



Search for the decay of the Higgs boson into two NMSSM pseudo-scalar particles

Lidija Živković

Institute of Physics, Belgrade,

On behalf of the ATLAS Collaboration



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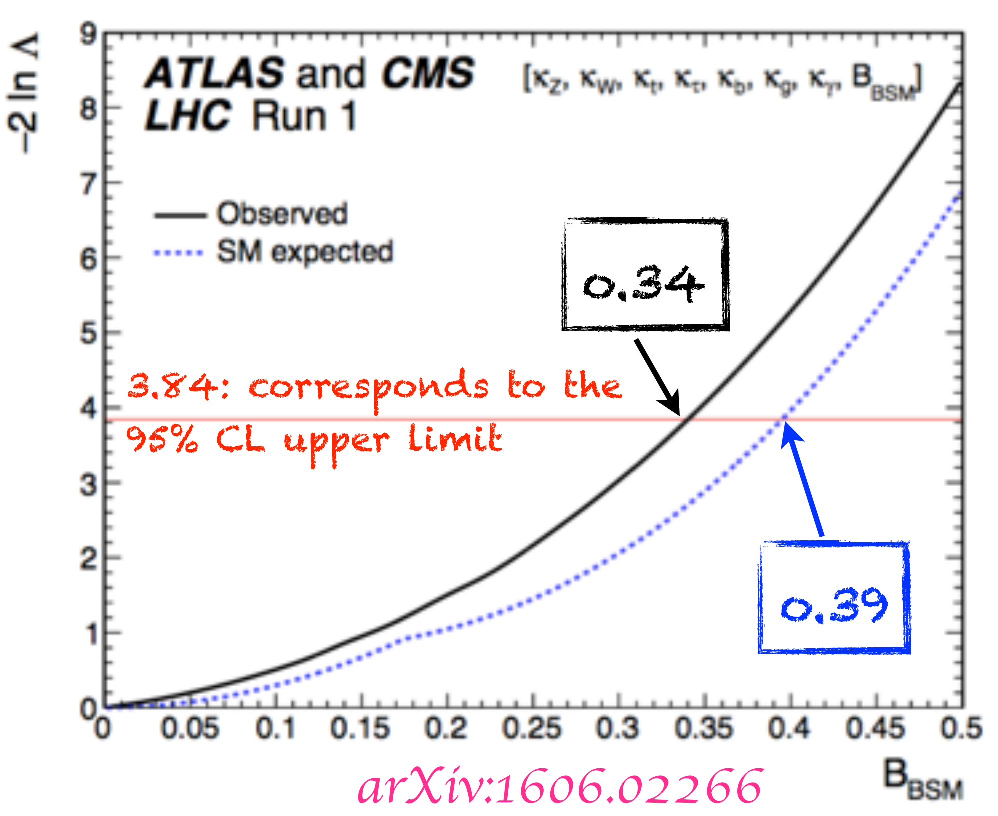
Motivation

- A scalar particle was discovered in 2012. Since then, it was confirmed that it is consistent with a SM Higgs boson
    - This discovery completes the SM, but many phenomena remain unexplained
- With present constraints and measurements, it is possible that 30% of the Higgs boson BR goes to the decays to exotic particles
    - Exotic decays are predicted in many BSM models including those with extended Higgs sector like NMSSM



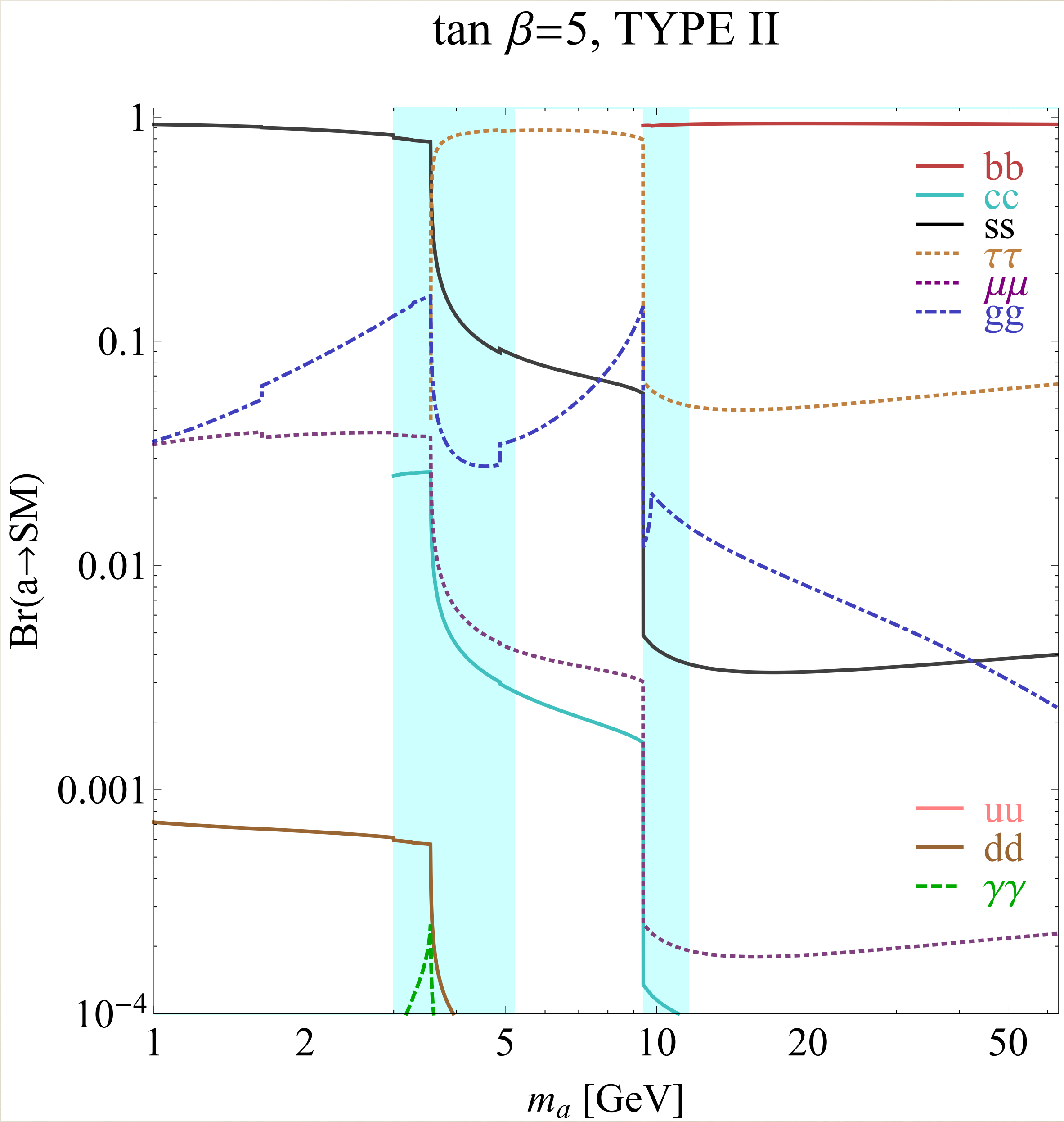
arXiv:1606.02266

- One of the most popular theories to explain phenomena beyond SM is SUSY and its minimal version MSSM
    - However, there is no experimental evidence of SUSY, and the μ-term in $\mu \hat{H}_u \hat{H}_d$ still requires fine tuning

NMSSM

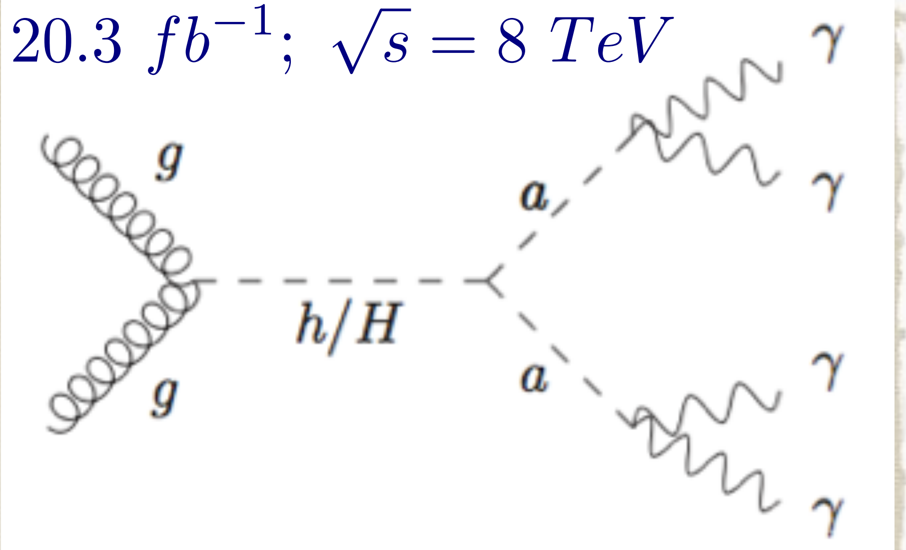
- In NMSSM a singlet S is introduced and the μ-term from MSSM is replaced with $\lambda \hat{S} \hat{H}_u \hat{H}_d$
- The Higgs sector in NMSSM contains an additional pseudoscalar (a_1, a_2) and an additional scalar (h_1, h_2, h_3) compared to the MSSM
  - MSSM parameters: μ, tanβ, M_A
  - NMSSM parameters: λ, κ, A_λ, A_κ, tanβ, μ_{eff}
- Light pseudoscalar is motivated by many theories, and three distinct regions define dominant decays

Belongs to general 2HDM+S models



$m_a < 2m_\tau$, $2m_\tau < m_a < 2m_b$, $m_a > 2m_b$

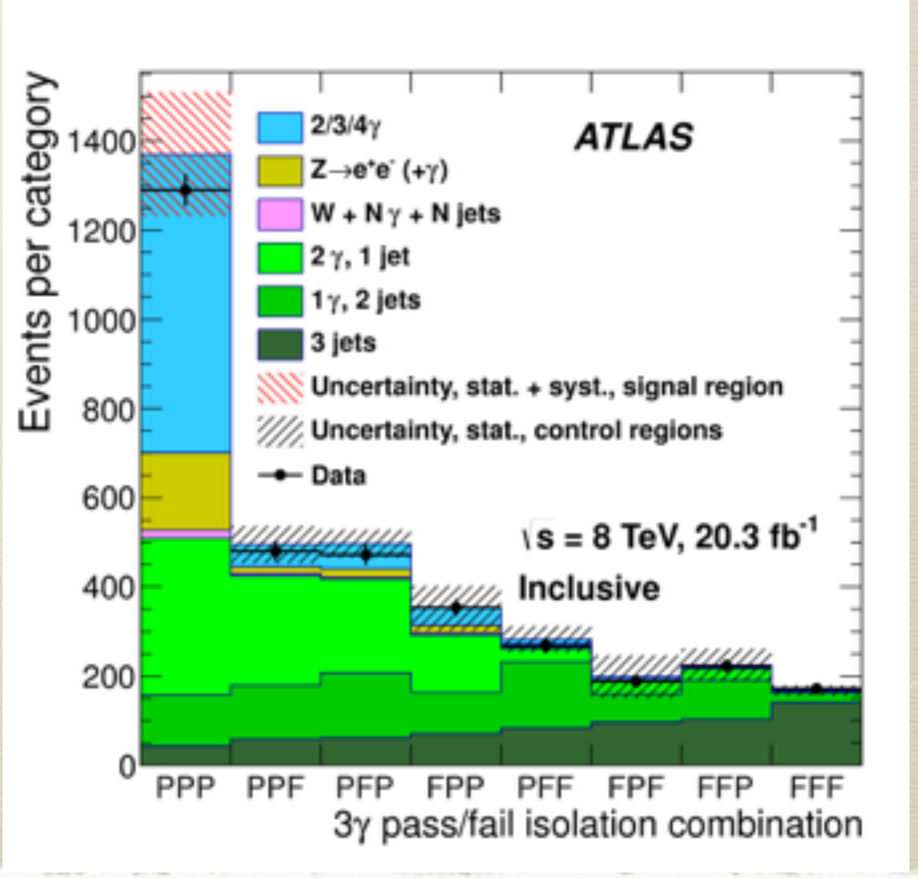
$h \rightarrow aa \rightarrow 4\gamma$



- Inclusive three photon search interpreted in NMSSM context for $10 < m_a < 62$ GeV
  - Select three tight (eff~85%, rej~5000) isolated ($E_T^{iso} < 4$ GeV) photons with $p_T > 22,22,17$ GeV

