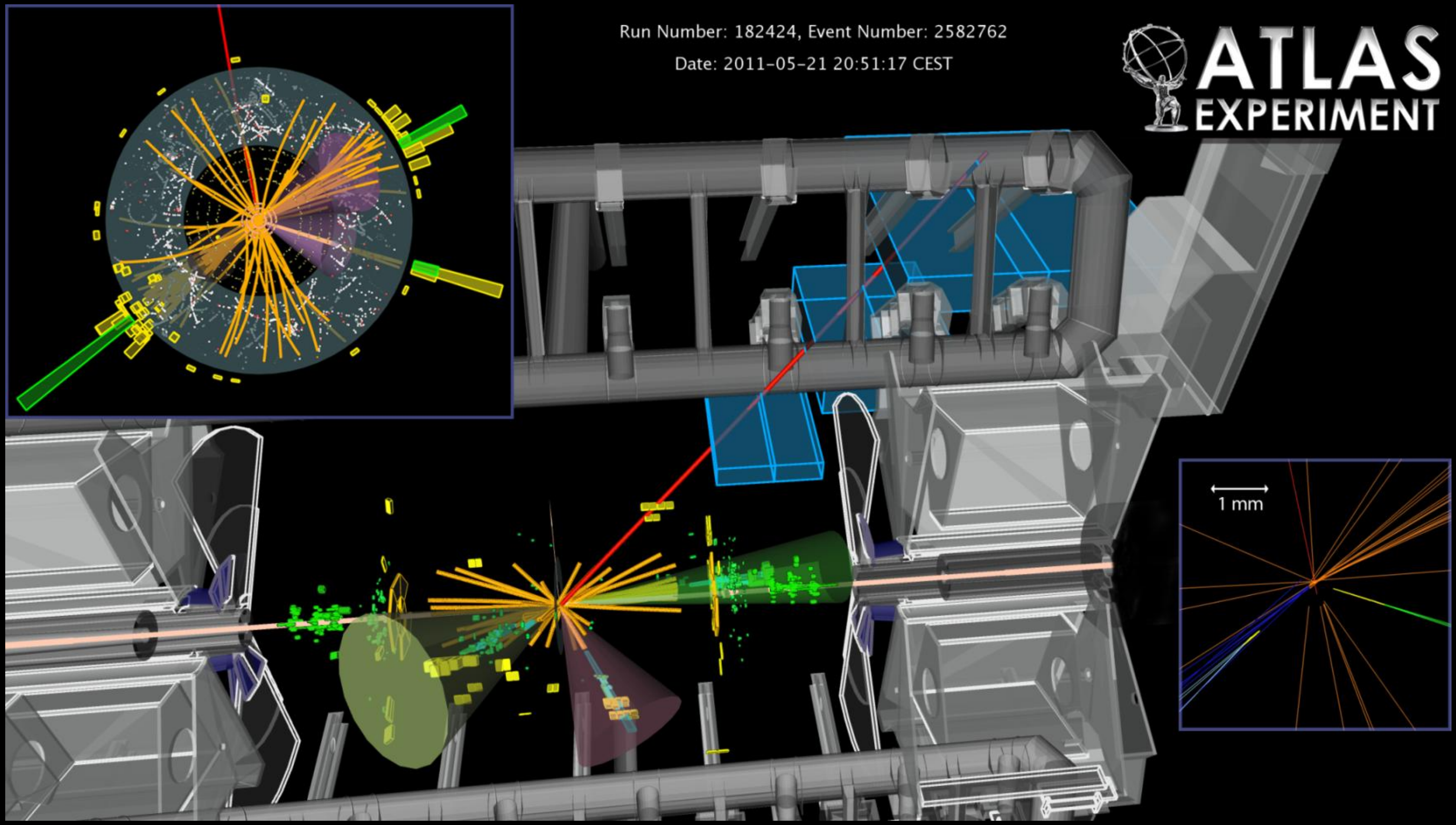
Top Quark *Pairs* at ATLAS



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Top quark physics

Behavior is determined by the large mass

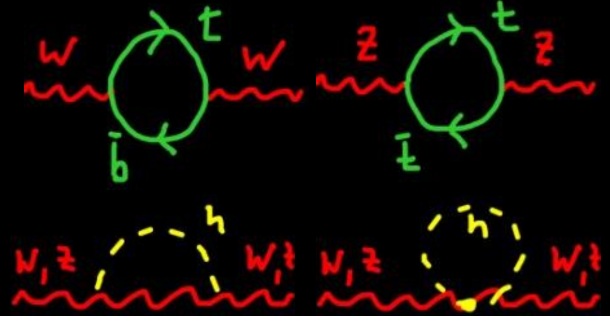
- m_{top} = 173.2 ± 0.9 GeV [arXiv:1107.5255v3] Tevatron average
- Late discovery at Tevatron (1995)

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]$$

Short lifetime ~$4 \cdot 10^{-25}$ s (no top hadrons)

- Decays faster than hadronisation
- Spin information passed to decay products

Radiative corrections

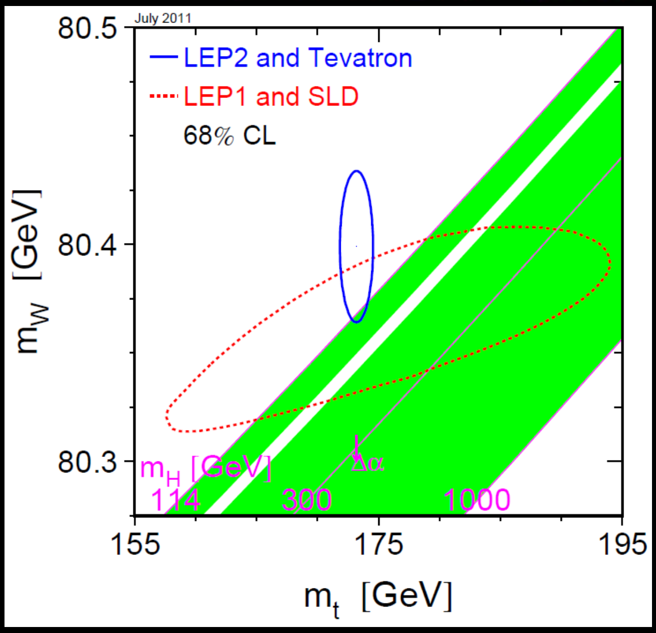


Mass close to ewk breaking scale

- Discovery potential of New Physics
- Allows for stringent tests of SM

Complementary to Tevatron

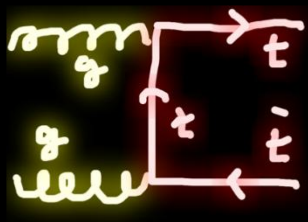
- Different production mechanism
- Higher centre-of-mass energy
- Larger samples available

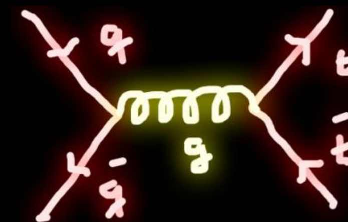


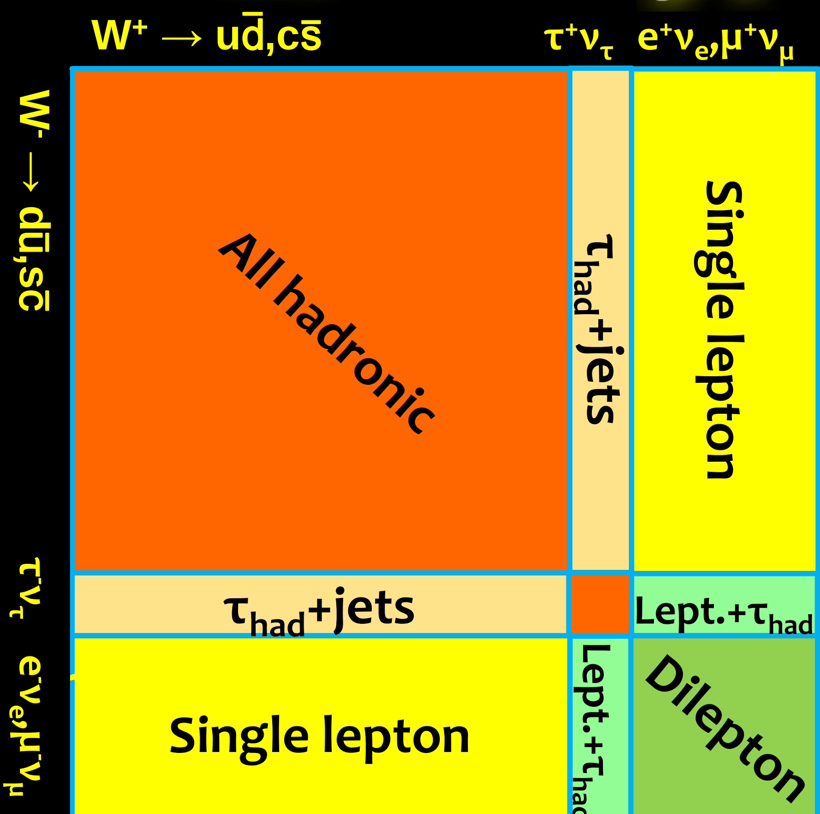
Top quark *pair* production and decay

Pair production through strong interaction

- Cross section: ~850 pb (14TeV), 160pb (7TeV)
- Producing $O(10^5)$ pairs/fb : LHC is a top factory







Top quarks decay to Wb ~ 100%

$$\frac{B(t \rightarrow bW)}{\sum_{q=b,s,d} B(t \rightarrow qW)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

Pair production signatures

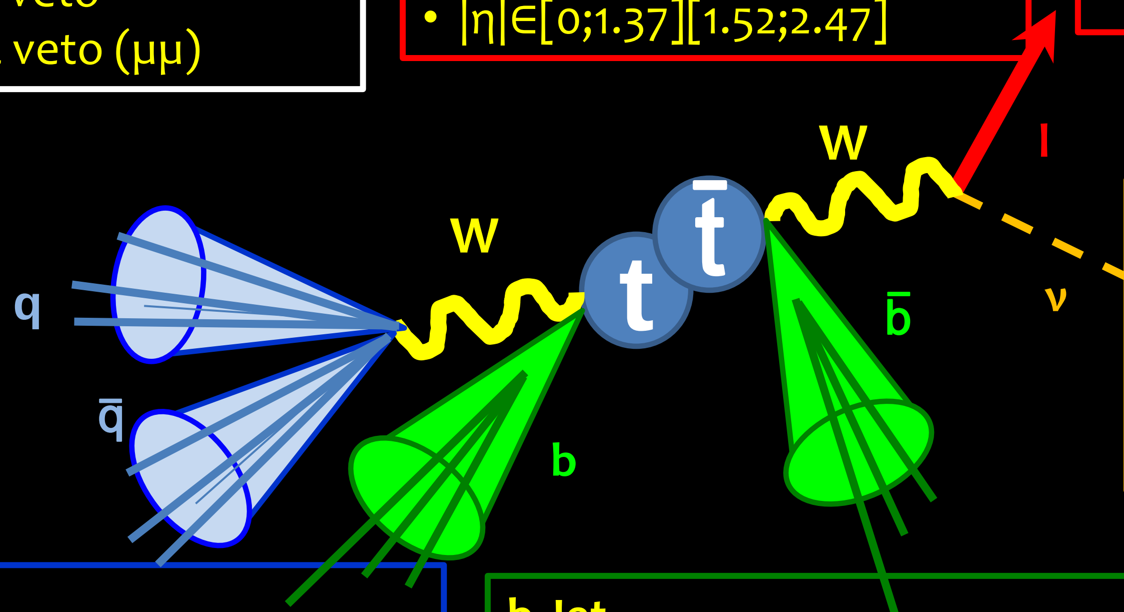
- Dilepton (2l + 2ν + 2b)
- Single lepton (1l + 1ν +2b + 2q)
- all hadronic (2b + 4q)

Selection of top quark pairs

Event cleaning
- Good run conditions
- PV at least 5 tracks
- Bad jet veto
- Cosmic veto (μμ)

Electron
- Good isolated calo object
- Matched to track
- $E_T > 25$ GeV
- $|\eta| \in [0;1.37][1.52;2.47]$

Muon
- Segments in tracker and muon detector
- Calo and track isolation
- $p_T > 20$ GeV $|\eta| < 2.5$

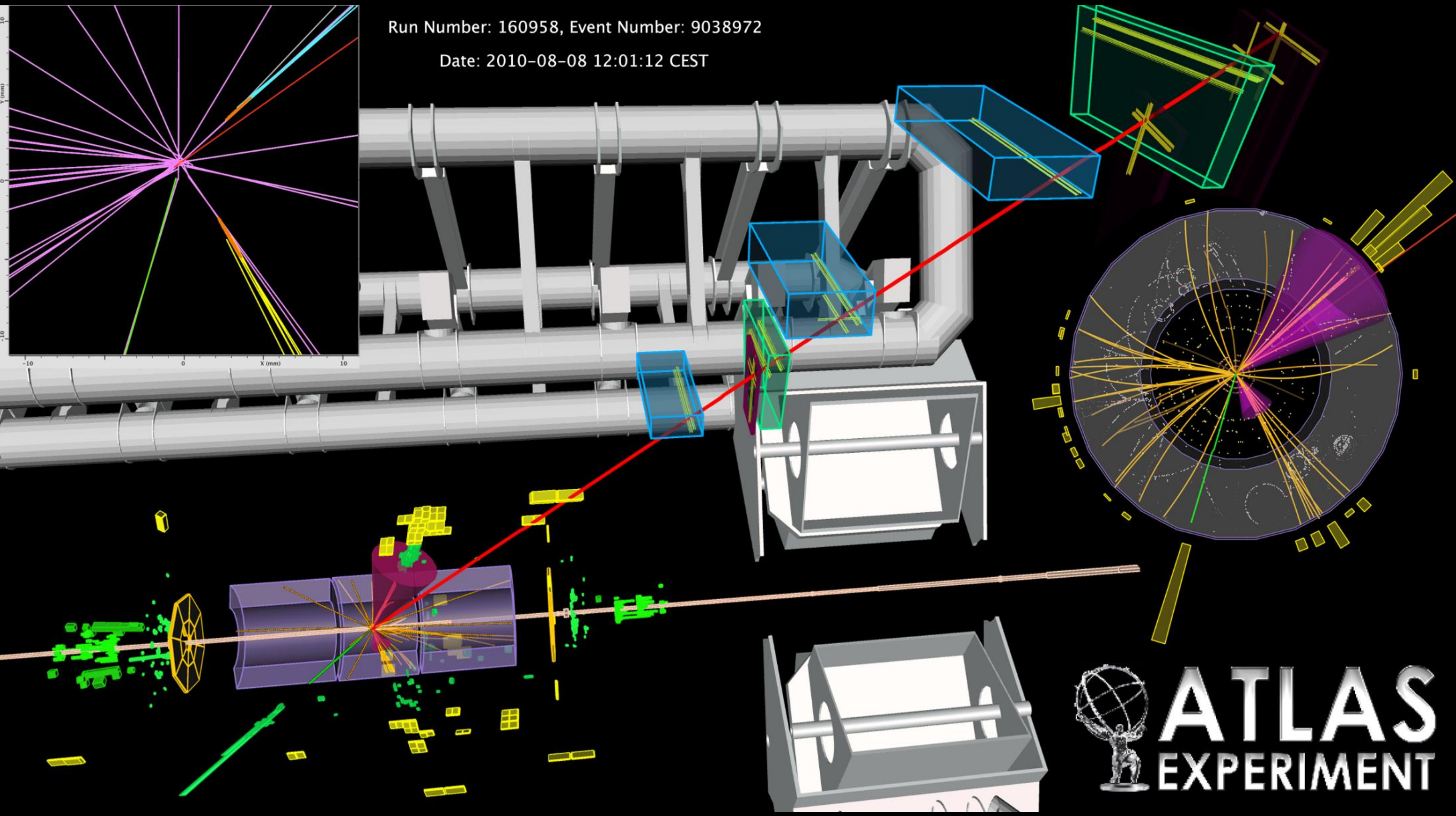


E_T^{miss}
- Vector sum of calo energy deposits
- Corrected for identified objects

