Search For Double Higgs Production in the $b\bar{b}WW^*$ Channel

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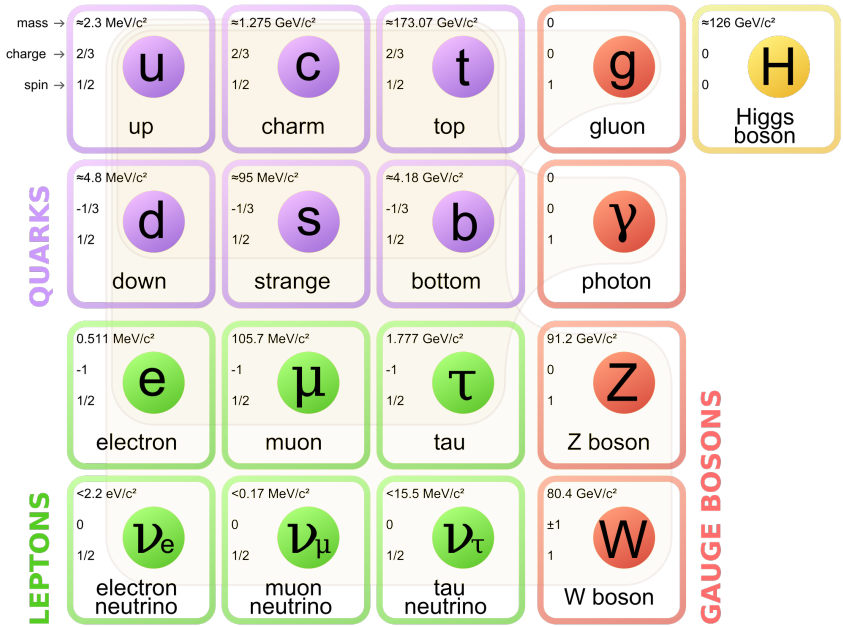
Overview

- The Standard Model
  - Higgs Physics
- BSM Di-Higgs Production
- The LHC and ATLAS
- $HH \to b\bar{b}WW^*$ Analysis
- Improvements to the Analysis
- Conclusion and Outlook

The Standard Model

- Describes matter (fermions) and force carriers (gauge bosons)
- Very successful model
- Final piece (Higgs Boson) discovered in 2012



Higgs Mechanism

Scalar Boson

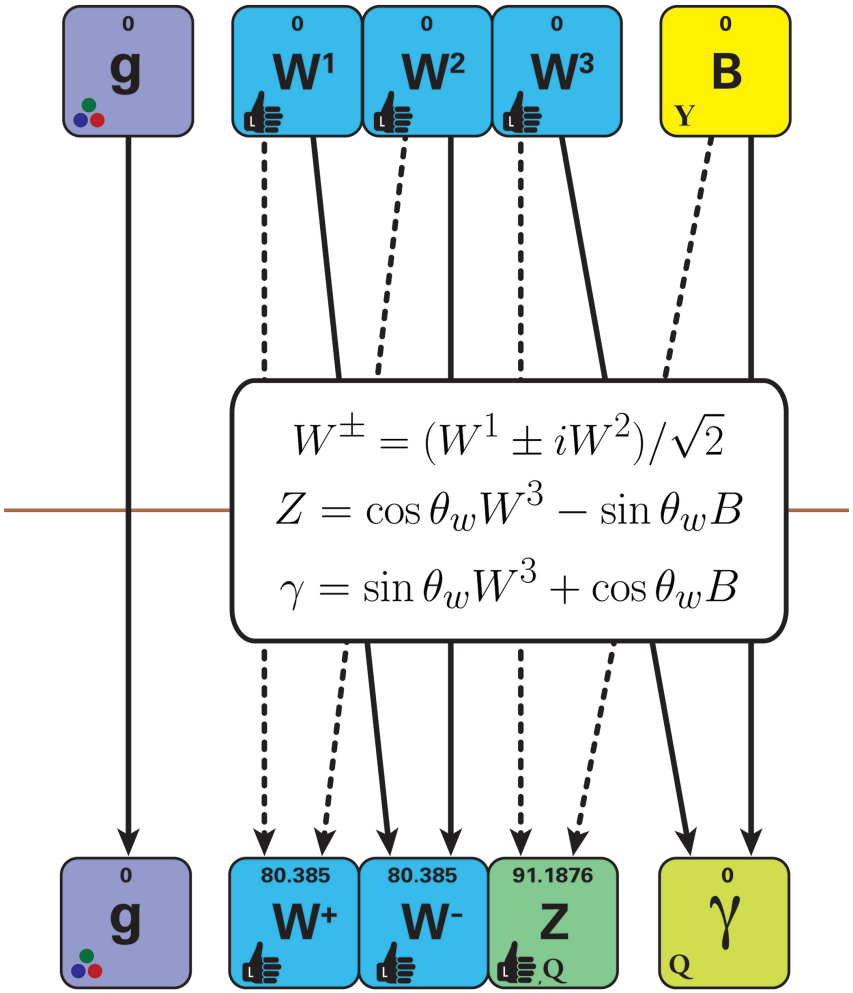
$$\phi_0 = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}$$

$$\Downarrow \text{ EWSB } \Downarrow$$

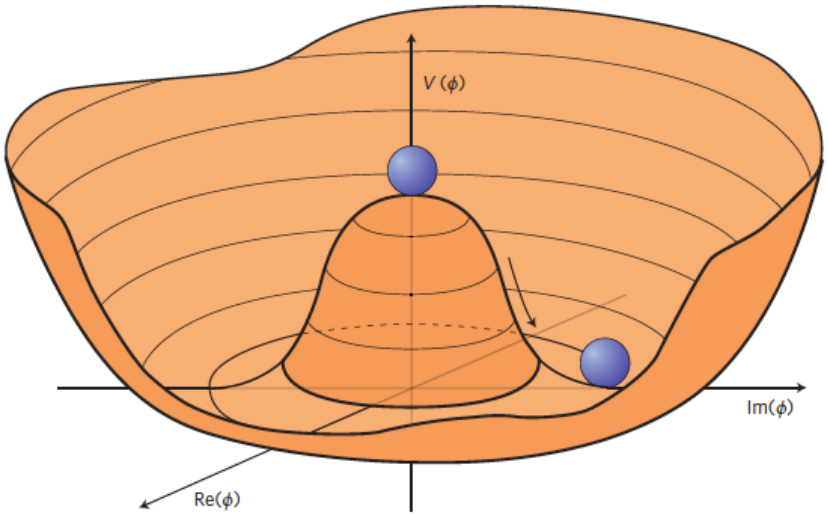
$$\phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+h(x)\end{pmatrix}$$

Coupling to Gauge Bosons gives
$W^{\pm}$, Z, $A(\gamma)$

$$M_W^2 = \tfrac{1}{4}g^2v^2$$
$$M_Z^2 = \tfrac{1}{4}(g^2+g'^2)v^2$$
$$M_A^2 = 0$$



Higgs Self-Coupling



Higgs Potential

$$V = \mu^2|\Phi^\dagger\Phi| + \lambda(|\Phi^\dagger\Phi|)^2$$

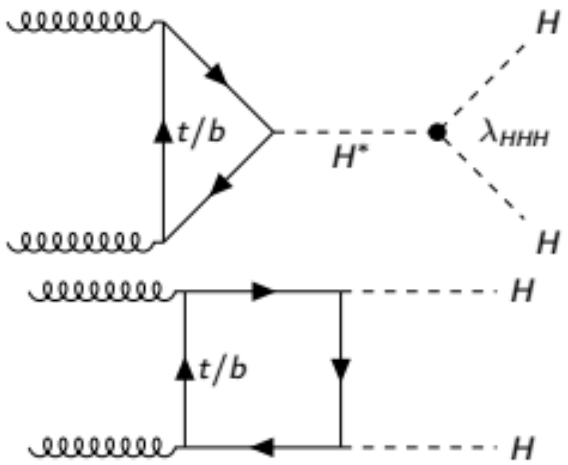
Expand self-coupling around VEV

$$V_{\text{self}-\text{coupling}} \supset \lambda v\Phi^3 + \frac{\lambda}{4}\Phi^4$$

Tri-linear Higgs coupling strength

$$\lambda_{HHH} \equiv \lambda v$$

Higgs Self-Coupling

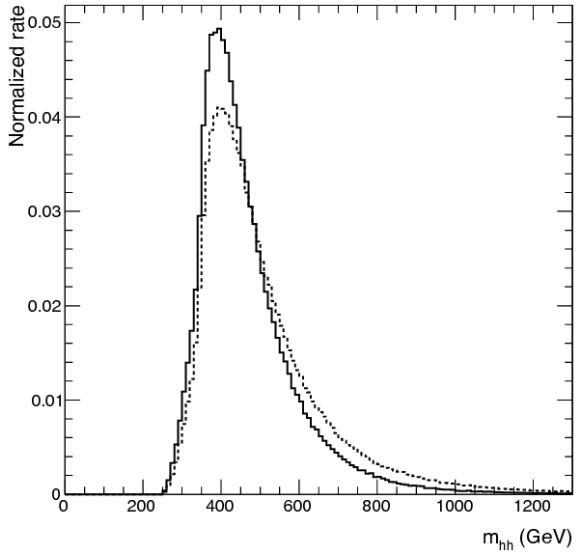


Two Dominant production modes at the LHC

Interfere destructively to give small theoretical cross section

SM Theory cross section:

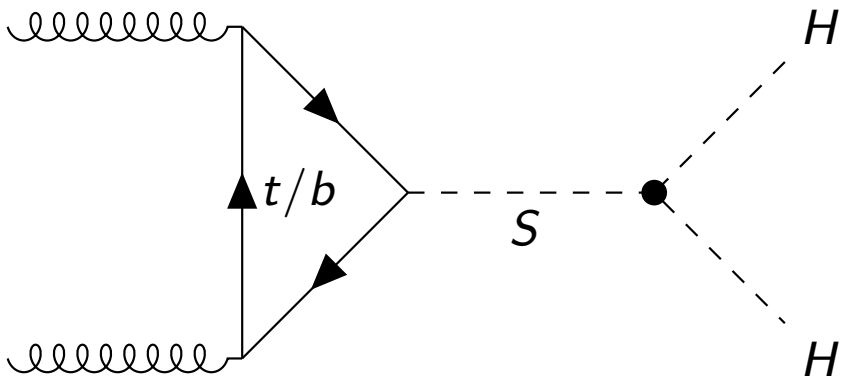
$\sigma_{\mathrm{HH}} \approx 33.53\mathrm{fb}$

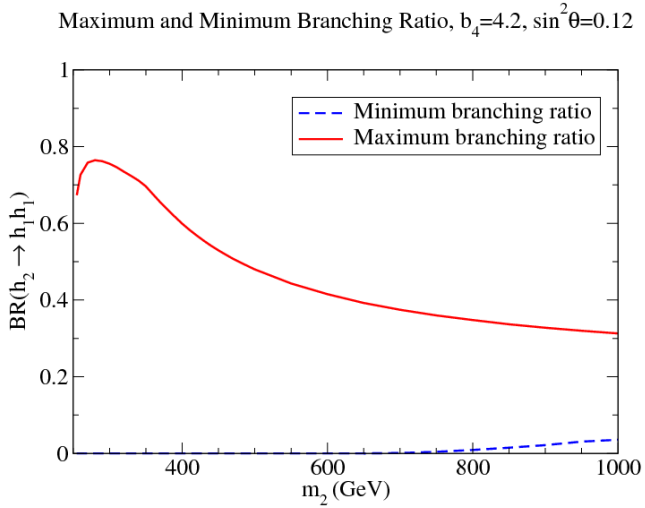


Motivation

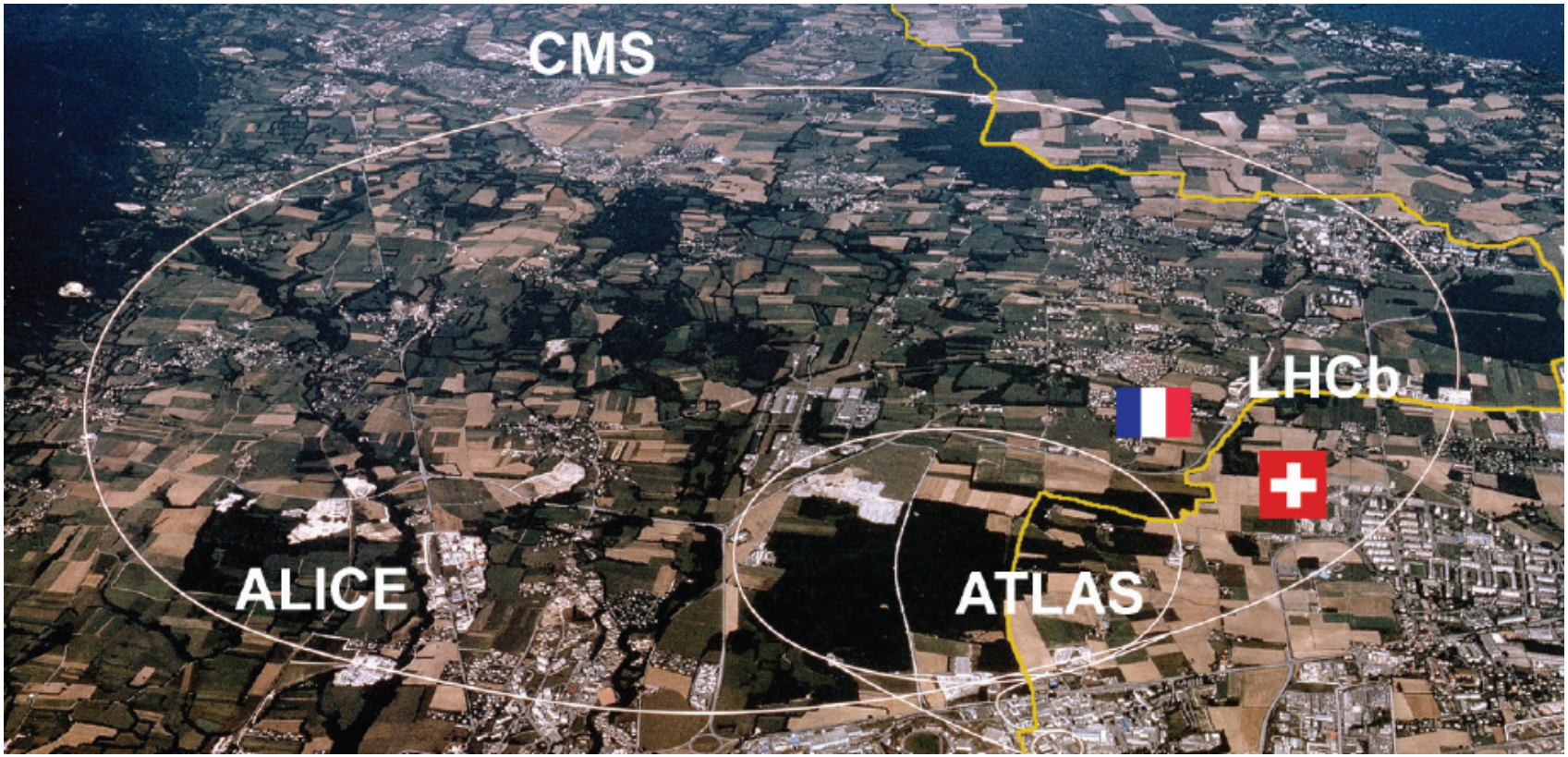
Resonant di-Higgs production

- A New process could decay to HH
- E.g. Real Higgs Singlet Extension
  - Couples to SM Higgs
  - Large enhancement to HH production rate
    - Up to 30 times SM



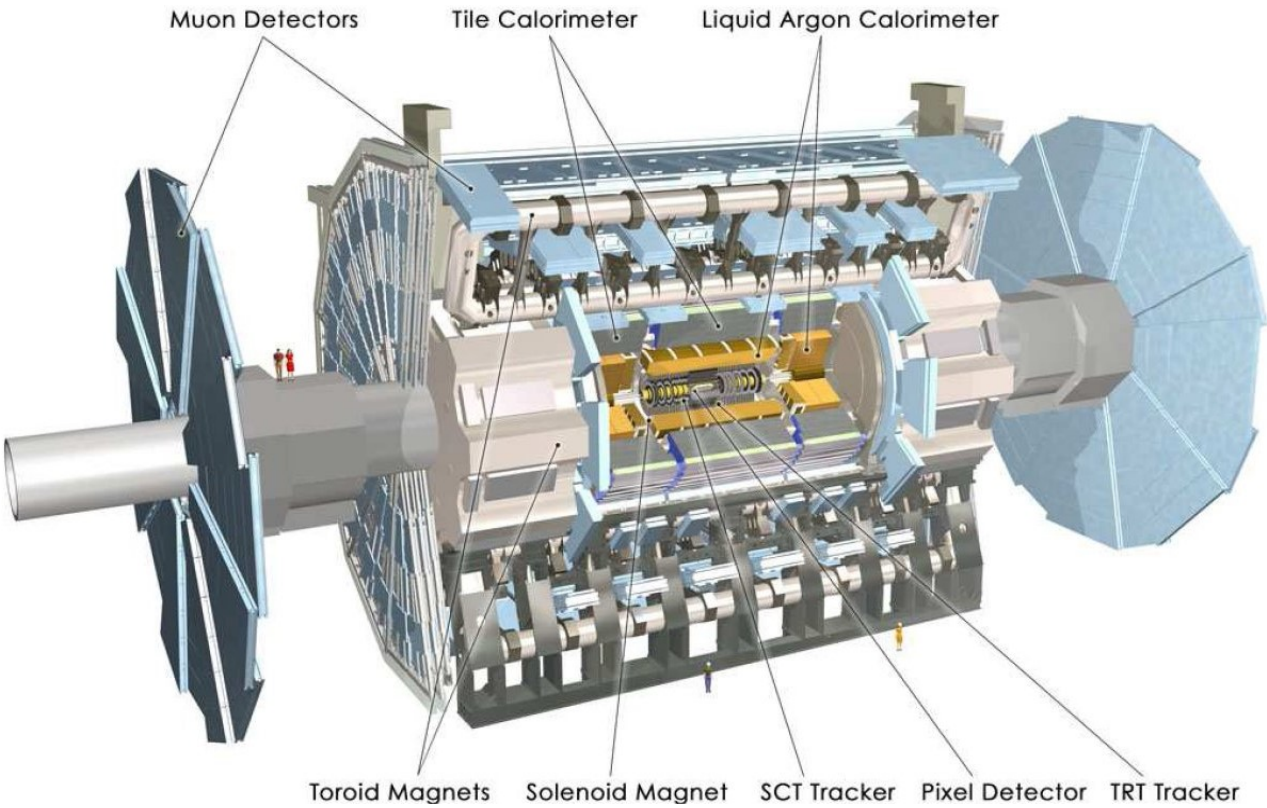


The Large Hadron Collider



- 13 TeV Proton-Proton Collider
- 27 Km Circumference under the French-Swiss border
- 4 primary interaction points, each with a dedicated detector

