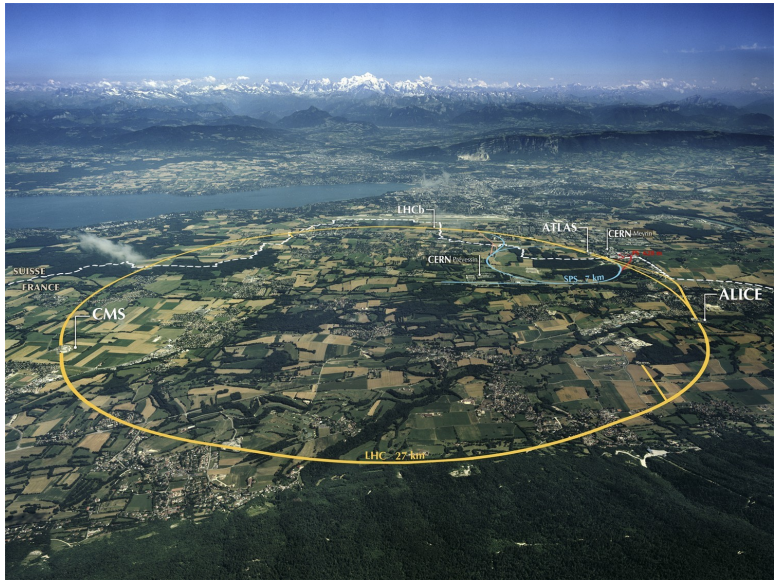
# Top quark property measurements at ATLAS & CMS



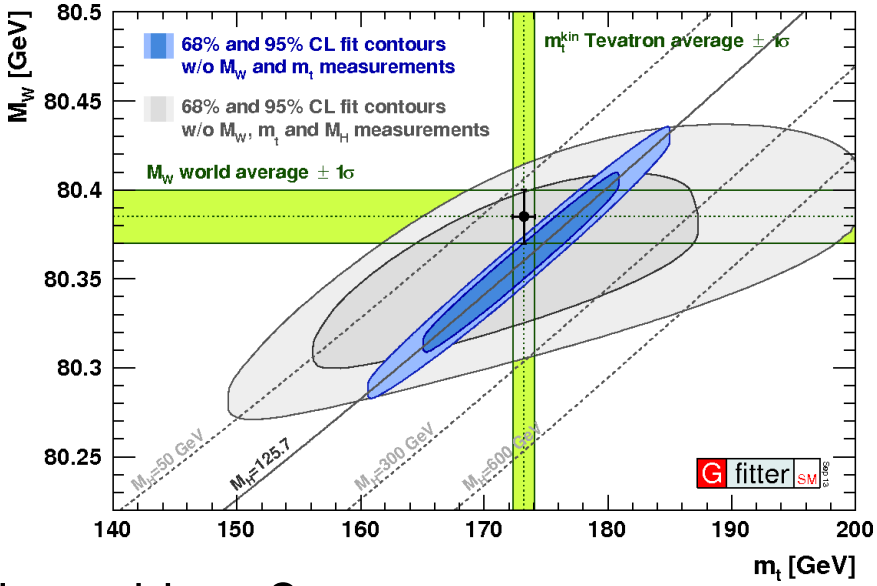

- (Introduction)
- Production asymmetries, spin correlations and *W* helicity
- Anomalous couplings
- $t\bar{t}$ + *W*, *Z*, $\gamma$ cross sections
- Conclusions & Outlook

Andreas Jung (Fermilab) for the ATLAS & CMS collaboration

Fermilab
International Workshop on DIS and related subjects
April 27th – 1st May 2015, Dallas

# Top quark introduction

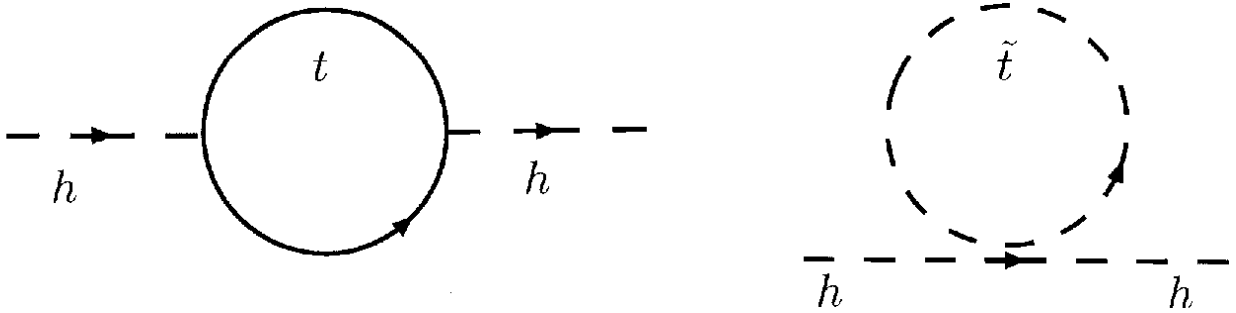
- Top is the heaviest fundamental particle discovered so far
  → $m_t$ = 173.34 ± 0.76 GeV [arxiv:1403.4427]




- Lifetime: $\tau \approx 5 \times 10^{-25}$ s << $\Gamma_{QCD}$
  → **Observe bare quark properties**

- Large Yukawa coupling to Higgs boson
  → $\lambda_t \sim 1$
  special role in electroweak symmetry breaking ?

- If we could calculate the Higgs mass:
  → Large corrections to the Higgs mass from top quark "loops"
  (Hierarchy problem)




**Top quarks as window to new physics**

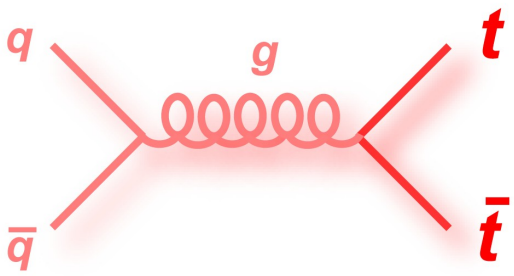
# Top quark introduction

- Strong interaction: Top pairs

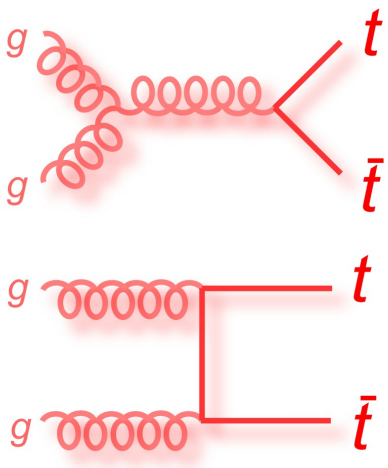
  LHC (7/8 TeV):

  $q\bar{q}$: ~15/13% (~10%, 14 TeV)

  $gg$: ~85/87% (~90%, 14 TeV)




$q\bar{q}$ annihilation




$gg$ fusion

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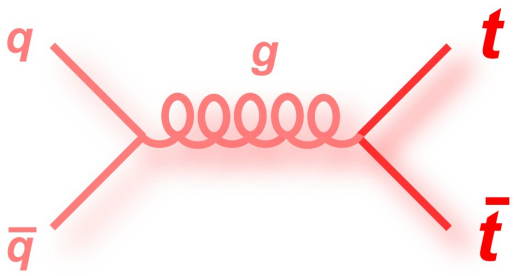
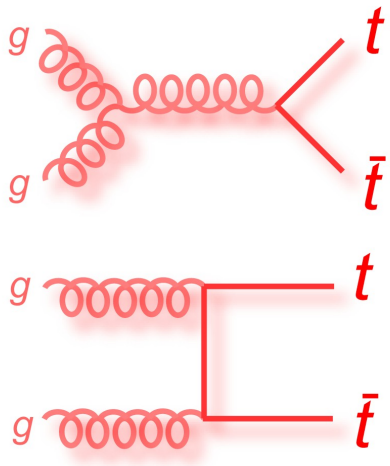
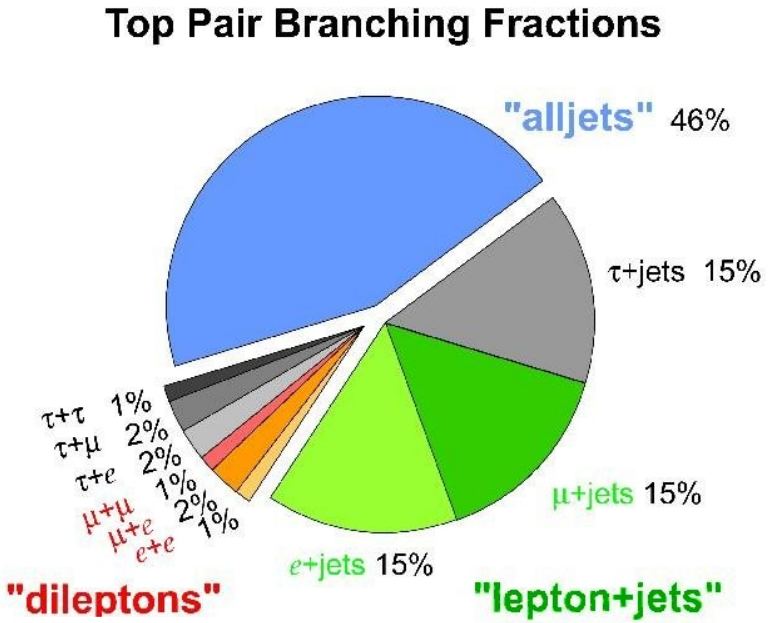


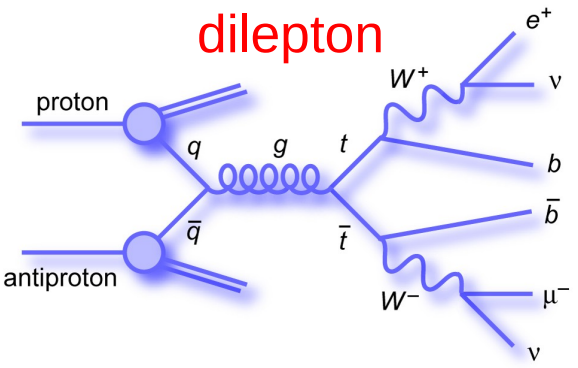

$gg$ fusion

- Decay channels:



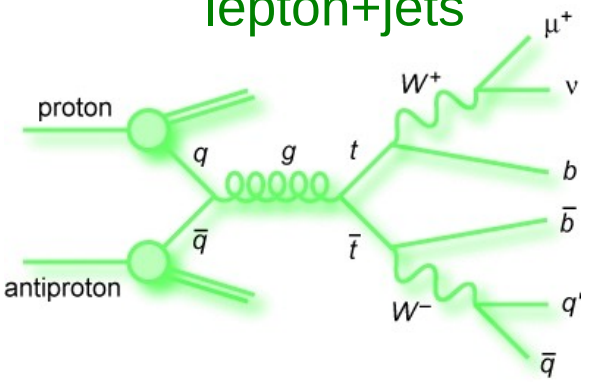

BR, bg increase

dilepton

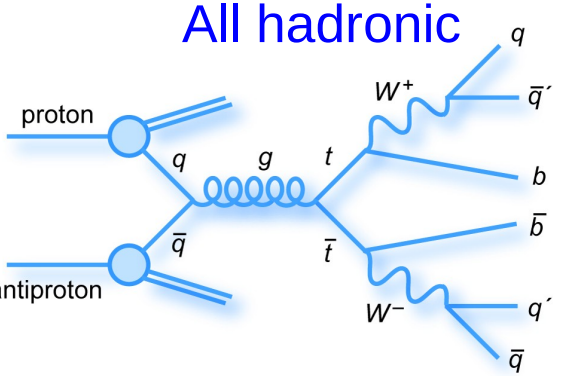



BR, bg decrease

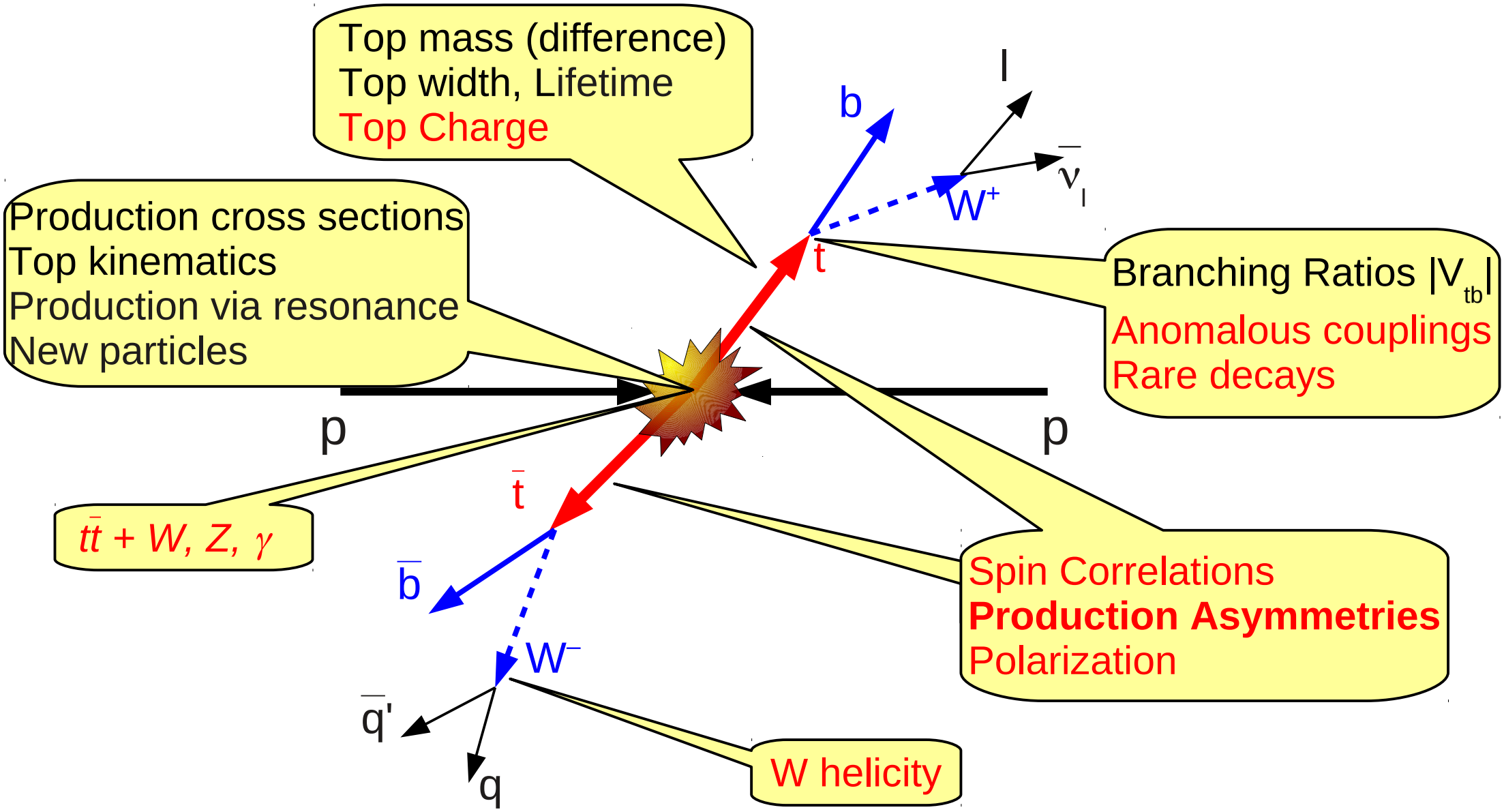
lepton+jets




All hadronic



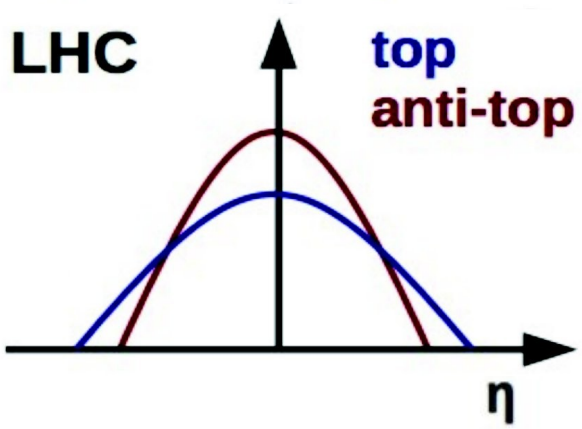
# Content




**→ Selection of results, focus on most recent and/or precise results**

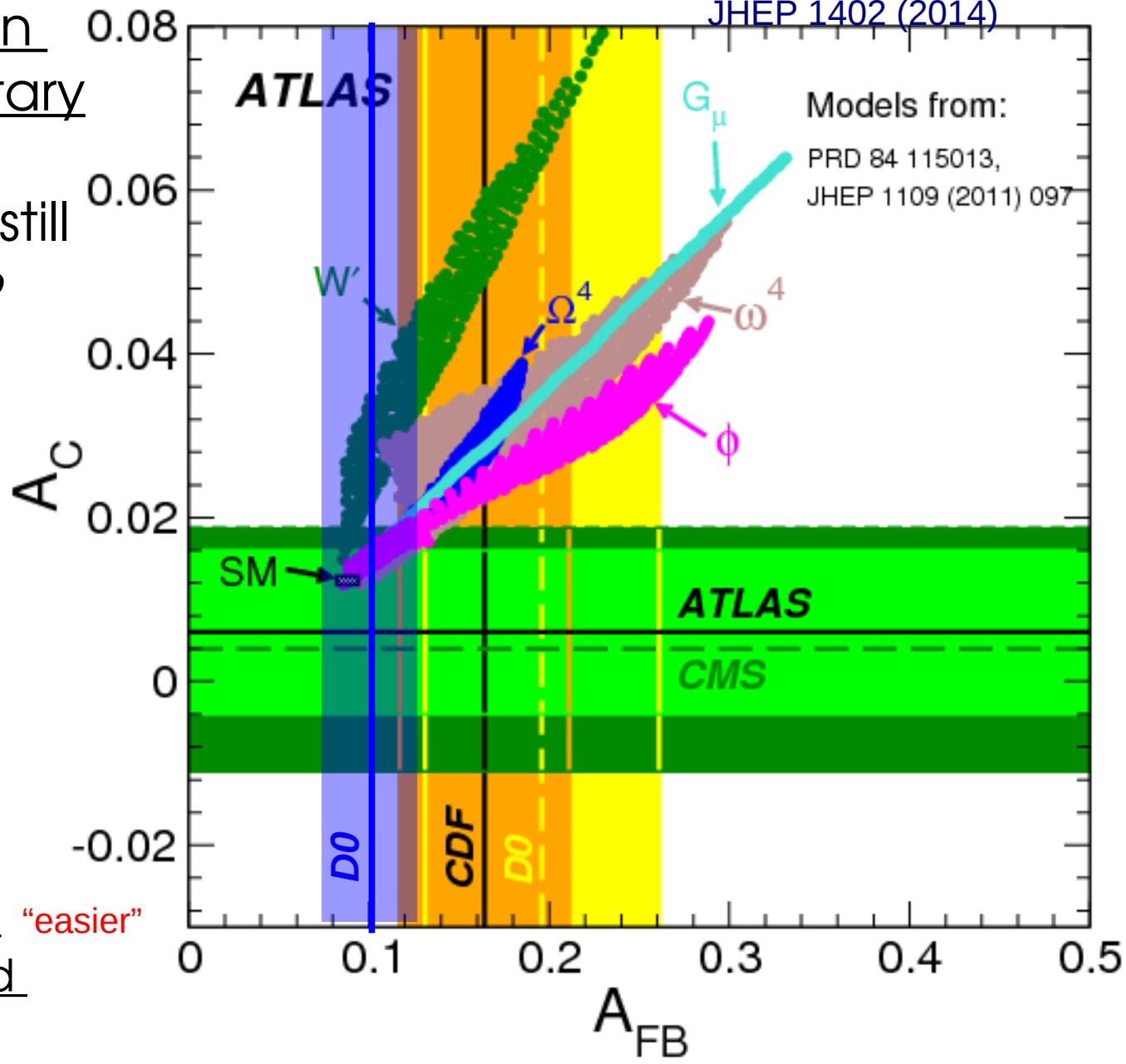
# Top quark asymmetries

- Measurements at Tevatron & LHC are complementary
  - Variety of models with wide parameter space still allowed → *W′, G, ω, φ, Ω*



