Searching for Di-Higgs→bbττ at ATLAS

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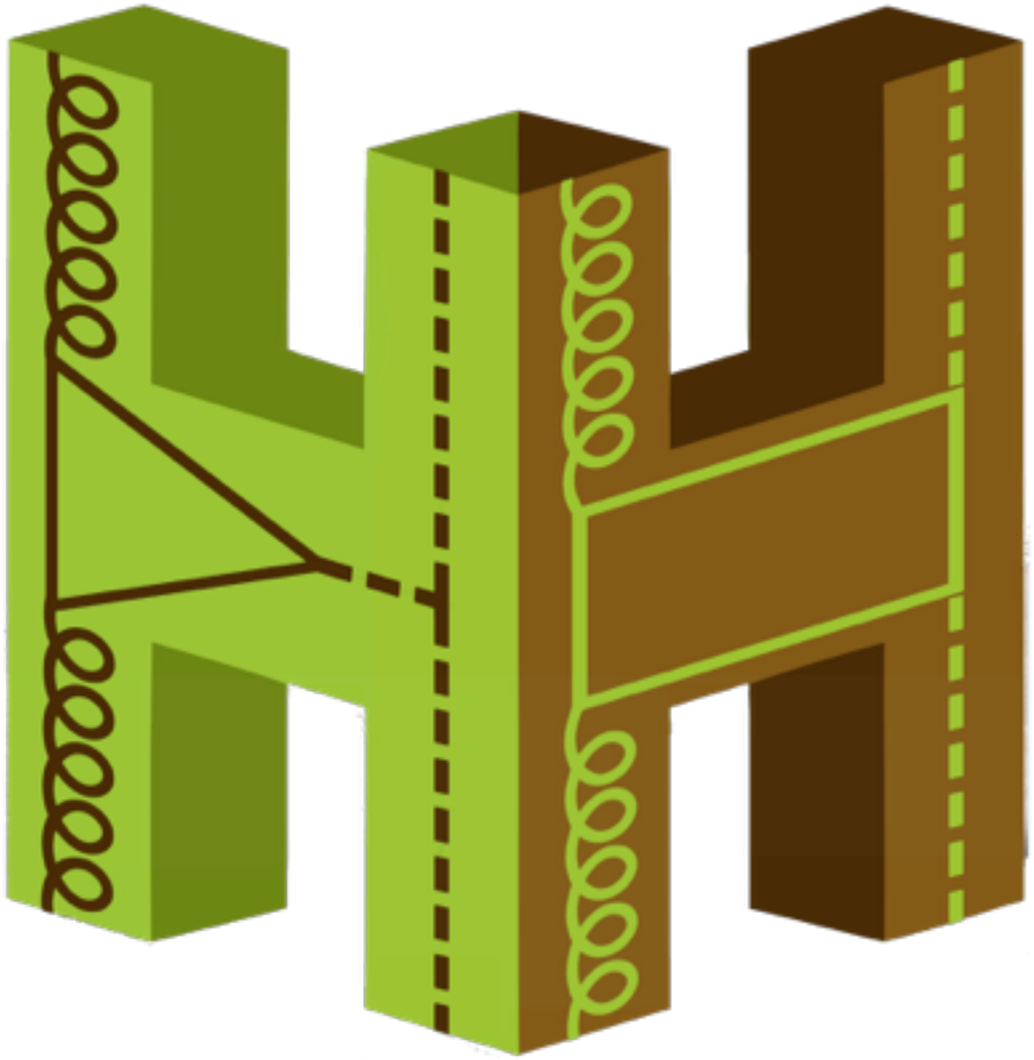
20th November 2015

Overview

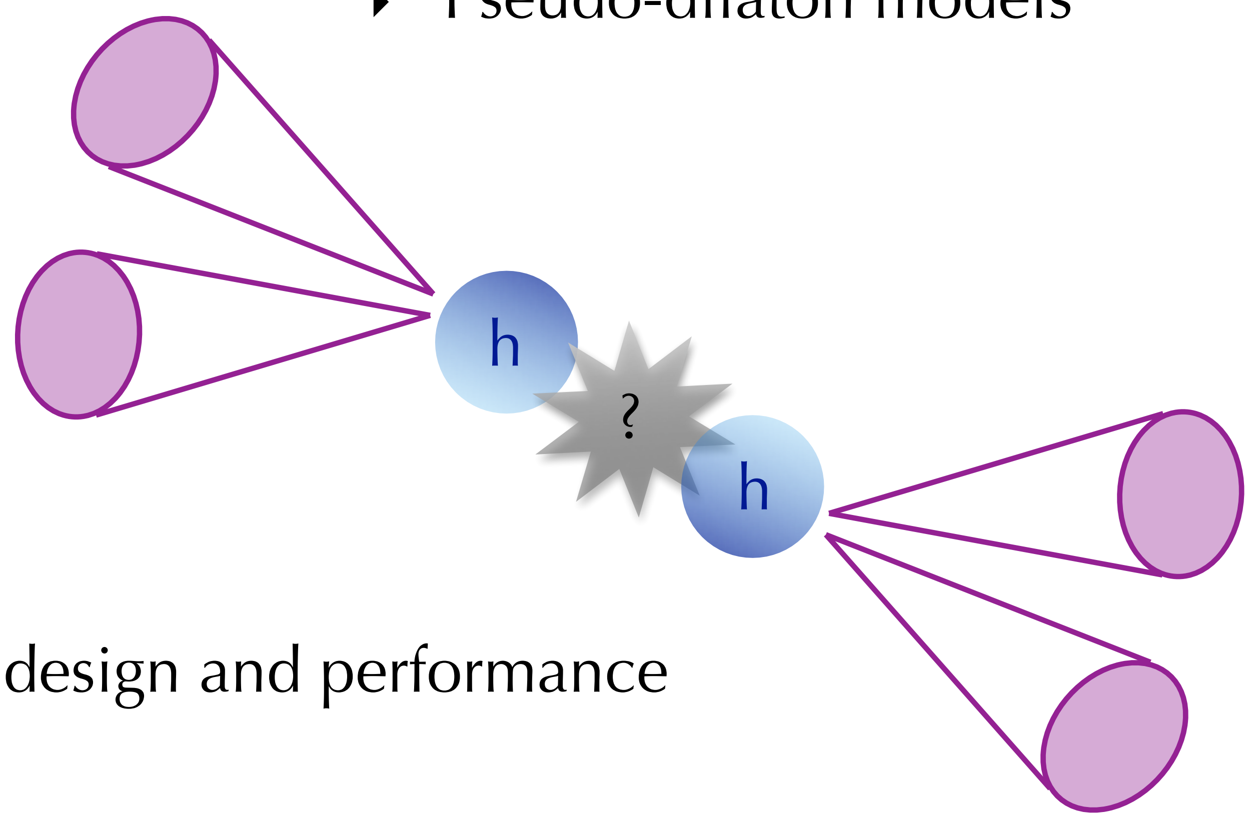
- Motivation for searching for di-Higgs pairs (and in the bbττ channel).
- ATLAS Run 1 HH→ bbττ analysis.
- Combination of all ATLAS HH channels.
- Prospects for HH→ bbττ searches in Run 2 and beyond.



Motivation

- TeV-scale resonances decaying to two 125 GeV Higgs bosons (h) predicted by several models, including:
  - RS KK Graviton
  - 2 Higgs Doublet Models (2HDM)
  - Higgs portal models
  - Composite models with hh resonances

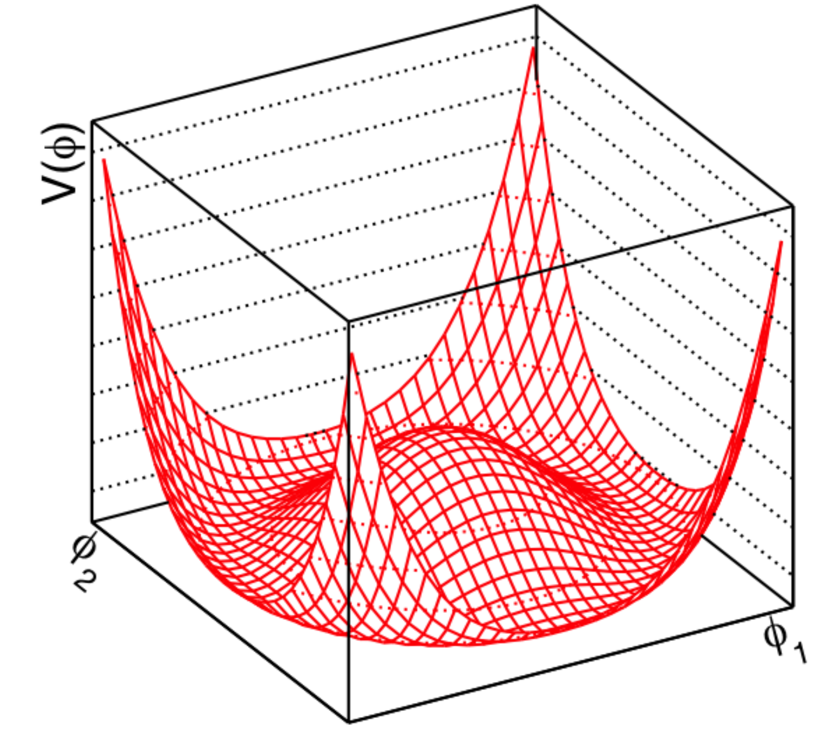
- Enhancement of non-resonant di-Higgs production, e.g.
  - Models with heavy top-partners
  - Composite Higgs models
  - Pseudo-dilaton models

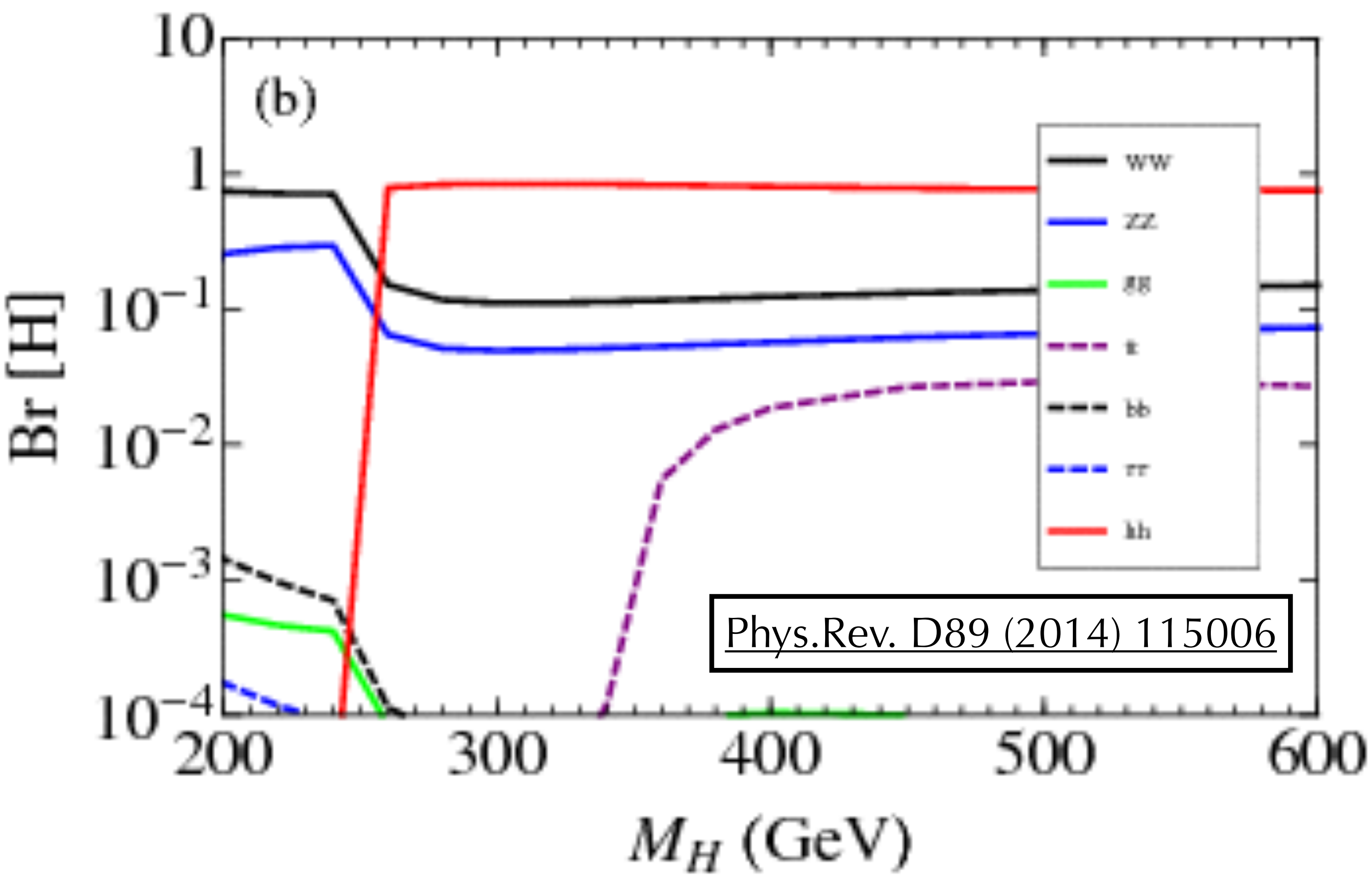


- SM di-Higgs production at HL-LHC.
  - Need ~3000 fb^{-1} to measure this.
  - Sensitivity studies now drive upgrade design and performance requirements.

SUSY & The Higgs Sector (2HDM)

- Supersymmetric extensions to Standard Model require two Higgs doublets → 5 observable Higgs bosons:
  - 3 neutral (h/A/H)
  - 2 charged ($H^{\pm}$)
- Assume the observed 125 GeV Higgs boson is the light Higgs (h).
- Heavy Higgs (H) can decay to a pair of light Higgses (h).





- Branching ratio to hh can be large, depending on parameters of model.
- Range m_H < 500 GeV theoretically favoured.
- Couplings can be expressed as functions of α (mixing angle) and tan β (ratio of vacuum expectation values).

Di-Higgs Decay Channels

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0053%

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bbbb

- Largest branching ratio
- Harder to trigger on (especially for low mass resonances and SM)

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xxWW,

- Take a hit on branching ratio to have events where W decays leptonically (~34%).
- Reconstructing hadronic W decays difficult (large QCD backgrounds).

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xxγγ

- Clean signature (thanks to di-photon pair in final state).
- Tiny branching ratios…

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ZZZZ

- Possibility to select clean final states with 2 or 4 leptons, but large hit on branching ratio.

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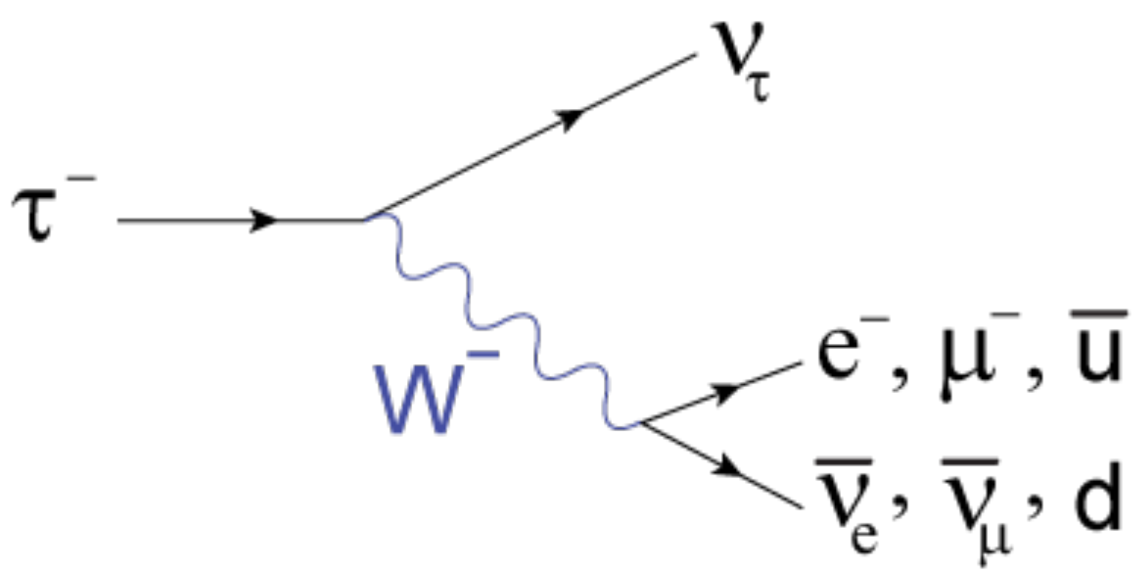
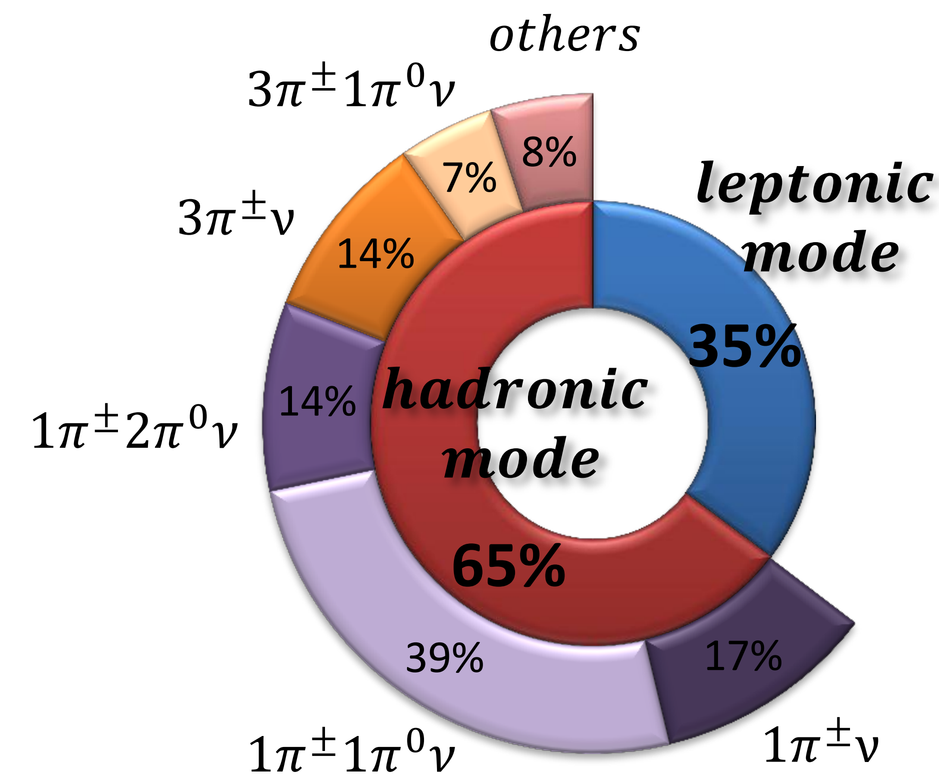
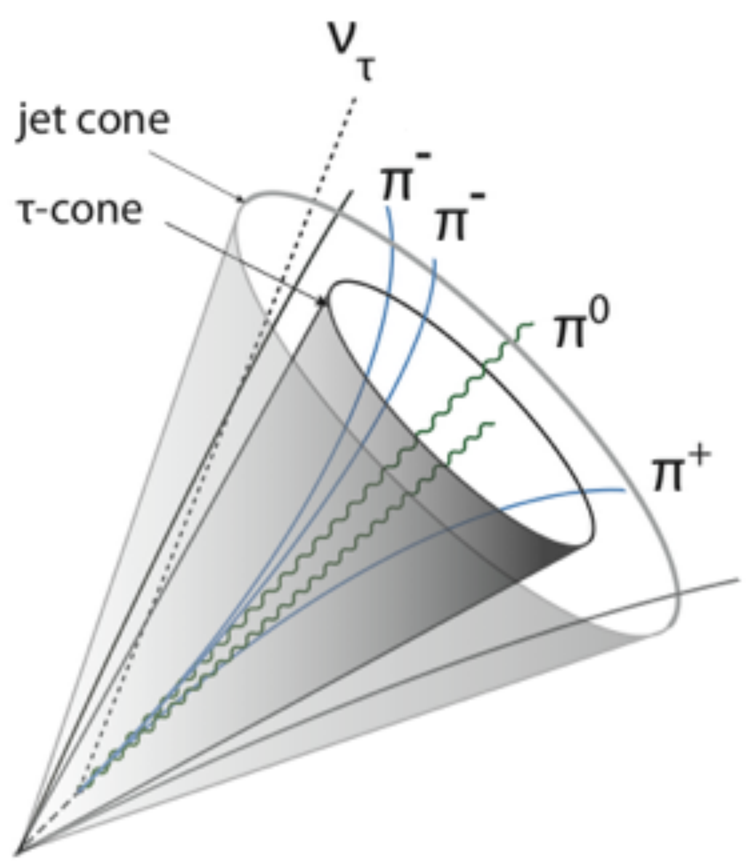
bbττ

- Possibility to trigger on lepton from tau decays (58% of events).
- Fully hadronic tau-tau channels have comparable sensitivity to $e\tau_h$ and $\mu\tau_h$ channels at ATLAS.

Tau Decay Characteristics



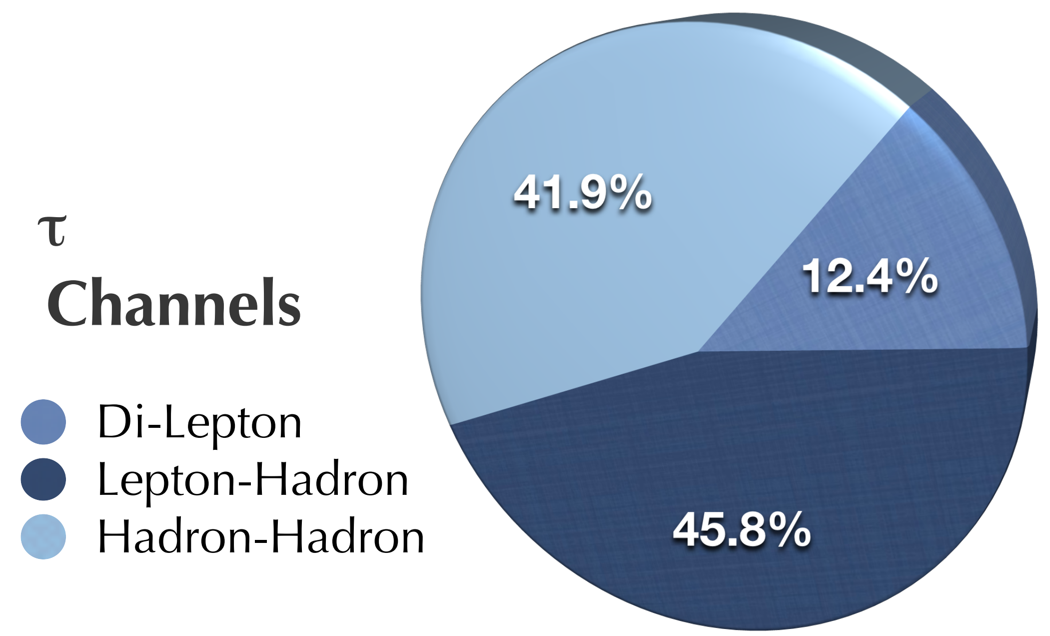




Hadronic

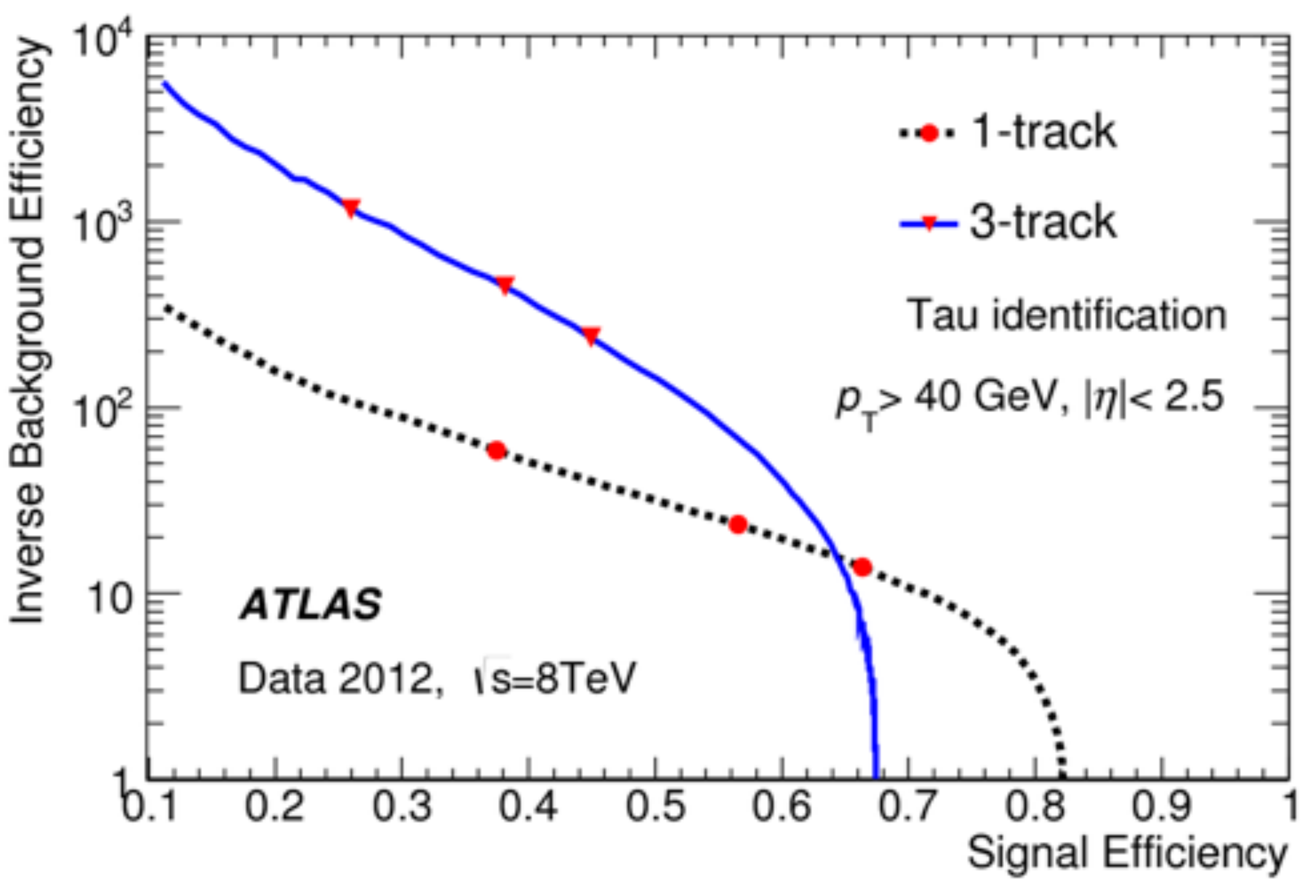
- Well collimated, low multiplicity jet
- Deposits in both hadronic and EM calorimeters.
- One or three tracks matching the calorimeter deposition.

