CHICAGO 2012 Workshop on LHC Physics in the Higgs Era

LHC Searches with Jets and Photons

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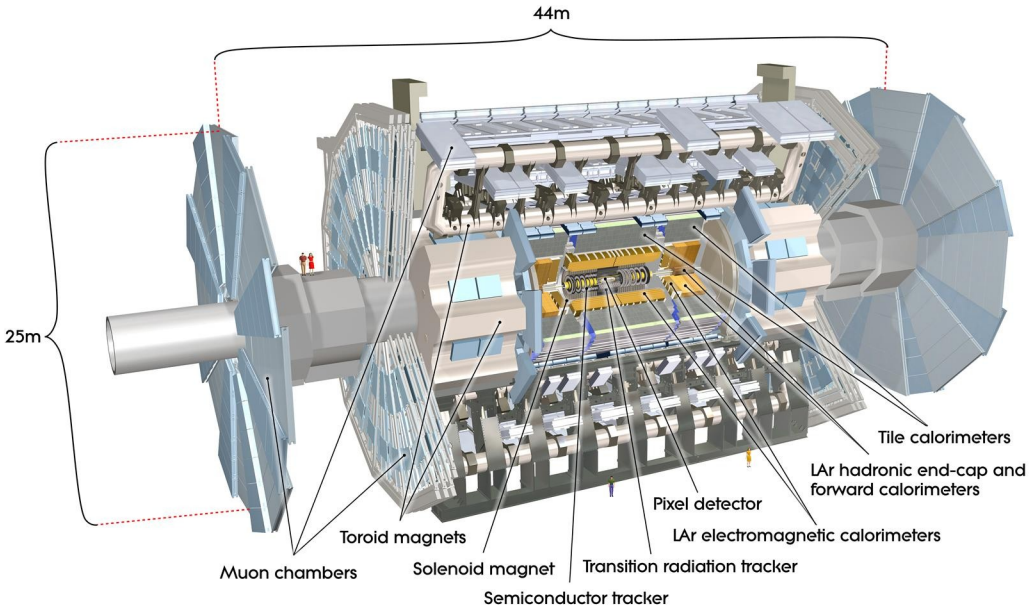
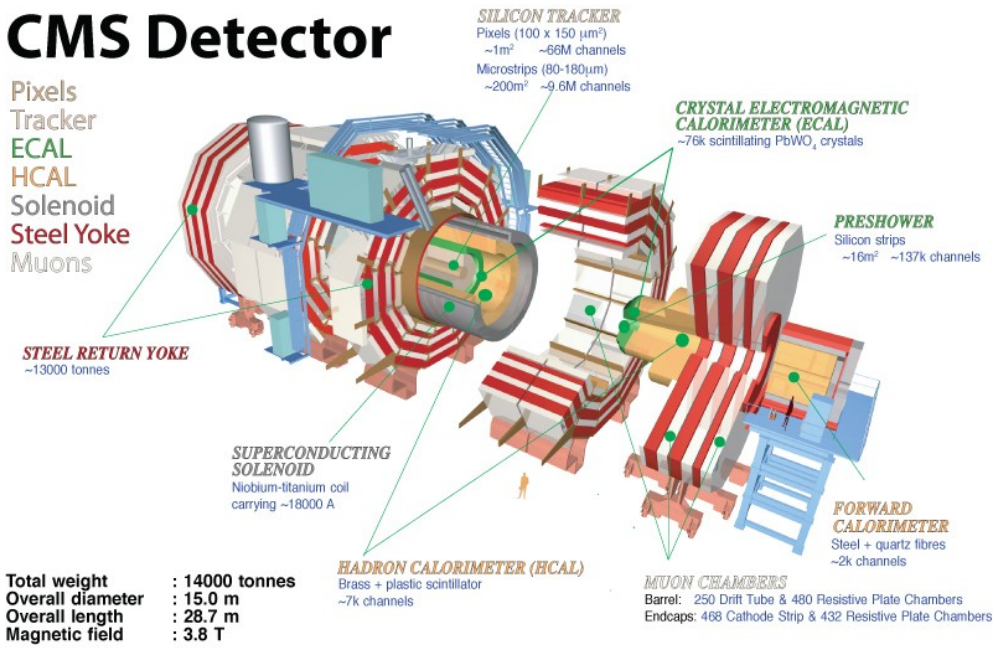
Outline

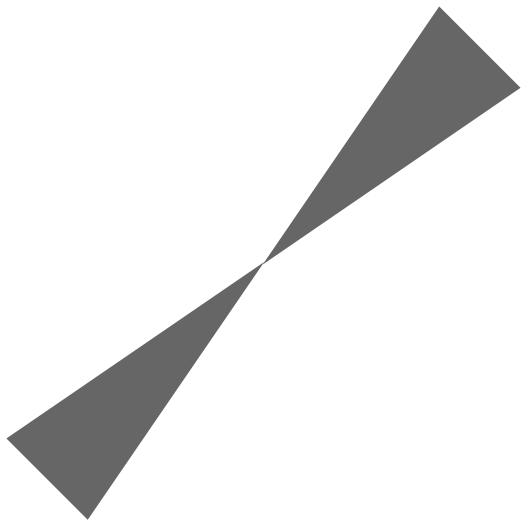
- This talk will cover ATLAS and CMS searches with jets and photons in the following final-state topologies:
  - Dijets
  - Photon+jet
  - Diphotons
  - Paired dijets
  - Paired trijets
  - 8-jet final states
- Above event topologies sensitive to the production of new particles, existence of new types of interactions, presence of extra dimensions, possible substructure of the fundamental constituents of matter
- To avoid overlaps with other sessions, searches involving MET (monojets, monophotons,...) and jet substructure will not be covered
- Also, due to the limited available time, searches for microscopic black holes will not be covered

ATLAS and CMS Detectors





Dijets

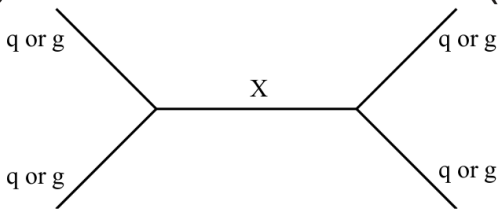


ATLAS: arXiv:1210.1718, ATLAS-CONF-2012-088

CMS: EXO-11-094+EXO-11-008 (arXiv:1210.2387), EXO-12-016, EXO-11-017 (arXiv:1202.5535), EXO-11-026

Dijet Mass Spectrum (√s=7 TeV)

- Searching for resonant structures ("bumps") in a smoothly falling dijet mass spectrum



ATLAS

- Using a single jet trigger
- Jets reconstructed from calorimeter clusters using the anti-k_T clustering algorithm with R=0.6
- Event selection:
  - $|\eta|<2.8$ and $|y^*|<0.6$, where $y^*=1/2(y_1-y_2)$
  - $m_{jj}>850$ GeV (driven by the requirement of fully efficient trigger)

CMS

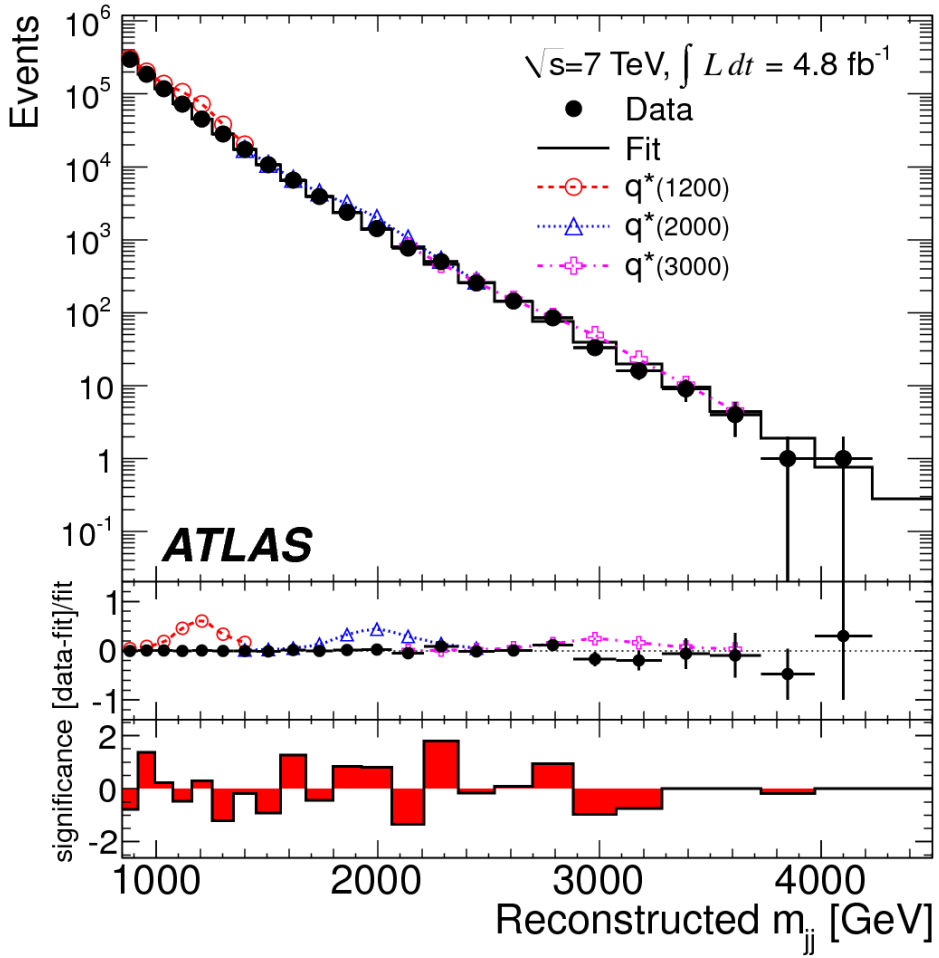
- Using H_T and dedicated dijet mass triggers
- Jets reconstructed from particle-flow particle candidates using the anti-k_T clustering algorithm with R=0.5 (AK5 jets)
- Using "wide jets" formed by clustering together all AK5 jets with $p_T>30$ GeV and $|\eta|<2.5$ within $\Delta R<1.1$ around the 2 leading AK5 jets (collects final-state radiation and improves dijet mass resolution)
- Event selection:
  - Wide jet $|\eta|<2.5$ and $|\Delta\eta|<1.3$
  - $m_{jj}>890$ GeV (driven by the requirement of fully efficient trigger)

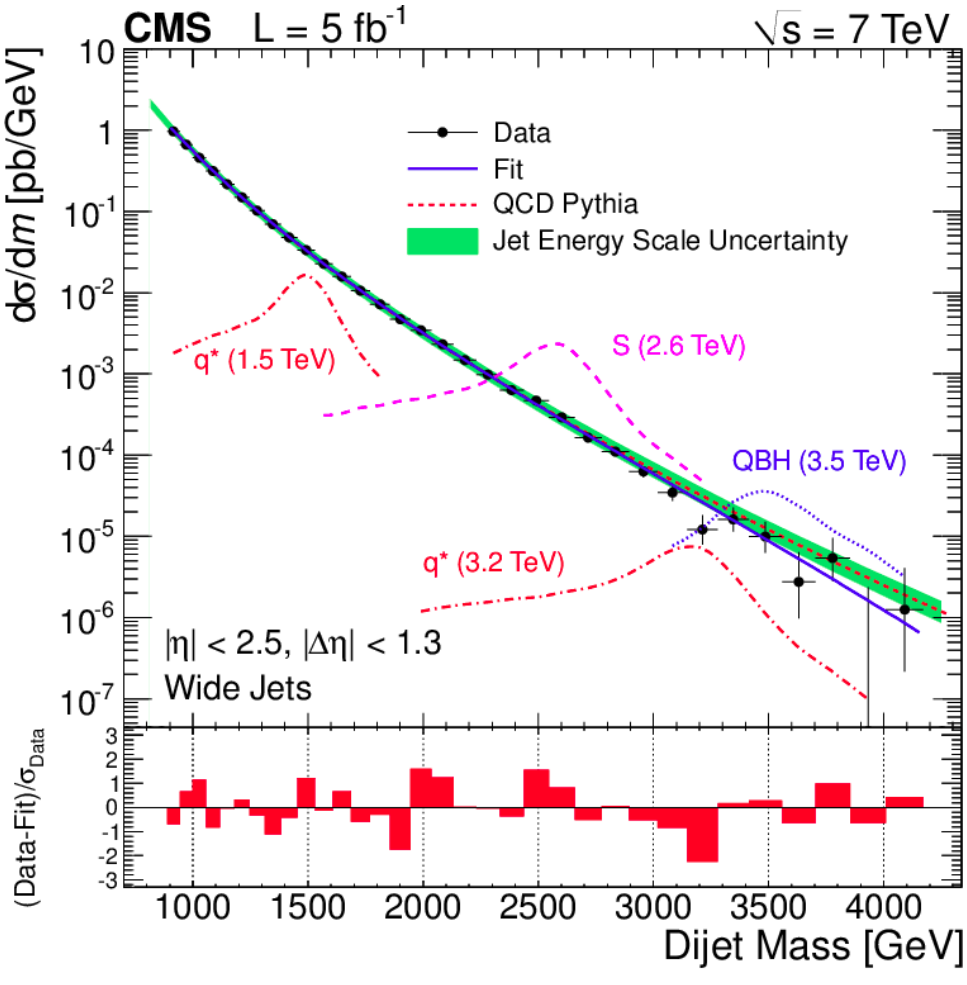
- Dijet mass spectrum is fit to a smooth functional form (which allows smooth variations but does not accommodate localized excesses)

$$\frac{d\sigma}{dm} = \frac{P_0(1-m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2+P_3\ln(m/\sqrt{s})}}$$

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] \qquad y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$
$$\Delta R = \sqrt{(\Delta\eta)^2+(\Delta\phi)^2}$$

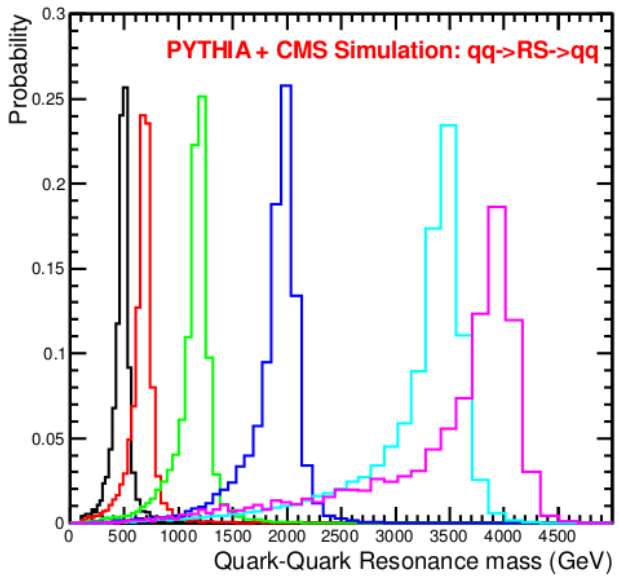
Dijet Mass Spectrum (√s=7 TeV)

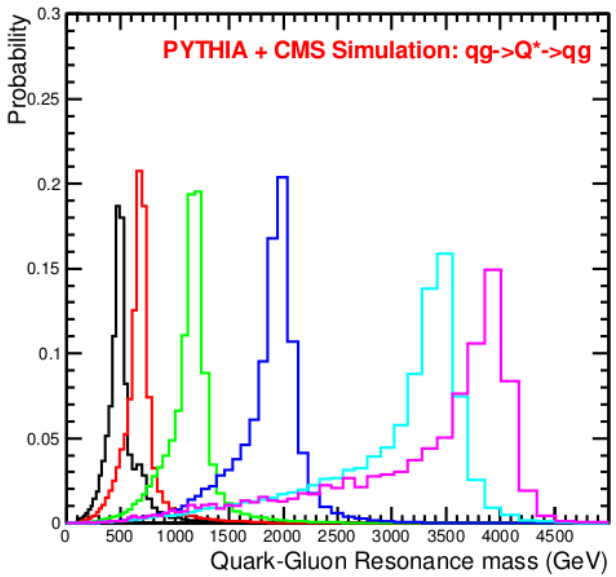


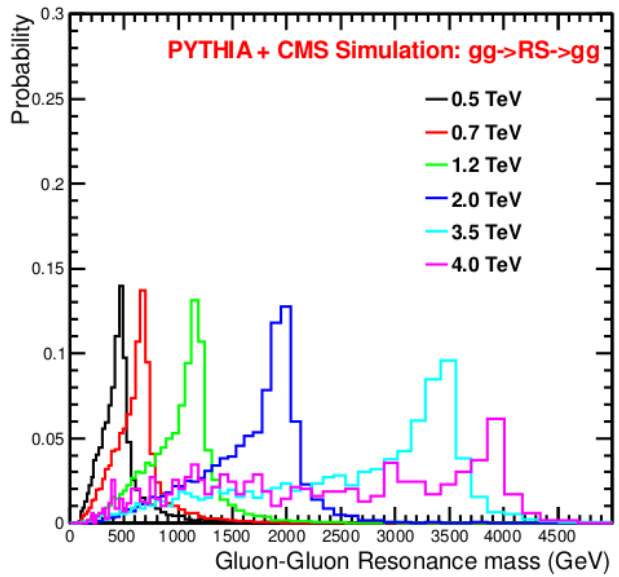


No evidence for new resonances in the dijet mass spectrum

Dijet Mass Spectrum (√s=7 TeV)





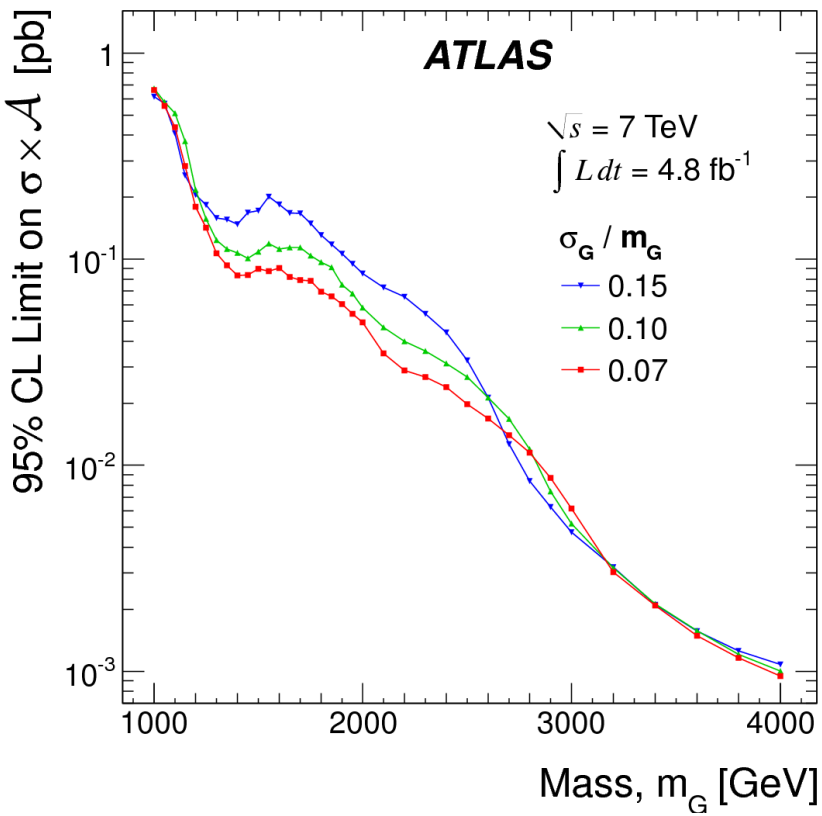


- CMS signal modeling:
  - Narrow resonances modeled using 3 types of resonance shapes based on parton pairings:
    - $q\bar{q}$ (or qq) (from PYTHIA6 G → $q\bar{q}$)
    - qg (from PYTHIA6 q* → qg)
    - gg (from PYTHIA6 G → gg)
  - QBH dijet mass shapes from QBH+PYTHIA6 simulation

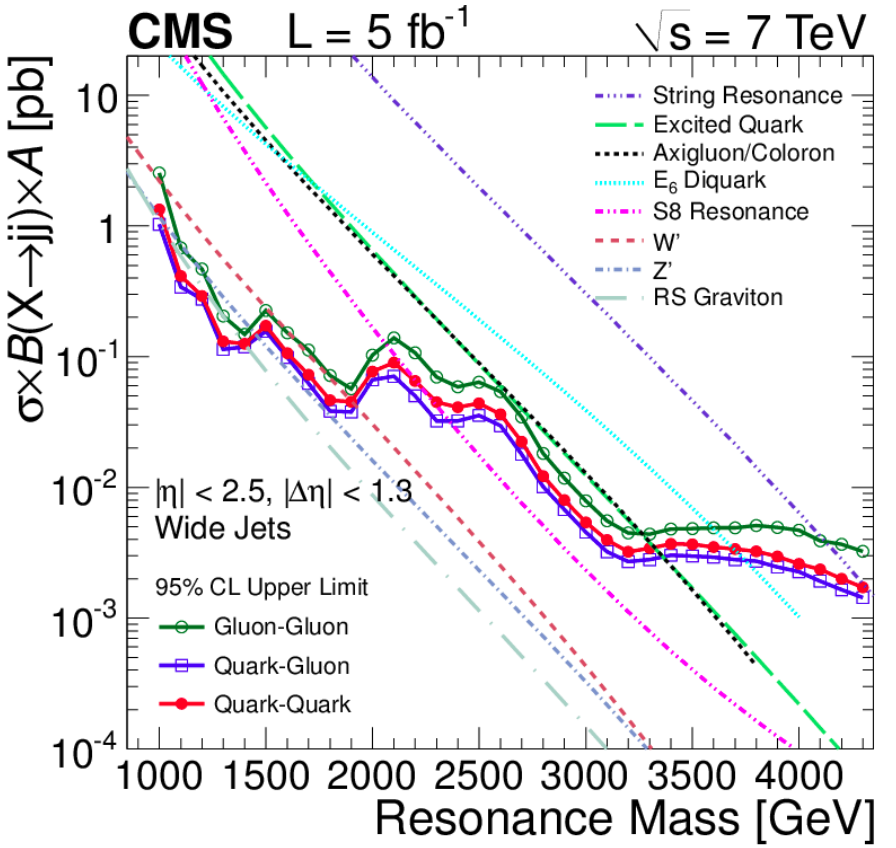
Gaussian core from jet energy resolution and low mass tail from QCD radiation and steeply falling PDFs

- ATLAS uses model-specific resonance shapes and Gaussian shapes for model-independent limits
- Dijet mass shapes, measured dijet mass spectrum, and the smooth background fit used to set limits

Dijet Mass Spectrum (√s=7 TeV)

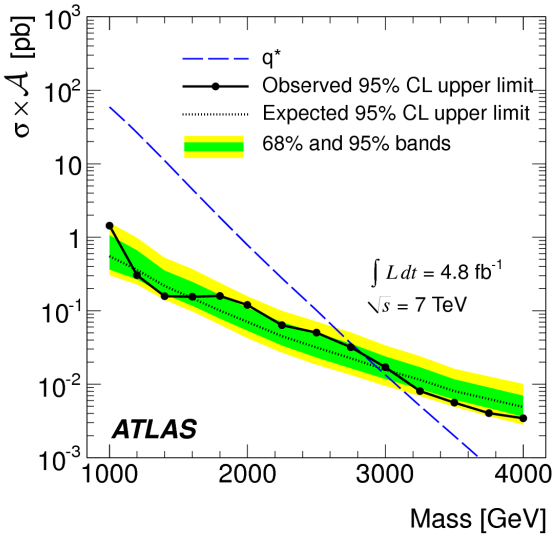


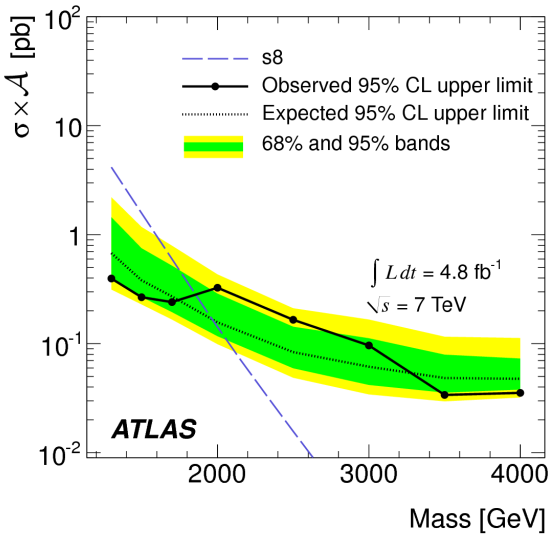
- Model-independent limits with Gaussian resonance shapes of varying widths

