Search for new resonances decaying to pairs of jets in proton-proton collisions at √s = 13 TeV

Ph.D. project
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Motivation

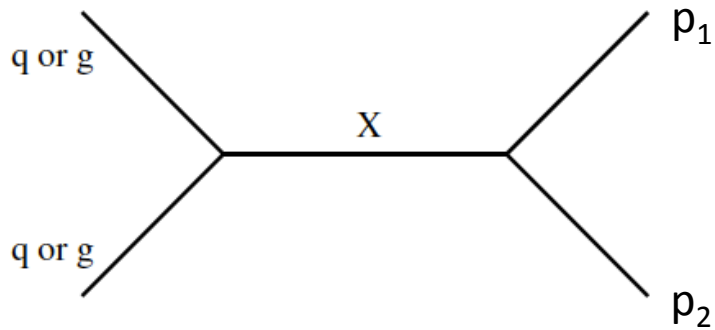
Standard Model (SM):
theory that summarizes **our current understanding of particle interactions**

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

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

- **Theory not complete.**
  - **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

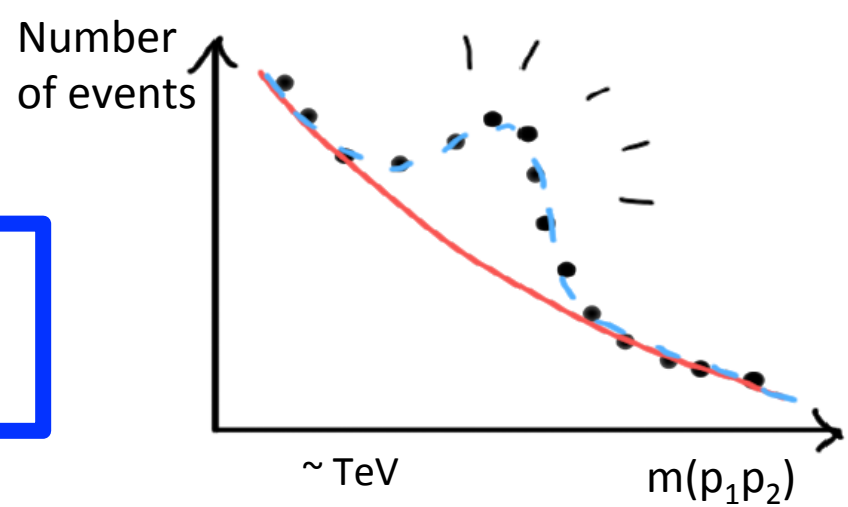
Search for resonances



Two bodies decay:
p_1 and p_2 two general particles

Reconstruct the invariant mass:

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



Search for a bump over the background

Some past discoveries

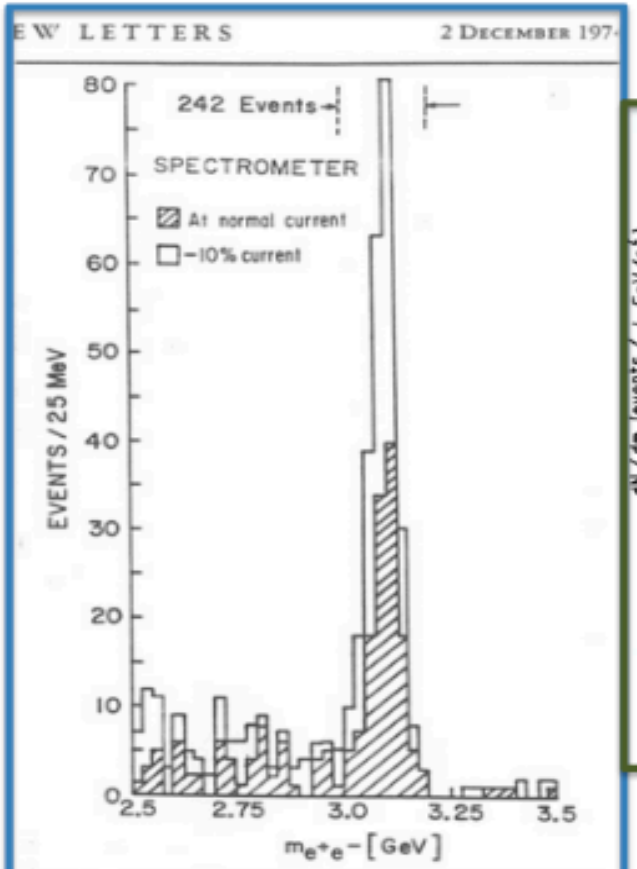
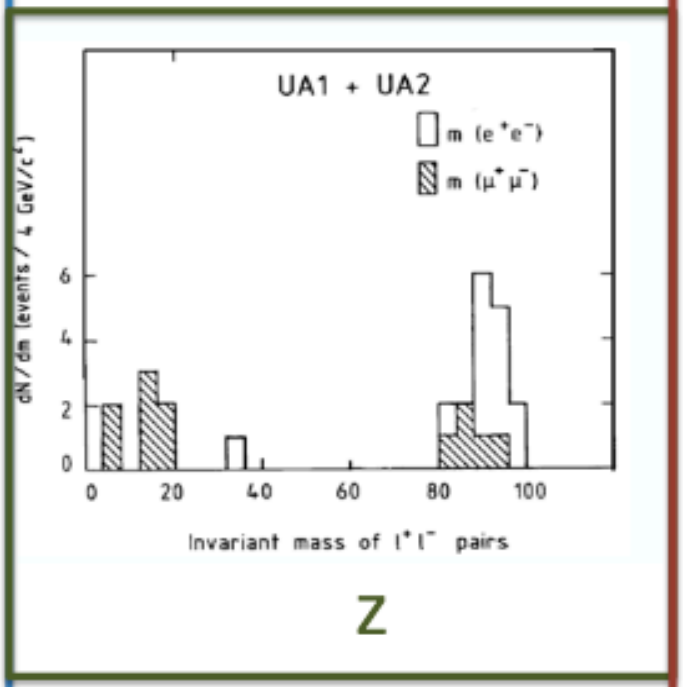
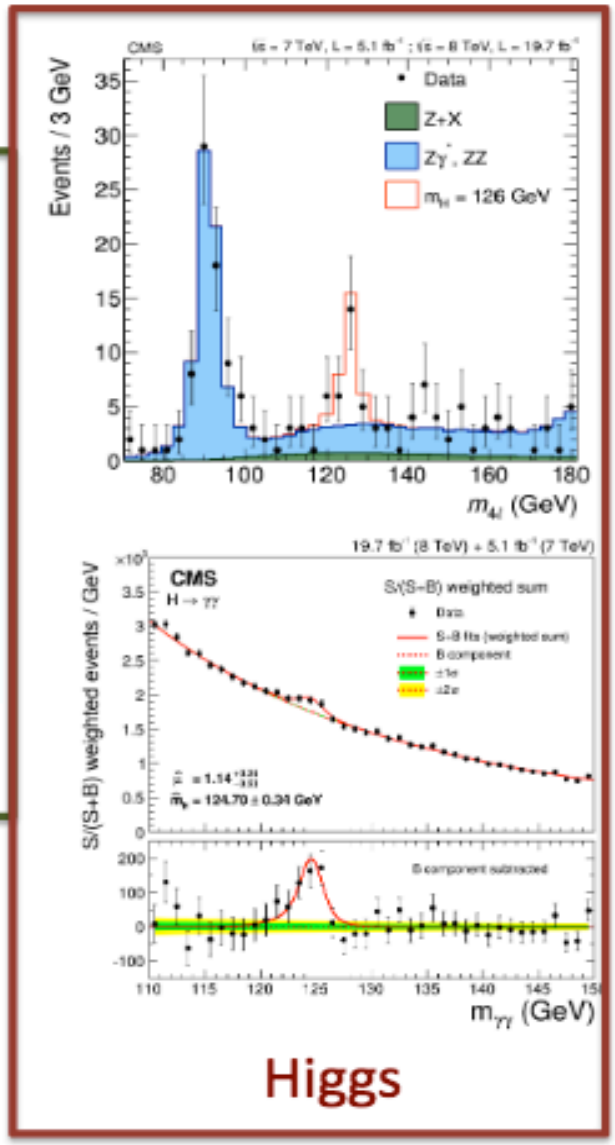


FIG. 2. Mass spectrum showing the existence of J. sults from two spectrometer settings are plotted wing that the peak is independent of spectrometer rents. The run at reduced current was taken two nths later than the normal run.

J/Psi



Z



Higgs

Large Hadron Collider

LHC:

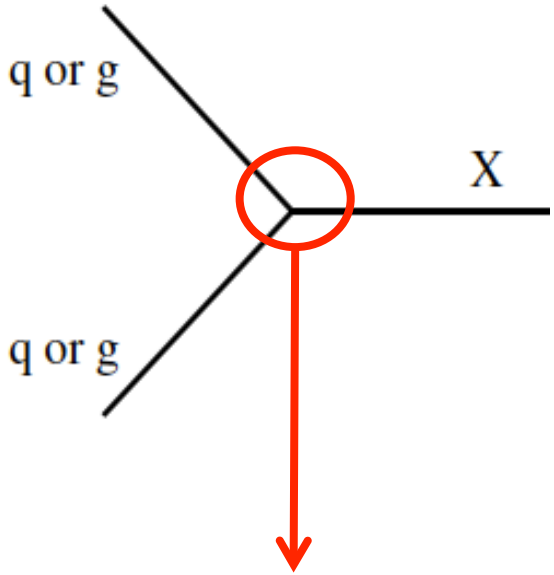
- 27 km length
- Hadronic collider: **proton-proton**
- **Run1:**
  - 2010/2011 @ 7 TeV → $\int L\,dt = 5\,\text{fb}^{-1}$
  - 2012 @ 8 TeV → $\int L\,dt = 20\,\text{fb}^{-1}$
- **Run2:**
  - 2015 @ 13 TeV → $\int L\,dt = 4\,\text{fb}^{-1}$
  - 2016/2017 @ 13 TeV
- 4 experiments: **CMS**, ATLAS, LHCb, ALICE

Next years:

- Data taking restarting in April 2016:
  - Data expected at the end of Run 2 (2017) $\int L\,dt =$ **100 fb^{-1}**
    - 25 times larger than now
    - Probe unexplored mass regions of resonance mass.

