Searches for Pseudoscalar Higgs Bosons using the ATLAS Detector

Eric Feng (ANL)

on behalf of the ATLAS Collaboration

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Introduction

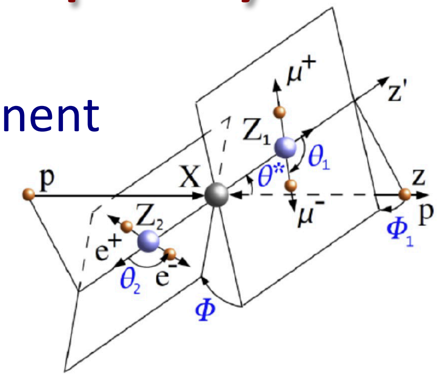
- Discovery and measurements of a SM-like Higgs boson have "completed" the Standard Model, but still insufficient to fully describe nature
- Supersymmetry provides a possible solution to hierarchy problem and dark matter
  - *Pseudoscalar Higgs bosons appear in variants of SUSY*
- Direct searches for pseudoscalar Higgs bosons
  - MSSM: Searches for A->$\tau\tau$, $\mu\mu$ (heavy A)
  - NMSSM: Searches for a->$\mu\mu$; h->aa->4γ (light a)
- Constraints from measurements of observed Higgs boson
  - Probe of Higgs CP in h->ZZ->4l
  - Coupling measurements with all channels -> MSSM, 2HDM
- **Searches for pseudoscalar Higgs bosons are important probe of new, fundamental physics at the TeV scale!**

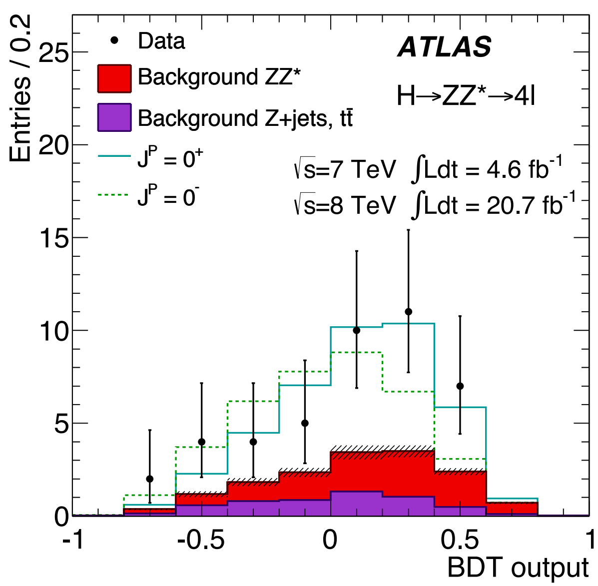
Pseudoscalars in extended Higgs sectors

Model	Higgs sector	CP-odd	SUSY partners
2HDM: Two-Higgs-Doublet-Model	Two doublets → 5 Higgs bosons (h, H, H^+, H^-, **A**)	**A (heavy)**	None
MSSM: Minimal Supersymmetric Standard Model	Two doublets → 5 Higgs bosons (h, H, H^+, H^-, **A**)	**A (heavy)**	+ sparticles
NMSSM: Next-to-minimal Supersymmetric Standard Model	Two doublets, one singlet → 7 Higgs bosons (h_1, h_2, h_3, H^+, H^-, $\mathbf{a_1}$, $\mathbf{a_2}$)	**$\mathbf{a_1}$, $\mathbf{a_2}$ (light)**	+ sparticles

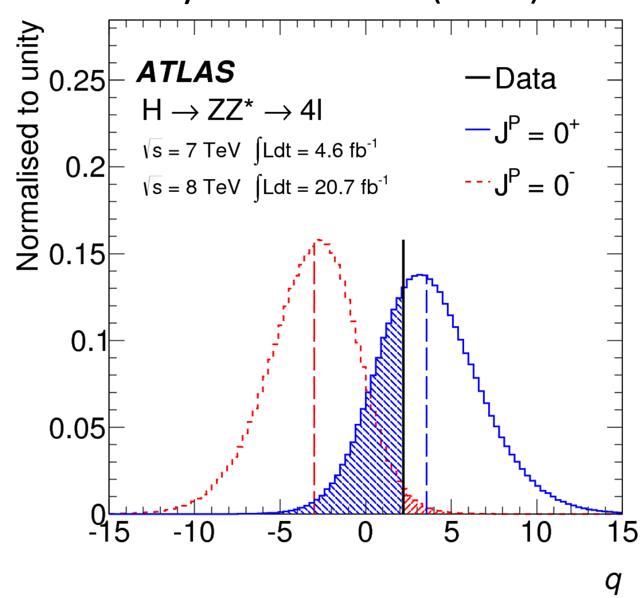
Probe of observed Higgs charge-parity

- Observed Higgs boson may have a pseudoscalar component
- BDT trained to use Z masses and lepton angles in h->ZZ->4l decays in 7-8 TeV data
- 0^- hypothesis excluded at 97.8% CL in favor of 0^+
  - However CP admixtures still compatible with data
  - At 14 TeV, CP-odd fraction f_{g4} < 0.18 (0.05) exp. with 300 (3000 fb-1)
    - ATL-PHYS-PUB-2013-013



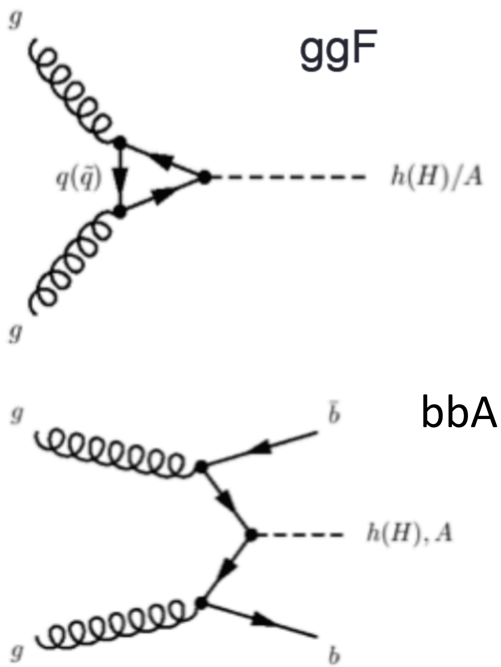


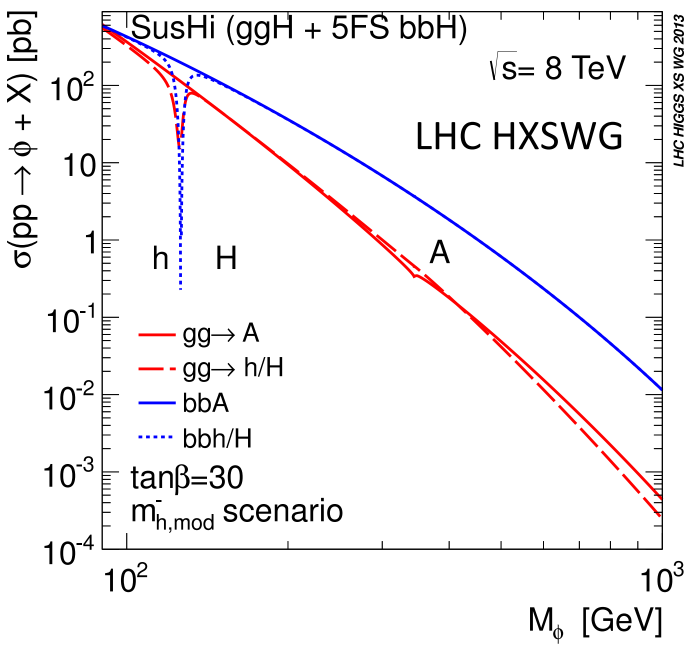
Phys. Lett. B 726 (2013) 120



MSSM: Production modes of *A*

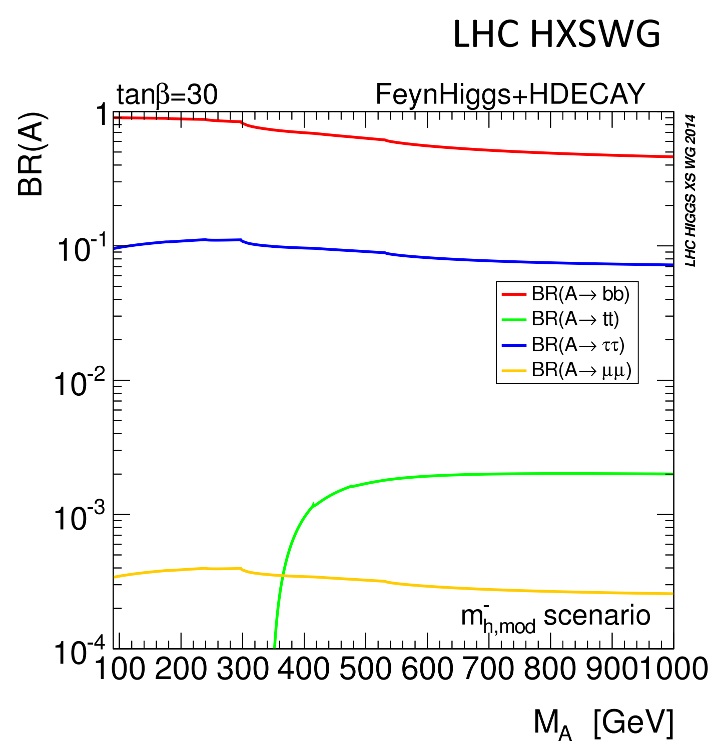
- Simplest low-energy SUSY model with rich & simple Higgs phenomenology
  - A has odd CP, while other Higgs bosons are CP-even
  - Two parameters: m_A and tan $\beta = \nu_2/\nu_1$
- Dominant production modes for A are gluon fusion and associated bbA
  - bbA can be significantly enhanced at large tan β → tag b-jets





