Charge Asymmetry Measurements in Top Quark Pair Events

Mohsen Naseri

On behalf of the **ATLAS** and **CMS** Collaborations

OLOMOUC, CZECH REPUBLIC
9th International Workshop on Top Quark Physics
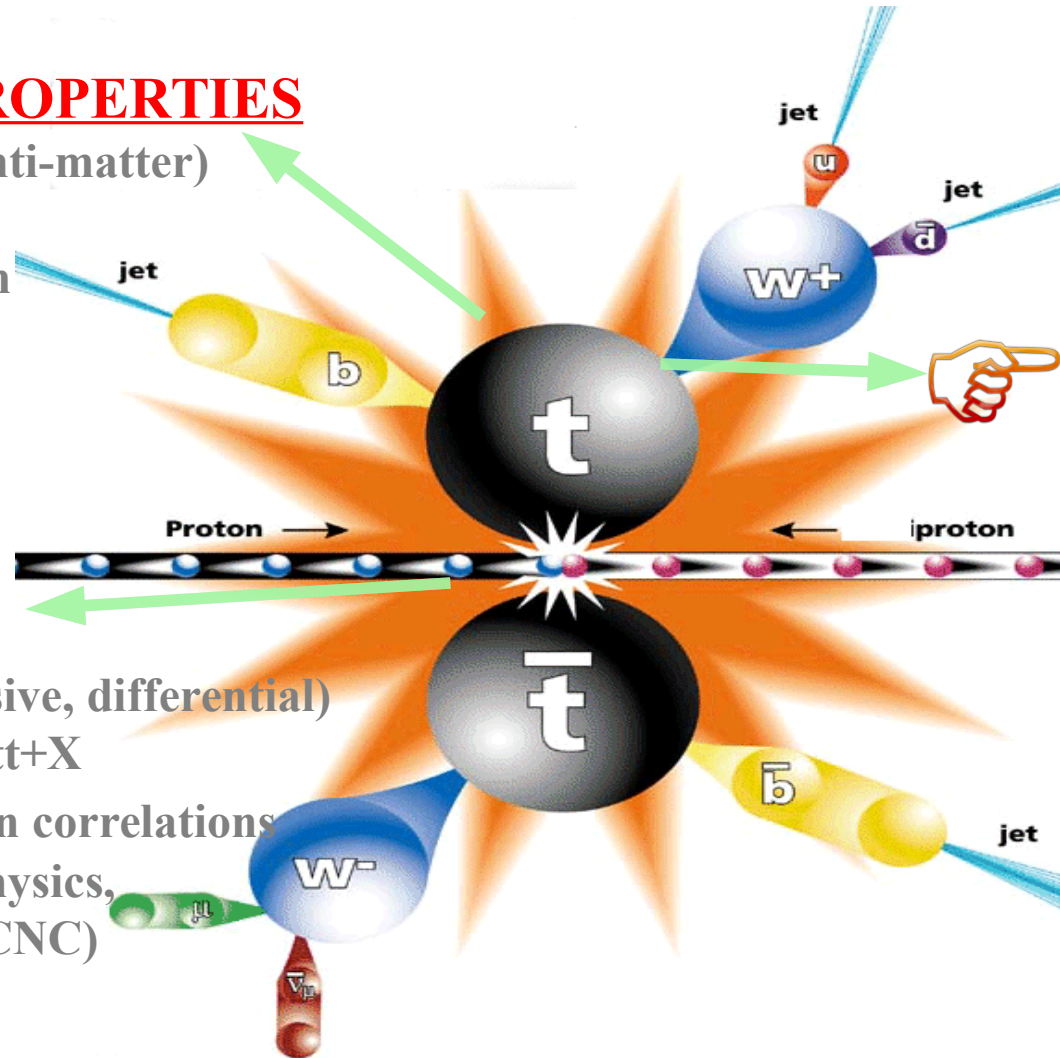19 – 23 September 2016

Top physics Menu

☞ **INTRINSIC PROPERTIES**

   Mass (matter vs. anti-matter)
   Charge, spin
   Life time and width

DECAY

   W helicity
   Couplings
   Branching ratios
   CKM matrix elements
   New particles
   $B(t \rightarrow Wb)$
   Rare decays (FCNC)

☞ **PRODUCTION**

   Cross section(inclusive, differential)
   QCD parameters, tt+X
   Asymmetries, spin correlations
   Resonances, new physics,
   Flavour physics (FCNC)

only charge asymmetry results will be shown with a focus on the most recent ones.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

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What is charge asymmetry?

Symmetry & Asymmetry

asymmetry = particle-antiparticle asymmetry

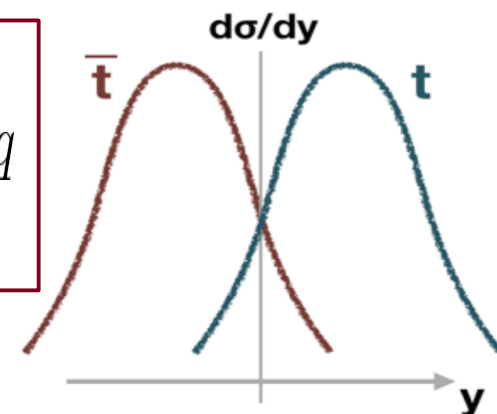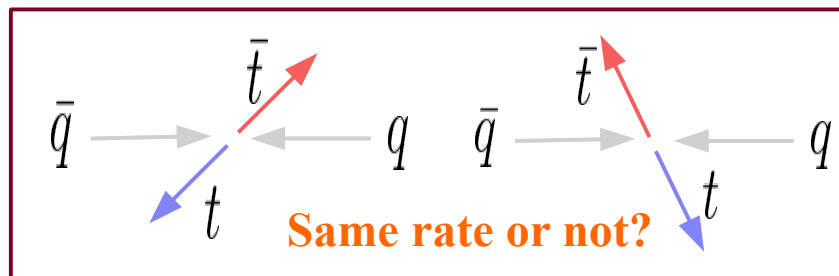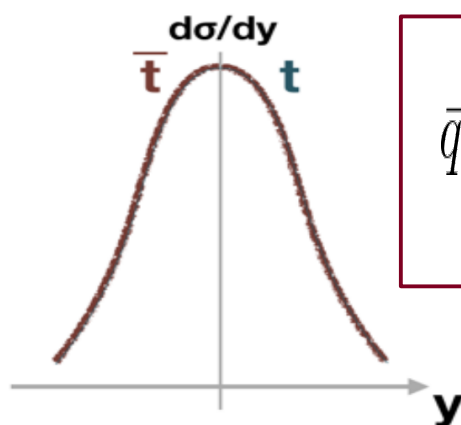A difference in the angular distribution of top quarks with respect to top antiquarks
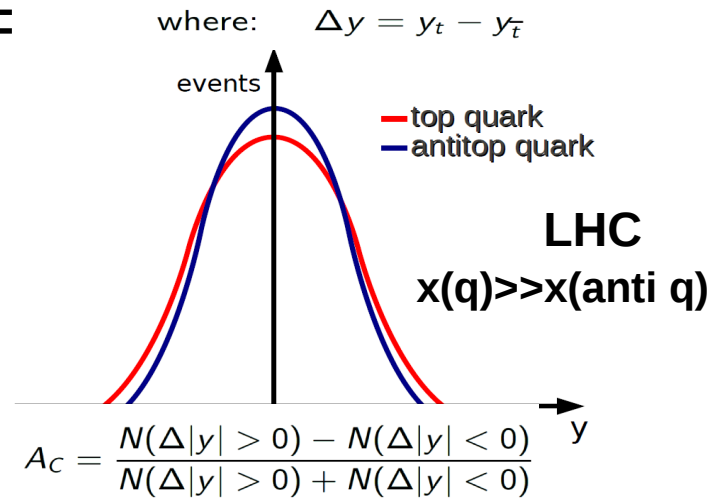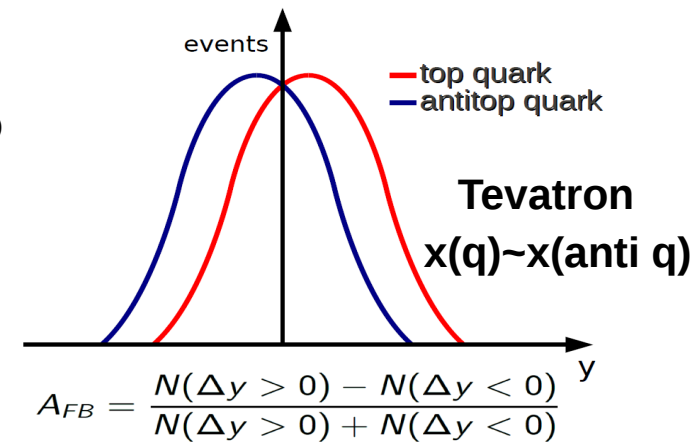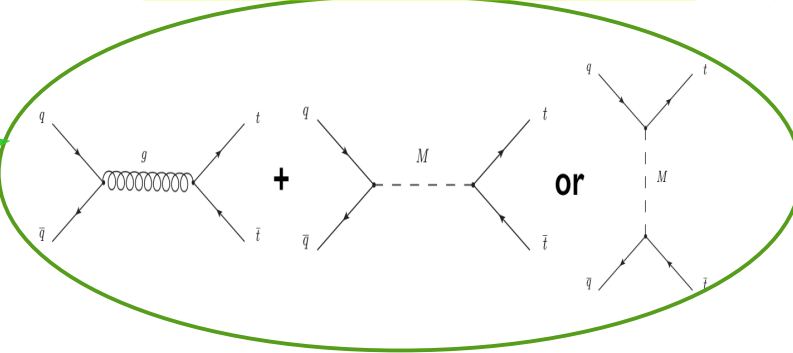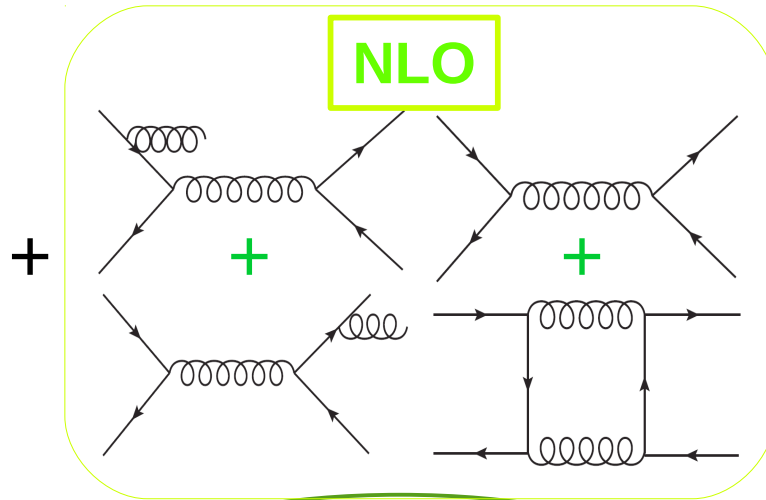

Symmetry

Asymmetry

Same rate or not?

Origin of asymmetry

SM predicts no asymmetry at **LO in QCD**, and a small asymmetry **at NLO**

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

where: $\quad \Delta y = y_t - y_{\bar{t}}$

New physics may increase asymmetry

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$
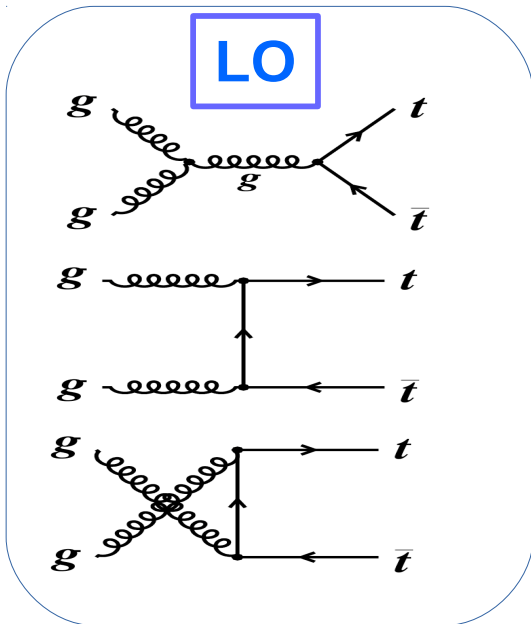
where: $\quad \Delta|y| = |y_t| - |y_{\bar{t}}|$

A_C @ LHC

- LHC is symmetric, top quarks (anti-quarks) are more forward (central)

- $q\bar{q} \to t\bar{t} \sim 20\%$ @ 8TeV $\longrightarrow$ large dilution

- SM asymmetry: $\sim 1\%$

A_{FB} @ Tevatron

- Tevatron is asymmetric, valence quarks and valence antiquarks of similar momenta collide

- $q\bar{q} \to t\bar{t} \sim 80\%$ $\longrightarrow$ small dilution

- SM asymmetry: $\sim 8\%$

- Small fraction of quark-antiquark annihilation at LHC

- Direction of incoming quark is not known

- Measured asymmetry disturbed by acceptance and resolution

  $\longrightarrow$ need to extrapolate to parton level!

- Significant uncertainty from modeling and extrapolation

- Inclusive measurement of A_C in full phase space and fiducial phase space
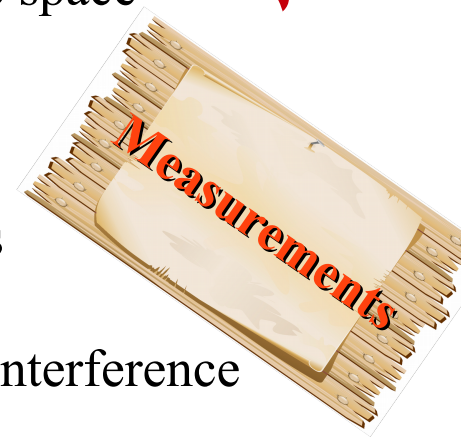
- Differential measurements:

  A_C vs $m_{t\bar{t}}$: expected different behavior for different BSM scenarios

  A_C vs $p_{t\bar{t}}$: expected sensitivity comes from negative ISR and FSR interference

  A_C vs $|y_{t\bar{t}}|$: sensitive to enhancement of asymmetry at higher rapidities (increased quark-antiquark annihilation process)

  A_C vs $|\beta_{z,t\bar{t}}|$: sensitivity to BSM at high values of $\beta_{z,t\bar{t}}$

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Semi-leptonic Measurements
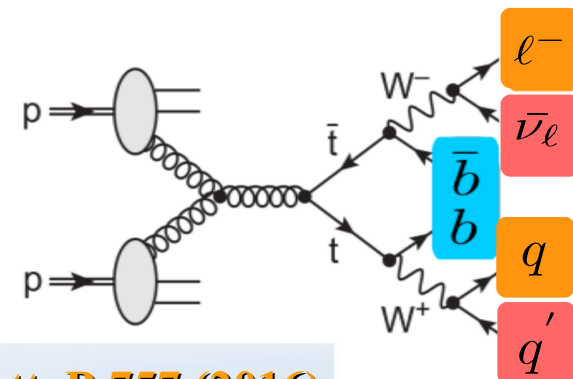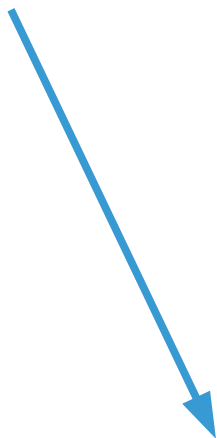
at 8 TeV(unfolding technique)

Semi-leptonic Measurements @ 8TeV

Eur. Phys. J. C76 (2016) 87

- Event separated by: $0, 1, \geq 2$ b-tag jets

- Main background: W+jets

- A kinematic fit assesses the compatibility of the observed event with the decays of a top-antitop pair.