Jet
- Topological clusters
- Anti-k_T (R=0.4)
- Calibration checked w/data
- $p_T > 25$ (20) GeV
- $|\eta| < 2.5$

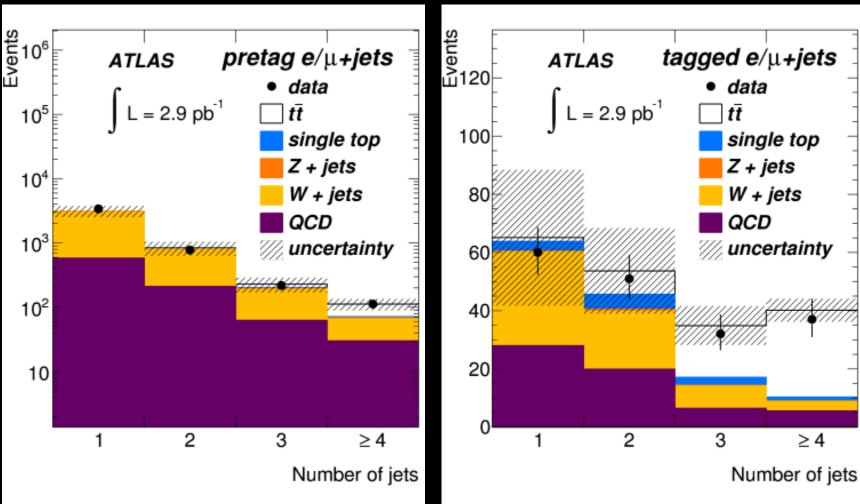
b-Jet
- Displaced tracks or secondary lepton
- SV0: reconstruct sec.vertex
- JetProb: track/jet compatibility with primary vertex
- IP3D+SV1 and JetFitter: advanced taggers

Selection of top quark pairs

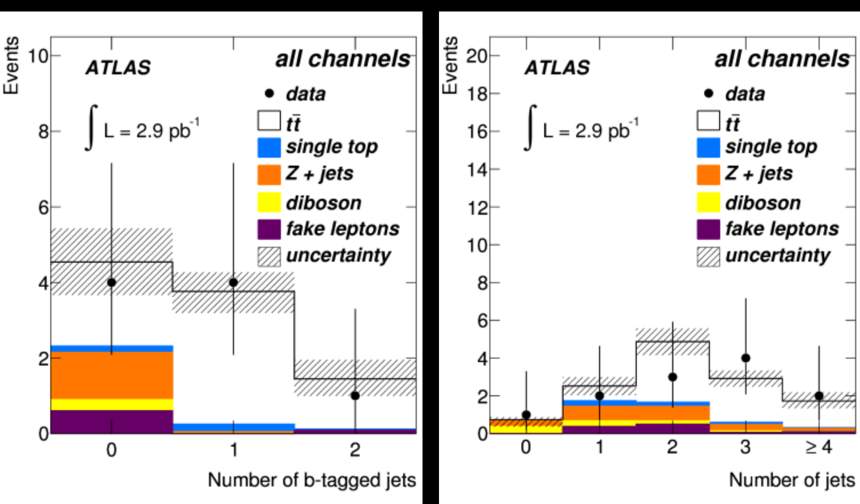


First measurements of $\sigma_{t\bar{t}}$

Eur. Phys. J C71 (2011) 1577
$\int L\, dt = 2.9\ pb^{-1}$



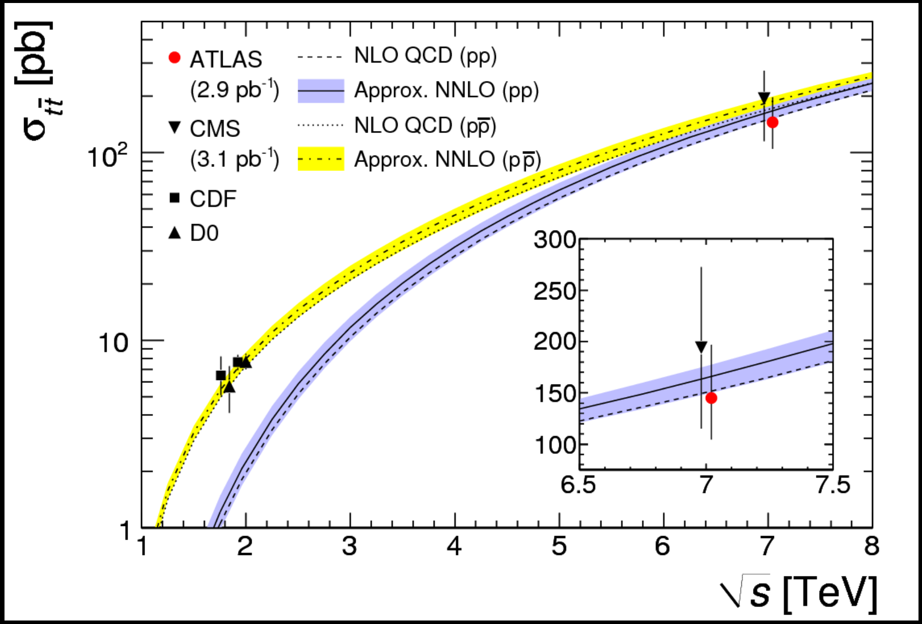
single lepton



dilepton

Cut-based analyses

- Single lepton and dilepton channel
- Data-driven determination of QCD and V+jets background
- Combined extraction



$\sigma_{t\bar{t}} = 145 \pm 31_{stat}{}^{+42}_{-27\,syst}$ pb

prec. 36%

Plan for today

Cross-section measurements $\sigma_{t\bar{t}}$

- Dilepton, single lepton channels
- μ+τ channel
- All hadronic channel

Properties of the top quark pair system

- Charge asymmetry
- Spin correlations

$t\bar{t}$+X

- Additional jets
- Additional photons
- Additional E_T^{miss}

Not here:
mass, charge, W helicity,
single top (t, Wt, s),
search for FCNC

More searches

- Search for resonances decaying to top quark pairs
- Search for same-sign tt production

Dilepton channel

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$\int L\,dt = 0.70\ fb^{-1}$

Reconstruct three final states (ee, μμ, eμ)

- with or without requiring b-tagging

Backgrounds

- Expected to be quite small
- Estimate from Monte-Carlo simulation
  - Single top, diboson, $Z \rightarrow \tau^+\tau^-$
- Estimated from data
  - Z/γ*+jets, fake leptons (W+jets, QCD multi-jets)

Common pre-selection

- Two oppositely charged, triggered, good quality, isolated leptons
- E_T (electrons) > 25 GeV; p_T (muons) > 20 GeV
- at least two jets with p_T > 25 GeV
- cosmic veto (μμ), well reconstructed event

$\sigma_{t\bar{t}}$ dilepton

Simple counting experiment

- then combine ee,μμ,eμ

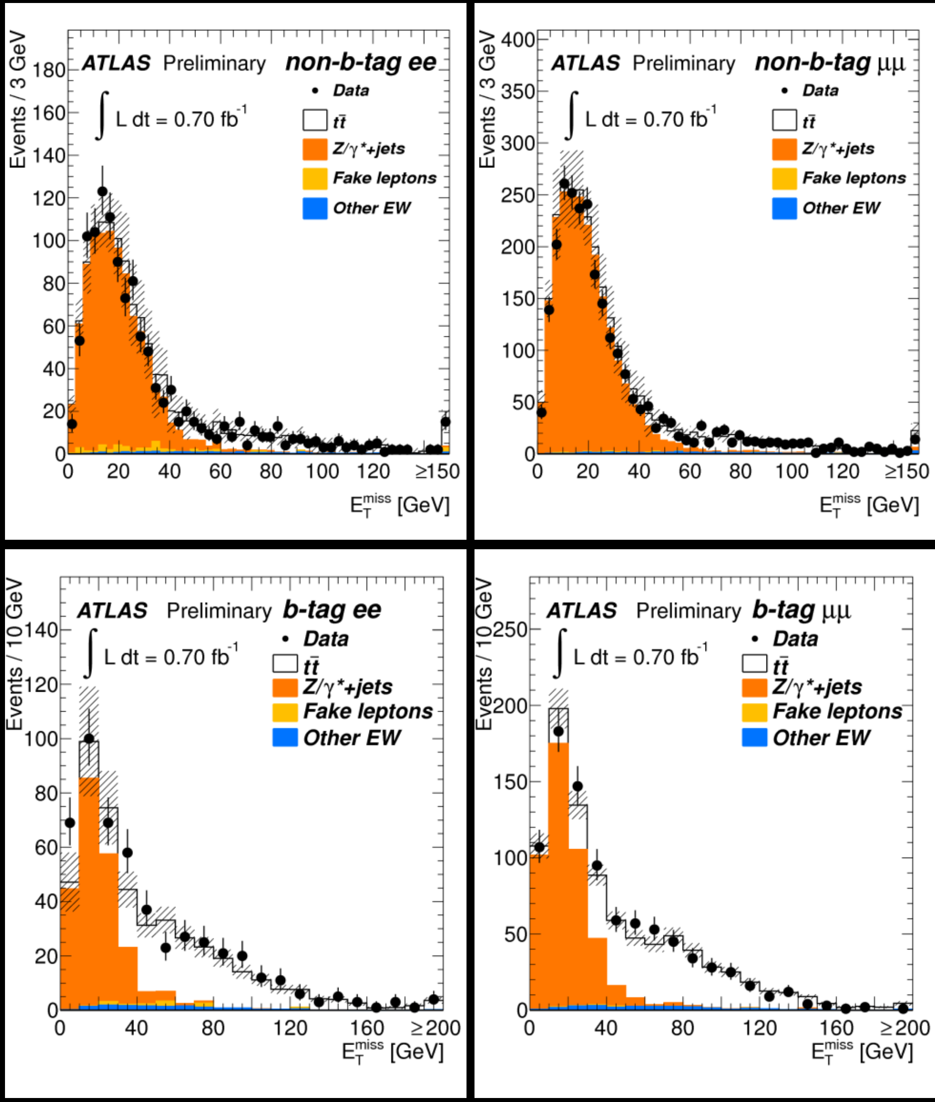
Untagged selection

- ee/μμ: $E_T^{miss} > 60$ GeV
  $|m_{ll} - m_Z| > 10$ GeV, $m_{ll} > 10$ GeV
- eμ: $H_T > 130$ GeV

Tagged selection

- ee/μμ: $E_T^{miss} > 40$ GeV
  $|m_{ll} - m_Z| > 10$ GeV, $m_{ll} > 10$ GeV
- eμ: $H_T > 140$ GeV
- Require one b-tagged jet
  (80% efficiency)

Designed to reduce Z/γ*+jets



Z+jets background

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$\int L\,dt$ = 0.70 fb^{-1}

Z/γ*+jets events contaminating signal region

- Large E_T^{miss} possible from mismeasurement
- Difficult to model in Monte-Carlo simulation

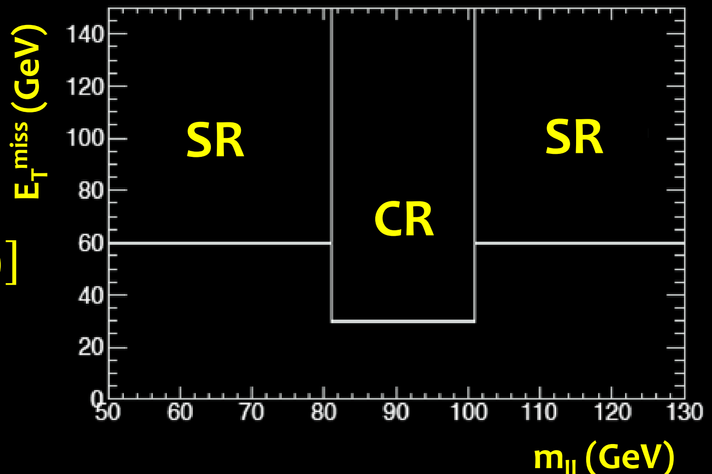
Define control region

- $|m_{ll} - m_Z| < 10$ GeV and $E_T^{miss} > 30$ GeV, same jet requirements

Determine scale factors

- after subtracting 'other' backgrounds

$$N_{Z+jets} = \frac{MC_{Z+jets}(SR)}{MC_{Z+jets}(CR)} \times [Data(CR) - MC_{other}(CR)]$$



	ee	$\mu\mu$	$e\mu$	b-tag ee	b-tag $\mu\mu$	b-tag $e\mu$
$Z/\gamma^*(\rightarrow ee/\mu\mu)$+jets	$3.8^{+2.5}_{-1.2}$	14.8 ± 4.7	-	$9.3^{+3.7}_{-1.9}$	$19.1^{+2.4}_{-1.6}$	-
$Z/\gamma^*(\rightarrow \tau\tau)$+jets	5.2 ± 2.6	11.2 ± 4.8	43 ± 16	$1.6^{+1.1}_{-0.9}$	$7.0^{+2.8}_{-3.2}$	$9.1^{+3.6}_{-3.7}$

Fake lepton background

Backgrounds with fake leptons

- W+jets (mainly), QCD, $t\bar{t}$ single lepton, single top, …

Determination with 2dim matrix method

- Define loose, tight leptons (isolation) → 4 observable states:
  - Loose-Loose, Loose-Tight, Tight-Loose and Tight-Tight
- Also 4 classes of background
  - Fake-Fake, Fake-Real, Real-Fake and Real-Real
- Matrix method results in a 4x4 equation system

$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} rr & rf & fr & ff \\ r(1-r) & r(1-f) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)(1-r) & (1-r)(1-f) & (1-f)(1-r) & (1-f)(1-f) \end{bmatrix} \begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix}$$

