Searches for new heavy resonances in final states with dileptons, diphotons and dijets in CMS

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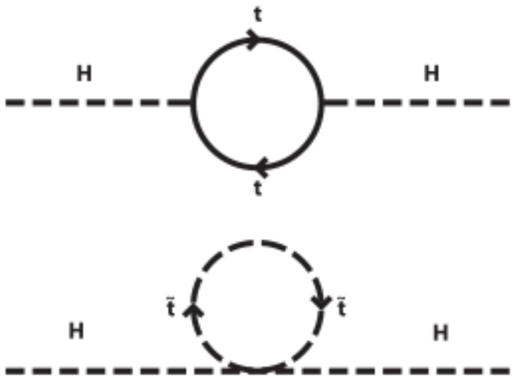
Outline

- Introduction
- The Physics we are after
- The CMS detector
- General analysis strategy
- Results :

Diphoton	: 10.1016/j.physletb.2017.01.027
Zγ	**: CMS-EXO-17-005 (New)**
Dilepton	: CMS-EXO-16-031
Dilepton + Dijet	: **CMS-EXO-16-045 (New) (W_R and heavy ν)**
Ditau	: 10.1007/JHEP02(2017)048
Dijet resolved	: CMS-EXO-16-056
Dijet boosted	: **CMS-EXO-17-001 (New)**

Introduction : SM incomplete

Theoretical point of view

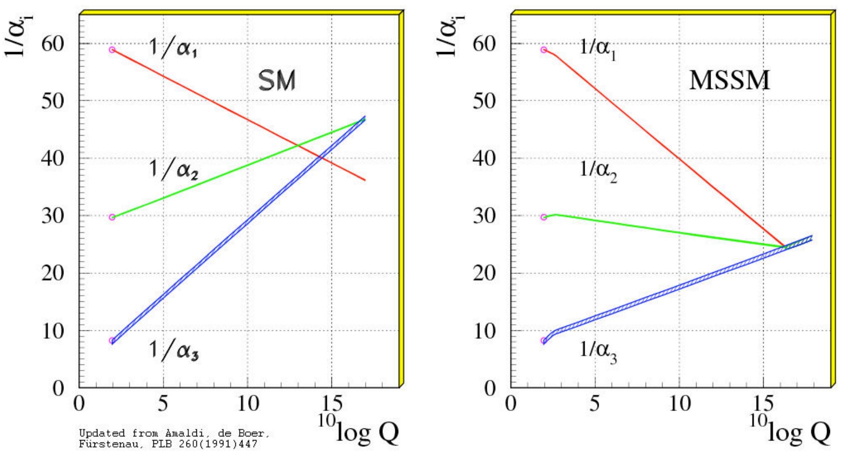


- **Quantum Gravity :** *SM describes three of the four fundamental interactions at the quantum level (microscopically) BUT gravity is only treated classically.*

- **Hierarchy Problem :** *Why is $M_{Pl}/M_{EW} \sim 10^{15}$ What is the mechanism of cancelation of quadratic divergencies?*

- **Unification of Gauge couplings** *: Why couplings are so different?*

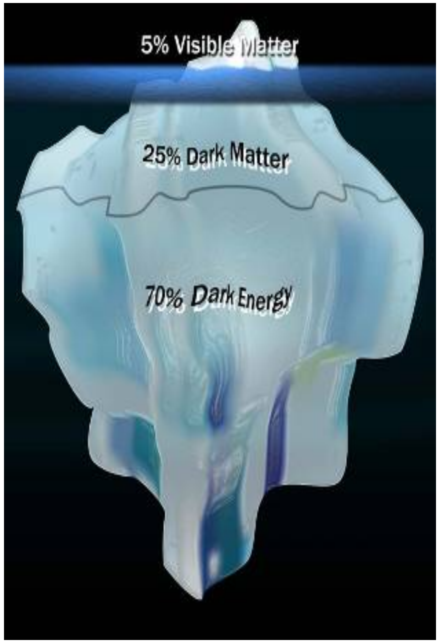
- **Origin of generations :** Why three?



Introduction : SM incomplete

Experimental point of view

- **Dark matter – Dark Energy :** *What is 95% of the Universe made off?*

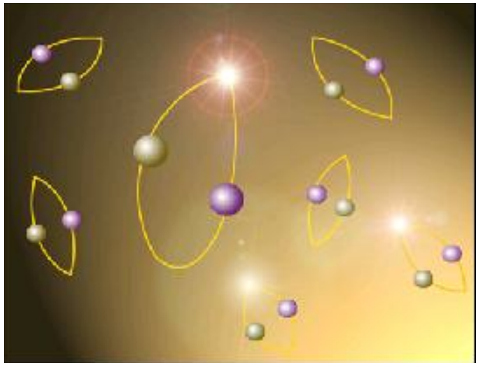


- **Cosmological constant** *: Why is vacuum energy SO small?*

  $\rho_{VAC} = M_{Pl}^4 = 10^{120} \rho_{VAC}^{obs}$ *(!!!)*

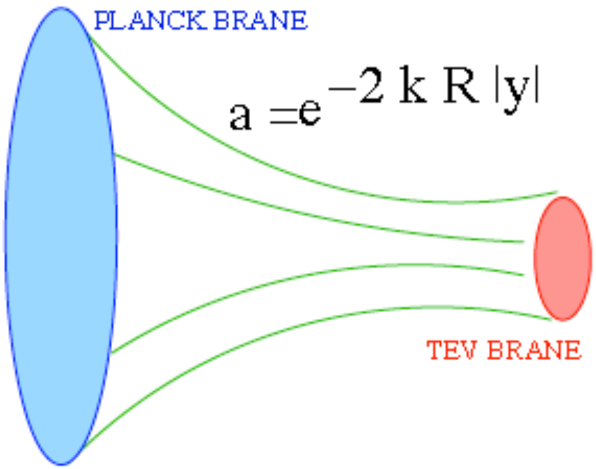
- **CP Violation***: Why are we here? OR What is the source of the dramatic matter-antimatter asymmetry in the Universe?*

- **Neutrino masses and mixings** *: What is the Origin of neutrino masses, what is the nature of neutrino, why are ν mixings so different than quark ones?*



New Resonances : Extra Dimensions

arXiv:hep-ph/0606153



- **Randall Sundrum** : A single "warped" extra dimension *so that large scales at the Planck brane are redshifted at the TeV brane*

- Then $M_w = e^{-2k\pi R} M_R$

arXiv:hep-ph/0606153

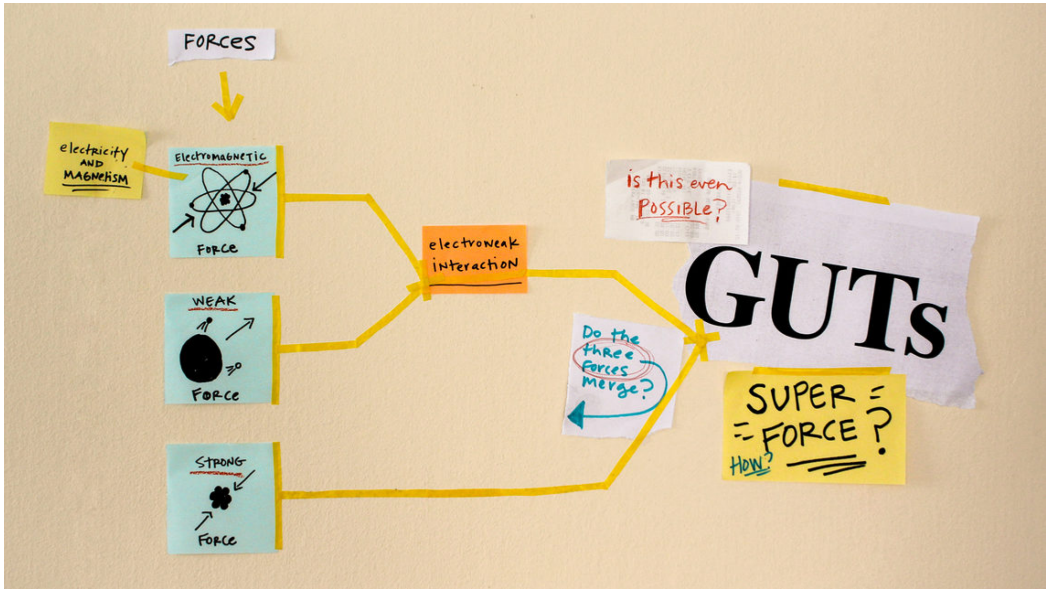
FLAT EXTRA DIMENSION

- **ADD** : n large extra dimensions where only gravity propagates, *then the Planck scale is "reduced" by the large compactification volume V ~ Rn.*

- Then $M_w \cong [M_{Pl} R]^{-\frac{n}{n+2}} M_{Pl}$

New Resonances: Grand Unified Theories

http://www.symmetrymagazine.org/article/a-gut-feeling-about-physics

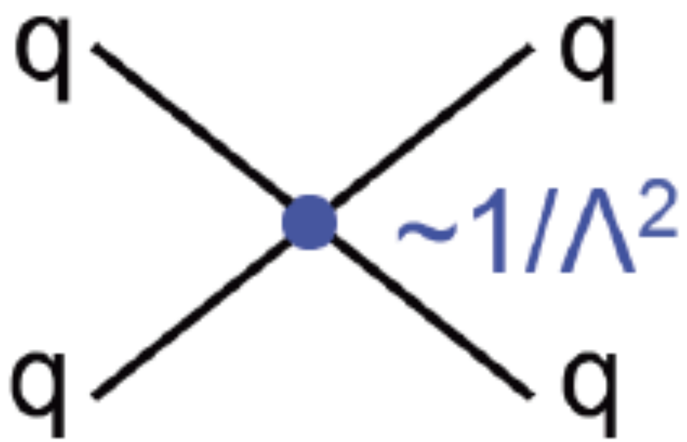


- Is there a larger gauge group containing SU(3) x SU(2) x U(1) making the extremely successful SM the low-energy limit of a more fundamental theory?

- Extended gauge group models always predict new heavy neutral and charged resonances.

