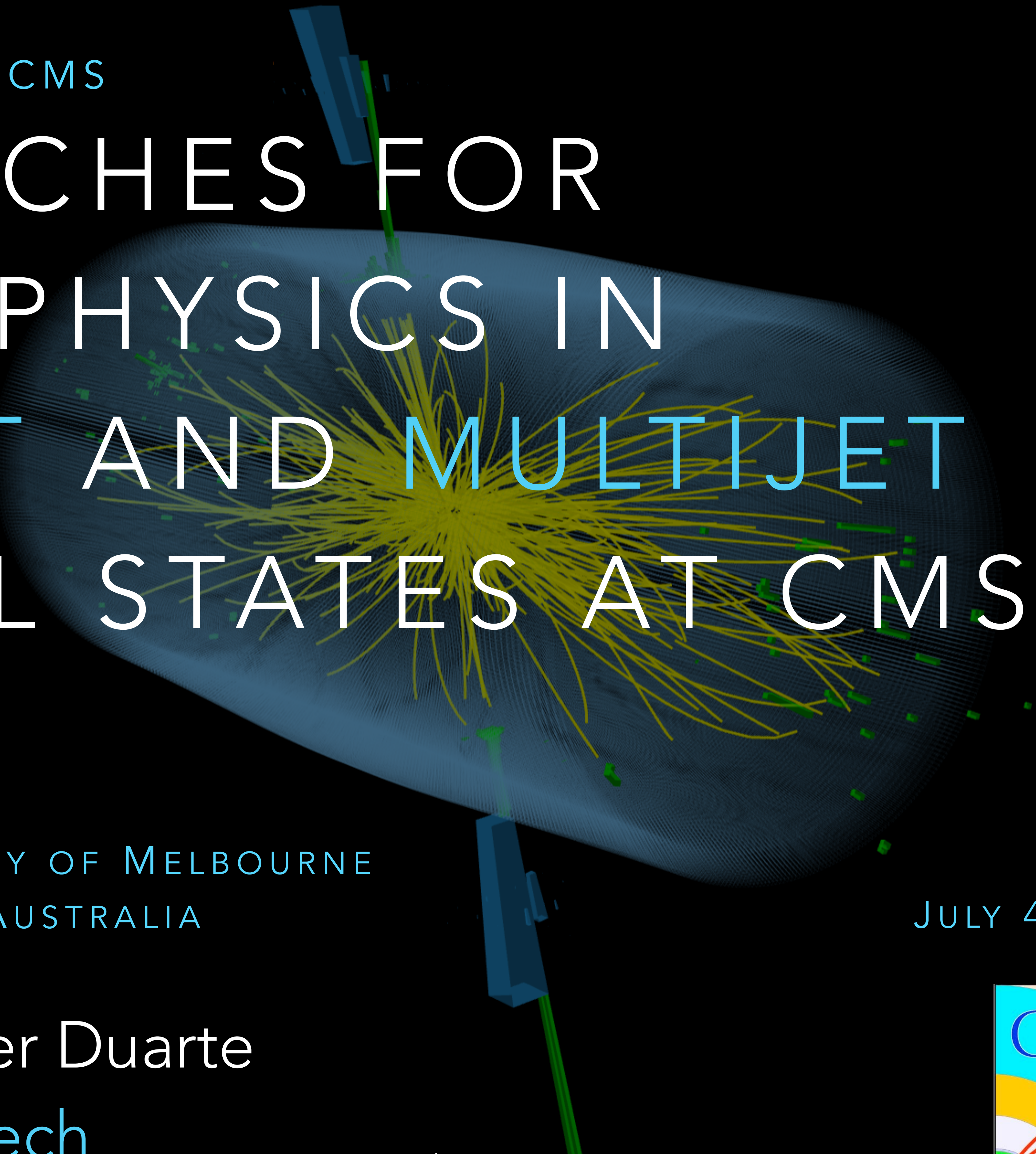
SEARCHES @ CMS

SEARCHES FOR BSM PHYSICS IN DIJET AND MULTIJET FINAL STATES AT CMS



SUSY 2016

The University of Melbourne

Melbourne, Australia

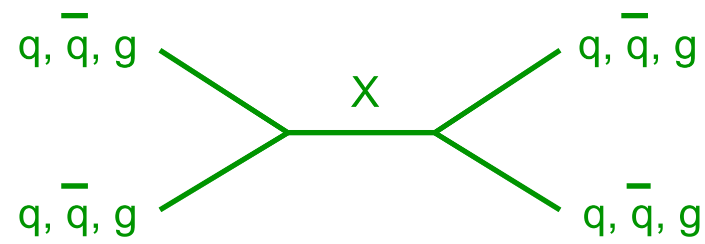
July 4, 2016

Javier Duarte

Caltech

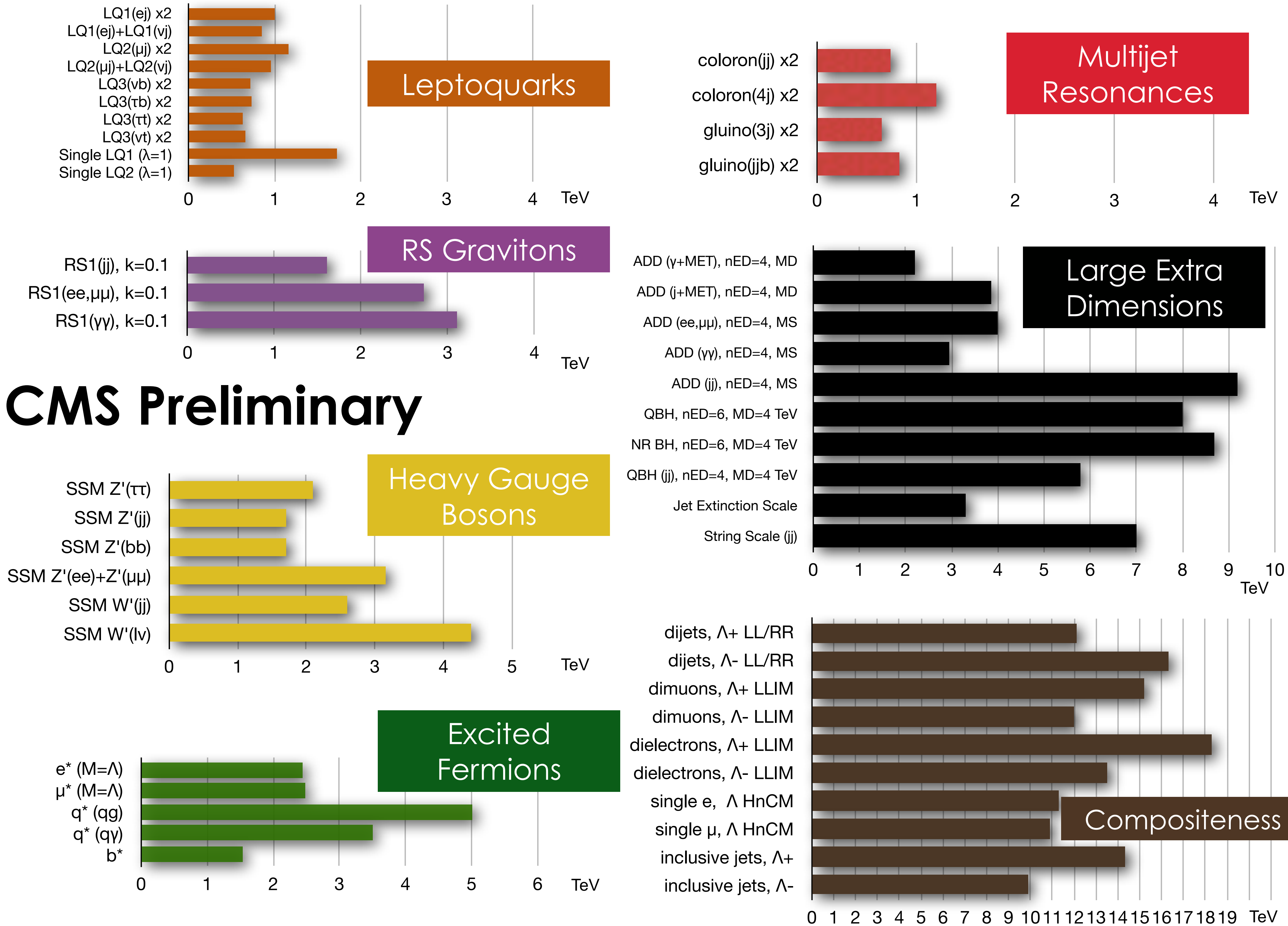
MOTIVATION AND OUTLINE

- **Powerful**: LHC in Run 2 is a dijet resonance factory at a new energy scale



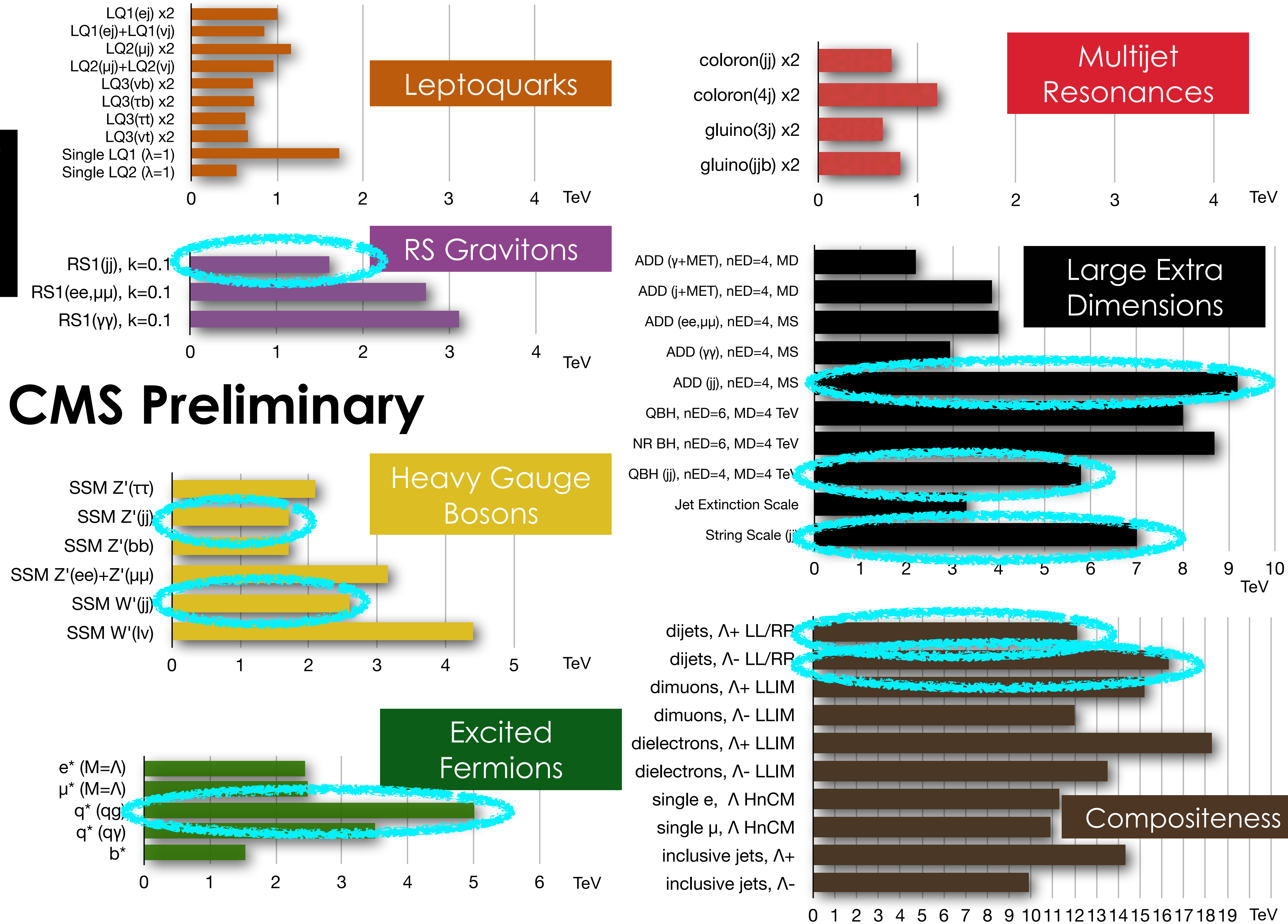
- **Broad**: Many BSM phenomena can be searched for
- **Model independent**: search results are applicable to any model that predicts narrow quark-quark, quark-gluon, or gluon-gluon resonances
- This talk:
  - High-mass search at 13 TeV with 2015 data
  - Low-mass search at 8 TeV with "data scouting"
  - Data scouting at 13 TeV

EXTENSIVE CMS EXO PROGRAM!



EXTENSIVE CMS EXO PROGRAM!

REACH OF DIJET SEARCHES



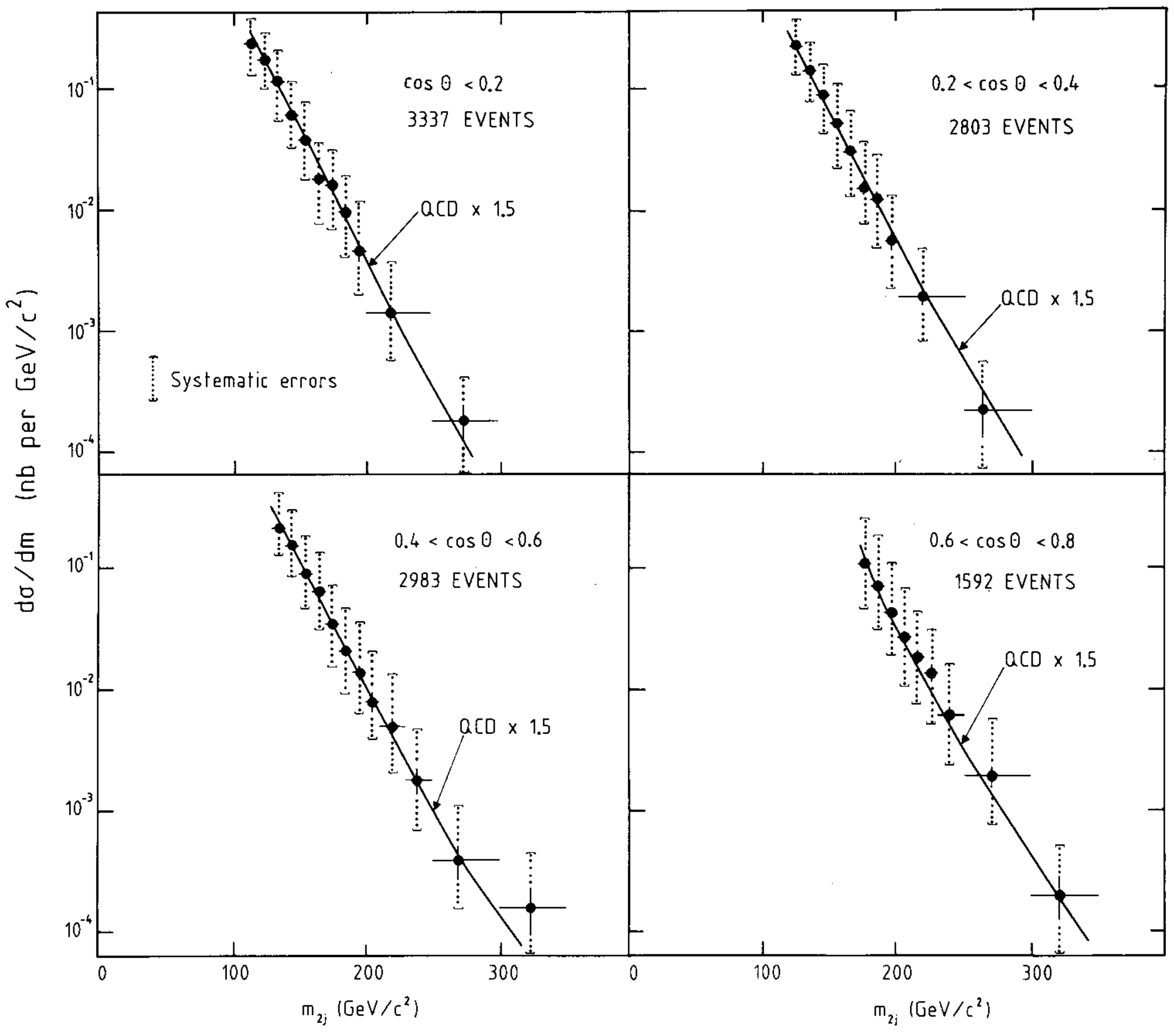
LONG HISTORY

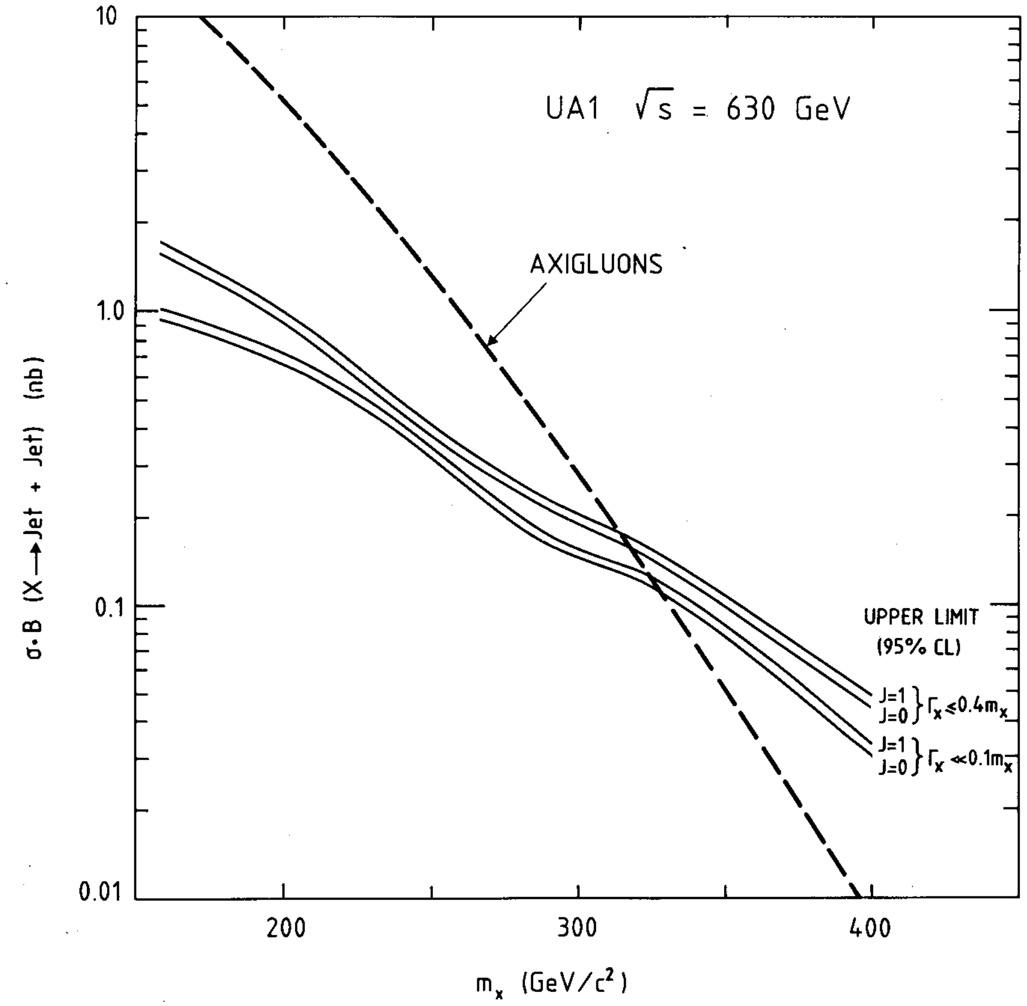
EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

