$t\bar{t}$ Spin Correlation at the LHC

Christian Schwanenberger

University of Manchester

on behalf of the ATLAS Collaboration

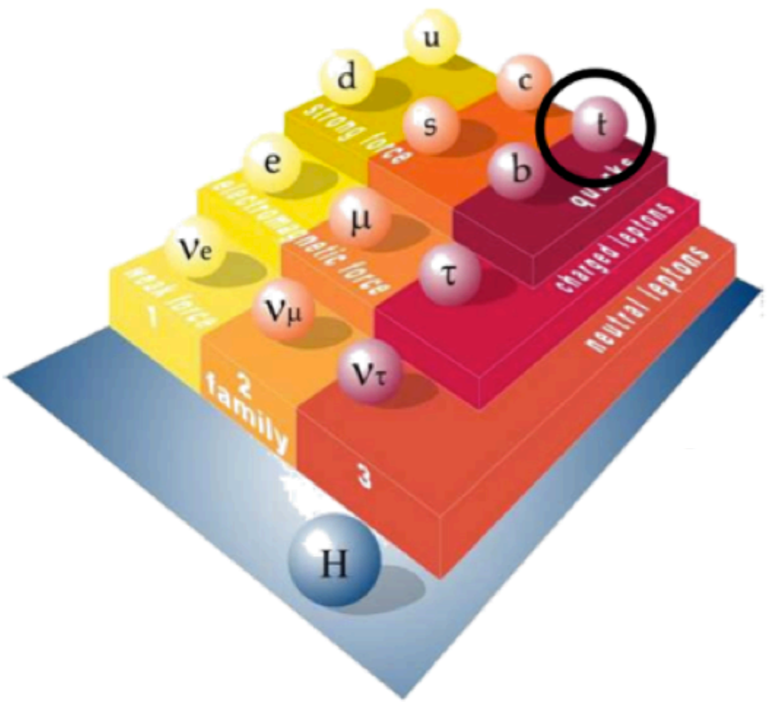
4th International Workshop on Top Quark Physics (TOP 2011)

Sant Feliu de Guixols

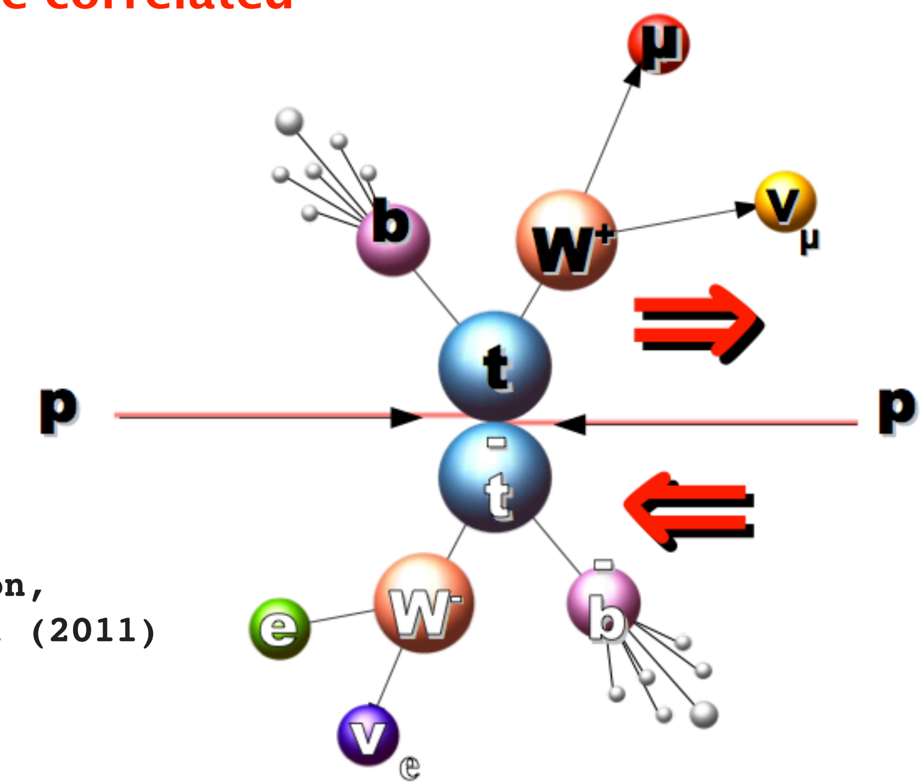
Spain

29 September 2011

Top Pair Spin Correlation



- top quark: discovered in 1995 by CDF&DØ
- does the top quark have spin 1/2?
- top quark pair production: top quarks are not polarised, but spin of top and anti-top quarks are correlated



- top quarks have short lifetime:

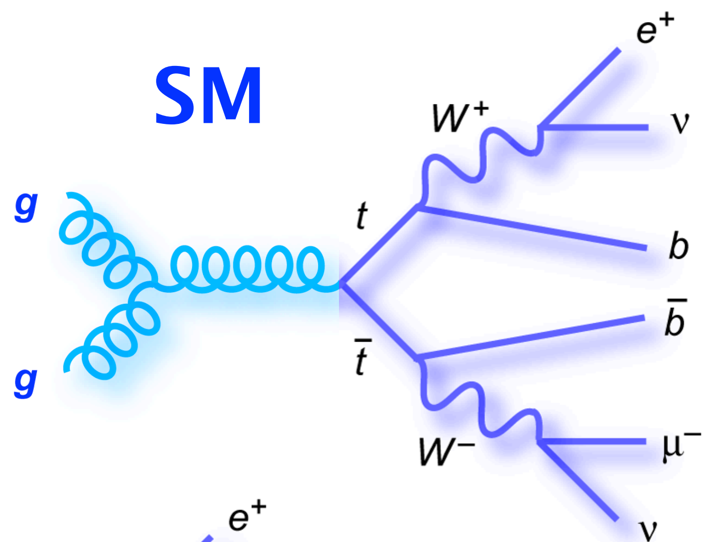
$$\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}\ \mathrm{s}$$

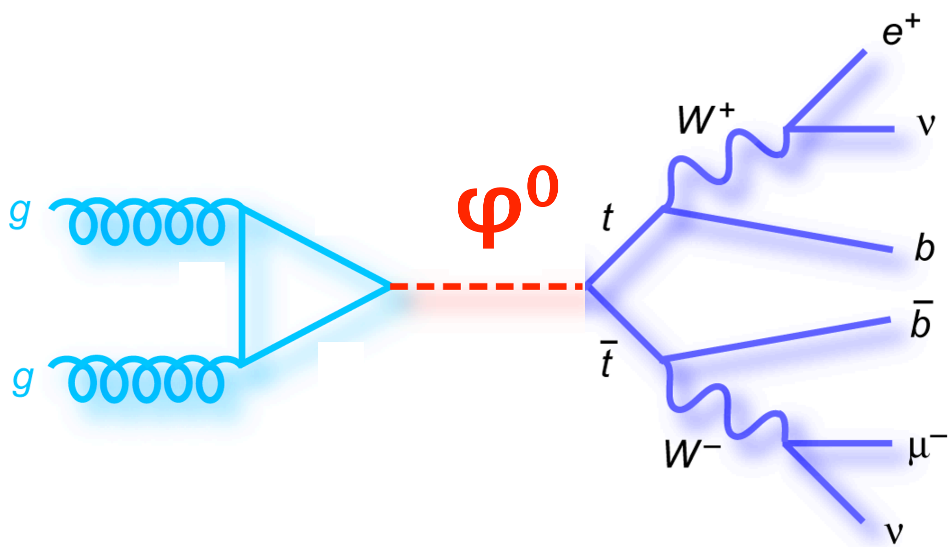
DØ Collaboration, PRL 106, 022001 (2011)

- decay before spins can flip
- spin information is contained in decay product
- measure $t\bar{t}$ spin correlation: consistent with SM prediction for a spin 1/2 particle?