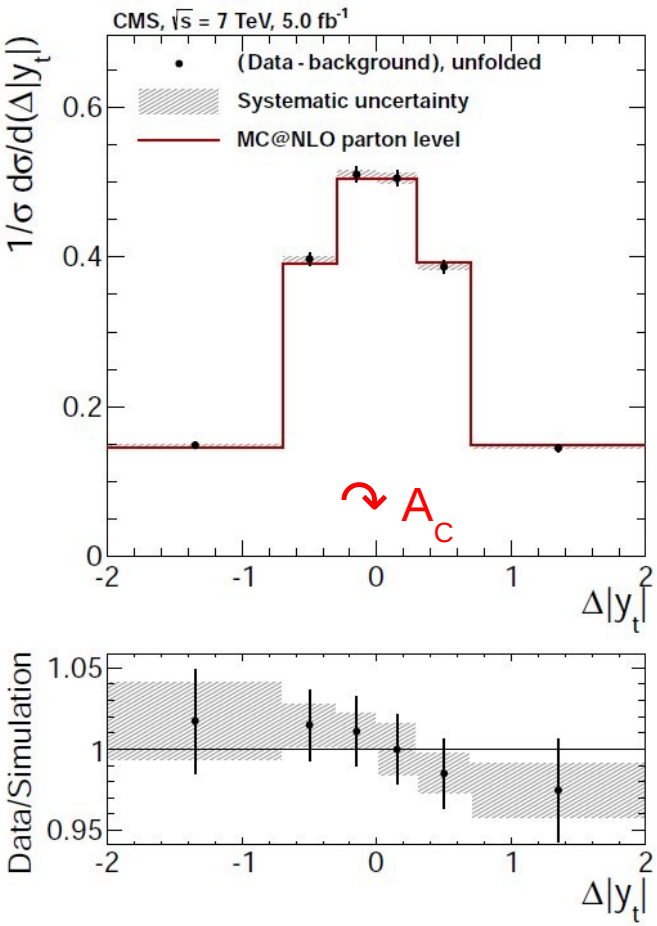

$$A_C = \frac{N(\Delta|y_t| > 0) - N(\Delta|y_t| < 0)}{N(\Delta|y_t| > 0) + N(\Delta|y_t| < 0)}$$

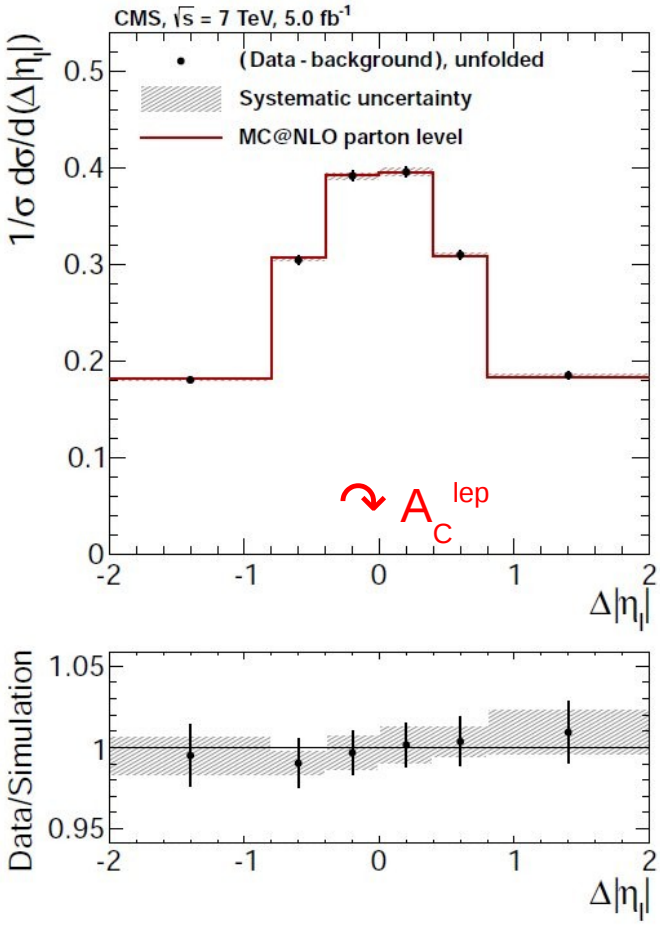
- Asymmetries based on decay leptons or fully reconstructed top quarks "harder" "easier"



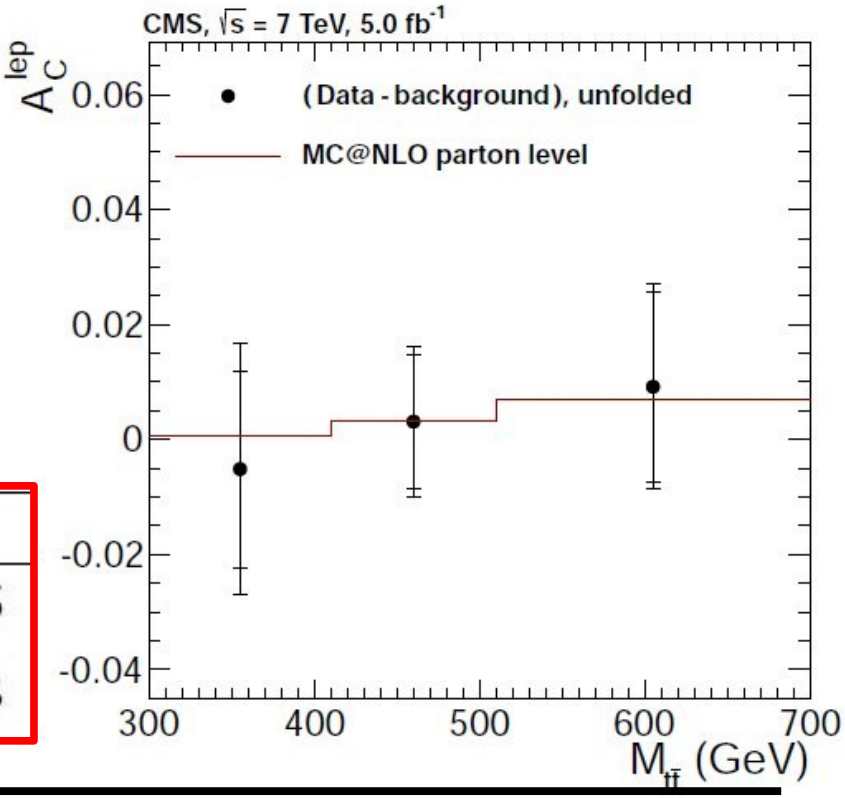
# Charge asymmetries

JHEP 04 (2014) 191




- Dilepton, ≥ 2 jets & ≥ 1 *b*-tags
- Top reconstruction via "Analytical Matrix Weighting Technique"
- Kinematic dependence of $A_C$, e.g. as a function of $m(t\bar{t})$

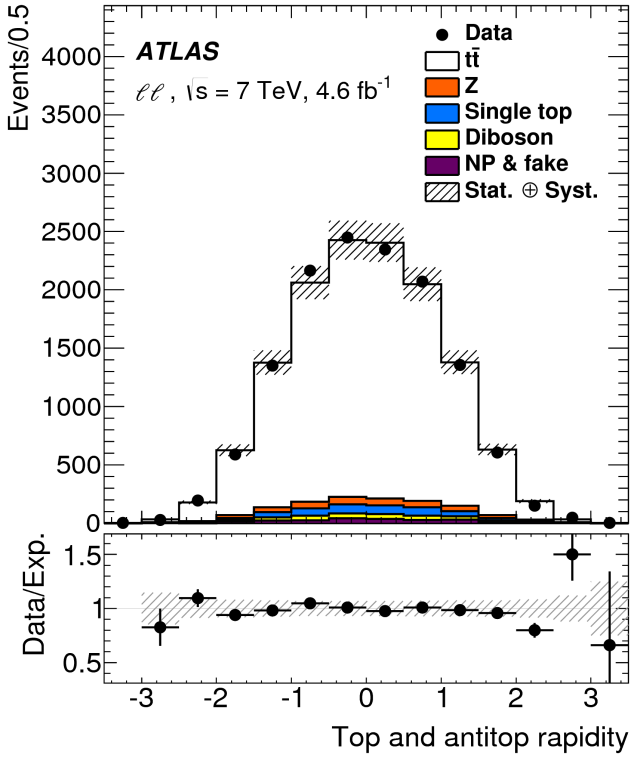


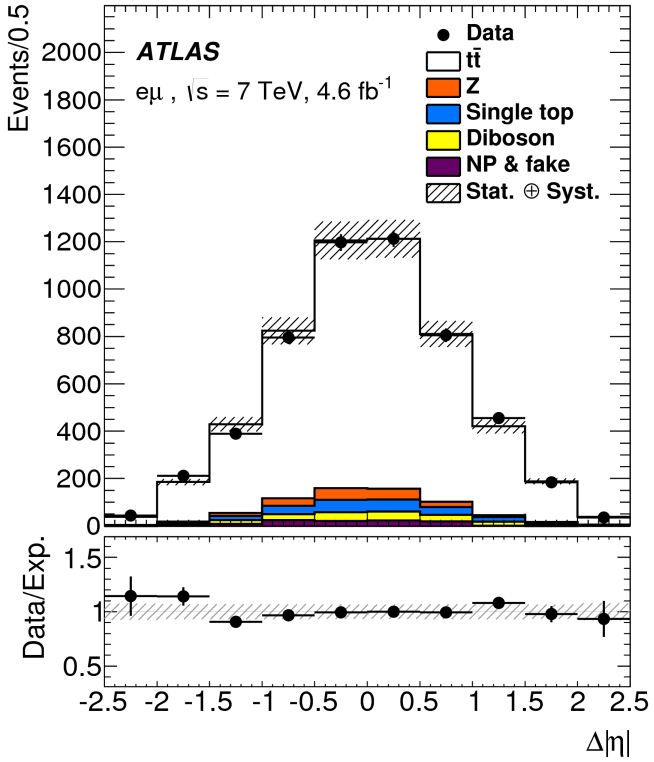

In agreement with SM:

| Variable | Data (unfolded) | NLO theory |
|---|---|---|
| $A_C$ | $-0.010 \pm 0.017 \pm 0.008$ | $0.0123 \pm 0.0005$ |
| $A_C^{lep}$ | $0.009 \pm 0.010 \pm 0.006$ | $0.0070 \pm 0.0003$ |

# Charge asymmetries

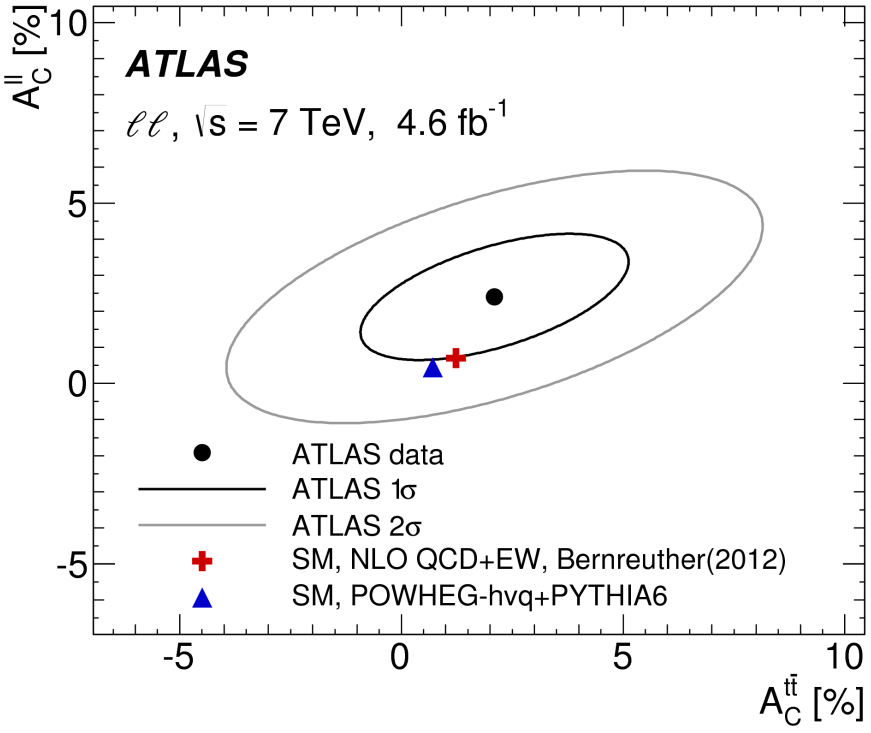
JHEP 04 (2014) 191




- Dilepton, ≥ 2 jets & ≥ 1 *b*-tags
- Top reconstruction via "Neutrino Weighting Technique"
- Individual channels (ee, μμ, eμ) are combined

→ Measure top and lepton based asymmetry




In agreement with SM:

$A_C^{ll} = 0.024 \pm 0.015\ (\text{stat.}) \pm 0.009\ (\text{syst.})$

$A_C^{t\bar{t}} = 0.021 \pm 0.025\ (\text{stat.}) \pm 0.017\ (\text{syst.})$

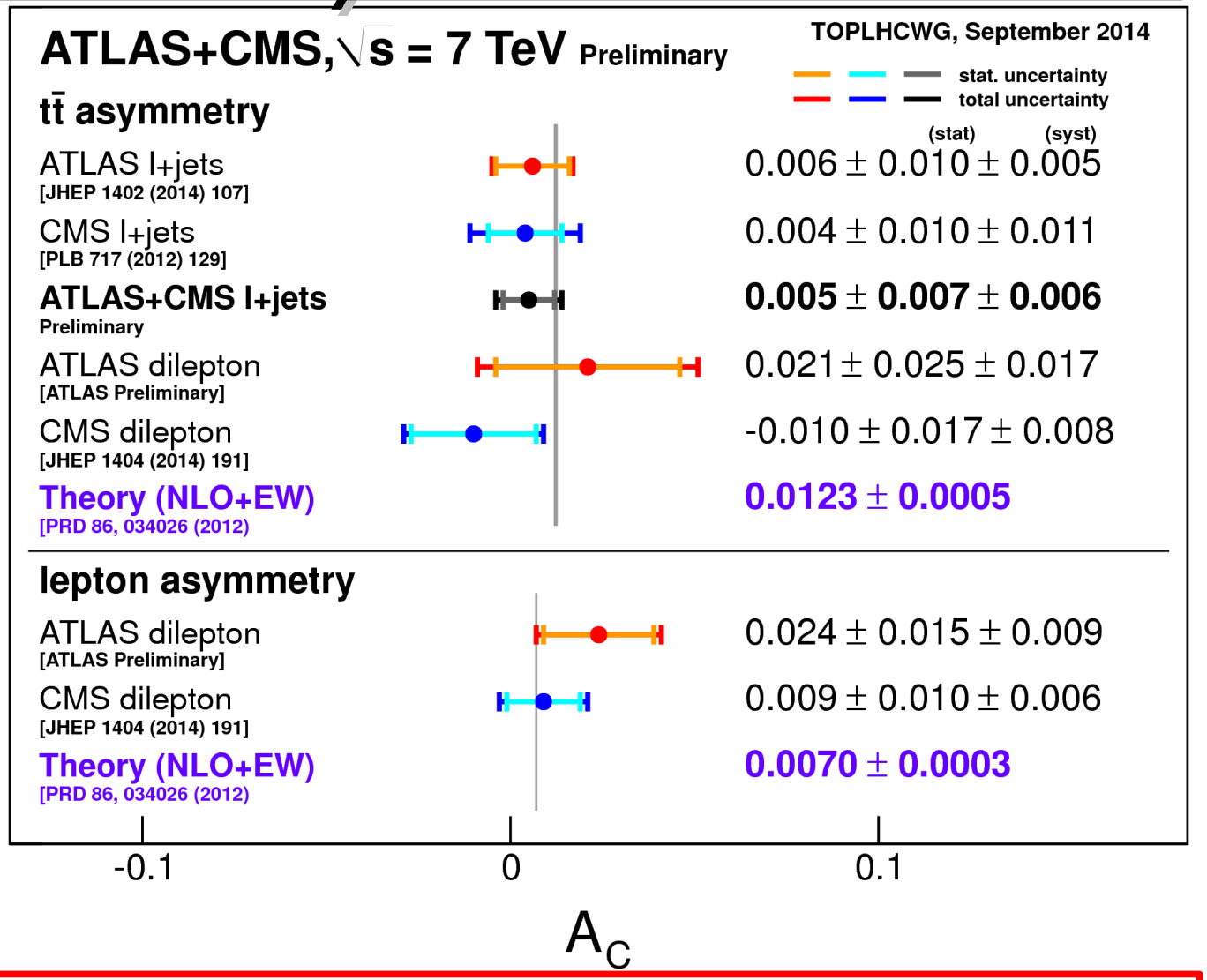
# Top quark asymmetries

Summary of the current Situation:

CMS PAS TOP-14-006

ATLAS-CONF-2014-012

- Experiment: Dominated by statistical uncertainties & signal model dominates systematic unc's
- Theory: Need QCD predictions at NNLO

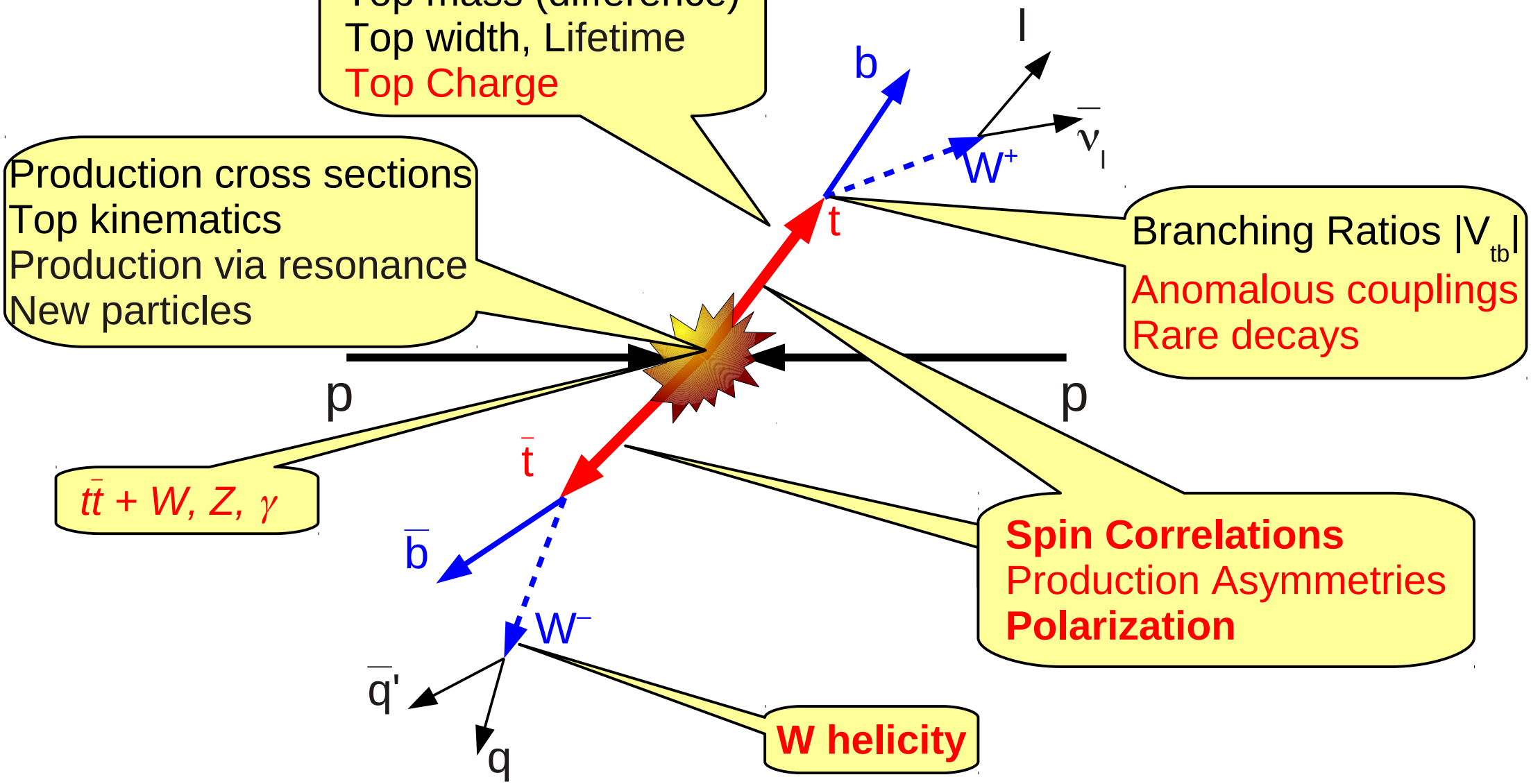



→
- All measurements are (so far) in agreement with SM
- At increased √s expect to observe SM asymmetries
  - Larger gg fraction reduces them → improved methods, e.g. [arxiv:1309.2889]