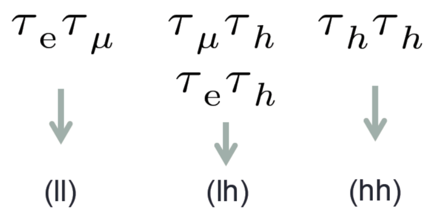
MSSM: Decay modes of *A*

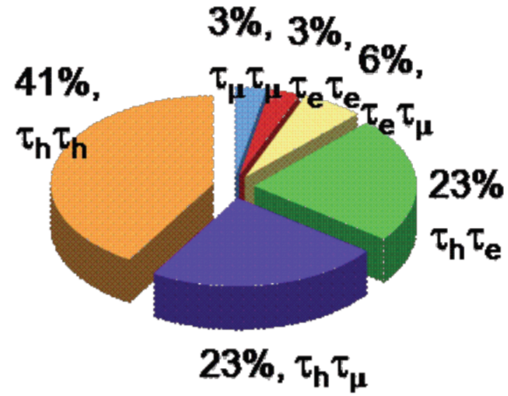
- Branching ratios for pseudoscalar Higgs
- Dominant decay modes to b-quarks and taus, particularly at large tan β
- BR(A->$\tau\tau$) ~ 10%
  - Better sensitivity at low mass than A->bb due to large QCD backgrounds
    - Categorized in turn by decay mode of each τ
  - BR(A->$\mu\mu$) ~ 0.04% but clean signature



Search for A->ττ

- 4.7 fb^{-1} of 7 TeV data
  - Categorize by final state depending on τ decay



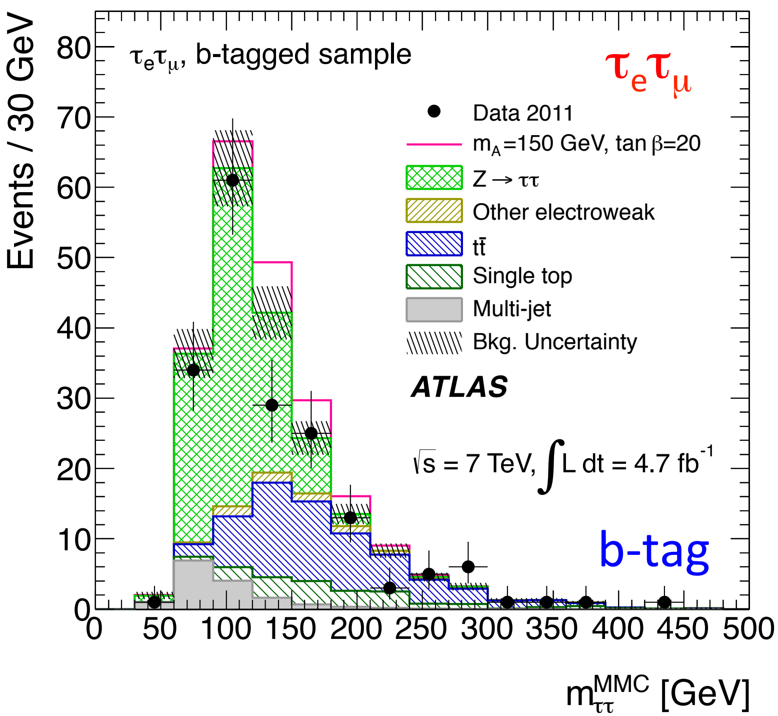


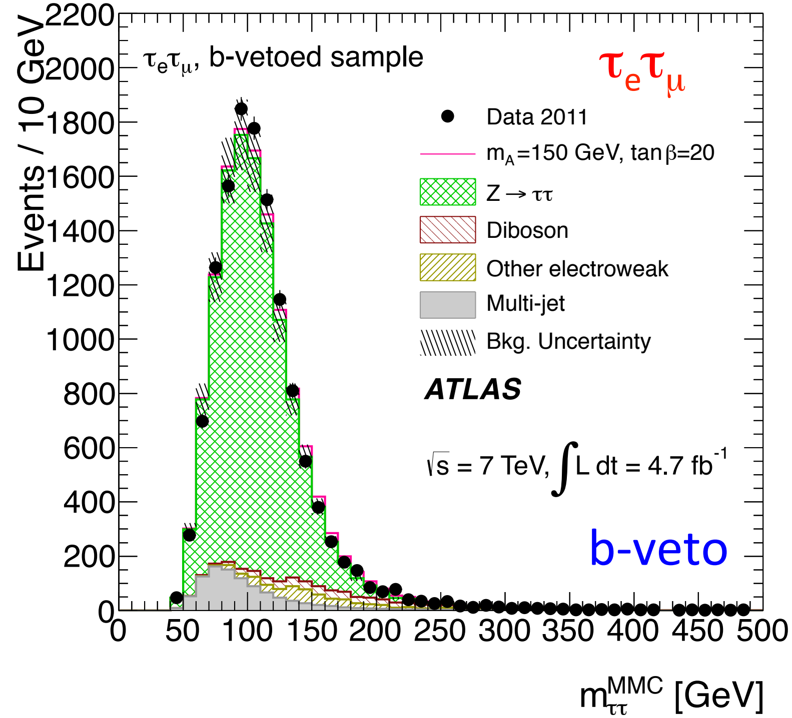
- Triggers:
  - $\tau_e\tau_m$ ($\tau_{lep}\tau_{had}$): Single or di-lepton (single lepton only)
  - $\tau_{had}\tau_{had}$: Two hadronic taus
- Samples split by b-tag or b-veto to distinguish bbA vs. ggF production
- Discriminating variable, $m_{\tau\tau}$, estimated via Missing Mass Calculator (MMC)
  - Assume missing E_T due entirely to neutrinos
  - Scan over angles between neutrinos and tau decay products
  - Pick most likely invariant mass of ττ pair
- Dominant irreducible background from Drell Yan: Z/γ*->ττ
  - Embed simulated taus into Z/γ*->μμ data & normalize to simulation
- Multi-jet background:
  - ABCD method for charge correlation & lepton isolation
- Systematic uncertainties:
  - Data-driven backgrounds
  - Cross-sections and acceptance for MC samples, including theory
  - Trigger & ID for electrons, muons, and hadronic taus
  - Energy/momentum scale and resolution of objects, particularly calorimeter

A->$\tau_e\tau_\mu$

- Dilepton: Exactly one electron and one opposite-charge muon, with $m_{e\mu}$ > 30 GeV
  - Electron (muon) pT > 15 (10) GeV for eμ trigger, or 24 (20) GeV for single lepton trigger
- Low MET and large $\Delta\phi$(e,μ) required to reject ttbar & diboson backgrounds
  - Low H_T required to reduce jet-related backgrounds

JHEP 02 (2013) 095





A->$\tau_{lep}\tau_{had}$

- Semi-leptonic channel:
  - Single isolated electron (muon) with pT > 25 (20 GeV)
  - Hadronic tau required to have opposite charge as lepton
- Demand m_T(*l*, MET) < 30 GeV to avoid W+jets and ttbar
- Top backgrounds smaller here due to one lepton

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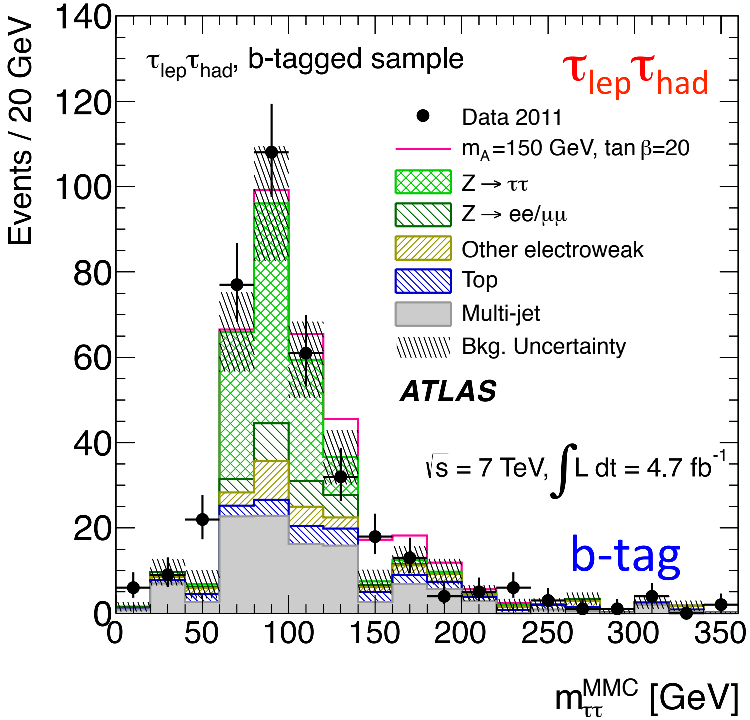