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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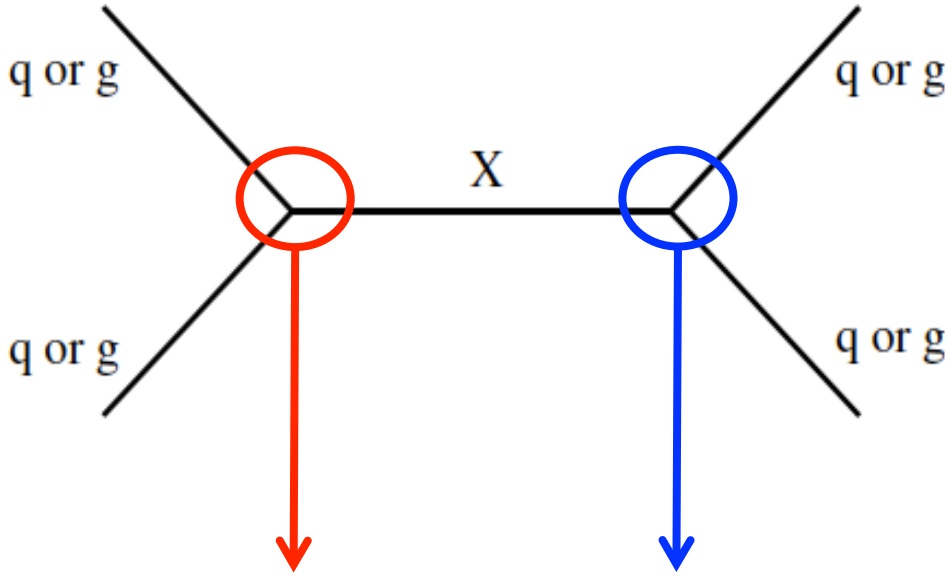
- At high energy, **asymptotic freedom**

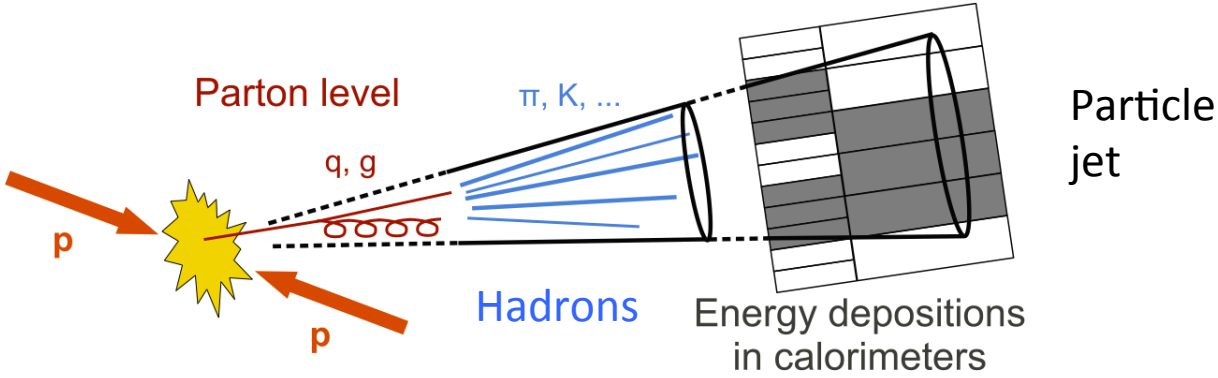


If a resonance is produced by a proton-proton collision

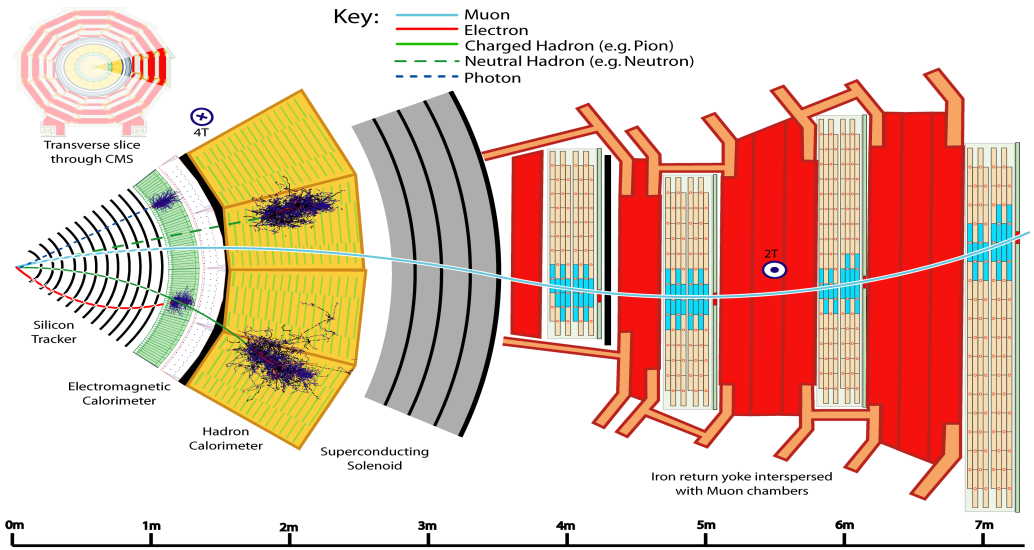
it must couple to quarks and gluons

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

Road map: traveled

Nov. 2014 → Start of Ph.D

2015 → Jet energy calibration

2016 → Search for dijet resonances with **mass > 1 TeV**
- Add more data at 13 TeV
- Analysis improvements (e.g. **Angular analysis)**

2016 → Search for dijet resonances with **mass < 1 TeV**
- Use novel **data scouting** approach

2017 → End of Run 2: Publication of dijet resonance searches with full Run 2 dataset

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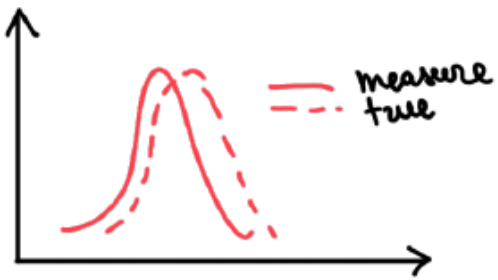
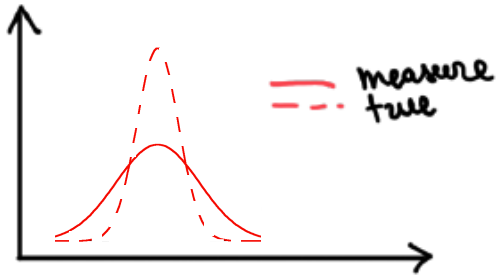
Jet energy scale and resolution

$$m\left(j_1 j_2\right)=\sqrt{m_1^2+m_2^2+2\left(E_1E_2-\vec{p}_1\cdot\vec{p}_2\right)}$$

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



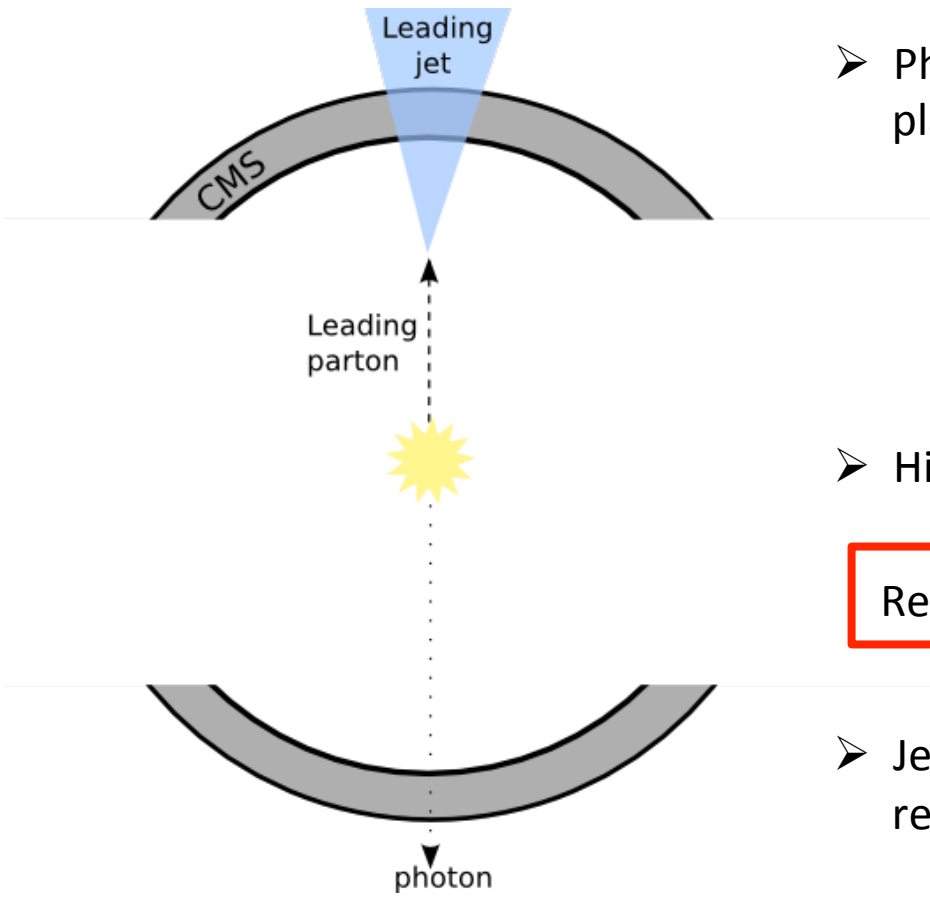
  - **jet energy resolution** → direct impact on the sensitivity of the analysis in presence of the large multijet background.



