Searches for Di-Boson and Di-Lepton Resonances at the LHC

(w/new results for La Thuile 2018!)

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on behalf of the
ATLAS and CMS Collaborations

Introduction

Searches for new resonances are a critical part of the LHC physic program

Generic signatures that arise in many models of new physics

Di-Boson Resonances:

Discovered a new particle with di-boson resonances: ***ZZ / γγ / WW***
Recent development improve acceptance/sensitivities at high P_T
With Higgs, more di-boson final states to search

Di-Lepton Resonances:

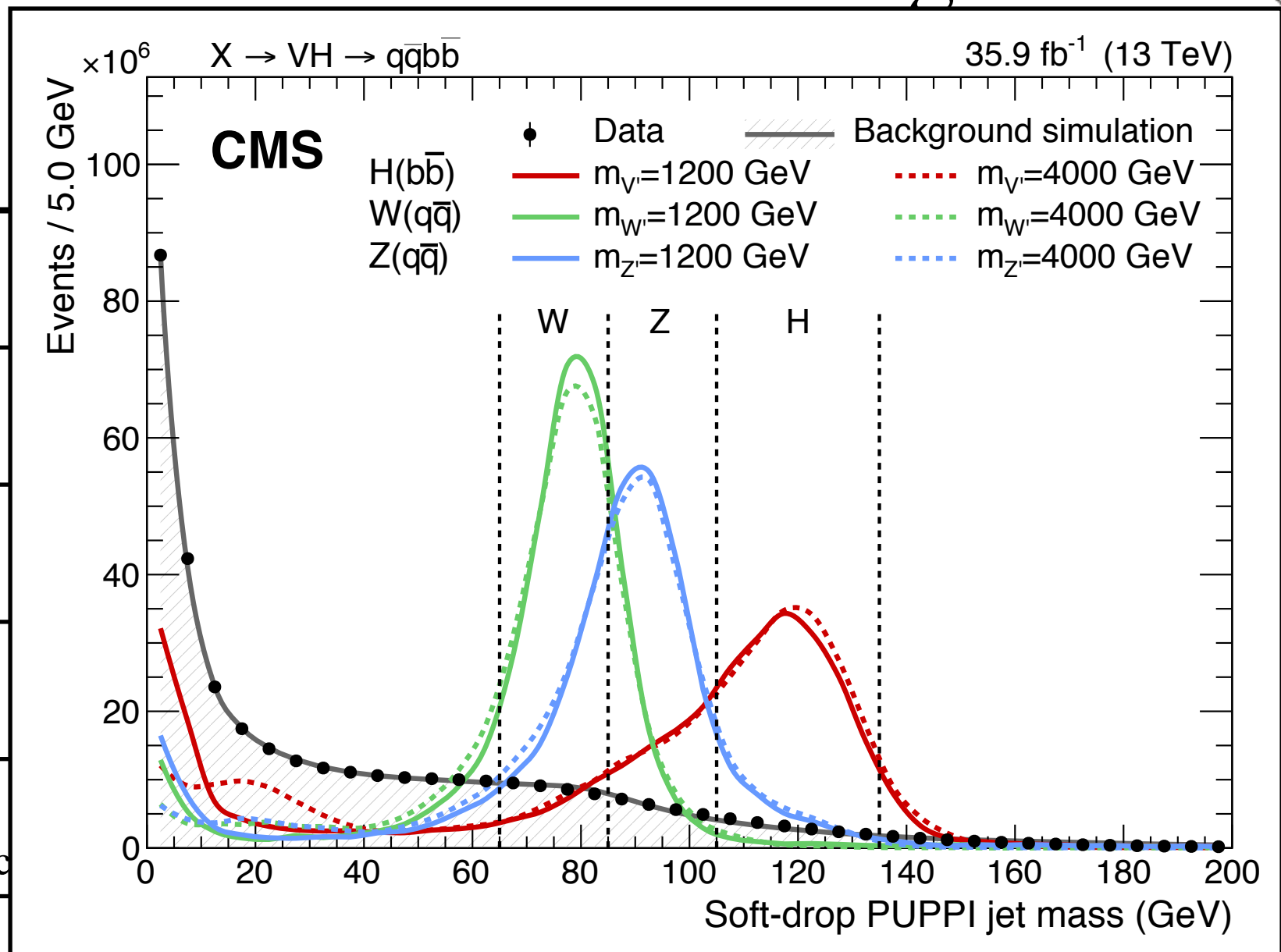
Z'→ll/W'→lν flagship searches
Lepton resonances also have a rich history of discoveries in the field:
charm / bottom / W / Z / ...

Di-Boson Search Program

	g	γ	W	Z	W/Z (hadronic)	H
g	arXiv:1703.09127 PAS-EXO-16-056	arXiv:1709.10440 arXiv:1711.04652			- arXiv:1708.05379	
γ		arXiv:1707.04147 arXiv:1606.04093	arXiv:1407.8150	arXiv:1708.00212 PAS-EXO-16-034	*Coming Soon* PAS-EXO-16-035	*Coming Soon*
W			arXiv:1710.01123 PAS-HIG-16-023	*Coming Soon*	arXiv:1710.07235 PAS-B2G-16-029	CONF-2017-055
Z				arXiv:1712.06386 PAS-HIG-17-012	arXiv:1708.09638 arXiv:1802.09407	CONF-2017-055
W/Z (hadronic)					arXiv:1708.04445 arXiv:1708.05379	arXiv:1707.06958 arXiv:1707.01303
H						CONF-2016-049 arXiv:1710.04960

ATLAS
CMS

Di-Boson Search Program



g	
γ	*Soon*
W	7-055
Z	7-055
W/Z (hadronic	.06958 .01303
H	6-049 arXiv:1710.04960

Di-Boson Search Program

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H						CONF-2016-049 arXiv:1710.04960

ATLAS
CMS

Covered in this Talk

$X \rightarrow VV \quad (V = W \text{ or } Z)$

Ws and Zs, in turn, decay into...

	W	Z
leptons (e/μ)	~ 25%	~10 %
hadrons	~ 75%	~75 %
neutrinos	-	~15 %

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Clean/Rare

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Common/Dirty

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Clean/Rare

Common/Dirty

At high-masses,

- Backgrounds fall steeply
- Hadronic decays become increasingly more sensitive

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Clean/Rare

Common/Dirty

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Decay products become collimated at high W/Z boosts.

- Dedicated reconstruction techniques targeting boosted topology
- Widely used in searches / Whole industry devoted to this subject

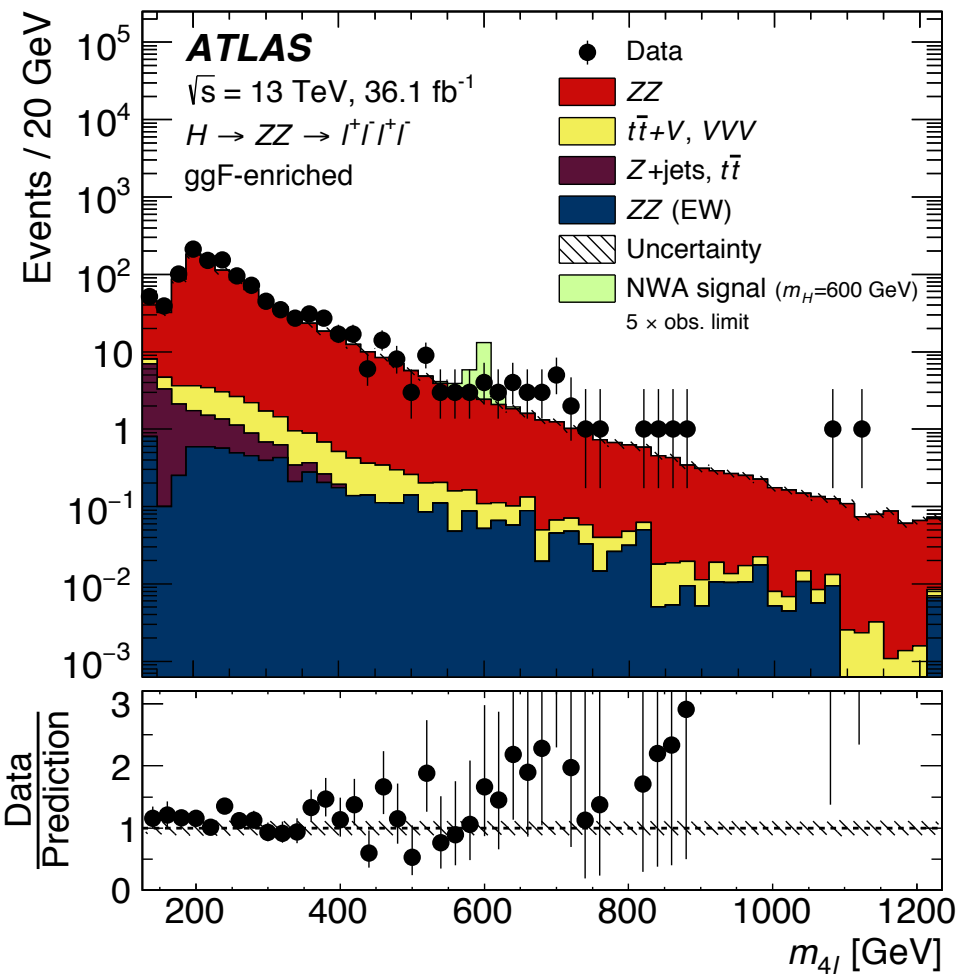
$X \rightarrow ZZ \rightarrow 4l$

arXiv:1712.06386

Clean final state / Background dominated by ZZ production

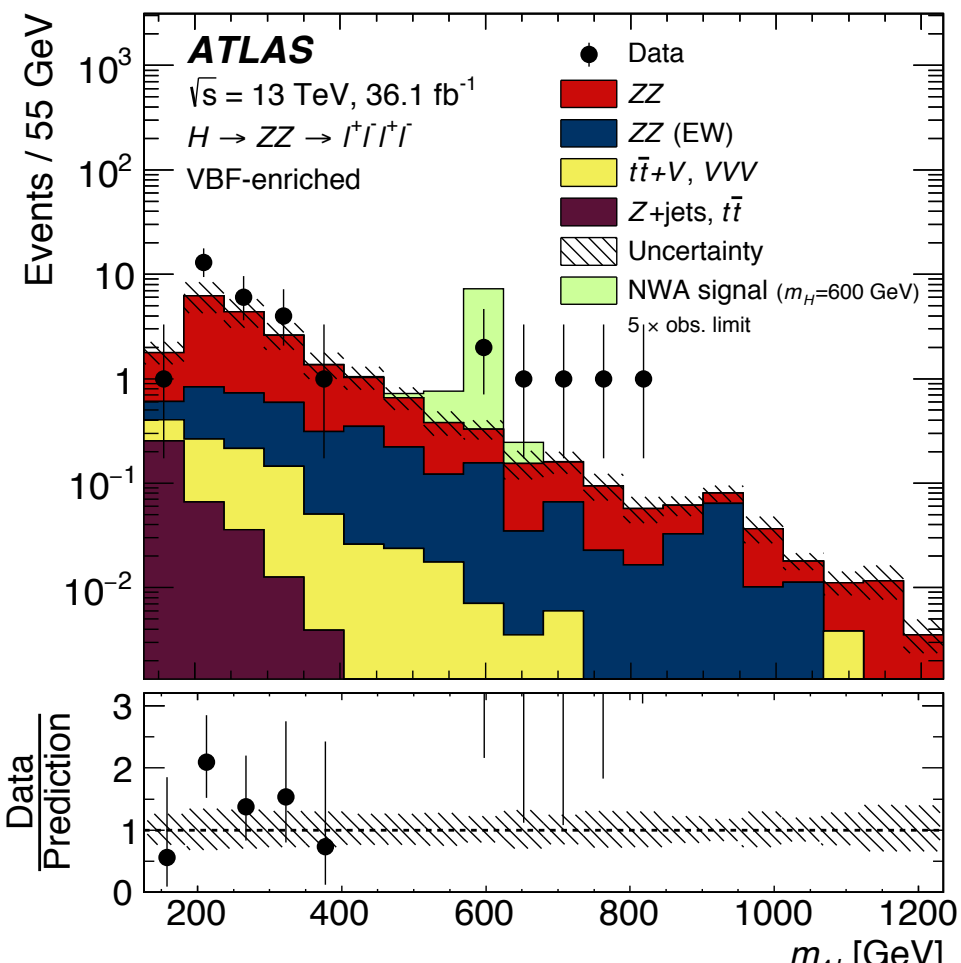
gluon fusion production

inclusive events selection



Vector Boson Fusion

$M_{jj} \geq 400$ GeV



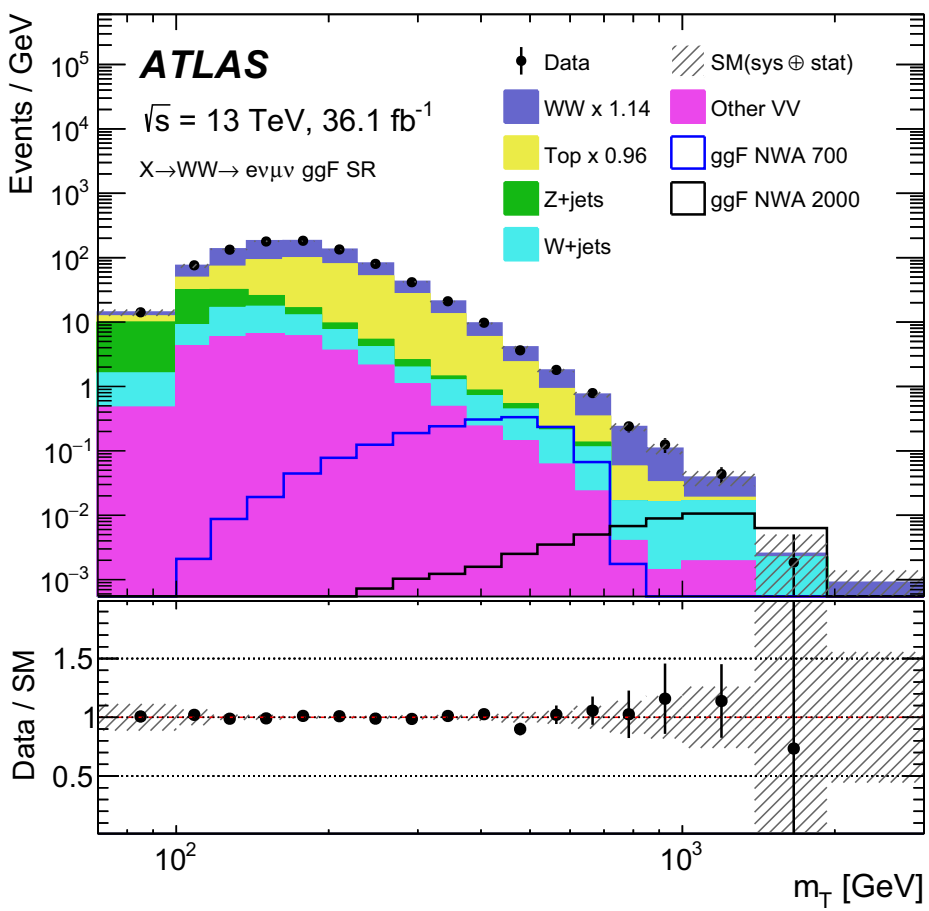
$X \rightarrow WW \rightarrow e\nu\mu\nu$

arXiv:1710.01123

- eμ requirement kills dominant Drell-Yan background
- Left with WW and ttbar production *(constrained w/data using control regions)*

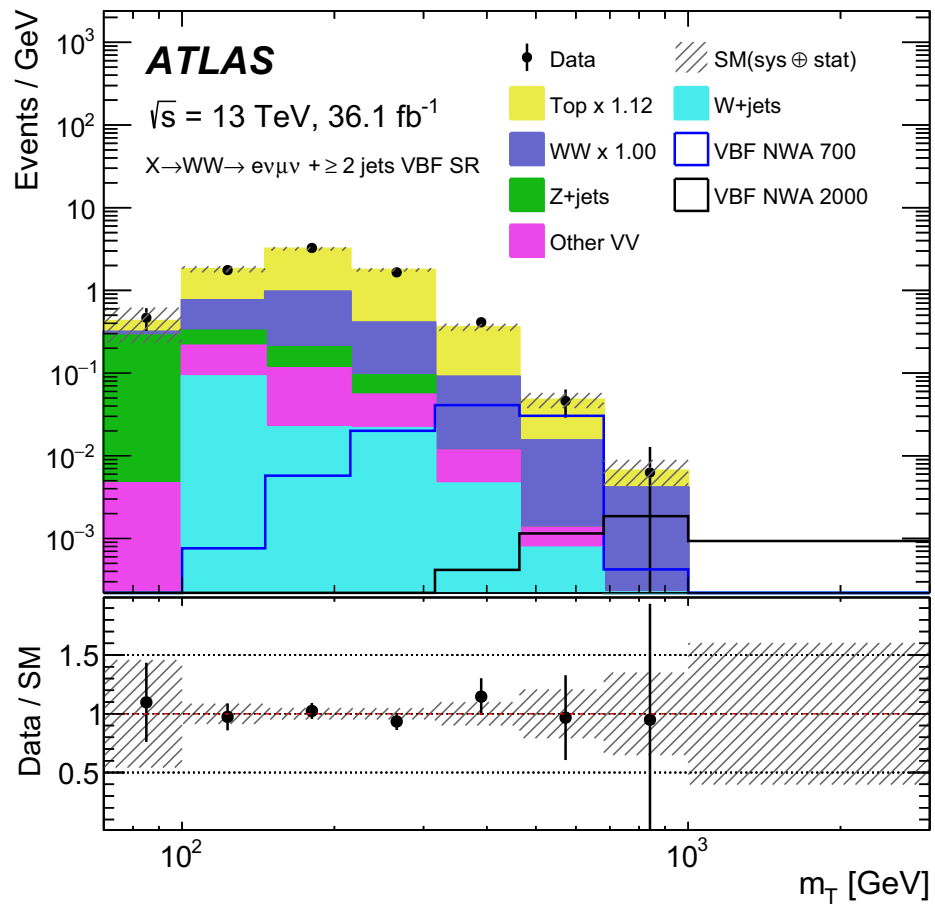
Gluon fusion production

jet-veto



Vector Boson Fusion

$M_{jj} \geq 500$ GeV / b-jet veto



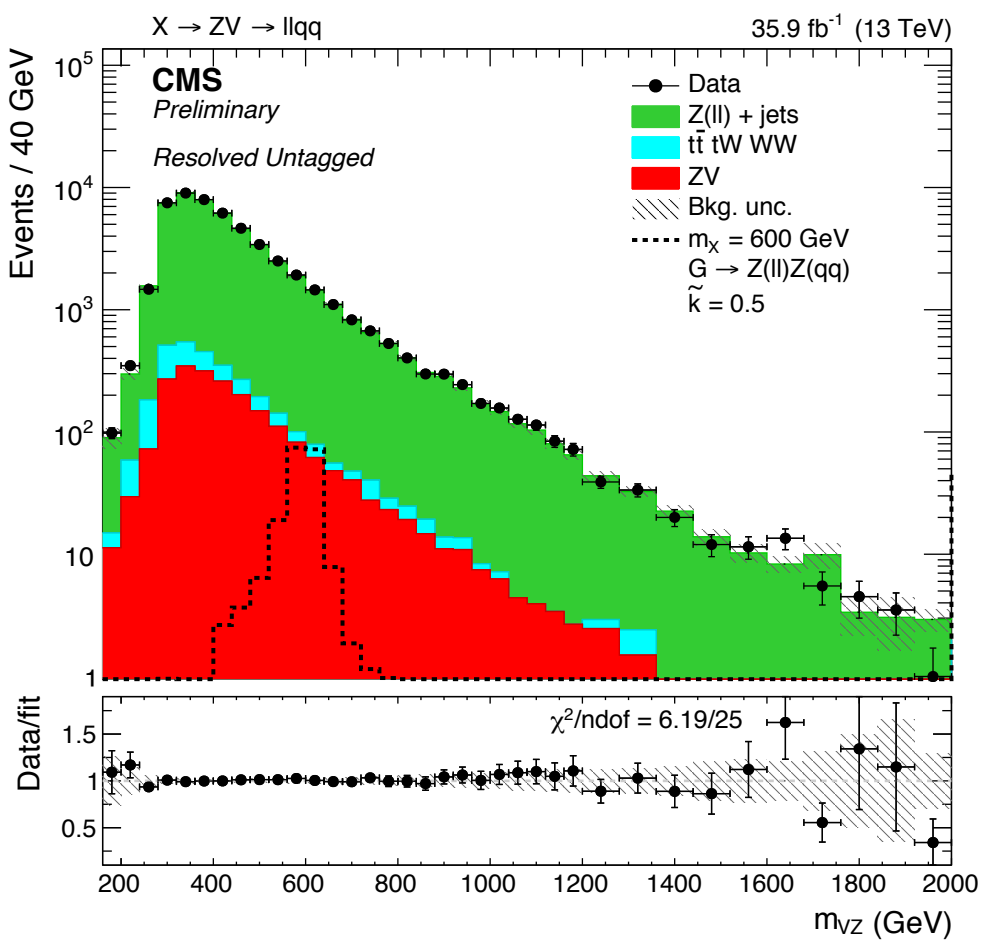
X → ZV → llqq

PAS-B2G-17-013

Z→ll (e/μ) provides triggers / kills non-EW/top background

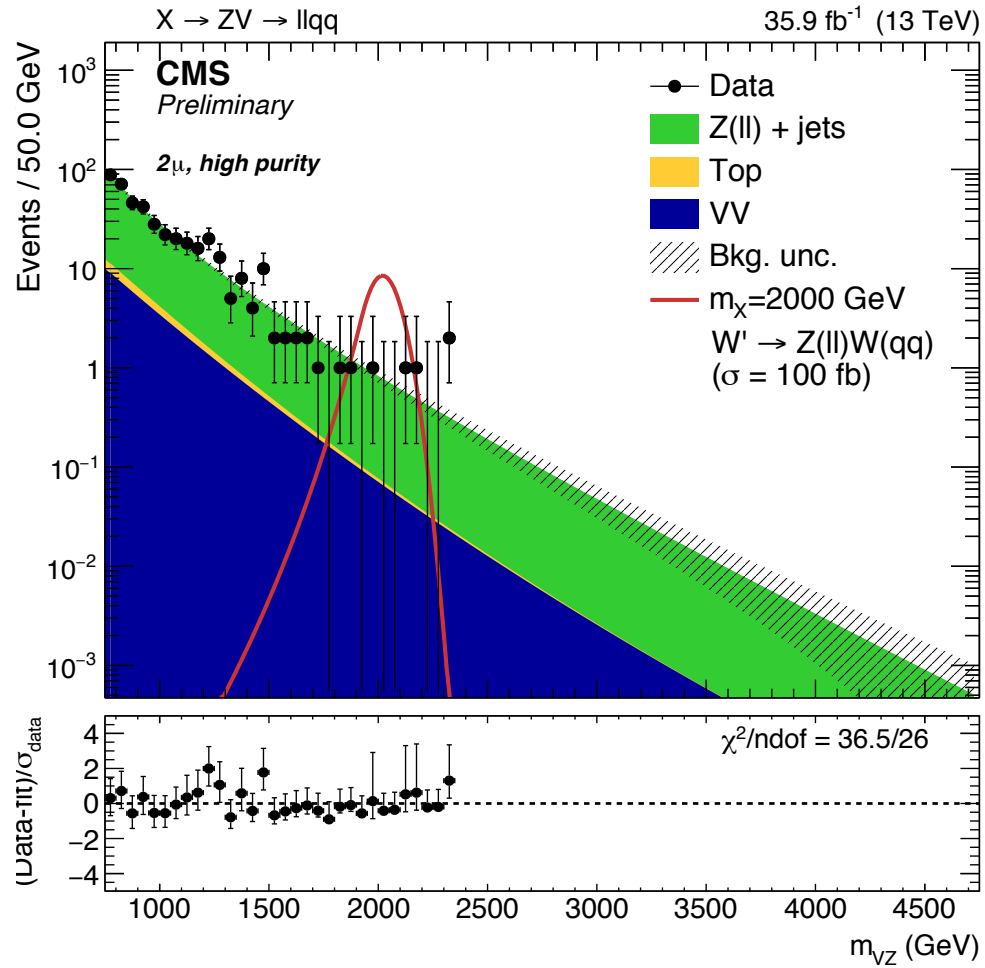
Low Mass Channel

jets (r = 0.4)



