Search for quark compositeness & New diboson resonance at 13 TeV at CMS Experiment

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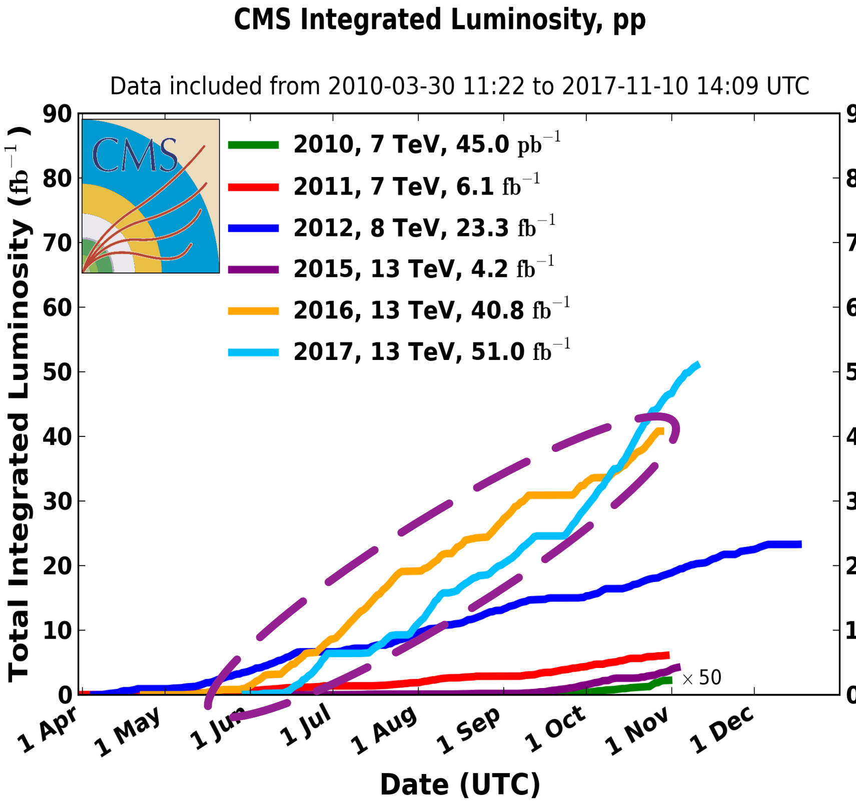
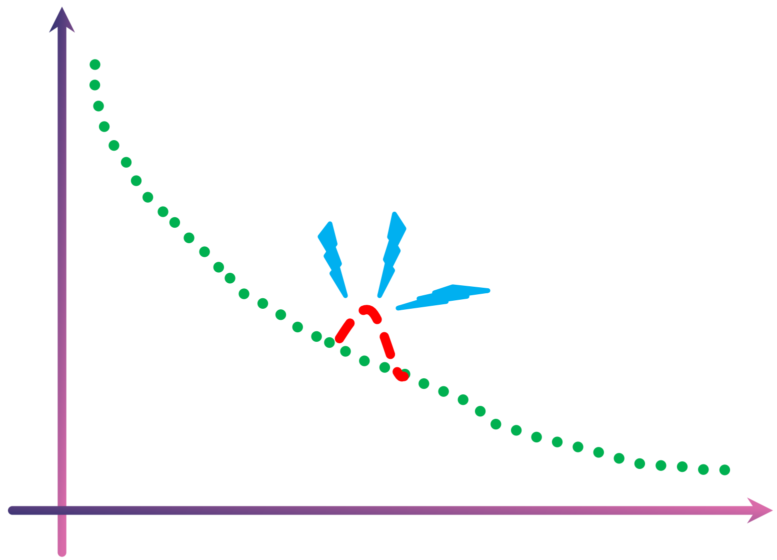
SUSY2017 Conference, TIFR, Mumbai, India
December 11-15, 2017

THE LHC MACHINE



Results based on 2016 data of Run-II collected by the CMS Experiment



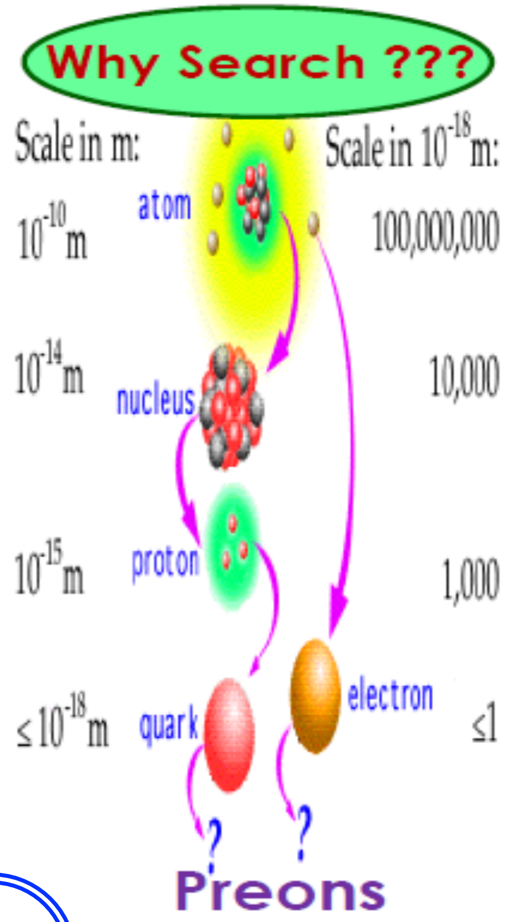
SEARCH FOR QUARK COMPOSITENESS

MOTIVATION

Int. J. Mod. Phys. A 2 (1987) 1285, Phys. Rev. D **42** (1990) 815

- ✓ Quarks may not be fundamental ➪ Preons
- ✓ Quark compositeness – Possible explanation of three generation of fermions.
- ✓ Compositeness ➢ Look for excited states
- ✓ Relevant part of the Lagrangian, i.e. the (chromo-) magnetic transitions between ordinary states and excited states:

$$\boxed{\mathcal{L}_{int} = \frac{1}{2\Lambda}\,\overline{q_R^*}\sigma^{\mu\nu}\left[\textstyle\sum_i g_i f_i T_i^a G_{i\mu\nu}^a\right]q_L + h.c.}$$



HOW TO LOOK FOR THEM?

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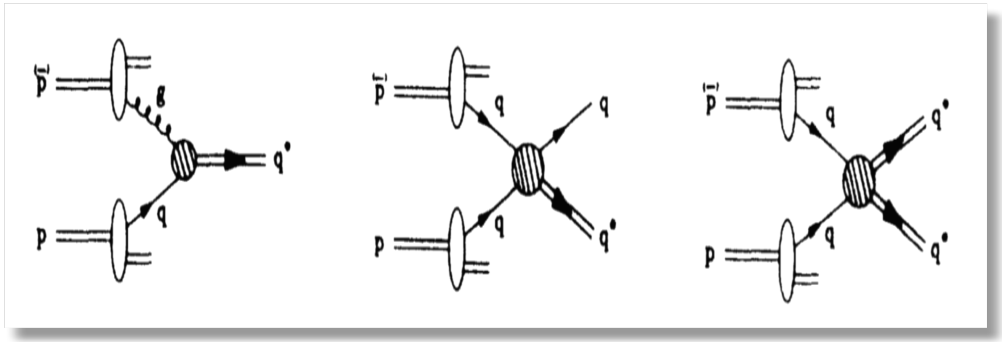
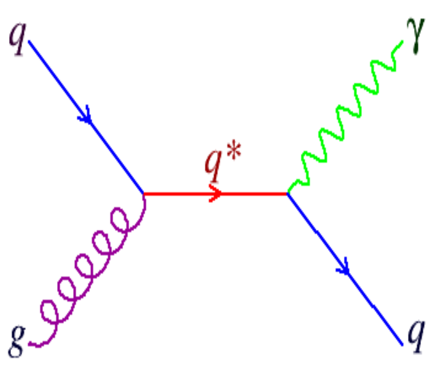
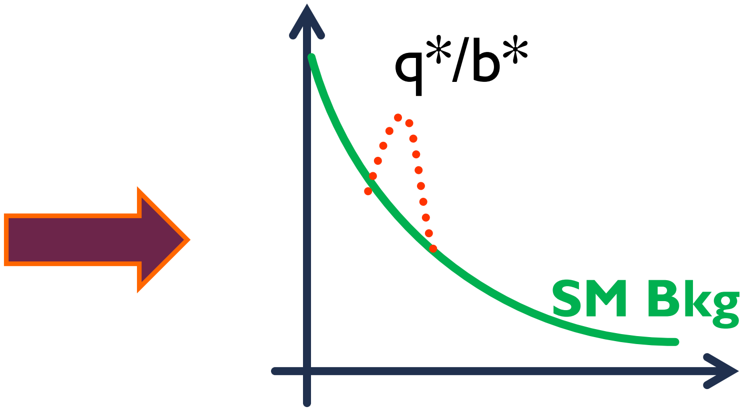
- Excited quarks can be produced either singly or pair-wise
- Can occur through
  - ✓ gluonic excitation of quark
  - ✓ quark-antiquark annihilation
  - ✓ gluon-gluon fusion



