ATLAS Searches for Higgs Bosons Beyond the Standard Model

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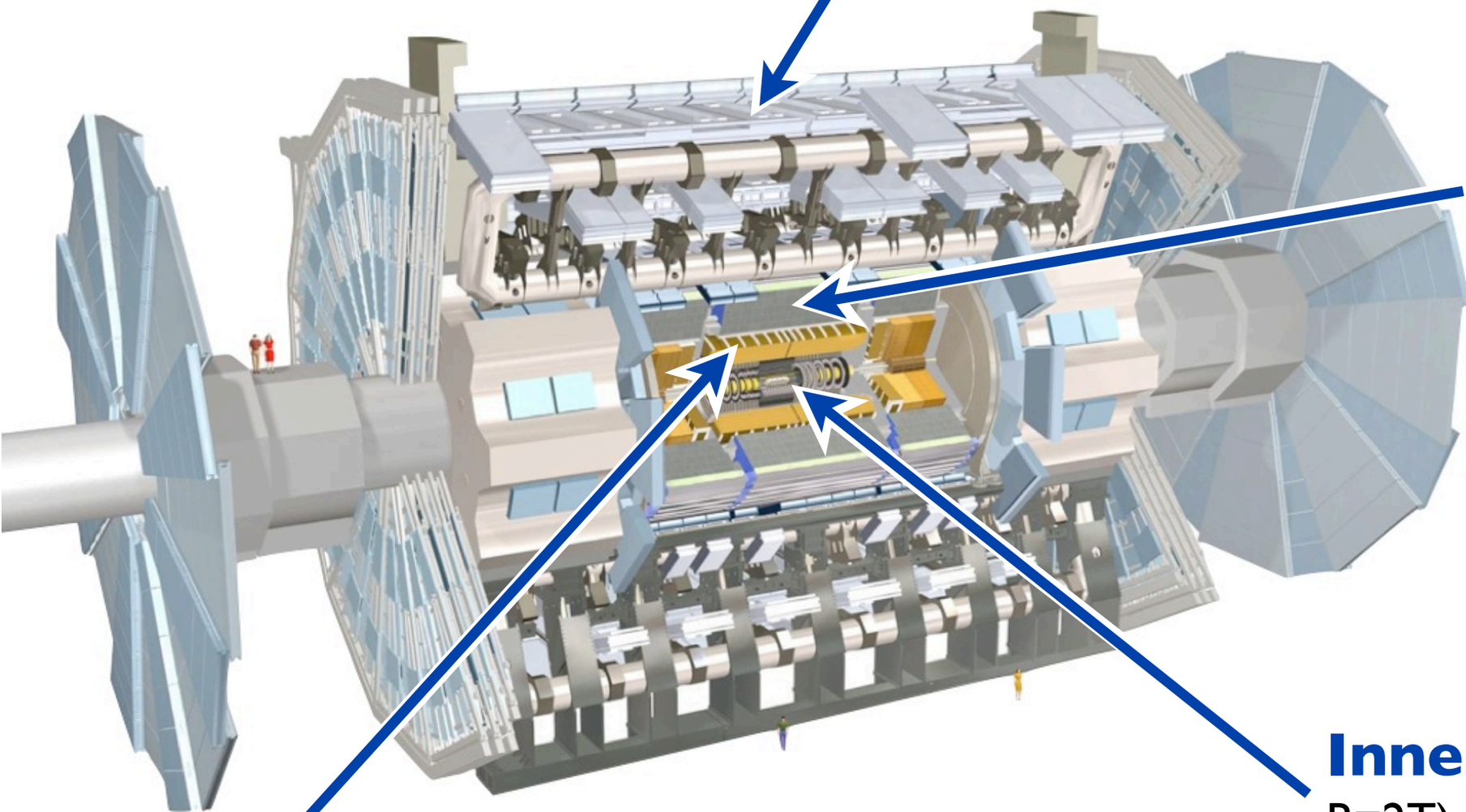
The ATLAS Experiment at the CERN LHC

3-Level Trigger
Reducing the rate from
40 MHz to 200-300 Hz

Muon Spectrometer
($|\eta|<2.7$): Air-core toroids with gas-based muon chambers; Muon trigger and measurement with momentum resolution < 10% up to $p_\mu \sim 1$ TeV

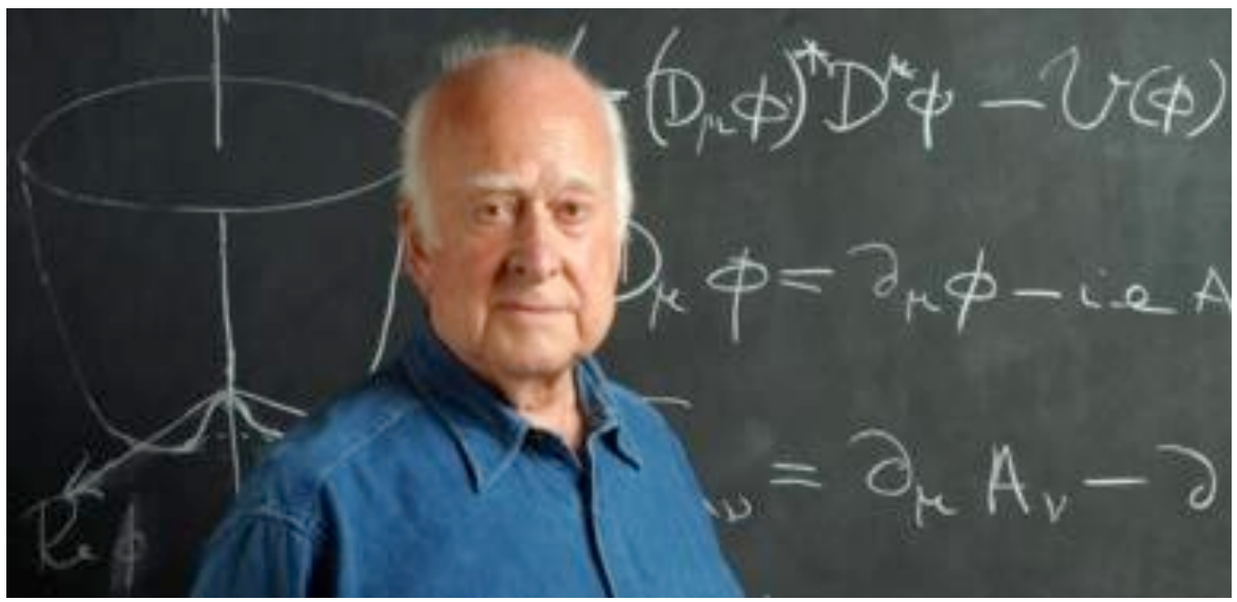


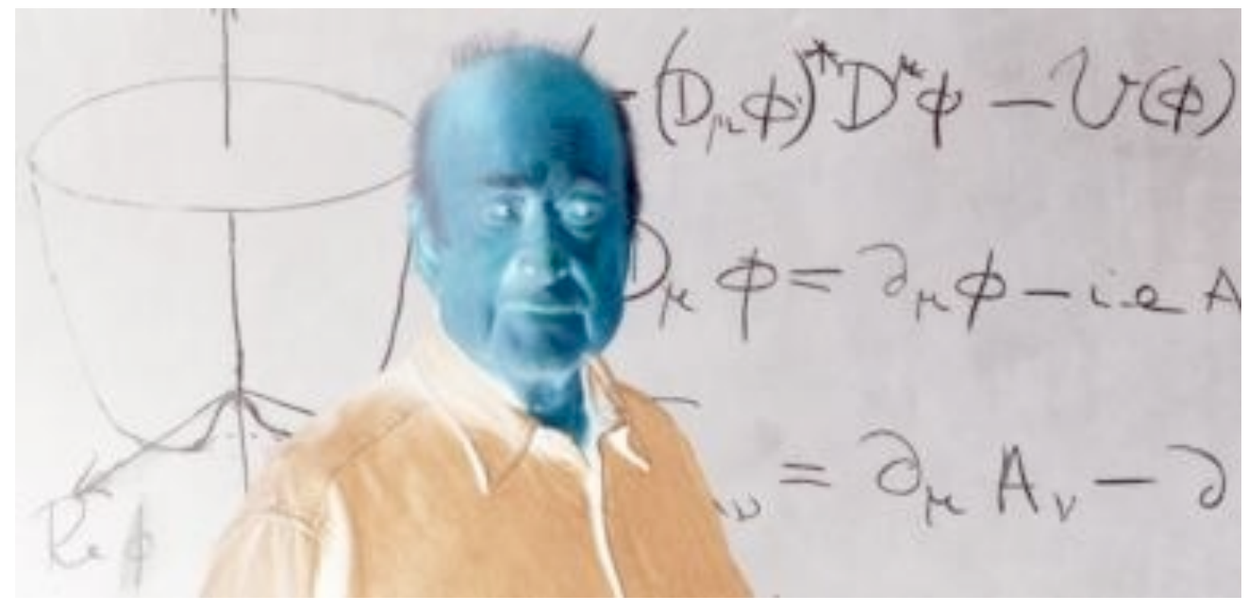
HAD calorimetry
($|\eta|<5$): hermetic and highly segmented; Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution:
$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

Inner Detector ($|\eta|<2.5$, B=2T): Si Pixels, Si strips, Transition Radiation detector (straws); Precise tracking and vertexing, allows for e/π separation; Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T$ (GeV) $\oplus$ 0.015
i.e. σ/p_T <2% for p_T < 35 GeV

EM Calorimeter ($|\eta|<3.2$):
Pb-LAr Accordion; allows for e/γ triggering, identification and measurement;
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

Recent Higgs Search Results in ATLAS





Standard Model Higgs

(Joost Vossebeld's presentation from Tuesday)

- $H \to \gamma\gamma$
- $H \to WW \to l\nu l\nu$
- $H \to WW \to l\nu qq$
- $H \to ZZ \to 4l$
- $H \to ZZ \to ll\nu\nu/llqq$
- Combined Search (ATLAS-CONF-2011-112)

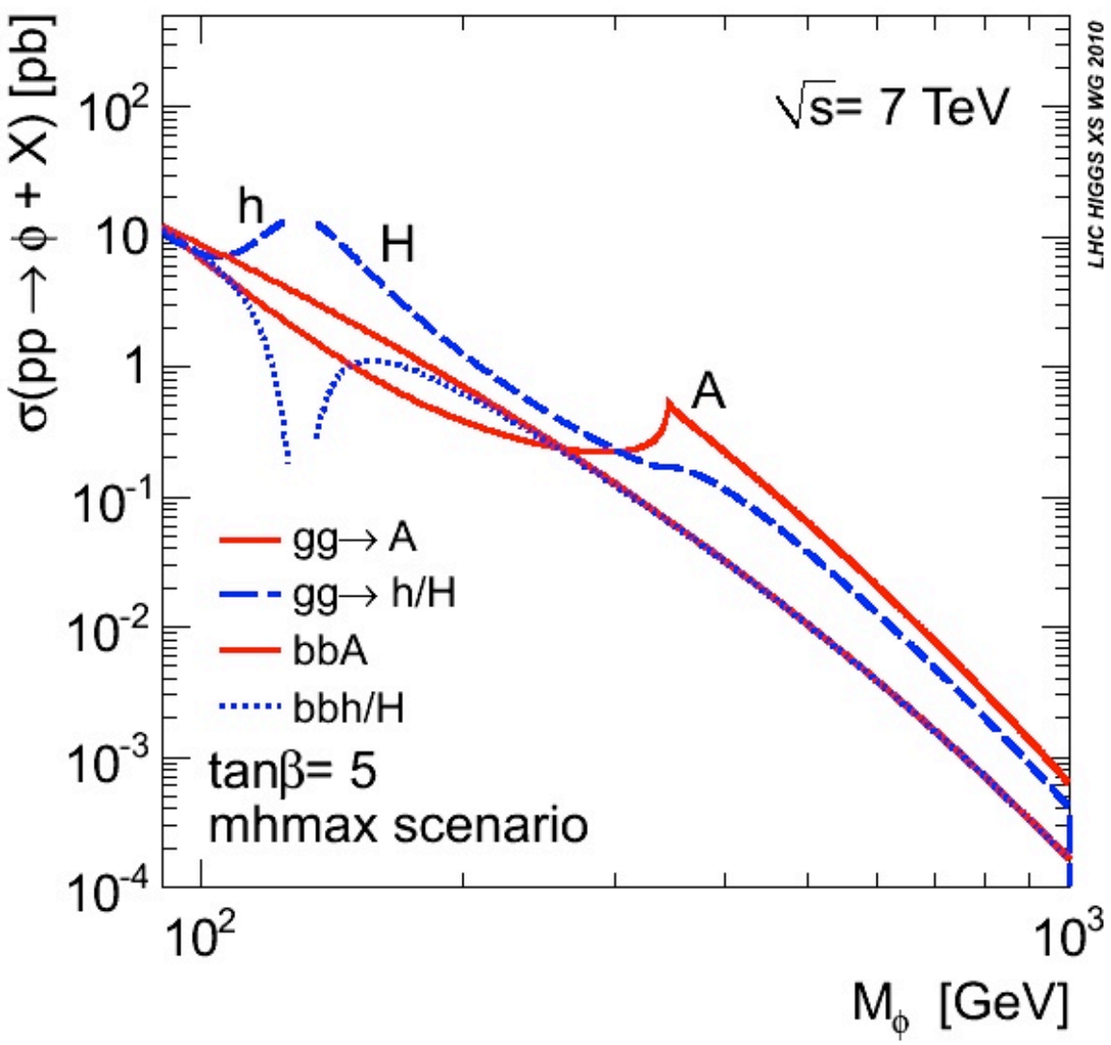
Beyond the SM Higgs

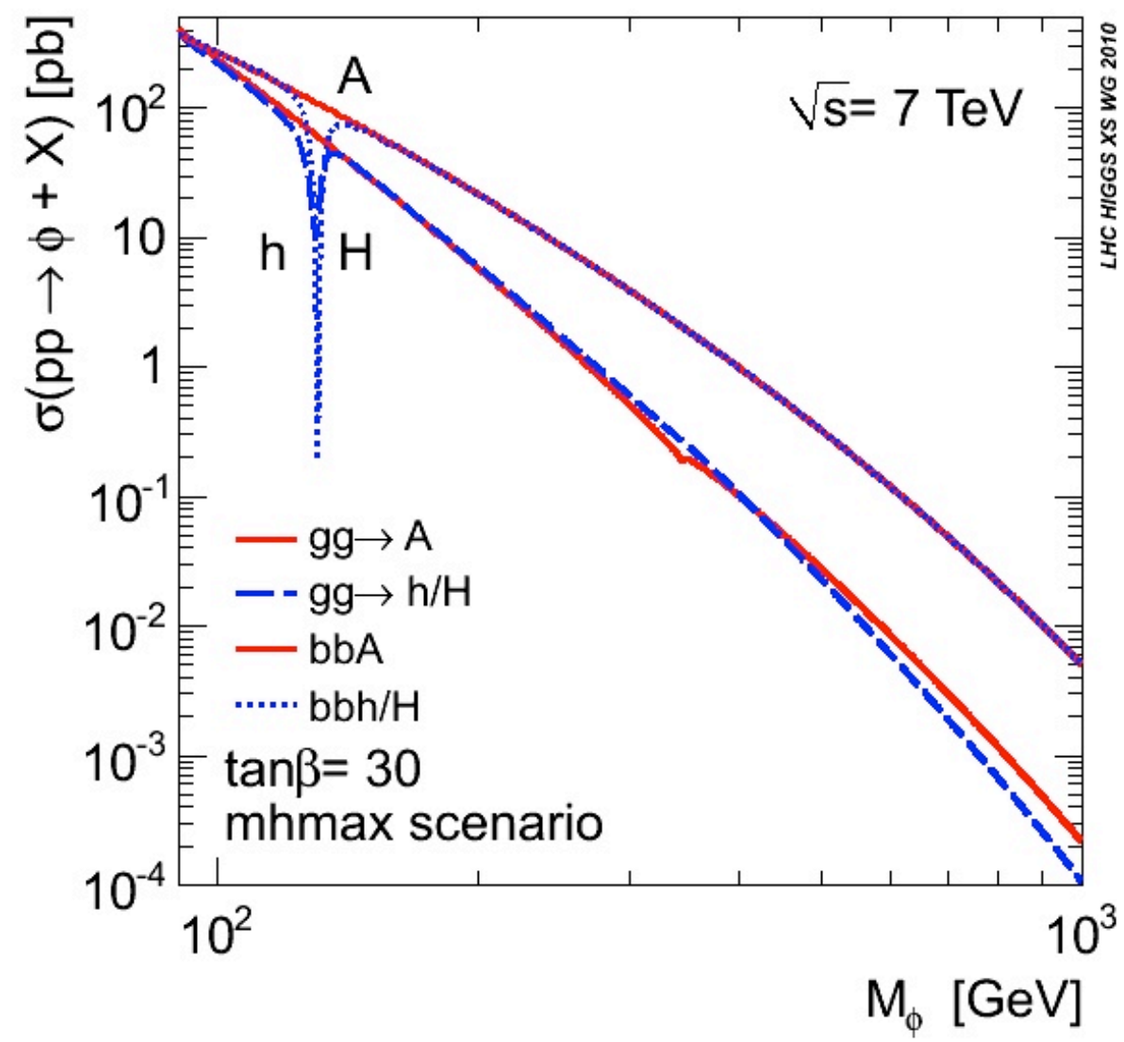
(this presentation)

- MSSM $h/A/H \to \tau_l\tau_h$ (arXiv:1107.5003)
- $H^+ \to cs$ (ATLAS-CONF-2011-094)
- $H^+ \to \tau_l\nu$ (ATLAS-CONF-2011-018)
- $H^+ \to \tau_h\nu$ (ATLAS-CONF-2011-051)

MSSM Higgs Sector

- 2 Higgs doublets give rise to 5 physical Higgs bosons: h, H, A, $H^{\pm}$
  - Enhanced coupling to 3rd generation; strong coupling to down-type fermions (at large tanβ get strong enhancements to h/A/H production rates)
  - Neutral ϕ=h/A/H produced through gg-fusion or b-associated processes