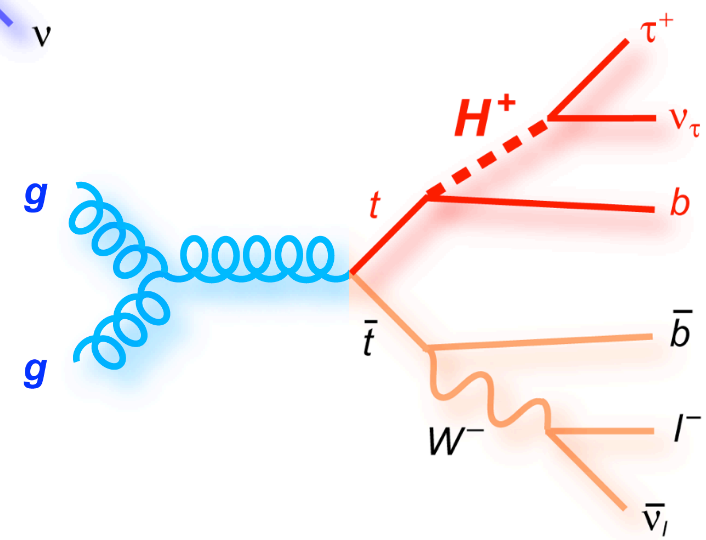
New physics impact on spin correlations

- important test of SM and sensitive search for physics beyond
- analyse the whole chain of top pair production and top decay





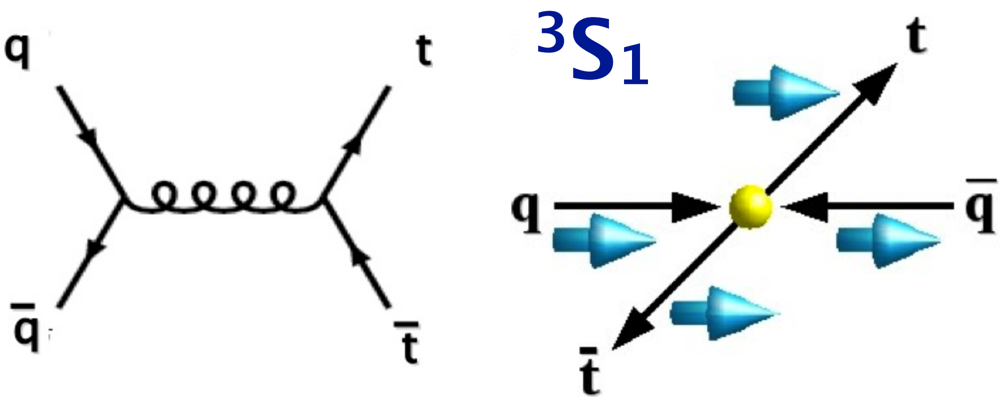
Higgs, KK gravitons, Z’, stop pairs, ...



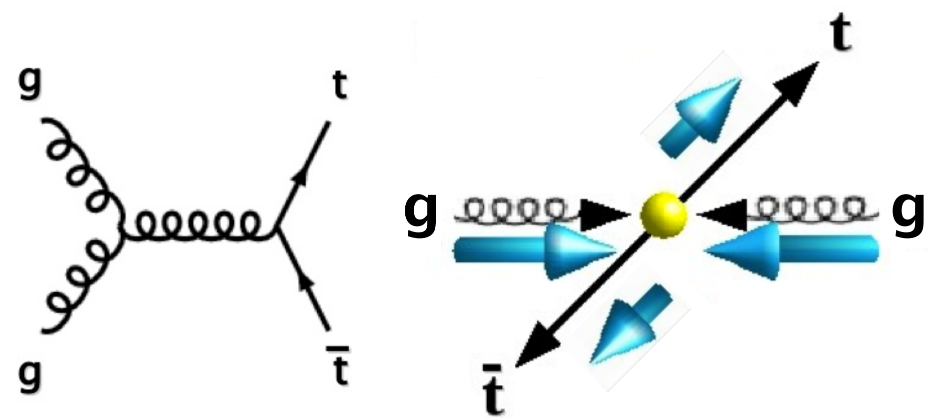
charged Higgs, b’, ...

Spin correlation strength

$$A=\frac{N_{\uparrow\uparrow}+N_{\downarrow\downarrow}-N_{\uparrow\downarrow}-N_{\downarrow\uparrow}}{N_{\uparrow\uparrow}+N_{\downarrow\downarrow}+N_{\uparrow\downarrow}+N_{\downarrow\uparrow}}$$



Tevatron



LHC

Tevatron

- dominated by $q\bar{q}$ annihilation
- $t\bar{t}$ pairs close to the threshold
- beam axis as spin quantisation axis
  NLO QCD: A = 0.78
- optimised "off-diagonal" basis

LHC

- dominated by gg fusion
- $t\bar{t}$ pairs far off the threshold
- helicity basis as spin quantisation axis
  NLO QCD: A = 0.32
- maximal basis

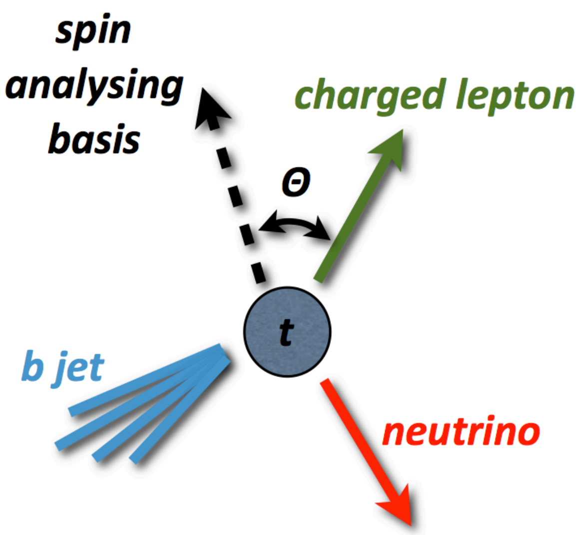
Bernreuther, Brandenburg, Si, Uwer, Nucl. Phys. B690, 81 (2004)

complementary between Tevatron and LHC

Polarisation power

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i}=\frac{1}{2}(1+\alpha_i\cos\theta_i)$$

in $t\bar{t}$ ZMF frame



in top quark rest frame

dilepton channel promises largest sensitivity

Brandenburg, Si, Uwer,
Phys. Lett. B539, 235 (2002)

	b-quark	W^+	l^+	$\bar{d}$-quark or $\bar{s}$-quark	u-quark or c-quark
α_i (LO)	-0.41	0.41	1	1	-0.31
α_i (NLO)	-0.39	0.39	0.998	0.93	-0.31

