Searches for decays to h+X

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on behalf of CMS and ATLAS collaborations

11.4.14 BSM Higgs Workshop @ LPC, Fermilab

h+X

- **LHC Run I legacy**

H

$J^P = 0^+$

$m_H = 125.03 \pm 0.26$ (stat.) $\pm$ 0.14 (syst.) GeV

production and decay rates are consistent with a SM Higgs boson

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

$h(b\bar{b})$ highest BR, large statistic

$h(\gamma\gamma)$ narrow resonance

New physics shall preferentially couple to EWK sector

hh **Warped Extra Dimensions**

bulk model reduce fermionic couplings and enhance V/H couplings to Graviton

hh/Z **2HDM** or **(N)MSSM** like models

heavy h_2 can couple to hh (WW, ZZ are suppressed), for low h_2 mass $t\bar{t}$ not yet opened

$hh+t\bar{t}/b\bar{b}$ **Vector Like Quarks**

decay to t/b quarks together with a V/H

hh/V + MET **SUSY**

Pair production of neutralinos and/or charginos see S.Padhi's talk

h(b$\bar{b}$), h(γγ) as tools for discovery

h(b$\bar{b}$)

as pure as leptonic/γγ channels by exploiting boosted topology

highest BR: larger statistics, 10-100 times
(vs. Z(b$\bar{b}$): BR=15% vs 58%)

high b-tag efficiency
multi-light jets background is highly reduced
gluons splitting + t$\bar{t}$ as the main backgrounds
t$\bar{t}$, MC or top enriched data samples
QCD, data driven methods

	b	c	light [%]
ATLAS	70	20	<1
CMS	70	15	1

m_{H1} vs m_{H2}
X →hh →4b HIG-14-013; ATLAS-CONF-2014-005
$m_{\gamma\gamma b\bar{b}}$ or $m_{\gamma\gamma}$
X→ hh→ b$\bar{b}$γγ HIG-13-032; arXiv:1406.5053
m_h or n-btags
t'$\bar{t}$' → t$\bar{t}$ + h(b$\bar{b}$)h(b$\bar{b}$)+X B2G-14-002
b'$\bar{b}$'→ b$\bar{b}$ +h(b$\bar{b}$)h(b$\bar{b}$)+X B2G-14-001

h(γγ)

simple topology, clean final state
two isolated energetic photons
($p_T/m_{\gamma\gamma}$ > 0.35, 0.25)

excellent mass resolution
search for an excess in the $m_{\gamma\gamma}$

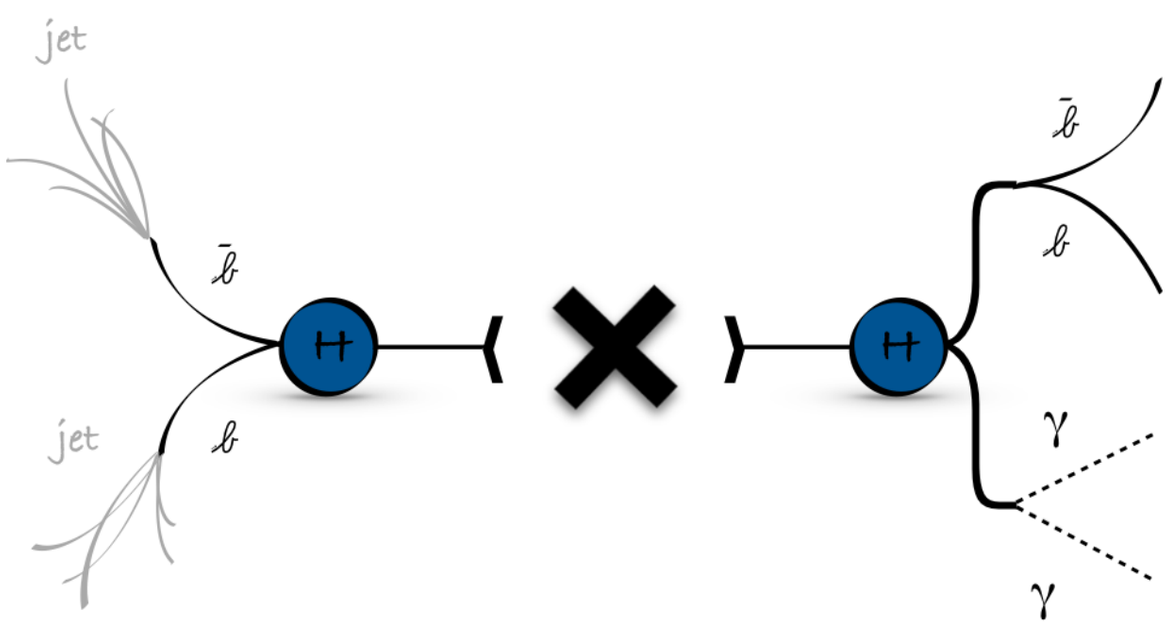
	H →γγ	H → b$\bar{b}$
BR	0.23%	58%
mass resolution	1%	10%

hh resonant production

SM predicts an extremely low rate for hh production (~10 fb)
Significantly enhanced in many BSM scenarios
gluon fusion production of a massive X - resonant hh state
(negligible 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
    - for $m_X < 350$ GeV and low tanβ values the **MSSM** scenario predicts $\sigma(h_2 \rightarrow hh) \sim 0.7$ pb
- From 500 GeV up to 1 TeV the mass range is interesting for **warped extra dimensions** models (spin-0 Radion and spin-2 KK-Graviton)

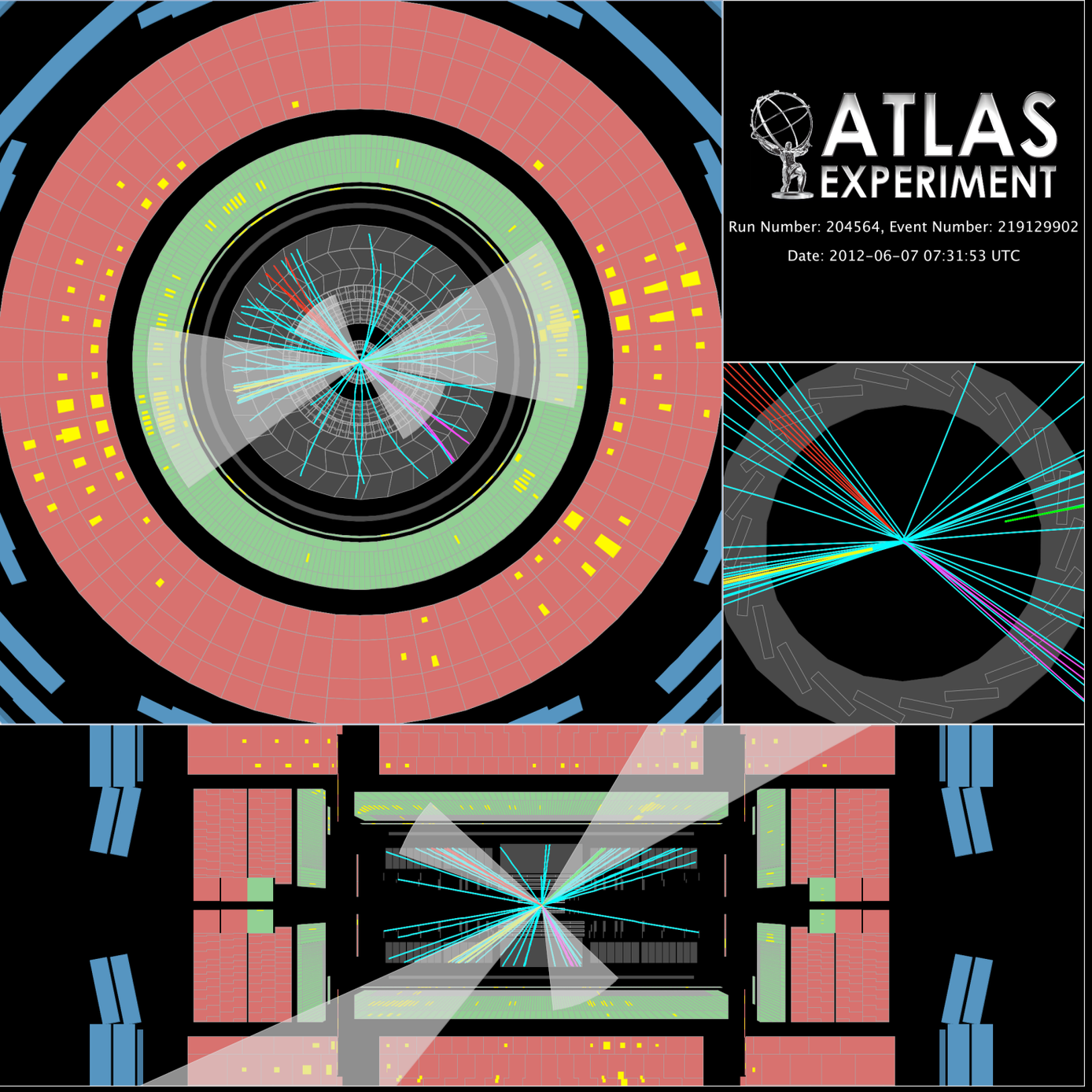


Final State:

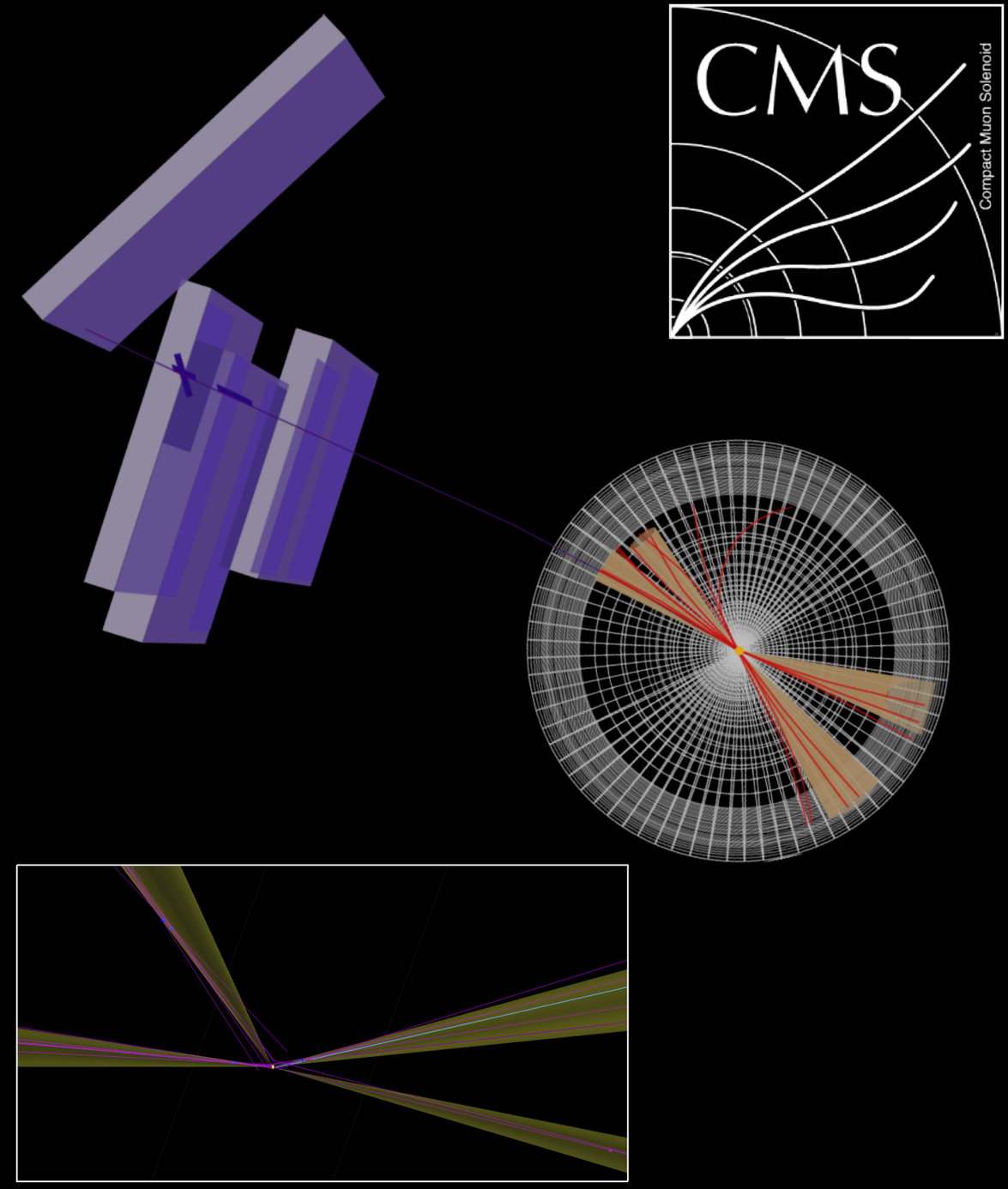
- $X \rightarrow HH \rightarrow (\gamma\gamma)(b\bar{b})$
- $X \rightarrow HH \rightarrow (b\bar{b})(b\bar{b})$

$m_H = 125$ GeV

B.R.
0.26%
33.3%



CONF-2014-005



HIG-14-013

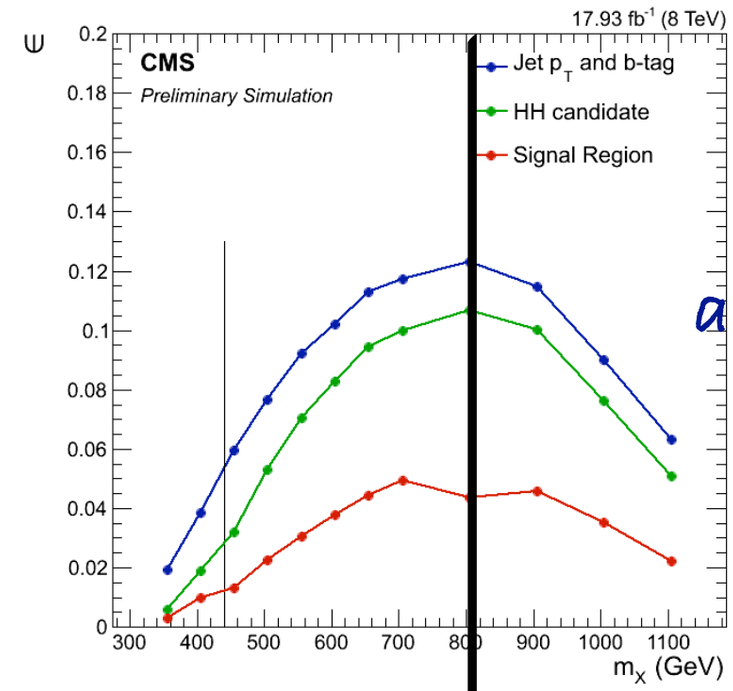
$X \rightarrow h(b\bar{b})h(b\bar{b})$

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

HIG-14-013

*4 jets b-tag with $p_T > 40$ GeV

* hh candidates
  * **Low Mass** $m(b\bar{b})$ in [90,160] GeV
  * **High Mass** $\Delta R(b\bar{b})<1.5$ & $p_T(b\bar{b}) > 300$ GeV
* 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