New Resonances : Compositeness

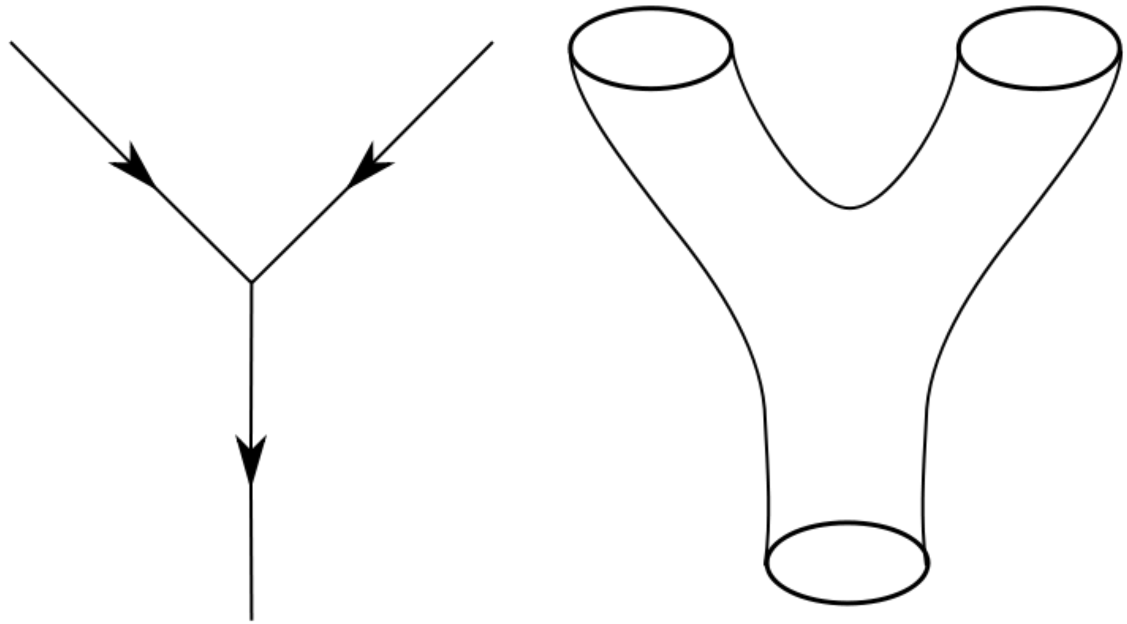
$$\frac{d\sigma}{d\Omega} = \mathrm{SM}(s,t) + \varepsilon \cdot \mathrm{C}_{\mathrm{Int}}(s,t) + \varepsilon^2 \cdot \mathrm{C}_{\mathrm{NewPh}}(s,t)$$



E. Eichten, K. Lane, and M. Peskin, "New Tests for Quark and Lepton Substructure", Phys. Rev. Lett. **50 (1983) 811, doi:10.1103/PhysRevLett.50.811.**

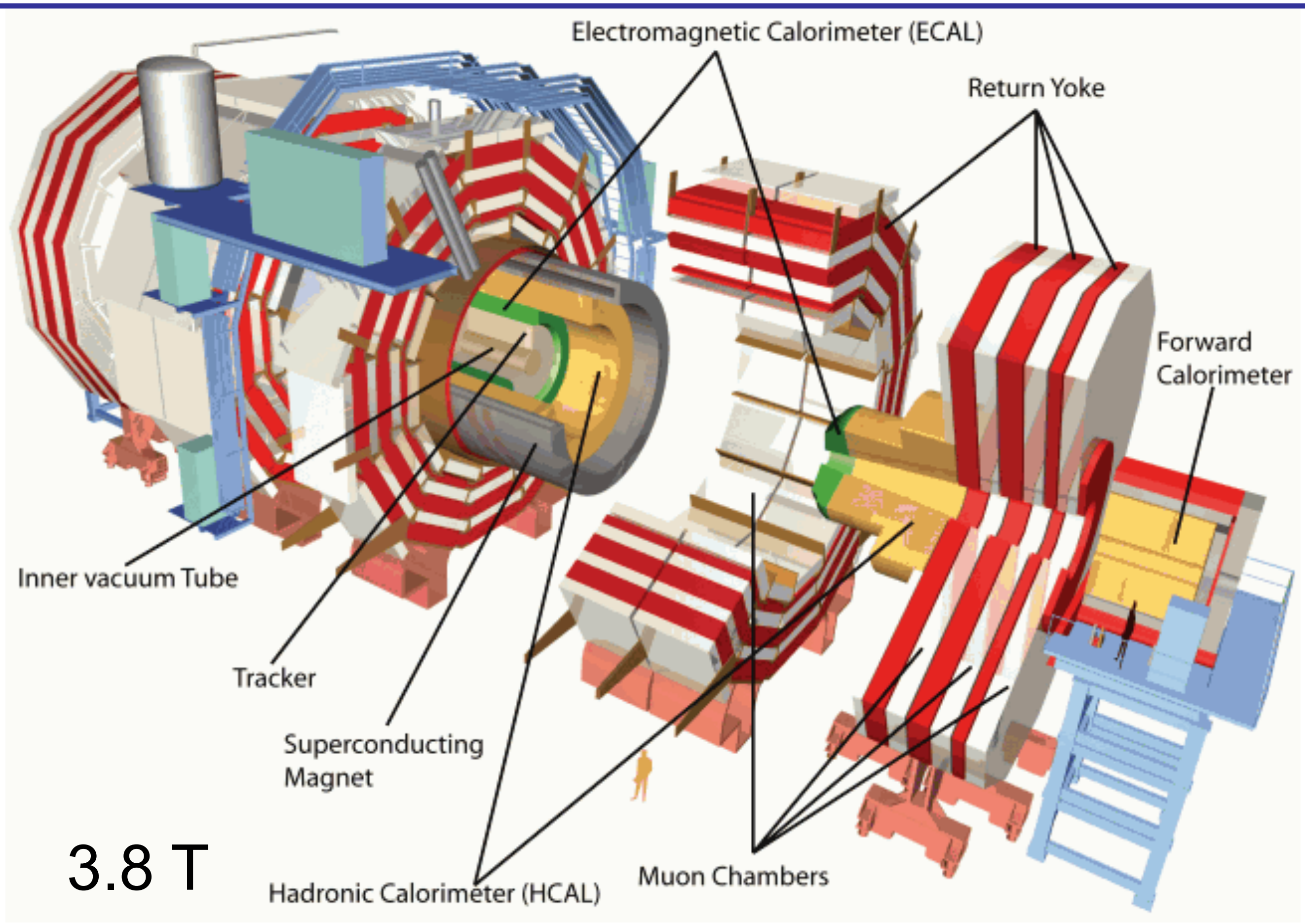
"The proliferation of quarks and leptons has naturally led to the speculation that they are composite structures, bound states of more fundamental constituents which are often called "preons. "

New Resonance : String Theory



- Our world might be composed from string-like rather than point-like objects.
- Strings can incorporate gravitational physics in a way that remains valid down to the smallest scales that are ruled by the laws of quantum physics.

The CMS Detector



Pixels

$\sigma(p_T)/p_T \sim 1.5 \cdot 10^{-4} p_T\,(\mathrm{GeV}) \oplus 0.005$

Electromagnetic Calorimeter

$\sigma(E)/E \approx 2.9\%/\sqrt{E(\mathrm{GeV})} \oplus 0.5\% \oplus 0.13\mathrm{GeV}/E$

Hadronic Calorimeter

$\sigma(E)/E \approx 120\%/\sqrt{E(\mathrm{GeV})} \oplus 6.9\%$

Muon Spectrometer

$\sigma(p_T)/p_T \approx 1\%$ for low pT muons

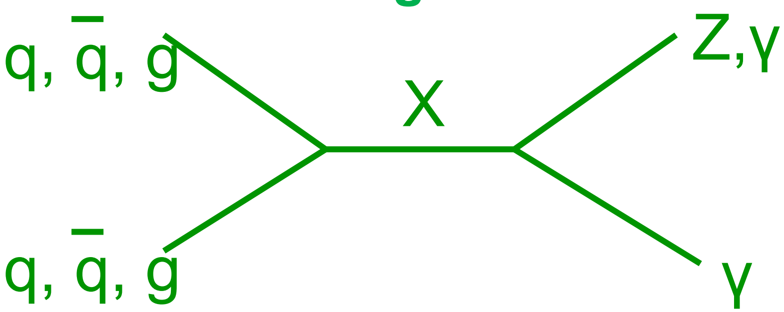
$\sigma(p_T)/p_T \approx 5\%$ for 1 TeV muons

General Analysis Methodology

- **Analysis Strategy :** search for a narrow resonance on top of a smoothly falling background.
- **Background Estimation :**
  - **Data-driven :** Fitting the invariant di-object mass with an empirical function (resolved dijets, diphotons, Zγ)
  - **Semi data-driven :** Predicting the SM background from control regions (ditau, W_R and heavy ν, boosted dijets).
  - **Using simulation** for the SM template, validating it with data when possible (dileptons)
- **Signal Modelling :** Intrinsic signal shape (for most of the analyses with width smaller than the detector resolution) convoluted with the CMS detector resolution.
- **Limit extraction :** Fitting the invariant mass spectrum using the background and signal shapes and systematics as nuisance parameters