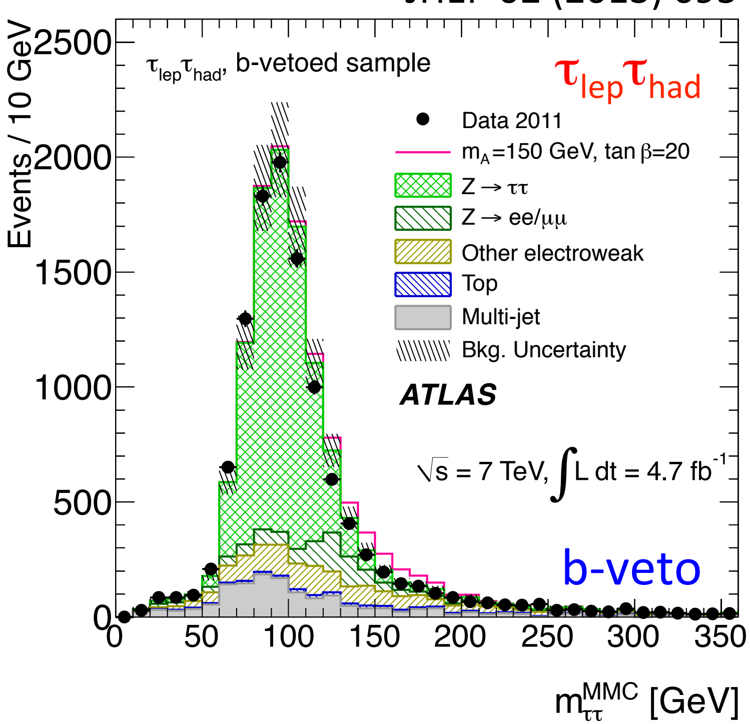

A->$\tau_{had}\tau_{had}$

- Fully hadronic channel:
  - Two hadronic taus, one "tight" and one "medium"
  - Opposite charge and p_T>45 & 30 GeV
- Veto on electrons (muons) with p_T > 15 (10) GeV
- MET > 25 GeV for neutrinos and suppress QCD multijets
  - Dominant background coming from multijets, then DY

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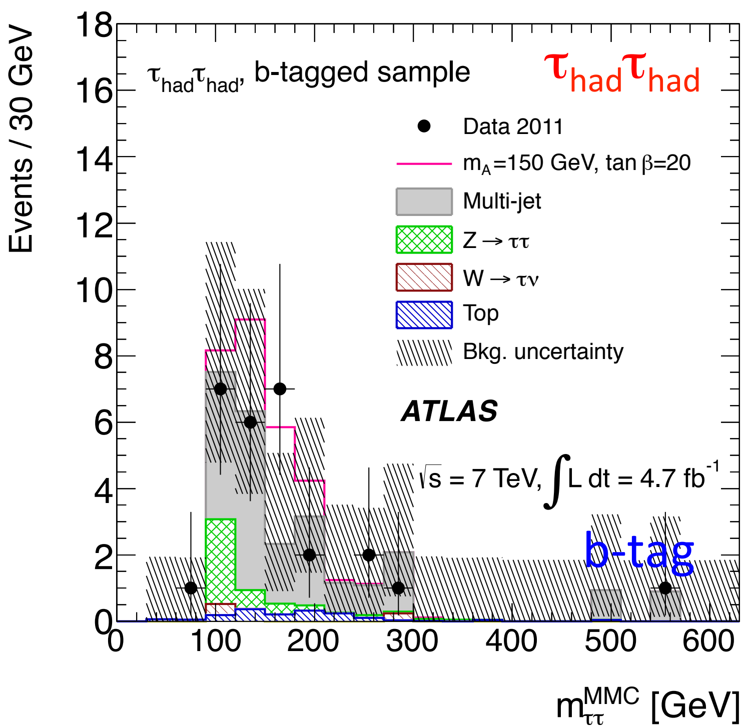

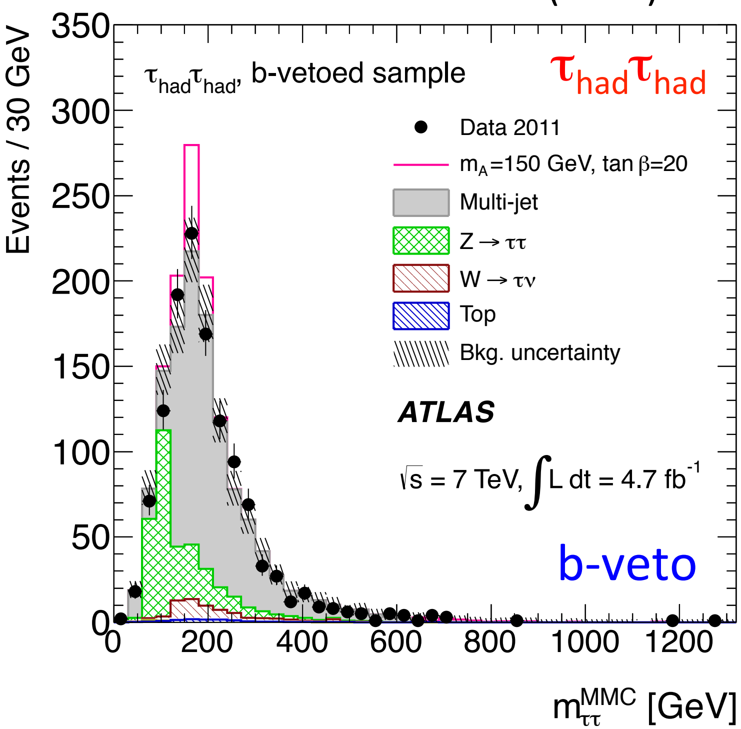

Search for A->μμ

- Two isolated muons with p_T> 20 & 15 GeV
  - MET < 45 GeV to reduce ttbar background
- Samples with/without tagged b-jet for bbA vs. ggF and to reject Drell-Yan
- Smooth backgrounds expected to be dominated by Z->μμ and ttbar (left)
- Actual analysis fits smooth background in sidebands above Z pole (right)

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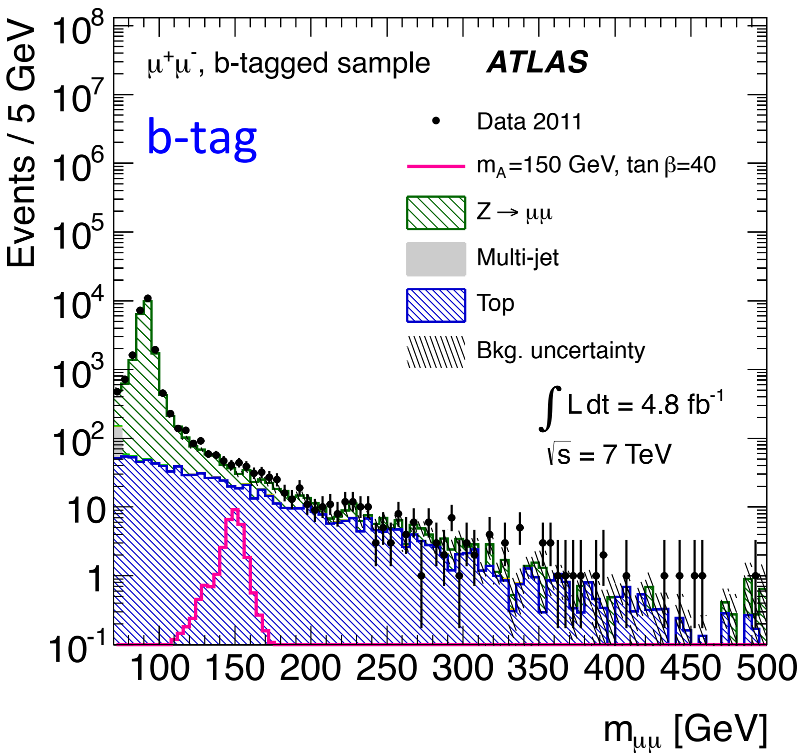