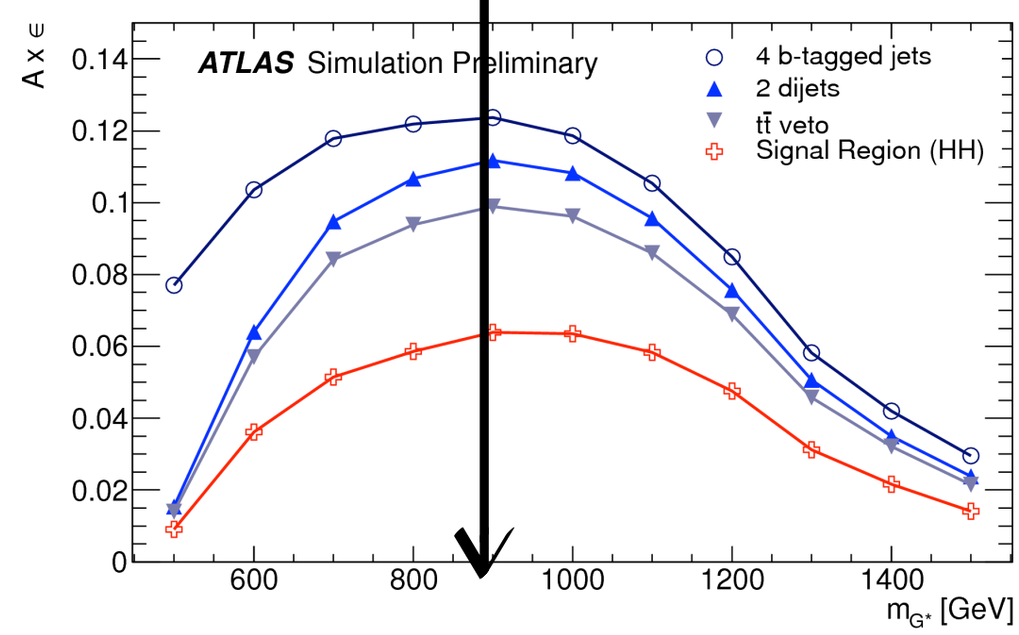
anti-k_T 0.5 vs anti-k_T 0.4

CONF-14-005

*4 jets b-tag with $p_T > 40$ GeV
* hh candidates
  $\Delta R(b\bar{b}) < 1.5$ and $p_T(b\bar{b}) > 200$ GeV
* top veto
* Signal Region

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

$\sigma = 0.1m$, $m^{\text{lead}} = 124$ GeV $m^{\text{subl}} = 115$ GeV



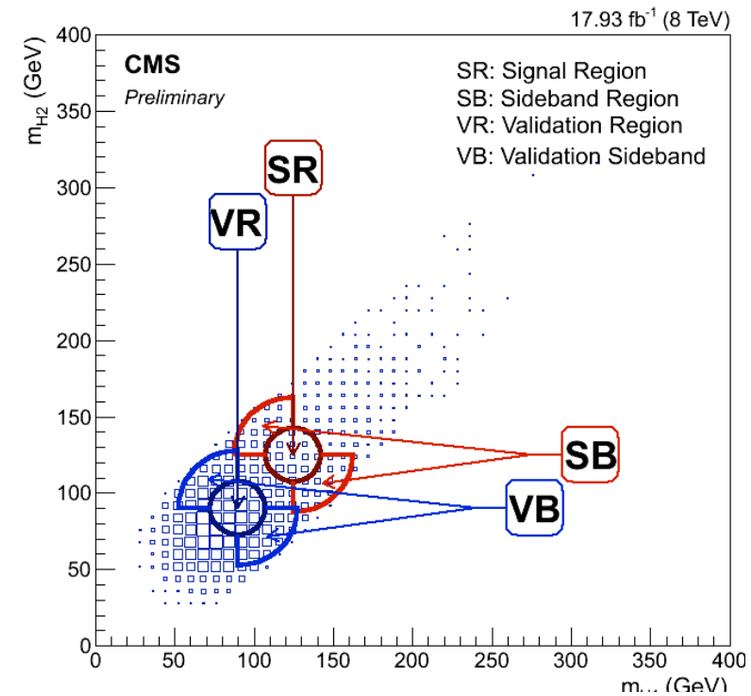
similar efficiencies

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

non-resonant $b\bar{b}b\bar{b}$ **QCD** production is dominant
plus contribution from $b\bar{b}c\bar{c}$
thanks to b-tagging jjjj and bbjj are highly reduced
modeled in data
$t\bar{t}$ mainly from c mis-identified as b-jet ($t \rightarrow bcs$)

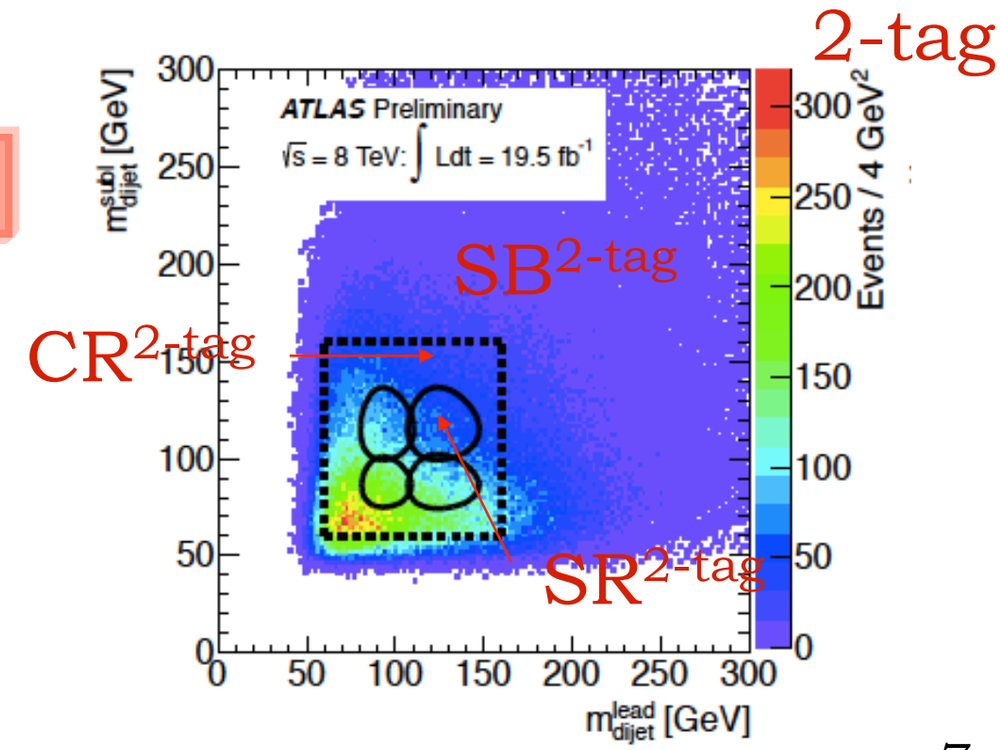
QCD ~ 75% modeled in data
SB used to infer the model
VR/VB used to test its flexibility
3-tag region also exploited
$t\bar{t}$ ~ 25% modeled in simulation

HIG-14-013



QCD 90% modeled in data
Use 2-tag events to model 4-tag SR
CR and SR to normalize, re-weight and test
$t\bar{t}$ 10% modeled in simulation
Highly reduced by applying as veto

CONF-14-005



(a) 2-tag data sample

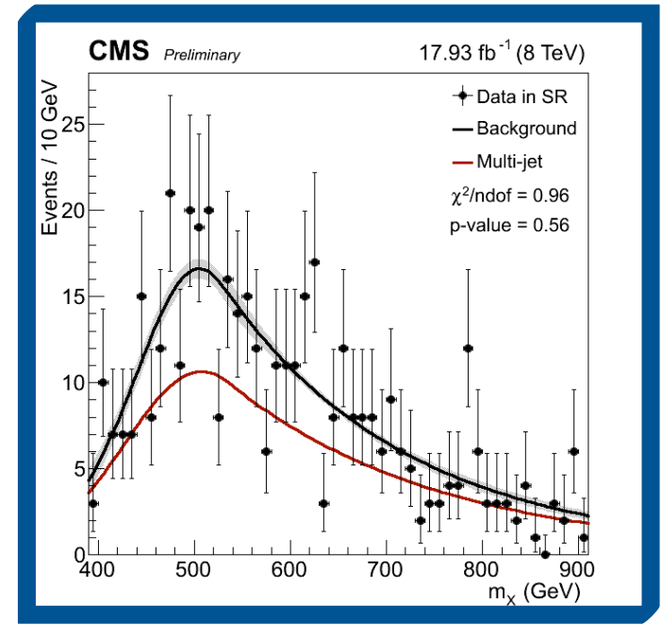
$$X_{tt} = \sqrt{\left(\frac{m_W - 80.4}{0.1 m_W}\right)^2 + \left(\frac{m_t - 172.5}{0.1 m_t}\right)^2} > 3.2$$

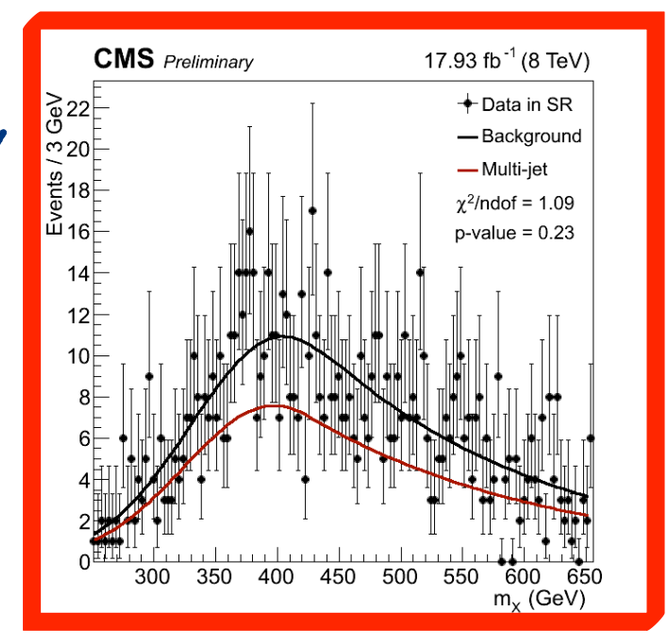
$X \rightarrow h(b\bar{b})h(b\bar{b})$, Signal Extraction

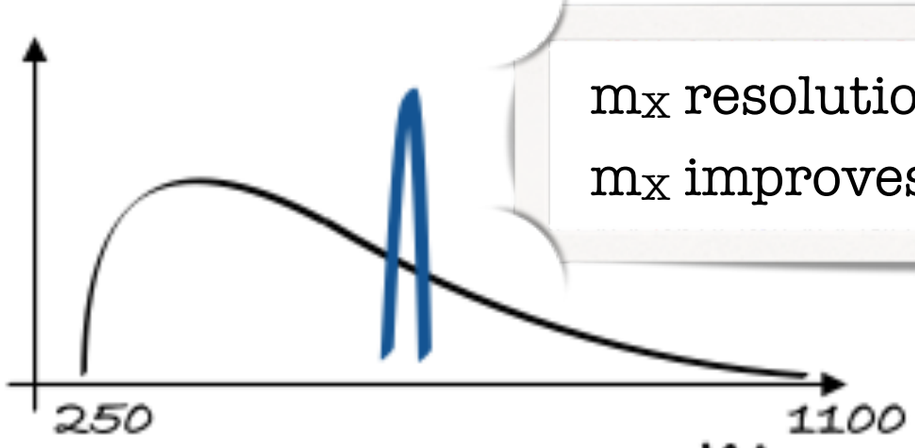
HIG-14-013

- A fit to a resonance and a smooth background in the m_X distribution
  - **signal**
    - modeled with a Gaussian + exp/Gaussian for the tails
    - using spin-0 RS1 as benchmark
  - **multi-jet** modeled in data in the SB
    - Gauss-Exp function
    - 2-30% systematic derived by using polynomials as an alternative model
  - **$t\bar{t}$**
    - modeled in simulation
    - same model as multi-jet
      - 15% uncertainty on the yield
- **m_X resolution** improved by kinematic fit
  - each $m(b\bar{b})$ should be compatible with m_H
  - m_H is well known

$$\left.\begin{matrix} m(b\bar{b})_1 \\ m(b\bar{b})_2 \end{matrix}\right\} \sim 125\ \text{GeV}$$