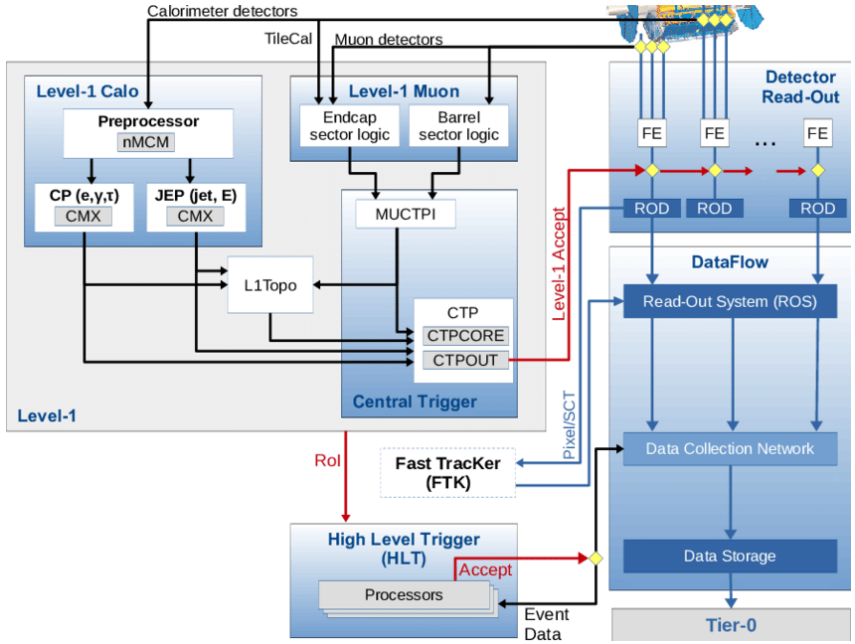
The ATLAS Detector



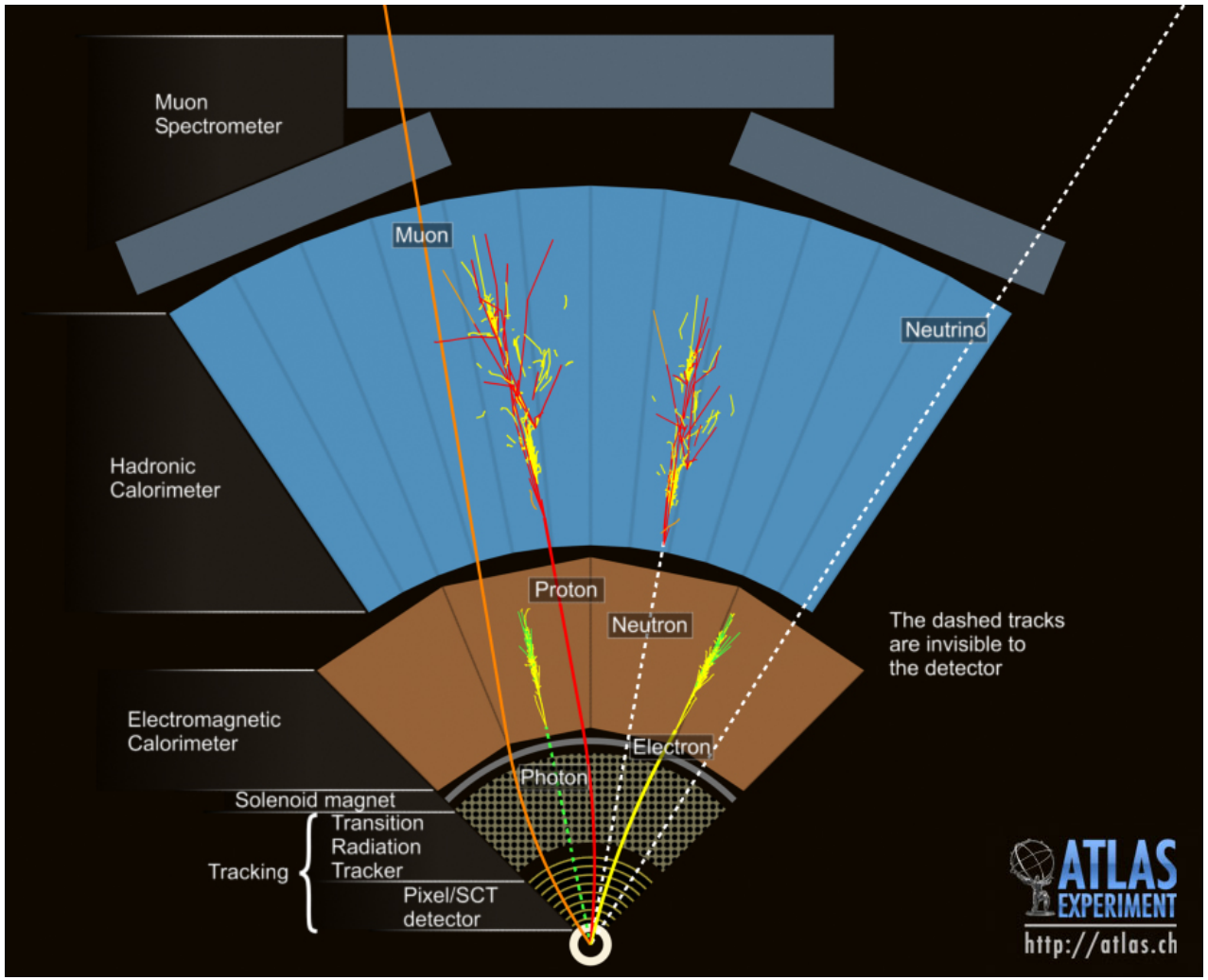
- General purpose detector
- 3.9 T Toroid

ATLAS Trigger

- LHC has 40 MHZ Collision Rate
  - ∼64 TB/s
- 2 Level Trigger System
  - Level-1 Trigger (L1)
  - High Level Trigger (HLT)
- Reduces rate from 40MHz to ∼2 kHz (∼3 GB/s)



Particles in the Detector



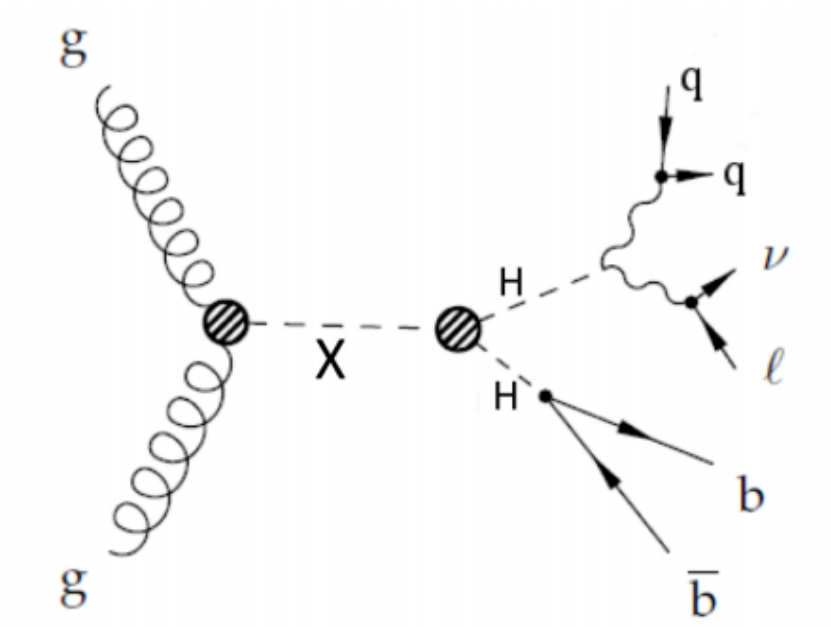
$b\bar{b}WW^*$ semi-leptonic channel

- $b\bar{b}WW^*$ has the second highest BR behind $b\bar{b}b\bar{b}$
  - One of the W bosons is off-shell
- $bbl\nu$ final state
  - Lepton helps against QCD
  - Neutrino makes reco. more challenging