-> Defined 160 categories based on kinematics and Pass or Fail isolation
-> PPP: signal region
-> Any F: control region
-> Fits performed to obtain sample composition

- Estimate background from MC and data
  - Multi photon from MC with K factors obtained from higher order calculations
  - Reducible background with jet(s) misidentified as photon(s) obtained from data
    - Select photon-like jet sample using "non-tight" photon candidates
    - Normalize it in the tail of E_T^{iso} (> 7 GeV) distribution

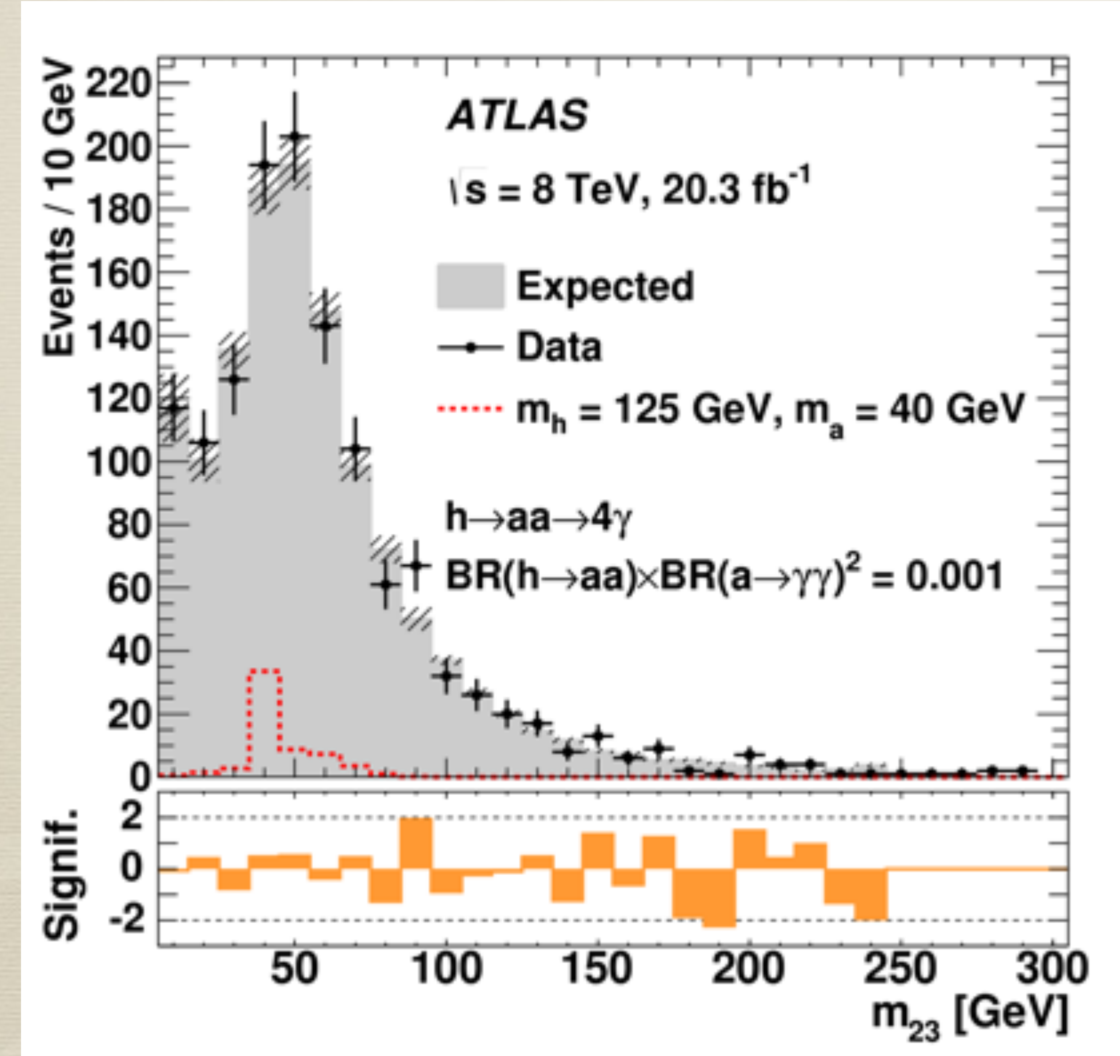


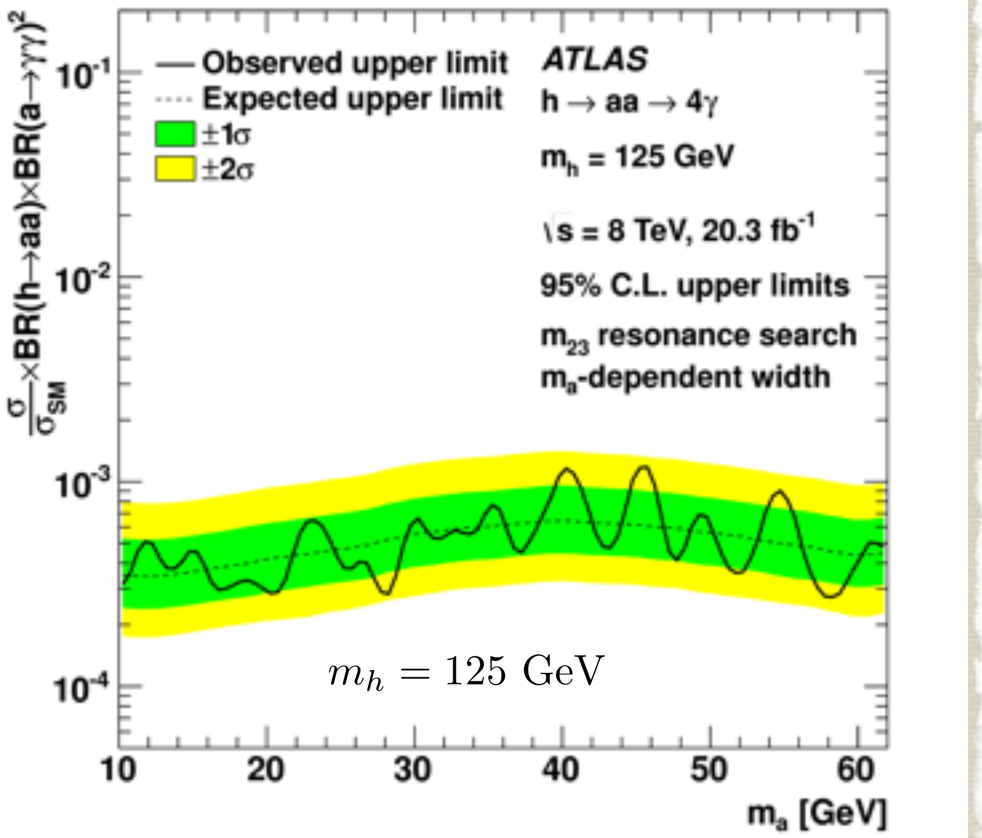
Eur. Phys. J. C (2016) 76: 210

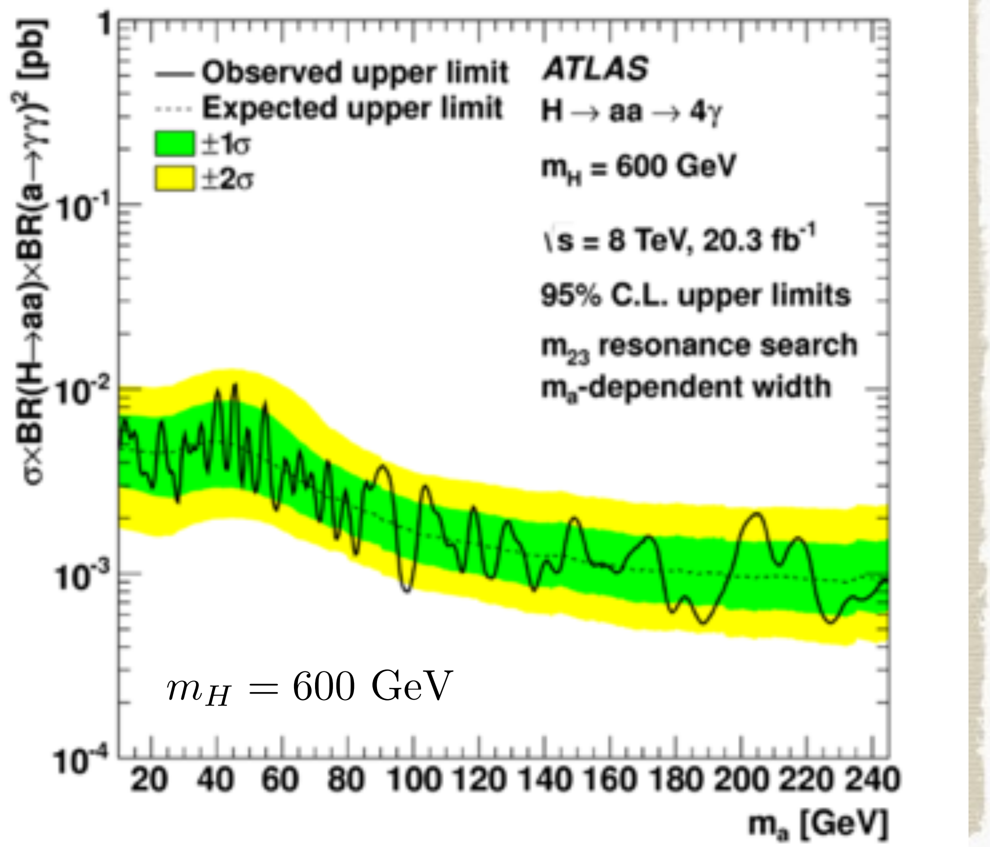
$h \to aa \to 4\gamma$

$20.3\ fb^{-1};\ \sqrt{s} = 8\ TeV$

- Search for excesses in diphoton invariant mass
  - Limits on $(\sigma/\sigma_{SM}) \times BR(h \to aa) \times BR(a \to \gamma\gamma)^2$ are obtained for SM Higgs (m=125 GeV) and for heavier scalars with h(H)->aa







