Searches for 4th generation quarks with the ATLAS detector

Rocco Mandrysch

Humboldt-University of Berlin
(On behalf of the ATLAS Collaboration)

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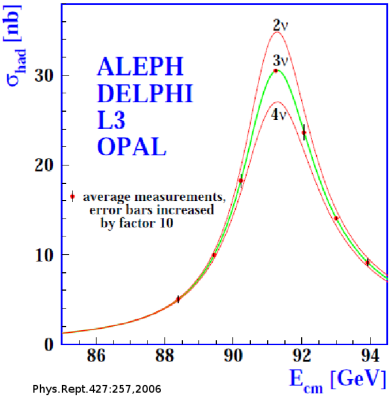
Contents

Present situation

- Number of families not fixed by Standard Model
- $N_\nu = 3$ with $m_\nu < m_Z/2$ (LEP) $\Rightarrow m_{\nu_4} > m_Z/2$
- 4th generation not excluded by EW precision measurements



Phys.Rept.427:257,2006

Motivation

- Important role in EW symmetry breaking
- Contributions to oblique EW corrections: Higher Higgs mass possible

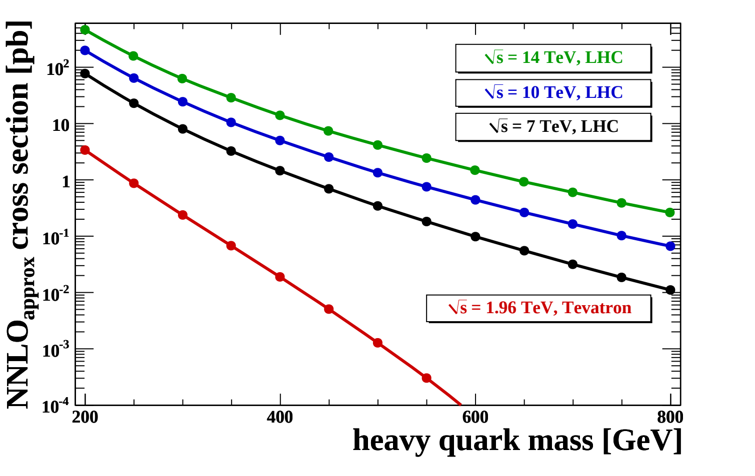
Mass limits for 4th generation particles

- Mass limits depend on CKM elements and mass of other heavy quark
- Current mass limits on short-lived particles @ 95% CL:
  (assuming 100% BF in search channel)

Particle	Signature	m_{min} [GeV]	Experiment
ℓ_4	$\ell_4 \to \nu + W$	100	L3 (PRL B 517, 75 (2001))
ν_4 (Dirac)	$\nu_4 \to \ell + W$	90.3	L3 (PRL B 517, 75 (2001))
ν_4 (Majorana)	$\nu_4 \to \ell + W$	80.5	L3 (PRL B 517, 75 (2001))
t'	$t' \to qW$	335	CDF (CDF note 10110)
b'	$b' \to tW$	372	CDF (Phys.Rev.Lett.106:141803)

- If tiny mixing angles between 4th and other families
  and $|m_{t'} - m_{b'}|$ small
  $\to$ particles could have long lifetime and escape detection
  (Hung et al, Phys.Rev.D77:037302,2008)

4th generation quark pair production cross sections

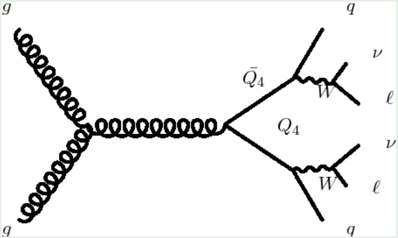


- M. Aliev, H. Lacker, U. Langenfeld, S.Moch and P. Uwer
  HATHOR - HAdronic Top and Heavy quarks crOss section calculatoR
  Comput.Phys.Commun.182:1034-1046,2011