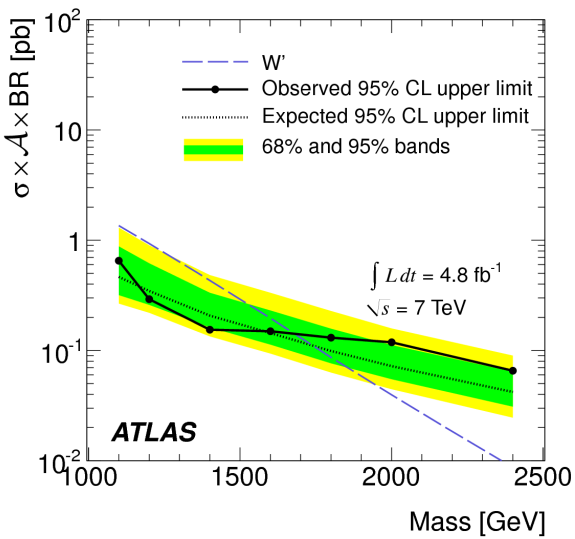


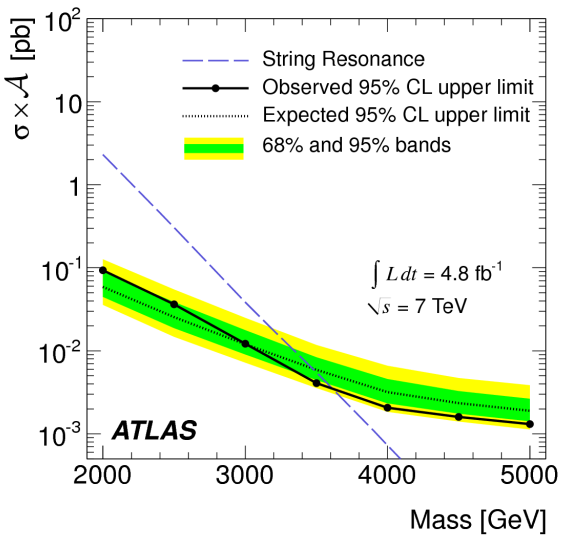
- Model-independent limits on qq, qg, and gg resonances

Dijet Mass Spectrum (√s=7 TeV)

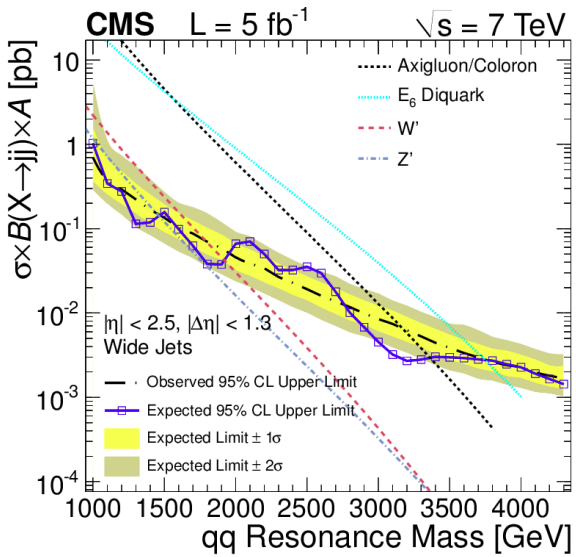


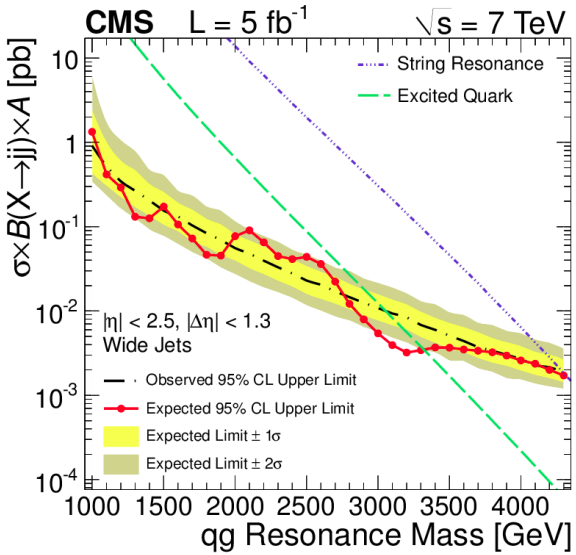


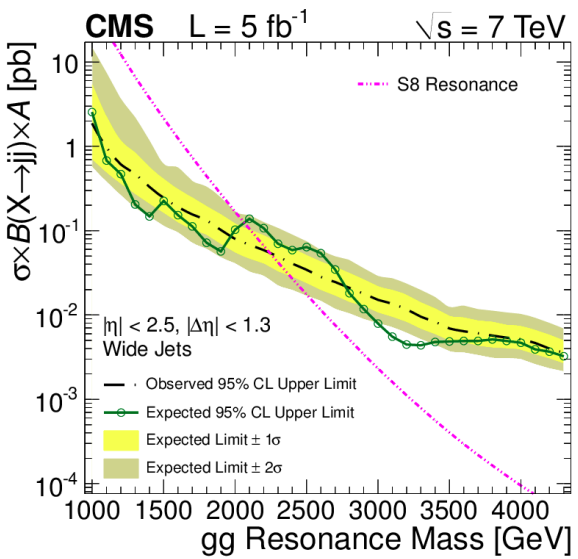


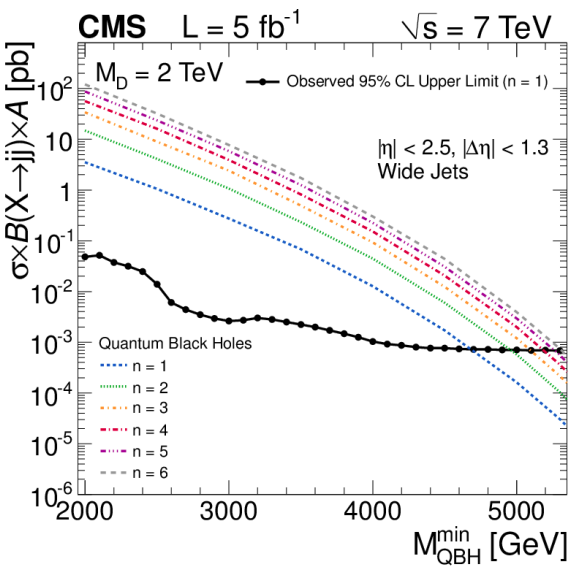


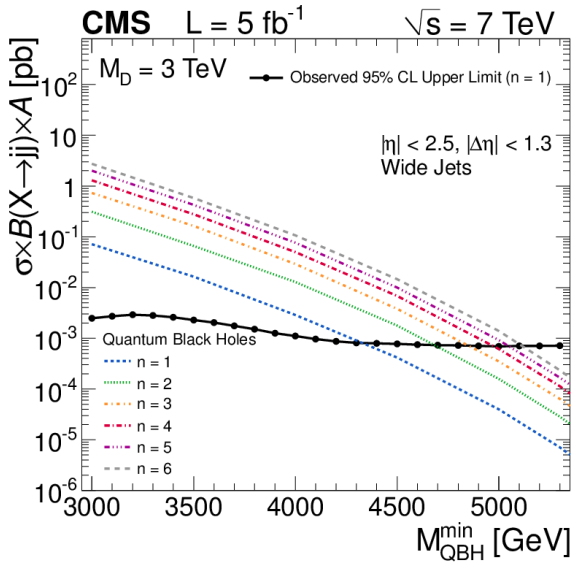
Dijet Mass Spectrum (√s=7 TeV)

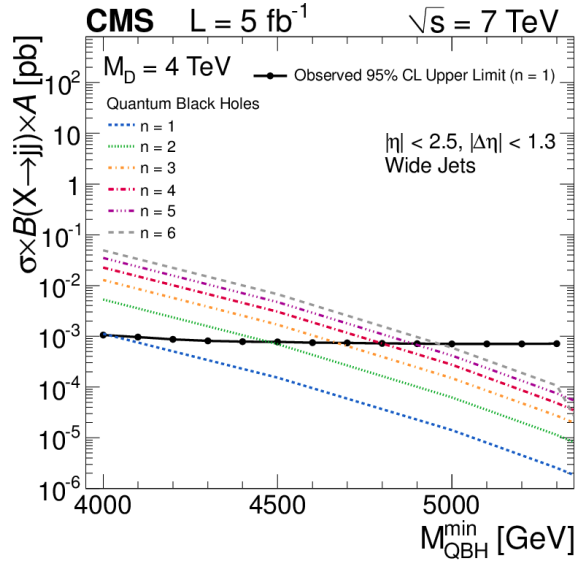










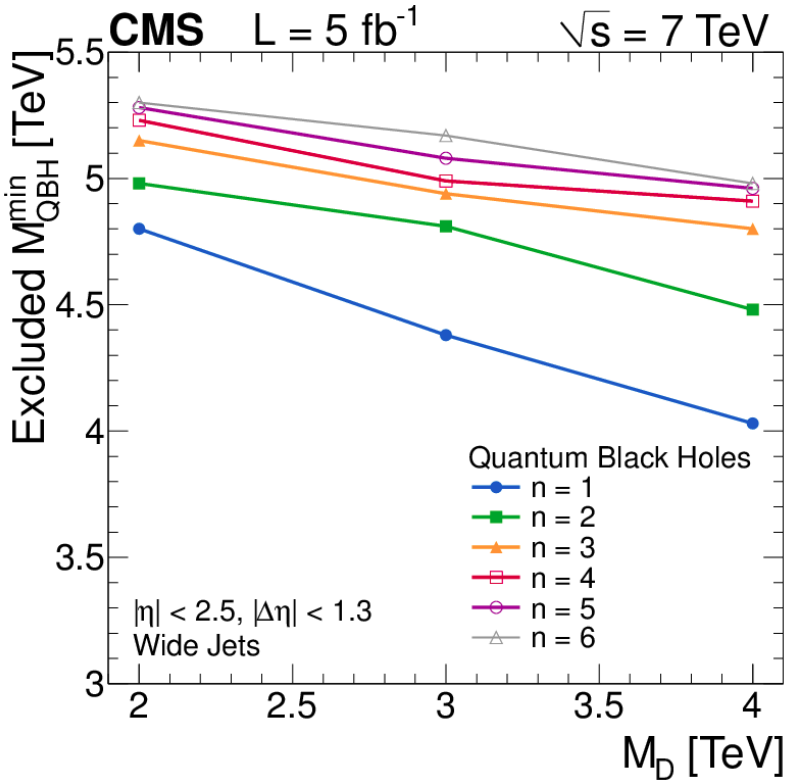


Dijet Mass Spectrum (√s=7 TeV)

- ATLAS resonance mass limits:

Model and Analysis Strategy	95% CL Limits [TeV] Expected	Observed
Excited quark, mass of q^*		
Resonance in m_{jj}	2.94	2.83
Colour octet scalar, mass of s8		
Resonance in m_{jj}	1.97	1.86
Heavy W boson, mass of W'		
Resonance in m_{jj}	1.74	1.68
String resonances, scale of SR		
Resonance in m_{jj}	3.47	3.61

- CMS QBH limits:

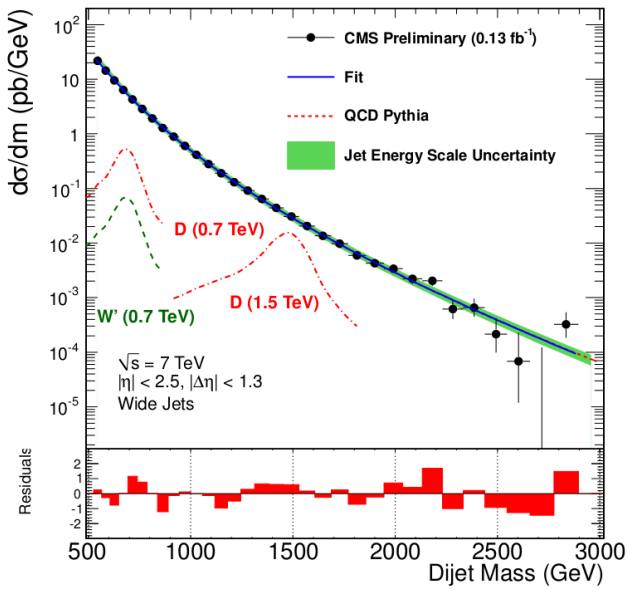


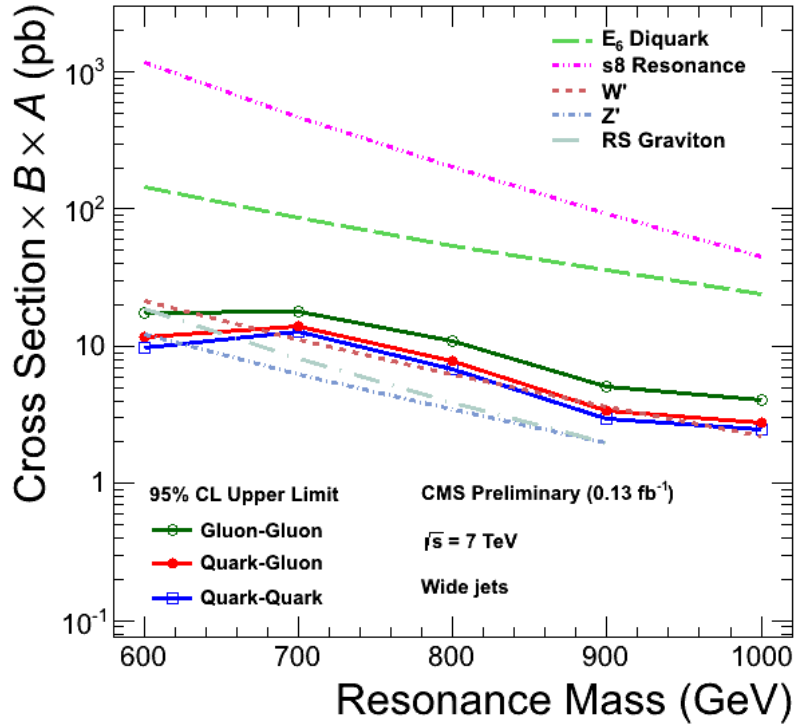
- CMS resonance mass limits:

Model	Final State	Exp. Mass Exclusion [TeV]	Obs. Mass Exclusion [TeV]
String Resonance (S)	qg	[1.0, 4.29]	[1.0, 4.31]
Excited Quark (q*)	qg	[1.0, 3.05]	[1.0, 3.32]
E_6 Diquark (D)	qq	[1.0, 3.74]	[1.0, 3.75]
Axigluon (A) / Coloron (C)	$q\bar{q}$	[1.0, 3.16]	[1.0, 3.36]
S8 Resonance (S8)	gg	[1.0, 2.24]	[1.0, 2.07]
W′ Boson (W′)	$q\bar{q}$	[1.0, 1.78]	[1.0, 1.92]
Z′ Boson (Z′)	$q\bar{q}$	[1.0, 1.45]	[1.0, 1.47]

Dijet Mass Spectrum (√s=7 TeV)

- Complementary low-mass search performed using novel triggering and data acquisition strategy introduced in the last few fills of the 2011 run
- Lower trigger thresholds lead to higher event rate → Storing reduced data format (HLT jets) in order to keep the total used bandwidth under control



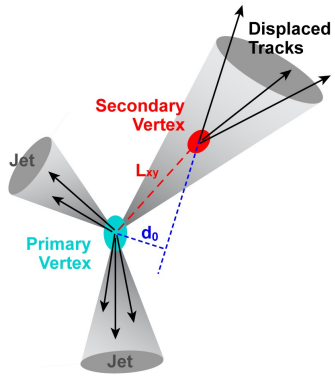


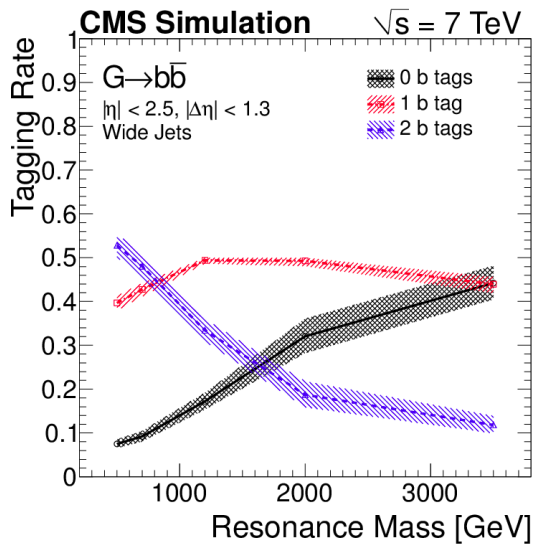
Model	Final State	Obs. Mass Exclusion [TeV]	Exp. Mass Exclusion [TeV]
String Resonance (S)	qg	[0.6, 4.32]	[0.6,4.28]
Excited Quark (Q*)	qg	[0.6, 3.27]	[0.6,3.05]
E_6 Diquark (D)	qq	[0.6, 3.75]	[0.6,3.72]
Axigluon (A) / Coloron (C)	$q\bar{q}$	[0.6, 3.34]	[0.6,3.17]
s8 Resonance (s8)	gg	[0.6, 2.07]	[0.6,2.25]
W′ Boson (W′)	$q\bar{q}$	[0.60, 0.69]	
		[0.82, 0.96]	[0.60, 0.88]
		[1.0,1.90]	[1.0, 1.77]
Z′ Boson (Z′)	$q\bar{q}$	[1.0, 1.45]	[1.0,1.44]

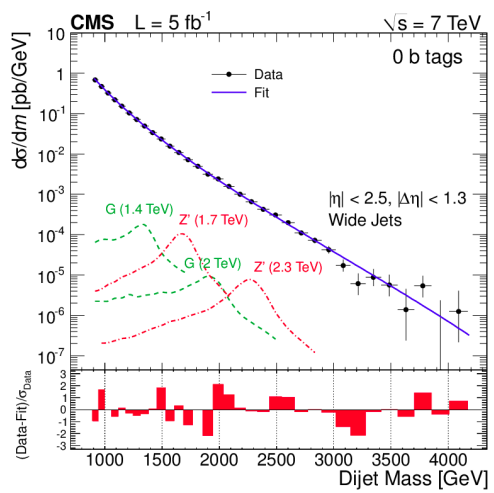
No evidence for new resonances in low-mass search

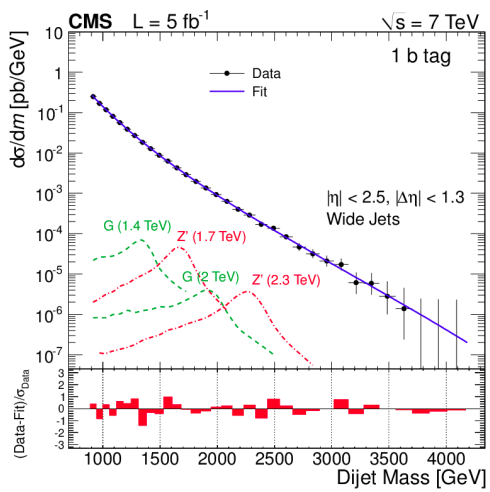
Dijet Mass Spectrum+b tagging (√s=7 TeV)

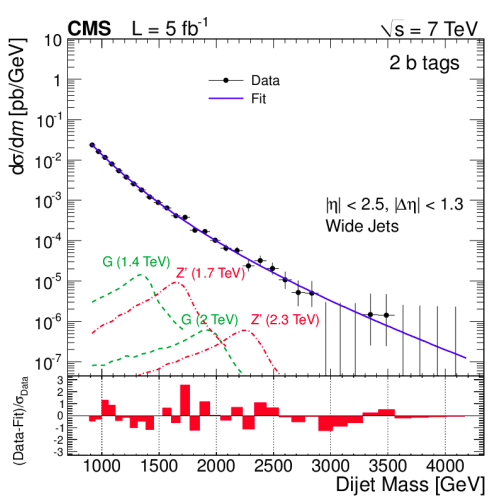
- Extension of the standard dijet resonance search
- Considering information on possible presence of a secondary vertex inside the jet → Increased sensitivity to resonances preferentially decaying to b jets
- Only 2 leading jets considered for b-tagging → Events grouped into 3 exclusive categories: 0, 1, and 2 b-tags
- Search performed in all 3 categories simultaneously

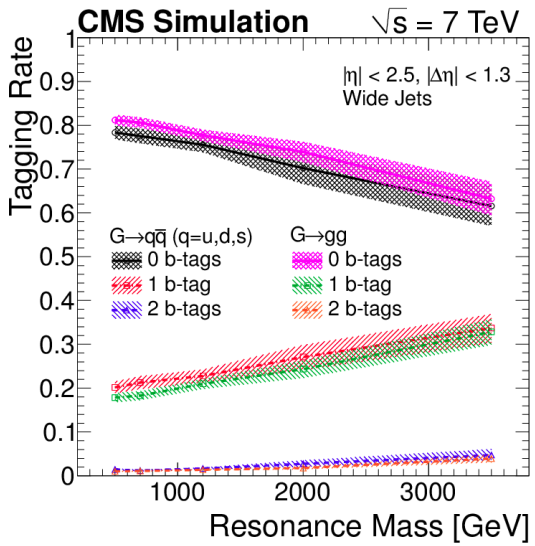








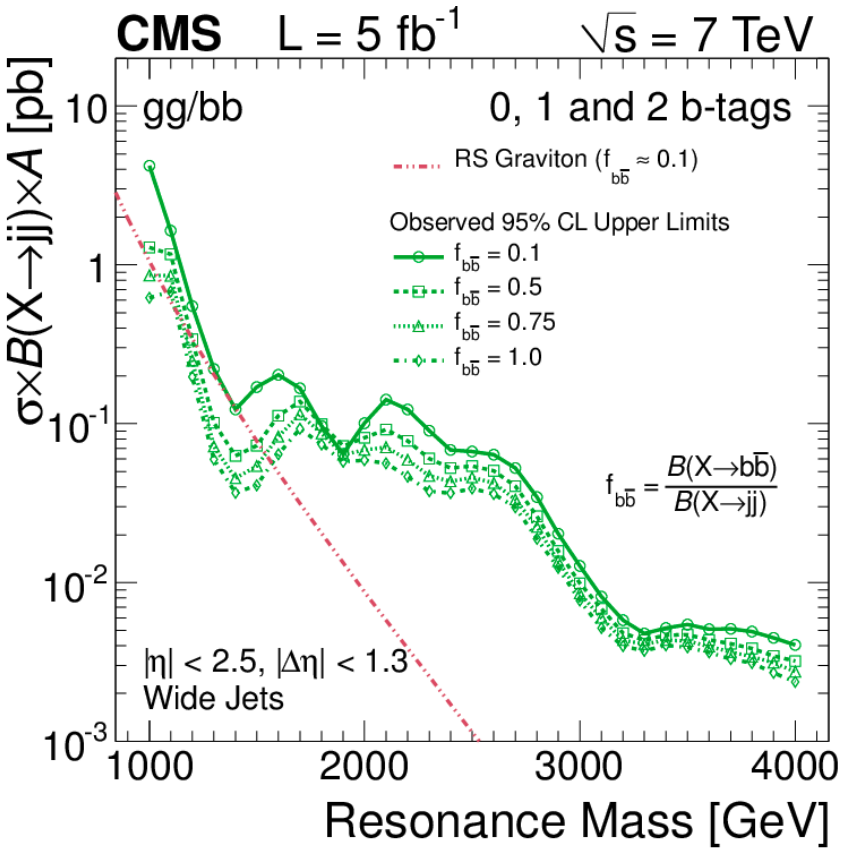


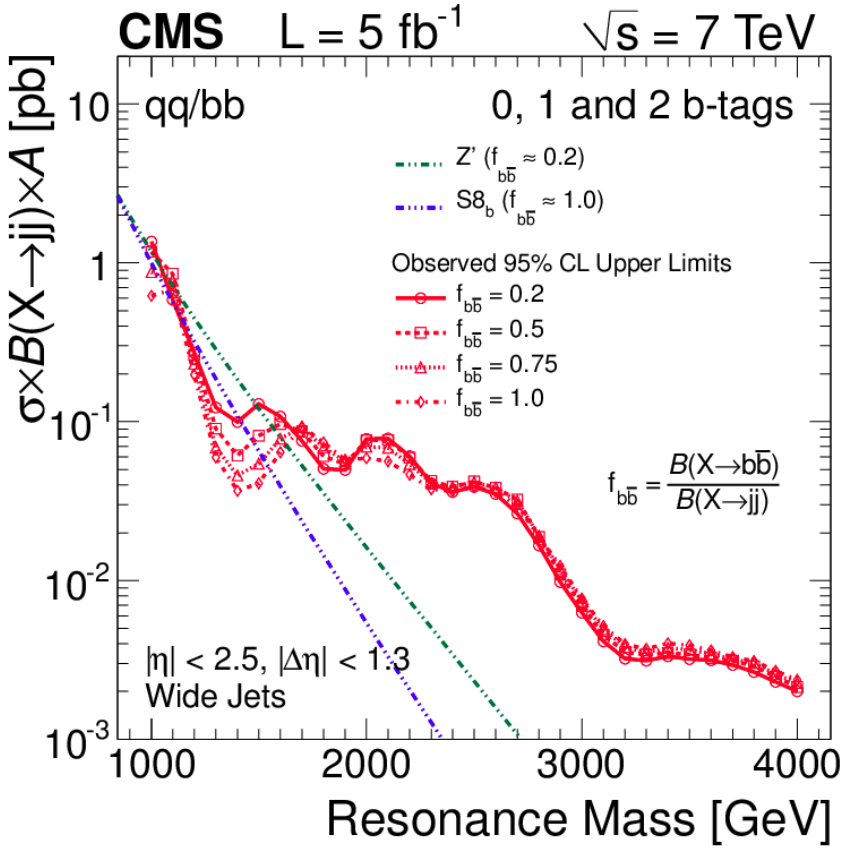


Dijet Mass Spectrum+b tagging (√s=7 TeV)

