Search for light CP-odd and charged Higgs bosons at ATLAS

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on behalf of the **ATLAS** Collaboration

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Outline

- H+ with leptonic τ decays:
  - Introducing and testing new discriminating variables
- H+ searches with hadronic τ decays
  - Test of data-driven background estimates
- $a_1 \rightarrow \mu\mu$
  - Limits on cross section times branching ratio

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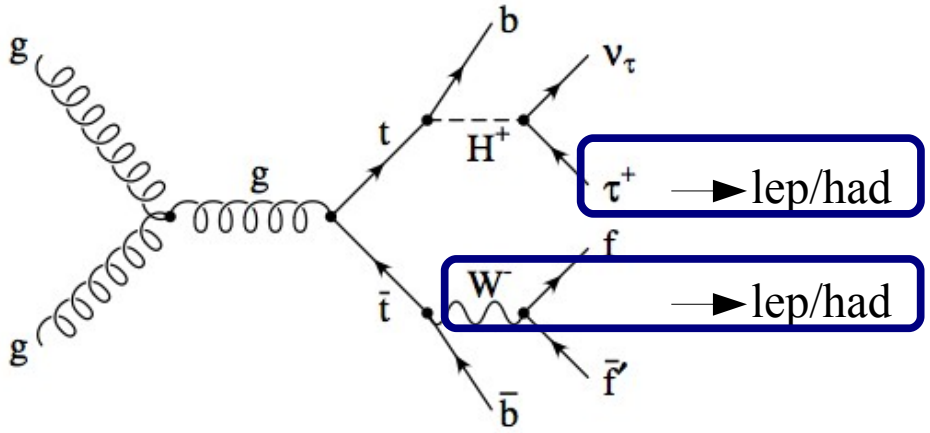
Charged Higgs boson

Charged Higgs bosons at ATLAS

- Large cross section possible for $m_{H+} < m_t$
- Dominant in the MSSM: $H^+ \rightarrow \tau\nu$ $[m_{H+} < m_t]$



- Four channels can be investigated:
  → ATLAS studies all of them

pp→tt, t→bH+	H	qq
-"-	H	l
-"-	Λ	qq
-"-	Λ	l

H+ with leptonic τ decays, W→qq

- Event selection:
  - =1 electron/muon (trigger-matched),
  - >=4 jets,
    out of which =2 b-tagged,
  - p_T(miss) > 40 GeV,
  - 100 < m_{jjb} [GeV] < 250.

MC vs data

Cuts	Data	$t\bar{t}$	Single top-quark	Z+jets	W+jets	Di-boson	$\sum$ MC
Trigger	11082387	1943.3	606.3	7.4×10^4	4.3×10^5	628.8	5.1×10^5
Exactly 1 lepton	589664	1202.5	393.5	3.1×10^4	3.1×10^5	404.7	3.4×10^5
At least 4 jets	4794	770.0	54.4	409.3	1433.8	22.1	2690
Exactly 2 b-jets	226	184.1	7.4	0.9	7.0	0.2	200
$p_T^{\text{miss}} > 40$ GeV	131	124.2	4.7	0.2	4.4	0.1	134
Top mass window	119	110.4	3.3	0.2	3.3	0.1	117

Disagreement in first three rows because QCD is non-negligible there

H+ with leptonic τ decays, W→lν

- Event selection:
  - =2 leptons (ee/μμ/eμ; opposite sign; one is trigger-matched),
  - >=2 jets,
  - ee/μμ:
    - $|m_{ll}-m_Z|>10$ GeV, $m_{ll}>15$ GeV,
    - $p_T(\text{miss}) > 40$ GeV.
  - eμ:
    - $H_T(\text{leptons, jets})>130$ GeV.

MC vs data

Cuts	Data	$t\bar{t}$	Single top-quark	Z+jets	W+jets	Di-boson	$\sum$ MC
Trigger	11082387	1943.3	606.3	7.4×10^4	4.3×10^5	628.8	5.1×10^5
Exactly 2 leptons	21283	109.6	11.1	2.0×10^4	3.2	72.3	2.0×10^4
At least 2 jets	1595	96.8	5.6	1529.7	0.5	28.3	1661
Z veto, p_T^{miss}/H_T	105	79.5	4.4	9.0	0.3	2.1	95

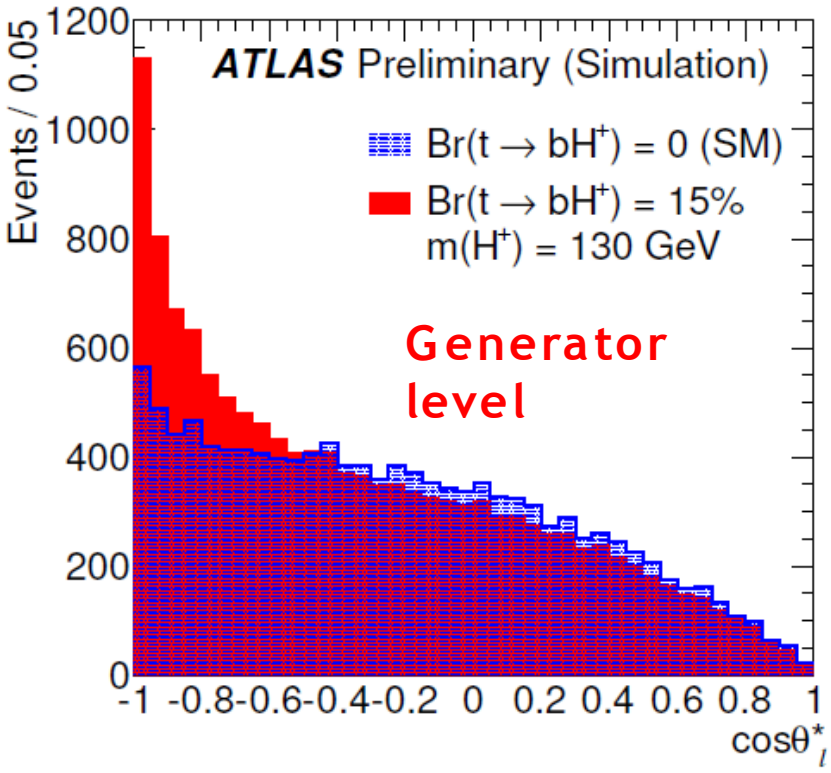
cos θ*

- For W → lν, angle of lepton momentum wrt the helicity axis in the W rest frame:

$$\cos\theta_l^* = \frac{2m_{bl}^2}{m_{\text{top}}^2 - m_W^2} - 1 \simeq \frac{4\,p^b \cdot p^l}{m_{\text{top}}^2 - m_W^2} - 1$$

