Searches for Heavy Stable Charged Particles, Leptoquarks, W′ and Dijet Resonance at CMS

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Outline

- ✓ Heavy Stable Charged Particles
- ✓ Leptoquarks Searches at CMS
- ✓ Dijet Resonance:
  - Untagged
  - b-tagged
- ✓ W′ Search
- ✓ Summary

Results presented in this talk are also available as public results of CMS at the following link:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

Heavy Stable Charged Particle

Motivation: Heavy Stable Charged Particles(HSCP) are predicted by many Beyond Standard Model(BSM) theories

✓ HSCP Phenomenology:
- Gauge Mediated SuperSymmetry Breaking(GMSB): stable *stau*
- Split SUSY: R-Hadron
- Hidden valley models, extra dimensions

✓ Two main classes:
- Lepton like : no strong interactions
- Hadron like : color-charged, strongly interacting particles form stable states

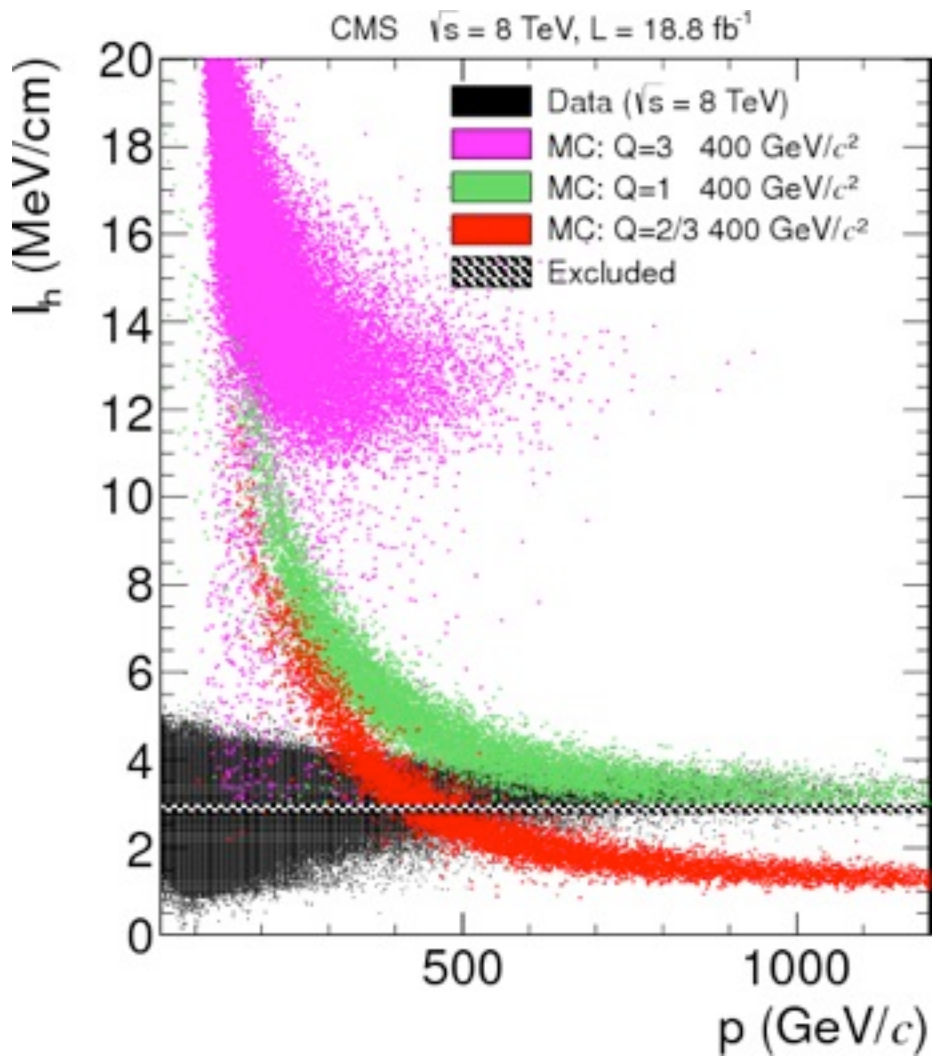
✓ Detector signatures:
- High momentum tracks
- Displaced tracks
- Large Time-Of-Flight (TOF)
- Highly ionizing tracks

Heavy Stable Charged Particles - II

Many benchmark signal model considered which could have non negligible cross section with small SM background

CMS-EXO-12-026

- ✓ Lepton Like :
  - GMSB SPS7 model with *stau* as NLSP [100-494] GeV
- ✓ Hadron Like :
  - *stop* pair production
  - *gluino* pair production [300-1500] GeV (split SUSY with M_{squark} > 10 TeV)
  - Fraction of *gluinos* hadronizes into *gluino-gluon* bound states with unknown f (= 0.1, 0.5,1.0)
- ✓ Modified DY production of lepton like fermion
  - [100 - 1000] GeV, |Q| =1/3, 2/3, 1, 2, 3, 4, 5e



Strategy for discovery:

- ✓ Tracker Only: uses dE/dx
- ✓ Muon System: Time-Of-Flight
- ✓ Calculated mass from dE/dx estimator:
  - same as Bethe Block within few %
  - K and C are measured from proton line

$$I_h = K\frac{m^2}{p^2} + C.$$

Heavy Stable Charged Particles - III

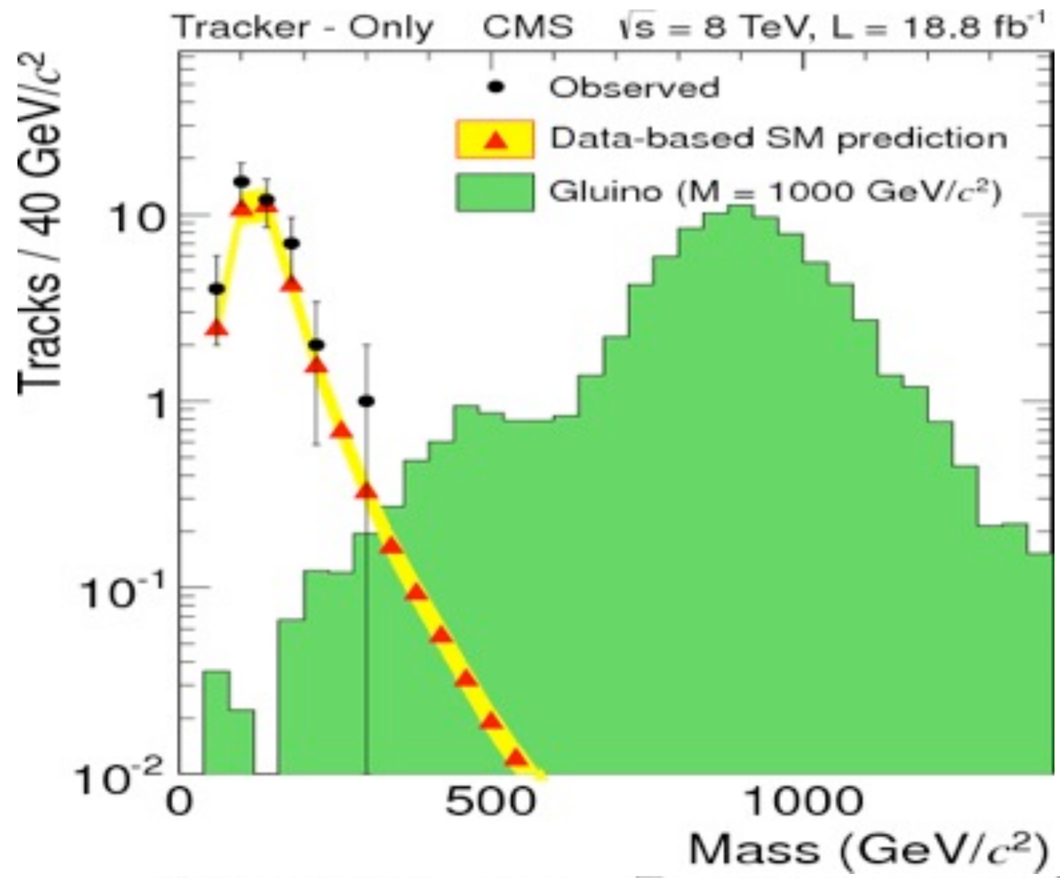
✓ Muon Trigger: for particles which remain charged outside the tracker

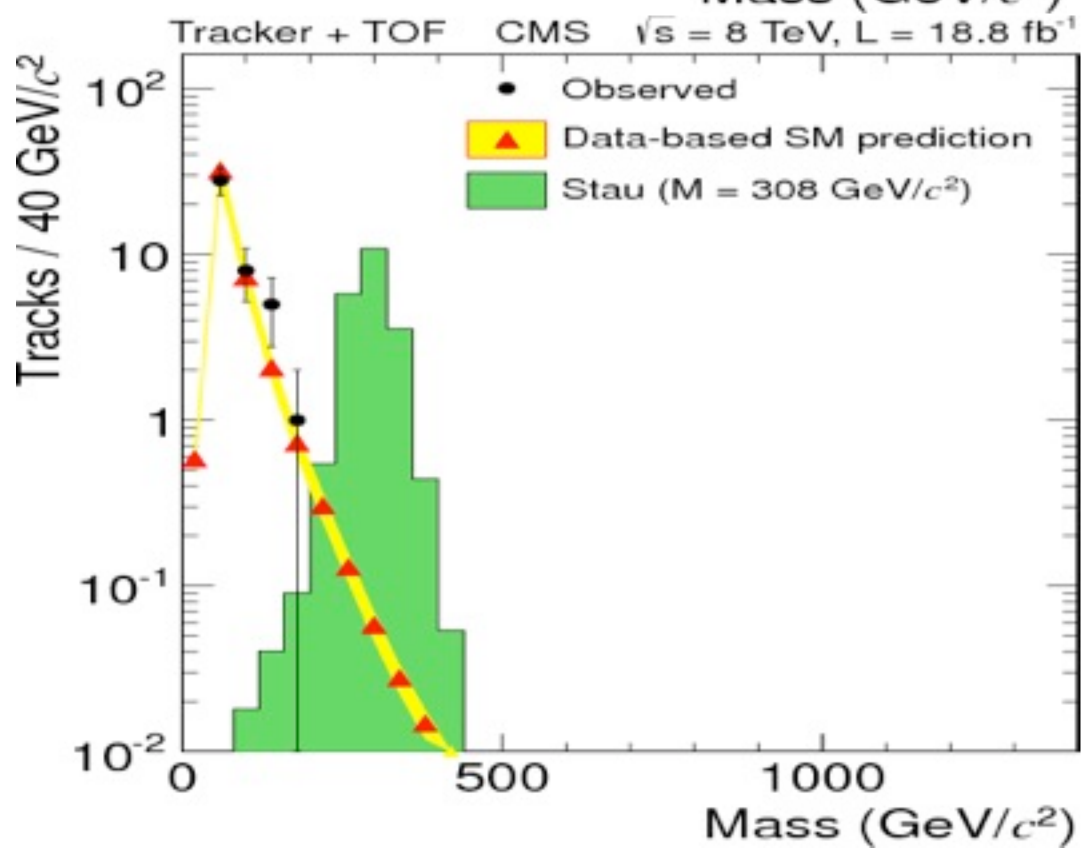
✓ Missing-E_T Trigger: those particles which become neutral after interaction

✓ Selection on:
- P_T
- dE/dx incompatibility
- T.O.F

✓ Background estimation:
- Independence of P_T and dE/dx selection provides way to get data-driven background
- ABCD method is used based on pair of uncorrelated selection variables

✓ Signal extraction:
- Count event in a mass window of (M_{reco}-2σ) to 2 TeV





Heavy Stable Charged Particles: Results

Main systematics:

-Background prediction: ~20%

-Signal efficiency: up to ~30% (tracker only)

-Trigger: ~10%

-pile up: ~5%

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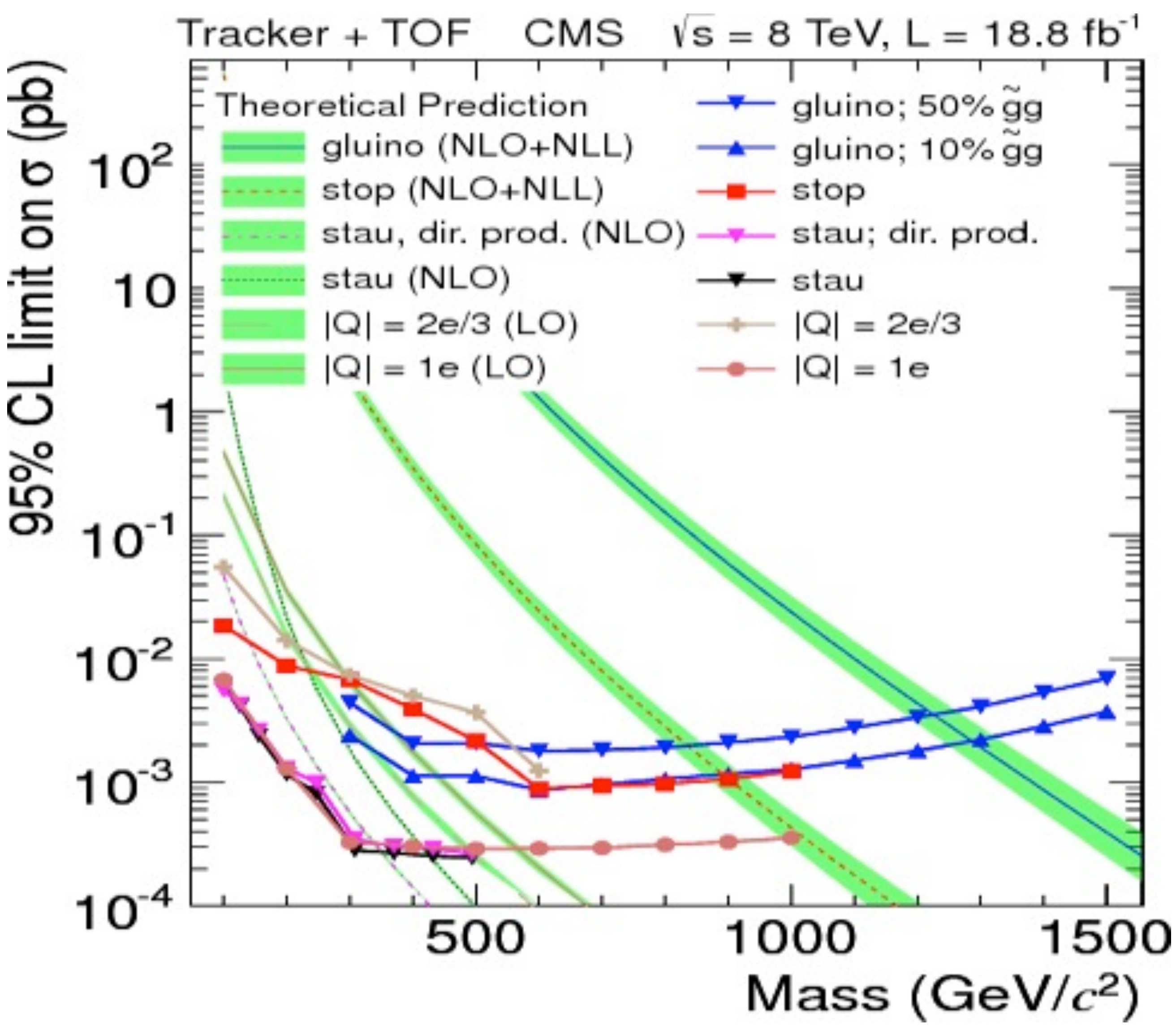
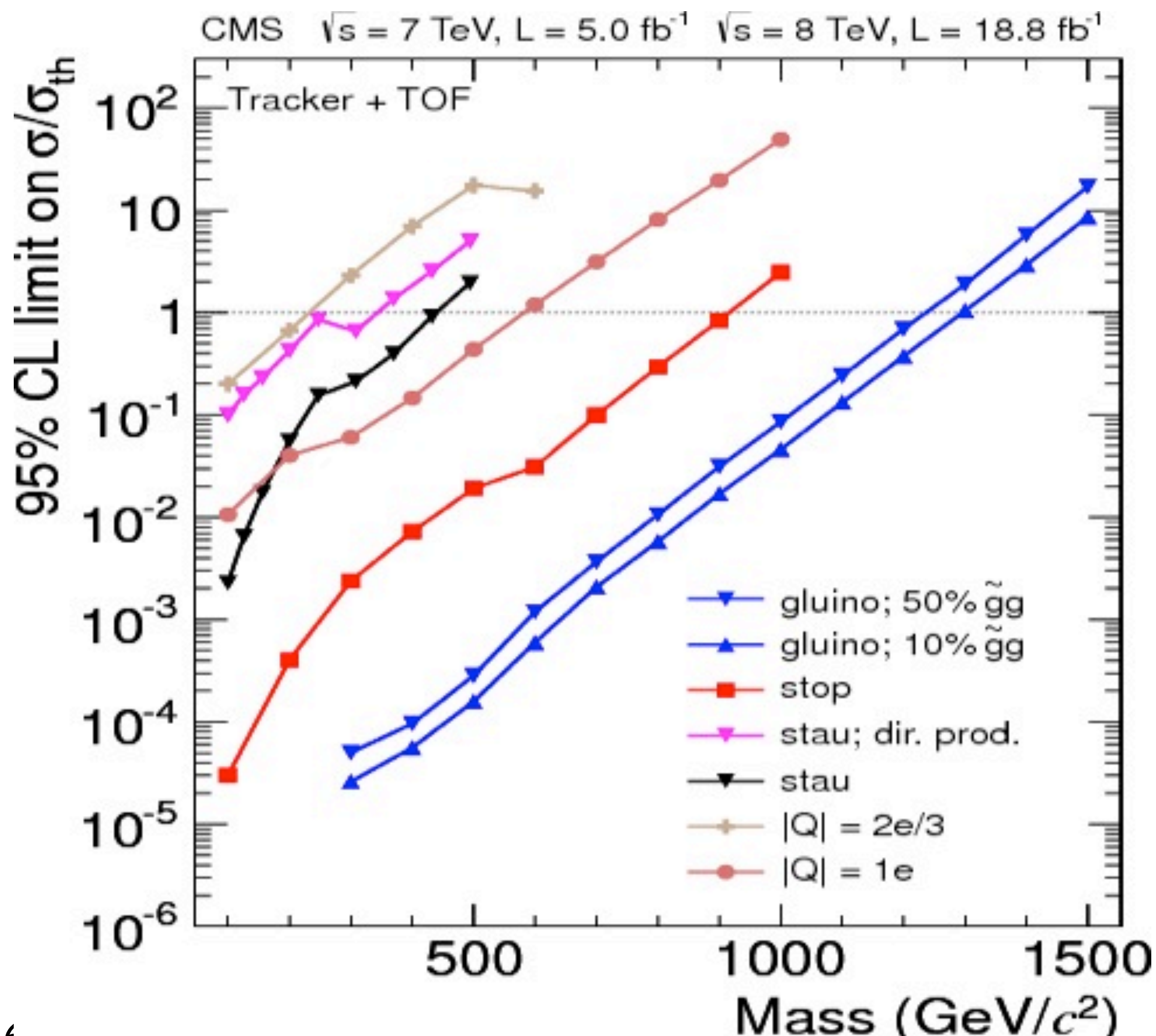
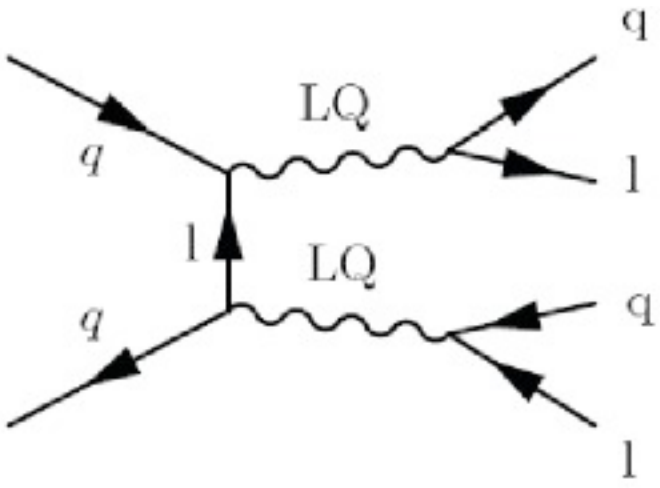




