ATLAS Searches for Higgs Bosons Beyond the Standard Model

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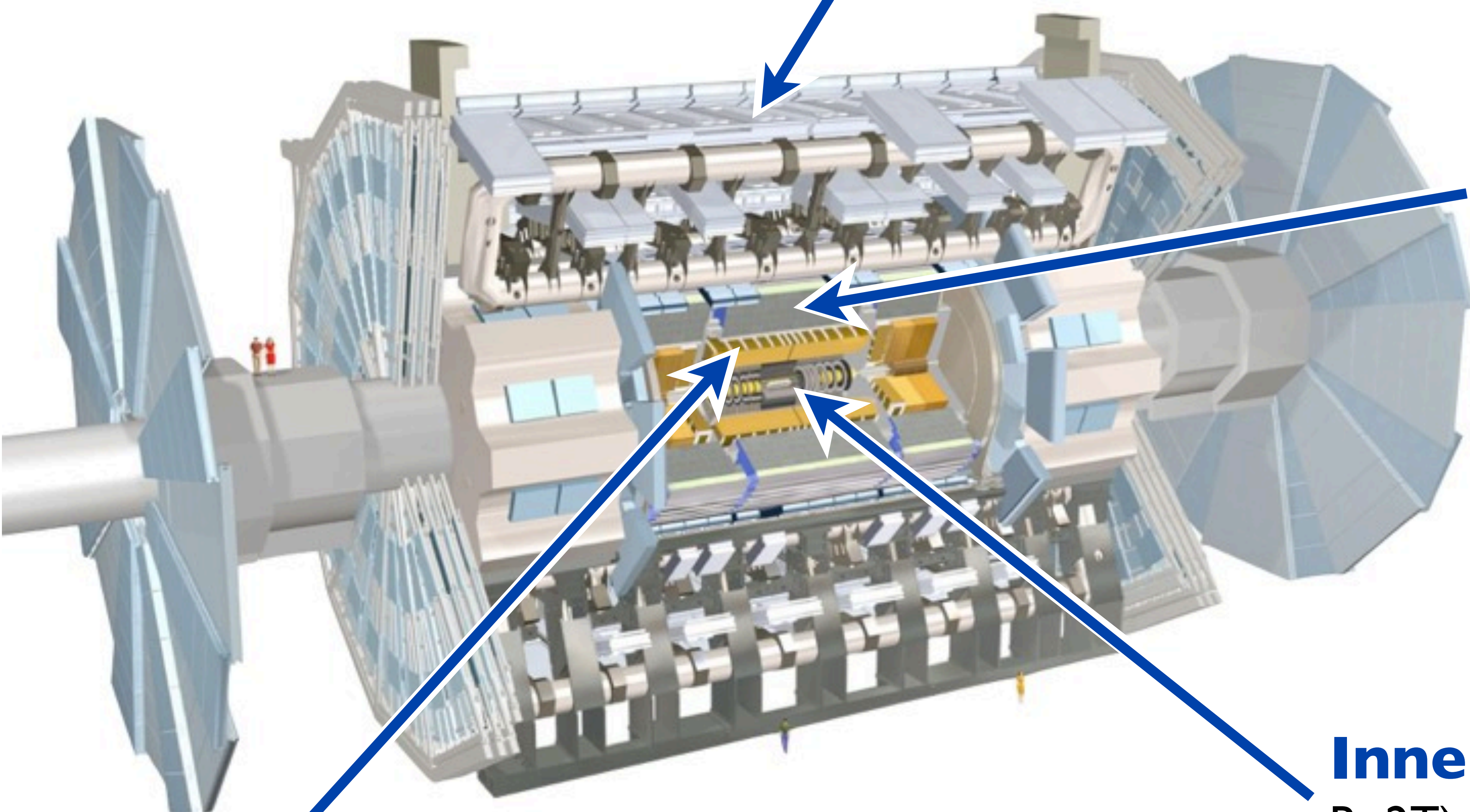
Origin of Mass Workshop, Stockholm, Sweden

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_μ ~ 1 TeV



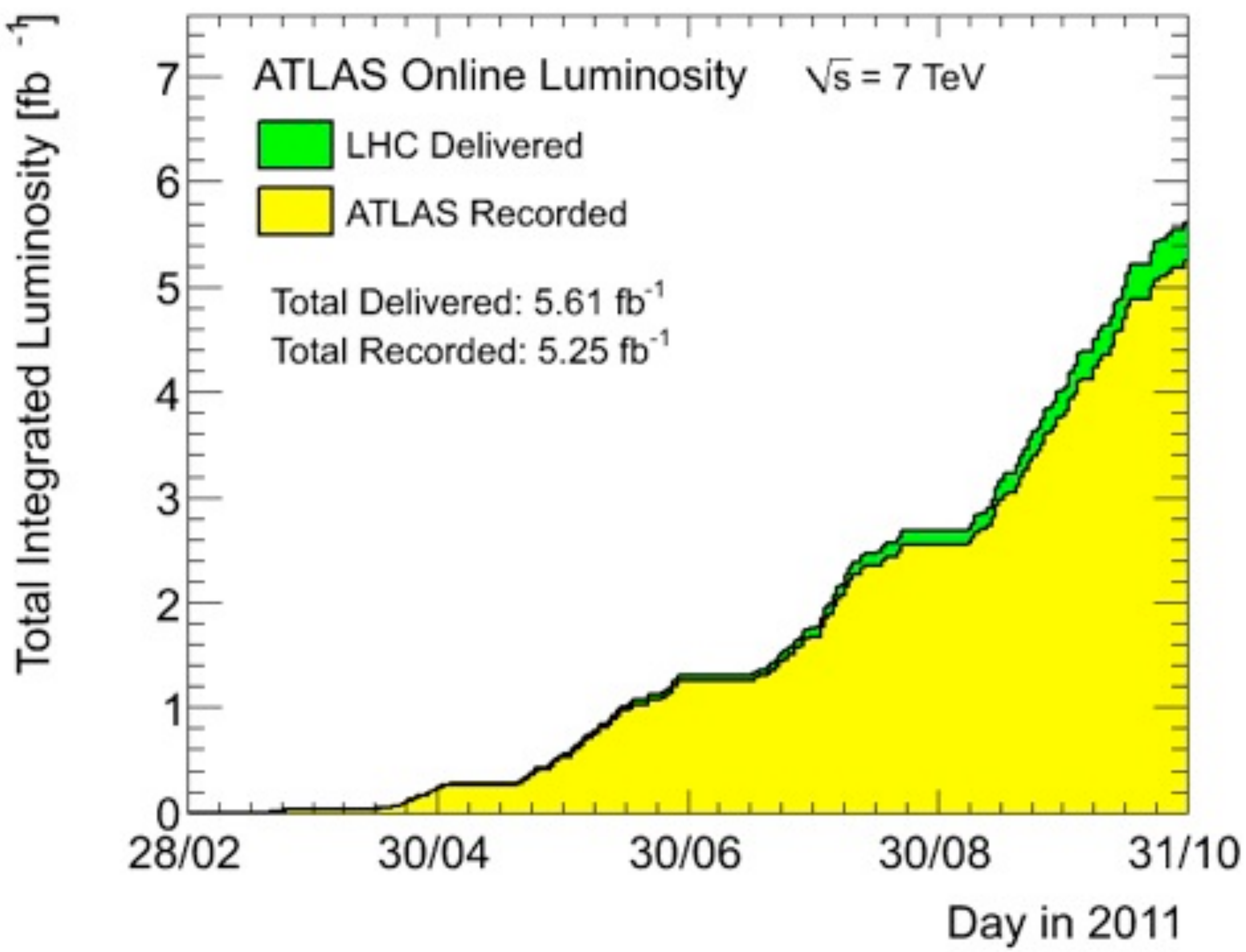
HAD calorimetry
($|\eta|<5$): hermetic and highly segmented; Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution:
$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

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:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T\,(\mathrm{GeV}) \oplus 0.015$
i.e. σ/p_T <2% for p_T < 35 GeV

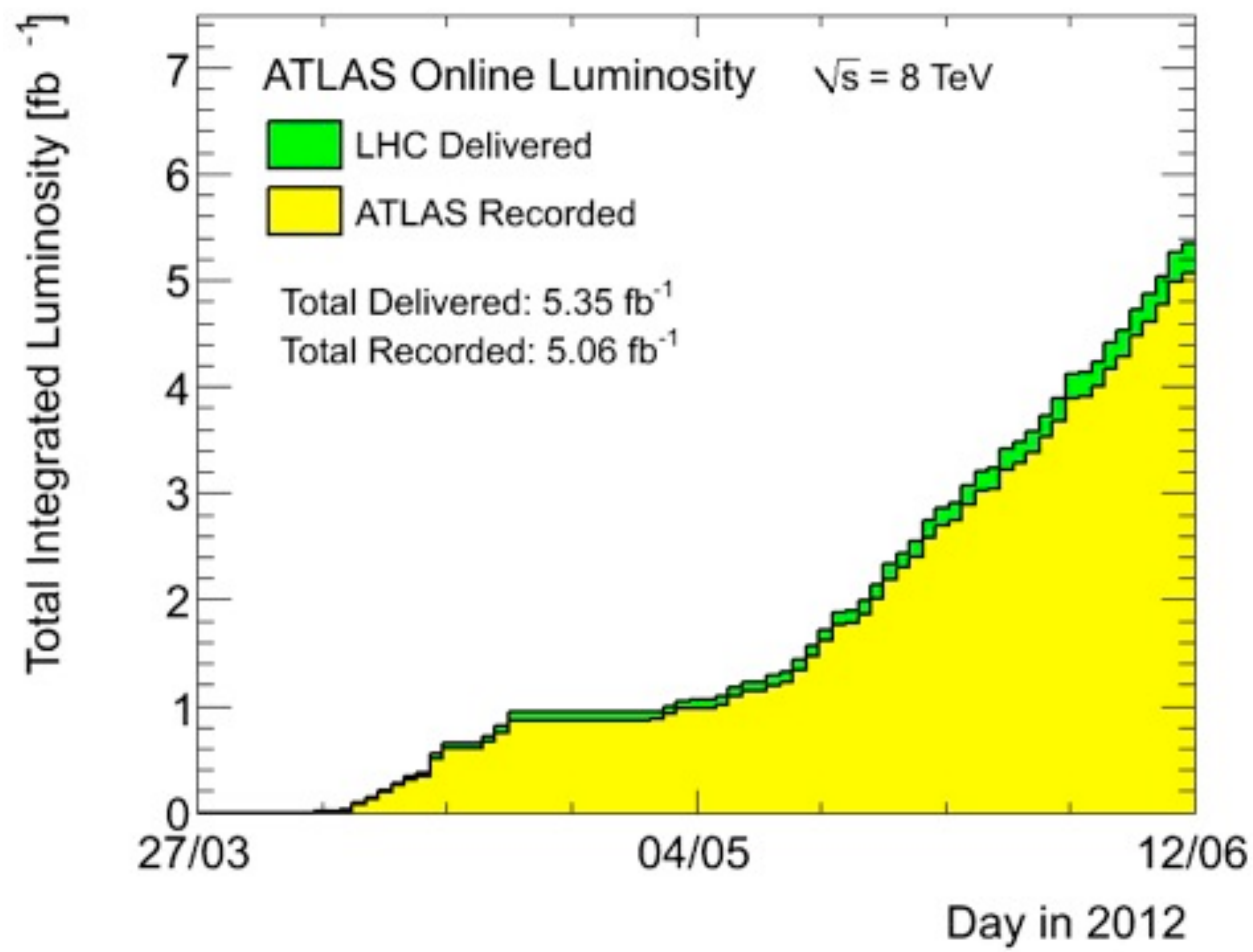
EM Calorimeter ($|\eta|<3.2$):
Pb-LAr Accordion; allows for e/γ triggering, identification and measurement;
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

ATLAS Datasets

2011 7 TeV

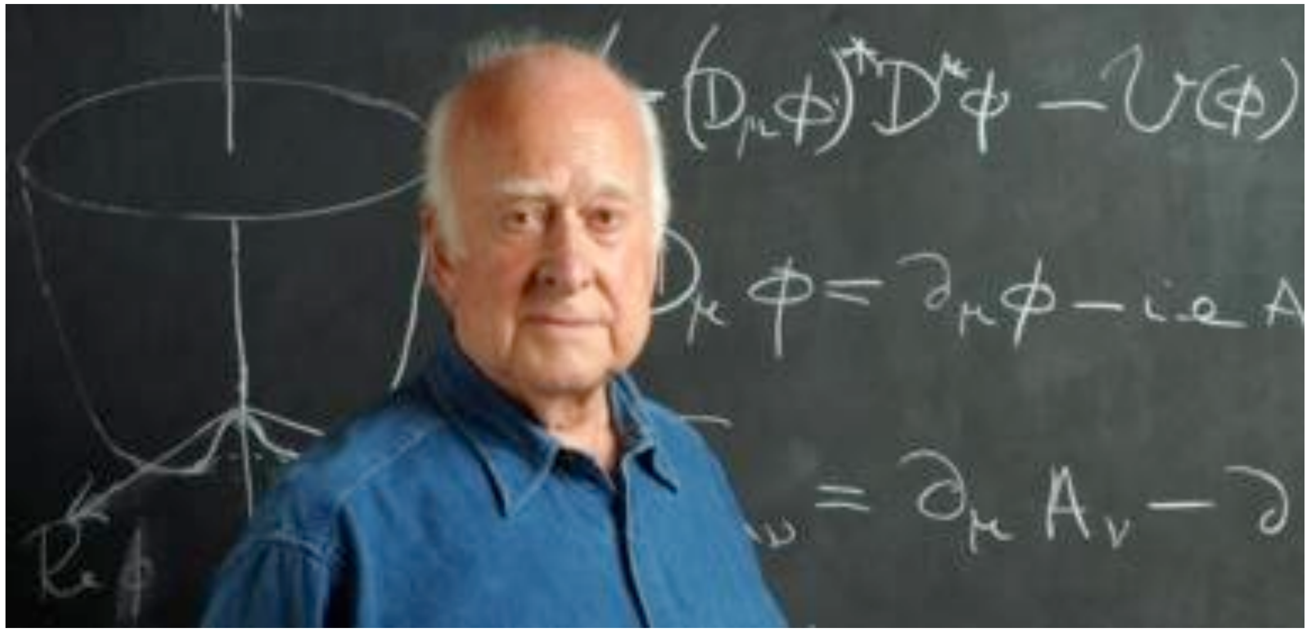


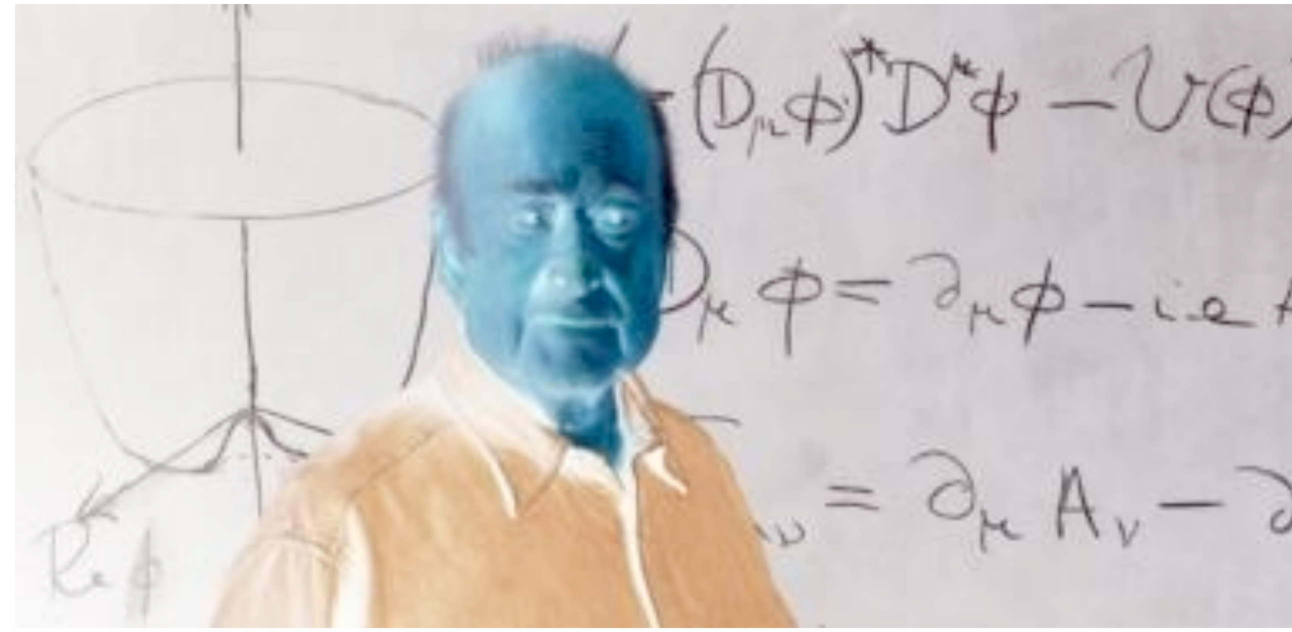
2012 8 TeV



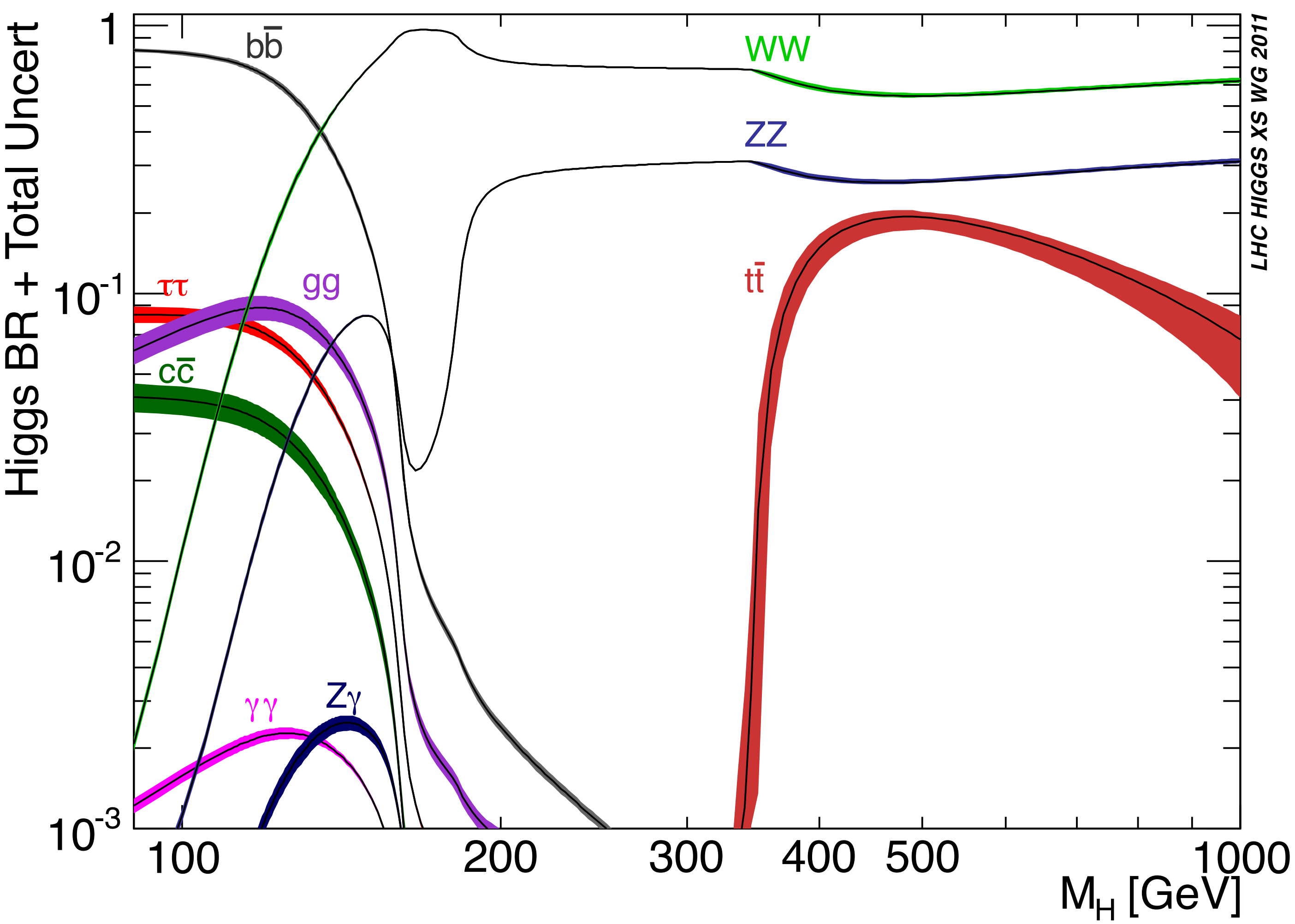
- ATLAS results shown today will all be from the 7 TeV 2011 dataset

If the (light) Higgs weighs ~125 GeV...

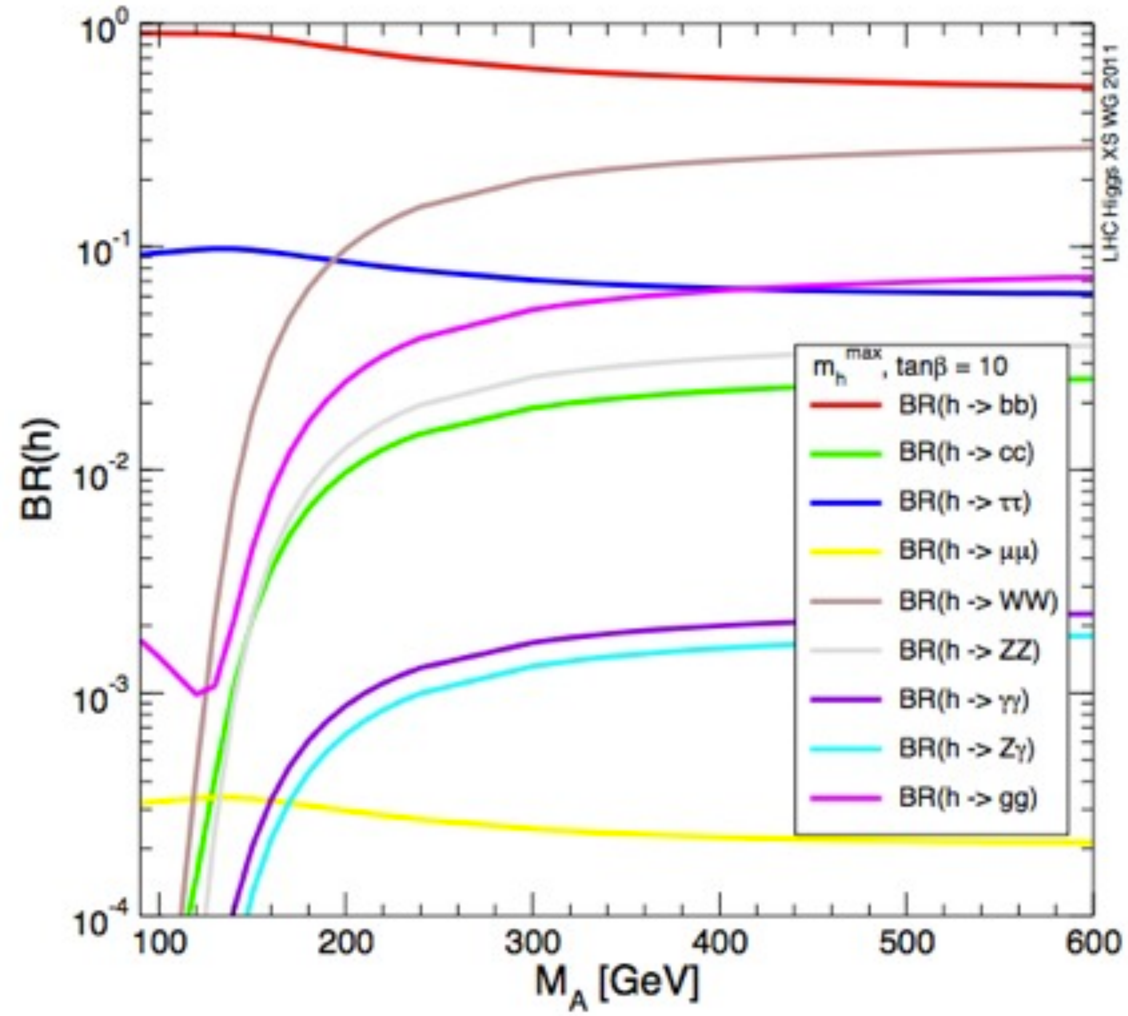




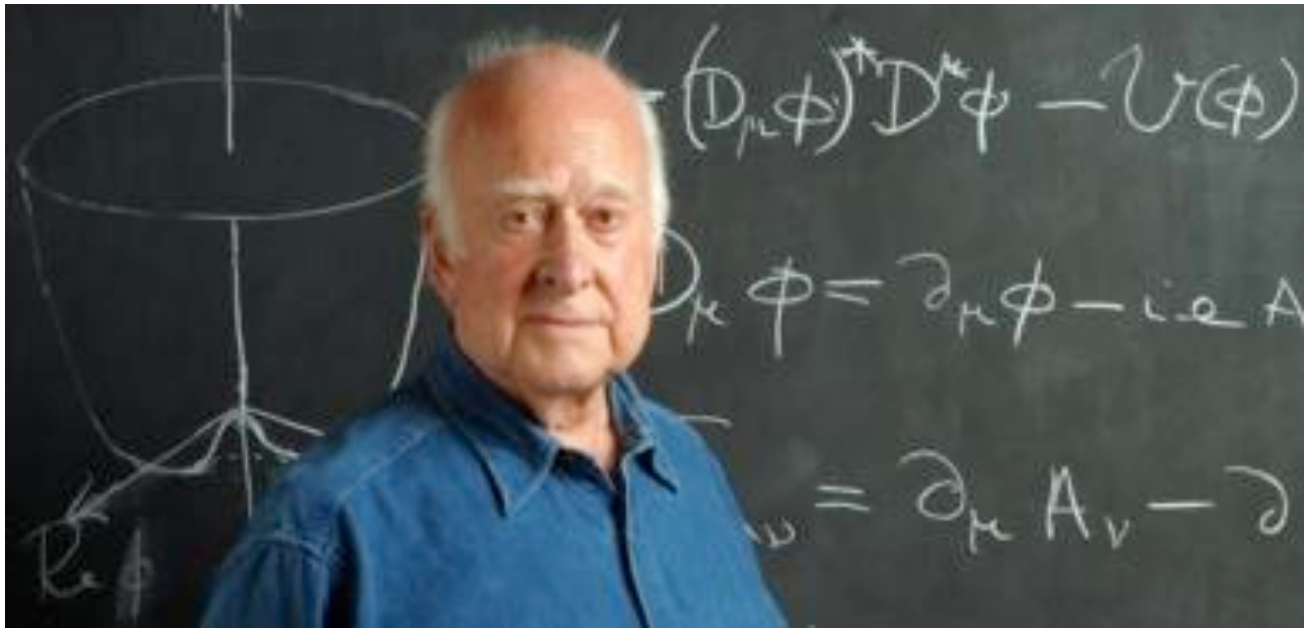
Standard Model Higgs



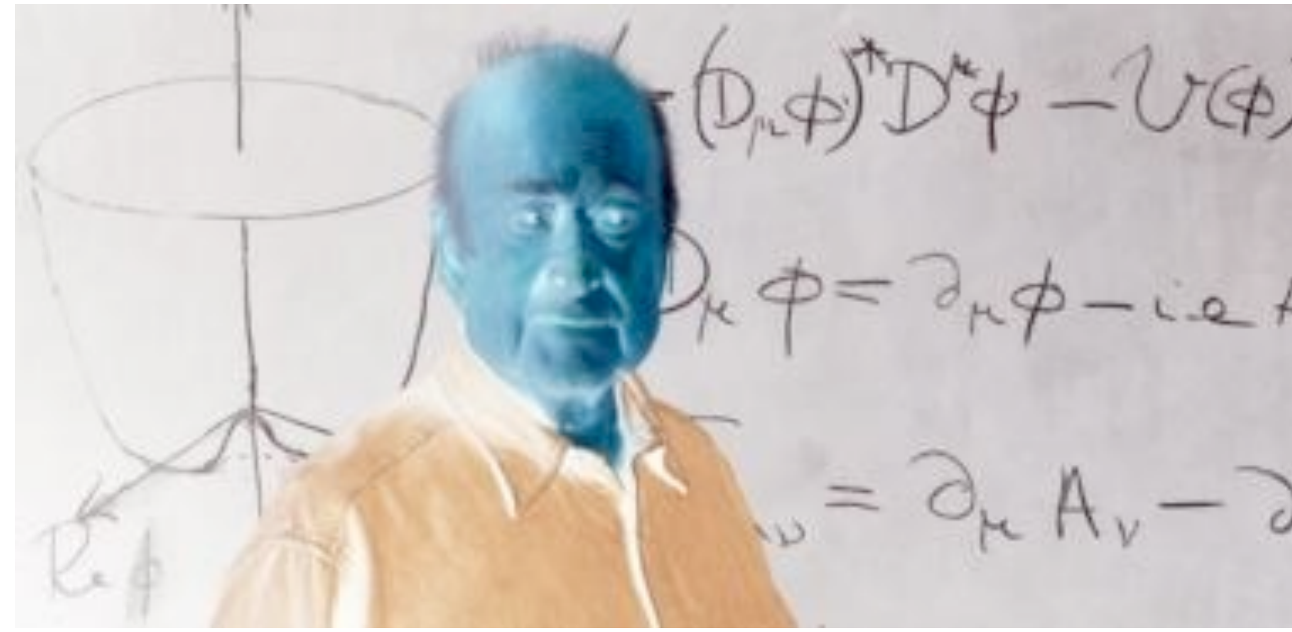
Beyond the SM Higgs



If the (light) Higgs weighs ~125 GeV...



