Search for diboson resonances at CMS

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on behalf of the CMS Collaboration

Lake Louise, Canada
22/02/2017

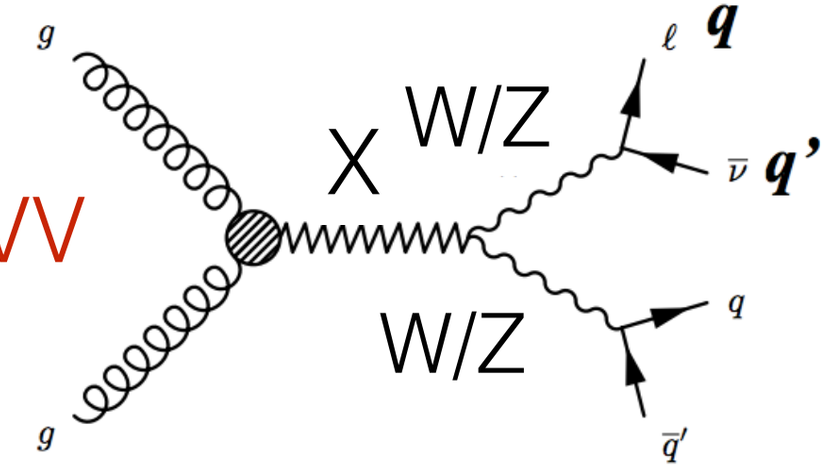
Phenomenology of diboson resonances

- One of the most direct ways to find new physics at the TeV scale
- Clear experimental signature: peak in the VV invariant mass spectrum
- Experimental challenges:
  - many final states: WW, WZ, ZZ, VH, HH
  - different channels, different physics: all-hadronic, semileptonic
  - high energy: merging object, huge backgrounds

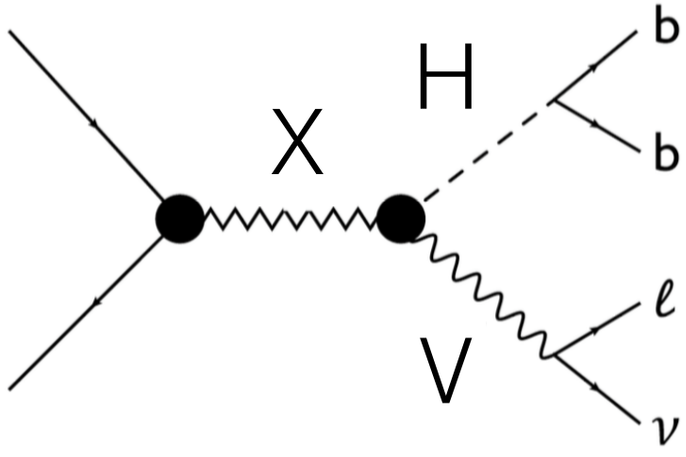
Resonances Production Topology

$$gg \to X \to VV$$
$$gg \to X \to VH$$
$$gg \to X \to HH$$

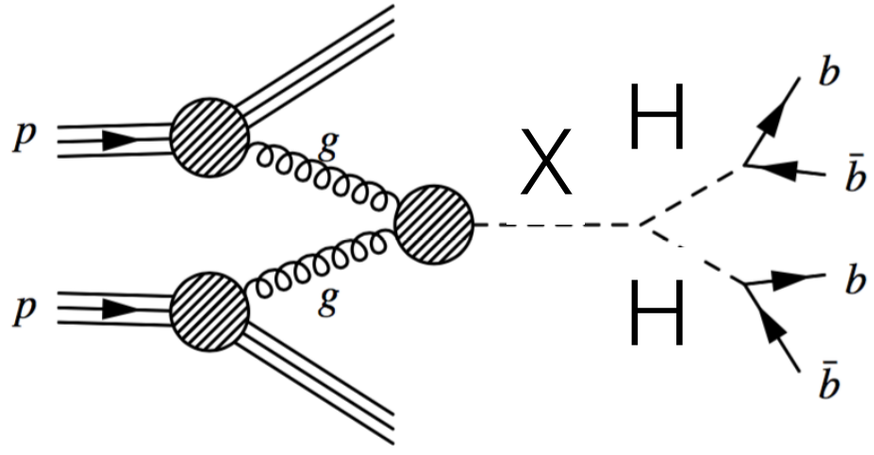
X->VV



X->VH



X->HH



Phenomenology of diboson resonances

Some very famous models we would like to test at LHC

Warped Extra Dimension

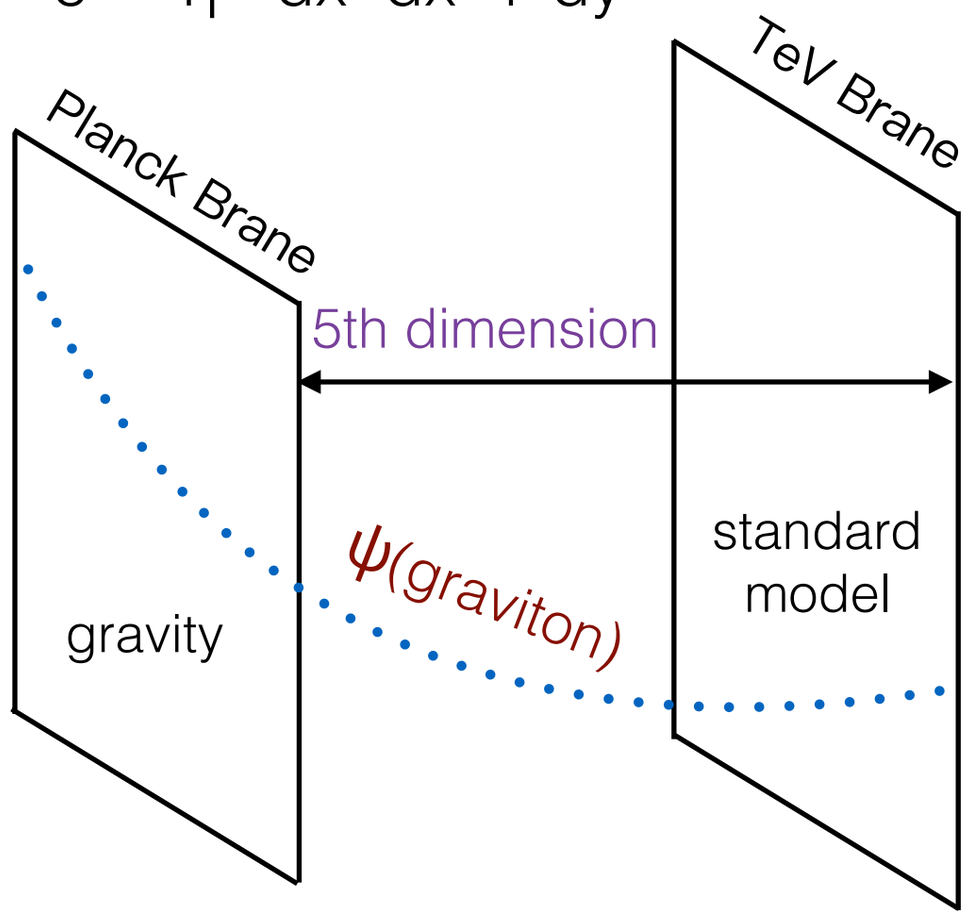
$ds^2 = e^{-2ky} \eta^{\mu\nu} dx^\mu dx^\nu + dy^2$

we live in a 4D slice of a 5D world

we live in a *brane* where the Higgs wave function is localised

Gravity wave function dies exponentially from the 5D to us

G* (graviton) s=2 **R (radion) s=0**



Heavy Vector Triplet

EWSB is due to a new strong interacting composite sector

spin-1 composite resonances

$$\begin{pmatrix} \mathbf{W'+\ (s=1)} \\ \mathbf{W'-\ (s=1)} \\ \mathbf{Z'(s=1)} \end{pmatrix}$$

2HDM

additional heavy scalar bosons in the Higgs Sector

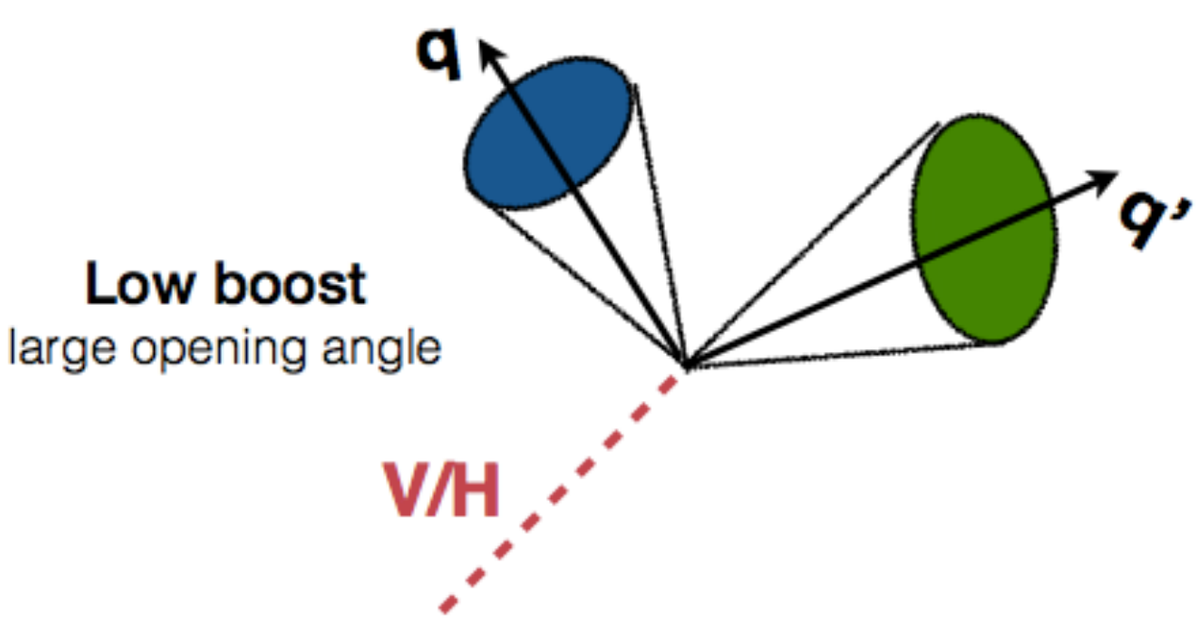
A0

H+

H-

Boosted Topologies

- For high mass resonances bosons get high boost (pT > 200 GeV)
- Hadronic VV/VH final states might merge into a single V/H-jet
- Leptonic VV/VH final states: at high boost leptons overlap in the isolation cones -> special reconstruction applies
- V/H-jet reconstructed with the CA algorithm with large ΔR

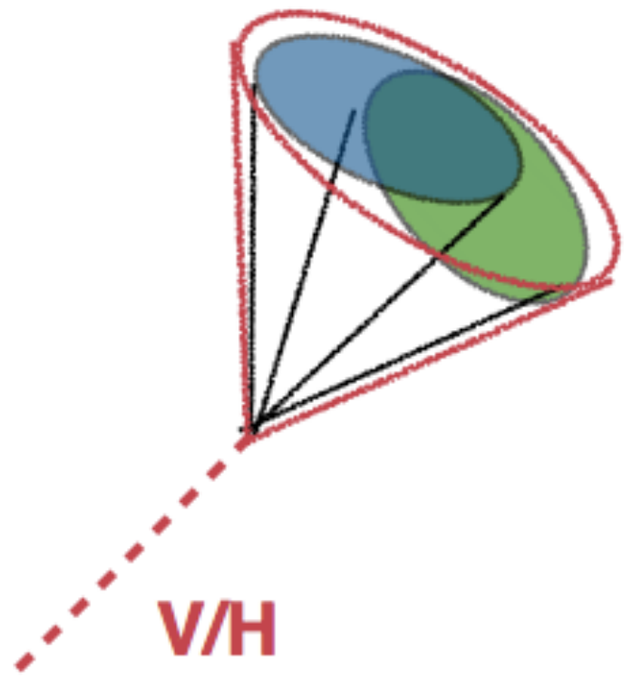


High p_T boson

$$\Delta R_{qq}^{min} \approx 2\frac{M_V}{p_{T,V}}$$

M^X = 2 TeV
$p_{T,V}$ ~ 1 TeV
M_V ~ 100 GeV

→ $\Delta R_{qq}^{min} \approx 0.2$



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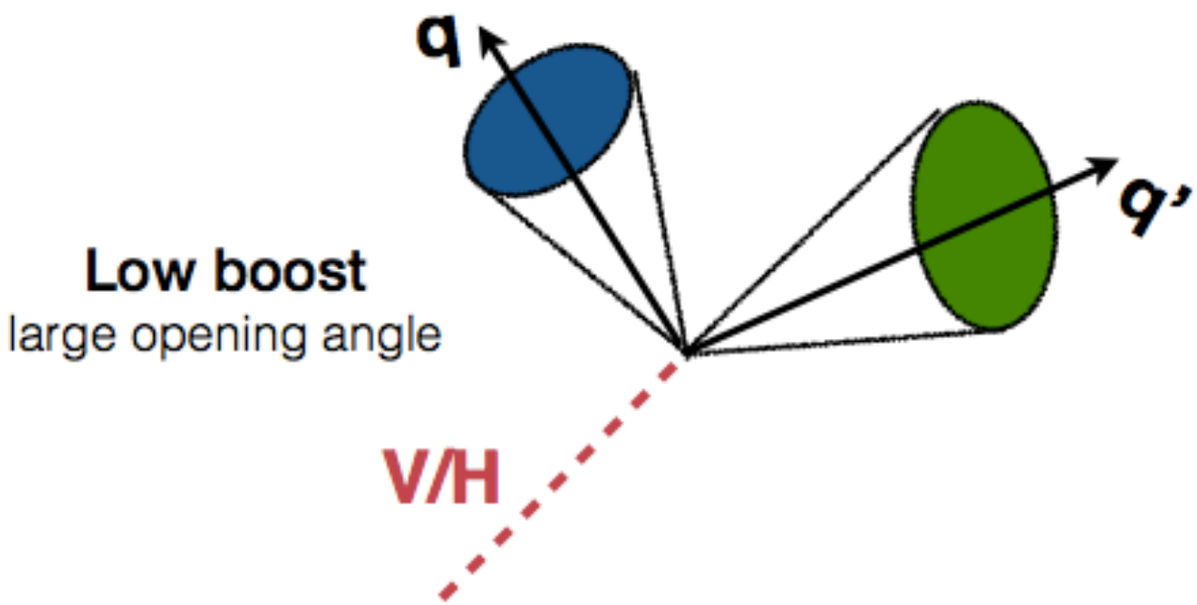

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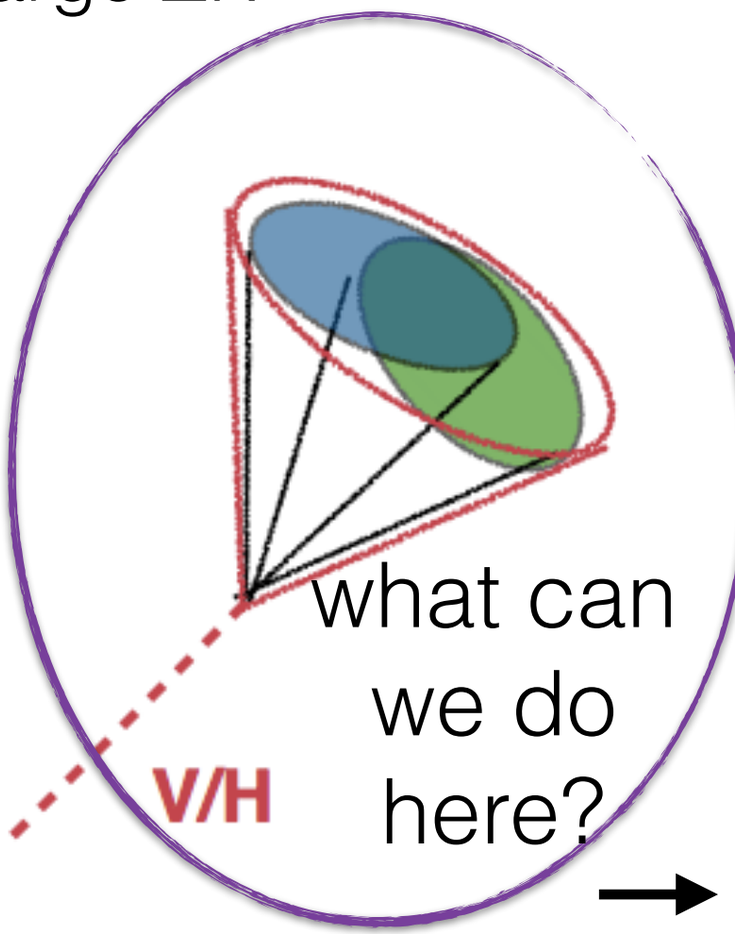


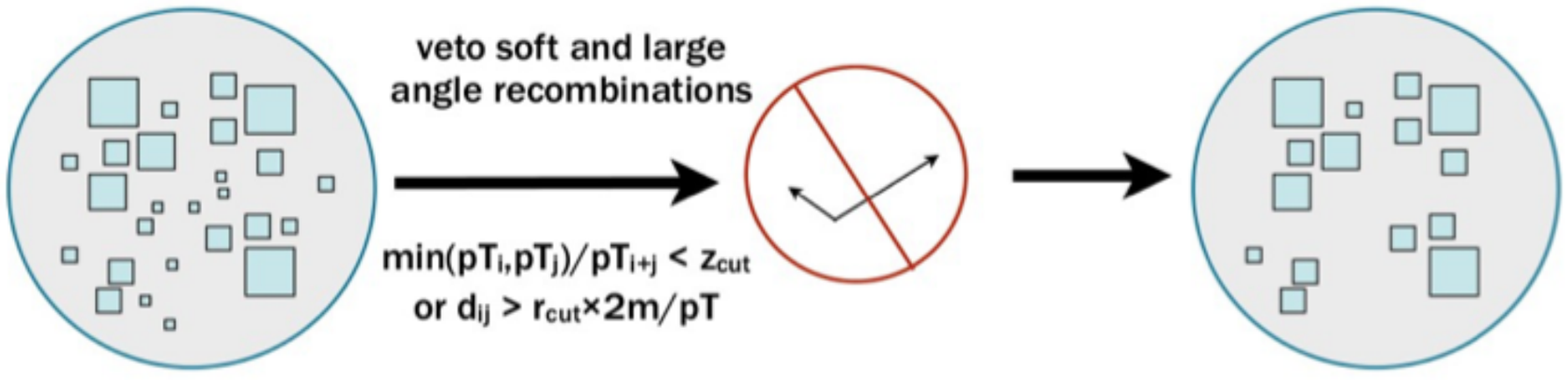
Jet Substructure - basic concepts

Pruning

[Phys.Rev.D 80 051501]

attempts to remove from the jets those constituents that are unlikely to be associated with the jet

depends on two parameters: *z, r*

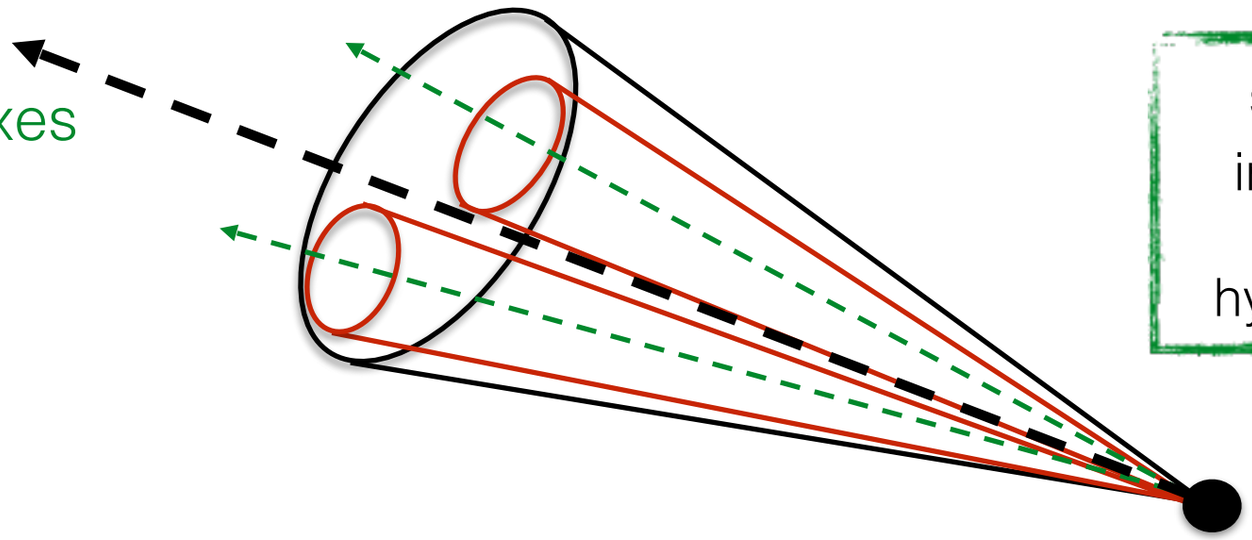


removes soft and wide angle radiation (PU, UE)

N-Subjettines

[JHEP03(2011)015]

Quantifies to what degree jet can be regarded as a jet composed of N jets
Discriminate a composite jet w.r.t. a “standard” QCD jet



$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} min\{\Delta R_{1,k}, ..., \Delta R_{N,k}\}$$

p_T-weighted sum over all jet constituents of their distance w.r.t. the closest of N axes in a jet

Boosted Higgs Boson Reconstruction

- Crucial aspect of the search strategy is the H→bb reconstruction
- highly boosted Higgs produce collimated pairs of b jets
- merged into a single b jet (*fat-b jet*) [using AK08]
- exploiting the jet substructure and the b tagging
- b tagging : CSVv2 algorithm

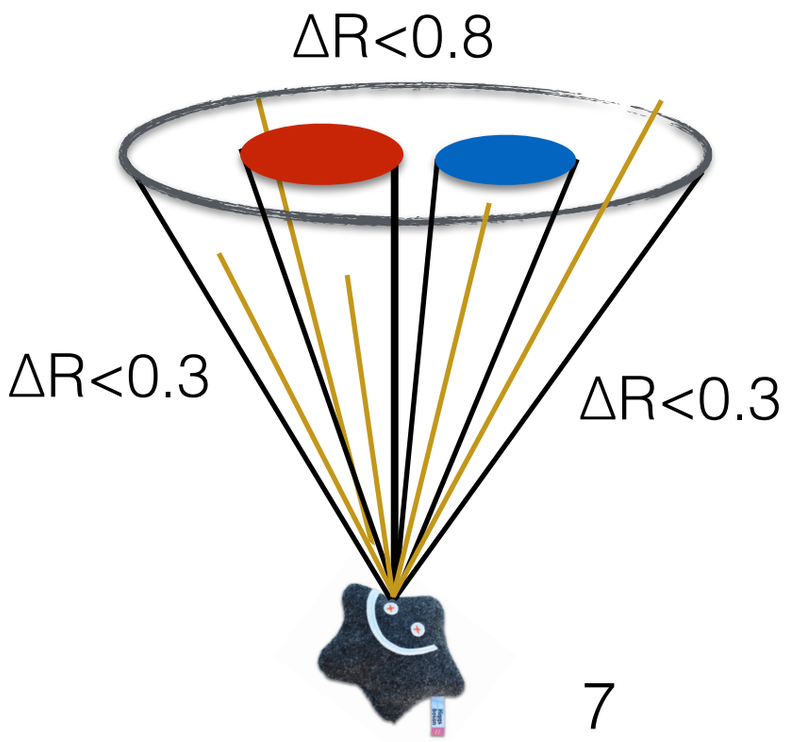
$\Delta R(bb) \sim 2m^H / p_T^H$

Two Approaches in CMS

subjet b tagger

identify the two subjets by undoing the last iteration of the clustering

apply the b tagging on them



double b tagger

reconstructing the 2 B hadrons within the same fat jet (inclusive vertex finder)