High-Mass Channel

jets (r = 0.8) / mass mV



X → ZV → llqq

PAS-B2G-17-013

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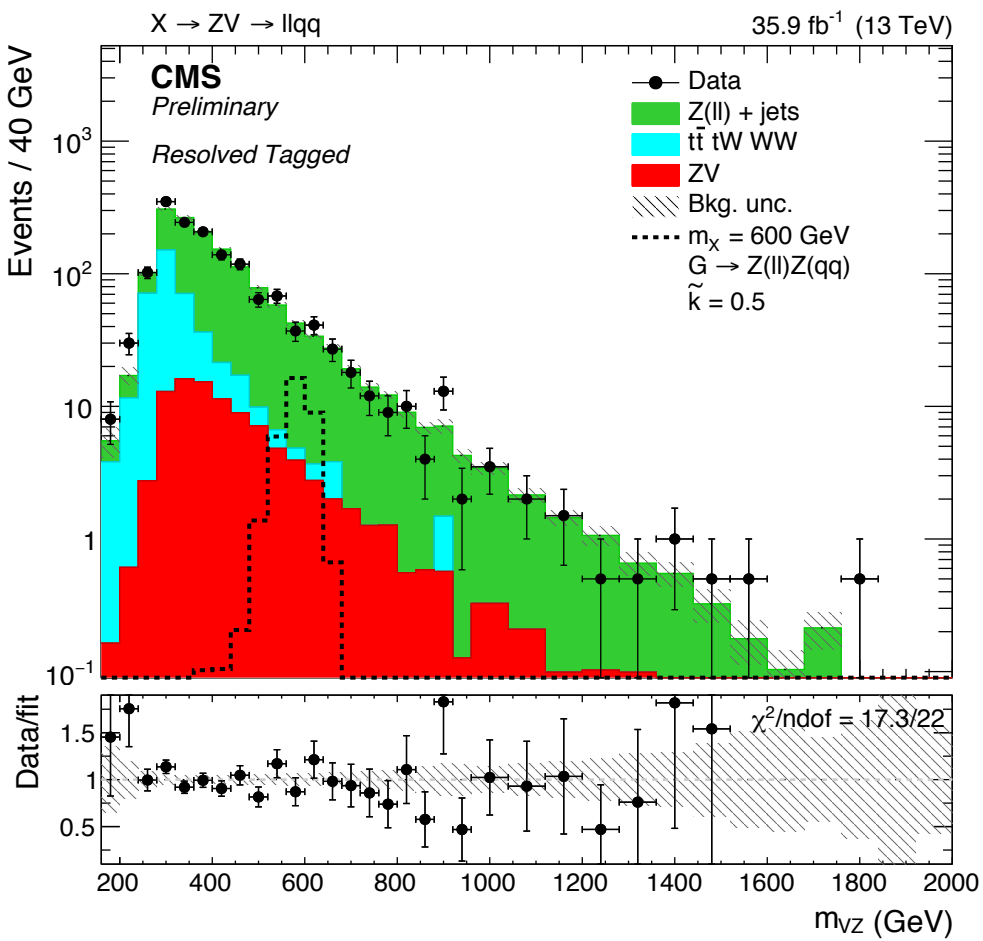
Low Mass Channel

jets (r = 0.4) / b-tag channel



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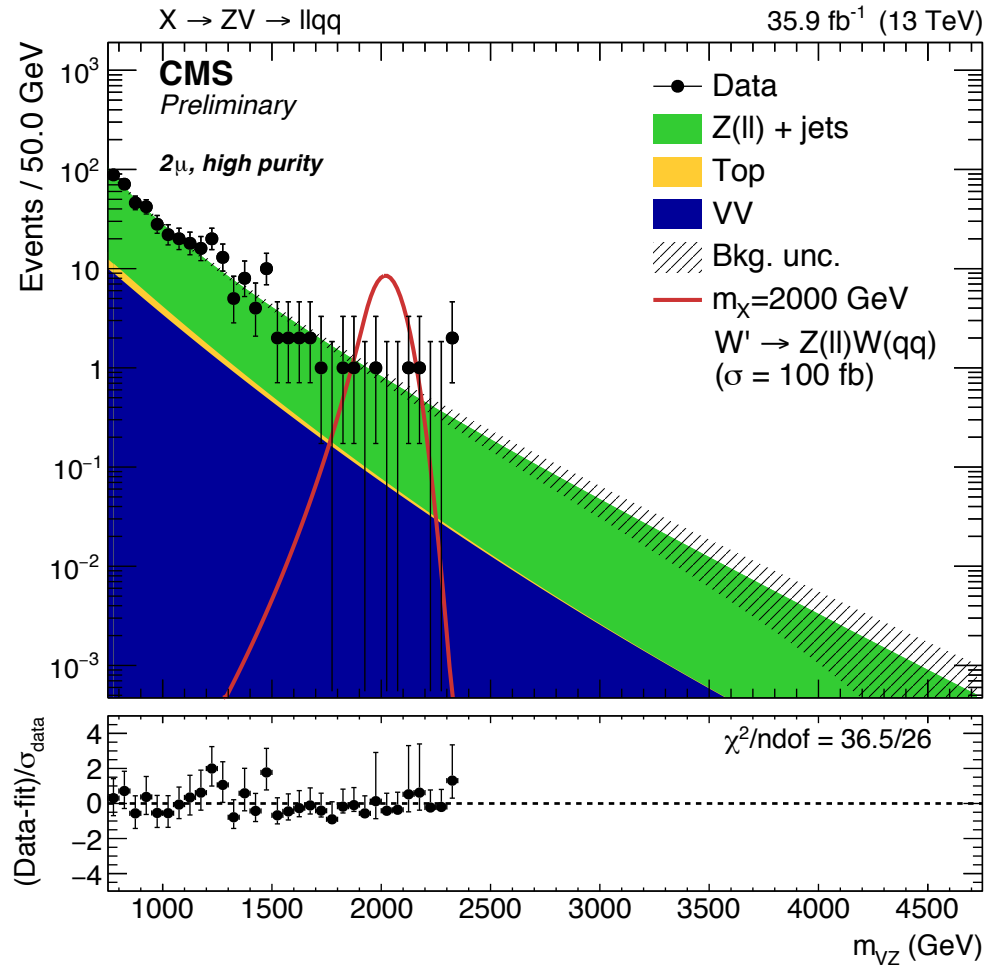
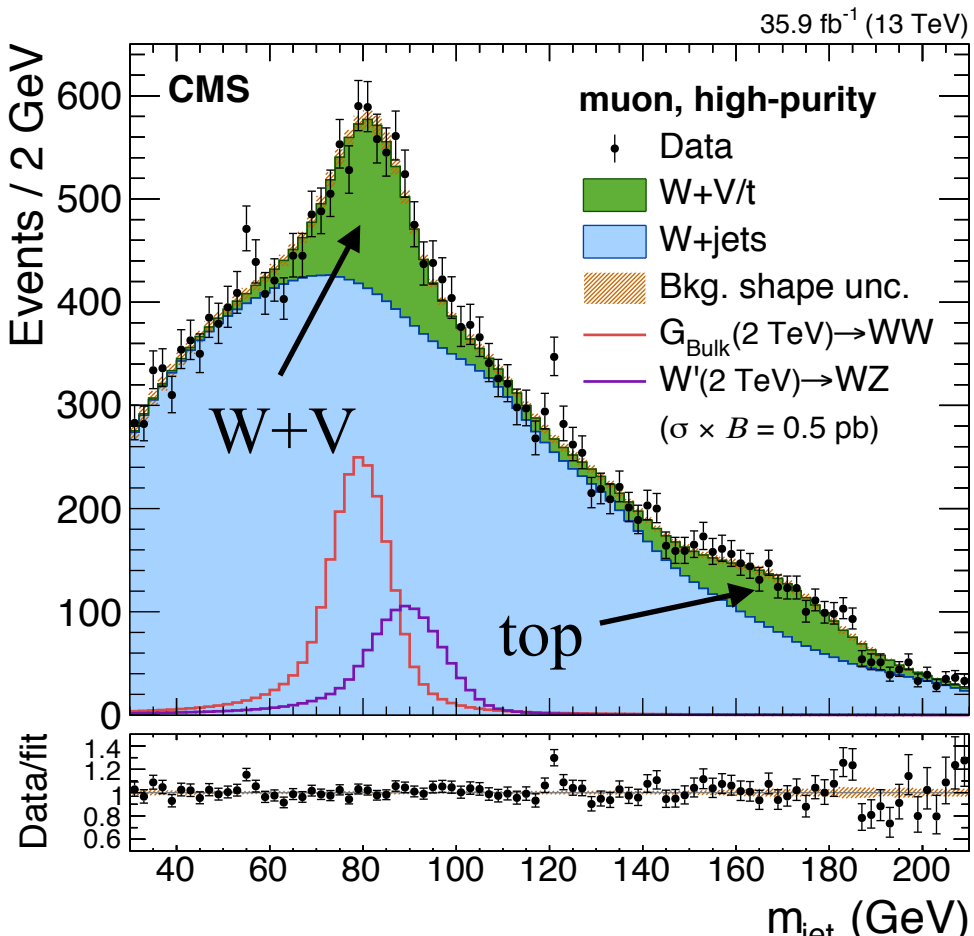


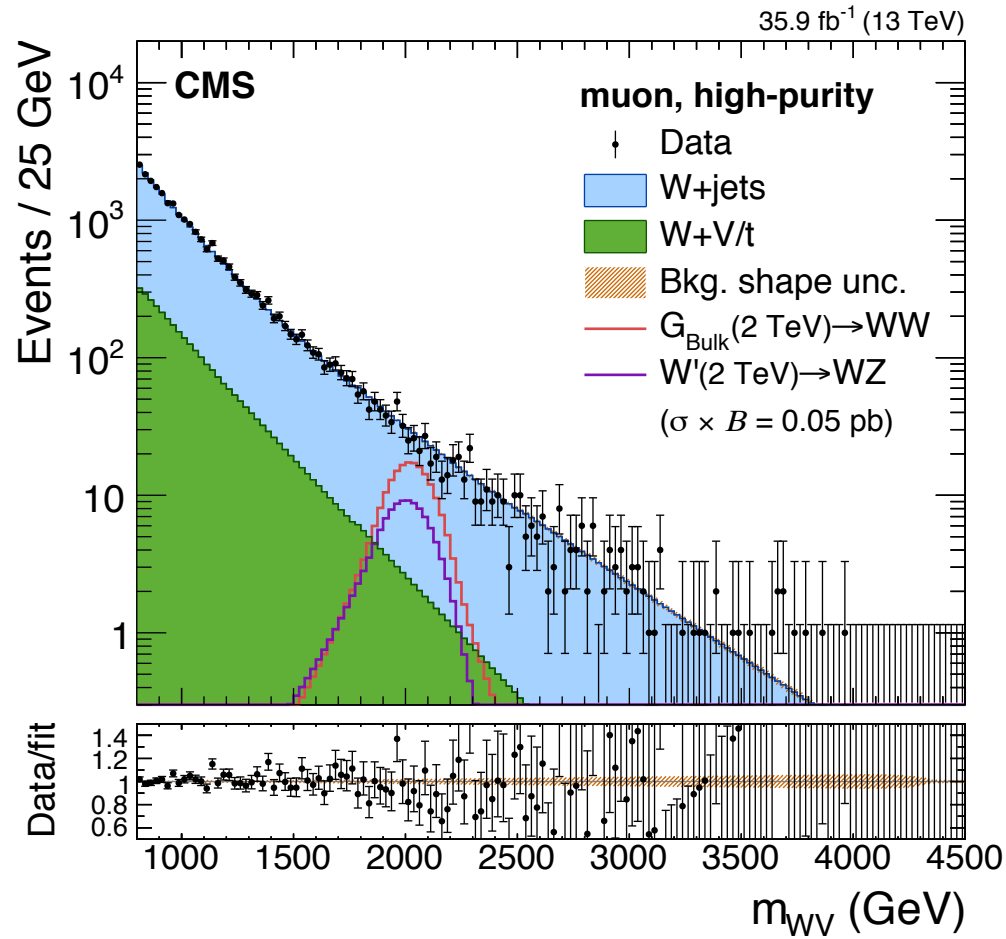
X → WV → lνqq

arXiv:1802.09407

W → lν / trigger (fit for $P_z(\nu)$ using m_W constraint)
Larger jet mass window ($30 < m_J < 310$ GeV)

Background estimation: 2D likelihood fit to (m_J, m_X)

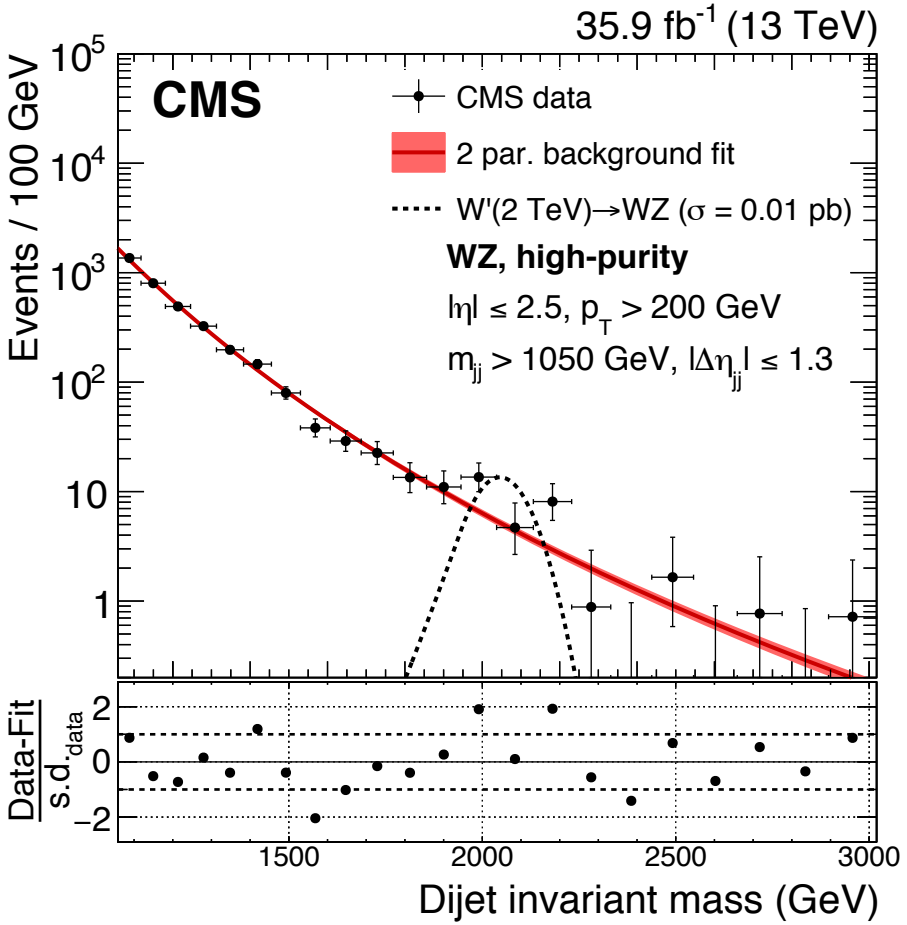




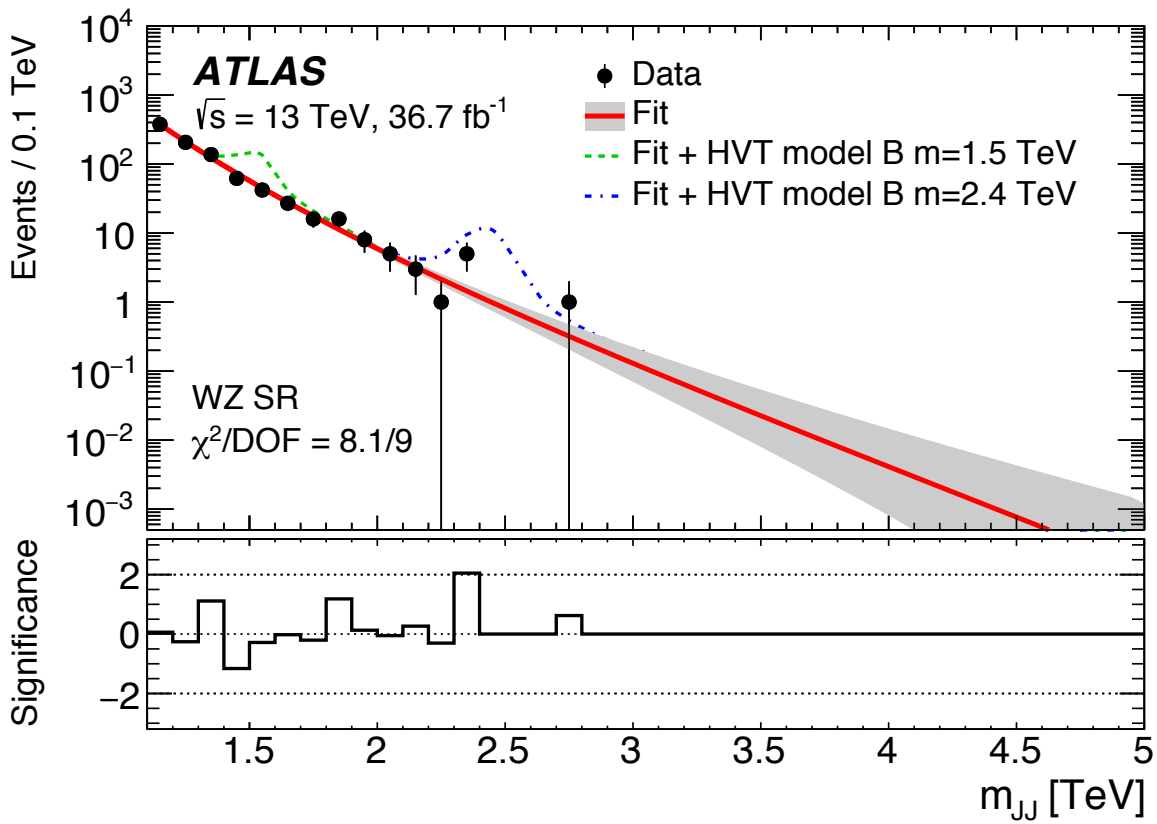
X → VV → qqqq

arXiv:1708.04445
arXiv:1708.05379

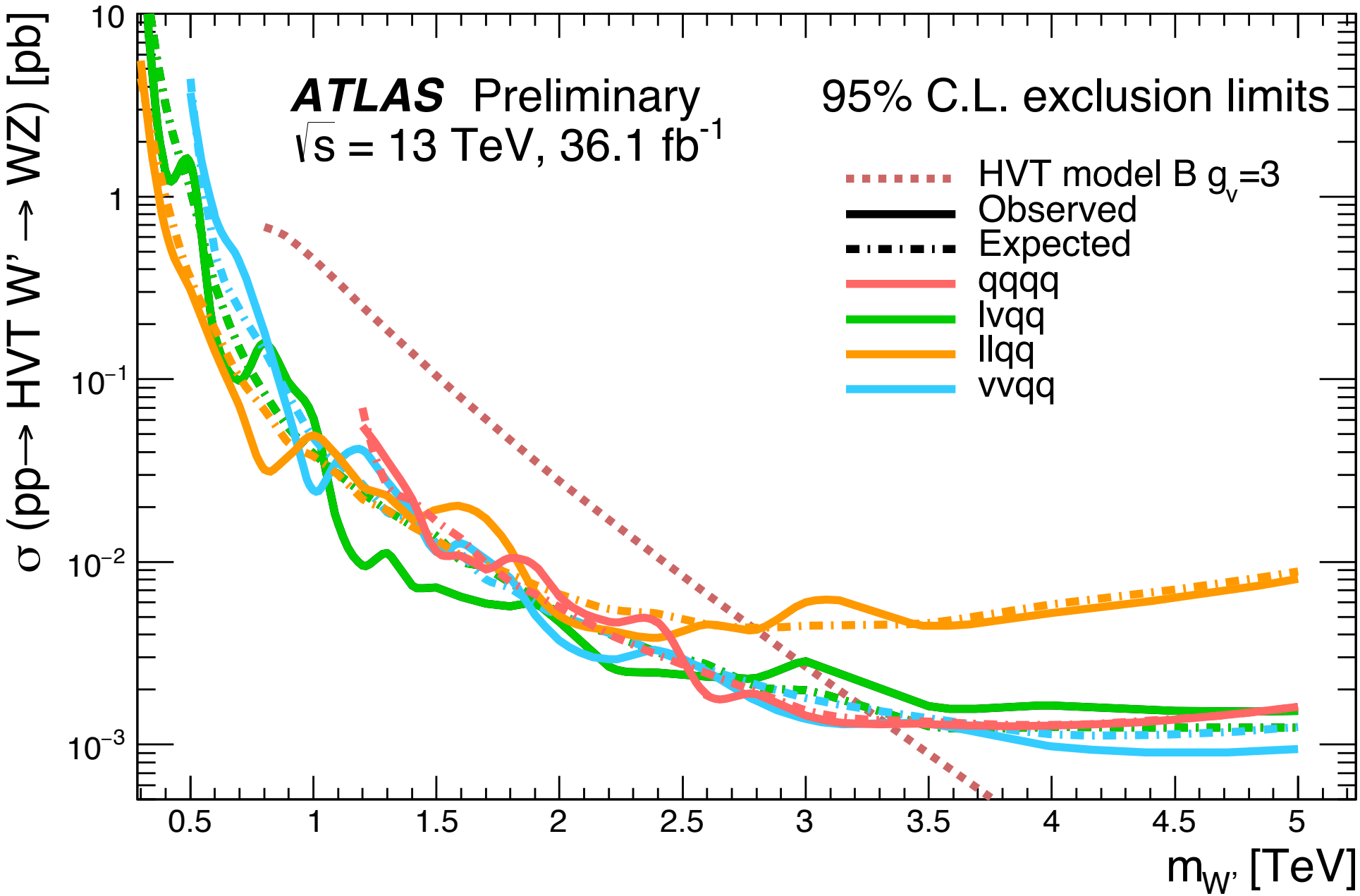
Hadronic trigger + 2 large-R jets w/mass ~mV
Dominated by QCD multi-jet background.
Background shape from MVV fit to data *(using empirical parametric function)*
Sensitive to signals with localized excess



