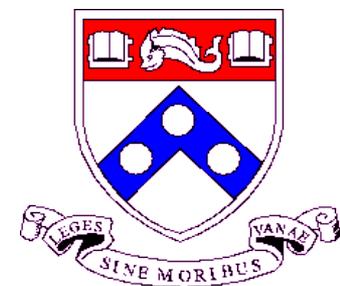


*Search for High Mass
Resonances Decaying to
Tau Pairs with the
ATLAS Detector*



Peter Wagner
University of Pennsylvania

On behalf of the ATLAS Collaboration

Motivation and Existing Limits

- **Many theories** beyond the standard model (SM) predict heavy gauge bosons: extended gauge sectors, string theories, KK, E_6 , ...
- Many models with extended weak or hypercharge gauge groups predict **enhanced coupling to third generation fermions**
- Typical benchmark model to compare experiments: **Sequential Standard Model (SSM)**; same couplings as SM \rightarrow signal model used in this analysis

Existing limits:

- SSM $Z' \rightarrow ee/\mu\mu$: Excluded $m < 2.3$ TeV (2.2 TeV) by CMS (ATLAS)
- Non-universal Z' bosons: Excluded $m < 1090$ GeV by precision electroweak measurements at LEP
- Searches for SSM $Z' \rightarrow \tau\tau$ performed by:
 - **CDF** (Phys.Rev.Lett. 95 (2005) 131801)
 - Most stringent published mass limit by **CMS** at 1.4 TeV using 4.9 fb^{-1} (arXiv:1206.1725 [hep-ex])

This analysis:

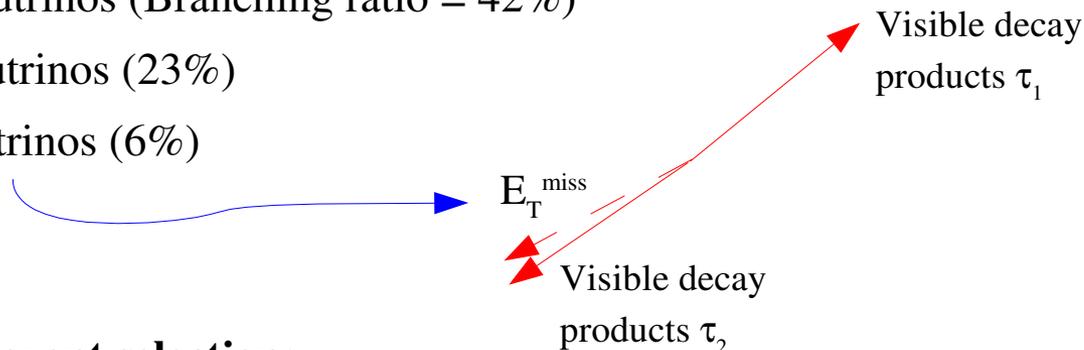
- **First $Z' \rightarrow \tau\tau$ search** at ATLAS: [ATLAS-CONF-2012-067](#)
- Integrated luminosity: **4.7 fb^{-1}**



Analysis Overview and Strategy

Decay channels studied in this analysis based on leptonic and hadronic decays of tau lepton:

- $\tau\tau \rightarrow \tau_h\tau_h + \text{neutrinos}$ (Branching ratio = 42%)
- $\tau\tau \rightarrow \mu\tau_h + \text{neutrinos}$ (23%)
- $\tau\tau \rightarrow e\mu + \text{neutrinos}$ (6%)



Simple, **common event selection**:

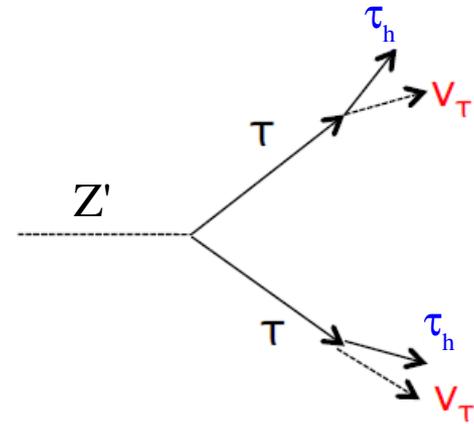
- Select only tau decay products; no additional electrons (muons) with $p_T > 15$ GeV (10 GeV)
- Visible tau decay products back-to-back
- Opposite charge, to suppress multijet background (except in $e\mu$ channel)

Choice of signal region:

- Z' typically has narrow intrinsic width: $\sim 3\%$ of mass – but $\tau\tau$ mass resolution degraded due to the undetected neutrinos
- Decay products from TeV-mass particles “central” (low- η) and high p_T

=> Count events with high transverse mass: calculated between visible tau decay products and E_T^{miss}

$$M_T(\tau_1, \tau_2, \text{MET}) = \sqrt{2 \left[p_{T,1} p_{T,2} (1 - \cos \Delta\phi_{1,2}) + E_T^{\text{miss}} p_{T,1} (1 - \cos \Delta\phi_{1,\text{Miss}}) + E_T^{\text{miss}} p_{T,2} (1 - \cos \Delta\phi_{2,\text{Miss}}) \right]}$$



$\tau_h \tau_h$ – Channel

$\tau_h \tau_h$ – Selection

Accept events that pass either di-tau trigger with $E_T > 29$ GeV and 20 GeV or single-tau trigger with $E_T > 125$ GeV

Particle Selection

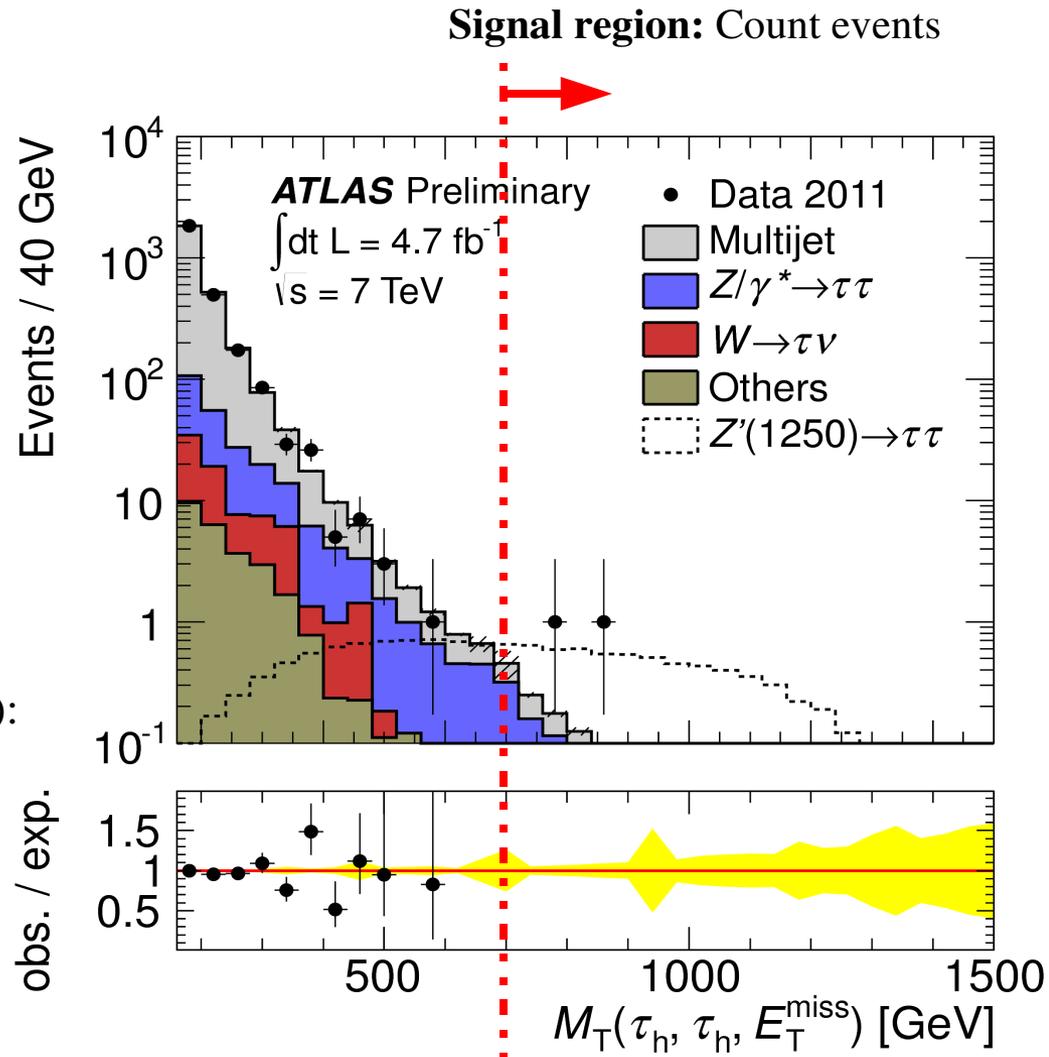
- Two τ_h with 1 or 3 prong, $p_T > 50$ GeV

Apply **common event selection** with back-to-back requirement $\Delta\phi(\tau_{h,1}, \tau_{h,2}) > 2.7$

Dominant Backgrounds

- Multijet: data-driven estimate
- $Z/\gamma^* \rightarrow \tau_h \tau_h$: estimated from MC