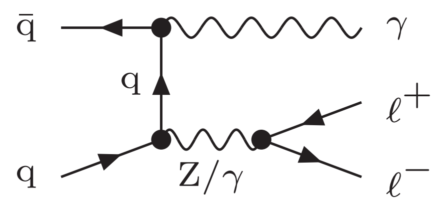
Zγ, γγ searches in a nutshell

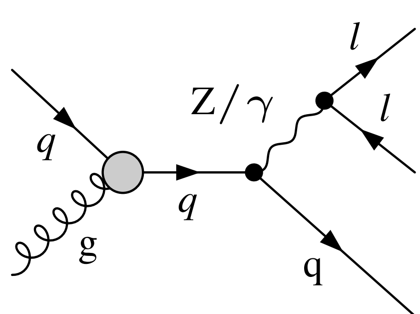
Signal



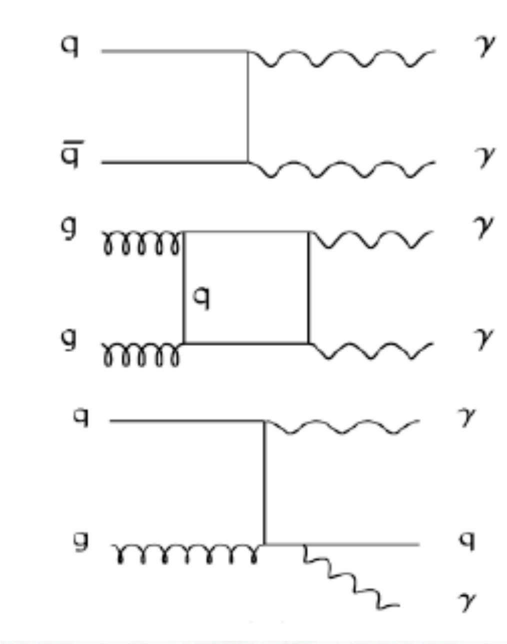
SM Backgrounds

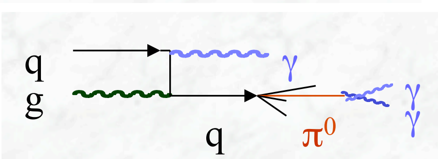
Zγ production Z+jets





γγ production γ+jet, jet+jet



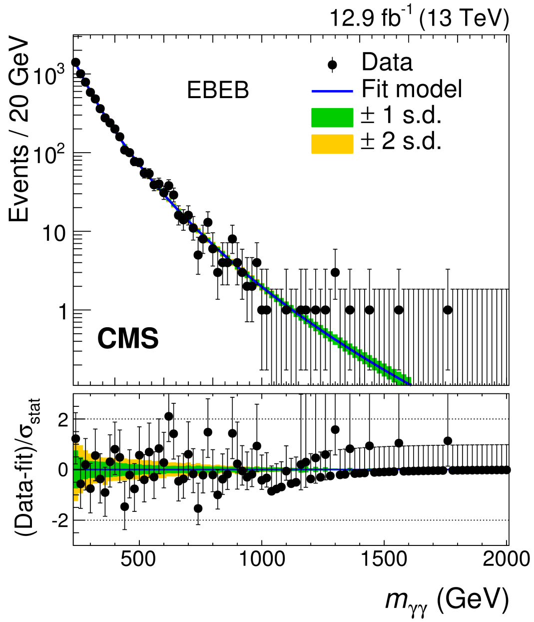


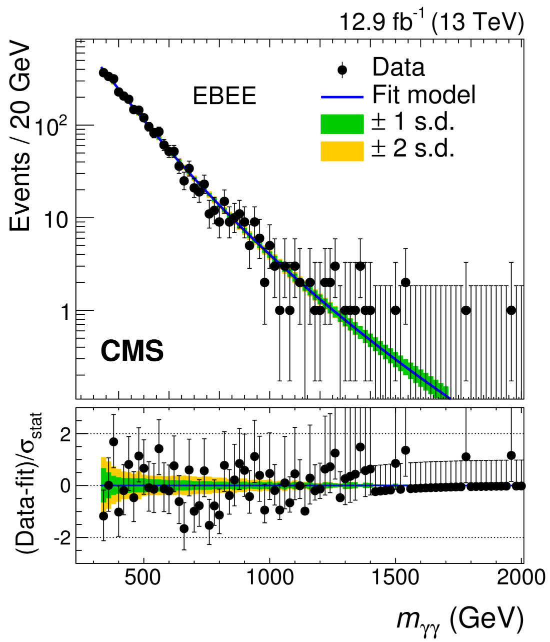
- **Reconstructed objects**

- Photons

- **Physics observables**

M(γγ): Resonance Mass in different η(γ) to take into account better resolution in barrel.





- **Event selection**

1. at least two isolated photons with p_T>75 GeV and $|\eta|$<2.5
2. $M_{\gamma\gamma}$>230 GeV for EBEB (both photons with $|\eta|$<1.4) and > 300 GeV for EBEE (one photon with $|\eta|$<1.4).

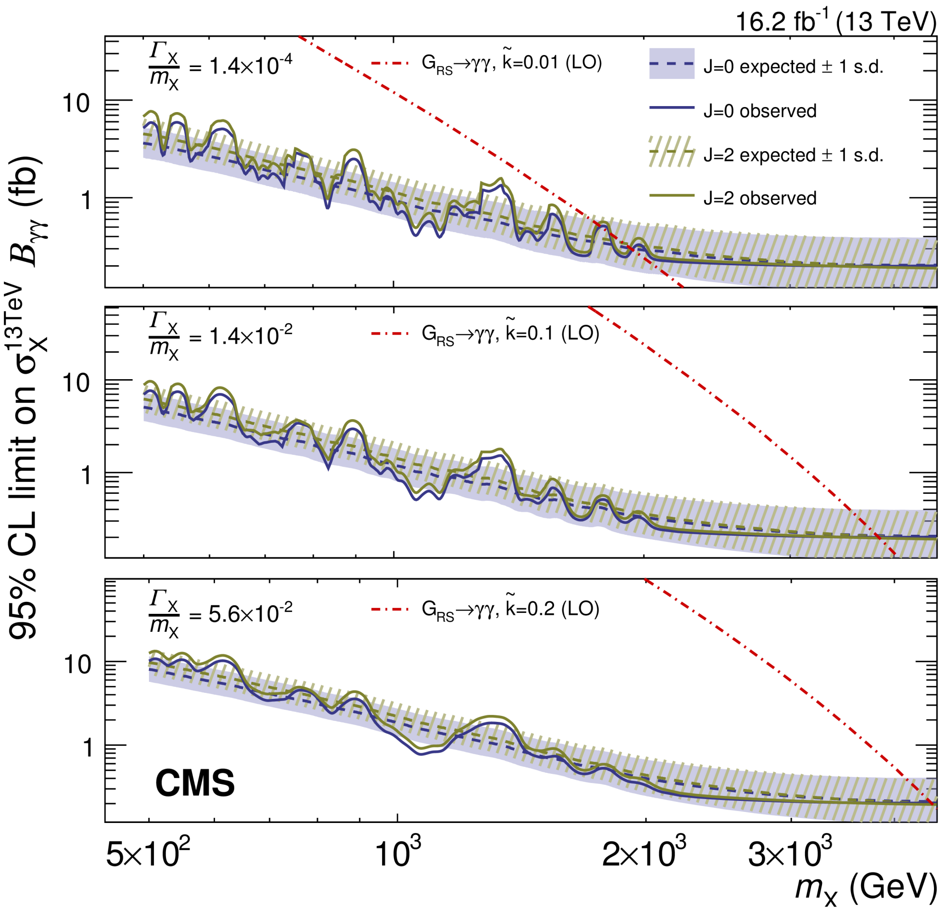
- **Background Modeling**

An empirical parametric form is used to model the SM background :

$$f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\,\log(m_{\gamma\gamma})}$$

parameters a and b are treated as unconstrained nuisance parameters in the hypothesis testing.

γγ : Cross section limits



Signal Modeling : Intrinsic shape of resonance with Pythia 8.2 convoluted with the detector resolution. $\frac{\Gamma_X}{m_X}$: $1.4 \times 10^{-4}, 1.4 \times 10^{-2}, 5.6 \times 10^{-2}$

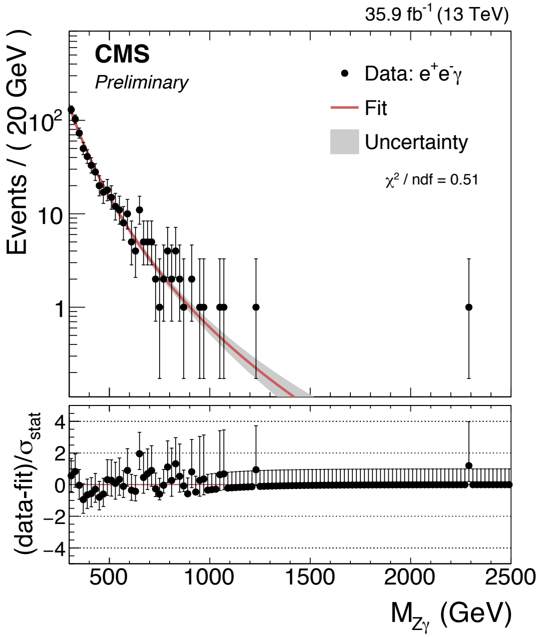
- **Fitting:** The following likelihood ratio is used as the test statistic:

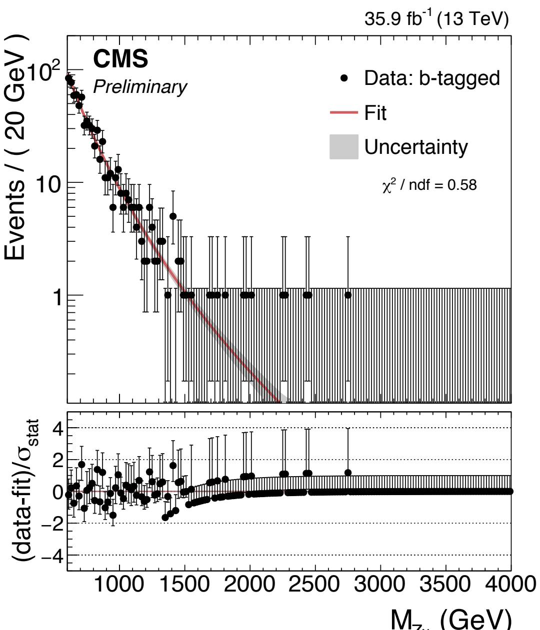
$$q(\mu) = -2\log\frac{L(\mu S + B|\hat{\hat{\theta}}_\mu)}{L(\hat{\mu}S + B|\hat{\theta})}$$

and modified frequentist CLs for limit setting.

- **Systematic uncertainties:** Only related to signal modeling : luminosity, PDF scale, efficiency, energy scale (1%) and resolution (10%). Analysis is statistics limited.

Zγ : Experimental Results





- **Event selection**

Z(ll)γ : Two same flavor isolated leptons with leading p_T > 65 (52) GeV for electrons (muons), subleading p_T >10 GeV, |η| < 2.5 (2.4) and 50 GeV < M_{ll} < 130 GeV. One isolated photon with p_T > 40 GeV. And $M_{ll\gamma}$ > 250 (300) GeV for muons (electrons).