- Need to calibrate the jets

Jet energy calibration: ingredients

My main activity in 2015



- 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

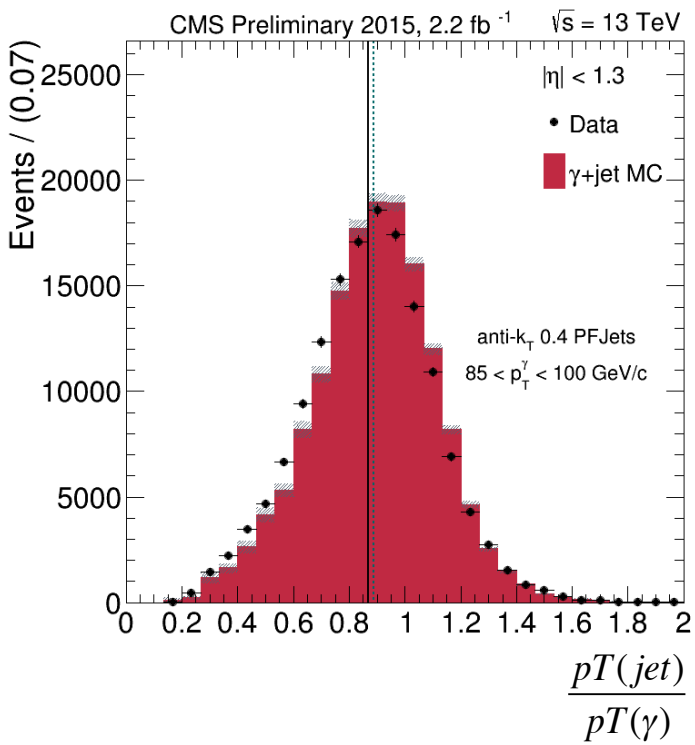
Resolution (γ) much better than Resolution (jet)

- Jet energy calibration using the photon as a reference

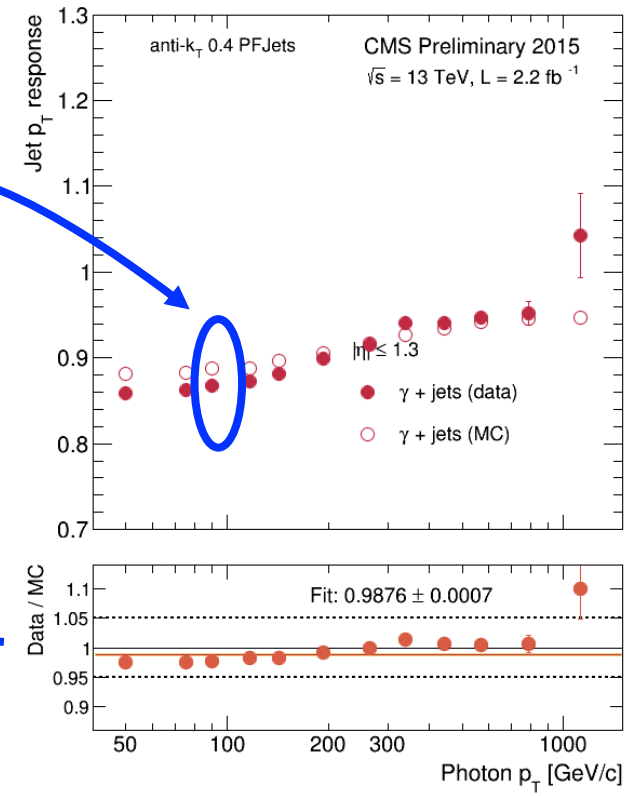
Jet energy calibration

My main activity in 2015

- Jet response = $\frac{pT(jet)}{pT(\gamma)}$
- Calibration in bins of pT and pseudorapidity



fit



Ratio between data and simulation → Corrector factor

Road map: to go

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Dijet resonance search at 13 TeV

Event selection:

- ➢ m(jj) > 1 TeV (★)
  - Due to the trigger threshold
- ➢ cosθ* < 0.57 (★)
  - suppress QCD and enhance signal

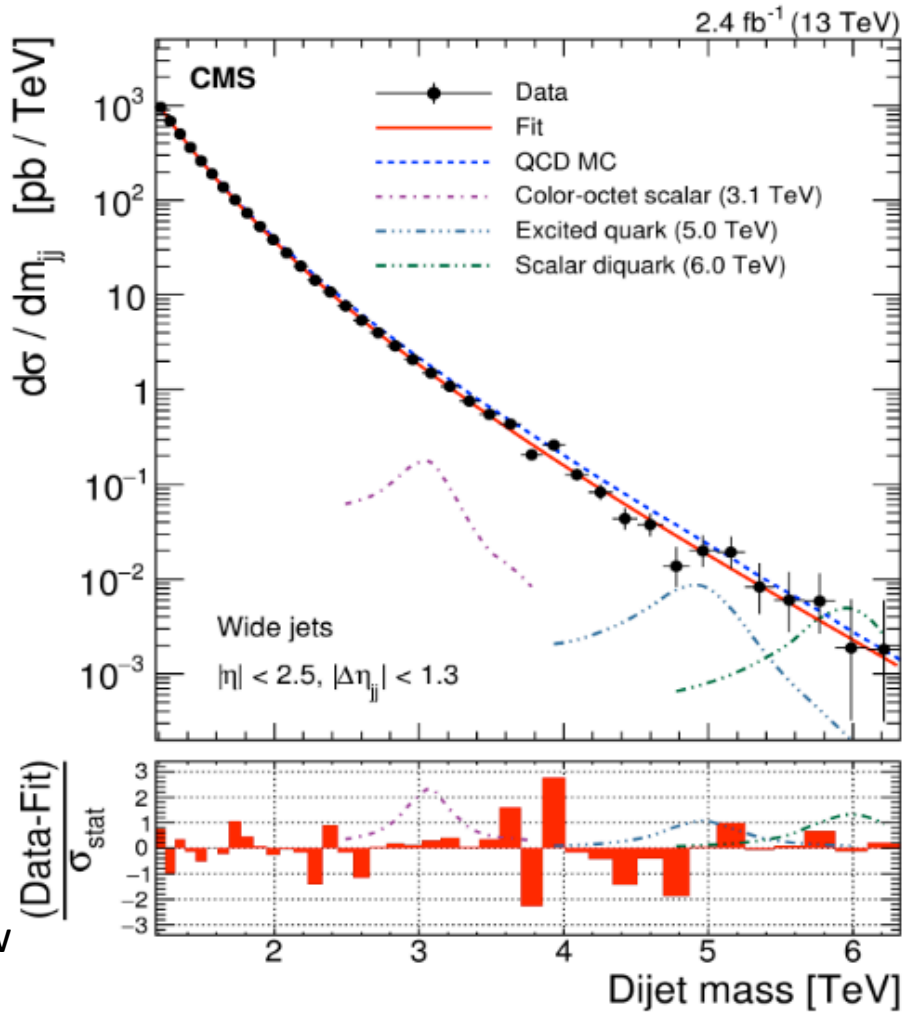
✧ Data fitted with the function:

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0 (1-x)^{p_1}}{x^{p_2 + p_3 \ln(x)}} \quad \text{where} \quad x = \frac{m}{\sqrt{s}}$$

✧ Signal hypothesis superimposed

✧ No excess of events observed

✧ Exclusion limits on the cross section of new resonances



★See next slides

Future perspectives

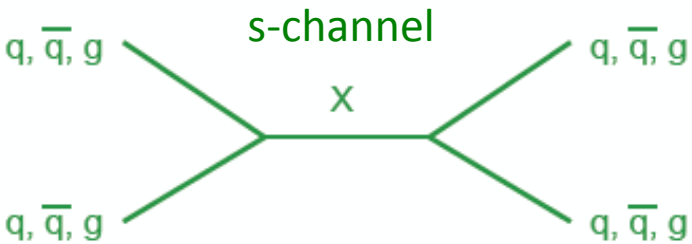
- LHC: energy in the center of mass = 13 TeV
- Expected new data (end of 2017): $\int L\,dt$ = 100 fb^{-1} (25 times larger than 2015)
  - Improvement in sensitivity to new physics
- Analysis extension in order improve the sensitivity to new physics:

Main topics of my PhD project

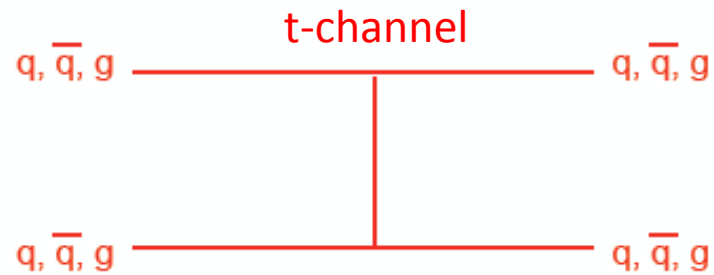
- **Angular analysis**
- **M(jj) < 1 TeV region**