m_X resolution is **4-30 GeV**

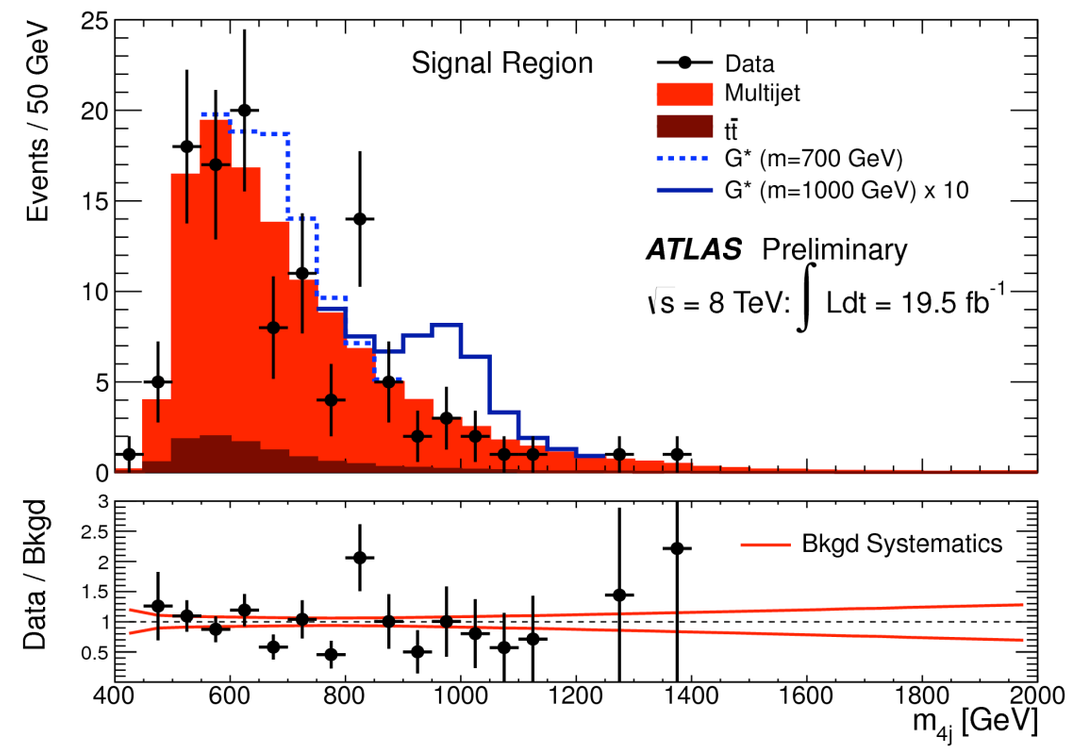
m_X improves by **30-60%**

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

CONF-14-005

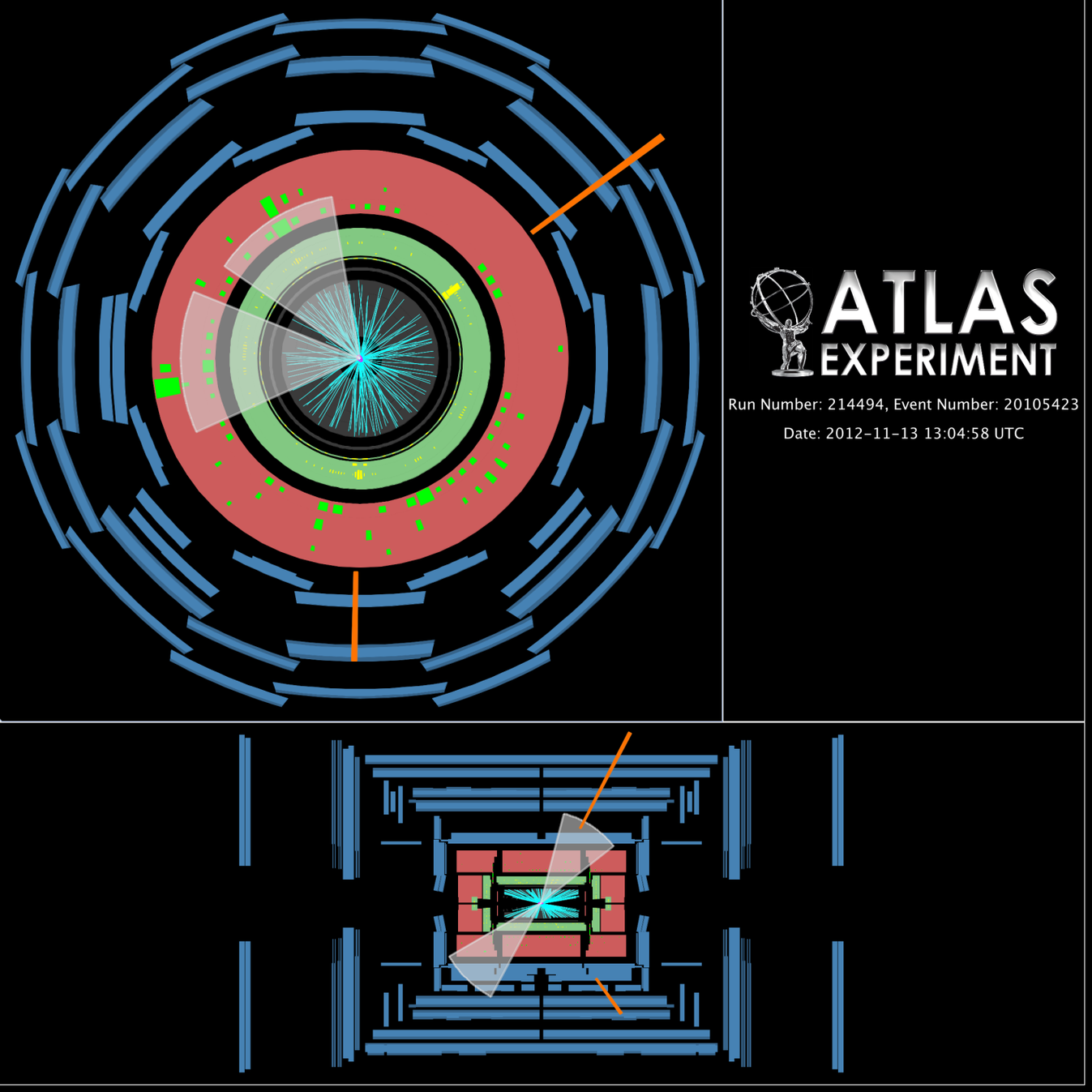
- **signal**
  - using spin-2 KK-Graviton as benchmark

- **$t\bar{t}$** modeled in simulation from the 2-tag region
  - The yield is derived in data in a $t\bar{t}$ enriched control region
  - Systematic uncertainty by comparing the 2-tag and 4-tag m4j distributions in MC
    - 59% - yield, 27-60% -shape

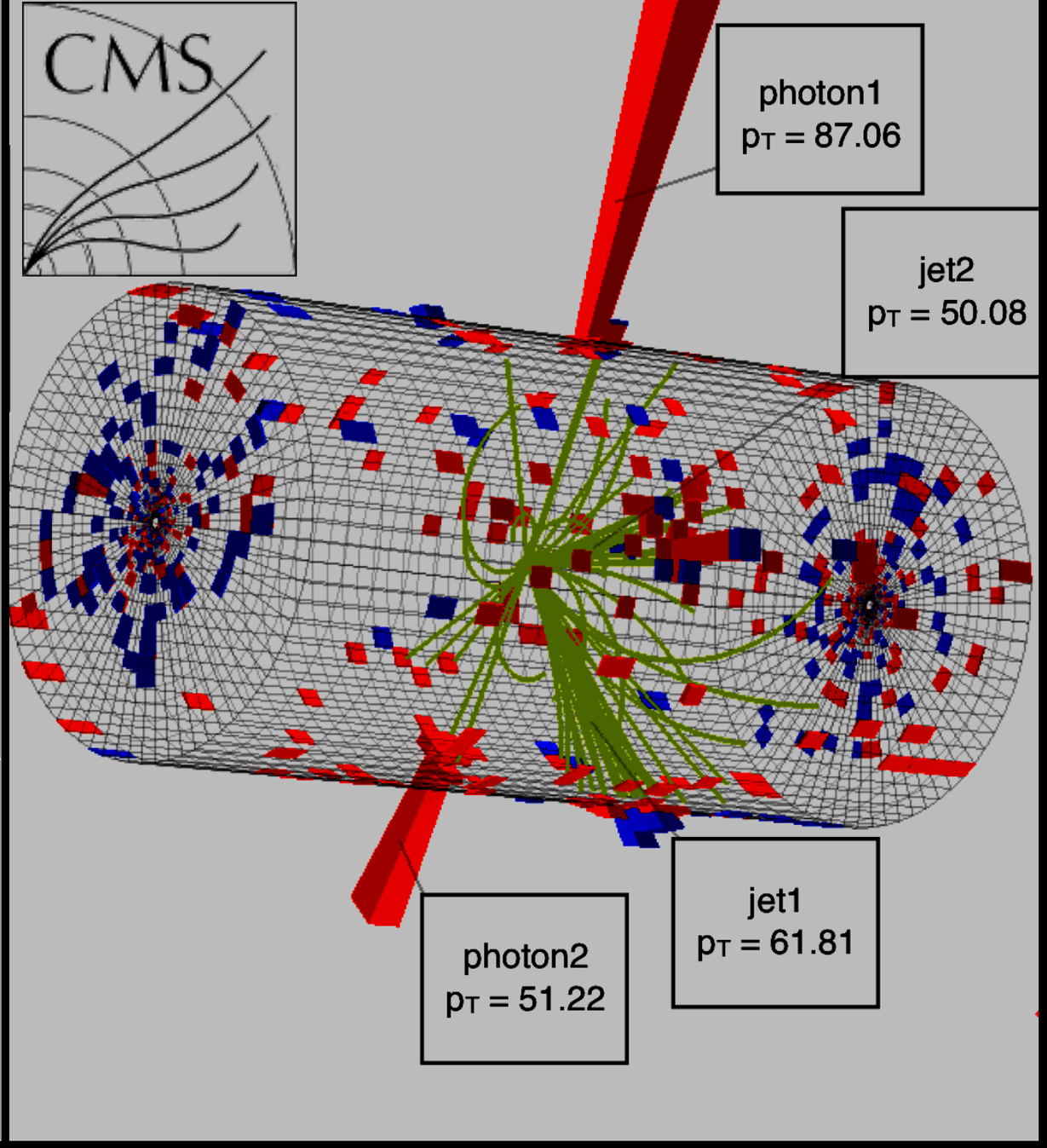


- **multi-jet** modeled in data in the 2-tag region
  - The yield in the 2-tag sample is scaled such that the number of events in the SB is the same in 2-tag and 4-tag regions
  - Shape corrected by kinematic re-weighting
    - dijet p_T , dR(jj) , dR(hh) in the $SB^{2\text{-tag}}$ are forced to match those in the $SB^{4\text{-tag}}$
  - Systematic uncertainty is derived from the CR
    - 5% - yield, 7-15% -shape

Type	Signal Region
Multijet	109 ± 5
$t\bar{t}$	10 ± 6
Z+jets	0.7 ± 0.2
Total Bkgd	120 ± 8
Data	114



arXiv:1406.5053



HIG-13-032

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

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

HIG-13-032

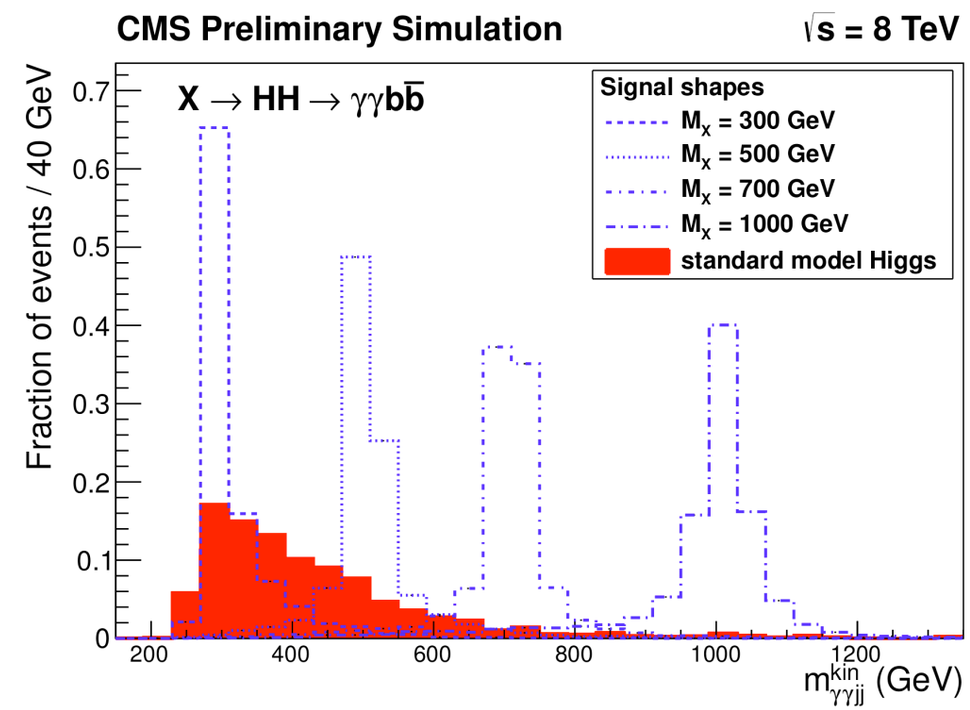
- Two γs following $h \rightarrow \gamma\gamma$ selection
  $100 < m(\gamma\gamma) < 180$ GeV
- 2 jets with $p_T > 25$ GeV
  - highest dijet pair in the event
- Uses 1 and 2-tag signal regions

low mass $260 \text{ GeV} \leq m_X \leq 400 \text{ GeV}$

high mass $400 \text{ GeV} < m_X \leq 1100 \text{ GeV}$

Axε is 5-10% (m_X in 260-1000 GeV)

Kinematic fit to improve m_X resolution
$m(b\bar{b})$ constrained to 125 GeV

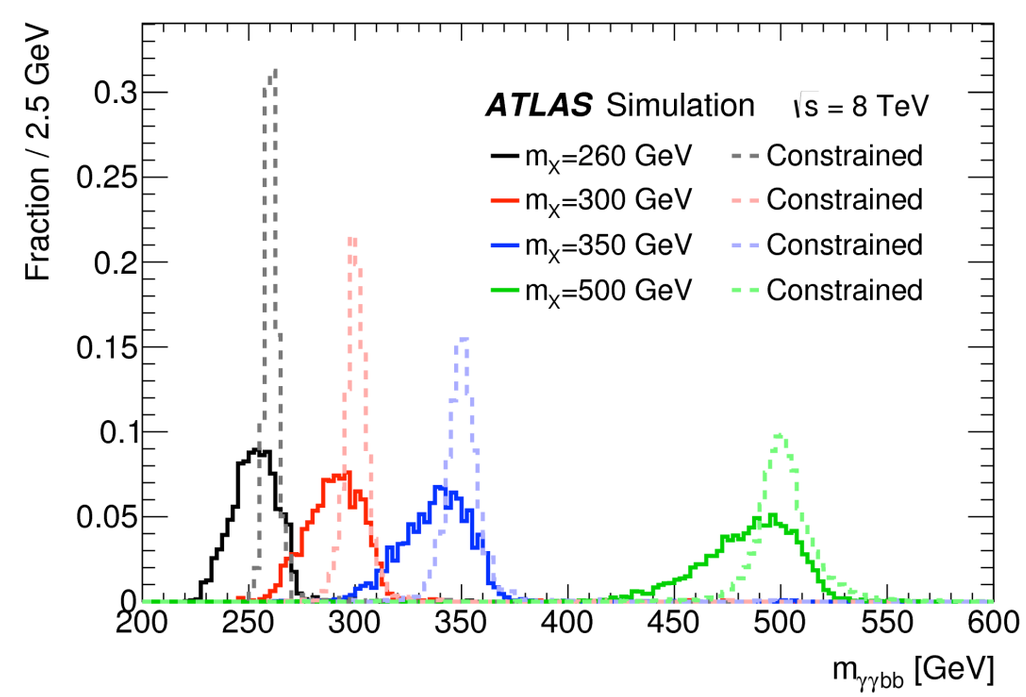


arXiv:1406.5053

- Two γs following $h \rightarrow \gamma\gamma$ selection
  $105 < m(\gamma\gamma) < 160$ GeV
- 2 b-jets ($p_T > 55/35$ GeV)
  - $95 \text{ GeV} < m(b\bar{b}) < 135$ GeV

Axε is 3.8-8% (m_X in 260-500 GeV)

$m_{\gamma\gamma}$ constrained to m_h
m_X resolution improves by 30-60%
m_X width is 17-60 GeV

