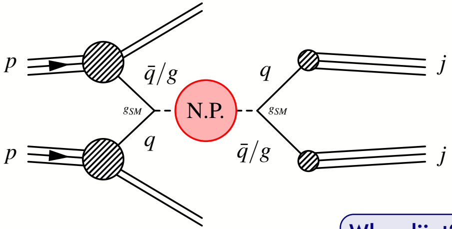
Istituto Nazionale
di Fisica Nucleare

Matteo Bauce
on behalf of the ATLAS and CMS collaborations

Search for new physics in dijet final states in ATLAS and CMS

LHCP, 15-20/05/17, Shanghai

Search for new physics - dijet final states

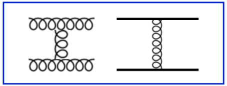


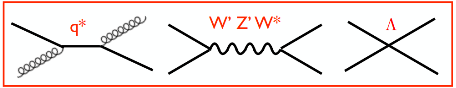
Why dijet?

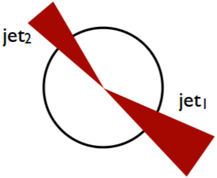
Any new physics contribution produced in hadronic collision can produce hadrons in its decay

- Dijet events provide a clear signature for many models
- Interesting searches even with low statistics

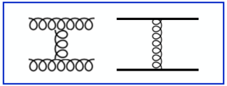
Search for dijet resonance

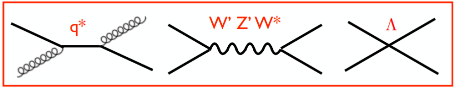


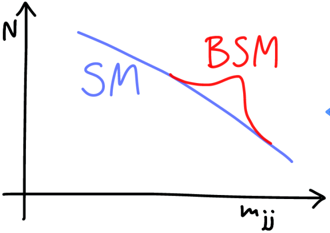


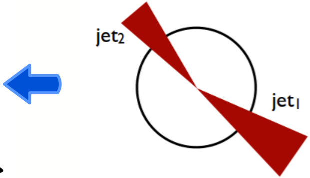


Search for dijet resonance









- QCD smoothly falling background
  - can be estimated with a functional fit
- Signal visible as a resonance peak
- Sensitive to narrow *s*-channel resonances

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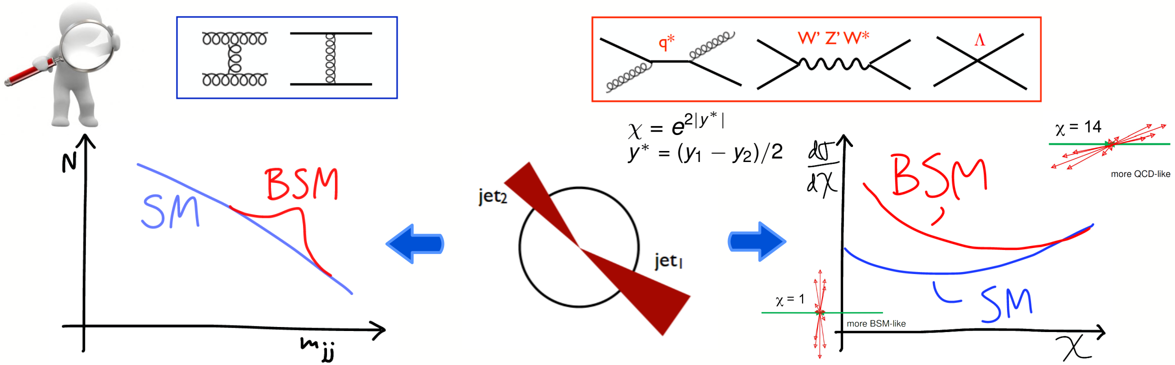

$$\chi = e^{2|y^*|}$$
$$y^* = (y_1 - y_2)/2$$

- QCD smoothly falling background
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- QCD produced at small polar angles
  - modelled using MC simulation
- BSM contributions more isotropic
  - expected at low χ and high m_{jj}
- Sensitive to tails of contact interactions with a very high scale

Basic event selection

ATLAS

- Trigger $p_T(j_1) > 380$ GeV
- $p_T^{j_1}(p_T^{j_2}) > 440$ (60) GeV
- Event specific:

1703.09127 [hep-ex]

Resonance	W^* (chiral)	Angular
$\lvert y^*\rvert < 0.6$	$\lvert y^*\rvert < 1.2$	$\lvert y^*\rvert < 1.7$ $\lvert y^B\rvert < 1.1$
m_{jj} >1.1 TeV	m_{jj} >1.7 TeV	m_{jj} >2.5 TeV