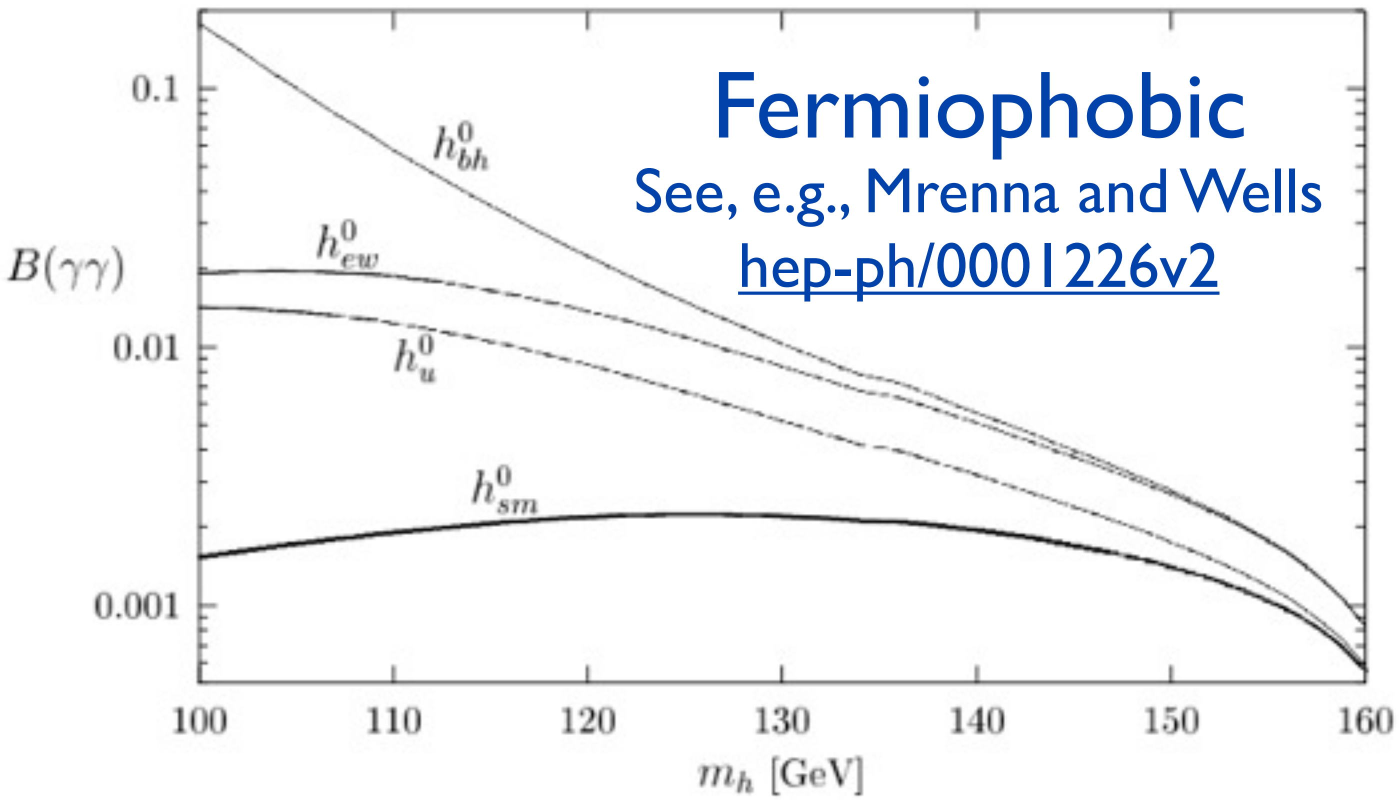
Standard Model Higgs



Beyond the SM Higgs

- Suppose that this is not a Standard Model Higgs
  - Higgs with different couplings? ⇒ MSSM, SM4, Fermiophobic
  - More complicated Higgs sector? ⇒ MSSM, Doubly-charged Higgs
  - Light scalar Higgs? ⇒ NMSSM
  - Hidden Higgs sector? ⇒ Higgs to long-lived particles

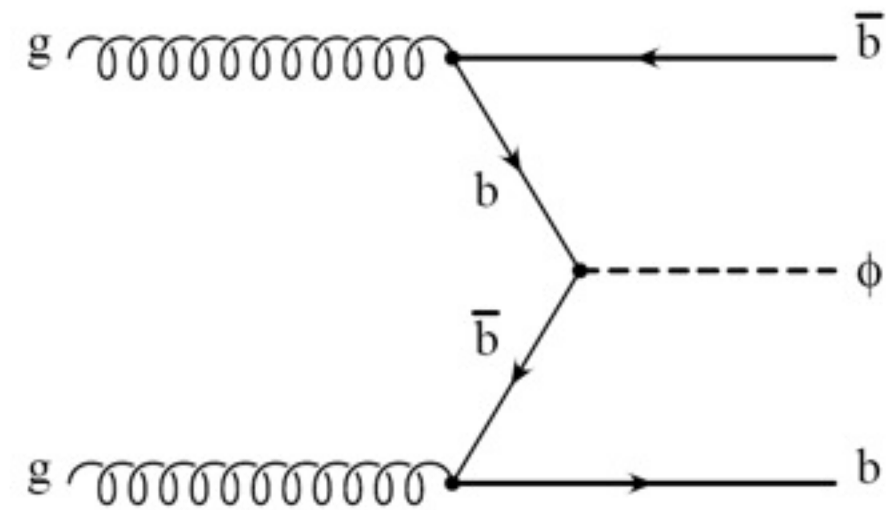
Beyond the Standard Model Higgs Bosons



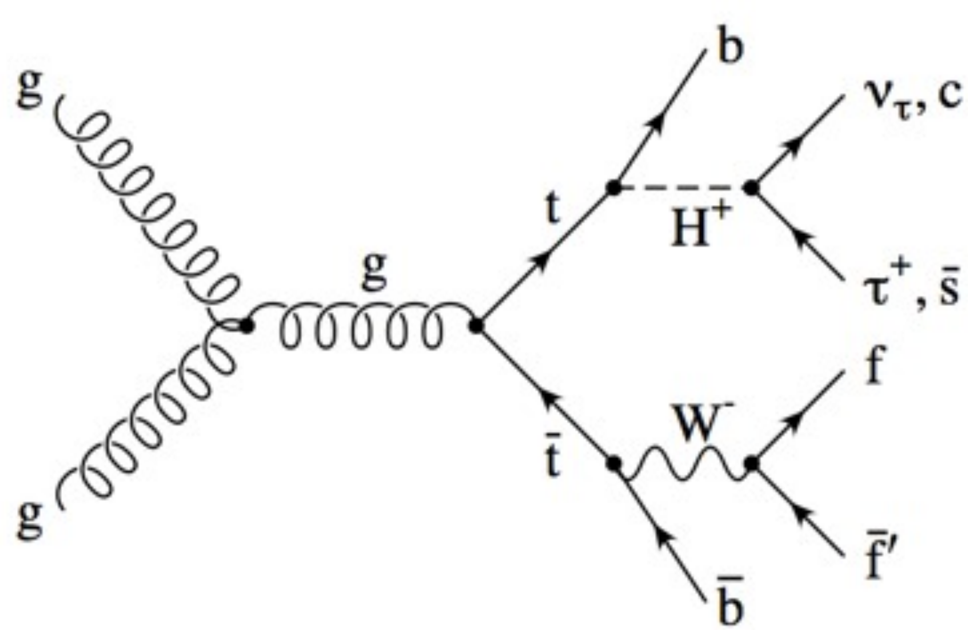
Fermiophobic

See, e.g., Mrenna and Wells

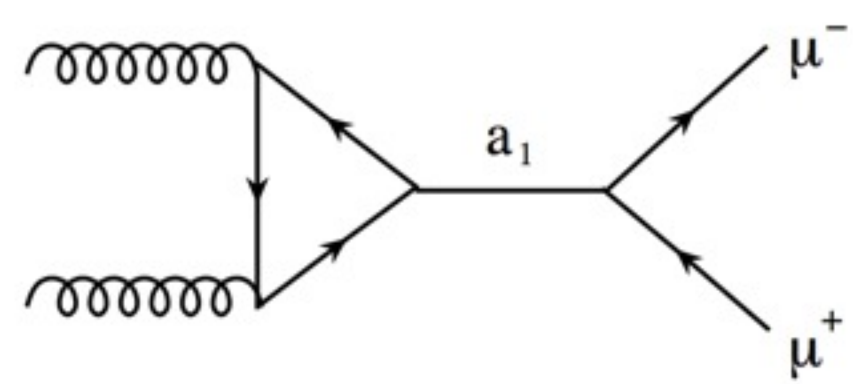
hep-ph/0001226v2



MSSM ϕ=h/A/H



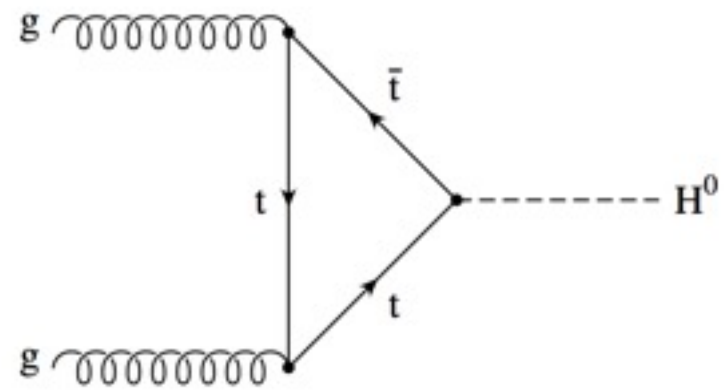
Charged Higgs $H^\pm$



NMSSM $a_1 \to \tau^+\tau^-, \mu^+\mu^-$

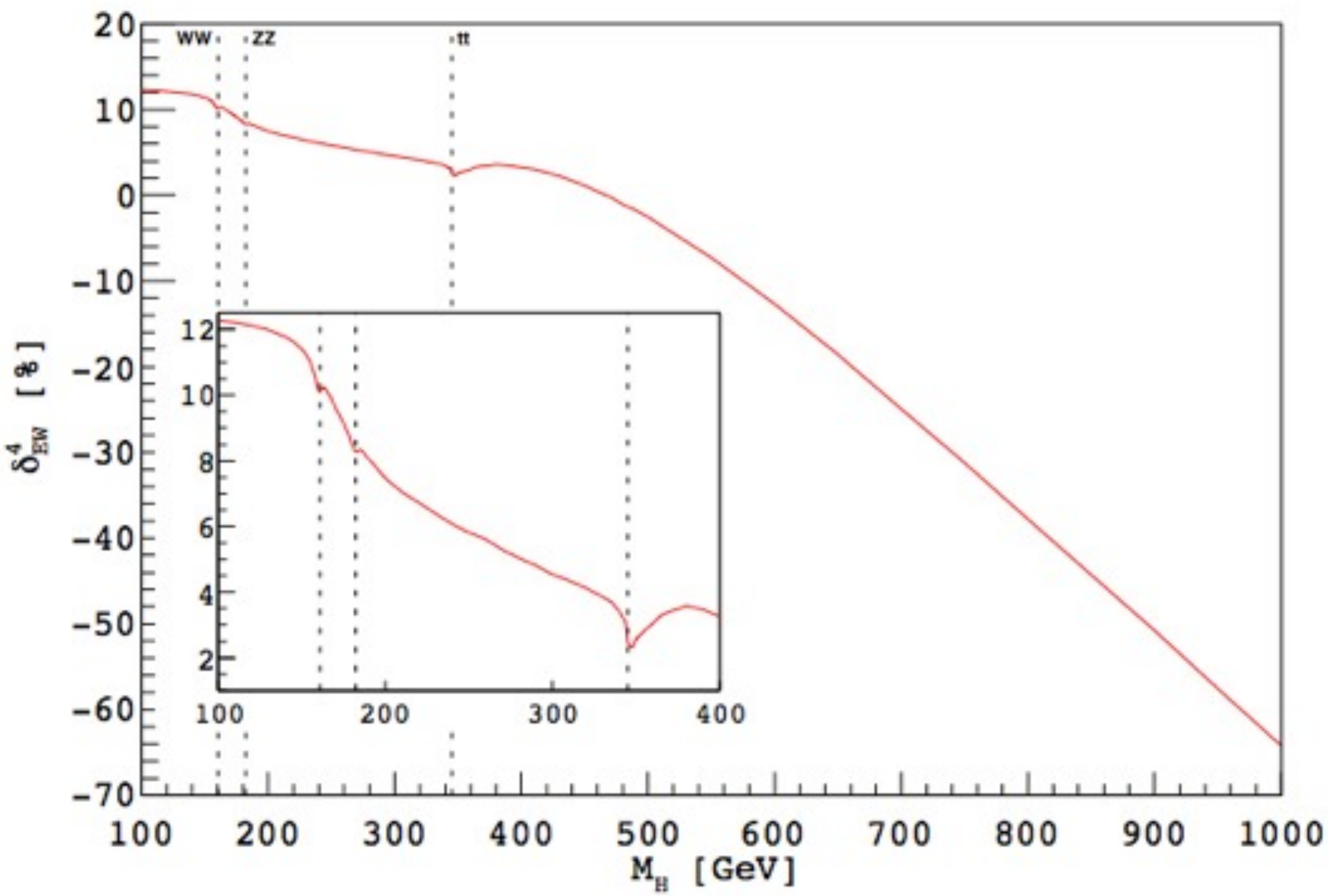
SM4 Higgs Search

- An additional 4th generation of fermions modifies the gg fusion production mode and the Higgs decay branching ratios

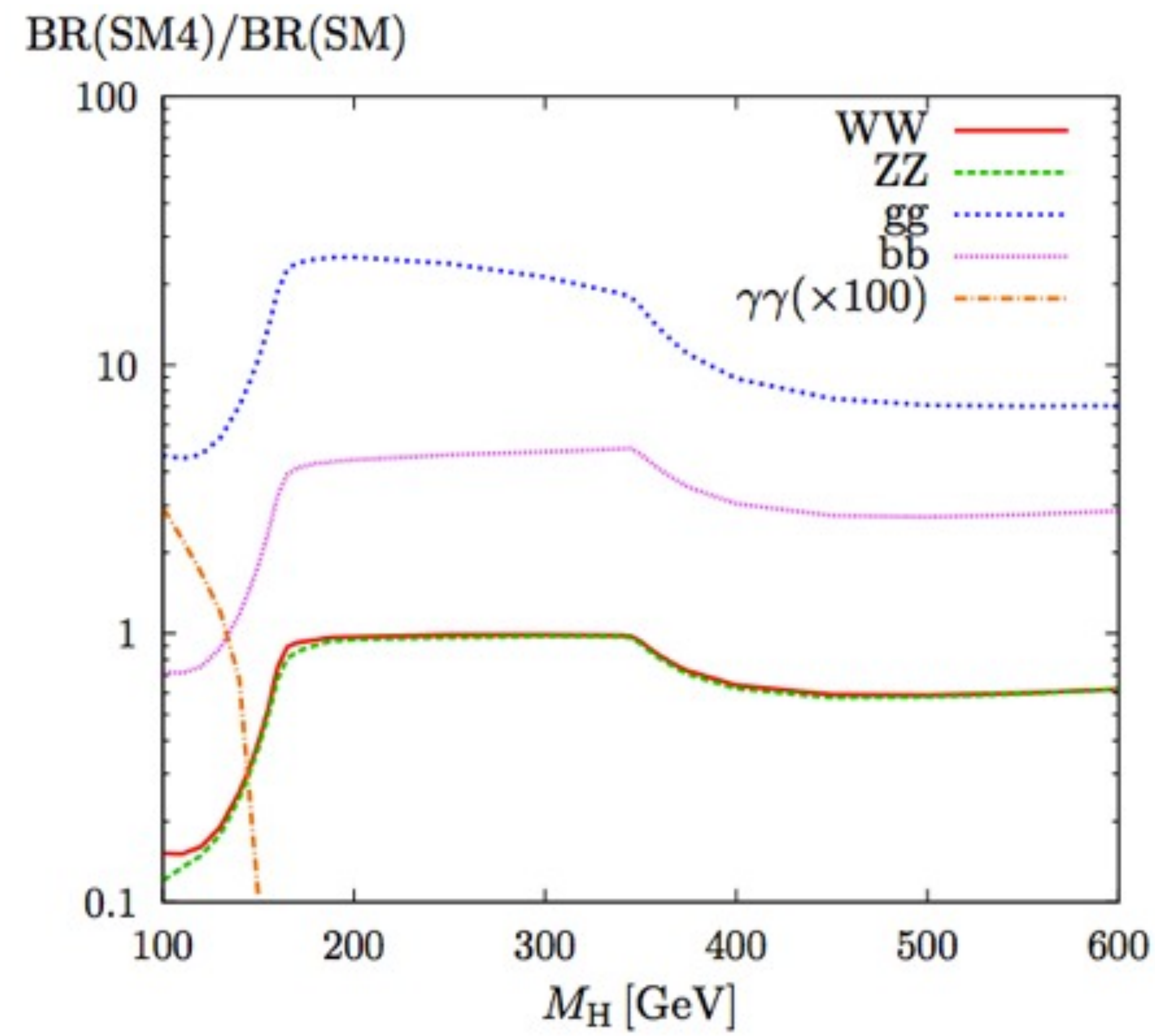


LHC Higgs XS Group
Yellow Report 2
arXiv: 1201.3084

NLO EWK correction to
the ggF Higgs production
in SM4



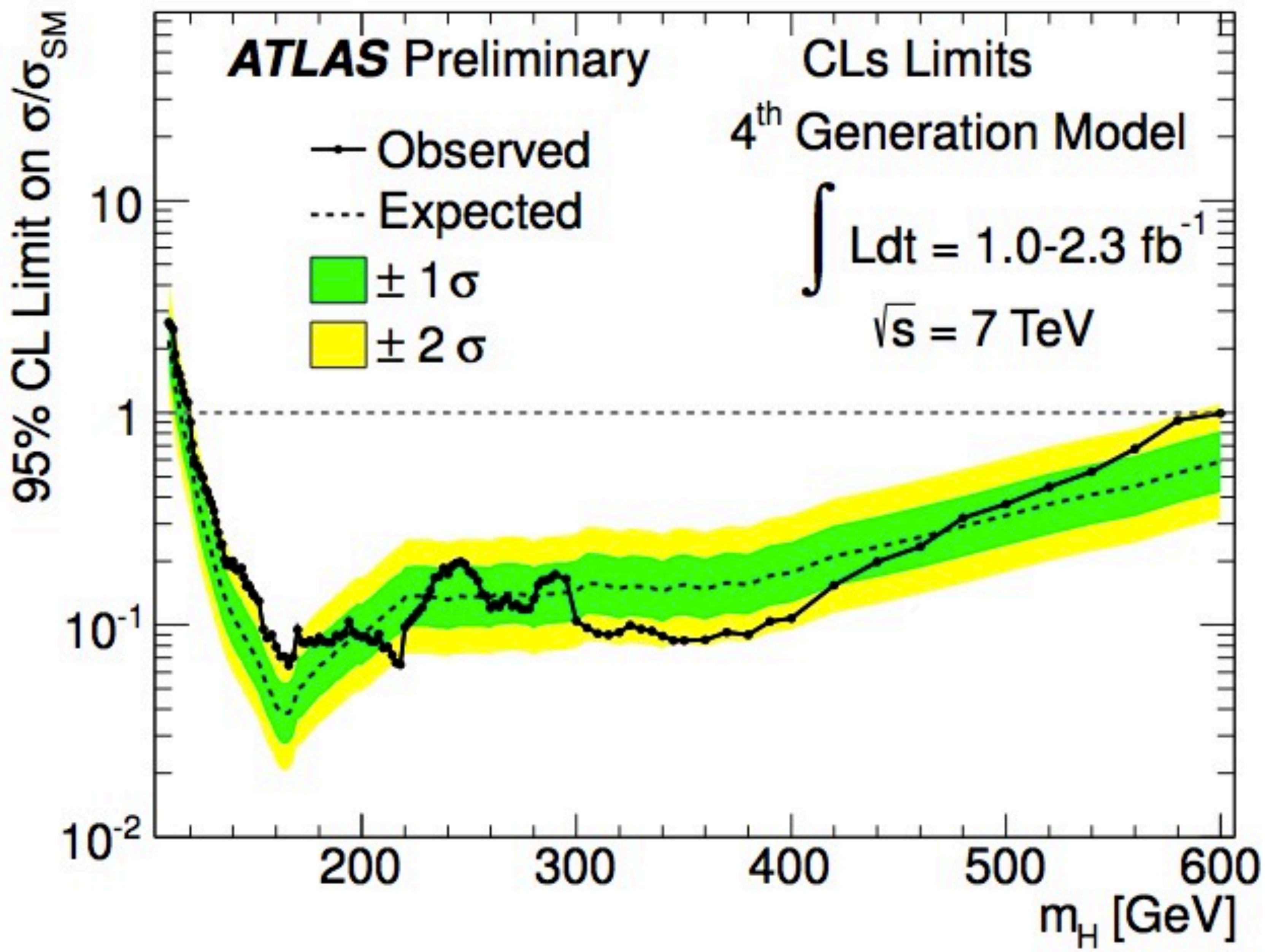
mD4 = mL4 = 600 GeV and
mU4 − mD4 = (50 + 10 ln(mH/115[GeV])) GeV



Ratio of BRs in SM4/SM
(calculated using Prophecy4f
and HDECAY)

SM4 Higgs Search

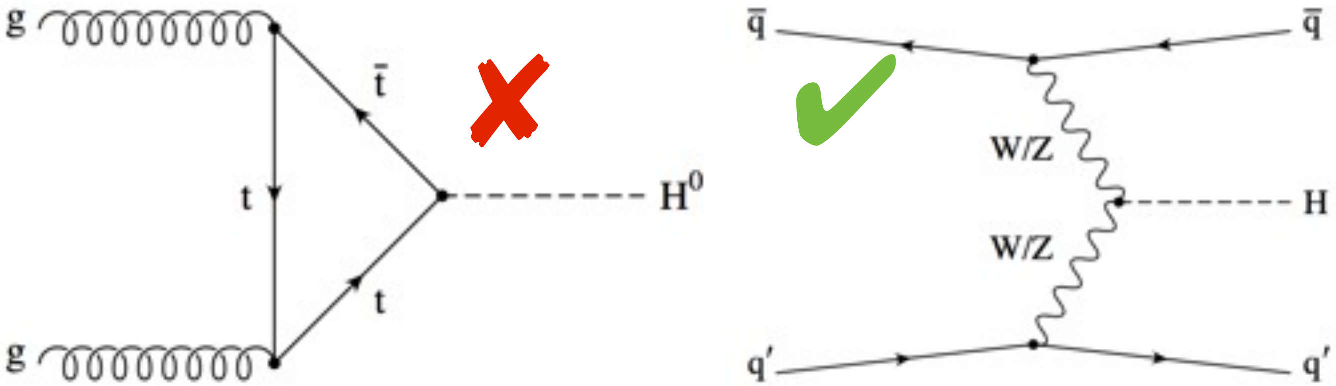
- The enhanced cross section relative to the SM allows for an exclusion of large parts of the parameter space
  - Higgs mass range of 120−600 GeV is excluded at the 95% CL