CERN-EP/88-54
April 28th, 1988

Two - Jet Mass Distributions at the CERN Proton - Antiproton Collider

UA1 Collaboration, CERN, Geneva, Switzerland

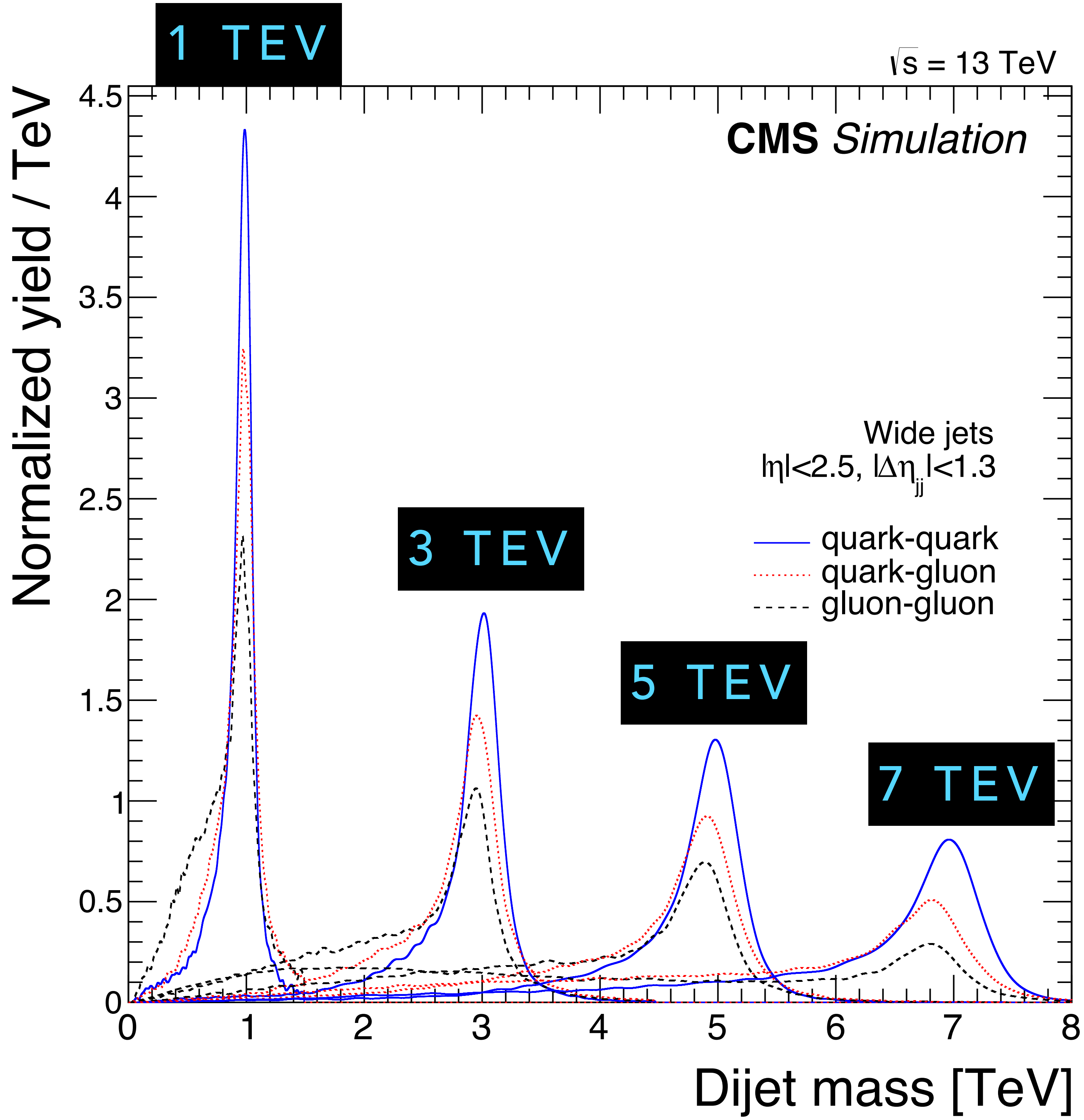




PRL 116 (2016) 071801

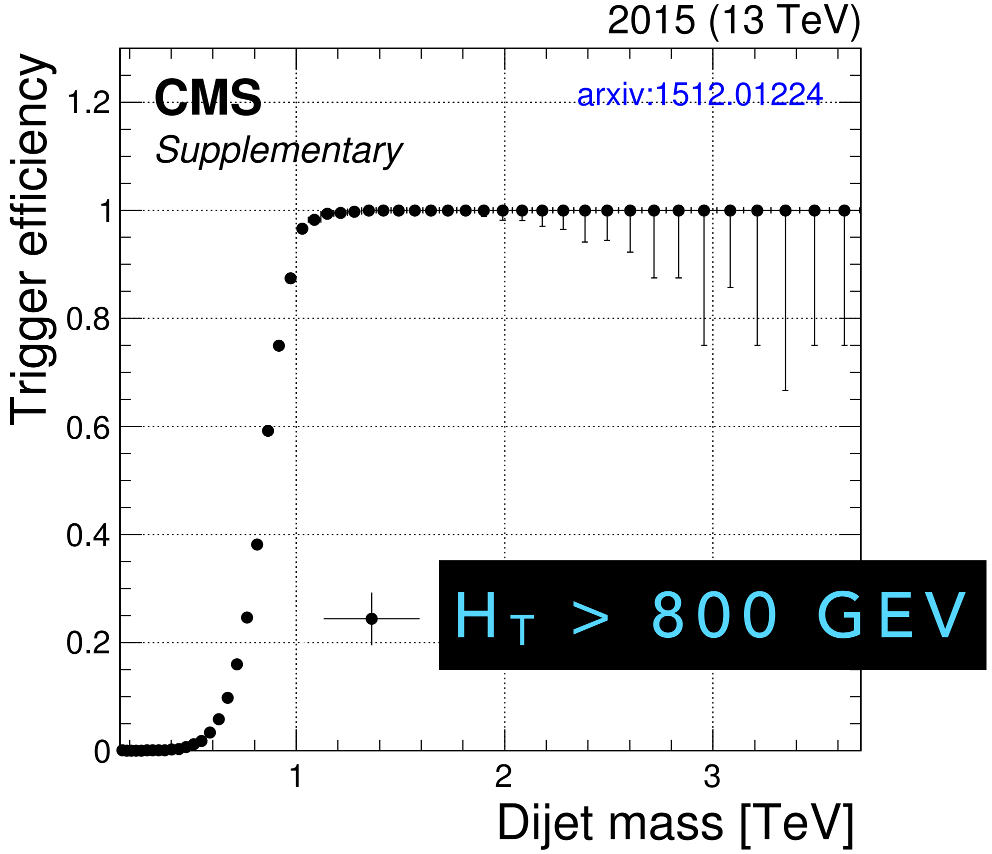
SIGNAL MODELS

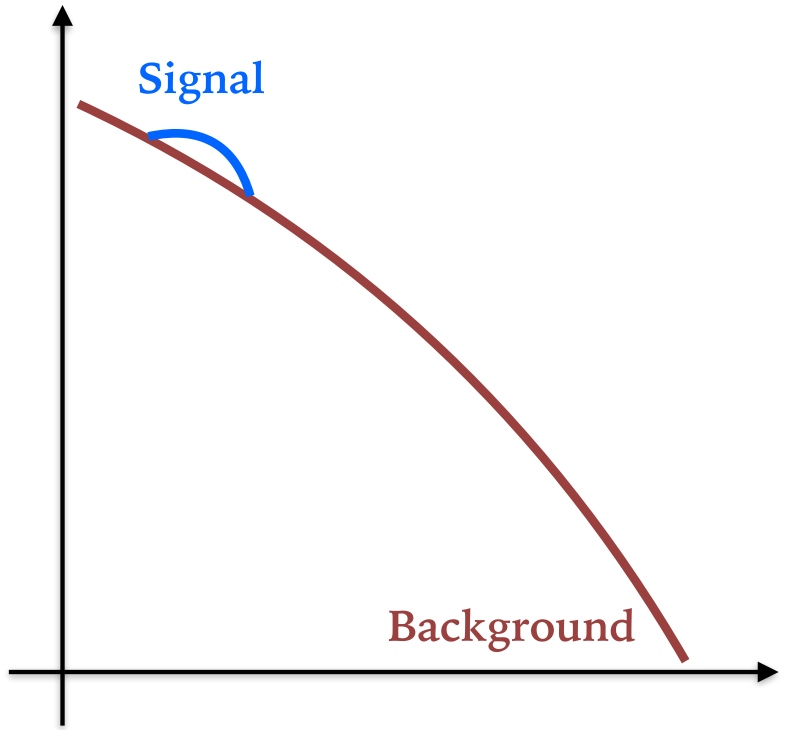
- quark-quark
  - **axigluons**: axial-vector particles predicted in a model where the QCD symmetry group $SU(3)_C$ is replaced by the chiral symmetry $SU(3)_L \times SU(3)_R$
  - **colorons**: vector particles predicted by the flavor-universal coloron model, in which the $SU(3)_C$ is embedded in a larger gauge group
  - **W′**, **Z′**, …
- quark-gluon
  - **excited quarks**: predicted in quark compositeness models
  - **string resonances**, …
- gluon-gluon
  - **RS graviton**: predicted in the RS model of extra dimensions, with 5-dimensional anti de Sitter space and reduced Planck mass
  - **S8** (color octet scalar) resonances, …



BASICS OF A DIJET SEARCH

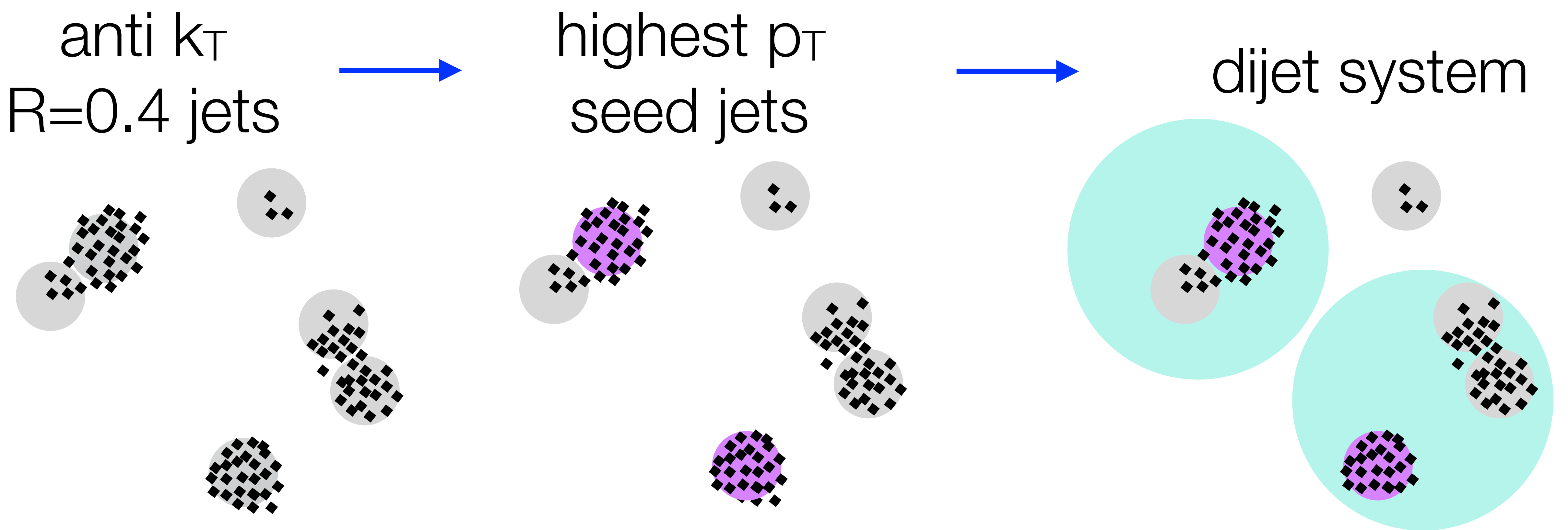
- Collect (lots of) data with a trigger based on hadronic activity
- Cluster "wide jets"
- Select events based on wide jet properties
- Search for a bump on a smoothly falling dijet mass spectrum
- Set limits





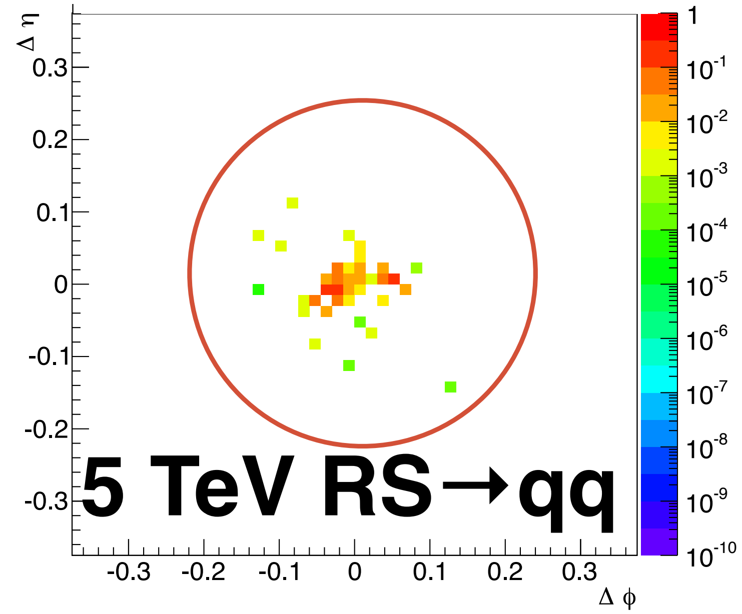
WIDE JETS

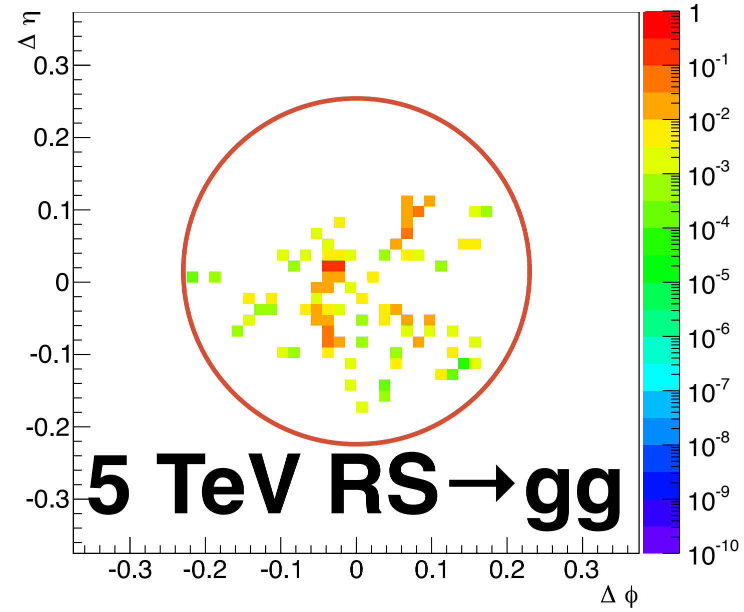
- Jets initially reconstructed with anti-k_T algorithm with R=0.4
- "Wide jet" algorithm uses two leading jets as seeds
  - Adds neighboring jets to nearest leading jet if within $\Delta R < 1.1$
  - Recover loss in mass response due to radiation

