# Search for MSSM Higgs Bosons $A/H/h \rightarrow \tau^+\tau^-$ with the ATLAS Experiment

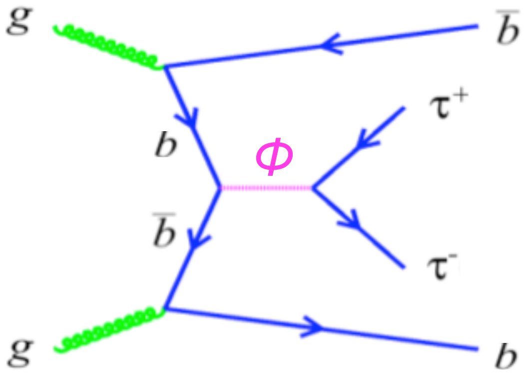
Jochen Dingfelder
University of Bonn
(for the ATLAS Collaboration)

LPCC Higgs+BSM Workshop
CERN, 11 April 2011

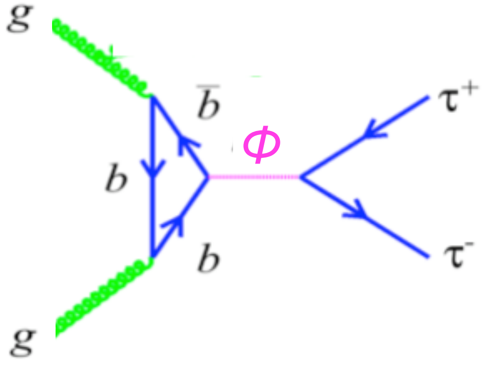
# MSSM Higgs at LHC

- MSSM: 2 Higgs doublets ⇒ 5 Higgs bosons Φ = h, H, A, $H^\pm$
- 2 parameters: $m_A$, tanβ
- Enhanced coupling to 3rd generation fermions in large regions of parameter space

Dominant production processes:



Direct bbΦ
(SHERPA)



gg → Φ
(MC@NLO)

MSSM Higgs BF’s:

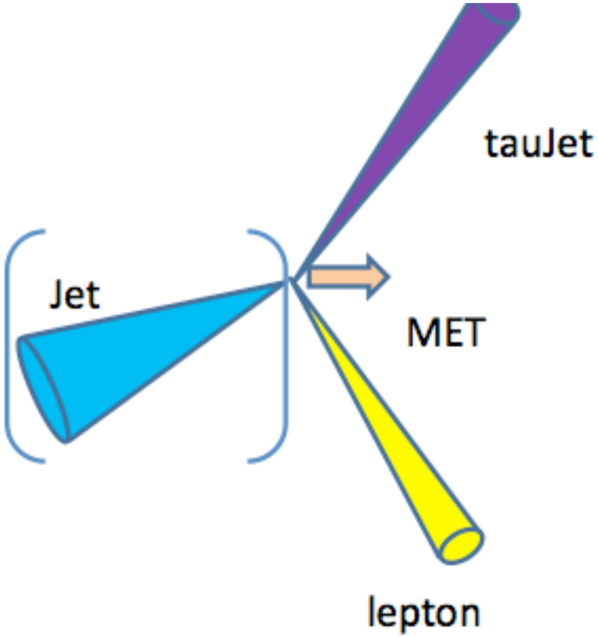
~90% bb, ~10% $\tau^+\tau^-$

τ-pair decay BF’s:

τ τ → ℓ ℓ ~1/9
τ τ → ℓ h ~4/9
τ τ → h h ~4/9

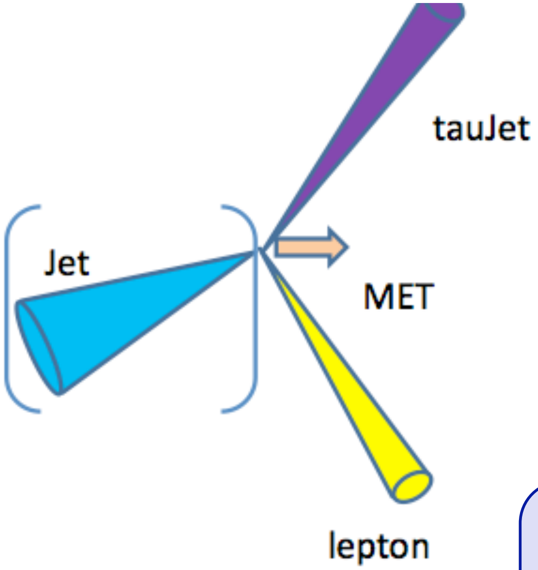
⇒ This analysis: Study lepton-hadron channel

# Background Processes



| Process | $\sigma \times$ BR [pb] | |
|---|---|---|
| $W \to \ell$+jets ($\ell = e, \mu, \tau$) | $10.46 \times 10^3$ | ALPGEN |
| $Z/\gamma^* \to \ell^+\ell^-$+jets ($m_{\ell\ell} > 10$ GeV) | $4.96 \times 10^3$ | ALPGEN |
| $t\bar{t}$ | 164.6 | MC@NLO |
| Single-$t$ ($t-$, $s-$ and $Wt$-channels) | 58.7, 3.9, 13.1 | MC@NLO |
| Di-boson ($WW$, $WZ$ and $ZZ$) | 46.2, 18.0, 5.6 | MC@NLO |

# Event Selection



No b-tagging, $N_{jet}$ requirement

⇒ inclusive analysis

for first data (36 $pb^{-1}$)

- Trigger (e or μ trigger)
- Isolated e or μ with $p_T^e > 20$ GeV or $p_T^\mu > 15$ GeV
- Di-lepton veto (⇒ suppress Z and tt bkg)
- $\tau_{had}$ candidate with $p_T^{\tau,vis} > 20$ GeV, $Q(\ell) \cdot Q(\tau) = -1$
- $E_T^{miss} > 20$ GeV (⇒ suppress QCD bkg)
- $M_T < 30$ GeV (⇒ suppress W bkg)

