Recent exotic results in “Jets + X” From CMS

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On behalf of the CMS Collaboration

N. Saoulidou HEP May 2016,
Thessaloniki, Greece

Outline

- **Introduction**

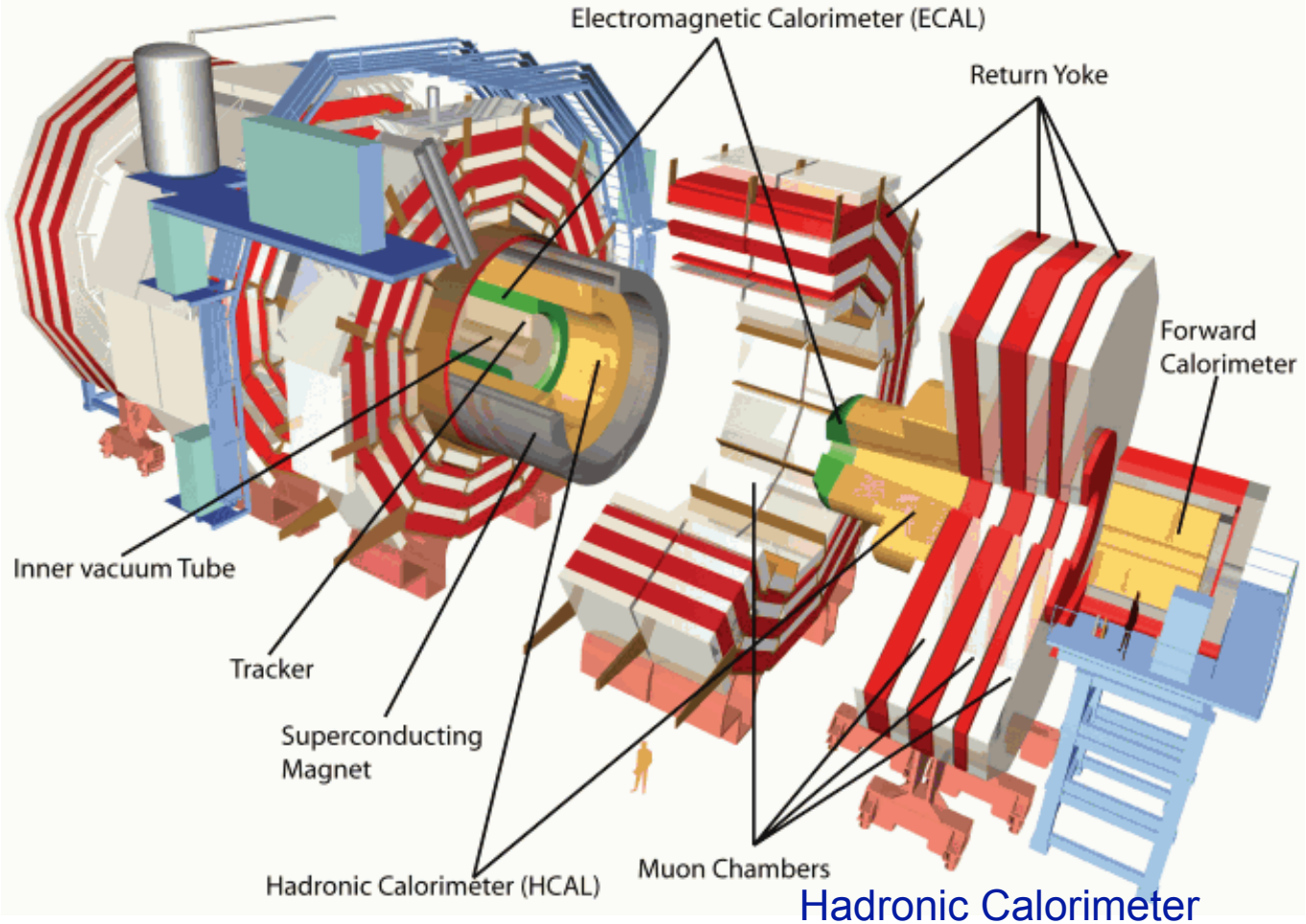
- **Few Selected Results:**

  - Searches using jets only the quickest/first to be performed, later accompanied by additional leptons, missing transverse energy etc.

  - **Dijet chi** [CMS PAS EXO-15-009]
  - **Black Holes** [CMS PAS EXO-15-007]
  - **Dijet Resonance searches** [CMS 10.1103/PhysRevLett.116.071801]
  - **Lepto-Quarks** [CMS PAS EXO-16-007]
  - **Dark Matter searches** [CMS PAS EXO-16-013]

- **Summary - Conclusions**

The CMS Detector



3.8 T

Pixels

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

Electromagnetic Calorimeter

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

Hadronic Calorimeter

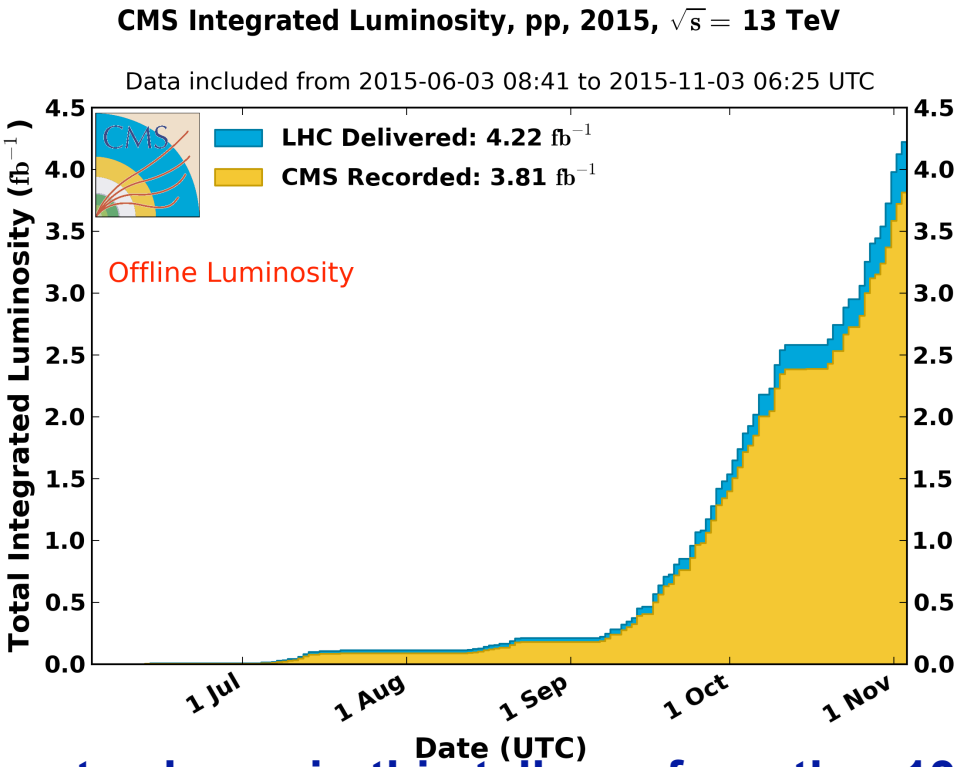
$\sigma E/E \approx 120\%/\sqrt{E(GeV)} \oplus 6.9\%$

Muon Spectrometer

$\sigma pT/pT \approx 1\%$ for low pT muons

$\sigma pT/pT \approx 5\%$ for 1 TeV muons

Data Collection



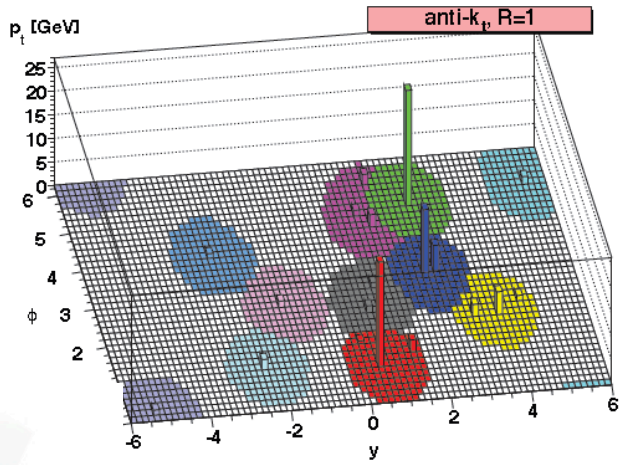
- **The measurements shown in this talk are from the 13 TeV running period with total luminosity ~2.5 fb-1 thanks to the excellent accelerator performance.**

- **Looking forward to a similar one for the 2016 Running which has just started, expecting ~30 fb-1 by the end of the year.**

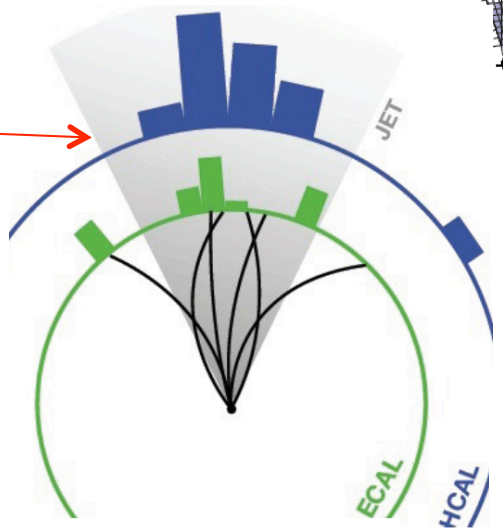
Public Results twiki CMS
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

Jet Reconstruction

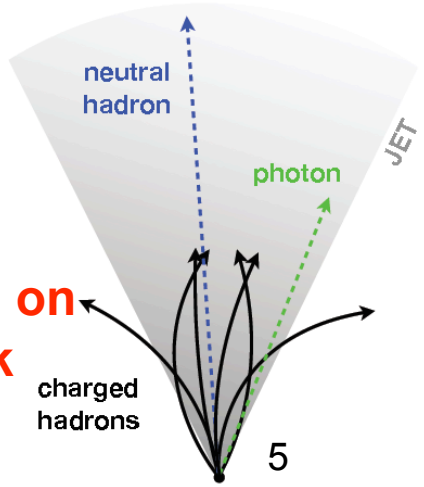
- **Anti-kt clustering algorithm :** with a cone R = 0.4, and 0.8 which is infrared and collinear safe, geometrically well defined, and tends to cluster around the hard energy deposits.



- **Calorimeter Jets : Clustering** of Calorimeter Towers composed of ECAL and HCAL energy deposits

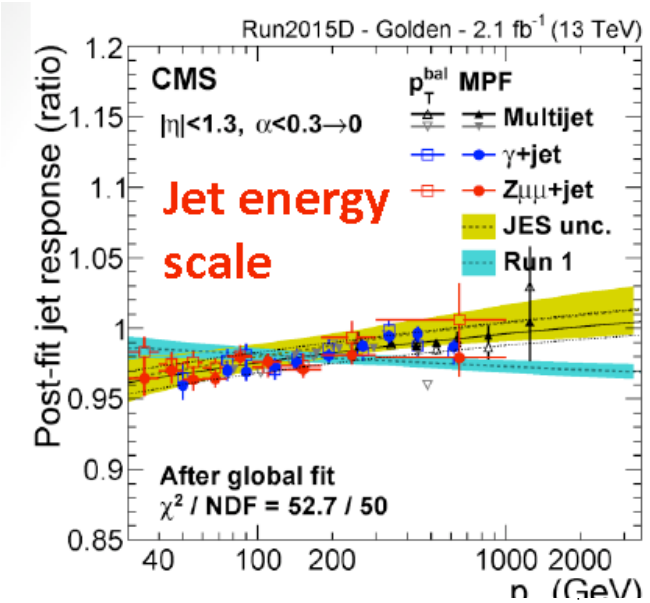


- **Particle Flow Jets :** Clustering of Particle Flow candidates constructed combining information from all sub-detector systems.