MVA combining tracks associated to tau-axes and svtx observables to separate Hbb to QCD jets

[CMS-PAS-BTV-15-002]

Some Highlights from CMS VV and VH Searches

channel	final state	model tested	reference
ZZ	$\ell\ell qq; \ell\ell J$	*Z' HVT type A, bulk Graviton*	**CMS-PAS-B2G-16-021**
WZ	$\ell\ell qq$	*W' HVT type A,B, bulk Graviton, RS Graviton*	**CMS-PAS-B2G-16-022**
WW	$\ell\nu qq + qqqq$ $\ell\nu qq + qqqq$	*bulk Graviton*	**CMS-PAS-B2G-16-021**
WH	$\ell\nu bb$	*W' HVT type B*	**arXiv:1610.08066**
ZH	$\ell\ell bb$	*Z' HVT type B*	
HH	$4b$	*bulk Graviton, Radion*	**CMS-PAS-B2G-16-008**
combination	**all**	*HVT, bulk Graviton*	**CMS-PAS-B2G-16-007**

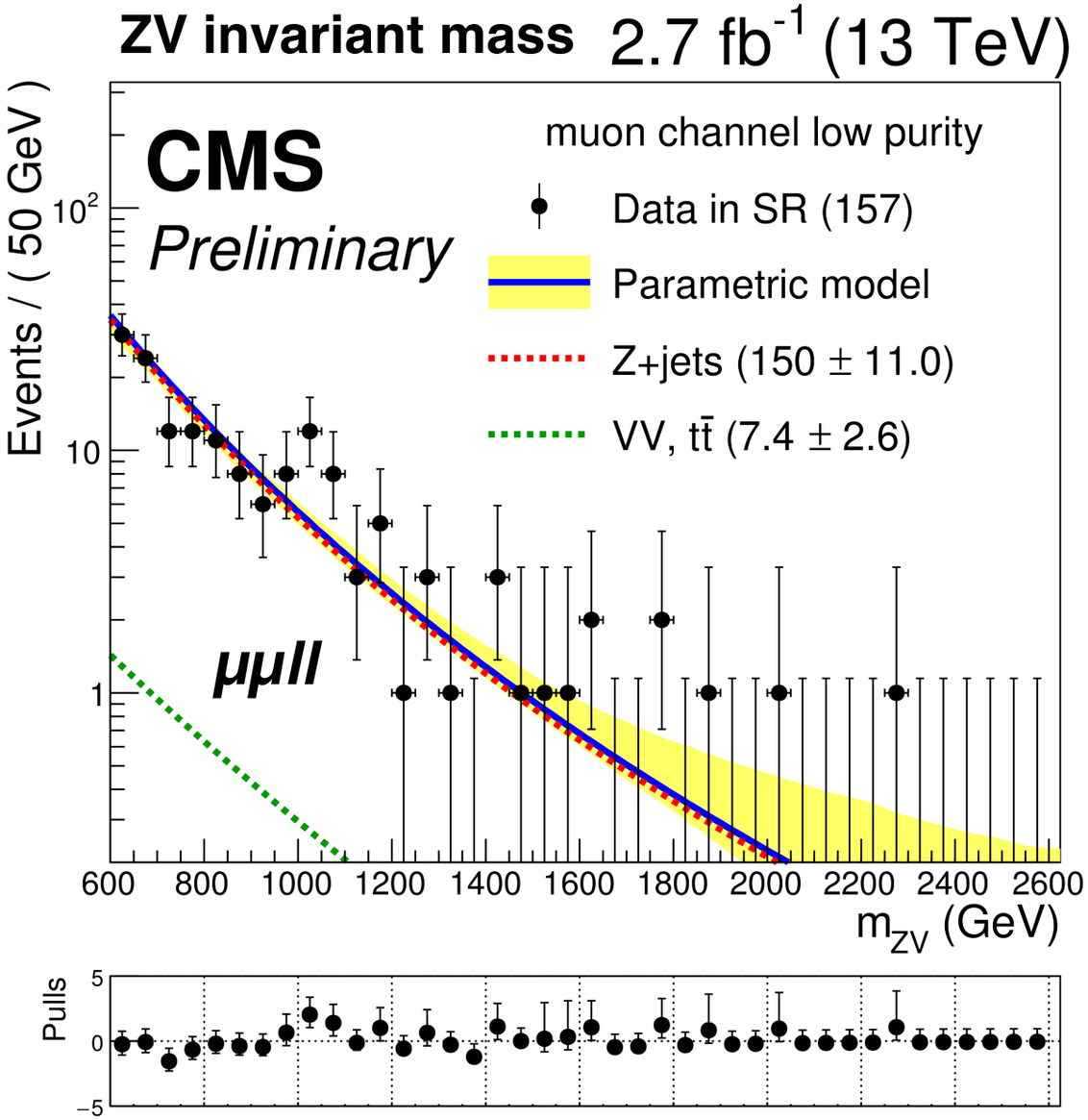
Results for X ⟶ ZV

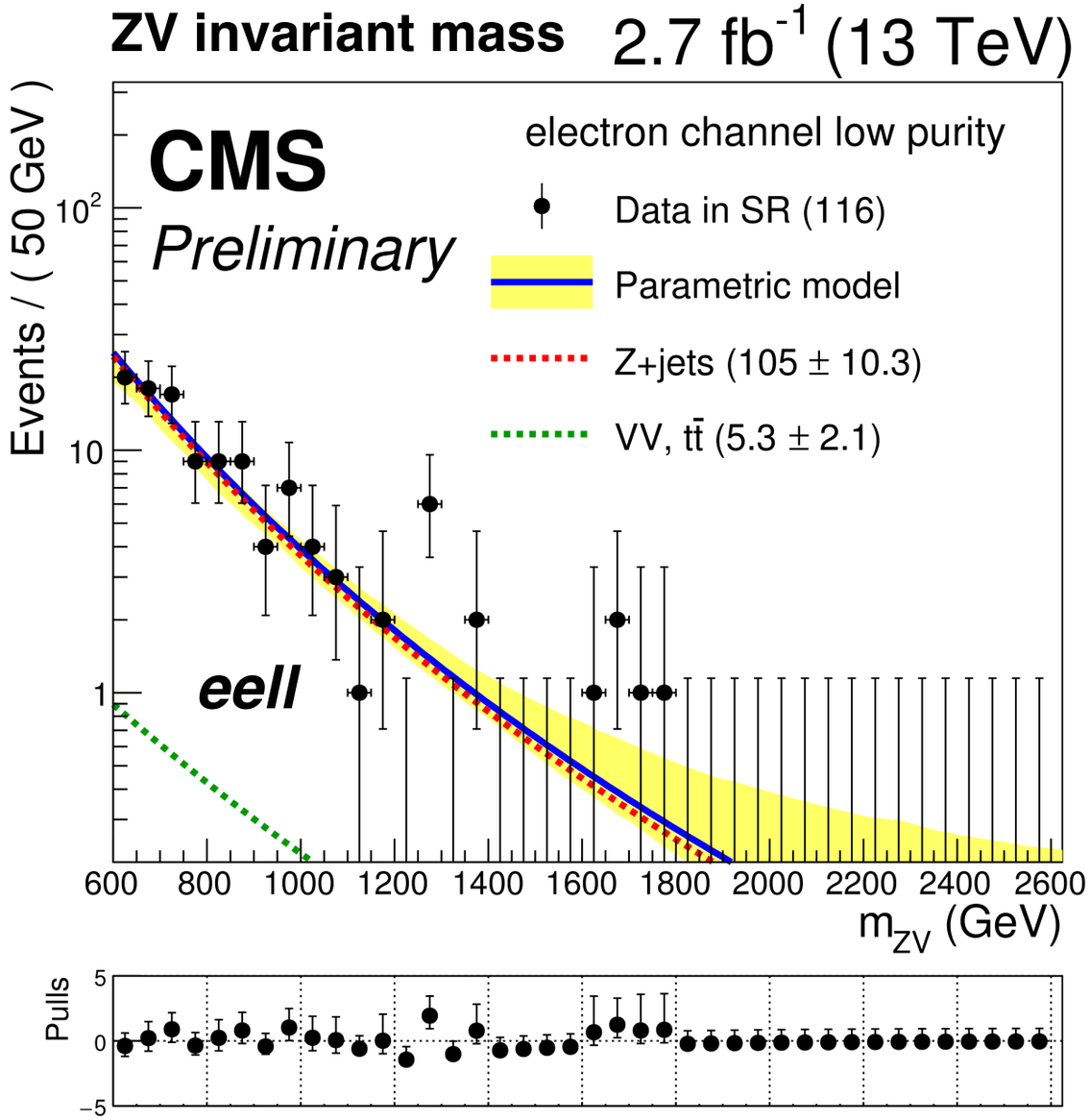
semileptonic+fully hadronic

$$X \to VV \to J(q\bar{q})J(q\bar{q})$$

$$X \to VW \to J(q\bar{q})\ell\nu$$

divided into low(τ_{21} < 0.40)
high(0.40 < τ_{21} < 0.75) purity



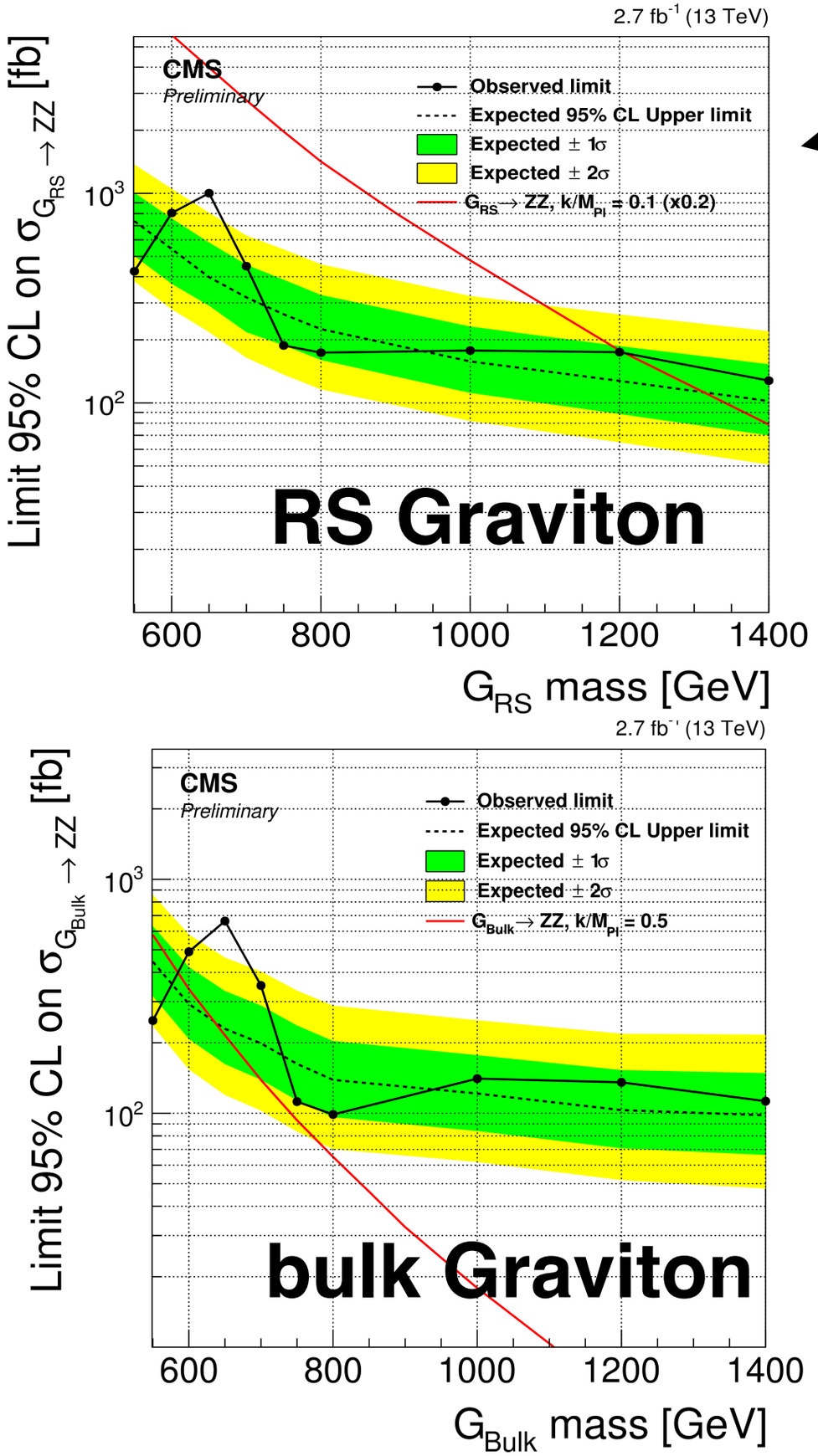


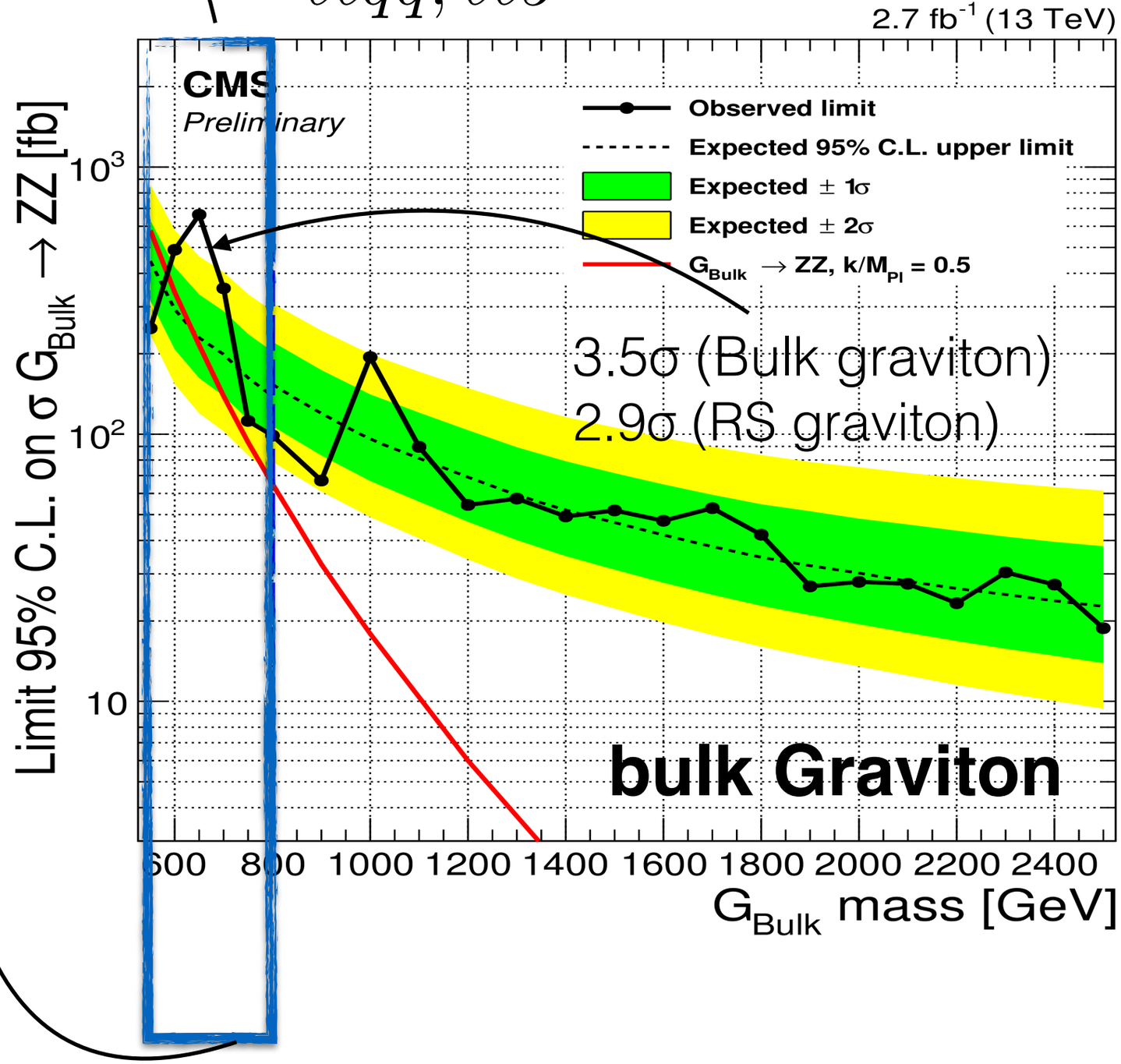
several regions for JJ and Jlv combined in a single likelihood

Results for X ⟶ ZV

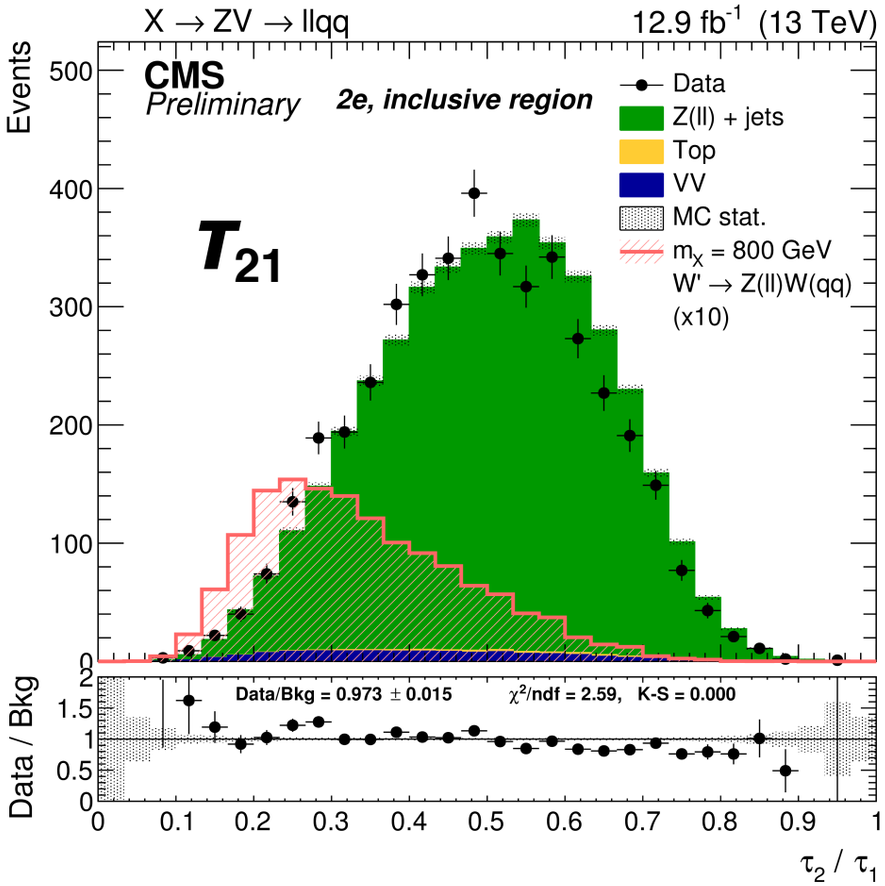
$$X \to VZ \to J(q\bar{q})\ell\ell$$

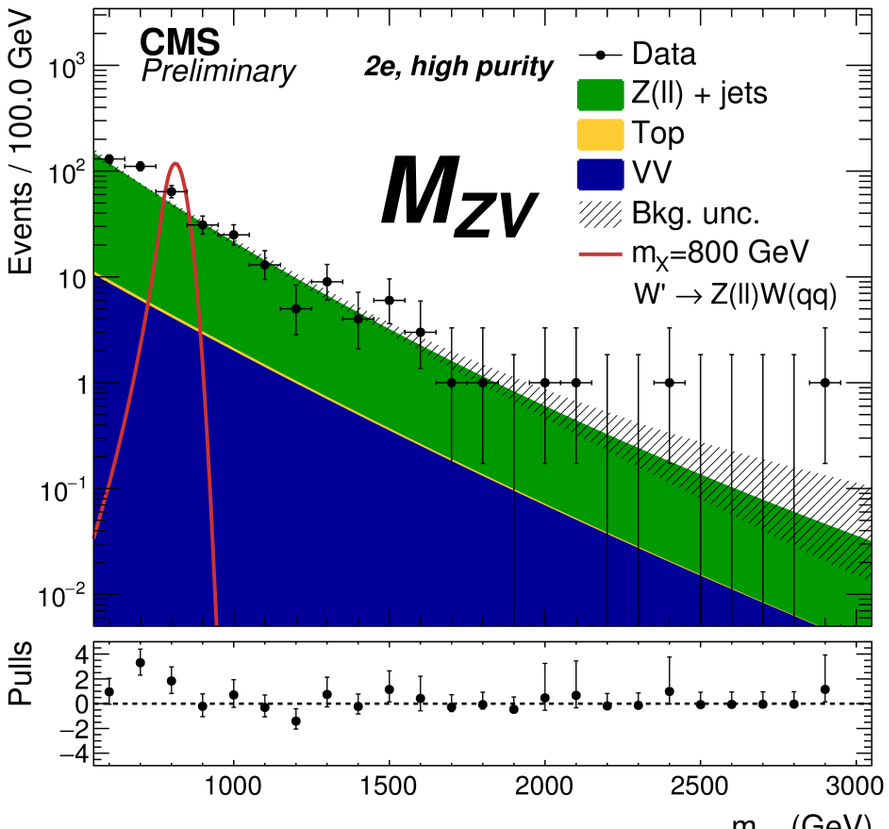
resolved(low mass)+
boosted(low+high mass)
$\ell\ell qq; \ell\ell J$



