Search for resonances in dijet final states at √s=13 TeV

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Motivation

Standard Model (SM):
theory that summarizes **our current understanding of particle interactions**

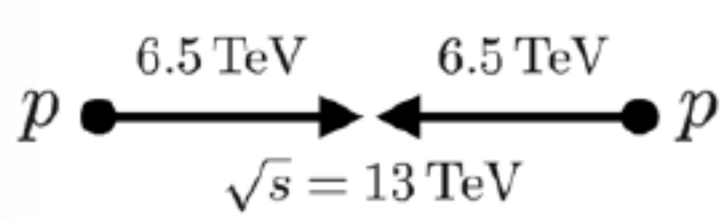
Predictions confirmed by many experiments.
Last success: Higgs boson discovery (2012)

Some unexplained aspects.
E.g.:
- Matter-Antimatter asymmetry;
- Dark matter

- **New theories**: include SM and try to solve these problems
  - Prediction of the **existence of new particles** at the TeV scale
    - Could be observed at particle colliders

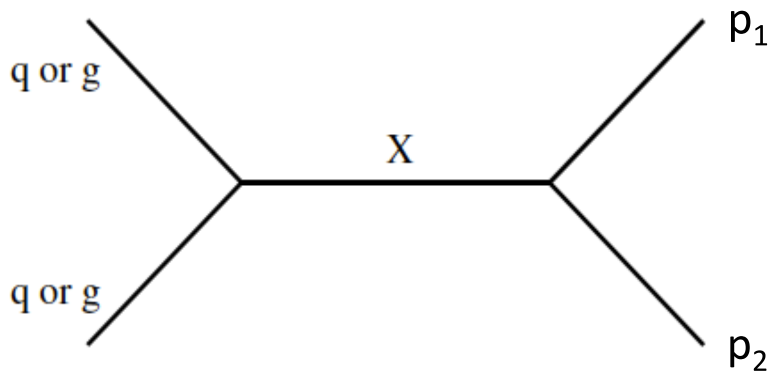
Large Hadron Collider

- 27 km length
- Hadronic collider: **proton-proton**
- Run2: **2015-2017**



- $\int L\,dt =$ **~22 fb^{-1} (total now)**
- $\int L\,dt =$ **12.9 fb^{-1} (shown at ICHEP)**

Search for resonances

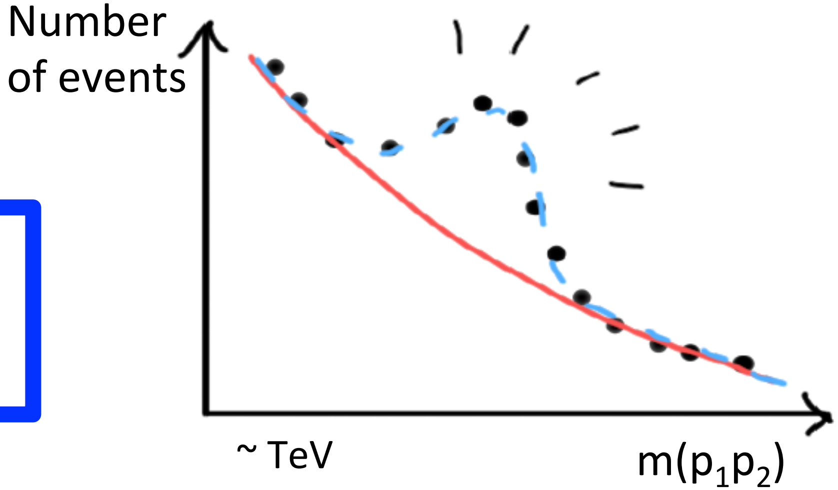


Two bodies decay: p_1 and p_2 two general particles

Reconstruct the invariant mass:

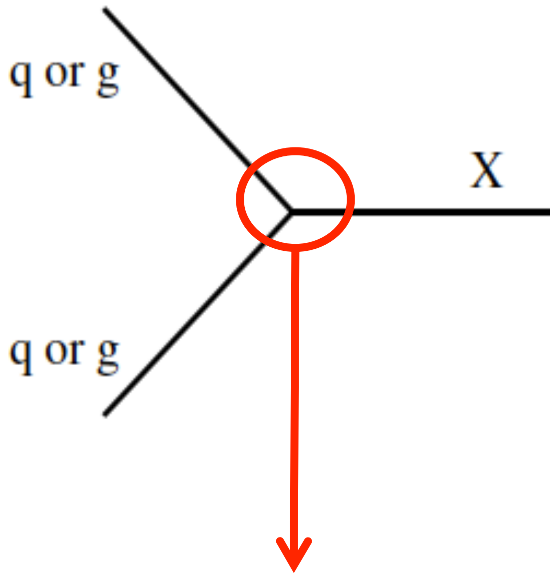
$$m(p_1 p_2) = \sqrt{m_1^2 + m_2^2 + 2\left(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2\right)}$$

Search for a bump over the background



Why dijet resonances

- Proton sub-structure: **quarks and gluons**
- At high energy, **asymptotic freedom**



If a resonance is produced
by a proton-proton collision

Why dijet resonances

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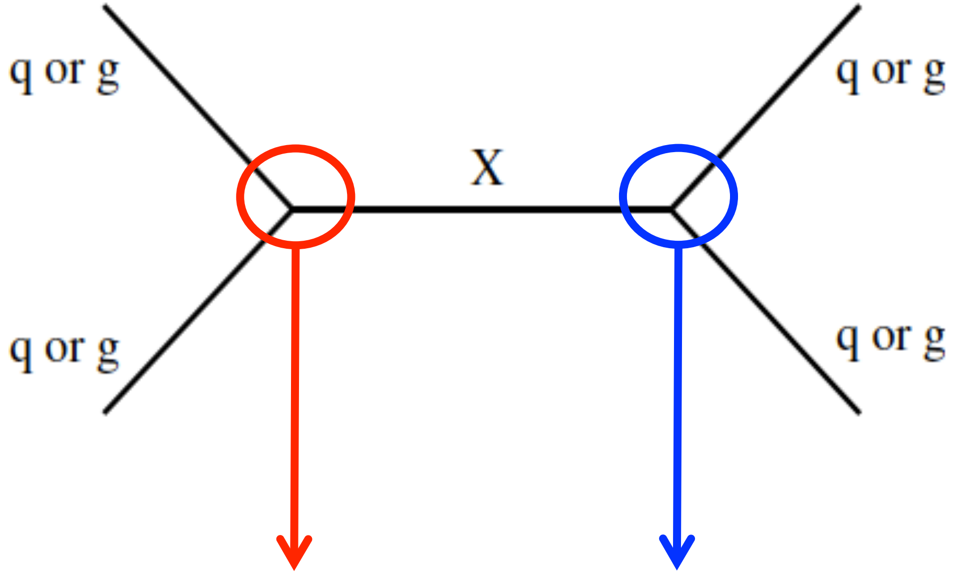
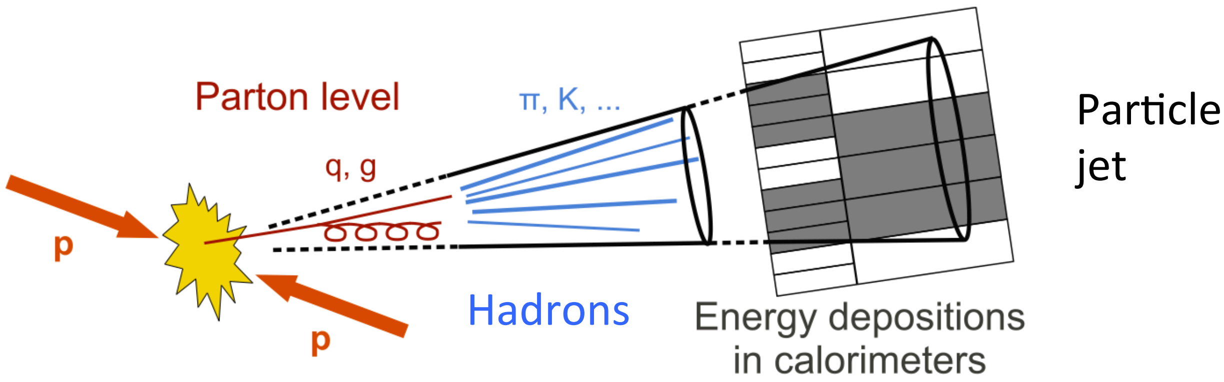