Leptoquarks (LQ)

✓ Possibility of a fundamental relationship between quarks and leptons through leptoquarks
- they are colored and have fractional charge
- couples to quarks and leptons with coupling λ
- branching fractions are denoted as: β(*lq*) and 1- β (*νq*)

✓ **CMS has performed searches for all 3 generation of leptoquarks with following final states:**
- *lljj* (β =1) where *l* = *e*, *μ*
- *lνjj* (β =0.5)
- *bbνν*



✓Limits are set on mass of leptoquarks (M_{LQ})

2^{nd} Generation Scalar Leptoquarks

μμ+jj final state:

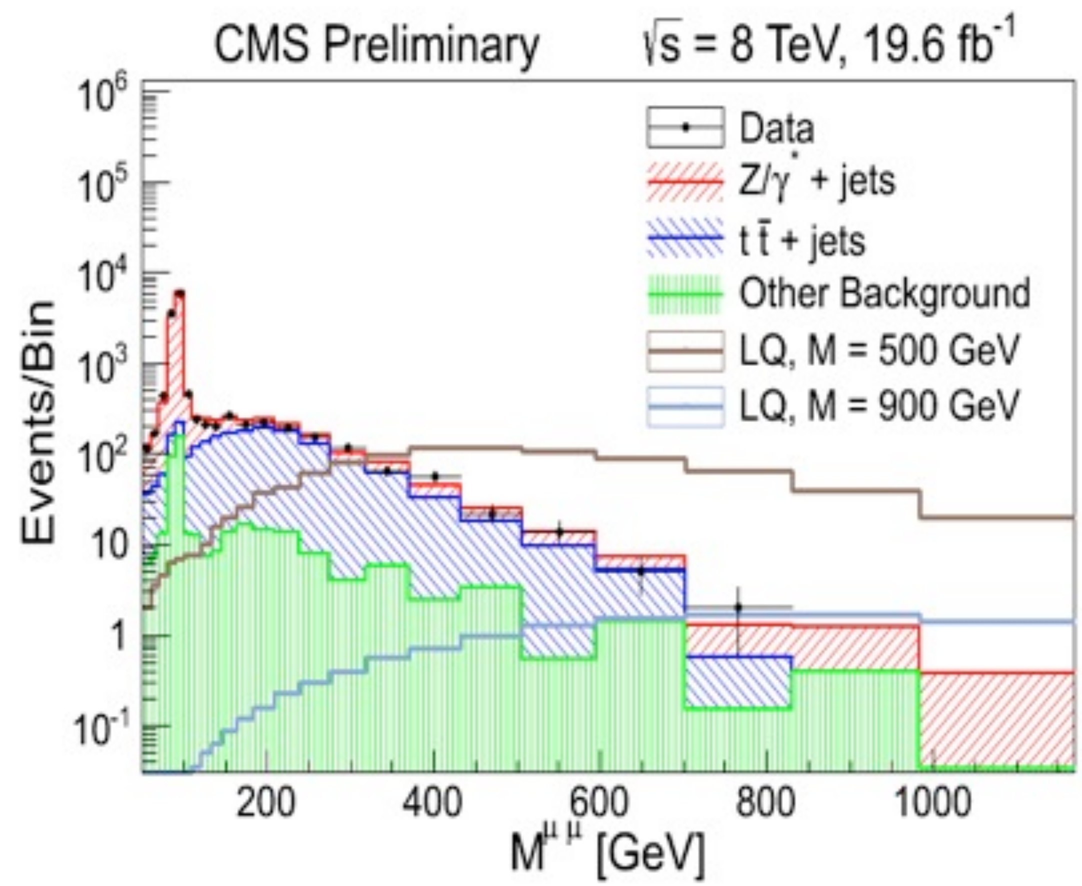
- $P_T(\mu)$> 45 GeV, |η|< 2.1
- $M_{\mu\mu}$> 50 GeV
- $P_T(j1)$> 125 GeV, $P_T(j2)$> 45 GeV, |η|< 2.4
- Well separated μ and jets, ΔR > 0.3
- S_T > 300 GeV
  where: $S_T = P_T(l_1) + P_T(l_2) + P_T(j_1) + P_T(j_2)$

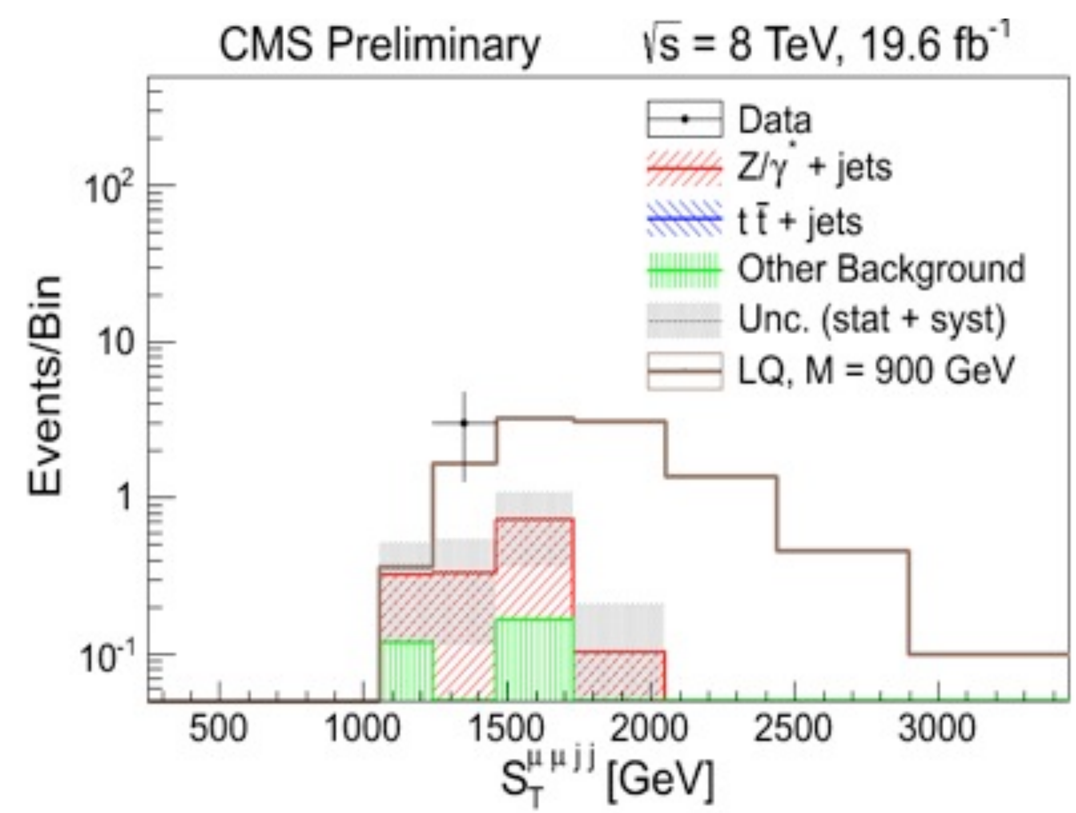
After preselection the S/√S+B is optimized for three variables:

- $M_{\mu\mu}$, S_T , and min($M_{\mu j}$)
- min($M_{\mu j}$) is for that μ-j combination which minimizes the mass difference of the two LQ

Main Backgrounds:

- Z/γ+jets, ttbar, VV+jets, W+jets and multijet QCD





CMS-EXO-12-042

2^{nd} Generation Scalar Leptoquarks - II

μ+missing-E_T+jj final state:

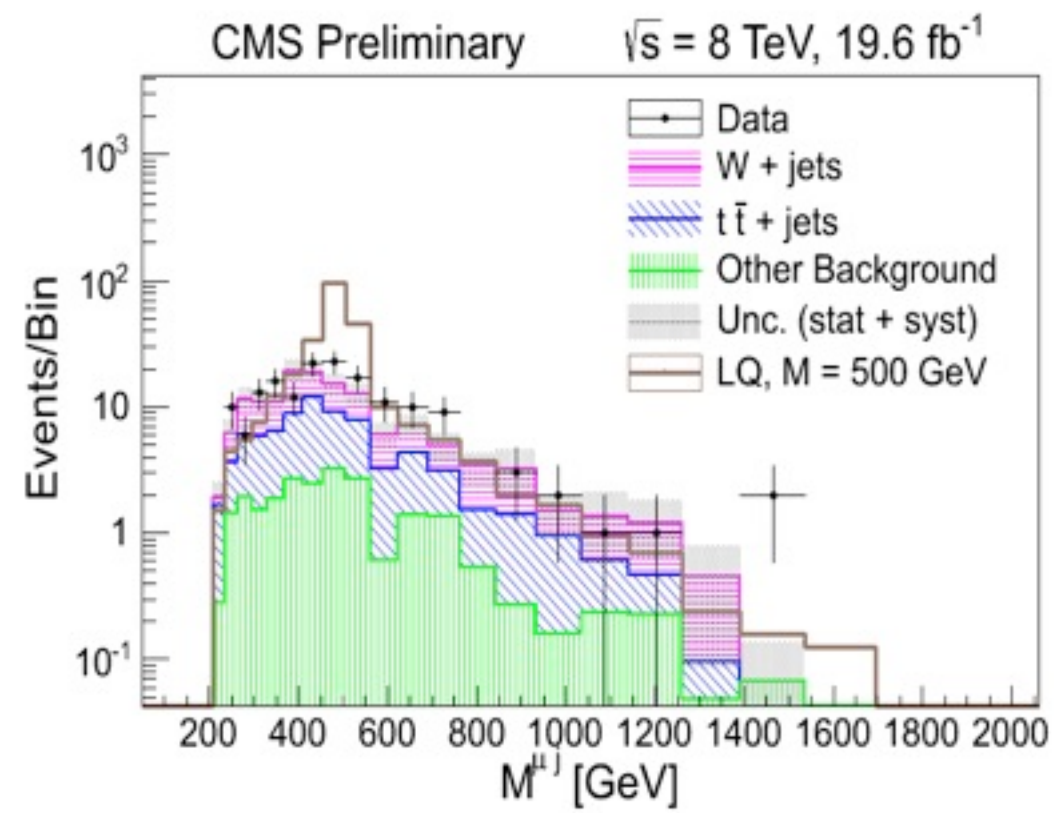
- $P_T(\mu) > 45$ GeV, $|\eta| < 2.1$
- $M_T > 50$ GeV
- missing-$E_T > 55$ GeV
- $P_T(j1) > 125$ GeV, $P_T(j2) > 45$ GeV, $|\eta| < 2.4$
- Well separated missing-ET and jet, $\Delta\phi > 0.5$
- Well separated missing-ET and μ, $\Delta\phi > 0.8$
- $S_T > 300$ GeV

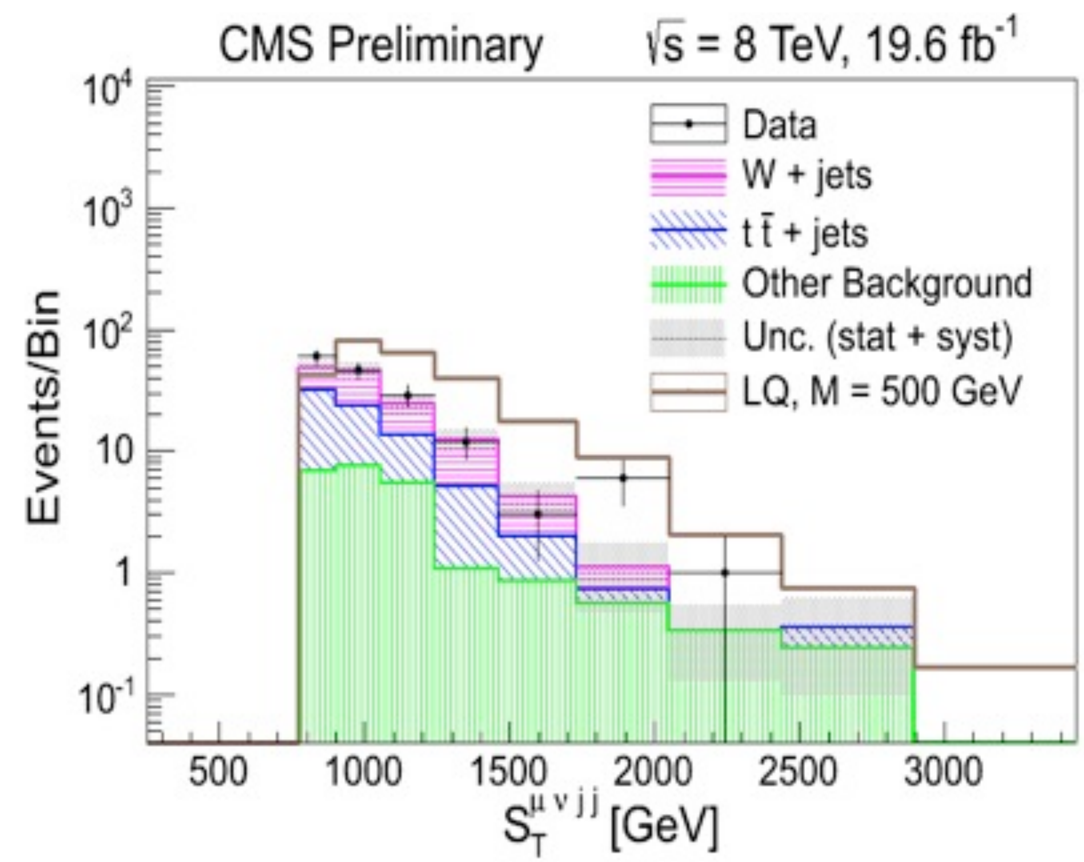
After preselection the similar $S/\sqrt{S+B}$ optimization is performed for three variables:

- $M_{\mu\mu}$, S_T, and $\min(M_{\mu j})$

Backgrounds:

- W+jets, ttbar, single top, WW, ZZ, Z/+jets
- instrumental backgrounds
- Multijet QCD is negligible



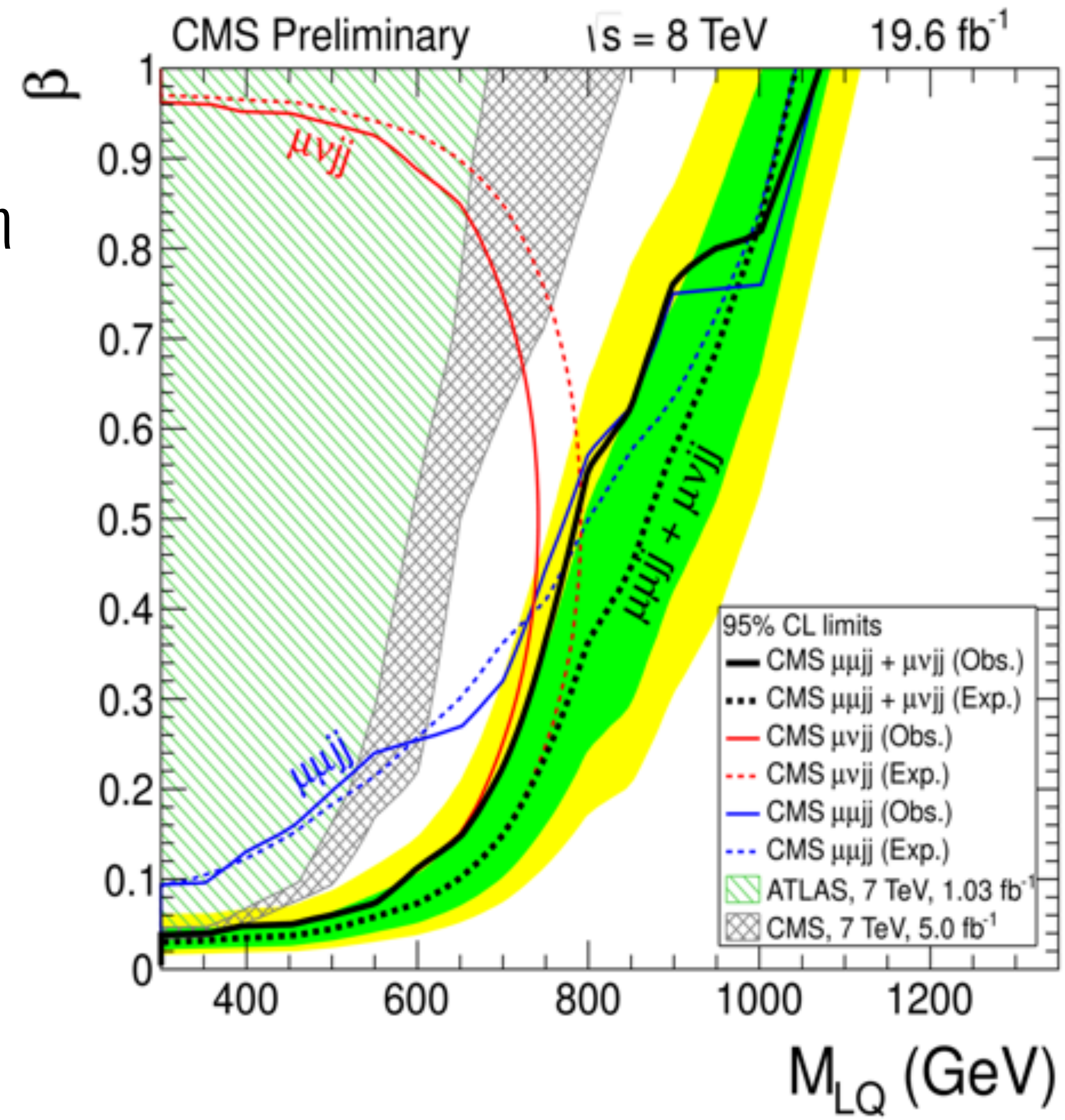


CMS-EXO-12-042

2nd Generation Scalar Leptoquarks: Results

Systematics:

- ✓ Luminosity : 4.4 %
- ✓ Jet Energy Scale (JES) dependent on P_T and η
- ✓ muon momentum uncertainty: 5% P_T /TeV
- ✓ Data/ MC scale factor: 1-2%
- ✓ ttbar, W+Jet shape uncertainties are determined by varying the factorization, normalization scale by a factor of two
- ✓ PDF uncertainty:
  - μ+missing-E_T+jj: 2-21% (2%) for background (signal)
  - $\mu\mu$+jj: 2-12% (2%) for background (signal)



Limits:

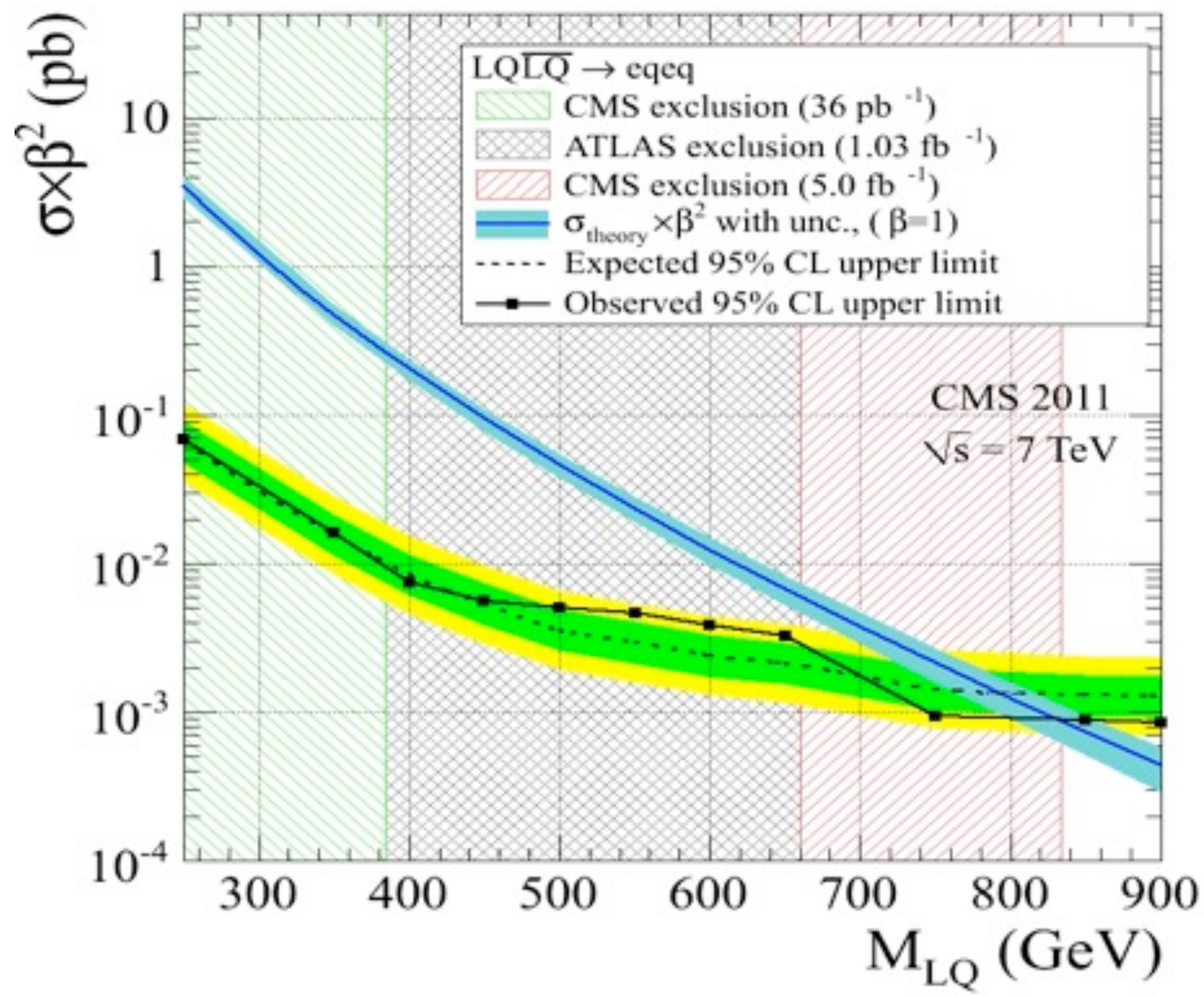
- $M_{LQ} > 1070$ GeV (β=1.0)
- $M_{LQ} > 785$ GeV (β=0.5)

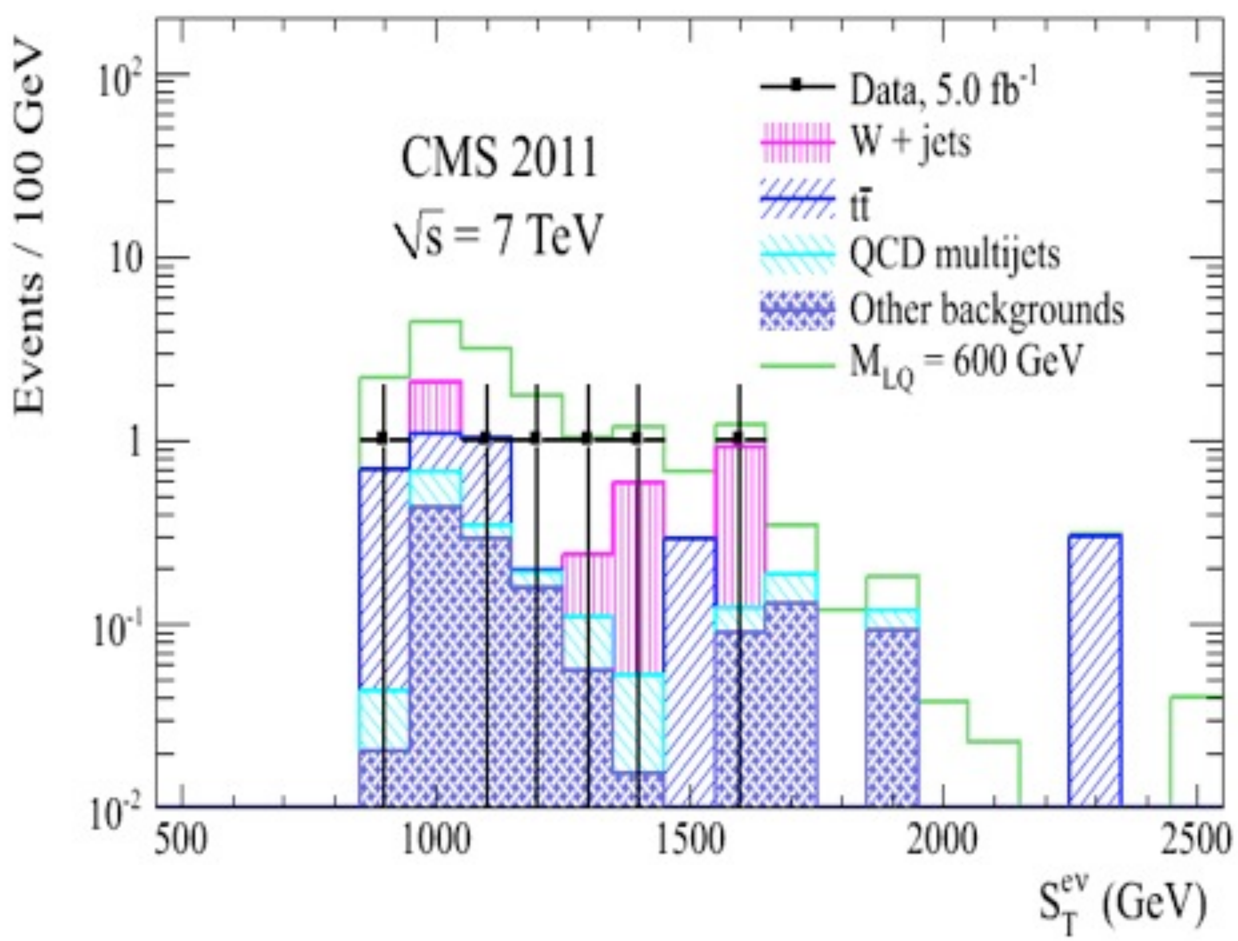
CMS-EXO-12-042

1st Generation Leptoquarks

Similar search is performed in ee+jj and eν+jj final states

✓ Main Backgrounds:
- ttbar, W+jets (for eνjj)
- ttbar, Z+jets (for *eejj*)
- Other backgrounds are negligible





Limits with *L = 5 fb^{-1}*:
- **M_{LQ} > 830 GeV (β=1.0)**
- **M_{LQ} > 640 GeV (β=0.5)**

CMS-EXO-11-027

Dijet Resonances

✓ **Heavy narrow resonance production and decay into two jets**

A generic search and could be applied to many models e.g.,

✓ Strong couplings:
- -Excited quarks
- -E6 diquark
- -Axigluon
- - Coloron
- -s8 Resonance

✓ Weak couplings :
- -Heavy W
- -Z´ and
- -RS Graviton

X = Z′, RS Graviton, s8, q*, W′

✓ **Search strategy:**
- Measurement of inclusive dijet mass spectrum using two highest P_T jets
- Look for bump over the mass spectrum
- The presence of bump tested by fitting a smooth parameterization
- Set upper limits on production cross section and lower limit on mass

Dijet Resonances - II

✓Background parameterization using a smooth fit function

$$\frac{d\sigma}{dm} = p_0 \frac{(1-X)^{p_1}}{X^{p_2+p_3\ln(X)}} \qquad x = m_{jj}/\sqrt{s}$$

✓The fit function describe the data reasonably well with χ/NDF= 30.6/35

-Wide jets: Two leading AK5 PF jets are used as seed for wide jets. All other AK5 PF jets with P_T> 30 GeV and $|\eta|$< 2.5 added to the closest leading jet if within ΔR< 1.1

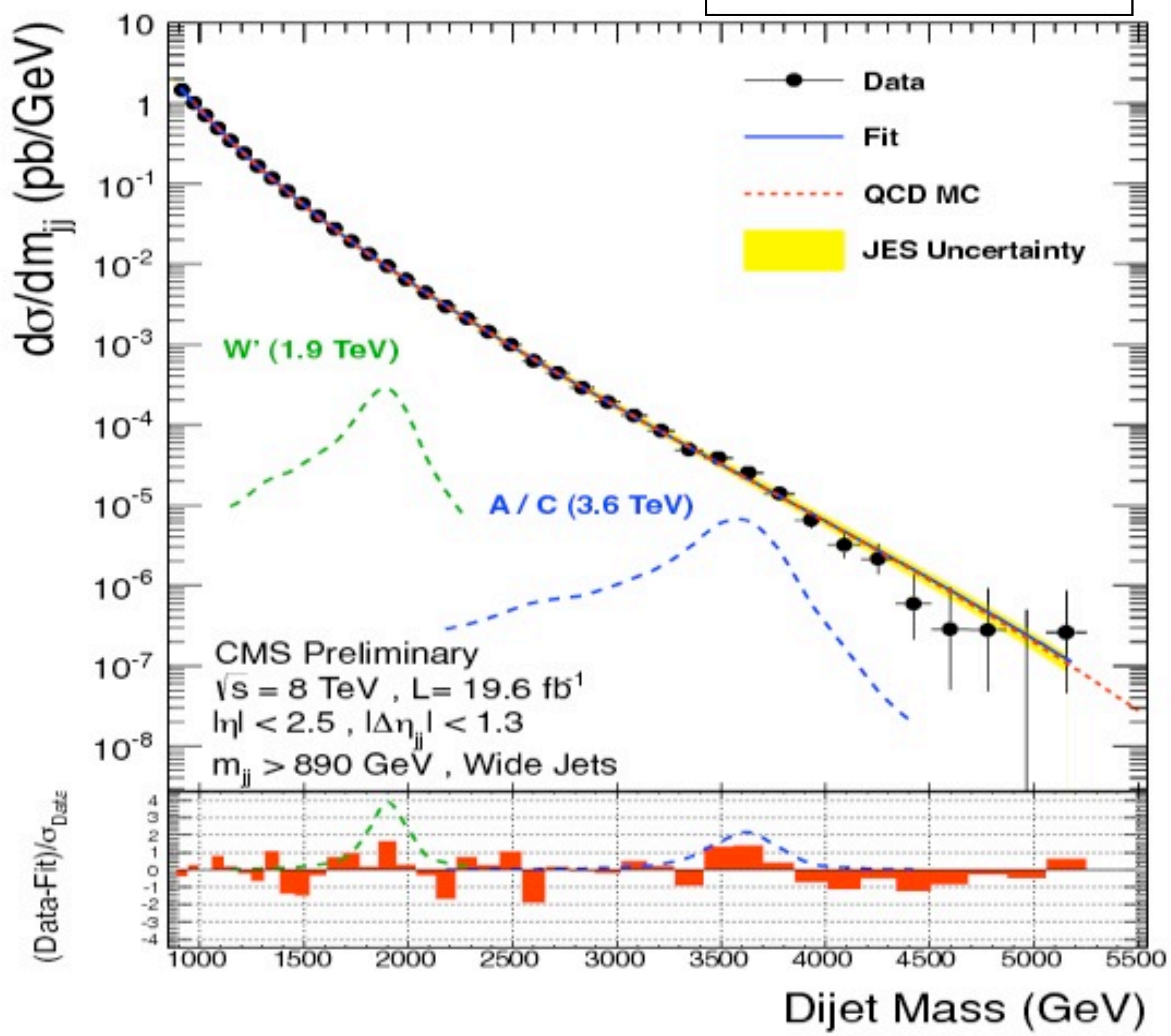
- $|\Delta\eta|$ < 1.3 (suppress QCD background)