- Model-independent limits set as a function of the $b\bar{b}$ decay fraction

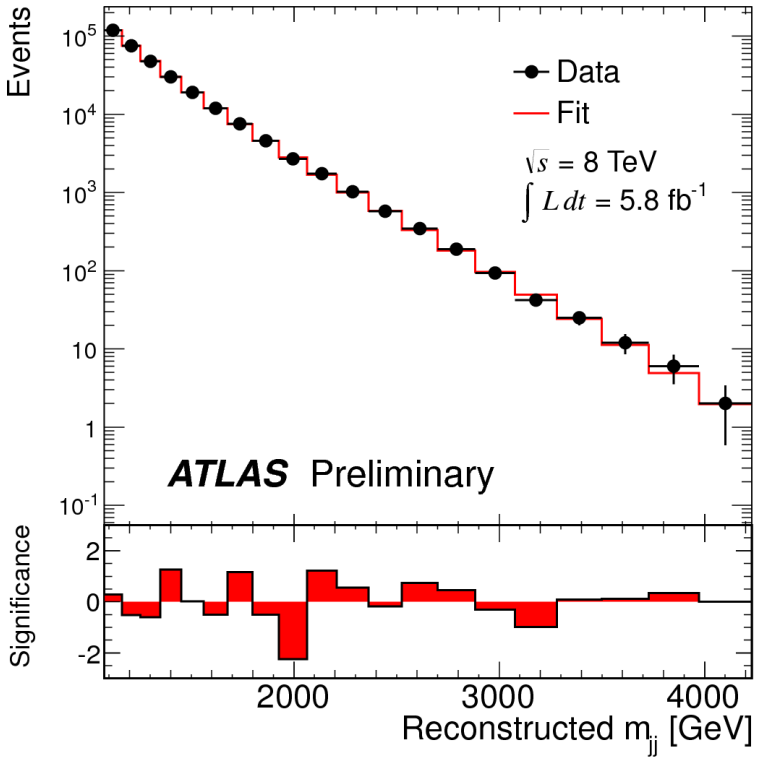
$$f_{b\bar{b}} = \frac{\mathrm{BR}(X \to b\bar{b})}{\mathrm{BR}(X \to jj)}$$

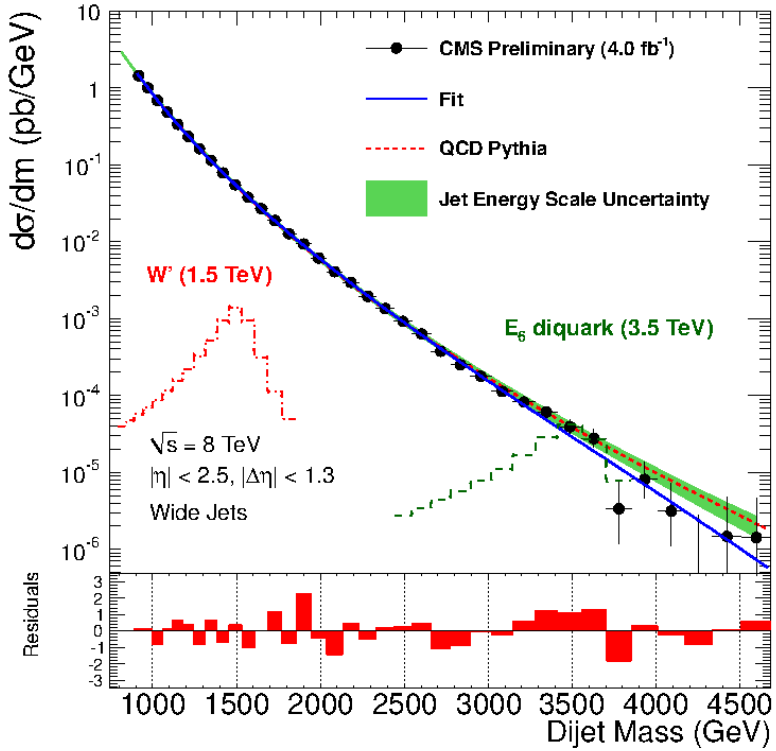




Dijet Mass Spectrum (√s=8 TeV)

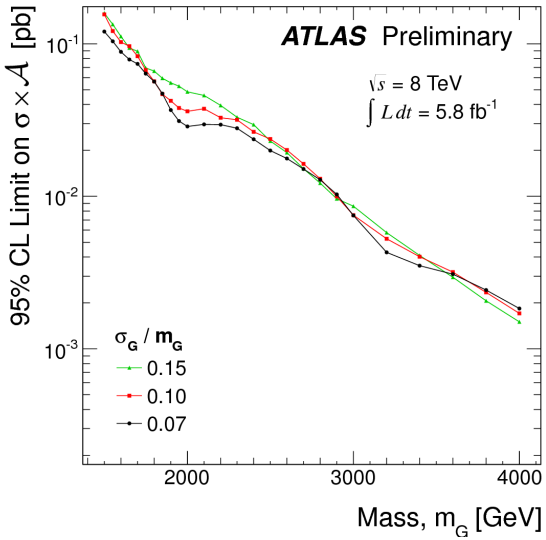
- The same analysis strategy as with √s=7 TeV data
- Increased center-of-mass energy leads to enhanced signal cross sections

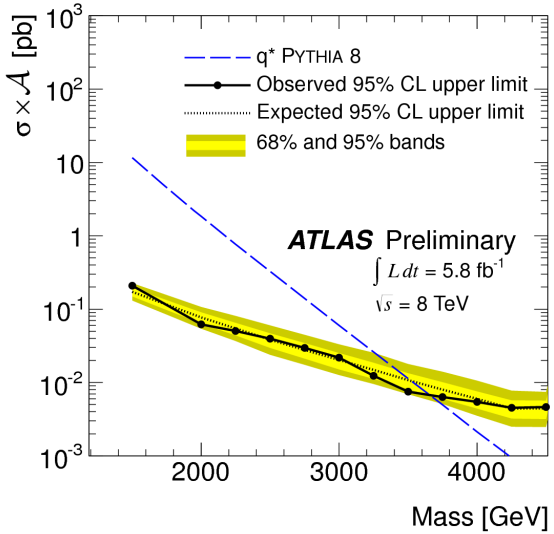


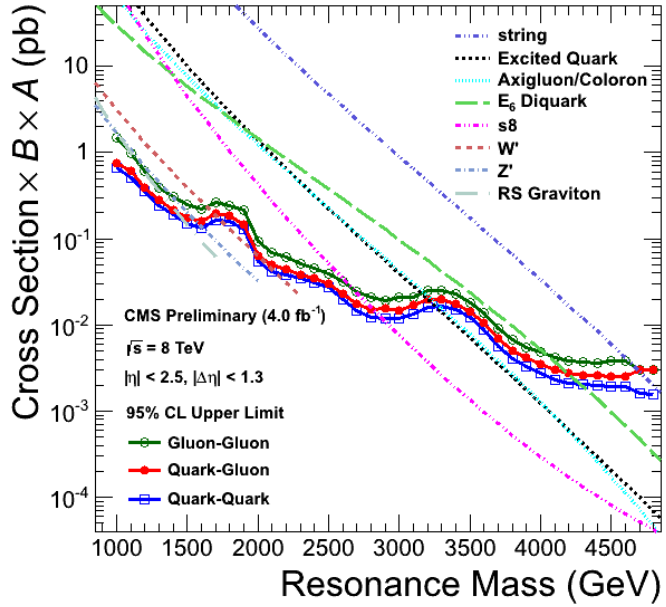


No evidence for new resonances in the dijet mass spectrum

Dijet Mass Spectrum (√s=8 TeV)





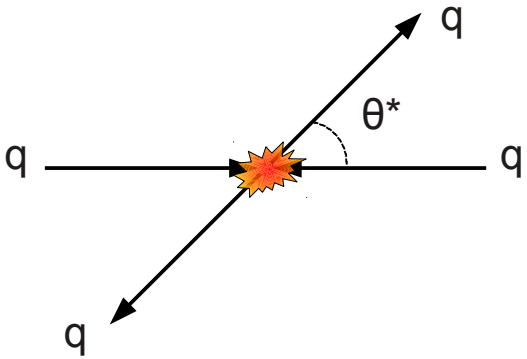


- Compared to √s=7 TeV results, CMS limits extended for most benchmark models (with less data)

Model	Final State	Obs. Mass Excl. [TeV]	Exp. Mass Excl. [TeV]
String Resonance (S)	qg	[1.0, 4.69]	[1.0,4.64]
Excited Quark (Q*)	qg	[1.0, 3.19]	[1.0,3.43]
E_6 Diquark (D)	qq	[1.0, 4.28]	[1.0,4.12]
Axigluon (A)/Coloron (C)	$q\bar{q}$	[1.0, 3.28]	[1.0,3.55]
s8 Resonance (s8)	gg	[1.0, 2.66]	[1.0,2.53]
W′ Boson (W′)	$q\bar{q}$	[1.0, 1.74] [1.97, 2.12]	[1.0,1.92]
Z′ Boson (Z′)	$q\bar{q}$	[1.0, 1.60]	[1.0,1.50]
RS Graviton (RSG)	$q\bar{q}$+gg	[1.0, 1.36]	[1.0,1.20]

Dijet Angular Distribution ($\sqrt{s}$=7 TeV)

- Dijet angular distribution sensitive to new physics
  - QCD jets tend to be produced at small scattering angles (due to the *t*-channel pole in the scattering amplitude)
  - Most models of new physics predict essentially isotropic angular distribution



$$\text{Angular dist.} \equiv \frac{1}{\sigma}\frac{d\sigma}{d\chi}$$

Flat for Rutherford scattering, approximately flat for QCD, peaking at low values of χ for new physics

$$\chi = e^{2|y^*|} \xrightarrow[m\to 0]{} \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}, y^* = \frac{1}{2}(y_1 - y_2), y_B = \frac{1}{2}(y_1 + y_2)$$

- In addition to dijet angular distributions measured in different dijet mass bins, the following dijet angular ratio variables can be employed

$$F_\chi(m_{jj}) \equiv \frac{\mathrm{d}N_{\text{central}}/\mathrm{d}m_{jj}}{\mathrm{d}N_{\text{total}}/\mathrm{d}m_{jj}}$$

$$R(m_{jj}) \equiv \frac{\mathrm{d}N_{\text{central}}/\mathrm{d}m_{jj}}{\mathrm{d}N_{\text{forward}}/\mathrm{d}m_{jj}}$$

where *N* is the number of events in a predefined region of χ or $|\Delta\eta|$

Dijet Angular Distribution ($\sqrt{s}$=7 TeV)

ATLAS

- Using single jet triggers with varying thresholds
- Anti-k_T R=0.6 calorimeter jets
- Event selection:

  Angular distribution χ
  - $|y^*|<1.7$ ($\chi<30$) and $|y_B|<1.1$
  - $m_{jj}>800$ GeV

  Angular ratio F_χ
  - $|y^*|<1.7$ ($\chi<30$) and $|y_B|<1.1$
  - $m_{jj}>800$ GeV
  - $N_{central}$: $|y^*|<0.6$

CMS

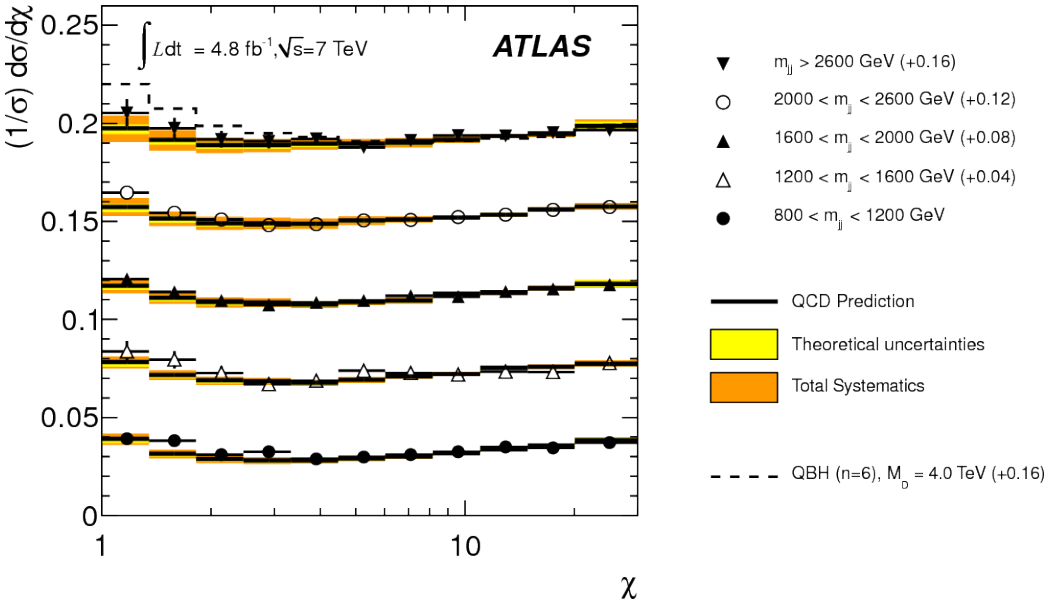
- Using single jet triggers with varying thresholds

  Angular distribution χ
- Anti-k_T R=0.5 particle-flow jets
- Event selection:
  - $\chi<16$ and $|y_B|<1.11$

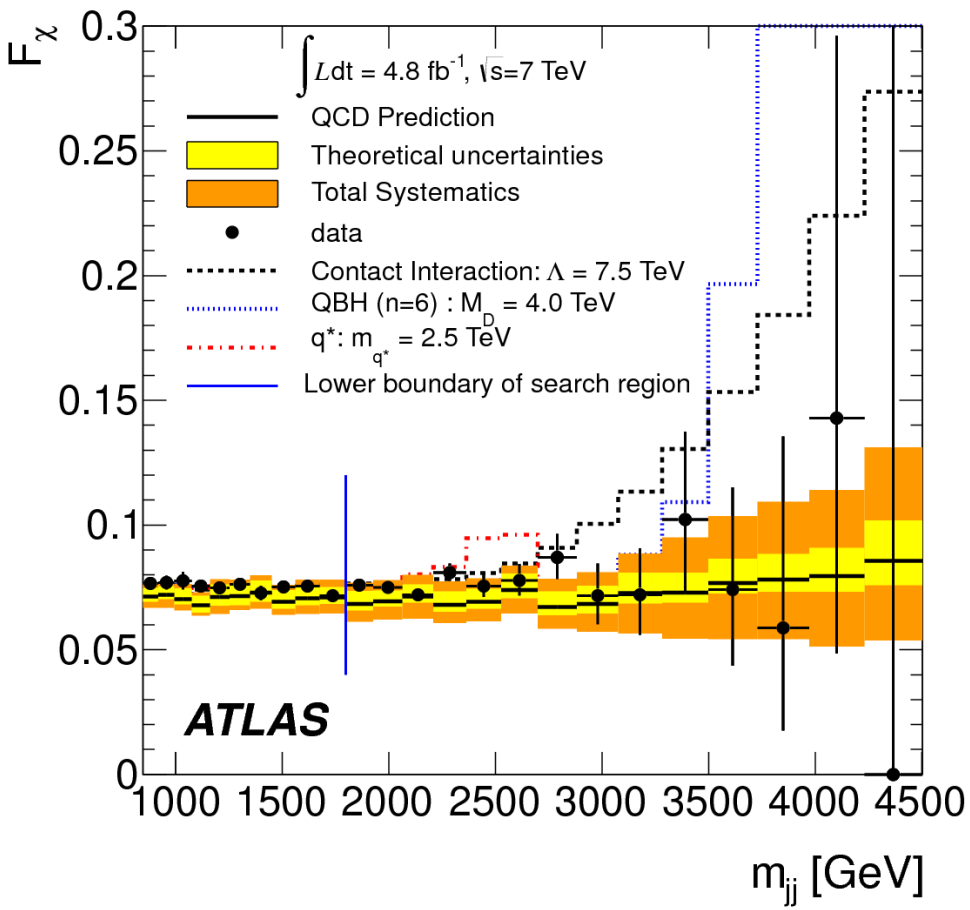
  Angular ratio R
- Anti-k_T R=0.7 calorimeter jets
- Event selection:
  - $|\eta|<2.5$ for two leading jets
  - $N_{central}$: $|\Delta\eta|<1.3$, $N_{forward}$: $1.3<|\Delta\eta|<3.0$

- Signal and background modeled by Monte Carlo simulation

Dijet Angular Distribution (√s=7 TeV)



Data consistent with background prediction

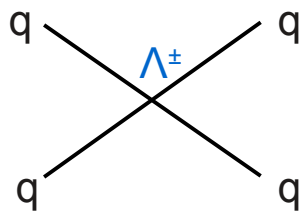


Dijet Angular Distribution ($\sqrt{s}$=7 TeV)

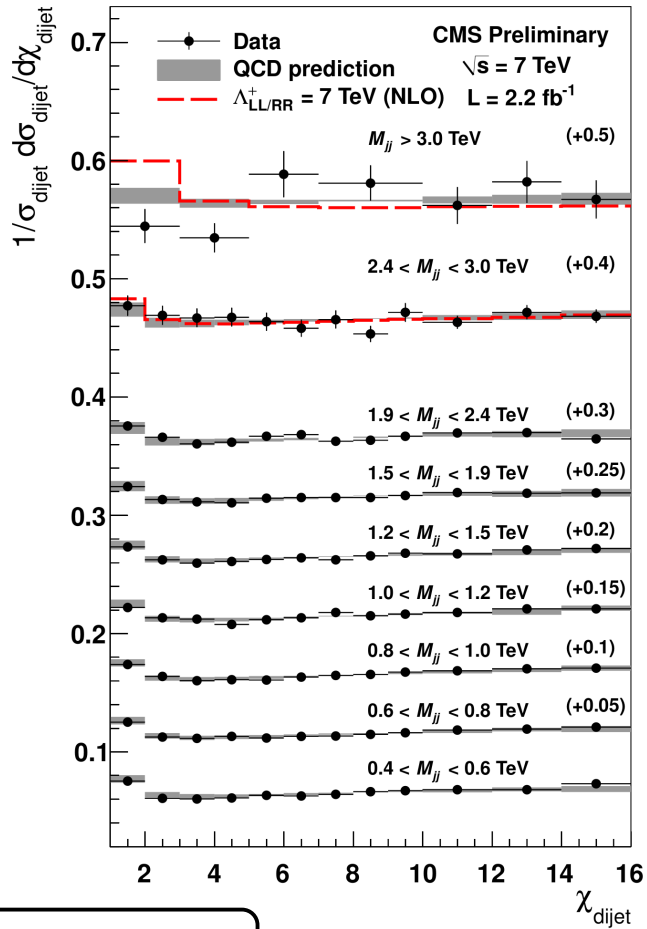
- CMS investigated the following contact interaction scenarios in the angular distribution analysis:

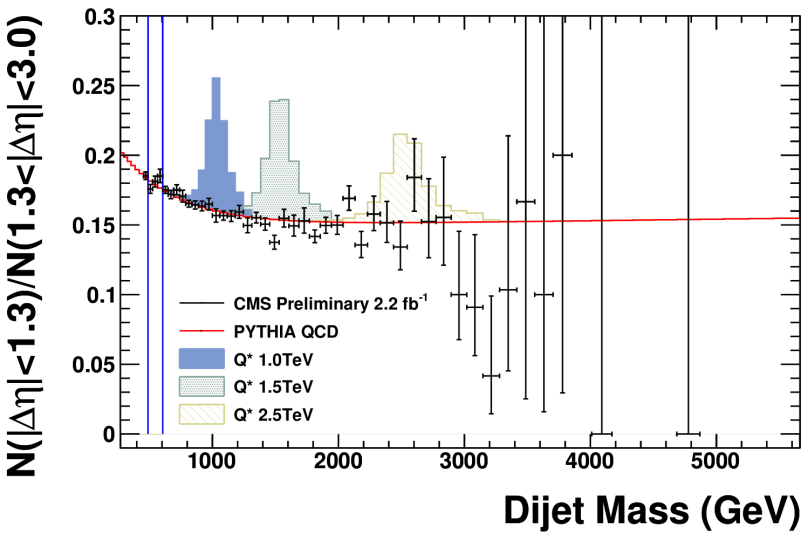
$$L_{qq} = \frac{2\pi}{\Lambda^2}\left[\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L) + \eta_{RR}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_R\gamma_\mu q_R) + 2\eta_{RL}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_L\gamma_\mu q_L)\right]$$

$$\Lambda = \Lambda^{\pm}_{LL} \text{ for } (\eta_{LL},\eta_{RR},\eta_{RL}) = (\pm1,0,0)$$
$$\Lambda = \Lambda^{\pm}_{RR} \text{ for } (\eta_{LL},\eta_{RR},\eta_{RL}) = (0,\pm1,0)$$
$$\Lambda = \Lambda^{\pm}_{VV} \text{ for } (\eta_{LL},\eta_{RR},\eta_{RL}) = (\pm1,\pm1,\pm1)$$
$$\Lambda = \Lambda^{\pm}_{AA} \text{ for } (\eta_{LL},\eta_{RR},\eta_{RL}) = (\pm1,\pm1,\mp1)$$
$$\Lambda = \Lambda^{\pm}_{(V-A)} \text{ for } (\eta_{LL},\eta_{RR},\eta_{RL}) = (0,0,\pm1)$$



Λ^+ → Destructive interference between CI and QCD
Λ^- → Constructive interference between CI and QCD





Angular ratio *R* distribution

Data consistent with background prediction

Dijet Angular Distribution (√s=7 TeV)

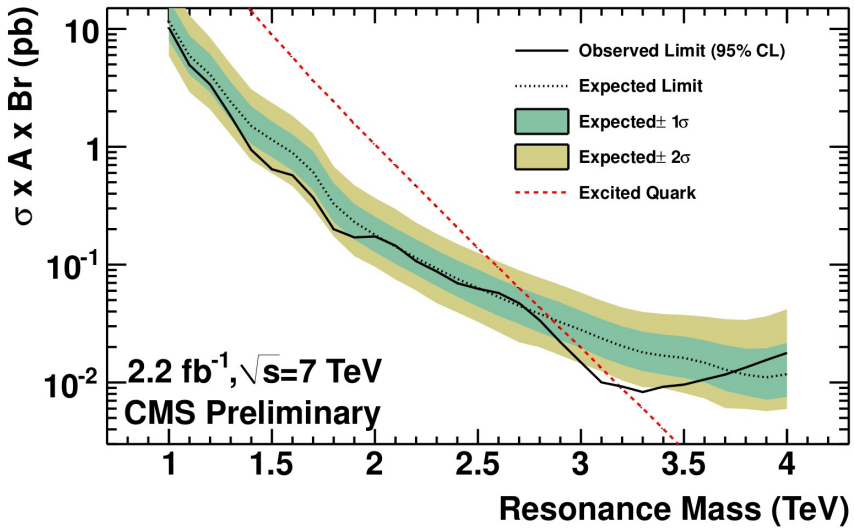
- ATLAS limits:

Model and Analysis Strategy	95% CL Limits [TeV] Expected	Observed
Excited quark, mass of q^*		
Resonance in $F_\chi(m_{jj})$	2.85	2.75
Quantum Black Hole for $n = 6$, M_D		
$F_\chi(m_{jj})$	4.16	4.03
χ , $m_{jj} > 2.6$ TeV	4.20	4.11
Contact interaction, Λ, destructive interference		
$F_\chi(m_{jj})$	7.7	7.6
χ , $m_{jj} > 2.6$ TeV	7.7	7.6

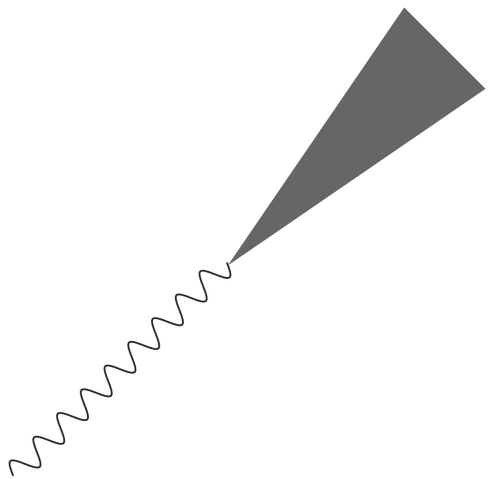
- CMS limits from the χ analysis:

CI model	Observed limit (TeV)	Expected limit (TeV)
NLO $\Lambda^+_{LL/RR}$	7.5	$7.0^{+0.4}_{-0.6}$
NLO $\Lambda^-_{LL/RR}$	10.5	$9.7^{+1.0}_{-1.7}$
LO $\Lambda^+_{LL/RR}$	8.4	$7.9^{+0.5}_{-0.7}$
LO $\Lambda^-_{LL/RR}$	11.7	$10.9^{+1.7}_{-2.4}$
LO $\Lambda^+_{VV/AA}$	10.4	$9.5^{+0.5}_{-1.0}$
LO $\Lambda^-_{VV/AA}$	14.5	$13.7^{+2.9}_{-2.6}$
LO $\Lambda^\pm_{(V-A)}$	8.0	$7.8^{+1.0}_{-1.1}$

- CMS limit from the angular ratio *R* analysis:



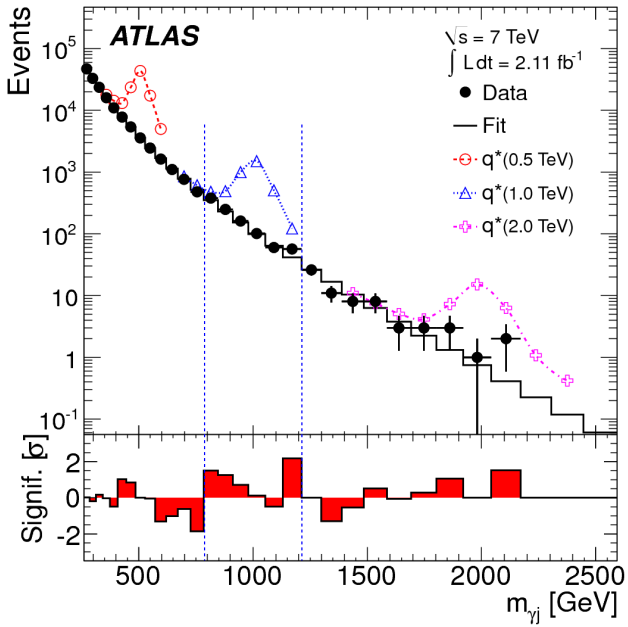
Photon+jet



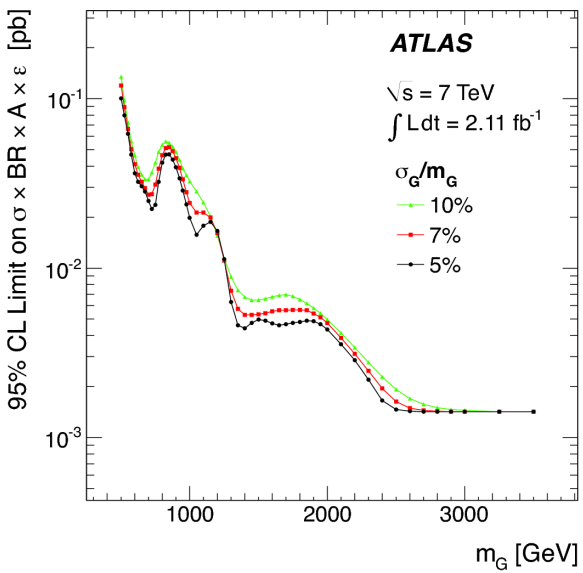
ATLAS: arXiv:1112.3580

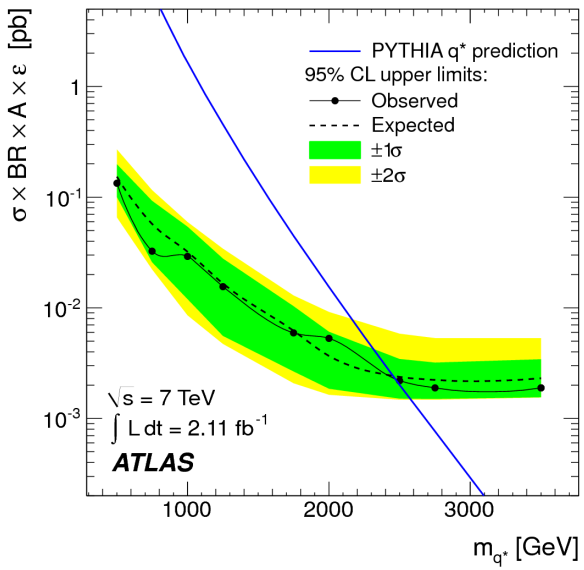
Photon+jet Resonances

- Searching for bumps in a smoothly falling photon+jet mass spectrum using the same analysis strategy as in the dijet resonance search
- Using single photon trigger with photon p_T>80 GeV
- Anti-k_T R=0.6 calorimeter jets
- Event selection:
  - Photon p_T>85 GeV and $|\eta|$<1.37
  - Jet p_T>30 GeV and $|\eta|$<2.8
  - $|\eta_\gamma - \eta_j|$<1.4

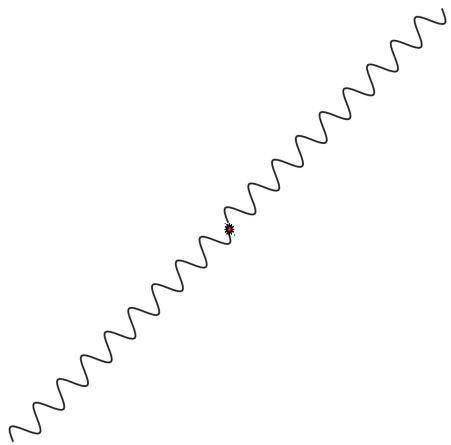


No evidence for new resonances in the photon+jet mass spectrum





Diphotons

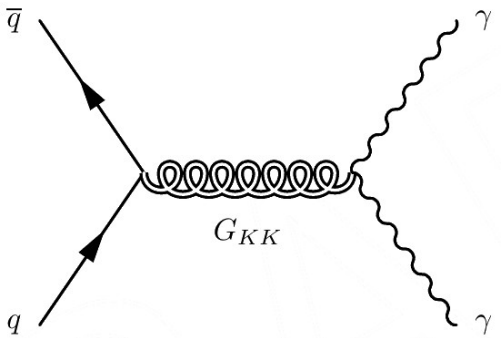


ATLAS: arXiv:1210.8389

CMS: EXO-11-038 (arXiv:1112.0688)

Extra Dimensions

- ADD and RS models of extra dimensions proposed to resolve the hierarchy problem
- Both predict the existence of gravitons that preferentially decay into two gauge bosons



  - RS model predicts well separated Kaluza-Klein (KK) graviton excitations → Gravitons appear as resonances in the diphoton mass spectrum
    - Phenomenology can be described in terms of the mass of the lightest KK graviton mode M and the dimensionless coupling to the SM fields $\tilde{k}=k/\overline{M}_{Pl}$
- ADD model predicts closely spaced KK graviton excitations → Results in a non-resonant enhancement of the diphoton mass spectrum, particularly at high masses
  - Summation over KK modes results in a divergence → UV cutoff scale M_S is imposed
  - The overall effect on the diphoton cross section parameterized by the single variable η_G

$$\eta_G = \mathcal{F}/M_S^4$$

$$\mathcal{F} = 1, \ \text{(GRW)}$$

$$\mathcal{F} = \begin{cases} \log\left(M_S^2/\hat{s}\right) & n = 2 \\ 2/(n-2) & n > 2 \end{cases}, \ \text{(HLZ)}$$

$$\mathcal{F} = \pm 2/\pi, \ \text{(Hewett)}$$

Extra Dimensions

ATLAS

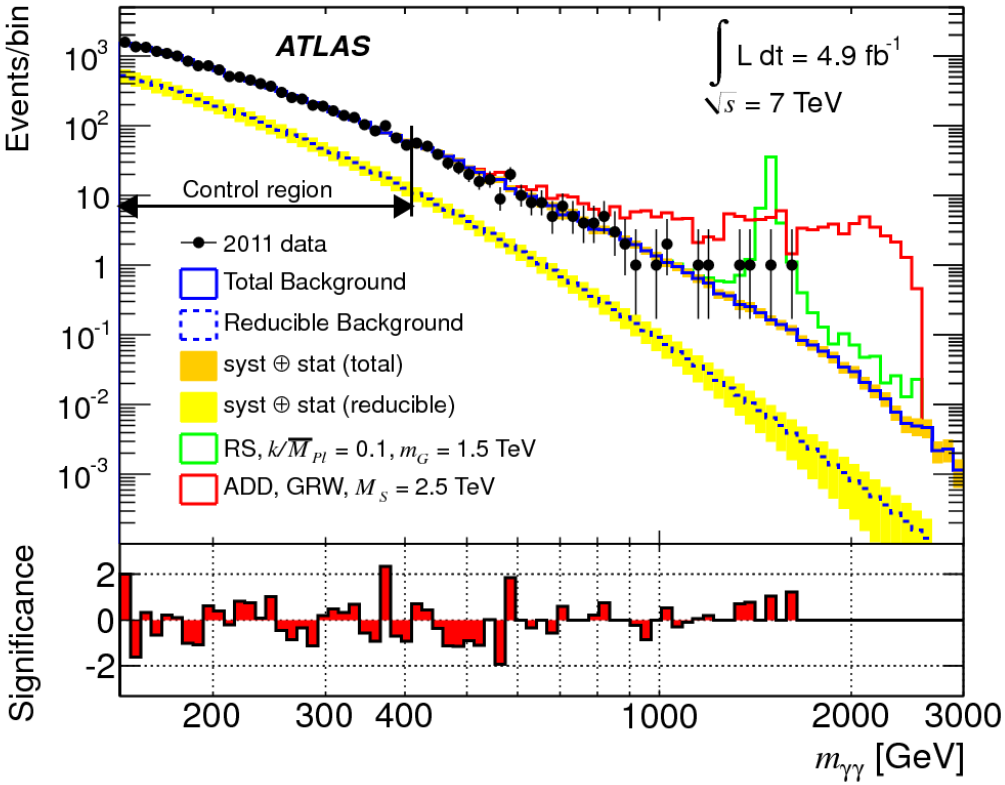
- Using diphoton trigger with photon E_T>20 GeV
- Event selection:
  - Two isolated tight photons with E_T>25 GeV and |η|<1.37, 1.52<|η|<2.37
  - $m_{\gamma\gamma}$>142 GeV

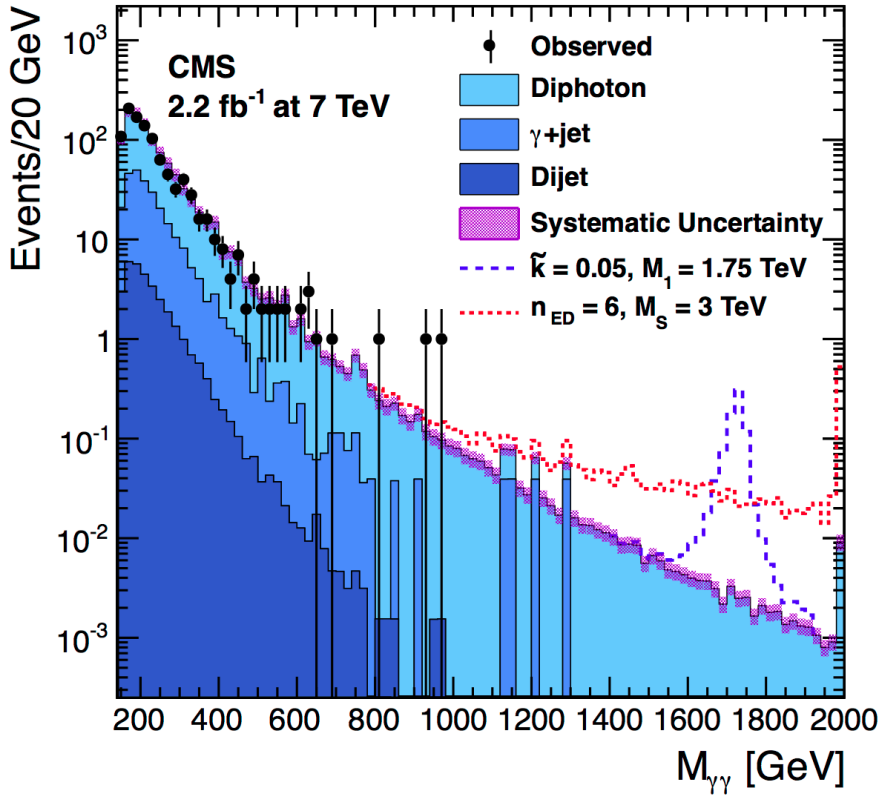
CMS

- Using diphoton triggers with varying E_T thresholds (33, 55, 60 GeV)
- Event selection:
  - Two isolated tight photons with E_T>70 GeV and |η|<1.44
  - $m_{\gamma\gamma}$>140 GeV

- Dominant sources of background:
  - SM diphoton production
  - γ+jet production
  - Dijet events
- Backgrounds estimated using a combination of Monte Carlo and data-driven techniques

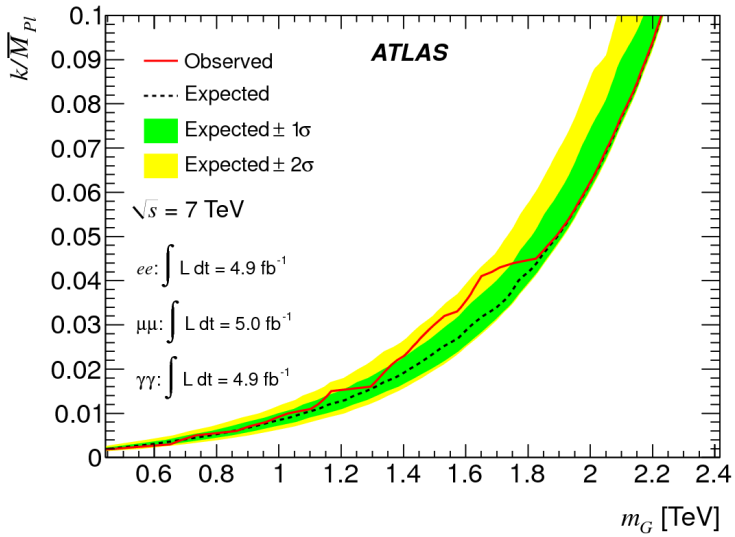
Extra Dimensions



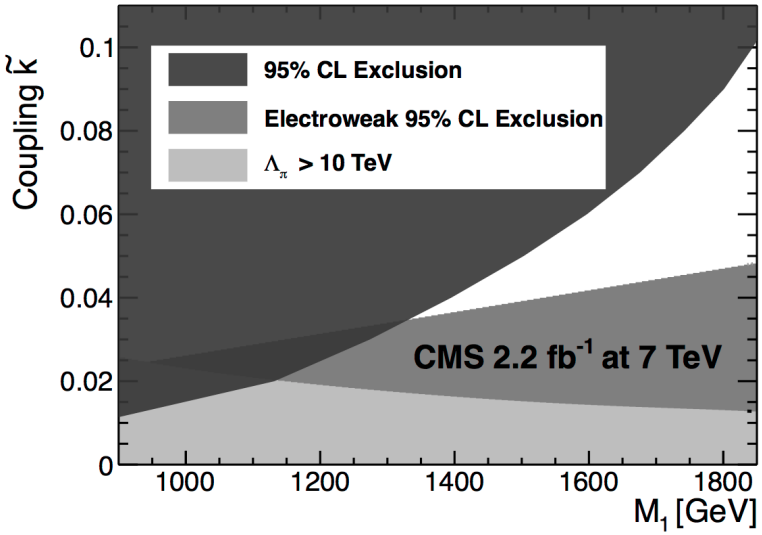


No evidence for new particle production in the diphoton mass spectrum

Extra Dimensions



Limits on RS model



K-factor value	Channel(s) Used	95 % CL Observed (Expected) Limit [TeV] k/M_{Pl} value 0.01	0.03	0.05	0.1
1	$G \to \gamma\gamma$	0.87 (0.88)	1.31 (1.36)	1.49 (1.60)	1.91 (1.92)
	$G \to \gamma\gamma/ee/\mu\mu$	0.91 (0.95)	1.39 (1.48)	1.62 (1.75)	2.10 (2.10)
1.75	$G \to \gamma\gamma$	1.00 (0.98)	1.37 (1.49)	1.63 (1.73)	2.06 (2.05)
	$G \to \gamma\gamma/ee/\mu\mu$	1.03 (1.08)	1.50 (1.63)	1.89 (1.90)	2.23 (2.23)

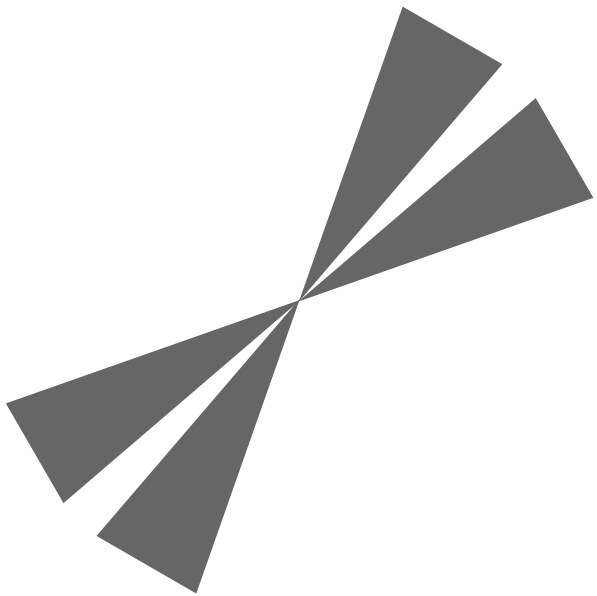
$\tilde{k}$	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11
M_1 [TeV]	0.86	1.13	1.27	1.39	1.50	1.59	1.67	1.74	1.80	1.84	1.88

Limits on ADD model

K-factor Value	ADD Parameter	GRW	Hewett Neg.	Hewett Pos.	HLZ $n=3$	HLZ $n=4$	HLZ $n=5$	HLZ $n=6$	HLZ $n=7$
1	η_G	0.0115	−0.0191	0.0115			0.0115		
	M_s	3.05	2.40	2.73	3.63	3.05	2.76	2.57	2.43
1.70	η_G	0.0085	−0.0159	0.0085			0.0085		
	M_s	3.29	2.52	2.94	3.92	3.29	2.98	2.77	2.62

K factor	GRW	Hewett pos.	Hewett neg.	HLZ $n_{ED}=2$	HLZ $n_{ED}=3$	HLZ $n_{ED}=4$	HLZ $n_{ED}=5$	HLZ $n_{ED}=6$	HLZ $n_{ED}=7$
1.0	2.94	2.63	2.28	3.29	3.50	2.94	2.66	2.47	2.34
1.6	3.18	2.84	2.41	3.68	3.79	3.18	2.88	2.68	2.53

Paired Dijets



ATLAS: arXiv:1210.4826

CMS: EXO-11-016

Paired Dijet Resonances

- Searching for pair production of new colored particles, each decaying into dijets

ATLAS

- Benchmark model: pair production of scalar gluons ("sgluons") decaying into gluon pairs
- Using a multijet trigger that is fully efficient for events with 4 leading jets with p_T>80 GeV
- Anti-k_T R=0.4 calorimeter jets
- Event selection:
  - ≥4 jets with p_T>80 GeV and $|\eta|$<1.4
  - 4 highest-p_T jets separated by $\Delta R>0.6$
  - $p_T(4^{th}\ \text{jet})>\max(0.3\times m_{sgluon}+30)$ GeV to improve signal sensitivity
  - 4 highest-p_T jets paired by minimizing $|\Delta R_{pair1}-1|+|\Delta R_{pair2}-1|$. Event rejected if a pair has $\Delta R>1.6$
  - $|\cos(\theta^*)|<0.5$ and $|m_1-m_2|/(m_1+m_2)<0.15$ to suppress SM multijet background
- Signal acceptance: 0.6%