# Content

Top mass (difference)
Top width, Lifetime
Top Charge

Production cross sections
Top kinematics
Production via resonance
New particles




Branching Ratios $|V_{tb}|$
Anomalous couplings
Rare decays

$t\bar{t} + W, Z, \gamma$

**Spin Correlations**
Production Asymmetries
**Polarization**

**W helicity**

**→ Selection of results, focus on most recent and/or precise results**

# Top quark polarization

- In $t\bar{t}$ production: New physics polarizes top quarks
- Polarization introduced by CP conserving or violating process:

→ $\alpha_l P_{CPC} = -0.035 \pm 0.014\ (\text{stat.}) \pm 0.037\ (\text{syst.})$

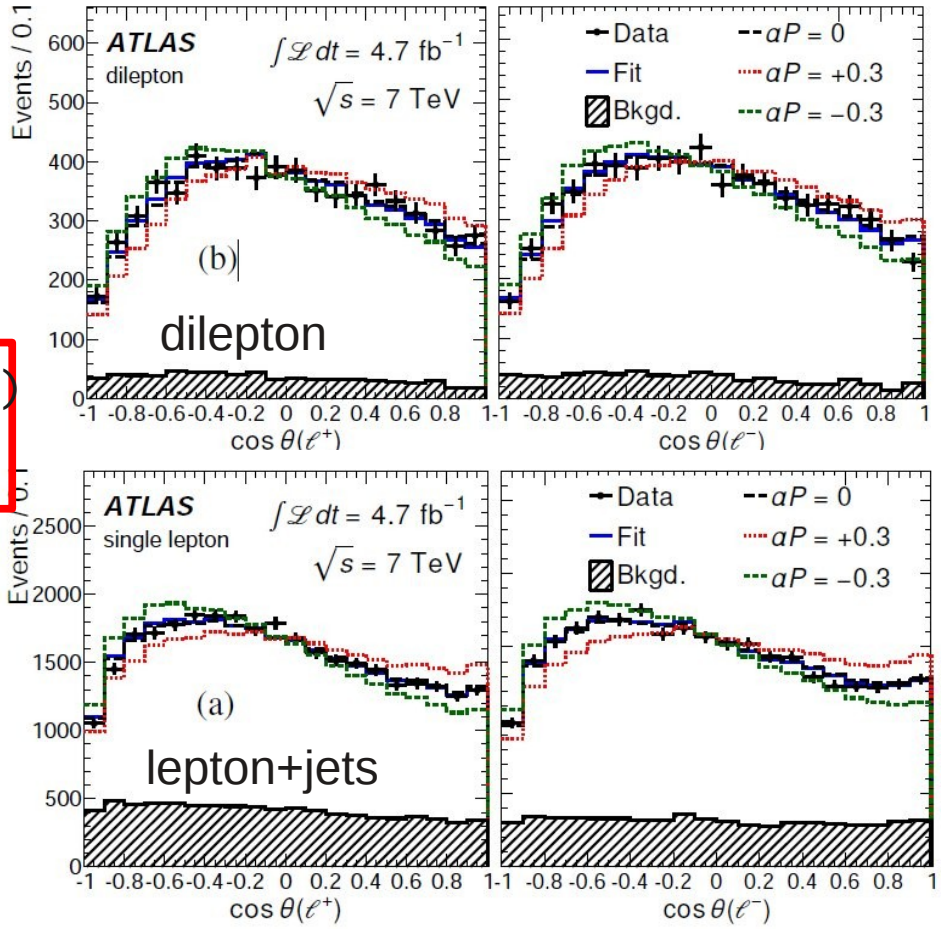
$\alpha_l P_{CPV} = 0.020 \pm 0.016\ (\text{stat.}) \pm {}^{0.013}_{0.017}\ (\text{syst.})$

$\alpha_l$: Spin analyzing power, $P_{CPX:}$ top quark polarization

PRL 111, 232002 (2013)

- Systematic uncertainties dominated by: jet reconstruction & signal model
- Good agreement with SM (negligible polarization), also seen by:→ CMS: PRL 112 (2014) 182001

→ D0: PRD 87, 011103(R) (2013)



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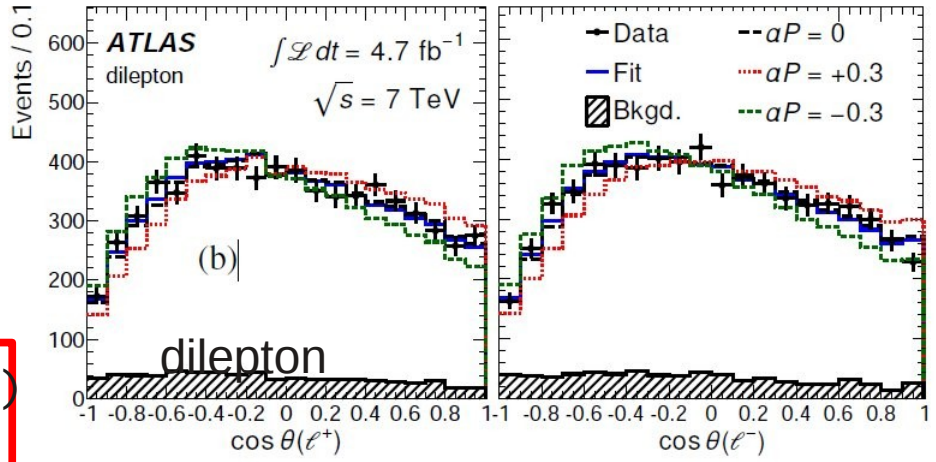
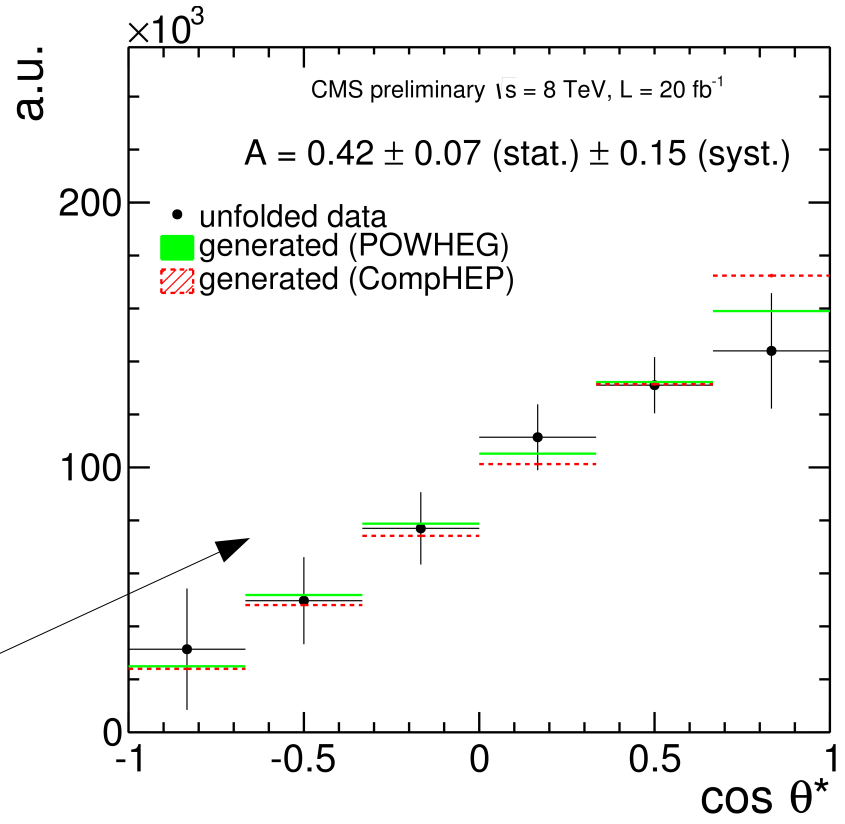



- Good agreement with SM (negligible polarization), also seen by:→ CMS: PRL 112 (2014) 182001
  → D0: PRD 87, 011103(R) (2013)

- In single top production, measure polarized top quarks as expected

→ $P_t = 0.82 \pm 0.12\ (\text{stat.}) \pm 0.32\ (\text{syst.})$

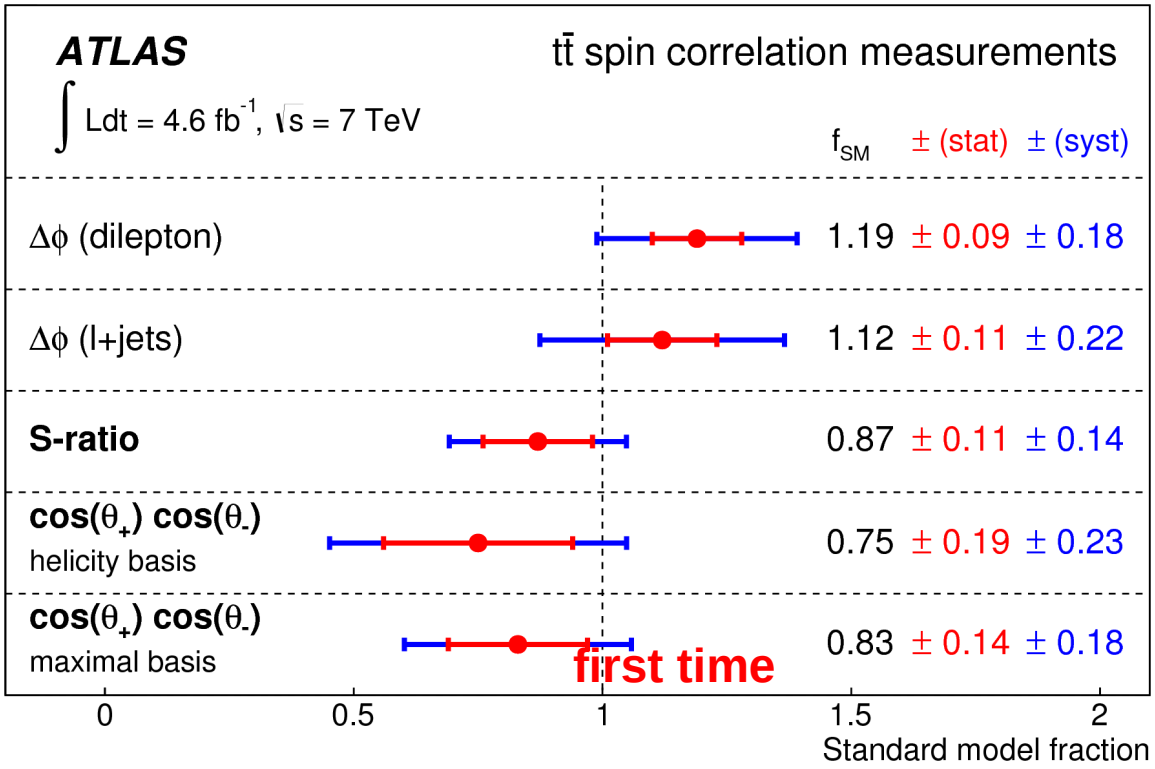
CMS-PAS-TOP-13-001

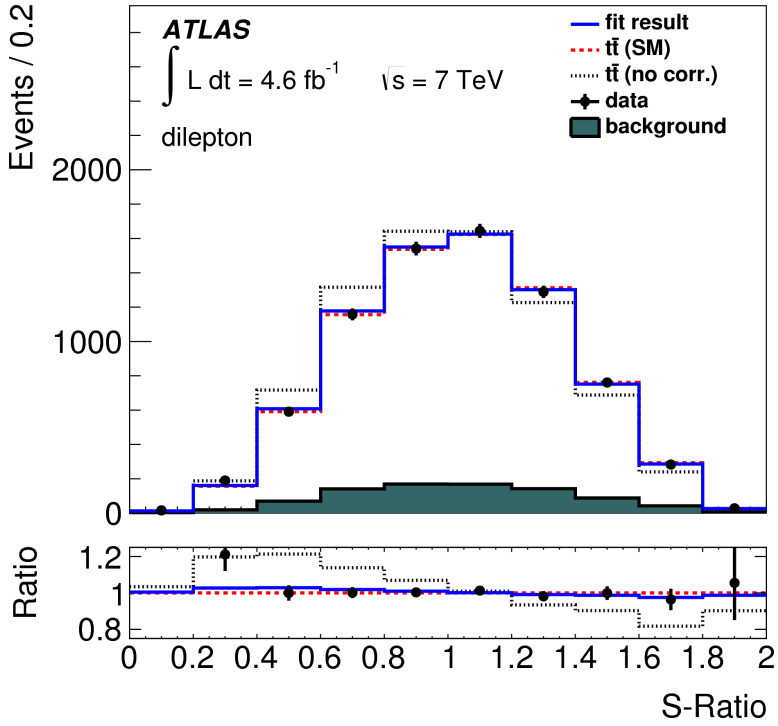


# Top quark spin correlations

- Top quark spins expected to be correlated in SM
- Reconstruction based on leptons
  - → Dilepton decay channel, ≥ 2 jets
  - → L+jets decay channel, ≥ 4 jets
    - For the first time use a simultaneous fit to azimuthal angles $\Delta\varphi(l,d)$ & $\Delta\varphi(l,b)$
- Dominated by: hadronization uncertainties (ATLAS)

PRD 90 112016 (2014)



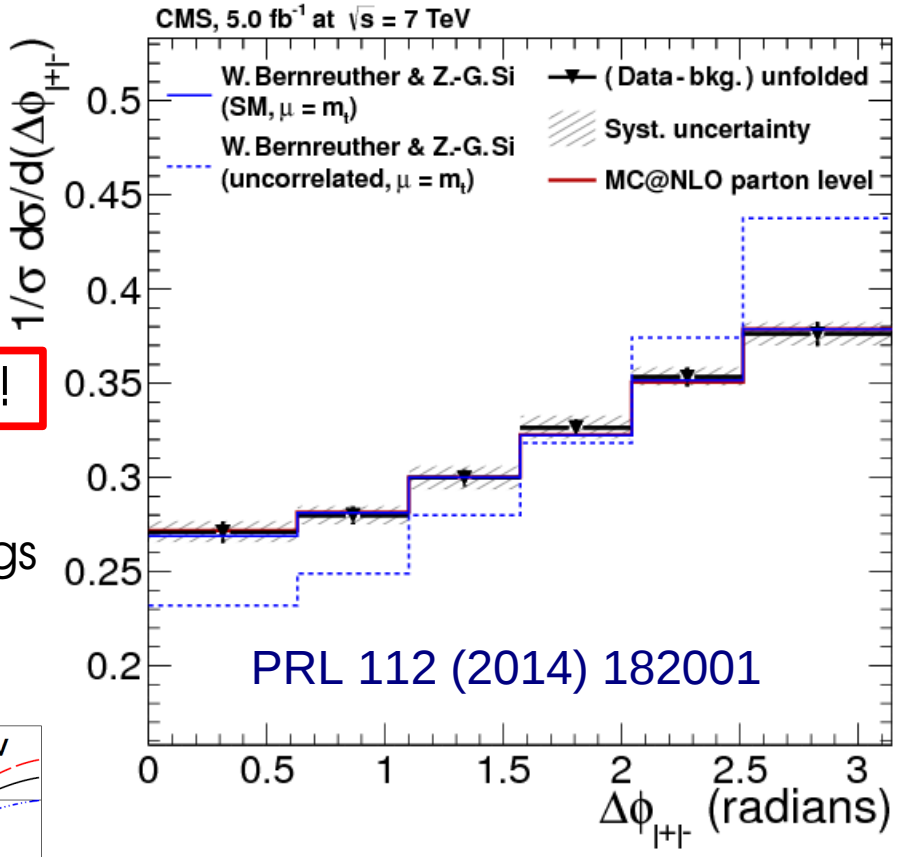




→ Results agree with NLO QCD: Spins correlated!

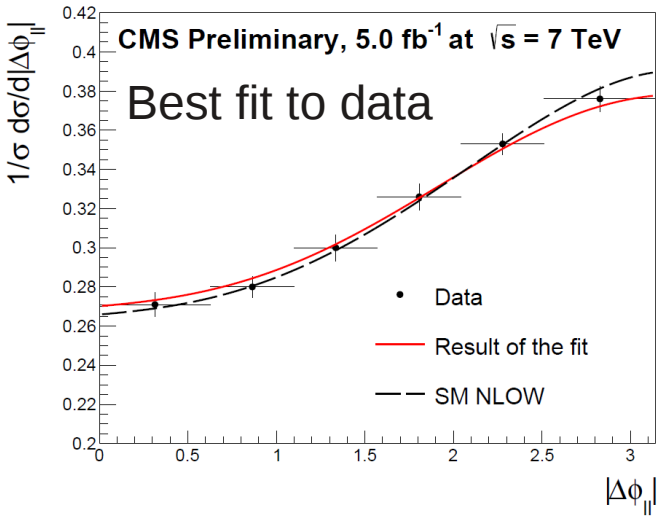
# Top quark spin correlations

- Top quark spins expected to be correlated in SM
- Reconstruction based on leptons
  → Dilepton decay channel, ≥ 2 jets
- Unfold to parton level by reg. Unfolding
- Dominated by: Unfolding & top $p_T$ reweighting

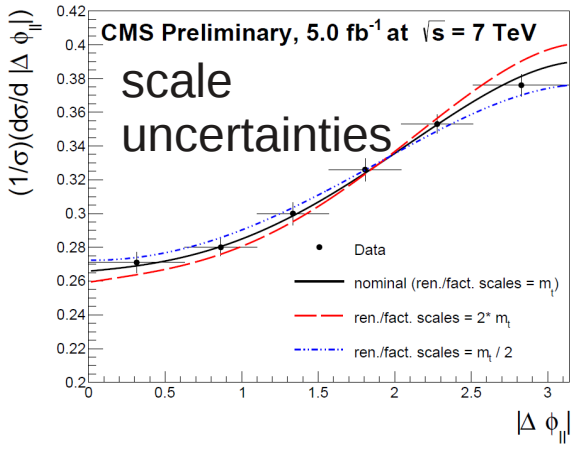
→ Results agree with NLO QCD: Spins correlated!