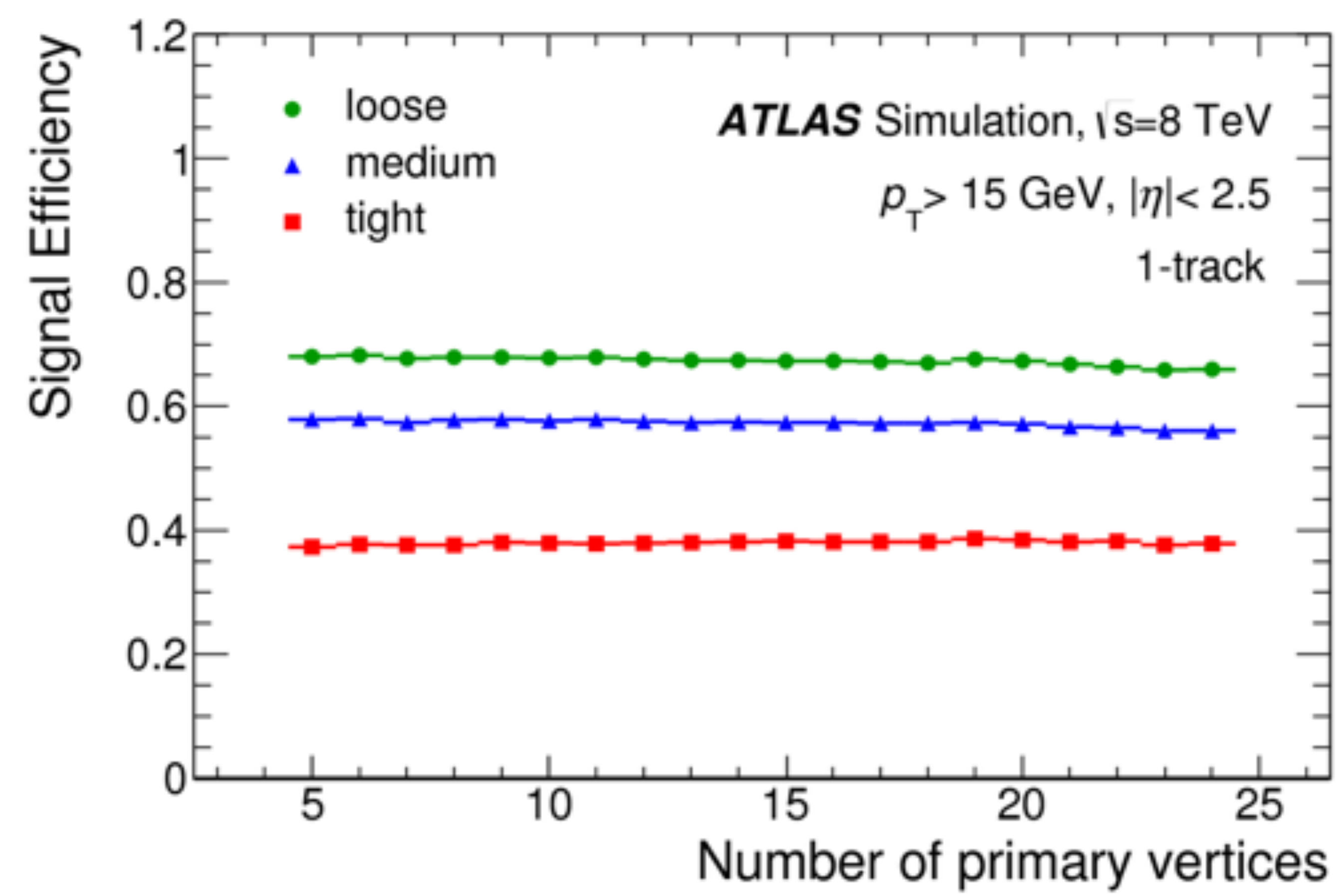
τ **Channels**



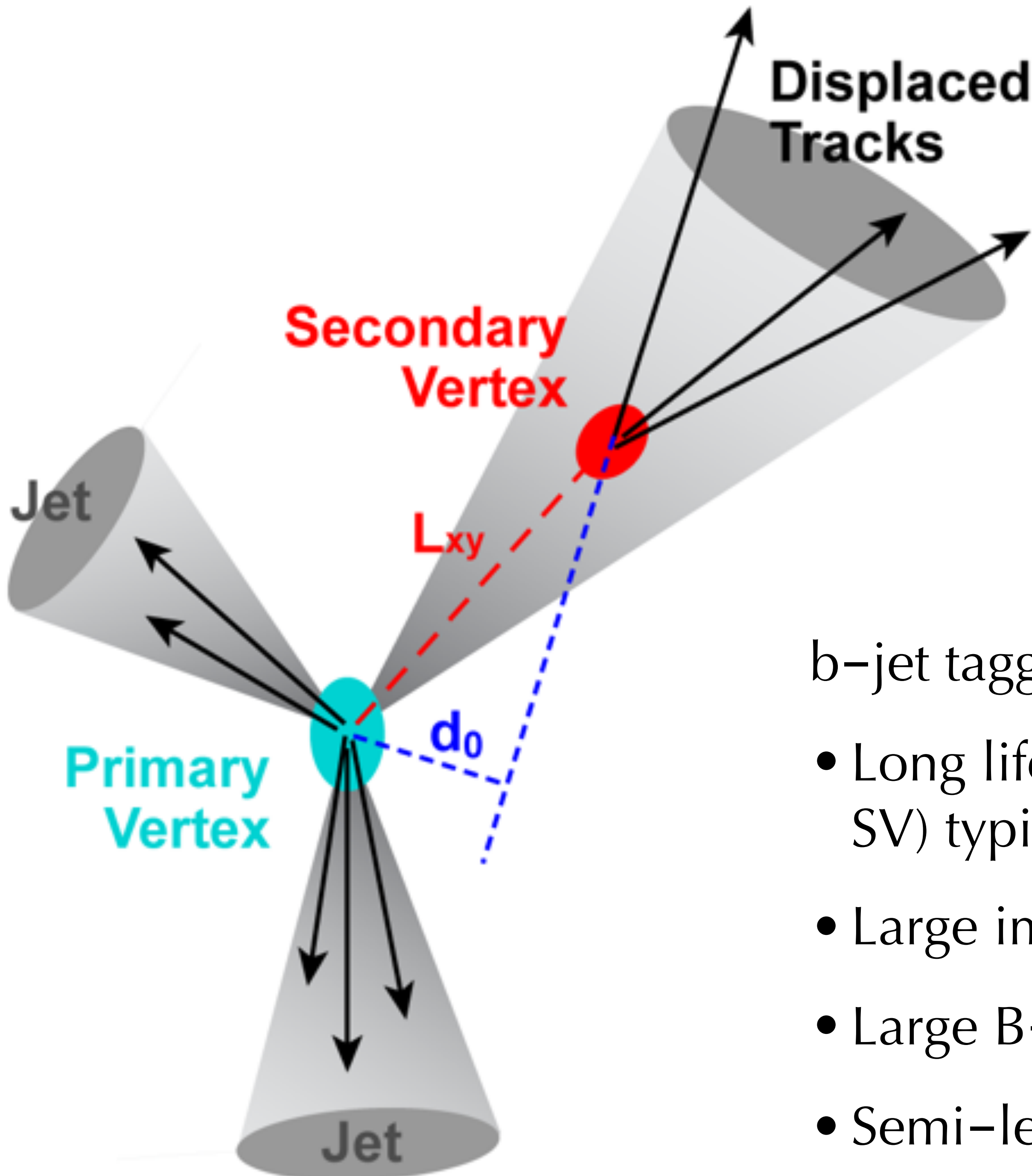
Tau Reconstruction and ID in ATLAS

- Taus seeded from anti-k_t jets with $\Delta R = 0.4$.
- Candidates required to be associated with 1 or 3 tracks within a core region $\Delta R < 0.2$.
- Isolated in annulus $0.2 < \Delta R < 0.4$.
- Various discriminating variables combined in Boosted Decision Trees to reject tau-fakes from electrons and jets.
  - BDTs trained separately for 1 and 3-prong taus.





b-Jet Decay Characteristics

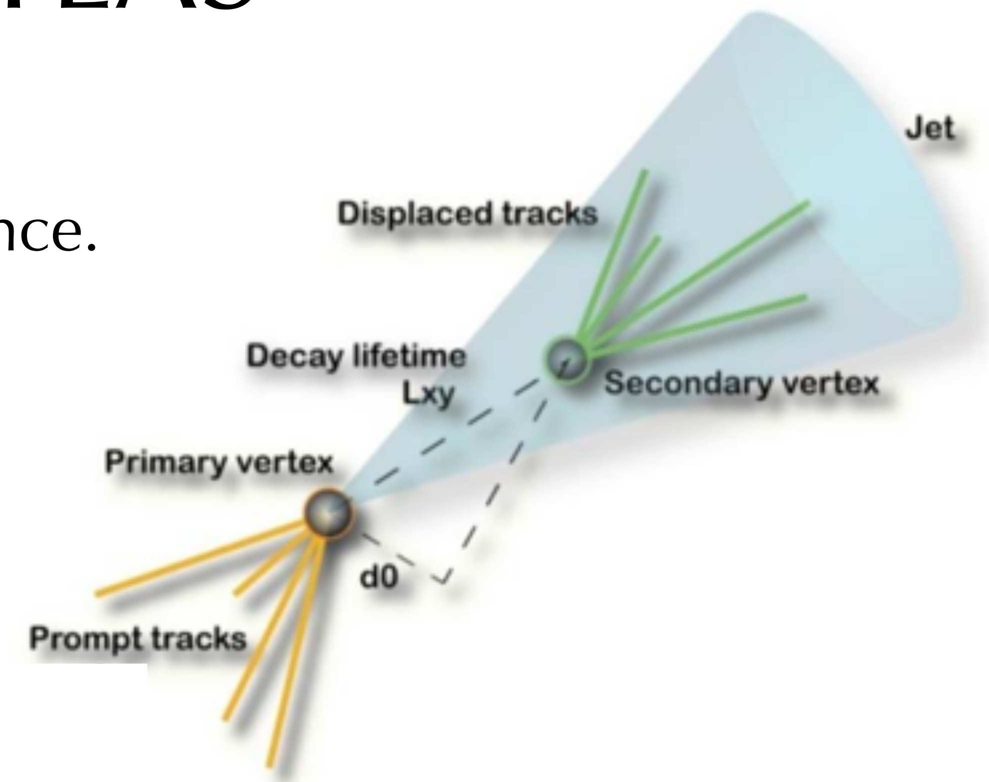


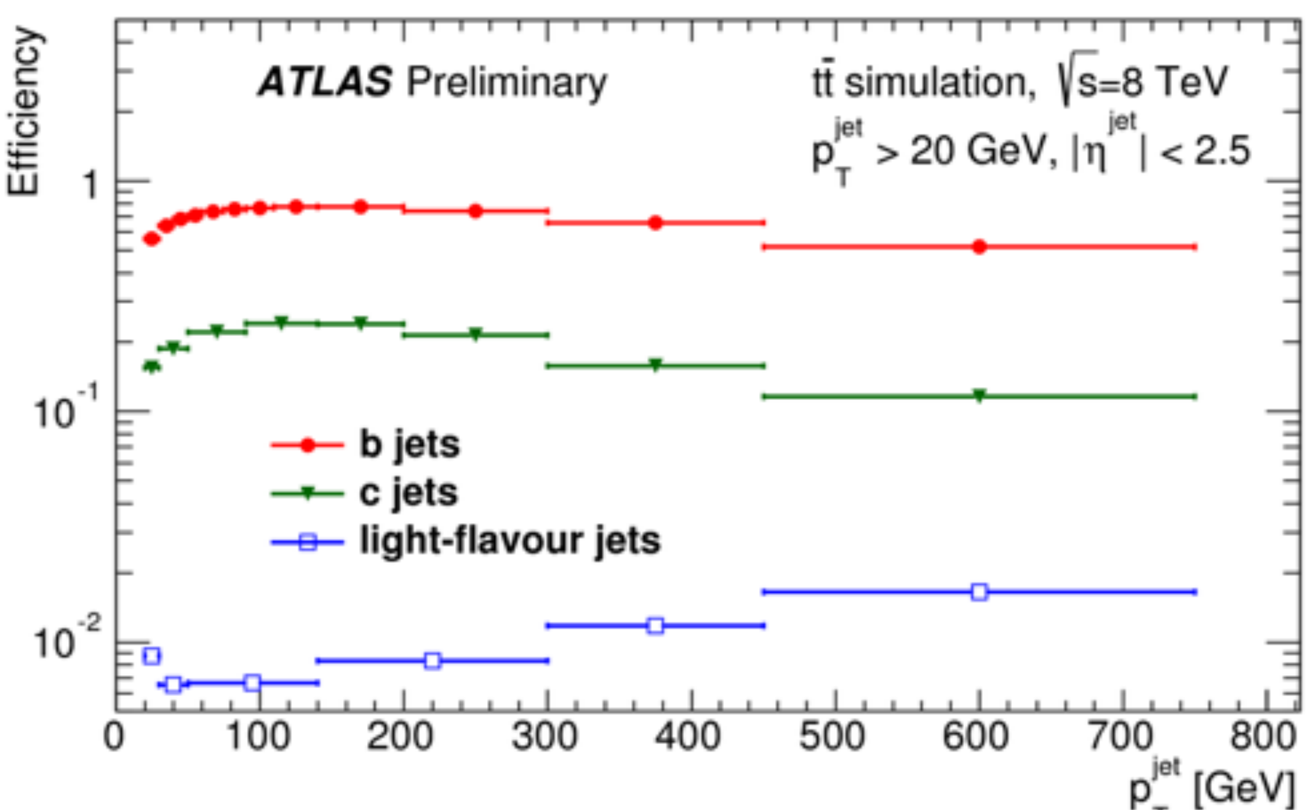
b−jet tagging relies on B−hadron properties:

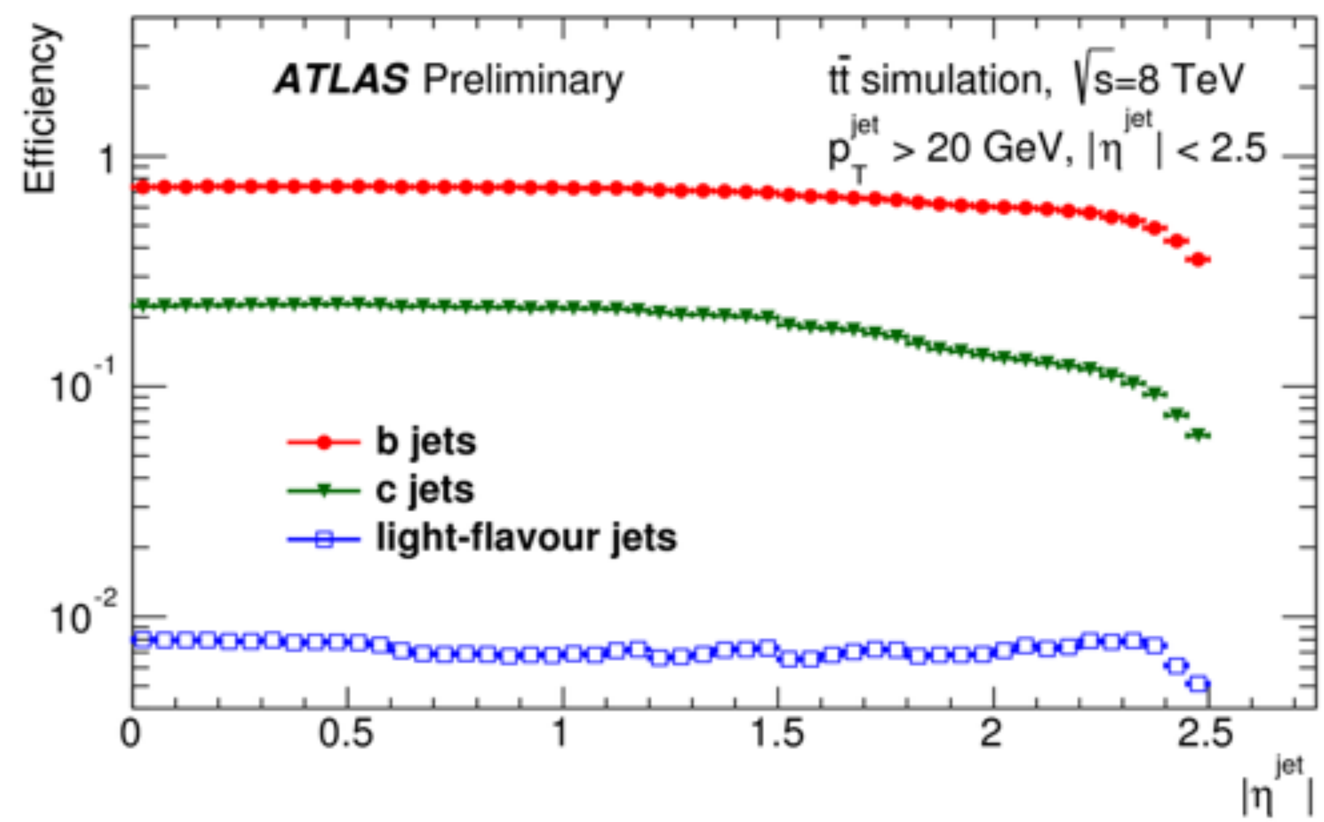
- Long lifetime → displaced vertex (secondary vertex, SV) typically few mm from primary vertex (PV).
- Large impact parameter (d0).
- Large B−hadron mass.
- Semi−leptonic (e/μ) decay of B−hadron
  - (~40% including b→c→$\ell\nu$X decay).

b-Tagging in ATLAS

- Use outputs of 3 algorithms as inputs to MVA:
  - IP3D: Use transverse and longitudinal IP significance.
  - SV1: Reconstruct SV and use information about:
    - SV mass
    - $\Sigma(P_T$ SV tracks$)/\ \Sigma(P_T$ all tracks in jet$)$
    - Number of two−track vertices
    - ΔR (jet−direction, PV→SV direction)
  - JetFitter: Exploit the topology of weak B/C−hadron decay chain (b→c→X) inside jets.







Run 1 HH → bbττ Analysis

Preselection
- Select all objects in bbττ final state ($\ell + \tau +$ 2-jets).
- Only lepton-hadron decay mode considered in Run 1.

Phys. Rev. D 92, 092004 (2015)

Event Preselection
Single lepton trigger
One isolated lepton (e/μ), $p_T > 26$ GeV
Di-lepton veto
One hadronic tau, $p_T > 20$ GeV
Charge correlation between lepton and tau
Two or more jets, $p_T > 30$ GeV

Kinematic Cuts
- Addition rejection against Z+jets, W+jets and ttbar.

Event Categorisation
- Number of b-jets.
- p_T of τ-pair.

Resonant Search
- m(ττ) cut
- Final discriminant: m(bbττ).

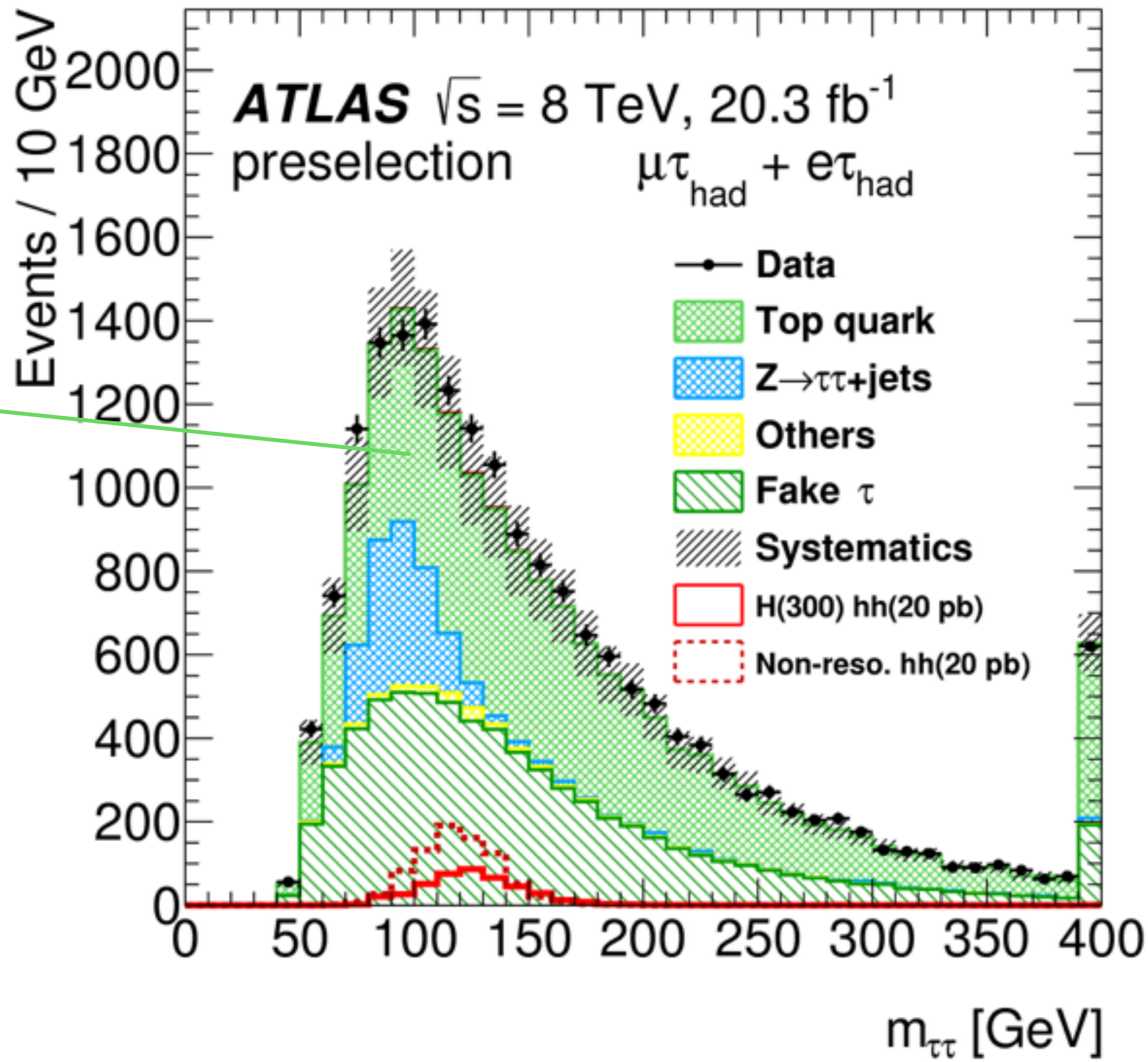
Non-Resonant Search
- Final discriminant: m(ττ)

$\sqrt{s} = 8$ TeV
$\int \mathcal{L} = 20\ \mathrm{fb}^{-1}$

Backgrounds

Top-Pair Production

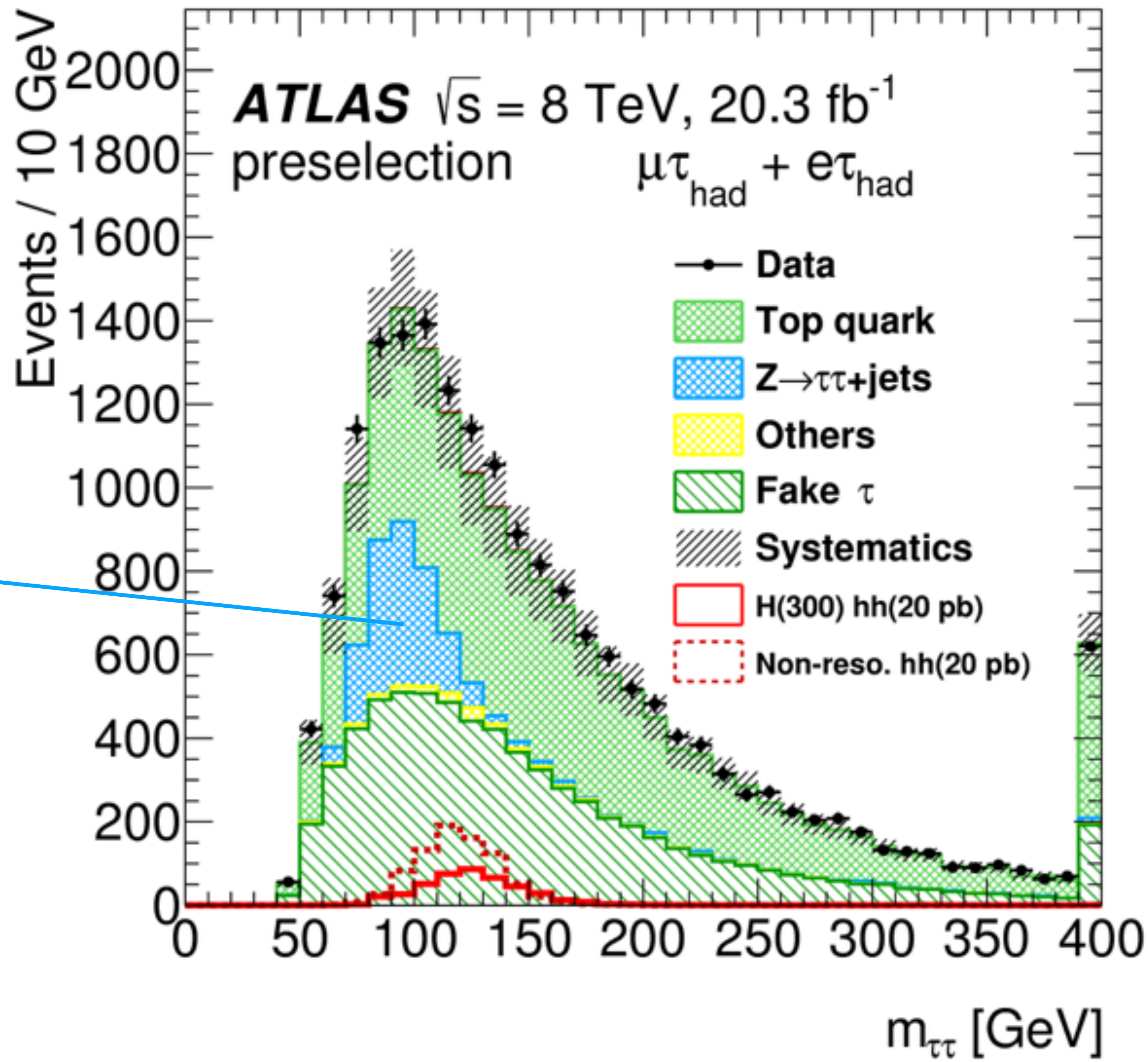
- Contribution where the hadronic tau is real estimated from MC (Powheg).
- Fraction where hadronic W-decay fakes tau calculated separately (see later slide).



Backgrounds

Z→ττ Background

- Estimated from data using embedding method:
  - Z→μμ events selected from data.
  - Muons replaced with simulated taus.
  - Missing E_T corrections applied.
- Normalised to data in $40 < M^{vis}(\tau\tau) < 70$ GeV region.