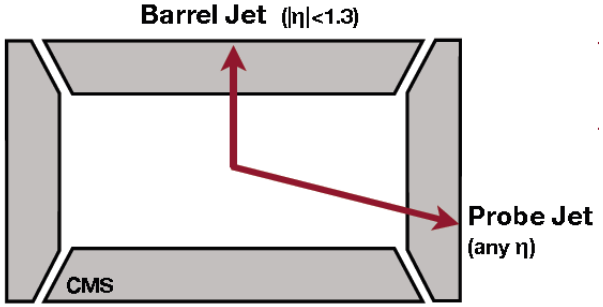
More on Jet Identification on M. Diamantopoulou's talk

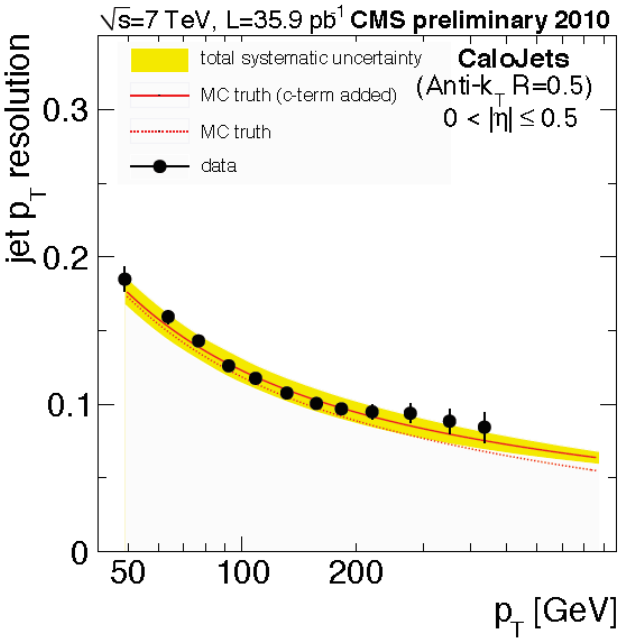
Jet Energy Scale and Resolution

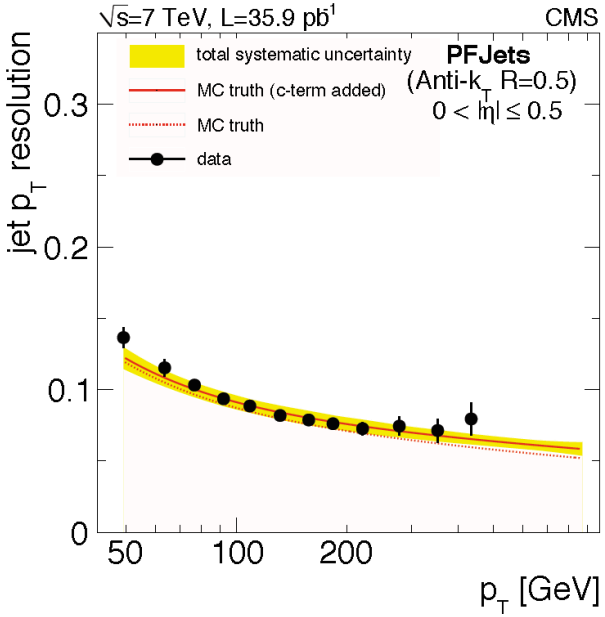


Data driven methods used

- **Dijet Asymmetry**

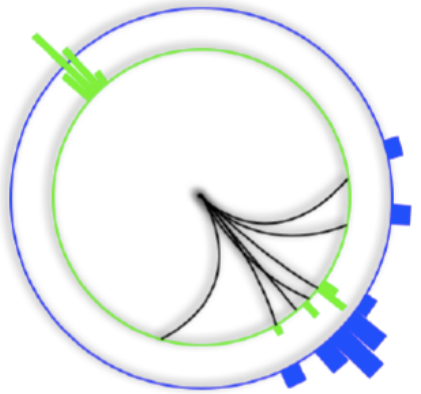






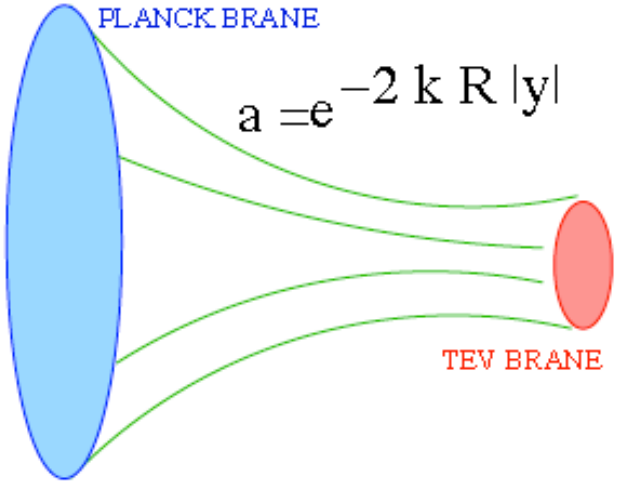
Photon plus Jet Balance

γ+Jet events:



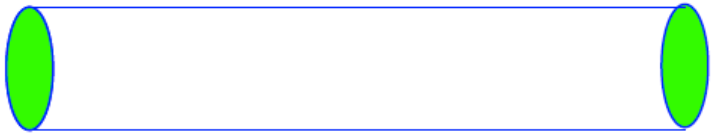
Exotic New Physics : RS Gravitons – Large extra dimensions

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 $M_W = e^{-2k\pi R} M_{Pl}$

arXiv:hep-ph/0606153

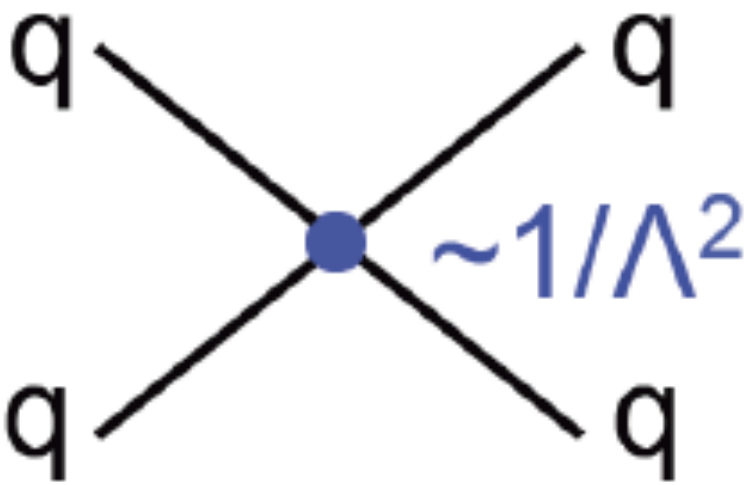


FLAT EXTRA DIMENSION

- **ADD** : n large extra dimensions where only gravity propagates, then the Planck scale is "reduced" by the large compactification volume V ~ Rn.
- Then $M_W \simeq [M_{Pl}\, R]^{-\frac{n}{n+2}}\, M_{Pl}$

Exotic New Physics : Compositeness

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

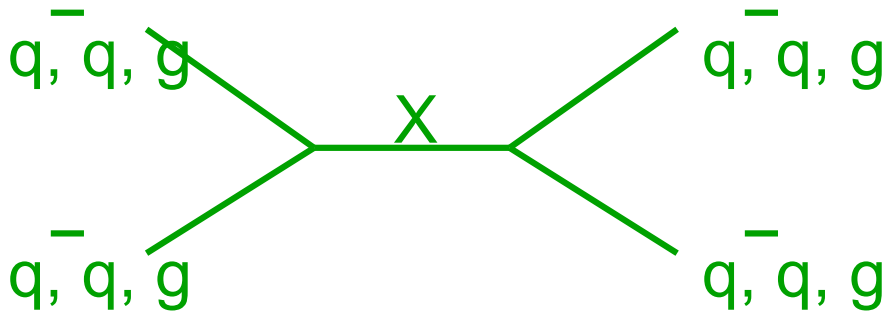


E. Eichten, K. Lane, and M. Peskin, "New Tests for Quark and Lepton Substructure", Phys. Rev. Lett. **50 (1983) 811, doi:10.1103/PhysRevLett.50.811.**

"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. "

Dijet Resonance Search

Dijet Resonance Search

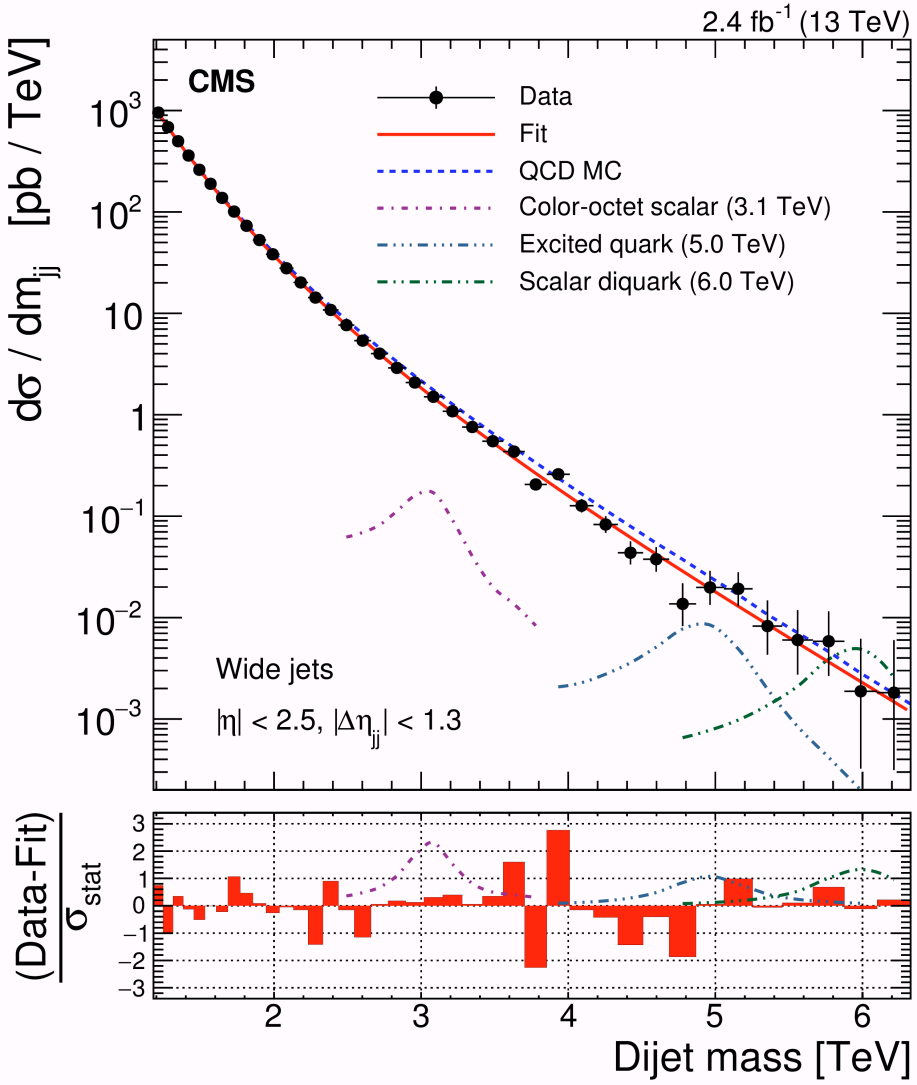


LHC at 13TeV is dijet resonance factory at a new energy scale.
Broad: search for many sources of new physics in a single simple search:

