Spin measurements in top-quark events at the LHC

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on behalf of the ATLAS and CMS collaborations

TOP2015
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Outline

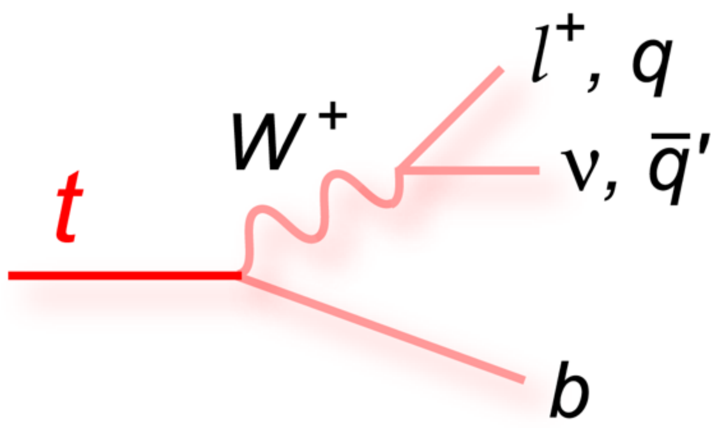
- Today I'll show recent top quark spin measurements from ATLAS and CMS
  - top quark polarisation
    - in $t\bar{t}$ and single top (t-channel) events
  - $t\bar{t}$ spin correlations

Introduction

- Top decays before QCD interactions can affect its spin

top lifetime < QCD timescale ≪ spin-flip timescale

$10^{-25}\,\mathrm{s} \;<\; 10^{-24}\,\mathrm{s} \;\ll\; 10^{-21}\,\mathrm{s}$

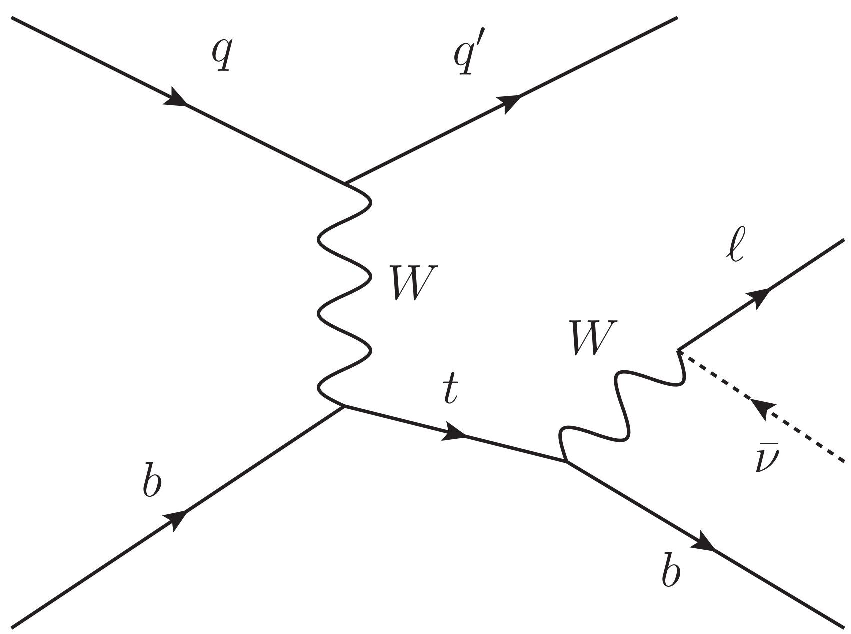


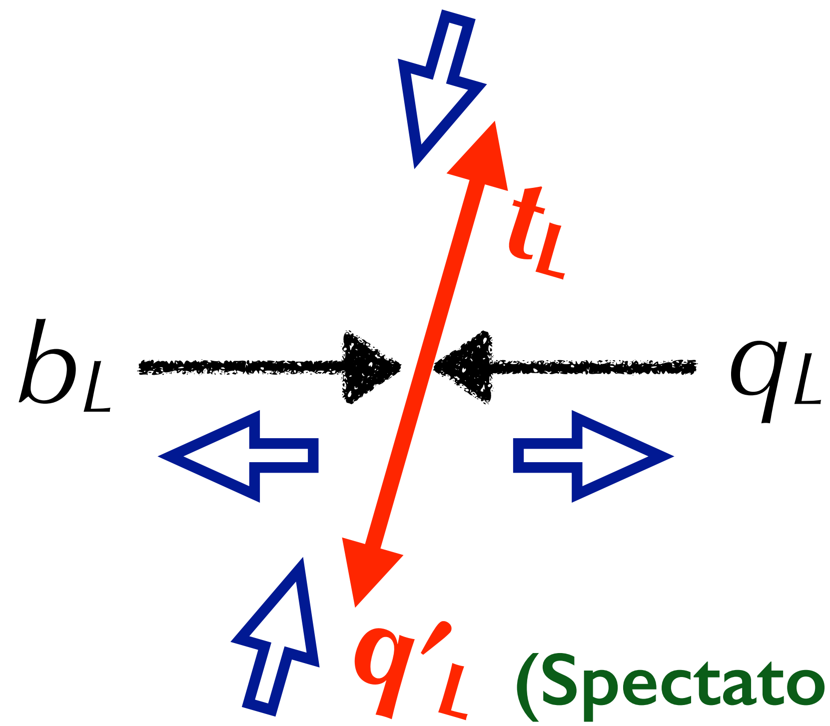
  - top decay products give us **direct access to its spin**
  - expect top spin variables to be **well predicted by perturbative QCD**
    - excellent test of SM
- Spin variables can be significantly **modified by new physics**
  - already being used to set limits

Top polarisation

Introduction to top quark spin

- Top spin **depends on production process** and on the basis (direction) for spin measurement
- Single top t-channel:
  - tops **100% L** chirality (because they have to couple to the W)
  - translates to **~95% spin up** in **spectator basis**





(Spectator quark)

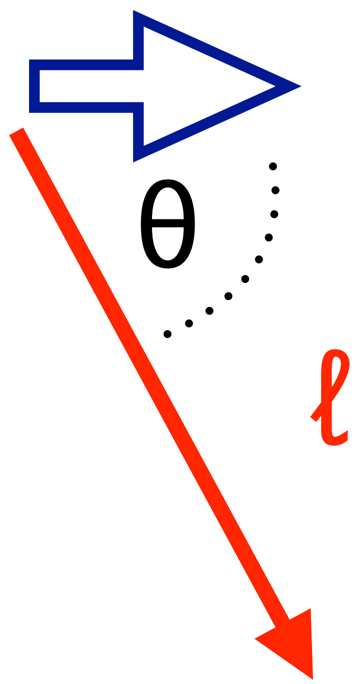
- $t\bar{t}$ production via strong interaction with **unpolarised incoming partons**
  - R and L tops equally likely
  - **no net polarisation at LO QCD** (usually measured in **helicity basis**)

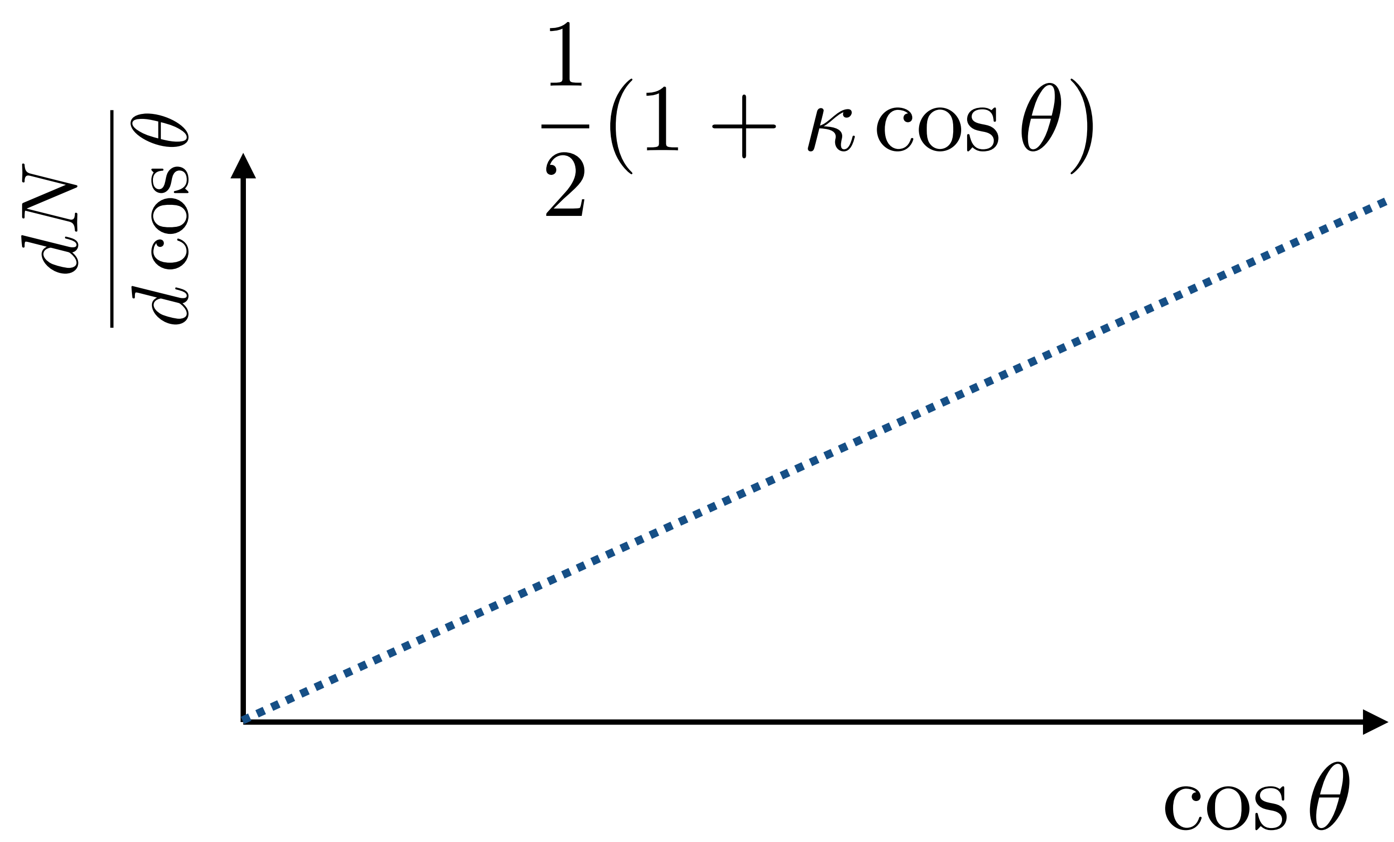
Polarized top quark decay

- The top quark's spin determines the angular distribution of its daughters when it decays
  - spin analysing powers: $\kappa_\ell = 1, \kappa_{\bar{d}} = 0.97, \kappa_u = -0.31, \kappa_b = -0.39$

    A. Brandenburg, Z. G. Si, P. Uwer (2002)
  - **lepton preferentially produced in top spin direction**

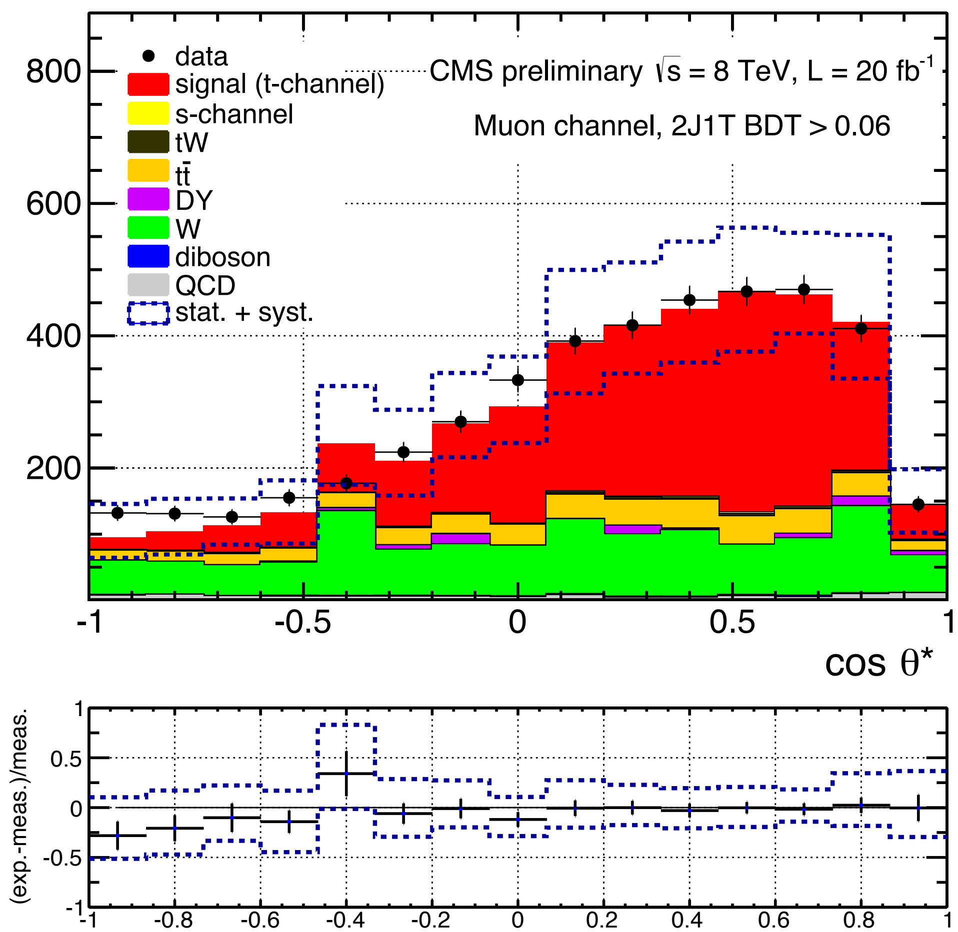
top rest frame

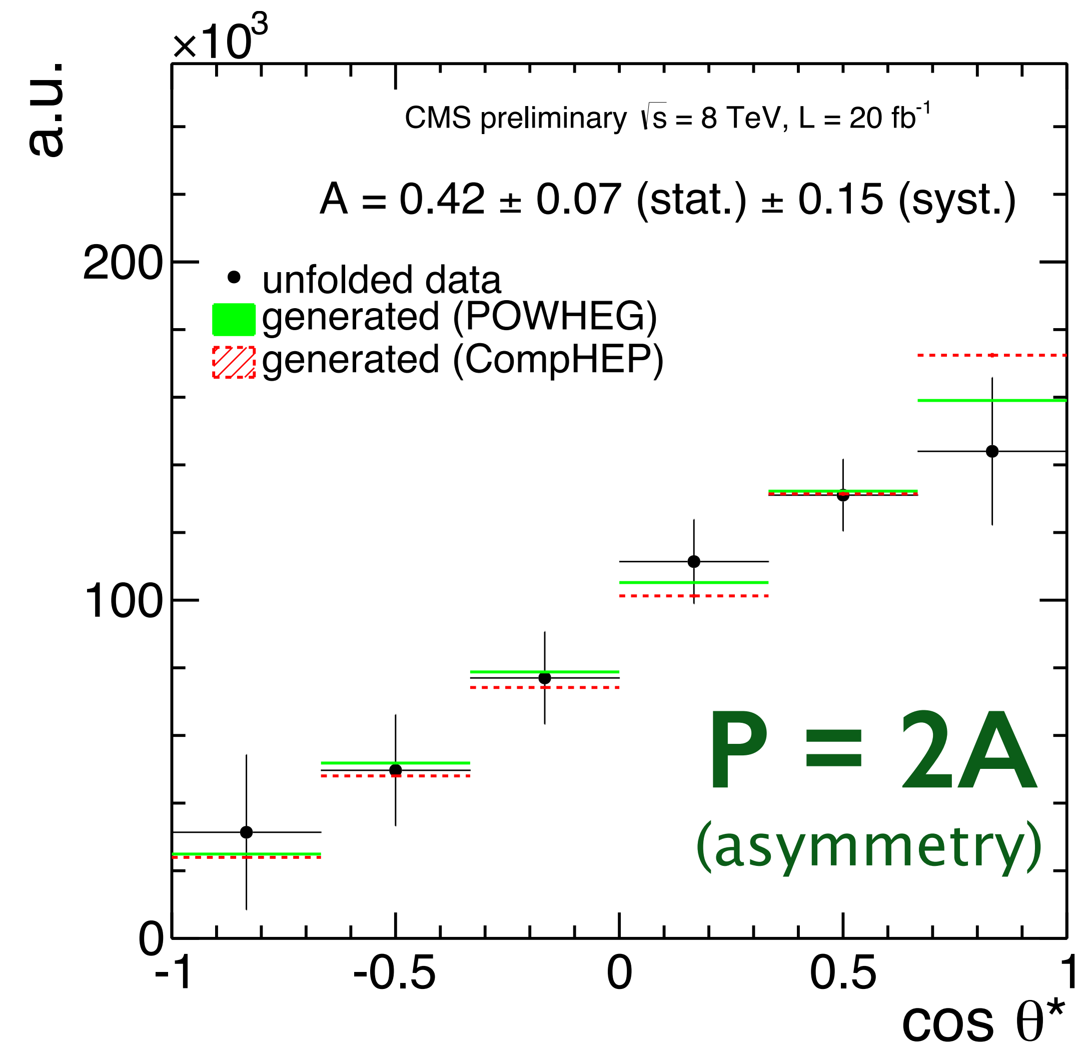




- Polarisation measures average spin: $$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}(1 + \kappa P \cos\theta)$$