If a resonance is produced by a proton-proton collision

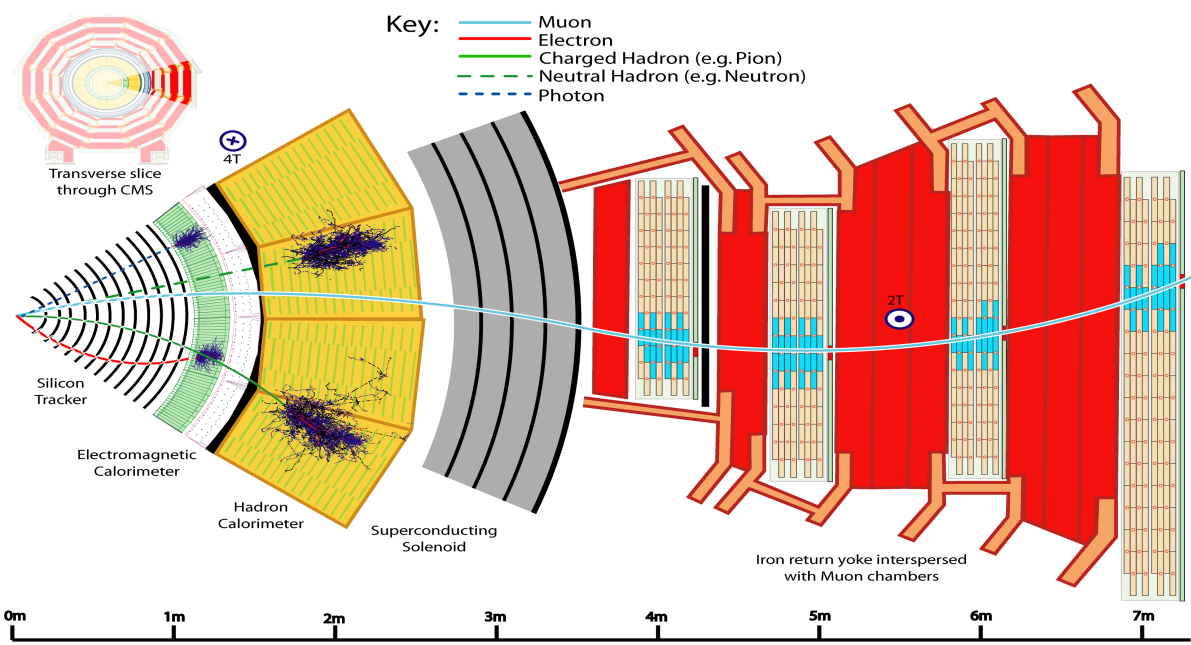
it must couple to quarks and gluons

Possible final states: X → quark-quark/ quark-gluon/ gluon-gluon

Quarks/gluons hadronization



Compact Muon Solenoid (CMS)



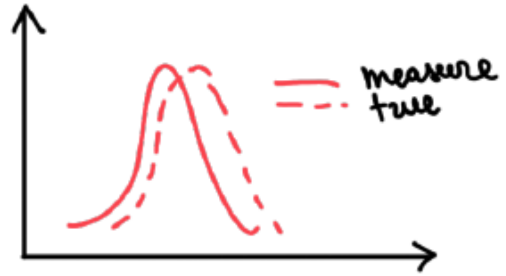
Sub-detectors mainly involved in jet reconstruction:

Tracker
Electromagnetic calorimeter
Hadronic calorimeter

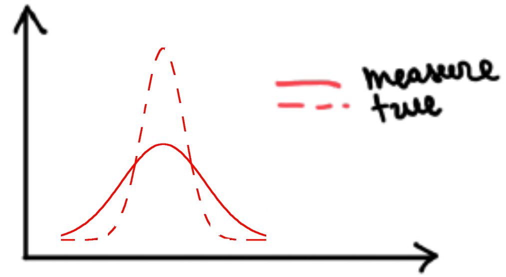
Jet energy scale and resolution

$$m(j_1 j_2) = \sqrt{m_1^2 + m_2^2 + 2\left(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2\right)}$$

- Need to know the right jet energy:
  - Wrong **jet energy scale** → wrong mass peak position for signal events.

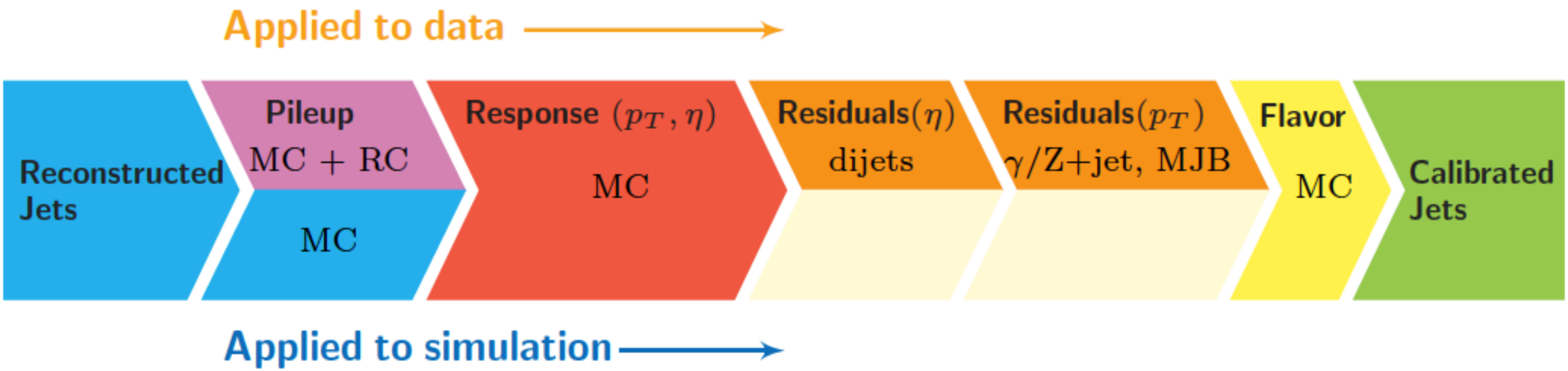


  - **jet energy resolution** → direct impact on the sensitivity of the analysis in presence of the large multijet background.



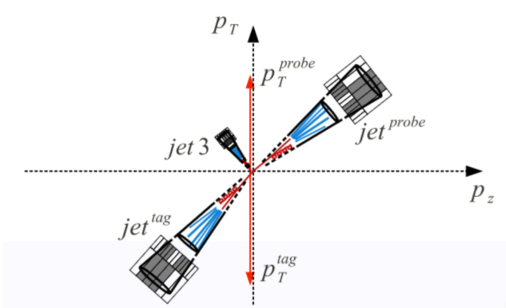
- **Need to calibrate the jets**

Jet energy calibration



Calibrate the jets with respect to a reference object and then Data with respect to MC

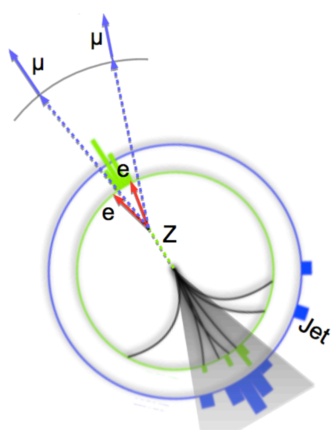
Dijet events



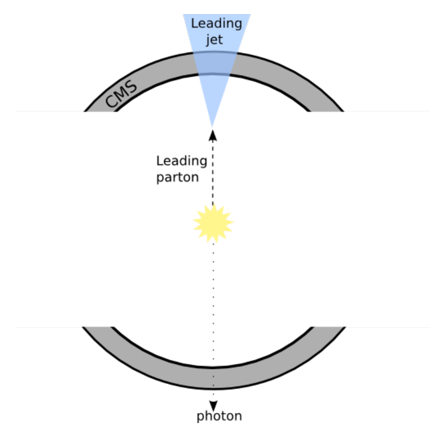
$$\mathcal{R}_{rel}(\eta^{probe}, \bar{p}_T) = \frac{1 + \langle \mathcal{A} \rangle}{1 - \langle \mathcal{A} \rangle}$$