- Analysis based on ATLAS-CONF-2011-022
- Search signature: $l^+l^- + 2jets$

Signal samples

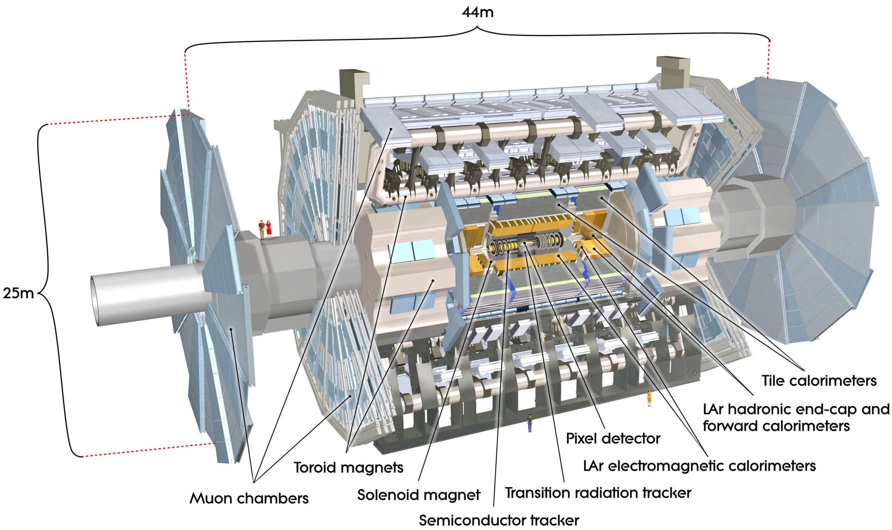
m_{Q_4}[GeV]	σ^{NNLO}_{approx}[pb]
250	23
300	8.0
350	3.2
400	1.4



Background samples

Process	σ[pb]
$t\bar{t}$	80.2
single top t-chan $\rightarrow l\nu$	21.5
single top s-chan $\rightarrow l\nu$	1.4
single top Wt	14.6
$Z \rightarrow ee$	850

Process	σ[pb]
$Z \rightarrow \mu\mu$	846
$Z \rightarrow \tau\tau$	845
WW	11.5
WZ	3.5
ZZ	1.0



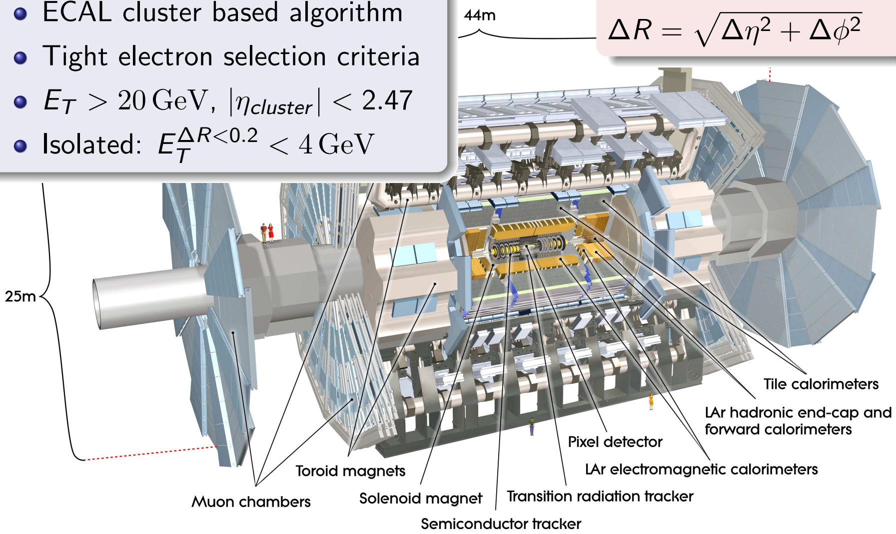
- Use multistage trigger system to select interesting events

Electron selection

- ECAL cluster based algorithm
- Tight electron selection criteria
- $E_T > 20\,\mathrm{GeV}$, $|\eta_{cluster}| < 2.47$
- Isolated: $E_T^{\Delta R<0.2} < 4\,\mathrm{GeV}$