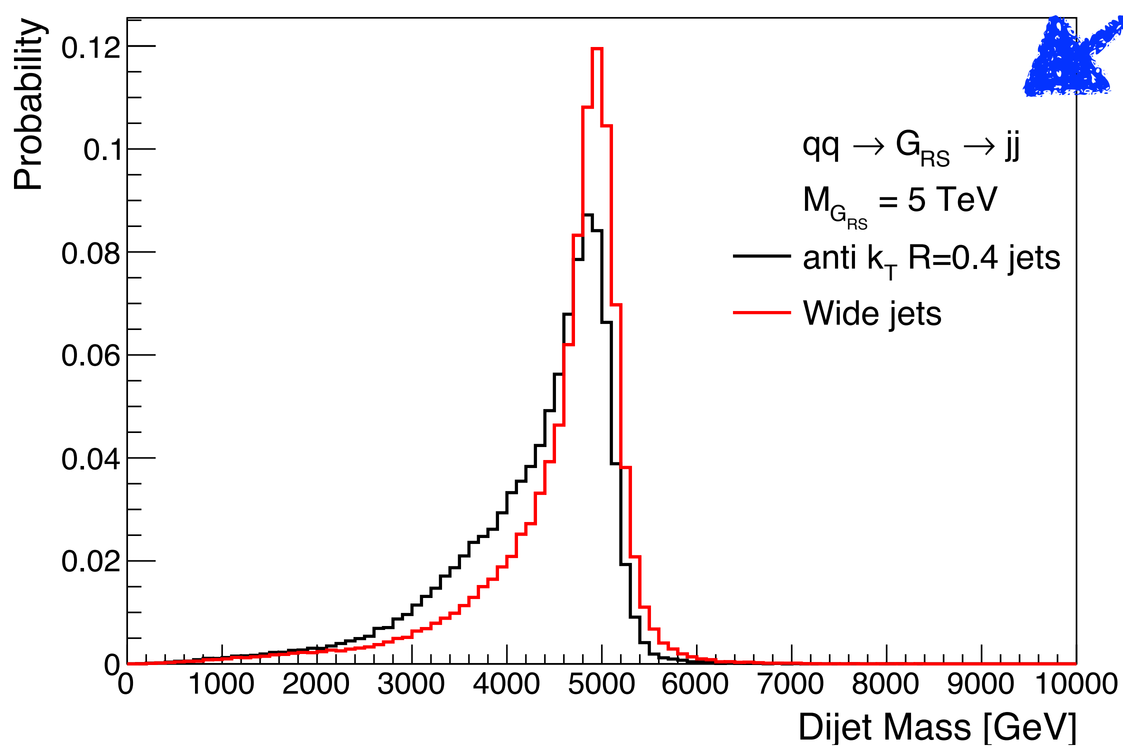


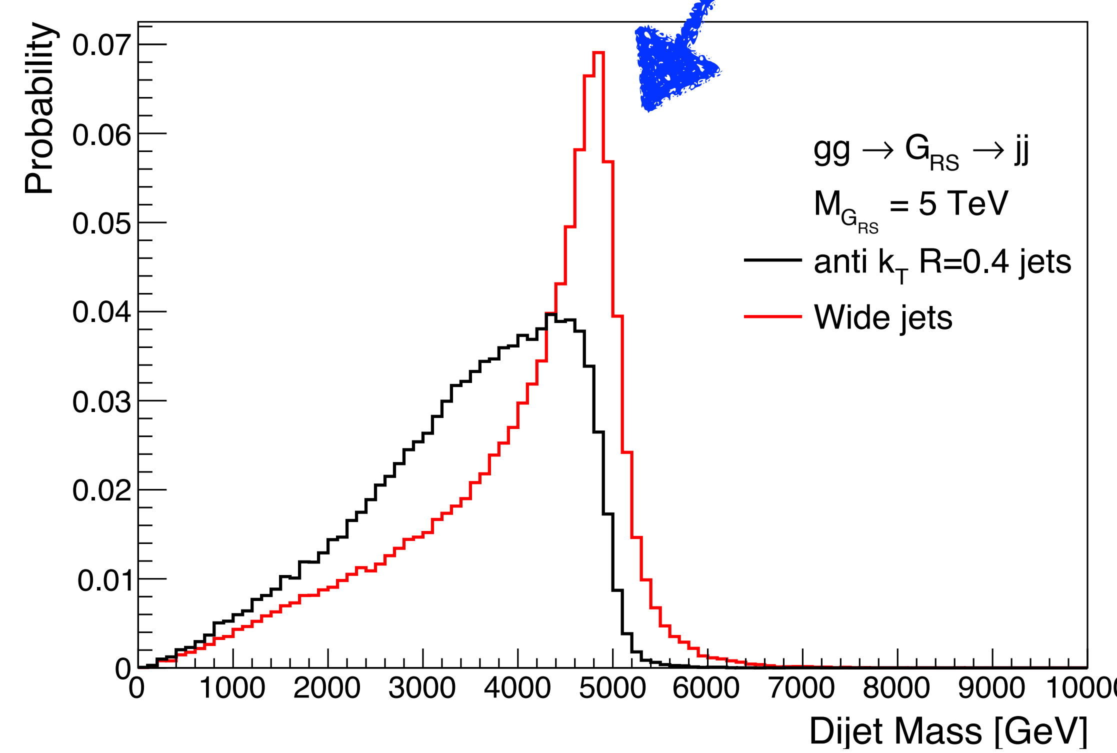
WIDE JETS

- Gluon-gluon resonances are wider than quark-quark resonances due to greater radiation (gluon color factor)
- Mass resolution improved with wide jets even in gluon-gluon case





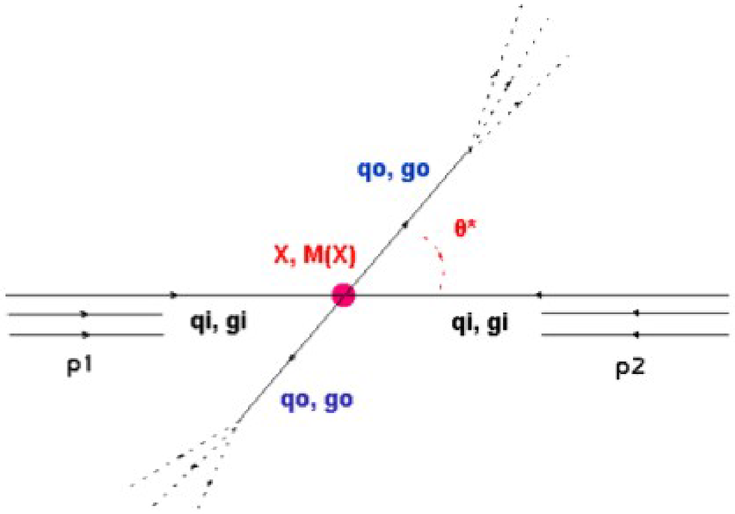




DIJET EVENT SELECTION

- At least one reconstructed vertex with $|z| < 24$ cm
  - Primary vertex is identified as the vertex with the highest sum of p_T^2
- At least 2 jets with $p_T > 30$ GeV and $|\eta| < 2.5$
- Wide jets $|\Delta\eta| < 1.3$ to suppress background from t-channel QCD dijet production

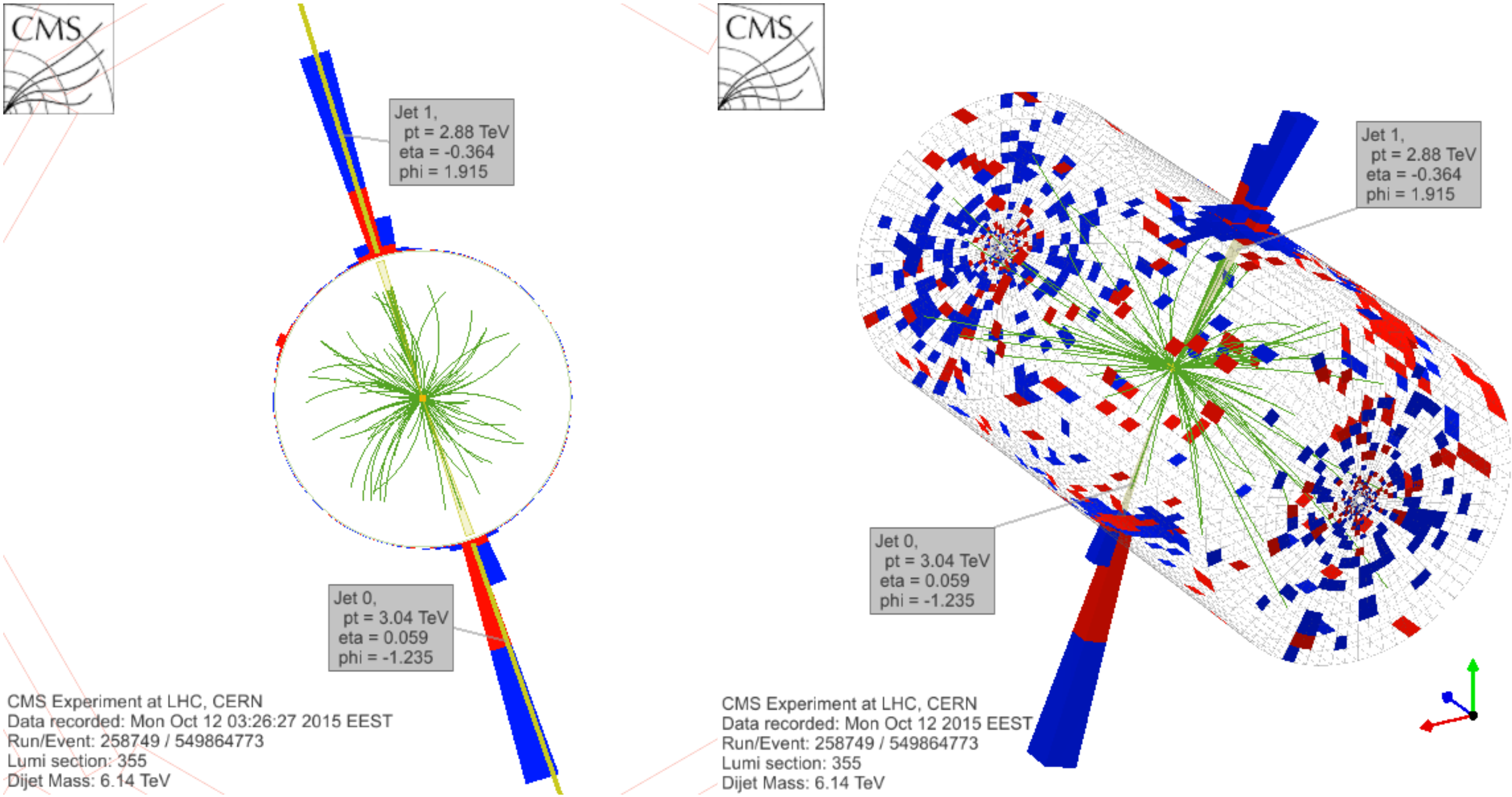
$$\Delta\eta_{12} = |\eta_{jet1} - \eta_{jet2}| = \ln\frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$



- $m_{jj} > 1.2$ TeV to ensure trigger fully efficient

HIGH MASS EVENT

- Highest dijet mass event $\mathbf{m_{jj} = 6.14}$ **TeV**



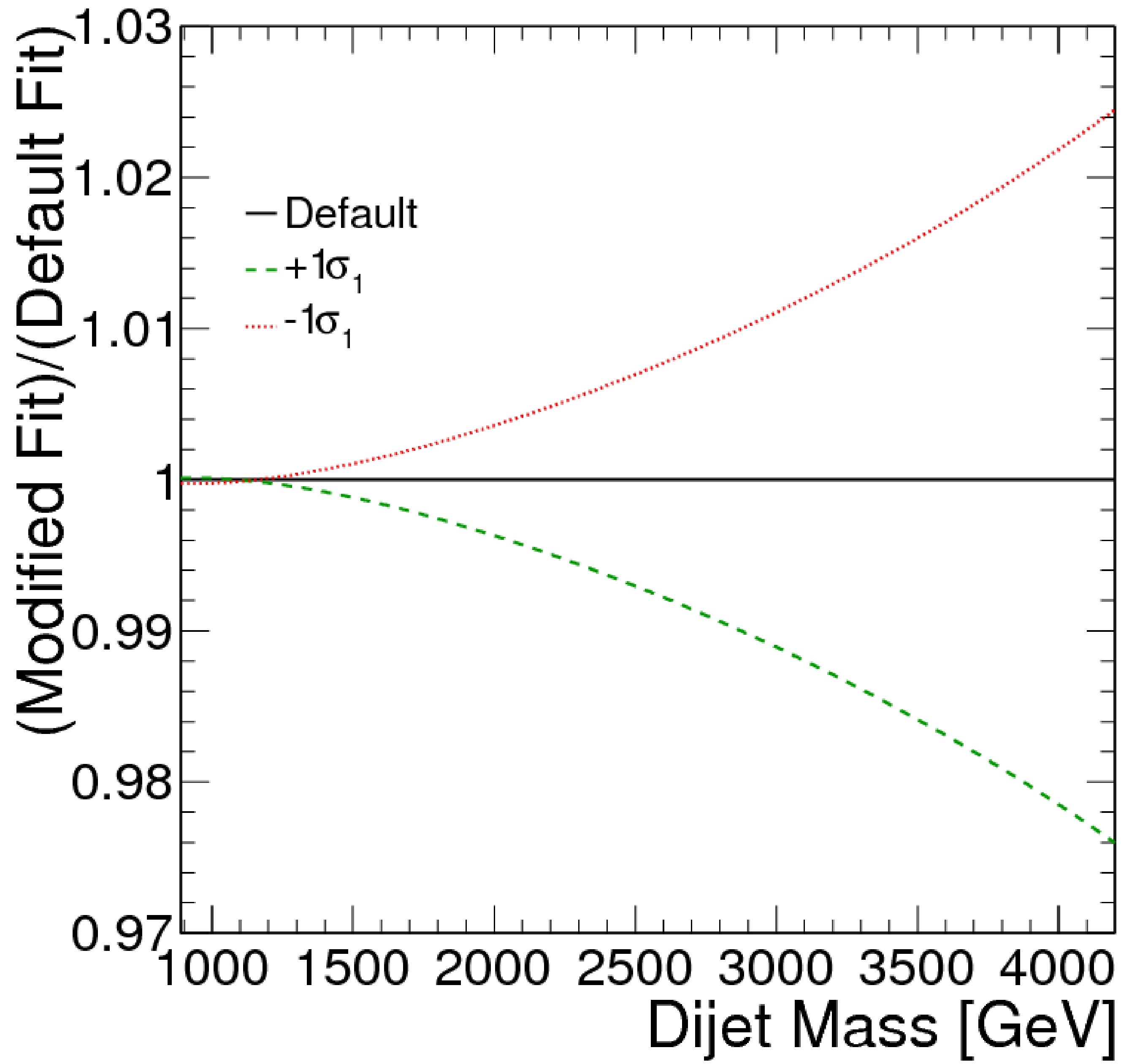
MODELING DIJET SPECTRUM

- Four-parameter empirical function to model dijet spectrum [1]:

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}, \quad x = m_{jj}/\sqrt{s}$$

- How do the parameters affect the shape?
  - Can look at the variations after diagonalizing the covariance matrix from a fit

LARGEST VARIATION AFFECTS THE CONCAVITY OF THE TAIL



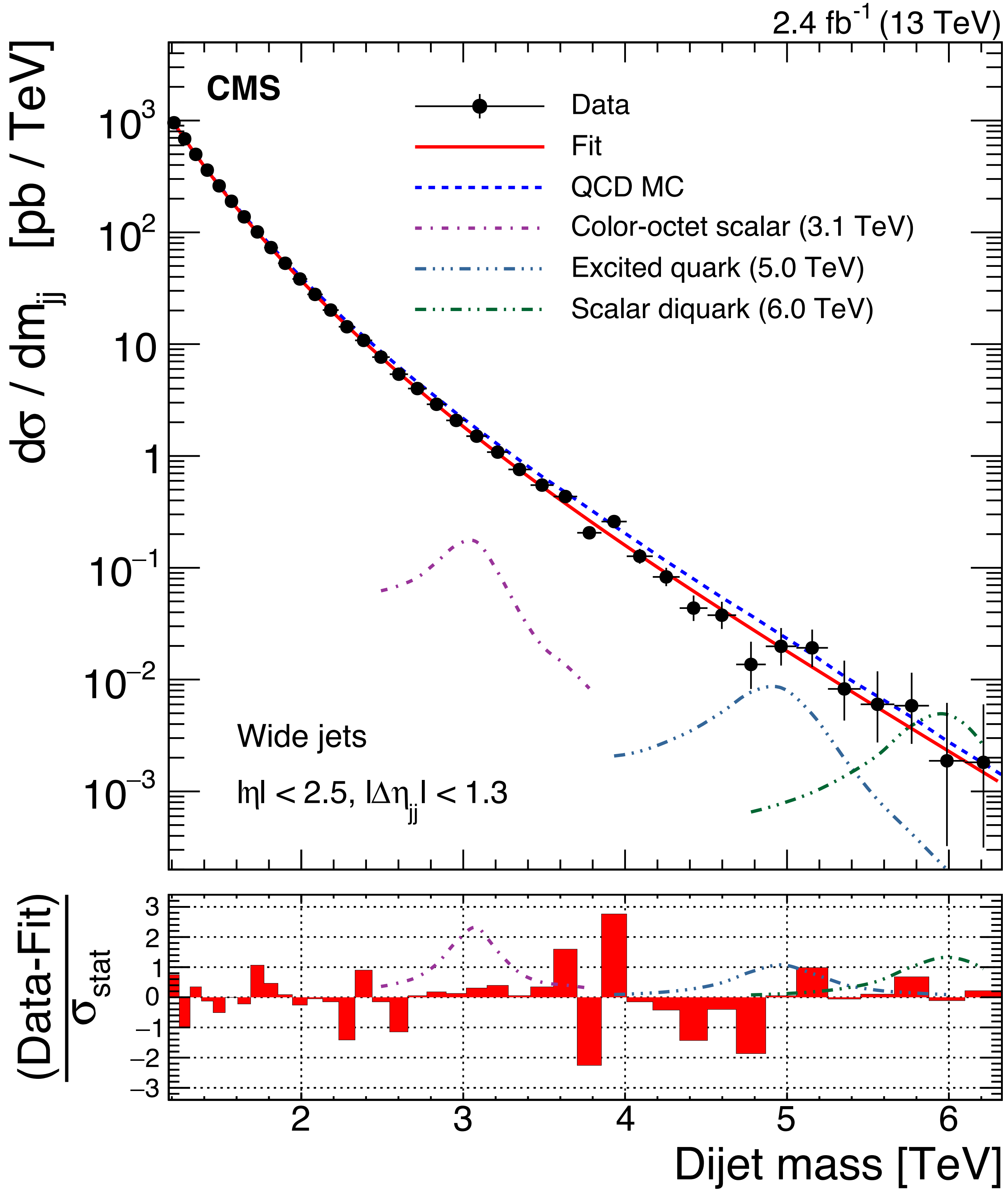
[1] Phys. Rev. D 79, 112002

Javier Duarte
Caltech

PRL 116 (2016) 071801

DIJET MASS FIT

- Dijet mass goodness of fit: $\chi^2 = 31$ for 35 degrees of freedom
- Four-parameter function fit (red solid curve)
- PYTHIA 8 QCD Monte Carlo (dashed blue curve)
- Three signal models with resonance masses corresponding to 95% CL exclusion limit (dash-dotted curves)
- Lower panel: difference between the data and the fitted parametrization, divided by the statistical uncertainty



