DM: Latest results in the mono-jet and di-jet channels

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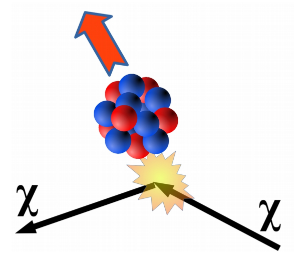
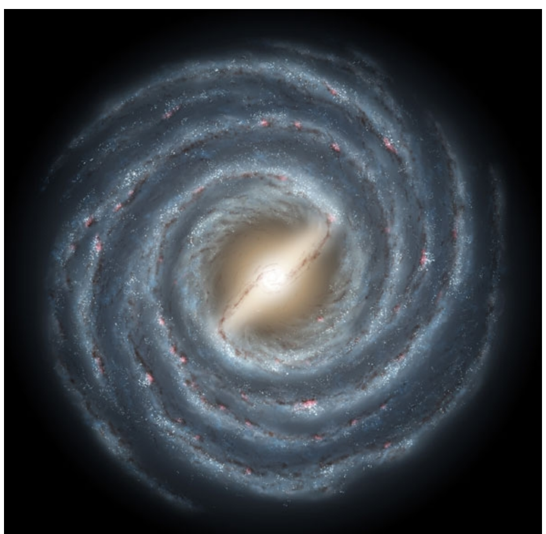
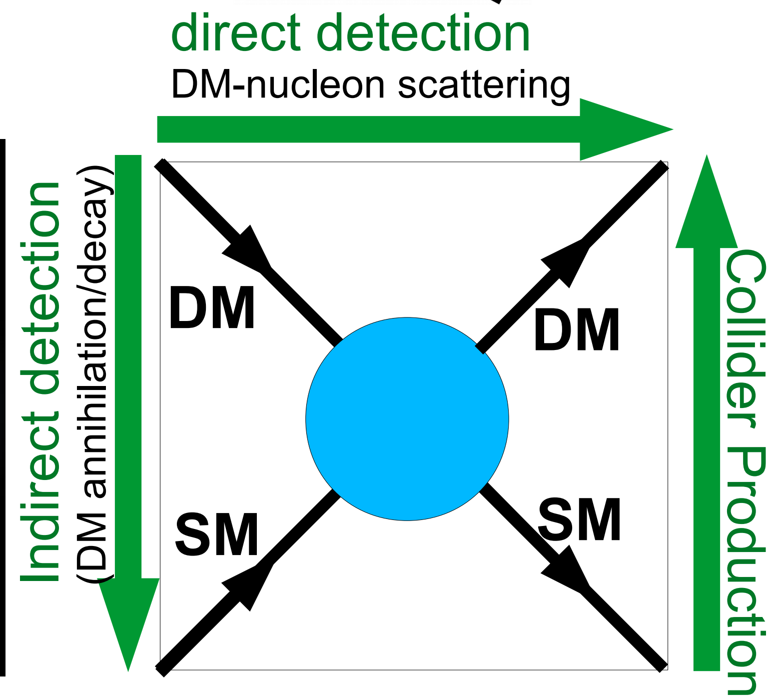
Introduction

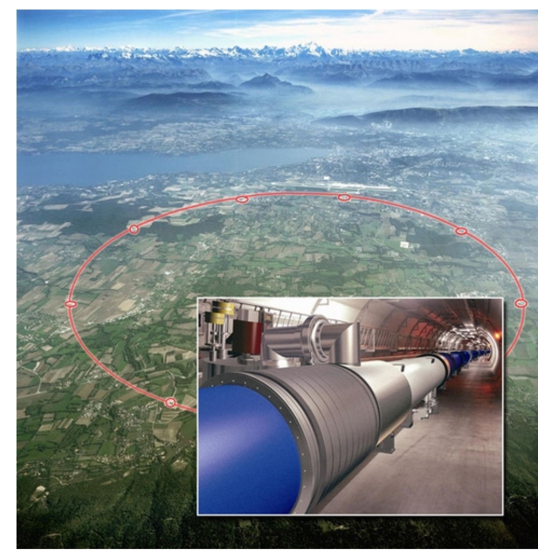
- Dark Matter (DM) well established:
  - Galaxy rotation
  - CMB measurements
- Three detection methods
  - Direct
  - Indirect
  - Production in collisions

  → LHC



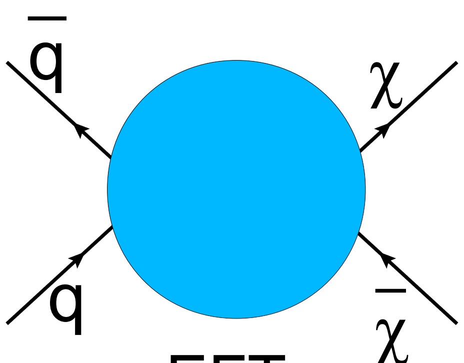




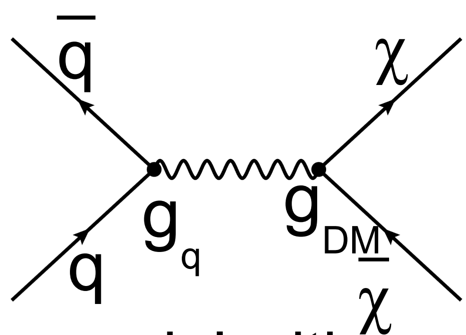


DM at LHC:Models

	Name	Initial state	Type	Operator
complex (Majorana)	C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
	C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
Dirac	D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
	D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
	D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
	D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
	D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$



EFT



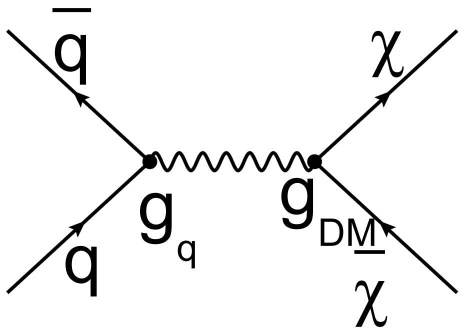
model with mediator

- Common: Effective Field Theory (EFT)
- Limited validity: $m_{mediator} >> E(\chi)$
- Integrate mediator out, Fermi constant G_F like coupling:

$$G_{DM} = \left(\frac{\sqrt{g_q g_{DM}}}{M_{mediator}} \right) = \frac{1}{(M_*)^n}$$

- Now mostly superseeded

DM at LHC:Models



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

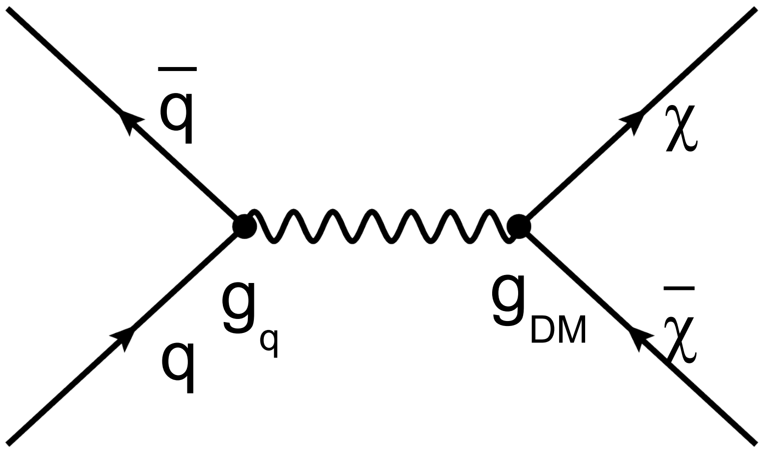
$$\mathcal{L}_{\text{axial-vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi .$$

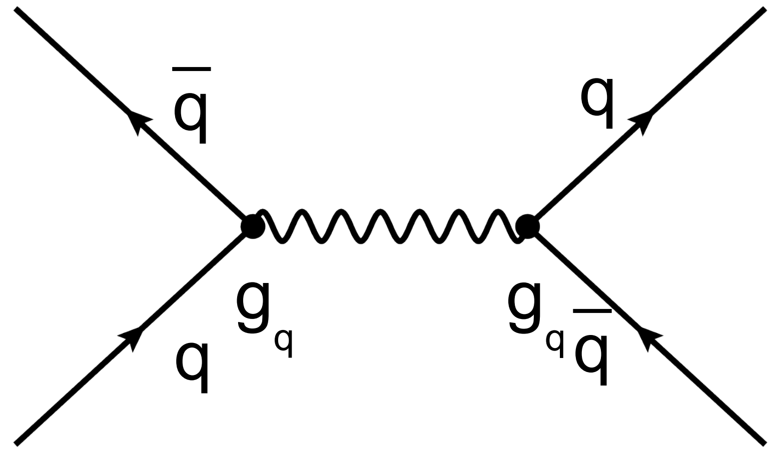
$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}}\phi\bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q \,,$$

$$\mathcal{L}_{\text{pseudo-scalar}} = -i g_{\text{DM}}\phi\bar{\chi}\gamma_5\chi - i g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}\gamma_5 q$$

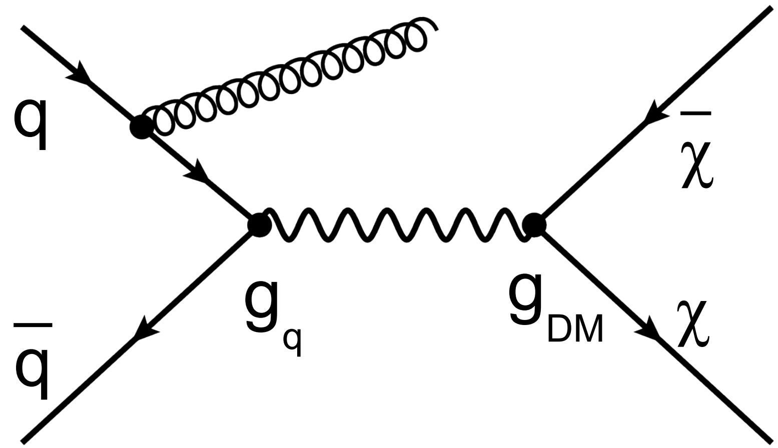
- Move towards simplified models
- → recommendations from DM@LHC14 (arXiv:hep-ph/1506.03116)
- → recommendations from LHCDMWG (arXiv:hep-ex/1603.04156, arXiv:hep-ex/1507.00966)
- Parameters: m_{DM}, $m_{mediator}$, g_{DM}, g_q
- Benchmark models
- m_{DM} vs $m_{mediator}$ plane, couplings
- Vector : $g_{DM} = 1$; $g_q = 0.25$
- Axial-Vector : $g_{DM} = 1$; $g_q = 0.25$
- Scalar : $g_{DM} = 1$; $g_q = 1$
- Pseudo-Scalar: $g_{DM} = 1$; $g_q = 1$