Study bkg shape in mJ sidebands



Relative VV Sensitivities



$X \rightarrow HH$

- Signature predicted in several models
  Extra-dimensions / 2HDM / …

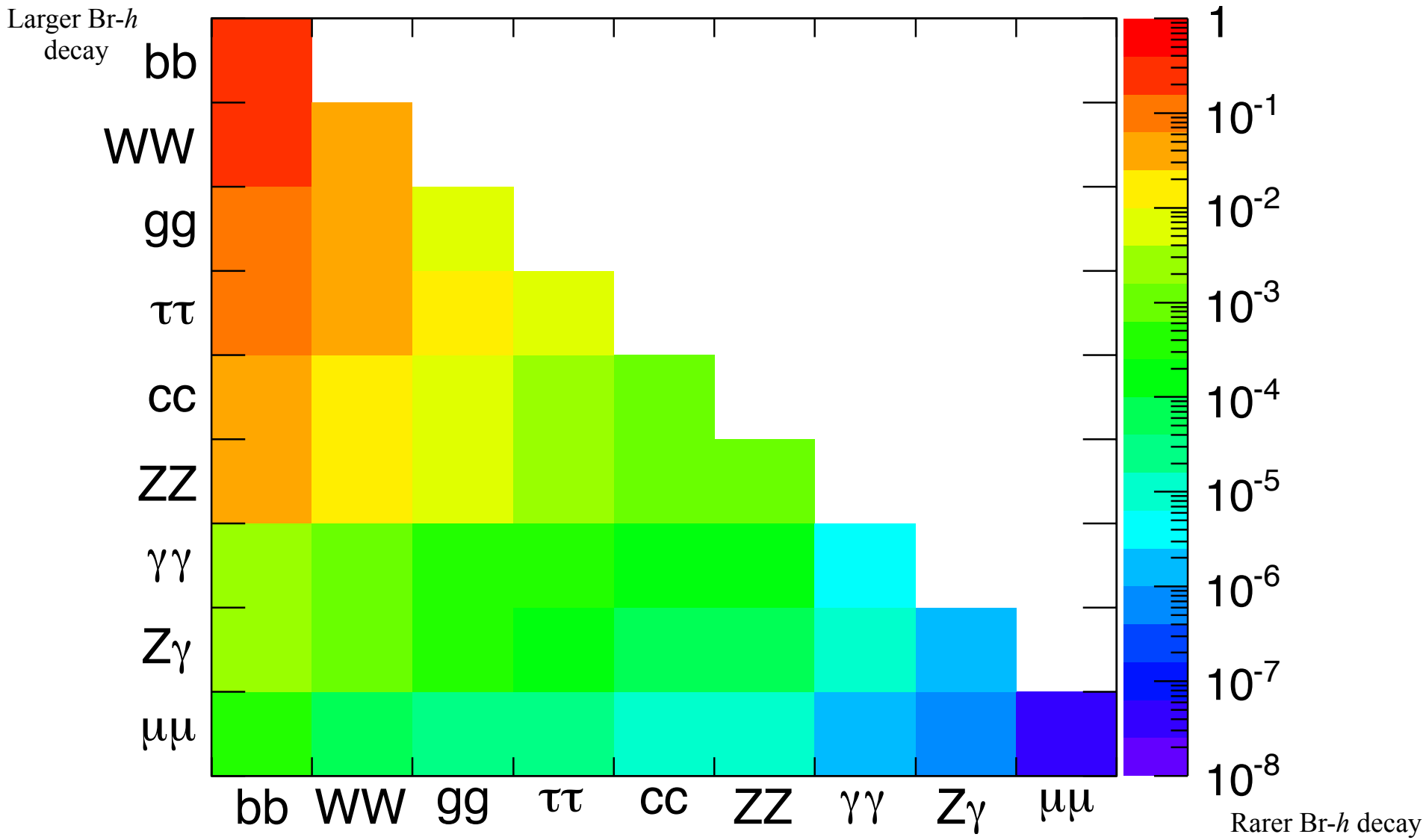
- Didn't know how to look for it at previous colliders
  Interesting at relatively low-masses/large couplings

- Potential large non-resonant enhancements in HH final state

- Long-term program to measure Higgs self-coupling

HH Final States

HH is an entire program in itself…



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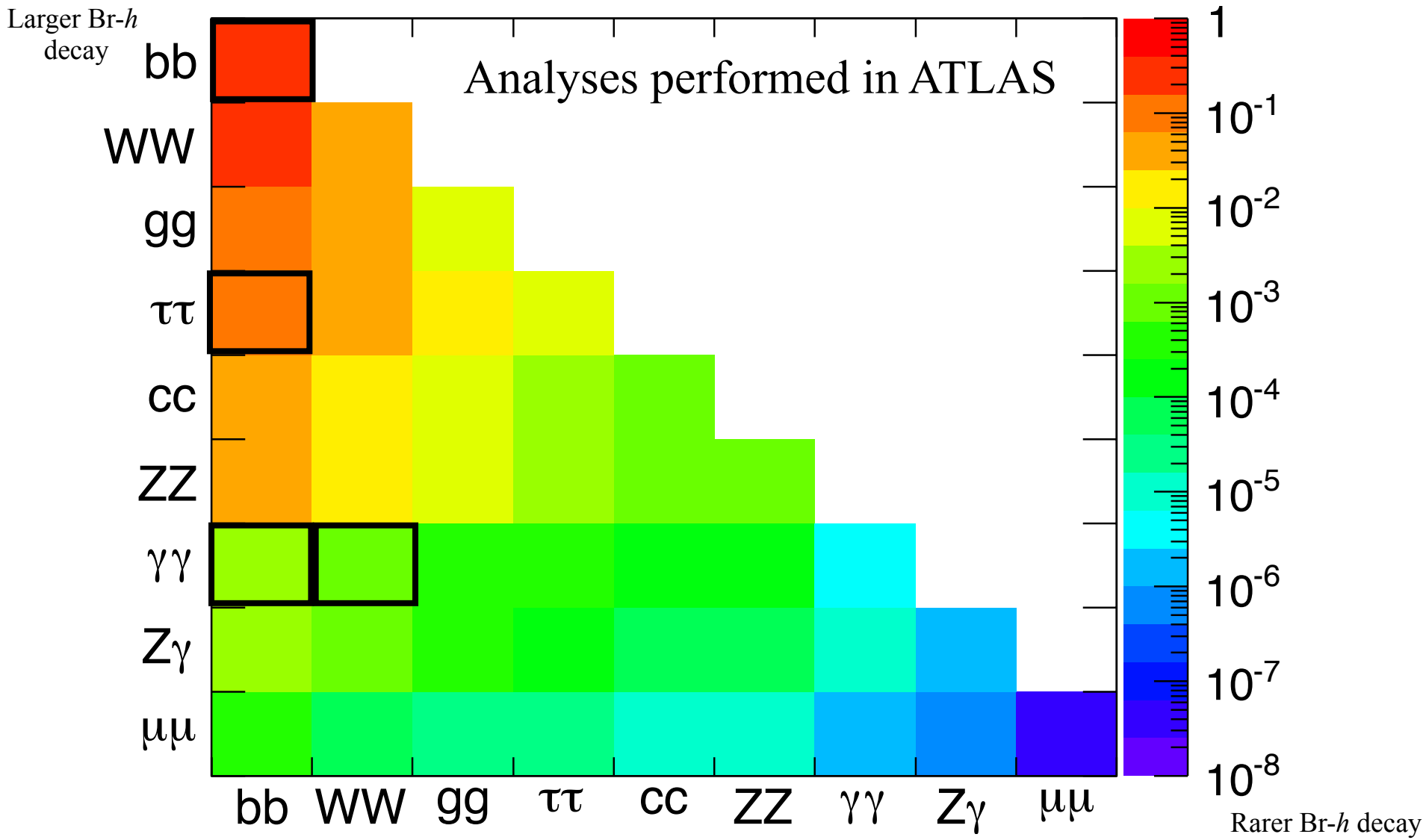

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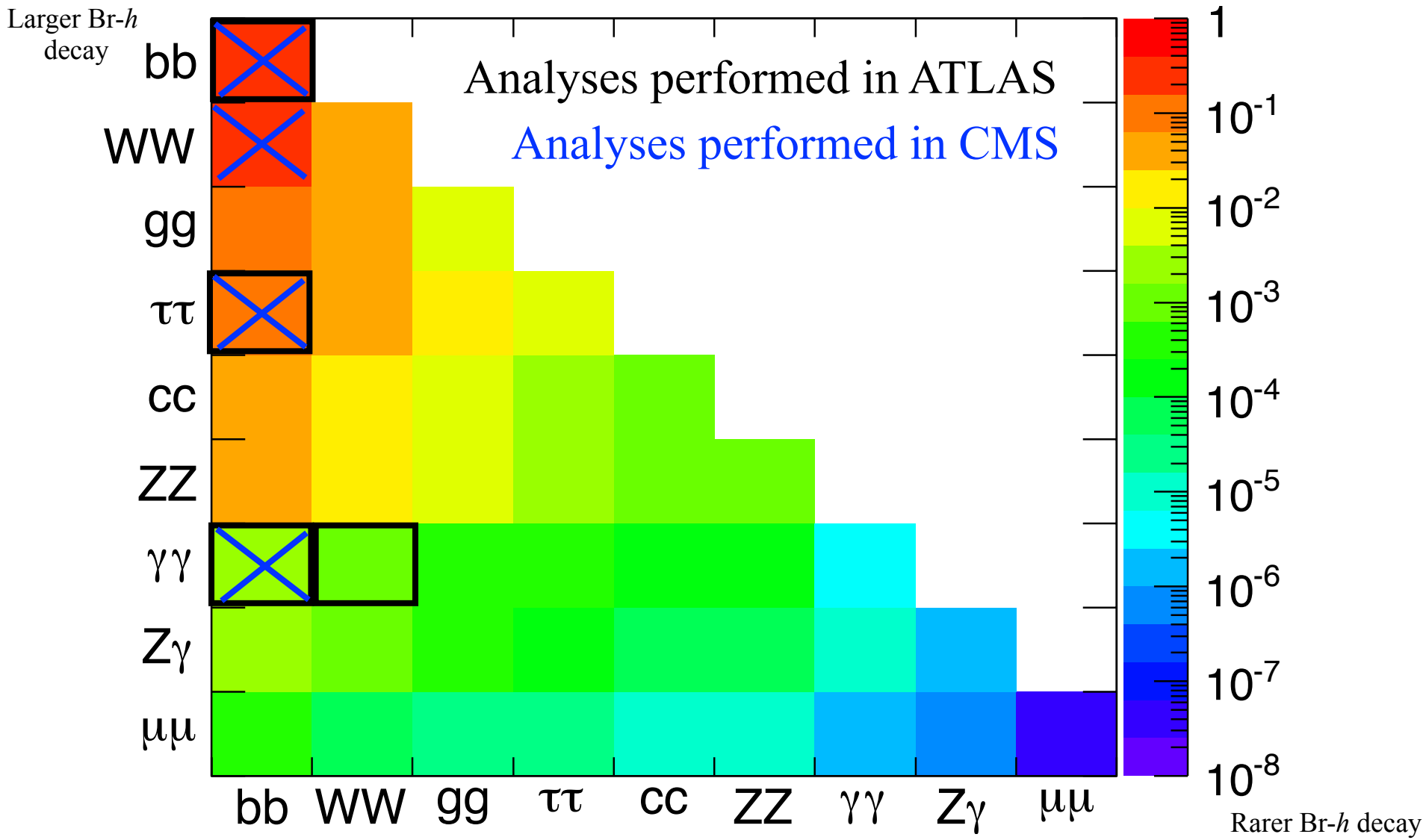
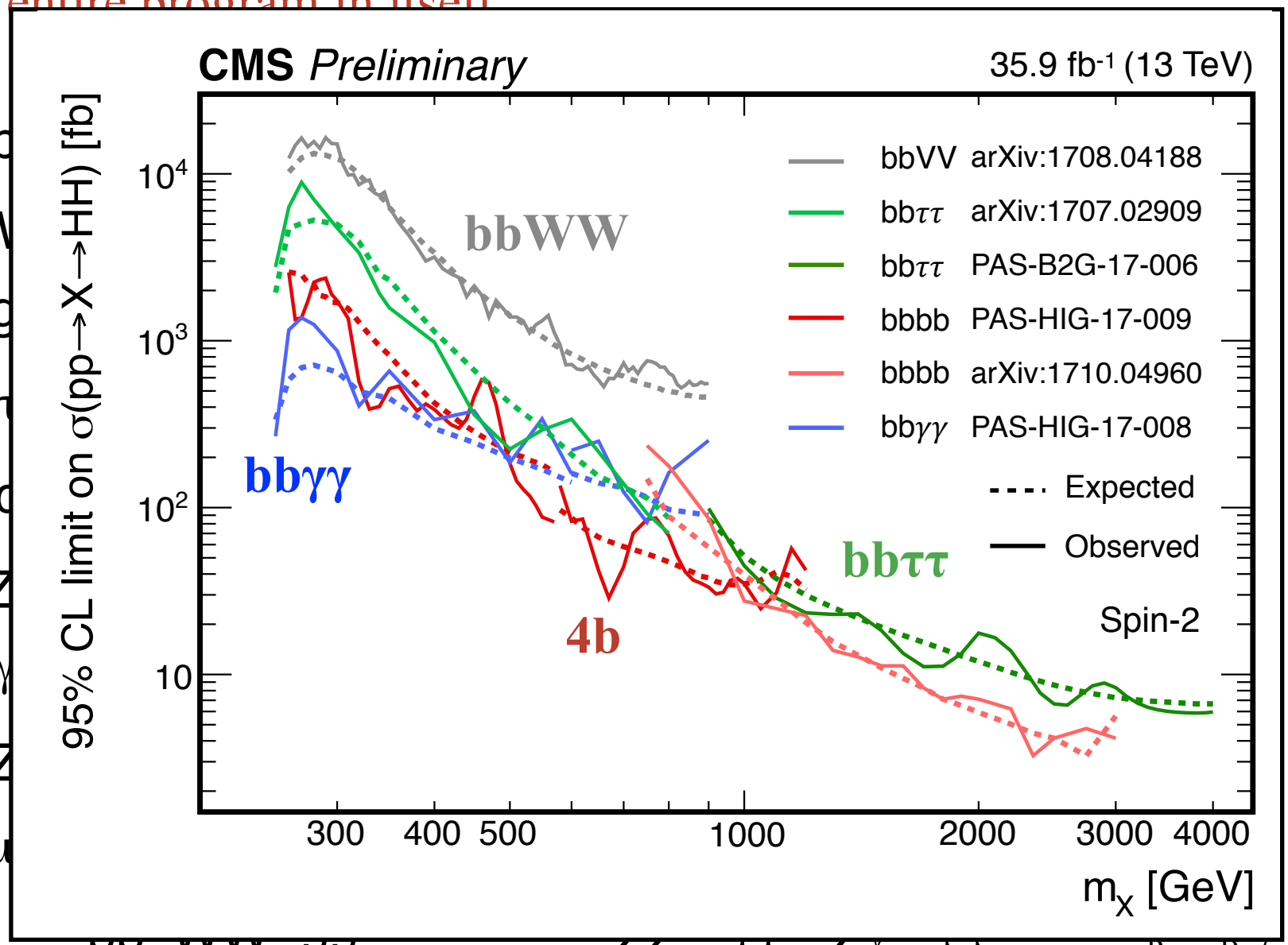


HH Final States

HH is entire program in itself

Larger Br-*h* decay



Rarer Br-*h* decay

HH Final States

HH is entire program in itself

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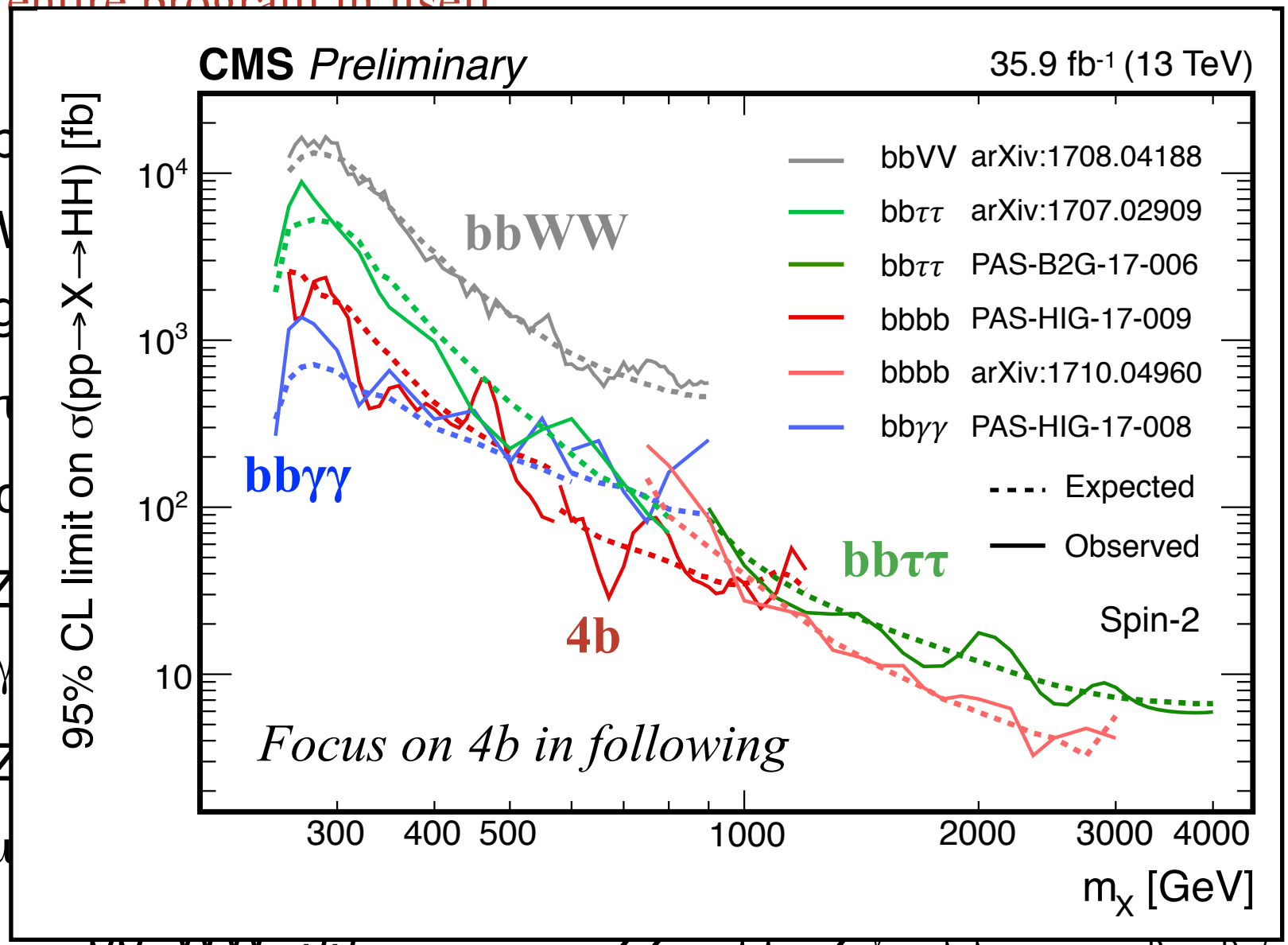


Rarer Br-*h* decay

$X \rightarrow HH \rightarrow 4b$

New for La Thuile 2018!