More on E. Tziaferi's and D. Karassava's talk

String resonances from string theory
Excited quarks from theories of quark compositeness
W`**, **Z`, and **scalar diquarks** from grand unified theory
Gravitons from the Randall-Sundrum model of extra dimensions
Axigluons, **Colorons**, and **Color Octect Scalars** from other models

Dijet Resonance Search



Parameterize the background from QCD:

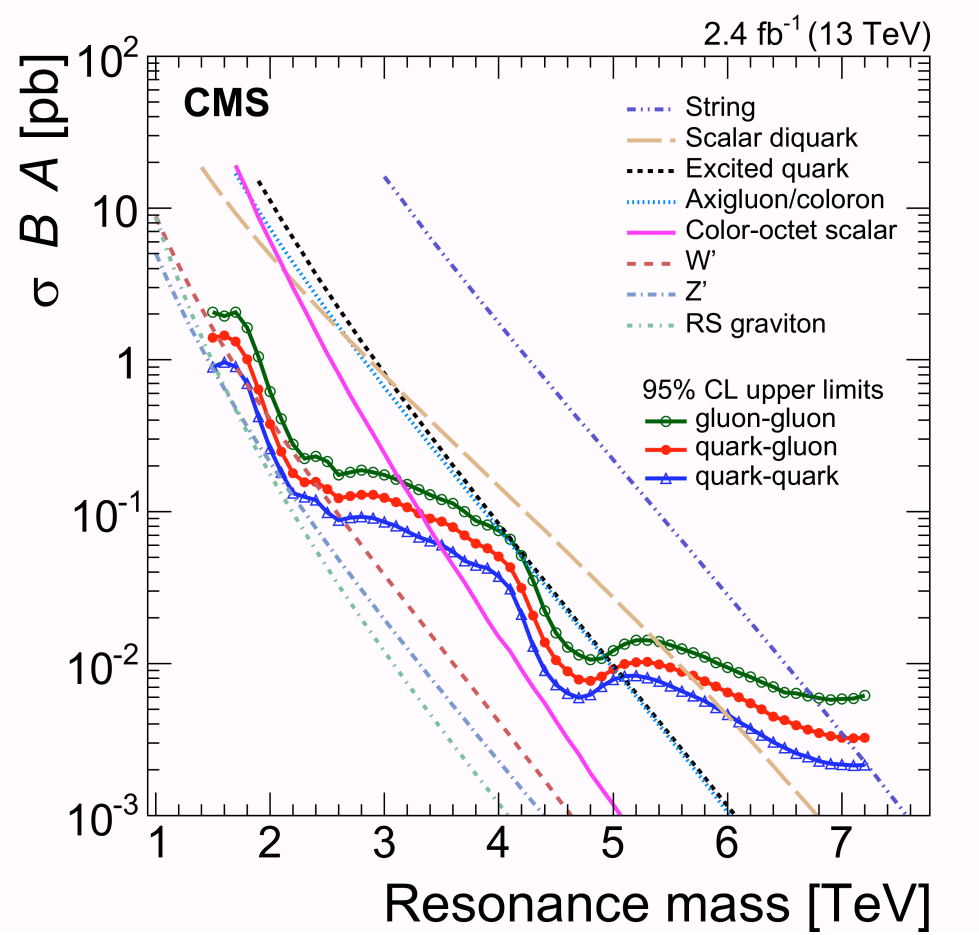
$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

$$x = m_{jj}^{Wide} / \sqrt{s}$$

Data is well fitted by the background parameterization

$$\chi^2 / ndf = 31/35$$

Dijet Resonance Search



Model	Final State	Obs. Mass Limit [TeV]	Exp. Mass Limit [TeV]
String	qg	7.0	6.9
Scalar diquark	qq	6.0	6.1
Axigluon/coloron	$q\bar{q}$	5.1	5.1
Excited quark (q*)	qg	5.0	4.8
Color-octet scalar	gg	3.1	3.3
Heavy W (W′)	$q\bar{q}$	2.6	2.3

No evidence on New Physics seen.

Probing the 750 GeV region with Dijets

Slide from A.Strumia's talk at Moriond EW 2016

Bounds on other decay modes

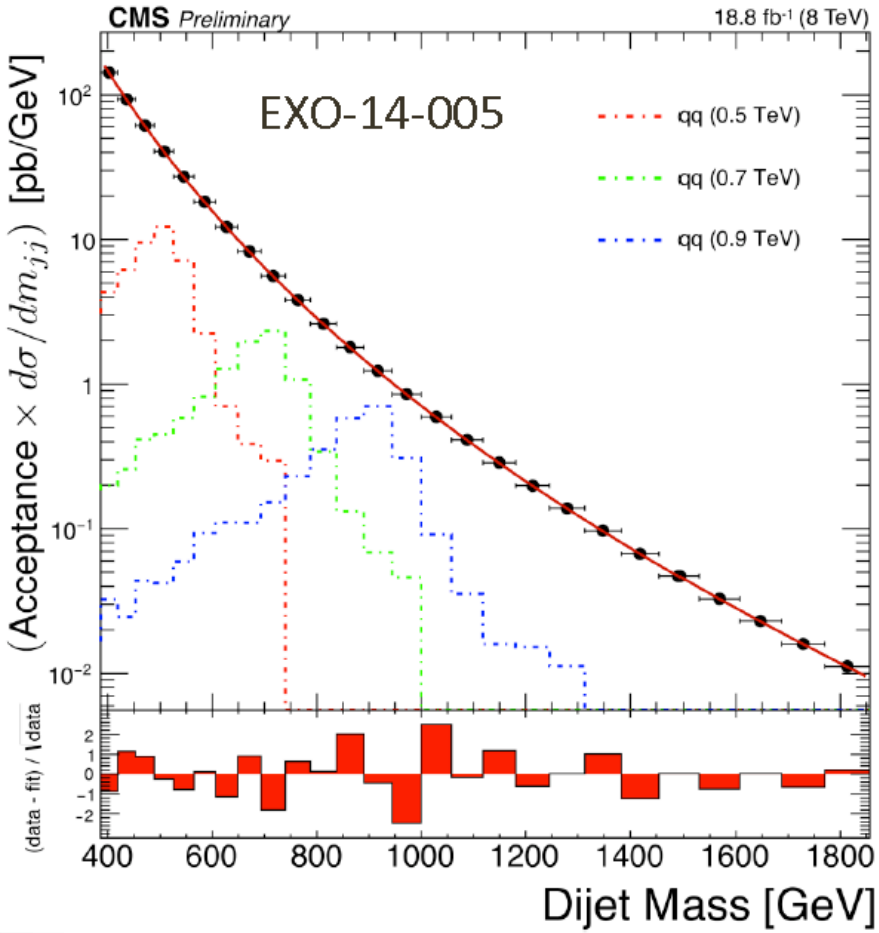
final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\text{obs}}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	$< 0.8\ (r/5)$
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	< 15 fb	$< 6\ (r/5)$
$Z\gamma$	< 11 fb	< 12 fb	$< 6\ (r/5)$
ZZ	< 12 fb	< 20 fb	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	$< 20\ (r/5)$
$t\bar{t}$	< 450 fb	< 600 fb	$< 300\ (r/5)$
invisible	< 0.8 pb	-	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	$< 1300\ (r/5)$

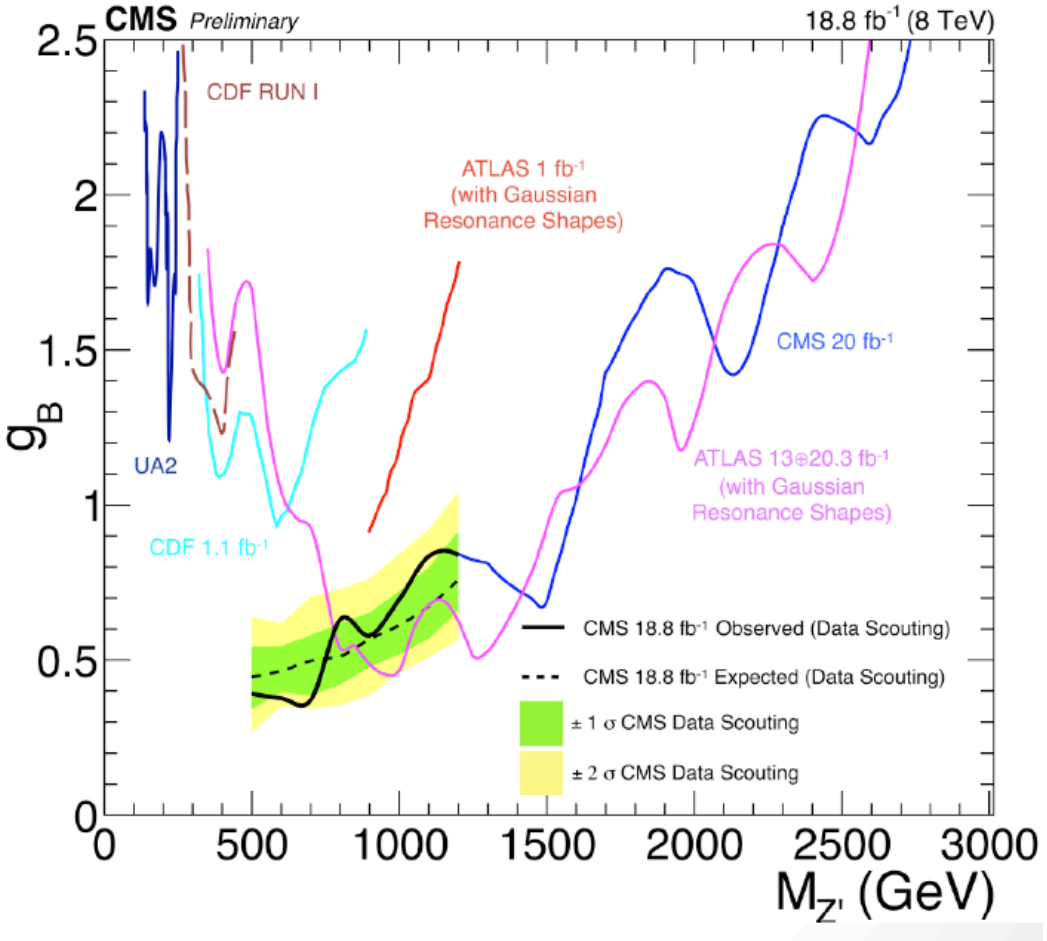
Here $r = \sigma_{13\,\text{TeV}}/\sigma_{8\,\text{TeV}}$. Using run 2 data only would be safer. Run 2 jj?