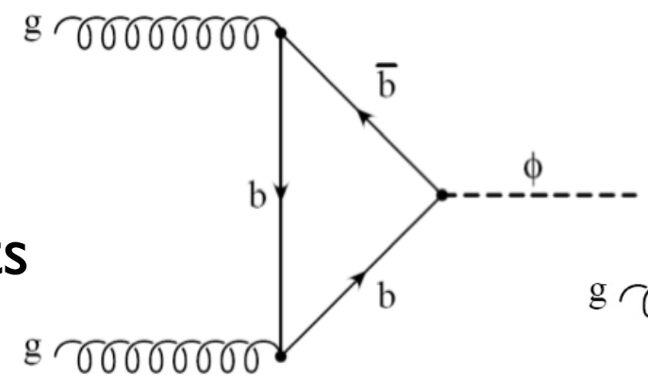


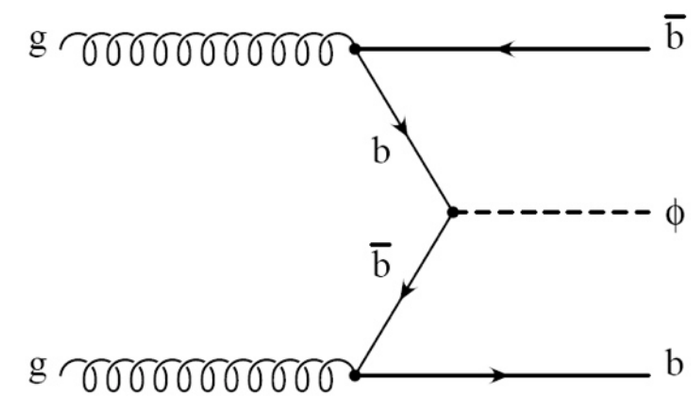
- Can parameterize the masses of the Higgs bosons with two free parameters: tanβ and m_A (or m_{H+})

$$\tan\beta = \frac{v_2}{v_1} = \frac{(v\sin\beta)}{(v\cos\beta)}$$

MSSM Neutral Higgs (h/A/H) Search

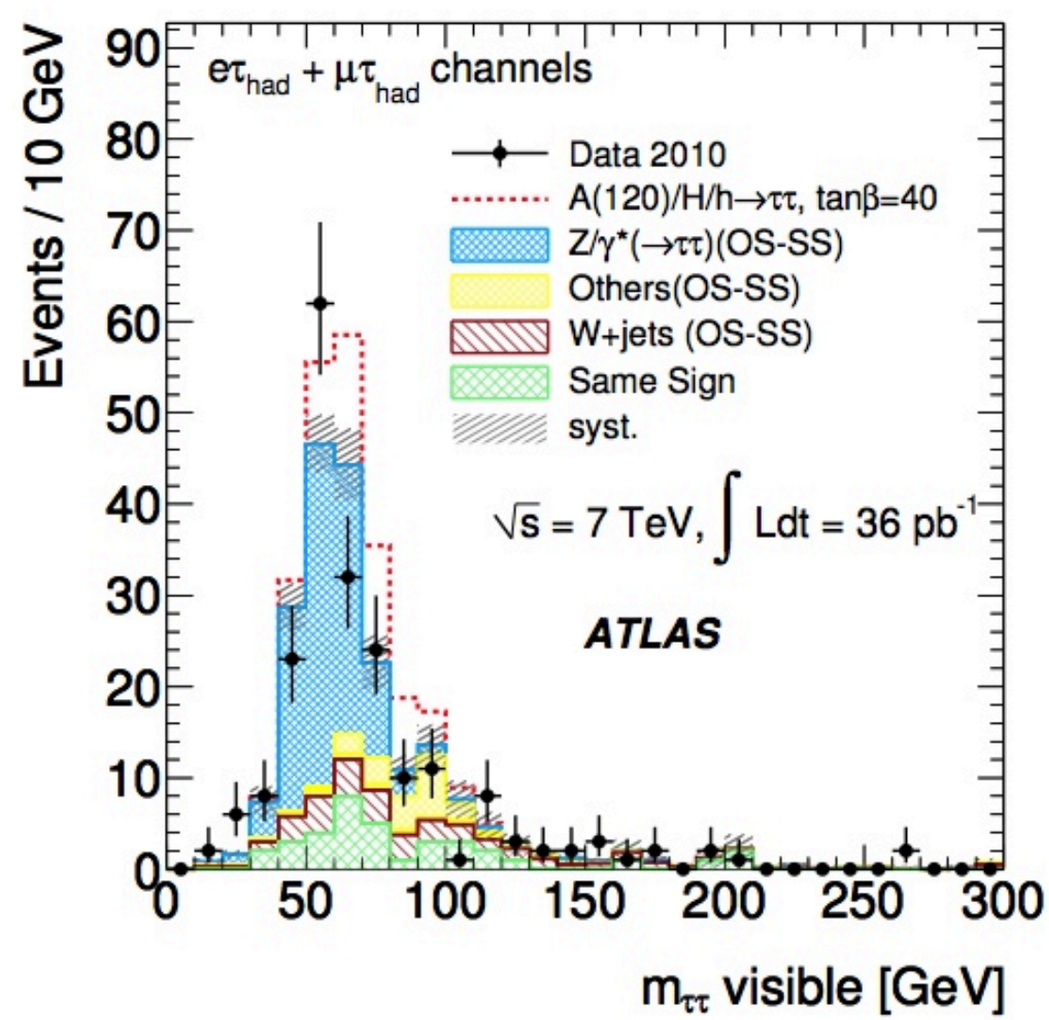
- Searching in three di-tau channels
  - 36 pb^{-1} of 7 TeV collision data
  - Inclusive analysis (do not reject events based on jet multiplicity)
  - Dominant backgrounds: $Z \rightarrow \tau\tau$ (irreducible), W+jets, ttbar, $Z \rightarrow ll$, QCD





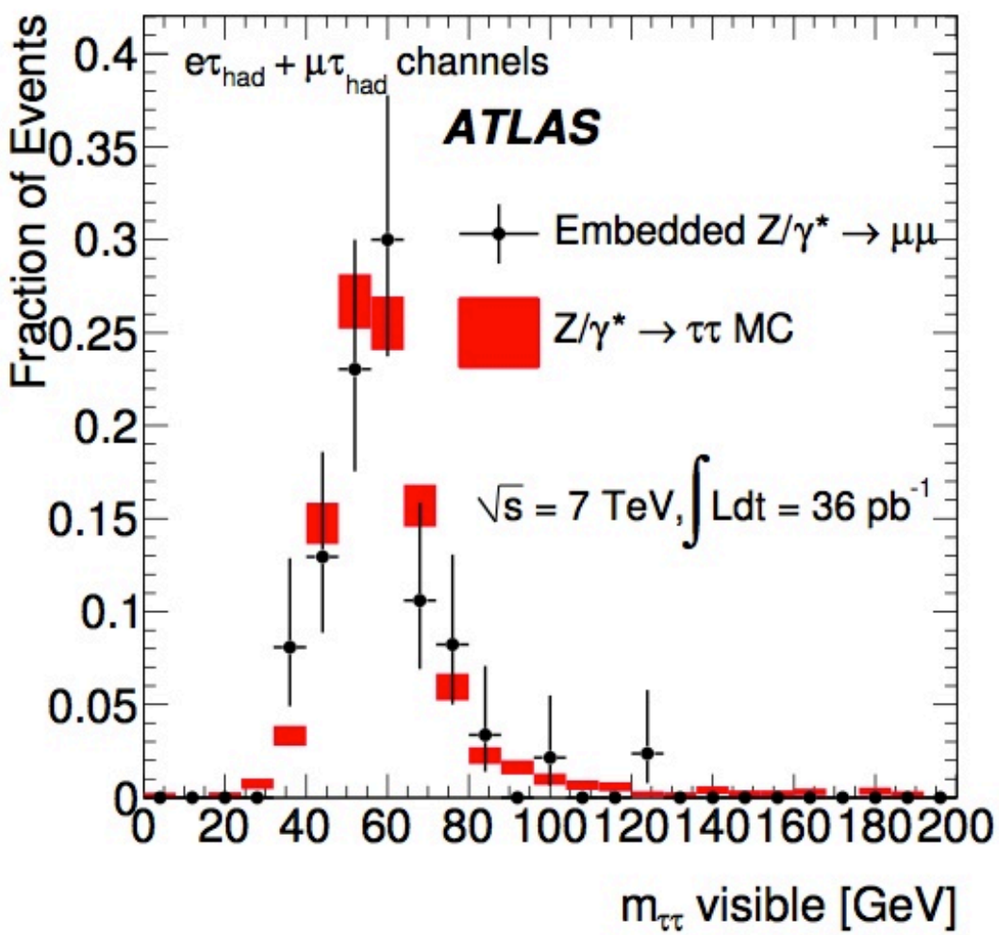
- $h/A/H \rightarrow \tau_l\text{-}\tau_{HAD}$ selection criteria:
  - Single isolated lepton
  - Single hadronic tau (tau jet)
  - Oppositely charged tau and lepton
  - Missing $E_T > 20$ GeV
  - Transverse mass requirement to reject W bosons ($M_T < 30$ GeV)
  - Discriminating variable: visible mass

$$M_T = \sqrt{2 p_T^{e/\mu} E_T^{miss} (1 - \cos\Delta\phi)}$$



MSSM Neutral Higgs (h/A/H) Search

- Background estimation using data-driven techniques
- $Z \rightarrow \tau\tau$ from MC cross-checked using embedding:
  - Select $Z \rightarrow \mu\mu$ events in data
  - Replace μ with τ from simulation



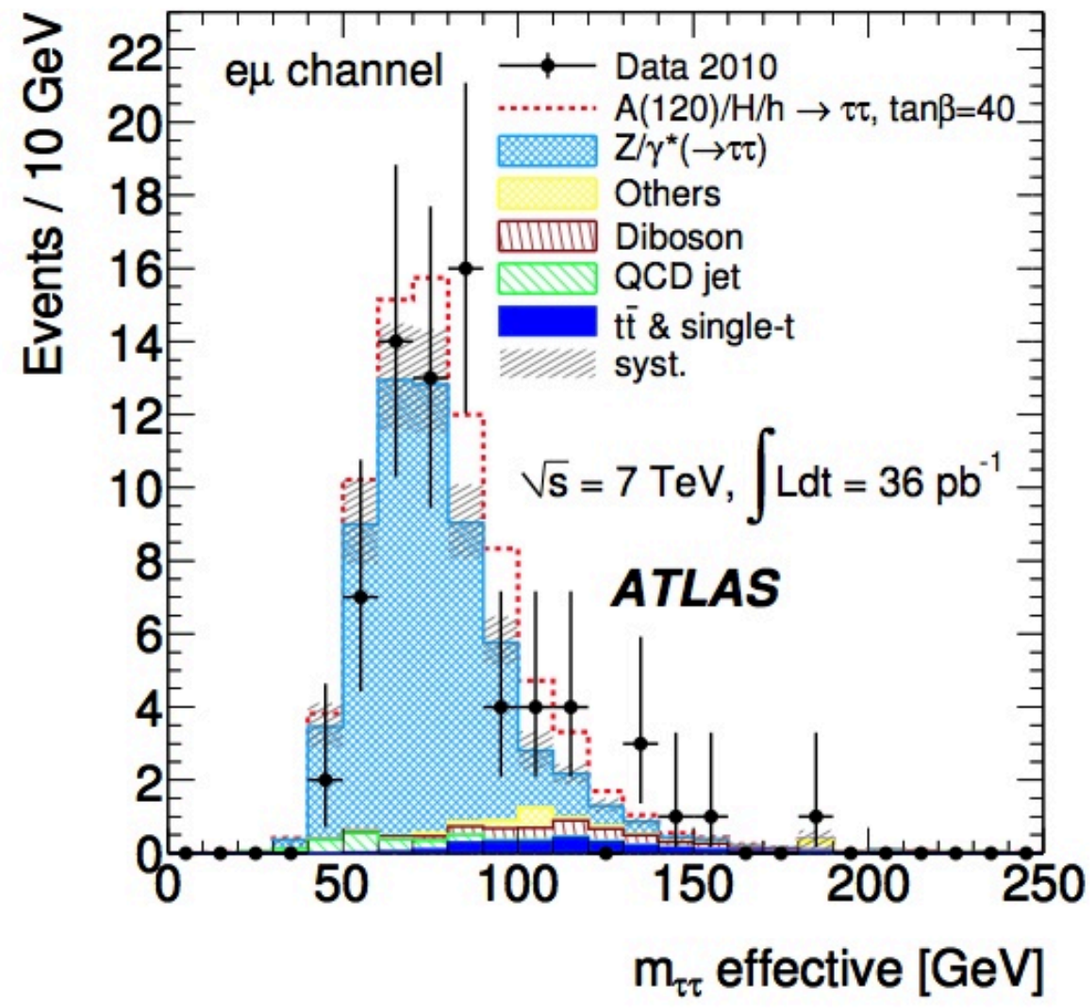
- QCD multi-jet and W+jets:
  - Assume that the QCD visible mass shape is the same for the opposite-sign (OS) and same-sign (SS) events (an assumption verified using simulated events)
  - Background estimated from the SS data sample.
  - Correction factor needed for W+jets n_{OS-SS} taken from data control region; shape from MC

$$n_{OS}^{Bkg} = n_{SS}^{Bkg} + \underbrace{n_{OS-SS}^{QCD}}_{\approx 0} + n_{OS-SS}^{W+Jets} + \cdot\, n_{OS-SS}^{Z} + \cdot\, n_{OS-SS}^{other}$$

- Dominant systematic uncertainties:
  - Experimental: jet and tau energy scale (signal 19%; $Z \rightarrow \tau\tau$ 30%)
  - Theoretical: cross section (signal 14%; $Z \rightarrow \tau\tau$ 5%)

MSSM Neutral Higgs (h/A/H) Search

- $h/A/H \rightarrow \tau_e\text{-}\tau_\mu$ selection criteria:
  - Single electron trigger
  - One e (p_T>20 GeV) and μ (p_T>10 GeV); opposite charge; isolated
  - $p_T(e) + p_T(\mu) + MET < 120$ GeV
  - $\Delta\phi(e, \mu) > 2$ rad (e.g., ttbar, single top and di-boson suppression)
  - Discriminating variable: effective mass