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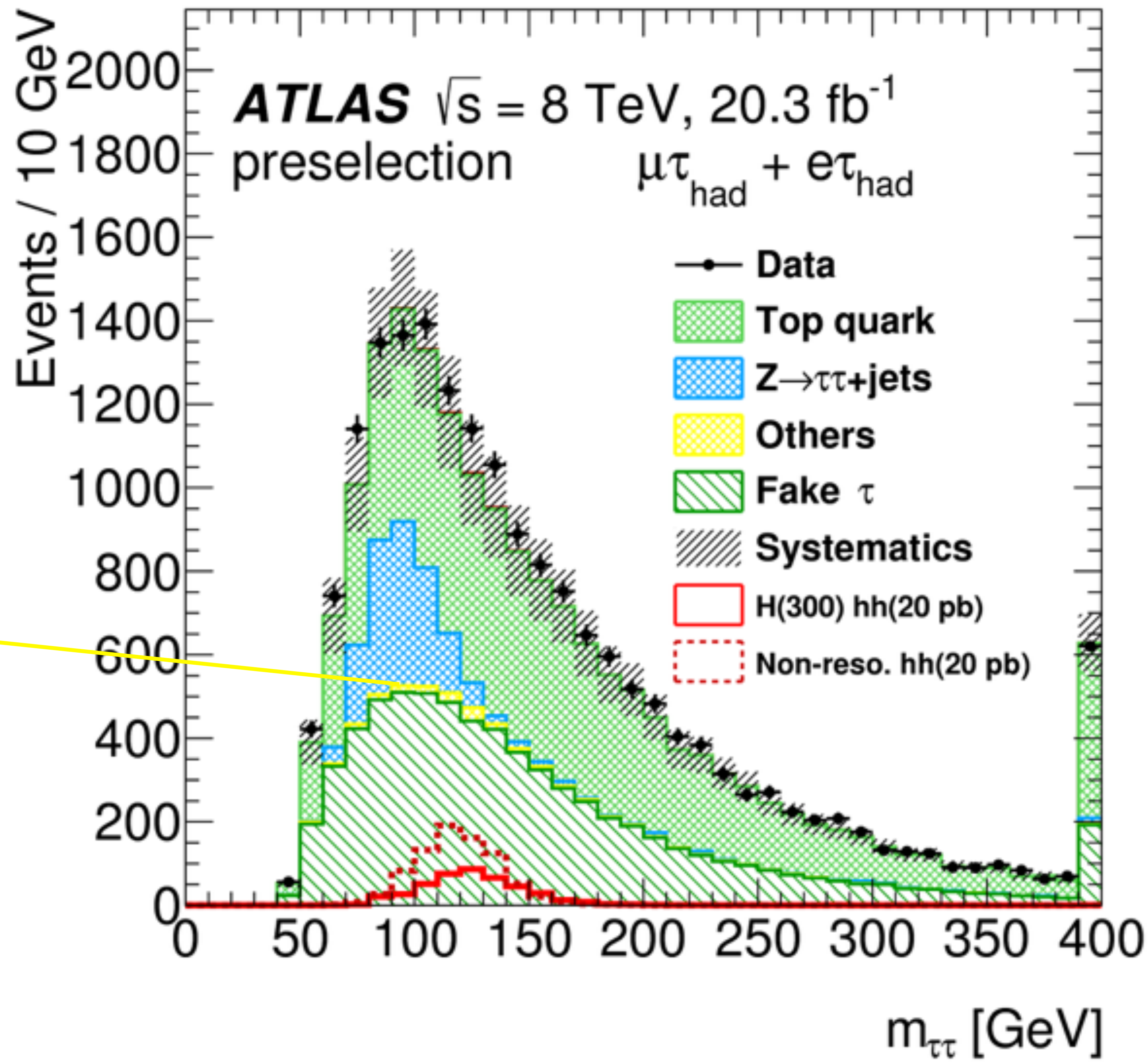


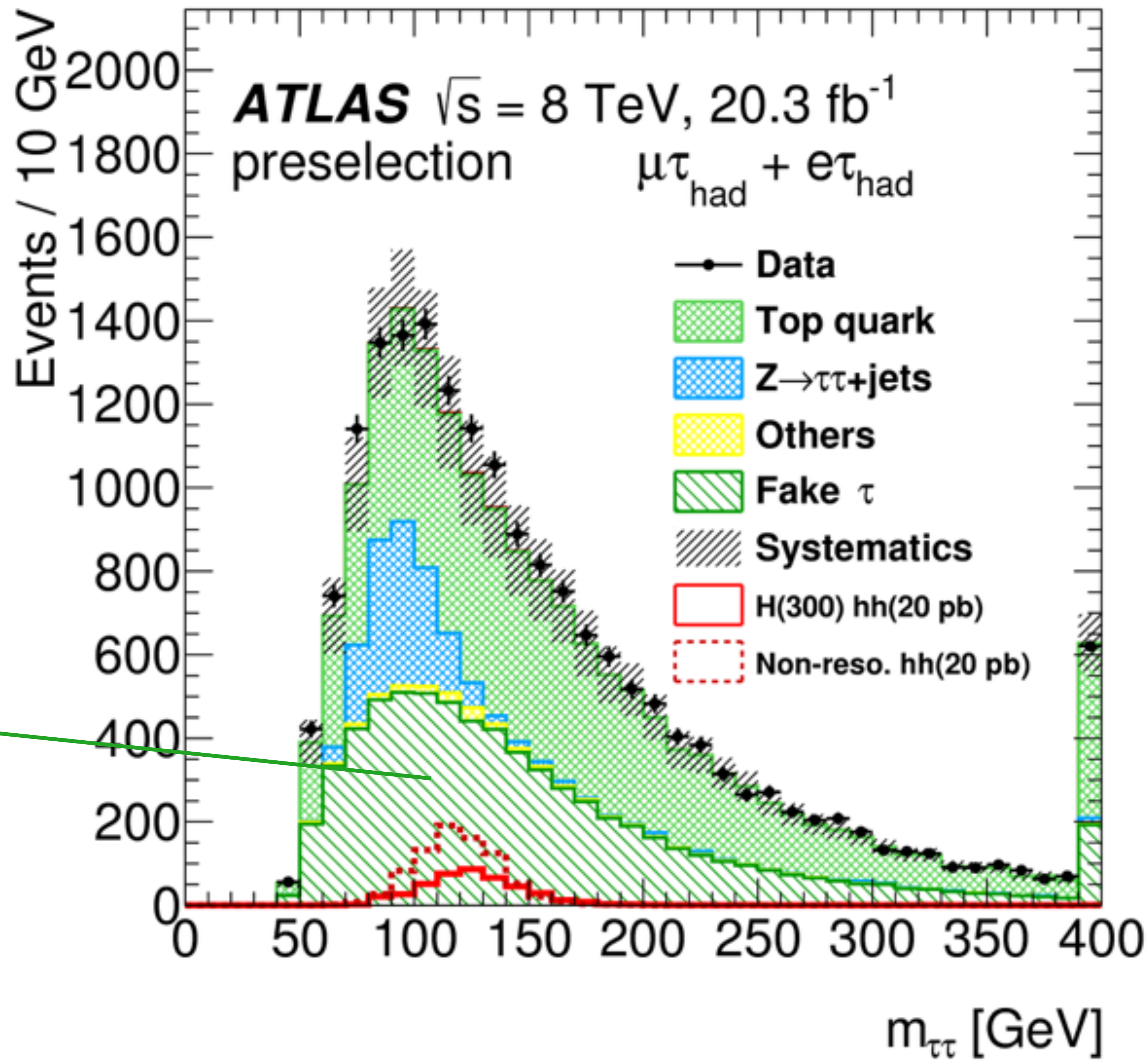
Others

- Single top, di-boson, $Z\rightarrow\ell\ell$ all estimated from MC.
- Small contribution.

Backgrounds

Fake Taus

- Fake-factor method to estimate all backgrounds where the tau is faked by a jet.
  - Multijets.
  - Semi-leptonic ttbar.
  - W+jets.
  - Z→ττ+jets (where one tau is missed).



Fake-Factor Method

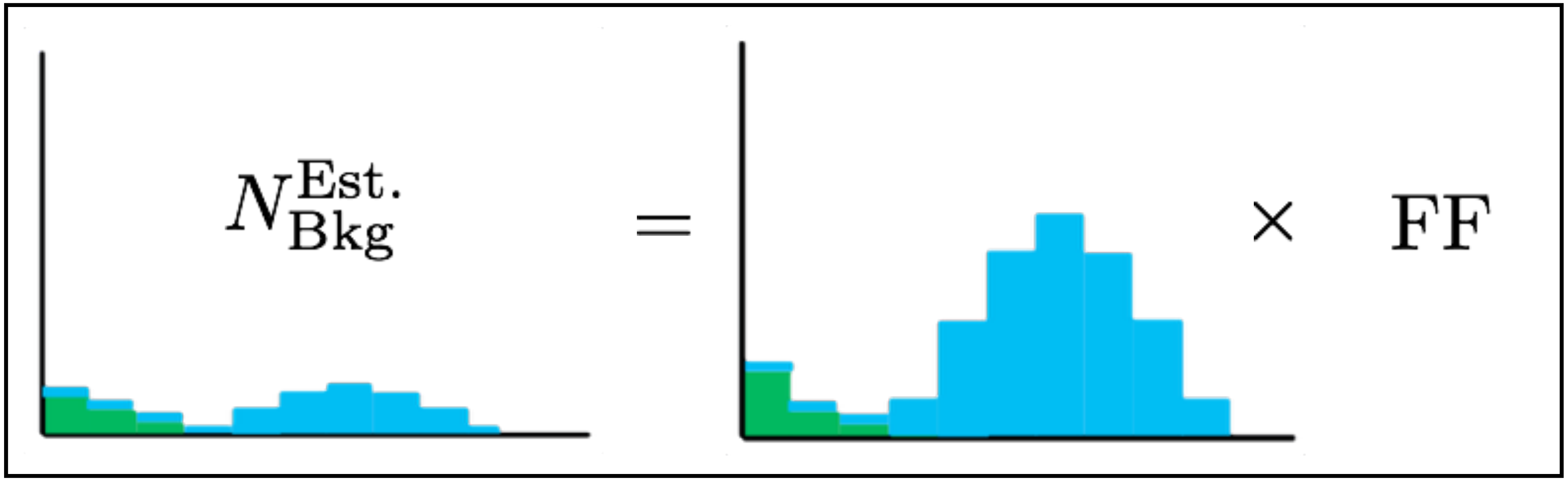
$$N^{\text{Est.}}_{\text{Bkg}} = (N^{\text{anti}-\tau}_{\text{data,SR}} - N^{\text{anti}-\tau}_{\text{true,SR}}) \times \text{FF}_{\text{CR}} \qquad \text{FF}_{\text{CR}} = \frac{N^{\text{identified}-\tau}_{\text{CR}}}{N^{\text{anti}-\tau}_{\text{CR}}}$$

- Number of anti-tau events (failing signal tau ID, but passing looser selection).
- Contribution from real taus subtracted.

- Separate FFs for each contributing process.
- Calculated as a function of p_T and #-tracks.

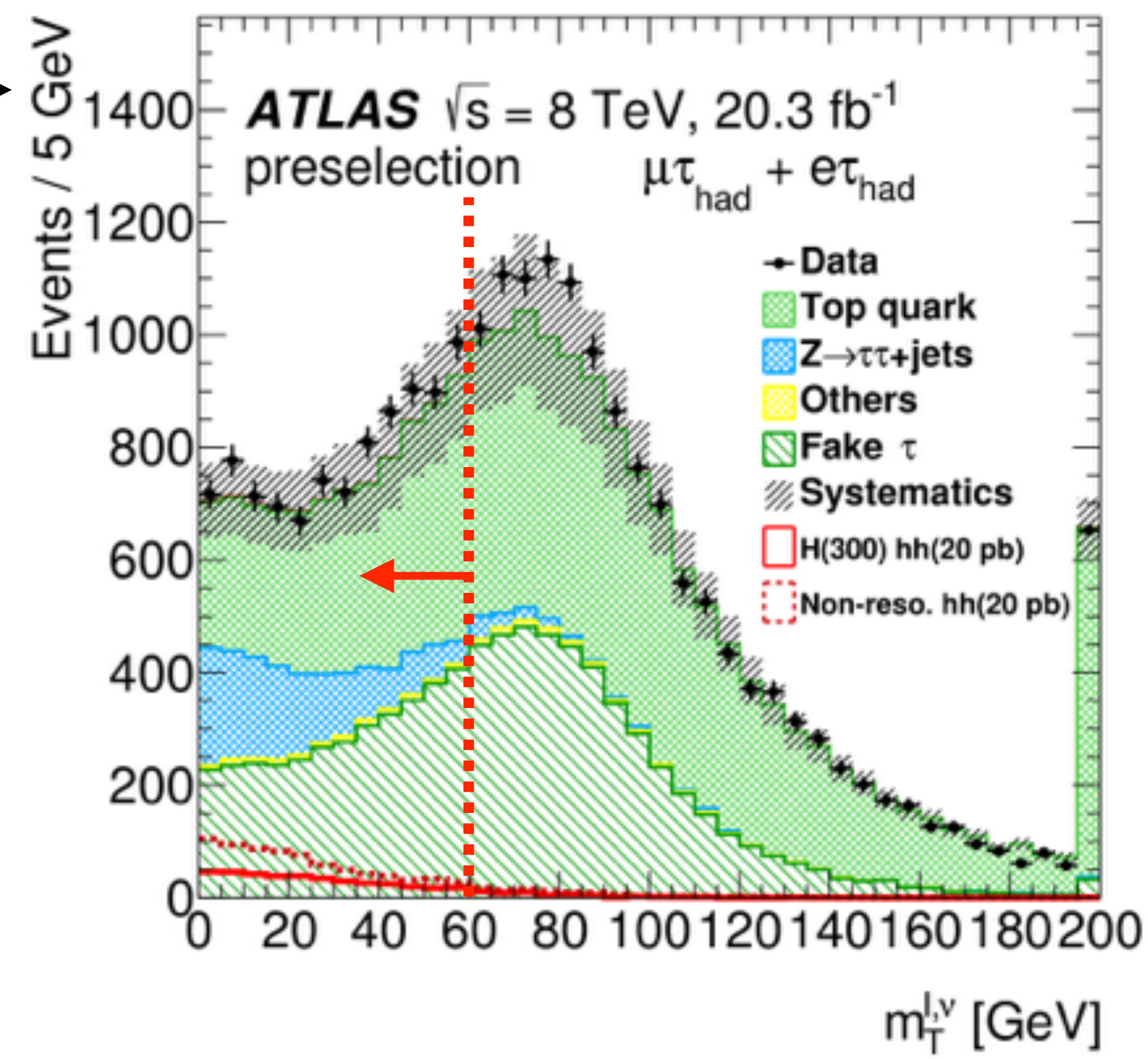
$$\text{FF}(p_{\text{T}}, n_{\text{prong}} = \sum_{i=\text{bkg}} R_i \, \text{FF}_i(p_{\text{T}}, n_{\text{prong}})$$

R_i = fraction of each source
FF_i = FF of each source



Kinematic Cuts

Transverse mass	Reject W+jets and ttbar $m_T < 60$ GeV
Missing E_T ϕ centrality	Missing E_T should point between the lepton and tau.
Lepton-tau p_T balance	$\Delta p_T(\ell,\tau) < 20$ GeV
m_W vs. m_{top}	Elliptical cuts on W and top masses
m_{bb} mass window	$90 < m_{bb} < 160$ GeV
$m_{\tau\tau}$ mass window	$100 < m_{\tau\tau} < 150$ GeV (only for resonant search)



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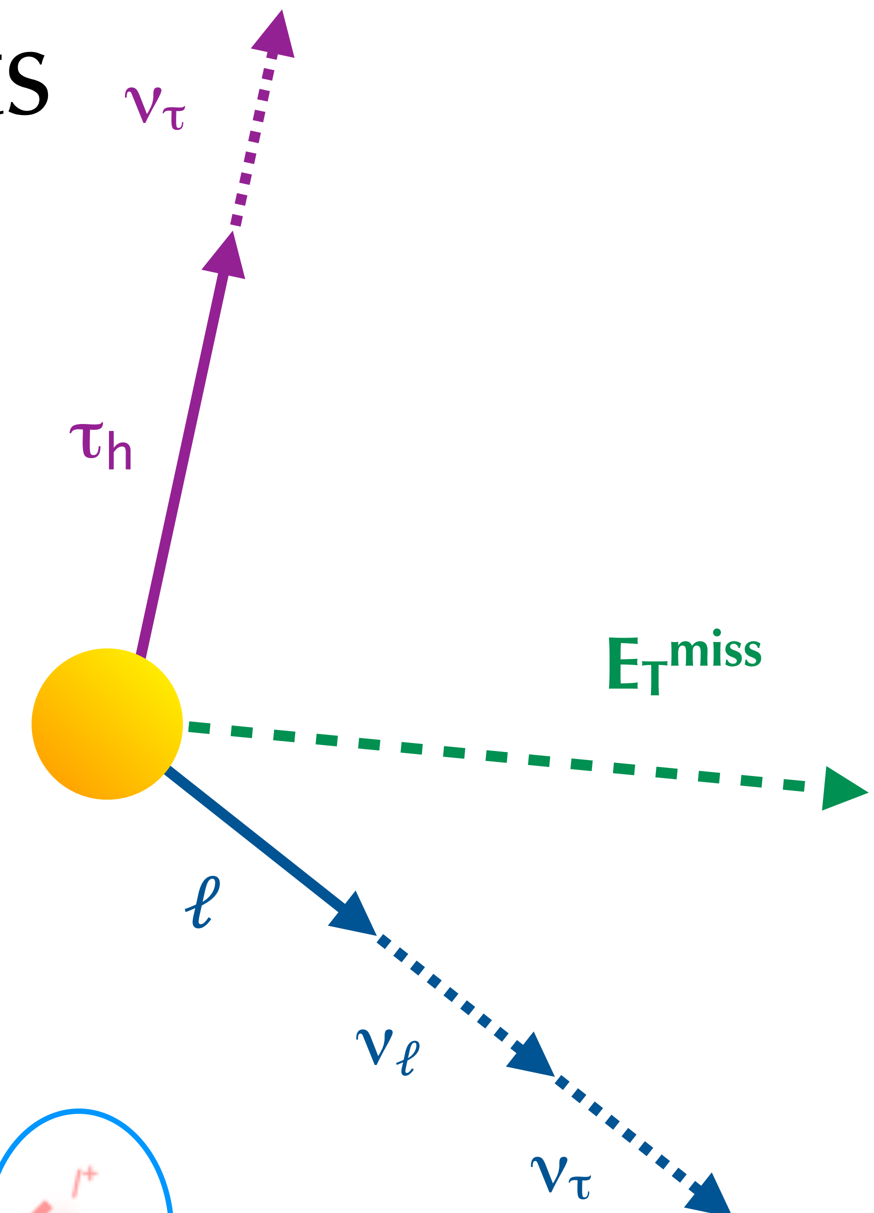

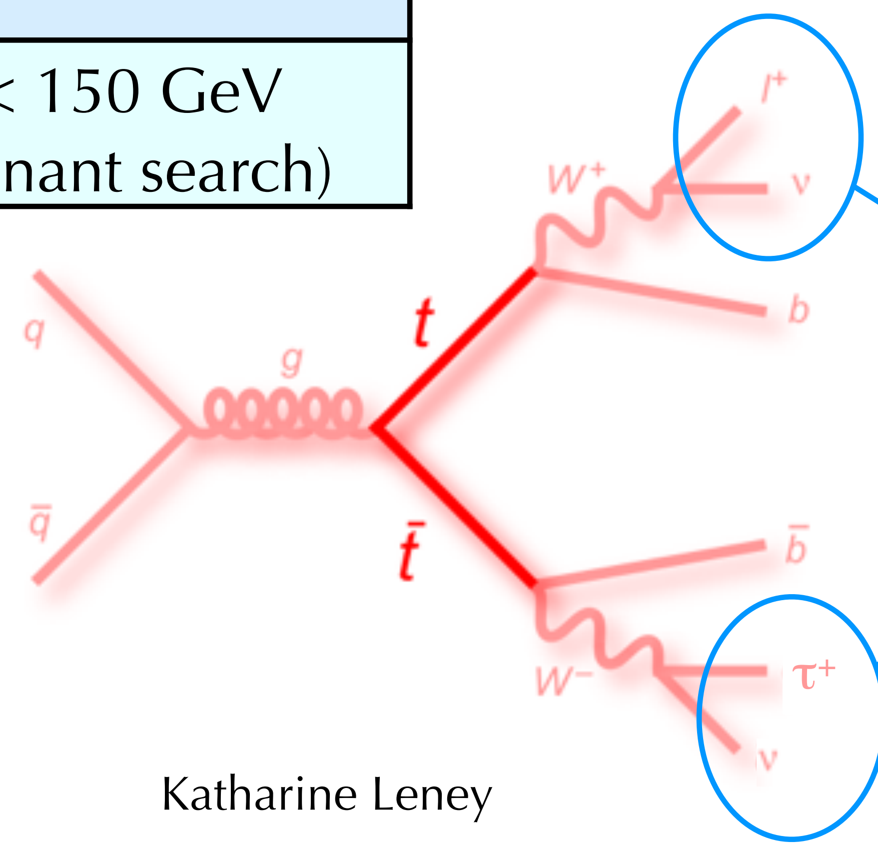

Leptons from W decay tend to be harder than those from taus because of number of accompanying neutrinos

Kinematic Cuts

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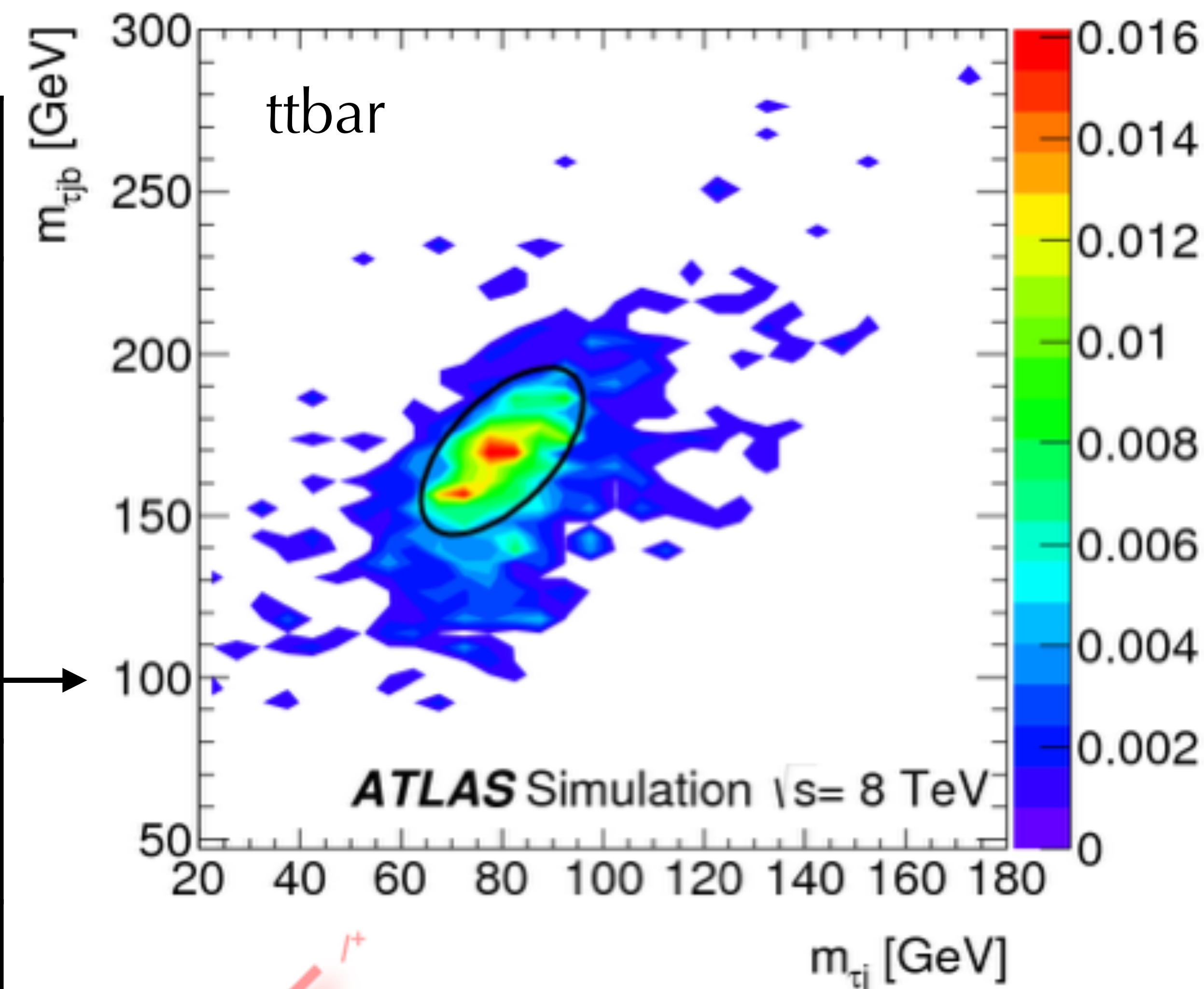

