Search for top squarks using spin correlation with the ATLAS experiment

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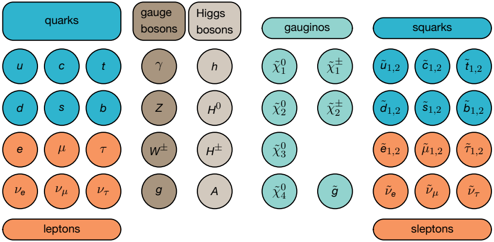
Introduction to Supersymmetry

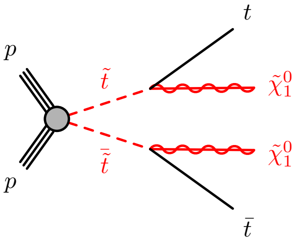


- Symmetry between fermions and bosons
- No sparticles observed so far $\longrightarrow$ broken symmetry
- Introduce R-parity conservation to avoid proton decay $\longrightarrow$ lightest supersymmetric particle (LSP) is stable
- Neutral LSP is ideal dark matter candidate

- SUSY close to TeV energy scale is one way to resolve the hierarchy problem
- Top squarks could be lighter, $\mathcal{O}(m_{\tilde{t}}) \approx$ TeV, than other squarks and gluinos
- LHC had center-of-mass energy of $\sqrt{s} = 8$ TeV (2012)

$\longrightarrow$ Sensitivity up to top squark masses of 700 GeV

- A variety of top squark decays is possible, depending on the SUSY particle mass spectrum
- There are 2 main top squark pair production and decay processes have been explored by ATLAS:



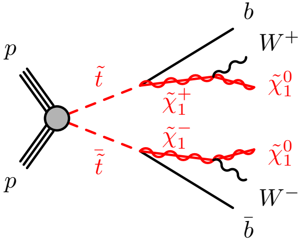
$\tilde{t} \rightarrow t$ (on-shell) $+ \tilde{\chi}_1^0$

210 GeV $< m_{\tilde{t}} <$ 640 GeV,

$m_{\tilde{\chi}_1^0} = 1$ GeV

excluded at 95% CL

from CERN-PH-EP-2014-143



$\tilde{t} \rightarrow b + \tilde{\chi}_1^+$

150 GeV $< m_{\tilde{t}} <$ 445 GeV,

$m_{\tilde{t}} \approx m_{\tilde{\chi}_1^+} + 10$ GeV and $m_{\tilde{\chi}_1^0} = 1$ GeV

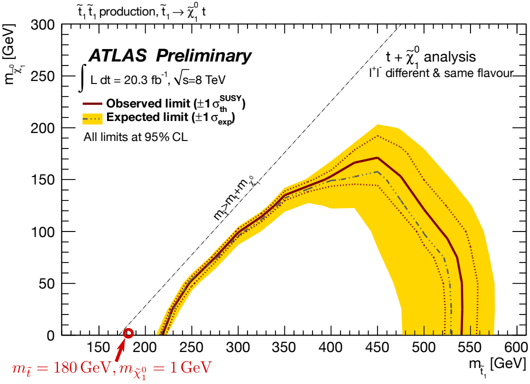
excluded at 95% CL

from CERN-PH-EP-2014-014

Recent exclusion limits from ATLAS

Challenges of $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$ search:

- Cross section for top squark production decreases with increasing top squark masses
- Light top squarks (i.e. $m_{\tilde{t}} \approx m_t \rightarrow m_{\tilde{\chi}_1^0} \approx 0$) not excluded, since signature is very similar to $t\bar{t}$ production
- For $t\bar{t}$ decays into 2 leptons $\ell \in \{e, \mu\}$: small $\mathcal{BR}(W^+W^- \rightarrow \ell^+\ell^-\nu_\ell\bar{\nu}_\ell) = \frac{4}{81}$

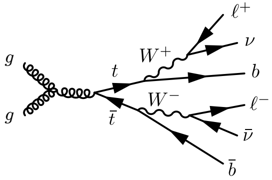


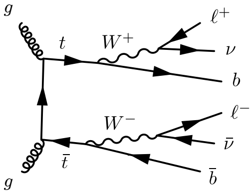
from ATLAS-CONF-2013-065

$\rightarrow$ Light $\tilde{t}$ and t only differ in their spin

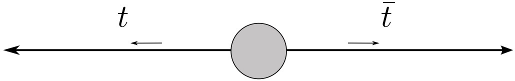
Spin correlation in $t\bar{t}$ production at the LHC