- BDT selects **~50% pure t-channel sample** — CMS-PAS-TOP-13-001
- Reconstruct $\cos\theta^*$, subtract background (W+jets largest), unfold to parton level, and combine e and μ channels
- Dominant systematics from JES and background subtraction

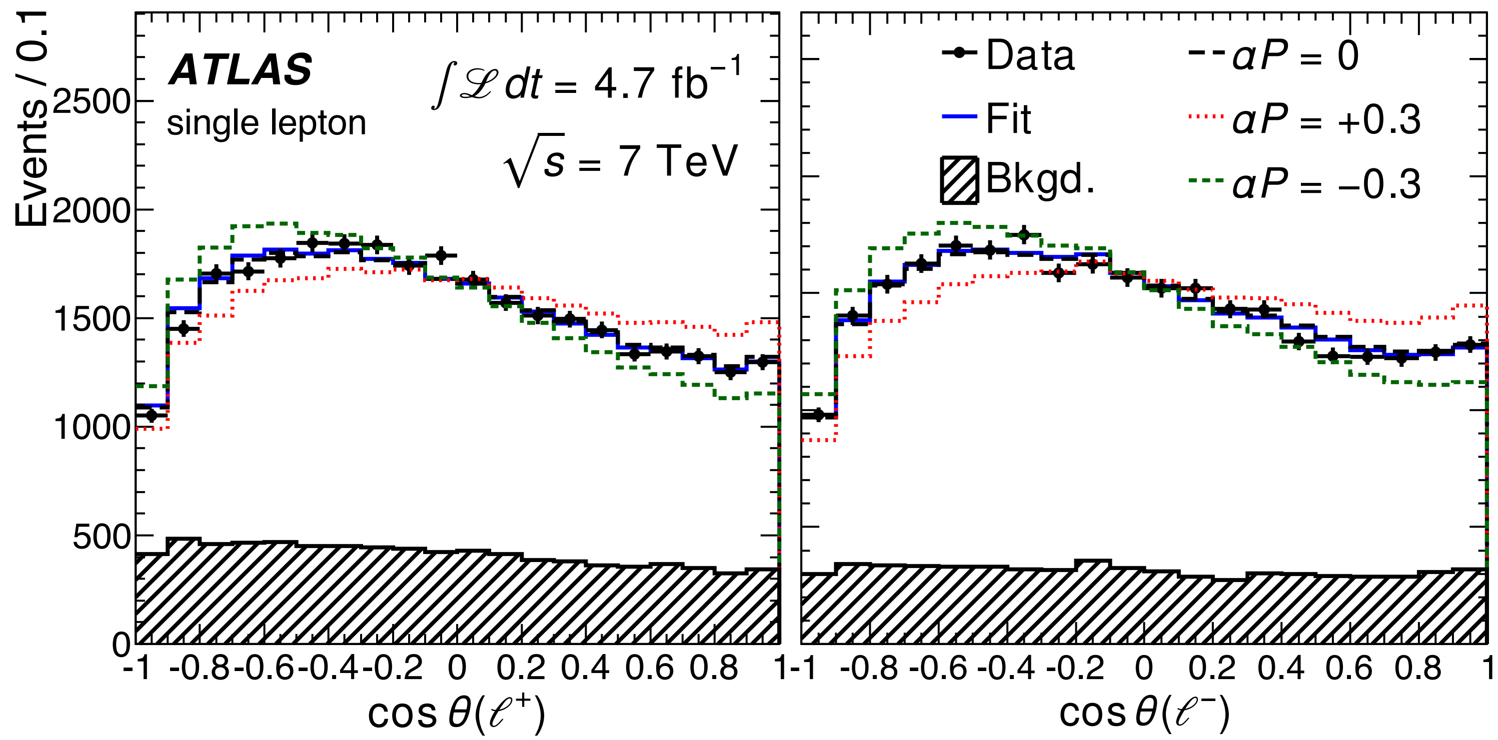




- Polarisation from distribution **asymmetry**: **P = (82 ± 12 ± 32)%**

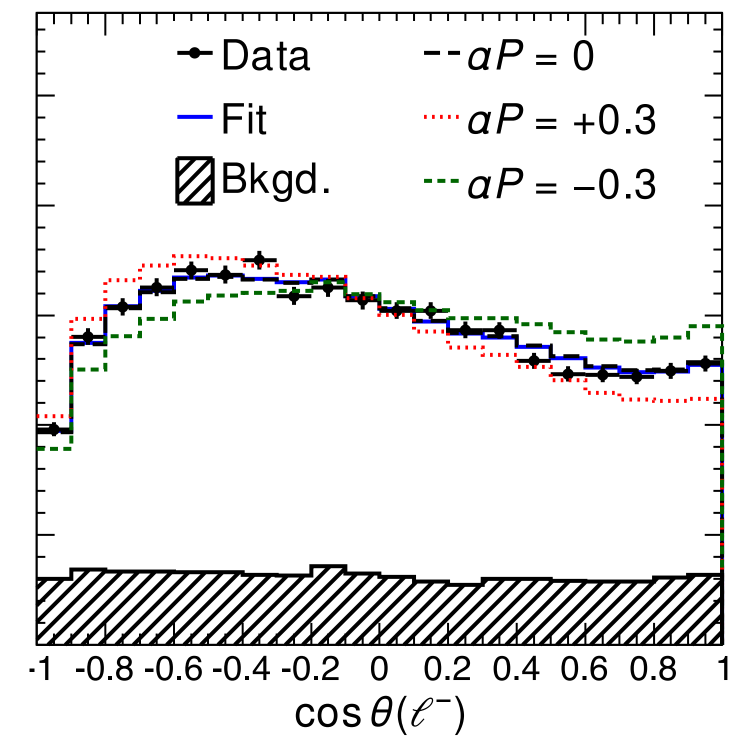
[PRL 111, 232002 (2013)](PRL 111, 232002 (2013))

- Template fit to $\cos\theta^*$ at reco-level using templates with **+30%** and **-30%** polarisation
  - 1ℓ, 2ℓ channels and $t, \bar{t}$ distributions (ℓ^+ and ℓ^-) fitted separately



- Two scenarios
  - **CP-conservation**: $P(t) = P(\bar{t})$
  - **Maximal CP violation**: $P(t) = -P(\bar{t})$
- Jet reconstruction dominant systematic

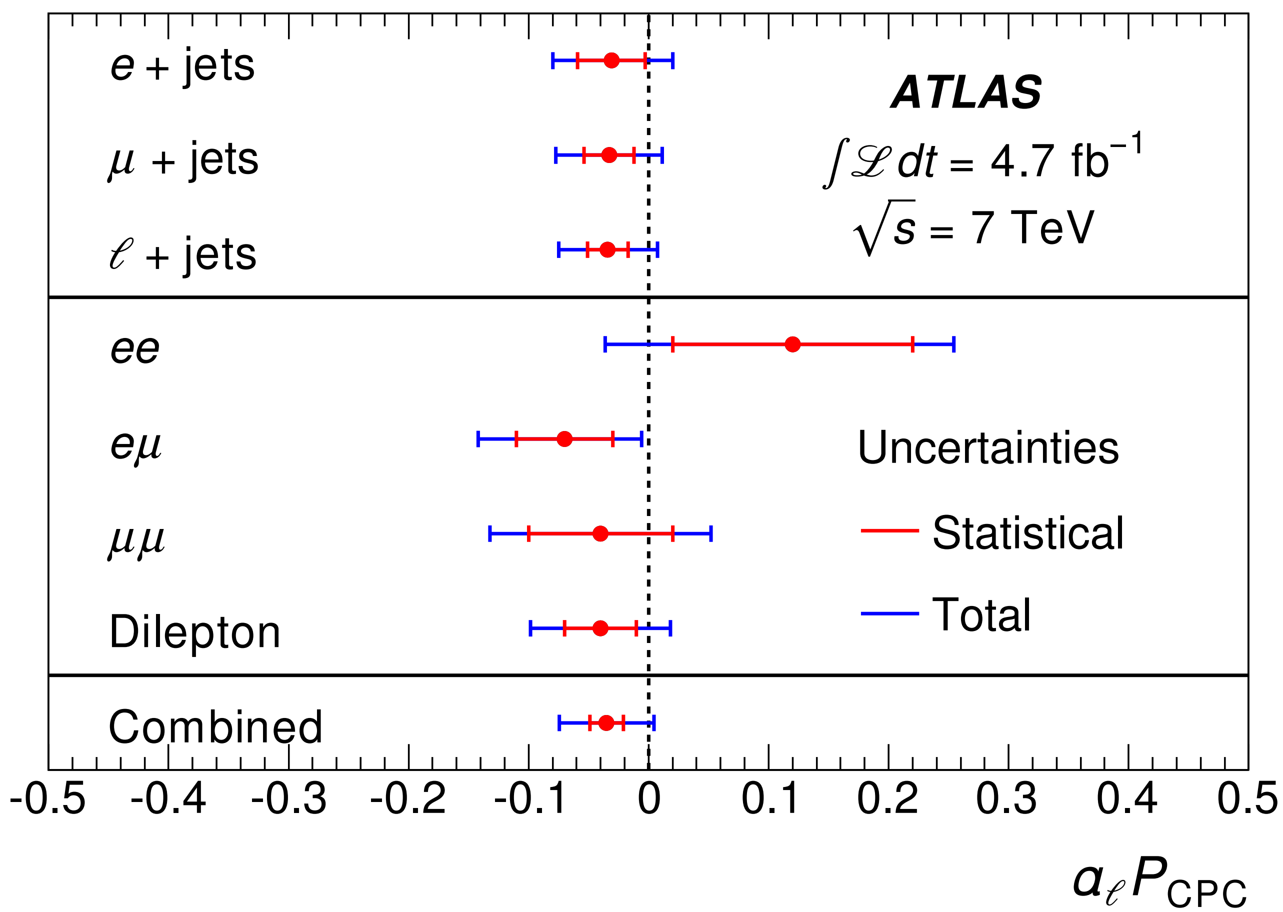
CP violating hypothesis: ℓ^+ templates unchanged and ℓ^- templates flipped so benefits from maximal cancellation of systematics

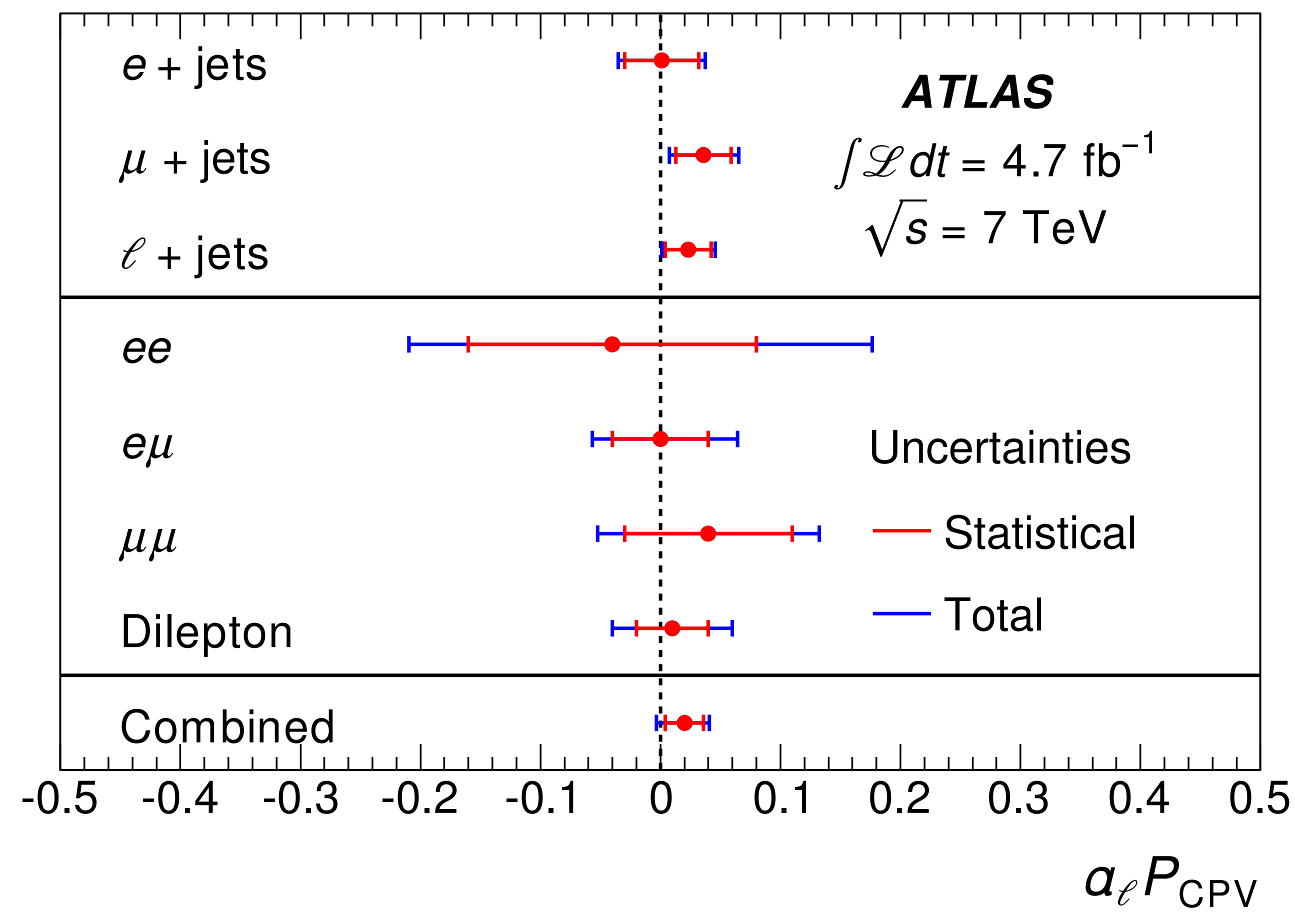


Polarisation ($t\bar{t}$) - ATLAS, 7 TeV

PRL 111, 232002 (2013)

- Results (assuming $\kappa_\ell = 1$):
  - **P_{CPC} = (-3.5 ± 1.4 ± 3.7)%**
  - **P_{CPV} = (2.0 ± 1.6 $^{+1.3}_{-1.7}$)%**