DM at LHC





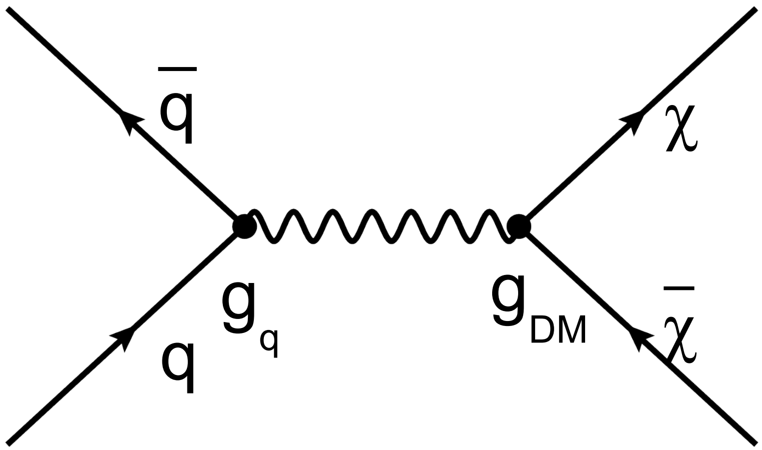
Di-jets



Mono-jets

- DM χ couples loosely to SM particles (quarks q) through a mediator
  → mediator couples to DM χ with g_{DM} and to SM quark with g_q
- Can't reconstruct DM in detector
  → need accompanying signature
- Mediator can decay into quark (jet) pairs

DM at LHC



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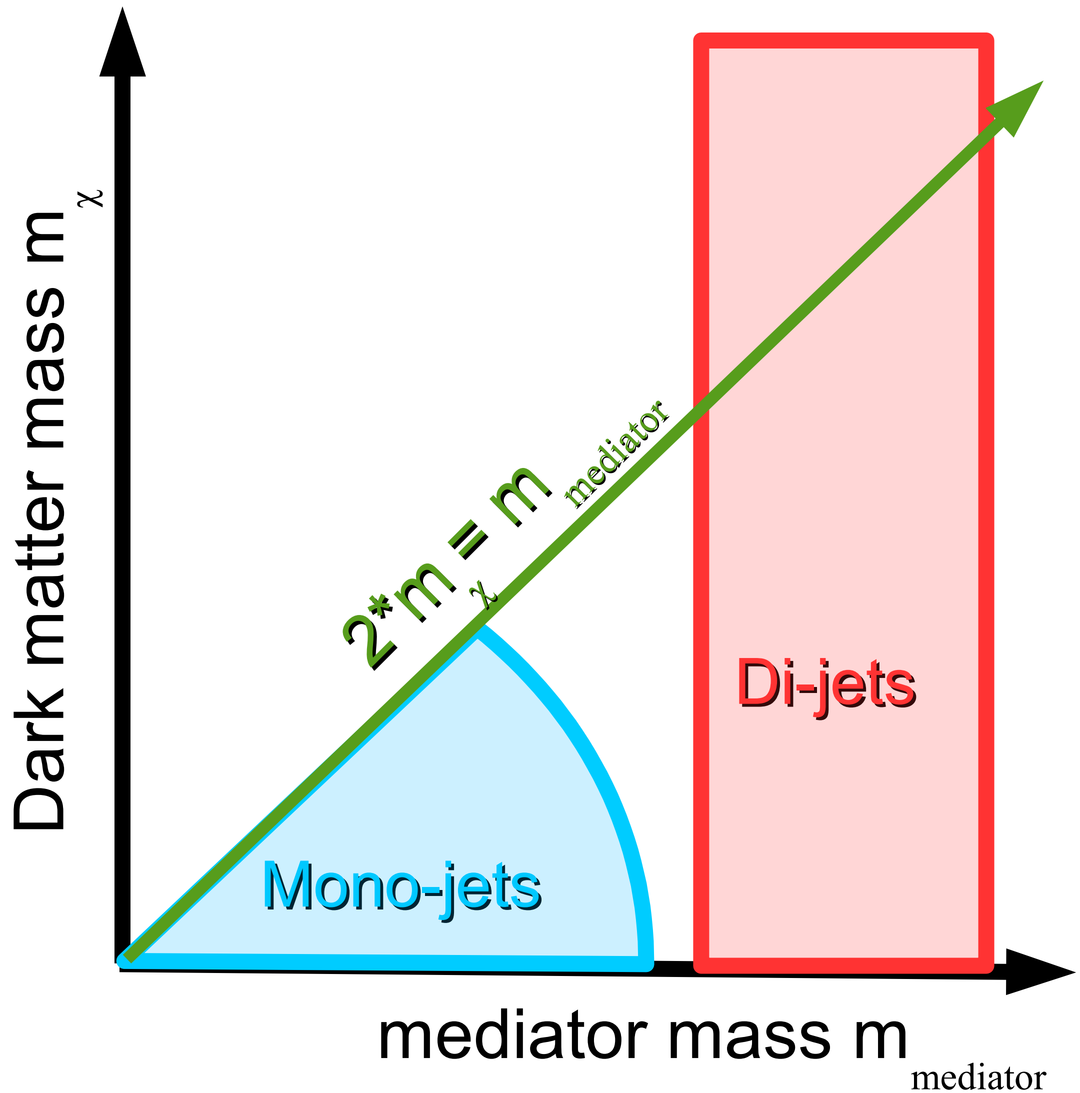
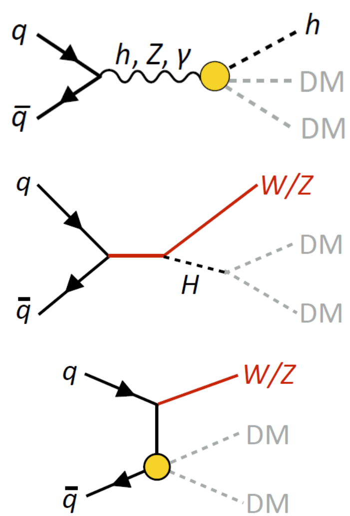
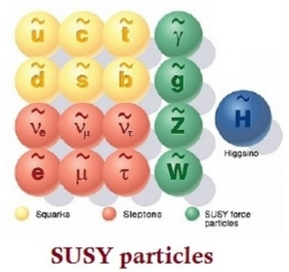


Other DM signals at the LHC

- Can't reconstruct DM in detector
  → missing momentum → need accompanying signature
- Differentiate channels by accompanying signature