- Search for top chromomagnetic anomalous couplings using differential cross section distribution




CMS PAS-TOP-14-005



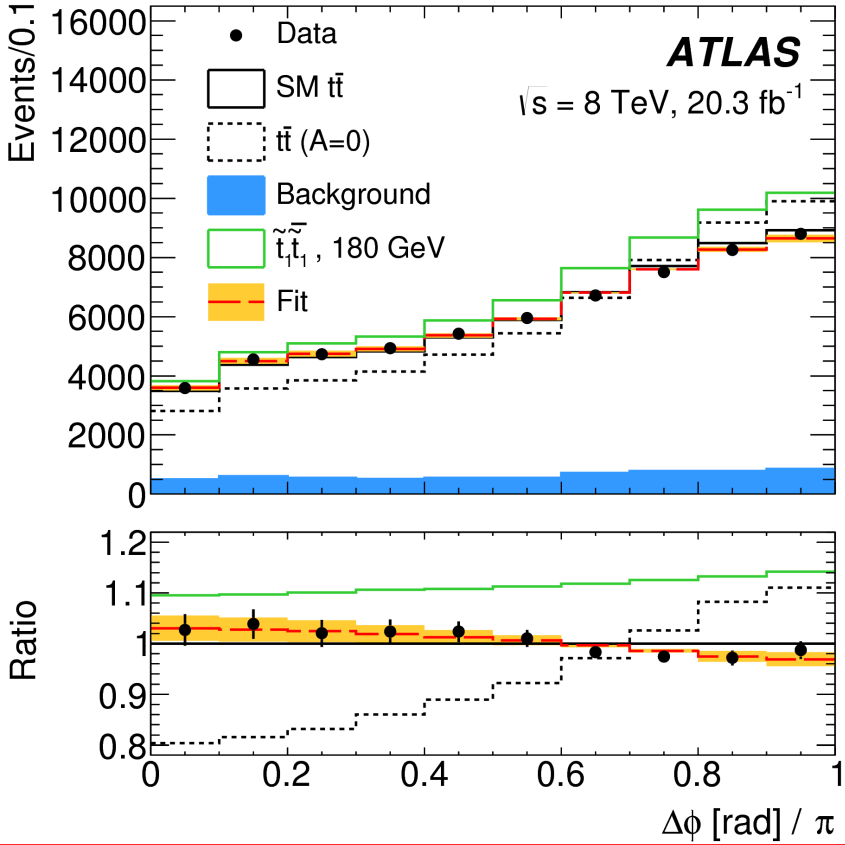

Limits on the chromomagnetic dipole moment $Re(\mu_t)$

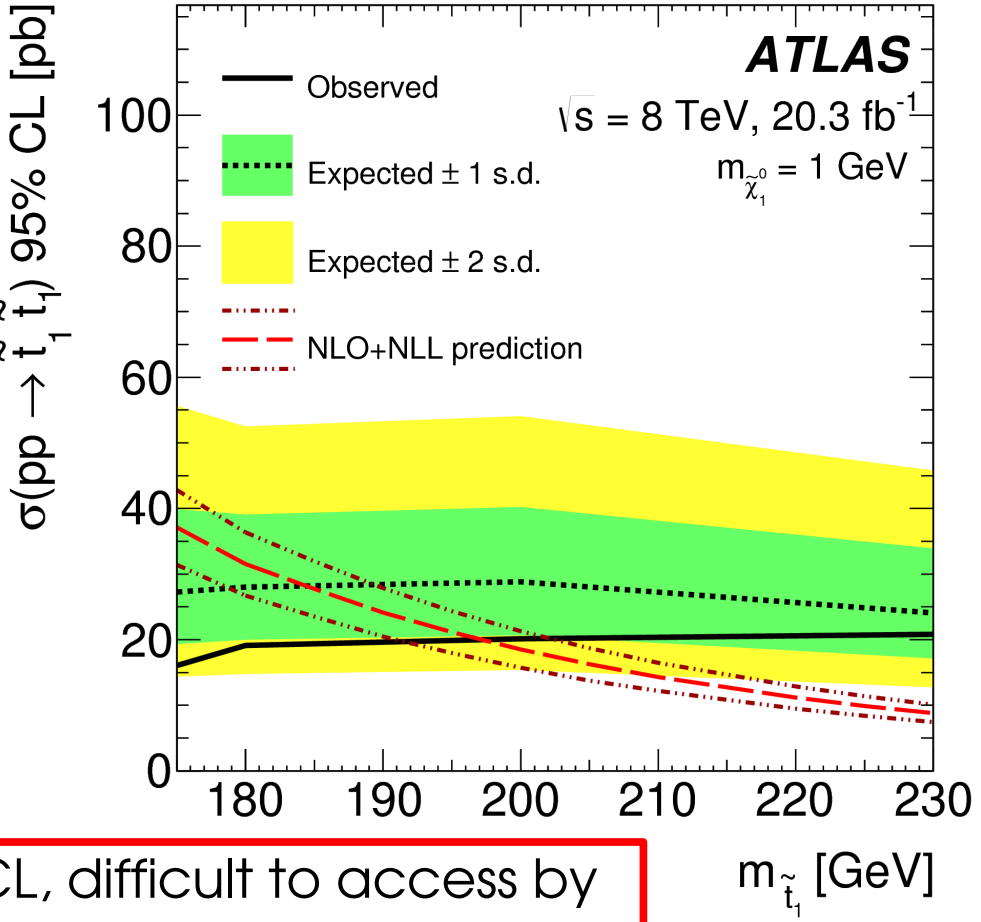
$Re(\mu_t) = 0.037 \pm 0.041$ (tot.)

$-0.043 < Re(\mu_t) < 0.117$ at 95% CL

# Top quark spin correlations

- High precision SM measurements, more and more important in Run II
- Access top squarks (MSSM: 100% $t \to \tilde{t}\chi^0$) of similar mass as $m_t$
- Uncertainties dominated by: signal model (Hadronization and ISR/FSR)



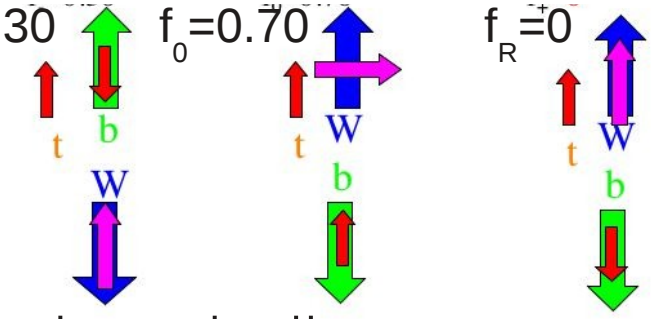




Exclusion between $m_t$ and 191 GeV at 95% CL, difficult to access by "standard" searches PRL 114, 142001 (2015)

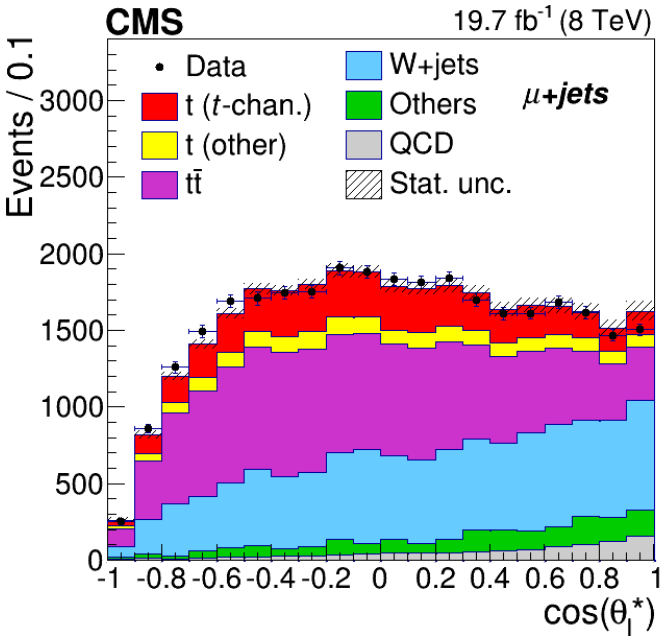
# W helicity in single top production

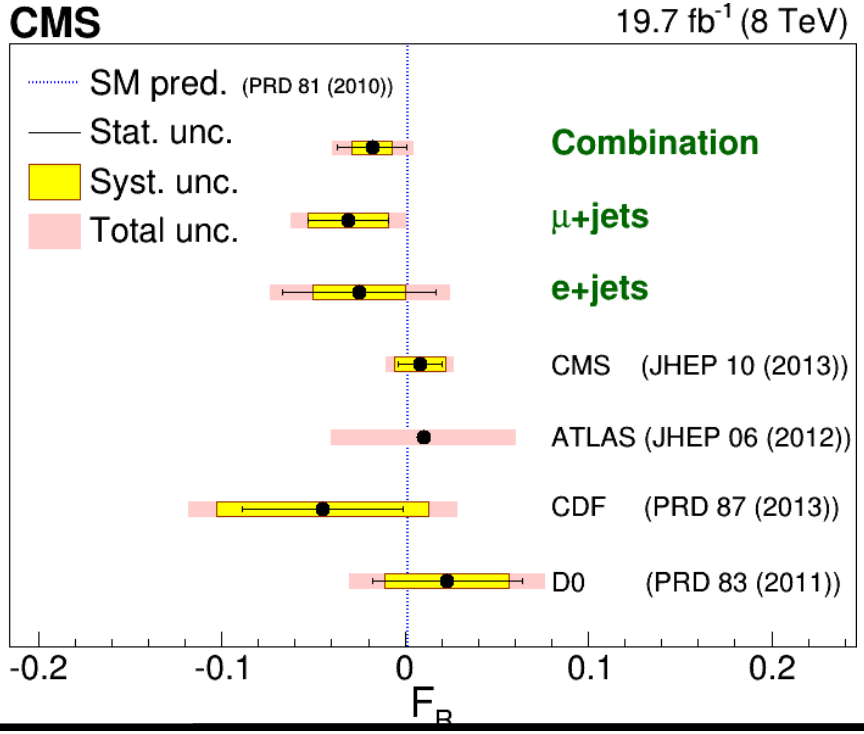
JHEP 01 (2015) 053

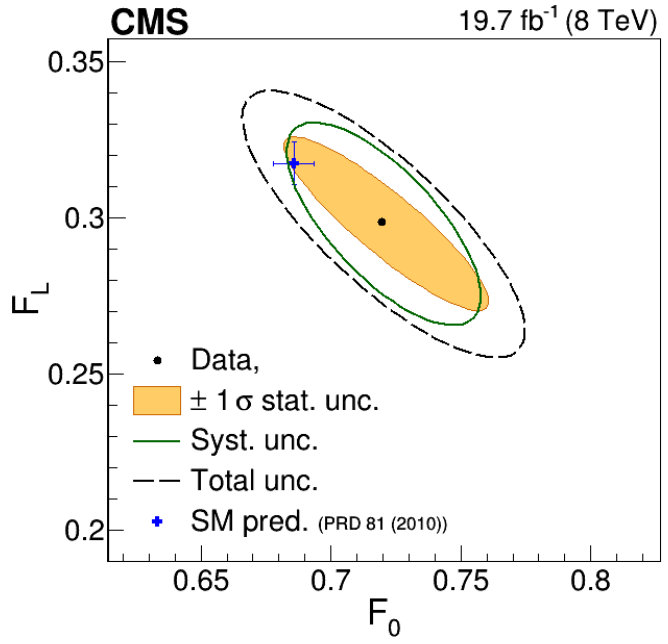
- W helicity in SM: $f_L$=0.30 $f_0$=0.70 $f_R$=0




- Complements results in pair production
- Similar precision but <u>orthogonal</u> systematic uncertainties in single top channels
  - Signal model & template statistics



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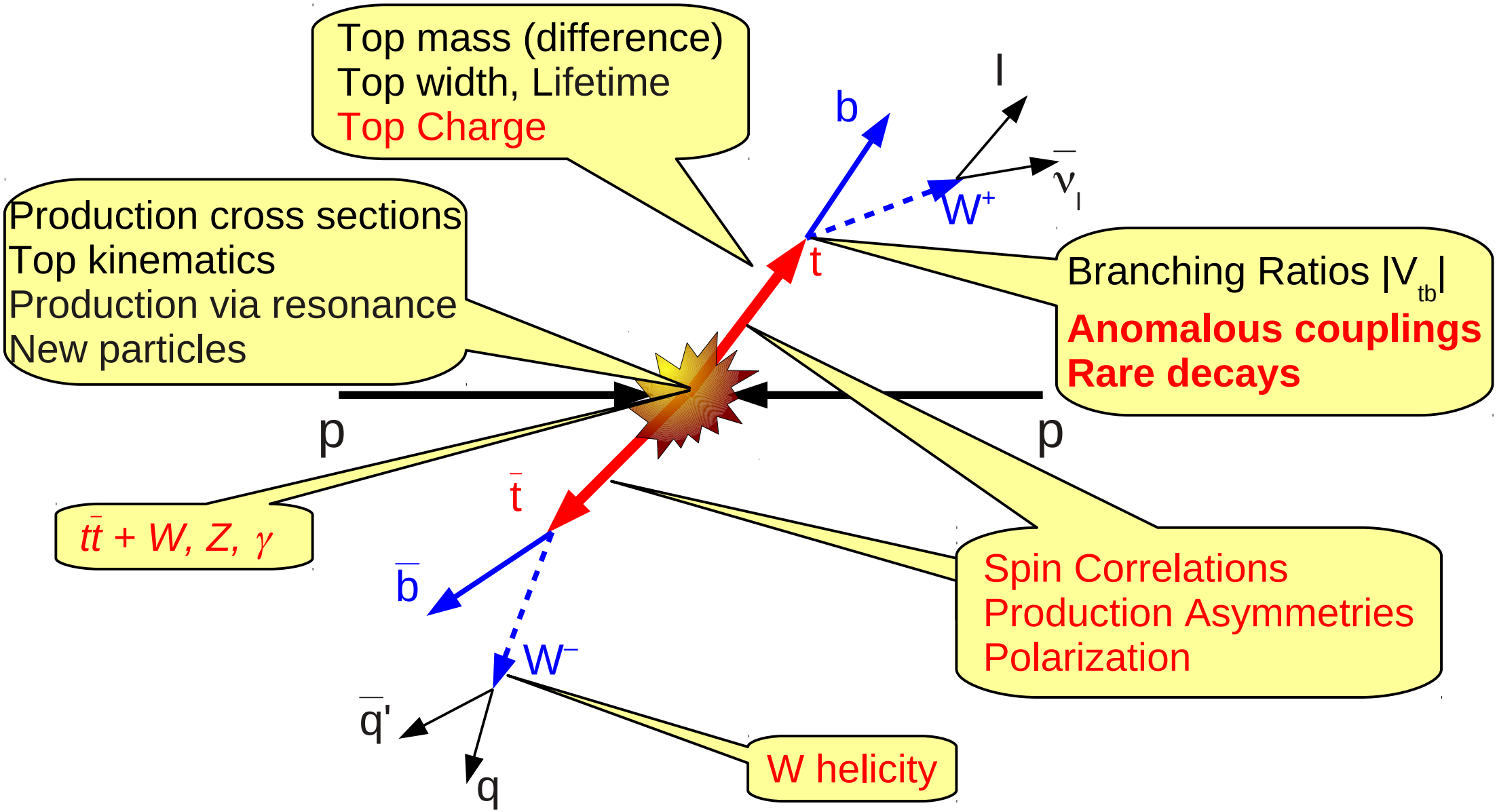



**→ Selection of results, focus on most recent and/or precise results**

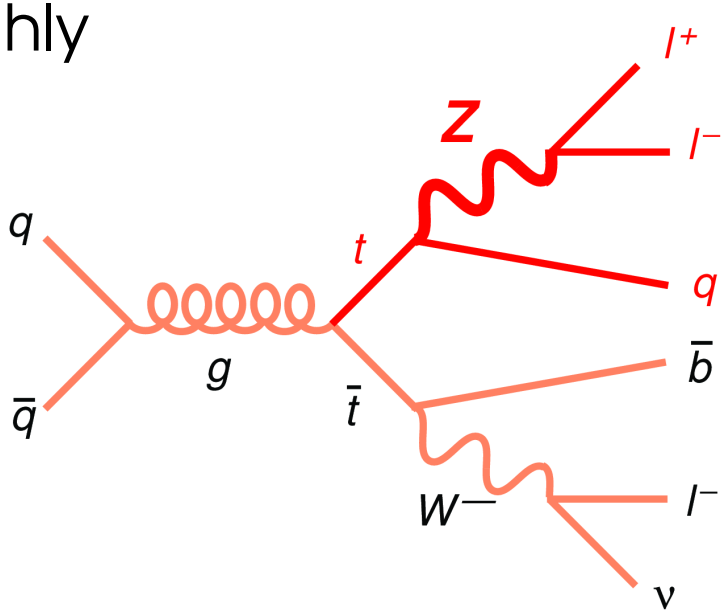
# Top quark: FCNC

CMS PAS-TOP-12-037
CMS-PAS-TOP-14-003

- Flavor Changing Neutral Currents are highly suppressed in SM, but enhancement in many models of new physics
- Search for FCNC involving Z bosons:

→ $B(t \to ug) < 5.7 \cdot 10^{-5}$ $B(t \to ug) < 3.55 \cdot 10^{-4}$
$B(t \to cg) < 2.7 \cdot 10^{-4}$ $B(t \to cg) < 3.44 \cdot 10^{-3}$

CMS PAS-TOP-12-037

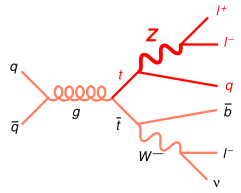


# Top quark: FCNC

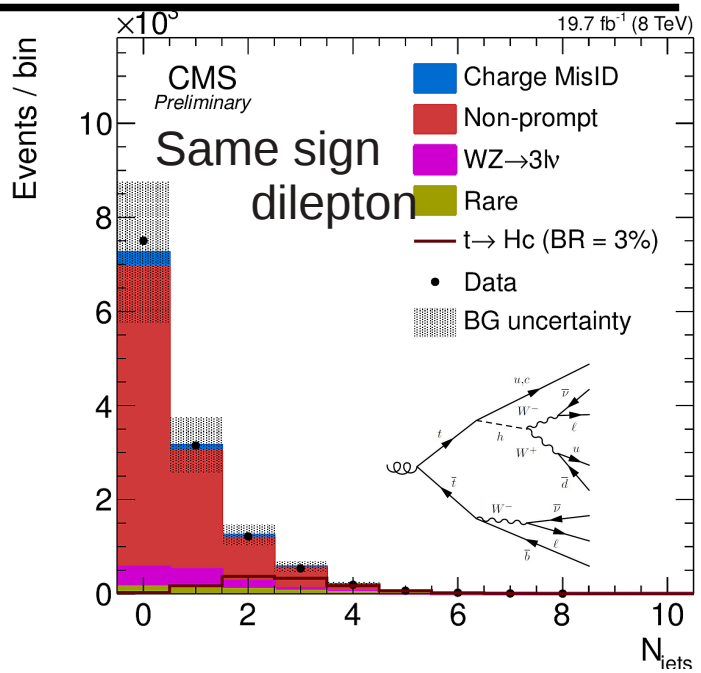
CMS PAS-TOP-13-017

- Flavor Changing Neutral Currents are highly suppressed in SM, but enhancement in many models of new physics
- Search for FCNC involving Z bosons:

→ $B(t \to ug) < 5.7 \cdot 10^{-5}$ $B(t \to ug) < 3.55 \cdot 10^{-4}$
$B(t \to cg) < 2.7 \cdot 10^{-4}$ $B(t \to cg) < 3.44 \cdot 10^{-3}$



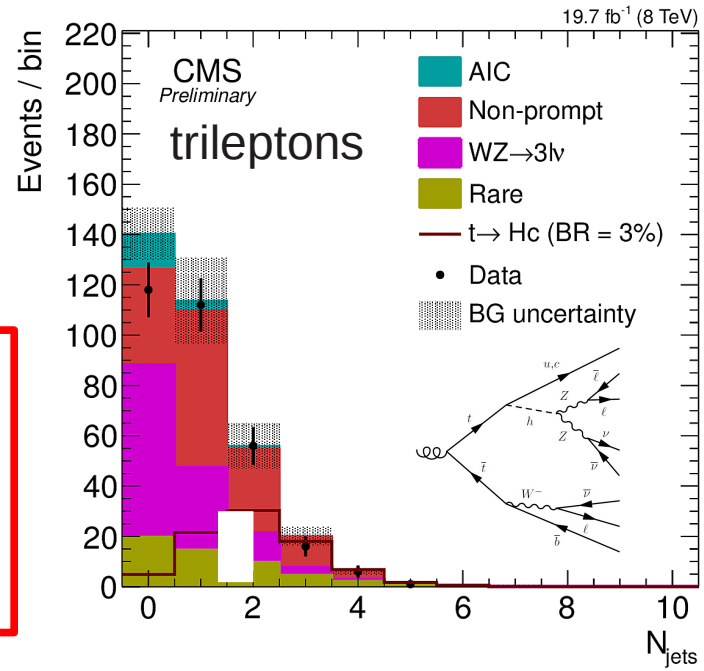

- Search for Higgs boson production in the dilepton (same sign) and trilepton channel
- Systematic uncertainties dominated by:
  Background modeling / cross sections