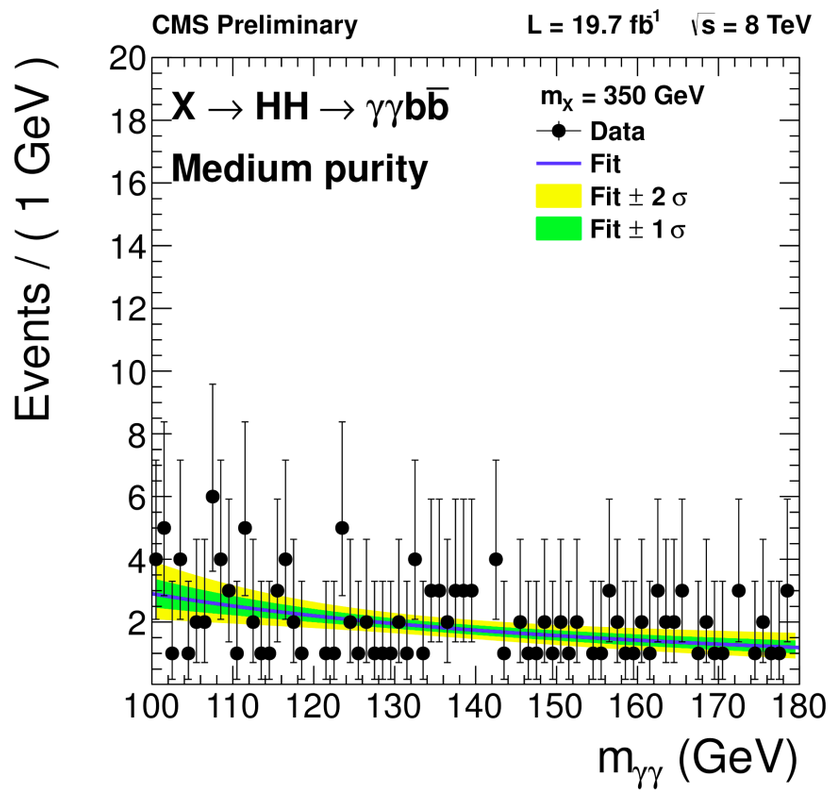


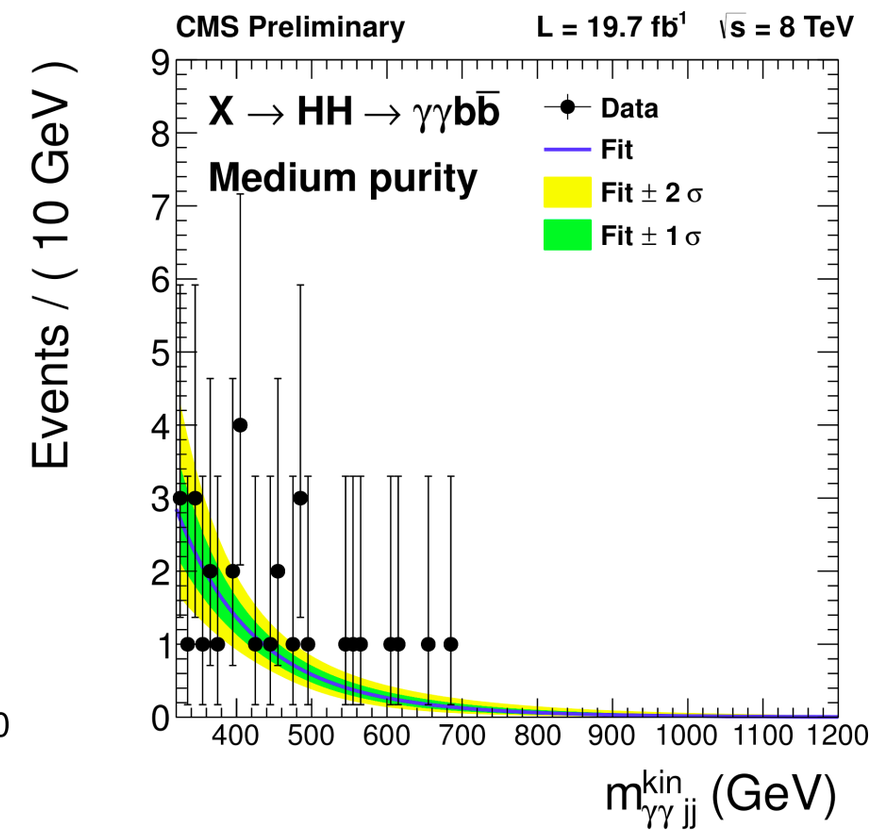
$X \rightarrow h(b\bar{b})h(\gamma\gamma)$, Signal Extraction

HIG-13-032

Main backgrounds:
- Non-resonant QCD
  γγbb (>80%)
  γjbb+jjbb (<20%)

A power law is used for the background model





Low-mass region
- Windows in $m(b\bar{b})$ and $m_{bb\gamma\gamma}$
- Fit $m(\gamma\gamma)$

High-mass region
- Require: $120 \leq m(\gamma\gamma) \leq 130$
- Fit in $m_{\gamma\gamma bb}$

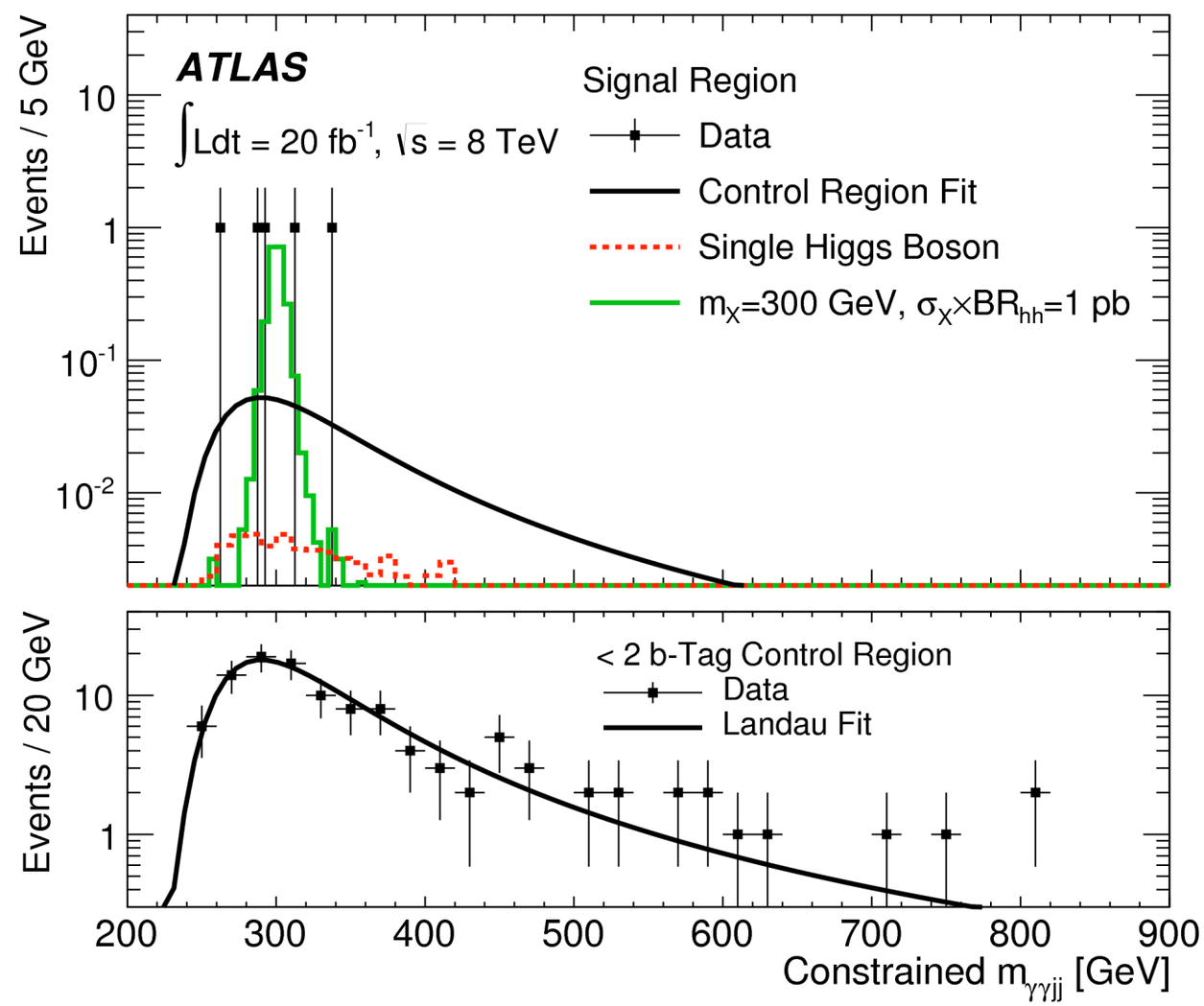
Statistically limited
Systematics have ~ 2 % impact on the expected median limit

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

arXiv:1406.5053

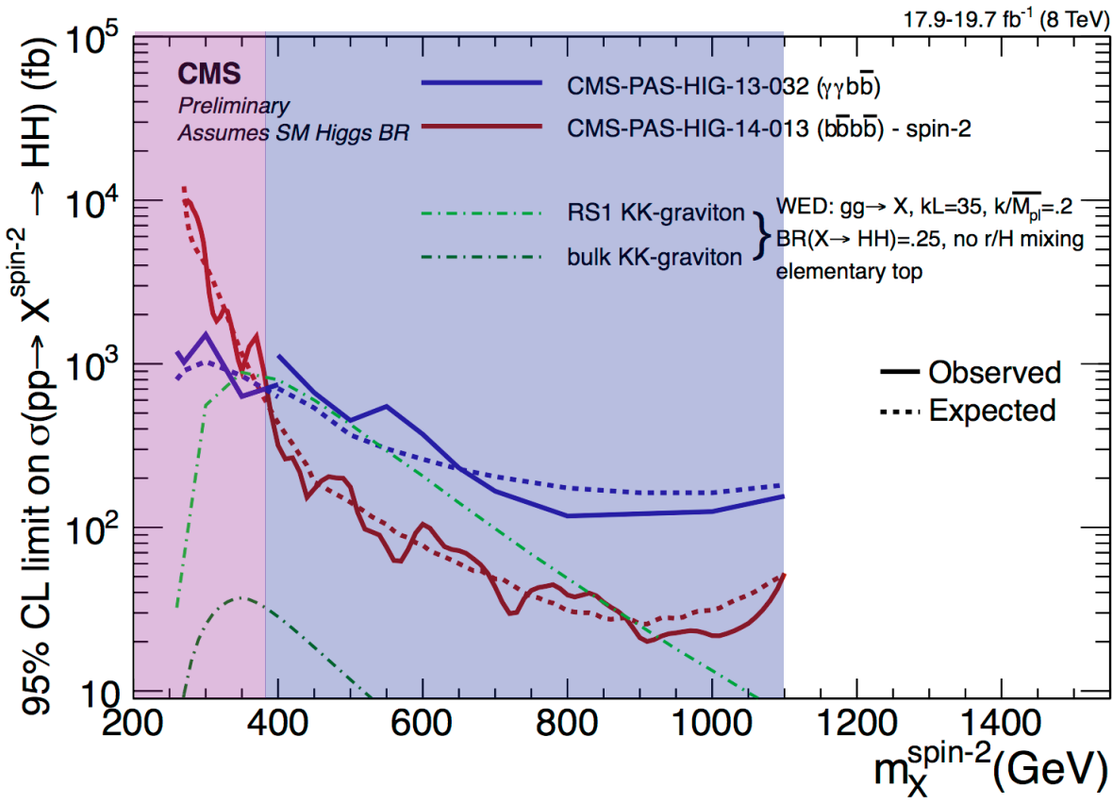
Main backgrounds:
- Non-resonant QCD
- $t\bar{t}$ (10%)

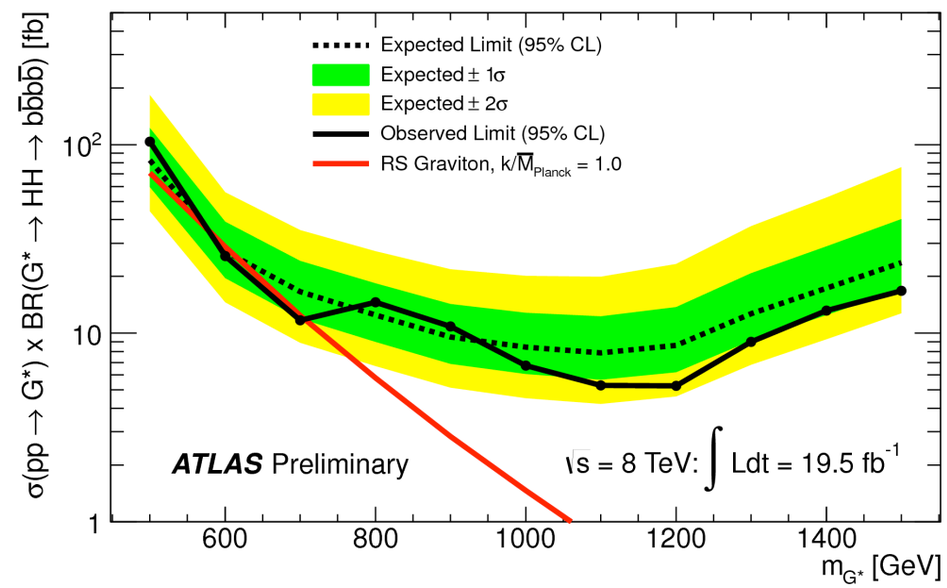
Counting experiment
- Background modeled in data
  - shape from < 2 b-tag control region
  - A Landau is used
    - 16-30% uncertainty
  - normalization from $m_{\gamma\gamma}$ side-band
- Window in $m_{bb\gamma\gamma}$