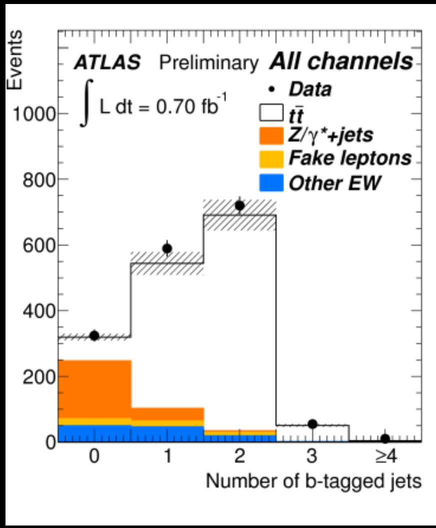
- Fractions *f, r* from control samples, then solve equation for $N_{RF/FR}, N_{FF}$
  - Fraction r measured from Z(→ll)+jets events
  - Fraction f measured from sample with single loose lepton

Likelihood model for $\sigma_{t\bar{t}}$ calculation

For each channel

$$\underbrace{N^{exp}(\sigma_{t\bar{t}},\alpha_j) = L\cdot\epsilon_{t\bar{t}}(\alpha_j)\cdot\sigma_{t\bar{t}}}_{t\bar{t}\ \text{signal}} + \underbrace{\sum_{bkg} L\cdot\epsilon_{bkg}(\alpha_j)\cdot\sigma_{bkg}(\alpha_j)}_{\text{MC backgrounds}} + \underbrace{N_{DD}(\alpha_j)}_{\text{data-driven backgrounds}}$$

$$\mathcal{L}(\sigma_{t\bar{t}},L,\alpha_j) = \underbrace{\text{Poisson}\left(N^{obs}\,|\,N^{exp}(\sigma_{t\bar{t}},\alpha_j)\right)}_{\text{Poisson model for channel event count}} \times \underbrace{\text{Gauss}(L_0|L,\delta_L)}_{\text{Luminosity uncertainty}} \times \underbrace{\prod_{j\in syst}\Gamma_j(\alpha_j)}_{\text{Other syst. uncertainties}}$$



Profile likelihood fit run with and without systematic uncertainty terms

- **Jet energy scale (6%), luminosity, b-tagging efficiency, data statistics**

Channel	Non-b-tag $\sigma_{t\bar{t}}$ (pb)	b-tag $\sigma_{t\bar{t}}$ (pb)
ee	$178 \pm 17\,^{+31}_{-34}\,^{+8}_{-7}$	$181 \pm 16\,^{+35}_{-29}\,^{+8}_{-7}$
$\mu\mu$	$159 \pm 10\,^{+20}_{-10}\,^{+7}_{-6}$	$164\,^{+11}_{-10}\,^{+18}_{-14}\,^{+7}_{-6}$
$e\mu$	$182 \pm 7\,^{+18}_{-14} \pm 8$	$193 \pm 8\,^{+20}_{-14}\,^{+8}_{-7}$
Combined	$177 \pm 6\,^{+17}_{-14} \pm 8$	$183 \pm 6\,^{+18}_{-14}\,^{+8}_{-7}$

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$\int L\,dt = 0.70\ fb^{-1}$

Uncertainty < 11%

Top pair production: single lepton

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$\int L\, dt = 0.70\ fb^{-1}$

Handling of background

- QCD: Stringent requirements on lepton isolation, E_T^{miss} and $m_T(W)$
- W+jets: identify few well-modeled variables

Analysis strategy

- Combine variables in likelihood in bins of jet mult. and lept. flavour
- Create templates for S and B
- Perform binned profile likelihood fit to constrain systematics

Details

- Simultaneous fit in six channels: e+jets, μ+jets with 3, 4, ≥5 jets
- Extract $\sigma_{t\bar{t}}$ and N_{bckgnd} (especially W+jets)
- treat (most) systematic uncertainties as nuisance parameters in fit and allow them to be constrained by data

Single lepton backgrounds

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$\int L\,dt = 0.70\ fb^{-1}$

Reject QCD multi-jet background by requiring

- a lepton: $p_T > 20$ GeV   a neutrino, $E_T^{miss} > 35$ (20) GeV for e(μ)

the combination to be consistent with a leptonic W decay

- $m_T(W) > 25$ GeV (e) $m_T(W) + E_T^{miss} > 60$ GeV (μ)

Remaining background estimated with matrix method (see dilepton)

In pp collisions more W^+ than W^-

- Ratio $r = W^+/W^-$ relatively well understood
- Other processes are charge symmetric (except single top)

Extract total number of W+jets

- with $D^{\pm}$ number of events after selection and $r_{MC} \sim 1.6$

$$N_{W^+} + N_{W^-} = \left(\frac{r_{MC} + 1}{r_{MC} - 1}\right) \cdot (D^+ - D^-)$$

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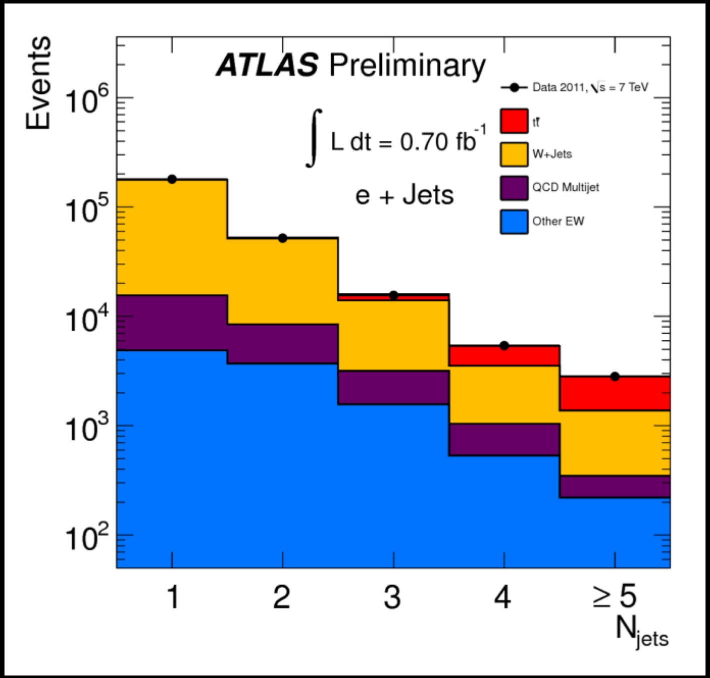
$\int L\,dt = 0.70\ fb^{-1}$

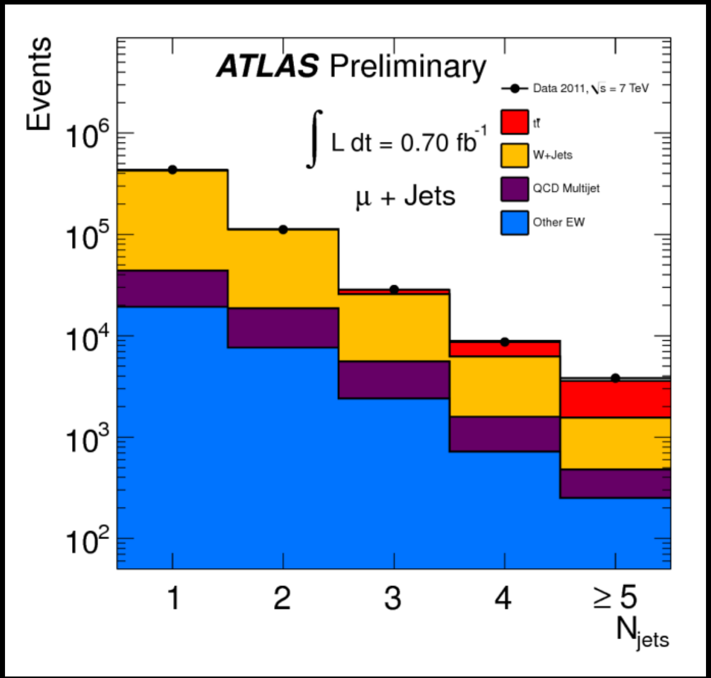
Background estimation

QCD multi-jets from data
- using matrix method

W+jets
- shape from Alpgen Monte-Carlo, normalisation from data

Other backgrounds
- taken from MC and normalised to theory (Z+jets, diboson, single top)





Input variables

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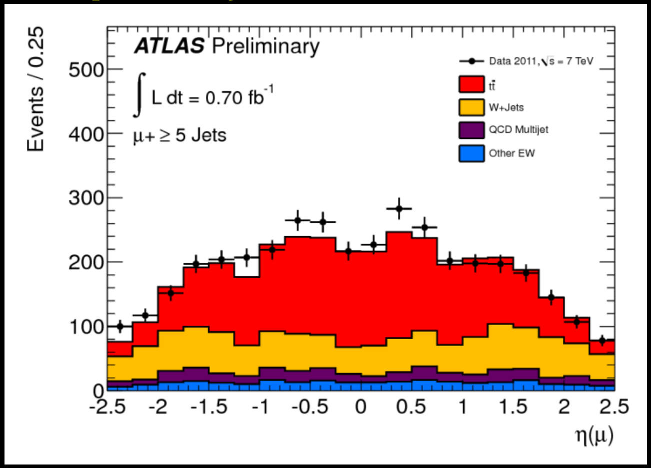
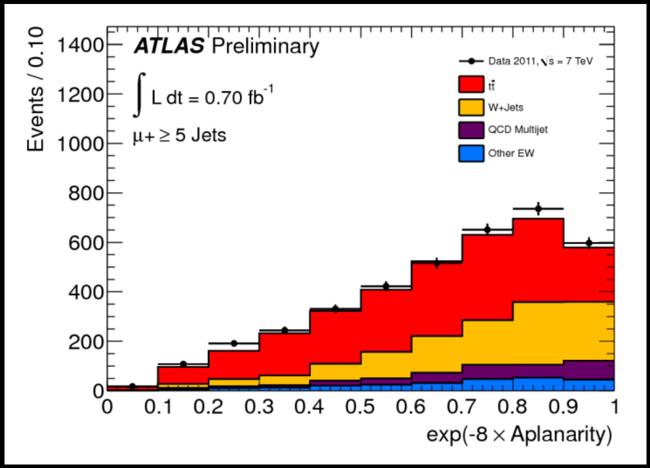
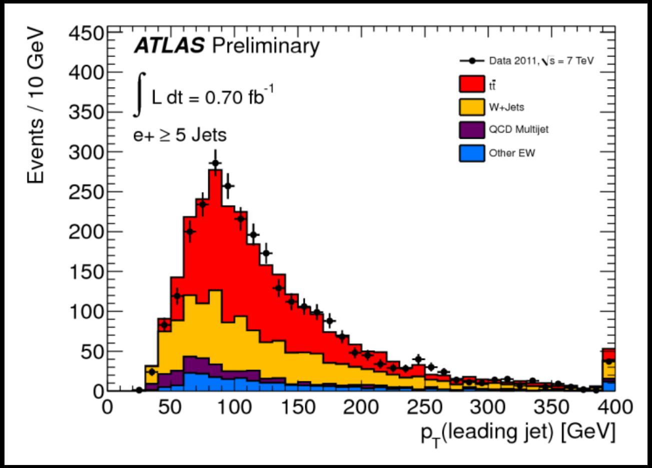
$\int L\,dt = 0.70\ fb^{-1}$

Lepton η: $t\bar{t}$ more central

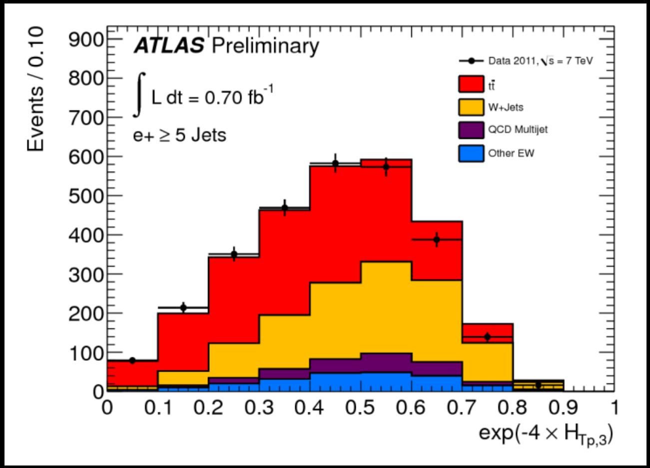


Aplanarity: $t\bar{t}$ more spherical





Jet p_T: $t\bar{t}$ more energetic



$$H_{T,3p} = \frac{\sum_{i=3}^{N_{jets}} |p_{T,i}|}{\sum_{j=1}^{N_{obj}} |p_{z,j}|}$$

Signal extraction

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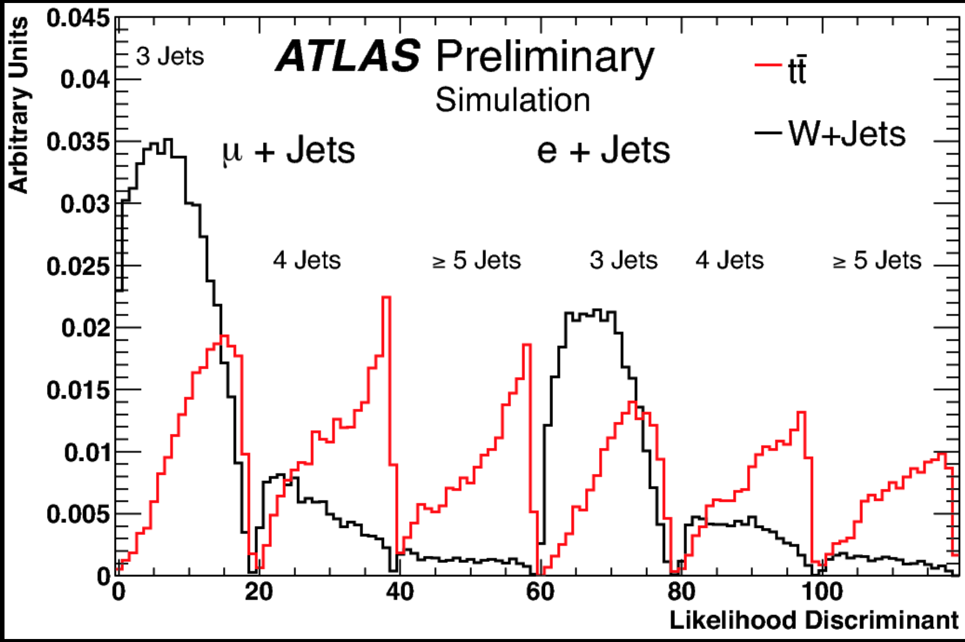
$\int L\,dt = 0.70\ fb^{-1}$



Likelihood fit $$\mathcal{L}(\vec{\beta},\vec{\delta}) = \prod_{k=1}^{120} \mathcal{P}(\mu_k, n_k) \times \prod_j \mathcal{G}(\beta_j, \Delta_j) \times \prod_i \mathcal{G}(\delta_i, 1)$$

Treatment of systematic uncertainties

- Reconstruction, identification and calibration of physics objects
  - Continuous systematic uncertainties
- Modeling of signal and backgrounds
  - Run pseudo-experiments comparing alternative model

Profile likelihood

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$\int L\,dt = 0.70\ \mathrm{fb}^{-1}$