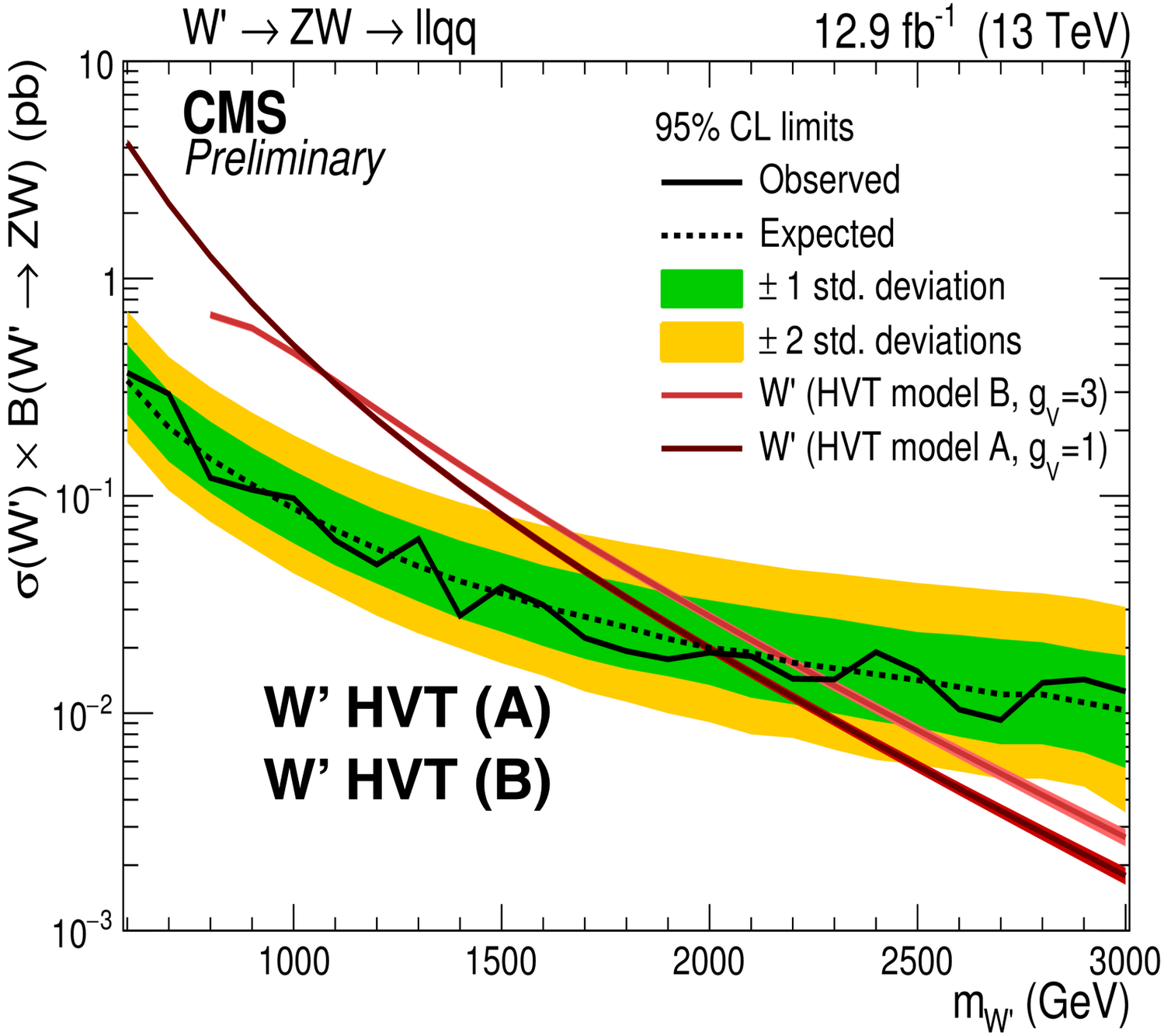


Results for X → WZ





$W' \to WZ \to \ell\ell qq$ (boosted)

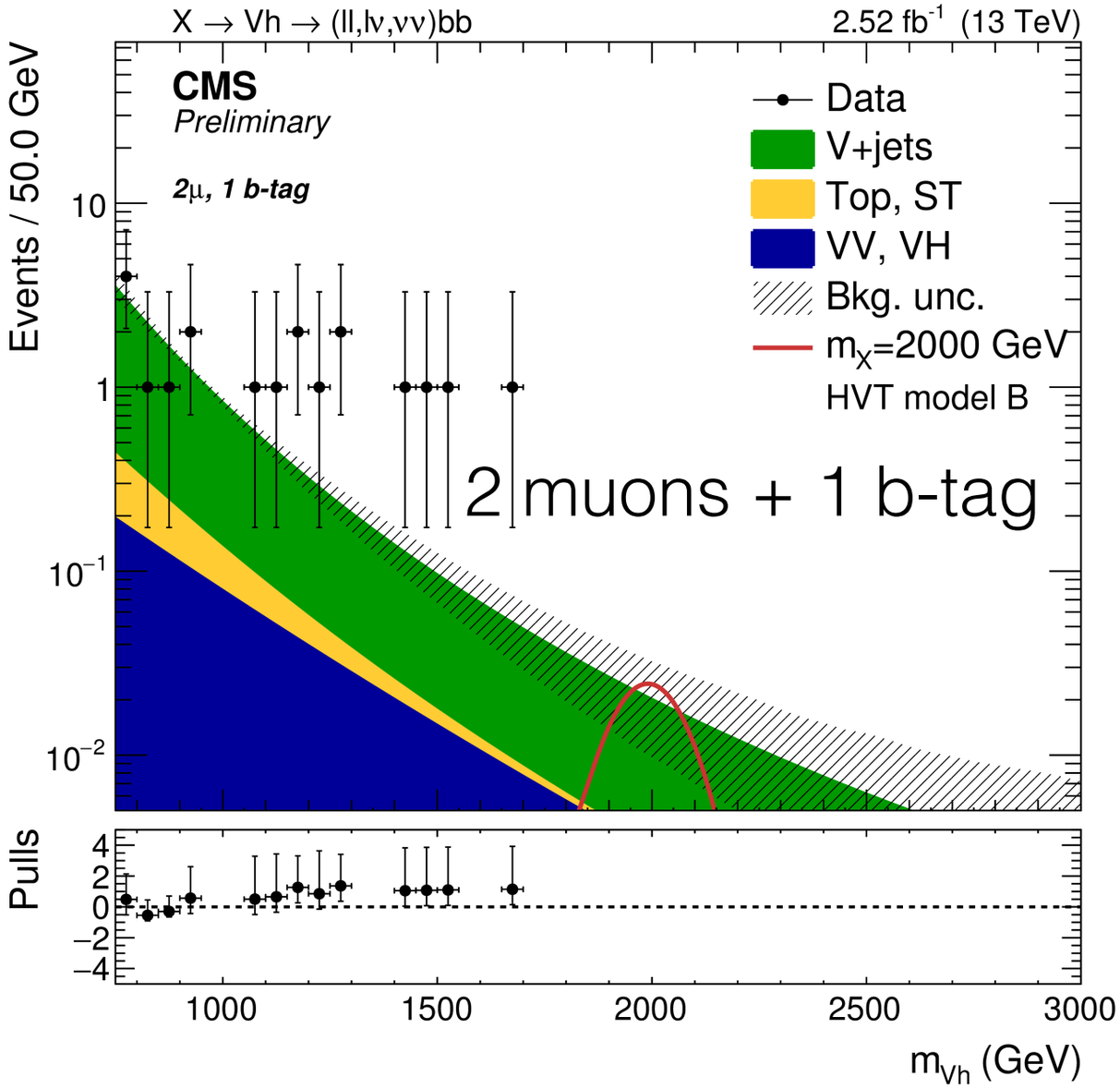


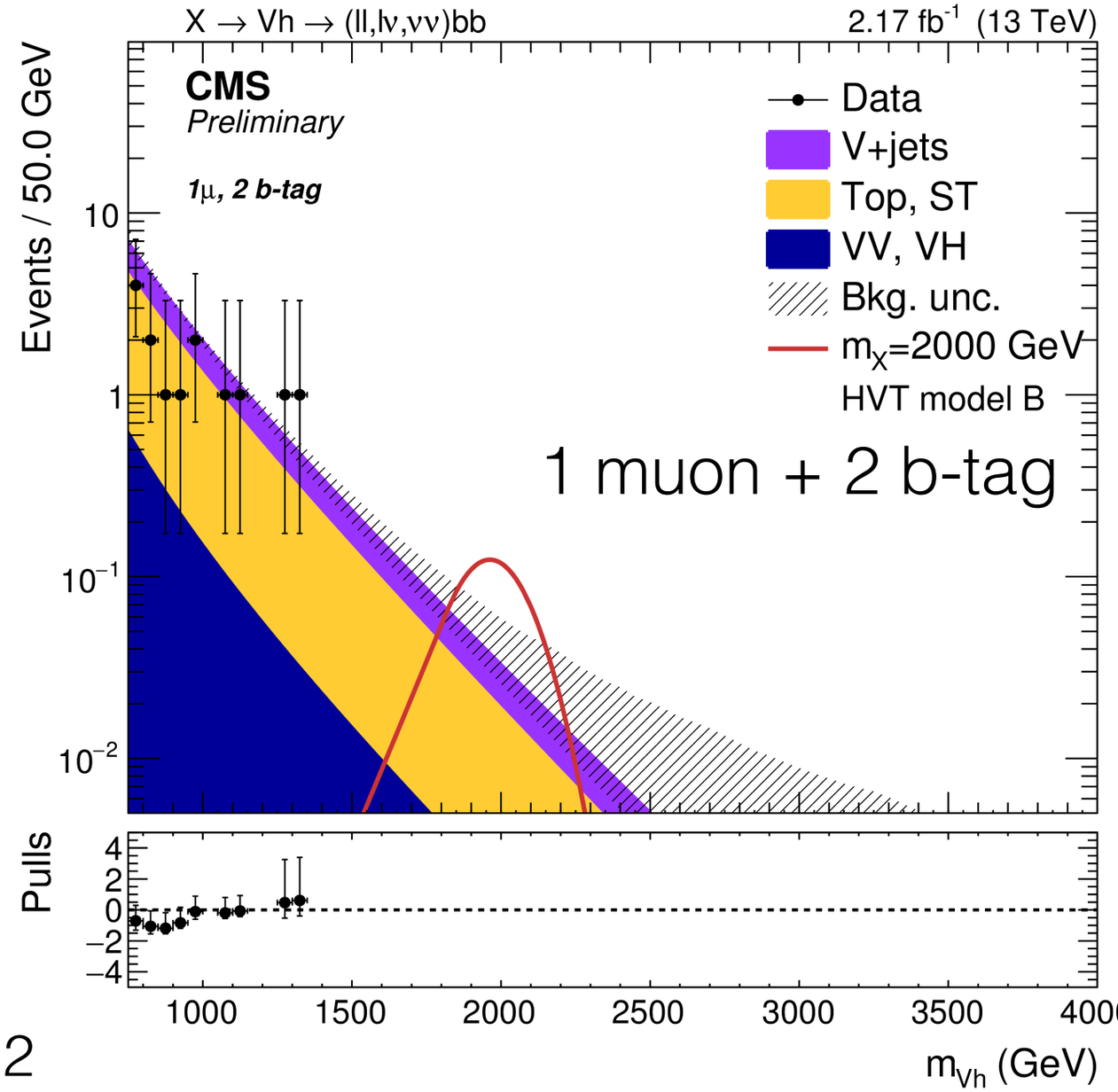
Results for X ⟶ VH

- Five channels: Z(ee)H(bb), W(en)H(bb), Z(μμ)H(bb), W(μn)H(bb), Z(nn)H(bb) + c.c.
- Shape+Normalisation in data using the *alpha method* :
- Jet Mass SideBands

V+jets background (40%/60% W/Z):

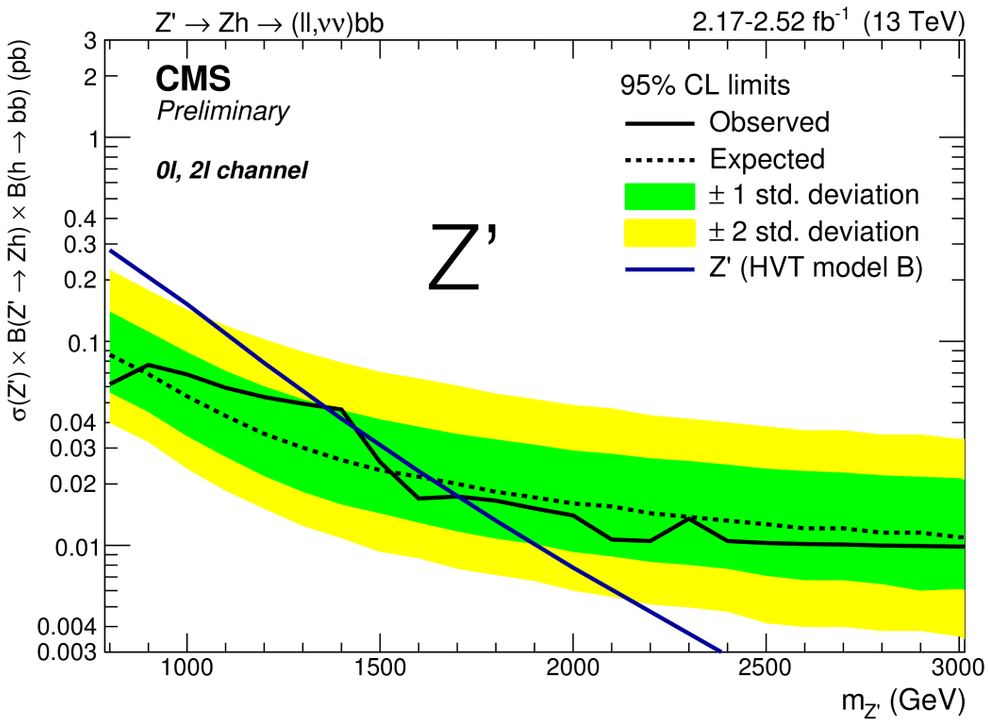
$$N_{SR}^{pred}(m_{\mathrm{Vh}}) = N_{SB}^{data,Vjet}(m_{\mathrm{Vh}}) \times \alpha(m_{\mathrm{Vh}}) + N_{SR}^{MC,Top}(m_{\mathrm{Vh}}) + N_{SR}^{MC,VV}(m_{\mathrm{Vh}})$$

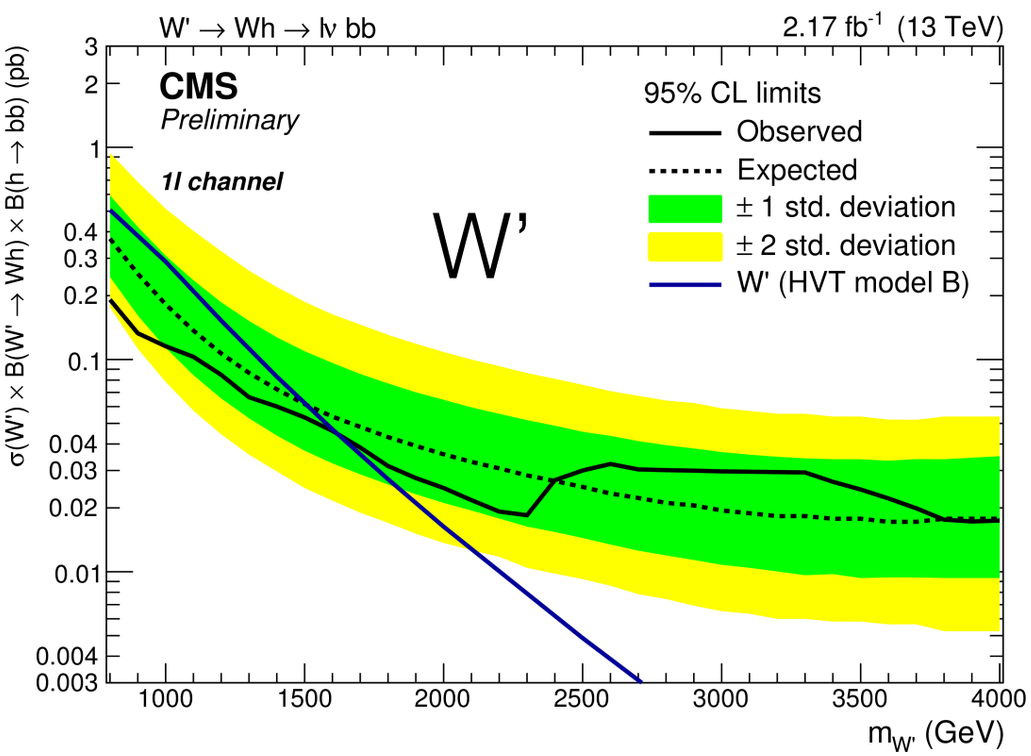


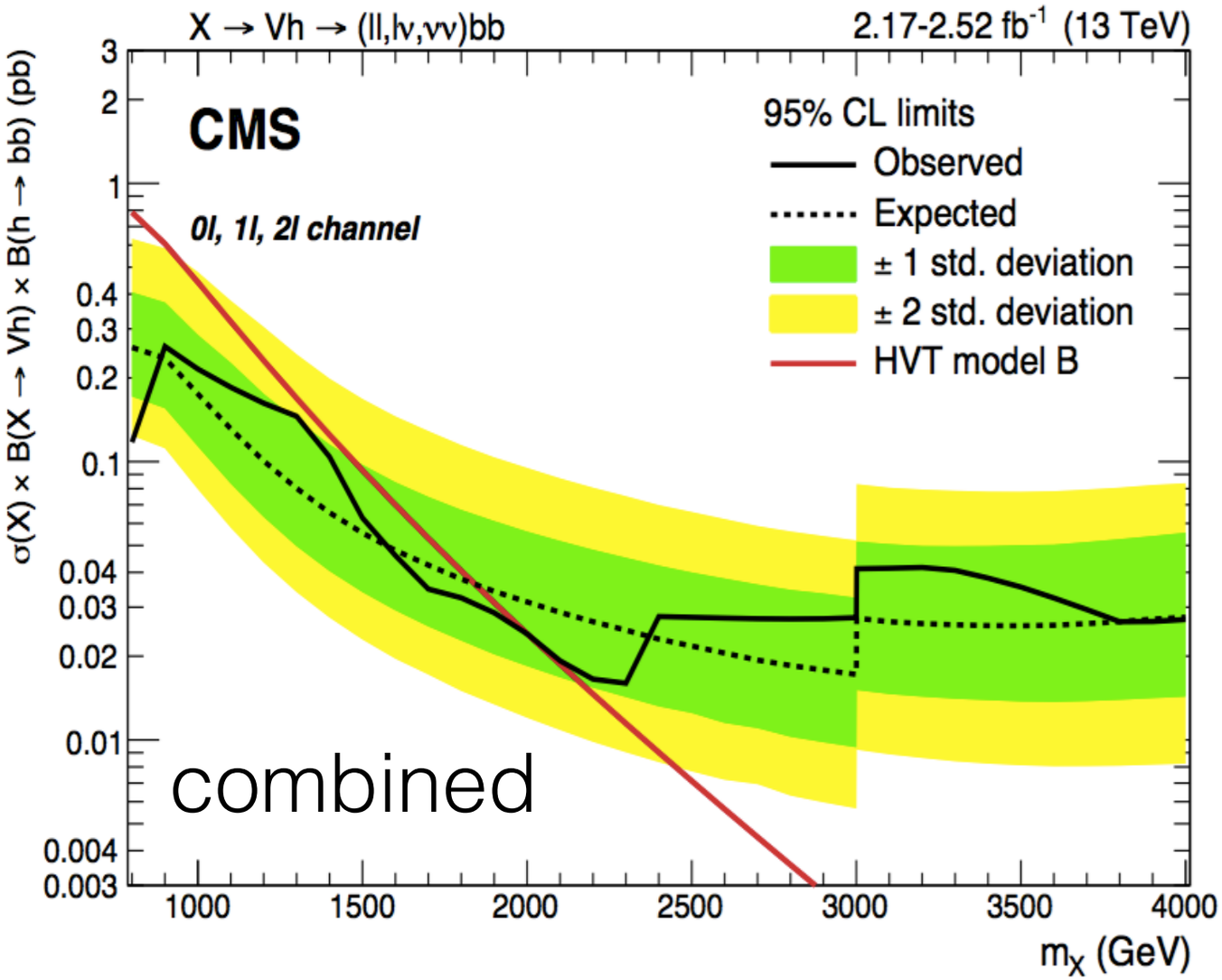


Results for X ⟶ VH

Observed and expected 95% CL upper limit on σ×BR(Z'→Zh)×BR(h→bb)



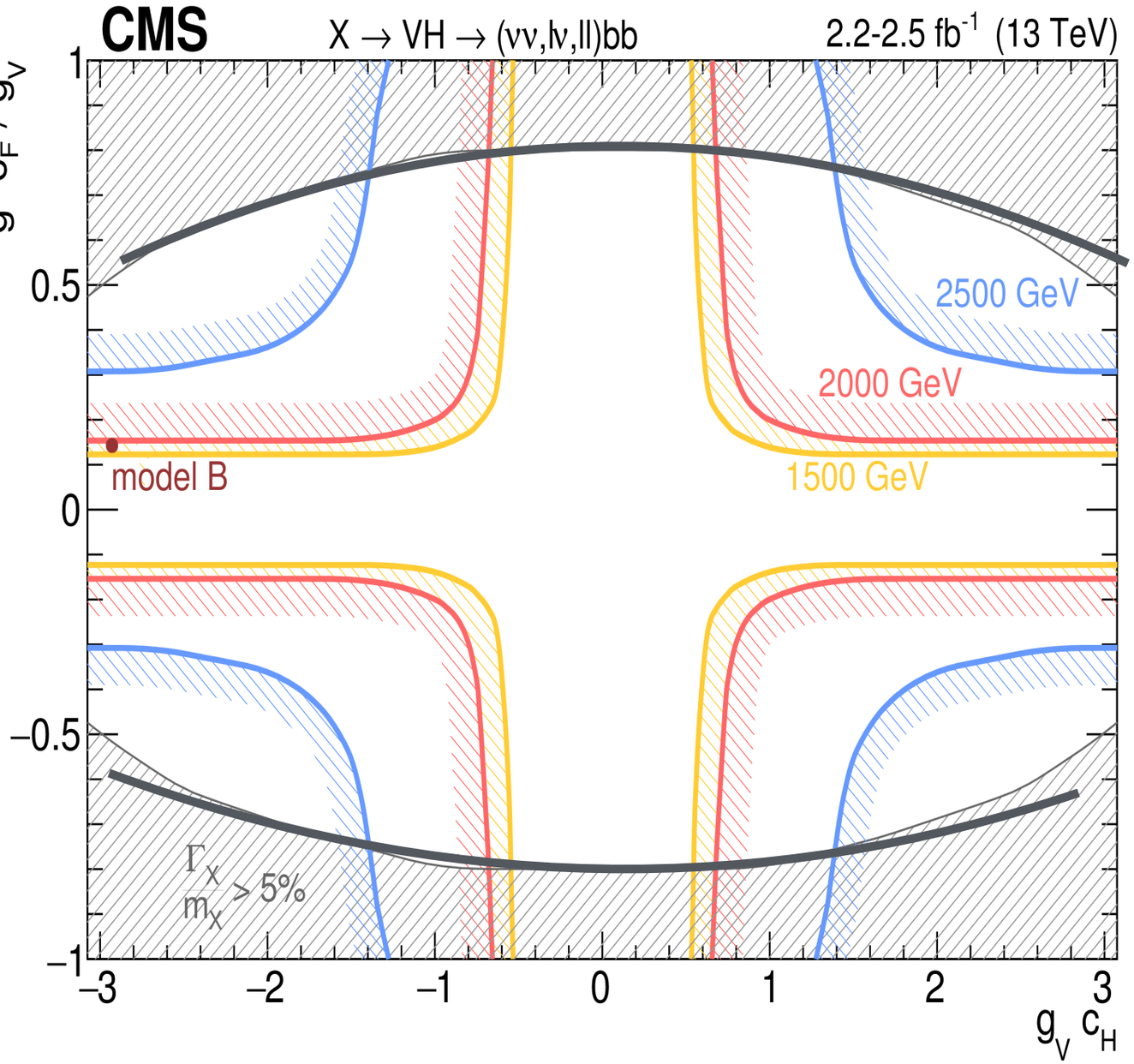




- HVT typeB Model

No excess seen

Results for X → VH



grey line:resonance natural width > experimental resolution (5%) (not in the narrow-width approximation)