where $A = \frac{p_T^{probe} - p_T^{tag}}{p_T^{probe} + p_T^{tag}}$

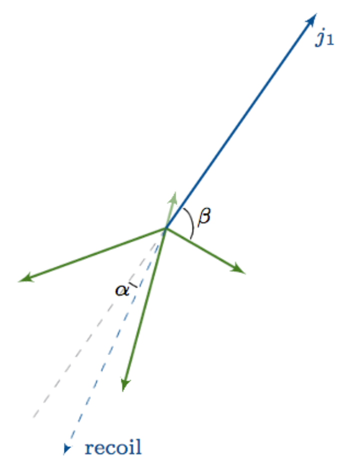
Z+jet events



Photon+jet events



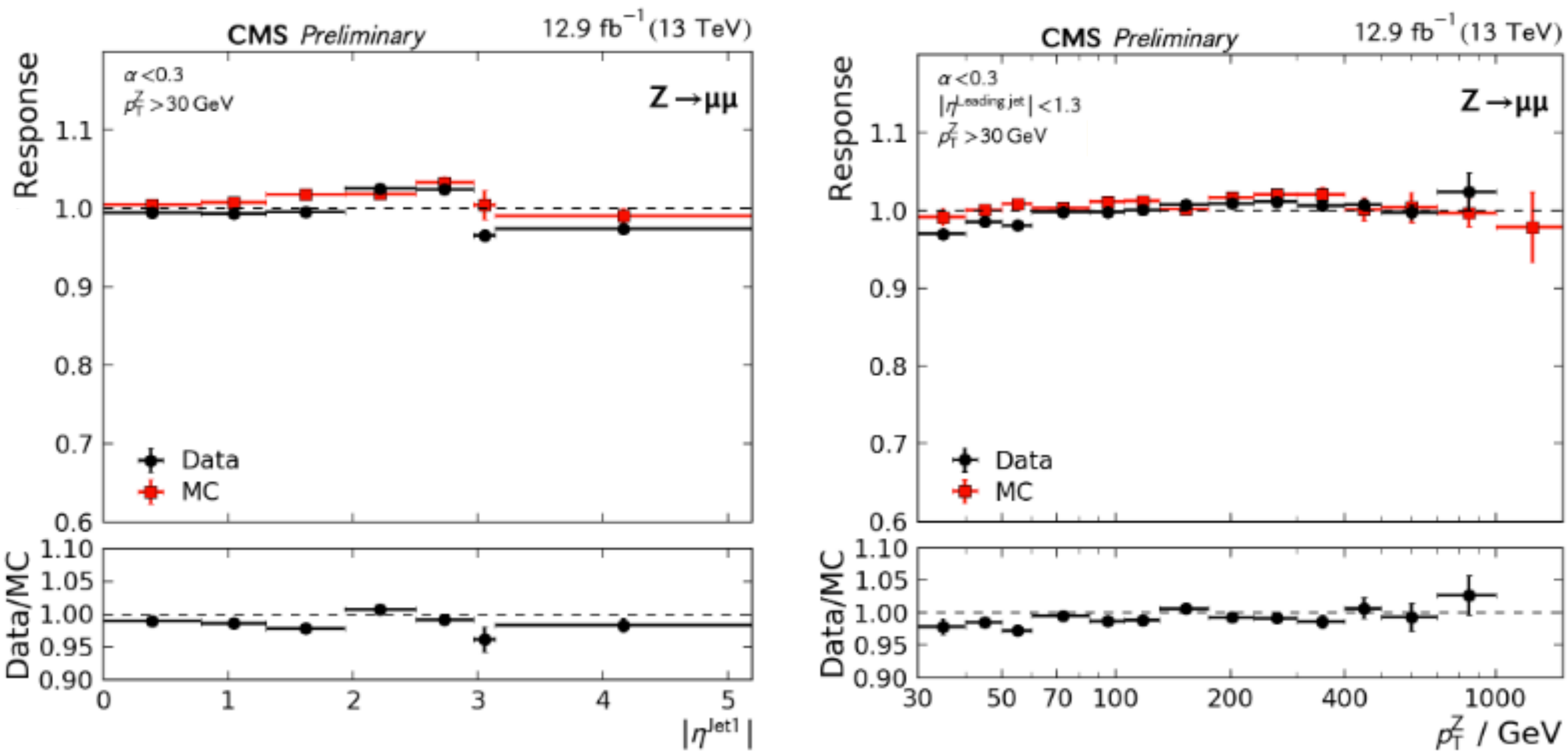
Multijets events



$$R(\eta_{jet}, pT_{ref}) = \frac{pT(jet)}{pT(ref)}$$

Jet energy calibration: results

- Applying all calibration chain on Z+jet



- Obtained a response equal to 1 and a good data/MC agreement

High-mass dijet spectra

- Trigger selection:

  $$H_T = \sum_{jets} p_T^i > 800\text{GeV}$$

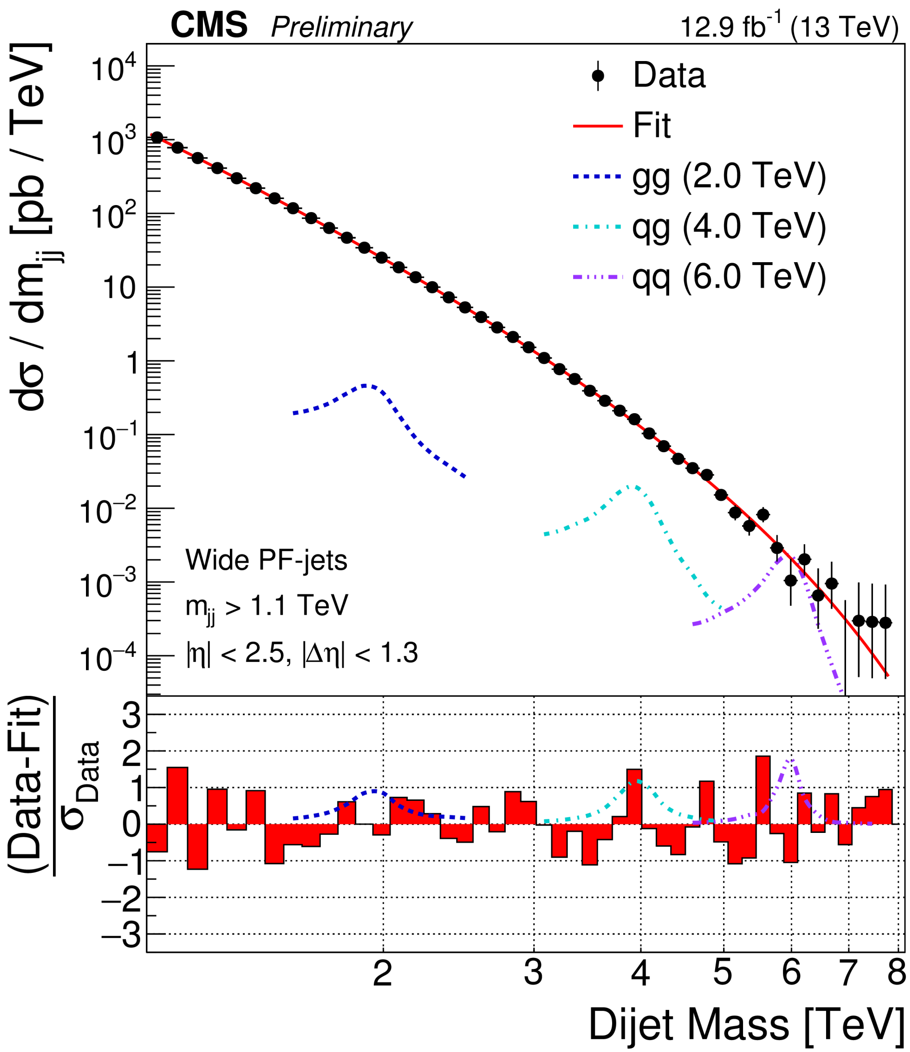
  Fully efficient from ~1 TeV

- 4-parameter function

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

- Data well described by the fit:
  χ^2 / NDF = 33.3/42

- No evidence for dijet resonance
  - Set limits

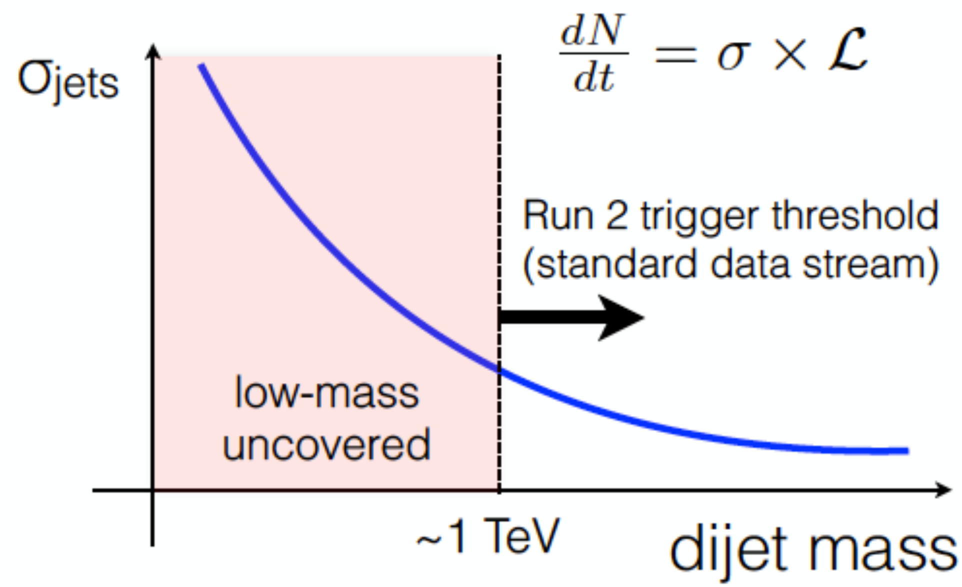


Low-mass dijet search

➢ **Important to cover the full mass range in BSM searches**

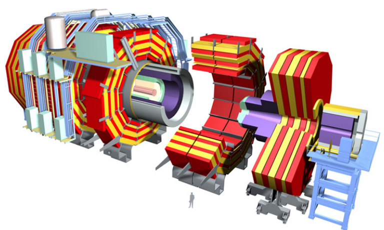
➢ **Experimental difficulties:**

- large dijet cross section at hadron colliders at low-mass
- limited resources to process and store data
- trigger thresholds raise with increasing inst. luminosity