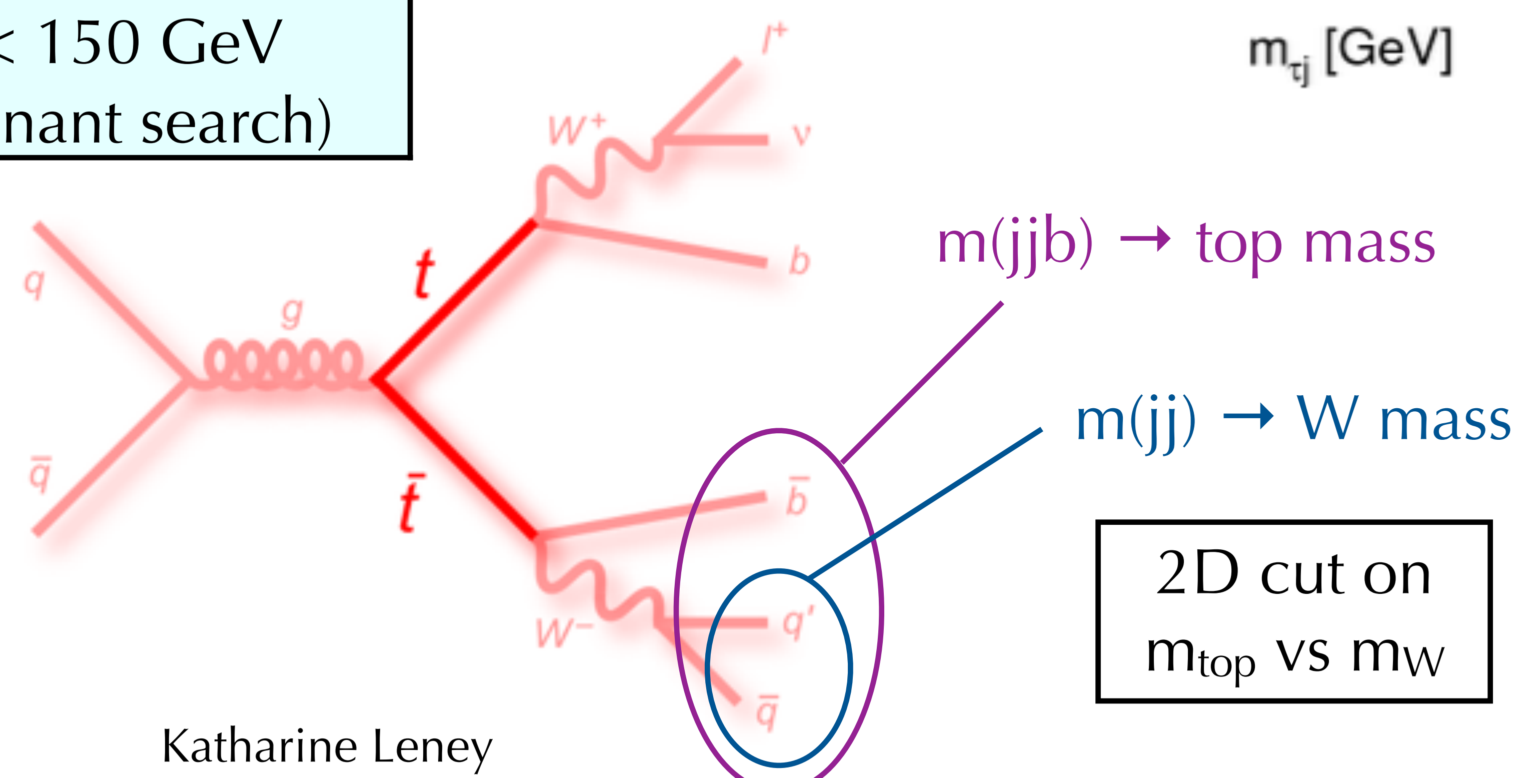

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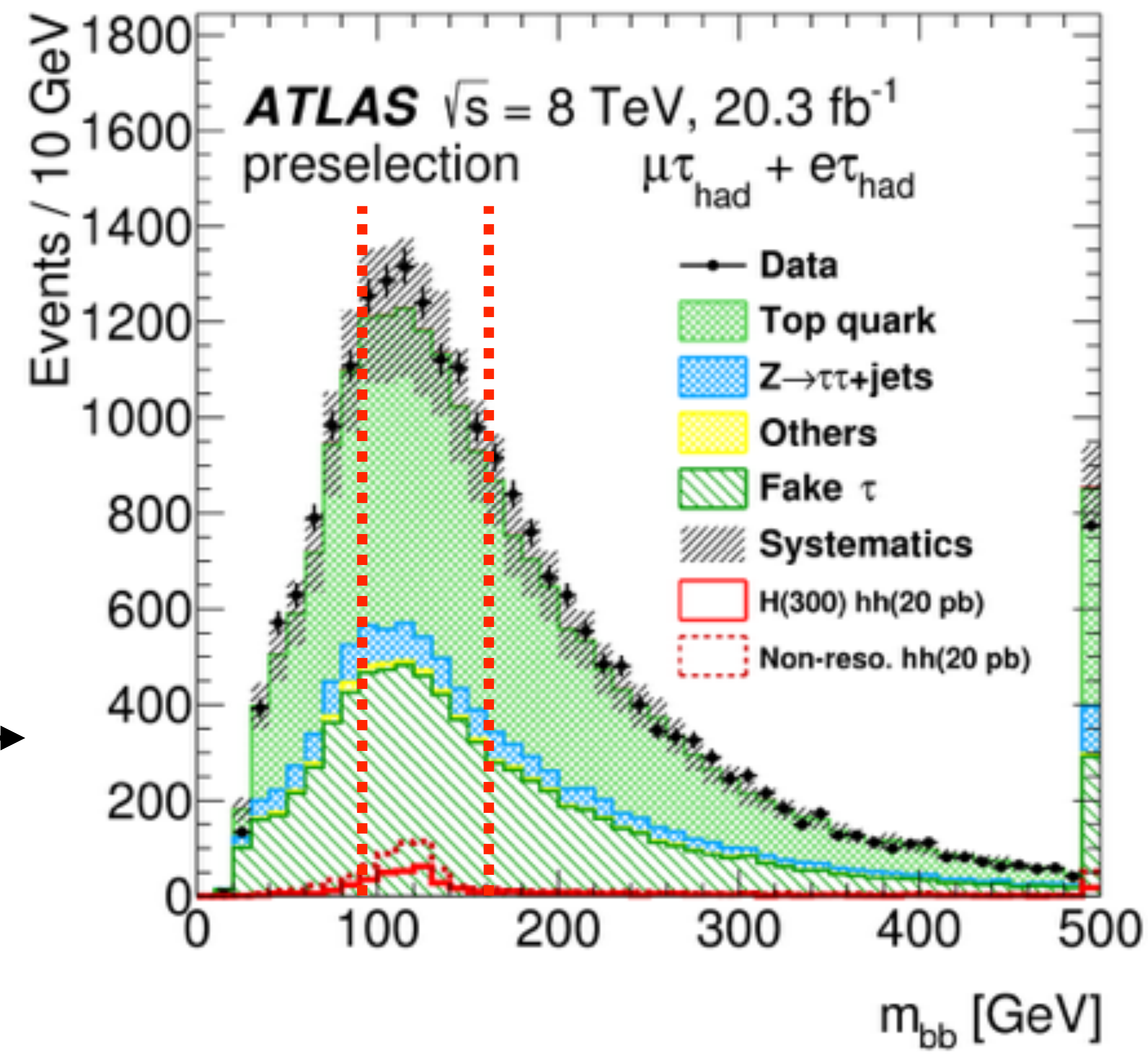

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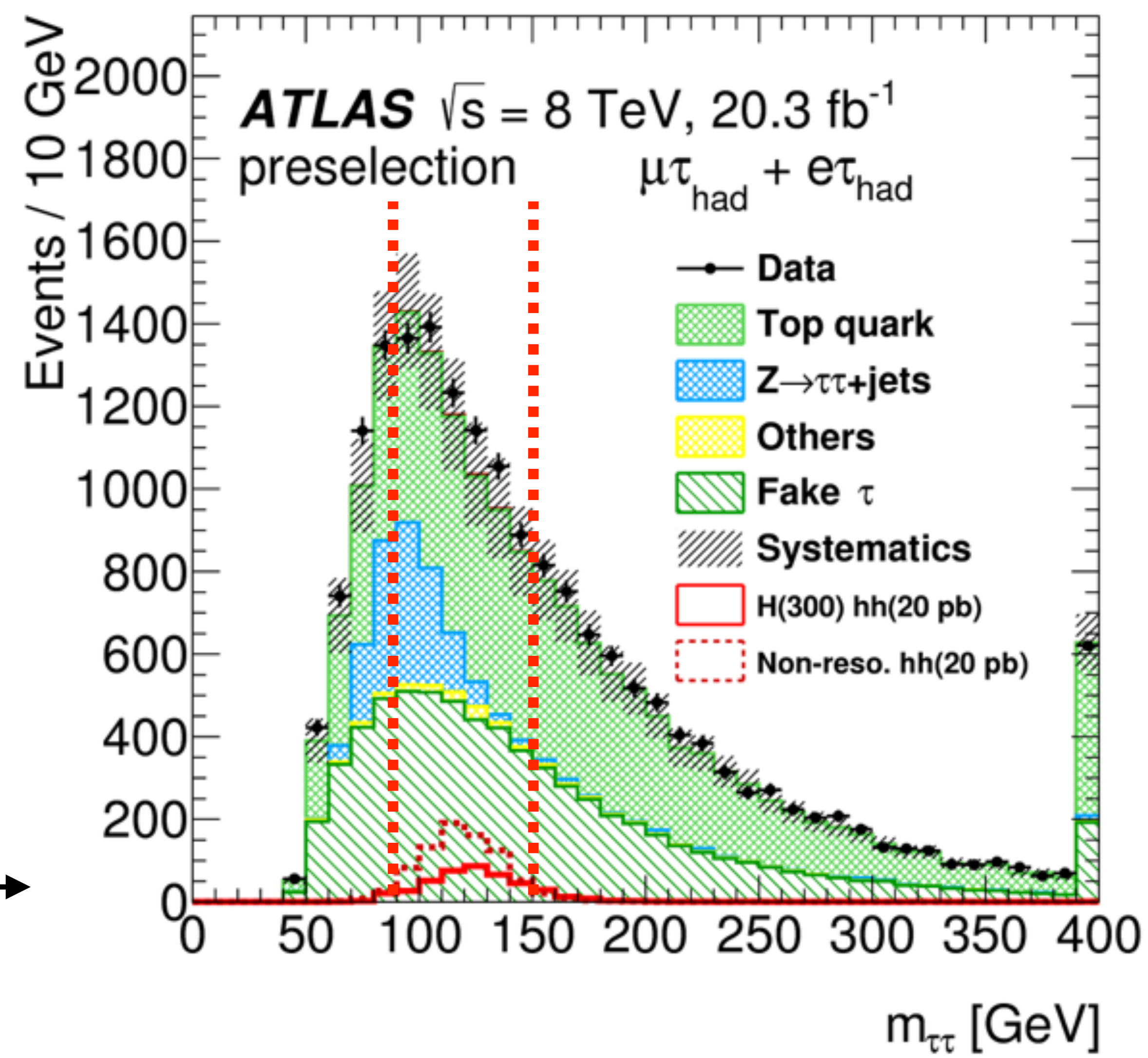
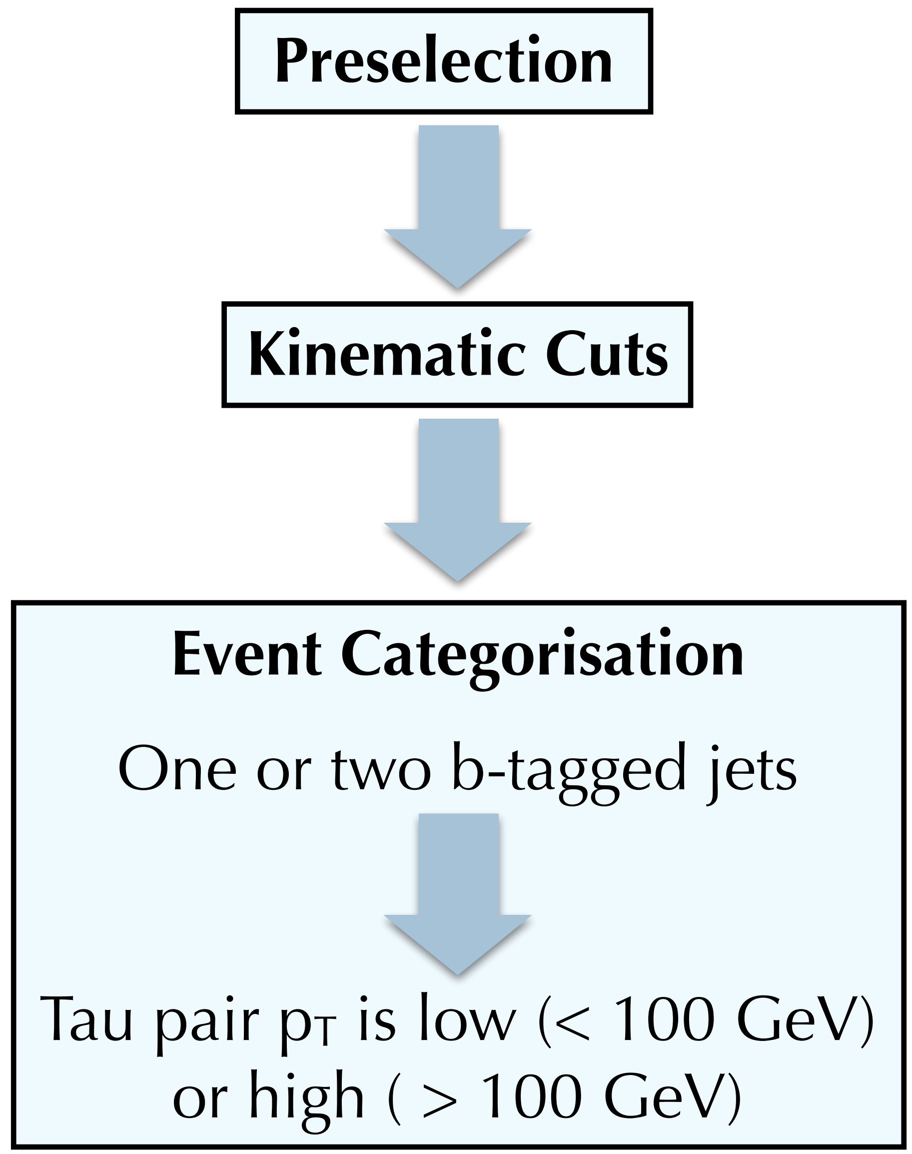


- $m_{\tau\tau}$ reconstructed using Missing Mass Calculator (MMC), arXiv: 1012.4686
- Weights the kinematically allowed τ decay solutions by a likelihood function.

Event Categorisation

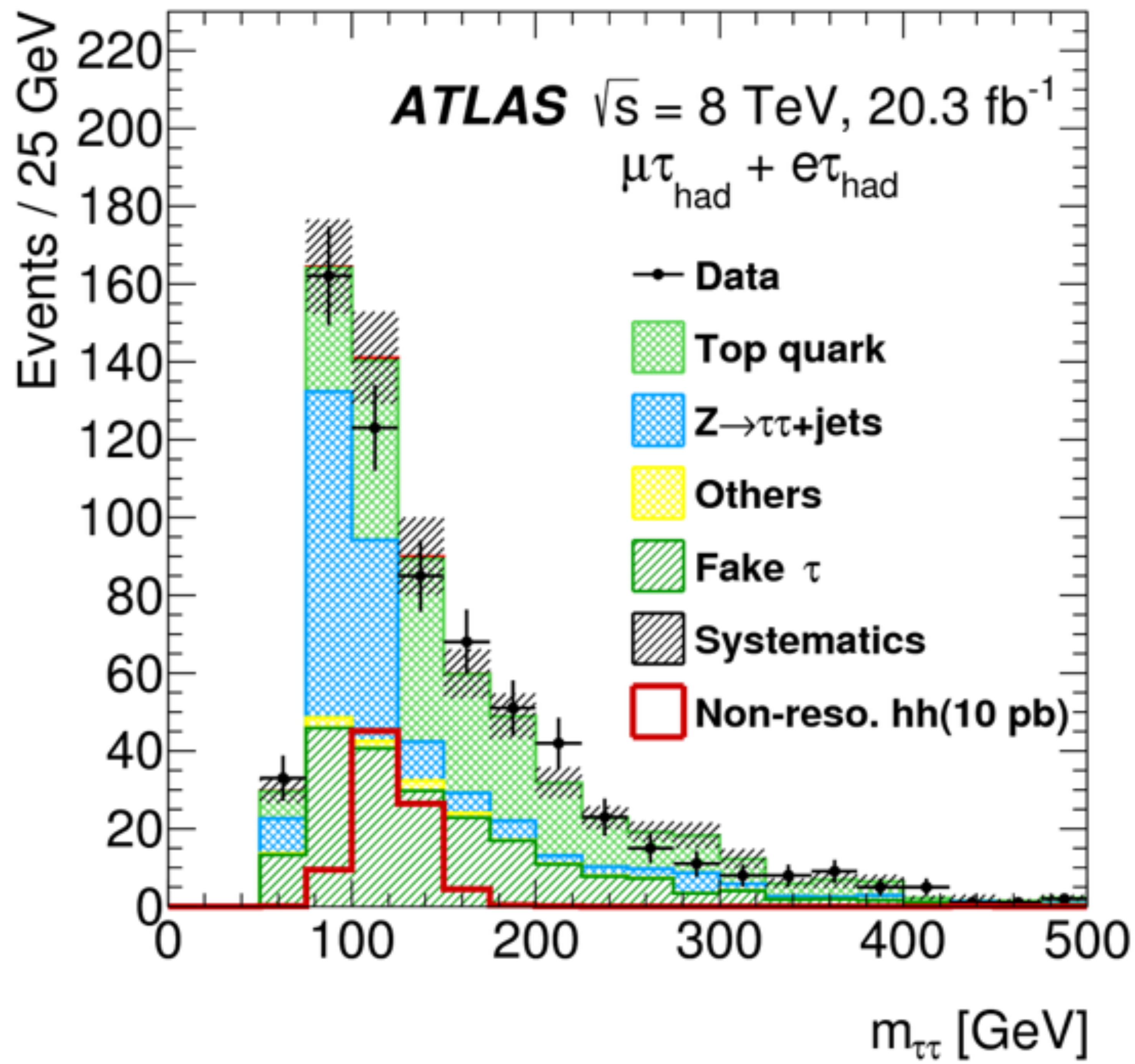


Non-Resonant Analysis

- Use $m_{\tau\tau}$ as final discriminant

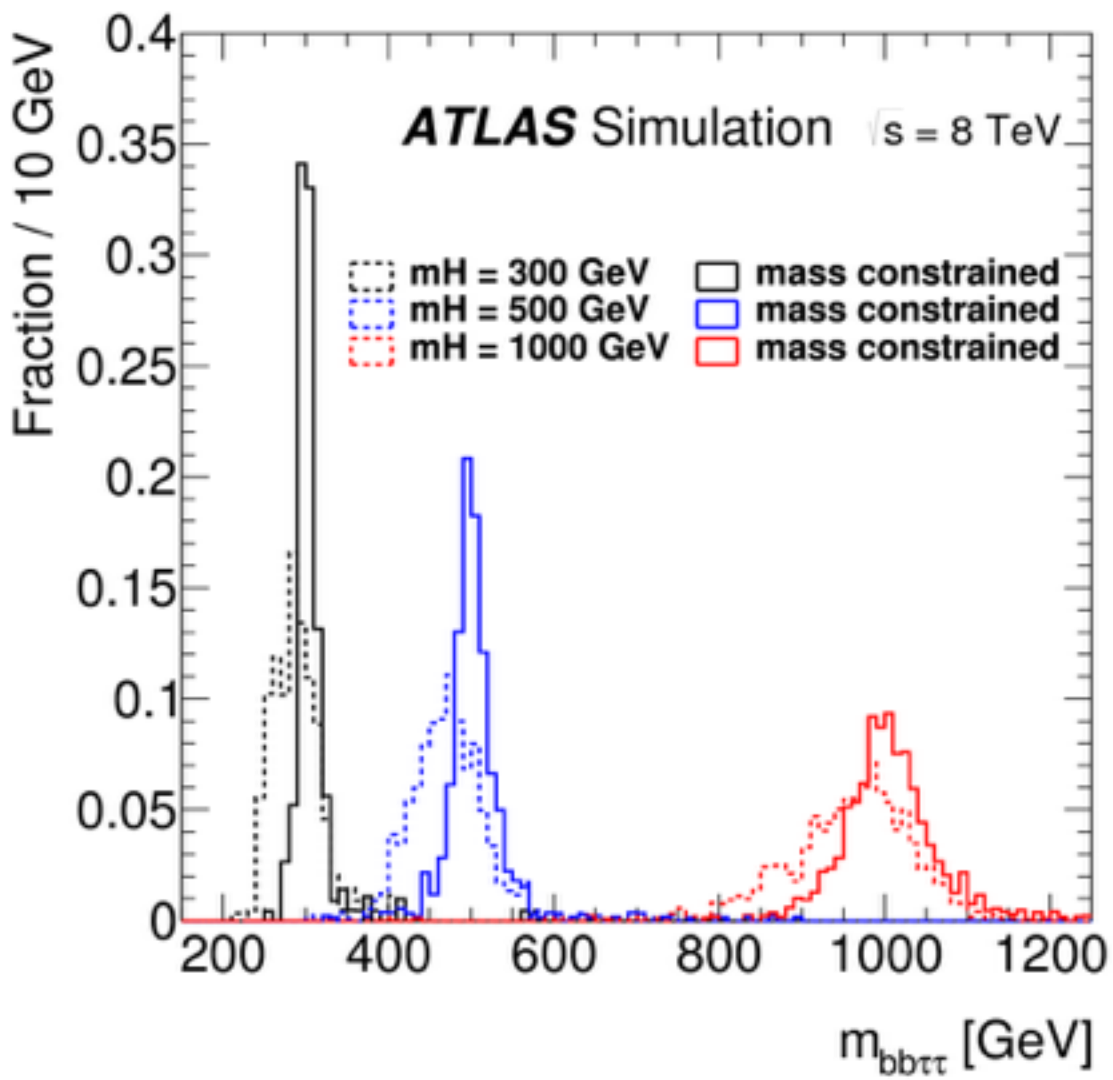
	Cross-section (upper limit)
Expected	1.3 pb
Observed	1.6 pb

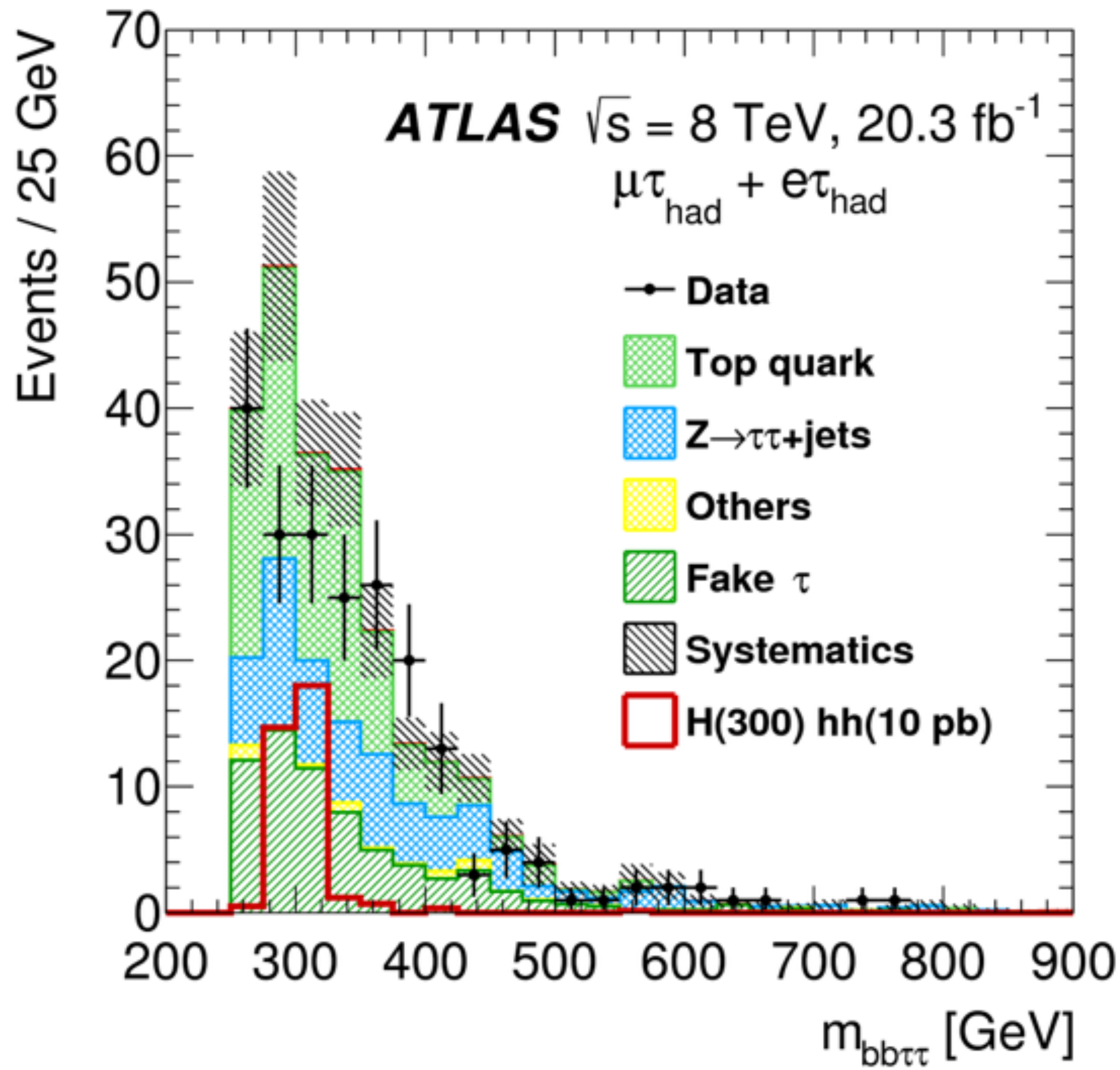
	Cross-section (upper limit) relative to SM
Expected	130
Observed	160



Resonant Analysis

- Apply scale factors m_h/m_{bb} and $m_h/m_{\tau\tau}$ to 4-momenta of bb and $\tau\tau$ systems.
  - m_h = 125 GeV (SM Higgs)
- Improves mass resolution of heavy resonances.





