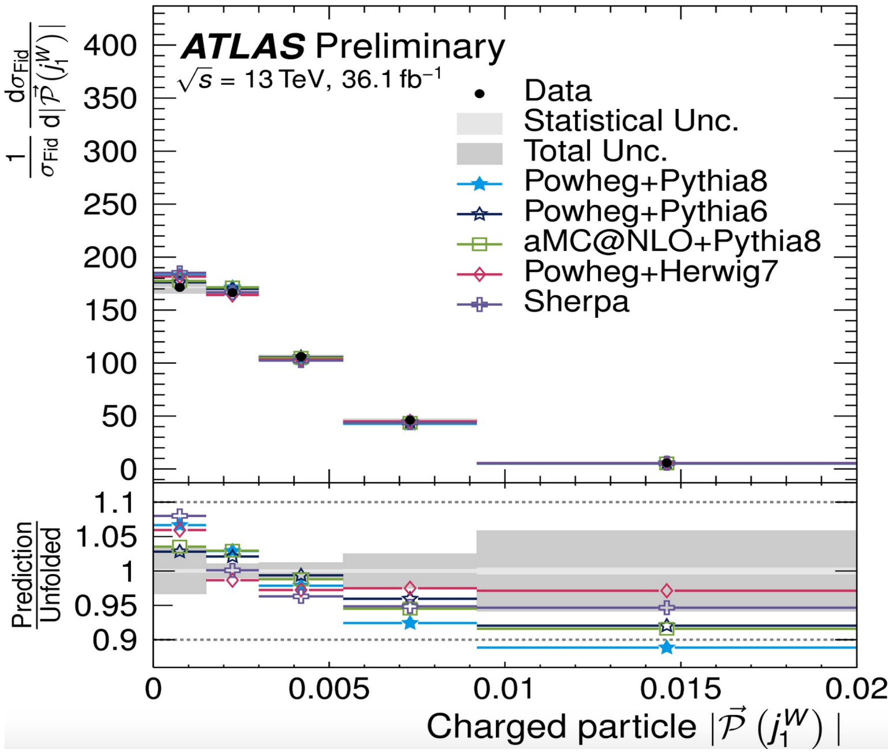


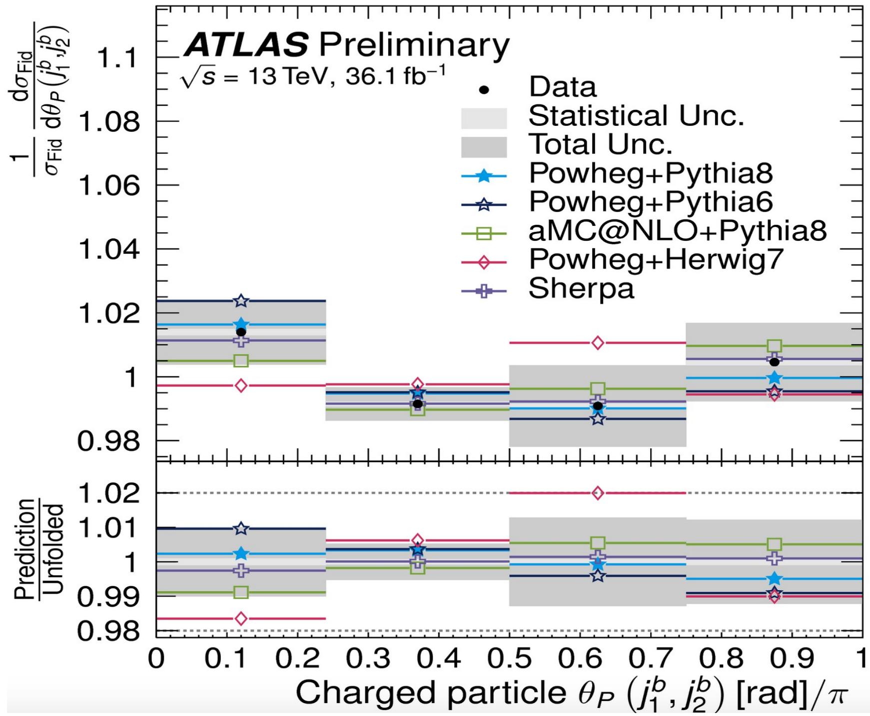


- MC modeling quite poor for these observables

Results for Magnitude and b-Pull

- Jet pull magnitude and pull angle of b-jets:

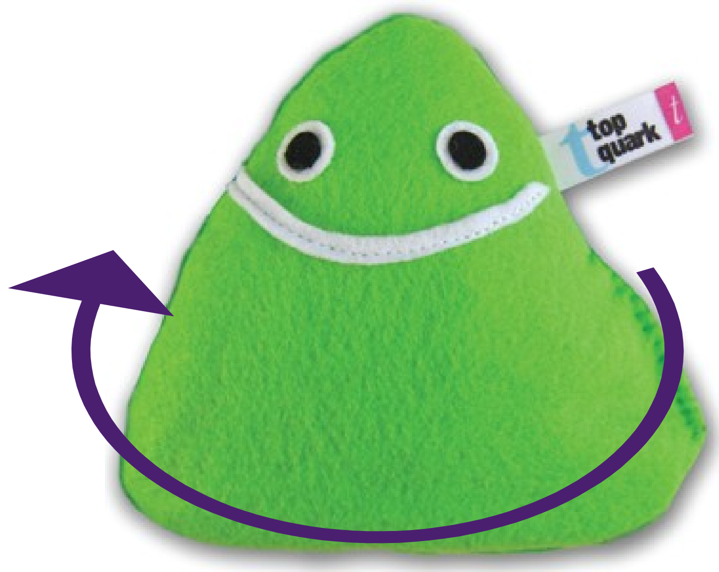




- Data seems to favor “wider” jets
- Jet pull: potential to search for NP
  - Mc modeling required?!

Summary

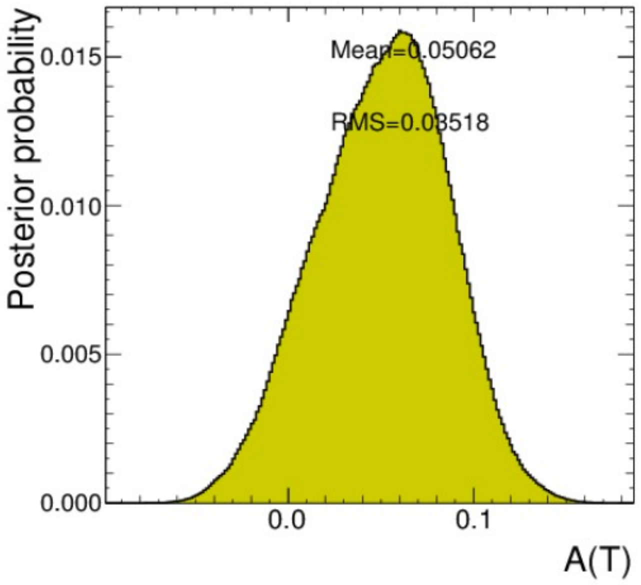
- Top Quark Physics: Probing the heaviest known elementary particle!
  - Precision measurements of polarization and spin correlations
    - probing the full top production and decay chain ever more precise
  - Jet pull: accessing colour-flow information between jets → information on colour-nature of mother particle
- Everything compatible with SM so far
- Tops were, are and stay awesome → much to learn about the SM and beyond