ATLAS

Phys. Lett. B 757 (2016) 154

- ≥ 1 b-tagged jet

- $\sim 60\%$ of total background: W+jets

- Calculate a probability to find the best top pair configuration
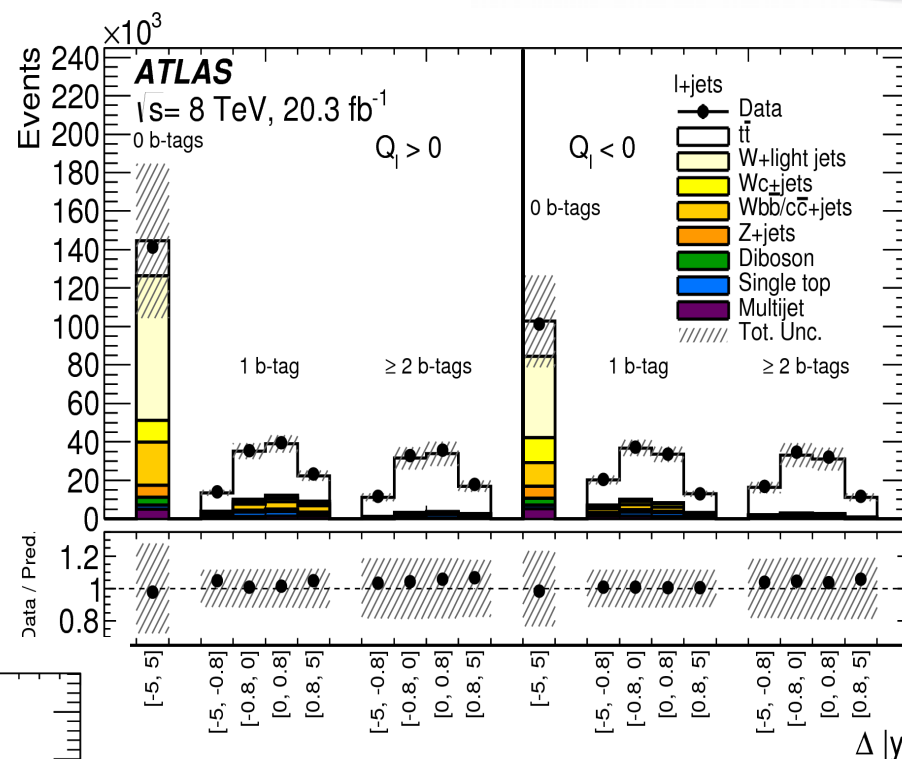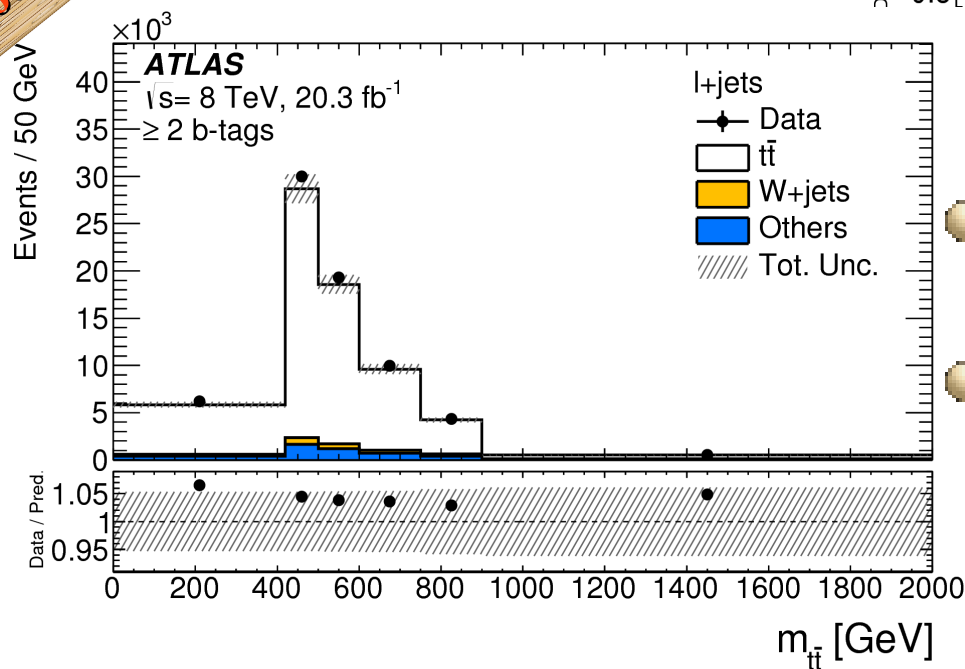
CMS

$$\psi = L_1(m_1) L_2(m_2) L_3(m_3) P_b(x_{b1}) P_b(x_{b2})(1 - P_b(x_{q1}))(1 - P_b(x_{q2}))$$

$$L = \mathcal{B}(\tilde{E}_{p,1}, \tilde{E}_{p,2} | m_W, \Gamma_W) \cdot \mathcal{B}(\tilde{E}_{lep}, \tilde{E}_\nu | m_W, \Gamma_W) \cdot \mathcal{B}(\tilde{E}_{p,1}, \tilde{E}_{p,2}, \tilde{E}_{p,3} | m_t, \Gamma_t) \cdot \mathcal{B}(\tilde{E}_{lep}, \tilde{E}_\nu, \tilde{E}_{p,4} | m_t, \Gamma_t) \cdot$$
$$\mathcal{W}(\hat{E}_x^{miss} | \tilde{p}_{x,\nu}) \cdot \mathcal{W}(\hat{E}_y^{miss} | \tilde{p}_{y,\nu}) \cdot \mathcal{W}(\hat{E}_{lep} | \tilde{E}_{lep}) \cdot \prod_{i=1}^{4} \mathcal{W}(\hat{E}_{jet,i} | \tilde{E}_{p,i}) \cdot \prod_{i=1}^{4} P(\text{tagged} \mid \text{parton flavour})$$

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Signal in 1(≥2) b-tag region:

~68% (89%) 0f total yield

The Δ|y| distribution split into four bins in all the channels except the zero b-jets channel

good agreement between the data and expectation
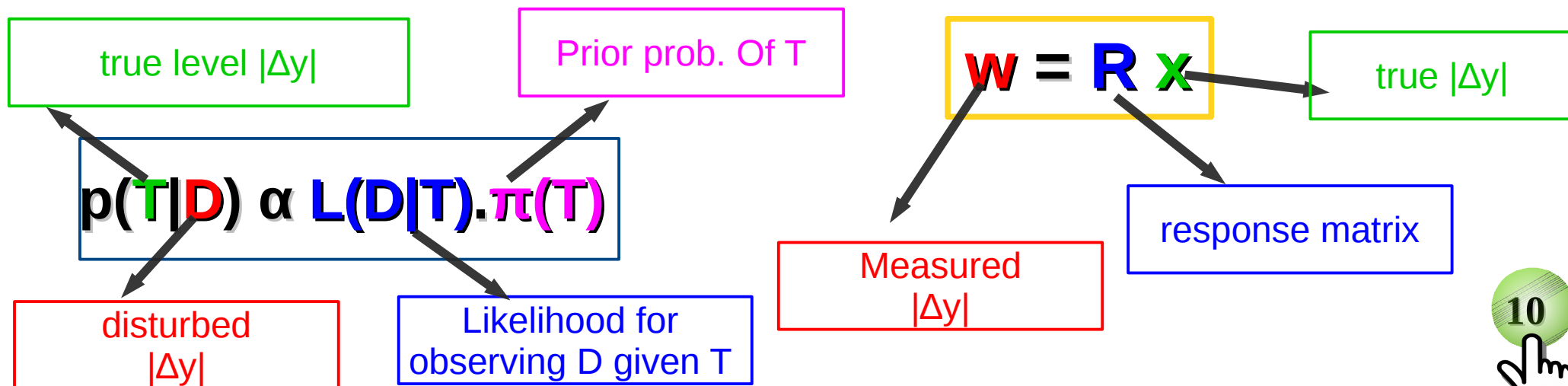
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Unfolding strategy

ATLAS

- Fully Bayesian Unfolding(FBU)

- The likelihood extended with nuisance parameters

- Unfolding and W+jets BG estimation performed simultaneously

- Measure A_c also as function of $M_{t\bar{t}}$, $p_{T,t\bar{t}}$, $\beta_{z,t\bar{t}}$

CMS

- BG subtracted distributions of $\Delta|y|$ unfolded based on generalized matrix inversion method

- Correction to fiducial volume and full phase space

- Extract asymmetry from unfolded spectra

- Measure A_c also as function of $M_{t\bar{t}}$,
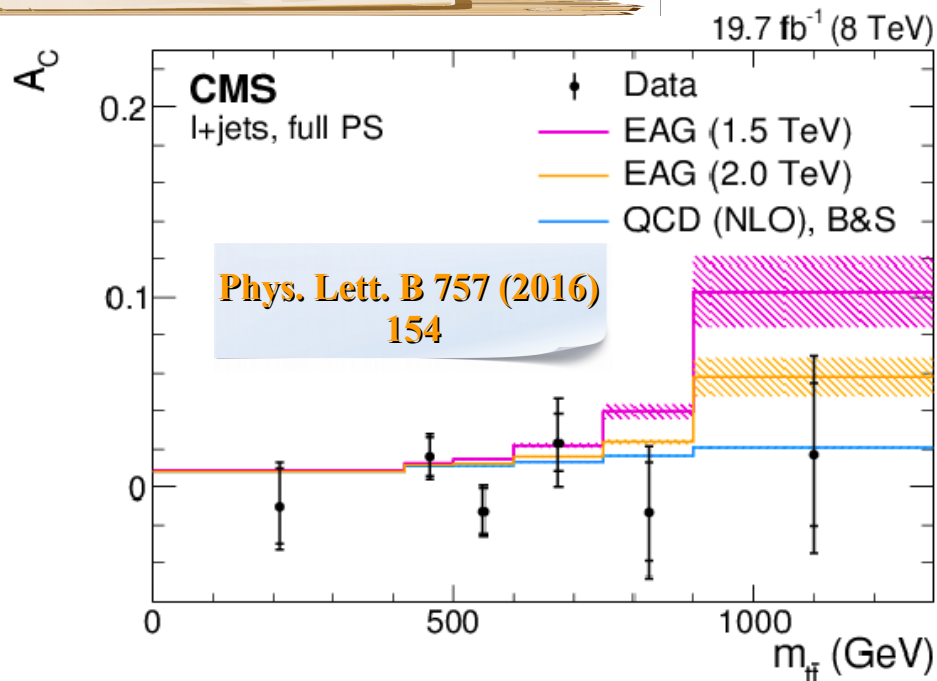- $p_{T,t\bar{t}}$, $|Y_{t\bar{t}}|$

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true level $|\Delta y|$

Prior prob. Of T

$$p(T|D) \propto L(D|T) \cdot \pi(T)$$

disturbed $|\Delta y|$

Likelihood for observing D given T

$$w = R x$$

true $|\Delta y|$

Measured $|\Delta y|$

response matrix

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Results from CMS and ATLAS

	stat	sys	
0.0010	± 0.0068	± 0.0037	**CMS(full PS)**
0.009	± 0.005		**ATLAS**
0.0111	± 0.0004		**Th. prediction: Phys. Rev. D 86 (2012) 034026**

−0.0035	± 0.0072	± 0.0031	**CMS, Fiducial**

agreement with SM prediction

statistically limited, agreement with SM prediction

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Phys. Lett. B 757 (2016) 154

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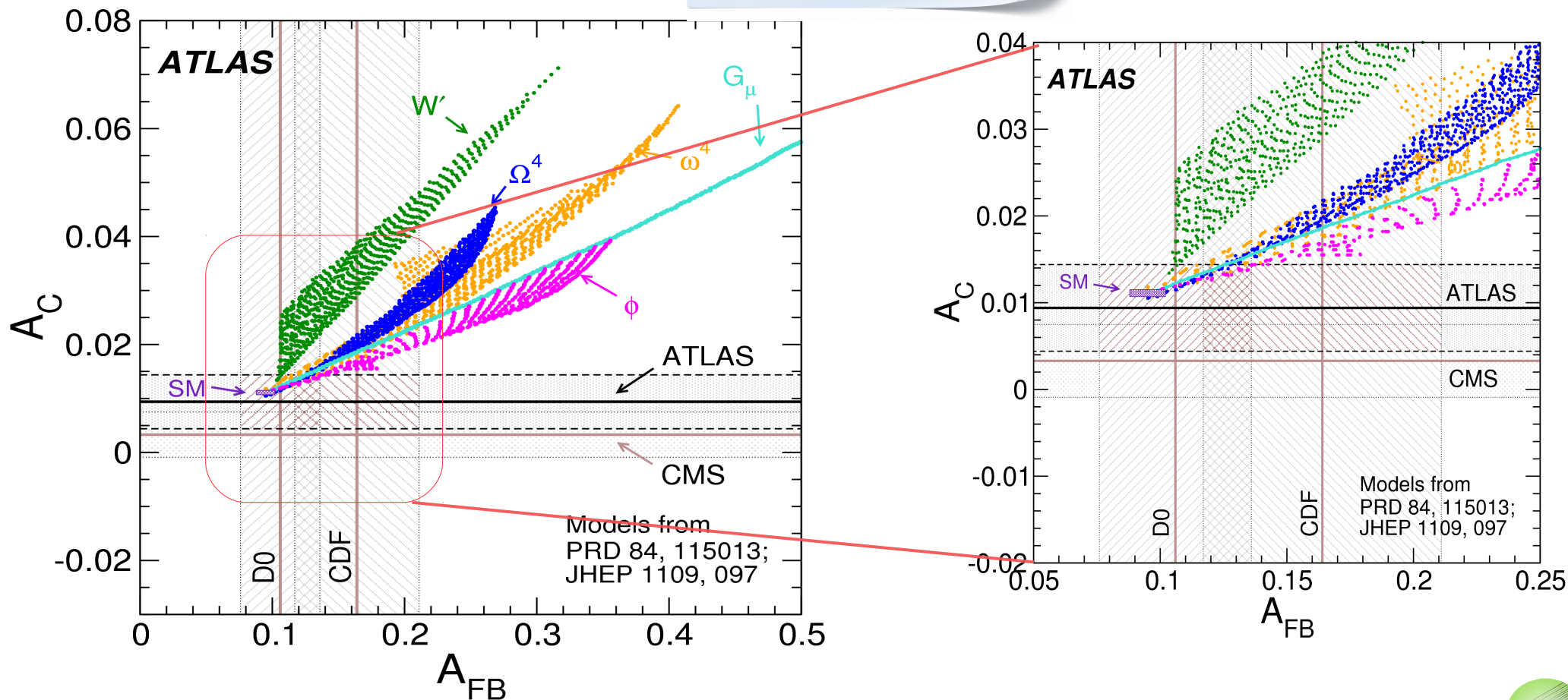
12
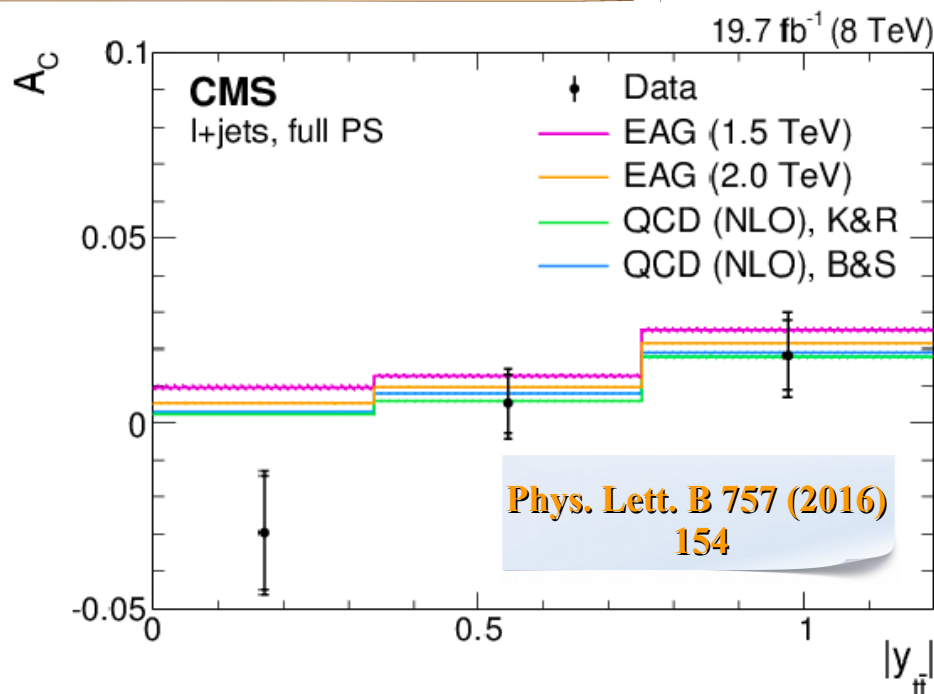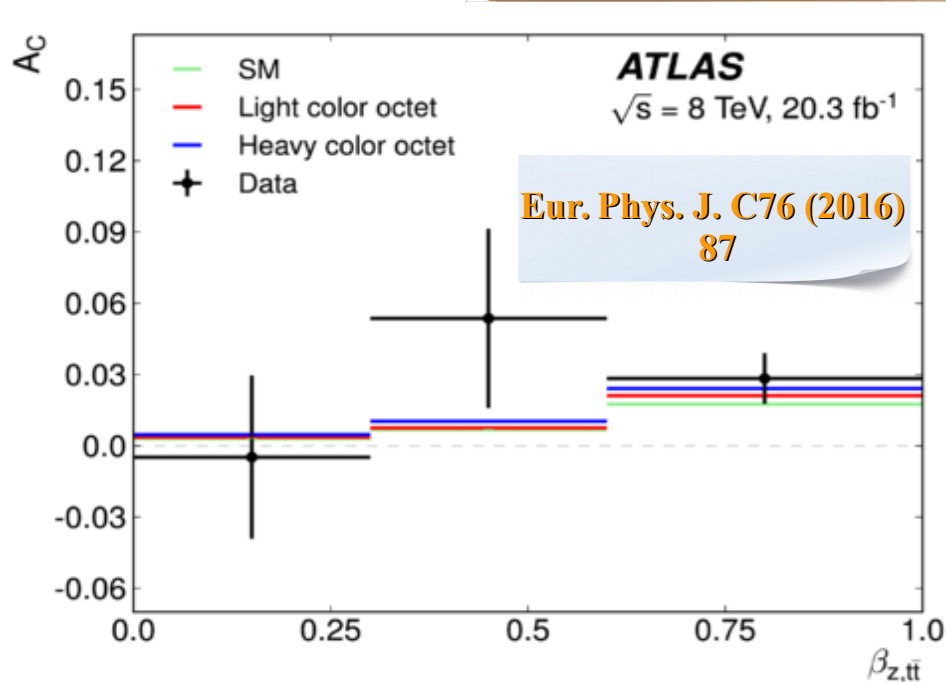
Measured inclusive charge asymmetries **A_C at the LHC** vs. **A_{FB} at Tevatron**

The uncertainty bands correspond to a 68% confidence level interval.