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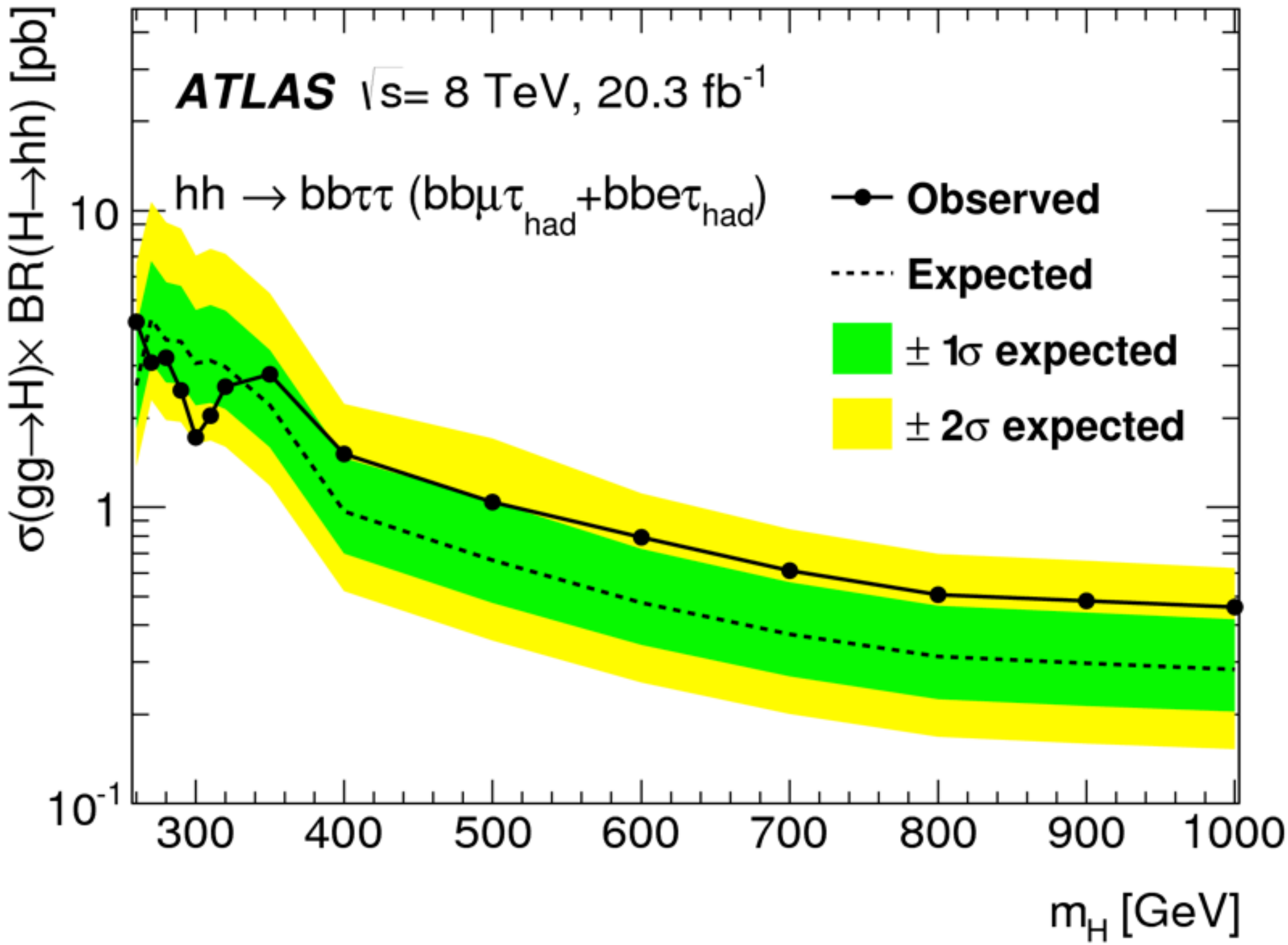
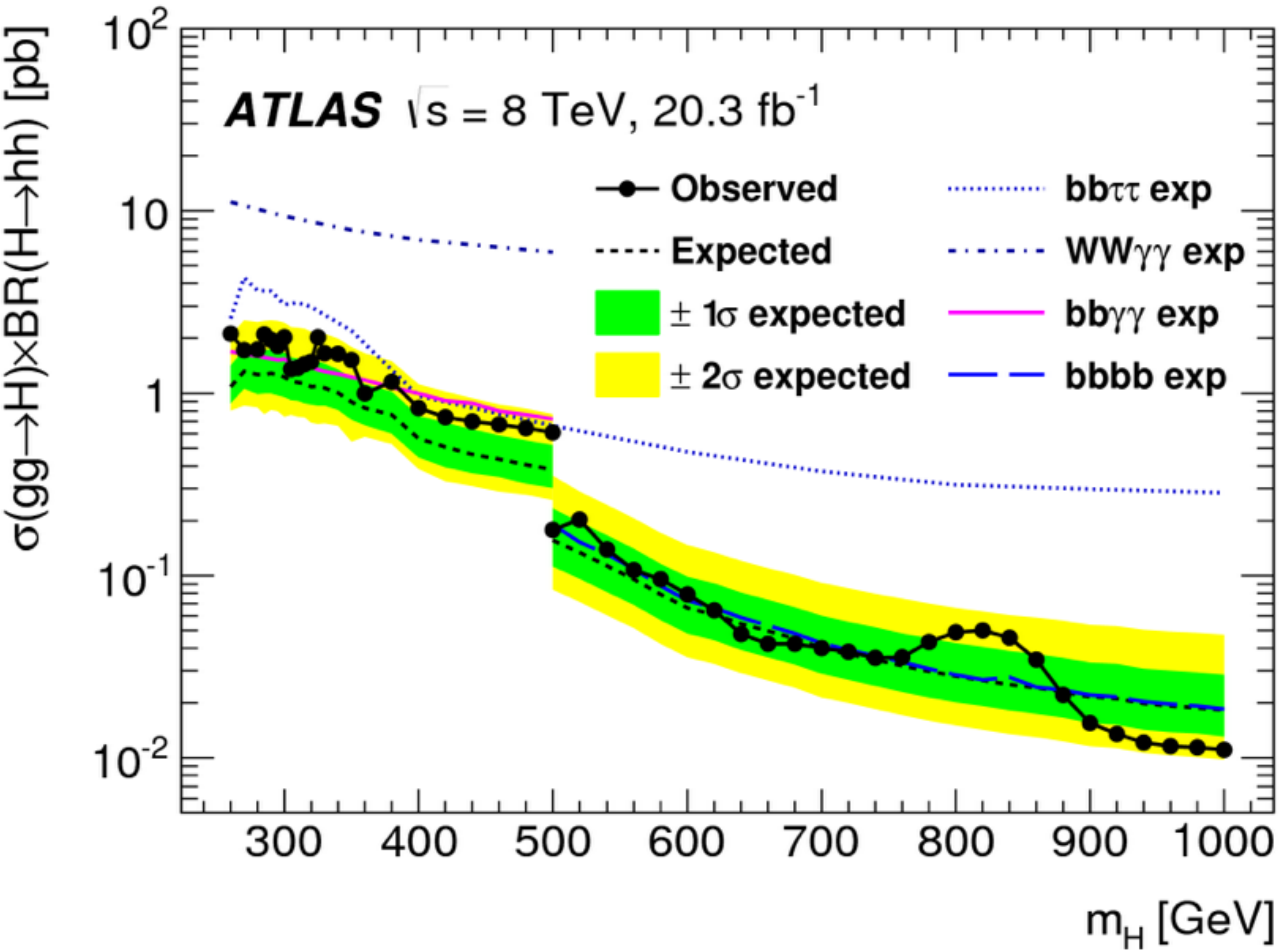
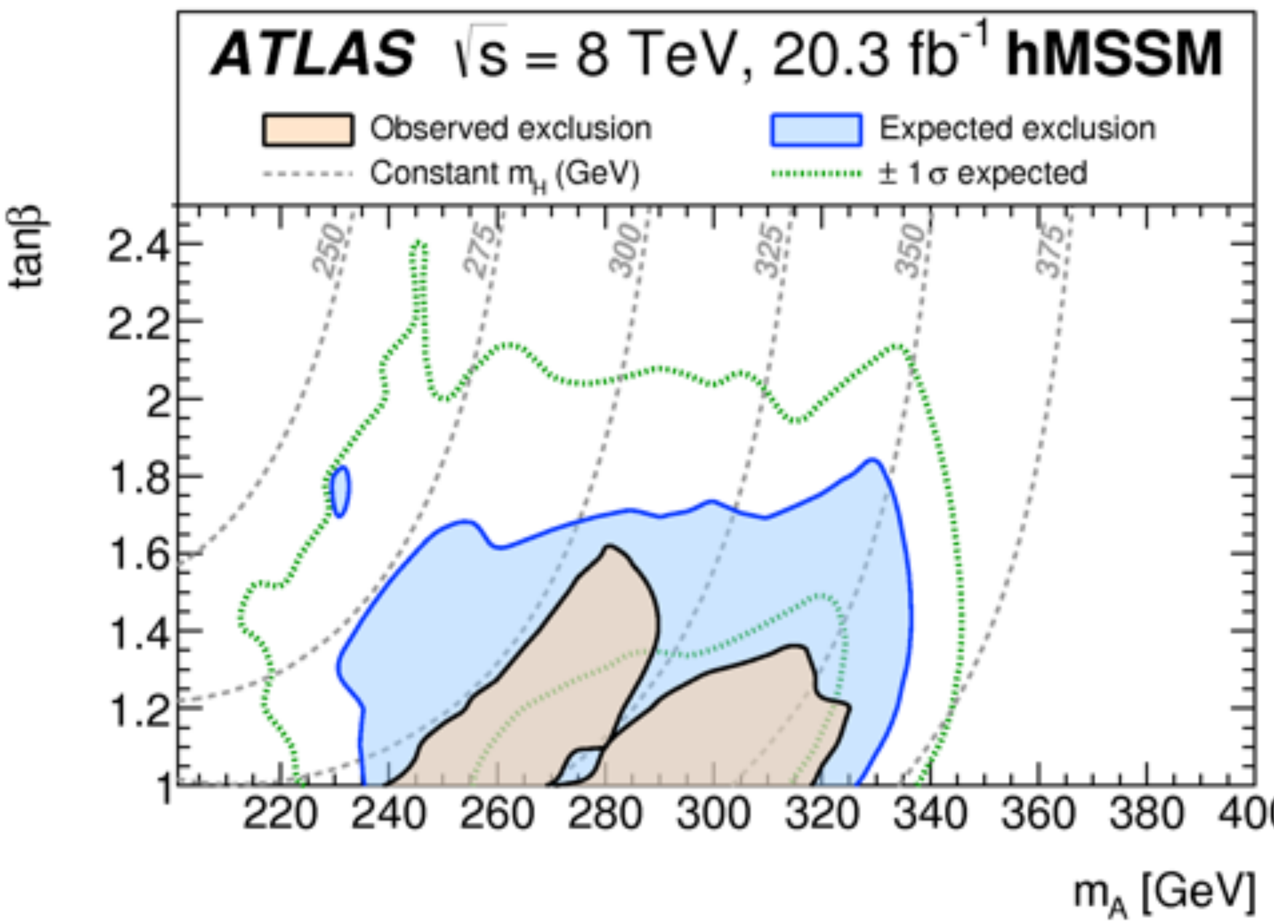
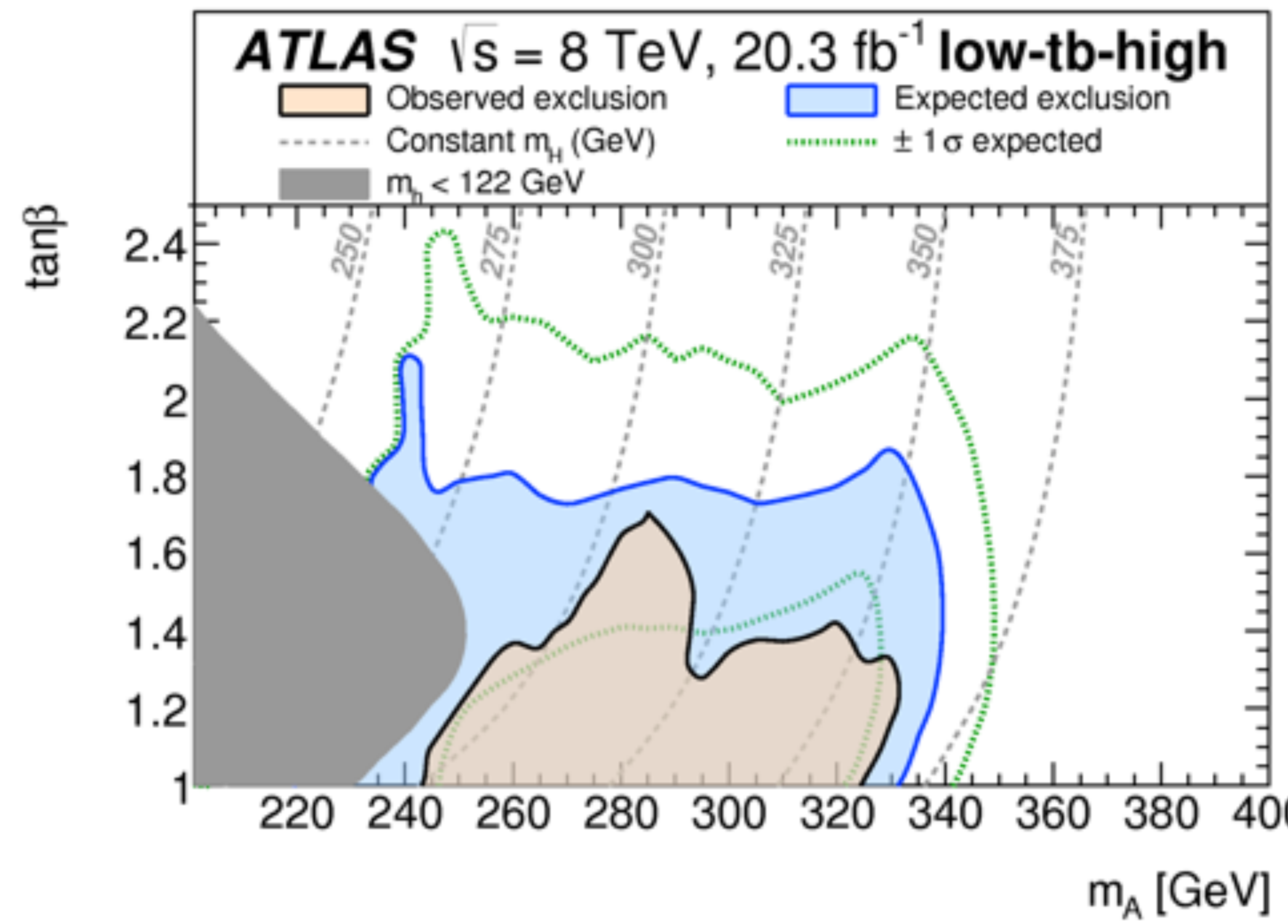


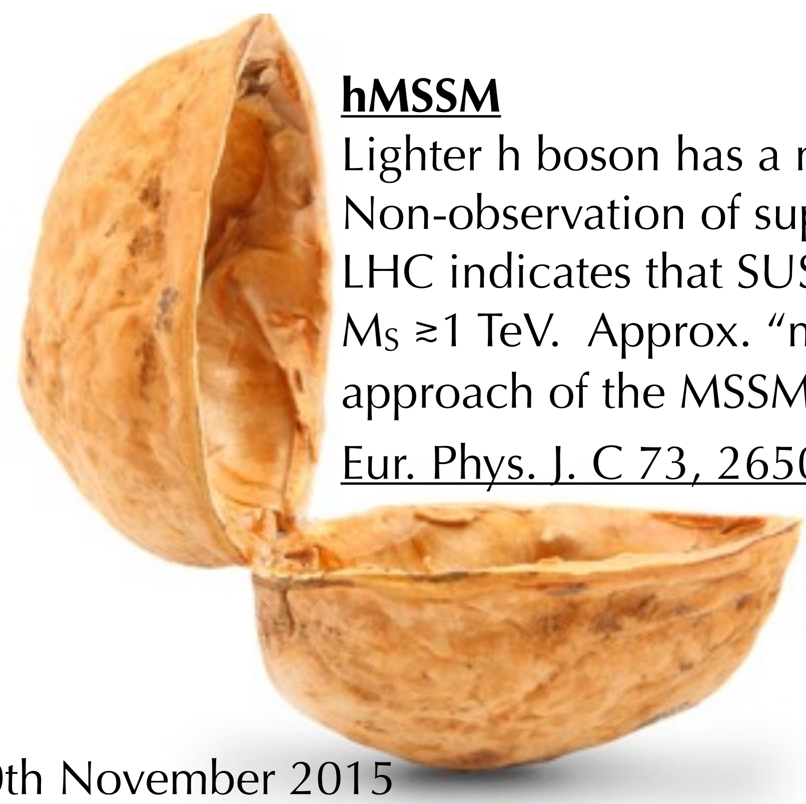
Combination With Other Channels



Constraints on 2HDM Models



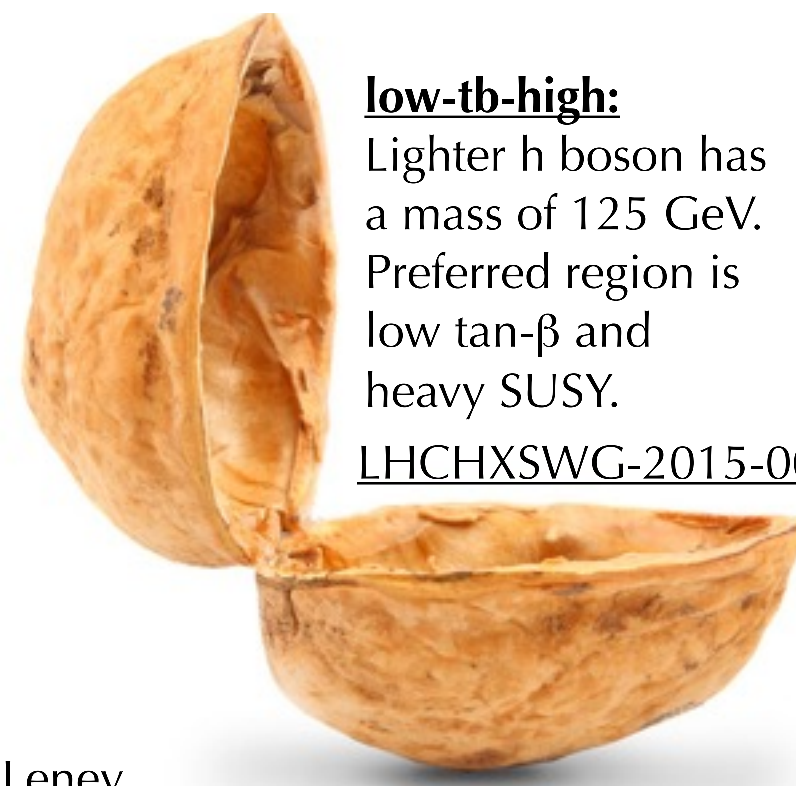




hMSSM

Lighter h boson has a mass of 125 GeV. Non-observation of superparticles at the LHC indicates that SUSY-breaking scale $M_S \gtrsim 1$ TeV. Approx. "model-independent" approach of the MSSM Higgs sector.

Eur. Phys. J. C 73, 2650 (2013)



low-tb-high:

Lighter h boson has a mass of 125 GeV. Preferred region is low tan-β and heavy SUSY.

LHCHXSWG-2015-002

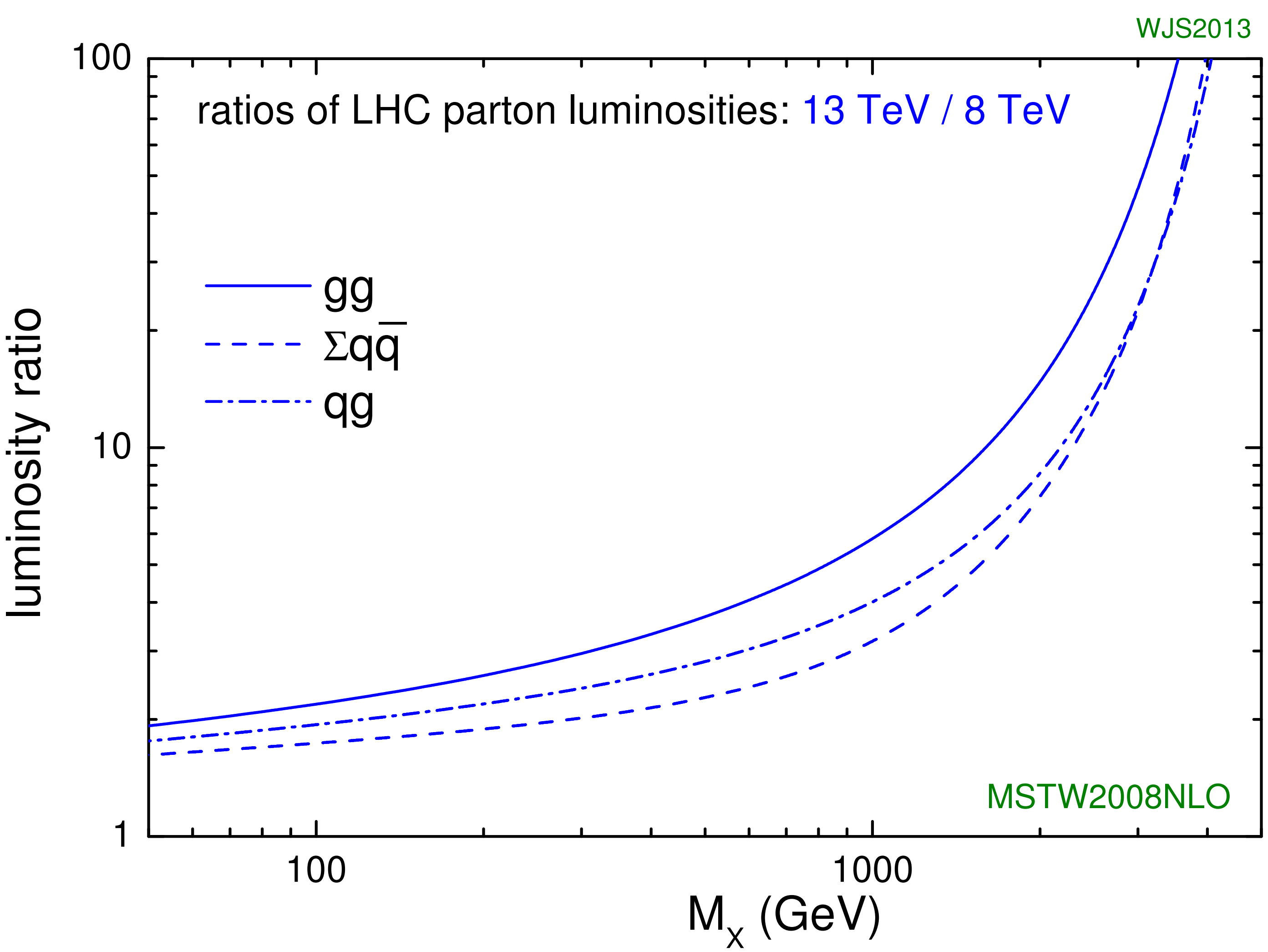

RUN 2
NEXT EXIT

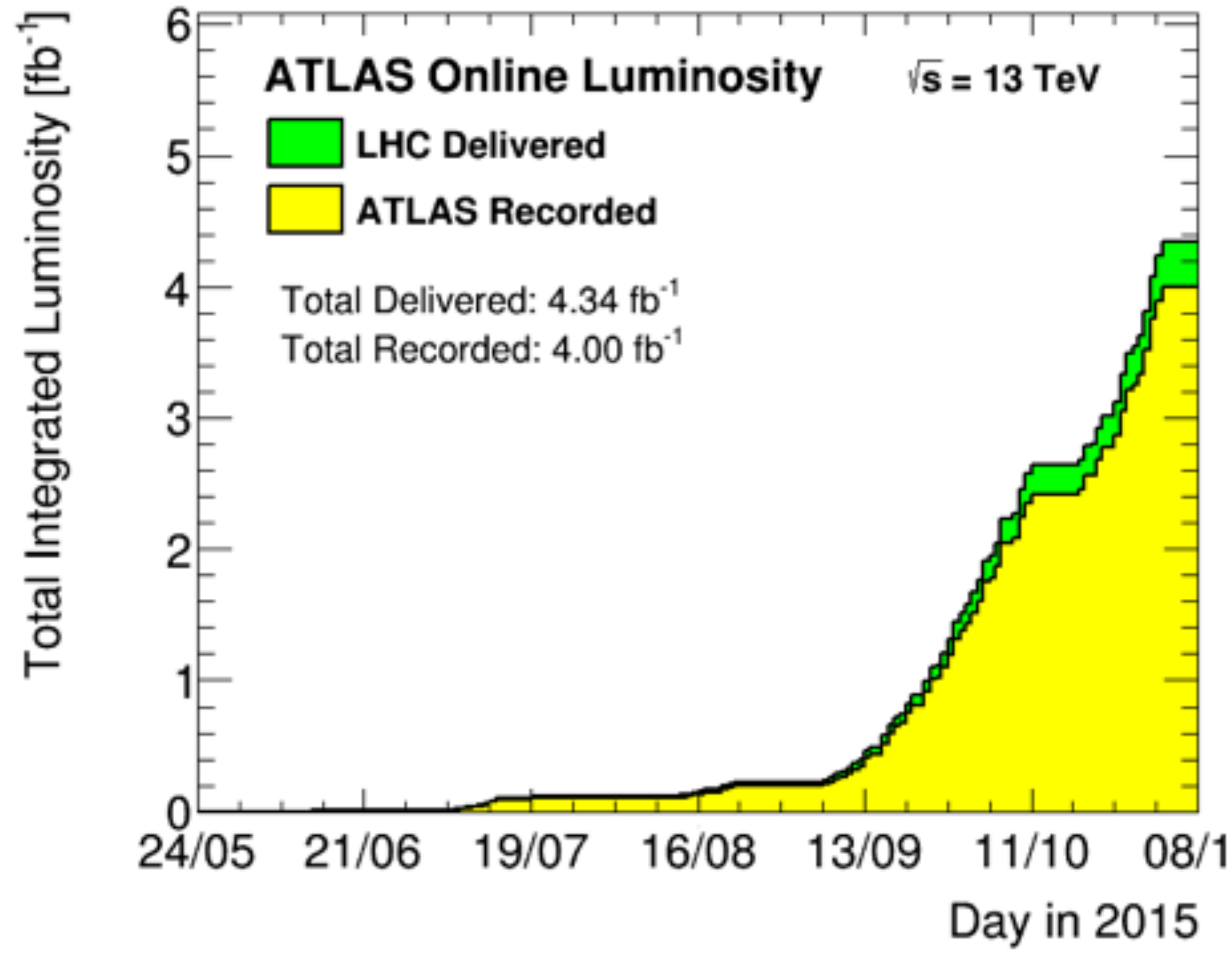
Expected Improvements For Run 2

LHC Run 2:

2015-2018
$\sqrt{s}$ = 13 TeV
100 fb^{-1}
μ = 50

→ Access processes with smaller cross-sections and/or higher mass





2015 Summary:

- 4 fb^{-1} collected (3.34 fb^{-1} after data quality requirements).
- Expect to have slightly better sensitivity to $X \rightarrow hh \rightarrow bb\tau\tau$ process than in Run 1 with the 2015 dataset.

Expected Improvements For Run 2

- Include fully hadronic tau-tau decay channel.
  - Similar sensitivity to lepton-hadron channel.
  - Fully leptonic channel adds very little, but can be useful as a cross-check.
- Further analysis optimisation.
- Improved object identification for Run 2.