Used here because it

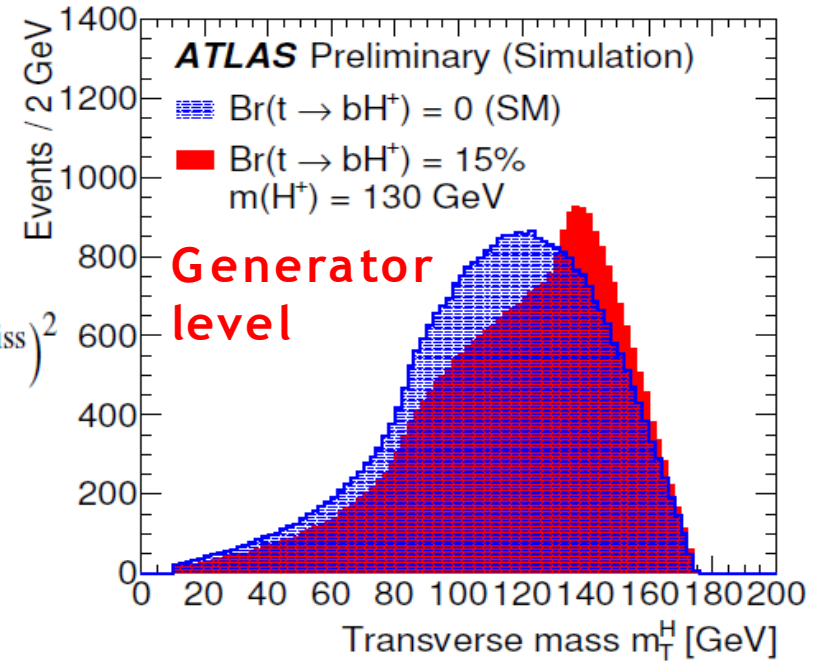
- allows discrimination between direct leptons, and τ → lνν,
- without much sensitivity to the H^+ mass.



$m_T(H)$ for $bqqbH^+$

- Novel method for the 3-neutrino-case:
  $H^+ \rightarrow \tau\nu$ with $\tau \rightarrow l\nu\nu$ [rest of event is fully reconstructed]
- Maximize $(m_T^H)^2 = \max_{\left\{ \substack{p_z^{\text{miss}}, E^{\text{miss}} \\ (p^{\text{miss}}+p^l+p^b)^2=m_{\text{top}}^2} \right\}} [(p^l + p^{\text{miss}})^2]$
  (1 constraint, 2 variables)
- Solution:

$$(m_T^H)^2 = \left(\sqrt{m_{\text{top}}^2 + (\vec{p}_T^{\,l} + \vec{p}_T^{\,b} + \vec{p}_T^{\,\text{miss}})^2} - p_T^b \right)^2 - \left(\vec{p}_T^{\,l} + \vec{p}_T^{\,\text{miss}} \right)^2$$



- By construction:
  - $m_W < m_T^H < m_t$ [background],
  - $m_{H^+} < m_T^H < m_t$ [signal]

m_{T2}^{H} for blνbH$^+$

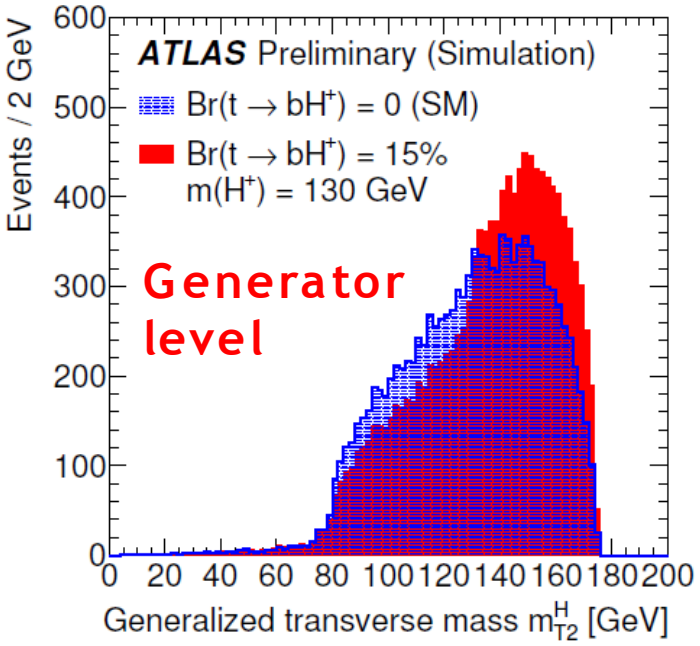
- Definition for tt->bW_1bW_2 (or H$^+$) with W_1 (or H$^+$) -> τν, τ->lνν and W_2->lν
- Maximize: $m_{T2}^{H} = \max_{\{constraints\}} [m_T^H(\vec{p}_T^{\,H^+})]$ with

$$(m_T^H(\vec{p}_T^{\,H^+}))^2 = \left(\sqrt{m_{\text{top}}^2 + (\vec{p}_T^{\,H^+} + \vec{p}_T^{\,b})^2} - p_T^b \right)^2 - \left(\vec{p}_T^{\,H^+} \right)^2$$

- 6 constraints, 8 variables: p^{H+}, p^{ν}
- Again:
  - $m_W < m_{T2}^H < m_t$ [background],
  - $m_{H+} < m_{T2}^H < m_t$ [signal]