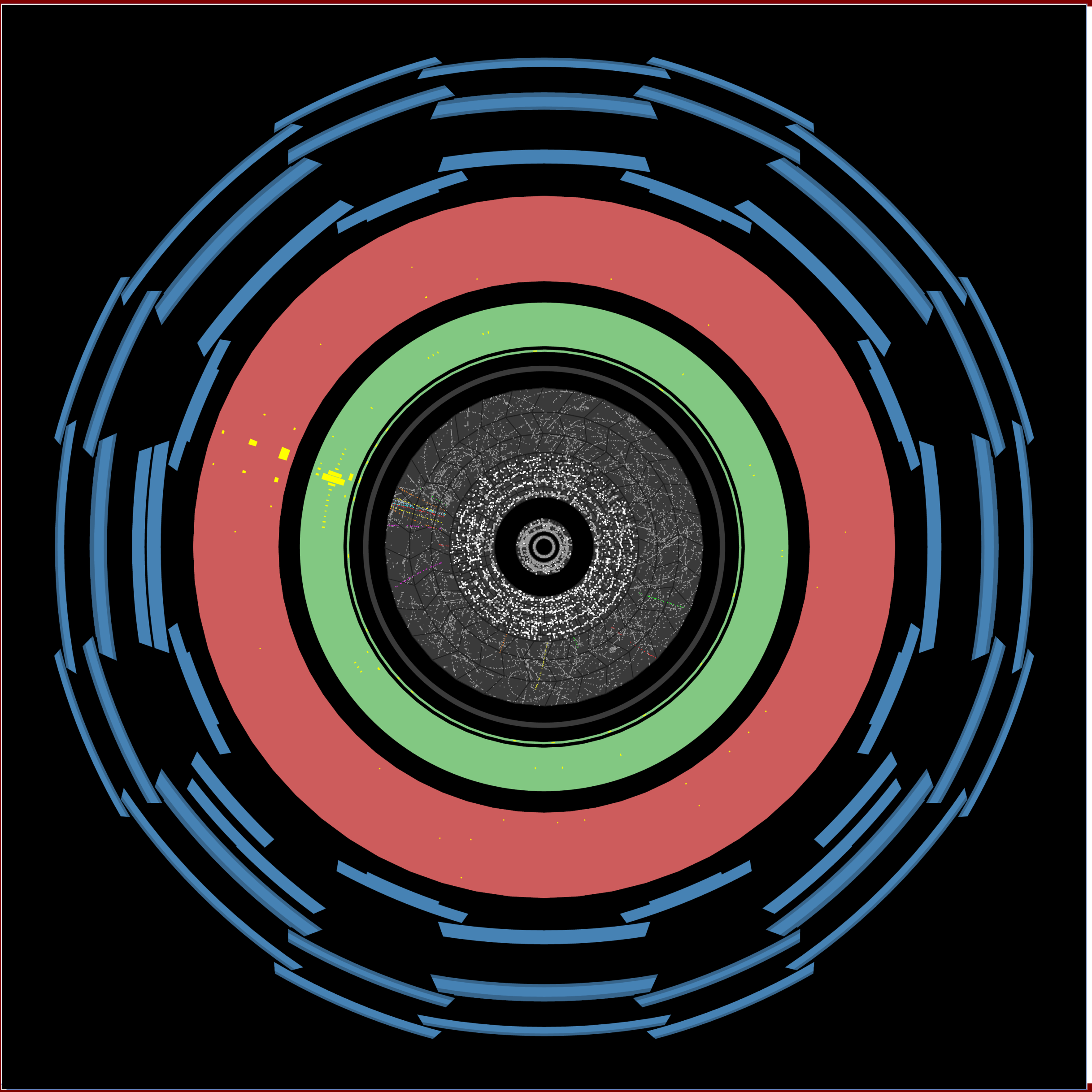


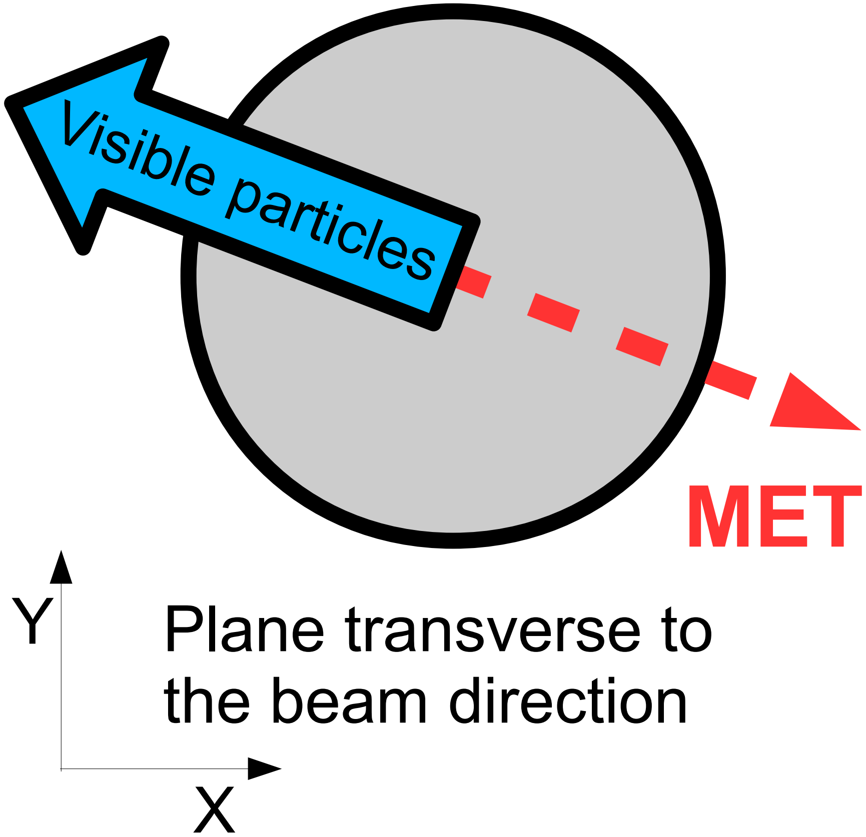
H → jj + MET
Z → jj + MET
W → jj + MET → see Kenji Hamano's talk



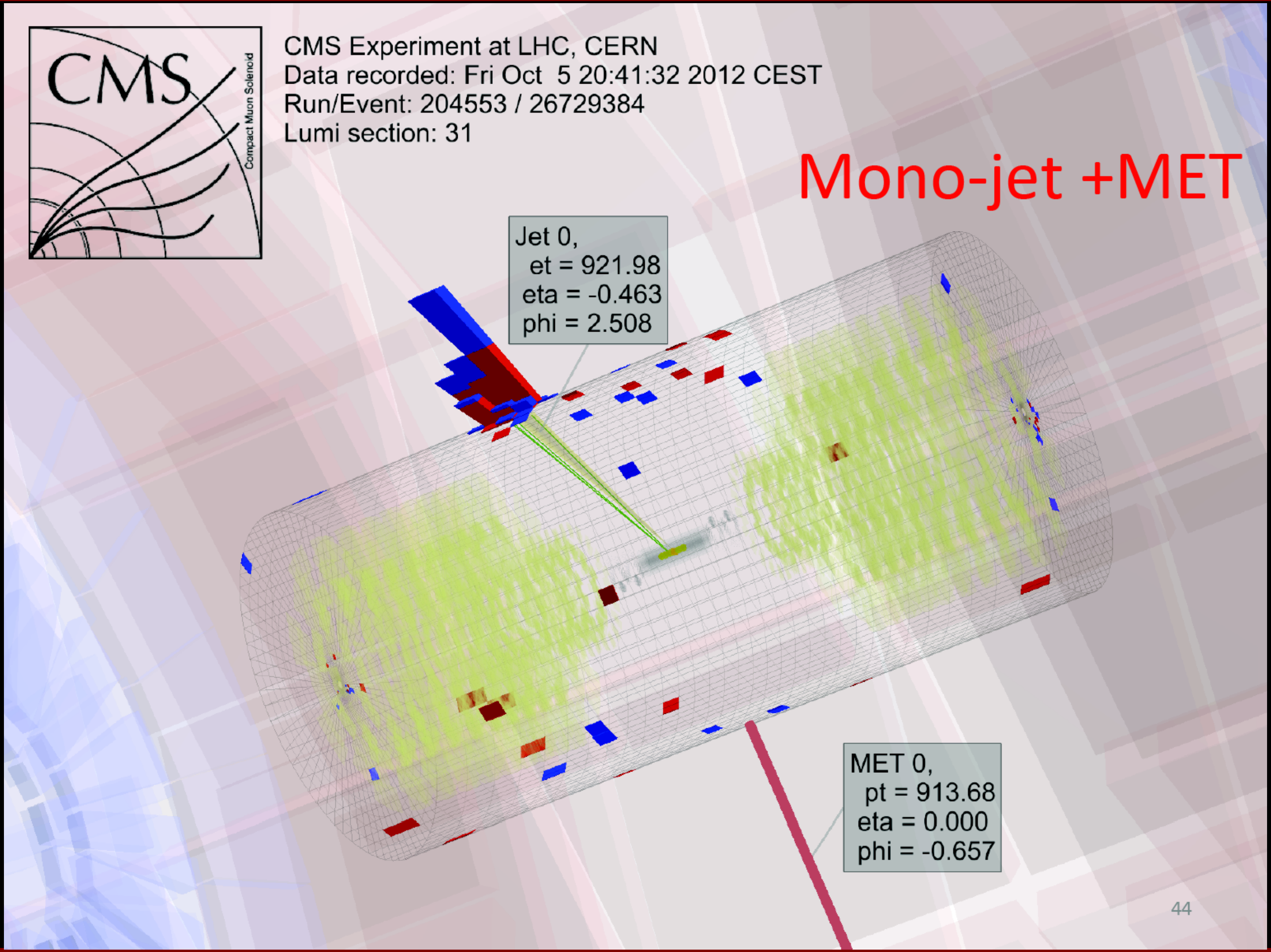
SUSY DM candidates → see George Redlingers talk

Missing transverse Energy MET



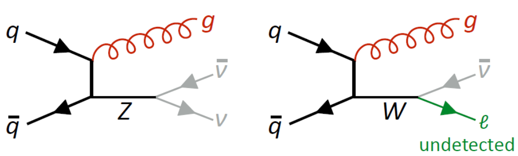


Mono-Jet

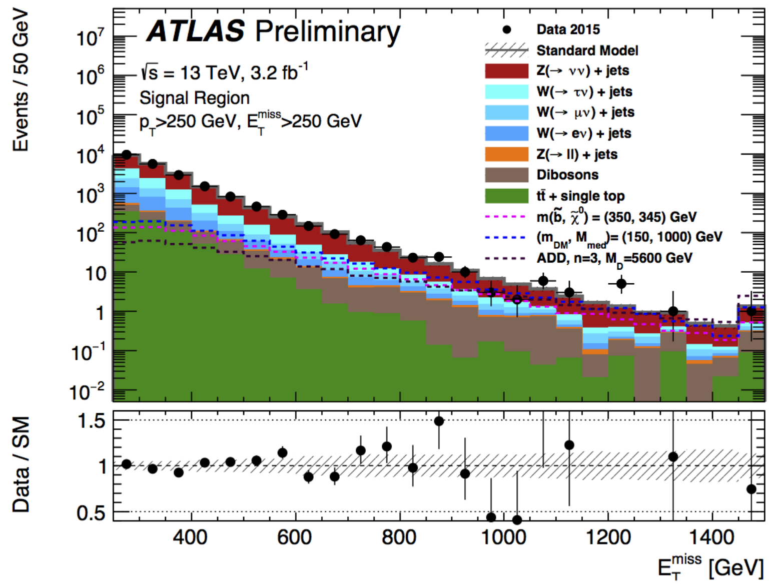

CMS
Compact Muon Solenoid
CMS Experiment at LHC, CERN
Data recorded: Fri Oct 5 20:41:32 2012 CEST
Run/Event: 204553 / 26729384
Lumi section: 31
Mono-jet +MET
Jet 0,
et = 921.98
eta = -0.463
phi = 2.508
MET 0,
pt = 913.68
eta = 0.000
phi = -0.657
44

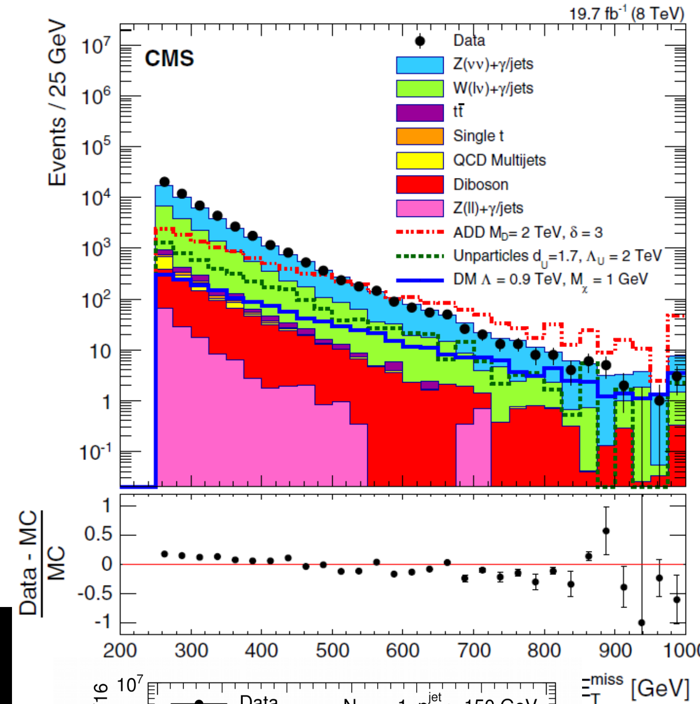
Mono-Jet: Backgrounds

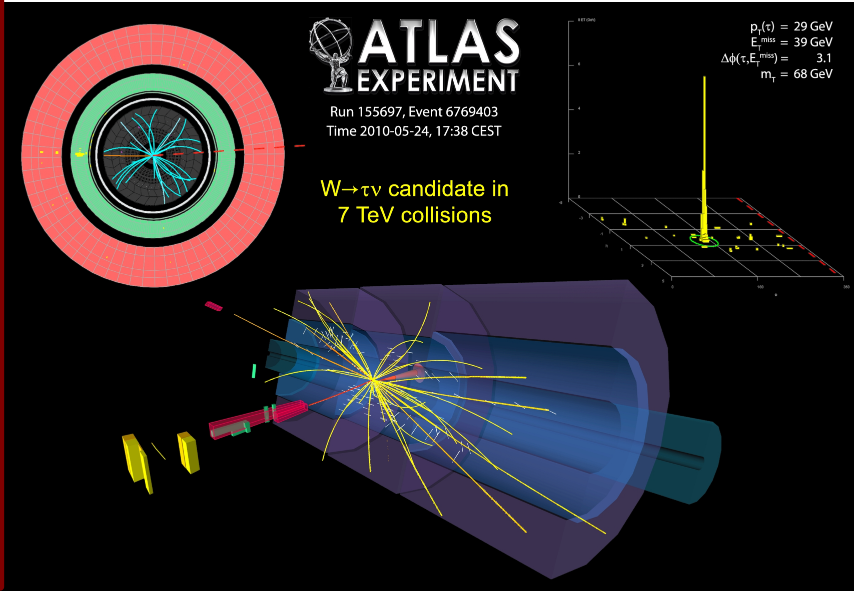
- MET hard to model
- Estimate/measure invisible decays (ν's)