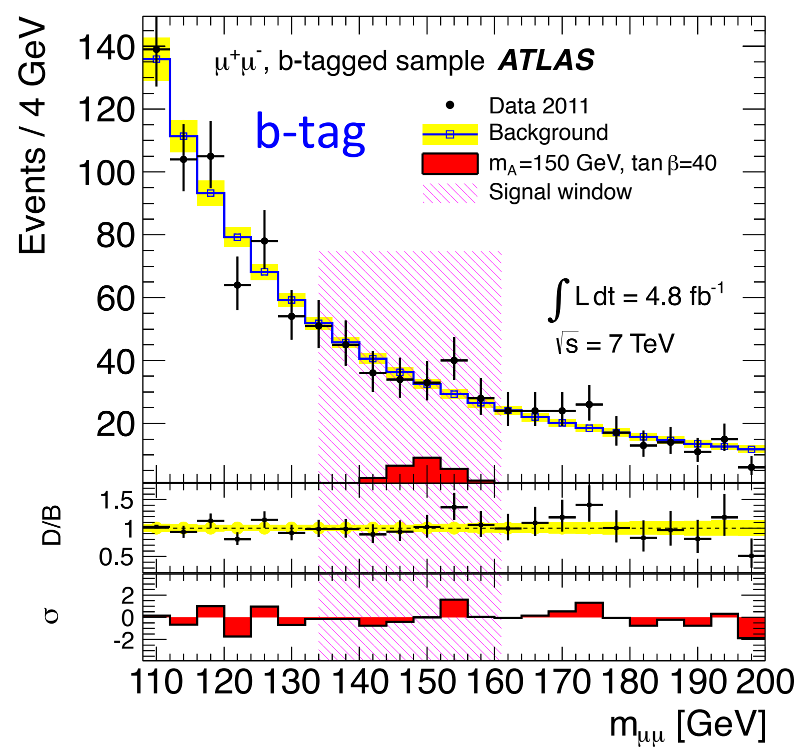

Limits on A->ττ, μμ

- No significant excess observed in any ττ nor μμ decay mode
  - Upper limits on $\sigma \times$ BR at sqrt(s)=7 TeV for decays into ττ and μμ (left)
- Translated into upper limits on tan $\beta = \nu_2/\nu_1$ as a function of m_A (right)
  - Dilepton: Sensitive at low mass where hadronic backgrounds are large
  - Semi-leptonic: Sensitive at wide range of masses due to lepton
  - Hadronic: Sensitive at high mass where hadronic backgrounds decrease
  - Tightest constraint is tan β < 9.3 for m_A = 130 GeV @ 95% CL

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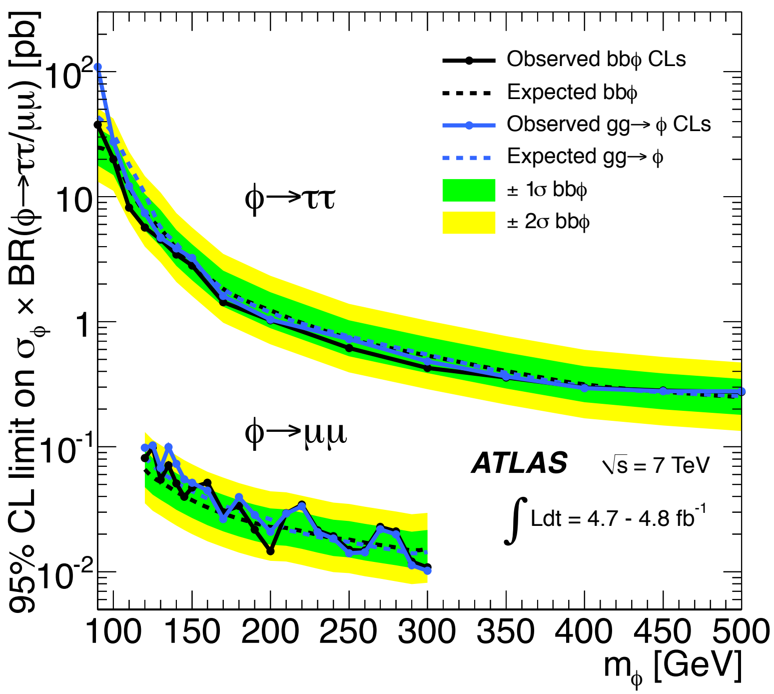

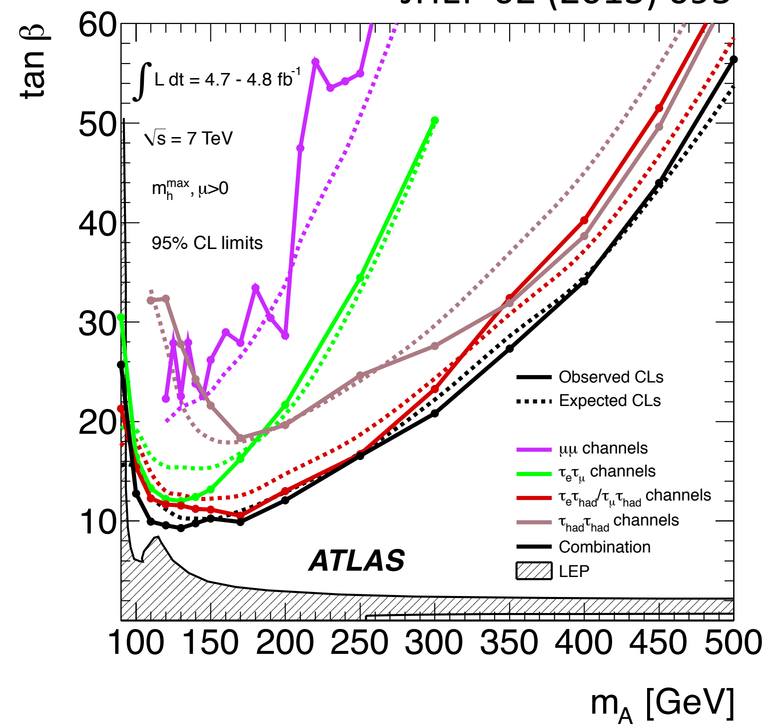

Search for Z'->ττ at high mass

- Search for high-mass Z' decaying via hadronic taus with 20 fb^{-1} of 8 TeV data
  - $\sigma(Z')\bullet BR(Z'\to\tau\tau) < 0.1$ pb at $m_{Z'} = 500$ GeV
- Search for pseudoscalar Higgs m_A<500 GeV similar, includes single-tau trigger
  - Kinematic acceptance and efficiencies specific for A instead of Z'
  - Work on-going to analyze 8 TeV data -- stay tuned for upcoming results!

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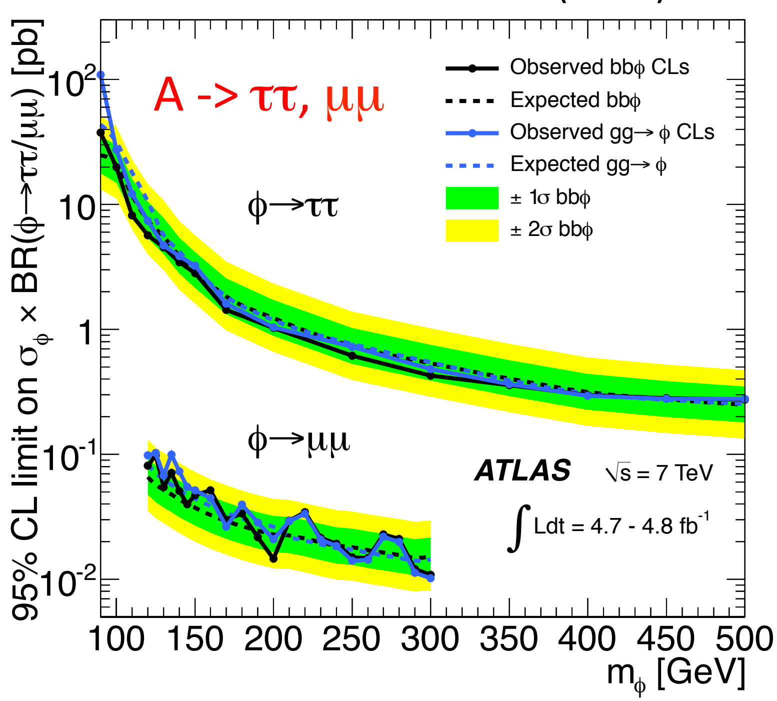
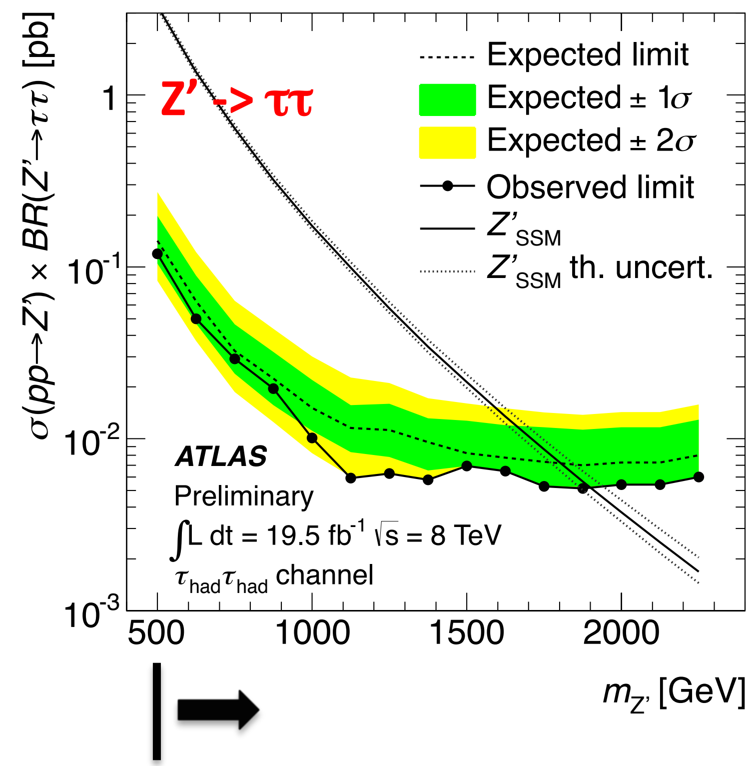