ATLAS

Select events with 4-b-tagged jets:

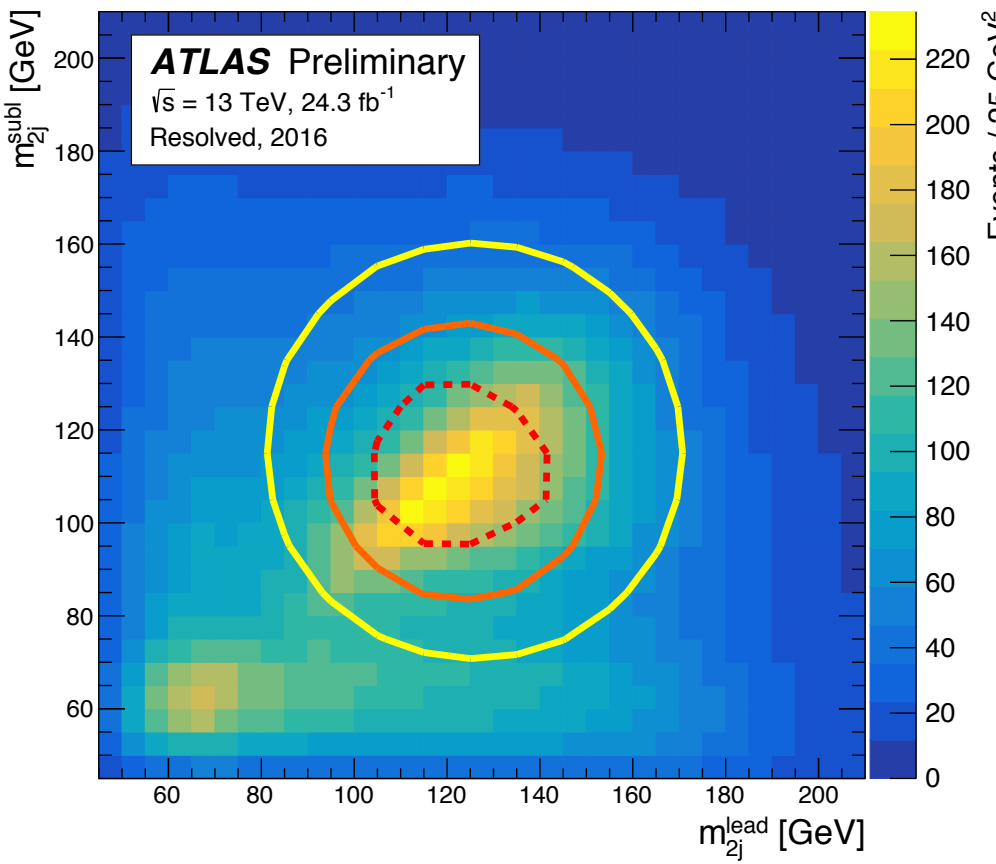
Low-mass search: jets (r = 0.4) / b-jet trigger

High-mass search: jets (r = 1.0) / b-tagging on sub-jet (track-jet)

Backgrounds: ***~90% Multi-jet***
~10% ttbar

2b+2j to model 4 b-jet background

Control regions using m_H sidebands



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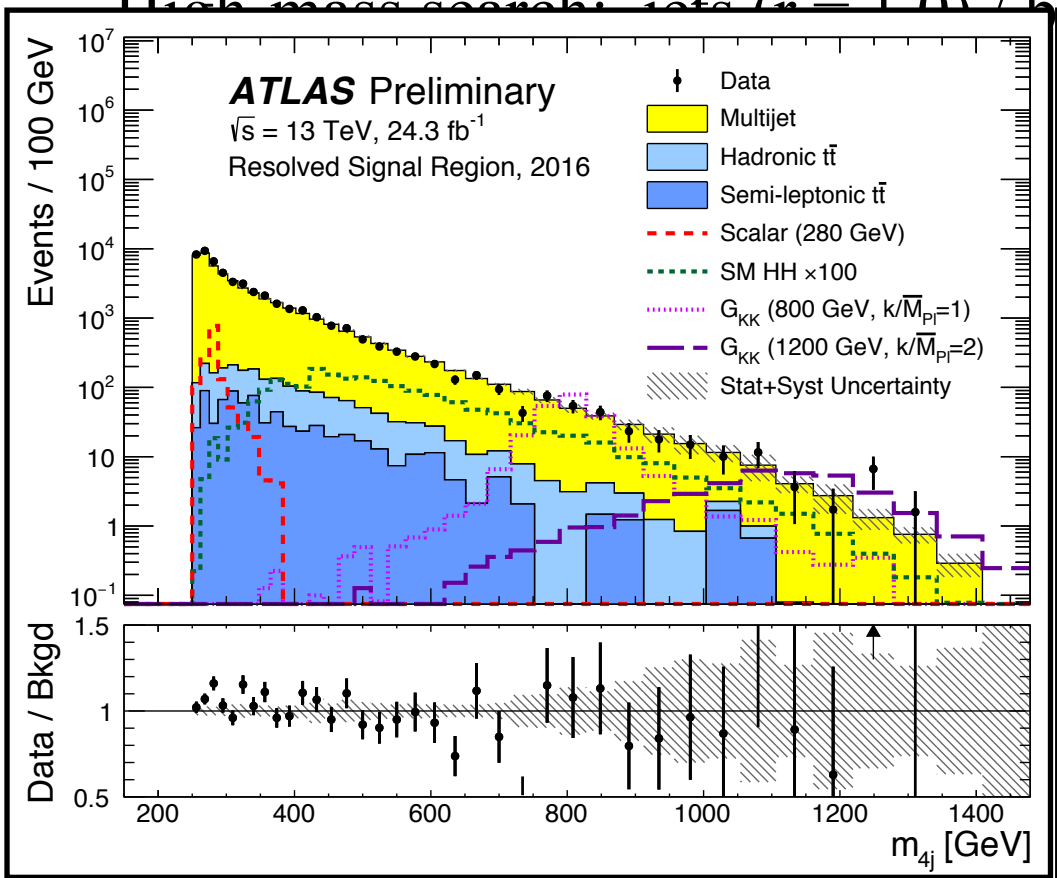

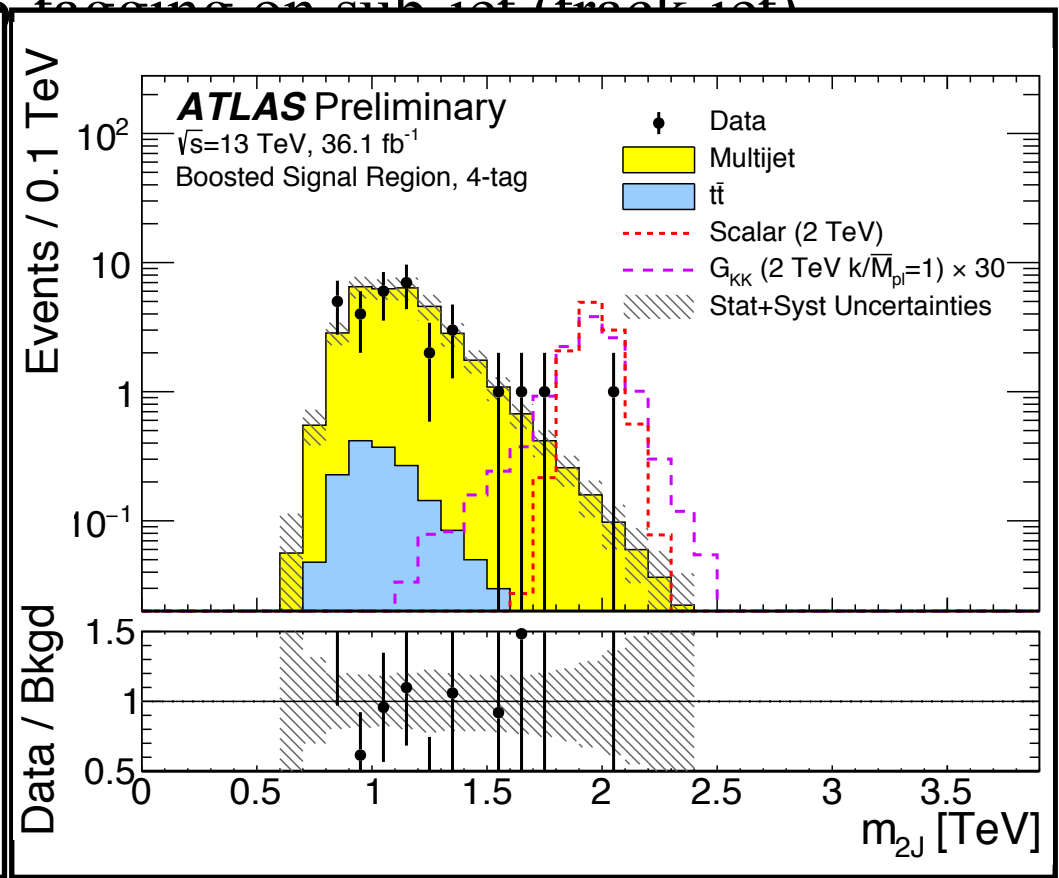

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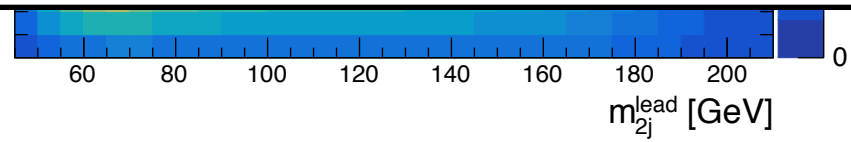

X → HH → 4b

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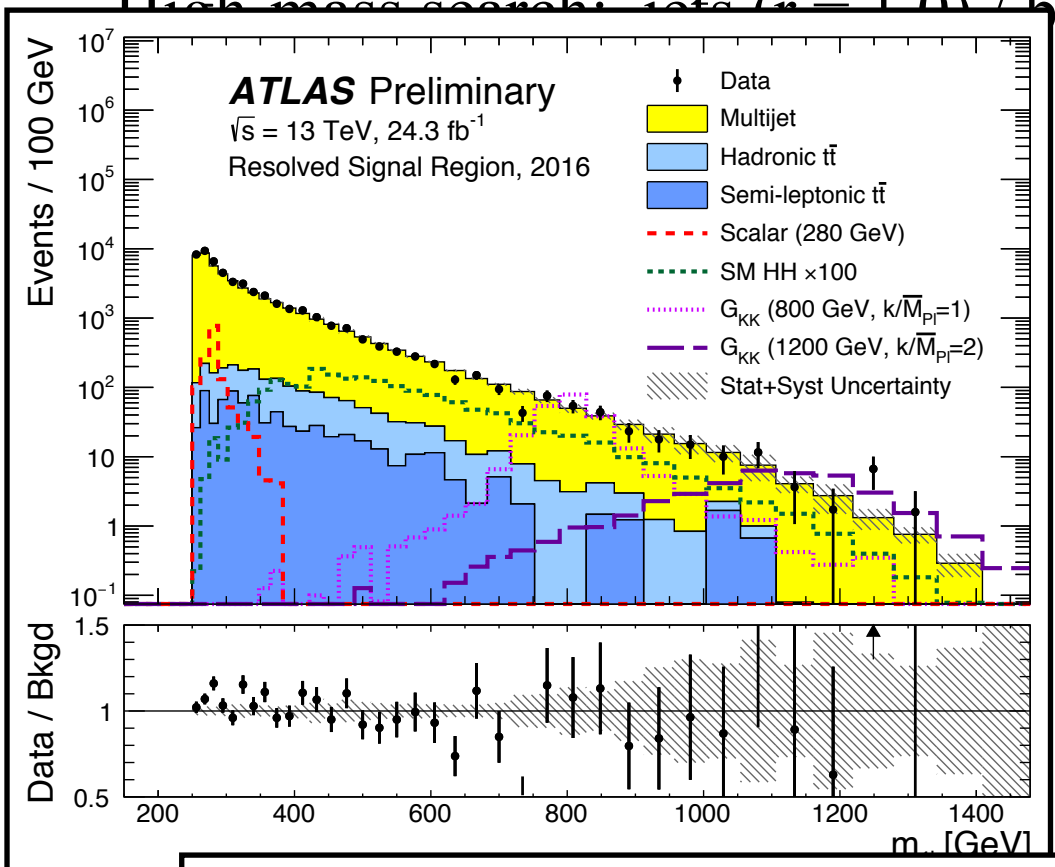
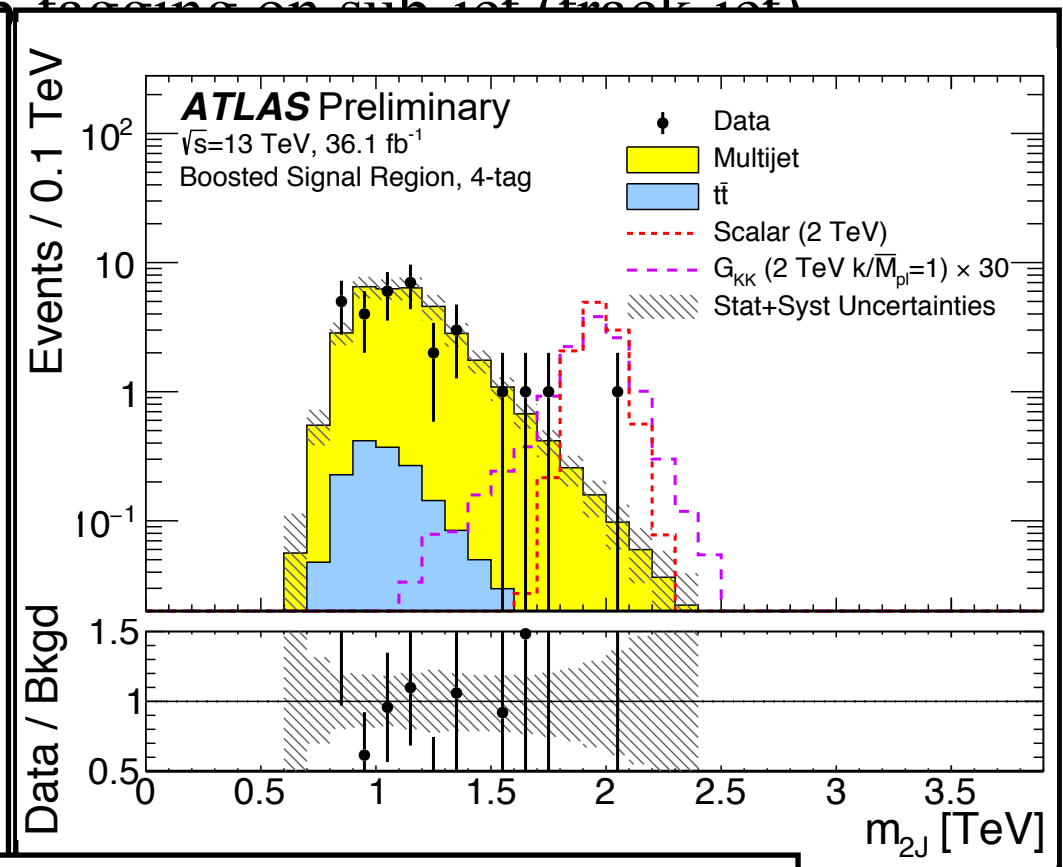




Con

non-resonant hh:

- μ_{hh} < 13.0 (20.7 expected) Strongest constraint on SM hh

X → VH → qqbb

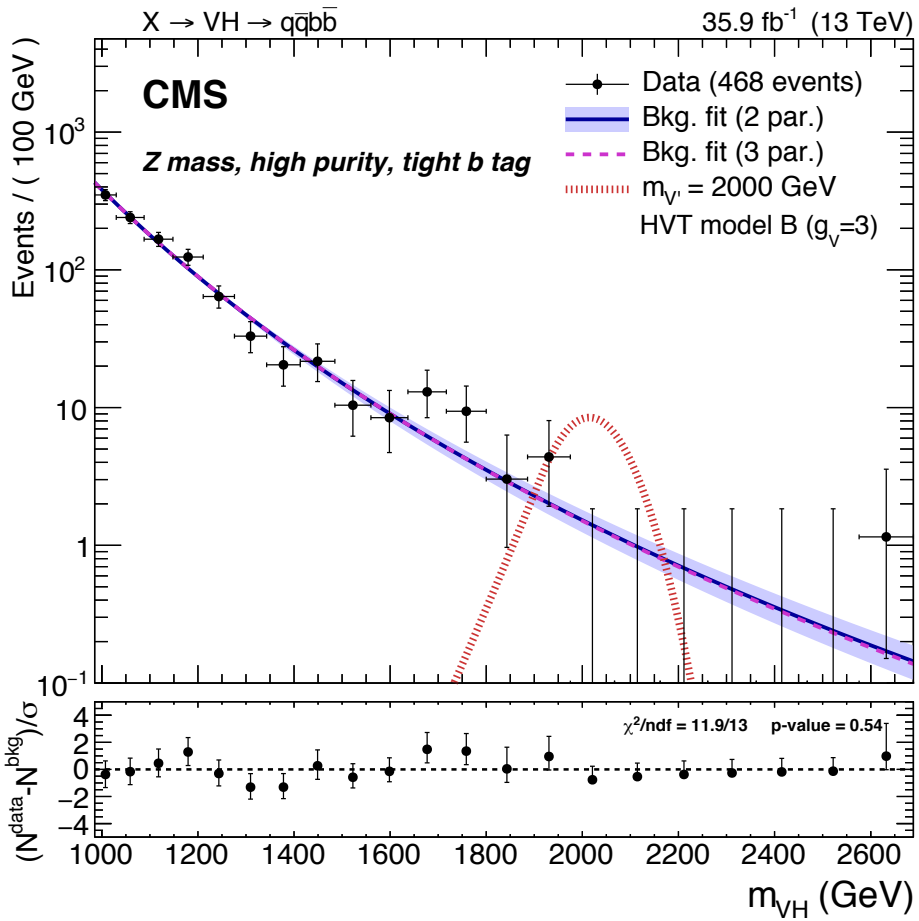
arXiv:1707.06958
arXiv:1707.01303

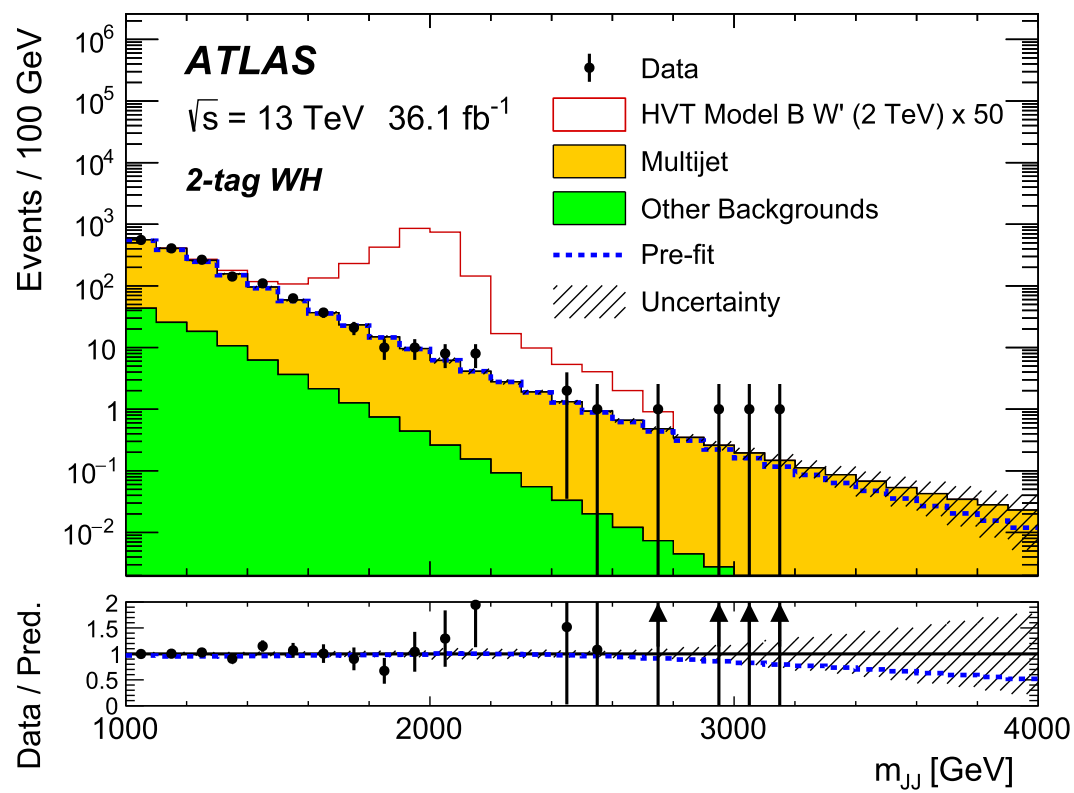
Two large-R jets: m_V one side / m_H with btags other

Background dominated by multi-jets:

CMS: parametric fit (*a la* X→VV)

ATLAS: extrapolate from 0-tags (*a la* X→HH)