	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%	0.0005%

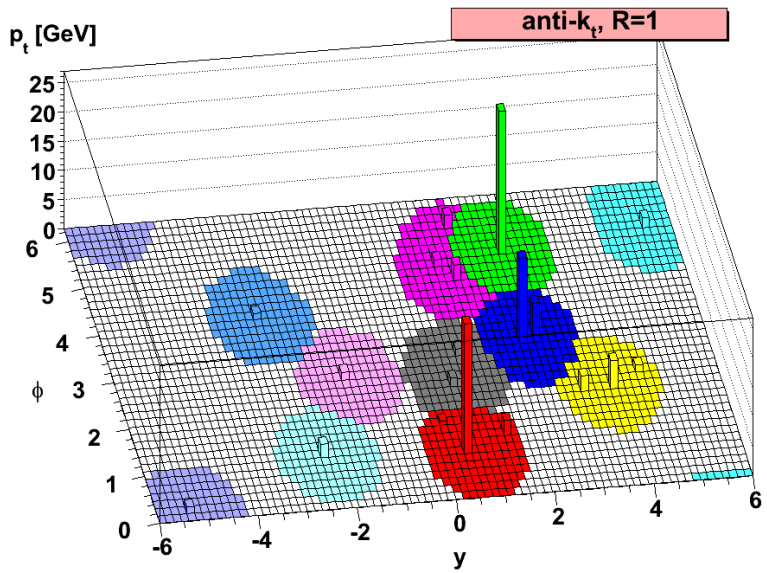
bblν Final State

- electron or muon
- 2 b quarks
- 2 light flavor quarks
- $\not{E_T}$



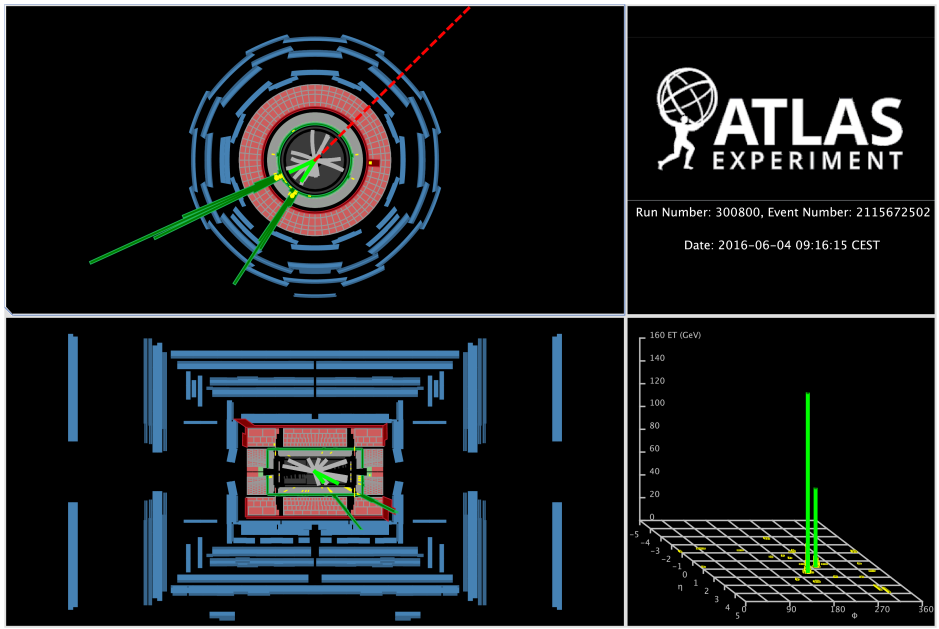
Jets

- Quarks hadronize before they interact with the detector
- Gives sprays of energy deposits
- Energy deposits grouped together into "Jets" by algorithms



Neutrinos

- Neutrinos do not interact with detector
- Have transverse (perpendicular to beam line) information from $\not{E_T}$
- Need another piece to fully reconstruct 4-momentum
  - This analysis used Higgs mass