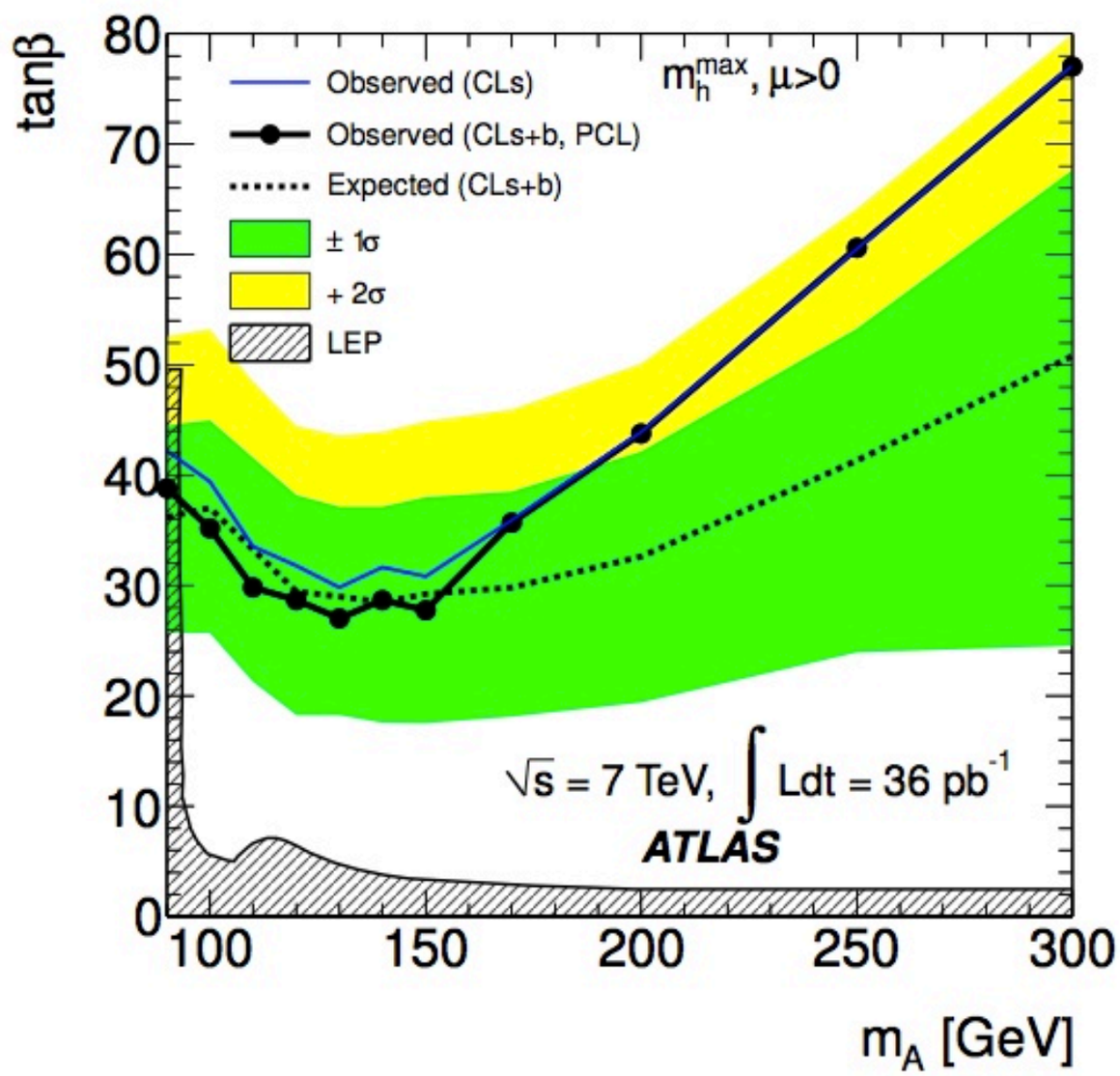


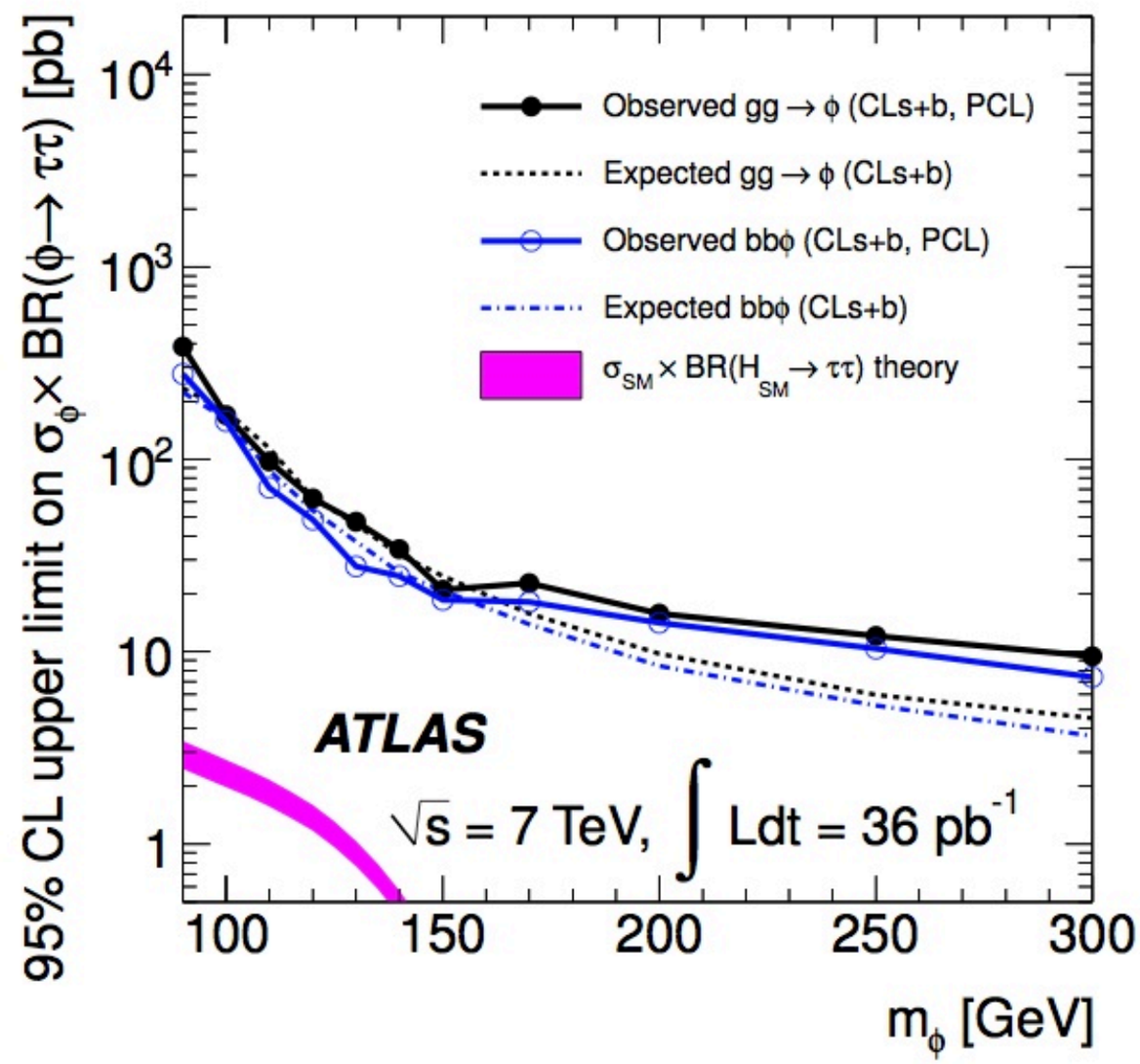
- Backgrounds:
  - $Z \rightarrow \tau\tau$ estimated from MC and shape validated using the embedding method
  - Multi-jet estimated from data using ABCD method (iso. and OS/SS)
- Systematics
  - MC background cross-sections (5-10%), multi-jet estimate (~20%)

Final state	Exp. Background	Data
$e\mu$	63 ± 7	70
$\ell\tau_{had}$	206 ± 35	206
Sum	269 ± 36	276

MSSM Neutral Higgs (h/A/H) Search

- Combine the τ_e-τ_{HAD}, τ_μ-τ_{HAD} and τ_e-τ_μ channels
- Exclusion limit calculated using a shape analysis with the visible and effective mass distributions with a profile likelihood approach
  - Limit with the m_h^{max} benchmark scenario

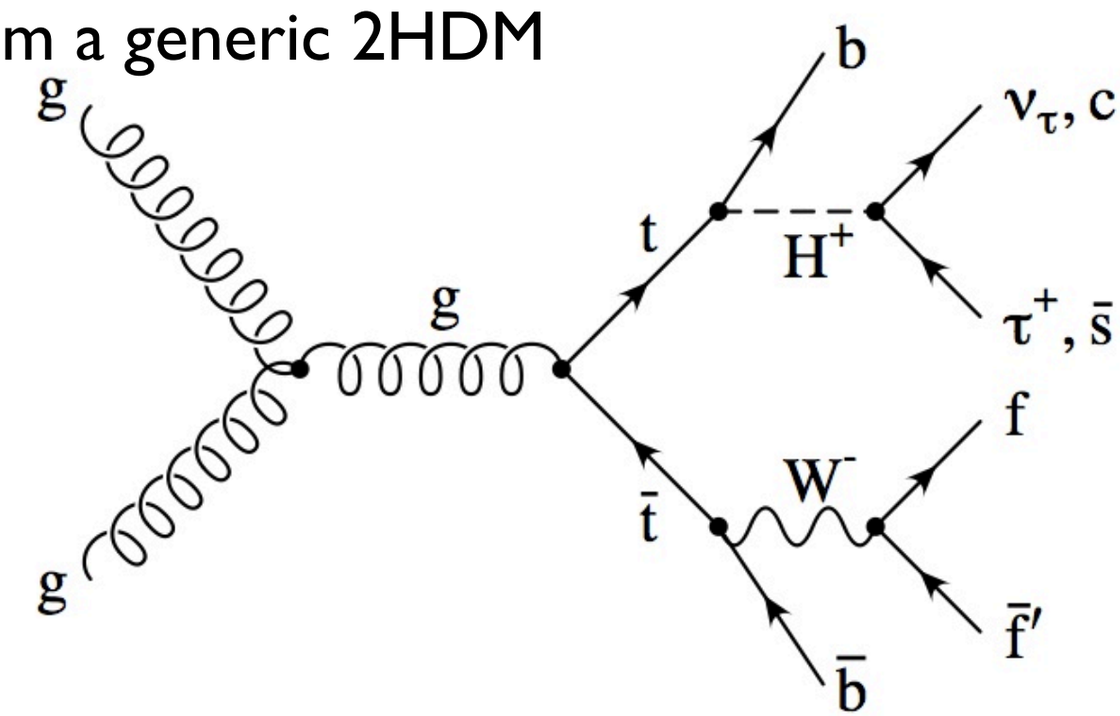




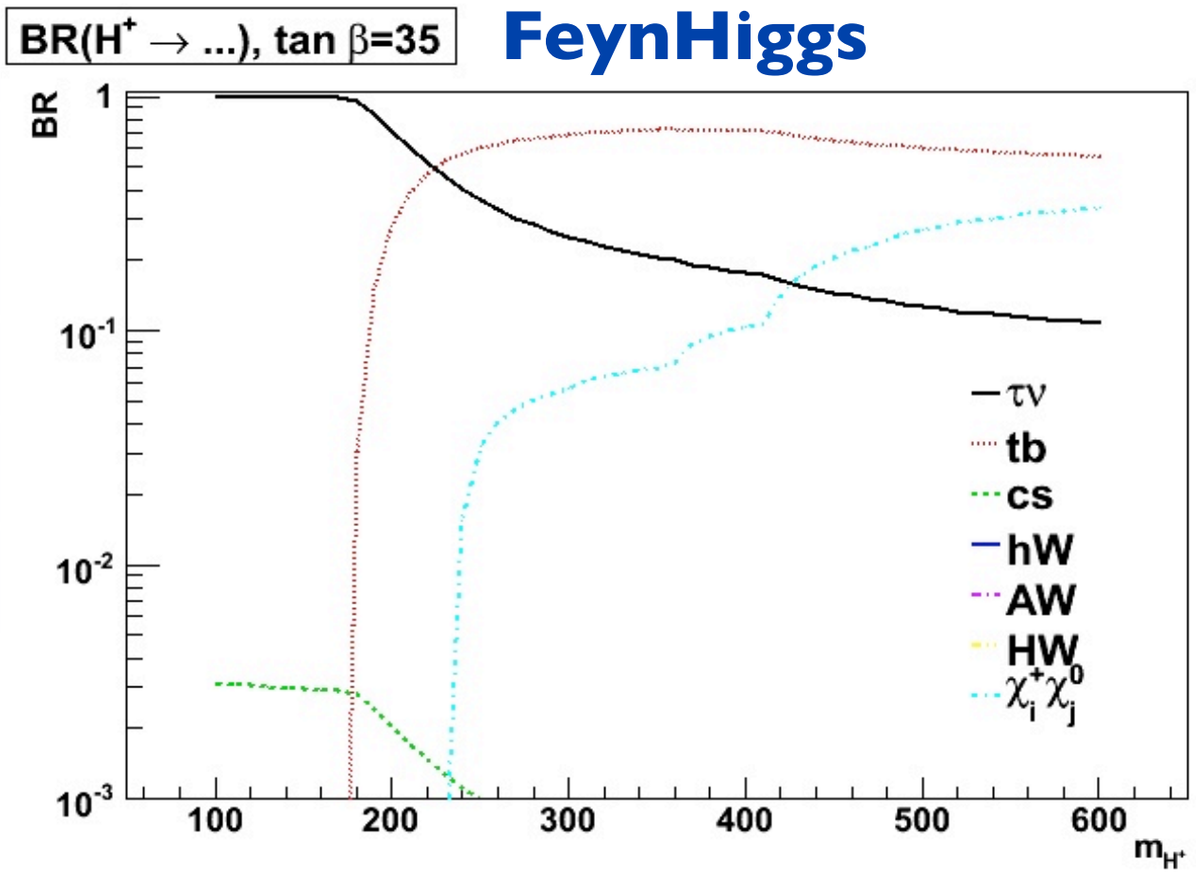
A Generic 2HDM: Charged Higgs Bosons

- Charged Higgs bosons could be produced from a generic 2HDM
- H+ Production:
  - Light H^+: $pp \rightarrow tt \rightarrow bW\, bH^+$
  - Heavy H^+: $gb \rightarrow tH^+$

- H+ Decay:
  - Light H^+: Almost exclusively to $\tau\upsilon$
  - Heavy H^+: tb; $\tau\upsilon$; $\chi^+\chi^0$

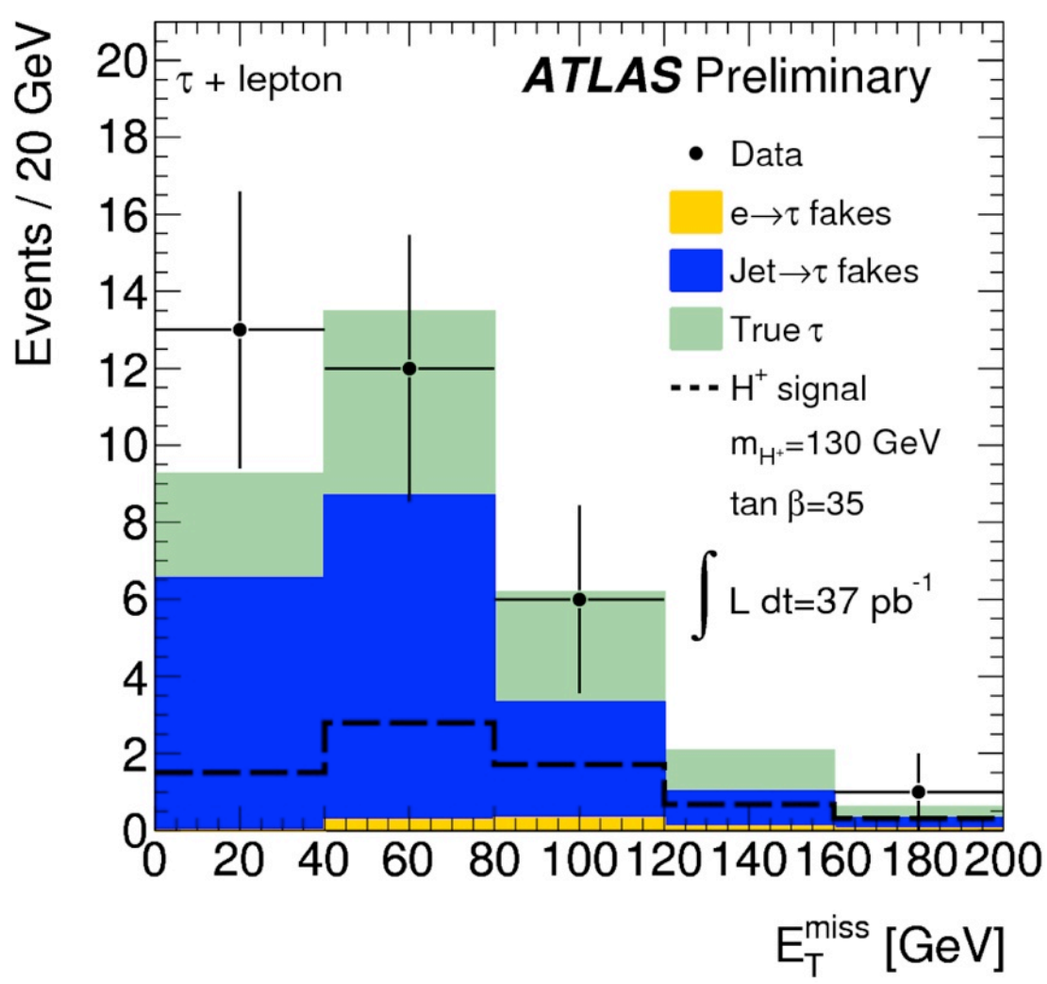


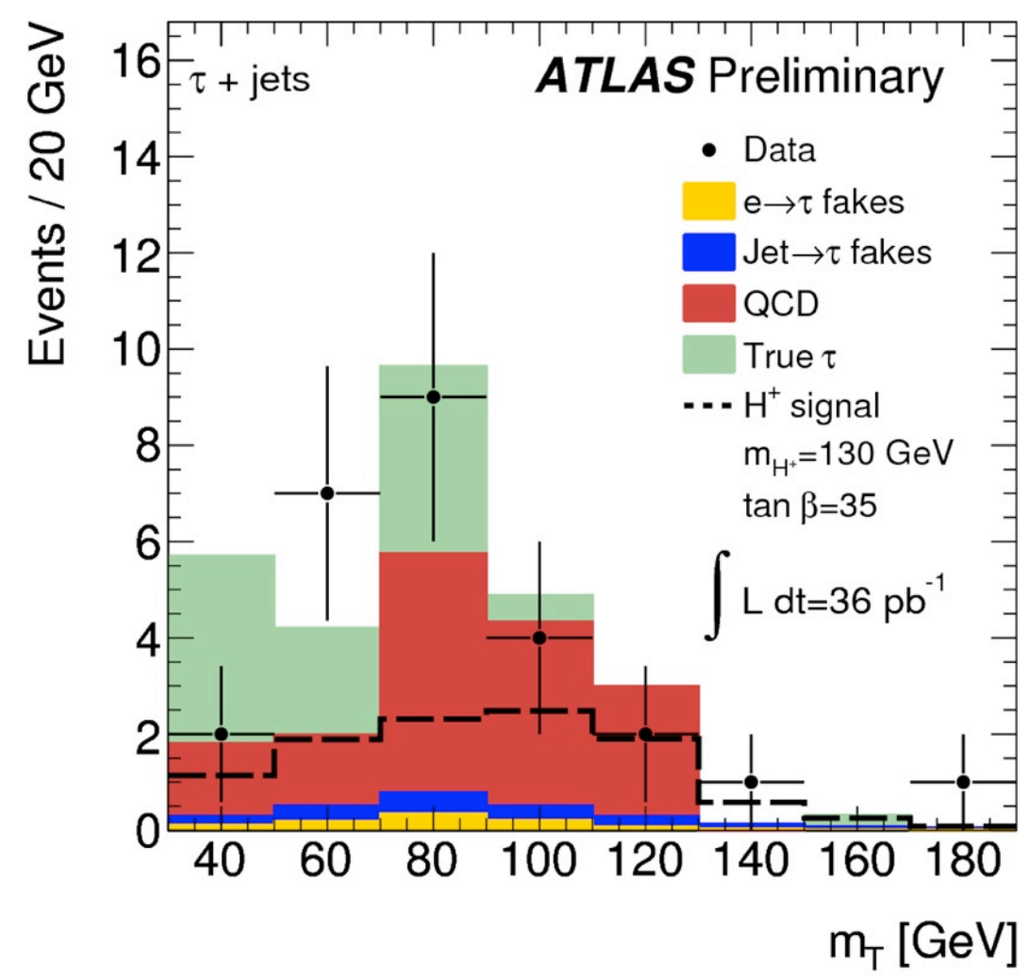
Production	H^+ Decay	W Decay
$pp \rightarrow tt$, $t \rightarrow bH^+$	$\tau_H\nu$	qq
$pp \rightarrow tt$, $t \rightarrow bH^+$	$\tau_H\nu$	$l\nu$
$pp \rightarrow tt$, $t \rightarrow bH^+$	$\tau_L\nu$	qq
$pp \rightarrow tt$, $t \rightarrow bH^+$	$\tau_L\nu$	$l\nu$
$pp \rightarrow tt$, $t \rightarrow bH^+$	cs	$l\nu$
$gb \rightarrow tH^+$	tb	qq, $l\nu$
$gb \rightarrow tH^+$	$\tau_H\nu$	qq



Charged Higgs: $H^+ \rightarrow \tau(had)\nu$

- Each of the backgrounds are determined in a data-driven way:
  - $e \rightarrow \tau$ fakes using tag-and-probe method with $Z \rightarrow ee$ in 7 TeV collision data
  - jet$\rightarrow\tau$ fakes using γ+jet events from data
  - QCD by inverting the tau selection to obtain a control sample in data
  - True τ backgrounds using an embedding method on ttbar data events with muons (with the exception of the τ+lepton final state)
- Reasonably good agreement with data in our final discriminating vars.
  - Working on H^+ searches in these final states with >1 fb^{-1} of data now