Even invisible modes are constrained

Probing the 750 GeV region with Dijets

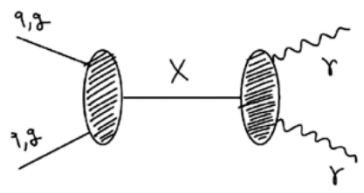
8 TeV Dijet "scouting" analysis



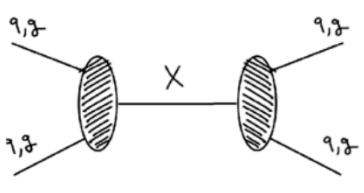


Probing the 750 GeV region with Dijets

IF

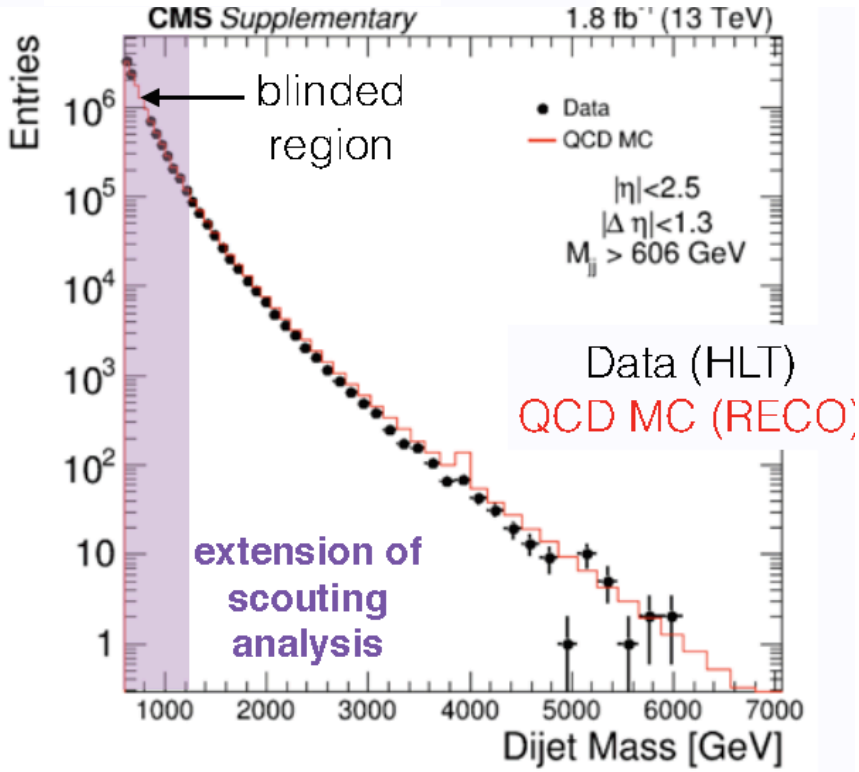


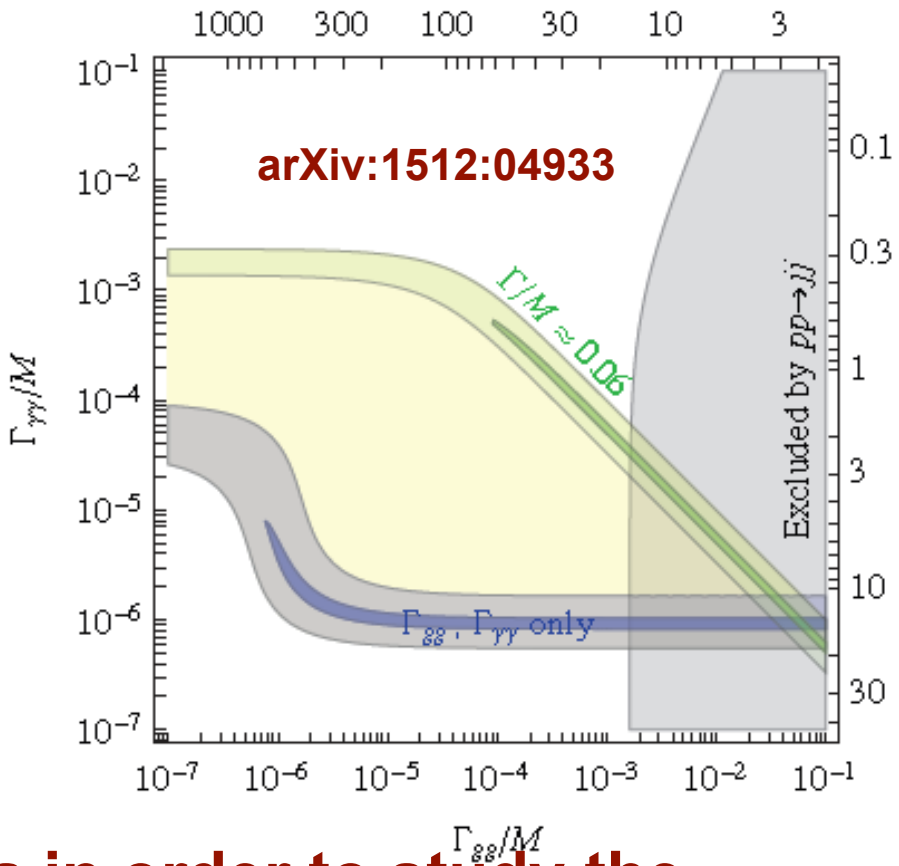
THEN



$$BR_{jj}/BR_{\gamma\gamma} \approx (\alpha_S/\alpha_{em})^2(Q_S/Q_{em})^4 \approx 10-10^3$$

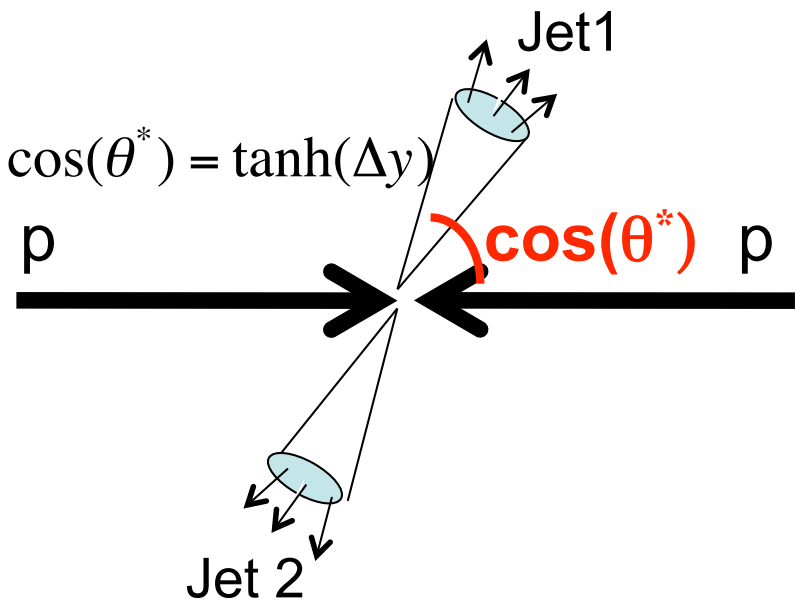
$$\sigma_{\gamma\gamma} \approx 10\,\text{fb} \rightarrow \sigma_{jj} \approx 0.1-10\,\text{pb} \quad @\ 13\ \text{TeV}$$

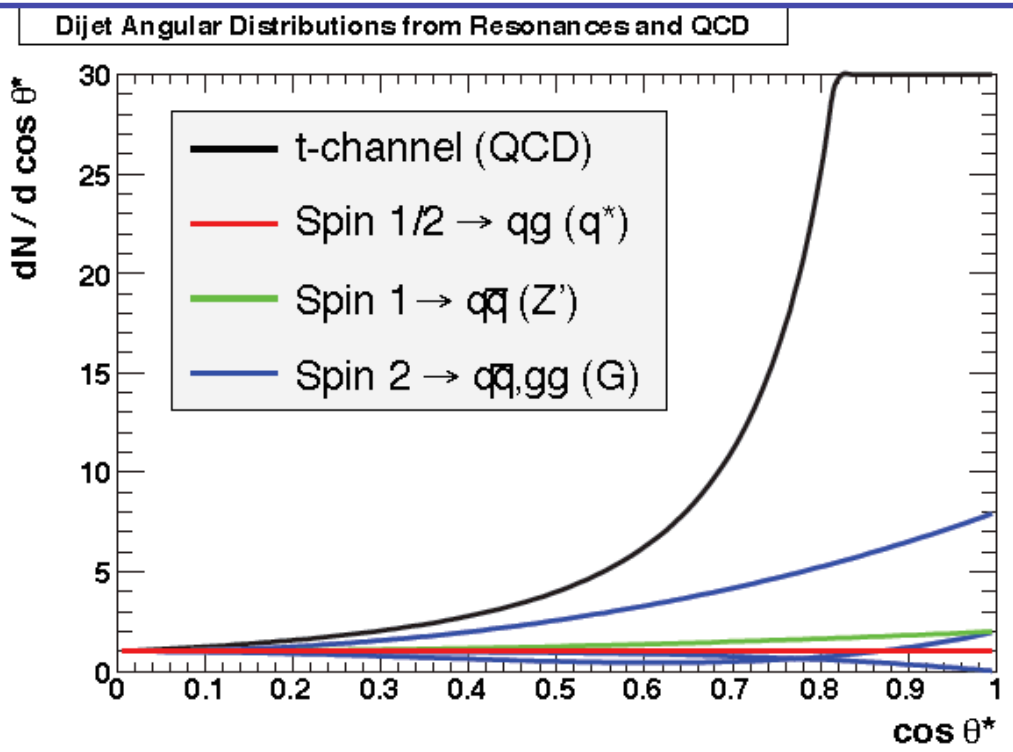




Now analyzing "scouting" data in order to study the 750 GeV region with dijets: Results expected soon