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2}=\frac{1}{4}(1-C\cos\theta_1\cos\theta_2)$$

$$\text{where } C=A\alpha_1\alpha_2$$

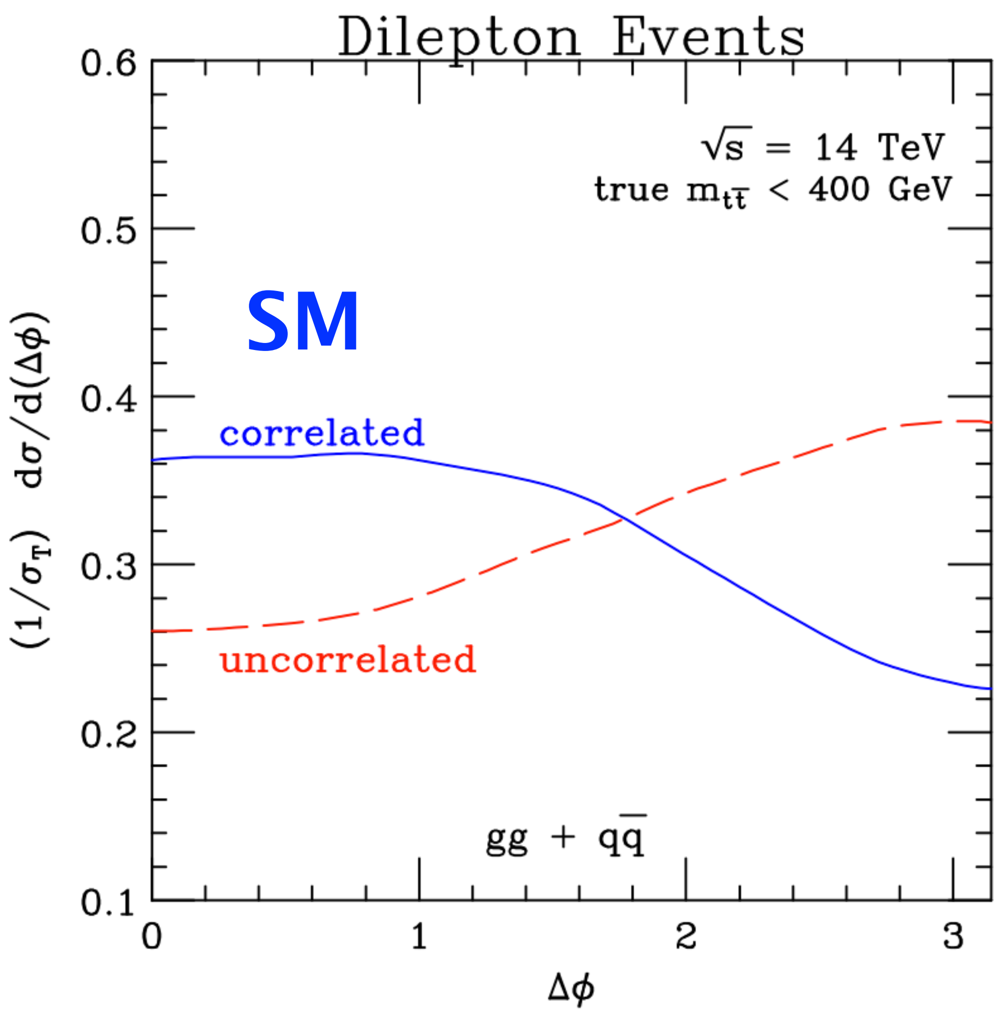
linear extraction:

A=C

Simple angular correlation

- $\cos\theta_1\cos\theta_2$: boost into top and anti-top rest frame requires event reconstruction
- difficult since kinematics is underconstrained due to 2 neutrinos

→ use azimuthal angle between charged leptons in lab frame (works well for LHC)



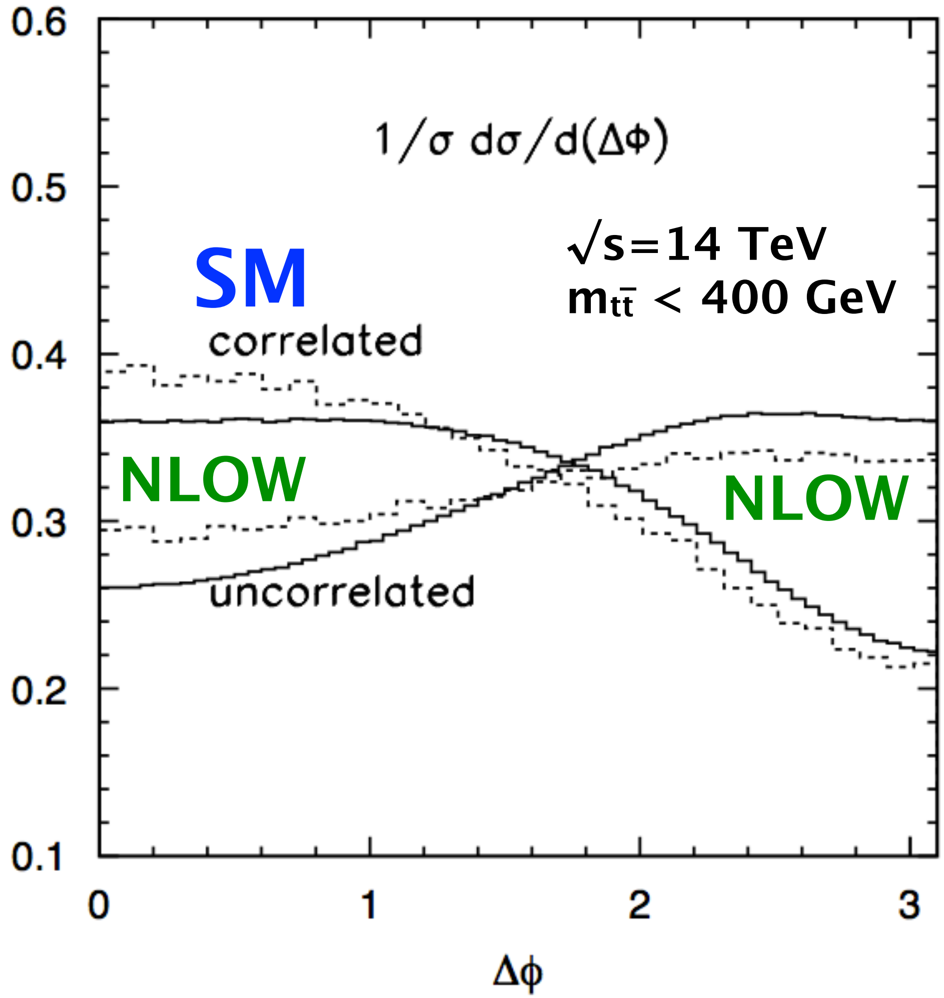
Mahlon, Parke, PRD D81, 074024 (2010)

Simple angular correlation

- $\cos\theta_1\cos\theta_2$: boost into top and anti-top rest frame requires event reconstruction
- difficult since kinematics is underconstrained due to 2 neutrinos

→ use azimuthal angle between charged leptons in lab frame (works well for LHC)

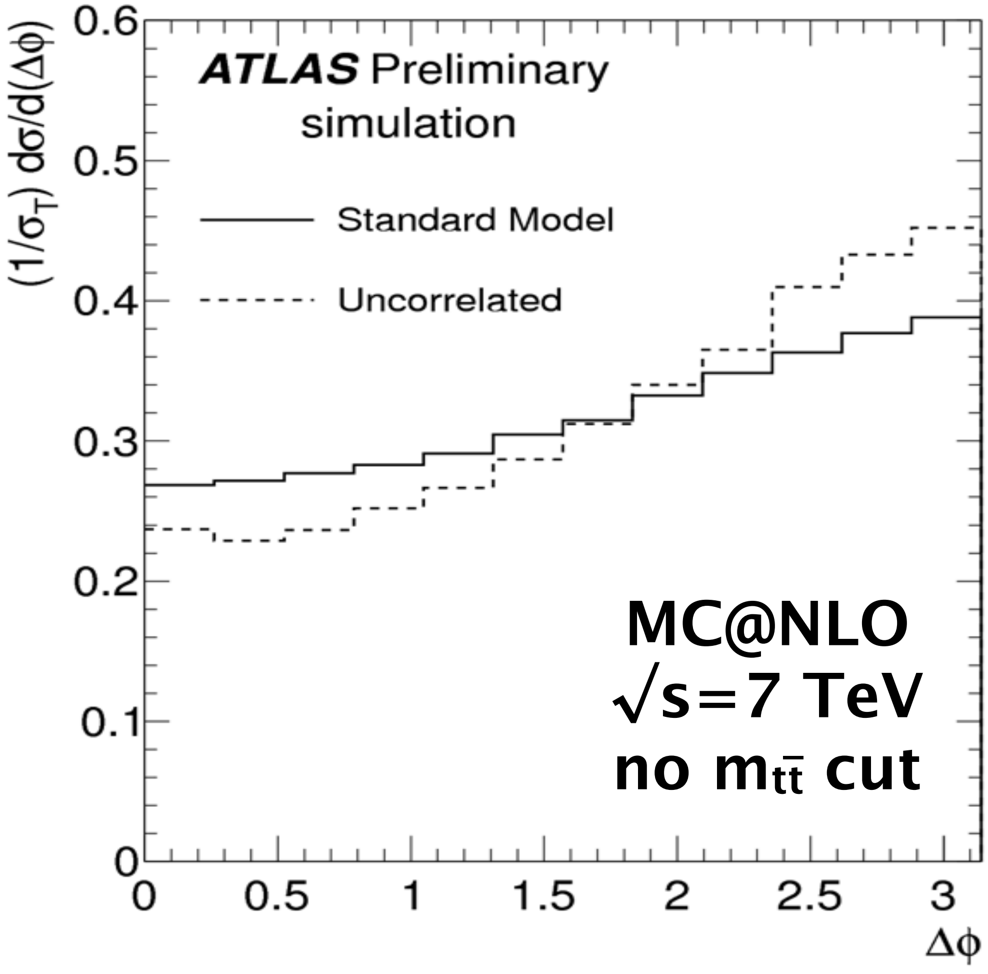
Bernreuther, Si, Nucl. Phys. B837, 90 (2010)