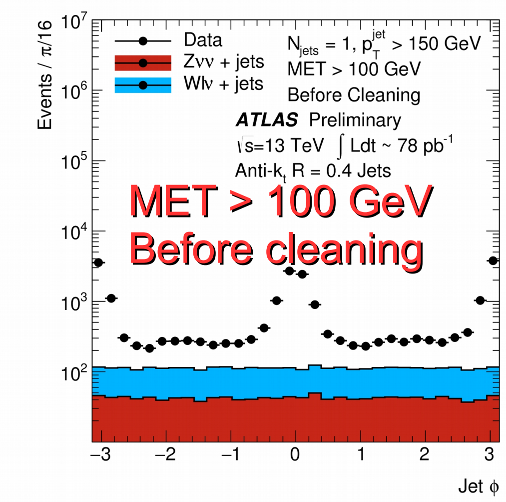


- use Z→ ll & W→ lν to model Z→ νν
- Detector effects & non-collision bkgs are very important too!
- Distributions rather well described

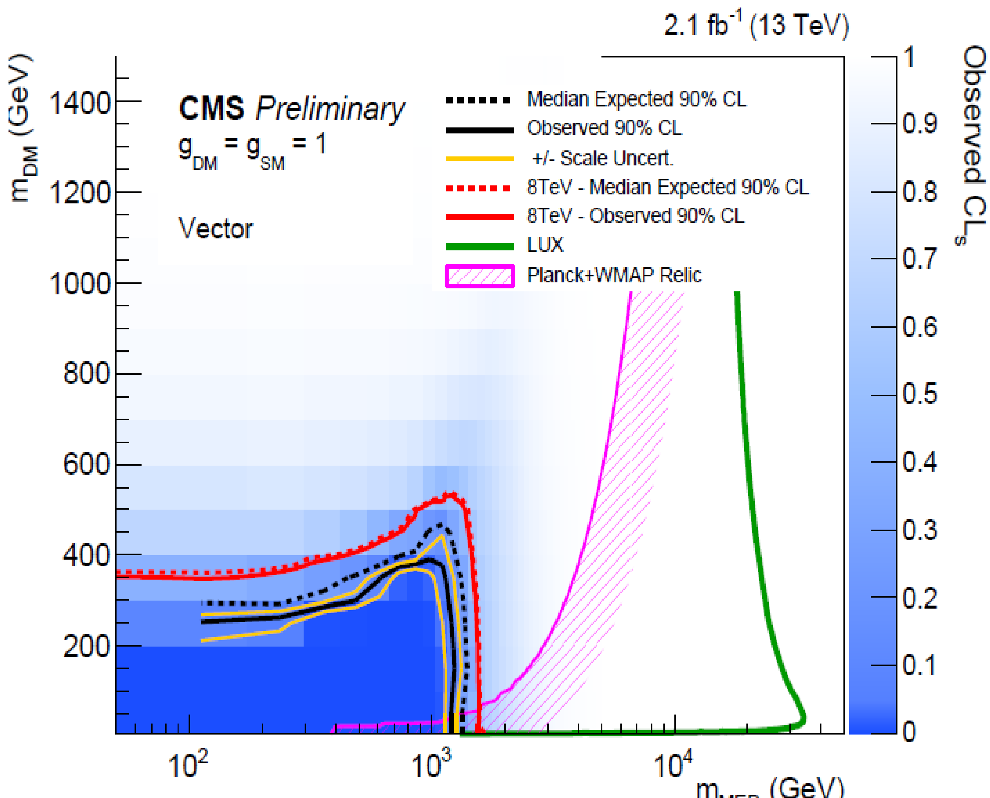


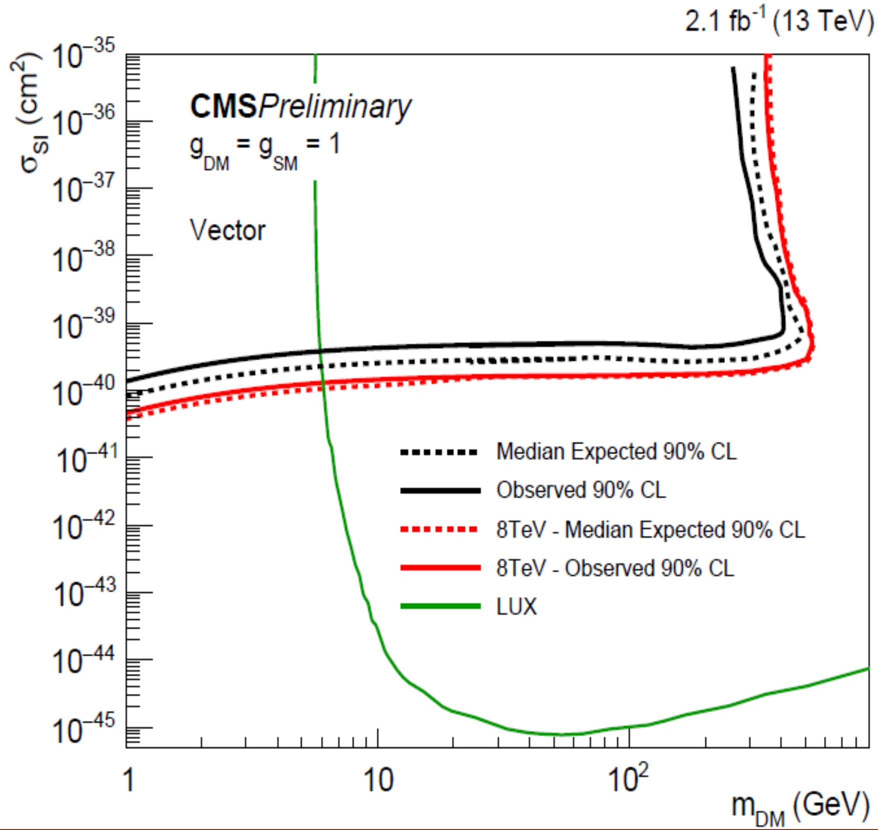






Mono-Jet

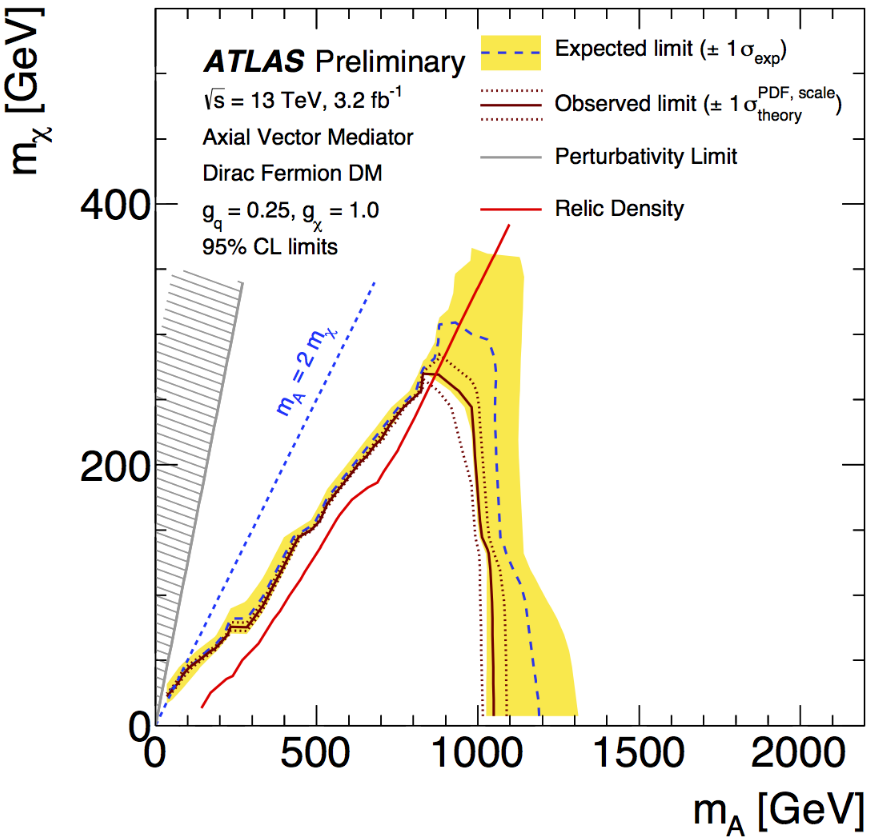


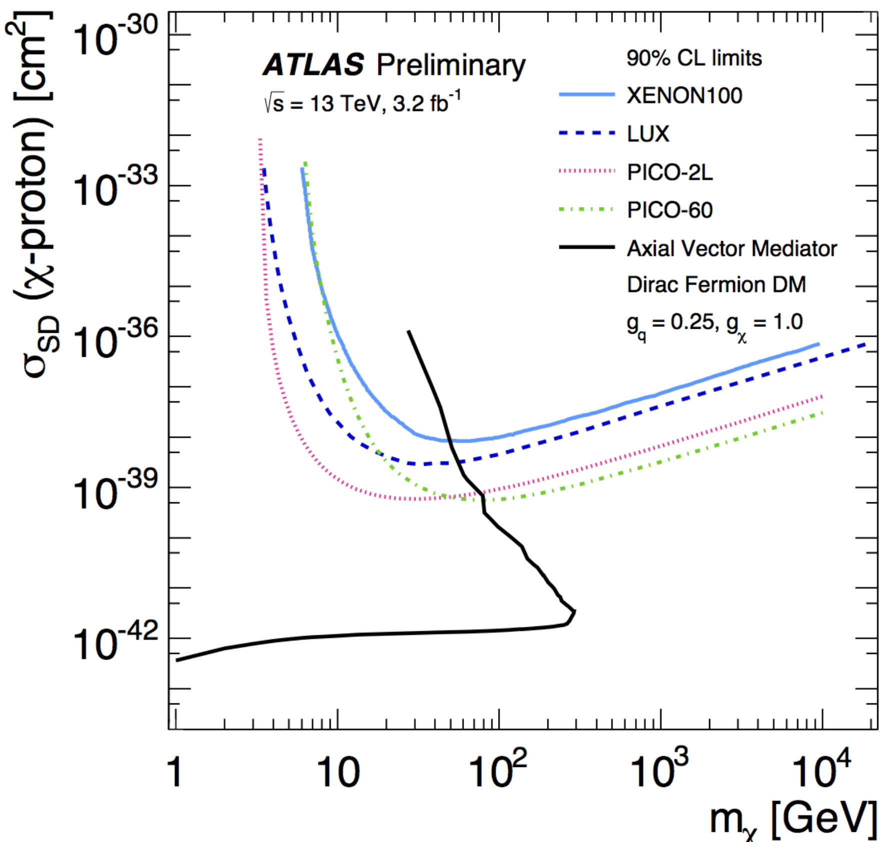


- Vector mediator: $g_{DM} = g_{SM} = 1$
- Selection:
  - Leading jet: $p_T > 100$ GeV; $|\eta| < 2.5$
  - $E_T^{miss} > 200$ GeV, Input Jets: $|\eta| < 5$

CMS PAS EXO-15-003

Mono-Jet



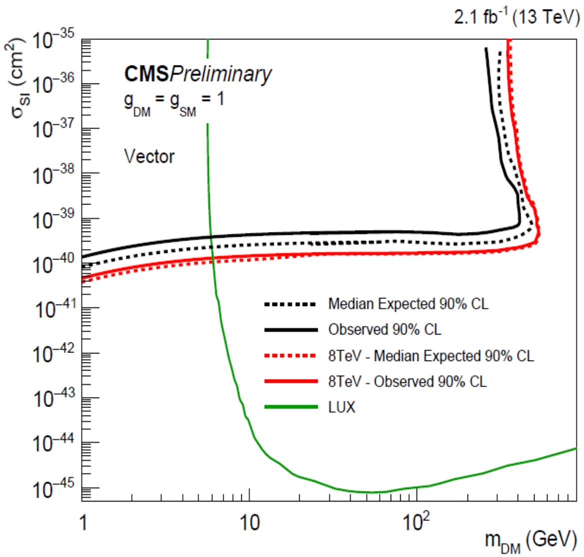