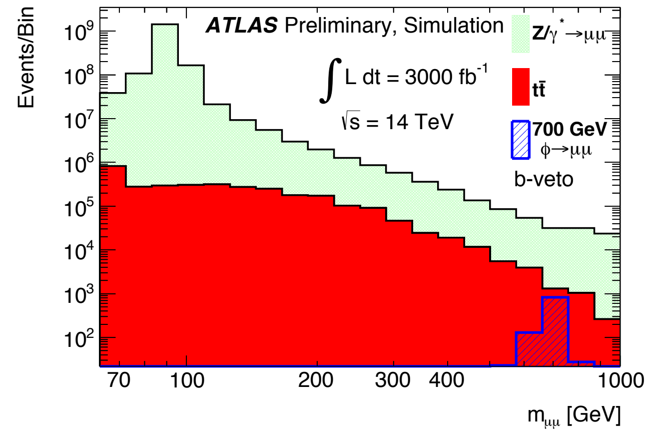
ATLAS-CONF-2013-066

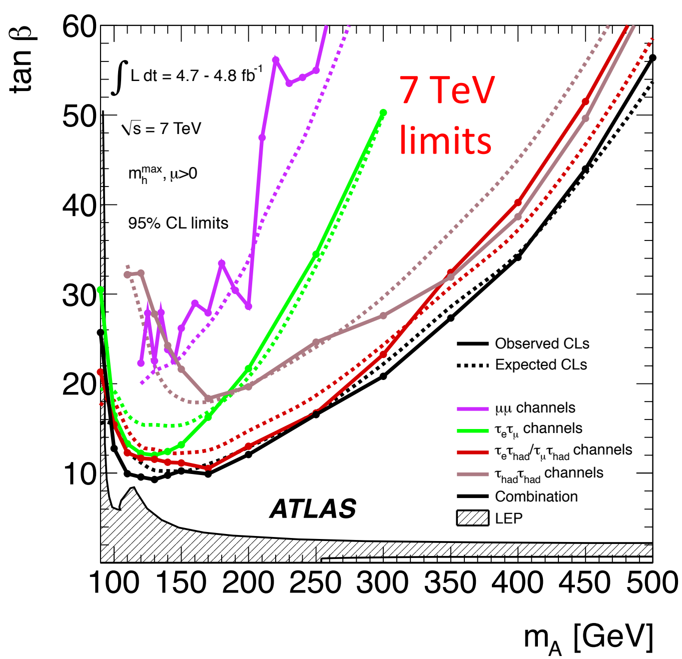


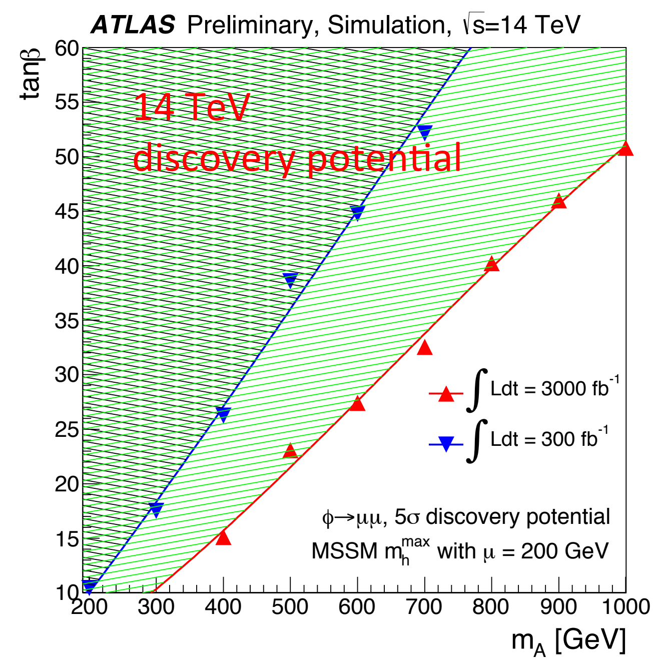
A->μμ prospects at 14 TeV

- Sensitivity projections at 14 TeV
- Regions with 5σ discovery potential
- Large improvement wrt 7-8 TeV, particularly at large m_A
  - tan β < 37 (23) for m_A=500 GeV at 300 (3000) fb^{-1} with A->μμ alone
- Expected exclusions even larger

ATL-PHYS-PUB-2013-016



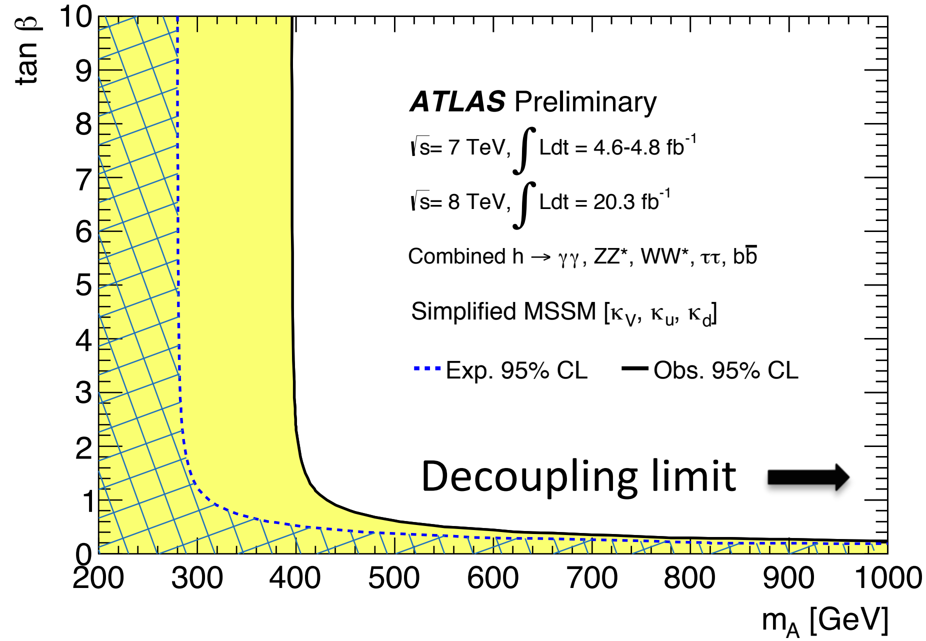




Simplified MSSM Constraints from Higgs Couplings

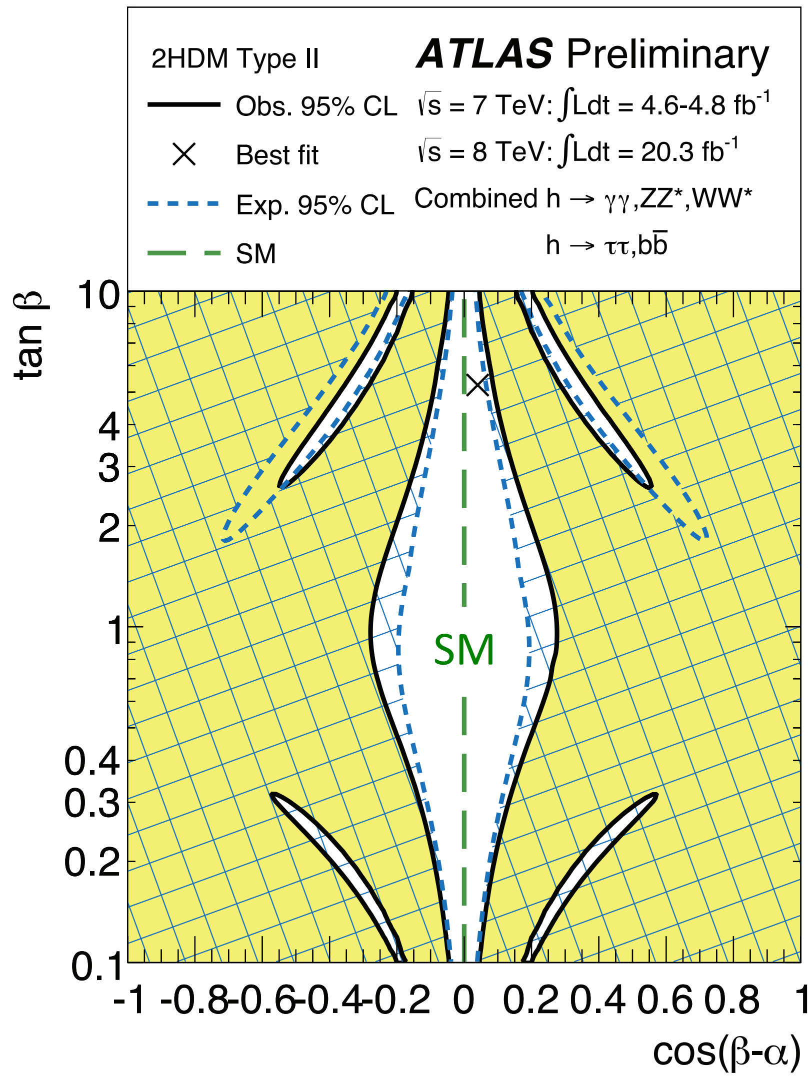
- Measured light Higgs couplings via combination of all channels in 7-8 TeV:
  - vector bosons (W/Z)
  - up-type fermions (top)
  - down-type fermions (b, tau)
- Higgs mass measured as: $m_h \sim 125.5$ GeV
- In MSSM, light Higgs mass m_h is a function of m_A and tan β: $m_h^2 = m_Z^2 \cos^2(2\beta) + \delta(m_A, \tan\beta, \ldots)$
- Couplings measurements used to constrain m_A and tan β:
  - For 2<tan β<10, m_A > 400 GeV obs. (290 GeV exp.) at 95% CL
  - Observed limits a bit tighter than expected for SM due to high h->$\gamma\gamma$ and h->ZZ rates
- *Lower limit on tan β for given m_A is complementary to upper limit from direct searches*