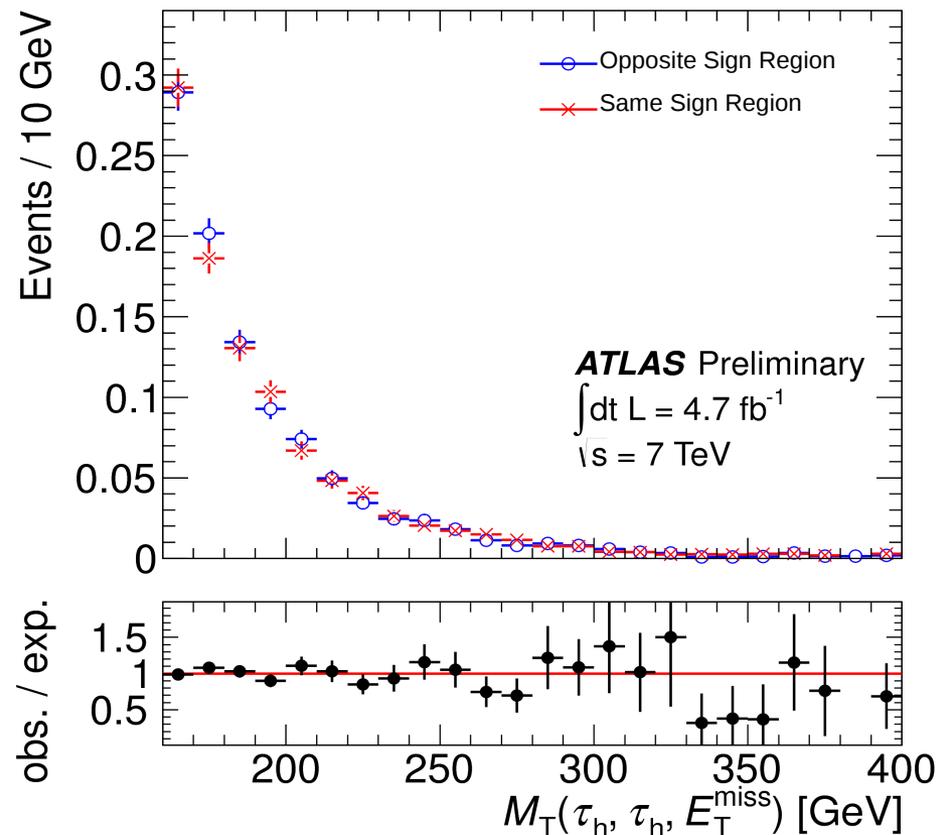
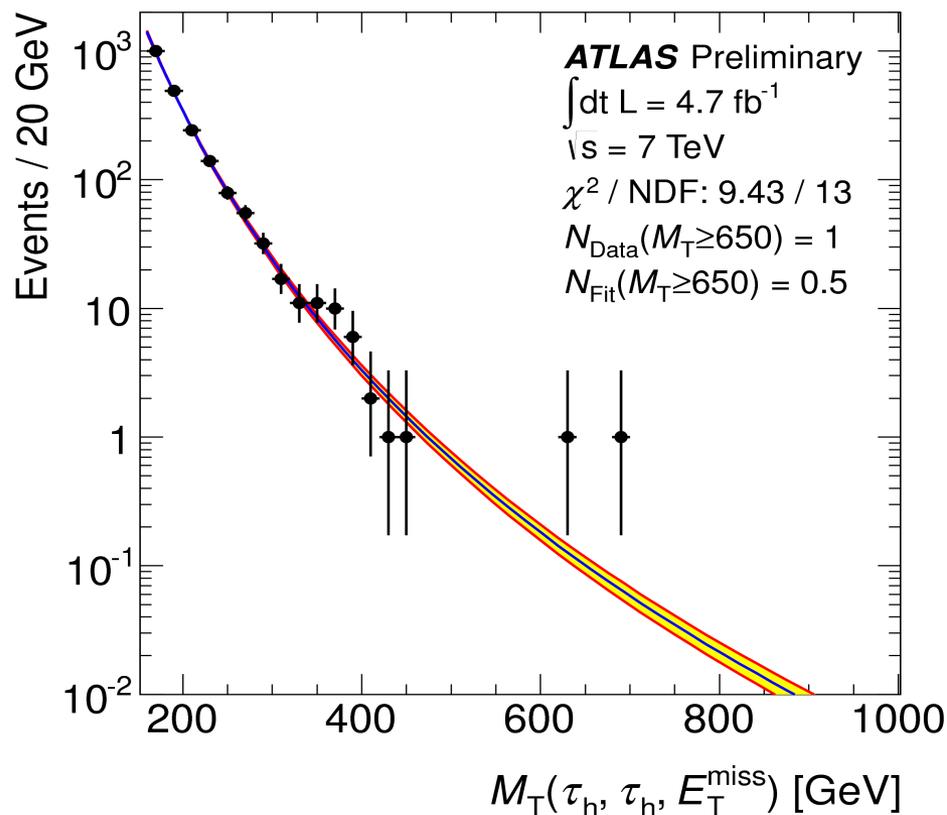
Other bkg (Z, W, tbar, diboson, single top): estimated from MC



$\tau_h \tau_h$ – Multijet Estimate

- Extract shape from fit to same-sign $\tau_h \tau_h$ events
- Statistical uncertainty on shape estimated using pseudo-experiments: 10-40% in high M_T signal region

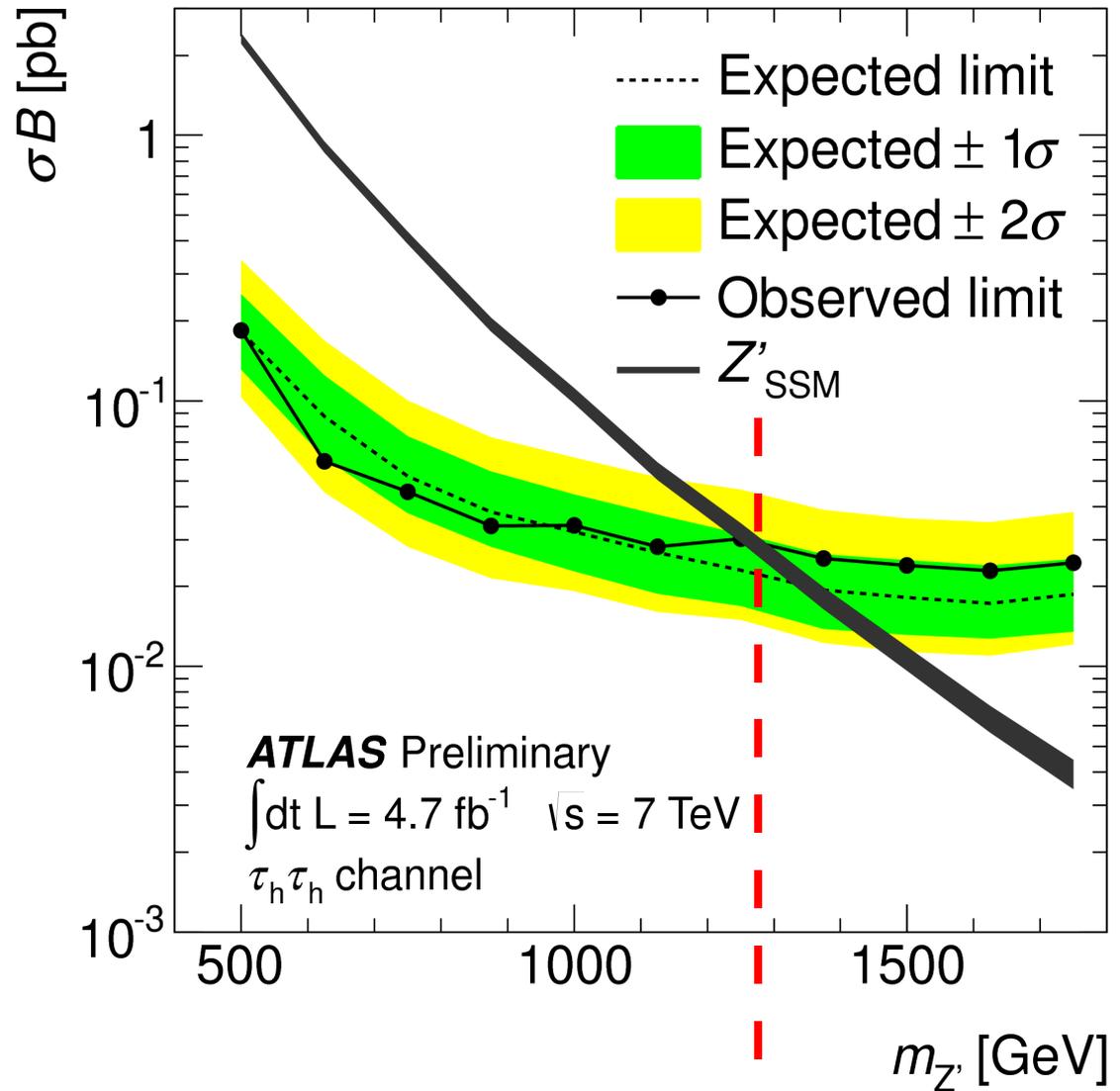
- Shape matches well with opposite sign events below signal region
- Normalize shape in low- M_T sideband ($160 < M_T < 200$ GeV) with statistical uncertainty $\sim 2\%$



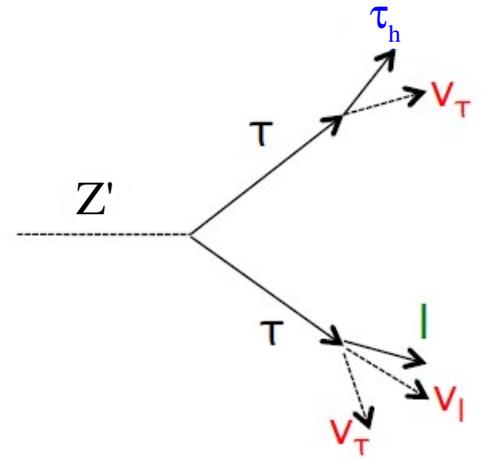
$\tau_h \tau_h$ – Summary

Achieve expected mass limit of 1.35 TeV with this channel alone!