Eur. Phys. J. C76 (2016) 87

Gμ : A heavy axigluon Ω4 : A colour-sextet scalar

Φ : A scalar isodoublet ω4 : A colour-triplet scalar

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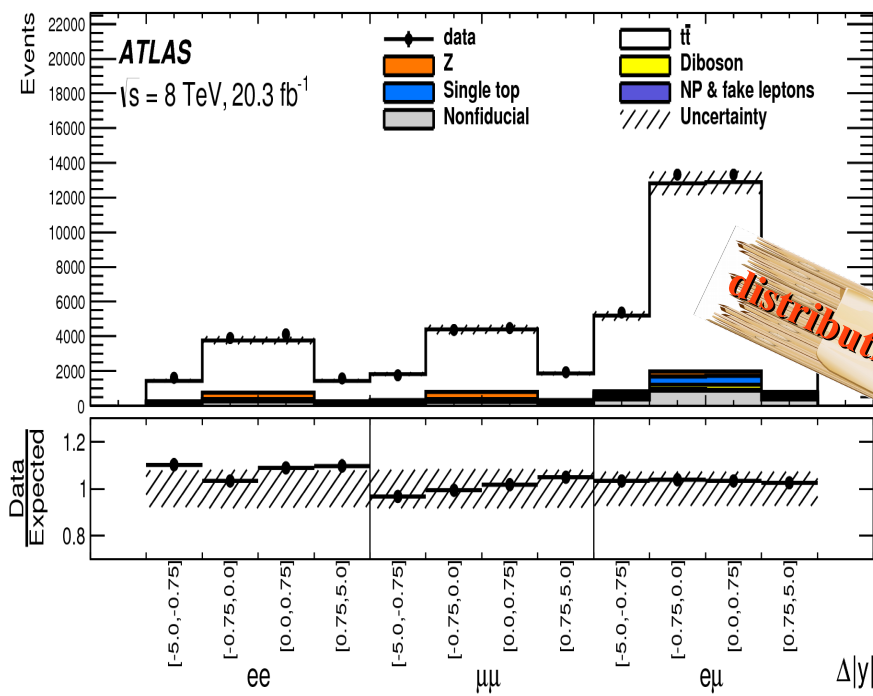# Di-leptonic Measurements

at 8 TeV

Please see Roger Naranjo
From ATLAS

Di-leptonic Measurements @ 8TeV: $A^{t\bar{t}}$ & A^{lep}

ATLAS

- Background: 15% of total yield

- Main background: Drell-Yan, single top

- Kinematic (KIN) method adopted to reconstruct top pair using kinematic constrains

- Fully Bayesian unfolding (FBU) technique

CMS

- Background: 9% of total yield

- Main background: Drell-Yan, single top

- "Analytical matrix weighting technique(AMWT) adopted to find most probable top pair

- Correcting migration and background effects by TUNFOLD package, using regularization

$$p\,(T|D) \propto \mathcal{L}\,(D|T) \cdot \pi\,(T)$$

distributions used for the measurement

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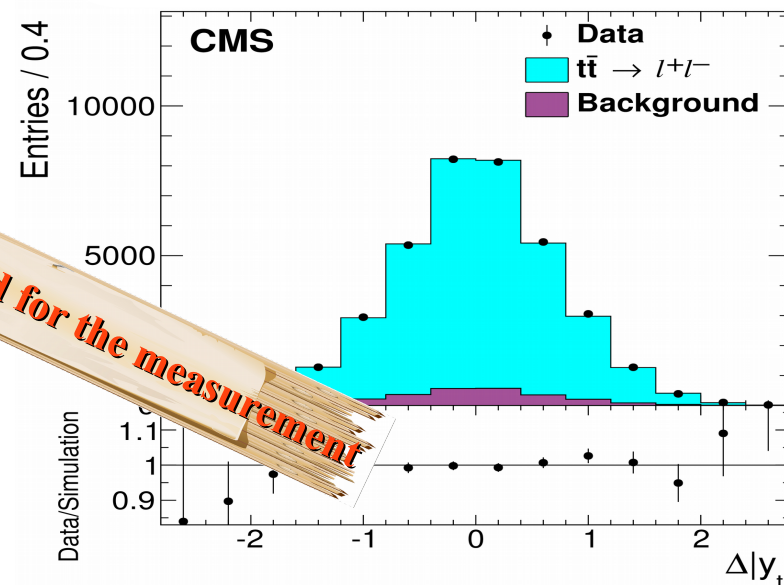
Inclusive results from CMS and ATLAS

agreement with SM prediction

observable		stat	sys	
$A^{t\bar{t}}$	0.011	± 0.011	± 0.007	**CMS**
A^{lep}	0.003	± 0.006	± 0.003	**CMS**
$A^{t\bar{t}}$	0.021	± 0.016		**ATLAS**
A^{lep}	0.008	± 0.006		**ATLAS**
$A^{t\bar{t}}$	0.0111	± 0.0004		**Prediction:Phys. Rev. D 86 (2012) 034026**
A^{lep}	0.0064	± 0.0003		**Perdiction: Phys. Rev. D 86 (2012) 034026**
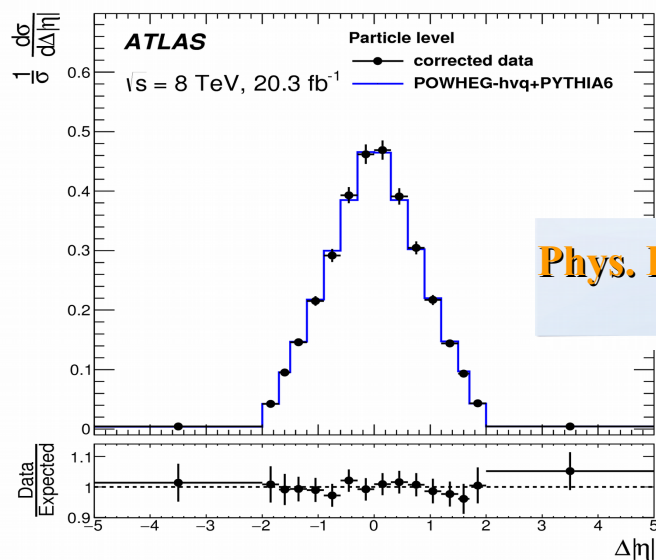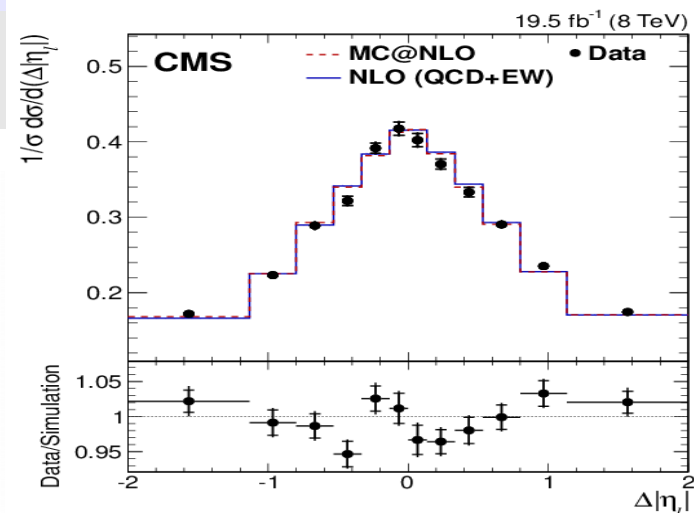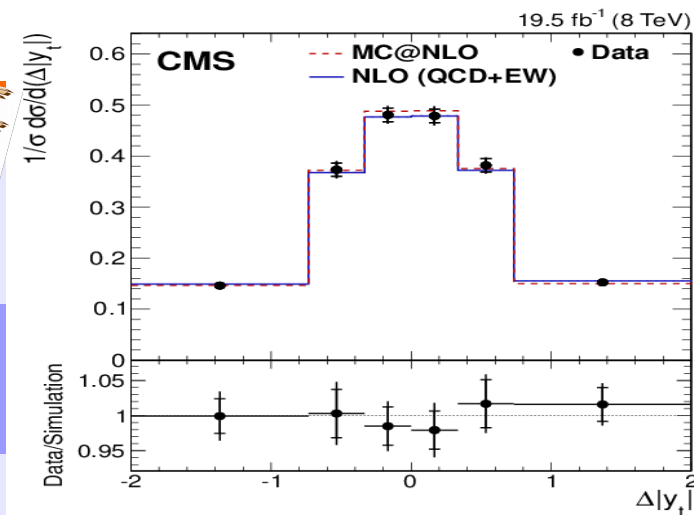
Phys. Rev. D 94, 032006 (2016)
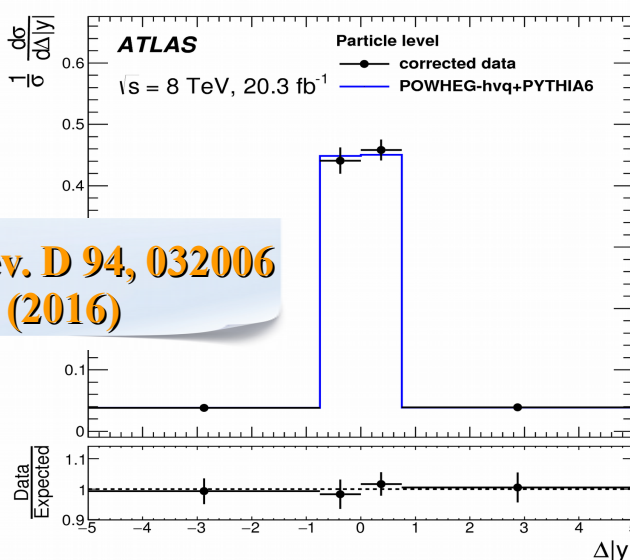
Please see Roger Naranjo From ATLAS

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differential results from ATLAS

- Differential measurements as a function of $m_{t\bar{t}}$, $p_{T,t\bar{t}}$, and $\beta_{z,t\bar{t}}$ both in the full phase space and in a fiducial phase space

- Largest uncertainty is statistical, followed by the reconstruction and the signal modeling uncertainties.

Compatible with SM prediction

Phys. Rev. D 94, 032006 (2016)

ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
ATLAS data
POWHEG-hvq+PYTHIA6

Inclusive		0.017 ± 0.018
$m_{t\bar{t}}$	0-500 GeV	0.007 ± 0.044
	500-2000 GeV	0.019 ± 0.026
$\beta_z^{t\bar{t}}$	0-0.6	0.036 ± 0.036
	0.6-1.0	-0.029 ± 0.028
$p_T^{t\bar{t}}$	0-30 GeV	-0.035 ± 0.048
	30-1000 GeV	0.048 ± 0.039

$A_C^{t\bar{t}}$ in the fiducial region

ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
ATLAS data
POWHEG-hvq+PYTHIA6
Bernreuther & Si. PRD 86, 034026.

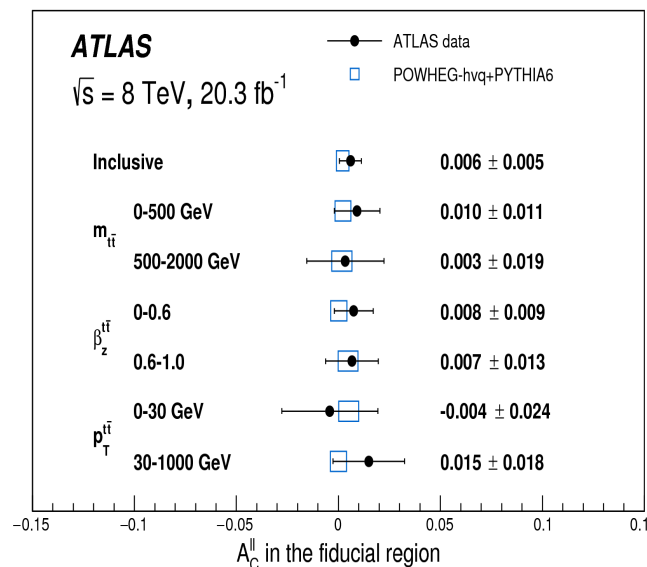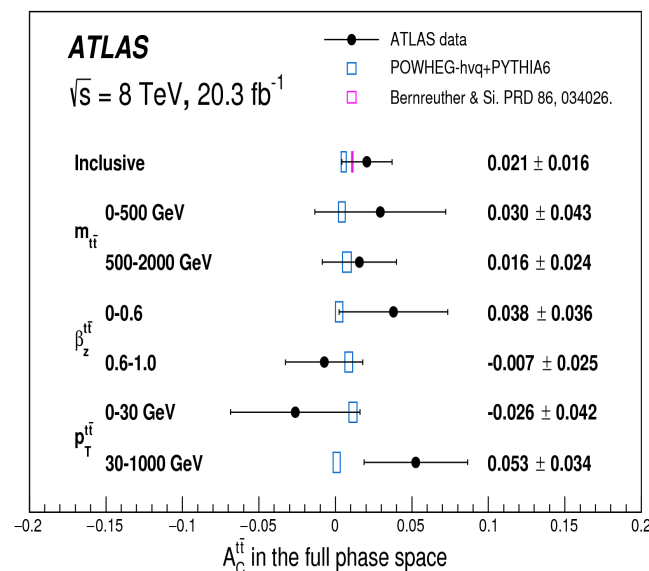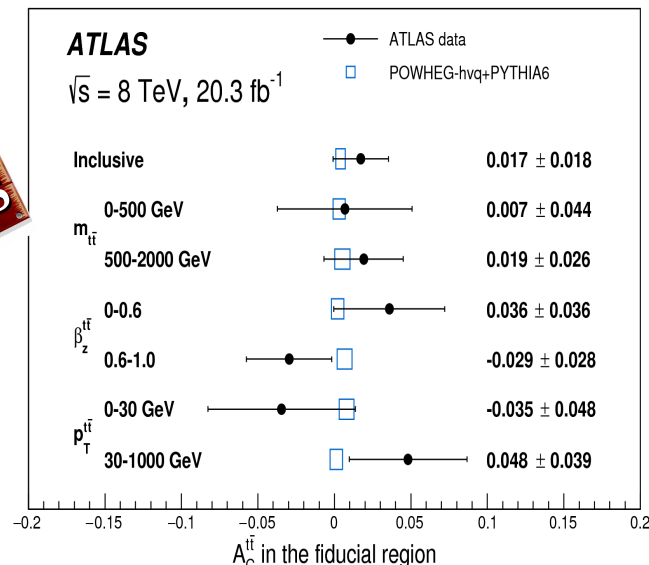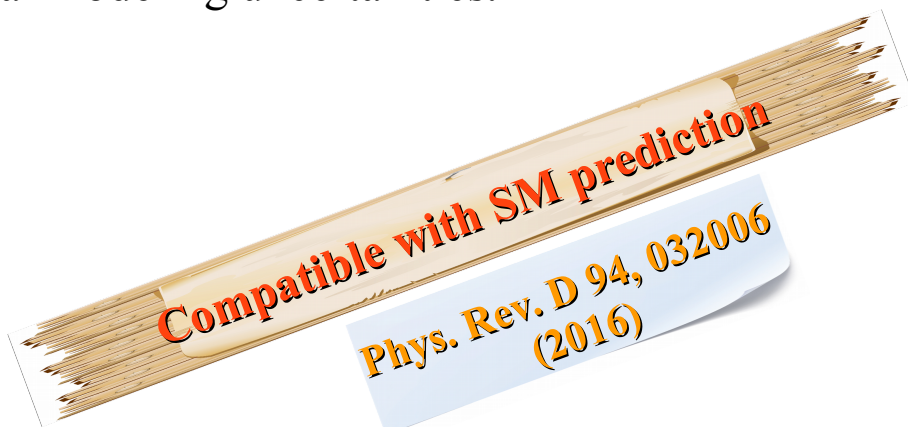|		
Inclusive		0.021 ± 0.016
$m_{t\bar{t}}$	0-500 GeV	0.030 ± 0.043
	500-2000 GeV	0.016 ± 0.024
$\beta_z^{t\bar{t}}$	0-0.6	0.038 ± 0.036
	0.6-1.0	-0.007 ± 0.025
$p_T^{t\bar{t}}$	0-30 GeV	-0.026 ± 0.042
	30-1000 GeV	0.053 ± 0.034