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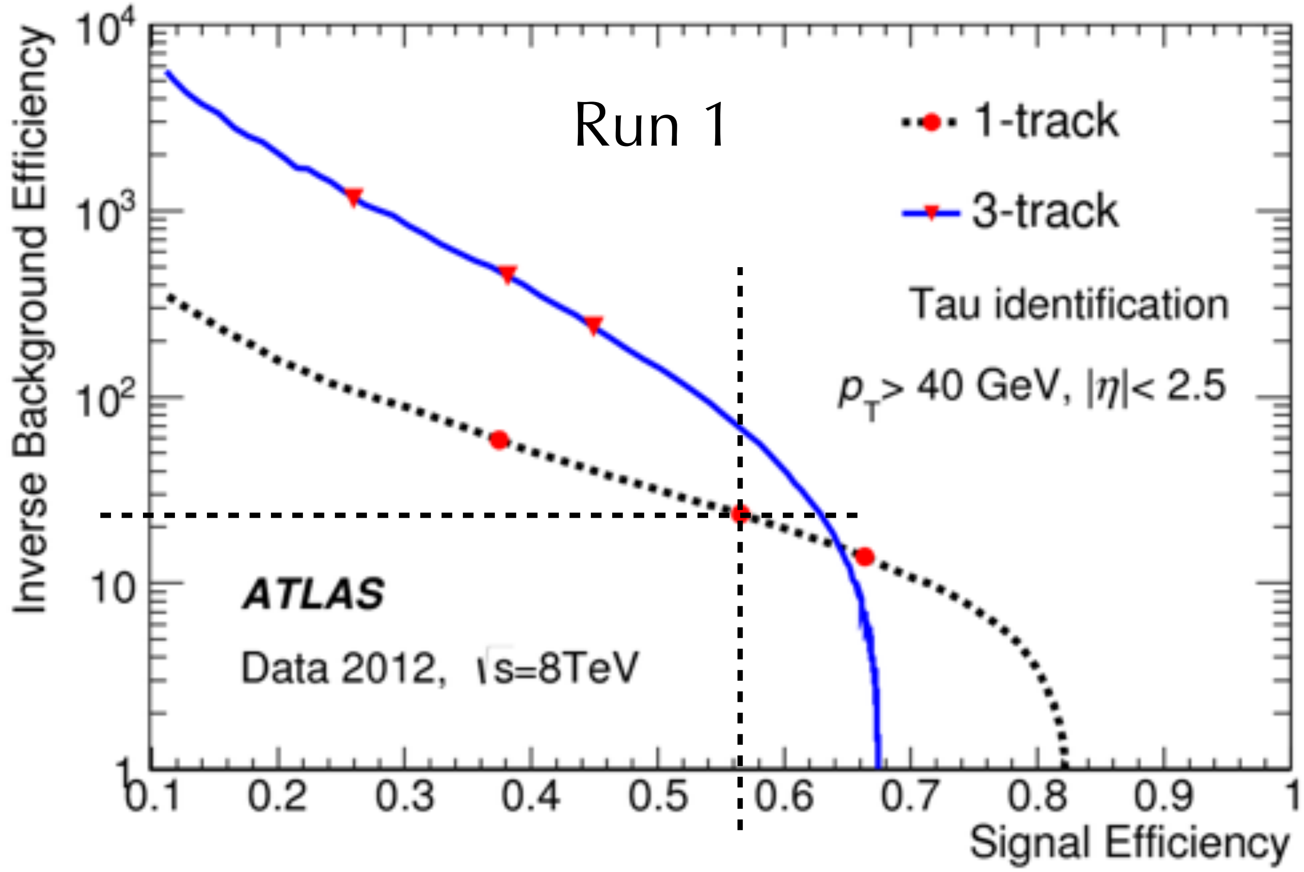
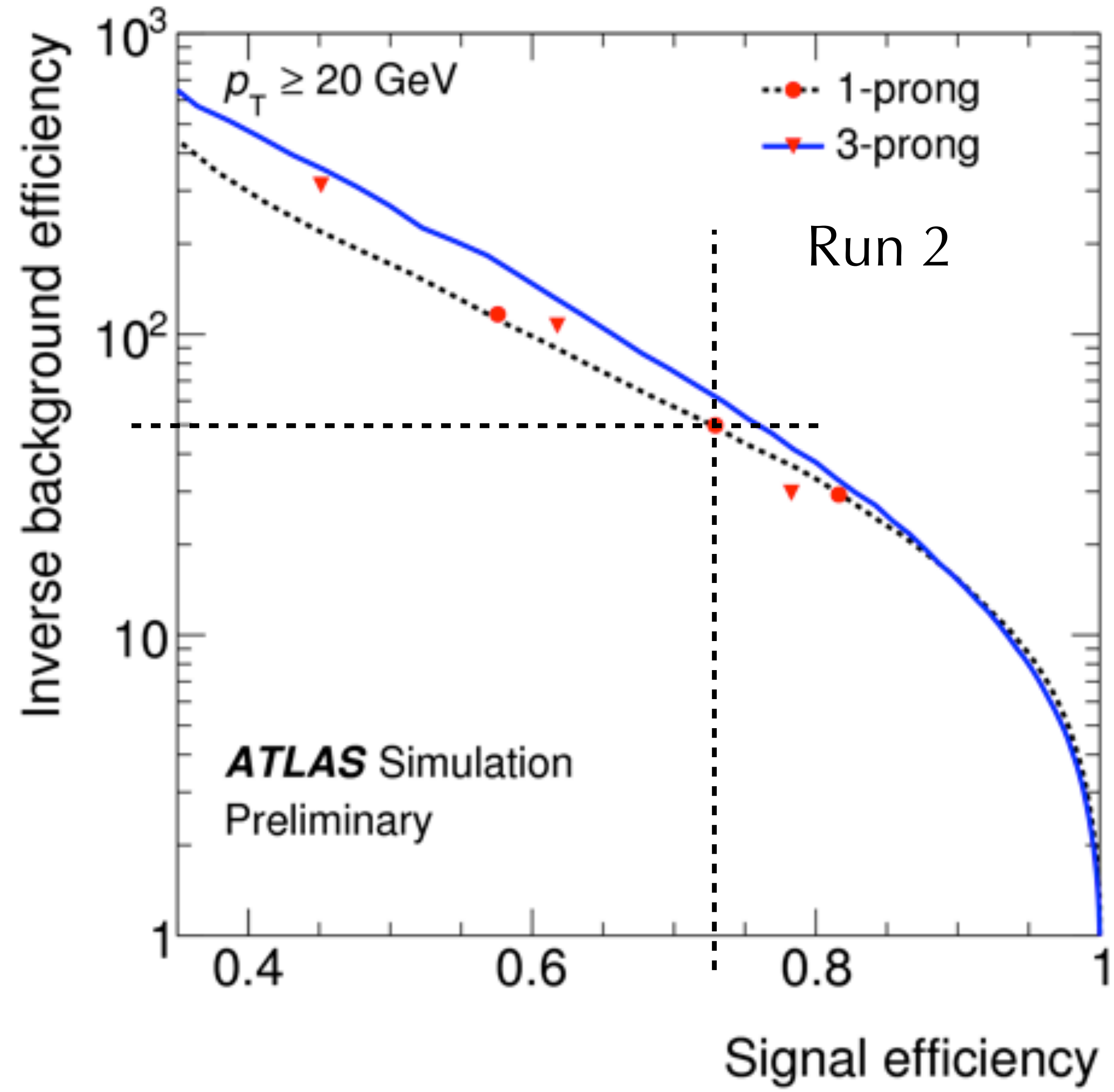
  - Taus





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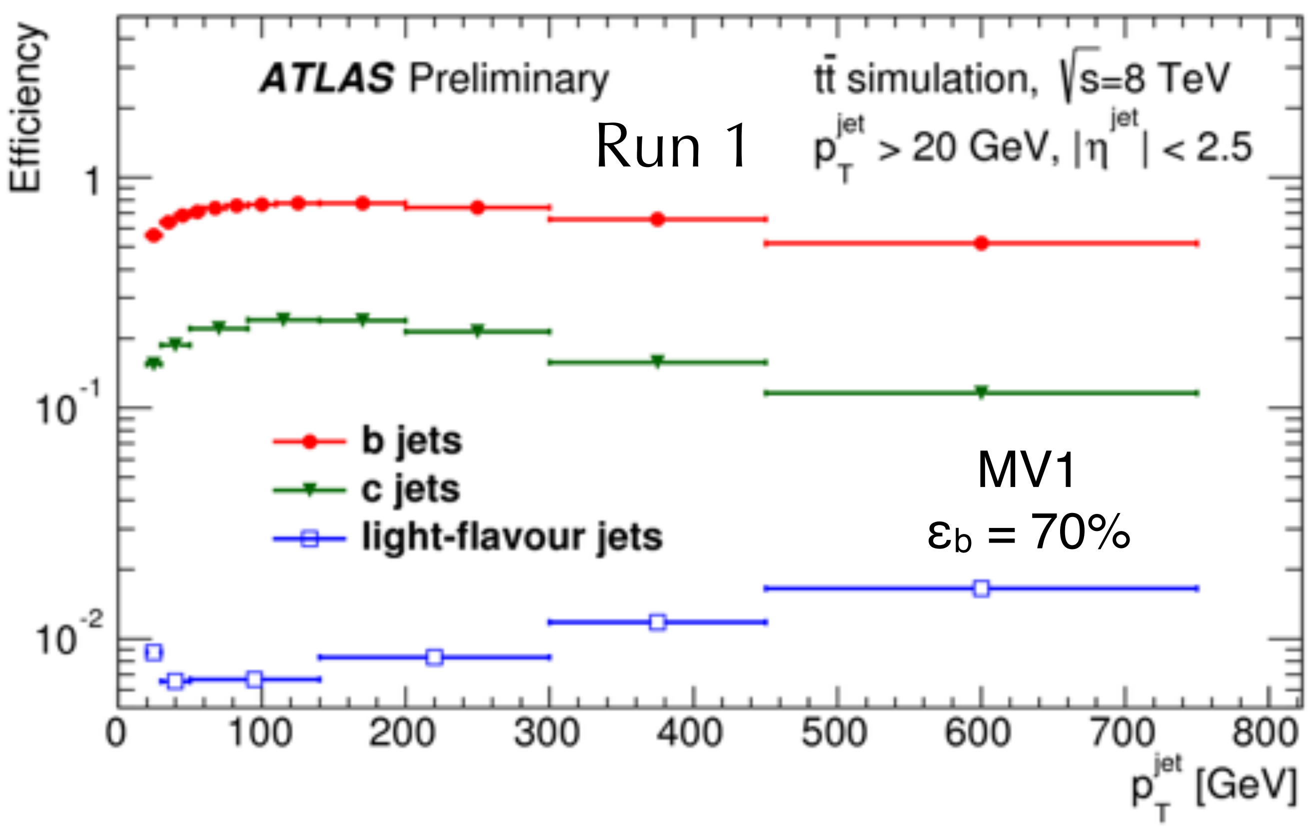
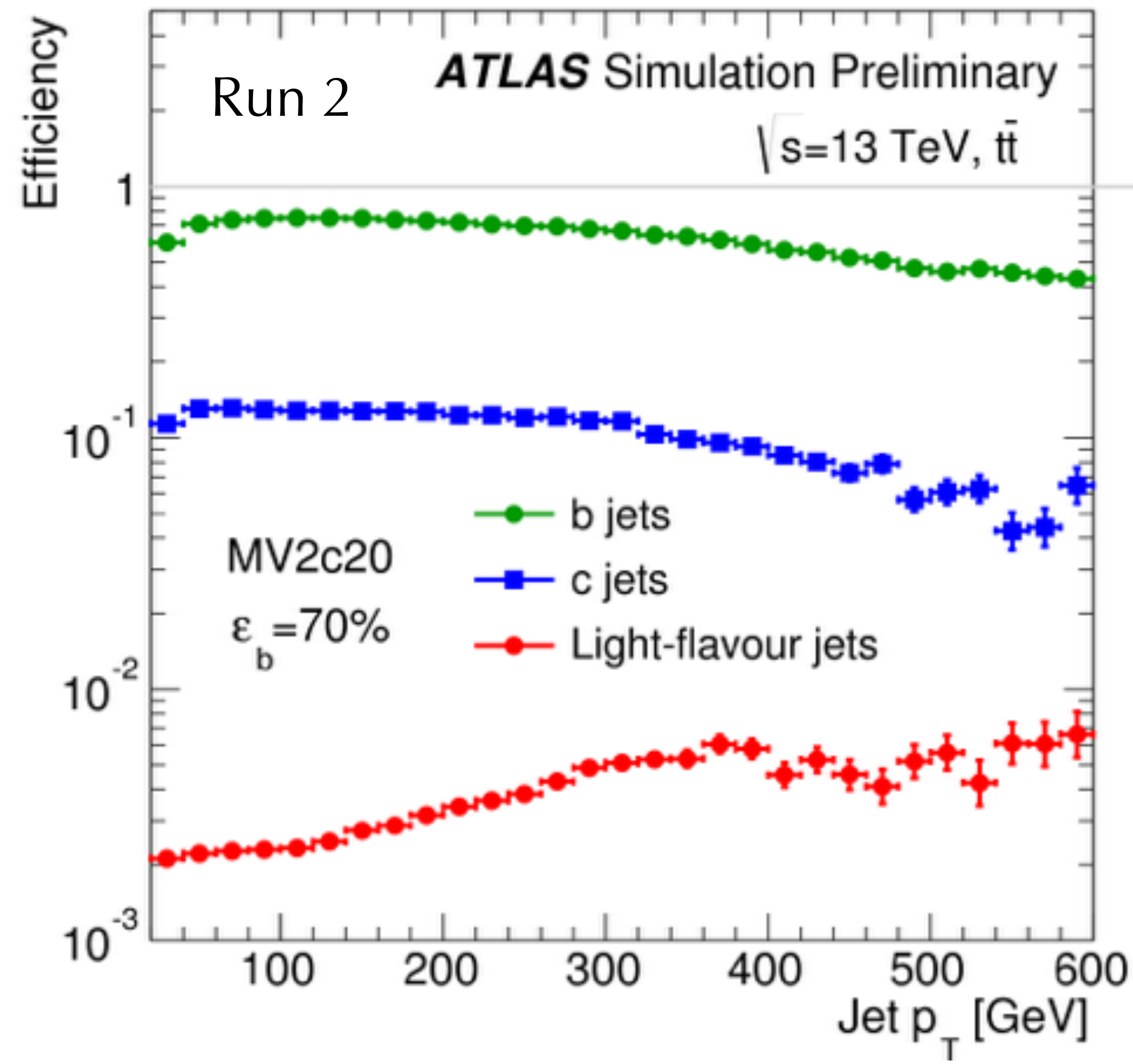
  - Taus
  - b-jets



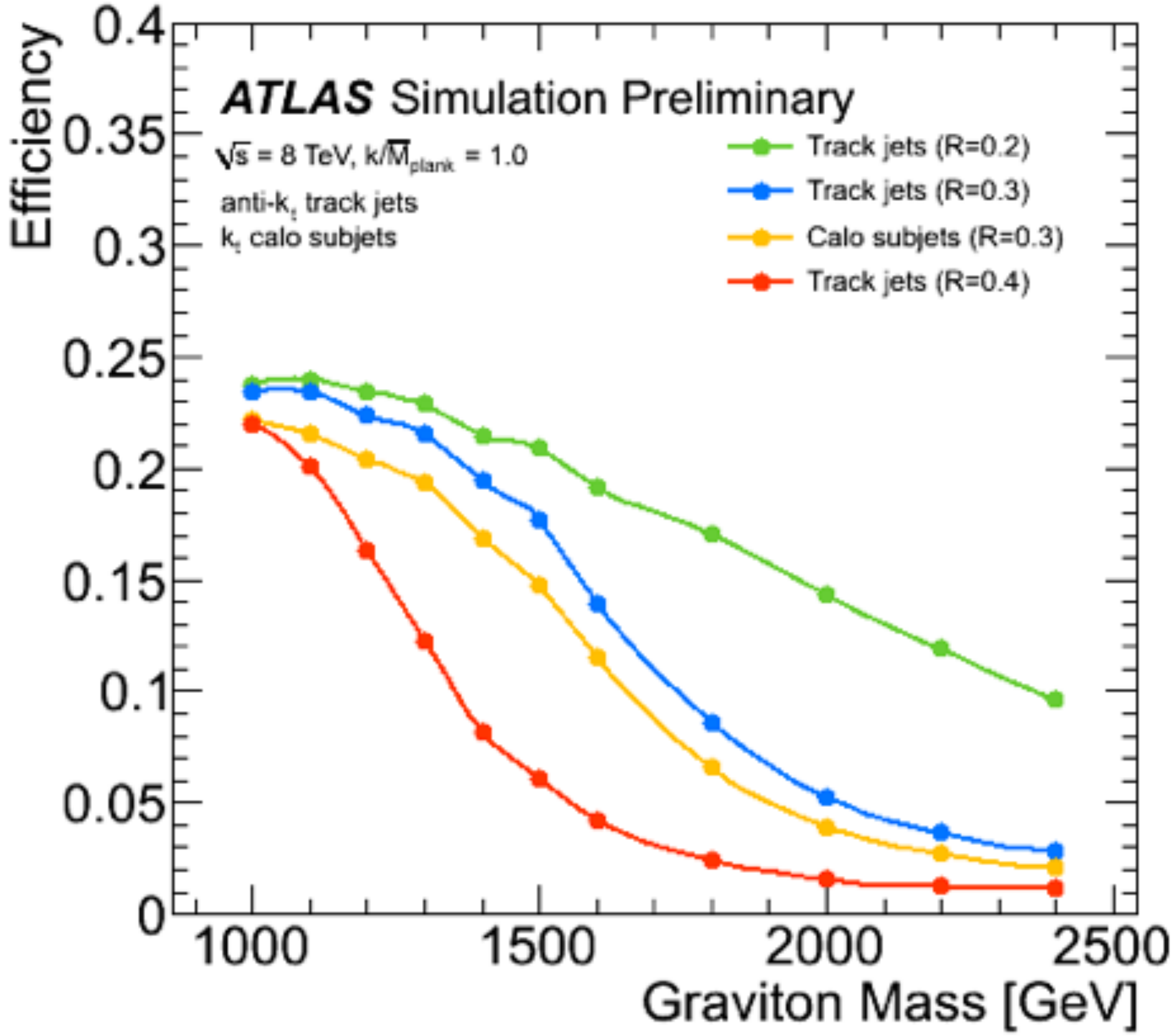


Expected Improvements For Run 2

- Dedicated analysis using sub-structure techniques to reconstruct boosted tau and b-jet pairs will follow later in 2016.

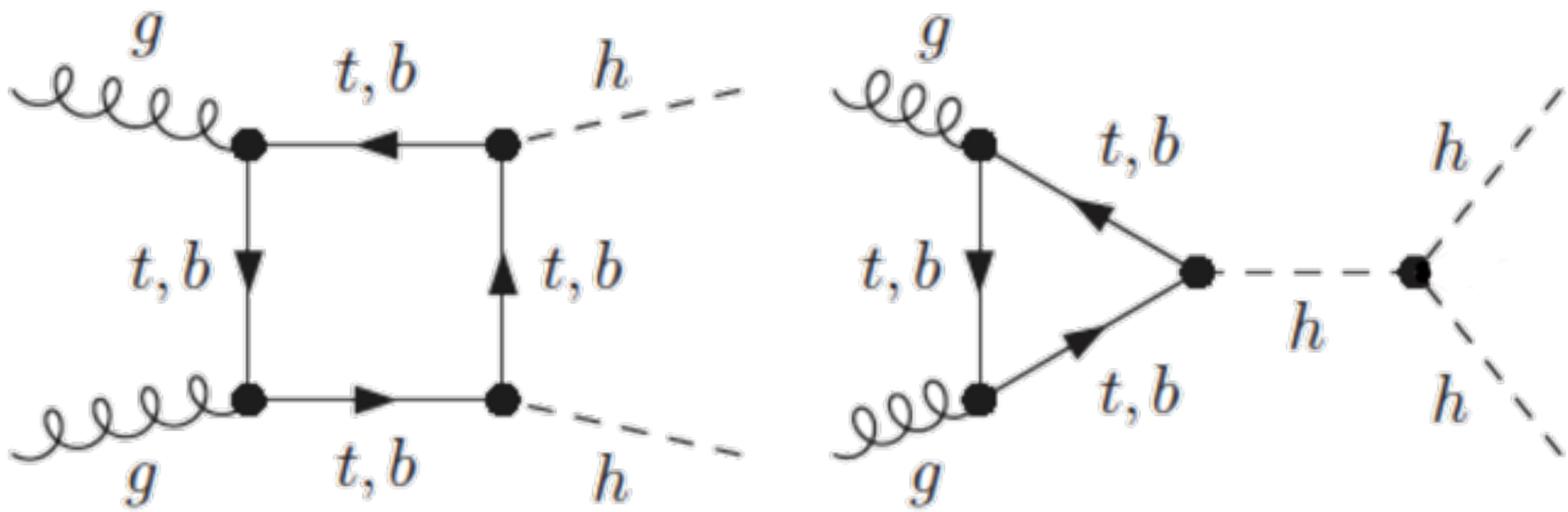
- Current analysis has a natural end-point of ~1 TeV, where $\Delta R(\tau,\tau)$ ~0.4 and tau ID fails.
  - Normal tau ID relies on an isolation annulus ($0.2 < \Delta R < 0.4$) so fails if the taus are too close together.
  - Dedicated boosted tau-pair finding algorithm to recover these events and extend mass reach of the analysis.

- b-tagging performance also degrades as a function of $\Delta R(b,b)$.
  - Less of a 'cliff' than tau ID.
  - Dedicated tagger for finding boosted pairs of b-jets developed.
  - $HH \rightarrow bbbb$ analysis shows significant gains when using it.

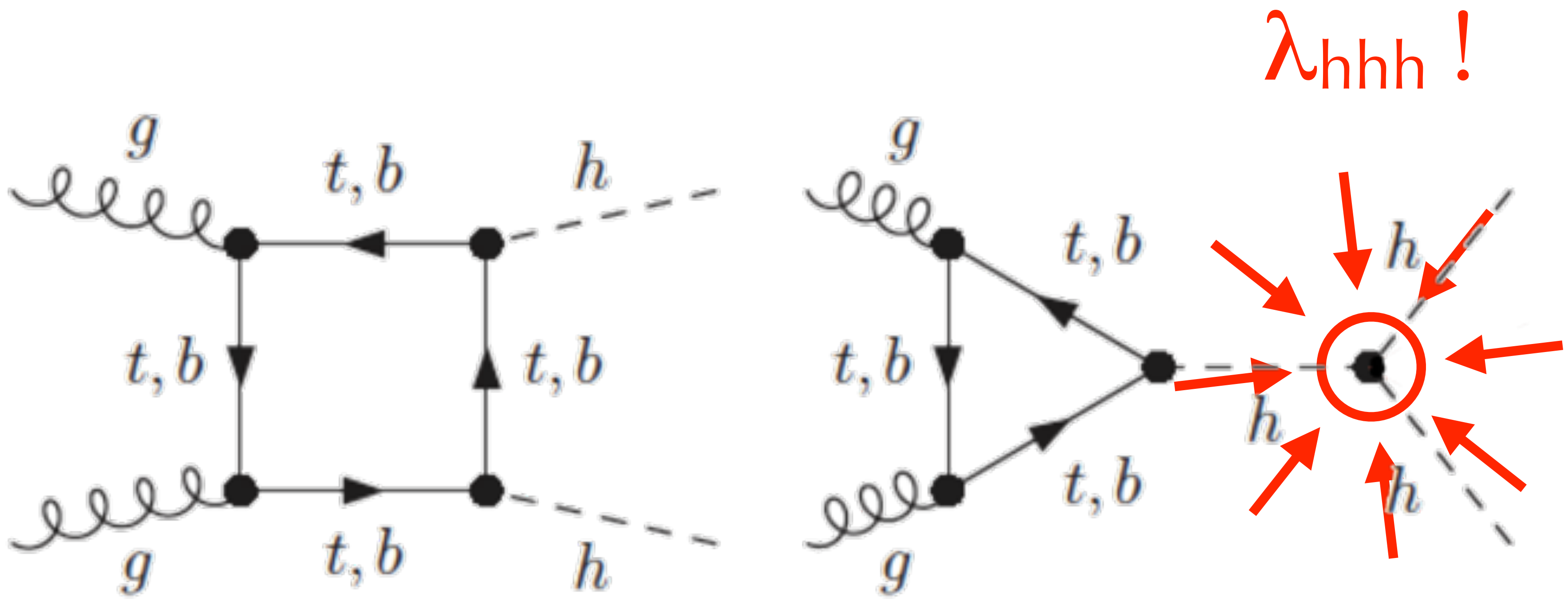



HL-LHC
QUITE A LONG WAY OFF
(2023-2035-ISH)

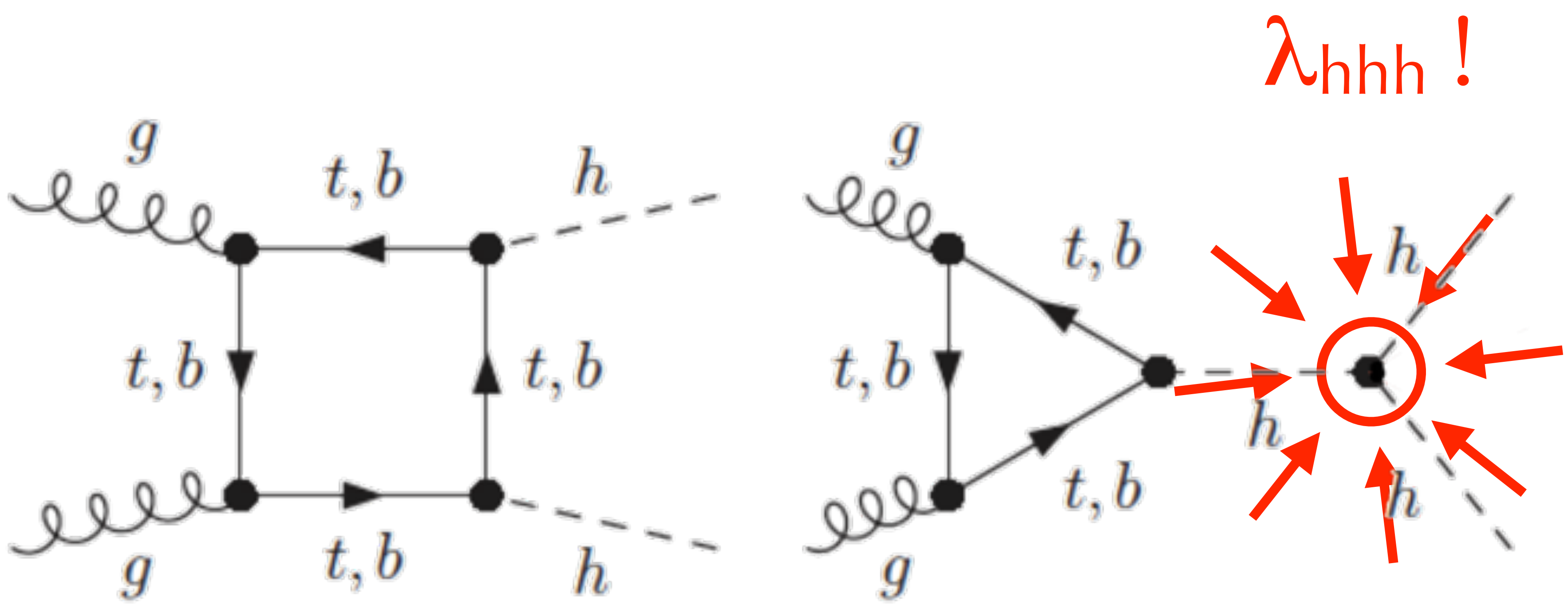
SM Higgs Pair Production



SM Higgs Pair Production

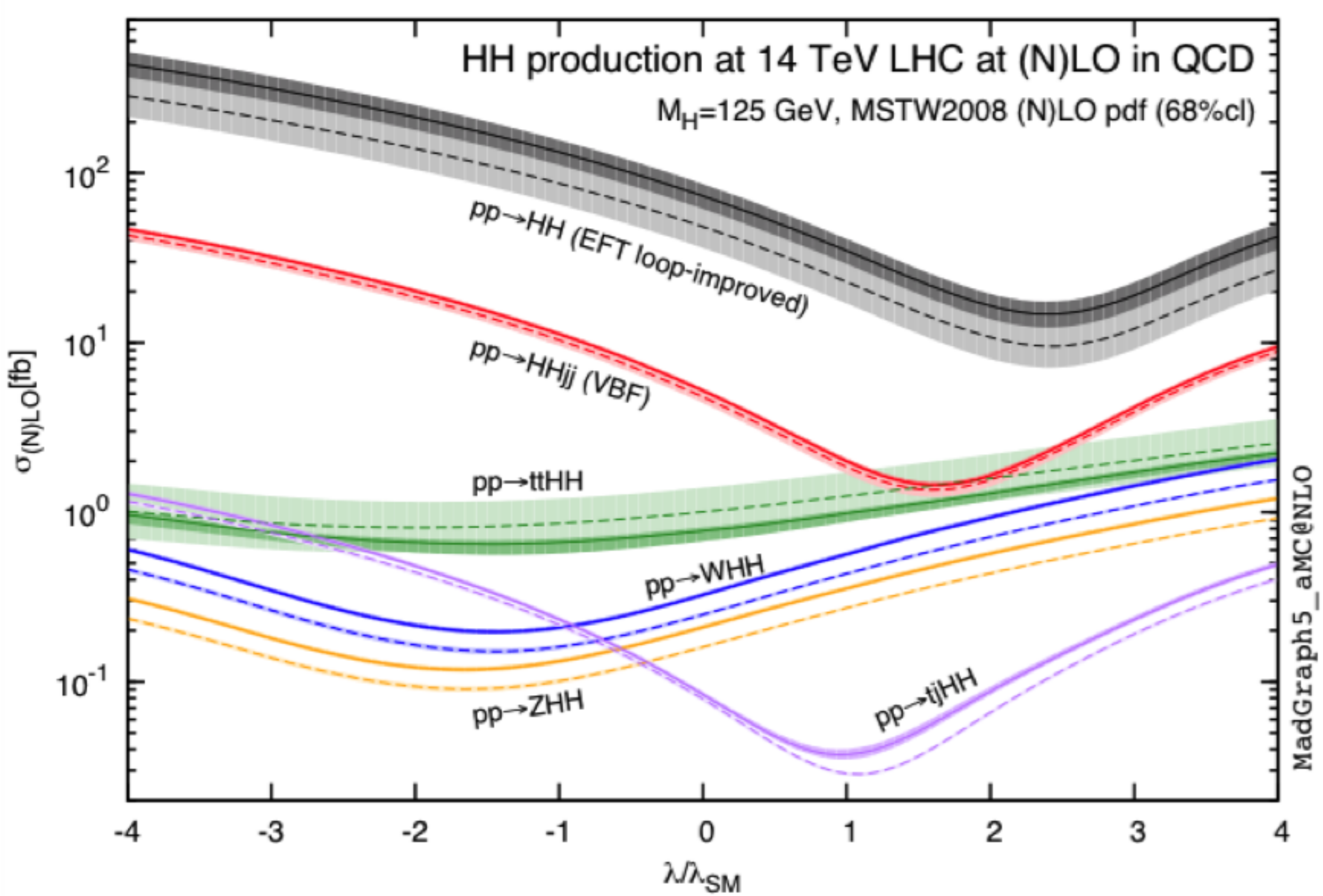


SM Higgs Pair Production



- Higgs self-coupling crucial check of EWSB mechanism.
- Possibly *the* most challenging measurement at the LHC!
- Direct measurement of the Higgs trilinear self-coupling (λ_{HHH}) can be made by studying Higgs pair-production.
- Need to dis-entangle top box-diagram and diagram containing the HHH vertex…
- Destructive interference with diagrams not containing the HHH vertex.
  - Box diagram dominates in boosted events.
  - Absolutely crucial to push down to lower p_T's in order to access λ_{HHH}.