-Fraction of muon energy inside the jet are required to be < 0.8

- MET/SumEt < 0.5 for noise rejection

- Mjj > 890 GeV

CMS-EXO-12-059



Dijet Resonances - III

CMS-EXO-12-059

Limit Setting Procedure:

✓Baysian formalism is used with uniform priors for background parameters to set upper limits of 95% CL on the qq, qg and gg resonance production cross section

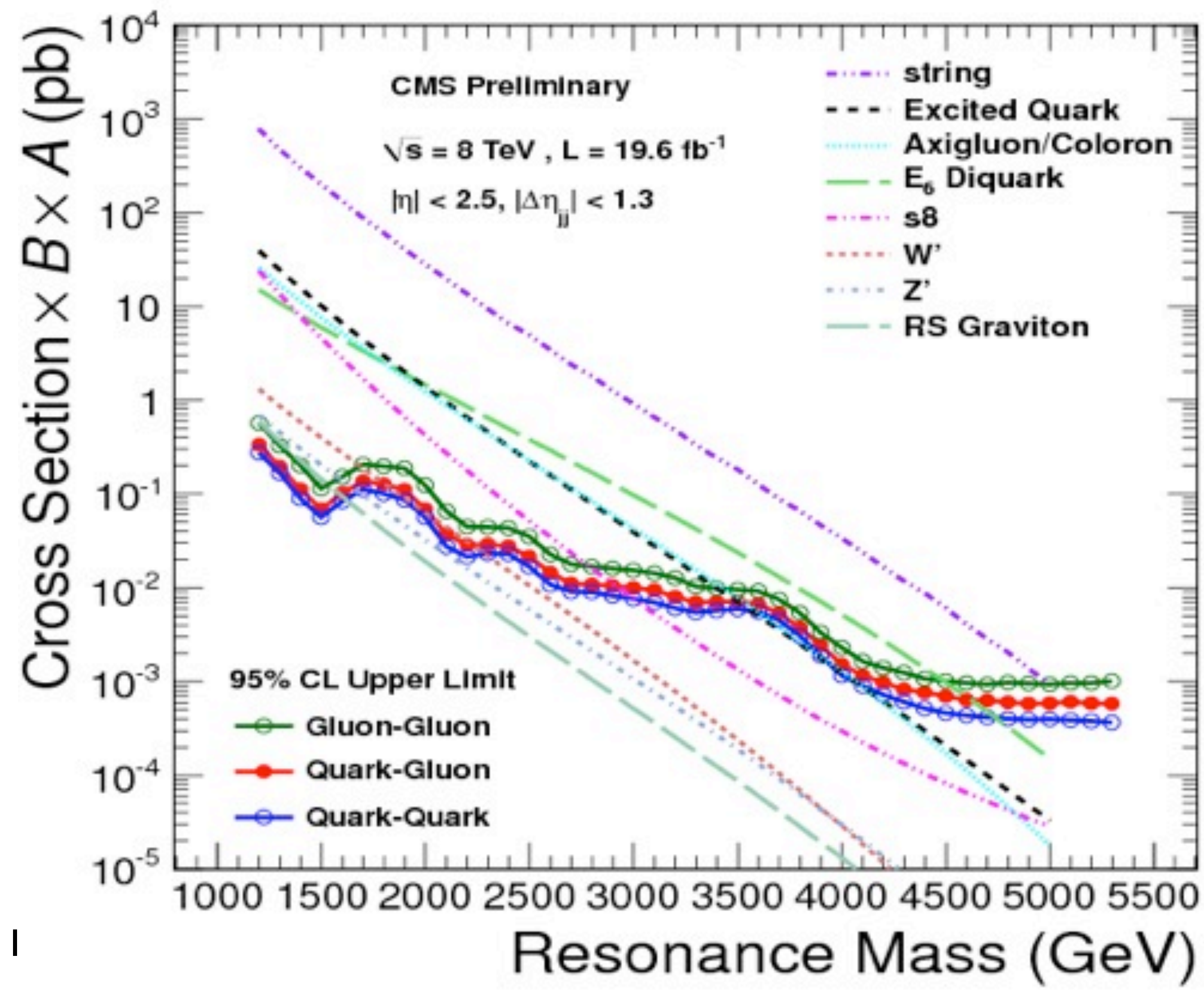
✓Upper limit is compared with theoretical predictions to set lower limit on the resonance mass

✓The background comes from the background component of *signal+background* fit to data

Systematics: are included as nuisance parameter in limit setting procedure and includes,

-Background parameterization
-Jet Energy Resolution: 10%
-Jet Energy Scale : 1.25%
-Luminosity : 4.4 %

The JER, JES and luminosity are used as log normal nuisance parameter in limit setting



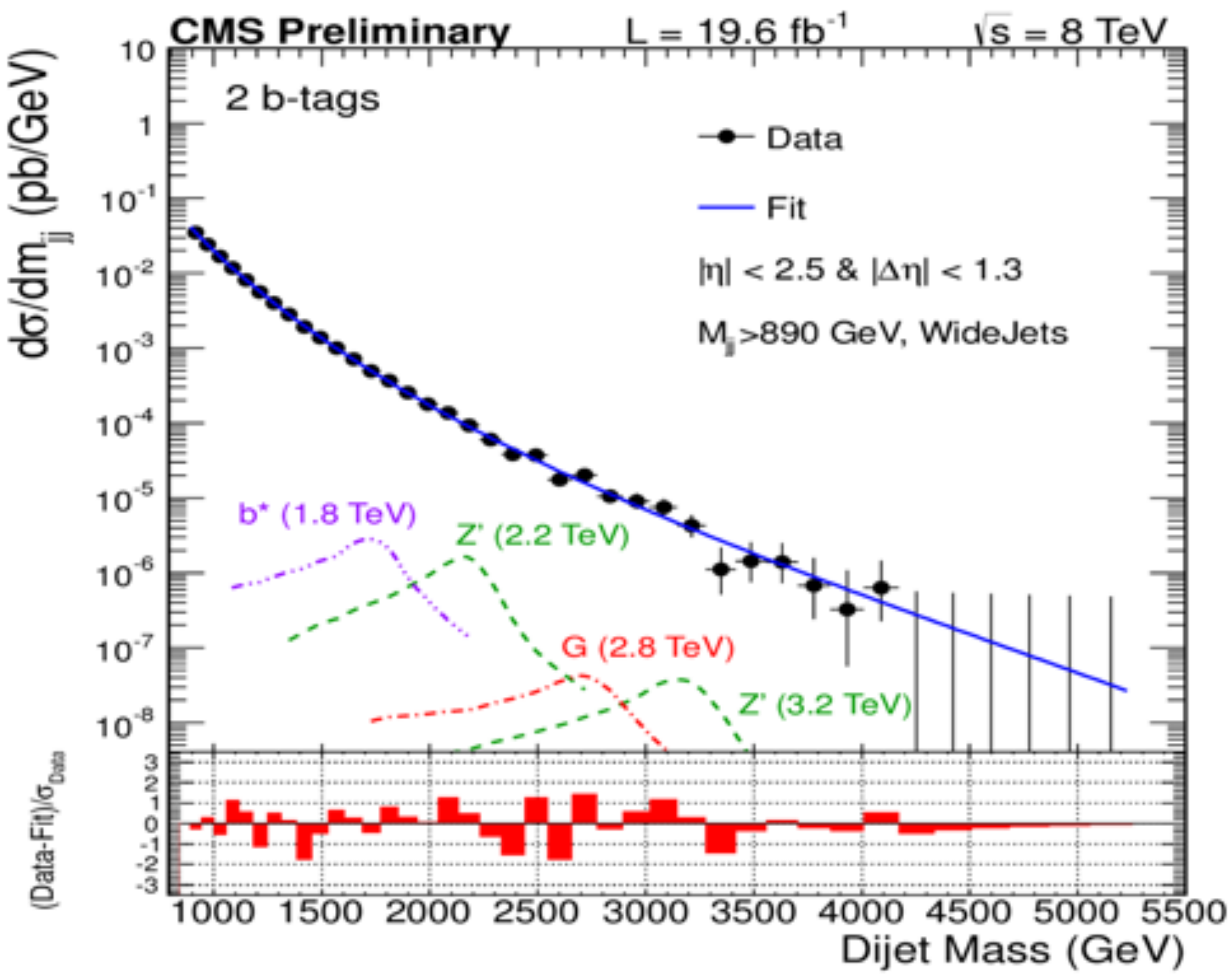
Dijet Resonances (b-tagged)- IV

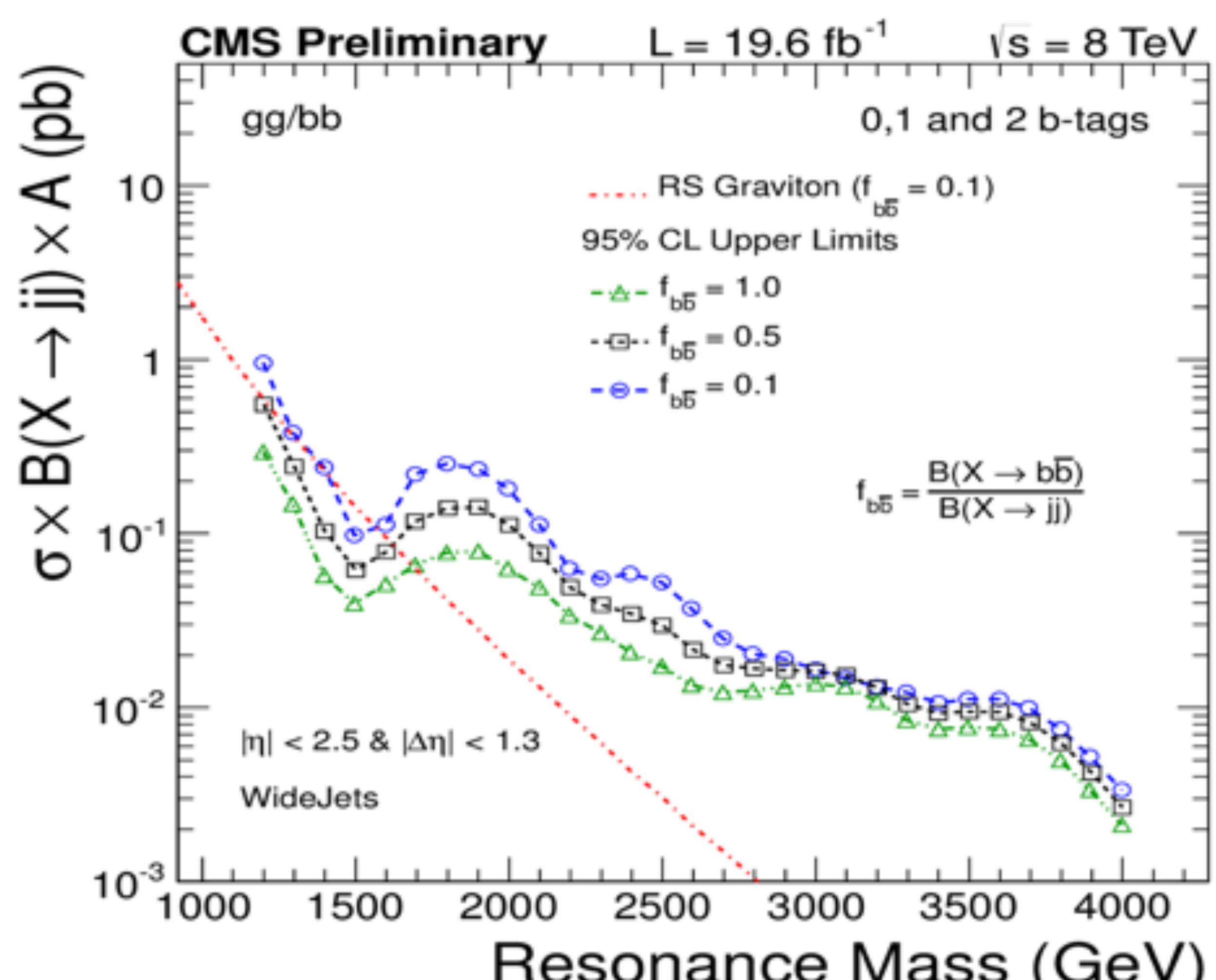
CMS-EXO-12-023

- ✓ Similar analysis but with the requirement of two b-jets
  - **Improved sensitivity due to b-tagging**

- ✓ bb and bg resonance shape differ from qq and gg shapes
- ✓ Reasonable agreement between data and MC
- ✓ Good description of the data by the fit function for different b-tag multiplicities

- ✓ b*, RS Graviton and Z′ resonance shapes are considered in this analysis





DiJet Resonances: Results

✓ Untagged inclusive search results:

Model	Final State	Obs. Mass Excl. [TeV]	Exp. Mass Excl. [TeV]
String Resonance (S)	qg	[1.20,5.08]	[1.20,5.00]
Excited Quark (q^*)	qg	[1.20,3.50]	[1.20,3.75]
E_6 Diquark (D)	qq	[1.20,4.75]	[1.20,4.50]
Axigluon (A)/Coloron (C)	$q\bar{q}$	[1.20,3.60] + [3.90,4.08]	[1.20,3.87]
Color Octet Scalar (s8)	gg	[1.20,2.79]	[1.20,2.74]
W′ Boson (W′)	$q\bar{q}$	[1.20,2.29]	[1.20,2.28]
Z′ Boson (Z′)	$q\bar{q}$	[1.20,1.68]	[1.20,1.87]
RS Graviton (G)	$q\bar{q}$+gg	[1.20,1.58]	[1.20,1.43]

✓ b-tagged search results:

Model	Observed Mass Limits (TeV)
Z'	[1.20-1.68]
RS Graviton	[1.42-1.56]
Excited b-quark	[1.36-1.53]

Search in Lepton+MET Final State : W′

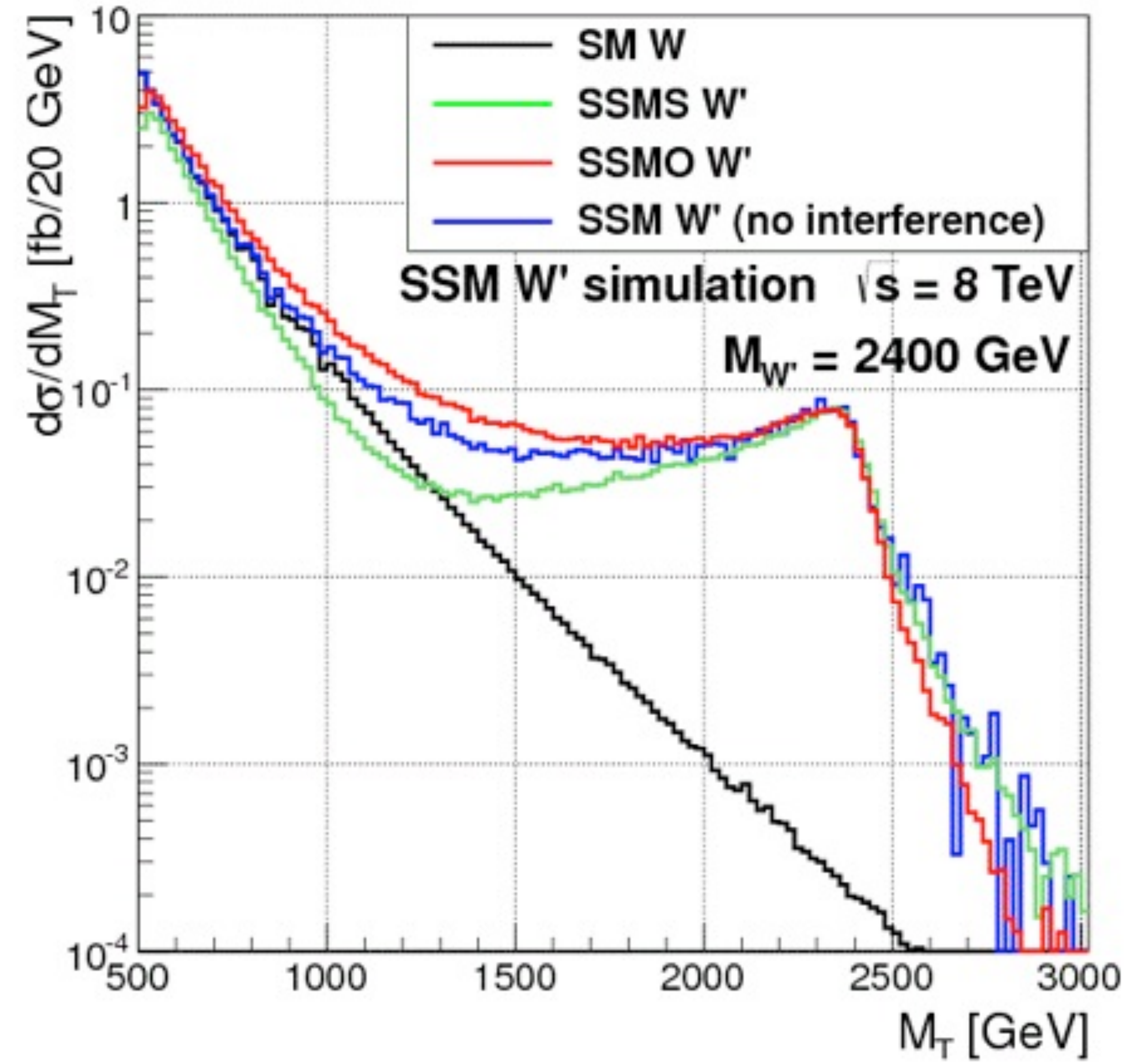
✓ **New heavy gauge bosons W′ has been predicted in many extensions of SM like:**