Z(qq)γ : One Anti-kT jet with R=0.8, p_T > 200 GeV, |η| < 2.0 and 75 GeV < M_J < 105 GeV. One isolated photon with p_T > 200 GeV and |η| < 1.44. And $M_{J\gamma}$ > 600 GeV. Sub-divided into three categories a) b-tagged b) anti b-tagged with N sub-jetiness high and c) anti b-tagged with N sub-jetiness low

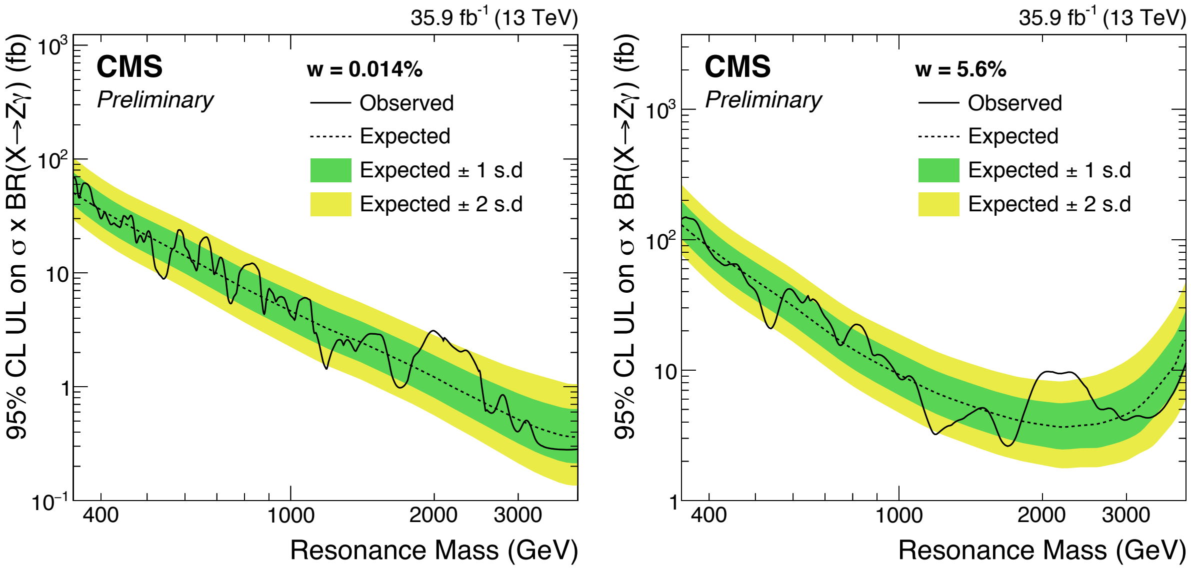
- **Background Modeling**

An empirical parametric form is used to model the SM background :

$$\frac{dN}{dM_{Z\gamma}} = P_0 \times (M_{Z\gamma}/\sqrt{s})^{P_1 + P_2 \times \log(M_{Z\gamma}/\sqrt{s})}$$

parameters a and b are treated as unconstrained nuisance parameters in the hypothesis testing.

Zγ : Cross section limits



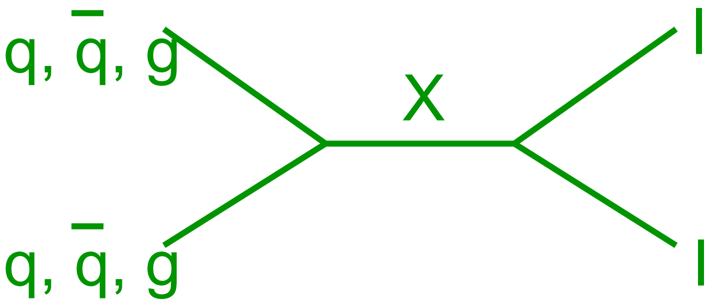
- **Signal Modeling :** Intrinsic shape of resonance parametrized with a Gaussian core and two power-law tails, an extended form of the Crystal Ball function $\frac{\Gamma_X}{m_X}$: $1.4 \text{ x } 10^{-4}, 5.6 \text{ x } 10^{-2}$

- **Fitting:** $q(\mu) = -2\log\frac{L(\mu S + B|\hat{\hat{\theta}}_\mu)}{L(\hat{\mu} S + B|\hat{\theta})}$ is used as the test statistic and modified frequentist CLs for limit setting.

- **Systematic uncertainties:** Only related to signal modeling : luminosity, PDF scale, efficiencies (triggers, b-tagging, reconstruction-selection etc) , energy scales and resolutions.

Dilepton Search in a nutshell

Signal



- **Reconstructed objects**

- Electrons, muons, taus

- **Physics observables**

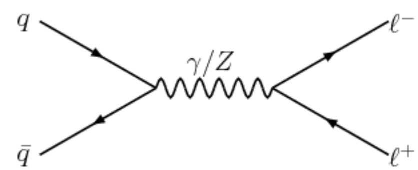
For Electrons and muons, M(ll): Resonance Mass in different η(l) to take into account better resolution in barrel and different backgrounds.

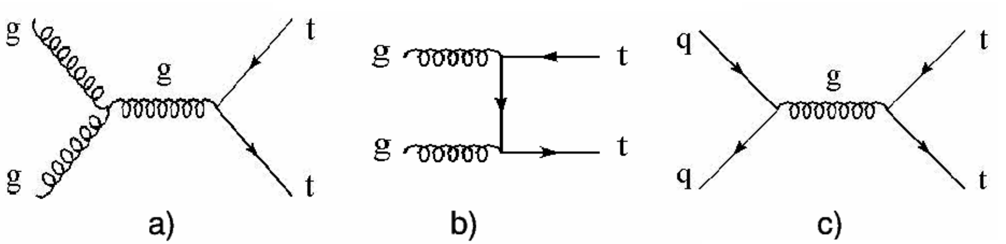
For taus

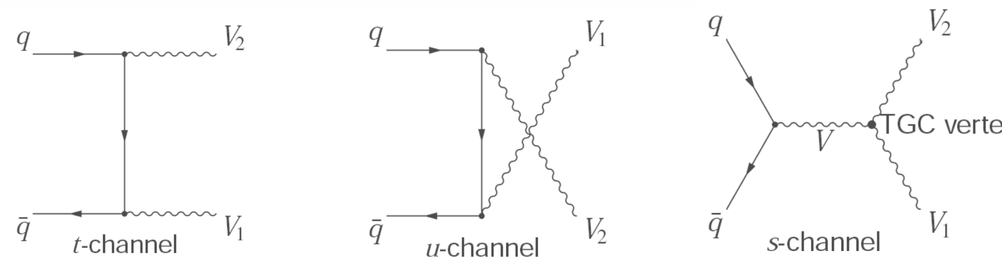
$$m(\tau_1, \tau_2, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) = \sqrt{(E_{\tau_1} + E_{\tau_2} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\vec{p}_{\tau_1} + \vec{p}_{\tau_2} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}})^2}.$$

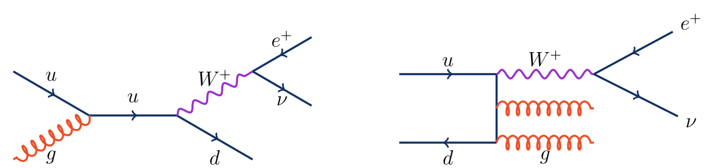
SM Backgrounds

DY, ttbar, WW,ZZ,WZ, W+jets…

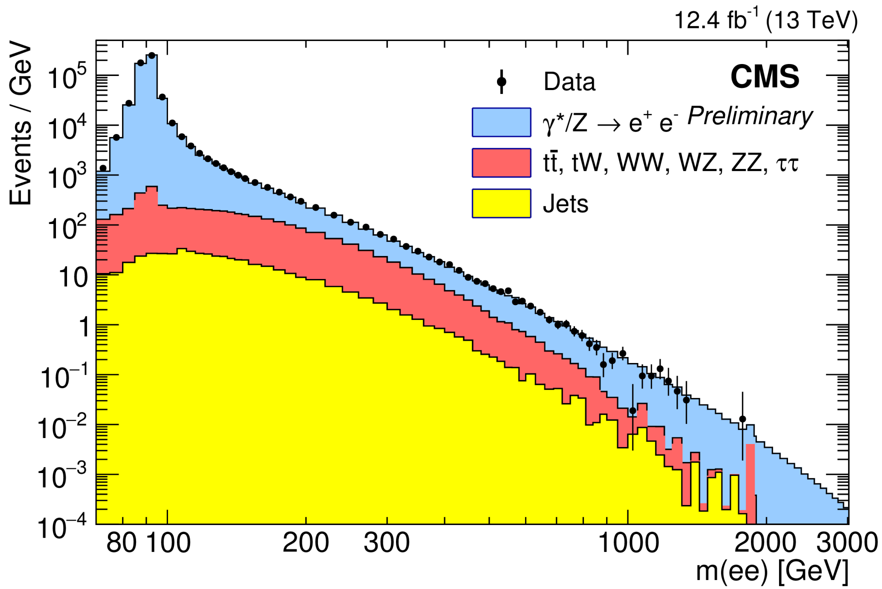


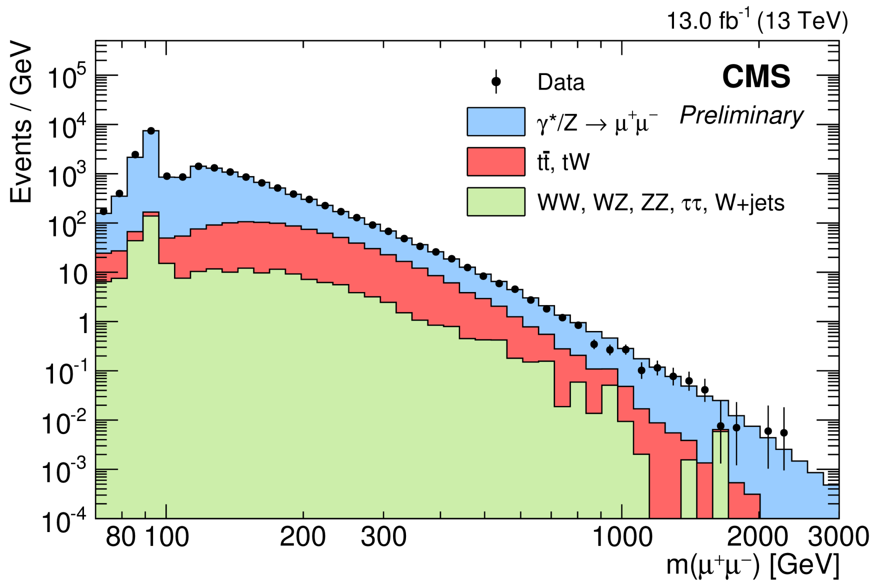






Dilepton : Experimental Results





- **Event selection**

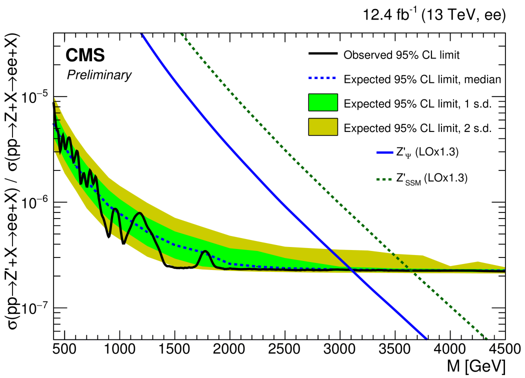
Two isolated electrons (muons) with E_T (p_T) > 35 (53) GeV and $|\eta|$ < 2.5 (2.4).