Observed exclusion in the HVT parameter plane

$g_V c_H$, $g^2 c_F / g_V$

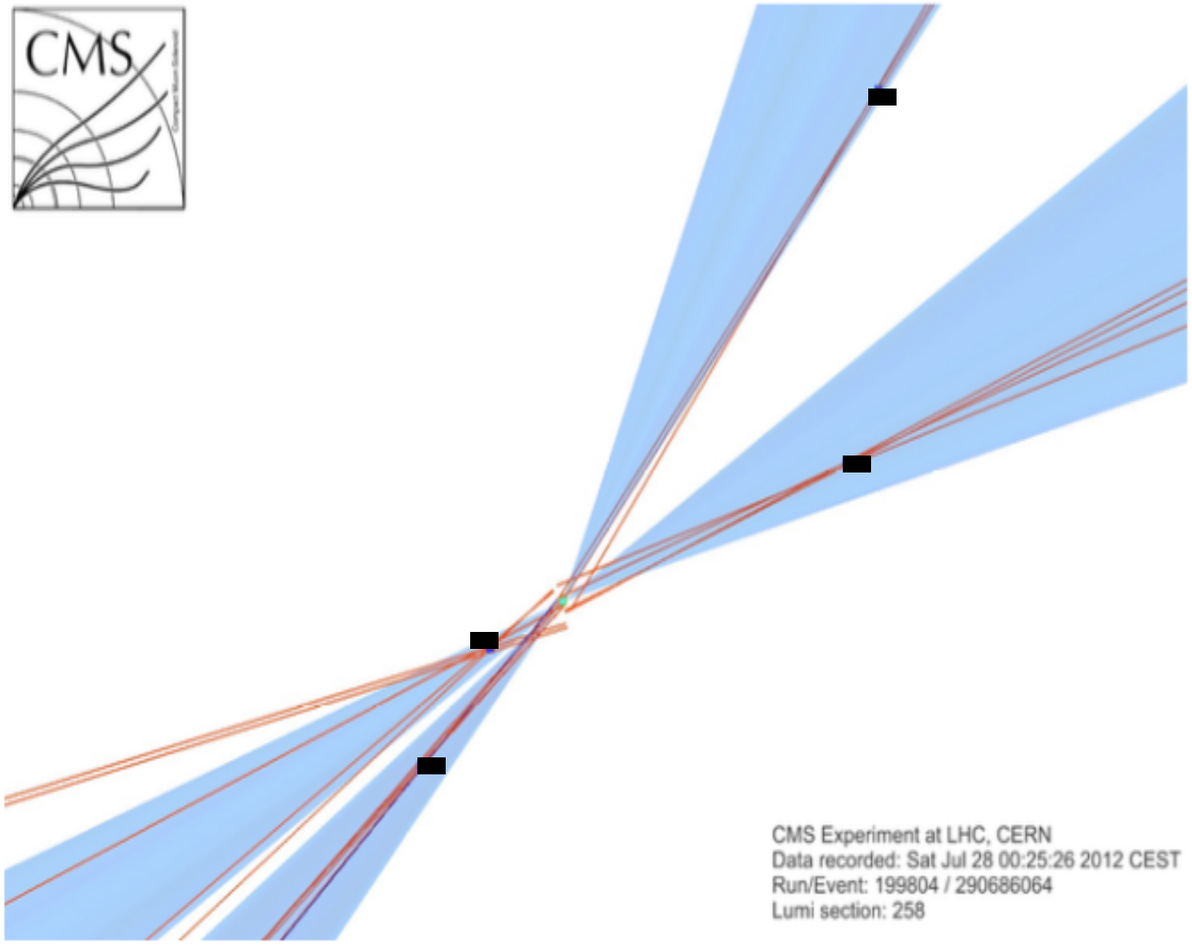
coupling between the Higgs boson and longitudinally polarised SM vector bosons

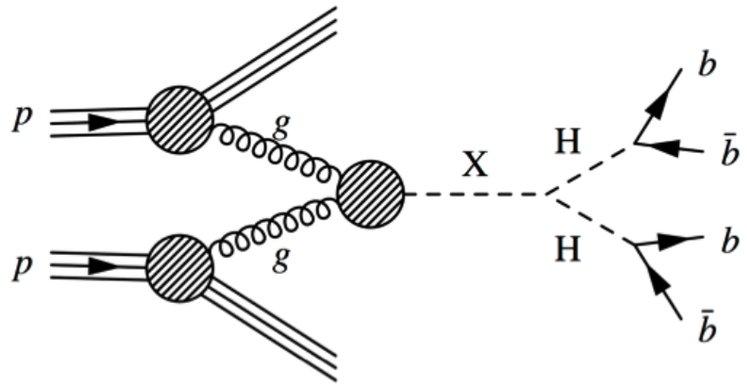
coupling strength of the new interacti on,

coupling with fermions .

$HH \longrightarrow b\bar{b}b\bar{b}$

Data: L = 2.3 fb^{-1}. $\sqrt{s}$ = 13 TeV





- highest HH branching ratio
  BR(H → bb) ~33% -> very high statistics
- huge QCD multijet background
- rely on the power of the newest b tagging algos
- model independent, benchmark models:
  bulk Graviton (spin2) and Radion (spin0)

Event Selection

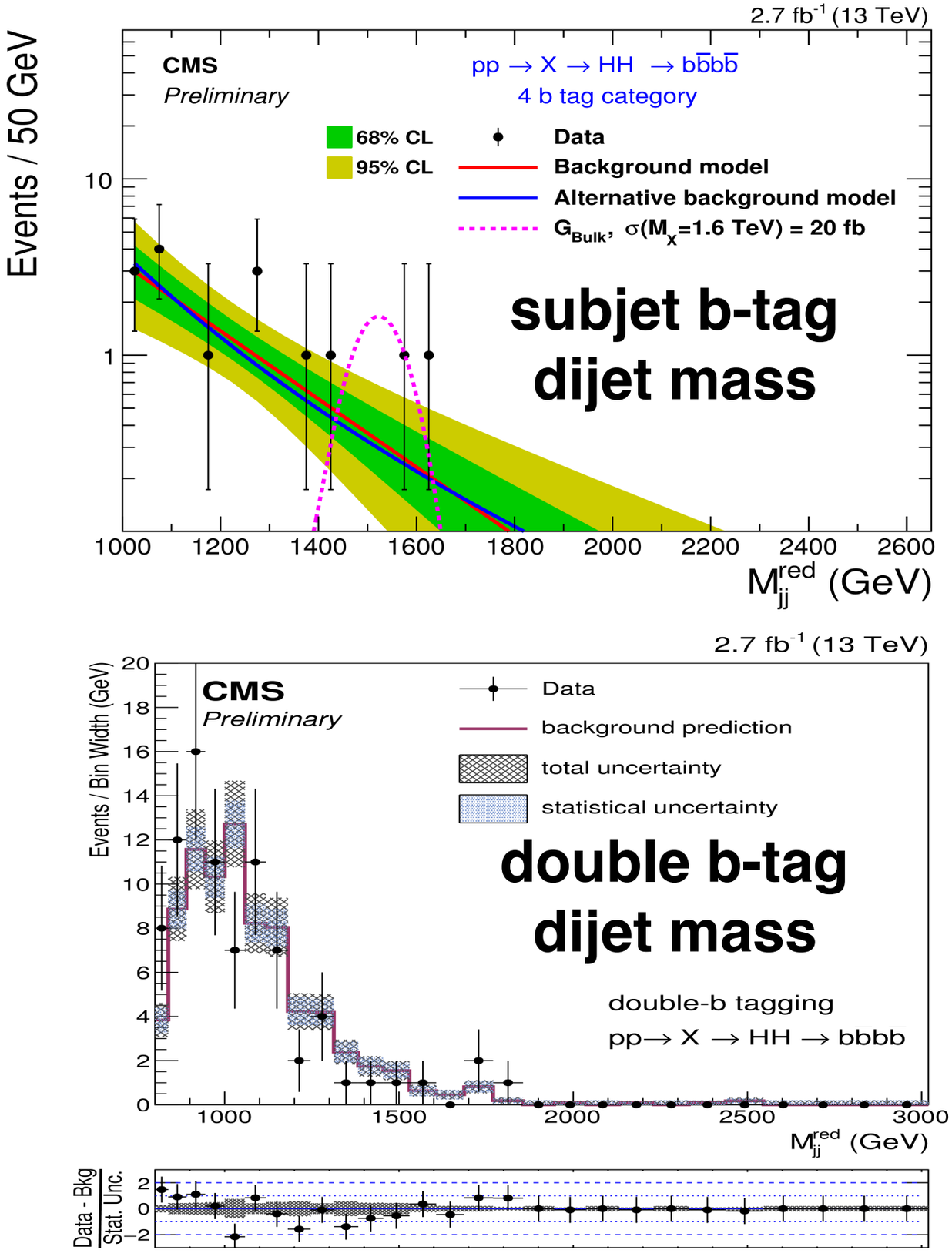
- at least 2 jets, pT > 200 GeV, |η| < 2.4
- τ21 < 0.6
- double b tag > 0.6 (eff ~65% for bb pairs)
- subjet btagging CSVloose > 0.6 (~50%) *or*

Signal Extraction: two parallel approaches

1) subjet b tagging + *smoothness test*
2) double b tagging + *Alphabet*

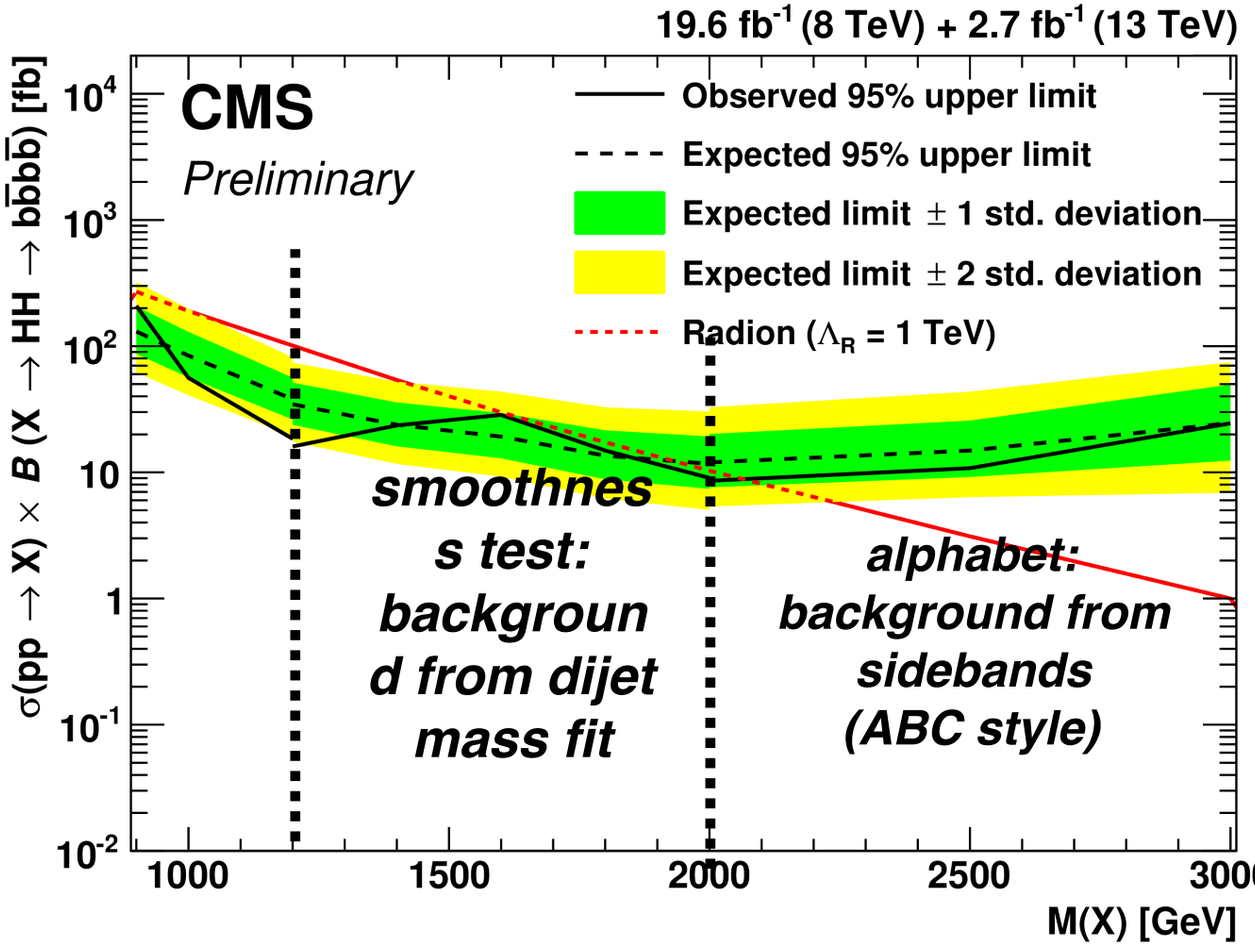
see next slide…

Results for X → HH → bb̄bb̄



[8+13 TeV Combination]

Radion

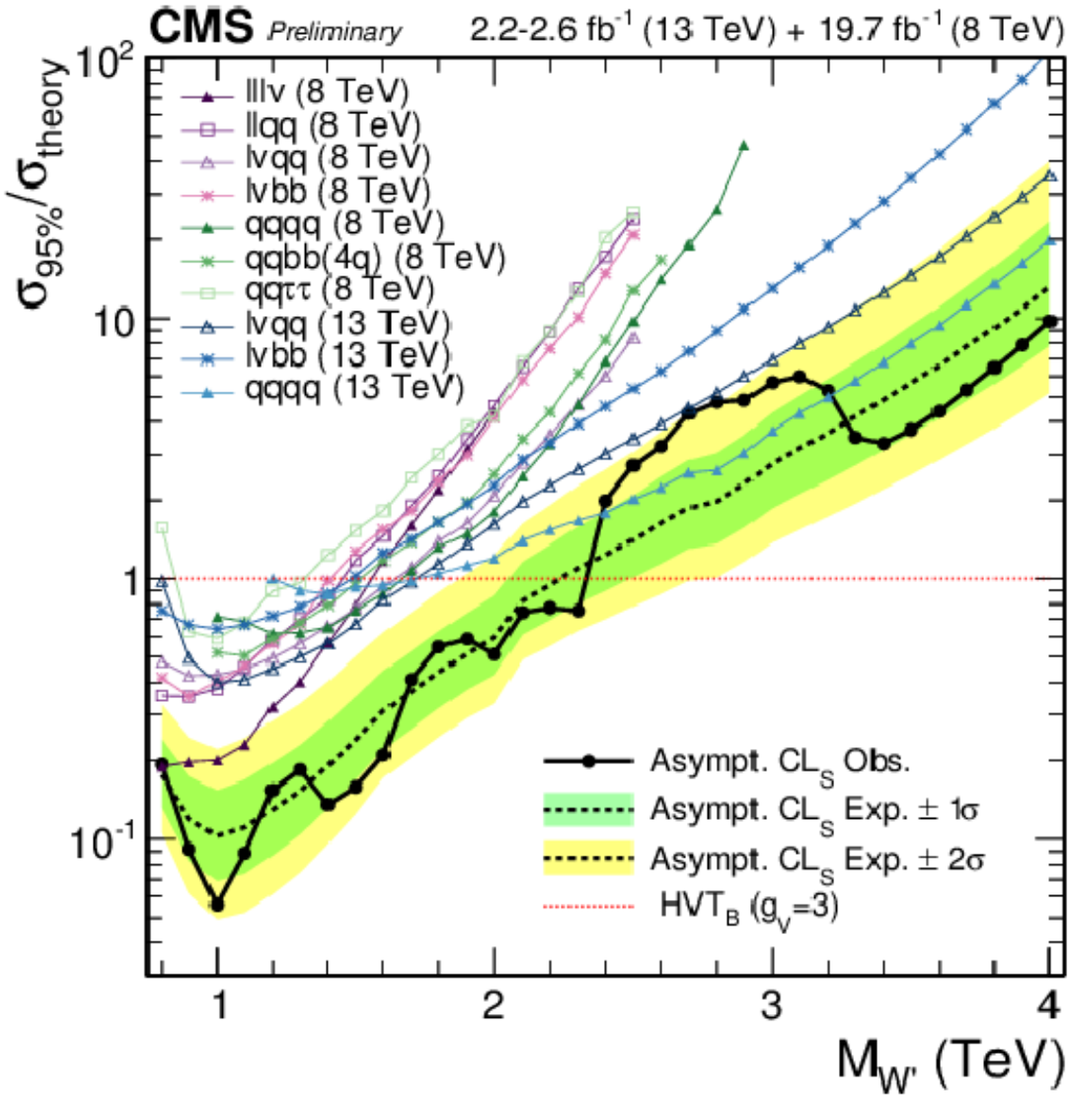


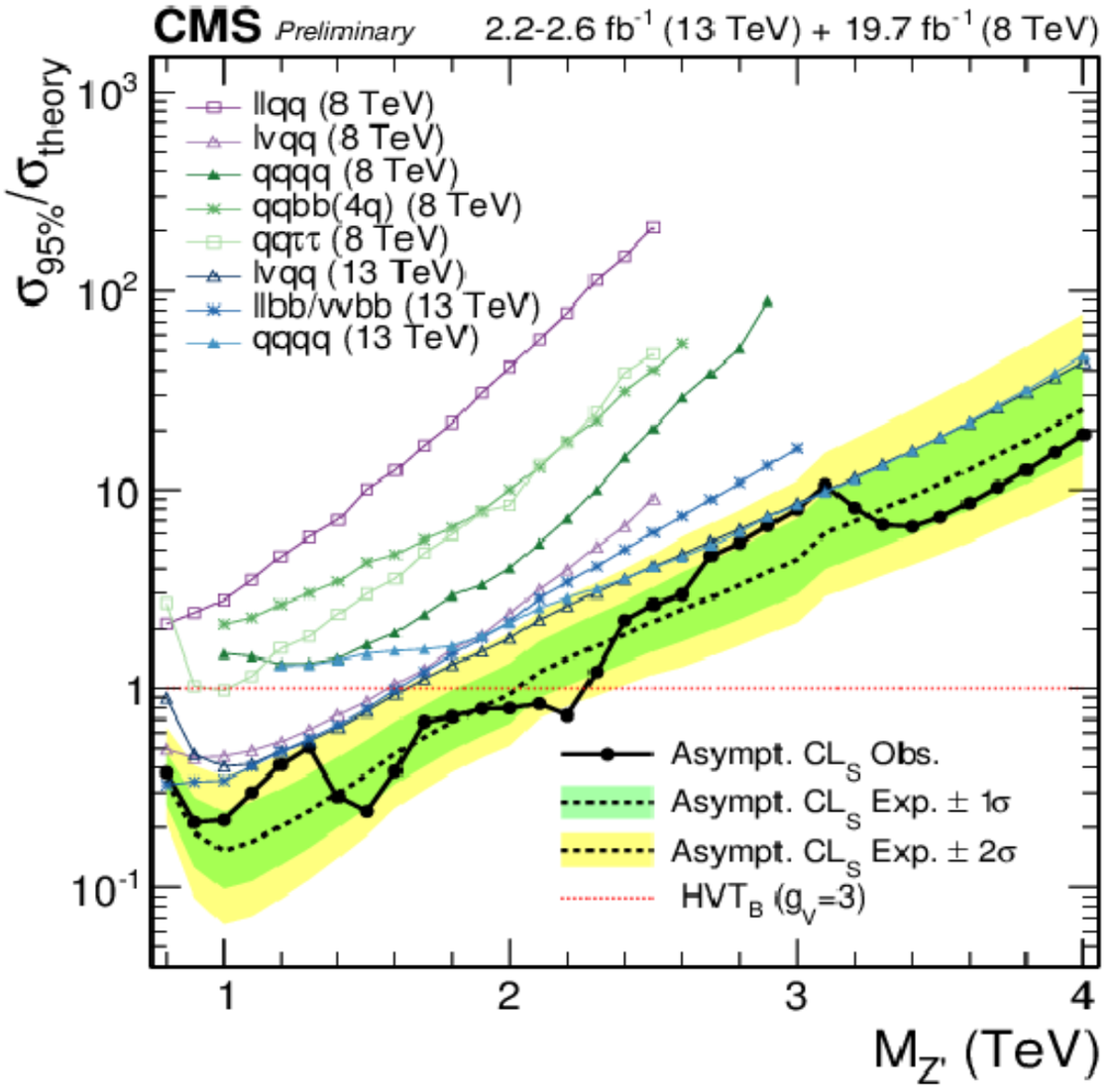
subjet b-tag double b-tag

Diboson Combination @13 TeV

CMS-PAS-B2G-16-007

signal strength VS M(V')





8 TeV (19.7 fb-1): 3lν, lνqq, llqq, qqqq, lνbb, qqbb/qqqqqq, qqττ

13 TeV (2.2-2.6 fb-1) : lνqq, qqqq, llbb, lνbb, νν̄bb

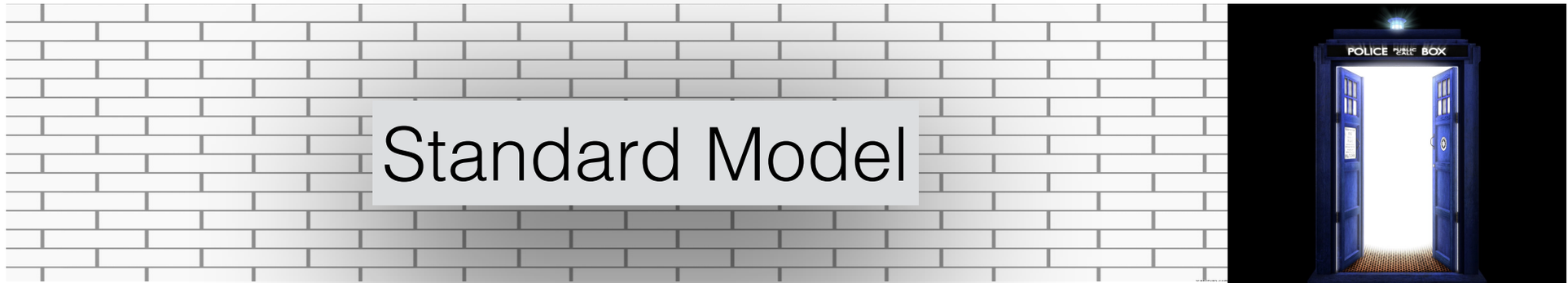
HVTB with gV=3

Excluding W' and Z' with masses up to about 2.3 TeV (HVT model B)

The key message of my talk in 3 points

- Searching for heavy resonances is one of the most direct ways to find new physics at TeV scale
- Rich phenomenology and final states VV,VH,HH: clear experimental signatures and allows cross check among different channels
- No significant excess observed in data (yet!)