**$\tau_{had}$ identification:**

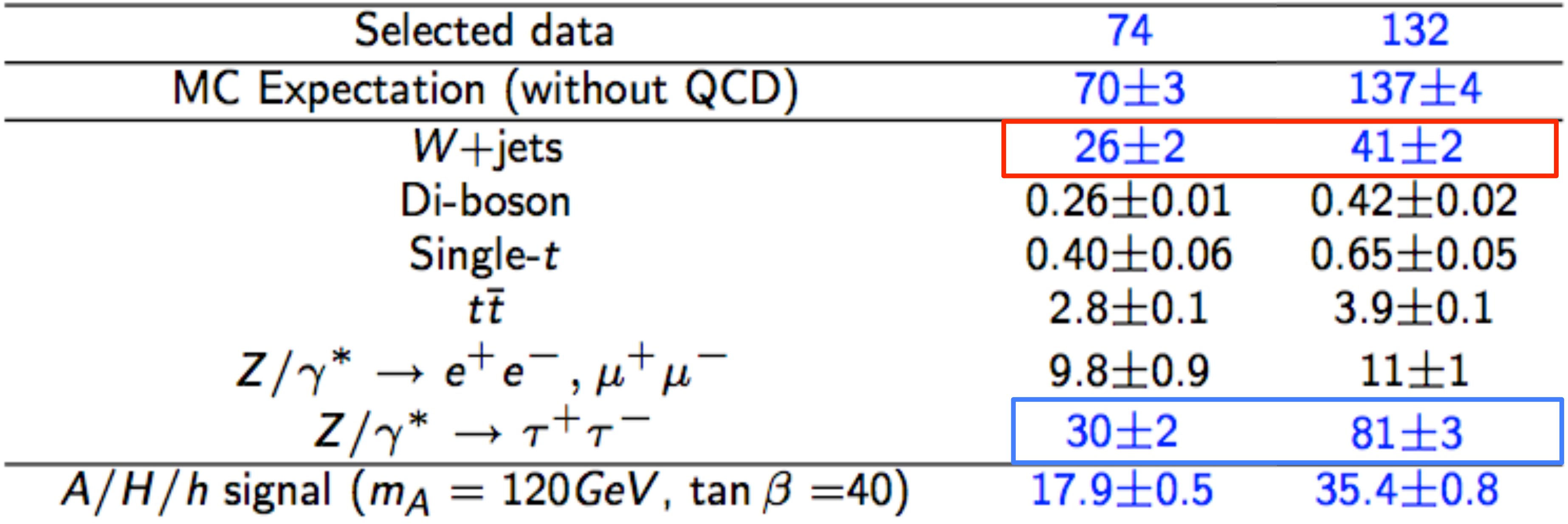
- Likelihood discrim.
- 1 or 3 tracks
- Charge = ±1
- e/μ vetos

Efficiency: 65% (60%)

Mis-ID: 10% (5%)

for 1-prong (3-prong)

# Data & Simulated Backgrounds



| | Electron | Muon |
|---|---|---|
| Selected data | 74 | 132 |
| MC Expectation (without QCD) | 70±3 | 137±4 |
| $W$+jets | 26±2 | 41±2 |
| Di-boson | 0.26±0.01 | 0.42±0.02 |
| Single-$t$ | 0.40±0.06 | 0.65±0.05 |
| $t\bar{t}$ | 2.8±0.1 | 3.9±0.1 |
| $Z/\gamma^* \rightarrow e^+e^-, \mu^+\mu^-$ | 9.8±0.9 | 11±1 |
| $Z/\gamma^* \rightarrow \tau^+\tau^-$ | 30±2 | 81±3 |
| $A/H/h$ signal ($m_A = 120 GeV$, tan $\beta$ =40) | 17.9±0.5 | 35.4±0.8 |

- 206 events observed in data
- Dominant backgrounds: $Z \rightarrow \tau^+\tau^-$ and W+jets
- QCD background has to be estimated from data!
- Signal efficiency: ~3% (8%) [×4/9] for $m_A$ = 120 (200) GeV

# Background Estimation

- Estimate background from same-sign (SS) data sample

$$n_{\mathrm{OS}}^{Bkg} = \boxed{n_{\mathrm{SS}}^{Bkg}} + n_{\mathrm{OS-SS}}^{\mathrm{QCD}} + n_{\mathrm{OS-SS}}^{W} + n_{\mathrm{OS-SS}}^{Z} + n_{\mathrm{OS-SS}}^{\mathrm{other}}$$

$$\approx \boxed{n_{\mathrm{SS}}^{Bkg}} + n_{\mathrm{OS-SS}}^{W} + n_{\mathrm{OS-SS}}^{Z} + n_{\mathrm{OS-SS}}^{\mathrm{other}}$$

- Assumption made for QCD: $\boxed{r_{\mathrm{QCD}} = n(OS)/n(SS) \approx 1}$

Checked with QCD-enhanced sample

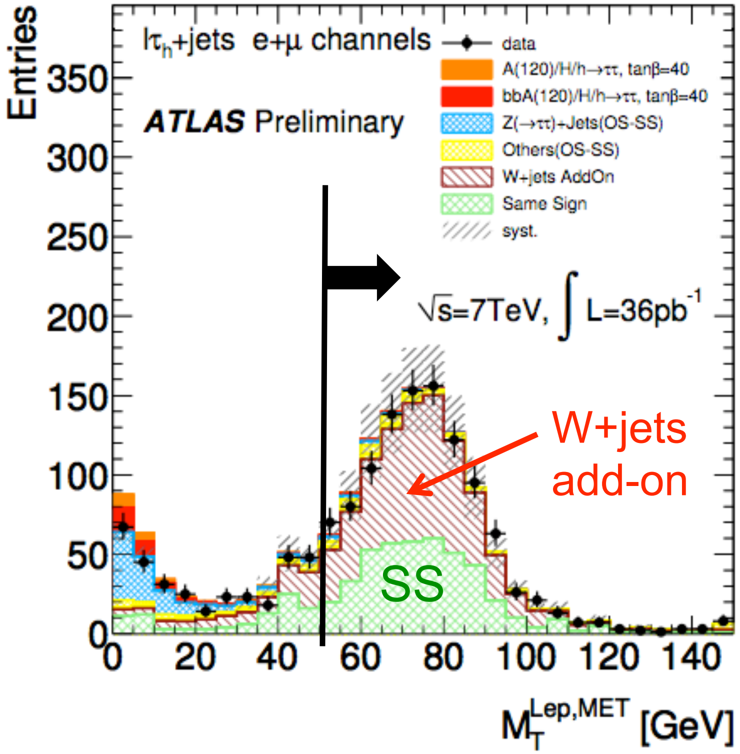
- $E_T^{miss} < 15$ GeV
- loosened lepton isolation

$$\boxed{\begin{aligned} r_{\mathrm{QCD}} &= 1.16 \pm 0.04^{stat} \pm 0.09^{syst} \\ r_{\mathrm{QCD}}^{MC} &= 1.06 \pm 0.13^{stat} \end{aligned}}$$

# Background Estimation

$$n_{\mathrm{OS}}^{Bkg} \approx \boxed{n_{\mathrm{SS}}^{Bkg}} + \underbrace{\boxed{n_{\mathrm{OS-SS}}^{W}} + \boxed{n_{\mathrm{OS-SS}}^{Z}} + \boxed{n_{\mathrm{OS-SS}}^{other}}}_{\text{OS-SS “add-on” due to } r_{\mathrm{OS/SS}} \neq 1}$$