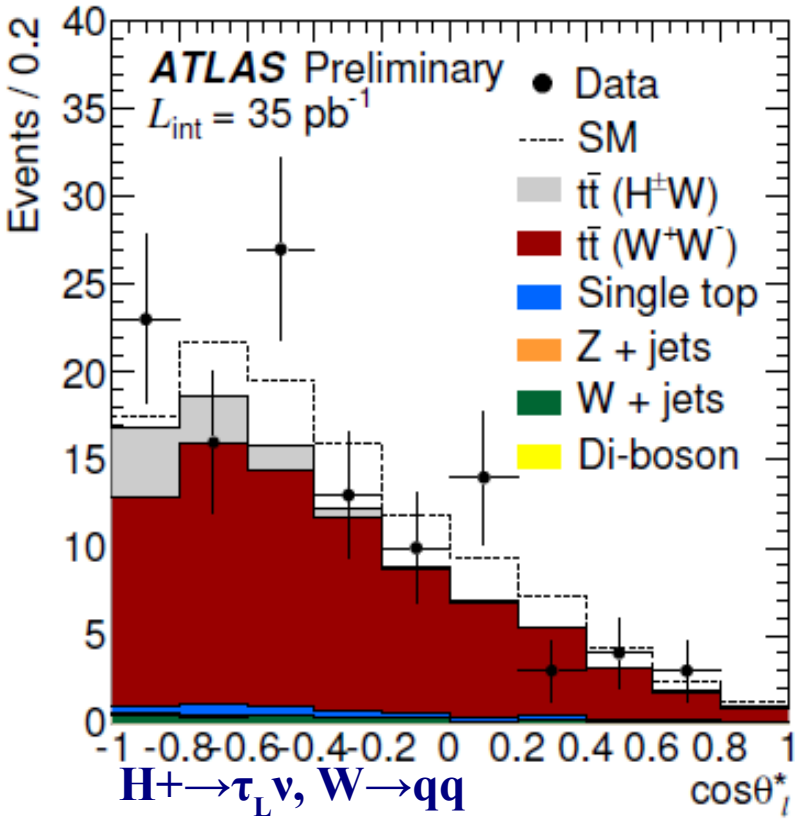
constraints:

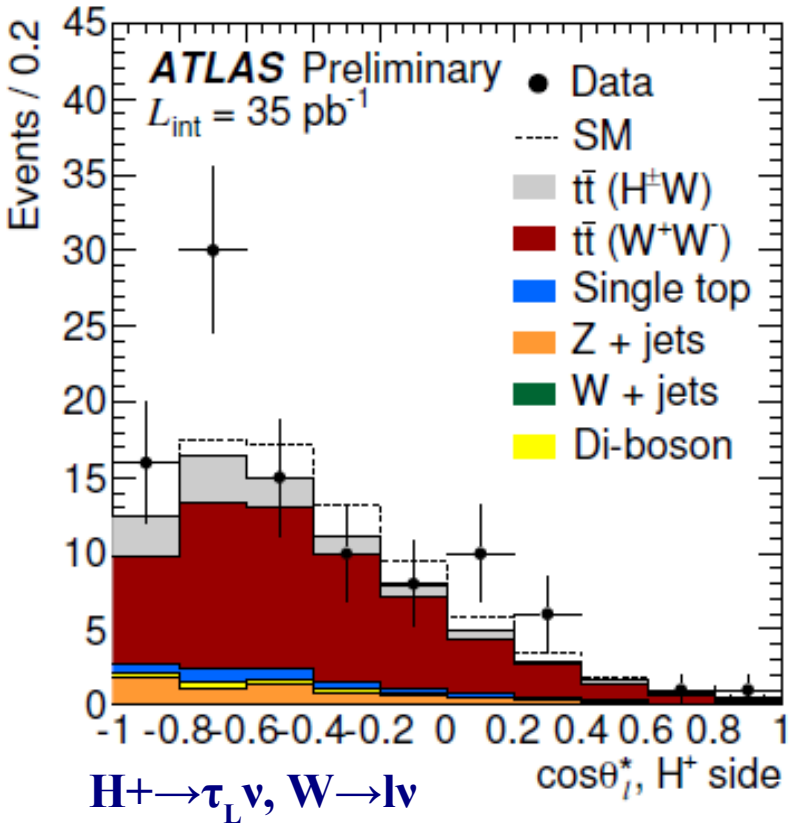
$$\begin{aligned}
(p^{H^+} + p^b)^2 &= m_{\text{top}}^2, \\
(p^{\ell^-} + p^{\bar{\nu}_\ell})^2 &= m_W^2, \\
(p^{\ell^-} + p^{\bar{\nu}_\ell} + p^{\bar{b}})^2 &= m_{\text{top}}^2, \\
(p^{\bar{\nu}_\ell})^2 &= 0, \\
\vec{p}_T^{\,H^+} - \vec{p}_T^{\,\ell^+} + \vec{p}_T^{\,\bar{\nu}_\ell} &= \vec{p}_T^{\,\text{miss}}
\end{aligned}$$



Results: cos θ*

Data vs simulation after all selection cuts:

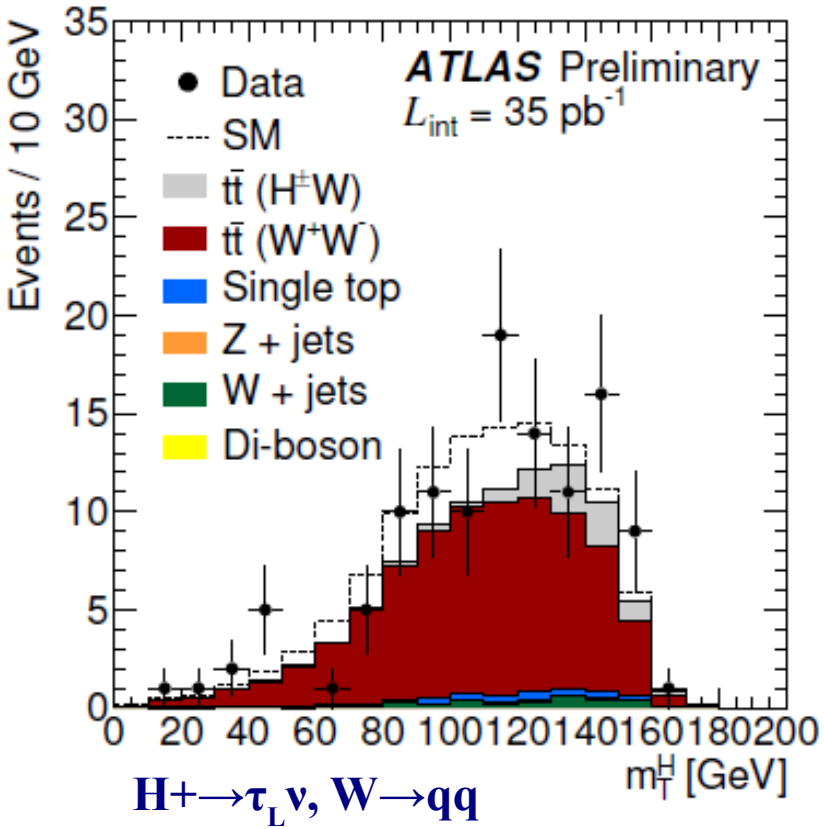




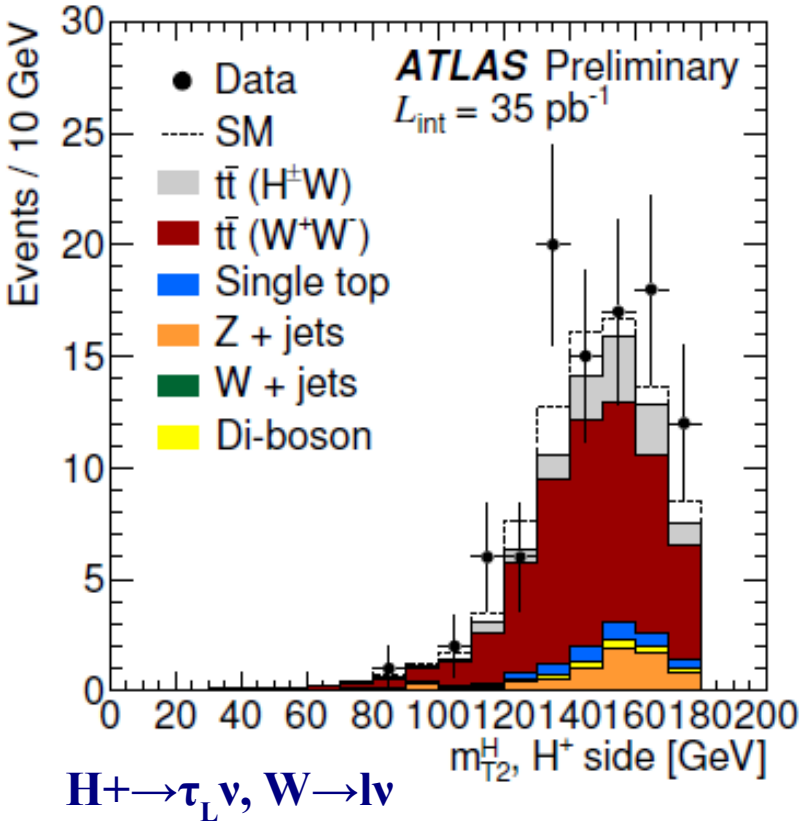
Solid: BR(t→bH+)=15%, mH+=130 GeV; statistical uncertainties only

Results: $m_T(H)$, $m_{T\ 2}(H)$

Solid: BR(t→bH+)=15%, mH+=130 GeV; statistical uncertainties only



H+→$\tau_L\nu$, W→qq



H+→$\tau_L\nu$, W→lν

H+ with hadronic τ decays, W→qq

- Event selection:
  - =1 τ jet with p_T>20 GeV (trigger-matched),
  - >=4 jets (>=1 b-tag),
  - no isolated lepton,
  - $E_T(miss) > 20$ GeV,
  - $E_T(miss) / \sqrt{E_T(sum)} > 3$ GeV$^{1/2}$,
  - $120 < m_{jjb}$ [GeV] < 240,
  - $m_T = \sqrt{2 p_T^{\tau} p_T^{miss} (1 - \cos\Delta\phi)}$ (no cut).

Data-driven estimates

	Expected					Observed
	True τ jets	Jet → τ fakes	e → τ fakes	QCD	Sum	Data
All events	$10.8 \pm 3.1^{+3.2}_{-2.4}$	$1.7 \pm 0.2 \pm 0.3$	$1.1 \pm 0.0 \pm 0.4$	$18.8 \pm 6.2 \pm 3.0$	$32 \pm 9 \pm 7$	33
m_T > 70 GeV	$4.7 \pm 1.3^{+1.4}_{-1.1}$	$1.2 \pm 0.2 \pm 0.2$	$0.7 \pm 0.0 \pm 0.3$	$11.3 \pm 3.7 \pm 1.7$	$18 \pm 5 \pm 4$	17

H+ with hadronic τ decays, W→lν

- Event selection:
  - =1 lepton (trigger-matched),
  - =1 τ jet with p_T>20 GeV (opposite charge to lepton)
  - >= 2 jets,
    at least one of them b-tagged,
  - E_T(sum)>200 GeV,
  - E_T(miss)>60 GeV.

Data-driven estimates

	Expected				Observed
	True τ jets	Jet $\rightarrow \tau$ fakes	$e \rightarrow \tau$ fakes	Sum	Data
Events	$6.9 \pm 0.3 \pm 1.4$	$7.9 \pm 1.1 \pm 1.6$	$0.65 \pm 0.01 \pm 0.04$	$15.5 \pm 1.4 \pm 3.0$	11

Backgrounds with fake τ jets

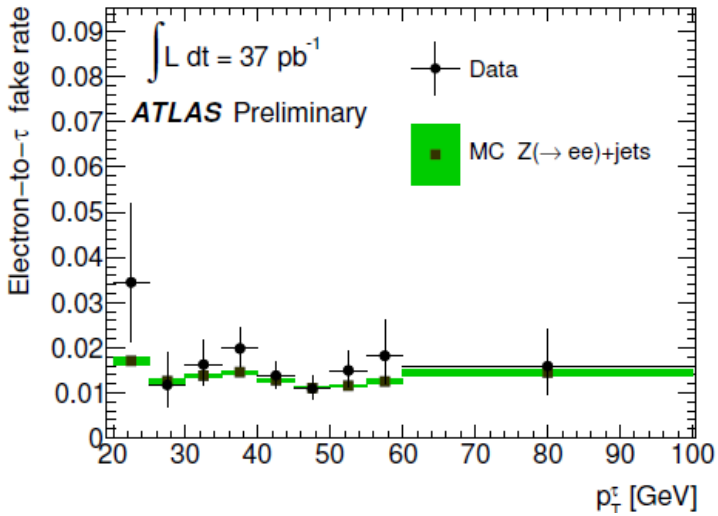
- Events with e→τ or jet→τ fakes are estimated by
  - measuring fake rate (function) in data (Z→ee and γ+jet events),
  - using simulation, but replacing the τ ID with the measured values
- Background to H+ searches: Good agreement with MC expectation