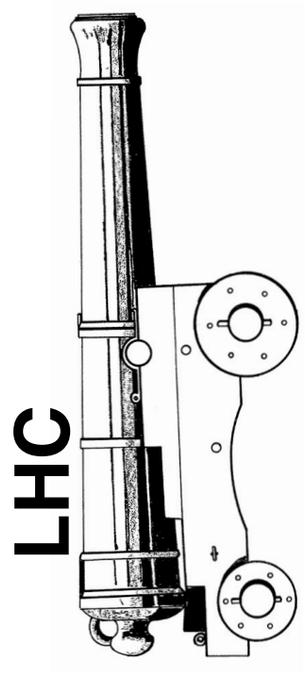
Stay tuned: exciting diboson results in preparation with the 2016-17 LHC data !!



backup

Introduction

- Phenomenology of diboson resonances
- Jets substructure algorithms
- V-tagging and H-tagging
- Resonance searches in the VV final state
- Resonance searches in the VH final state
- Resonance searches in the HH final state
- Conclusion and perspectives



Phenomenology of diboson resonances

- One of the most direct ways to find new physics at the TeV scale
- Clear experimental signature: peak in the VV invariant mass spectrum
- Experimental challenges:
  - many final states: WW, WZ, ZZ, VH, HH
  - different channels, different physics: all-hadronic, semileptonic
  - high energy: merging object, huge backgrounds

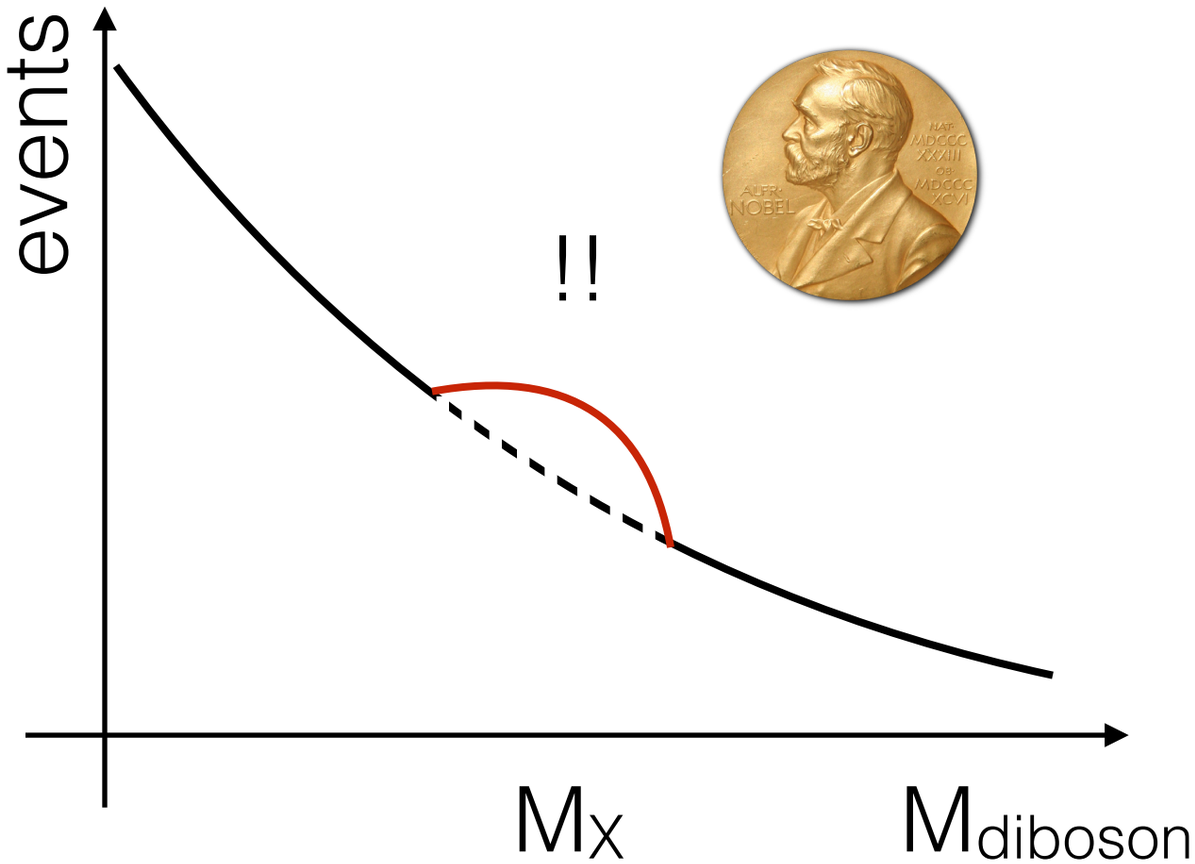
Resonances Production Topology

peak on a smoothly falling Standard Model background

Search for narrow resonances:

$\Gamma(\text{res}) < \sigma\ (\text{exp})$

usually: Drell-Yan or QCD Multijet (leptonic/hadronic final states)

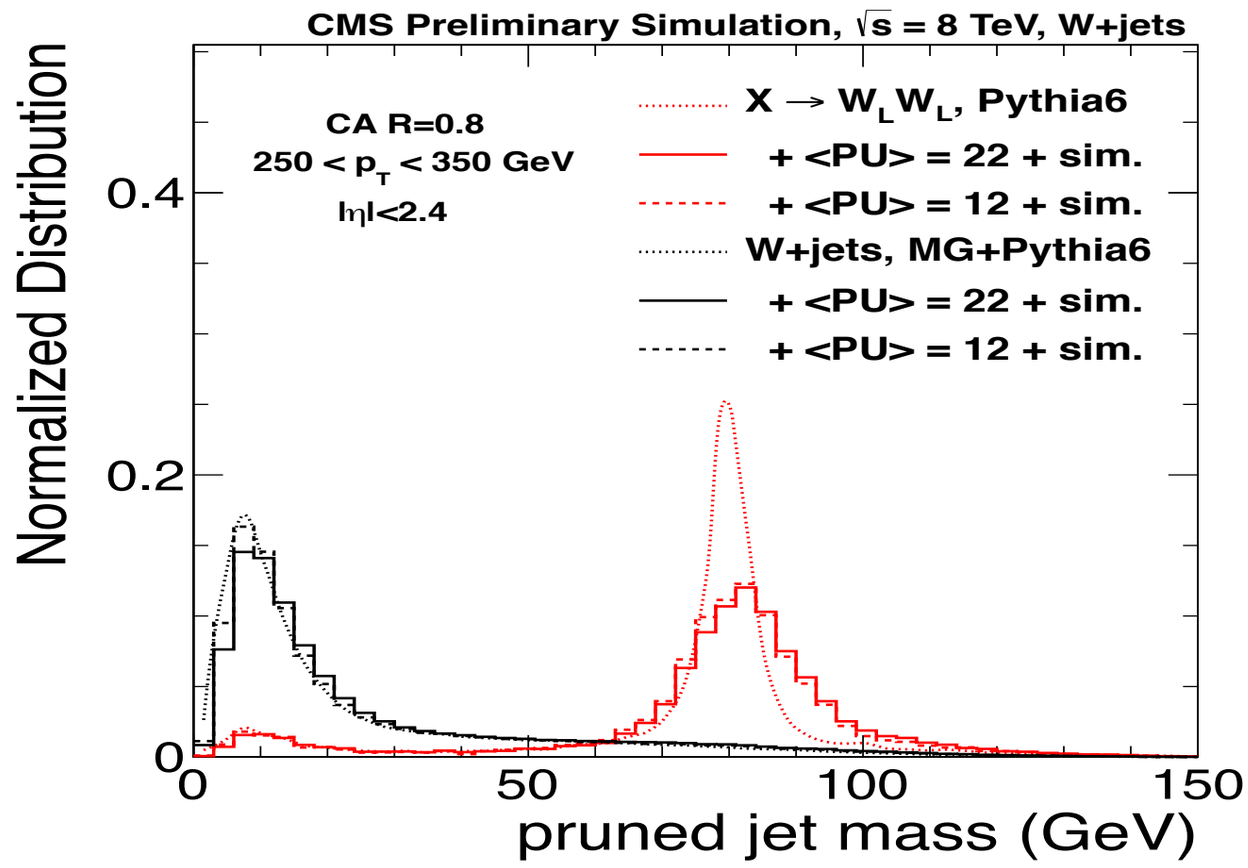


Jet Substructure - basic concepts

Pruning

[Phys.Rev.D 80 051501]

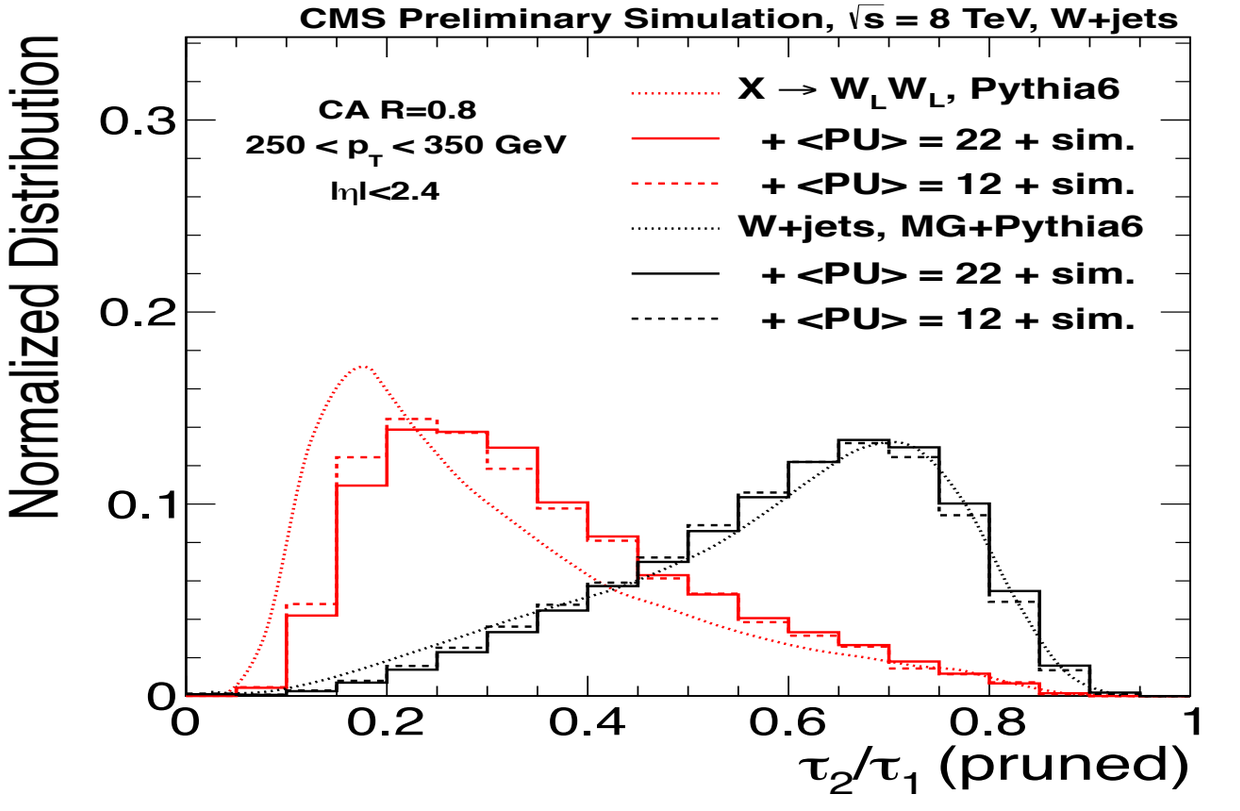
attempts to remove from the jets those constituents that are unlikely to be associated with the jet



N-Subjettines

[JHEP03(2011)015]

Quantifies to what degree jet can be regarded as a jet composed of N jets
Discriminate a composite jet w.r.t. a “standard” QCD jet



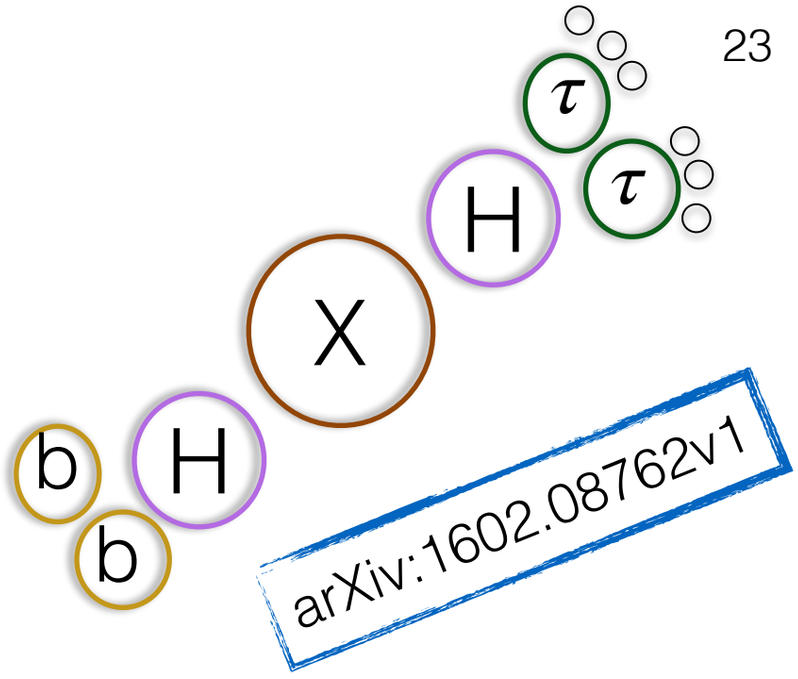
CMS-PAS-HIG-13-008

$HH \rightarrow b\bar{b}\tau^{+}\tau^{-}$

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

See Camilla's talk this afternoon!

- semileptonic τ decay : $\tau(\mathbf{h})\tau(\boldsymbol{\mu})$, $\tau(\mathbf{h})\tau(\mathbf{e})$ BR~23%
- background: mainly ttbar, data driven
- theory: Radion spin-0 to HH
- Isolated tau



arXiv:1602.08762v1

H $\rightarrow \tau\tau$ reconstruction

Event Selection

leptons

$p_{T,\tau vis} > 35$ GeV, $p_{T,\ell} > 10$ GeV
$0.1 < \Delta R_{\ell,\tau vis} < 1.0$, $m_{vis}(\ell, \tau_{vis}) > 10$ GeV
$|\vec{p}_T^{miss}| > 50$ GeV

taus

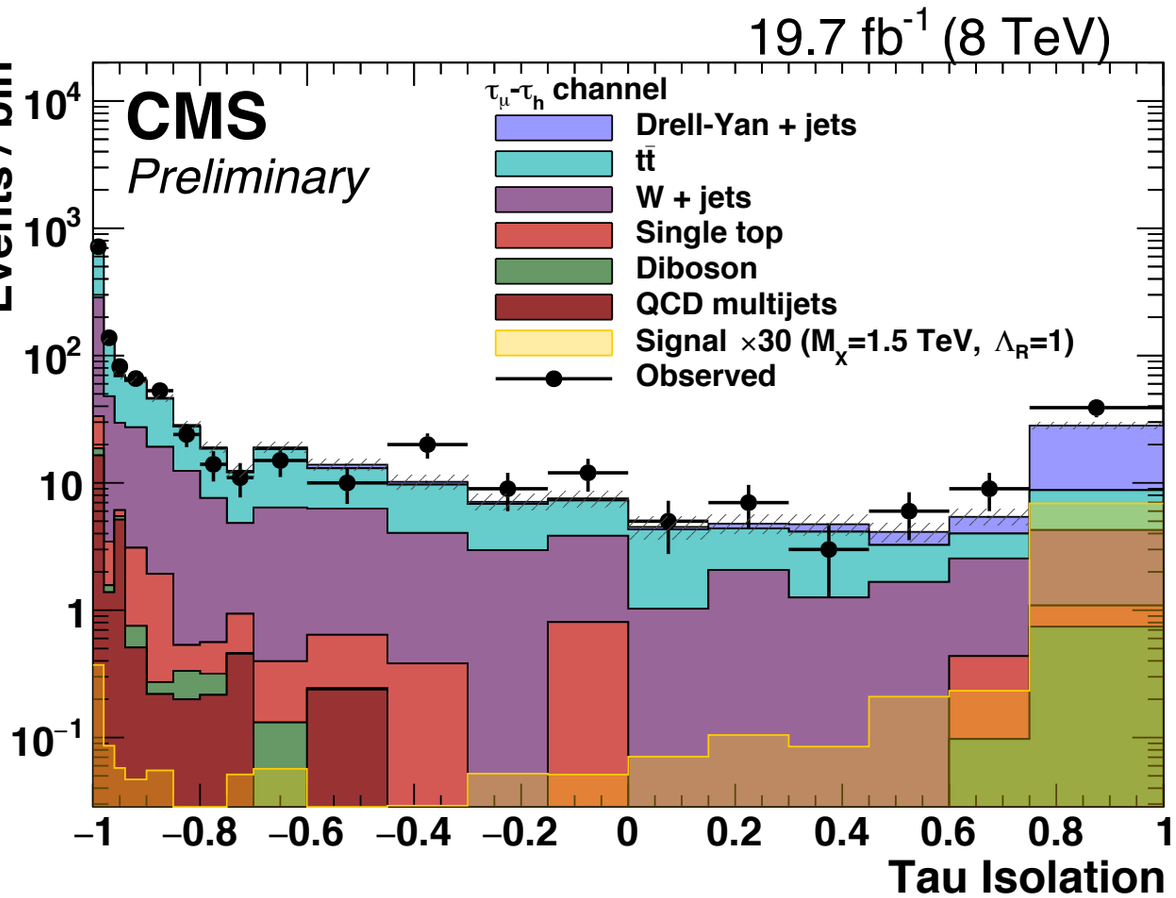
$p_T(\tau\tau)$ from SVFit > 100 GeV

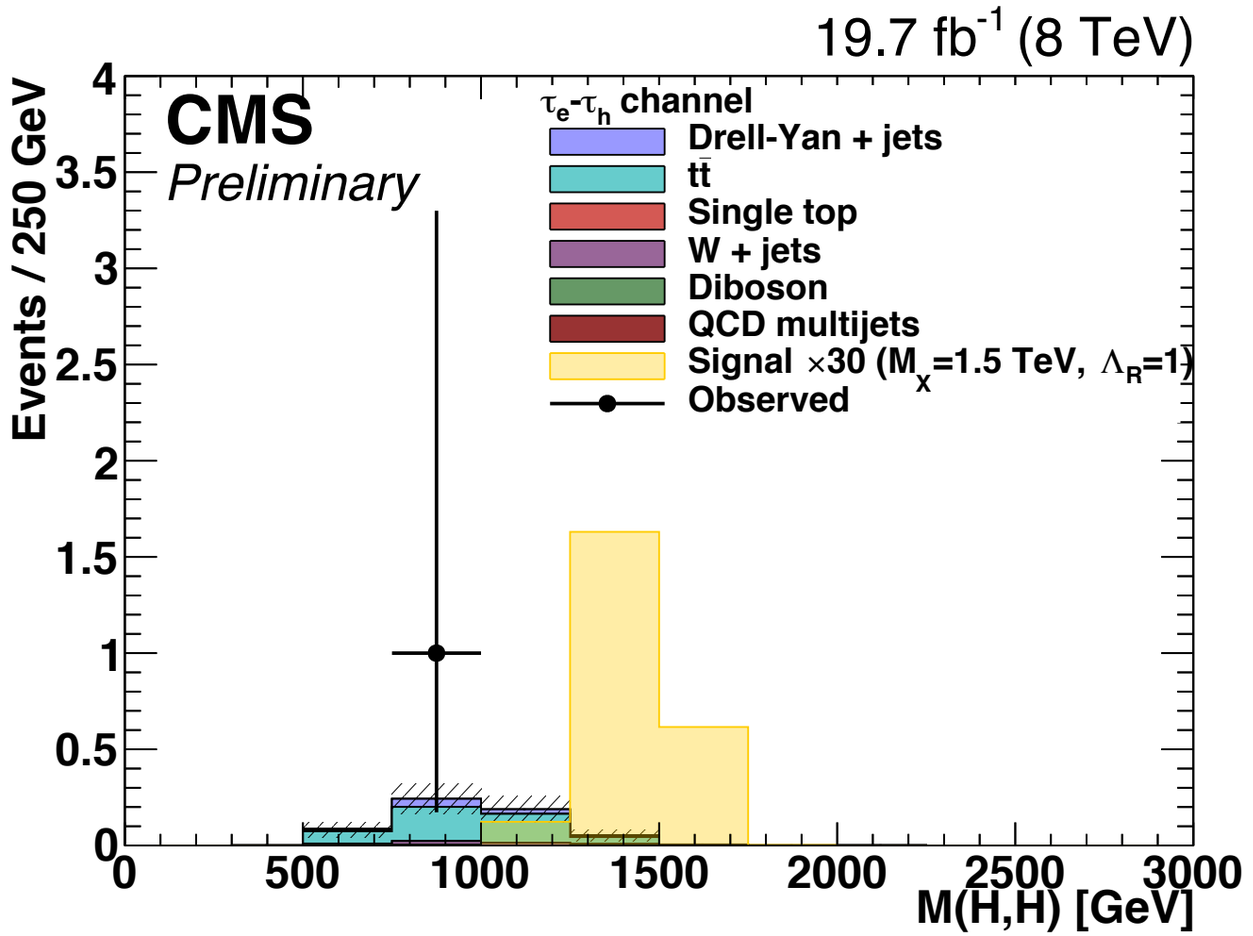
jets

$p_{T,jet} > 400$ GeV and $|\eta_{jet}| < 1$
$100 < m_{jet}^{P} < 140$ GeV, $\tau_{21} < 0.75$
Higgs-b-tagging: 1 CSVL-tagged fat jet if $\Delta R(sj1,sj2) < 0.3$
or 2 CSVL-tagged subjets if $\Delta R(sj1,sj2) > 0.3$
$N_{b\text{-tagged jets}} = 0$

- algorithm for $\tau\tau$ invariant mass reconstruction
- Maximise likelihood on event-by-event basis
- consider the MET as coming entirely from the τ invisible products
- Measured METx and METy combined including terms for the τ decay visible +MET resolution

$HH \rightarrow b\bar{b}\tau^{+}\tau^{-}$

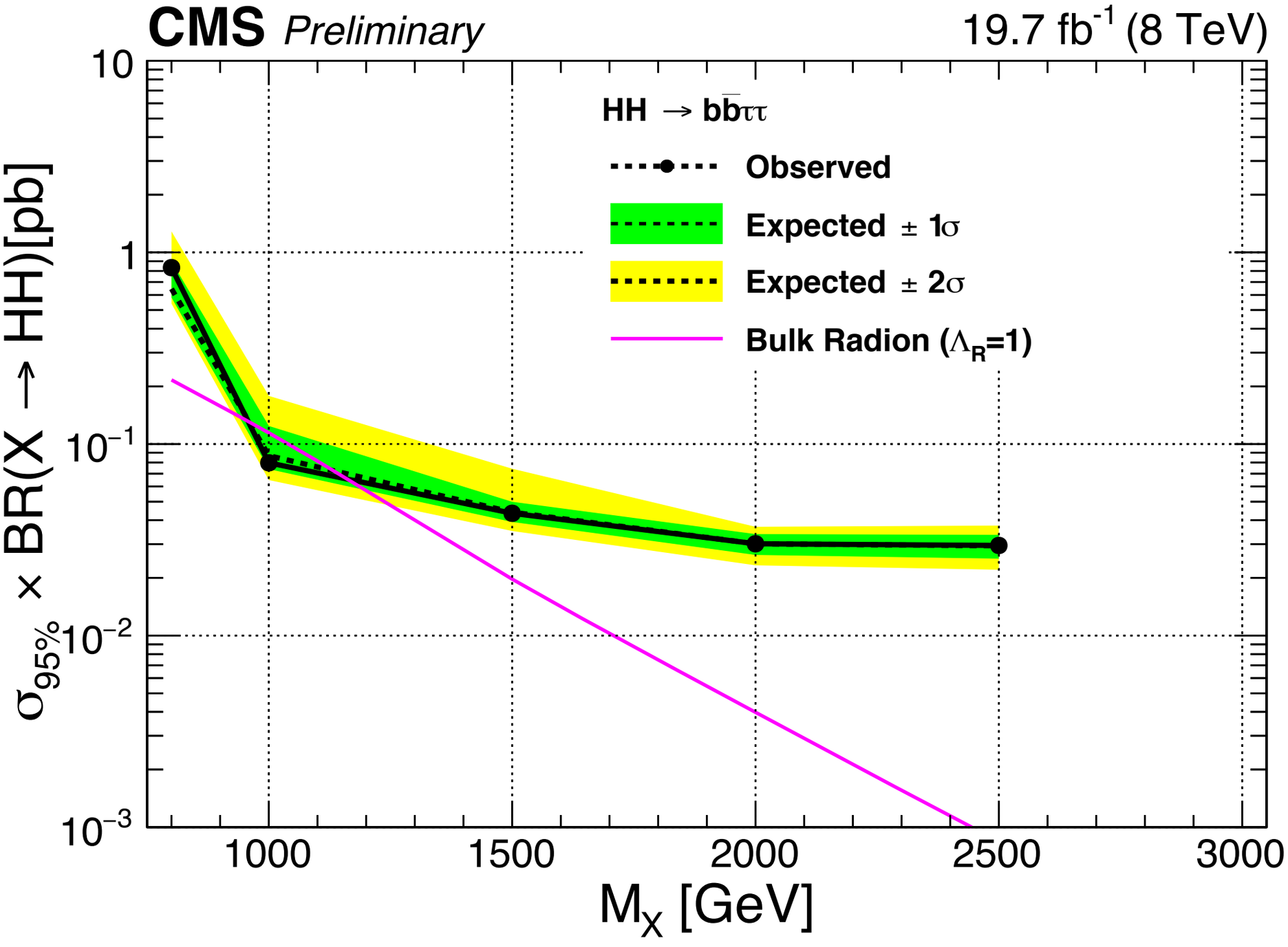




tau isolation in the μ-had channel
data/MC comparison
nice agreement

HH invariant mass

$HH \rightarrow b\bar{b}\tau^{+}\tau^{-}$

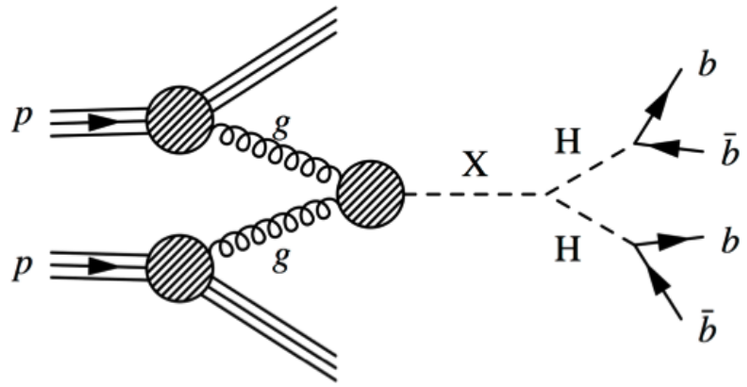


95% Exclusion Limit in the Asymptotic Approximation, spin-0 Radion L=1 ranging from 850 to 30 fb for resonance masses between 800 and 2500 GeV