Background

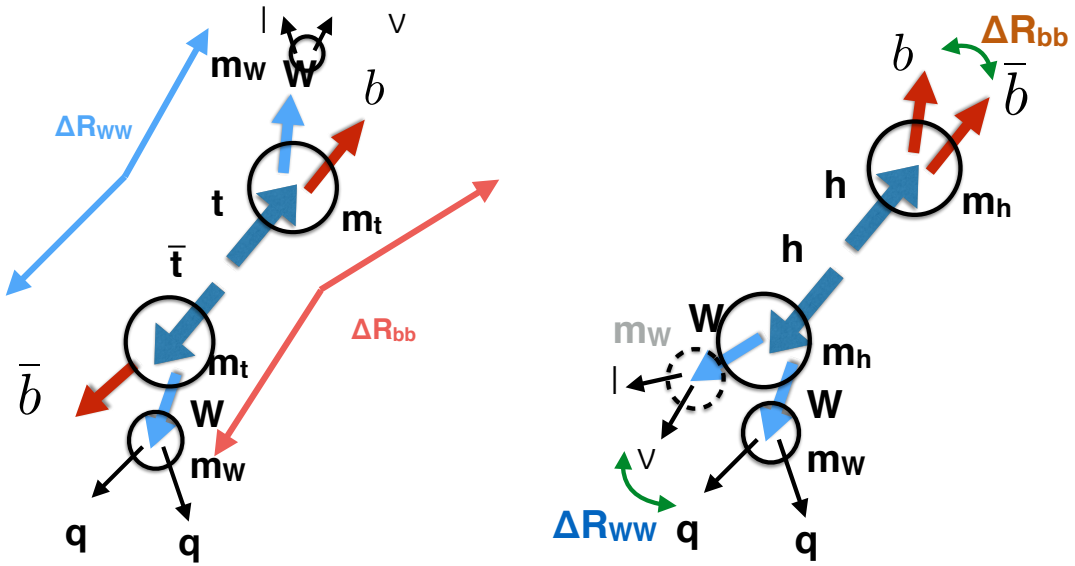
Major

- $t\bar{t}$
- W+Jets
- QCD multijet

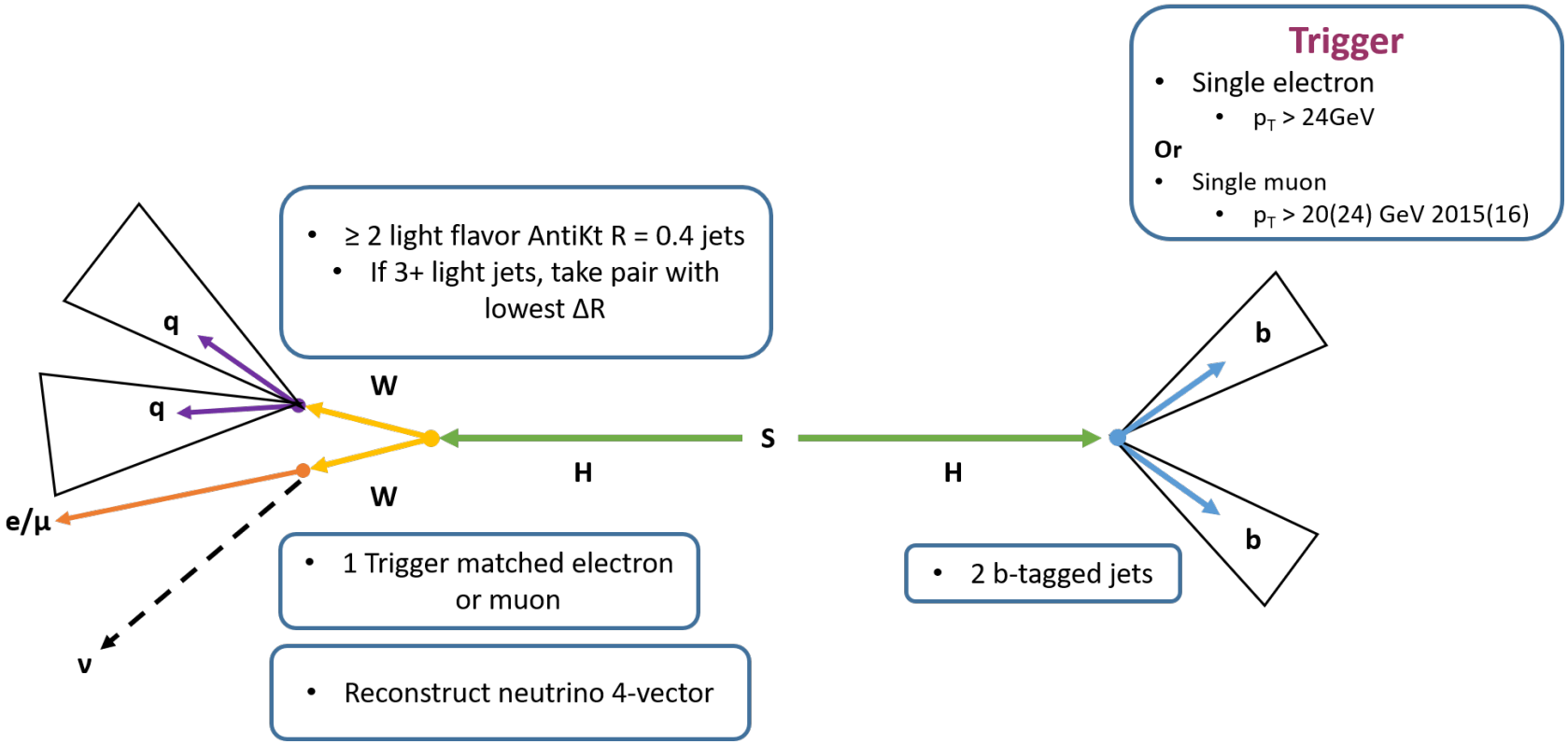
Minor

- Z+Jets
- Single Top
- Diboson

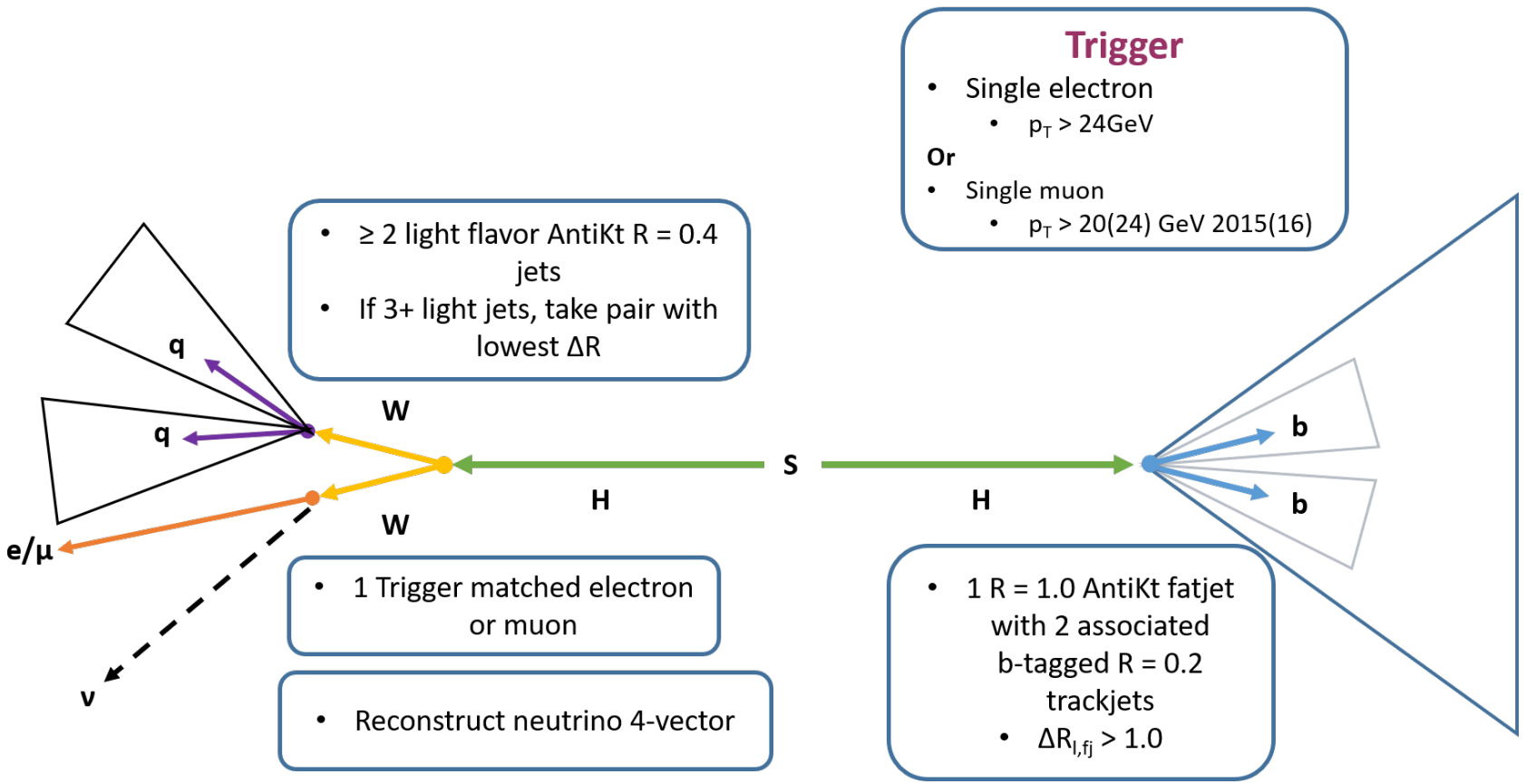
$t\bar{t}$ vs signal



Resolved Event Selection



Boosted Event Selection



Signal Region

Resolved

- $\not{E}_T$
- p_T^{bb}
- p_T^{WW}
- $m_{bb} \sim m_H$
- $m_{HH} \sim m_S$

Boosted

- $\not{E}_T$
- $m_{\text{Large-R jet}} \sim m_H$

Resolved Background Determination

$t\bar{t}$

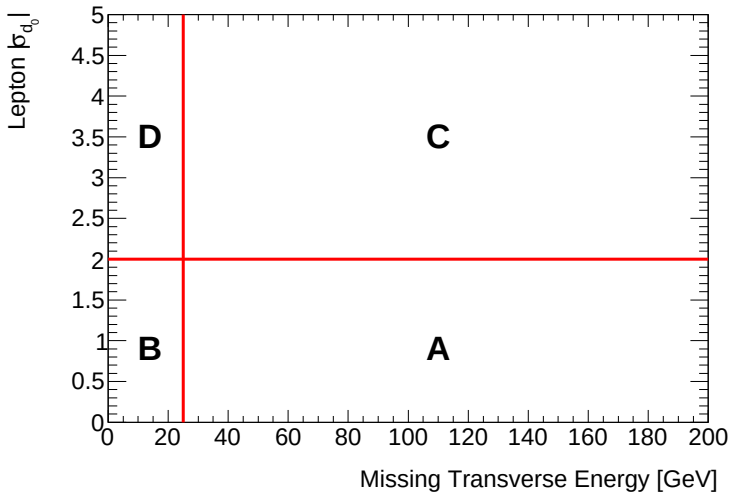
- Normalized in m_{bb} CR
  - Boosted $t\bar{t}$ VR

Other MC Bkg.

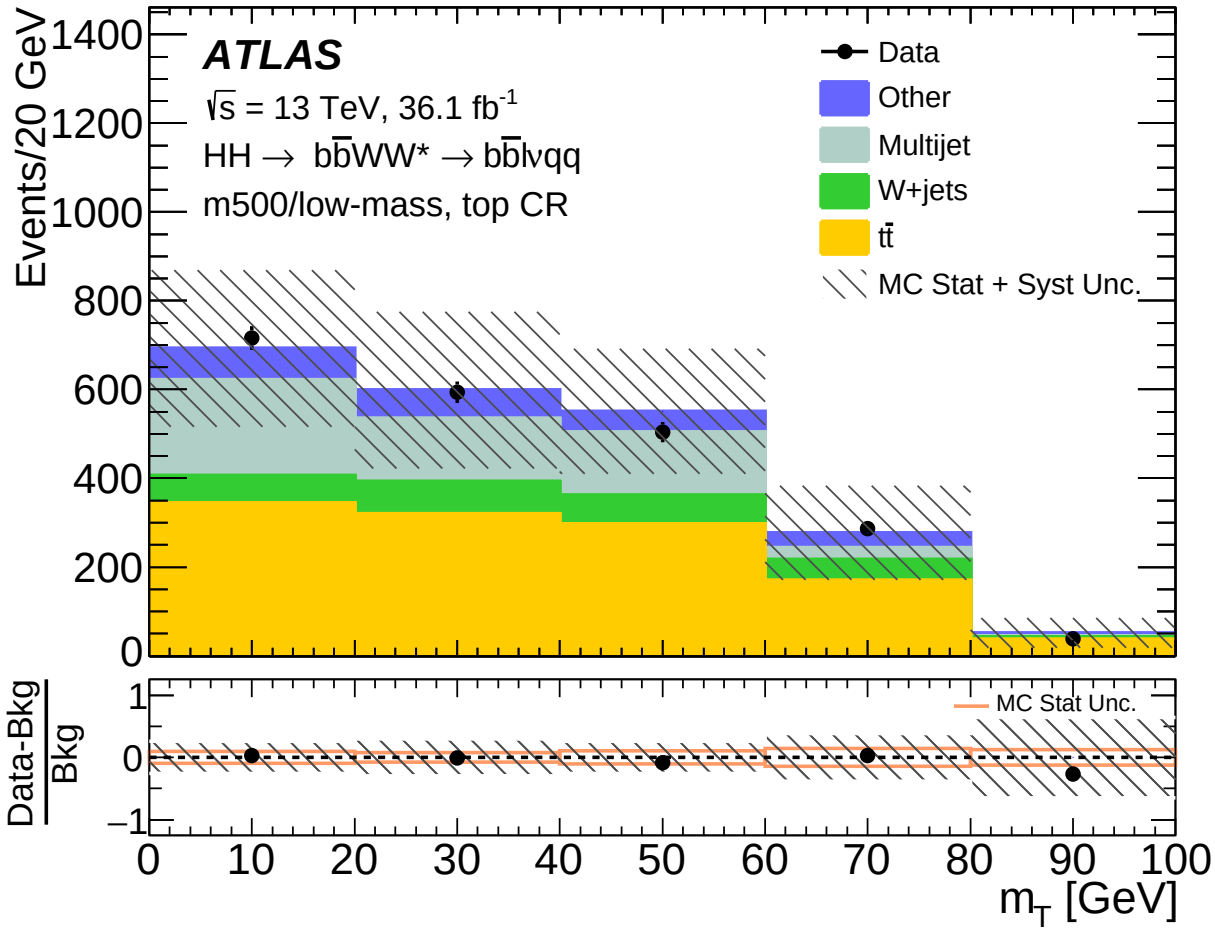
- Modeled using MC and normilized to SM XSec

QCD multi-jet background

- ABCD data driven estimate
  - $N_A = F N_C N_B / N_D$
  - F is a correction factor determined earlier in the cutflow
  - Boosted uses $\not{E}_T > 50$ GeV
    - Takes shape from 1 b-tag C Region