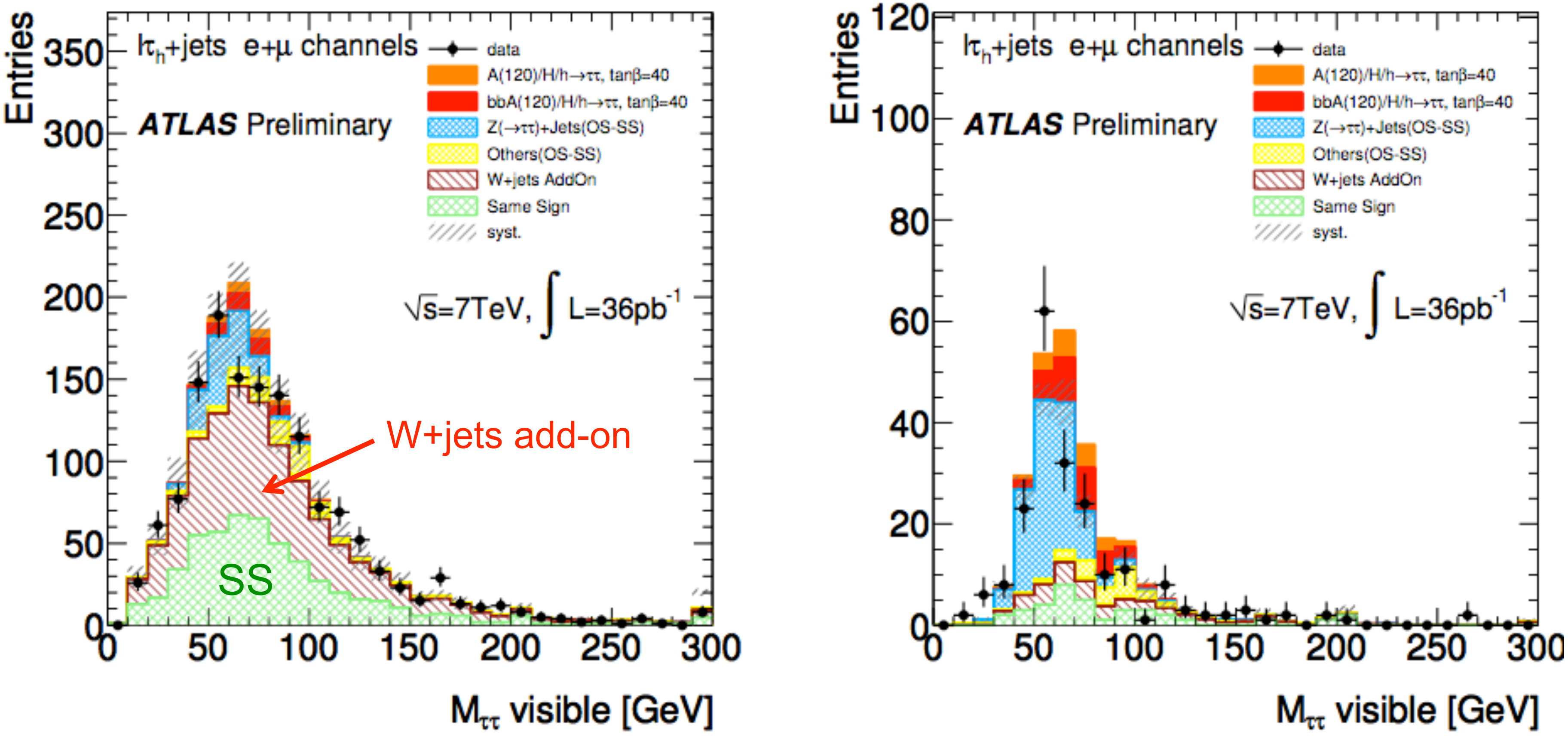
- $n_{SS}$ from nominal selection with $Q(\ell)\cdot Q(\tau) = +1$
- $Z \rightarrow \tau^{+}\tau^{-}$ and other background OS-SS “add-on” from simulation
- W+jets OS-SS “add-on”:
  - normalization from $M_T > 50$ GeV control sample
  - shape from simulation



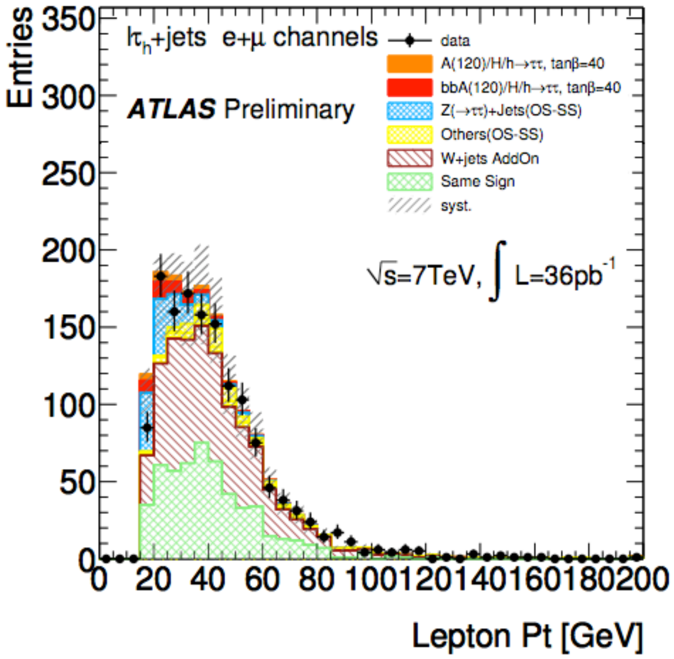
# Visible $\tau^{+}\tau^{-}$ Mass

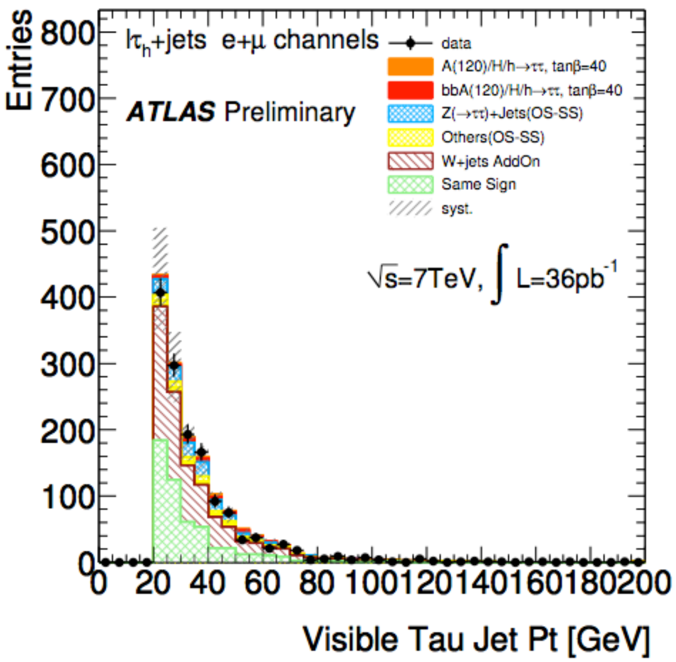
$$n^{Bkg}_{\mathrm{OS}} \approx \boxed{n^{Bkg}_{\mathrm{SS}}} + \underbrace{\boxed{n^{W}_{\mathrm{OS-SS}}} + \boxed{n^{Z}_{\mathrm{OS-SS}}} + \boxed{n^{\mathrm{other}}_{\mathrm{OS-SS}}}}$$