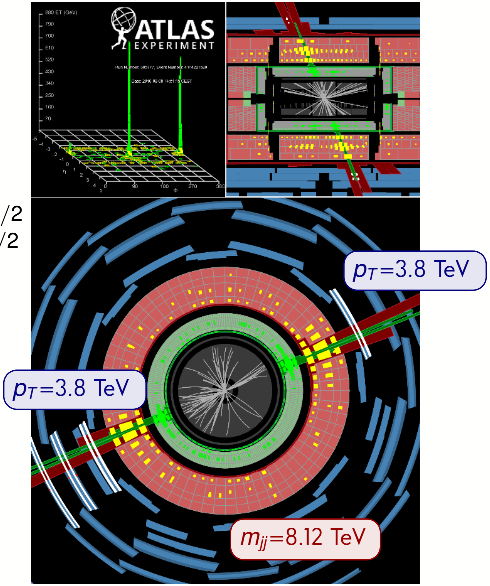
$y^* = (y_1 - y_2)/2$

$y^B = (y_1 + y_2)/2$

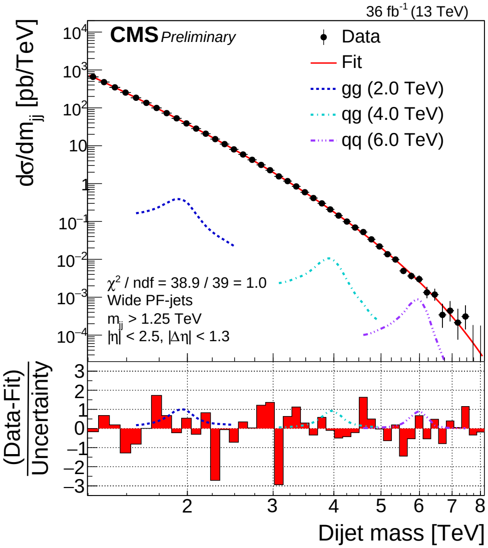
CMS

- Particle flow jets: $p_T > 30$ GeV, $|\eta| < 2.5$
- Trigger: $H_T = \sum_{jets} p_T > 900$ GeV
- $m_{jj} > 1.25$ TeV
- $|\eta_{j_1} - \eta_{j_2}| < 1.3$
- Close-by jets merged into wide jets (ΔR=1.1)
  - reduce gluon final-state radiation dependence

CMS PAS EXO-16-056



Background modeling



⇐ Monte Carlo simulation unable to reproduce QCD background at the precision needed

Fit a smoothly falling background with an analytical function to search for bumps

$$\frac{dN}{dm_{jj}} = \frac{p_1 \cdot (1 - z)^{p_2}}{z^{p_3 + p_4 \ln z}} \qquad z = m_{jj}/\sqrt{s}$$

- Variable number of parameters needed
  - fit across large range
- Fit complexity increase with luminosity
  - more data - more parameters needed

CMS PAS EXO-16-056

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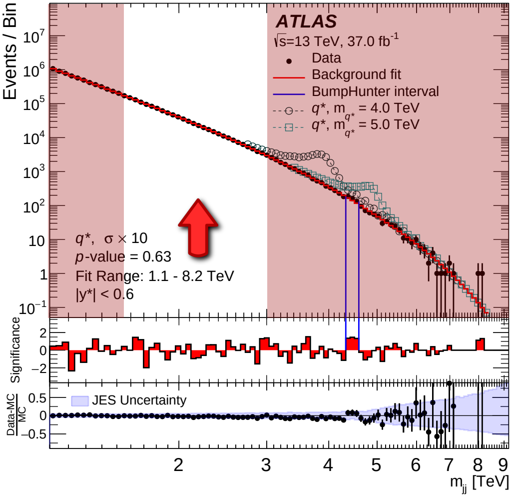

SWiFt: Sliding Window Fit

- Fit spectra in restricted regions (*window*)
- Fit with simpler function

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- Slide the window centre bin-by-bin
- Extract background prediction at window center

Fit stable when increasing statistics!

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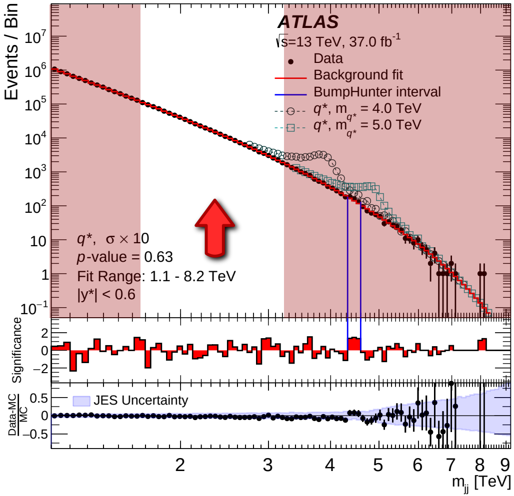

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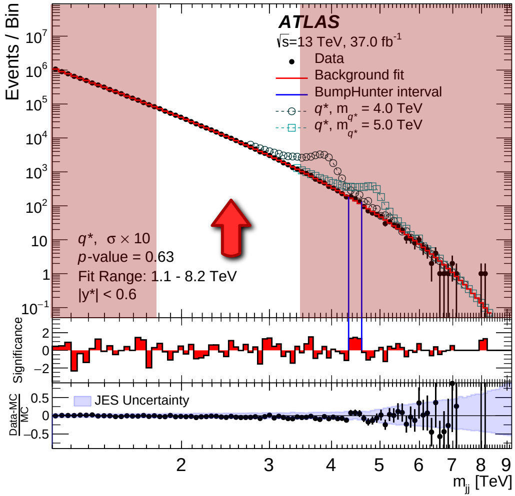