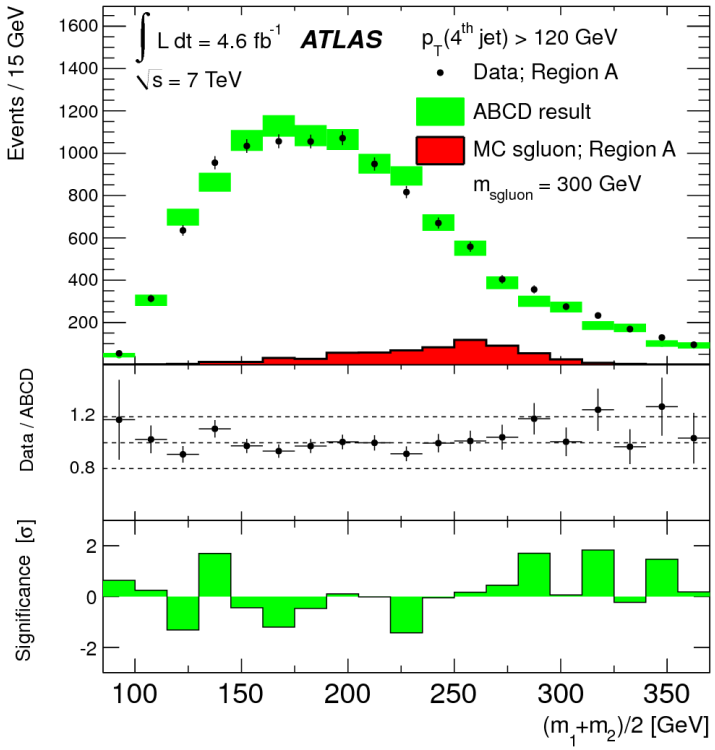
CMS

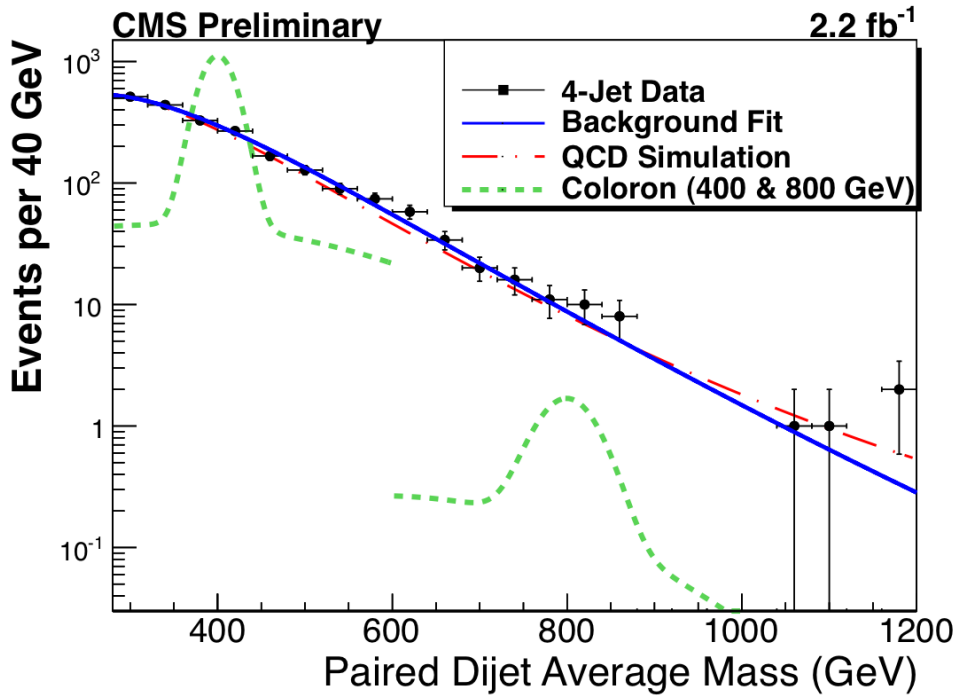
- Benchmark model: pair production of colorons decaying into $q\bar{q}$ pairs
- Using H_T and quadruple jet triggers that are fully efficient for events with 4 leading jets with p_T>140 GeV
- Anti-k_T R=0.5 particle-flow jets
- Event selection:
  - ≥4 jets with p_T>150 GeV and $|\eta|$<2.5
  - 4 highest-p_T jets separated by $\Delta R>0.7$
  - 4 highest-p_T jets paired by minimizing $\Delta m/m_{avg}$. $\Delta m/m_{avg}$<0.15 to suppress SM multijet background
  - Δ>25 GeV to ensure a smoothly falling average dijet mass spectrum

$$\Delta = \sum_{i=1,2} (p_T)_i - m_{avg}$$

- Signal acceptance: 3% for m=300 GeV, 13% for m=1000 GeV

Paired Dijet Resonances





- ATLAS uses an ABCD method to estimate background

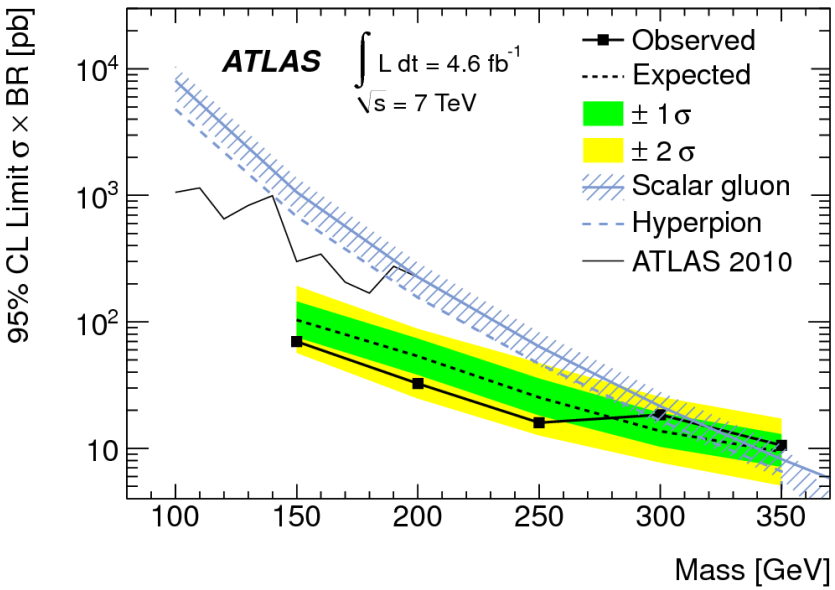
$$N'_A = N_B \frac{N_C}{N_D}$$

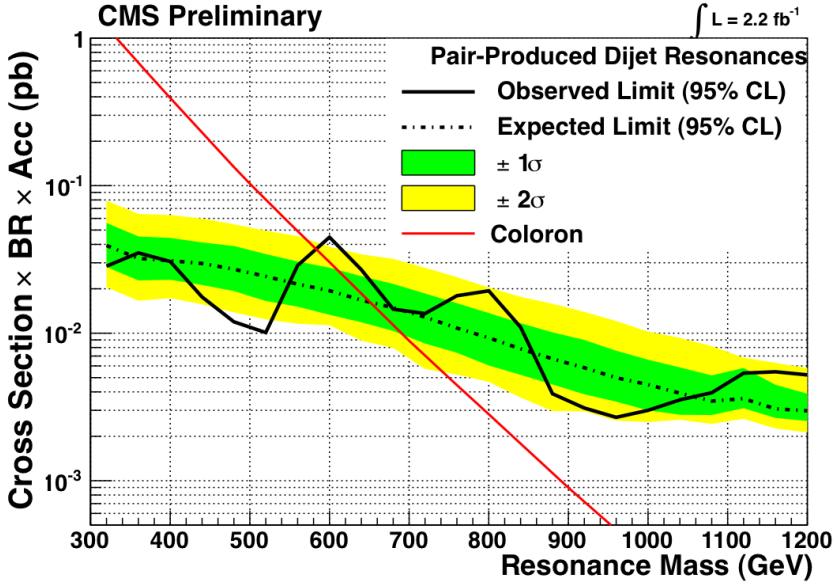
Region	$\lvert\cos(\theta^*)\rvert$	$\lvert m_1 - m_2\rvert/(m_1 + m_2)$
A	< 0.5	< 0.15
B	> 0.5	< 0.15
C	< 0.5	> 0.15
D	> 0.5	> 0.15

- CMS follows the same background estimation strategy as in the dijet resonance search and uses a smooth fit function to estimate background

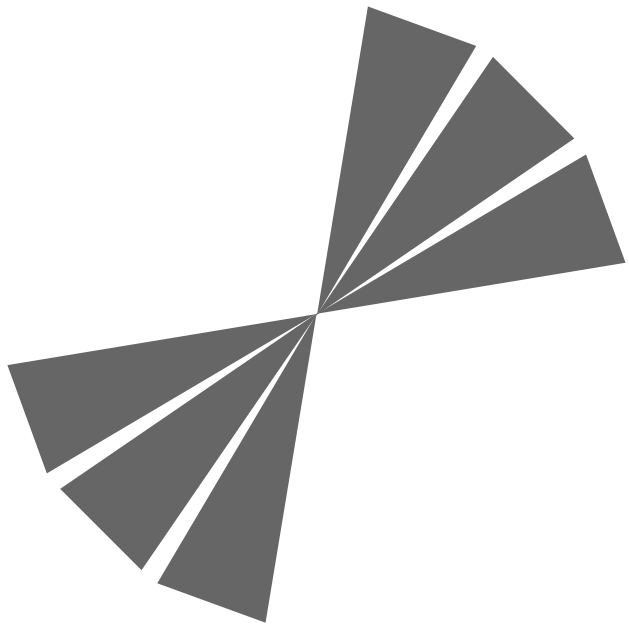
No evidence for new particle production in the average dijet mass spectrum

Paired Dijet Resonances





Paired Trijets



ATLAS: arXiv:1210.4813

CMS: EXO-11-060 (arXiv:1208.2931)

Paired 3-jet Resonances

- Searching for pair production massive colored particles, each decaying into 3 jets

ATLAS

- Analysis divided into 2 search channels: resolved and boosted. We will focus on the resolved analysis channel
- Benchmark model: pair production of RPV gluinos decaying into 3 jets
- Using single-jet and multijet triggers
- Anti-k_T R=0.4 calorimeter jets
- Event selection:
  - ≥6 jets with $|\eta|<2.8$
  - Jet p_T threshold optimized separately for each gluino mass

    p_T>80 GeV (m=100 GeV)

    p_T>120 GeV (m=200, 300 GeV)

    p_T>160 GeV (m=400, 500, 600, 800 GeV)
- Signal acceptance: 0.098% (m=100 GeV), 0.21% (m=400 GeV), 5.73% (m=800 GeV)

CMS

- Search performed in the triplet mass spectrum using the jet ensemble technique
- Benchmark model: pair production of RPV gluinos decaying into 3 jets
- Using H_T triggers with varying thresholds
- Anti-k_T R=0.5 particle-flow jets
- Event selection:
  - ≥6 jets with $|\eta|<3.0$, p_T>70 GeV, and H_T>900 GeV
  - 6 leading jets combined into all possible unique triplet combinations → 20 combinations

$$M_{jjj} < \sum_{i=1}^{3} p_T^i - \Delta \qquad \Delta = 160 \text{ GeV}$$

- Signal acceptance: 0.25% (m=250 GeV), 1.5% (m=450 GeV), 2.6% (m=1.5 TeV)

Paired 3-jet Resonances

- Searching for pair production massive colored particles, each decaying into 3 jets

ATLAS

- Analysis divided into 2 search channels: resolved and boosted. We will focus on the resolved analysis channel
- Benchmark model: pair production of RPV gluinos decaying into 3 jets
- Using single-jet and multijet triggers
- Anti-k_T R=0.4 calorimeter jets
- Event selection:
  - ≥6 jets with $|\eta|<2.8$
  - Jet p_T threshold optimized separately for each gluino mass

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CMS

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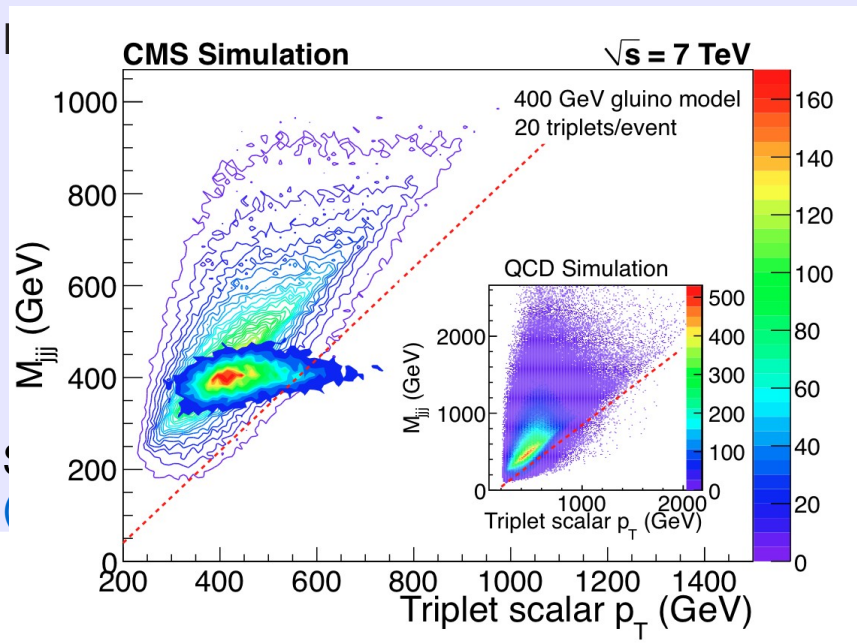
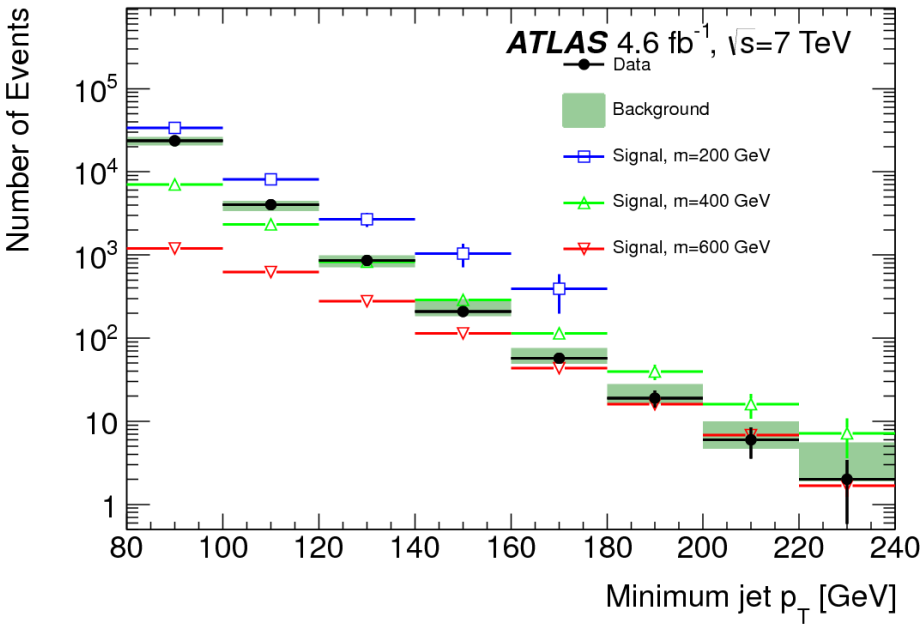
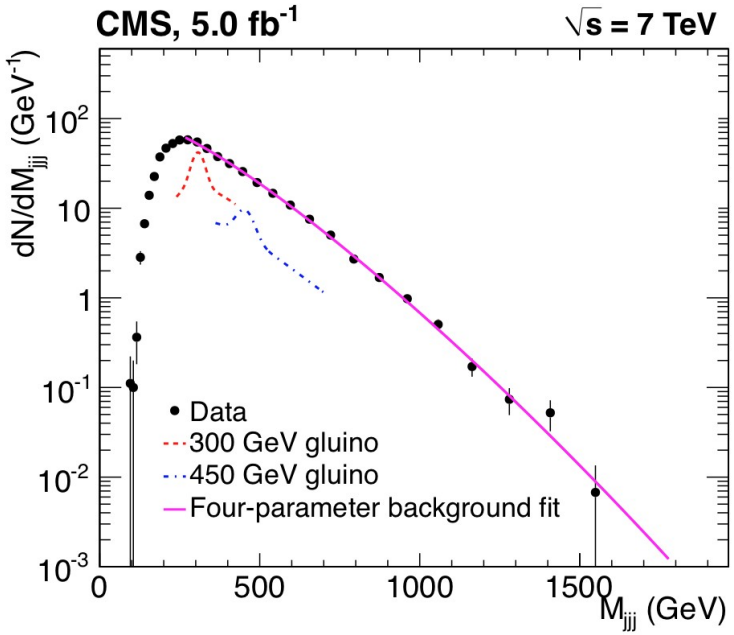


Paired 3-jet Resonances





- ATLAS performs a counting experiment in the resolved analysis channel and uses a data-driven technique to estimate background

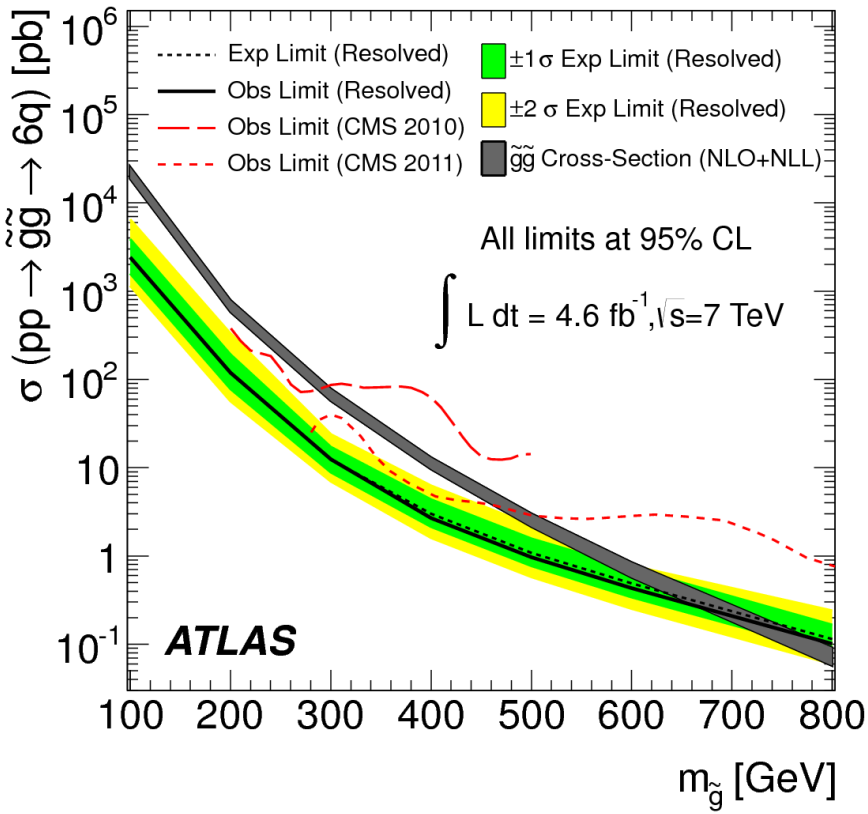
$$N_{data}^{\mathrm{n}-jet} = N_{data}^{\mathrm{m}-jet} \frac{N_{MC}^{\mathrm{n}-jet}}{N_{MC}^{\mathrm{m}-jet}}$$

$$\mathrm{m} = 3 \qquad \mathrm{n} \geq 6$$

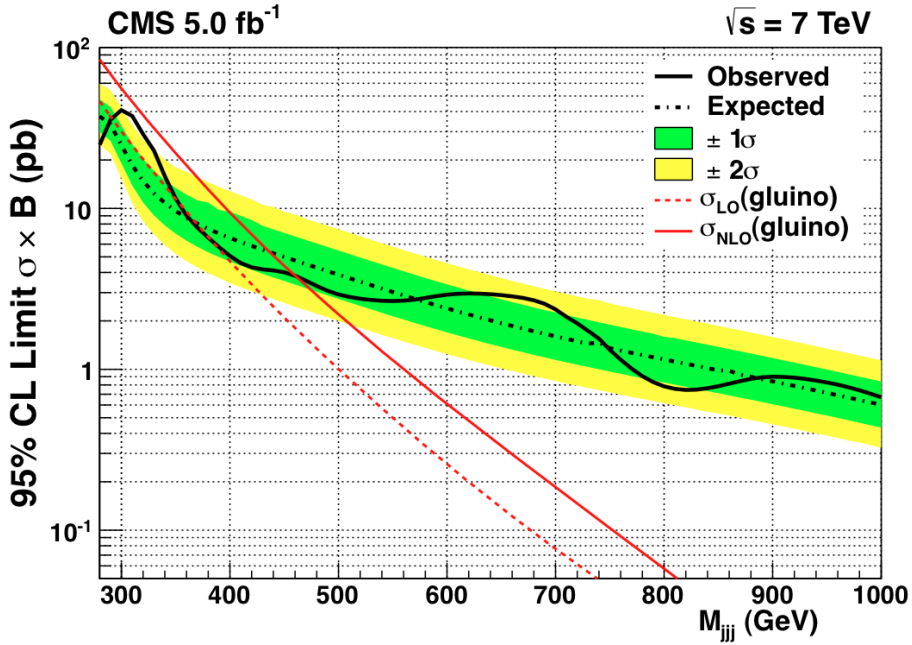
- CMS follows the same background estimation strategy as in the dijet resonance search and uses a smooth fit function to estimate background

No evidence for new particle production

Paired 3-jet Resonances

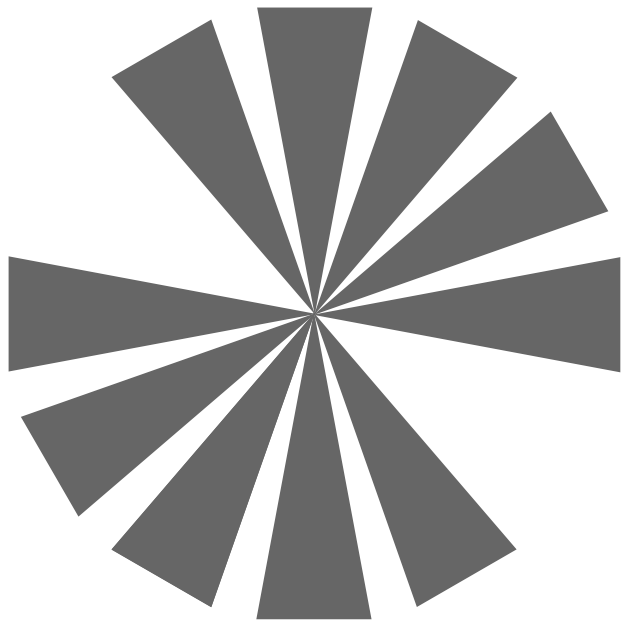


- Observed 95% CL mass exclusion 100<m<666 GeV



- Observed 95% CL mass exclusion 280<m<460 GeV extends the previous CMS exclusion 200<m<280 GeV

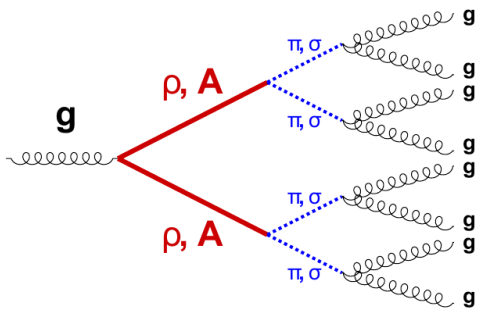
Multijets



CMS: EXO-11-075

8-jet Final State

- Searching for pair production of massive vector boson, each decaying into a pair of scalar particles, which further decay to 2 gluons → 8-jet final state



  - The presence of initial- and final-state radiation makes the traditional approach of trying to identify correct doublets and quartets ineffective → Doublet and quartet mass resolution significantly degraded
  - Instead, a multivariate method is used

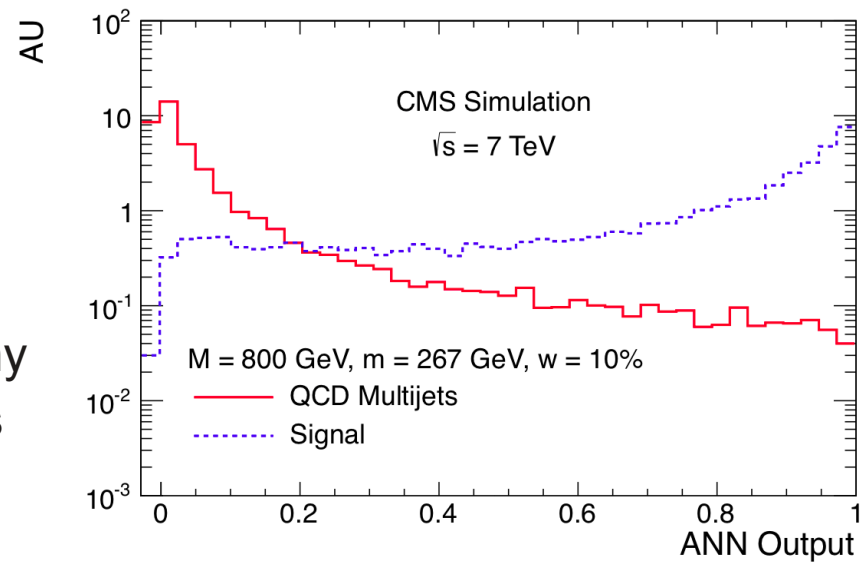
- Using H_T triggers with varying thresholds (550 to 750 GeV depending on the run period)
- Anti-k_T R=0.5 particle-flow jets
- Event selection:
  - ≥8 jets with pT>30 GeV and |η|<2.5
  - H_T>750 GeV

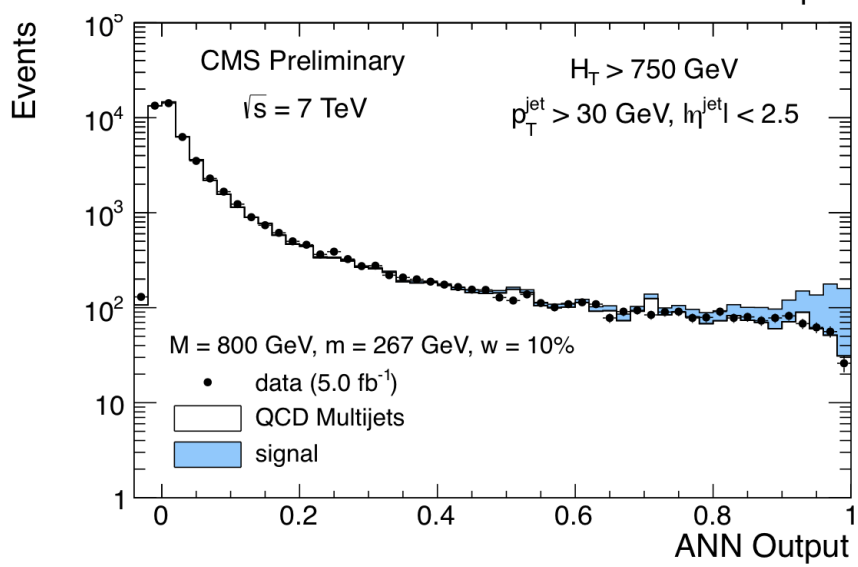
$$H_T = \sum_{n=1}^{8} p_{T,n}$$

- The following signal hypotheses considered:
  - Vector boson mass in the range from 400 GeV to 1.5 TeV
  - Vector boson width of 10% and 20%
  - Mass of intermediate scalar particle of 1/3 and 1/4 of the vector boson mass