- Top quarks are mainly produced via gluon fusion at the LHC





- Mahlon, Parke (arXiv:1001.3422v2 [hep-ph]): At LHC energies, the collision of gluons with the same helicity is dominant and therefore the production of same-helicity $t\bar{t}$ pairs dominates.
- *Simplified* picture:



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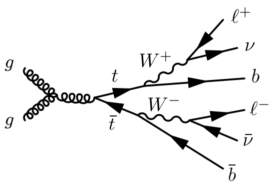

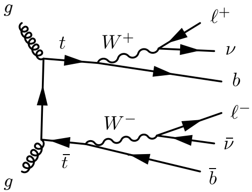

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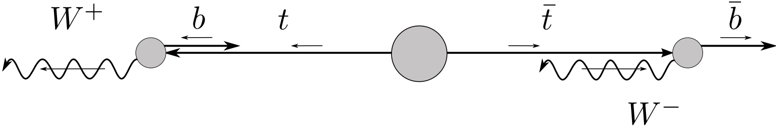

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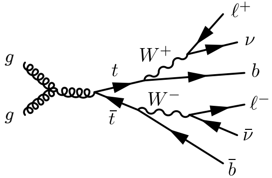

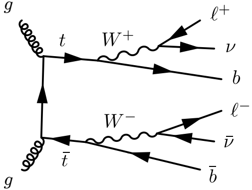

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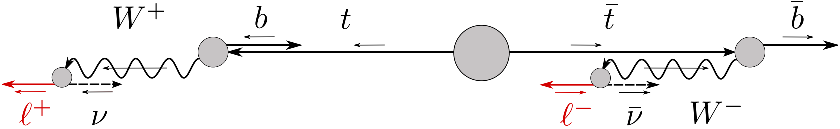
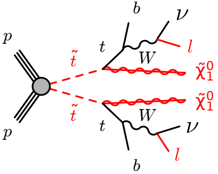


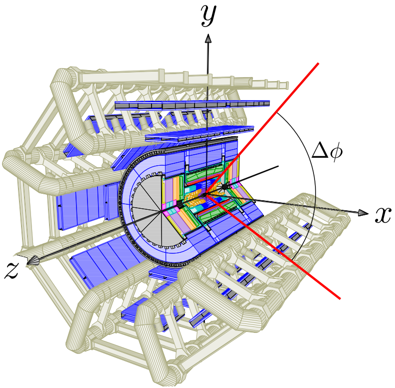
$\rightarrow$ Here, the leptons have the same direction of flight

$\rightarrow$ Direction of flight of decay leptons is sensitive to spin correlation of $t\bar{t}$ pairs

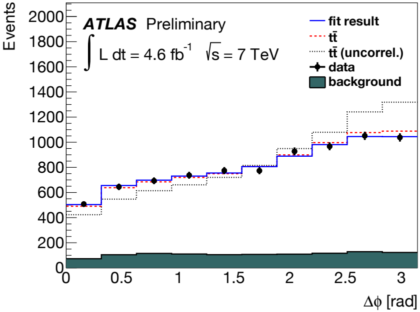
Measurement of the azimuthal dilepton opening angle $\Delta\phi$

- Mahlon, Parke: $t\bar{t}$ spin correlations can be detected in the distribution of the azimuthal angle difference $\Delta\phi$ in the laboratory frame of the two leptons from semileptonic t and $\bar{t}$ decays
- $t\bar{t}$ system does not have to be fully reconstructed