- Limit on top-charm flavor-violating Higgs Yukawa coupling & upper limits for branching fractions:

→ • $\sqrt{(|\lambda^H_{tc}|^2 + |\lambda^H_{ct}|^2)} < 0.18$ at 95% CL

| | $-\sigma$ | $BR_{exp}(t \to Hc)$ | $+\sigma$ | $BR_{obs}(t \to Hc)$ |
|---|---|---|---|---|
| trilepton | 0.95 | 1.33 | 1.87 | 1.26 |
| same-sign dilepton | 0.68 | 0.93 | 1.26 | 0.99 |
| combined | 0.65 | 0.89 | 1.22 | 0.93 |

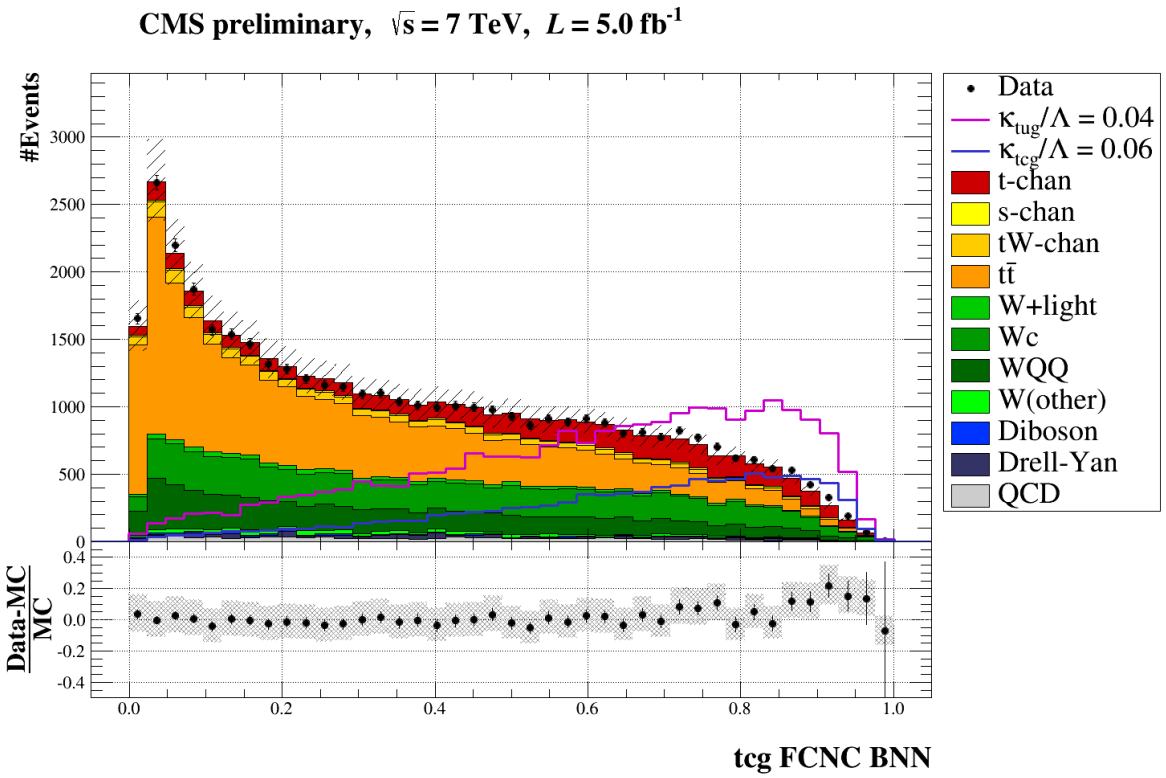


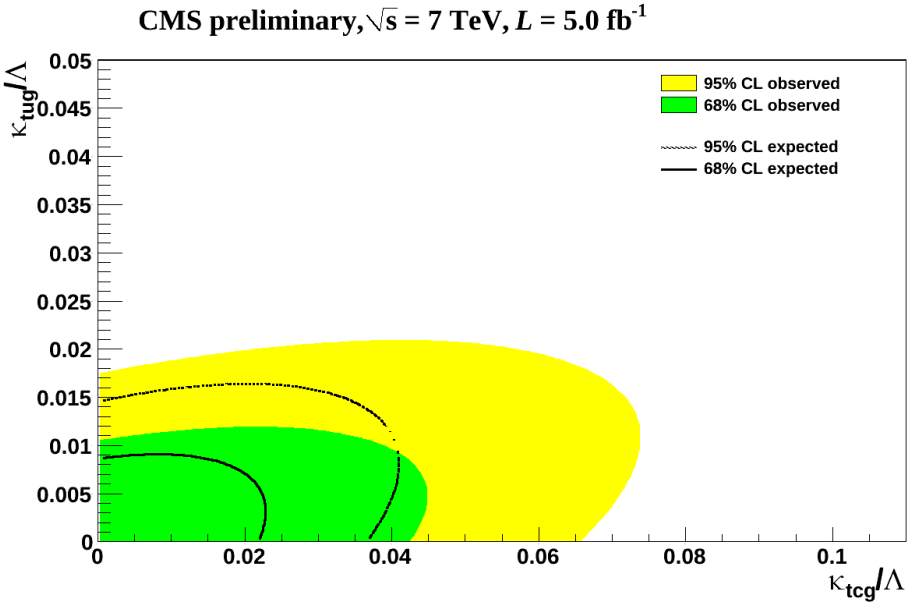
# Top quark: FCNC

- Search in single top production (t-channel)
- MVA technique to: suppress QCD, separate signal & bg, search for *Wtb* couplings & FCNC interactions
- Systematic uncertainties dominated by: Background normalization

CMS-PAS-TOP-14-007

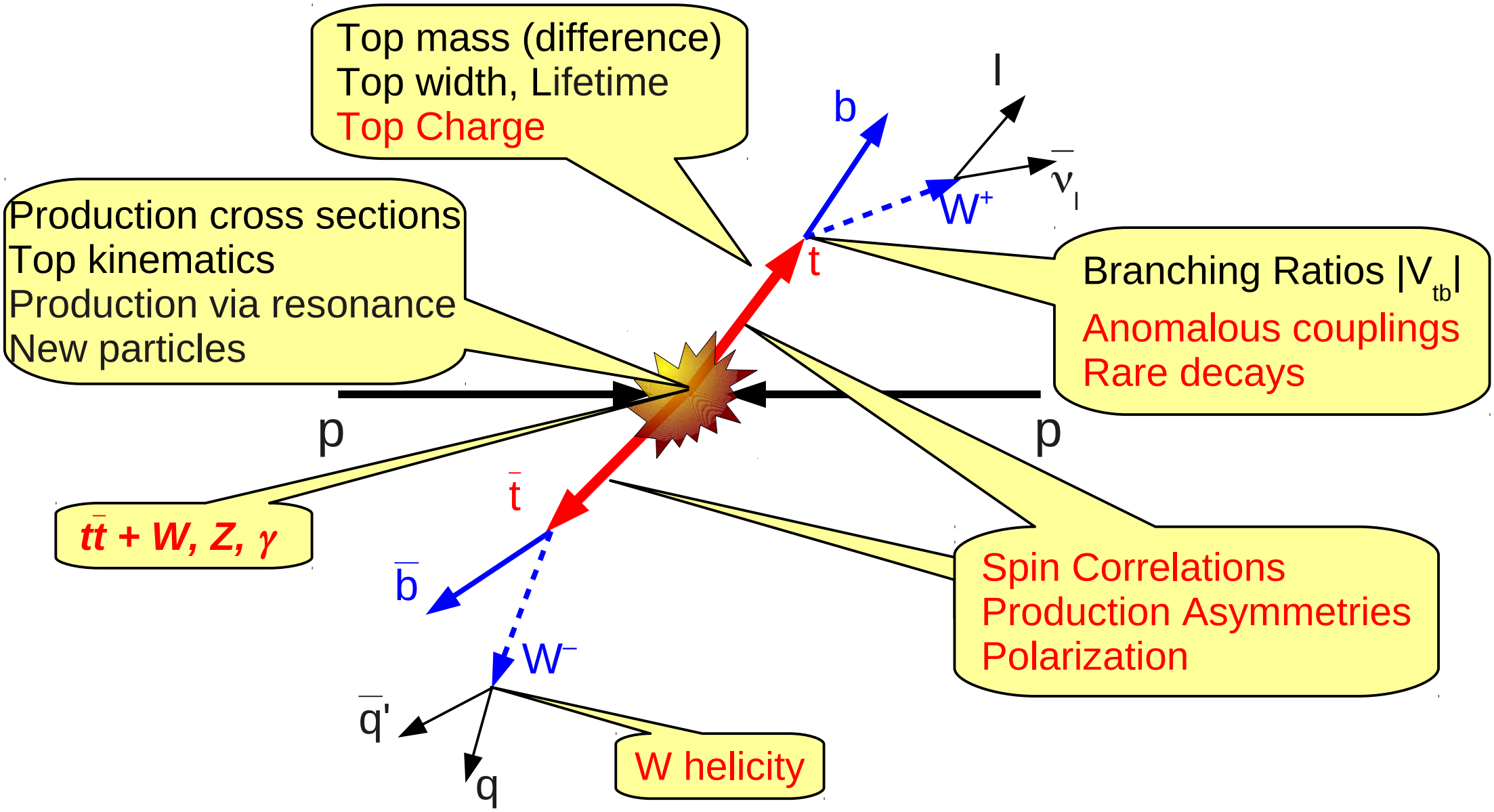
| Process | Uncertainty |
|---|---|
| top-quark pair production | 15% |
| single top, *s*-channel | 15% |
| single top, tW-channel | 13% |
| W+jets, "WQQ" | 100% |
| W+jets, "Wc" | 100% |
| W+jets, "W+light" | 50% |
| W+jets, "WQX (UE)" | 50% |
| QCD (data-driven) | 100% |
| Drell-Yan process | 30% |
| WW, WZ, ZZ | 30% |




(Limits on left & right vector and tensor couplings in backup)

# Content



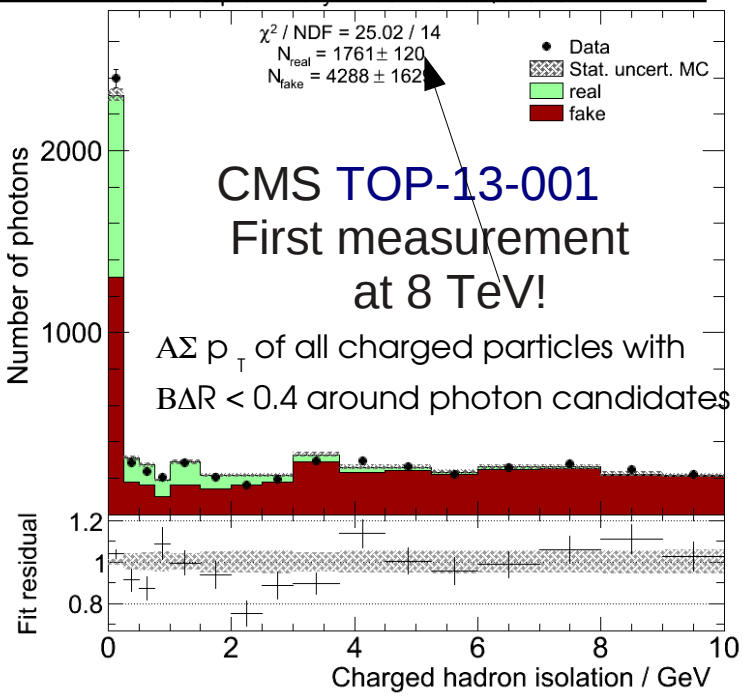

→ **Selection of results, focus on most recent and/or precise results**

# Ttbar + X: W, Z, γ

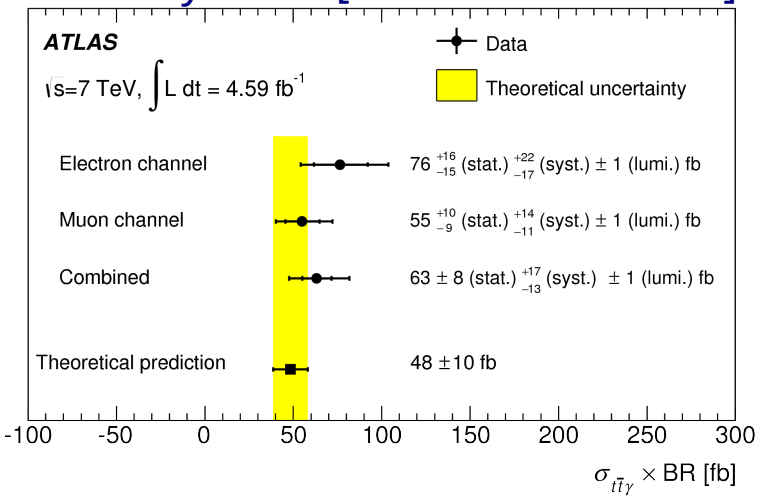
- Tight photon ID requirements and cuts to suppress the bg
- Observation at 7 TeV by ATLAS and first measurement at 8 TeV by CMS

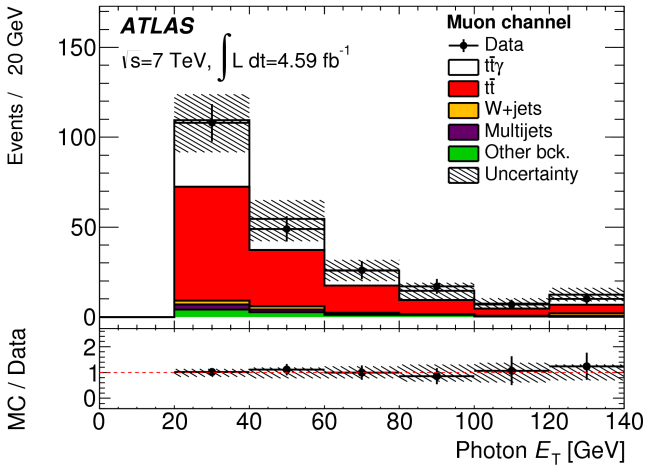
$$R = \sigma_{\bar{t}t+\gamma}/\sigma_{\bar{t}t}$$
$$= (1.07 \pm 0.07(\text{stat.}) \pm 0.27(\text{syst.})) \cdot 10^{-2}$$

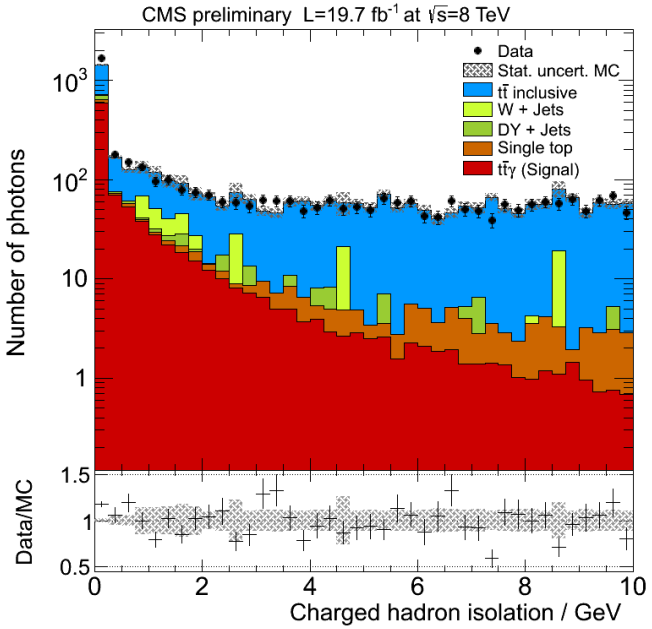
$$\sigma_{t\bar{t}+\gamma} = R \cdot \sigma_{\bar{t}t}^{\text{CMS}}$$
$$= 2.4 \pm 0.2(\text{stat.}) \pm 0.6(\text{syst.})\,\text{pb}$$




Acc. by PRD [arXiv:1502.00586]



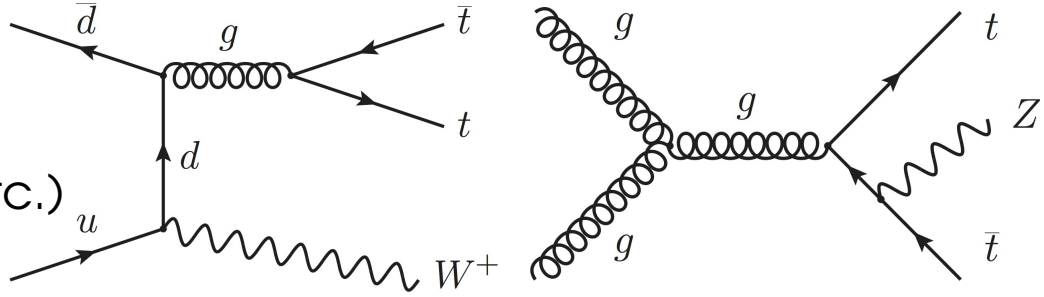



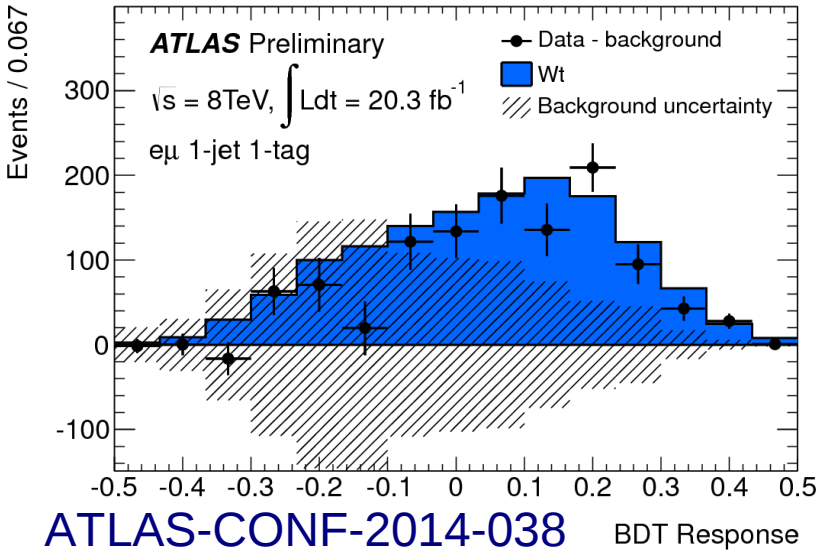




- Dominated by object IDs (jets, photon, btag) and signal model related

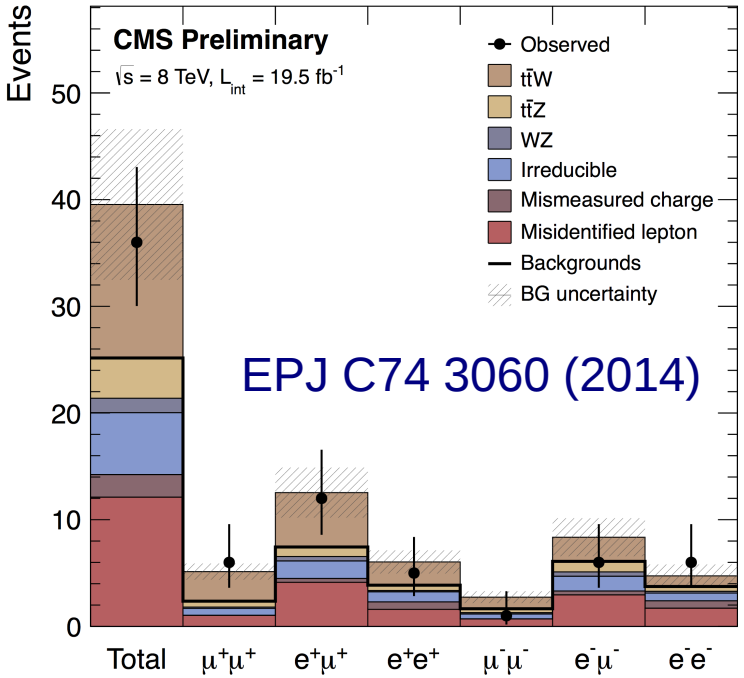
# Ttbar + X: W, Z, γ

- Associated production of *W* and *Z* in the SM (different mechanisms)
- Both experiments use data driven approaches of non-prompt bg
- Exploit full potential → many channels
  (opposite/same sign dilepton, 2/3 leptons, etc.)
- Stringent cuts to reduce bg
  (various cuts on number of jets, b-tags)
- Mostly counting, ATLAS use 7 variables & NN to search for *ttW* and *ttZ* in OS di-l
- Systematic unc's dominated by:
  Lepton ID, signal model