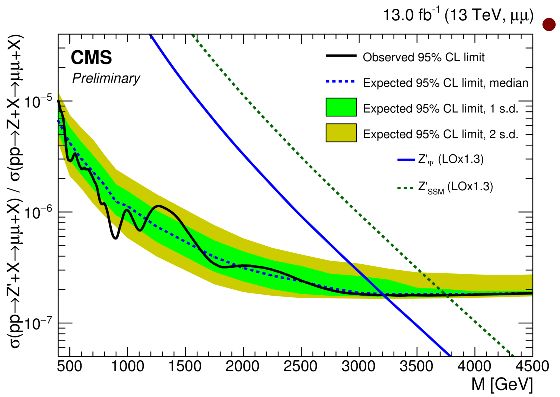
- **Background Modeling**

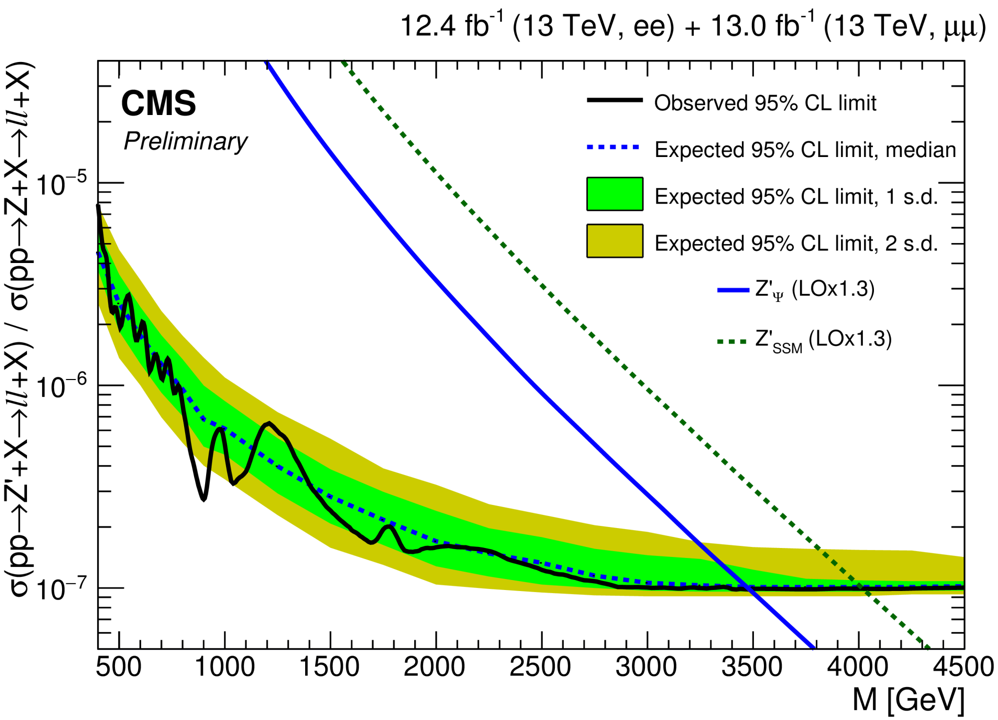
❖ Simulation is used, with POWHEG v2 next-to-leading order (NLO) event generator, with parton showering and hadronization described by the PYTHIA 8.2, validated with eμ event samples.

❖ For each channel, the background shape parameters of the pdfs are obtained by fitting the simulated background distribution between 200 and 5500 GeV.

Dilepton : Cross section limits





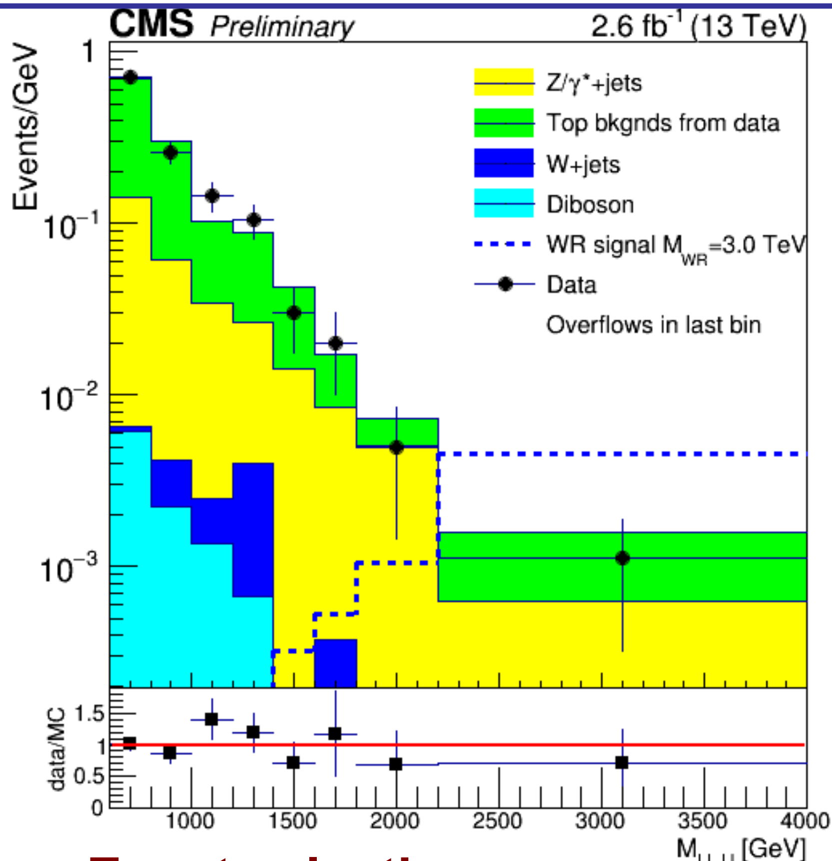


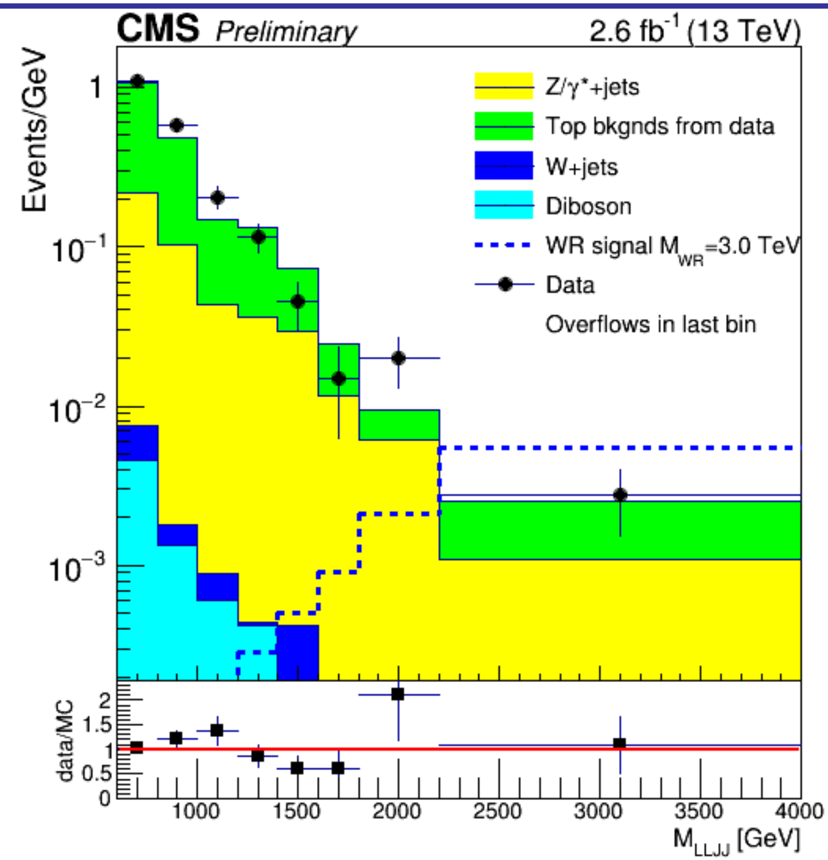
- **Signal Modeling** : pdf is convolution of a nonrelativistic Breit-Wigner with a Gaussian for detector resolution effects. Narrow resonances considered with $\frac{\Gamma_X}{m_X}$: $0.6 \times 10^{-2}, 3.0 \times 10^{-2}$

- **Fitting:** limits are set on the ratio of the cross section for dilepton production through a Z' to that through a Z or γ*in a mass window of 60 to 120 GeV to cancel and reduce the impact of many experimental and theoretical uncertainties.

- **Systematic uncertainties:** Signal efficiency and relative calibration, background shape due to PDFs, background efficiency and resolution.