Syst. uncert. considered as nuisance parameters δ_i

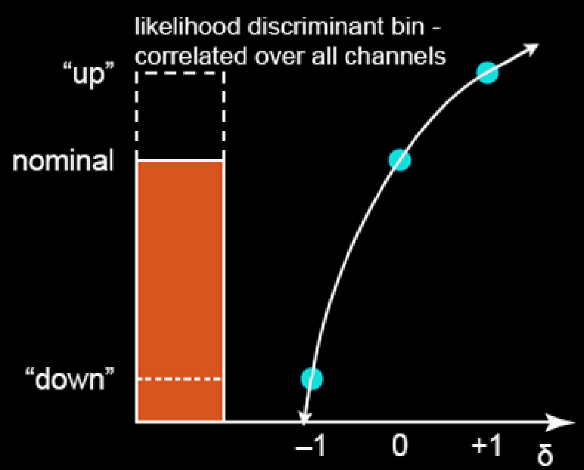
- construct 'up' and 'down' templates from ±1σ variation

Each nuisance parameter assumed Gaussian with mean 0

- vertical morphing of templates → continuous parameters δ_i
- quadratic interpolation for $|\delta_i| < 1$; linear extrapolation

Systematics enter as parameters in the minimisation

- let data adjust the size of corresponding uncertainty



process	parameters	constraints	normalization before fit
ttbar	β_0	-	theory
W+jets	β_1-β_6 (separate for six channels)	3 jets: 42% 4 jets: 48% ≥5 jets: 54% (Behrends scaling and theory)	W charge asymmetry measurement
Z+jets	β_7	30 %	theory
single top	β_8	3.7% ⊕ 10% (lumi⊕theory)	theory
diboson	β_9	3.7% ⊕ 5% (lumi⊕theory)	theory
QCD	β_{10}-β_{15} (separate for six channels)	50 %	matrix method

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$\int L\,dt = 0.70\ fb^{-1}$

Systematic uncertainties

Jets
- Energy resolution
- Reconstruction efficiency

Leptons
- Trigger efficiency
- Identification efficiency
- Lepton energy calibration
- Lepton energy resolution

E_T^{miss}
- Take into account from
- Pile-up simulation
- Additionally: soft jets and unclustered energy

Generator
- Powheg vs MC@NLO

Hadronization
- Herwig vs Pythia

ISR/FSR
- Vary Pythia parameters
- Compatible with data

QCD shape
- Alternative control region

W+jets shape
- Vary Alpgen parameters
  - Parton matching threshold
  - Factorisation scale

PDF
- Alternatives to CTEQ6.6

Uncertainty	up (%)	down (%)
Statistical	2.2	−2.2
Detector simulation		
Jets	1.8	−2.4
Muon	2.3	−2.3
Electron	1.5	−1.7
E_T^{miss}	1.1	−0.9
Signal model		
Generator*)	3.0	−3.0
Hadronization*)	0.5	−0.5
ISR/FSR	1.7	−1.3
PDF*)	1.0	−1.0
Background model		
QCD shape*)	0.4	−0.4
W shape*)	0.5	−0.5
Monte Carlo statistics*)	1.8	−1.8
Systematic	5.0	−5.0
Stat. & Syst.	5.4	−5.4
Luminosity	3.7	−3.7
Total	6.6	−6.6

*) evaluated outside the fit

Result single lepton channel

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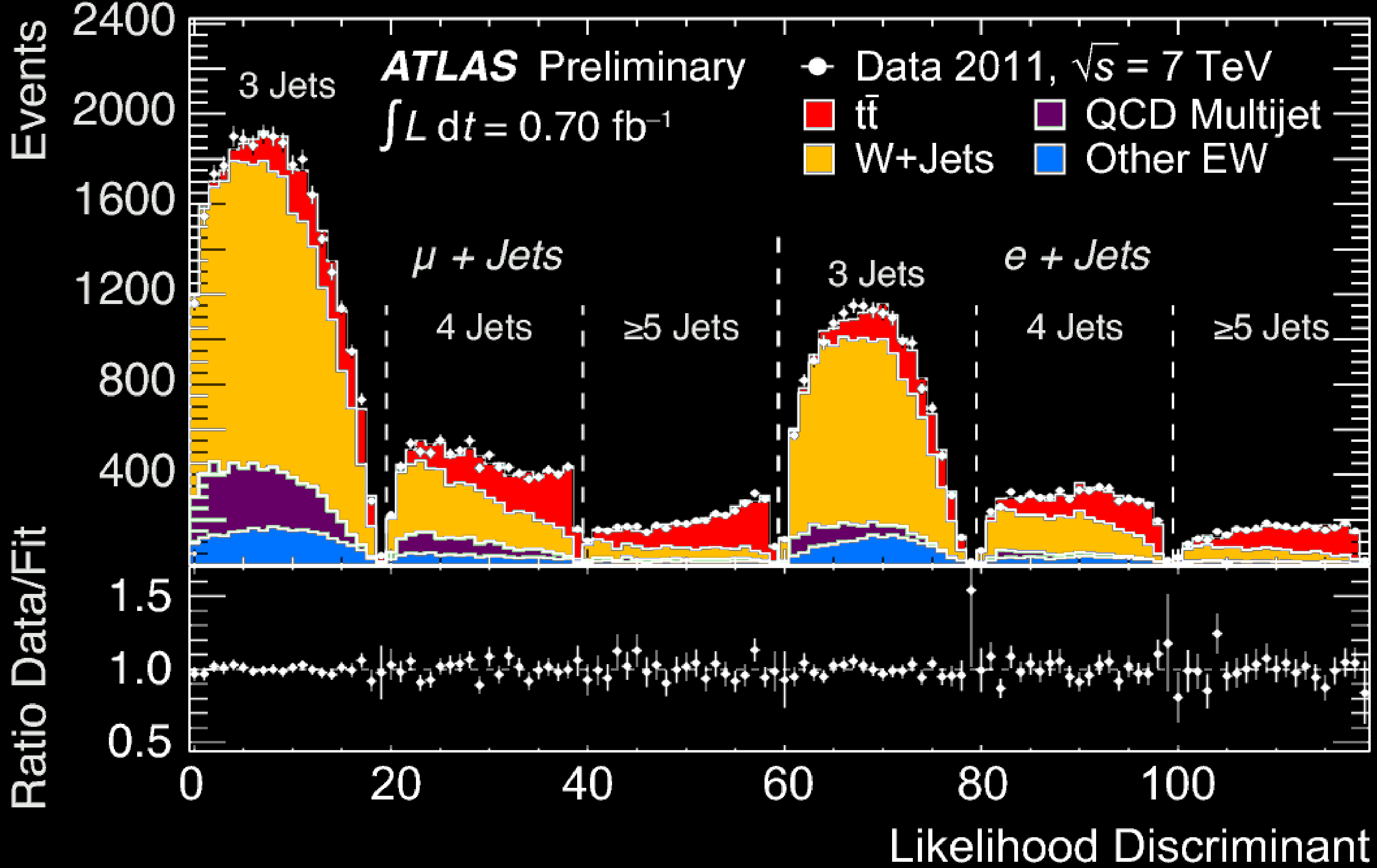
$\int L\,dt$ = 0.70 fb⁻¹



$\sigma_{tt} = 179.0 \pm 9.8_{stat+syst} \pm 6.6_{lumi}$ pb

Uncertainty < 7%

All hadronic channel

ATLAS-CONF-2011-140
$\int L\, dt$ = 1.02 fb^{-1}

Six jets and no leptons in the final state

- Rely on multi-jet trigger (5 jets E_T>30 GeV at event filter)

Selection

- ≥5 jets : $|\eta|$<4.5 and E_T>55 GeV, 6th jet 30GeV
- 2 b-tagged jets (JetFitter+IP3D) ε_b~60%, R_{light}~350, $\Delta R_{b\bar{b}}$ > 1.2
- Veto against electroweak processes
  - $E_T^{miss}/\sqrt{H_T}$ <3 and no lepton with p_T >20 GeV
- Signal efficiency 1.1%

Analysis strategy

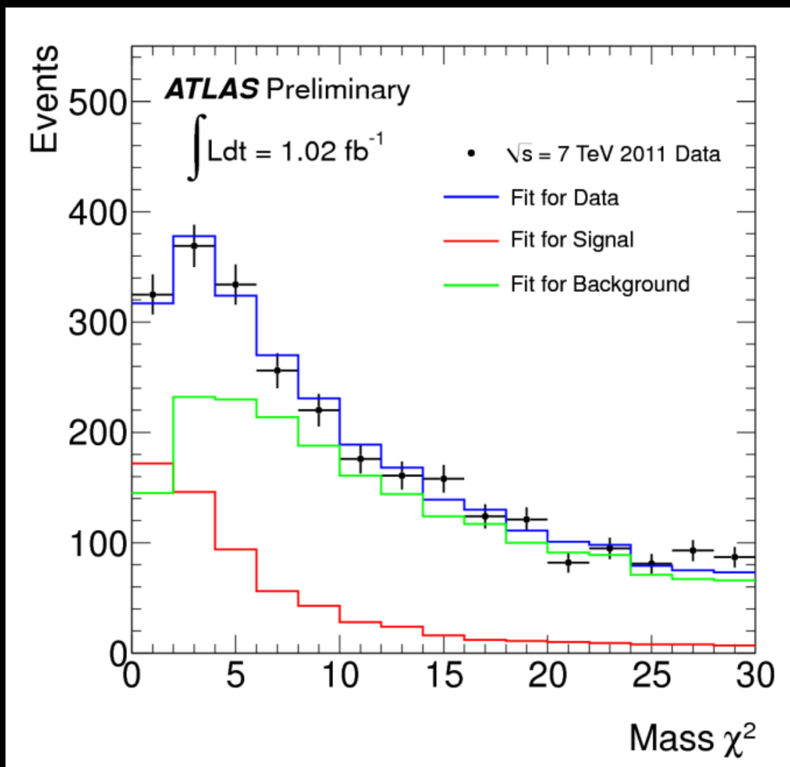
- Jets assignment minimizing $\chi^2 = \frac{(m_{j_1,j_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_1,j_2,b_1} - m_t)^2}{\sigma_t^2} + \frac{(m_{j_3,j_4} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_3,j_4,b_2} - m_t)^2}{\sigma_t^2}$
- Binned likelihood fit to χ^2 distribution with templates
- Background mainly from QCD multi-jet events: use event mixing

All hadronic channel

ATLAS-CONF-2011-140
$\int L\,dt = 1.02\ fb^{-1}$

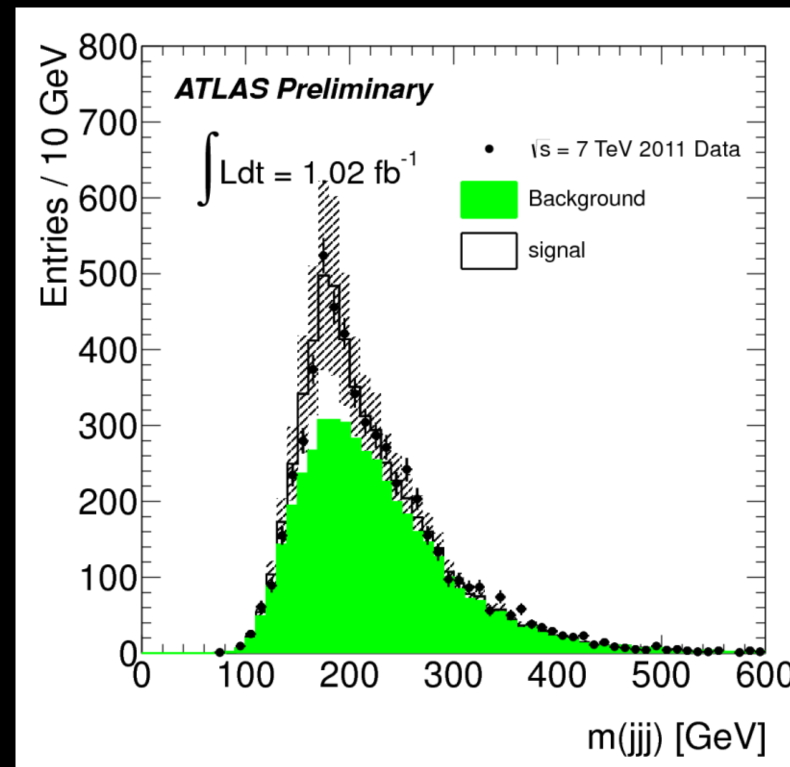
Fit to data

- Signal fraction 24%



Releasing m_{top} constraint

- Using Δm(jjj) instead



- Dominating systematics
  - JES, b-tagging, ISR/FSR

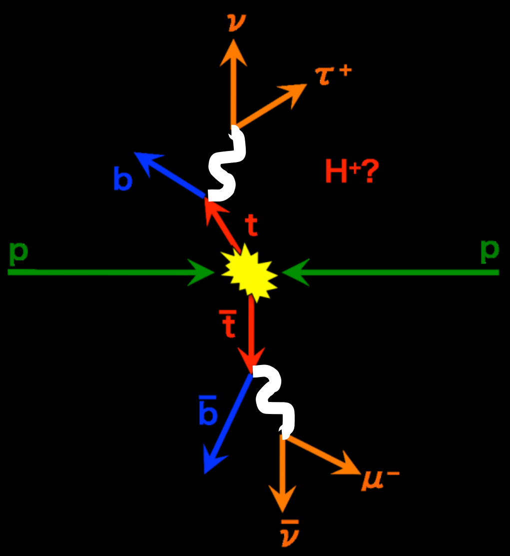
$\sigma_{t\bar{t}} = 167 \pm 18_{stat} \pm 78_{syst} \pm 6_{lumi}$ pb

$\mu+\tau$ channel

ATLAS-CONF-2011-119
$\int L\,dt = 1.08\ fb^{-1}$

Interesting but challenging channel

- BF could be modified by presence of H^+
- So far $\delta\sigma/\sigma$ measured to ~ 25% accuracy



Selection

- One μ, $N(\tau_{had})\geq 1$, $N_{jets}(p_T>25GeV)\geq 2$ (≥1 b-jets), $E_T^{miss}>30GeV$, $H_T+E_T^{miss}>200GeV$

τ_{had} candidate

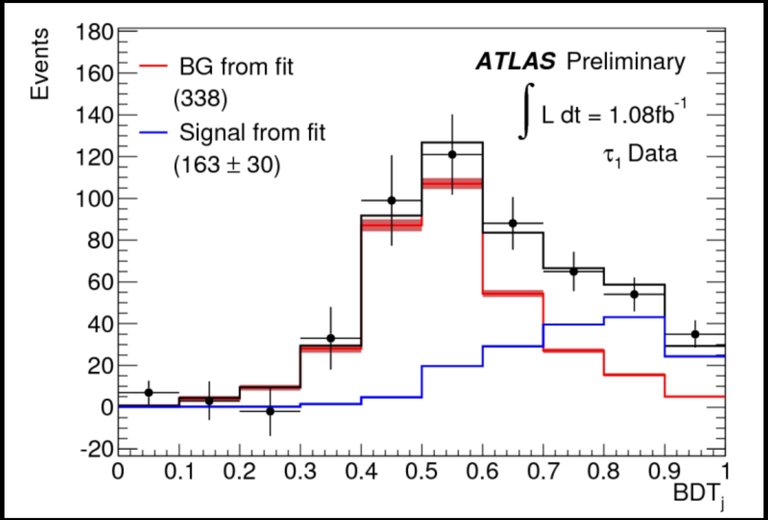
- Reconstructed with anti-k_T on calo seeds
- Count associated tracks w/ $p_T>1GeV$, leading track $p_T>4GeV$
- $N_{trk}=1$ (1-prong τ_1); $N_{trk}=2,3$ (3-prong τ_3)
- Charge $\Sigma q_{trk} \neq 0$
- 20 GeV < p_T (τ_{had}) < 100 GeV, $|\eta|<2.3$
- No overlap with μ, e, b-jet

$\mu+\tau$ channel

ATLAS-CONF-2011-119
$\int L\,dt = 1.08\,fb^{-1}$

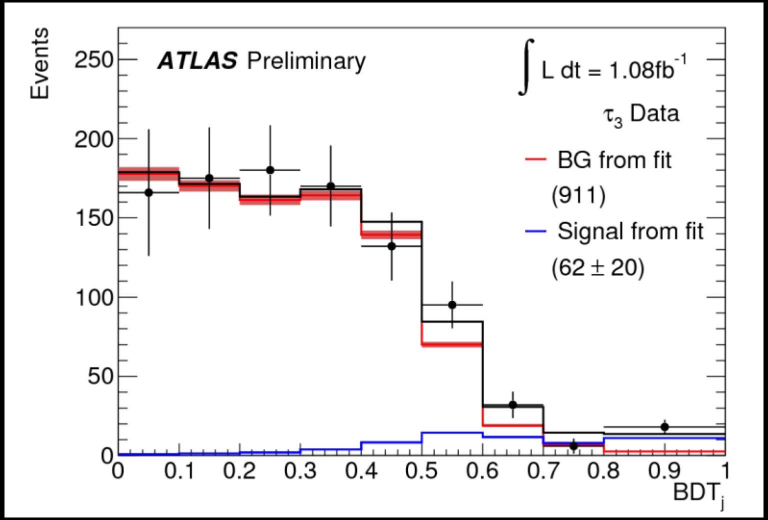
Reduce misidentification

- Boosted Decision Tree against $e\to\tau_{had}$
- QCD estimated from non-isolated μ's
- Need Boosted Decision Tree for τ_{had} id.