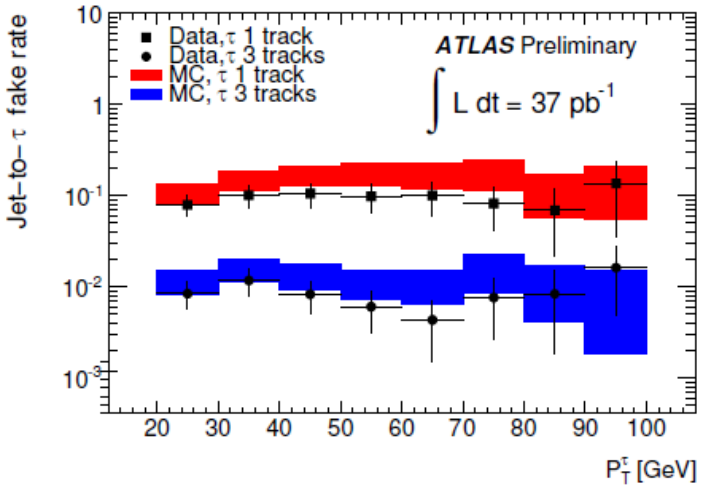
jet→τ

Selection	Sample	Fake rate prediction [num. of events]	MC prediction [num. of events]
τ+jets	$t\bar{t}$	1.7 ± 0.2 (stat) ± 0.3(syst)	1.9 ± 0.2 (stat)
τ+lepton	$t\bar{t}$	6.7 ± 1.0 (stat) ± 1.4(syst)	6.0 ± 0.2 (stat)

e→τ

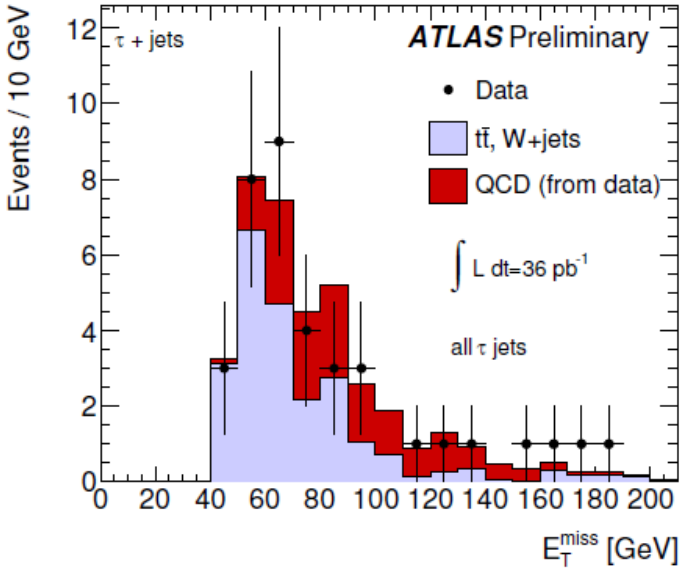
Selection	Sample	Fake rate prediction [num. of events]	MC prediction [num. of events]
τ+jets	$t\bar{t}$	1.08 ± 0.01(stat) ± 0.38(syst)	1.50 ± 0.09(stat)
τ+lepton	$t\bar{t}$	0.65 ± 0.01(stat) ± 0.04(syst)	0.79 ± 0.08(stat)





QCD jets estimate

- Take shape of the MET distribution for QCD from a control region (requiring a loose τ and rejecting a tight tau)



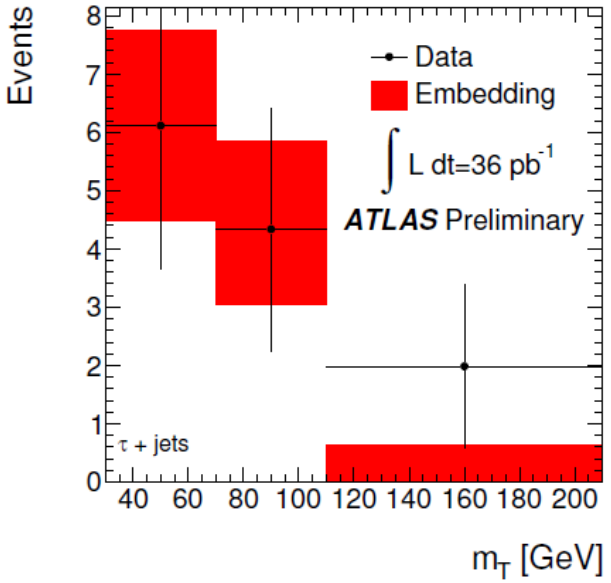
- Perform a fit to data using this QCD shape; and the ttbar/W+jets shape
- The normalization is a result of the fit
- Estimate for τ+jets: 57±19% of events after full event selection is from QCD jets
- Will be less critical in 2011 when we can afford tighter cuts

Embedding

- Idea: Select a pure sample of μ+jets (tt, W+jets, s-top) events
- Remove muon from event (tracks, calorimeter deposition)
- Replace with a simulated tau with the same (rescaled) properties
- Use these events instead of MC to estimate true-τ background

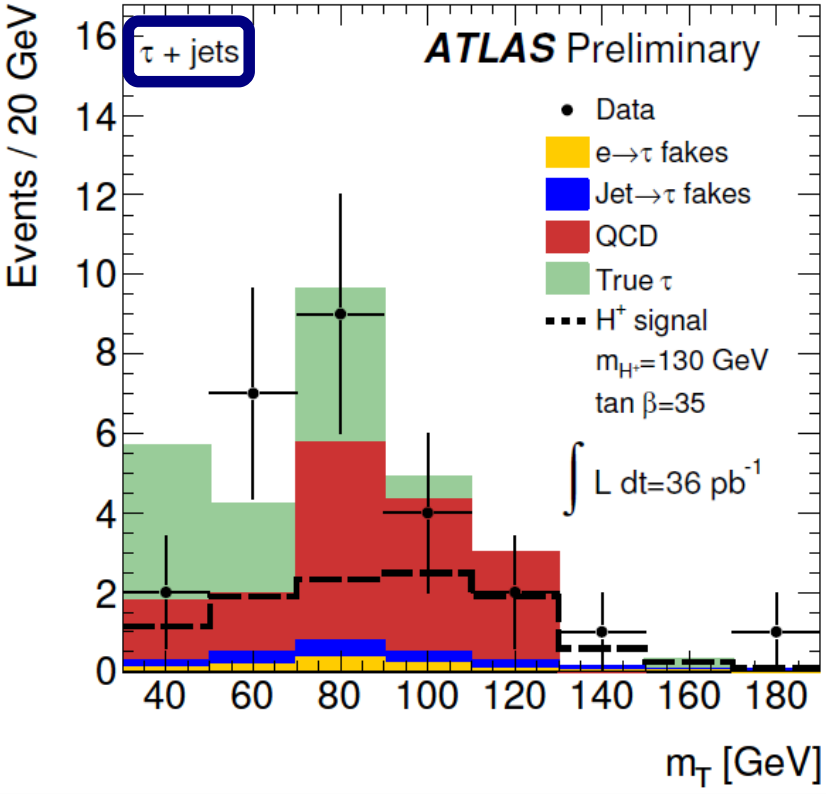
- τ+jets:
  Normalize m_T distribution to data for
  $30<m_T<70$ GeV (after subtracting
  results from all other data-driven estimates)