Angular analysis

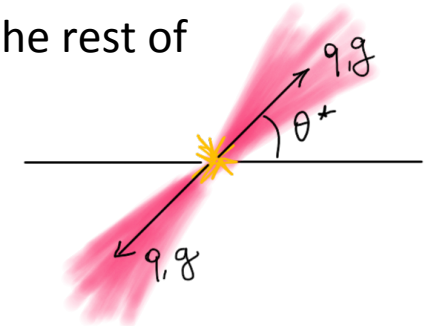
Resonance Signal

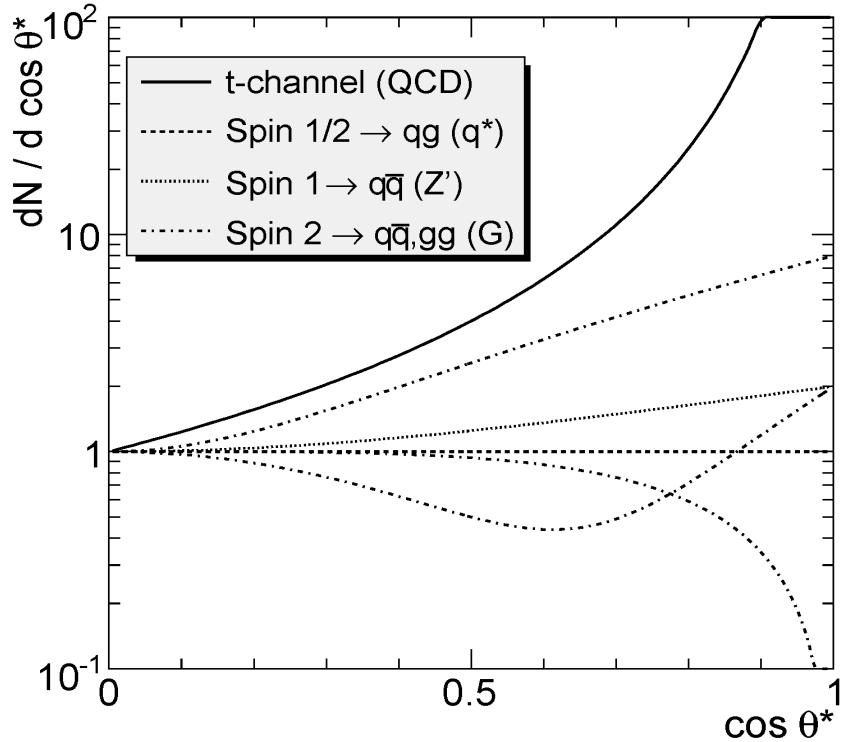


QCD Background



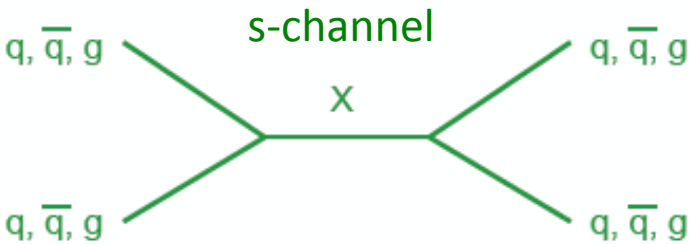
θ* = scattering angle in the rest of frame of the resonance





Angular analysis

Resonance Signal



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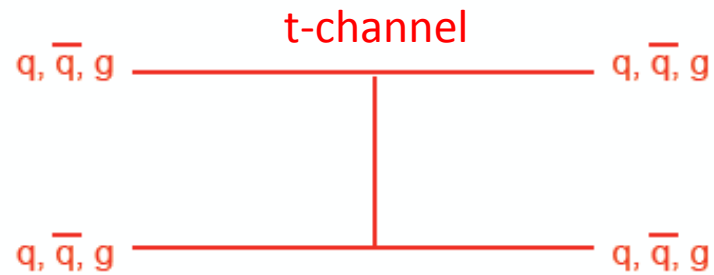

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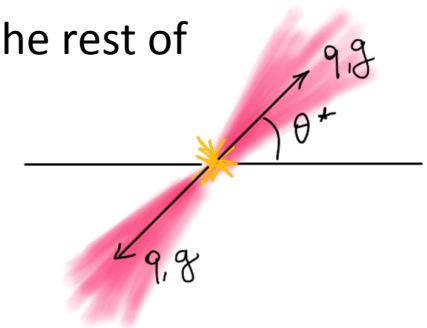
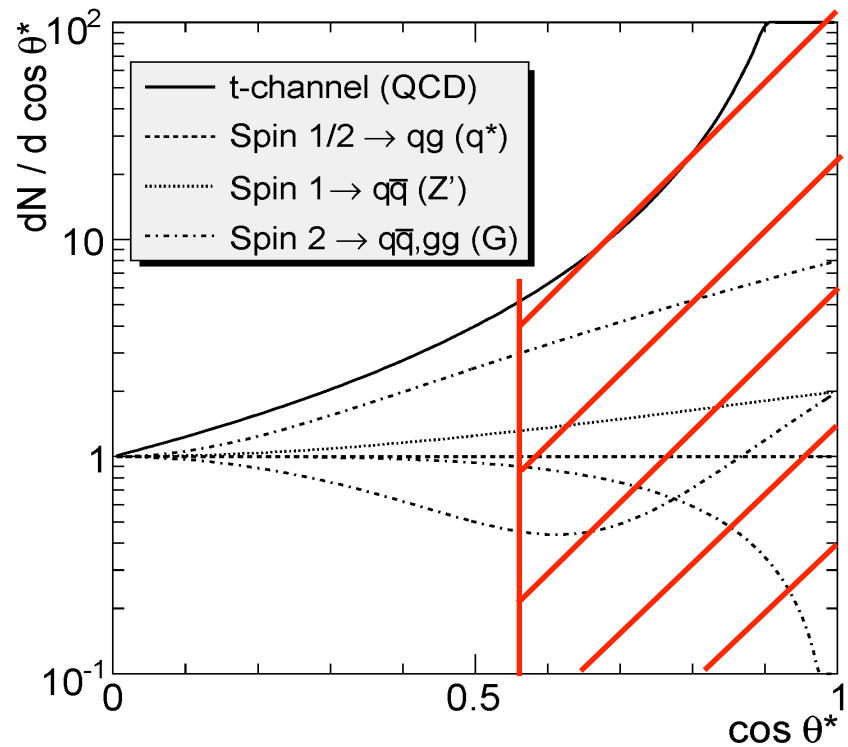
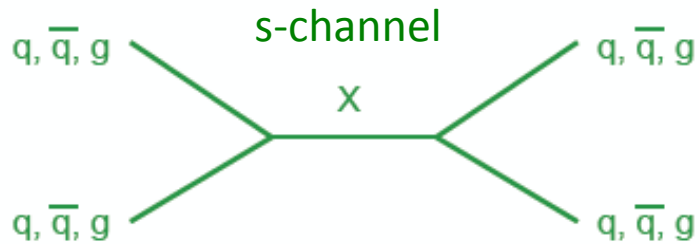




- **Cut in cosθ*:**
  Suppress QCD and enhance the signal
- A signal could be lost in the excluded region

Angular analysis

Resonance Signal



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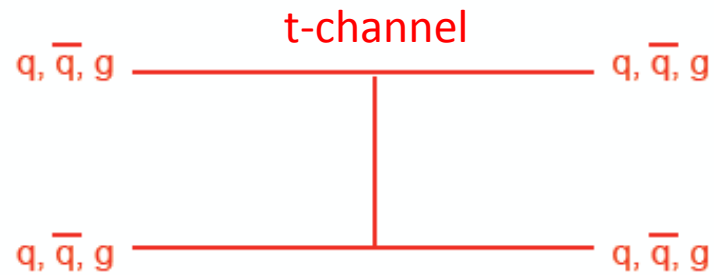

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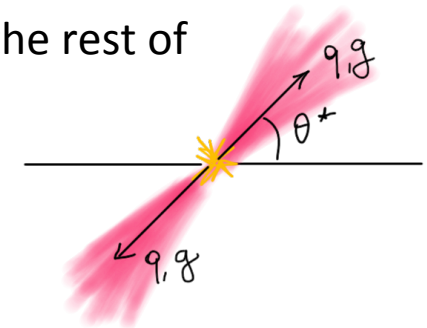
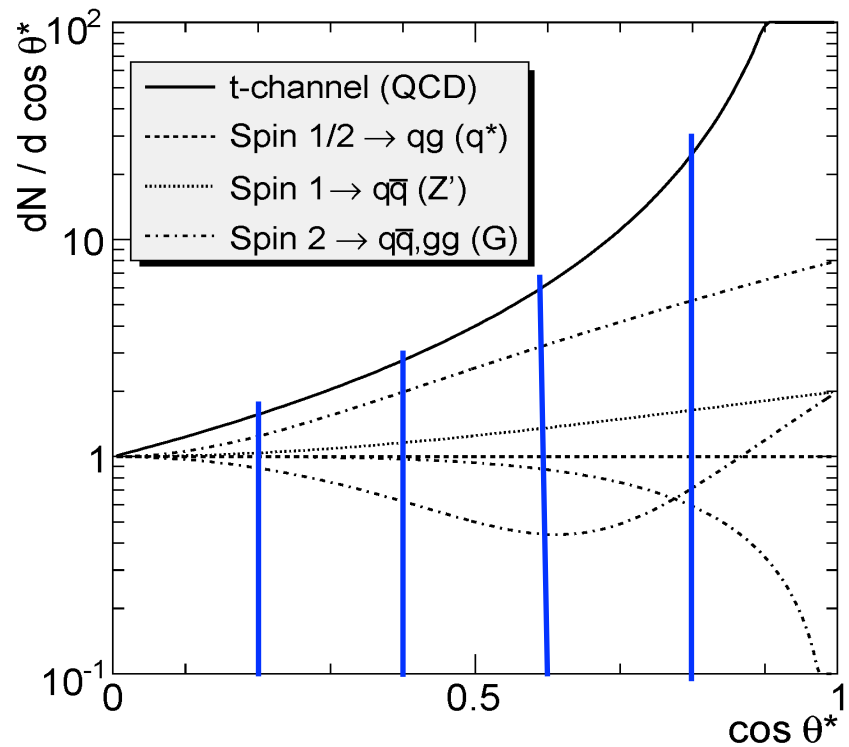


- **Bins of cosθ*:**
  - Whole cosθ* region covered
  - Global sensitivity improved combining the results in different bins
  - Analysis optimized for different hypotheses on the resonance spin