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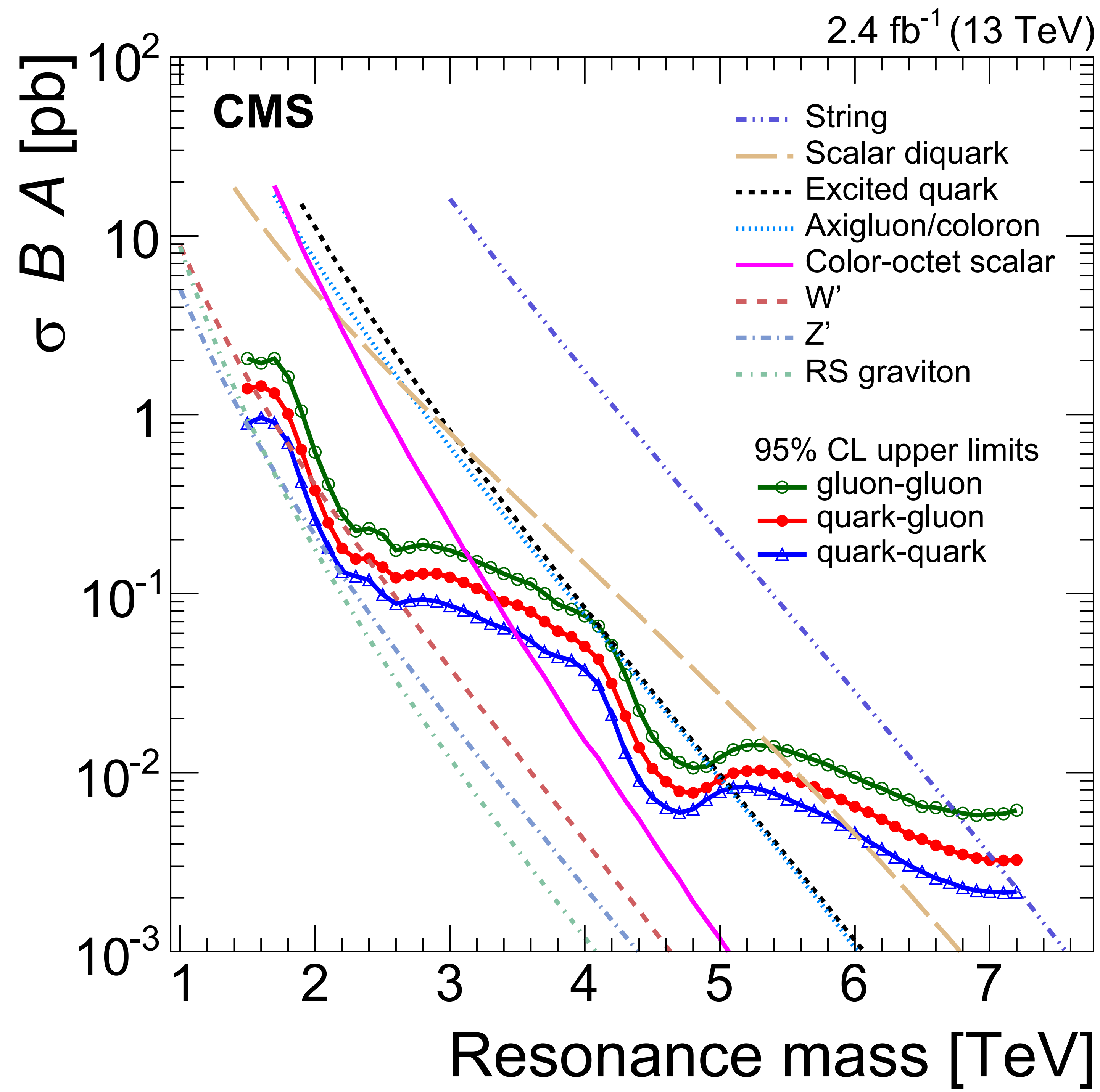
LIMITS

- Mass limits in Run 2 (13 TeV) show significant improvement in sensitivity over previous Run 1 (8 TeV) limits from CMS
- String resonances: 5.0 TeV → **7.0 TeV**
- Scalar diquarks: 4.7 TeV → **6.0 TeV**
- Axigluon/coloron: 3.6 TeV → **5.1 TeV**

Model	Final state	Observed mass limit [TeV]	Expected 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

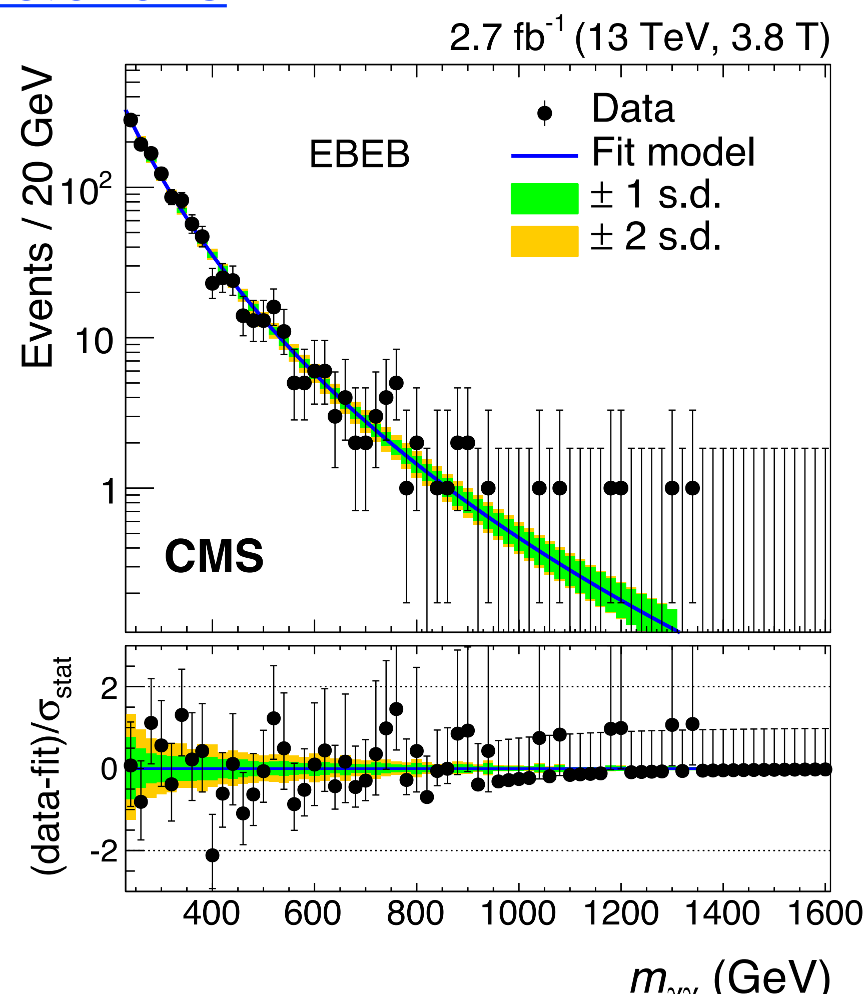


Q: WHAT ABOUT 750 GEV?

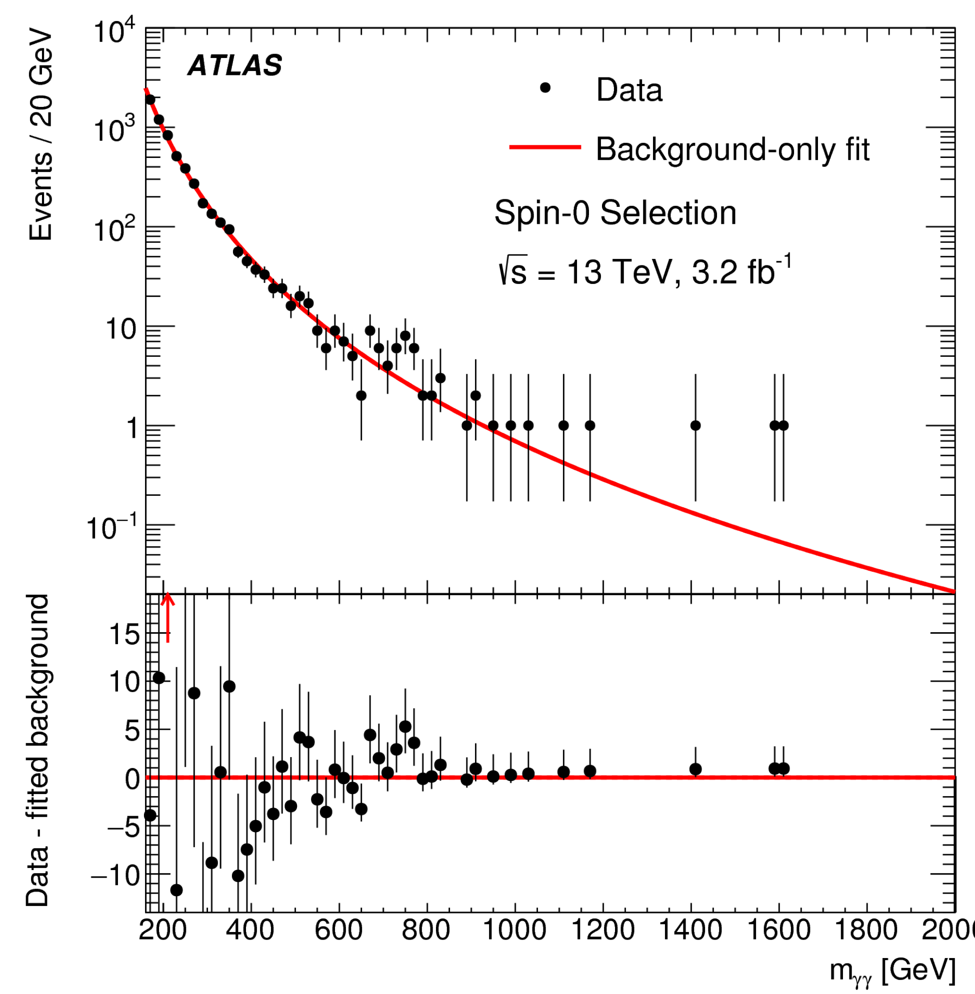
- Possible resonance seen at 750 GeV in diphotons; could expect 10-10^3× more events in dijets
- To record events with ~100% trigger efficiency down to m_{jj} ~ 500 GeV need to trigger at least H_T > 400 GeV

$$\boxed{BR(X \to JJ)/BR(X \to \gamma\gamma) \sim (\alpha_S/\alpha)^2(Q_S/Q)^4 \sim 10 - 10^3}$$

arXiv:1606.04093



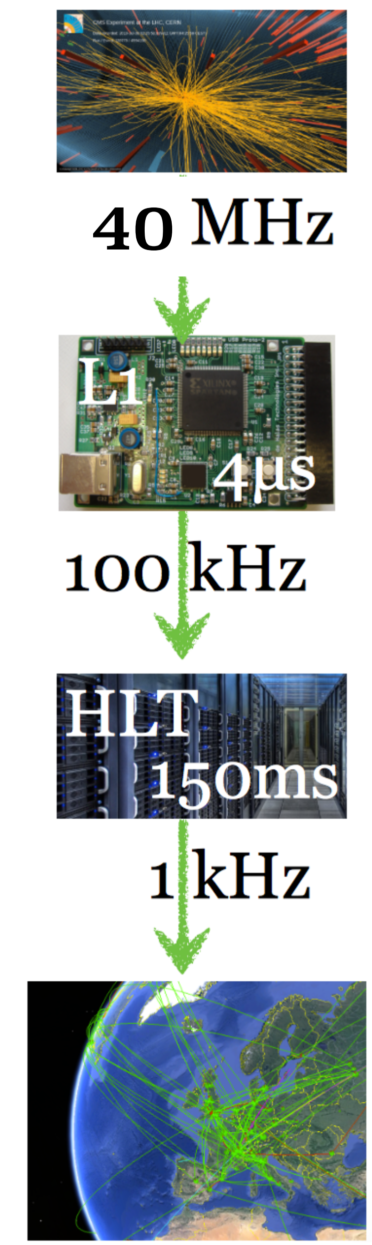
arXiv:1606.03833



TRIGGER SYSTEM

CMS

- How can we trigger down to $H_T > 400$ GeV?
- Two limitations:
  - Bandwidth = event rate × event size limited by read-out of O(100M) detector channels, disk storage, and everyone else's favorite physics channel
  - CPU time limited by computing resources for online reconstruction



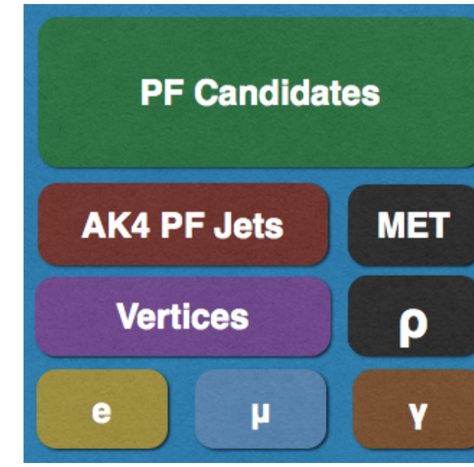
H. Brun, LP 2015

Total Reco.
BW: 1 kHz × 1 MB
CPU time: 150 ms

A: DATA SCOUTING

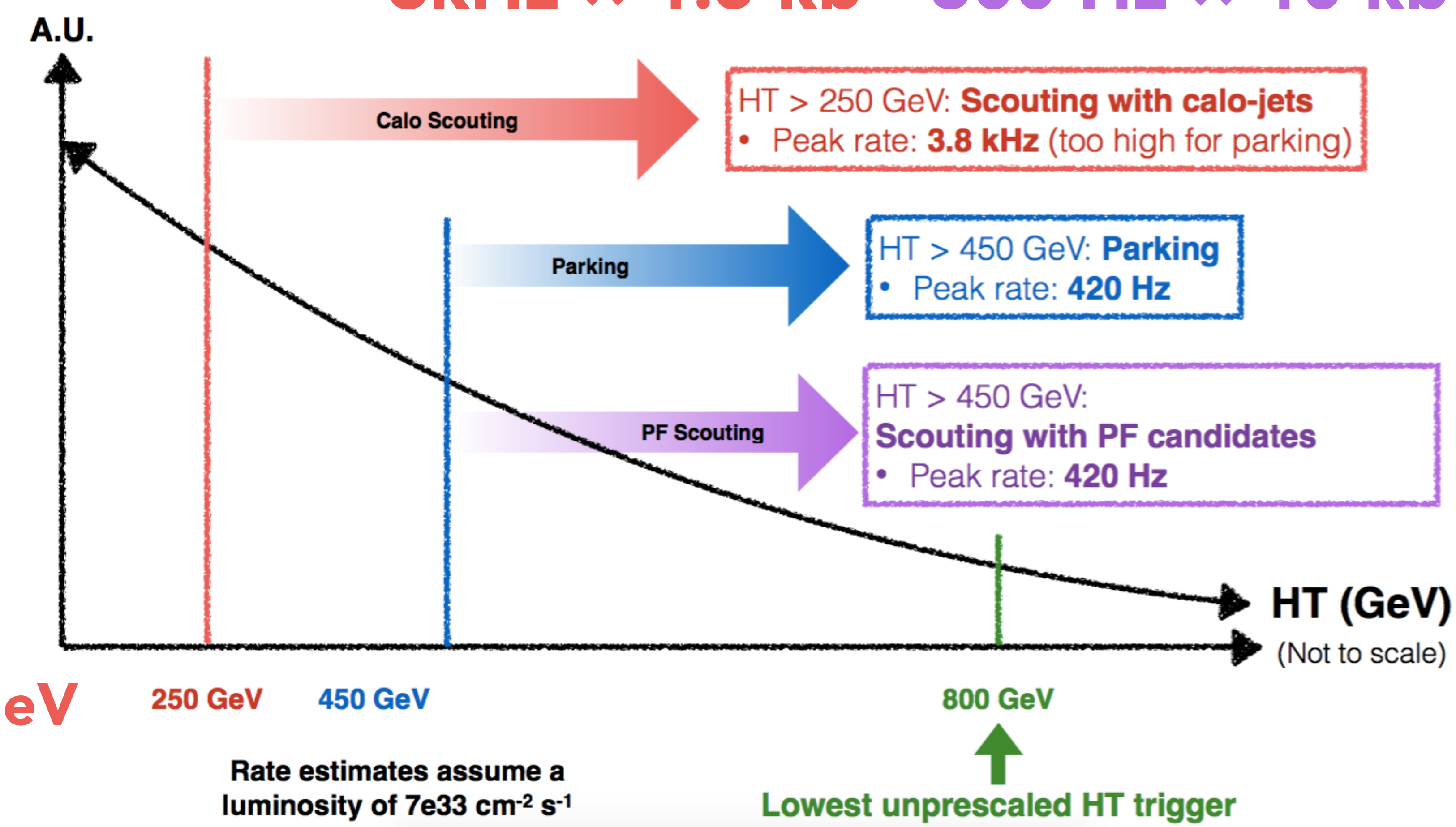
[D. Anderson "Data Scouting at CMS" 2015 IEEE NSS/MIC]

- Technique of data scouting (implemented in 8 TeV and 13 TeV LHC runs)
  - Reconstruct/save only necessary information to perform analysis → record more events
  - "**PF Scouting**" limited by CPU time: allows us to get down to H_T > 450 GeV
  - **Improved in 2015:** "**Calo Scouting**" allows us to get down to **H_T > 250 GeV**
  - **New in 2016:** Saving tracking information around Calo jets to allow us to perform b-tagging down to **H_T > 250 GeV**