$A_C^{t\bar{t}}$ in the full phase space

ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
ATLAS data
POWHEG-hvq+PYTHIA6

Inclusive		0.006 ± 0.005
$m_{t\bar{t}}$	0-500 GeV	0.010 ± 0.011
	500-2000 GeV	0.003 ± 0.019
$\beta_z^{t\bar{t}}$	0-0.6	0.008 ± 0.009
	0.6-1.0	0.007 ± 0.013
$p_T^{t\bar{t}}$	0-30 GeV	-0.004 ± 0.024
	30-1000 GeV	0.015 ± 0.018

$A_C^{\parallel}$ in the fiducial region

ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
ATLAS data
POWHEG-hvq+PYTHIA6
Bernreuther & Si. PRD 86, 034026.

Inclusive		0.008 ± 0.006
$m_{t\bar{t}}$	0-500 GeV	0.009 ± 0.012
	500-2000 GeV	0.009 ± 0.019
$\beta_z^{t\bar{t}}$	0-0.6	0.010 ± 0.010
	0.6-1.0	0.004 ± 0.013
$p_T^{t\bar{t}}$	0-30 GeV	-0.002 ± 0.025
	30-1000 GeV	0.015 ± 0.018

$A_C^{\parallel}$ in the full phase space

differential results from CMS

- Differential measurements as a function of $m_{t\bar{t}}$, $p_{T,t\bar{t}}$, and $|Y_{t\bar{t}}|$

- Largest uncertainty statistical uncertainty

- Future measurements at $\sqrt{s}$ = 13 TeV with larger data sets expected to have better statistical precision

statistically limited, agreement with SM prediction
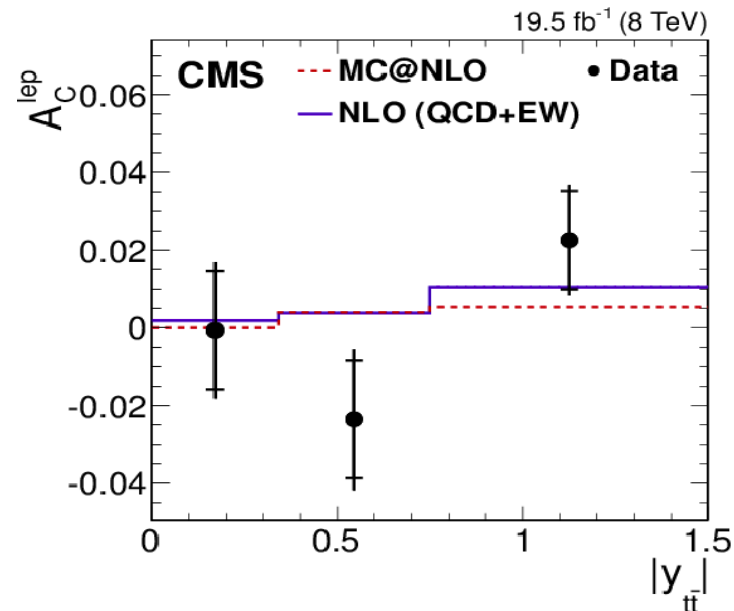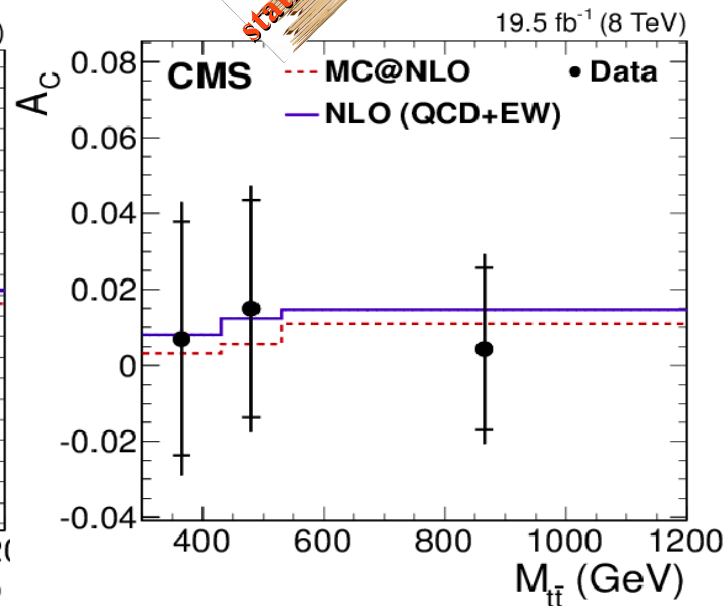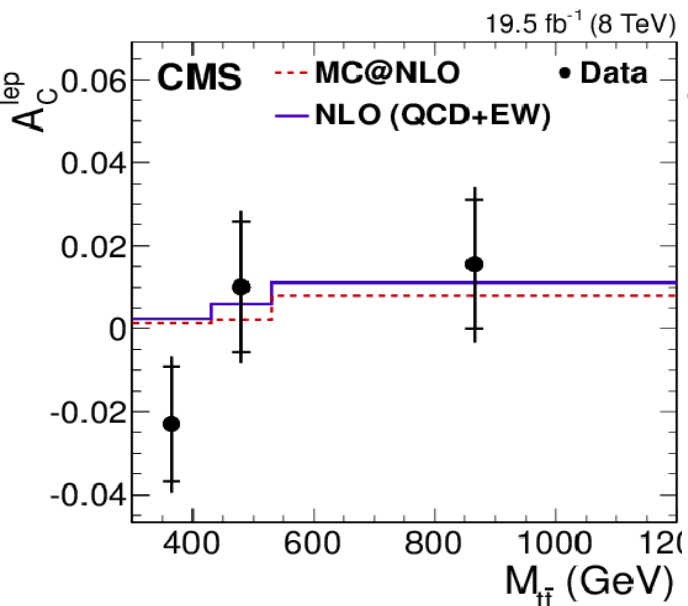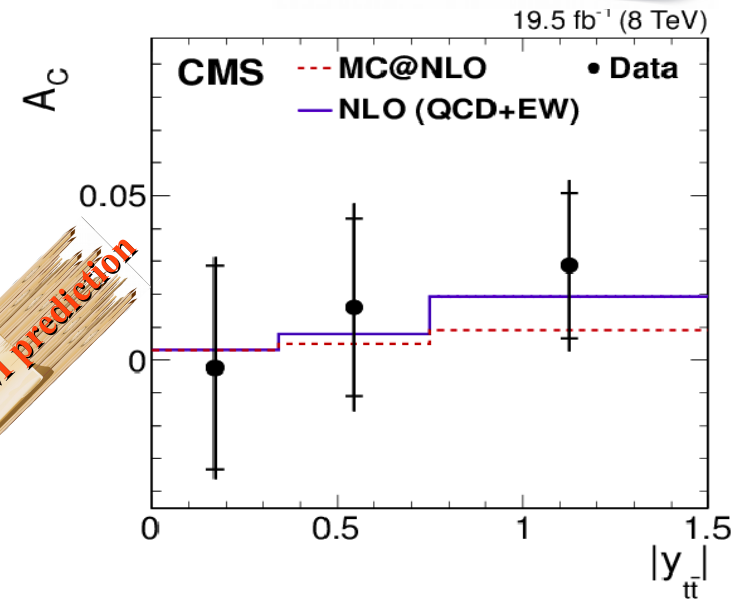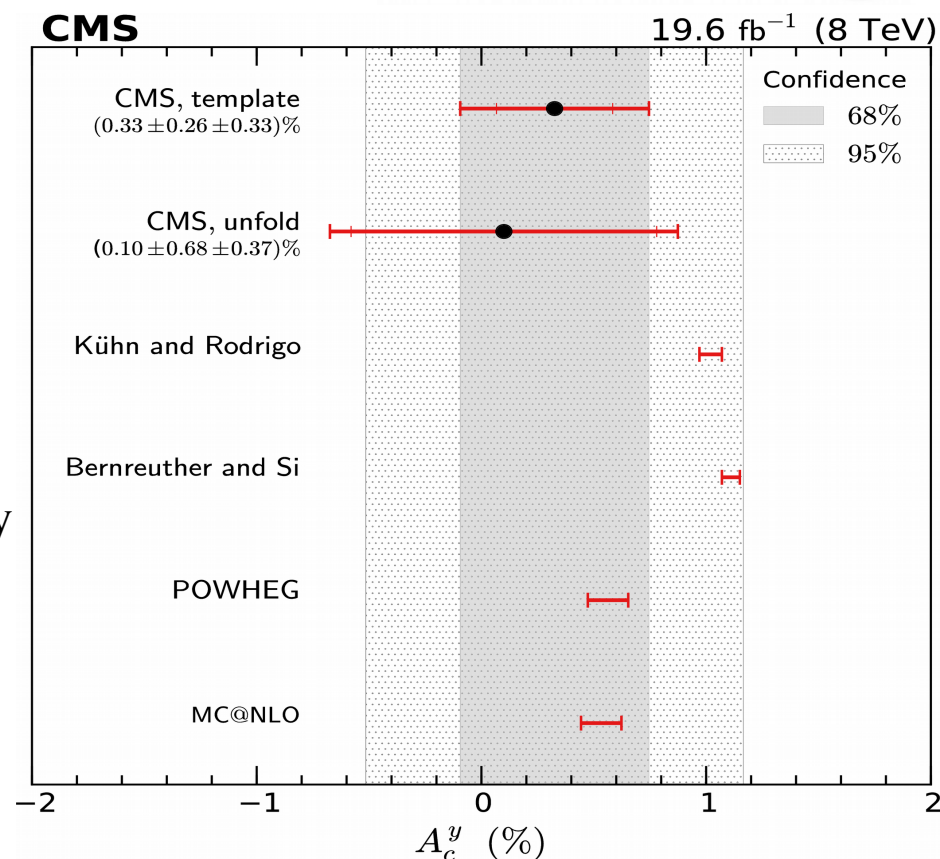
Semi-leptonic Measurements

at 8 TeV(Template method)

Charge asymmetry: template method

- Symmetric and asymmetric component of MC template fit to **sensitive variable**

$$Y_{t\bar{t}} = \tanh\left(\Delta|y|\right)$$

- In comparison to unfolding, measured A_c is more precise with significantly smaller stat. uncertainty

- Larger model dependence, reflected in the sys. uncertainty

- Total sys. uncertainty comparable to the stat. uncertainty

CMS — 19.6 fb^{-1} (8 TeV)

- CMS, template $(0.33 \pm 0.26 \pm 0.33)\%$
- CMS, unfold $(0.10 \pm 0.68 \pm 0.37)\%$
- Kühn and Rodrigo
- Bernreuther and Si
- POWHEG
- MC@NLO

Confidence: 68%, 95%

A_c^y (%)

Source	A_c^y (%)
e+jets	0.09 ± 0.34 (stat)
μ+jets	0.68 ± 0.41 (stat)
Combined	0.33 ± 0.26 (stat) ± 0.33 (syst)
POWHEG CT10	0.56 ± 0.09
MC@NLO	0.53 ± 0.09
Kühn and Rodrigo [8]	1.02 ± 0.05
Bernreuther and Si [9]	1.11 ± 0.04

Semi-leptonic Measurements
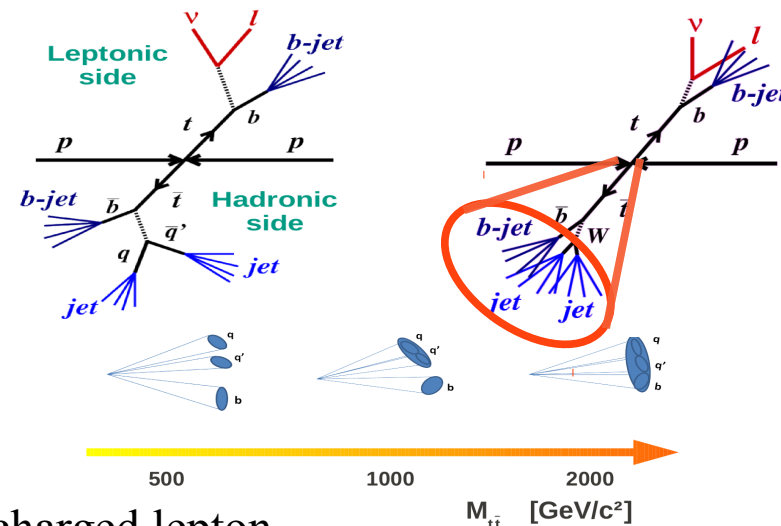## at 8 TeV(boosted events)

Boosted measurement in the TeV range

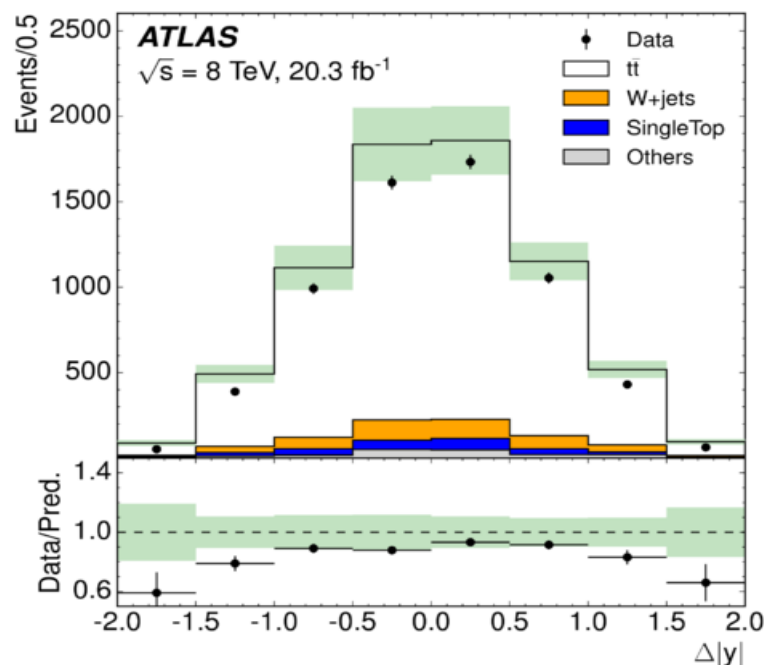**Physics Letters B (2016),
Vol. 756, pp. 52-71**

Lepton+jets channel

- Improved reconstruction at high energy
- Decay products collimated for boosted top quarks