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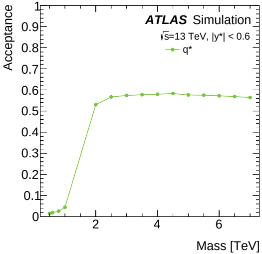
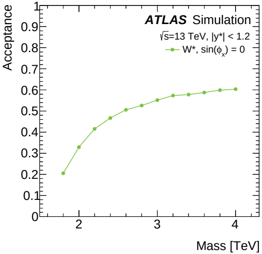
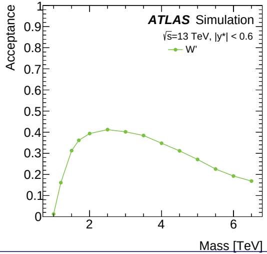
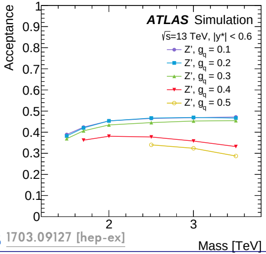
Signal models

- Several benchmark models considered by both experiments:
  - q^*, QBH, W^*, W', Z', strings, RS graviton, ...









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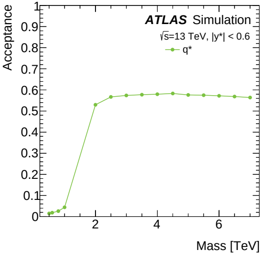

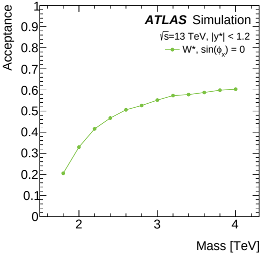

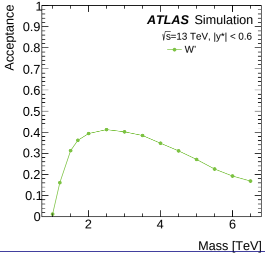

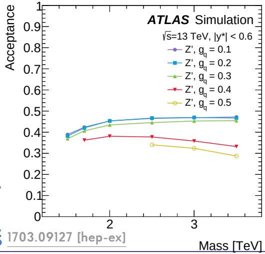

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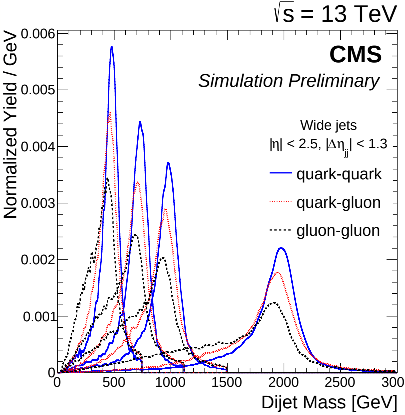
Consider different signal shapes for different di-jet flavors: *qq*, *qg*, *gg*

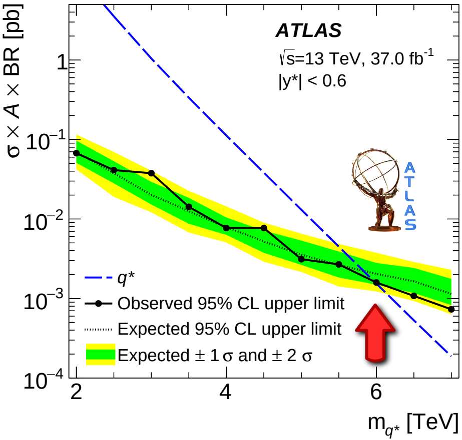


CMS PAS EXO-16-056

Statistical analysis, exclusion results

- Several benchmark models considered by both experiment:
  - q^*, QBH, W^*, W', Z', strings, RS graviton, ...

Similar reach from both experiments!



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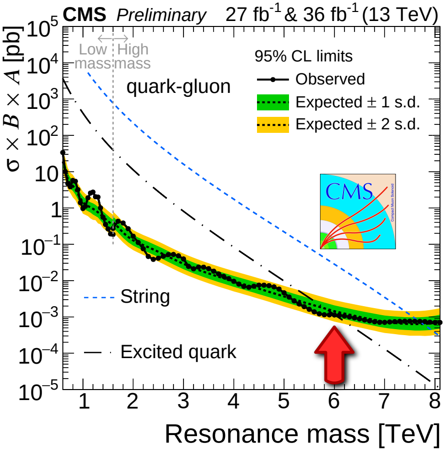
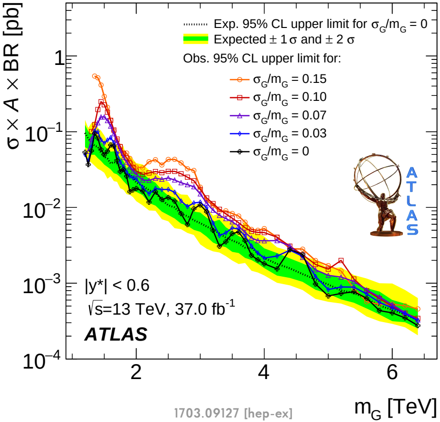