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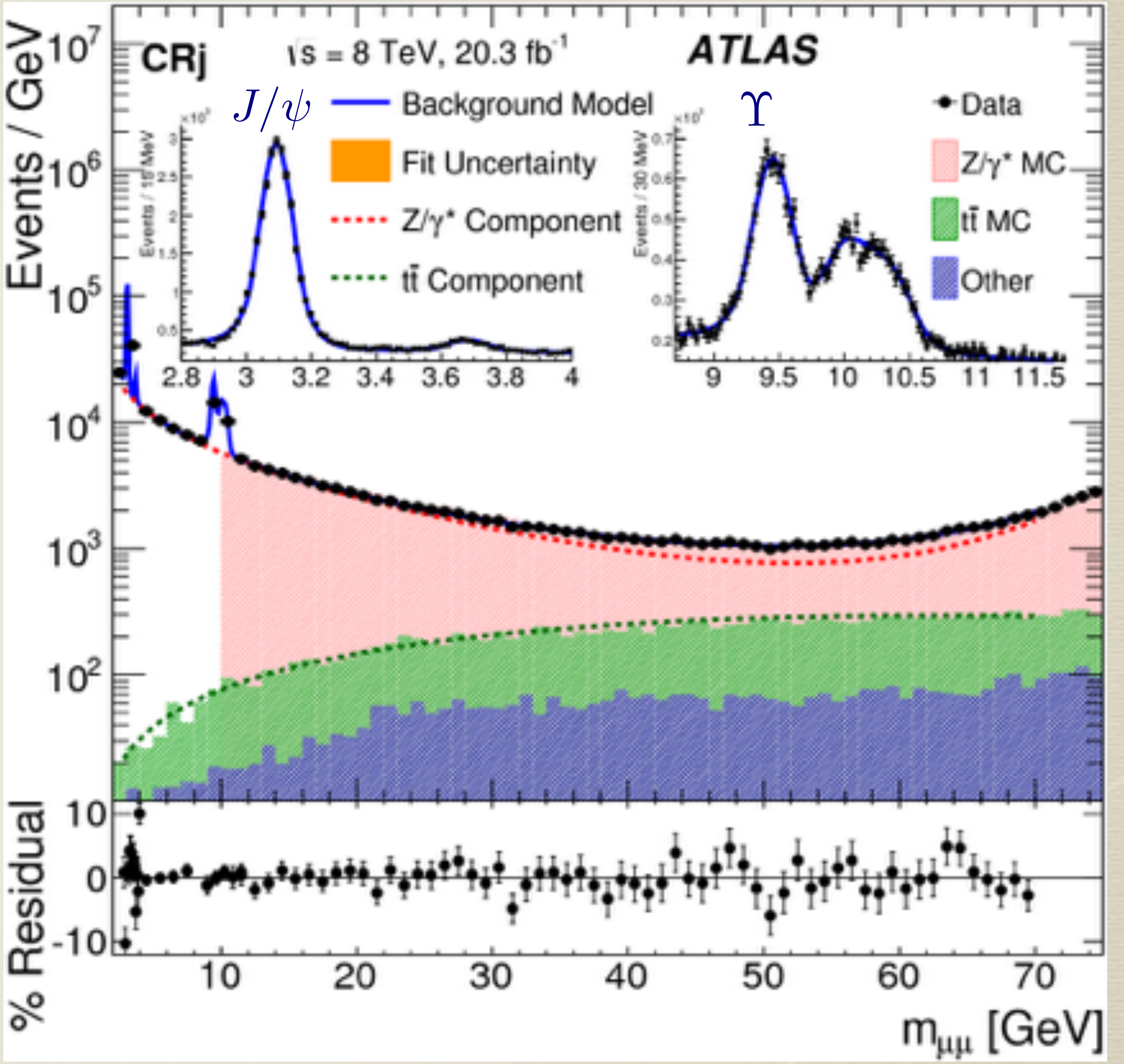
$h \to aa \to \mu\mu\tau\tau$

$20.3\ fb^{-1};\ \sqrt{s} = 8\ TeV$

- Search for SM-like Higgs boson (125 GeV) decaying to a pair of pseudoscalars with masses 3.7-50 GeV, and for heavy scalar m = 100-500 GeV decaying to a pair of pseudoscalars with a mass of 5 GeV
    - Optimized for $m_a <$ 10 GeV
- Assumption: there is no decay to quarks
    - One a decays to muons - loss in production rate (compared to both decaying to pair of τ), but gain in trigger efficiency, higher signal-to-background ratio and narrow dimuon mass resonance as a strong discriminant
- Selection:
    - $a \to \mu\mu$: two high p_T opposite sign muons
    - $a \to \tau\tau$: 1 e or μ and 1 or three tracks (e, μ, τ_{had})



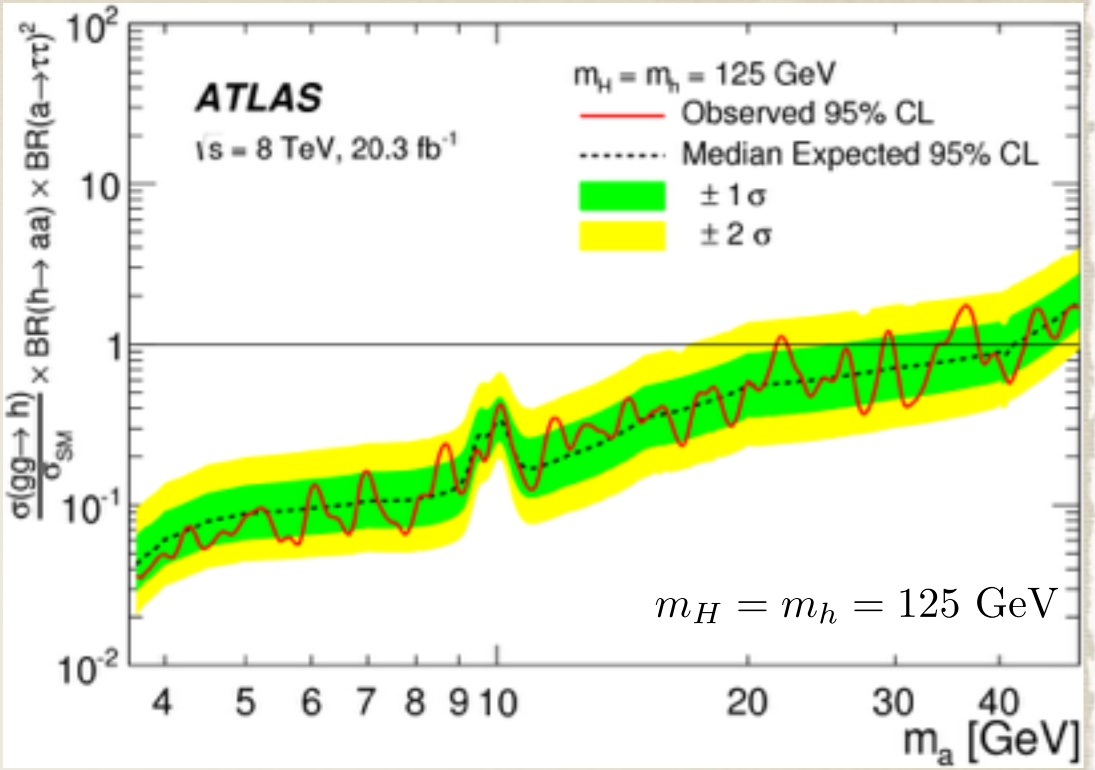
- Signal and resonant backgrounds are modeled with a double-sided Crystal Ball function, backgrounds are constrained with data in two control regions, light and heavy favor dominated

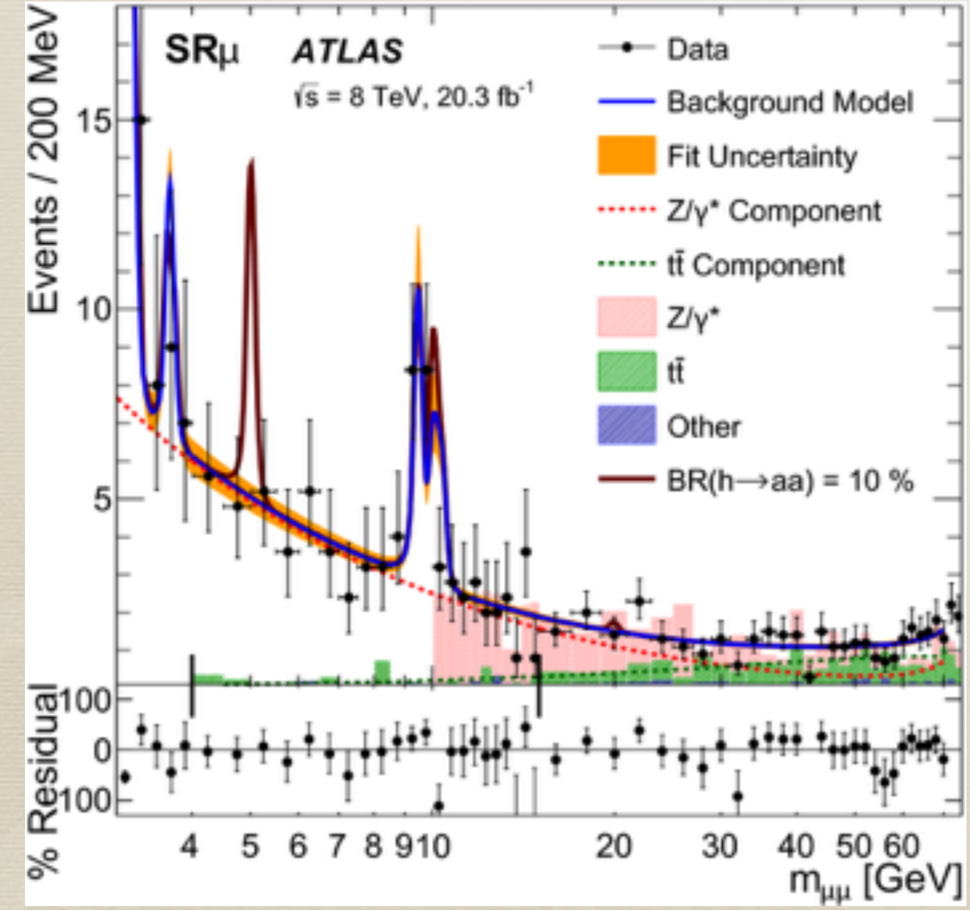
Phys.Rev. D92 (2015) no.5, 052002

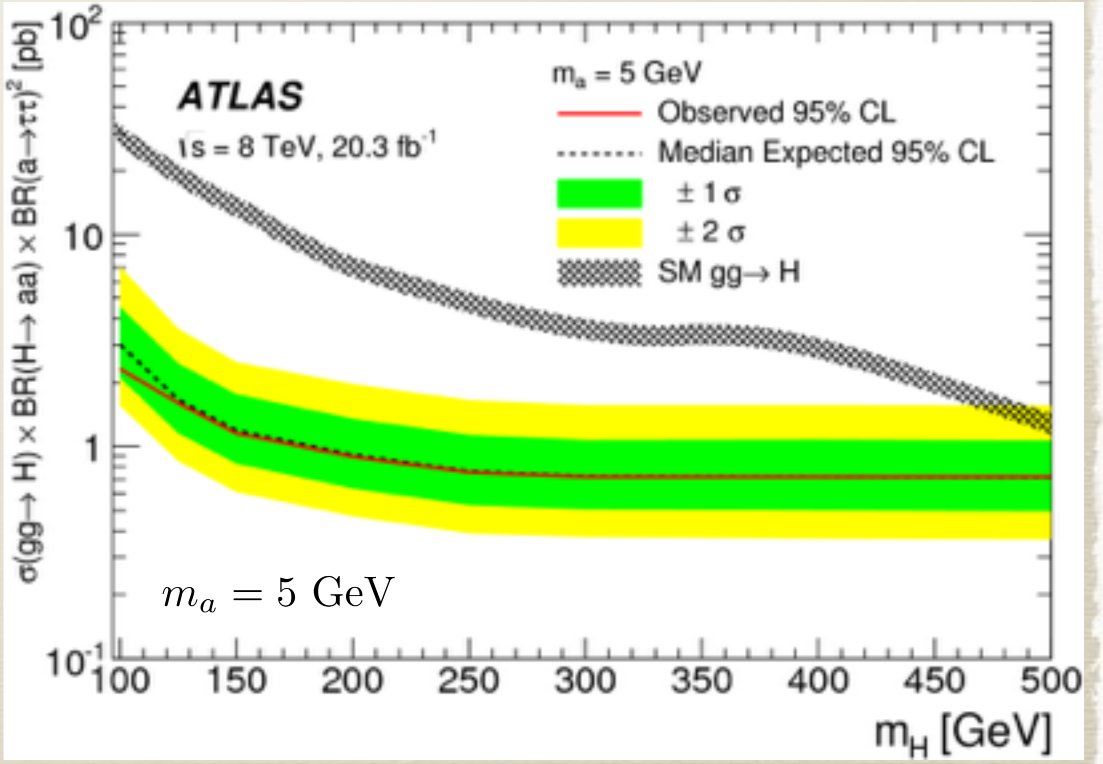
$h \to aa \to \mu\mu\tau\tau$

$20.3\ fb^{-1};\ \sqrt{s} = 8\ TeV$

- Two different signal and validation regions are identified based on the flavor of the third lepton, e or μ
    - In the validation region, the lepton and accompanying track are required to have the same sign
- No evidence for NMSSM Higgs production