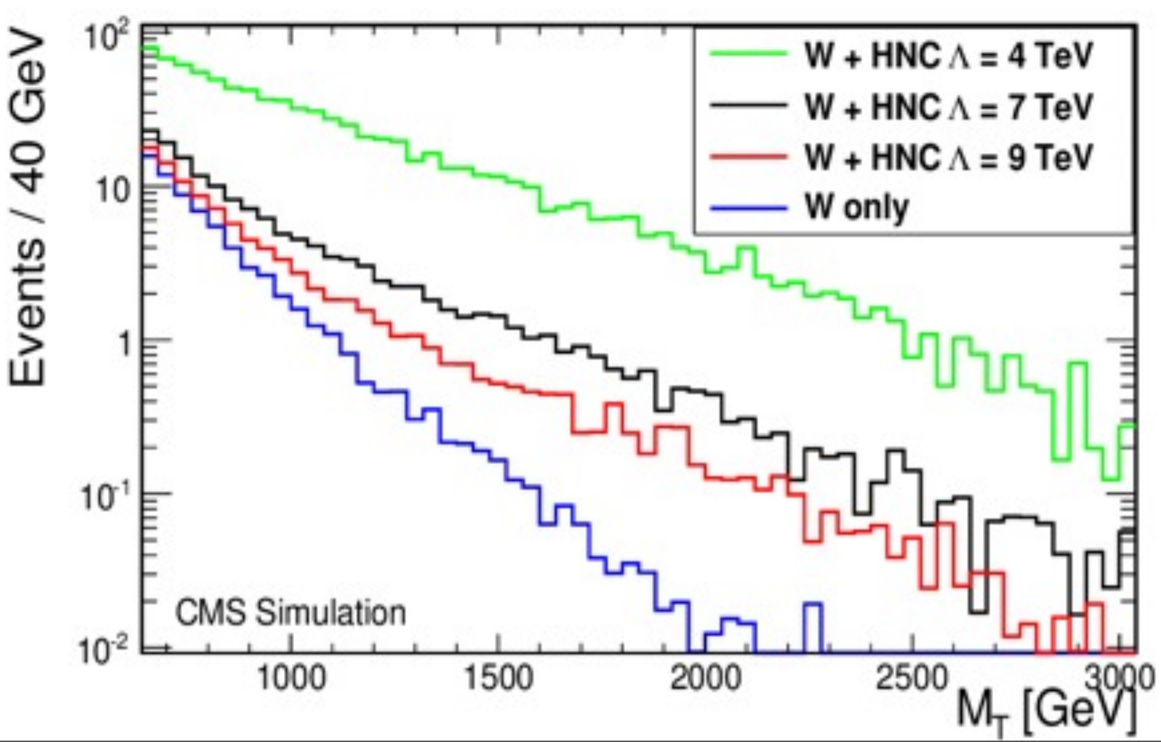
- Sequential SM (SSM): W′ Jacobean peak
- Split UED : SM particles have KK partners
- Four fermion contact interactions: unstructured excess

CMS-EXO-12-060

Selection:

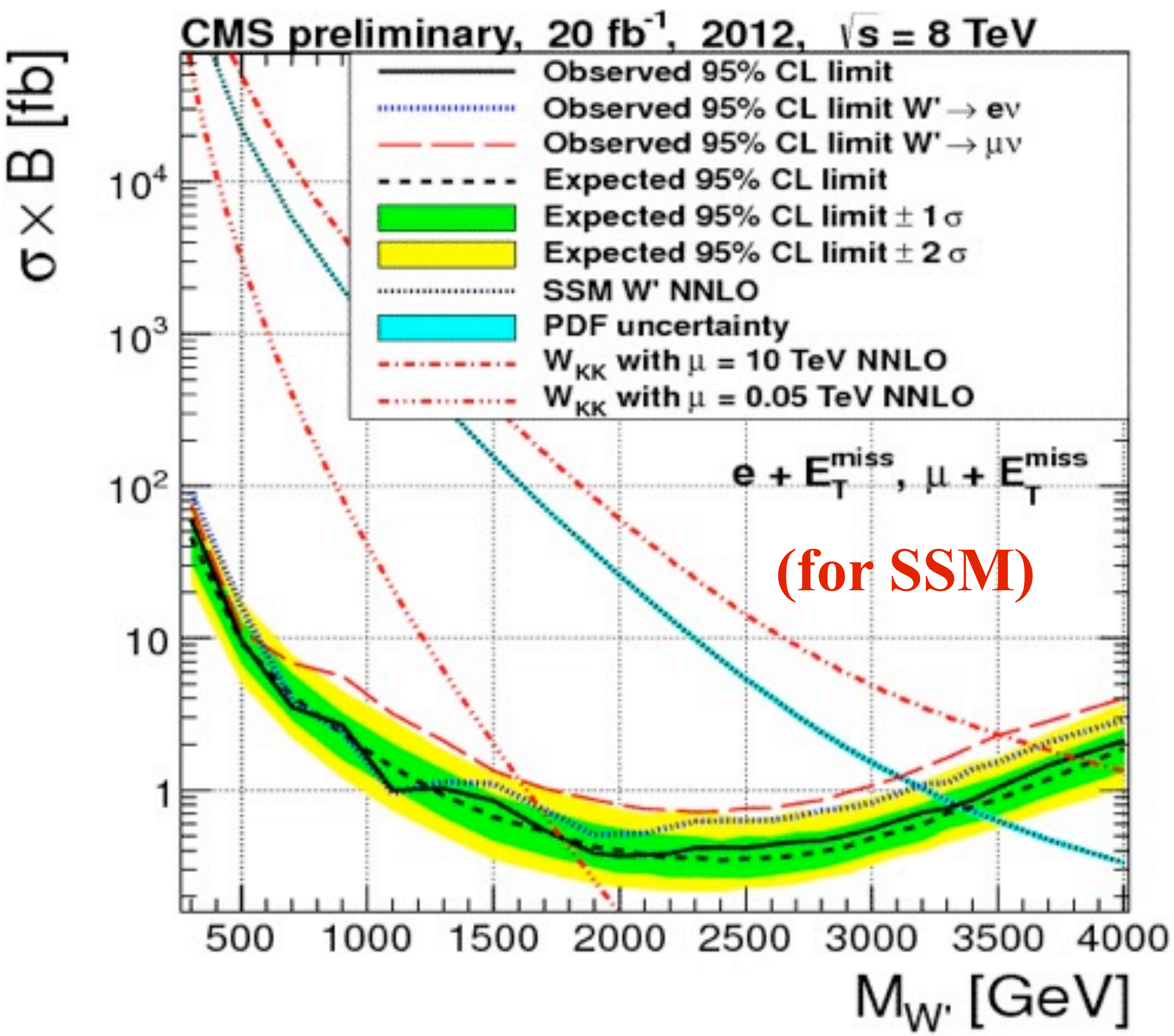
- P_T>45 GeV (μ), P_T> 100 GeV (e)
- $|\eta| < 2.1$ (μ), $|\eta| < 2.5$(e)
- $0.4 < P_T/MET < 1.5$
- $\Delta\phi > 0.8\pi$
- K-factor were applied for multijet QCD and W production for background

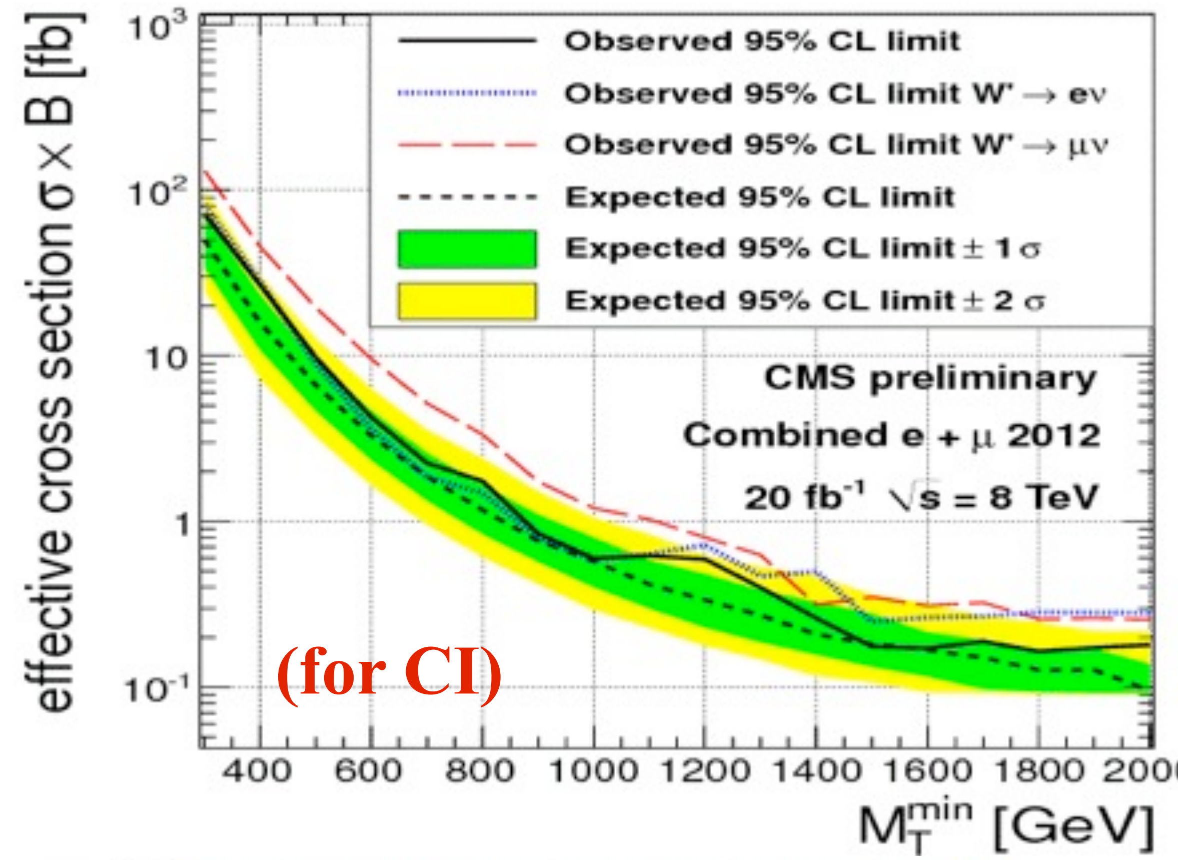


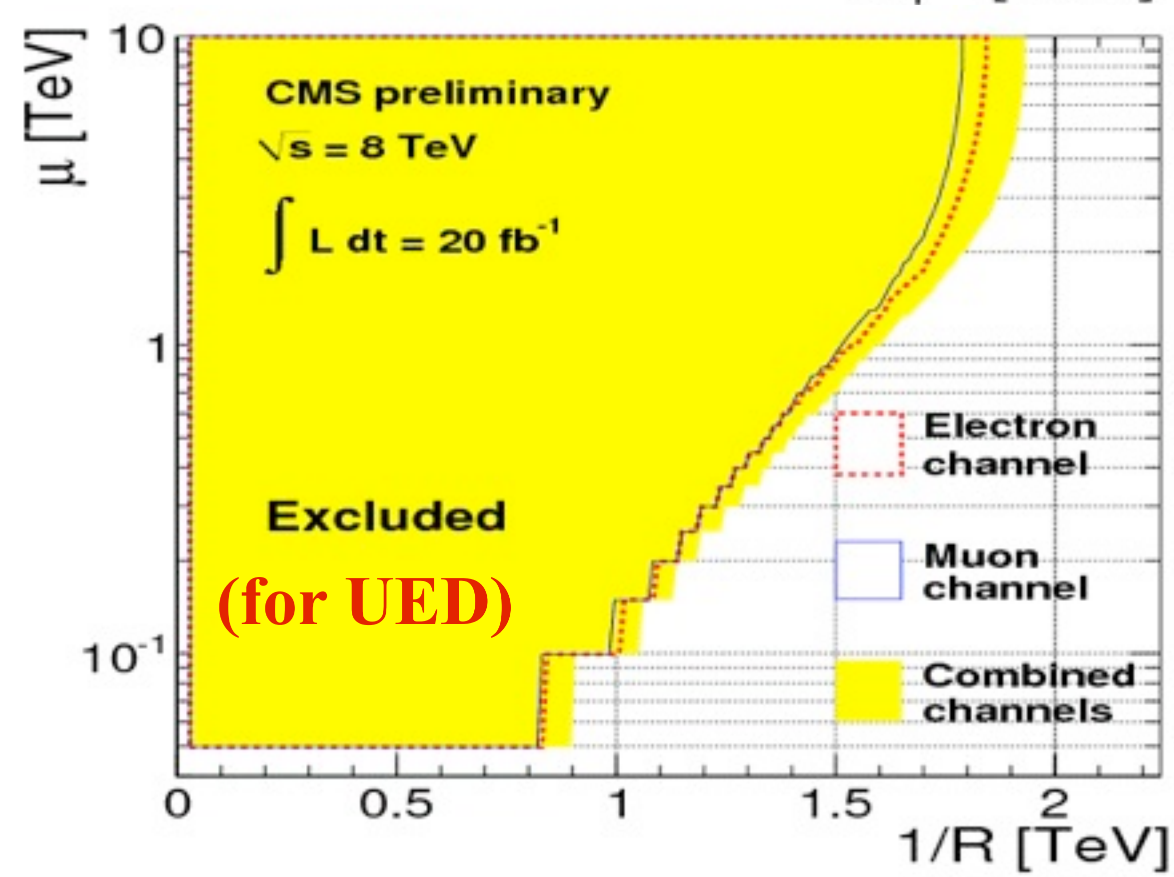


Search in Lepton+MET Final State: W′ - II

✓ **No significant excess over SM expectation is observed**







CMS-EXO-12-060

Systematics and Exclusion:

CMS-EXO-12-060

- ✓ Lepton energy and scale: By varying between 1% and 10 %, are applied to M_T distribution
- ✓ missing-E_T: Each energy deposition is assigned to its corresponding(tau, photon, muon...) object and then varied as per its type and then uncertainty on MET is estimated
- ✓ For each systematics uncertainty the M_T is shifted by ± 1σ and difference with default is taken as uncertainty on the number of background events

Model	Channel	Observed limit	Expected limit
SSM	e	$m_{W'} < 3.20$TeV	$m_{W'} < 3.25$TeV
SSM	μ	$m_{W'} < 3.15$TeV	$m_{W'} < 3.10$TeV
SSM	combined	$m_{W'} < 3.35$TeV	$m_{W'} < 3.40$TeV
SSMO	e	$m_{W'} < 3.60$TeV	$m_{W'} < 3.60$TeV
SSMO	μ	$m_{W'} < 3.05$TeV	$m_{W'} < 3.30$TeV
SSMO	combined	$m_{W'} < 3.60$TeV	$m_{W'} < 3.60$TeV
SSMS	e	$m_{W'} < 3.00$TeV	$m_{W'} < 3.10$TeV
SSMS	μ	$m_{W'} < 2.80$TeV	$m_{W'} < 2.90$TeV
SSMS	combined	$m_{W'} < 3.10$TeV	$m_{W'} < 3.20$TeV
W^2_{KK}	μ=0.05 TeV, combined	$m_{W^2_{KK}} < 1.7$TeV	$m_{W^2_{KK}} < 1.7$TeV
W^2_{KK}	μ=10.0 TeV, combined	$m_{W^2_{KK}} < 3.7$TeV	$m_{W^2_{KK}} < 3.6$TeV
HNC CI	e	$\Lambda < 13.0$ TeV	$\Lambda < 13.3$ TeV
HNC CI	μ	$\Lambda < 10.9$ TeV	$\Lambda < 12.2$ TeV