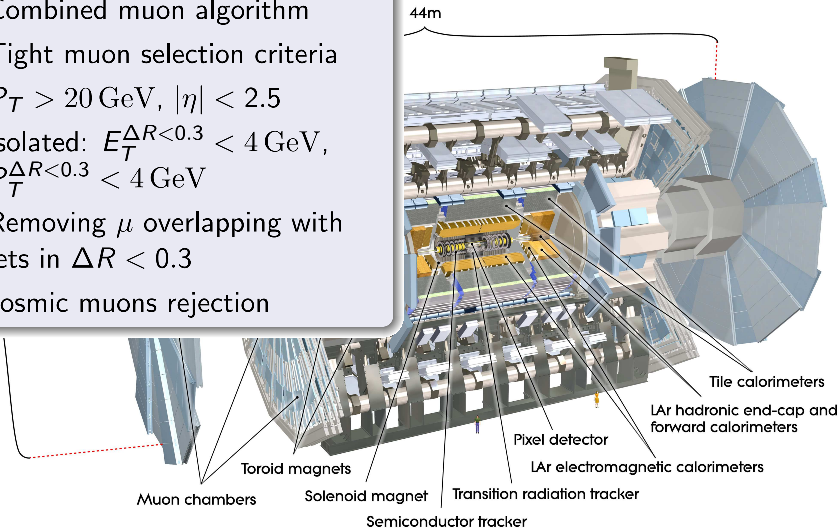
$$\eta = -\ln\left[\tan\left(\theta/2\right)\right]$$

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



Muon selection

- Combined muon algorithm
- Tight muon selection criteria
- $P_T > 20\,\mathrm{GeV}$, $|\eta| < 2.5$
- Isolated: $E_T^{\Delta R<0.3} < 4\,\mathrm{GeV}$, $P_T^{\Delta R<0.3} < 4\,\mathrm{GeV}$
- Removing μ overlapping with jets in $\Delta R < 0.3$
- cosmic muons rejection

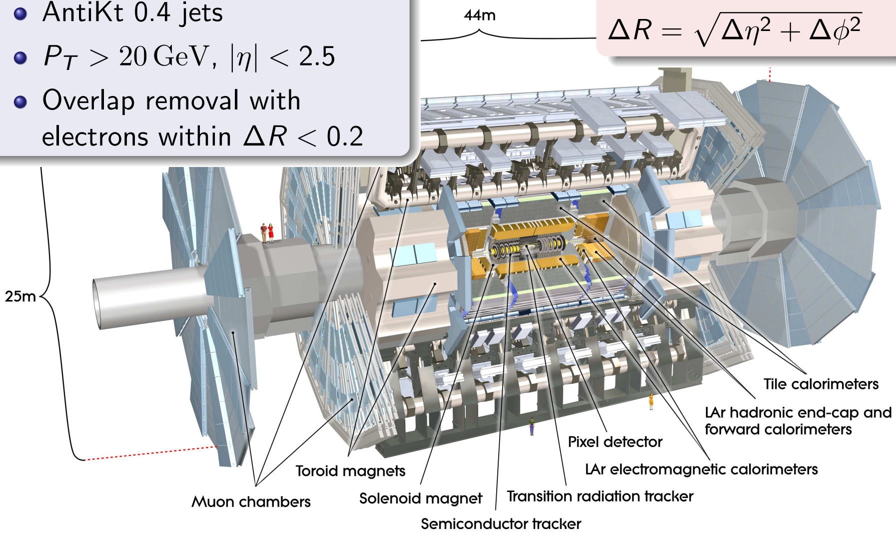


Jet selection

- AntiKt 0.4 jets
- $P_T > 20\,\mathrm{GeV}$, $|\eta| < 2.5$
- Overlap removal with electrons within $\Delta R < 0.2$

$$\eta = -\ln\left[\tan\left(\theta/2\right)\right]$$

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



Basic selection

- Exactly two leptons (e or μ) of opposite charge (one of which fire an electron or muon trigger)
- One reconstructed primary vertex

Reducing $Z \rightarrow ll + jets$ background

- At least two jets
- e^+e^- and $\mu^+\mu^-$ events must satisfy:
  - missing transverse energy: $\not{E}_T > 40\,\mathrm{GeV}$
  - $m_{e^+e^-,\mu^+\mu^-} < 81\,\mathrm{GeV}$ or $101\,\mathrm{GeV} < m_{e^+e^-,\mu^+\mu^-}$

Reducing $t\bar{t}$ background

- Perform $\approx$ mass reconstruction of heavy quark: $M_{Collinear}$
- Neutrinos escape detector