→ Hadronic decay as a single trimmed jet

→ Leptonic decay as a small-R jet close to lepton single charged lepton

Events with $m_{t\bar{t}} > 750$ GeV

- One isolated lepton, $p_T > 25$ GeV
- MET>20 GeV
- MET+M_T^W>60 GeV

- one Anti-kT R=1.0, Large-R jet
- Trimmed:rsub=0.3
- P_T >300 GeV
- M_{jet}^{trim}>100 GeV

Further requirements:
- $\Delta\varphi$(lep., large-R jet)>2.3
- ΔR(lep., small-R jet)<1.5
- ΔR(small-R, lage-R)>1.5
- $\geq$ 1 b-tagged jet

- $\Delta|Y|$ corrected to parton level with Fully bayesian unfolding
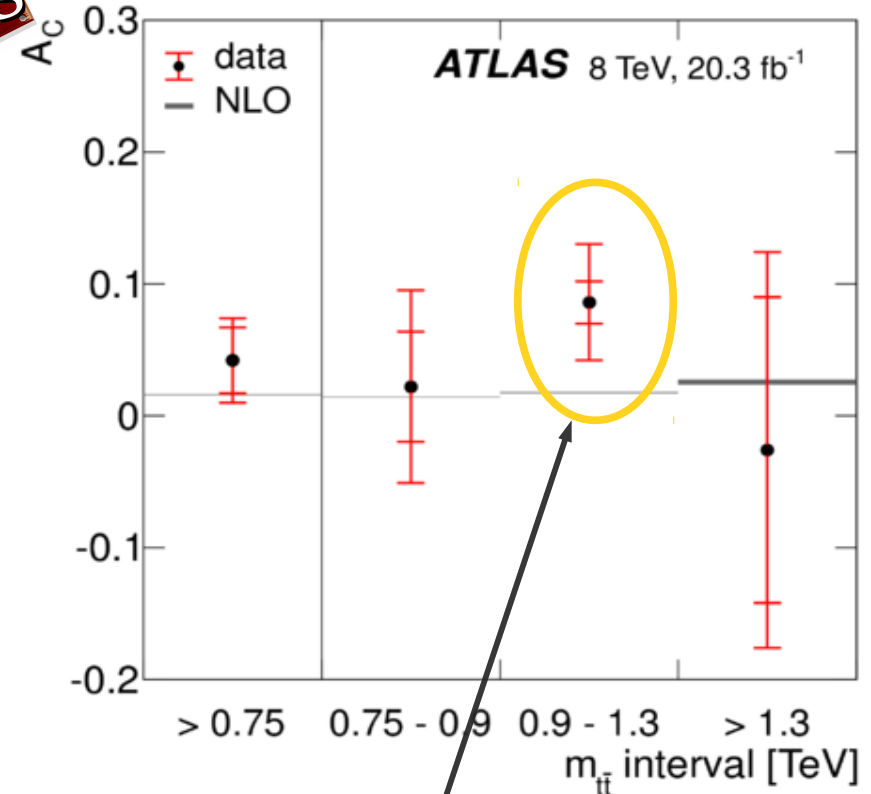- Measurement performed in fiducial region

  * $-2 < \Delta|y| < 2$, 750 GeV $< m_{t\bar{t}}$

- Differential measurement: 3 interval in $m_{t\bar{t}}$

- Inclusive measurement for $m_{t\bar{t}} > 750$ GeV
  $A_C = (4.2 \pm 3.2)\%$, less than 1σ from SM prediction of $1.60 \pm 0.04\%$
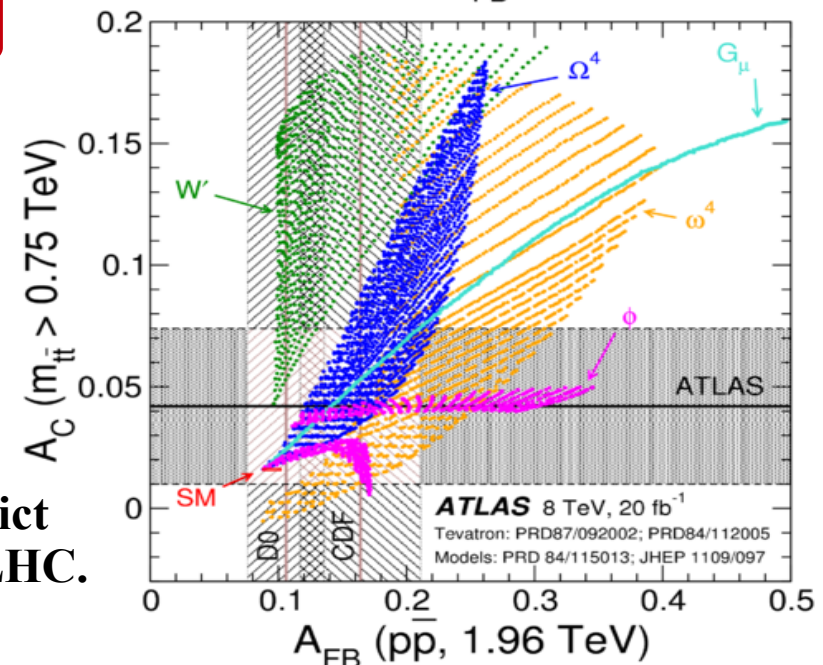 - Dominant source of uncertainty: signal modeling and data statistic

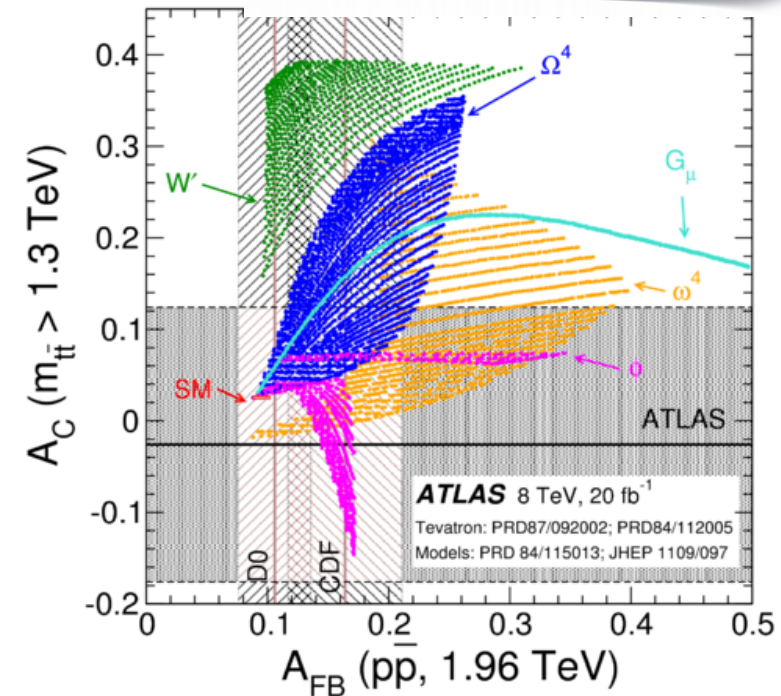**Almost all results are consistent with SM**

Most significant deviation w.r.t. SM, 1.6 σ

$m_{t\bar{t}}$ interval	> 0.75 TeV	0.75 – 0.9 TeV	0.9 – 1.3 TeV	> 1.3 TeV
Measurement	$(4.2 \pm 3.2)\%$	$(2.2 \pm 7.3)\%$	$(8.6 \pm 4.4)\%$	$(-2.9 \pm 15.0)\%$
SM prediction	$(1.60 \pm 0.04)\%$	$(1.42 \pm 0.04)\%$	$(1.75 \pm 0.05)\%$	$(2.55 \pm 0.18)\%$

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Impact on extension of the SM

- **Gμ : A new color-octet neutral vector boson**

- **W′: A charged color-singlet vector boson**

- **φ : A color-singlet scalar doublet**

- **Ω4 : A charge 4/3 scalar color sextet**

- **ω4 : A charge 4/3 scalar color triplet**

- **Higher sensitivity for the SM asymmetry**

- **Constraint on the extension of the SM**

- **Complementary to other measurements**

- **Extensions of the SM with heavy particles can predict an enhanced high-mass charge asymmetry at the LHC.**

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charge and CP asymmetries in b-hadron decays

using top-quark events (ATLAS)

Please see Jacob Julian Kempster talk
From ATLAS

■ LHC as top quark factory allow us to perform, **for the first time**, the measurements of CP asymmetries in heavy flavour mixing and decay from top-quark decay products.

NEW

■ Select top pair events with exactly one lepton and at least four jets, one of which must be tagged with both a displaced-vertex b-tagging algorithm and the **SMT algorithm**.

■ The charge asymmetries are formed from the charge of the lepton from the top-quark decay and from the charge of the soft muon from the semileptonic decay of a b-hadron.

$$A^{ss} = \frac{P\left(b \to \ell^+\right) - P\left(\bar{b} \to \ell^-\right)}{P\left(b \to \ell^+\right) + P\left(\bar{b} \to \ell^-\right)}, \qquad A^{os} = \frac{P\left(b \to \ell^-\right) - P\left(\bar{b} \to \ell^+\right)}{P\left(b \to \ell^-\right) + P\left(\bar{b} \to \ell^+\right)},$$

$$P\left(b \to \ell^+\right) = \frac{N\left(b \to \ell^+\right)}{N\left(b \to \ell^-\right) + N\left(b \to \ell^+\right)} = \frac{N^{++}}{N^{+-} + N^{++}} = \frac{N^{++}}{N^+},$$

$$P\left(\bar{b} \to \ell^-\right) = \frac{N\left(\bar{b} \to \ell^-\right)}{N\left(\bar{b} \to \ell^-\right) + N\left(\bar{b} \to \ell^+\right)} = \frac{N^{--}}{N^{--} + N^{-+}} = \frac{N^{--}}{N^-},$$

$$P\left(b \to \ell^-\right) = \frac{N\left(b \to \ell^-\right)}{N\left(b \to \ell^-\right) + N\left(b \to \ell^+\right)} = \frac{N^{+-}}{N^{+-} + N^{++}} = \frac{N^{+-}}{N^+},$$

$$P\left(\bar{b} \to \ell^+\right) = \frac{N\left(\bar{b} \to \ell^+\right)}{N\left(\bar{b} \to \ell^-\right) + N\left(\bar{b} \to \ell^+\right)} = \frac{N^{-+}}{N^{--} + N^{-+}} = \frac{N^{-+}}{N^-},$$

$N^{\alpha\beta}$ represent the number of SMT muons observed with a charge β in conjunction with a W-boson lepton of charge α.

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The CP asymmetries related to $B_q - \bar{B}_q$ **mixing** and direct **CP violating b- and c-decays** are defined as:

$$A^{b\ell}_{mix} = \frac{\Gamma\left(b \to \bar{b} \to \ell^+ X\right) - \Gamma\left(\bar{b} \to b \to \ell^- X\right)}{\Gamma\left(b \to \bar{b} \to \ell^+ X\right) + \Gamma\left(\bar{b} \to b \to \ell^- X\right)},$$

$$A^{bc}_{mix} = \frac{\Gamma\left(b \to \bar{b} \to \bar{c} X\right) - \Gamma\left(\bar{b} \to b \to c X\right)}{\Gamma\left(b \to \bar{b} \to \bar{c} X\right) + \Gamma\left(\bar{b} \to b \to c X\right)},$$

$$A^{b\ell}_{dir} = \frac{\Gamma\left(b \to \ell^- X\right) - \Gamma\left(\bar{b} \to \ell^+ X\right)}{\Gamma\left(b \to \ell^- X\right) + \Gamma\left(\bar{b} \to \ell^+ X\right)},$$

$$A^{c\ell}_{dir} = \frac{\Gamma\left(\bar{c} \to \ell^- X_L\right) - \Gamma\left(c \to \ell^+ X_L\right)}{\Gamma\left(\bar{c} \to \ell^- X_L\right) + \Gamma\left(c \to \ell^+ X_L\right)},$$

$$A^{bc}_{dir} = \frac{\Gamma\left(b \to c X_L\right) - \Gamma\left(\bar{b} \to \bar{c} X_L\right)}{\Gamma\left(b \to c X_L\right) + \Gamma\left(\bar{b} \to \bar{c} X_L\right)},$$

The observed charge asymmetries can be used with decay fractions to extract the various CP asymmetries.

$$N_{r_b} = N\left[t \to \ell^+ \nu \left(b \to \bar{b}\right) \to \ell^+ \ell^+ X\right],$$

$$N_{r_c} = N\left[t \to \ell^+ \nu \left(b \to c\right) \to \ell^+ \ell^+ X\right],$$

$$N_{r_{c\bar{c}}} = N\left[t \to \ell^+ \nu \left(b \to \bar{b} \to c\bar{c}\right) \to \ell^+ \ell^+ X\right],$$

$$N_{\tilde{r}_b} = N\left[t \to \ell^+ \nu b \to \ell^+ \ell^- X\right],$$

$$N_{\tilde{r}_c} = N\left[t \to \ell^+ \nu \left(b \to \bar{b} \to \bar{c}\right) \to \ell^+ \ell^- X\right],$$

$$N_{\tilde{r}_{c\bar{c}}} = N\left[t \to \ell^+ \nu \left(b \to c\bar{c}\right) \to \ell^+ \ell^- X\right].$$

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- ■ Backgrounds subtracted from the data, unfolded to a well-defined fiducial region where the charge asymmetries are measured.

- ■ The observed charge asymmetries found to be compatible with zero

NEW

	Data (10^{-2})		MC (10^{-2})		Existing limits (2σ) (10^{-2})	SM prediction
A^{ss}	-0.7	± 0.8	0.05	± 0.23	-	$< 10^{-4}$
A^{os}	0.4	± 0.5	-0.03	± 0.13	-	$< 10^{-4}$
A^b_{mix}	-2.5	± 2.8	0.2	± 0.7	< 0.1	$< 10^{-5}$
$A^{b\ell}_{dir}$	0.5	± 0.5	-0.03	± 0.14	< 1.2	$< 10^{-7}$
$A^{c\ell}_{dir}$	1.0	± 1.0	-0.06	± 0.25	< 6.0	$< 10^{-11}$
A^{bc}_{dir}	-1.0	± 1.1	0.07	± 0.29	-	$< 10^{-9}$

- ■ Both the data and the MC are compatible with the SM expectations,

- ■ The dominant uncertainty on all asymmetry measurements reported is statistical.
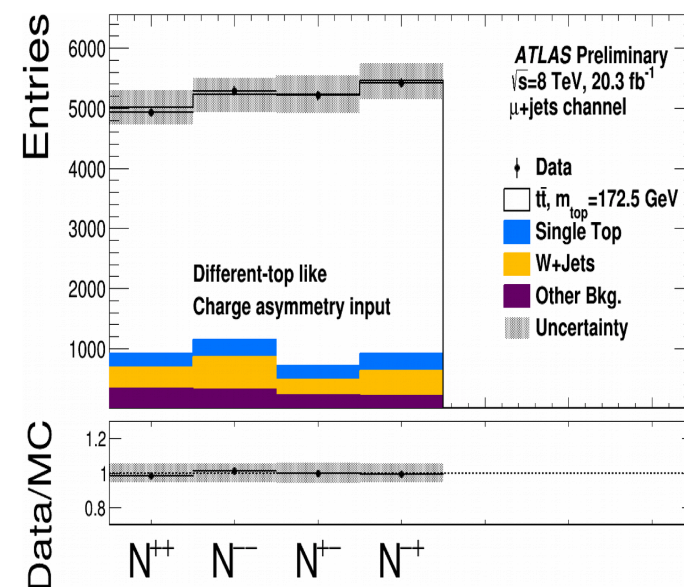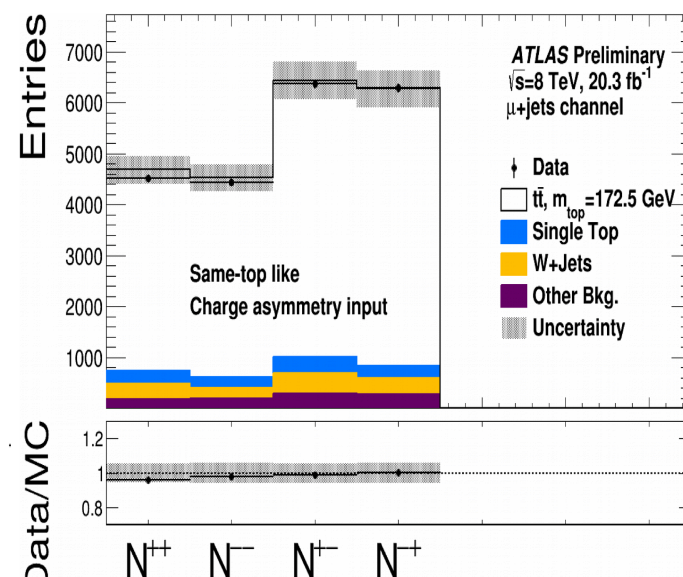
+

