Status and prospects for di-Higgs searches and λ_{hhh} measurement

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on behalf of CMS and ATLAS collaborations

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Why di-Higgs

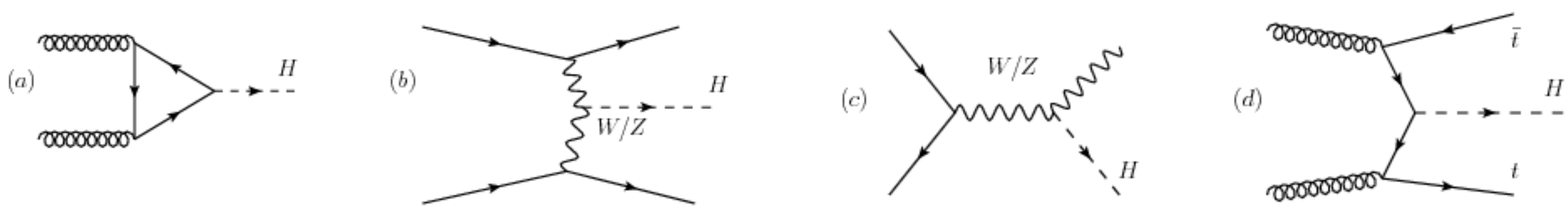
LHC Run I legacy

H

$J^P = 0^+$

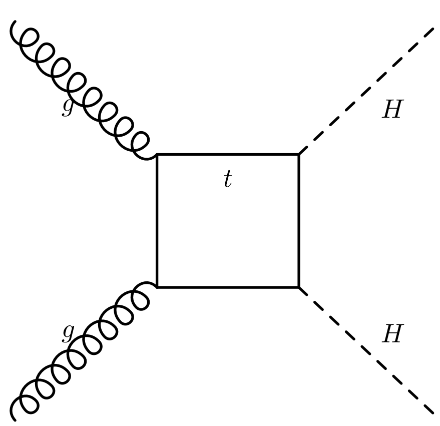
m_h = 125.03 ± 0.26 (stat.) ± 0.14 (syst.) GeV

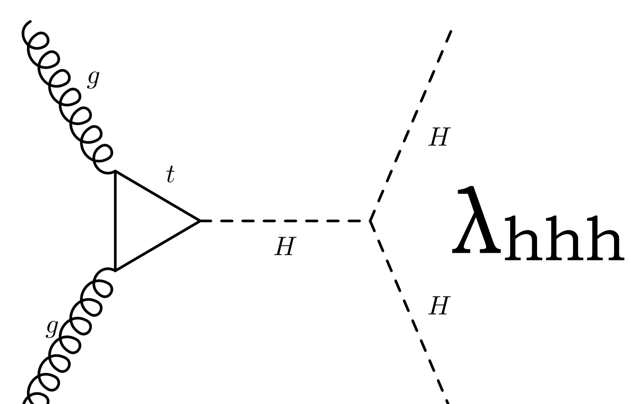
production and decay rates are consistent with a SM Higgs boson



SM predicts an extremely low rate for hh production (10 fb at 8 TeV)

1000 times smaller than the single Higgs boson production





Why di-Higgs

SM predicts an extremely low rate for hh production

Significantly enhanced in many BSM scenarios

- New physics shall preferentially couple to EWK sector
- gluon fusion production of a massive X - resonant hh state (small natural width)

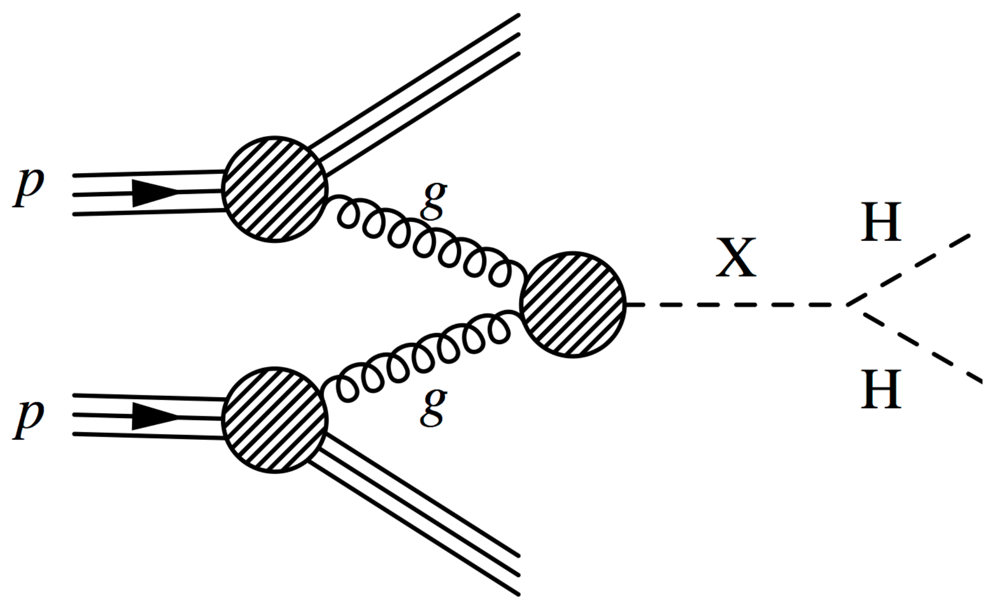
Depending on the m_X value of the new state different models can be probed

- The invariant mass range around 300-500 GeV is interesting for (N)MSSM
- From 500 GeV interesting for **warped extra dimensions** models
  - spin-0 Radion and spin-2 KK-Graviton

Higgs, as a new powerful tool to search for new physics

- $h(b\bar{b})$ highest BR, large statistic
- $h(\gamma\gamma)$ narrow resonance

hh resonant production



Final State: **B.R.**

- $X \to hh \to (b\bar{b})(b\bar{b})$ 33.3%
- $X \to hh \to (b\bar{b})(\tau\tau)$ 7.4%
- $X \to hh \to (b\bar{b})(WW)$ 25.3%
- $X \to hh \to (b\bar{b})(\gamma\gamma)$ 0.26%

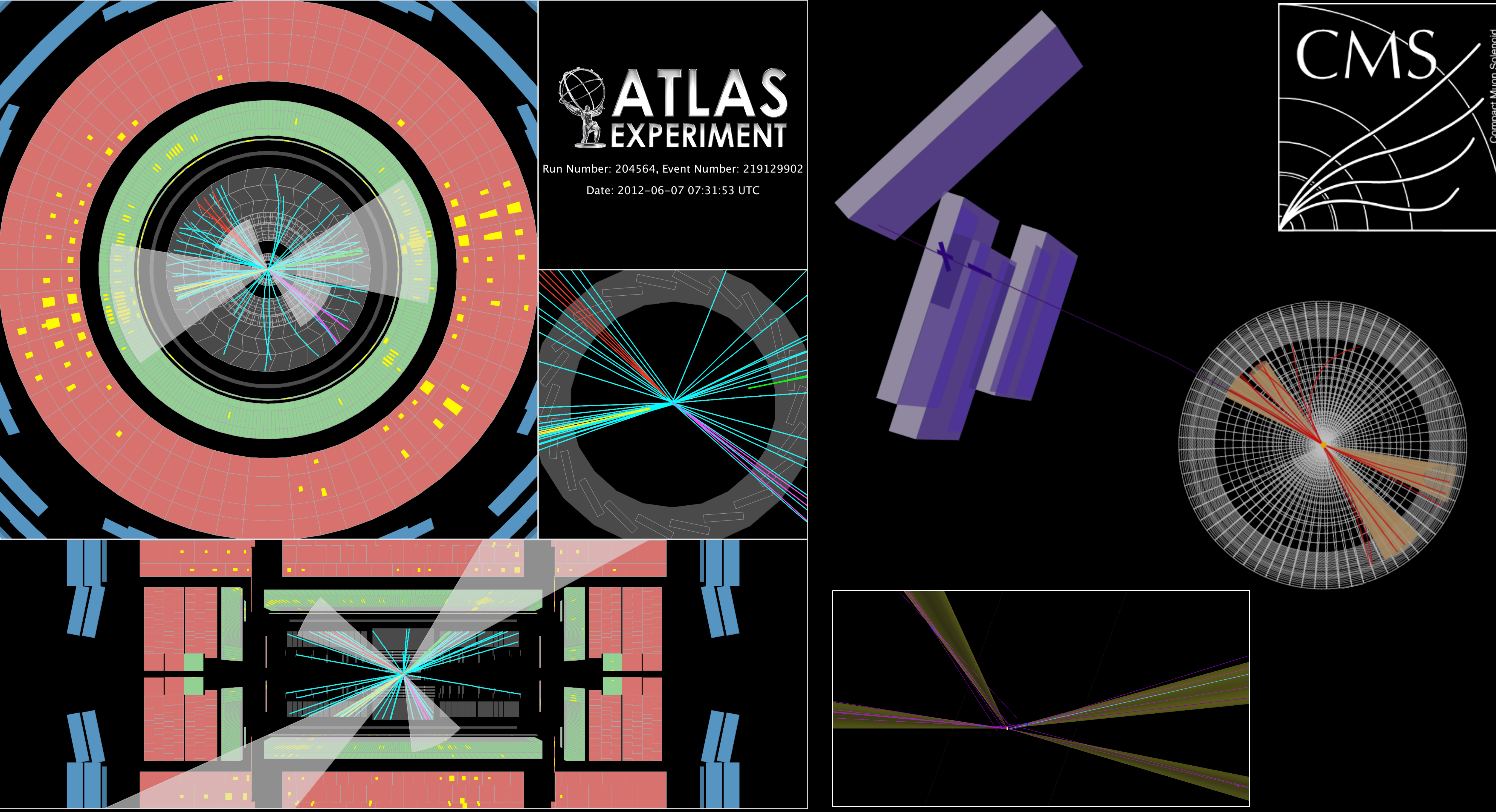
m_h = 125 GeV

$h(b\bar{b})$

highest BR: larger statistics, 10-100 times
high b-tag efficiency and low fake rate
multi-light jets background is highly reduced
as pure as leptonic/γγ channels by exploiting boosted topology

h(γγ)

simple topology, clean final state
Limited by small BR
excellent mass resolution



$X \to h(b\bar{b})h(b\bar{b})$ candidates

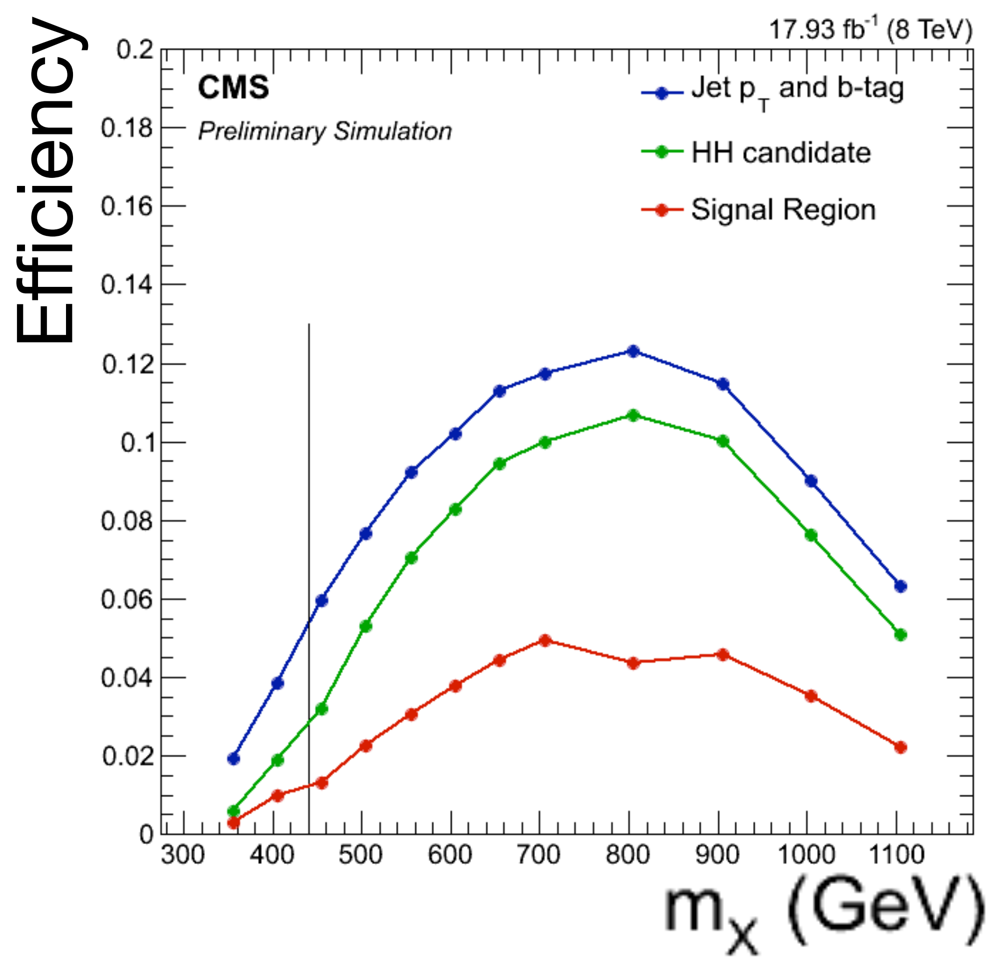
$X \to h(b\bar{b})h(b\bar{b})$

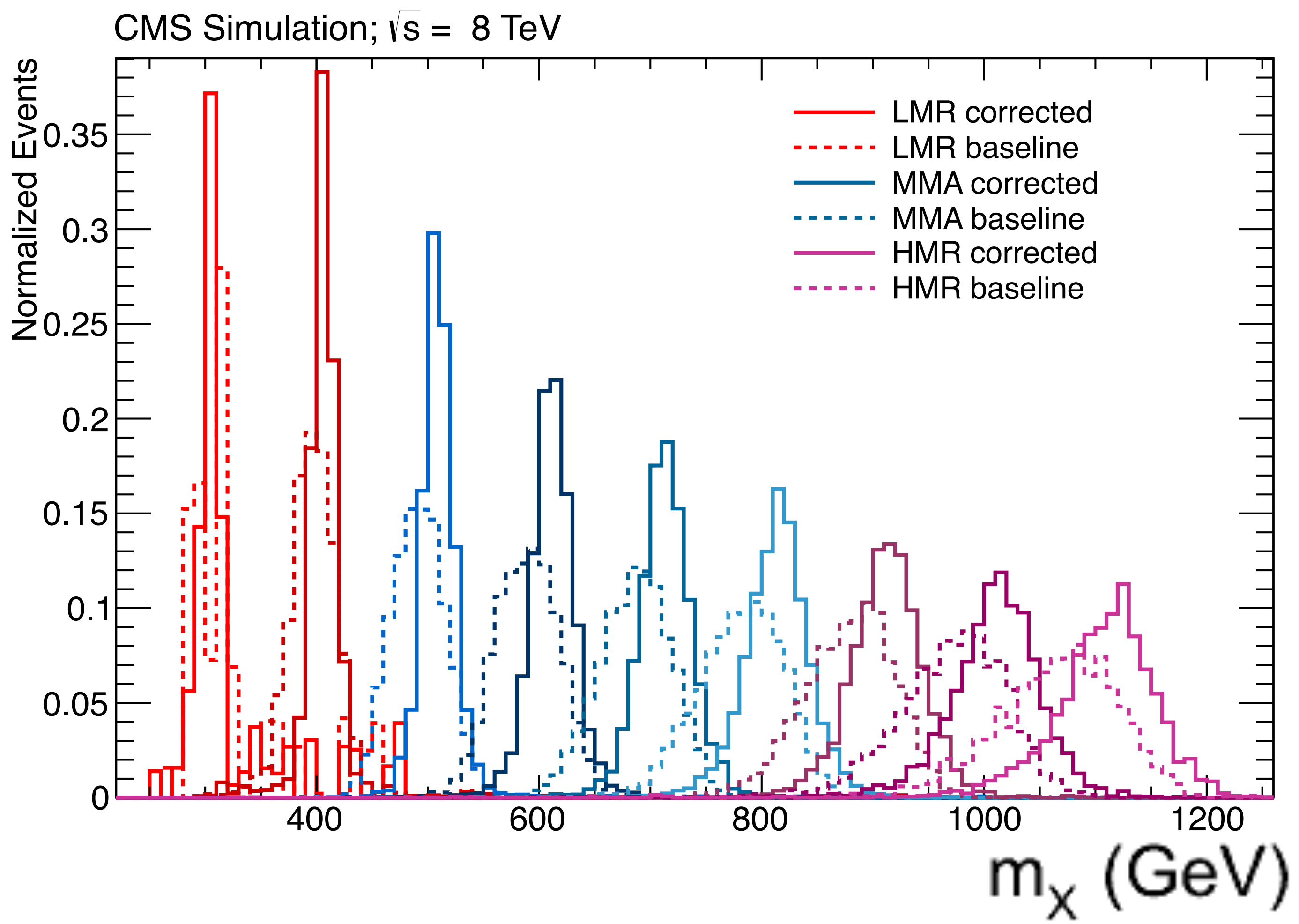
PLB 749 (2015) 5601; EXO-12-053 (CMS)
Eur. Phys. J. C (2015) 75:412 (ATLAS)

$X \rightarrow h(b\bar{b})h(b\bar{b})$, Event Selection

RESOLVED
PLB 749 (2015) 560

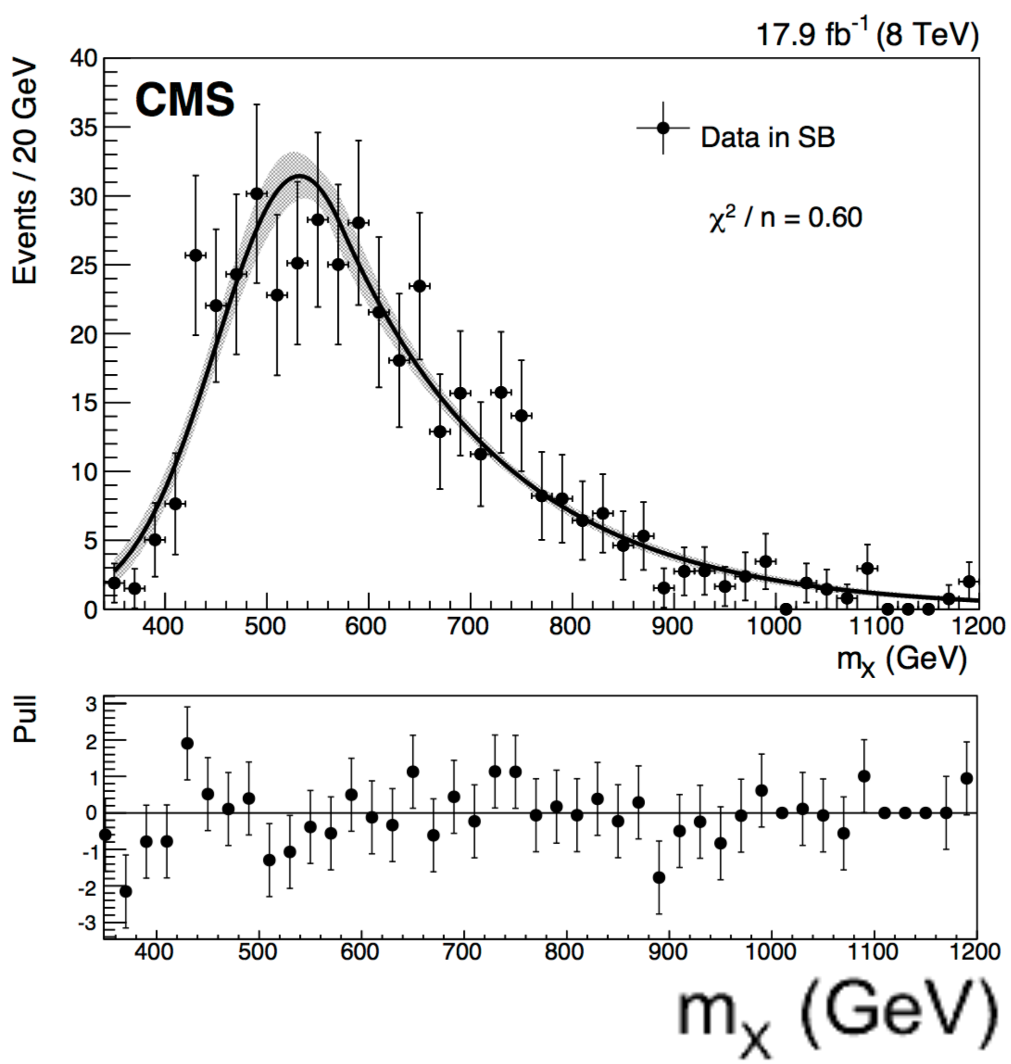
- Multi-b-jet trigger
- Events with 4 b-tagged jets with $p_T > 40$ GeV are selected
- Efficiency limited by trigger at low mass and by merging of jets at higher mass
  - The analysis is split in 3 mass regions and optimized selections are applied (Low Mass, Medium Mass and High Mass Region)
- Use kinematic fit to improve four body mass resolution by constraining each dijet mass to m_h