- Excited quarks can give signature decay to different final states:
  - ✓ Photon + Jet (arXiv:1711.04652)
  - ✓ Jet + Jet (CMS PAS EXO-16-056)
  - ✓ Photon + W/Z



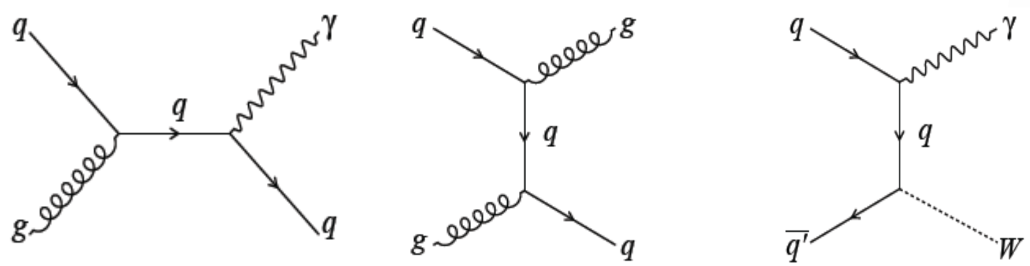


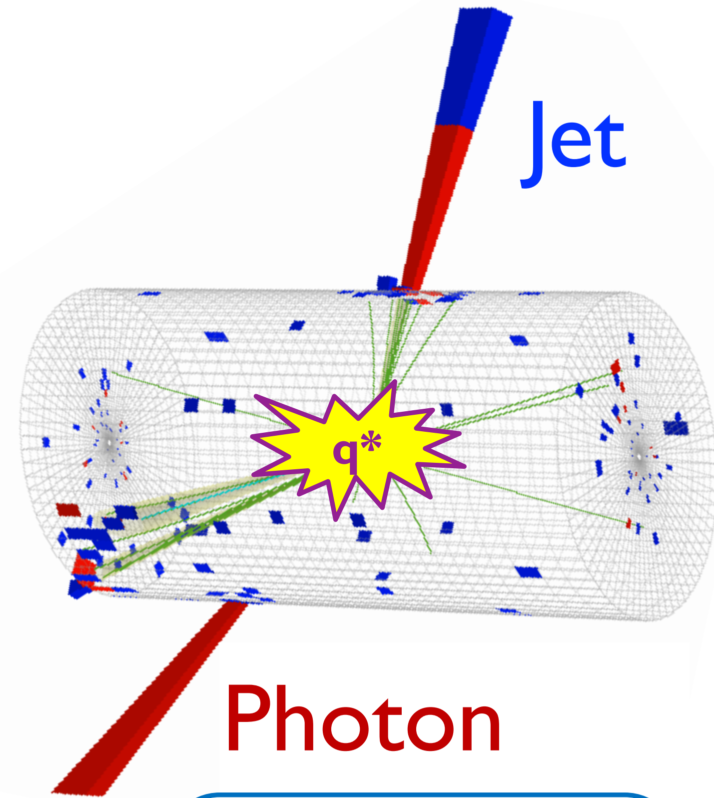
EXCITED QUARKS: PHOTON + JET

arXiv:1711.04652 , CMS PAS EXO-17-002

Main Backgrounds:

- SM Photon + jet production
- Di-jet or multi-jet final state
- $W\gamma$ and $Z\gamma$





- Bump hunt in the γ + jet mass spectrum
- High pT photon (> 200 GeV) and jet (> 170 GeV) in the barrel region
- Angular selections between γ and the jet to reduce the SM backgrounds.