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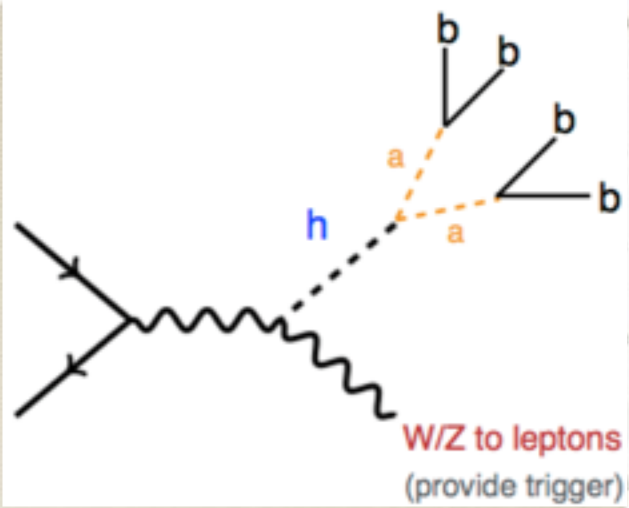
$3.2\ fb^{-1};\ \sqrt{s} = 13\ TeV$

New

$Wh \to Waa \to \ell\nu bbbb$



- Associated production with a W boson which decays to a lepton necessary for triggering
  - The first search for 4b final state from low mass resonances at the LHC
- SM-like Higgs boson decaying to a pair of pseudoscalars with masses 20-60 GeV
  - Events with one isolated lepton and at least three jets, with at least two tagged as b-jets, are selected
    - b-tagging efficiency: 77%
light-jet rejection: 126
c-jet rejection: 5
hadronically decaying τ: 10

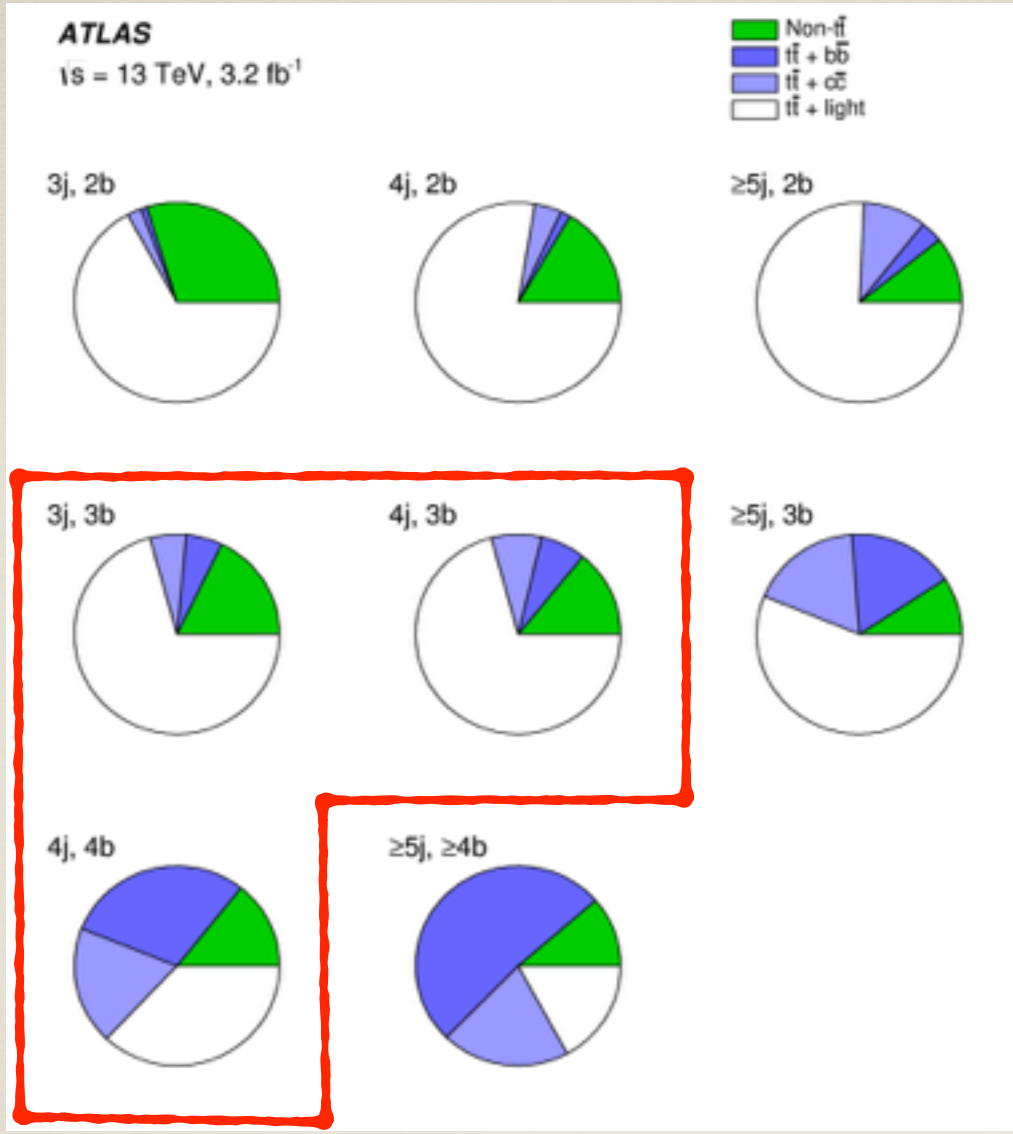
- Main backgrounds: $t\bar{t}$+light jets and $t\bar{t}$+HF
  - Modeled with POWHEG-Box interfaced to PYTHIA (HERWIG and MADGRAPH are used as alternatives)
  - Normalized to NNLO from Top++
  - $t\bar{t}$+HF kinematics (shape) was corrected to NLO from SHERPA+OpenLoops
- Others include single top, W/Z+jets and dibosons from simulation
- And multijet background obtained from data using matrix method

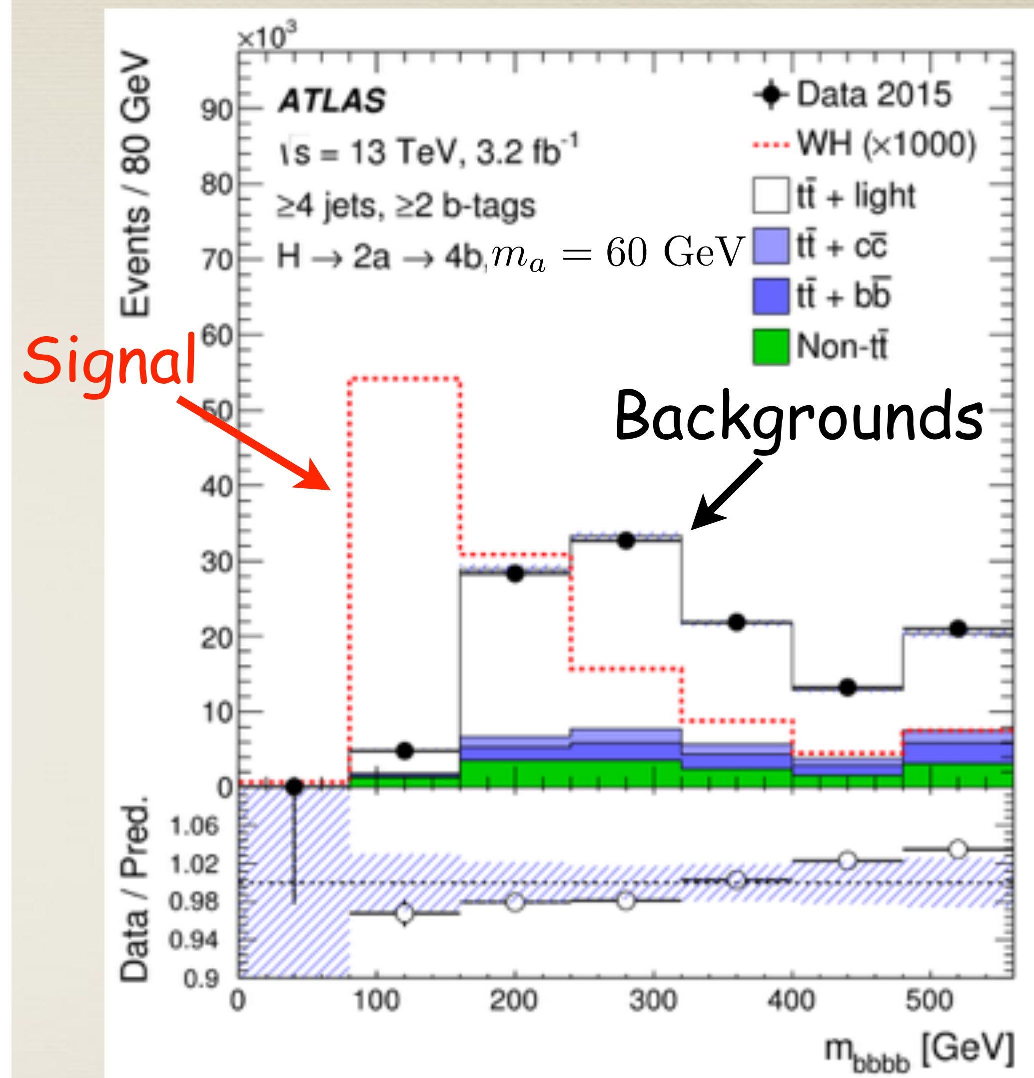
arXiv:1606.08391, Submitted to EPJC

$3.2\ fb^{-1};\ \sqrt{s} = 13\ TeV$

Analysis strategy

- Define signal and control regions based on b- and light-jets multiplicity





- Use BDT trained for m_a = 60 GeV for final discrimination between signal and background