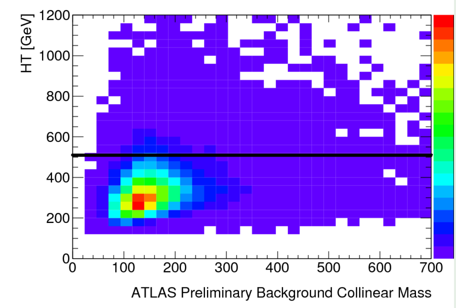
  $\rightarrow$ Complete mass reconstruction impossible
- Feature of heavy quarks: large $\vec{p}$ of $W^{\pm}$ daughters

  $\rightarrow$ often $\approx$ collinear decay products
- Assume: two neutrinos sole contributors to $\not{E}_T$

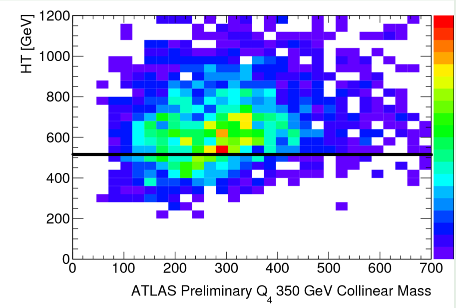
  and $\approx$ collinear with leptons

Reduce $t\bar{t}$ background

$t\bar{t}$ background



signal: $m_{Q_4} = 350\,\mathrm{GeV}$



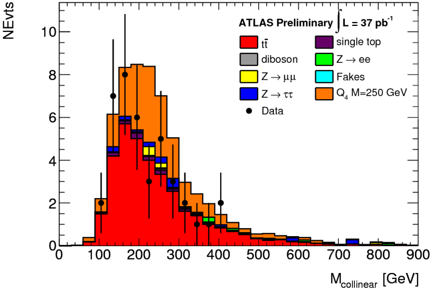
- $H_T = \Sigma E_T^{jet,lepton} + \not{E}_T$
- Remove background by 2D-cut in $H_T - M_{Colinear}$ plane depend on M_{Q_4} mass

- After final selection in data with $\mathcal{L} = 37\,\mathrm{pb}^{-1}$
  (*ee*, $\mu\mu$ and $e\mu$ channel combined)

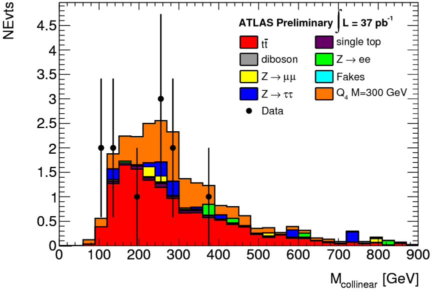
Q_4 Mass [GeV]	250	300
Total BG	$40.4 \pm 0.7 \pm 3.9$	$16.8 \pm 0.5 \pm 1.7$
Signal	$20.7 \pm 0.5 \pm 1.9$	$7.1 \pm 0.2 \pm 0.3$
Observed	40	11

Q_4 Mass [GeV]	350	400
Total BG	$10.1 \pm 0.4 \pm 0.1$	$6.3 \pm 0.4 \pm 0.8$
Signal	$3.0 \pm 0.1 \pm 0.2$	$1.4 \pm 0.1 \pm 0.1$
Observed	8	5

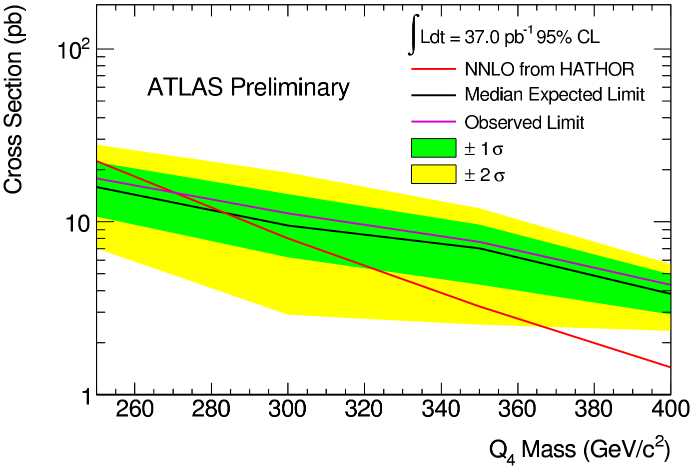
$m_{Q_4} = 250\,\mathrm{GeV}$



$m_{Q_4} = 300\,\mathrm{GeV}$



- Sum of *ee*, $\mu\mu$, and $e\mu$ channels after all cuts
- Use a binned maximum likelihood technique to measure the cross section with $M_{Collinear}$ for $m_{Q_4} = 250\,\mathrm{GeV}, 300\,\mathrm{GeV}, 350\,\mathrm{GeV}, 400\,\mathrm{GeV}$