"Data scouting" in CMS

Physics Goal: recover sensitivity to new physics in phase space not accessible via the standard trigger selection



High Level Trigger

Scouting → Analysis

Raw data → Events reconstruction → Analysis

	Main data stream	Data scouting
Trigger selection	All CMS triggers ex. for dijet $H_T > 800\text{GeV}$	Low-pT jet triggers $H_T > 250\text{GeV}$
Event rate	~1 KHz	~4 KHz
Event content	FULL (RAW data + offline reconstruction)	REDUCED (store calo jets reconstructed at trigger level)
Bandwidth	~1 GB/s	~0.01 GB/s

Bandwidth → Event rate X Event content

Low-mass dijet spectra

- Trigger selection:

  $$H_T = \sum_{jets} p_T^i > \text{ 250 GeV}$$

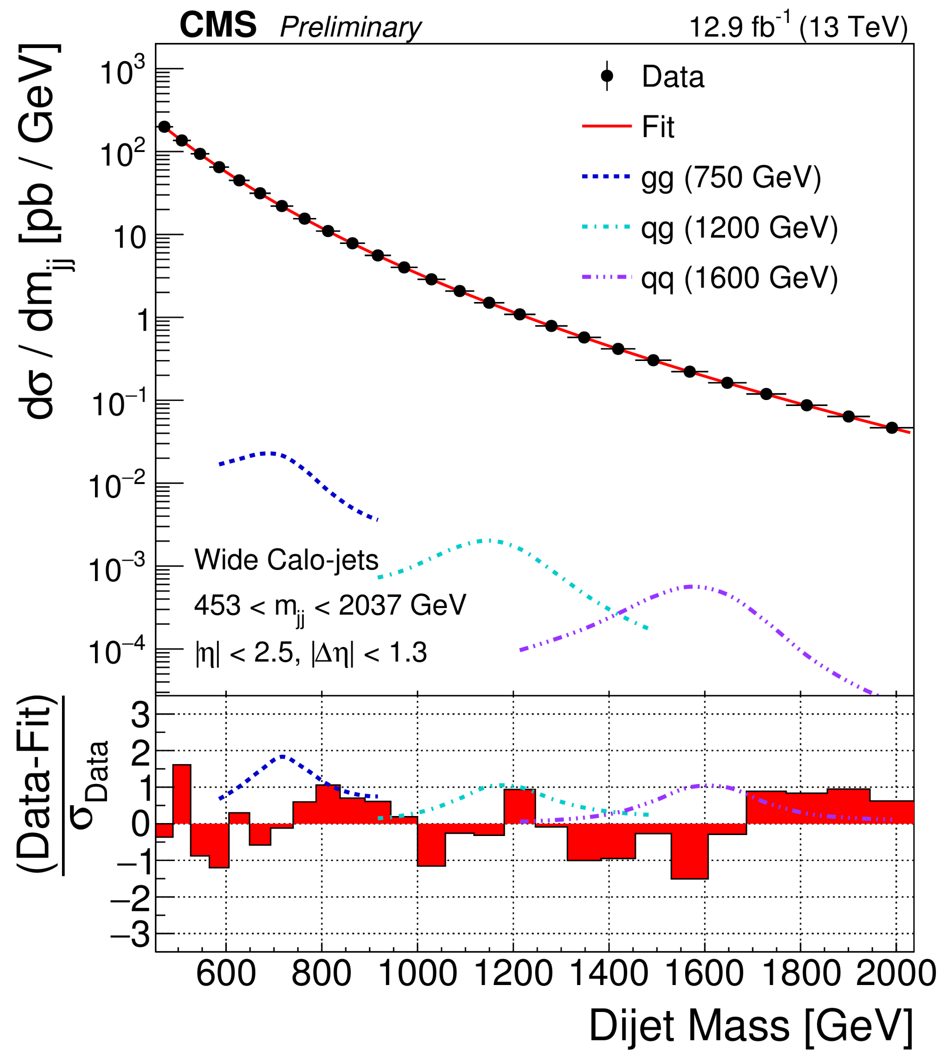
  Fully efficient from ~450 GeV

- 4-parameter function

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

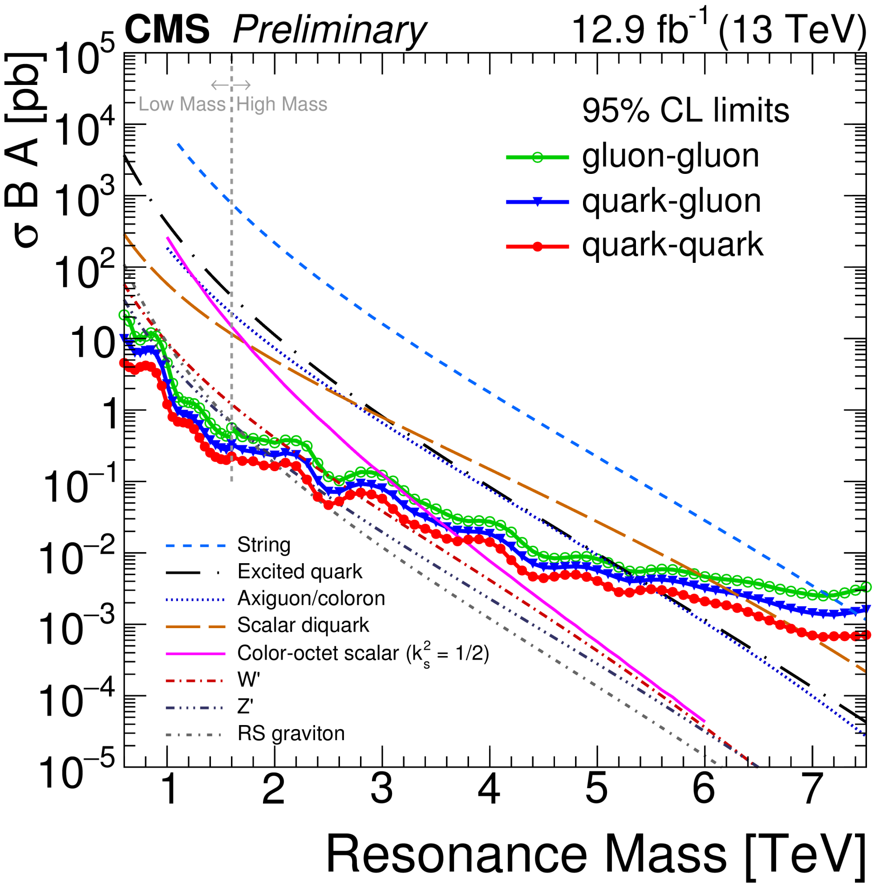
- Data well described by the fit:
  χ^2 / NDF = 17.3/22

- No evidence for dijet resonance
  - Set limits



Limits

- Many theoretical models can be probe with dijet analysis



Model	Final State	Observed (expected) mass limit [TeV] 12.9 fb^{-1} 13 TeV	2.4 fb^{-1} 13 TeV	20 fb^{-1} 8 TeV
String	qg	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	$q\bar{q}$	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.0 (3.3)	—	—
W′	$q\bar{q}$	2.7 (3.1)	2.6 (2.3)	2.2 (2.2)
Z′	$q\bar{q}$	2.1 (2.3)	—	1.7 (1.8)
RS Graviton	$q\bar{q}$, gg	1.9 (1.8)	—	1.6 (1.3)

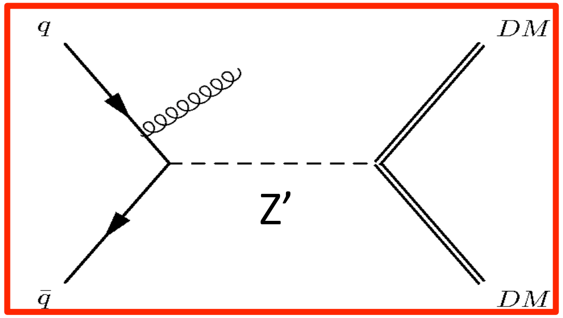
Limits improved

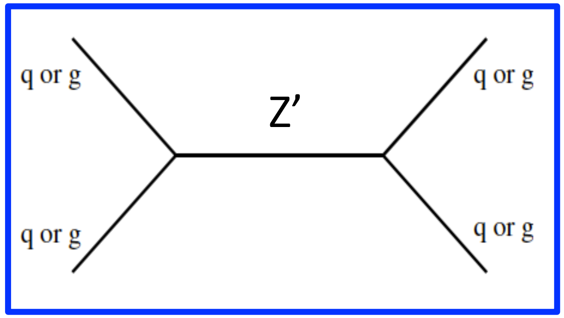
- from 8 TeV to 13 TeV
- From 2.4 fb^{-1} to 12.9 fb^{-1}