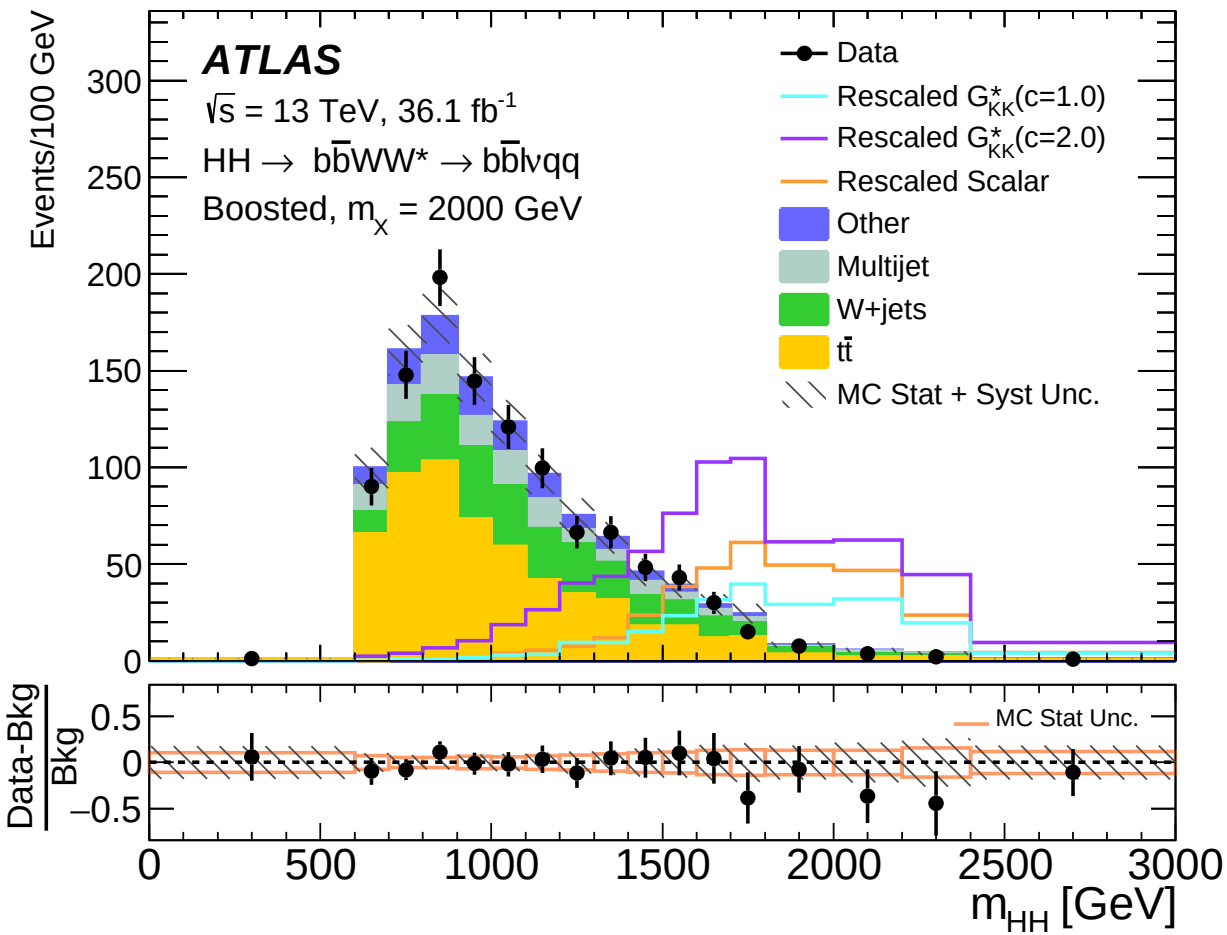


Background Shape Check

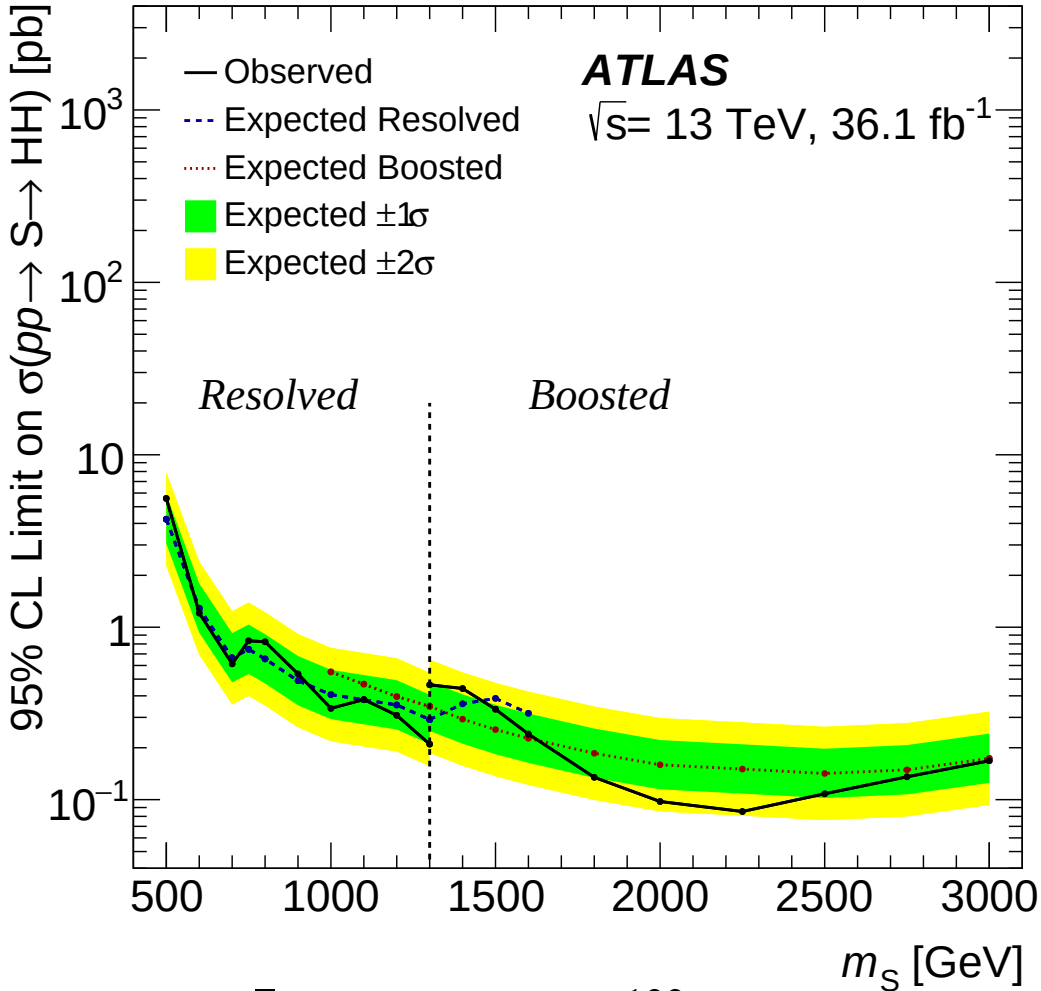


$$m_T = \sqrt{2 p_T^l \not{E}_T \times (1 - \cos \Delta\phi)}$$

Results


ATLAS
√s = 13 TeV, 36.1 fb-1
HH → bb̄WW* → bb̄lνqq
Boosted, mX = 2000 GeV
Data
Rescaled G*KK(c=1.0)
Rescaled G*KK(c=2.0)
Rescaled Scalar
Other
Multijet
W+jets
tt̄
MC Stat + Syst Unc.
Events/100 GeV
Data-Bkg / Bkg
MC Stat Unc.
mHH [GeV]

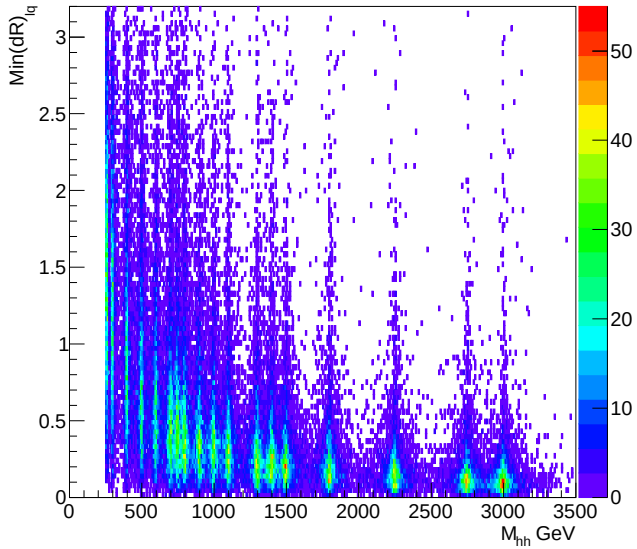
Combined Limit



$$\sigma(pp \to HH)B(HH \to b\bar{b}WW^*) < 300^{+100}_{-80} \times SM$$

Motivation

- $H \rightarrow WW$ becomes boosted around 1 TeV
- Quarks become too close together to use 0.4 jets
- Overlap removal with leptons kill efficiency
- A "Fully-Boosted" selection recovers lost efficiency at high m_S