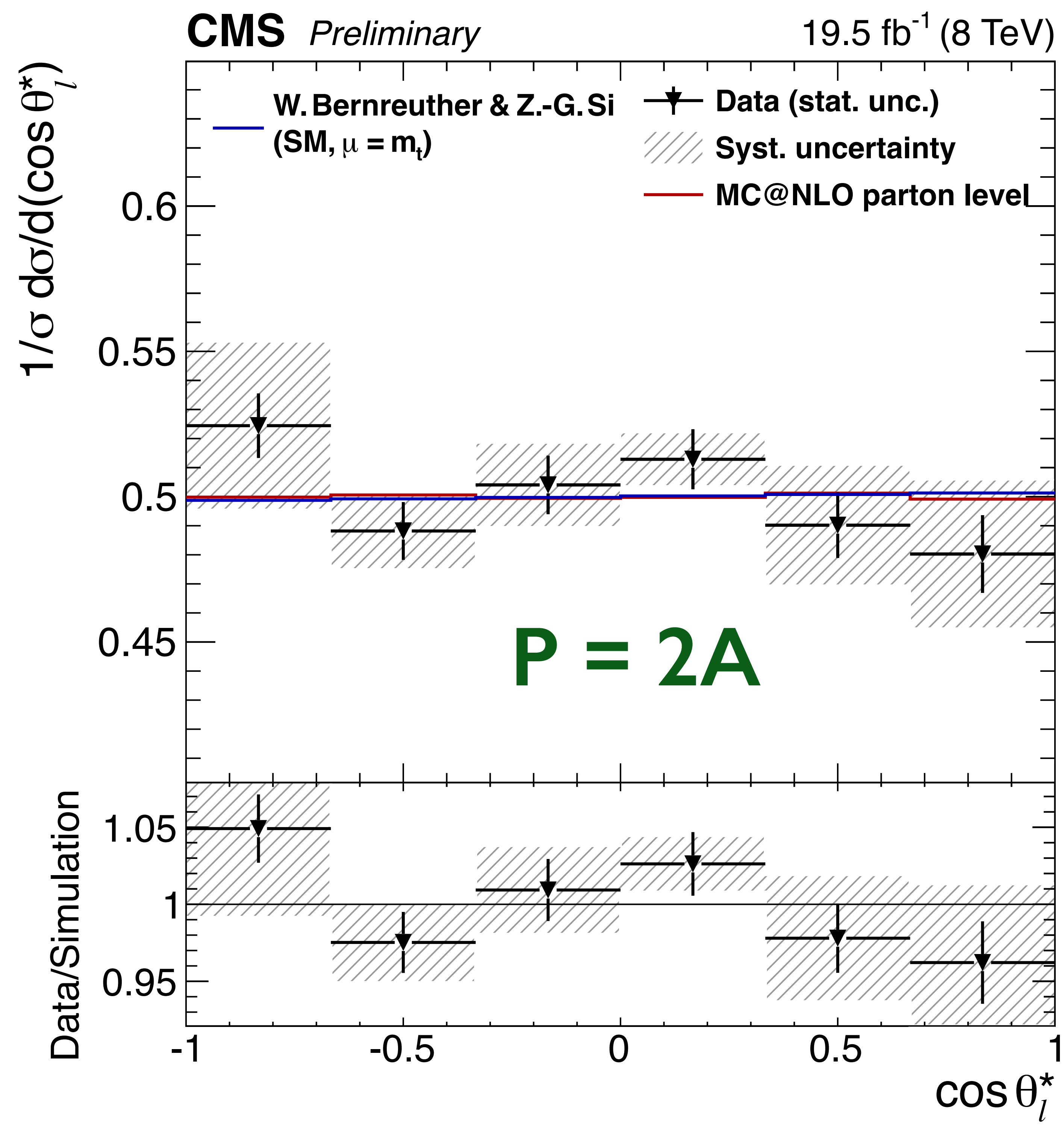


α = κ = spin analysing power

Polarisation ($t\bar{t}$) - CMS, 8 TeV

CMS TOP-14-023

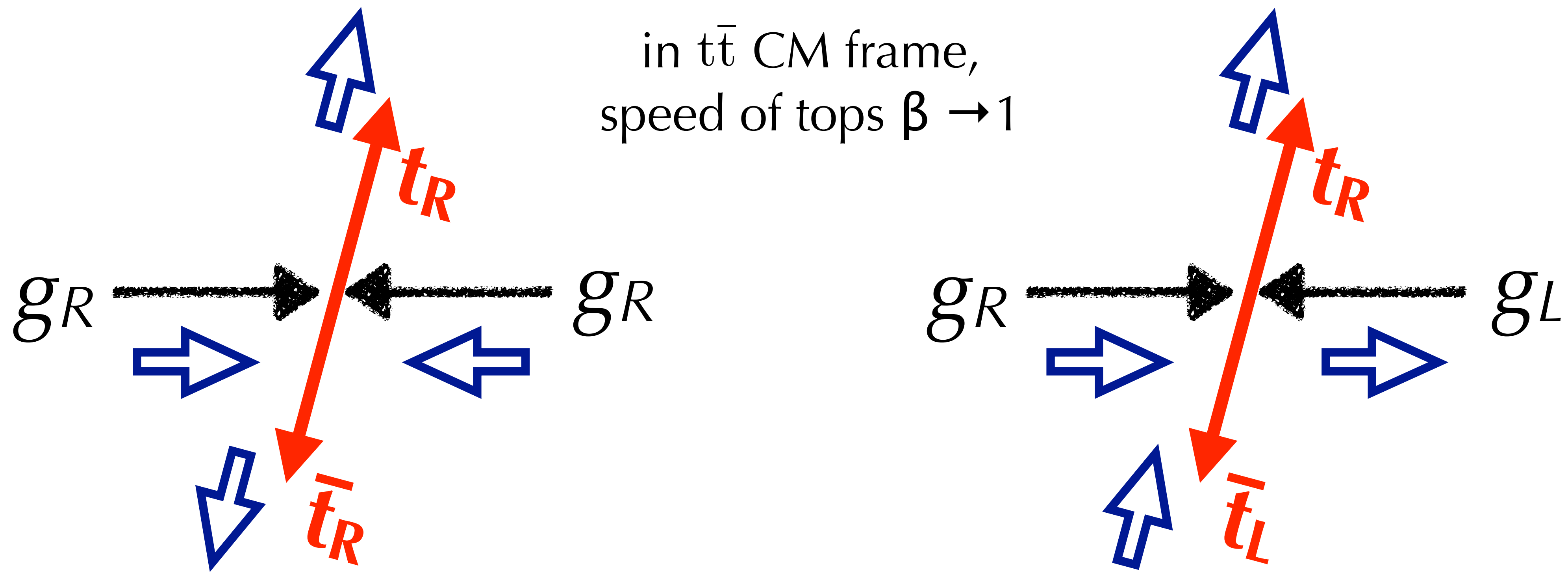
- $\cos\theta^*$ distribution **unfolded to parton level** (dilepton channel)
- P measured from **asymmetry of distribution**
- Two measurements per event (ℓ^+ and ℓ^-)
- Combined assuming CP conservation and violation
- **$P_{CPC} = (-2.2 \pm 5.9)\%$**
  - JES dominant systematic
- **$P_{CPV} = (-0.0 \pm 1.7)\%$**
  - cancellation of systematics



$t\bar{t}$ spin correlations

Introduction to spin correlations

- **Same** and **opposite** helicity gluon fusion contributions **impart different spin correlations to the top quark pairs**



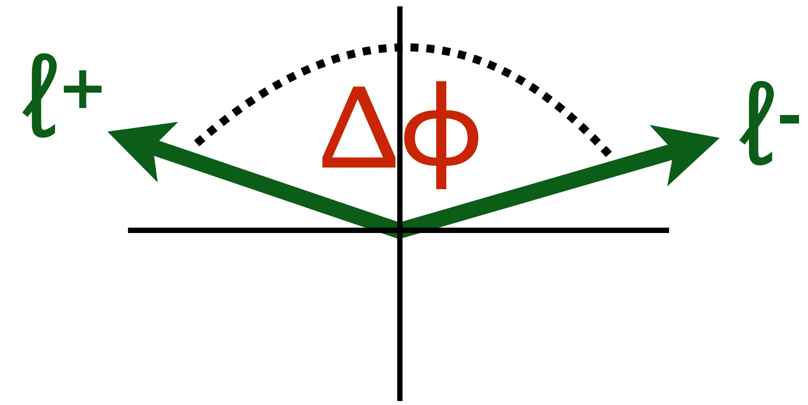
Same helicity gluons
Positive spin correlations

Opposite helicity gluons
Negative spin correlations

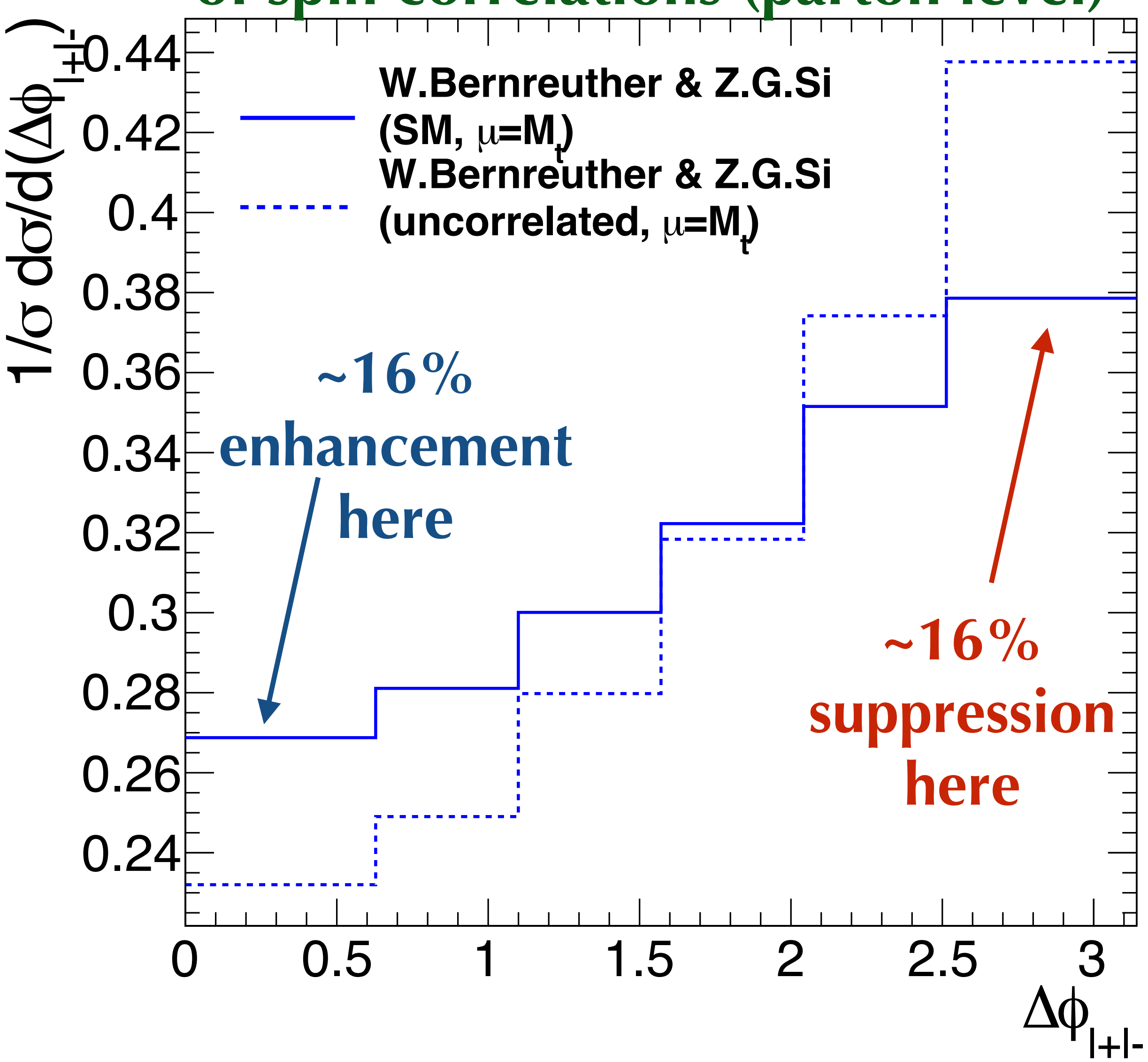
- **Same helicity** contribution is **dominant near threshold**
- Opposite helicity dominant when $E_t >> m_t$ (helicity conservation)
- Expected net spin correlation strength of about **+30%** at the LHC
  - **modified in many new physics scenarios**

Dilepton Δϕ distribution

- Spin correlations in same-helicity gluon fusion result in aligned lepton decays
  - alignment **strongest in Δϕ** (lab frame azimuthal angle between two leptons)



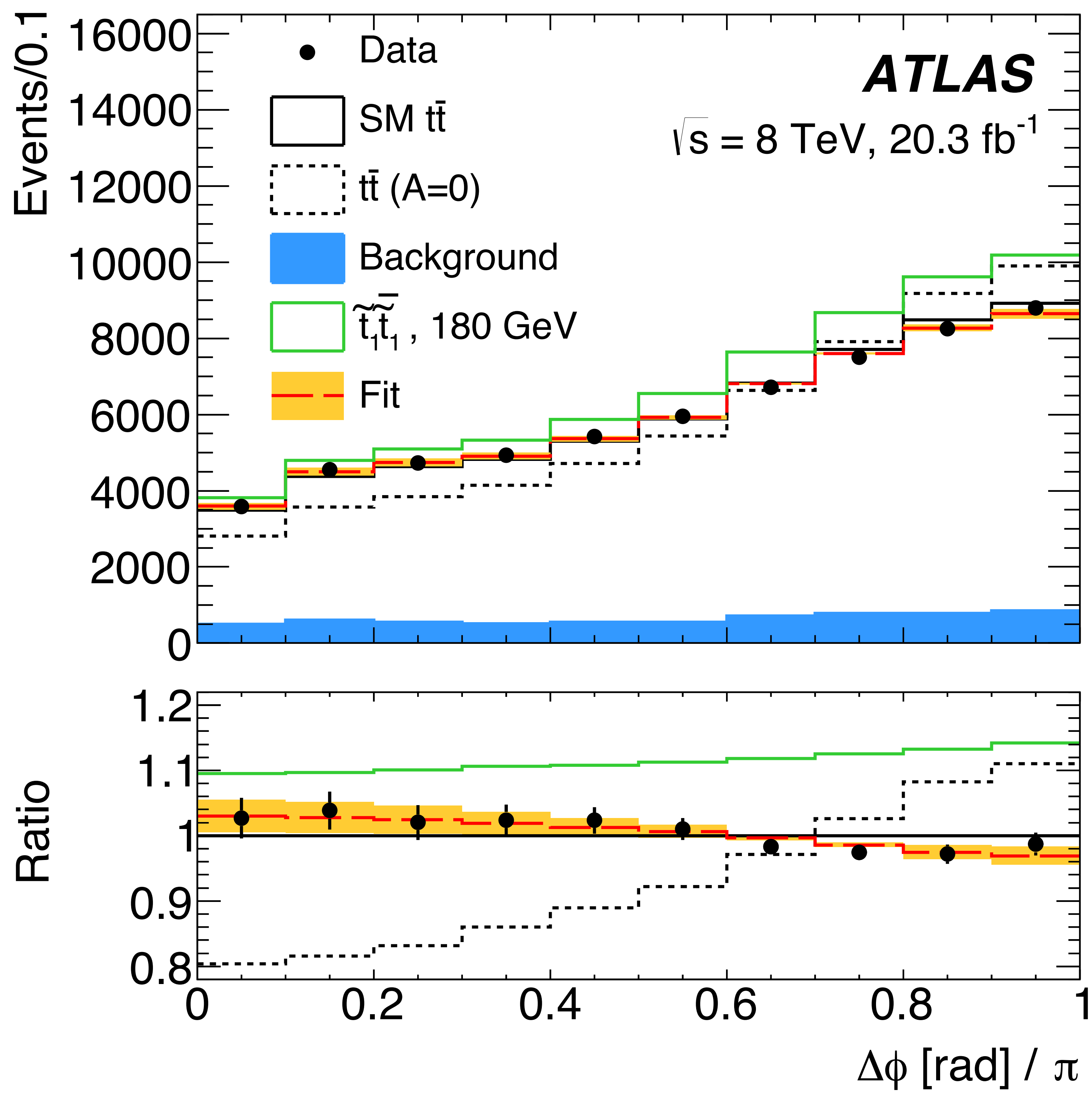
Δϕ distribution in presence and absence of spin correlations (parton level)



- Kinematically, large Δϕ is preferred because tops are produced back to back
  - **relative enhancement at low Δϕ due to spin correlations**
- Lepton angles have excellent experimental resolution
  - Δϕ most precise probe of spin correlations (unique to LHC)

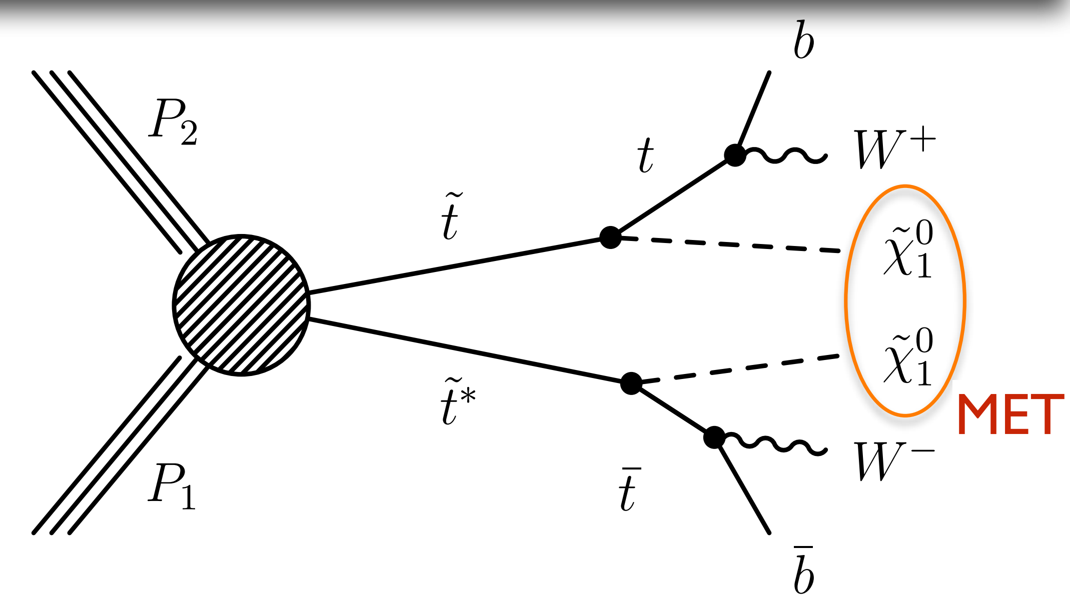
- Select $t\bar{t}$ events in dilepton final state
  - data-driven prediction for dominant Z/γ^{*}+jets background
- Quantify spin correlation strength as **fraction "f_{SM}" of SM expectation**
  - template fit using simulated correlated and uncorrelated $t\bar{t}$
- **f_{SM} = 1.20 ± 0.05 ± 0.13**

PRL 114, 142001 (2015)