8-jet Final State

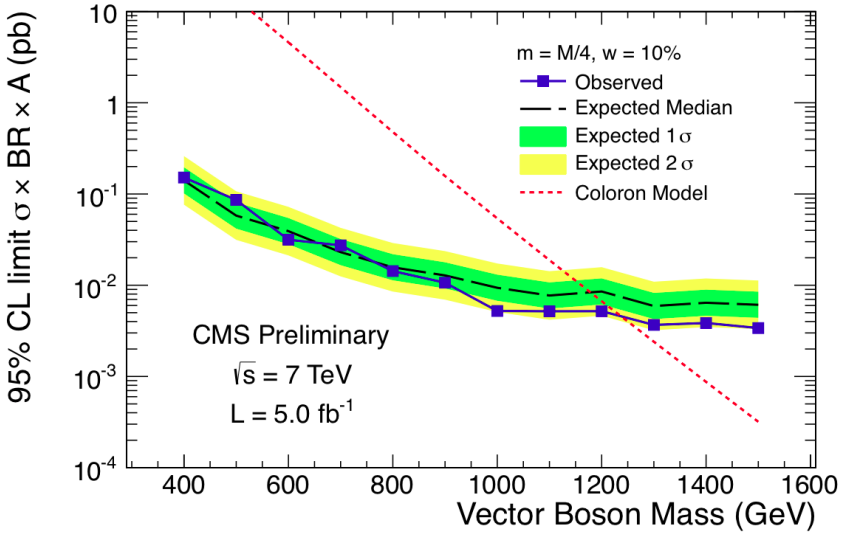
- The following 6 observables are fed into an artificial neural network (ANN)
  - p_T of the first, fourth, seventh, and eighth jet
  - H_T
  - 8-jet mass
- ANN taking advantage of a strong jet p_T hierarchy and weak correlation between H_T and 8-jet mass in QCD (in contrast to signal)
- Dedicated training performed for each signal hypothesis
- QCD templates taken from Monte Carlo simulation after confirming good agreement between data and simulation

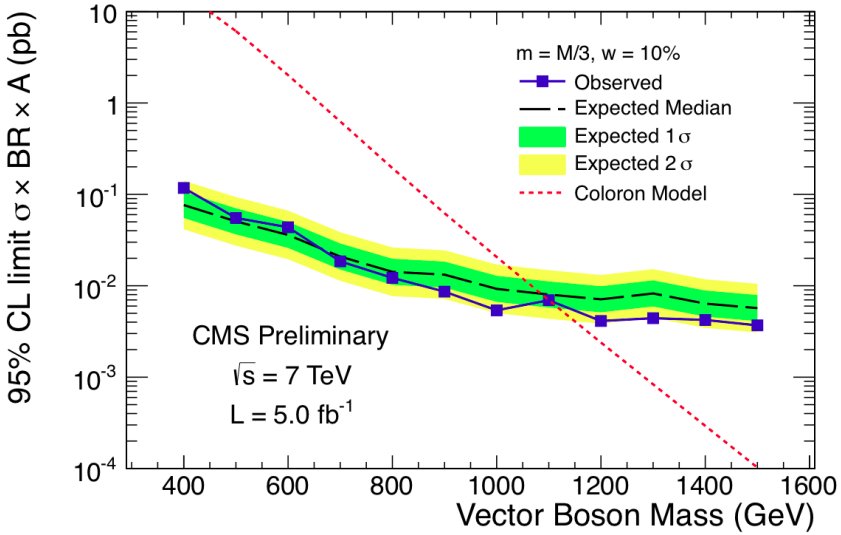


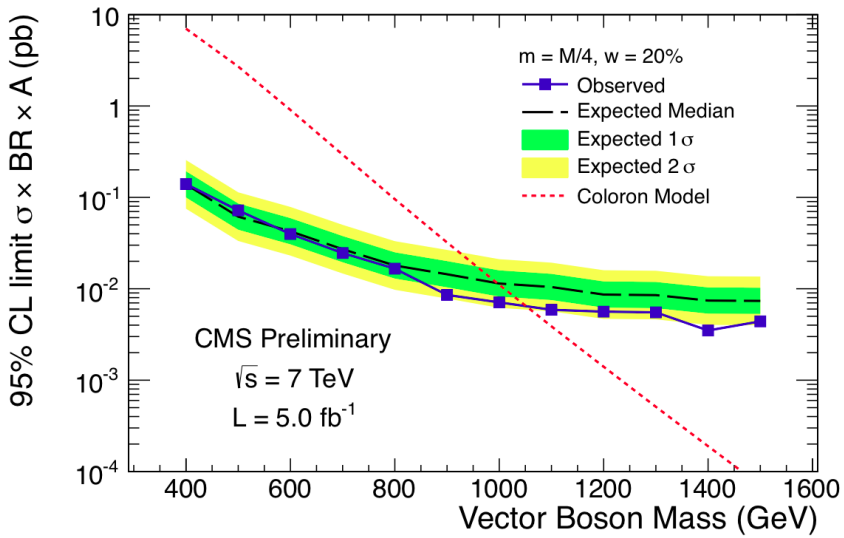


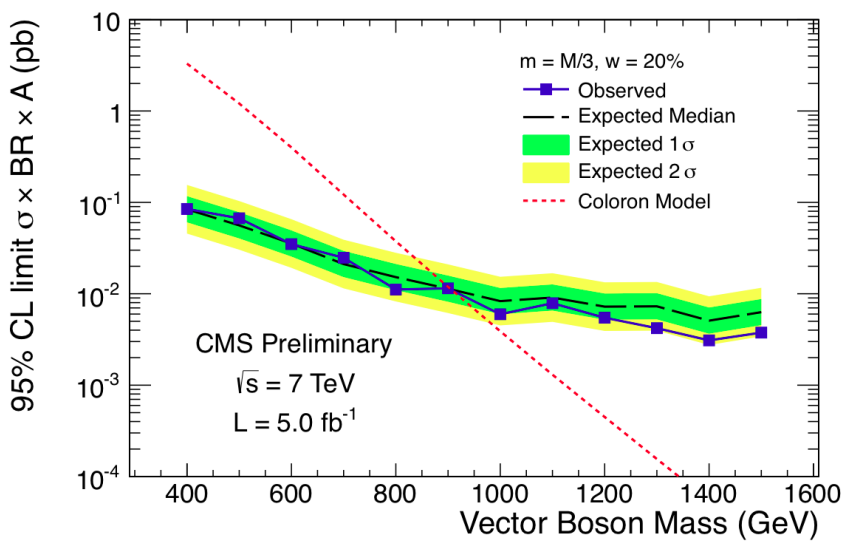
No evidence for new particle production

8-jet Final State









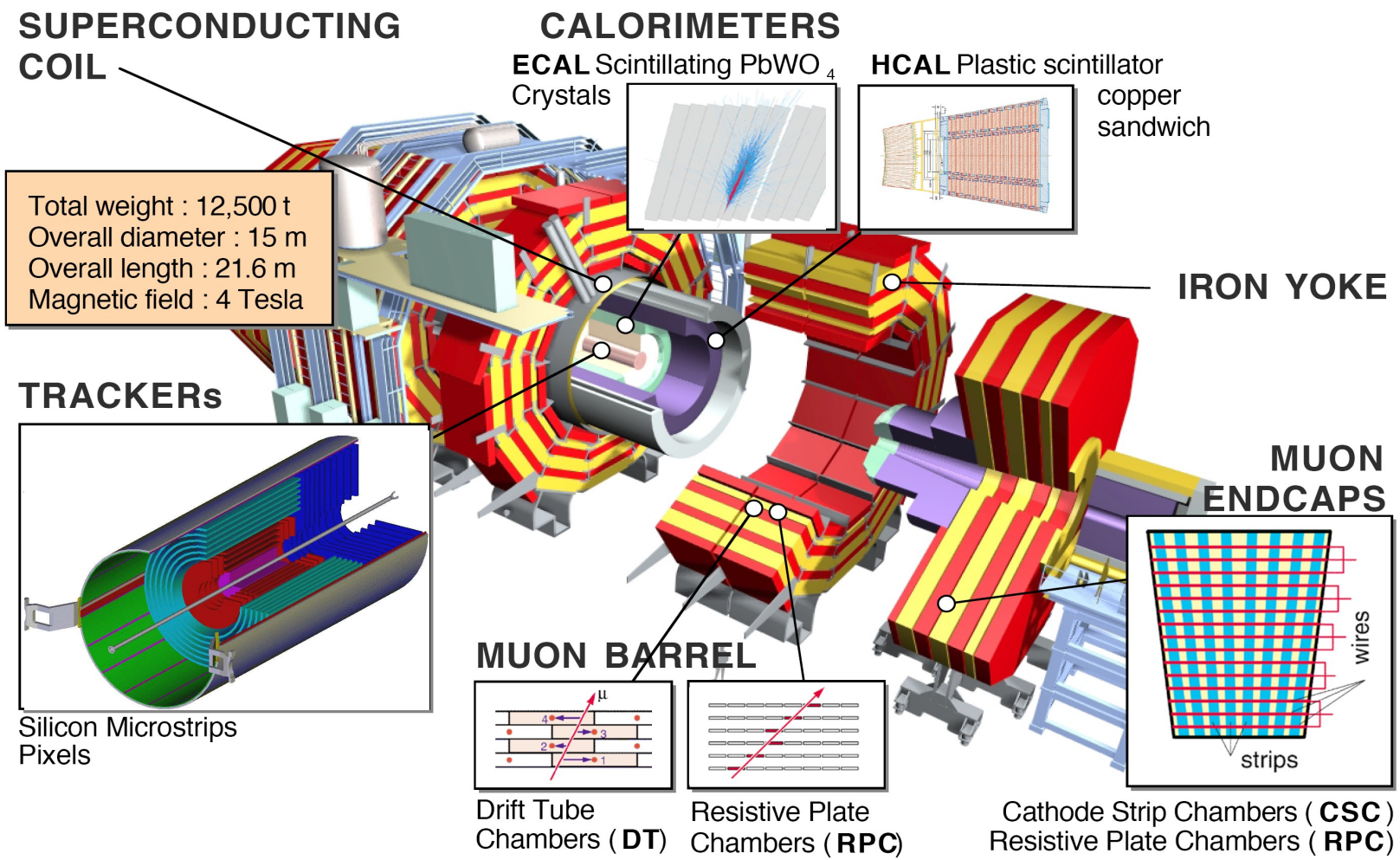
Summary and Outlook

- ATLAS and CMS have a rich program of searches with jets and photons
- No significant deviations from Standard Model predictions observed so far
  - Wide ranges of particle masses and model parameters have been excluded
- New or updated searches being planned or well underway
  - Further explore possible ways to probe lower masses of new particles
  - Incorporate b tagging into more of the already studied final-state topologies (motivated, for example, by RPV SUSY scenarios)
  - Further benefit from the jet substructure techniques (improved W/Z tagging, Higgs tagging,...)
  - ...
- All approved ATLAS and CMS results can be found at:
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

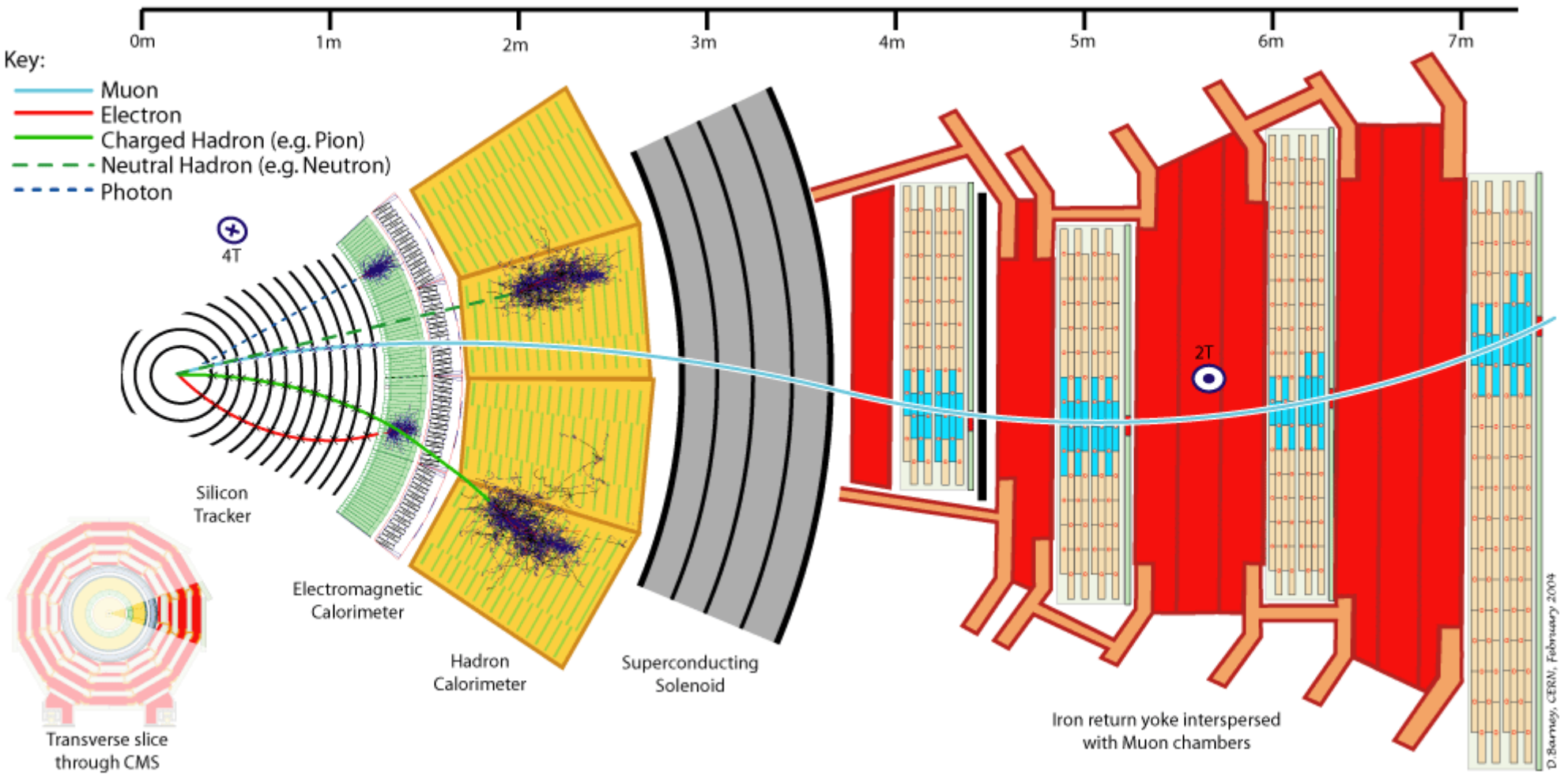
Backup Slides

Compact Muon Solenoid Detector

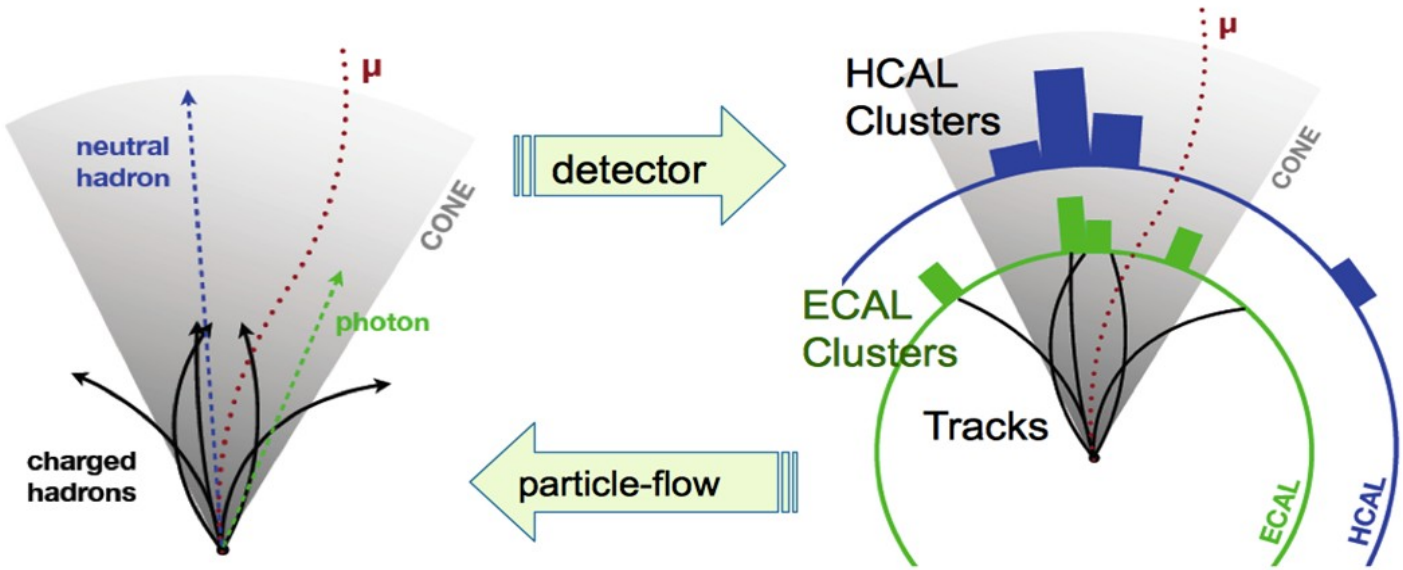
The Compact Muon Solenoid (CMS)



Event Reconstruction



Event Reconstruction



- Particle-flow algorithm combines information from all CMS subdetectors
- Returns a list of reconstructed long-lived particles:
  - e, μ, γ, charged and neutral hadrons
  - Used as building blocks for other higher-level objects
- Made possible by the granularity of the CMS detector and high magnetic field

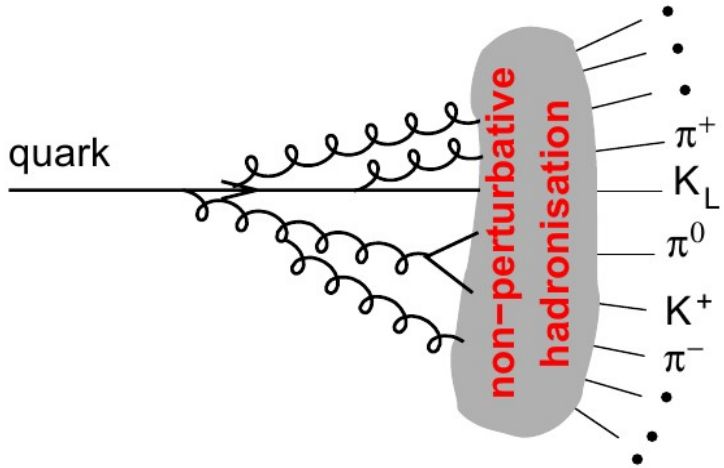
Jet Clustering Algorithms

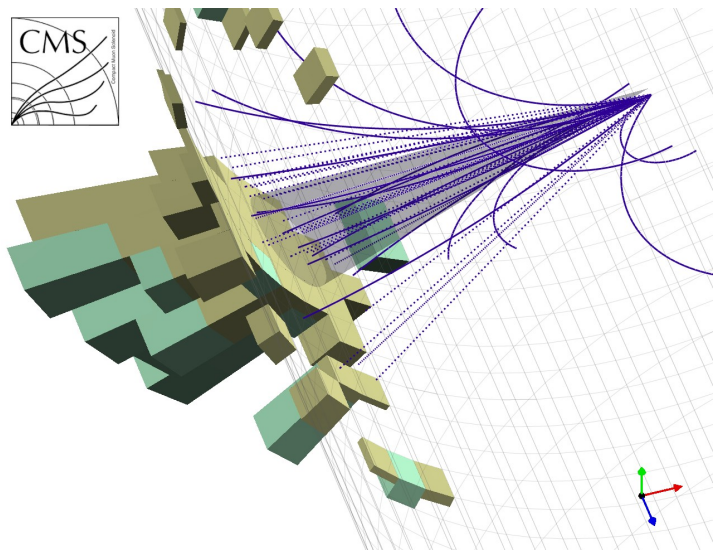
- Quarks and gluons never directly detectable → Immediately after being produced, they fragment and hadronize, leading to a collimated spray of hadrons called jet
- Jet clustering algorithm = set of rules for grouping particles into jets and assigning their momenta
- Sequential recombination algorithms

$$d_{ij} = \min(p_{Ti}^{2n}, p_{Tj}^{2n})\Delta R_{ij}^2/R^2 \qquad \Delta R_{ij}^2 = \sqrt{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}$$

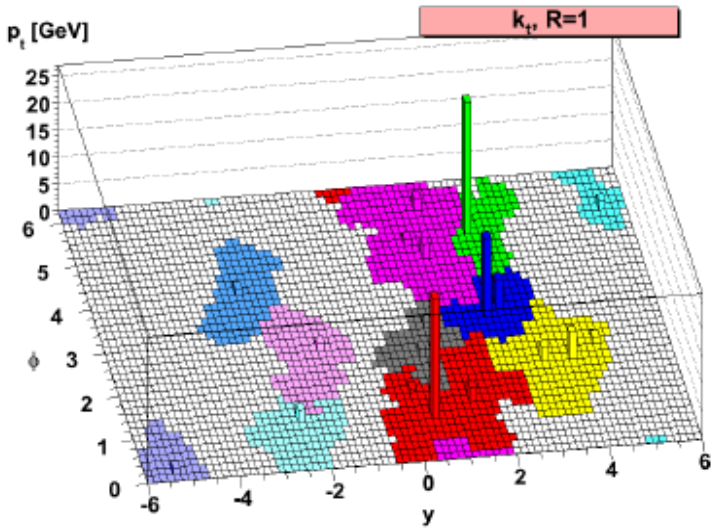
$$d_{iB} = p_{Ti}^{2n} \qquad R \text{ - dimensionless param.}$$

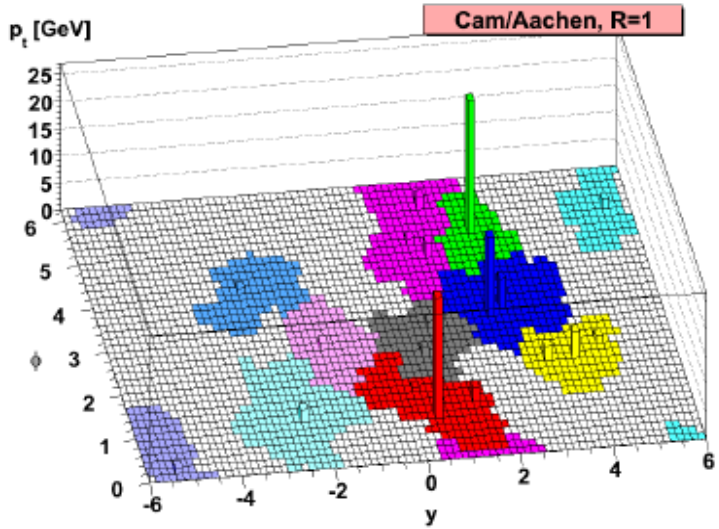
1. Find smallest of d_{ij}, d_{iB}
2. If *ij*, recombine *i* and *j* into a pseudoparticle (by adding their 4-momenta)
3. If *iB*, call *i* a jet and remove from list of (pseudo)particles
4. Repeat from step 1 until no (pseudo)particles left

