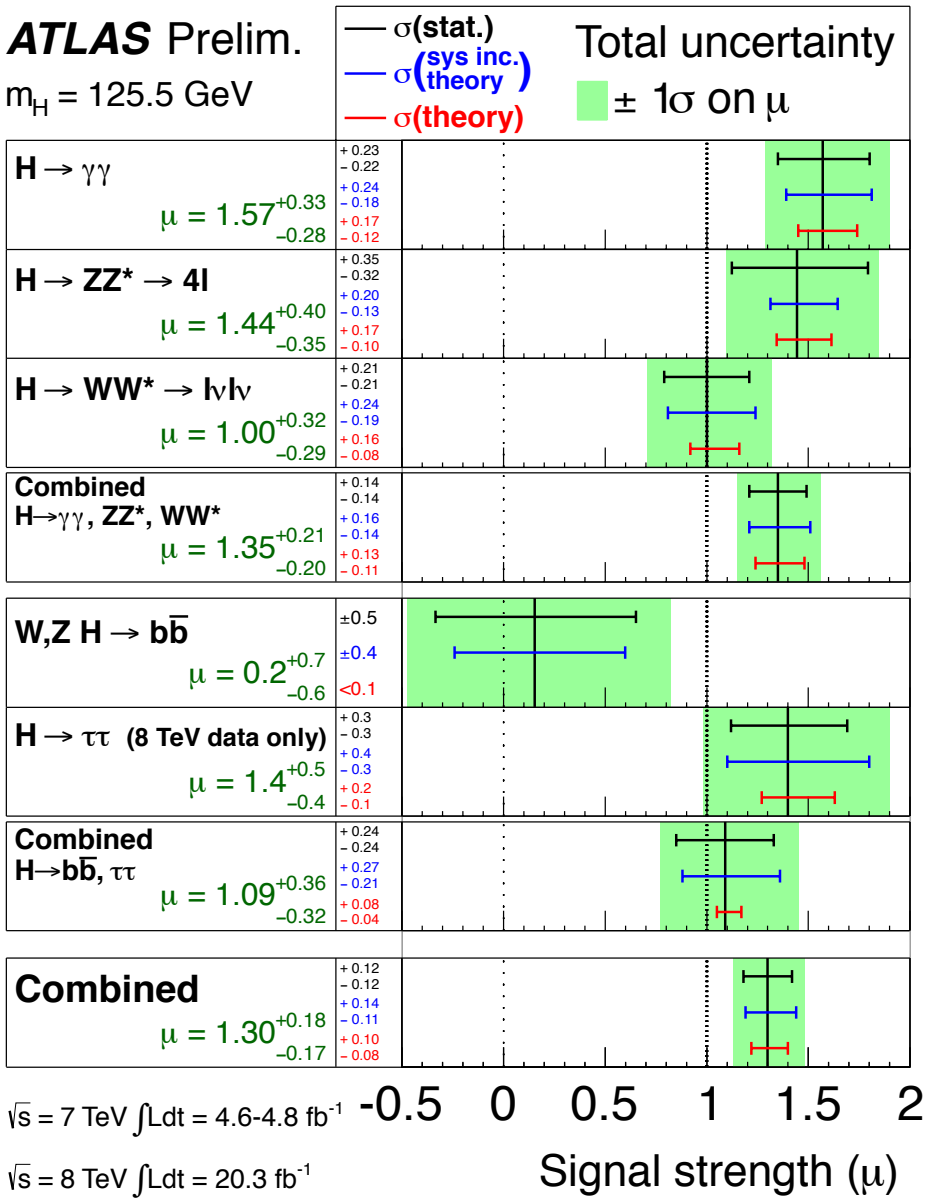
Searches for new physics at ATLAS using pair production of Higgs bosons

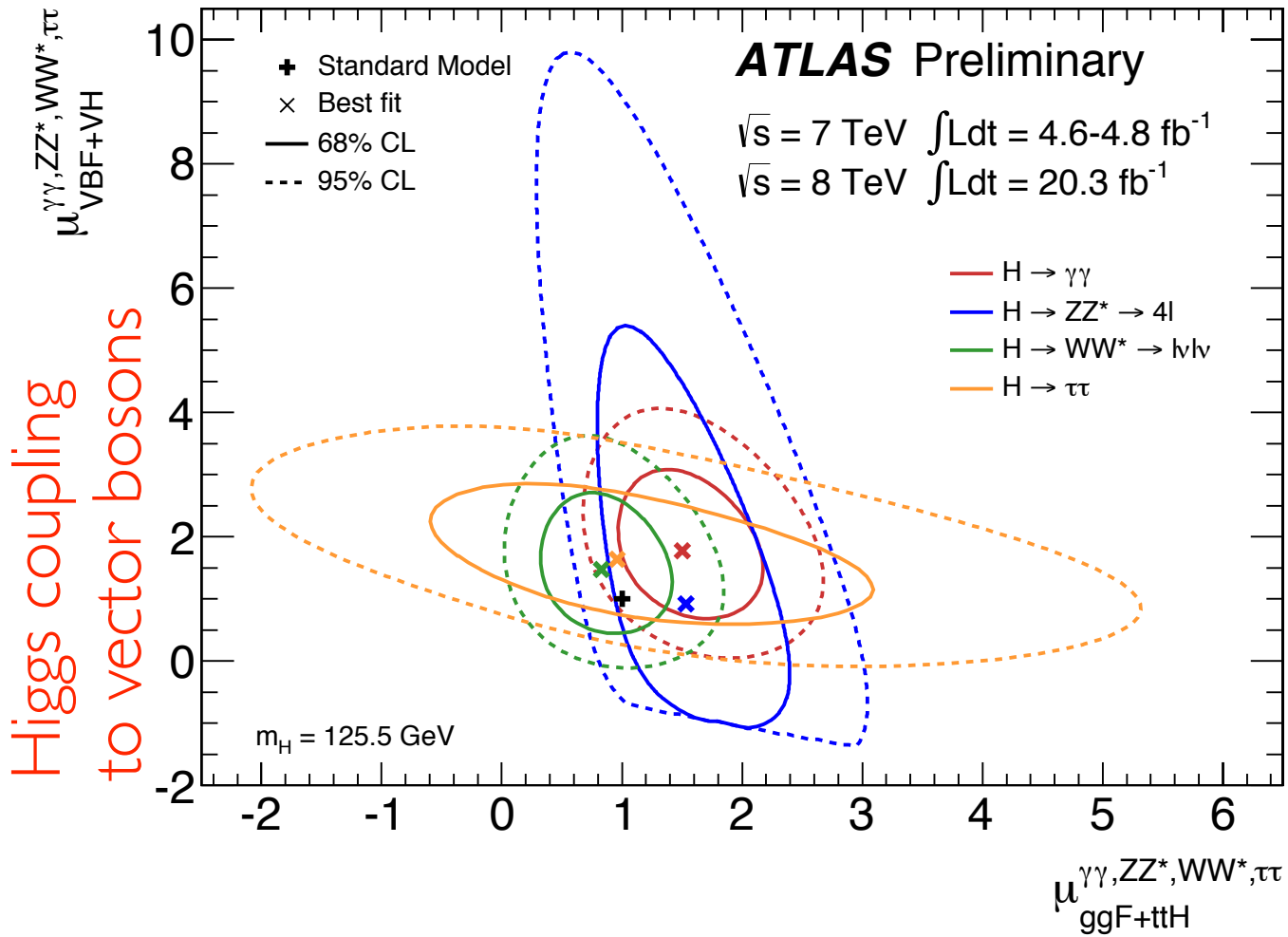
Status of the Higgs boson back across the ocean

ATLAS-CONF-2014-009



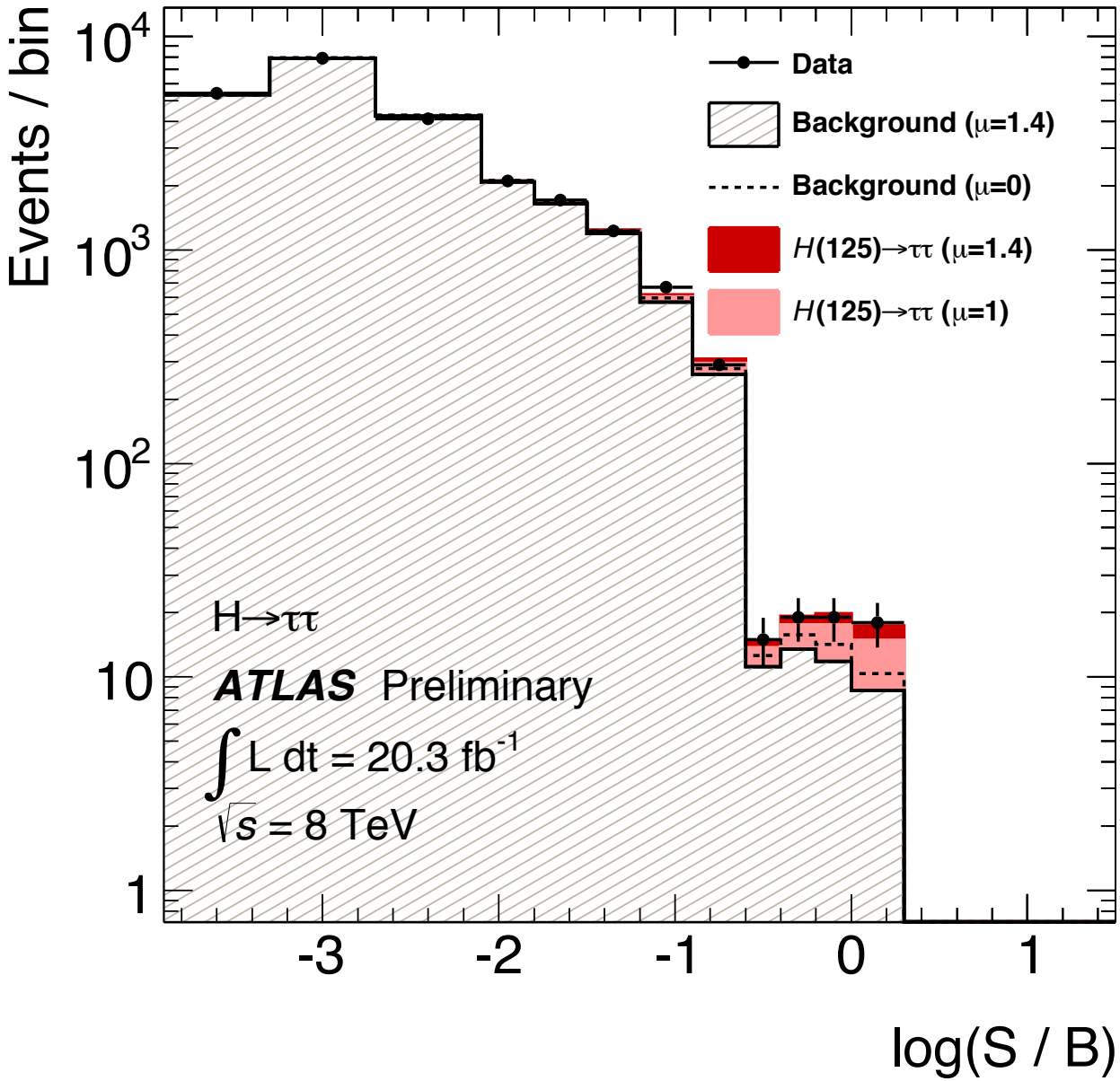
So far, no major discrepancies from SM predictions

Status of the Higgs boson back across the ocean



Higgs boson-like resonance really looks like the SM Higgs boson

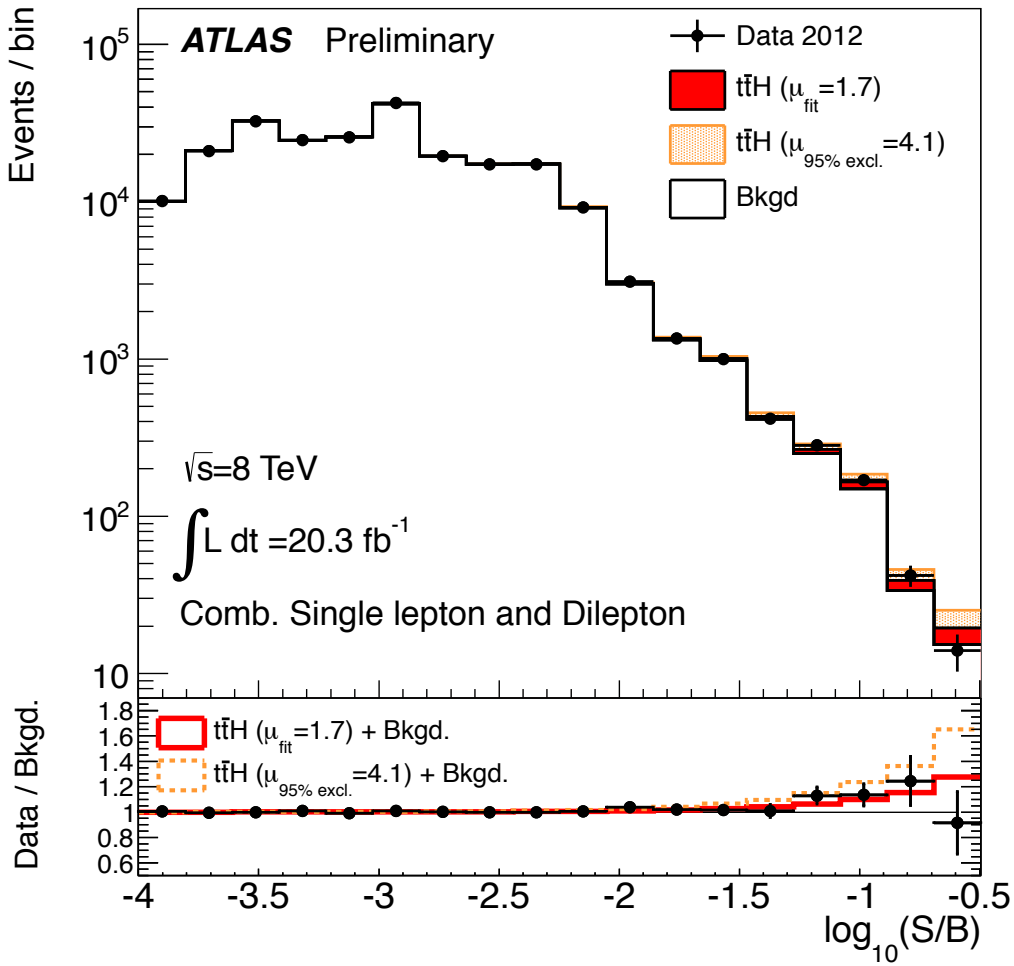
Higgs coupling to fermions

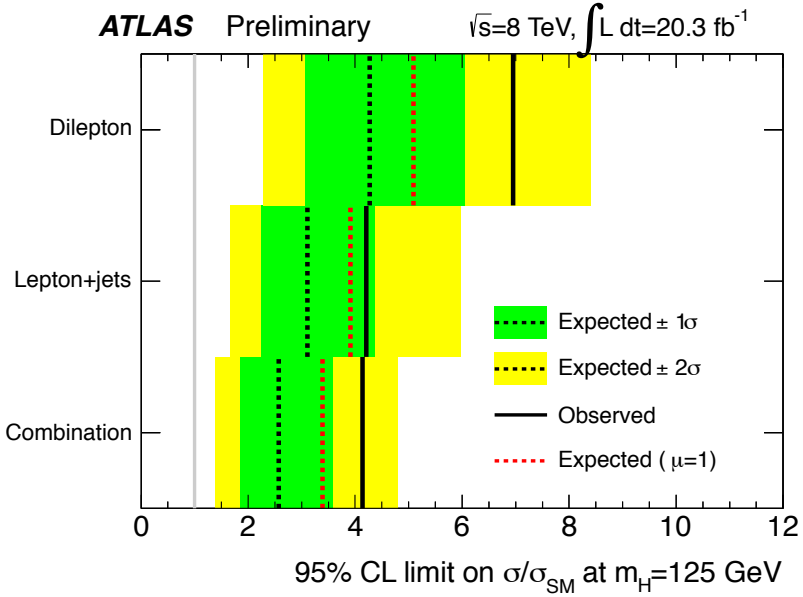


4.1 σ evidence for $h \rightarrow \tau\tau$ decays

And also the more rare production mechanisms (ttH)

ATLAS-CONF-2014-011





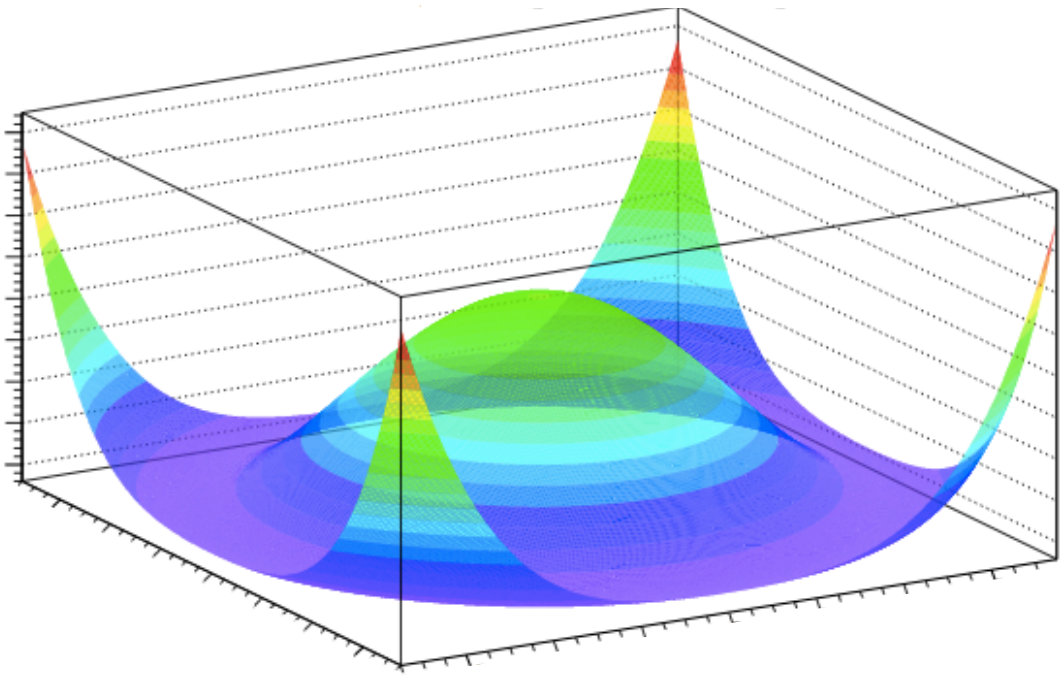
Limits of 4.1x SM expectation for ttH production, just from bb channel

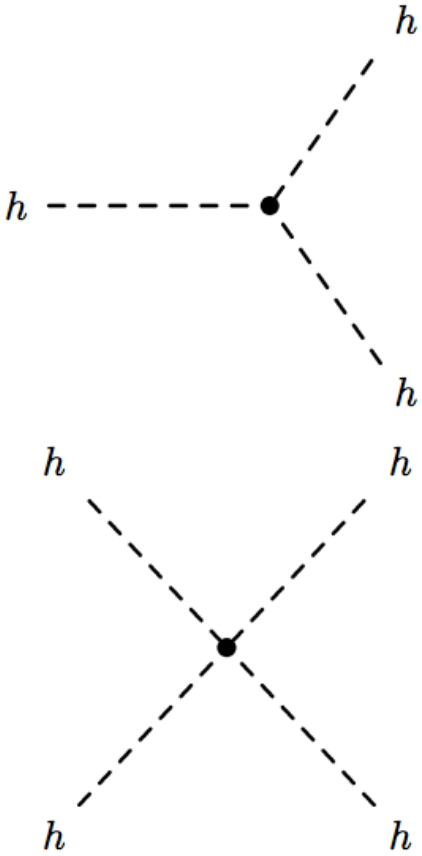
We are just being to probe and test this new particle

One long-term LHC goal

arXiv:1212.5581, among many

Observe the Higgs boson self-coupling, crucial to testing if the Higgs potential is the one predicted in the SM

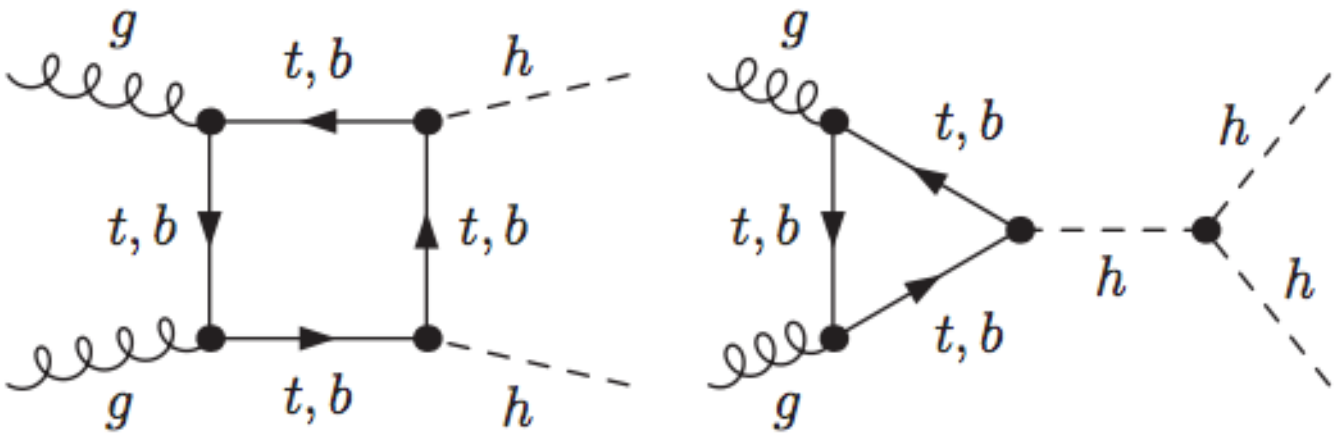




$$\mathcal{L}_V = -\lambda v^2 h^2 - \lambda v h^3 - \frac{\lambda}{4} h^4$$

SM Dihiggs production at the LHC

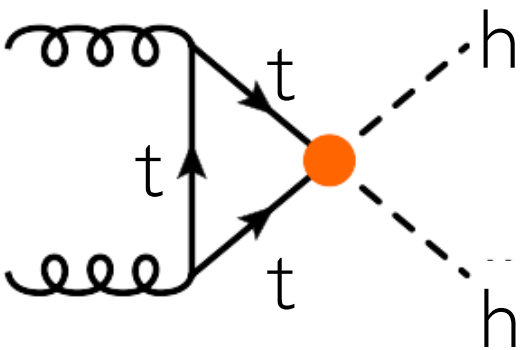
- SM hh production dominated by box diagram, not hh self-coupling, with destructive interference between the two
- Total SM hh cross section at 8 TeV ~9 fb not expected to be seen by us any time soon