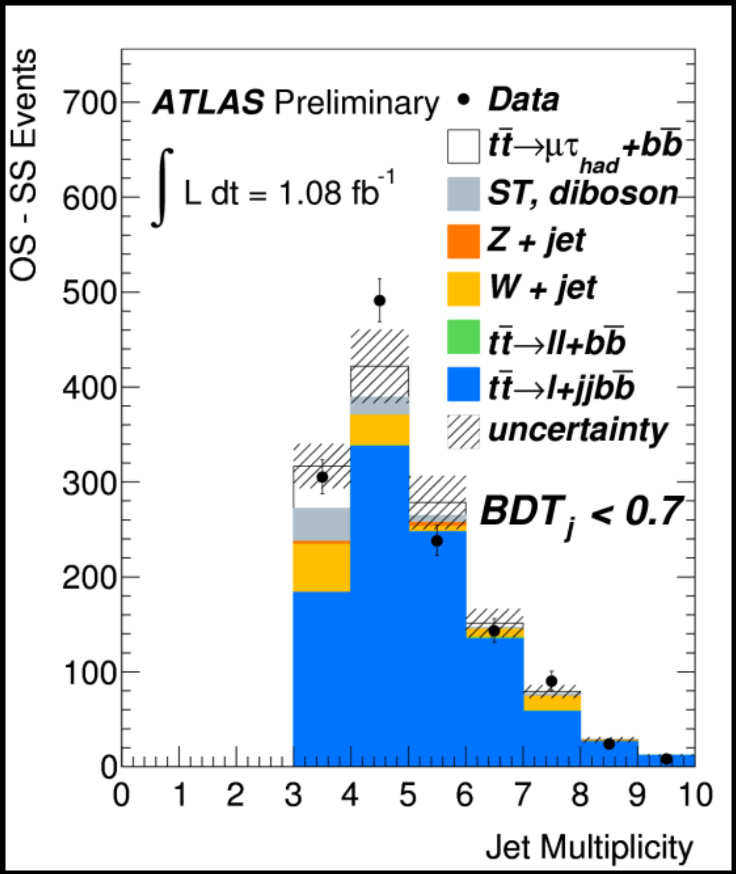
Strategy

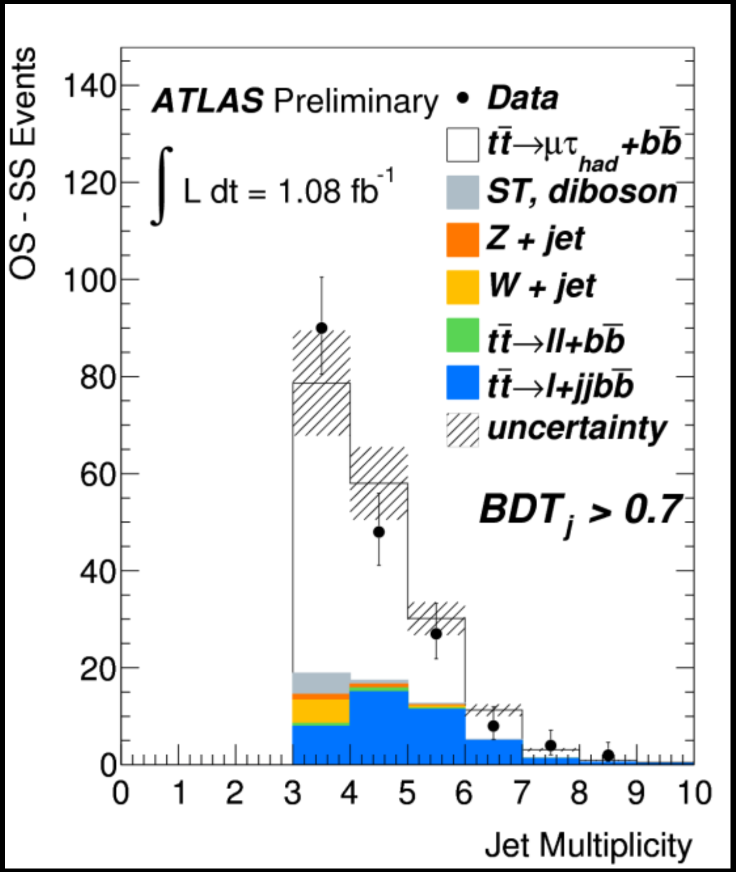
- Remaining background: μ+jets events
- Fake rate depends on jet composition
- Split sample into OS($\mu^+\tau^-$) and SS($\mu^+\tau^-$)
  - OS and SS have same shape for gluons and light quark jets
- Narrow jet cone, low N_{trk} $\longrightarrow$ BDT_j score



Cross section in μ+τ channel

ATLAS-CONF-2011-119
$\int L\,dt = 1.08\ fb^{-1}$





$$\sigma_{t\bar{t}} = 142 \pm 21_{stat}\ {}^{+20}_{-16 syst} \pm 5_{lumi}\ \text{pb}$$

Summary table cross-sections

Channel	Data	σ (pb)	stat. (pb)	syst. (pb)
Single lepton	**0.70 fb^{-1}**	**179**	**±12**	
Dilepton	0.70 fb^{-1}	177	±6	+19-16
Dilepton b-tag	0.70 fb^{-1}	183	±6	+20-16
All hadronic	1.02 fb^{-1}	142	±21	+21-17
μ+τ	1.08 fb^{-1}	167	±18	±78

In agreement with approximate NNLO QCD prediction:

$$\sigma_{t\bar{t}} = 164^{+11}_{-16} \text{ pb}$$

Plan for today

Cross-section measurements $\sigma_{t\bar{t}}$

- Dilepton, single lepton channels
- $\mu+\tau$ channel
- All hadronic channel

Properties of the top quark pair system

- Charge asymmetry
- Spin correlations

$t\bar{t}$+X

- Additional jets
- Additional photons
- Additional E_T^{miss}

More searches

- Search for resonances decaying to top quark pairs
- Search for same-sign tt production

Charge asymmetry

QCD (NLO) predicts asymmetry A for $q\bar{q} \rightarrow t\bar{t}$

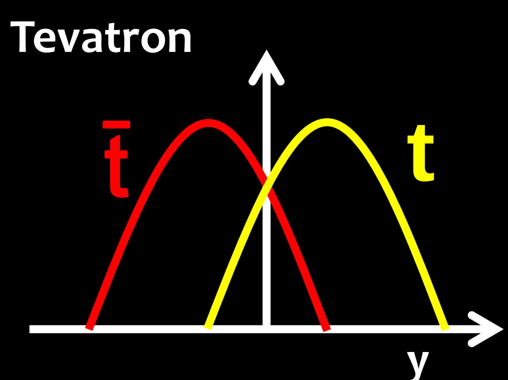
- top emitted preferably in direction of incoming quark, antitop in direction of antiquark

Beyond SM processes can alter this asymmetry

- interest to measure A, complementary to $m_{t\bar{t}}$

Measurements at Tevatron

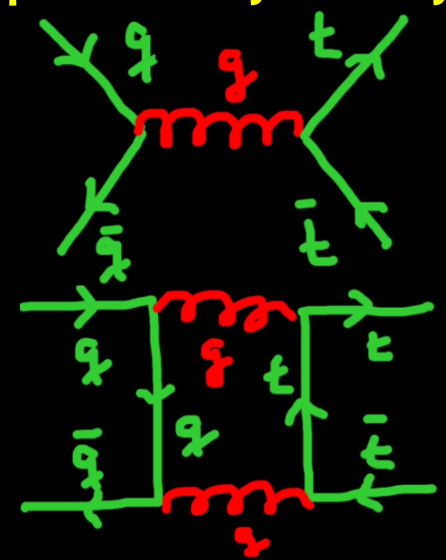
- mainly $q\bar{q}$ production
  - with CP conservation: forward-backward A
- D0: ~2σ excess over SM predictions arXiv:1107.4995
- CDF: 3.4σ excess for $m_{t\bar{t}}$>450GeV PRD83, 112003 (11)



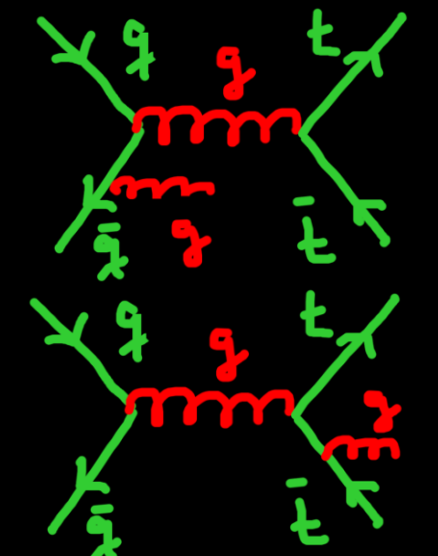
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$\Delta y \equiv y_t - y_{\bar{t}}$$

positive asymmetry



negative asymmetry

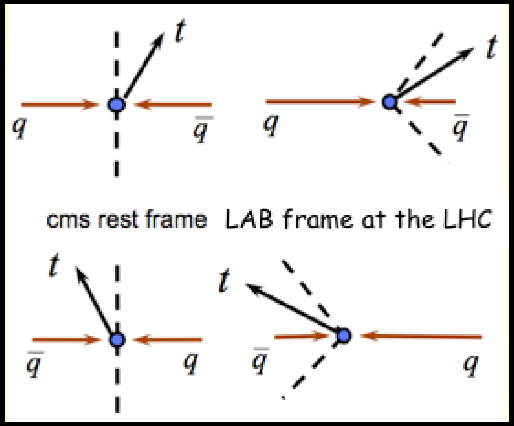


Charge asymmetry at the LHC

ATLAS-CONF-2011-106
$\int L\,dt = 0.70\ fb^{-1}$

At LHC production mainly via gg fusion (symmetric)

- still small asymmetry from $q\bar{q}$
- in lab frame, top preferentially emitted in fwd/bckwd direction antitop more centrally

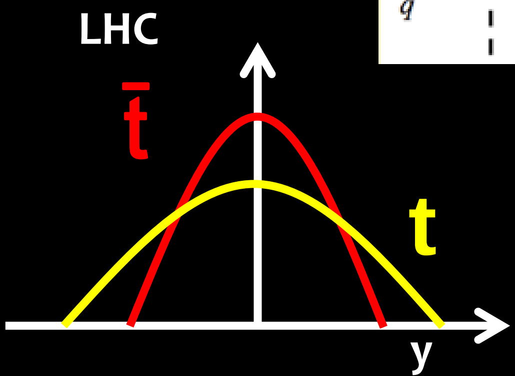


Charge asymmetry observable

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

$$\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$$

- A_C(MC@NLO) = 0.006



Strategy

- same single lepton selection as $\sigma_{t\bar{t}}$ with one SV0 b- jet, ε=50%
- backgrounds: QCD (matrix method), W+jets (charge asymmetry)
- $t\bar{t}$ kinematic likelihood fit
- unfold to truth level

ATLAS-CONF-2011-106
$\int L\,dt = 0.70\ fb^{-1}$

Charge asymmetry

Need reconstruction of full top quark pair kinematics

Use a kinematic likelihood fit

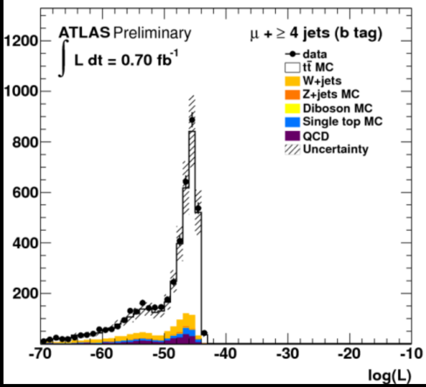
- Inputs: p_T, η, φ for lepton and 5 hardest jets, E_T^{miss}
- Model: $t\bar{t}$ decay from MC. M(W), M(top) and widths fixed

Basic principle

- $\mathcal{B}$: Breit-Wigner parameterisation of measured vs partonic energies
- $\mathcal{W}$: Transfer func. to associate reconstructed and partonic quantities
- $\mathcal{P}$: b-tagging probability for each jet in the likelihood

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

$\varepsilon_{t\bar{t}} = 74\%$



- Loop over the jet combinations assigning a probability to each event. Then choose the best 4-jets combination.