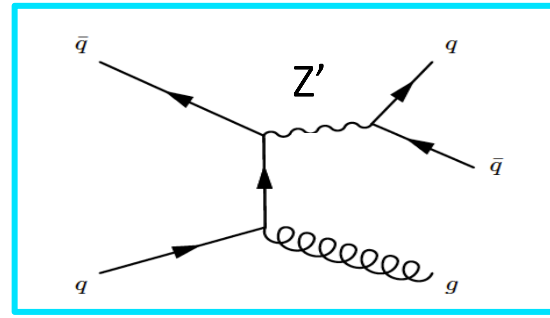
Dark Matter interpretation

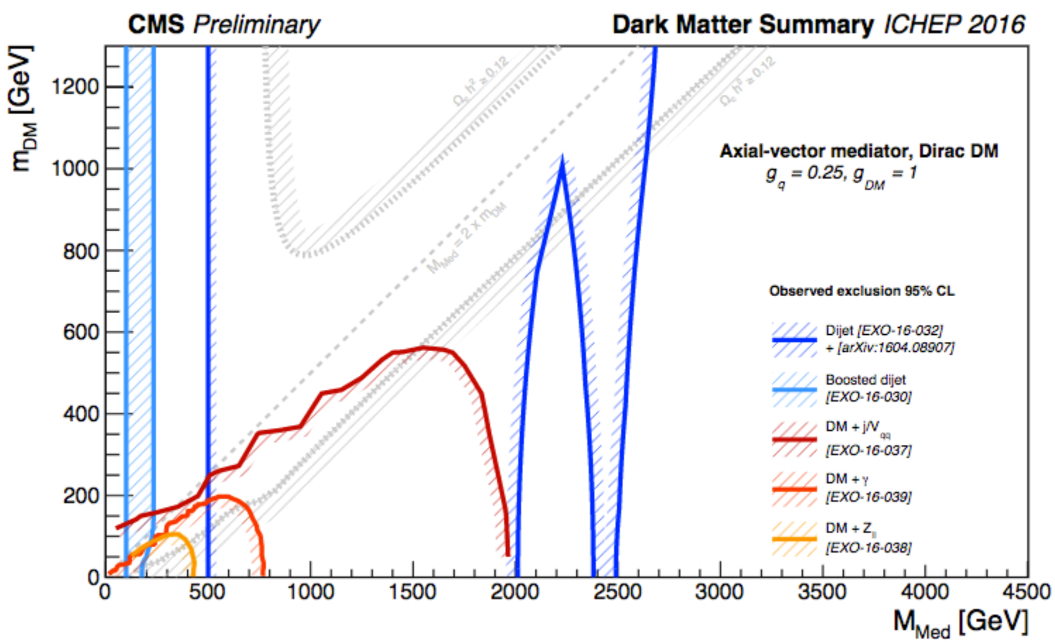
New result

Particular theoretical model: Z' lepto-phobic



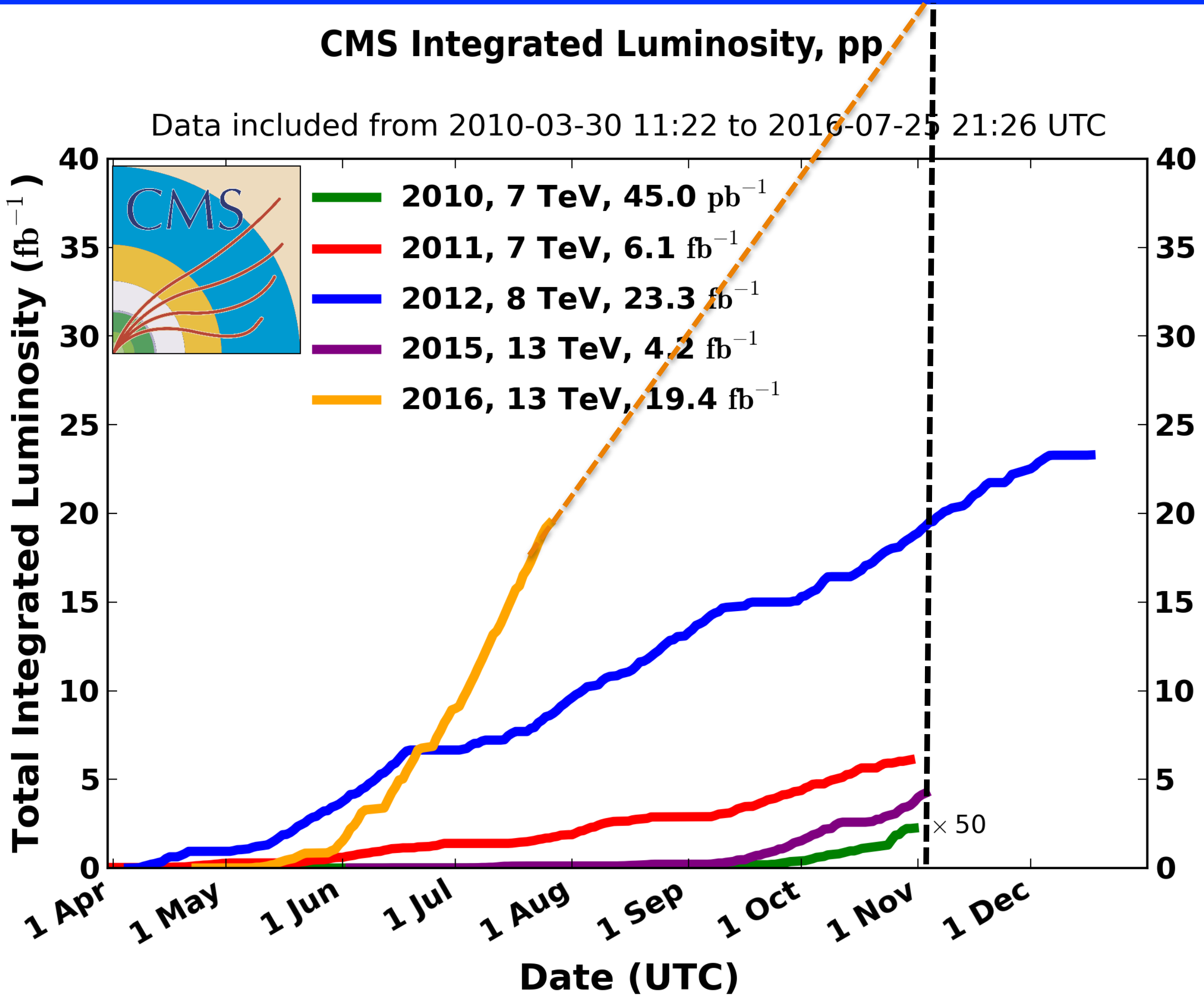






- Exclusion region depends on couplings (here: $g_q = 0.25$ and $g_{DM} = 1$)
- Large region excluded with dijet analysis.

Future prospective



Excellent LHC performance in 2016 → Lumi expected by the end of the year ~50 fb^{-1}

Conclusions

- Search for resonances in dijet final state was presented
  - Search in the low-mass region (mjj < 1TeV)
  - Search in the high-mass region (mjj > 1TeV)
- No evidence for new resonances was observed
- Limits on dijet invariant mass were set
  - Low-mass search excluded all considered models
  - 2016 high-mass search improved the limits set in 2015
- New result: dijet analysis for dark matter constrains.
- Further improvement with new incoming data