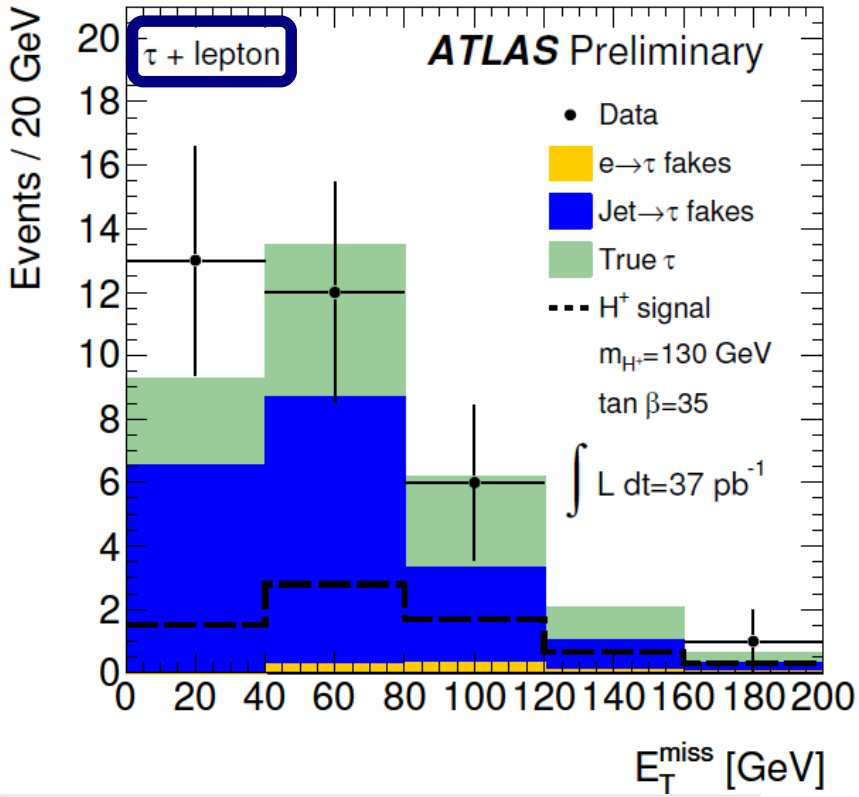
- Currently huge statistical uncertainties
  - Looking forward to 500pb^{-1} in summer...



H+ → τ(had) Results

- Shape comparison after all selection cuts
- Large statistical uncertainties
  - Results compatible with the Standard Model.





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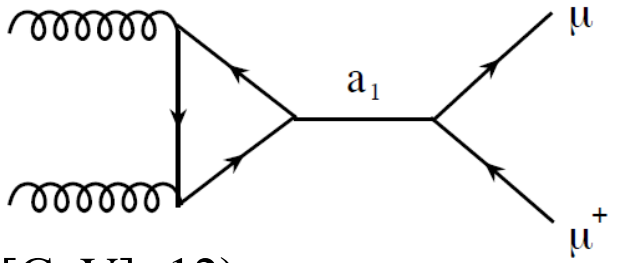
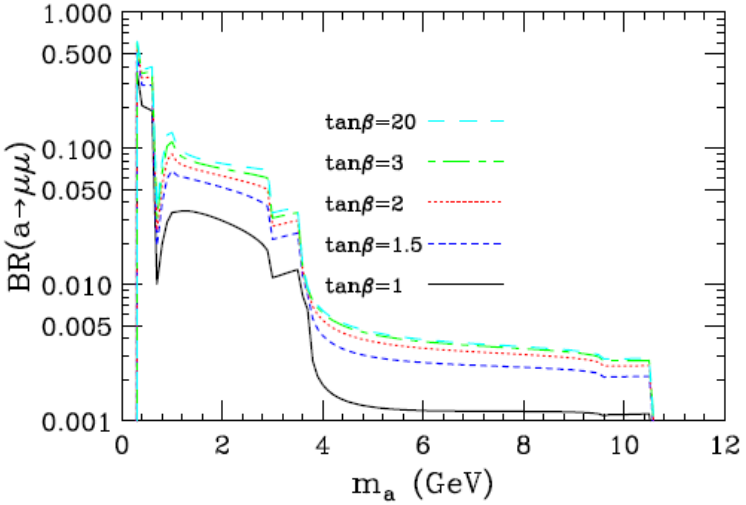
Light CP-odd Higgs boson