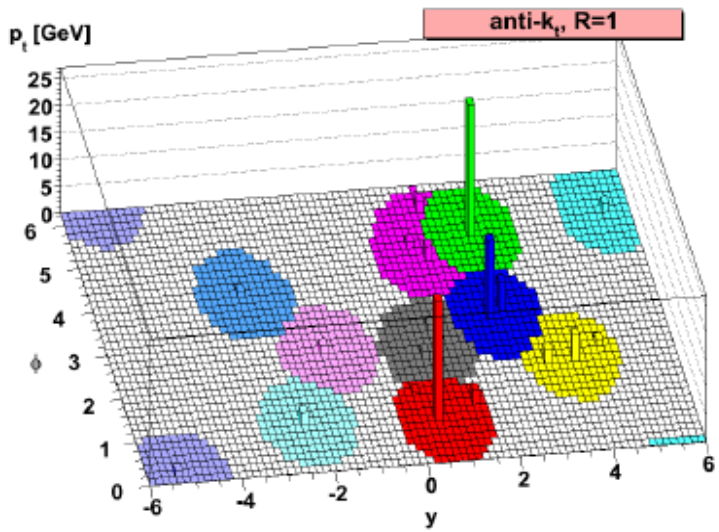




Jet Clustering Algorithms







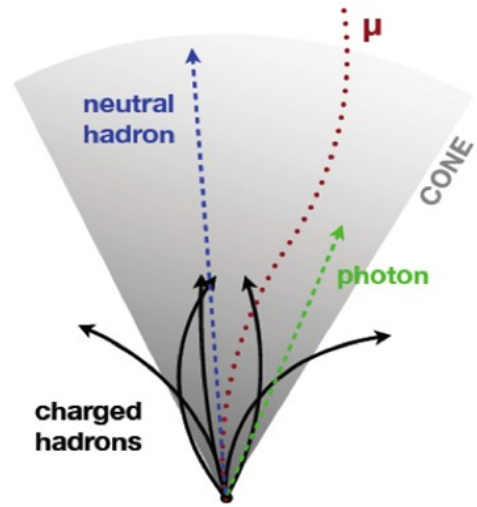
$n = 1 \rightarrow k_T$ algorithm

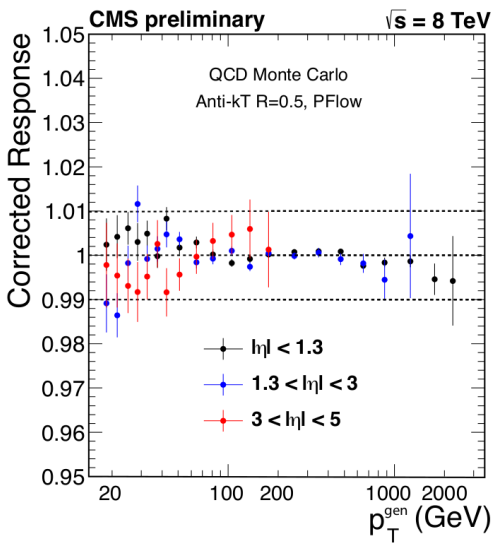
$n = 0 \rightarrow$ Cambridge/Aachen algorithm

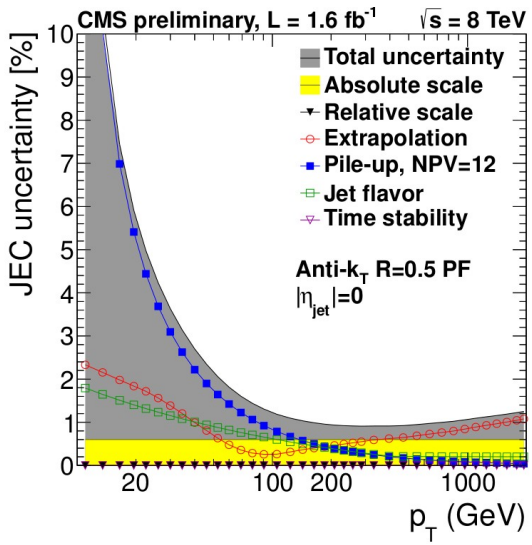
$n = -1 \rightarrow$ anti-k_T algorithm

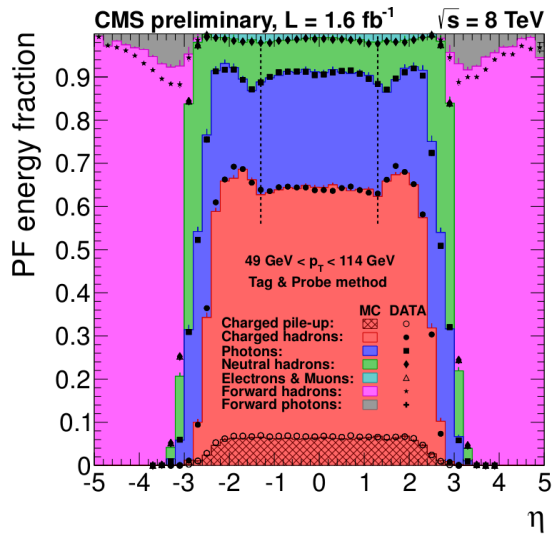
Jet Reconstruction in CMS

- Particle-flow jets clustered from reconstructed particle candidates
- Default jet clustering algorithm: Anti-k_T with R=0.5 and 0.7
- Jet energy scale calibrated using jet energy corrections
  - Extra energy from pile-up accounted for on an event-by-event basis using jet areas
  - Jet calibration vs η better than 1%
  - Jet energy scale uncertainty: ≈1% for p_T>150 GeV, jet energy resolution: 10% at p_T=100 GeV

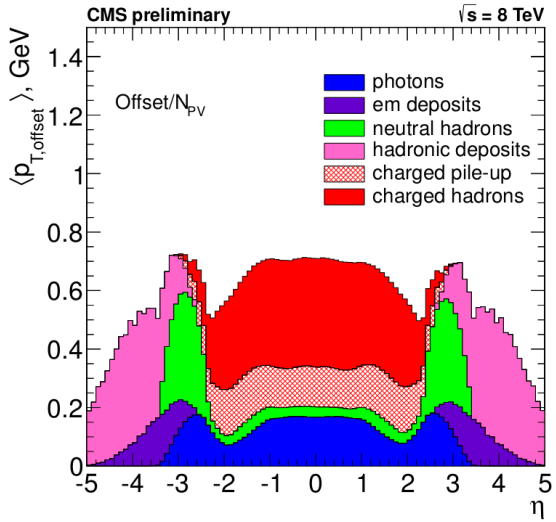


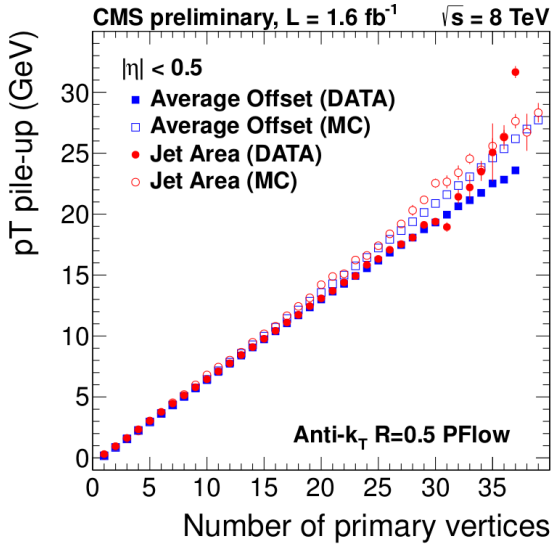


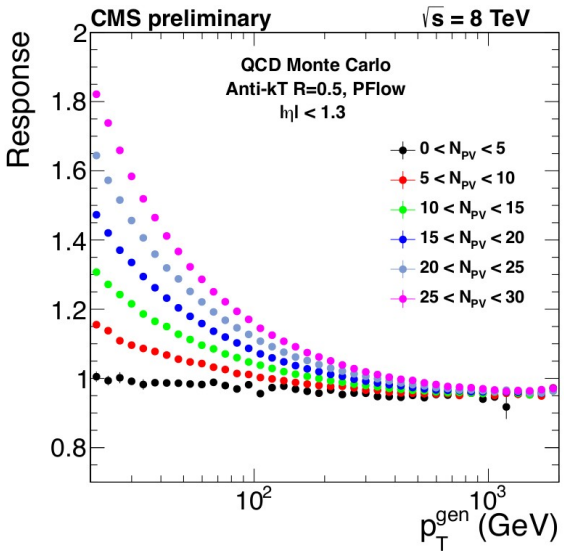


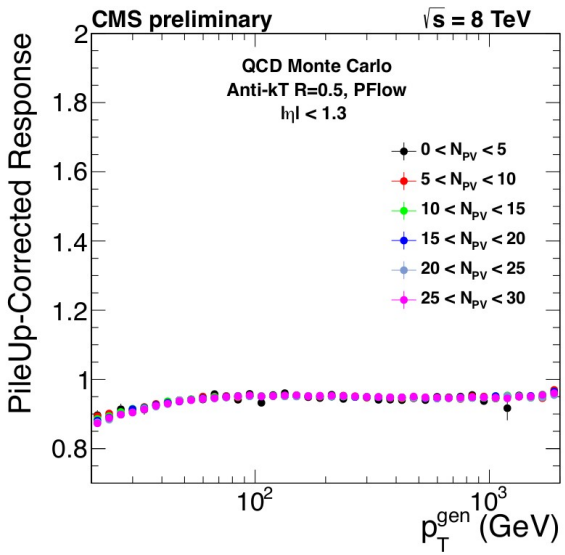


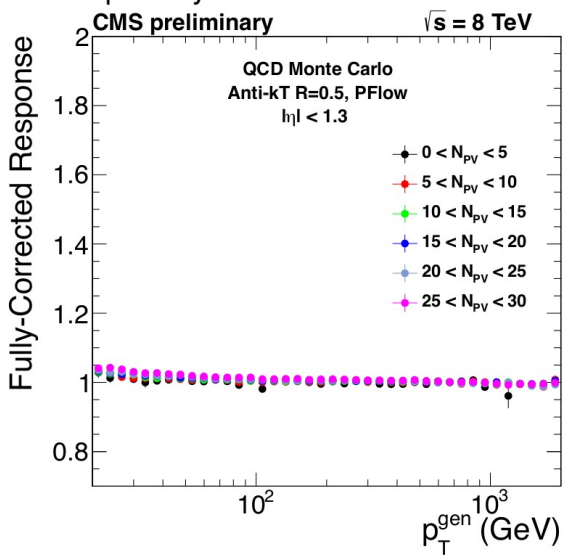
Jet Reconstruction in CMS



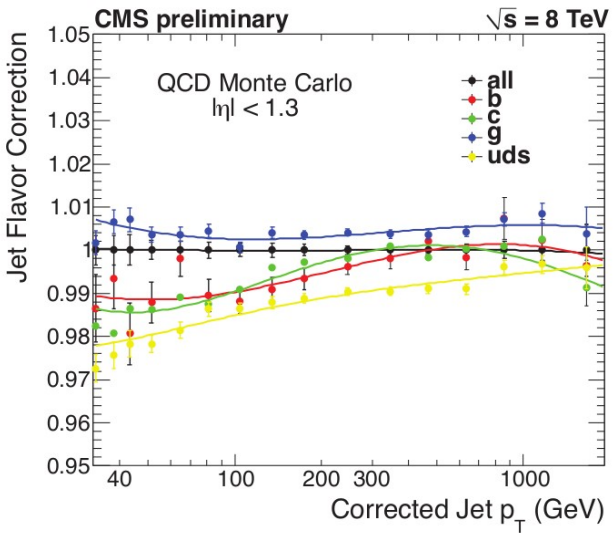


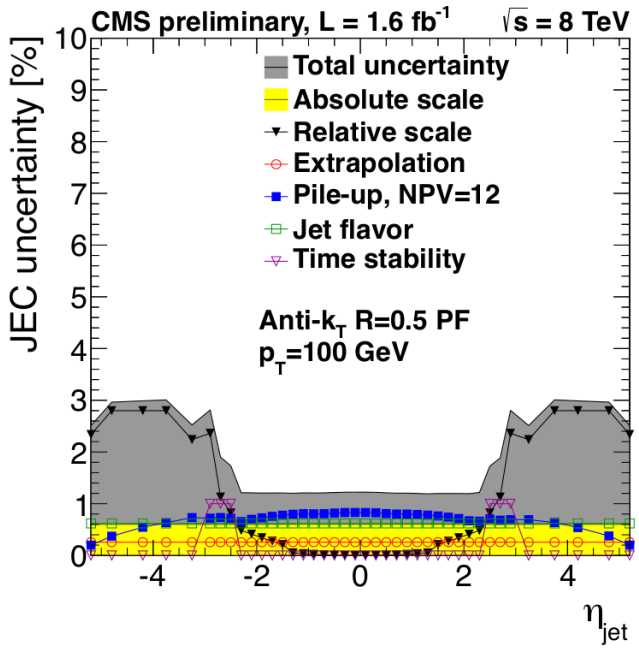


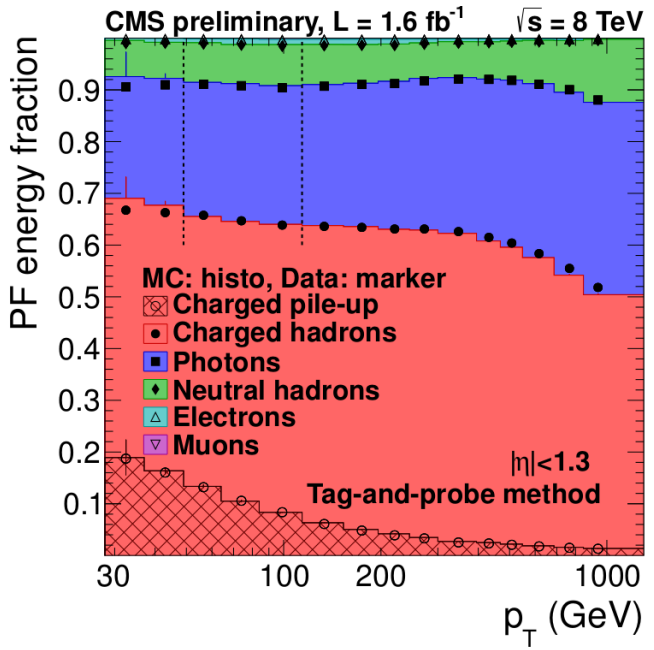




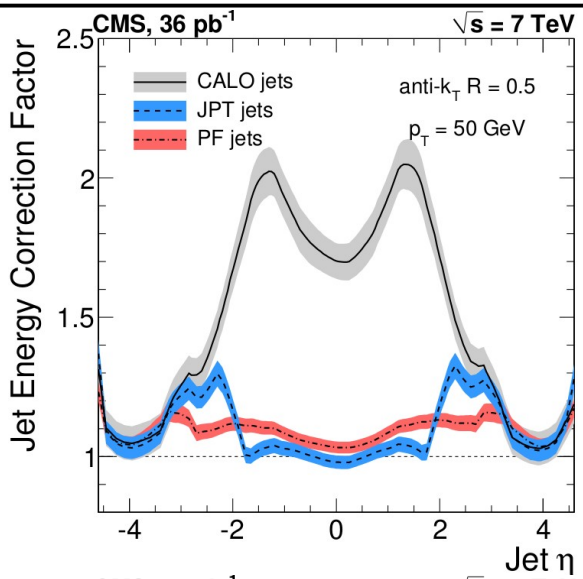
Jet Reconstruction in CMS

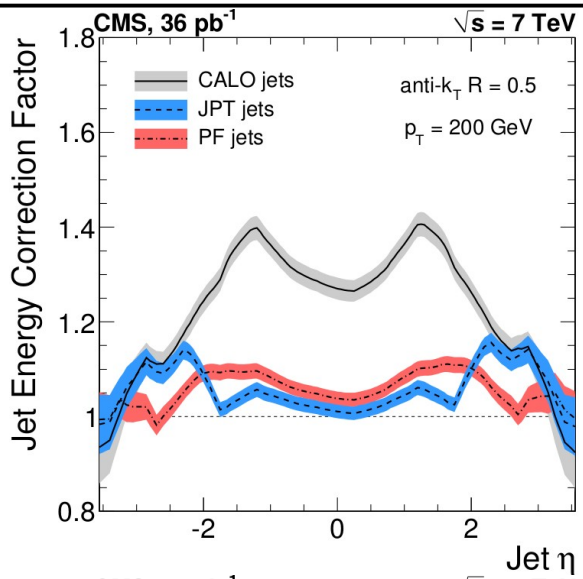






Jet Energy Corrections





$$p_\mu^{\text{cor}} = \mathcal{C} \cdot p_\mu^{\text{raw}}$$

$$\mathcal{C} = C_{\text{offset}}(p_{\text{T}}^{\text{raw}}) \cdot C_{\text{MC}}(p'_{\text{T}}, \eta) \cdot C_{\text{rel}}(\eta) \cdot C_{\text{abs}}(p''_{\text{T}})$$

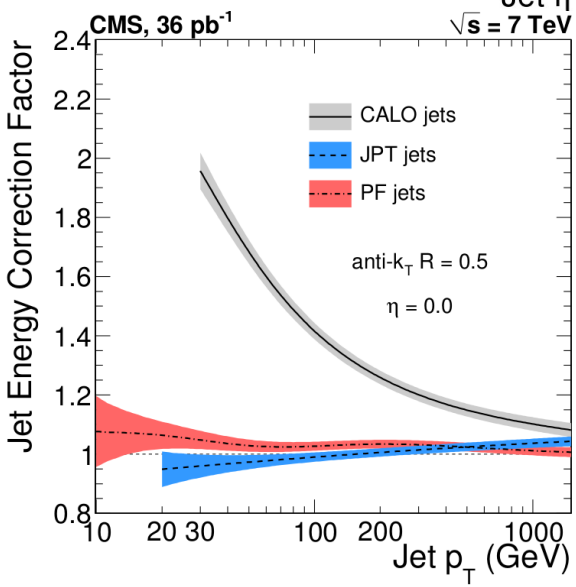
$\mathcal{C}$ - Overall correction factor

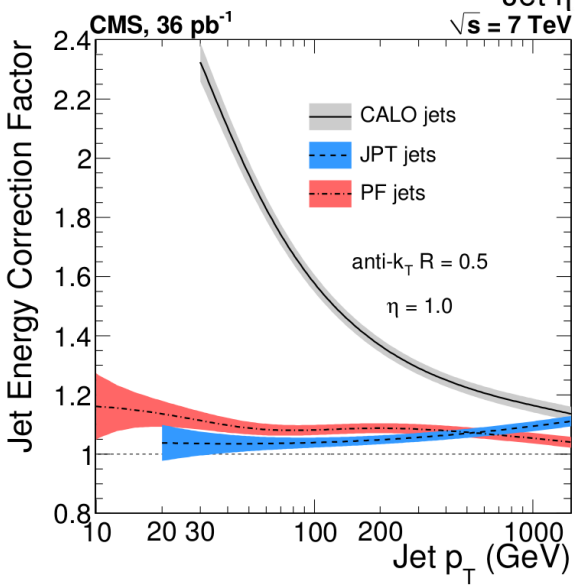
C_{offset} - Offset correction factor

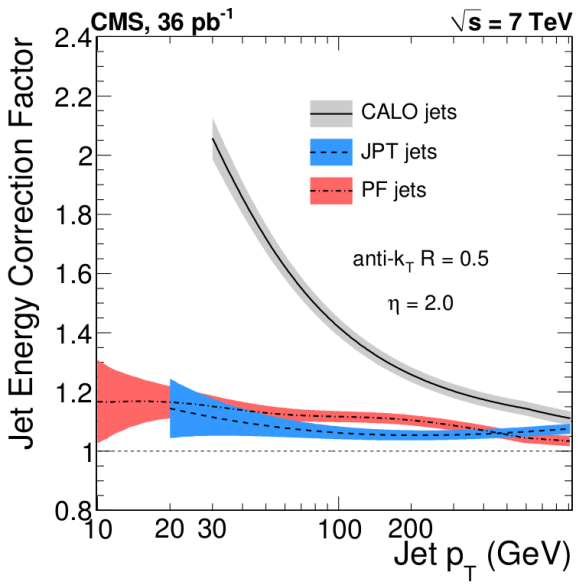
C_{MC} - MC calibration factor

C_{rel} - Residual relative calibration factor

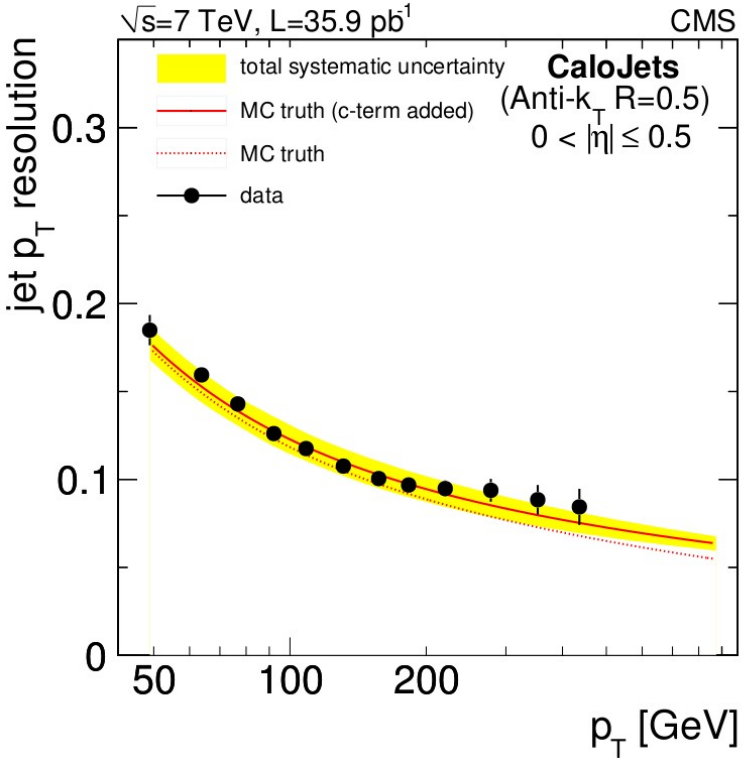
C_{abs} - Residual absolute calibration factor

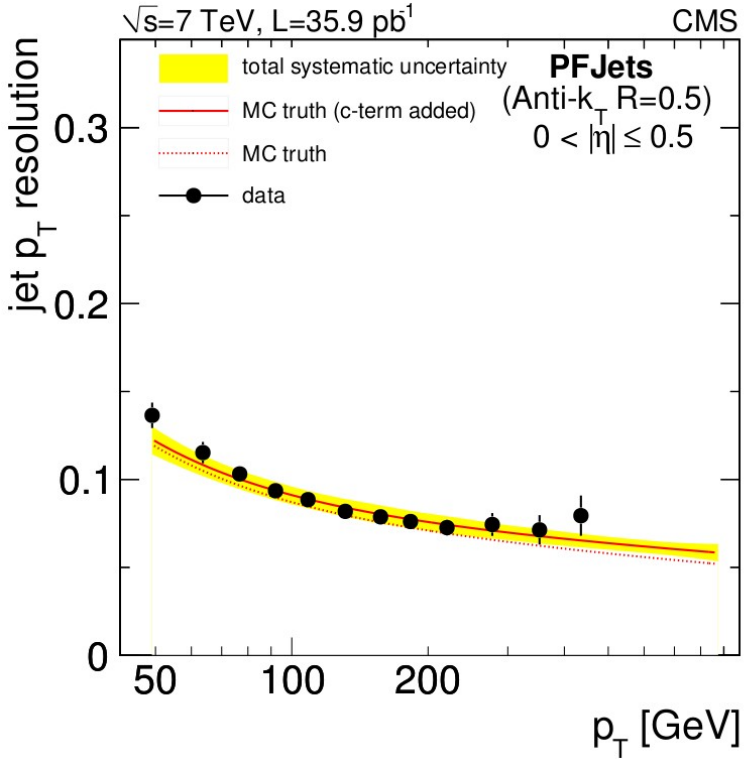






Jet p_T Resolution





$$\frac{\sigma(p_T)}{p_T} = \sqrt{\mathrm{sgn}(N)\cdot\left(\frac{N}{p_T}\right)^2 + S^2\cdot p_T^{(M-1)} + C^2}$$

N - Noise term

S - Stochastic term

C - Constant term

Dijet Resonances

Properties of some resonance models

Model Name	X	Color	J^P	$\Gamma/(2M)$	Chan
Excited Quark	q^*	Triplet	$1/2^+$	0.02	qg
E_6 Diquark	D	Triplet	0^+	0.004	qq
Axigluon	A	Octet	1^+	0.05	$q\bar{q}$
Coloron	C	Octet	1^-	0.05	$q\bar{q}$
RS Graviton	G	Singlet	2^+	0.01	$q\bar{q}$, gg
Heavy W	W′	Singlet	1^-	0.01	$q\bar{q}$
Heavy Z	Z′	Singlet	1^-	0.01	$q\bar{q}$
String	S	mixed	mixed	0.003 – 0.037	qg, $q\bar{q}$, gg