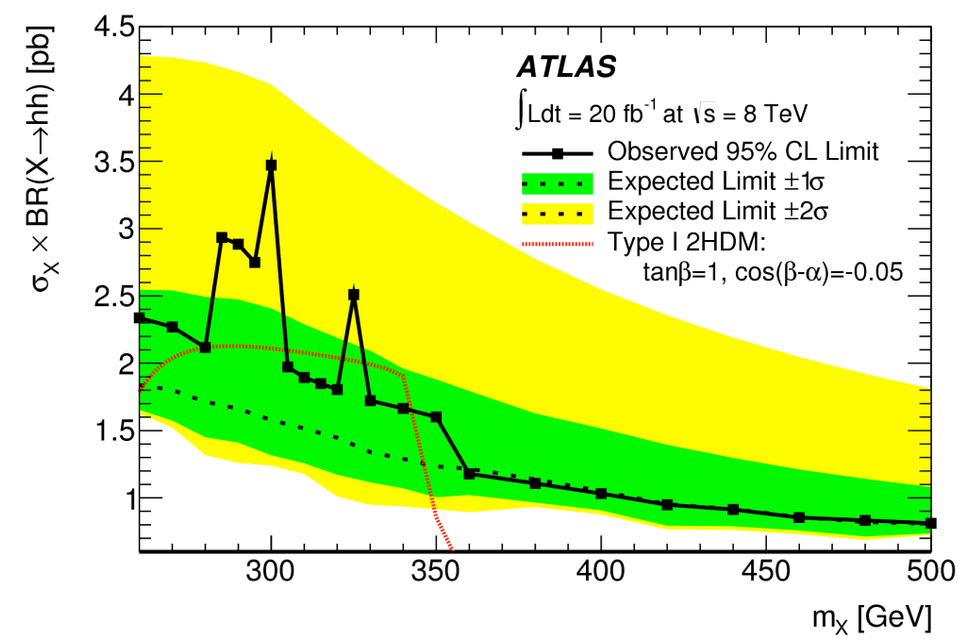


Statistically limited

X→hh, Results







No significant deviation from expectation

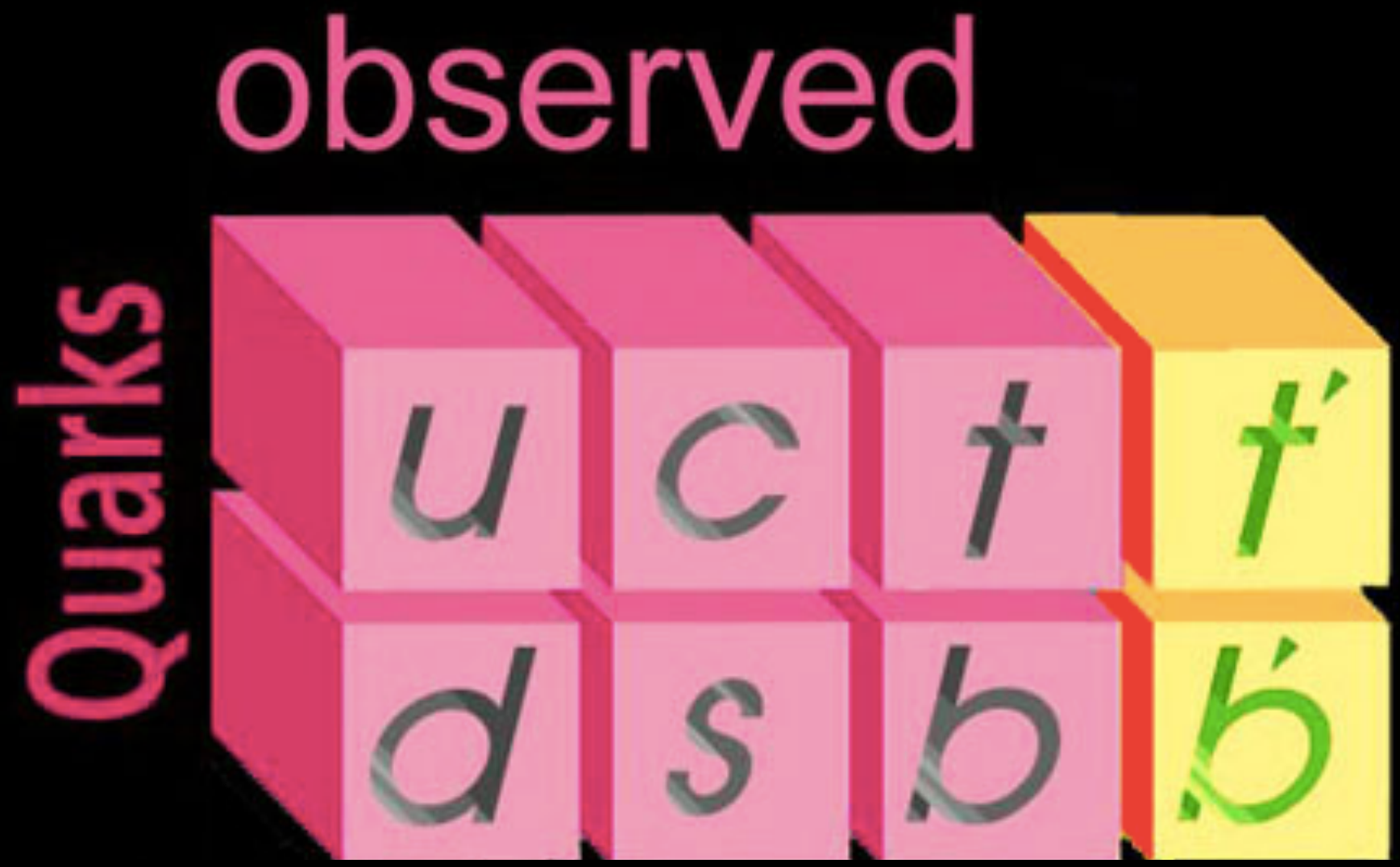
h(γγ)h($b\bar{b}$) h($b\bar{b}$)h($b\bar{b}$) complementary

hh(4b) results are sensitive to spin hypothesis

best channel for m_X > 400 GeV

Constraints on WED (Radion and Graviton), 2HDM

Overall hh is competitive with VV searches to test WED



CONF-2013-018
B2G-2014-002
B2G-2014-003
Phys.Lett.B 729 (2014) 149

B2G-2014-001

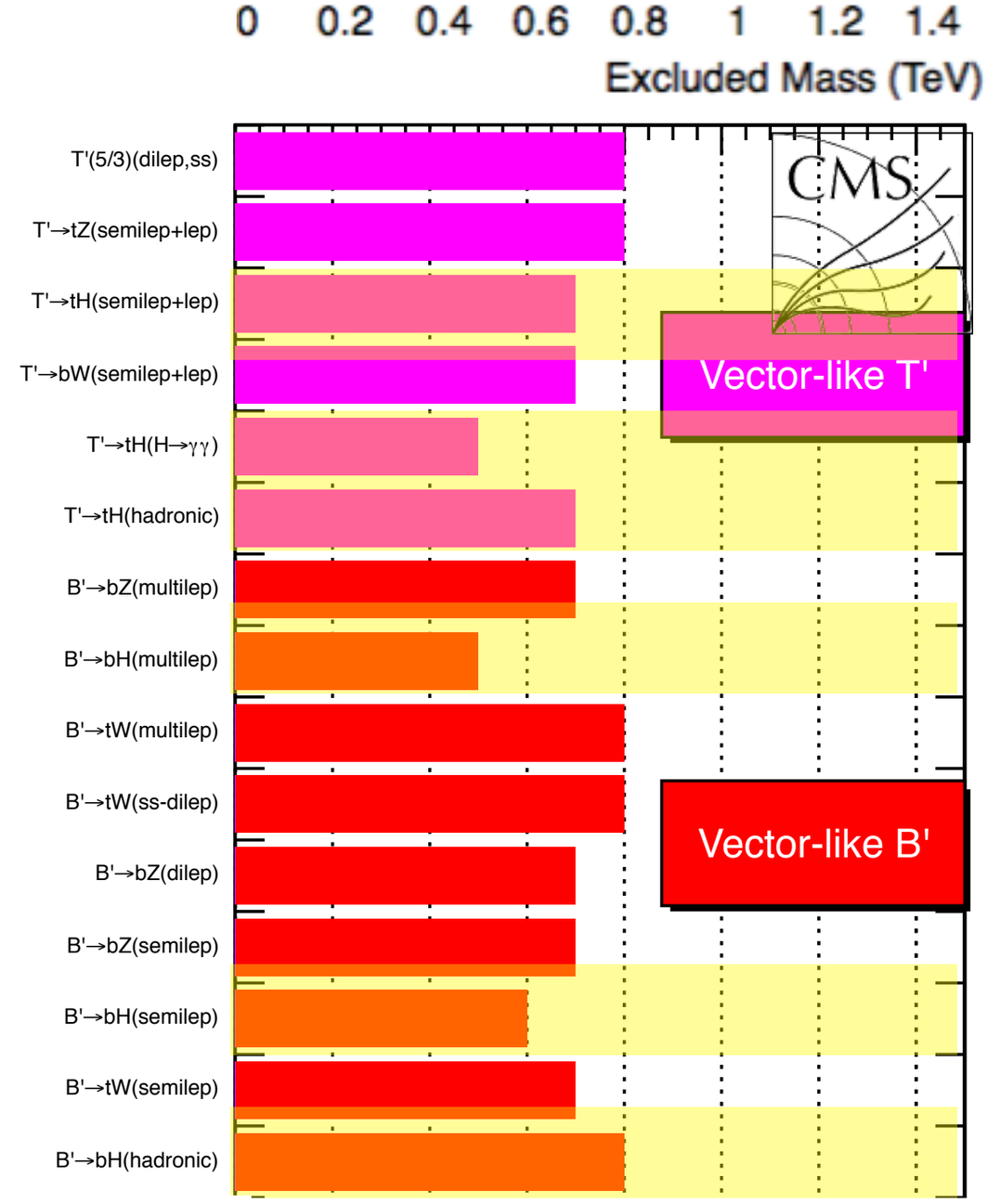
Vector Like Quarks

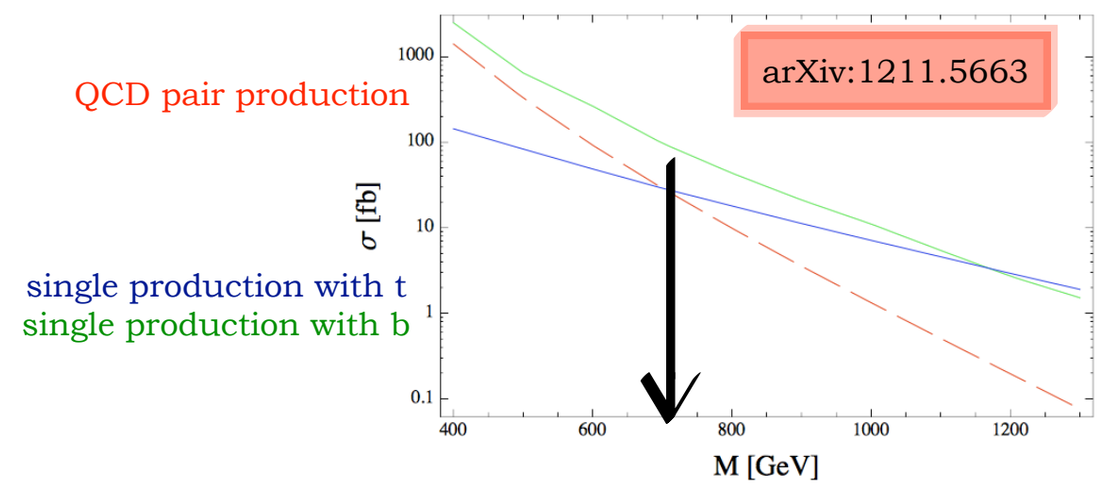
Vector-Like Quarks

- "Vector-like" quarks predicted by many models
- Transforms as (3,1,+2/3) under $SU(3)_C SU(2)_L U(1)_Y$
  - produced in pairs by strong interactions
    - less model dependent
  - mixes proportional to the mass of the SM quarks

  t' → bW, tZ, tH

  b' → bZ, bH, tW
- Complementary to SUSY searches
  - analogue signatures but no MET
- Mass independent from their coupling to H
- Cross sections are 570-0.05 fb in the 500 GeV-1.5 TeV mass range
- Different final states possible
  - Leptonic and hadronic decays of V, H
  - b-tagging in boosted topology leads to high sensitivity also in the fully hadronic final state





t' → th($b\bar{b}$) in lepton+jets

CONF-13-018

24 (60) GeV electron or 24 (36) GeV muon
at least 6 jets

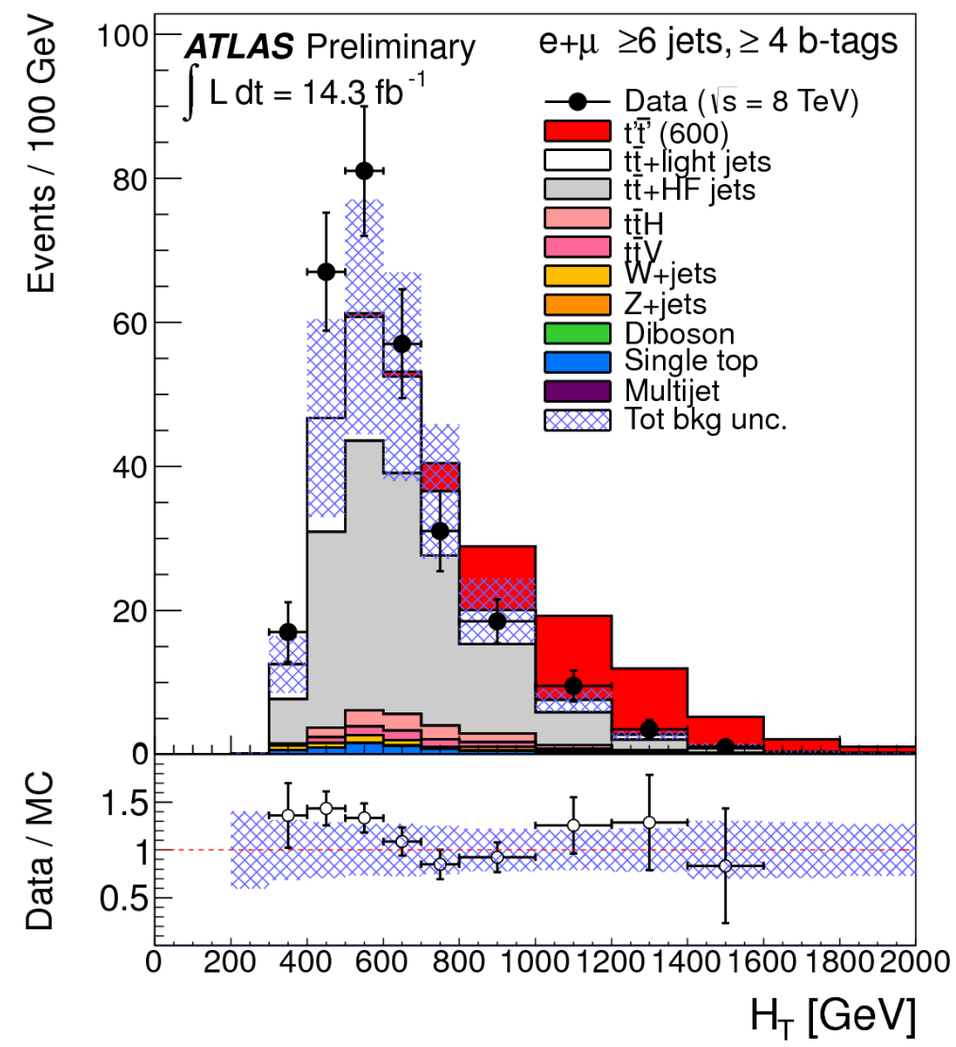
Three event categories based on the number of b-jets (2,3,4)

Sensitive to $t'\bar{t}'$ → HtHt, ZtHt, WbHt
at least one h($b\bar{b}$)