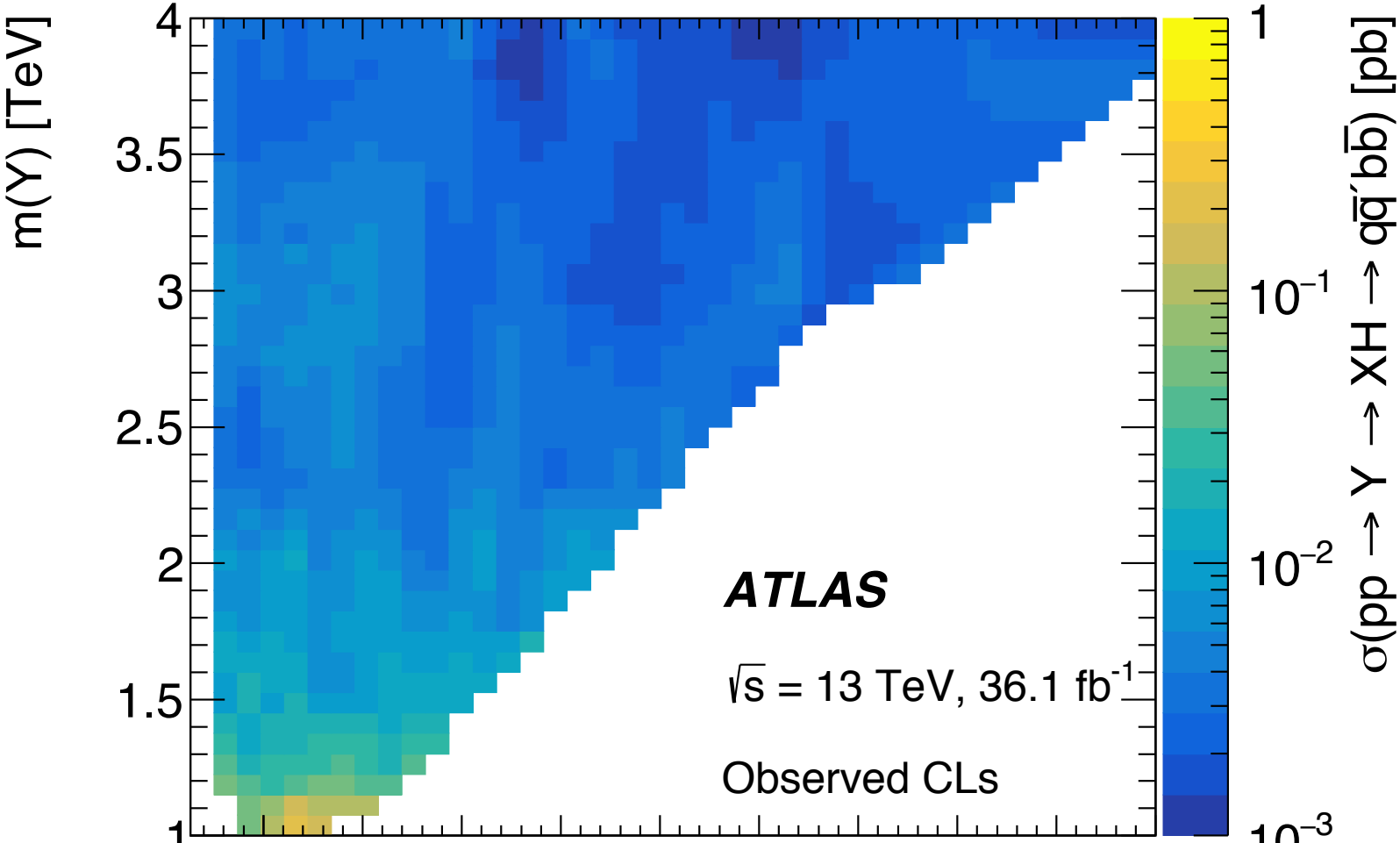




$X \rightarrow VH \rightarrow qqbb$

Two
Back

Harbinger of things to come: $Y \rightarrow XH \rightarrow qqbb$



arXiv:1709.06783

06958
01303

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Di-Lepton Search Program

	e	μ	τ	ν
e	arXiv:1707.02424 PAS-EXO-16-031	arXiv:1607.08079 arXiv:1802.01122	arXiv:1607.08079	arXiv:1706.04786 arXiv:1612.09274
μ		arXiv:1707.02424 PAS-EXO-16-031	arXiv:1607.08079	arXiv:1706.04786 arXiv:1612.09274
τ	ATLAS CMS		arXiv:1709.07242 PAS-HIG-17-020	arXiv:1801.06992 PAS-EXO-16-006
ν				arXiv:1711.03301 arXiv:1712.02345

Di-Lepton Search Program

	e	μ	τ	ν
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τ			arXiv:1709.07242 PAS-HIG-17-020	arXiv:1801.06992 PAS-EXO-16-006
ν				arXiv:1711.03301 arXiv:1712.02345

ATLAS
CMS

Covered in this Talk

$X \rightarrow e\mu$

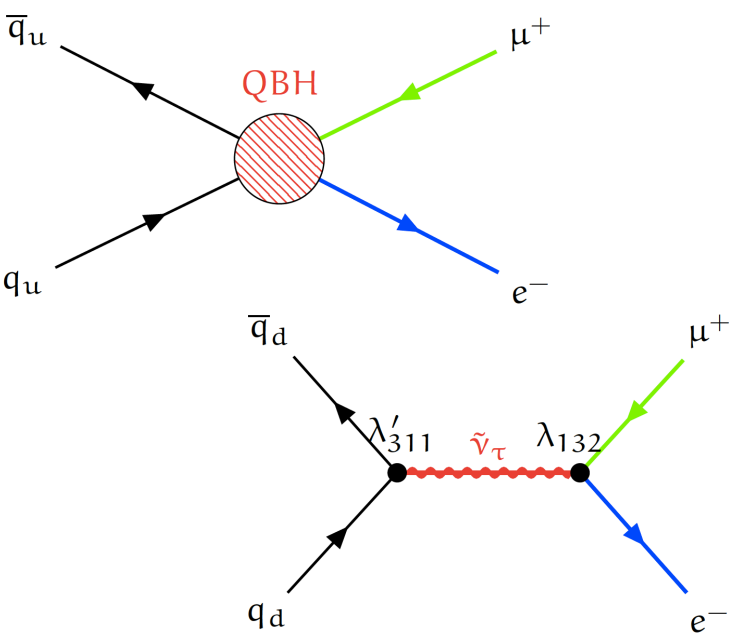
arXiv:1802.01122

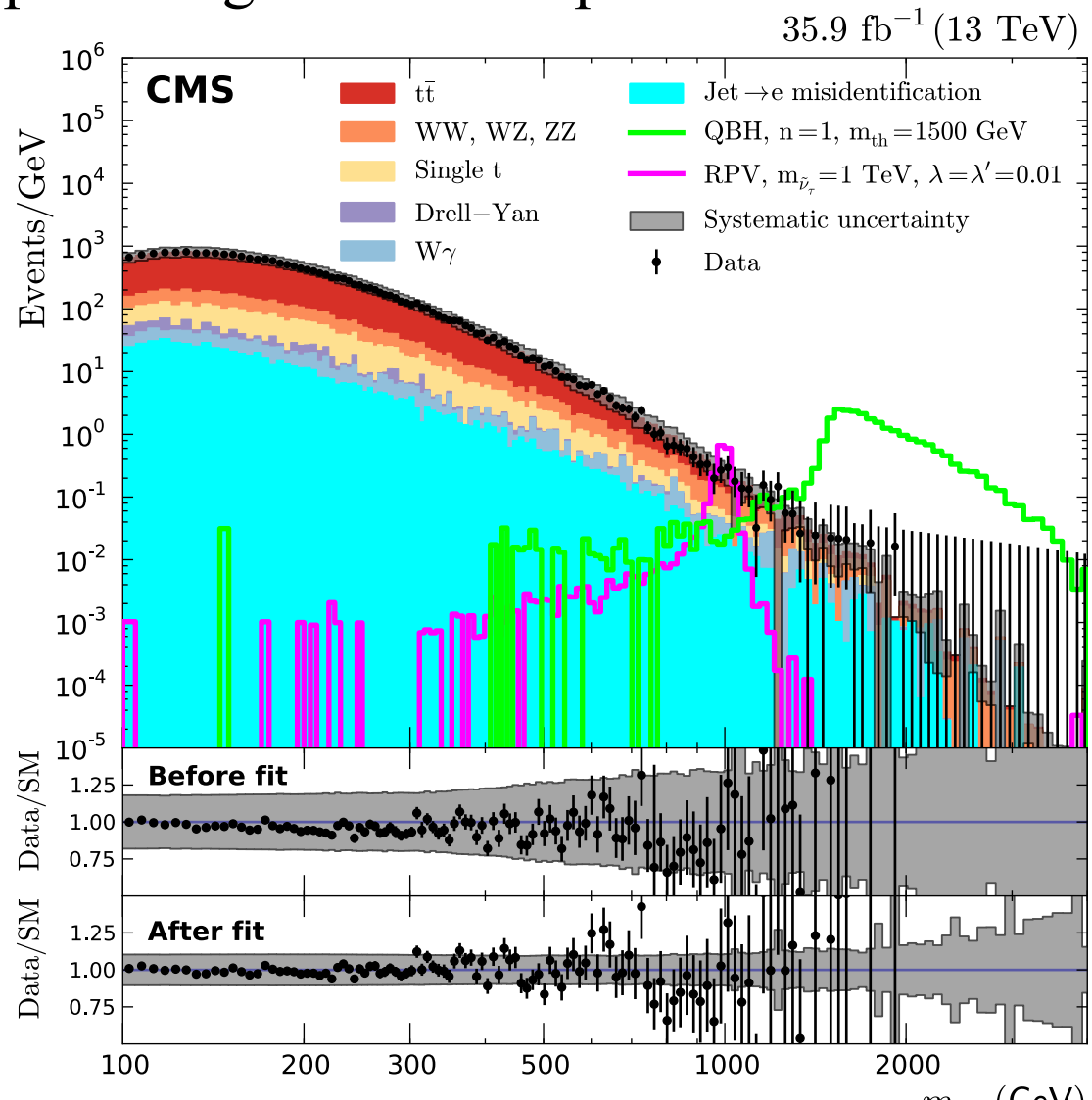
Targets models with lepton flavor violation
Different flavor requirement suppress large Drell-Yan production

Inclusive Selection:

e/μ: $P_T > 53$ GeV

Sensitive to variety of models





$X \rightarrow \tau\tau$

arXiv:1709.07242

Critical channel search heavy Higgs 2HDM (MSSM)

ATLAS 36.1 fb^{-1} (CMS 35.9 fb^{-1})

Separate event selection targeting different:

Production modes: gluon-fusion / associated b-jet production

τ-decay modes: $\tau_{lep}\tau_{had}$ / $\tau_{had}\tau_{had}$ (had-had stronger sensitivity)

(P_T: 30+25 165+45 GeV)

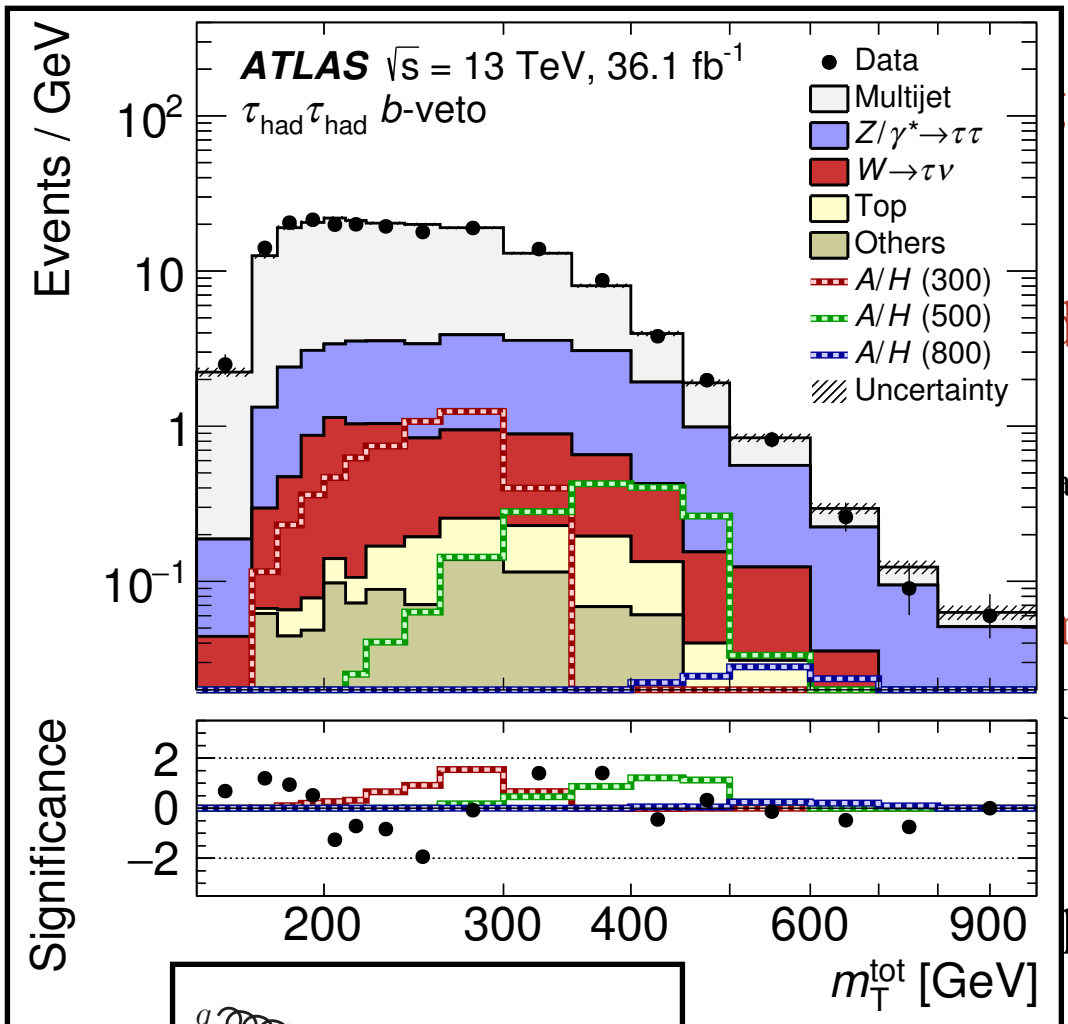
Most important background from multijets w/fake τs

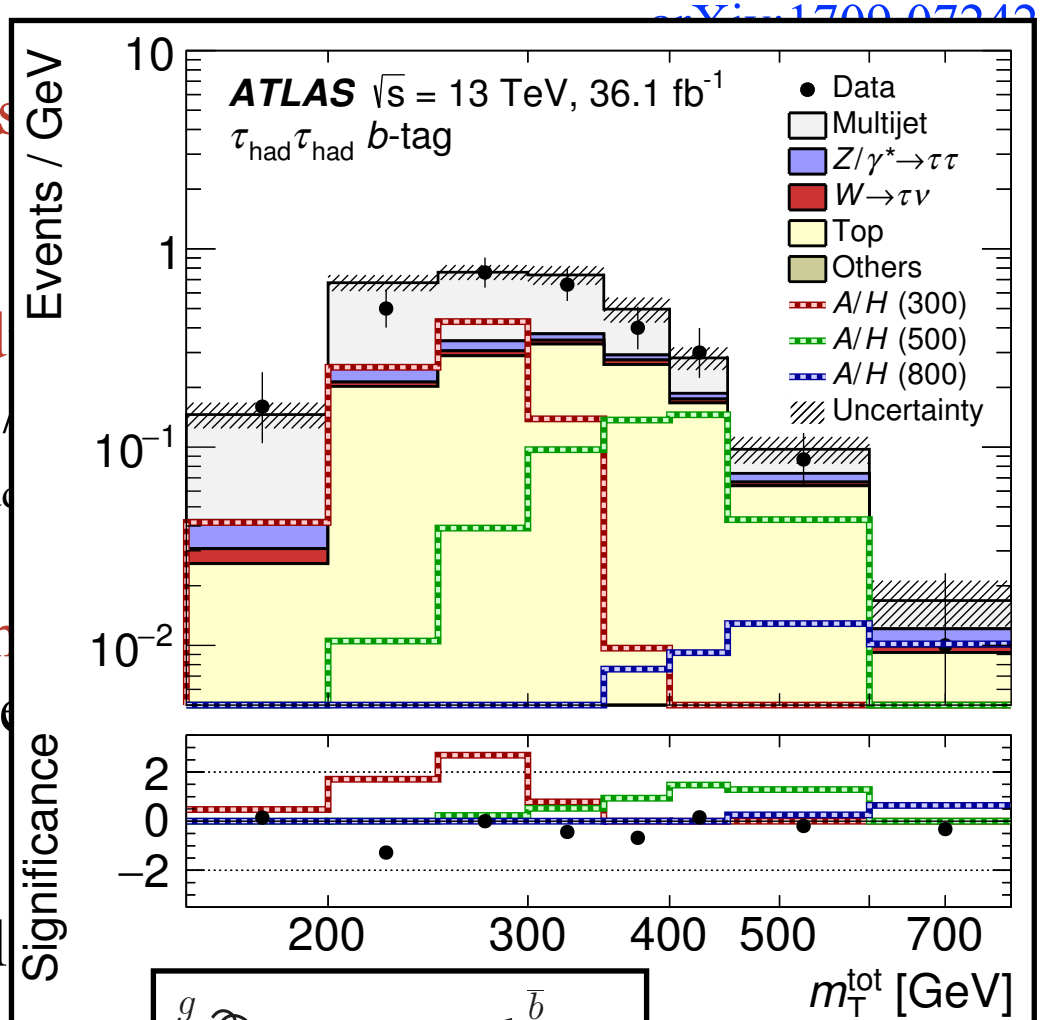
- Data-driven modeling using fake-factors
- Systematic uncertainty varies between 10% — 50 %

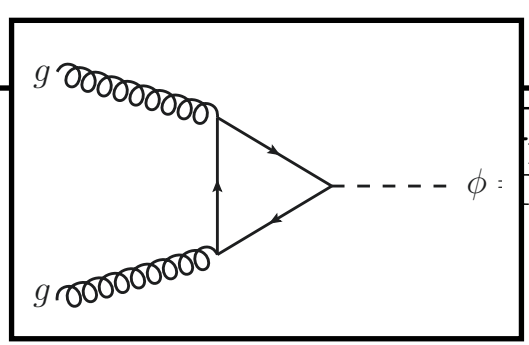
Total transverse mass used for final discriminant:

$$m_{\mathrm{T}}^{\mathrm{tot}} \equiv \sqrt{(p_{\mathrm{T}}^{\tau_1} + p_{\mathrm{T}}^{\tau_2} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{p}_{\mathrm{T}}^{\tau_1} + \mathbf{p}_{\mathrm{T}}^{\tau_2} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