CMS PAS EXO-16-056

Generalized limit results

- Limits on gaussian signal for ease of reinterpretation
- Factorize out detector effect on jet energy to provide information at particle level

- Limits on generic models related to quark-gluon combination



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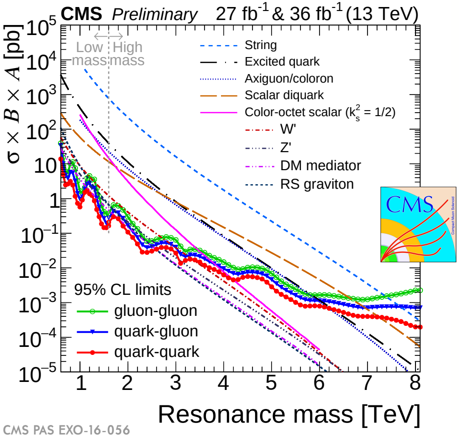

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m_G=gaussian peak mass

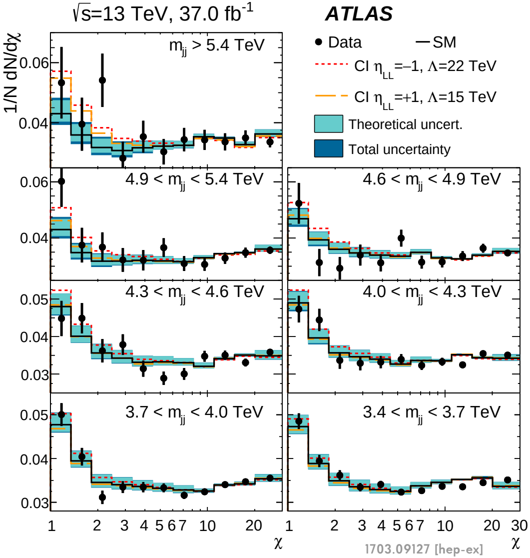
Dijet angular correlation

Explore dijet angular separation

$$\chi = e^{2|y^*|} \qquad |y^*| < 1.7 \qquad \frac{|y_1 + y_2|}{2} < 1.1$$

- Background prediction from MC simulation
  - include NLO QCD + LO EW corrections
  - Dominant uncertainties from jet energy reconstruction (scale), and choice of factorization and renormalization scales
- Combined fit in different m_{jj} regions
  - constrain theo. and exp. uncertainties

No significant deviation observed with respect to Standard Model prediction



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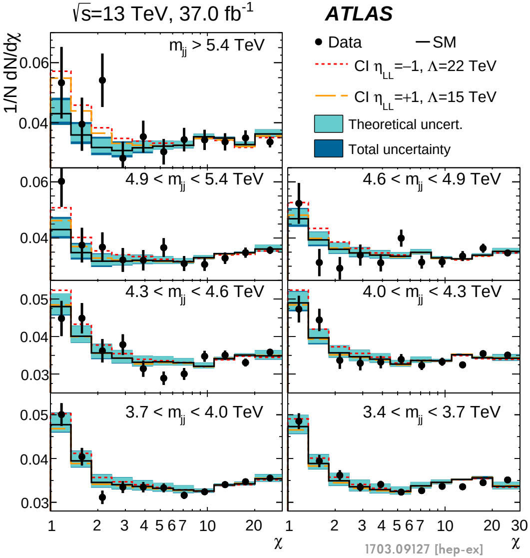
- Limits on $q\bar{q} \to q\bar{q}$ Contact Interaction

$$\mathcal{L}_{qq} = \frac{2\pi}{\Lambda^2}\left[\, \eta_{\mathrm{LL}}(\bar{q}_{\mathrm{L}}\gamma^{\mu} q_{\mathrm{L}})(\bar{q}_{\mathrm{L}}\gamma_{\mu} q_{\mathrm{L}}) + \eta_{\mathrm{RR}}(\bar{q}_{\mathrm{R}}\gamma^{\mu} q_{\mathrm{R}})(\bar{q}_{\mathrm{R}}\gamma_{\mu} q_{\mathrm{R}}) + 2\eta_{\mathrm{RL}}(\bar{q}_{\mathrm{R}}\gamma^{\mu} q_{\mathrm{R}})(\bar{q}_{\mathrm{L}}\gamma_{\mu} q_{\mathrm{L}})\right]$$

  - consider constructive/destructive interference with SM



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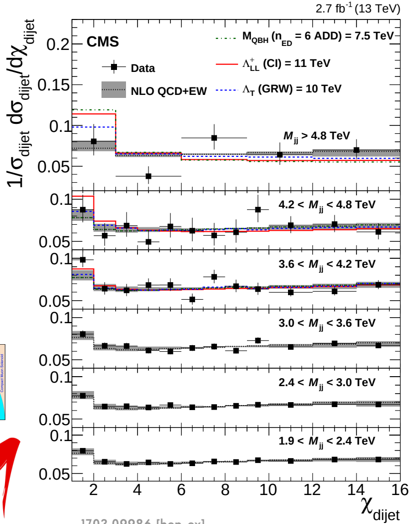
  - consider constructive/destructive interference with SM
- Apply energy folding for particle-level distributions