Main background is **$t\bar{t}$+jets** modeled in simulation
SF to correct the yields derived from a CR in data
Multi-jets modeled in data
sideband obtained by using non-prompt leptons
Matrix Element method used to get normalization and shape
W+jets
shape from simulation
normalization from data

H_T - sum of leptons and jets p_T and MET -
to discriminate S/B

100% t'→ tH
observed (expected) limit on $m_{t'}$ > 790 (640) GeV



t’ → th($b\bar{b}$) in lepton+jets

Physics Letters B 729 (2014) 149
hep-ex:1311.7667

one 32 GeV electron or muon
at least 3 jets (p_T >120, 90, 50 GeV)
1 CA8 W-tagged jet with p_T > 200 GeV or 1 jet with p_T >35 GeV
MET> 20 GeV

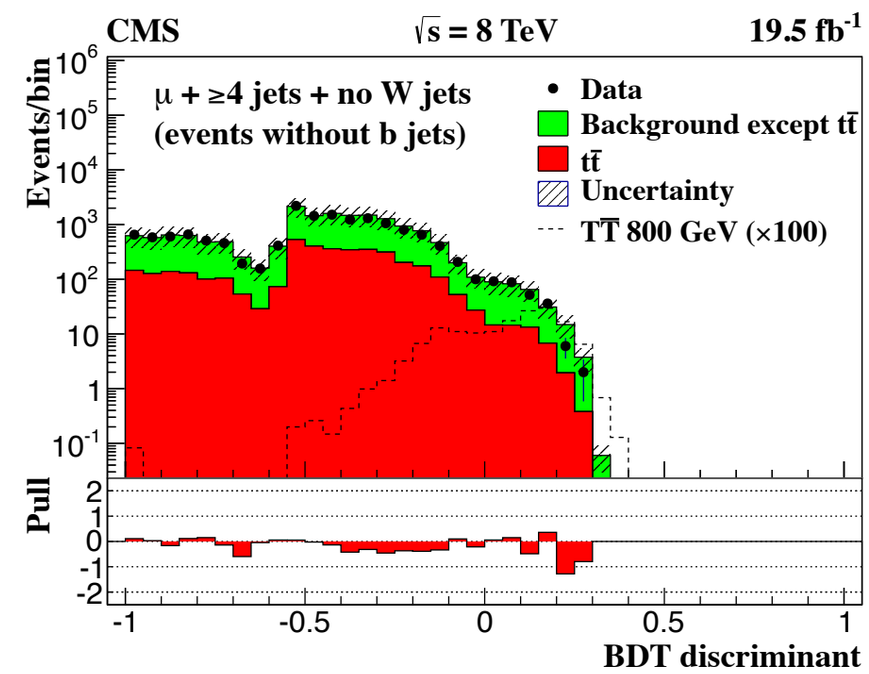
Four event categories based on
- 3 jets + W-jet (w and w/o b-jets)
- 4 jets and no W-jet (w and w/o b-jets)

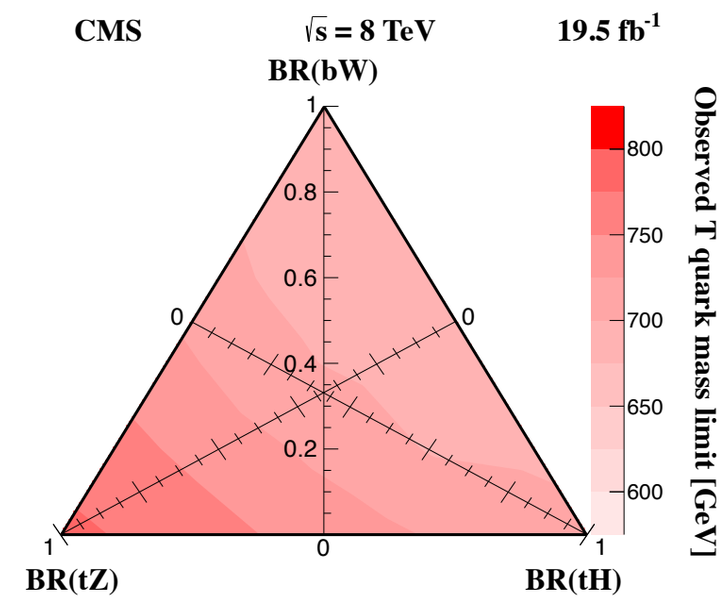
sensitive to t’$\bar{t}$’ → HtHt, ZtHt, WbHt
- mostly sensitive to h($b\bar{b}$)

Main backgrounds are
$t\bar{t}$+jets modeled in simulation
W+jets modeled in simulation
- SF normalization in control regions
- different for W+ heavy and light flavors

BDT to discriminate S/B
- jet multiplicity, b-tagged jet multiplicity, H_T, MET, lepton p_T, p_T of the third/fourth jet

100% t’→ tH
observed (expected) limit on $m_{t'}$ > 706 (770) GeV





t'→th(γγ) as target

B2G-14-003

Targeting t'→th(γγ)
- orthogonal to other samples
- t' mass fully reconstructed
- di-photon mass used for limit setting

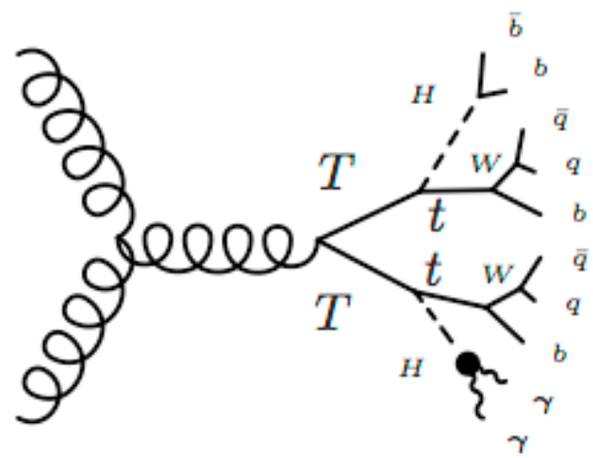
High H_T region, at least 2 jets
Two γs following h→γγ selection

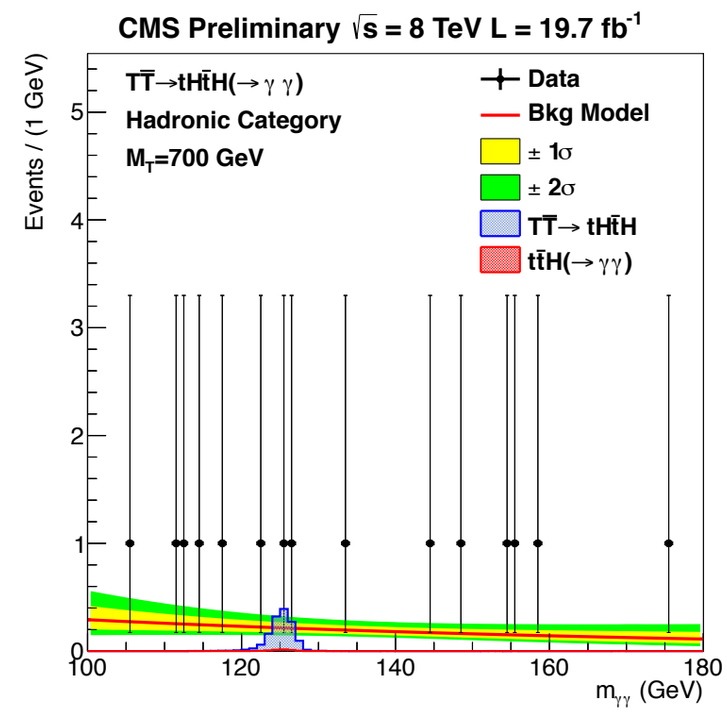
Two categories to account for both
- leptonic and hadronic W decay

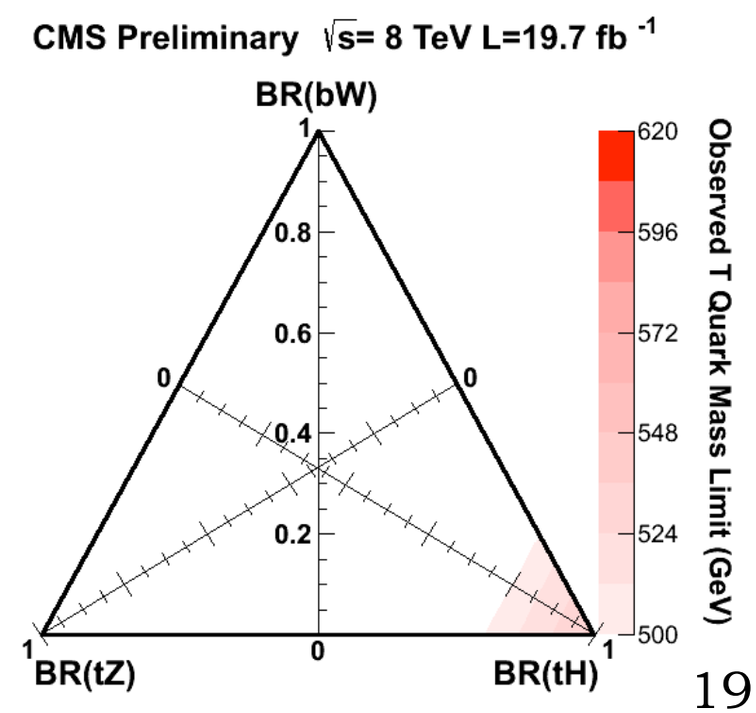
QCD (γγ+jets, $t\bar{t}$+jets, tγγ)
- modeled in data from $m_{\gamma\gamma}$ sideband

$t\bar{t}$, $t\bar{t}H$ modeled in simulation

senstitivity in the t'→tH corner
100% t'→ tH
observed (expected) limit on $m_{t'}$> 540 (607) GeV







t' → th($b\bar{b}$) in fully hadronic

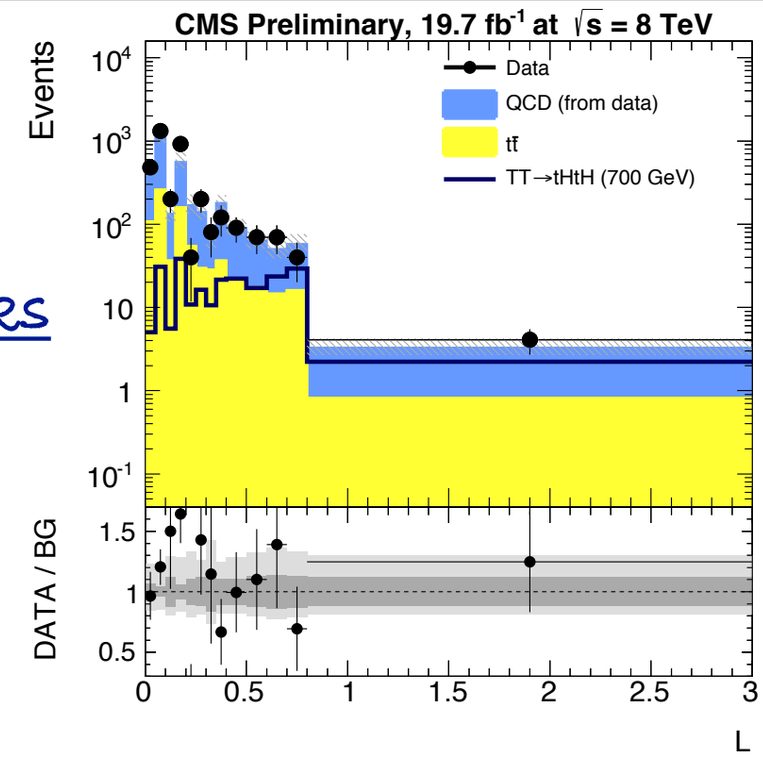
B2G-14-002

t' → bbbjj is the main final state (57% * 66% = ~ 38%)
First attempt to probe this all-hadronic final state

highly **boosted topology**
- top and Higgs tagging combined to b-tagging
- b-tagging in sub-jets
- multi-jet background reduced significantly

see N.Tran & D.Ferencek talks

2 CA15 jets with p_T > 150 GeV
one top-tagged
one higgs-tagged (2 b-tagged sub-jets)
Two event categories based on numbers of Higgs-tags