Observed limit: 1.25 TeV



$\mu\tau_h$ - Channel



$\mu\tau_h$ – Selection

- Accept events that pass single muon trigger with $p_T > 18$ GeV

Particle Selection

- Exactly one isolated μ with $p_T > 25$ GeV
- Exactly one τ_h with 1 prong, $p_T > 35$ GeV

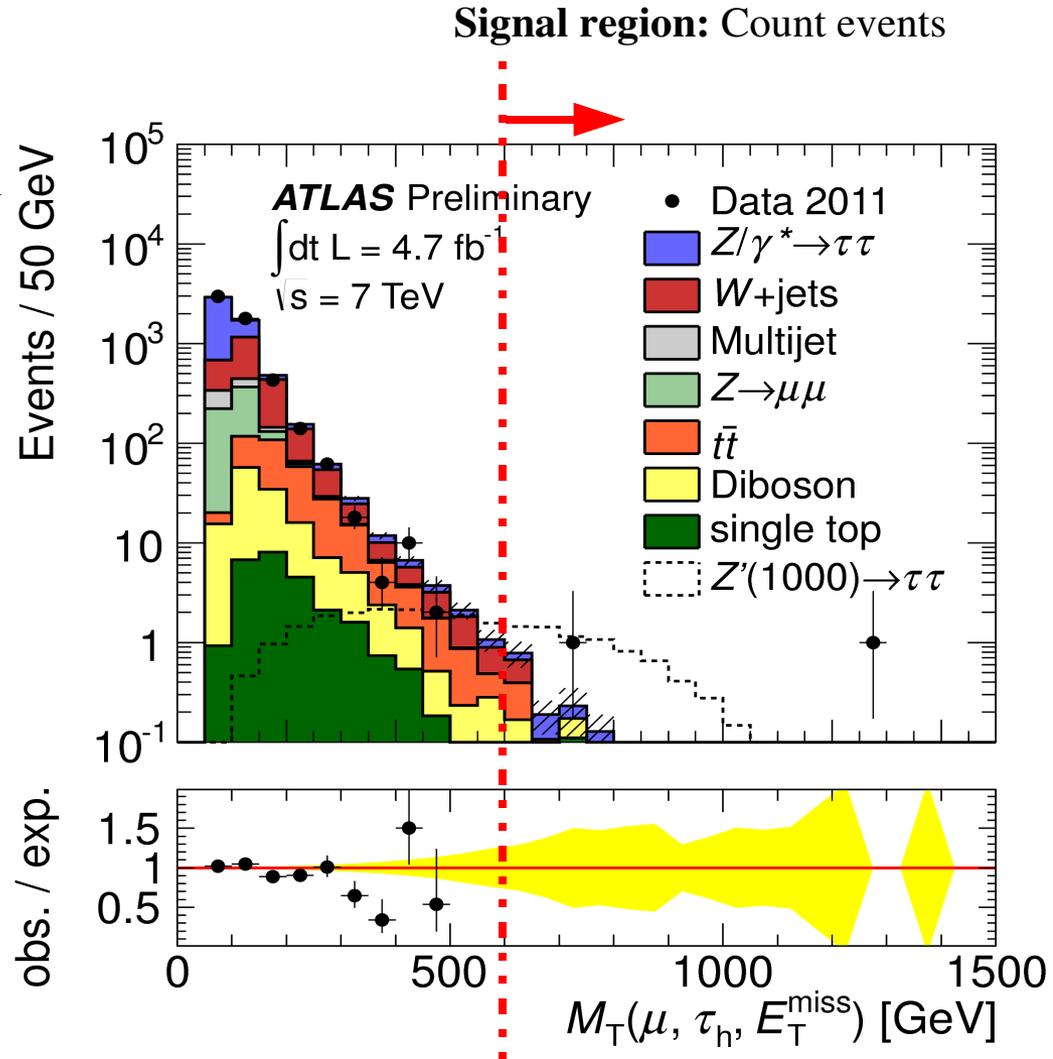
Apply **common event selection** with back-to-back requirement $\Delta\phi(\mu, \tau_h) > 2.7$

Dominant Backgrounds

- W+jets: data-driven estimate
- $Z/\gamma^* \rightarrow \mu\tau_h$: estimated from MC

Other bkgs

- Multijets negligible: data-driven estimate
- Z, W, t \bar{t} , diboson, single top: estimated from MC



$\mu\tau_h$ – Multijet and W +jets Estimates

Use fake factors measured in control regions to weight events that:

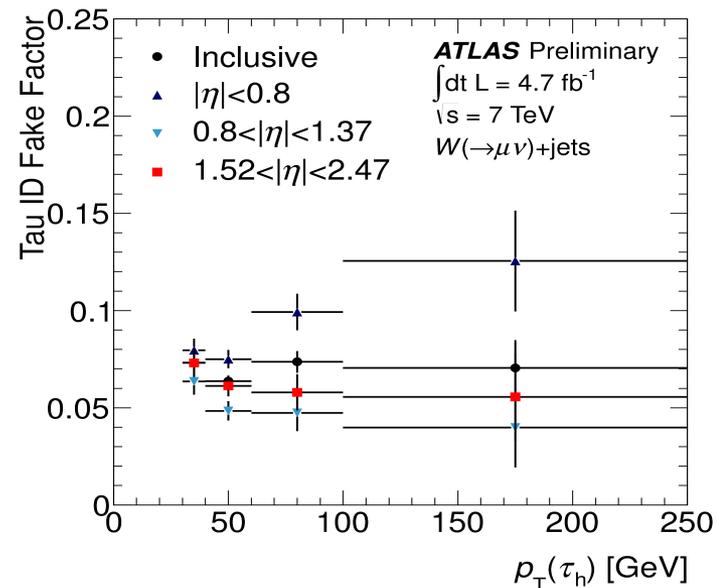
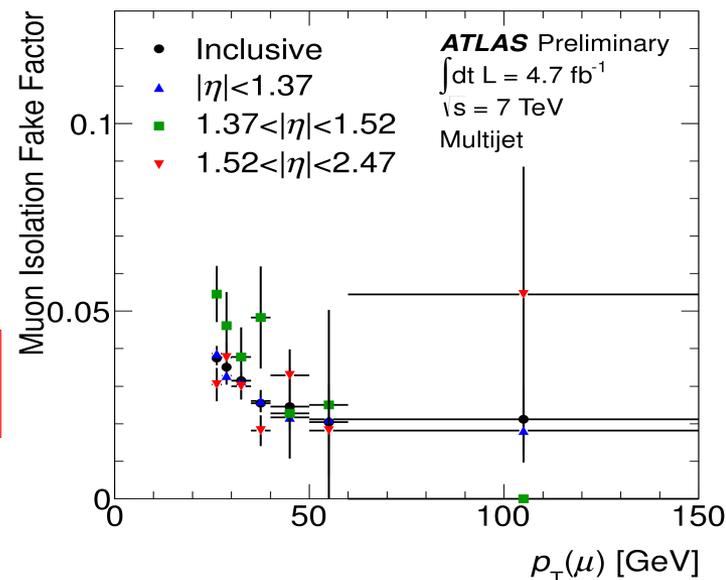
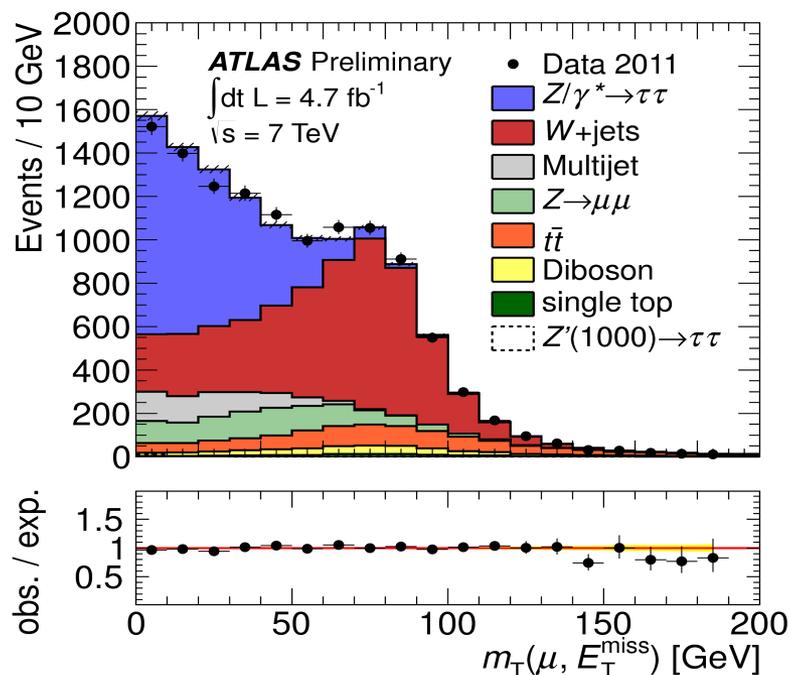
- fail muon isolation \rightarrow Multijets estimate

$$N_{\text{multijet}}(p_T, \eta, x) = \frac{N_{\text{pass } \mu\text{-iso}}(p_T, \eta)}{N_{\text{fail } \mu\text{-iso}}(p_T, \eta)} \Big|_{\text{multijet-CR}} \cdot \left(N_{\text{data}}^{\text{fail } \mu\text{-iso}}(p_T, \eta, x) - N_{\text{MC}}^{\text{fail } \mu\text{-iso}}(p_T, \eta, x) \right)$$