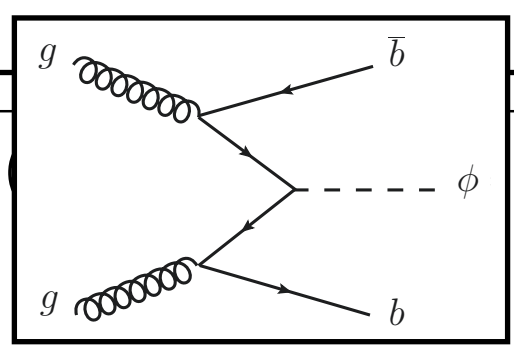
$X \to \tau\tau$



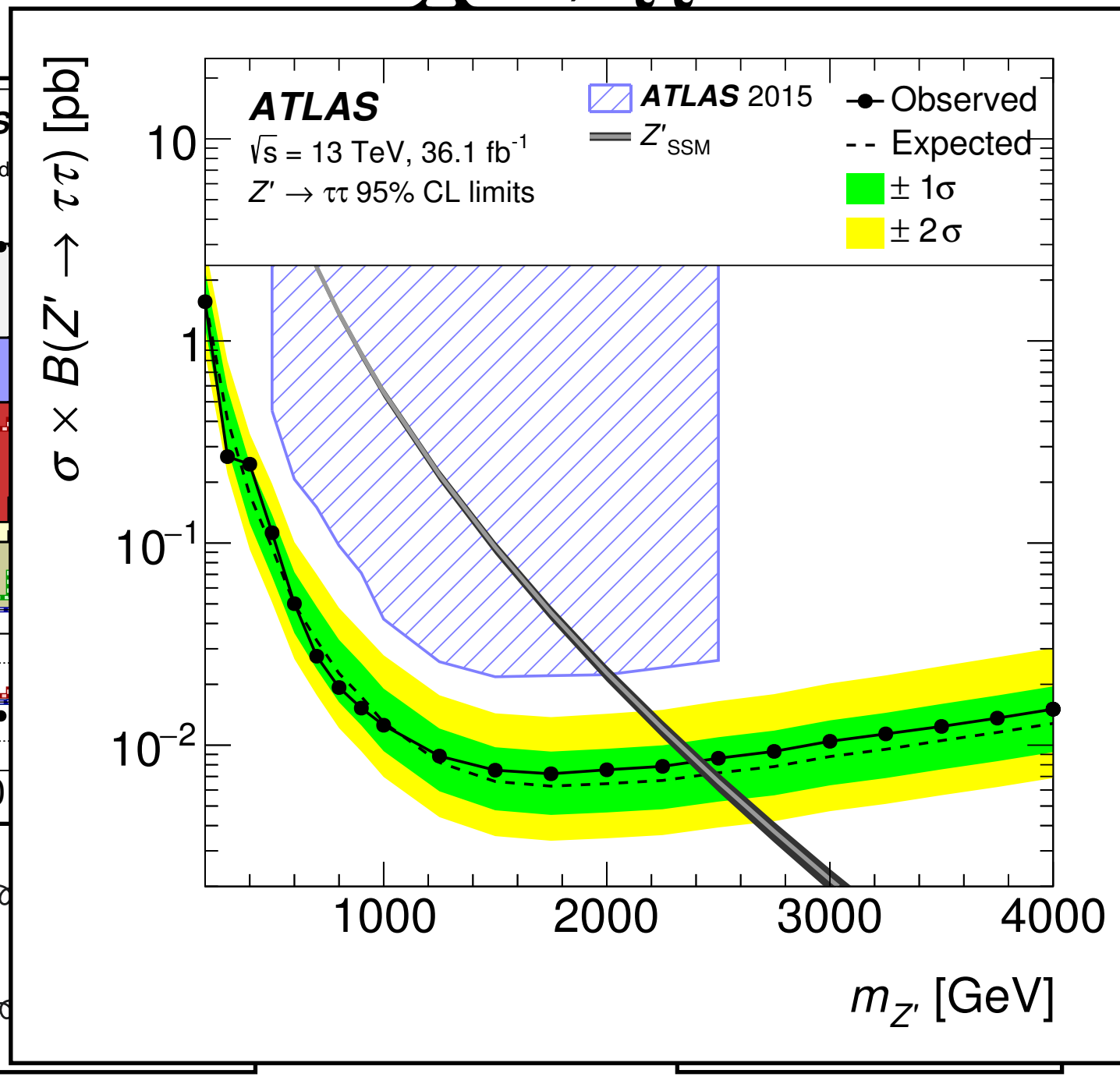


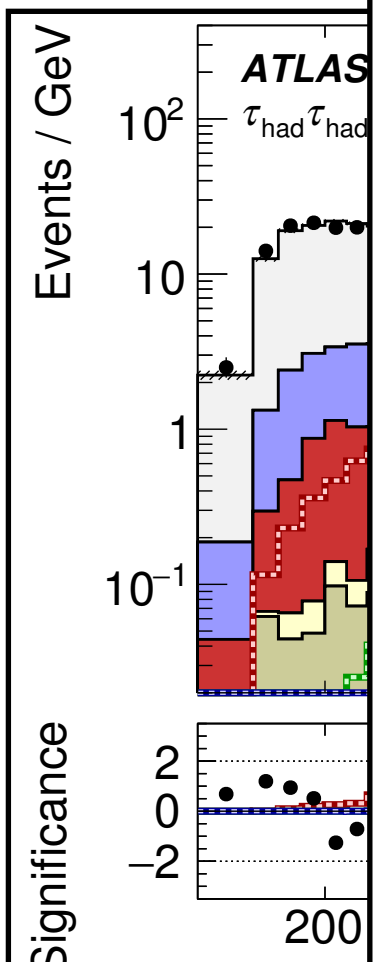


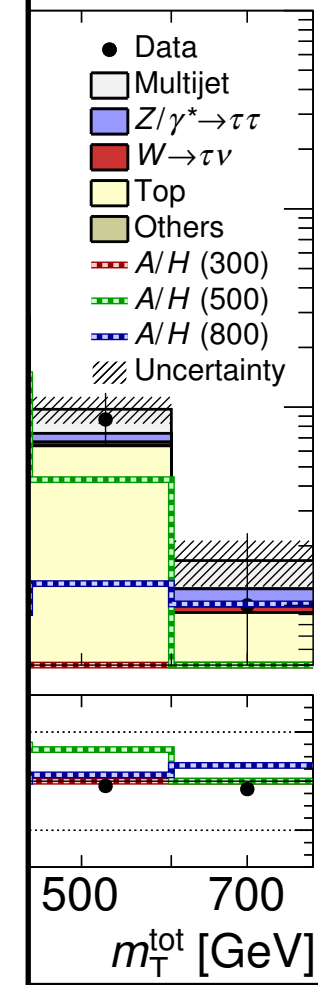
$$(p_{\mathrm{T}}^{\tau_1} + p_{\mathrm{T}}^{\tau_2} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - \quad 2$$

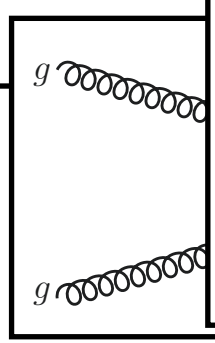


$X \rightarrow \tau\tau$









$X \rightarrow \tau_{had}\nu$

arXiv:1801.06992

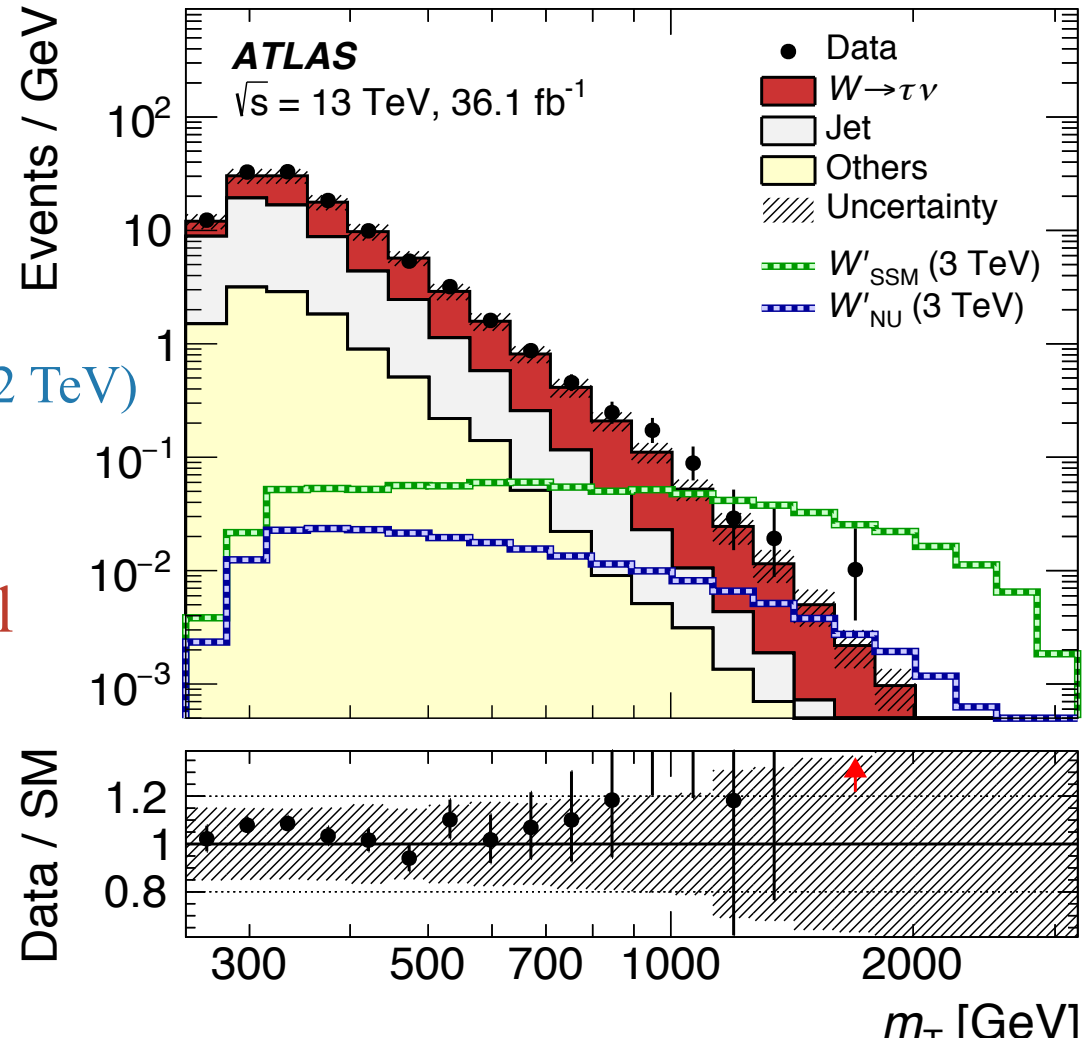
Mono-τ_{had} signature / Interpreted in W' scenario
Particularly important in models with enhanced 3rd generation couplings

Event Selection:

- MeT Trigger
- MeT > 150 GeV
- P_T tau > 50 GeV
- τ-ID: ε ~ 60% @ 100GeV (~30% @ 2 TeV)

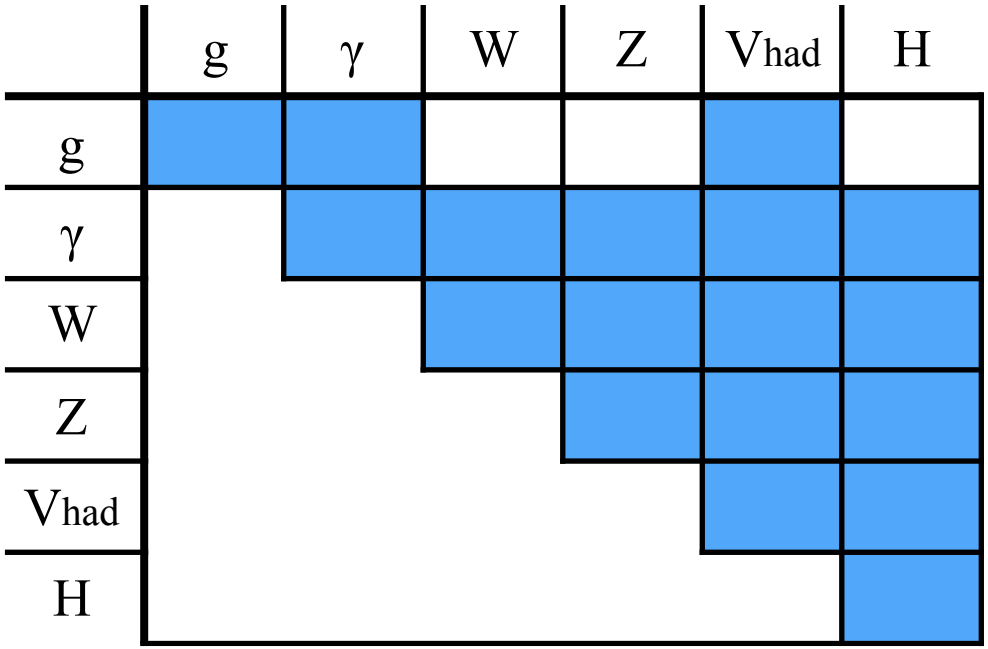
Counting experiment in m_T in tail

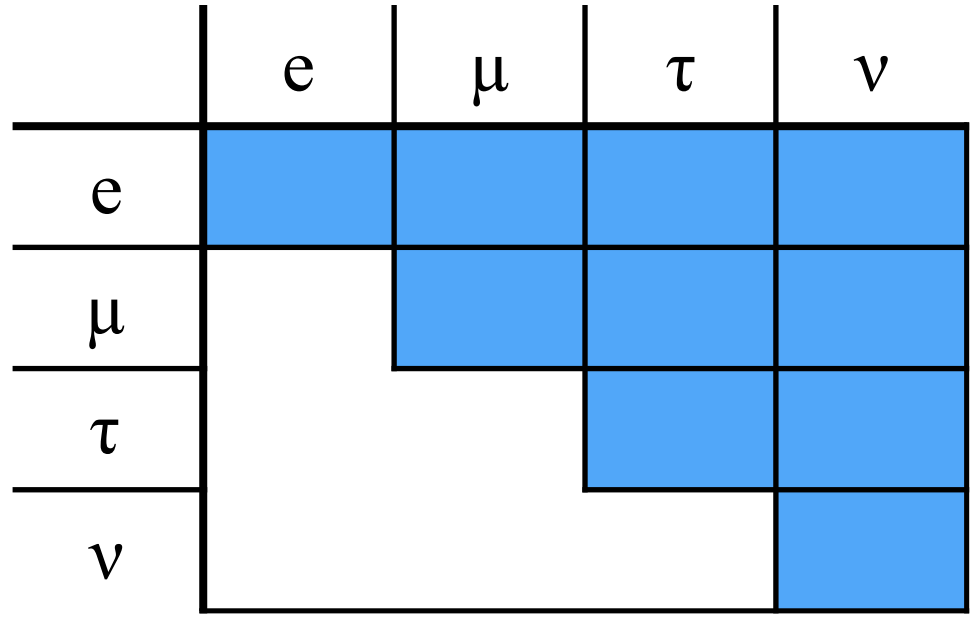
Bkg Uncertainties: 10 – 30%



Conclusions

Rich program of resonance searches at LHC. *Lot I could not cover !*





Broad coverage targeting ~all relevant final states:

- Trend of targeting different production modes will continue
- Look for more relaxing of mass cuts: *1D searches → 2D scans*

Expect updates with full run-2 data (~150/fb) set next spring/summer.

Backup

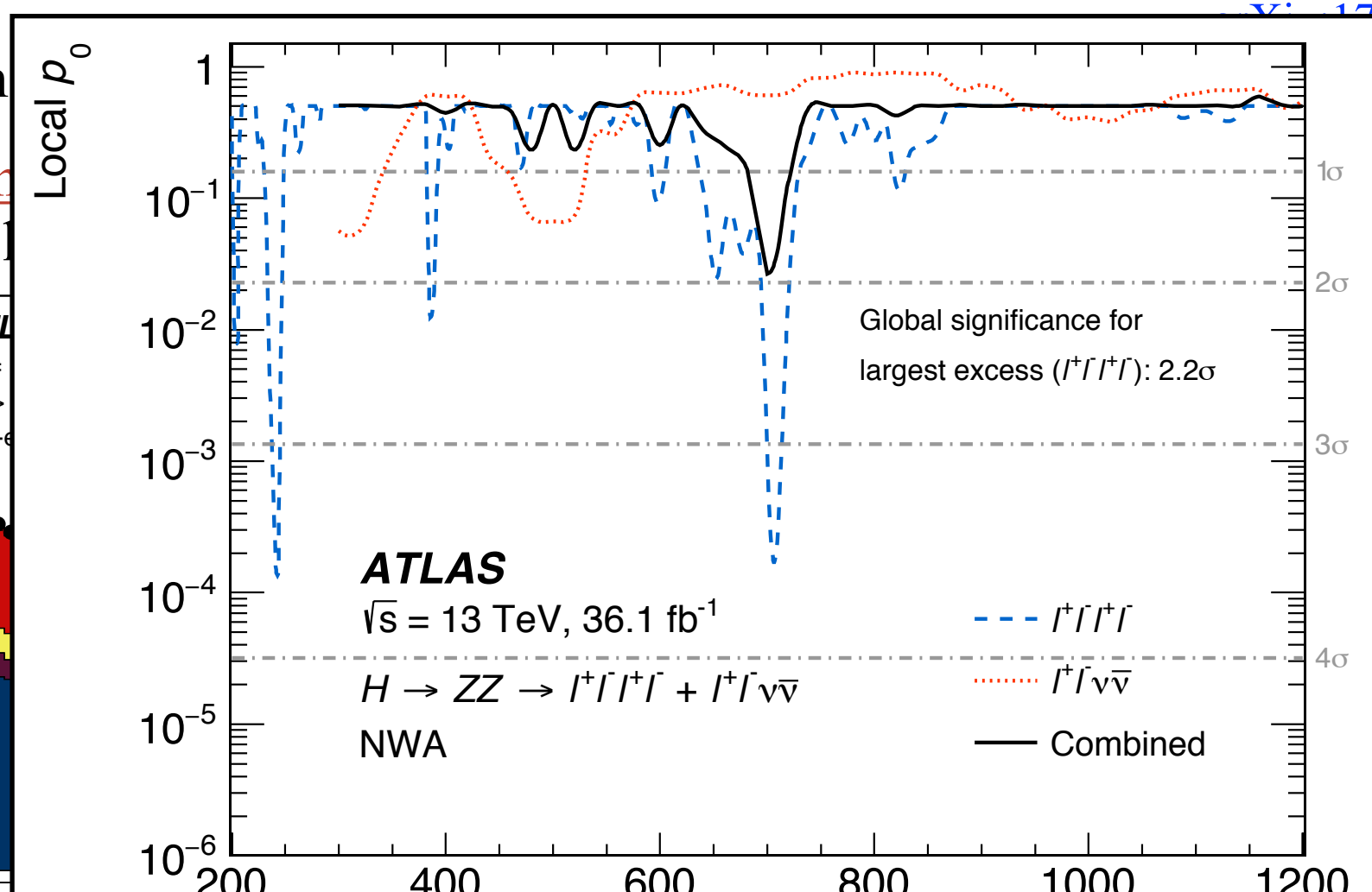
$X \to ZZ \to 4l$

Clean fin

gluor

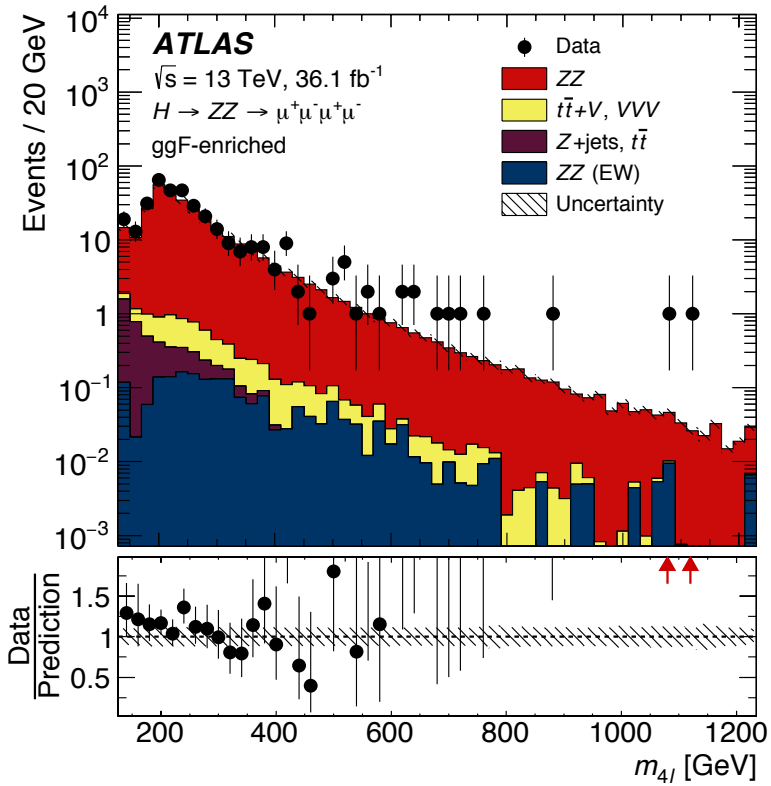
incl

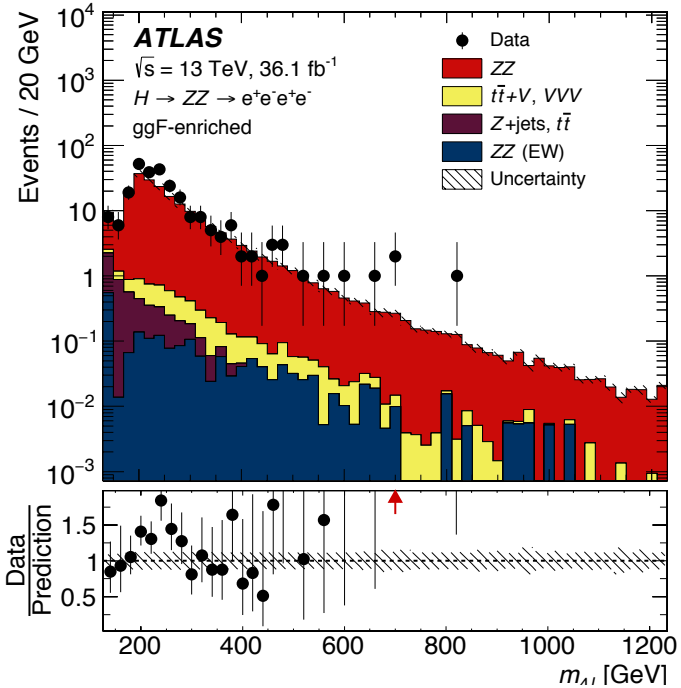
1712.06386

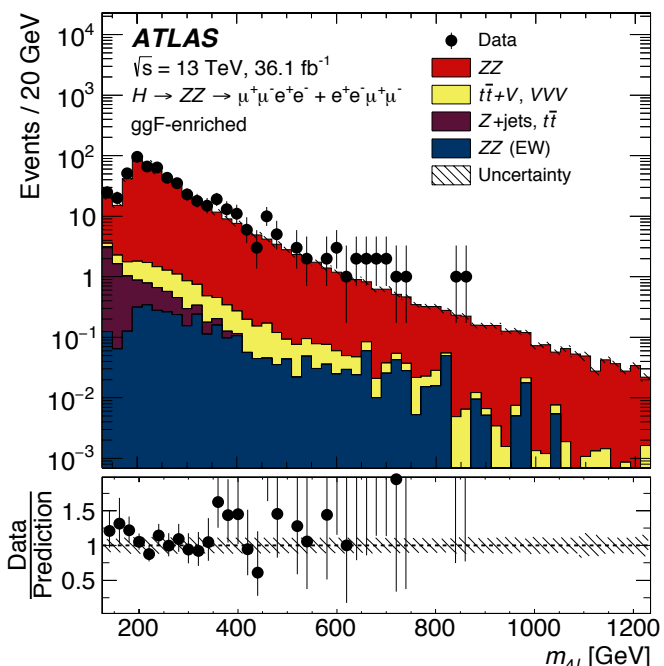


No excess seen in CMS CMS-PAS-HIG-17-012

X → ZZ → 4l


ATLAS
√s = 13 TeV, 36.1 fb-1
H → ZZ → μ+μ-μ+μ-
ggF-enriched
Data
ZZ
tt̄+V, VVV
Z+jets, tt̄
ZZ (EW)
Uncertainty
Events / 20 GeV
Data / Prediction
m4l [GeV]


ATLAS
√s = 13 TeV, 36.1 fb-1
H → ZZ → e+e-e+e-
ggF-enriched
Data
ZZ
tt̄+V, VVV
Z+jets, tt̄
ZZ (EW)
Uncertainty
Events / 20 GeV
Data / Prediction
m4l [GeV]