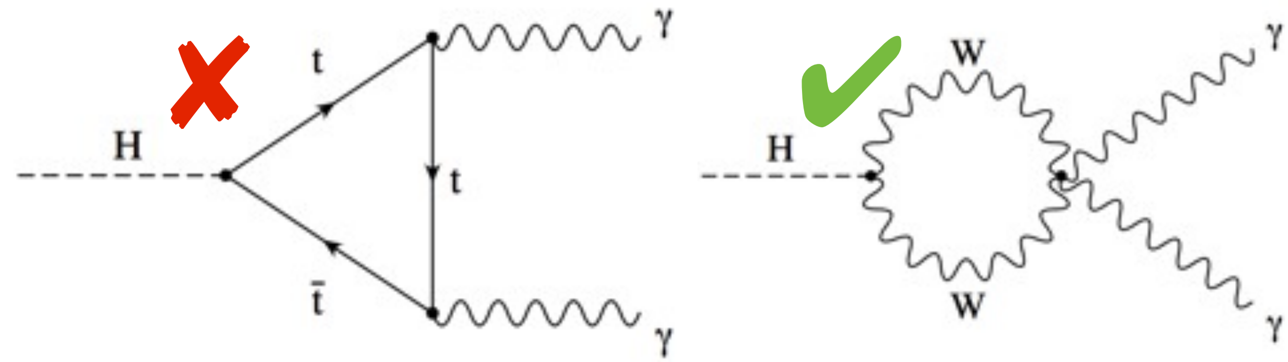


ATLAS-CONF-2011-135

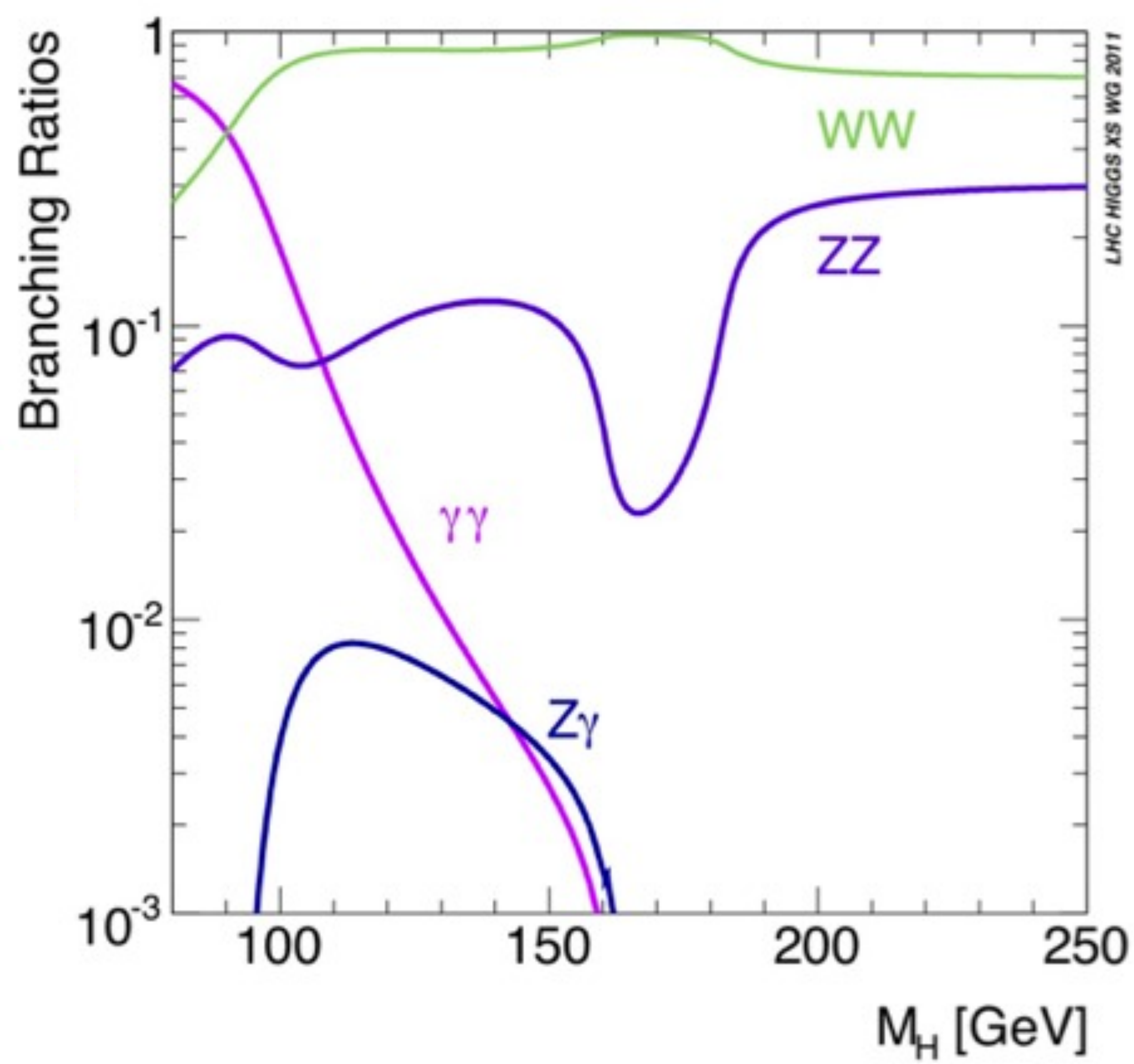
Fermiophobic Higgs Searches

- Couplings to all fermion generations substantially suppressed (two Higgs doublet models or Higgs triplet models)





- No couplings to fermions
- Production via VBF and VH
- Decay via γγ, ZZ, WW and Zγ
- ATLAS search very similar to the SM Higgs → γγ search

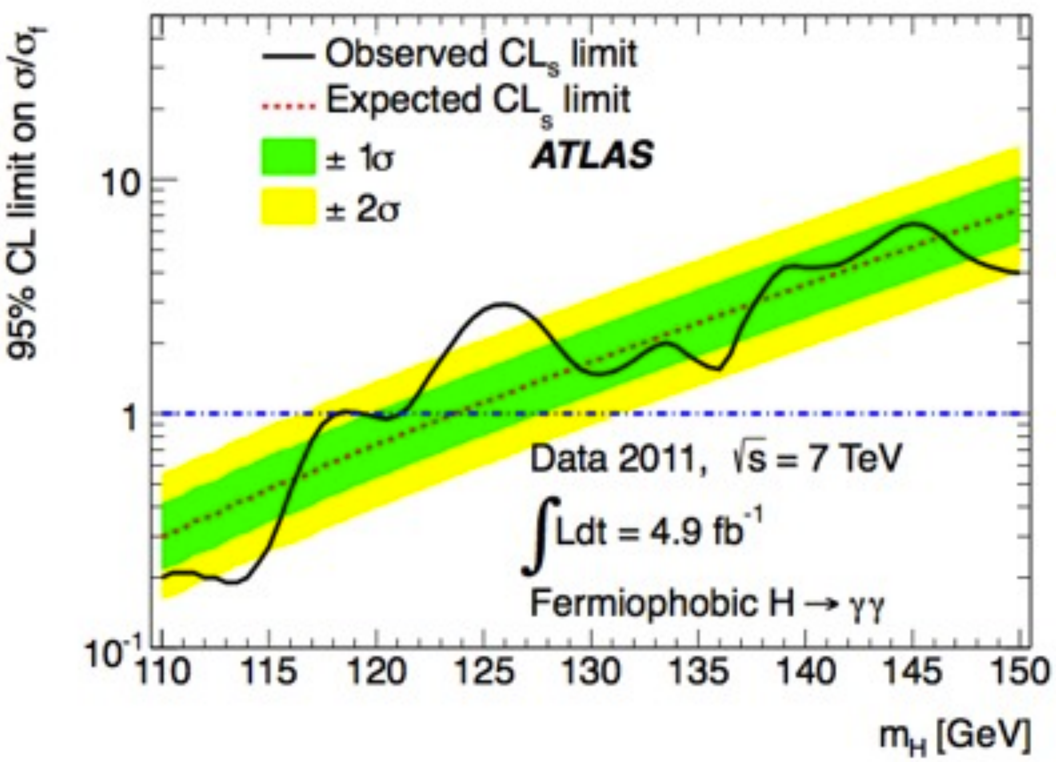


Fermiophobic Higgs Searches

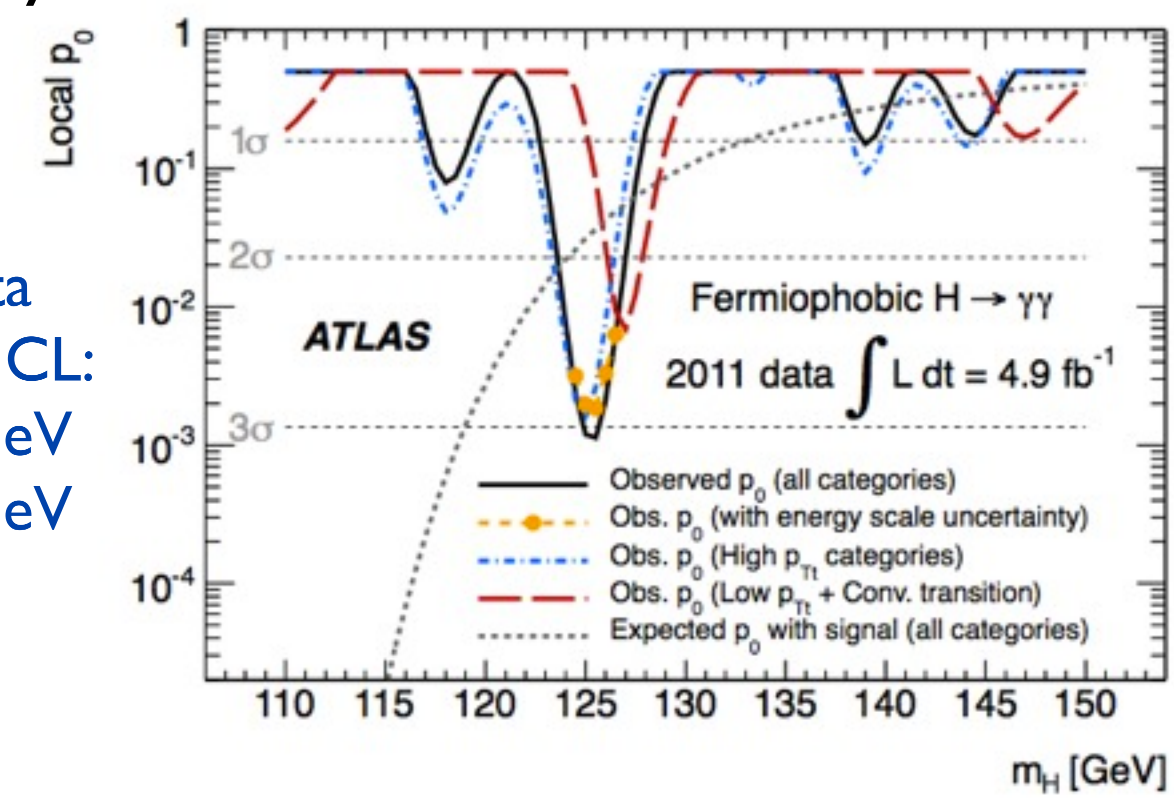
- Fermiophobic Higgs search results from ATLAS only for the $\gamma\gamma$ analysis
  - Same event selection as used in the SM $\gamma\gamma$ analysis; see Jonas' talk from Monday

2 photons pT > 40 / 25 GeV
Categories based on conversions, η and di-photon pT
Signal modelled with "crystal ball" (= gaussian core+power law low-end tail)+gaussian; bkg with exponential

- Will include results from the WW and ZZ analyses in the near future



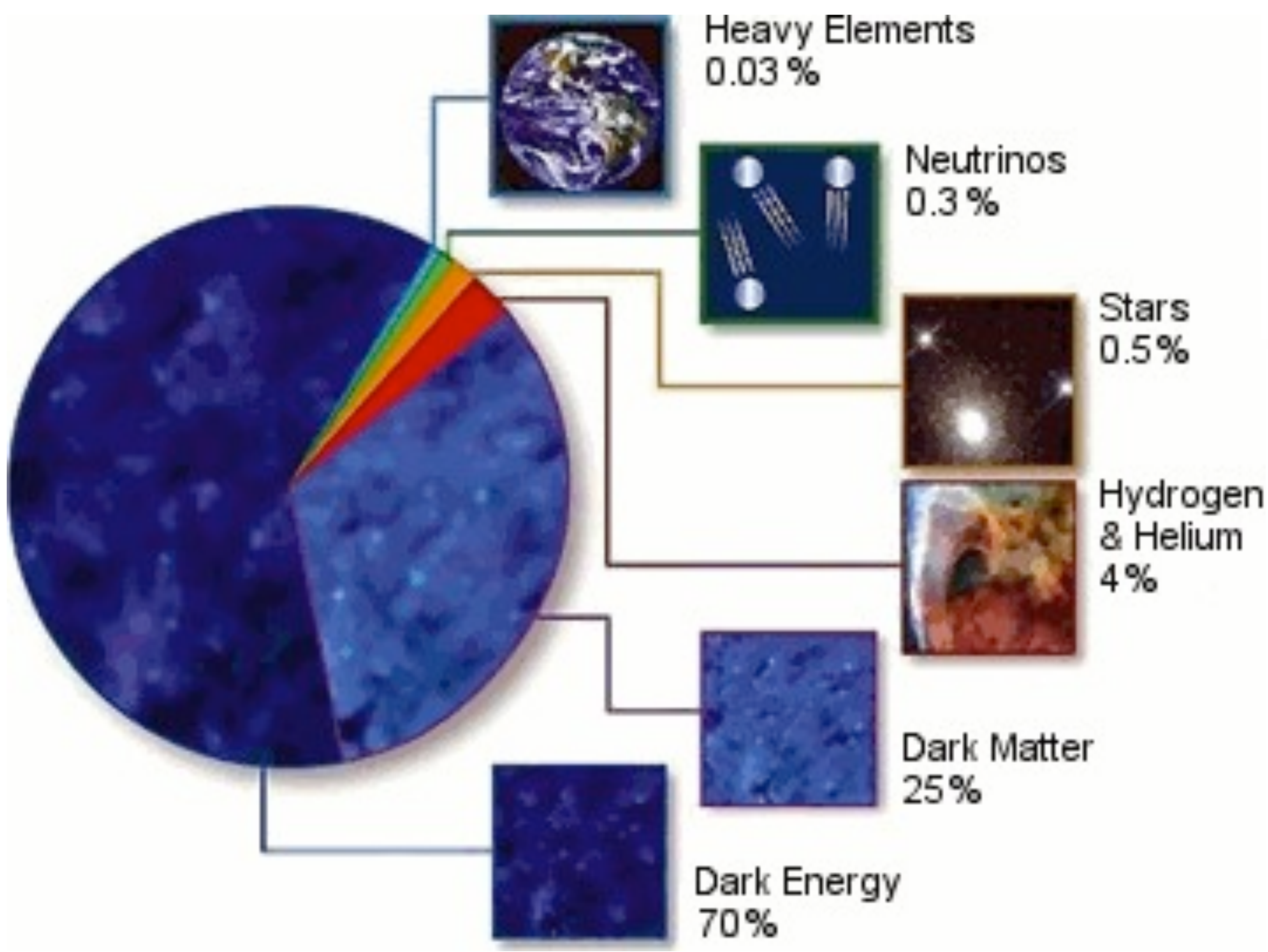
With 2011 data excluded at 95% CL:
110.0 – 118.0 GeV
119.5 – 121.0 GeV

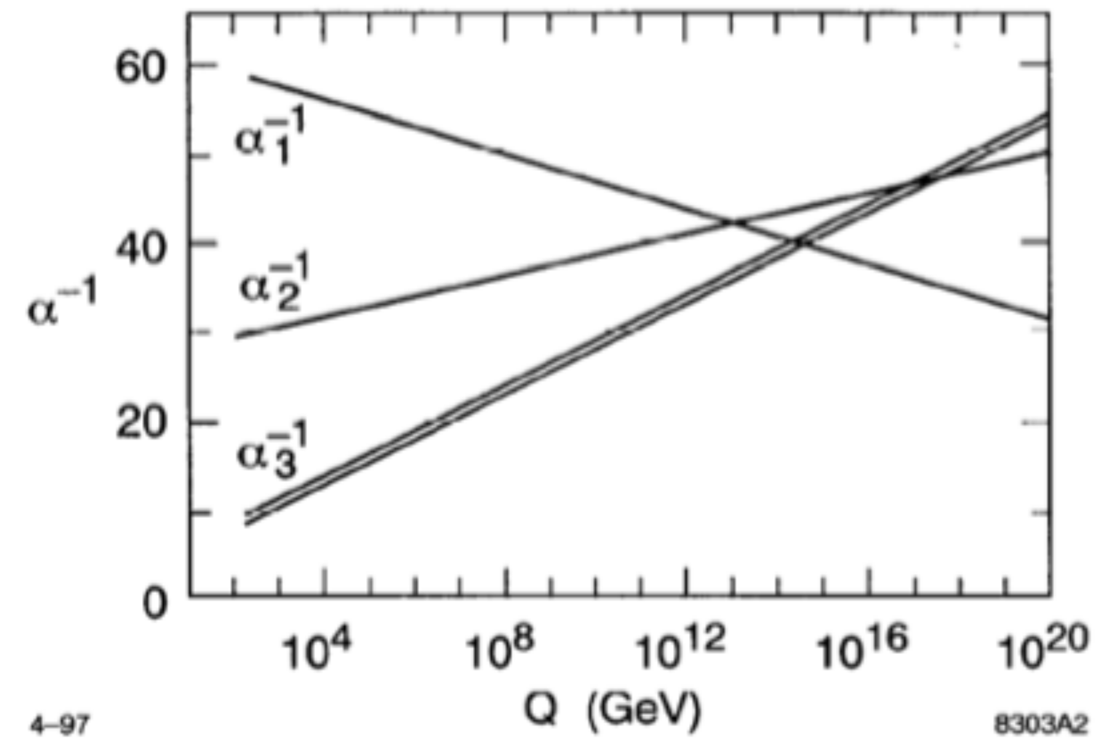


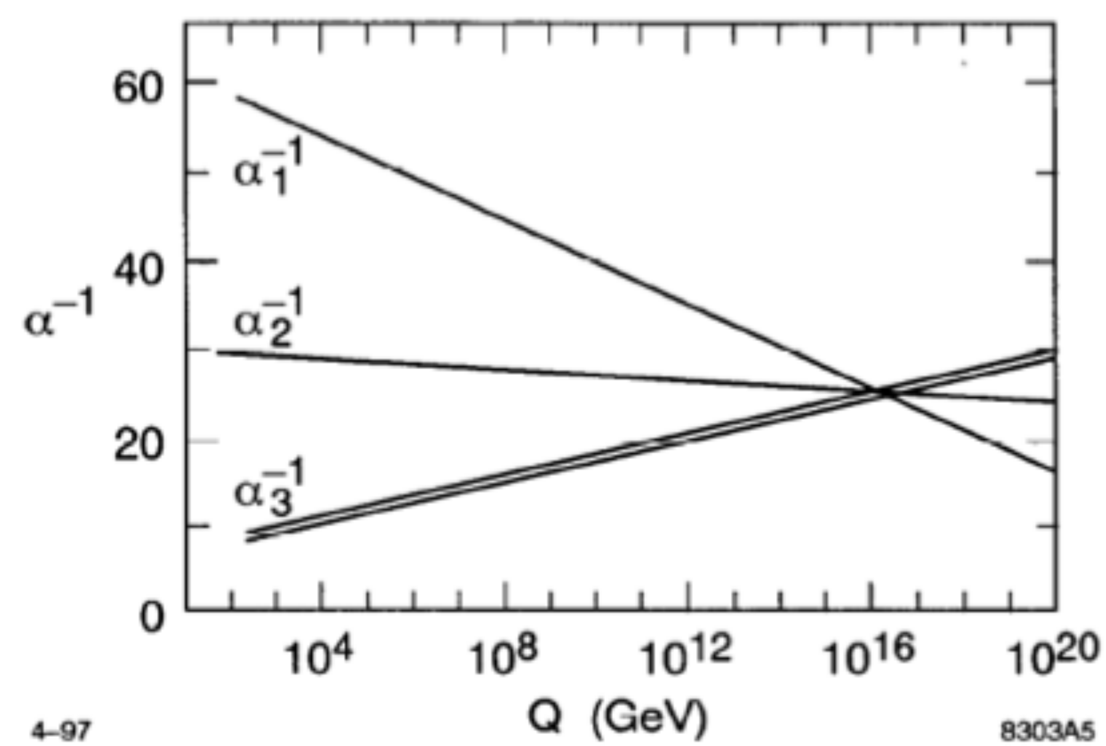
[Eur. Phys. J. C (arXiv: 1205.0701)]

Motivation for Supersymmetry

- Motivation for Supersymmetry:
  - Naturalness (Hierarchy Problem)
  - Unification of the forces (gauge couplings)
  - Provides a candidate for Dark Matter

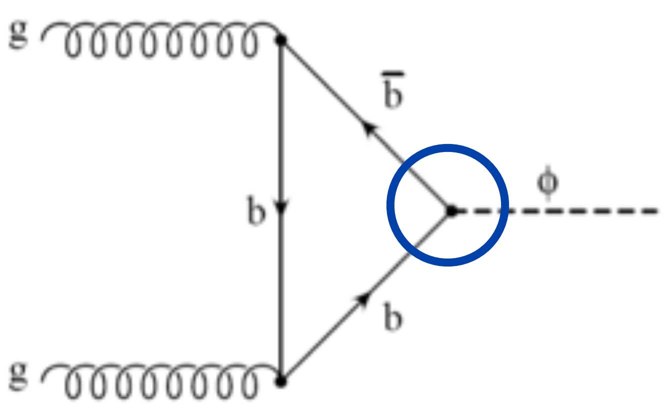


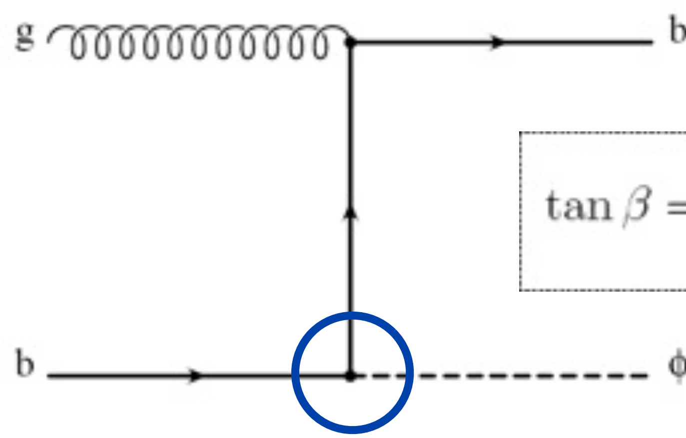




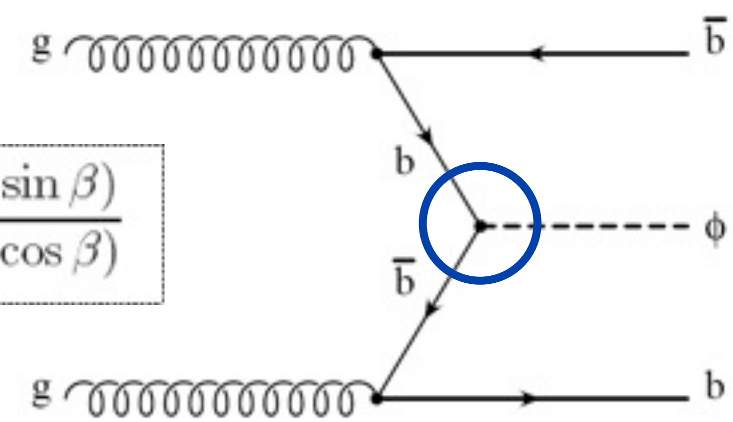
MSSM Higgs Sector

- Consider the case of an MSSM Higgs at the LHC
  - 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/H/A production rates)
  - Diagrams with bbϕ vertex enhanced proportional to $\tan^2\beta$ where ϕ=h,H,A