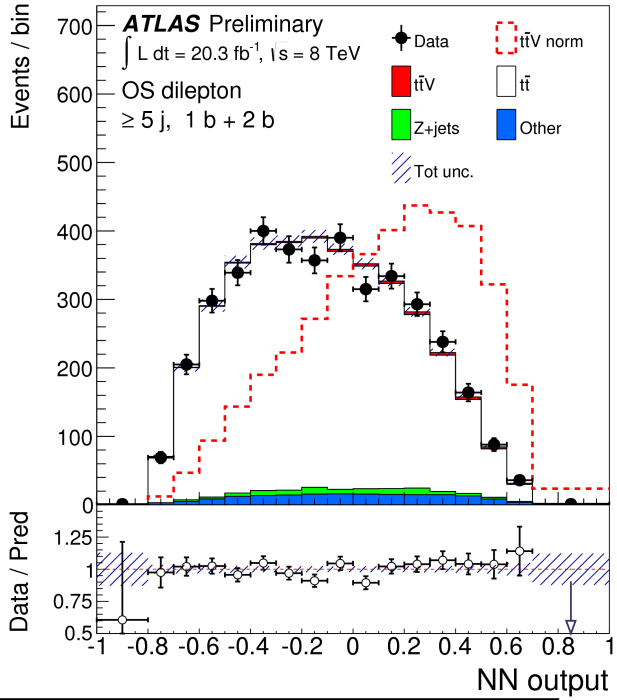



ATLAS-CONF-2014-038

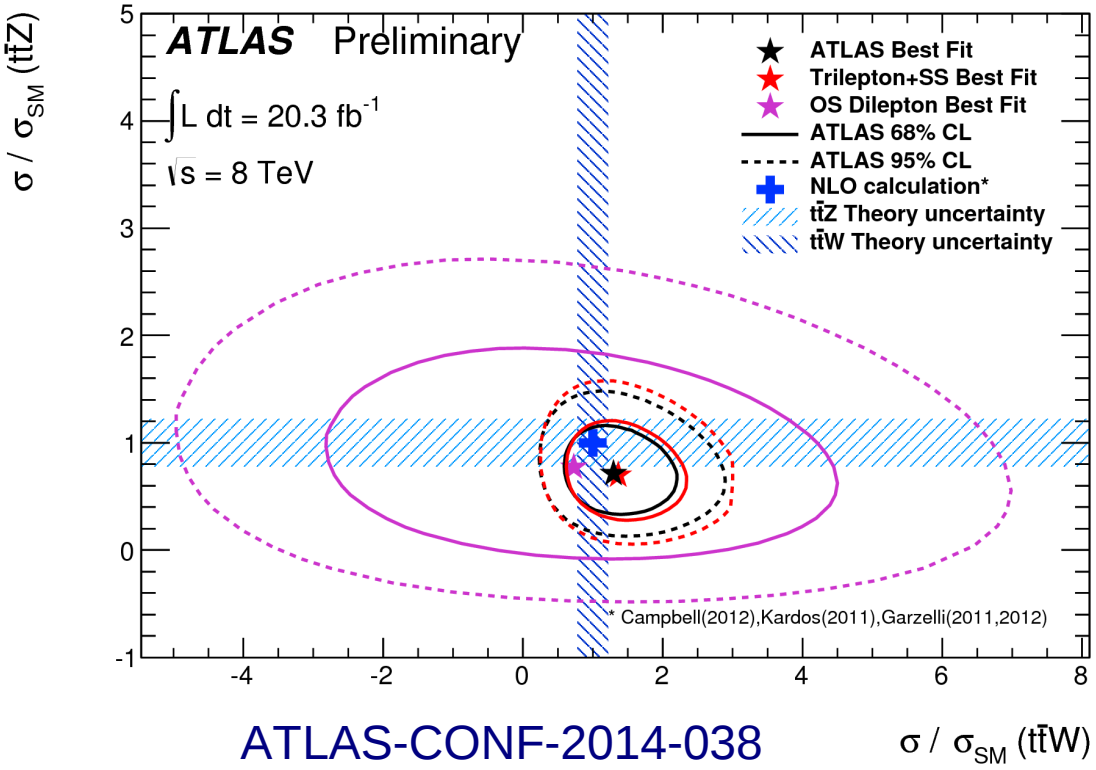



EPJ C74 3060 (2014)



# Ttbar + X: W, Z, γ

- 2D fit of *ttW* and *ttZ* cross sections, dominated by statistical unc's
- SM (NLO): σ(ttZ) = 206 ± 29 fb and σ(ttW) = 203 ± 25 fb

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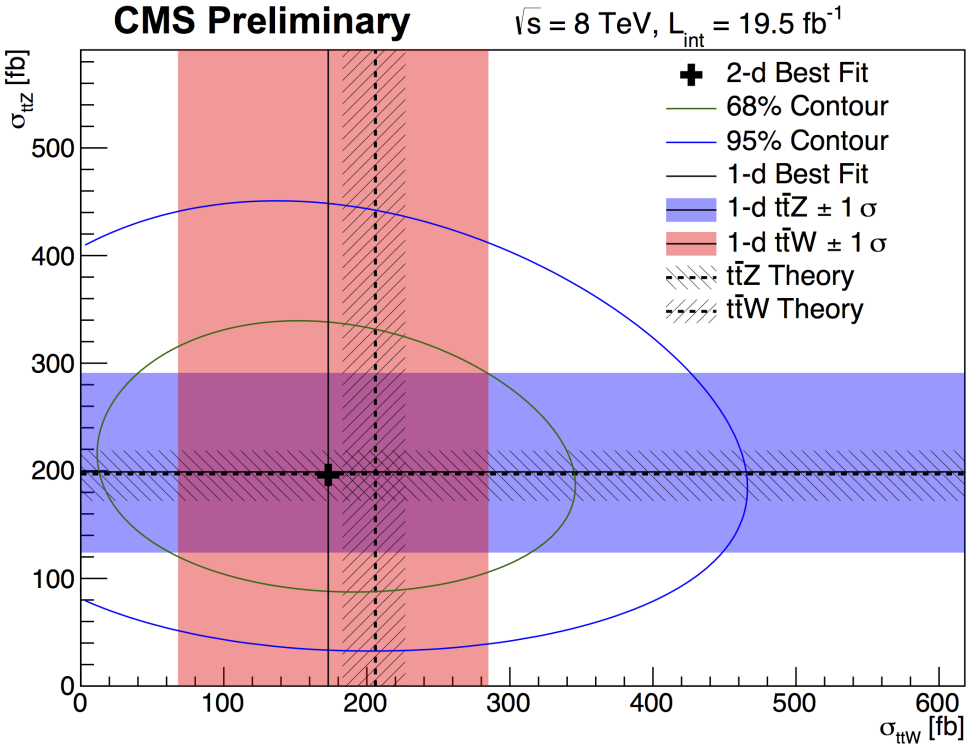



EPJ C74 3060 (2014)

| Process | Cross section | Sign. |
|---|---|---|
| *ttZ* | $150^{+55}_{-50}$ (stat.) ± 21 (syst.) fb | 3.1σ |
| *ttW* | $300^{+120}_{-100}$ (stat.) $^{+70}_{-80}$ (syst.) fb | 3.1σ |

| Process | Cross section | Significance |
|---|---|---|
| $t\bar{t}W$ | $170^{+90}_{-80}(\text{stat.})^{+70}_{-70}(\text{syst.})$ fb | 1.6 $\sigma$ |
| $t\bar{t}Z$ | $200^{+80}_{-70}(\text{stat.})^{+40}_{-30}(\text{syst.})$ fb | 3.1 $\sigma$ |
| $t\bar{t}W + t\bar{t}Z$ | $380^{+100}_{-90}(\text{stat.})^{+80}_{-70}(\text{syst.})$ fb | 3.7 $\sigma$ |

# Conclusions & Outlook

- Remarkable precision: Signal modeling is **the future topic**
- High precision top quark property measurement, also accessible now in **single top quark production** (*t*-channel)

- Results on Asymmetry are not yet completely conclusive...

- **Evidence** for associated production of $W, Z, \gamma$

- No significant deviations seen from SM expectations at LHC Run I: **→ Waiting for next LHC run …**

Only small limited selection of results shown, more information:

ATLAS Top Web pages  CMS Top Web pages

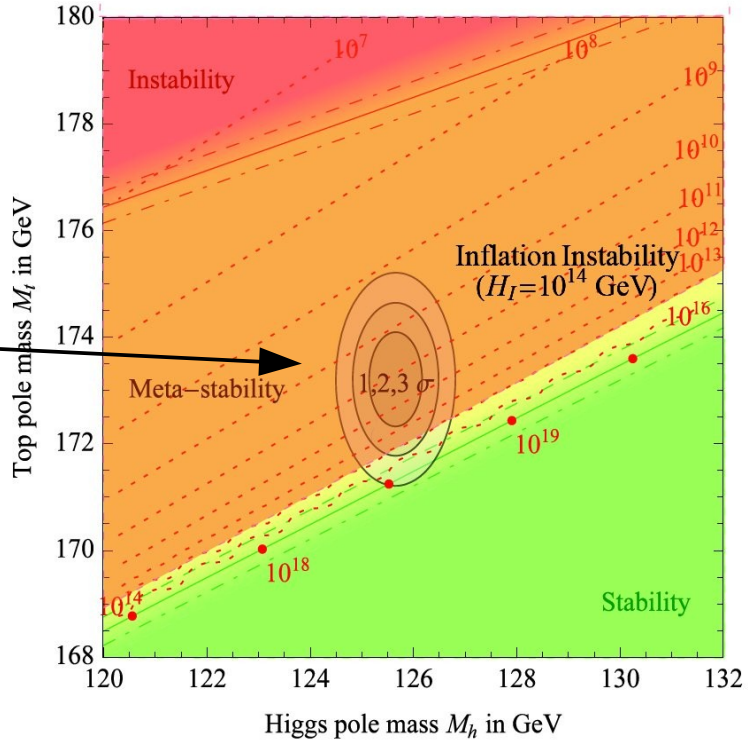
Thank you!

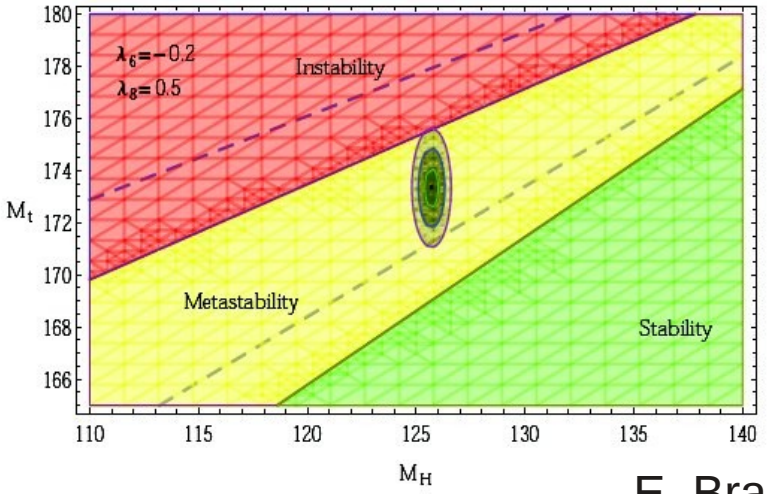
# Backup

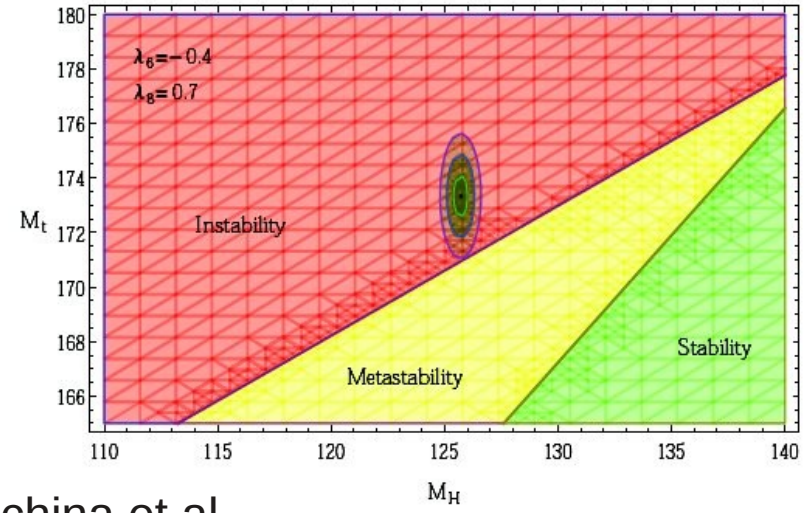
# SM vacuum stability

- With the Higgs discovery the SM can be extrapolated to Planck scale energies
- "Test" the stability of the electroweak vacuum, under assumption of no new physics:
  → meta-stable, life time > $O(10^{80})$ $t_{universe}$

**→ but new physics can change that dramatically**

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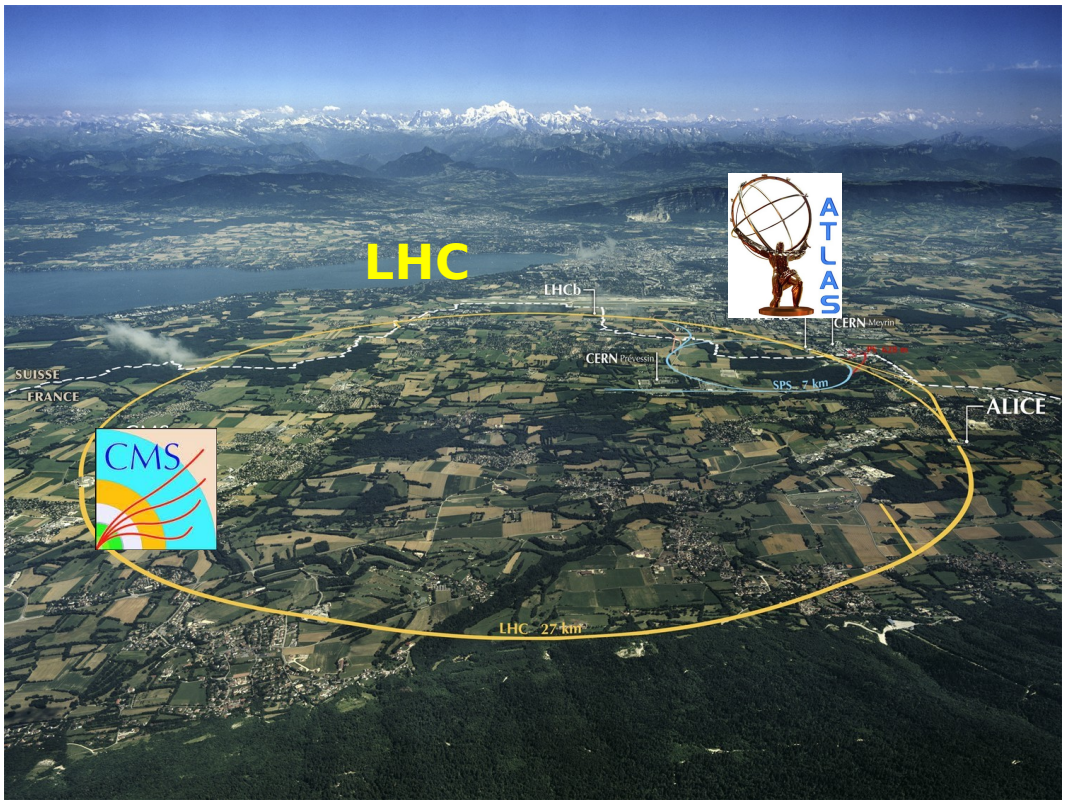
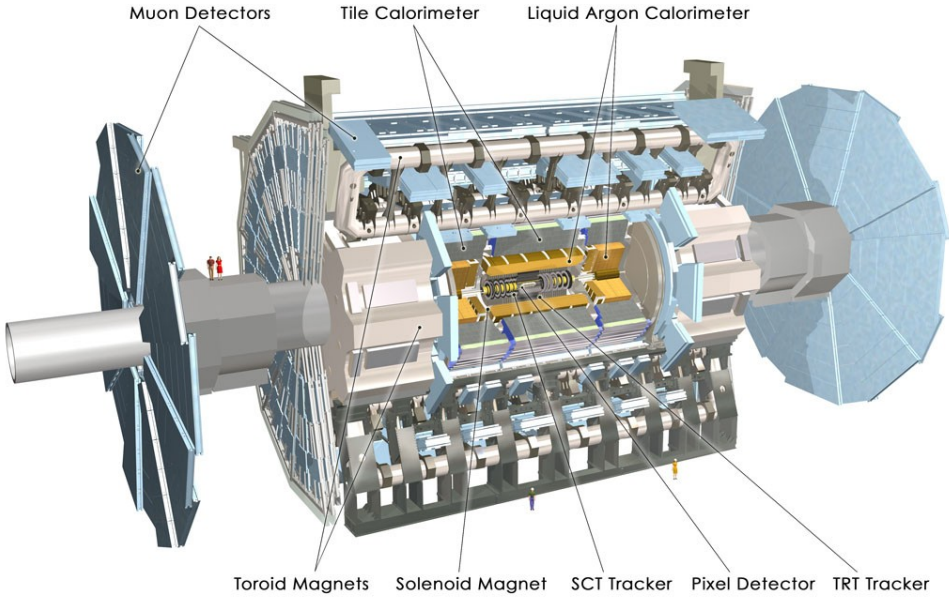
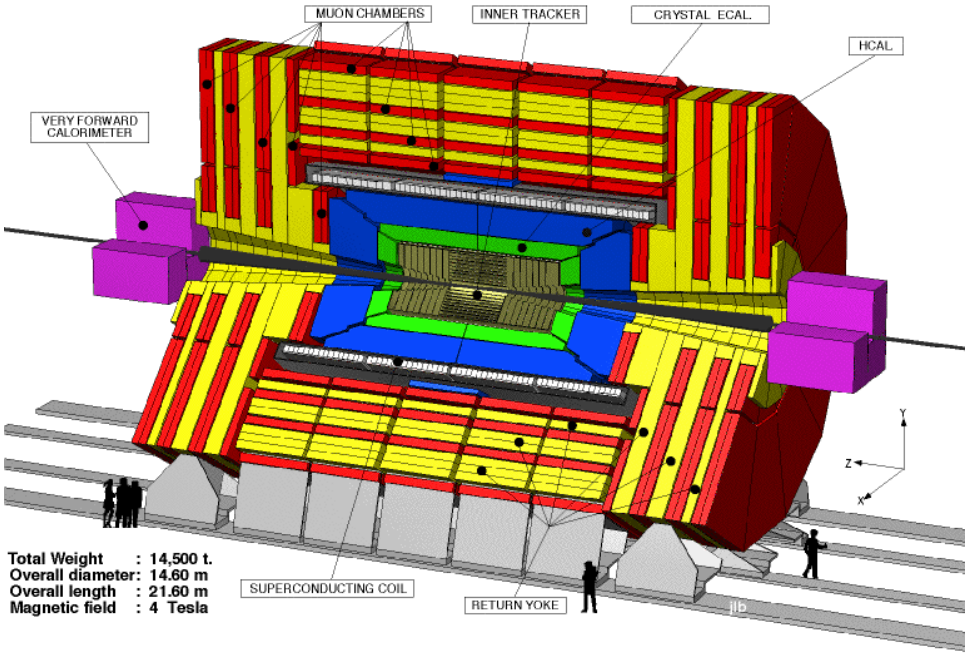
# LHC and detectors