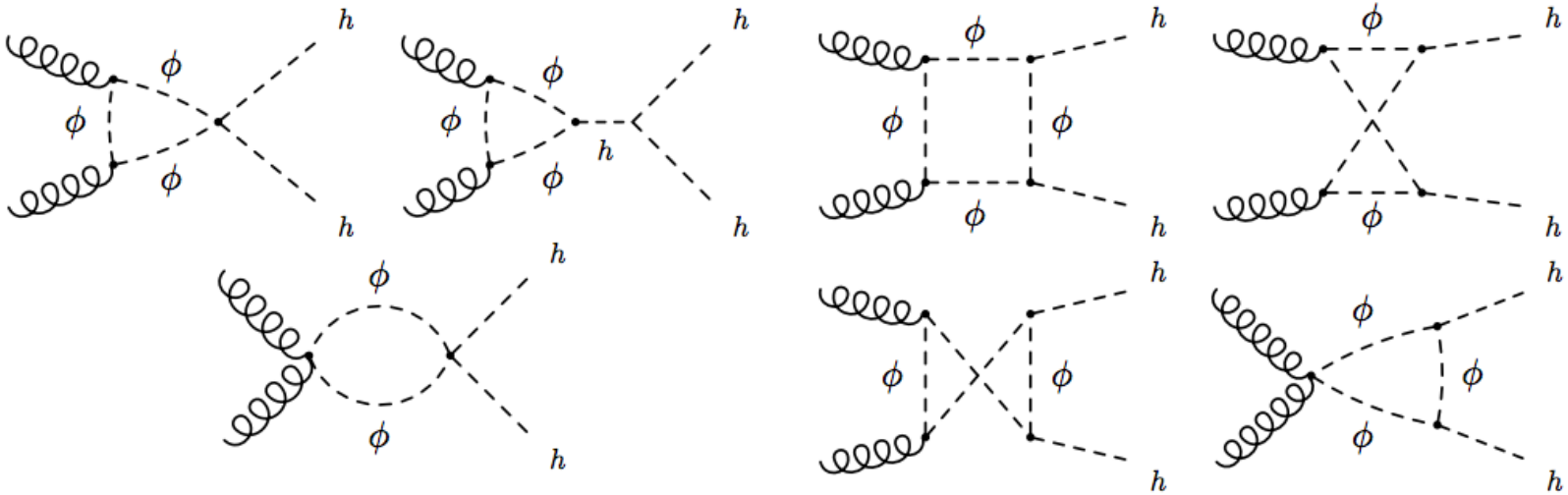


What about extensions to the SM?

arXiv:1205.5444, 1207.4496, 1212.5581

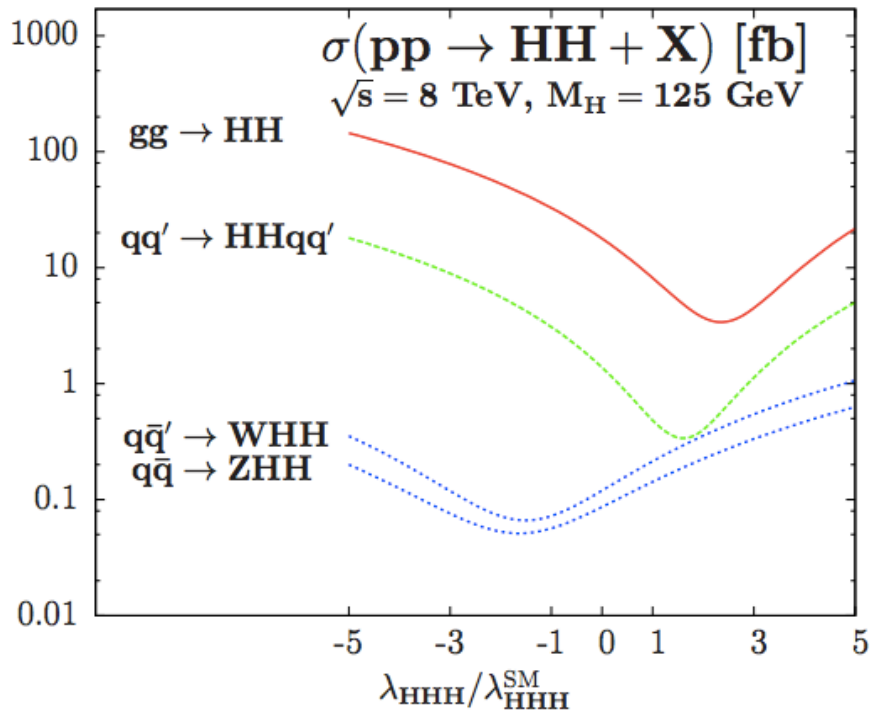
- Can enhance non-resonant hh production in many extensions to the SM
  - tthh interactions, light colored scalars, or if Higgs boson self-coupling were altered

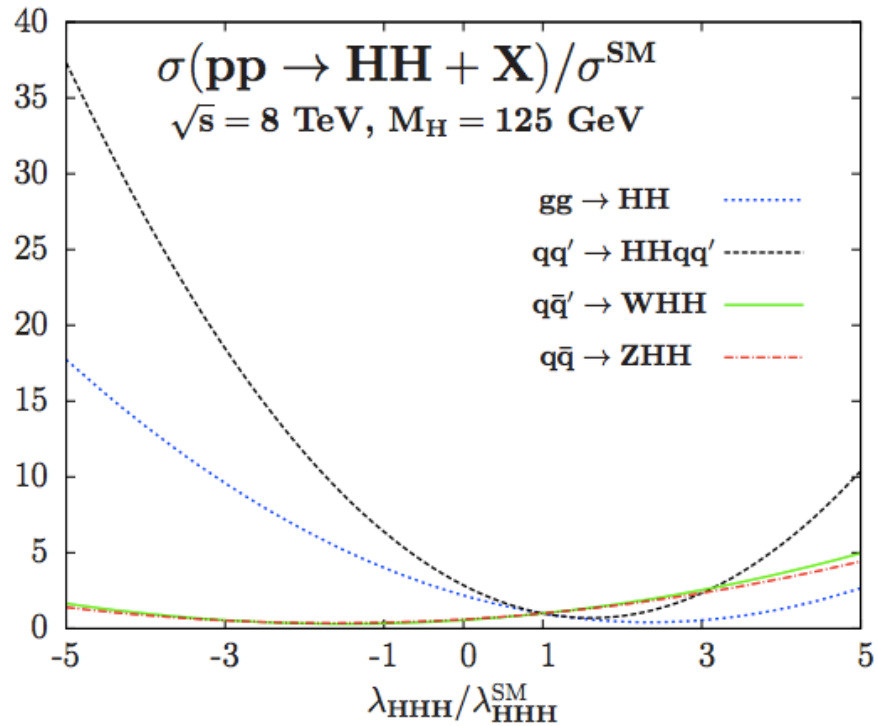




What about extensions to the SM?

arXiv:1212.5581



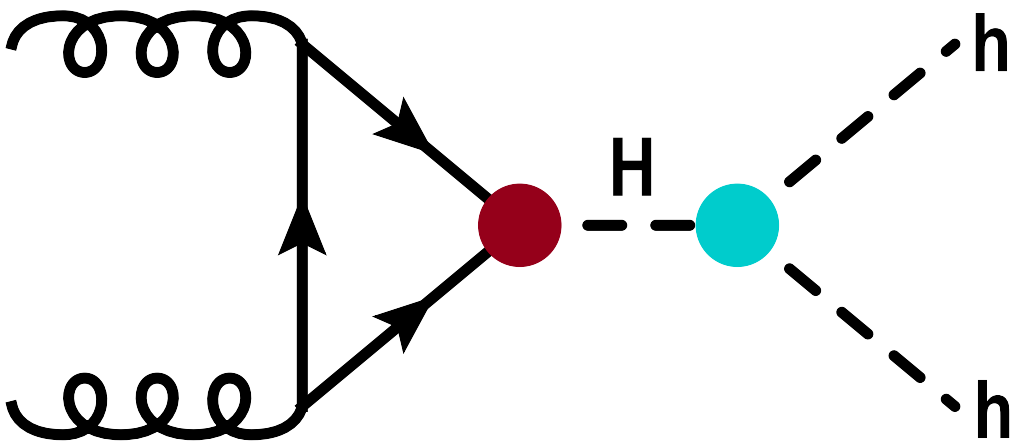


Altered self-coupling can significantly increase hh production rates

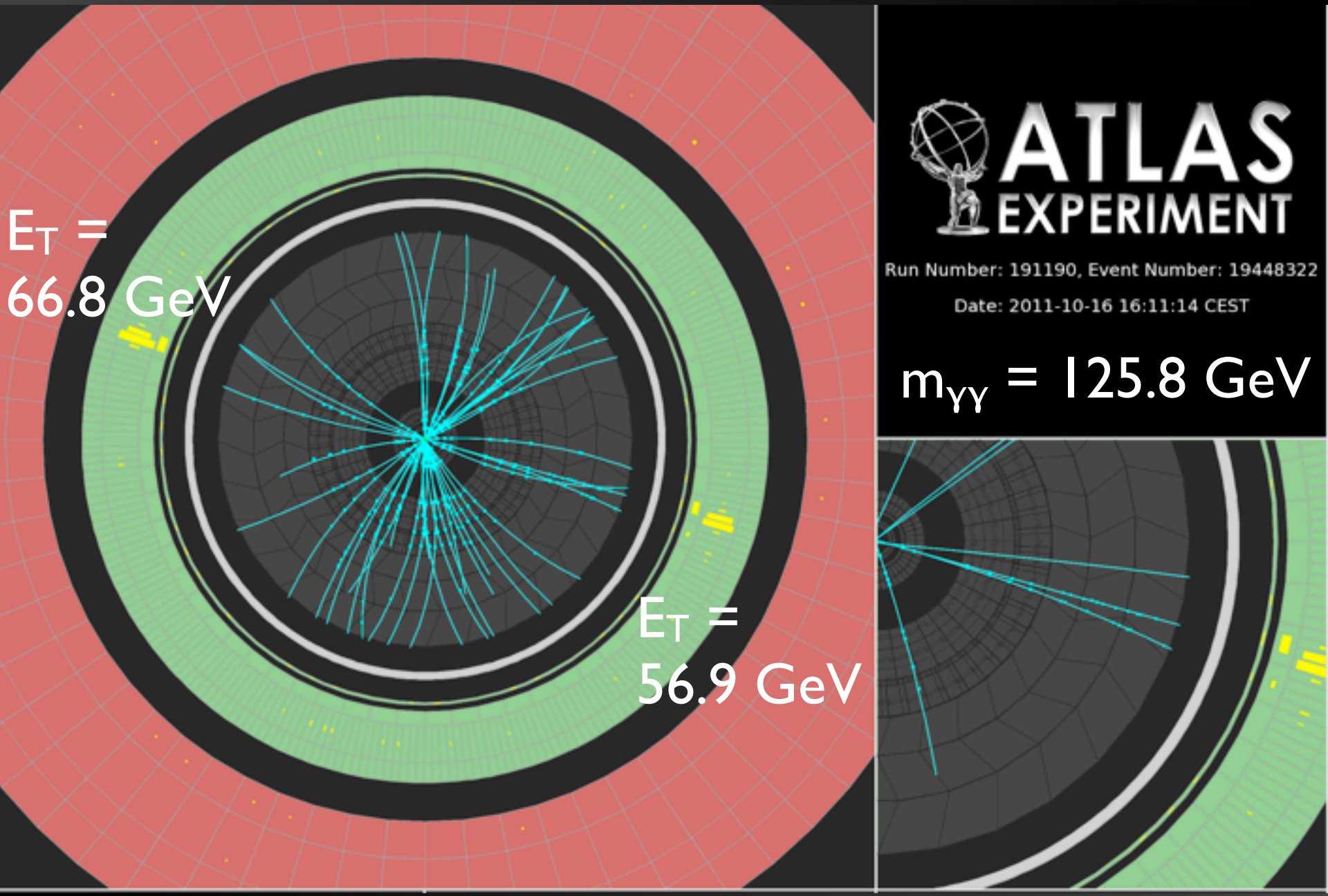
Resonant production?

arXiv:hep-ph/0009232, hep-ph/0503173, 1403.1253, 1305.2424,1206.6949, 1404.0996, among many

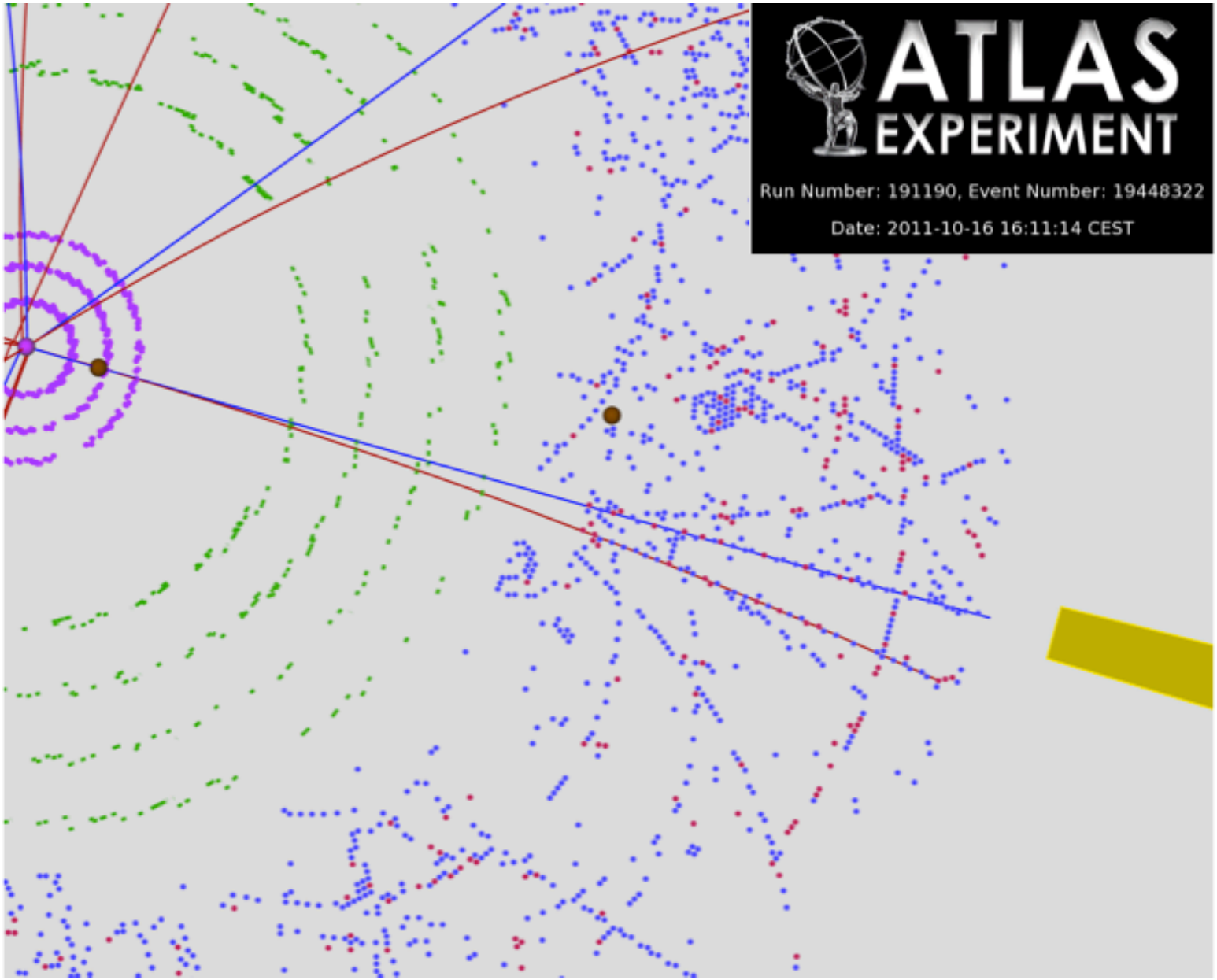
- Can enhance hh production resonantly as well
  - Two Higgs doublet models, Randall-Sundrum gravitons, radions, stoponium, ...



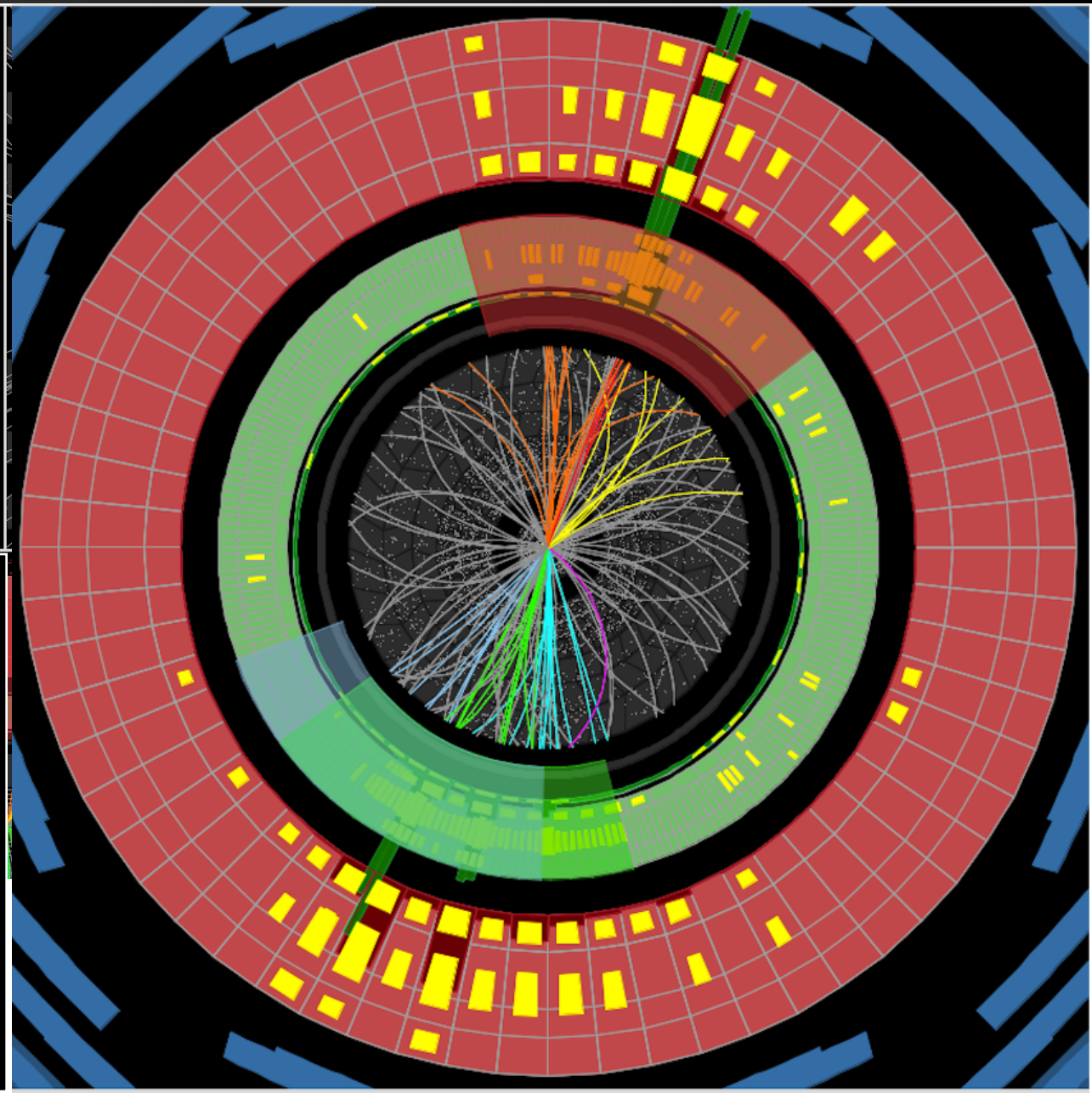
How to go about looking for Higgs bosons?



Zooming in on a converted photon

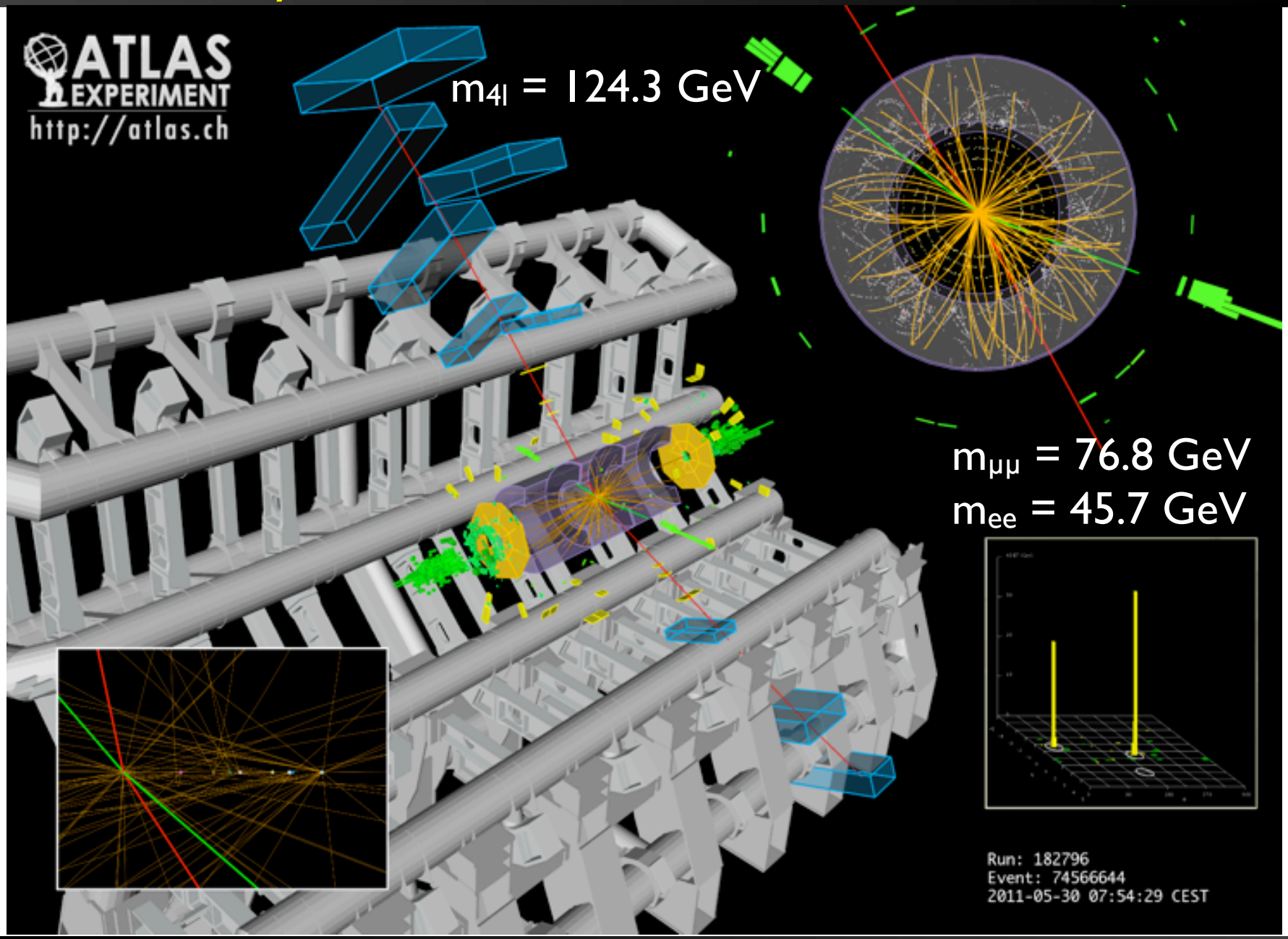


The calorimeters in action



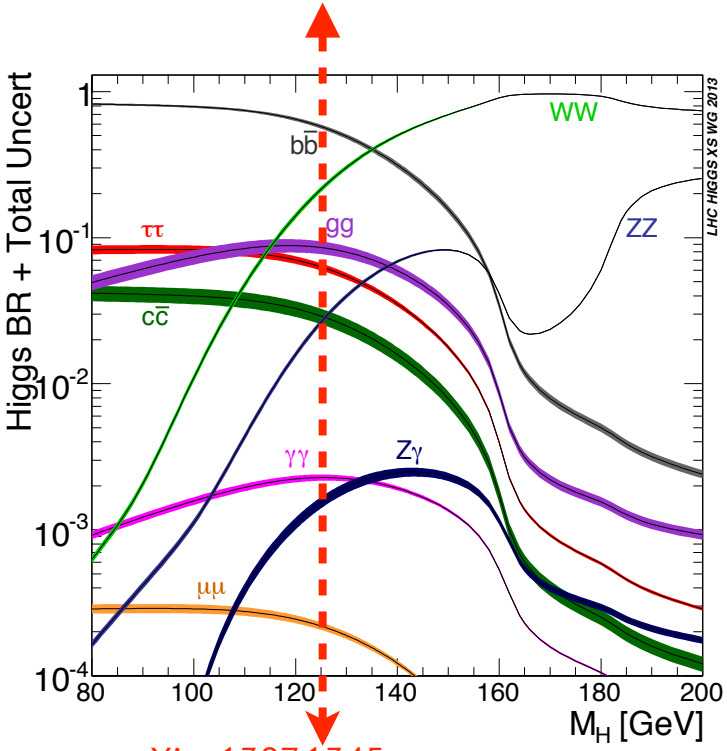
Invariant mass of two most energetic jets = 4.1 TeV

The muon subsystems



Looking for hh→bbγγ. Why?