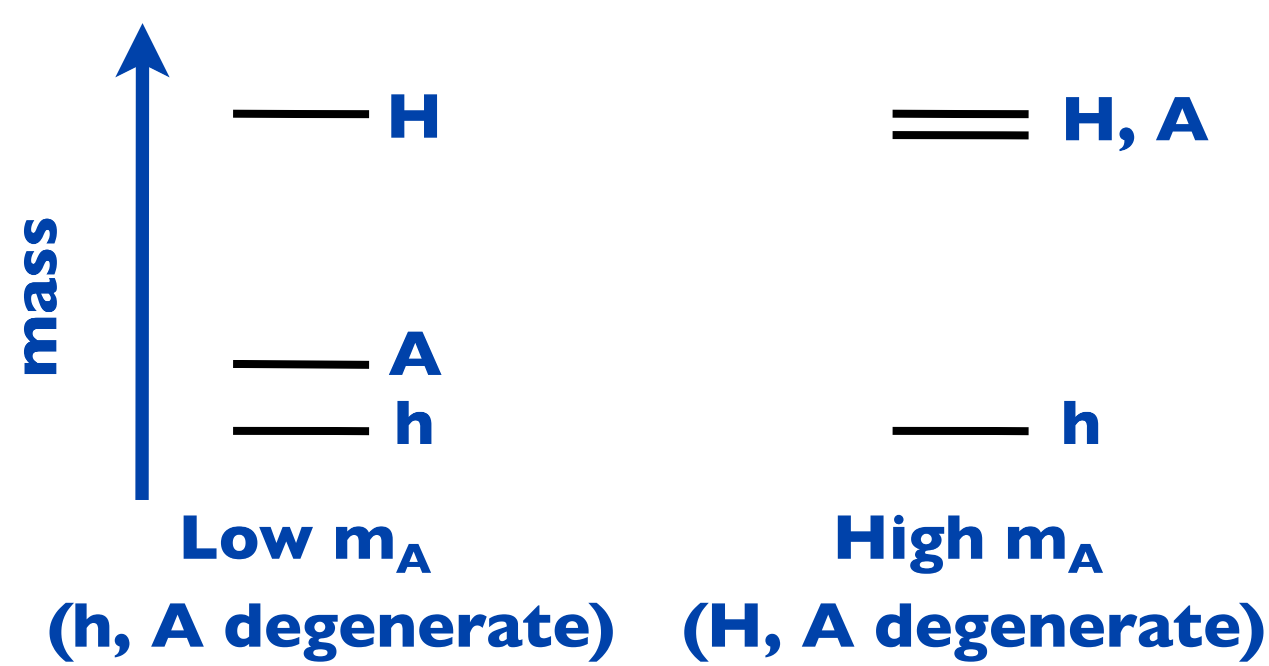


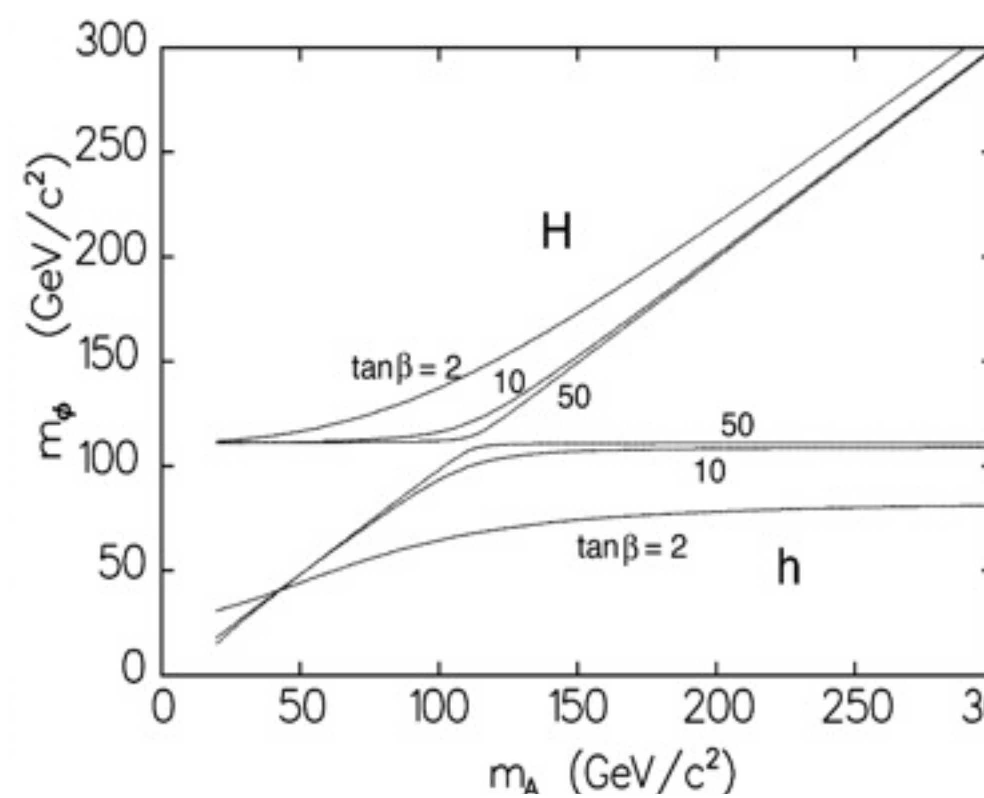


$$\tan\beta = \frac{v_2}{v_1} = \frac{(v\sin\beta)}{(v\cos\beta)}$$



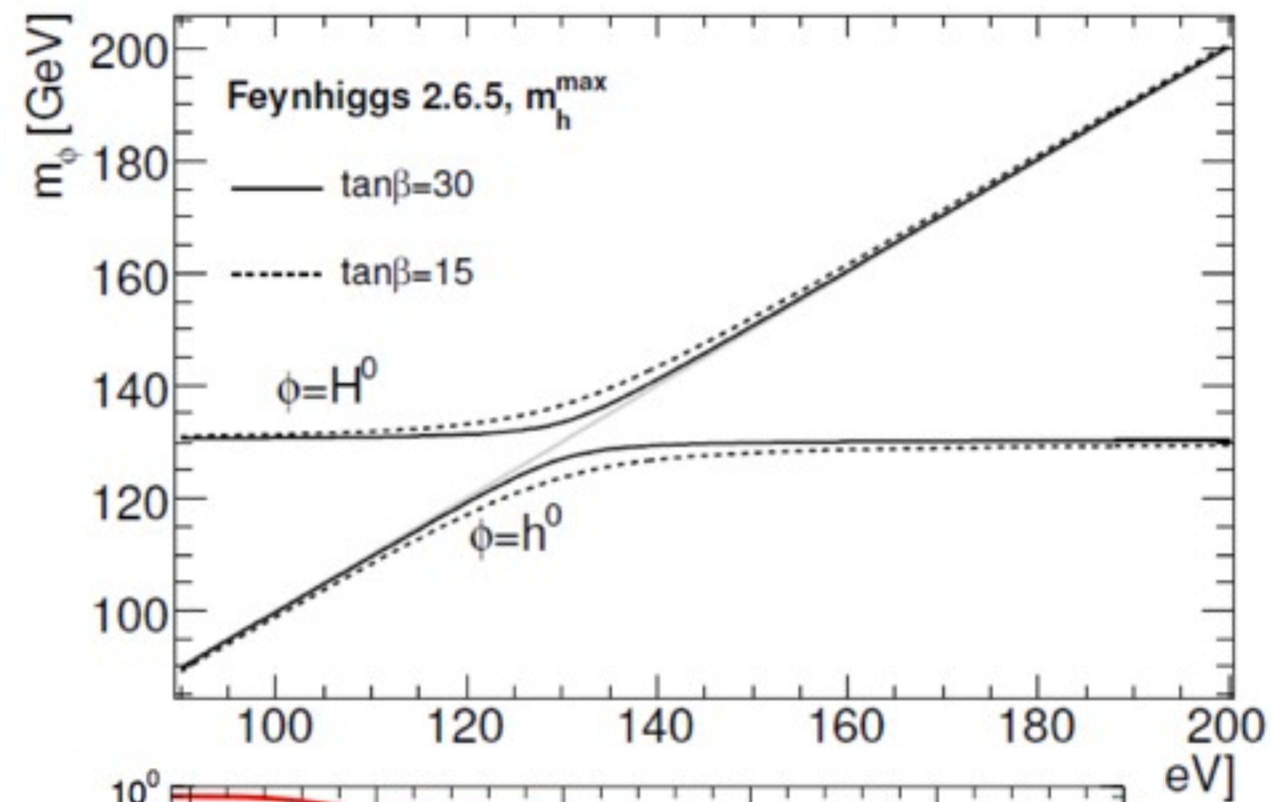
  - Can parameterize the masses of the Higgs bosons with two free parameters: tanβ and m_A

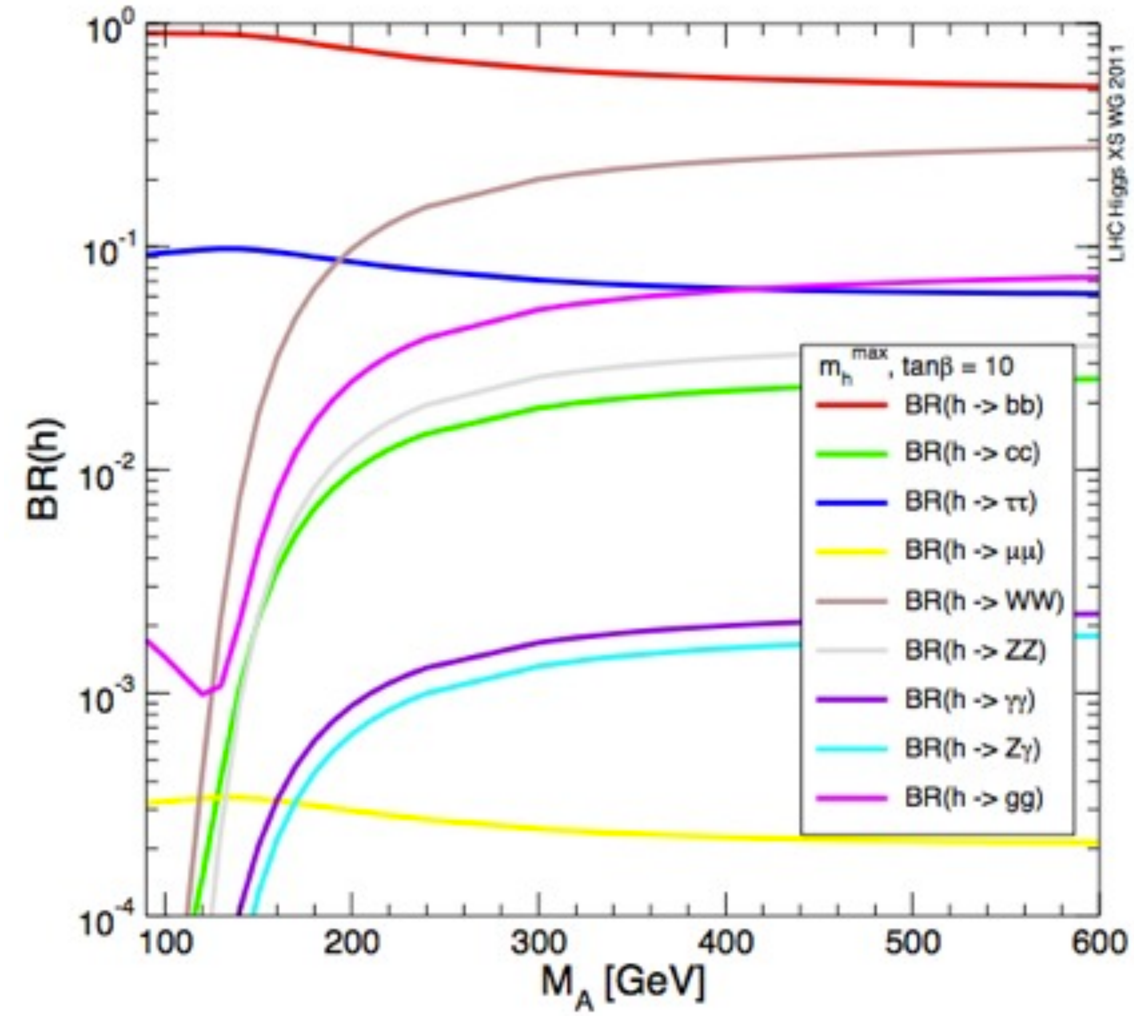


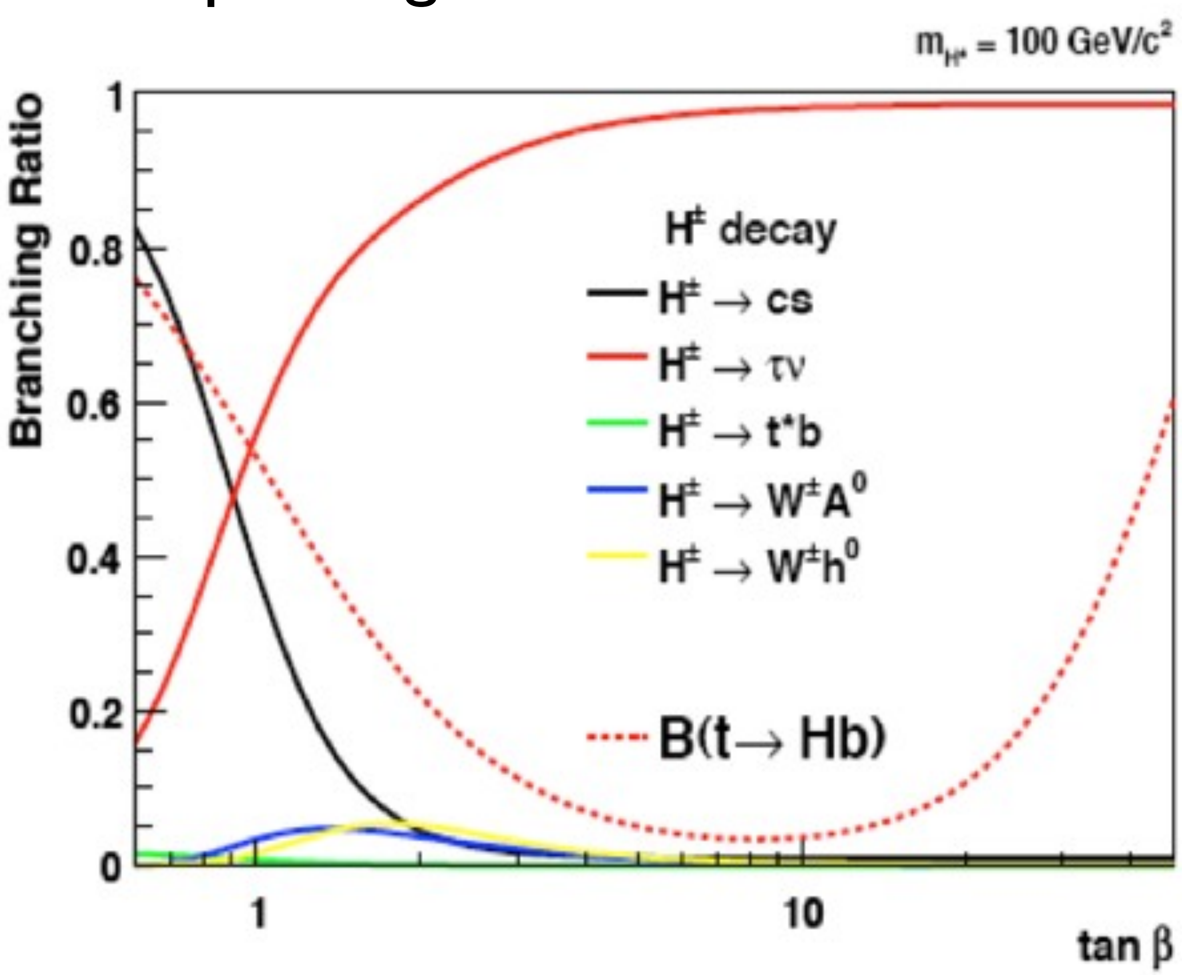


MSSM Higgs Sector

- A popular and well-studied extension of the Standard Model
  - Mass of h < 135 GeV
  - For large parts of parameter space $H \rightarrow \tau\tau$ and $H^{\pm} \rightarrow \tau^{\pm}\nu$ decays are dominant, WW / ZZ decays are suppressed
  - Charged Higgs produced mainly in top decays or in association with tb, depending on its mass







Mass Reconstruction with τ leptons

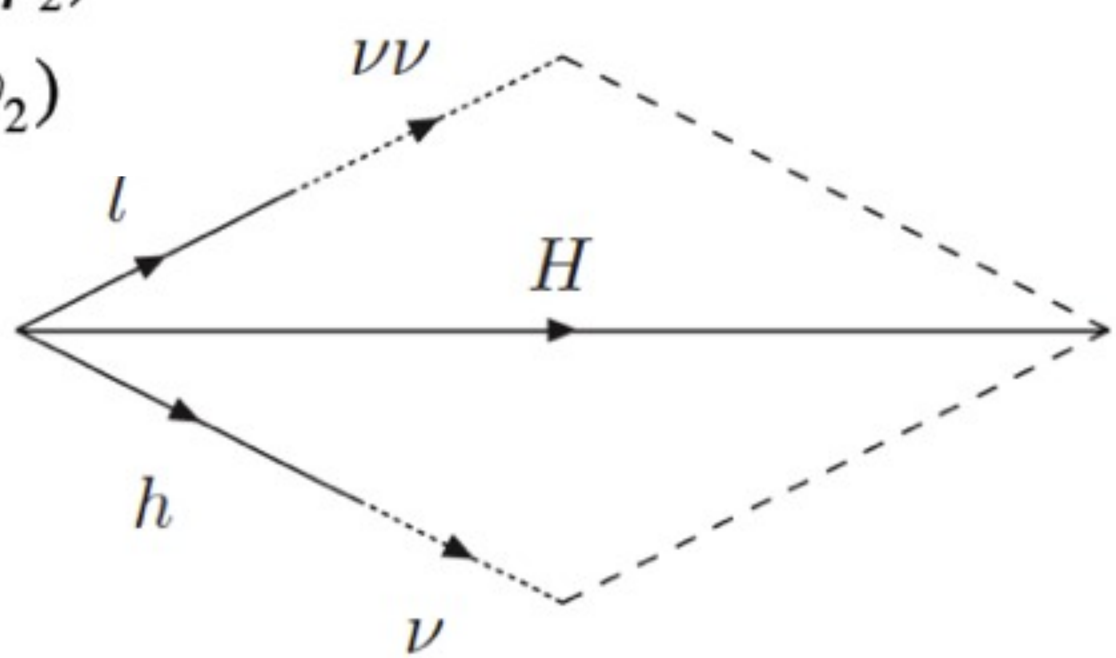
- Visible mass:
  - Invariant mass of the visible τ decay products
- Effective mass
  - Invariant mass of the visible τ decay products + MET
- Collinear mass:
  - Assume that neutrinos are emitted parallel to the visible τ decay products' direction ⇒ 2 equations and 2 unknowns

$$\not{E}_X = P_{\nu 1} \cdot \cos(\theta_1) \cdot \cos(\varphi_1) + P_{\nu 2} \cdot \cos(\theta_2) \cdot \cos(\varphi_2)$$

$$\not{E}_Y = P_{\nu 1} \cdot \cos(\theta_1) \cdot \sin(\varphi_1) + P_{\nu 2} \cdot \cos(\theta_2) \cdot \sin(\varphi_2)$$

$$m_{collinear} = \frac{m_{vis}}{x_1 x_2}$$

$x_{1,2}$ are the momentum fractions carried away by the visible τ products



Mass Reconstruction with τ leptons

- Missing Mass Calculator technique
  - A step beyond the "collinear mass"
  - Assume the angle between the neutrinos and the visible hadronic τs (Δθ) is non-zero
  - End up with more unknowns than equations

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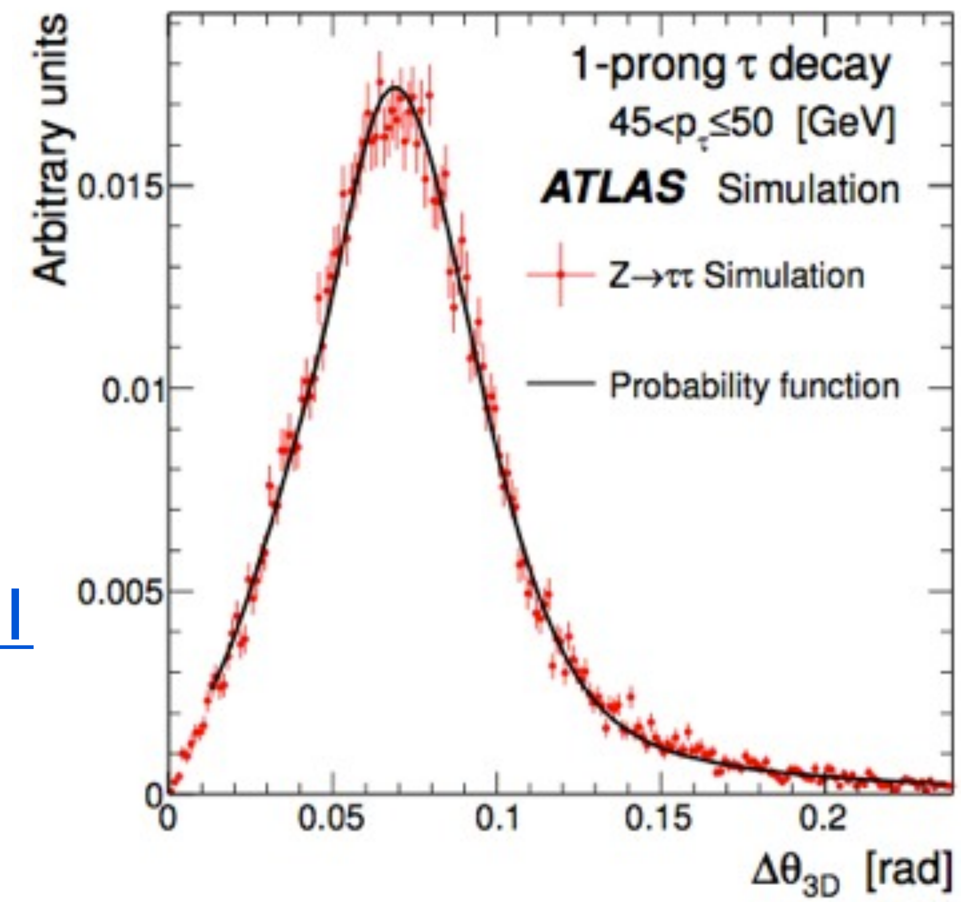


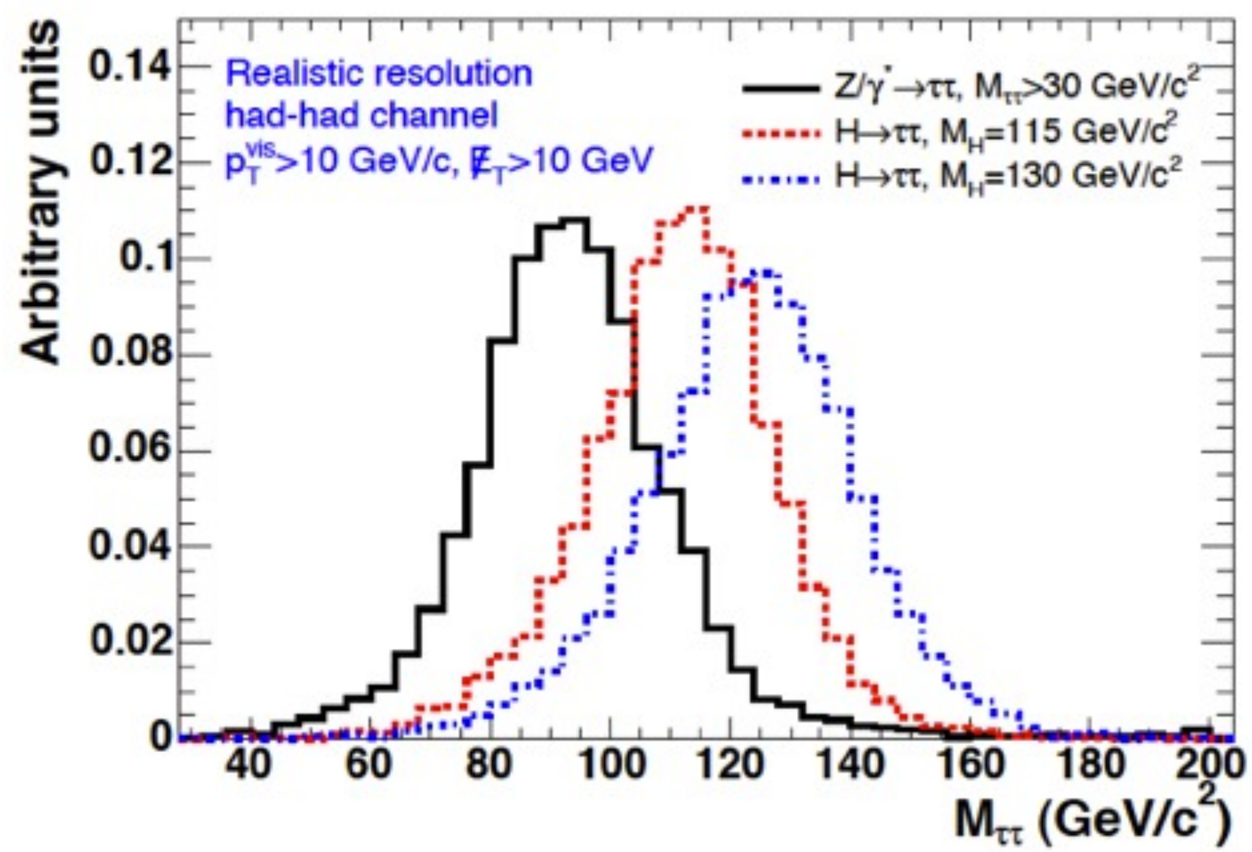
$$\not{E}_{T_x} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \cos\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \cos\phi_{\text{mis}_2}$$

$$\not{E}_{T_y} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \sin\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \sin\phi_{\text{mis}_2}$$

$$M_{\tau_1}^2 = m_{\text{mis}_1}^2 + m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{mis}_1}^2 + m_{\text{mis}_1}^2} - 2p_{\text{vis}_1}p_{\text{mis}_1}\cos\Delta\theta_{vm_1}$$