Summary

✓ **2011+2012 data taking at CMS was very successful, many new and updated analyses with different final states**

✓ **Many new stringent limits from these searches. In a nutshell:**

- For HSCP : Excluded <1322 GeV for *gluino*
- For leptoquarks the lower limits on mass are set to $M_{LQ} > 1070(785)$ GeV for $\beta=1.0(0.5)$ from 2nd generation searches
- The dijet resonance searches for various model have been extended up to 5 TeV for string resonances and 3.5 TeV for q^*
- W′ (SSM): $M_{W'} < 3.35$ TeV in lepton+MET channel

✓ **No evidence of new physics beyond SM**

✓ **Many more to come....... stay tuned !!!**

back-up

HSCP Pre-Selection

- ✓ Muon Trigger: $pT > 40$ GeV
- ✓ MET Trigger: $MET > 50$ GeV

Tracker only:

- ✓ $pT > 45$ GeV, $sigma/pT < 0.25$, dz and dxy < 0.5 cm
- ✓ $E/p < 0.3$, $I_h > 3$ MeV/cm, $\sum pT < 50$ GeV

Muon System Only:

- ✓ $pT > 80$ GeV, dz and dxy < 15 cm, $1/\beta > 1$

Tracker+Muon:

- ✓ Same as Tracker only + a reconstructed muon matched to track in inner detector

Fractionally Charged:

- ✓ Same as Tracker only + $I_h < 2.8$ MeV/cm

Multiple Charged:

- ✓ Same as combined + E/p is excluded

HSCP: Background Estimation

✓ Tracker Only:
pT> 70 GeV , $I_{as} > 0.4$ MeV/cm

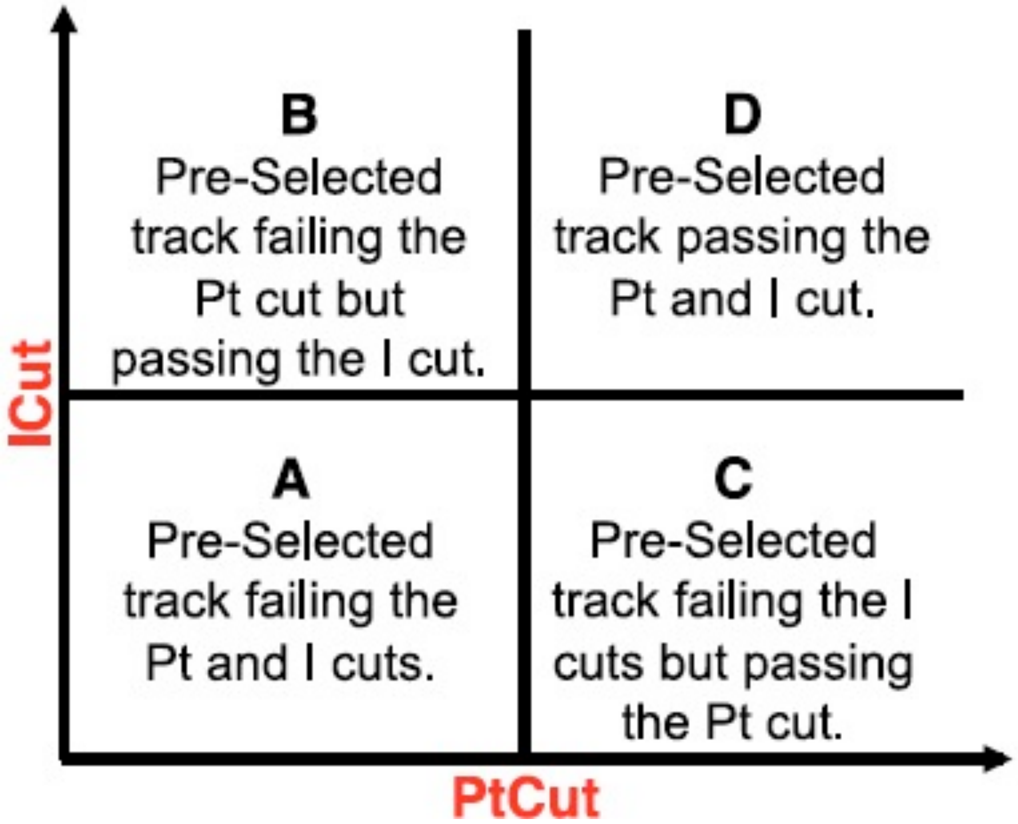
Muon System Only:
✓ pT> 130 GeV, $1/\beta > 1.4$

Tracker Only + Muon System:
✓ pT> 70 GeV, $I_{as} > 0.125$ MeV/cm, $1/\beta > 1.255$

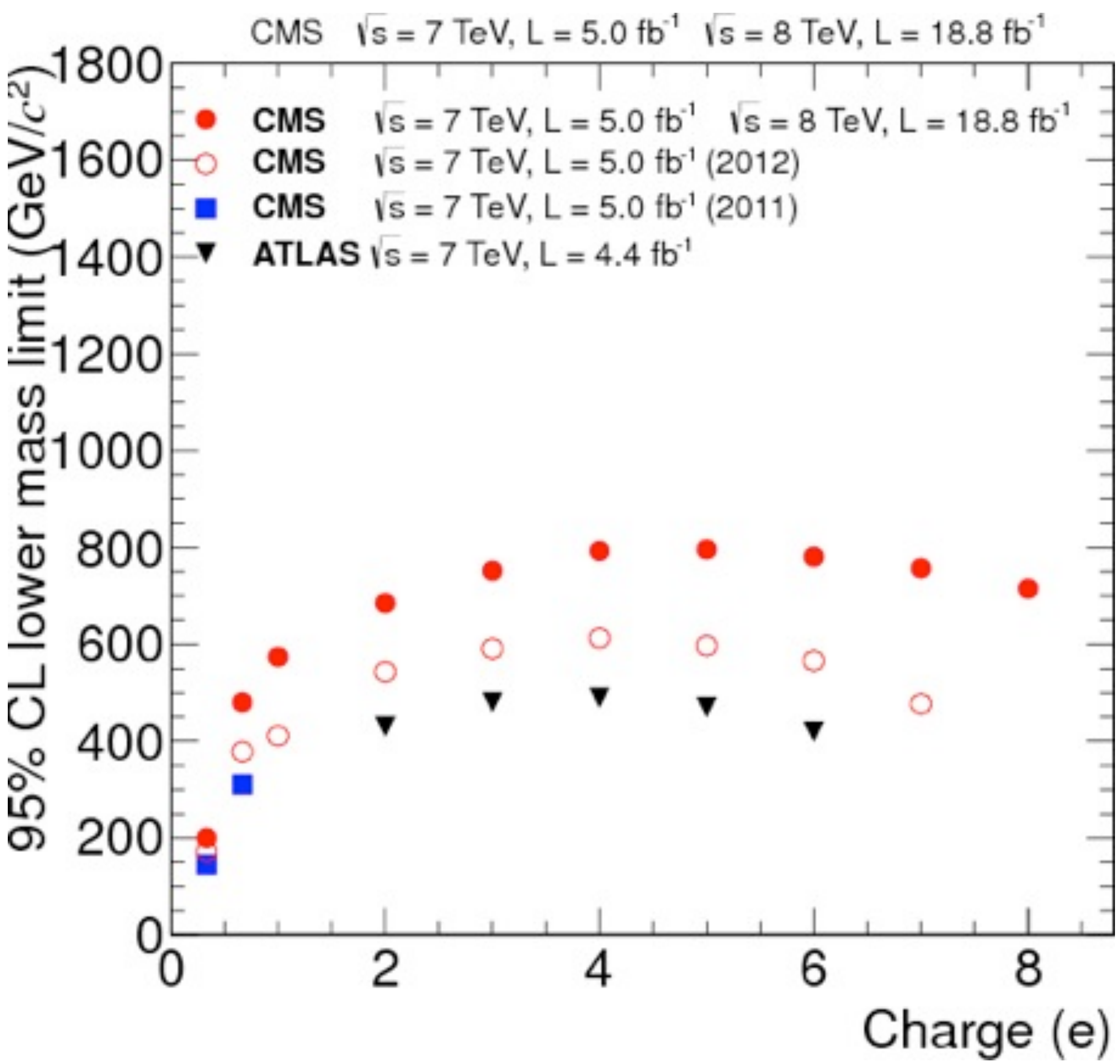
Fractionally Charged:
✓ pT> 125 GeV, $I_{as} > 0.275$ MeV/cm

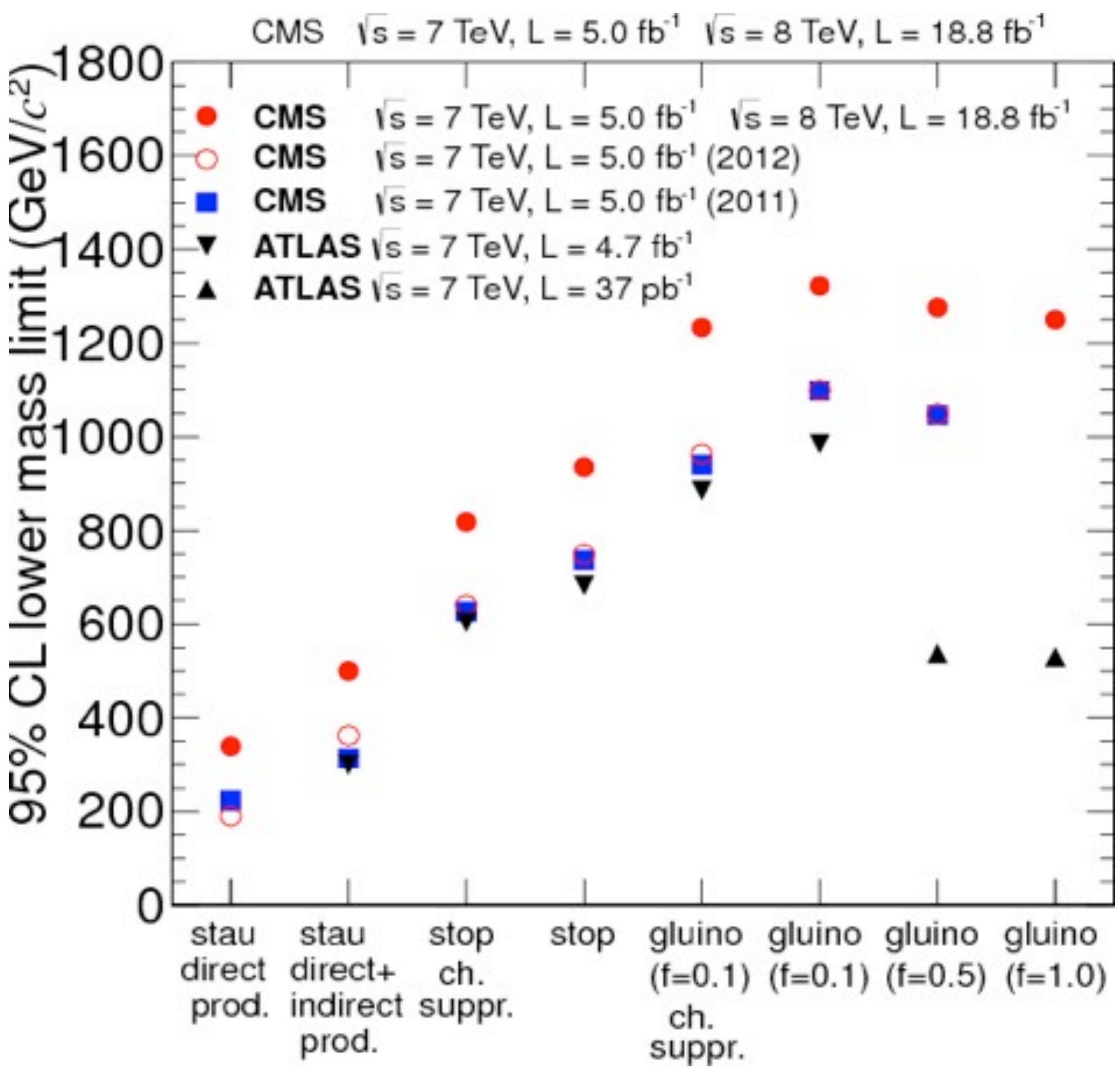
Multiple Charged:
✓ $I_{as} > 0.5$ MeV/cm, $1/\beta > 1.2$

D= BC/A



HSCP: Results





3rd Generation Scalar Leptoquarks

✦The analysis is designed to kinematically discriminate the pair production of heavy particle from SM background with making strong assumption about missing-E_T

✦Force every event to *dijet-topology* by combining all jets in the event into two *mega jets* and defined Razor variable as

Razor Variable: $$R \equiv \frac{M_T^R}{M_R}$$

Where,

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

Peaks at leptoquark mass

$$M_T^R \equiv \sqrt{\frac{\not{E}_T(p_T^{j1} + p_T^{j2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})}{2}}$$

CMS EXO-11-030

3rd Generation Scalar Leptoquarks

Final state: bbνν

CMS Search in 1.8 fb $^{-1}$

- Used *razor* variable $R \equiv \frac{M_T^R}{M_R}$

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

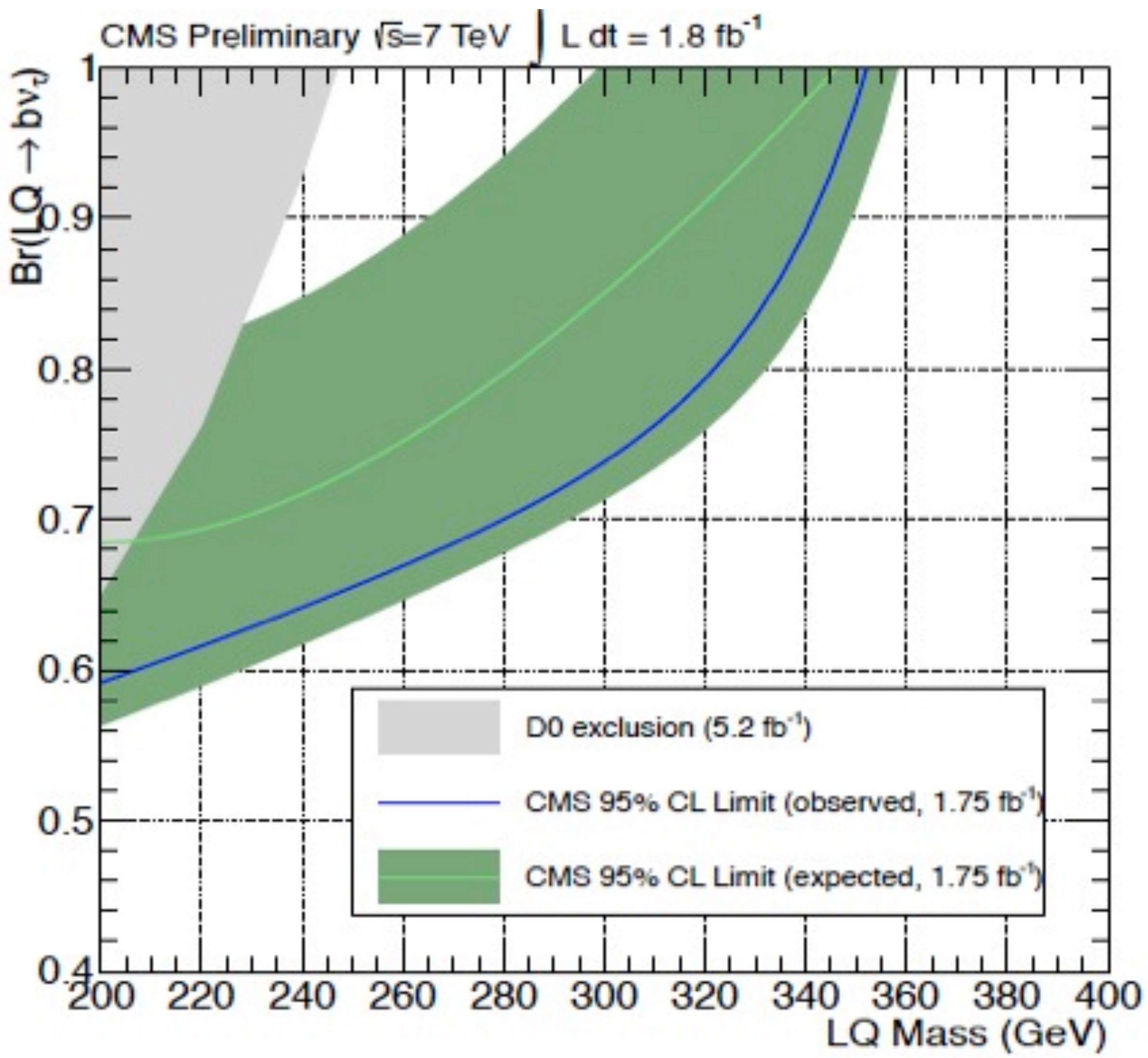
$$M_T^R \equiv \sqrt{\frac{\not{E}_T(p_T^{j1} + p_T^{j2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$