Spin correlation measurements



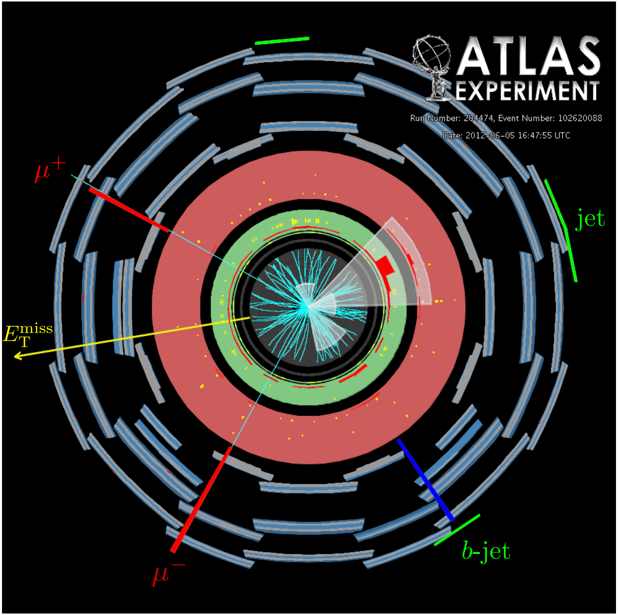
from ATLAS-CONF-2013-101

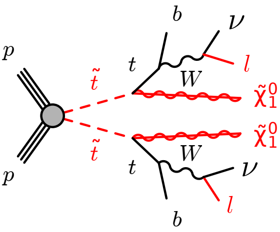
- First $t\bar{t}$ spin correlation measurement in ATLAS performed with $\mathcal{L} = 4.6\ fb^{-1}$ of data from 2011 at a center-of-mass energy of $\sqrt{s} = 7$ TeV
- Good agreement with SM prediction

$\rightarrow$ Since top squarks are scalar particles, there spins are uncorrelated

$\rightarrow$ Measure $\Delta\phi$ distribution of lepton pairs (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$) with $\mathcal{L} = 20.3\ fb^{-1}$ of data taken 2012 at a center-of-mass energy of $\sqrt{s} = 8$ TeV and compare with spin-1/2 $t\bar{t}$-production

$\rightarrow$ Sensitive to light top squarks

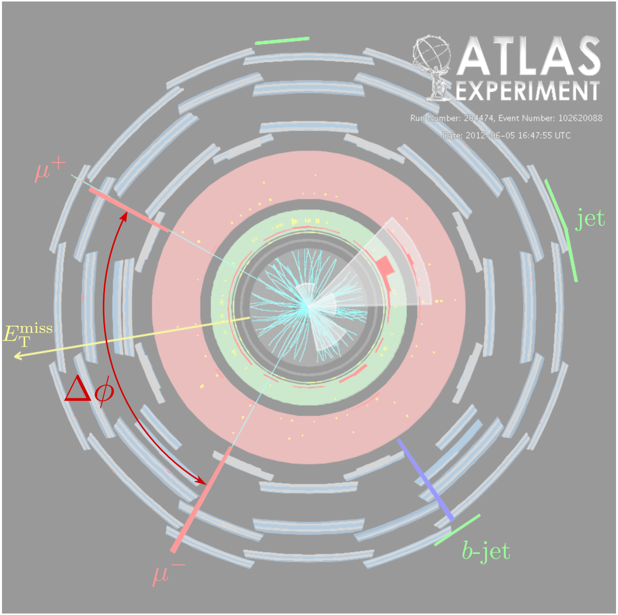


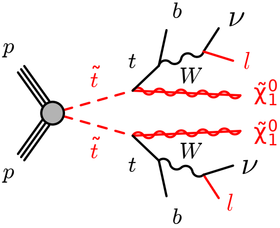


$\mu^+\mu^-$ channel

$E_T^{miss} = 31.8$ GeV

$m_{\mu^+\mu^-} = 119.8$ GeV





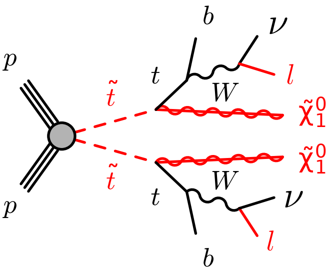
$\mu^+\mu^-$ channel

$E_T^{miss} = 31.8$ GeV

$m_{\mu^+\mu^-} = 119.8$ GeV

$\rightarrow \Delta\phi_{\mu^+\mu^-} = 1.559$

Event selection



- Exactly 2 opposite charged leptons: e^+e^-, $\mu^+\mu^-$ or $e^\pm\mu^\mp$
- At least two jets
- At least one of them has to be a *b*-jet
- Missing transverse energy $E_T^{\text{miss}} > 30$ GeV for e^+e^-, $\mu^+\mu^-$
- Z-veto: $|m_{ll} - m_Z| > 10$ GeV, Υ- and J/ψ-veto: $m_{ll} > 15$ GeV for e^+e^-, $\mu^+\mu^-$
- $(Z \to \tau^+\tau^- \to e^\pm\mu^\mp)$-veto: $H_T = \sum_{\text{lept}} p_T + \sum_{\text{jets}} p_T > 130$ GeV for $e^\pm\mu^\mp$