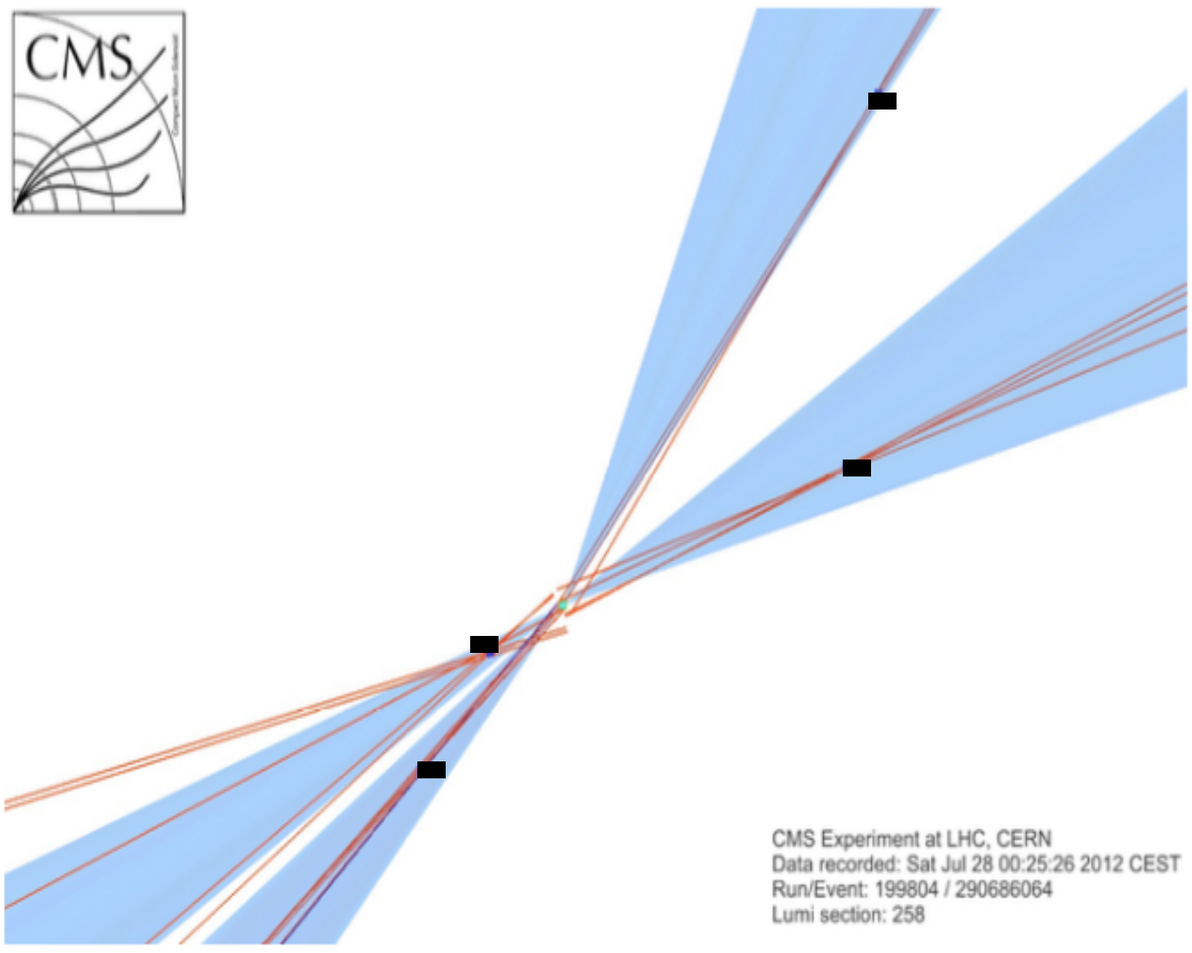
$HH \longrightarrow b\bar{b}b\bar{b}$

NEW!

B2G-PAS-16-008



Data: L = 2.3 fb^{-1}. $\sqrt{s}$ = 13 TeV



- highest HH branching ratio
  BR(H → bb) ~33% -> very high statistics
- huge QCD multijet background
- rely on the power of the newest b tagging algos
- model independent, benchmark models:
  bulk Graviton (spin2) and Radion (spin0)

Event Selection

- at least 2 jets, pT > 200 GeV, |η| < 2.4
- τ21 < 0.6
- double b tag > 0.6 (eff ~65% for bb pairs)
- subjet btagging CSVloose > 0.6 (~50%) *or*

Signal Extraction: two parallel approaches

1) subjet b tagging + *smoothness test*
2) double b tagging + *Alphabet*

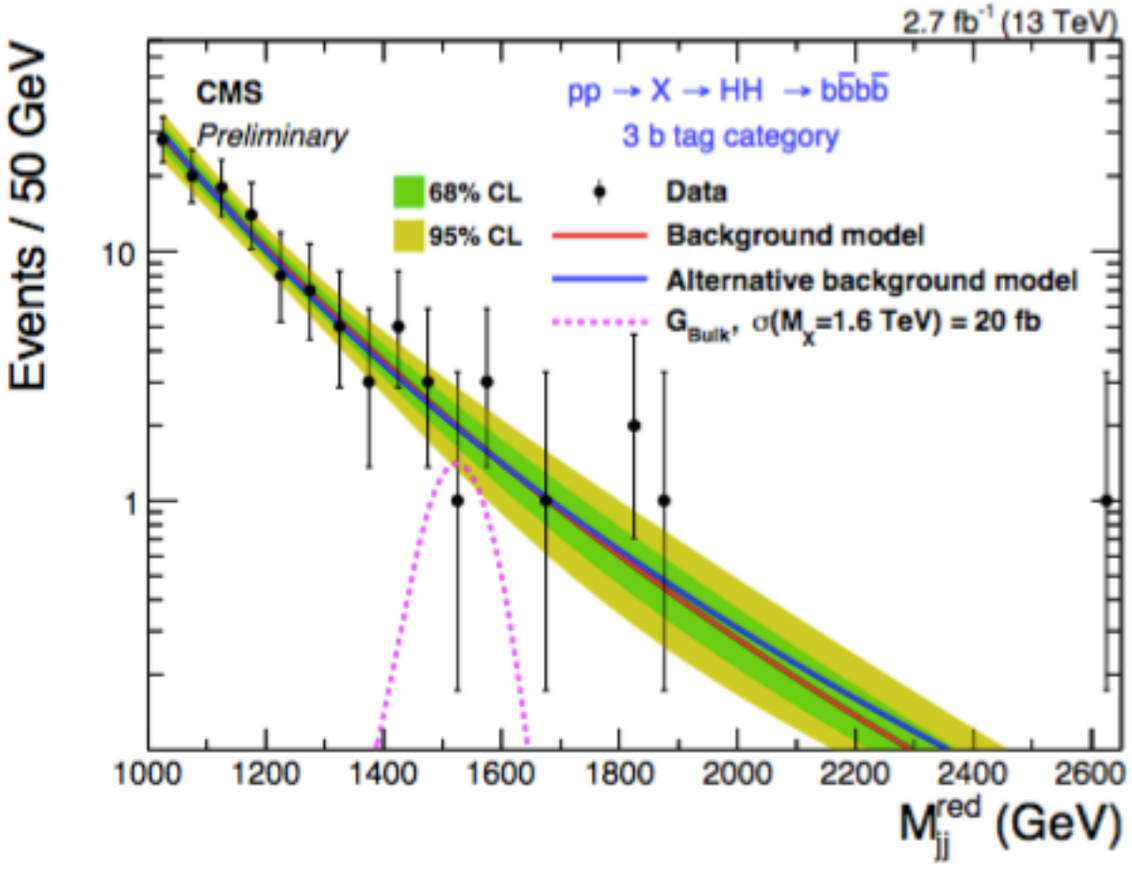
see next slide…

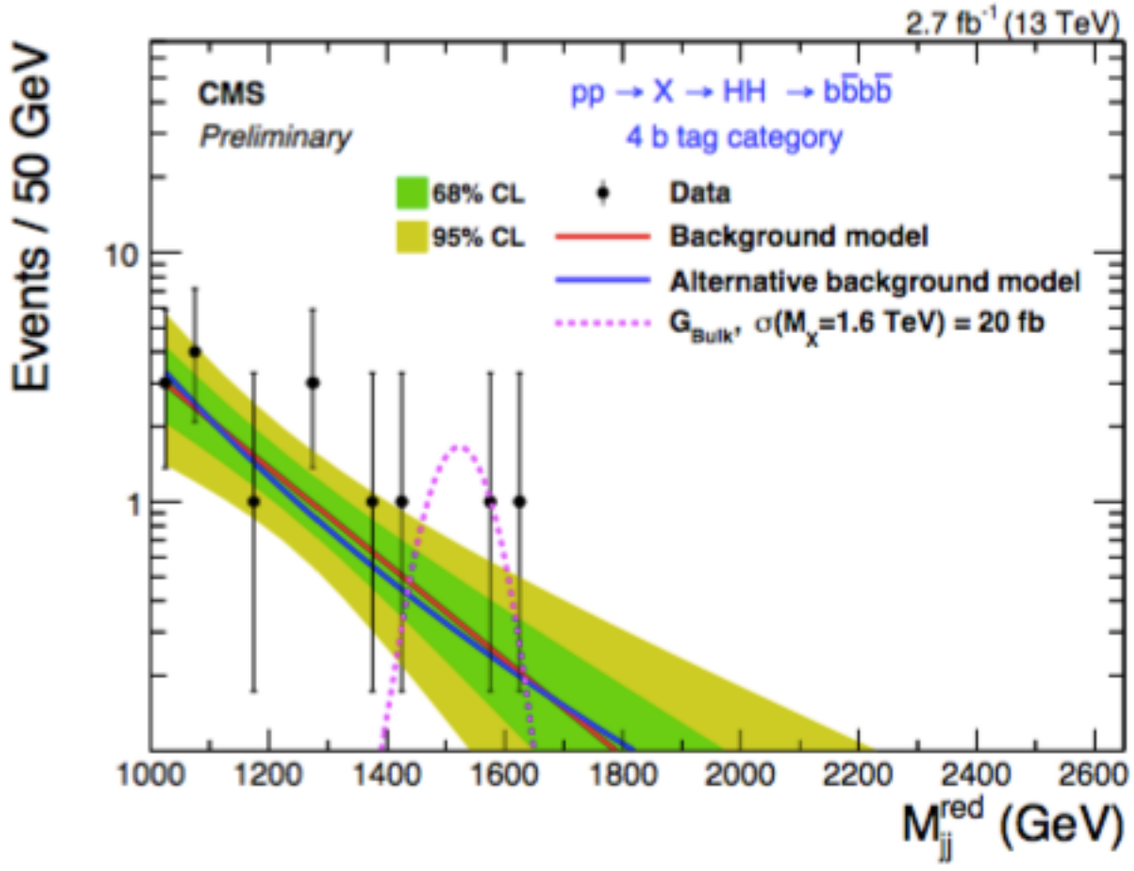
HH → $b\bar{b}b\bar{b}$: "smoothness test"

NEW!

Sub-jet b tagging +smoothness test results M_{jj}^{red} >1TeV

$$M_{jj}^{red} = M_{jj}-(M_{j1}-M_H)-(M_{j2}-M_H)$$





- Background only hypothesis VS. M_{jj}^{subtr}
- Fit: levelled exp w/ 68% and 95% CL bands
  exponential
  power law (cross checks)

M_{jj}^{red} :
resolution ~8-10% better @1-3TeV

$$\frac{dN_{\text{Background}}}{ds} = N_B \cdot e^{-ax/(1+a\cdot b\cdot x)}$$

VH Resonances: Strategy Overview

CMS-PAS-B2G-16-003

- Full 2015 dataset, L=2.17–2.52 fb^{-1} @$\sqrt{s}$=13 TeV
- Five channels: Z(ee)H(bb), W(en)H(bb), Z(μμ)H(bb), W(μn)H(bb), Z(nn)H(bb) + c.c.

Objects

Higgs Reconstruction

- AK8 jet
- p_T>200 GeV,
- pruned mass 105<mJ<135 GeV (jec)
- 1/2 b-tag sub-jets.

$\ell\ell$+bb Selection

- $p_T(\mu)$ > 55 GeV, $p_T(e)$>135 GeV
- 70< M_{ll} < 110
- $p_T(Z)$ > 200 GeV
- |Δη(ll,jet)|<5
- Δϕ (ll,jet) >2.5

$\ell\nu$+bb Selection

- pT(μ) > 55 GeV, pT(e)>135 GeV
- veto extra leptons
- $\not{E}_T$>80 GeV
- $p_T(W)$ > 200 GeV

$\nu\nu$+bb Selection

- $\not{E}_T$>200 GeV; p_T>200 GeV
- Δϕ(jet, $\not{E}_T$) > 2
- b-jet veto

VH Resonances: Strategy Overview

CMS-PAS-B2G-16-003

- Full 2015 dataset, L=2.17–2.52 fb^{-1} @$\sqrt{s}$=13 TeV
- Five channels: Z(ee)H(bb), W(en)H(bb), Z(μμ)H(bb), W(μn)H(bb), Z(nn)H(bb) + c.c.

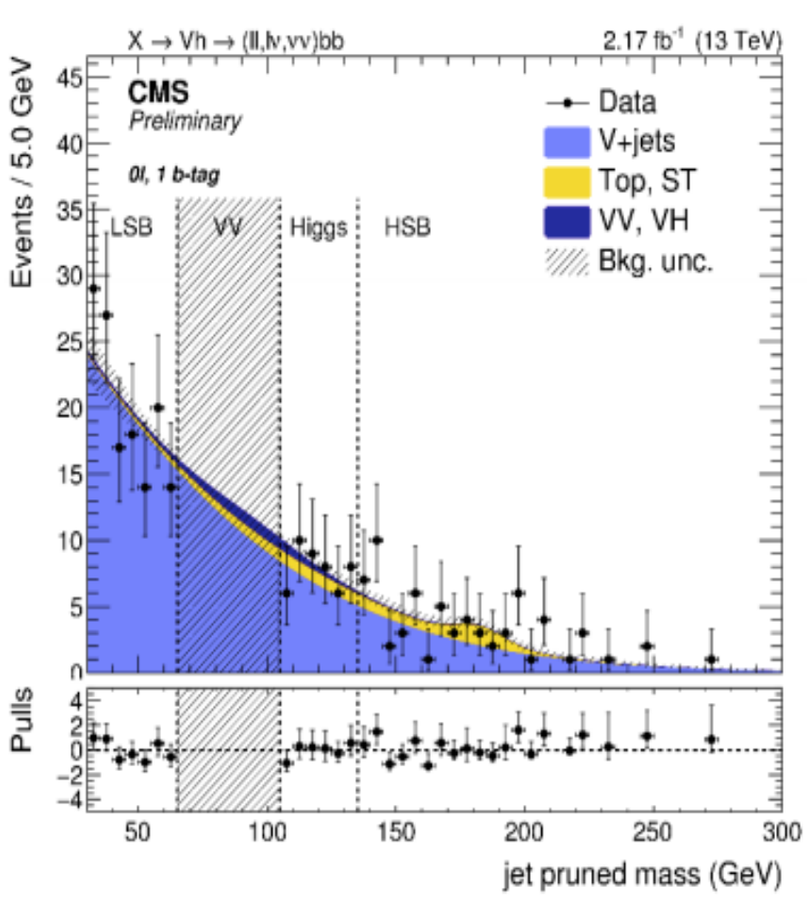
V+jets background

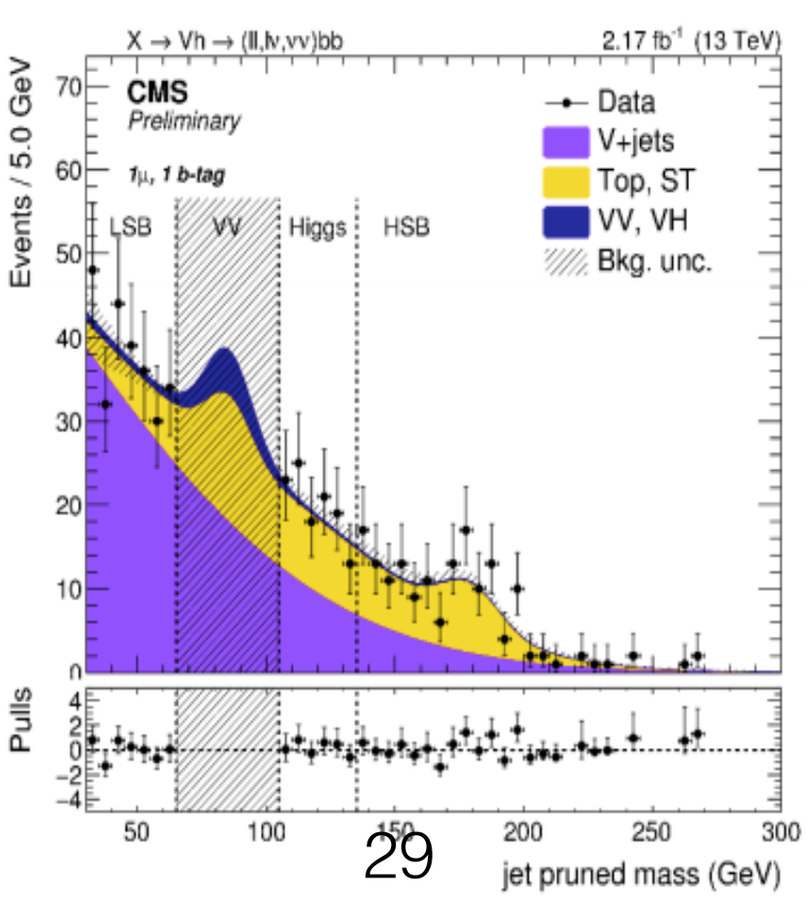
$$N_{SR}^{pred}(m_{\mathrm{Vh}}) = N_{SB}^{data,Vjet}(m_{\mathrm{Vh}}) \times \alpha(m_{\mathrm{Vh}}) + N_{SR}^{MC,Top}(m_{\mathrm{Vh}}) + N_{SR}^{MC,VV}(m_{\mathrm{Vh}})$$

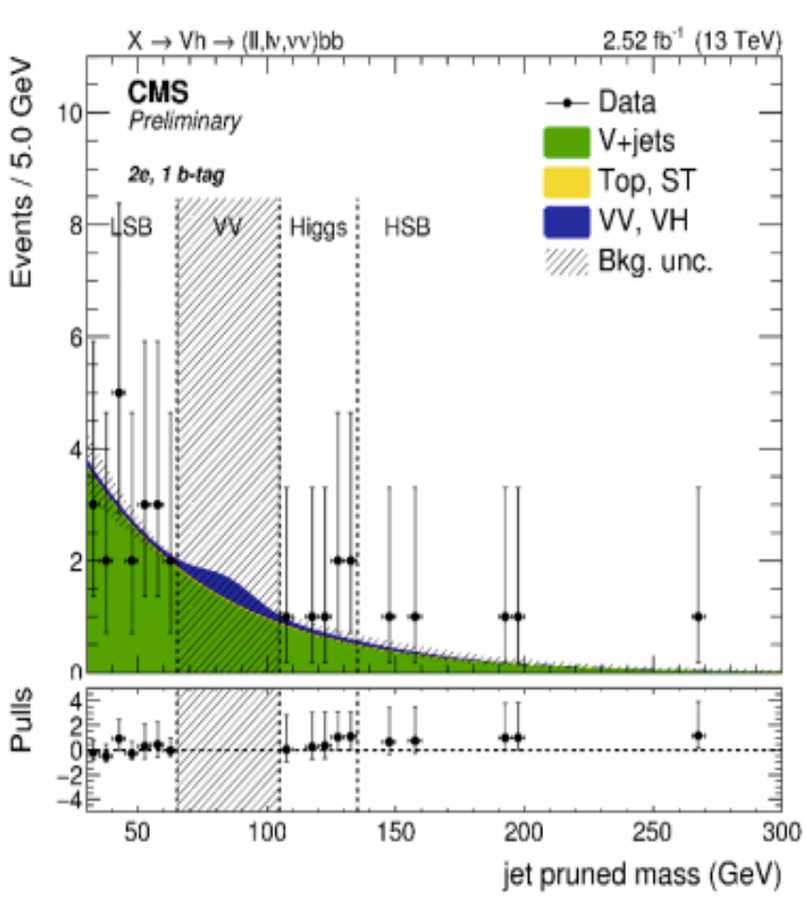
- Main Background (40%/60% W/Z)
- Shape+Normalisation in data using the *alpha method* :
- Jet Mass SideBands
- Separate V+jets from VV (MC) and top (enriched CR)
- Systematics cancels out in the ratio

[from MC]

$$\alpha(m_{\mathrm{Vh}}) = \frac{N_{SR}^{Vjet}(m_{\mathrm{Vh}})}{N_{SB}^{Vjet}(m_{\mathrm{Vh}})}$$