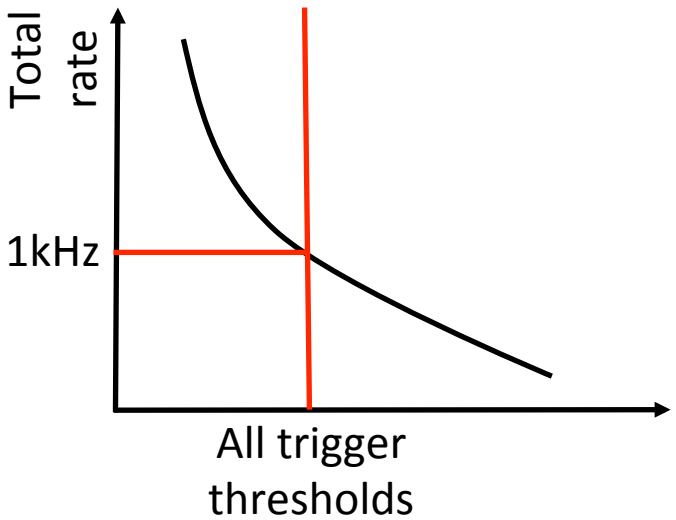


Example of binning

Probing the region below 1 TeV

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

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



Two possible approaches:

- **Raise trigger thresholds**

pT_{jet} > 500 GeV → analysis: M(jj) > 1.2 TeV

"standard" analysis → **can not** probe resonances with mass below 1.2 TeV

- **Decrease trigger threshold + Reduce event size = data scouting**
  → event size = 10 kB/event
  → Can afford large event rate

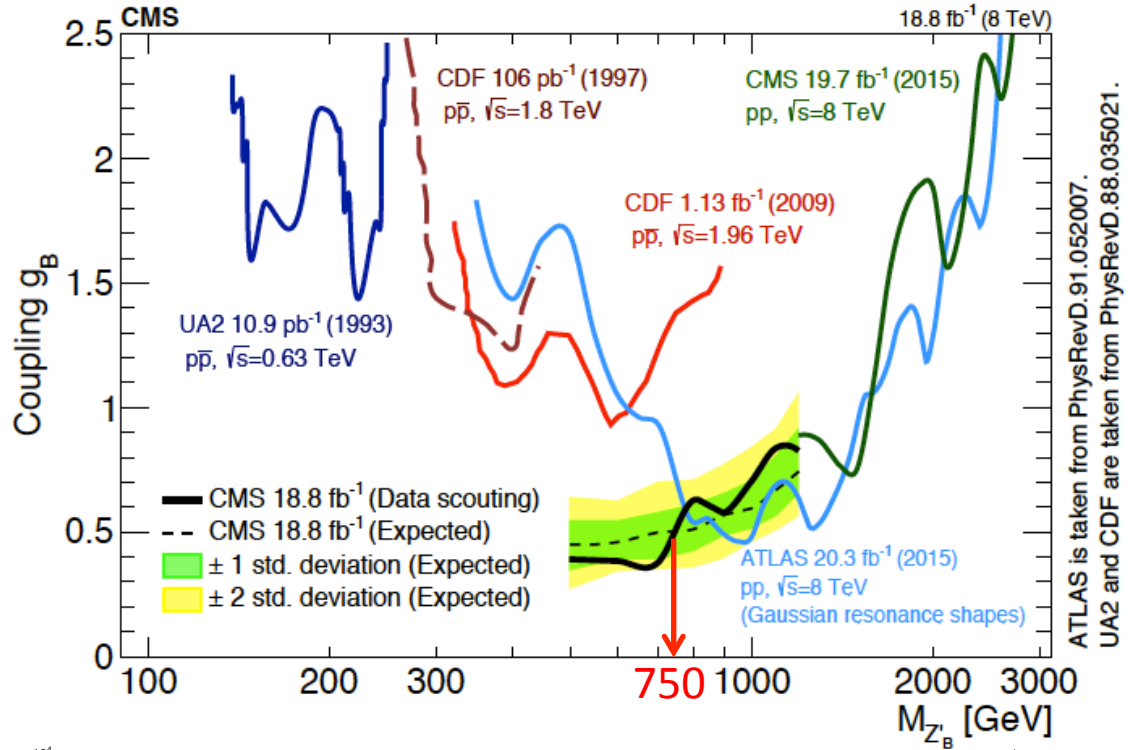
pT_{jet} > 200 GeV → analysis: M(jj) > 600 GeV

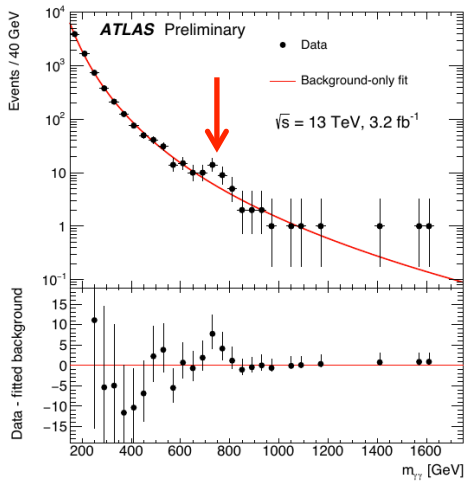
Data scouting results at 8 TeV

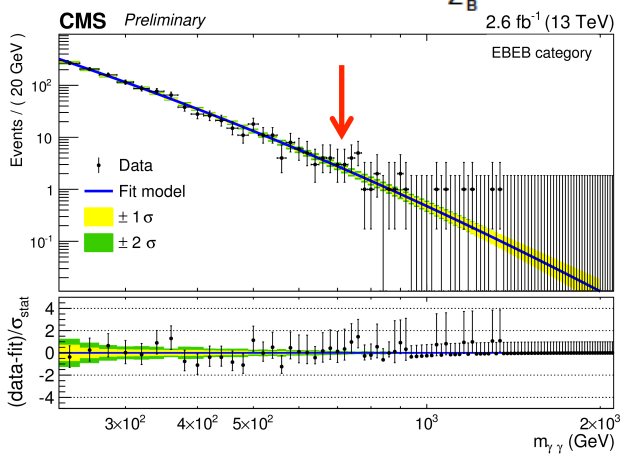
- **Run 1 result**:
  - data scouting covered
    500 GeV < mjj <1.2 TeV
  - Limits improved compared to previous experiments
  - Sensitivity at small coupling with data scouting

- **Run 2:** Much more data → higher sensitivity than Run 1

- Low mass region also interesting given the last ATLAS and CMS result in the final state X → $\gamma\ \gamma$







Road map

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2016 → Search for dijet resonances with **mass > 1 TeV**

- Add more data at 13 TeV
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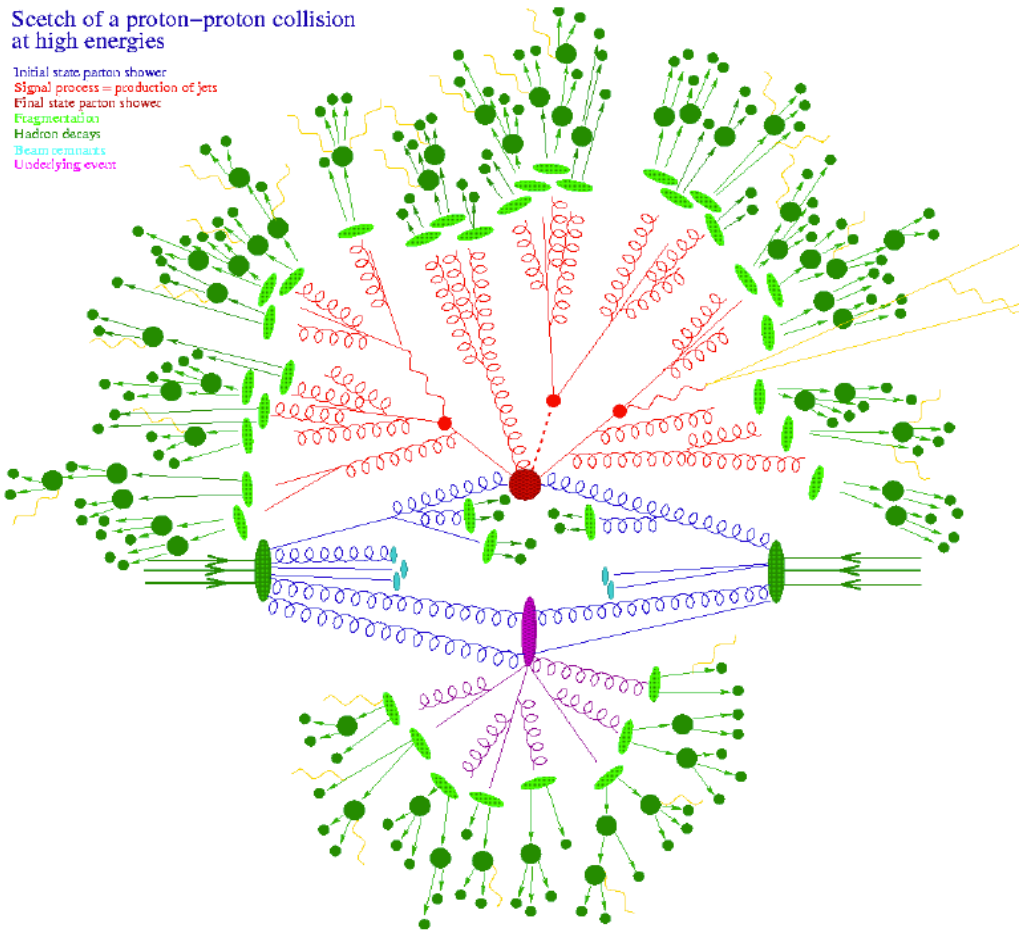
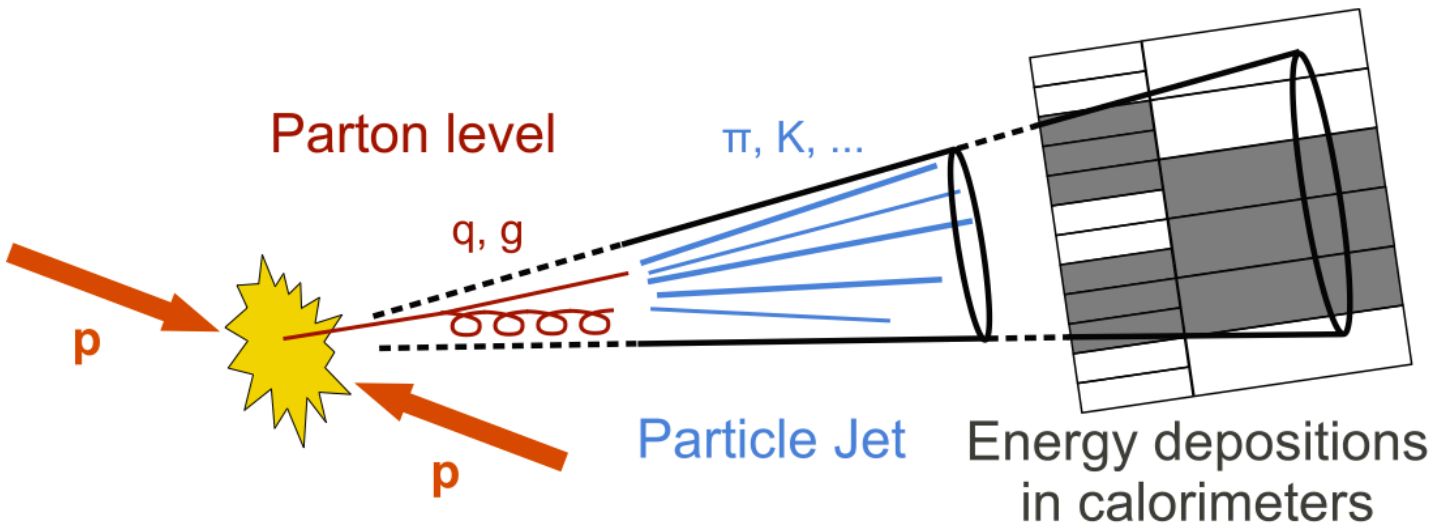
BACKUP