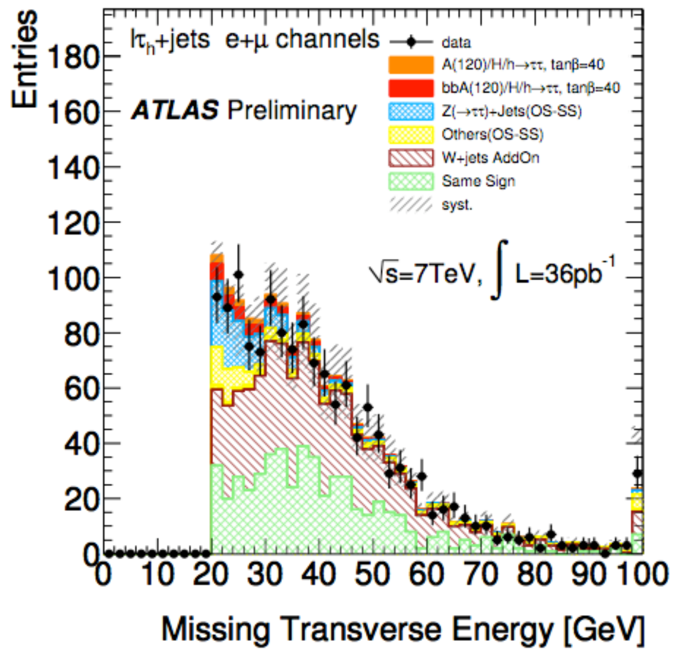
OS-SS “add-on”
due to $r_{OS/SS} \neq 1$

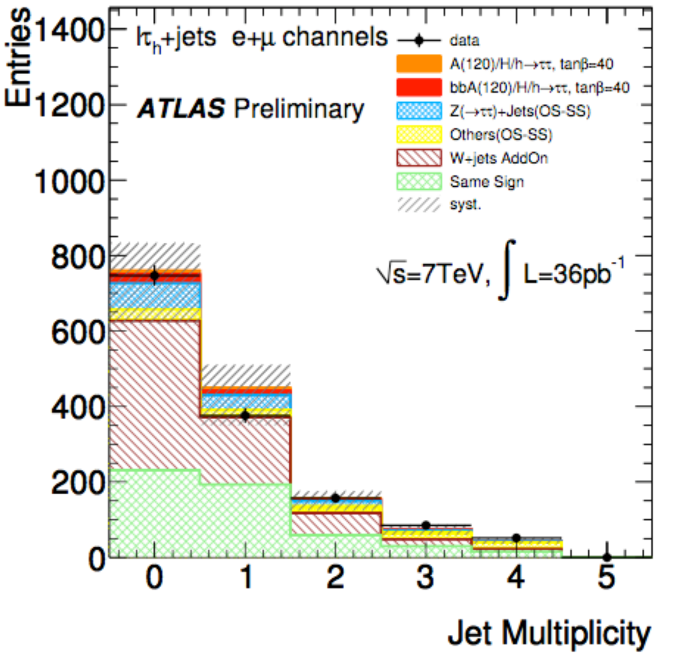


# Data-MC Comparison for other Distributioms









Good agreement between data and estimated bkg:

- ℓ and τ kinematics
- $E_t^{miss}$
- $N_{jet}$
- …

# Alternative Background Estimation

- Second background estimation method to:
  - estimate QCD and W+jets backgrounds separately
  - cross-check ratio $r_{QCD}$

- W+jets: - Normalization from $70 < M_T < 120$ GeV control sample
  - Shape from simulation

- QCD: "ABCD" method with charge product and lepton isolation

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} OS + Isolation & OS + Inverted\ \ Isolation \\ SS + Isolation & SS + Inverted\ \ Isolation \end{pmatrix}$$

Obtain QCD shape from region C, scale by ratio B/D

$$\boxed{n_A^{QCD} = r_{B/D} \times n_C^{(data-non\ \ QCD\ \ MC)}}$$

# Alternative Background Estimation: QCD

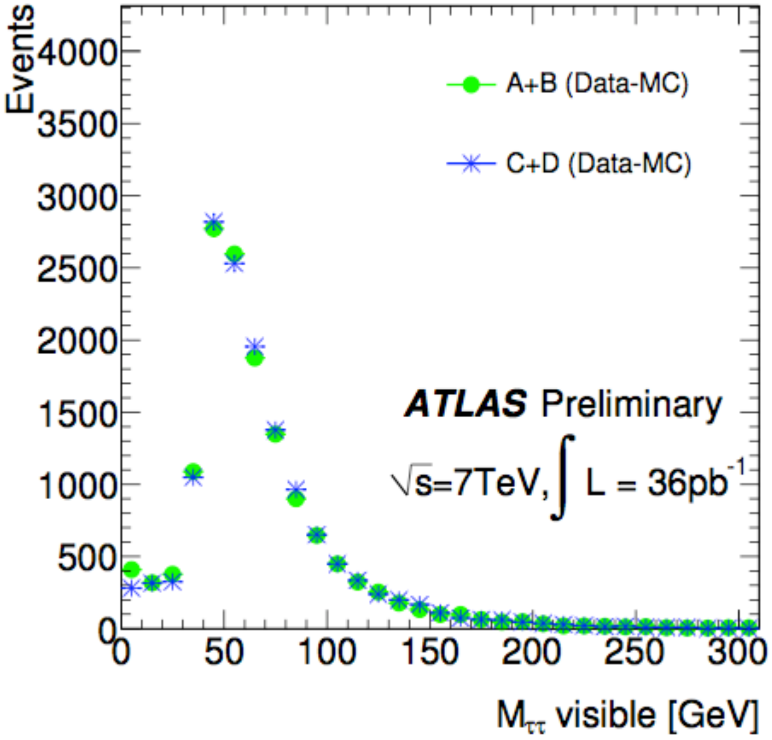
$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} OS + Isolation & OS + Inverted\ Isolation \\ SS + Isolation & SS + Inverted\ Isolation \end{pmatrix}$$

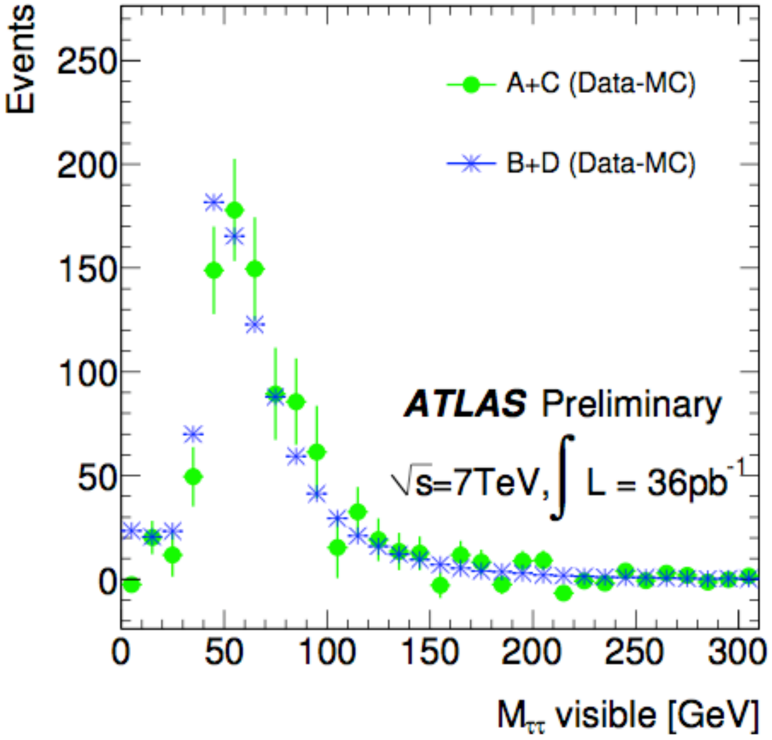
- Check necessary assumptions:
  - Shapes in A (OS) and C (SS) are the same
  - Ratio $r_{A/C} = r_{B/D}$, i.e. variables uncorrelated