- At known m_H, h→bb has highest Higgs BR (0.57)
- h→γγ has high efficiency and good mass resolution
  - Can perform full mass reconstruction
- h→ττ and h→WW have poor mass resolution vs γγ
- h→ZZ few events after require leptonic decays

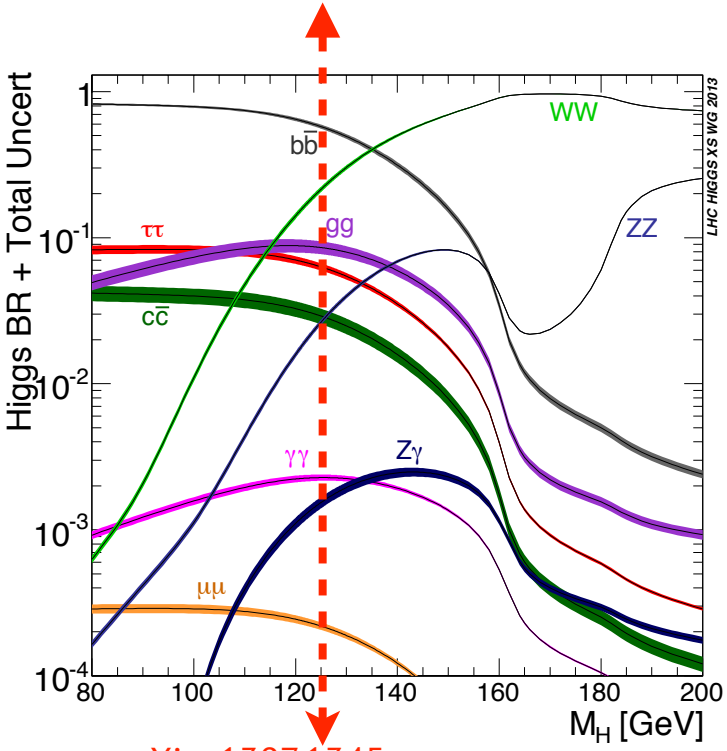


arXiv: 1307.1345

Looking for hh→bbγγ

ATLAS-CONF-2013-012

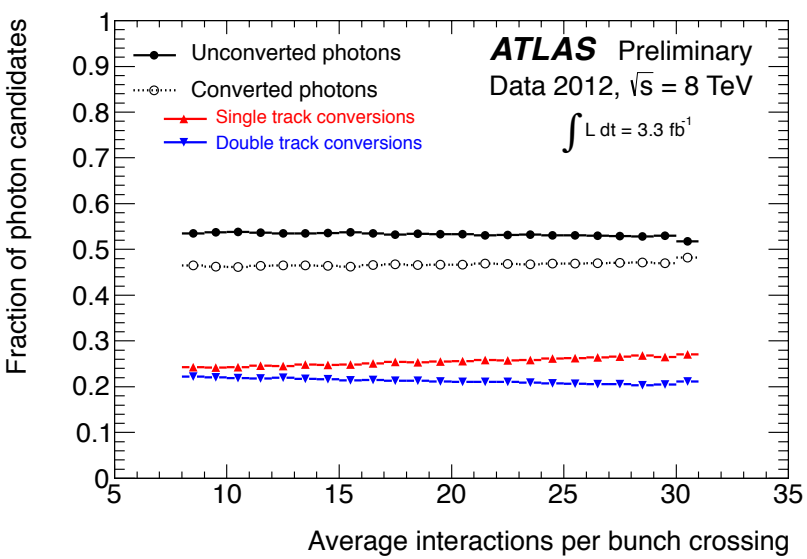
- Start with common ATLAS h→γγ selection
  - Loose diphoton trigger nearly 100% efficient for offline cuts
  - $p_T > 0.35(0.25)m_{\gamma\gamma}$ for leading (subleading) photon
  - $|\eta| < 2.37$ excluding $1.37 < |\eta| < 1.56$

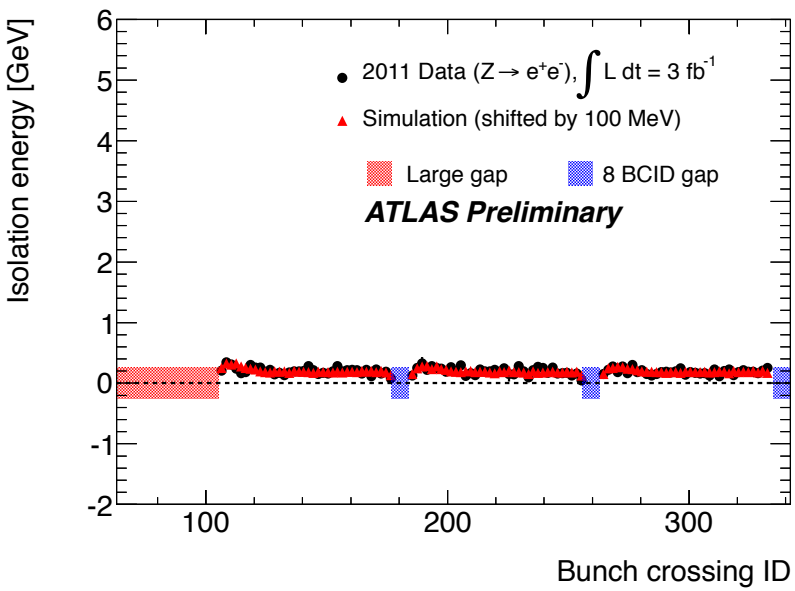


arXiv: 1307.1345

Photons for Higgs analyses

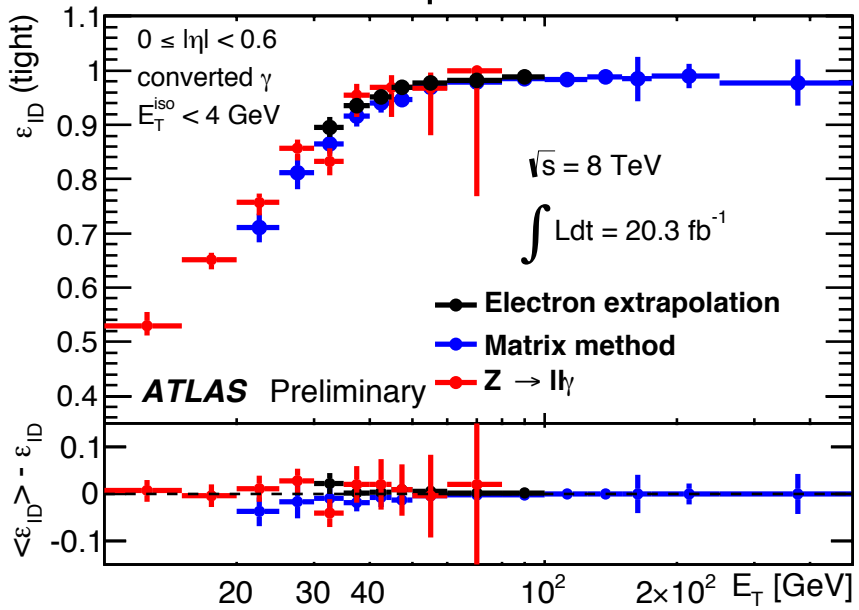
- Use "tight" photon ID. Can have unconverted, 1-track converted or 2-track converted photons, all isolated
  - Σp_T (tracks with pT > 1 GeV) in cone dR < 0.2 from photon < 2.6 GeV
  - ΣE_T (calorimeter) in cone dR < 0.4 from photon < 6 GeV, corrected for γ energy leakage and pileup



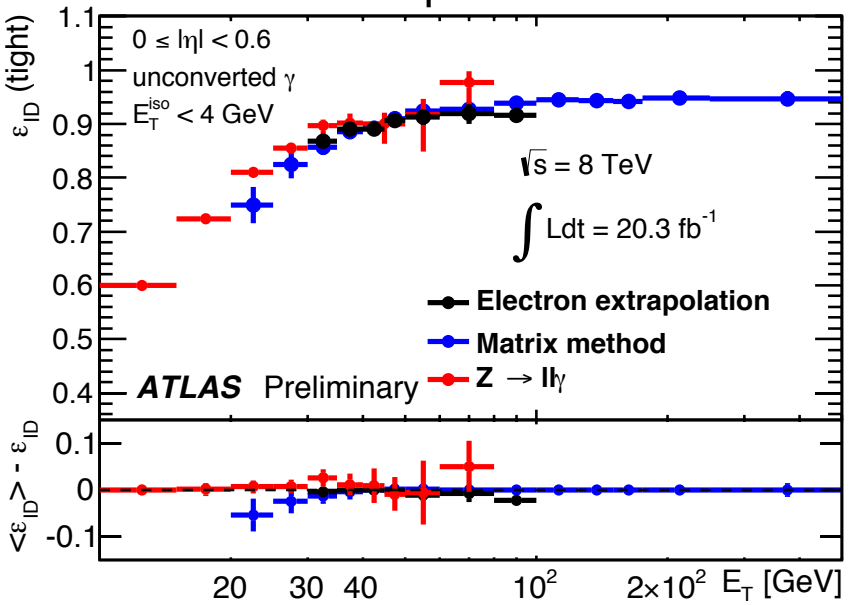


Efficiency extrapolated from Z→ee and measured in Z→llγ + matrix method using track isolation sidebands

Converted central photons



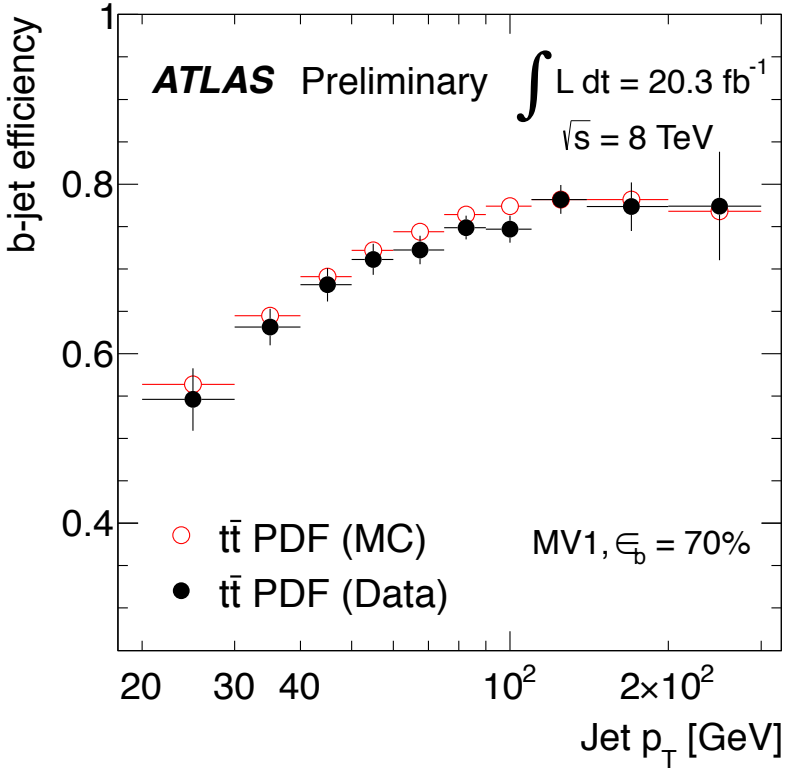
Unconverted central photons



Jets and b-tagging

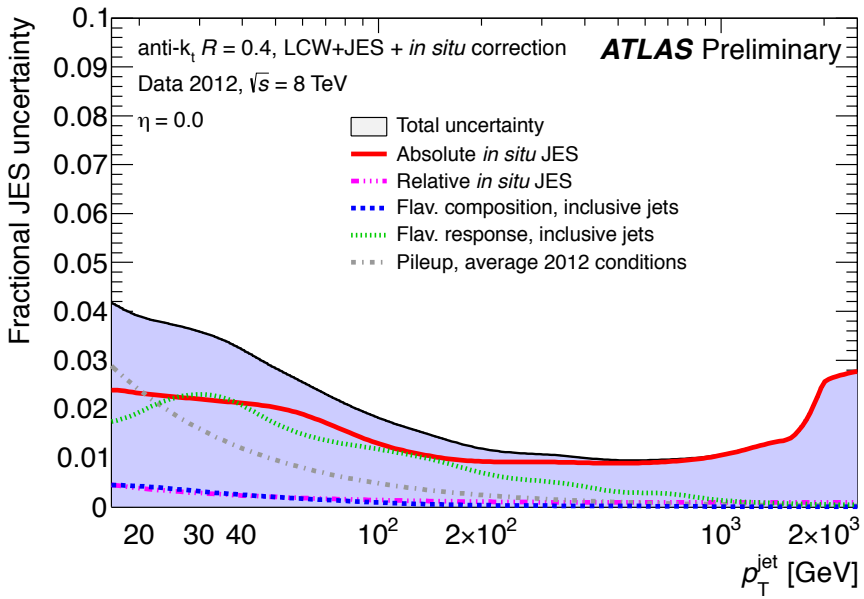
ATLAS-CONF-2014-004

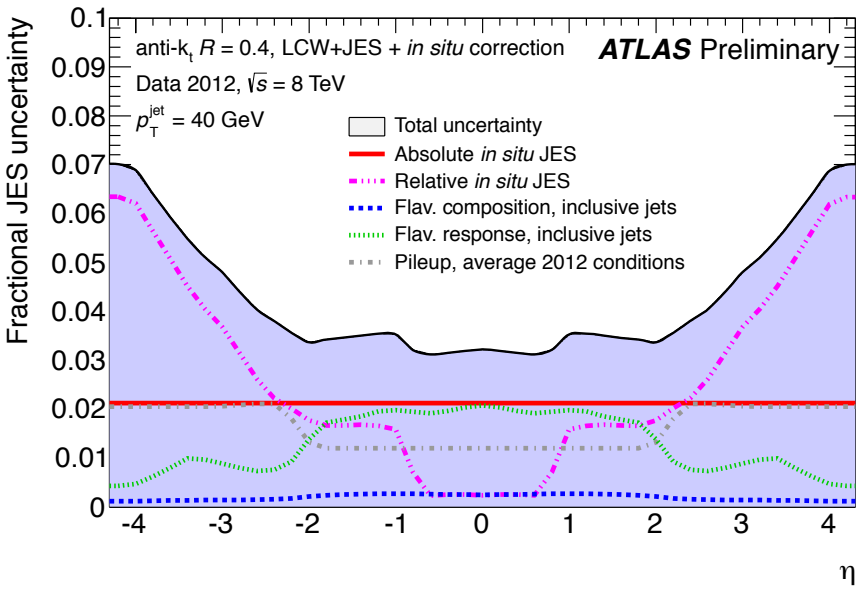
- Require two anti-k_T R=0.4 jets with $|\eta| < 2.5$
- Perform b-tagging using neural network tagger at 70% efficiency for b-jets in simulated ttbar events
  - Rejection factor 130x (4x) for light quark (charm) jets
  - Calibrate b-tag scale factors using dilepton ttbar events



Jets and bb invariant mass

- Leading jet pT > 55 GeV, subleading pT > 35 GeV after adding in 4-vectors of any muons with pT > 4 GeV with dR < 0.4 to jet
- Require 95 < m_{bb} < 135 [GeV], 75% efficiency for hh
  - Asymmetric cut optimized in simulation and largely due to energies losses from escaping neutrinos





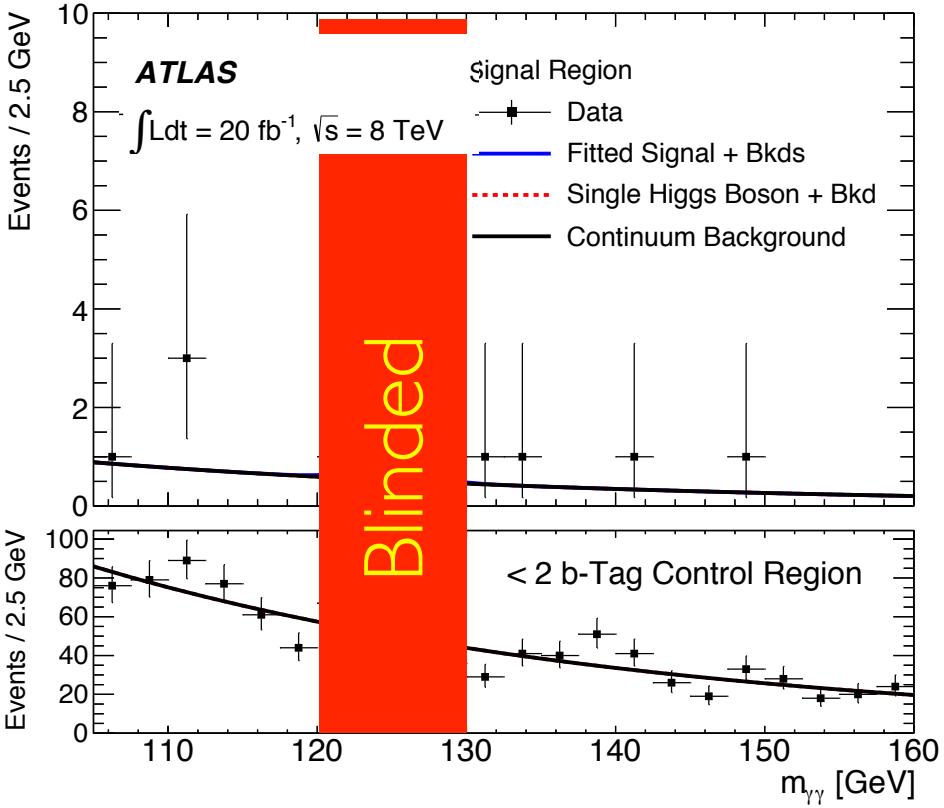
Strategy for hh→bbγγ

- Start by looking for non-resonant production of hh→bbγγ
  - Signal region is two photons with invariant mass consistent with m_h + two b-tagged jets with mass loosely consistent with m_h
- Cuts optimized for discovery while trying to maintain as simple a selection as possible at the same time

Continuum background estimation for hh→bbγγ

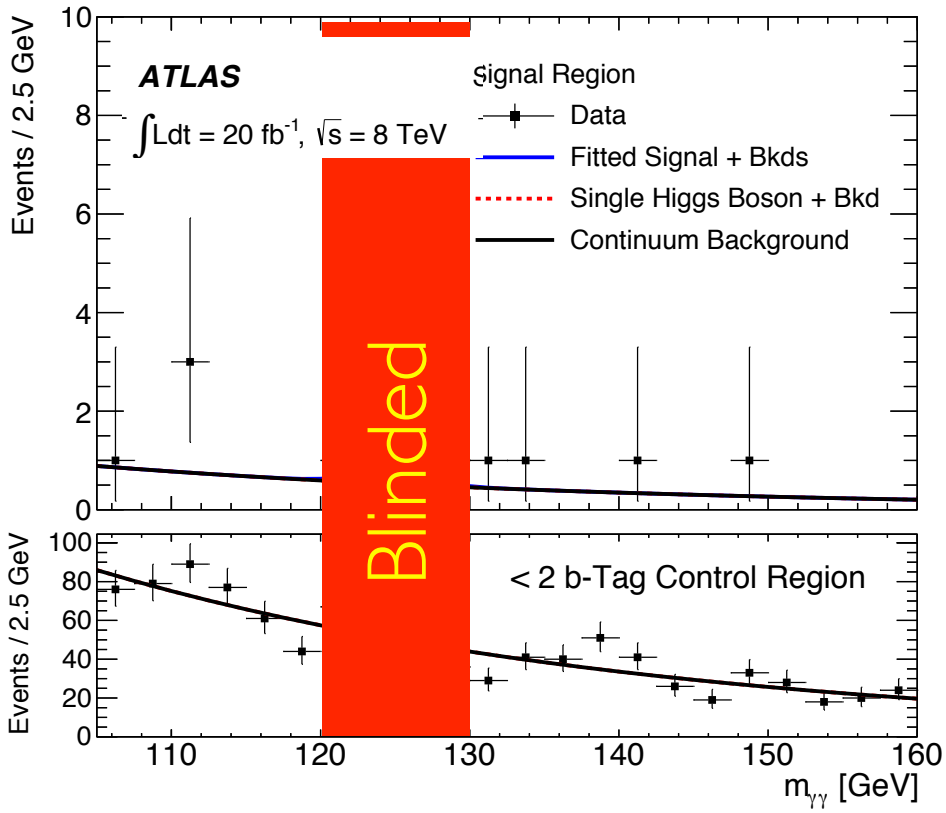
arXiv:1406.5053

- All backgrounds without a Higgs boson estimated using m($\gamma\gamma$) sideband, which is fit to an exponential and extrapolated to signal region
  - Normalization comes from sidebands
  - Slope of the exponential constrained by fitting events with < 2 b-tags



Continuum background estimation for hh→bbγγ

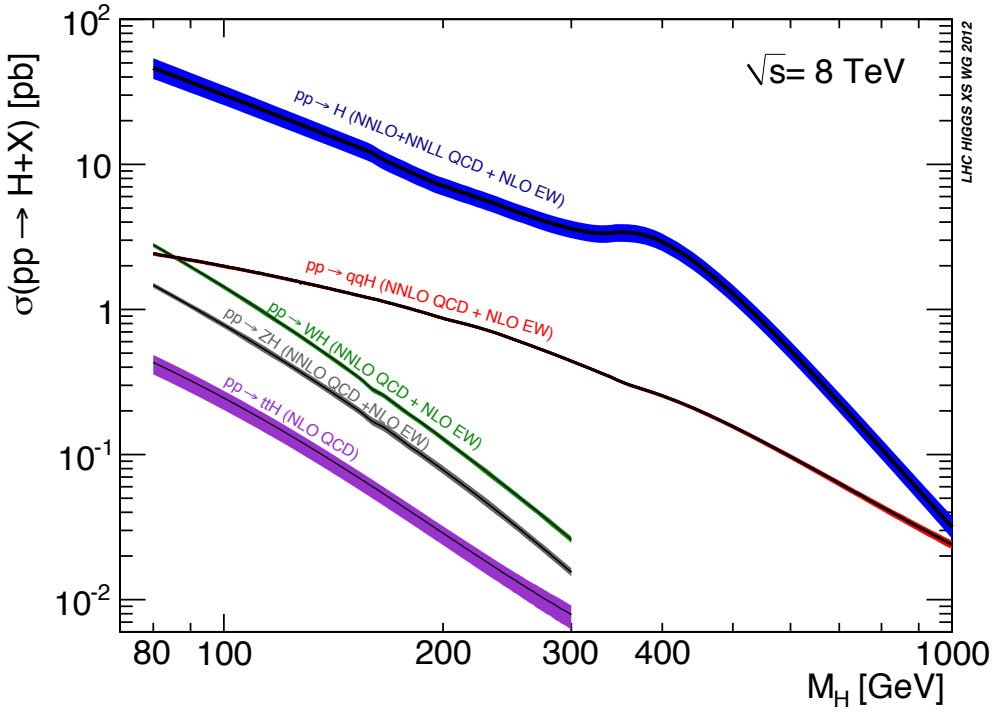
- Take advantage of good diphoton mass resolution ~1.6 GeV
- Note the normalization uncertainty of ~30-35% that cannot be avoided