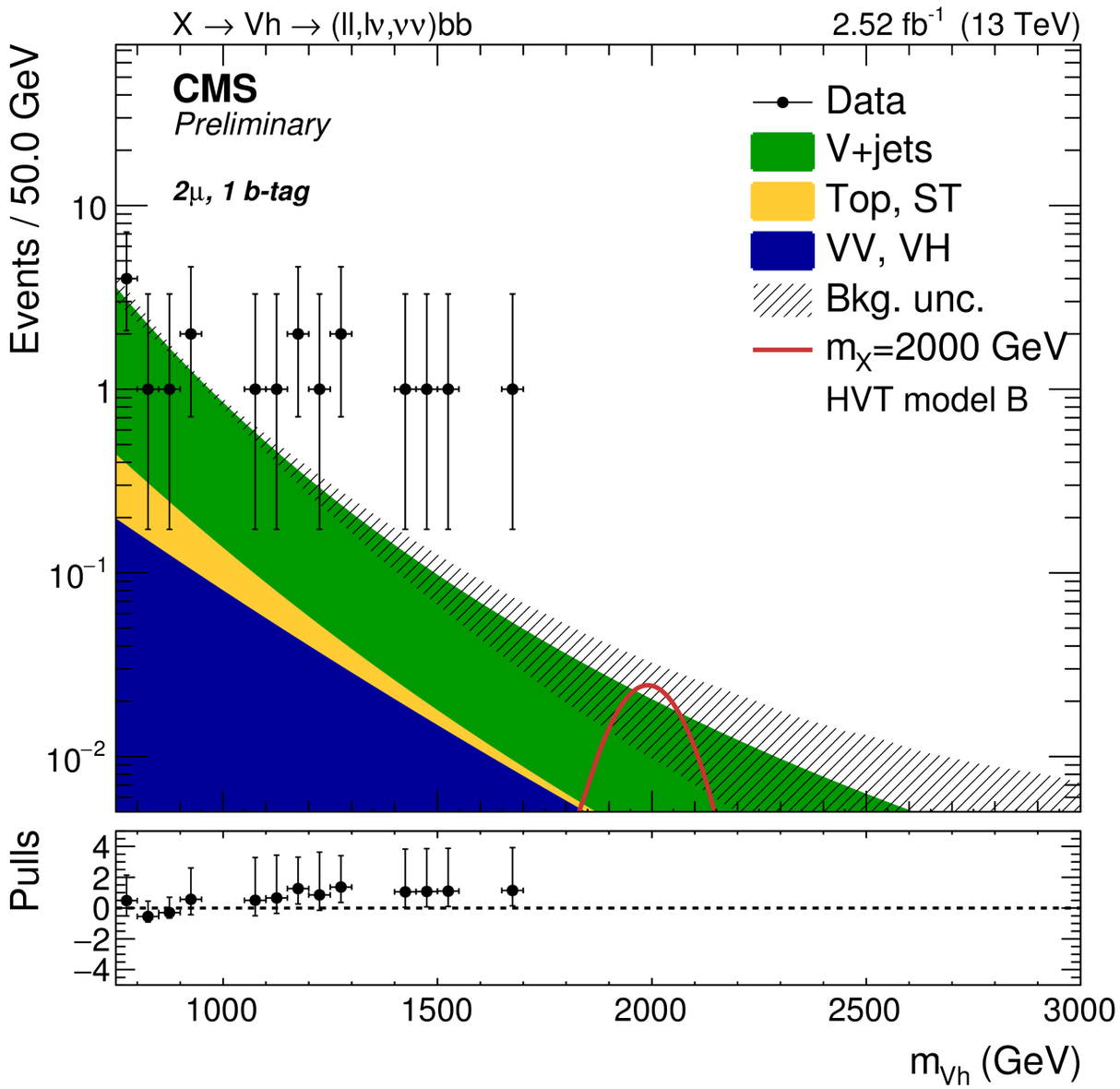




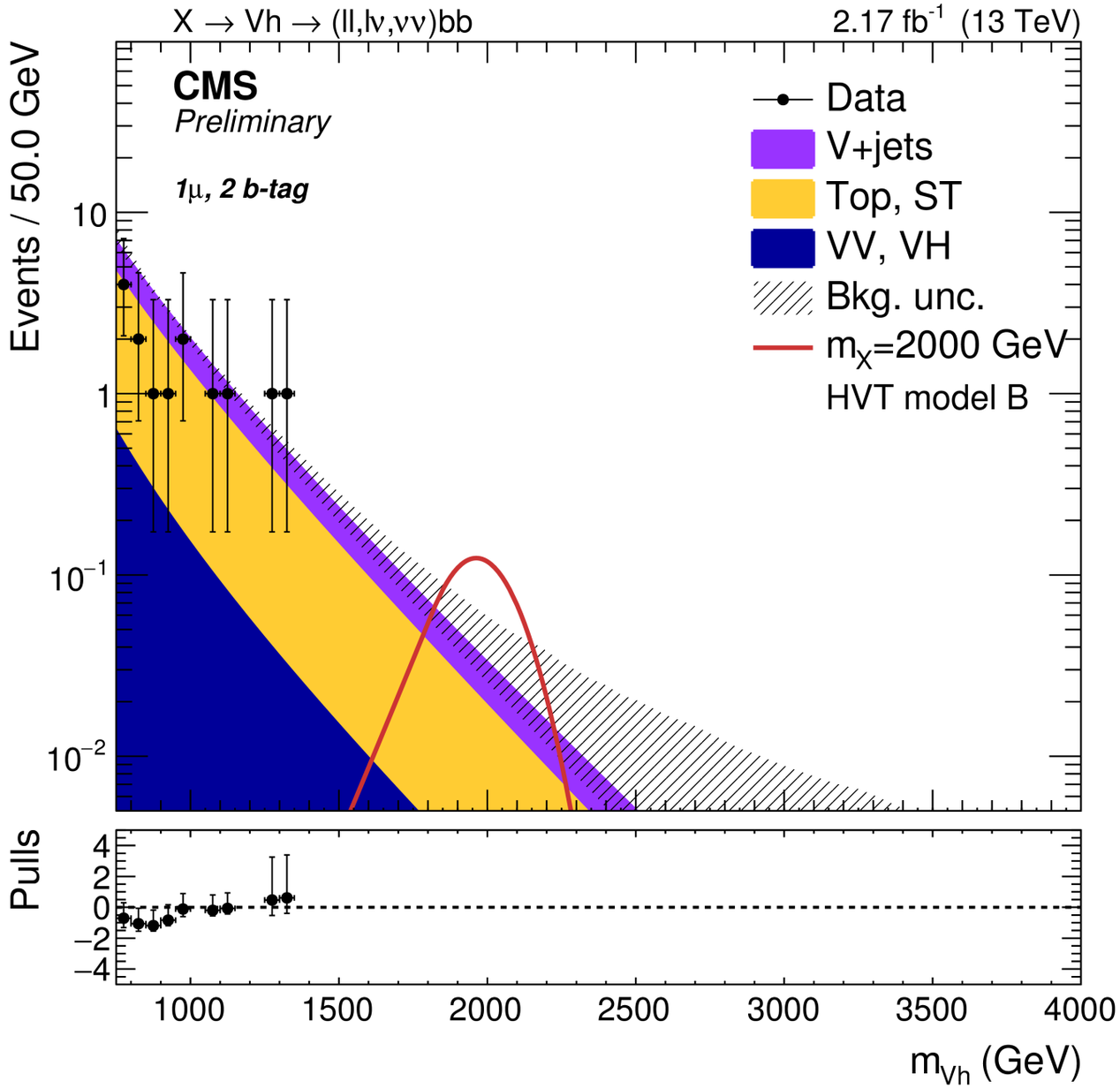
VH Resonances: Results

observed events on Vh invariant mass

CMS-PAS-B2G-16-003



2 muons + 1 b-tag

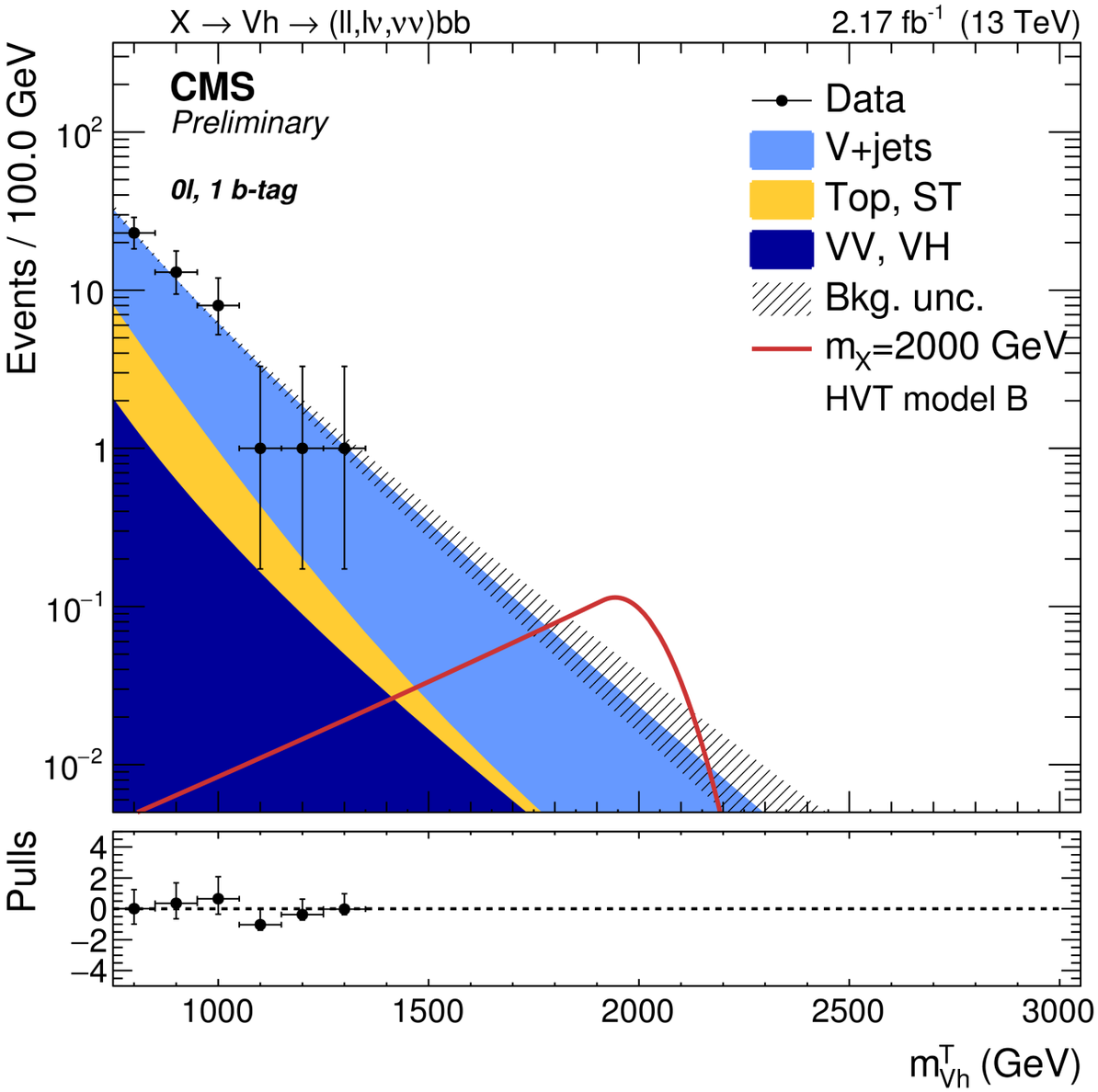


1 muon + 2 b-tag

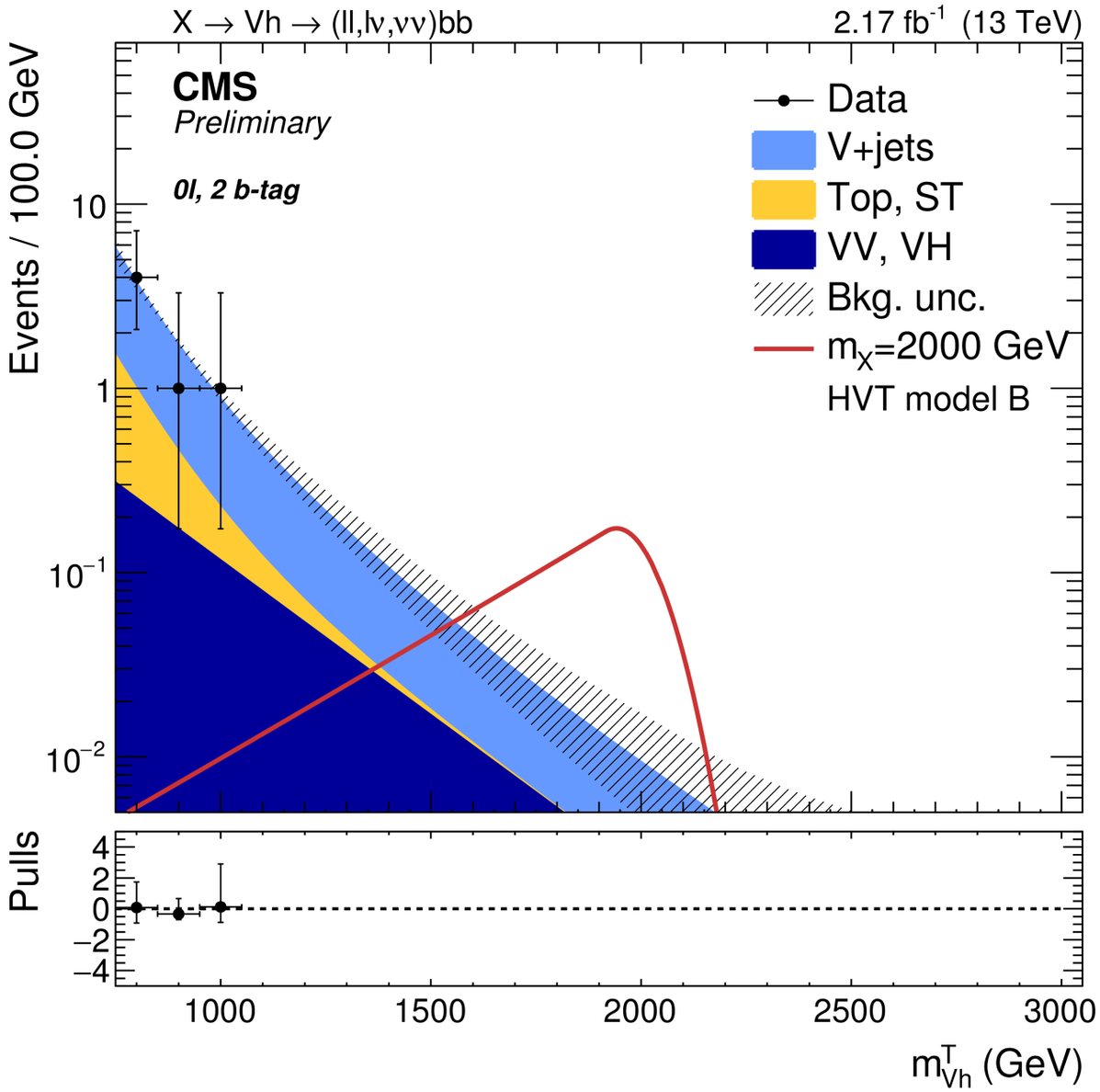
VH Resonances: Results

observed events on Vh invariant mass

CMS-PAS-B2G-16-003



0 lepton + 1 b-tag

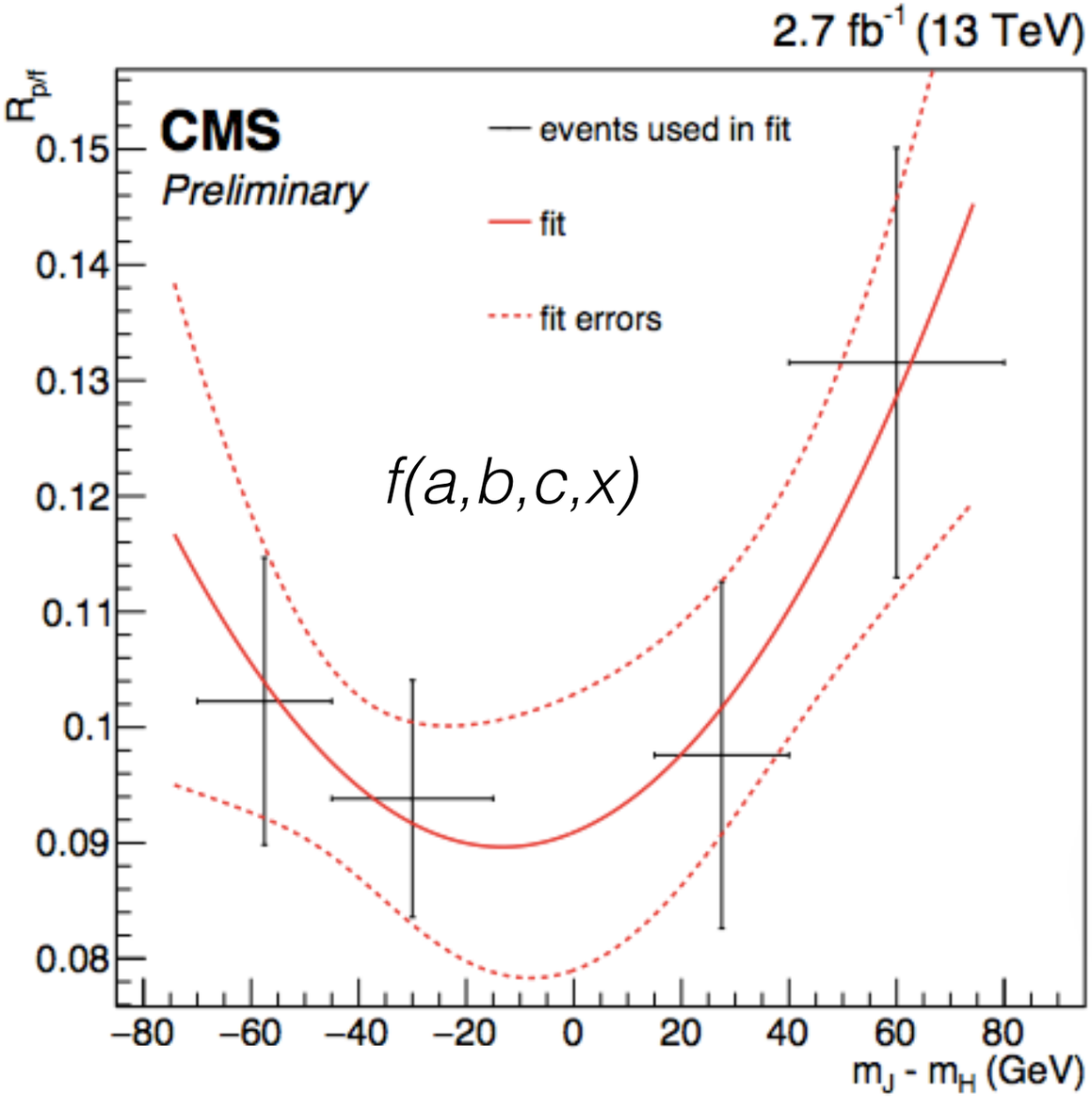


0 lepton + 2 btag

HH ⟶ $b\bar{b}b\bar{b}$: "alphabet method"

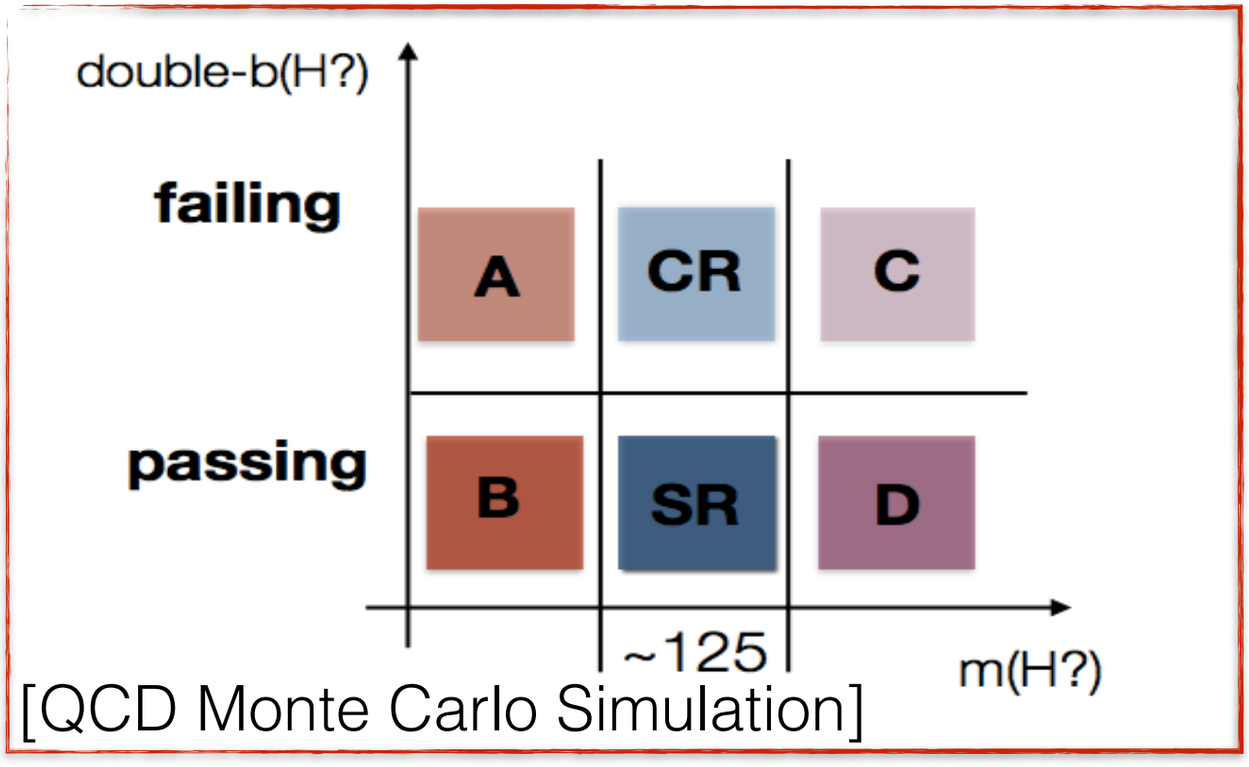
NEW!