CP-violation asymmetries

in tt̄ events(CMS)

- First measurement at the LHC of CP-violation asymmetries in $t\bar{t}$ events

- In the SM, CP-violation effects very small but enhanced by BSM
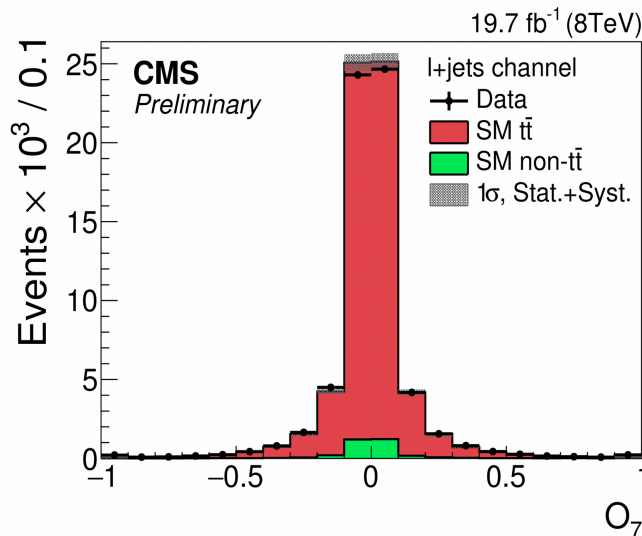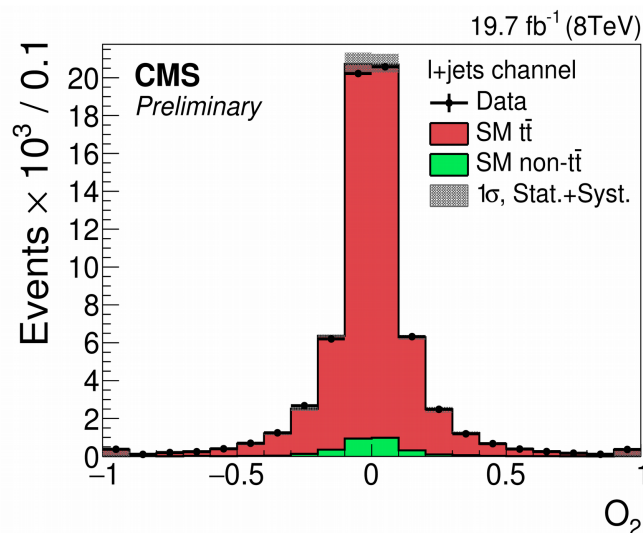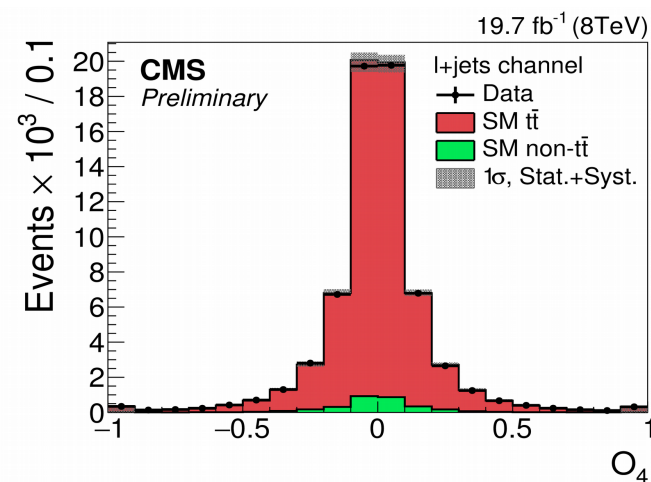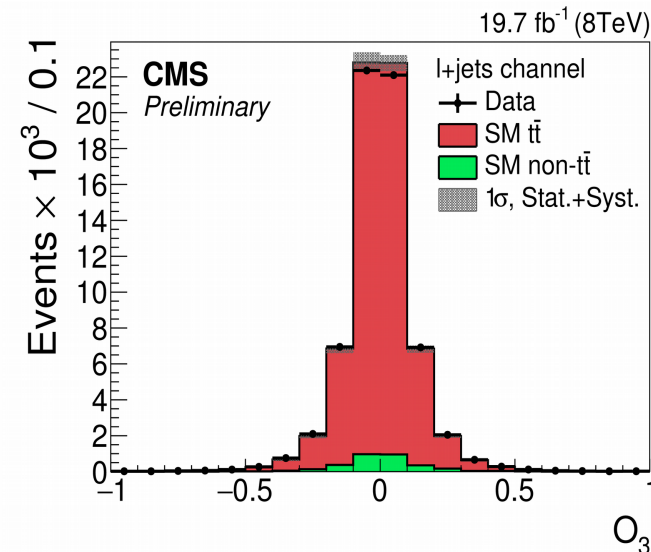
- Measure asymmetry with 4 T-odd triple product observables (O_i) using the composition of momenta of $t\bar{t}$ +jets events

$$CP(O_i) = -O_i$$

- The background-subtracted distributions of the observables used to compute the asymmetry A_{CP}:

$$A_{CP}(O_i) = \frac{N_{events}(O_i > 0) - N_{events}(O_i < 0)}{N_{events}(O_i > 0) + N_{events}(O_i < 0)},$$

- Any non-zero A_{CP} would be already a strong hint of new physics

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■ The measured asymmetries show no evidence for CP-violation effects in $t\bar{t}$ events within uncertainties

■ Most of the systematic effects are canceled in the A_{CP} measurement

■ The total uncertainty dominated by the statistical component
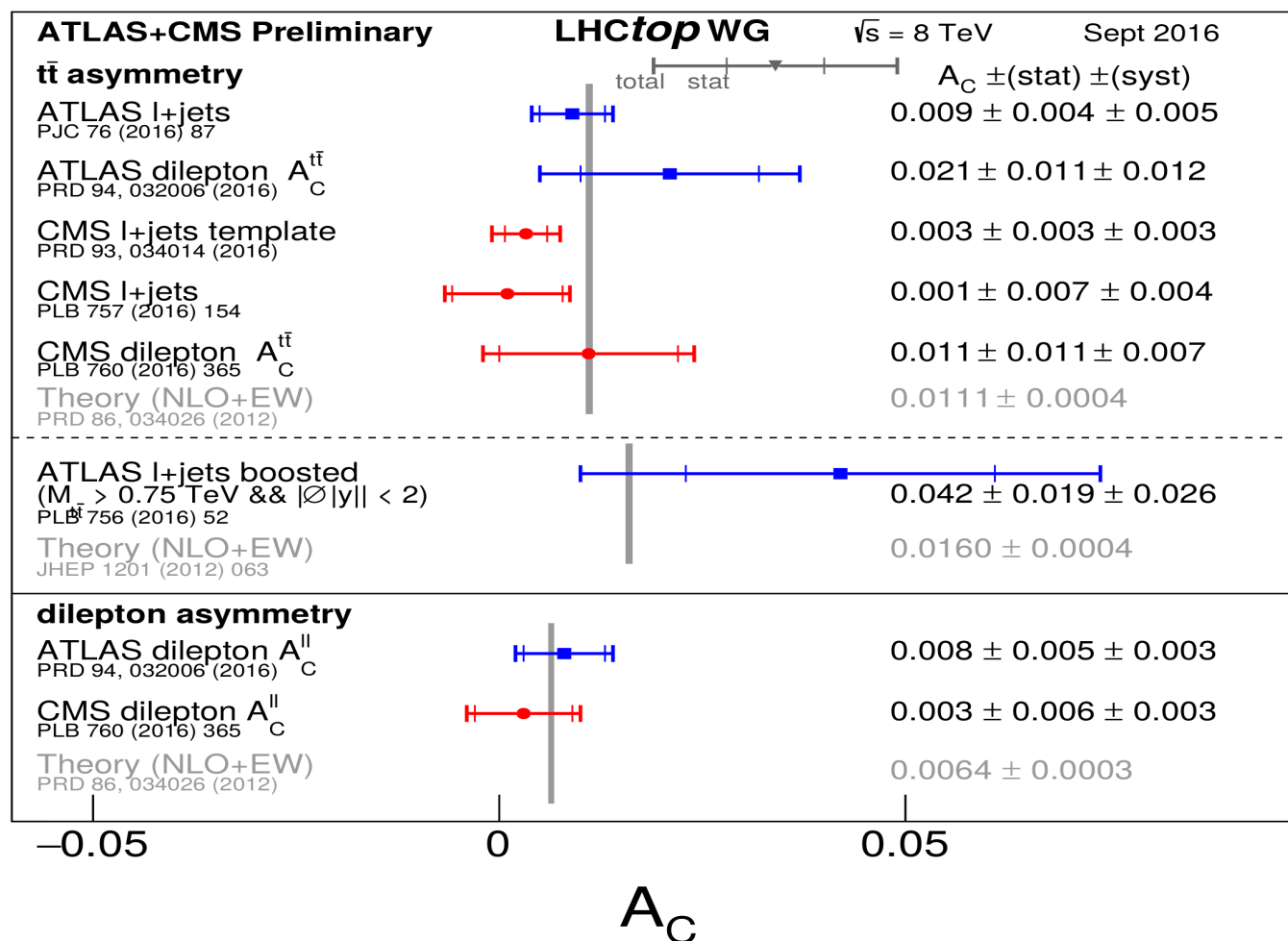 -The systematic uncertainty lower than 1% of the total uncertainty
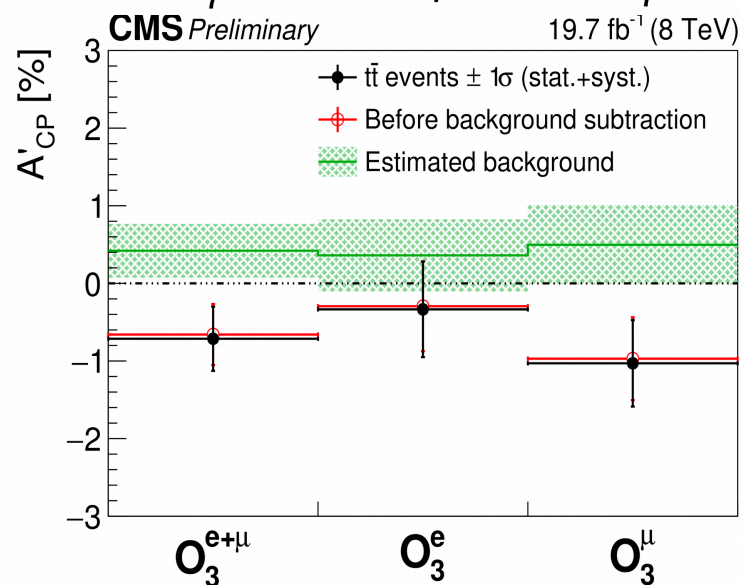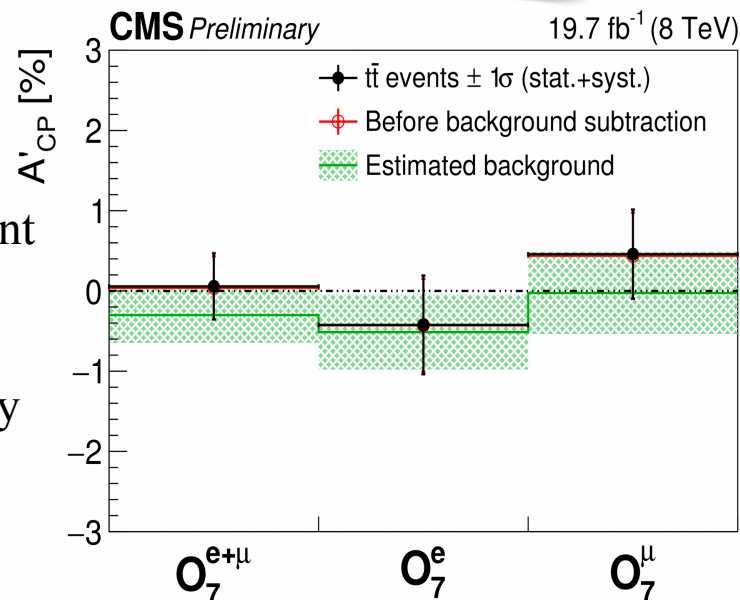
tension observed for the combined A_{CP} (O_3) , at 2σ-level

$A'_{CP}(O_i)$	e+jets	μ+jets	ℓ+jets
O_2	$-0.01 \pm 0.61 \pm 0.01$	$+0.50 \pm 0.56 \pm 0.02$	$+0.27 \pm 0.41 \pm 0.01$
O_3	$-0.34 \pm 0.61 \pm 0.02$	$-1.03 \pm 0.56 \pm 0.04$	$-0.71 \pm 0.41 \pm 0.03$
O_4	$-0.24 \pm 0.61 \pm 0.02$	$-0.49 \pm 0.56 \pm 0.04$	$-0.38 \pm 0.41 \pm 0.03$
O_7	$-0.42 \pm 0.61 \pm 0.00$	$+0.46 \pm 0.56 \pm 0.01$	$-0.06 \pm 0.41 \pm 0.01$

The first (second) uncertainty is of statistical (systematic) nature. The values quoted are in %.

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Where we are and where we are going?

ATLAS+CMS Preliminary — LHC*top* WG — $\sqrt{s}$ = 8 TeV — Sept 2016

$t\bar{t}$ asymmetry	$A_C \pm$(stat) $\pm$(syst)
ATLAS l+jets — PJC 76 (2016) 87	$0.009 \pm 0.004 \pm 0.005$
ATLAS dilepton $A_C^{t\bar{t}}$ — PRD 94, 032006 (2016)	$0.021 \pm 0.011 \pm 0.012$
CMS l+jets template — PRD 93, 034014 (2016)	$0.003 \pm 0.003 \pm 0.003$
CMS l+jets — PLB 757 (2016) 154	$0.001 \pm 0.007 \pm 0.004$
CMS dilepton $A_C^{t\bar{t}}$ — PLB 760 (2016) 365	$0.011 \pm 0.011 \pm 0.007$
Theory (NLO+EW) — PRD 86, 034026 (2012)	0.0111 ± 0.0004
ATLAS l+jets boosted ($M_{t\bar{t}} > 0.75$ TeV && $|\varnothing|y|| < 2$) — PLB 756 (2016) 52	$0.042 \pm 0.019 \pm 0.026$
Theory (NLO+EW) — JHEP 1201 (2012) 063	0.0160 ± 0.0004
dilepton asymmetry	
ATLAS dilepton A_C^{ll} — PRD 94, 032006 (2016)	$0.008 \pm 0.005 \pm 0.003$
CMS dilepton A_C^{ll} — PLB 760 (2016) 365	$0.003 \pm 0.006 \pm 0.003$
Theory (NLO+EW) — PRD 86, 034026 (2012)	0.0064 ± 0.0003

A_C

◆ ATLAS report the first experimental measurement of A_{dir}^{bc} strengthens the existing 2 σ limit on $A_{dir}^{c\ell}$ and present an equivalent 2 σ limit on $A_{dir}^{b\ell}$.