Higgs background estimation for hh→bbγγ

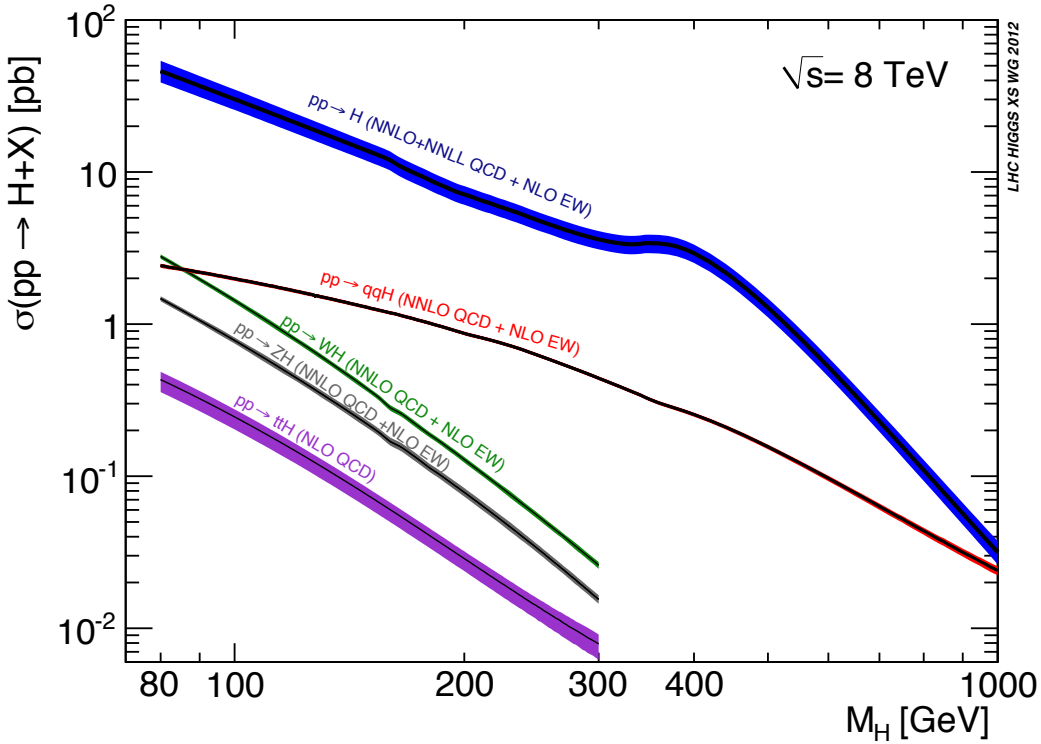
arXiv: 1307.1345

- Smaller backgrounds with single Higgs boson estimated from simulation
  - W/Z/tt + Higgs from Pythia8
    - WH xsec at NLO with EW corrections
    - ZH xsec at NNLO with EW corrections
    - ttH xsec at NLO



Higgs background estimation for hh→bbγγ

- gg and VV fusion with Powheg-Box
  - ggF xsec at NNLO+leading-log resummation and EW corrections
  - VV fusion at NLO+EW and approximate NNLO corrections
- bbH estimated to be negligible with our p_T and mass cuts



Signals for hh→bbγγ

- SM pair production of hh produced with Madgraph5+Pythia8, including interference between diagrams
- Resonant hh production modeled with a gluon-initiated spin-0 resonant state in a narrow-width approximation (NWA)
  - qq-initiated NWA signals give very similar kinematics and efficiencies
  - Radions would be in the NWA
  - Gravitons would not be in the NWA
  - Most interesting regions ($2m_h < m_H < 2m_t$) of 2HDM phase space are in the NWA

Systematic uncertainties for hh→bbγγ

All small compared to statistical uncertainties

Systematic uncertainty		Non-Resonance Analysis		
		Single h Bkgd	hh Signal	Continuum
Trigger	[%]	0.5		–
Luminosity	[%]	2.8		–
Photon	Identification [%]	2.4		–
	Isolation [%]	2		–
Mass	Resolution [%]	Resolution: 13		–
	Position	Value: +0.5/-0.6 GeV		–
Shape	$m_{\gamma\gamma}$ Continuum Shape [%]	–		11
	$m_{\gamma\gamma b\bar{b}}$: Statistical [%]	–		–
	$m_{\gamma\gamma b\bar{b}}$: jj vs bb [%]	–		–
	$m_{\gamma\gamma b\bar{b}}$: Fit Model [%]	–		–
Jets	b-Tagging [%]	3.3	1.8	–
	Energy Scale [%]	6.5	1.4	–
	b-jet Energy Scale [%]	2.6	0.3	–
	Energy Resolution [%]	4.8	6.3	–
Theory	PDF+Scale [%]	8.4	–	–
	Single h+HF [%]	14	–	–

Fit sidebands to 0-tag data, 1-tag, data with non-isolated photons, and using flat function (largest=11%)

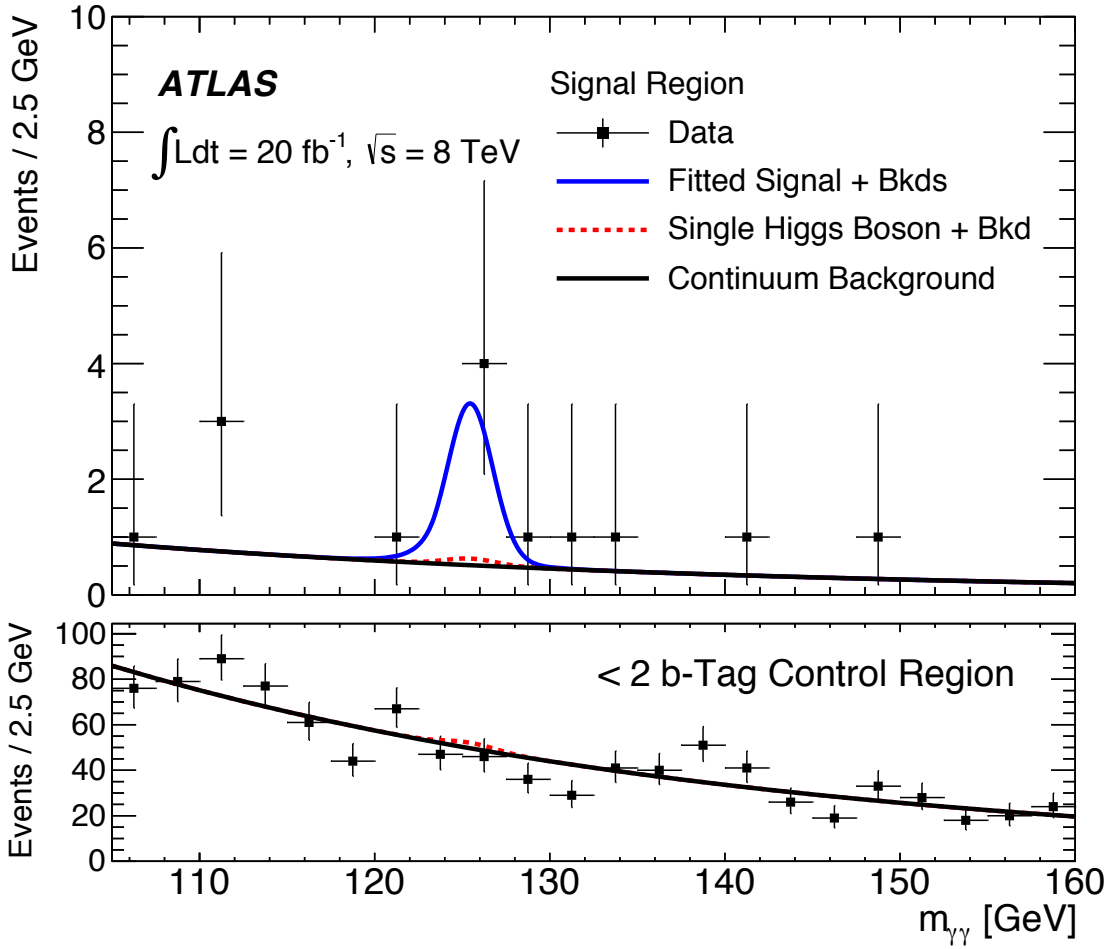
100% uncertainty on gg and VBF due to HF content

Backgrounds for hh→bbγγ

Process	Fraction of total
ggH	11%
qqH	2%
WH	1%
ZH	17%
$t\bar{t}H$	69%
Total	0.17 ± 0.04 Events

- Compares with 0.04 hh events and 1.3 events from continuum backgrounds in $\pm 2\sigma(m_{\gamma\gamma})$
- Continuum split evenly between $\gamma\gamma$jj and γjjj
  - j can be b, c or light
  - ttbar ~ 10% of the total

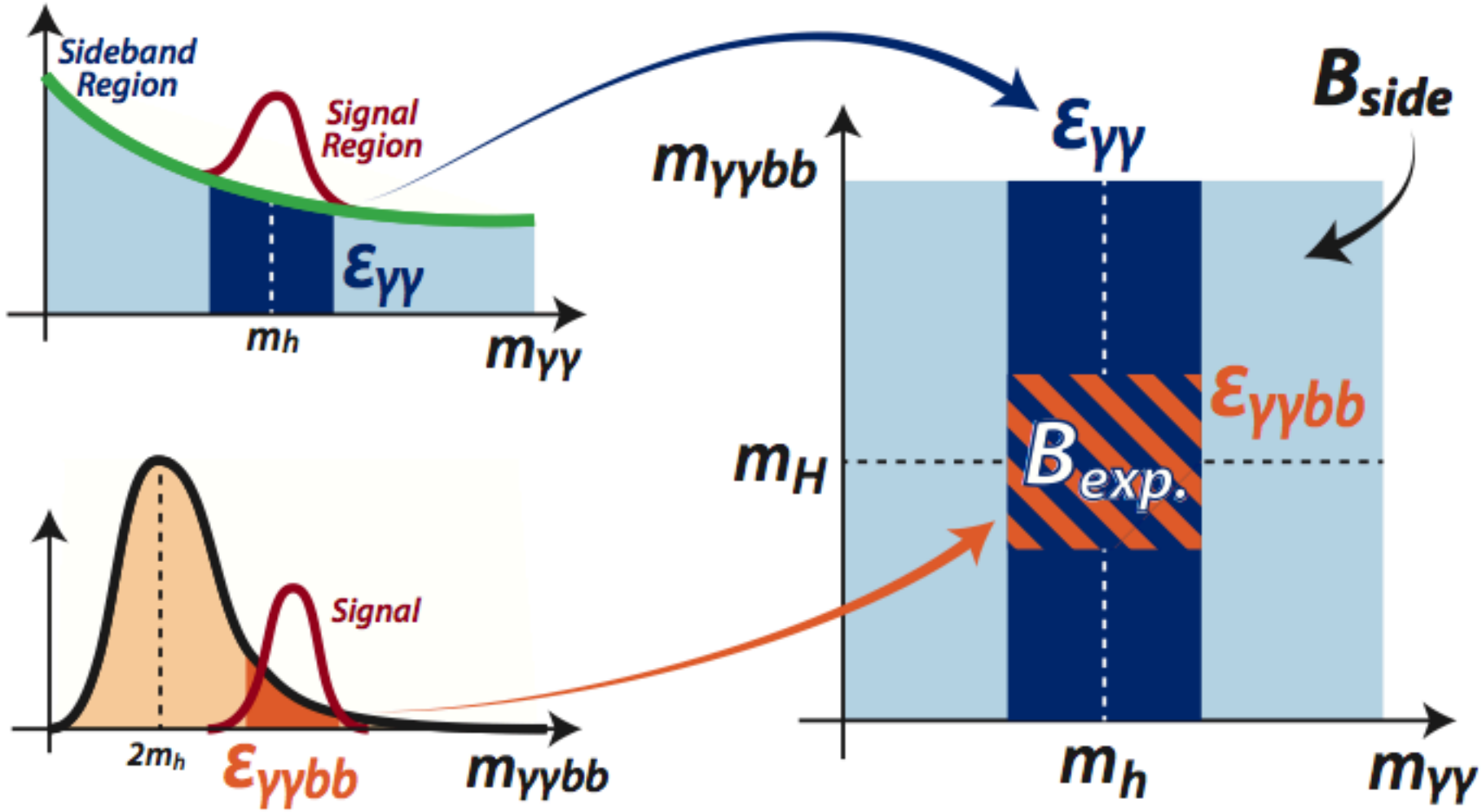
Results for non-resonance hh→bbγγ search



- 1.5 background events expected
- 5 events observe
  - 2.4σ from background-only hypothesis
- 95% CL upper limit on hh production of 2.2 pb (expected 1.0 pb)

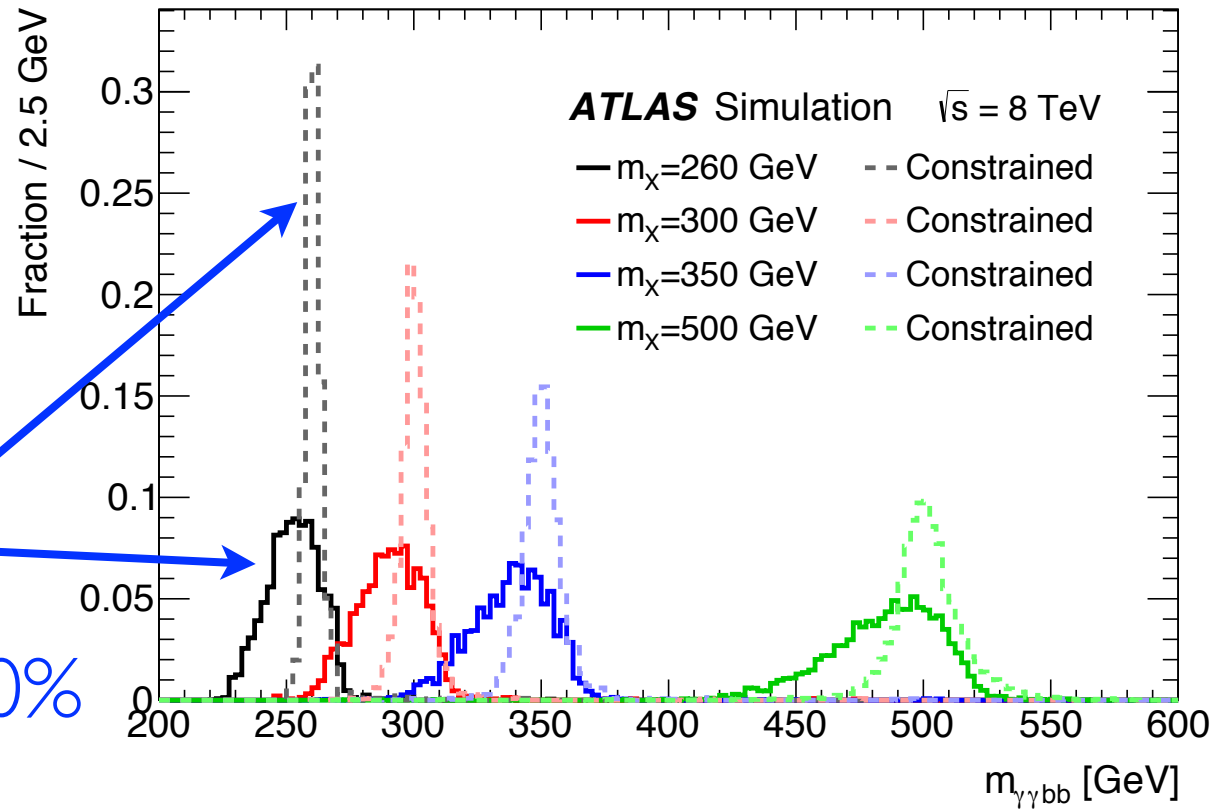
Continue with previous analysis but add additional feature of resonance in 4-object invariant mass

The resonance search



Searching for X→hh→bbγγ

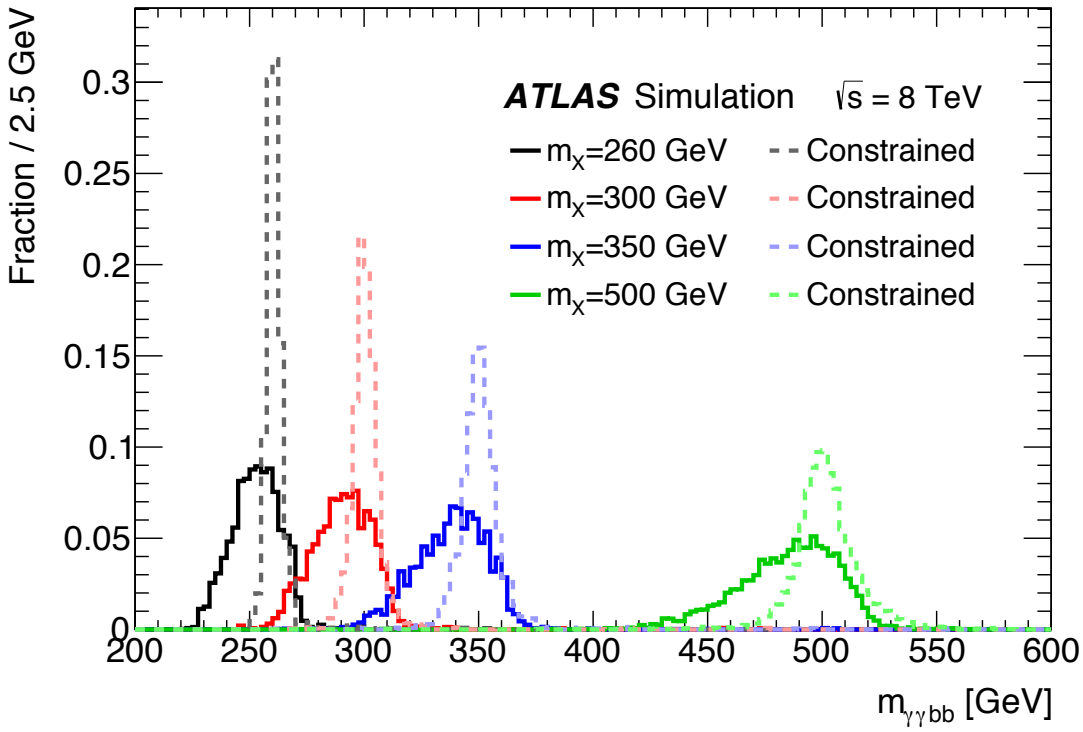
- Useful to improve 4-object invariant mass resolution as much as possible to reject background while maintaing signal efficiency
  - Once we select objects, require m_{bb} to give back 125 GeV (by scaling the combined bb 4-vector)



Improves mass resolution by 30-60%

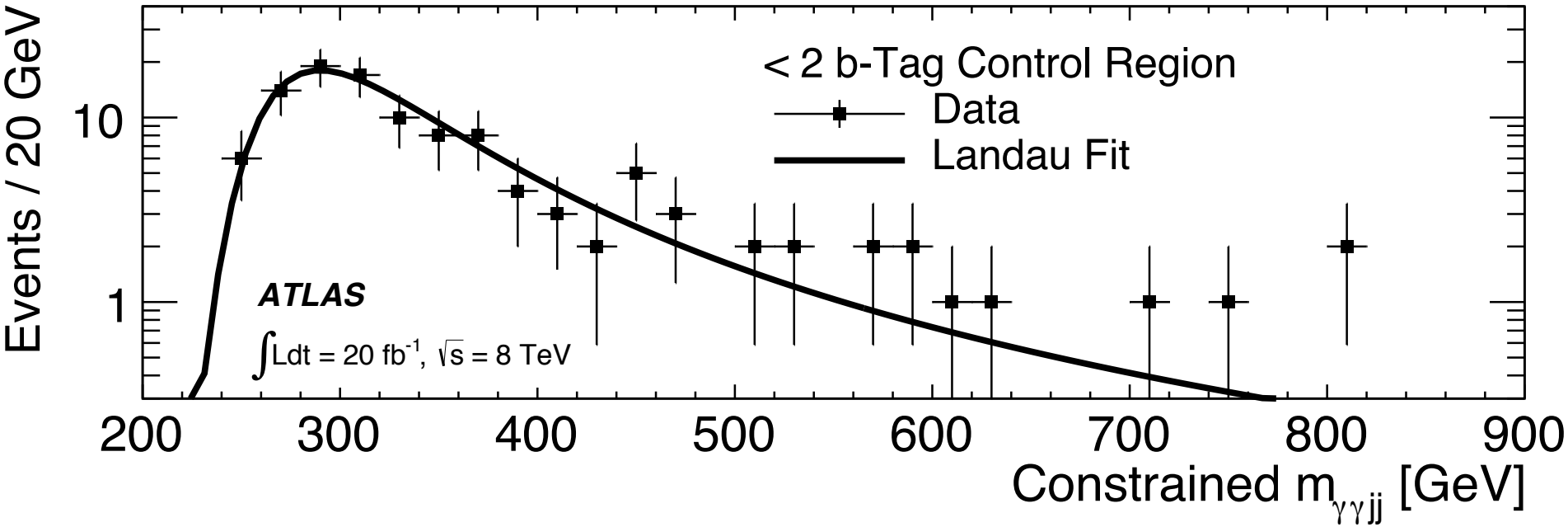
How to use rescaled mass

- Require $m_{\gamma\gamma bb}$ to be within window around resonance mass m_H with 95% signal efficiency
  - Window varies from 17 GeV (m_X = 260 GeV) to 60 GeV (m_X = 500 GeV)



Efficiency for continuum to pass this cut?

- Measure efficiency of continuum to pass this cut using events with <2 b-tags, fit with a priori Landau function
  - For m_X = low (260 GeV) and high (500 GeV) m_H, efficiency for continuum < 8%
  - For m_X = 300 GeV, 18% of continuum cut



How to perform the resonance search?