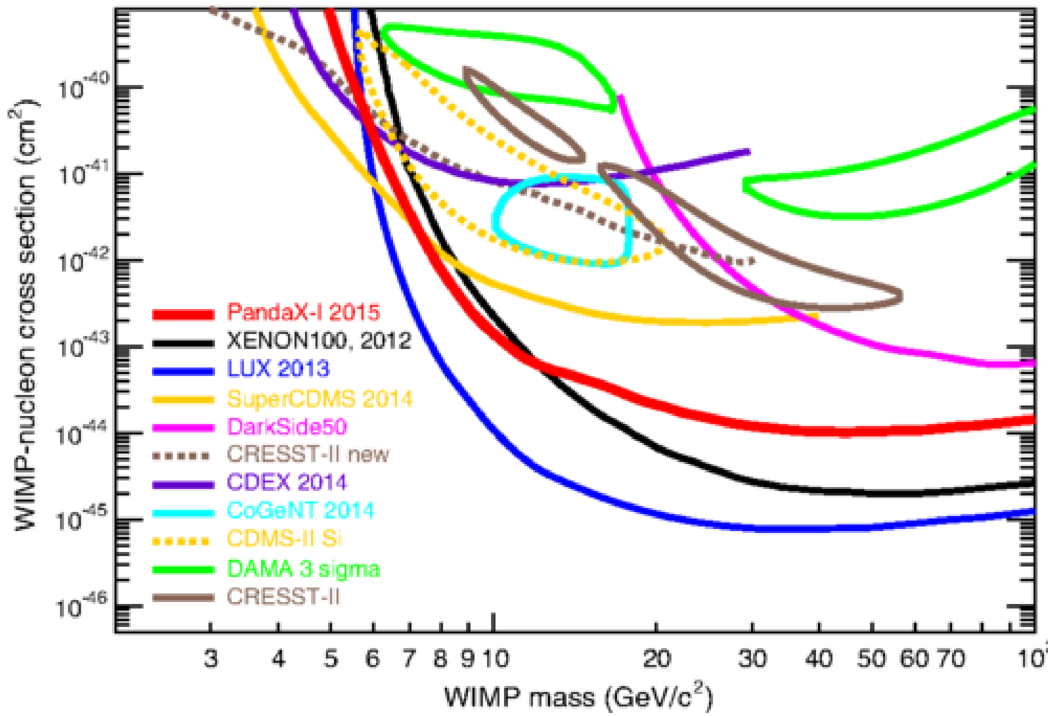
- Axial Vector Mediator: $g_{DM} = 0.25$ $g_{SM} = 1$

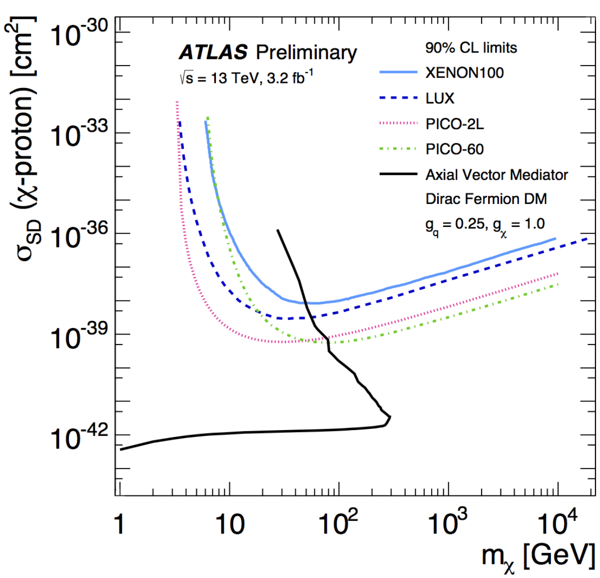
EXOT-2015-03

- Selection
  - Leading jet: $p_T > 250$ GeV; $|\eta| < 2.8$
  - $E_T^{miss} > 250$ GeV, Input Jets: $p_T > 20$ GeV; $|\eta| < 4.9$

Comparison with Direct Detection

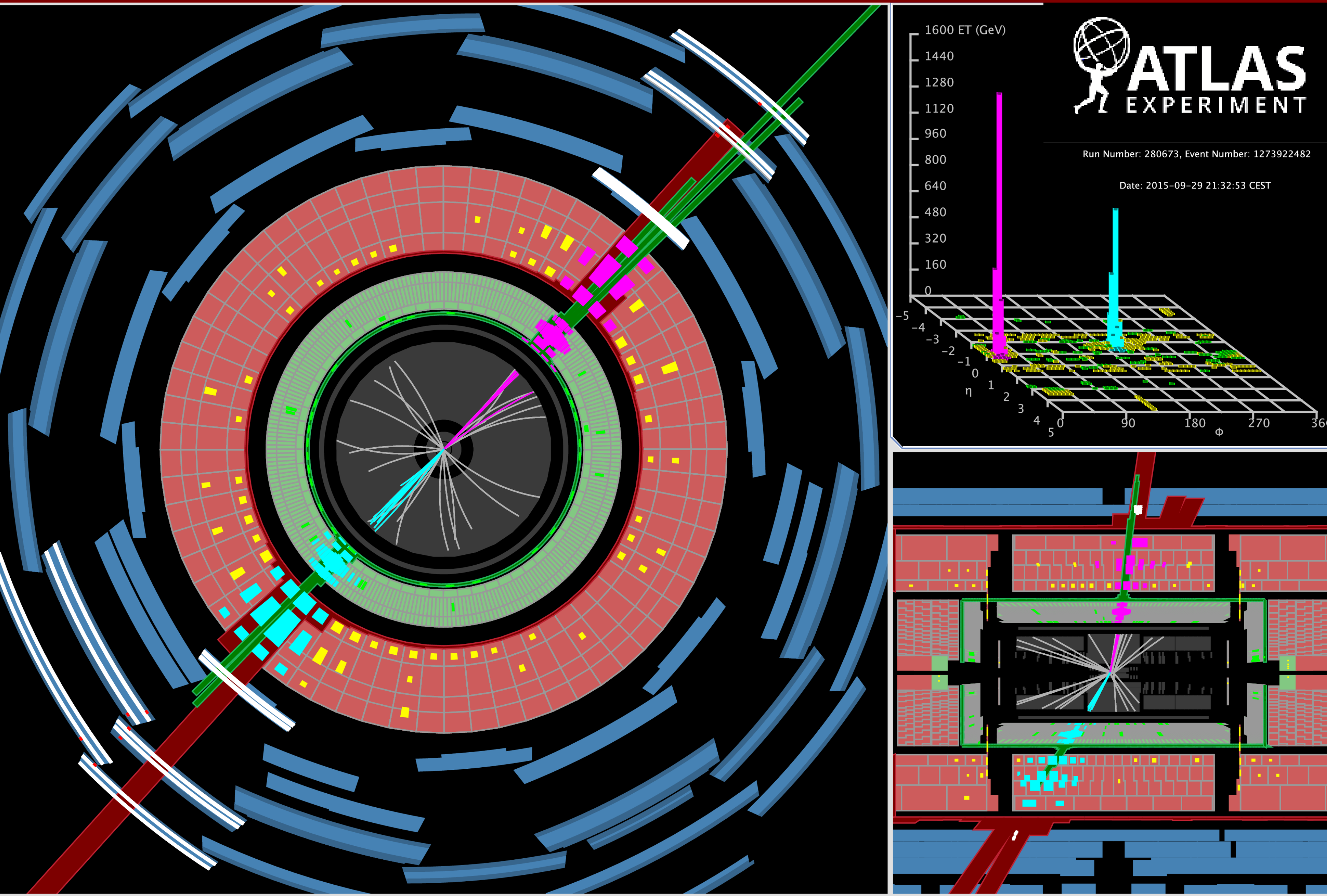






- Translate into DM-nucleon cross sections
- Spin dependent (SD) or independent (SI) according to mediator model used
- Note: Comparisons model dependent!
- LHC experiments provide complementary coverage!