Simple angular correlation

- boost into top and anti-top rest frame requires top and anti-top reconstruction
- difficult since kinematics is underconstrained due to 2 neutrinos

→ use azimuthal angle between charged leptons in lab frame (works well for LHC)



measure by template fit to data assuming 2 hypotheses:

- SM correlation: N_{SM} events
- no correlation: N_0 event
- any mixing fraction of N_{SM} or N_0

$$f^{SM} = N_{SM} \,/\, (N_{SM} + N_0)$$

$$A^{SM} = A^{SM}_{theory} \cdot f^{SM}$$

helicity $h = \vec{S} \cdot \hat{p}, \qquad \hat{p} = \vec{p}/|\vec{p}|$

and maximal basis

Event Selection

identical to dilepton cross section measurement

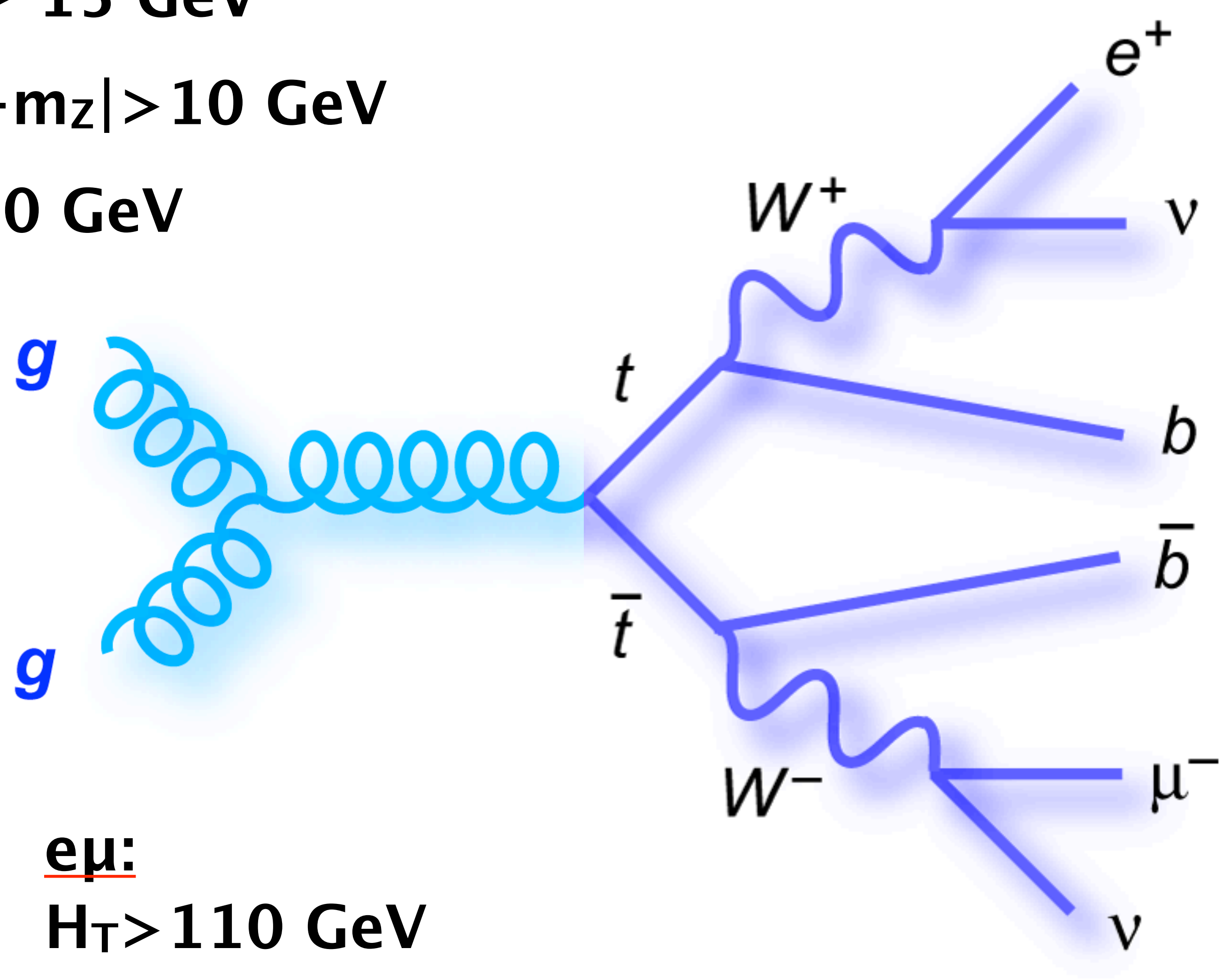
0.70 fb^{-1}

ee, μμ:

$m_{\ell\ell} > 15$ GeV

$|m_{\ell\ell} - m_Z| > 10$ GeV

$\not{E}_T > 60$ GeV



e^+: $p_T > 25$ GeV

b: $p_T > 25$ GeV

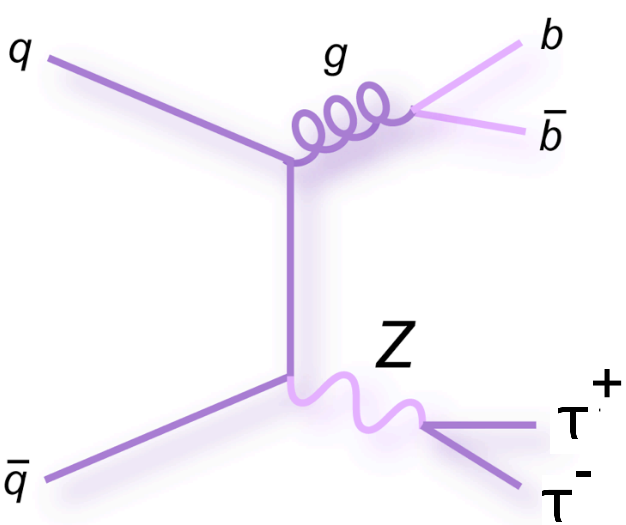
$\bar{b}$: $p_T > 25$ GeV

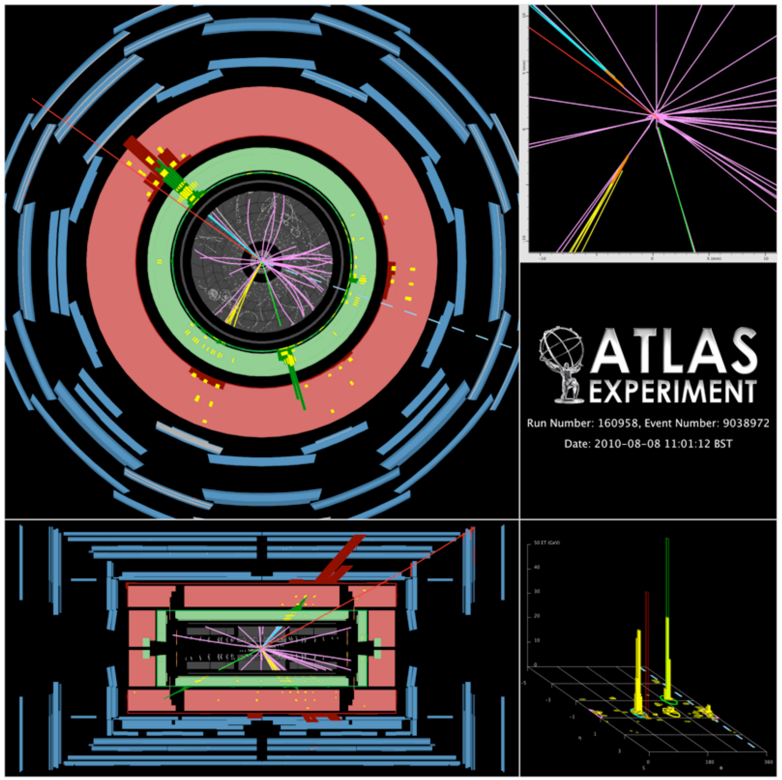
μ^-: $p_T > 20$ GeV

eμ:

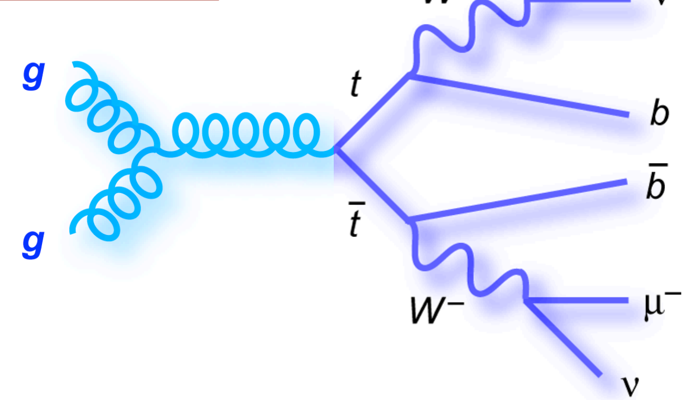
$H_T > 110$ GeV

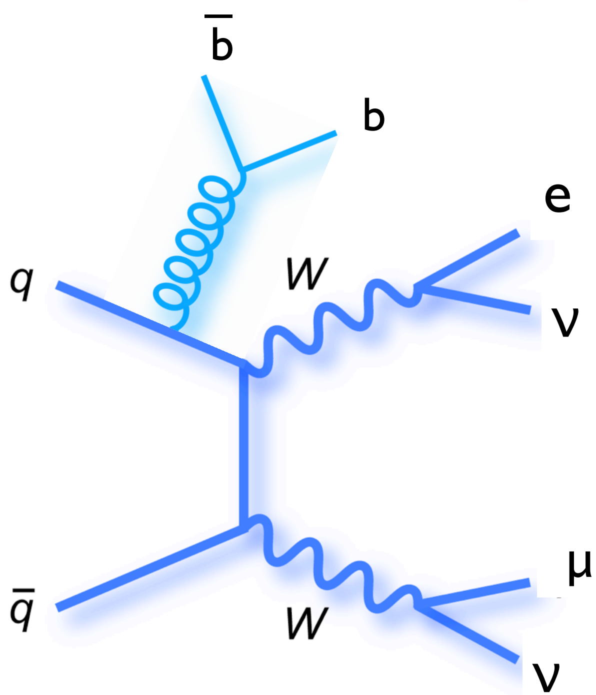
Signal and background

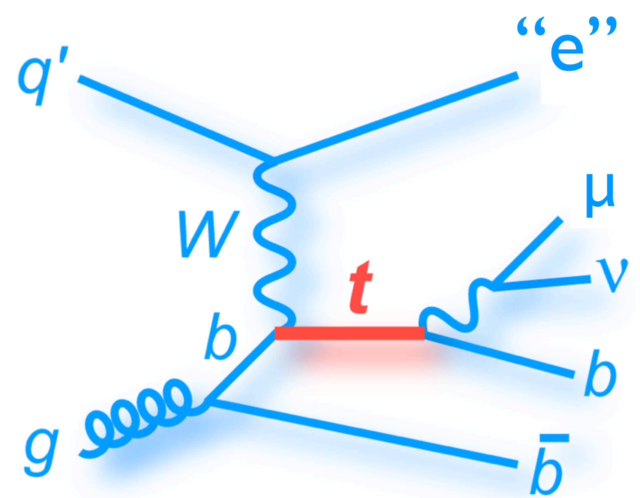




signal

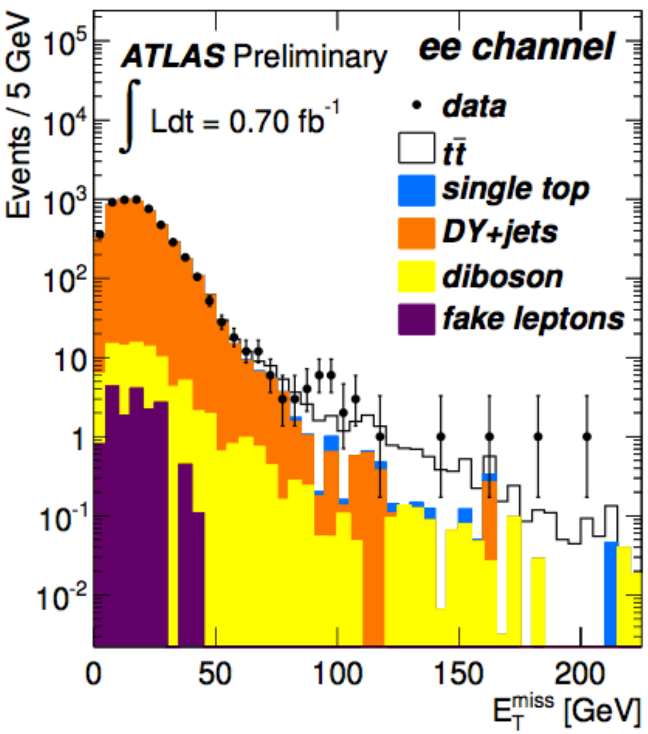






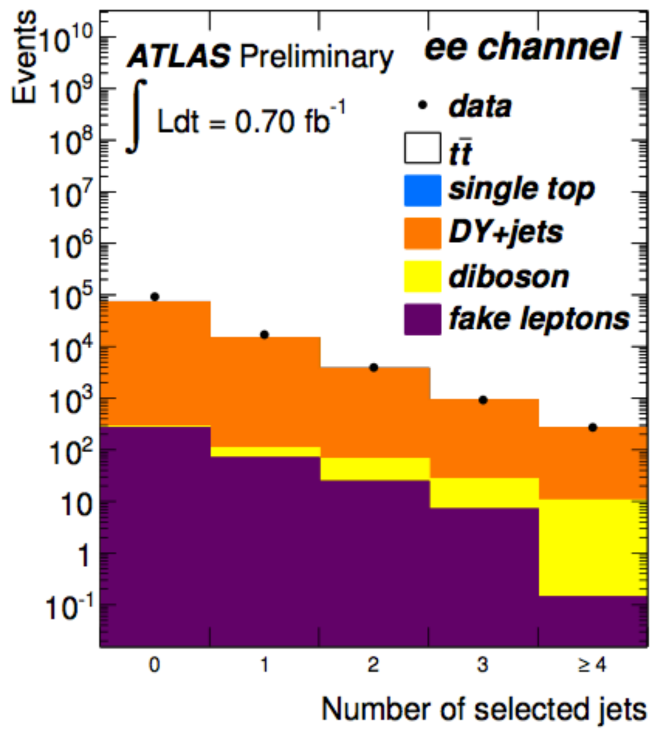
+ fake leptons

Background dominated ee samples



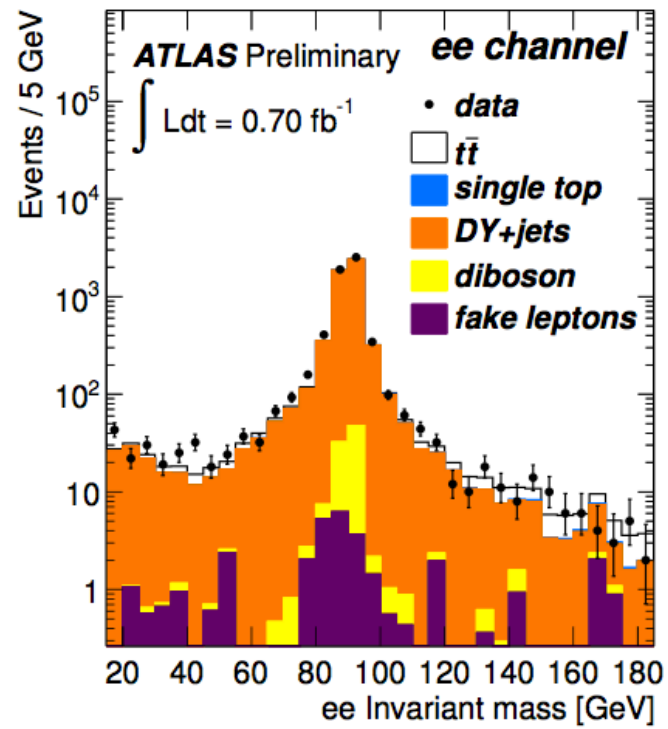
$|m_{\ell\ell} - m_Z| < 10$ GeV

$n_{jet} \geq 2$



$|m_{\ell\ell} - m_Z| < 10$ GeV

$\not{E}_T < 60$ GeV

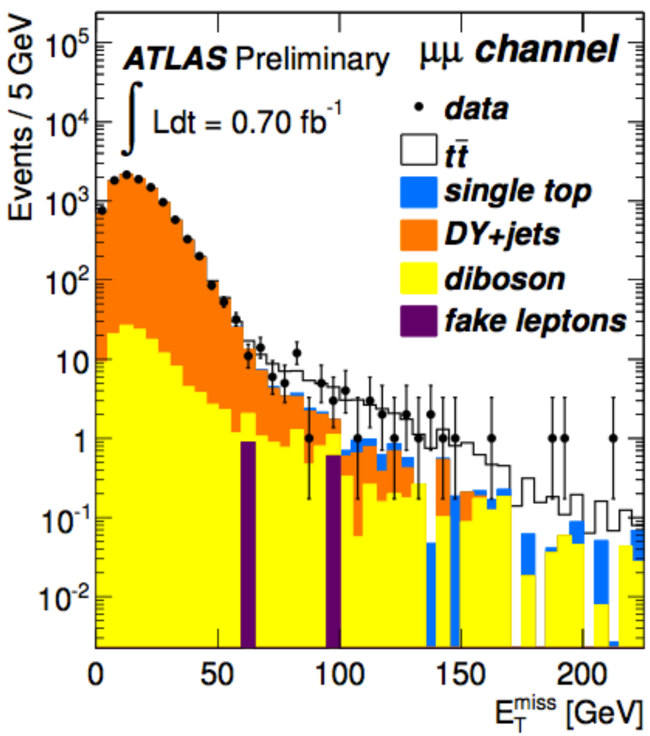


$n_{jet} \geq 2$

$\not{E}_T < 60$ GeV

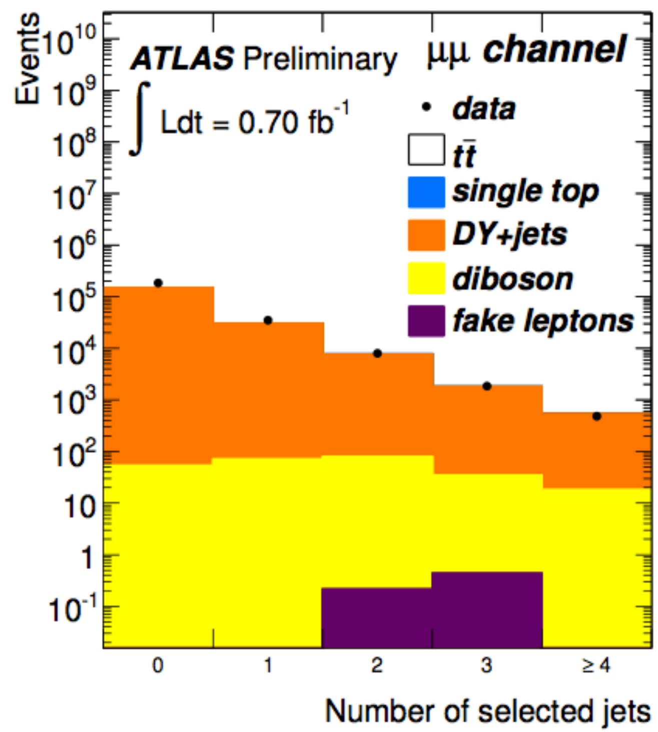
→ **good description**