Assumptions

Compositenss scale,

$\Lambda = M_{q*}$ & $\Lambda < \sqrt{s}$

Coupling multiplier,

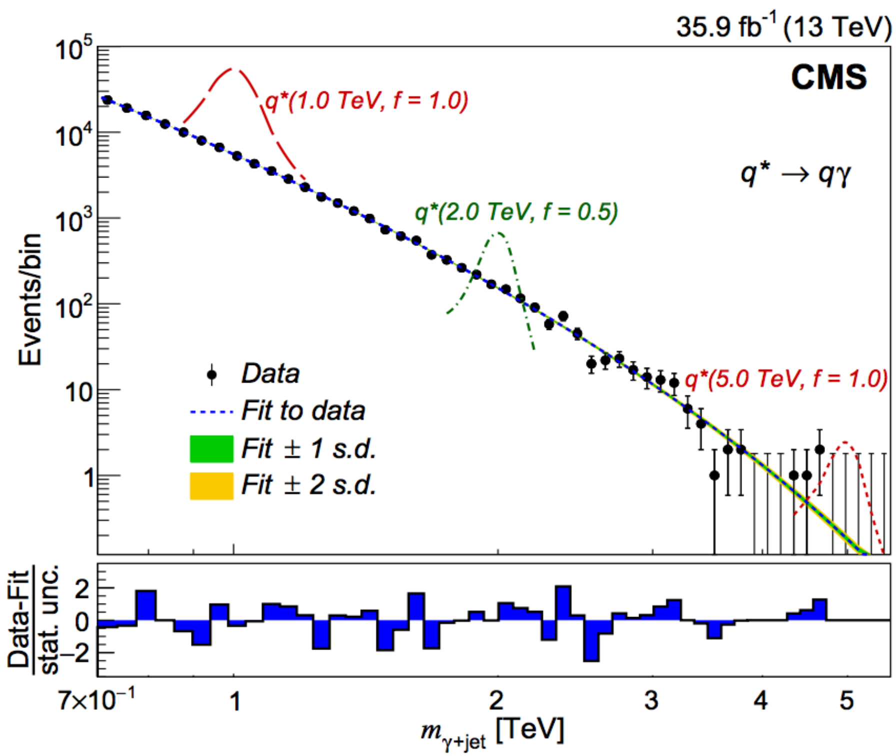
$f = f' = f_s$

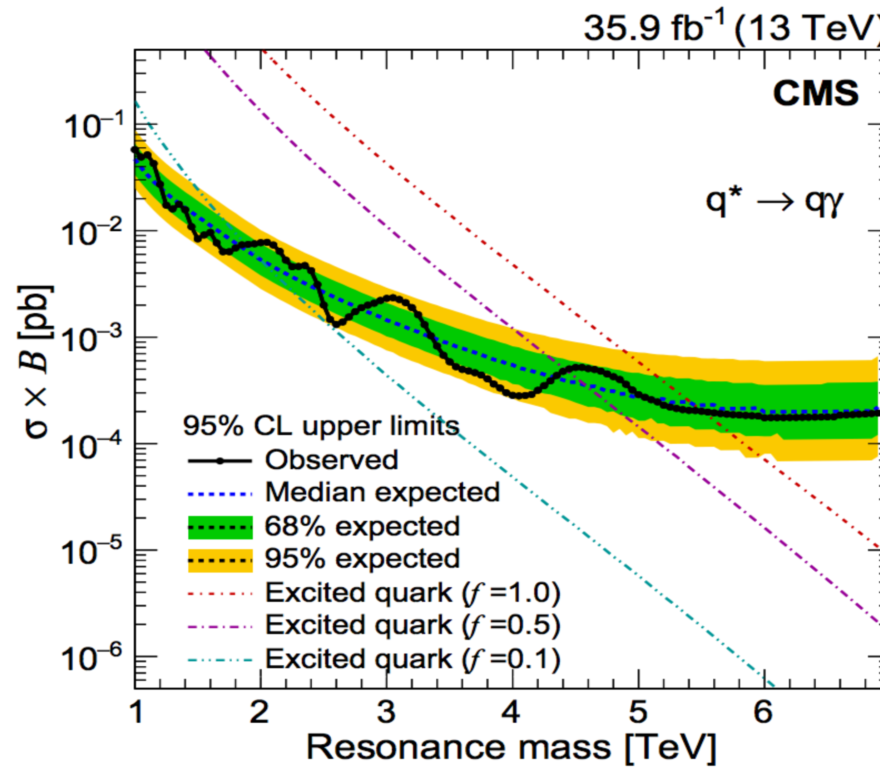
RESULTS: q*

arXiv:1711.04652 , CMS PAS EXO-17-002

Background contributions are modeled using parameteric fit function,

$$\frac{d\sigma}{dm} = \frac{P_0(1-m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2+P_3 ln(m/\sqrt{s})}}$$



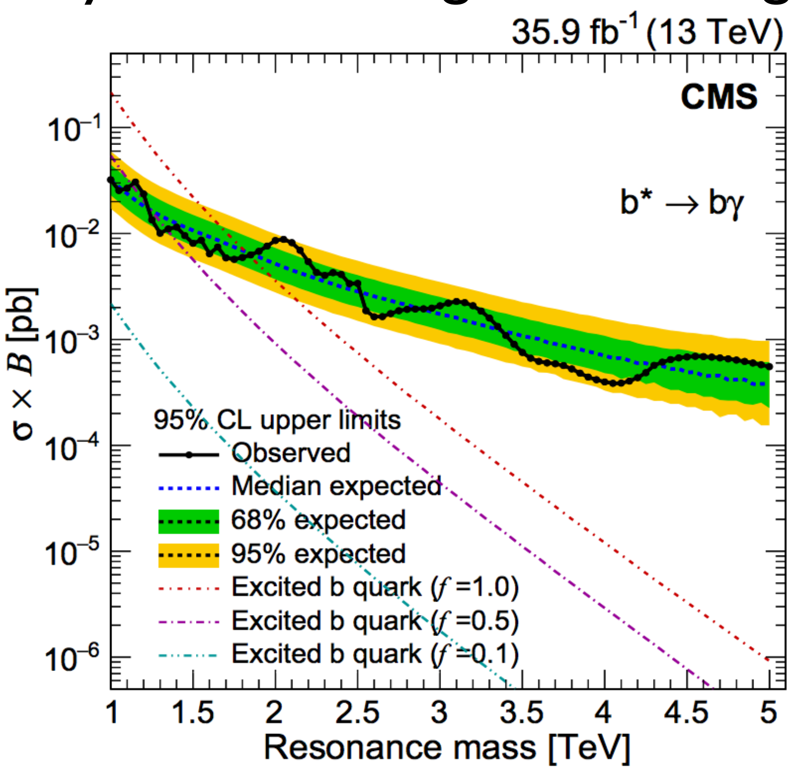


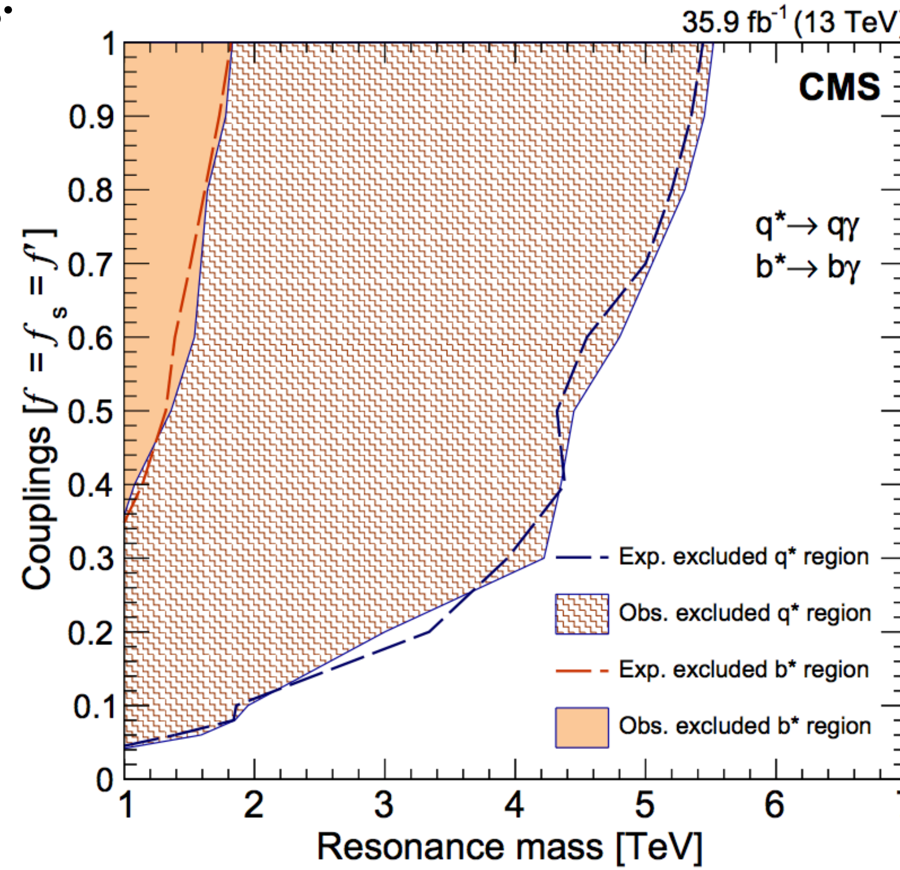
M_{q^*} < 5.5 TeV (f = 1.0) @ 95% CL

RESULTS: b*

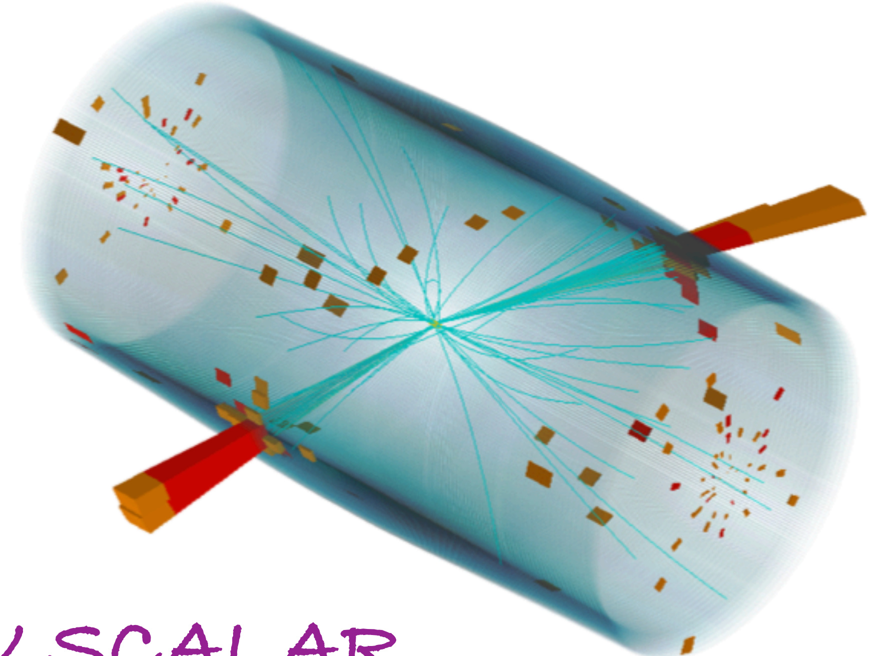
arXiv:1711.04652 , CMS PAS EXO-17-002

Search is extended to excited states of heavy flavor making use of b-tagging.