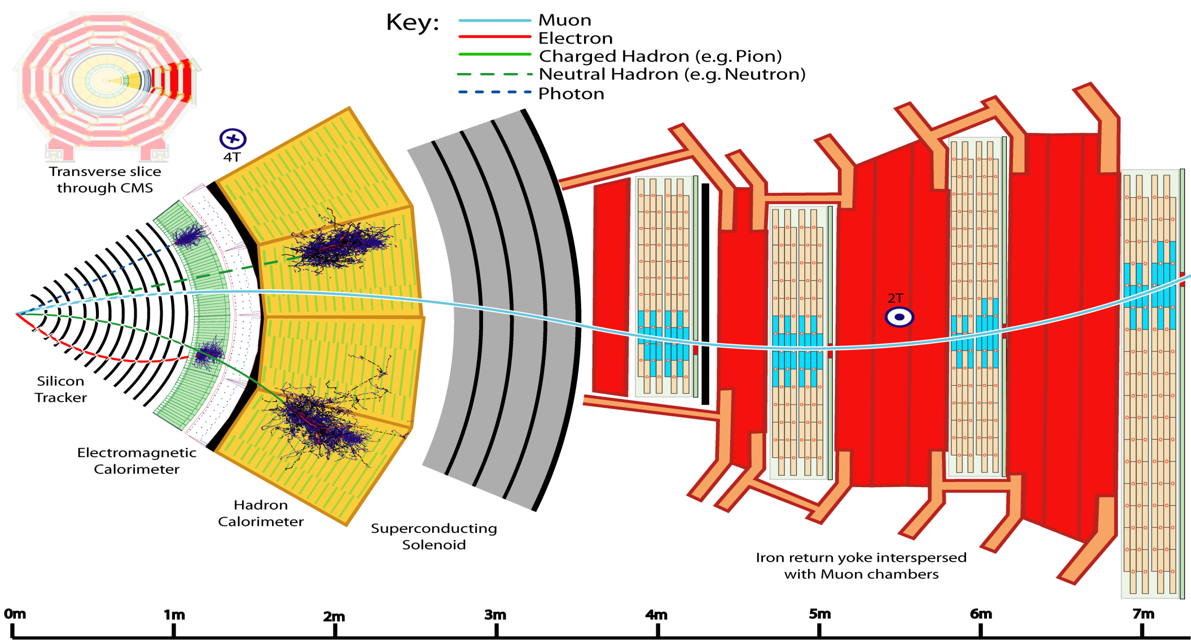
Backup

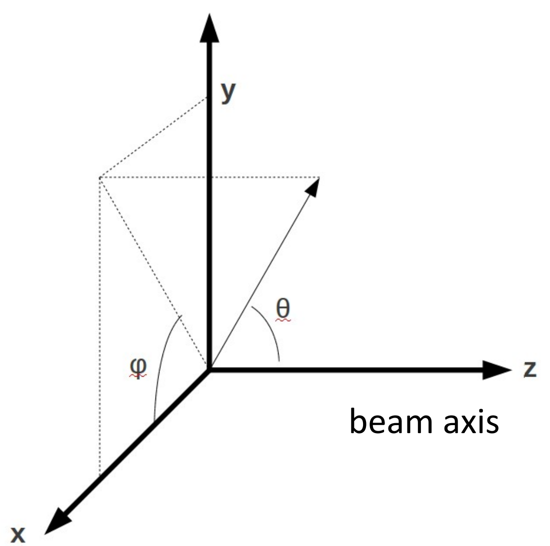
Quarks/gluons hadronization

Sub-detectors mainly involved in jet reconstruction:

Tracker
Electromagnetic calorimeter
Hadronic calorimeter

Compact Muon Solenoid (CMS)





Pseudo-rapidity $\eta = -\ln \tan \frac{\theta}{2}$

Large Hadron Collider

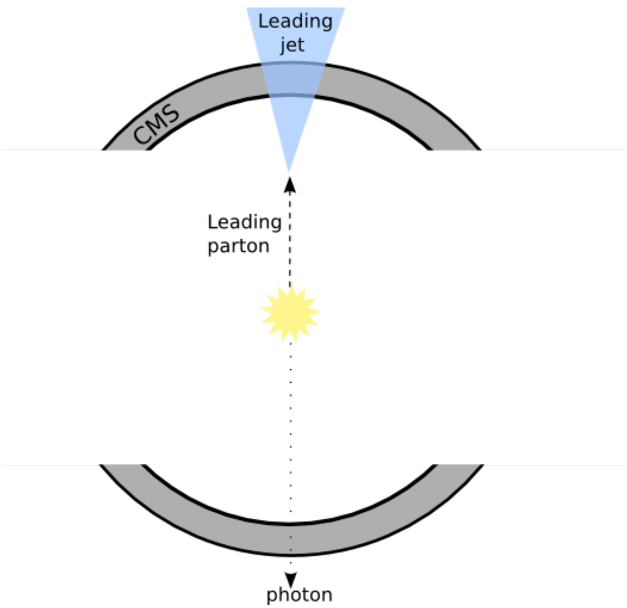
LHC:

- 27 km length
- Hadronic collider: **proton-proton**
- **Run1:**
  - 2010/2011 @ 7 TeV → $\int L\,dt = 5\text{fb}^{-1}$
  - 2012 @ 8 TeV → $\int L\,dt = 20\ \text{fb}^{-1}$
- **Run2 @ 13 TeV:**
  - 2015 → $\int L\,dt = 4\ \text{fb}^{-1}$
  - 2016 (today) → $\int L\,dt = 21\ \text{fb}^{-1}$
- 4 experiments: **CMS**, ATLAS, LHCb, ALICE

Next years:

- Data expected at the end of Run 2 (2017) $\int L\,dt = \mathbf{100\ fb^{-1}}$
  - 5 times larger than now
  - Probe unexplored mass regions of resonance mass.

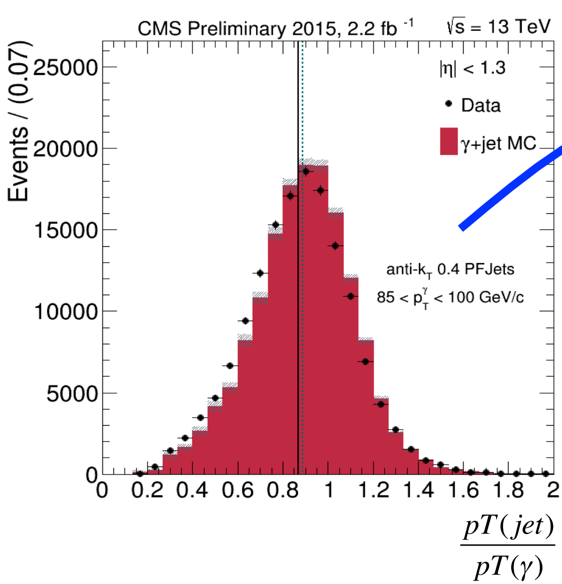
Jet energy calibration: Photon+jet

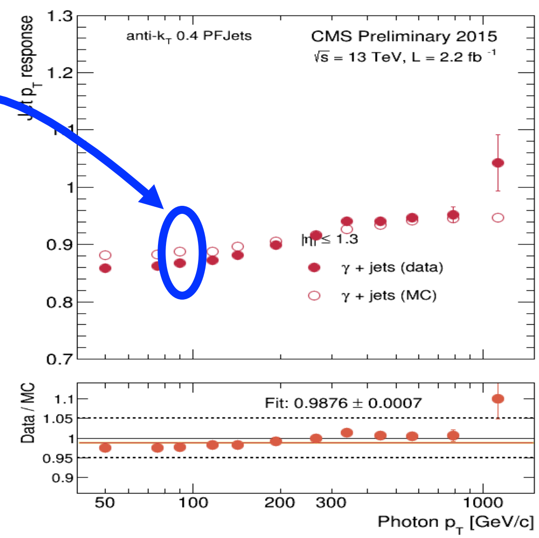


- E.g.:Photon + jet events
- Photon and jet back-to-back in the transverse plane
  - → Balancing in transverse energy

$$p_T(\gamma) = p_T(jet)$$

- High precision in the photon reconstruction
  - Resolution (γ) much better than Resolution (jet)
- Jet energy calibration using the photon as a reference
- Jet response = $\dfrac{pT(jet)}{pT(\gamma)}$





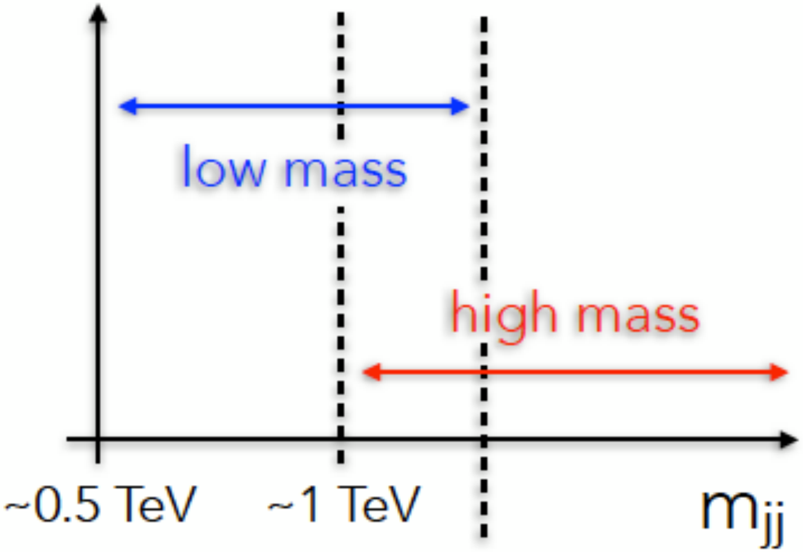
Ratio between data and MC
→ Corrector factor

Two searches

Data transfer rate [kB/sec] = event rate [evt/sec] X event size [kB/evt]

- Event size = 500 kB/event
- **High rate of dijet events at LHC**
  → data transfer rate too high

Two possible searches:



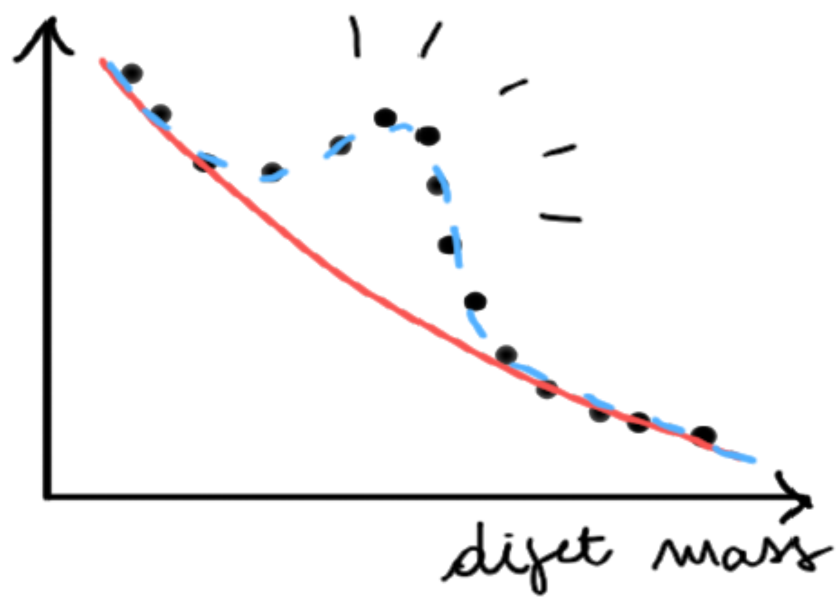
- **High-mass search:**
  Raise trigger thresholds:
  pT_{jet} > 500 GeV → analysis: M(jj) > 1.2 TeV
  Fully reconstructed jets (**RECO jets**)

- **Low-mass search:**
  Decrease trigger threshold + Reduce event size
  → Event size = 10 kB/event
  → Can afford large event rate **BUT** less information
  pT_{jet} > 200 GeV → analysis: M(jj) > 500 GeV
  Jet saved at trigger level (**HLT jets**)

Analysis strategy

- **Trigger:** use data above dijet mass threshold where trigger is fully efficient
- **Data/MC agreement:** check for understanding and stability of data to ensure we are looking at dijets not noise
    - MC is used to “guide the eye”
- **Data:** measure dσ/dmjj
- **Background:** use 4-parameter function to fit data for background
- **Results:** estimate significance, set limits

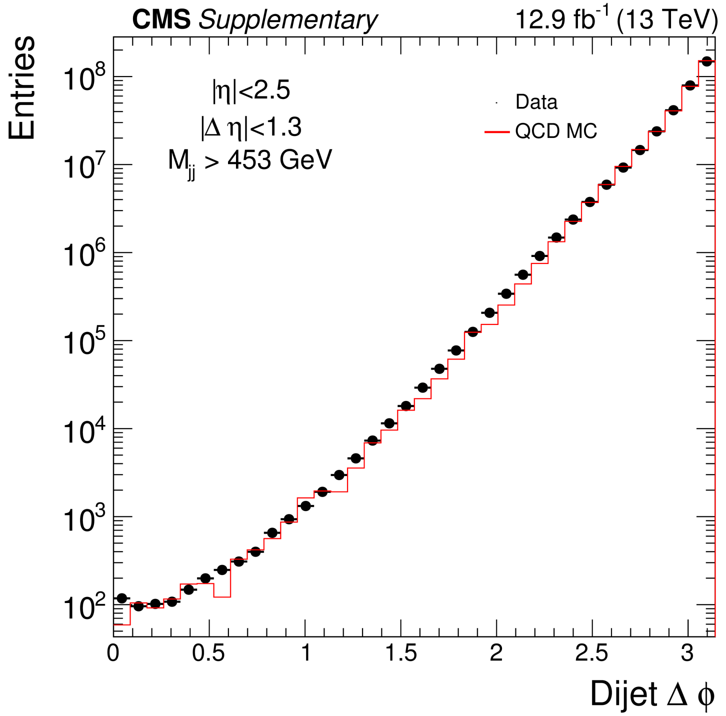
SEARCH FOR BUMPS ON A FALLING SPECTRUM



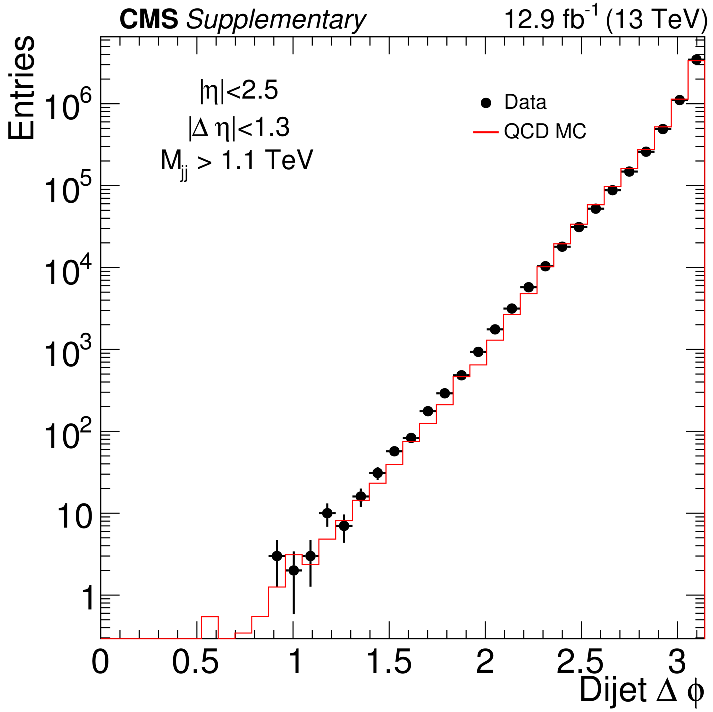
Data/MC comparison (I)

Δφ(jj) shows back-to-back dijet events

Low-mass region



High-mass region

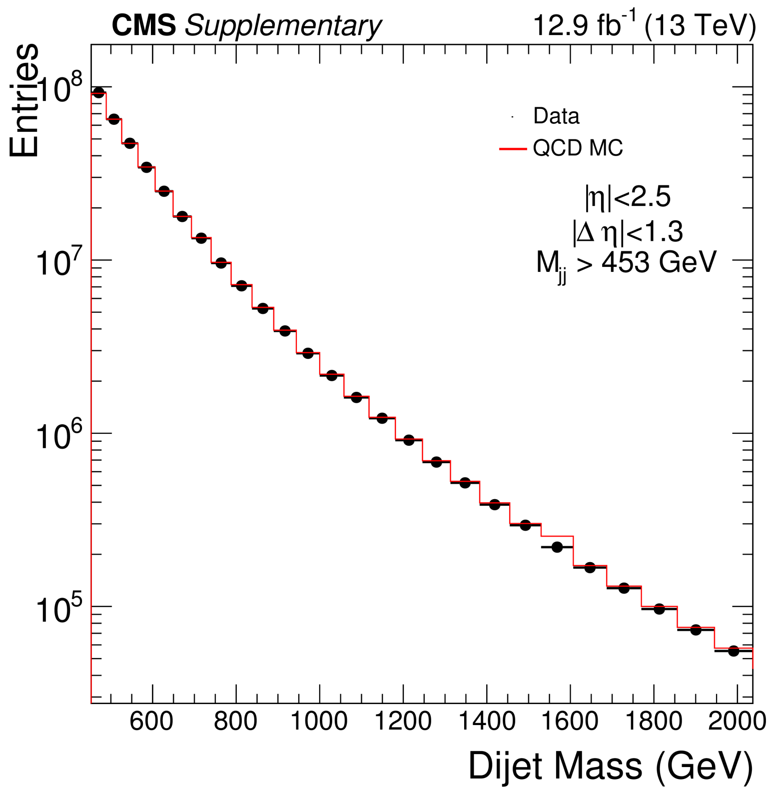


Good data/MC agreement

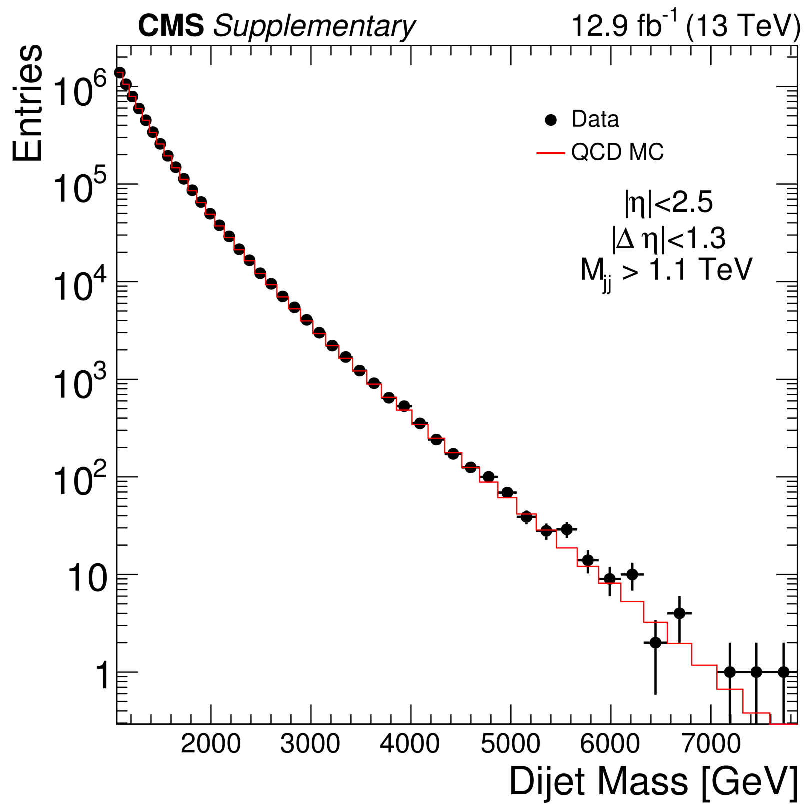
Data/MC comparison (II)