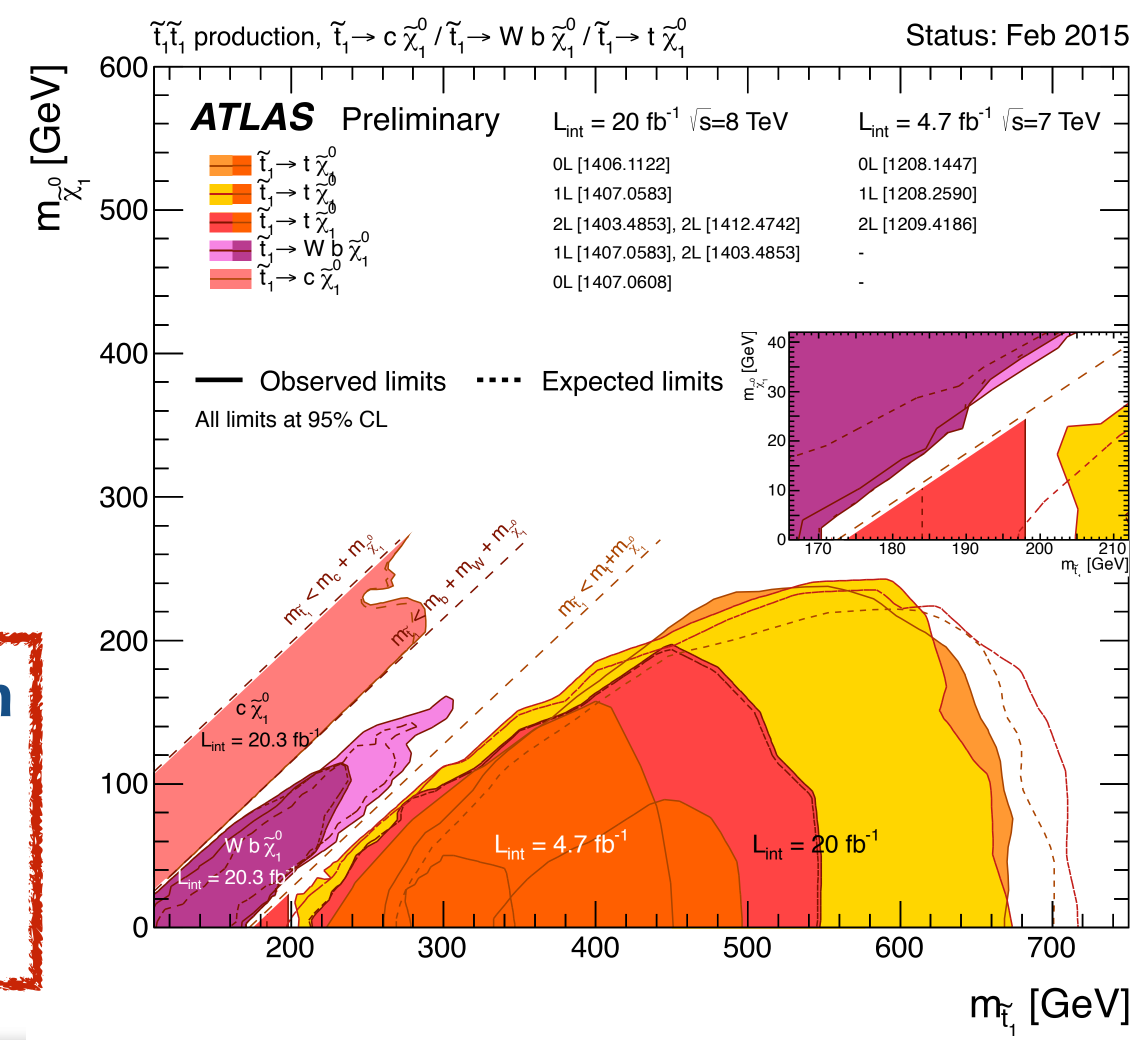


Probing SUSY with spin correlations

- Supersymmetric top squark pair production looks like $t\bar{t}$ + **MET**
- Squarks have spin-zero
  - daughter top quarks look similar to **uncorrelated** $t\bar{t}$ events
  - but only ~1/6 of the $t\bar{t}$ cross section for $m_{stop} = m_t$
- **Total cross section measurement** also sensitive to stops
- Combining the two, ATLAS excludes **$m_t < m_{stop} < 191$ GeV**



Direct searches insensitive when $\tilde{\chi}_1^0$ soft



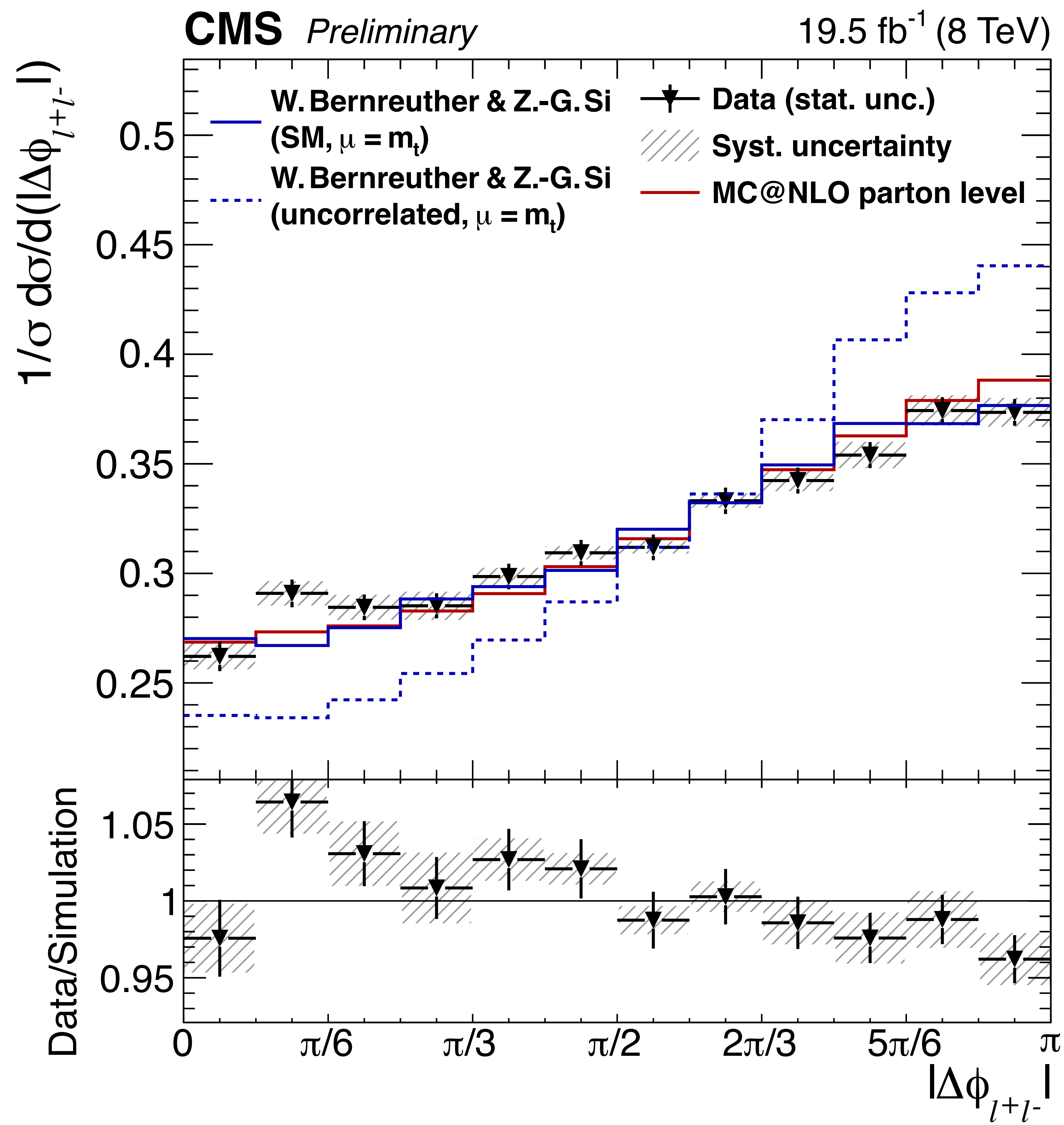
Important region to probe based on naturalness considerations

[PRL 114, 142001 (2015)]

Δϕ - CMS, 8 TeV

CMS TOP-14-023

- Δϕ distribution **unfolded to parton level**
- Compared to theoretical predictions at NLO with and without spin correlations
- The data agree with the SM prediction
  - **top p_T modelling** dominant experimental systematic
- **f_{SM} = 1.18 ± 0.18**
  - dominant uncertainty from **scale uncertainties in the NLO predictions**



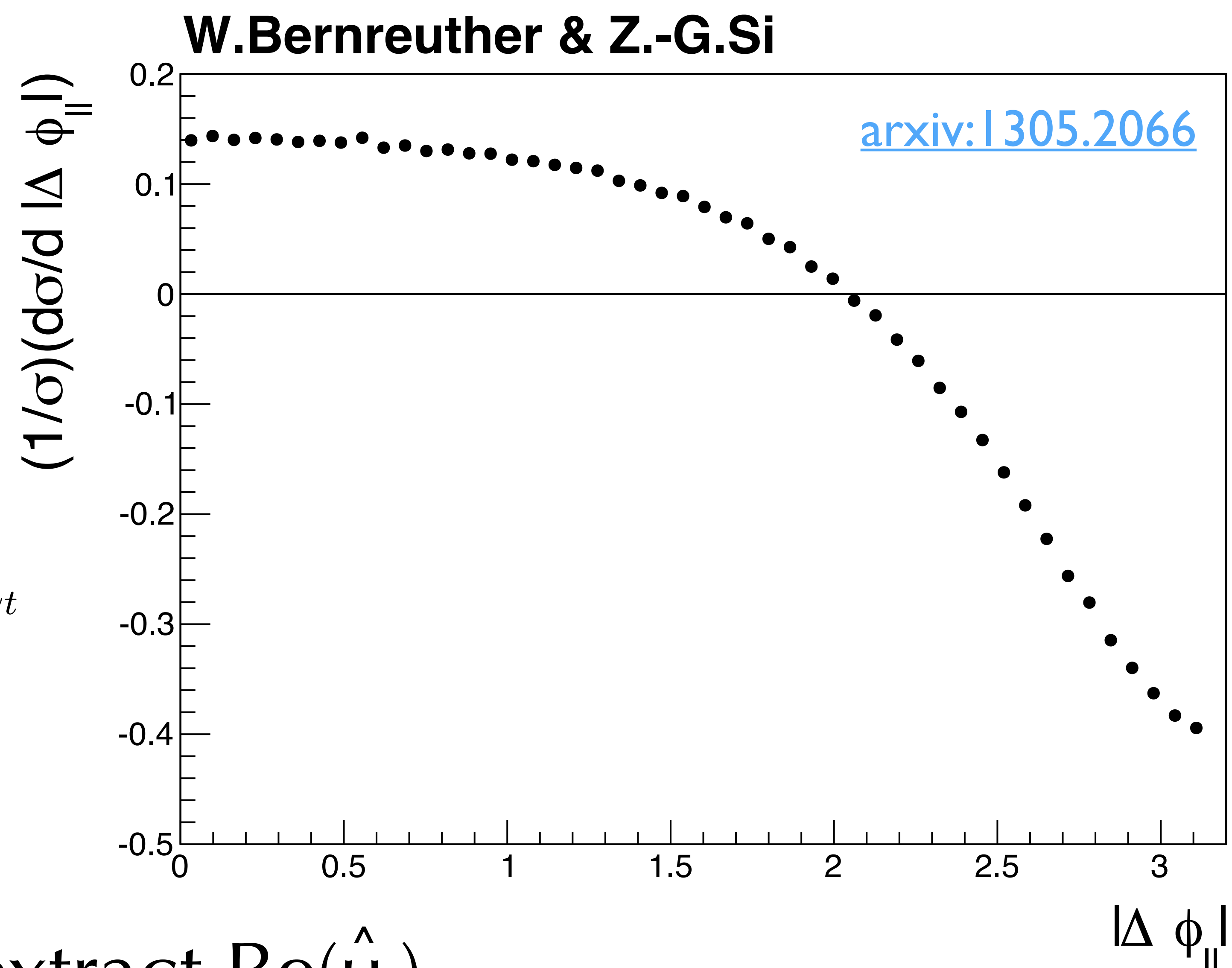
Top Chromo-Magnetic Dipole Moment

- **Heavy particle exchange** in $t\bar{t}$ production can **modify spin correlations** by introducing colour dipole ttg couplings
- Model-independent effective Lagrangian:
  - $\mathcal{L}_{eff} = \mathcal{L}_{SM} - \frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu}$
  - $\tilde{\mu}_t$= anomalous CMDM
- For small $\tilde{\mu}_t$:

$$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi} = \left(\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}\right)_{SM} + \left(\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}\right)_{NP} \mathrm{Re}\hat{\mu}_t$$

  - dσ only sensitive to Re($\tilde{\mu}_t$)

New physics contribution to $\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi}$