Charge asymmetry: unfolding

ATLAS-CONF-2011-106
$\int L\, dt = 0.70\ fb^{-1}$

Goal: relate reconstructed asymmetry to truth asymmetry

- need to correct for reconstruction/selection and acceptance

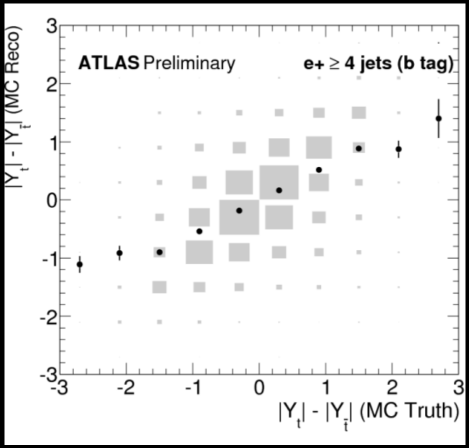
Unfolding

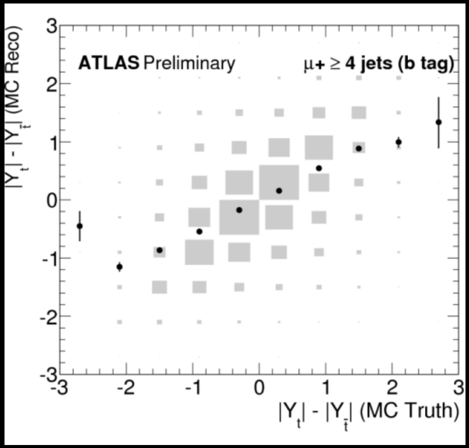
- T_j true distribution; S_i reconstructed; R_{ij} response (from MC)
- need to invert R_{ij} to obtain T_j

$$S_i = \sum_j R_{ij}\, T_j$$

Method: Bayesian iterative unfolding

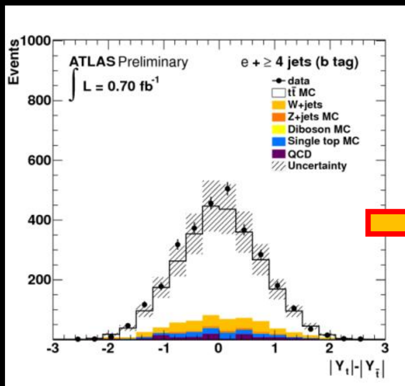
- Bayes' theorem applied iteratively to invert R_{ij}
- truth used as prior, posterior used for next iteration

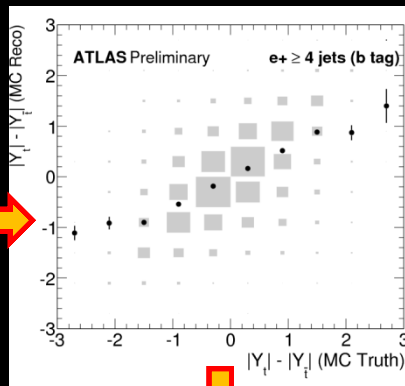


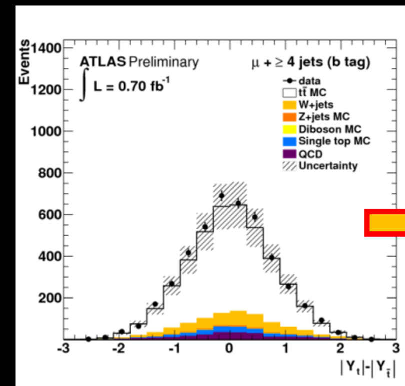


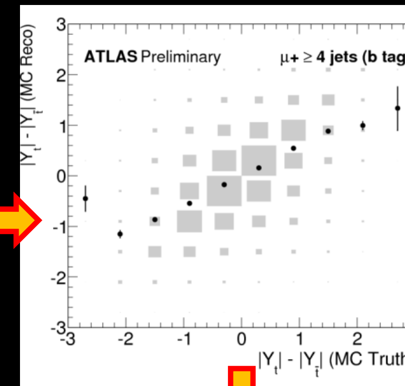
Charge asymmetry result

ATLAS-CONF-2011-106
$\int L\,dt = 0.70\ fb^{-1}$

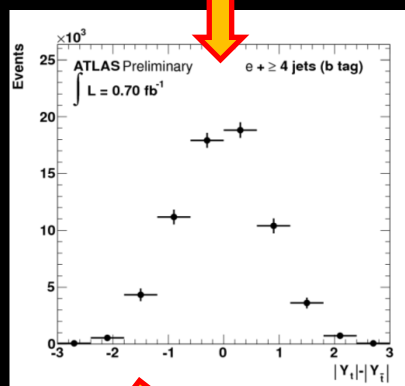




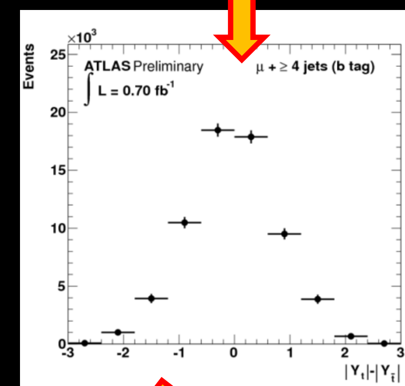




e+jets channel



μ+jets channel



$A_C = -0.9 \pm 2.3_{stat} \pm 3.2_{syst}\ \%$

$A_C = -2.8 \pm 1.9_{stat} \pm 2.2_{syst}\ \%$

Combined with BLUE $A_C = -2.4 \pm 1.6_{stat} \pm 2.3_{syst}\ \%$

A_C(MC@NLO) = 0.6%

Top pair spin correlations

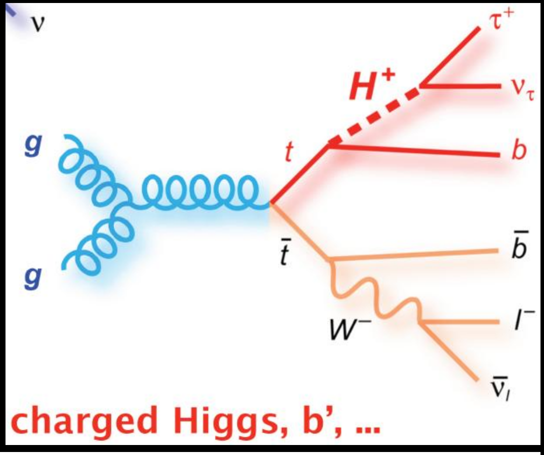
Does the top quark really have spin ½ ?

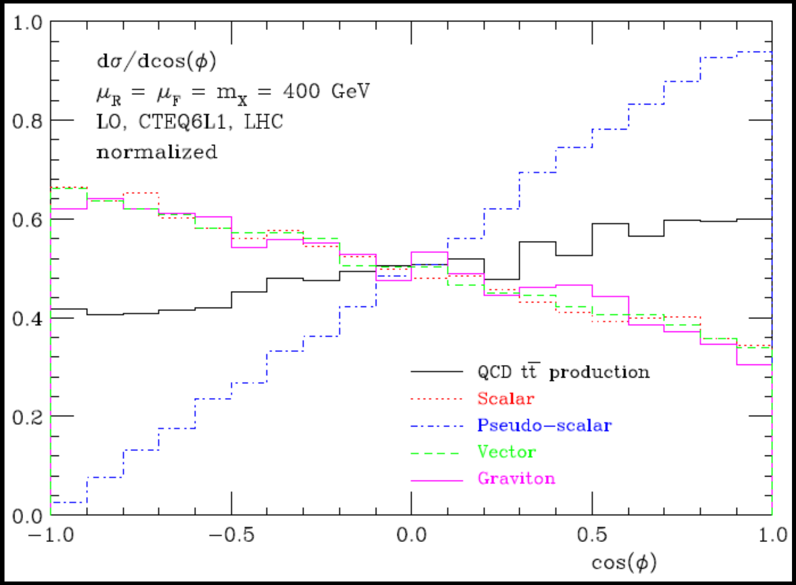
Top quark pair production

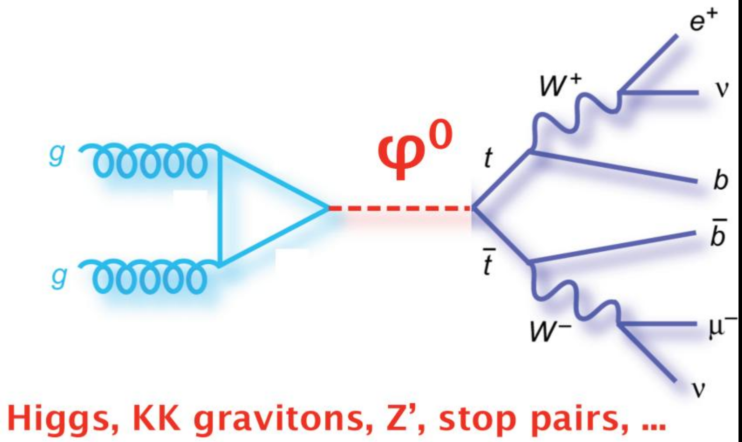
- Top quarks are not polarised, but spins are correlated
- Short lifetime → decay before spin flip
- Spin information contained in decay products

Important test of QCD

- can be modified by BSM



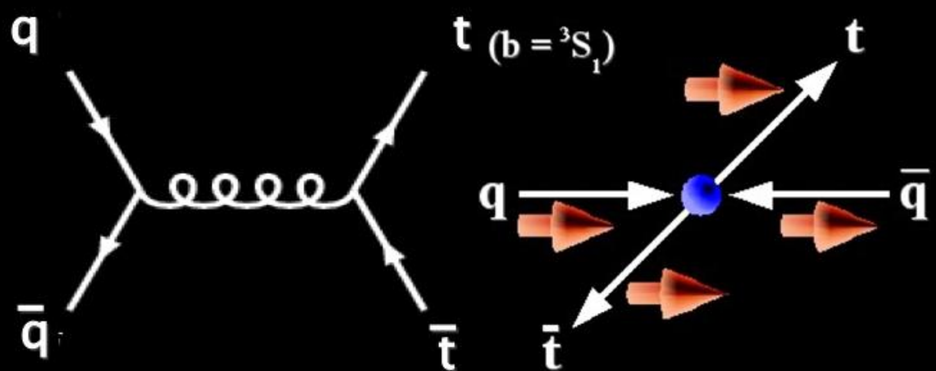




Spin correlation strength

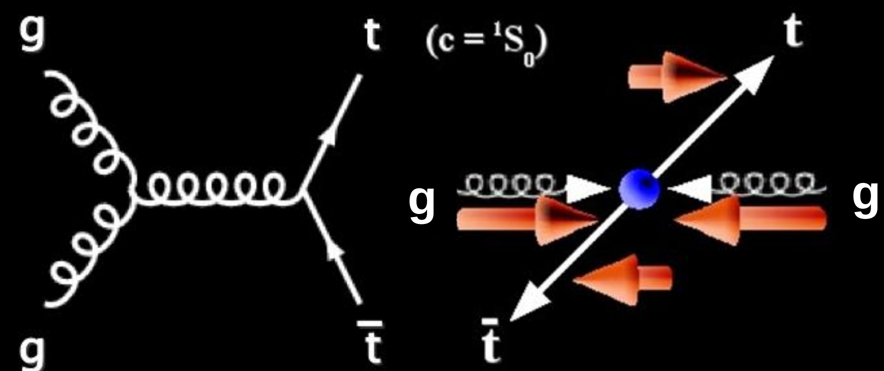
$$A = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}} = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

Tevatron



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

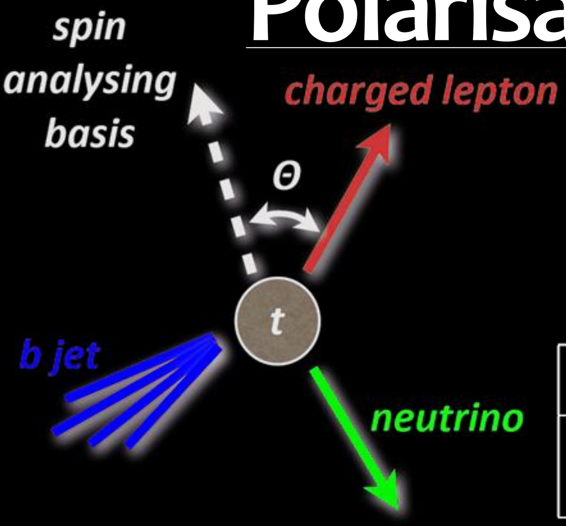
LHC



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

Complementarity between LHC and Tevatron

Polarisation & angular correlation



ATLAS-CONF-2011-117
$\int L\,dt = 0.70\ fb^{-1}$

$$\frac{1}{N}\frac{dN}{d\cos(\theta_i)} = \frac{1}{2}\left[1 + \alpha_i \cos(\theta_i)\right]$$

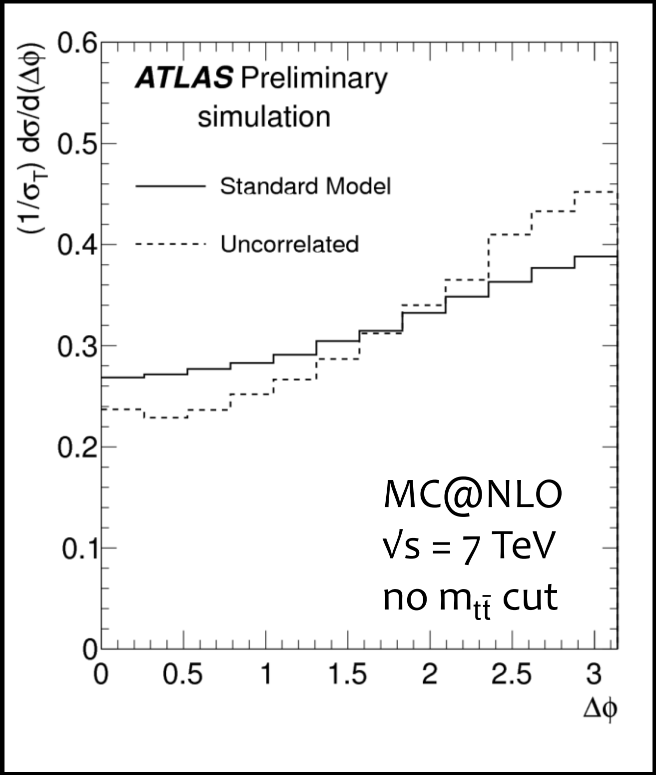
	b-quark	W^+	l^+	$\bar{d}$-quark or $\bar{s}$-quark	u-quark or c-quark
α_i (LO)	-0.41	0.41	1	1	-0.31
α_i (NLO)	-0.39	0.39	0.998	0.93	-0.31

Dilepton channel promises largest sensitivity

- Measurement of angles requires full reconstruction
- Difficult: kinematics underconstrained

Azimuthal angle between leptons in lab

- Mahlon, Parke, PRD 81, 074024 (2010)