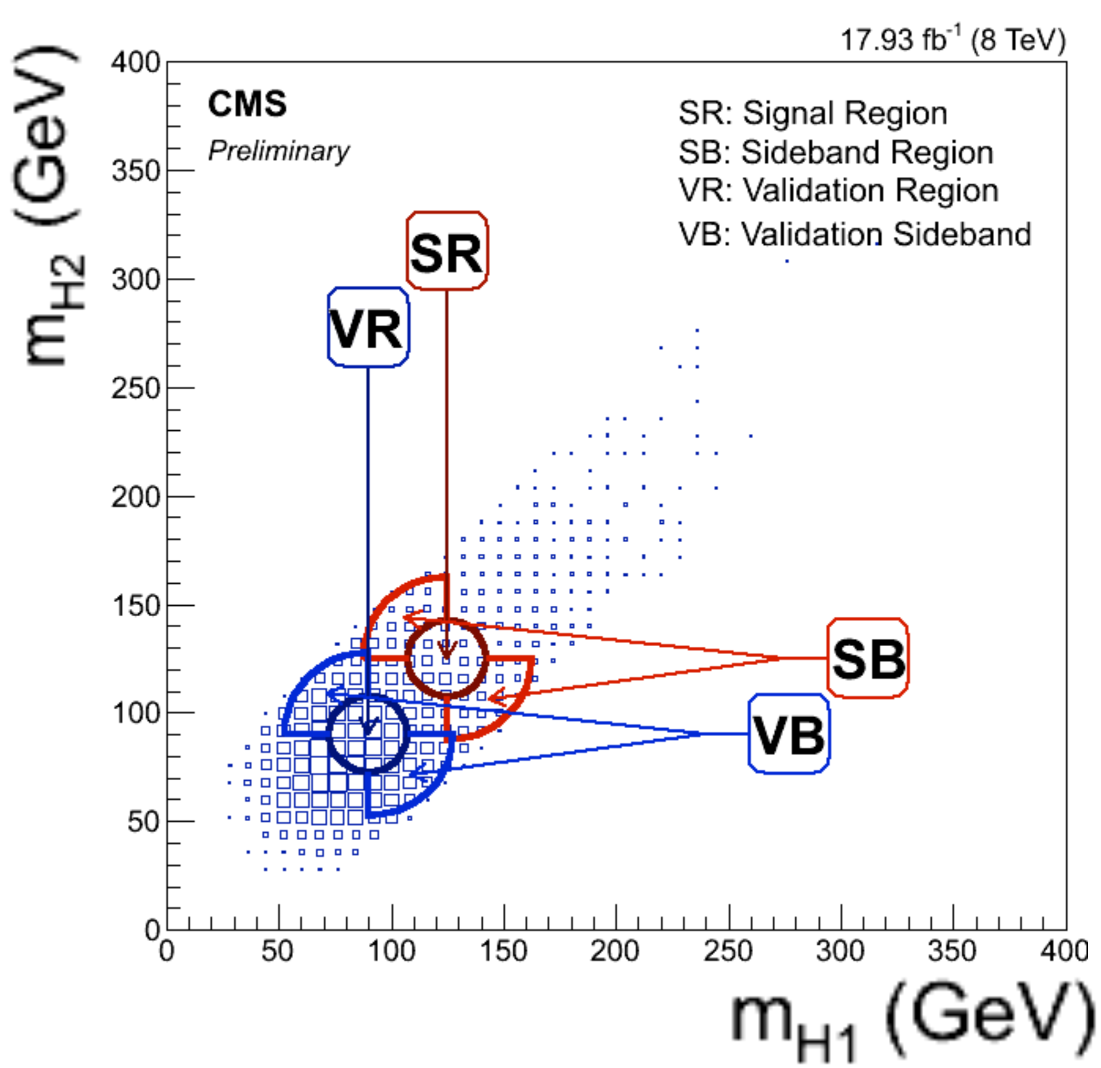




$X \to h(b\bar{b})h(b\bar{b})$, Backgrounds

- Largest **backgrounds**
  - QCD multijet (75%) modeled in data
  - $t\bar{t}$ production (25%) modeled in simulation
- Modeling of background based on fits in several control
  - mass and b-tag sidebands





$X\rightarrow h(b\bar{b})h(b\bar{b})$, Signal Extraction

RESOLVED
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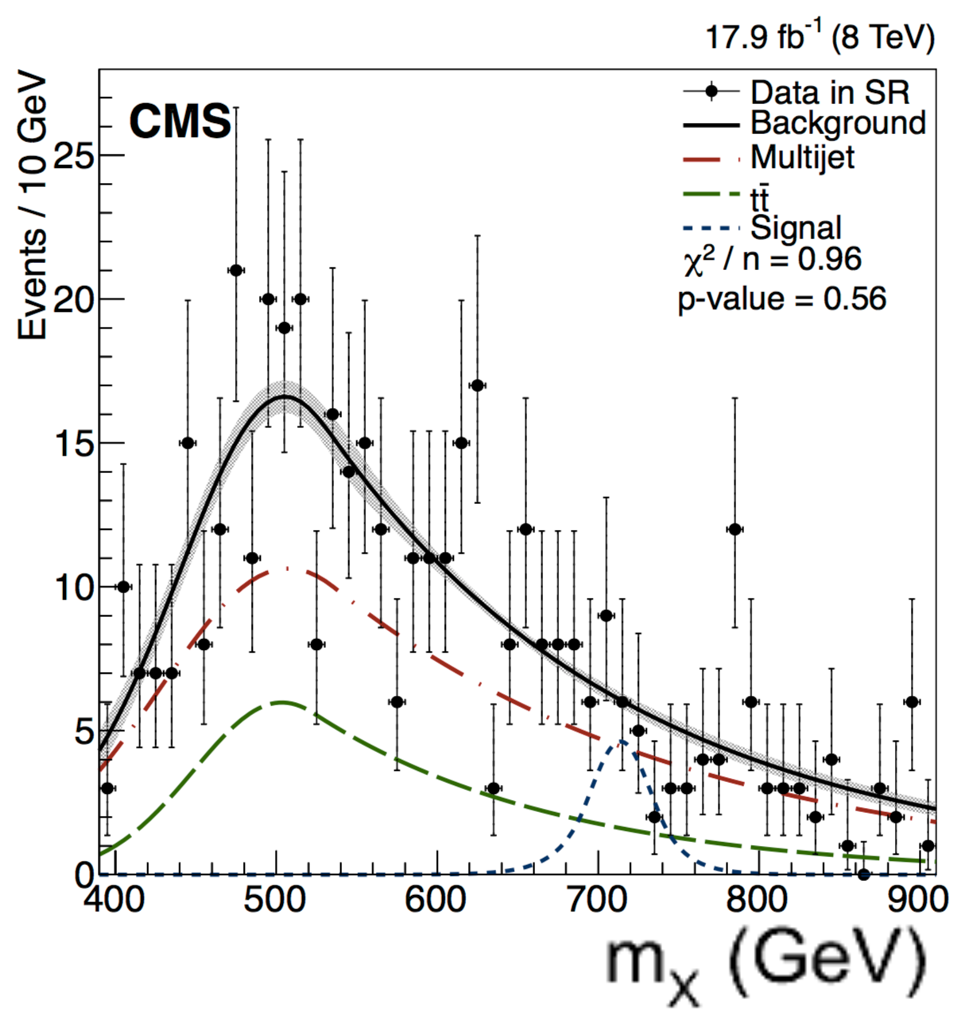
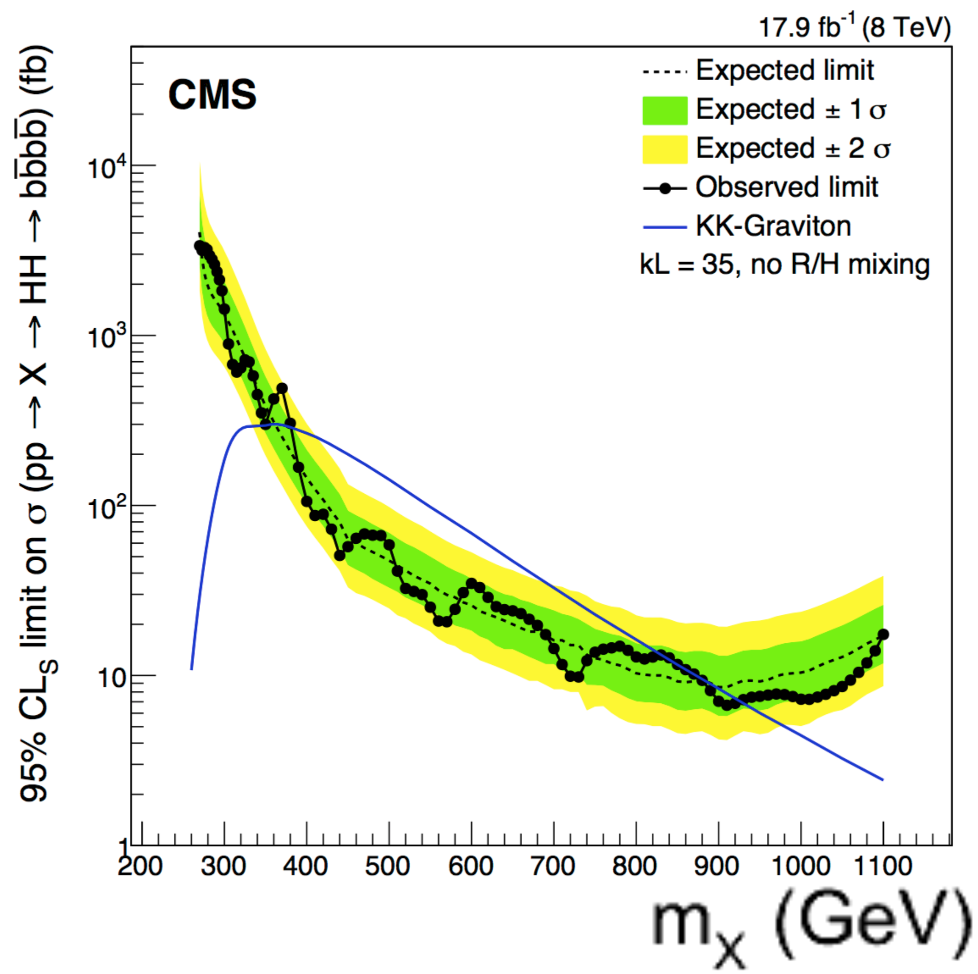
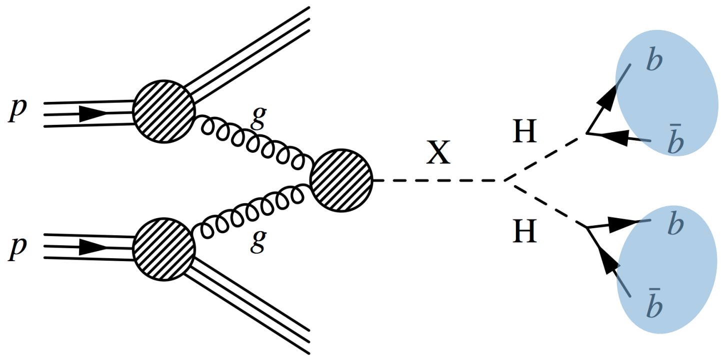
- A fit to a resonance and a smooth background in the m_X distribution
- A fit including a narrow peak signal on top of multijet+$t\bar{t}$ backgrounds is performed in each region
- Slightly different acceptance for spin-0 and spin-2 hypotheses
    - Results are interpreted in spin-0 and spin-2 hypotheses and compared to some benchmarks (Radion, KK graviton)
- No significant excess observed

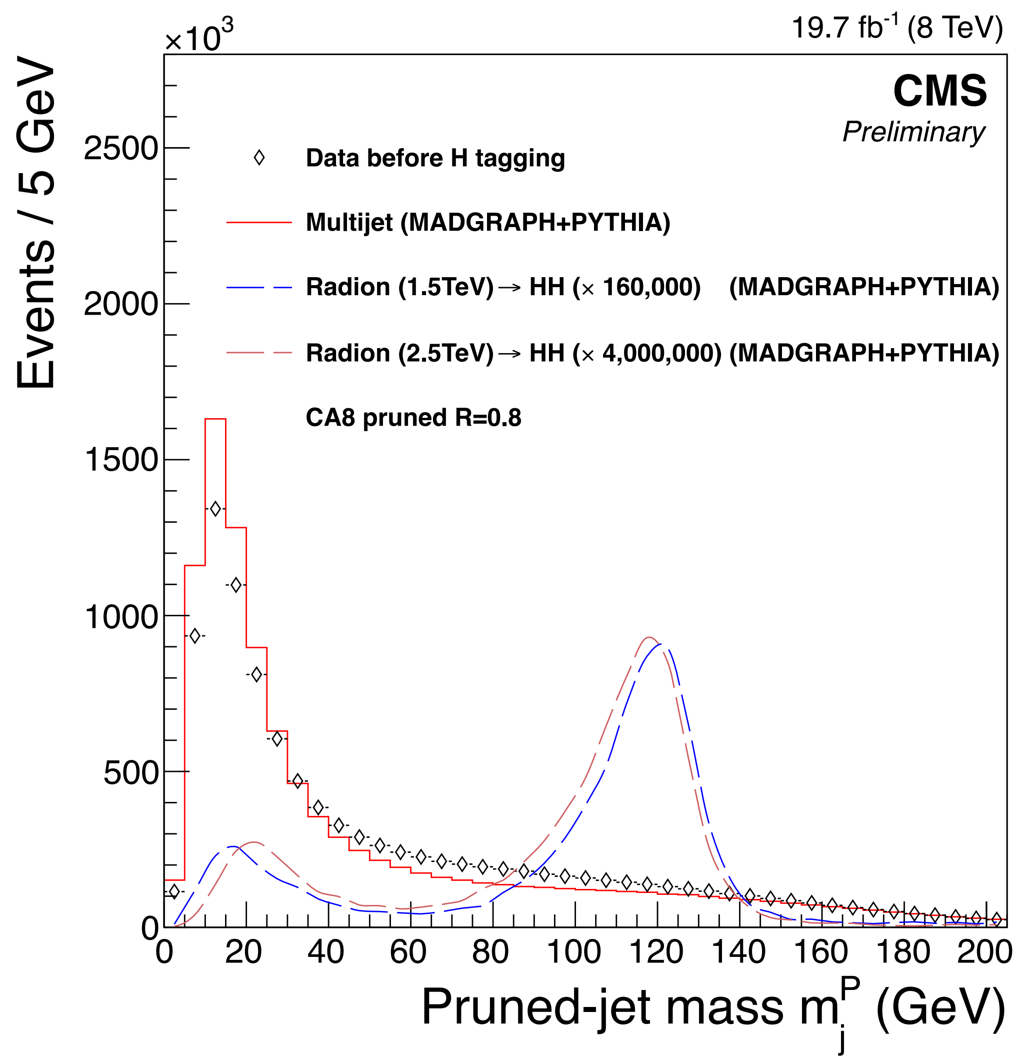


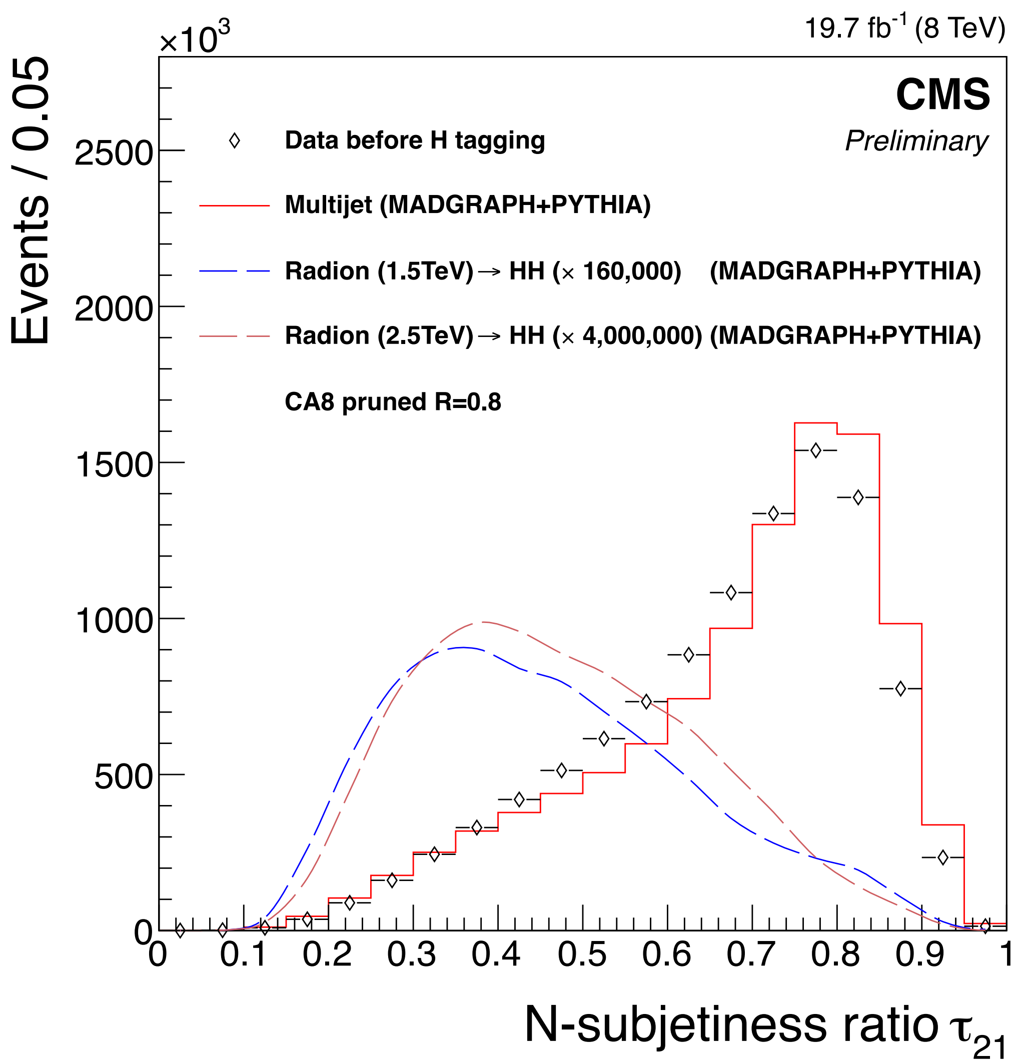


$X \to h(b\bar{b})h(b\bar{b})$, boosted

- Above ~1 TeV significant merging takes place (one fat-jet instead of two resolved b jets)
- Using substructures techniques and b-tagging to identify H-jets
  - mass (pruned)
  - consistency with two sub-jets (N-subjetiness ratio)
  - b-tagging for the two sub-jets in the fat-jet cone