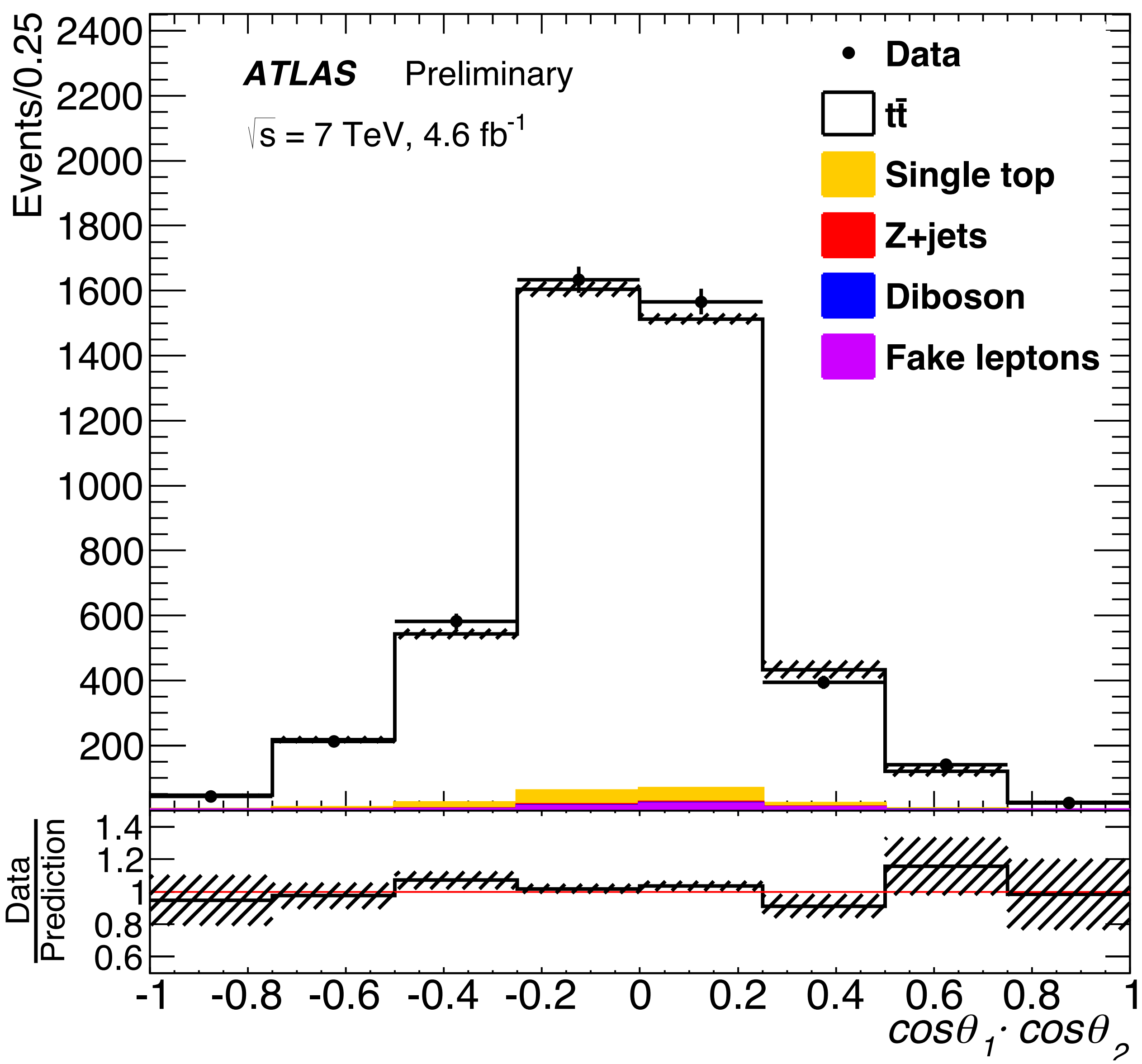


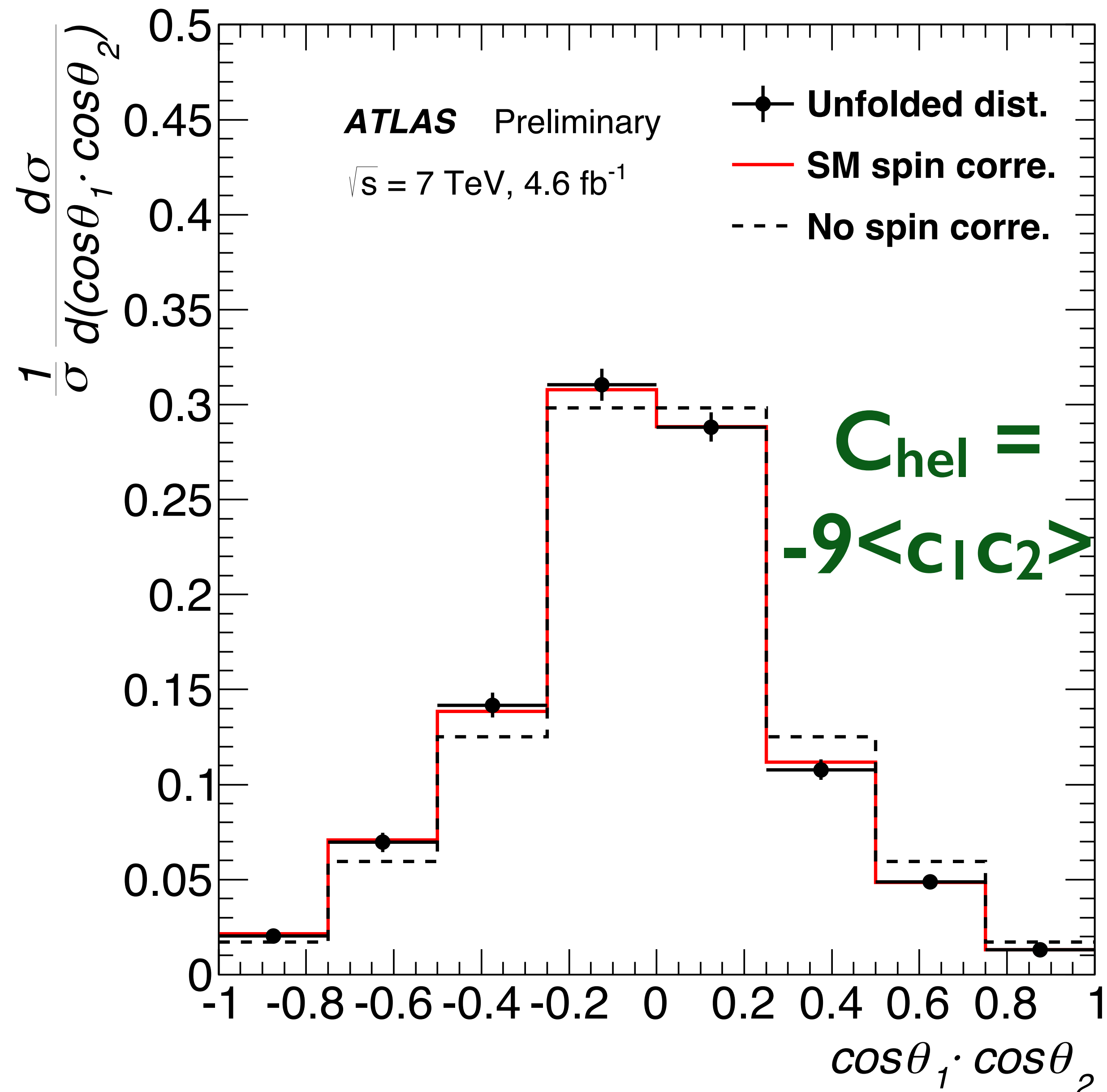
- Template fit to SM+NP to extract Re($\hat{\mu}_t$)
  - **$-0.050 < \mathrm{Re}(\hat{\mu}_t) < 0.076$ (95% CL)** (CMS TOP-14-023)

Direct measurement - ATLAS, 7 TeV

Paper in preparation

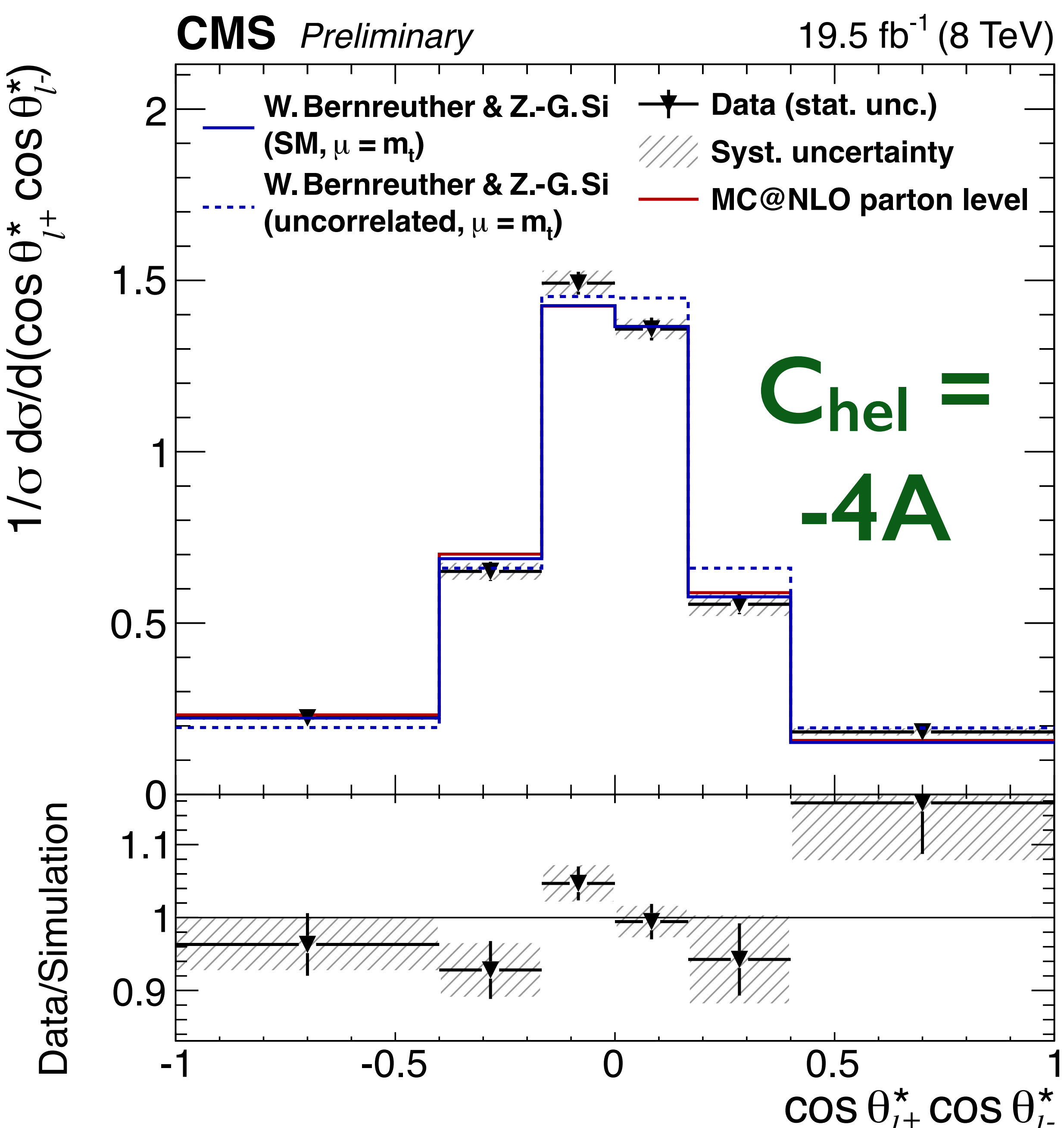
- Direct measurement requires **full $t, \bar{t}$ reconstruction**
- **Lepton directions** in parent top CMs used as a **proxies for the top spins**
  - C_{hel} coefficient from distribution of product of top spins: $\cos\theta^*_{\ell+} \cos\theta^*_{\ell-}$

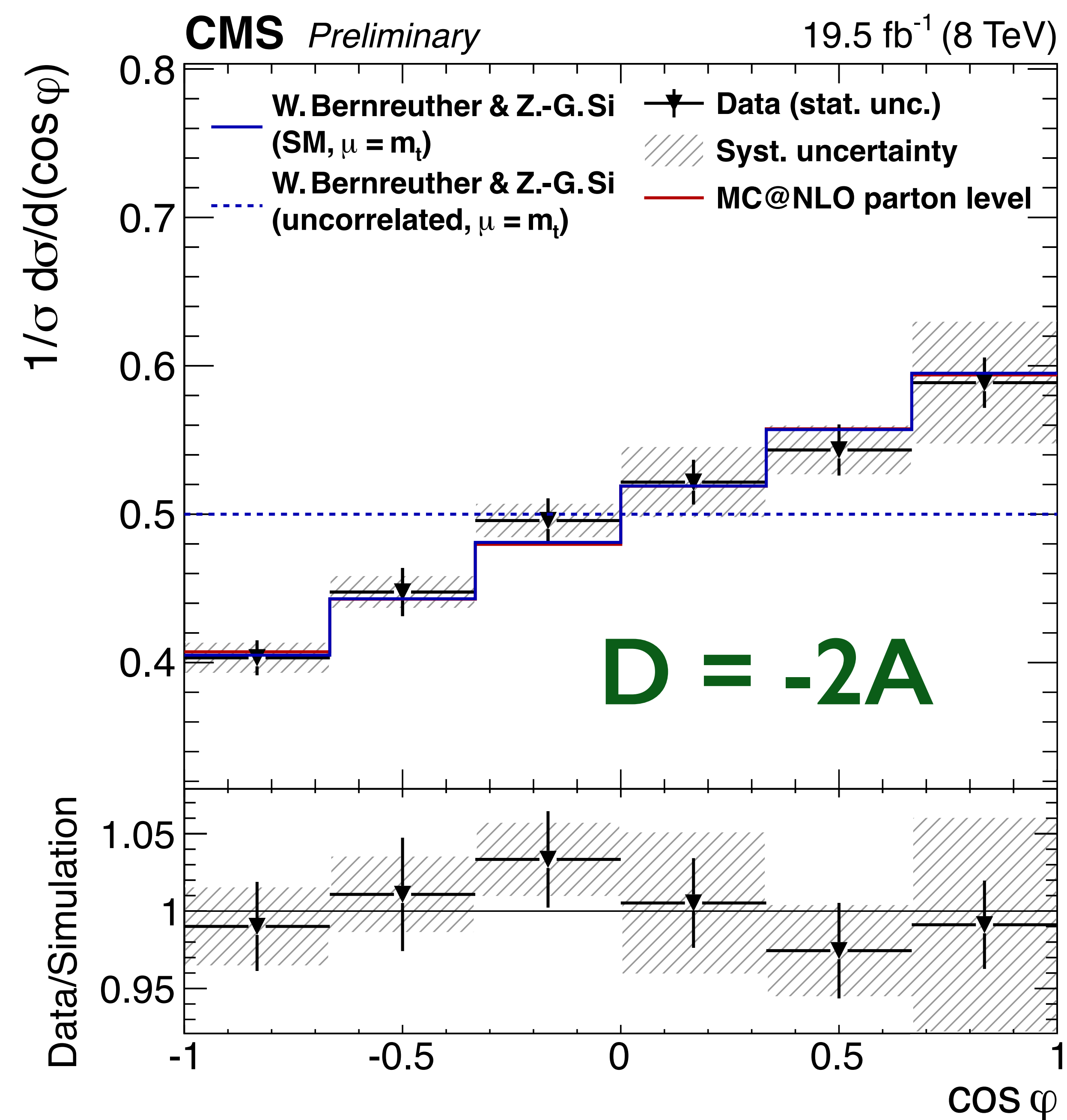




- C_{hel} = **0.315 ± 0.061 ± 0.049**
- f_{SM} = **1.02 ± 0.26** **(unoffical)**

- Direct measurement requires **full $t, \bar{t}$ reconstruction** — CMS TOP-14-023
- **Lepton directions** in parent top CMs used as a **proxies for the top spin**
  - D coefficient from distribution of angle between the spins: $\varphi = \angle(\hat{\ell+}, \hat{\ell-})$

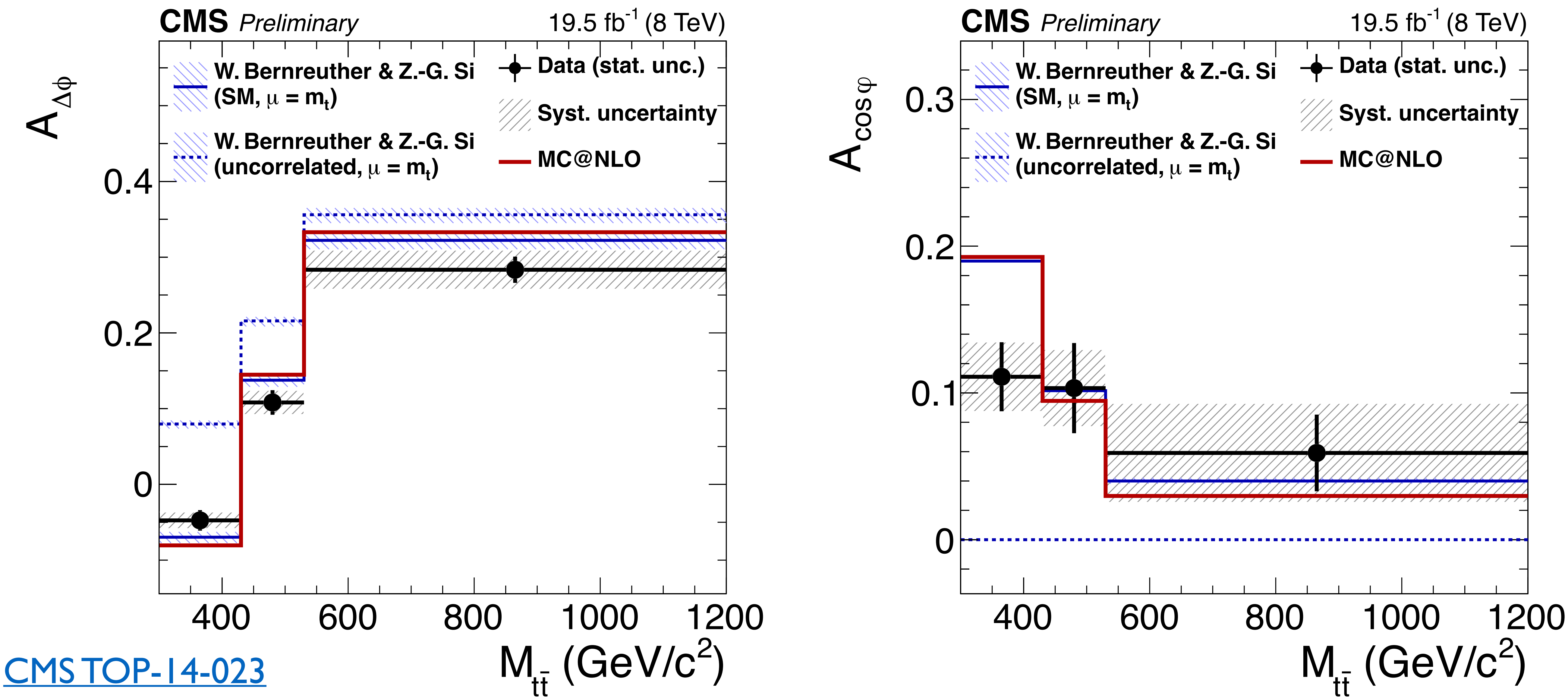




- $f_{SM} = 0.87 \pm 0.27$
- $f_{SM} = 0.90 \pm 0.16$

Differential measurements - CMS, 8 TeV

- Asymmetry variables measured **differentially** wrt $M_{t\bar{t}}, |y_{t\bar{t}}|, p_T^{t\bar{t}}$