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Summary of models and exclusions

Resonance excluded in the few-TeV range.
Contact Interaction NP contribution excluded up to ∼30 TeV

Model	95% CL exclusion limit	
	Observed	Expected
Quantum black hole	8.9 TeV	8.9 TeV
W'	3.6 TeV	3.7 TeV
W^*	3.4 TeV 3.77 TeV – 3.85 TeV	3.6 TeV
Excited quark	6.0 TeV	5.8 TeV
Z' ($g_q = 0.1$)	2.1 TeV	2.1 TeV
Z' ($g_q = 0.2$)	2.9 TeV	3.3 TeV
Contact interaction ($\eta_{\mathrm{LL}} = -1$)	21.8 TeV	28.3 TeV
Contact interaction ($\eta_{\mathrm{LL}} = +1$)	13.1 TeV 17.4 TeV – 29.5 TeV	15.0 TeV

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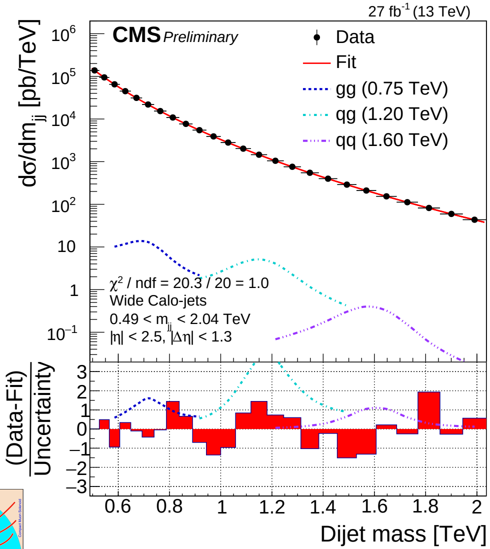
Model	Final State	Observed (expected) mass limit [TeV]			
		36 fb^{-1} 13 TeV	12.9 fb^{-1} 13 TeV	2.4 fb^{-1} 13 TeV	20 fb^{-1} 8 TeV
String	qg	7.7 (7.7)	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	7.2 (7.4)	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	$\mathrm{q\bar{q}}$	6.1 (6.0)	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	6.0 (5.8)	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.4 (3.6)	3.0 (3.3)	—	—
W′	$\mathrm{q\bar{q}}$	3.3 (3.6)	2.7 (3.1)	2.6 (2.3)	2.2 (2.2)
Z′	$\mathrm{q\bar{q}}$	2.7 (2.9)	2.1 (2.3)	—	1.7 (1.8)
RS Graviton ($k/M_{\mathrm{PL}} = 0.1$)	$\mathrm{q\bar{q}}$, gg	1.7 (2.1)	1.9 (1.8)	—	1.6 (1.3)
DM Mediator ($m_{\mathrm{DM}} = 1$ GeV)	$\mathrm{q\bar{q}}$	2.6 (2.5)	2.0 (2.0)	—	—

Model	Observed lower limit (TeV)	Expected lower limit (TeV)
$\Lambda^+_{\mathrm{LL/RR}}$ (NLO)	11.5	12.1±1.2
$\Lambda^-_{\mathrm{LL/RR}}$ (NLO)	14.7	17.3±3.4
Λ^+_{VV} (NLO)	13.3	13.9±1.2
Λ^-_{VV} (NLO)	18.6	22.2±5.4
Λ^+_{AA} (NLO)	13.3	13.9±1.2
Λ^-_{AA} (NLO)	18.6	22.1±5.1
$\Lambda^+_{(\mathrm{V-A})}$ (NLO)	8.4	9.5±1.6
$\Lambda^-_{(\mathrm{V-A})}$ (NLO)	8.4	9.5±1.7
ADD Λ_{T} (GRW)	9.4	9.8±1.2
ADD M_{S} (HLZ) $n_{\mathrm{ED}} = 2$	10.1	10.6±1.3
ADD M_{S} (HLZ) $n_{\mathrm{ED}} = 3$	11.2	11.7±1.4
ADD M_{S} (HLZ) $n_{\mathrm{ED}} = 4$	9.4	9.8±1.2
ADD M_{S} (HLZ) $n_{\mathrm{ED}} = 5$	8.5	8.9±1.1
ADD M_{S} (HLZ) $n_{\mathrm{ED}} = 6$	7.9	8.2±1.0
$n_{\mathrm{ED}} = 6$ ADD QBH M_{QBH}	7.8	7.7±0.3
$n_{\mathrm{ED}} = 1$ RS QBH M_{QBH}	5.3	5.3±0.4

1703.09986 [hep-ex]

Explore Lower Masses - Trigger Level Analysis



CMS PAS EXO-16-056

Exploit reduced information from HLT level jets

- Calorimeter jets: $p_T > 40$ GeV, $|\eta| < 2.5$
- Trigger $H_T > 250$ GeV, $|\eta_{j_1} - \eta_{j_2}| < 1.3$