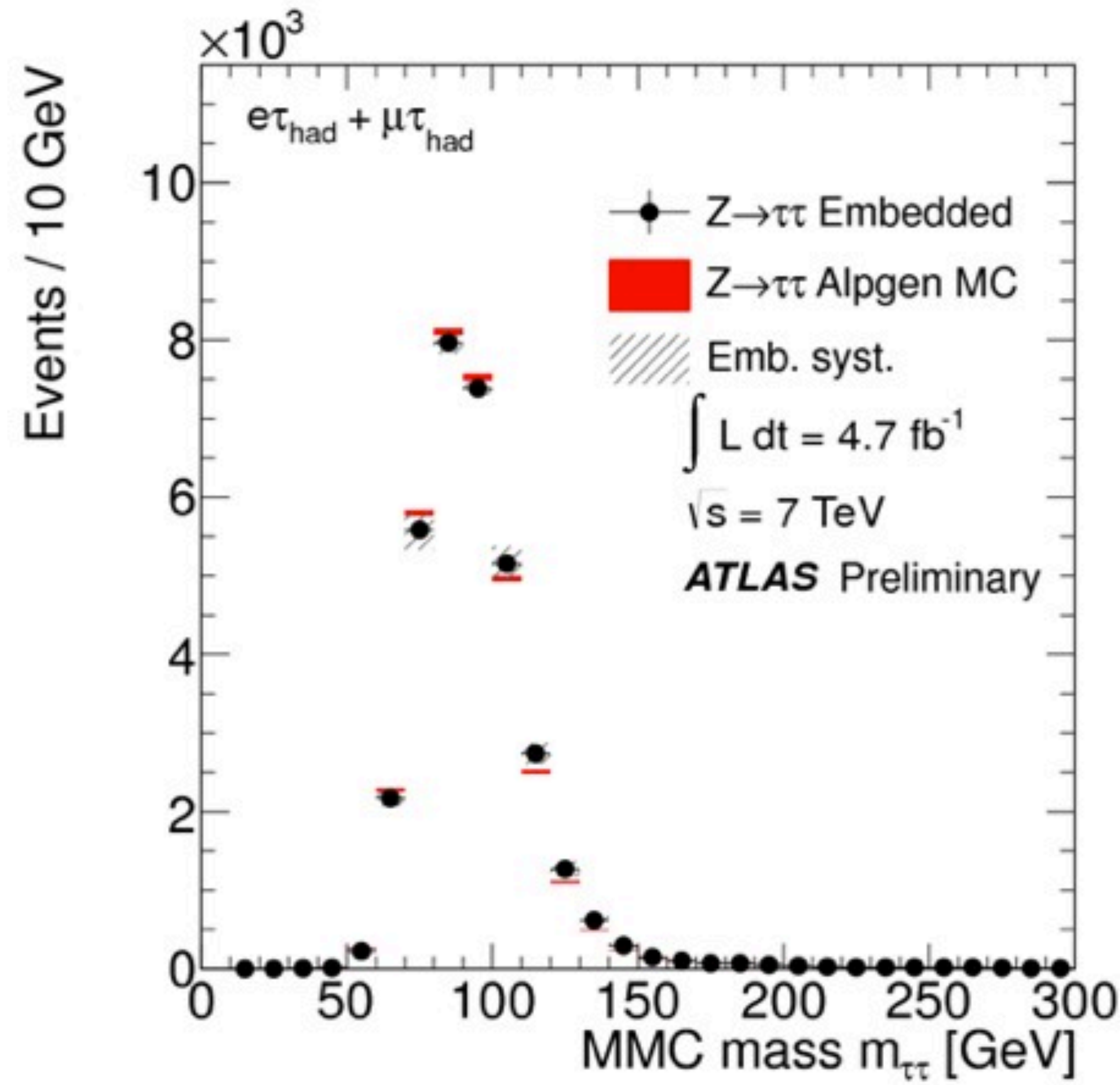
$$M_{\tau_2}^2 = m_{\text{mis}_2}^2 + m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2}\sqrt{p_{\text{mis}_2}^2 + m_{\text{mis}_2}^2} - 2p_{\text{vis}_2}p_{\text{mis}_2}\cos\Delta\theta_{vm_2}$$

- Use a likelihood to solve an under-constrained set of equations
  - Solve the equations in a grid of angles Δθ and choose the best one



Special Techniques Used with τ leptons

- $Z \rightarrow \tau\tau$ is the most important (irreducible) background source for di-τ final states
- Embedding technique ("τ-embedded" $Z \rightarrow \mu\mu$ data events):
- A semi-data-driven method: select an adequately pure $Z \rightarrow \mu\mu$ event sample from data and then replace the muons with simulated taus
- Pile-up, underlying event, kinematics, etc. are all taken directly from the data
- ATLAS charged Higgs search also uses embedding for ttbar backgrounds

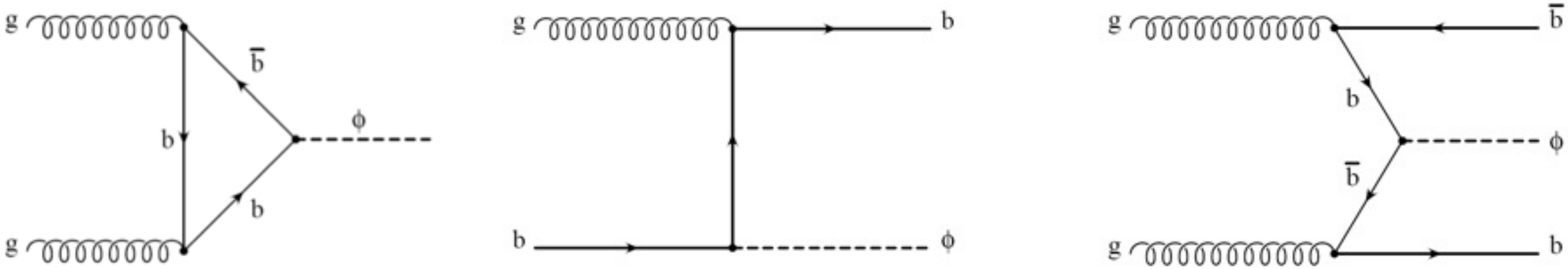


MMC di-τ mass for "tau embedding" and Alpgen simulation

Neutral MSSM Higgs Search

- MSSM Neutral Analysis (three main channels, depending on the τ decay)
  - For the fully-hadronic channel a double-τ trigger is used

ATLAS-CONF-2011-132



τ(lep)τ(lep) using eμ	τ(lep)τ(had)	τ(had)τ(had)
1 isolated e with p_T > 25 GeV	**isolated e / μ** with p_T >25/20 GeV	**2 τhad** with p_T > 30/45 GeV
1 isolated μ with p_T > 20 GeV	exactly **one τhad** with p_T > 20 GeV	
Opposite sign	**Opposite sign**	**Opposite sign**
Sum of lepton pT and MET < 120 GeV, ΔΦ(e,μ)>2	MET > 20 GeV, MT<30 GeV	MET > 25 GeV

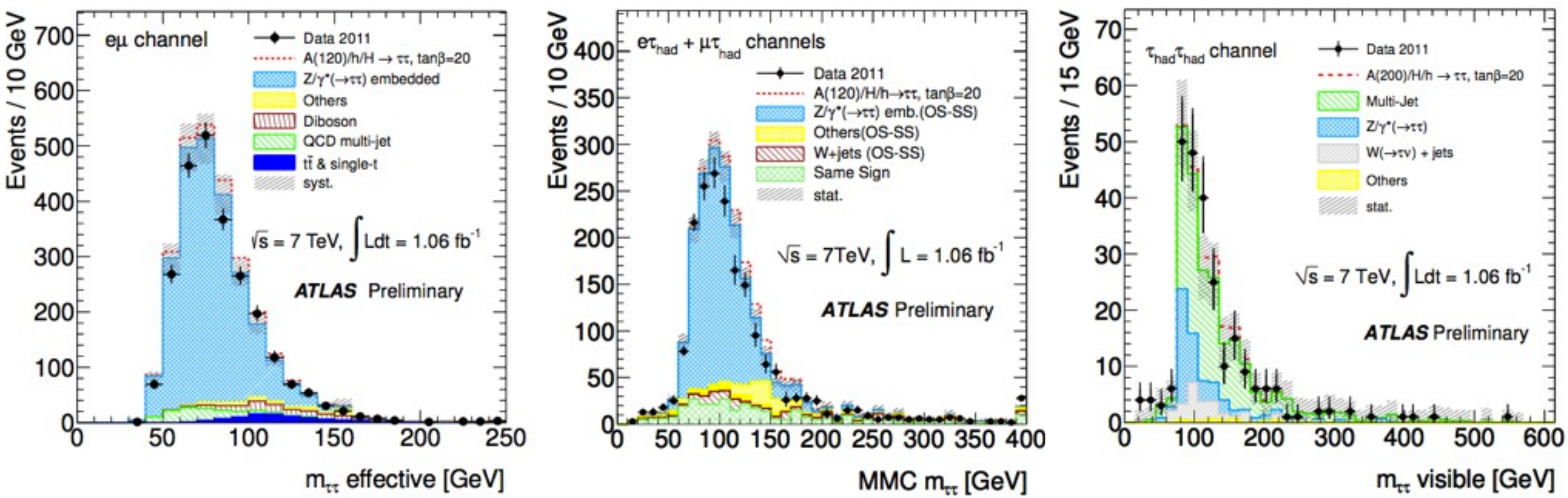
- Dominant backgrounds:
  - Z+jets (irreducible), multi-jet events, W+jets, ttbar, di-boson
- Dominant systematics:
  - Energy scale (~25%), signal cross-section (~15%), tau efficiency & fake rate (~12%)

Neutral MSSM Higgs Search

- MSSM Neutral Analysis (three main channels, depending on the τ decay)
  - For the fully-hadronic channel a τ trigger is used ATLAS-CONF-2011-132

τ(lep)τ(lep) using eμ	τ(lep)τ(had)	τ(had)τ(had)
1 isolated e with $p_T > 25$ GeV	**isolated e / μ** with p_T >25/20 GeV	**2** τ_{had} with $p_T > 30/45$ GeV
1 isolated μ with $p_T > 20$ GeV	exactly **one** τ_{had} with $p_T > 20$ GeV	
Opposite sign	**Opposite sign**	**Opposite sign**
Sum of lepton pT and MET < 120 GeV, ΔΦ(e,μ)>2	MET > 20 GeV, MT<30 GeV	MET > 25 GeV

Mass distributions:



MSSM Neutral Higgs Search

- Combine the τ_{lep}-τ_{had}, τ_{had}-τ_{had} and τ_e-τ_μ channels for one exclusion limit
  - Limit with the m_h^{max} benchmark scenario
  - Also determine a σ x BR limits

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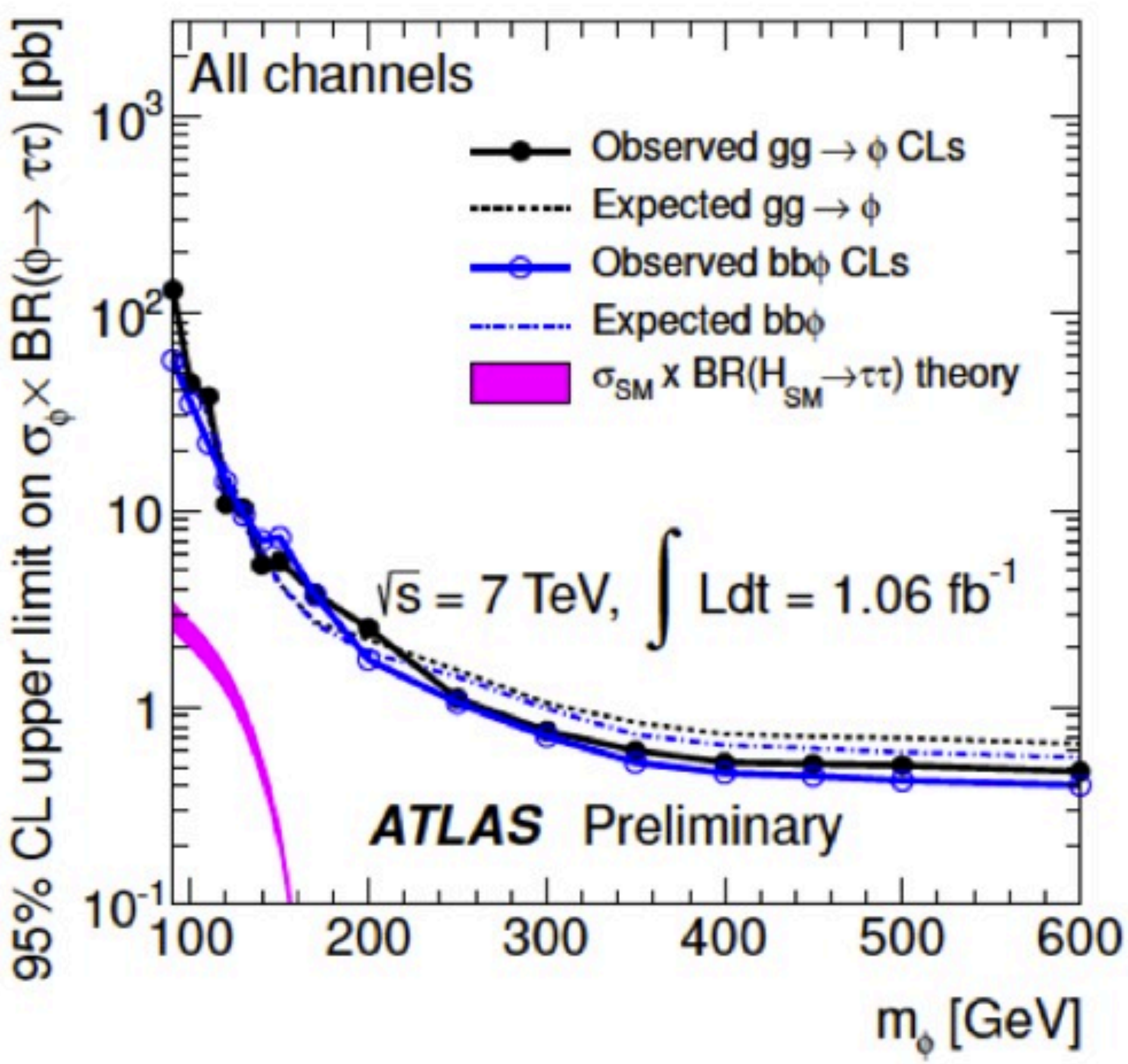
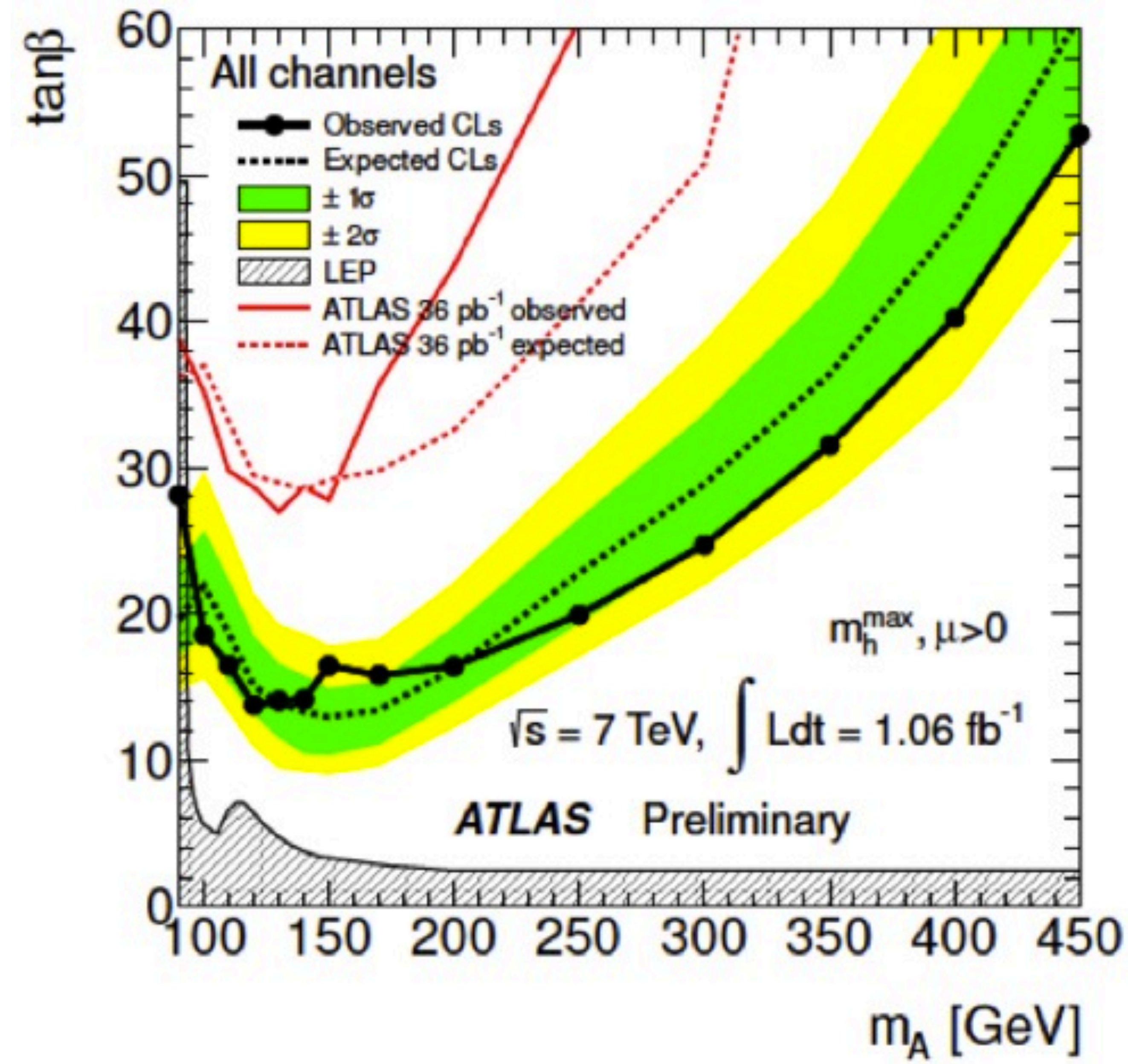


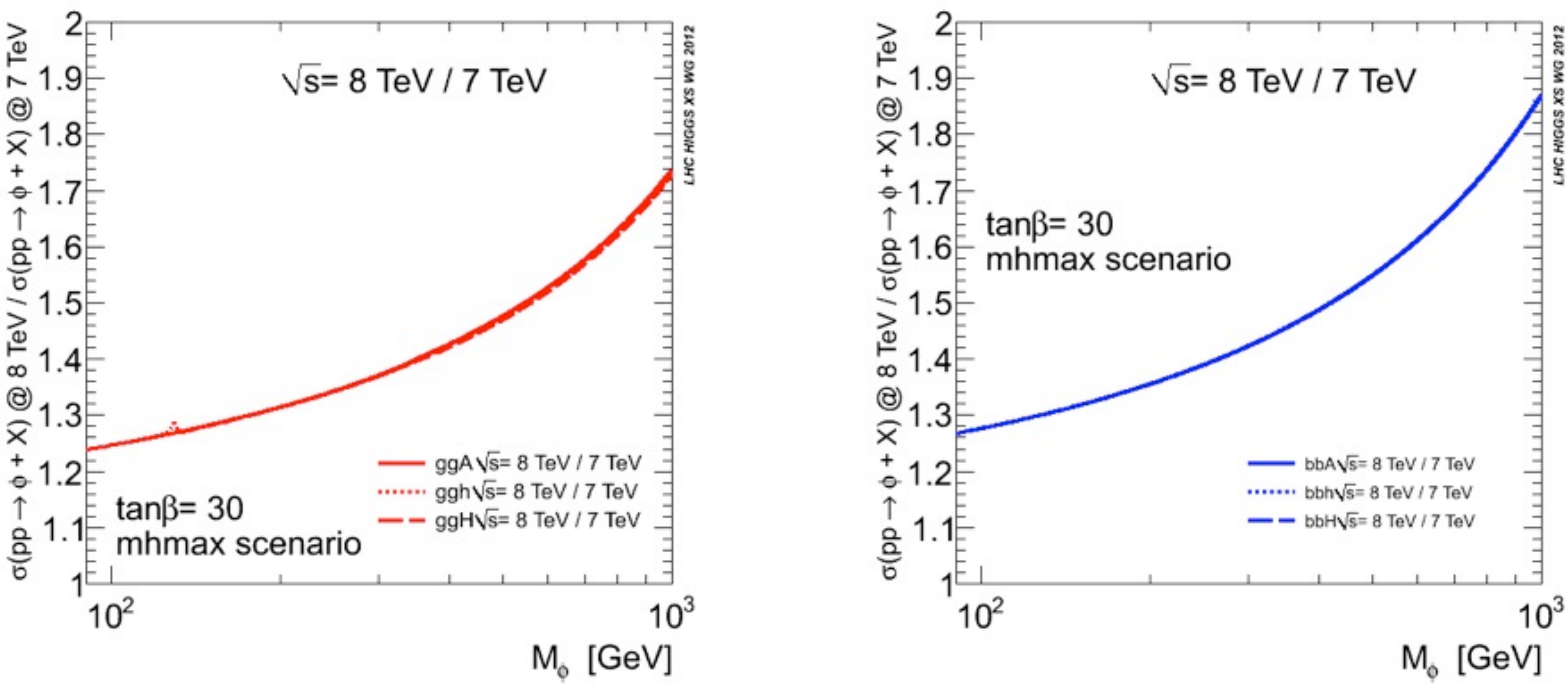


MSSM Neutral Higgs with 8 TeV

- 8 TeV MSSM signal cross sections now available on the LHC Higgs XS TWiki (for both the m_h-max and no-mixing scenarios)

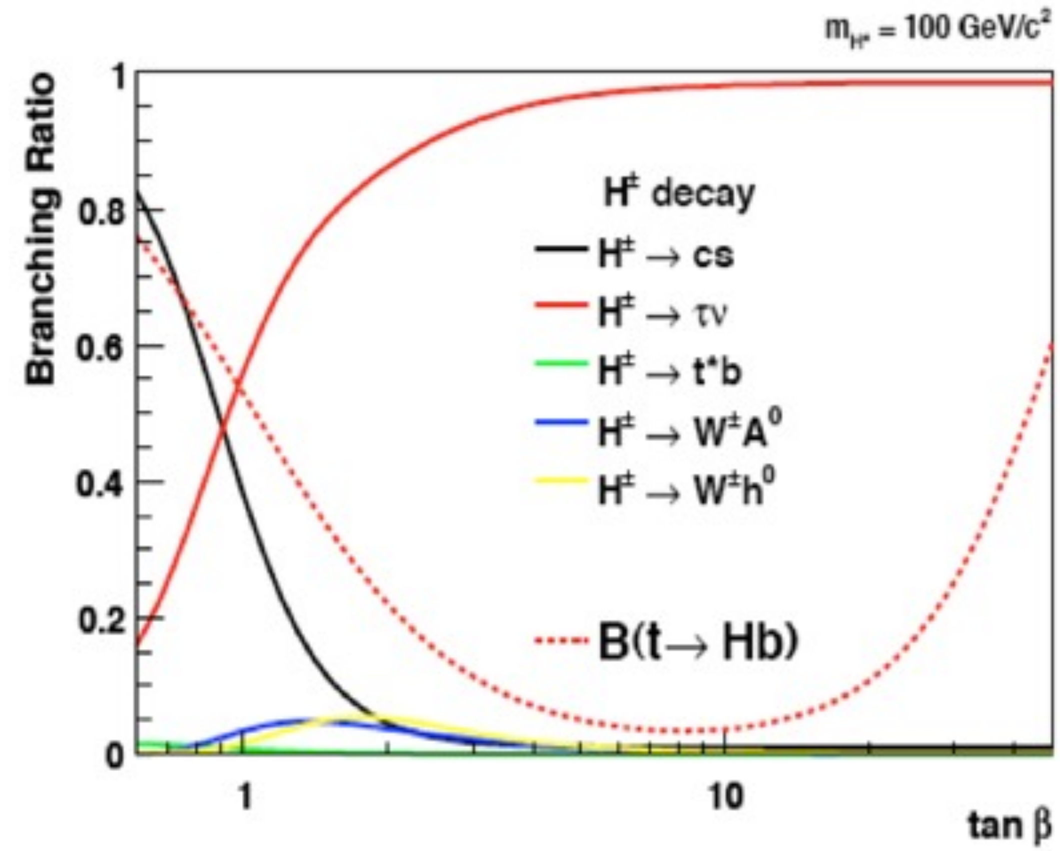
  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/MSSMNeutral

  - Significant enhancement of the production cross sections over those at 7 TeV
  - Scan .root files will eventually include WW and gamma-gamma BRs (recast our SM Higgs limits in the context of the MSSM)
  - Stay tuned...