  - Designed to search for a pair of "heavy particles"

- 2 b-tagged jets

- Main Bkg: 1) Heavy Flavor (HF) Multi-jet
  2) ttbar+jets and W/Z+HF jets

- Systematics: background shape and b-tagging efficiency



- **Limit: M_{LQ} >350 @ 95%CL**

CMS EXO-11-030

Dijet Resonance Properties

Model Name	X	Color	J^P	$\Gamma/(2M)$	Decay Channel
String	S	mixed	mixed	0.003 – 0.037	$qg, q\bar{q}, gg$
Strongly coupling models					
Excited Quark	q*	Triplet	$1/2^+$	0.02	qg
E_6 Diquark	D	Triplet	0^+	0.004	qq
Axigluon	A	Octet	1^+	0.05	$q\bar{q}$
Coloron	C	Octet	1^-	0.05	$q\bar{q}$
s8 Resonance	s8	Octet	$0^?$	??	gg
Weakly coupling models					
Heavy W	W′	Singlet	1^-	0.01	$q\bar{q}$
Heavy Z	Z′	Singlet	1^-	0.01	$q\bar{q}$
RS Graviton	G	Singlet	2^+	0.01	$q\bar{q}$, gg

Dijet: Limit Setting Procedure

✓Baysian formalism is used

$$L(n|\mu) = \prod_i \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}$$

Measured # of events in data

$$\mu_i = \alpha N_i(S) + N_i(B).$$

# of event from signal

Expected # of event from background

Posterior PDF

$$P_{post}(\sigma) = \frac{L(n|\mu)P(\sigma)}{\int_0^\infty L(n|\mu)P(\sigma)d\sigma}$$

$$\int_0^{\sigma_{95\%}} P_{post}(\sigma)d\sigma = 0.95$$

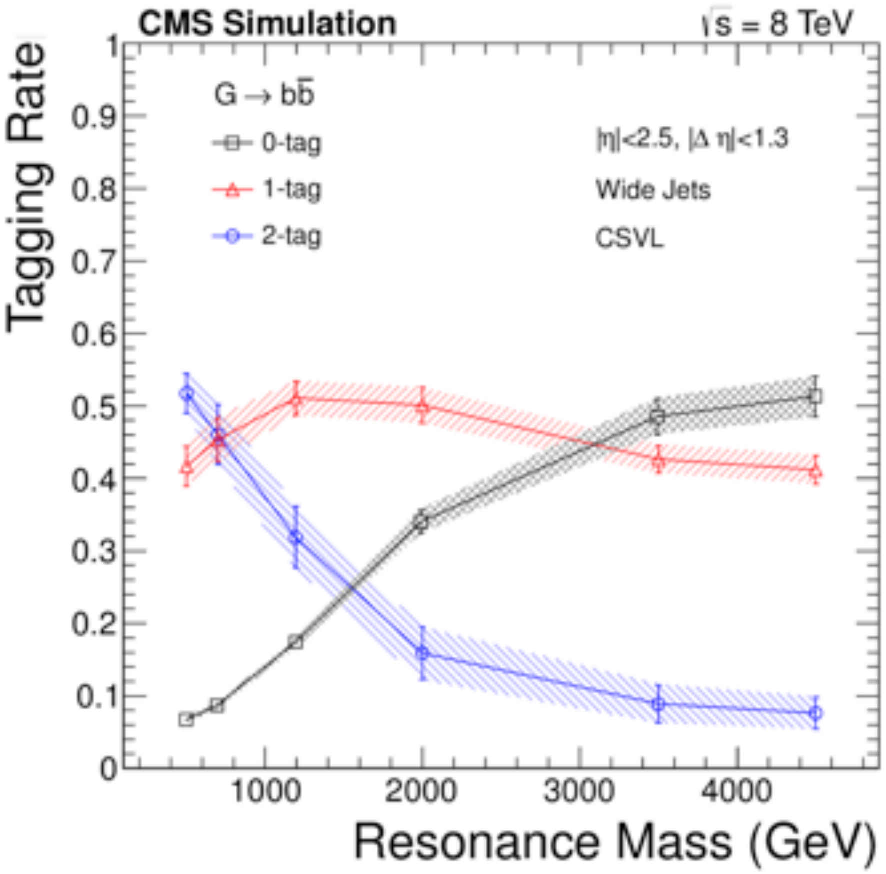
✓For JES, JER, and luminosity nuisance parameters, lognormal priors are used, and these uncertainties affect only signal

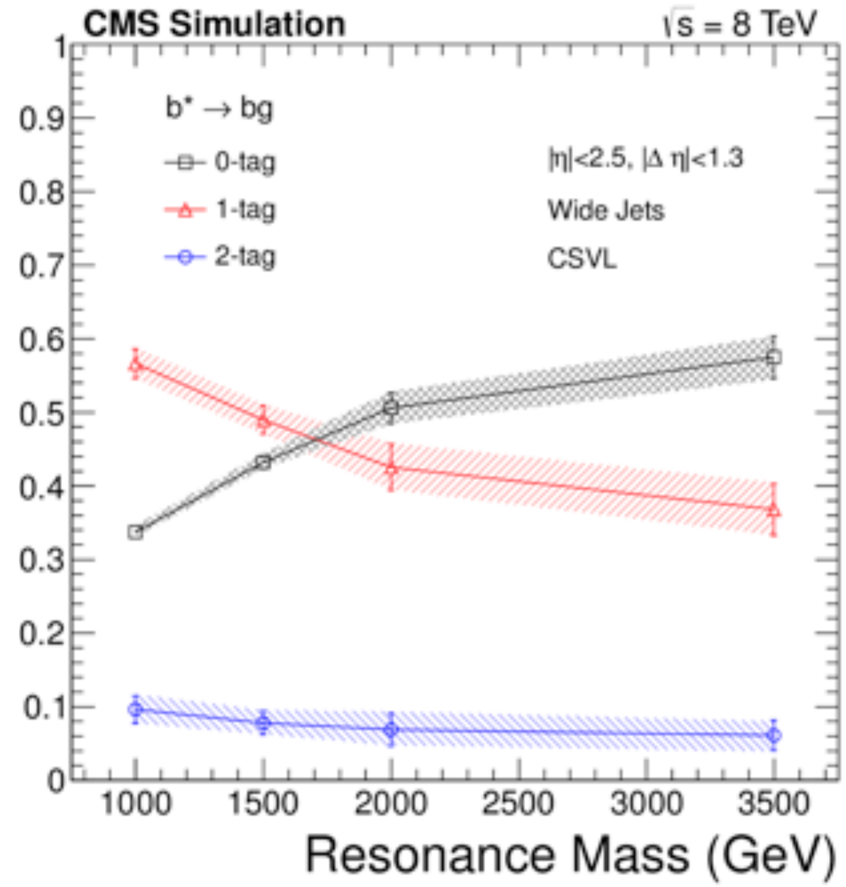
✓For background nuisance parameters flat priors are used and marginalization is performed over a sufficiently large range around the best-fit value such that the final limits are found to be stable

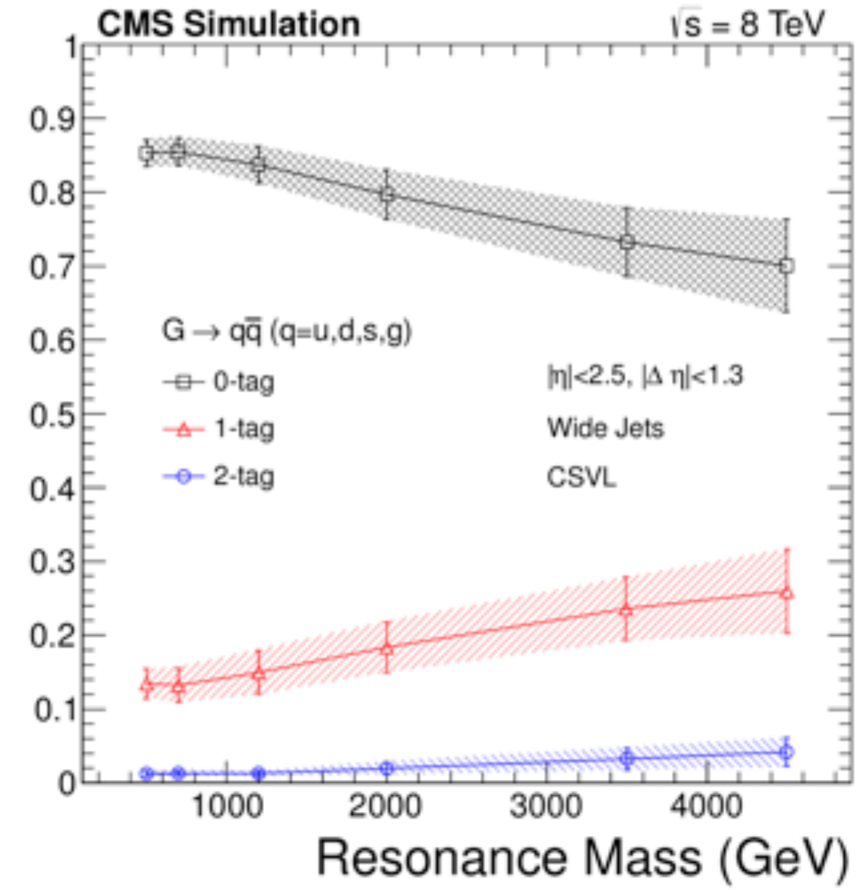
- Evaluated by varying the fit parameters along the eigenvector of covariance matrix

Dijet Resonance: b-tagged

b-tagging rates







Dijet Resonance: b-tagged

✓ Because of sizable mistag rate and decreasing b-tagging rate with the increasing resonance mass, it is not possible to study the bb final state isolated from the rest of the jet-jet final state

✓ 0-,1-, and 2-tagging rate for a generic narrow resonance X defined as:

$$\epsilon^i = \epsilon^i_{\mathrm{h}} f_{\mathrm{b\bar{b}}} + \epsilon^i_{\mathrm{l}} (1 - f_{\mathrm{b\bar{b}}})$$

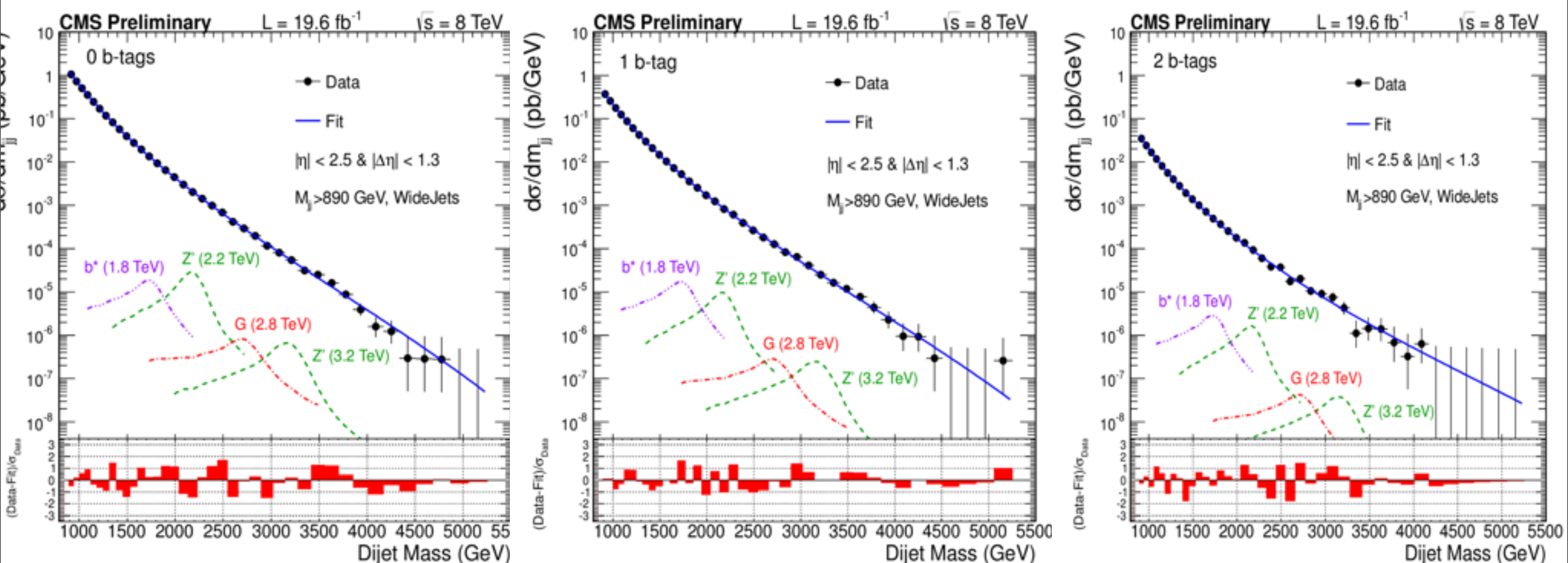
$$\epsilon^i_l = \epsilon^i_{q\bar{q}}$$

$$f_{\mathrm{b\bar{b}}} = \frac{\mathrm{BR}(\mathrm{X} \to \mathrm{b\bar{b}})}{\mathrm{BR}(\mathrm{X} \to \mathrm{jj})}$$

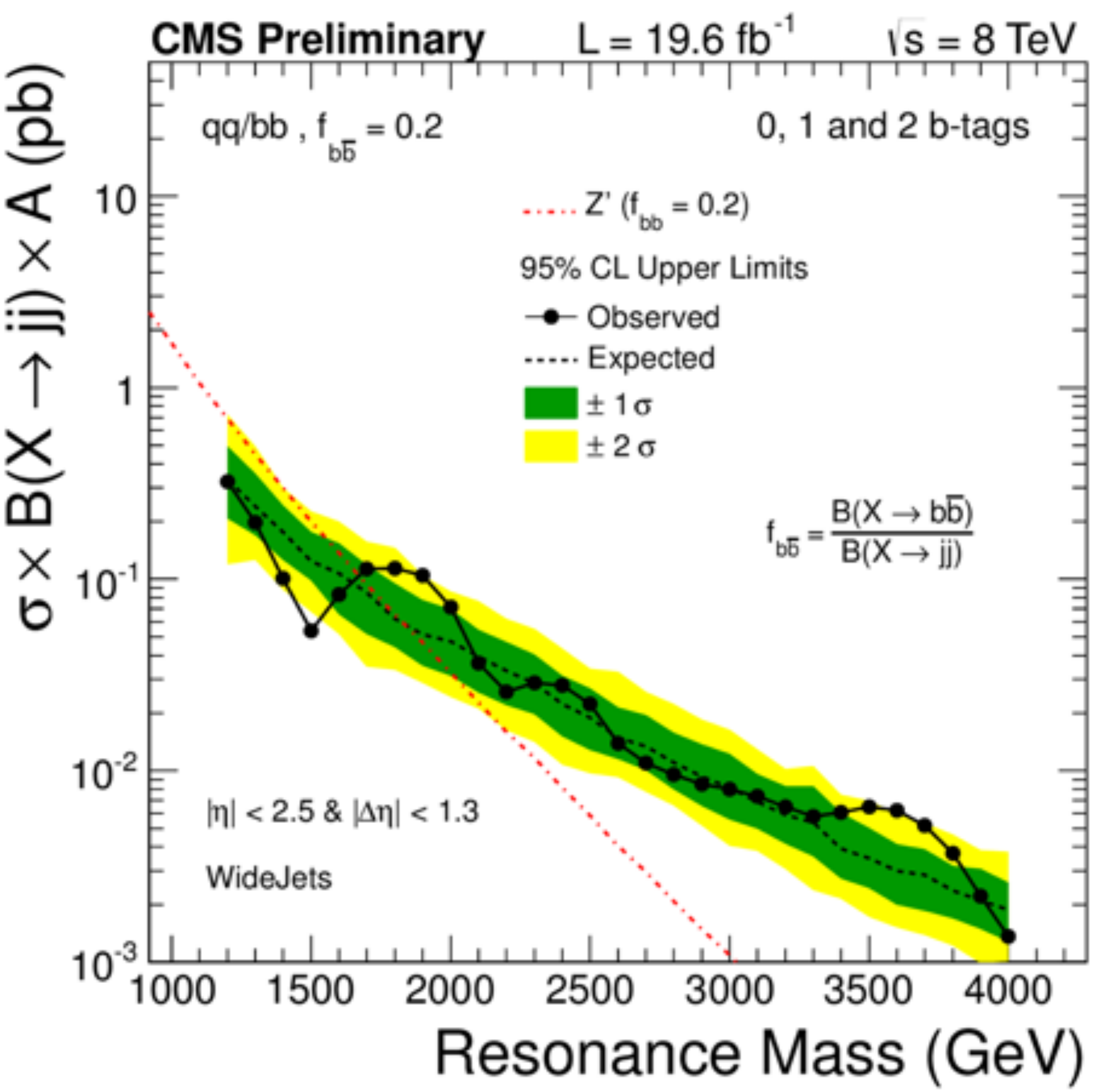
$$\epsilon^i_h = \epsilon^i_{b\bar{b}},$$