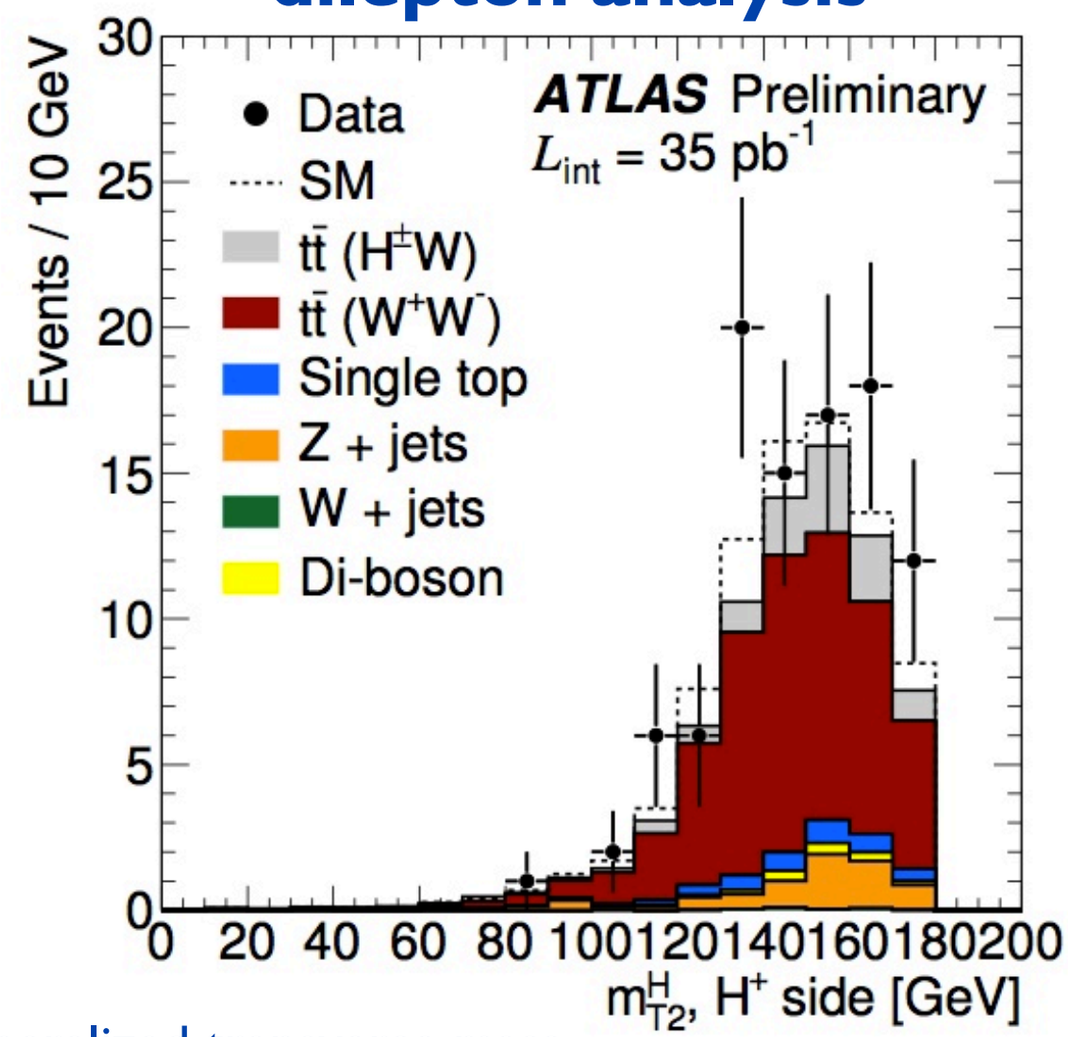




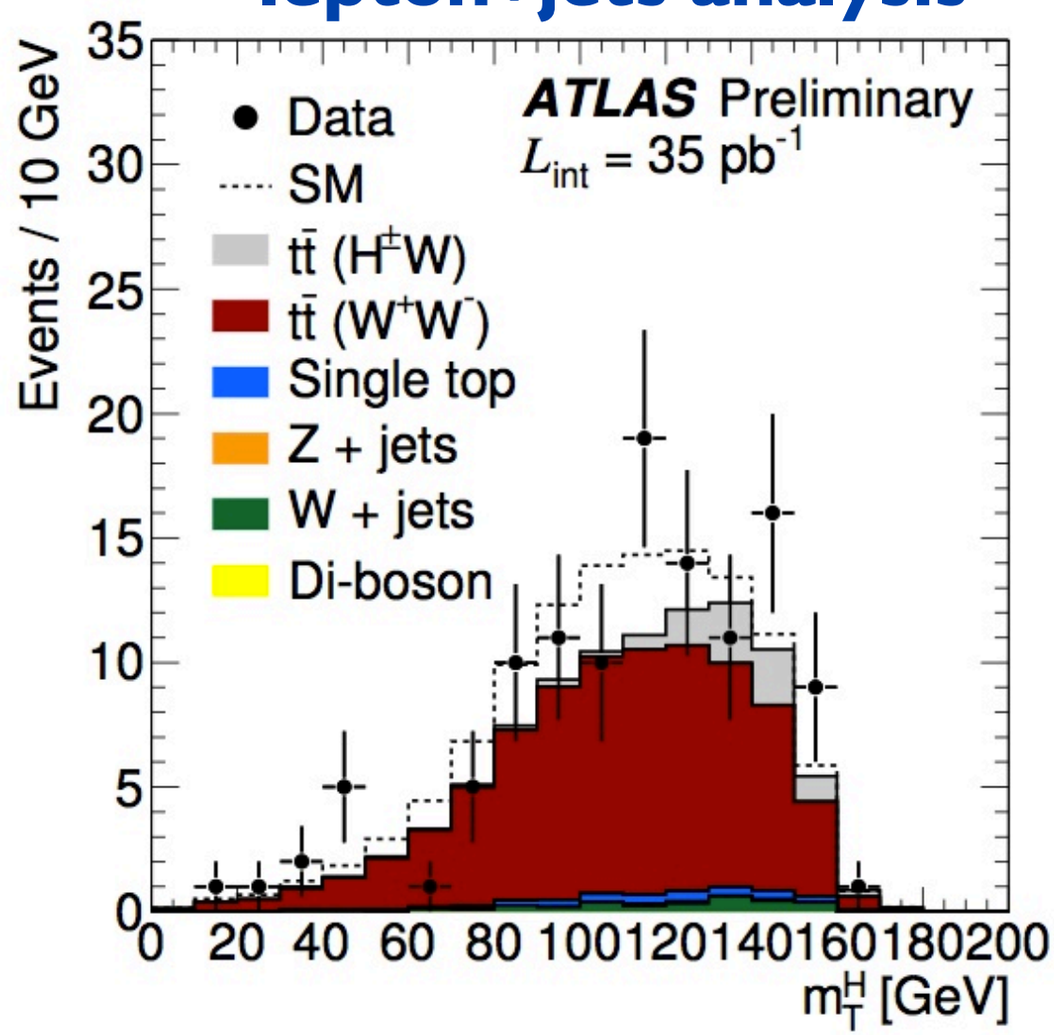
Charged Higgs: $H^+ \rightarrow \tau(\text{lep})\nu$

- As a first step, used 2010 data to test our data-driven background estimates and discriminating variables that had been recently introduced
- Reasonably good agreement with data in our final discriminating vars.
  - Working on H^+ searches in these final states with >1 fb^{-1} of data now

dilepton analysis



lepton+jets analysis



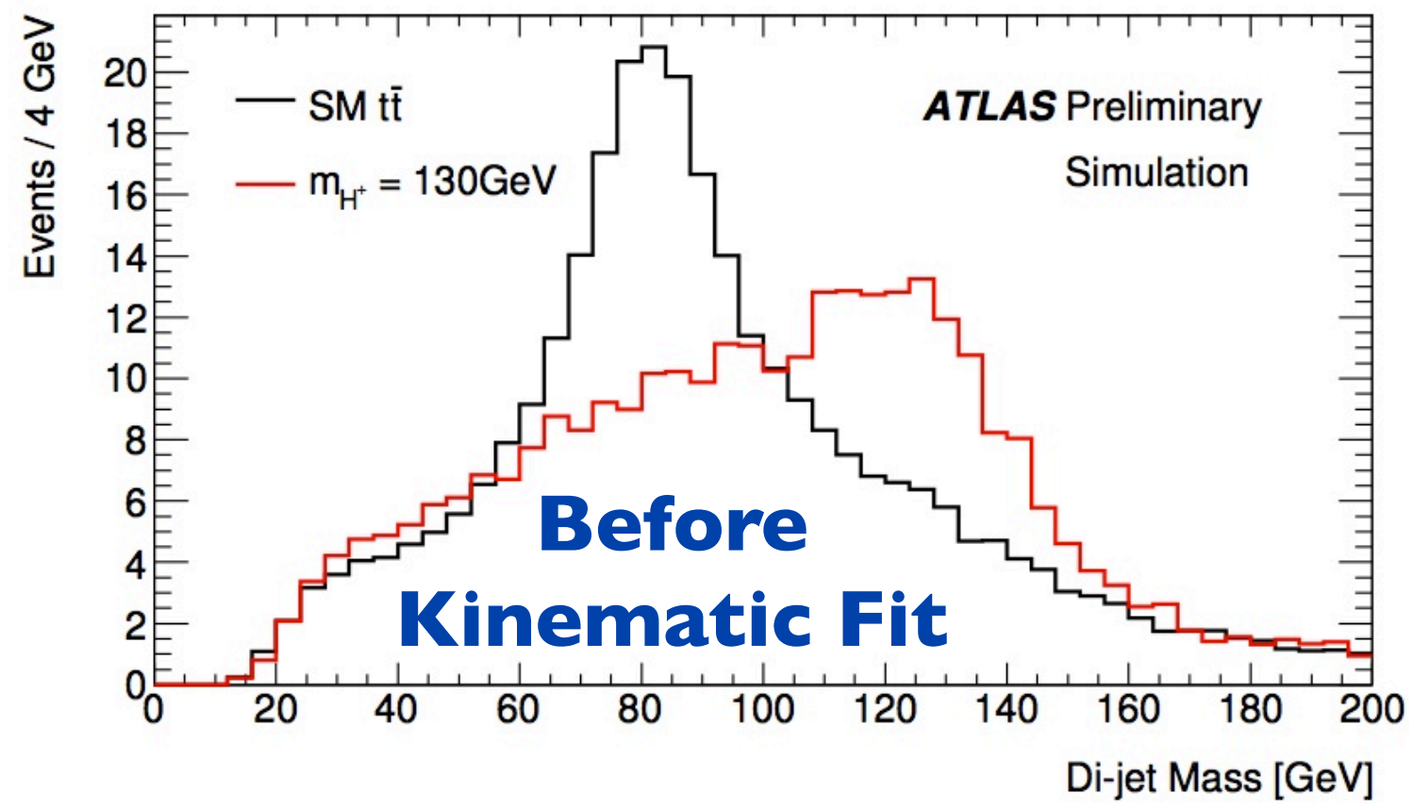
Generalized transverse mass,
E. Gross, O.Vitells, Phys. Rev. D81, 055010 (2010)

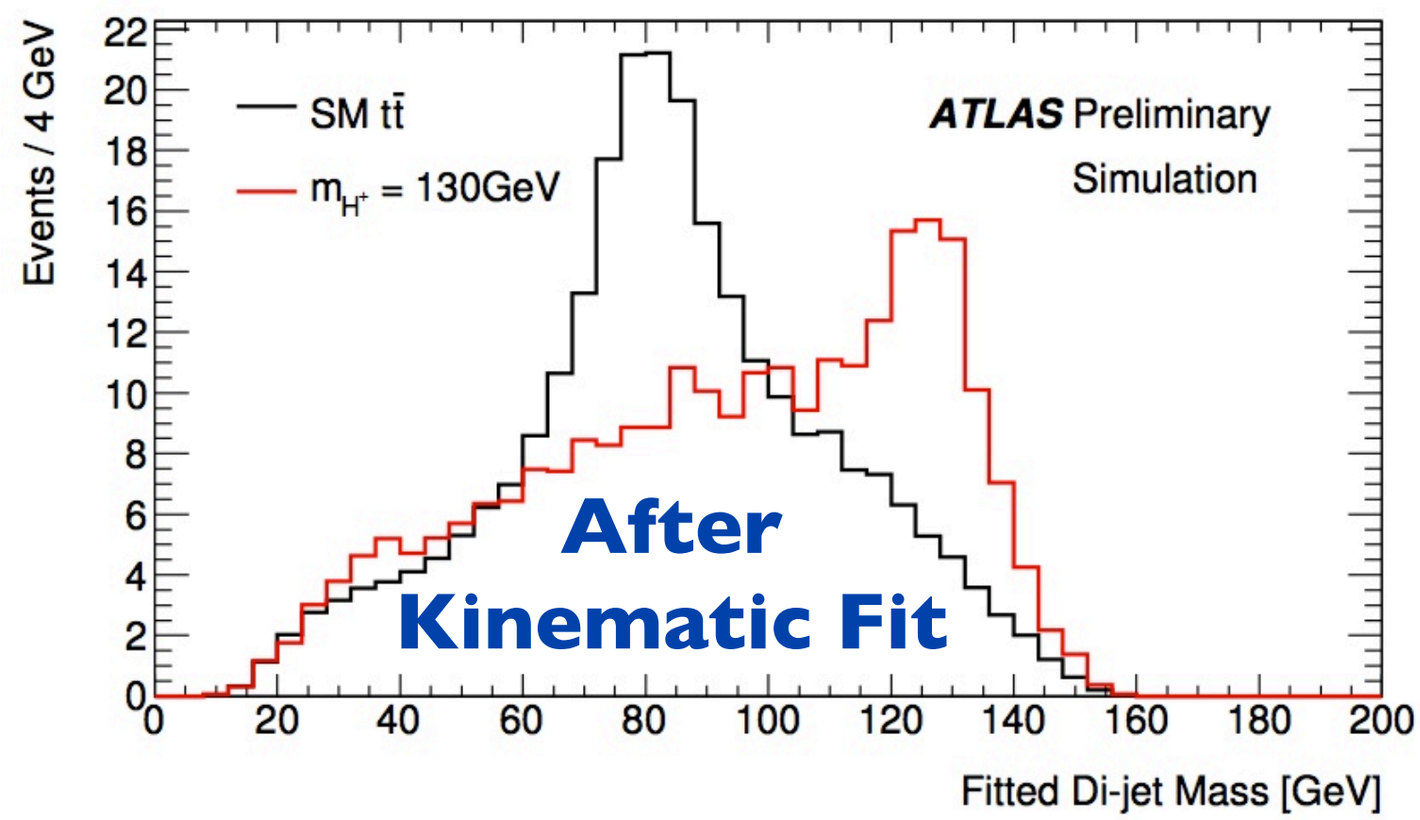
Charged Higgs: $H^+ \rightarrow c\bar{s}$

- Final state allows for full reconstruction of the H^+ candidates

- Selection criteria:
  - Isolated lepton
  - MET requirement
  - ≥4 jets
  - ≥1 b-tag
  - m_T requirement
  - Entire event reconstructed using a χ^2 fitter

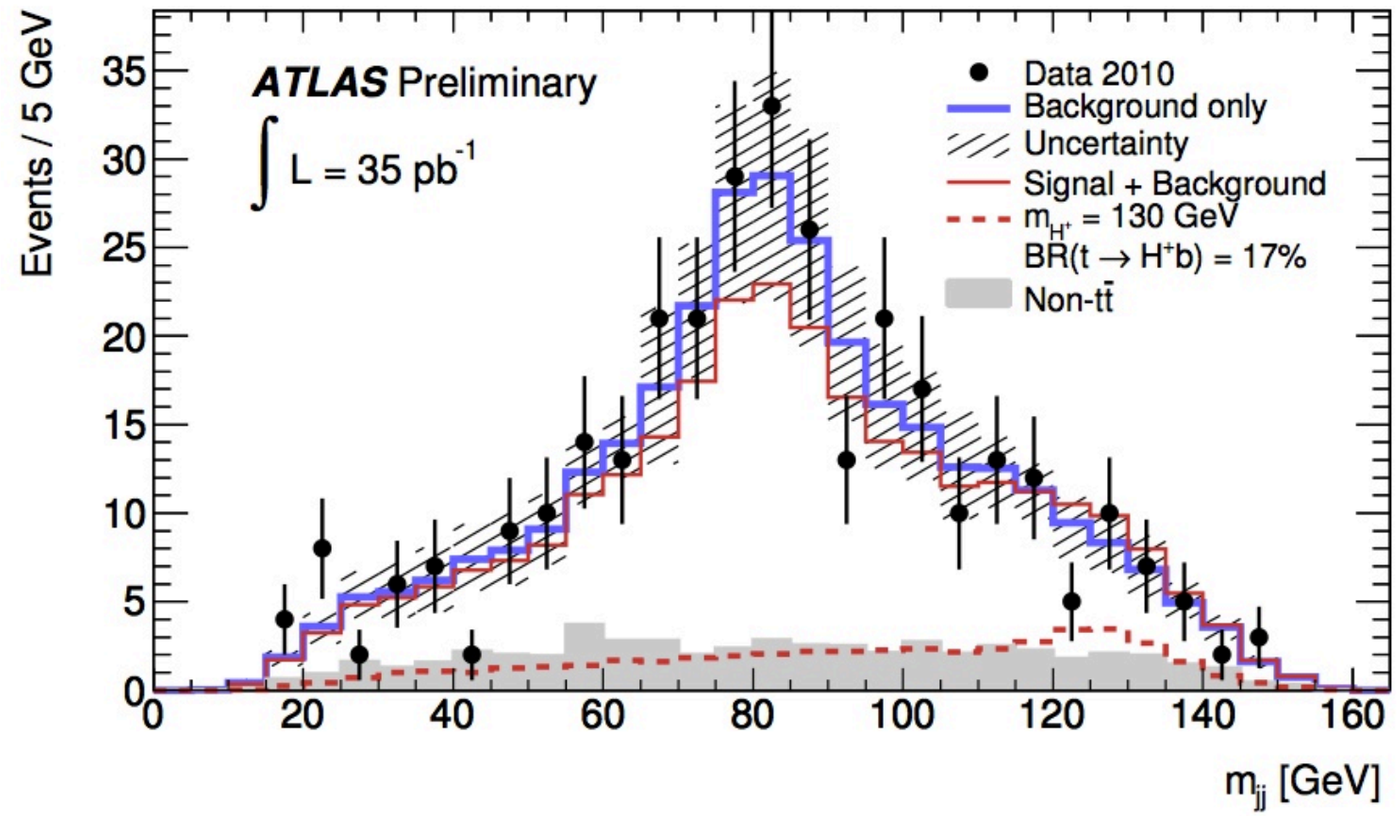
$$\chi^2 = \sum_{i=l,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_{UE}^2} + \sum_{k=bjj,bl\nu} \frac{(M_k - M_{top})^2}{\sigma_{top}^2}.$$