ATLAS-CONF-2014-010



2HDM Type II Constraints from Higgs Couplings

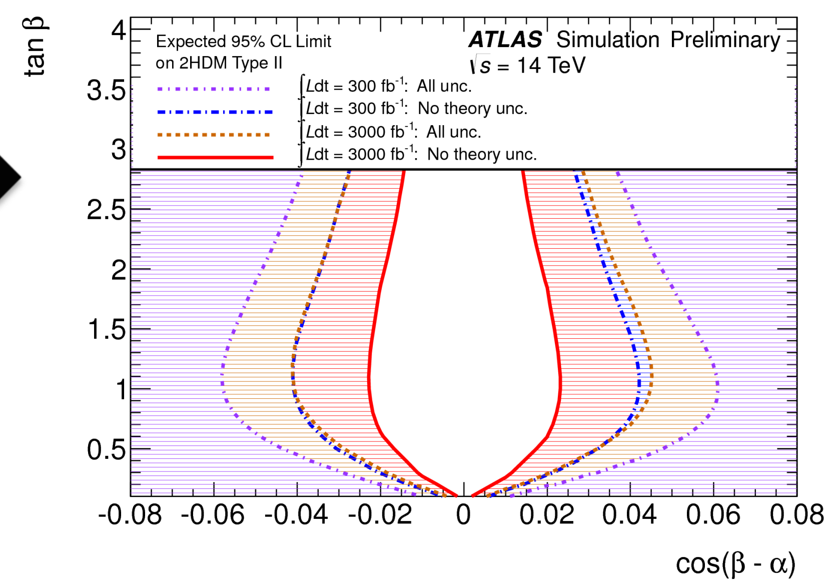
7-8 TeV ATLAS-CONF-2014-010



- 7-8 TeV measurements of Higgs couplings to vector bosons, up-type & down-type fermions via combination of all channels
  - Use to set limits on 2HDM Type II (left)

  → Limits on pseudoscalar couplings (scale as cot β for top quark, tan β for b-quark & τ)
  - Doesn't depend on mixing angle α between h,H at tree level
- Higher sensitivity at 14 TeV (right)

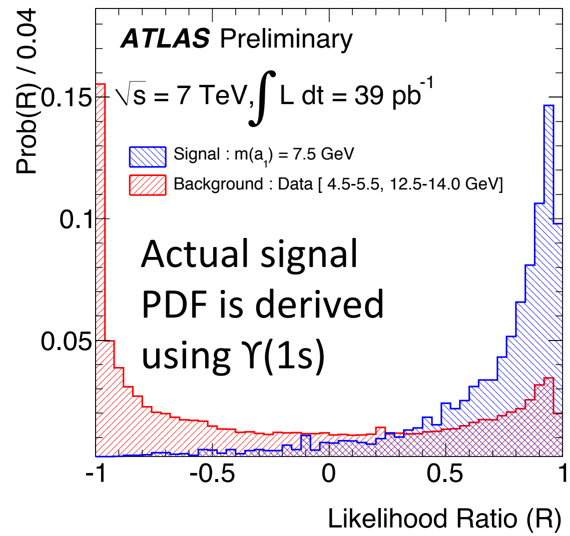
14 TeV ATL-PHYS-PUB-2013-015

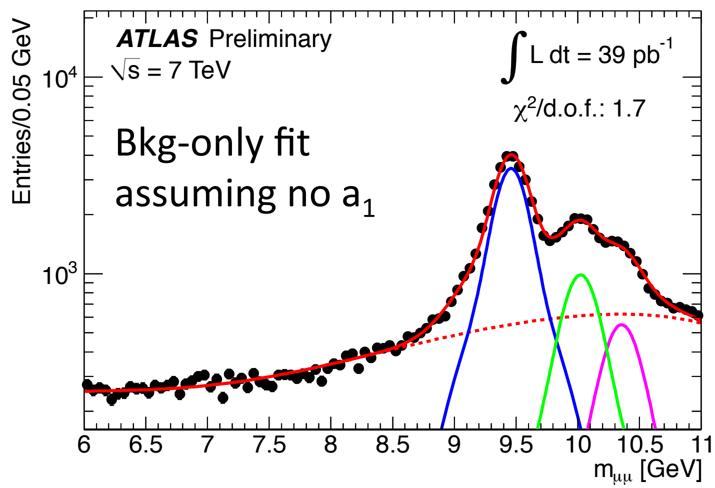


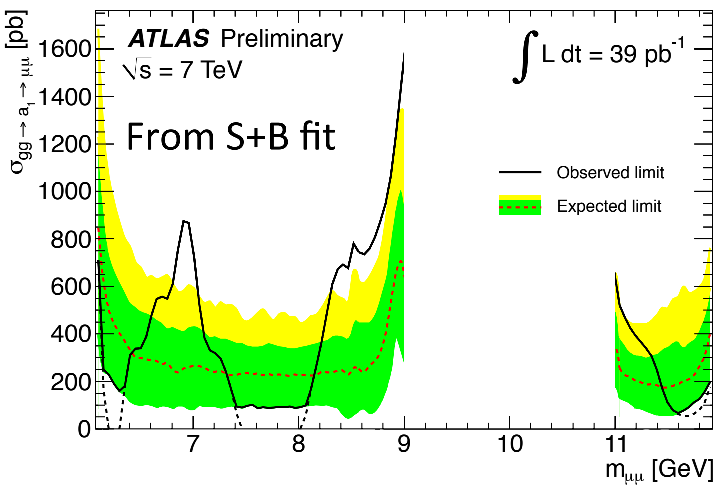
NMSSM: Search for a->μμ

- nMSSM: Add scalar singlet to MSSM
  - **2 CP-odd Higgs bosons: a_1, a_2 (typically light)**
- Search for inclusive a->μμ with 39 pb^{-1} at 7 TeV
  - Active analysis with 8 TeV data
- Require two muons triggered with p_T>4 GeV
- Likelihood ratio using vertex fit and isolation
  - PDFs derived using sidebands
- No significant excess wrt background-only prediction with ϒ states
  - Upper limit on rate of 0.1-1.6 nb

ATLAS-CONF-2011-020



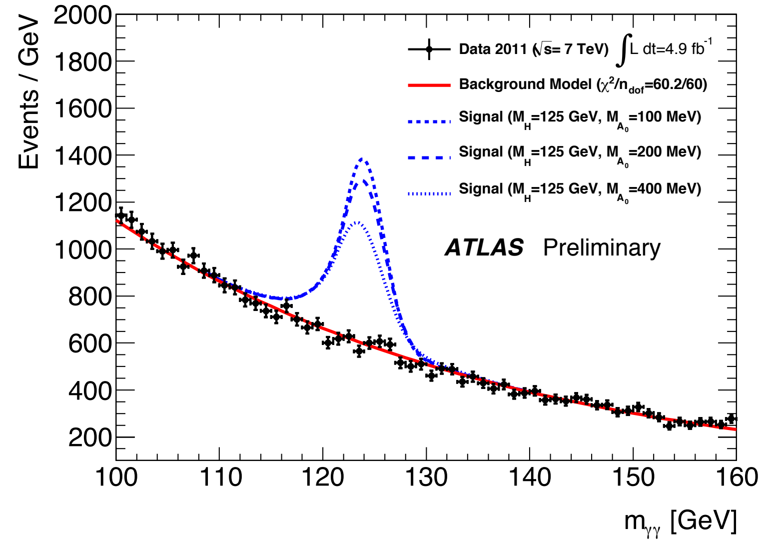


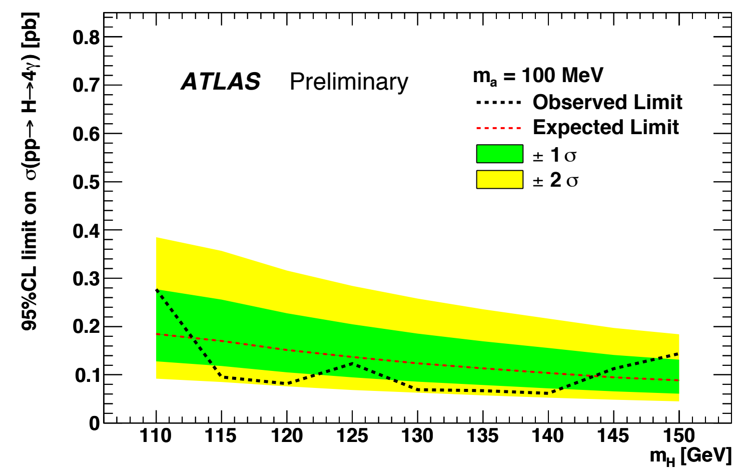


NMSSM: Search for h->aa->4γ

- Search for two collimated (unresolved) pairs of photons using 4.9 fb^{-1} of 7 TeV data
- Two photons with p_T > 40, 25 GeV
  - Loosened shower shape requirements sensitive to internal structure of EM shower
  - Categories of kinematics not used to be more model-independent
    - Thus h->γγ contamination is small
- Smooth backgrounds (dominated by QCD diphotons) fitted with sidebands
- No excess observed
  - σ*BR < 0.15 pb for m_a = 100 MeV at sqrt(s)=7 TeV