Compare “projections”:

AB vs. CD

AC vs. BD





# Alternative Background Estimation: QCD

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} OS + Isolation & OS + Inverted\ \ Isolation \\ SS + Isolation & SS + Inverted\ \ Isolation \end{pmatrix}$$

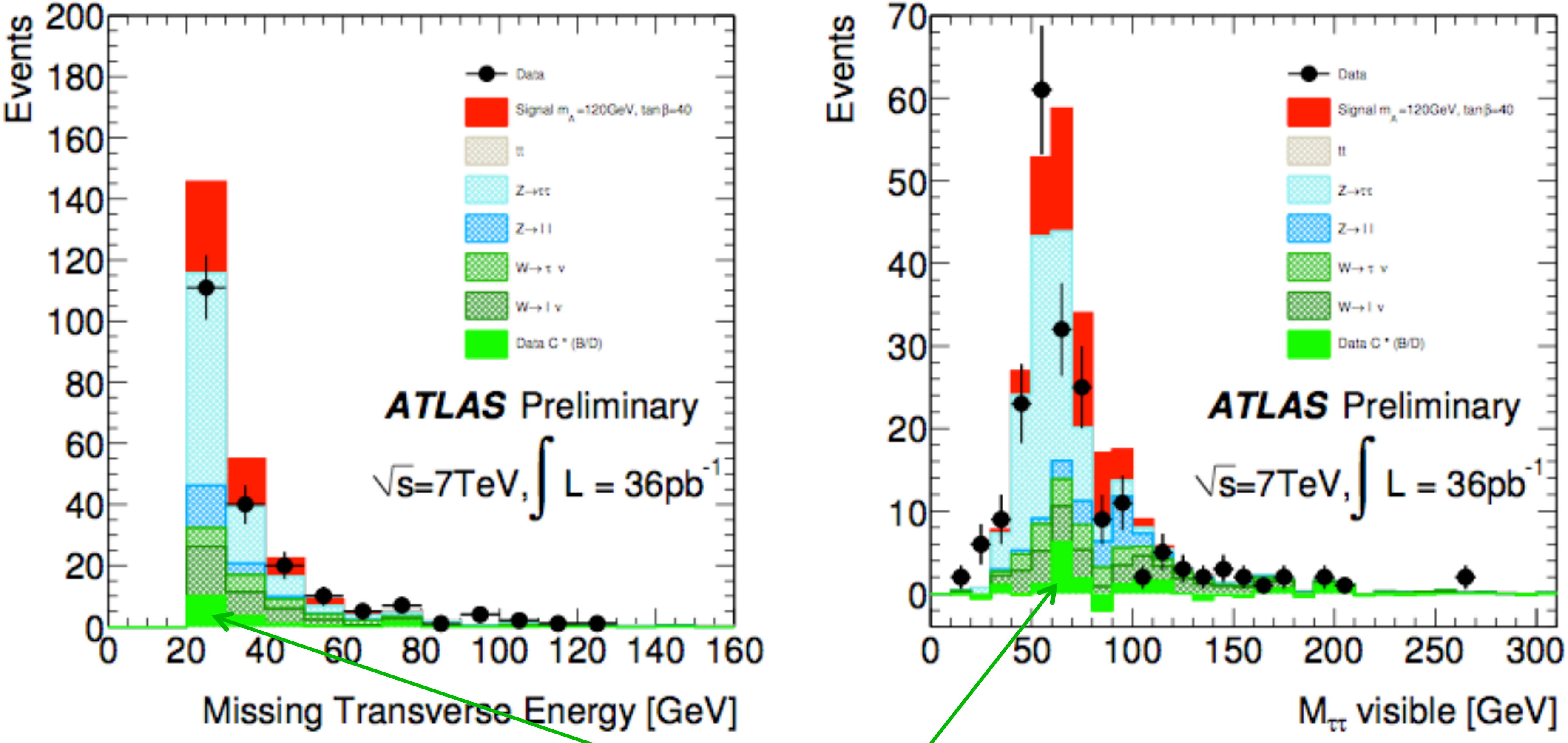
| | A | B | C | D |
|---|---|---|---|---|
| Data | 203 | 1372 | 36 | 1195 |
| Signal ($m_A = 120$ GeV) | $55.2 \pm 1.0$ | $2.2 \pm 0.2$ | $0.6 \pm 0.1$ | $0.11 \pm 0.03$ |
| $W \to \ell\nu +$ jets | $36.8 \pm 1.8$ | $3.0 \pm 0.5$ | $13.5 \pm 1.1$ | $0.8 \pm 0.3$ |
| $W \to \tau\nu +$ jets | $21.7 \pm 1.4$ | $2.8 \pm 0.6$ | $5.7 \pm 0.7$ | $0.5 \pm 0.2$ |
| $Z \to \ell^+\ell^- +$ jets | $18.7 \pm 1.3$ | $1.8 \pm 0.4$ | $2.4 \pm 0.5$ | $0.3 \pm 0.1$ |
| $Z \to \tau^+\tau^- +$ jets | $103 \pm 3$ | $4.4 \pm 0.6$ | $3.8 \pm 0.6$ | $0.2 \pm 0.1$ |
| $t\bar{t}$ | $0.0070 \pm 0.0002$ | $0.0050 \pm 0.0002$ | $0.0020 \pm 0.0001$ | $0.0049 \pm 0.0002$ |

Subtract non-QCD background using MC

$$\boxed{r_{\mathrm{QCD}} = r_{B/D} = 1.14 \pm 0.05}$$

$$\boxed{n_A^{QCD} = r_{B/D} \times n_C^{(data-non\ \ QCD\ \ MC)} = 12.1 \pm 7.1}$$