Dijet Angular Distributions





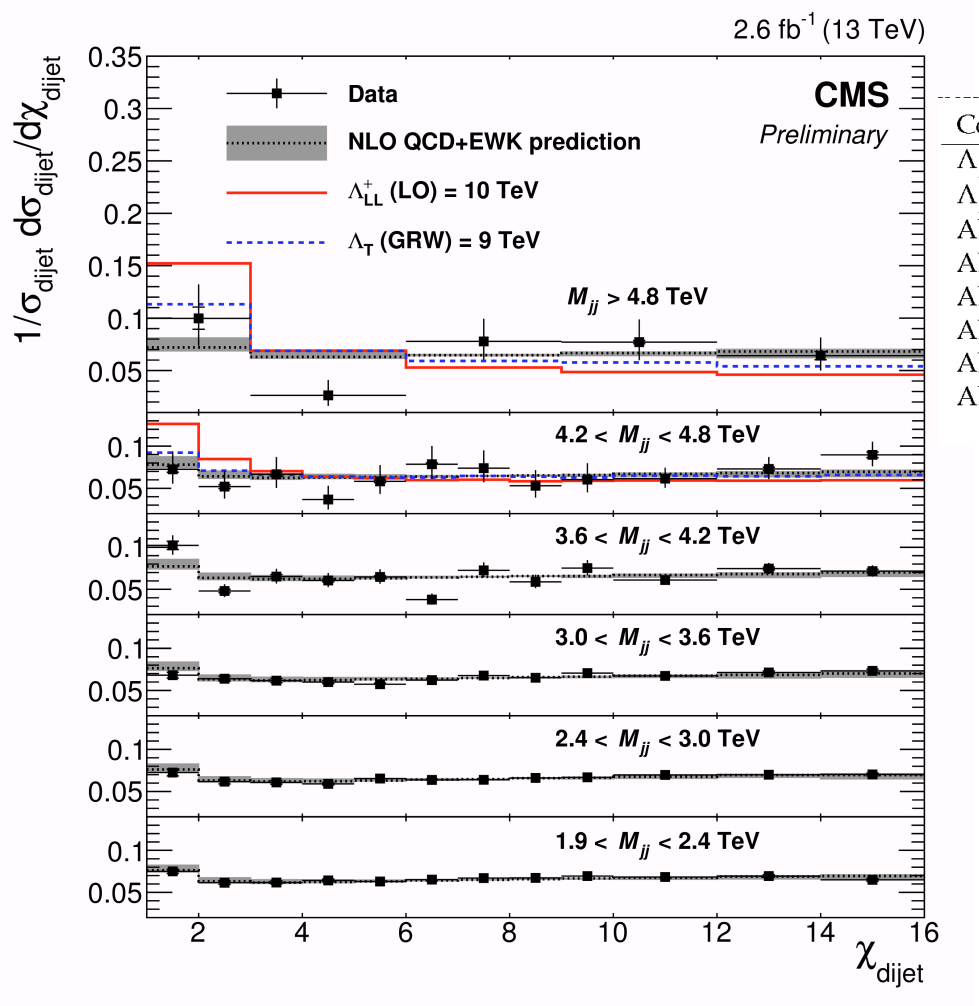
- Parton-parton scattering in QCD is t-channel dominated.
- Stringent test of pQCD with no dependence on PDFs.
- **New physics would show deviations from expectation at large scattering angles.**

Dijet Angular Distributions

$$\chi = e^{|y_1 - y_2|} \approx \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$

- χ chosen since QCD flat as a function of χ.
- Experimental uncertainties dominated by jet resolution and relative (vs η) JES (absolute cancels)
- Theoretical uncertainties dominated by non perturbative corrections and renormalization scale.

Dijet Angular Distributions



Compositeness model	Observed lower limit (TeV)	Expected lower limit (TeV)
$\Lambda^{+}_{LL/RR}$ (LO)	12.1	12.0 ± 1.1
$\Lambda^{-}_{LL/RR}$ (LO)	16.3	15.3 ± 2.4
ADD Λ_T (GRW)	9.1	9.0 ± 0.7
ADD M_S (HLZ) $n_{ED} = 2$	9.7	9.6 ± 0.7
ADD M_S (HLZ) $n_{ED} = 3$	10.8	10.7 ± 0.8
ADD M_S (HLZ) $n_{ED} = 4$	9.2	9.0 ± 0.7
ADD M_S (HLZ) $n_{ED} = 5$	8.3	8.1 ± 0.6
ADD M_S (HLZ) $n_{ED} = 6$	7.7	7.6 ± 0.6

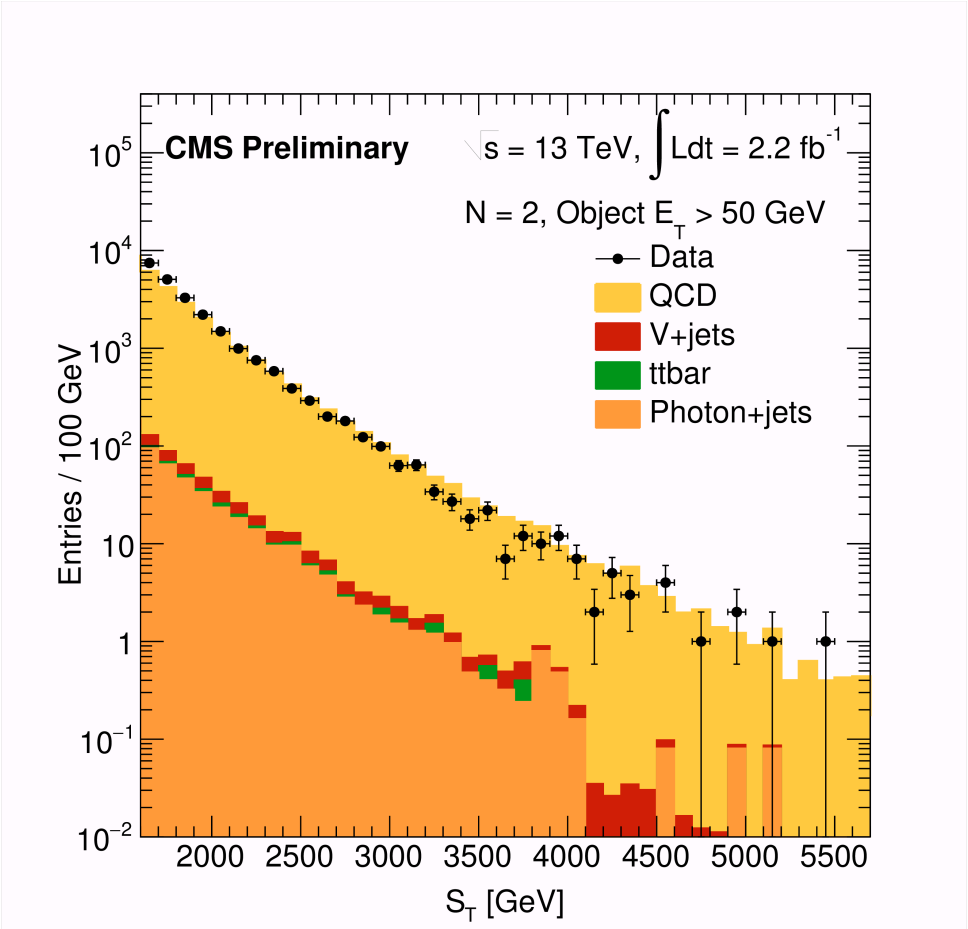
- **Good agreement between data and theory. Highest mass bins sensitive to contact interactions and large extra dimensions**

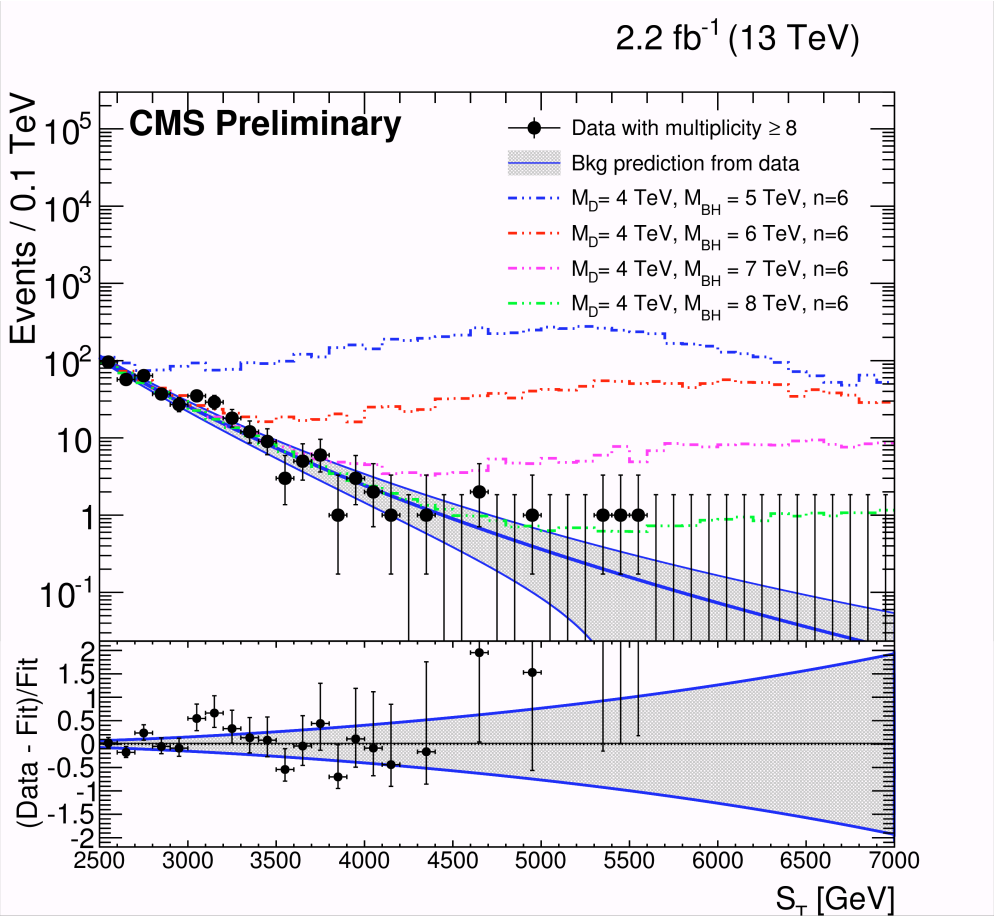
Black Holes

$$S_{\mathrm{T}} = \left(\sum_{i=1}^{N} E_{T,i} \right) + (E_T^{\mathrm{miss}} > 50\,\mathrm{GeV})$$

- S_T "invariance" as a function of jet multiplicity is used in order to differentiate between SM and New Physics.
- Data-driven method exploited in SM background estimation, hence minimizing experimental systematic uncertainties.
- Theoretical uncertainties dominated by PDFs and final state radiations ones.