CMS TOP-14-023

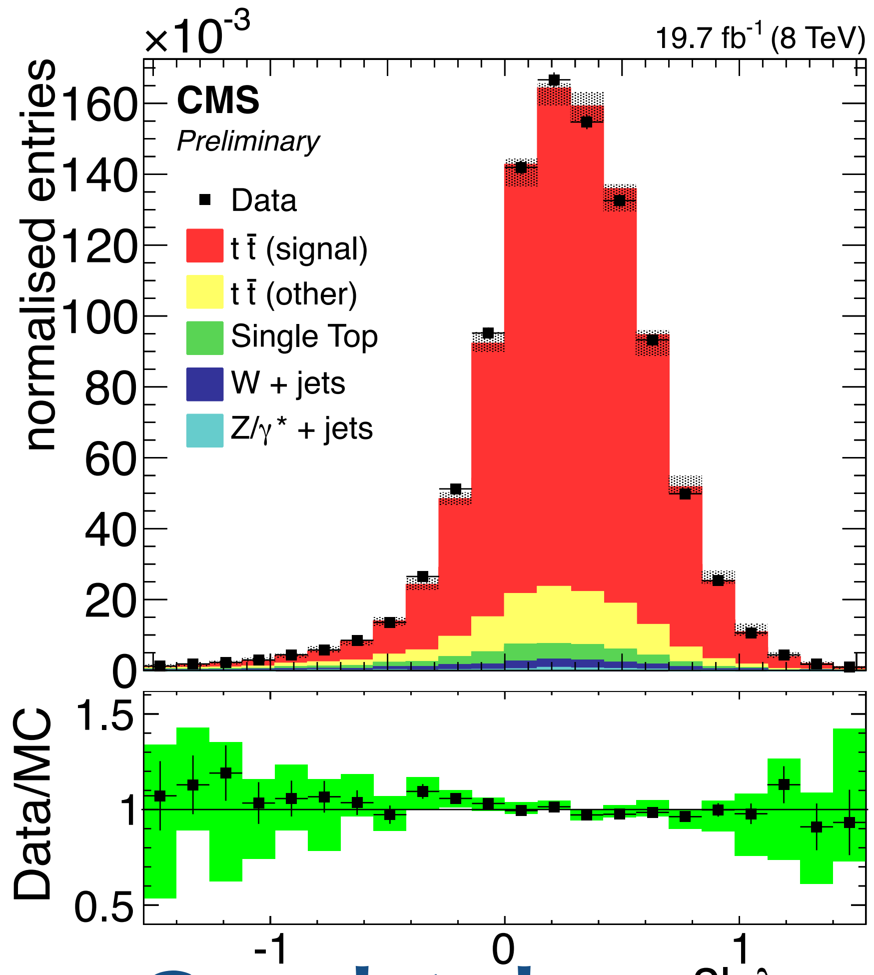
- SM spin correlations have most structure wrt $M_{t\bar{t}}$
- Unfolding wrt $M_{t\bar{t}}$ **minimises the Δϕ top p_T systematic:**
  - **f_{SM} = 1.16 ± 0.15** (but still limited by NLO scale uncertainties)

CMS-PAS-TOP-13-015

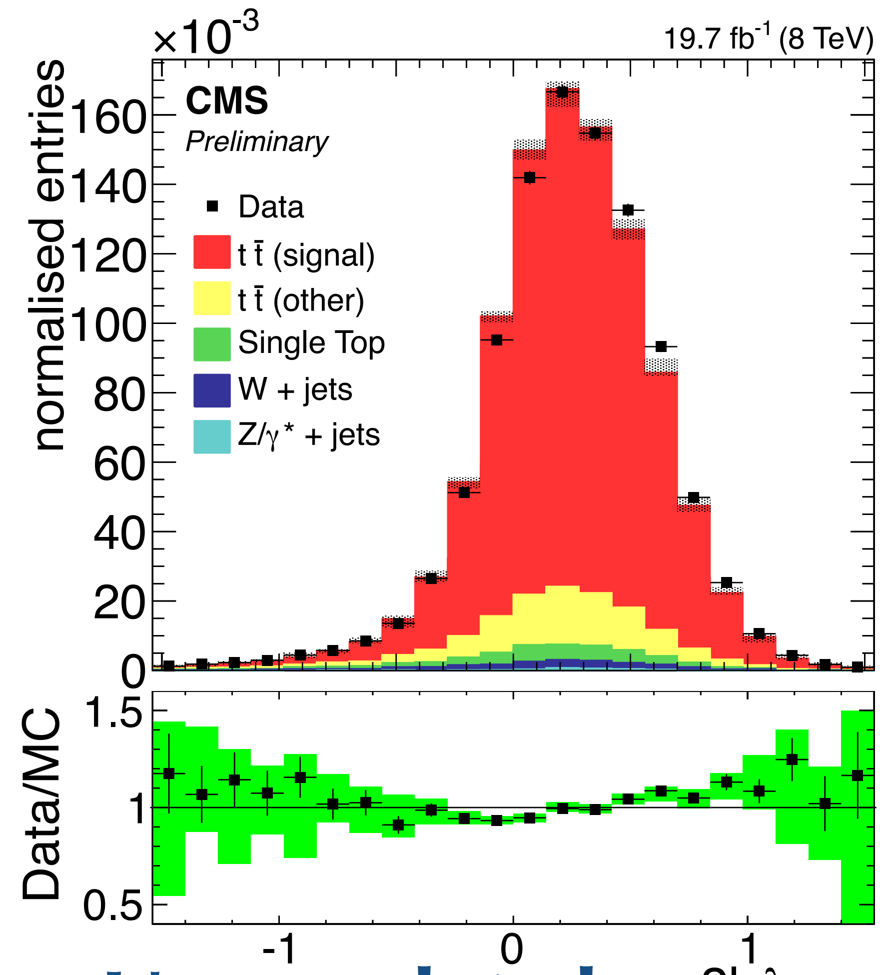
- In 1ℓ events, $\Delta\phi$ distribution is not as sensitive
  - don't know whether light jet is u $(\kappa = -0.31)$ or d $(\kappa = 0.97)$
  - b-jet also has small spin analysing power $(\kappa = -0.39)$
- Use **matrix element method** to extract more information from each event

$$\lambda_{event} = \frac{P_{uncor}}{P_{cor}} = \frac{\text{Event probability using LO \textbf{uncorrelated} ME}}{\text{Event probability using LO \textbf{correlated} ME}}$$

- Create templates using simulated correlated and uncorrelated $t\bar{t}$



Correlated



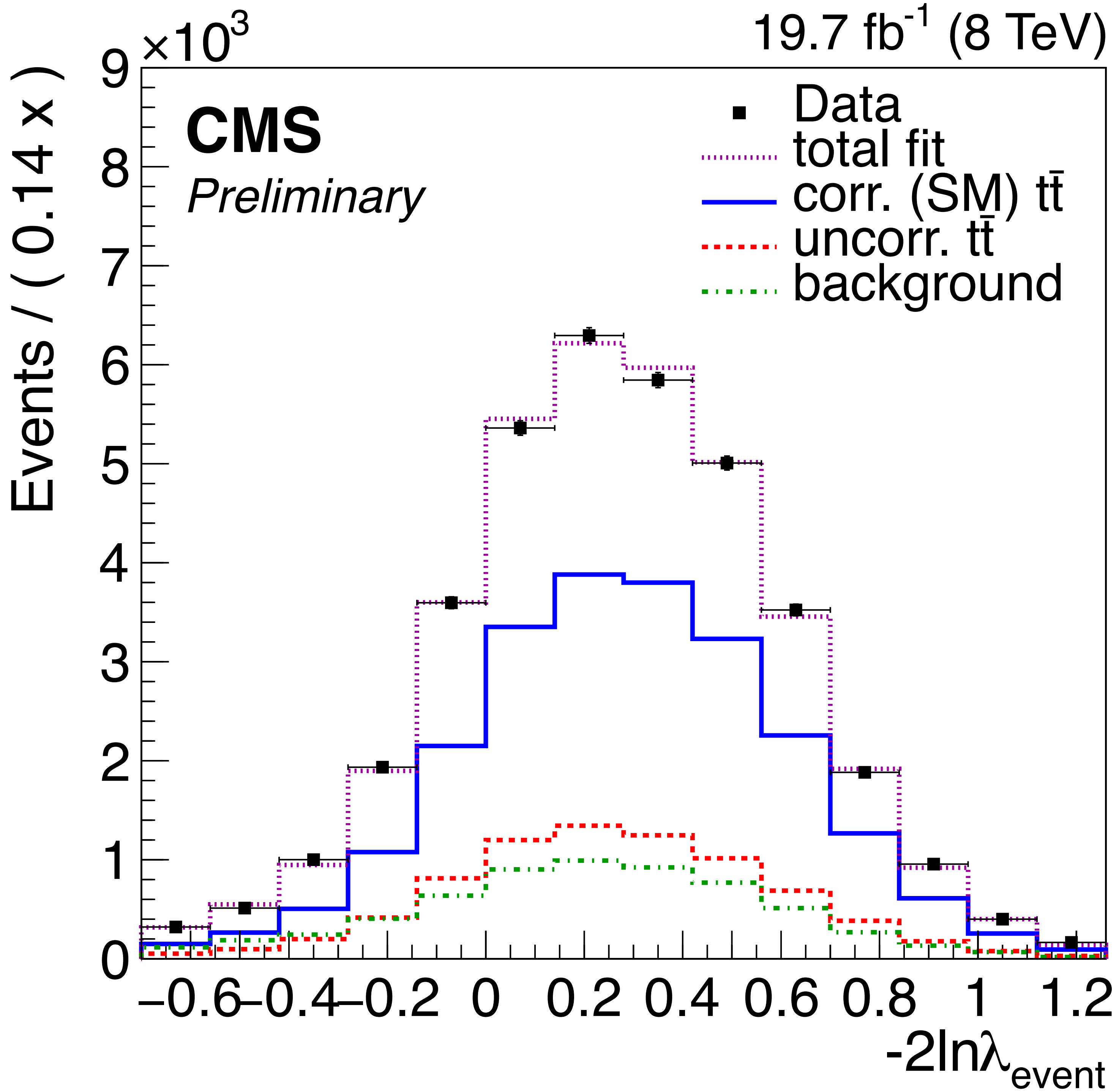
Uncorrelated

Matrix element method results

CMS-PAS-TOP-13-015

- Fit $-2\ln\lambda_{event}$ distribution using **correlated** and **uncorrelated** templates
- Q^2 and JES dominant systematics

$$\lambda_{event} = \frac{P_{uncor}}{P_{cor}}$$



$$f_{SM} = 0.72 \pm 0.09\ (\text{stat})\ ^{+0.15}_{-0.13}\ (\text{syst})$$

Spin correlations summary

- Summary of most precise f_{SM} measurements

Variable	Channel	Collaboration	f_{SM}
$\Delta\phi$	dilepton	ATLAS (8 TeV)	1.20 ± 0.14
ME-based (S-ratio)	dilepton	ATLAS (7 TeV)	0.87 ± 0.18 *
$\Delta\phi$	lepton+jets	ATLAS (7 TeV)	1.12 ± 0.25
$\Delta\phi$	dilepton	CMS (8 TeV)	1.16 ± 0.15
D	dilepton	CMS (8 TeV)	0.90 ± 0.16
ME-based	lepton+jets	CMS (8 TeV)	0.72 ± 0.17

* ATLAS 7 TeV dilepton $\Delta\phi$ measurement has lower relative uncertainty (f_{SM}=1.19±0.20), improved on by 8 TeV result (above)

- All consistent with $f_{SM} = 1$
- $f_{SM} = 0$ strongly disfavoured
- Proof top really behaves like a bare quark!

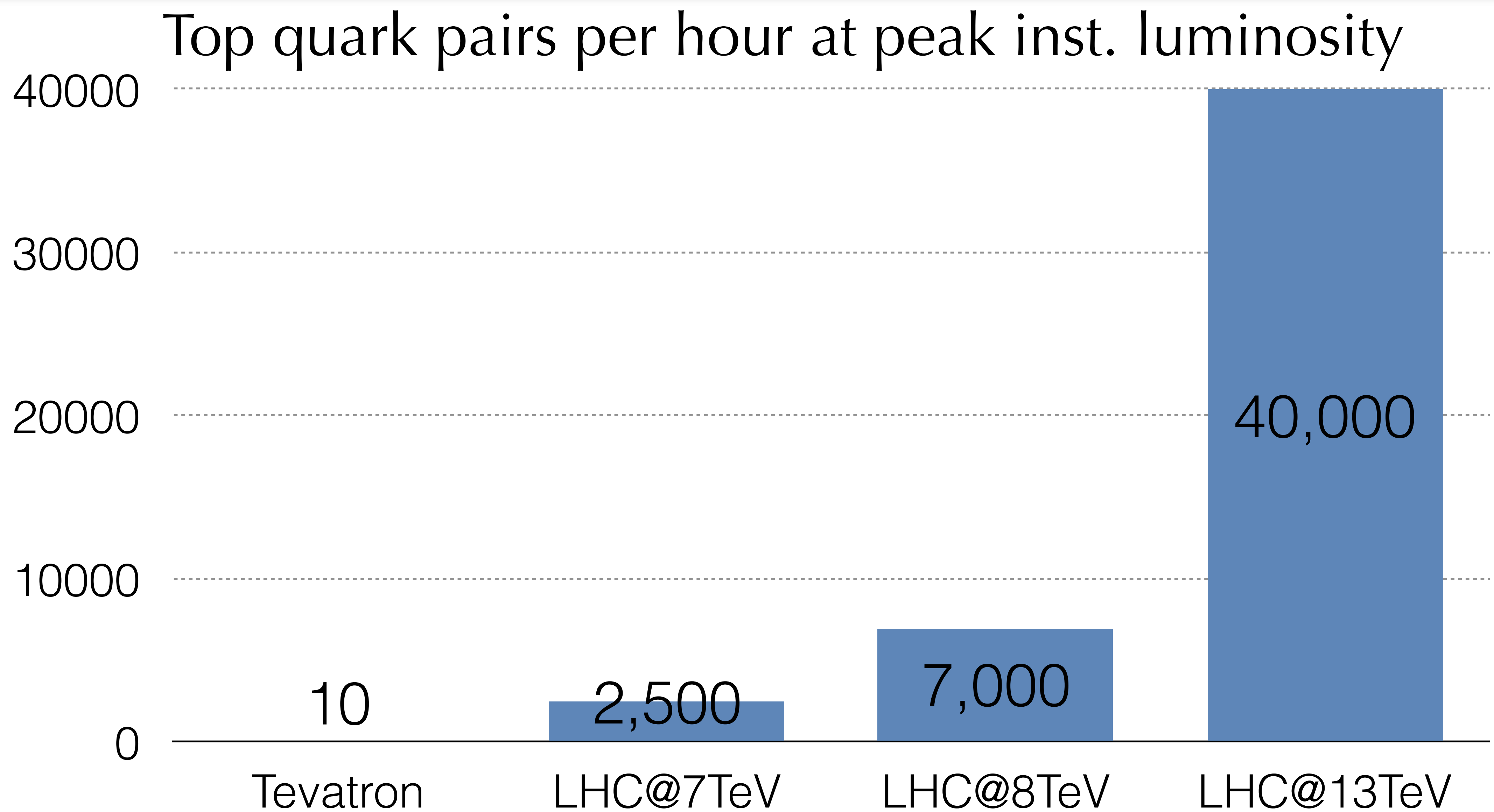
Summary and Outlook

Summary

- Top quark spin variables are an excellent test of the SM and probe for NP
- So far the results are very consistent with SM expectations

- Inclusive measurements systematics limited
  - both experimental and theory systematics
- Differential results mostly still statistics limited

Outlook



cross sections from arXiv:1303.6254: Tevatron ~7pb, LHC@7TeV ~172pb, LHC@8TeV ~246pb, LHC@13TeV ~806pb
peak inst. luminosity: Tevatron: ~$4\times10^{32}cm^{-2}s^{-1}$, LHC@7TeV: ~$4\times10^{33}cm^{-2}s^{-1}$, LHC@8TeV: ~$8\times10^{33}cm^{-2}s^{-1}$, LHC@13TeV: ~$1.3\times10^{34}cm^{-2}s^{-1}$

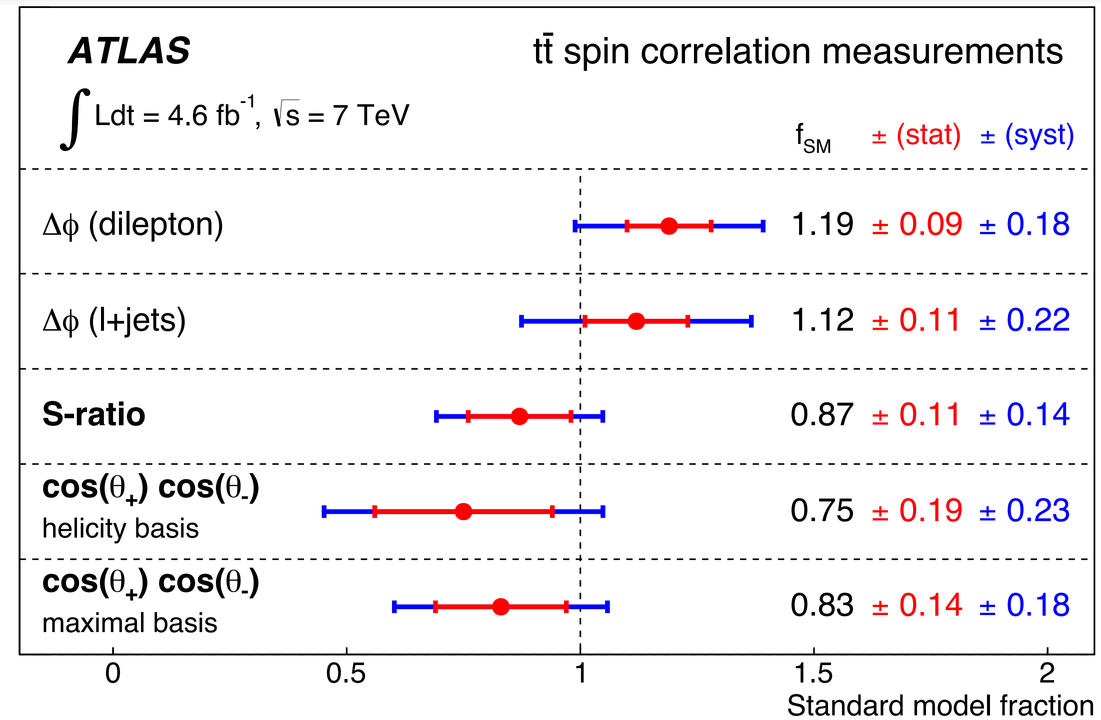
- In Run 2 we have another order of magnitude increase for $t\bar{t}$ pair production
- Improvements in systematic and theoretical uncertainties essential to keep pace
- Could new physics show up first in top spin variables in Run 2?