A Generic 2HDM: Charged Higgs Searches

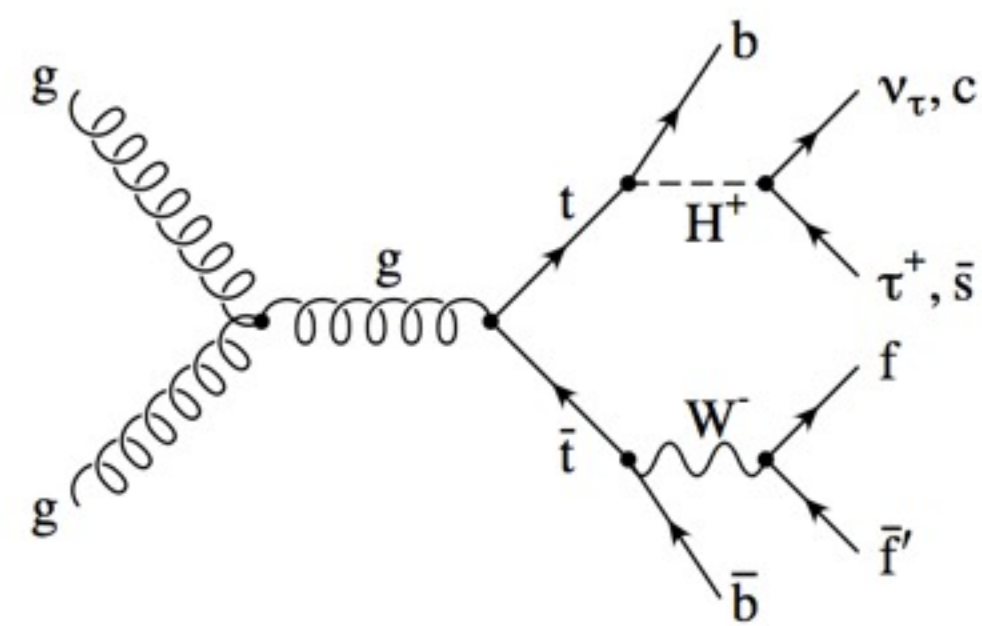
- Charged Higgs bosons could be produced from a generic 2HDM
- H+ Production:
  - Light H^+: pp → tt → bW bH^+
  - Heavy H^+: gb → tH^+ and gg → tbH^+



- H+ Decay:
  - Light H^+: Almost exclusively to τν (at low tanB predominantly to $c\bar{s}$)
  - Heavy H^+: tb; τν; $\chi^+\chi^0$

- ATLAS charged Higgs searches with taus:

tau(had)+W(→lv): tt → bbWH → bb (lv) (τ_{had}v)
tau(had)+W(→jets): tt → bbWH → bb (qq) (τ_{had}v)
tau(lep)+W(→jets): tt → bbWH → bb (qq) (τ_{lep}v)



- ATLAS charged Higgs search with $c\bar{s}$:

H^+(→$c\bar{s}$)+W(→lv): tt → bbWH → bb (lv) ($c\bar{s}$)

Charged Higgs: $H^+ \to \tau\nu$

- Perform this search in three channels: JHEP (arXiv: 1204.2760)

Tau(lep) + W(→ jets)	Tau(had) + W(→ jets)	Tau(had) + W(→ lν)
1 isolated e/μ, p_T > 25/20 GeV	1 τ_{had} with p_T > 40 GeV	1 isolated e/μ, p_T > 25/20 GeV
		1 τ_{had} with p_T > 20 GeV
At least 4 jets (pT>20 GeV) with exactly 2 b-tagged	At least 4 jets (pT>20 GeV) with at least 1 b-tagged	At least 2 jets (pT>20 GeV), with at least 1 b-tagged
MET & Topological cuts	MET & Topological cuts	vertex ΣpT > 100 GeV

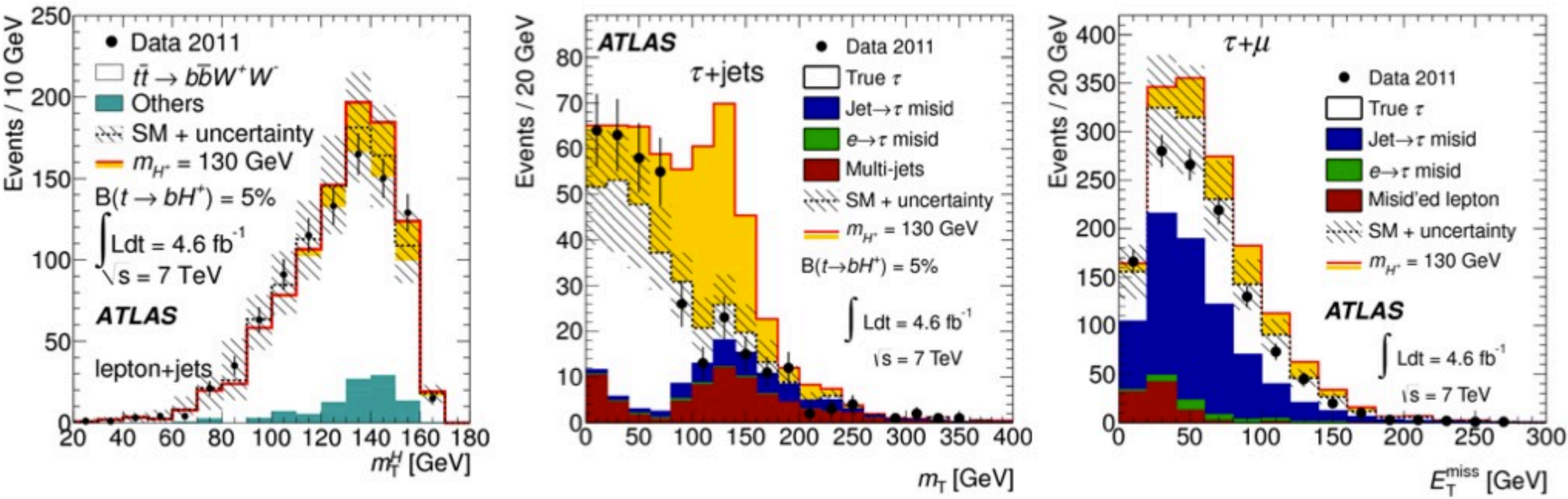
- Dominant backgrounds:
  - ttbar, single-top, multi-jets, W+jets, Z+jets, di-boson, multi-jet events

- Dominant systematics:
  - Jet energy resolution / scale (10-30%), b-tagging efficiency (5-17%), misidentification probability (e.g., jet→τ or e→τ; 12-21%)

Charged Higgs: $H^+ \to \tau\nu$

JHEP (arXiv: 1204.2760)

- The final discriminants for each channel:



- Our most sensitive channel for this search is the τ+jets
- The lepton+jets channel ($H^+ \to \tau^+\nu \to l^+\nu\nu\nu$) has a very similar signature to $W^+ \to l^+\nu$, so rely on kinematics for discrimination
  - cosθ* (exploit W boson polarization from top decay)
  - Charged Higgs transverse mass m_T^H
  - b-jet-to-top association important for both; done with a χ^2

Maximize the lν invariant mass using MET and the top mass as constraints:

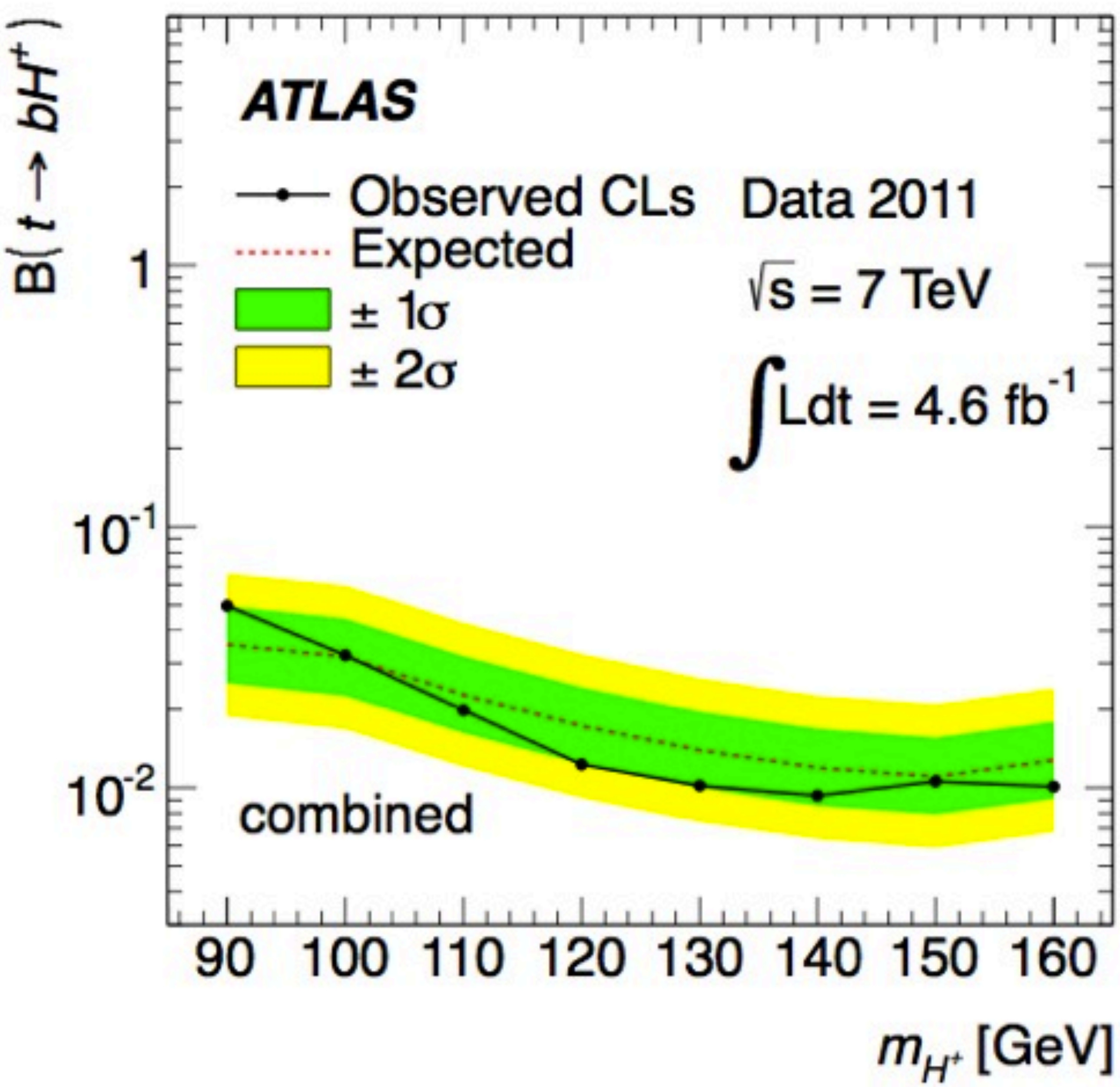
$$(m_T^H)^2 = \left(\sqrt{m_{top}^2 + (\vec{p_T}^l + \vec{p_T}^b + \vec{p_T}^{miss})^2} - p_T^b\right)^2 - \left(\vec{p_T}^l + \vec{p_T}^{miss}\right)^2$$

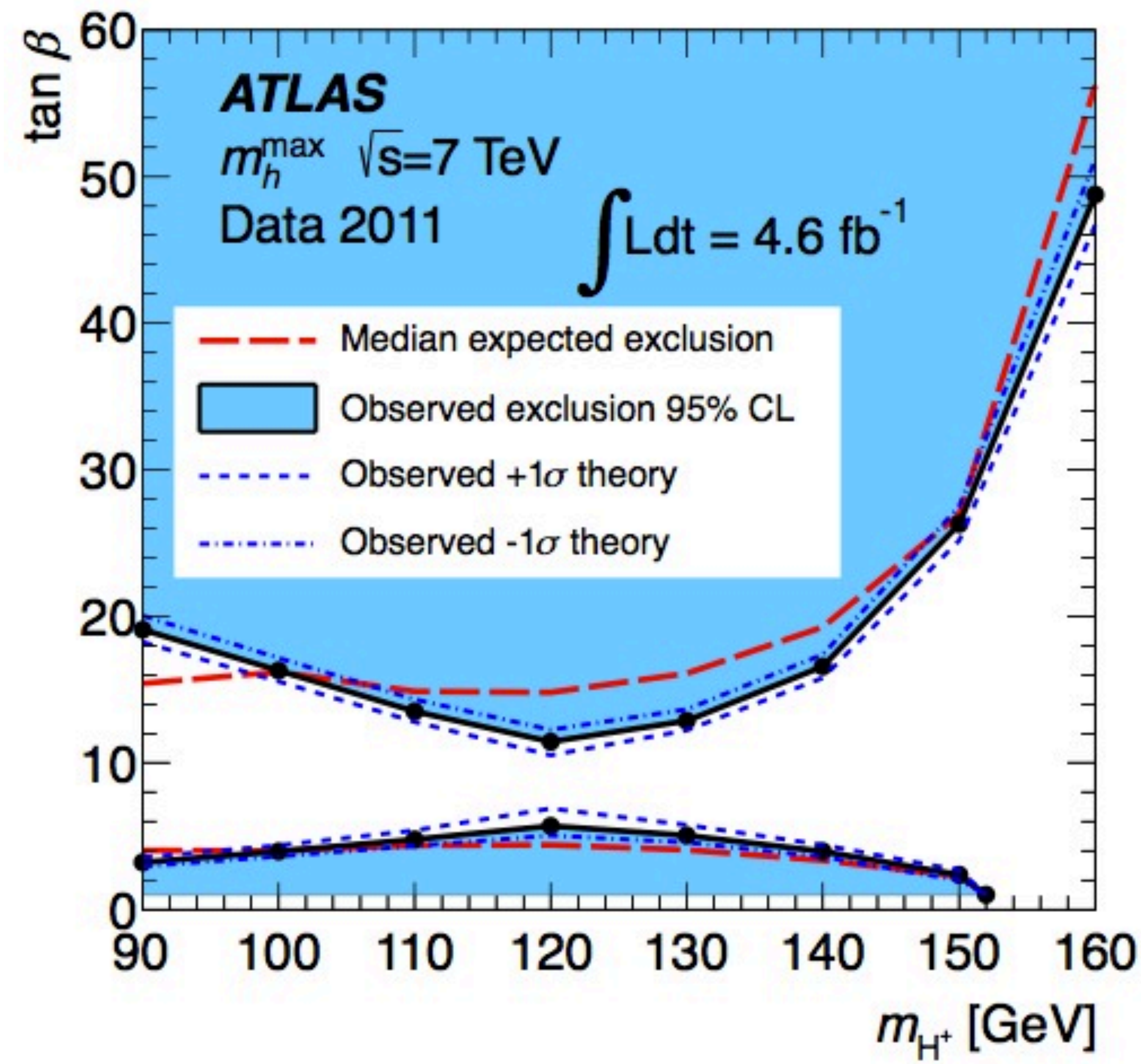
$$\chi^2 = \frac{(m_{jjb} - m_{top})^2}{\sigma_{top}^2} + \frac{(m_{jj} - m_W)^2}{\sigma_W^2}$$

Charged Higgs: $H^+ \rightarrow \tau\nu$

- ATLAS results heavily constrain the allowed phase space for a charged Higgs in the MSSM scenario
- Limit is also presented on the $BR(t \rightarrow bH^+)$

JHEP (arXiv: 1204.2760)



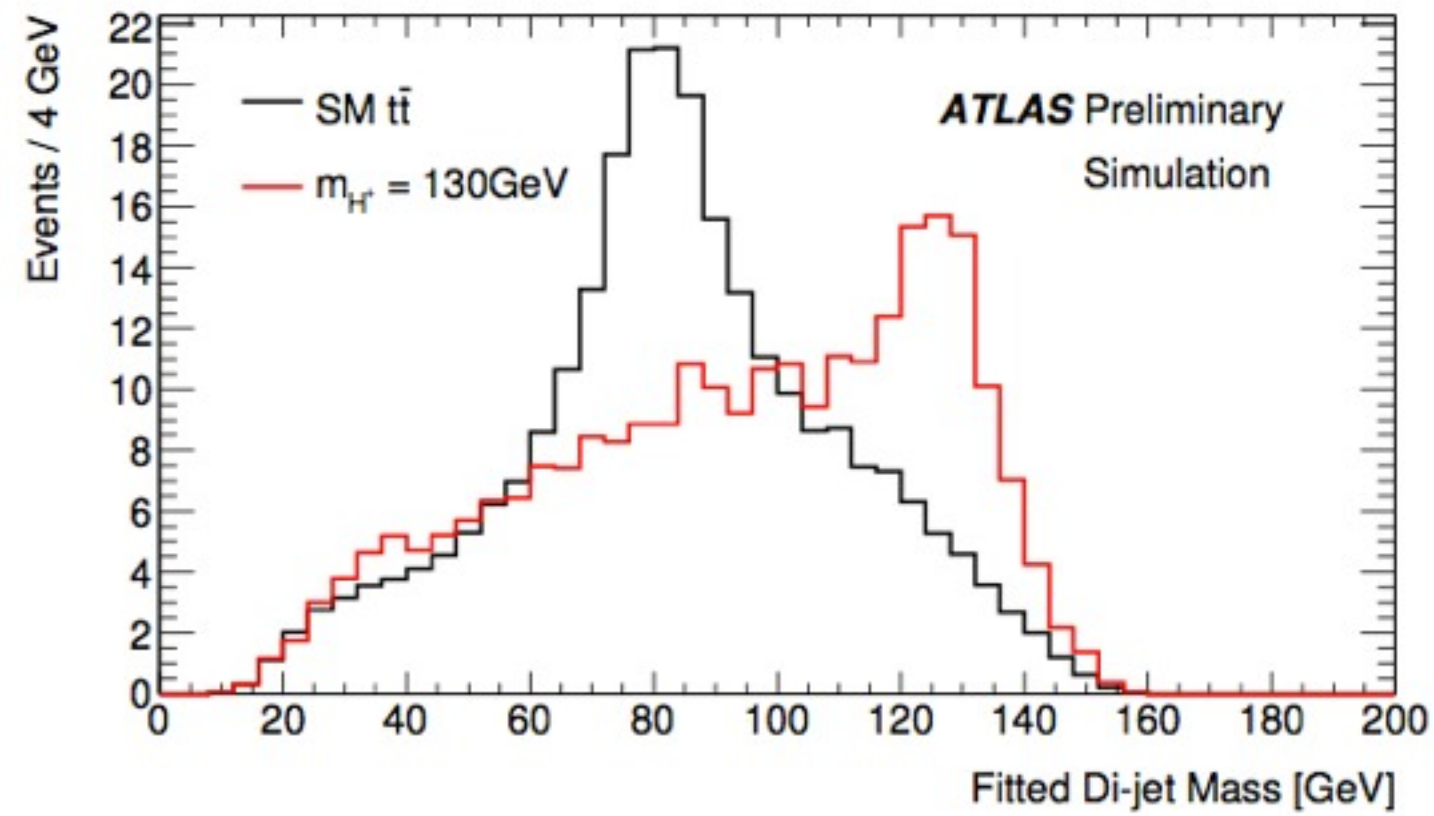


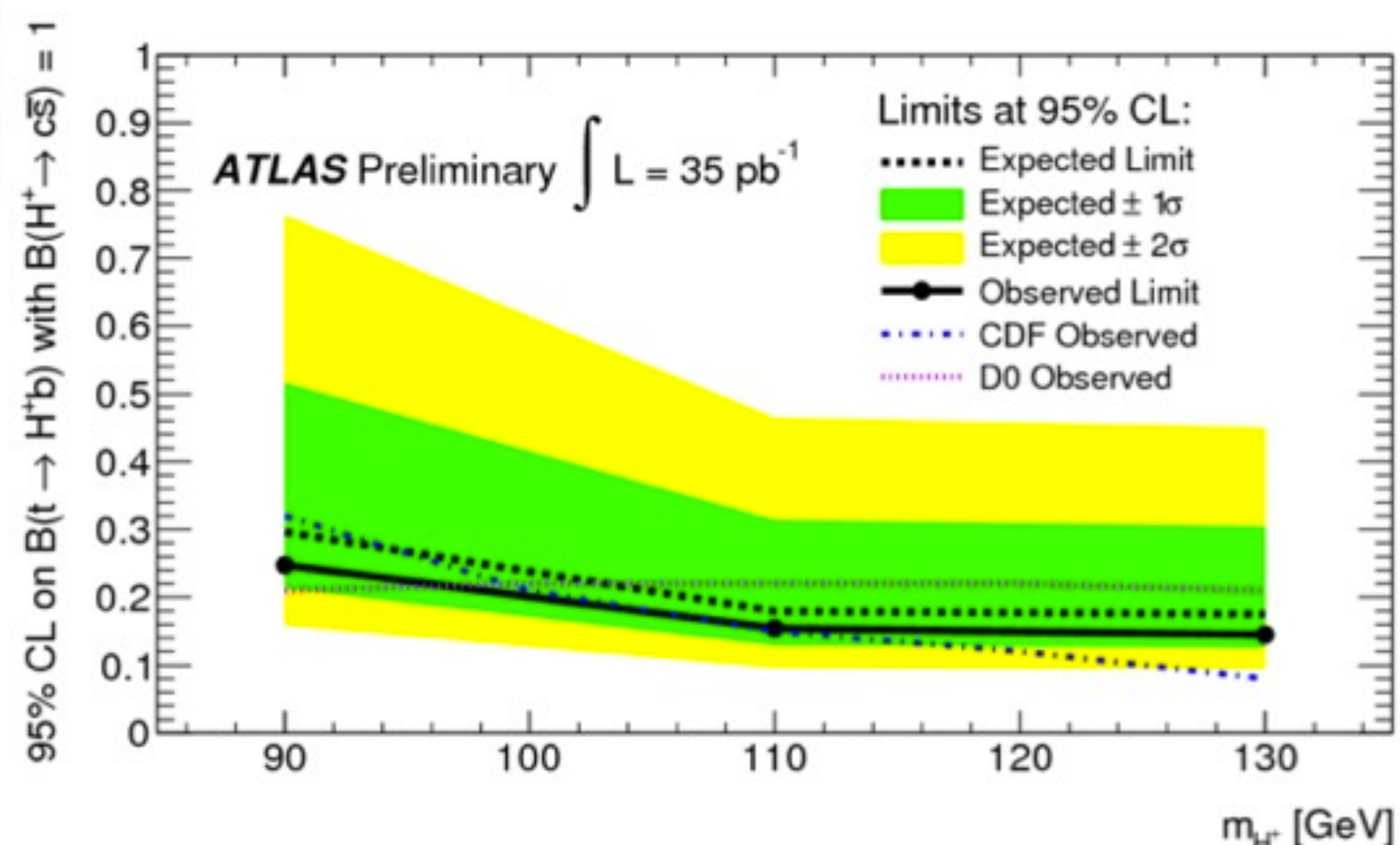
Charged Higgs: $H^+ \to c\bar{s}$

- Final state allows for full reconstruction of the H^+ candidates
- Examine the di-jet spectrum and look for a second peak

$tt \to bW\, bH^+ \to b\,(e/mu)\,\nu\;\; b\,cs$
1 isolated e/μ, $p_T > 20$ GeV
At least 4 jets, pT>20 GeV; one b-Tagged jet
MET/MT cuts: MT>25 GeV (e); MT+MET>60GeV

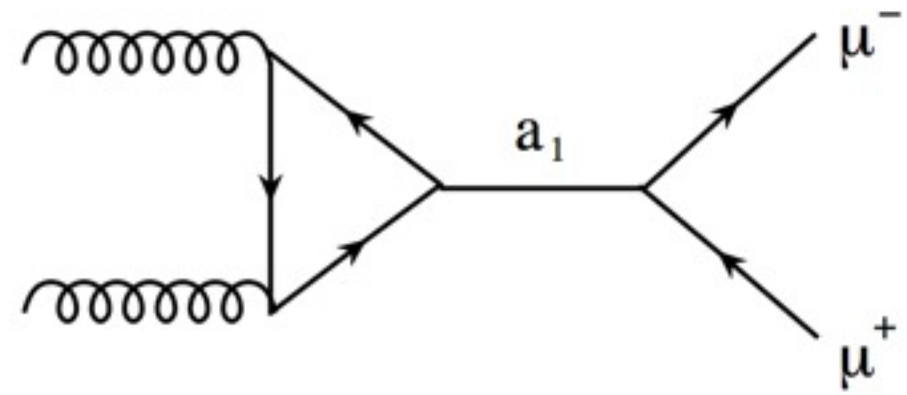
$$\chi^2 = \sum_{i=l,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_{UE}^2} + \sum_{k=bjj,bl\nu} \frac{(M_k - M_{top})^2}{\sigma_{top}^2}.$$