ATLAS-CONF-2012-079





Conclusions

- Searches performed for pseudoscalar Higgs bosons well-motivated by various scenarios (MSSM, NMSSM, 2HDM)
- **No evidence found in direct searches with 7 TeV data**
    - Indirect constraints from Higgs CP and coupling measurements (8 TeV data) also consistent with SM
- Although large regions of MSSM parameter space excluded, significant SUSY regions remain compatible with observed Higgs boson!
    - **Direct searches on-going with 8 TeV data, which have greater sensitivity**
    - Discovery potential will be further enhanced with 14 TeV data
- *Stay tuned for further results!*

ADDITIONAL INFORMATION

More information (I)

- ATLAS Collaboration. "Search for the neutral Higgs bosons of the Minimal Supersymmetric Standard Model in *pp* collisions at sqrt(s) = 7 TeV with the ATLAS detector." JHEP 02 (2013) 095. http://dx.doi.org/10.1007/JHEP02(2013)095

- ATLAS Collaboration. "A search for high-mass ditau resonances decaying in the fully hadronic final state in *pp* collisions at √s=8 TeV with the ATLAS detector." ATLAS-CONF-2013-066 (2013). https://cds.cern.ch/record/1562841

- ATLAS Collaboration. "Constraints on New Phenomena via Higgs Coupling Measurements with the ATLAS Detector." ATLAS-CONF-2014-010 (2014). https://cds.cern.ch/record/1670531

- ATLAS Collaboration. "Evidence for the spin-0 nature of the Higgs boson using ATLAS data." Phys. Lett. B 726 (2013) 120. http://dx.doi.org/10.1016/j.physletb.2013.08.026

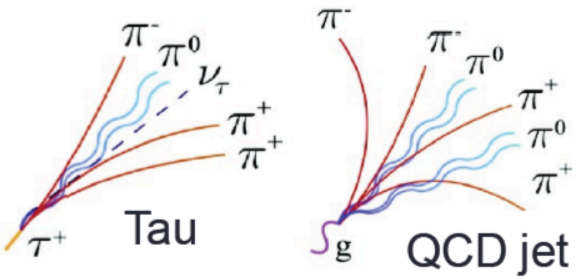
- ATLAS Collaboration. "Sensitivity to New Phenomena via Higgs Couplings with the ATLAS Detector at a High-Luminosity LHC." ATL-PHYS-PUB-2013-015 (2013). https://cds.cern.ch/record/1611189

More information (II)

- ATLAS Collaboration. "Beyond Standard Model Higgs boson searches at a High-Luminosity LHC with ATLAS." ATL-PHYS-PUB-2013-016 (2013). https://cds.cern.ch/record/1611190
- ATLAS Collaboration. "A Search for a Light CP-Odd Higgs Boson Decaying to $\mu^+\mu^-$ in ATLAS." ATLAS-CONF-2011-020 (2011). https://cds.cern.ch/record/1336749
- ATLAS Collaboration. "Search for a Higgs boson decaying to four photons through light CP-odd scalar coupling using 4.9 fb-1 of 7 TeV pp collision data taken with ATLAS detector at the LHC." ATLAS-CONF-2012-079 (2012). https://cds.cern.ch/record/1460391

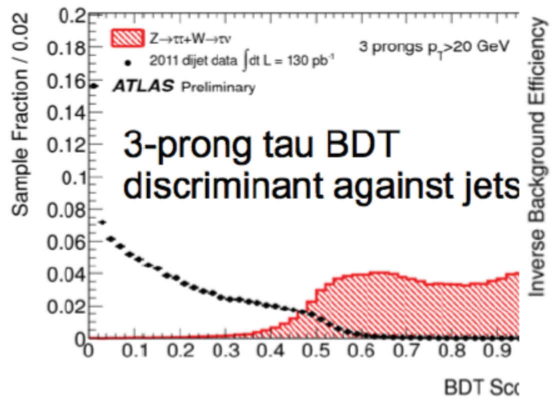
Tau reconstruction and ID

Tau jet reconstruction

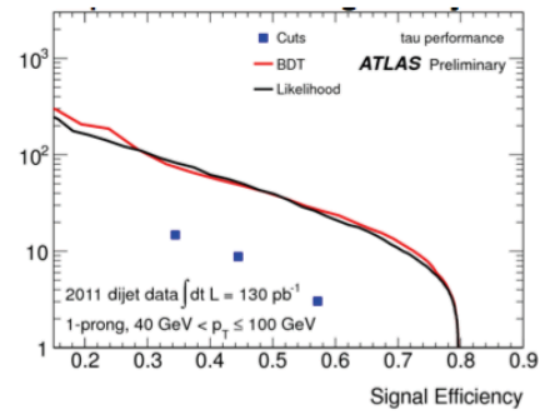


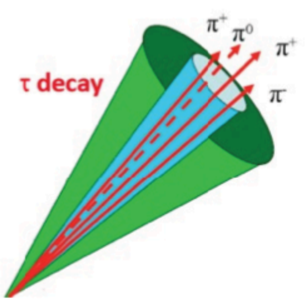
Seed from aK_T jets in calorimeter (ΔR=0.
Associated tracks in ΔR=0.2 of jet axis

Tau jet identification



1-prong tau-ID performance against jets

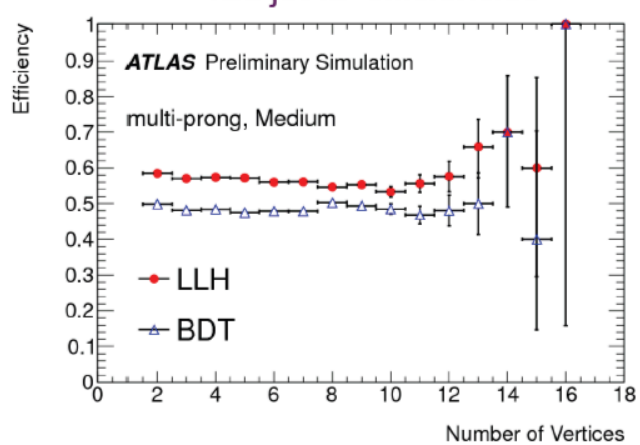




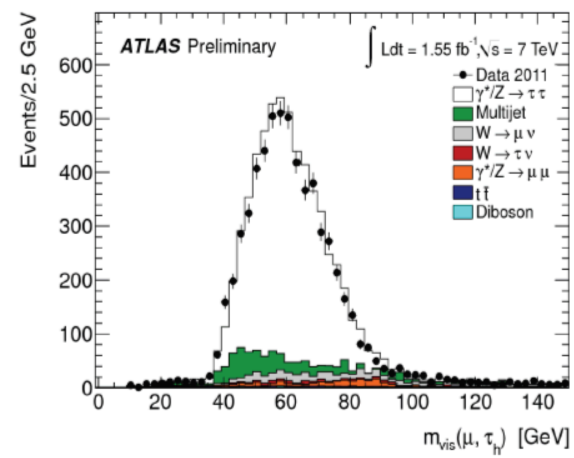
Use MVA BDTs and likelihoods using:
low track multiplicities,
isolation, shower shapes (collimation),
EM/HAD fractions and angular separic

- Discriminate against QCD jets
- Electron/Tau separation

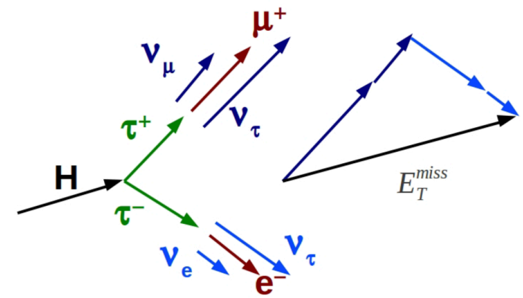
Tau jet ID efficiencies



Tau jets in DATA



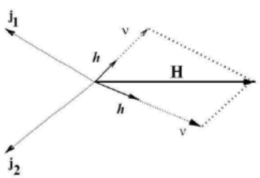
Di-tau invariant mass reconstruction



Effective (visible or transverse) mass →

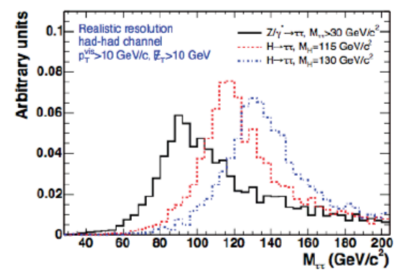
$$m_{\tau\tau} = \sqrt{(p_{\text{vis}_1} + p_{\text{vis}_2} + p_{\text{mis}})^2}$$
$$p_{\text{mis}} = (E_T^{\text{mis}}, E_{T_x}^{\text{mis}}, E_{T_y}^{\text{mis}}, 0)$$