$M_{b*} < 1.8$ TeV (f = 1.0) @ 95% CL



SEARCH FOR A NEW SCALAR DECAYING TO A PAIR OF Z'S

MOTIVATION

- There is a H(125), all its measured properties consistent with the standard Model. Why bother?
- Short answer: the SM is not perfect!
  - Higgs Mass
  - Dark matter
  - …?
- Higgs acquires mass from coupling to weak vector bosons, fermions & itself!
  - No symmetry in the SM protects the higgs mass.
  - "Natural" explanation would be to go to (heavier scale) ➤ New particles
- Several theories predict new resonances decaying to boson pairs
  - 2-Higgs Doublet Model (2HDM),
  - Heavy Vector Triplets (HVT), etc…

DIBOSON RESONANCES

CMS PAS HIG-17-012

A number of possible final state combinations

Channel	V= W/Z Final states						
$\gamma\gamma$	$\gamma\gamma$						
$V\gamma$	$ll\gamma$	$l\nu\gamma$	$qq\gamma$				
VV	4l	$ll\nu\nu$	llqq	$l\nu qq$	$\nu\nu qq$	4q	
VH	llbb	$l\nu bb$	$\nu\nu bb$	qqbb	$l\nu\tau\tau$	$ll\tau\tau$	$qq\tau\tau$
qV	qqq						

- Expect to observe excitations/resonance/ fluctuations
- Spin – 0, 1, or 2

- Collimated decay products $\Rightarrow$ Need to develop dedicated reconstruction methods
- Hadronic decays of bosons:
  - Boson tagging
  - Exploit substructure of jets (Jet grooming, N-subjettiness,…)
- Leptonic Decays
  - Special isolaton for dileptopic decays

X➛ZZ SEARCH

CMS PAS HIG-17-012

- This talk presents latest results from X➛ZZ ➛4ℓ, $2\ell 2q$, $2\ell 2\nu$
- Most BSM models allow X➛ZZ decay
- We look for
  - Production mechanism: gluon-gluon fusion (ggH) and Electroweak (EW)
  - Dominated by Vector Boson Fusion (VBF)
  - Three parameters, m_x , Γ_x , *and* f_{VBF} *are scanned over a wide range.*
    - m_x , Γ_x – *mass & width that enters propagator*
    - f_{VBF} – *Fraction of EM production cross section w.r.t. the total cross section*
  - Spin-0 scalar, narrow or wide
  - Interference with SM background and H(125) is taken into effect.
  - Mass range: 130 GeV to 3 TeV

X ➛ ZZ SEARCH

CMS PAS HIG-17-012

- ZZ ➛ 4ℓ
  - Categorized based on production mechanism and to improve lepton efficiencies (VBF-tagged, untagged and RSE)
  - Observable: $m_{4\ell}$ and $\mathcal{D}^{\mathrm{kin}}_{\mathrm{bkg}}$

$$\mathcal{D}^{\mathrm{kin}}_{\mathrm{bkg}} = \left[1 + \frac{\mathcal{P}_{\mathrm{q\bar{q}}\to 4\ell}(\vec{\Omega}^{\mathrm{X}\to 4\ell}|m_{\mathrm{ZZ}})}{\mathcal{P}_{\mathrm{X}\to 4\ell}(\vec{\Omega}^{\mathrm{X}\to 4\ell}|m_{\mathrm{ZZ}})}\right]^{-1}$$

- ZZ ➛ $2\ell 2$q
  - Reconstruction techniques – "Resolved" and "merged"
  - Categories: VBF tagged, b-tagged, and untagged
  - Discrimation based on N-subjettiness - $m_{\mathrm{ZZ}}, \mathcal{D}^{\mathrm{Zjj}}_{\mathrm{bkg}}$

$$\mathcal{D}^{\mathrm{Zjj}}_{\mathrm{bkg}} = \left[1 + \frac{\mathcal{P}_{\mathrm{Zjj}}(\vec{\Omega}^{\mathrm{X}\to 2\ell 2q}|m_{\mathrm{ZZ}})}{\mathcal{P}_{\mathrm{X}\to 2\ell 2\mathrm{q}}(\vec{\Omega}^{\mathrm{X}\to 2\ell 2\mathrm{q}}|m_{\mathrm{ZZ}})}\right]^{-1}$$

- ZZ ➛ $2\ell 2\nu$
  - Observable – Transverse mass

$$m_{\mathrm{T}}^2 = \left(\sqrt{p_{\mathrm{T}}(\ell\ell)^2 + m(\ell\ell)^2} + \sqrt{E_{\mathrm{T}}^{\mathrm{miss}\,2} + m_{\mathrm{Z}}^2}\right)^2 - (\vec{p}_T(\ell\ell) + \vec{E}_T^{\mathrm{miss}})^2$$

INTERFERENCE

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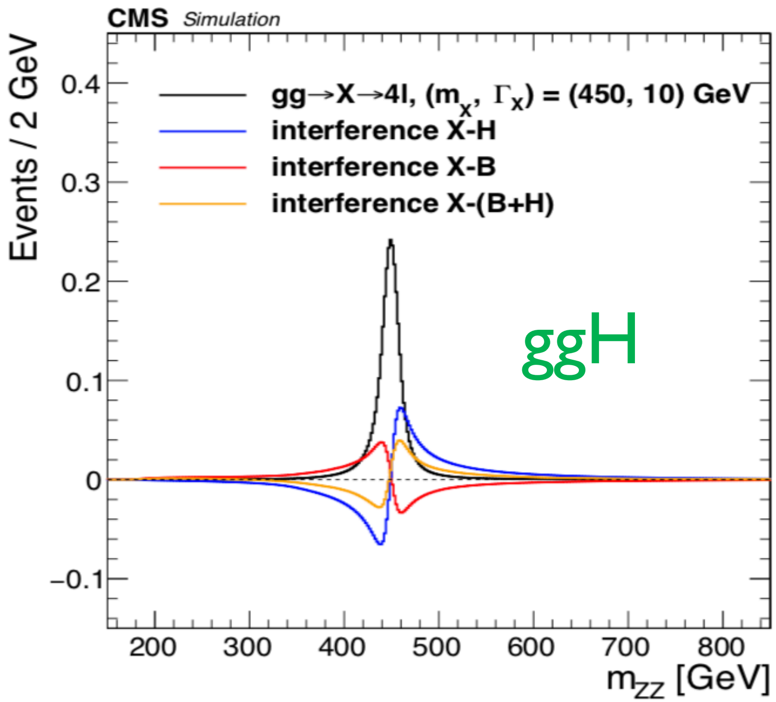

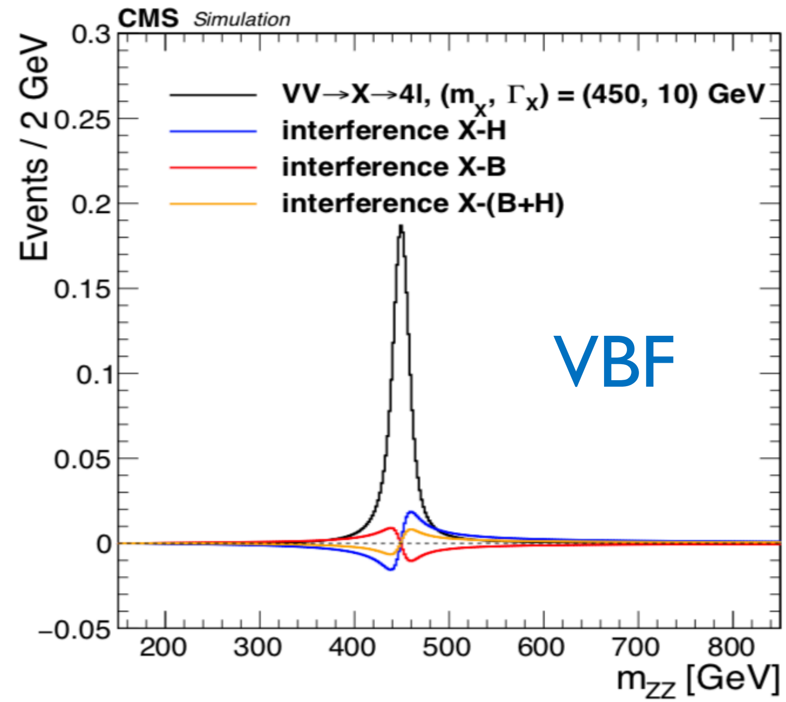

- Parameterization of the four-leptons invariant mass for both production modes, *for mass = 450 GeV, width = 10 GeV.*
- The interference contributions from H(125) and gg → ZZ or VV → ZZ background