Calo Scouting
3kHz × 1.5 kb

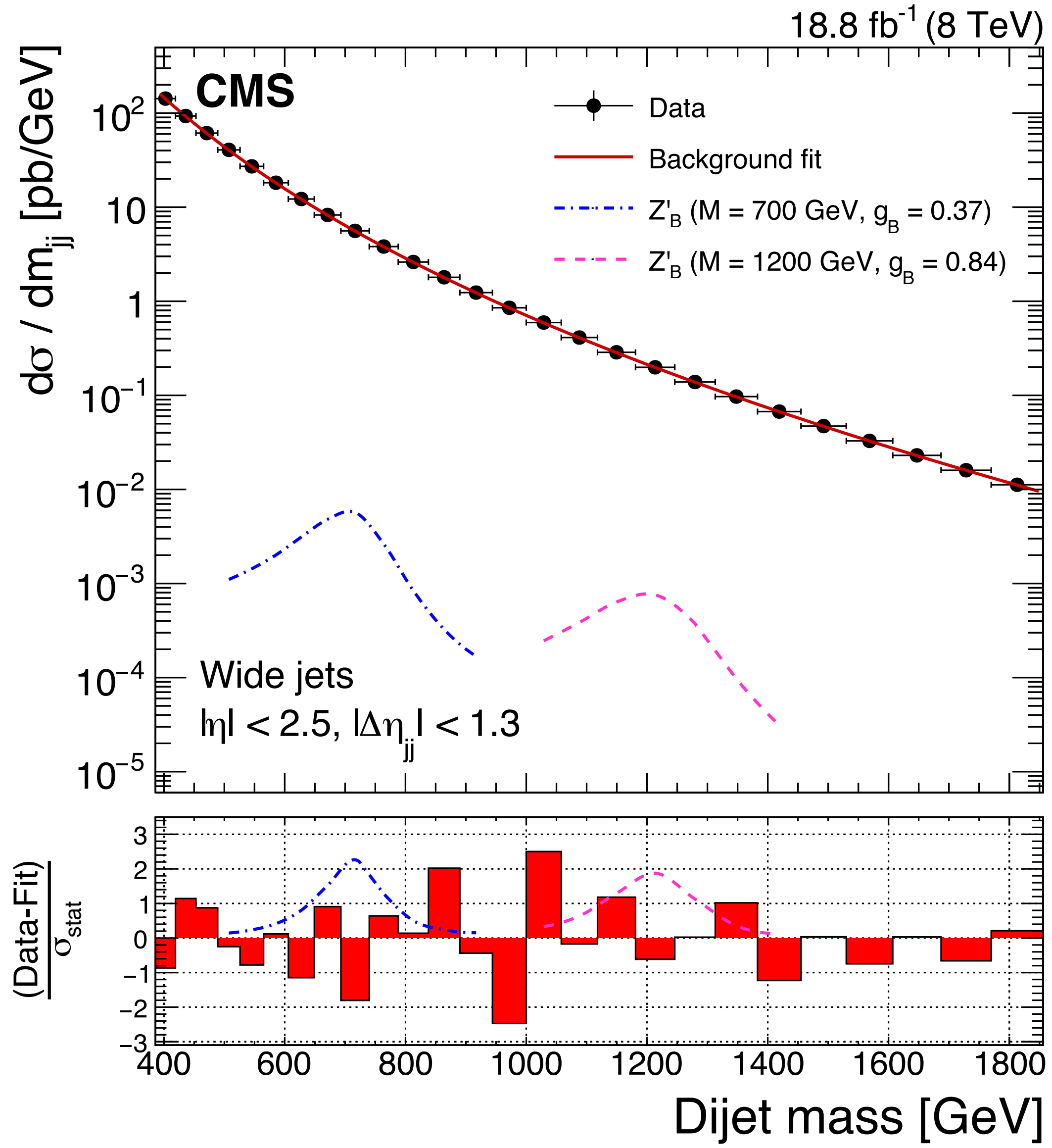
PF Scouting
300 Hz × 10 kb

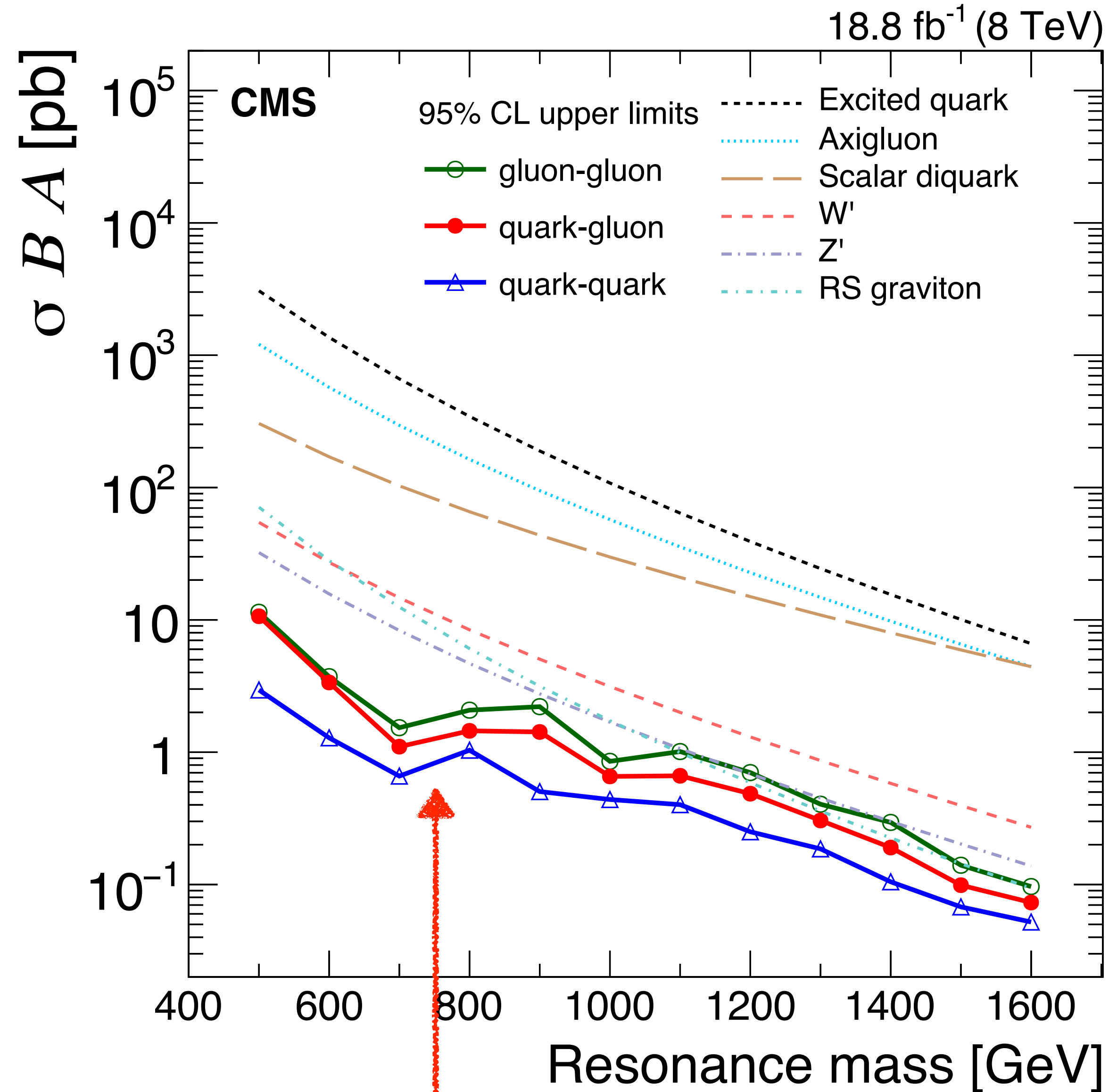


arXiv:1604.08907

RUN 1 DATA SCOUTING RESULT

- Run 1 result already provides constraint at 750 GeV!



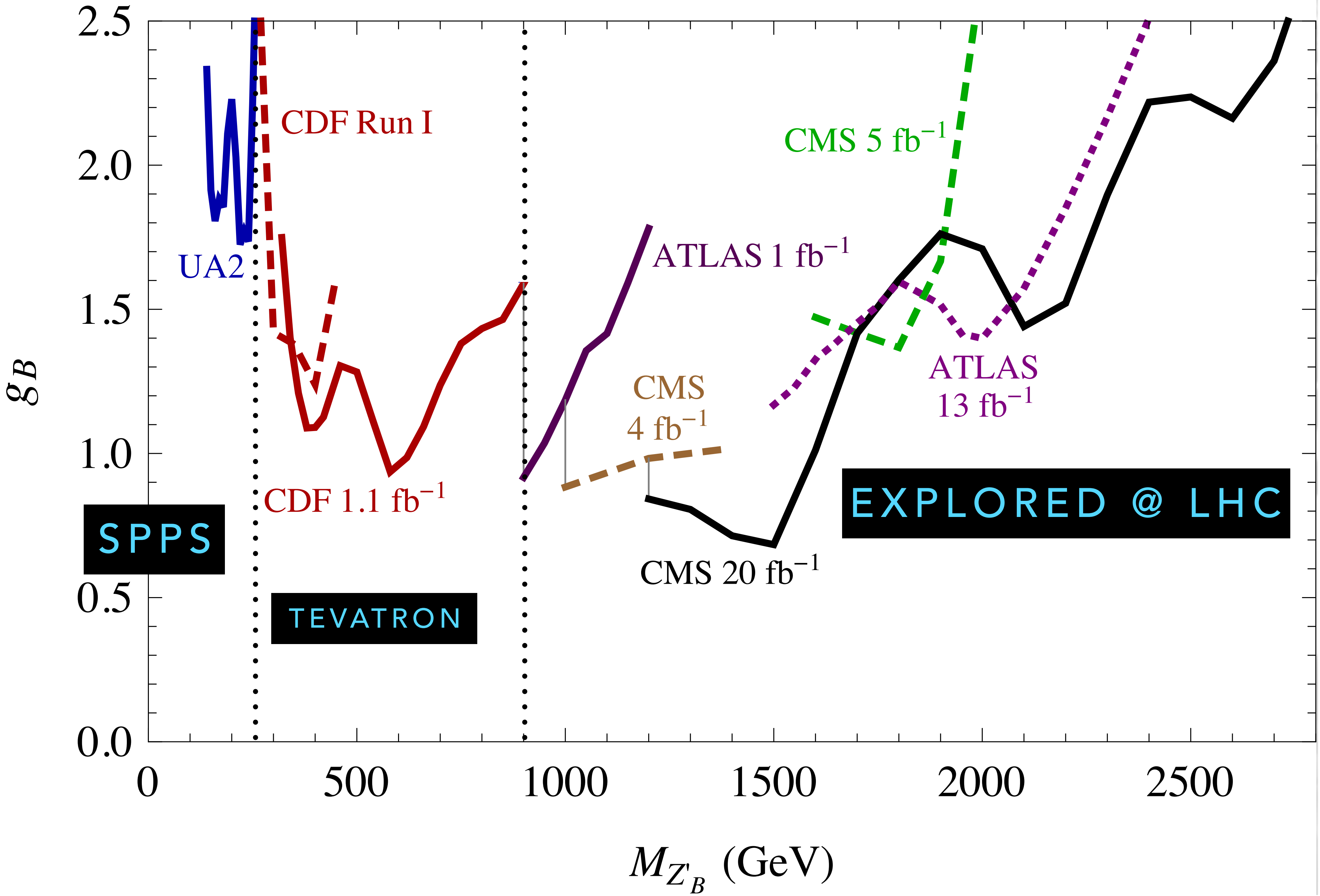


limit ~1-3 pb at 750 GeV
depending on gg or qq

BEFORE DATA SCOUTING

arXiv:1306.2629

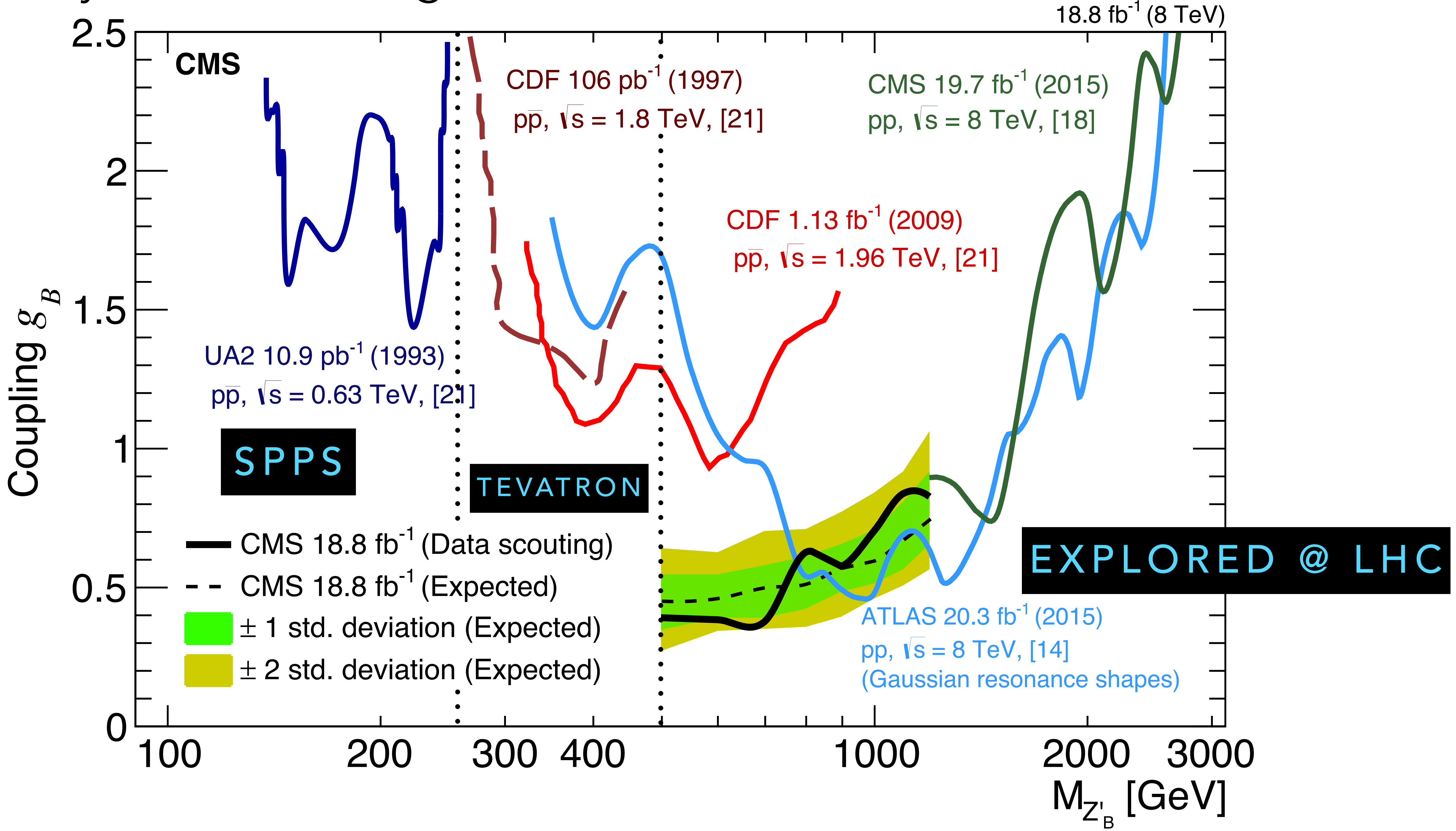
- Run 1 result also extends sensitivity to Z′ in coupling-mass plane to previously uncovered regions!



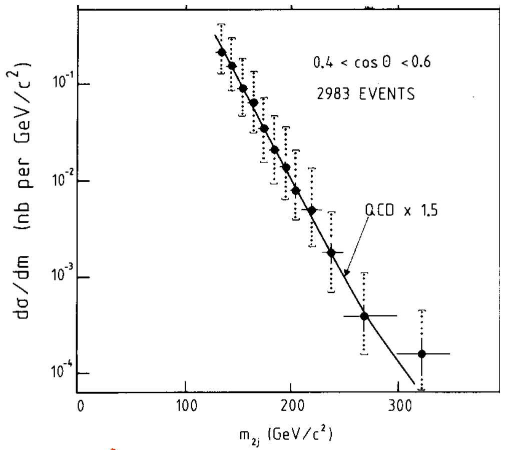
arXiv:1604.08907

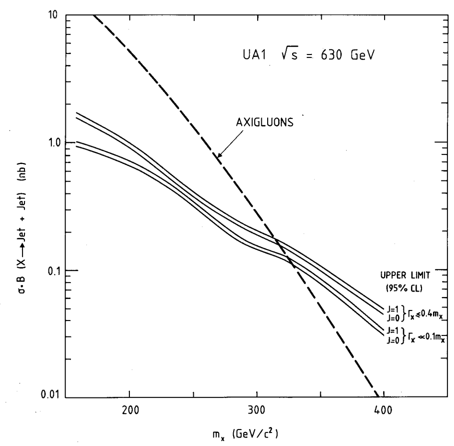
AFTER DATA SCOUTING

- Run 1 result also extends sensitivity to Z′ in coupling-mass plane to previously uncovered regions!