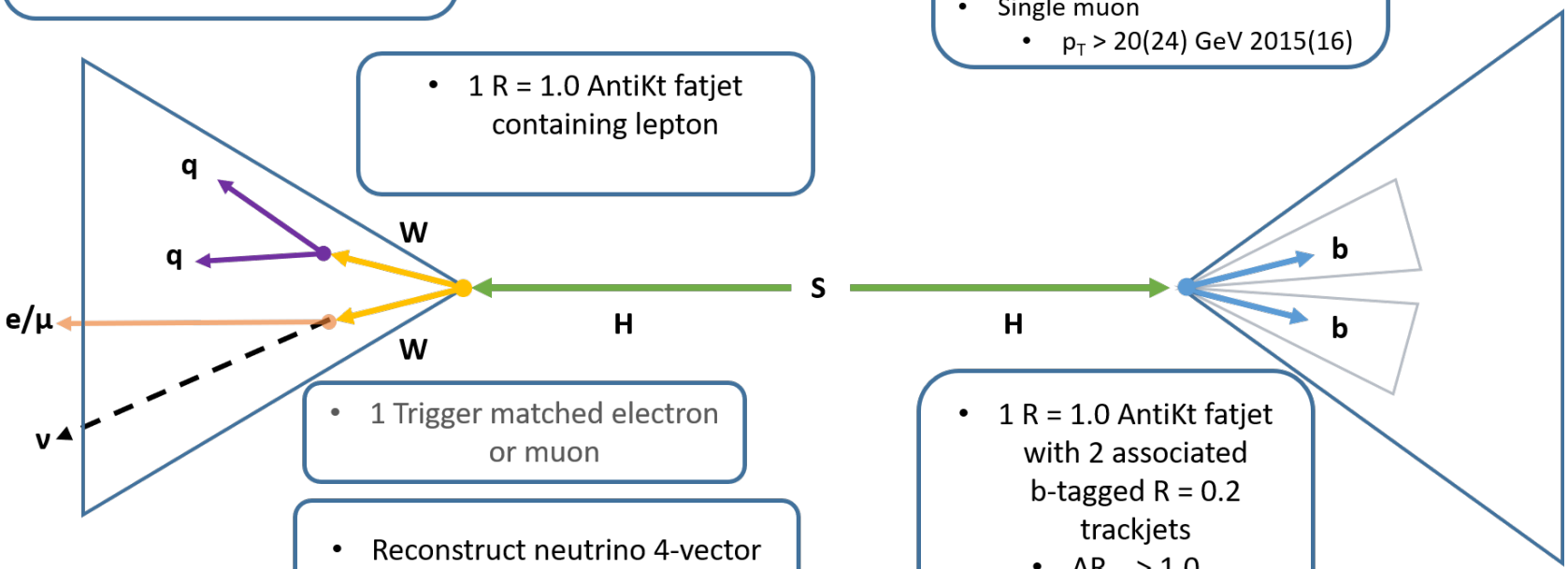
Fully Boosted Event Selection

H->WW
- Fatjet+muon+neutrino

OR
- Fatjet+neutrino

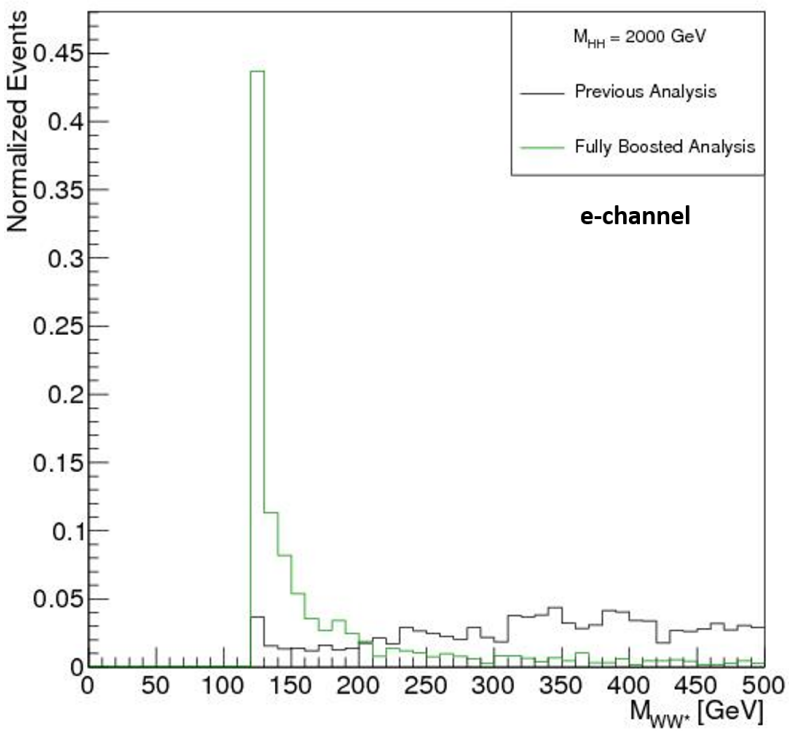
Trigger
- Single electron
  - p_T > 24GeV

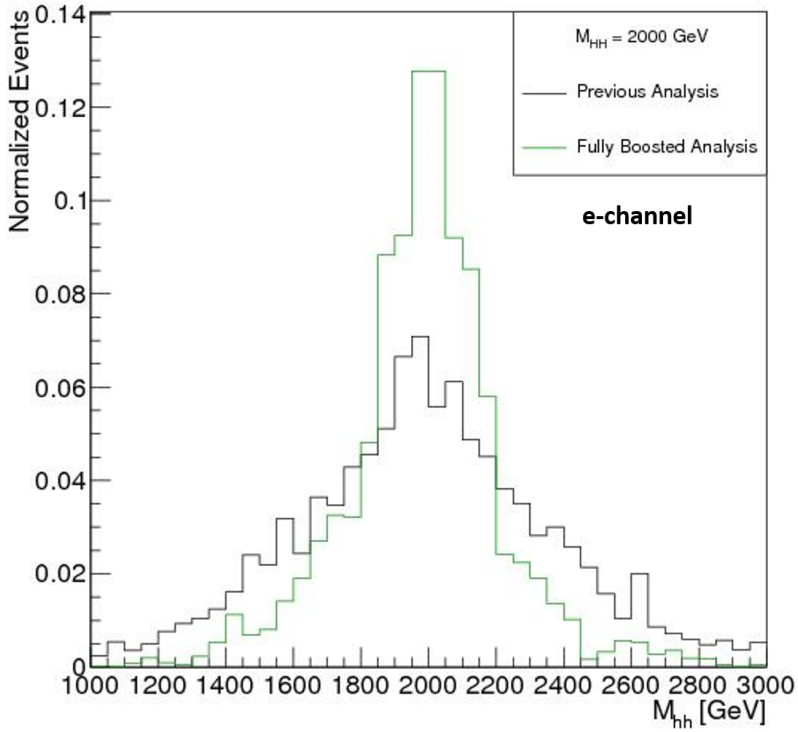
Or
- Single muon
  - p_T > 20(24) GeV 2015(16)



- 1 R = 1.0 AntiKt fatjet containing lepton
- 1 Trigger matched electron or muon
- Reconstruct neutrino 4-vector
- 1 R = 1.0 AntiKt fatjet with 2 associated b-tagged R = 0.2 trackjets
  - $\Delta R_{l,fj} > 1.0$