Cannot fit sidebands after resonance selection (likely no events left).
Instead, perform cut-and-count analysis around $\pm 2\sigma$ of m_h (in $m_{\gamma\gamma}$) and our window of $m_{\gamma\gamma bb}$

Systematic uncertainties in resonance search

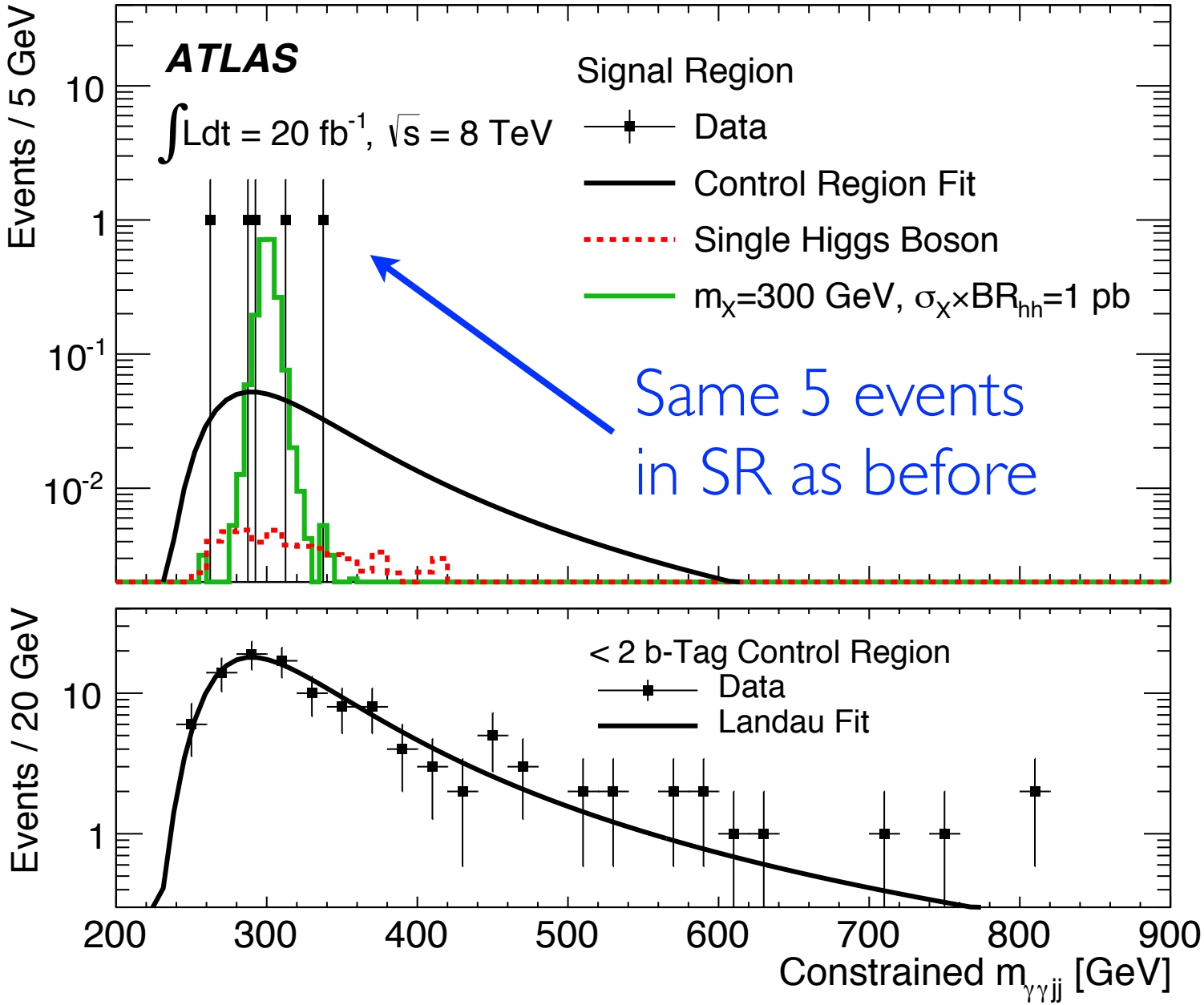
All very small compared to statistical uncertainties

Systematic uncertainty		Resonance Analysis		
		SM $h + hh$ Bkgd	$H \to hh$ Signal	Continuum
Trigger	[%]	0.5		–
Luminosity	[%]	2.8		–
Photon	Identification [%]	2.4		–
	Isolation [%]	2		–
Mass	Resolution [%]	Migration: 1.6		–
	Position	Migration: 1.7%		–
Shape	$m_{\gamma\gamma}$ Continuum Shape [%]	–		11
	$m_{\gamma\gamma b\bar{b}}$: Statistical [%]	–		3-18
	$m_{\gamma\gamma b\bar{b}}$: jj vs bb [%]	–		0-30
	$m_{\gamma\gamma b\bar{b}}$: Fit Model [%]	–		16-30
Jets	b-Tagging [%]	3.4	2.4	–
	Energy Scale [%]	19	3.8	–
	b-jet Energy Scale [%]	6.5	2.2	–
	Energy Resolution [%]	15	9.3	–
Theory	PDF+Scale [%]	+18/-15	–	–
	Single h+HF [%]	14	–	–

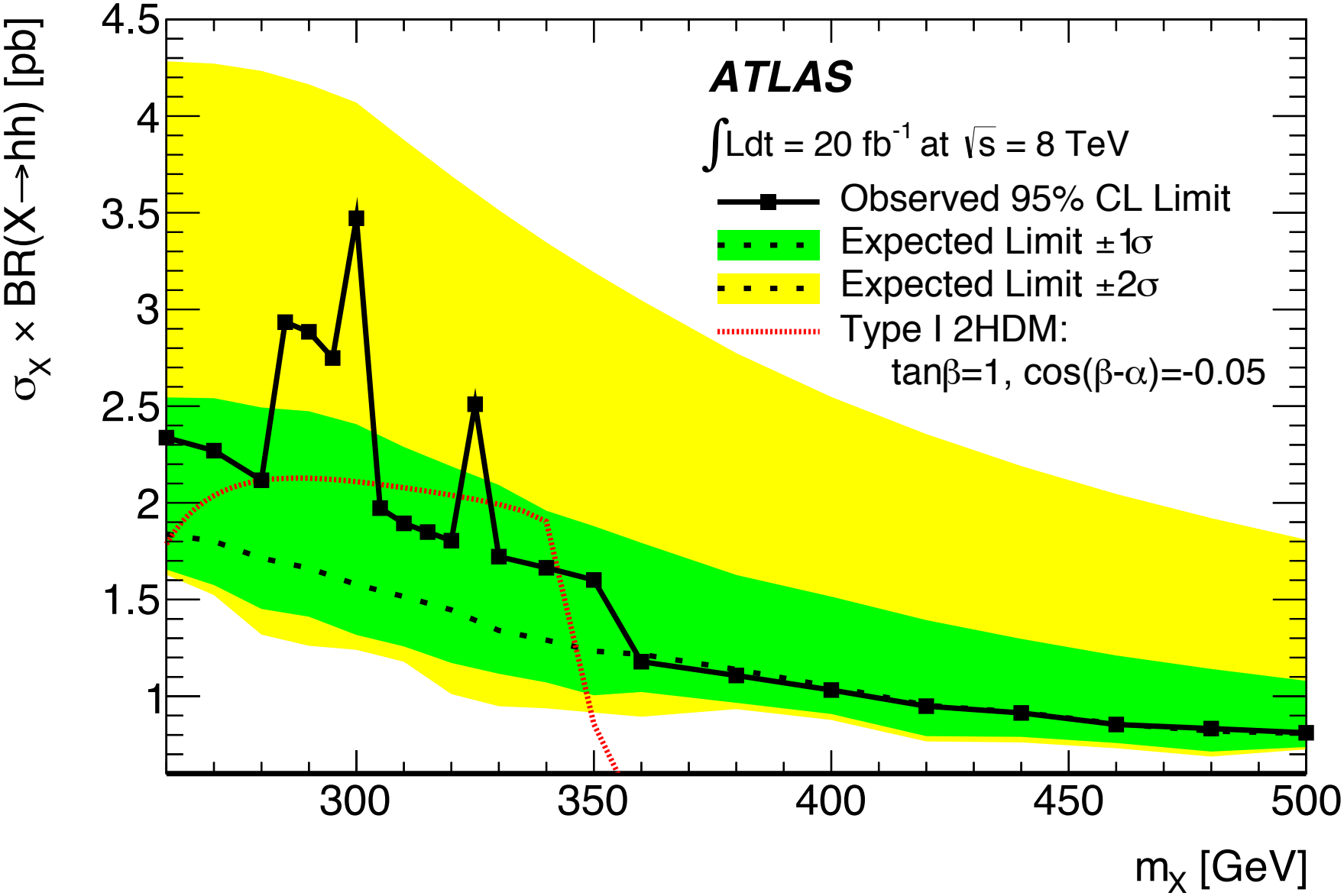
Use simulation to evaluate differences in shape between γγbb and γγjj masses

Use alternate fit functions to Landau distribution

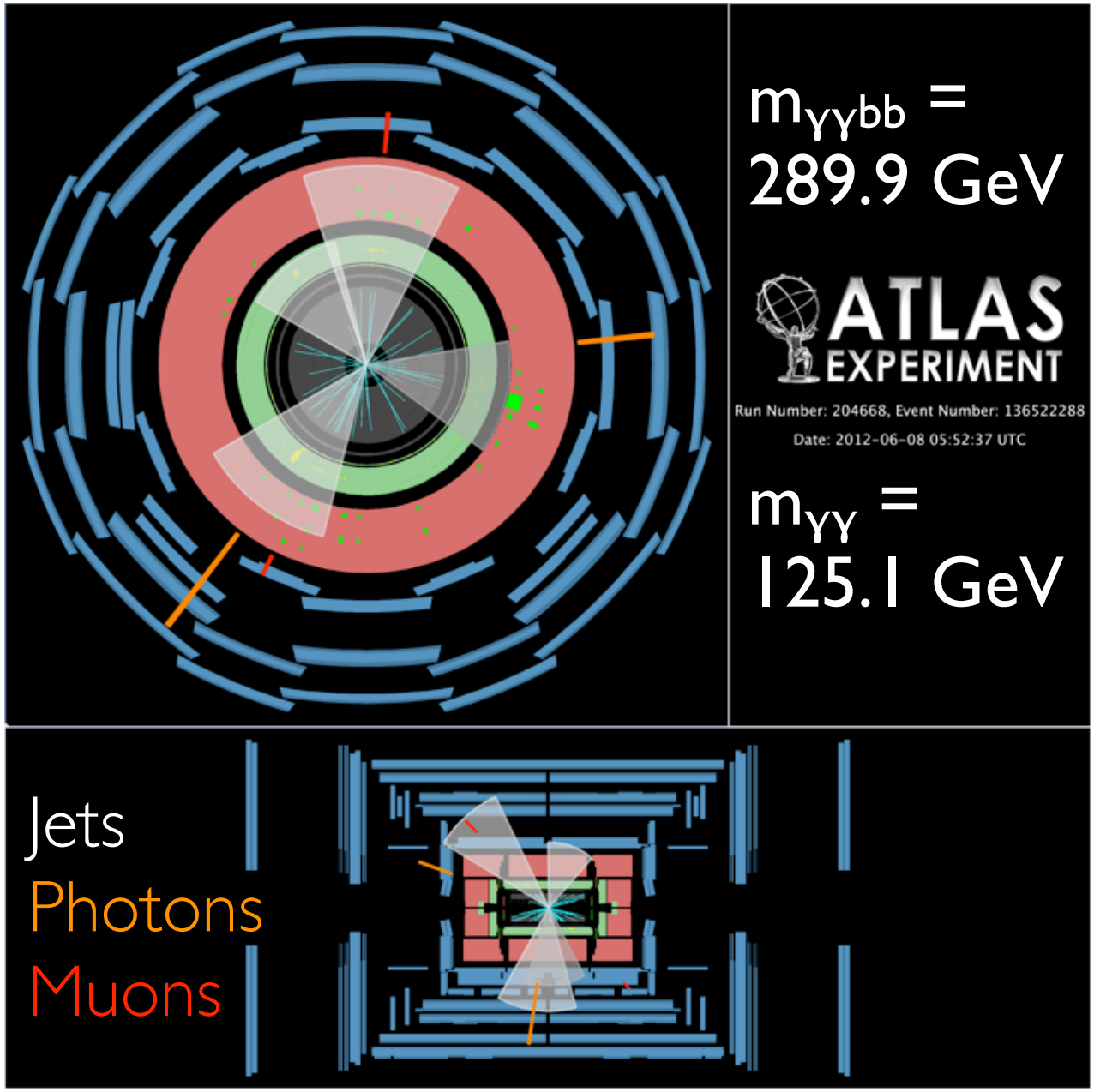
$m_{\gamma\gamma bb}$ mass in resonance search



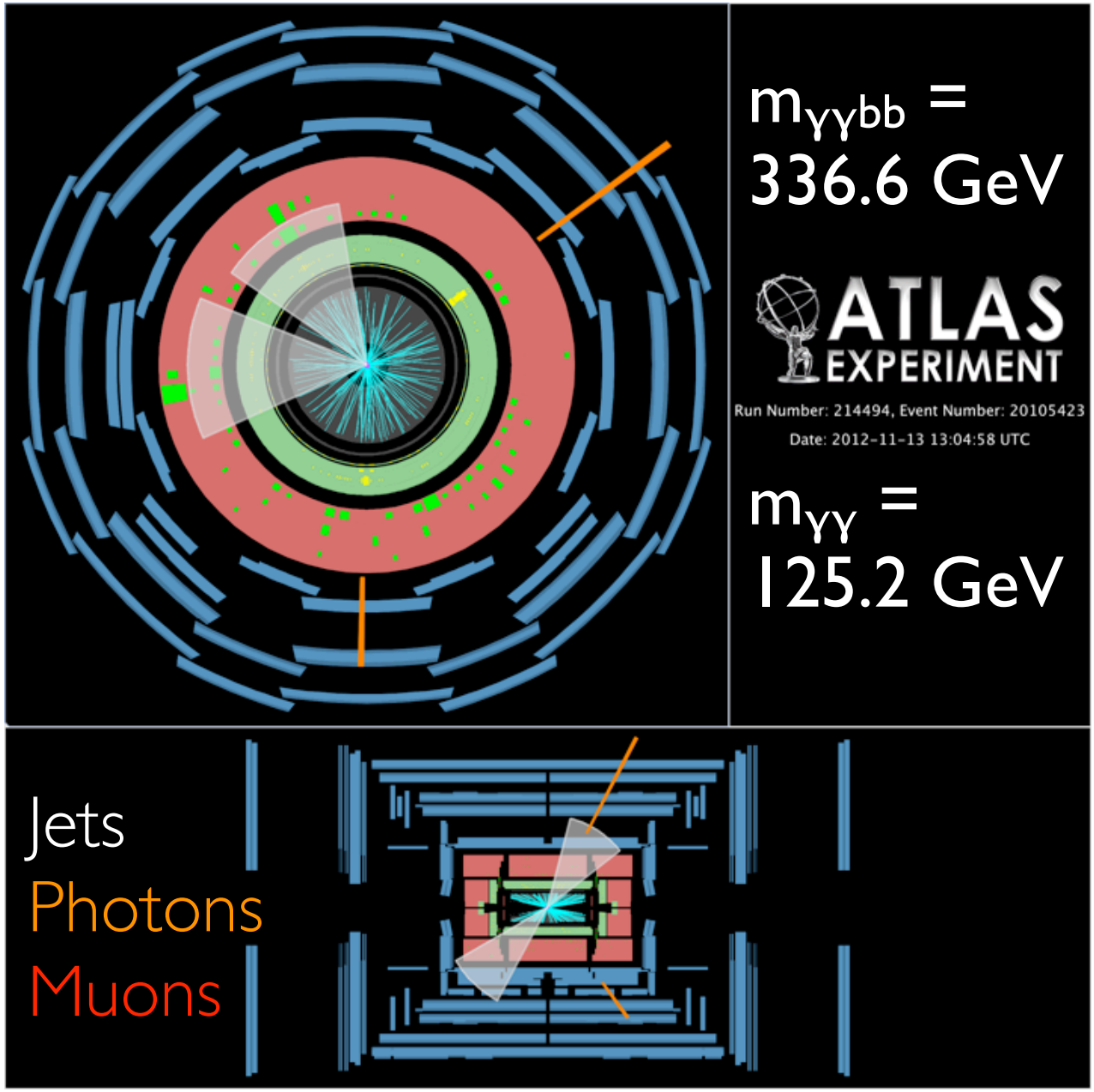
Limits in resonance search



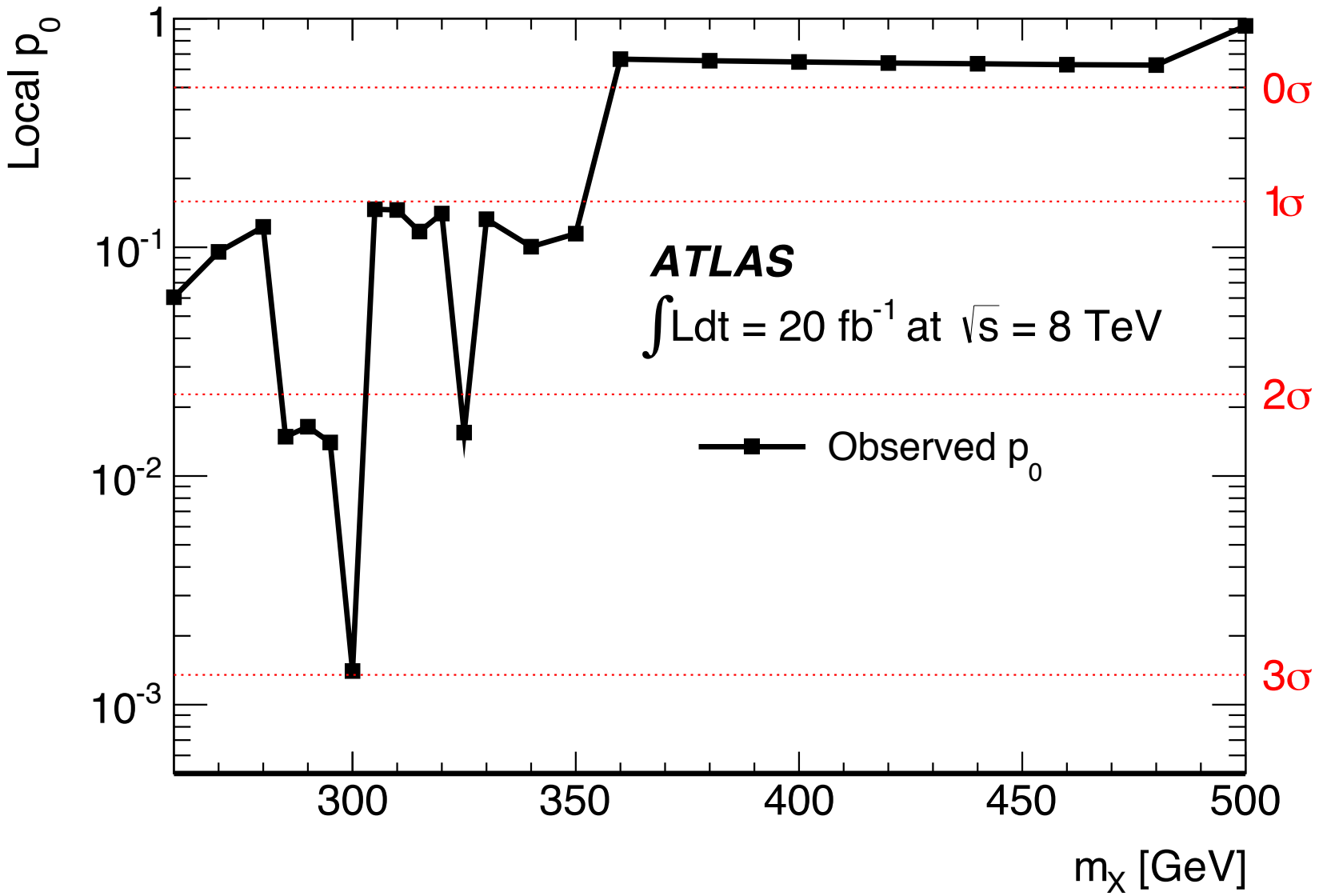
Event displays



Event displays



p-values in resonance search



Global p-value = 2.1σ

Those who pay attention to these things may have noticed that CMS also has a recent CONF note searching for hh resonances in the $\gamma\gamma$bb channel

Comparing ATLAS and CMS

CMS-PAS-HIG-13-032

	ATLAS	CMS
Jet p_T	55/35 GeV	25 GeV
Tag requirement	≥ 2tag	Separate 1tag and ≥2tag regions for signal
m_{jj} range	95-135 GeV	85-155 GeV
m_{jj} method	4-vector scaling	Kinematic fit
Resonance limit method	Counting experiment	Sideband fit
Non-resonance limit	Yes	No
Signal at 300 GeV	CMS ~50% larger in 2-tag channel	
Background at 300 GeV	CMS ~400% larger in 2-tag channel	
Limit at 300 GeV	CMS ~50% better (expected)	

Switching topics again

Searching for X→hh→bbbb

Search for resonant pair production of Higgs bosons via X→hh→bbbb

Dominant background is multi-jet background, subleading background is ttbar production

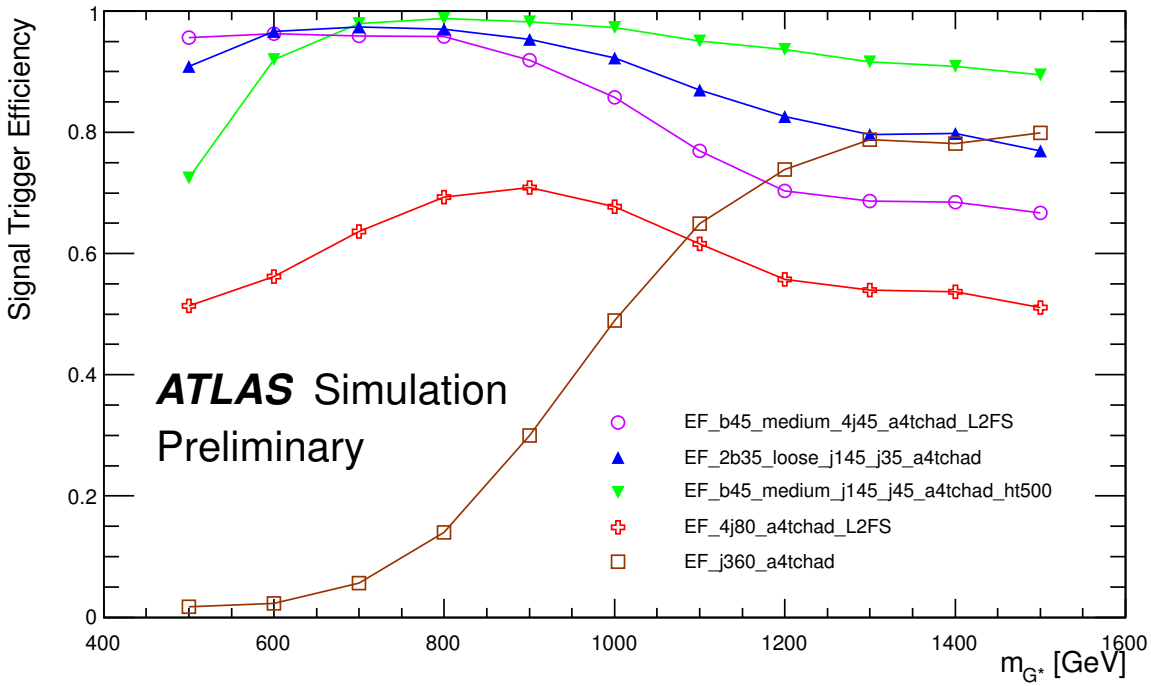
Searching for X→hh→bbbb

ATLAS-CONF-2014-005

- 4b analysis much more sensitive at high m_X, where the backgrounds can be kept to a manageable rate
  - Look for m_X starting at 500 GeV
- Larger signals, but multijet backgrounds require data-driven methods to trust predictions
- Benchmark signal model: Randall-Sundrum graviton with a warped extra dimension
  - $k/\bar{M}_{pl}$ set to unity
  - Resonance smaller than 4j mass resolution
  - Modeled with Madgraph interfaced to Pythia8

4b triggers

ATLAS-CONF-2014-005



Combination of 5 non-prescaled triggers → > 99.5% efficiency with respect to offline selection for mass range of interest

4b event selection

- Require 4 b-tagged jets with $p_T > 40$ GeV
- Look for dijet systems with pt(jj) > 200 GeV and dR(j,j) < 1.5
- Look for extra jets with pT > 30 GeV and dR(jj) < 1.2 to form ttbar system, and calculate:

$$X_{tt} = \sqrt{\left(\frac{m_W - \tilde{m}_W}{\sigma_{m_W}}\right)^2 + \left(\frac{m_t - \tilde{m}_t}{\sigma_{m_t}}\right)^2}$$