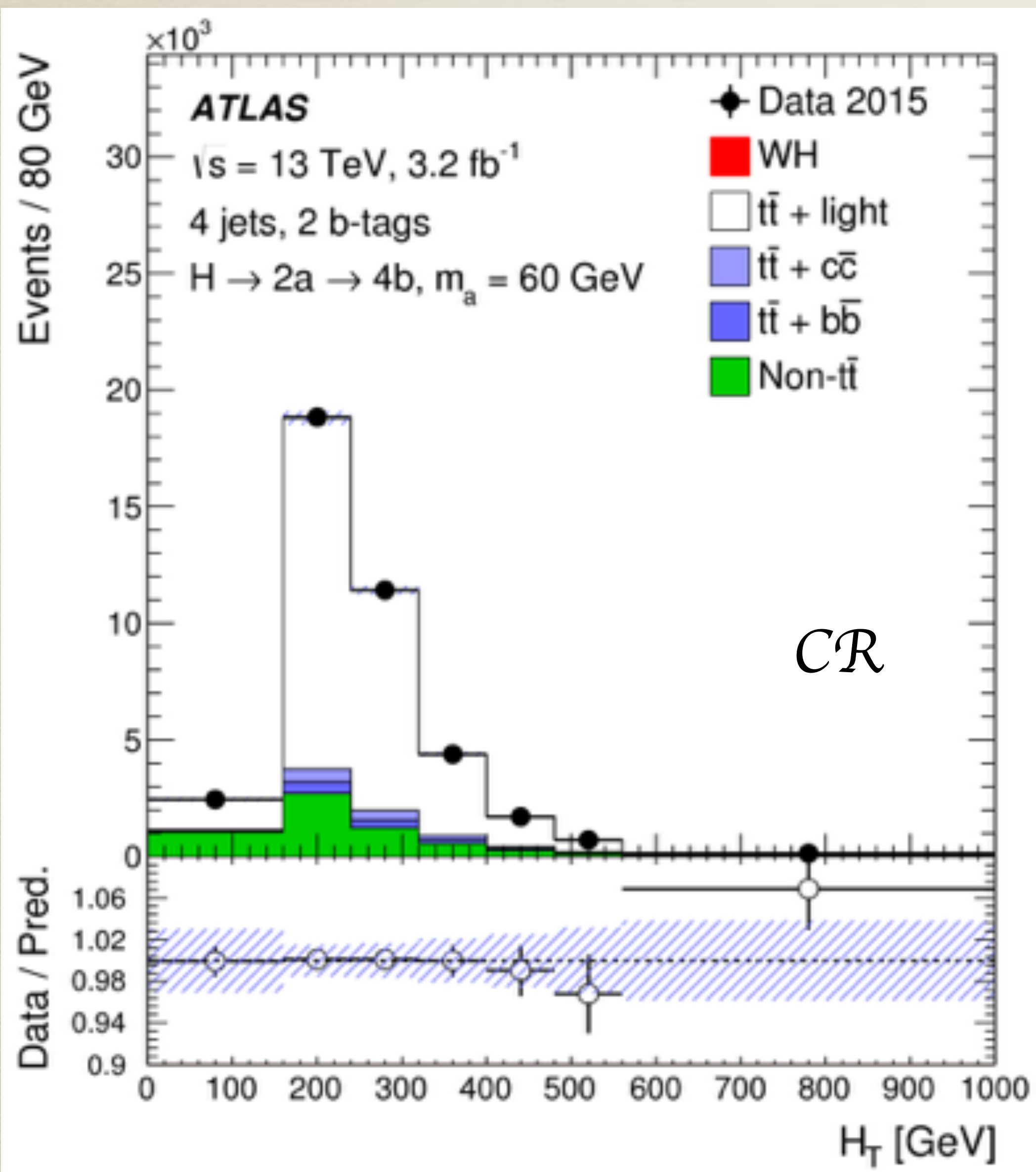
Region		m_{bbb}	m_{bbbb}	$\Delta m^{bb}_{\mathrm{min}}$	H_{T}	p^{W}_{T}	$\Delta R^{bb}_{\mathrm{av}}$	$\Delta R^{\ell b}_{\mathrm{min}}$	m_{bbj}	m_{T2}
Signal	(3j, 3b)	✓			✓	✓	✓	✓		
	(4j, 3b)	✓			✓	✓	✓		✓	
	(4j, 4b)		✓	✓	✓		✓			✓
Control					✓					

New

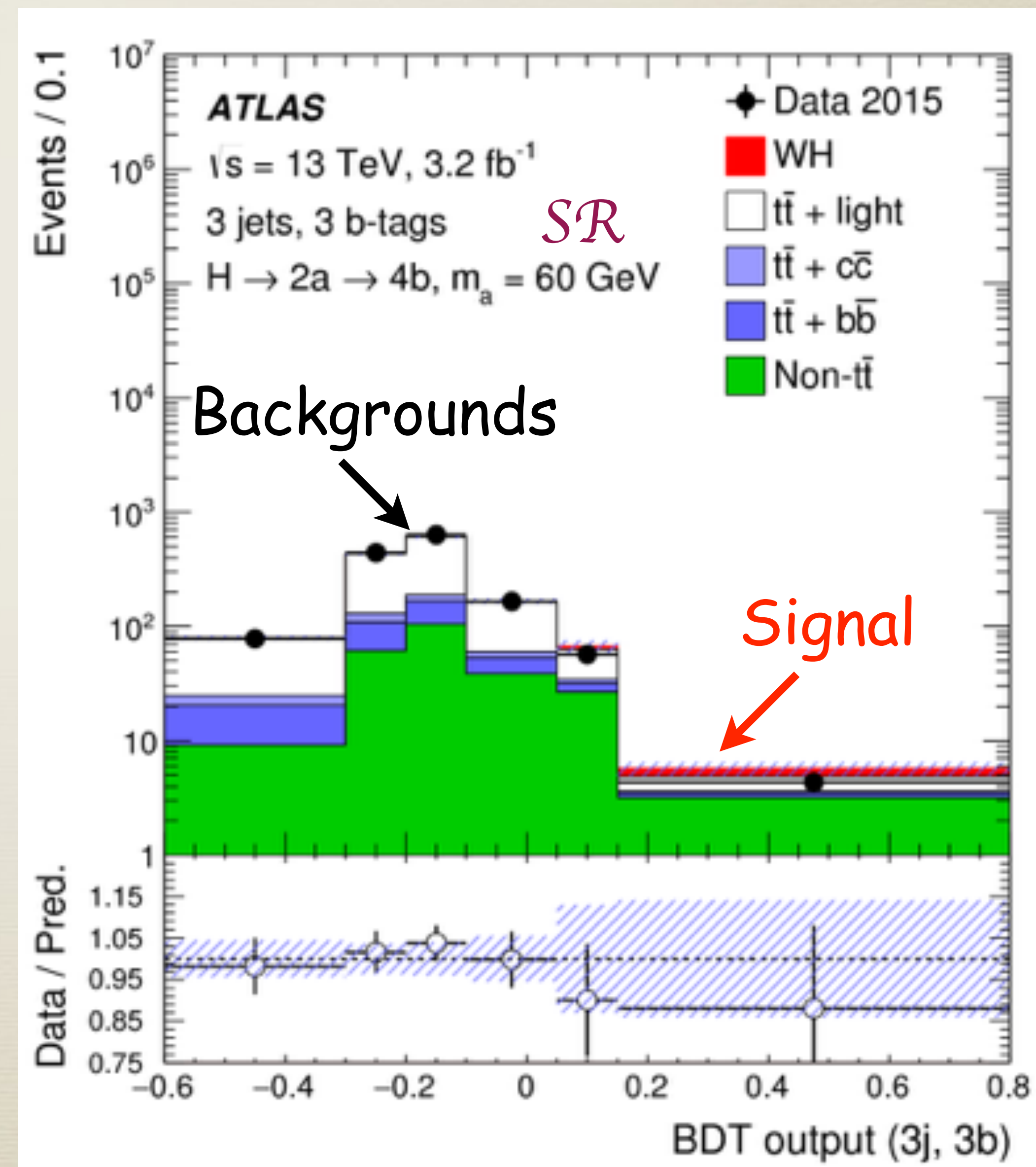
$3.2\ fb^{-1};\ \sqrt{s} = 13\ TeV$

Final discriminants

- The distributions of the final discriminants in all eight channels are combined to test the presence of a signal
  - BDT is used in signal regions and H_T in control regions to constrain backgrounds and reduce impact of systematic uncertainties



New



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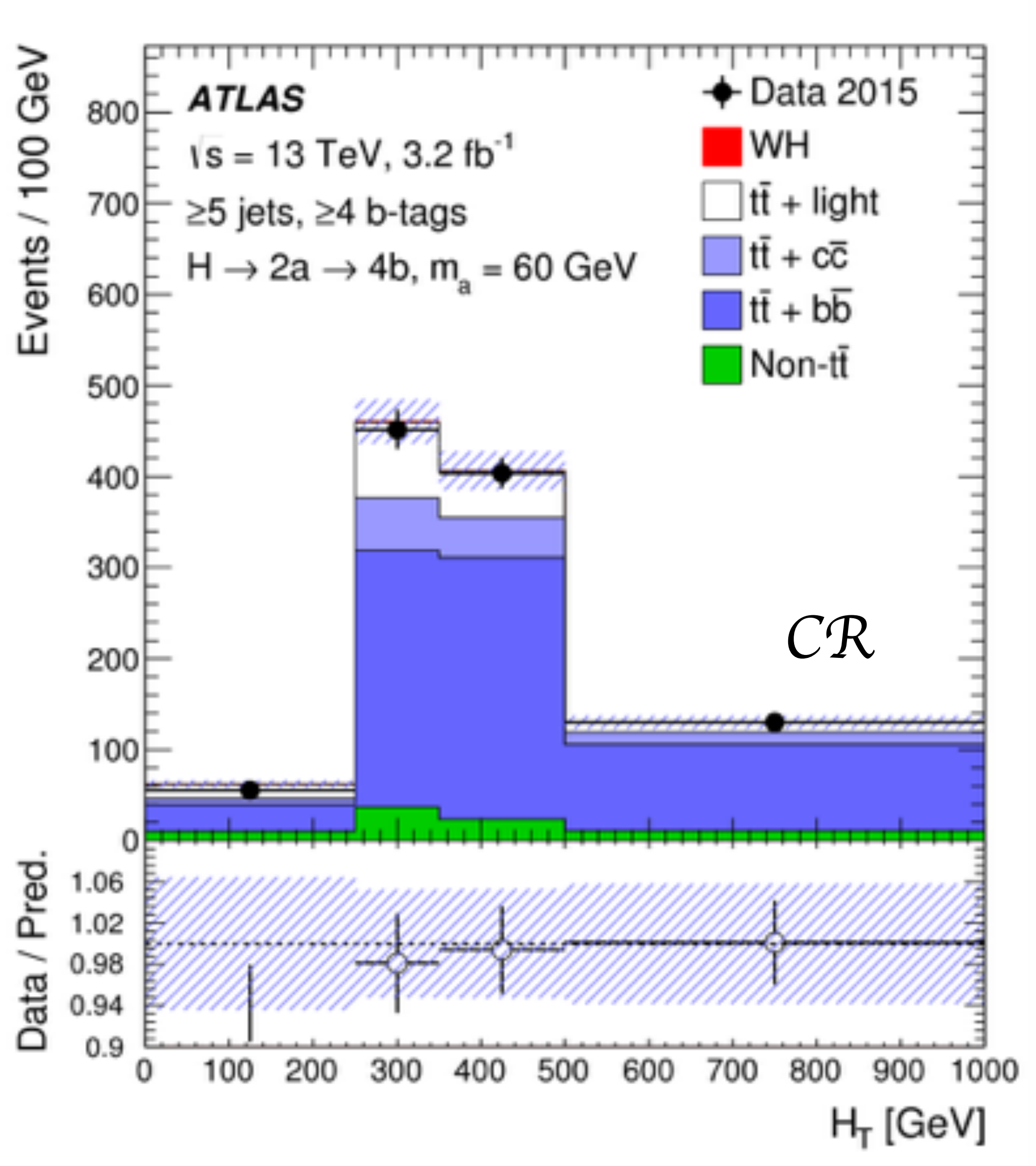