Dijet mass agrees at high and low mass

Low-mass region



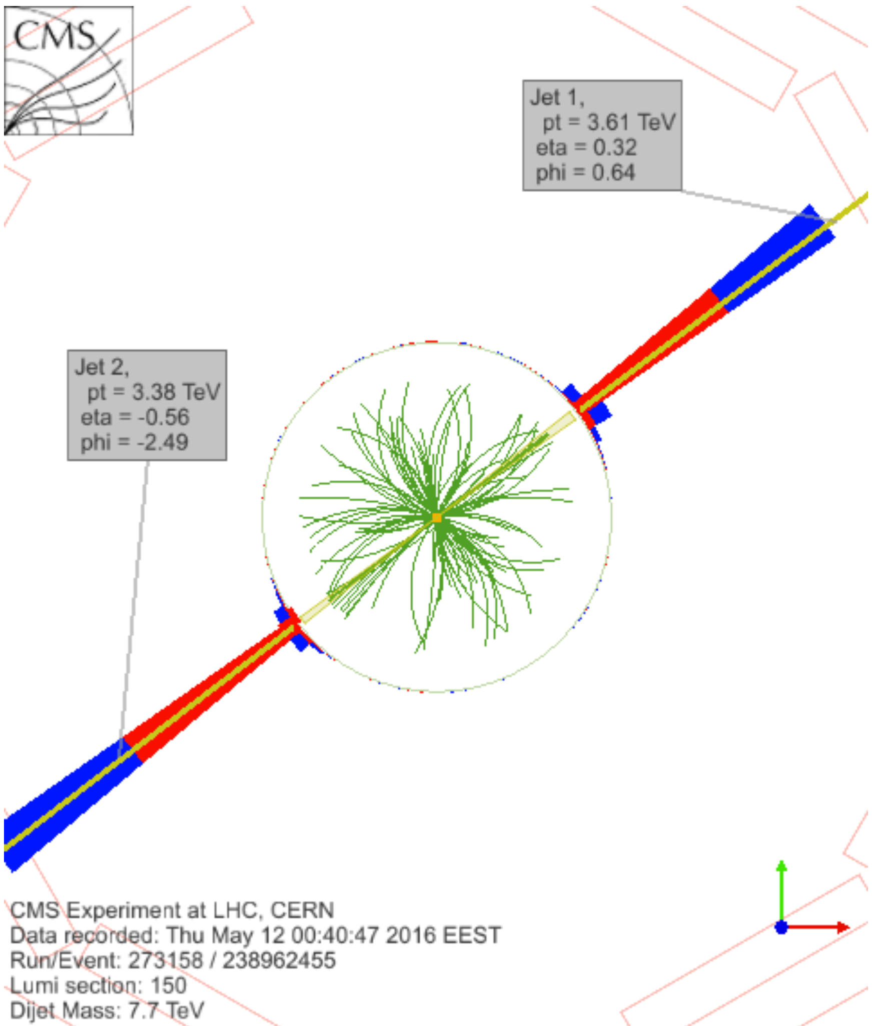
High-mass region

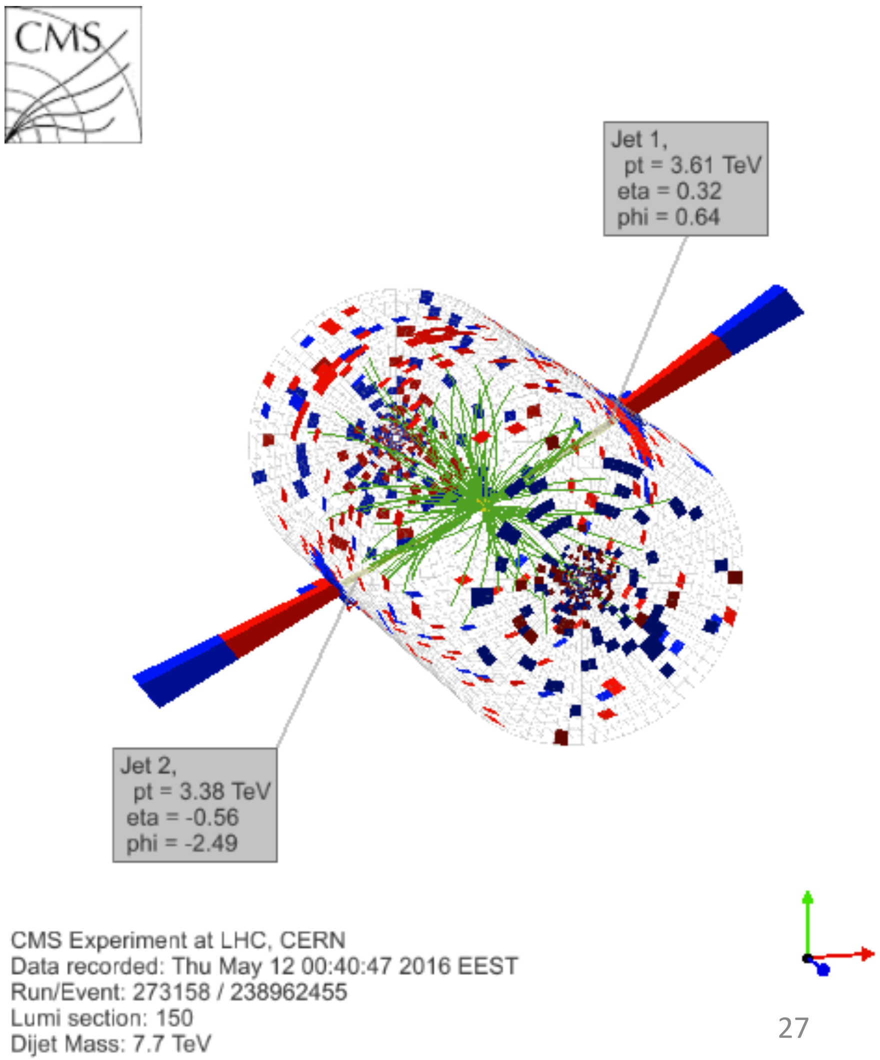


Highest event: mjj = 7.7 TeV

Event display

- Highest dijet mass event mjj = 7.7 TeV

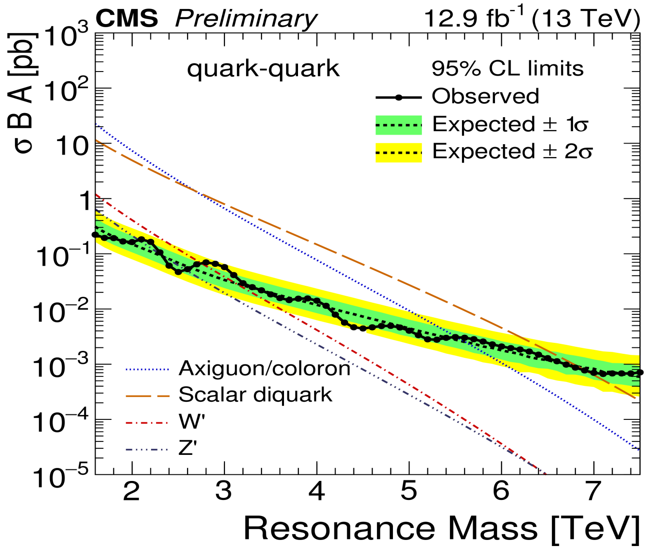




Limits

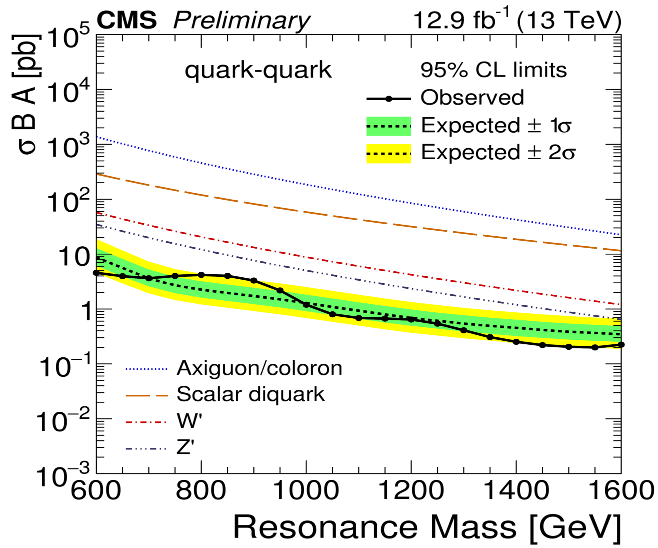
Reported few theoretical lines just for example

High-mass search



2016 limits improve compared to 2015

Low-mass search



It excludes all models shown

Title