Hadron Collisions



- Proton sub-structure:
  quarks and gluons
- At high energy, **asymptotic freedom**
- Most of the interactions at low energy, **many soft particles produced**
- **Head-on collisions:**
  Hard interactions
- **Color confinement**
  Quarks and gluons hadronization:
  jets of collimated particles

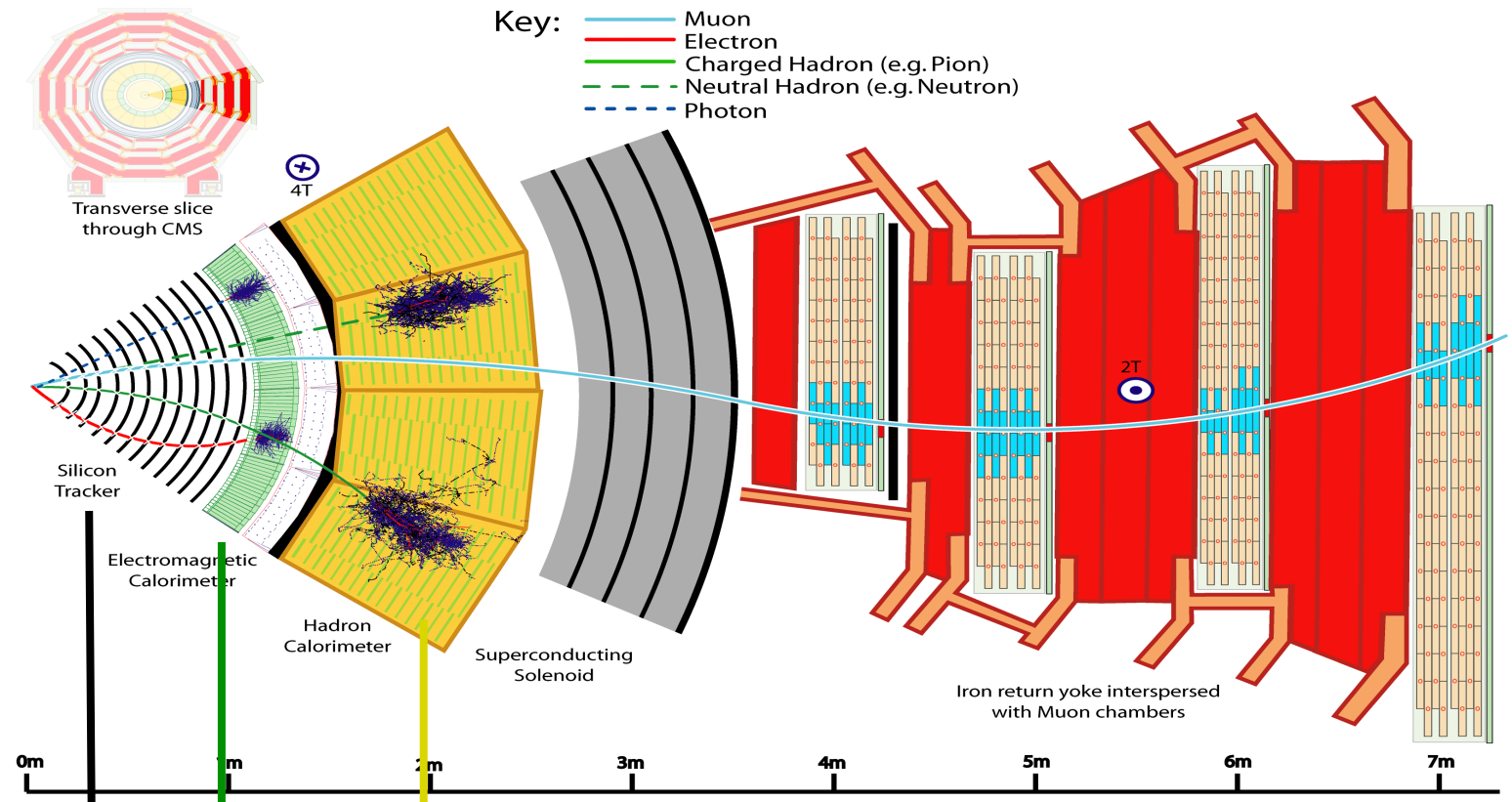
Quarks/gluons hadronization



- Proton-proton collision produces quarks and gluons
- Confinement: Quarks and gluons do not exist as free particle → hadrons produced
- Hadrons form a collimated jet of particles

Two quarks/gluons → Hadronization → **Final state: two jets**

Compact Muon Solenoid



Tracker

Electromagnetic calorimeter

Hadronic calorimeter

Sub-detector information used to reconstruct single particle that form a jet

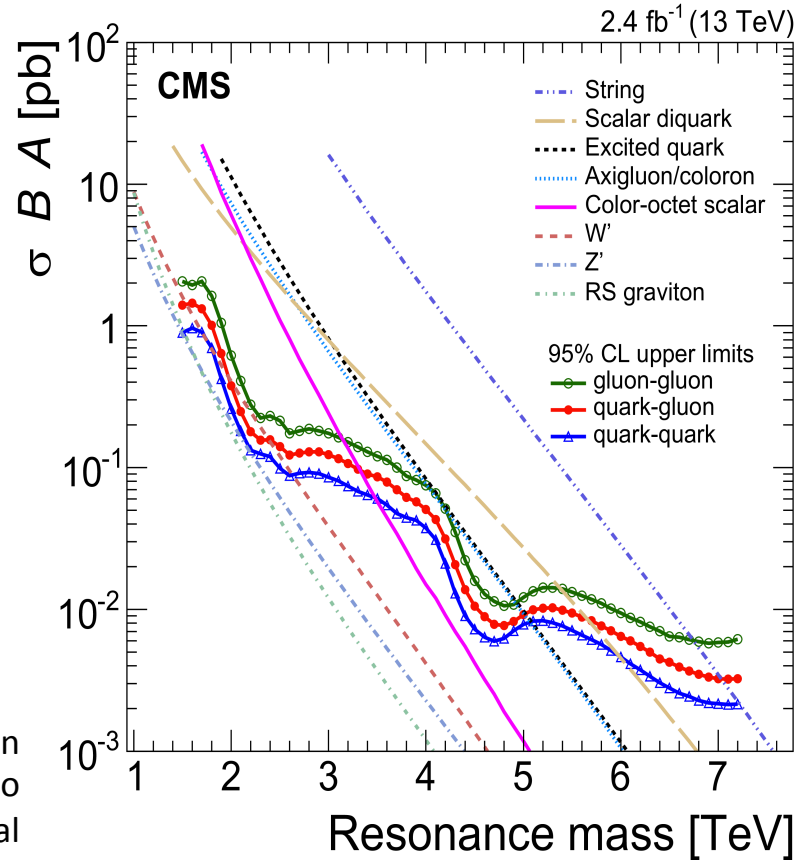
Exclusion limits

No excess observed in the dijet mass spectrum

Exclusion limits on cross section

Upper limits on cross sections: Highest cross section for the signal hypothesis given the data observed (@ 95 % C.L.)

$\sigma_{th} > \sigma_{upper\ limit}$ **excluded** (@95% C.L.)