# Alternative Background Estimation

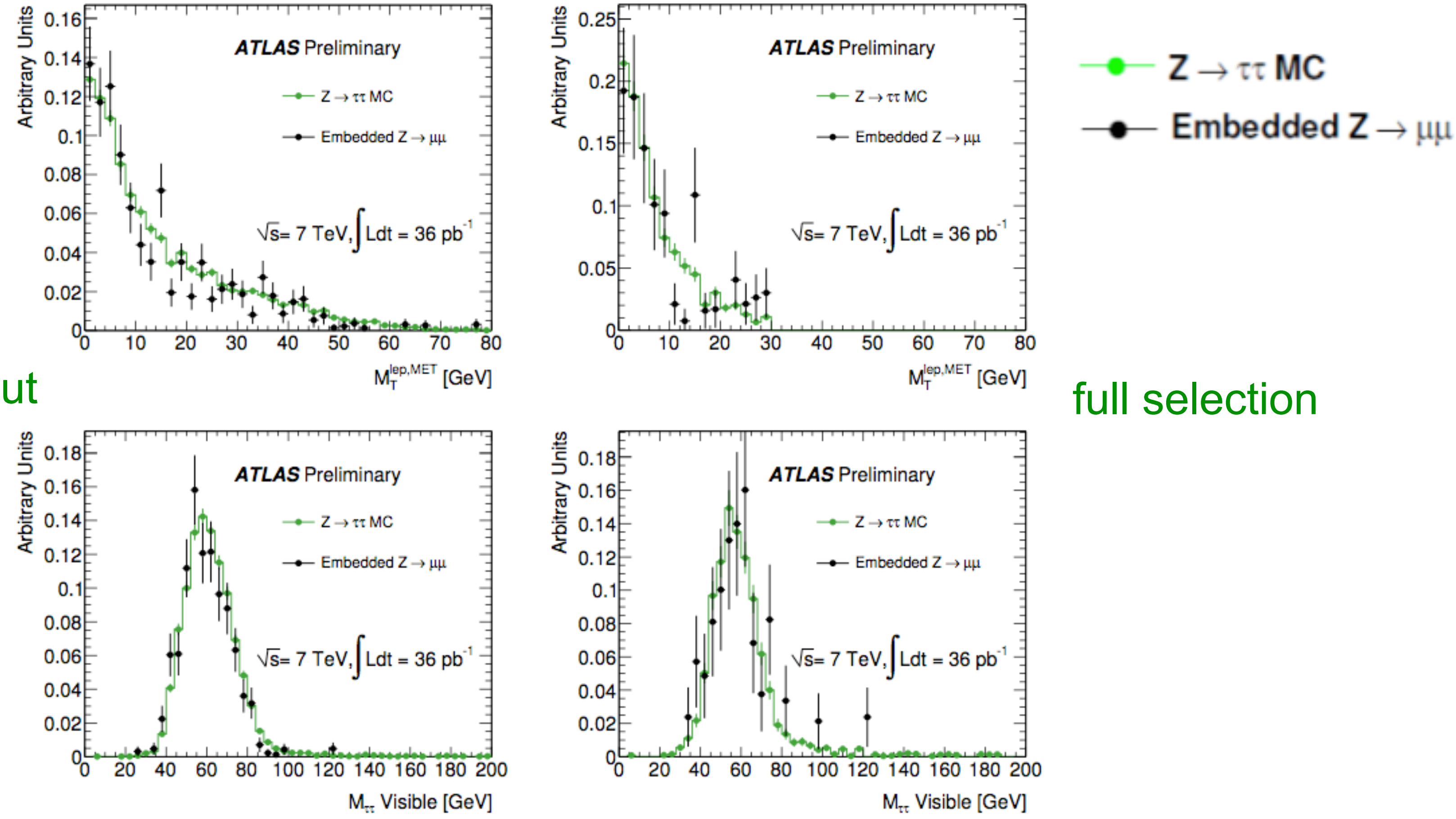


Estimated QCD background
(rather small)

Both background estimation methods give consistent results!

# $Z \rightarrow \tau^+\tau^-$ Background

- Estimate $Z \rightarrow \tau^+\tau^-$ background from high-purity $Z \rightarrow \mu\mu$ sample using ”τ-embedding” technique
- Remove μ’s (track & calo. cells), replace by simulated τ’s