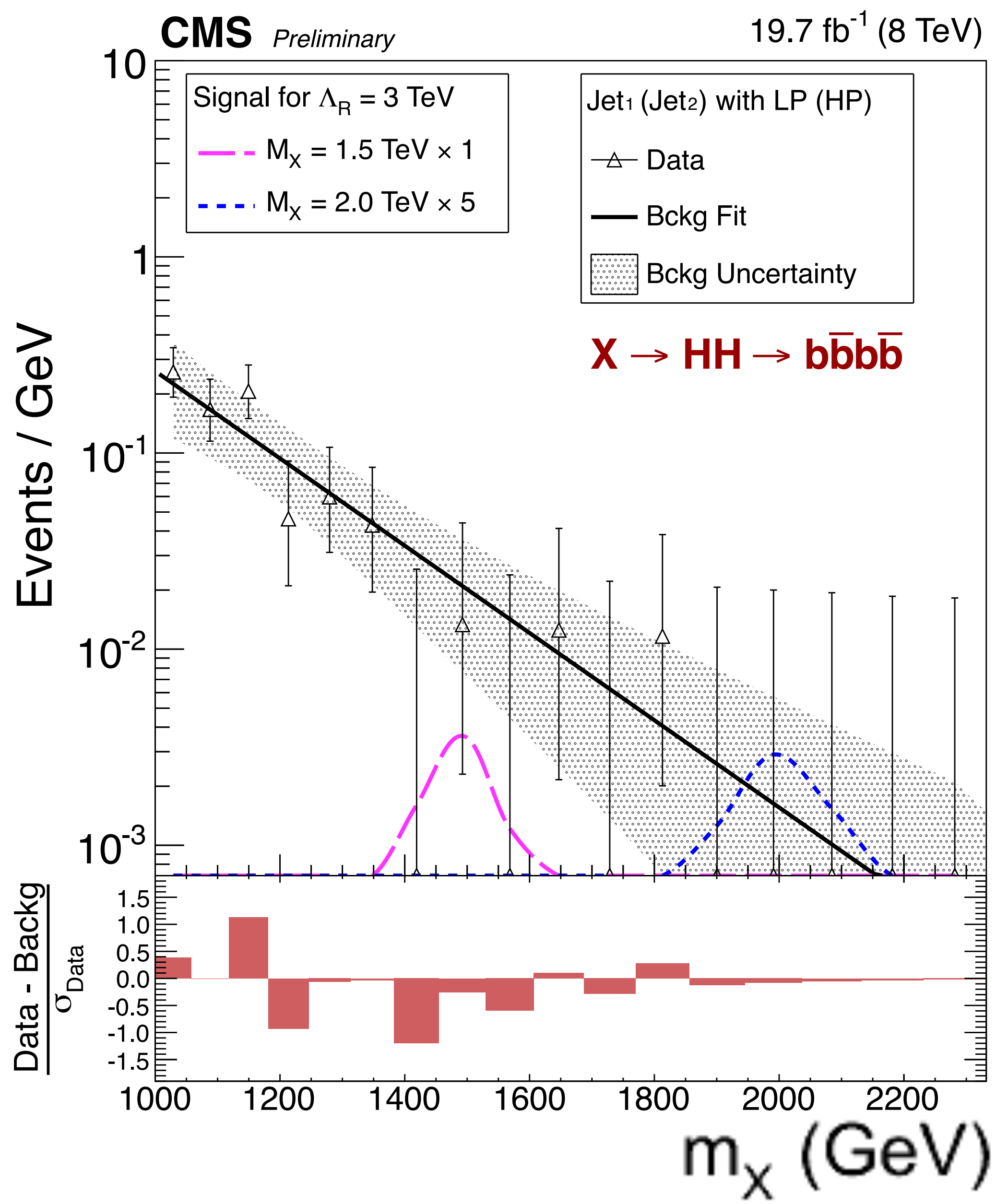


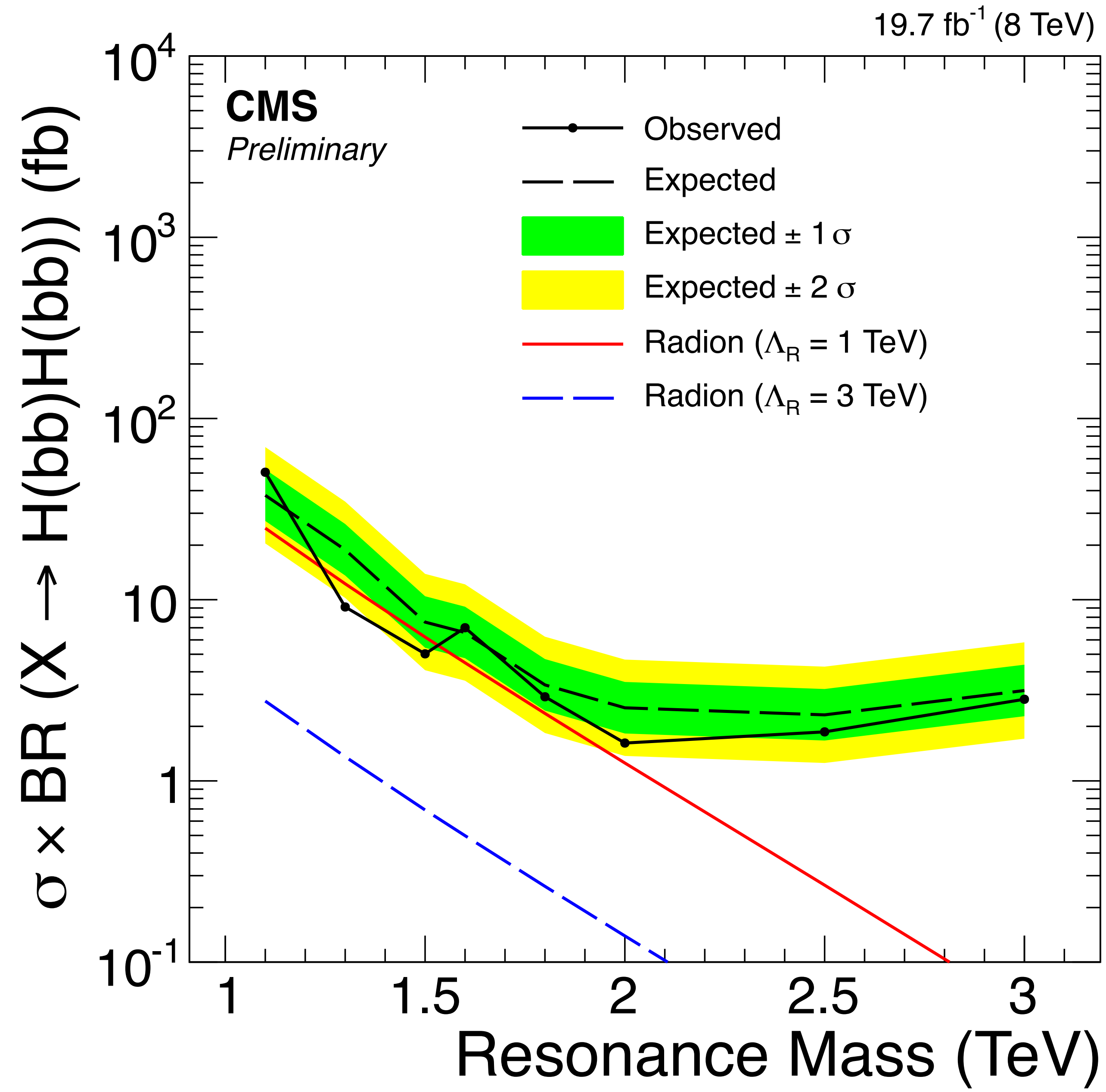




$X \rightarrow h(b\bar{b})h(b\bar{b})$, boosted

No significant excess in the range 1-3 TeV

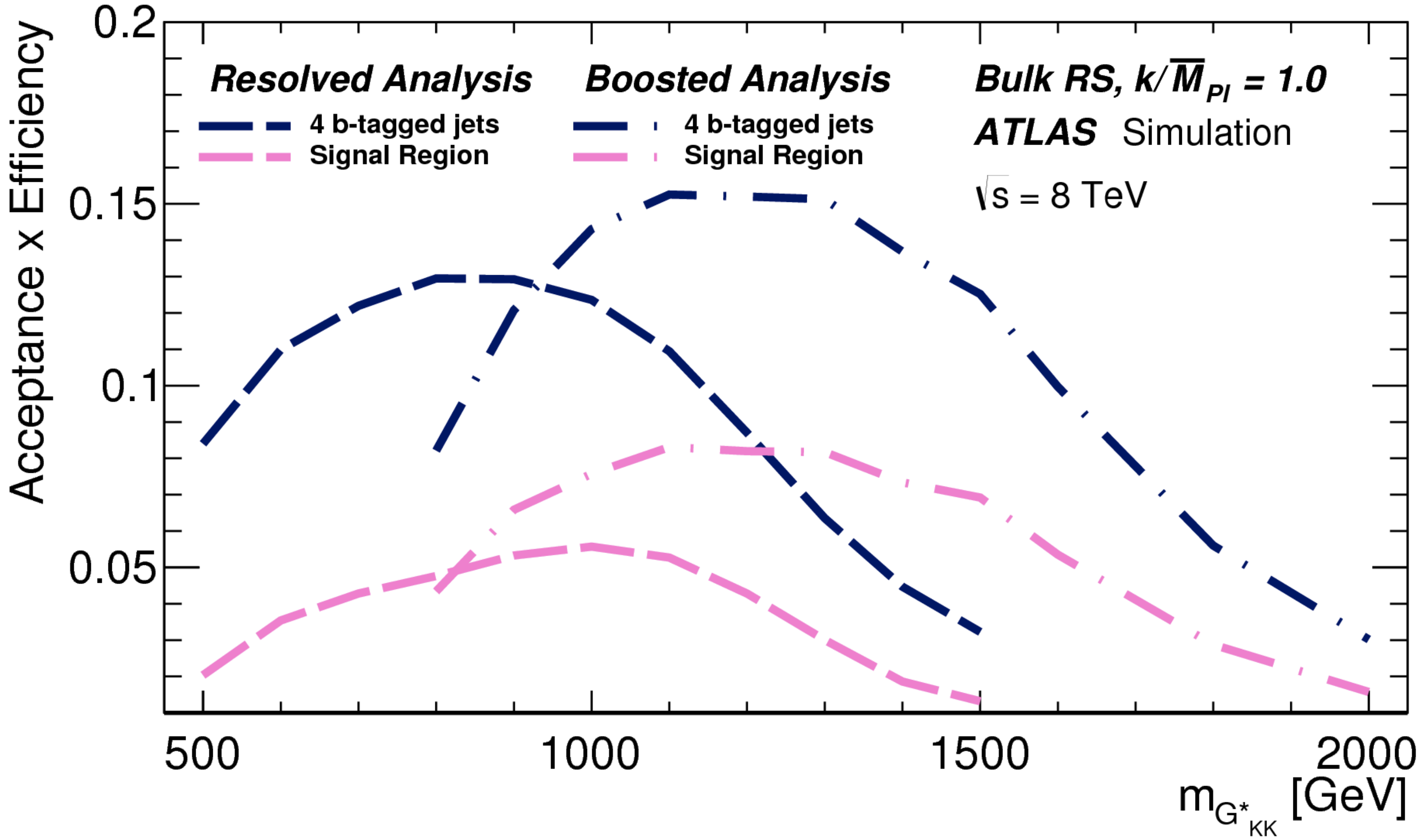




$X \to h(b\bar{b})h(b\bar{b})$, Event Selection

Eur. Phys. J. C (2015) 75:412

- Resolved analysis: 4 Jets, $p_T > 40$ GeV, b-tag
  - Top background rejection cuts 90% eff
- Boosted analysis: 2 Jets(R=1.0), $p_T >250$ GeV
  - Trimming to reduce pile-up effects
  - Track jets b-tag (R=0.3)
  - Use jet mass to test Higgs mass compatibility



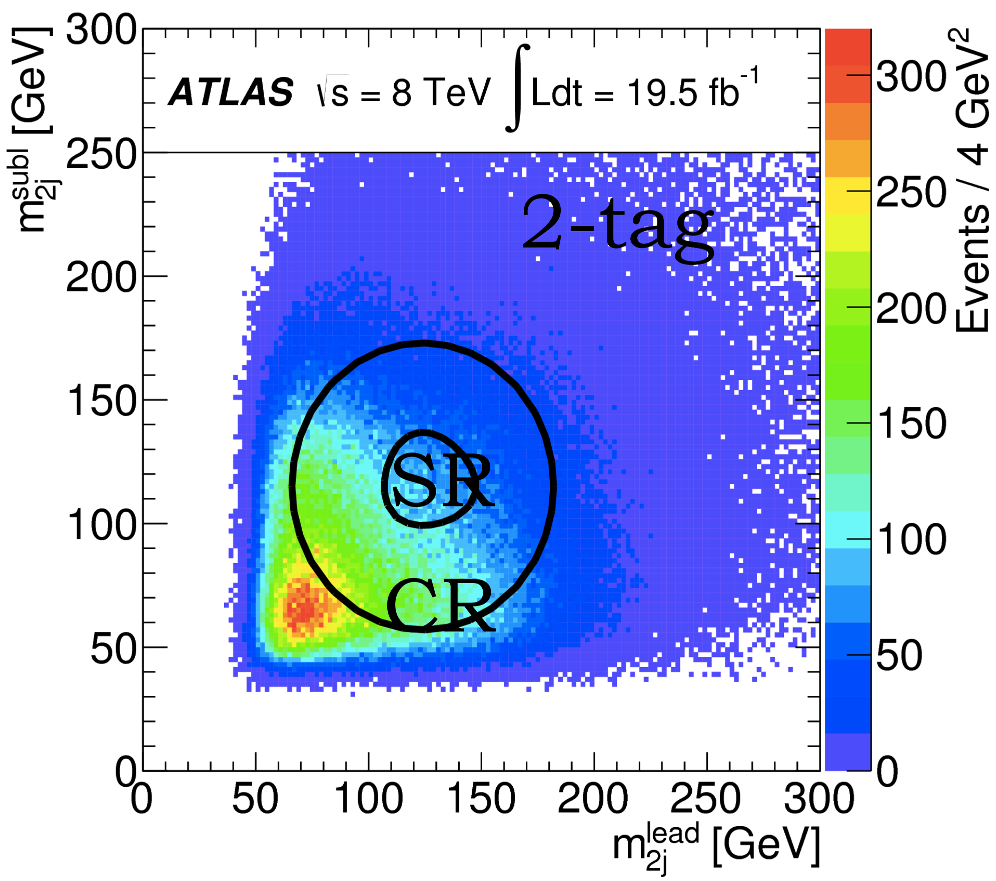
Resolved and boosted analysis have large overlapping phase space, performance crossing around 1 TeV

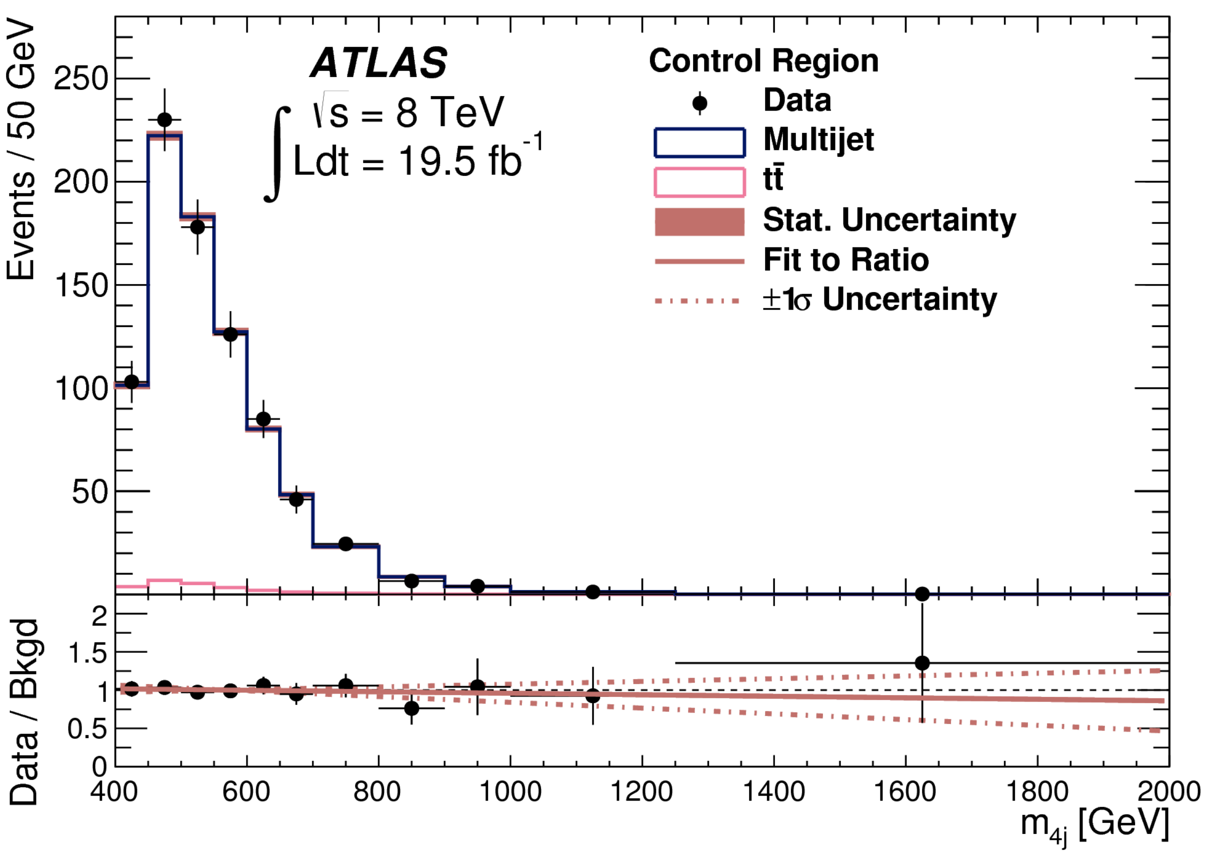
$X \to h(b\bar{b})h(b\bar{b})$, Backgrounds

Eur. Phys. J. C (2015) 75:412

RESOLVED

- Background model built from sidebands
- **QCD** 90%, modeled in data
  - Use 2-tag events to model 4-tag SR
  - the uncertainty in the estimated multi-jet yield is ±6%
- **$t\bar{t}$** 10%, modeled in simulation
  - Highly reduced by applying veto using information from additional jets





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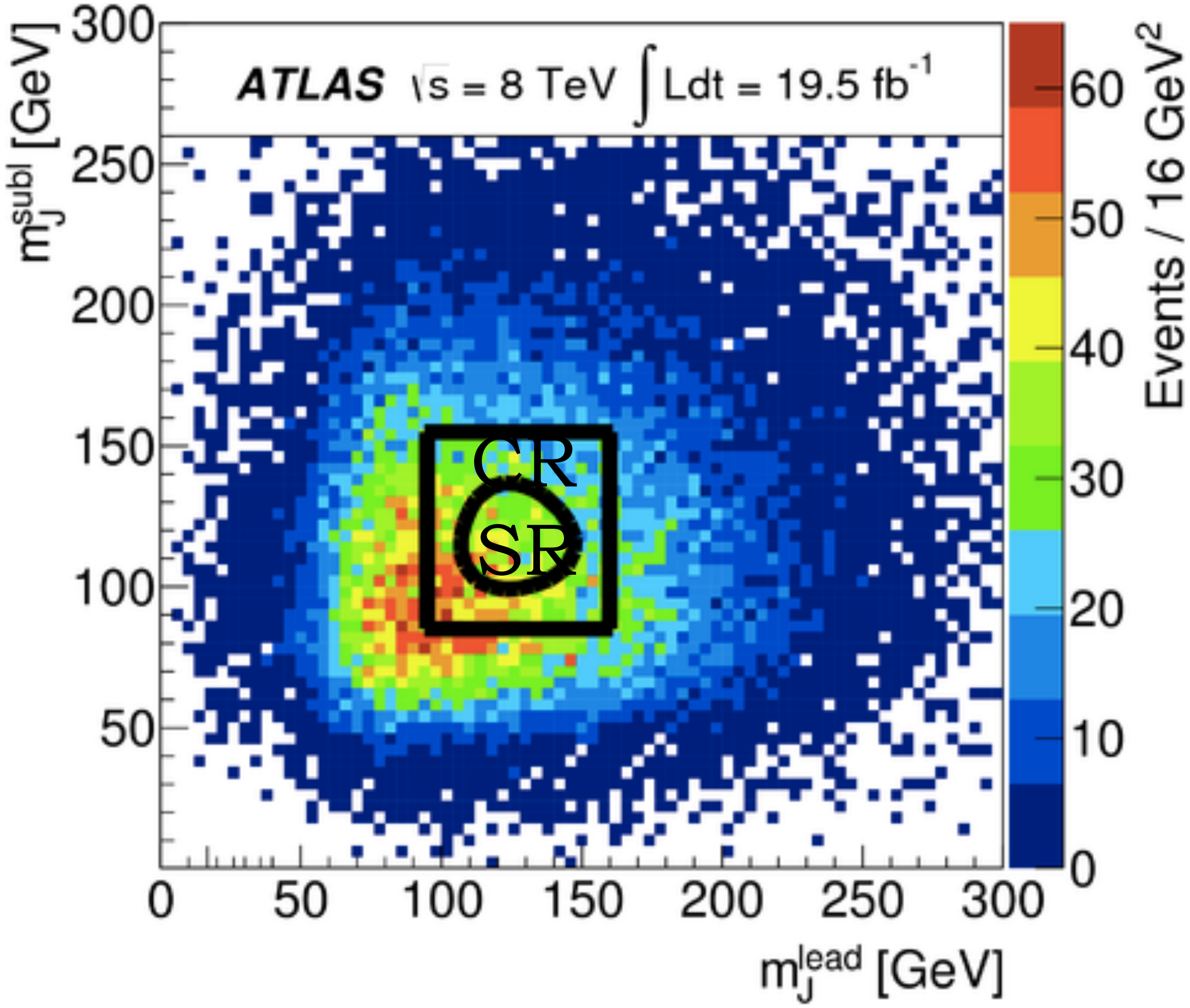
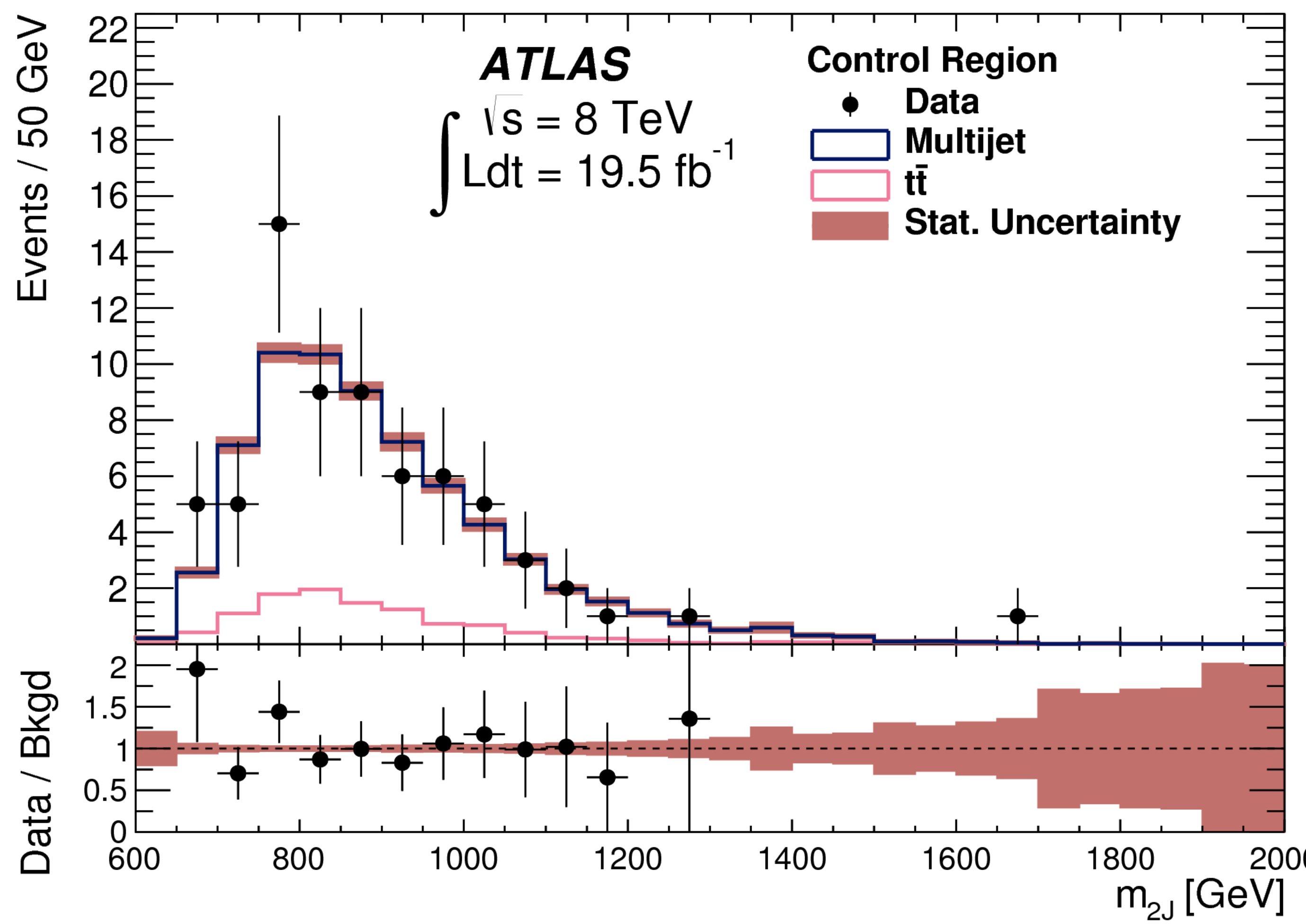
Background model built from sidebands