NMSSM & $a_1 \rightarrow \mu\mu$

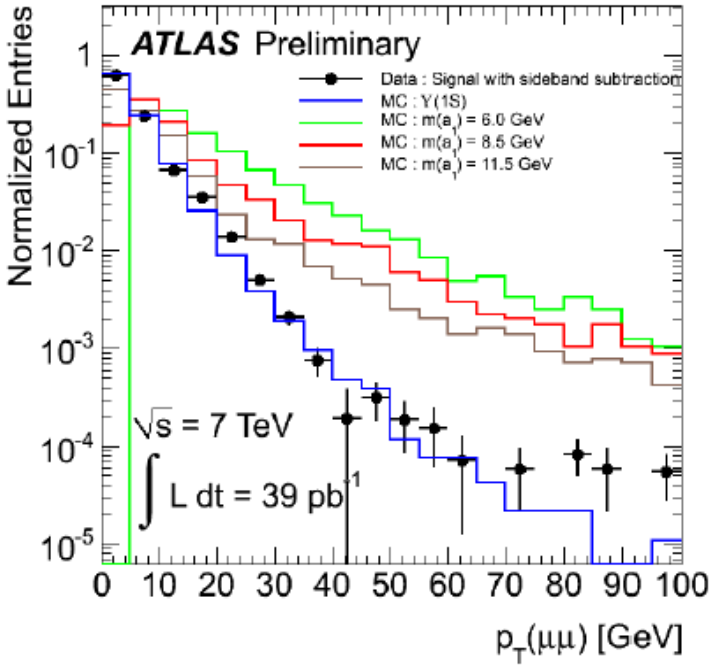
- NMSSM Higgs content: h_1, h_2, h_3, a_1, a_2, h^+, h^-.
- Ideal Higgs scenario: $m_{a1} < 2m_B$
  - Escapes the LEP limit on $a_1 \rightarrow bb$
  - Could account for g-2 discrepancy (for $9.2 < m_{a1}$ [GeV] < 12)
  - Could explain (disputed) discrepancy in $\Gamma(\Upsilon \rightarrow \tau^+\tau^-)/\Gamma(\Upsilon \rightarrow \mu^+\mu^-)$
  - If $h_1 \rightarrow a_1 a_1$ is large, searches could miss the SM Higgs (even below 114 GeV).
  - Important parameters: tan β; cos θ_A (non-singlet component of a_1)
  - $\sigma(gg \rightarrow a_1) \cdot BR(a_1 \rightarrow \mu\mu)$, example values:
    - 3 pb (m_{a1}= 8 GeV, cos θ_A=0.1, tan β=10)
    - 300 pb (same, but cos θ_A=1)

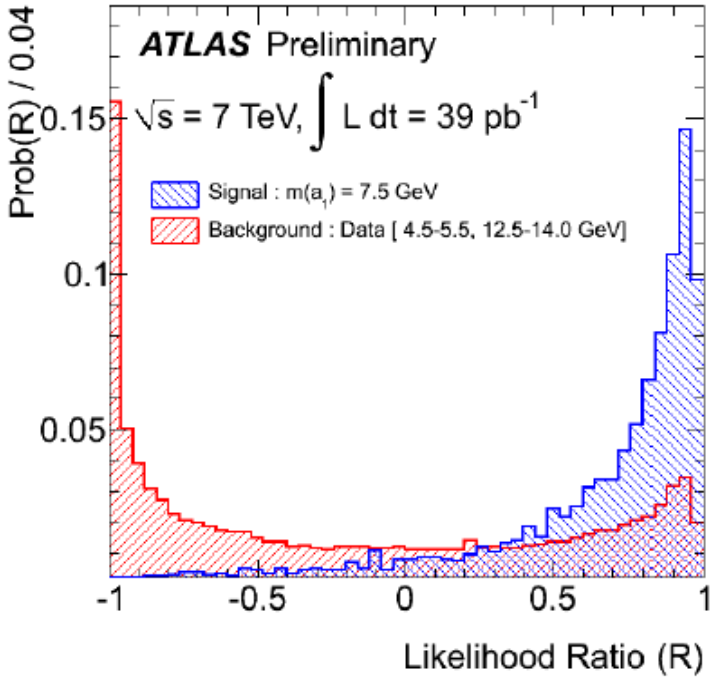




$a_1 \rightarrow \mu\mu$ candidate selection

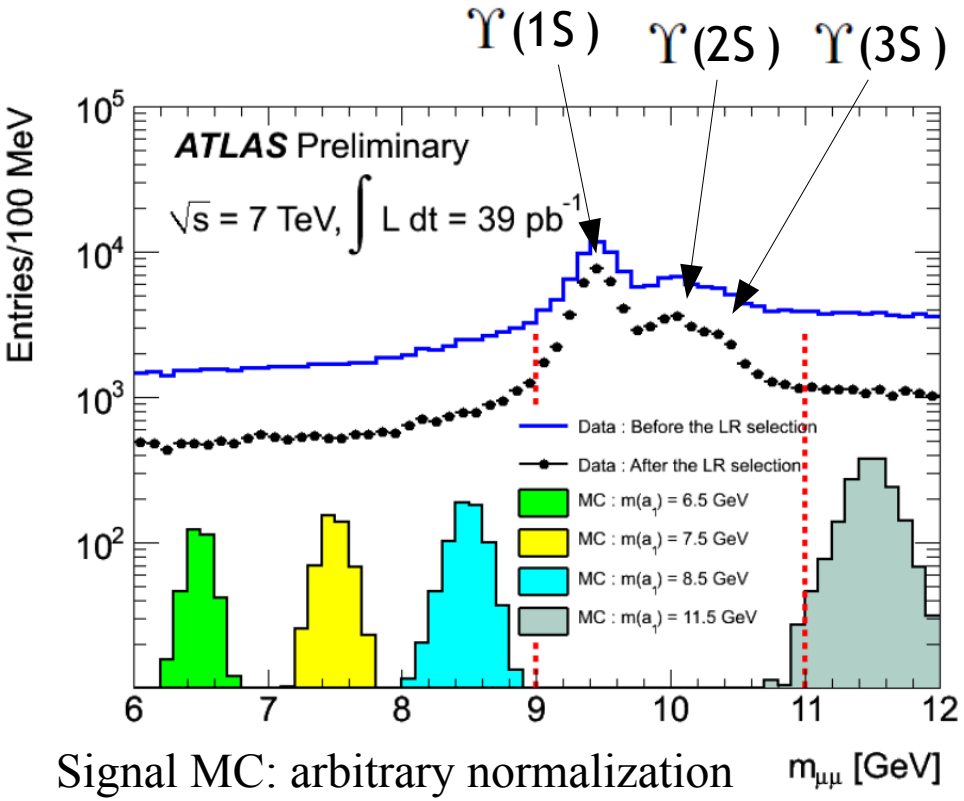
- Find muon pair with $4.5 < m_{\mu\mu}[\text{GeV}] < 14$, opposite sign, $p_T(\mu) > 4$ GeV
- Build likelihood ratio based on dimuon vertex fit quality and μ isolation
  - PDFs based on data in $m_{\mu\mu}$ Upsilon sideband regions for signal, and flat sideband regions for background