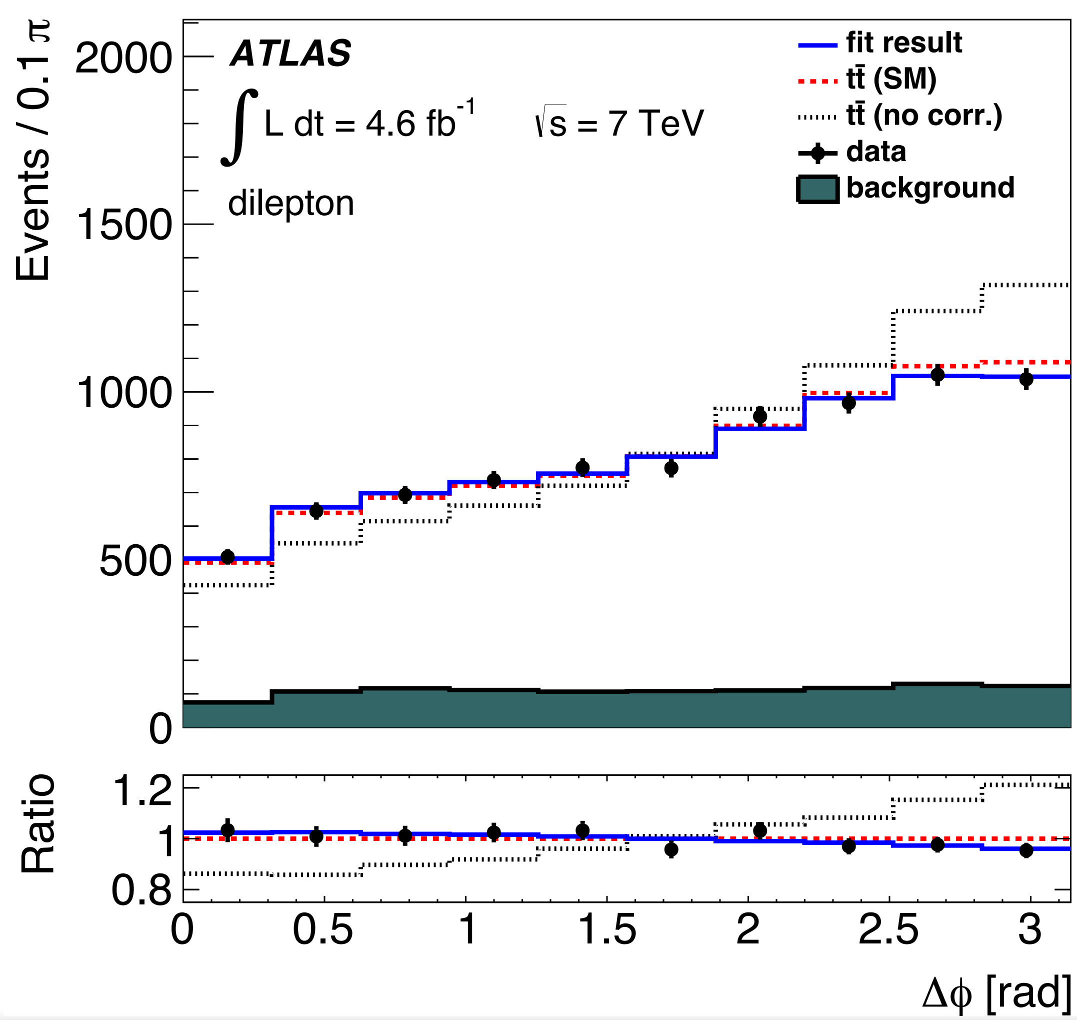
Backup

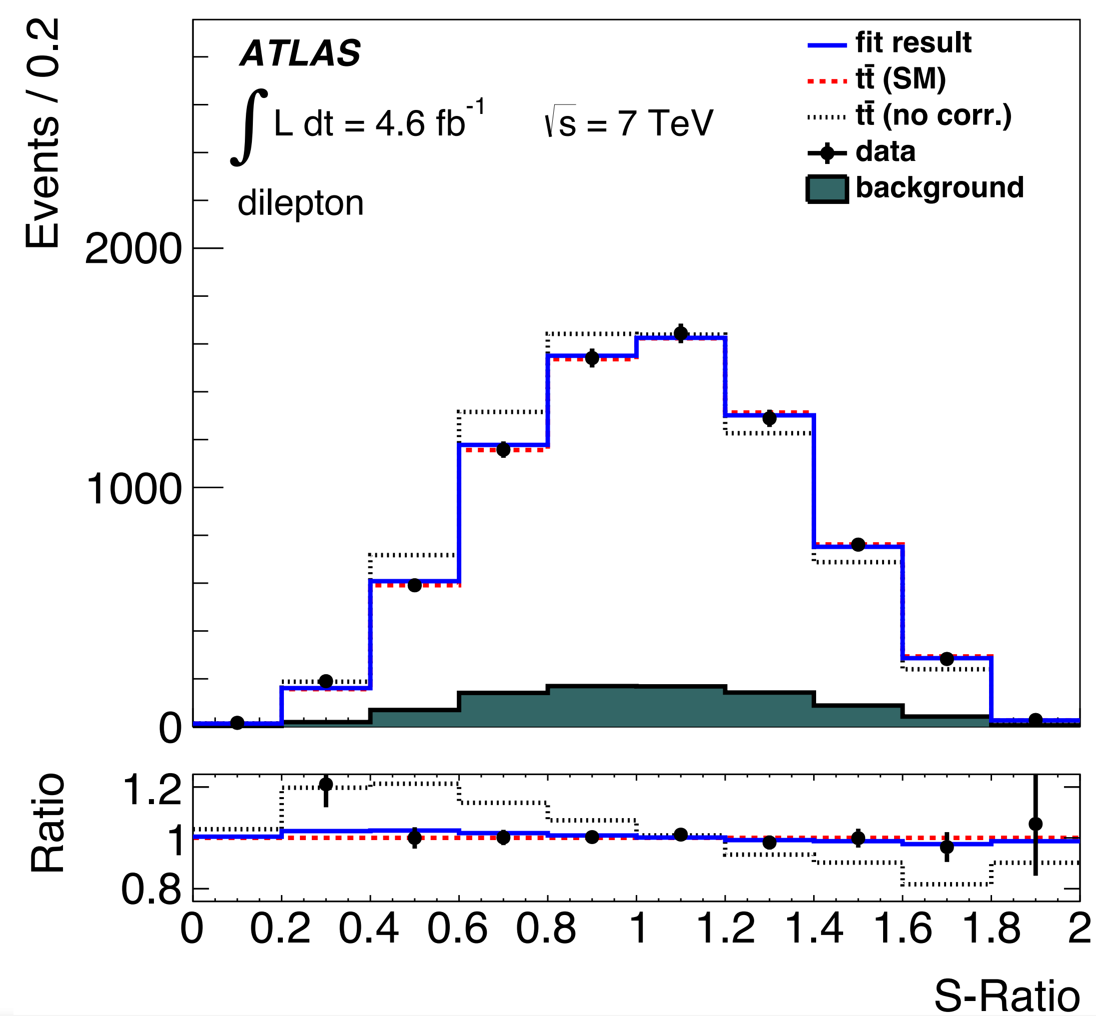
ATLAS spin correlations (1ℓ+2ℓ), 7 TeV

Phys. Rev. D. 90, 112016 (2014)

- ATLAS 7 TeV analysis measured large suite of variables in 1ℓ and 2ℓ channels
  - template fit using simulated correlated and uncorrelated $t\bar{t}$
  - dilepton Δϕ and S-ratio most precise

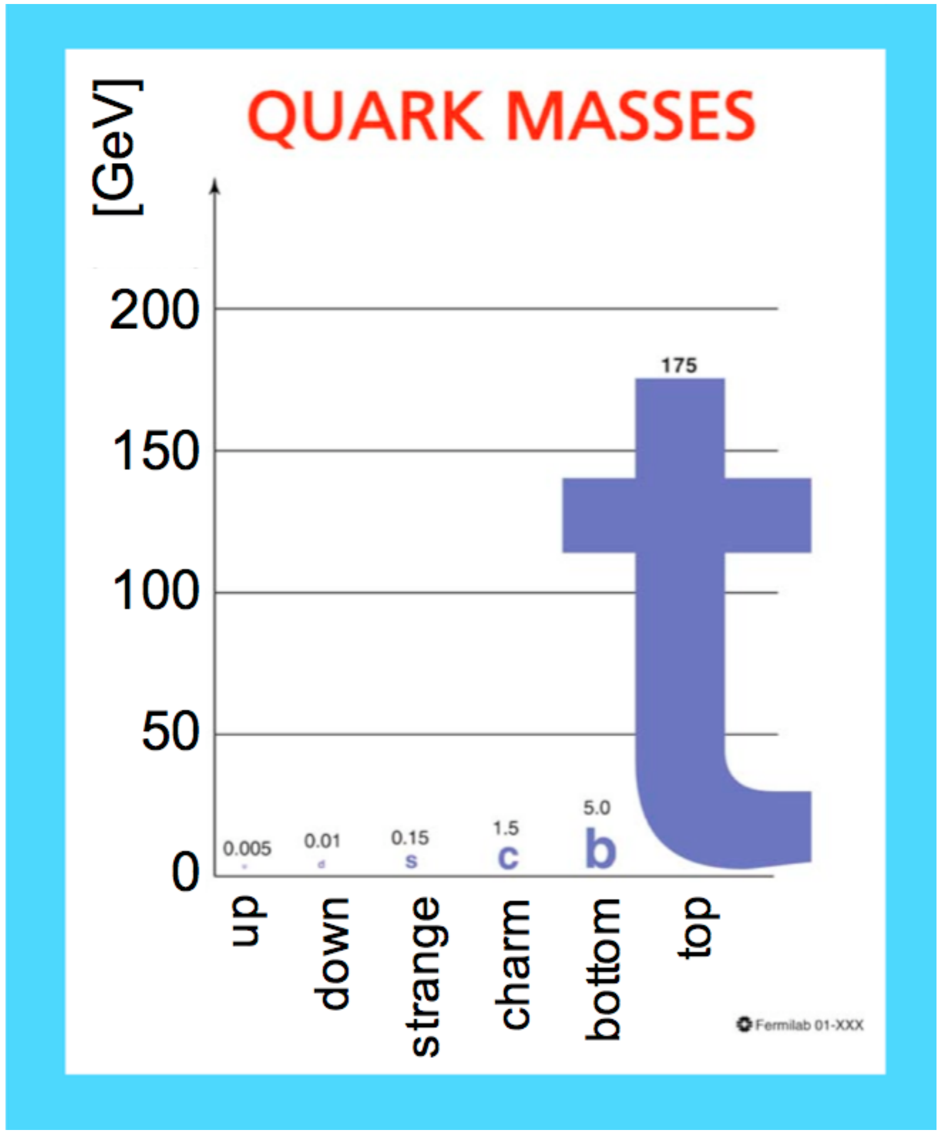


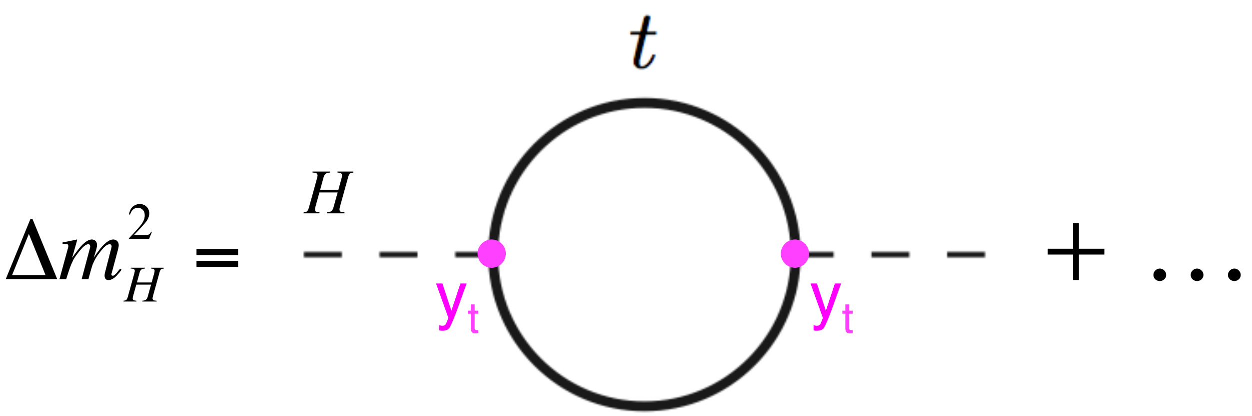




Top quark properties

- Why are **top properties** interesting?
  - top quark **decays before it can form bound states**
    - unique opportunity to study a “bare” quark (using the decay products)
  - **heaviest elementary particle known** ($m_t \sim 173$ GeV)
    - large coupling to Higgs boson suggests special role in EWSB
  - top properties measurements test SM and **probe new physics**

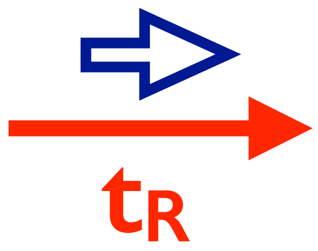




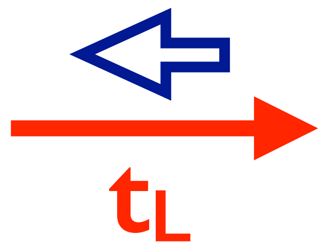
Top quark spin and helicity

- The measurements rely on an understanding of the helicities of the top quarks we produce
  - reminder: helicity is the particle's spin component along its momentum direction
- I'll denote particle momenta and spin directions with solid and open arrows:

Right-handed top quark



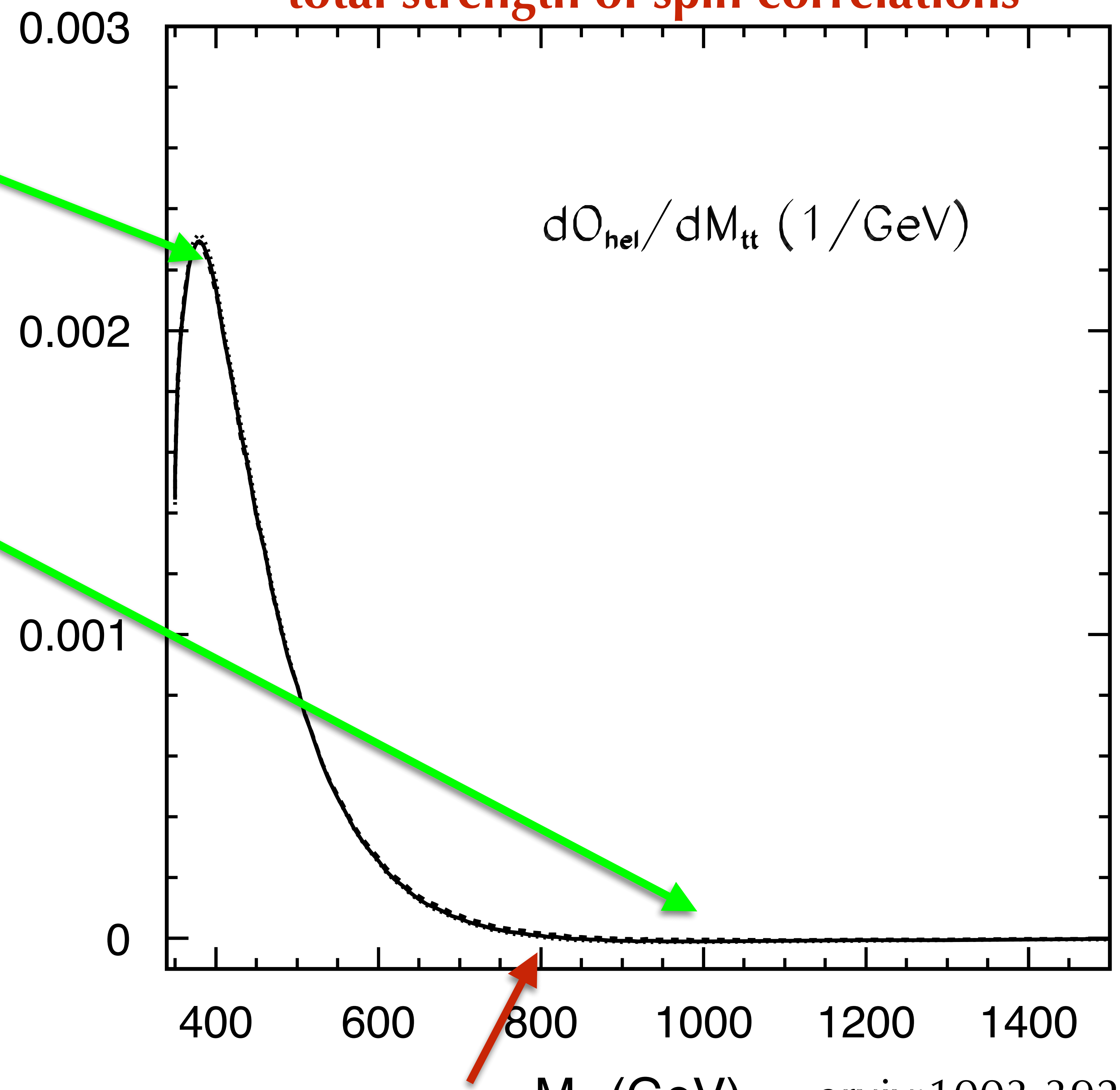
Left-handed top quark



SM spin correlations

- **Same helicity** contribution is **dominant near threshold**
- Opposite helicity becomes dominant when $E_t >> m_t$
  - helicity conservation
- Net spin correlation strength of **~30%** (LHC)