◀ Allow to explore $m_{jj} \in [0.49\text{-}2.0]$ TeV

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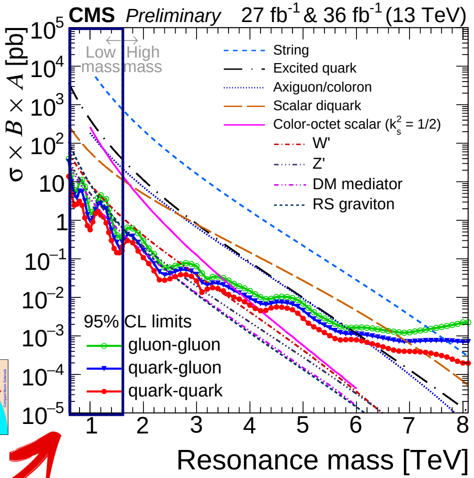

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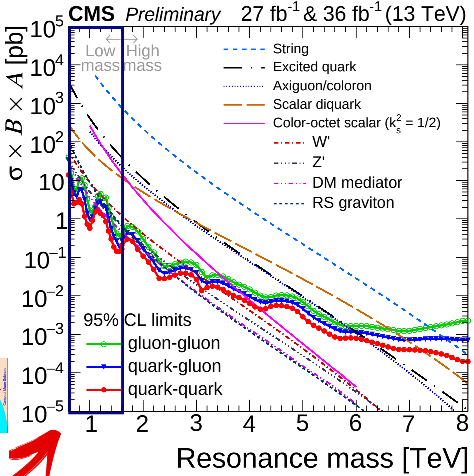
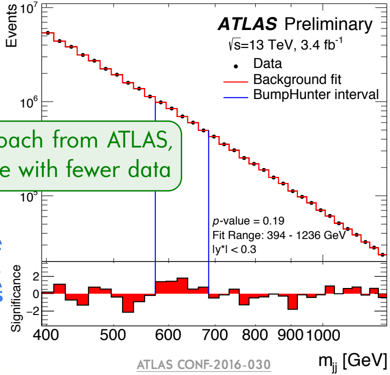


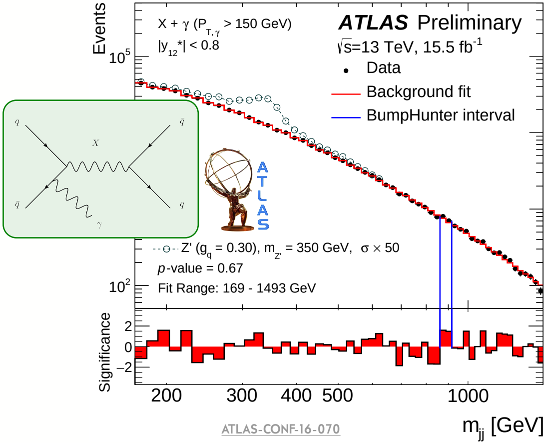
CMS PAS EXO-16-056

Similar approach from ATLAS, analysis done with fewer data



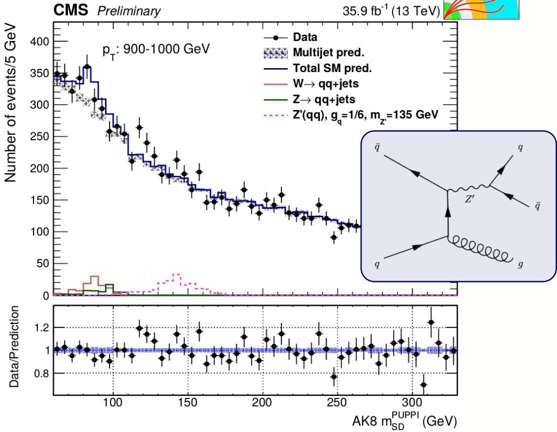
ATLAS CONF-2016-030

Explore Lower Masses - Dijet+ISR (γ/g)



ATLAS-CONF-16-070

Select events with an additional high-$p_T\gamma$(/g) from I.S.R., used for the trigger.



Boosted topologies in low-mass region

CMS PAS EXO-17-001

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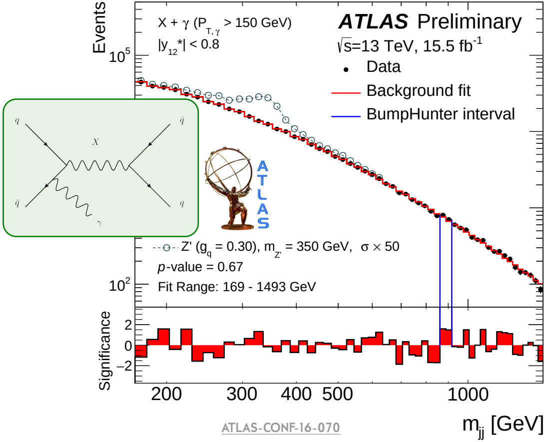