Background dominated μμ samples



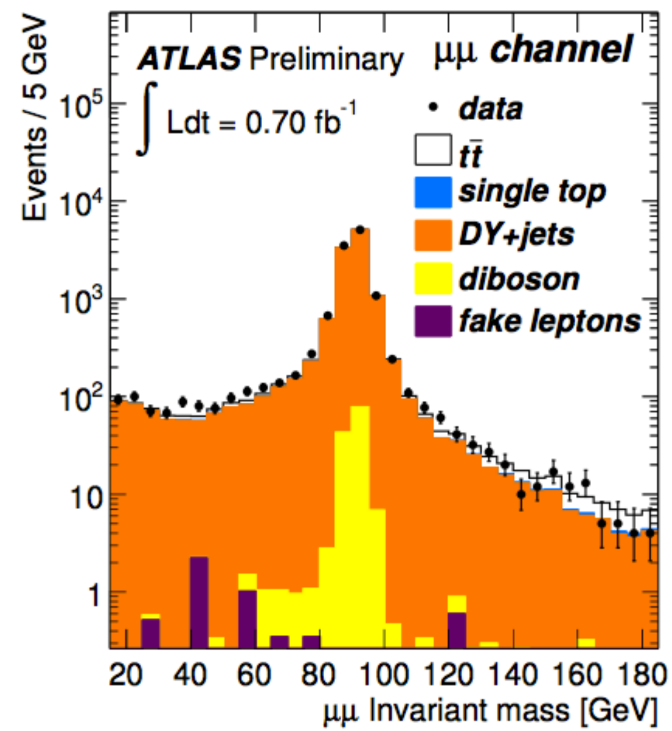
$|m_{\ell\ell} - m_Z| < 10$ GeV

$n_{jet} \geq 2$



$|m_{\ell\ell} - m_Z| < 10$ GeV

$\not{E}_T < 60$ GeV



$n_{jet} \geq 2$

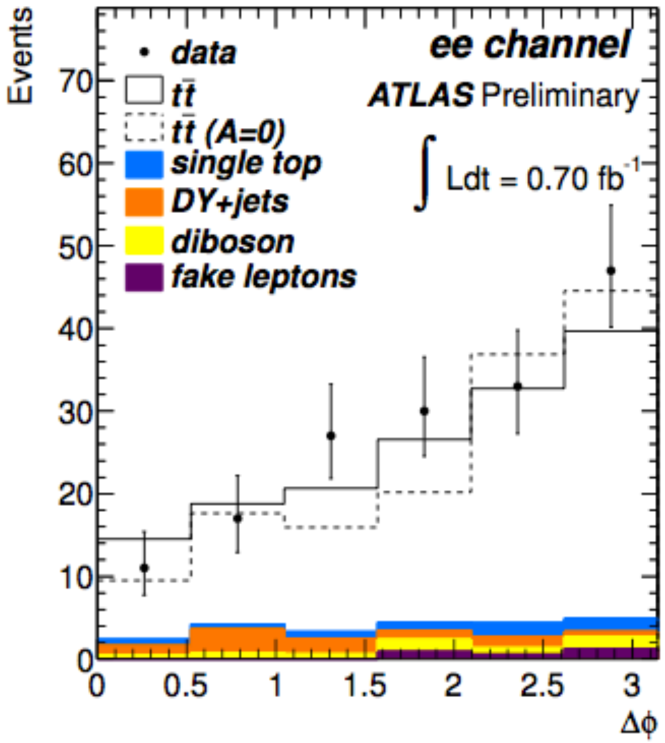
$\not{E}_T < 60$ GeV

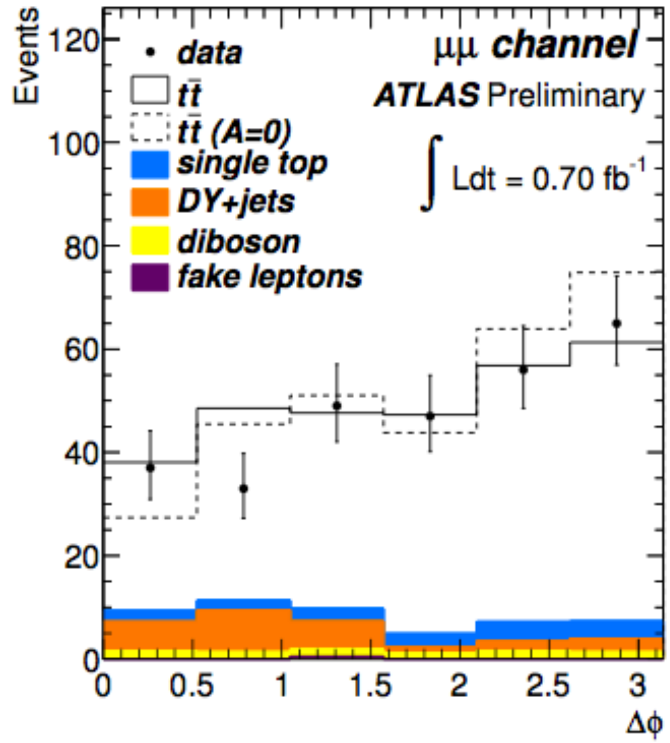
→ good description

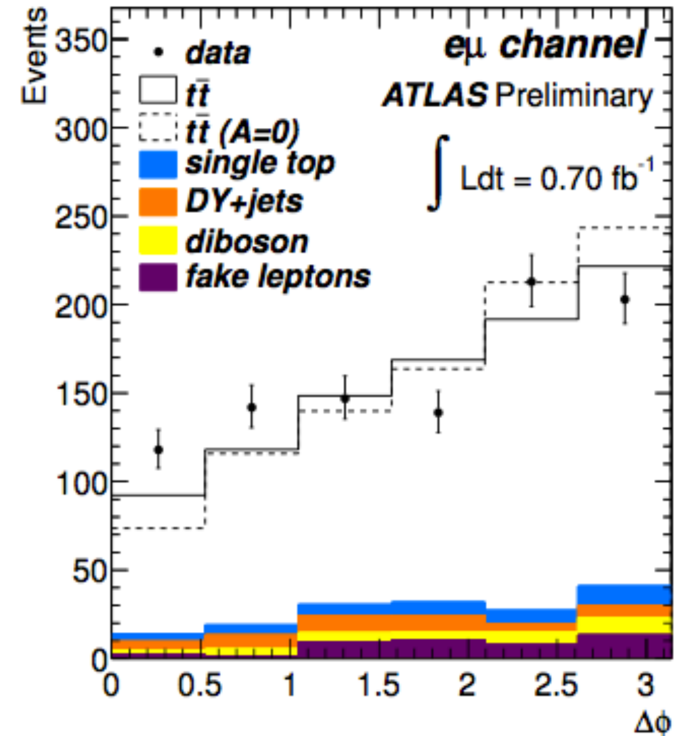
Results of single channels

<u>extraction using binned likelihood fit:</u>

SM: $f^{SM} = 1$



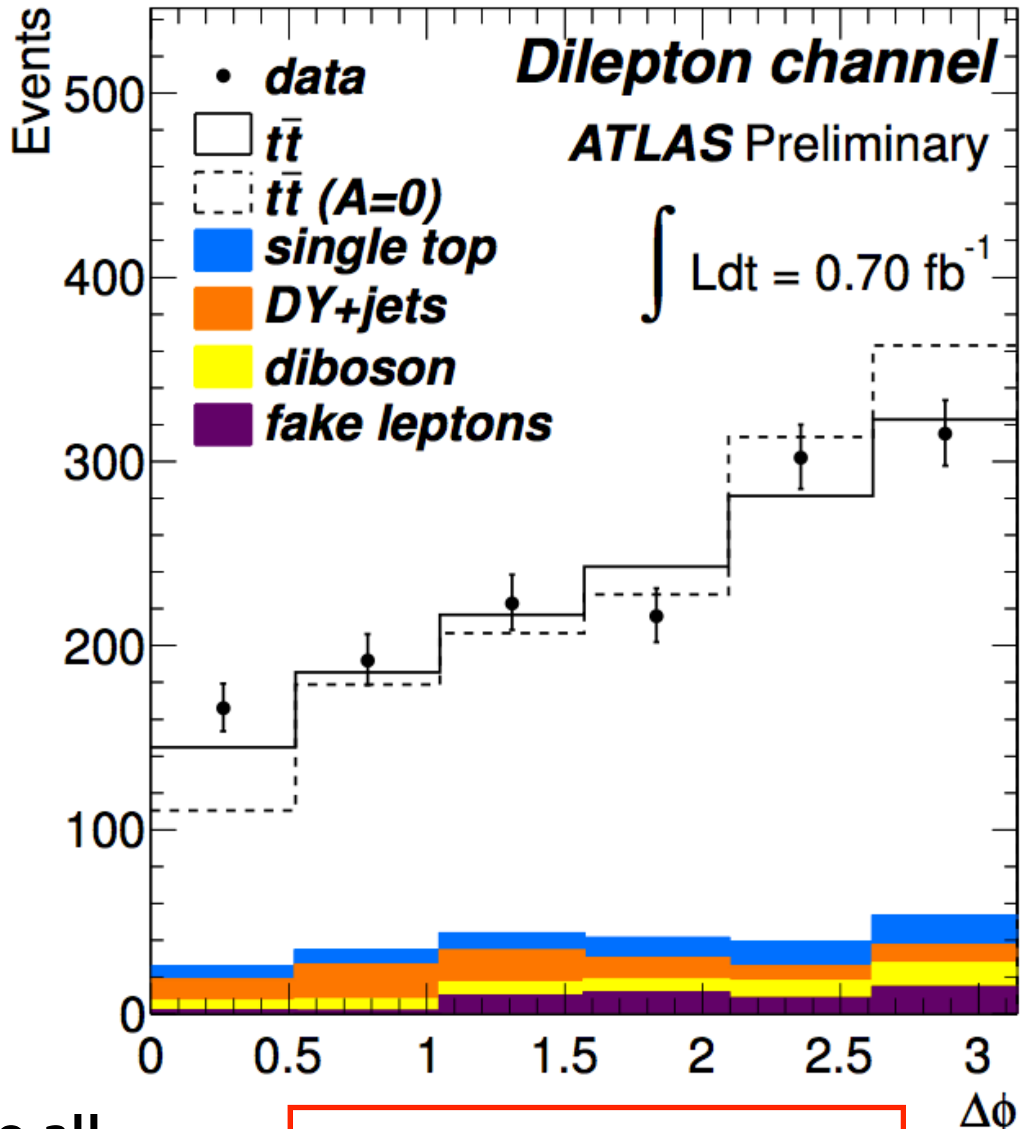




$f^{SM} = 0.89 \pm 0.59$ $f^{SM} = 0.67^{+0.62}_{-0.48}$ $f^{SM} = 1.46 \pm 0.61$