◆ Run 2 can probe some accessible regions of BSM models via more precise measurements or highly boosted events

◆ Future measurements at $\sqrt{s}$ = 13 TeV with larger data sets are expected to have better statistical precision

◆ With higher statistics, profit from associated productions **(tt+W/photon/jet)** to probe further A$_c$
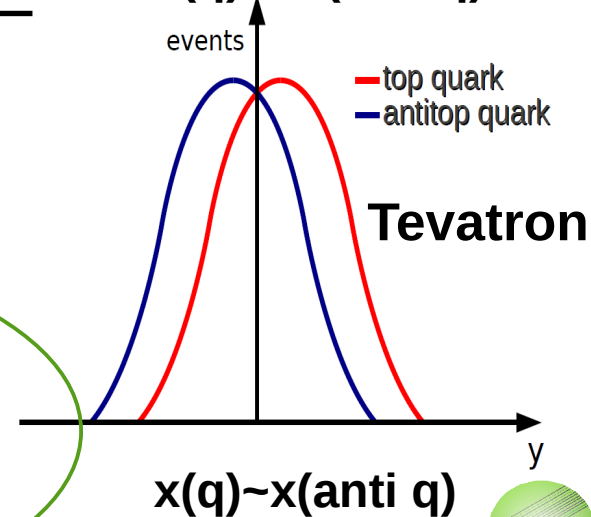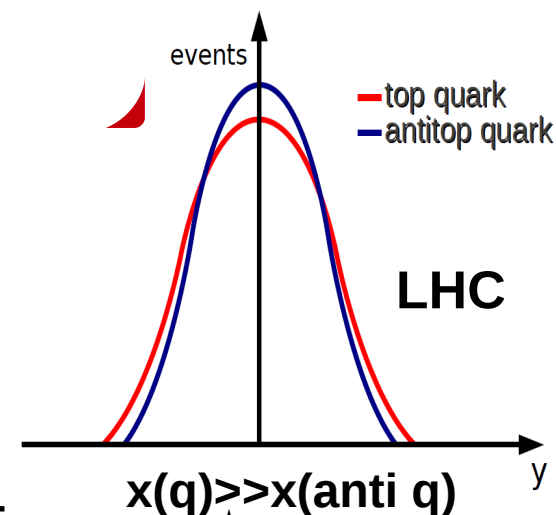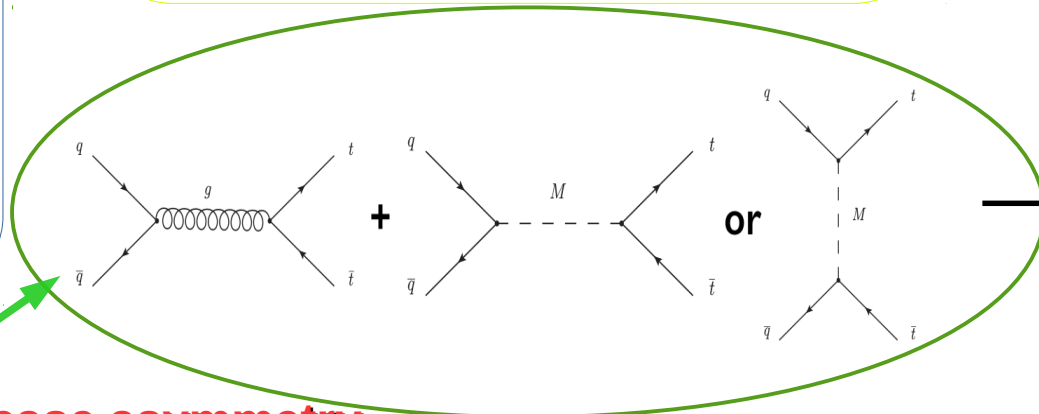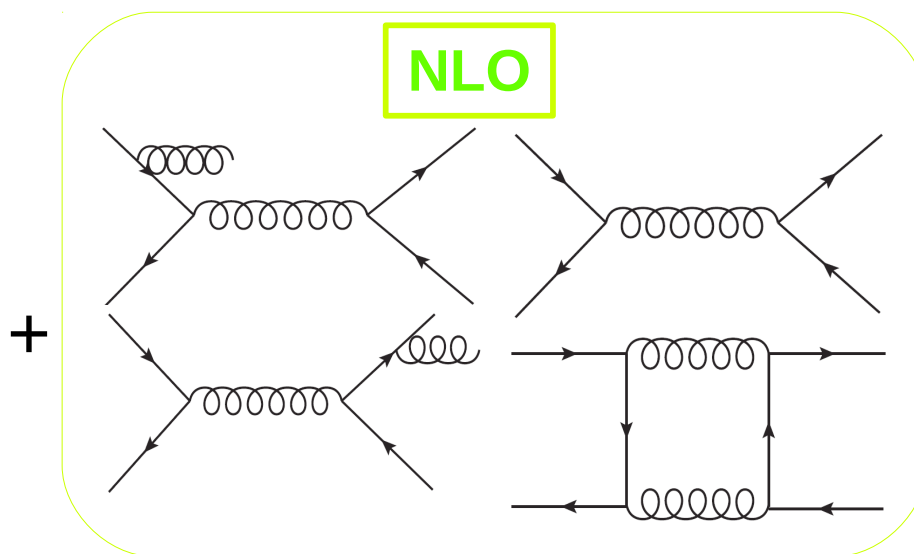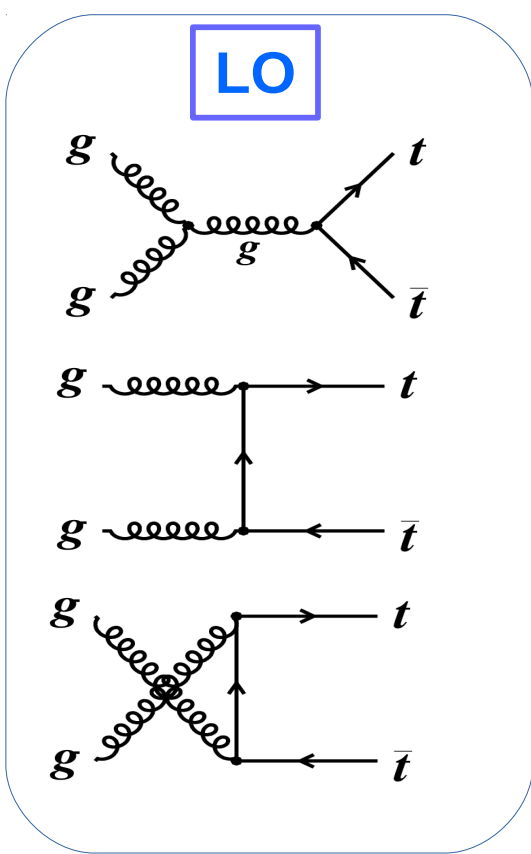
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Backup

SM predicts no asymmetry at **LO in QCD**, and a small asymmetry **at NLO**

Tevatron is asymmetric, valence quarks collide with valence anti quarks

LHC is symmetric, valence quarks collide with sea anti quarks
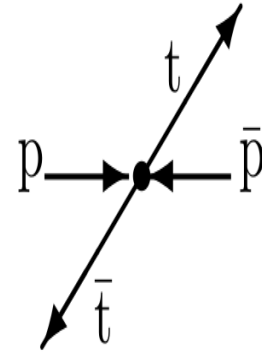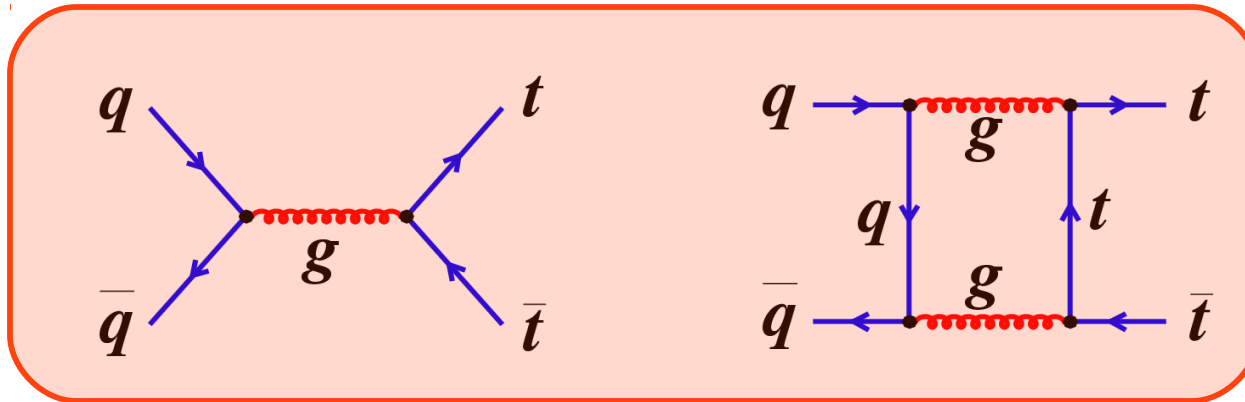   g-g dominated (symmetric) top pair factory: asymmetry is diluted

LO + **NLO** =

LHC

x(q)>>x(anti q)

Tevatron

x(q)~x(anti q)
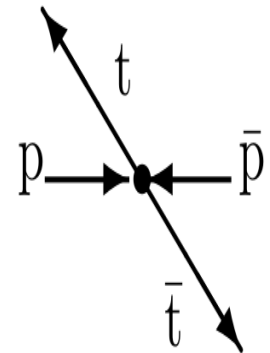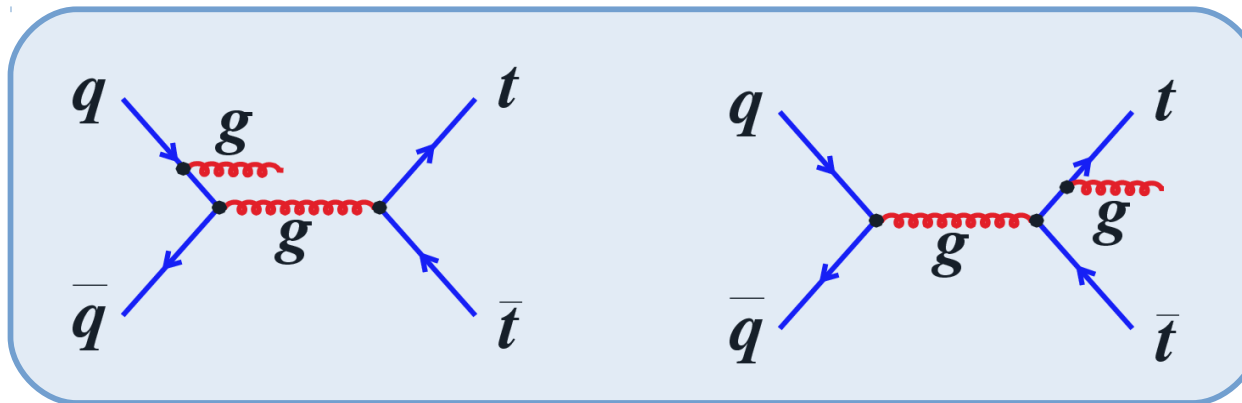
New physics may increase asymmetry

Origin of asymmetry

SM predicts no asymmetry at **LO in QCD**, and a small asymmetry **at NLO**.

(+) Interference between Born and box diagrams leads to a positive asymmetry value

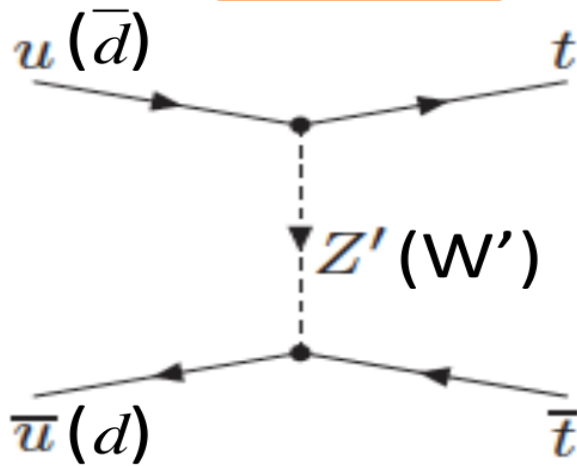**(-) Interference between ISR and FSR diagrams leads to a negative asymmetry value**

Origin of asymmetry

Could new physics be responsible to increase the charge asymmetry?

- ⦾ Many theoretical models include new particles changing SM asymmetry prediction

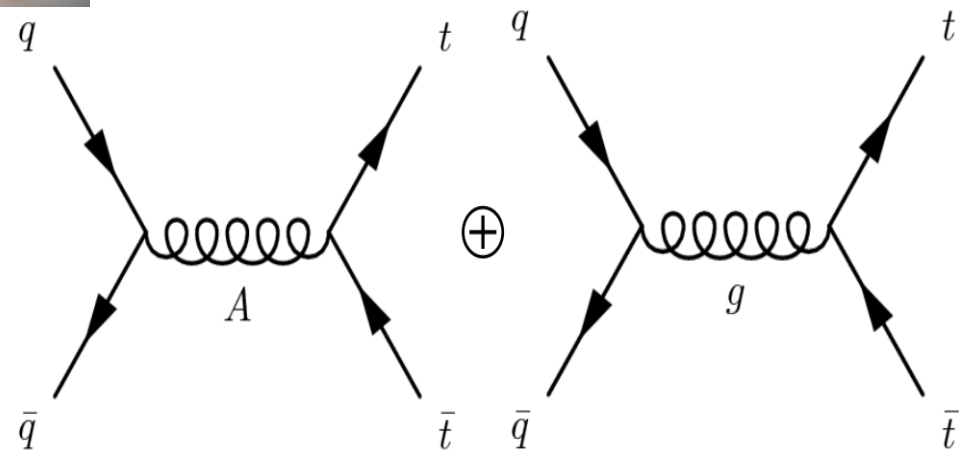- ⦾ Interference between SM and new physics amplitudes can give sensitivity

Z' / W'

Axigluon

t-channel mediator:
Exotic flavor changing vector bosons

s-channel mediator:
Interference between SM QCD and exotic gluons with axial coupling
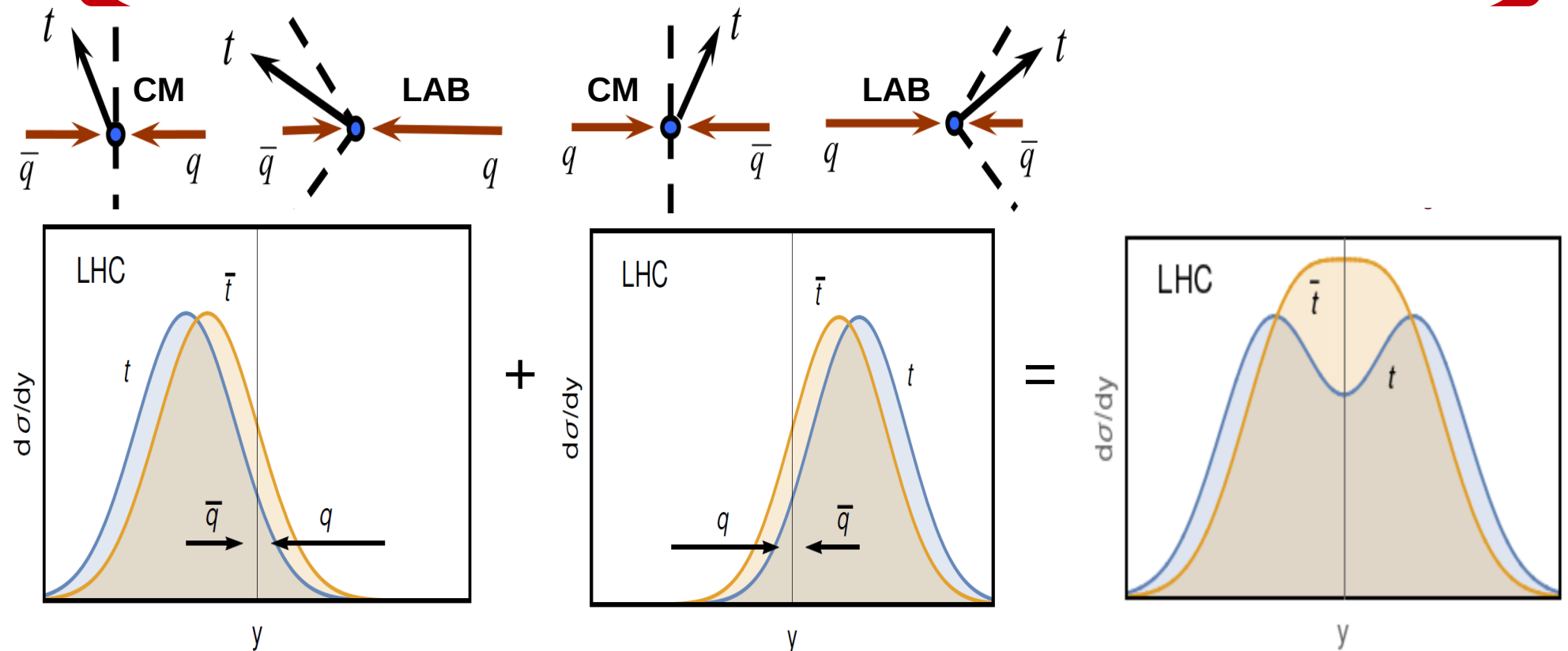
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From Tevatron to LHC

Tevatron is asymmetric, valence quarks collide with valence anti quarks

► Forward-backward asymmetry

LHC is symmetric, valence quarks collide with sea anti quarks

► No forward-backward asymmetry

at LHC top quarks tend to be more forward than anti tops in the lab frame.