$0.1 m_W$ $0.1 m_t$

- m_t from 3-jet mass, m_W mass of extra jet and b-jet with lowest b-tag probability
- Reject events if $X_{tt} < 3.2$ (keeps 90% signal, rejects 60% ttbar background)

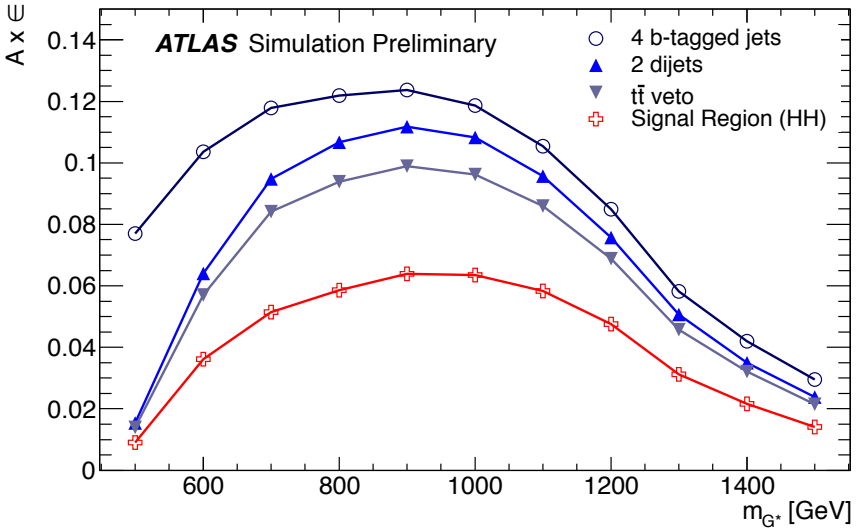
4b event selection

- Form X_{HH} from pairs of dijets:

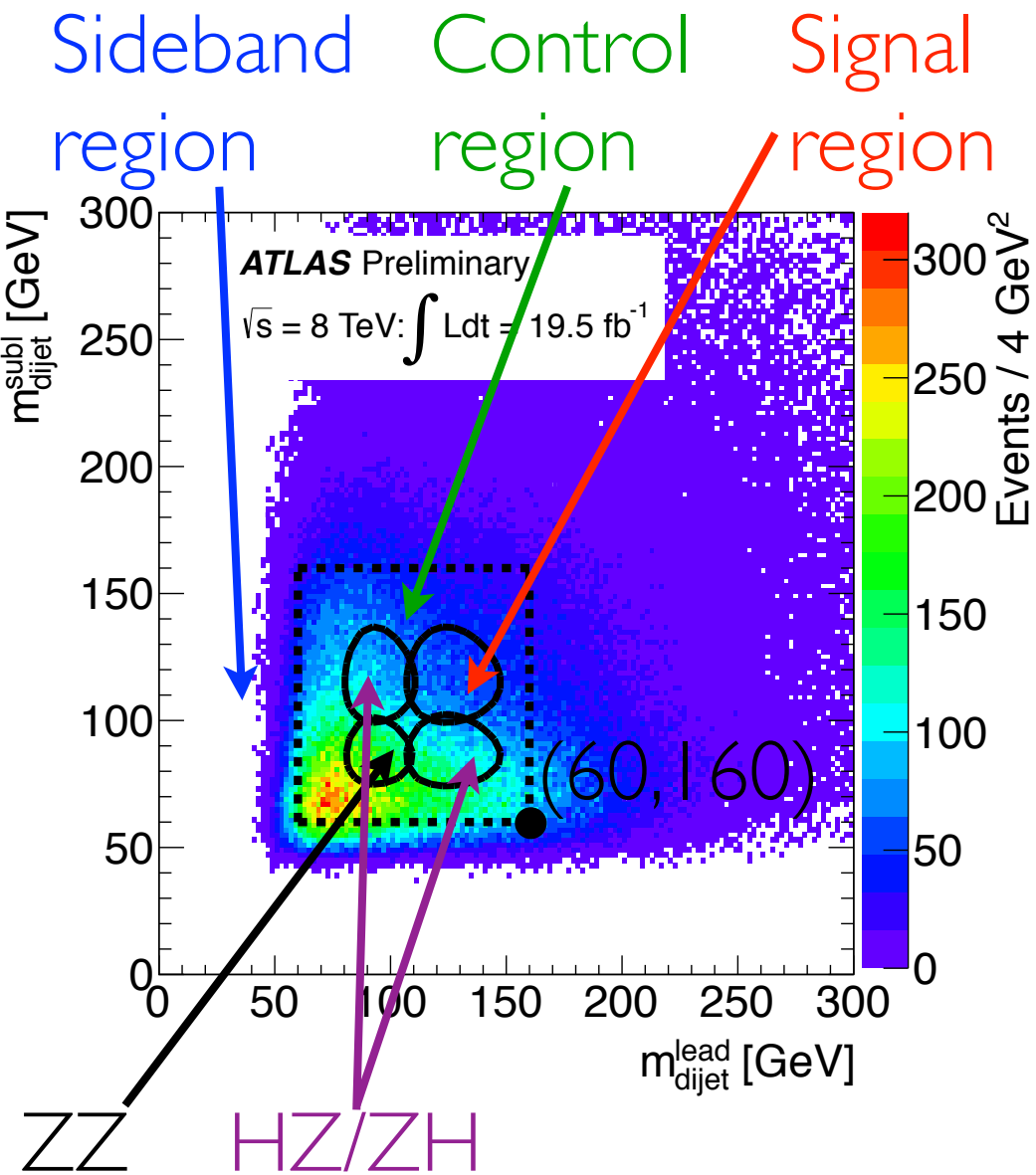
$$X_{HH} = \sqrt{\left(\frac{m_{\text{dijet}}^{\text{lead}} - \tilde{m}_{\text{dijet}}^{\text{lead}}}{\sigma_{m_{\text{dijet}}^{\text{lead}}}}\right)^2 + \left(\frac{m_{\text{dijet}}^{\text{subl}} - \tilde{m}_{\text{dijet}}^{\text{subl}}}{\sigma_{m_{\text{dijet}}^{\text{subl}}}}\right)^2}$$

$0.1\,m_{lead}$ $0.1\,m_{subl}$

- $\tilde{m}^{lead} = 124$ GeV, $\tilde{m}^{subl} = 115$ GeV, optimized in simulation
- Require $X_{HH} < 1.6$ to be in signal region

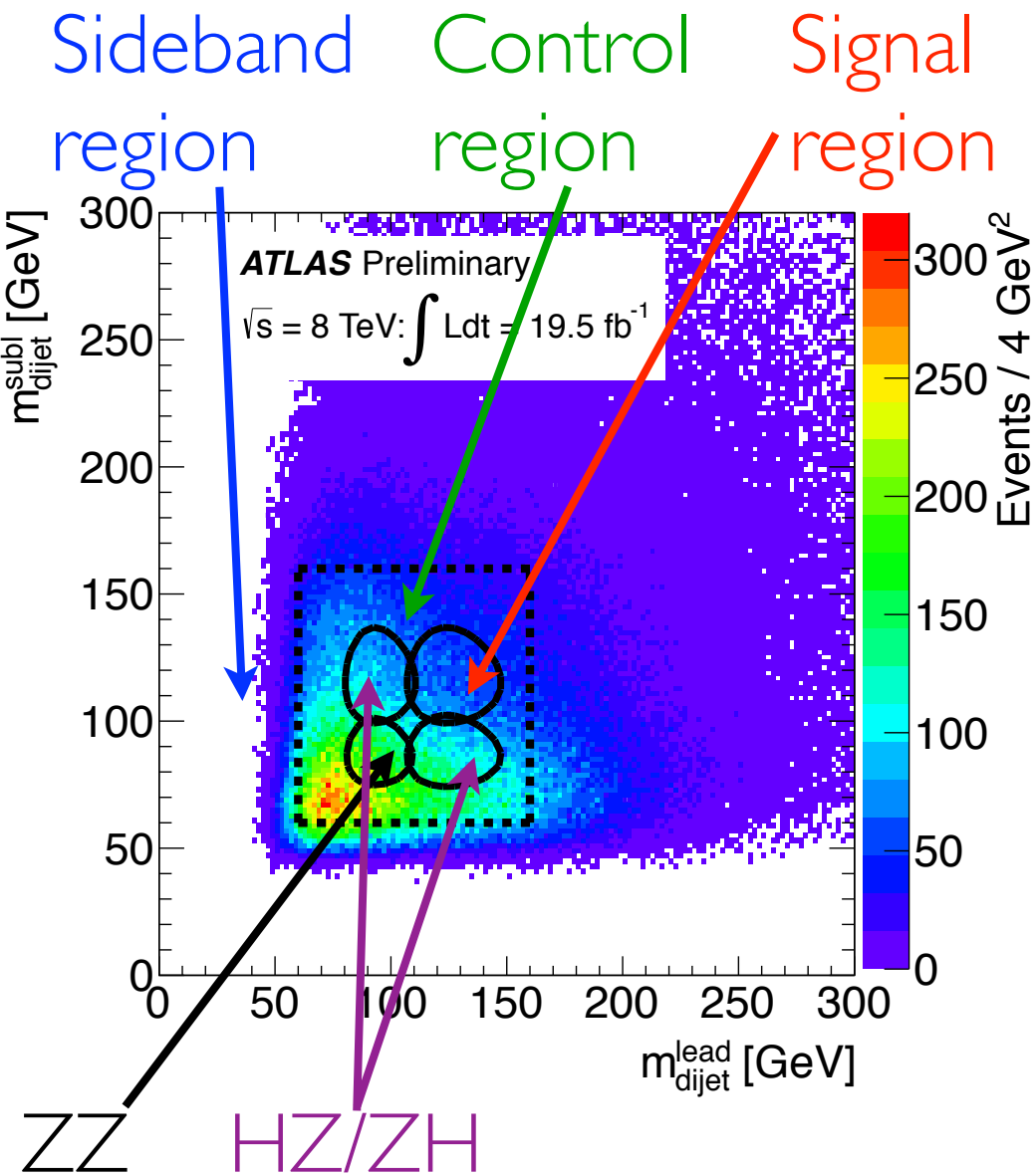


4b multijet estimate in 2tag data



- ZZ, HZ, ZH regions defined in same way as HH but with masses set for consistency with different final states
- Two-tag data used to estimate multijet background in 4tag data

4b multijet estimate

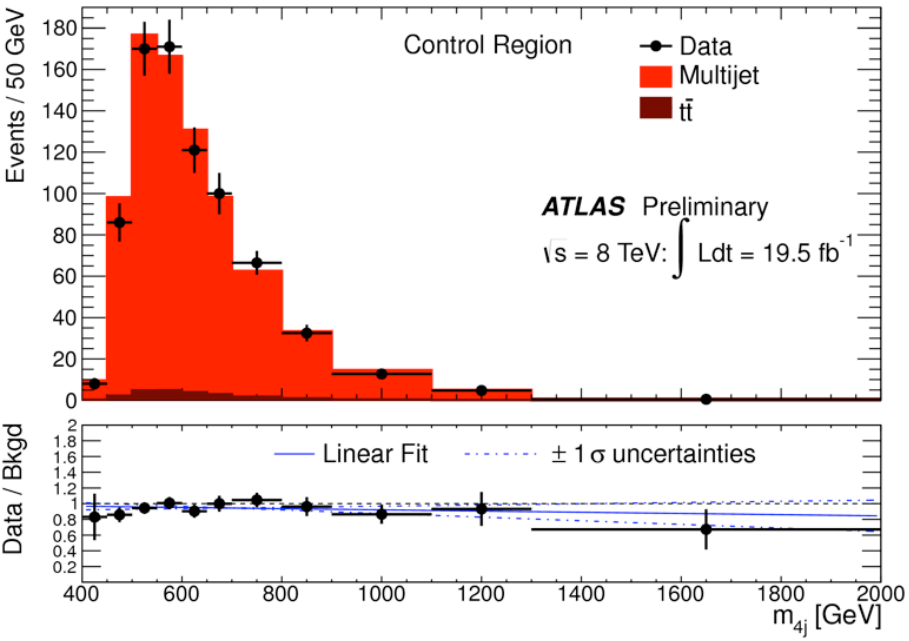


Refine kinematics by reweighting from sideband events in leading dijet p_T, dR(j,j) in subleading dijet, dR(dijets)

$$\mu_{\text{multijet}} = \frac{N^{\text{Sideband}}_{4-\text{tag}} - N^{\text{Sideband}}_{t\bar{t},4-\text{tag}} - N^{\text{Sideband}}_{Z+\text{jets},4-\text{tag}}}{N^{\text{Sideband}}_{2-\text{tag}}}$$

$\mu = 0.0064 \pm 0.0002$ from 1.4e5 2tag events

4b check in control region



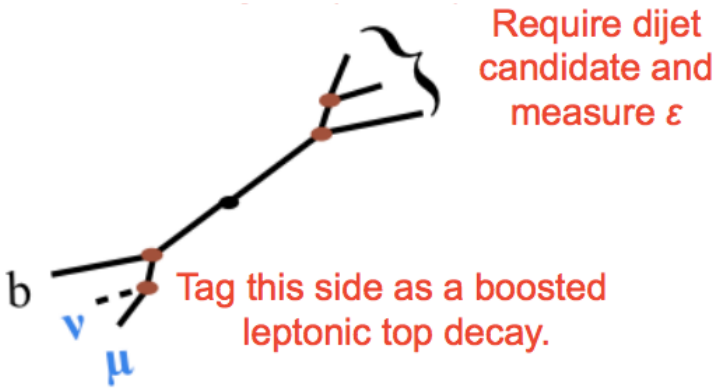
Type	Sideband Region	Control Region
Multijet	903 ± 3	935 ± 3
$t\bar{t}$	19.0 ± 0.2	26.7 ± 0.3
Z+jets	11 ± 1	17 ± 1
Total Bkgd	933 ± 3	979 ± 3
4-tag Data	933	933
G^* (m_{G^*} = 500 GeV)	0.75 ± 0.10	3.9 ± 0.2
G^* (m_{G^*} = 700 GeV)	0.48 ± 0.04	3.0 ± 0.1

Residual normalization and shape differences taken as uncertainty

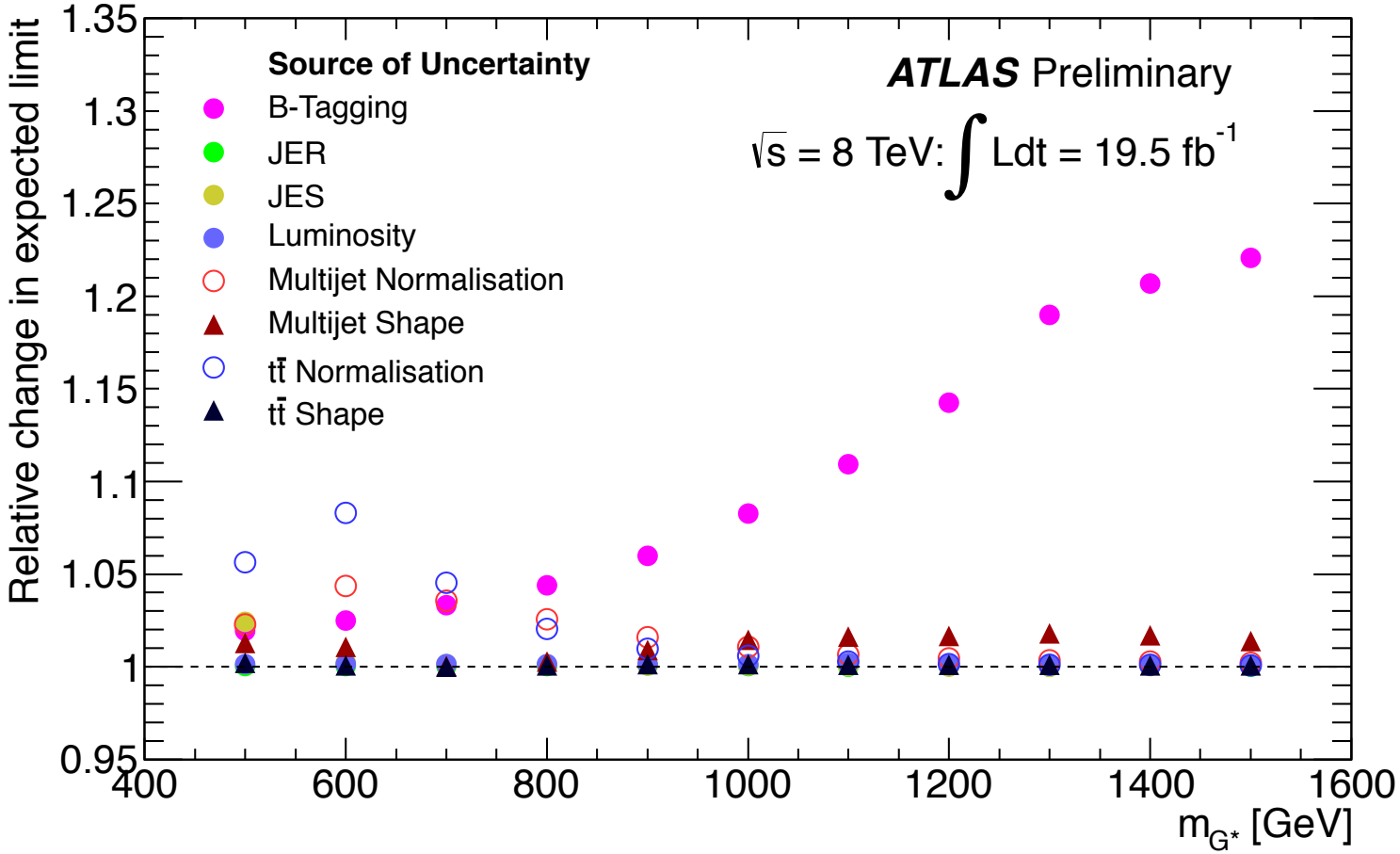
4b ttbar estimate

- ttbar contribution estimated from events where at least one dijet system fails X_{tt}
  - Extrapolation to signal region from semi-leptonic ttbar events in data
  - Shape of ttbar events taken from simulation
  - Large statistical uncertainties, but ttbar background is small compared to multijet background

$$N_{t\bar{t}}^{Bkg} = \frac{\epsilon_{t\bar{t}}^2}{1-\epsilon_{t\bar{t}}^2} \times N_{t\bar{t}}^{CR}$$

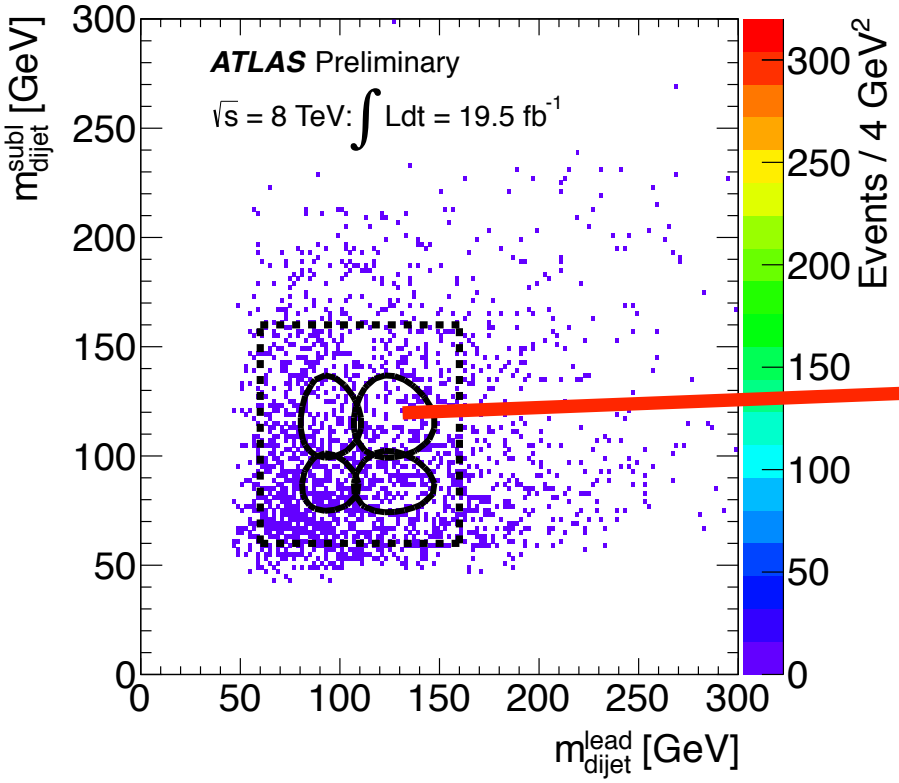


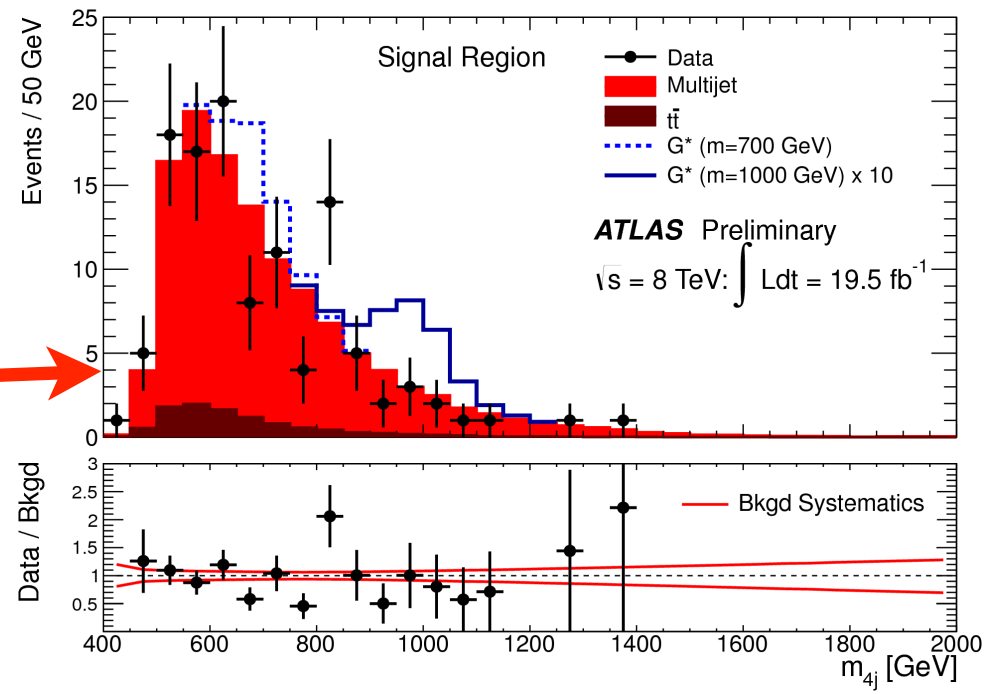
4b systematic uncertainties



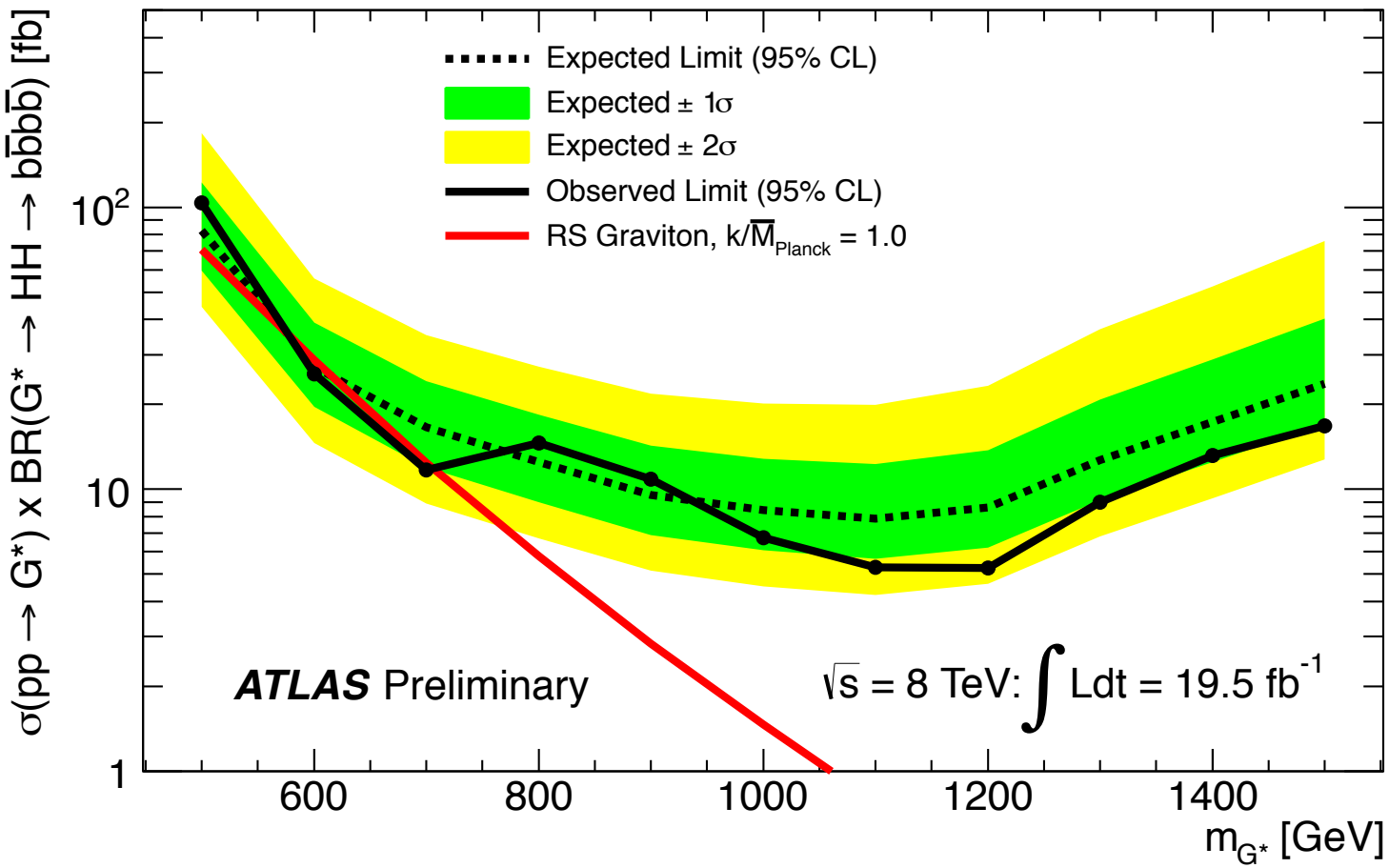
B-tagging scale factor uncertainties for jets with p_T > 300 GeV large (not enough data - purely from simulation)

