Search for top squarks using spin correlation measurements with the ATLAS detector

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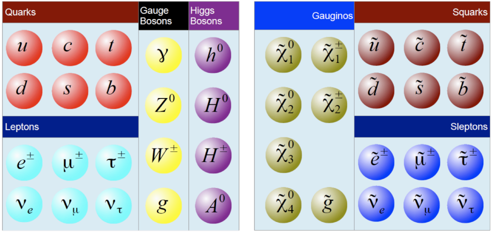
Introduction to Supersymmetry

- Symmetry between fermions and bosons
- No SUSY sparticles observed so far in SM mass range $\rightarrow$ broken symmetry
- SUSY close to TeV energy scale is one way to resolve the hierarchy problem
- Introduce quantum number R-parity to avoid proton decay $\rightarrow$ existence of lightest supersymmetric particle (LSP)



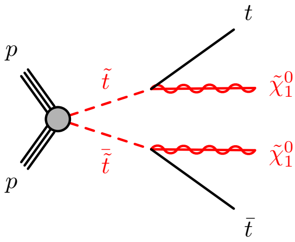
SM particles and MSSM sparticles (from Mike Flowerdew)

- Top squarks should be light ($\lesssim 1$ TeV)
- LHC has center-of-mass energy of $\sqrt{s} = 8$ TeV (2012)

$\rightarrow$ Potential sensitivity up to stop masses of 1 TeV

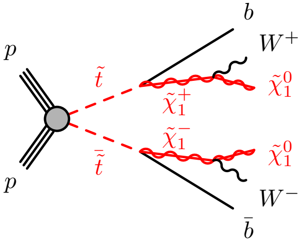
- SUSY with neutralino $\tilde{\chi}_1^0$ as LSP gives dark matter candidate

- There is a variety of top squark decays
- Main production processes (with two lepton decays) explored by ATLAS



$\tilde{t} \rightarrow t$ (on-shell) $+\tilde{\chi}_1^0$
220 GeV $< m_{\tilde{t}} < 520$ GeV
excluded at 95% CL

from ATLAS-CONF-2013-065



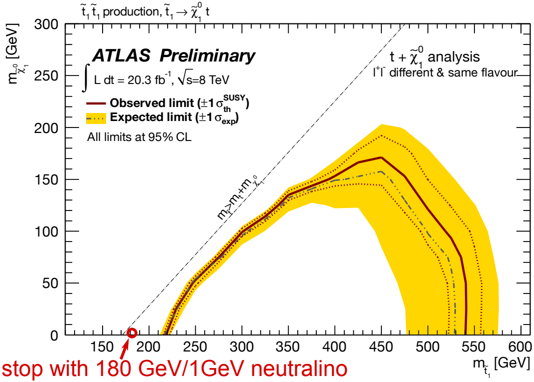
$\tilde{t} \rightarrow b + \tilde{\chi}_1^+$
150 GeV $< m_{\tilde{t}} < 442$ GeV,
$m_{\tilde{\chi}_1^+} \approx m_t$ and $m_{\tilde{\chi}_1^0} = 1$ GeV
excluded at 95% CL

from ATLAS-CONF-2013-048

Recent exclusion limits from ATLAS

Problems of $\tilde{t} \to t + \tilde{\chi}_1^0$-Search:

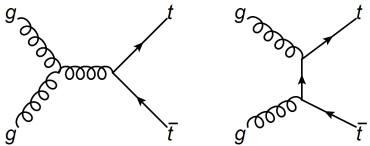
- Small BR of $t \to b + W^+ \to b + l^+ + \nu_l$ for dileptonic decay (BR($t\bar{t} \to W^+W^- \to l^+l^-\nu_l\bar{\nu}_l$)$= \frac{4}{81}$ for $l^\pm = e, \mu$)
- Small cross section for on-shell top production
- Light top squarks (stealth stops, $m_{\tilde{t}} \gtrsim m_t$) not excluded, since signature is very similar to top quarks



from ATLAS-CONF-2013-065

Spin correlation measurements

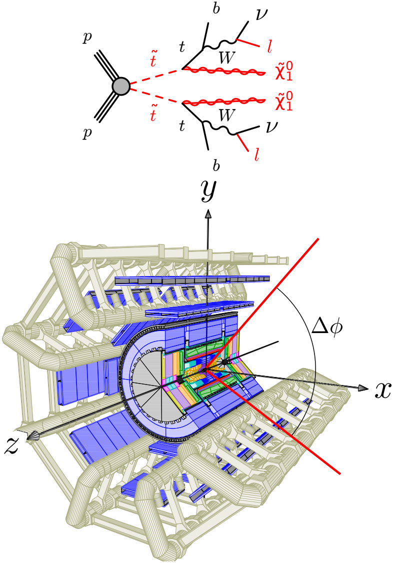
- Top quarks are mainly produced via gluon fusion at the LHC