W_R and Heavy ν : Experimental Results



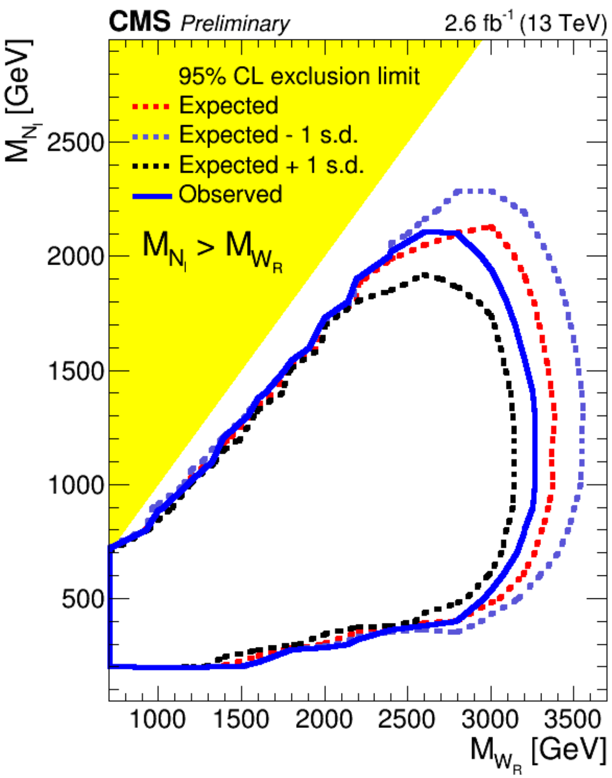


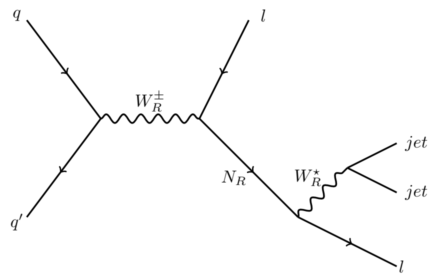
- **Event selection :**

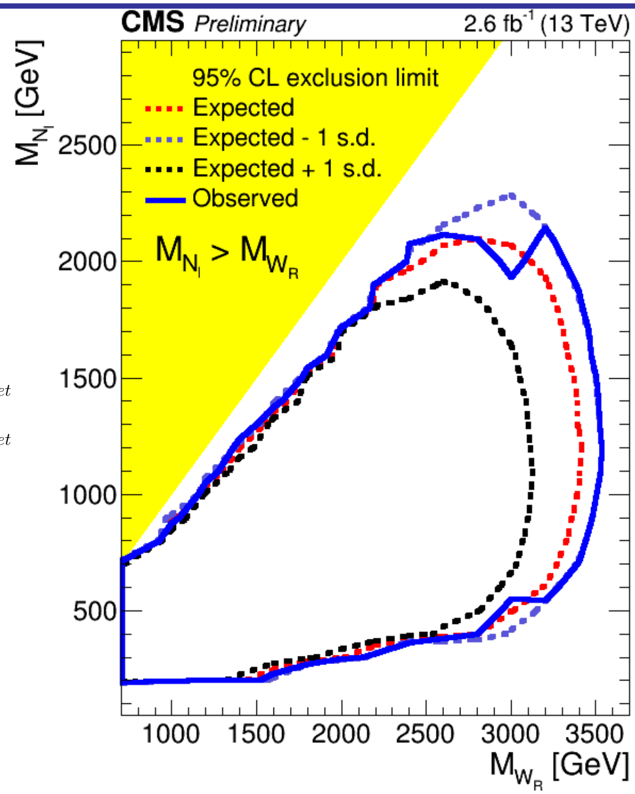
p_T > 60 (53) GeV leading(subleading) lepton, p_T > 40 GeV both jets
ΔR > 0.4 between all final state particles, $|\eta|$ < 2.4 for leptons and jets
M_{lljj}> 600 GeV : defines the "interesting" region, M_{ll} > 200 GeV to suppress DY

- **Background Modeling**: Data-driven for ttbar, control regions for DY.

W_R and Heavy ν : Cross section limits

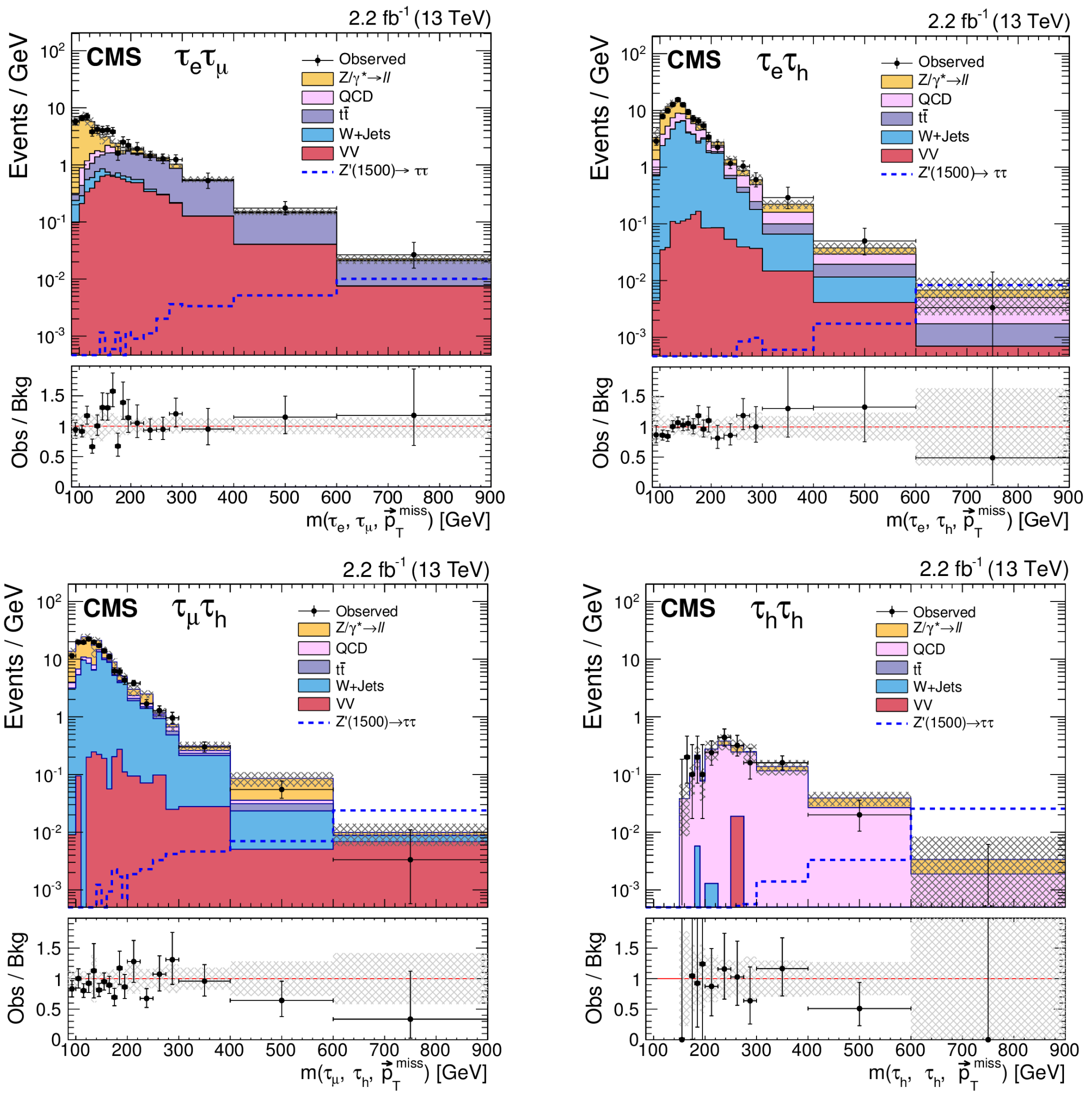






- **Signal Modeling** : Signal samples are generated assuming $M_{N_l} = \frac{1}{2} M_{W_R}$ with PYTHIA 8.1 with NNPDF23 PDF.
- **Fitting :** limits are calculated using a Bayesian approach assuming a flat prior.
- **Systematic uncertainties:** on lepton ID and isolation, and lepton and jet energy scale and resolution, DY shape difference between data and simulation.

Ditau : Experimental Results



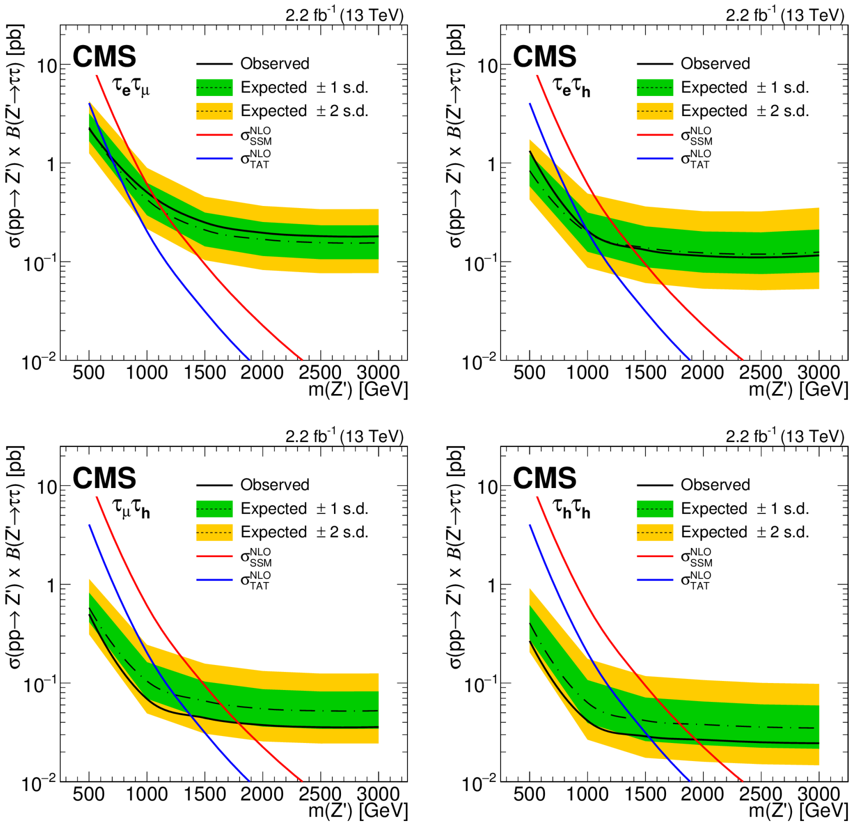
- **Event selection**

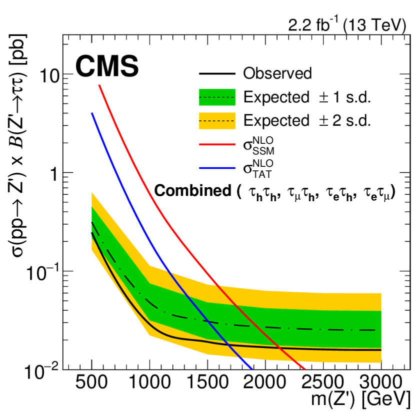
Two isolated tau leptons with $p_T > 35$ (30) GeV for electrons (muons), $|\eta| < 2.1$, and $\tau_{had} > 20(60)$ GeV for $\tau_{had}\,\tau_l$ ($\tau_{had}\,\tau_{had}$), $E_{Tmiss} > 30$ GeV, $\Delta R\,(\tau_1,\tau_2)>0.5$ and $\Delta\varphi(\tau_1,\tau_2)<-0.95$

- **Background Modeling**

❖ For main backgrounds, several data control regions enhanced in this specific background, are utilized.

Ditau : Cross section limits

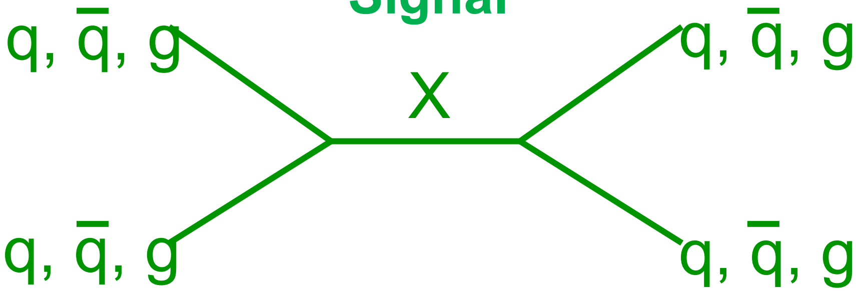




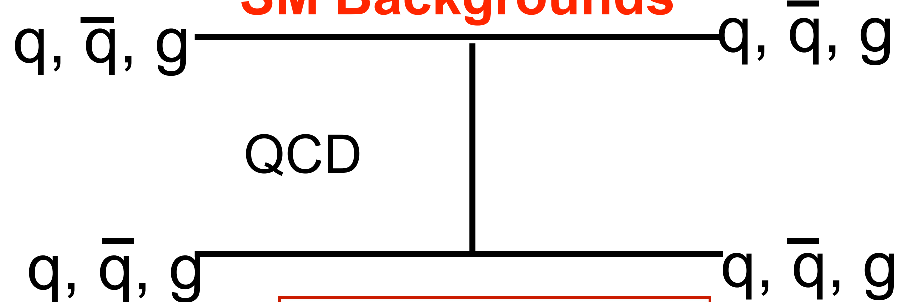
- **Limit setting:** A cut-and-count method is used and modified frequentist CLs to set upper limits.
- **Systematic uncertainties:** Several sources of systematic uncertainties considered with the dominant one being in the estimation of the background, due to the limited number of events in the data control regions.