BOOSTED

2/3-tag

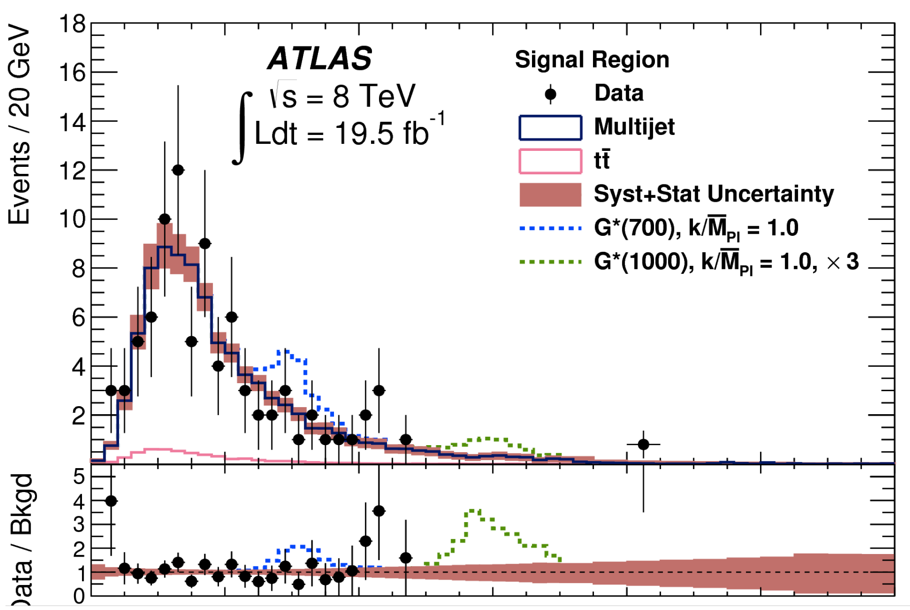


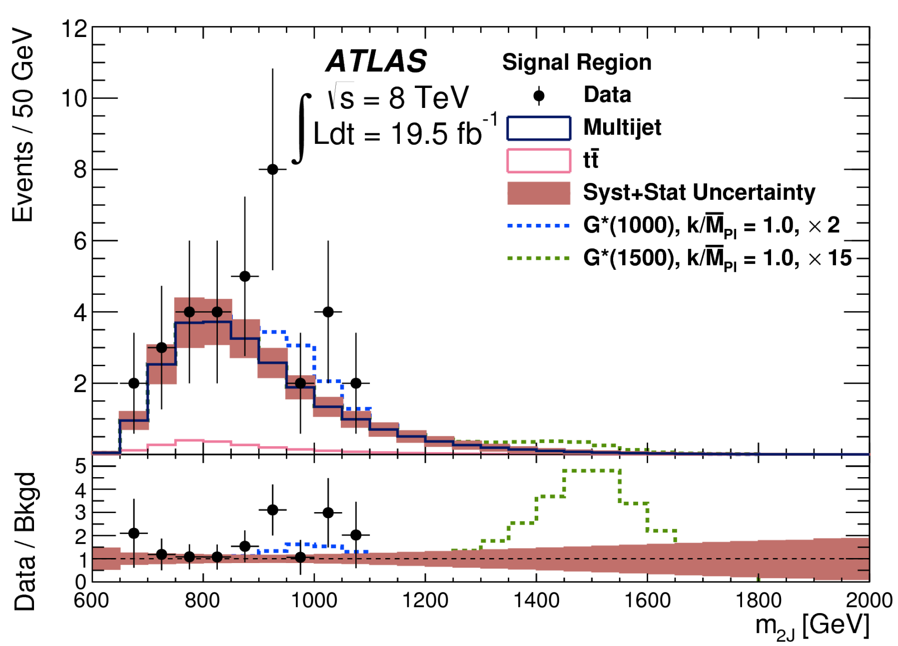


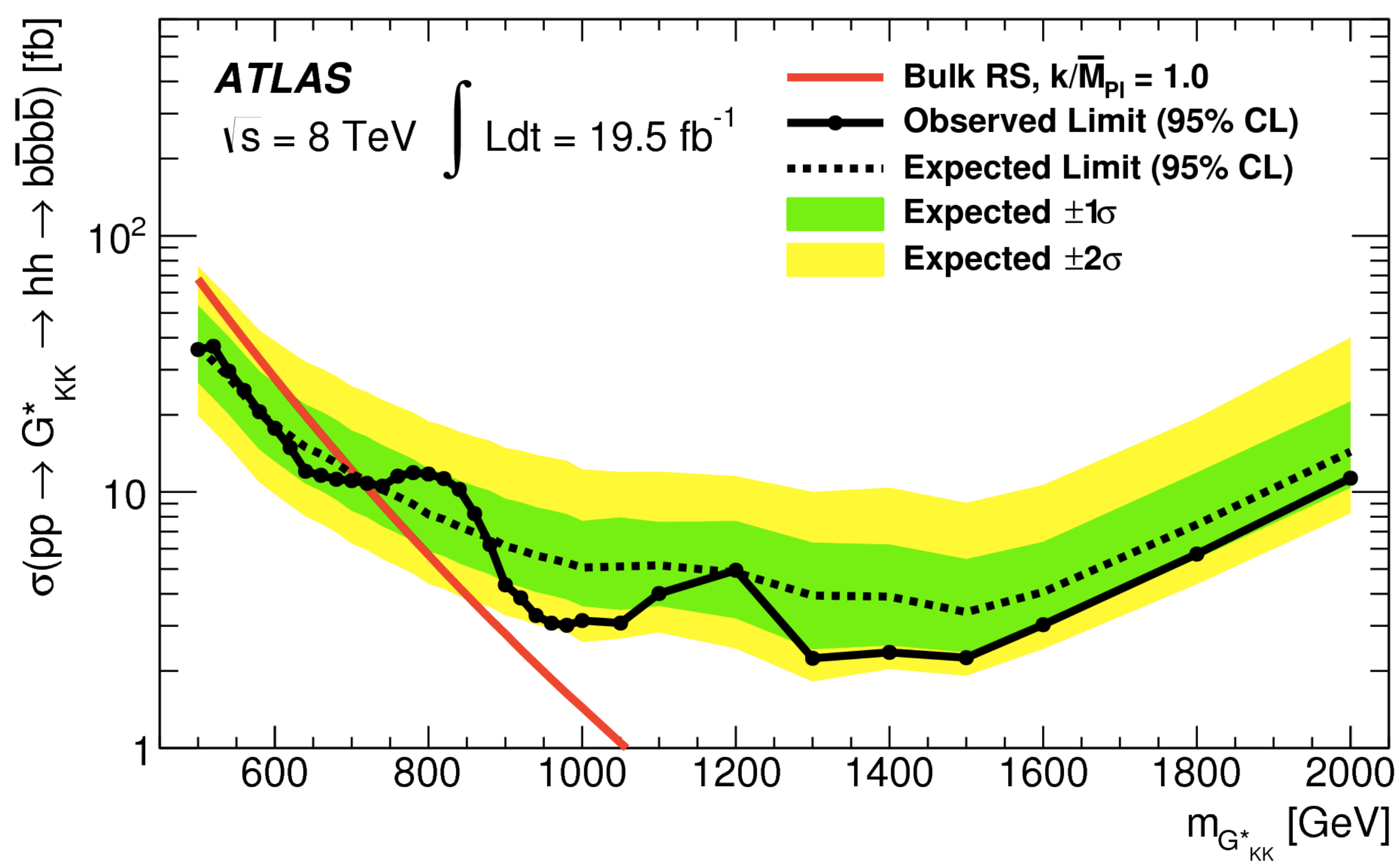
$X \to h(b\bar{b})h(b\bar{b})$, Signal Extraction

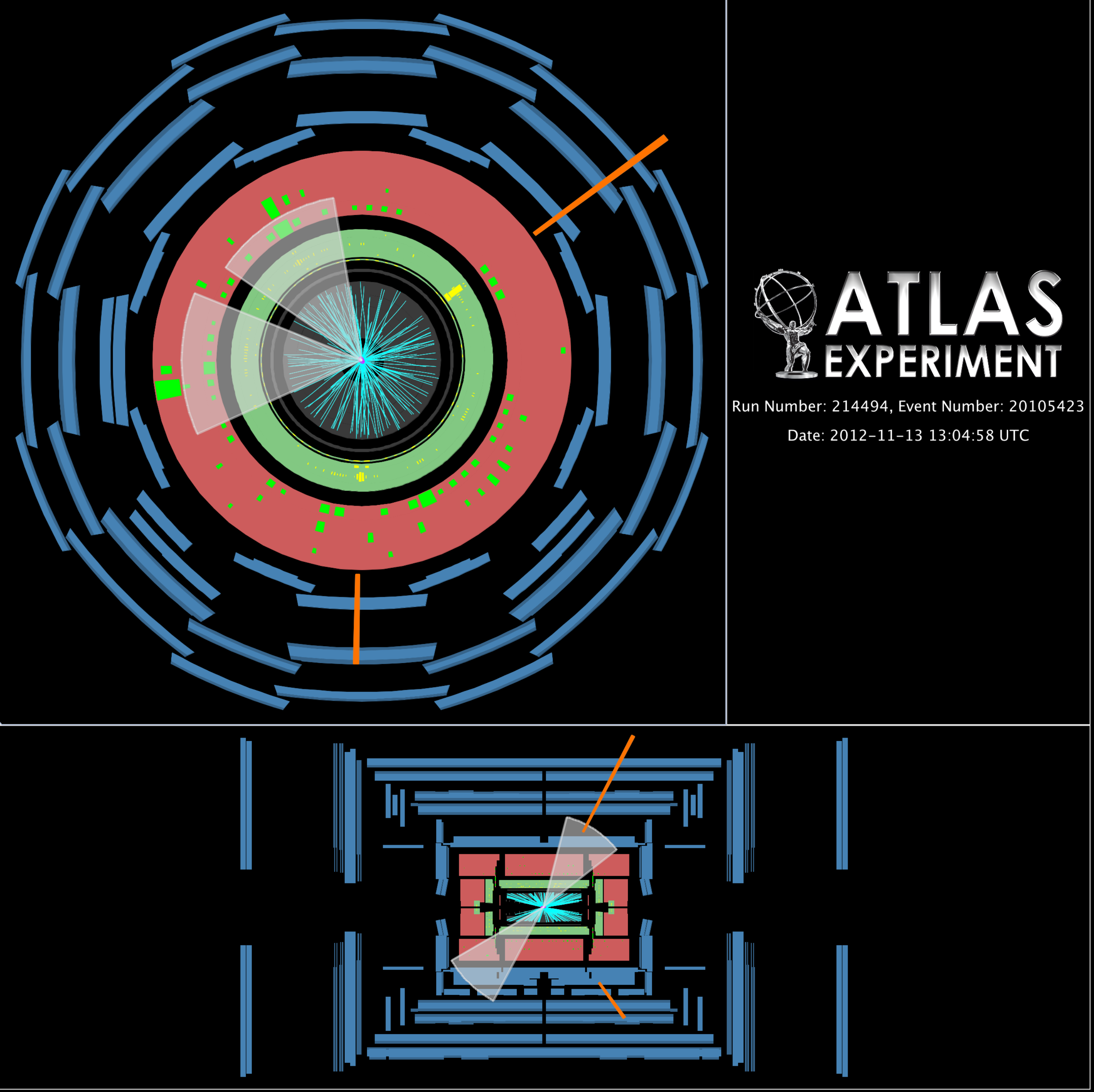
Eur. Phys. J. C (2015) 75:412

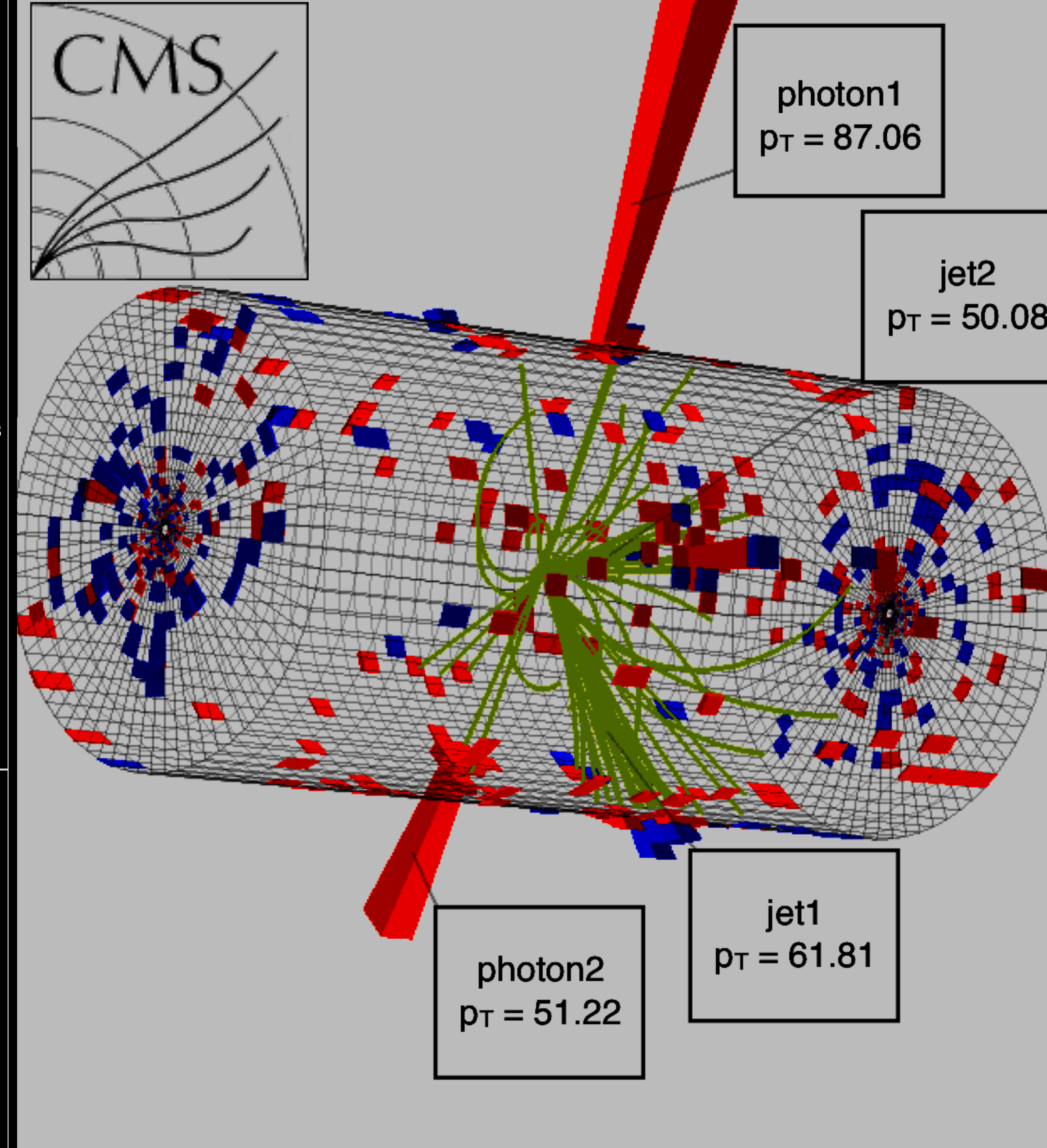
- No significant excess observed in [500 GeV, 2 TeV]
- Systematics dominated by b-tagging and Jet uncertainties











$X \to h(b\bar{b})h(\gamma\gamma)$ candidates

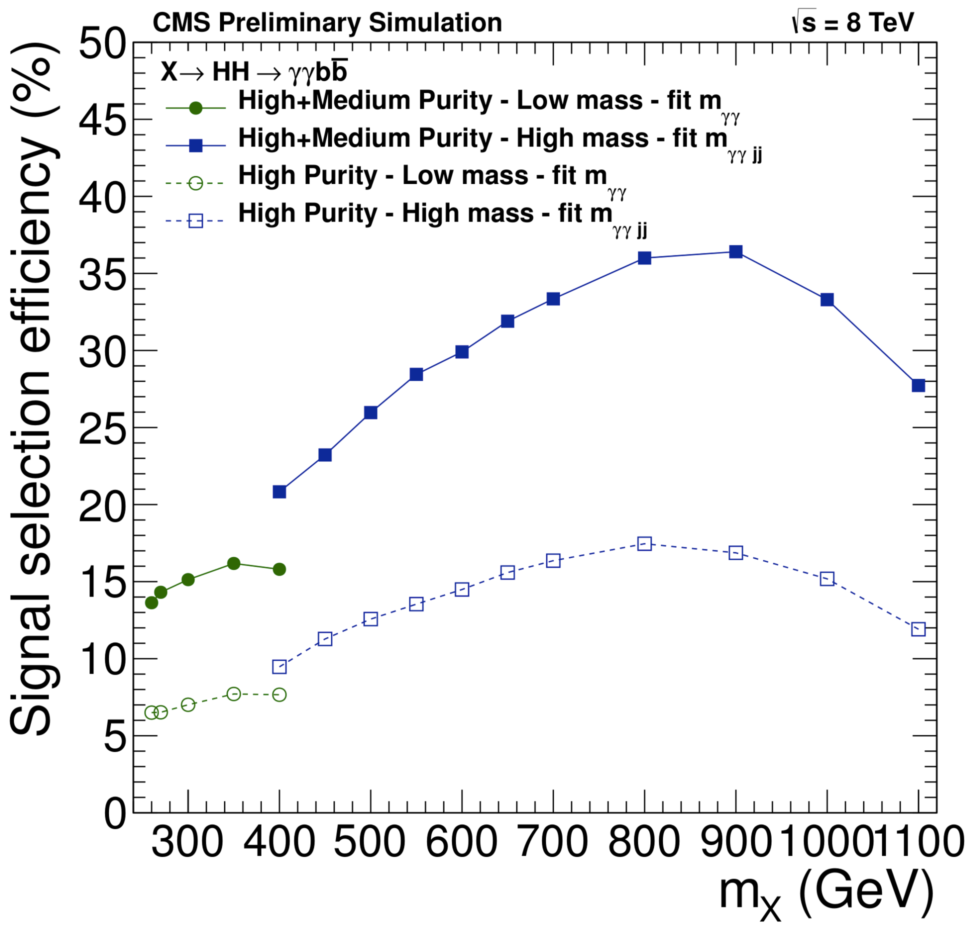
$X \to h(b\bar{b})h(\gamma\gamma)$

HIG-13-032 (CMS)
Phys. Rev. Lett. 114, 081802 (2015) (ATLAS)