- fail tau identification \rightarrow W +jets estimate

$$N_{W+\text{jets}}(p_T, \eta, x) = \frac{N_{\text{pass } \tau\text{-ID}}(p_T, \eta)}{N_{\text{fail } \tau\text{-ID}}(p_T, \eta)} \Big|_{W\text{-CR}} \cdot \left(N_{\text{data}}^{\text{fail } \tau\text{-ID}}(p_T, \eta, x) - N_{\text{multijet}}^{\text{fail } \tau\text{-ID}}(p_T, \eta, x) - N_{\text{MC}}^{\text{fail } \tau\text{-ID}}(p_T, \eta, x) \right)$$

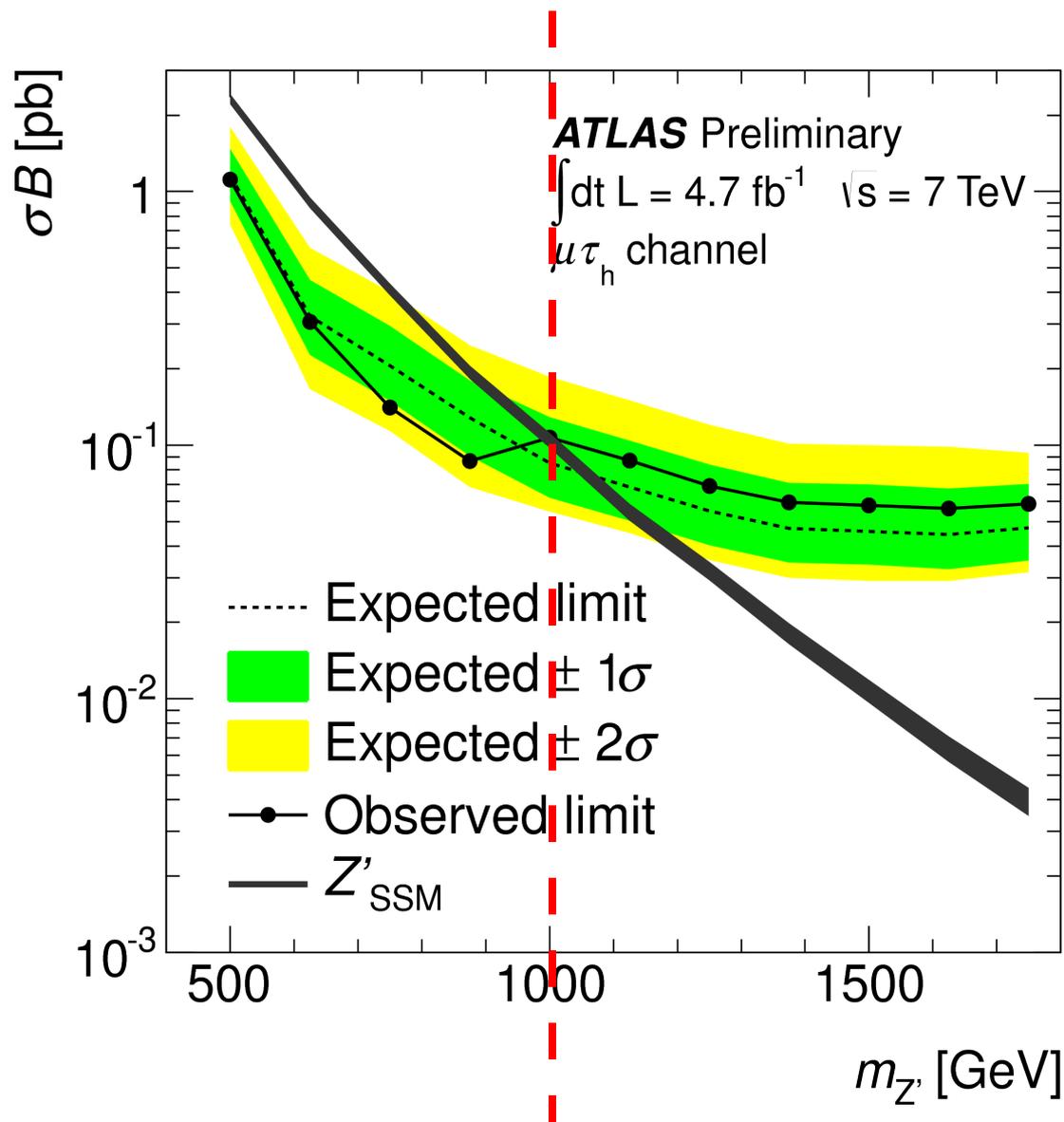
Good agreement after object selection:



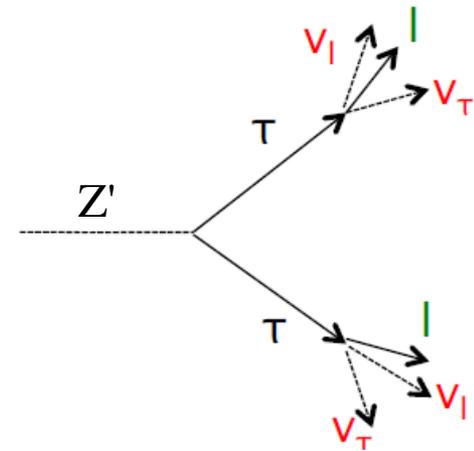
$\mu\tau_h$ – Summary

Mass limit:

- observed: 1.0 TeV
- expected: 1.05 TeV



$e\mu$ – Channel



$e\mu$ – Selection

- Accept events that pass single muon trigger with $p_T > 18$ GeV

Particle Selection

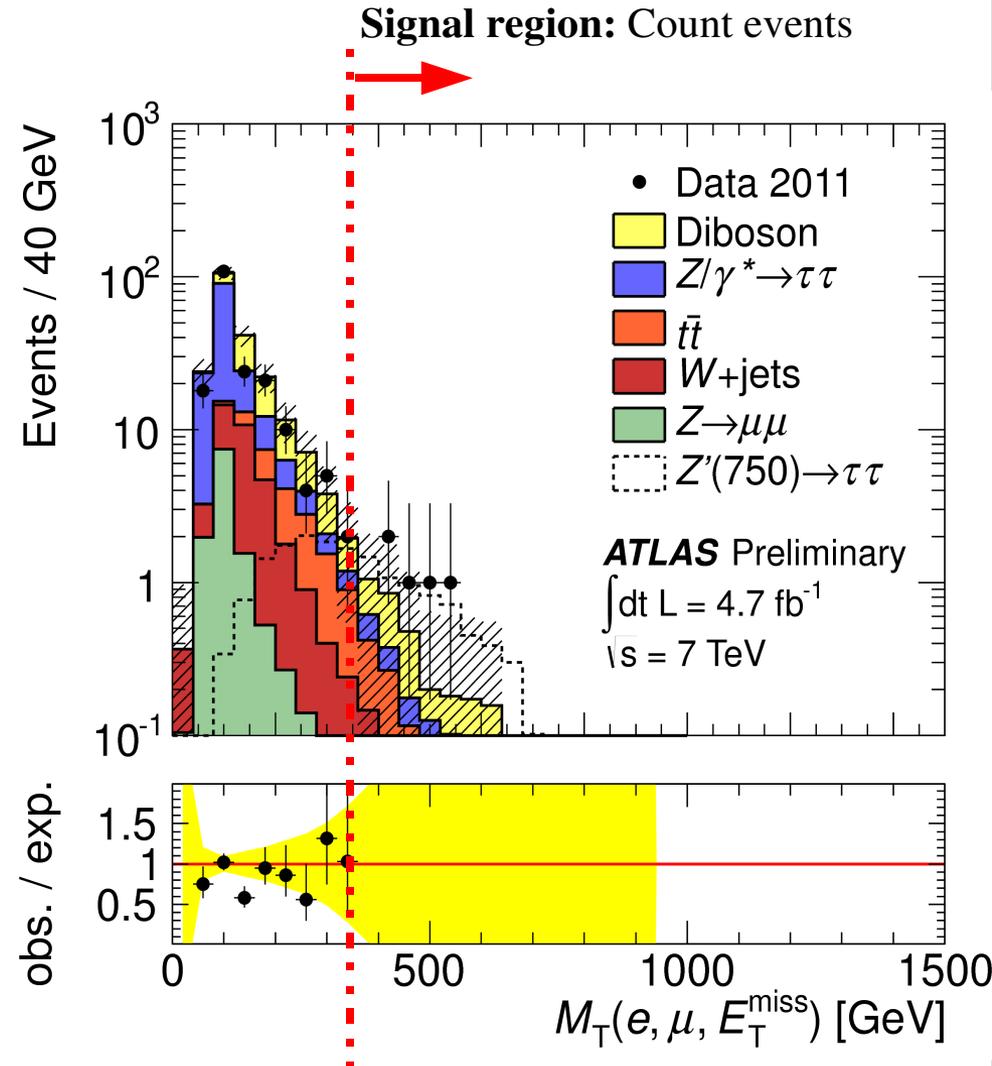
- Exactly one isolated μ with $p_T > 25$ GeV
- Exactly one isolated e with $p_T > 35$ GeV