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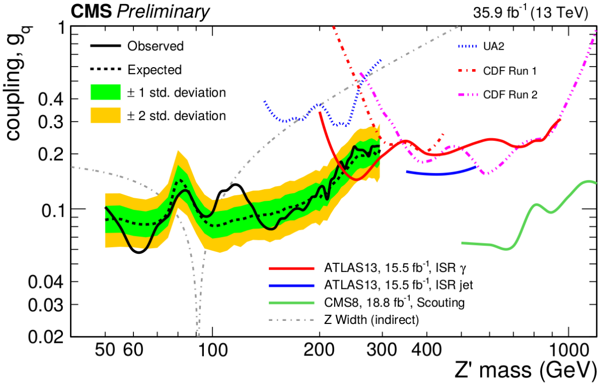


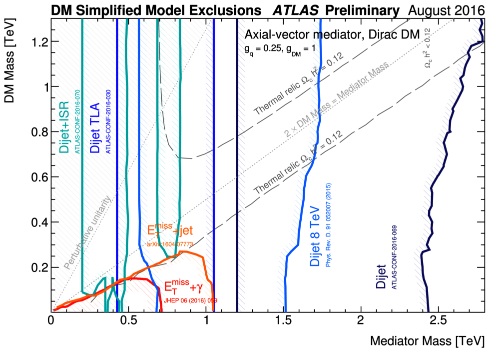
Boosted topologies in low-mass region

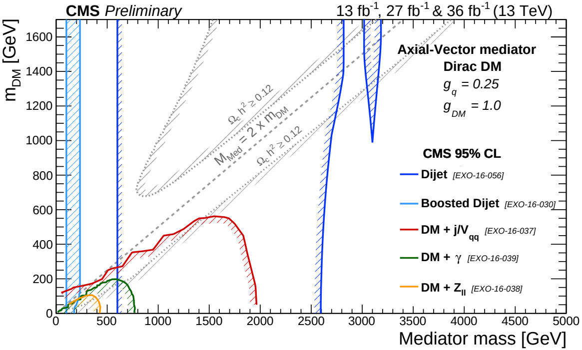
CMS PAS EXO-17-001

Dark Matter constraint interpretation

▶ **Interpretation of searches according to DM candidate Z'-like simplified models**

(details in 1507.00966[hep-ex], 1503.0591[hep-ph])





More information in C. Alpigiani and R. Khurana talks!

CMS PAS EXO-16-056

Conclusions

- 13 TeV collisions are an unprecedented dataset to search for new physics
- Di-jet signature is one of the best signatures to hunt for new physics in the few-TeV scale
- Results of main analyses updated to the full collected Run II dataset, $\sim$37 fb^{-1}
    - no excess seen so far, improved constraints on resonance mass by 40-50% on many models w.r.t. Run I
    - further results expected in the upcoming months (weeks)
- Systematic and coordinated searches will continue in the upcoming years - exploring dijet-based more complex signatures

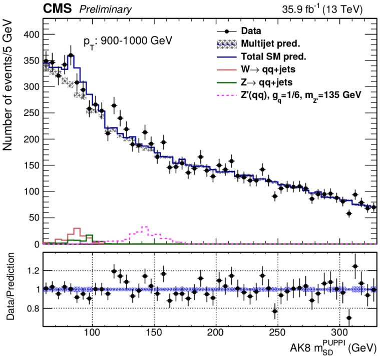
Related results:

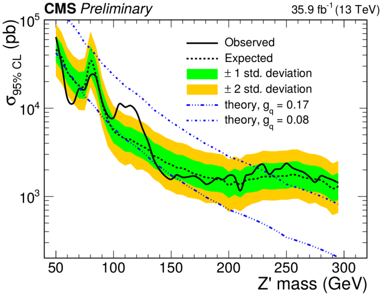
- Di-b-jets - see H. Zhang talk
- dijet pair production - see M. Tripiana and K. Yoshihara talks
- Dark Matter searches in jet signatures - see R. Khurana and C. Alpigiani talks