RESULTS ($4\ell, 2\ell 2q, 2\ell 2\nu$ Combined)

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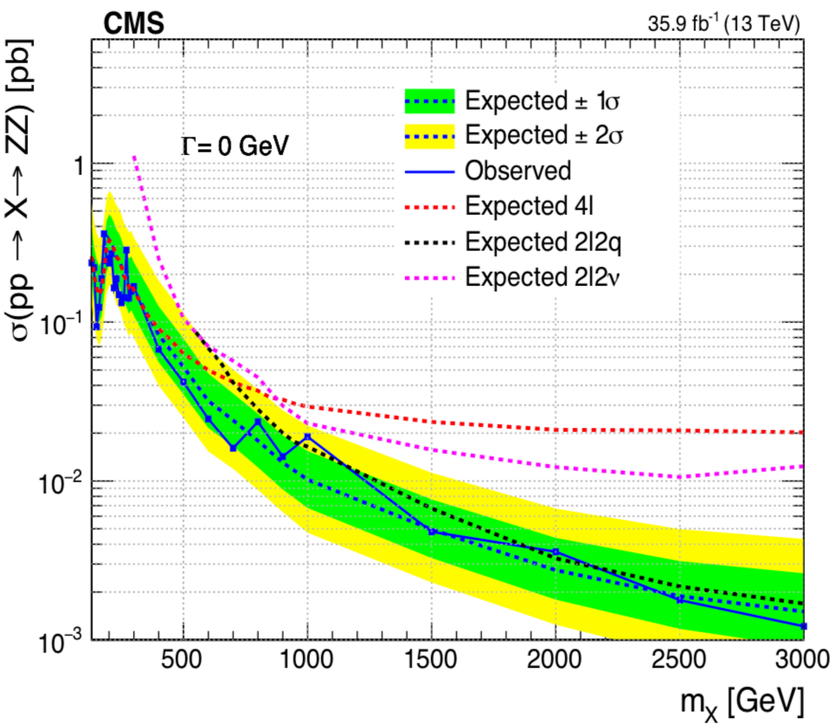
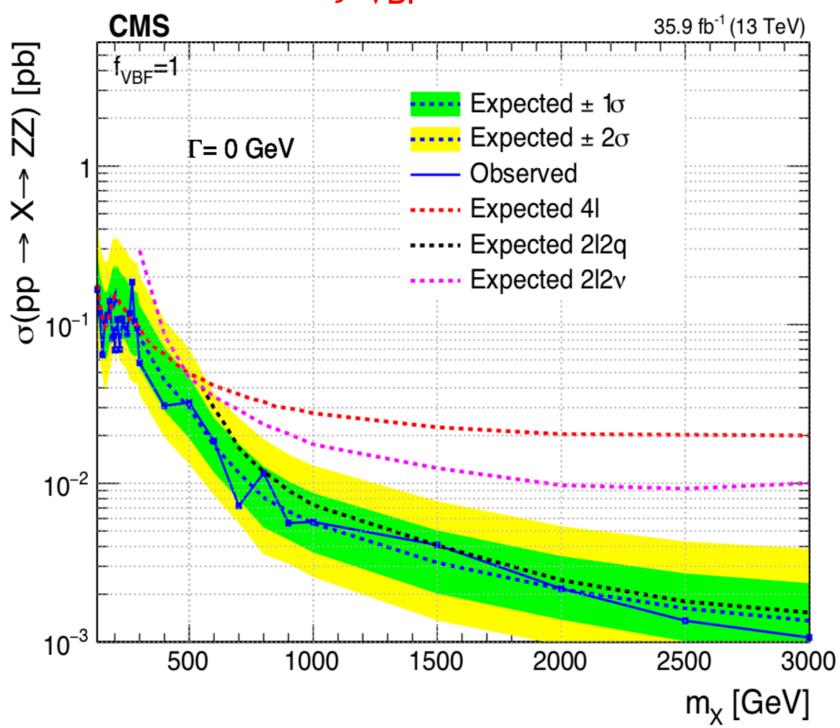
NEW

f_{VBF} = free parameter



f_{VBF} = 1



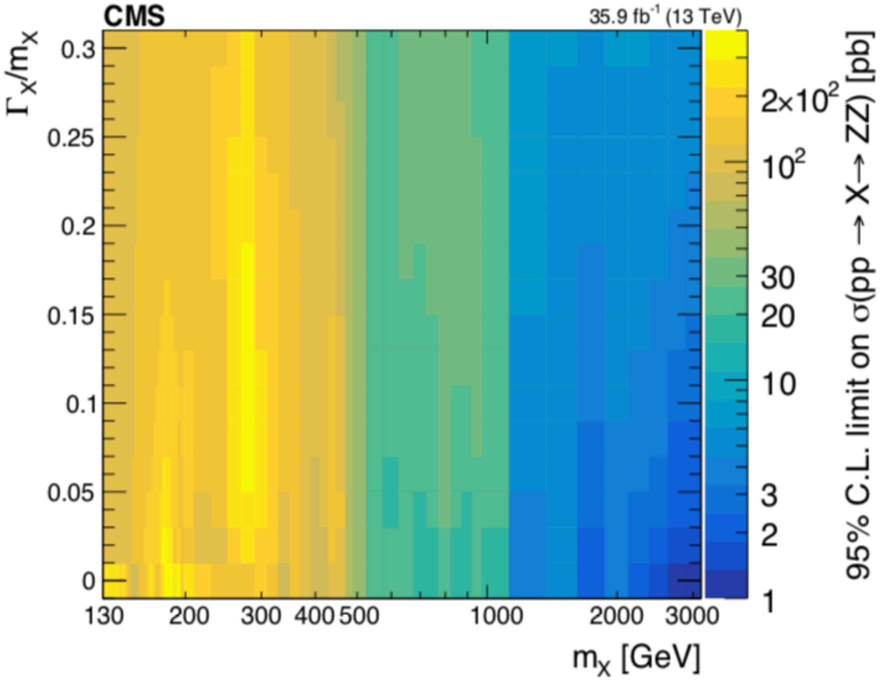
Upper limits at the 95% CL on the pp → X → ZZ cross section $\sigma_X \times \mathcal{B}_{X \to ZZ}$ as a function of m_x for $\Gamma_x = 0$ GeV

RESULTS (4ℓ, 2ℓ2q, 2ℓ2ν Combined)