$X \to h(b\bar{b})h(\gamma\gamma)$, Event Selection

CMS-HIG-13-032

- Two γs following $h \to \gamma\gamma$ selection
    - $100 < m(\gamma\gamma) < 180$ GeV
- 2 jets with $p_T > 25$ GeV
    - highest dijet pair in the event
- Uses 1 and 2-tag signal regions (0-tag used as control region)
- Kinematic fit to improve m_X resolution
    - $m(b\bar{b})$ constrained to m_h (125 GeV)



Axε is 5-10% (m_X in 260-1000 GeV)

X→h(bb̄)h(γγ), Signal Extraction

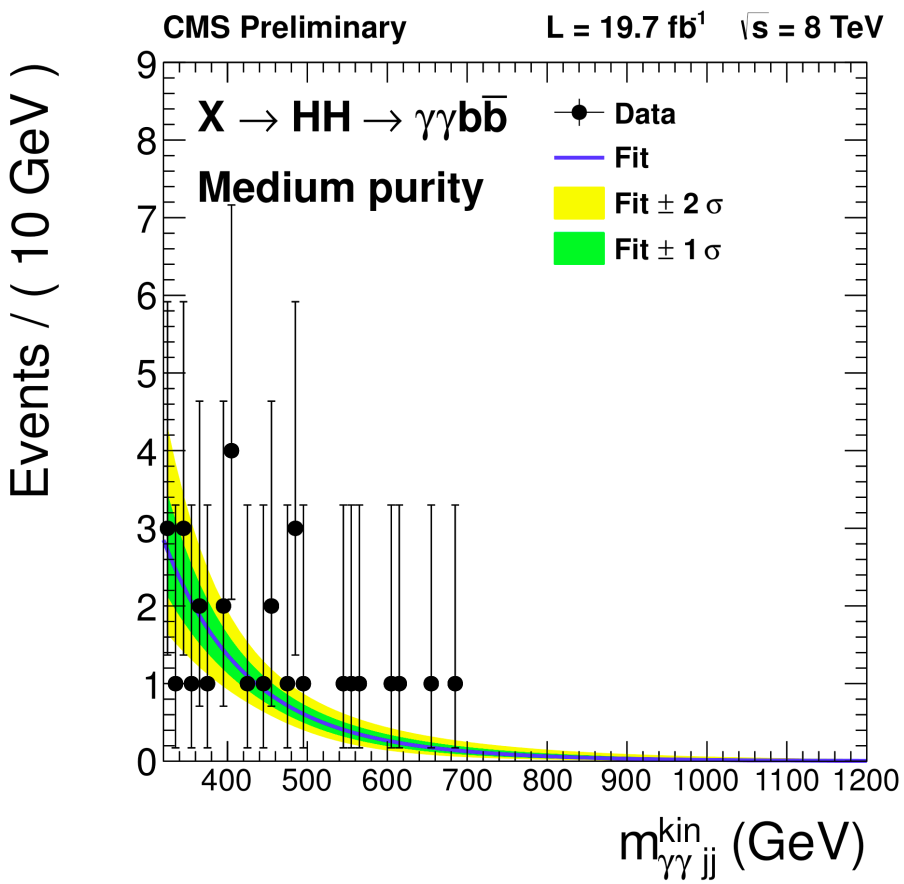
Main backgrounds:

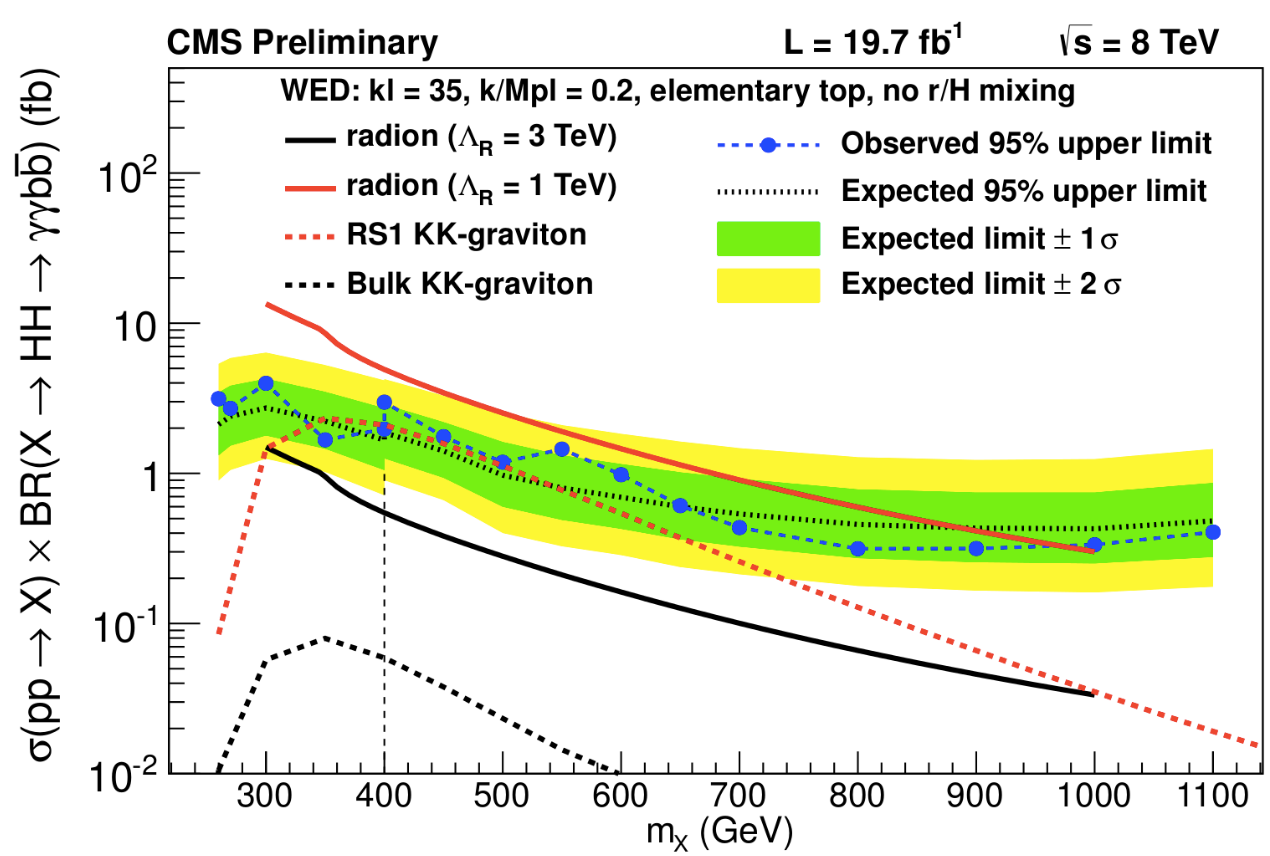
- Non-resonant QCD

  γγbb (>80%)

  γjbb+jjbb (<20%)

A power law is used for the background model





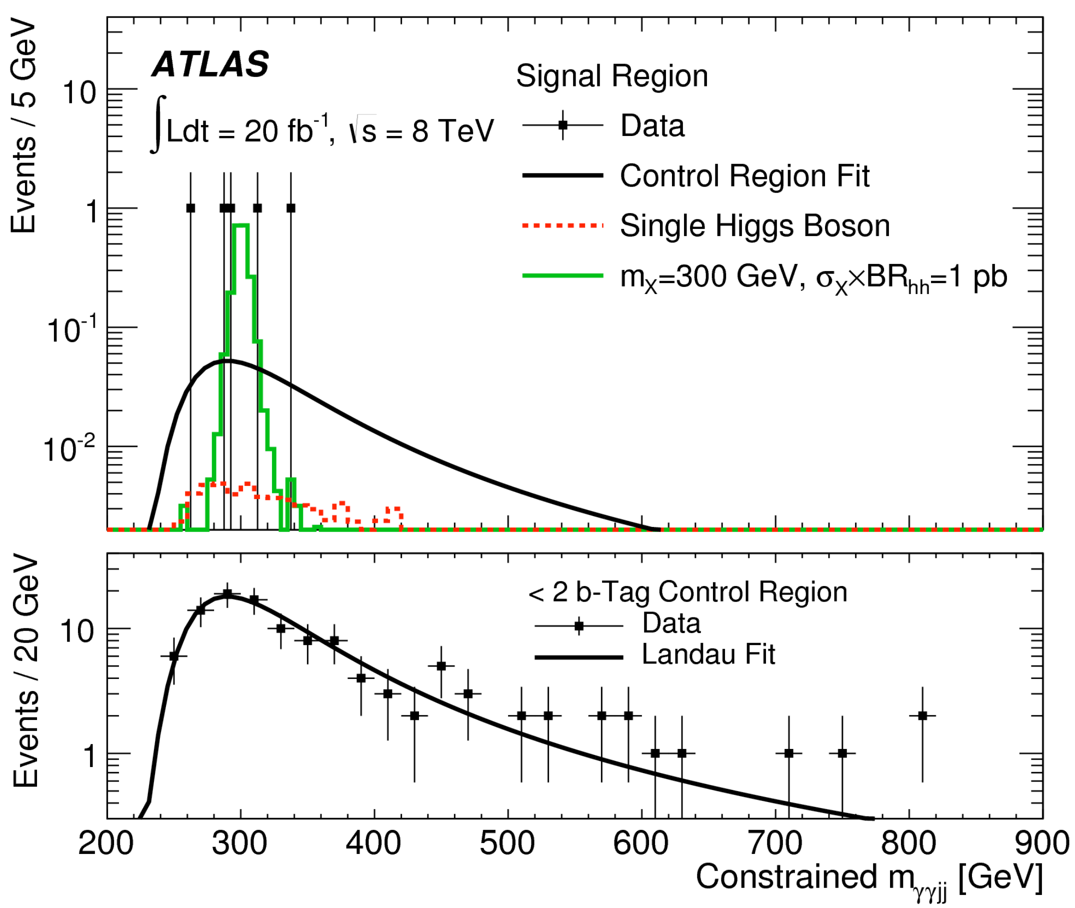
Statistically limited

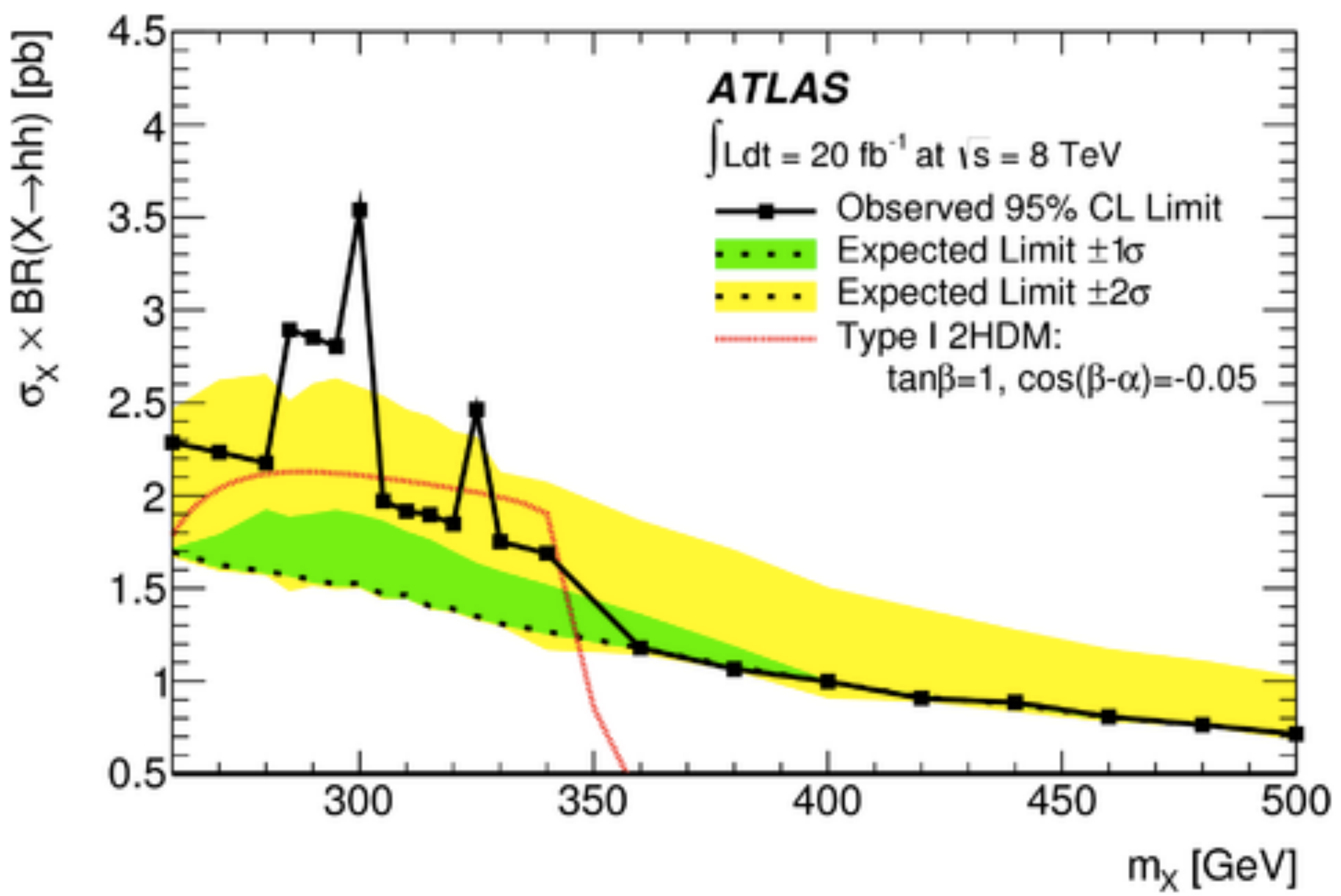
Systematics have ~ 2 % impact on the expected median limit

$X \rightarrow h(b\bar{b})h(\gamma\gamma)$, Signal Extraction

Phys. Rev. Lett. 114, 081802 (2015)

- Counting experiment and event selections similar to CMS
- Fit continuum background from data to the m_X distribution
    - Landau shape from < 2 b-tag control region
- **Resonant** analysis sets limit around 1 pb at high mass



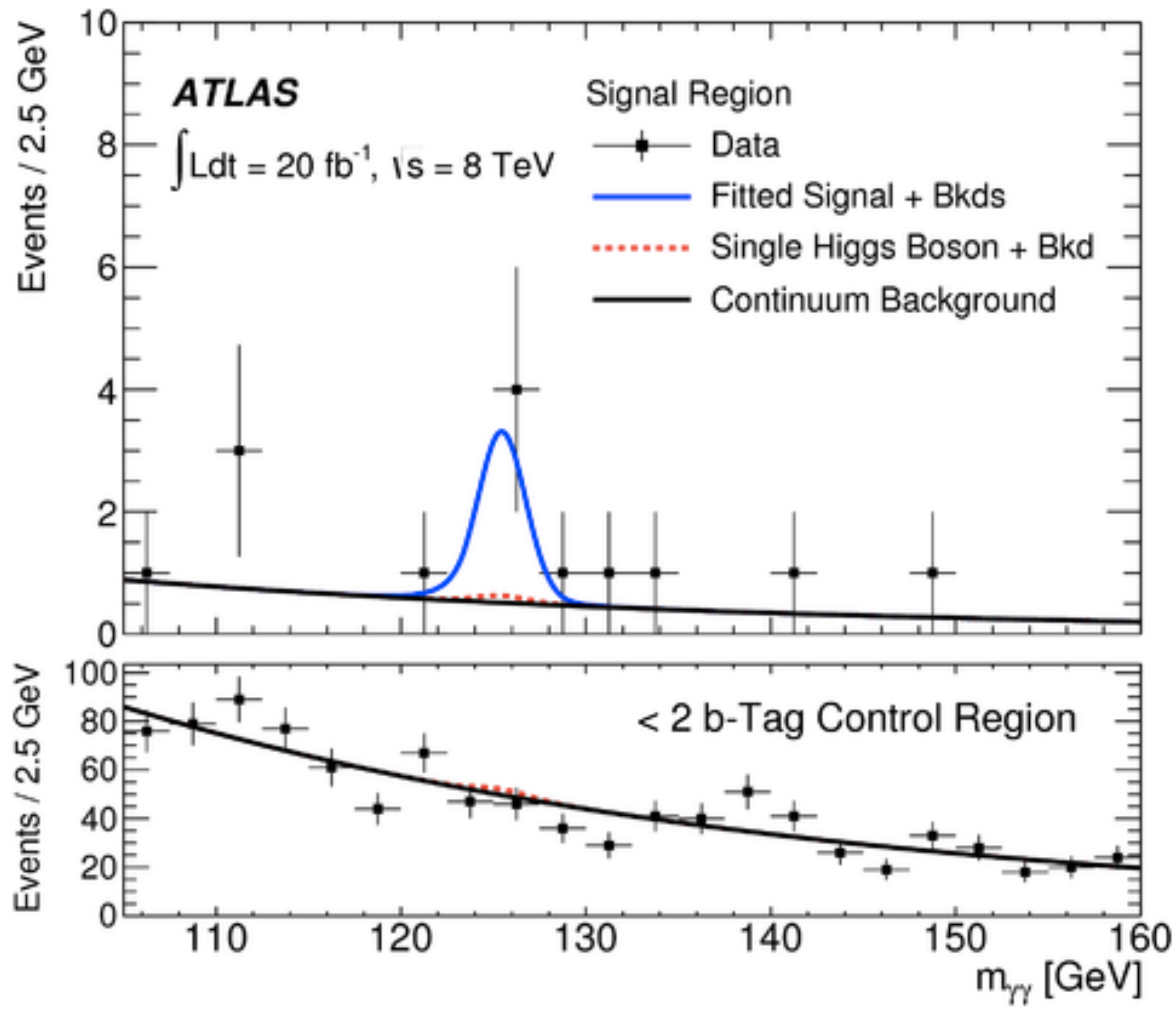


Local excesses below 350 GeV raising the observed limits to up to 3.5 pb

$X \to h(b\bar{b})h(\gamma\gamma)$, Signal Extraction

Phys. Rev. Lett. 114, 081802 (2015)

- Fit to the m(γγ) distribution
- Limit on **non resonant** production:
    - Expected: $1.0^{+0.2}_{-0.5}$ pb
    - Observed: 2.2 pb
- 2.4σ from the background-only hypothesis.