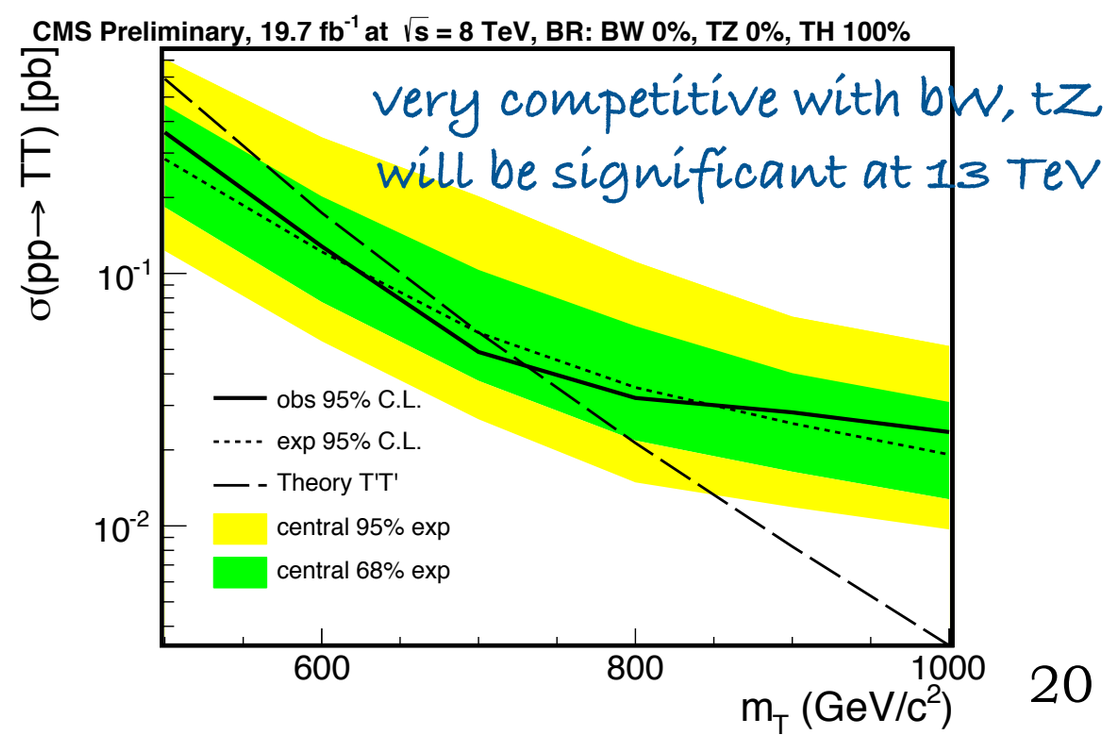


multi-jet modeled in data from sideband
- reverting sub-structure criteria

$t\bar{t}$ modeled in simulation
- $t\bar{t}H$ found to be negligible

Two observables combined in Likelihood
- H_T and m_h

100% t'→ tH
observed (expected) limit on $m_{t'}$> 745 (773) GeV



b'→bh($b\bar{b}$) in fully hadronic

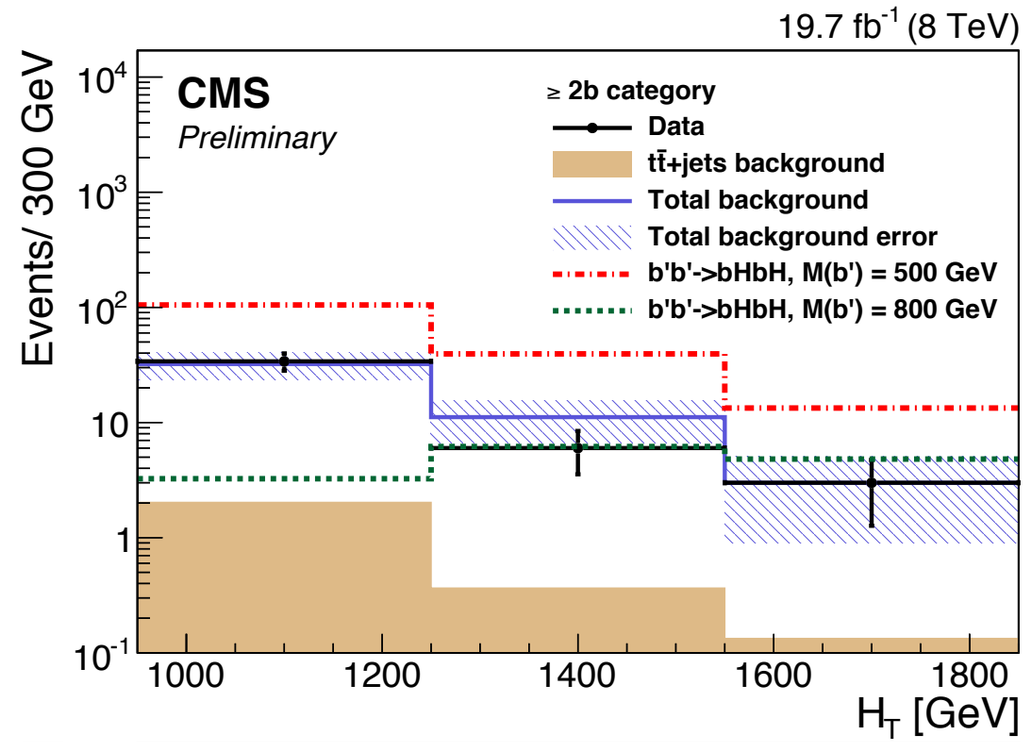
B2G-14-001

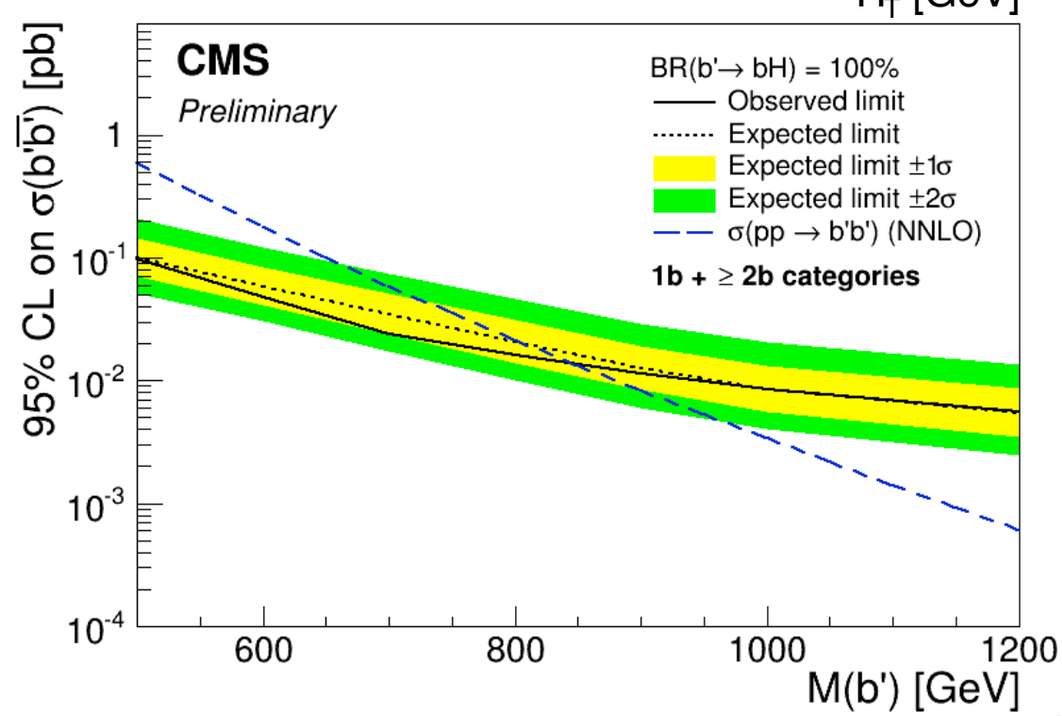
More sensitive than leptonic final state
Significant gain in phase space at high mass b'
  large suppression of background thanks to boosted techniques
  substructure b-tagging

High H_T region (> 950 GeV)
1 CA8 jet with p_T> 300 GeV
  Jet mass in [90, 140] GeV
  Cut on N-subjettiness, both b-tagged
At least one additional b-tagged (AK5) jet

Two categories according to number of b-tagged jets
  $t\bar{t}$+jets from simulation
  multi-jet in data from control regions
Fit to H_T distribution

100% b'→ bH
obs (exp) limit on $m_{b'}$ > 846 (811) GeV
best sensitivity so far
  from multi-leptonic final state $m_{b'}$ > 520 GeV
  from semi-leptonic final state $m_{b'}$ > 634 GeV
  from b'→ tW/bZ $m_{b'}$ > 700 GeV





Conclusions & Outlook

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

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

- Heavy resonances decaying to hh
  - limits on cross section production below ~ 10 fb for highest mass points (4b final state)
  - $h(\gamma\gamma)h(b\bar{b})$ clean final state to investigate the low mass scenario
  - 4b final state also sensitive to spin hypothesis

- Searches for Vector Like Quarks benefit from th and bh final states
  - $h(b\bar{b})$ enhances the sensitivity in the high mass scenario
  - $h(\gamma\gamma)$ in the low mass scenario allows to fully reconstruct the VLQ mass

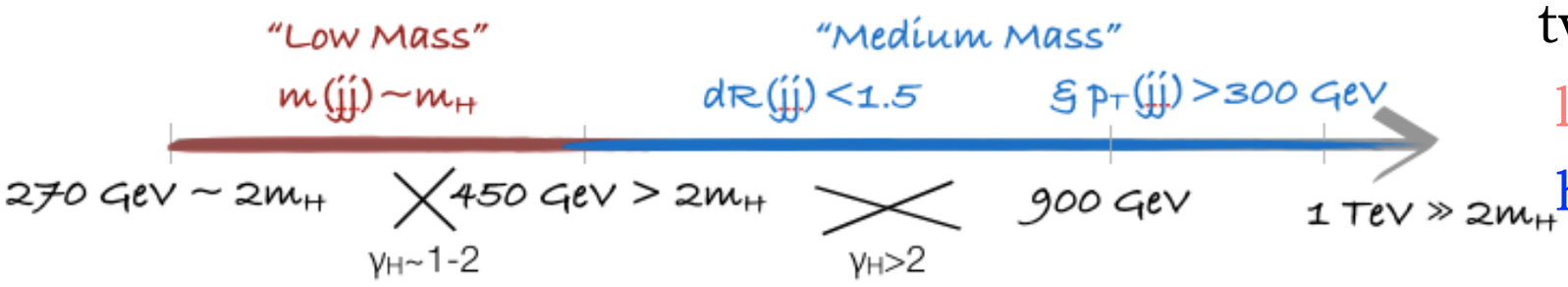
- Sub-structure techniques allows to exploits boosted topology in fully hadronic final states
  - open new phase space to look for new physics using the discovered Higgs Boson

Additional Material

$X(b\bar{b})(b\bar{b})$ Strategy

HIG-14-013

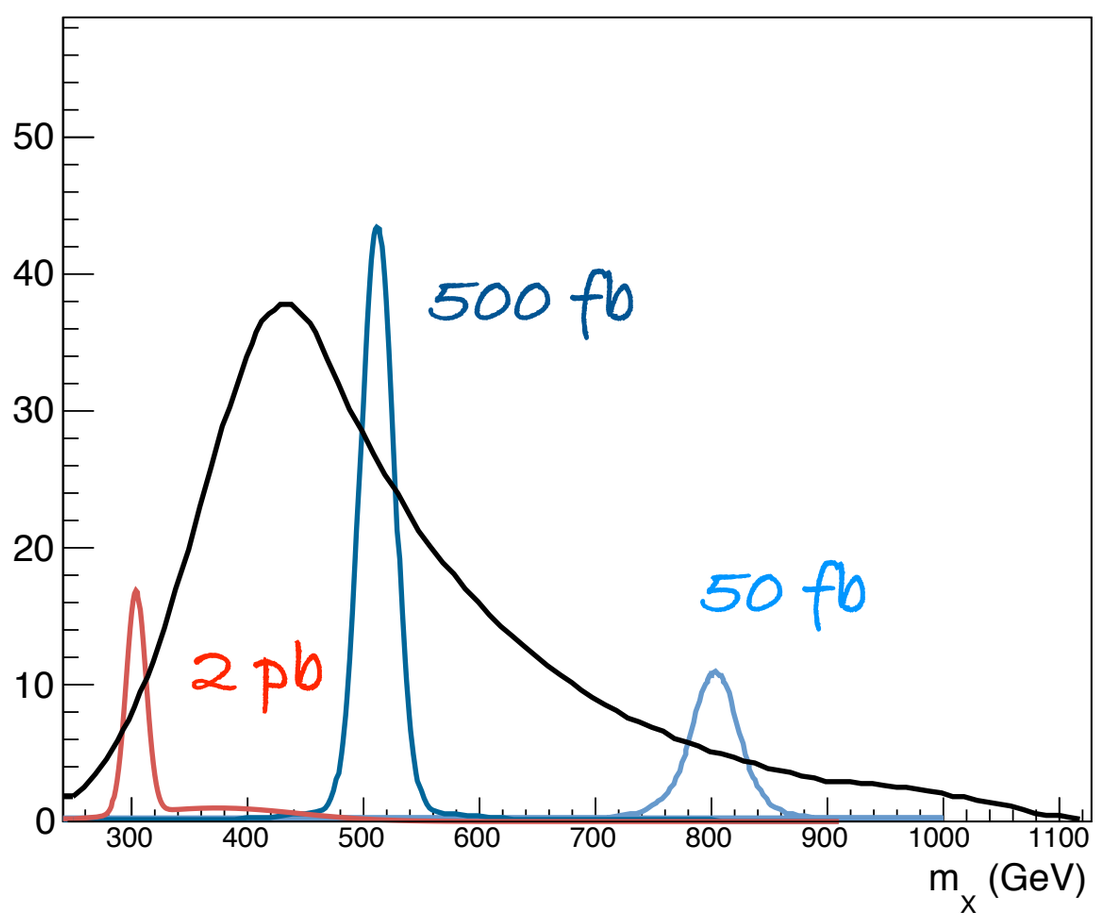
270 GeV - 1.1 TeV mass range



two kinematic regimes

low mass $270 \leq m_X \leq 450$ GeV

high mass $450 < m_X \leq 1100$ GeV



Kinematic Fit

$$\left.\begin{array}{l} m(b\bar{b})_1 \\ m(b\bar{b})_2 \end{array}\right\} 125 \text{ GeV}$$

resolution improves by 30-60%

Final m_X resolution is 2-3%

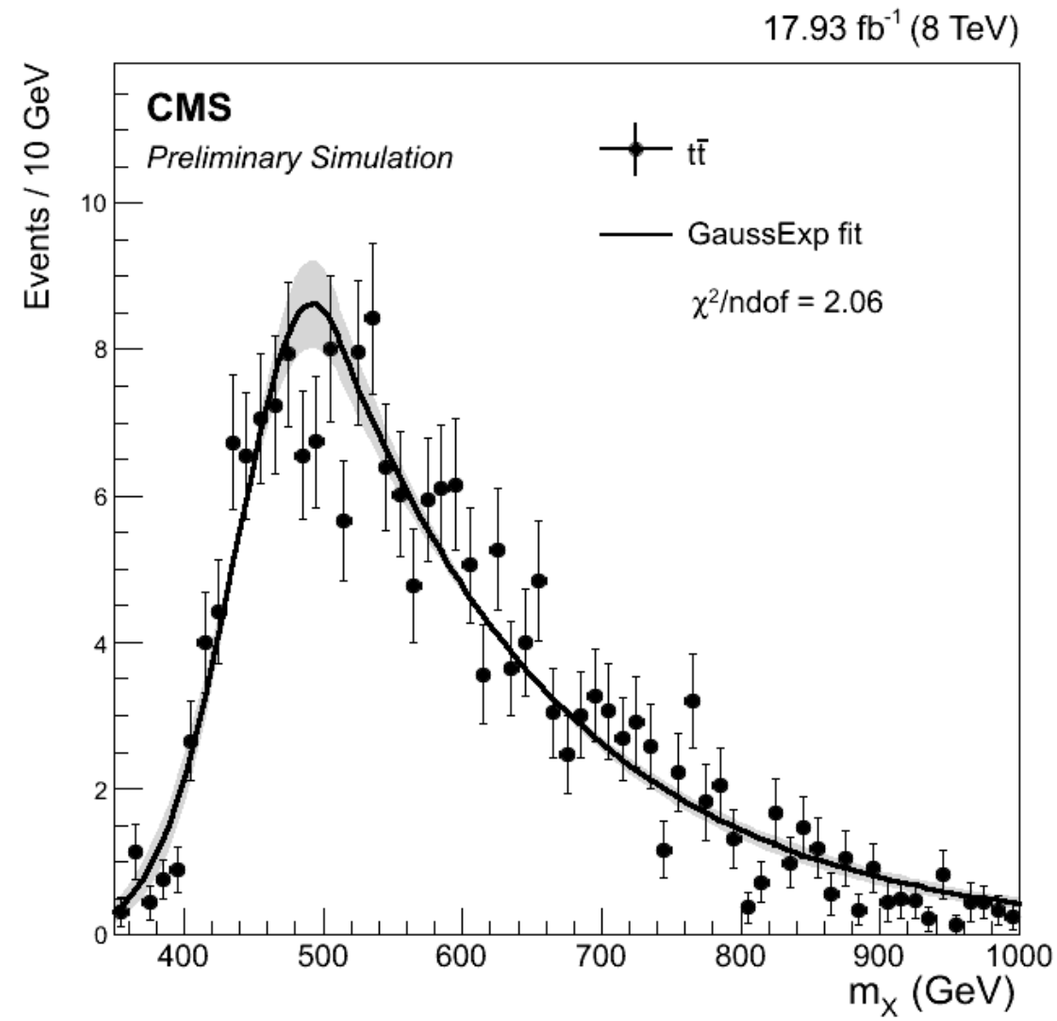
$X(b\bar{b})(b\bar{b})$ Event Selection

HIG-14-013

- 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
  - $\Delta R(b\bar{b})<1.5$ & $p_T(b\bar{b}) > 300$ GeV
  - 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