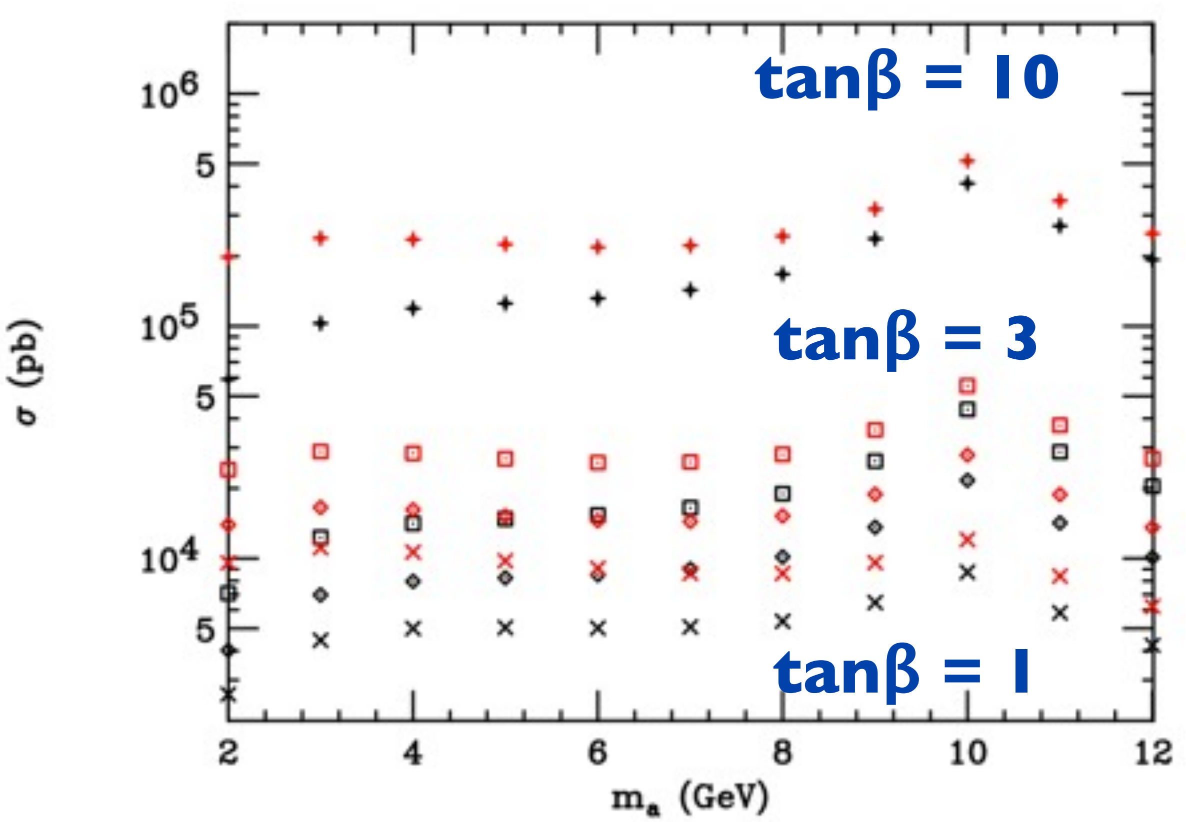
ATLAS-CONF-2011-094

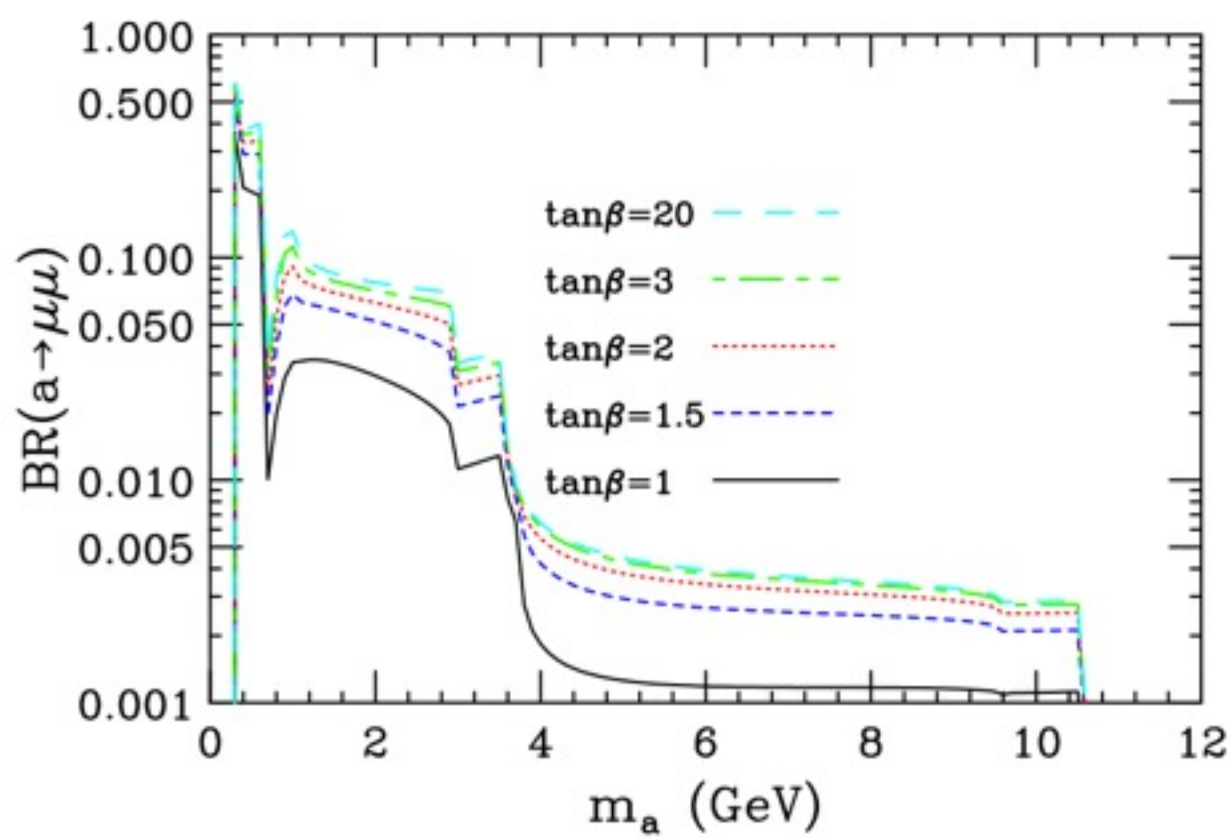
The NMSSM: μμ channel



- 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

arXiv: 0911.2460





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

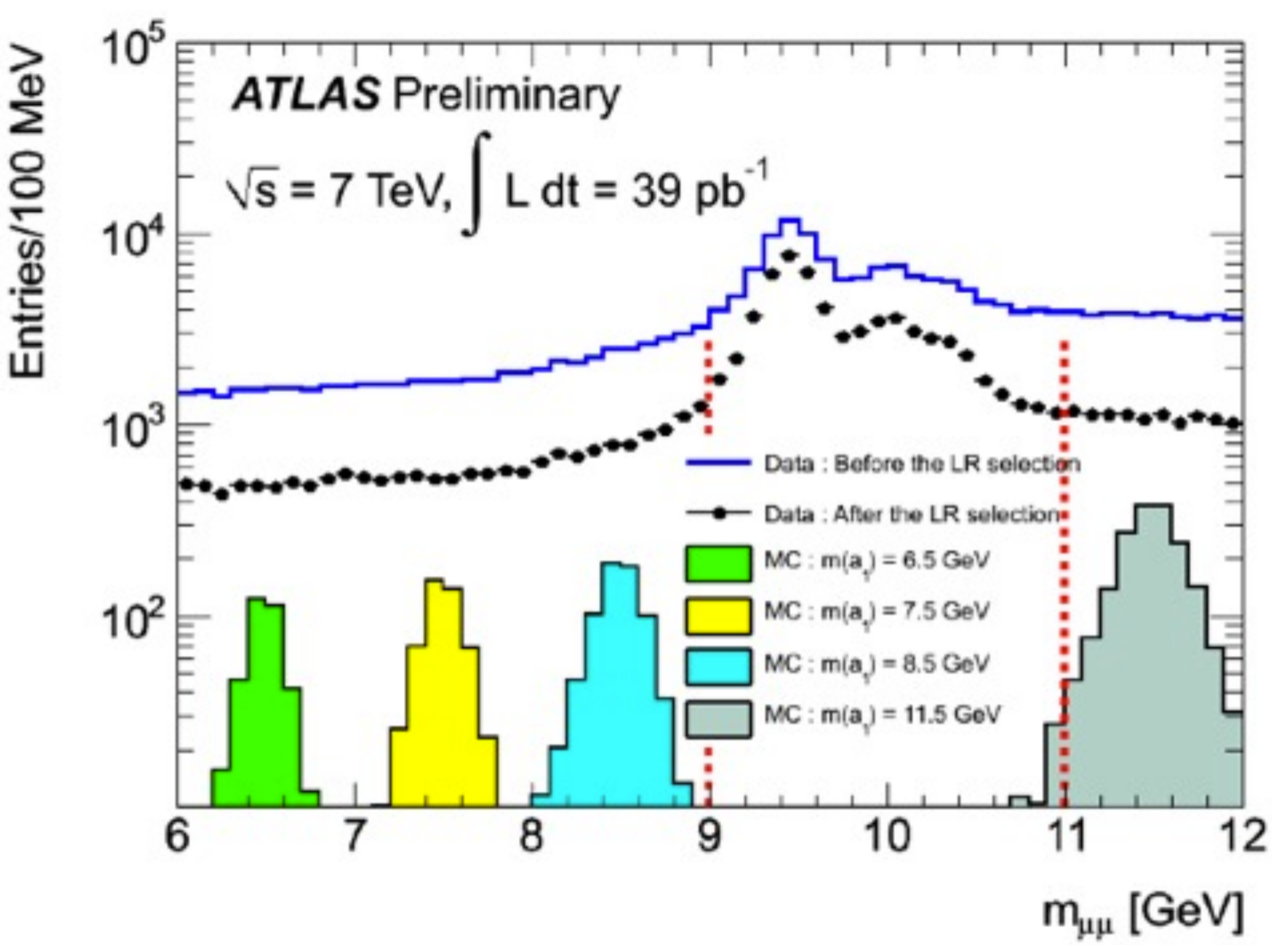
- Search for this Higgs in the region to either side of the ϒ

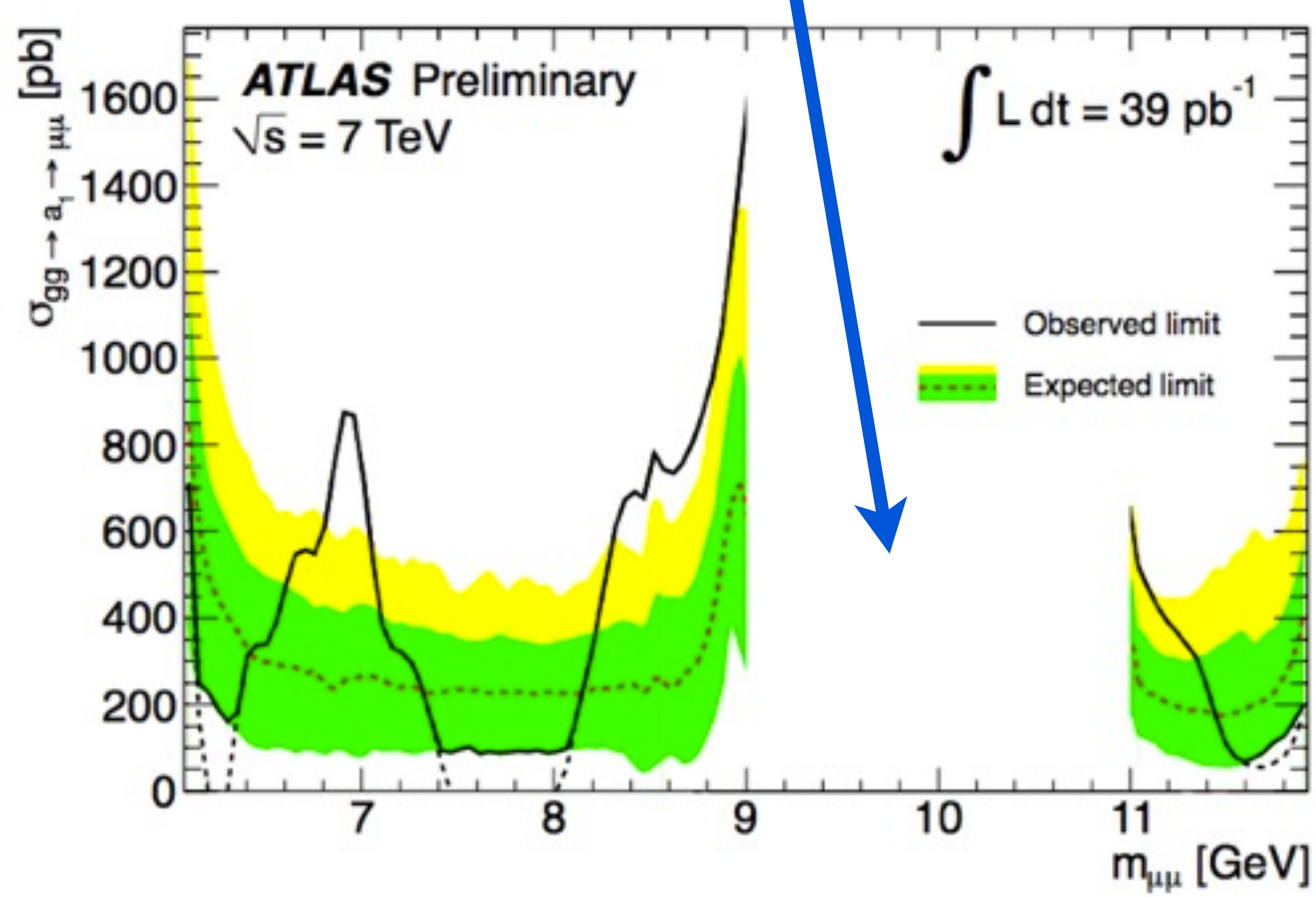
$H \to \mu\mu$ (NMSSM)
2 isolated μ, $p_T > 4$ GeV, opposite sign
Multivariate technique to reject muons not coming from the decay of a single particle
Sidebands $m_{\mu\mu}$: 6-9 GeV and 11-12 GeV

The signal over background ratio is enhanced by cutting on a Likelihood ratio based on the di-muon vertex fit and on muon isolation variables

Uncertainties in the expected rate of ϒ production make it difficult to distinguish an additional resonance in this mass range

ATLAS-CONF-2011-020





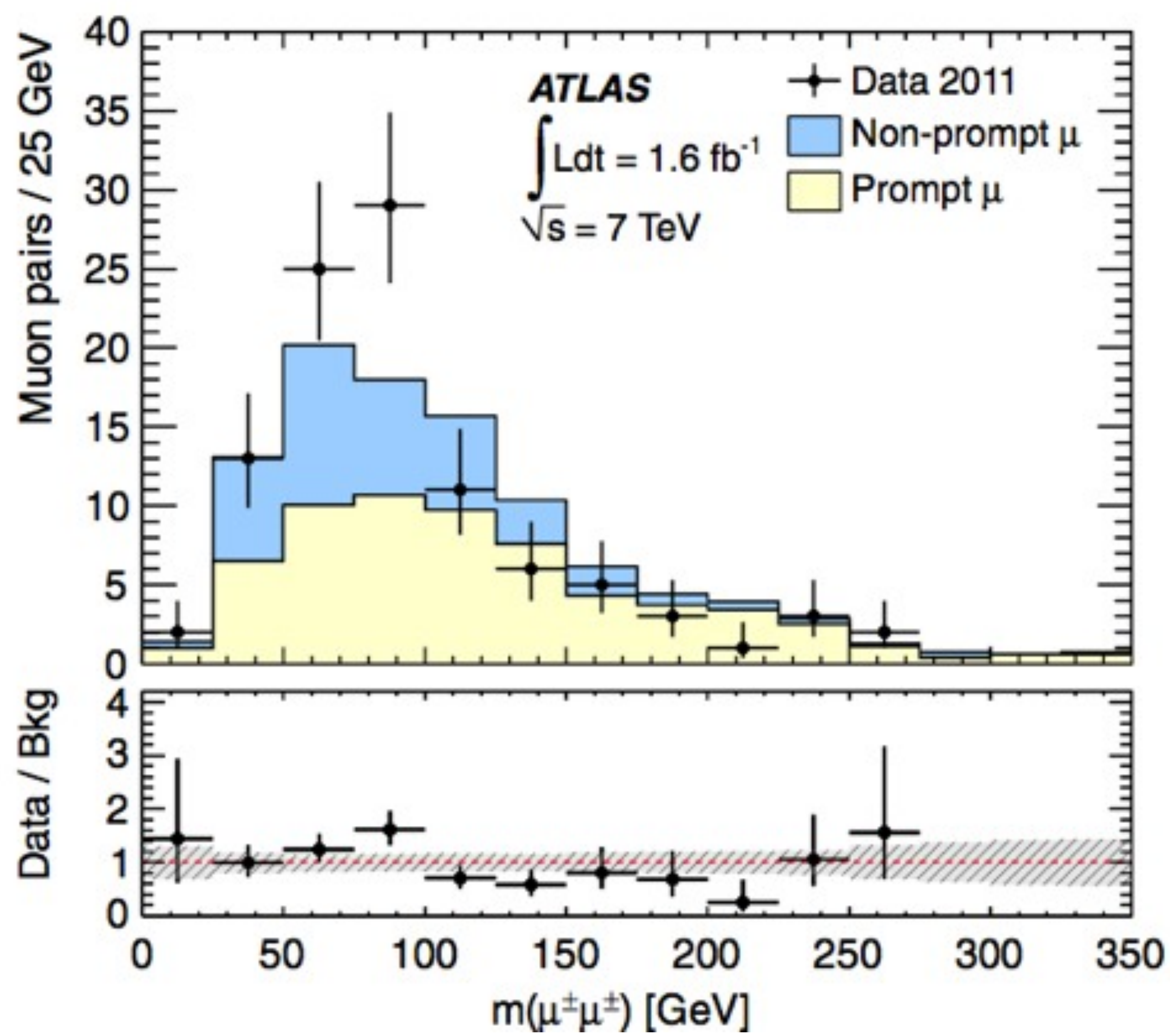
Doubly Charged Higgs (H^{++})

- Predicted by many models
  - Left-Right symmetric models, "Seesaw Type-II" models including Higgs triplet models (H^0, H^+, H^{++}) and "Little Higgs" models
  - Possible observation of H^{++} at the LHC could provide more insight into neutrino masses
  - Predominantly produced in pairs via Drell-Yan $pp \rightarrow H^{++}H^{--}$
- This is performed as a generic same-sign di-muon spectrum search

$H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$
2 isolated μ, p_T > 20 GeV, **same sign**

Dominant background at low masses comes from non-prompt muons (from heavy-flavor decays, or decays in-flight of pions or kaons)

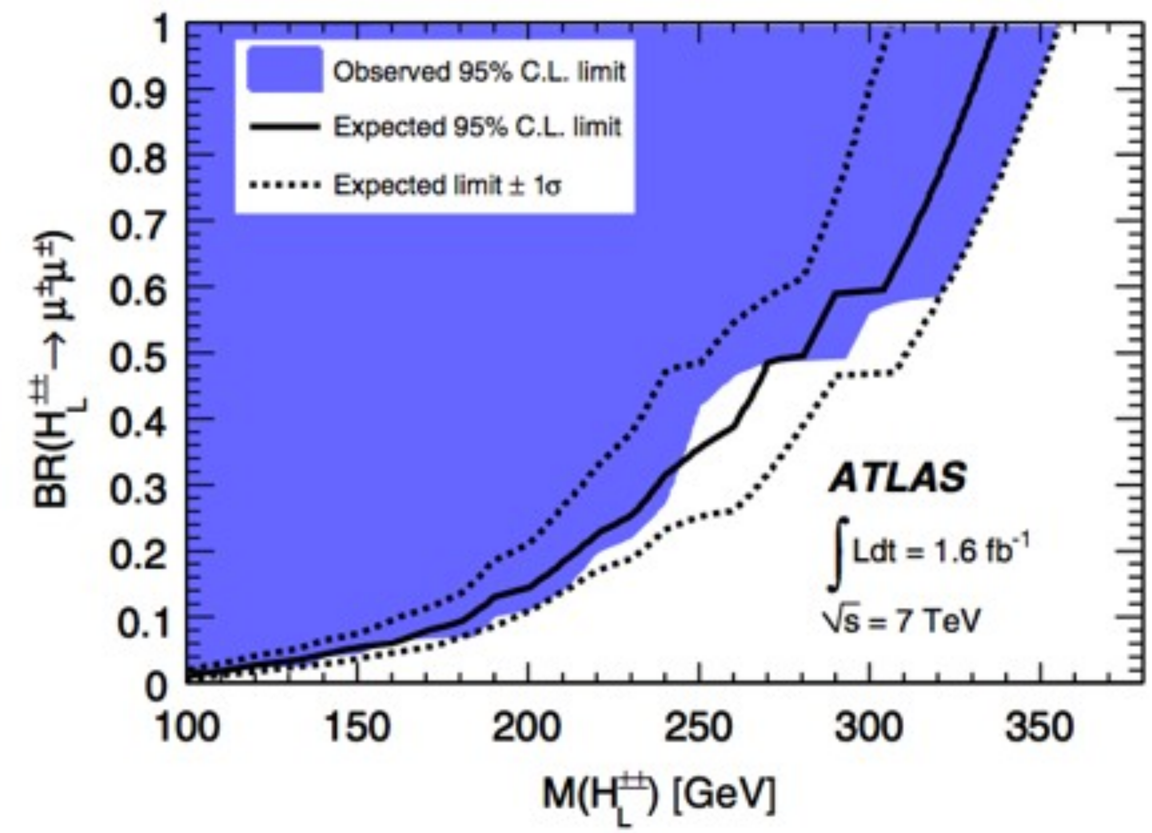
Phys. Rev. D 85, 032004 (2012)



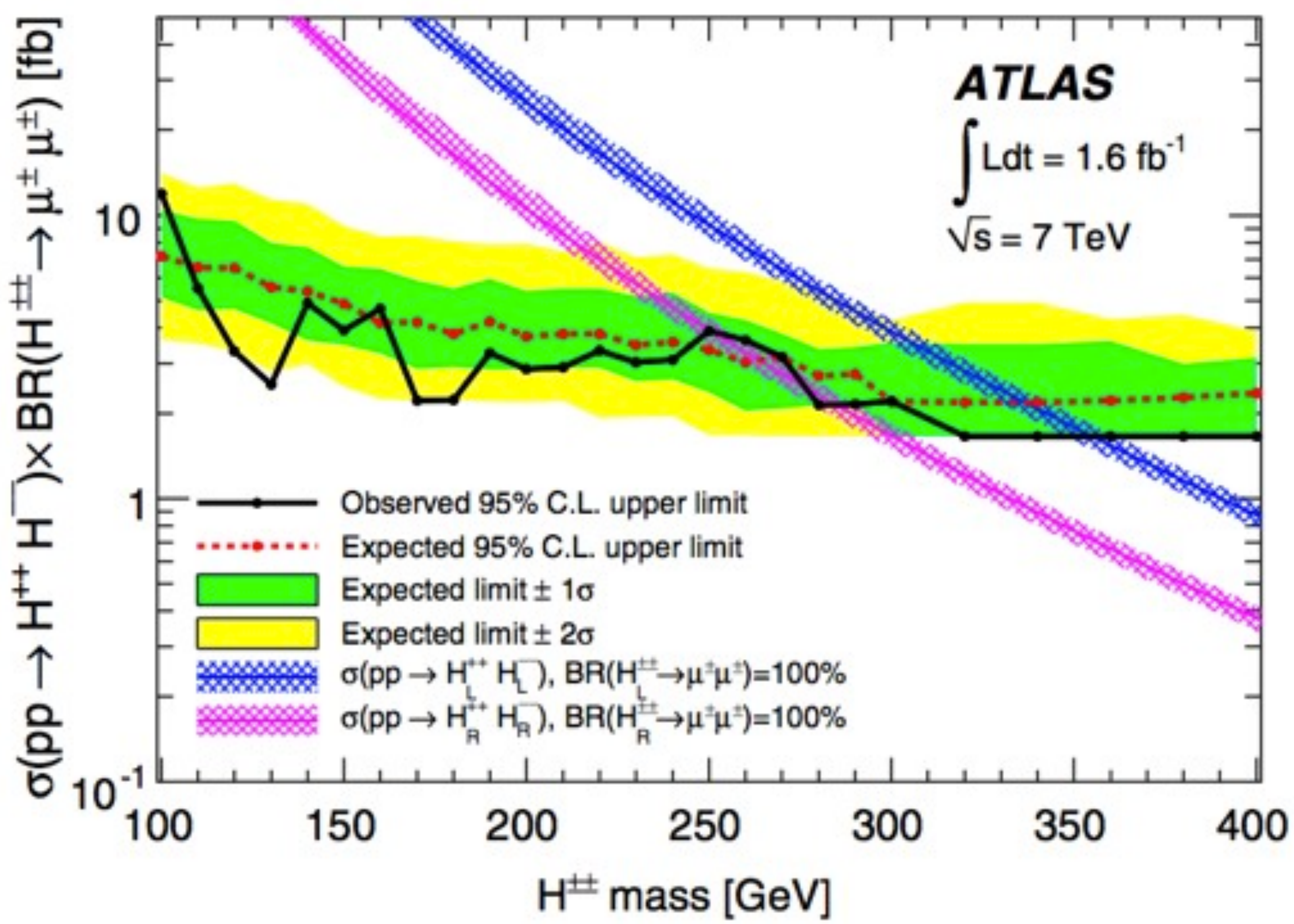
Doubly Charged Higgs (H^{++})

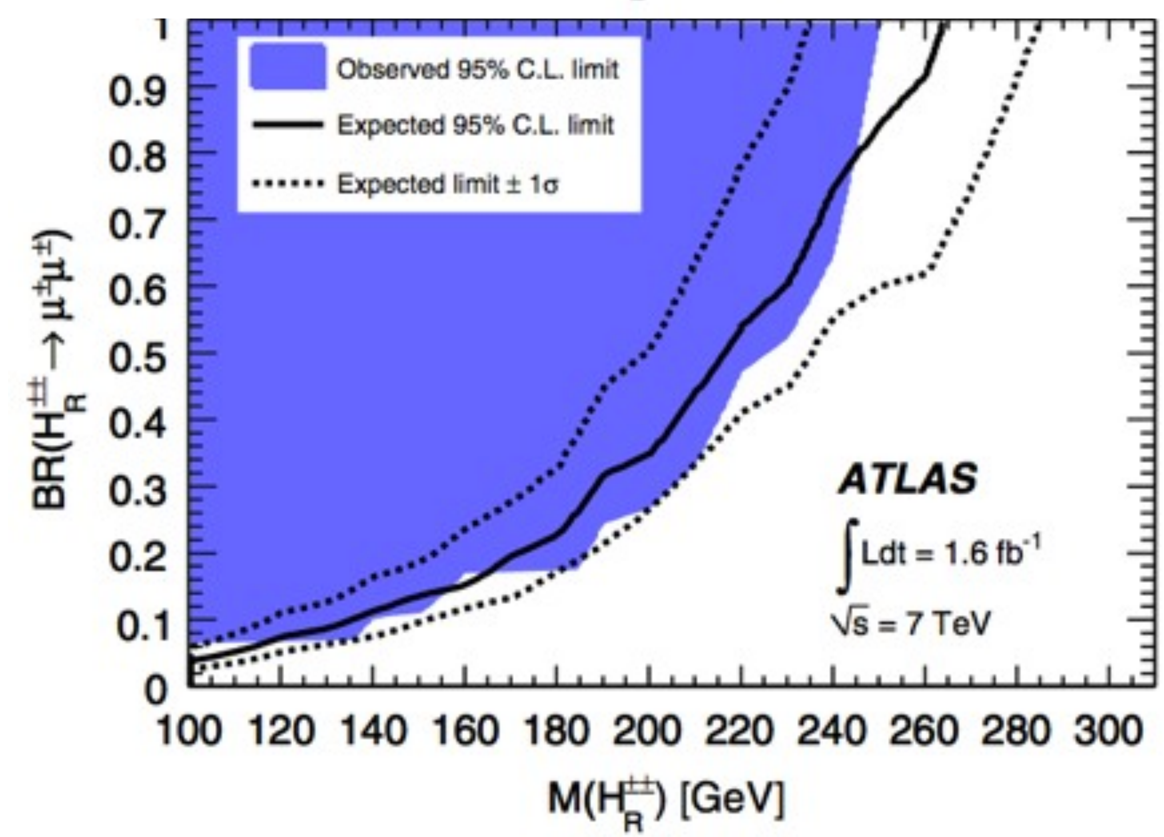
- Exclusion limits in 1.6 fb^{-1}
  - Assuming $qq \rightarrow Z/\gamma^* \rightarrow H^{++}H^{--} \rightarrow \mu^+\mu^+ \mu^-\mu^-$
  - Limits on H^{++} mass of 251 GeV (355 GeV) for right-handed (left-handed) production; BR=100%

Phys. Rev. D 85, 032004 (2012)