Semi-leptonic Measurements @ 8TeV

Eur. Phys. J. C76 (2016) 87

Event Selection

- One isolated lepton, $p_T > 25$ GeV, $|\eta_c| < 2.47$(e), $|\eta| < 2.5$(μ)

- ≥ 4 jets with $p_T > 25$ GeV and $|\eta| < 2.5$

- Event separated by: $0, 1, \geq 2$ b-tag jets

- MET + $m_T^W > 60$ GeV for 0,1 b-tag events, MET > 40 (20) GeV for 0 (1) b-tag events

- Main background: W+jets

- Signal in 1($\geq$2) b-tag region: ~68% (89%) 0f total yield

Phys. Lett. B 757 (2016) 154

Event Selection

- One isolated lepton, $p_T > 30$ GeV (e), 26 GeV (μ), $|\eta| < 2.5$ (e), $|\eta| < 2.1$ (μ)

- ≥ 4 jets with $p_T > 30$ GeV and $|\eta| < 2.5$

- ≥ 1 b-tagged jet

- m_T^W used in fit to constrain QCD background

- ~ 60% of total background W+jets

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Di-leptonic Measurements @ 8TeV

charge asymmetry measured by: pseudorapidity of the leptons or the rapidity of the top quarks.

Event Selection

ATLAS

- e-e, μ-μ, e-μ channels

- Two isolated leptons, $p_T > 25$ GeV, $|\eta_{cl}| < 2.47(e)$, $|\eta| < 2.5(\mu)$

- ≥ 2 jets with $p_T > 25$ GeV and $|\eta| < 2.5$

- $|m_{ll} - m_Z| > 10$ GeV(e-e, μ-μ)

- $H_T > 130$ GeV(e-μ)

- Signal Regions ≥ 1b-tag(e-e, μ-μ)

- MET > 30 GeV(e-e, μ-μ)

- Background: 15% of total yield

- Main background: Drell-Yan, single top

Event Selection

CMS

- e-e, μ-μ, e-μ channels

- Two isolated lepton, $p_T > 20$ GeV, $|\eta| < 2.4$

- ≥ 2 jets with $p_T > 30$ GeV and $|\eta| < 2.4$

- $|m_{ll} - m_Z| > 15$ GeV (e-e, μ-μ)

- Signal region with ≥ 1b-tag

- MET > 40 GeV(e-e, μ-μ)

- Background: 9% of total yield

- Main background: Drell-Yan, single top

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Charge asymmetry: template method

- Electron(muon)+jets channel

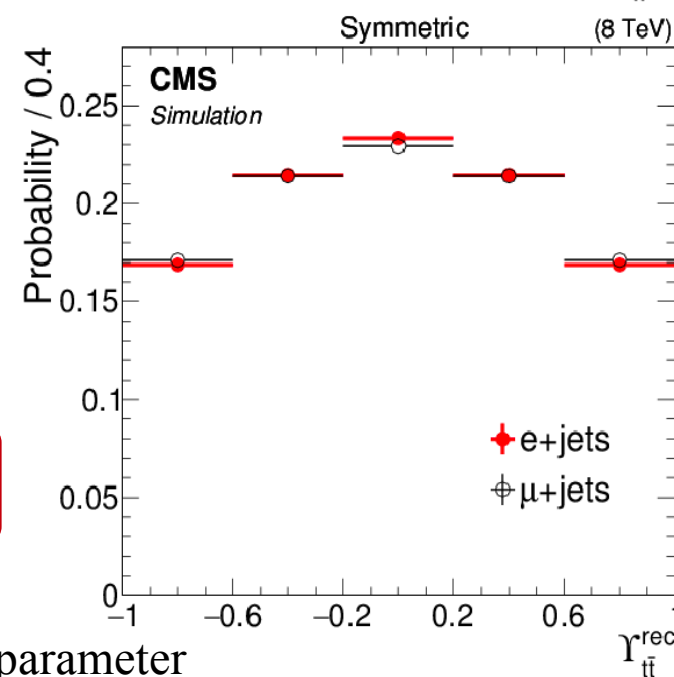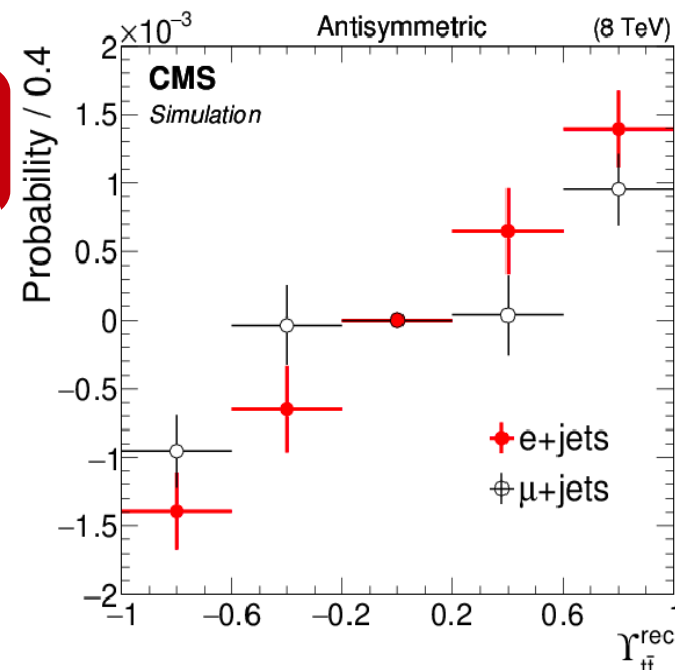- A template technique based on a parametrization of the SM

- Symmetric and asymmetric component of MC template fit to **sensitive variable**

$$Y_{t\bar{t}} = \tanh\left(\Delta|y|\right)$$

$$\rho(Y_{t\bar{t}}) = \frac{1}{\sigma}\frac{d\sigma}{dY} \begin{cases} \rho^{\pm}(Y_{t\bar{t}}) = [\rho(Y_{t\bar{t}}) \pm \rho(-Y_{t\bar{t}})]/2 \\ \\ \rho(\alpha) = \rho^{+} + \alpha\,\rho^{-} \qquad A_C^{Y} = \alpha\,\hat{A}_C^{Y} \end{cases}$$

$$\hat{A}_C^{Y} = 2\int \rho^{-}\,dY$$
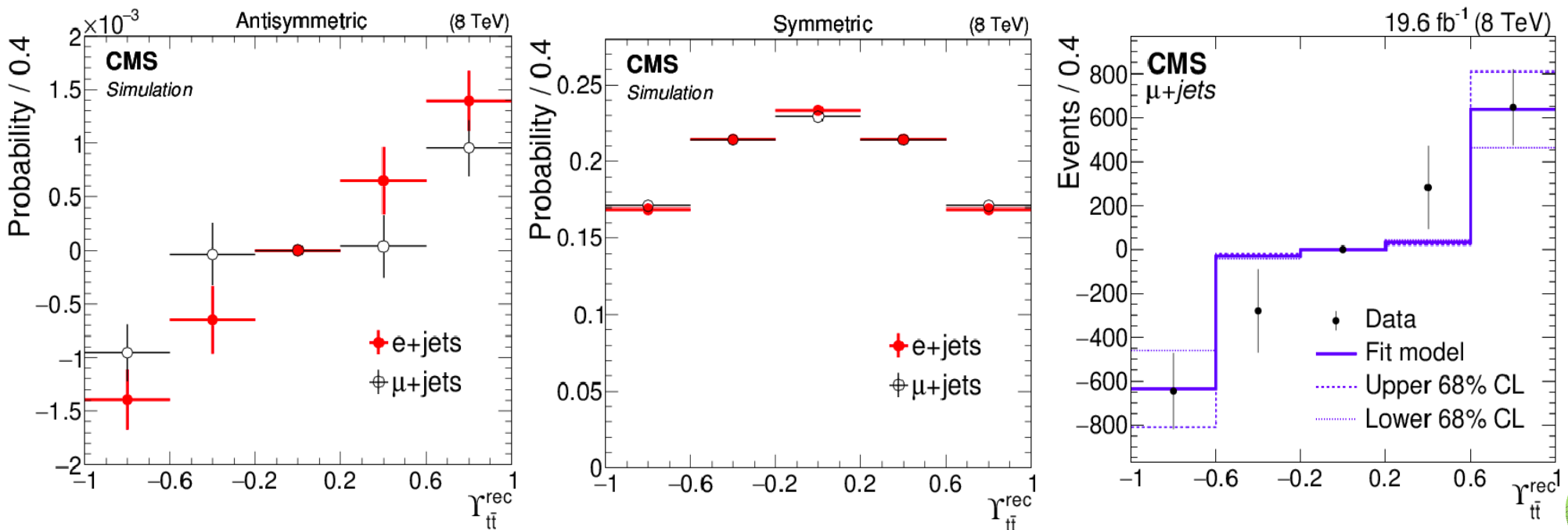
base model charge asymmetry

■ Template fit to the reconstructed $Y_{t\bar{t},rec}$ distribution to extract α parameter

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- Template fit to the reconstructed $Y_{t\bar{t},rec}$ distribution to extract α parameter

$$\rho(\alpha) = \rho^+ + \alpha\,\rho^- \qquad A_C^Y = \alpha\,\hat{A}_C^Y$$

Charge asymmetry: template method

- Symmetric and asymmetric component of MC template fit to **sensitive variable**

$$Y_{t\bar{t}} = \tanh\left(\Delta|y|\right)$$

- Total sys. uncertainty comparable to the stat. uncertainty

- Measured A_c compatible with unfolding method but significantly smaller stat. uncertainty

- Larger model dependence, reflected in the sys. uncertainty

- Sys. uncertainty dominated by the statistical uncertainty in the templates,
 - will be reduced through increased numbers of events
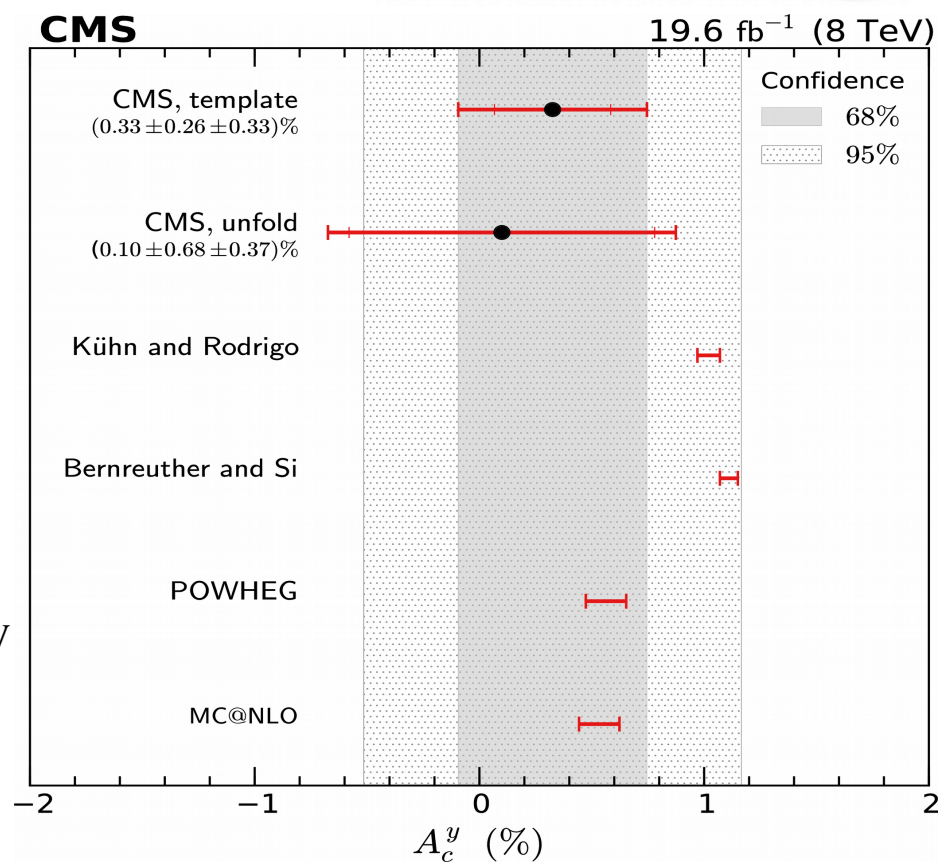
Source	A_c^y (%)
e+jets	0.09 ± 0.34 (stat)
μ+jets	0.68 ± 0.41 (stat)
Combined	0.33 ± 0.26 (stat) ± 0.33 (syst)
POWHEG CT10	0.56 ± 0.09
MC@NLO	0.53 ± 0.09
Kühn and Rodrigo [8]	1.02 ± 0.05
Bernreuther and Si [9]	1.11 ± 0.04

Boosted measurement

- Perform accurate measurements in events with a $t\bar{t}$ invariant mass in the TeV range.

- Decay products collimated for boosted top quarks

- Improved reconstruction at high energy
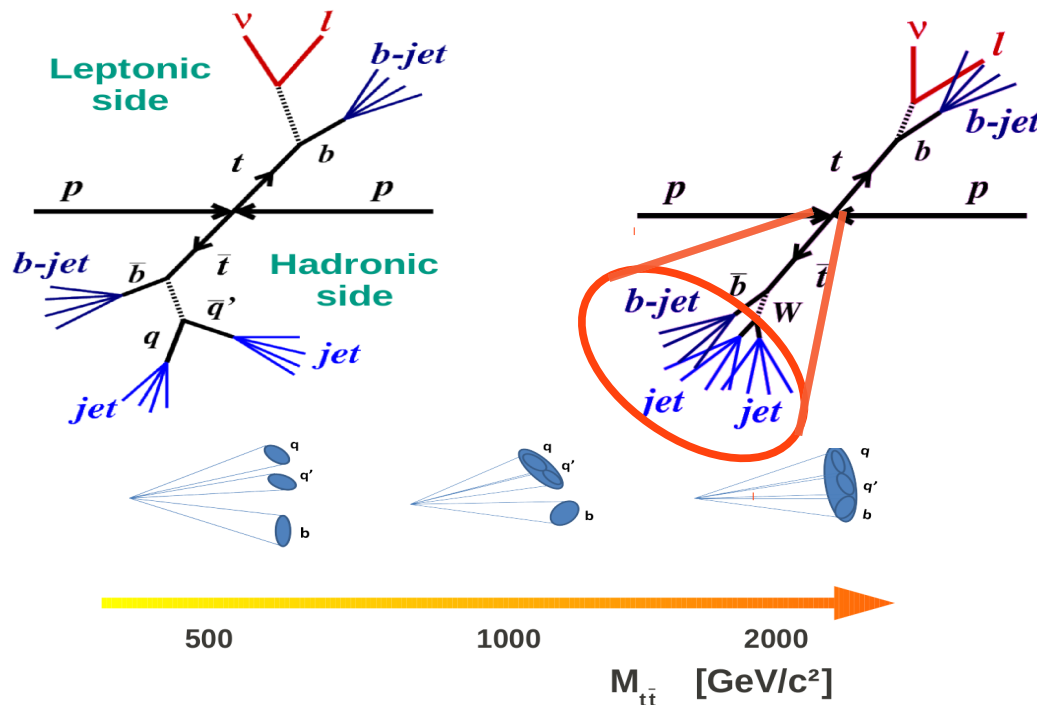
○ One isolated lepton, $p_T > 25$ GeV
○ ≥ 1 small-R jet close to lepton
○ MET>20 GeV
○ MET$+M_T^W>60$ GeV

Hadronic decay as a single trimmed jet:
○ one Anti-kT R=1.0, Large-R jet
○ Trimmed:rsub=0.3
○ $P_T >300$ GeV
○ $M_{jet}^{trim}>100$ GeV

Further requirements:
○ $\Delta\varphi$(lep., large-R jet)>2.3
○ ΔR(lep., small-R jet)<1.5
○ ΔR(small-R, lage-R)>1.5
○ ≥ 1 b-tagged jet
○ $m_{t\bar{t}}->750$GeV