SM Higgs: Pair Production



- For $\lambda_{HHH}/\lambda_{HHH}^{SM}$ = 0/1/2, cross-section = 71/34/16 fb.
- With 3000 fb^{-1} a ~3σ combined measurement by ATLAS+CMS should be possible.

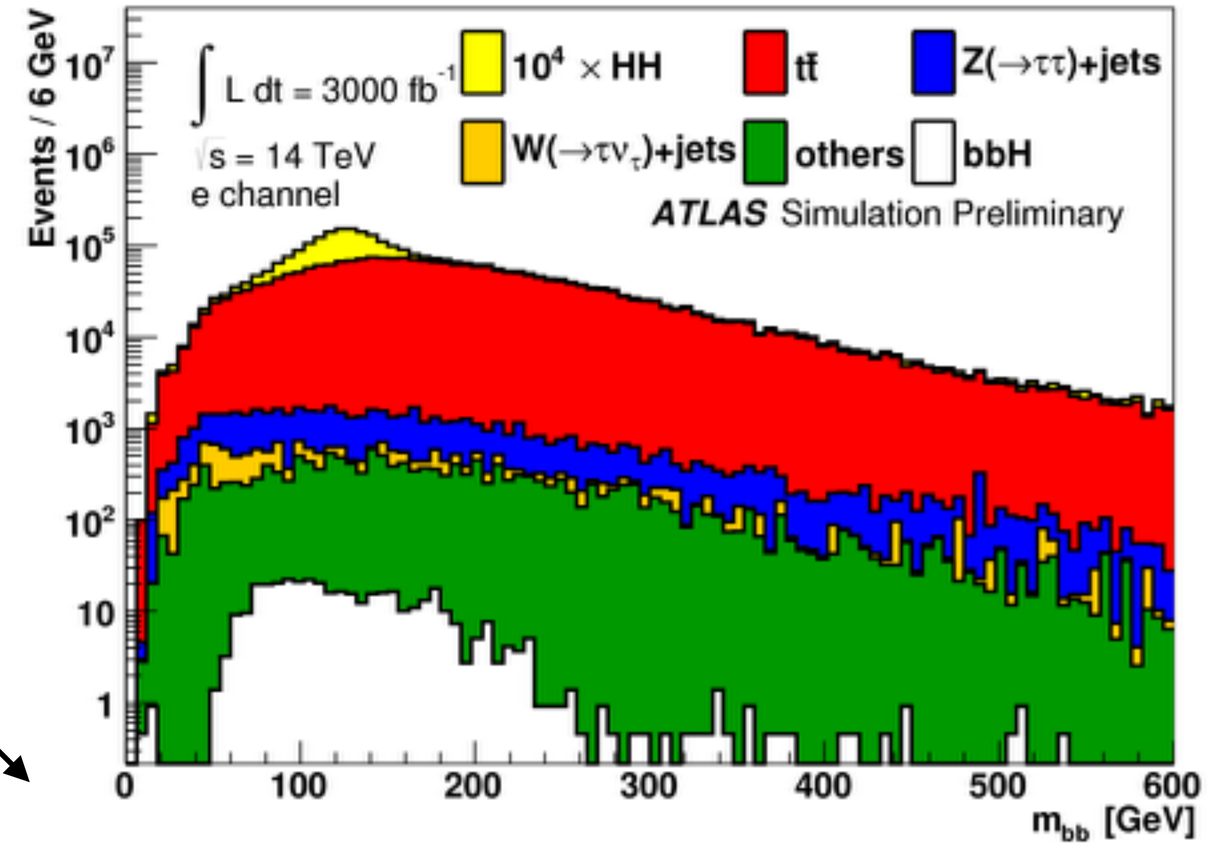
SM HH→bb$\tau\tau$ Sensitivity Study

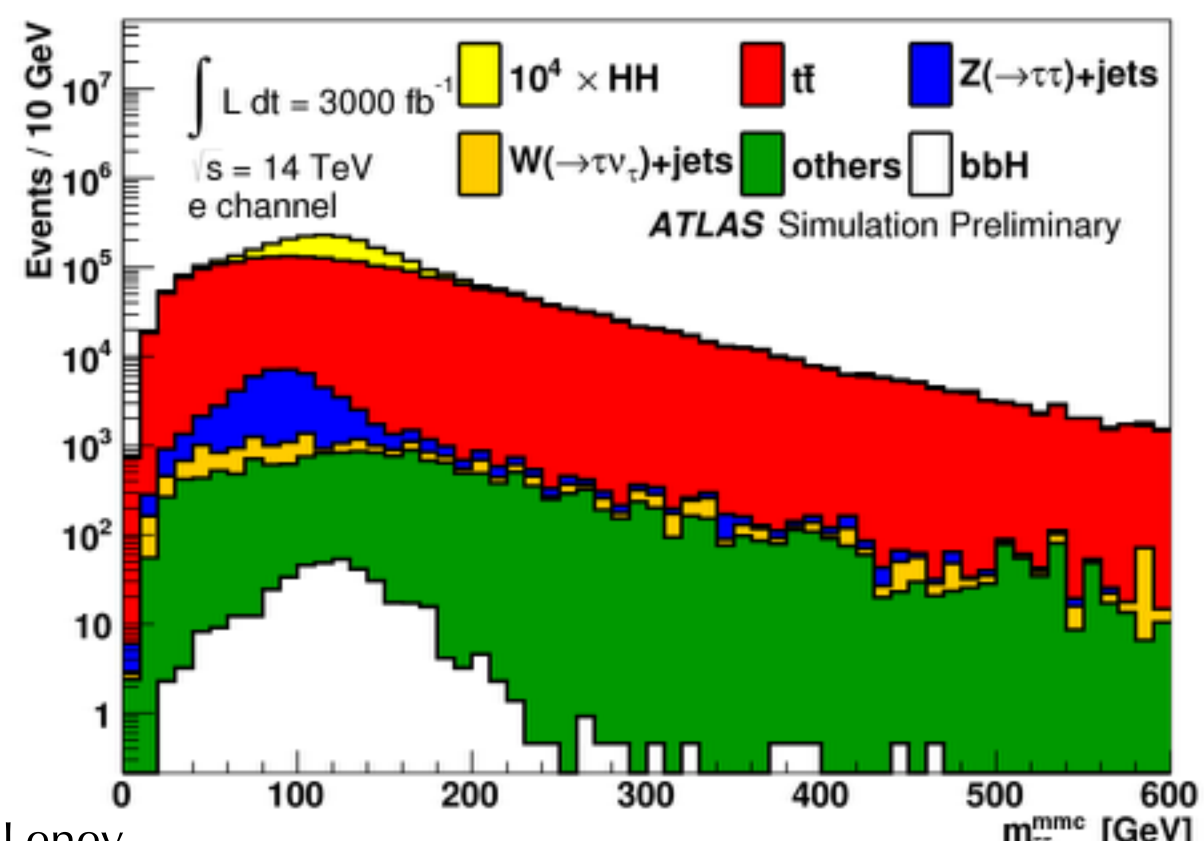
ATL-PHYS-PUB-2015-046

- Truth-level, `cut-and-count' study for first estimate of sensitivity.
  - Detector response parameterised.
  - More sophisticated analyses (using MVAs) will be necessary.
- Assume 3000 fb^{-1} data, $\sqrt{s}$ = 14 TeV, and 140 proton-proton collisions per bunch-crossing.
- All tau-tau decay modes considered:
  - Fully leptonic ($\tau_\ell\tau_\ell$)
  - Semi-leptonic ($\tau_\ell\tau_h$)
  - Fully hadronic ($\tau_h\tau_h$)
- SM Higgs processes that have been negligible backgrounds in the new physics searches so far become more important.
  - e.g. VH, ttV, ttH
- Higgs bosons produced by λ_{HHH} process have low p_T.
  - Those produced via top box-diagram are more boosted.
  - Lower p_T objects harder to separate from multi-jets backgrounds.
  - Need to find the right balance…

Event Selection

	Example Cut Value*
m_{bb} mass window	$95 < m_{bb} < 145$ GeV
$m_{\tau\tau}$ mass window	$90 < m_{\tau\tau} < 160$ GeV
$p_T(bb)$	$p_T(bb) > 200$ GeV
bb-pair separation	$\Delta R(bb) < 1.0$
Transverse mass	$m_T < 80$ GeV
Stransverse mass	$m_{T2} > 180$ GeV





* Slight variations in exact cut values between channels

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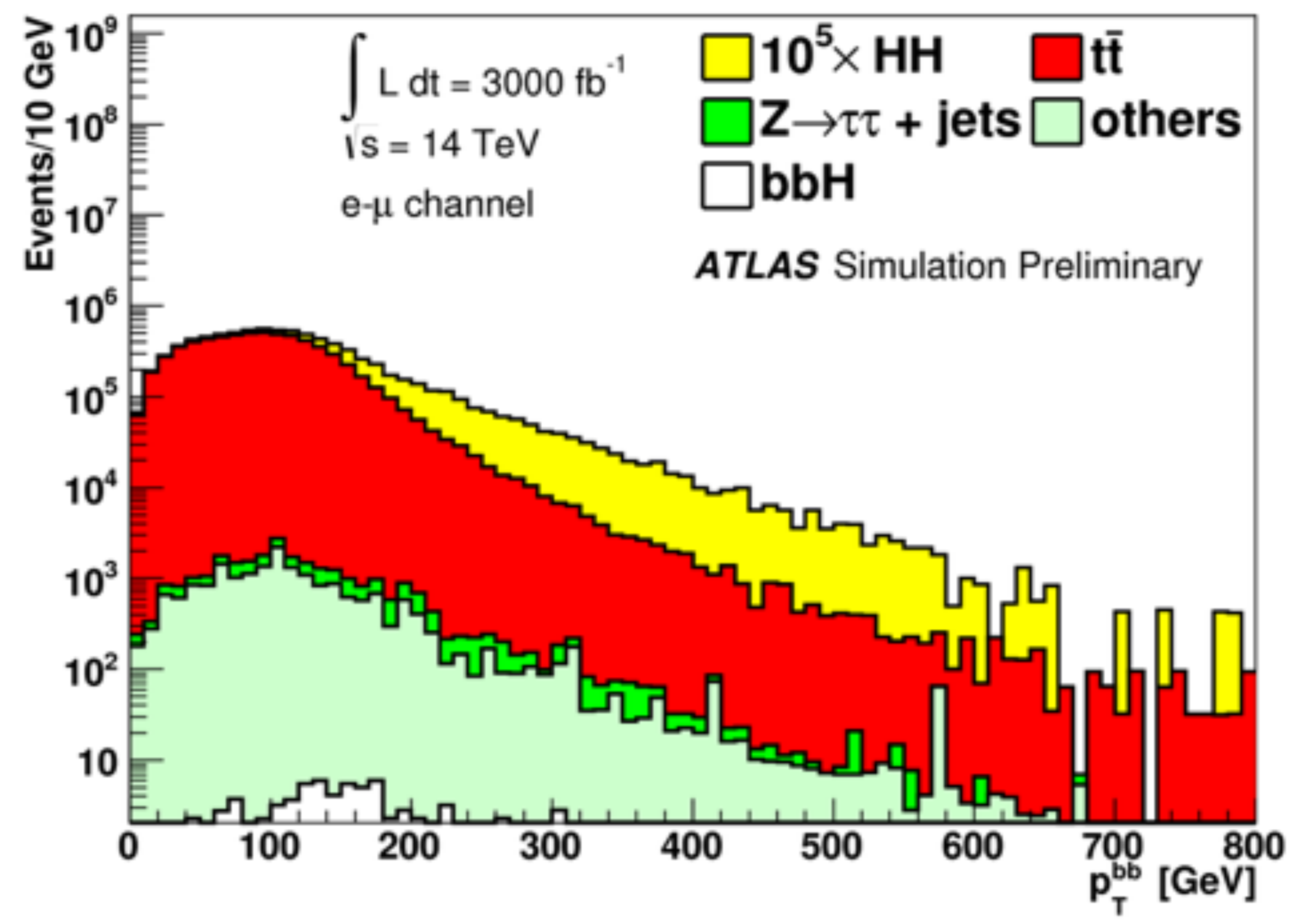

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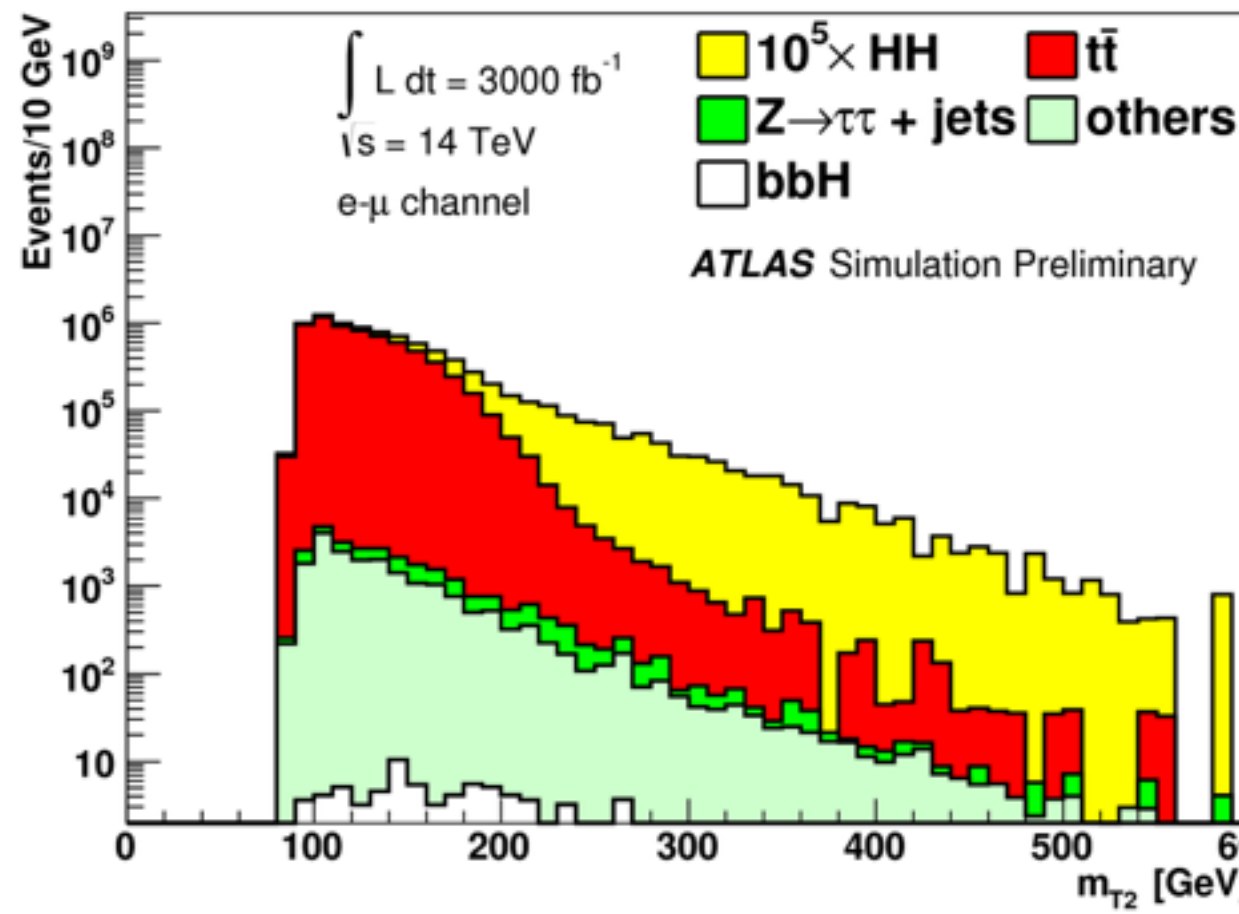
* Slight variations in exact cut values between channels

<u>Stransverse mass</u>: Generalisation of the transverse mass when applied to signatures with two (or more) invisible particles in the final state.

<u>Phys.Lett. B463 (1999) 99–103</u>



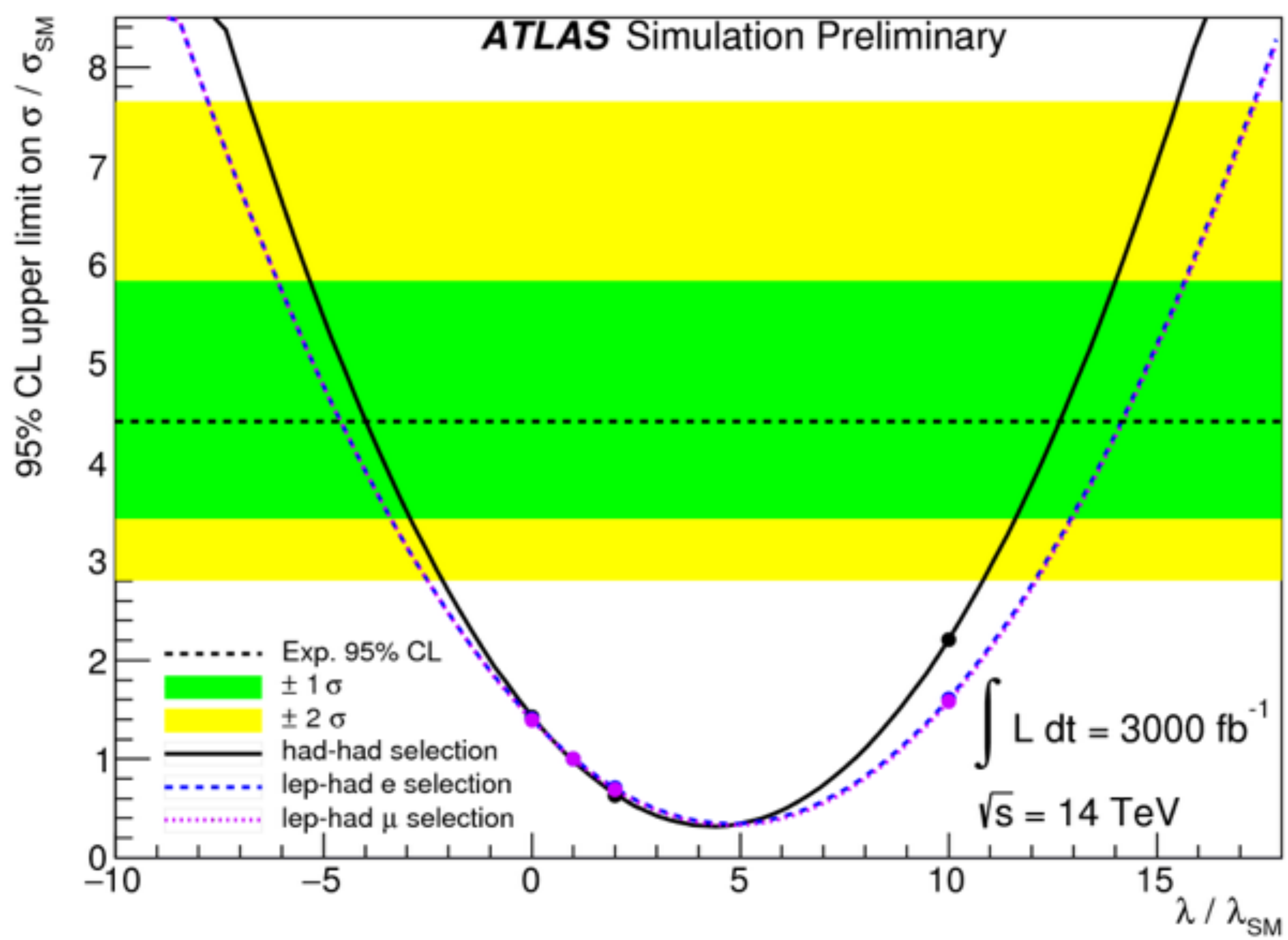
Prospects for Measuring λ_{HHH} at the HL-LHC

Channel	Significance	Combined in channel	Total combined
e + jets	0.31	0.43	0.60
μ+jets	0.30		
$\tau_{\rm had}\tau_{\rm had}$	0.41	0.41	

$\tau_\ell\tau_\ell$ channels order of magnitude less sensitive than $\tau_\ell\tau_h$ or $\tau_h\tau_h$ channels.

- Use of more sophisticated analysis techniques can improve sensitivity.
- Combination across many channels will be necessary.
- Large correlation between total di-Higgs production cross-section and λ_{HHH}.
  - λ_{HHH} better studied using shape analysis of key observables.

σ / σ_{SM} as a function of λ / λ_{SM}



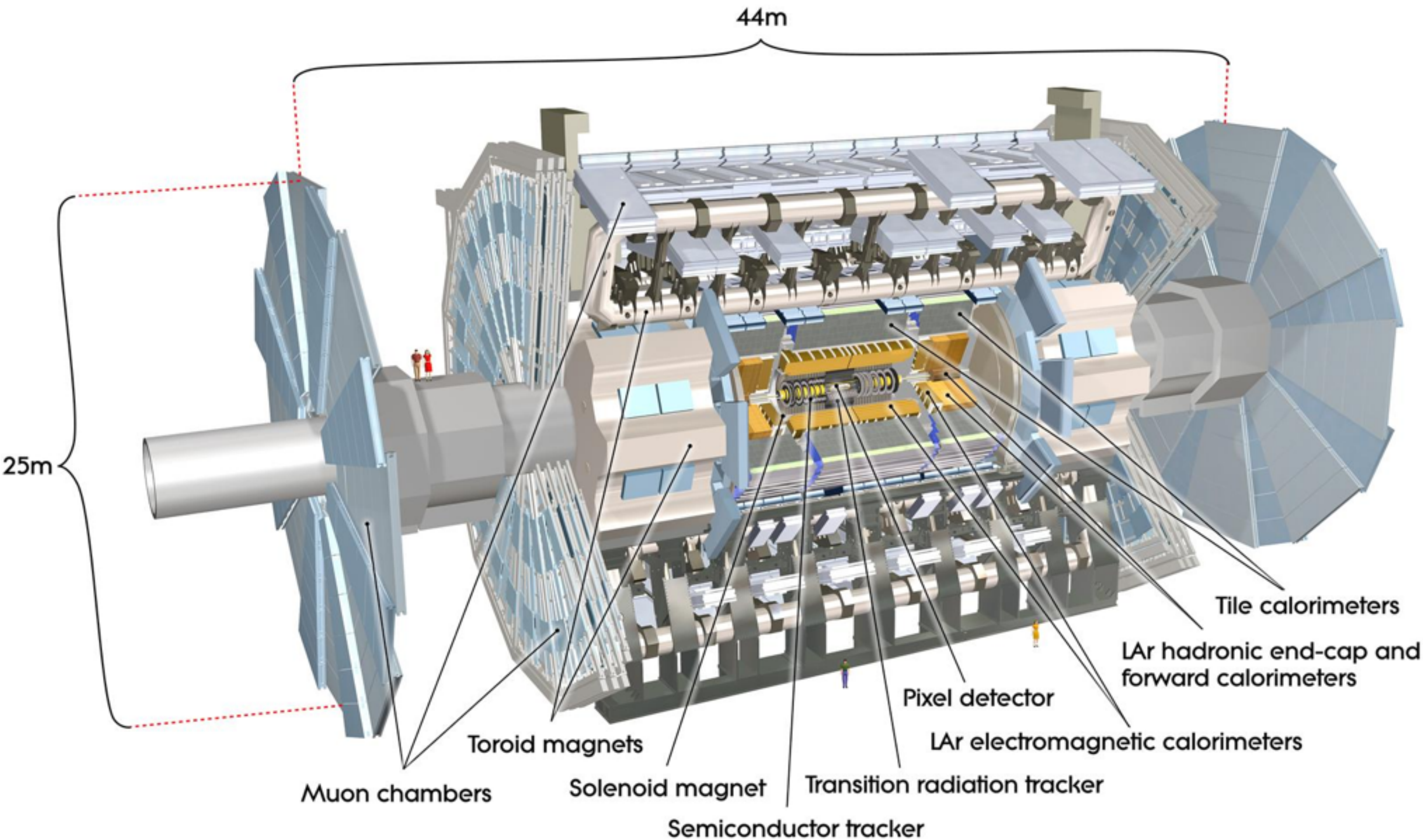
Summary & Conclusions

- Di-Higgs physics is a new and exciting avenue for searching for new physics.
  - Many new physics models predict enhanced rates, either as resonant or non-resonant production.
  - Also predicted by the SM where it will be a crucial test of the Higgs mechanism.
  - $bb\tau\tau$ is a promising channel, particularly in the SM/lower mass/non-resonant regime.
- Run 1 searches showed no signal in the $bb\tau\tau$, or any other channel.
  - Limits set on resonant and non-resonant HH production.
- Will significantly extend this reach during the LHC Run 2.
  - Even with 2015 data alone should do better than Run 1.
  - Extra analysis optimisations will improve the sensitivity further, particularly at higher masses.
- The $bb\tau\tau$ channel is a promising one for measuring di-Higgs production and λ_{HHH} at the HL-LHC.