Event Selection

- μ and e are back-to-back: $p_\zeta^{\text{vis}} < 10$ GeV
- Not more than one jet, to suppress $t\bar{t}$ background
- $\Delta\phi(\text{leading lepton}, E_T^{\text{miss}}) > 2.6$

Dominant Backgrounds

- $Z/\gamma^* \rightarrow e\mu$, $t\bar{t}$, diboson: estimated from MC, cross checked in high purity control regions
- Multijet estimated negligible using data-driven method



$e\mu$ – Background Estimates

Diboson control region:

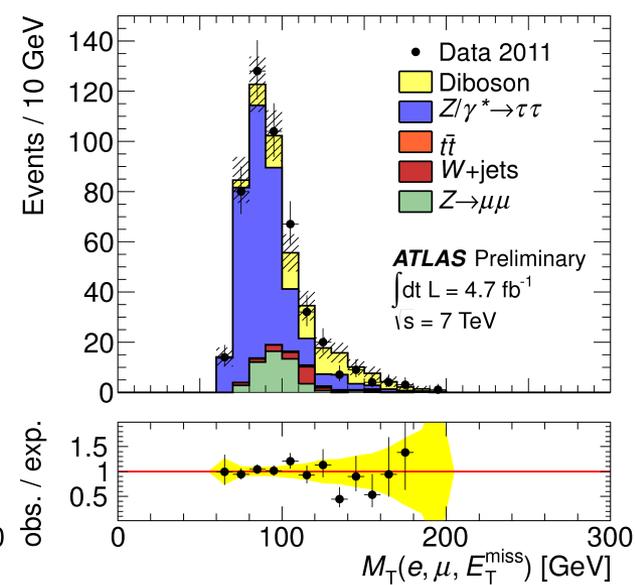
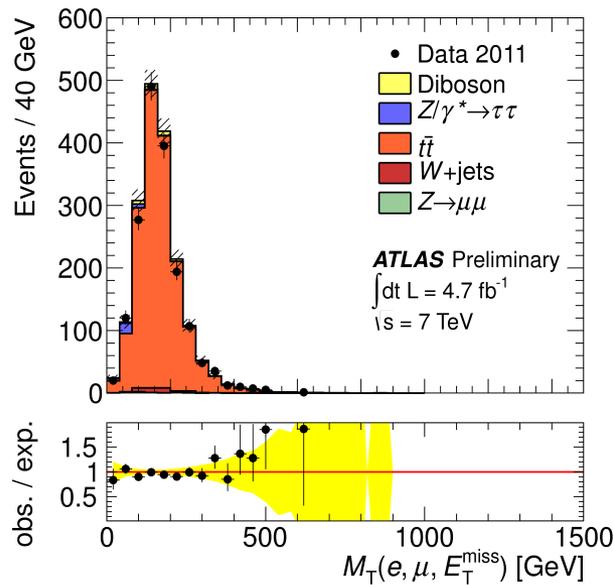
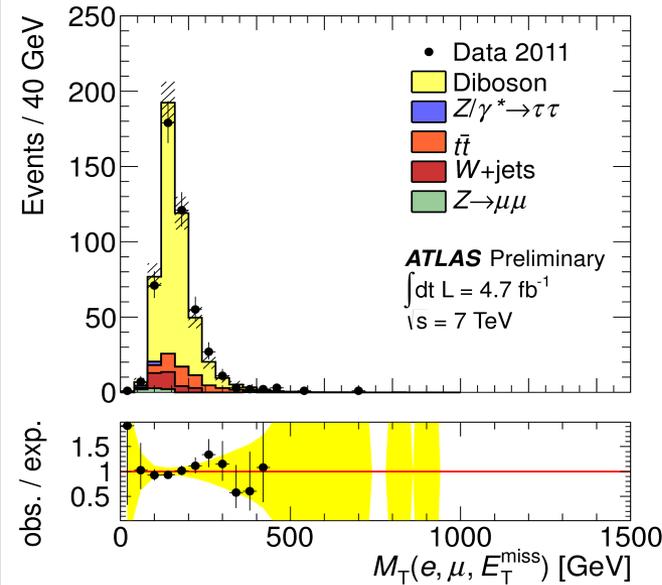
- remove $\Delta\phi$ selection
- reverse P_{ζ}^{vis}
- require no jets

$t\bar{t}$ control region:

- remove P_{ζ}^{vis} and $\Delta\phi$ selection
- require at least 3 jets

$Z/\gamma^* \rightarrow e\mu$ control region:

- remove $\Delta\phi$ selection
- require no jets and $M_T < 200$ GeV

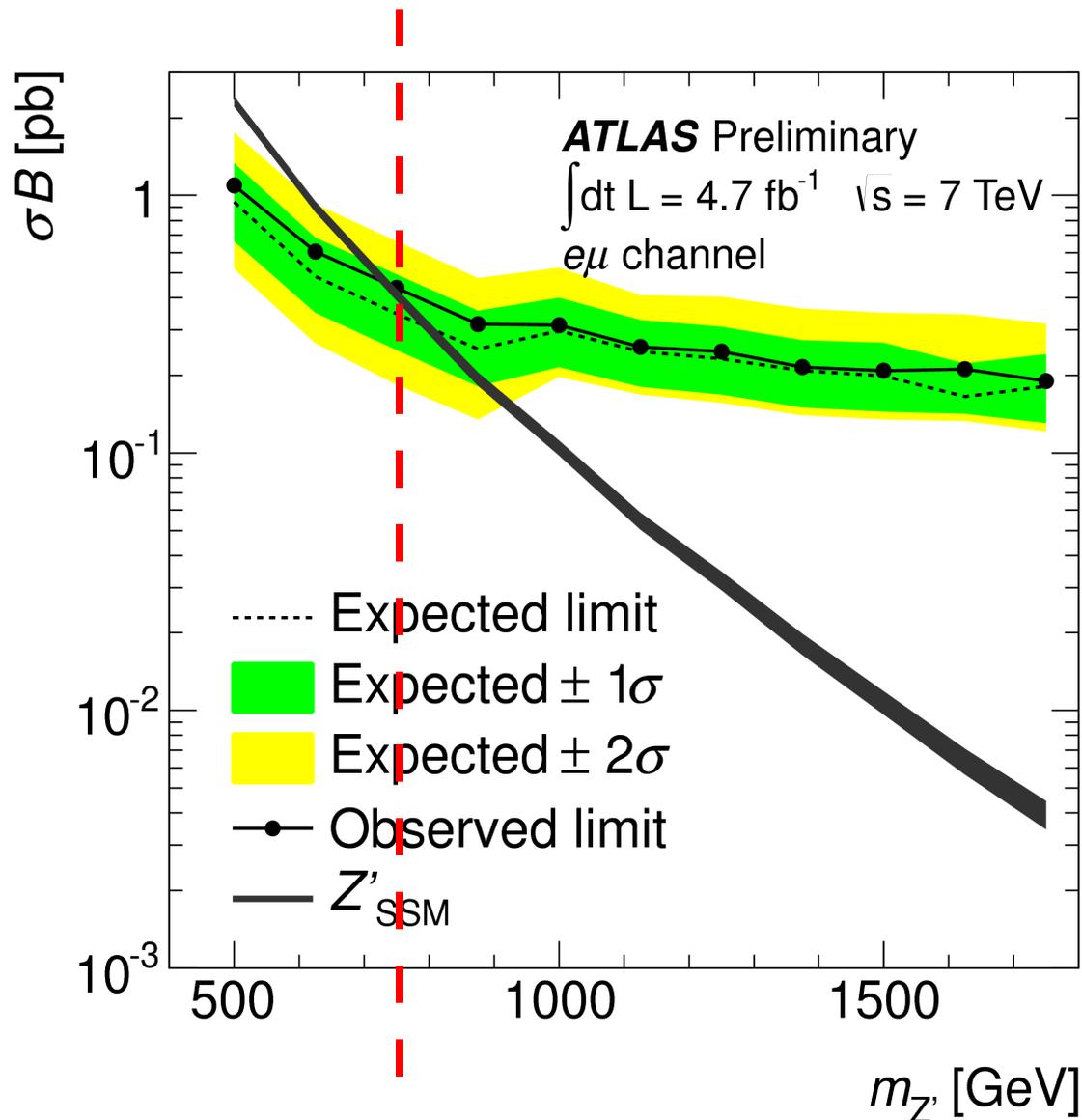


=> Backgrounds well modeled

$e\mu$ – Summary

Mass limit:

- observed: 0.74 TeV
- expected: 0.80 TeV



Systematic Uncertainties

Dominant signal uncertainty

- τ_h ID efficiency

Dominant background uncertainties

- $\tau_h \tau_h$: Shape of multijets estimate, τ_h energy scale
- $\mu \tau_h$: Statistical uncertainty on data-driven W+jets estimate
- $e\mu$: Statistical uncertainty on MC samples