Combined result

ATLAS-CONF-2011-117



SM: $f^{SM} = 1$

simultaneous fit to all three channels:

$$f^{SM} = 1.06^{+0.46}_{-0.34}$$

Uncertainties

	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$	combination
Uncertainty source	Δf^{SM}	Δf^{SM}	Δf^{SM}	Δf^{SM}
Data statistics	±0.40	±0.37	±0.33	±0.21
MC template statistics	±0.19	±0.16	±0.27	±0.12
Luminosity	±0.03	±0.00	±0.01	±0.02
e/μ energy scale	±0.05	0.01 / 0.03	0.04 / 0.02	±0.00
e/μ energy resolution	±0.02	-0.03 / 0.01	0.05 / 0.02	±0.00
e/μ scale factor	0.03 / 0.01	±0.03	±0.00	±0.00
Jet energy scale	-0.05 / -0.01	±0.13	-0.03 / 0.07	±0.05
Jet energy resolution	±0.01	±0.02	±0.03	±0.01
Jet reconstruction efficiency	±0.02	±0.03	±0.03	±0.02
NLO generator	±0.13	±0.00	±0.20	±0.16
Parton shower and fragmentation	±0.13	±0.16	±0.28	±0.01
ISR / FSR	-0.33 / 0.29	-0.11 / 0.42	-0.26 / 0.23	-0.15 / 0.33
PDF uncertainty	±0.09	±0.09	±0.05	±0.04
top quark mass	±0.00	±0.01	±0.01	±0.03
$t\bar{t}$ normalisation	-0.01 / -0.03	±0.02	±0.01	0.03 / -0.06
Diboson normalisation	±0.02	0.01 / -0.04	±0.00	±0.01
Single top normalisation	0.01 / 0.04	±0.03	±0.00	±0.00
DY method	±0.08	±0.03	±0.01	±0.02
Fake leptons	-0.04 / 0.06	0.02 / 0.01	-0.04 / 0.01	±0.01
Calorimeter readout	±0.01	±0.01	±0.02	±0.00
All Systematics	±0.44	-0.30 / 0.50	±0.51	-0.27 / 0.40
Statistical + Systematic	±0.59	-0.48 / 0.62	±0.61	-0.34 / 0.45

→ statistical uncertainties ≈ systematic uncertainties for single channels

Spin correlation strength

$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

Channel	f^{SM}	$A_{helicity}$	$A_{maximal}$
e^+e^-	0.89 ± 0.40 (stat) ± 0.44 (syst)	0.28 ± 0.13 (stat) ± 0.14 (syst)	0.39 ± 0.18 (stat) ± 0.19 (syst)
$\mu^+\mu^-$	0.67 ± 0.37 (stat) $^{+0.50}_{-0.30}$ (syst)	0.22 ± 0.12 (stat) $^{+0.16}_{-0.10}$ (syst)	0.30 ± 0.16 (stat) $^{+0.22}_{-0.13}$ (syst)
$e^\pm\mu^\mp$	1.46 ± 0.33 (stat) ± 0.51 (syst)	0.47 ± 0.11 (stat) ± 0.16 (syst)	0.64 ± 0.15 (stat) ± 0.23 (syst)
combination	1.06 ± 0.21 (stat) $^{+0.40}_{-0.27}$ (syst)	0.34 ± 0.07 (stat) $^{+0.13}_{-0.09}$ (syst)	0.47 ± 0.09 (stat) $^{+0.18}_{-0.12}$ (syst)

data	$1.06^{+0.46}_{-0.34}$	$0.34^{+0.15}_{-0.11}$	$0.47^{+0.20}_{-0.15}$
NLO QCD	1	0.32	0.44

→ **good agreement with NLO QCD calculations**

→ **exclude no spin correlation hypothesis with ~3σ significance**

Summary

- first measurement of spin correlation between top and anti-top quark in dilepton final states at the LHC
- azimuthal angle between charged leptons in laboratory frame

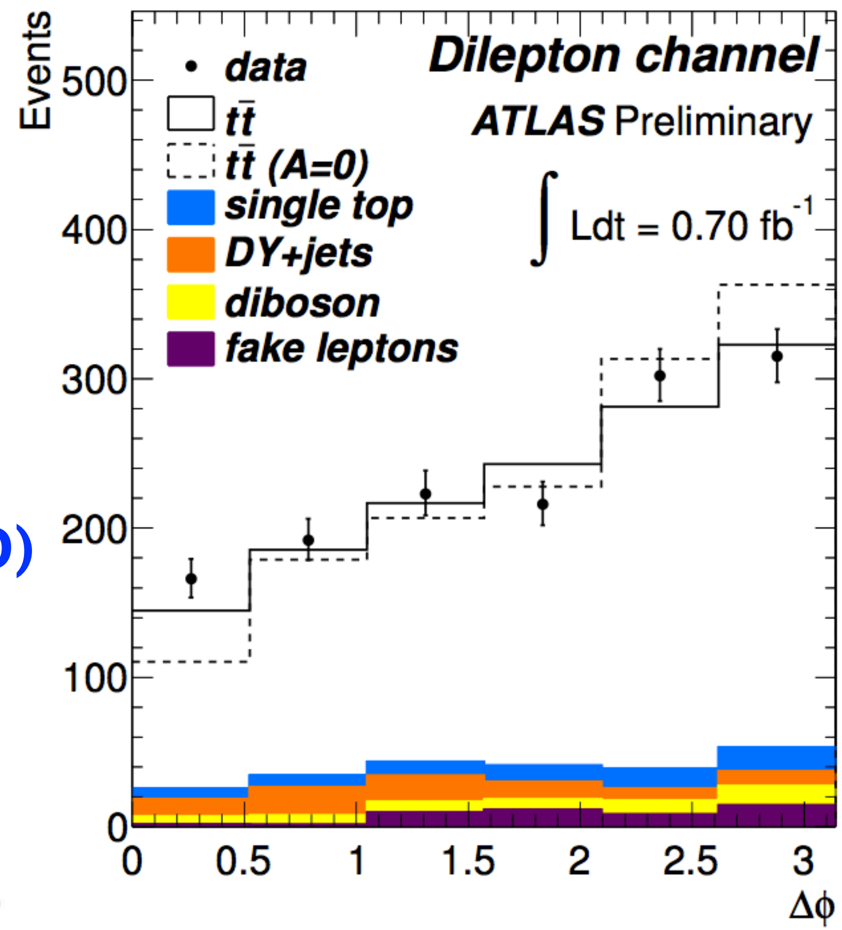
$f^{SM} = 1.06^{+0.46}_{-0.34}$ (=1 in NLO QCD)

$A_{helicity} = 0.34^{+0.15}_{-0.11}$ (=0.32 in NLO QCD)

comparison with Tevatron:

see talk by Alexander Grohsjean

ATLAS-CONF-2011-117



→ **correlation agrees with SM spin 1/2 hypothesis**

→ **exclude no spin correlation hypothesis ~3σ**

BACKUP

Signal and background