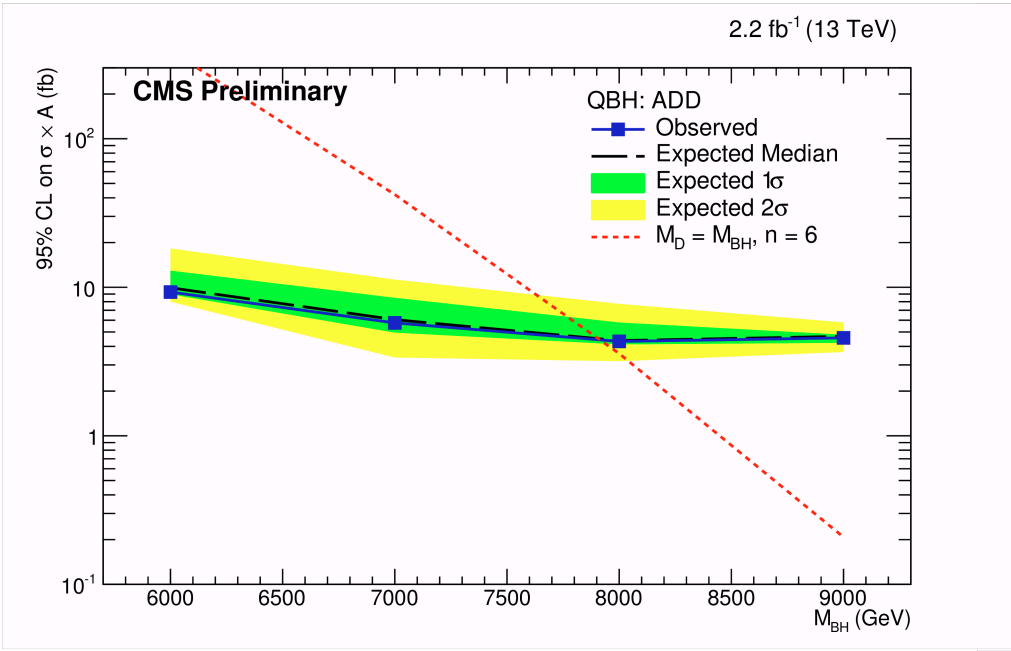
Black Holes

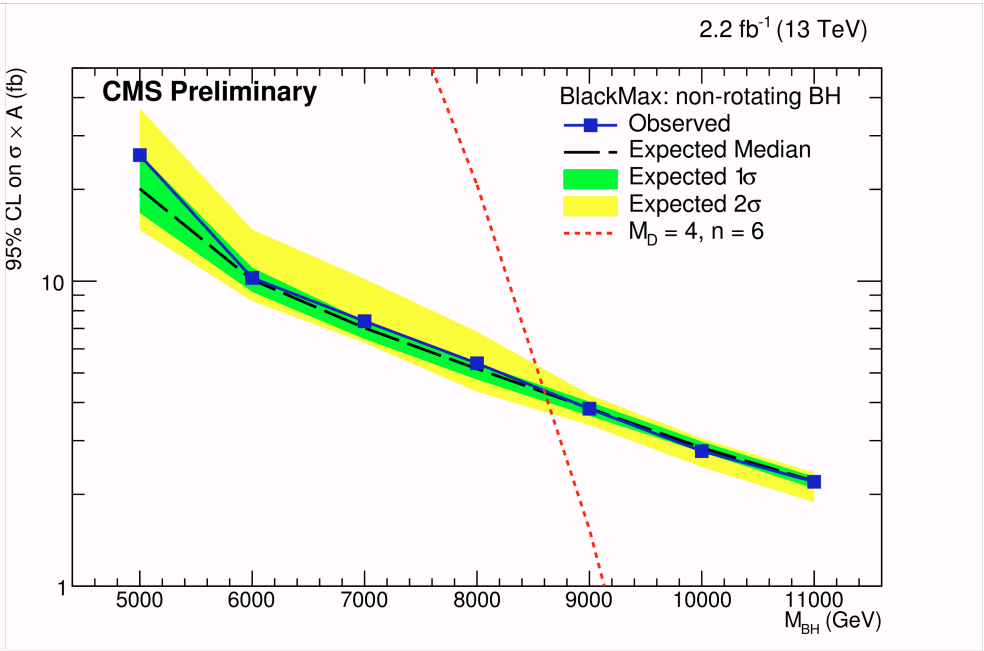




- The n-jet = 2 distribution is used in order to predict (shape – wise) higher jet multiplicities.

Black Holes





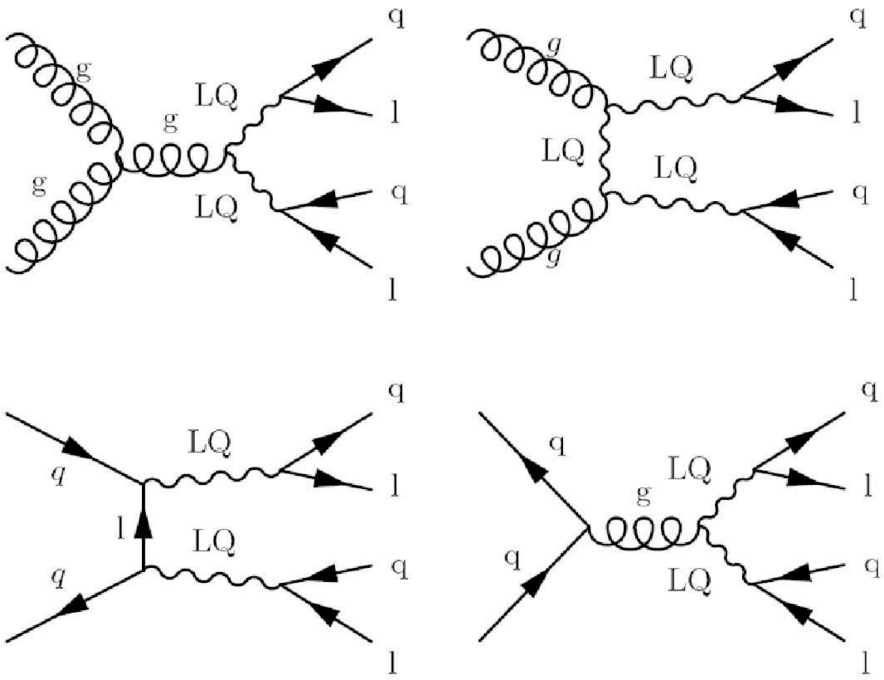
- Semi-classical black holes excluded below 8.9 TeV, Quantum black holes below ~ 8 TeV

Exotic New Physics : Lepto-Quarks

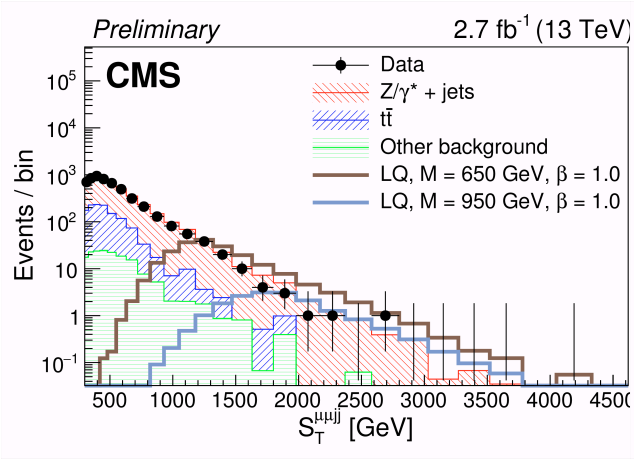
- Scalar of Vector Boson carrying both lepton and baryon number, fractional charge.

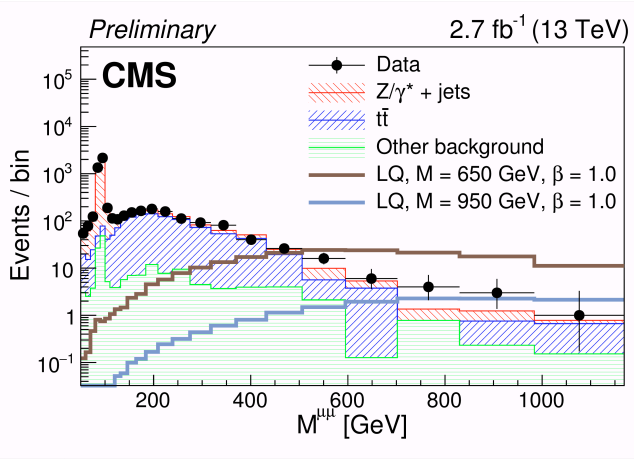
- Many extensions of SM like GUTs, technicolor, compositeness predict the existence of lepto-quarks.

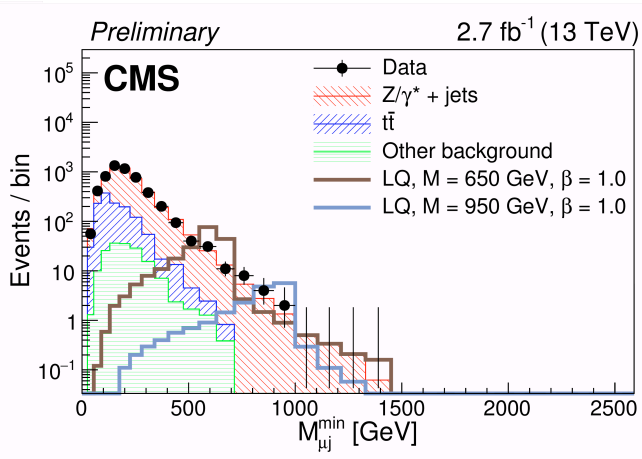
- Final states with leptons, depending on the free parameter β=BF(LQ→l±q)=1-BF(LQ→νq)



2nd generation Lepto-Quark Search

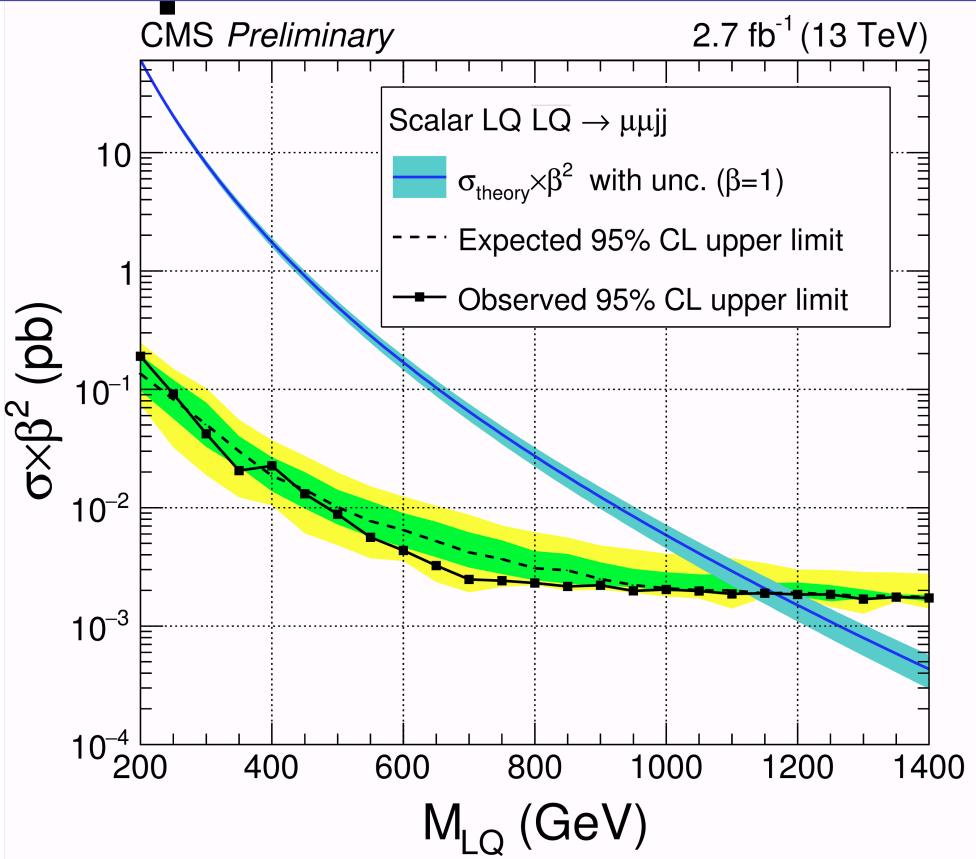






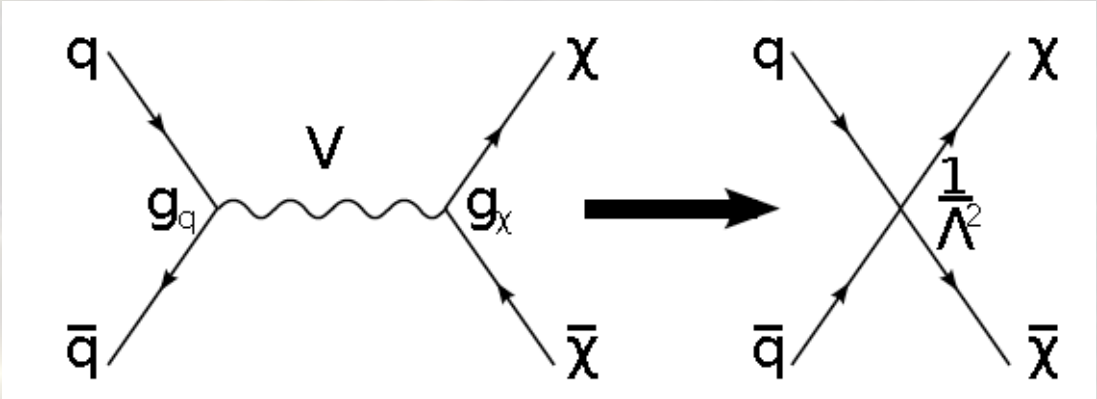
- Search utilizes events with at least two muons and two jets, imposing criteria on $M_{\mu\mu}$, S_T, $M_{(\mu,jet)}$
- Background estimation uses simulation and data-driven methods when possible.