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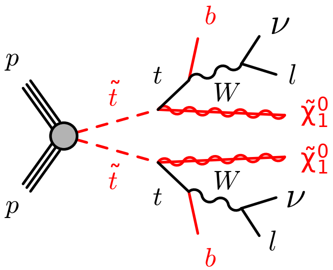

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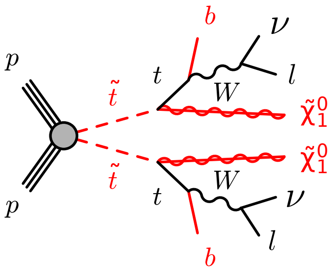

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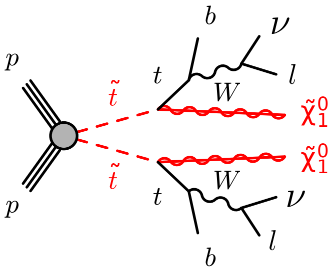

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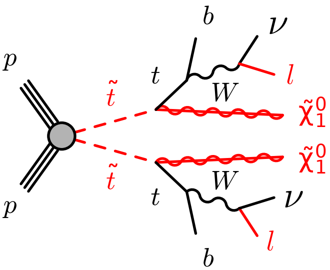

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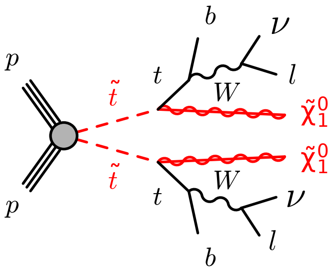

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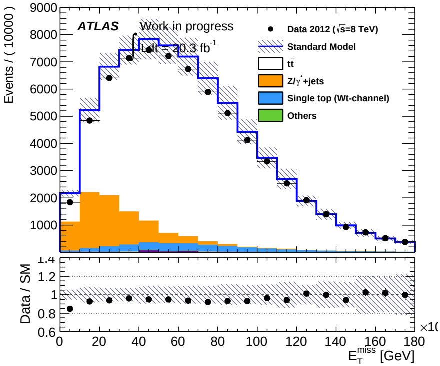
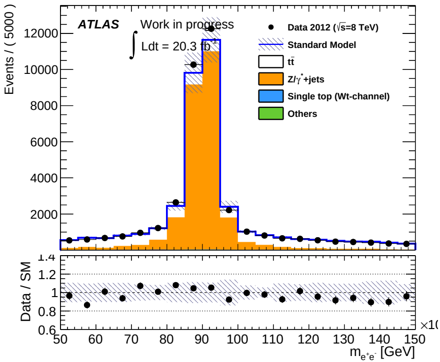
Data - MC comparison (e^+e^-, $\mu^+\mu^-$ and $e^\pm\mu^\mp$ merged)

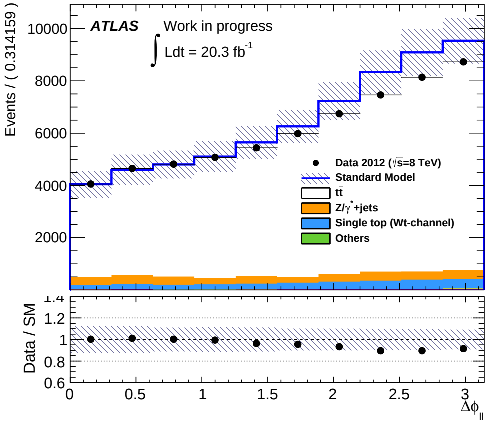




$\rightarrow$ E_T^{miss}-cut reduces $Z/\gamma^* +$ jets background in e^+e^-, $\mu^+\mu^-$ channels