	$\tau_h \tau_h$		$\mu \tau_h$		$e\mu$	
	sig.	bkg.	sig.	bkg.	sig.	bkg.
expected number of events	6.4	1.1	5.5	1.4	6.8	3.7
	Uncertainties (%)					
statistical uncertainty	negl.	5	2	20	3	7
trigger efficiency	4	3	negl.	negl.	negl.	negl.
e efficiency	–	–	–	–	negl.	3
e energy scale	–	–	–	–	negl.	2
τ_h ID efficiency	15	9	10	4	–	–
τ_h 3-prong reco. eff.	4	3	–	–	–	–
jet \rightarrow τ_h fake rate	–	negl.	–	3	–	–
$e \rightarrow \tau_h$ fake rate	–	–	–	16	–	–
jet energy scale	5	+20 -10	6	6	negl.	4
jet energy resolution	negl.	negl.	negl.	2	negl.	negl.
theoretical cross sections	–	8	–	5	–	5
luminosity	4	3	4	3	4	4
multijet shape	–	+10 -12	–	–	–	–
τ_h fake factor	–	–	–	6	–	–

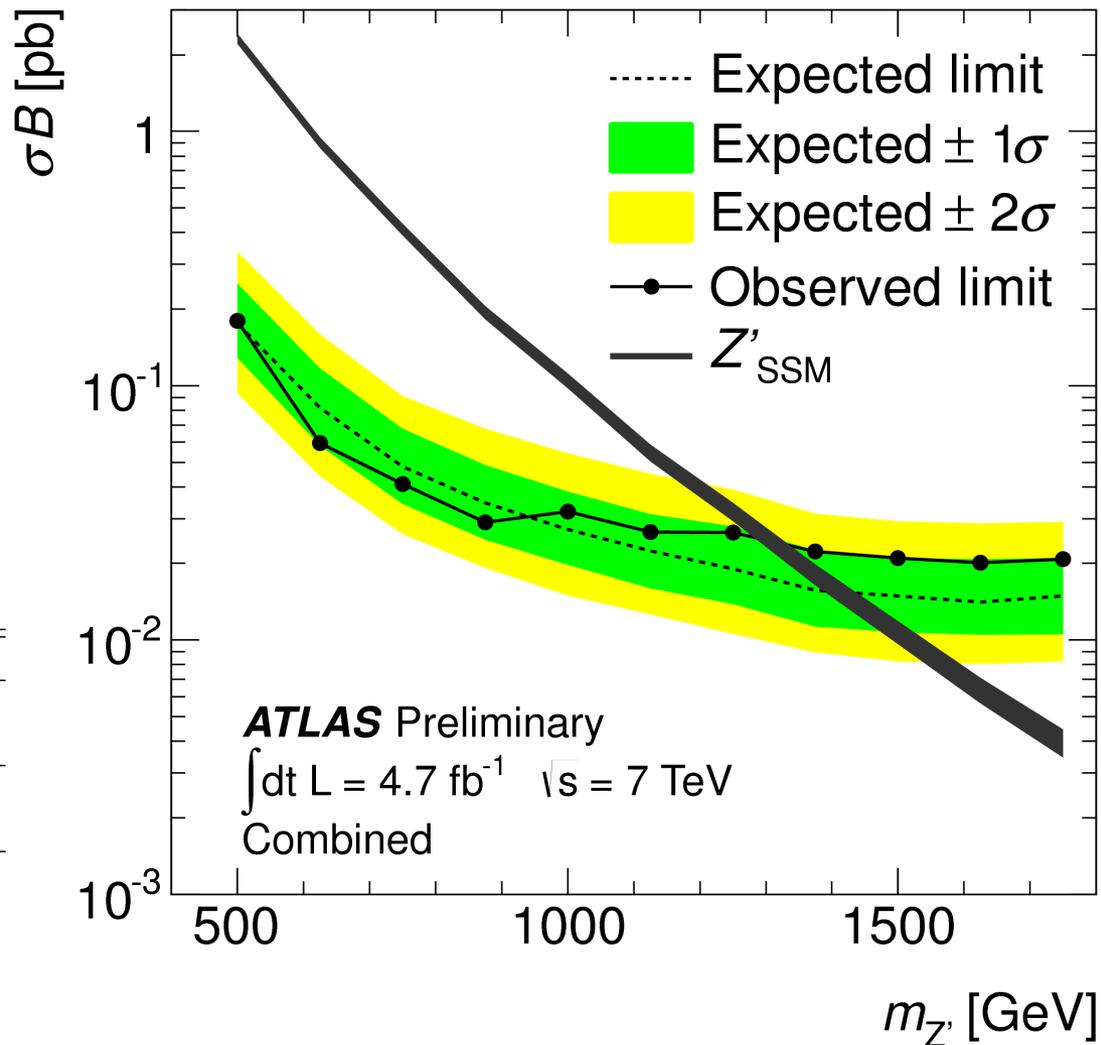
- : uncertainty not applicable

μ -related uncertainties negligible

Event Summary and Combination

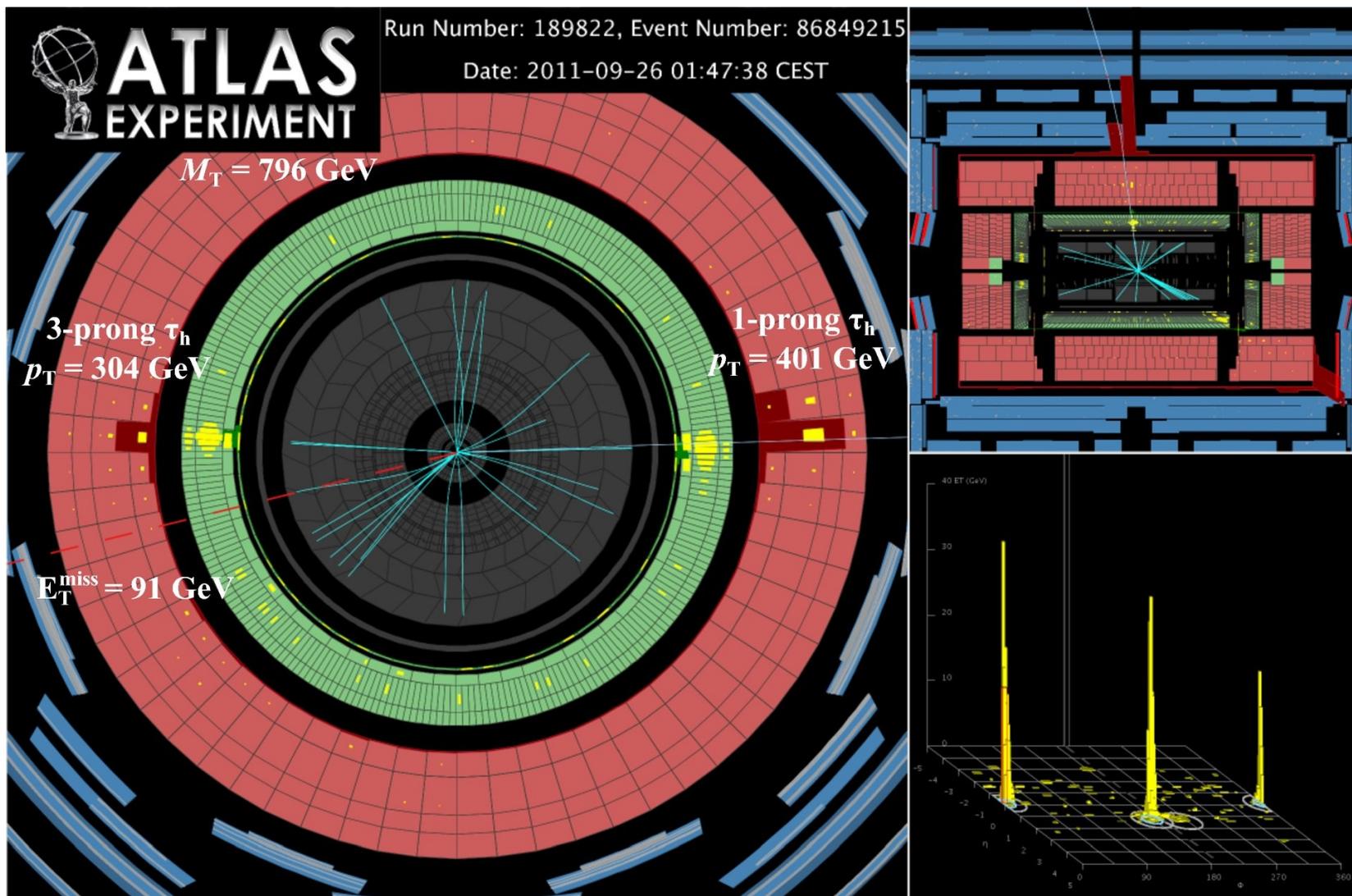
- No significant excess observed in data
- Exclude a $Z' \rightarrow \tau\tau$ below a Z' mass of 1.3 TeV using the combined result of the three channels
- Expected limit at 1.4 TeV

	$\tau_h\tau_h$	$\mu\tau_h$	$e\mu$
total expected background	1.1 ± 0.3	1.4 ± 0.3	3.7 ± 0.4
events observed	2	2	5
expected signal events	6.4 ± 0.1	5.5 ± 0.1	6.8 ± 0.4
signal efficiency (%)	4.3	1.1	0.4