ATLAS
√s = 13 TeV, 36.1 fb-1
H → ZZ → μ+μ-e+e- + e+e-μ+μ-
ggF-enriched
Data
ZZ
tt̄+V, VVV
Z+jets, tt̄
ZZ (EW)
Uncertainty
Events / 20 GeV
Data / Prediction
m4l [GeV]

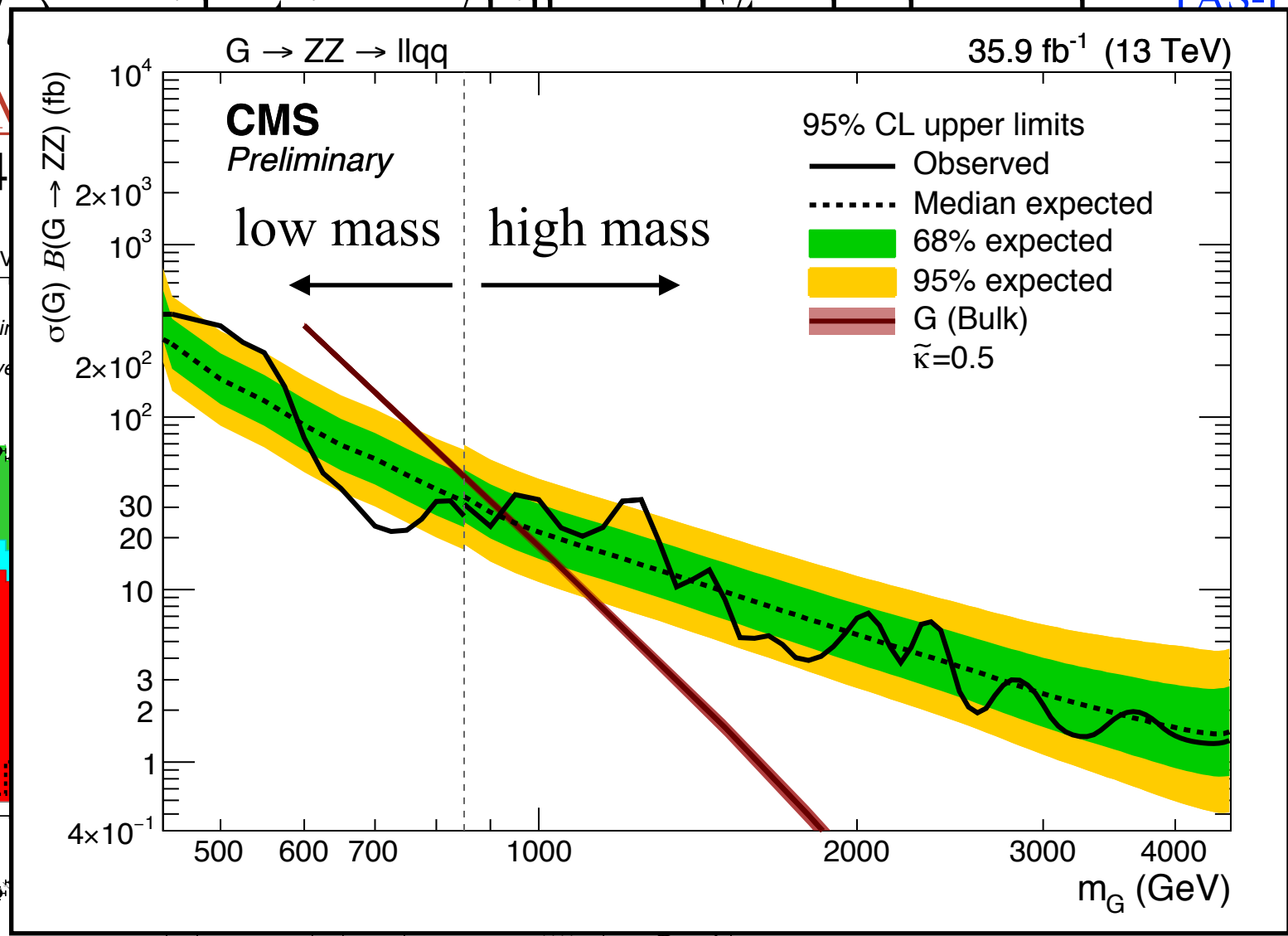
X → ZV → llqq

PAS-HIG-17-012

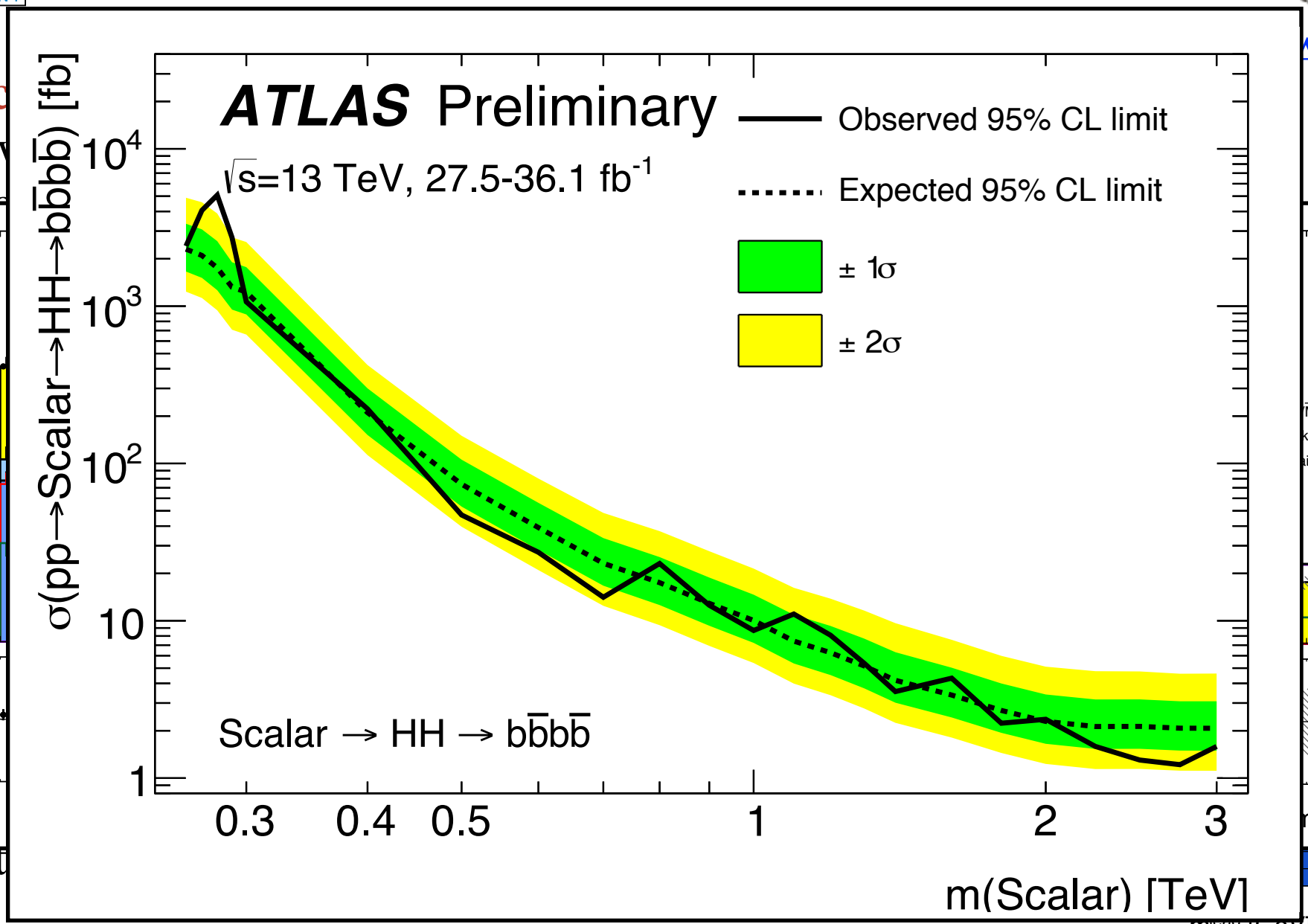
Z→ll (e/

Low M

ak4



$X \rightarrow HH \rightarrow 4b$



$X \rightarrow \tau_{had}\nu$

arXiv:1801.06992

Mono-τ_{had} S

Particularly

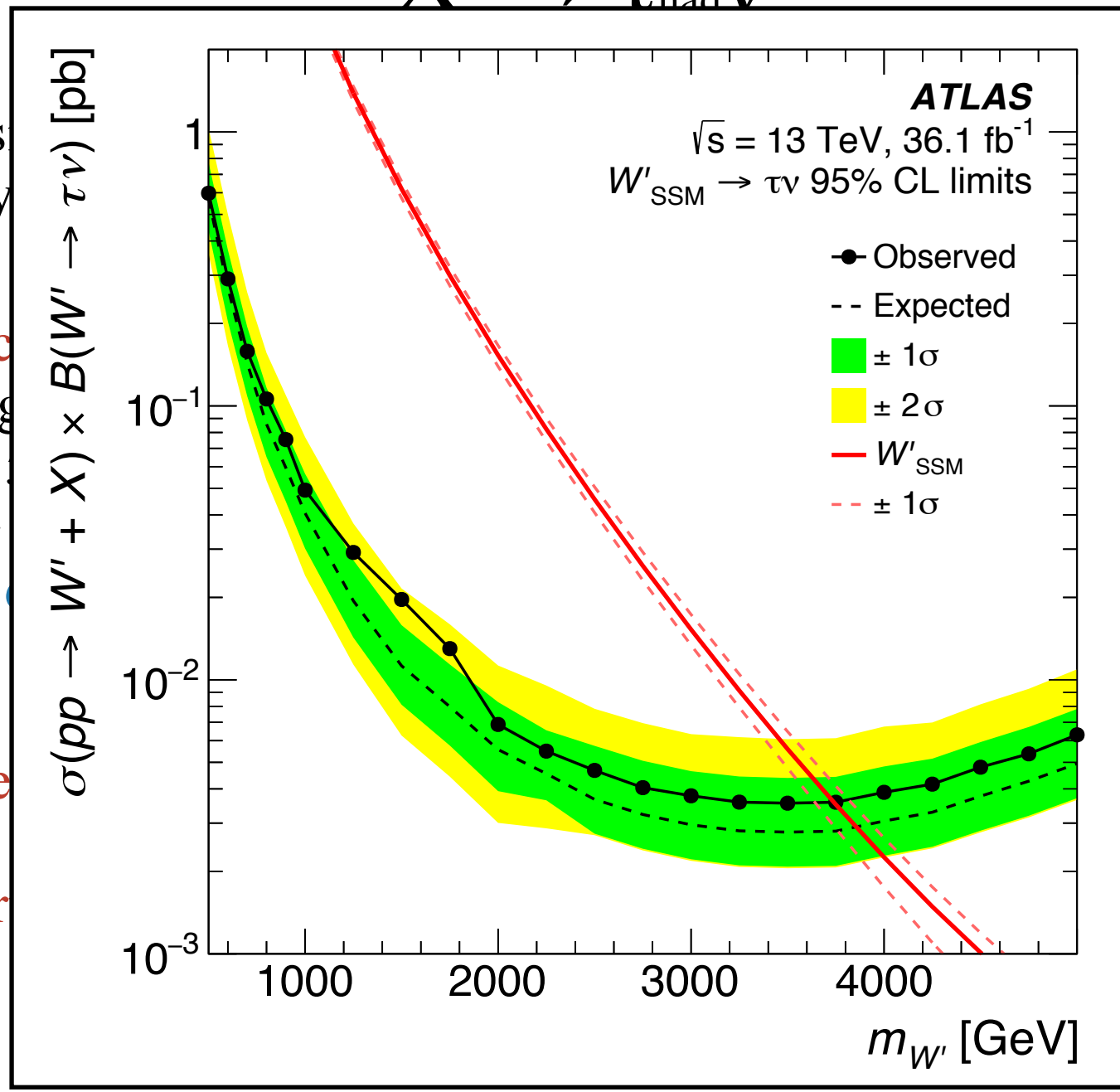
n couplings

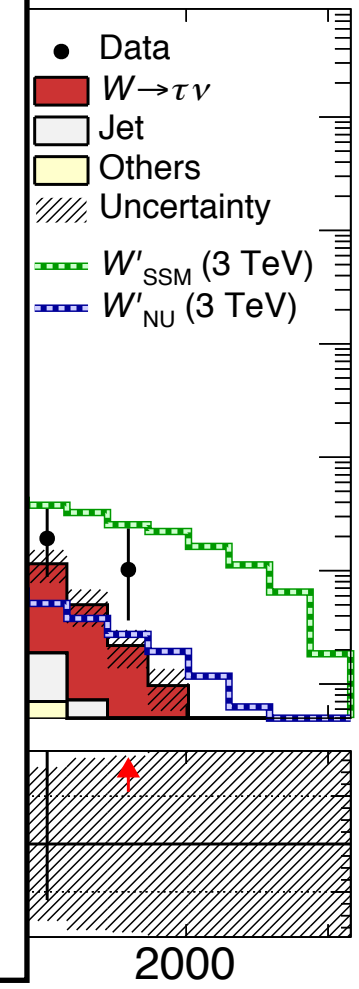
Event Selec

- MeT Trig
- MeT > 1
- PT tau >
- τ-ID: ε ~

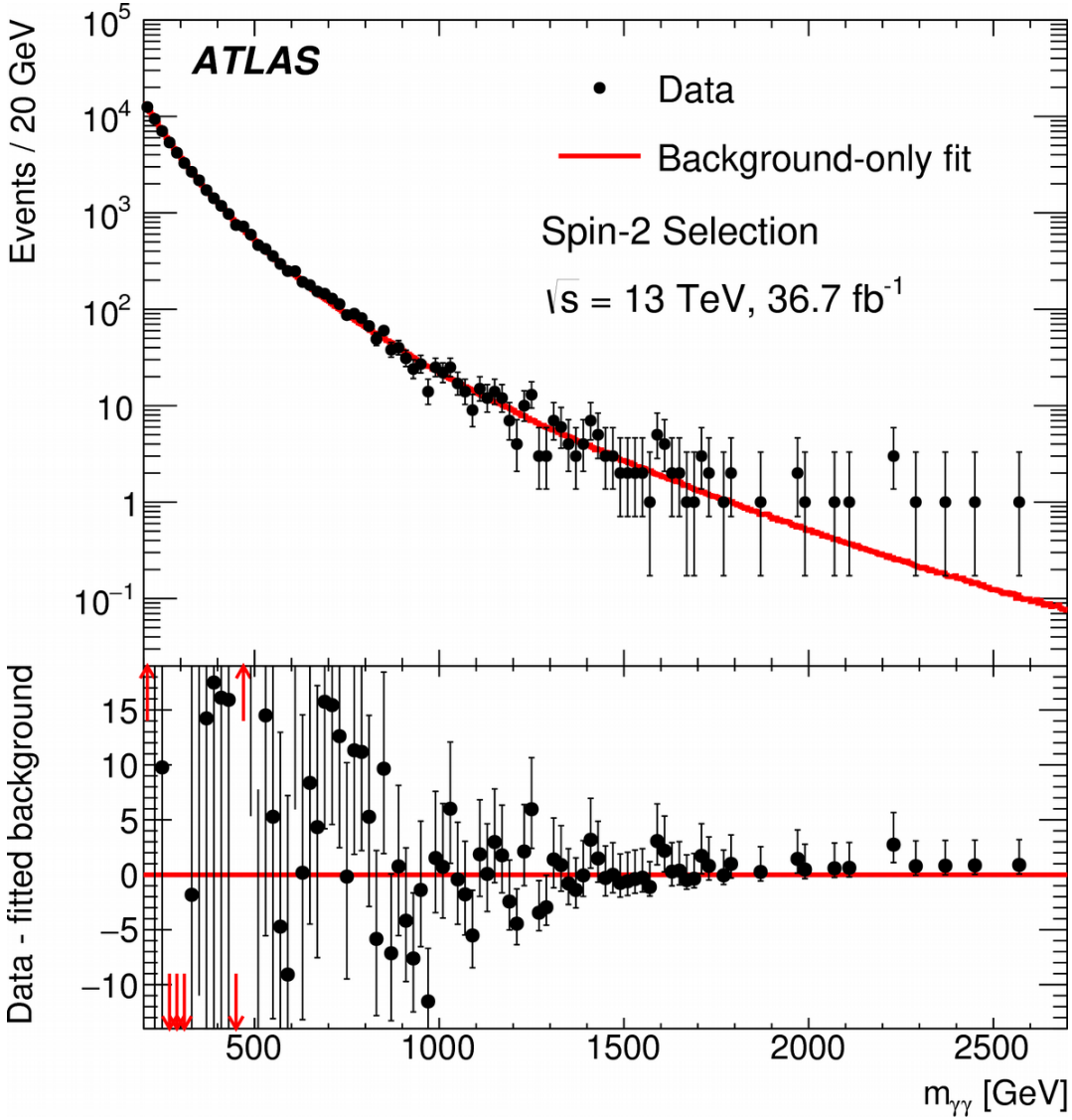
Counting e

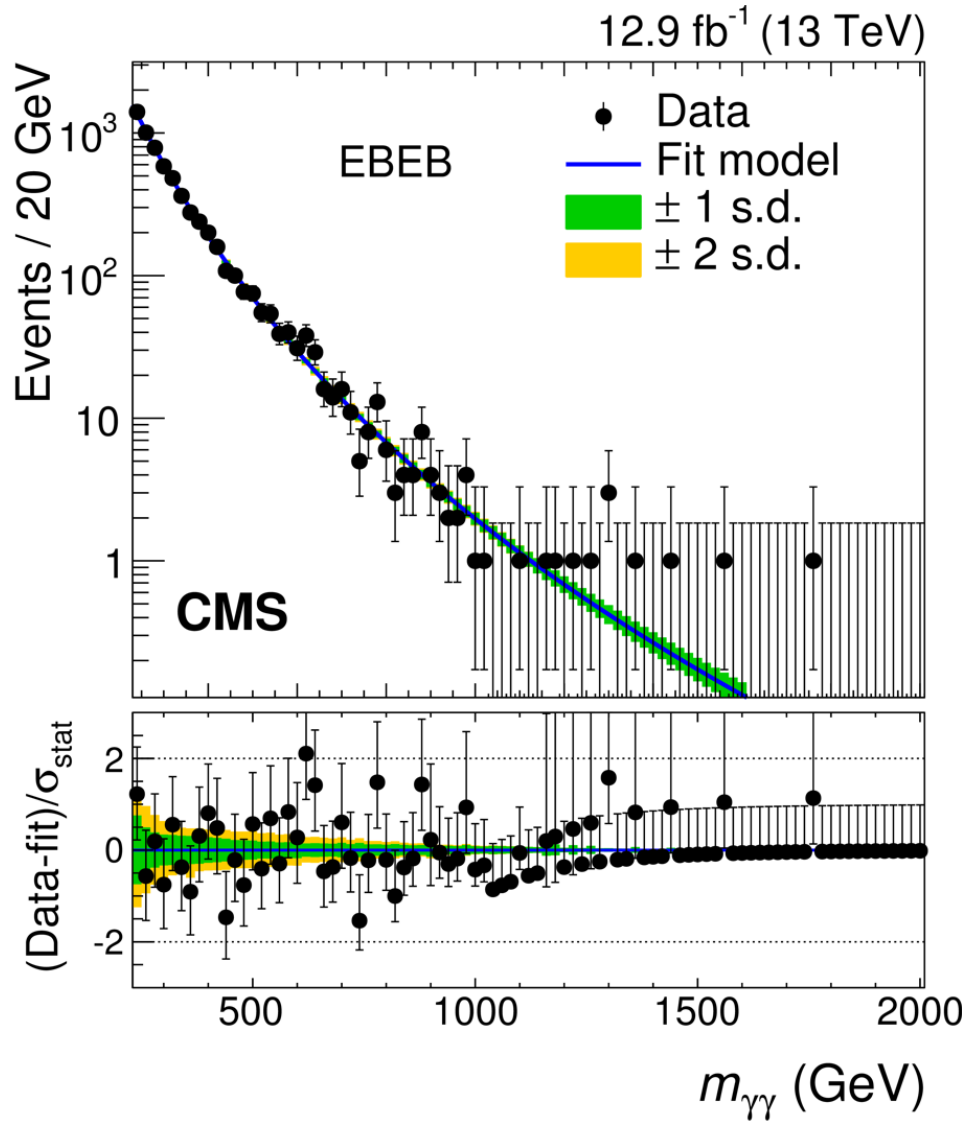
Bkg Uncer

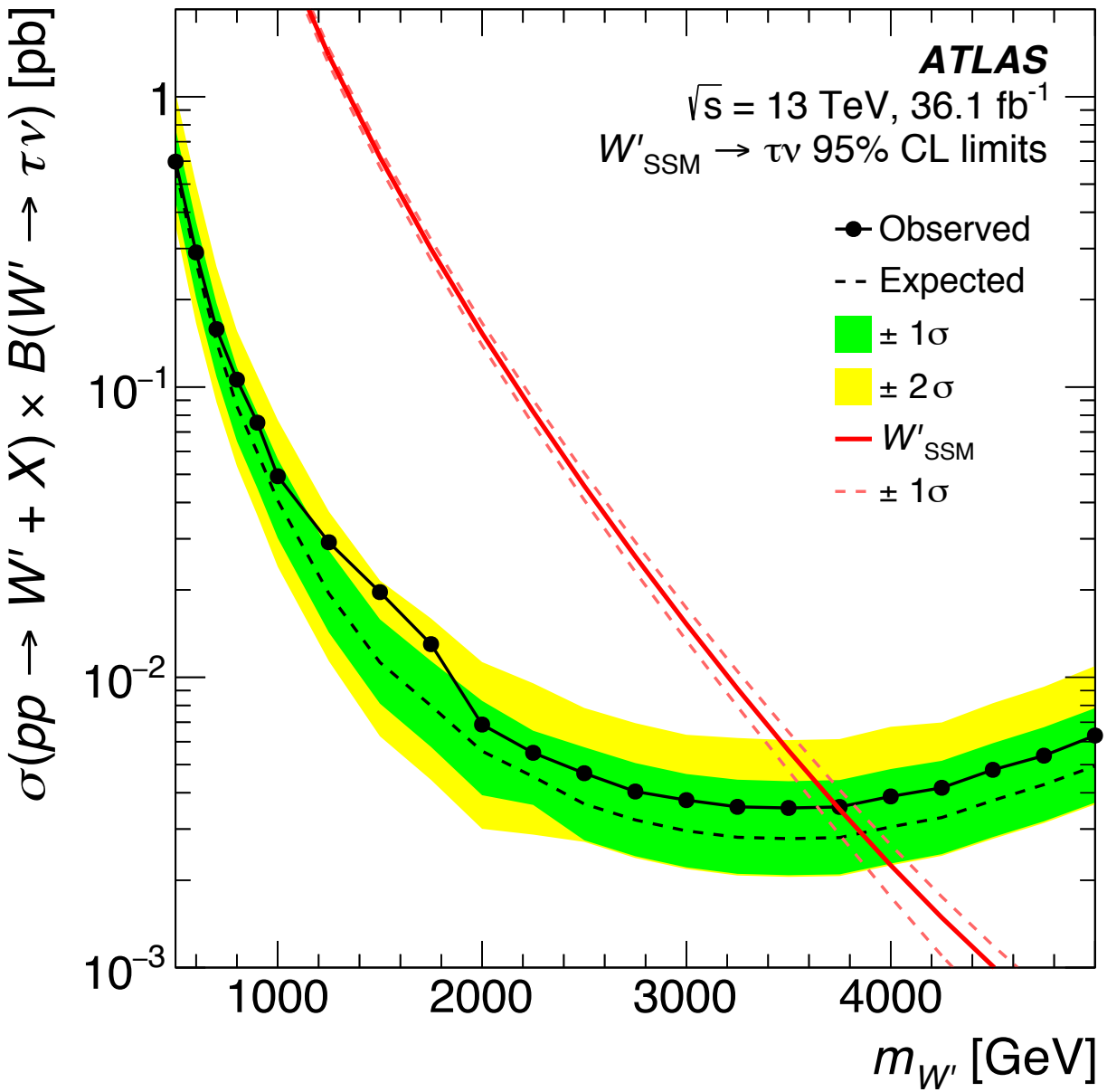


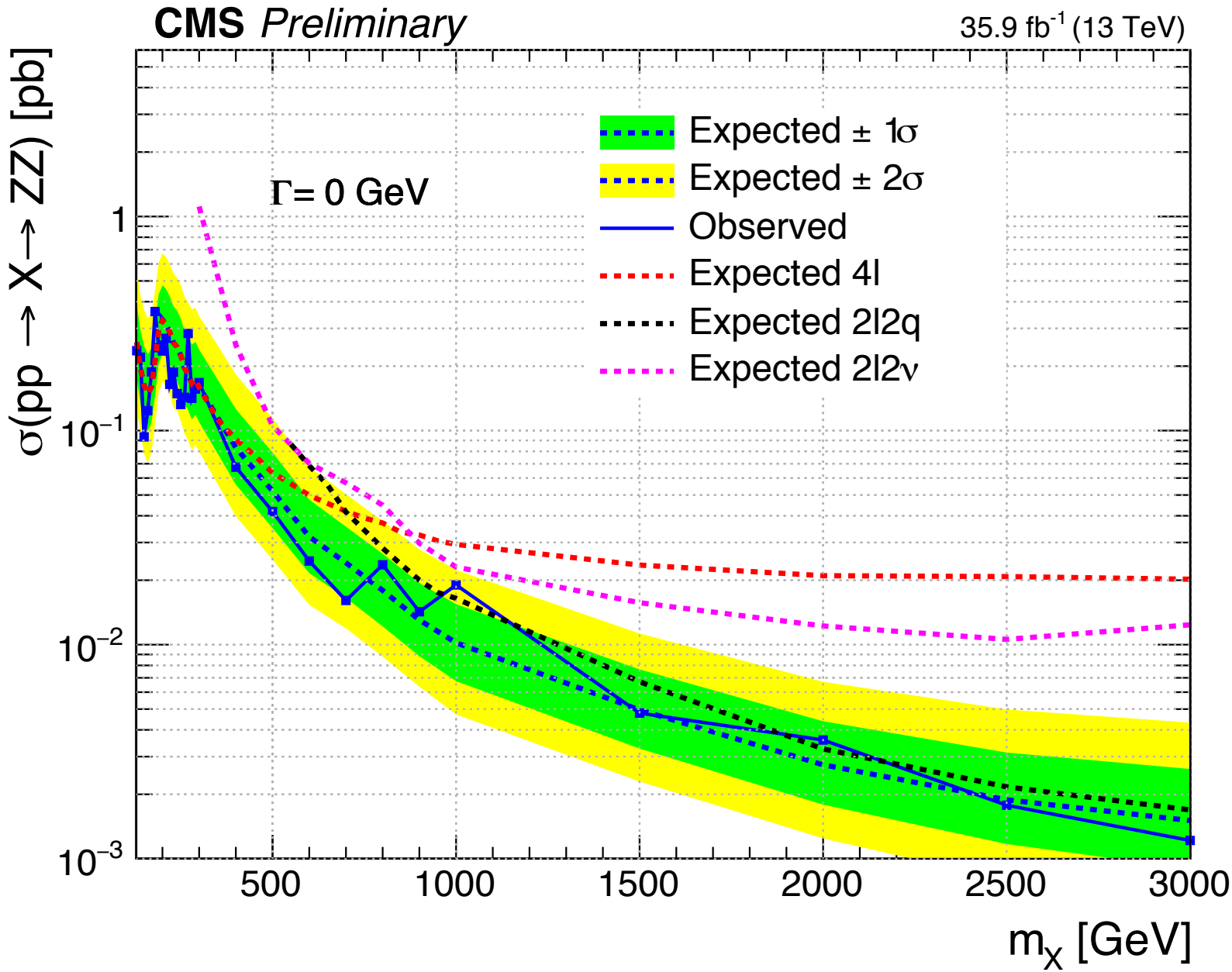


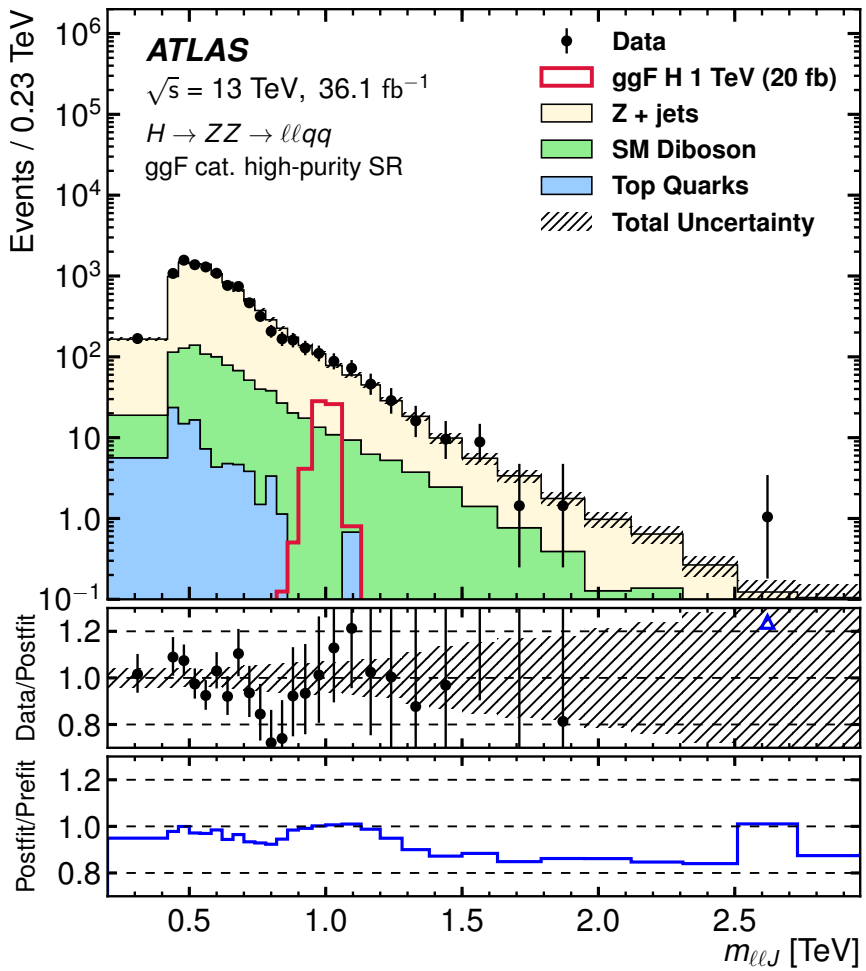
Di-Photons

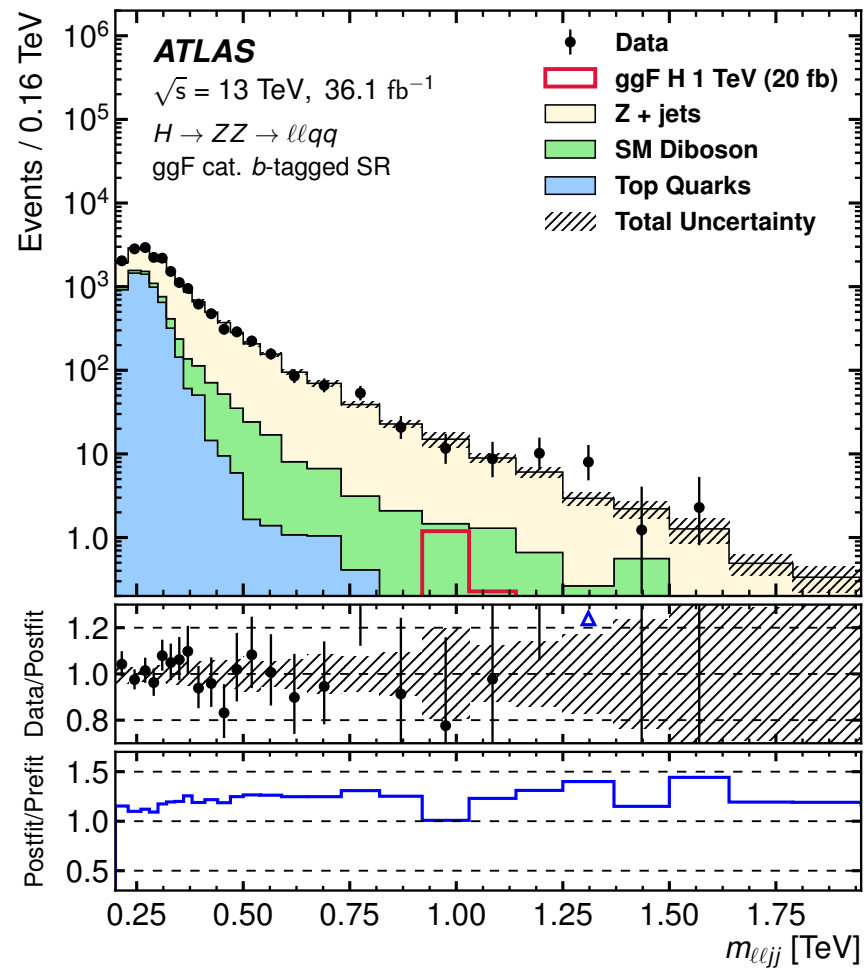

ATLAS
Data
Background-only fit
Spin-2 Selection
√s = 13 TeV, 36.7 fb-1
Events / 20 GeV
Data - fitted background
mγγ [GeV]


12.9 fb-1 (13 TeV)
CMS
EBEB
Data
Fit model
± 1 s.d.
± 2 s.d.
Events / 20 GeV
(Data-fit)/σstat
mγγ (GeV)

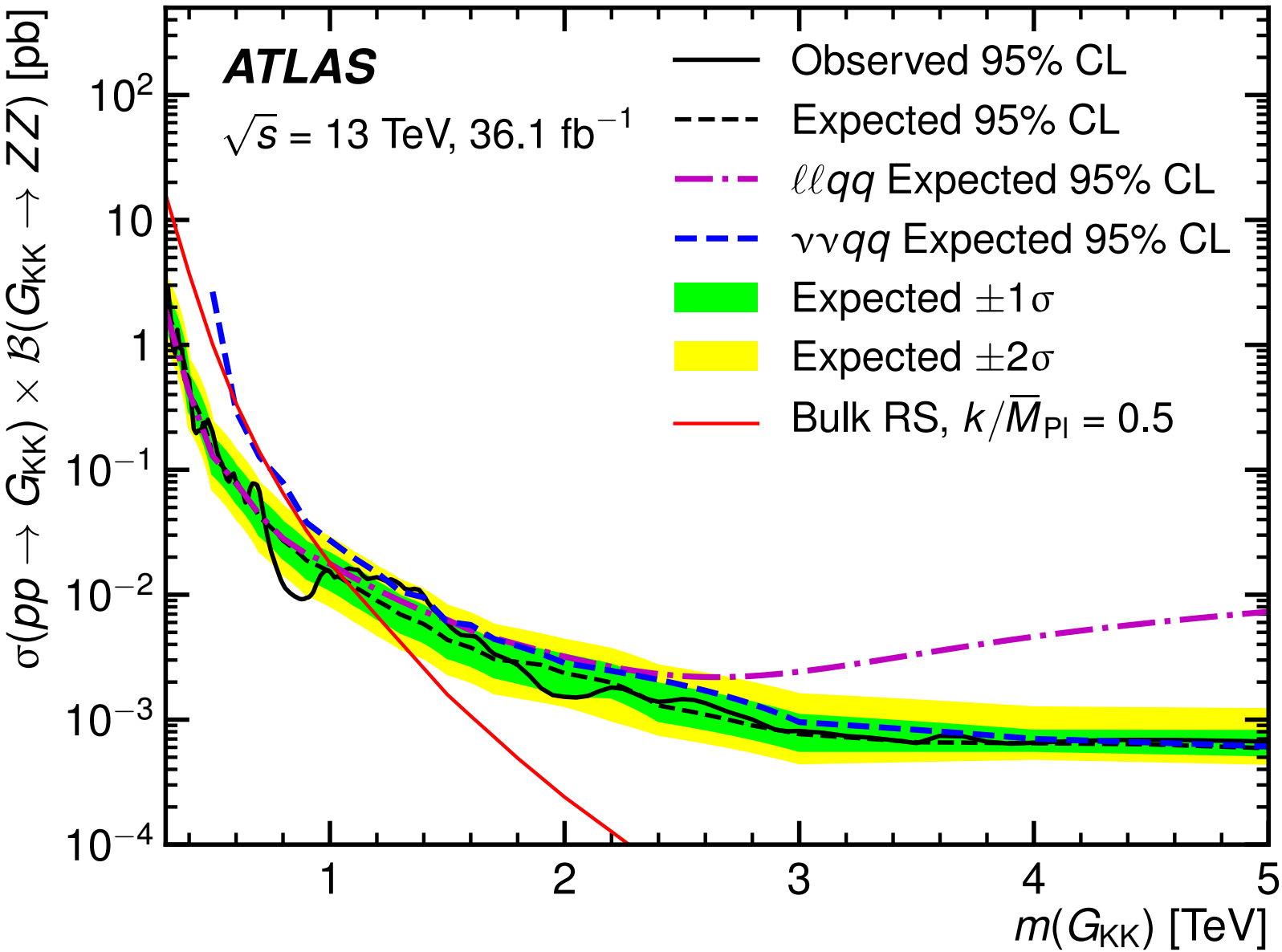

ATLAS
√s = 13 TeV, 36.1 fb-1
W'SSM → τν 95% CL limits
Observed
Expected
± 1σ
± 2σ
W'SSM
± 1σ
σ(pp → W' + X) × B(W' → τν) [pb]
1
10−1
10−2
10−3
1000
2000
3000
4000
mW' [GeV]

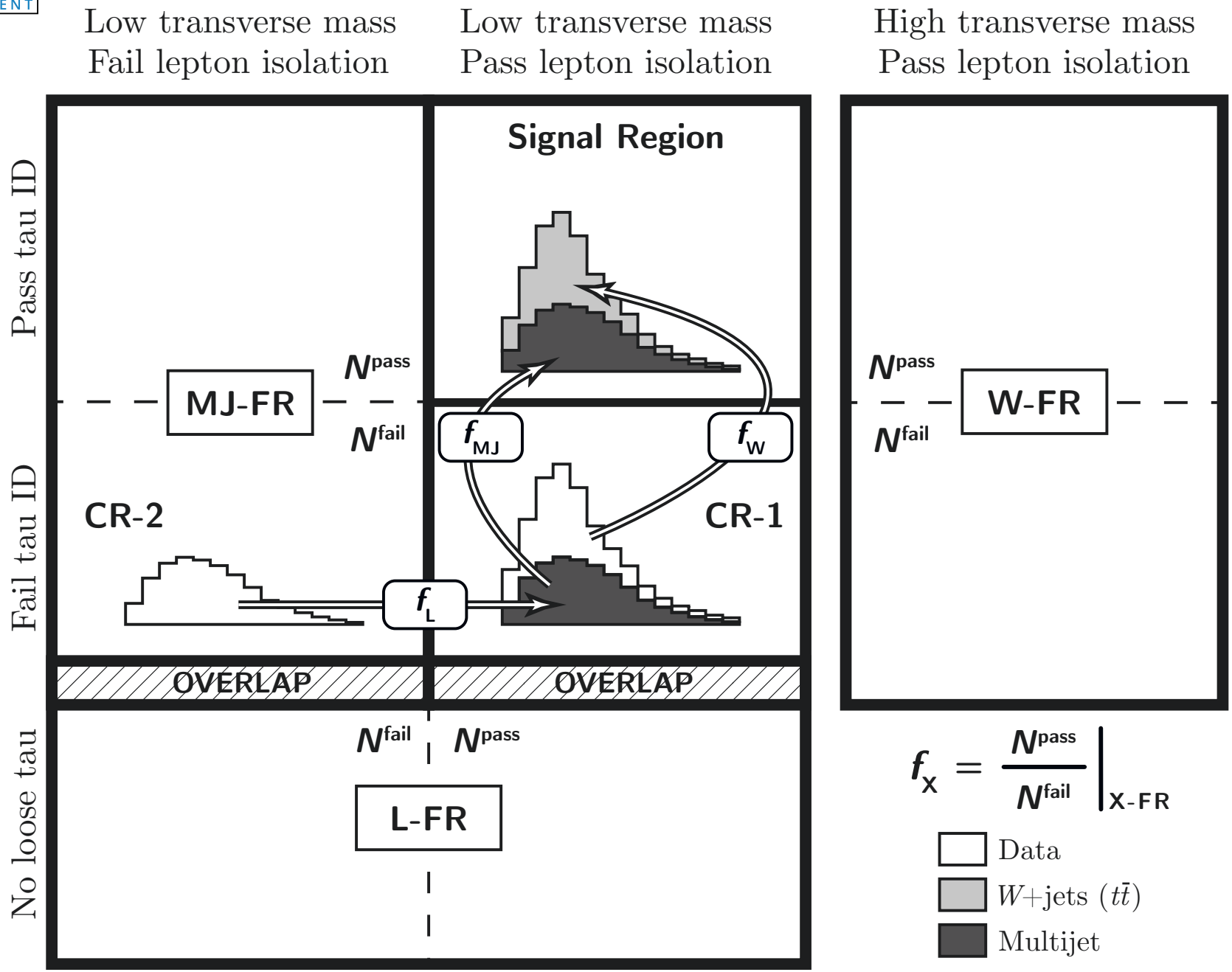

CMS Preliminary