- Peak luminosities: 8 x $10^{33}$ $cm^{-2}s^{-1}$
- ~5 (25) $fb^{-1}$/experiment recorded
- LHC consolidation/upgrades till 2015

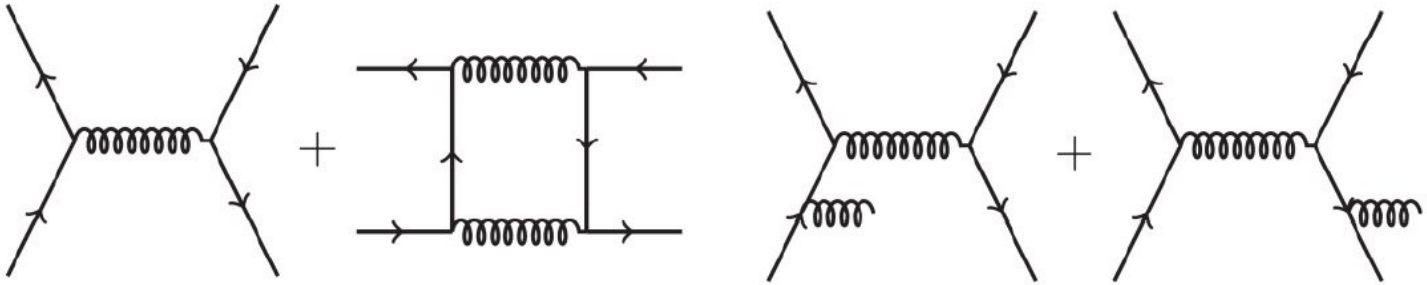


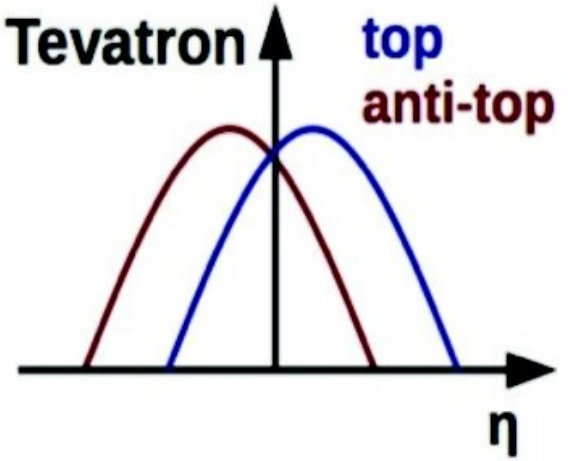
# Top quark asymmetries

- Interference appears at NLO QCD:



Positive asymmetry  Negative asymmetry

→ Only occurs in $q\bar{q}$ initial state; $gg$ is fwd-bwd symmetric

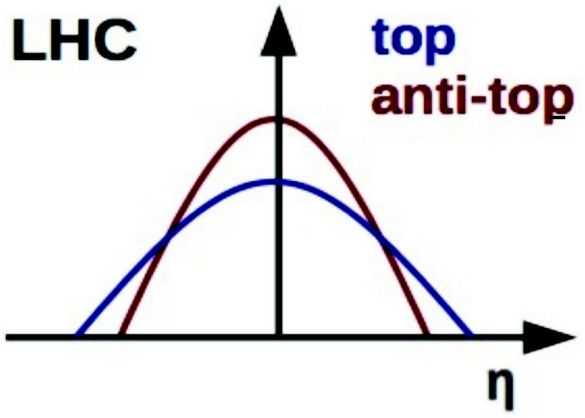



- This is a forward-backward asymmetry at Tevatron
- No valence anti-quarks at LHC → $\bar{t}$ more central

- SM predictions at NLO (QCD+EWK)

→ Tevatron: $\mathbf{A_{FB}}$ **~ 8-9 %** vs. LHC: $\mathbf{A_C}$ **~ 1 %**

(waiting for full NNLO pQCD predictions)




- Experimentally: Asymmetries based on decay leptons or fully reconstructed top quarks

"easier"

"harder"

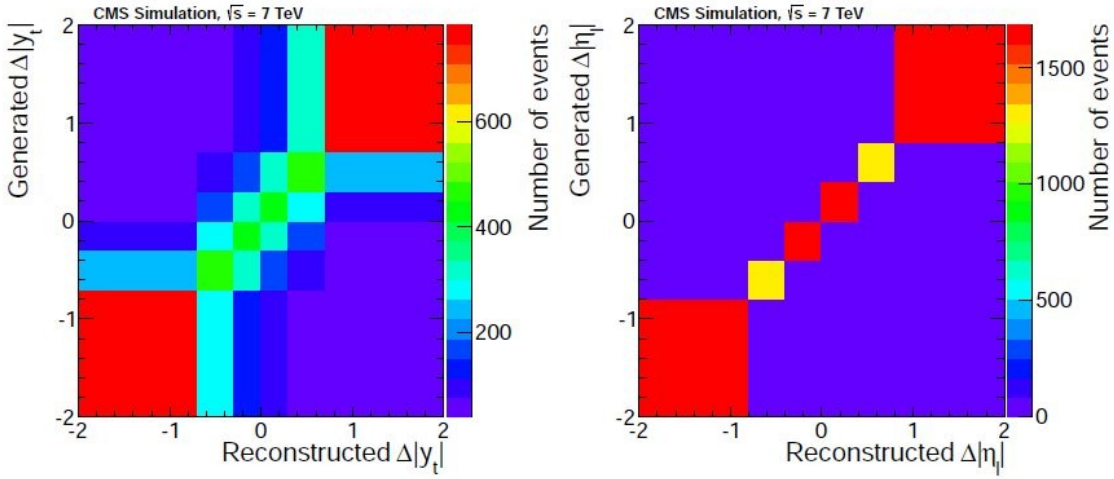
$$A_C = \frac{N(\Delta|y_t| > 0) - N(\Delta|y_t| < 0)}{N(\Delta|y_t| > 0) + N(\Delta|y_t| < 0)}$$

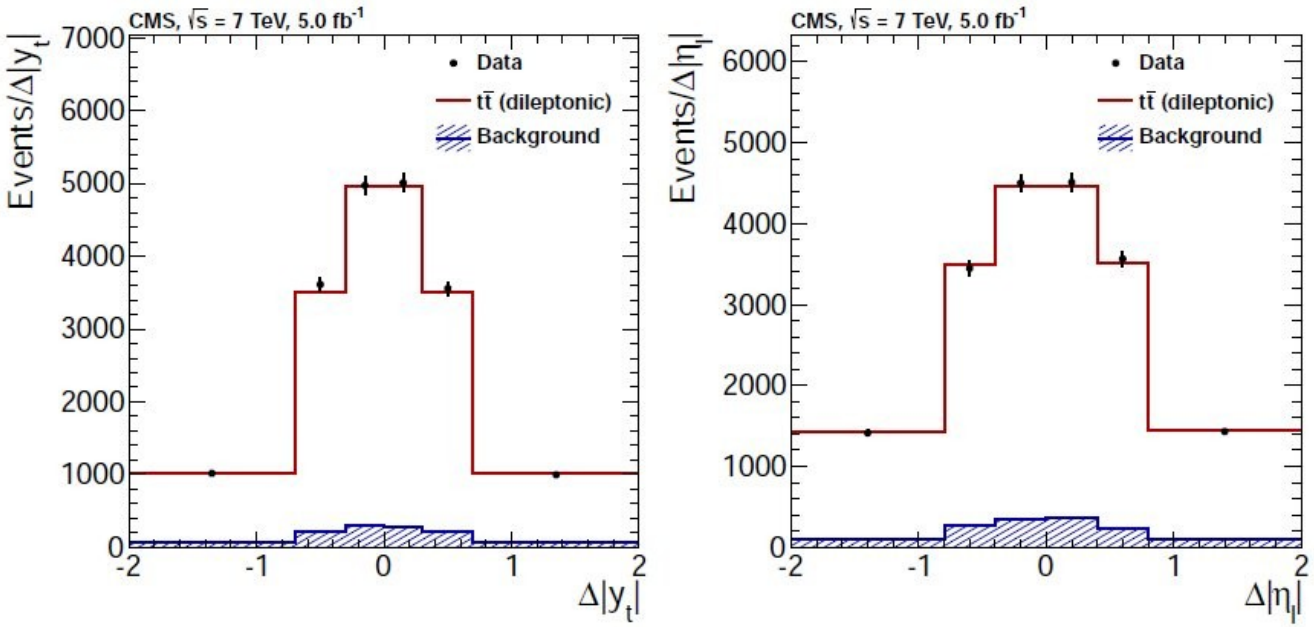
$$A_C^{lep} = \frac{N(\Delta|\eta_\ell| > 0) - N(\Delta|\eta_\ell| < 0)}{N(\Delta|\eta_\ell| > 0) + N(\Delta|\eta_\ell| < 0)}$$

# Top quark asymmetries

- Migration matrix shows superior resolution of leptonic based quantities

| Variable | $A_C$ | $A_C^{lep}$ |
|---|---|---|
| Experimental uncertainties | | |
| Jet energy scale | 0.003 | 0.001 |
| Lepton energy scale | <0.001 | <0.001 |
| Background | 0.001 | 0.001 |
| Jet energy resolution | <0.001 | <0.001 |
| Pileup | <0.001 | 0.001 |
| Scale factor for b tagging | <0.001 | <0.001 |
| Lepton selection | <0.001 | <0.001 |
| $t\bar{t}$ modelling uncertainties | | |
| Fact. and renorm. scales | 0.004 | 0.005 |
| Top-quark mass | 0.001 | 0.001 |
| Parton distribution functions | <0.001 | <0.001 |
| $\tau$-lepton decay | <0.001 | <0.001 |
| Top-quark $p_T$ reweighting | 0.001 | <0.001 |
| Unfolding | 0.006 | 0.001 |
| Total systematic uncertainty | 0.008 | 0.006 |

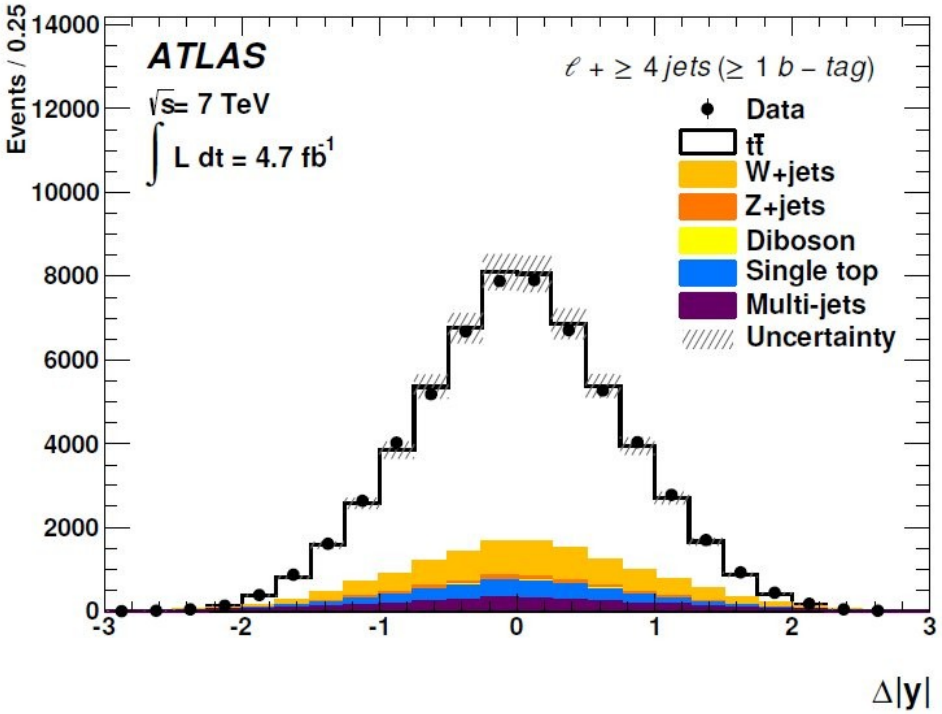


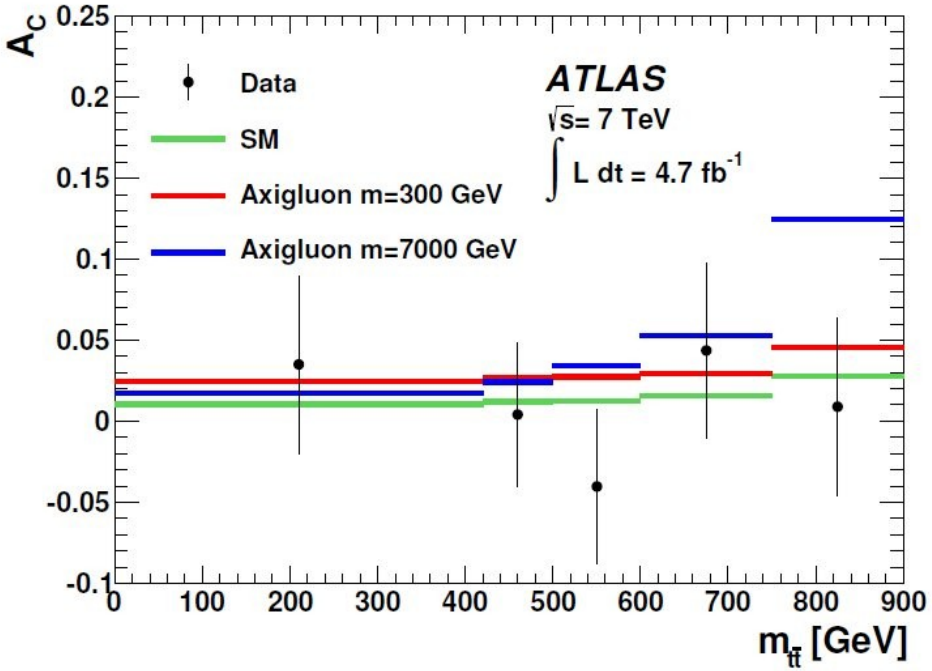



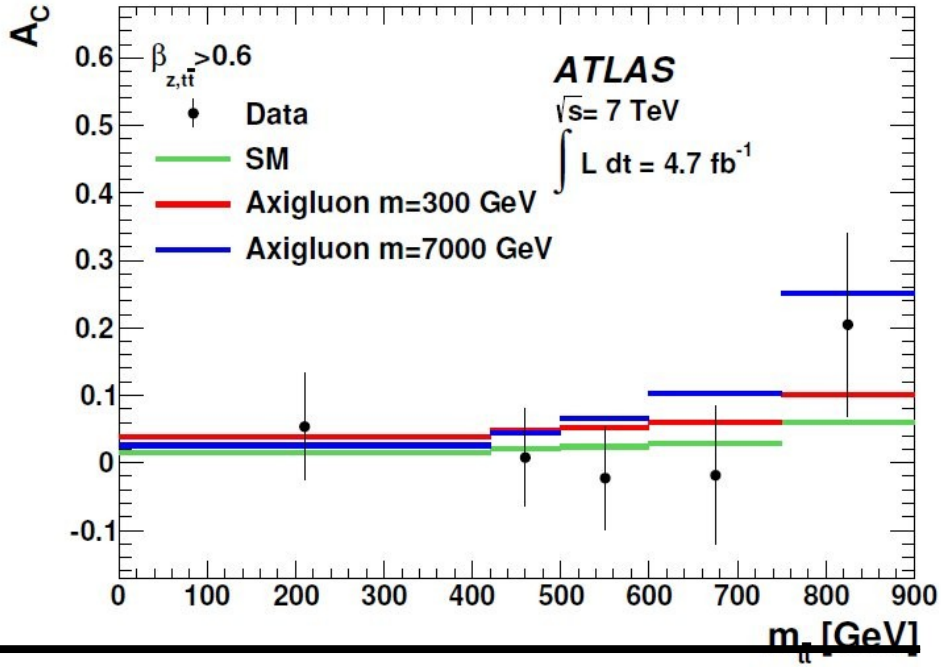
# Charge asymmetries

JHEP02(2014)107

- lepton+jets, ≥ 1 b-tag
- Kinematic dependencies of $A_C$ as a function of $m(t\bar{t})$, $\beta_z(t\bar{t})$ $z$-component $t\bar{t}$ velocity



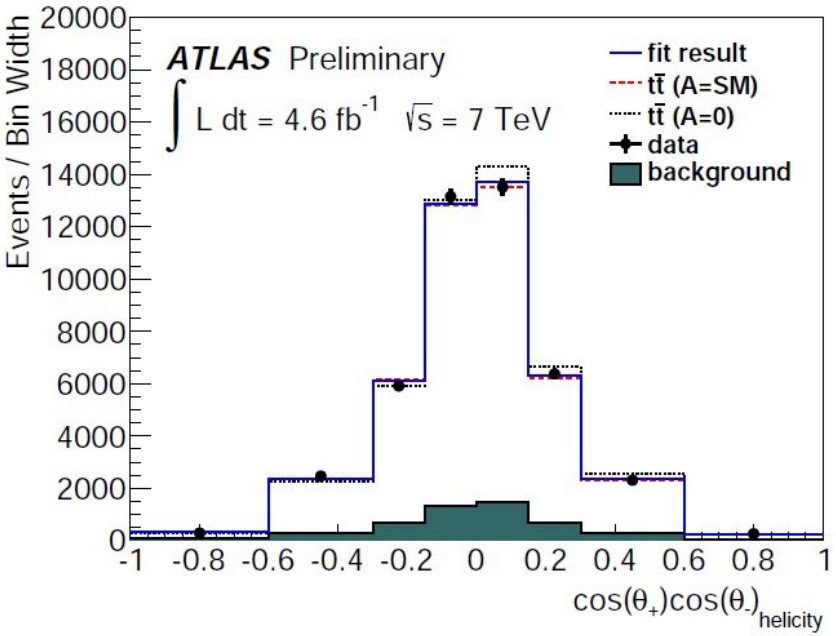



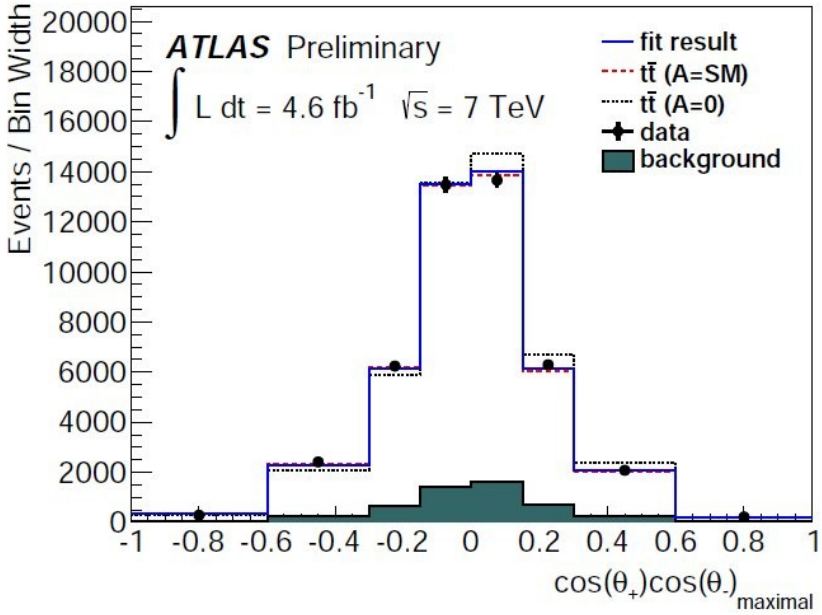

- In agreement with SM:

→

| $A_C$ | Data | Theory |
|---|---|---|
| | $0.006 \pm 0.010$ | $0.0123 \pm 0.0005$ |
| $m_{t\bar{t}} > 600$ GeV | $0.018 \pm 0.022$ | $0.0175^{+0.0005}_{-0.0004}$ |
| $\beta_{z,t\bar{t}} > 0.6$ | $0.011 \pm 0.018$ | $0.020^{+0.006}_{-0.007}$ |

# W helicity

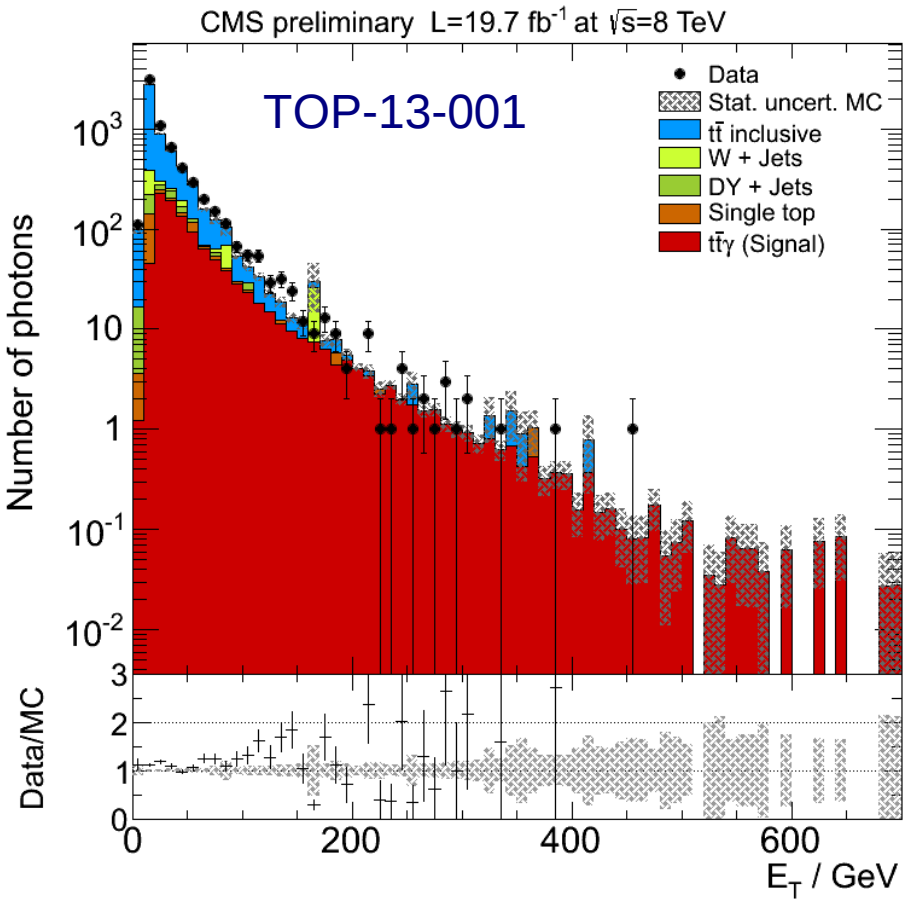



| channel | $f_{SM}(\Delta\phi)$ | $f_{SM}(S\text{-ratio})$ | $f_{SM}(\cos(\theta_+)\cos(\theta_-)_{helicity})$ | $f_{SM}(\cos(\theta_+)\cos(\theta_-)_{maximal})$ |
|---|---|---|---|---|
| $e^+e^-$ | $0.87 \pm 0.35 \pm 0.47$ | $0.81 \pm 0.35 \pm 0.39$ | $1.72 \pm 0.57 \pm 0.75$ | $0.48 \pm 0.41 \pm 0.52$ |
| $e^\pm\mu^\mp$ | $1.24 \pm 0.11 \pm 0.12$ | $0.95 \pm 0.12 \pm 0.12$ | $0.76 \pm 0.23 \pm 0.24$ | $0.86 \pm 0.16 \pm 0.18$ |
| $\mu^+\mu^-$ | $1.11 \pm 0.20 \pm 0.25$ | $0.53 \pm 0.26 \pm 0.38$ | $0.31 \pm 0.42 \pm 0.56$ | $0.97 \pm 0.33 \pm 0.44$ |
| Dilepton | $1.19 \pm 0.09 \pm 0.15$ | $0.87 \pm 0.11 \pm 0.12$ | $0.75 \pm 0.19 \pm 0.25$ | $0.83 \pm 0.14 \pm 0.17$ |

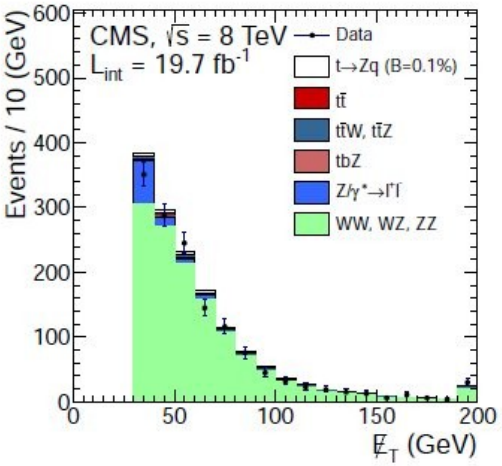
| Variable | Description | SM BNN | $f_V^L f_V^R$ BNN | $f_V^L f_T^L$ BNN | tug BNN | tcg BNN |
|---|---|---|---|---|---|---|
| $p_T(b_1)$ | $p_T$ of the leading-b-jet (the b-tagged jet with the highest $p_T$) — hereinafter we use the notations "leading" and "second-leading" for jets correspondingly to their order in $p_T$, the decreasing one | V | | V | V | V |
| $p_T(b_2)$ | $p_T$ of the second-leading b-jet | V | | | | V |
| $p_T(j_1 j_2)$ | a vector sum of $p_T$ of the first and the second-leading jets | V | | V | V | V |
| $p_T(\sum_{i \neq i_{best}} \vec{p_T}(j_i))$ | a vector sum of $p_T$ of all jets without the best jet. The notation "best jet" is used for the jet which gives the invariant mass of the top quark closest to the value of 172.5 GeV, which is used in the MC simulation | V | | | V | V |
| $p_T(j_L)$ | $p_T$ of the light-flavour jet (untagged jet with the highest value of $\|\eta\|$) | V | | | V | V |
| $p_T(\mu)$ | transverse momenta of the muon | V | V | V | | V |
| $p_T(W, b_1)$ | $p_T$ of the W boson and the leading-b-jet | V | | V | V | V |
| $p_T(W)$ | $p_T$ of the W boson | | | | V | V |
| $H_T$ | scalar sum of $p_T$ of all jets | | | V | | |
| $E_T^{miss}$ | missing transverse energy (energy of the reconstructed neutrino) | | V | | | V |
| $\eta(\mu)$ | $\eta$ of the muon | V | | | V | V |
| $\eta(j_L)$ | $\eta$ of the light-flavour jet | V | | V | V | V |
| $M(j_1 j_2)$ | the invariant mass of the leading-jet and the second-leading jets | V | | V | | |
| $M(\sum_{i \neq i_{best}}(j_i))$ | the invariant mass of all jets without the best one | V | | | | V |
| $M(jW)$ | the invariant mass of the W boson and all jets | V | | | | |
| $M(W, b_1)$ | the invariant mass of the W boson and the leading-b-jet | V | | | V | V |
| $M(\sum_i(j_i))$ | the invariant mass of all jets | | | | V | V |
| $\Delta R(j_1, j_2)$ | equal to $\sqrt{(\eta(j_1)-\eta(j_2))^2+(\phi(j_1)-\phi(j_2))^2}$ | V | | | V | V |
| $\Delta R(\mu, j_2)$ | equal to $\sqrt{(\eta(\mu)-\eta(j2))^2+(\phi(\mu)-\phi(j2))^2}$ | | | V | | |
| $\Delta\phi(\mu, E_T^{miss})$ | azimuthal angle between the lepton and the reconstructed neutrino | | | V | V | V |
| $cos(\theta_{\mu,j_L})\|_{top}$ | the cosine of the angle between the lepton and the light flavour jet in the top quark rest frame, the top quark is reconstructed with the leading-b-jet | V | V | | V | V |
| $cos(\theta_{\mu,W})\|_W$ | the cosine of the angle between the lepton and the W boson in the W boson rest frame | | V | V | V | V |
| $cos(\theta_{W,j_L})\|_{top}$ | the cosine of the angle between the W boson and the light-flavour jet in the top quark rest frame | | V | | | |
| $cos(\theta_{\mu,j_1})\|_{top}$ | the cosine of the angle between the lepton and the first jet in the top quark rest frame | | | | | V |
| $Q(\mu)$ | a charge of the lepton | | | | V | V |

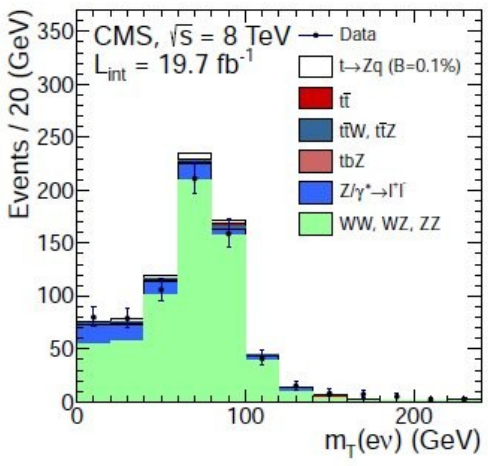
# Ttbar + X: W, Z, γ

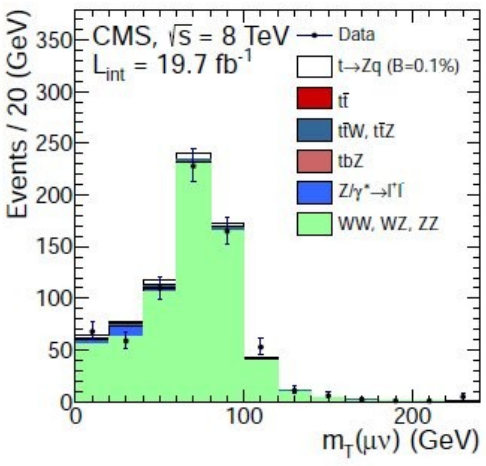


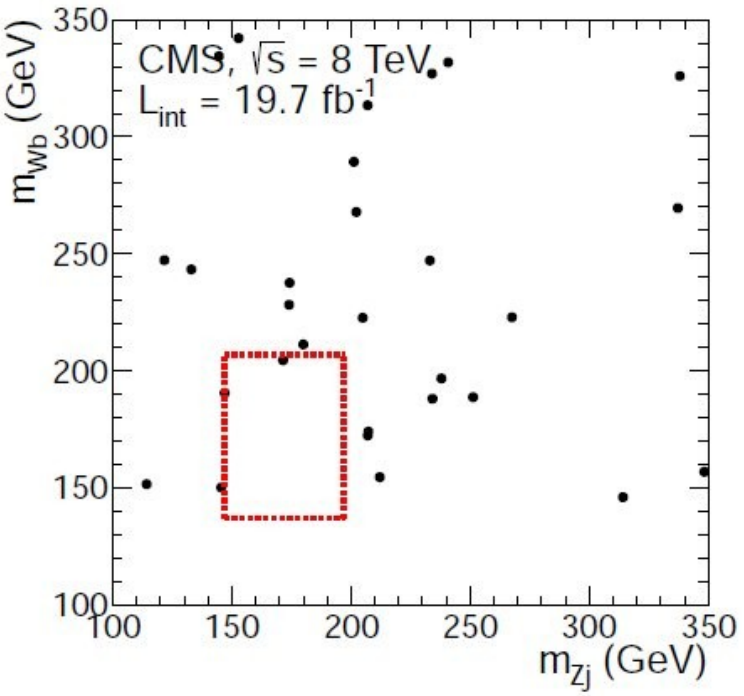

| Systematic source | Uncertainty, % |
|---|---|
| **Template modeling** | |
| - Bck. template modeling: $\gamma$ leakage | 3.7 |
| - Signal template modeling | 6.6 |
| **Signal modeling** | |
| - MC generator | 1.7 |
| - PDF | 1.1 |
| - Parton shower | 7.3 |
| - QED FSR | 3.4 |
| - Color reconnection | 0.2 |
| - Underlying event | 0.9 |
| - Ren/Fac. Scale | 1.1 |
| **Photon modeling** | |
| - Photon identification efficiency | 7.3 |
| - Photon scale | 2.7 |
| - Photon resolution | 4.0 |
| **Electron modeling** | |
| - Trigger efficiency | 0.3 |
| - Reconstruction efficiency | 0.5 |
| - Identification efficiency | 1.2 |
| - Energy scale | 0.3 |
| - Energy resolution | 0.1 |
| **Muon modeling** | |
| - Trigger efficiency | 1.7 |
| - Reconstruction efficiency | 0.4 |
| - Identification efficiency | 1.0 |
| - Momentum scale | 0.3 |
| - Momentum resolution | 0.7 |
| **Jet modeling** | |
| - Jet reconstruction efficiency | 0.1 |
| - Jet energy scale | 15.0 |
| - Jet energy resolution | 6.5 |
| - Jet vertex fraction | 2.6 |
| ***b*-tagging** | |
| - *b*-tag efficiency | 8.1 |
| - Mistag rate | 1.1 |
| **MET modeling** | |
| - Soft-jets and Cell-Out terms | 0.3 |
| - Pile-up | 0.9 |
| **Luminosity** | 1.8 |
| **Background contributions** | |
| - *e*-fakes | 5.0 |
| - QCD multijets+$\gamma$ | 1.5 |
| - $W$+jets+$\gamma$ | 5.4 |
| - $Z$+jets+$\gamma$ | 1.3 |
| - Dibosons+$\gamma$ | 0.4 |
| - Single top+$\gamma$ | 0.4 |

# Top quark: FCNC's

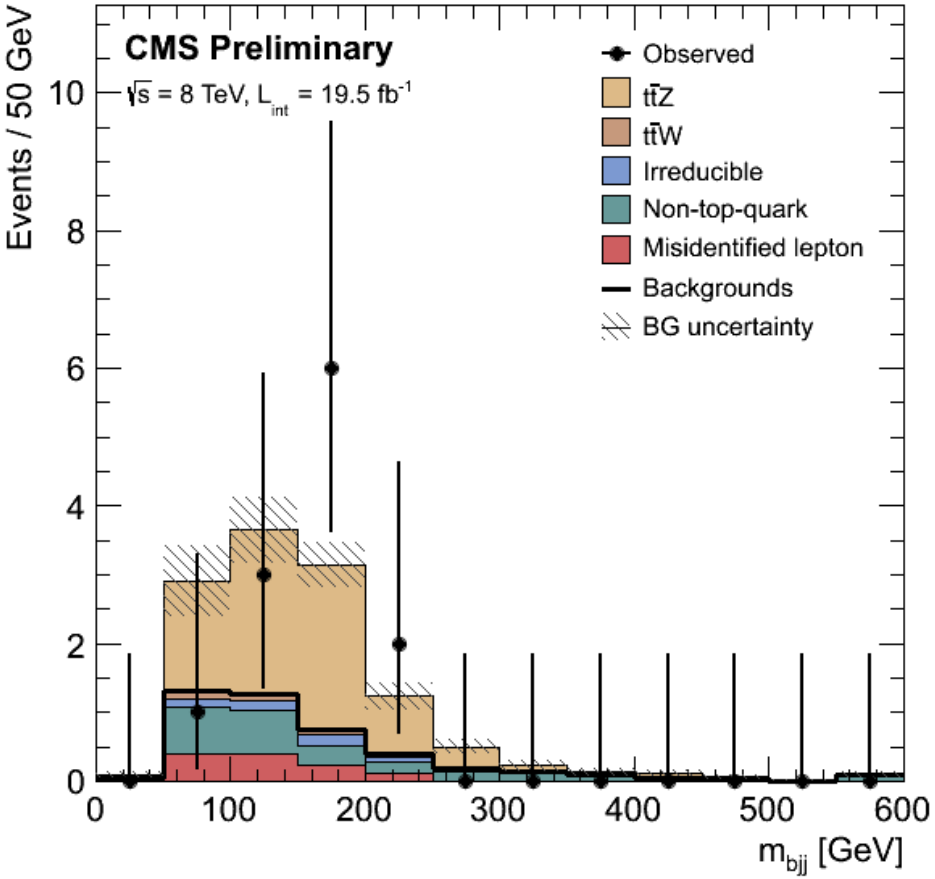


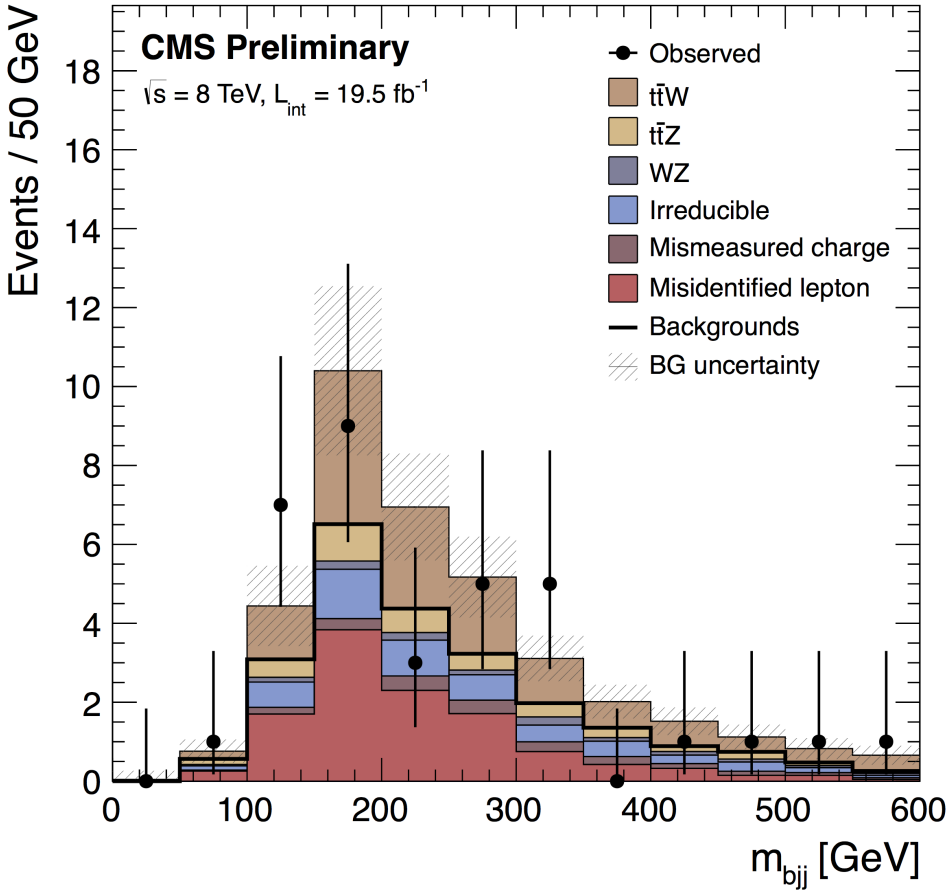



# Ttbar + X: W, Z, γ


CMS Preliminary
√s = 8 TeV, L_int = 19.5 fb^-1
Observed
tt̄Z
tt̄W
Irreducible
Non-top-quark
Misidentified lepton
Backgrounds
BG uncertainty
Events / 50 GeV
m_bjj [GeV]


CMS Preliminary
√s = 8 TeV, L_int = 19.5 fb^-1
Observed
tt̄W
tt̄Z
WZ
Irreducible
Mismeasured charge
Misidentified lepton
Backgrounds
BG uncertainty
Events / 50 GeV
m_bjj [GeV]