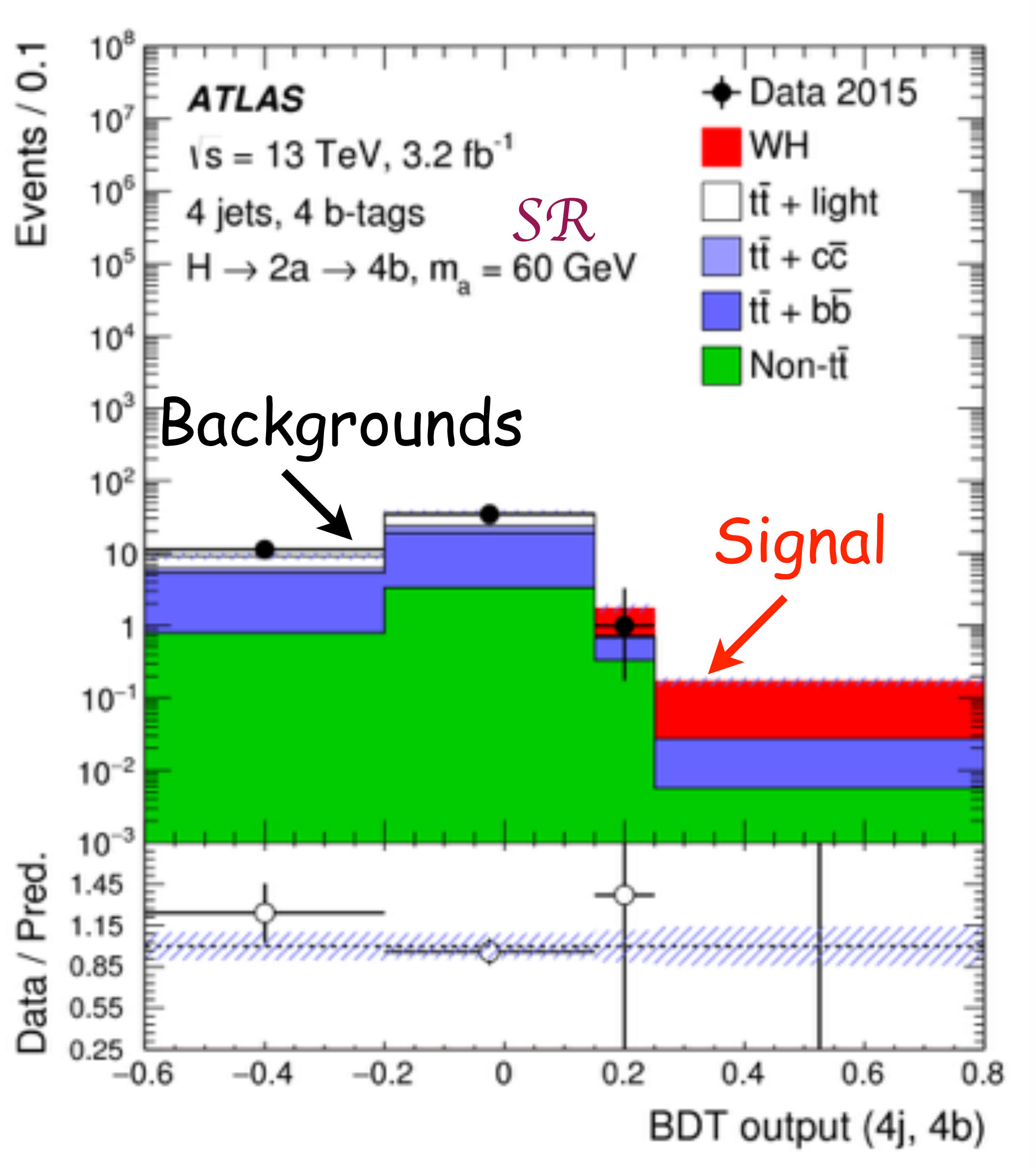

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$3.2\ fb^{-1};\ \sqrt{s} = 13\ TeV$

Systematics

New

- Dominant systematic uncertainties
  - b-tagging: b-jet, c-jet and light-flavour jet tagging scale factors
  - $t\bar{t}$ modeling: $t\bar{t}$ cross section, $t\bar{t}$+HF normalization, $t\bar{t}$+HF shape studied with different generators, models of parton shower and hadronization and initial and final state radiation

Systematic uncertainty [%]	WH, $H \to 2a \to 4b$	$t\bar{t}$ + light	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$
Luminosity	4	4	4	4
Lepton efficiencies	1	1	1	1
Jet efficiencies	6	4	4	4
Jet energy resolution	5	1	3	1
Jet energy scale	4	2	4	3
b-tagging efficiency	17	5	5	9
c-tagging efficiency	1	6	12	4
Light-jet-tagging efficiency	2	29	5	3
Theoretical cross sections	–	5	5	5
$t\bar{t}$: modelling	–	6	45	26
$t\bar{t}$+HF: normalisation	–	–	35	18
$t\bar{t}$+HF: modelling	–	–	–	5
Signal modelling	7	–	–	–
Total	21	31	54	21

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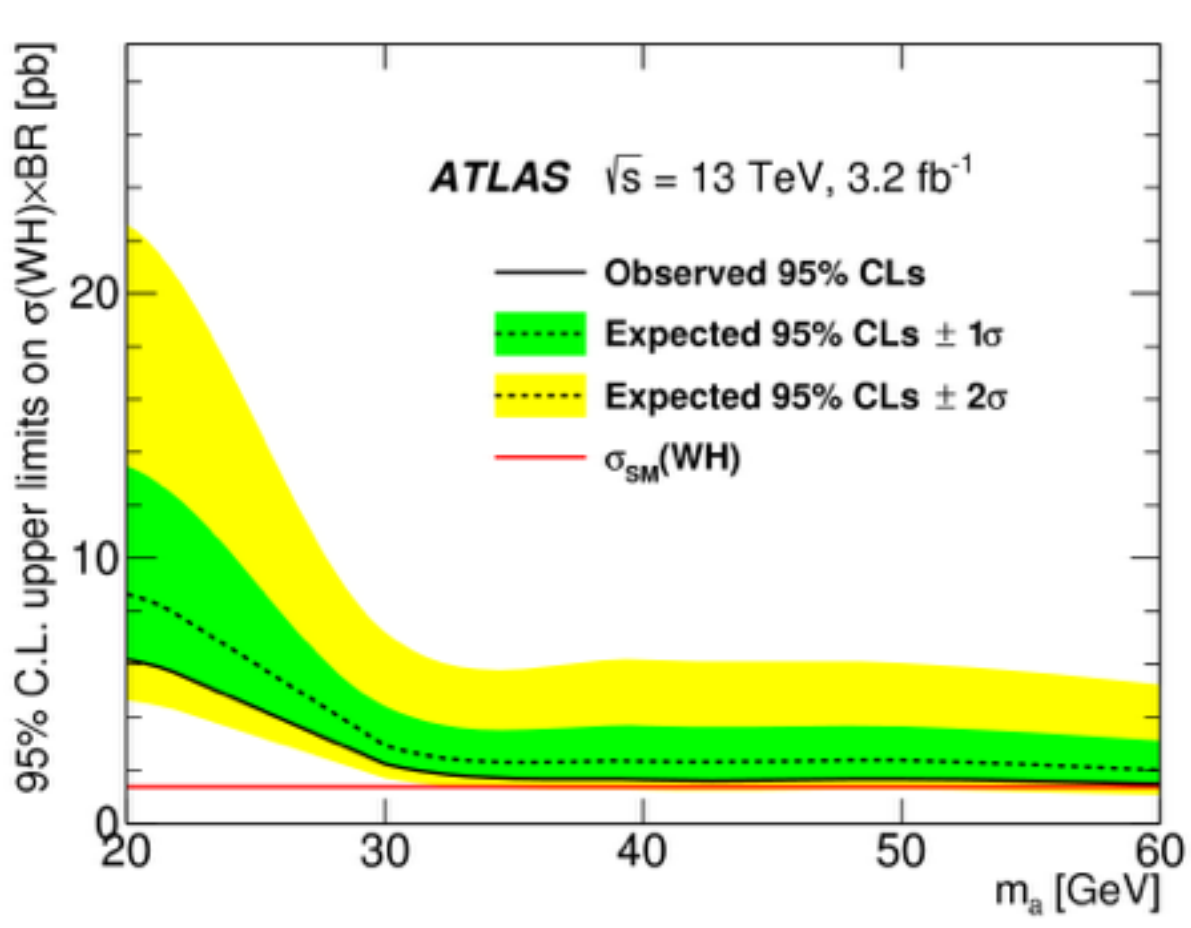
Results

$3.2\ fb^{-1};\ \sqrt{s} = 13\ TeV$

New

- No excess is seen
  - The observed (expected) 95% CL upper limits range from 6.2 (8.6) pb (m_a = 20 GeV), to 1.5 (2.0) pb (m_a = 60 GeV)

Process	(3j, 3b)	(4j, 3b)	(4j, 4b)
$t\bar{t}$ + light	1089 ± 76	2940 ± 180	53 ± 16
$t\bar{t} + c\bar{c}$	70 ± 28	280 ± 110	21 ± 11
$t\bar{t} + b\bar{b}$	172 ± 55	610 ± 160	74 ± 15
$t\bar{t} + \gamma/W/Z$	0.8 ± 0.1	4 ± 1	0.4 ± 0.1
W + jets	93 ± 31	129 ± 40	2 ± 1
Z + jets	18 ± 12	14 ± 10	–
Single-top-quark	135 ± 13	208 ± 17	8 ± 1
Multijet	48 ± 20	67 ± 28	4 ± 2
Dibosons	4 ± 1	9 ± 1	0.6 ± 0.4
$t\bar{t} + H$	0.7 ± 0.1	4 ± 1	0.8 ± 0.2
Total	1640 ± 58	4270 ± 130	165 ± 15
Data	1646	4302	166
$WH,\ H \to 2a \to 4b$			
$m_a = 60\ GeV$	10 ± 2	9 ± 1	3 ± 1
$m_a = 40\ GeV$	11 ± 2	10 ± 2	2 ± 1
$m_a = 20\ GeV$	6 ± 1	5 ± 1	0.7 ± 0.2



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Summary

- Searches for light pseudoscalars from the Higgs sector are performed in the range 3.7 < m_a < 62 GeV for a variety of decay modes.
- No excess was seen and decays of the Higgs boson to light pseudoscalars are further constrained
- With the rapid accumulation of 13 TeV data large sensitivity gains can be expected in these searches
  - Additional channels will be explored