BACKUP

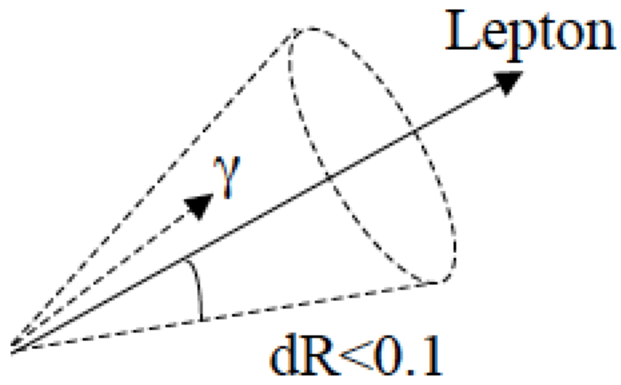
FBU

- 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

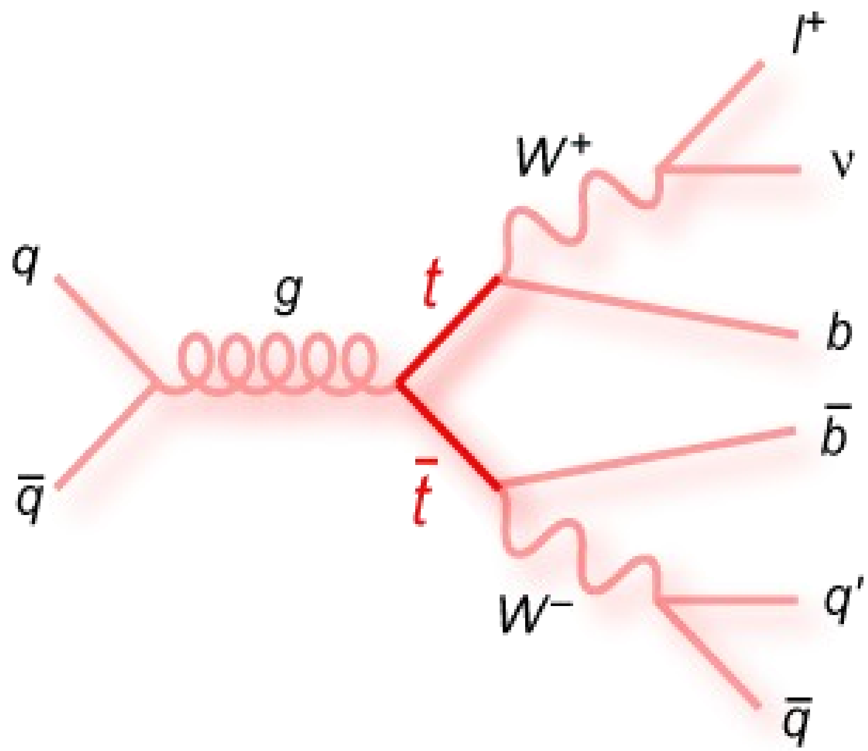
- Define “pseudo-tops” on particle level
  - In fiducial region
  - Easy to reproduce for theorists!



- 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

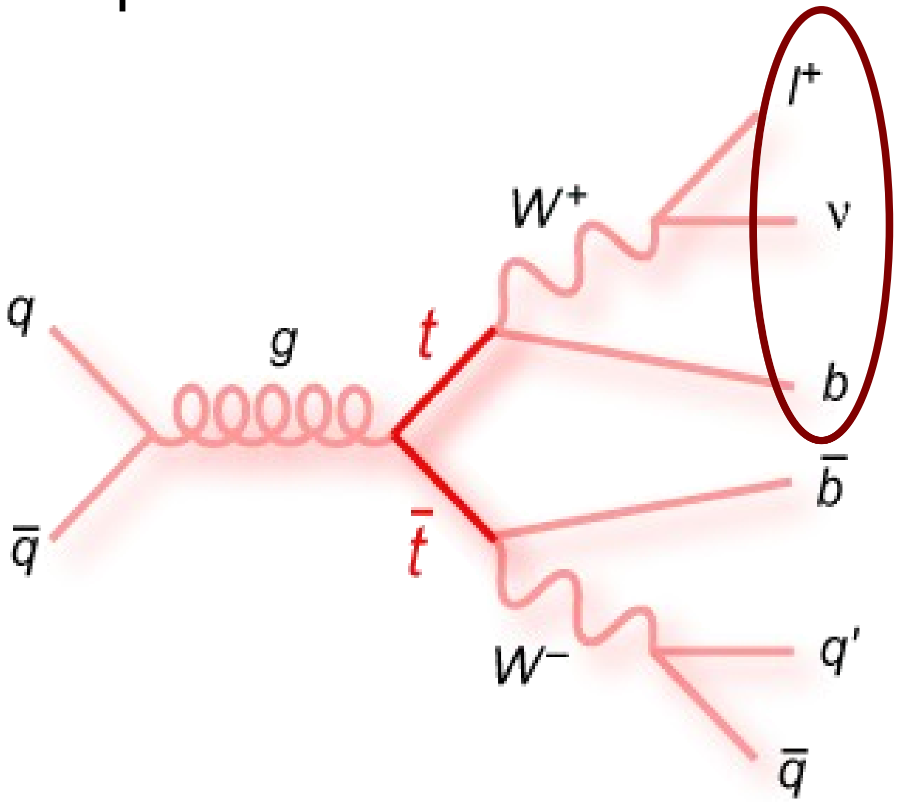
Missing p_T for neutrino ($\not{E}_T$): >30GeV