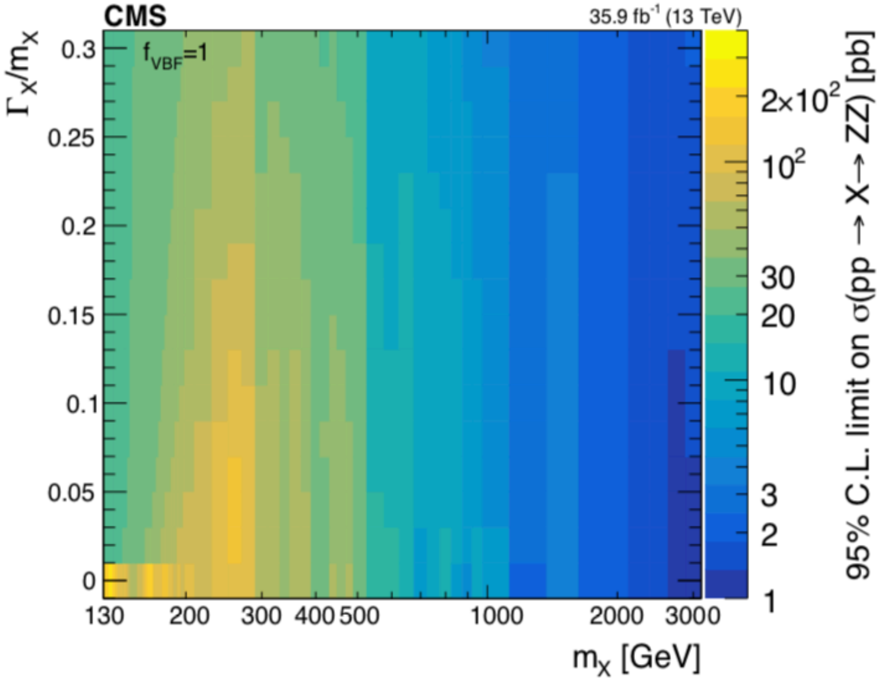
CMS PAS HIG-17-012

NEW

f_{VBF} = free parameter



$f_{\text{VBF}} = 1$

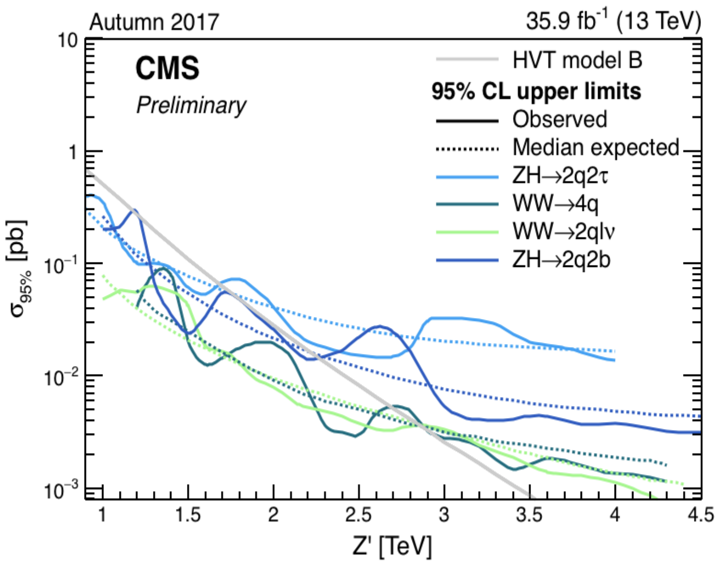


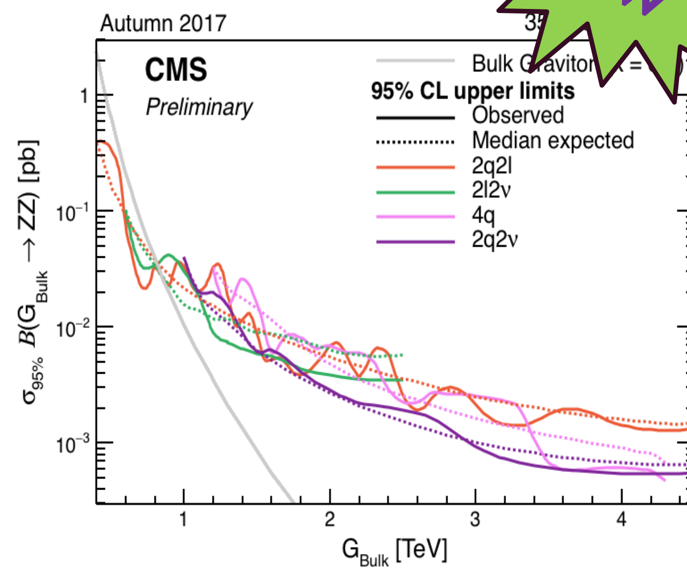
Observed upper limits at the 95% CL on the $pp \rightarrow X \rightarrow ZZ$ cross section as a function of m_x and Γ_x/m.

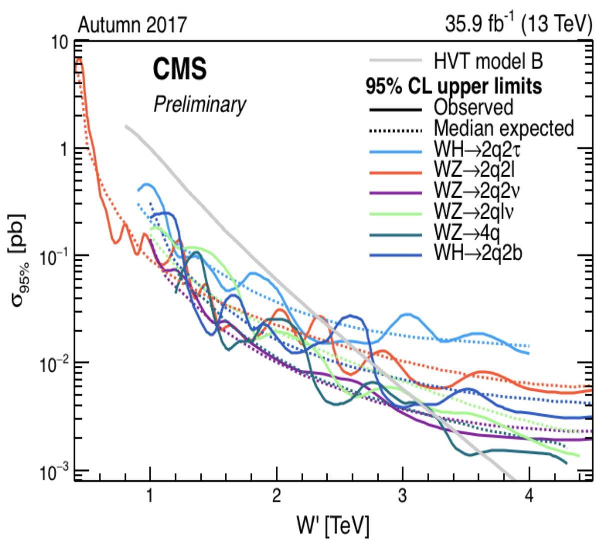
EXTENSIVE DIBOSON PROGRAM

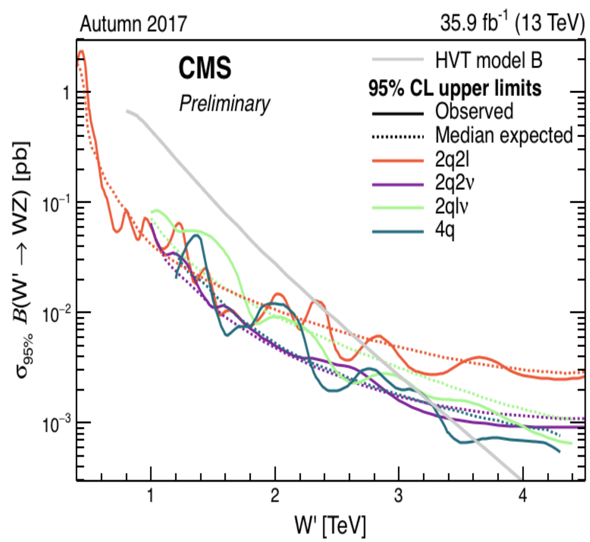
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2GDibosons