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2013-24/

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2014-02/

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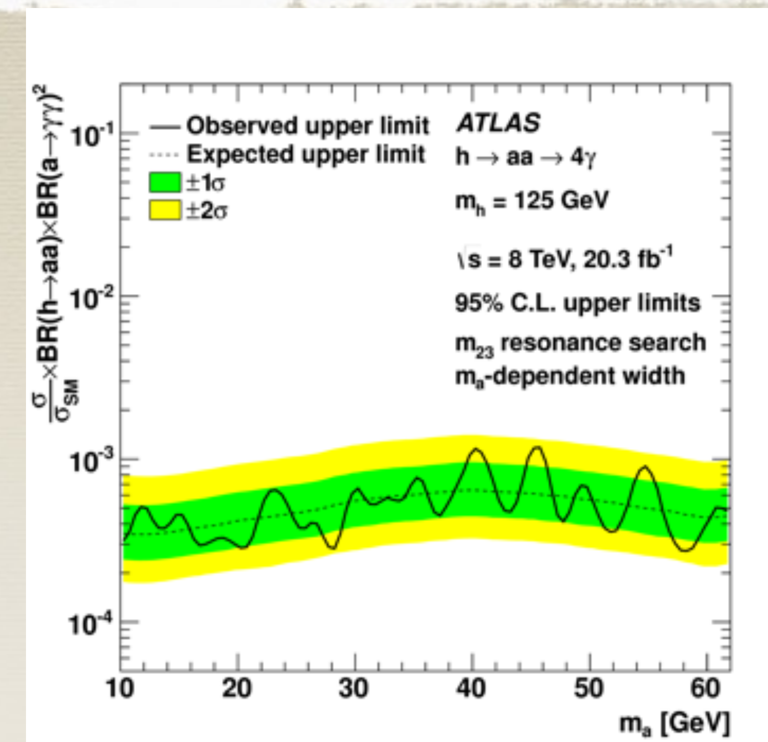
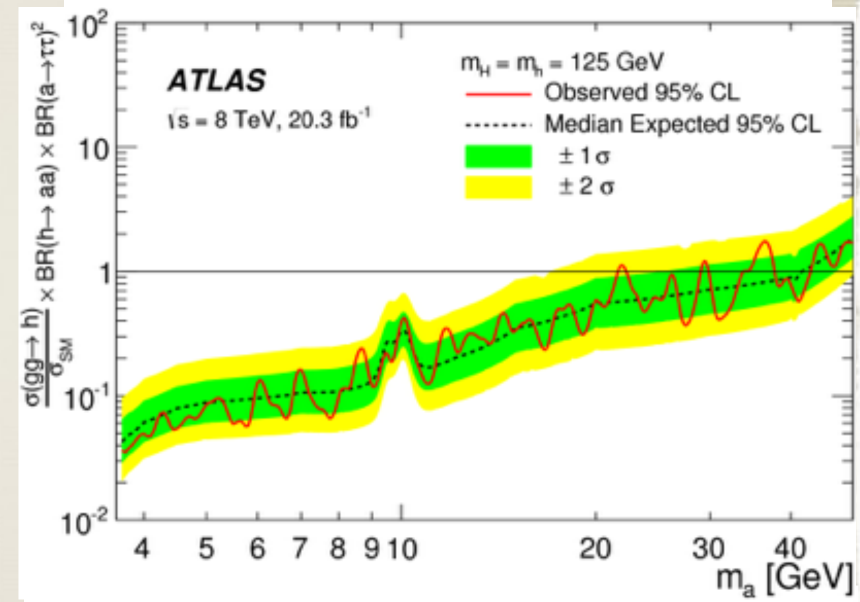
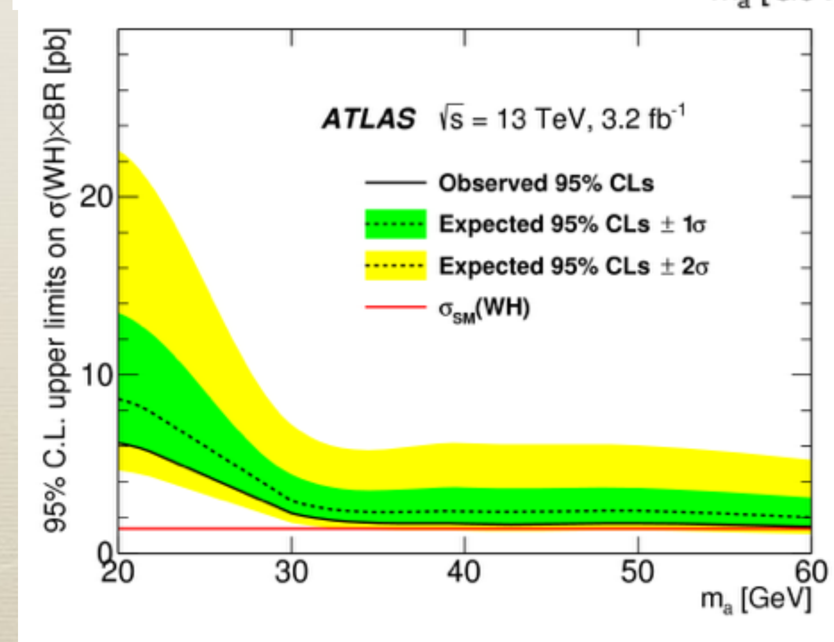