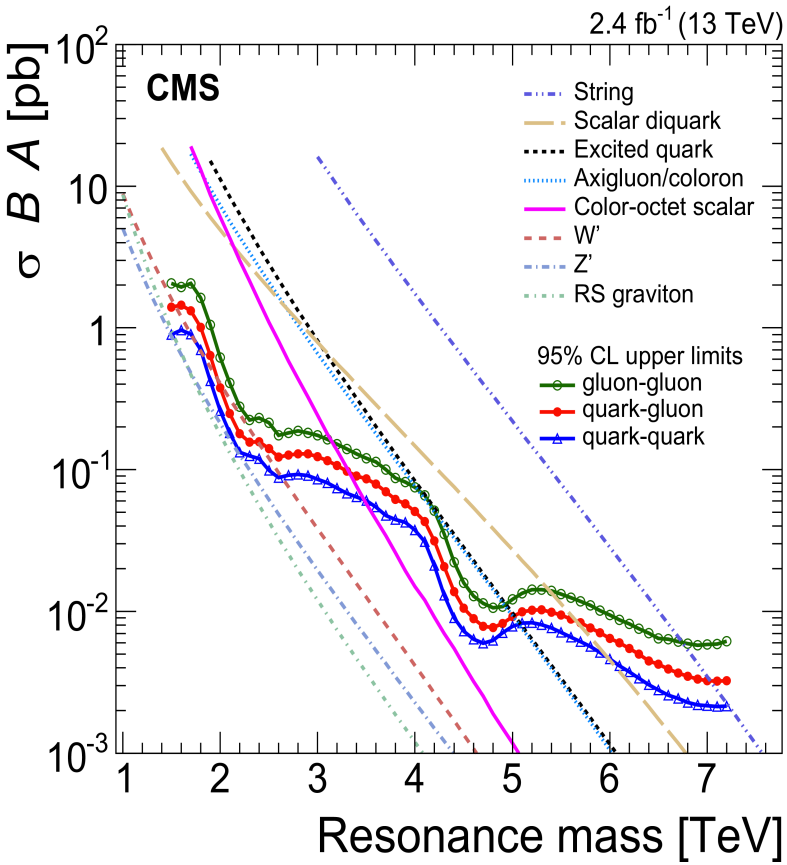


Sigma = cross section
B = Branching Ratio
A = geometrical acceptance of detector

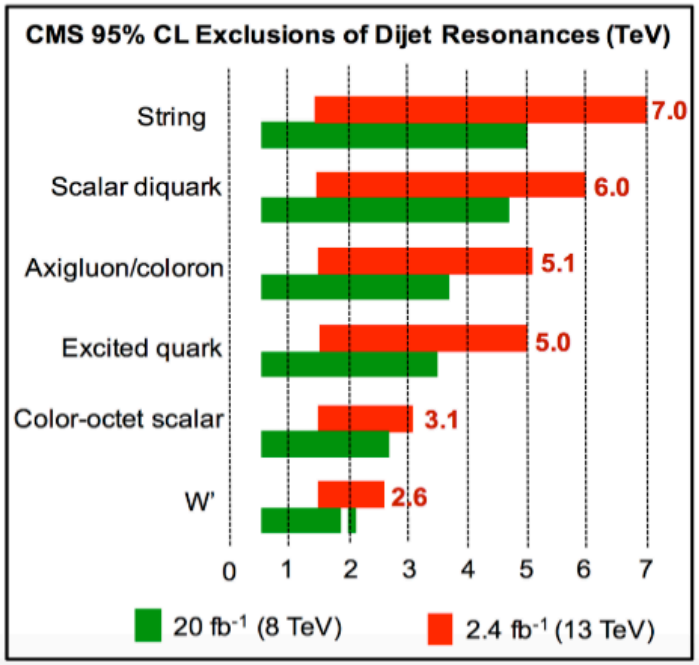
Limits

No excess observed in the dijet mass spectrum

Exclusion limits on cross section



Comparison with Run 1 results



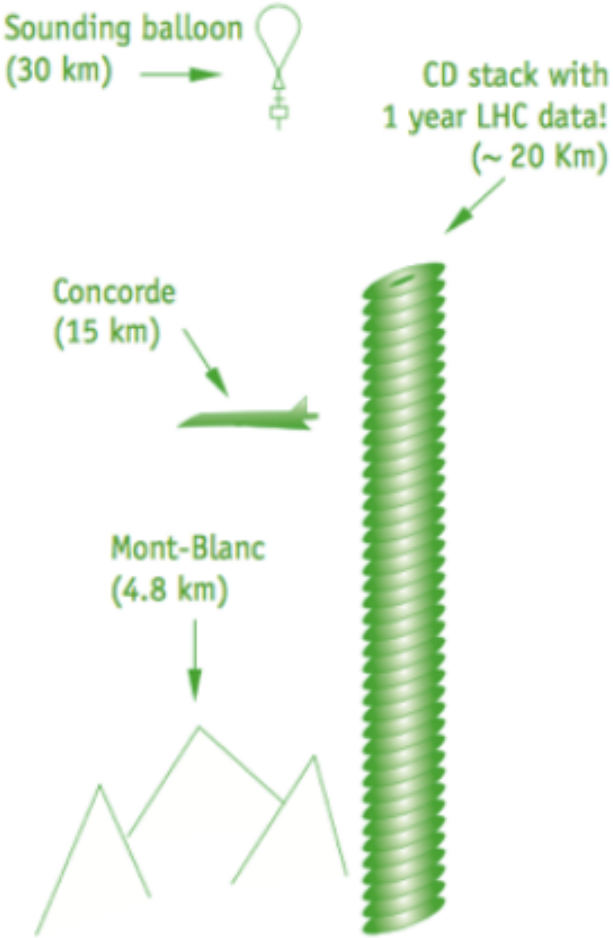
All limits already improved

Data @ LHC

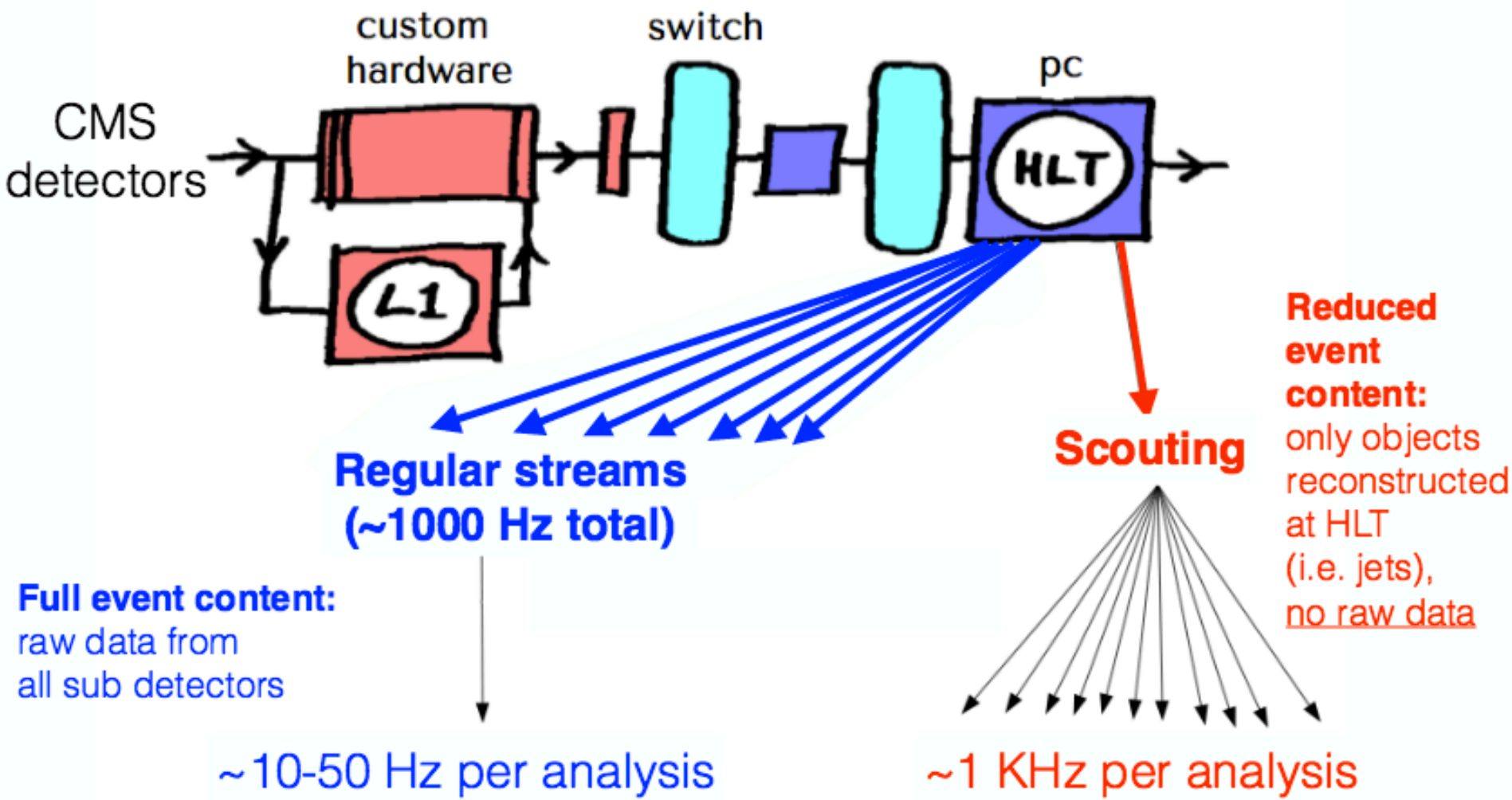
LHC:

- up to 40 million collisions/second (MHz)
- 1-1.5 MB/data per collision
- 40 MHz * 1 MB = 40 GB/s

Saved on CD → 20 Km of lenght!