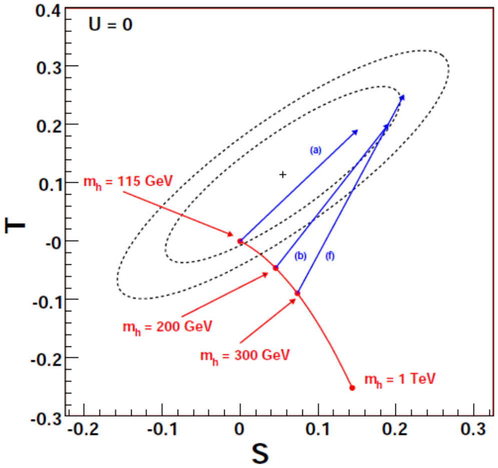
- Neymann construction with Feldman and Cousins to build a confidence band
- $m_{Q_4} > 270\,\mathrm{GeV}$ @ $95\,\%$ confidence level

Summary

- Production cross section @ LHC $\gtrsim 10\times$ higher than at Tevatron
  $\rightarrow$ first searches small lumi ($\mathcal{L} = 37\,\mathrm{pb}^{-1}$) possible
- First analysis with dilepton + jets search signature:
  $Q_4\bar{Q}_4 \rightarrow W^+qW^-\bar{q} \rightarrow q\bar{q}(l^+\nu)(l^-\nu)$
- Observed lower mass limit: $m_{Q_4} > 270\,\mathrm{GeV}$ @ $95\,\%$ confidence level
  (not yet competitive with Tevatron, will change with 2011 data
  with $\mathcal{L} = 267\,\mathrm{pb}^{-1}$)
- Currently analyses with refined but also different strategies
  in progress for 7 TeV

Backup slides

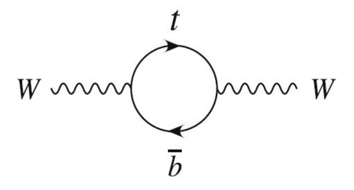
EW precision fit

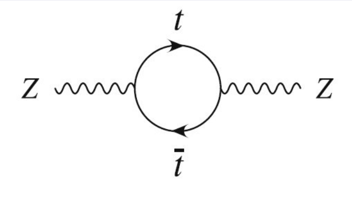


- Graham D. Kribs, Tilman Plehn, Michael Spannowsky and Tim M. P. Tait
  Four generations and Higgs physics
  Phys. Rev. D, 76(7):075016, Oct 2007

STU Formalism

- S: sensitive to chirally coupling fermion $\Longleftrightarrow$ $W^{\pm}, Z$ and H self energy diagrams
- T: sensitive to mass splitting $\Longleftrightarrow$ $W^{\pm}$ and H self energy diagrams



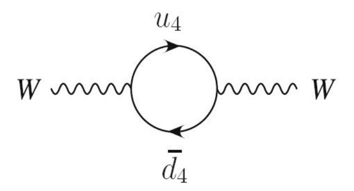


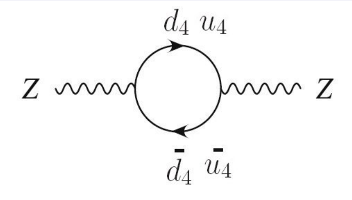
Mass splitting within a 4th Generation

Contributions to S and T:

(Kribs, Plehn, Spannowsky & Tait, Phys.Rev.D76, 075016, 2007)

- Additional one loop diagram with 4th gen. particles





- $\Delta S \propto \left(1 + \ln \frac{m^2_{\ell_4}}{m^2_{\nu_4}}\right) + N_C \left(1 - \frac{1}{3} \ln \frac{m^2_{u_4}}{m^2_{d_4}}\right)$
- $\Delta T \propto \left(N_C |m^2_{u_4} - m^2_{d_4}|^2 + |m^2_{\ell_4} - m^2_{\nu_4}|^2\right)$
- N_C: color factor