low

high



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

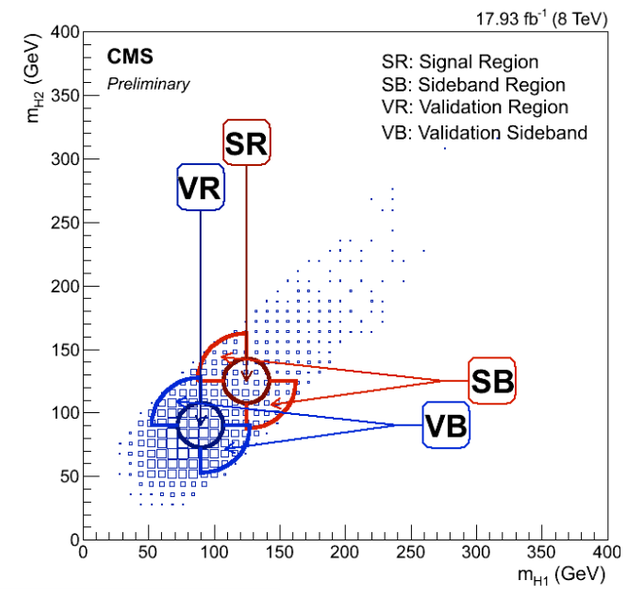
HIG-14-013

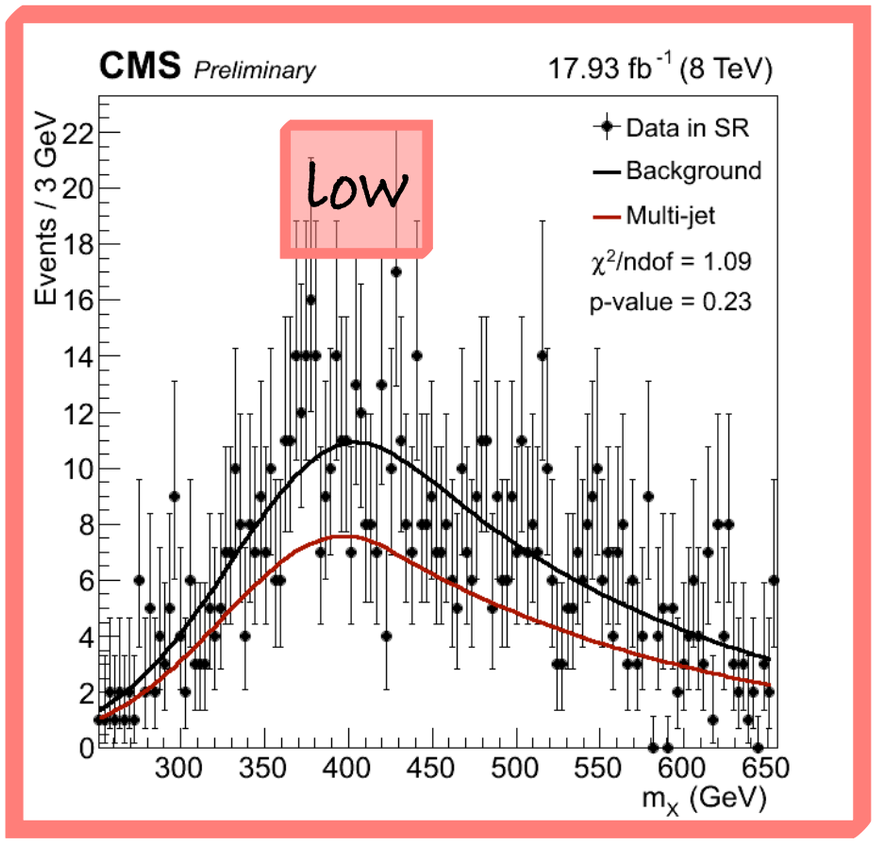
"Gauss-Exp" function is used to model the multi-jet background

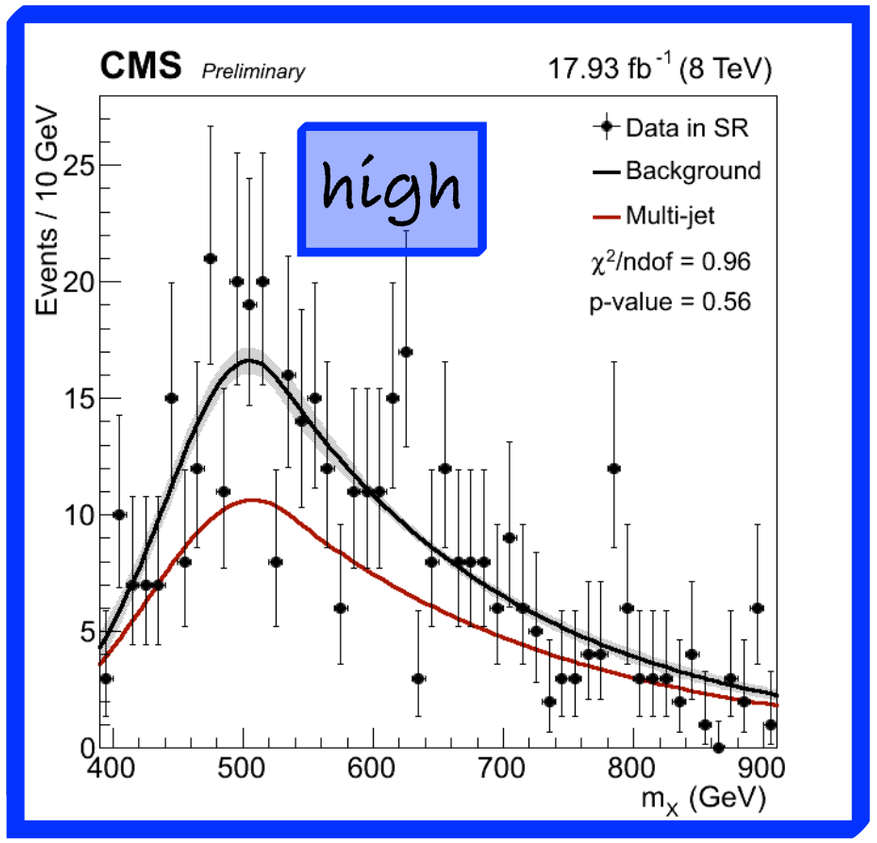
SB to test the background shape modeling
kinematically close
not signal-enriched

Flexibility of the model validated in VR/VB

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

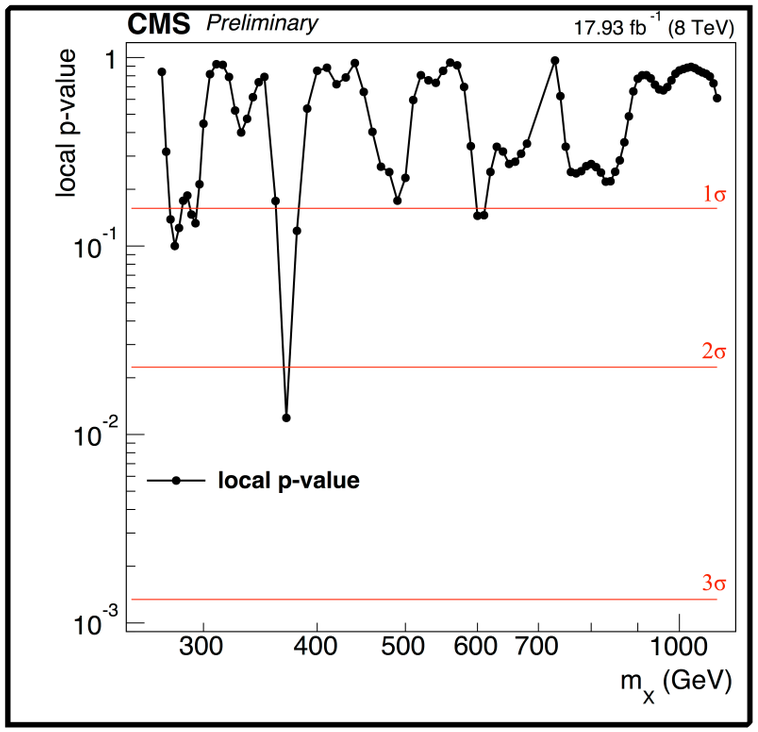




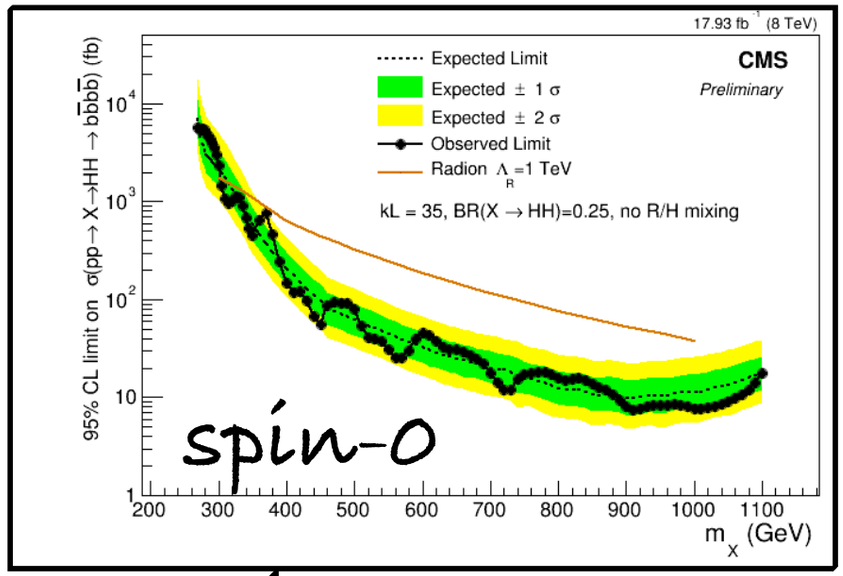


$X(b\bar{b})(b\bar{b})$ Results

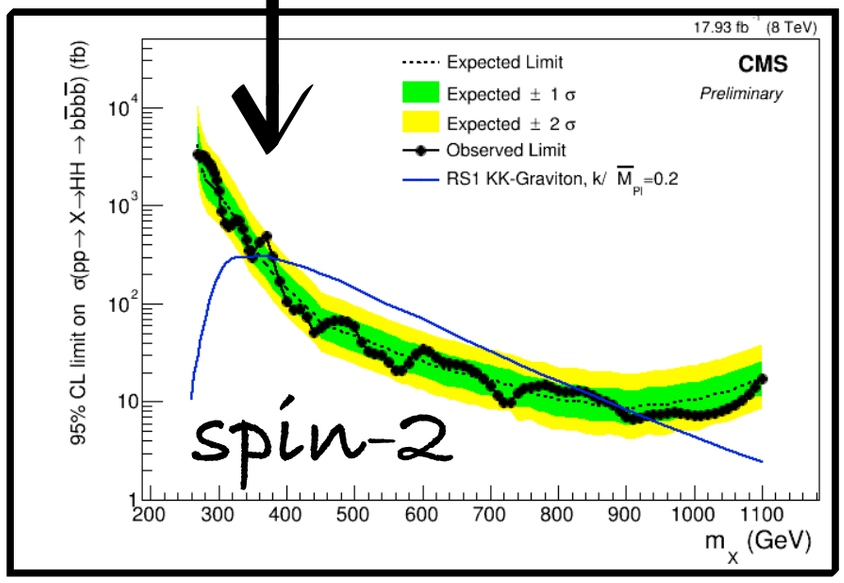
HIG-14-013



no excess, upper limits



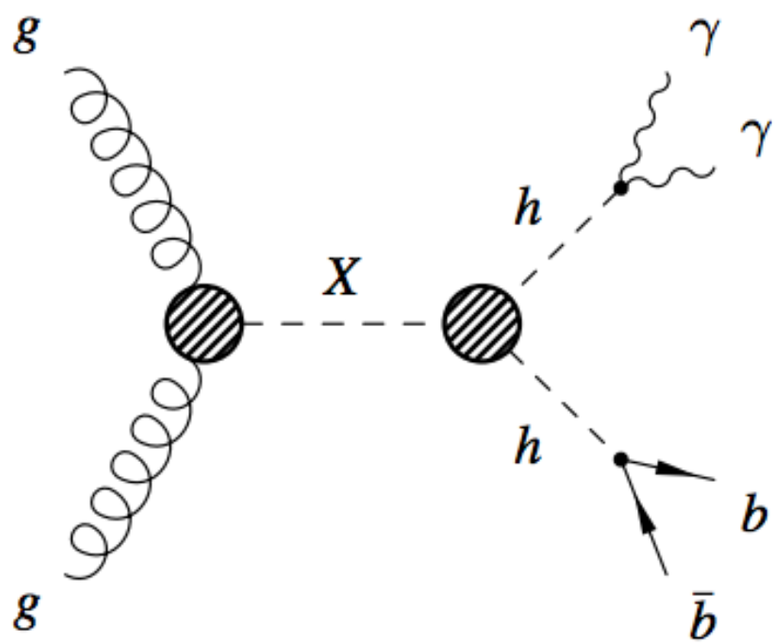
+20-30% signal eff.



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

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

HIG-13-032



Lowest BR (0.26%), but ...

- High photon reconstruction efficiency, >90%
- Ottima risoluzione per $m_H(\gamma\gamma)$
- small contribution QCD-background

L = 19.7 fb^{-1} $\sqrt{s}$ = 8 TeV

Two analysis strategies for each kinematic regime

low mass	260 GeV ≤ m_X ≤ 400 GeV
high mass	400 GeV < m_X ≤ 1100 GeV

Each regime is further categorized according to purity:

Medium	1 b-tagged jet
High	2 b-tagged jets

Central Photons and
$p_{T(\gamma 1)}/m(\gamma\gamma) > 1/3$
$p_{T(\gamma 2)}/m(\gamma\gamma) > 1/4$
$100 < m(\gamma\gamma) < 180$ GeV
central b-jets with p_T> 25 GeV
Eff 70%, mis-tag 1-2%

$X(b\bar{b})(\gamma\gamma)$ Results

HIG-13-032

No significant deviation from ...
The analysis is statistically limited
Systematic uncertainties worse the limit by 2%