DiJet Events

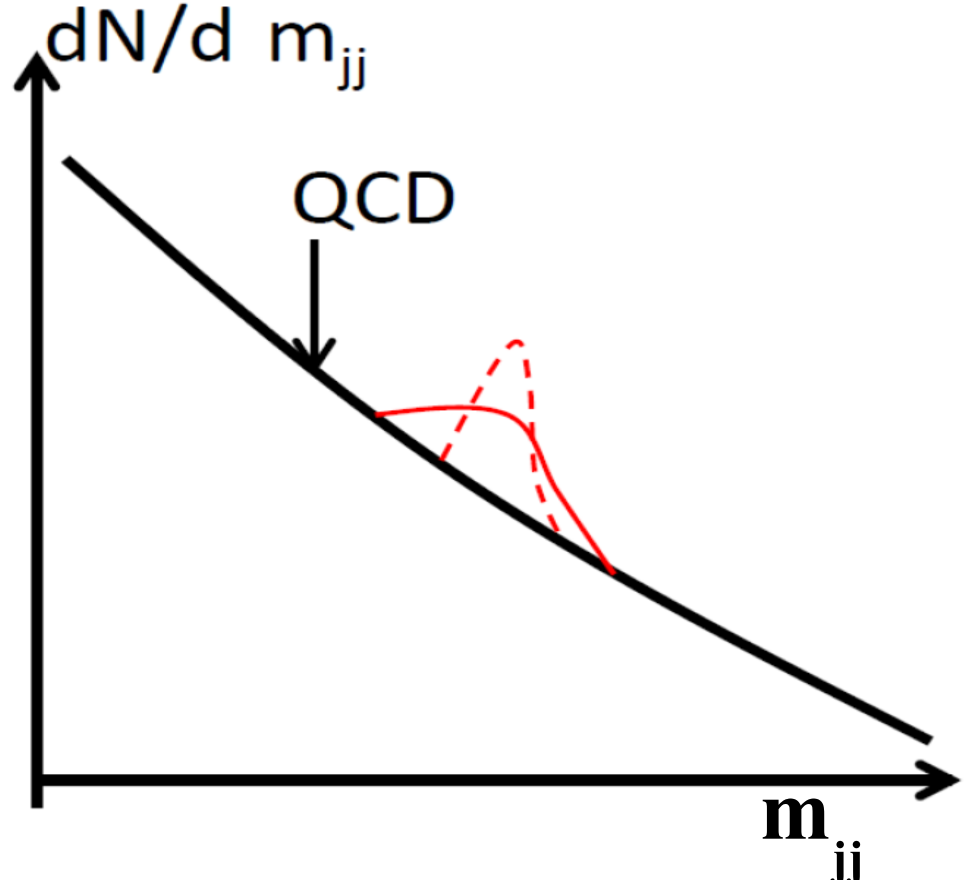


Introduction: Dijet resonances

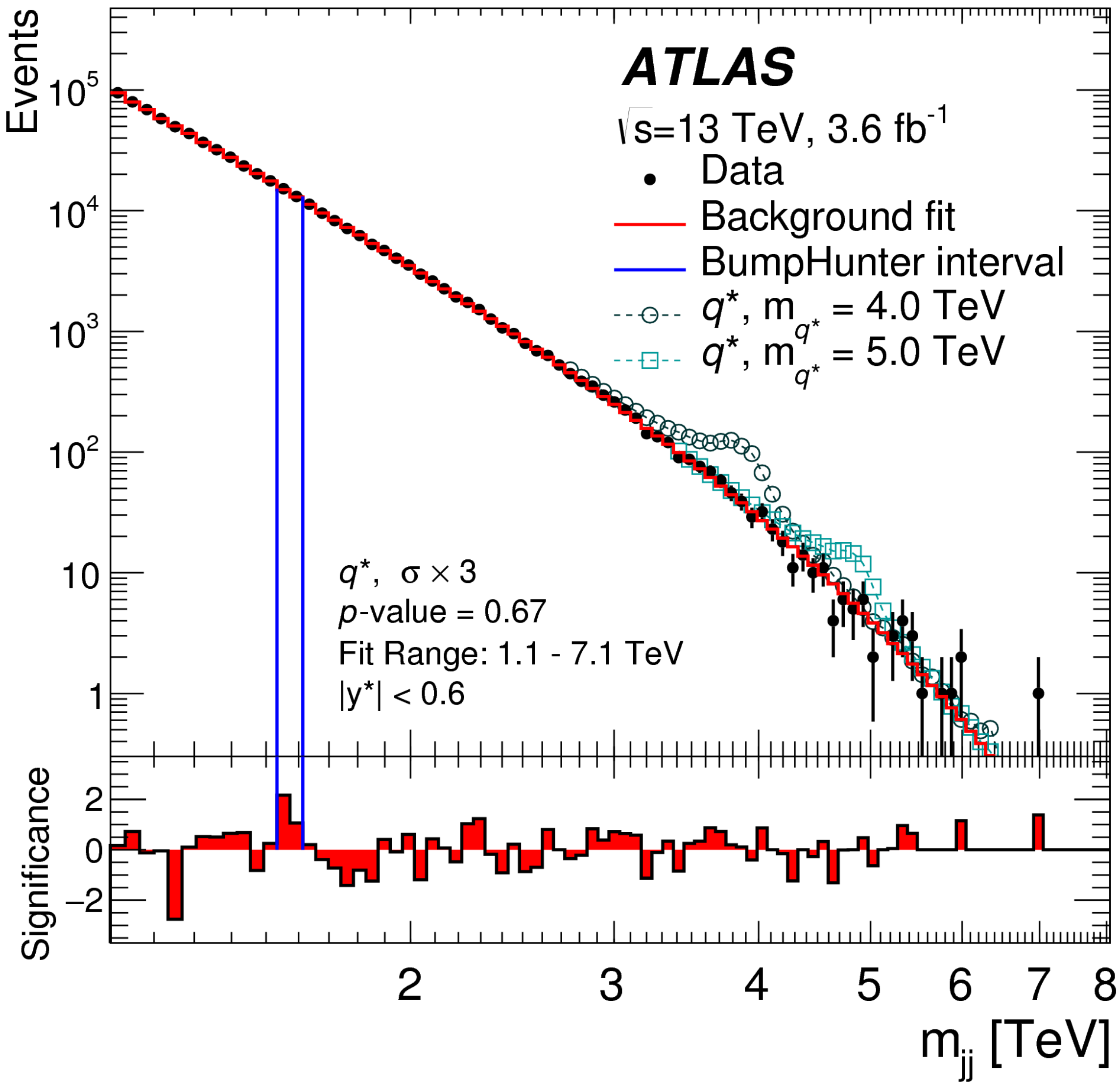
- Look for resonant qq, gq and gg states
- Benchmark search for new physics
- Construct dijet mass
- Fit smooth spectrum

$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x}$$

- Look for deviations
  → Bumphunter
  → Tailhunter
- Limits on acceptance times x-section and specific models



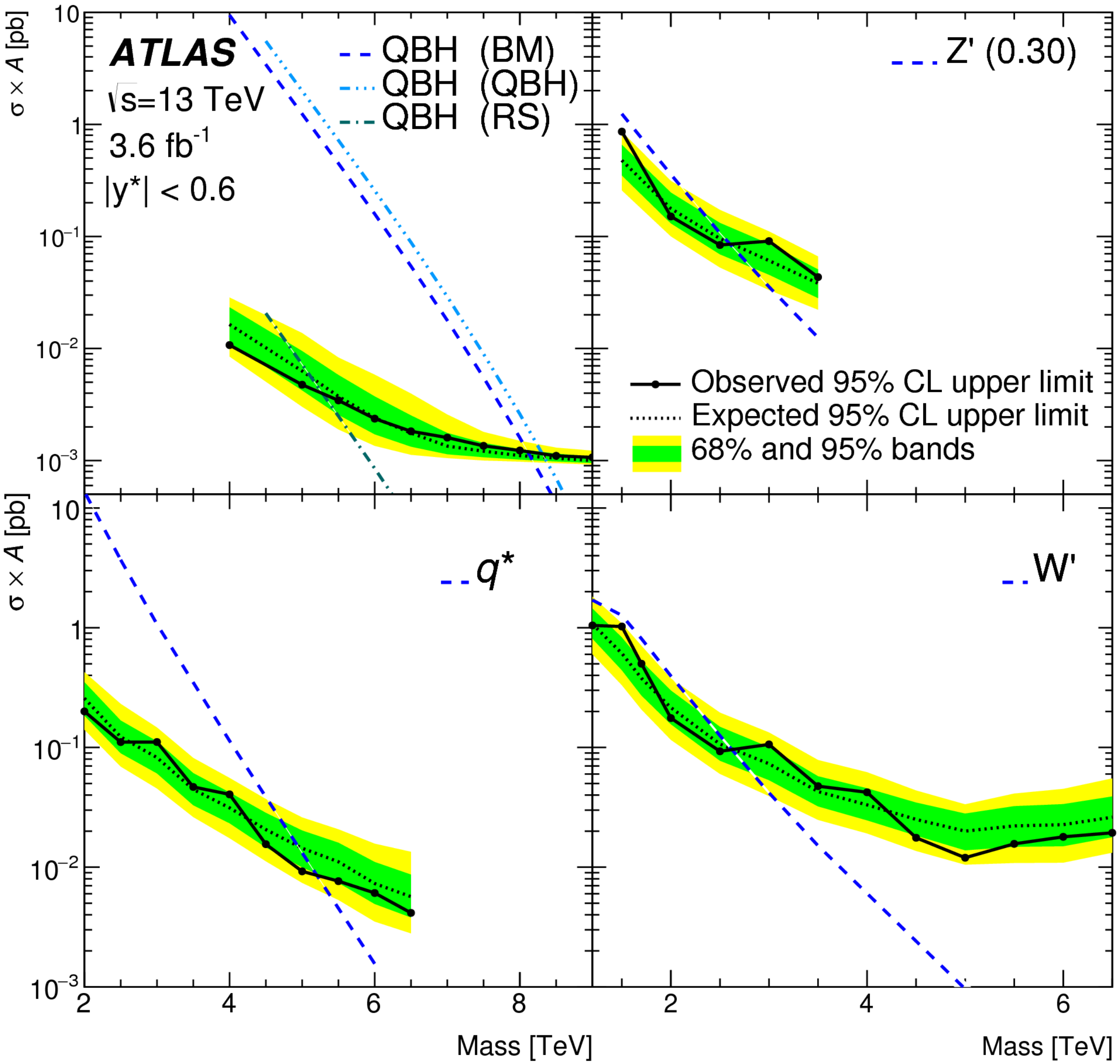
Dijet resonances



- Selection
  - $p_T > 440$ GeV
  - $|y^*| = ½\,|y_1 - y_2| < 0.6$
- Background from fit
- BumpHunter indicates most discrepant interval (not so exciting at all)