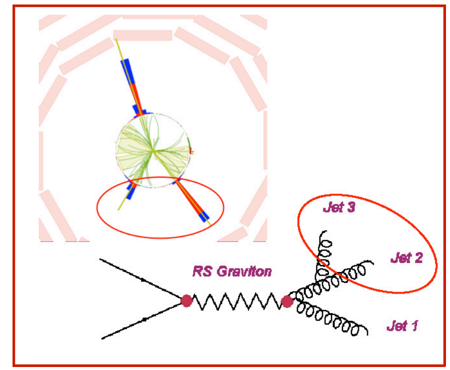
Dijet (resolved) Search in a nutshell

Signal



SM Backgrounds





- **Reconstructed objects**
-

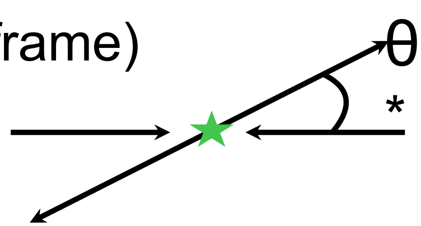
-Particle Flow Jets, Calorimeter Jets

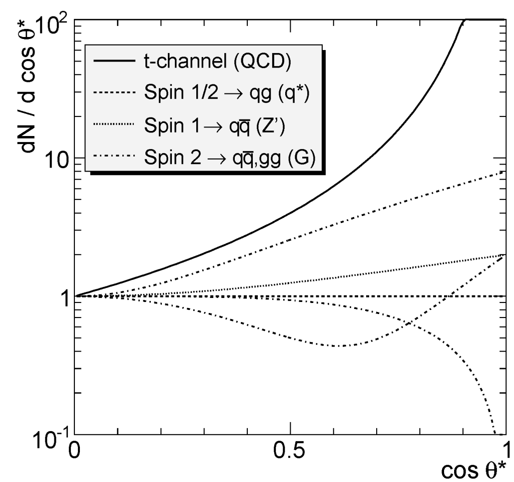
- **Physics observables**

M(jj) → Resonance Mass
Δη(jj) → Resonance Spin

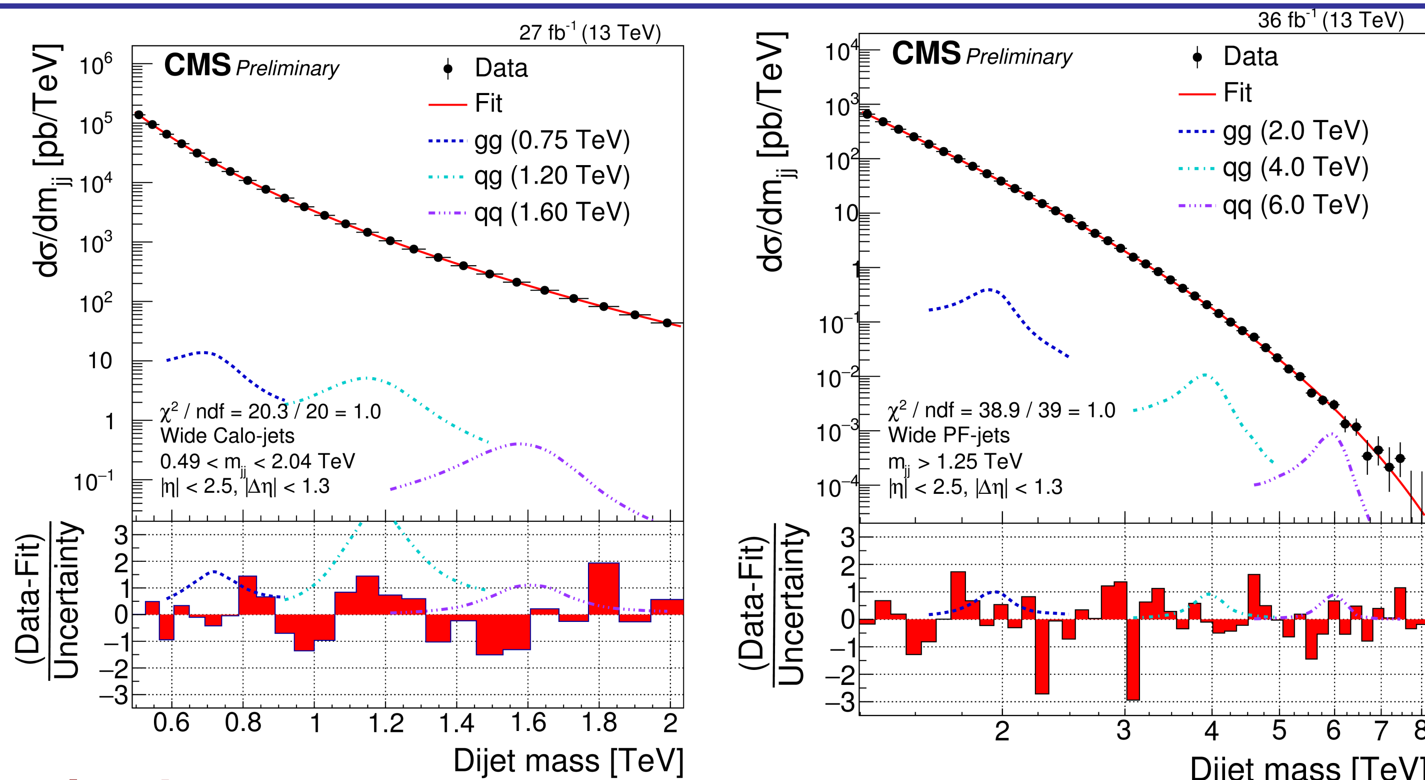
(X rest frame)

$$\Delta\eta_{12} = |\eta_{jet1} - \eta_{jet2}| = \ln\frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$





Dijet (resolved) : Experimental Results

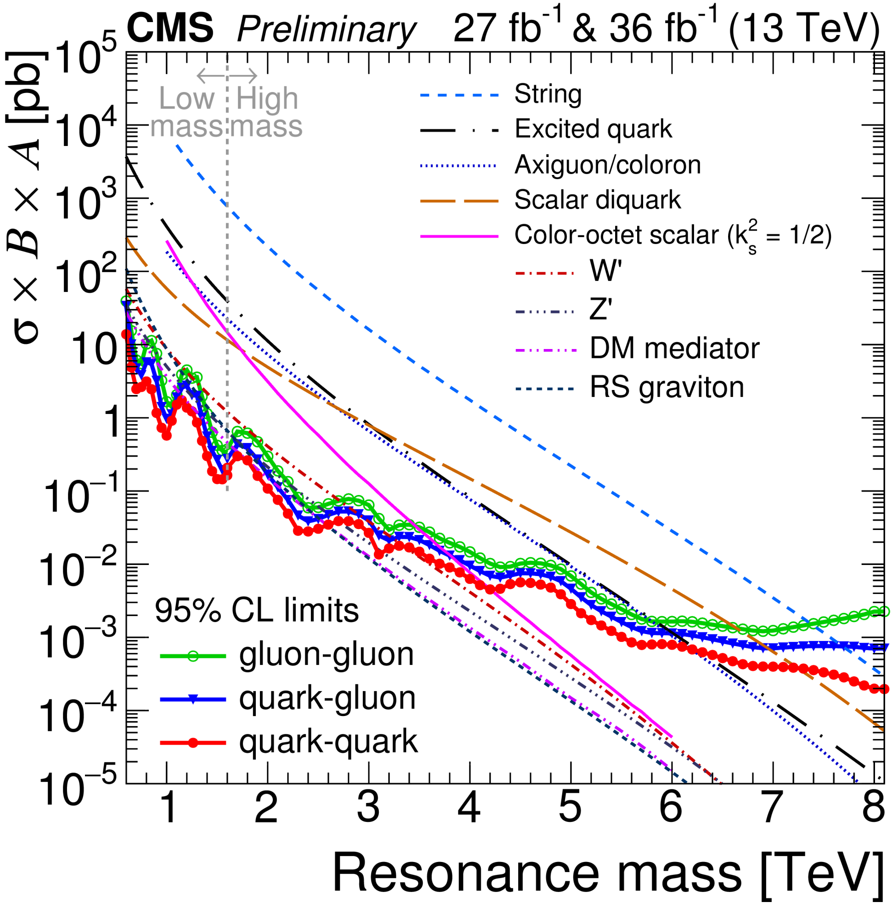


- **Event selection:** Two "wide" jets ($\Delta R<1.1$), formed from jets with p_T>30 GeV and $|\eta|<2.4$, $\Delta\eta(j,j) < 1.3$, M_{jj} > 1246 GeV (PF Jets), M_{jj} > 489 GeV (Calorimeter Jets)

- **Background Modeling :** A fit with an empirical parametrization is performed to the data , with its parameters are treated as unconstrained nuisance parameters in the hypothesis testing

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

Dijet (resolved) : Cross section limits



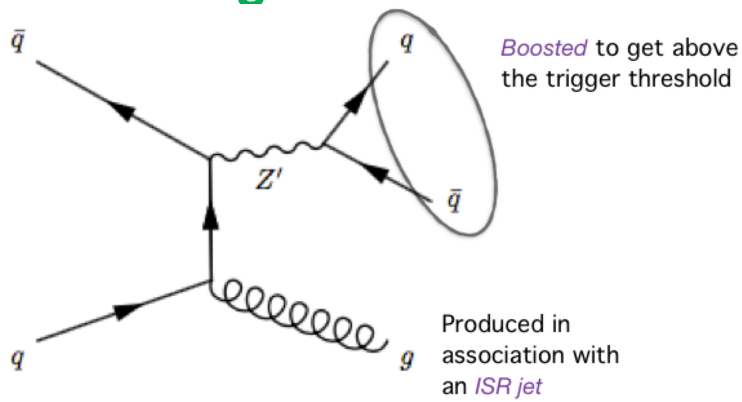
Signal Modeling : pdf is convolution of a nonrelativistic Breit-Wigner with a gaussian for detector resolution effects. Narrow resonances considered.