4b results


ATLAS Preliminary
√s = 8 TeV: ∫ Ldt = 19.5 fb-1
m_dijet^subl [GeV]
m_dijet^lead [GeV]
Events / 4 GeV²

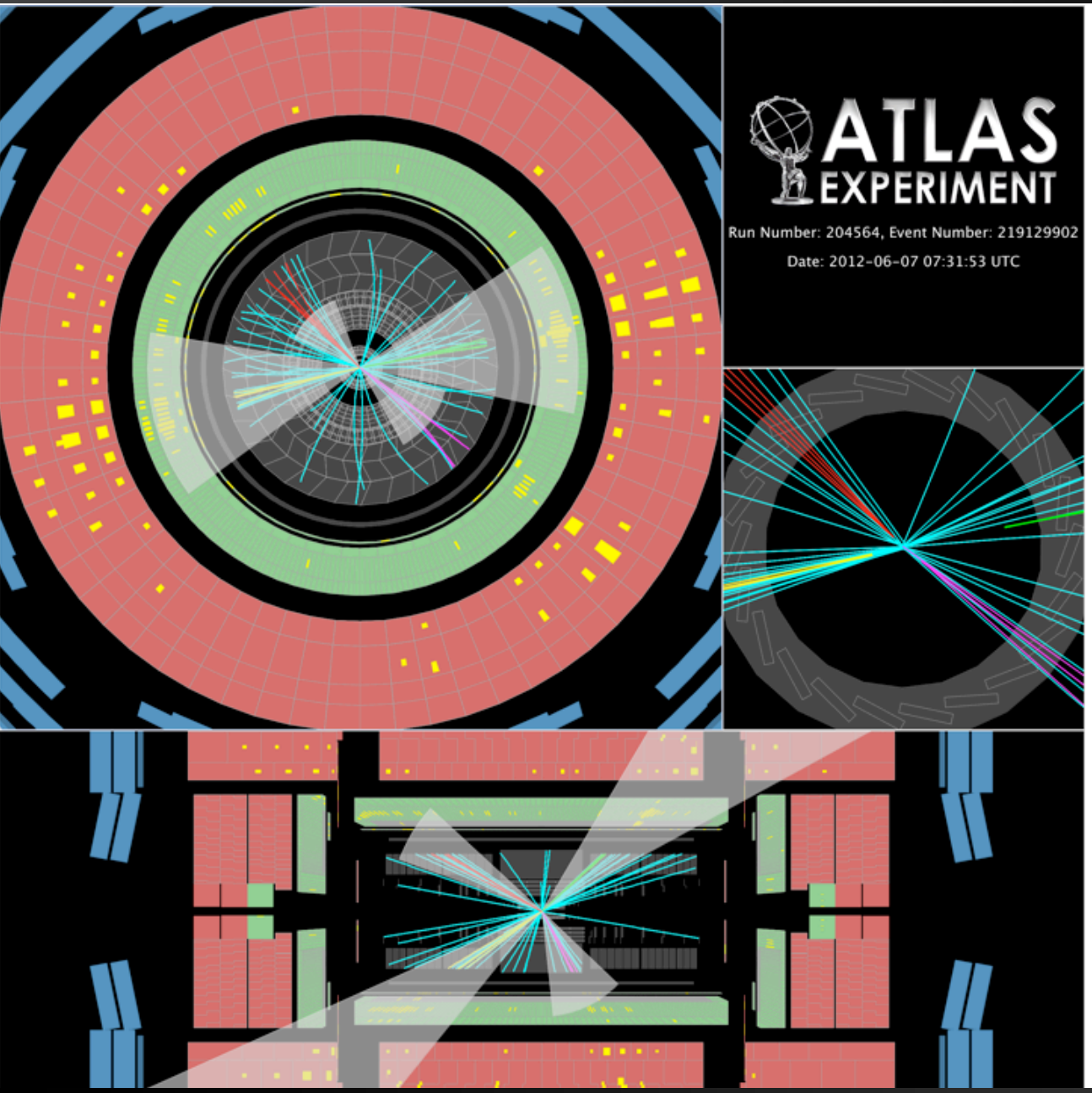

Signal Region
Data
Multijet
tt̄
G* (m=700 GeV)
G* (m=1000 GeV) x 10
ATLAS Preliminary
√s = 8 TeV: ∫ Ldt = 19.5 fb-1
Events / 50 GeV
Data / Bkgd
Bkgd Systematics
m_4j [GeV]

4b results



Exclude gravitons at 95% CL with mass 590-710 GeV (expected 590-630 GeV)

Event display



$m_{bb}(1) = 115$ GeV

$m_{bb}(2) = 112$ GeV

$m_{4b} = 834$ GeV

Conclusions

- Key LHC goal to explore the Higgs boson potential and study the Higgs self-coupling
  - For the near future, we are searching for new physics
  - In the long-term, we hope to begin to make measurements
    - A difficult path, but also a fun one

Conclusions

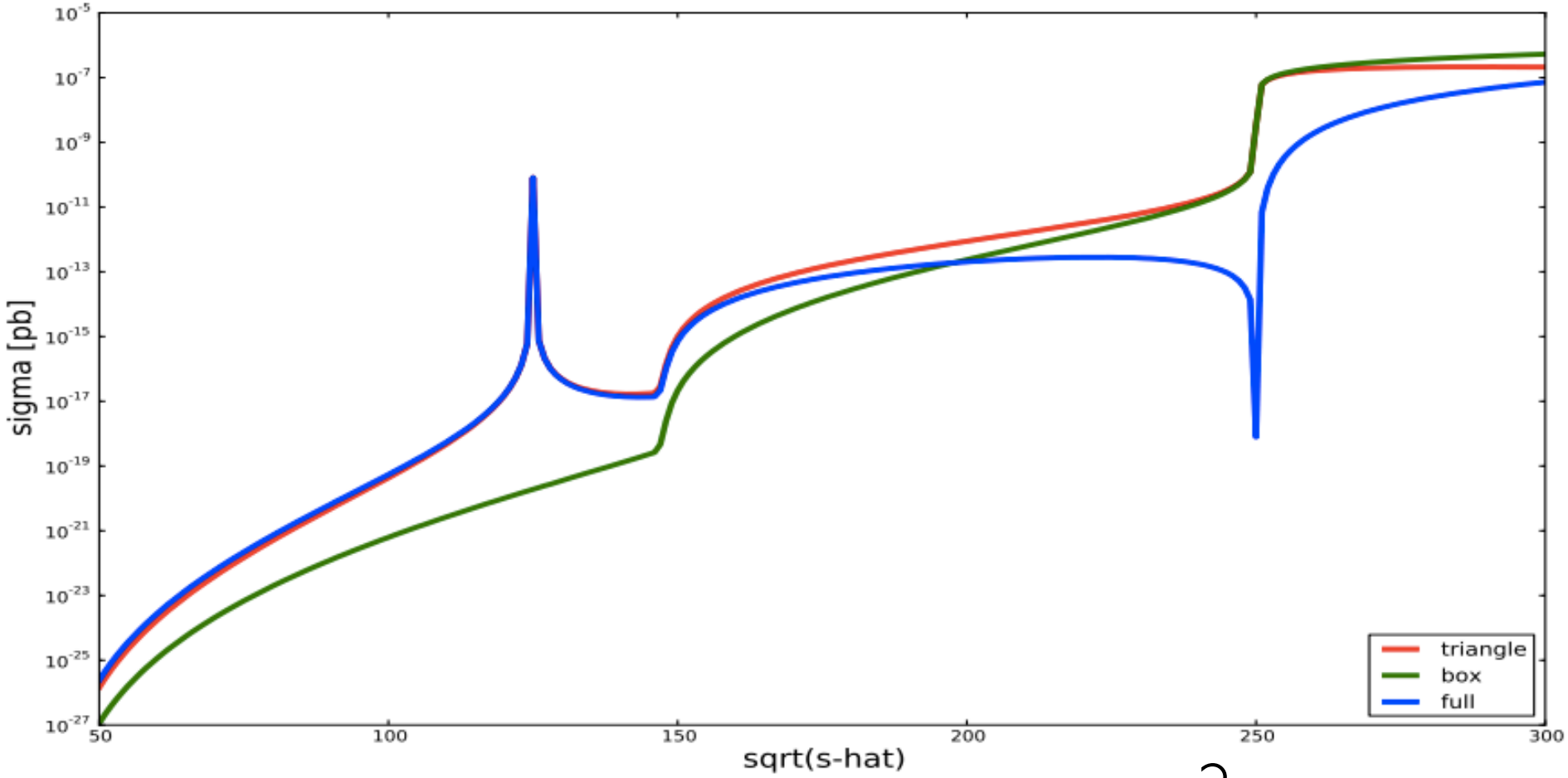
Look for $\gamma\gamma$bb and 4b searches in early Run 2, as well as $\tau\tau$bb and boosted-4b versions

Thank you!

Backup

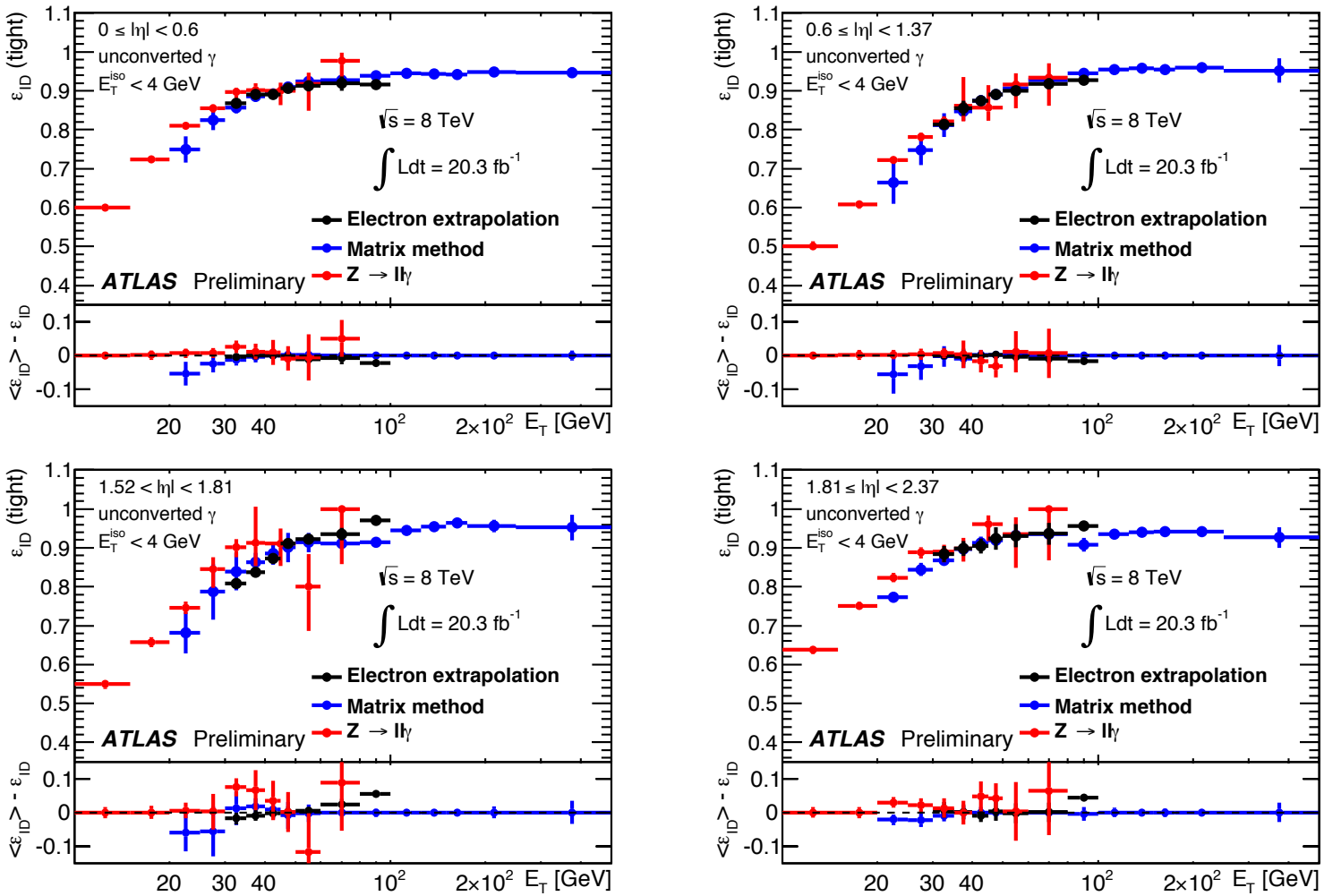
Production vs s-hat

courtesy Magdalena Slawinska

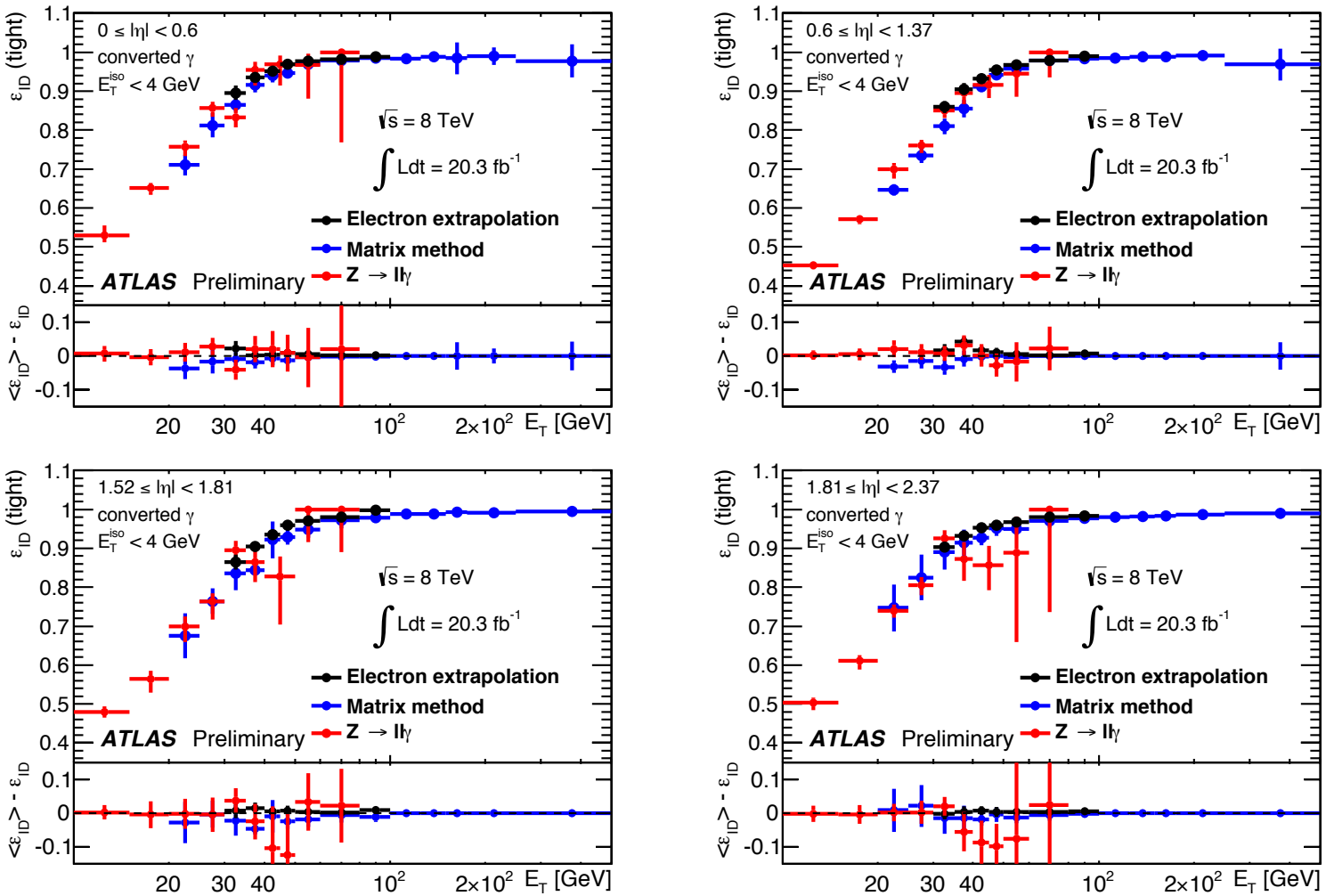


m_H $2m_H$

Photon ID


0 ≤ |η| < 0.6
unconverted γ
E_T^{iso} < 4 GeV
0.6 ≤ |η| < 1.37
1.52 < |η| < 1.81
1.81 ≤ |η| < 2.37
√s = 8 TeV
∫Ldt = 20.3 fb⁻¹
Electron extrapolation
Matrix method
Z → llγ
ATLAS Preliminary
ε_ID (tight)
<ε_ID> - ε_ID
E_T [GeV]