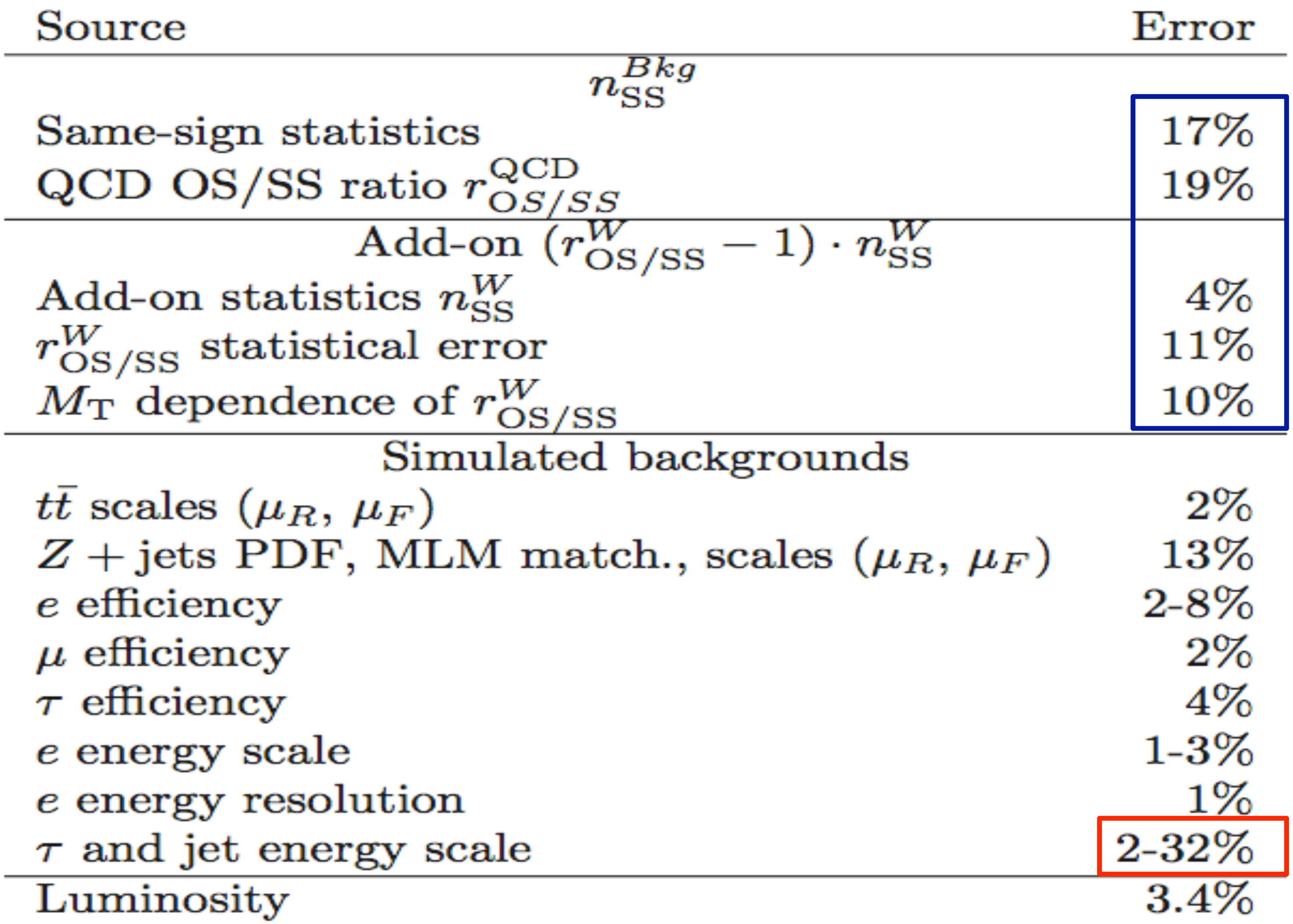


before $M_T$ cut

full selection

Good data-MC agreement ⇒ validation of $Z \rightarrow \tau^+\tau^-$ simulation

# Systematic Uncertainties

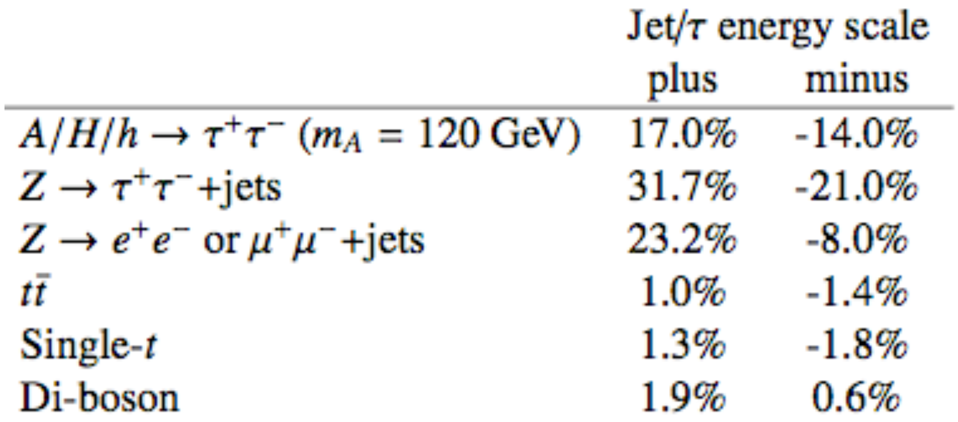


| Source | Error |
|---|---|
| $n_{\mathrm{SS}}^{Bkg}$ | |
| Same-sign statistics | 17% |
| QCD OS/SS ratio $r^{\mathrm{QCD}}_{OS/SS}$ | 19% |
| Add-on $(r^{W}_{\mathrm{OS/SS}} - 1) \cdot n^{W}_{\mathrm{SS}}$ | |
| Add-on statistics $n^{W}_{\mathrm{SS}}$ | 4% |
| $r^{W}_{\mathrm{OS/SS}}$ statistical error | 11% |
| $M_{\mathrm{T}}$ dependence of $r^{W}_{\mathrm{OS/SS}}$ | 10% |
| Simulated backgrounds | |
| $t\bar{t}$ scales $(\mu_R, \mu_F)$ | 2% |
| $Z+$jets PDF, MLM match., scales $(\mu_R, \mu_F)$ | 13% |
| $e$ efficiency | 2-8% |
| $\mu$ efficiency | 2% |
| $\tau$ efficiency | 4% |
| $e$ energy scale | 1-3% |
| $e$ energy resolution | 1% |
| $\tau$ and jet energy scale | 2-32% |
| Luminosity | 3.4% |

- Dominant uncertainties from:
  - data-driven bkg estimation (control-sample stat. & extrapol.)
  - jet and τ energy scales

# Systematic Uncertainties

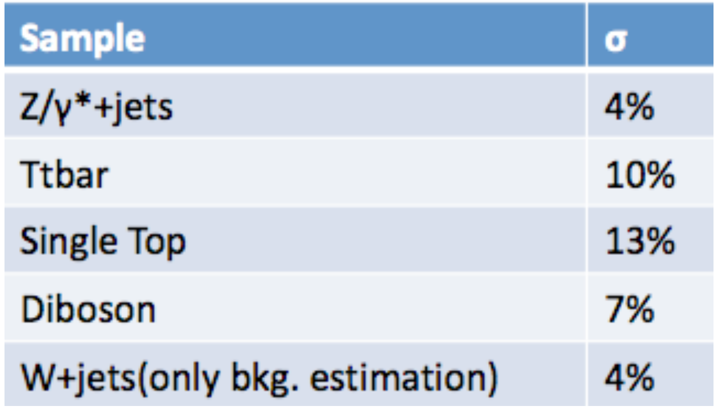
- Energy scale uncertainties:



| | Jet/$\tau$ energy scale | |
|---|---|---|
| | plus | minus |
| $A/H/h \to \tau^+\tau^-$ ($m_A$ = 120 GeV) | 17.0% | -14.0% |
| $Z \to \tau^+\tau^-$+jets | 31.7% | -21.0% |
| $Z \to e^+e^-$ or $\mu^+\mu^-$+jets | 23.2% | -8.0% |
| $t\bar{t}$ | 1.0% | -1.4% |
| Single-$t$ | 1.3% | -1.8% |
| Di-boson | 1.9% | 0.6% |

- Include shape uncertainty of visible mass due to energy scales

- Cross-section uncertainties:



| Sample | σ |
|---|---|
| Z/γ*+jets | 4% |
| Ttbar | 10% |
| Single Top | 13% |
| Diboson | 7% |
| W+jets(only bkg. estimation) | 4% |

Signal:

10-15% (gg→A/H/h, bbA/H/h) dependent on $m_A$ and tanβ

- Total signal-efficiency uncertainty: 24% (15%) for 120 (200) GeV

# Exclusion Limits

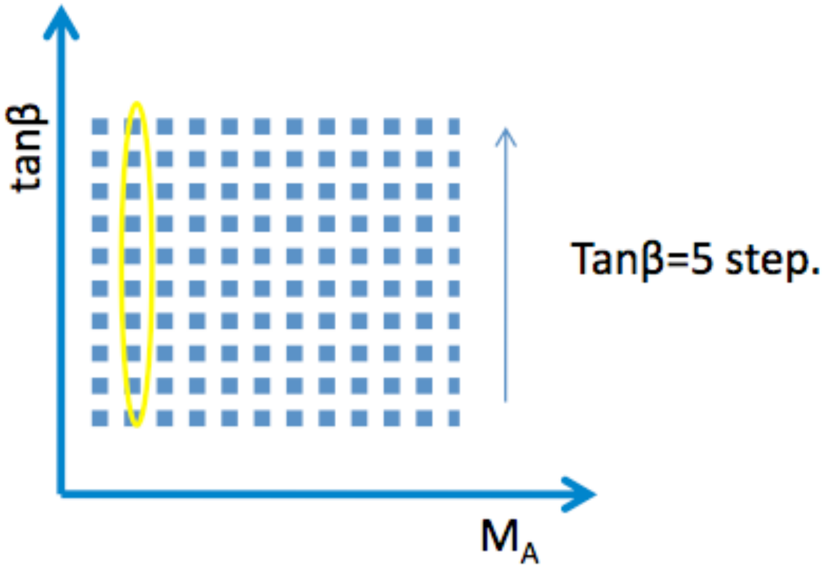
- Shape analysis of visible mass distribution using profile likelihood approach:

$$\mathcal{L}(\mu,\beta_{QCD},\vec{\theta}_s,\vec{\theta}_b,\vec{\theta}_{global}) = \text{Pois}(n|\underbrace{\mu_T}_{\text{Expected \# events}})\ \text{Pois}(\underbrace{n_{SS}|\beta_{SS}}_{\text{\# SS events control region}})\underbrace{\mathcal{L}(\vec{\theta}_s,\vec{\theta}_b,\vec{\theta}_{global})}_{\text{Nuisance parameters to include syst. errors}}$$