Collinear approximation



$$m_{\tau\tau} = \frac{m_{\text{vis}}}{(x_1 x_2)^{1/2}}$$
$$x_{1,2} = \frac{p_{\text{vis}_{1,2}}}{p_{\text{vis}_{1,2}} + p_{\text{mis}_{1,2}}}$$
$$\not{E}_{T_x} = p_{\text{mis}_1} \sin\theta_{\text{vis}_1} \cos\phi_{\text{vis}_1} + p_{\text{mis}_2} \sin\theta_{\text{vis}_2} \cos\phi_{\text{vis}_2}$$
$$\not{E}_{T_y} = p_{\text{mis}_1} \sin\theta_{\text{vis}_1} \sin\phi_{\text{vis}_1} + p_{\text{mis}_2} \sin\theta_{\text{vis}_2} \sin\phi_{\text{vis}_2}$$

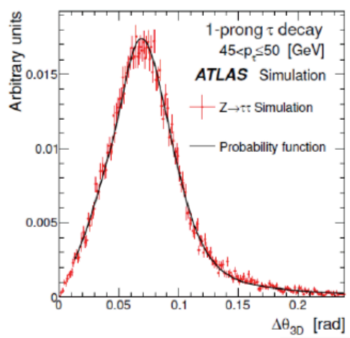
Collinear

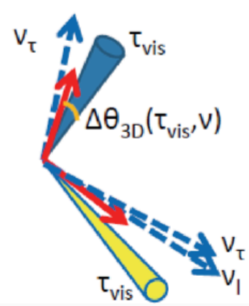


MMC
(Missing Mass Calculator)

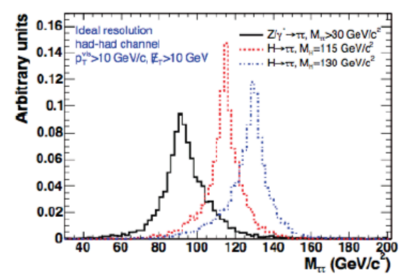
Event by event Mττ scanning over ν directions according to MC PDFs

$$\not{E}_{T_x} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \cos\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \cos\phi_{\text{mis}_2}$$
$$\not{E}_{T_y} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \sin\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \sin\phi_{\text{mis}_2}$$
$$M_{\tau_1}^2 = m_{\text{mis}_1}^2 + m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{mis}_1}^2 + m_{\text{mis}_1}^2} - 2p_{\text{vis}_1} p_{\text{mis}_1} \cos\Delta\theta_{\nu m_1}$$
$$M_{\tau_2}^2 = m_{\text{mis}_2}^2 + m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2}\sqrt{p_{\text{mis}_2}^2 + m_{\text{mis}_2}^2} - 2p_{\text{vis}_2} p_{\text{mis}_2} \cos\Delta\theta_{\nu m_2}$$





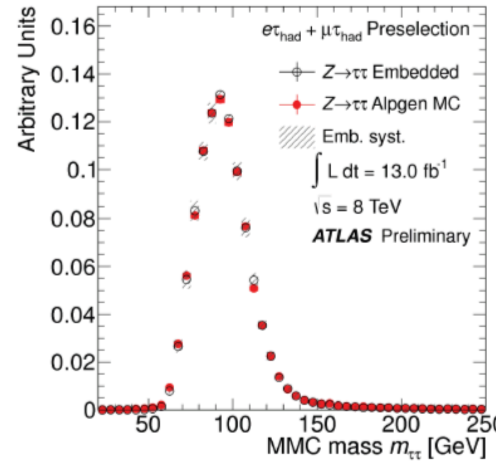
MMC



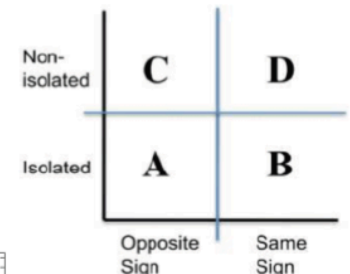
A. Elagin et. al, NIM A 654 (2011) 481

Backgrounds to A->ττ

- Z/γ*→ττ background estimated from data (all channels)
  - Select Z/γ*→μμ and replace the muon response with a tau response from MC
  - Apply selection to the embedded sample
  - Check agreement with Z/γ*→ττ simulation

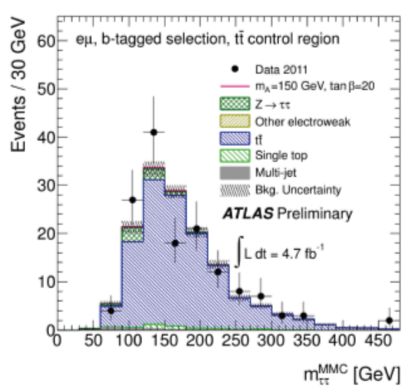


- QCD multijet backgrounds estimated from data (all channels)
  - Data-driven with ABCD method
  - eμ and lh channels: use SS/OS & lepton isolation
  - hh channel: use SS/OS & tau ID severity



$$n_A = n_B \times \frac{n_C}{n_D}$$

- Other backgrounds
  - Top (b-tag samples) from data CR
    - ll and lh channels
  - W+jets also from data CR
    - lh channel



CR (eμ sample, b-tagged): No HT cut, 2 b-tagged jets

$$n_{\text{top}}^{SR} = \alpha_{\text{top}} n_{\text{top}}^{CR}$$

from MC

$A \to \tau_e \tau_\mu$

- Event selection
  - Trigger: Single e (20 or 22 GeV) or μ (18 GeV), or combined e+μ (10 GeV and 6 GeV)
  - Exactly one e and opposite signed μ with E_T and p_T on trigger efficiency plateau, $m_{e\mu} > 30$ GeV
  - Events split by jet flavor: 1 b-tag and 0 b-tag
  - Reduce ttbar and diboson backgrounds: MET + $p_T^e + p_T <$ 125 GeV (b-tag) or < 150 GeV (b-veto)
  - $\Delta\phi(e,\mu) > 2.0$ (b-tag) or >1.6 (b-veto)
  - $\Sigma \cos \Delta\phi(\mathrm{MET}, l) > -0.2$ (b-tag) or > -0.4 (b-veto)
  - b-tag: scalar sum of jets, $H_T <$ 100 GeV
- Background estimation
  - Multi-jets: ABCD estimate using e/μ isolation requirements and charge correlation
  - ttbar: Extrapolated from control regions using 2 b-tagged sample

$A\text{->}\tau_{lep}\tau_{had}$

- Event selection
  - Trigger: Single e (20 or 22 GeV) or μ (18 GeV)
  - Exactly one *e* with p_T>25 GeV or one μ with p_T>20 GeV
  - One τ_{had} with E_T > 20 GeV
  - m_T(*l*, MET)<30 GeV
  - Split by b-tagging:
    - b-tagged sample: highest E_T jet is b-tagged and has 20 < E_T < 50 GeV
    - b-vetoed sample: highest E_T jet *not* b-tagged and MET > 20 GeV
- Background estimation
  - Multi-jets: ABCD estimate uses e/μ isolation requirements and charge correlation
  - ttbar: Derive correction factor for simulation using 2-btag selection

A->$\tau_{had}\tau_{had}$

- Event selection
  - Trigger: Di-τ_{had} (29 GeV and 20 GeV)
  - Two opposite-sign trigger-matched τ_{had} candidates. No *e* nor μ
    - Leading τ_{had}: E_T > 45 GeV , tight ID
    - 2nd leading τ_{had}: E_T > 30 GeV, medium ID
  - MET > 25 GeV
  - Split by b-tagging:
    - b-tagged sample: Highest E_T jet is b-tagged and has $20<E_T<50$ GeV
    - b-vetoed sample: Highest E_T jet *not* b-tagged and MET > 60 GeV
- Background estimation
  - Multi-jets: ABCD estimate uses τ ID requirements and opposite sign/ same sign events
  - Tau modeling: Correct simulation using Z->$\tau_{had}\tau_{\mu}$ (trigger/ID) and W(->μv)+jets (jet fake rate)

A->μμ

- Background modeled using smooth functions
- Signal modeled using Breit-Wigner convolved with Gaussian resolution, together with Landau function for low-mass tail
  - BW width fixed to FeynHiggs prediction

Two Higgs Doublet Models (2HDMs)

- Additional Higgs doublet could appear in SUSY or other BSM theories (hierarchy problem, dark matter)
  - Results in 5 Higgs bosons
- Four types (I, II, III, IV) of two Higgs-doublet models satisfy Glashow-Weinberg condition
  - No tree-level flavor changing neutral currents
- Light Higgs couplings are function of two parameters:
  - Mixing angle α between two CP-even states h, H
  - Ratio of vacuum expectation values of 2 doublets: $\tan(\beta)=v_2/v_1$
- Assume that observed Higgs boson is the light Higgs, h

Coupling strength	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

Prospects for A->Zh at 14 TeV

ATL-PHYS-PUB-2013-016

- Search for A->Zh->llbb
  - Example signal for m_A=360 GeV (top right)
- Expected limit with 14 TeV data (left)
  - Analysis of 8 TeV on-going now – stay tuned!
- Translated into limits on m_A & $\cos(\beta-\alpha)$ in Two-Higgs-Doublet-Model (2HDM) Type II i.e. "MSSM-like" Higgs sector (bottom right)