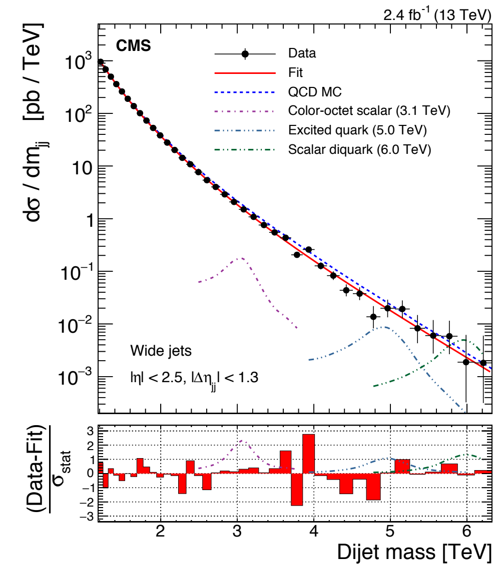


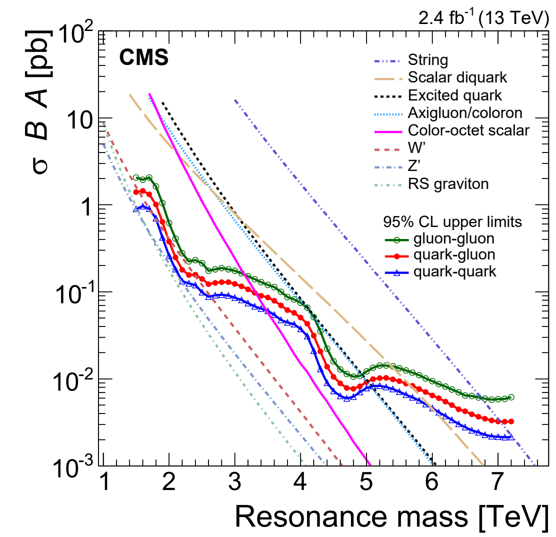
TIME IS A FLAT CIRCLE

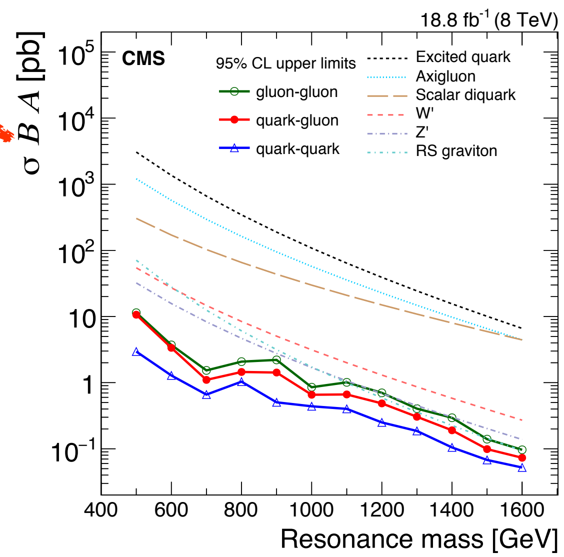


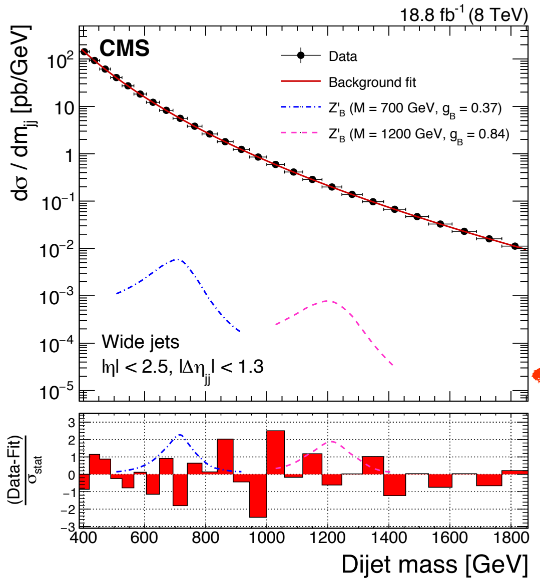


higher
energy







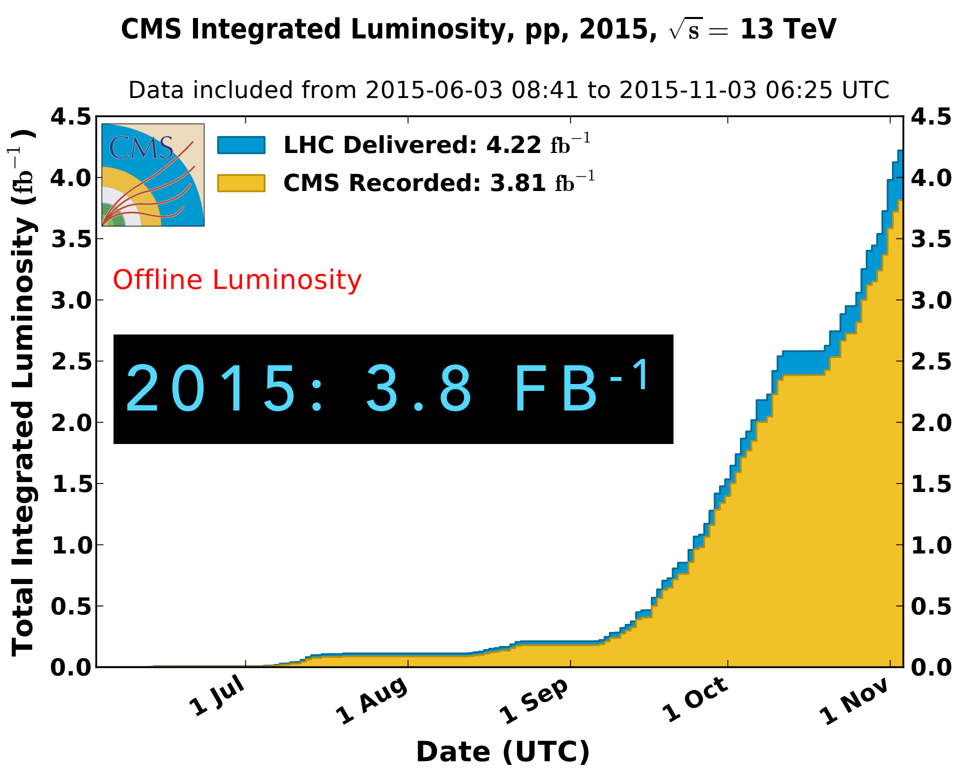


data
scouting

Javier Duarte
Caltech

SUMMARY AND OUTLOOK

- No evidence for new phenomena… yet
- Stringent limits on many new physics models from dijet searches with 2012 and 2015 data
- Data scouting technique allows us to probe lower in the dijet spectrum
- 2016 13 TeV run is ongoing! Lots of data collected
- Search for resonances at low mass (including 750 GeV) with **2015** and **2016** 13 TeV data forthcoming!



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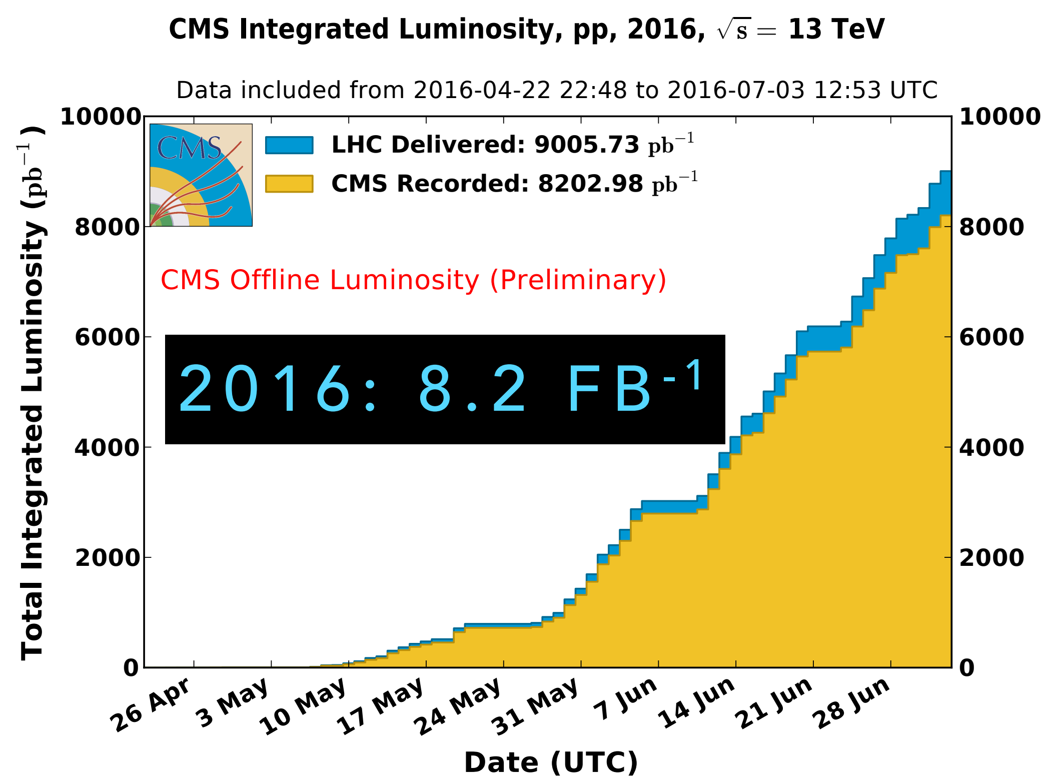
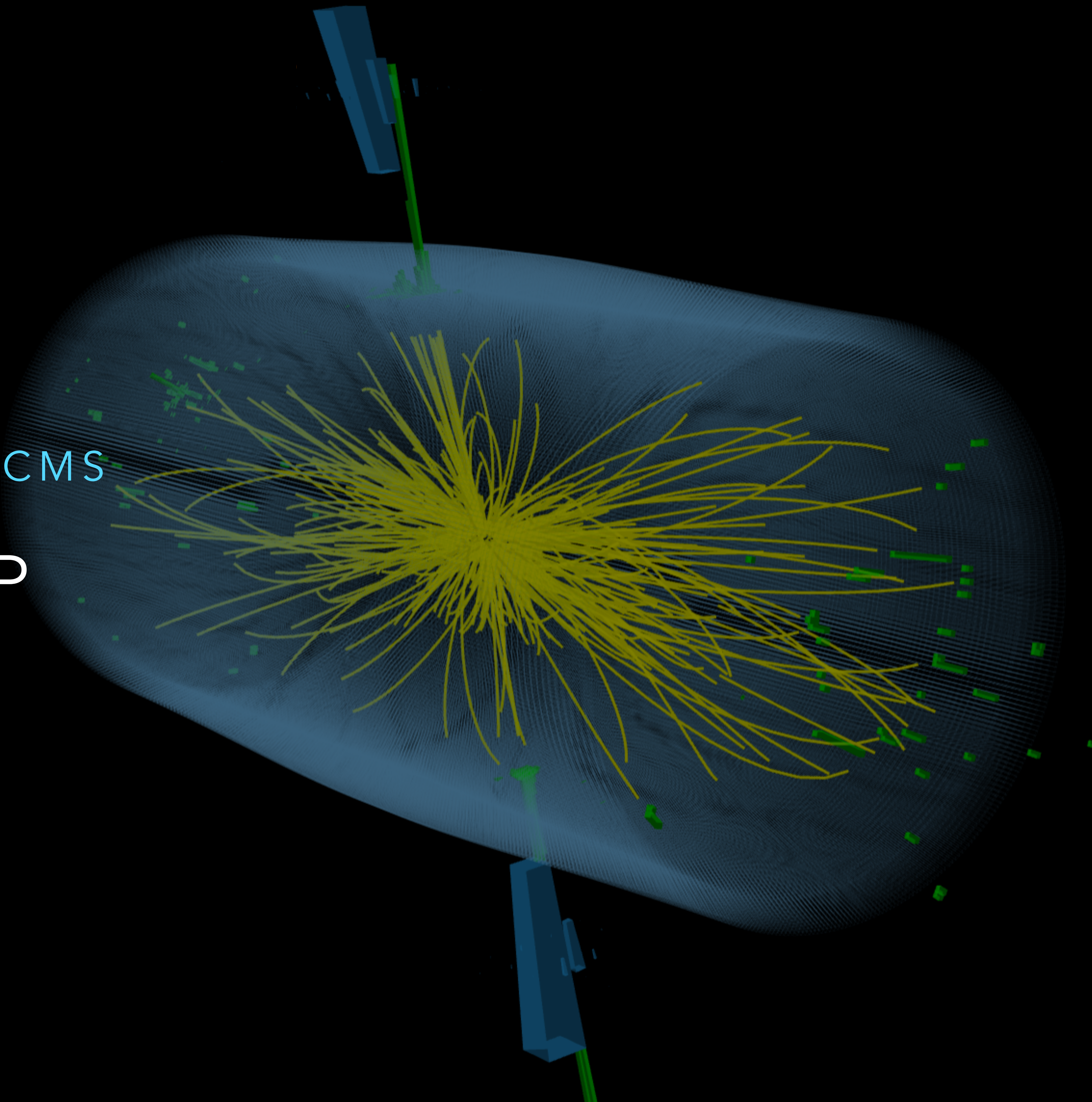


SEARCHES @ CMS

BACKUP



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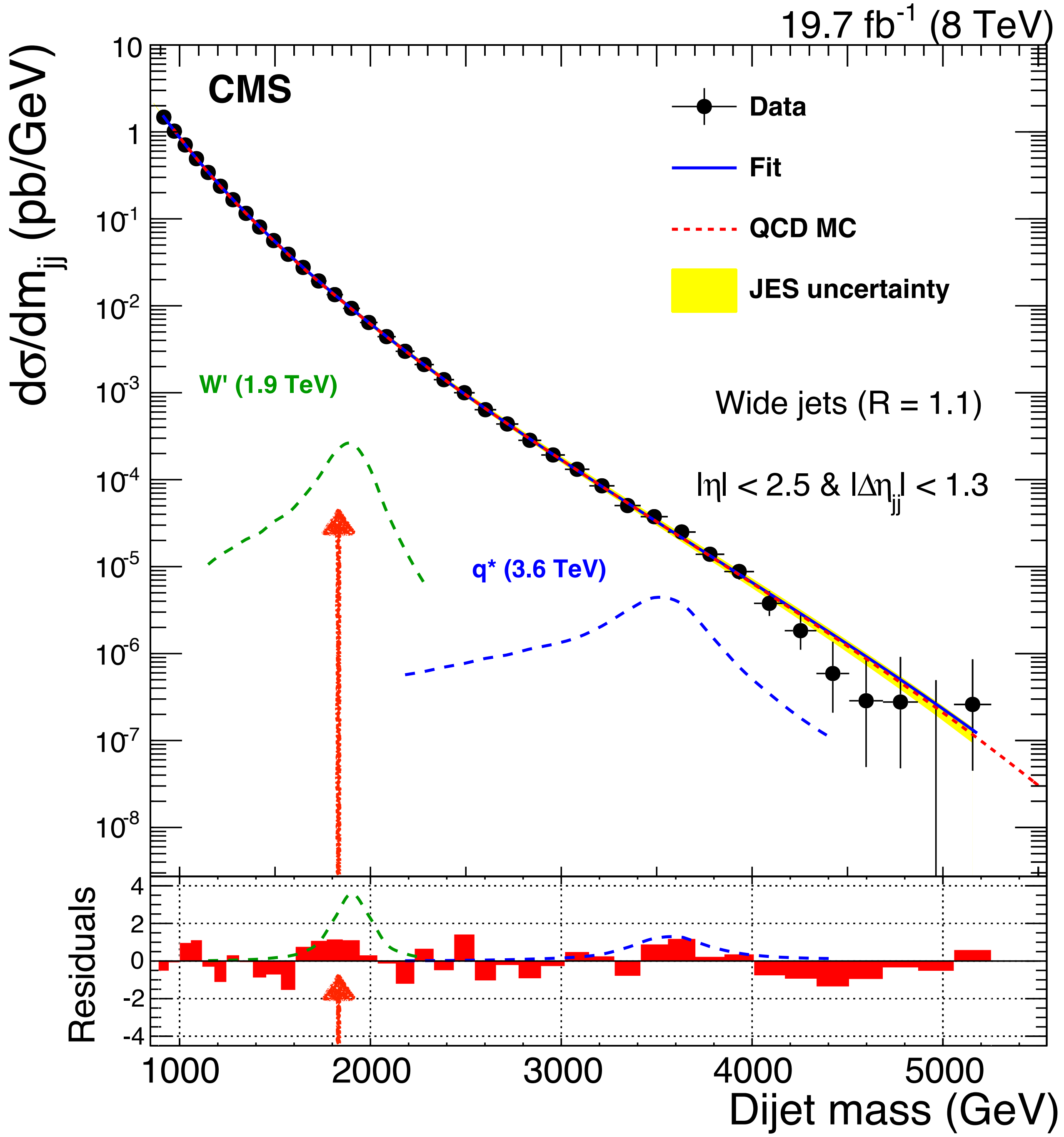
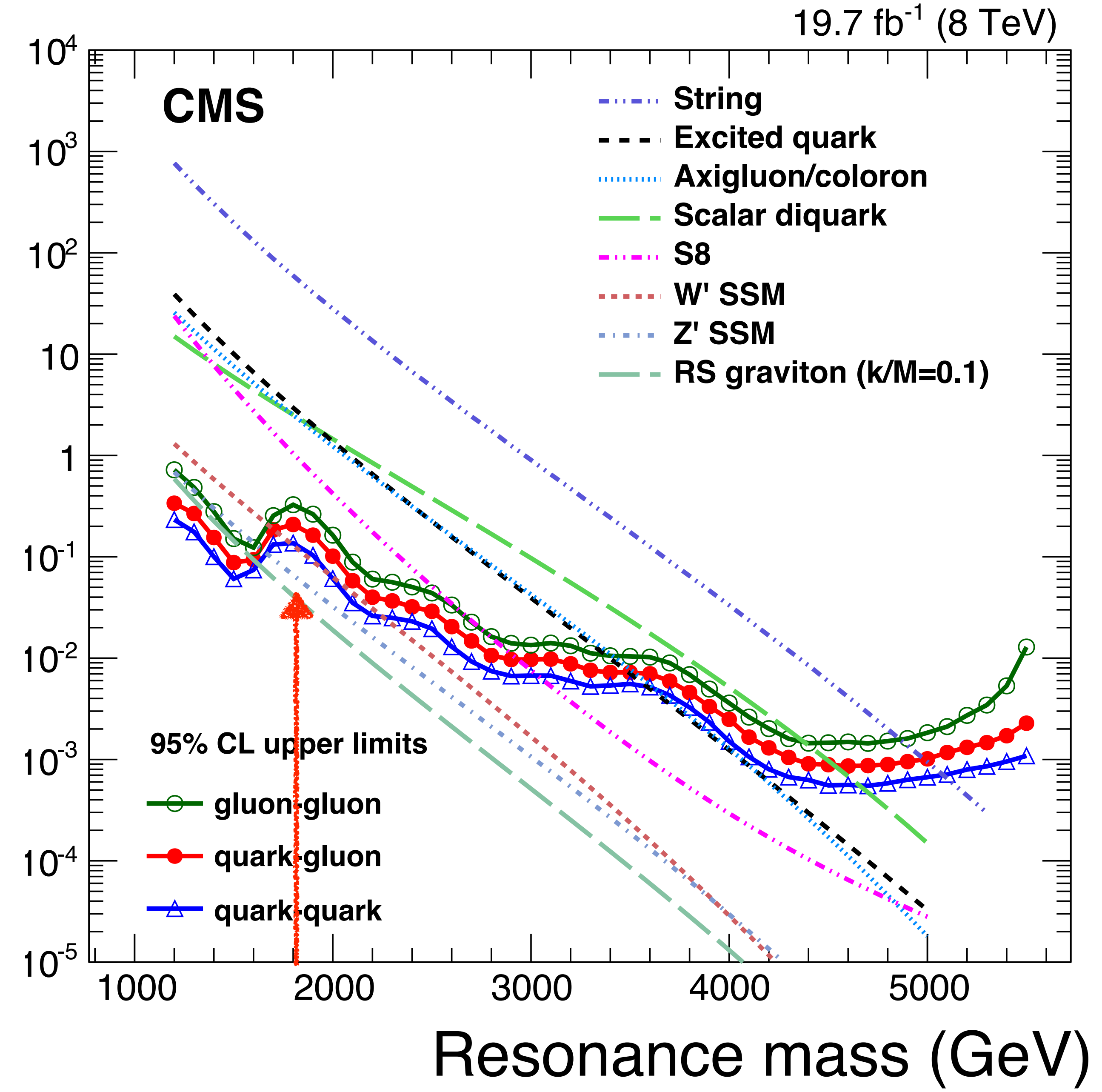
Q: WHAT ABOUT 2 TEV?