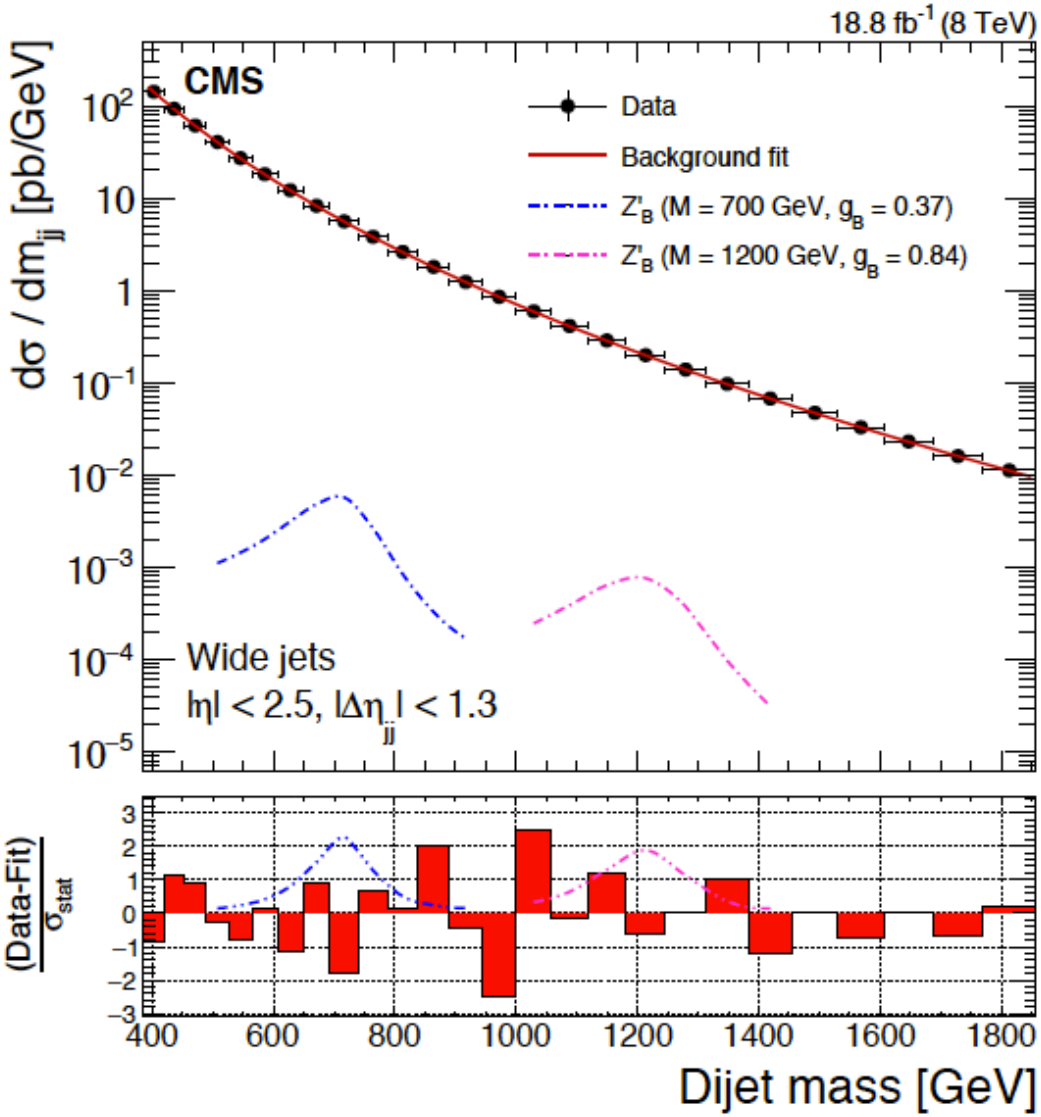


Data scouting



Run 1 data scouting

Analysis down to 400 GeV



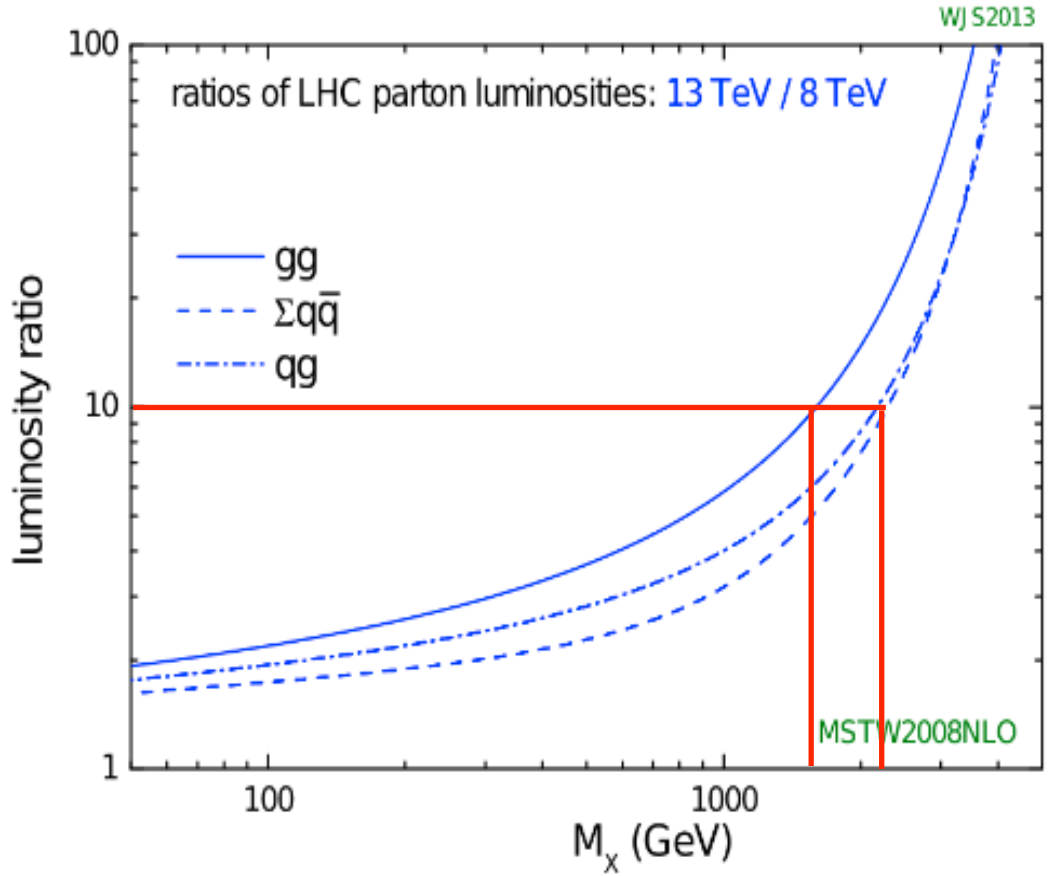
8 TeV vs 13 TeV

- The probability to produce a high mass resonance is much higher at 13 TeV w.r.t. 8 TeV

- @ 13 TeV → 2.4 fb^{-1}
- @ 8TeV → 20 fb^{-1}

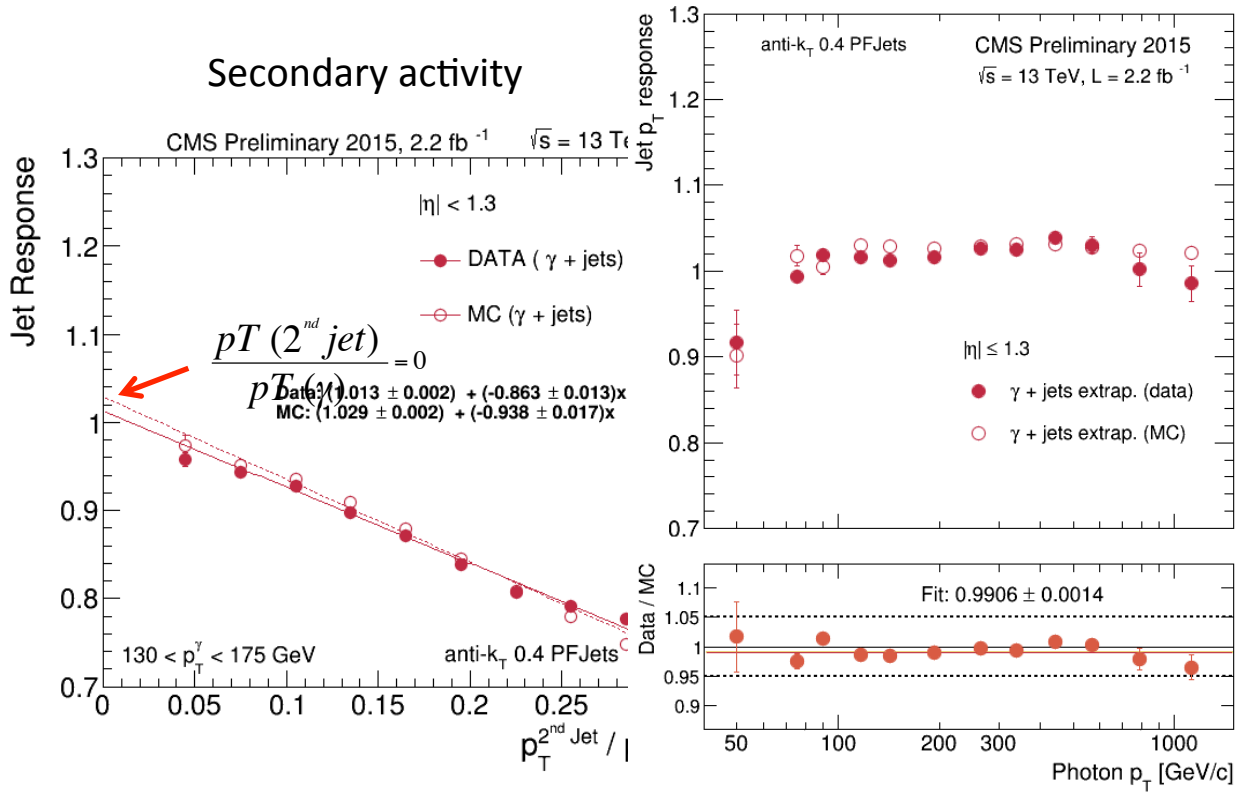
→ Ratio ~ 10

→ Dijet(13 TeV) higher sensitivity than Dijet(8 TeV) for mass > ~2 TeV



Response extrapolation

Secondary activity



$$\frac{pT\ (2^{nd}\ jet)}{pT\ (\gamma)} = 0$$

Likilehood

Binned likelihood

$$L = \prod_k \frac{\mu_k^{n_k} e^{-\mu_k}}{n_k!}$$

Where
n_k = measured number of events in the kth bins

$$\mu_k = N_k(B) + N_k(S)$$

= expected number of events in the kth bins

Probability density as a function of signal cross section