$F(\cos\theta^*) \equiv d\hat{\sigma}/d\cos\theta^*$ arXiv:1110.5302

- *E_6 diquark, color octet scalars:* $F(\cos\theta^*) = \text{const.}$
- *excited quark:* $F(\cos\theta^*) \sim 1 + \cos\theta^*$, which becomes $F(|\cos\theta^*|) = \text{const.}$ (odd in $\cos\theta^*$).
- *axigluon, coloron, W', Z':* $F(\cos\theta^*) \sim 1 + \cos^2\theta^*$.
- *RS gravitons:* $F(gg \to G \to q\bar{q}) = F(q\bar{q} \to G \to gg) \sim 1 - \cos^4\theta^*$, $F(gg \to G \to gg) \sim 1 + 6\cos^2\theta^* + \cos^4\theta^*$, and $F(q\bar{q} \to G \to q\bar{q}) \sim 1 - 3\cos^2\theta^* + 4\cos^4\theta^*$

CMS dijet mass resolution (wide jets):

qq :

$$\frac{\sigma}{M} = \frac{1.31}{\sqrt{M[GeV]}} + 0.018$$

$\approx 8\%\,(M = 0.5\text{ TeV}), \approx 4\%\,(M = 2.5\text{ TeV})$

qg :

$$\frac{\sigma}{M} = \frac{1.56}{\sqrt{M[GeV]}} + 0.027$$

$\approx 10\%\,(M = 0.5\text{ TeV}), \approx 6\%\,(M = 2.5\text{ TeV})$

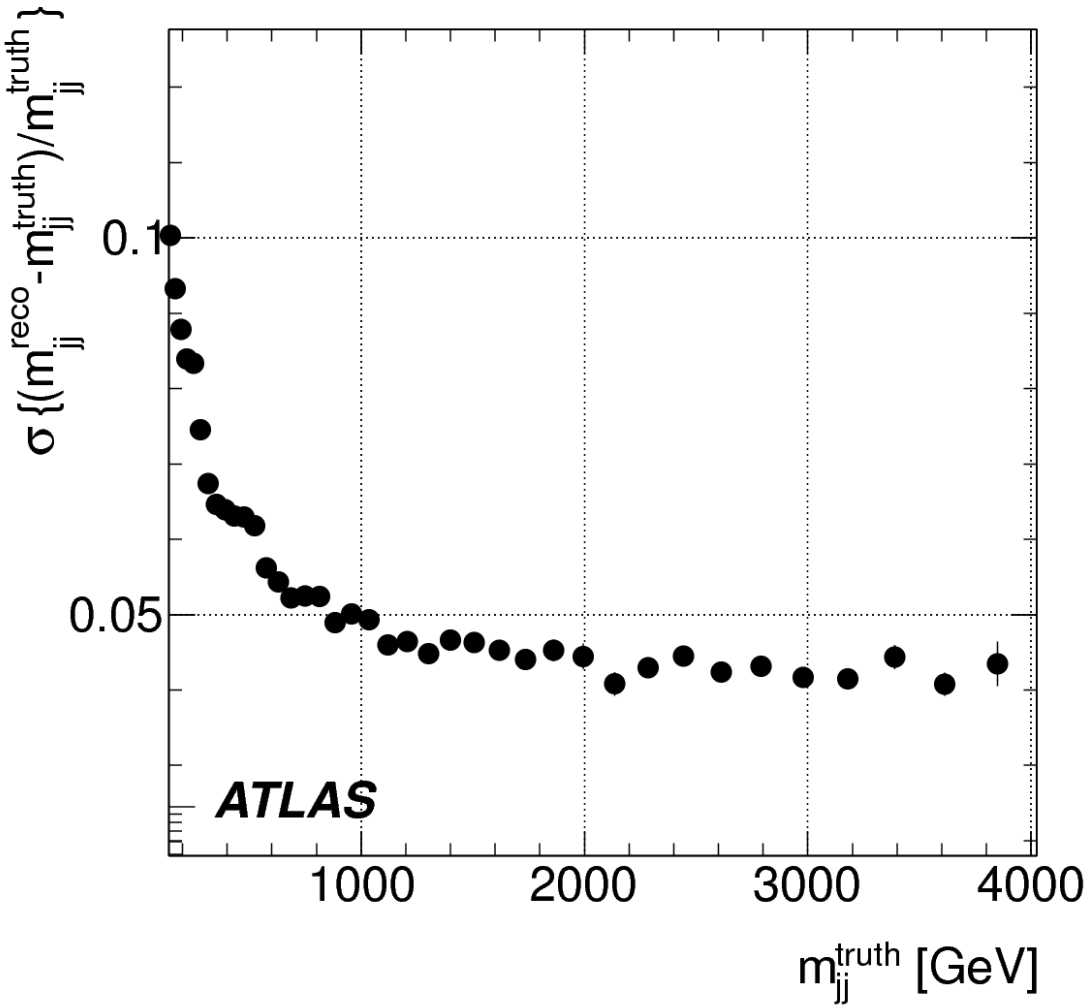
gg :

$$\frac{\sigma}{M} = \frac{2.09}{\sqrt{M[GeV]}} + 0.015$$

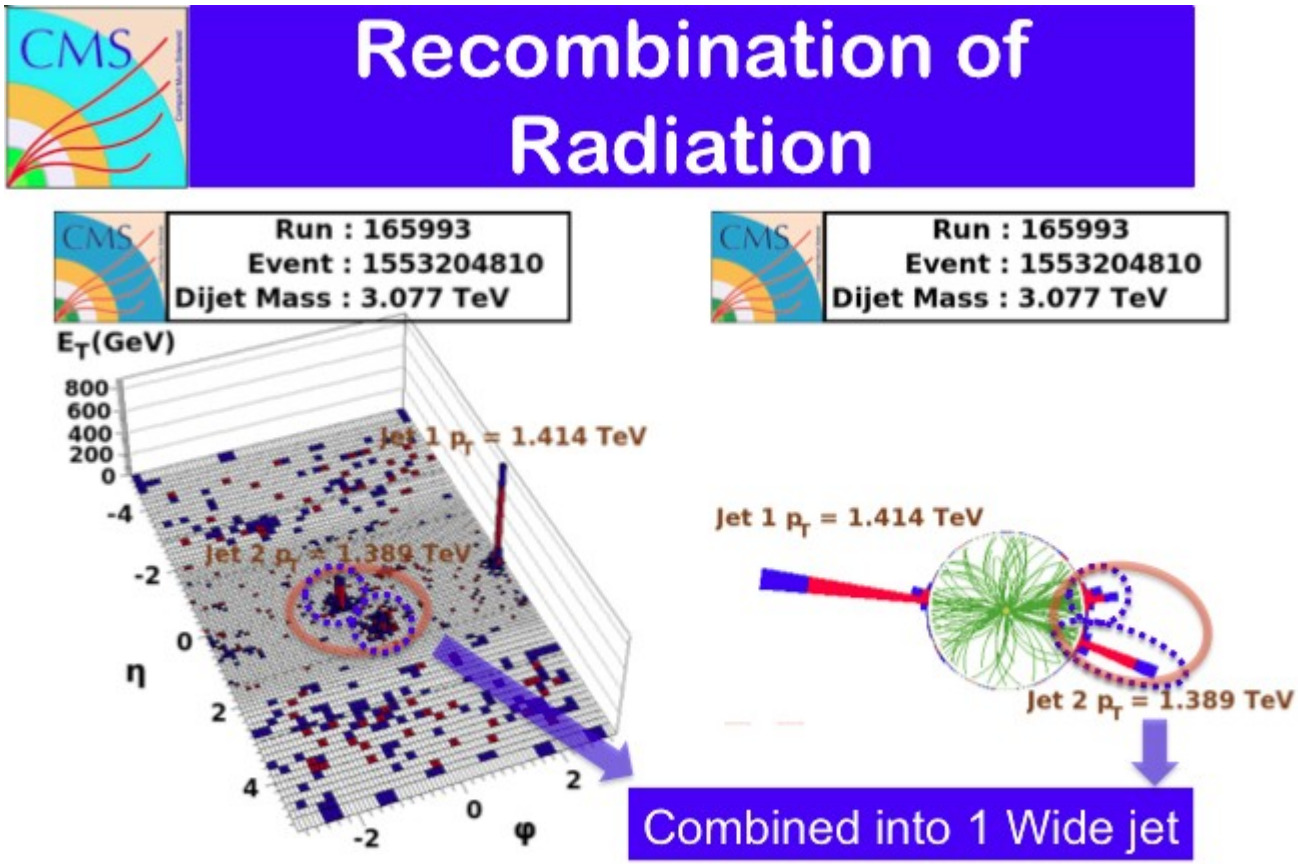
$\approx 11\%\,(M = 0.5\text{ TeV}), \approx 6\%\,(M = 2.5\text{ TeV})$

Dijet Resonances (cont'd)

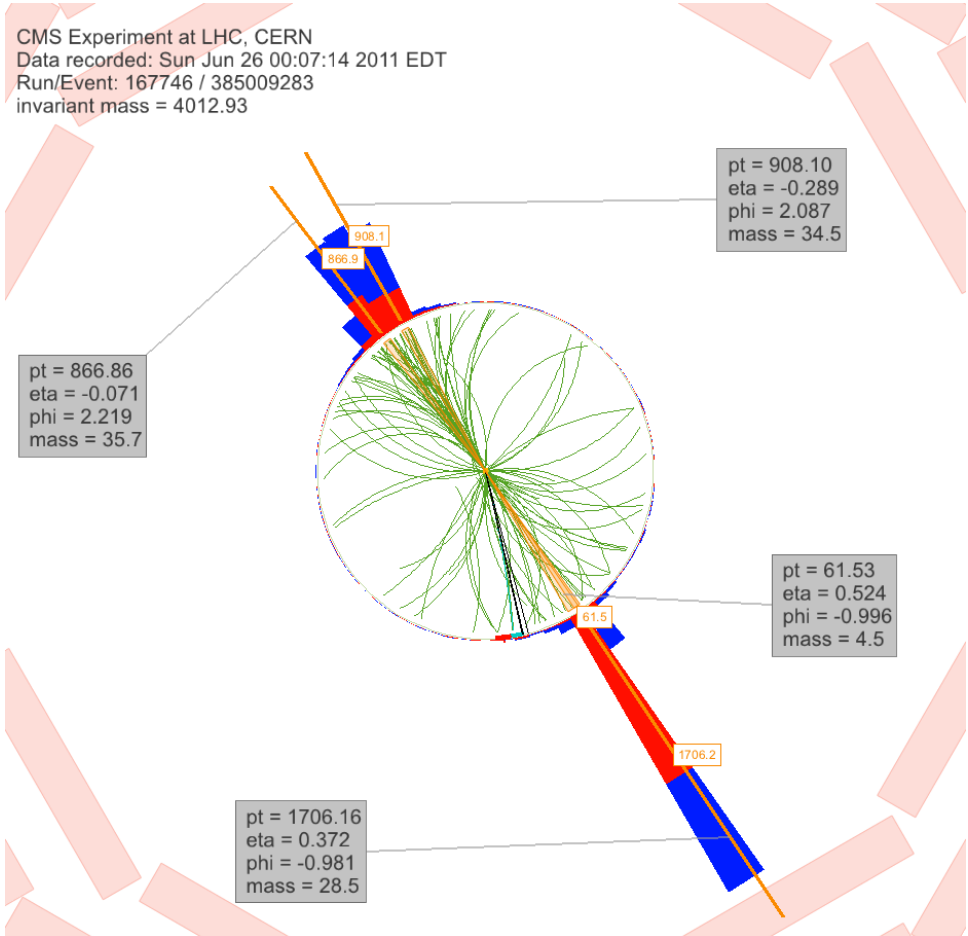
- ATLAS dijet mass resolution

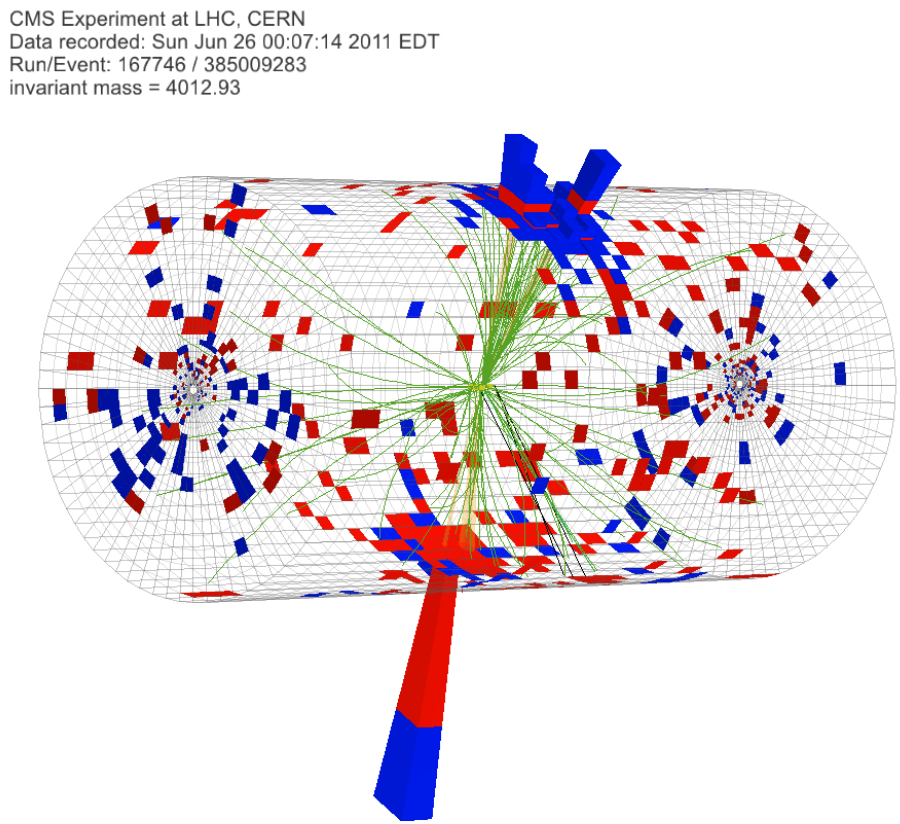


Wide Jets


Recombination of Radiation
Run : 165993
Event : 1553204810
Dijet Mass : 3.077 TeV
Run : 165993
Event : 1553204810
Dijet Mass : 3.077 TeV
E_T(GeV)
800
600
400
200
0
-4
-2
0
η
2
4
-2
0
2
φ
Jet 1 p_T = 1.414 TeV
Jet 2 p_T = 1.389 TeV
Jet 1 p_T = 1.414 TeV
Jet 2 p_T = 1.389 TeV
Combined into 1 Wide jet

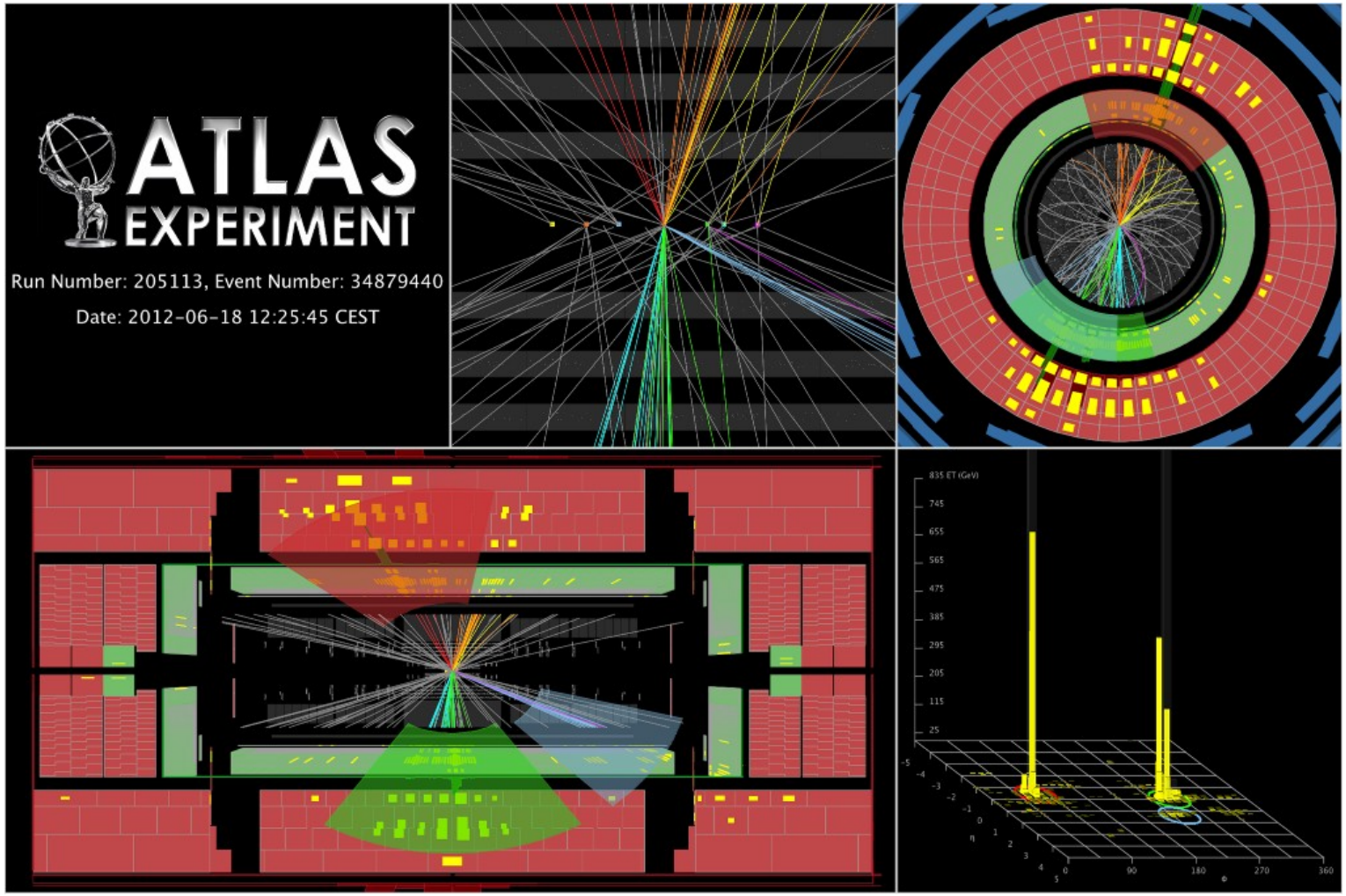
Dijet Mass Spectrum (√s=7 TeV)





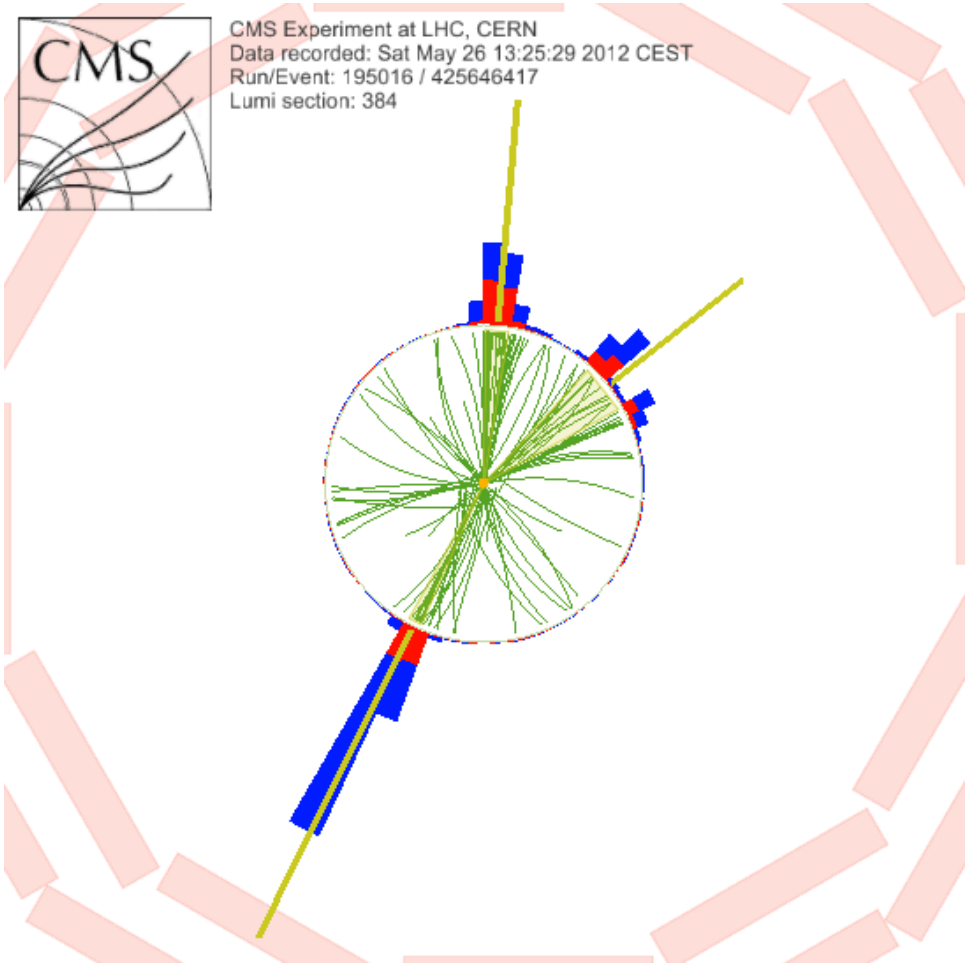
Highest dijet mass event (~4 TeV)

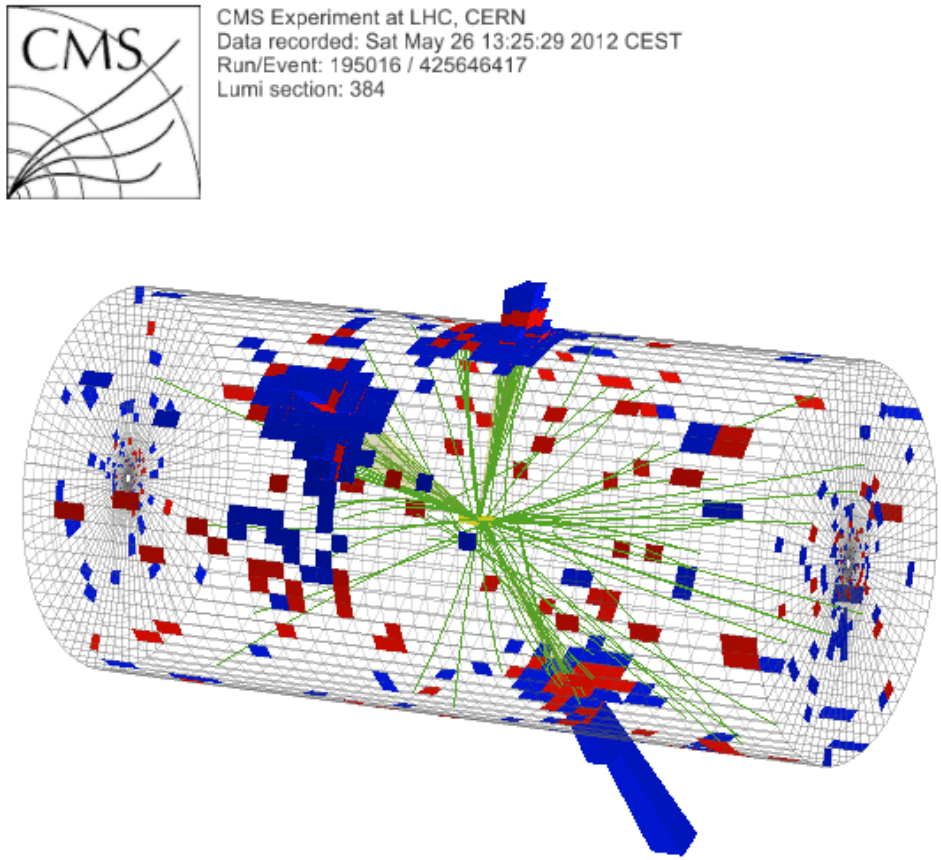
Dijet Mass Spectrum (√s=8 TeV)



Highest dijet mass event (~4.1 TeV)

Dijet Mass Spectrum (√s=8 TeV)





Highest dijet mass event (~4.5 TeV)