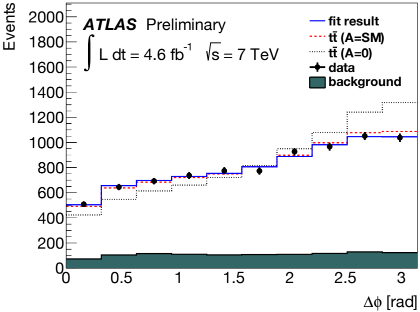
- Mahlon, Parke (arXiv:1001.3422v2 [hep-ph])
  - Without orbital angular momentum: due to gluon fusion $t\bar{t}$-pairs with the same helicity are dominant
  - Top quarks decay before they hadronize ($\Gamma_t > \Lambda_{\mathrm{QCD}}$)
  - W boson has helicity 0 or ± 1
  - Direction of spin of top quark 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

Measurement of $\Delta\phi$ distribution in ATLAS

- Gregory Mahlon, Stephen J. Parke: “Spin correlations can be easily observed by looking at the distribution of the difference in the azimuthal angles, $\Delta\phi$, of the dileptons decay products of the top quarks in the laboratory frame“(arXiv:1001.3422v2 [hep-ph])
- $t\bar{t}$-system does not need to be reconstructed
- Top quarks have to decay leptonically (into electrons or muons)



Spin correlation measurements



from ATLAS-CONF-2013-101

- $f_{SM} = N_{A=SM}/(N_{A=SM} + N_{A=0})$

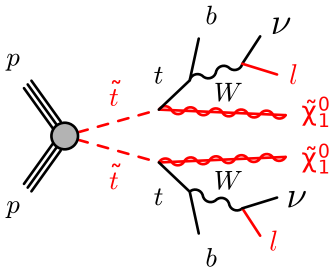
$\rightarrow$ $f_{SM} = 1.19 \pm 0.09 \pm 0.15$
(from ATLAS-CONF-2013-101)

$\rightarrow$ No sign for non-SM physics with $\mathcal{L} = 4.6\ fb^{-1}$ of data

- Top squarks have no spin
  $\rightarrow$ no correlation

$\rightarrow$ Measure $\Delta\phi$ between final state leptons (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$) for $\mathcal{L} = 21\ fb^{-1}$ and compare with spin-1/2 $t\bar{t}$-production, stops should look like the uncorrelated case ($A = 0$)

Event selection



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

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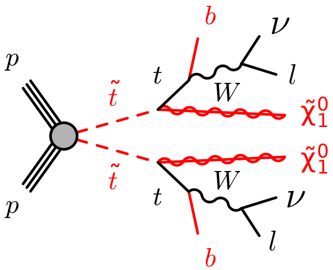

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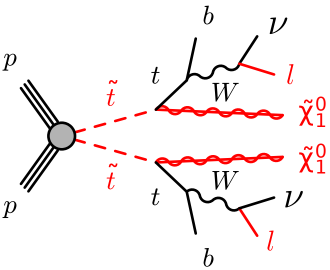

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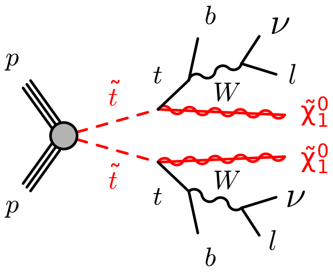

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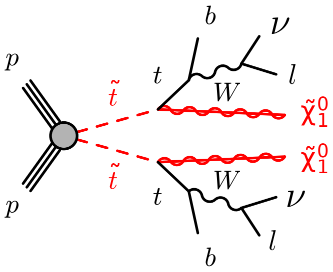