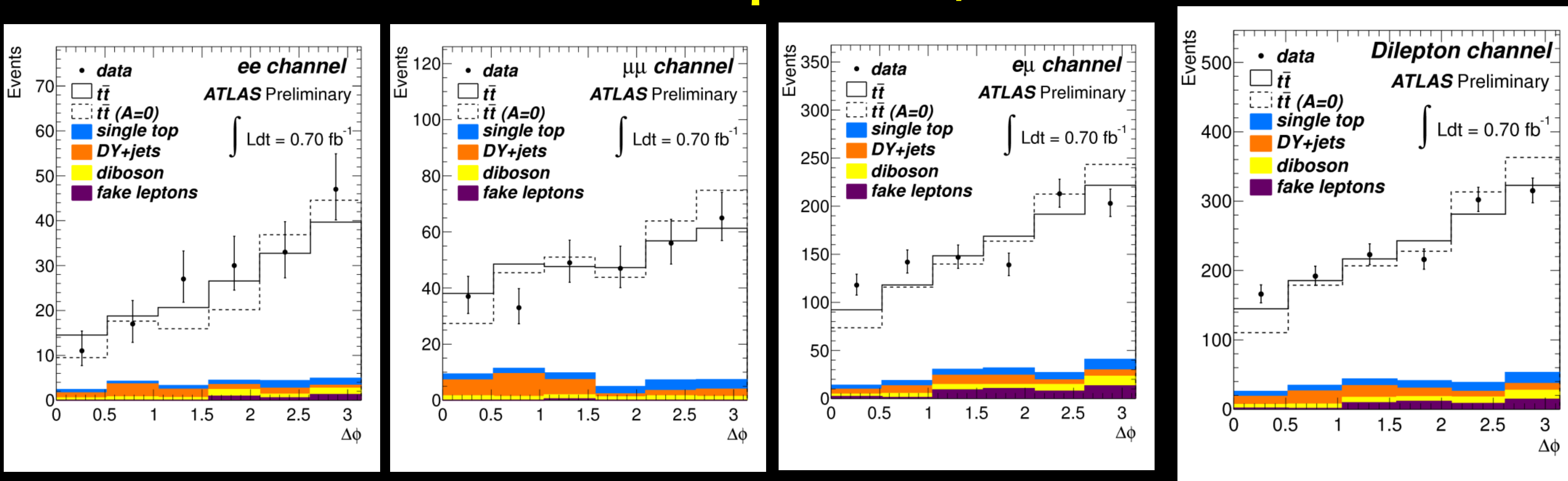


Spin correlation measurement

ATLAS-CONF-2011-117
$\int L\, dt = 0.70\ fb^{-1}$

Dilepton channel selection and backgrounds as for $\sigma_{t\bar{t}}$

Binned likelihood fit to templates w/wo correlation



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)

NLO QCD: 1.00 0.32 0.44

Plan for today

Cross-section measurements $\sigma_{t\bar{t}}$

- Dilepton, single lepton channels
- $\mu+\tau$ channel
- All hadronic channel

Properties of the top quark pair system

- Charge asymmetry
- Spin correlations

$t\bar{t}$+X

- Additional jets
- Additional photons
- Additional E_T^{miss}

More searches

- Search for resonances decaying to top quark pairs
- Search for same-sign tt production

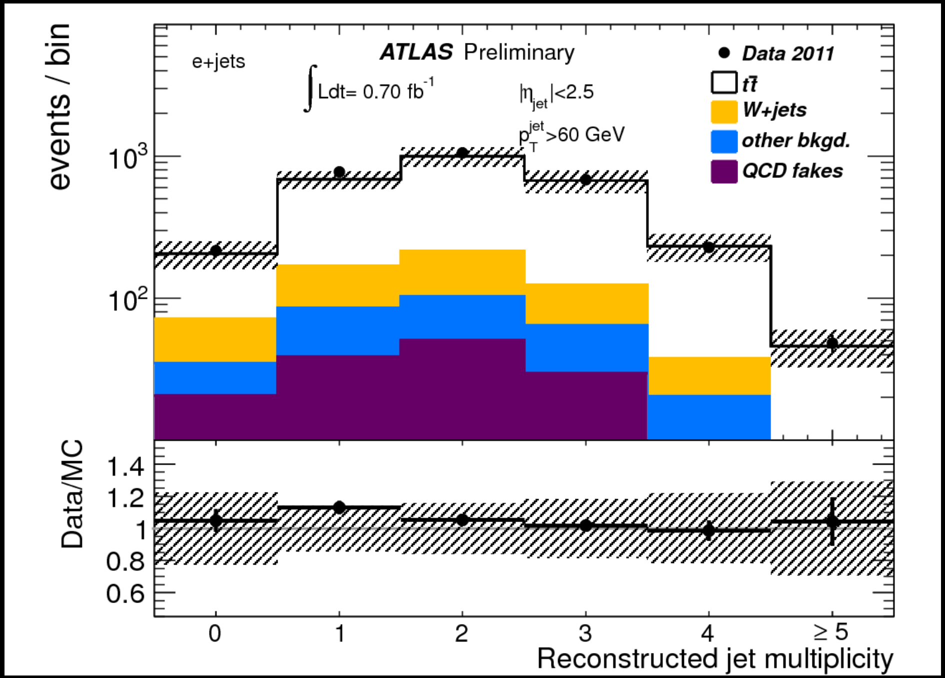
Extra jets

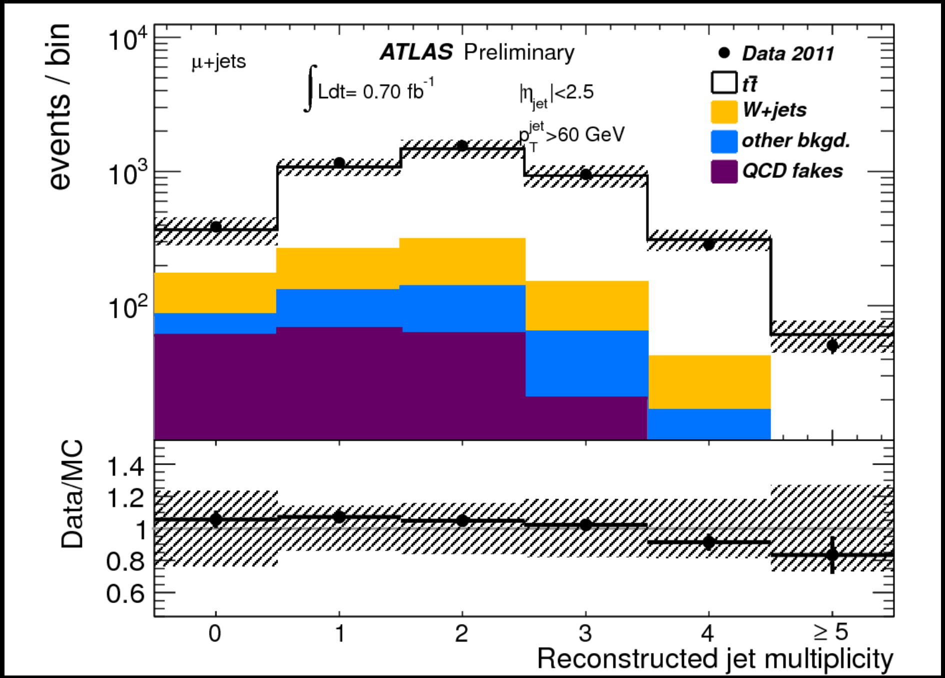
Motivation to study jet multiplicity in $t\bar{t}$ events

- Test of pQCD, study QCD radiation at high momentum scales
- Constrain generator models
- Background to SUSY, H^+, $t\bar{t}H$, technicolor, diboson scattering, …

Strategy

- Count jets in single lepton channel above p_T thresholds (25,40,60)





ATLAS-CONF-2011-142
$\int L\,dt = 0.70\ fb^{-1}$

Study of ISR

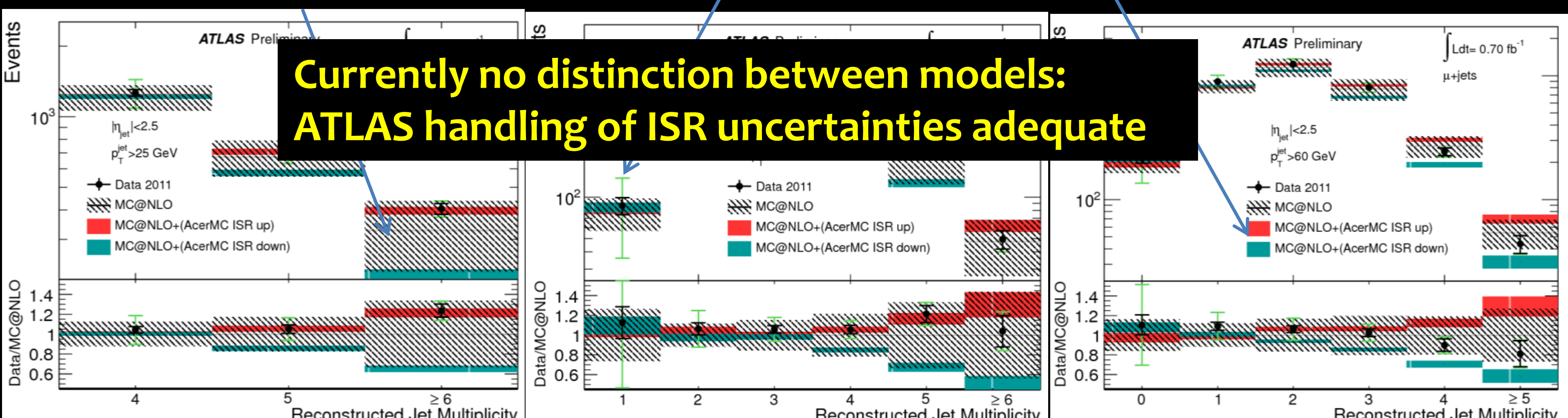
N_{jets} sensitive to initial state radiation

- ISR distribution expected to be harder than FSR
  - jet p_T threshold steps: sample spectrum
  - dominated by ISR at higher jet p_T thresholds
- Use AcerMC+PYTHIA relative diff. and apply it to MC@NLO
  - ISR (-,=,+) steered by PYHTIA6 parameters:
    PARP(67)= (1, 4, 6)   PARP(64)= (4, 1, 0.25)
- Compare background subtracted data with simulation

Signal accept. uncert.

Stat.+syst. due to bckg norm.

AcerMC/MC@NLO stat. uncert.



Currently no distinction between models: ATLAS handling of ISR uncertainties adequate

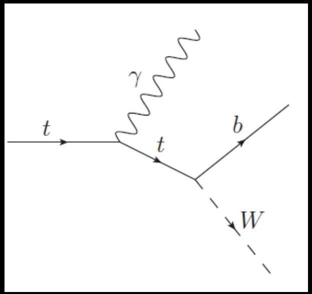
ATLAS-CONF-2011-153
$\int L\, dt = 1.04\ fb^{-1}$

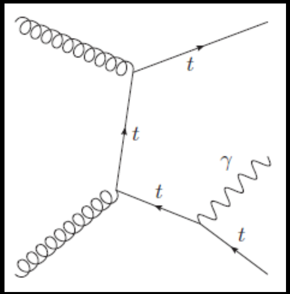
Extra photons

Sensitive to $t\bar{t}\gamma$ vertex

- Eventually probe vector and axial vector couplings
- Here: compare with SM prediction, could measure charge

Photon radiation off top quarks





- Radiative top quark production
- Radiative top quark decay
- Interference is taken into account
- Require m_{inv} of particle pairs > 5GeV and $p_T(\gamma)$ > 8 GeV
- Signal simulated with WHIZARD, overlap with MC@NLO removed

Photon reconstruction

- Converted or unconverted (shower shape, hadronic leakage)
- $0<|\eta|<1.37$ or $1.52<|\eta|<2.37$; $p_T(\gamma) > 15$ GeV
- no isolation required (used for background determination)
- Energy scale and resolution with $Z\rightarrow ee$ events
- Events with $\Delta R(\gamma, jet)<0.5$ removed

ATLAS-CONF-2011-153
$\int L\,dt = 1.04\ fb^{-1}$

Extra photons

Selection

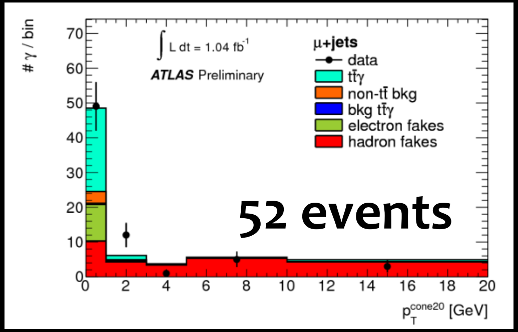
- single lepton channel, b-tagged jet, additional γ
- Remove events with $|m_{e\gamma} - m_Z| < 5$ GeV

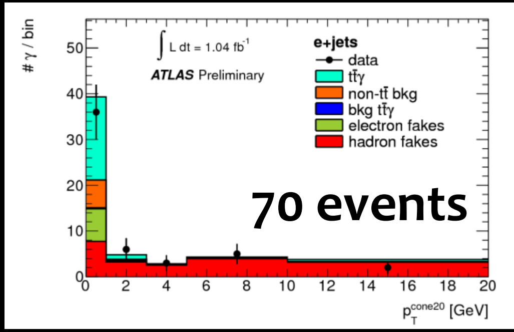
Strategy: template fit of track isolation variable p_T(cone20)

- prompt photons: from Z→ee data and small MC corrections
- hadron fakes: invert at least one requirement on shower shape

Backgrounds

- hadrons
- top pairs with electron faking γ: r=3.6% in data (2.6% in MC)
- other top pairs: radiation off (not identified) lepton
- W+jets+γ, QCD+γ, …





Sensitivity

- Expected 3.0 ± 0.9 σ
- Measured 2.7σ

$BR*\sigma_{tt\gamma} = 2.0 \pm 0.5_{stat} \pm 0.7_{syst} \pm 0.1_{lumi}$ pb

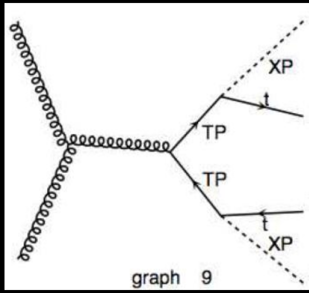
SM $p_T(\gamma)>8$ GeV :2.1±0.4 pb

Extra E_T^{miss}

arXiv: 1109.4725
accepted by Phys.Rev.Lett.
$\int L\, dt = 1.04\ fb^{-1}$

Generic signature

- Stop quark pair production in SUSY assuming stop to top+neutralino
- Little Higgs models with T-parity conservation
- Models with third generation scalar lepto-quarks
- Models with universal extra dimensions with Kaluza-Klein-parity
- Models in which baryon and lepton number conservation arises from gauge symmetries



Alwall, Feng, Kumar *et al.* (2010)
Berger, Cao (2009)

Benchmark model

- Pair-produced vector ‘quark’ T decaying to top and scalar neutral A_0
- A_0 is a dark matter candidate
- Cross section higher than stop due to spin states

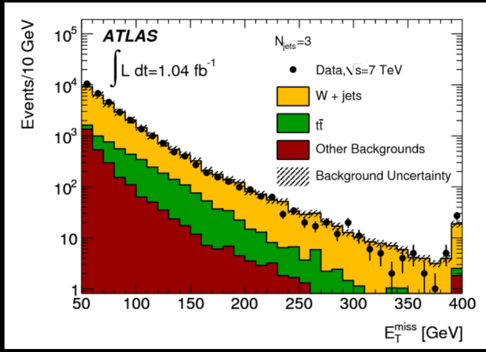
Extra E_T^{miss}

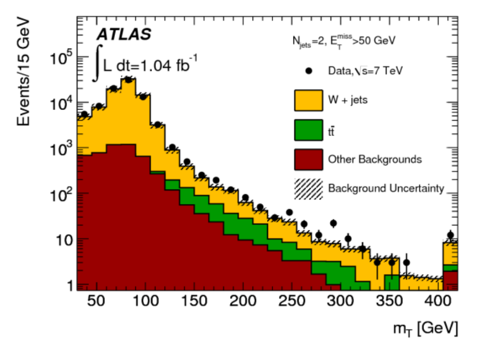
arXiv: 1109.4725
accepted by Phys.Rev.Lett.
$\int L\,dt = 1.04\ fb^{-1}$