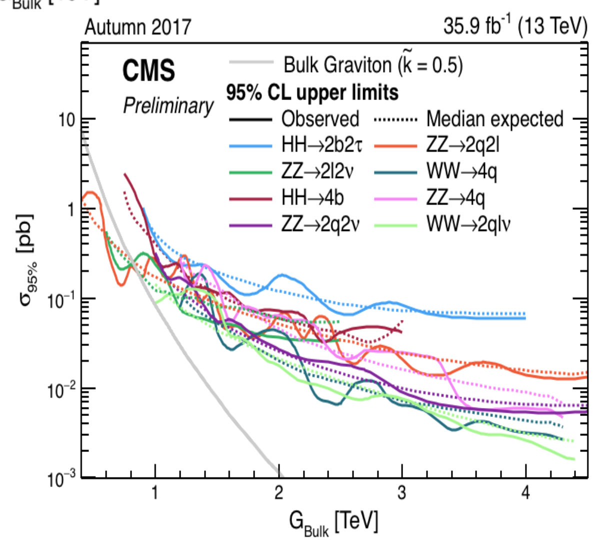
NEW









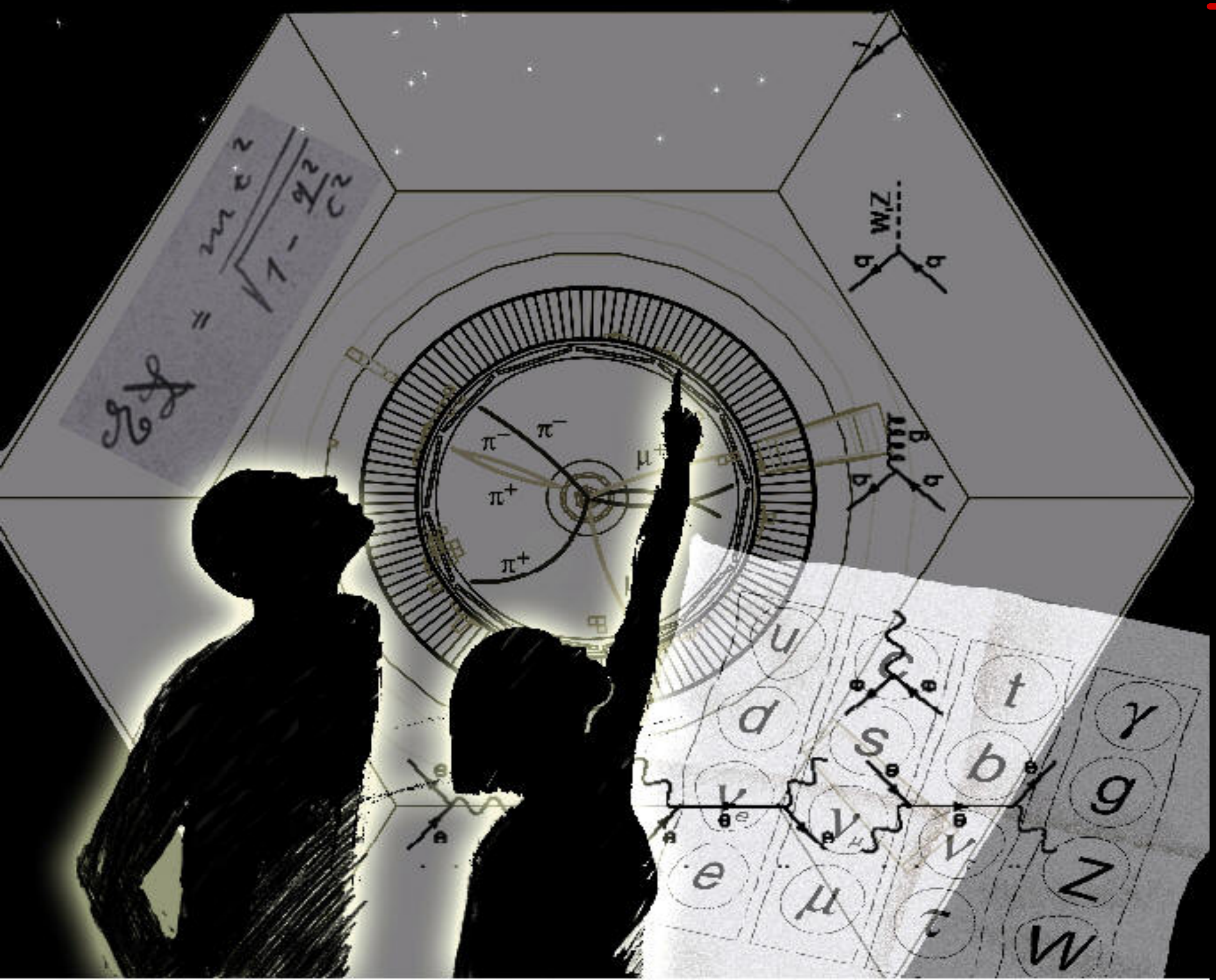


SUMMARY AND OUTLOOK

- Successful and wide search program conducted by CMS
- Boosted signatures key to high mass searches
  - Tools have reached impressive level of maturity

- No sign of new physics, yet…
- Setting more and more stringent limits
- Higher integrated luminosity will allow us to explore higher masses and smaller couplings

The LHC Landscape



The game is on!

Stay Tuned!
Lot more to come

Thank You

EXTRA MATERIAL

QSTAR MODEL SETUP

Int. J. Mod. Phys. A 2 (1987) 1285, Phys. Rev. D **42** (1990) 815

- Effective Lagrangian that explains the transitions between the excited state and the ground state is given by:

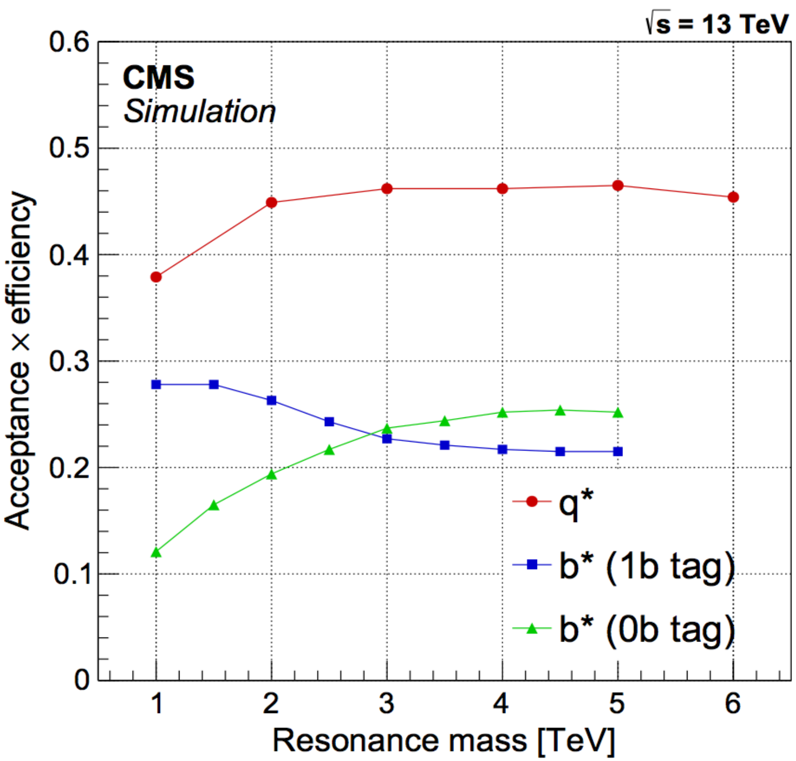
$$\boxed{\mathcal{L}_{int} = \frac{1}{2\Lambda}\,\overline{q_R^*}\sigma^{\mu\nu}\left[\sum_i g_i f_i T_i^a G_{i\mu\nu}^a\right] q_L + h.c.}$$

  - $G_{\mu\nu}{}^a$, $W_{\mu\nu}$, $B_{\mu\nu}$, are the field strength tensors of the SU(3), SU(2), and U(1) gauge fields
  - λ_a, τ, Y (g_s, g, g') are generators (gauge coupling constants)
  - f_s, f, f' – Coupling multipliers, determined by compositeness dynamics. Presumably of order unity
  - Λ: compositeness scale, assumed to be below the $\sqrt{s}$ of the LHC

q*/b*

arXiv:1711.04652 , CMS PAS EXO-17-002

Acceptance x Efficiency



Systematic Uncertainty

Source	Effect on the signal yield(%)
Integrated luminosity	2.5
Jet energy scale	~1
Jet energy resolution	0.2–0.4
Photon energy scale	~0.6
Photon energy resolution	0.2–0.4
Pileup	1–2
Photon ID efficiency	~2
Trigger efficiency	~5
Signal interpolation	0.5–1
PDF choice	1.5–3
b tag SF (only b*)	~1
b tag SF normalization (only b*)	~2