$\rightarrow$ $m_{\ell\ell}$-cut reduces $Z/\gamma^* +$ jets background in e^+e^-, $\mu^+\mu^-$ channels

$\Delta\phi$ distribution



all channels
(e^+e^-, $\mu^+\mu^-$ and $e^\pm\mu^\mp$ merged)

The main systematic uncertainties arise from:

- Jet energy resolution (normalisation)
- Jet energy scale (normalisation)
- Parton density functions (normalisation)
- MC generator (normalisation and shape)
- Renormalisation/factorisation scale used in MC (normalisation and shape)

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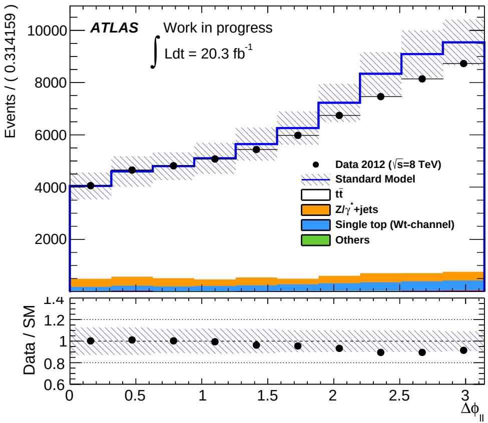

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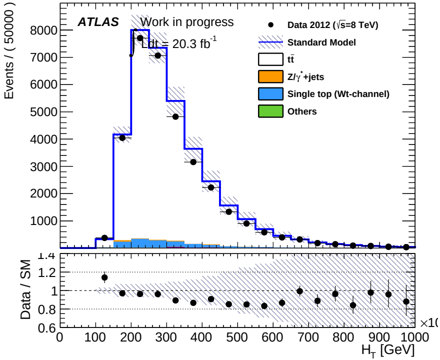
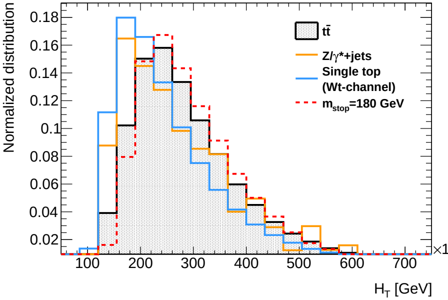
$\rightarrow$ Agreement of data and simulation within the systematic uncertainties. Try to constrain possible signal models in the $m_{\tilde{t}}$-$m_{\tilde{\chi}_1^0}$ plane.

Using a second variable in the fit

$$H_T = \sum_{\text{lept}} p_T + \sum_{\text{jets}} p_T$$

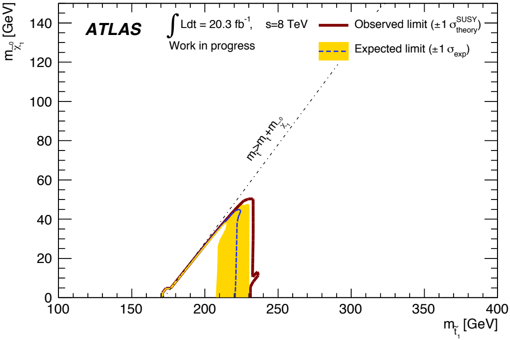
Simulated distributions





Non-$t\bar{t}$ backgrounds tend to have their maxima at lower H_{T} than the $t\bar{t}$ sample

Exclusion contour plot

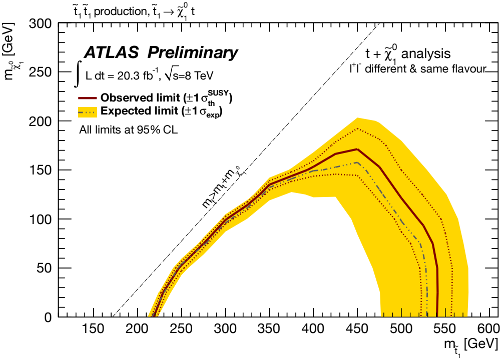


Using a frequentist approach for calculating exclusion limits at 95% confidence limit:

- Repeated hypothesis tests are run in the $m_{\tilde{t}}$-$m_{\tilde{\chi}^0_1}$ plane.
- By interpolation, get the line where CL_s value is equal to 0.05.
- The area below the red curve is excluded at 95% confidence limit.