Physics Letters B 754 (2016) 302–322
http://dx.doi.org/10.1016/j.physletb.2016.01.032

Limits on Dijet resonances



- Limits on benchmark models
  - Excited quarks q* (5.2 TeV)
  - Extra Gauge Bosons
    - Z' -Boson
    - W'-Boson (2.6 TeV)
- Quantum Black Holes (QBH)
  - Randall-Sundrum
    - QBH generator (5.3 TeV)
  - Arkani-Hamed-Dimopoulous-Dvali
    - QBH generator (8.3 TeV)
    - BlackMax generator (8.1 TeV)

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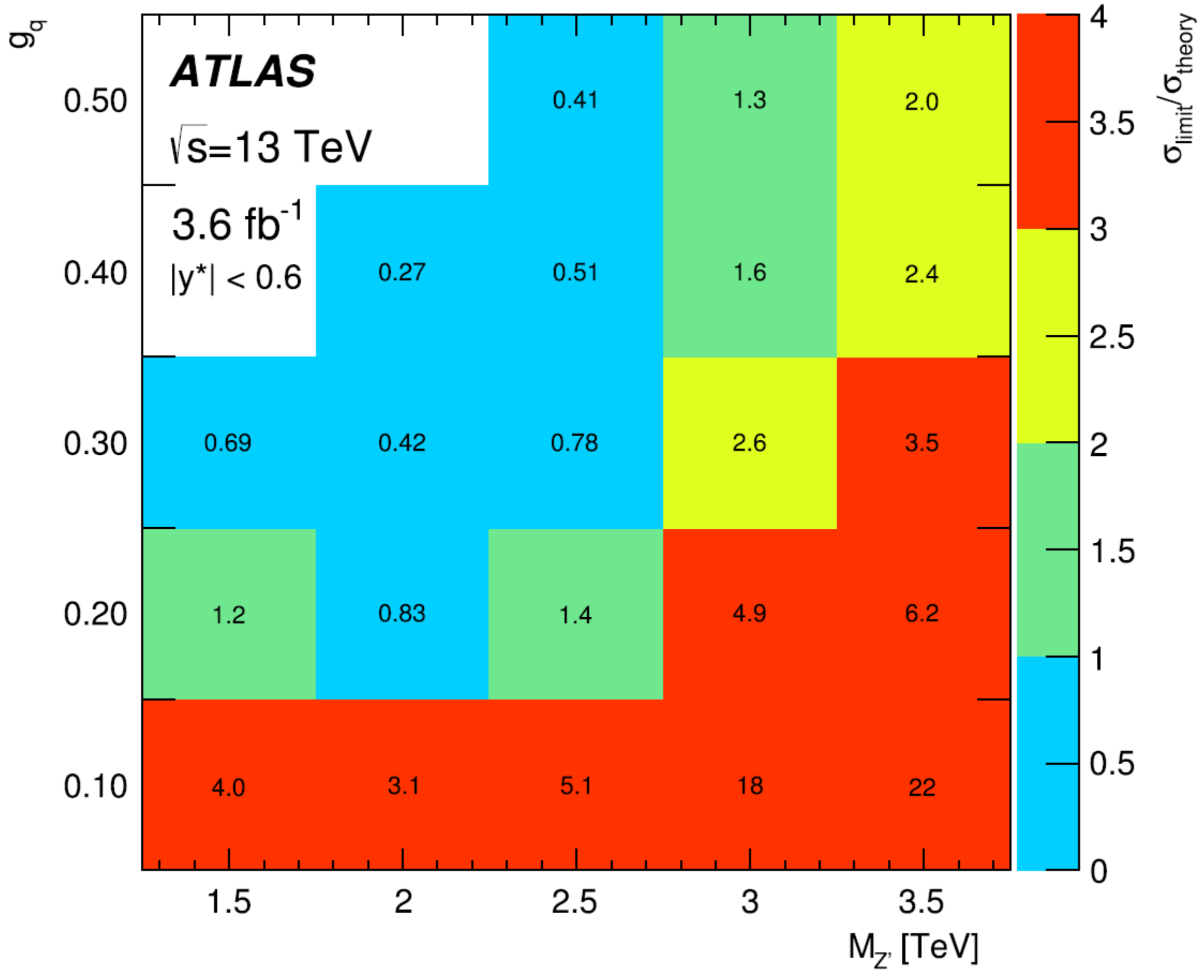
Limits on Dijet resonances



- Limits on benchmark models
  - Extra Gauge Z'-Boson
    - Leptophobic model
    - Provides dark matter mediator candidate
    - Limits on coupling g_q for different Z' masses

Physics Letters B 754 (2016) 302–322
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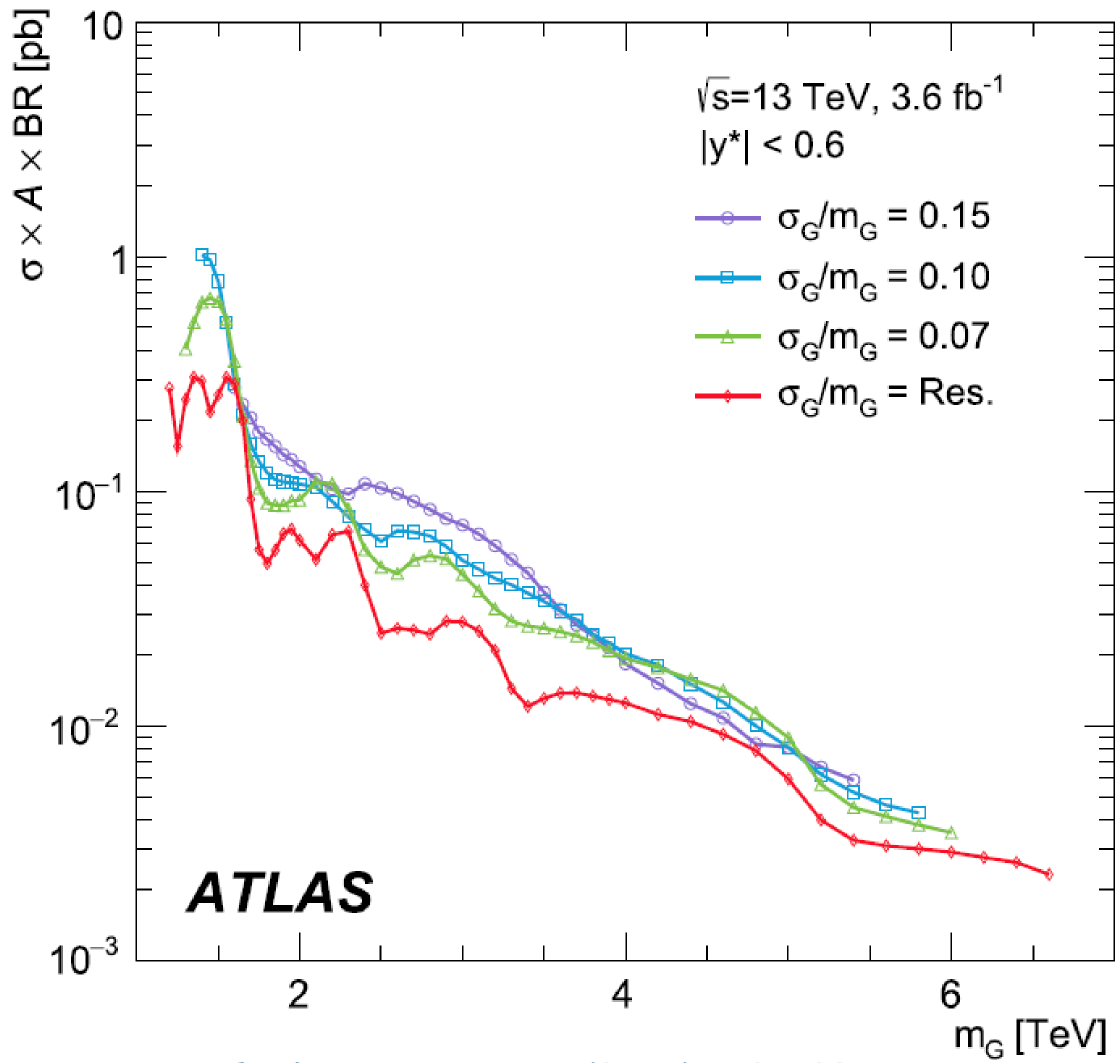
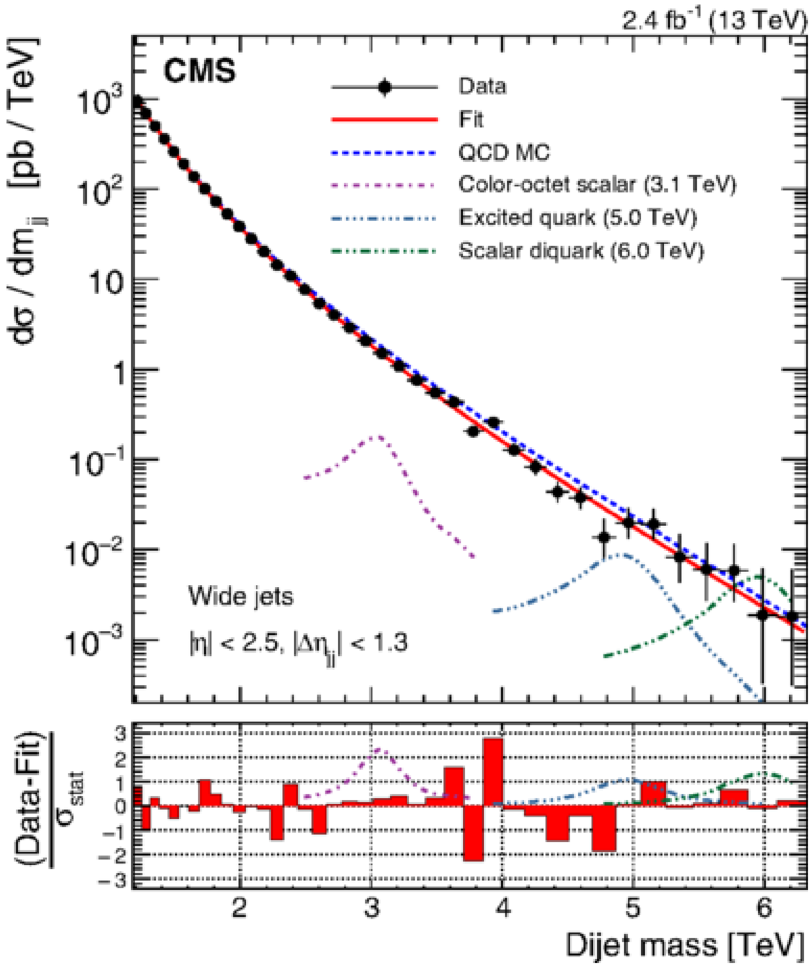
Limits on Dijet resonances