BRANCHING FRACTIONS – q*

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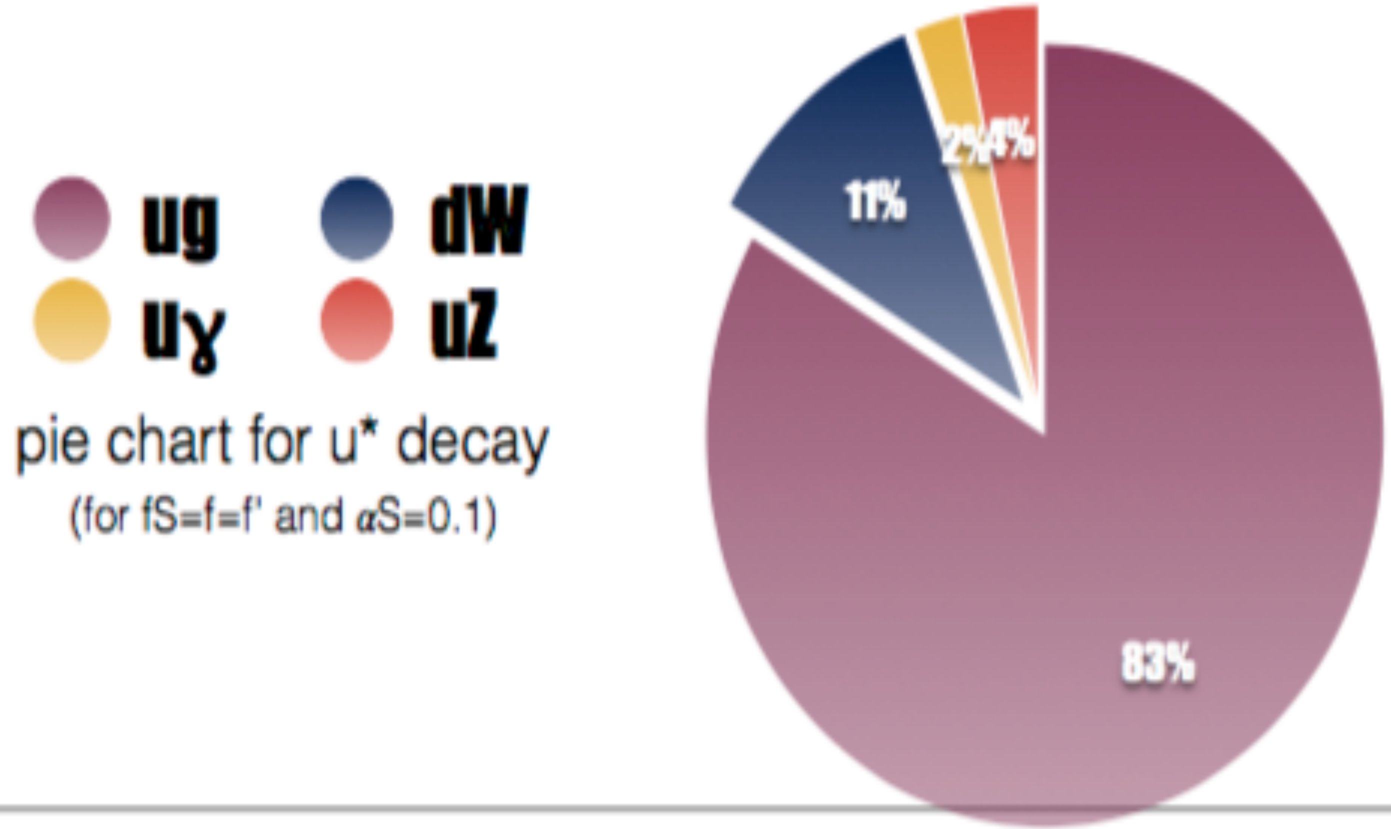

X → ZZ

CMS PAS HIG-17-012

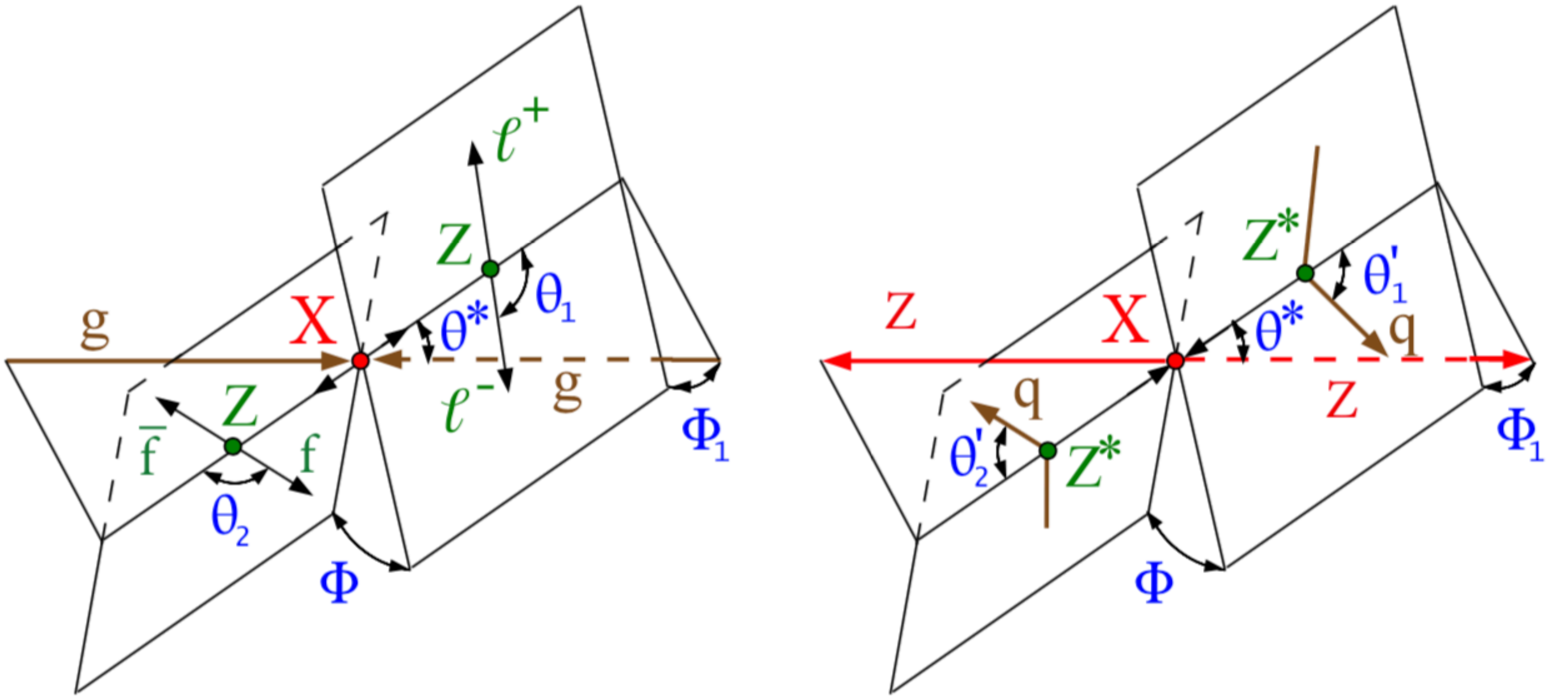

Figure 1: Illustration of an X boson production from ggH, $gg \to X \to ZZ \to (\ell^+\ell^-)(f\bar{f})$ (left) and VBF $qq' \to qq'X \to qq'ZZ$ (right).

X→ZZ (SYSTEMATIC UNCERTAINTIES)

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Source of uncertainty	$X \to ZZ \to 4\ell$	$X \to ZZ \to 2\ell 2\nu$	$X \to ZZ \to 2\ell 2q$
Experimental sources			
Luminosity	2.5	2.5	2.5
ℓ trigger and selection efficiency	2.5–9	6–8	4–8
ℓ mom./energy scale	0.04–0.3	0.01–0.3	0.1–0.3
ℓ resolution (*)	20	20	20
JES, JER, E_{T}^{miss} (*)	1–30	1–30	1–10
b-tag/mistag	-	2–4	5–7
Background estimates			
Z+jets	36–43	20–50	10–50
Top, WW	-	10	15
WZ, Wγ^*	-	15	3–10
Theoretical sources			
QCD scales	3–10	5–10	3–10
PDF set	3–4	1–4	3–5
EW corrections ($q\bar{q} \to ZZ$) (*)	1	2	1
NNLO (ggZZ) K factor	10	10	10

X→ZZ (ACCEPTANCE X EFFICIENCIES)

CMS PAS HIG-17-012