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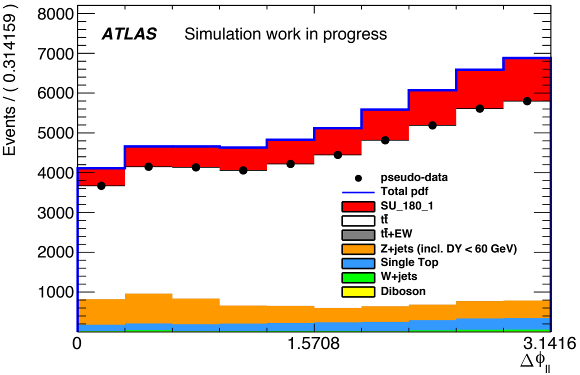
$\Delta\phi$ distributions (MC only)

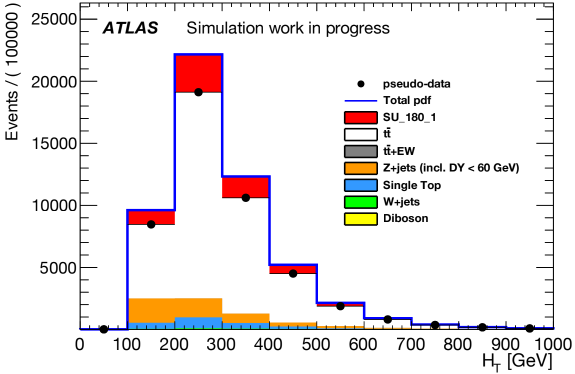


all channels
($e^{\pm}e^{\mp}$, $\mu^{\pm}\mu^{\mp}$ or $e^{\pm}\mu^{\mp}$)

signal: $m_{\tilde{t}} = 180$ GeV,
$m_{\tilde{\chi}_1^0} = 1$ GeV (177928)

systematic uncertainties:
`https://twiki.cern.ch/twiki/bin/view/AtlasProtected/SUSYSystematicUncertainties2012`

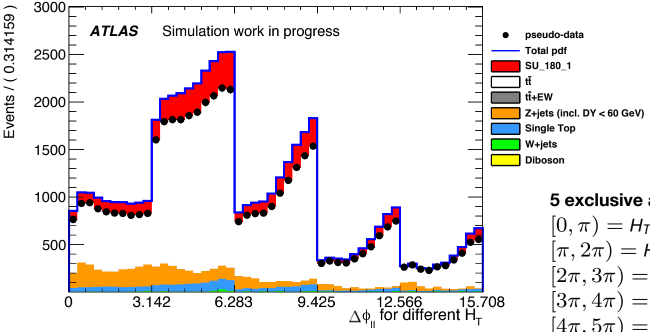
Looking at H_T as a second variable



- $H_T = \sum_{\text{lept}} p_T + \sum_{\text{jets}} p_T$
- H_T is a measure of activity in event
- could be used to distiguish signal from background

"2D distribution" ($\Delta\phi$ vs. H_T)

signal: $m_{\tilde{t}} = 180$ GeV, $m_{\tilde{\chi}_1^0} = 1$ GeV (177928)



5 exclusive areas of H_T:

$[0, \pi) = H_T \in [0, 200)$ GeV
$[\pi, 2\pi) = H_T \in [200, 300)$ GeV
$[2\pi, 3\pi) = H_T \in [300, 400)$ GeV
$[3\pi, 4\pi) = H_T \in [400, 500)$ GeV
$[4\pi, 5\pi) = H_T \in [500, \infty)$ GeV

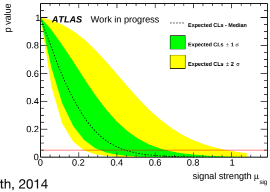
Setting exclusion limits

- 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)



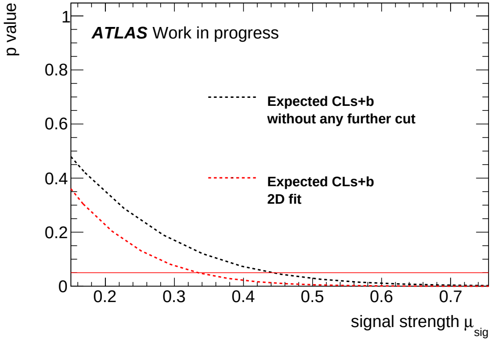
- Calculation of p values for each μ
- Exclude all signal strengths μ at 95% CL where p value is less than 0.05
- Expected exclusion limit: exclusion limit with n = number of SM background events