Summary

- Analysis to search for light top squarks using spin correllation
- No indication for top squarks found so far
- Kinematically challenging part of phase space excluded



Thank you for your attention!

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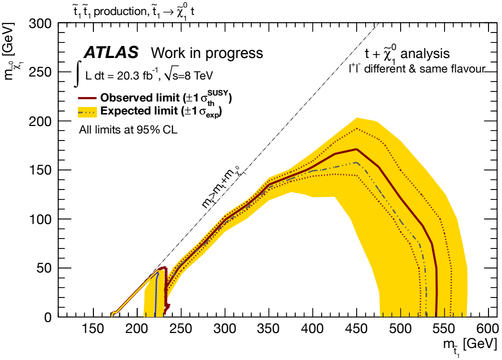


Thank you for your attention!

BACKUP

Backup - Event selection

Channel	Same flavour	Mixed flavour
Leptons	exactly 2 oppositely charged leptons with $p_{\mathrm{T}} > 25$ GeV, $p_{\mathrm{T}}^{\mathrm{cone}}/p_{\mathrm{T}} < 0.1$ for electrons, $p_{\mathrm{T}}^{\mathrm{cone}} < 1.8$ GeV for muons Triggers: e24vhi_medium1 for $e^{\pm}$, mu24i_tight for $\mu^{\pm}$	
	$e^{+}e^{-}$, $\mu^{+}\mu^{-}$	$e^{\pm}\mu^{\mp}$
Jets	≥ 2 jets with $p_{\mathrm{T}} > 25$ GeV, ≥ 1 b-jet	
Invariant mass	$\lvert m_{\ell\ell} - m_{Z}\rvert > 10$ GeV, $m_{\ell\ell} > 15$ GeV	- -
Missing transverse energy	$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV	-
Scalar sum of transverse momenta	-	$H_{\mathrm{T}} > 130$ GeV

see also ATLAS-CONF-2013-101

additional event selection in SUSYTools-00-03-21

`TPileupReweighting::SetDataScaleFactors(1./1.09)` for nominal tree

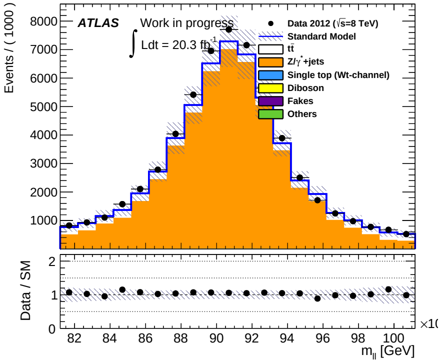
for jets: `SUSYObjDef::IsTileTrip`, `SUSYObjDef::IsGoodJet`, BCHTool, JVFcutNominal = 0.5

Backup

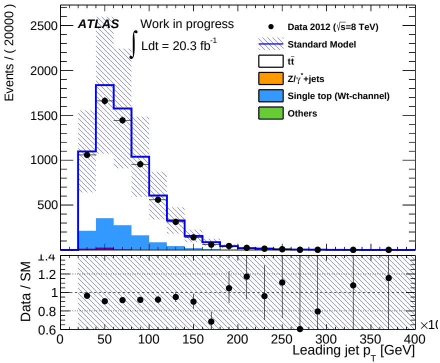
Control regions

Estimate background contributions in specific regions of phase space and extrapolate to region of interest.

$Z/\gamma^* + \text{jets}$



Single top quark production via the *Wt* channel



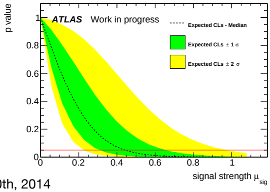
Backup - Setting exclusion limits

- Building probability density function (PDF):

$$\mathcal{P}(n, \mathrm{a}|\mu, \boldsymbol{\alpha}) = \mathrm{Pois}(n|\nu) \cdot \prod_{i \in \mathrm{Syst}} N(a_i|\alpha_i, 1)$$

  $\nu = \mu S(\boldsymbol{\alpha}) + B(\boldsymbol{\alpha})$: expected events, n: observed events, $\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{obs}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$: signal strength, $N(a_i|\alpha_i, 1)$: normalisation distribution of systematic with nuisance parameter α_i and auxiliary measurement a_i