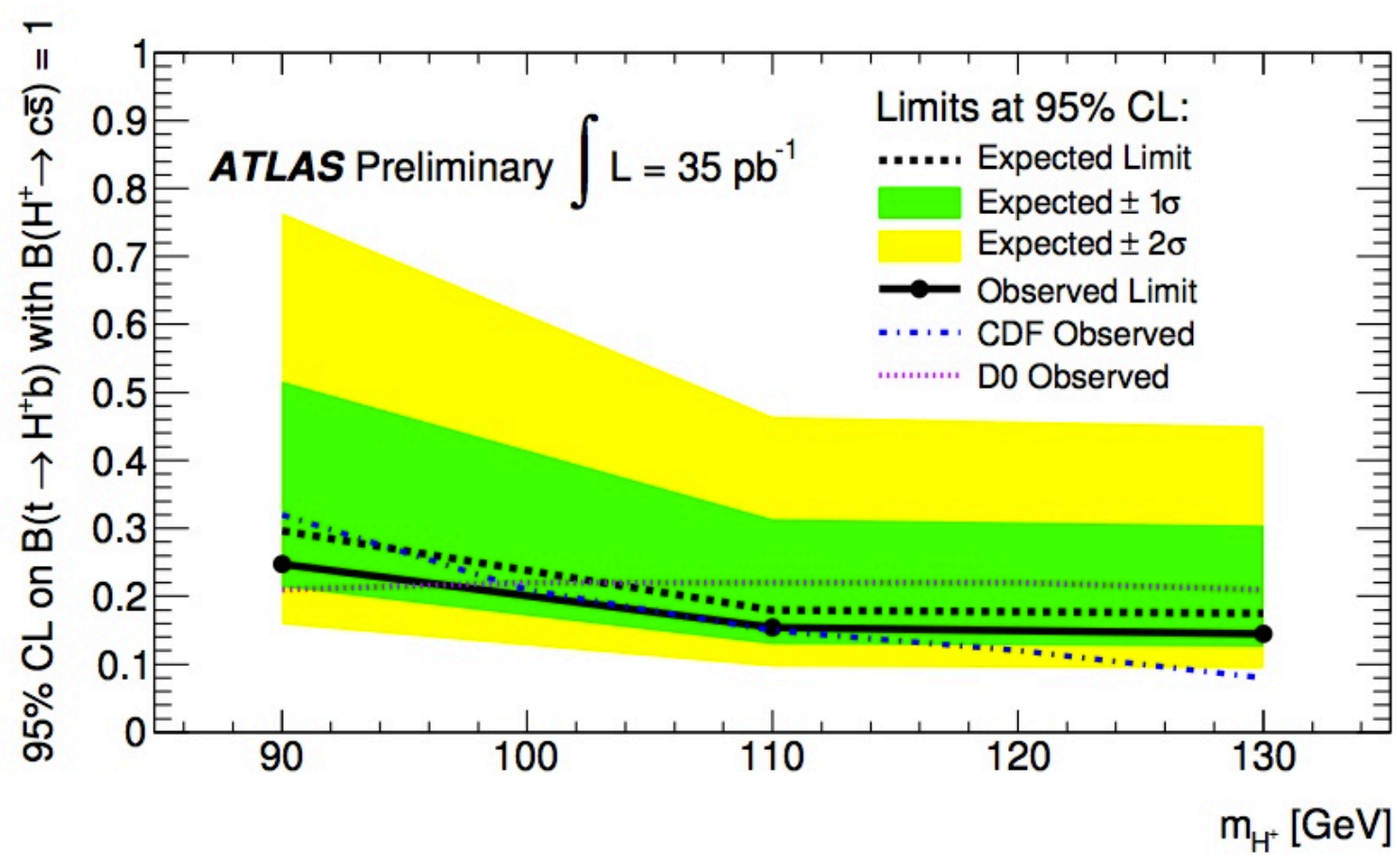


Charged Higgs: $H^+ \to c\bar{s}$

- Examine the di-jet spectrum from ttbar events and look for a second peak
  - After selection, ttbar background > 80%
  - Data-driven estimate for QCD
  - Number of events observed agrees with SM expectation

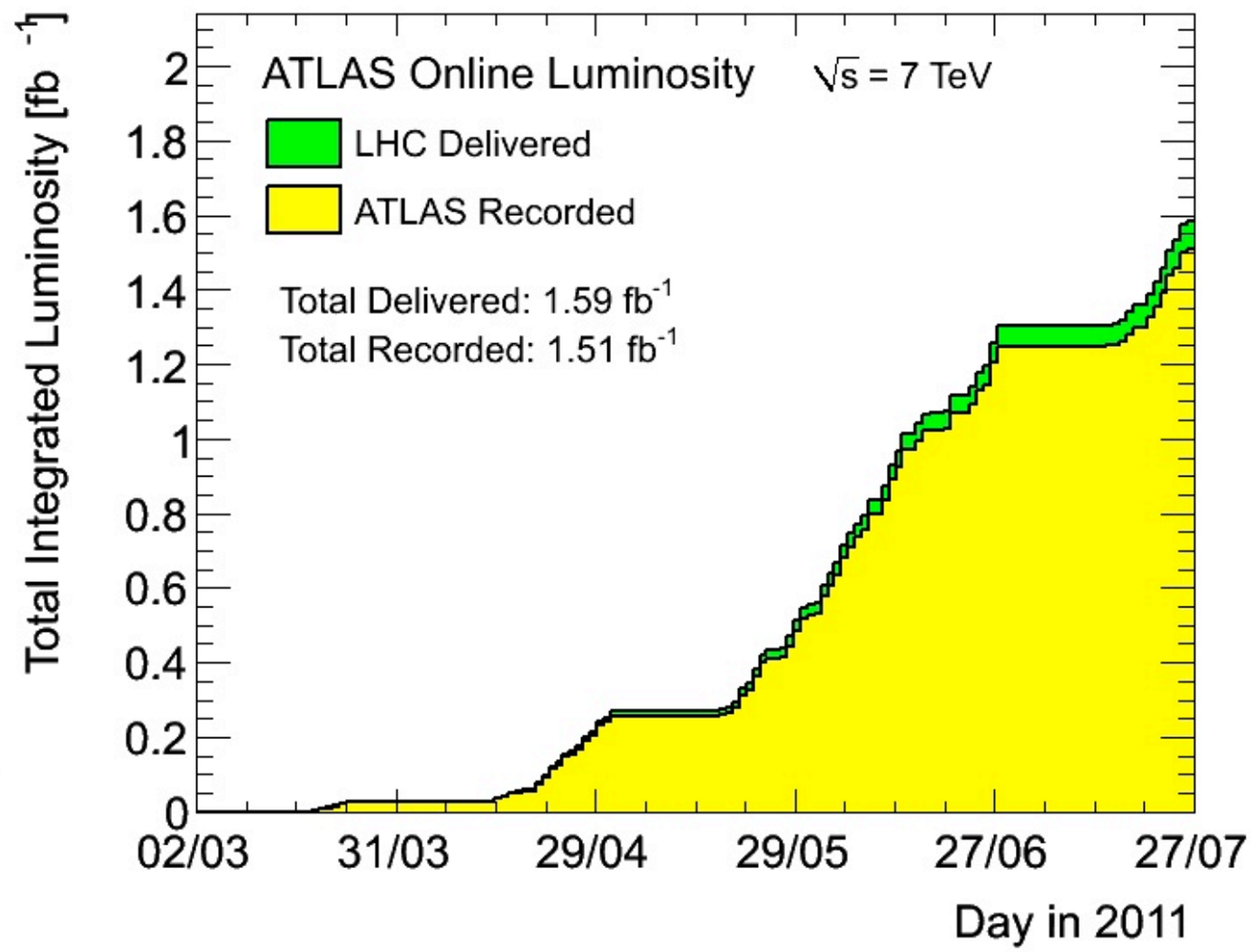


Channel	Muon	Electron
Data	193	130
SM $t\bar{t} \to W^+bW^-\bar{b}$	156^{+24}_{-29}	106^{+16}_{-20}
W/Z + jets	17 ± 6	9 ± 3
Single top	7 ± 1	5 ± 1
Diboson	0.30 ± 0.02	0.20 ± 0.02
QCD multijet	11 ± 4	6 ± 3
Total Expected (SM)	191^{+26}_{-30}	127^{+17}_{-21}
$\mathcal{B}(t \to H^+b) = 10\%$:		
$t\bar{t} \to H^+bW^-\bar{b}$	20^{+3}_{-4}	14^{+2}_{-2}
$t\bar{t} \to W^+bW^-\bar{b}$	127^{+19}_{-23}	86^{+13}_{-16}
Total Expected ($\mathcal{B} = 10\%$)	181^{+21}_{-25}	120^{+14}_{-17}



Conclusion

- The LHC era has begun!
  - Proton-proton collisions at world-record energies last year
  - ATLAS collected nearly 50 pb^{-1} of data in 2010
  - For 2011 ATLAS has collected >1.5 fb^{-1} thus far



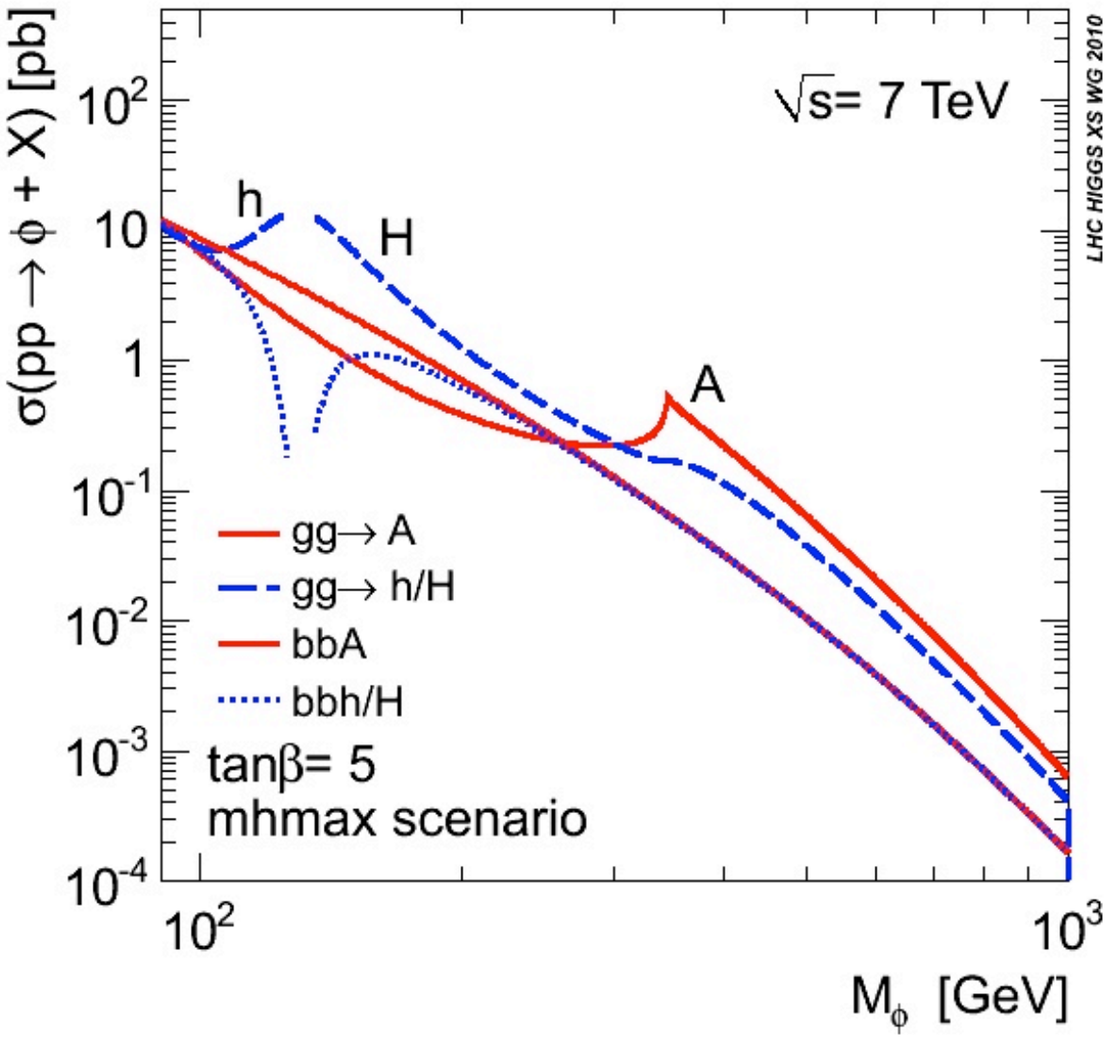
- First ATLAS limits with ~40 pb^{-1} on
  - MSSM $h/A/H \rightarrow \tau\tau$
  - MSSM $H^{\pm} \rightarrow cs$

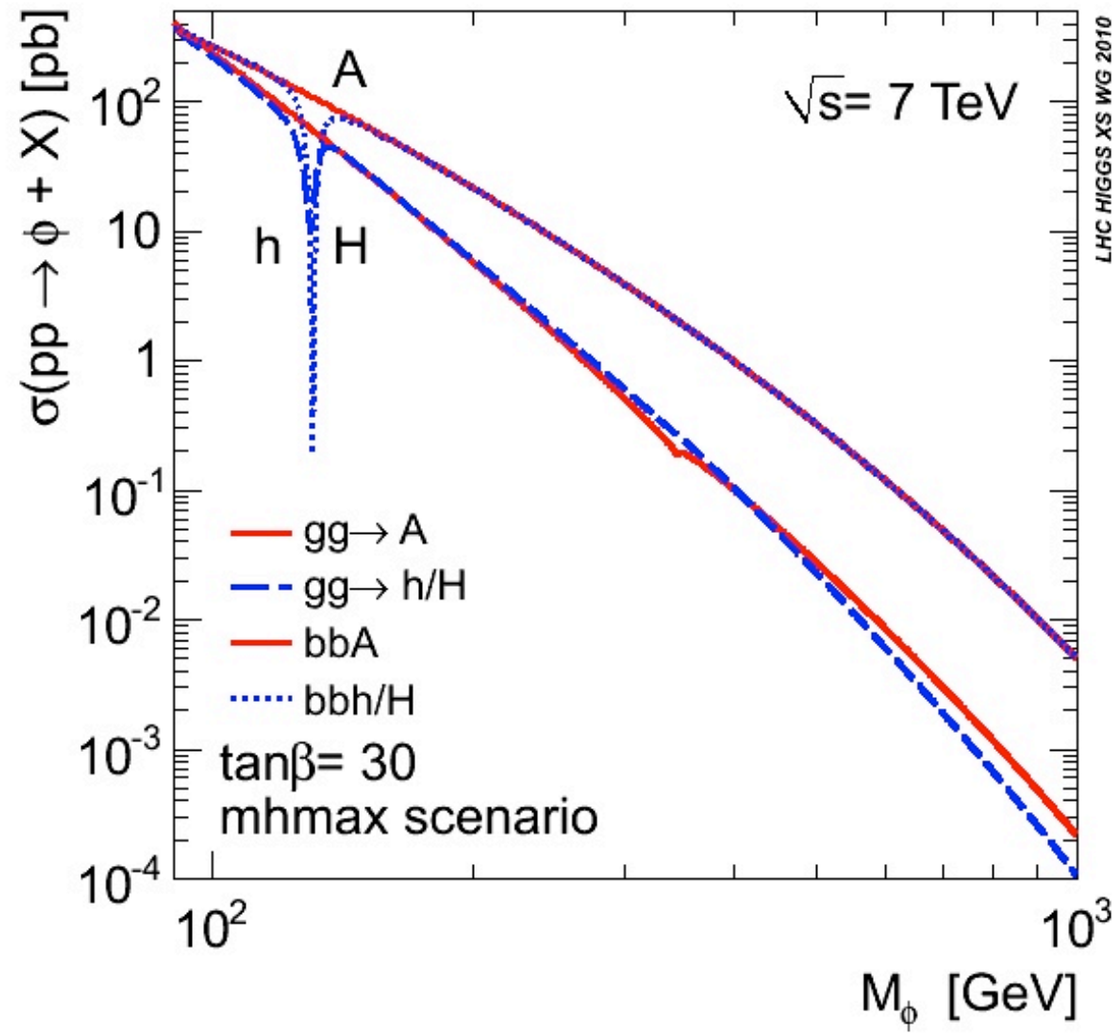
- Expected exclusion limits with ~1 - 2 fb^{-1} look very promising for BSM Higgs boson searches

- Or perhaps something even more exciting if Nature is kind...