A High M_T Event

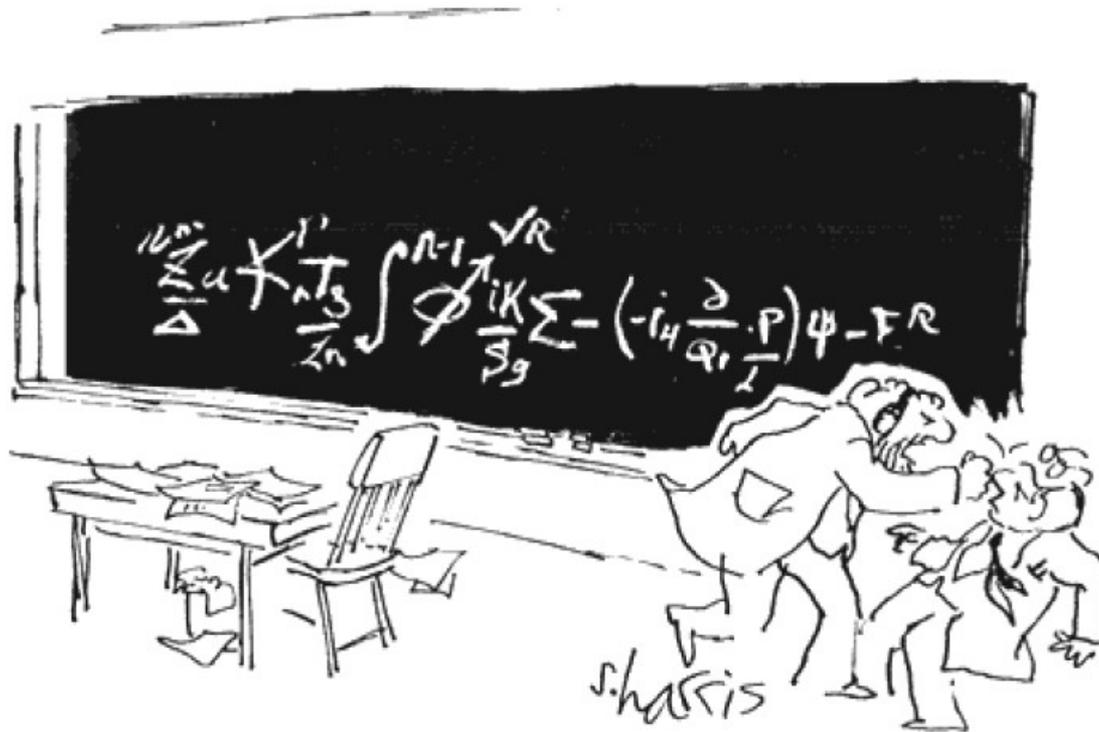
Likely a real $\tau_h\tau_h$ event:



Conclusion and Plans

- Performed the first $Z' \rightarrow \tau\tau$ at ATLAS with 4.7 fb^{-1} of data using 3 decay channels
- No significant excess over the predicted background is observed in data
- World's most stringent expected mass limit on SSM $Z' \rightarrow \tau\tau$ of 1.4 TeV, observed mass limit at 1.3 TeV comparable to CMS

Bonus

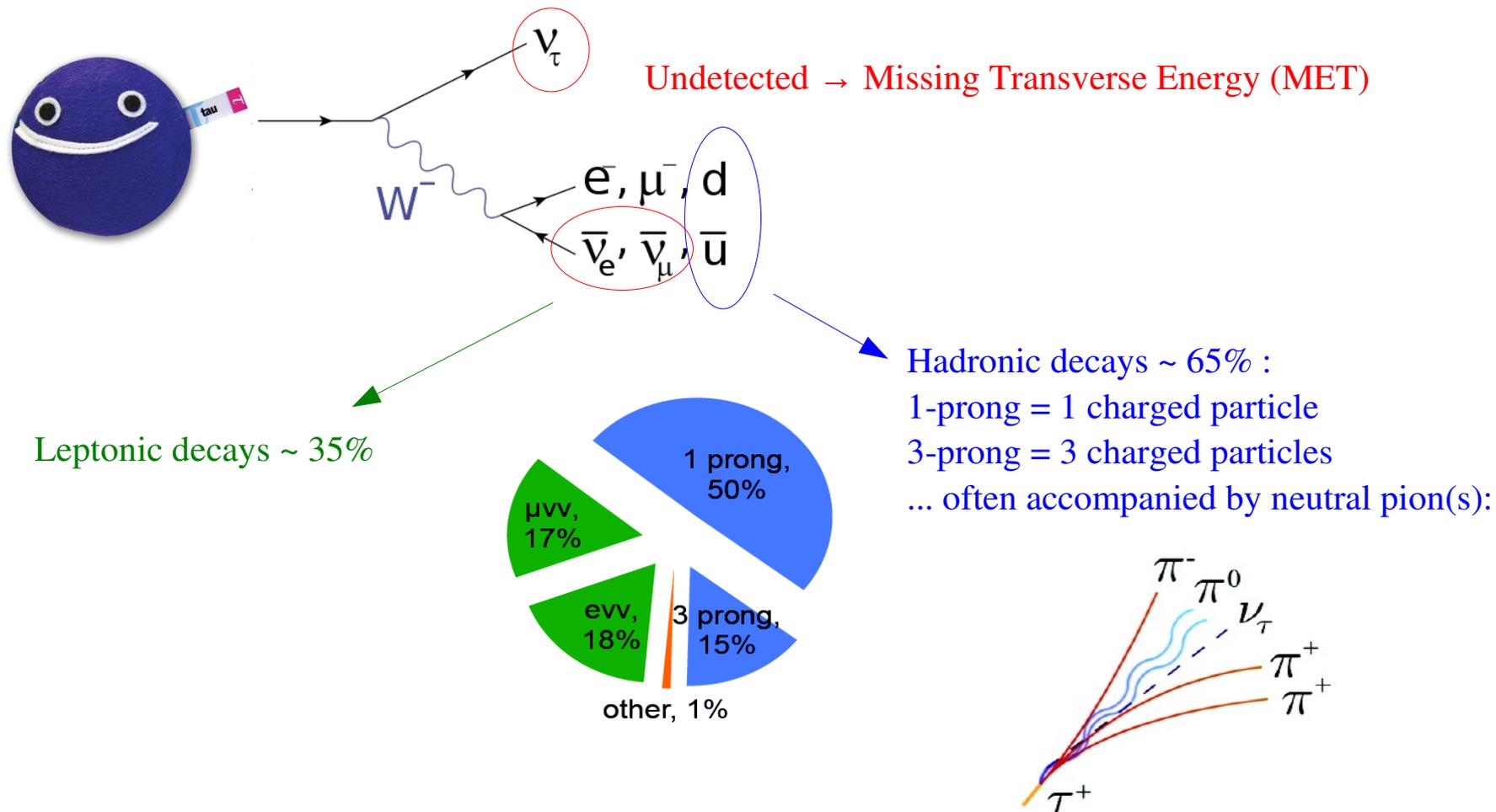


"You want proof? I'll give you proof!"

The Tau Lepton

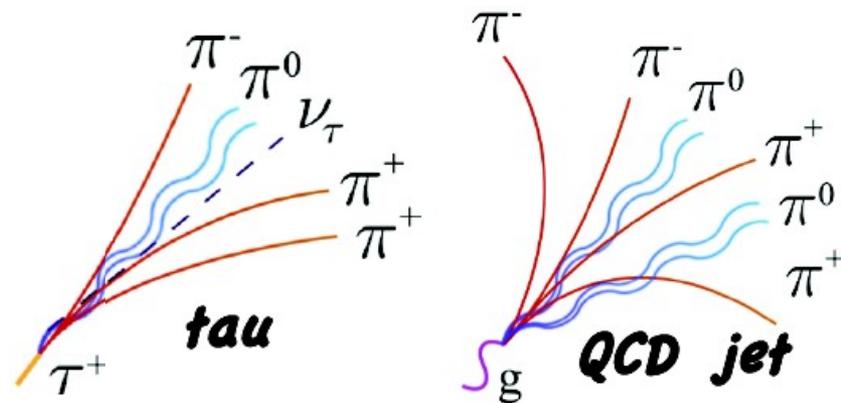
A few basics...