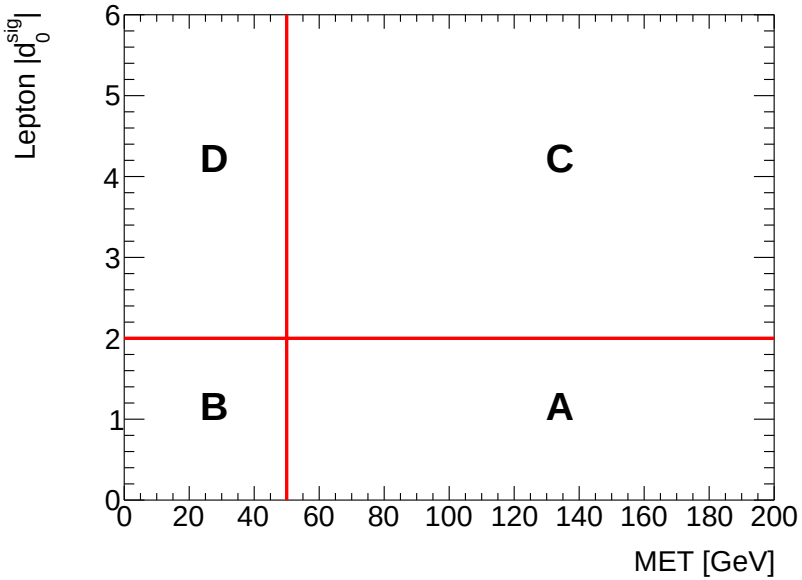
Signal Reconstruction



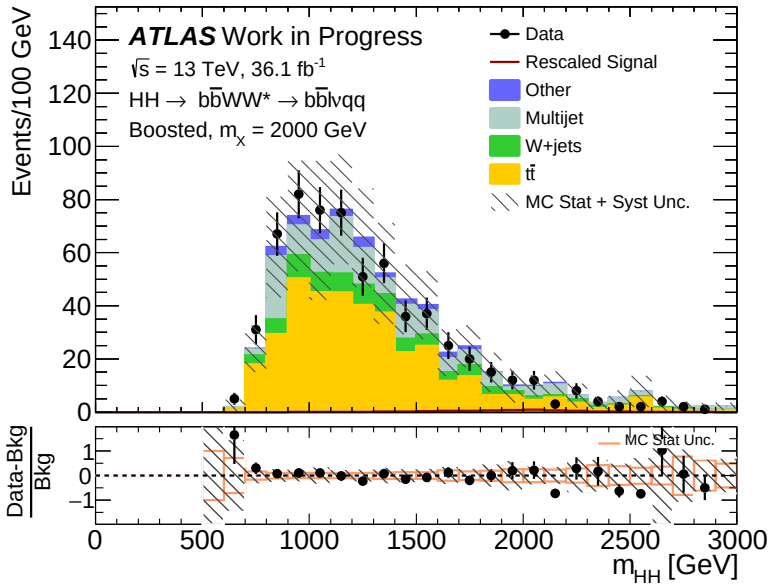


Background Modeling

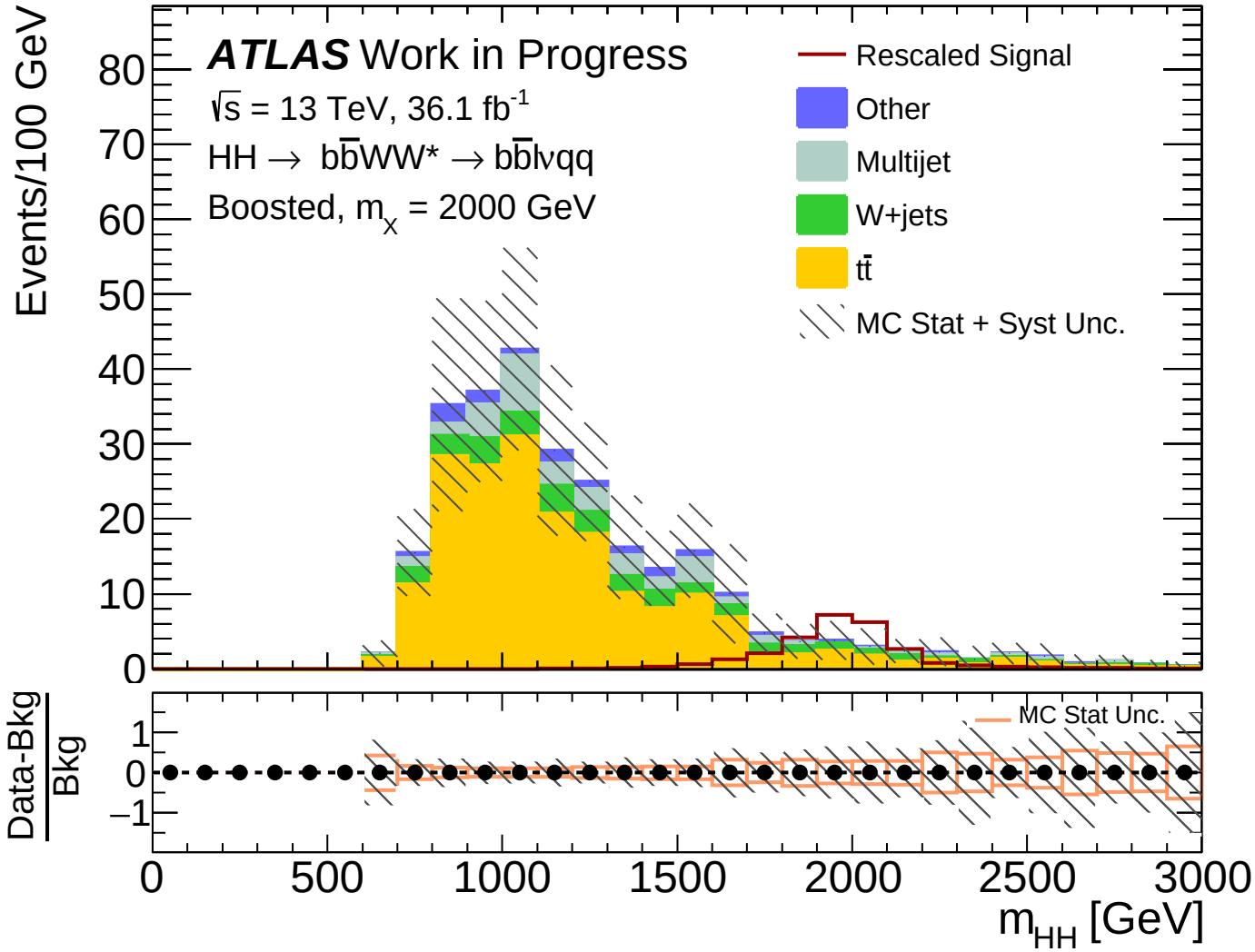
- Same procedure as boosted paper analysis
- Slightly looser selection to increase statistics
- Check shape in mBB control region



Background Shape Check



Results


ATLAS Work in Progress
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Boosted, mX = 2000 GeV
Rescaled Signal
Other
Multijet
W+jets
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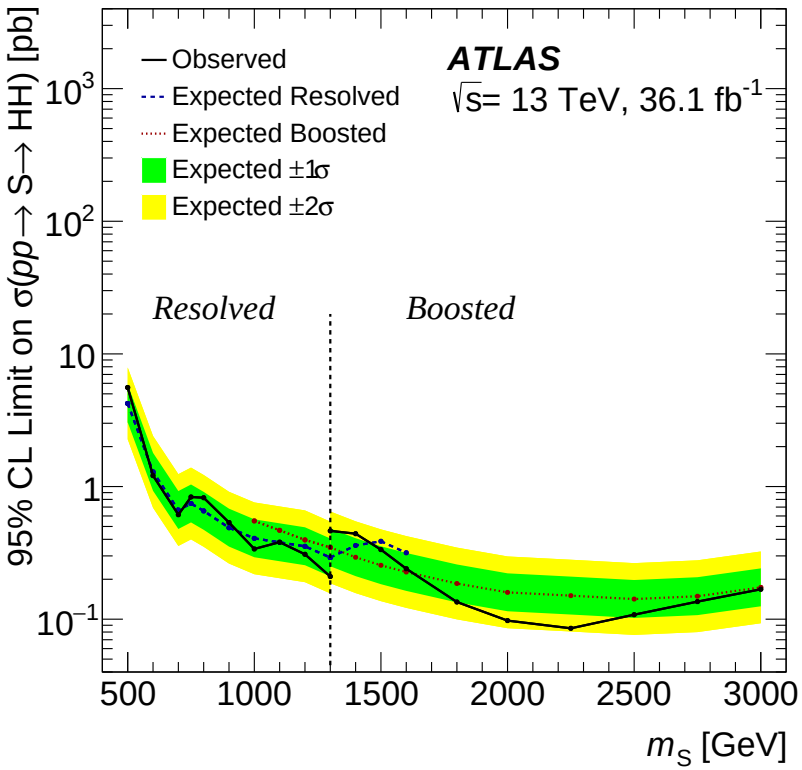
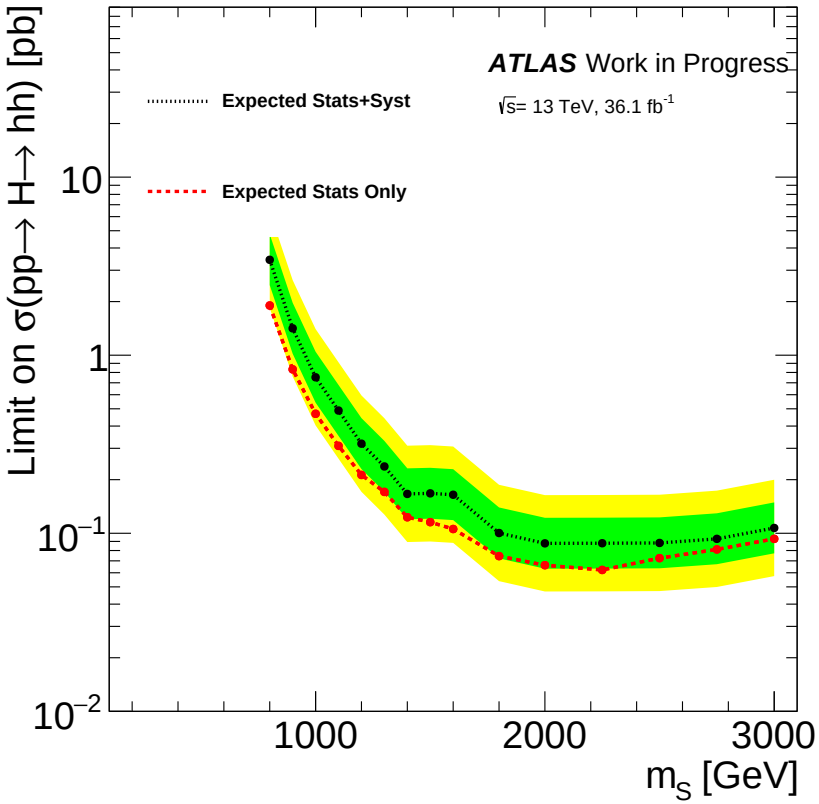
MC Stat + Syst Unc.
Events/100 GeV
Data-Bkg / Bkg
MC Stat Unc.
mHH [GeV]

Results

Published Analysis



Improved Analysis



Conclusion

- Set the first limits for HH resonant production over 1 TeV
- Developed analysis for SM HH production in $b\bar{b}l\nu$ channel
  - Set limit of 300 X SM cross section
- Improved the cross section upper limit for high resonant mass by $\sim$factor of 2

Outlook

- Move to Fatjet trigger
  - Lepton ID requirement in derivation limits the high mass analysis
- Neutrino reconstruction needs improved at high mass
  - Use $H \rightarrow b\bar{b}$ information
- ABCD estimate is limited by statistics
  - Move to alternate QCD estimate like MM

Thank you to my committee:
Eric Torrence (Advisor)
Stephanie Majewski (Chair)
Tim Cohen
Hank Childs
And a special thanks to Alison

Backup