M_{tt} dependence of contributions to total strength of spin correlations



change of sign

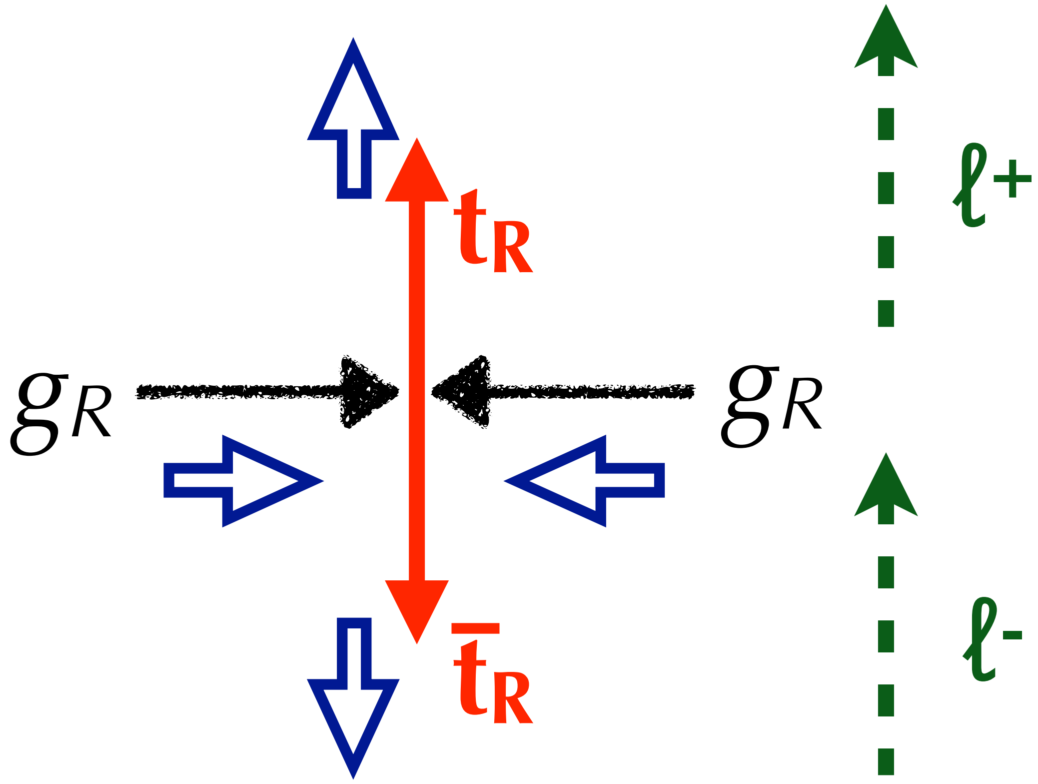
arxiv:1003.3926

SM spin correlations

- Initial state and invariant mass dependence of spin correlations makes them a **rich process to test our understanding of perturbative QCD**
  - future very high precision measurements sensitive to proton quark and gluon content

Measuring spin correlations

- **Direct measurement** of spin correlations requires **full reconstruction of t and $\bar{t}$**
- **Can we try something more simple?**
- Choose dilepton final state (charged leptons best spin analysers)
- Preferred lepton directions in the top rest frames given by top spins:

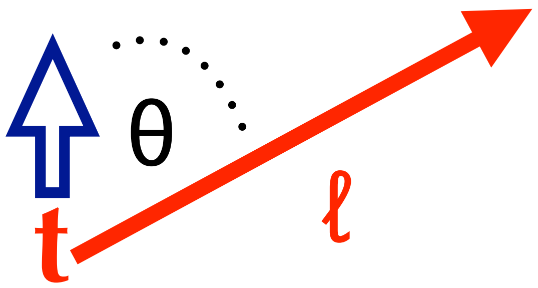


Same helicity gluons
Positive spin correlations

$\ell^{\pm}$ angular distributions:

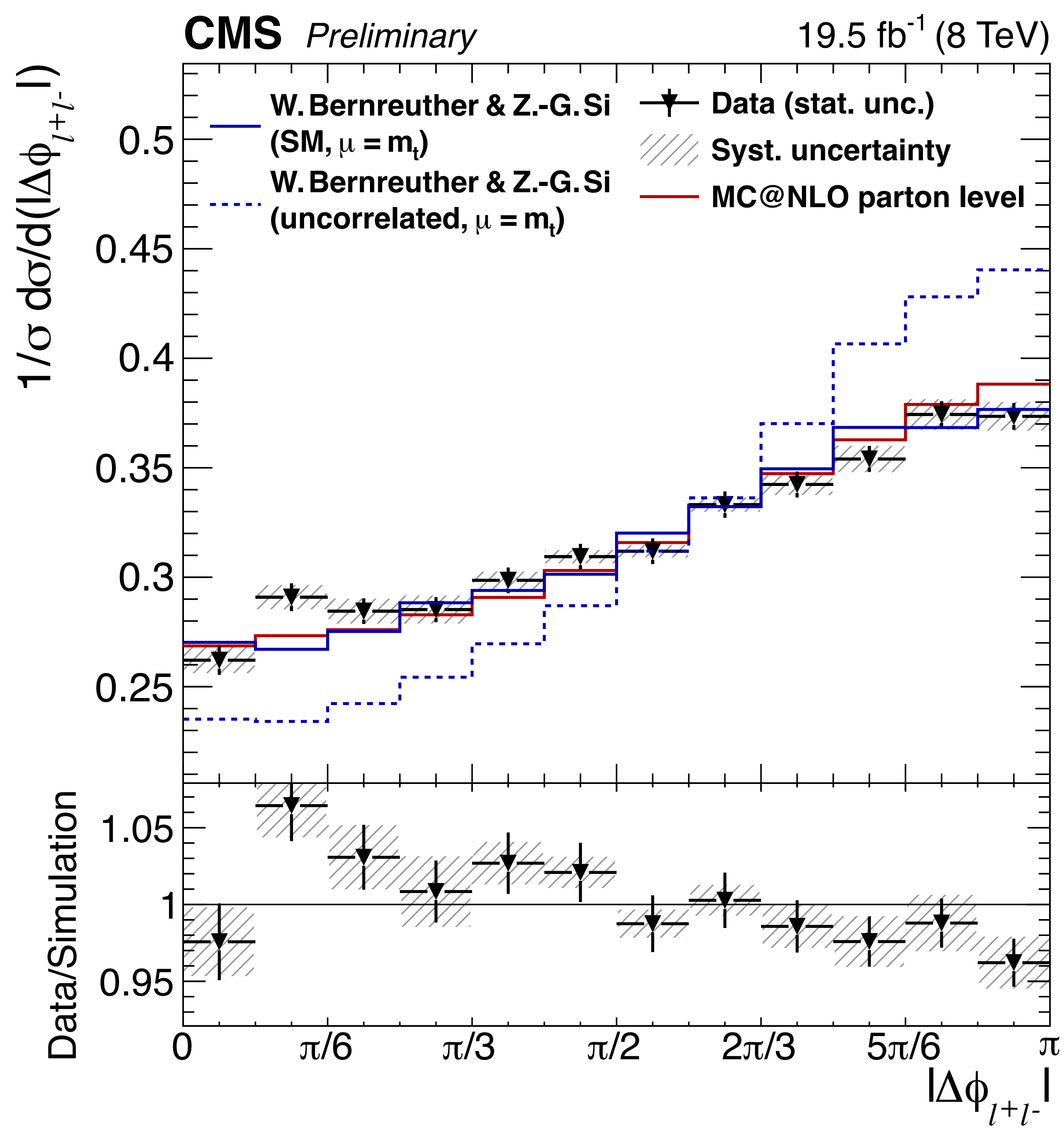
$$(1 \pm \cos\theta)/2$$

(parity violating weak decay)

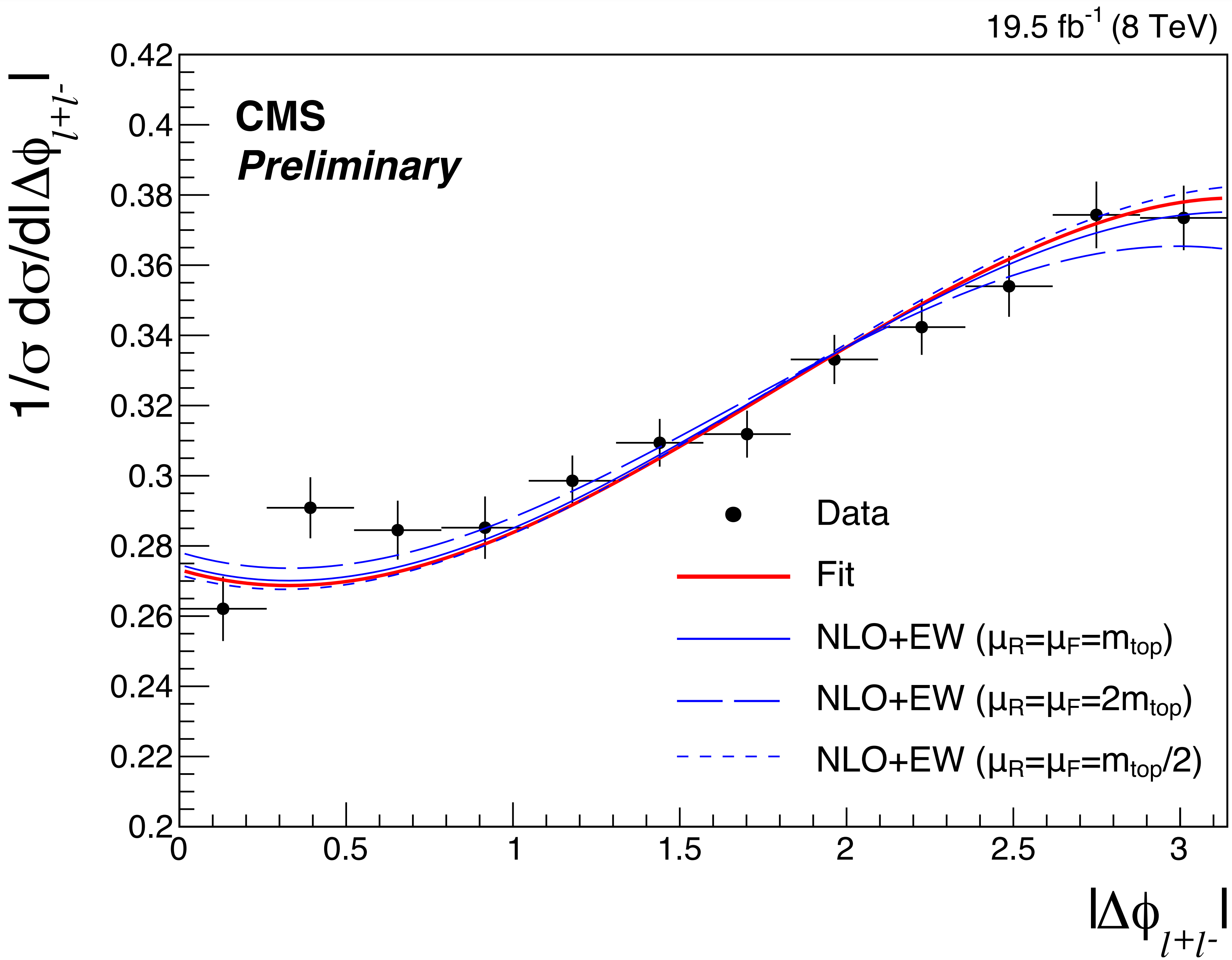


Δϕ interpretation

- Can reinterpret measured Δϕ distribution in terms of new physics that affects spin correlations
  - In general, new physics in $t\bar{t}$ production **due to heavy particle exchange** manifests as a **colour dipole coupling of top to gluons**
    - **modifies the expected spin correlations**
  - Supersymmetry
    - top quarks and antiquarks produced from **decay of scalar (spin0) particles** have **no way of being correlated**



Anomalous top CMDM results



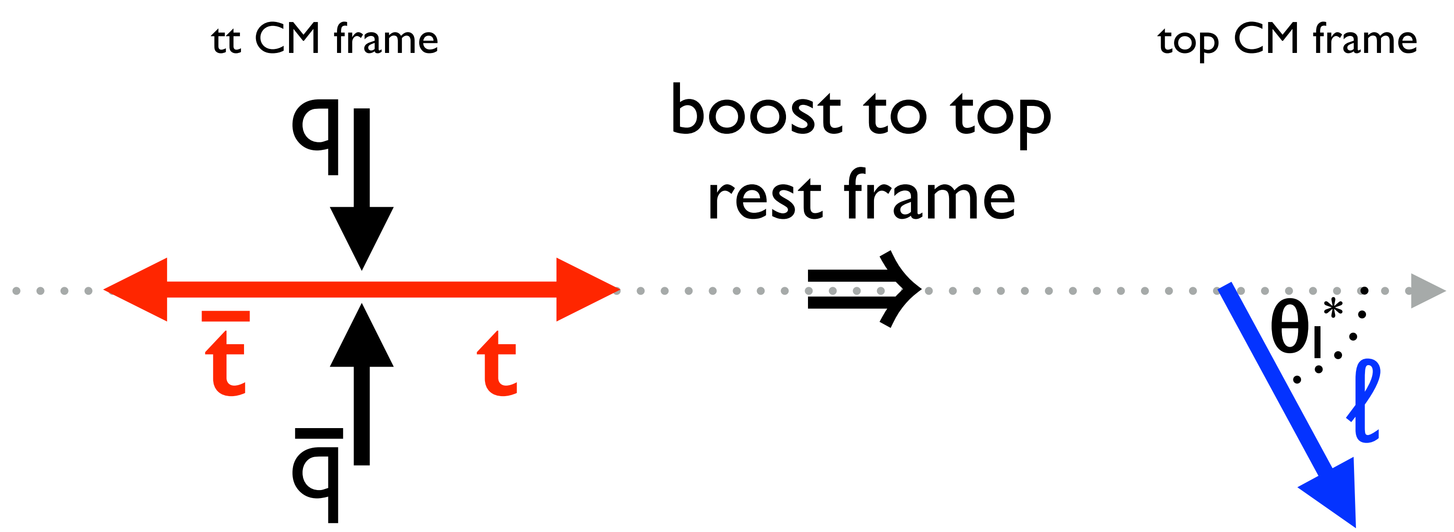
- A value of $\mathrm{Re}(\hat{\mu}_t)$ outside the range $-0.050 < \mathrm{Re}(\hat{\mu}_t) < 0.076$ is excluded at 95% CL
  - competitive with existing limits $\left(\tilde{\mu}_t = \frac{g_s}{m_t}\hat{\mu}_t\right)$
  - uncertainty dominated by scale variations in the theoretical predictions

Direct measurement of spin correlations

- Spin correlation quantified by relative numbers of same and opposite helicity $t\bar{t}$ pairs:

$$C \equiv \frac{\sigma(t_R\bar{t}_R + t_L\bar{t}_L) - \sigma(t_R\bar{t}_L + t_L\bar{t}_R)}{\sigma(t_R\bar{t}_R + t_L\bar{t}_L) + \sigma(t_R\bar{t}_L + t_L\bar{t}_R)}$$ "spin correlation coefficient"

- Lepton direction favours top spin direction, with distribution $(1 \pm \cos\theta^*_\ell)/2$
  - the measured $\cos\theta^*_\ell$ is a proxy for the top helicity (diluted by a factor of 2)



- Measure $\cos\theta^*_\ell$ for **both tops** in each event, and take the product ("c_1c_2")
  - $$A_{c_1c_2} = \frac{N(c_1 \cdot c_2 > 0) - N(c_1 \cdot c_2 < 0)}{N(c_1 \cdot c_2 > 0) + N(c_1 \cdot c_2 < 0)}$$ = -C/4
    - factor 1/4 because our helicity measurement is diluted by a factor of 2 for each top