2nd generation Lepto-Quark Search

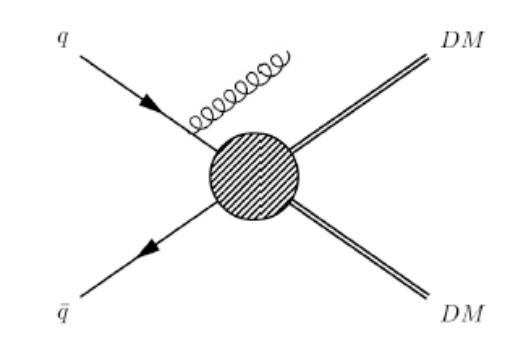


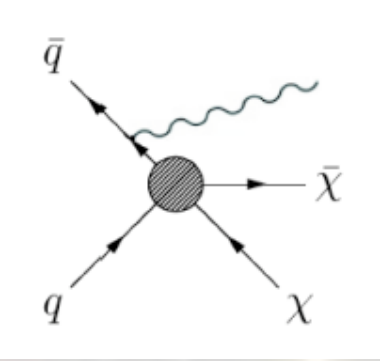
- Scalar lepto-quarks are excluded with masses below 1165 GeV for $\beta = 1$, and below 960 GeV for $\beta = 0.5$
- First (electron) and third (tau) generation LQ searches in progress.

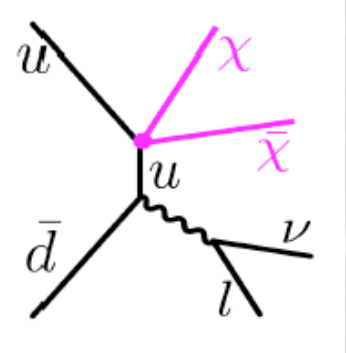
Exotic New physics : Dark Matter



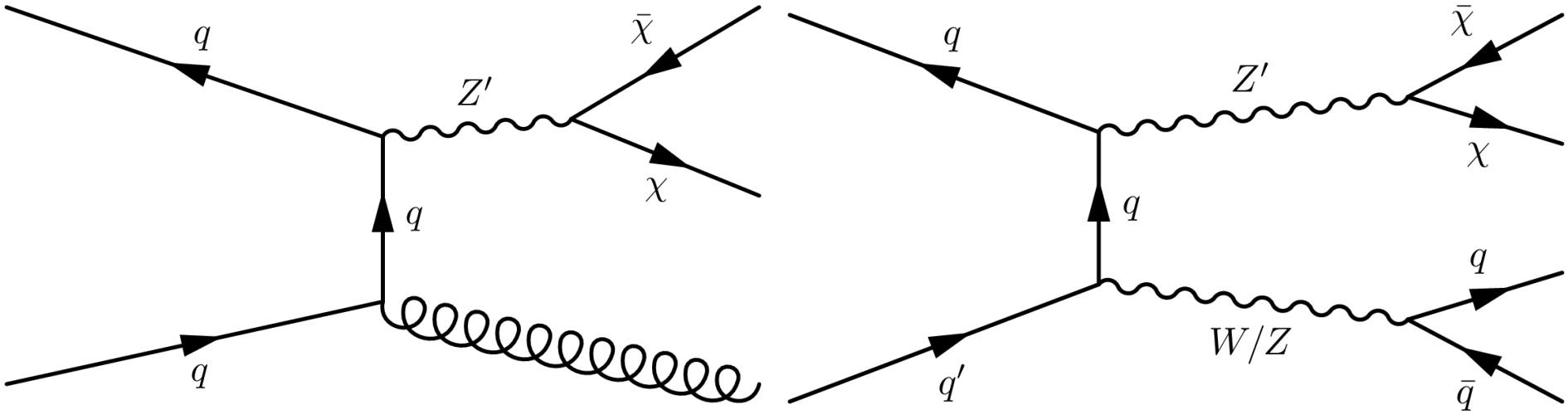
- **If mediator much heavier than typical energy transfer then EFT**
- **If mediator light enough to be produced at LHC then Simplified Theory**
- **If DM interacts weakly then not detected, hence signature is something + Missing Transverse Energy**





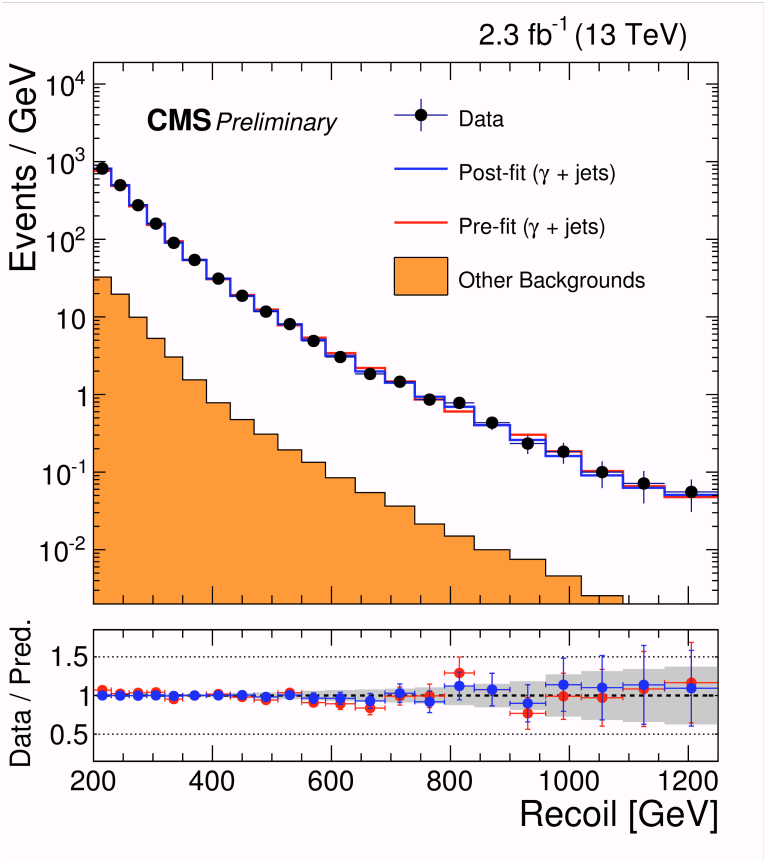


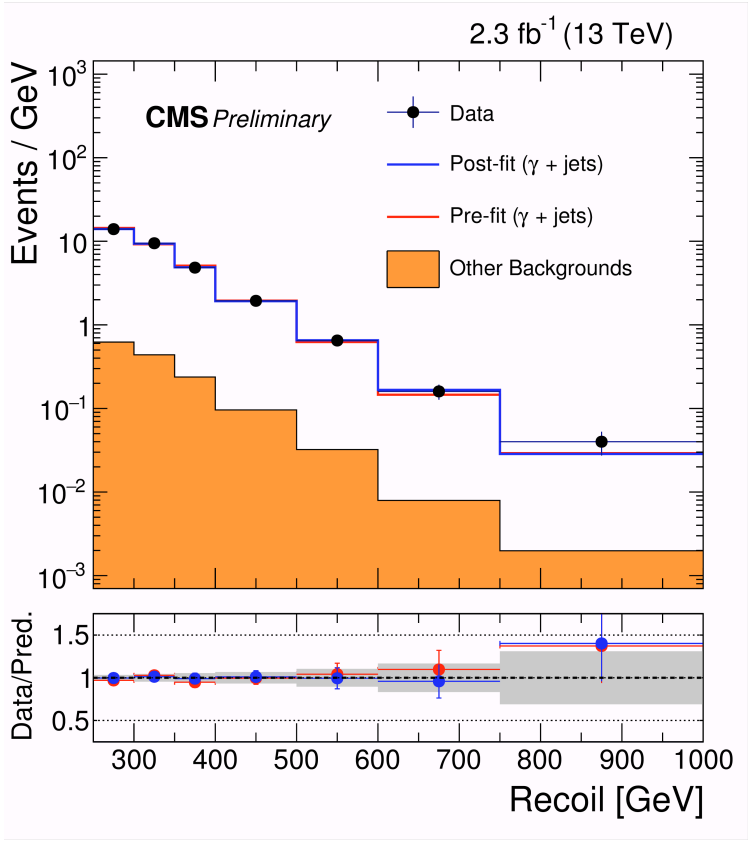
Mono-jet, Mono-V DM Search



- **Main analysis strategy:**
  - **Utilize Missing Transverse Energy (MET) as the search variable both using shape and normalization.**
  - **Utilize several control region, and most noticeably gamma+jet events to "predict/constraint" MET shape**