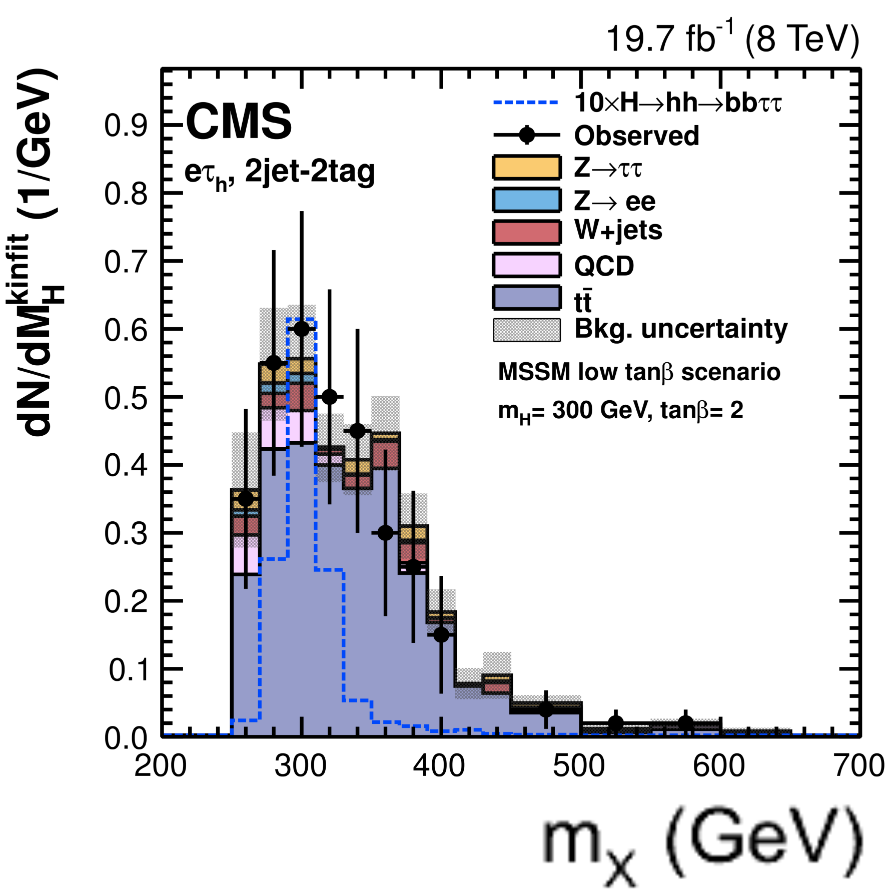
Other final states

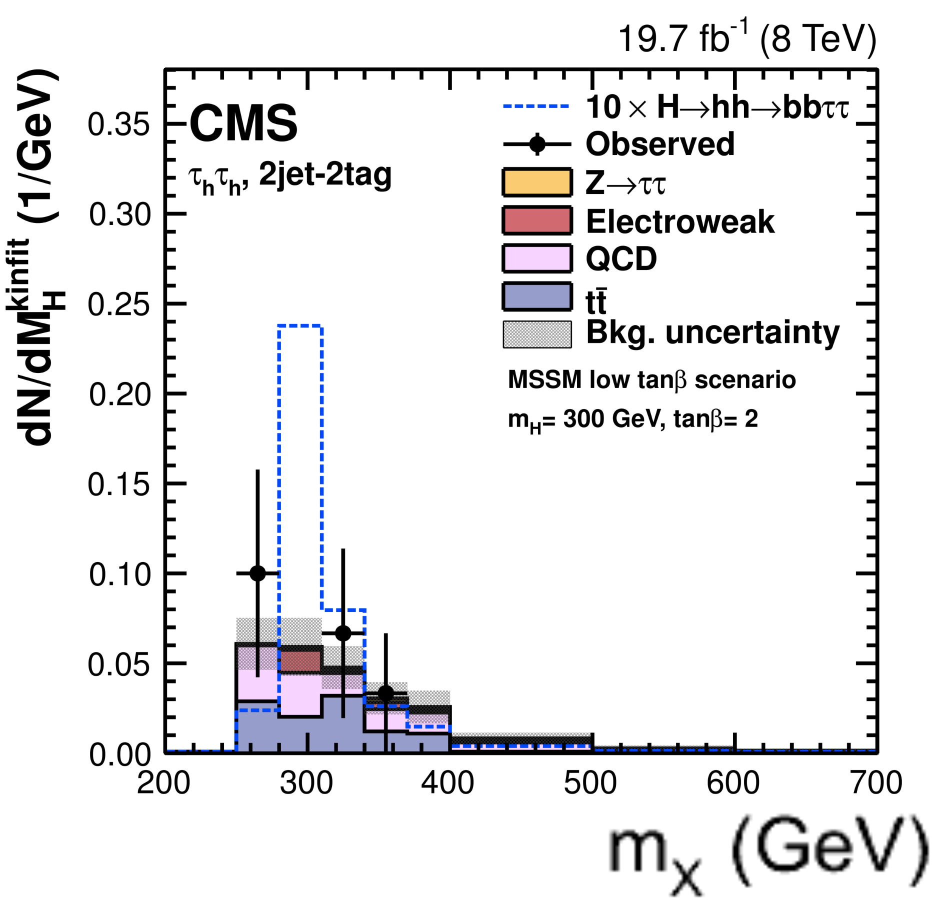
$X \rightarrow h(b\bar{b})h(\tau\tau)$
$X \rightarrow h(b\bar{b})h(WW)$
$X \rightarrow h(WW)h(\gamma\gamma)$

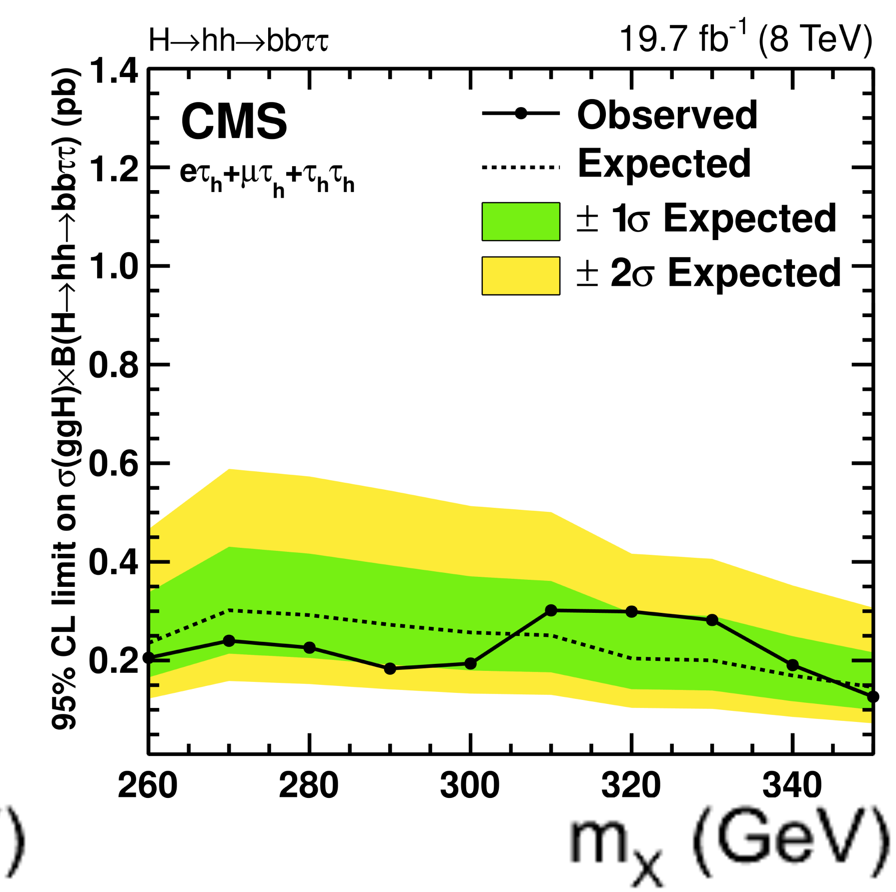
X→h(b$\bar{b}$)h(ττ)

CMS-HIG-14-034

- Selection follows the h→ττ analysis
    - 2 had and 1 had+1lep
- Categorization by number of b-tags (0/1/2 b-tags)
- Kinematic fit to improve final mass resolution

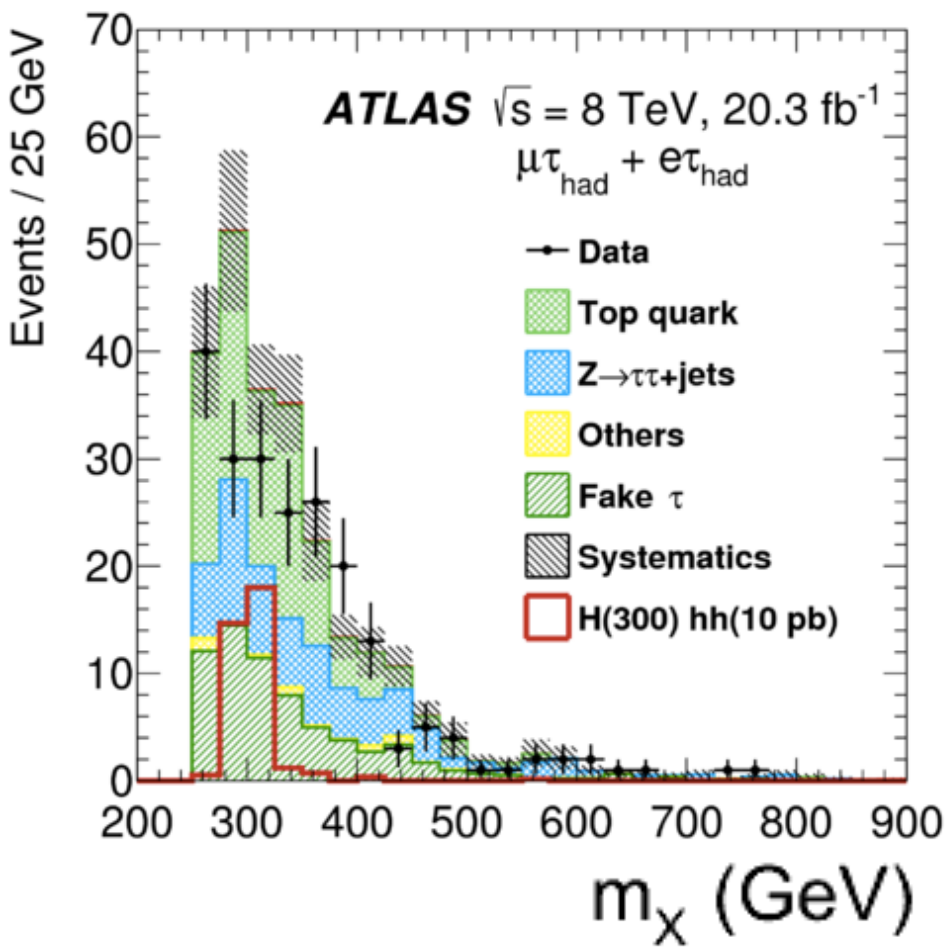


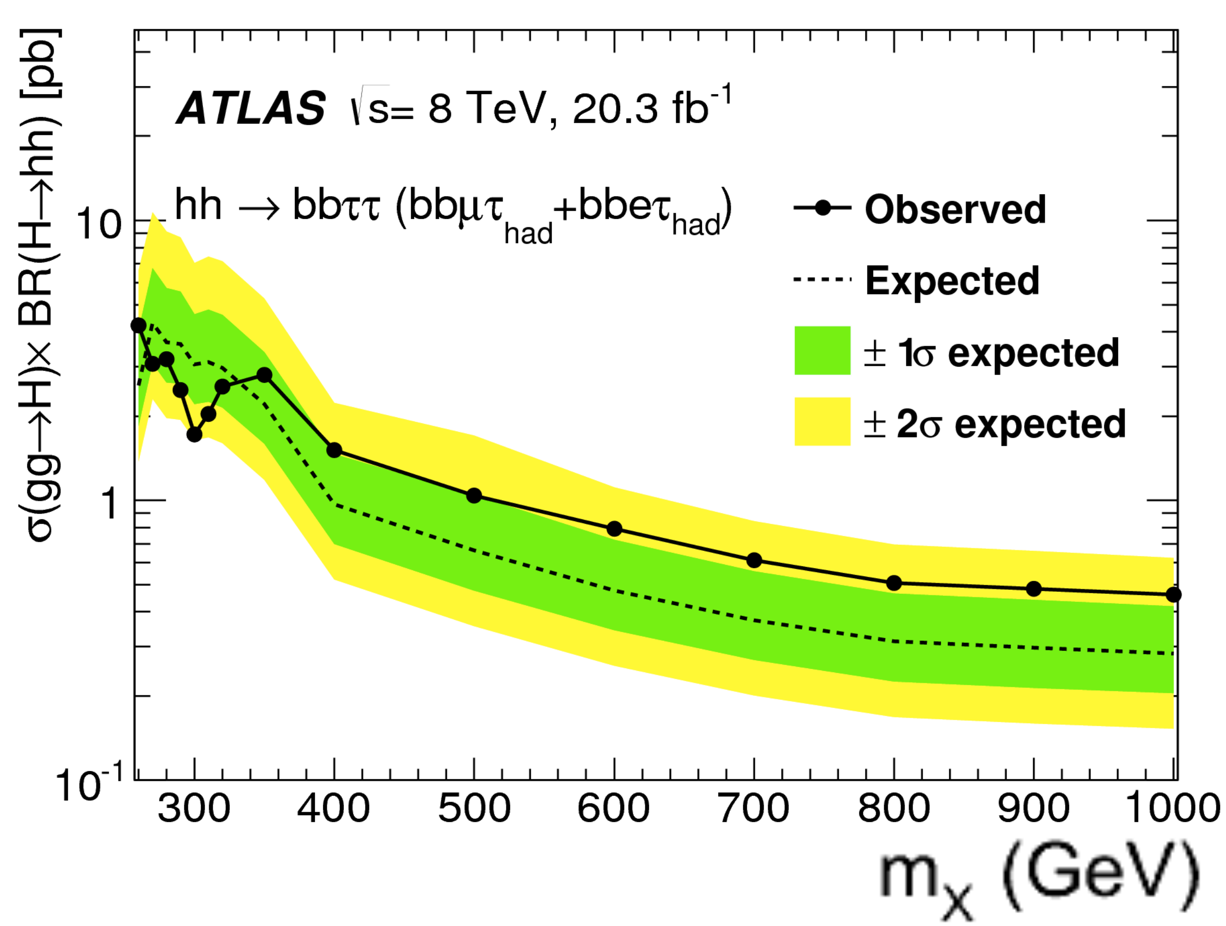




$X \rightarrow h(b\bar{b})h(\tau\tau)$

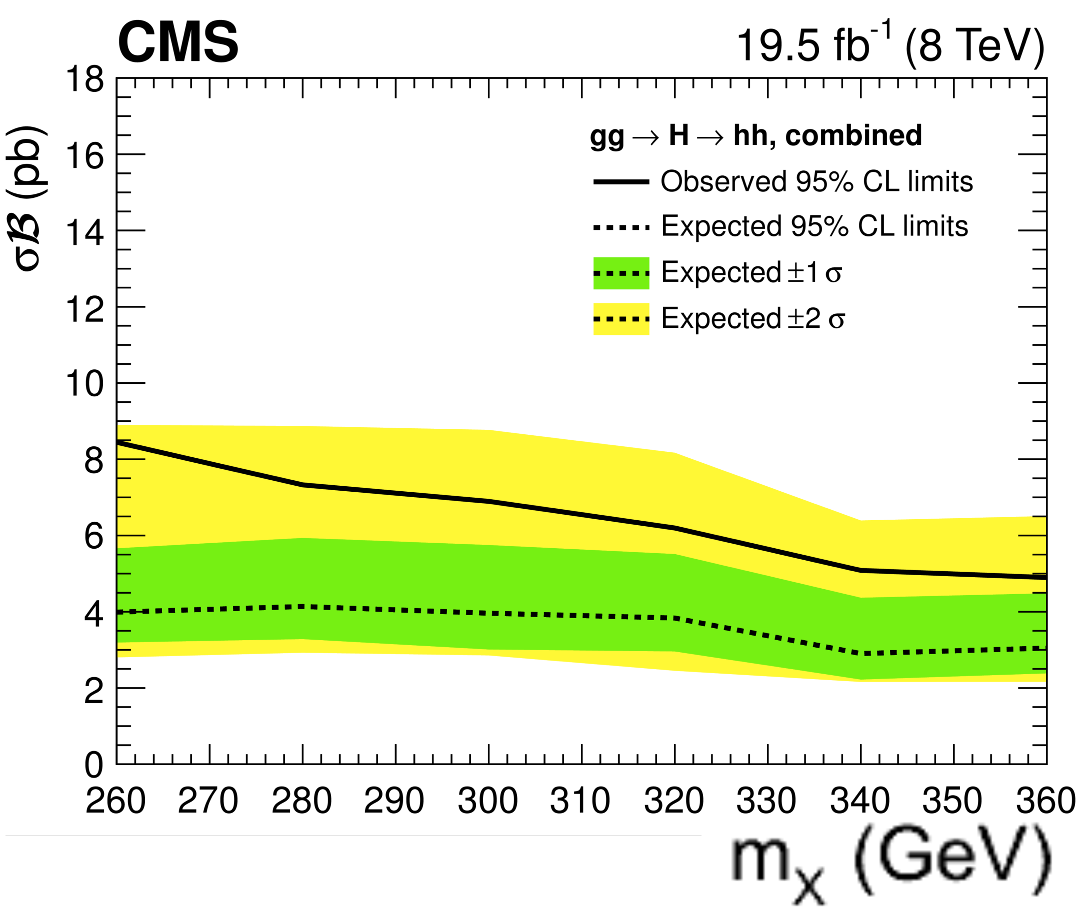
- only 1had+1lep
- two b-tag categories: 1/2 b-tag
- To improve resolution scale factors of $m_h/m_{b\bar{b}}$ and $m_h/m_{\tau\tau}$ are applied
    - final resolution improved by 3 at 260 GeV and 30% at 1 TeV