Table of systematics

Uncertainty of channel	SR180_1_DeltaPhi
Total background expectation	58125.85
Total statistical $(\sqrt{N_{\mathrm{exp}}})$	± 241.09
Total background systematic	± 7336.47 [12.62%]
main experimental systematics	
alpha_PILEUP	± 3902.45 [6.7%]
alpha_JES	± 1896.68 [3.3%]
alpha_BTAG	± 1097.44 [1.9%]
alpha_JER	± 676.49 [1.2%]
main theoretical systematics	
alpha_pdfUncertTtMc	± 4172.03 [7.2%]
alpha_tt_xsec	± 2591.73 [4.5%]
alpha_sig_xsec	± 1379.23 [2.4%]
alpha_PSGen	± 1169.05 [2.0%]
alpha_ttrensc	± 1139.12 [2.0%]
alpha_ttfasc	± 1089.48 [1.9%]
alpha_AcerMC_PS	± 1036.52 [1.8%]
alpha_sigGenerator	± 900.15 [1.5%]
alpha_pdfUncertSU_180_1	± 900.15 [1.5%]

Table: Breakdown of the dominant systematic uncertainties on background estimates in the various signal regions. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

Expected exclusion limits



signal: $m_{\tilde{t}} = 180$ GeV, $m_{\tilde{\chi}_1^0} = 1$ GeV (177928)

systematic uncertainties:
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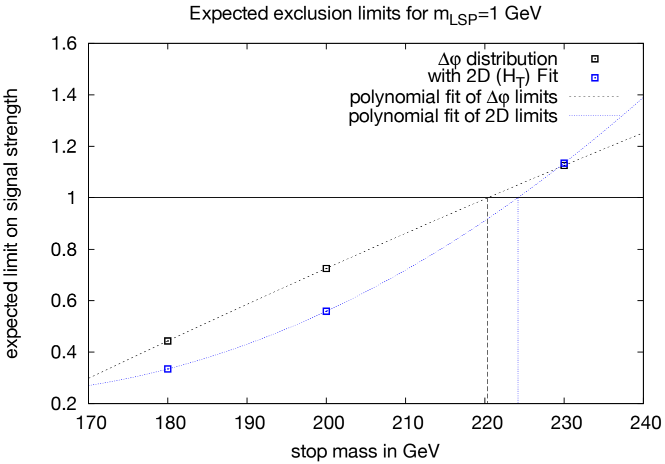
2D expected limits:
$0.334514^{+0.156514}_{-0.097307}$ (95% CL)

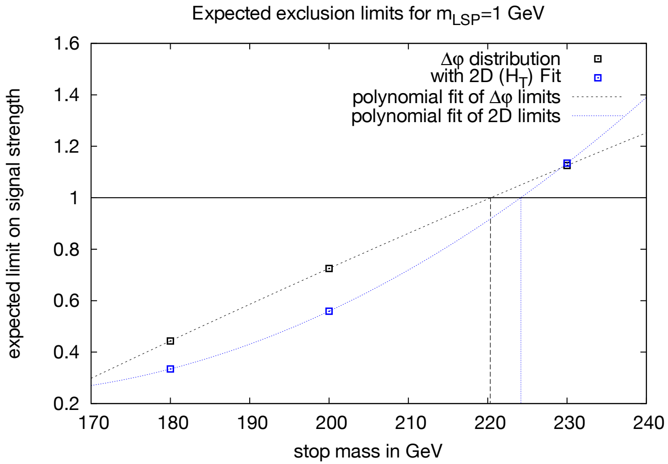
$\rightarrow$ 2D fit improves expected exclusion limits $\approx 24\%$

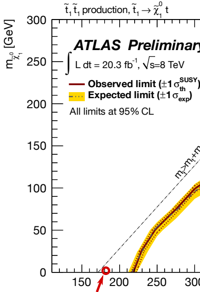
Expected exclusion limits for different stop masses



→ 2D fit improves expected exclusion limits

Expected exclusion limits for different stop masses





stop with 180 GeV/1GeV

→ 2D fit improves expected exclusion limits

Summary and Outlook

- Light top squarks ($\tilde{t} \rightarrow t$ (on-shell) $+\tilde{\chi}_1^0$) not excluded
- Analysis to search for light top squarks using spin correllations
- Included all experimental and theoretical systematics
- 2D Fit improves expected exclusion limits
- Next step: Looking into data

Thanks for your attention!