- Test statistic:

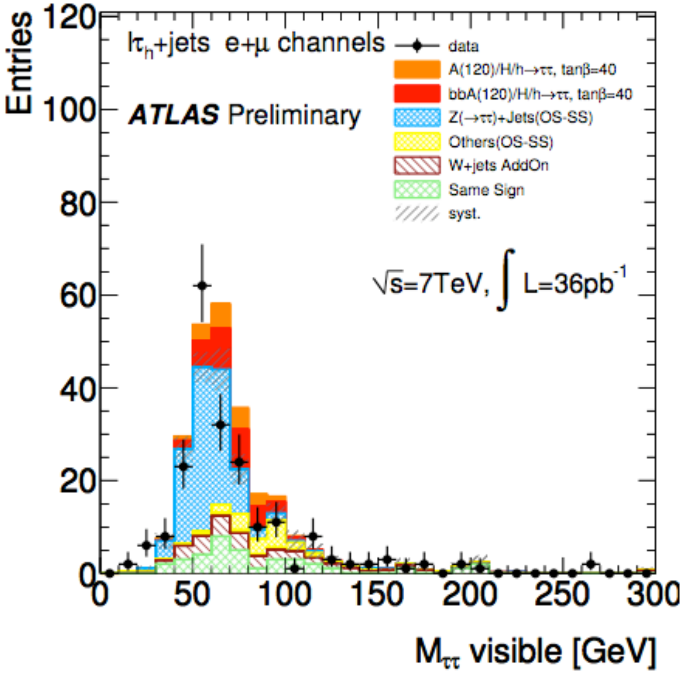
$$\tilde{q}_\mu = \begin{cases} -2\ln\frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(0,\hat{\hat{\theta}}(0))} & \hat{\mu} < 0\,, \\ -2\ln\frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} & 0 \le \hat{\mu} \le \mu\,, \\ 0 & \hat{\mu} > \mu\,. \end{cases}$$

⇒ $\text{CL}_{s+b}$ (1-sided, 95% CL)

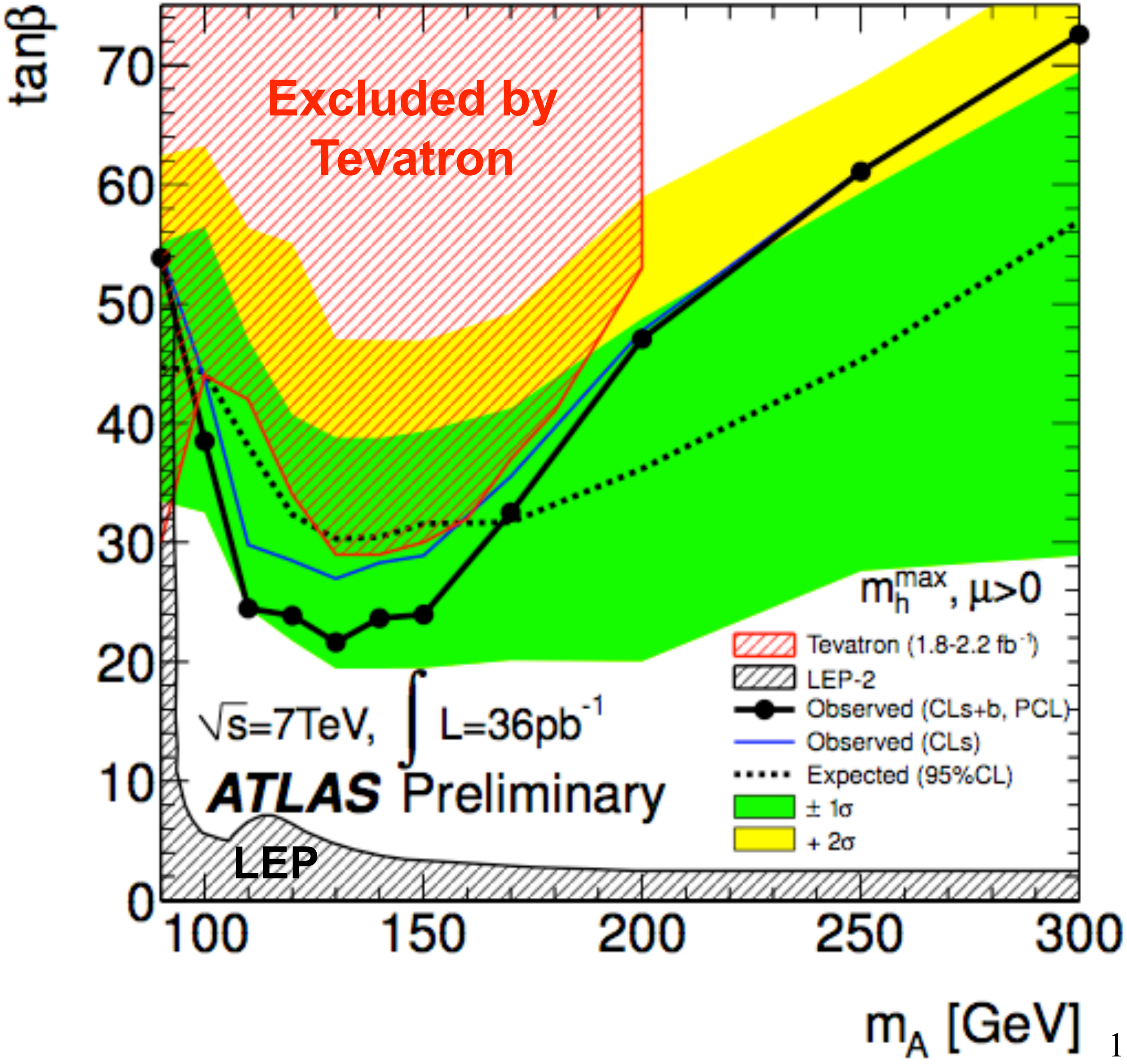


- Toy MC's from bkg-only PDF ⇒ expected limit and error bands

# Exclusion Limits in $m_A$-tanβ Plane



4-flavor scheme, $m_h^{max}$ scenario, μ>0



# Summary

- First search for neutral MSSM Higgs bosons with 2010 ATLAS data (36 $pb^{-1}$)

- No significant excess observed (data: 206, bkg: 195 ± 33)

- Set 95% CL exclusion limits in $m_A$-tanβ plane, reach down to
  - tanβ ~ 24 for $m_A$ = 110-150 GeV
  - tanβ ~ 60-70 for $m_A$ = 250-300 GeV

- Limits extend to regions of parameter space not excluded by Tevatron and LEP searches

- More exclusive analyses (b tagging, $N_{jet}$, …) may be promising with 2011 data