Fitting : Modified frequentist CLs is used for limit setting, performing a binned fit with a background and signal template.

Systematic uncertainties: Only related to signal modeling : luminosity, jet energy scale and jet resolution. Analysis at low masses starts to become systematics limited.

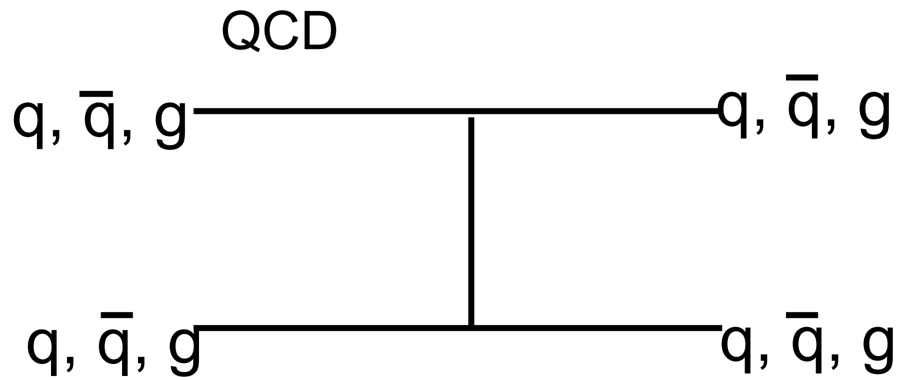
Dijet (boosted) Search in a nutshell

Signal



https://arxiv.org/pdf/1212.2221.pdf
https://arxiv.org/abs/1602.07727

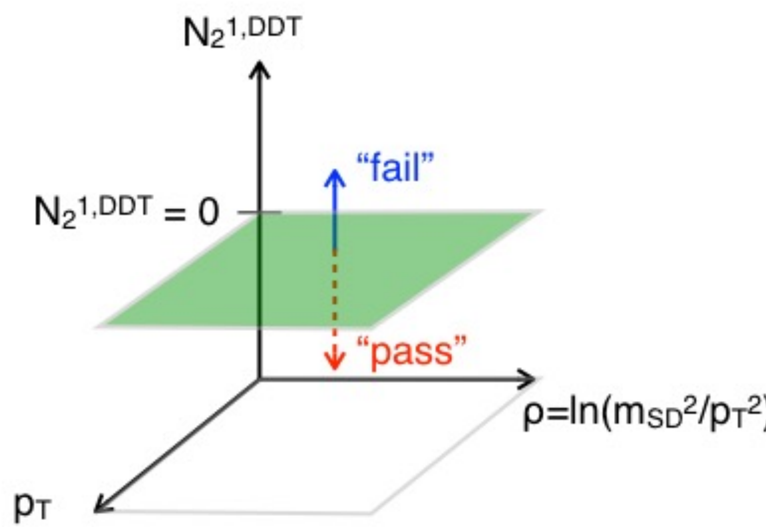
SM Backgrounds

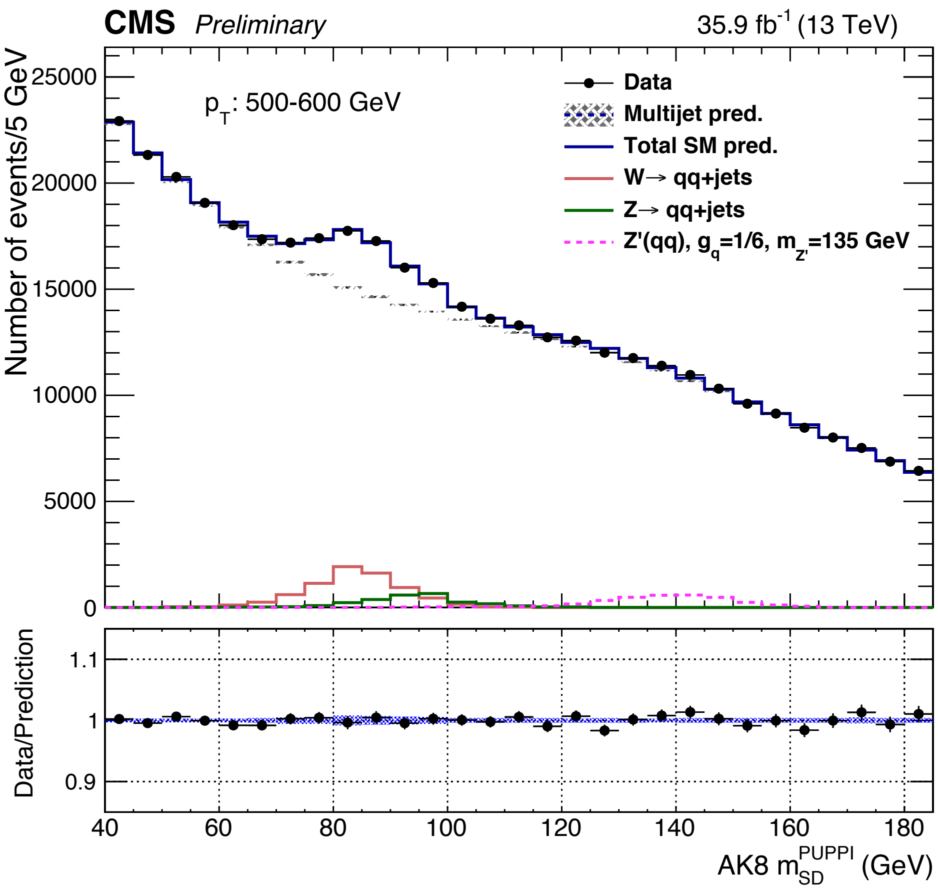


- **Reconstructed objects**
  -Particle Flow Jets

- **Physics observables**
  - Jet Mass → Resonance Mass

- Search exploits the use of a new substructure variable decorrelated from the jet mass and jet transverse momentum, which largely avoids sculpting of the jet mass distribution.





• Event selection :

Anti-kT jet with cone-size 0.8 with p_T>200 GeV and |η|<2.5 and jet sub-structure selection to reduce backgrounds. No electrons or muons.

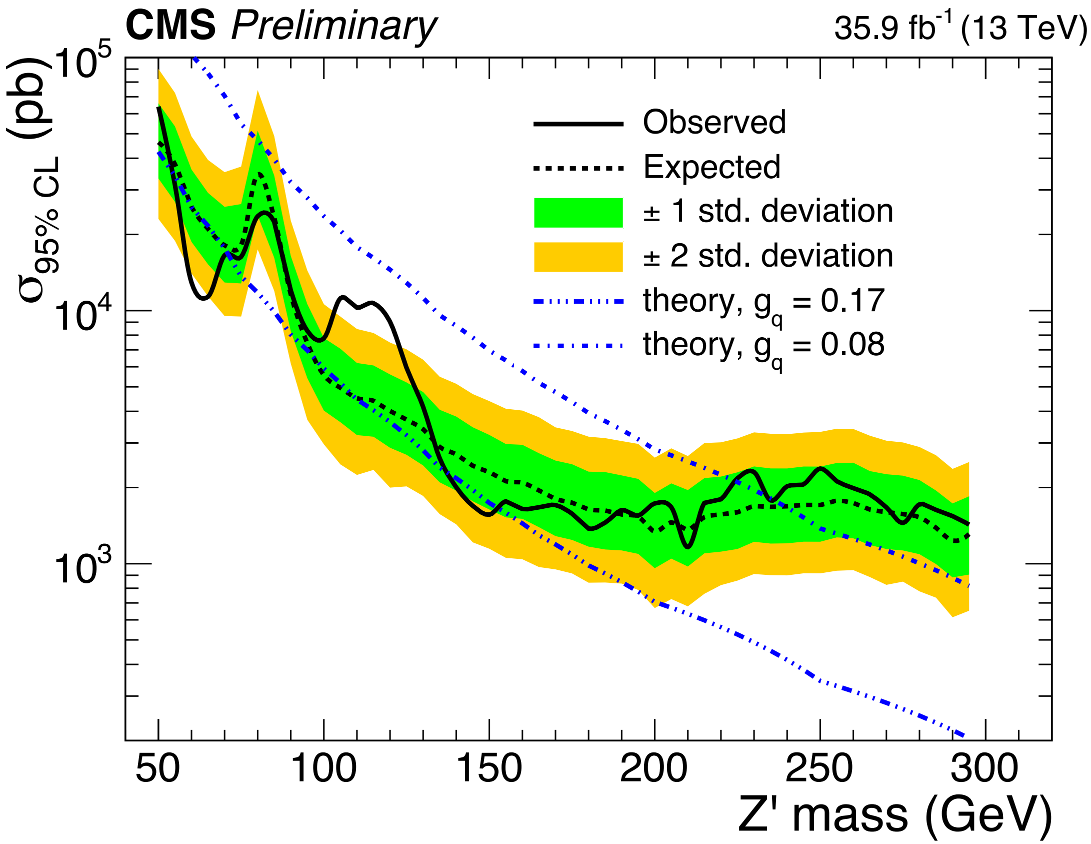
• Background Modeling:

- ❖ QCD predicted from a control region with a transfer factor, F, from simulation (fitted to the data).

$$p^{\mathrm{QCD}}_{\mathrm{pass}}(m_{SD}, p_{\mathrm{T}}) = \mathcal{F}(\rho(m_{SD}, p_{\mathrm{T}}), p_{\mathrm{T}}) \times p^{\mathrm{QCD}}_{\mathrm{fail}}(m_{SD}, p_{\mathrm{T}})$$

- ◦ background modeling uncertainties come from the parametric uncertainties on the transfer factor fit.
- ❖ W/Z backgrounds taken from simulation

Dijet (boosted) : Cross section limits



- **Signal Modeling** :The benchmark Z′ signal events are simulated using the MADGRAPH5)_AMC@NLO 2.2.2 generator
- **Fitting** : Upper limits are computed using the modified frequentist approach for confidence levels (CLs), taking the profile likelihood as the test statistic in the asymptotic approximation.
- **Systematic uncertainties:** Background related ones from the transfer factor from the control to signal region, several systematics on signal.

Summary and Outlook

- Many wonderful results from 2015-2016 running, no hint of new physics yet…
- After the "energy jump" from 8 TeV to 13 TeV analyses have to improve significantly both in terms of systematics and methodology in order to surpass previous results.
- Getting ready in order to be able to perform "precision measurements" with the new data that are imminent…