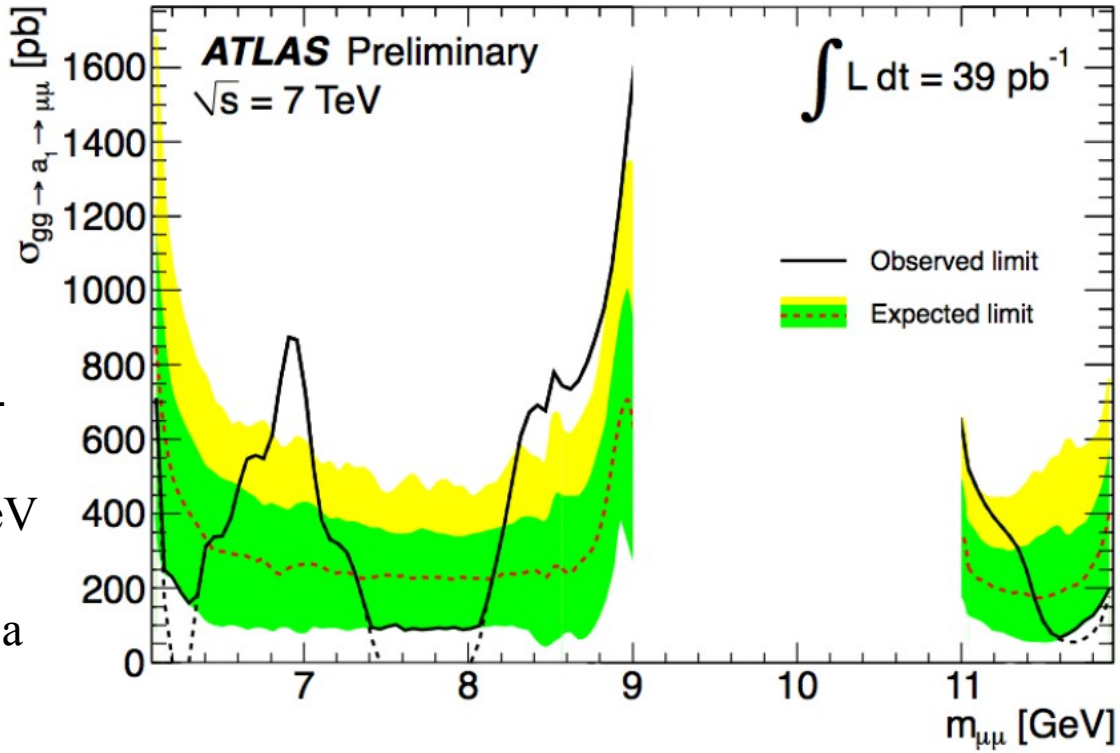
Observed dimuon mass spectrum

- Set Limits (no excess observed)
  - Count signal candidates in $m_{\mu\mu}$ bins, correct with selection effiency
  - Systematic uncertainties on efficiency/luminosity
  - Use profile likelihood method to set limits on $m_{\mu\mu}$ in regions 6-9 and 11-12 GeV [exclude 9-11 GeV until we have precise knowledge on the Υ rates]
  - Presented as power-constrained limit (→ next slide)



Signal MC: arbitrary normalization

Limit on $\sigma(gg \rightarrow a_1 \rightarrow \mu\mu)$



PCL

Taking into account the look-elsewhere-effect, the bump at 7 GeV has a 36% probability to be a fluctuation

Figure 9: Upper limits on $\sigma(gg \rightarrow a_1) \cdot BR(a_1 \rightarrow \mu^+\mu^-)$ at 95% confidence level. The black solid line is the observed upper limit, presented as a 16% power constrained limit using asymptotic formulas, while the dashed red line corresponds to the expected limit, assuming absence of a signal. The green/yellow areas represent the $\pm 1\sigma / +2\sigma$ uncertainties on the expected limit. The -2σ band is not displayed because it systematically goes to zero in this method.

Conclusions and outlook

- Searches for charged Higgs bosons ready for 2011 data
  - Studies on four channels shown
  - Variables and methods commissioned

- First direct limits on $a_1 \rightarrow \mu\mu$
  - already now cutting into the NMSSM parameter space

References

[1] A Search for a Light CP-Odd Higgs Boson Decaying to $\mu^+\mu^-$ in ATLAS, ATLAS-CONF-2011-020

[2] Study of discriminating variables for charged Higgs boson searches in tt events with leptons, using 35pb^{-1} of data from the ATLAS detector, ATLAS-CONF-2011-018

[3] Data-driven estimation of the background to charged Higgs boson searches using hadronically-decaying τ final states in ATLAS, ATLAS-CONF-2011-051

[4] E. Gross and O. Vitells, Transverse mass observables for charged Higgs boson searches at hadron colliders, Phys. Rev. D81 (2010) 055010

Backup Slides

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Object reconstruction:

- $\tau \rightarrow$ leptons:
  - Jets: pT>20 GeV, $|\eta|<2.5$
  - Leptons: pT>20 GeV, $|\eta^{\mu}|<2.5$ or $|\eta^{e}|$ in 0-1.37/1.52-2.47

- $\tau \rightarrow$ hadrons:
  - Jets: pT>20 GeV, $|\eta|<4.9$
  - Leptons: pT>20 GeV, $|\eta^{\mu}|<2.5$ or $|\eta^{e}|$ in 0-1.37/1.52-2.47
    for lepton veto: pT>10 GeV

Slide from Yi Yang

- Several previous searches for a_1
  - Basically exclude $m_{a1} < 2m_\tau$
  - Constrain $2m_\tau < m_{a1} < 2m_B$

Experiment	Year	Mode	Ref.
BaBar	2009	$\Upsilon \rightarrow \gamma a_1$	arXiv : 0905.4539
D0	2009	$h \rightarrow aa \rightarrow 2\tau + 2\mu\ ;\ 4\mu$	arXiv : 0905.3381
ALEPH	2010	$h \rightarrow aa \rightarrow 4\tau$	arXiv : 1003.0705

And even more recent:

- arXiv:1007.4646 [hep-ex] (BaBar „Ups(1S)-> gamma+invis“ [i.e. A0->chichi])
- https://oraweb.slac.stanford.edu/pls/slacquery/BABAR_DOCUMENTS.DetailedIndex?P_BP_ID=5939 (BaBar „Upsilon (2S) and Upsilon (3S) physics“)

Slide from Yi Yang

- ALEPH's latest result (arXiv:1003.0705)
  - 4 tau final state (h → a_1a_1 → ττ + ττ)
  - Only low tanβ points are favored
  - The production cross section of a is dropping from 5 x 10^5 to ~ $10^{3\text{-}4}$ pb (for tanβ = 1, 2) for M_a = 10 GeV