- Mass ~ 1.7 GeV \Rightarrow decay products have very small opening angle at few hundred GeV
- Weak decays:



Tau Reconstruction and Identification

- Hadronic taus (τ_h) are basically narrow isolated jets
- Classify τ_h by counting tracks within cone of $\Delta R < 0.2$ into 1-prong and 3-prong

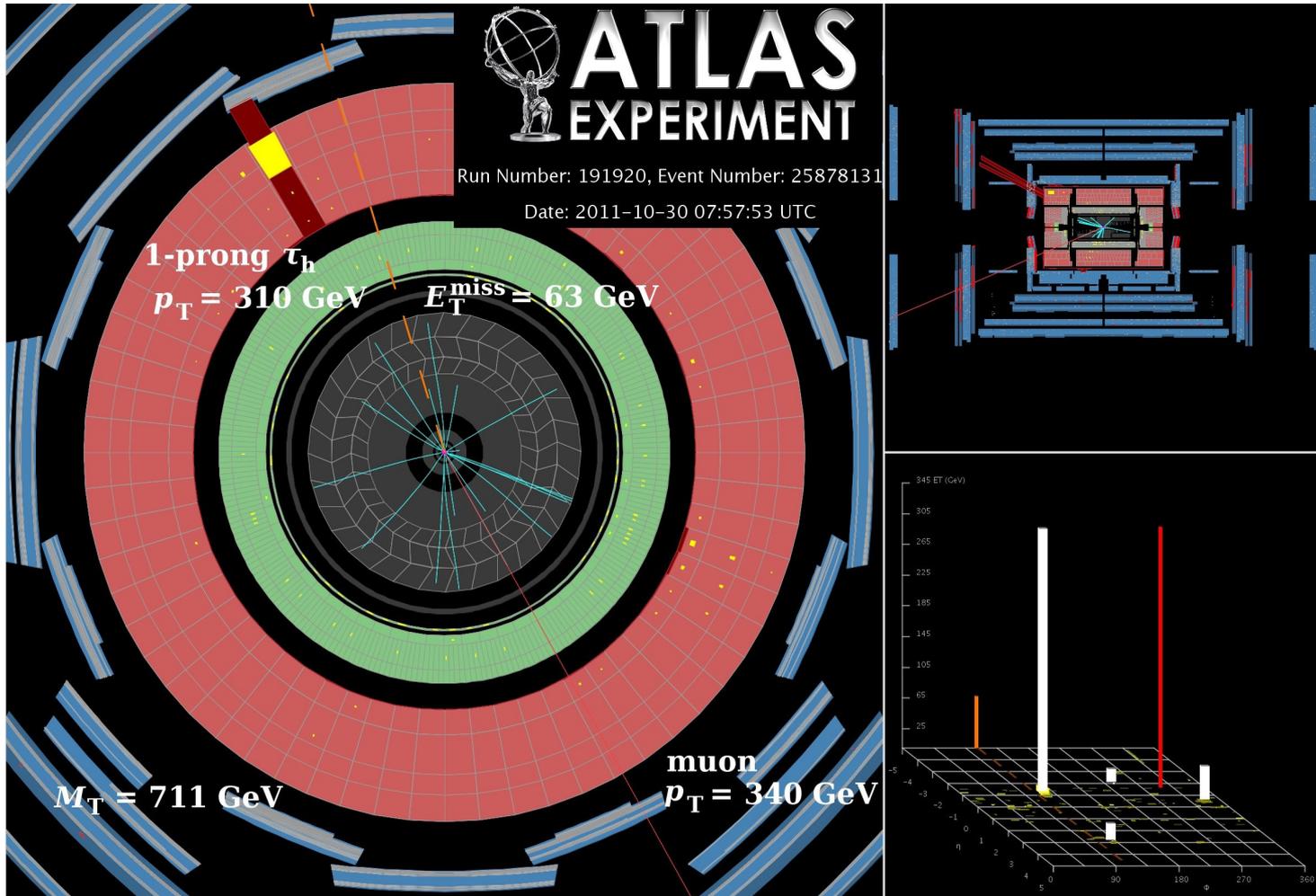


Identification: Discriminate τ_h from QCD jets using Boosted Decision Tree

- Variables sensitive to lateral shower width in calorimeter, ratio of track momentum to calorimeter energy, ...
- Apply separate ID criteria for 1- and 3-prong τ_h
- Depending on how much fake τ_h needs to be suppressed apply “loose” or “medium” ID criteria with ~60% (50%) efficiency for real τ_h at a jet rejection rate of ~30 (~100)

Another High M_T Event

- Observed in $\mu\tau_h$ analysis
- τ_h punched through to muon system
- 1-prong τ_h with EM fraction 1.5%
- likely a **real $\mu\tau_h$ event**



$\tau_h \tau_h$ – Backup Material

Event Selection:

	data	total SM	$Z/\gamma^* \rightarrow \tau\tau$	$W(\rightarrow \tau\nu)+\text{jet}$	others	Multijet	$Z'(1250)$
two τ_h candidates	22993	–	597(9)	166(10)	101(3)	–	14.4(1)
opposite charge taus	13225	–	568(9)	146(9)	84(3)	–	13.8(1)
$ \Delta\phi(\tau_1, \tau_2) > 2.7$	10297	–	291(5)	96(8)	41(2)	–	13.3(1)
$M_T > 700$ GeV	2	1.1(1)	0.7(1)	0	0	0.4(1)	6.4(1)

Multijet estimate:

- “Dijet” fit function: $f(M_T|p_0, p_1, p_2) = p_0 \cdot M_T^{p_1+p_2 \log M_T}$

$\mu\tau_h$ – Backup Material

Particle Selection

- Exactly one μ with $p_T > 25$ GeV and $|\eta| < 2.5$ and “isolated”
 - deposits $< 4\%$ of p_T in calorimeter within $0.05 < \Delta R < 0.2$
- Exactly one τ_h with 1 prong, $p_T > 35$ GeV
- Pass identification using BDT with $\sim 50\%$ efficiency

Event Selection:

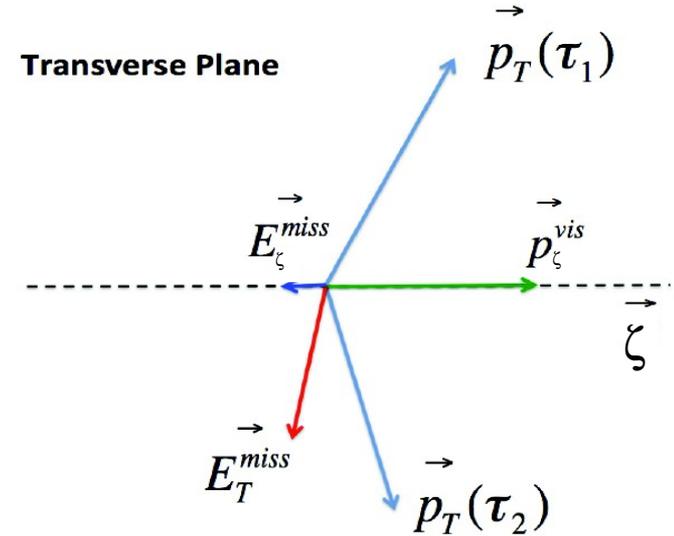
	data	total SM	$Z \rightarrow \tau\tau$	W +jets	multijet	$Z \rightarrow \mu\mu$	$t\bar{t}$	diboson	single top	$Z'(1000)$
one μ , one τ_h	11892	11989(48)	3976(36)	4980(21)	594(5)	945(21)	1029(7)	352(4)	114(3)	18.7(2)
$ \Delta\phi(\mu, \tau_h) > 2.7$	6192	6110(39)	2909(32)	1837(14)	409(4)	567(18)	233(3)	126(2)	28(2)	17.9(2)
opposite sign μ and τ_h	5424	5384(38)	2863(31)	1467(13)	217(3)	478(16)	219(3)	115(2)	26(1)	17.6(2)
$M_T > 300$ GeV	36	55(2)	7.5(2)	18(2)	0.6(1)	0.3(2)	18.5(9)	7.0(6)	3.3(5)	14.1(2)
$M_T > 600$ GeV	2	1.4(3)	0.38(2)	0.3(2)	< 0.02	< 0.1	0.3(1)	0.24(7)	0.2(1)	5.5(1)

$e\mu$ – Backup Material

Object Selection

- Exactly one μ with $p_T > 25$ GeV
- Exactly one e with $p_T > 35$ GeV that passes an ID with an efficiency of $\sim 90\%$
- Both are isolated: (1) see previous slide and (2) Σp_T of tracks with $p_T > 1$ GeV associated to μ (e) less than 6% (8%)

Explanation of p_ζ^{vis} :



Event summary:

	data	total SM	$t\bar{t}$	diboson	$Z/\gamma^* \rightarrow \tau\tau$	W +jets	$Z(\rightarrow \mu\mu)$ +jets	$Z'(750)$
one e , one μ	6115	6255(25)	3981(12)	1200(5)	648(12)	293(15)	133(8)	35.3(6)
$N(\text{jets}) \leq 1$	2615	2797(20)	701(5)	1073(4)	568(11)	202(13)	118(8)	30.5(5)
$p_\zeta^{\text{vis}} < 10$ GeV	682	667(13)	63(2)	169(2)	364(10)	34(6)	55(6)	21.2(4)
$ \Delta\phi(\ell, E_T^{\text{miss}}) > 2.6$	197	216(9)	13(1)	55(1)	116(5)	25(7)	12(2)	16.2(4)
$M_T > 350$ GeV	5	3.6(3)	1.0(2)	1.7(2)	0.56(2)	0.33(4)	0.06(1)	6.8(2)

Event Summary

	$\tau_h\tau_h$	$\mu\tau_h$	$e\mu$
$Z/\gamma^* \rightarrow \tau\tau$	0.7 ± 0.2	0.38 ± 0.02	0.56 ± 0.07
W +jets	0	0.3 ± 0.2	0.33 ± 0.10
$Z(\rightarrow \ell\ell)$ +jets	0	0	0.06 ± 0.02
$t\bar{t}$	0	0.3 ± 0.1	1.0 ± 0.2
diboson	0	0.24 ± 0.07	1.7 ± 0.3
single top	0	0.2 ± 0.1	0
multijet	0.4 ± 0.1	0	0
total expected background	1.1 ± 0.3	1.4 ± 0.3	3.7 ± 0.4
events observed	2	2	5
expected signal events	6.4 ± 0.1	5.5 ± 0.1	6.8 ± 0.4
signal efficiency (%)	4.3	1.1	0.4

A High M_T Event

- Both τ_h with high BDT scores
- Moderate E_T^{miss} in direction of subleading τ_h