Back-up Slides

MSSM Neutral Higgs Cross-Sections

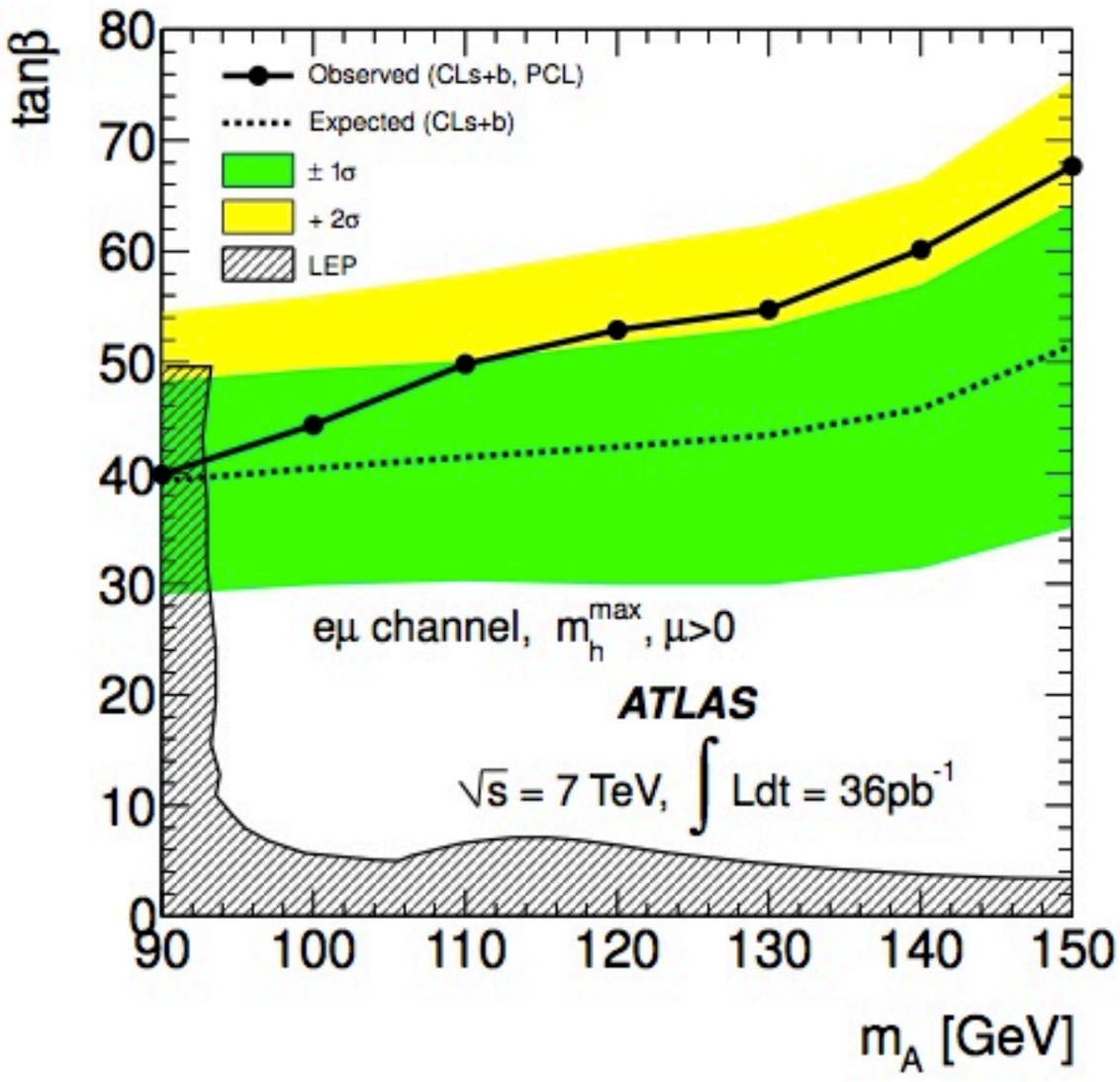


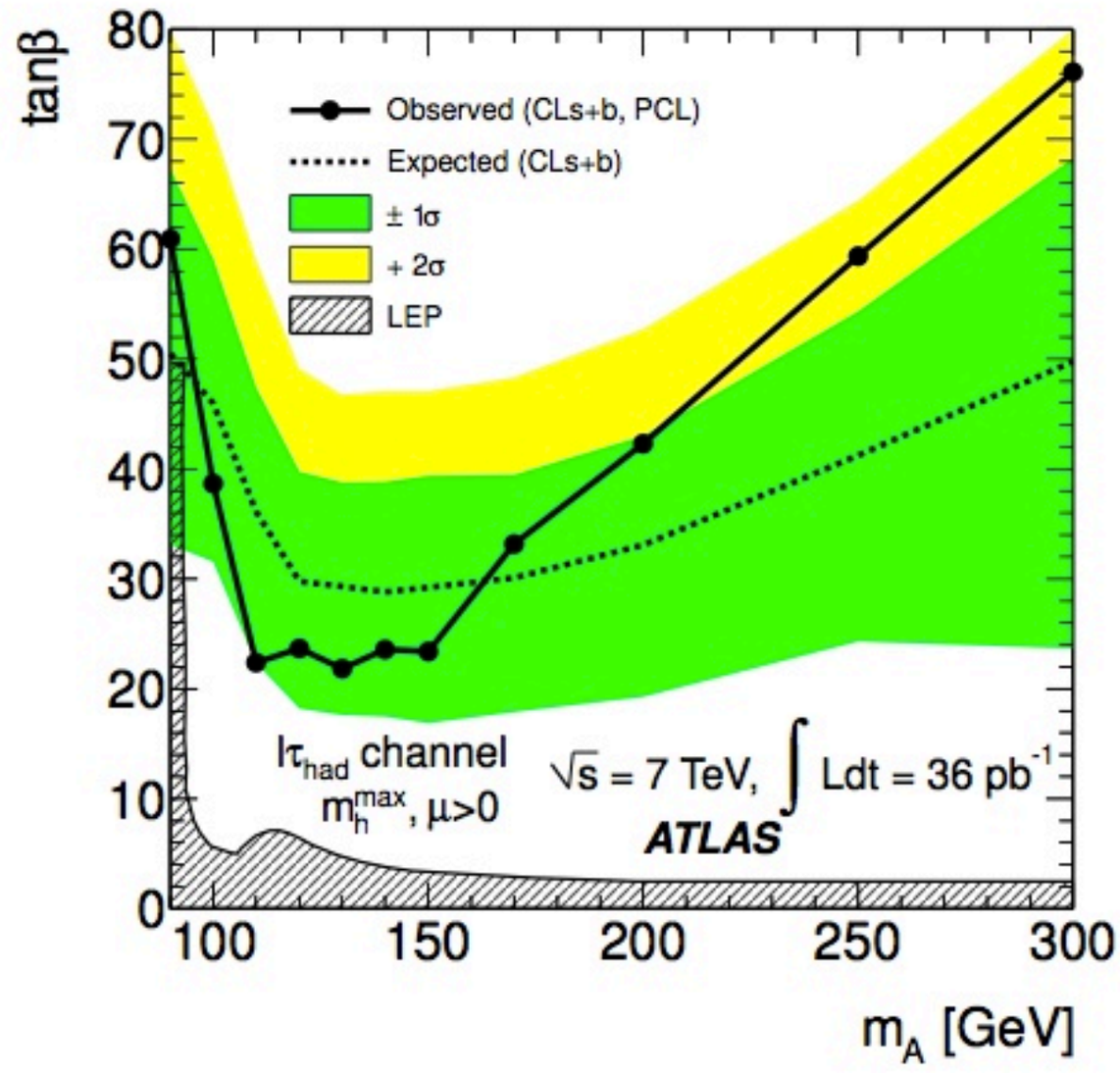


- Calculated using HIGLU and ggh@nnlo
- For bbh a matching scheme has been implemented to combine 4 (NLO QCD) and 5-flavor (NNLO QCD) calculations
- 4-flavor cross-sections are known to be more conservative (underestimates the cross-section for large Higgs boson masses)
- Error bands of both the 4FS and 5FS overlap at low masses
- "Santander matching" gives equal weight to both calculations at M_H=100 GeV and about 1/3 4FS and 2/3 5FS at M_H=300 GeV

MSSM Neutral Higgs (h/A/H) Search

- Limits for individual channels

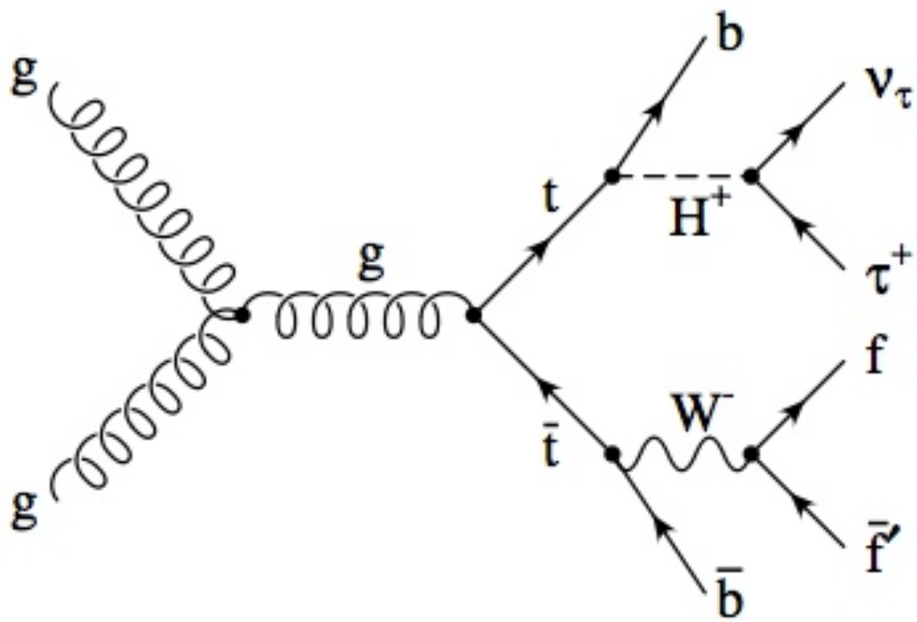


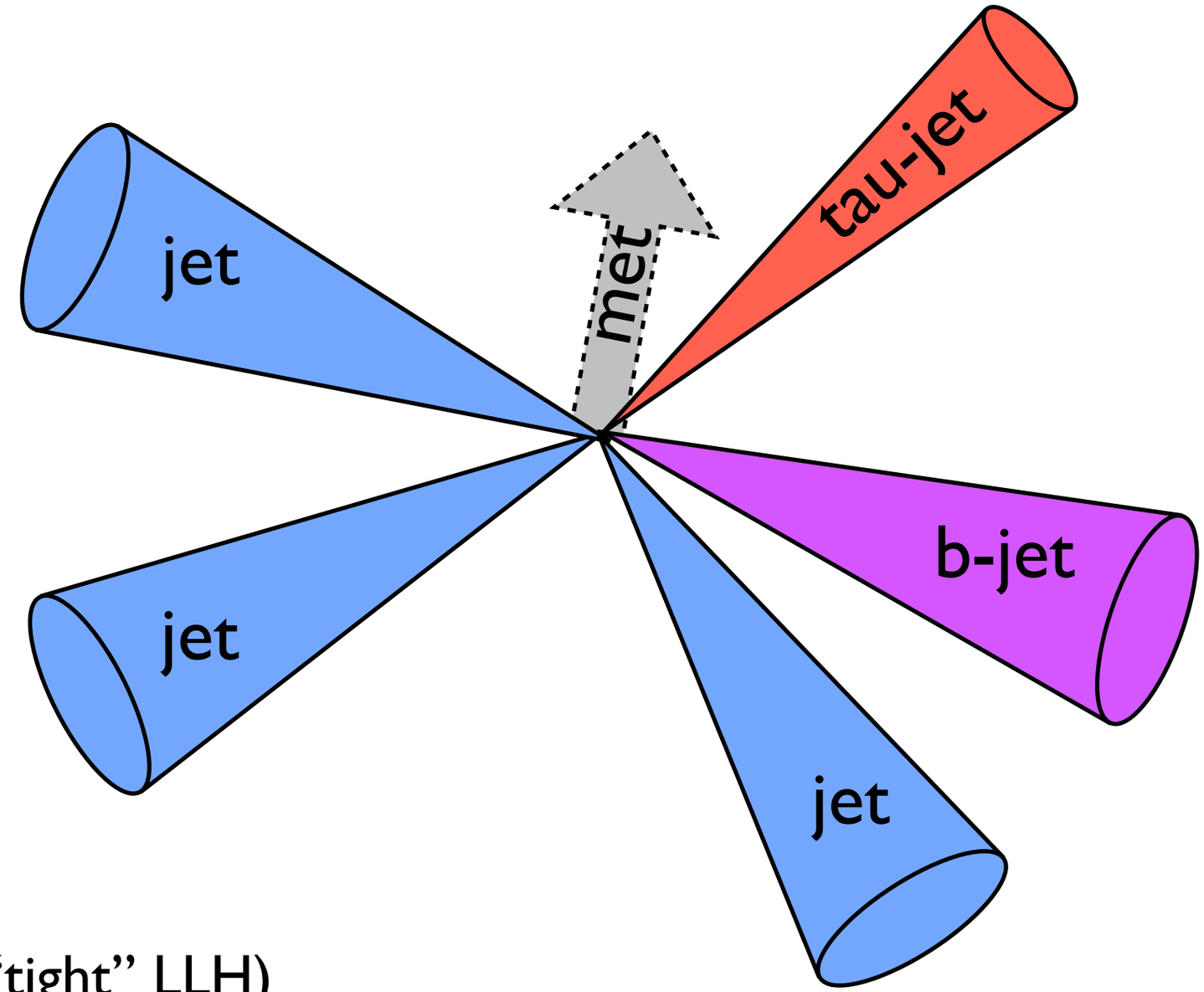


	Data	Total MC bkg (w/o QCD)	W+jets	Di-boson	$t\bar{t}$+ single-top	$Z/\gamma^* \to ee, \mu\mu$	$Z/\gamma^* \to \tau^+\tau^-$	Signal ($m_A = 120$ GeV, $\tan\beta = 40$)
$e\mu$	70	60.4±1.2	0.7±0.5	2.8±0.1	2.5±0.1	0.8± 0.1	53.5±1.0	16.0±0.3
$e\tau_{had}$	74	72.8±2.7	25.1±1.8	0.37±0.02	4.1±0.2	10.6±1.0	32.6±1.8	18.7±0.5
$\mu\tau_{had}$	132	145.2±3.9	41.5±2.1	0.59±0.03	5.9±0.2	11.5±1.1	85.7±3.1	36.6±0.8

Charged Higgs: τ+jets channel

- Event selection criteria:

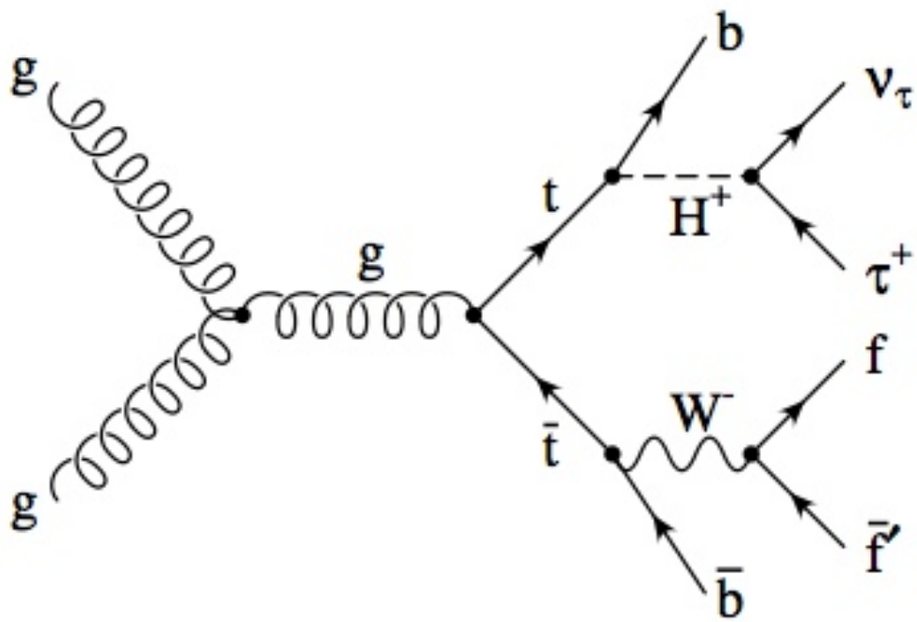


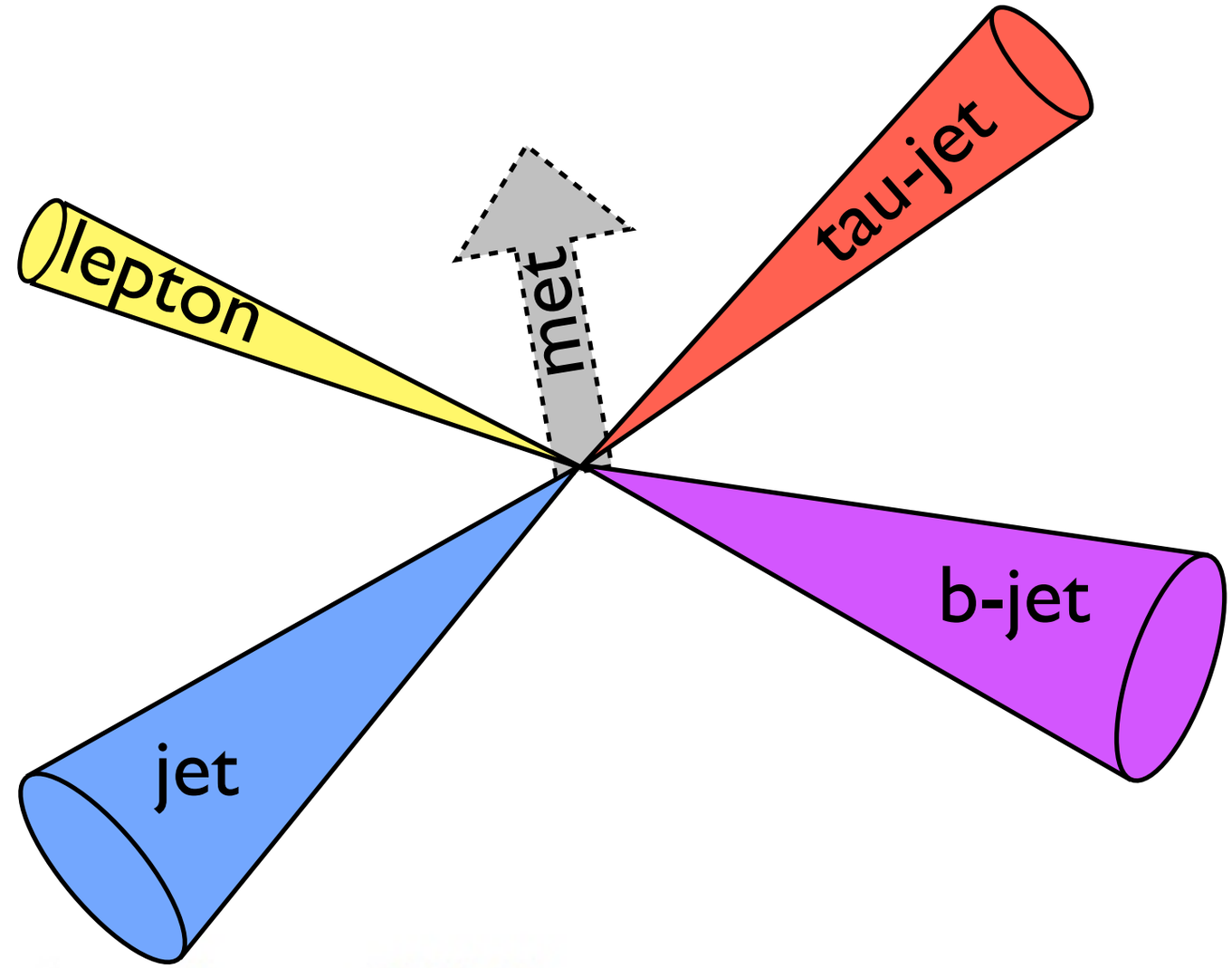


1. Event preselection:
   (a) Event-level cleaning cuts.
   (b) $E_{\mathrm{T}}^{\mathrm{miss}}$ plus τ-trigger.
   (c) At least 4 jets with $p_T > 20$ GeV.
2. Exactly one τ jet with $p_T > 20$ GeV. ("tight" LLH)
3. Veto identified electrons and muons.
4. $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV.
5. $E_{\mathrm{T}}^{\mathrm{miss}} / \sqrt{\sum E_{\mathrm{T}}} > 3$ GeV$^{1/2}$.
6. At least one b-tagged jet.
7. The jjb candidate with the highest p_T^{jjb} value must satisfy $m(jjb) \in [120, 240]$ GeV.