Double b tagging + *alphabet* results M_{jj}^{red} >1000 GeV



Quartic fit to R = double b tag pass/fail ratio

two orthogonal variables
- Pruned jet mass
- Double b tagger discriminator



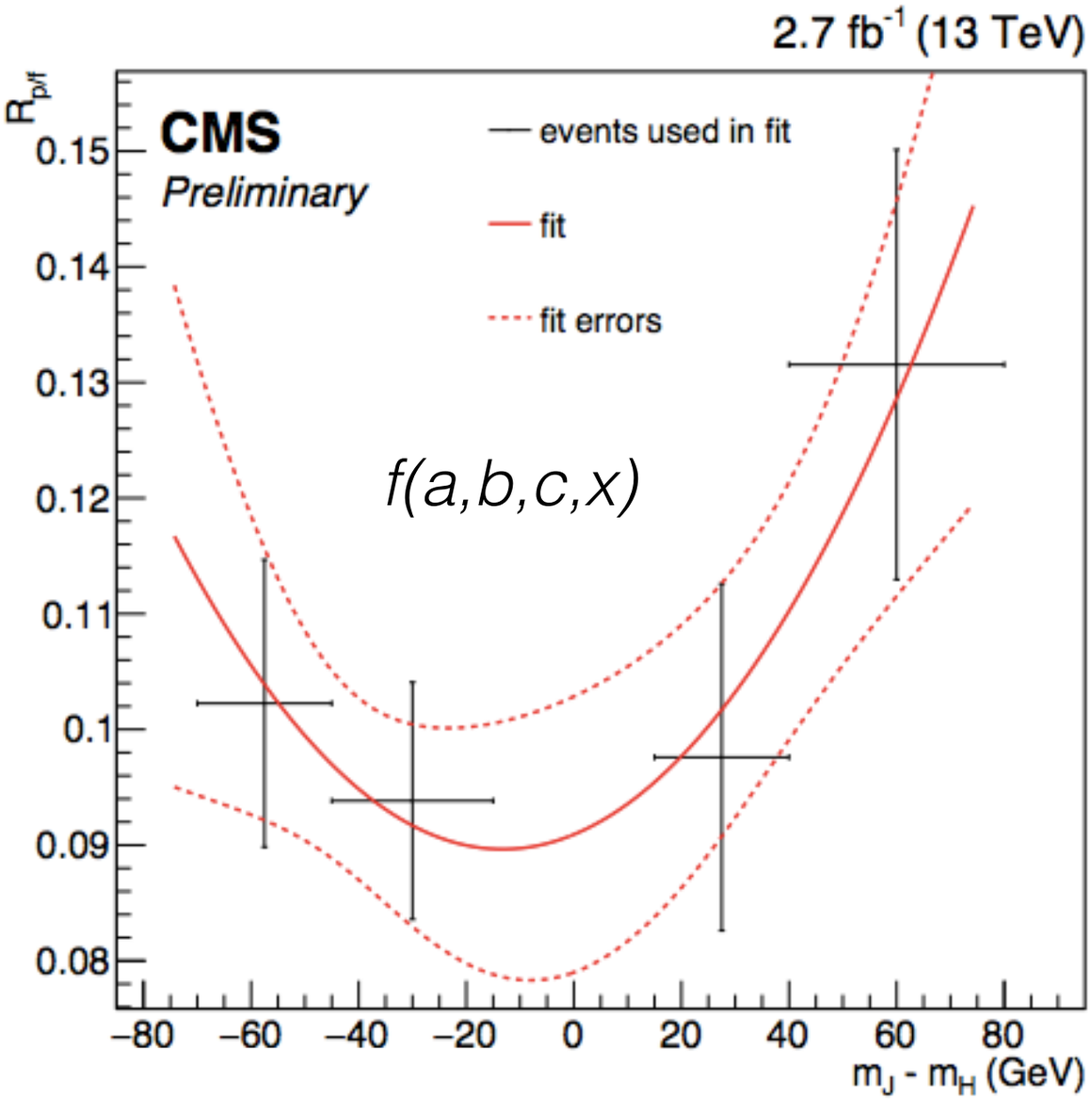
[QCD Monte Carlo Simulation]

- Predicting background normalisation and Mjj shape based on several sidebands (generalised ABCD method)
- R obtained as a function of the pruned mass in the sidebands

HH ⟶ $b\bar{b}b\bar{b}$: "alphabet method"

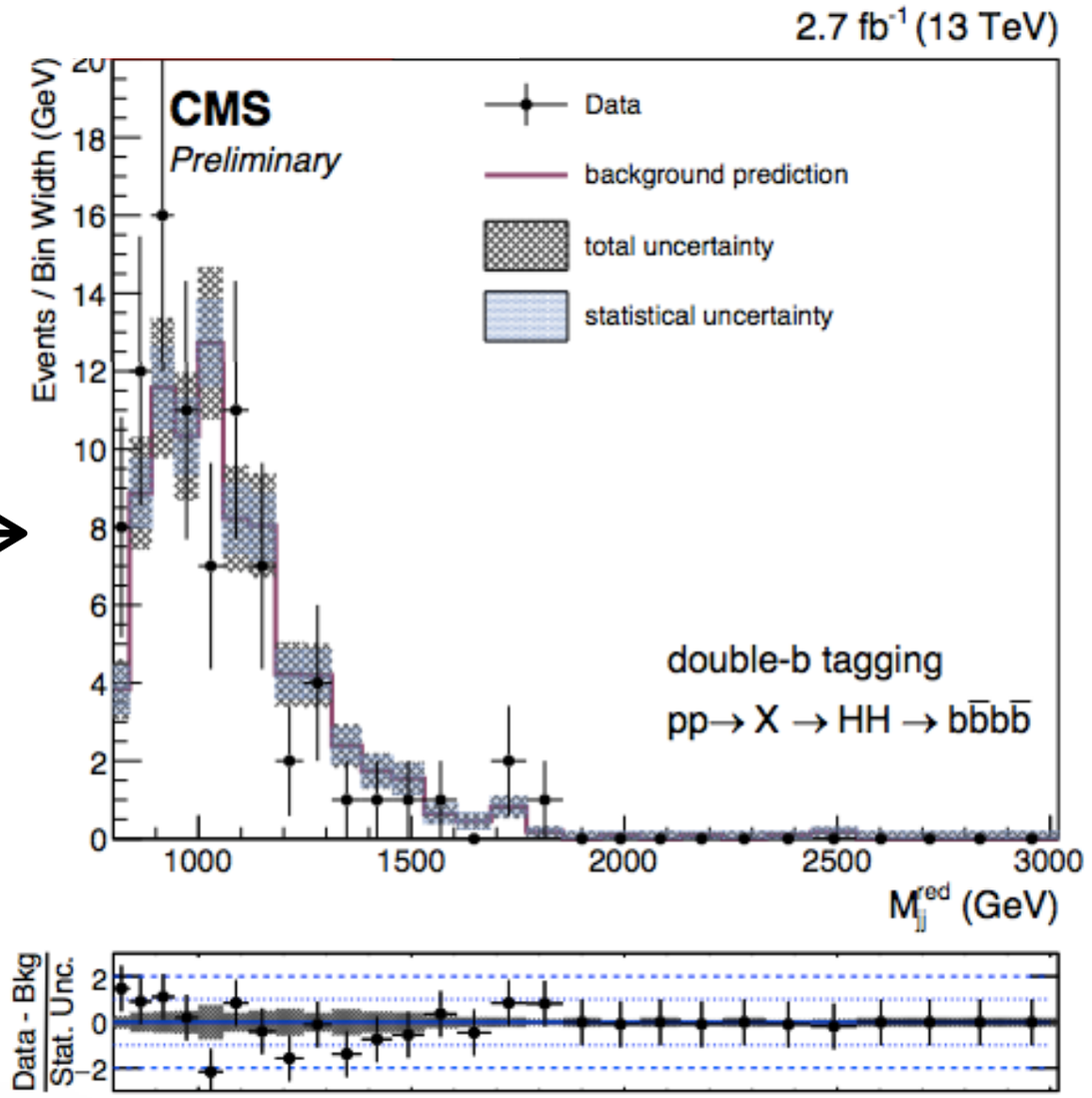
NEW!

Double b tagging + *alphabet* results M_{jj}^{red} >1000 GeV



Quartic fit to R = double b tag pass/fail ratio

predicted M^{red} background distribution in the jj signal region, after applying the "Alphabet" method

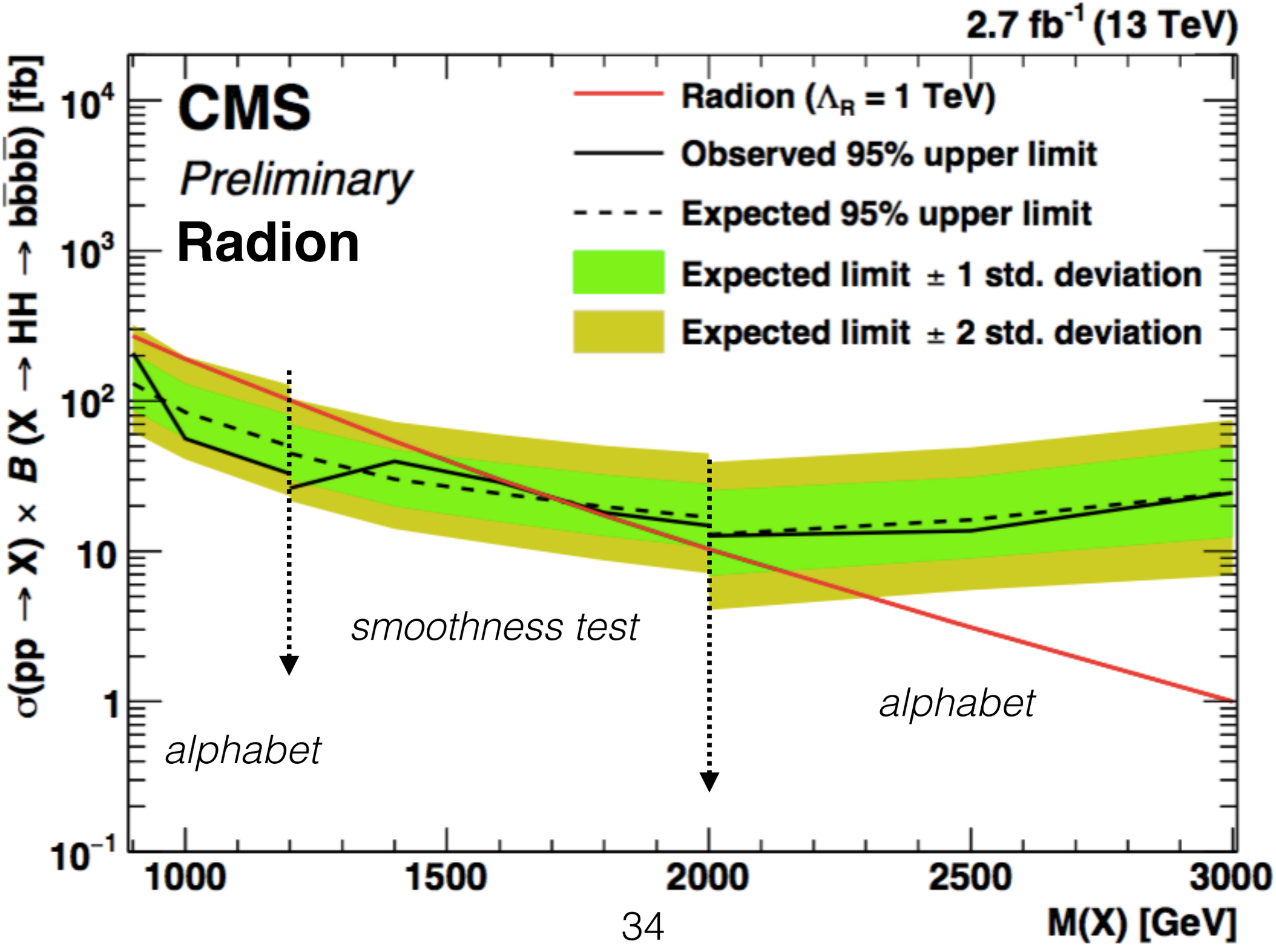


- each event in the anti-tag region is scaled by the appropriate pass fail ratio given its pruned jet mass.

HH $\longrightarrow b\bar{b}b\bar{b}$: limit extraction

NEW!

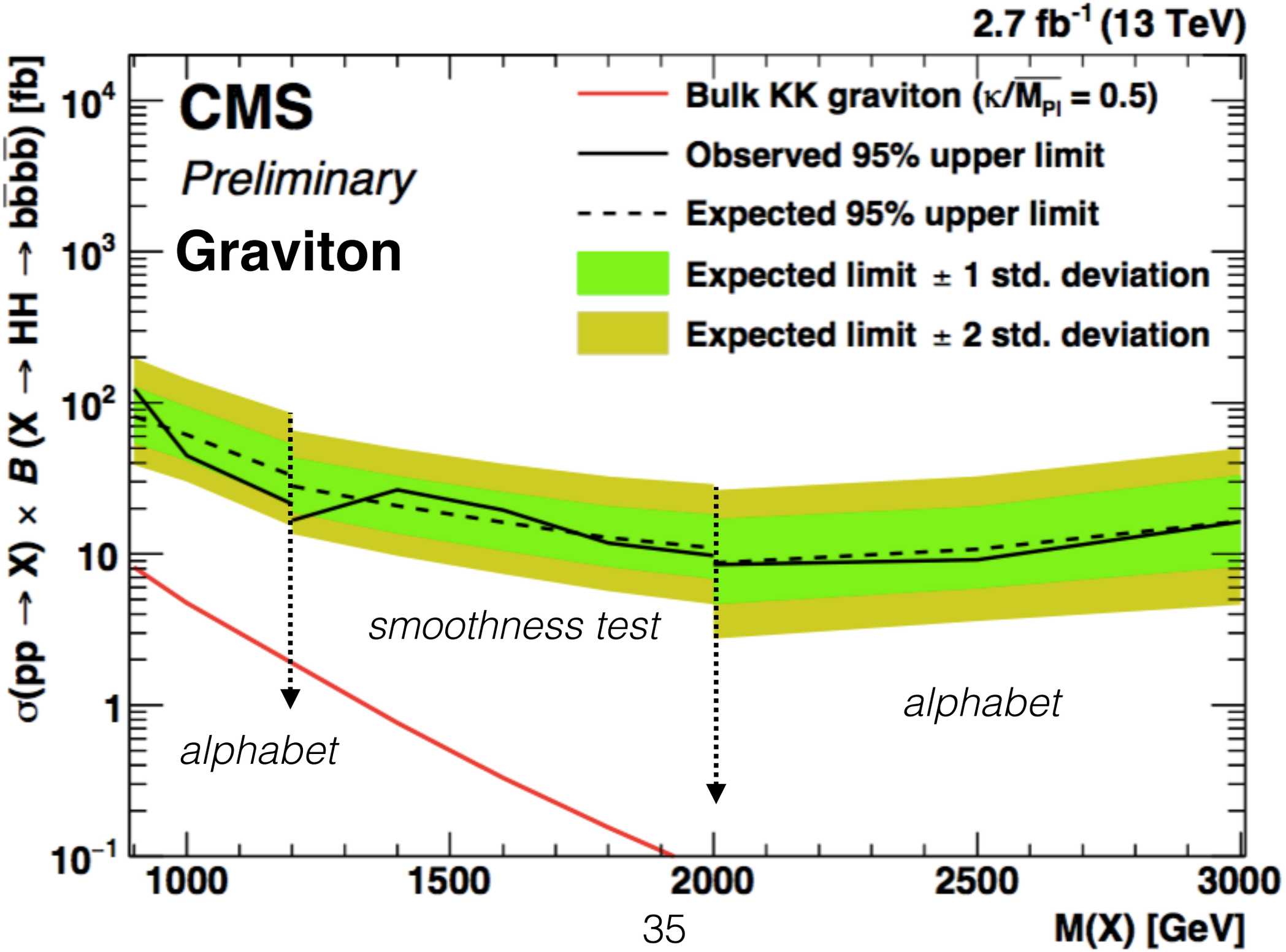
Final results exploiting all the information from the two separate approaches



HH → $b\bar{b}b\bar{b}$: limit extraction

NEW!

Final results exploiting all the information from sub-jet and double b taggers



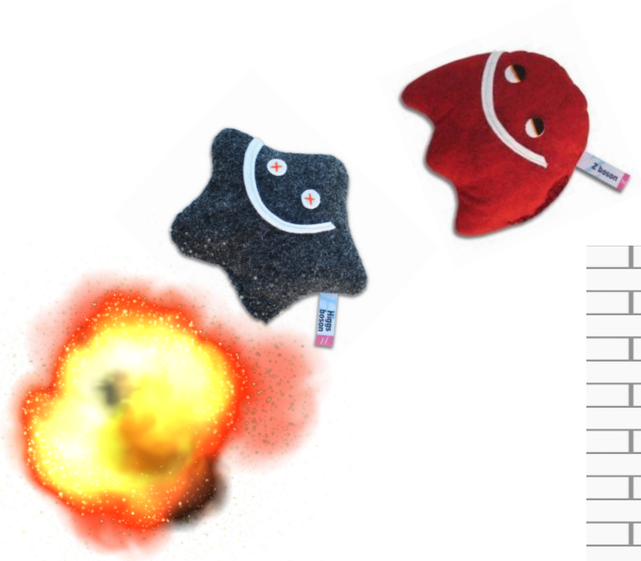
Conclusion and Perspectives

Boosted Higgs bosons are a central part of the new physics searches in CMS in Run II

- Several HH results
  8 TeV (4b, bb$\tau\tau$) and 13 TeV (VH, HH4b)
- Many other HH results in preparation
  (bb$\tau\tau$, bb$\gamma\gamma$, Combination @ 13 TeV)
- Tools and performance well tested and stable
  (double b tagger, subjet, Higgs reconstruction)

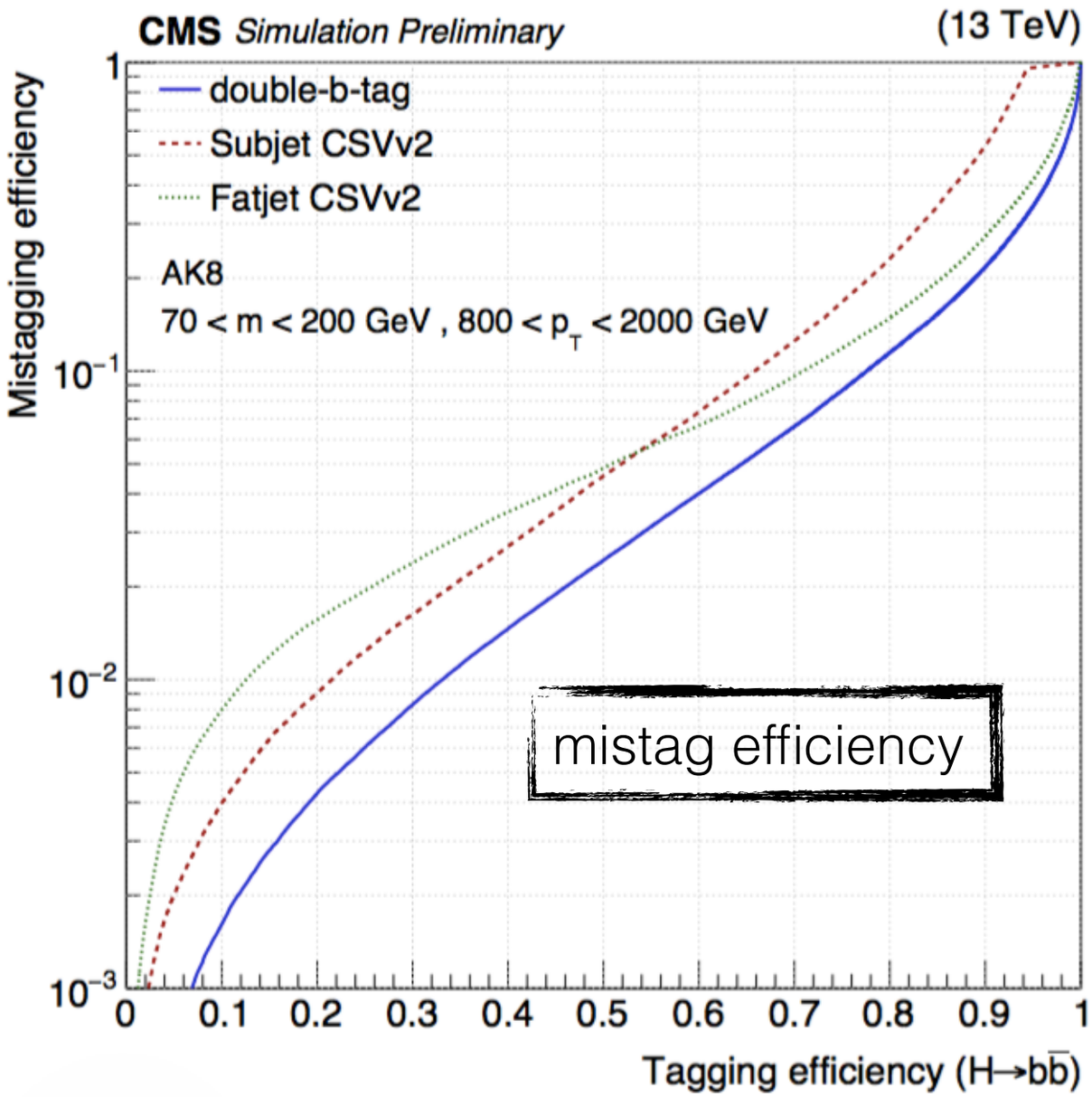
Many other results available in CMS

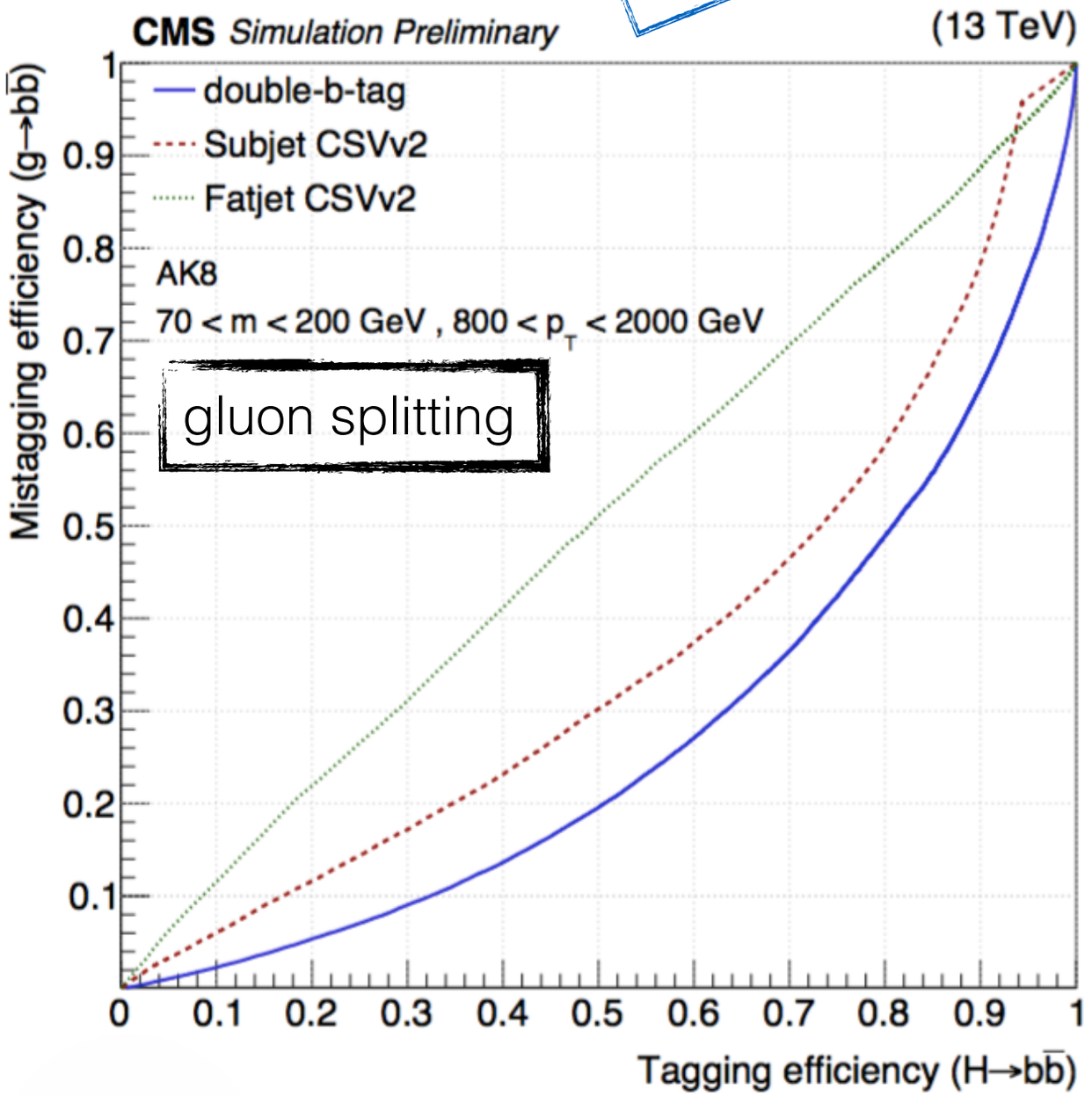
Ready to use the Higgs to finally cross the Standard Model!



Boosted Higgs Boson Reconstruction

CMS-PAS-BTV-15-002





- signal H→ bb from simulation
- b tagging algorithm: CSVv2
- simulated QCD jets w/ 0/1/2 b tag
- AK08 jets

Remember Dinko's talk