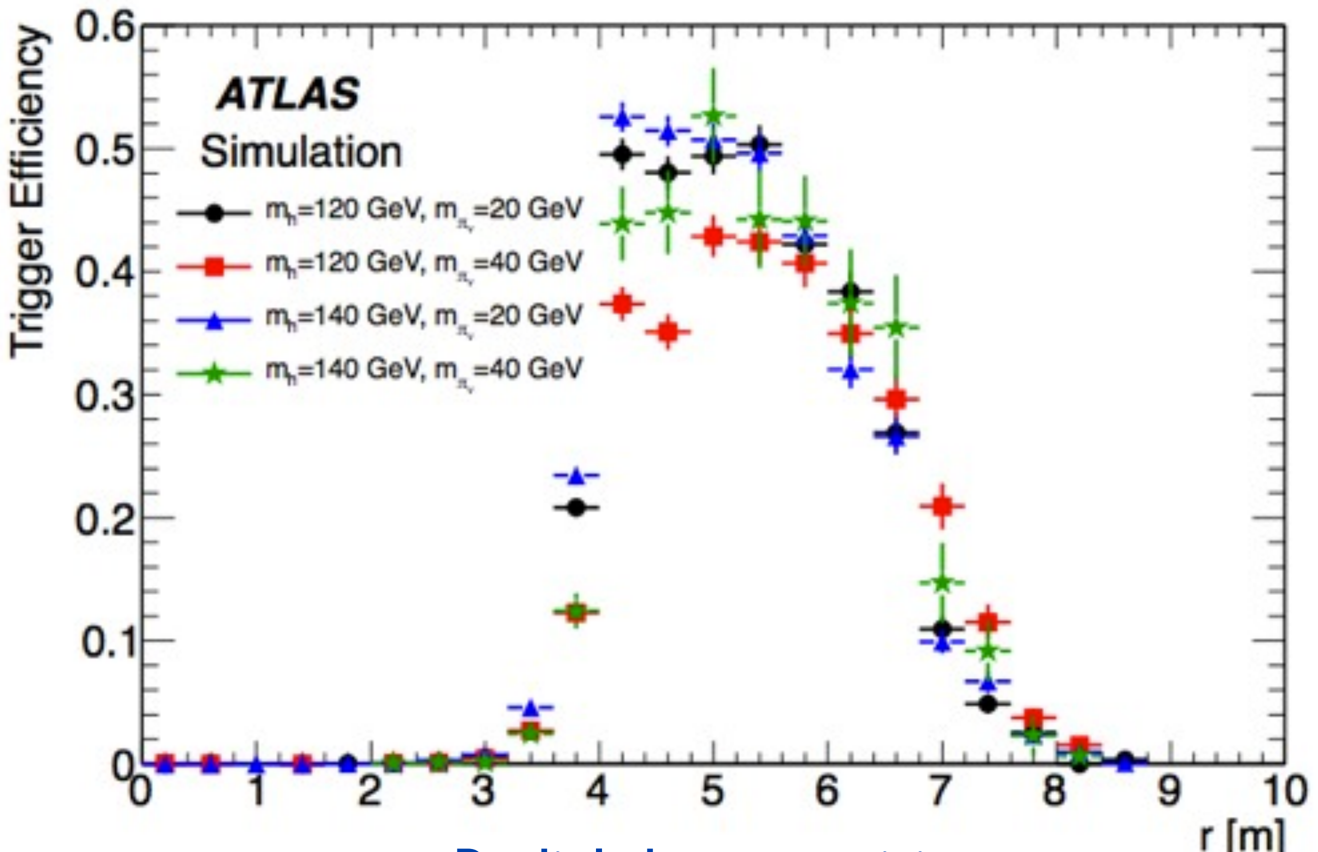
$H_L^{\pm\pm}$ couple to both the Z and photons
$H_R^{\pm\pm}$ only couple to photons





Higgs Decaying to Long-Lived Particles

- A number of models include Higgs decaying to long-lived particles
  - For example, the so-called "Hidden Valley Model"
  - SM is weakly coupled to a hidden sector by some communicator particle
  - Here the Higgs is the communicator and can decay to long-lived particles
  - Search for $h \to \pi_v \pi_v$ (the long-lived π_v has a displaced decay to fermion-anti-fermion pairs; decay predominantly to bb, cc and $\tau\tau$)
- ATLAS has a dedicated trigger for long-lived particles decaying in the outer parts of the detector

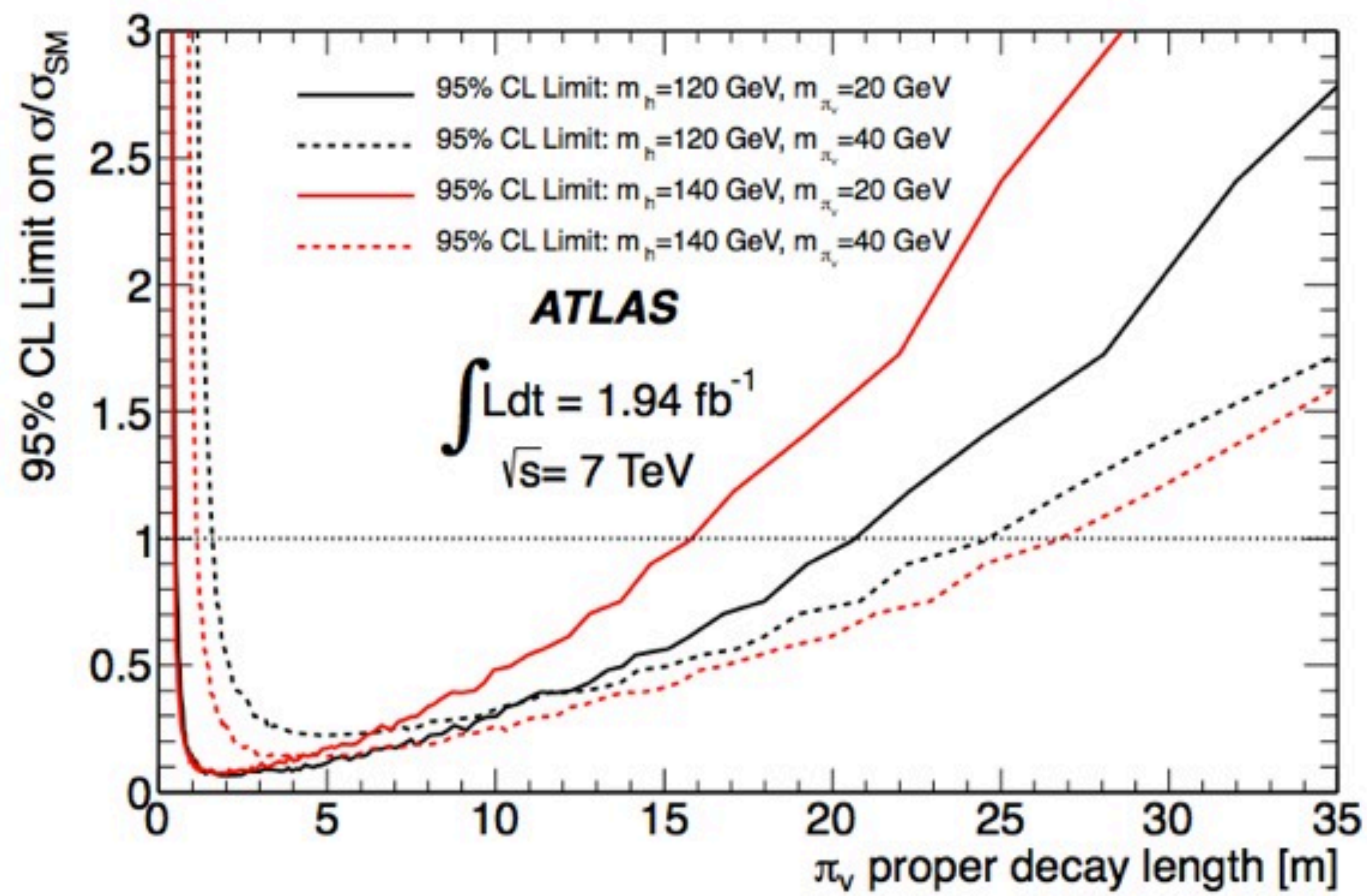


Radial decay position
of the long-lived particle

arXiv: 1203.1303

Higgs Decaying to Long-Lived Particles

- Searching for a light Higgs in the "Hidden Valley" context with the long-lived particles decaying in the hadronic calorimeter, and then those decay products are detected in the muon system



arXiv: 1203.1303

m_{h^0} (GeV)	m_{π_v} (GeV)	Excluded Region
120	20	$0.50 < c\tau < 20.65$ m
120	40	$1.60 < c\tau < 24.65$ m
140	20	$0.45 < c\tau < 15.8$ m
140	40	$1.10 < c\tau < 26.75$ m

TABLE II: The excluded proper decay lengths ($c\tau$) of the π_v, at 95% CL, for each of the signal samples, assuming 100% branching ratio for the channel $h^0 \to \pi_v \pi_v$.

Conclusions and Outlook

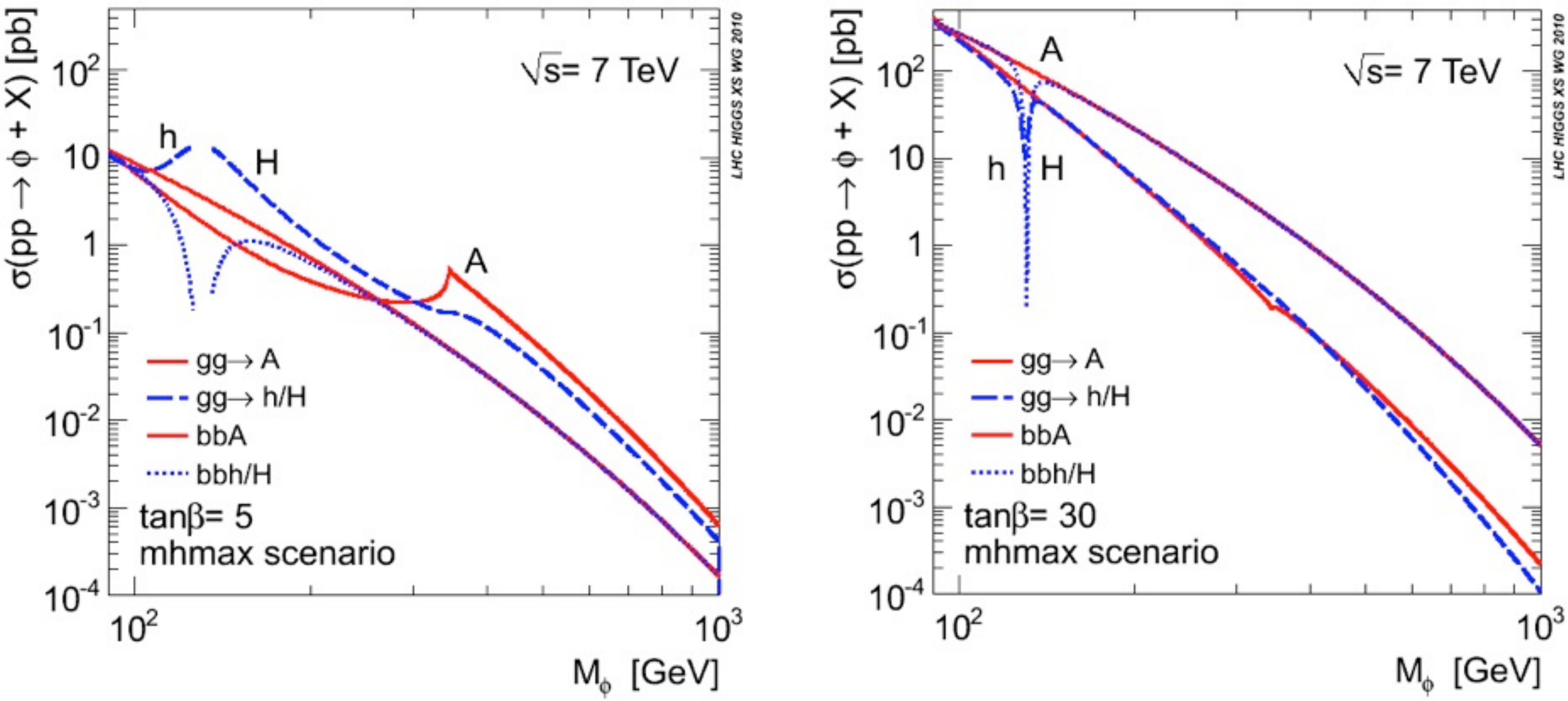
- ATLAS has a very active search program for Beyond the Standard Model Higgs bosons
  - We have already pushed the constraints further than previous searches
  - Still wrapping up some publications on the full 2011 data

- Even if a SM-like Higgs is observed, BSM Higgs searches will continue to be relevant
- Stay tuned for first results on the 8 TeV 2012 data
- These are very exciting times!

Back-up Slides

MSSM Higgs Cross Sections at 7 TeV

- Neutral ϕ=h/A/H produced through gg-fusion or b-associated processes
  - ggF cross sections based on HIGLU and ggH@NNLO
  - bbH cross sections based on bbh@NNLO (5 flavor)
  - Higgs masses and couplings calculated with FeynHiggs 2.7.4



MSSM Neutral Higgs

	Data	Total MC bkg (w/o QCD)	W+jets	Di-boson	$t\bar{t}$+ single-top	$Z/\gamma^* \to ee,\mu\mu$	$Z/\gamma^* \to \tau^+\tau^-$	A/H/h signal
$e\mu$	2472	2496±27	30±15	109±5	100±2	40±4	2217±22	155±6
$e\tau_{had}$	626	775±40	188±31	4.1±0.5	33± 3	64±5	486±24	41±4
$\mu\tau_{had}$	1287	1378±43	239±33	5.4±0.6	51±4	105±7	978±26	75±5
$\tau_{had}\tau_{had}$	245	76± 7	25±5	1.4±0.3	2.0±0.9	-	48±5	19±1

Table 5: Observed numbers of events in data, for an integrated luminosity of 1.06 fb^{-1}, and total expected background contributions for the final states considered in this analysis, with their combined statistical and systematic uncertainties.

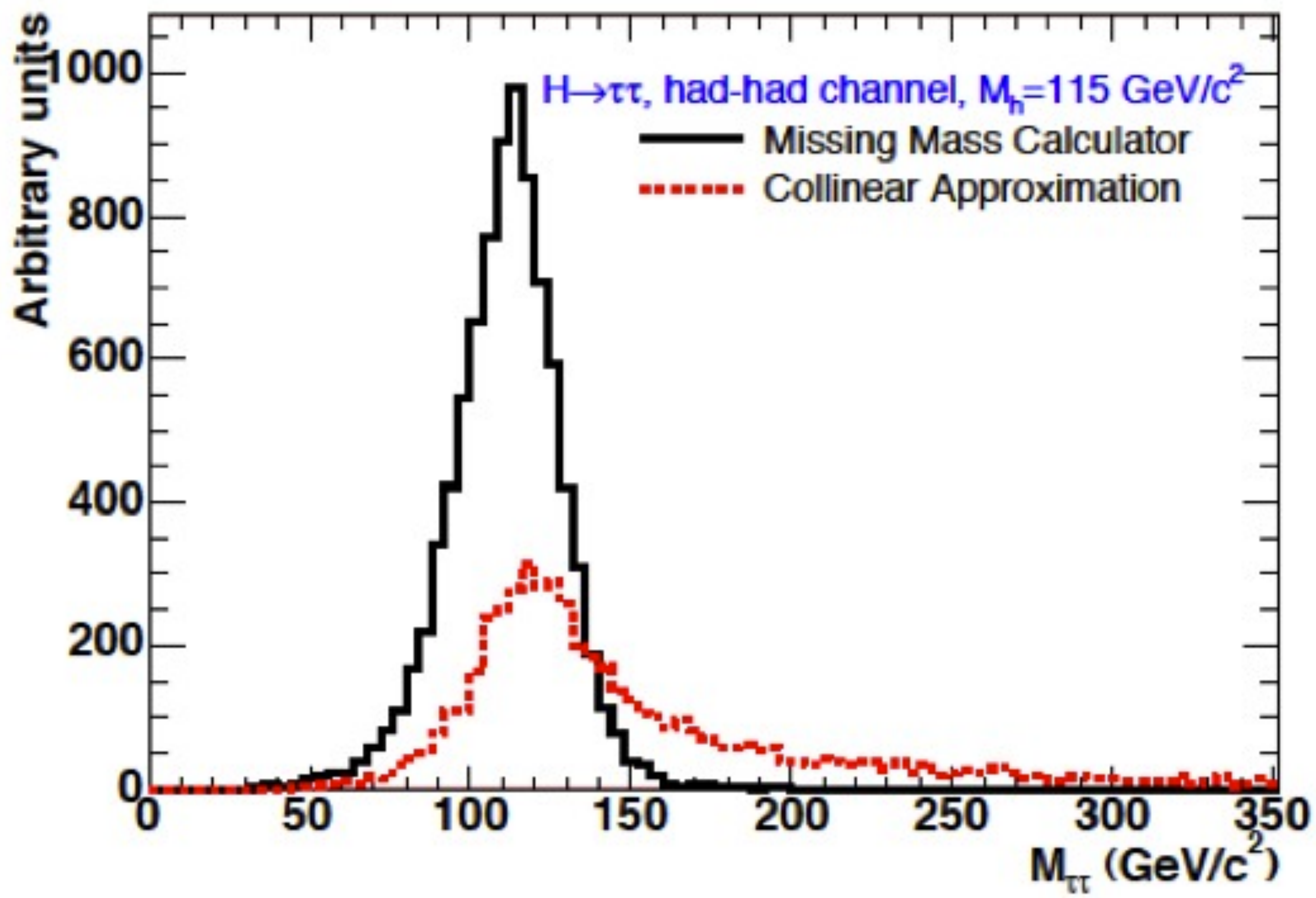
Final state	Exp. Background	Data
$e\mu$	$(2.6 \pm 0.2) \times 10^3$	2472
$\ell\tau_{had}$	$(2.1 \pm 0.4) \times 10^3$	1913
$\tau_{had}\tau_{had}$	$233\,^{+44}_{-28}$	245
Sum	$(4.9 \pm 0.6) \times 10^3$	4630

MSSM Neutral Higgs

	W+jets	Di-boson	$t\bar{t}$+ single-top	$Z/\gamma^* \to ee,\mu\mu$	$Z/\gamma^* \to \tau^+\tau^-$	Signal
$\sigma_{inclusive}$	-/-/5	7	10	5/5/-	5	14/14/16
Acceptance	-/-/20	4/2/7	3/2/9	2/14/-	5/14/14	5/7/9
e efficiency	-/-/0.8	4/3.1/0.5	4/3.6/0.3	4/3.1/-	4/3.0/0.5	4/3.6/0.1
μ efficiency	-/-/0.3	2/1.2/0.4	2/1.1/0.0	2/1.3/-	2/1.8/0.4	2/1.0/0.1
τ efficiency and fake rate	-/-/21	-/9.1/15	-/9.1/13	-/48/-	-/9.1/15	-/9.1/15
Energy scales and resolution	-/-/$^{+34}_{-21}$	2/$^{+19}_{-9}$/$^{+26}_{-12}$	6/$^{+5}_{-4}$/12	1/$^{+39}_{-25}$/-	1/11/$^{+63}_{-23}$	1/$^{+30}_{-23}$/$^{+9}_{-8}$
Luminosity	-/-/3.7	3.7	3.7	3.7/3.7/-	3.7	3.7
Total uncertainty	-/-/$^{+45}_{-36}$	10/$^{+23}_{-16}$/$^{+32}_{-22}$	13/15/23	8/$^{+64}_{-56}$/-	9/21/$^{+67}_{-31}$	16/$^{+35}_{-30}$/$^{+26}_{-25}$

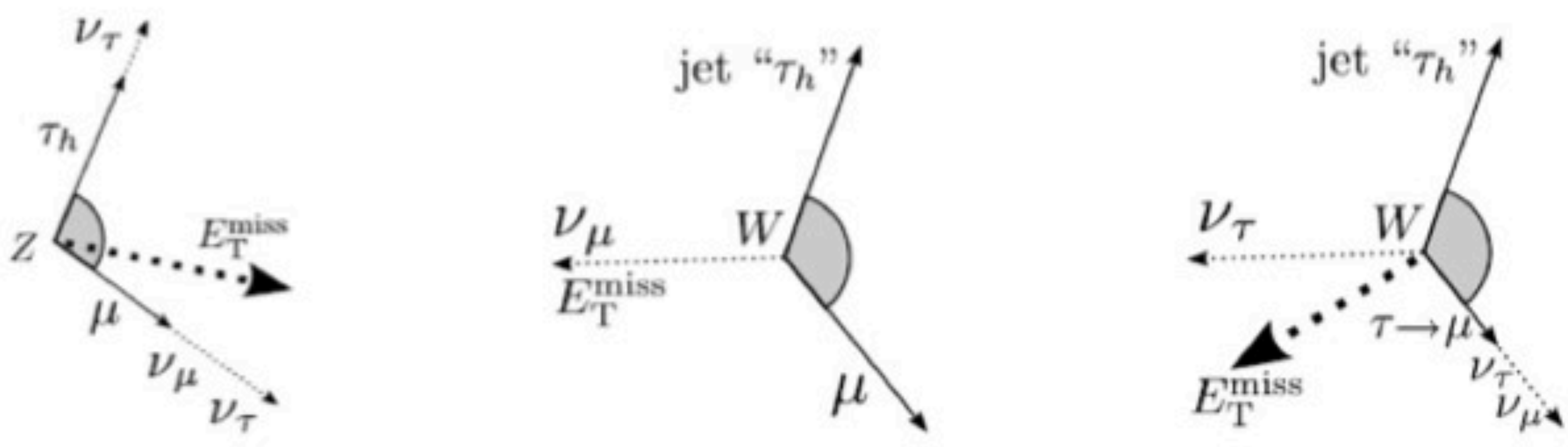
eμ / lep-had / had-had

MMC vs Collinear Mass



SumCosDeltaPhi

SumCosDeltaPhi:



(a) $Z \to \tau\tau \to \mu\tau_h$ (b) $W \to \mu\nu$ (c) $W \to \tau\nu \to \mu\nu\nu\nu$

Charged Higgs (→τν)

Sample	Event yield (lepton+jets)
$t\bar{t}$	$840 \pm 20 \pm 150$
Single top quark	$28 \pm 2\ ^{+8}_{-6}$
W+jets	$14 \pm 3\ ^{+6}_{-3}$
Z+jets	$2.1 \pm 0.7\ ^{+1.2}_{-0.4}$
Diboson	$0.5 \pm 0.1 \pm 0.2$
Misidentified leptons	$55 \pm 10 \pm 20$
All SM backgrounds	$940 \pm 22 \pm 150$
Data	933
$t \to bH^+$ (130 GeV)	$120 \pm 4 \pm 25$
Signal+background	$990 \pm 21 \pm 140$

Sample	Event yield (τ+lepton)	
	$\tau + e$	$\tau + \mu$
True τ+lepton	$430 \pm 14 \pm 59$	$570 \pm 15 \pm 75$
Misidentified jet $\to \tau$	$510 \pm 23 \pm 86$	$660 \pm 26 \pm 110$
Misidentified $e \to \tau$	$33 \pm 4 \pm 5$	$34 \pm 4 \pm 6$
Misidentified leptons	$39 \pm 10 \pm 20$	$90 \pm 10 \pm 34$
All SM backgrounds	$1010 \pm 30 \pm 110$	$1360 \pm 30 \pm 140$
Data	880	1219
$t \to bH^+$ (130 GeV)	$220 \pm 6 \pm 29$	$310 \pm 7 \pm 39$
Signal+background	$1160 \pm 30 \pm 100$	$1570 \pm 30 \pm 130$

Sample	Event yield (τ+jets)
True τ (embedding method)	$210 \pm 10 \pm 44$
Misidentified jet $\to \tau$	$36 \pm 6 \pm 10$
Misidentified $e \to \tau$	$3 \pm 1 \pm 1$
Multi-jet processes	$74 \pm 3 \pm 47$
All SM backgrounds	$330 \pm 12 \pm 65$
Data	355
$t \to bH^+$ (130 GeV)	$220 \pm 6 \pm 56$
Signal+background	$540 \pm 13 \pm 85$

Charged Higgs (→τν)

Source of uncertainty	Normalisation uncertainty	Shape uncertainty
lepton+jets: lepton misidentification		
Choice of control region	6%	-
Z mass window	4%	-
Jet energy scale	16%	-
Jet energy resolution	7%	-
Sample composition	31%	-
τ+lepton: jet $\to \tau$ misidentification		
Statistics in control region	2%	-
Jet composition	11%	-
Object-related systematics	23%	3%
τ+lepton: $e \to \tau$ misidentification		
Misidentification probability	20%	-
τ+lepton: lepton misidentification		
Choice of control region	4%	-
Z mass window	5%	-
Jet energy scale	14%	-
Jet energy resolution	4%	-
Sample composition	39%	-
τ+jets: true τ		
Embedding parameters	6%	3%
Muon isolation	7%	2%
Parameters in normalisation	16%	-
τ identification	5%	-
τ energy scale	6%	1%
τ+jets: jet $\to \tau$ misidentification		
Statistics in control region	2%	-
Jet composition	12%	-
Purity in control region	6%	1%
Object-related systematics	21%	2%
τ+jets: $e \to \tau$ misidentification		
Misidentification probability	22%	-
τ+jets: multi-jet estimate		
Fit-related uncertainties	32%	-
$E_{\mathrm{T}}^{\mathrm{miss}}$-shape in control region	16%	-

Charged Higgs (→cs)

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}

Systematic Source	
Jet energy scale	+11, −13% (SM $t\bar{t}$)
	+9, −12% (signal)
b-Jet energy scale	±0.5%
Jet energy resolution	±1%
b-tagging efficiency	+4, −9%
MC generator	±4%
Parton shower	±3%
ISR/FSR	±1%
Additional Interactions	±4%
Luminosity	±3.4%
Electron reconstruction	±1.6%
Muon reconstruction	±0.2%
Electron trigger	±0.2%
Muon trigger	±0.5%
$t\bar{t}$ cross section	+7, −9%
t quark mass	±7%

NMSSM Higgs search

Source	Relative Uncertainty (%) at $m(a_1)$ (GeV)							
	6.0	6.5	7.0	7.5	8.0	8.5	11.0	11.5
Luminosity	±3							
PYTHIA vs MC@NLO	±67	±55	±49	±40	±36	±32	±20	±20
Dimuon Efficiency	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+15}_{-14}$	$^{+15}_{-14}$
Trigger Correction	±8							
MC Statistics	±10	±10	±10	±10	±10	±10	±9	±9
Likelihood Ratio Modeling	±3							
Total (Pythia vs MC@NLO)	±70	±59	±53	±45	±41	±37	±28	±28