- Inserting data (n, a) into PDF $\mathcal{P}(n, \mathrm{a}|\mu, \boldsymbol{\alpha}) =: L(\mu)$ gives likelihood function $\rightarrow$ Maximizing $L(\mu)$ gives signal strength μ and constrains nuisance parameters $\boldsymbol{\alpha}$
- *Maximum likelihood ratio test* method gives so-called *p value* (probability to observe a given signal strength caused by statistical fluctuations of SM background)



- Calculation of p values for each μ
- Exclude all signal strengths μ at 95 CL where p value is less than 0.05
- Expected exclusion limit: exclusion limit with n = number of SM background events

Backup

Spin correlation in $t\bar{t}$ production at the LHC

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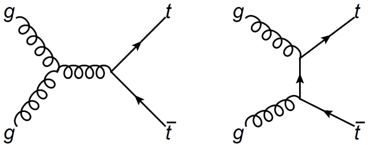
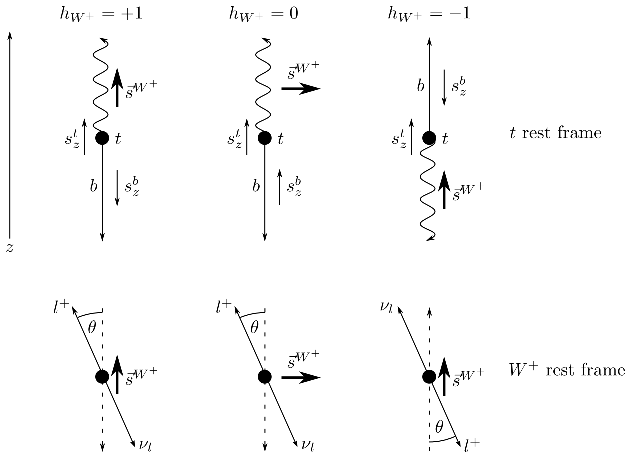


- Mahlon, Parke (arXiv:1001.3422v2 [hep-ph])
  - Without orbital angular momentum: due to gluon fusion $t\bar{t}$-pairs with the same helicity are dominant
  - Top quarks decay before they hadronize ($\Gamma_t > \Lambda_{\mathrm{QCD}}$)
  - W boson has helicity 0 or ± 1
  - Direction of spin of top quark is related to direction of flight of lepton
- Spins of $t\bar{t}$-pairs are correlated (fermions) while spins of $\tilde{t}\bar{\tilde{t}}$-pairs are not

Backup

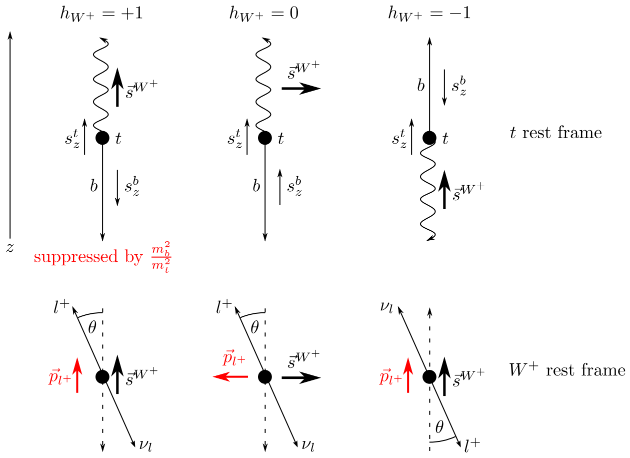
Helicity of the W Bosons in $t\bar{t}$ decays



$|\mathcal{M}|^2 \propto (1+\cos(\theta))^2$ $|\mathcal{M}|^2 \propto \sin^2(\theta)$ $|\mathcal{M}|^2 \propto (1-\cos(\theta))^2$

Backup

Helicity of the W Bosons in $t\bar{t}$ decays



$|\mathcal{M}|^2 \propto (1+\cos(\theta))^2$ $\rightarrow \theta = 0$

$|\mathcal{M}|^2 \propto \sin^2(\theta)$ $\rightarrow \theta = \pi/2$

$|\mathcal{M}|^2 \propto (1-\cos(\theta))^2$ $\rightarrow \theta = \pi$