Single lepton channel selection

- Further reduce W+jets: $E_T^{miss} > 100$ GeV + $m_T(W) > 150$ GeV
- Reduce $t\bar{t}$ dilepton: veto on second lepton or isolated tracks

Validate background estimates in control regions

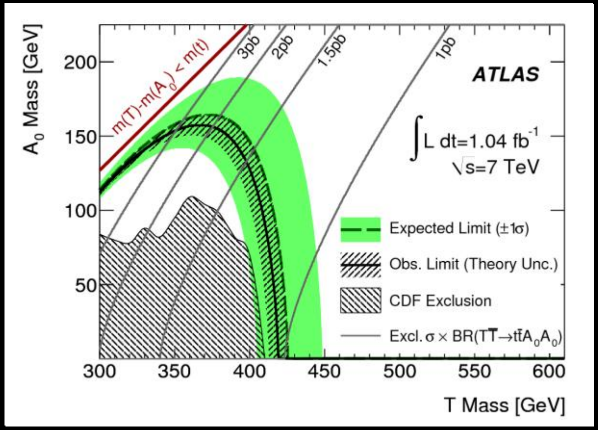


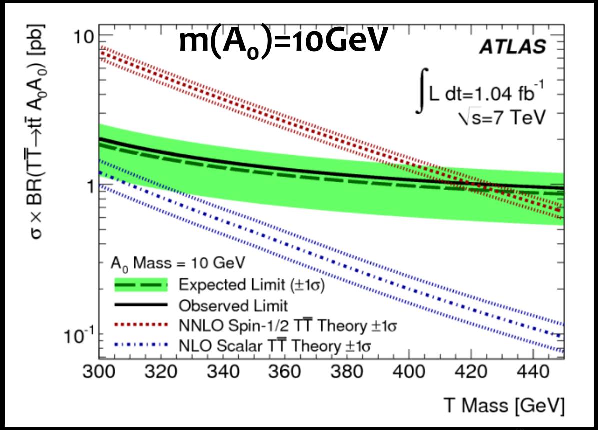


Source	Number of events
Single lepton $t\bar{t}/W$+jets	33.1 ± 3.8
Dilepton $t\bar{t}$	61.7 ± 14.8
Z+jets	0.9 ± 0.3
Dibosons	0.9 ± 0.2
Single top	3.5 ± 0.8
QCD multi-jet	1.2 ± 1.2
Total	101.3 ± 15.9
Data	105

No excess found

- Can set limits on T,A_0





Plan for today

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- Dilepton, single lepton channels
- μ+τ channel
- All hadronic channel

Properties of the top quark pair system

- Charge asymmetry
- Spin correlations

$t\bar{t}$+X

- Additional jets
- Additional photons
- Additional E_T^{miss}

More searches

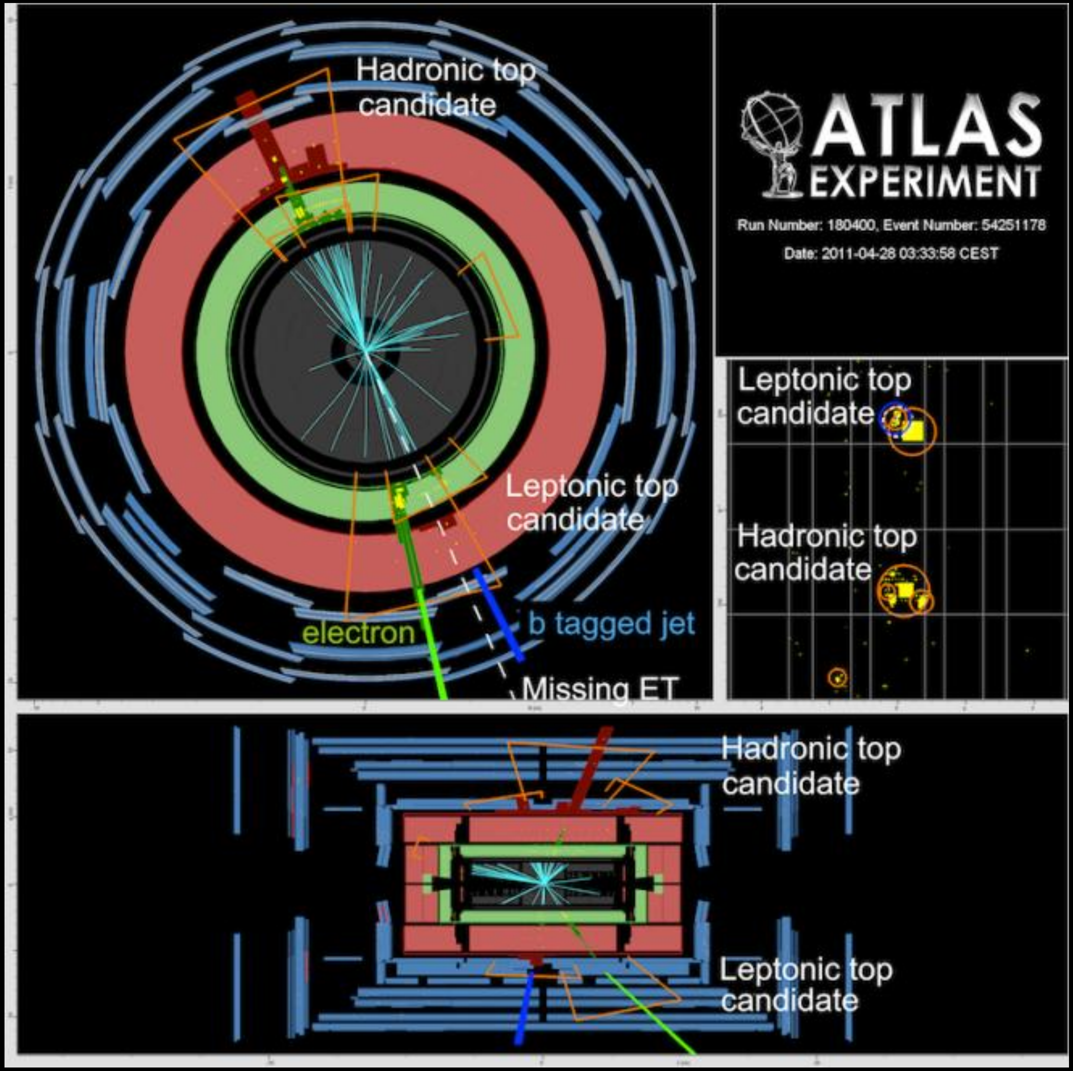
- Search for resonances decaying to top quark pairs
- Search for same-sign tt production

Search for resonances in $t\bar{t}$

ATLAS-CONF-2011-087
$\int L\,dt = 200\ \text{pb}^{-1}$

Massive objects in BSM theories can alter $m_{t\bar{t}}$ spectrum

- Leptophobic topcolor Z'
- Randall-Sundrum Kaluza-Klein gluon g_{KK}
- Quantum black holes (n=6)



high-mass candidate event $m_{t\bar{t}} = 1602$ GeV

Single lepton channel:
exclude g_{KK} resonances with mass below 650 GeV at 95% C.L.

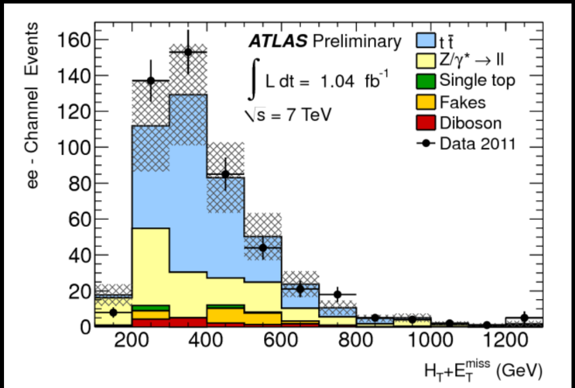
$t\bar{t}$ resonances (dilepton)

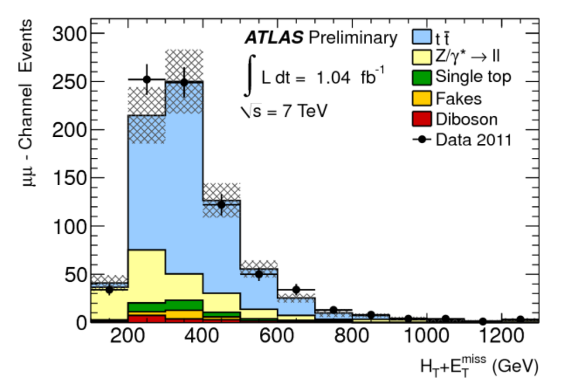
ATLAS-CONF-2011-123
$\int L\,dt = 1.04\ fb^{-1}$

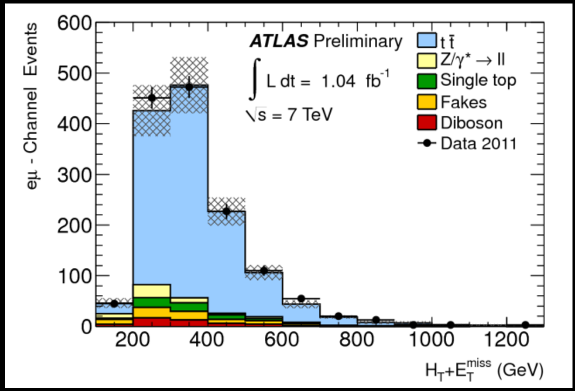
Direct mass reconstruction not possible (underconstrained)

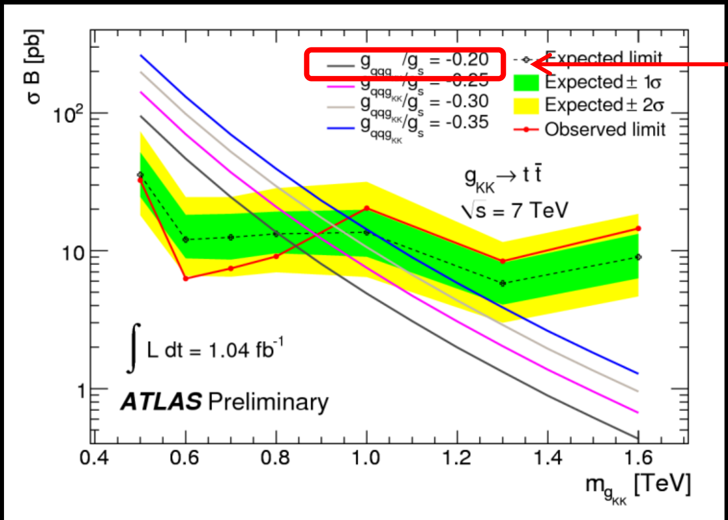
Use $H_T + E_T^{miss}$ spectrum instead

- scalar sum of visible and missing transverse energy









Standard RS coupling

exclude g_{KK} resonances with mass below 840 GeV at 95% C.L.

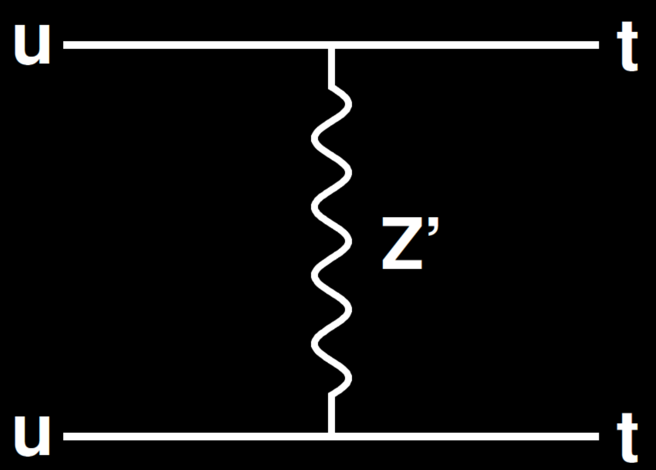
ATLAS-CONF-2011-139
$\int L\,dt = 1.6\ fb^{-1}$

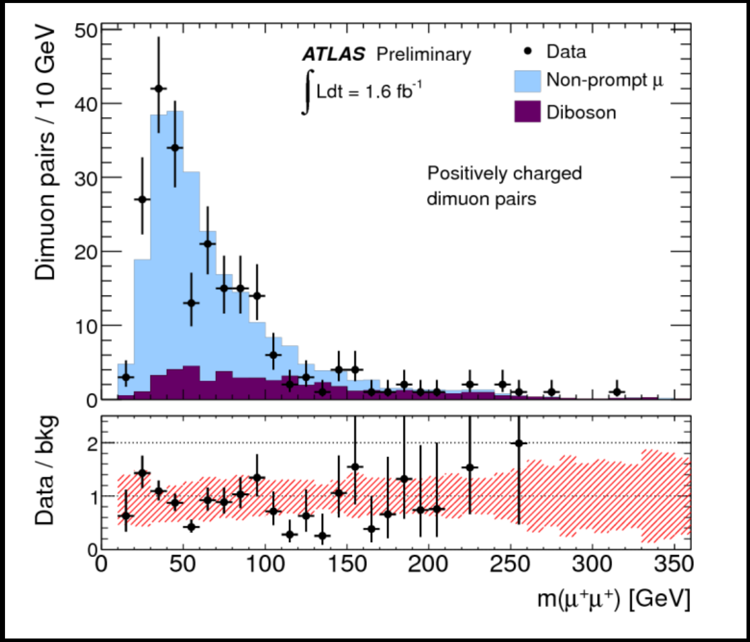
Like-sign top quark pairs

Rate could be enhanced by FCNC Z'

- Current interest as one possible explanation of A_{FB} at Tevatron

Select pair of μ^+ with p_T>20 (10) GeV





Exclude at 95%C.L. production cross-sections of tt in the range 2.9 to 4.1 (m(Z')=100 GeV) pb

Conclusion

With O(1 fb^{-1}) many measurements of top quark pair production and decay

- SM expectations confirmed so far

Analyses are mostly systematics limited

- currently working to improve theoretical and detector understanding

Could not cover all top physics measurements here

Stay tuned for exciting new results with full 2011 dataset

Top Quark Pairs: References

Production cross-section

- Dilepton (arXiv:1108.3699), single lepton (ATLAS-CONF-2011-121), μ+τ (-119), all hadronic (-140)

Properties

- Charge asymmetry (-106), spin correlation (-117)

Extra objects

- Jets (-142), photons (-153), E_T^{miss} (arXiv:1109.4725)

Searches

- Resonances: Single lepton (-087), dilepton (-123)
- Same-sign top pairs(-139)

All results available at the TopPublicResults Twiki page

Not discussed today

Single top quark production

- t-channel (-101)
- Wt-channel (-104)
- Search in s-channel (-118)

Top quark properties

- Mass (-120)
- Charge (-141)
- W helicity from top decay (-122)

Exotic top decays

- $t \to Zq$ (-154)