Event selection

	$e^+e^-/\mu^+\mu^-$ - final state	$e^\pm\mu^\mp$ - final state
Leptons	exactly 2 opposite charged leptons $e^\pm e^\mp$ or $\mu^\pm\mu^\mp$	$e^\pm\mu^\mp$
	$p_T > 15$ GeV (one with $p_T > 25$ GeV) $e^\pm$: $\lvert\eta\rvert < 2.47$ (medium), $\mu^\pm$: $\lvert\eta\rvert < 2.4$	
Jets	min. 2 with $p_T > 25$ GeV min. 1 b-Jet (70% efficiency)	
Overlap	jets within $\Delta R = 0.2$ of $e^\pm$ removed leptons within $\Delta R = 0.4$ of jets removed	
Invariant mass	$\lvert m_{ll} - m_z\rvert > 10$ GeV, $m_{ll} > 15$ GeV	
Transv. Energy	$E_T^{\mathrm{miss}} > 30$ GeV	
$H_T = \sum_{\mathrm{lept}} p_T + \sum_{\mathrm{jets}} p_T$		$H_T > 130$ GeV
Trigger	e24vhi_medium1 for $e^\pm$, mu24i_tight for $\mu^\pm$	

see also ATLAS-CONF-2013-101

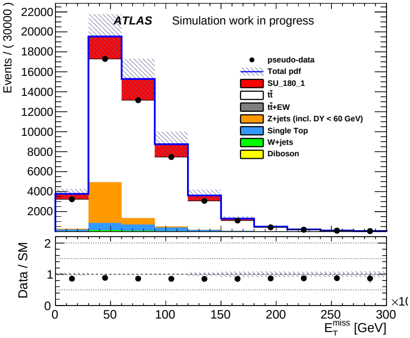
additional event selection in SUSYTools-00-03-21

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

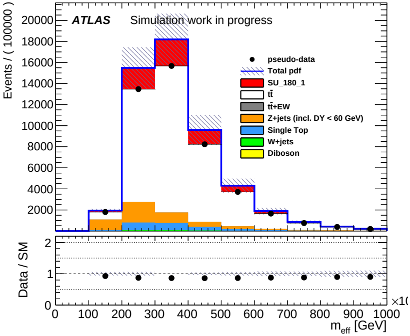
for jets: `SUSYObjDef::IsTileTrip`, `SUSYObjDef::IsGoodJet`, BCHTool, JVFcutNominal = 0.5

Using other variables in 2D Fit

$$E_T^{\text{miss}}$$

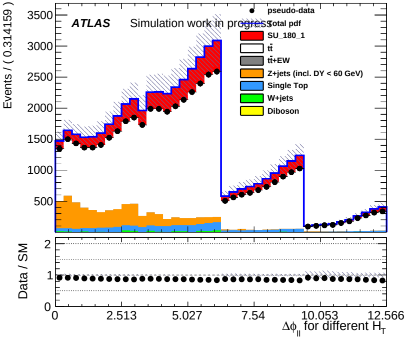


$$m_{\text{eff}} = H_T + E_T^{\text{miss}}$$
$$= \sum_{\text{lept}} p_T + \sum_{\text{jets}} p_T + E_T^{\text{miss}}$$



Using other variables in 2D Fit

E_T^{miss}



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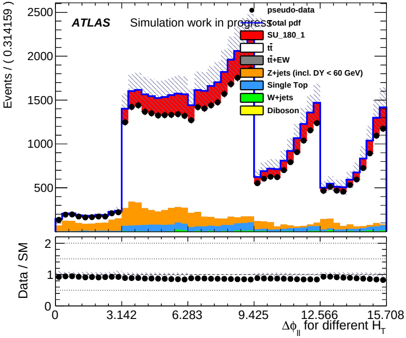

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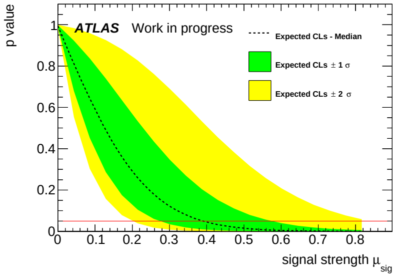

2D expected limits:

$0.390419^{+0.185182}_{-0.115342}$ (95% CL)

$$m_{\mathrm{eff}} = H_T + E_T^{\mathrm{miss}}$$
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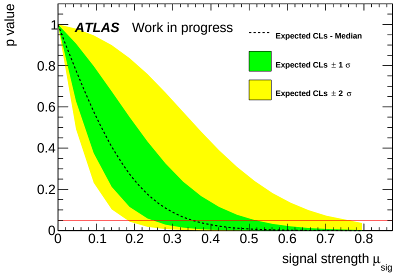
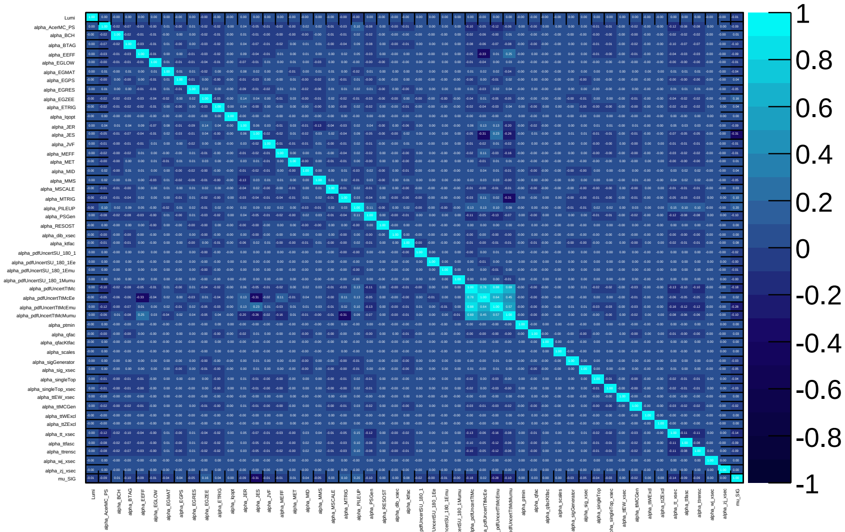


2D expected limits:

$0.353652^{+0.161698}_{-0.105463}$ (95% CL)

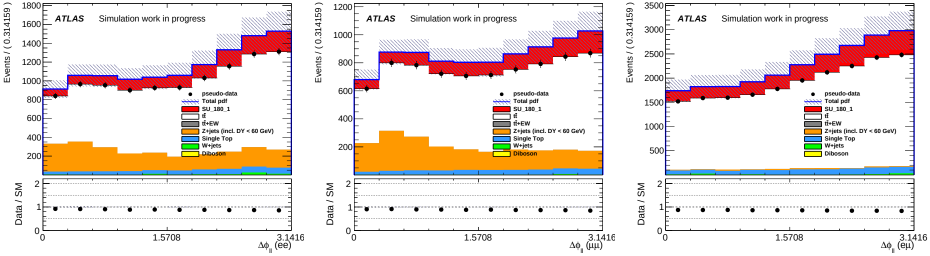
Backup

Correlation matrix for SU_180_1 (medium BCH), channels: *ee*, $\mu\mu$, $e\mu$, all



Backup

different final states without any further cut (tight BCH) beforeFit



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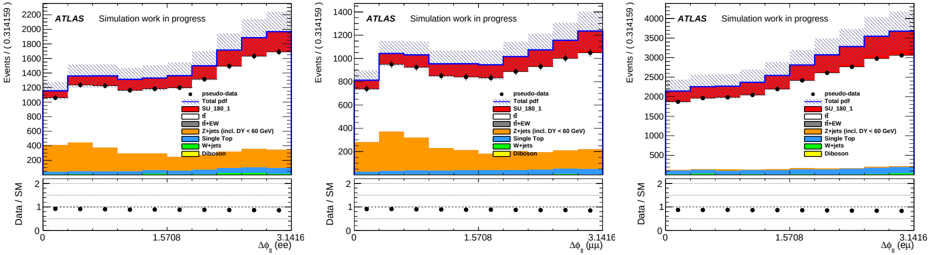
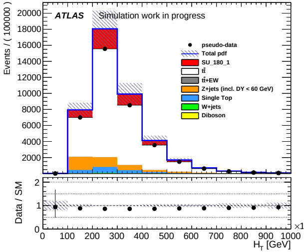
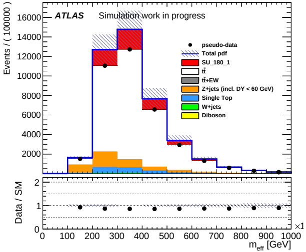
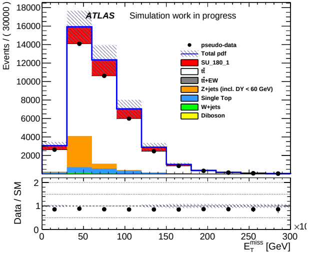