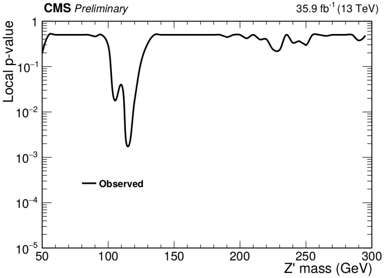
谢谢

BACKUP

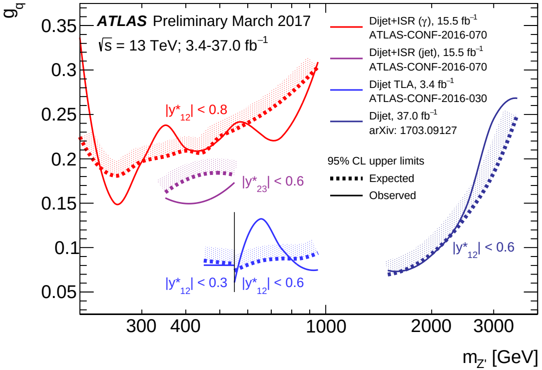
CMS PAS EXO-17-001

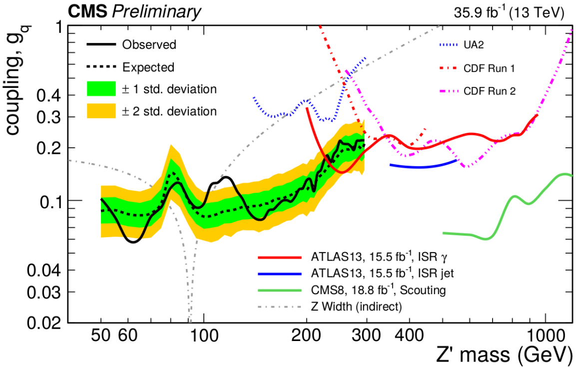






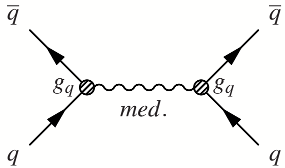
Z' combined interpretation

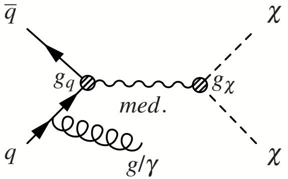




Simplified models: di-X & mono-X interplay

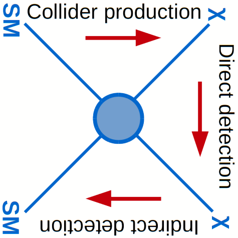
- Why Z' extension is good for Dark Matter? A good simplified model





$$\mathcal{L}_{AV} = g_q \sum_{q=u,d,c,s,b,t} Z'_\mu \bar{q}\gamma^\mu\gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu\gamma^5 \chi$$

4 pars : $[g_q, g_\chi, m_\chi, M_{med}]$

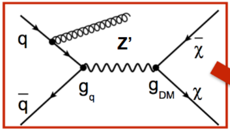


- Extend the SM with an axial-vector mediator Z' [U(1)-like]
- Add a Dirac fermion WIMP candidate (χ)
- couple Z' to χ
- This is a simple model, different ones can be considered
  - details in 1507.00966[hep-ex] and 1503.05916[hep-ph]

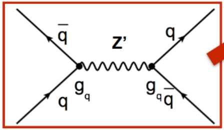
DM simplified models

- **DM simplified model** for **spin-1 mediator** is equivalent to the **leptophobic Z'** explored in **dijet searches**
- **Difference:** the addition of a **DM candidate** modifies the **total width** of the **mediator**

Monojet production



Dijet production



Mediator Width

$$\Gamma^{\rm tot}_{\rm AV} = \Gamma^{\chi\bar{\chi}}_{\rm AV} + 3\times\sum_{q=u,d,s,c,b,t}\Gamma^{q\bar{q}}_{\rm AV}$$

$$\Gamma^{q\bar{q}}_{\rm AV} = \frac{g_q^2 M_{\rm med}}{4\pi}\left(1-4\frac{m_q^2}{M_{\rm med}^2}\right)^{3/2}$$

$$\Gamma^{\chi\bar{\chi}}_{\rm AV} = \frac{g_{\rm DM}^2 M_{\rm med}}{12\pi}\left(1-4\frac{m_{\rm DM}^2}{M_{\rm med}^2}\right)^{3/2}$$

Interesting scenarios

$m_{MED} >> m_{DM}$: the relative branch fraction of monojet and dijet is proportional to $N_c N_q\, g_{SM}^2/g_{DM}^2$

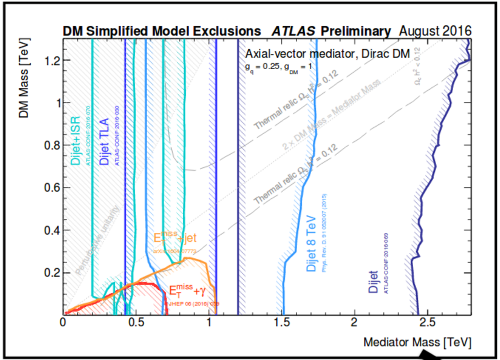
$g_{SM} << g_{DM}$, $g_{DM} \sim 1$: narrow resonance but BR monojet larger than dijet one

$g_{DM} >> g_{SM}$, $g_{DM} > 1$: resonance not narrow anymore BR monojet larger than dijet one

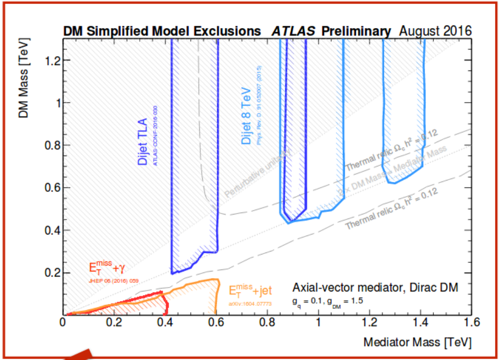
$2m_{DM} >> m_{MED}$: no partial width into dark matter so the Z' model reduces to the standard one used in dijet searches

DM Coupling choice

g_{SM} = 0.25, g_{DM} = 1



g_{SM} = 0.10, g_{DM} = 1.5



For "relatively large" quark coupling (g_{SM}) → **dijet constraints are very strong**

As **g_{SM} gets weaker** compared to **g_{DM}** → **dijet constraints** becomes **complementary** to **mono-X**

Constraining power in the off-shell region remains strong