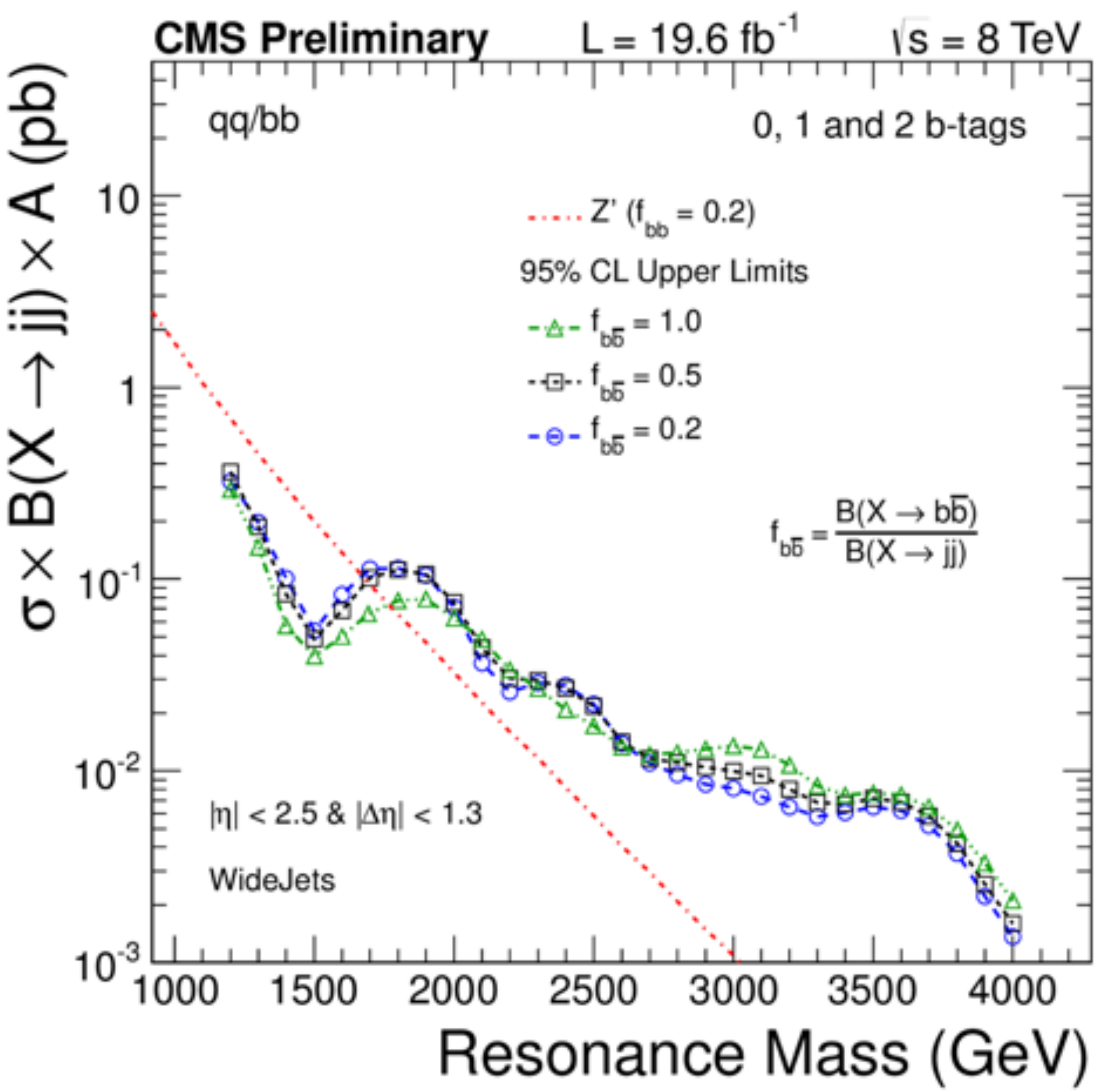
✓ Here it is assume that c quark has the same tagging rate as other light quark

✓ Background fit function for different b-tag multiplicities



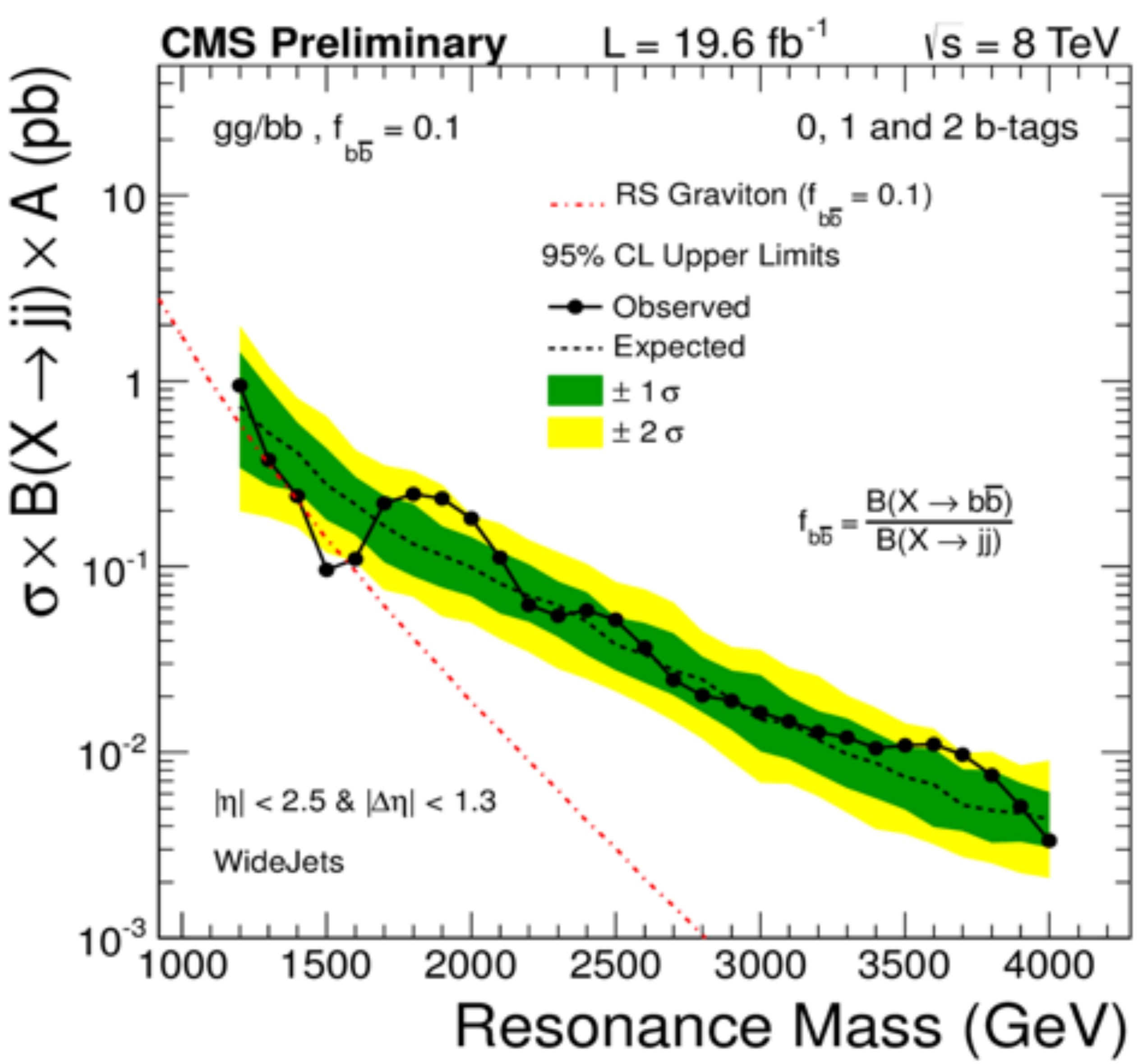
Z' Search


CMS Preliminary
L = 19.6 fb^{-1}
$\sqrt{s}$ = 8 TeV
qq/bb , $f_{b\bar{b}}$ = 0.2
0, 1 and 2 b-tags
Z' (f_{bb} = 0.2)
95% CL Upper Limits
Observed
Expected
± 1 σ
± 2 σ
$f_{b\bar{b}} = \frac{B(X \to b\bar{b})}{B(X \to jj)}$
|η| < 2.5 & |Δη| < 1.3
WideJets
$\sigma \times B(X \to jj) \times A$ (pb)
Resonance Mass (GeV)

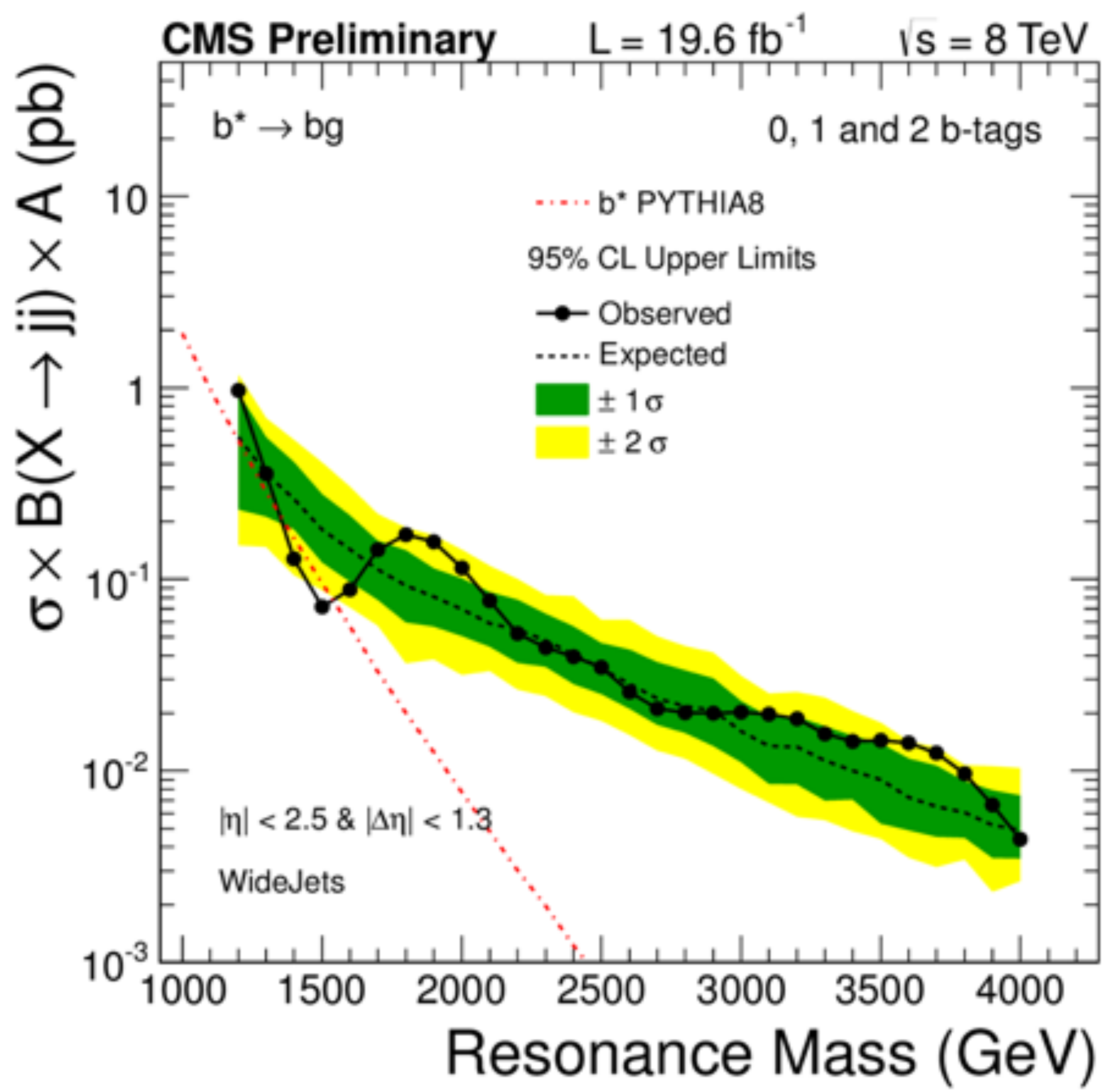

CMS Preliminary
L = 19.6 fb^{-1}
$\sqrt{s}$ = 8 TeV
qq/bb
0, 1 and 2 b-tags
Z' (f_{bb} = 0.2)
95% CL Upper Limits
$f_{b\bar{b}}$ = 1.0
$f_{b\bar{b}}$ = 0.5
$f_{b\bar{b}}$ = 0.2
$f_{b\bar{b}} = \frac{B(X \to b\bar{b})}{B(X \to jj)}$
|η| < 2.5 & |Δη| < 1.3
WideJets
$\sigma \times B(X \to jj) \times A$ (pb)
Resonance Mass (GeV)

Dijet Resonance: b-tagged

RS Graviton Search

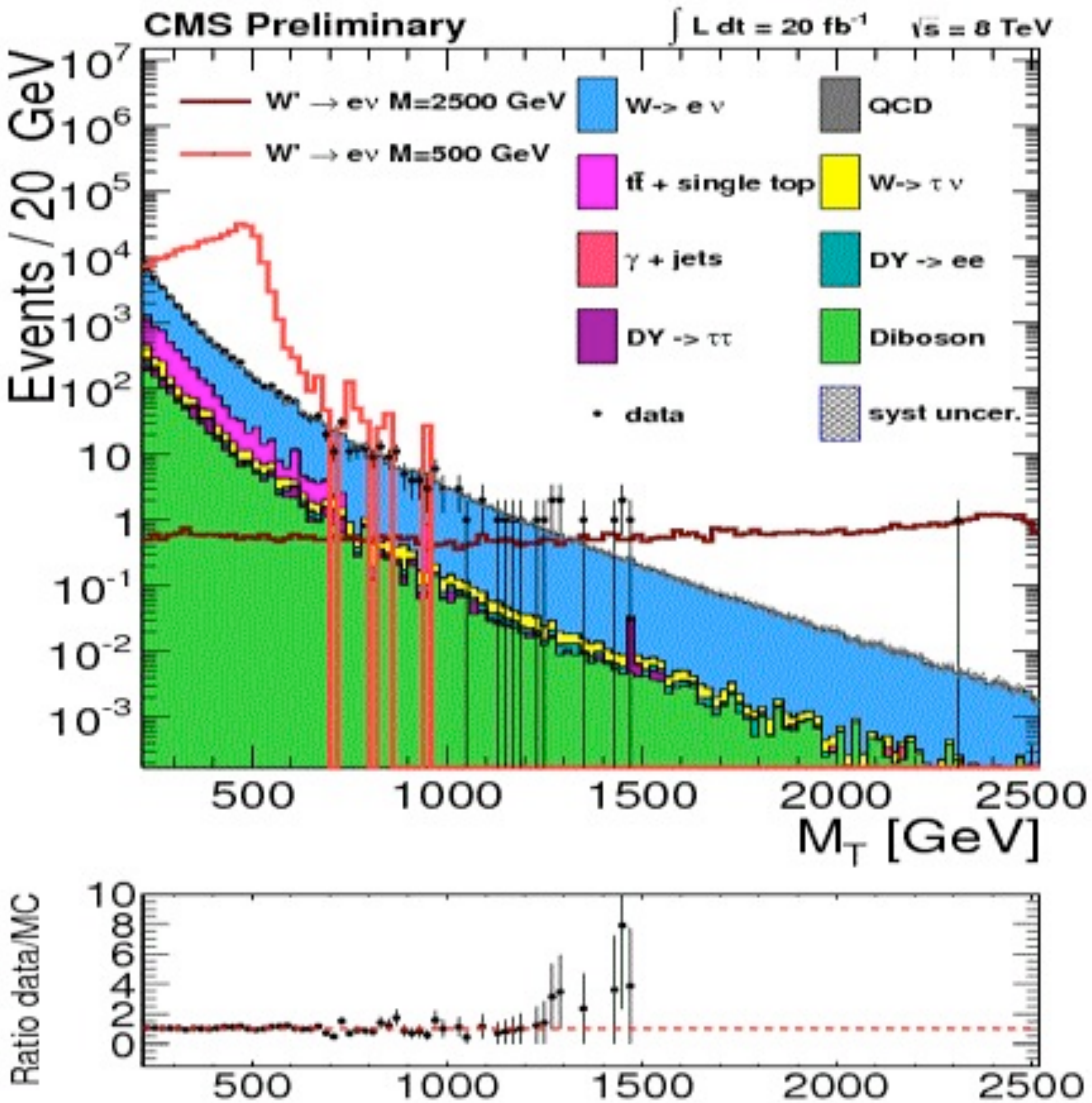


b* Search



W′ Search: SSM

Electron



Muon