Systematic uncertainties

Systematic uncertainties for background and $350\,\mathrm{GeV}$ signal

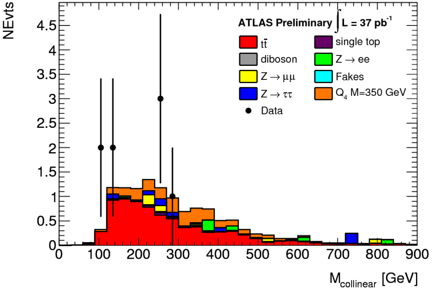
Source	Effect	Size[%]
Electron and trigger reconstruction	Yield	$1.6\,\%$
Electron ID	Yield	$2-9\%$
Muon ID and reconstruction	Yield	$0.3\,\%$
Muon trigger	Yield	$0.1-1.3\%$
Electron energy scale	Shape	$0.6\,\%$
Muon momentum scale	Shape	$0.1\,\%$
Jet energy scale	Shape and Yield	$12\,\%$
Gluon radiation	Shape and Yield	$15\,\%$
Signal cross section	Yield	$14\,\%$
Background cross section	Yield	$5-30\%$
Fake lepton background	Shape and Yield	$50\,\%$
Luminosity	Yield	$11\,\%$

Reduce $t\bar{t}$ background

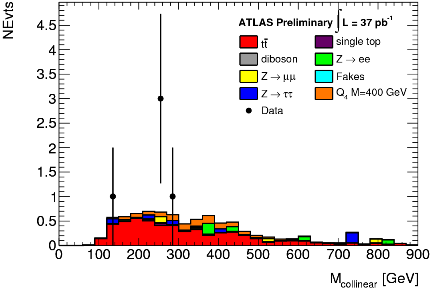
Q_4 Mass (GeV)	Final selection
250	$H_T > 500 - 0.7 \times M_{Collinear}$
300	$H_T > 600 - 0.5 \times M_{Collinear}$
350	$H_T > 600 - 0.2 \times M_{Collinear}$
400	$H_T > 700 - 0.3 \times M_{Collinear}$

New limit on quark mass

$m_{Q_4} = 350\,\mathrm{GeV}$



$m_{Q_4} = 400\,\mathrm{GeV}$



- Sum of ee, $\mu\mu$, and $e\mu$ channels after all cuts
- Use a binned maximal likelihood technique to measure the cross section with $M_{Collinear}$ for $m_{Q_4} = 250\,\mathrm{GeV}, 300\,\mathrm{GeV}, 350\,\mathrm{GeV}, 400\,\mathrm{GeV}$

Calculation of $M_{Collinear}$

- Setup neutrino four momentum vector via $\not{E}_T$ and η^{lepton}
- Combining the neutrinos, leptons, and jets to calculate the two $M_{Collinear}$ objects in the event
- Check all jet combinations and minimize the difference between the two calculated $M_{Collinear}$ values
- Require: not using the same jet for both calculations
- Perform all of the above calculations for a series of ($\Delta\eta$,$\Delta\phi$) points around each lepton and recalculate $|(M^1_{Collinear} - M^2_{Collinear})|$ for each value for $\Delta\eta$ and $\Delta\phi$
- Calculate values for both neutrinos at the same time

CKM^{4x4} matrix

$$|V_{CKM}^{4x4}| = \begin{pmatrix} 0.97414^{+0.00032}_{-0.00023} & 0.2245^{+0.0012}_{-0.0012} & (4.200^{+0.090}_{-0.910}) \cdot 10^{-3} & 0.025^{+0.011}_{-0.025} \\ 0.2256^{+0.0011}_{-0.0059} & 0.9717^{+0.0024}_{-0.0105} & (41.09^{+0.45}_{-1.45}) \cdot 10^{-3} & 0.057^{+0.097}_{-0.057} \\ 0.001^{+0.035}_{-0.001} & 0.062^{+0.044}_{-0.062} & 0.910^{+0.079}_{-0.080} & 0.41^{+0.15}_{-0.27} \\ 0.013^{+0.039}_{-0.013} & 0.04^{+0.12}_{-0.04} & 0.41^{+0.14}_{-0.27} & 0.910^{+0.078}_{-0.083} \end{pmatrix}$$