Charged Higgs: τ+lepton channel

- Event selection criteria:





1. Event preselection:
   (a) Event-level cleaning cuts.
   (b) Lepton trigger.
   (c) Exactly one trigger-matched isolated lepton with $p_T > 20$ GeV.
2. Exactly one τ jet with $p_T > 20$ GeV. ("tight" LLH)
3. At least two jets with $p_T > 20$ GeV.
4. At least one of the jets is b-tagged.
5. $E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV.
6. $\sum E_{\mathrm{T}} > 200$ GeV.
7. Selected τ jet and lepton have opposite charge.

Hadronic Tau Reconstruction in ATLAS

- Reconstruction seed jets
  - Calorimeter jets reconstructed with the anti-kT algorithm (starting from topological clusters)
  - Distance parameter R = 0.4

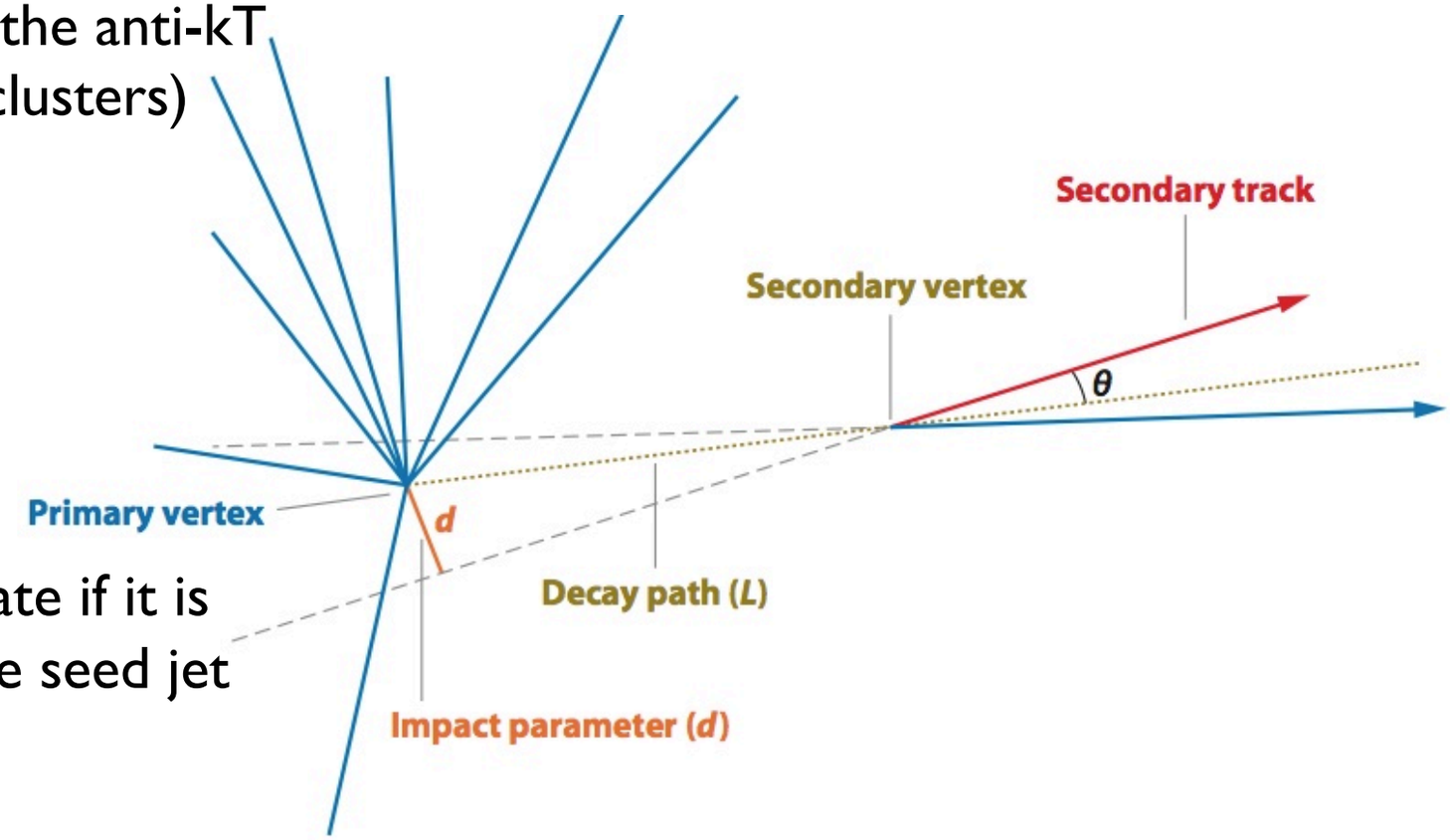


Image from: Luciano Ristori and Giovanni Punzi, Annual Review of Nuclear and Particle Science Vol. 60: 595-614 (2010)

- Track Association
  - A track is associated with tau candidate if it is within the core cone ($\Delta R < 0.2$ of the seed jet axis)
  - Also pass the following criteria:
    - $p_T > 1$ GeV
    - At least 7 hits in the silicon tracker (B-layer ≥ 1, pixel ≥ 2)
    - Requirements on transverse and longitudinal impact parameters ($|d_0| < 1.0$ mm and $|z_0 \sin\theta| < 1.5$ mm)

- But, hadronic tau reconstruction alone is not enough...

Hadronic Tau Identification in ATLAS

- Use discriminating variables that give us the upper hand

$$R_{\text{track}} = \frac{\sum_i^{\Delta R_i<0.4} p_{\text{T},i}\,\Delta R_i}{\sum_i^{\Delta R_i<0.4} p_{\text{T},i}}$$

Track Radius

$$f_{\text{track}} = \frac{p_{\text{T},1}^{\text{track}}}{p_{\text{T}}^{\tau}}$$

Leading Track Momentum Fraction

$$R_{\text{EM}} = \frac{\sum_{i\in\{\text{EM 0–2}\}}^{\Delta R_i<0.4} E_{\text{T},i}^{\text{EM}}\,\Delta R_i}{\sum_{i\in\{\text{EM 0–2}\}}^{\Delta R_i<0.4} E_{\text{T},i}^{\text{EM}}}$$

Electromagnetic Radius

$$f_{\text{core}} = \frac{\sum_{i\in\{\text{all}\}}^{\Delta R_i<0.1} E_{\text{T},i}^{\text{EM}}}{\sum_{i\in\{\text{all}\}}^{\Delta R_i<0.4} E_{\text{T},i}^{\text{EM}}}$$

Core Energy Fraction

$$S_{\text{T}}^{\text{flight}} = \frac{L_{\text{T}}^{\text{flight}}}{\delta L_{\text{T}}^{\text{flight}}}$$

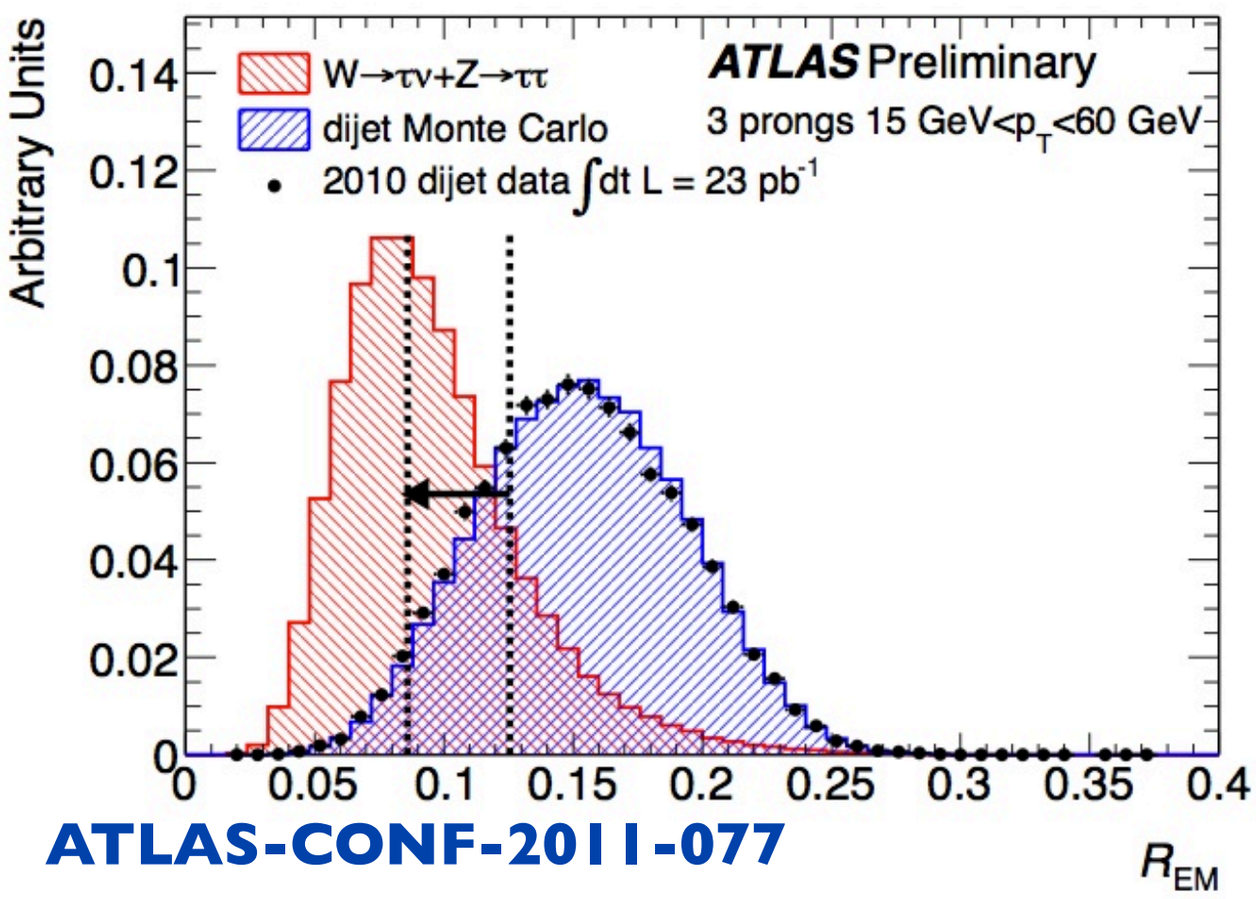
Transverse Flight Path Significance

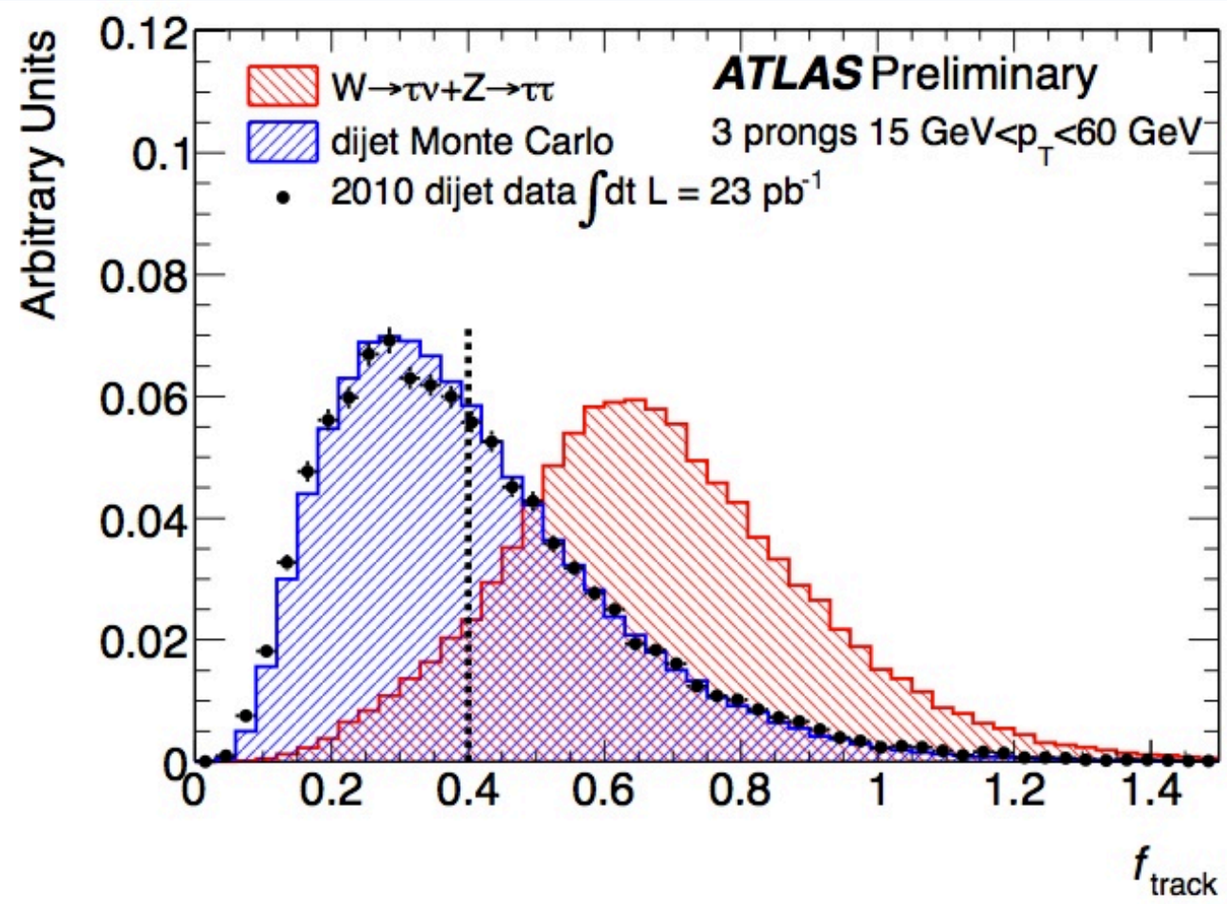
Electromagnetic Fraction

$$f_{\text{EM}} = \frac{\sum_{i\in\{\text{EM 0–2}\}}^{\Delta R_i<0.4} E_{\text{T},i}^{\text{EM}}}{\sum_{j\in\{\text{all}\}}^{\Delta R_j<0.4} E_{\text{T},j}^{\text{EM}}}$$

Cluster Mass

Track Mass





ATLAS-CONF-2011-077

Tau Identification in 7 TeV Data

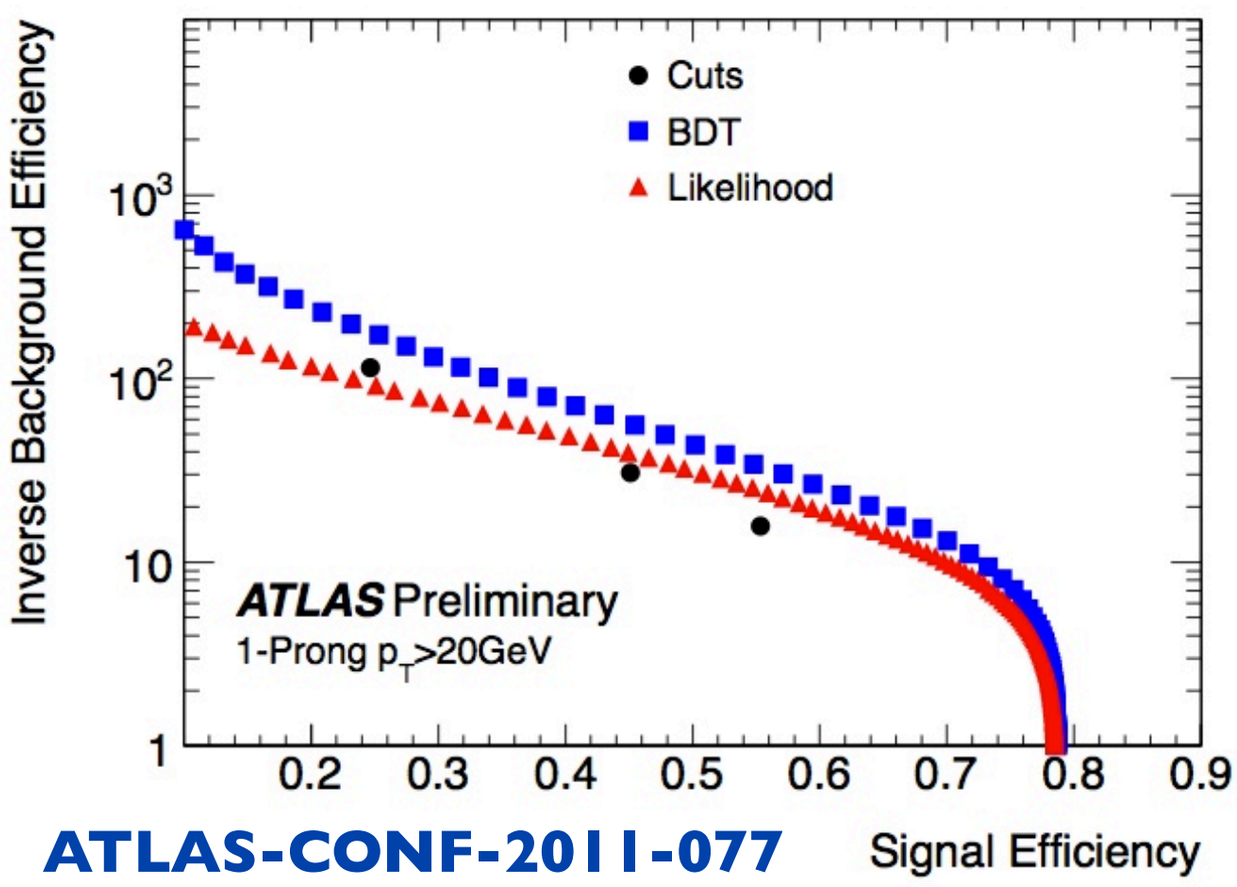
- To distinguish between tau leptons and jets, investigated three independent identification algorithms:
  - Simple cut-based, projective likelihood (LLH), and Boosted Decision Tree (BDT)
  - Cut-based ID uses a subset of the discriminating variables
  - Trained separately based on number of prongs
  - Distinction between an electron and tau is made using an electron veto
  - Tau ID tuned for signal efficiencies of ~30% (tight) and ~60% (loose)