≥4 jets with p_T>25GeV; $|\eta|$<2.5

≥2 jets b-tagged

Differential

- Top reconstruction



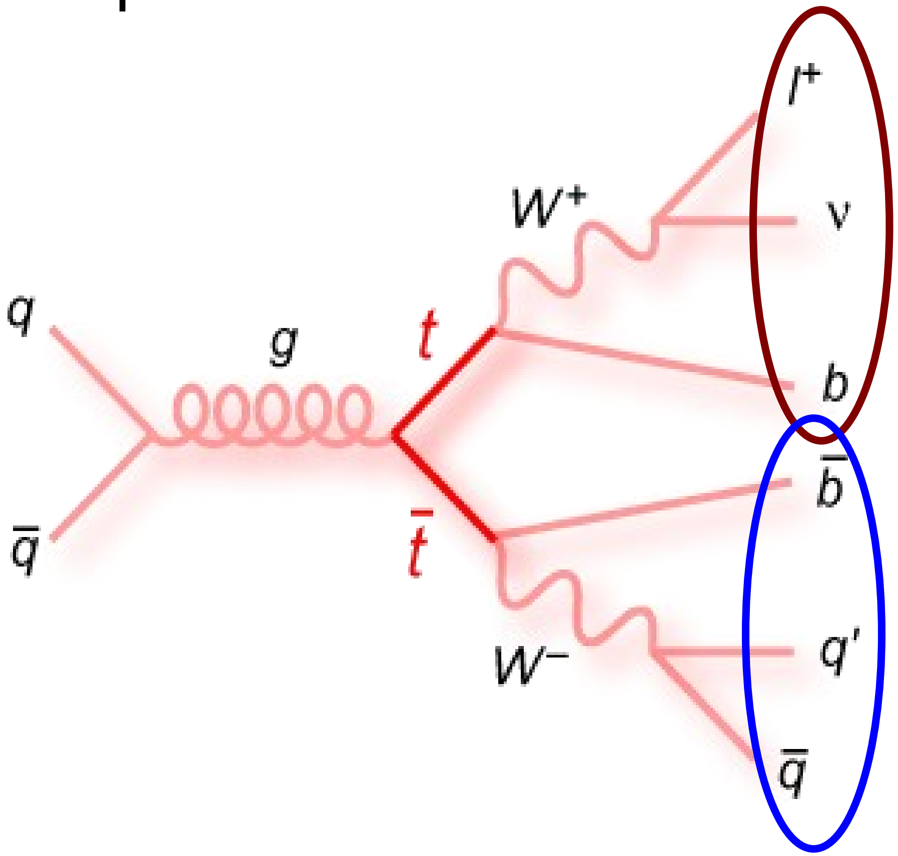
Leptonic pseudo-top:

- 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