- Slight excess seen in dijets at ~2 TeV in Run 1 (also in dibosons)
- Not confirmed in Run 2





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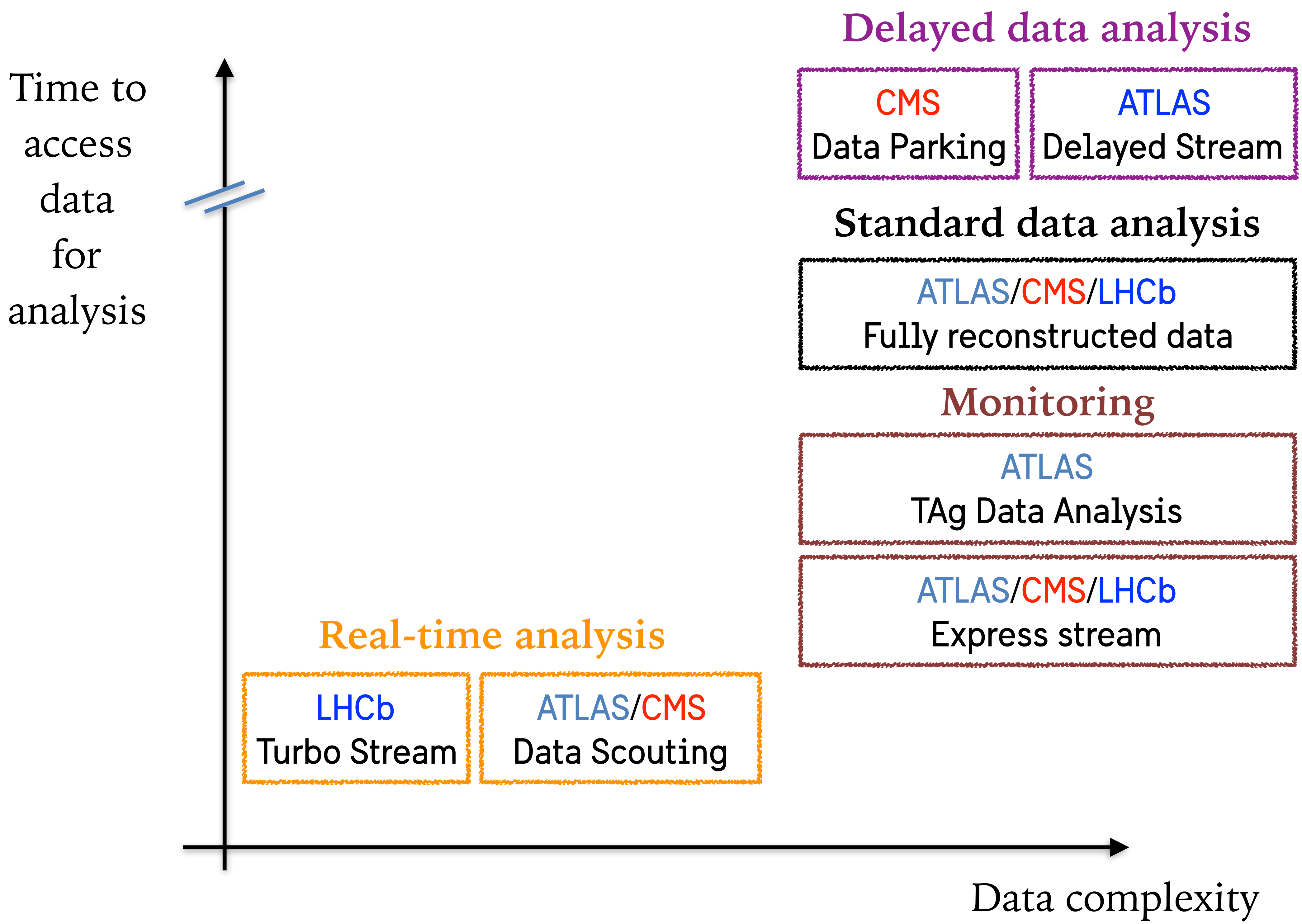
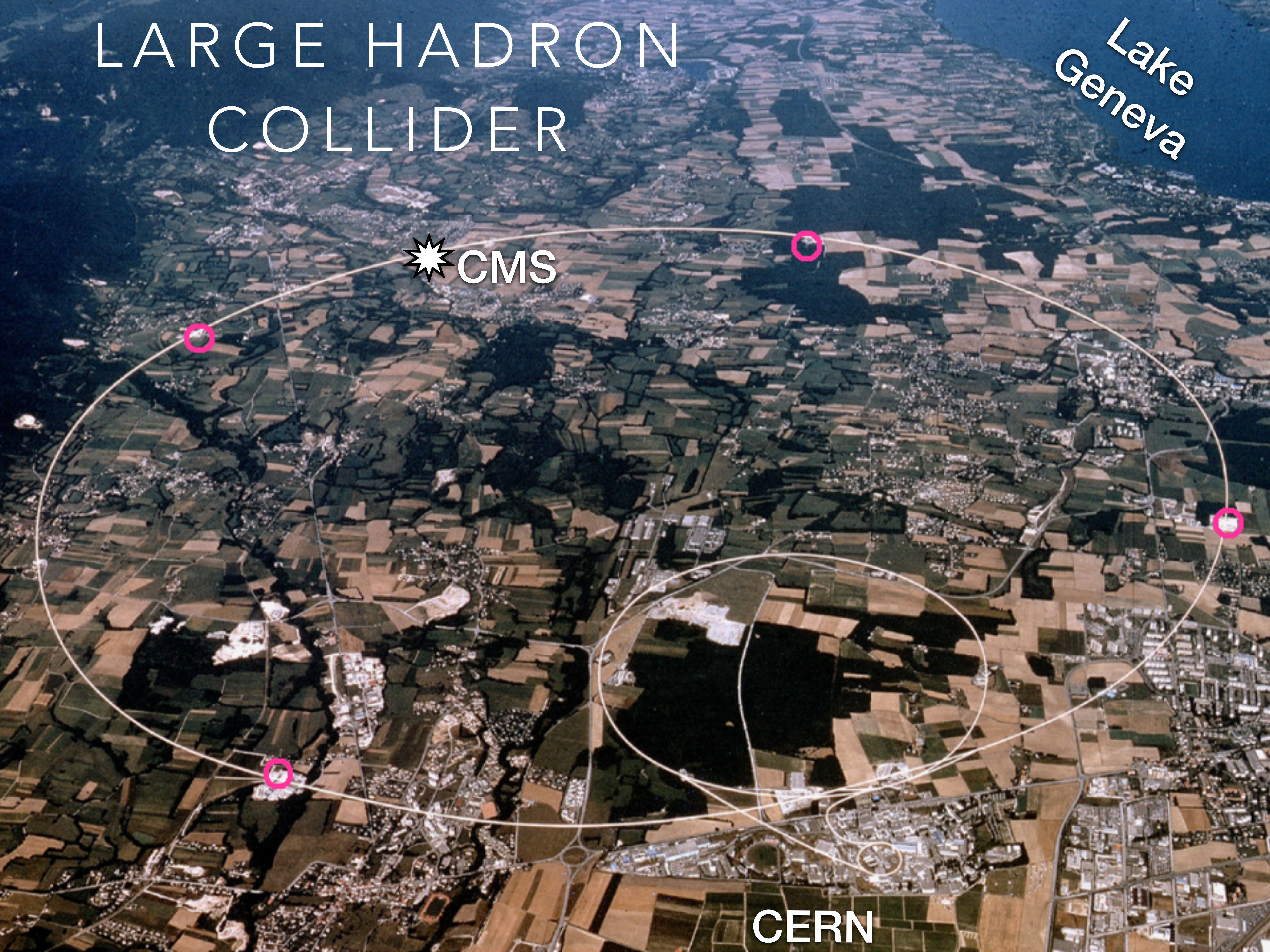
SIGNAL MODELS

- String resonances (S), which are Regge excitations of quarks and gluons in string theory and decay predominantly to qg [1, 2].
- Scalar diquarks (D), which decay to qq and $\overline{\mathrm{q}}\overline{\mathrm{q}}$, predicted by a grand unified theory based on the E_6 gauge symmetry group [3].
- Mass-degenerate excited quarks (q^*), which decay to qg, predicted in quark compositeness models [4, 5]; the compositeness scale is set to be equal to the mass of the excited quark.
- Axial-vector particles called axigluons (A), which decay to $\mathrm{q}\overline{\mathrm{q}}$, predicted in a model where the symmetry group SU(3) of QCD is replaced by the chiral symmetry $\mathrm{SU}(3)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{R}$ [6].
- Color-octet colorons (C), which also decay to $\mathrm{q}\overline{\mathrm{q}}$; these are vector particles predicted by the flavour-universal coloron model, in which the SU(3) gauge symmetry of QCD is embedded in a larger gauge group [7].
- Scalar color-octet resonances (S8) [8] that appear in many dynamical electroweak symmetry breaking models such as Technicolor. We consider the decay channel into a pair of gluons.
- Massive scalar color-octet resonances ($\mathrm{S8_b}$) [9] that result from the breaking of an $\mathrm{SU}(3) \times \mathrm{SU}(3)$ gauge symmetry down to the QCD gauge group and that may have generically large couplings to b quarks. We consider the production of a coloron that subsequently decays into an $\mathrm{S8_b}$ and a light scalar singlet. We fix the singlet mass to 150 GeV. The $\mathrm{S8_b}$ and scalar singlet have branching fractions (B) of approximately 100% to $\mathrm{b}\overline{\mathrm{b}}$ and gg, respectively. The tangent of the mixing angle θ between the two SU(3) gauges is set to 0.15. This resonance search is inclusive of extra jets, so the search strategy is insensitive to the decay of the low-mass singlet state.
- New gauge bosons (W' and Z'), that decay to $\mathrm{q}\overline{\mathrm{q}}$, predicted by models that include new gauge symmetries [10]; the W' and Z' bosons are assumed to have standard-model-like couplings. Consequently, the ratio between the branching fraction of the Z' to $\mathrm{b}\overline{\mathrm{b}}$ and the branching fraction to a pair of quarks (excluding the top quark) is approximately 0.22.
- Randall-Sundrum (RS) gravitons (G), which decay to $\mathrm{q}\overline{\mathrm{q}}$ and gg, predicted in the RS model of extra dimensions [11]. The value of the dimensionless coupling $k/\overline{M}_\mathrm{Pl}$ is chosen to be 0.1, where k is the curvature scale in the 5-dimensional anti de Sitter space and $\overline{M}_\mathrm{Pl}$ is the reduced Planck scale. The ratio between the branching fraction of the RS graviton to $\mathrm{b}\overline{\mathrm{b}}$ and the branching fraction to a pair of quarks (excluding the top quark) or gluons is approximately 0.1 [12].