35.9 fb-1 (13 TeV)
Γ= 0 GeV
Expected ± 1σ
Expected ± 2σ
Observed
Expected 4l
Expected 2l2q
Expected 2l2ν
σ(pp → X→ ZZ) [pb]
1
10−1
10−2
10−3
500
1000
1500
2000
2500
3000
mX [GeV]


ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
$H \to ZZ \to \ell\ell qq$
ggF cat. high-purity SR
Data
ggF H 1 TeV (20 fb)
Z + jets
SM Diboson
Top Quarks
Total Uncertainty
Events / 0.23 TeV
Data/Postfit
Postfit/Prefit
$m_{\ell\ell J}$ [TeV]


ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
$H \to ZZ \to \ell\ell qq$
ggF cat. b-tagged SR
Data
ggF H 1 TeV (20 fb)
Z + jets
SM Diboson
Top Quarks
Total Uncertainty
Events / 0.16 TeV
Data/Postfit
Postfit/Prefit
$m_{\ell\ell jj}$ [TeV]

ATLAS Z→llqq


ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Observed 95% CL
Expected 95% CL
$\ell\ell qq$ Expected 95% CL
$\nu\nu qq$ Expected 95% CL
Expected ±1σ
Expected ±2σ
Bulk RS, $k/\bar{M}_{Pl}$ = 0.5
$\sigma(pp \to G_{KK}) \times \mathcal{B}(G_{KK} \to ZZ)$ [pb]
$m(G_{KK})$ [TeV]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
2
3
4
5


Low transverse mass
Fail lepton isolation
Low transverse mass
Pass lepton isolation
High transverse mass
Pass lepton isolation
Pass tau ID
Fail tau ID
No loose tau
Signal Region
MJ-FR
W-FR
L-FR
CR-2
CR-1
OVERLAP
OVERLAP
N^{pass}
N^{fail}
f_{MJ}
f_W
f_L
$f_x = \frac{N^{pass}}{N^{fail}}\Big|_{X\text{-}FR}$
Data
W+jets ($t\bar{t}$)
Multijet