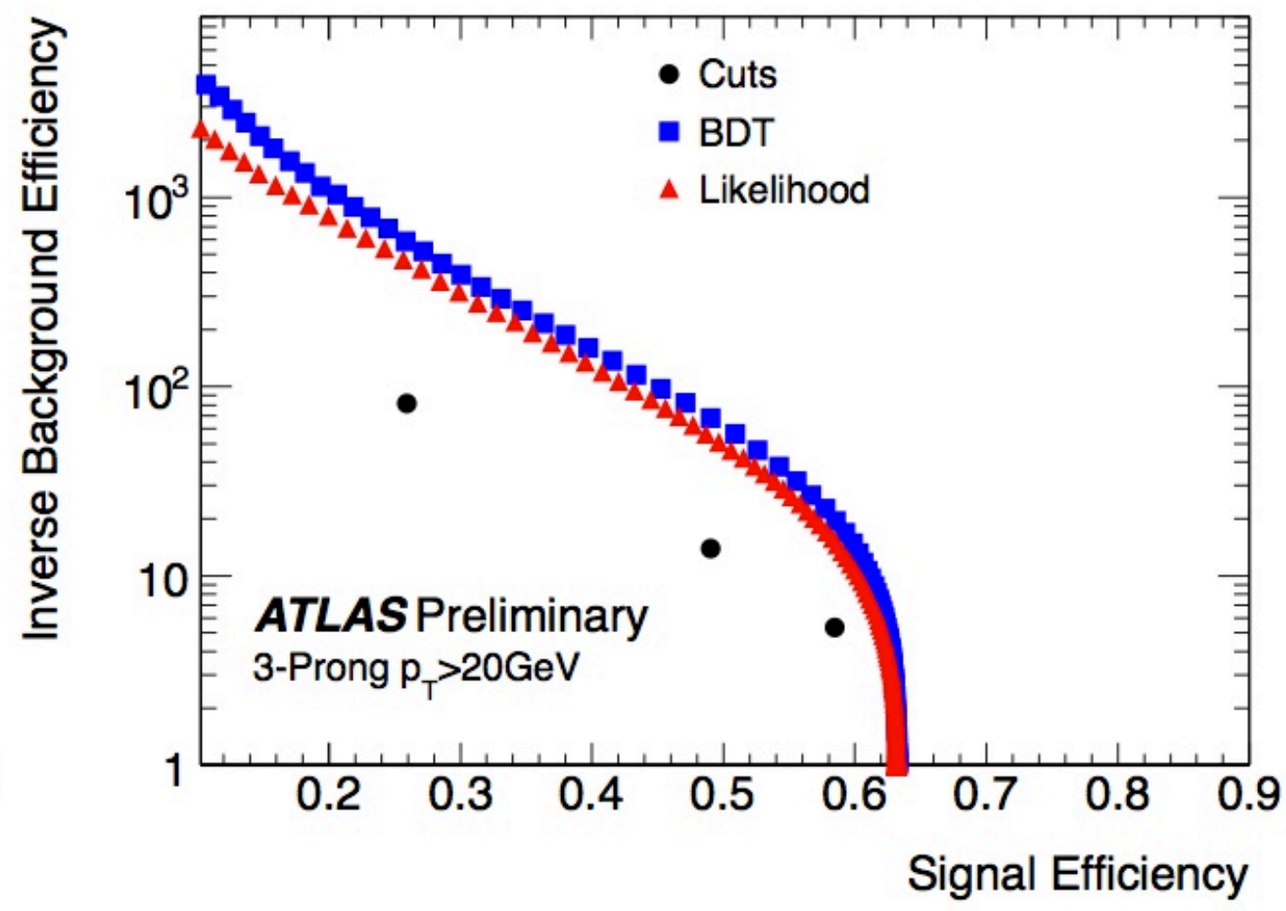
$$\varepsilon_{\text{sig}} = \frac{N^{\tau}_{\text{pass,match}}}{N^{\tau}_{\text{match}}}$$

- Background efficiency measured using collision data
  - Used 7 TeV collision data collected late in 2010
  - Background sample taken from di-jet events

$$\varepsilon_{\text{bkgd}} = \frac{N^{\text{bkgd}}_{\text{pass}}}{N^{\text{bkgd}}_{\text{total}}}$$

Signal: Monte Carlo
Background: Di-jet Data





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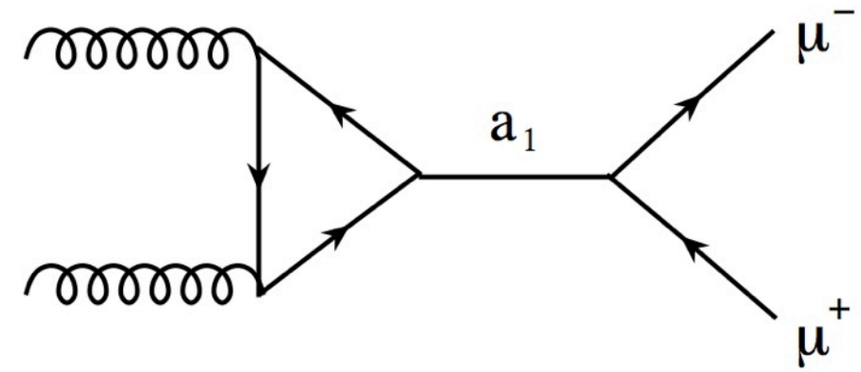
The NMSSM: μμ channel

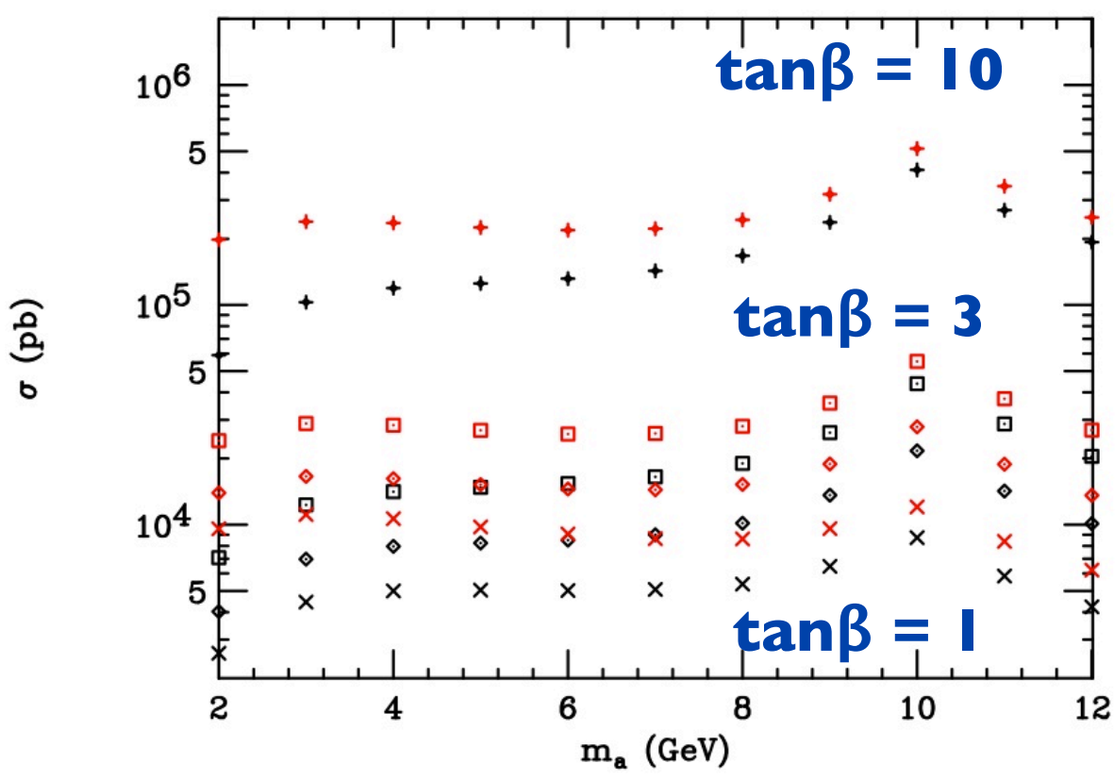
- The Next-to-MSSM
  - Introduces a complex singlet scalar field
  - Higgs sector expands as a result:
  - 3 CP-even scalars: h_1, h_2, h_3
  - 2 CP-odd scalars: a_1, a_2
  - 2 Charged scalars: $H^{\pm}$

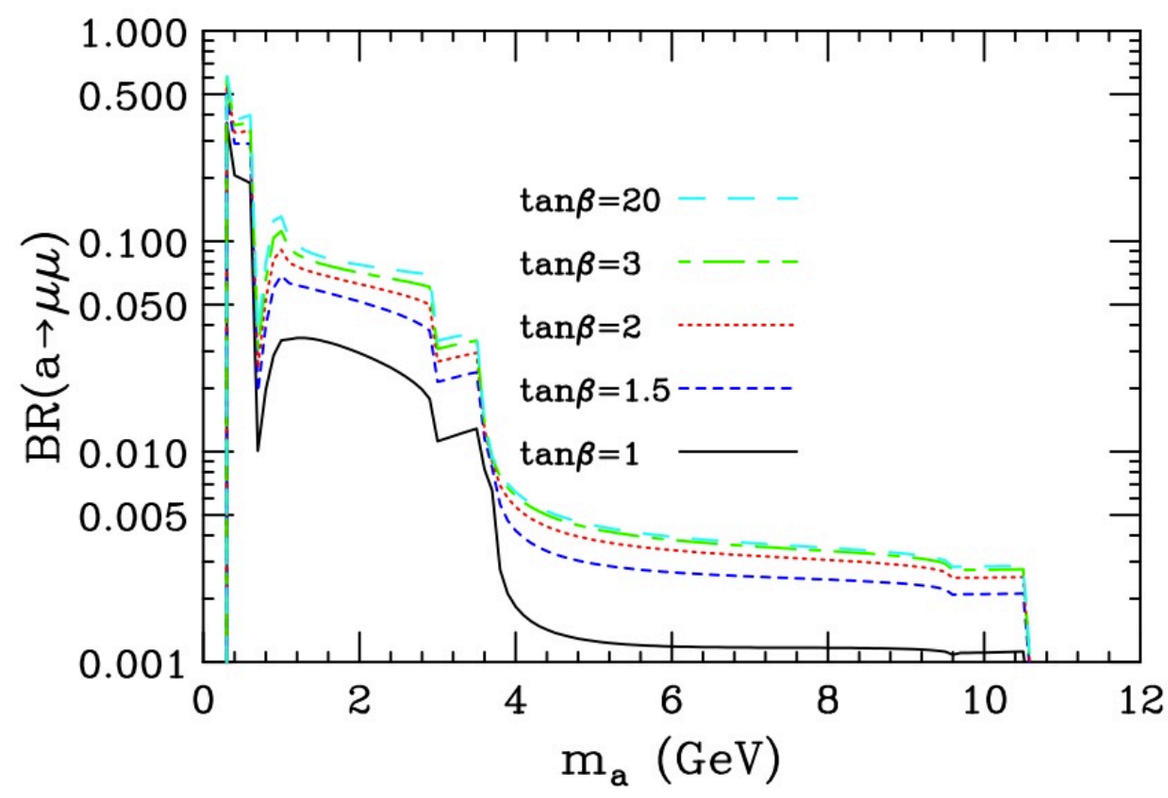
- The light CP-odd Higgs, a_1
  - Could be very light, e.g. ~10 GeV
  - Could have dominant production mode $h \rightarrow a_1 a_1$



- In the ideal scenario
  - $m_{a1} < 2\, m_B$
  - Dominant decay modes into ττ, cc, gg
  - μμ final state is a clean search channel

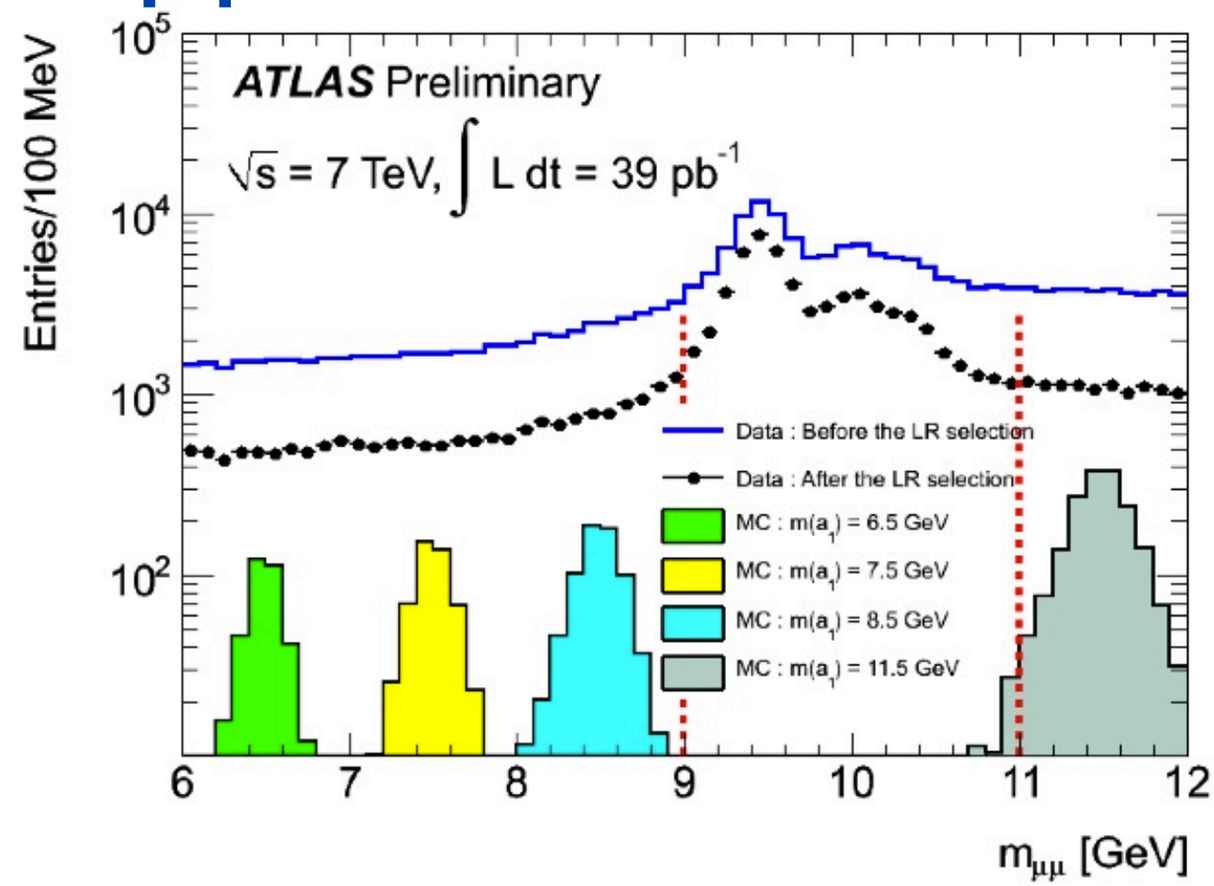
Plots from arXiv:0911.2460v5

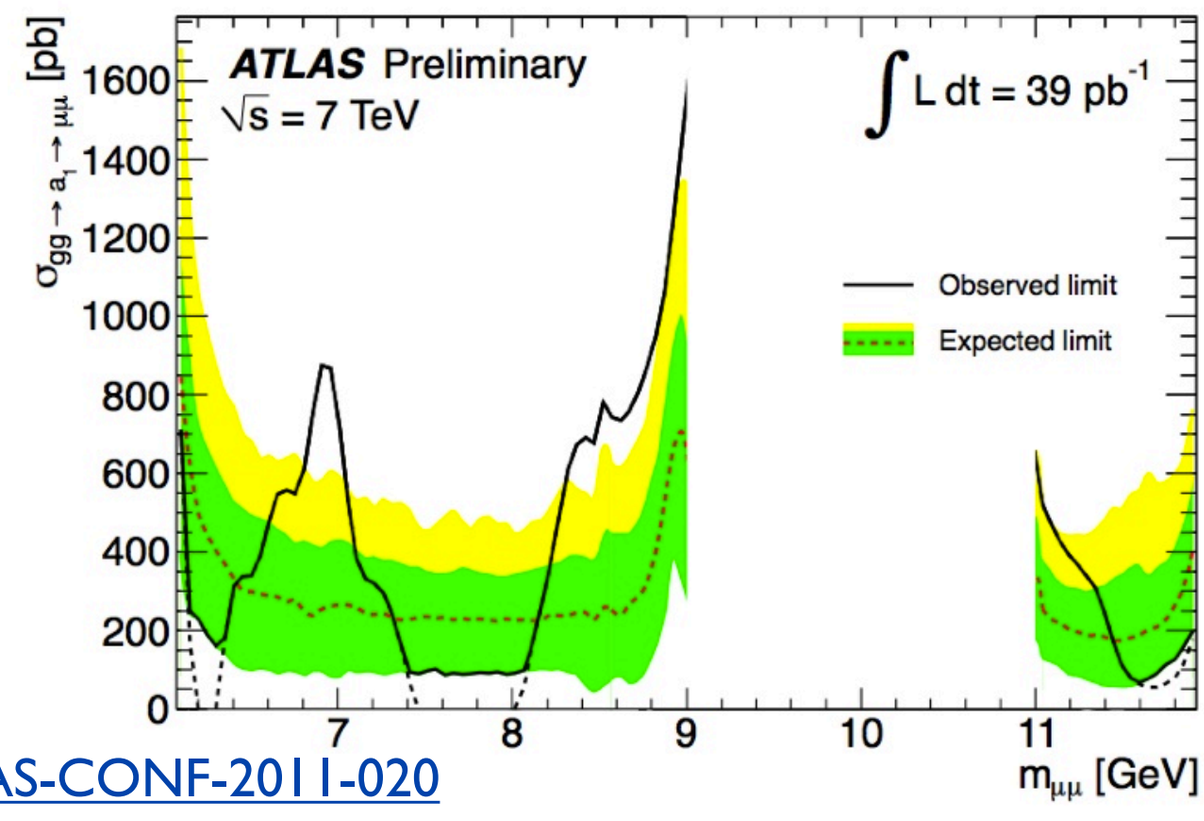




The NMSSM: $a_1 \rightarrow \mu\mu$ channel

- Event selection criteria:
  - $\geq 2\mu$ with $p_T > 4$ GeV; $|\eta| < 2.5$
  - Oppositely-charged muon pairs in the range $4.5 < m_{\mu\mu} < 14$ GeV are analyzed using a likelihood ratio
- Use a Likelihood Ratio:
  - Use di-muon vertex fit quality and isolation
  - Signal PDFs taken from $\Upsilon(1S)$; background subtracted from sidebands: $6 < m_{\mu\mu} < 7.5$ GeV and $11.5 < m_{\mu\mu} < 12$ GeV
  - Background estimated from sidebands: $4.5 < m_{\mu\mu} < 5.5$ GeV and $12.5 < m_{\mu\mu} < 14$ GeV
- Limits:
  - Likelihood function with 50 MeV bins
  - Separate fits in the regions 6-11 GeV and 9-12 GeV





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