Mono-jet, Mono-V DM Search

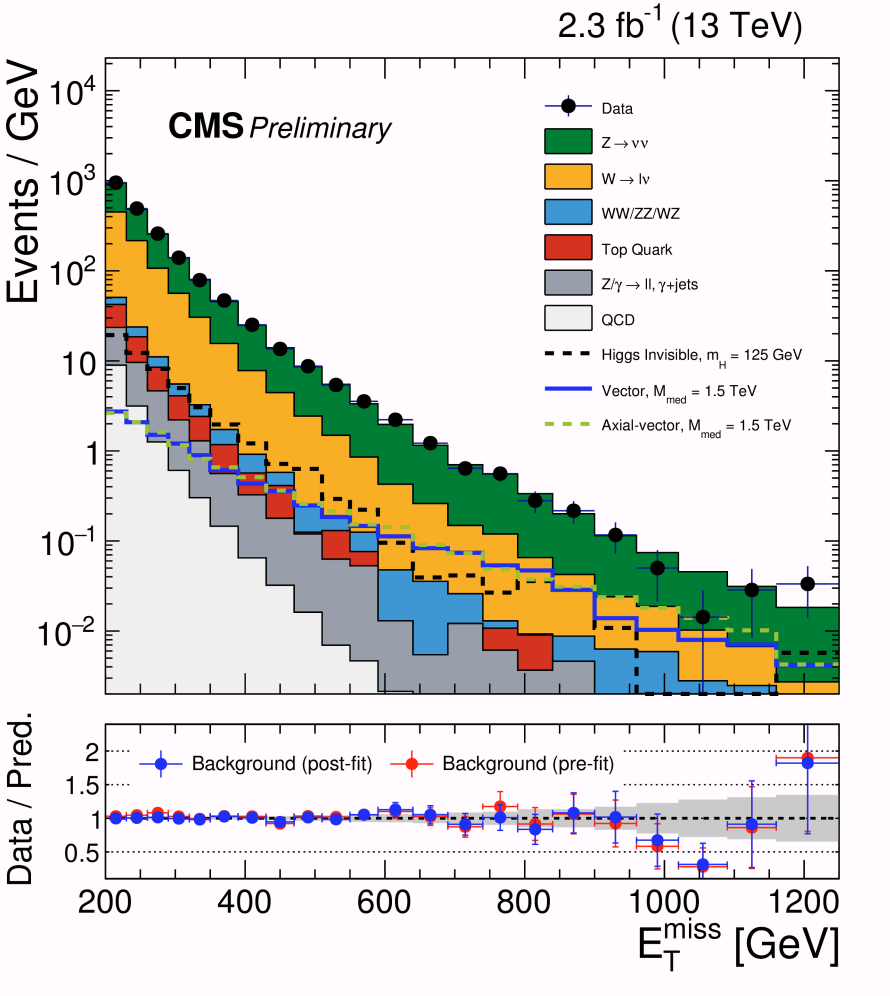


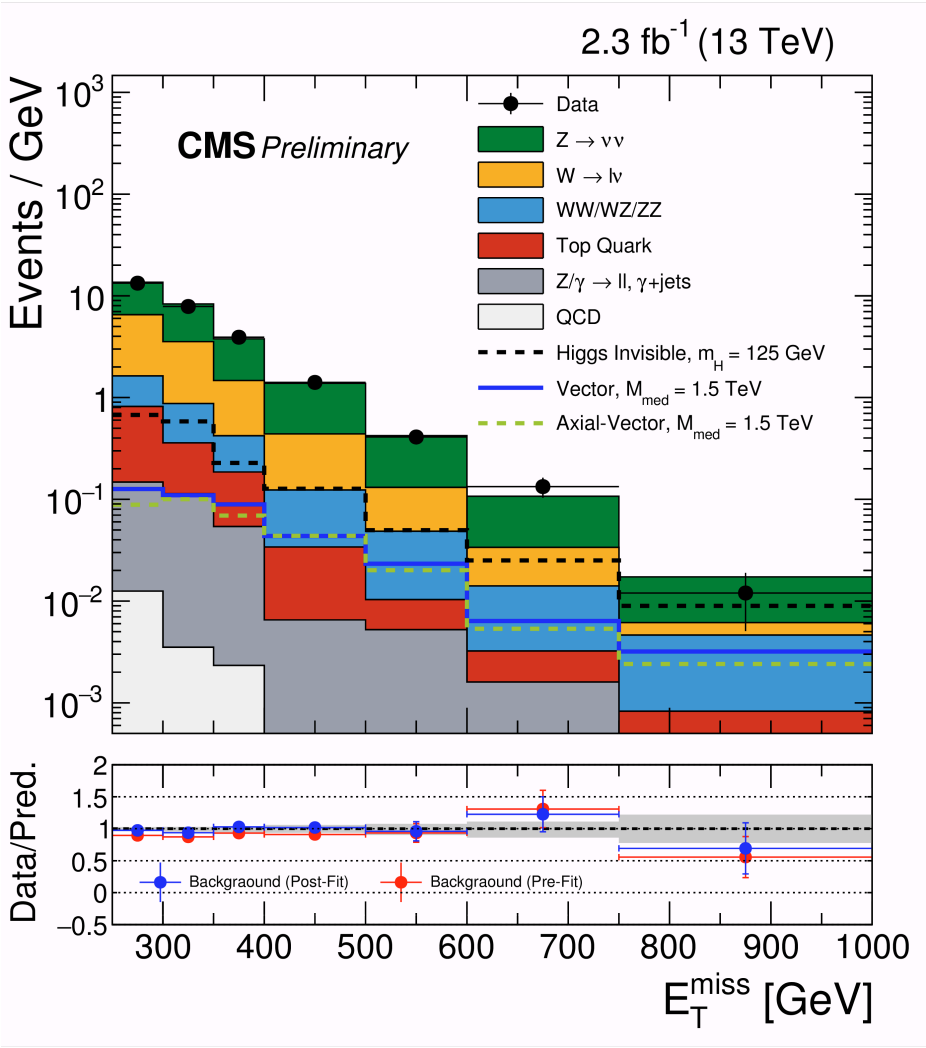


- Missing transverse energy (MET) in signal region (mainly coming from Z->νν +jets) predicted using data control regions (γ+jets) and a transfer factors factors from simulation.

- Nice agreement between data and simulation before and after fitting in the MET distribution of gamma+jet events

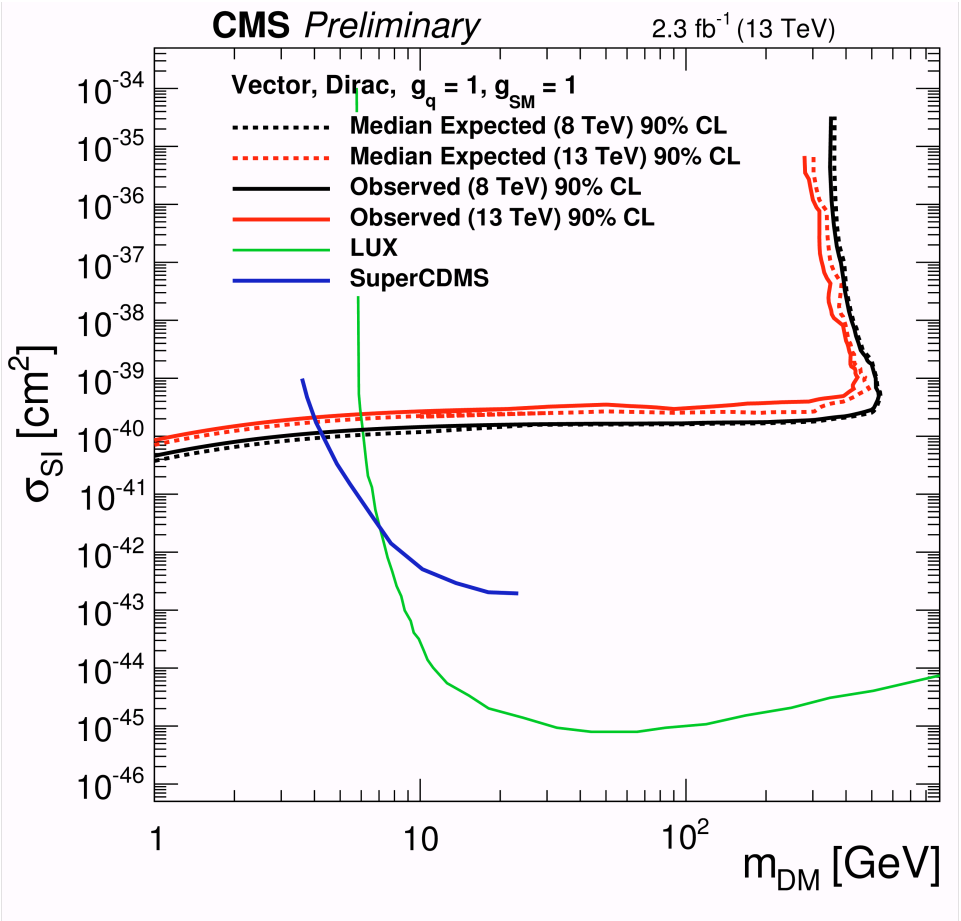
Mono-jet, Mono-V DM Search

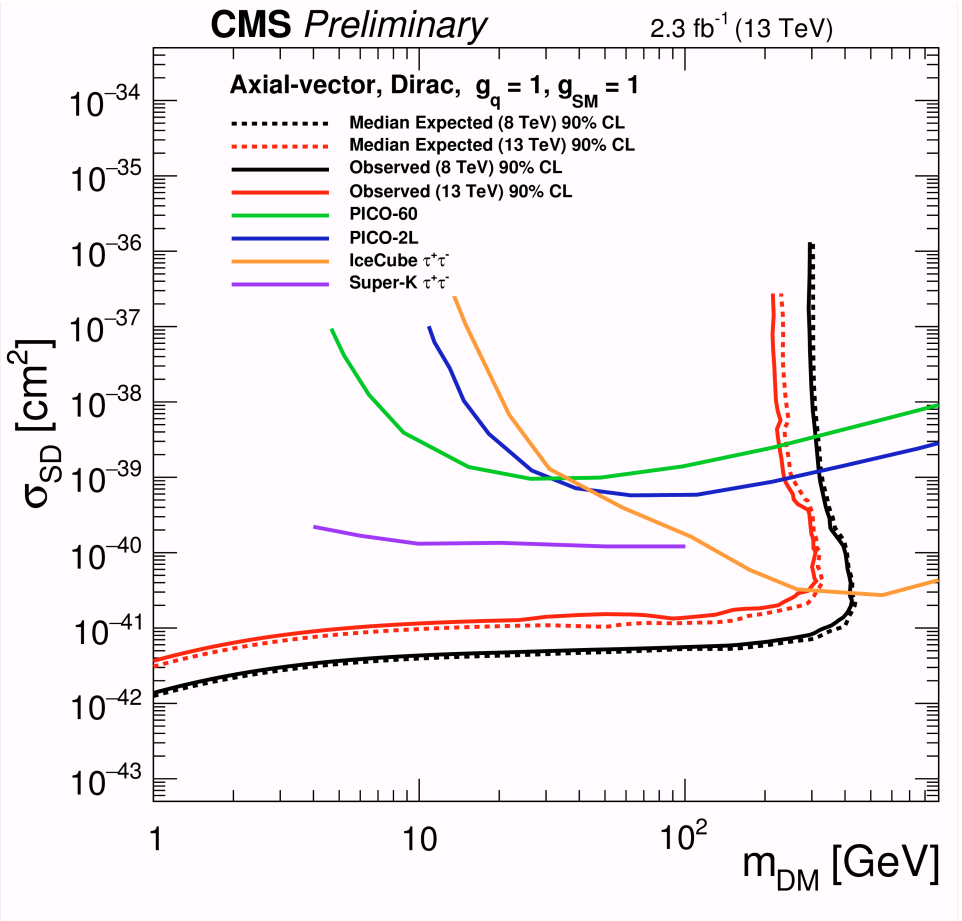




- Nice agreement between prediction data in the MET distribution of mono-jet and mono-V event categories.

Mono-jet, Mono-V DM Search





- Limits competitive with direct detection experiments.

Summary

- **CMS is performing, a wealth of physics "exotic" searches in final states with "Jets+X". There are many ongoing analyses to be public soon : searches for Right-handed W, Heavy neutrinos, first and third generation lepto-quarks.**

- **In view of the di-photon excess at 750 GeV, the dijet low mass searches have attracted even more attention recently. And will be reporting on results soon.**

- **The forthcoming Run has some possibility to revolutionarize the field with a quick major discovery**

- **So, please stay tuned…**

Ευχαριστώ!

Jet Calibration

- **Dijet asymmetry**

Raw Jet × Offset Correction (pile up) × Relative Response (vs. η) × Absolute Response (vs. p_T) = Calibrated Jet (Physics Object)

- **Photon+Jet Balance**