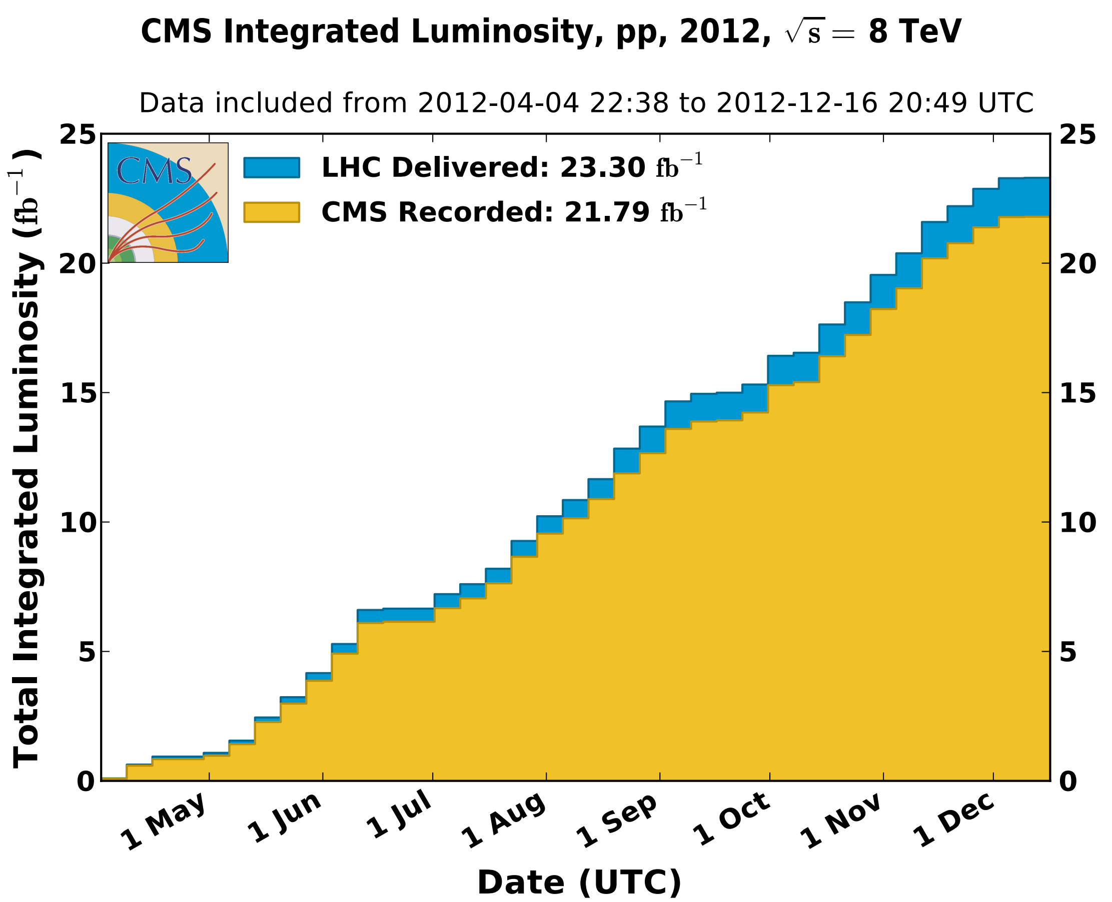
DATA SCOUTING

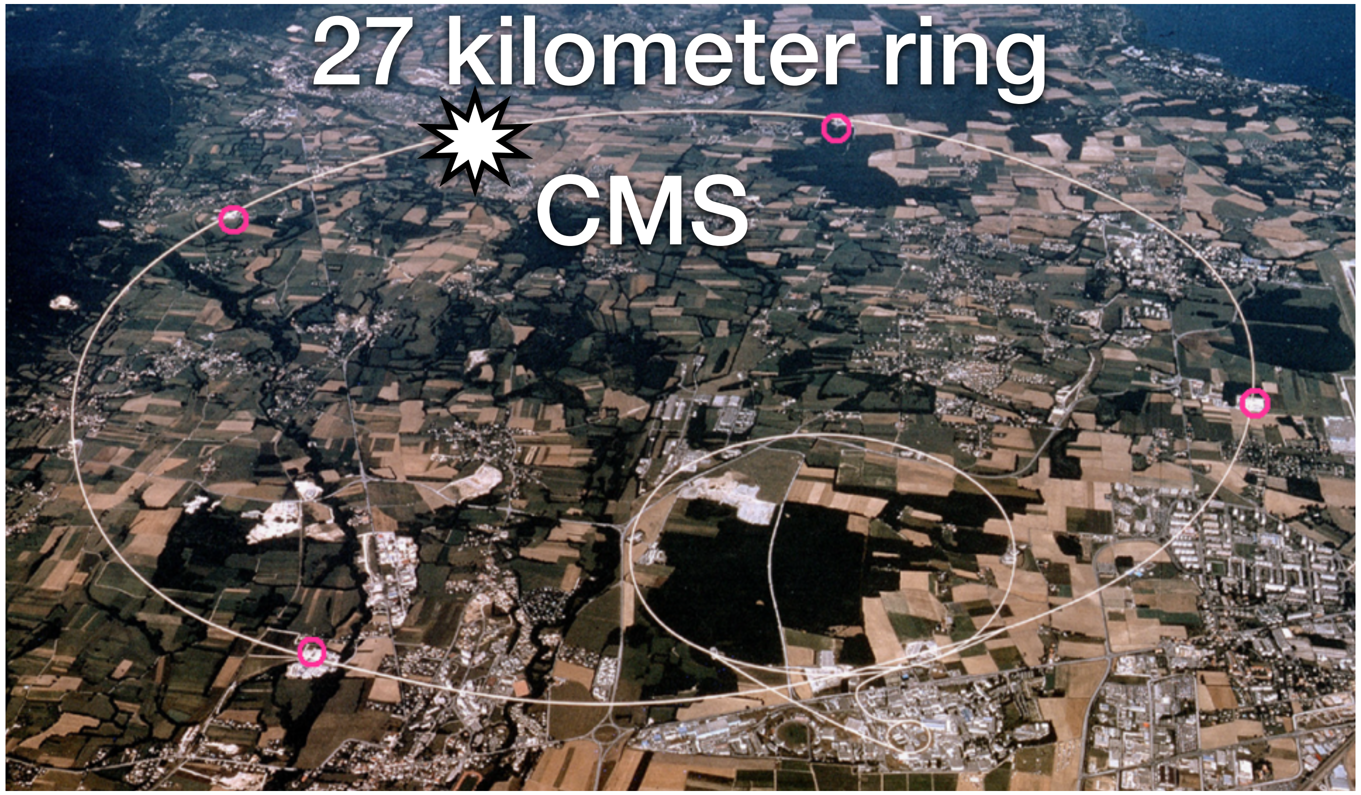



LARGE HADRON
COLLIDER
Lake
Geneva
CMS
CERN

LARGE HADRON COLLIDER

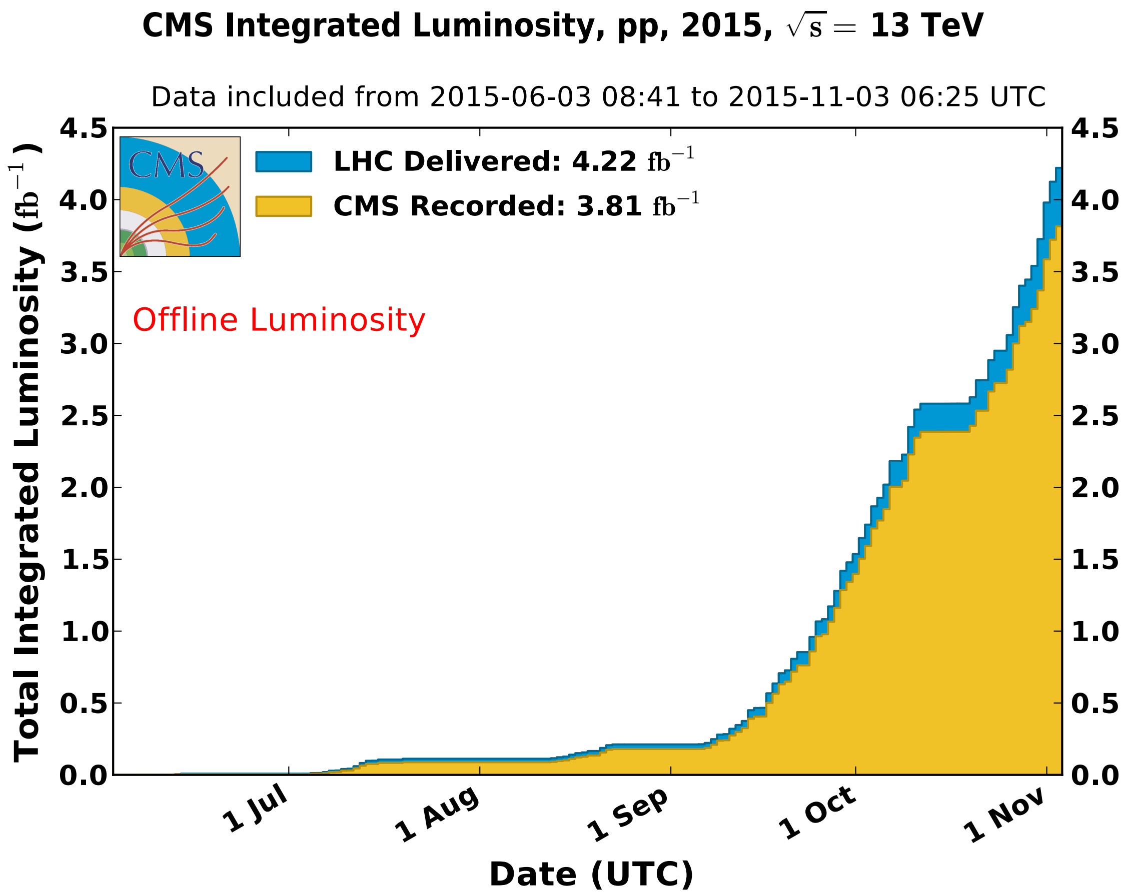
- Proton-proton collisions at 8 TeV in 2012

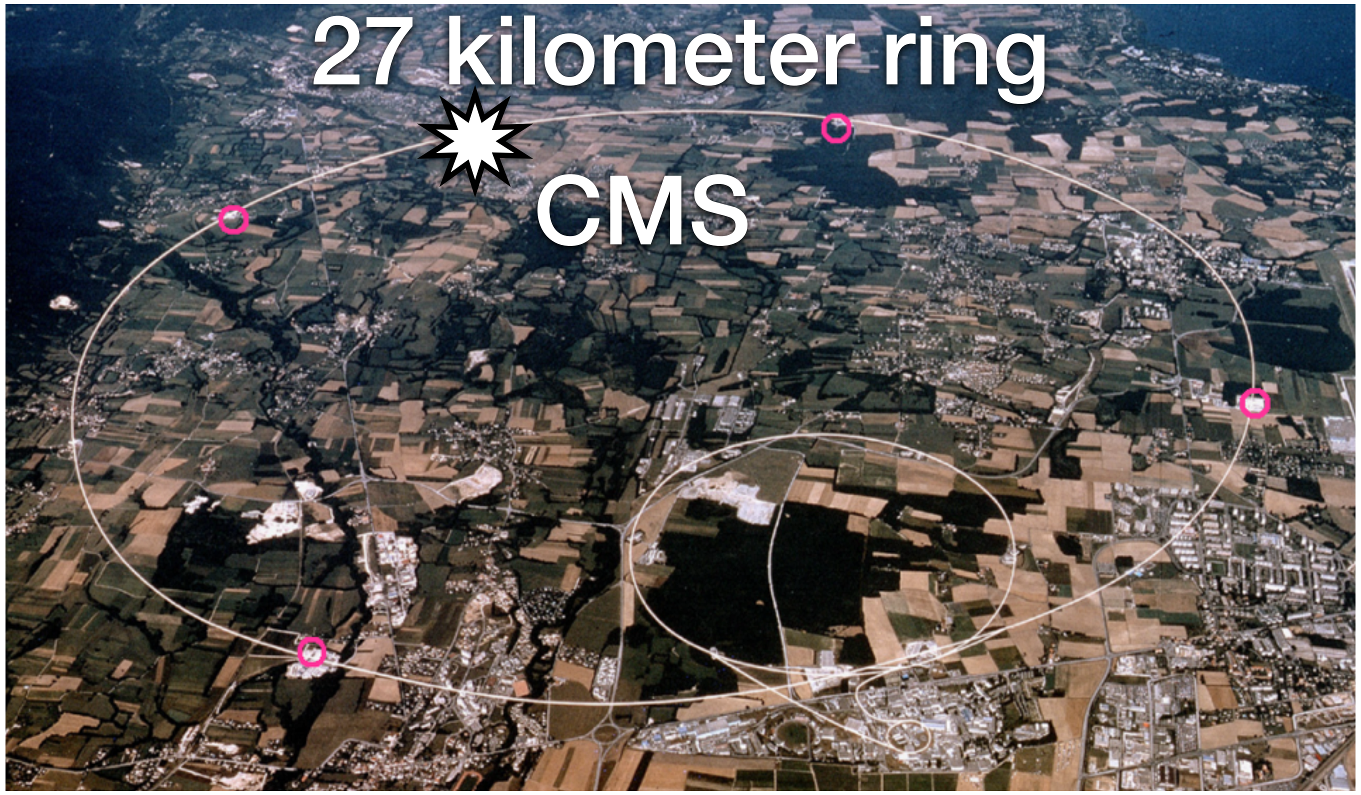




LARGE HADRON COLLIDER

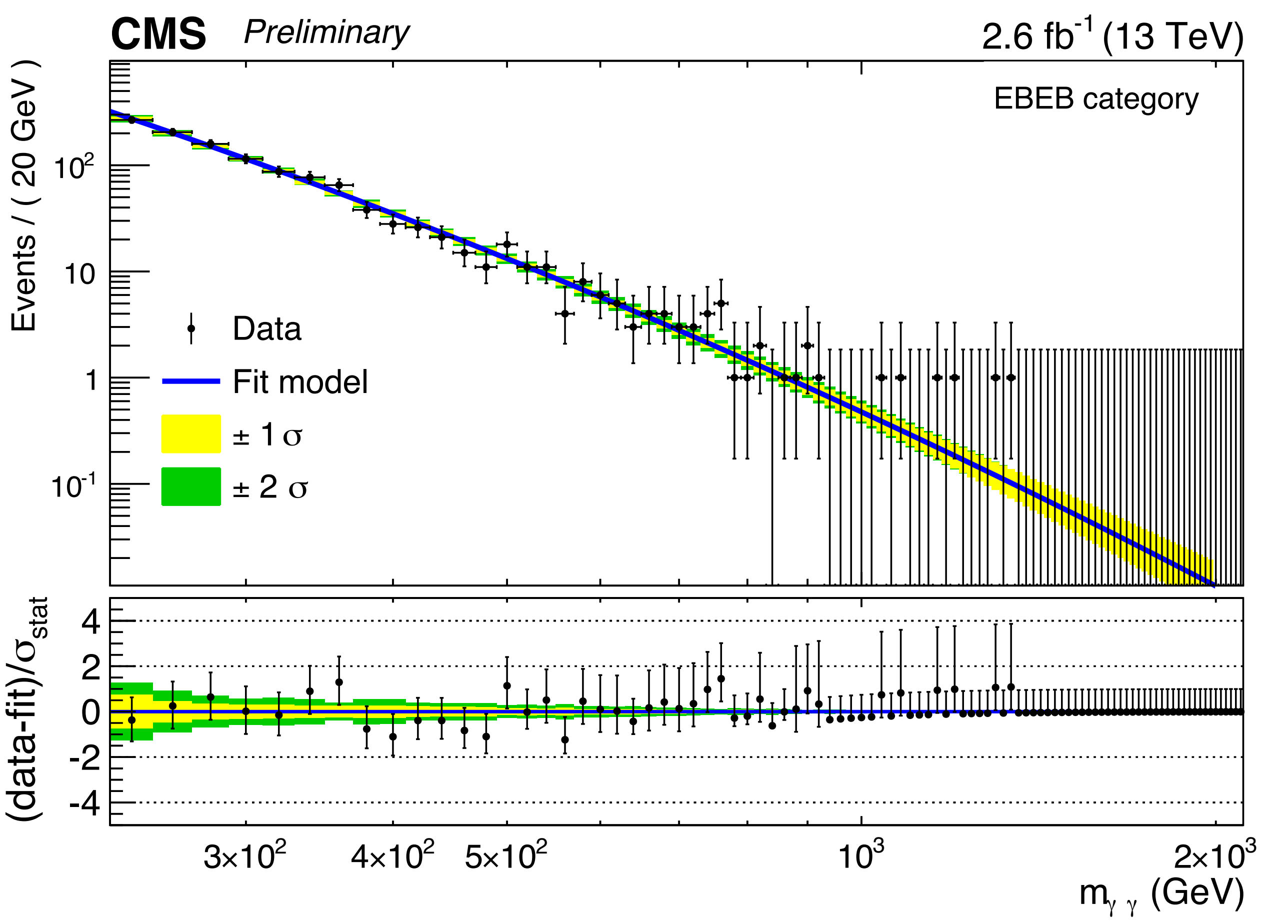
- Proton-proton collisions at 13 TeV in 2015

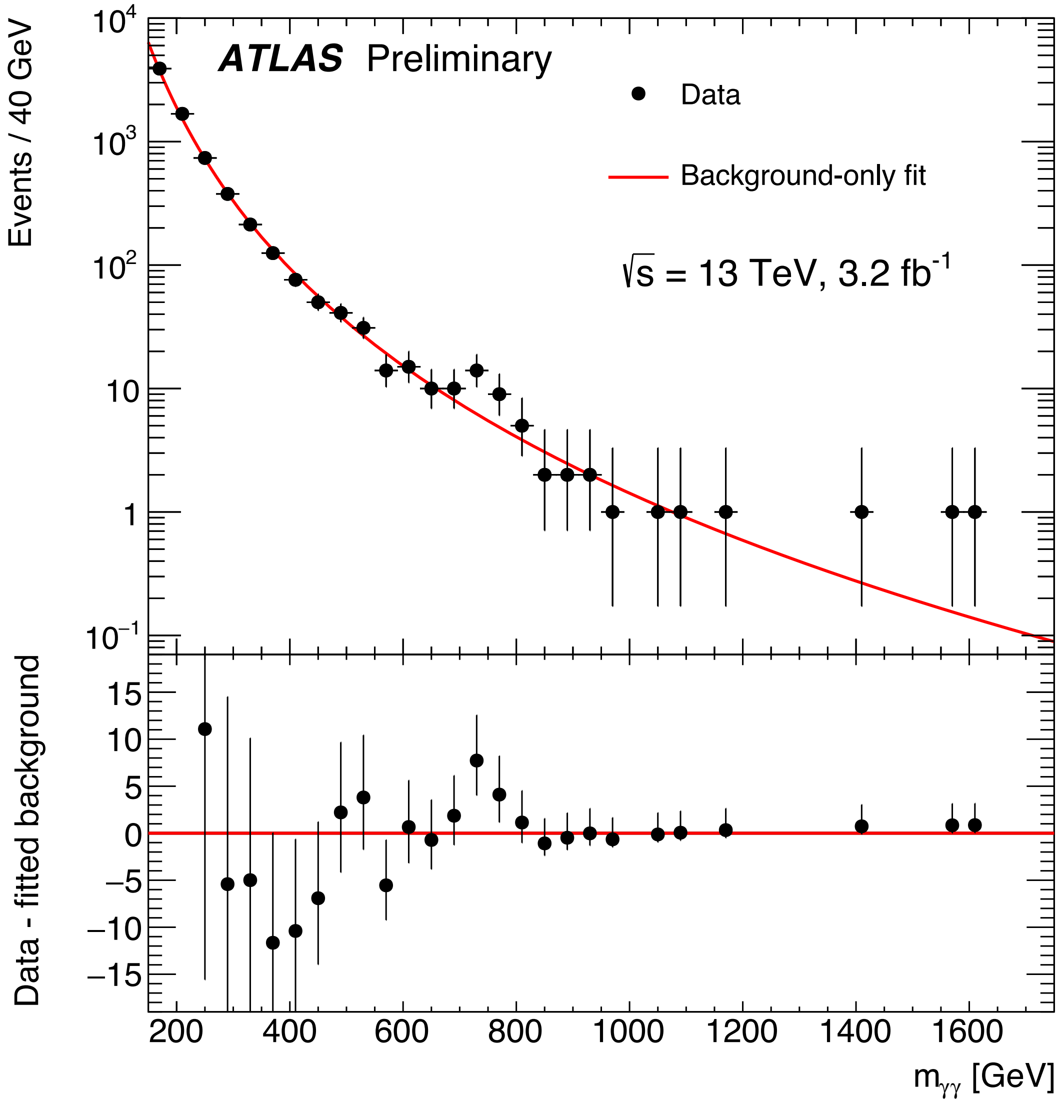




750 GEV γγ RESONANCE?

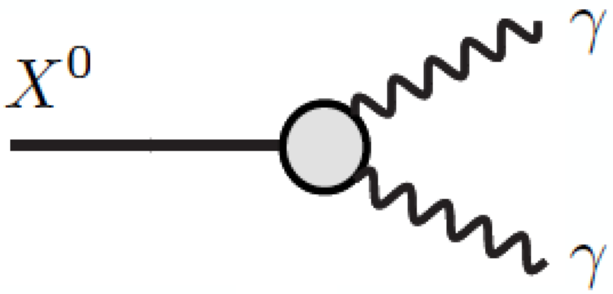
- Excess seen in CMS (2.6σ local, 1.2σ global at 760 GeV) and ATLAS (3.6σ local, 2.0σ global at 750 GeV)
- Possible resonance is not easily explained within MSSM (tension between preferred small tanβ and 125 GeV Higgs mass)





750 GEV γγ RESONANCE?

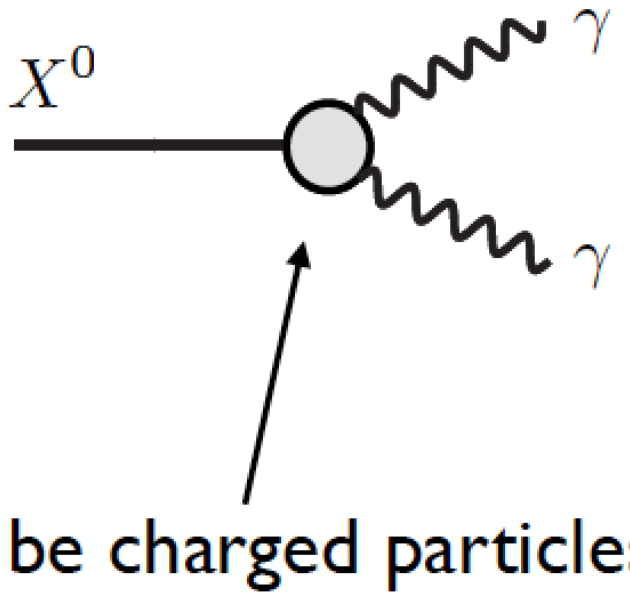
- What do we know?



- Can be spin 0 or 2.
  - Not spin-1. Landau-Yang theorem.
  - Completely identical to the argument of the 125 GeV di-photon resonance.
- Spin 0 is much more compelling than spin-2.
  - Very difficult to write down a complete model of spin-2.

750 GEV γγ RESONANCE?

- How can a neutral particle decay to photons, which only couples to charged particles?



For the SM higgs, they are top quark and W boson

Can top and/or W do it for the X(750)?

750 GEV γγ RESONANCE?

- Can top quark and/or W boson do it for X(750)?

  - Say X couples to top and or W, with arbitrary coupling.
    - BR(di-photon) is less than 10^{-4}.
    - 4 fb to di-photon means 10s -100 pb to ttbar and or WW.
    - A factor of 4 or 5 in the production rates between 8 and 13 TeV.
    - ttbar and/or WW signal of at least pb at 8 TeV.

750 GEV γγ RESONANCE?

- Is it possible that there is a tt or WW resonance with a cross section of ≳1 pb in the LHC Run 1 data?

- No.

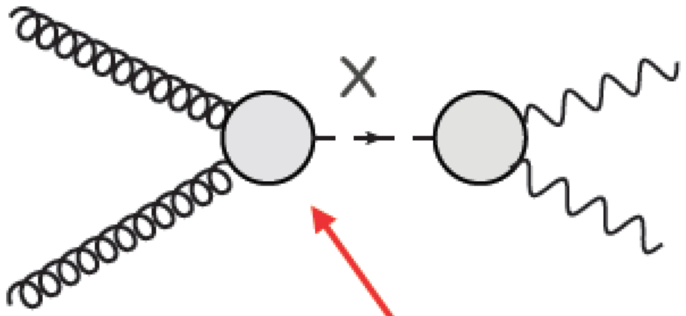
final state	700 GeV	750 GeV	
$t\bar{t}$ (narrow)	540 fb	450 fb	CMS [6]
$t\bar{t}$ (wide)	620 fb	520 fb	CMS [6]
WW ($\ell\nu jj$)	60 fb	70 fb	ATLAS [10]

- Must be more new physics in addition to the 750 GeV resonances!!

750 GEV γγ RESONANCE?

- What about its production?

  - Unlikely from qqbar.
    - Suppressed by small quark masses, otherwise suffer from sever flavor constraints.
  - Possibly (like the Higgs)



Need more new physics here as well, colored!