Photon ID


0 ≤ |η| < 0.6
converted γ
E_T^{iso} < 4 GeV
0.6 ≤ |η| < 1.37
1.52 ≤ |η| < 1.81
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√s = 8 TeV
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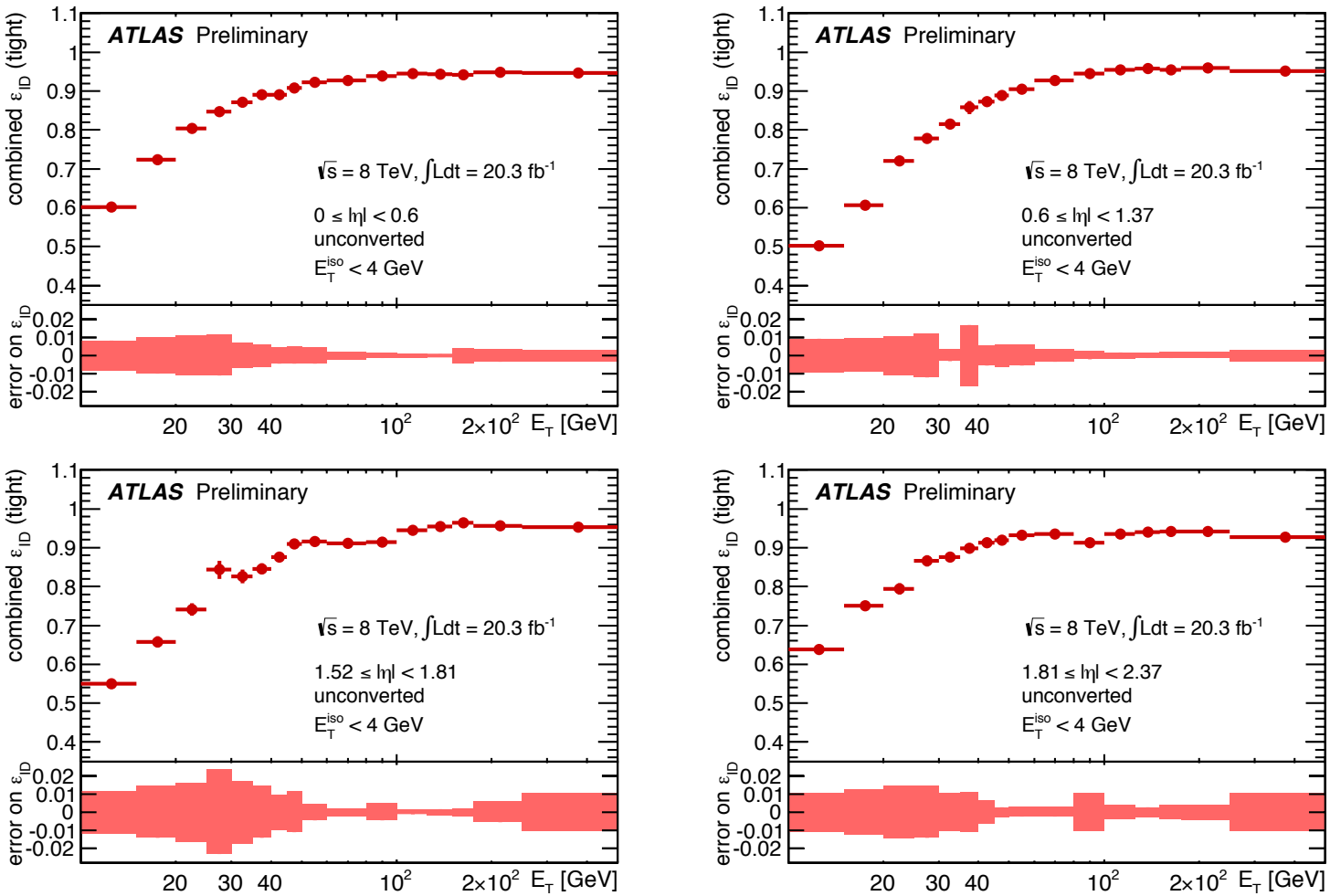
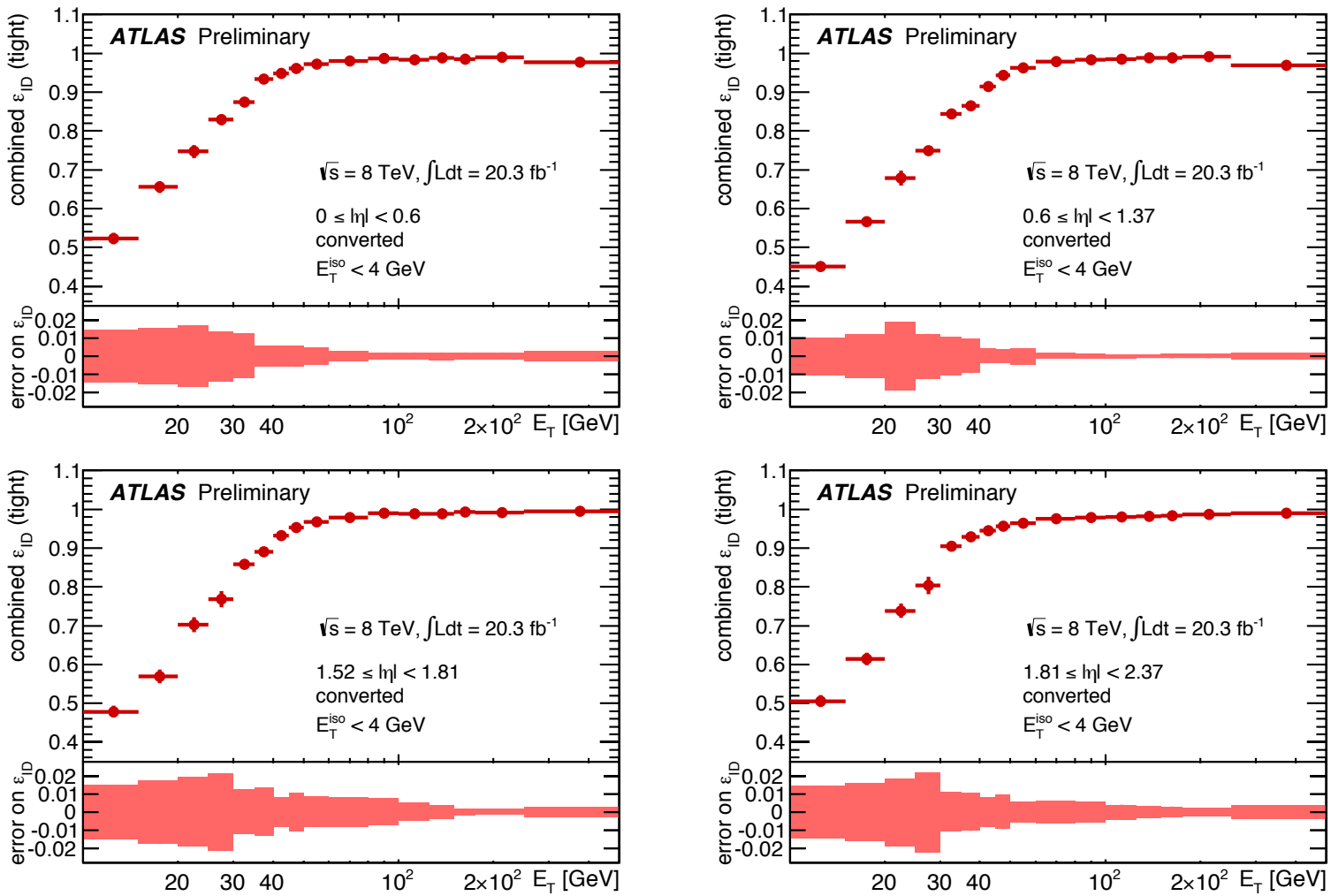
Electron extrapolation
Matrix method
Z → llγ
ATLAS Preliminary
ε_ID (tight)
<ε_ID> - ε_ID
E_T [GeV]

Photon ID


ATLAS Preliminary
√s = 8 TeV, ∫Ldt = 20.3 fb-1
0 ≤ |η| < 0.6
unconverted
E_T^iso < 4 GeV
0.6 ≤ |η| < 1.37
unconverted
E_T^iso < 4 GeV
1.52 ≤ |η| < 1.81
unconverted
E_T^iso < 4 GeV
1.81 ≤ |η| < 2.37
unconverted
E_T^iso < 4 GeV
combined ε_ID (tight)
error on ε_ID
E_T [GeV]

Photon ID


ATLAS Preliminary
√s = 8 TeV, ∫Ldt = 20.3 fb-1
0 ≤ |η| < 0.6
converted
E_T^iso < 4 GeV
0.6 ≤ |η| < 1.37
converted
E_T^iso < 4 GeV
1.52 ≤ |η| < 1.81
converted
E_T^iso < 4 GeV
1.81 ≤ |η| < 2.37
converted
E_T^iso < 4 GeV
combined ε_ID (tight)
error on ε_ID
E_T [GeV]

hh xsections in SM

http://arxiv.org/abs/1212.5581

$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}_{gg\to HH}$ [fb]	$\sigma^{\rm NLO}_{qq'\to HHqq'}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{\rm LO}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb]
8	8.16	0.49	0.21	0.14	0.21
14	33.89	2.01	0.57	0.42	1.02
33	207.29	12.05	1.99	1.68	7.91
100	1417.83	79.55	8.00	8.27	77.82

yybb events

Run/Event Number	214494/20105423	208261/19675029	205016/21379303	204668/136522288	204265/8266739
Leading γ ($p_T/\eta/\phi$)	(110/0.5/0.6)	(73/-1.2/-1.3)	(52/-0.3/2.9)	(65/-0.1/-2.2)	(65/0.4/-2.6)
Subleading γ ($p_T/\eta/\phi$)	(44/0.7/-1.6)	(34/0.6/-3.1)	(46/-2.3/-2.0)	(37/-1.7/0.1)	(42/-0.9/0.4)
$m_{\gamma\gamma}$	125.2	125.6	128.5	125.1	125.4
$p_T^{\gamma\gamma}$	90.4	73.7	76.6	47.7	24.0
$m_{b\bar{b}}$ unconstrained	125.9	130.4	124.7	134.0	105.4
p_T^{bb} unconstrained	110.7	108.1	44.9	107.5	36.5
$m_{\gamma\gamma b\bar{b}}$ constrained	336.6	312.7	291.7	289.9	264.5
$m_{\gamma\gamma b\bar{b}}$ unconstrained	337.7	319.4	291.3	300.2	243.7
$p_T^{\gamma\gamma bb}$ constrained	69.2	52.5	44.3	63.7	24.6
Leading jet ($p_T/\eta/\phi$/E)	(68/-0.9/-3.1/100)*	(121/-1.1/1.4/196)*	(65/-1.5/1.0/157)*	(103/-0.8/1.5/140)*	(66/-0.6/1.9/80)*
Subleading jet ($p_T/\eta/\phi$/E)	(58/0.6/2.1/71)*	(47/-1.9/0.4/157)	(65/-2.1/0.0/258)	(66/0.9/-2.0/97)	(43/-0.4/-0.7/48)*
3rd jet ($p_T/\eta/\phi$/E)		(47/-1.0/-2.8/73)*	(59/-2.2/-1.5/273)*	(52/0.2/-0.2/53)*	
4th jet ($p_T/\eta/\phi$/E)			(34/-0.7/2.5/43)	(36/0.4/2.2/39)	
$E_T^{miss}(E_T/\phi)$	(26/-2.8)	(52/-0.8)	(4/-2.7)	(23/2.1)	(50/-0.1)

TABLE II: Kinematics of the five events in the non-resonant signal region. Units of GeV are assumed everywhere, as appropriate. The star (*) for a jet indicates a b-tag. Only jets above 30 GeV are considered. Unconstrained (constrained) refers to values before (after) constraining the $b\bar{b}$ mass to 125 GeV.

2HDM

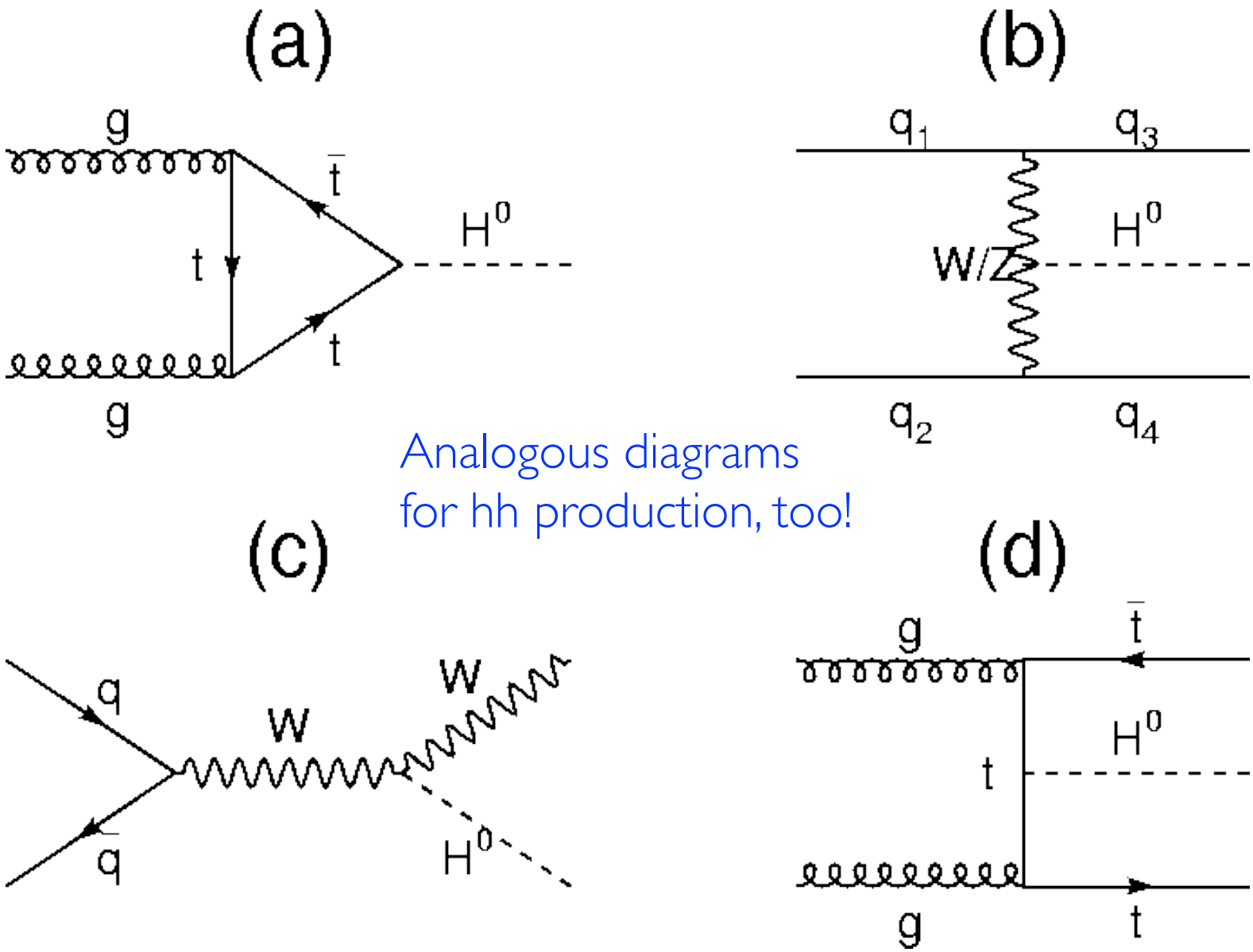
arXiv: hep-ph/0503173

- Extend the Higgs sector to a second Higgs doublet
  - Type 1: All fermions couple to one doublet
  - Type 2: Up-type quarks couple to one doublet, down-type quarks and leptons to the second doublet
  - Type 3: Quarks couple to one doublet, leptons to second doublet
  - Type 4: Up-type quarks and leptons couple to one doublet, down-type quarks to the second doublet
  - tan β = ratio of vev of both doublets
  - α determines mixing between two neutral scalars

Φ	$g_{\Phi\bar{u}u}$		$g_{\Phi\bar{d}d}$		$g_{\Phi VV}$
	Type I	Type II	Type I	Type II	Type I/II
h	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
H	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
A	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\tan\beta$	0

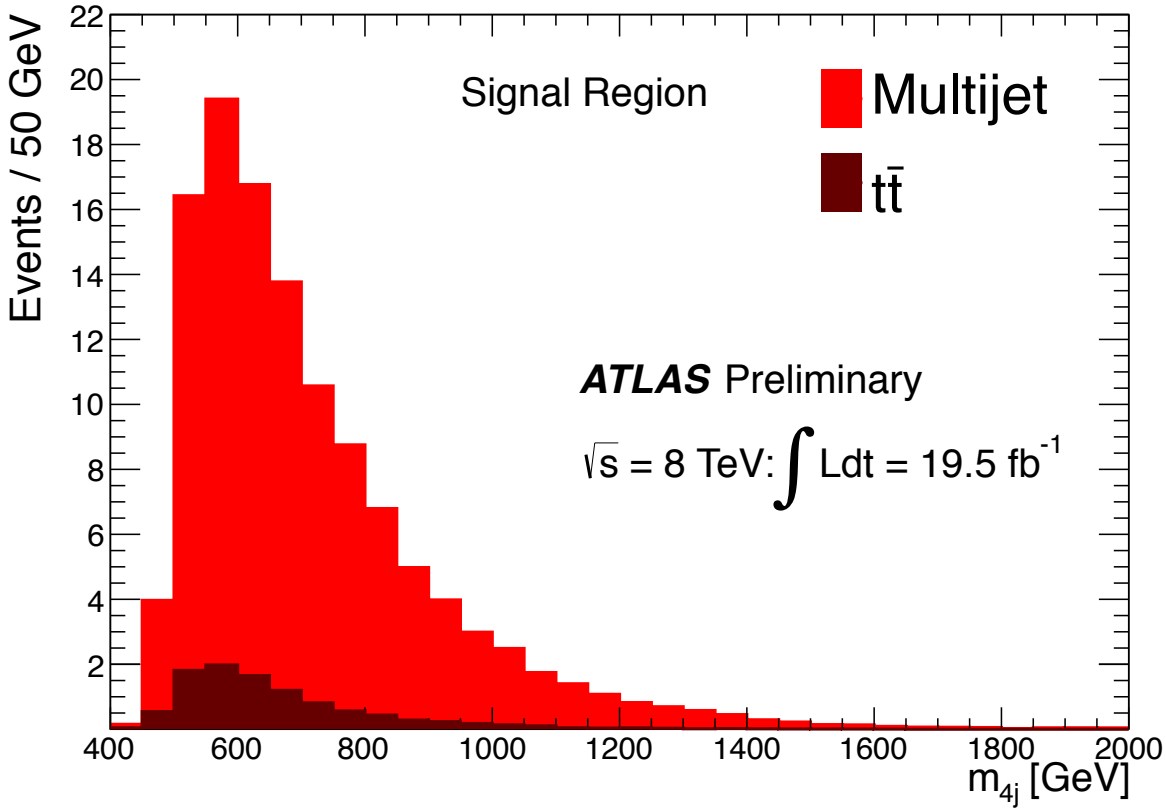
Table 1.4: The neutral Higgs couplings to fermions and gauge bosons in 2HDMs of Type I and II compared to the SM Higgs couplings. The $H^{\pm}$ couplings to fermions follow that of A.

Higgs boson production

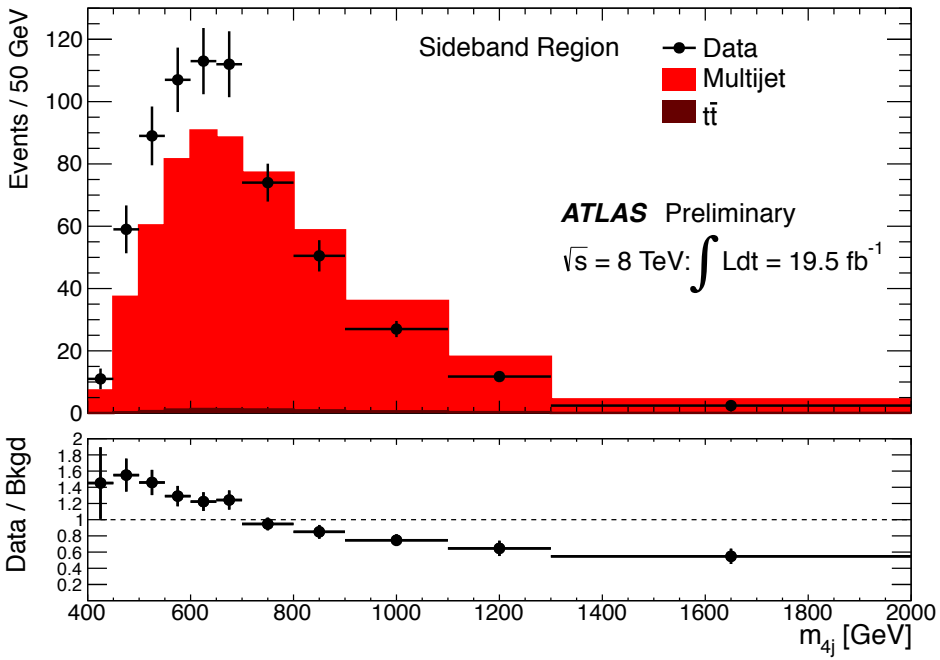


Analogous diagrams
for hh production, too!

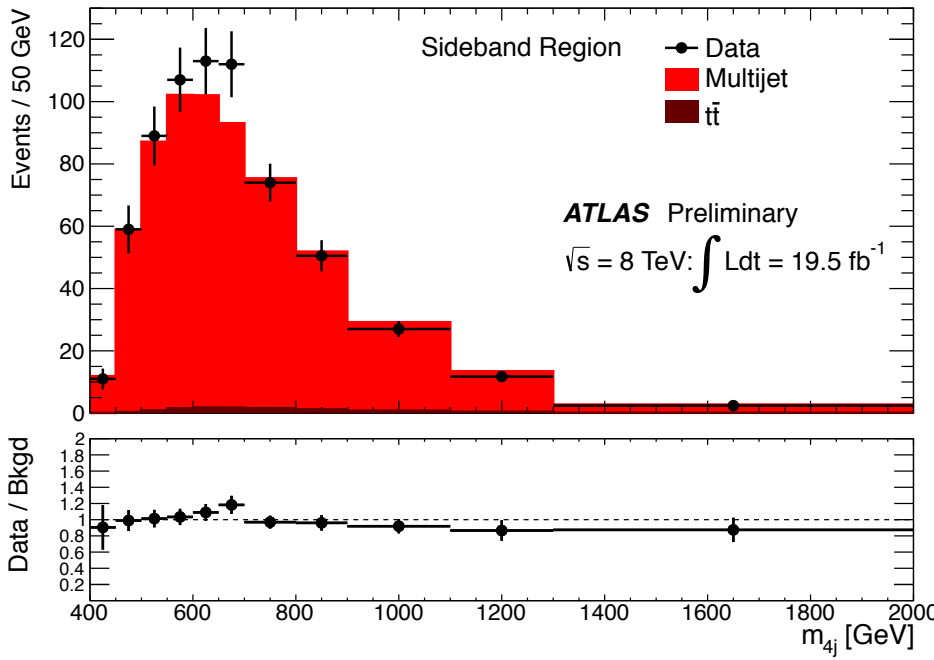
4b background



4b multijet estimate

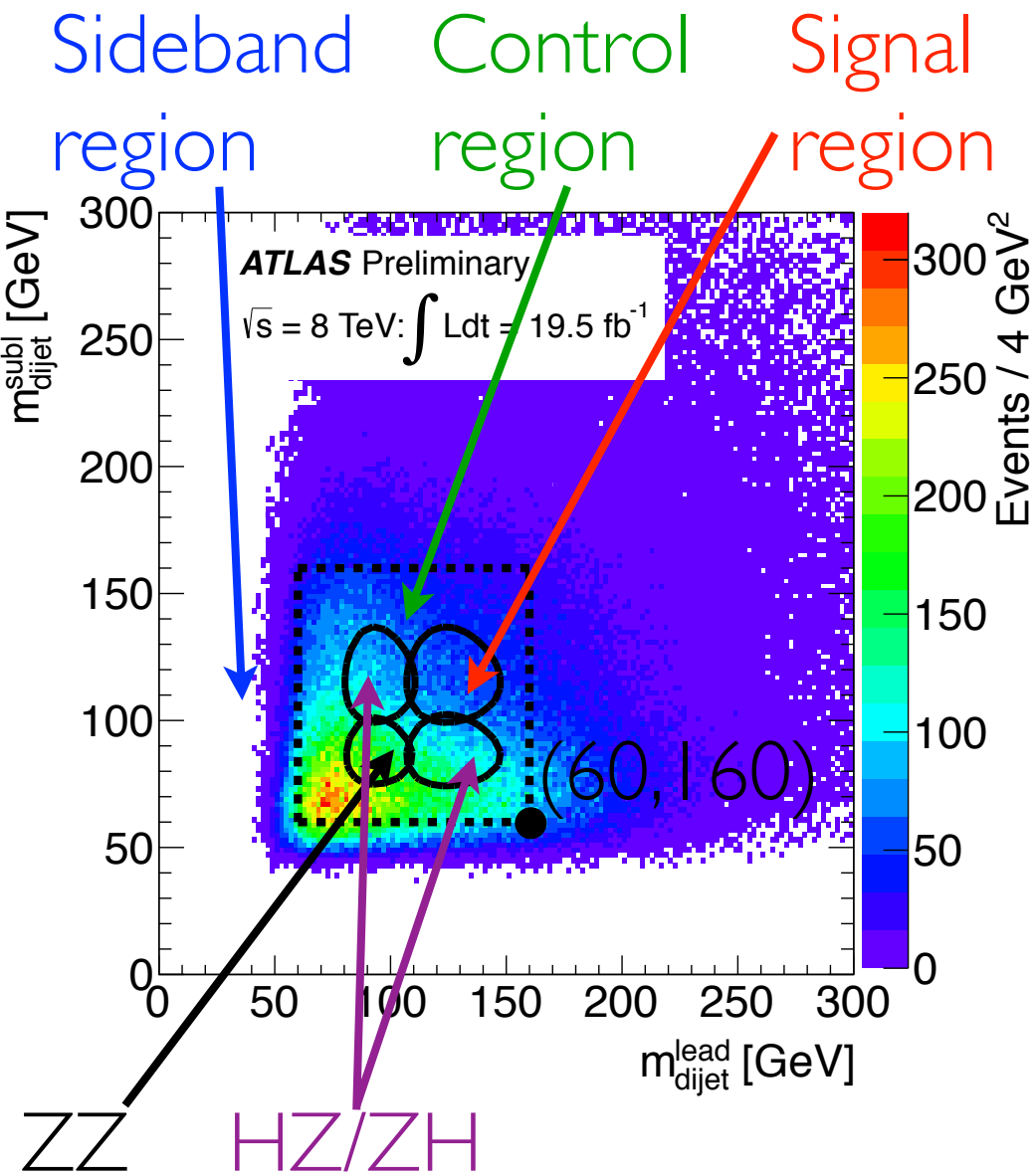


Before reweighting



After reweighting

4b multijet estimate in 2tag data



- ZZ region defined in same way as HH but with masses set to 86 and 93 GeV, and $X_{ZZ} < 1.5$
- HZ (ZH) region has mass windows set to 124/86 (93/115) GeV and $X < 1.6$
- Two-tag data used to estimate multijet background in 4tag data