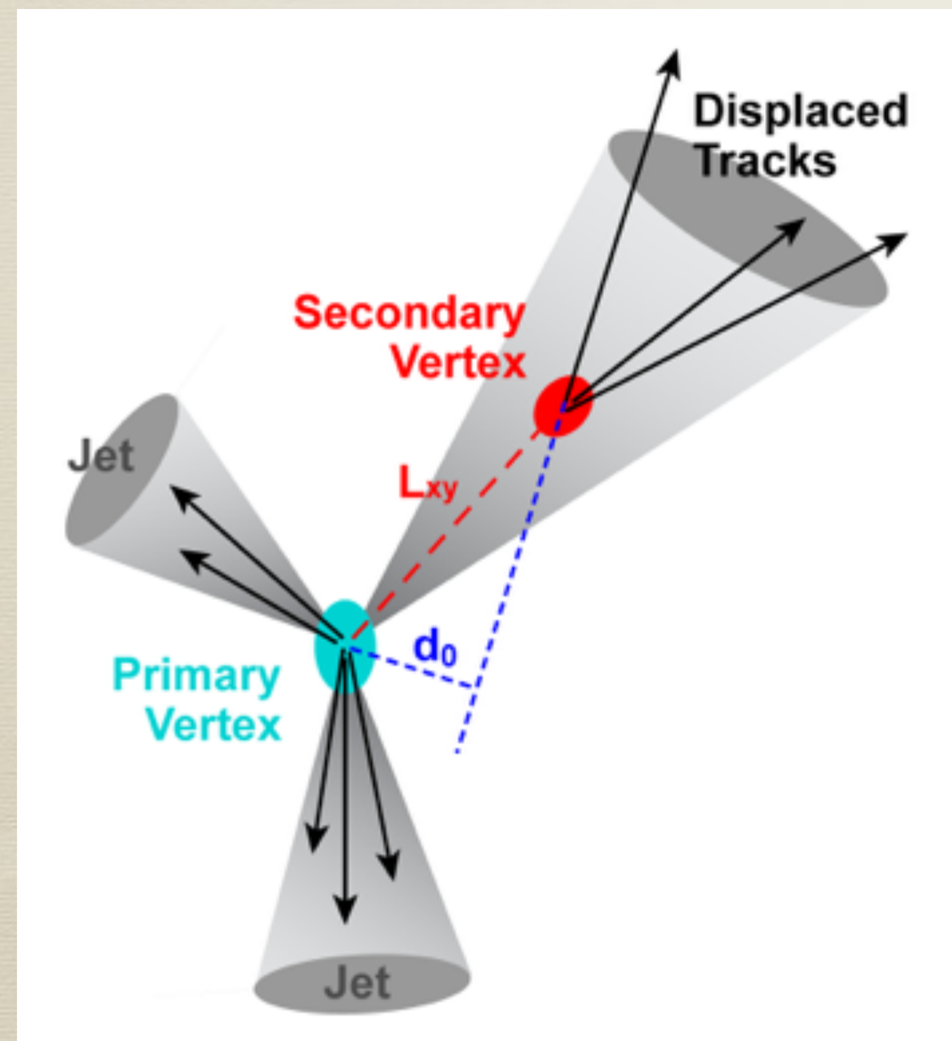
Backup

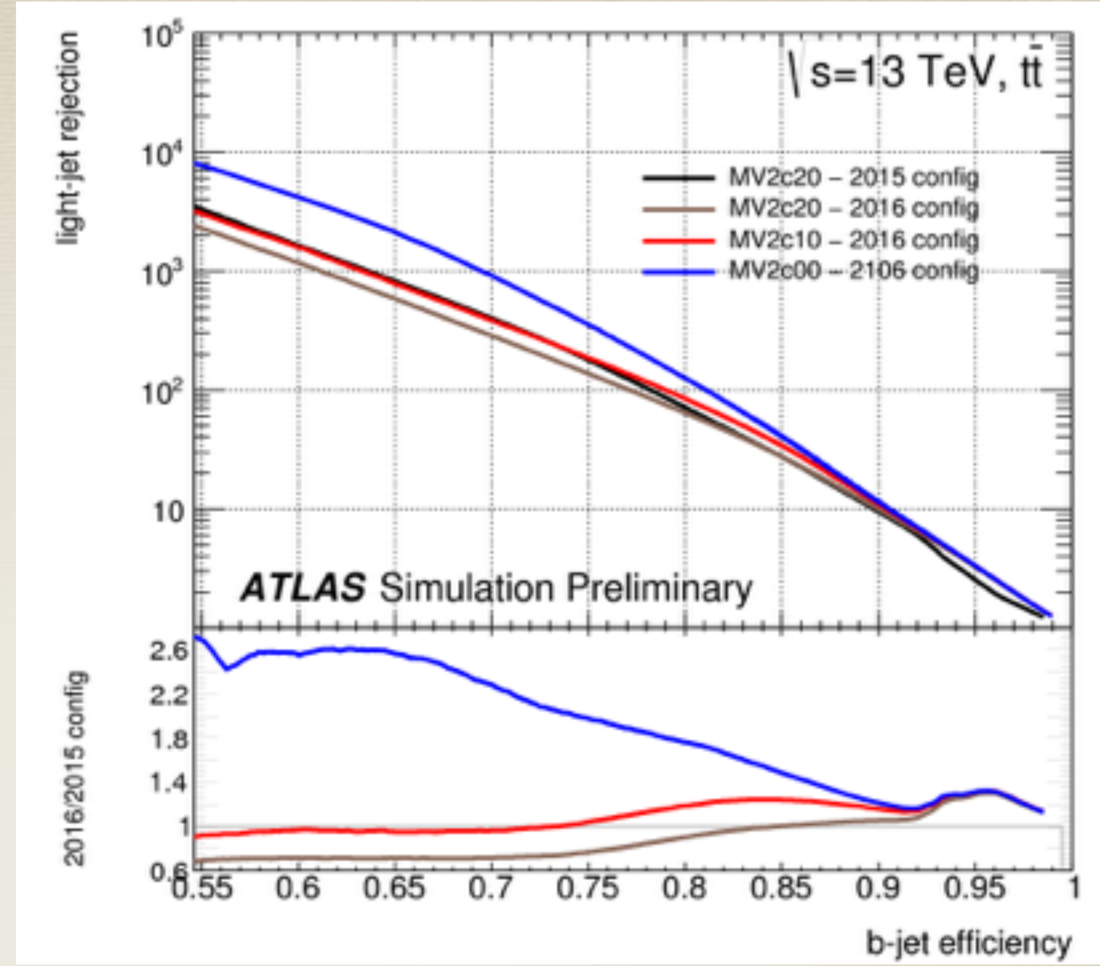
MSSM and NMSSM

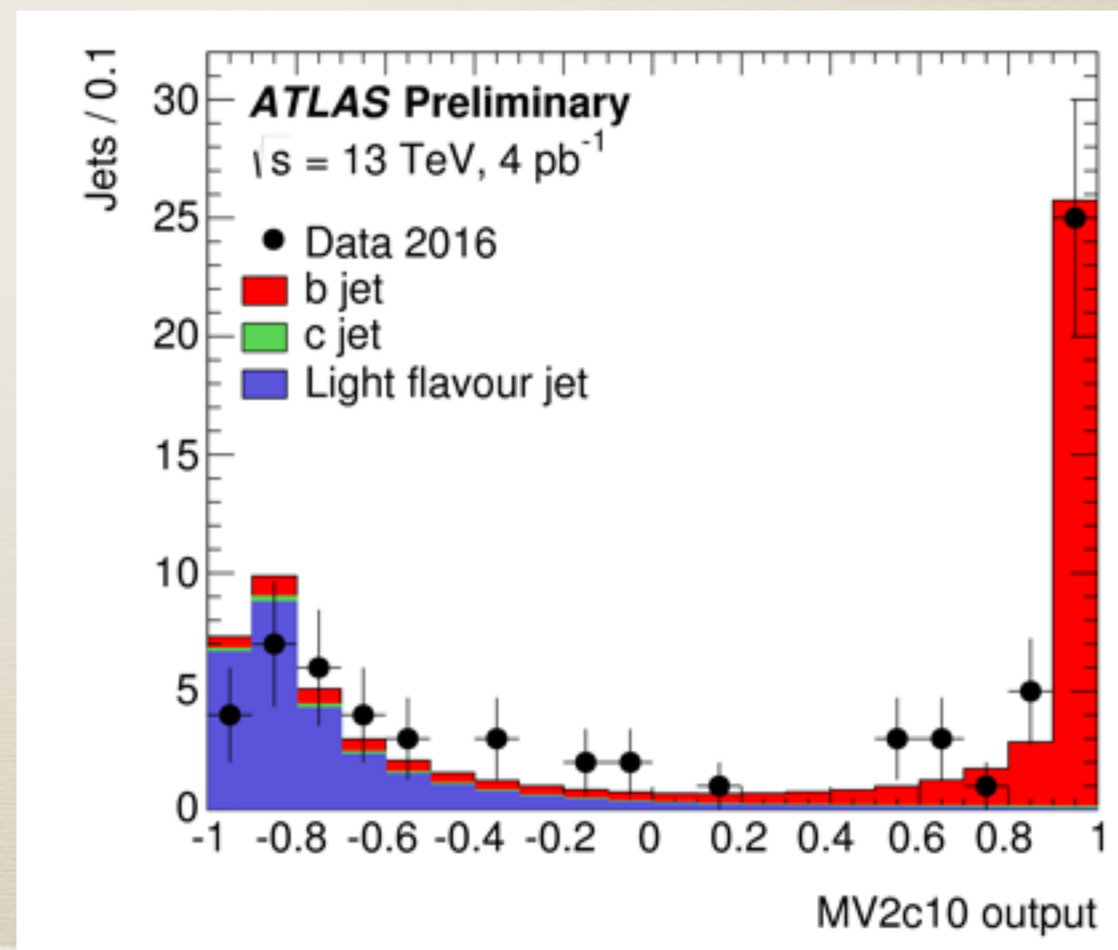
- SUSY is able to explain many shortcomings of the SM: hierarchy, coupling unification at GUT scale, dark matter, CP violation, etc
  - Extension of the Higgs sector requires two Higgs doublets, Hd and Hu, giving a mass to up-type and down-type fermions
- Its minimal model, MSSM, contains SUSY mass term, μ-term $\mu \hat{H}_u \hat{H}_d$
  - It is of the order of the SUSY breaking scale M_{SUSY}, but for natural EWSB it should be bellow at the EW scale => μ-problem
- NMSSM solves it by introducing additional scalar field, so $\mu \to \mu_{eff} = \mu \langle S \rangle$

b-tagging

- Use MVA id based on impact parameter and secondary vertex properties

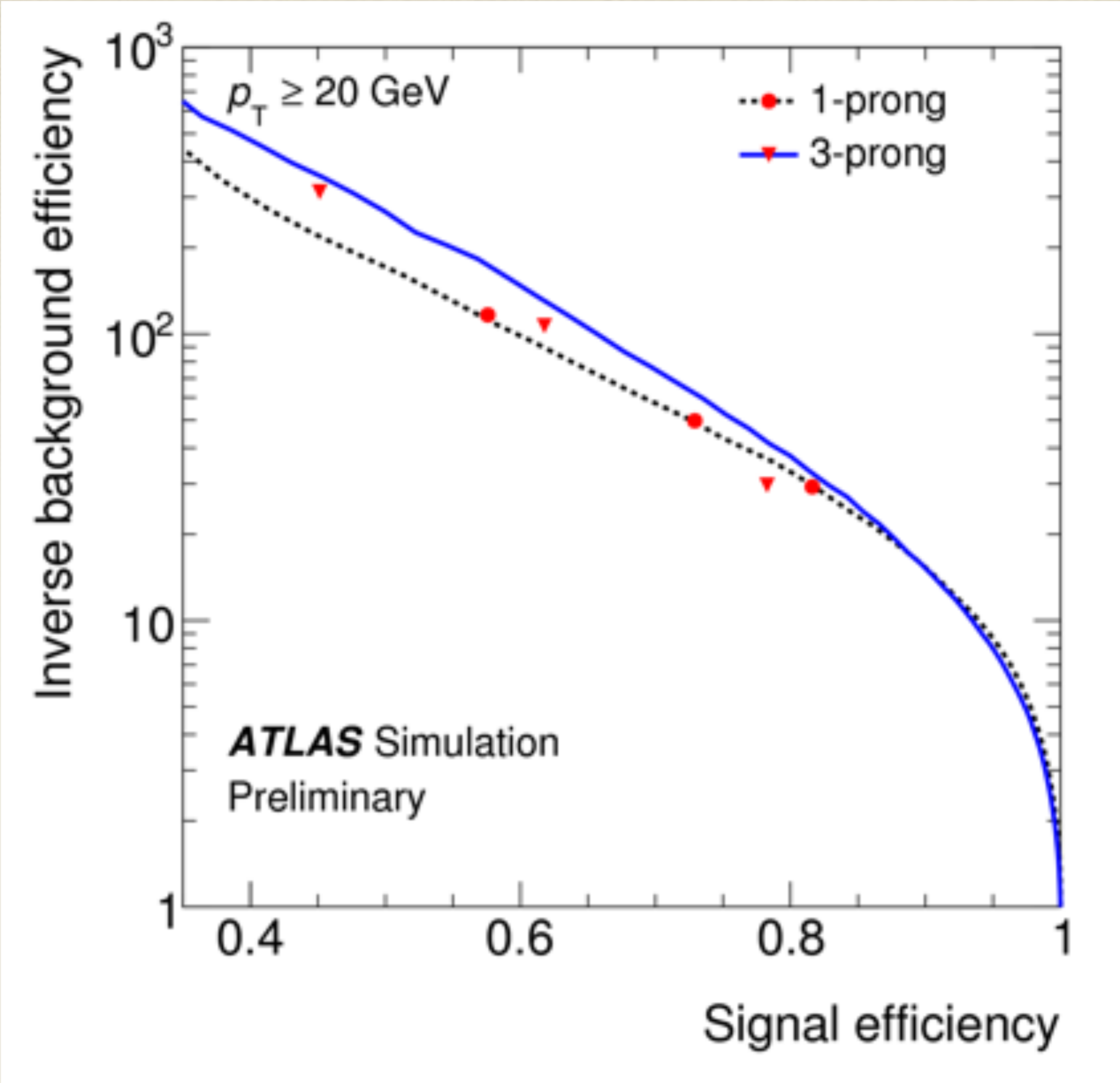


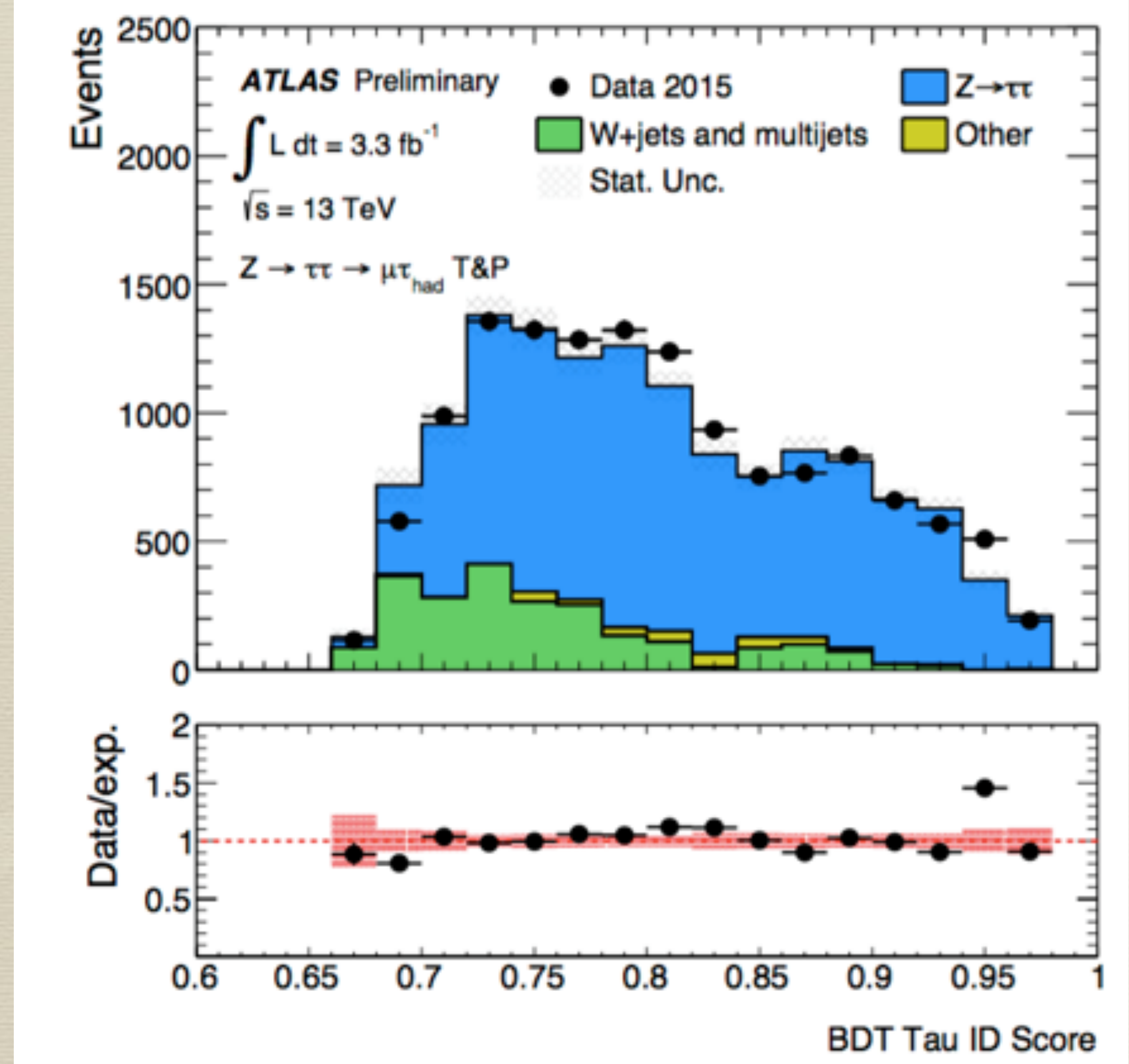


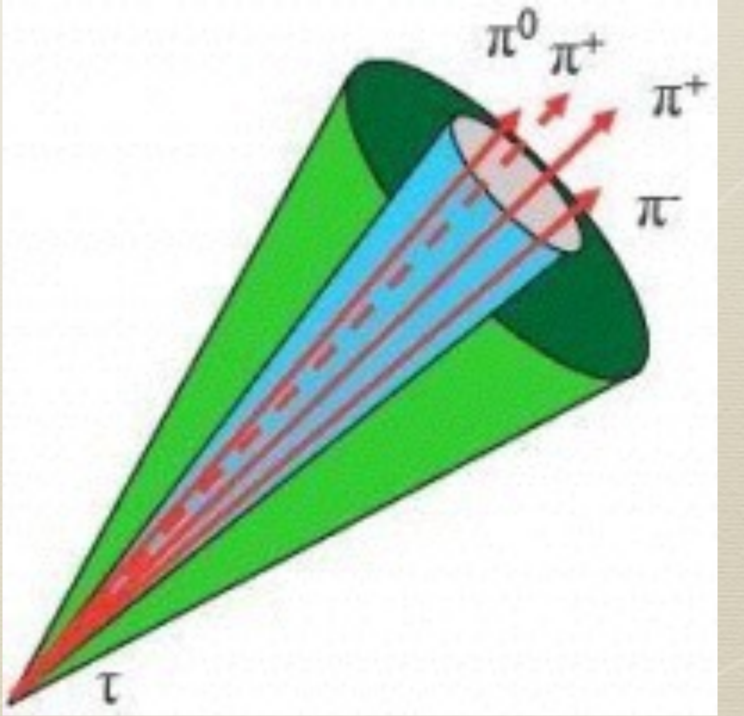


τ-id

- Look for 1 or 3 prong jets in a cone of 0.2
  - define isolation
- Use BDT for discrimination







Luminosity 2011-2016