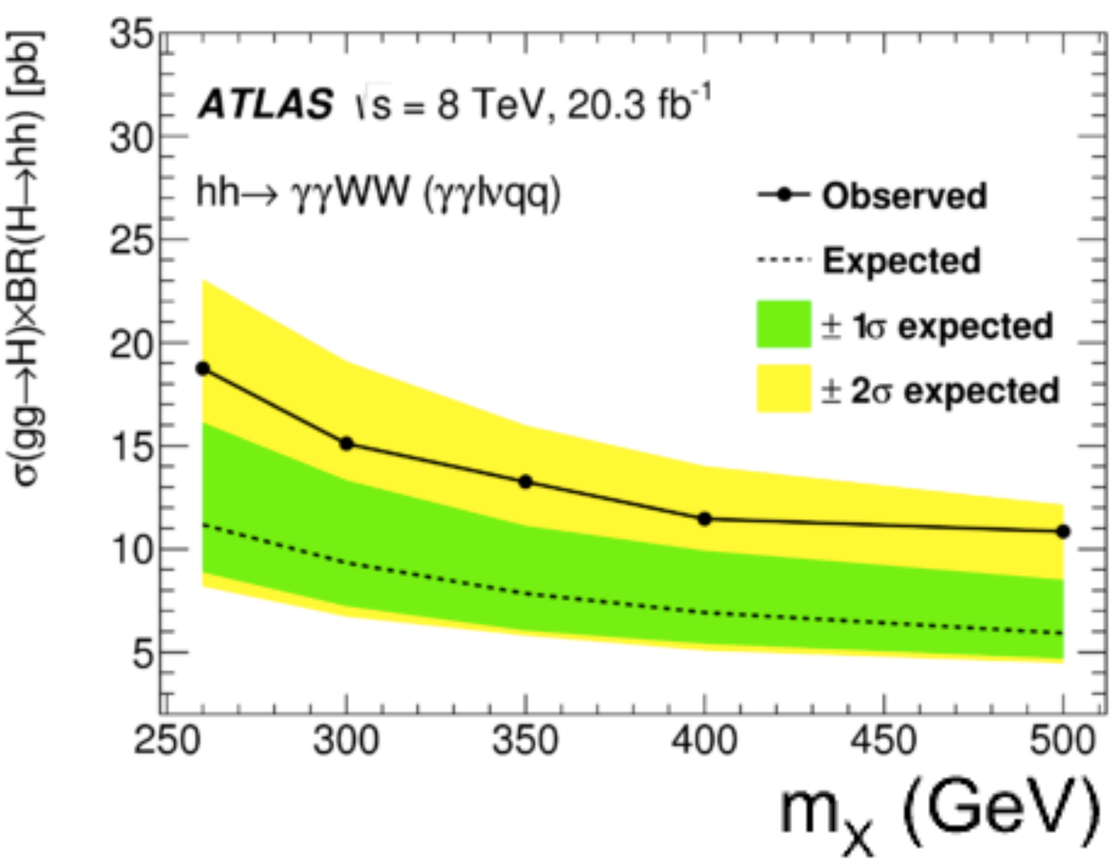




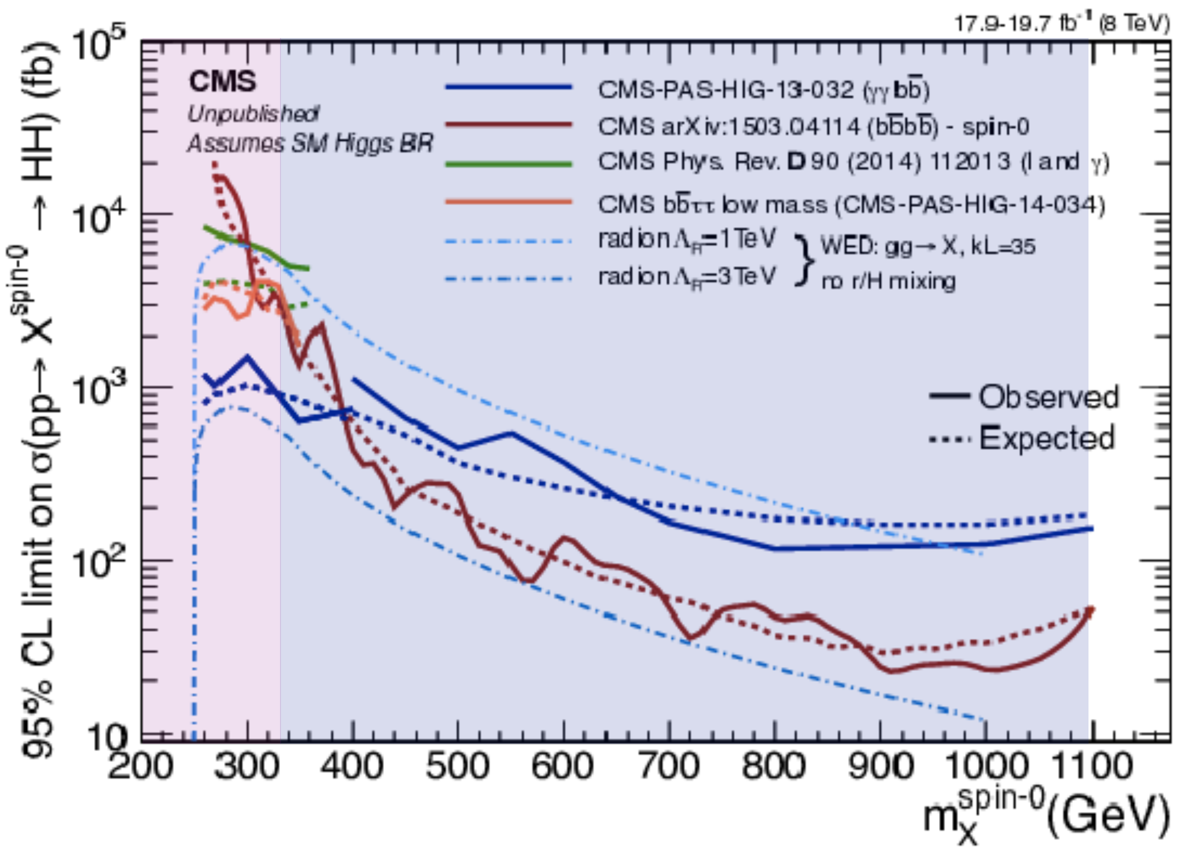
Other final state

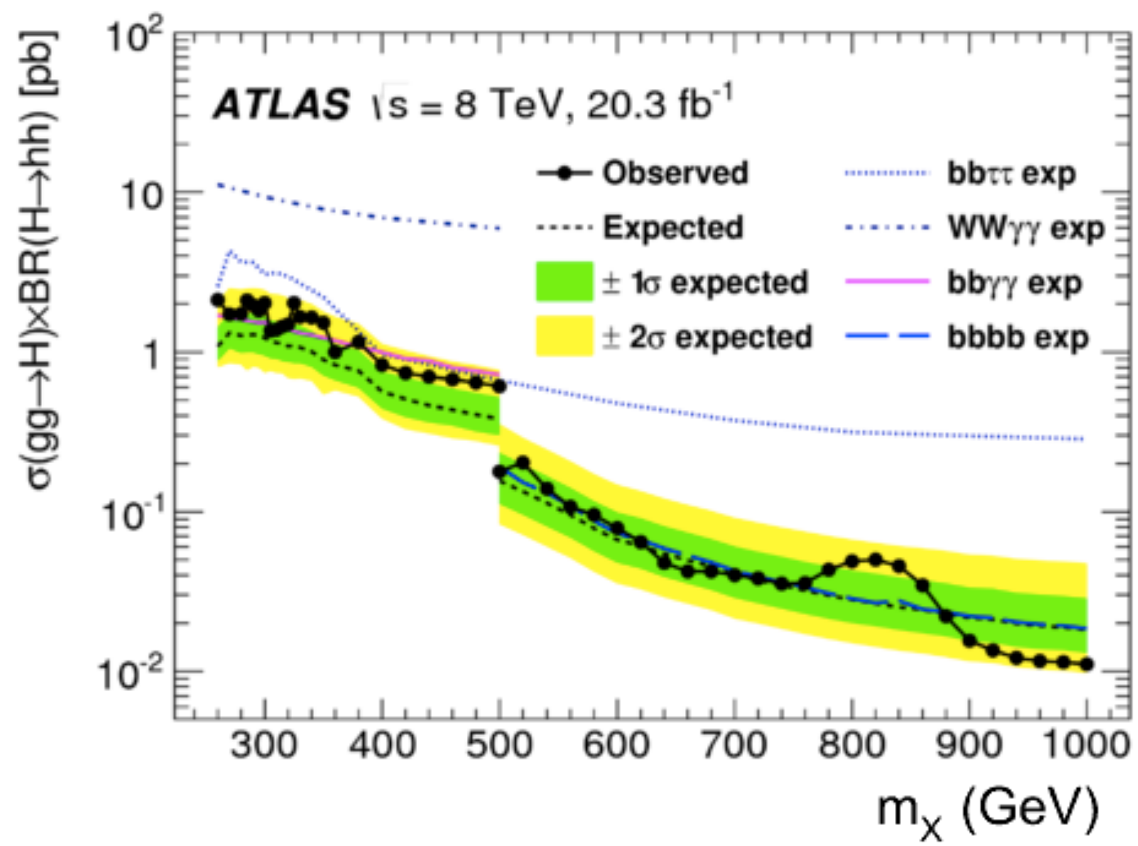
- CMS analysis targets multi-lepton and lepton plus photon final states
  - at least 3 leptons or 2 photons plus at least one lepton
  - Cover several final states WWγγ, WWWW, WWZZ, WWττ, etc...
- ATLAS analysis targets WWγγ
  - h→γγ side following single H analysis
  - Additional lepton+jets (b-tag veto) to select WW





X→hh, Results





h(bb̄)h(bb̄) best sensitive channel for $m_X > 400/500$ GeV

h(γγ)h(bb̄) complement in the low mass or non-resonant regime

Constraints on Warped Extra Dimension (Radion and Graviton), 2HDM

Overall hh is competitive with VV searches to test WED

In Run II at 13 TeV - Sensitivity to high-mass objects production much enhanced

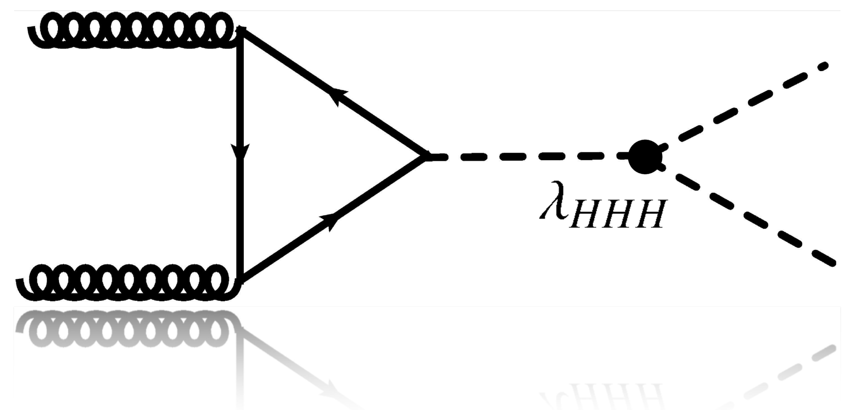
parton luminosity increases

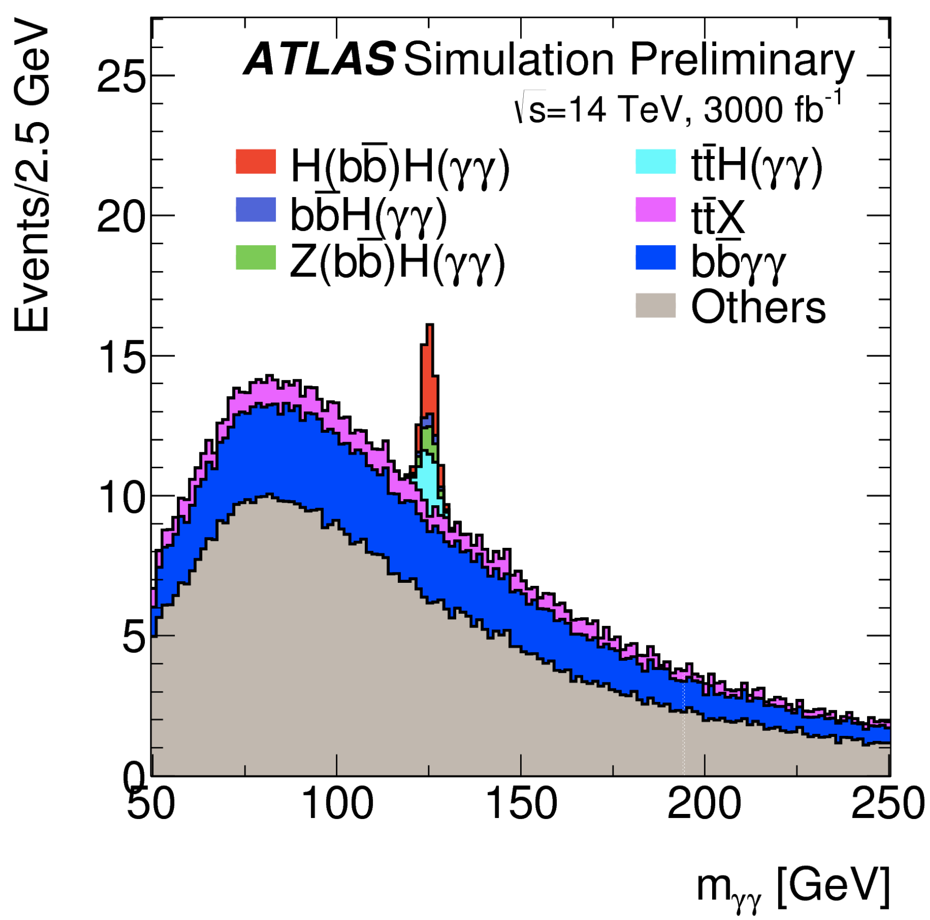
at $m_X = 500$ GeV we gain a factor 4, 10 at 2 TeV

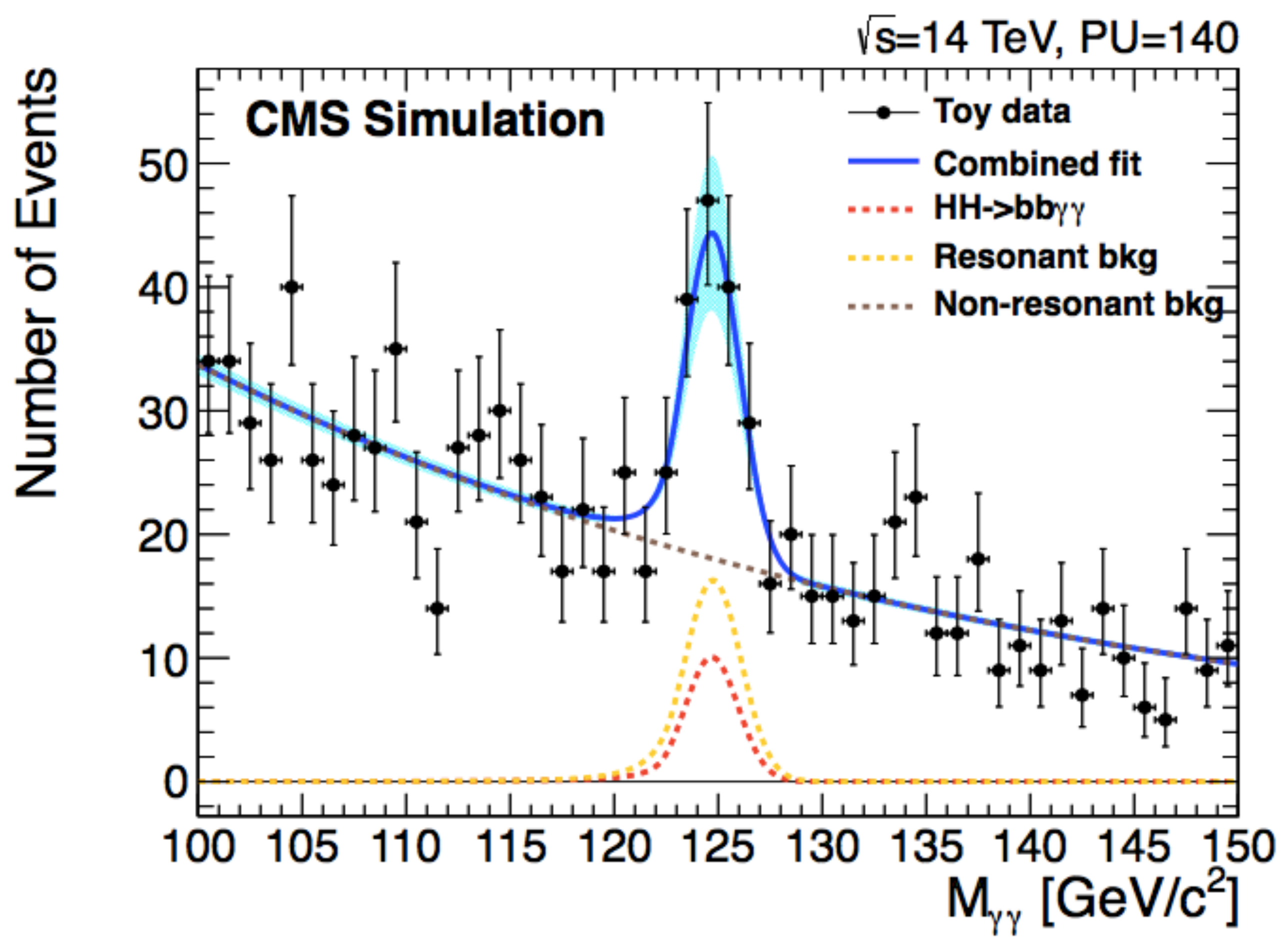
λ_{hhh} at HL-LHC

CMS-FTR-15-002
ATL-PHYS-PUB-2014-019

- Very preliminary studies are being performed for the experiment upgrades at HL-LHC
- Cross section for SM hh production is 40.7 fb at 14 TeV
- Sensitivity to non resonant SM hh production can reach
  - ~1.5σ per experiment in the bbγγ channel
  - ~1.9σ combination of bbγγ, bbWW, bbττ







Conclusions & Outlook

Higgs boson, as a new powerful tool to search for new physics

hh production as one of the most interesting physics processes where to look for new physics in the Higgs sector.

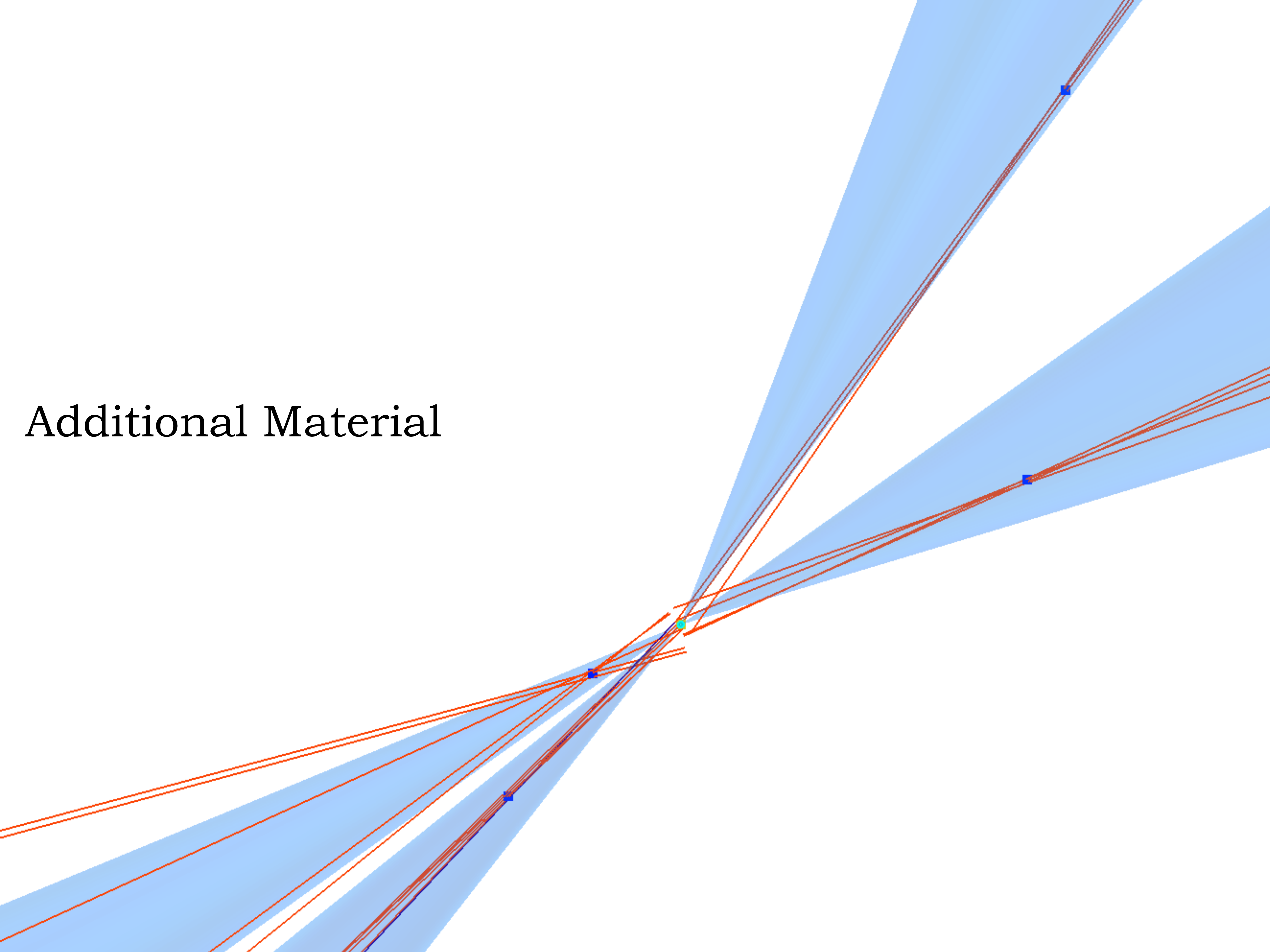
- **h($b\bar{b}$) very promising** to look for heavy new state
  - large statistic being the highest BR
  - boosted topology helps to reduce multi-jet background
- h(γγ), clean signature to study precisely the excess if/when found

- Both CMS and ATLAS have searched for heavy resonances decaying to **hh in Run I at 8 TeV**
  - **limits on cross section production** set on wide mass range
    - below ~ 10 fb for highest mass points (4b)
  - h(γγ)h($b\bar{b}$) clean final state to investigate the low mass scenario
  - h($b\bar{b}$)h($b\bar{b}$) final state also sensitive to spin hypothesis

- **Non-resonant search** are far from SM sensitivity (>50x SM)
  - but new physics can be probed

- **Sensitivity to SM hh** production can be reached combining different channels and the two experiments **at the HL-LHC**

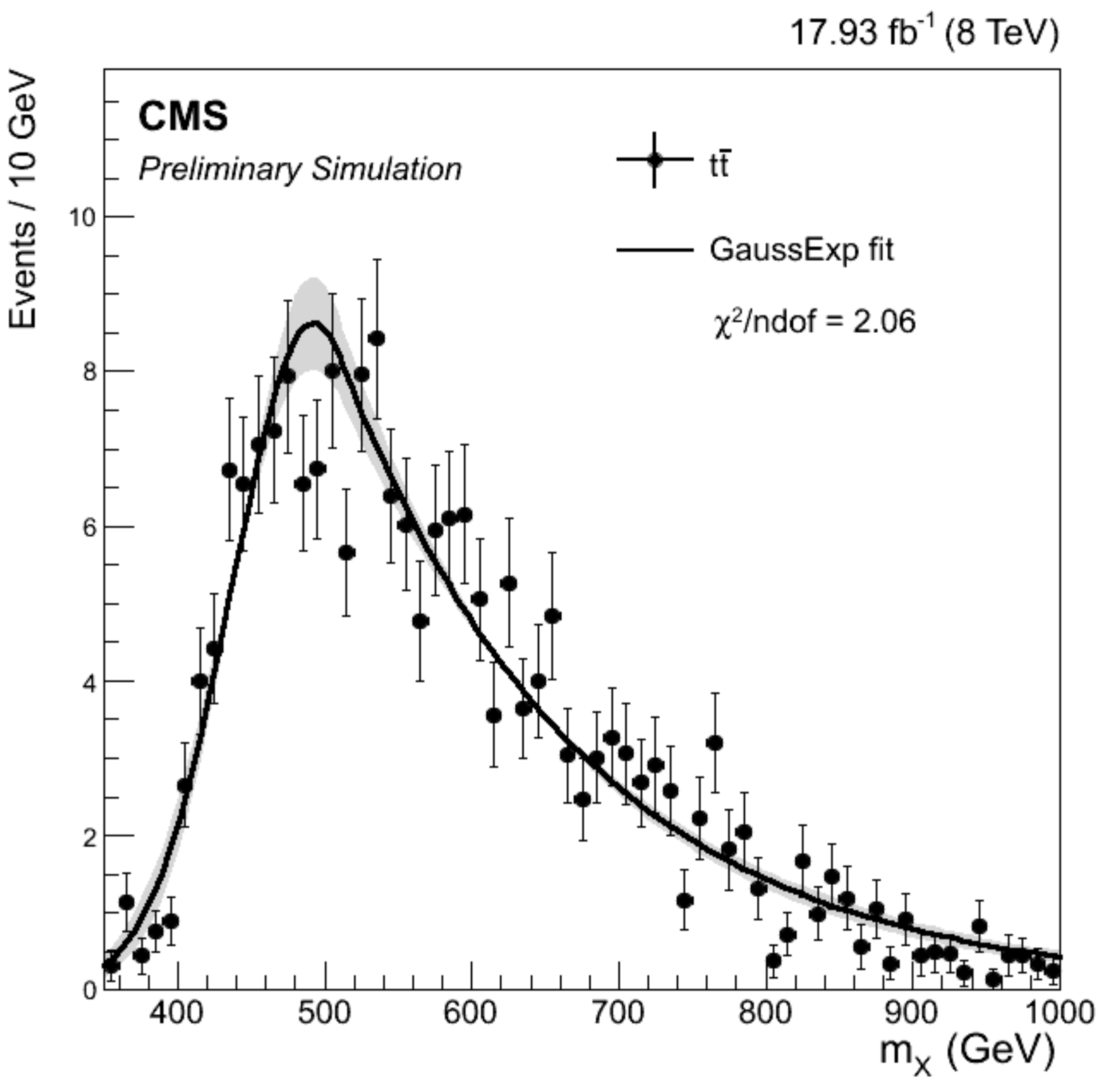
Additional Material



$X(b\bar{b})(b\bar{b})$ Event Selection

RESOLVED
PLB 749 (2015) 560

- PF anti-k_T jet (0.5)
- 4 central jets - $|\eta|<2.4$ - with $p_T >$ 40 GeV and b-tagged
- HH candidates :
  - $m(b\bar{b})$ in [90,160] GeV — low
  - $\Delta R(b\bar{b})<1.5$ & $p_T(b\bar{b})$ > 300 GeV — high
  - Signal Region
    $\Delta m^2_{H1} + \Delta m^2_{H1} < (17.5\ \text{GeV})^2$
    with $\Delta m_{H1,2} = m_{H1,2} - 125$ GeV