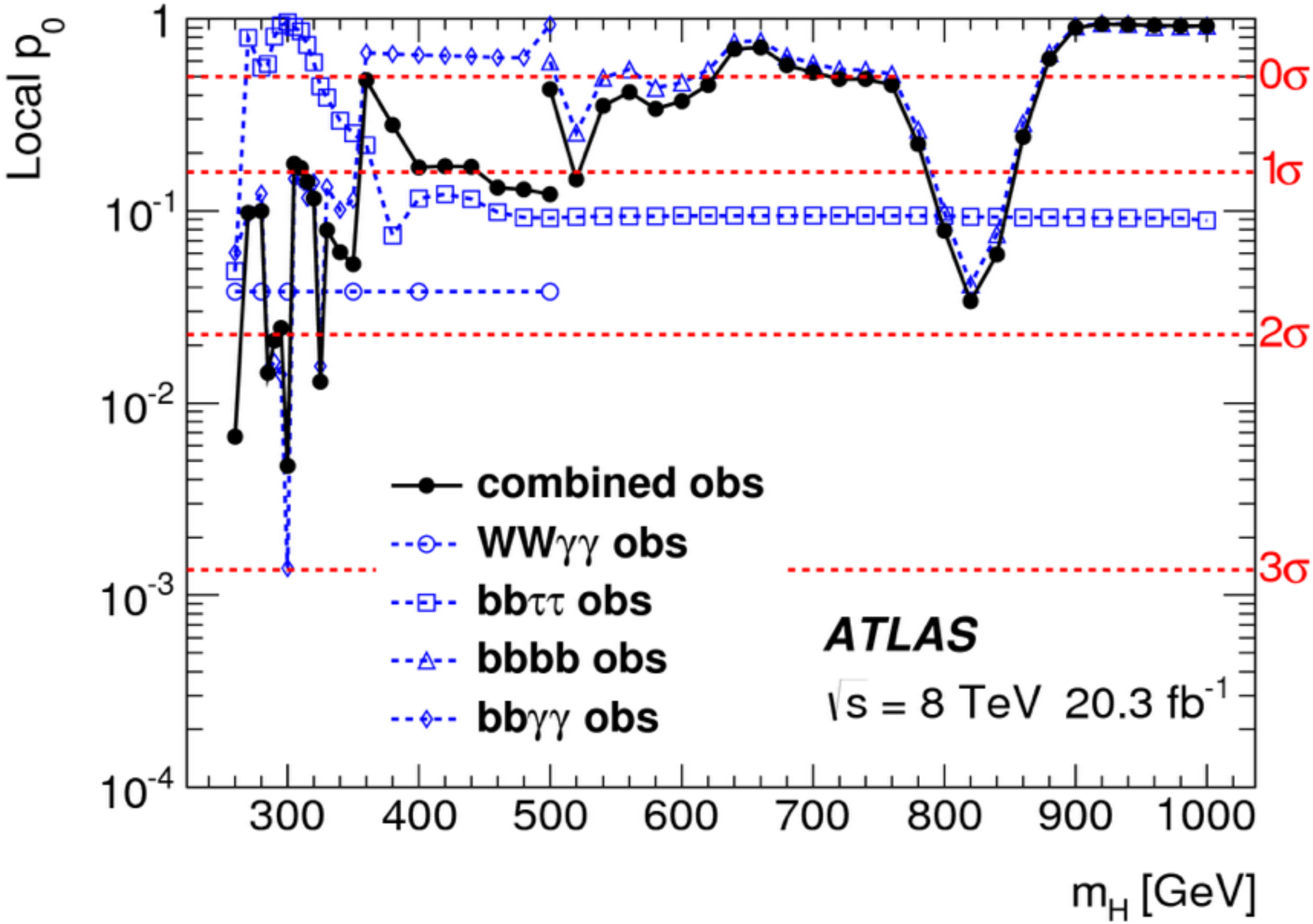
Is there anything beyond the Standard Model?

Back Up

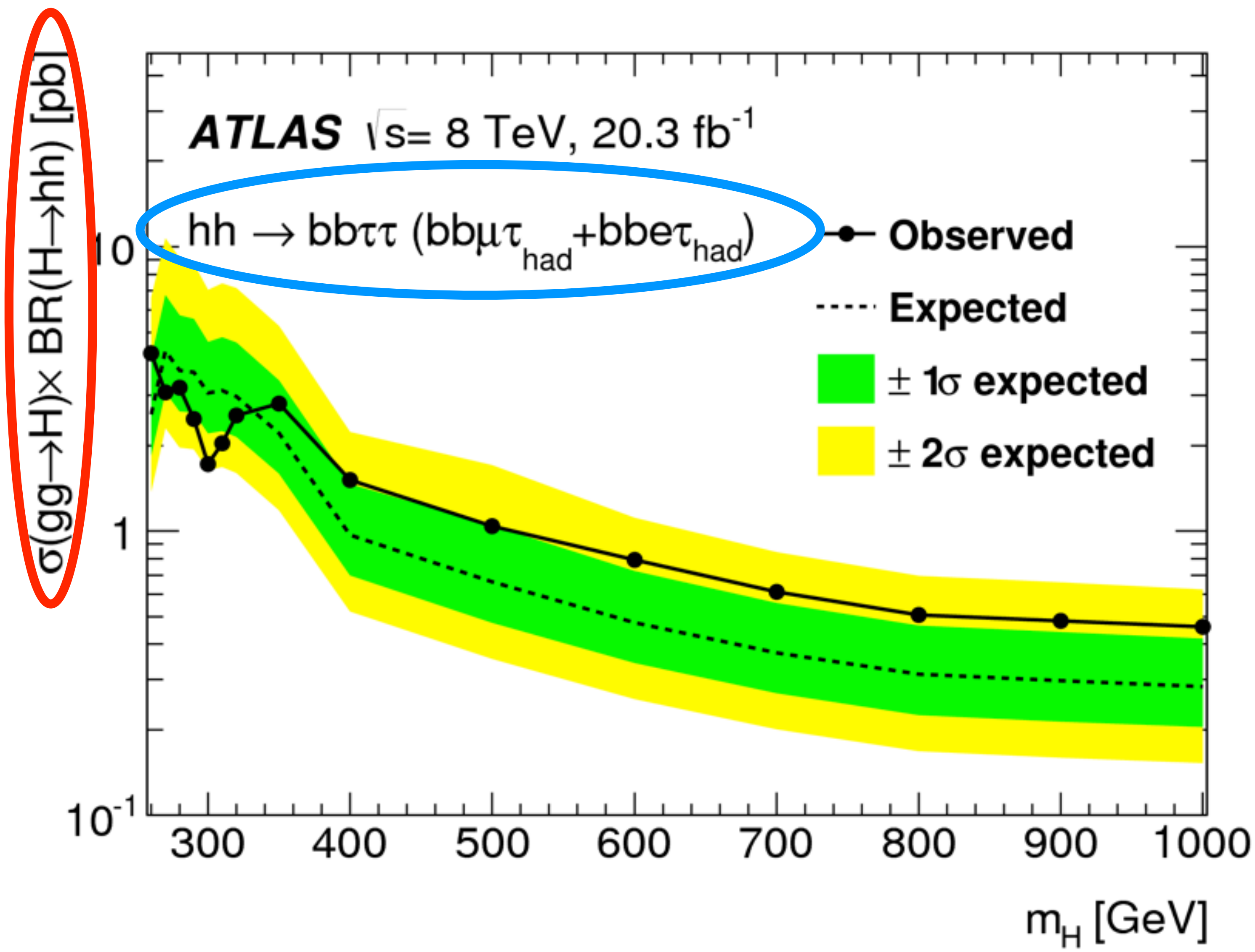
Obligatory ATLAS Detector Slide

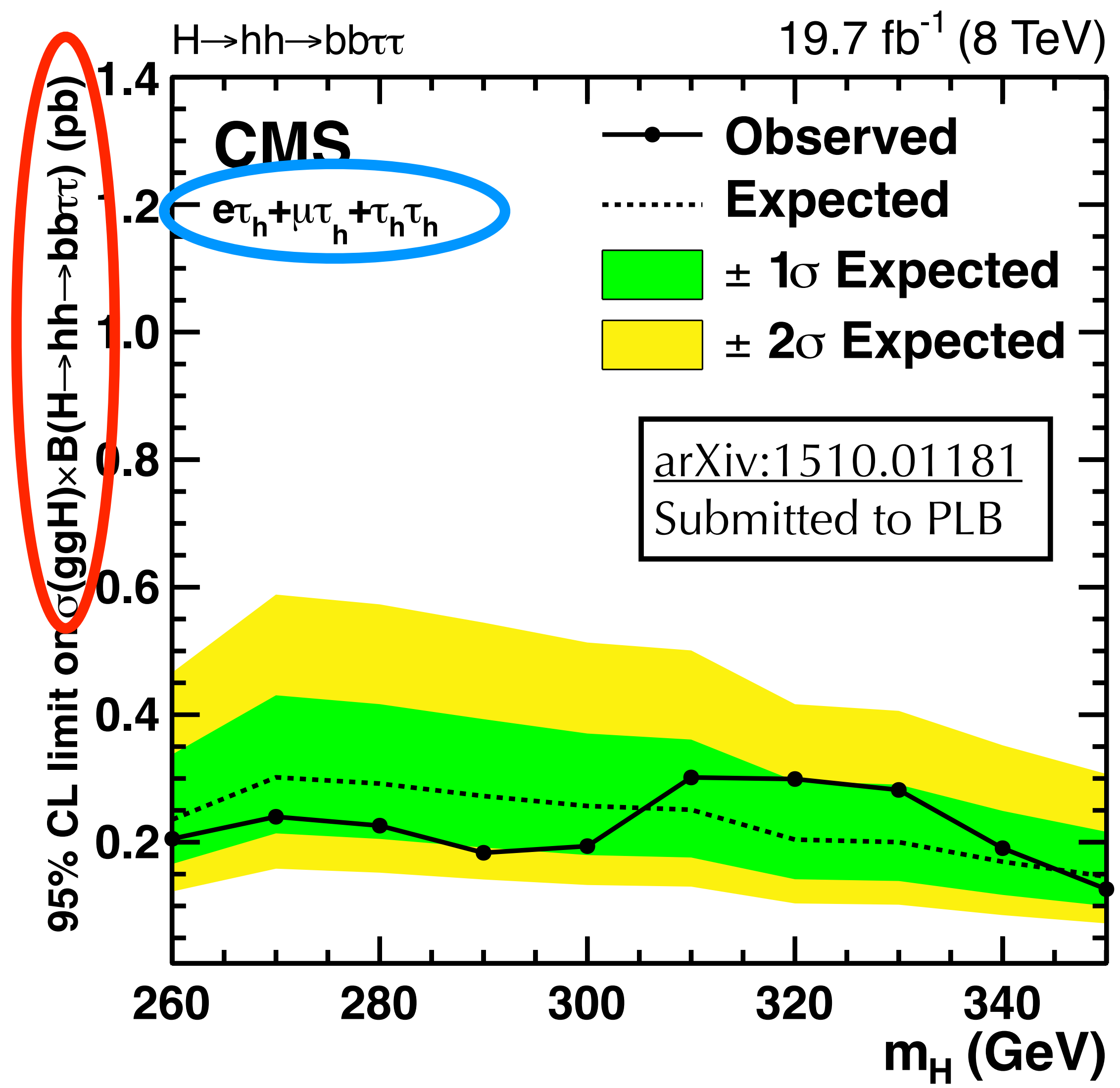


Combination With Other Channels



Resonant Analysis - Comparison with CMS



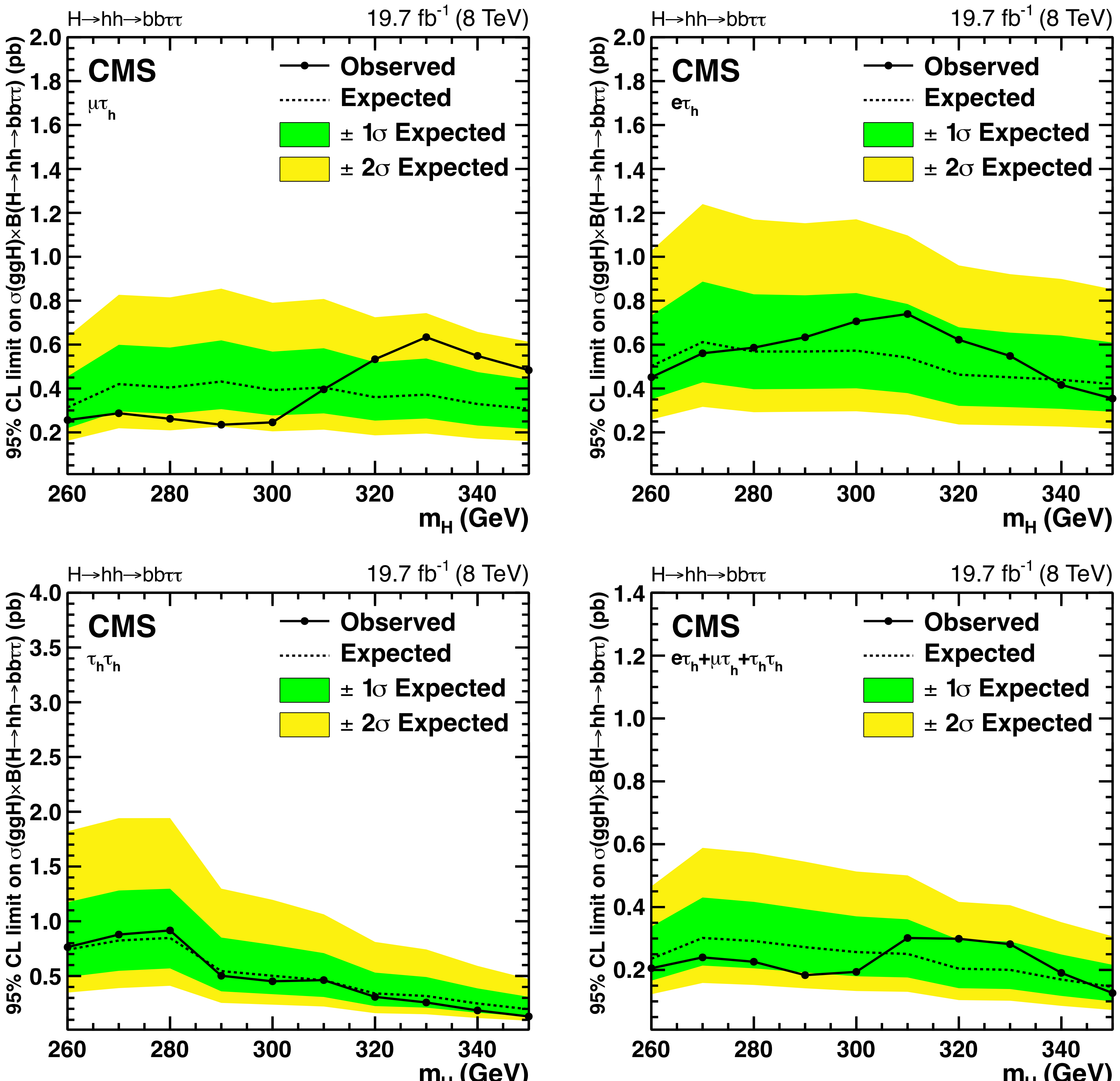


ATLAS: Only $\tau_\ell\tau_h$ channels
CMS: $\tau_\ell\tau_h$ and $\tau_h\tau_h$ channels.

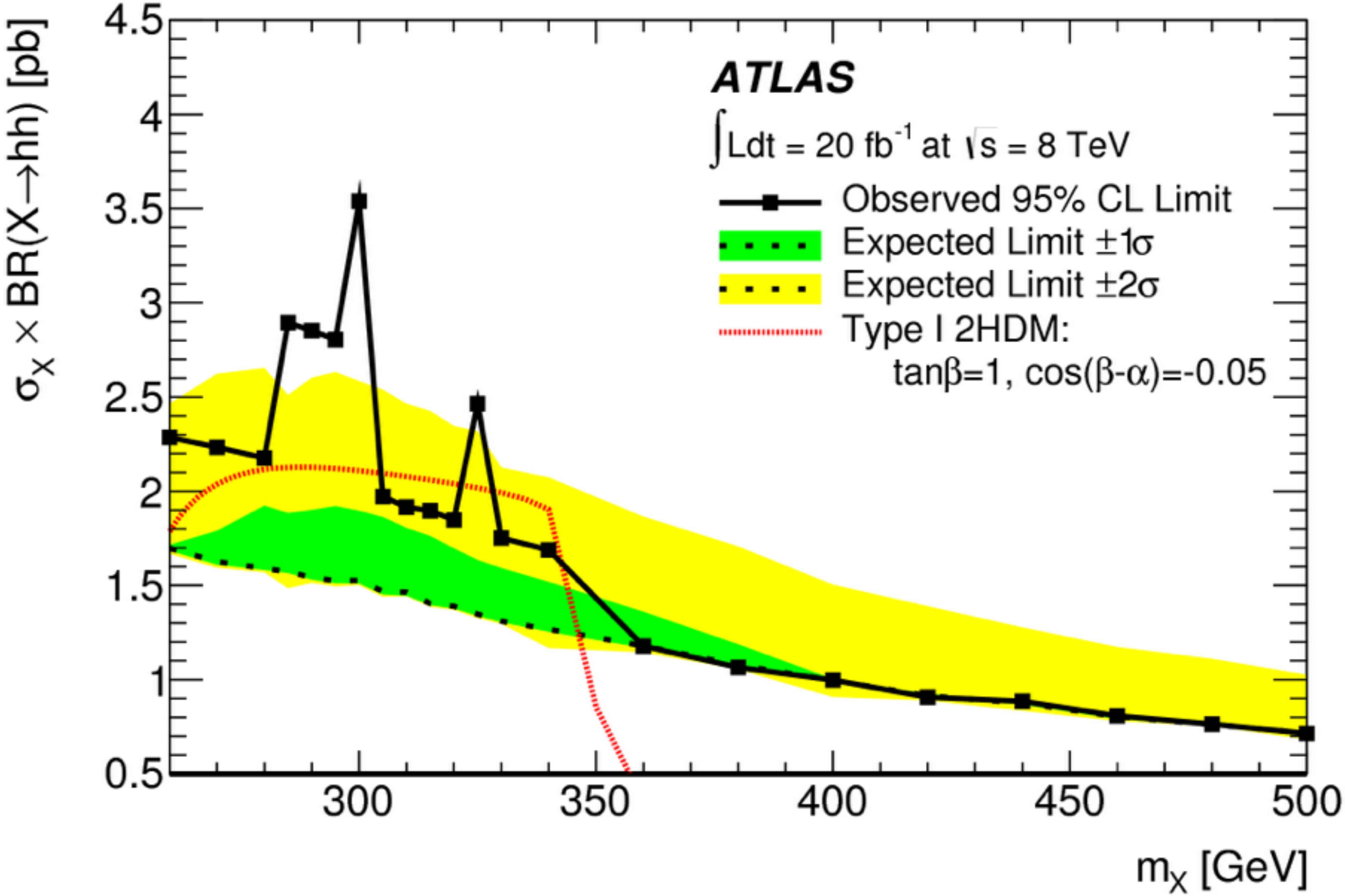
ATLAS: σxBR(H→hh)
CMS: σxBR(H→hh→bbττ)

Limit at 300 GeV:
ATLAS: 3 pb x BR(hh→bbττ) = 0.21 pb
CMS: 0.2 pb

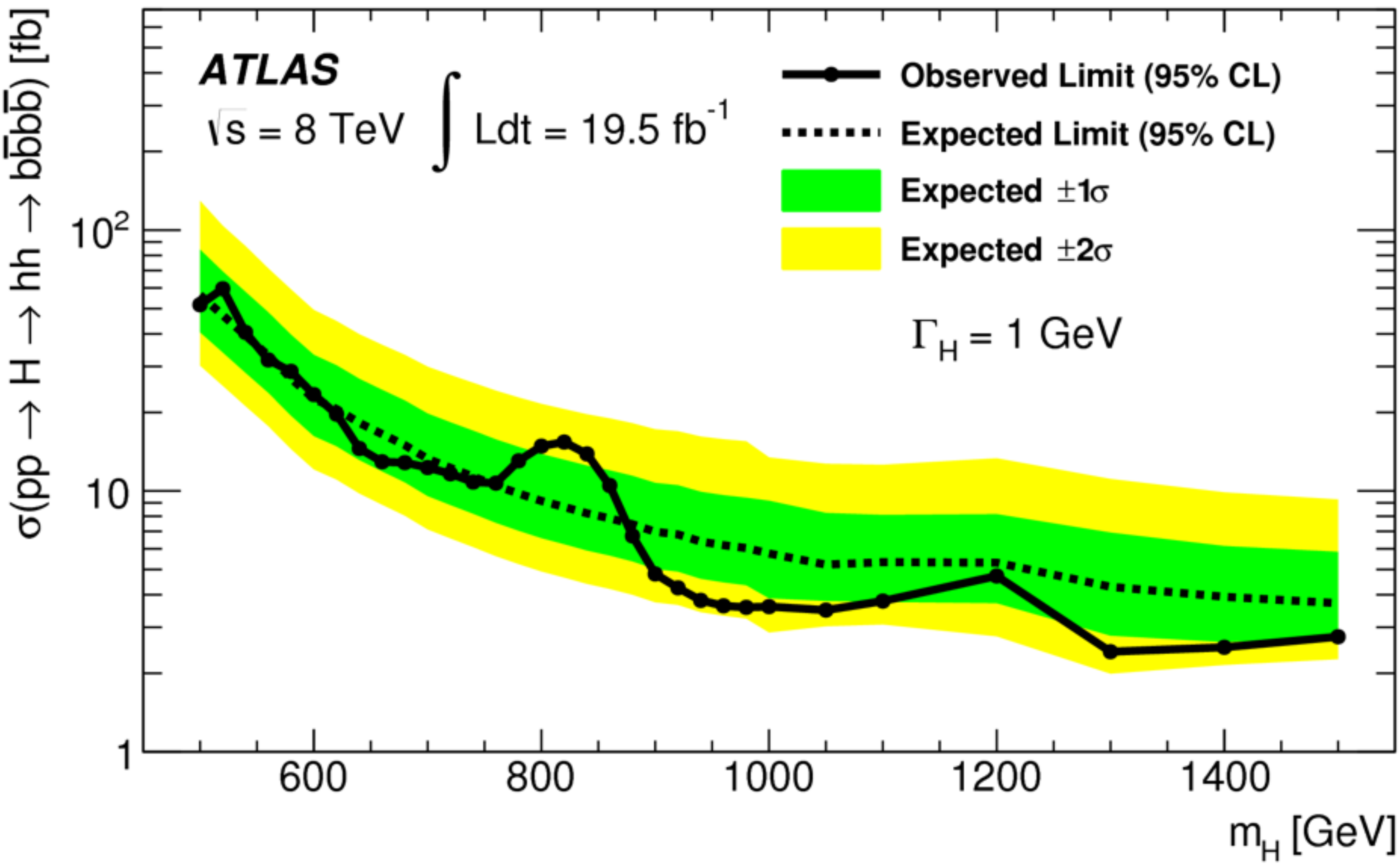
CMS hh→ bbττ Results



ATLAS H→hh→ bbγγ



ATLAS H→hh→ bbbb



2HDM Models

- Higgs sector of 2HDM models described by parameters:
  - 4 Higgs masses
  - tan-β (ratio of vacuum expectation values, vev)
  - α (mixing between the two neutral CP even states h,H).

- Several different 'types' of 2HDM:
  - Type I: One doublet couples to V("fermiophobic"), one to fermions.
  - Type II: "MSSM like" model, one doublet couples to up-type quarks, one to down-type quarks.
  - Type III: "Lepton-specific" model, Higgs bosons have same couplings to quarks as type I and to leptons as in type II.
  - Type IV: "Flipped" model, Higgs bosons have same couplings to quarks as in type II and to leptons as in type I.

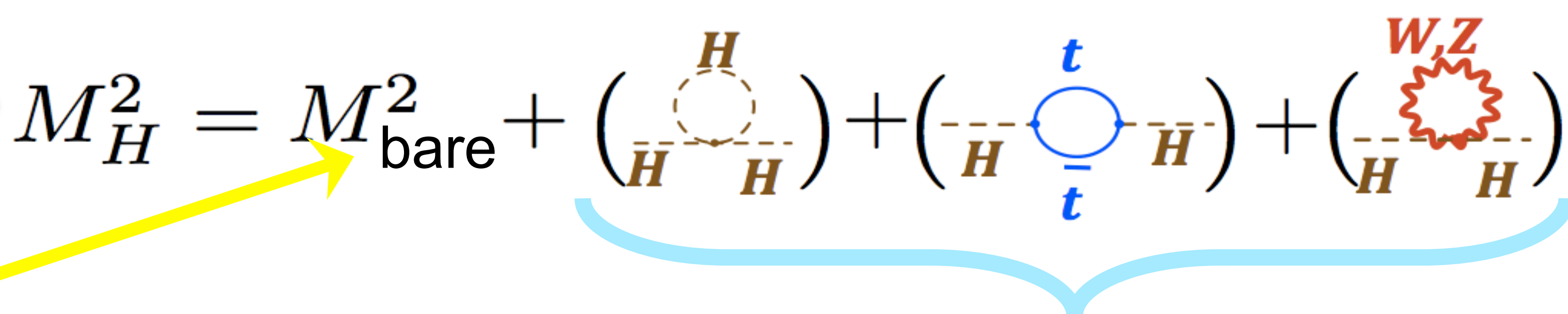
- For more specific MSSM models m_h fully determined at tree level by m_A and tan-β.

Prospects for Measuring λ_{HHH} at the HL-LHC

Signal Signifcance	had-had	lep-had (e channel)	lep-had (μ channel)	lep-lep (ee channel)	lep-lep ($\mu\mu$ channel)	lep-lep ($e\mu$ channel)
$S/\sqrt{B}$ ($\lambda = 0\lambda_{\rm SM}$)	0.66	0.49	0.45	0.044	0.055	0.091
S/B ($\lambda = 0\lambda_{\rm SM}$)	0.023	0.023	0.023	0.00092	0.0016	0.0017
$S/\sqrt{B}$ ($\lambda = 1\lambda_{\rm SM}$)	0.47	0.35	0.33	0.033	0.036	0.062
S/B ($\lambda = 1\lambda_{\rm SM}$)	0.016	0.016	0.017	0.00069	0.0010	0.0012
$S/\sqrt{B}$ ($\lambda = 2\lambda_{\rm SM}$)	0.29	0.25	0.23	0.023	0.025	0.044
S/B ($\lambda = 2\lambda_{\rm SM}$)	0.010	0.012	0.011	0.00048	0.00074	0.00084
$S/\sqrt{B}$ ($\lambda = 10\lambda_{\rm SM}$)	1.0	0.56	0.52	0.062	0.072	0.14
S/B ($\lambda = 10\lambda_{\rm SM}$)	0.036	0.027	0.026	0.0013	0.0021	0.0027

The Unbearable Lightness of M_H…

Observed mass (~125GeV)



Bare mass to cancel radiative corrections

Radiative corrections, top loop dominates: $\sim m_t^2\Lambda^2$
Λ^2: the energy scale at which the SM breaks down

Need a cancellation to 33 digits if Λ is at the Planck scale ($\sim 10^{19}$ GeV) - fine tuning!

Very strong motivation for new physics at TeV scale!