Backup

more distributions (tight BCH)







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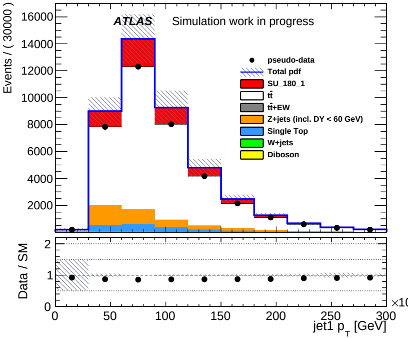
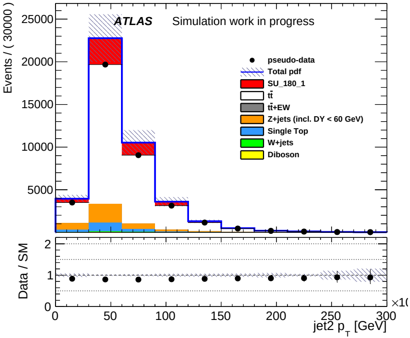
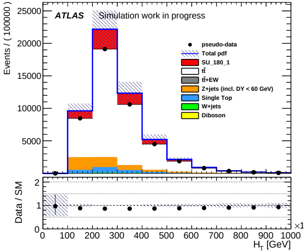
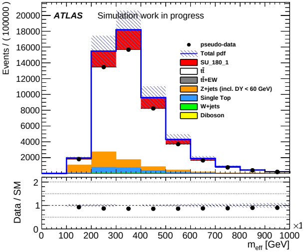


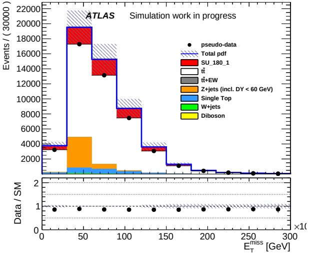


Backup

more distributions (medium BCH)







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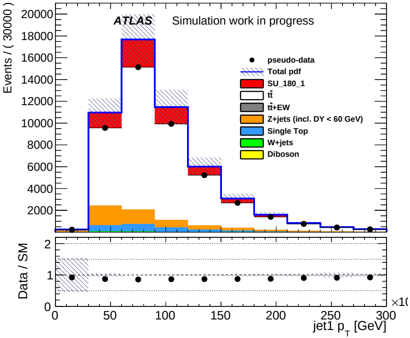
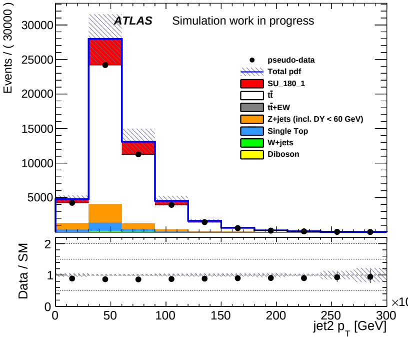
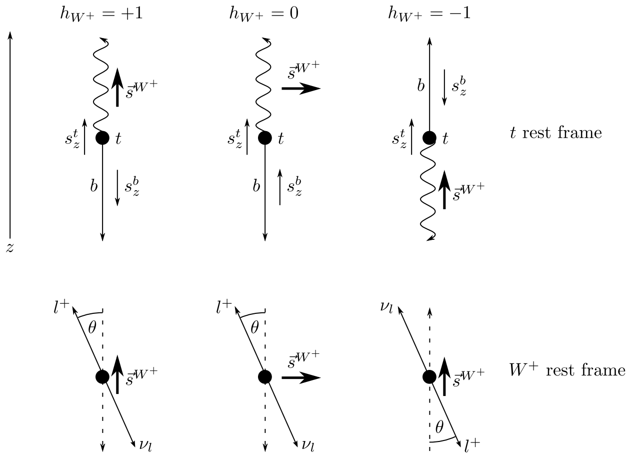




Backup

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



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

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