Signal:
Parametric Model in simulation

Background:

* $t\bar{t}$ ~ 25-30%	Parametric Model in simulation
* QCD multi-jet ~ 70-75 %	Data

$X(b\bar{b})(b\bar{b})$ QCD model

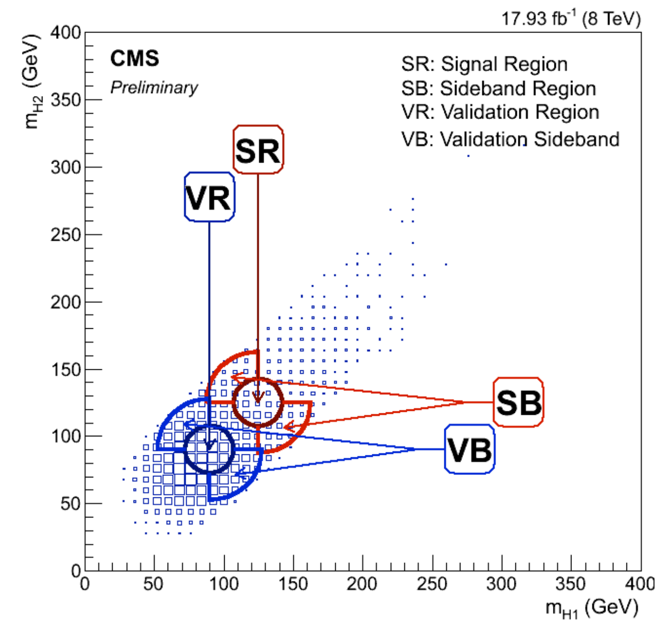
RESOLVED
PLB 749 (2015) 560

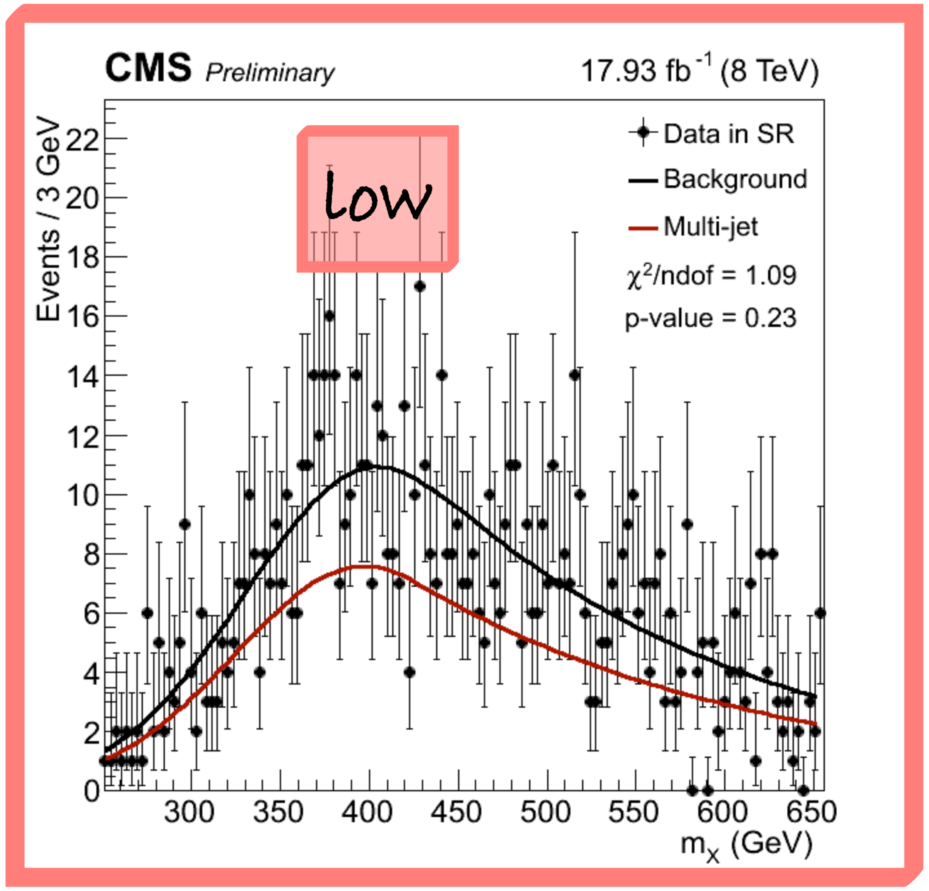
"Gauss-Exp" function is used to model the multi-jet background

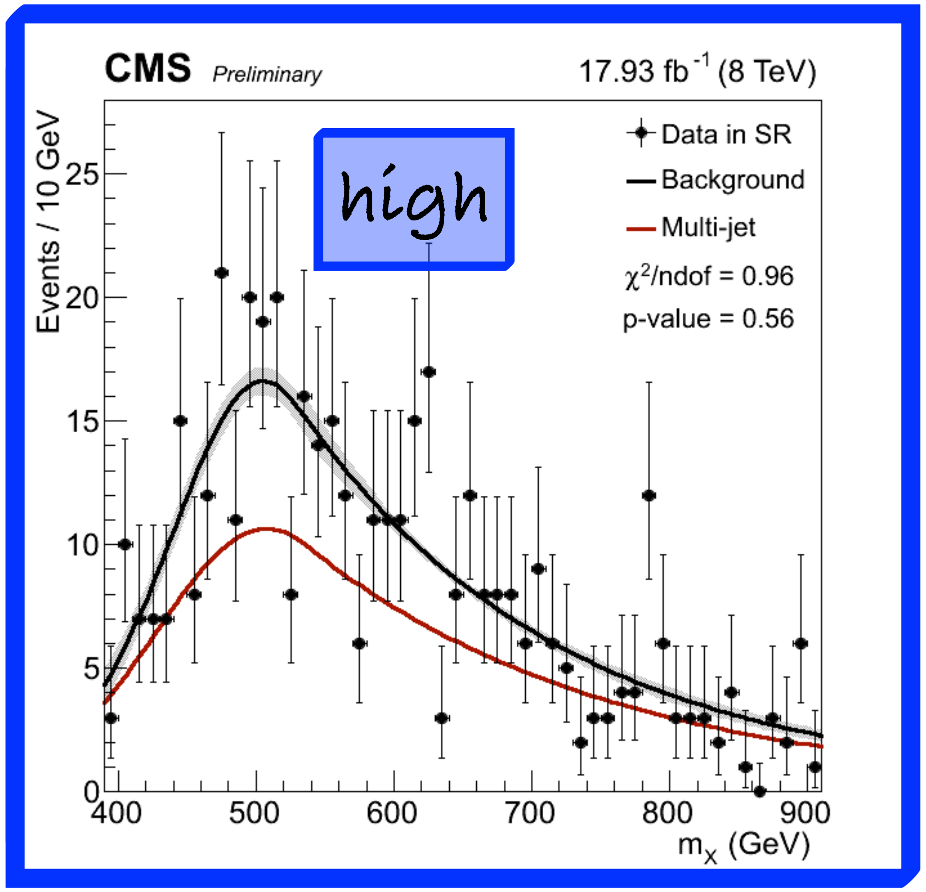
SB to test the background shape modeling
- kinematically close
- not signal-enriched

Flexibility of the model validated in VR/VB

A fit of the mX distribution in SR to a combination of signal and backgrounds



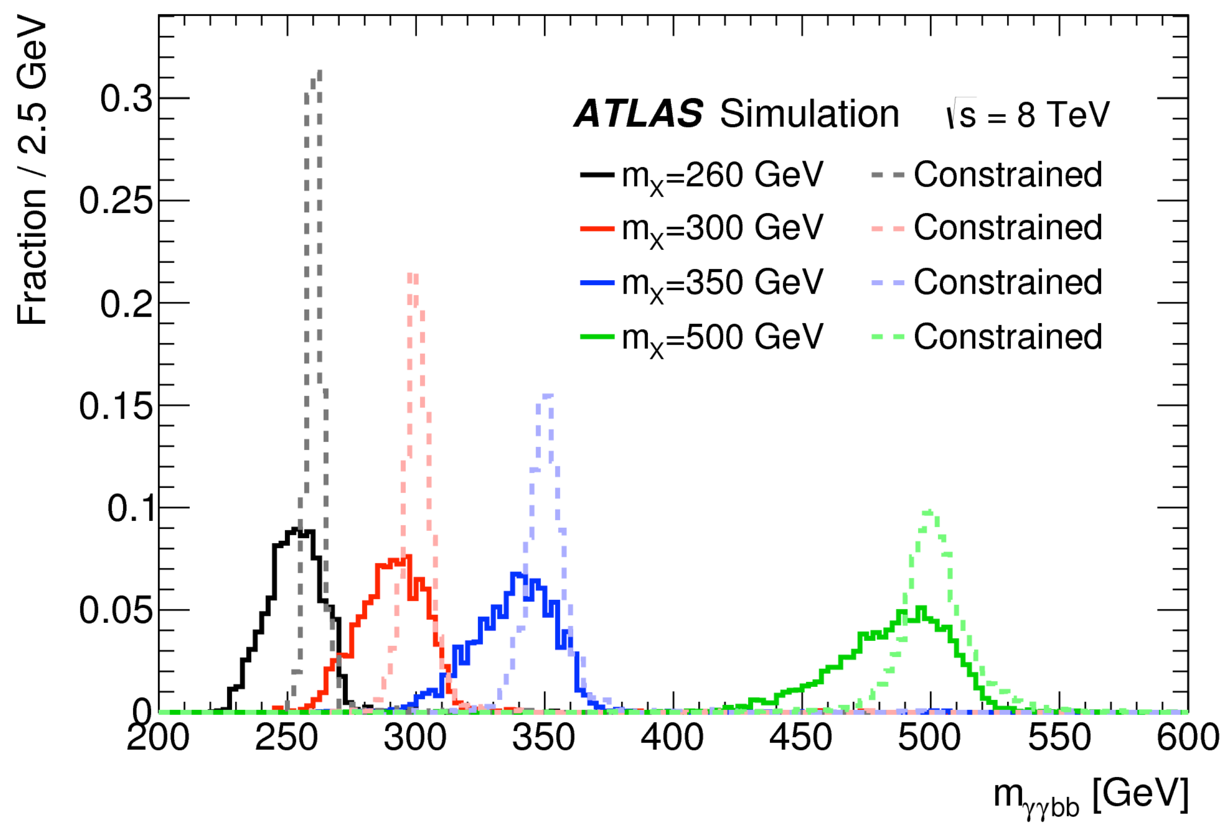




$X \to h(b\bar{b})h(\gamma\gamma)$, Event Selection

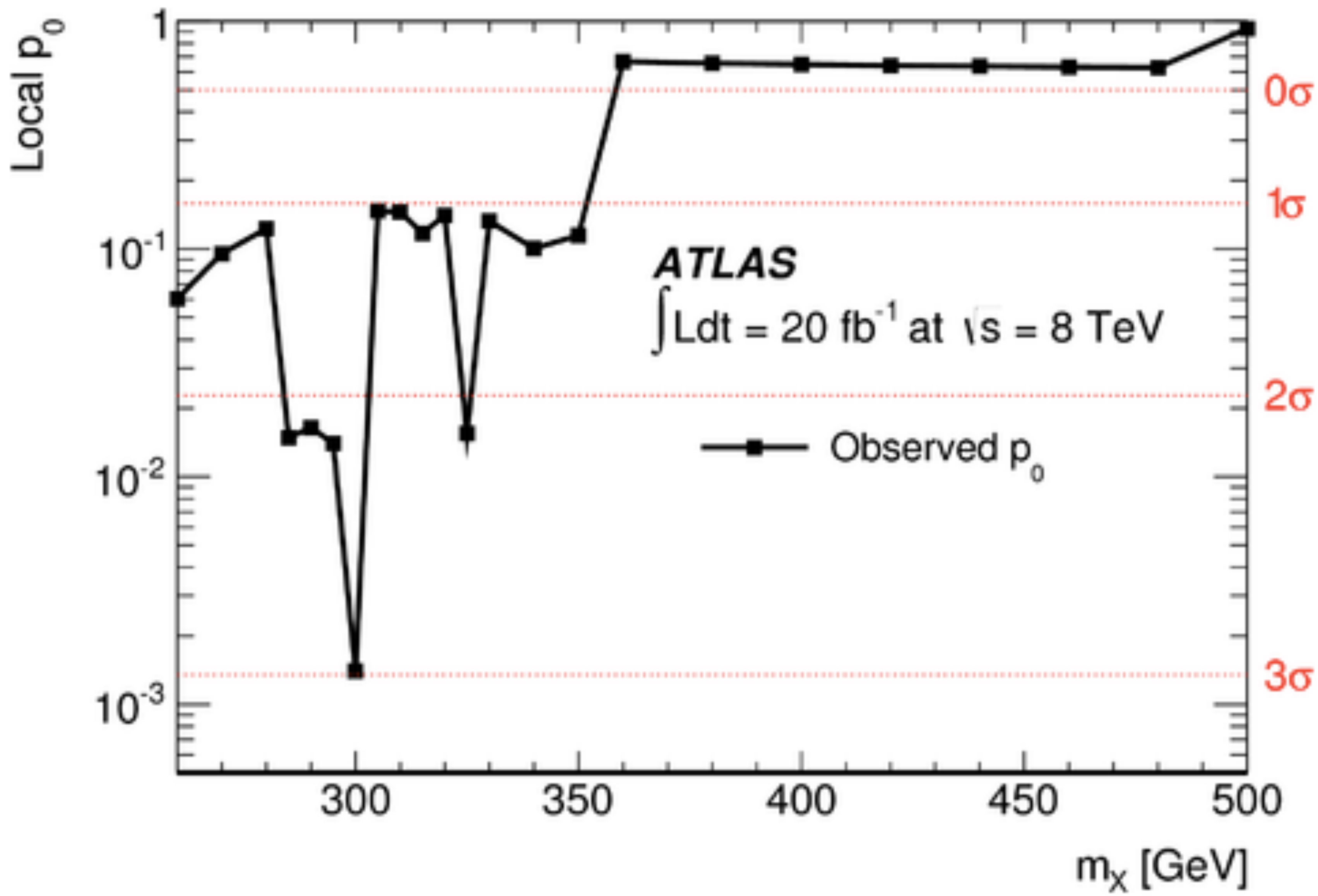
Phys. Rev. Lett. 114, 081802 (2015)

- Two γs following h→γγ selection
  - 105 < m(γγ) < 160 GeV
- - 2 b-jets (p_T > 55/35 GeV)
  - - 95 GeV < $m(b\bar{b})$ < 135 GeV
- **Axε** is 3.8-8% (m_X in 260-500 GeV)
- m_{bb} constrained to m_h
  - m_X resolution improves by 30-60%
  - experimental m_X width is 17-60 GeV



X→h(b$\bar{b}$)h(γγ)

Phys. Rev. Lett. 114, 081802 (2015)

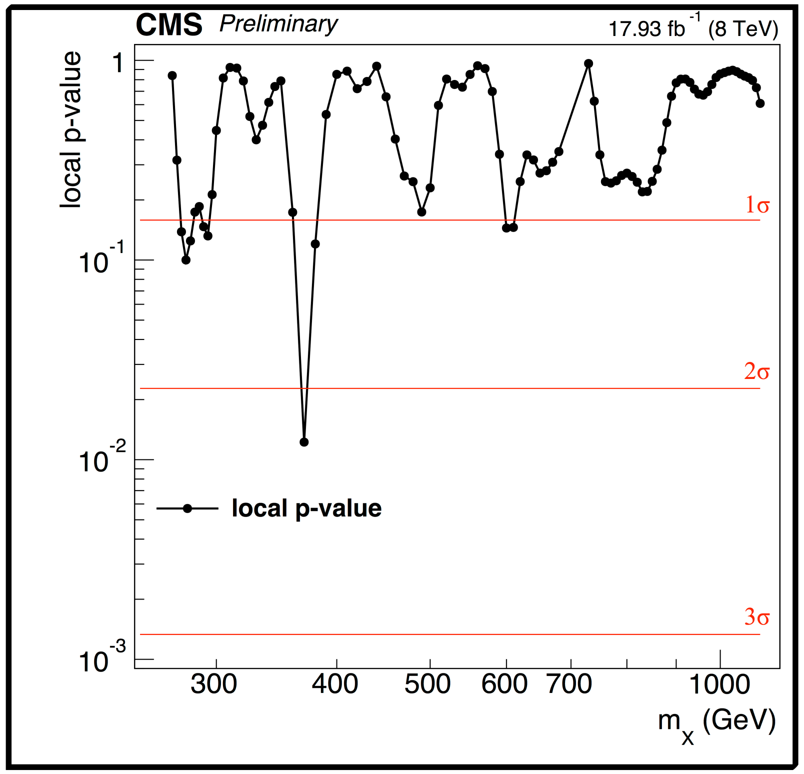


- Local excesses below 350 GeV raising the observed limits to up to 3.5pb

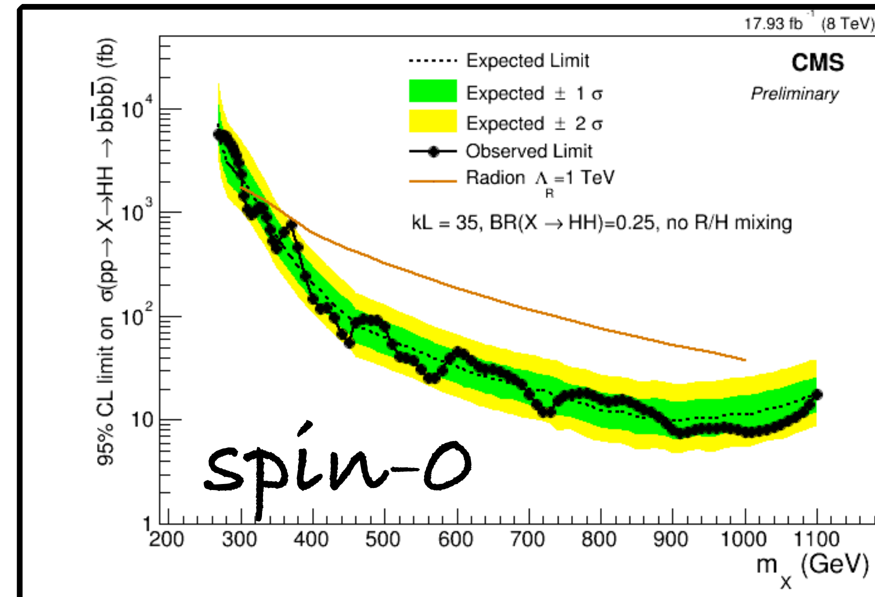
$X \to h(b\bar{b})h(b\bar{b})$, Results

RESOLVED

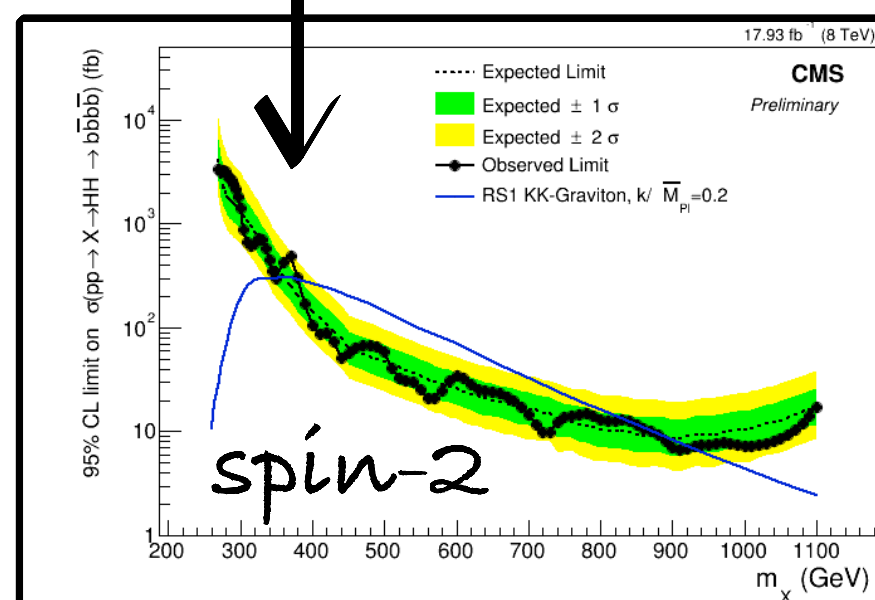
PLB 749 (2015) 560



no excess, upper limits



+20-30% signal eff.



The systematic uncertainty due to the particular choice of the function used to model the multi-jet degrades the upper limit by 2-32%

$X \rightarrow h(b\bar{b})h(\tau\tau)$

CMS-HIG-14-034