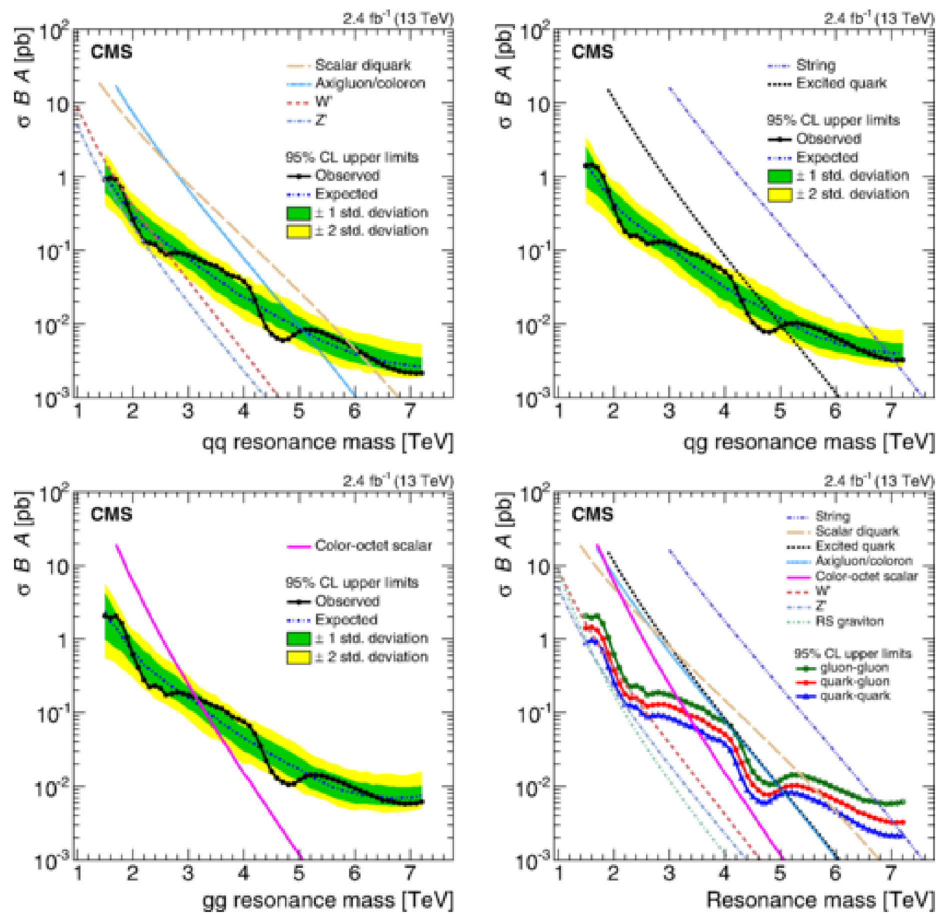


Physics Letters B 754 (2016) 302–322
http://dx.doi.org/10.1016/j.physletb.2016.01.032

- Limits on Gaussian contributions to observed cross section
- Model independent approach
- Narrow width approximation
- Apply selection
  - leading jet p_T > 440 GeV
  - |y*|<0.6
- Truncate signal to approximate Gaussian core
  → useful to translate limit to other models not considered

Limits on Dijet resonances





PRL **116,** 071801 (2016)
DOI: 10.1103/PhysRevLett.116.071801

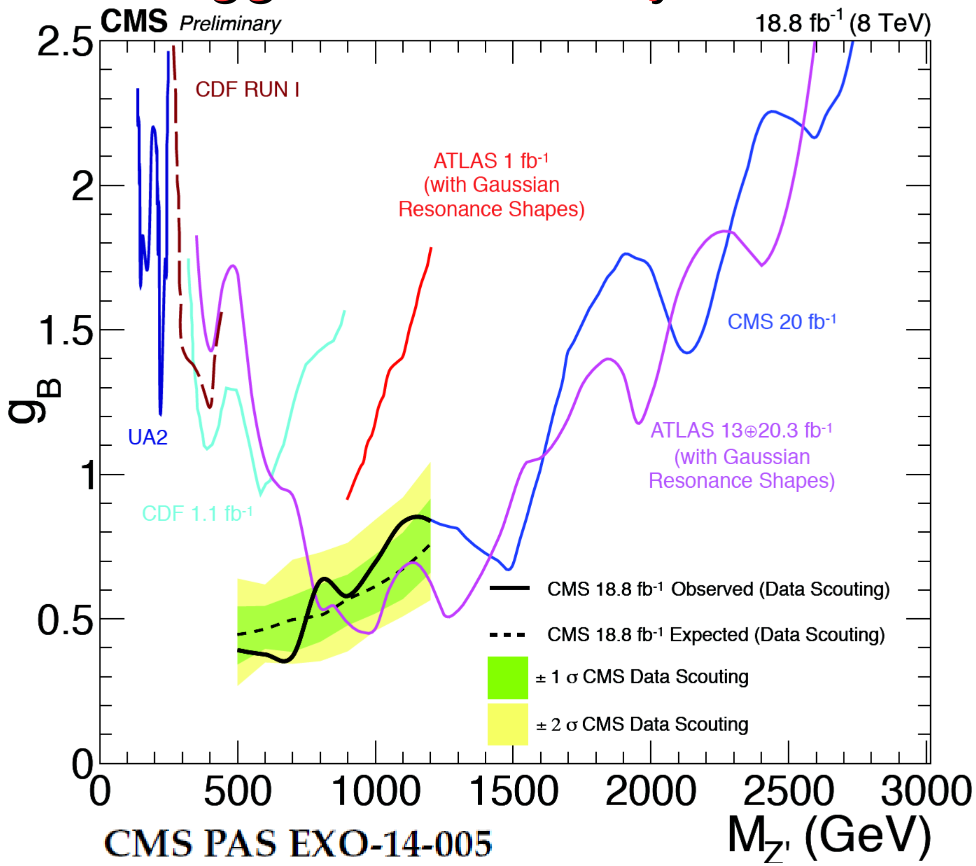
- Excluded masses: String resonance (7.0 TeV) , scalar di-quark (6.0 TeV), axigluon (5.1 TeV), excited quark q* (5.0 TeV), Heavy W' (2.6 TeV)

Dijet Events at low mass

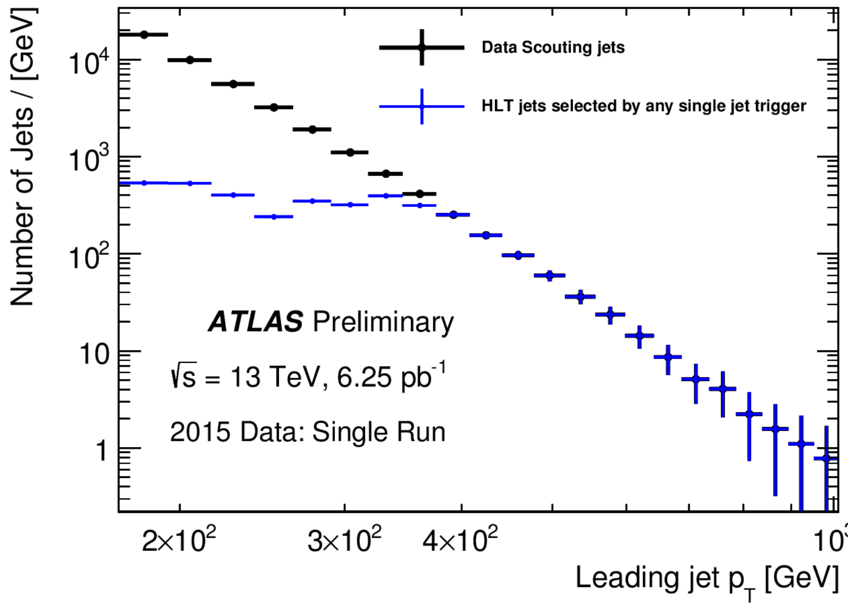
- At low mass → low jet pT threshold
- Data rate to high to write out

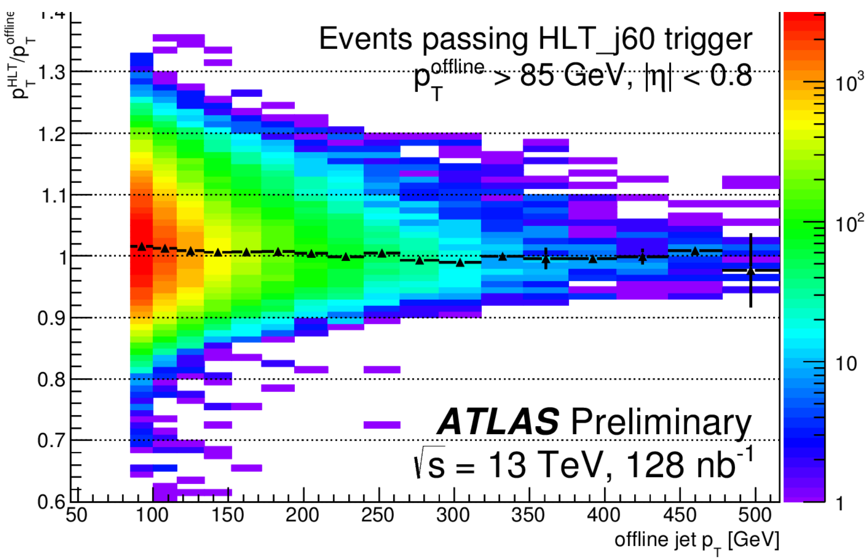
→ Online data scouting

Trigger Level Analysis

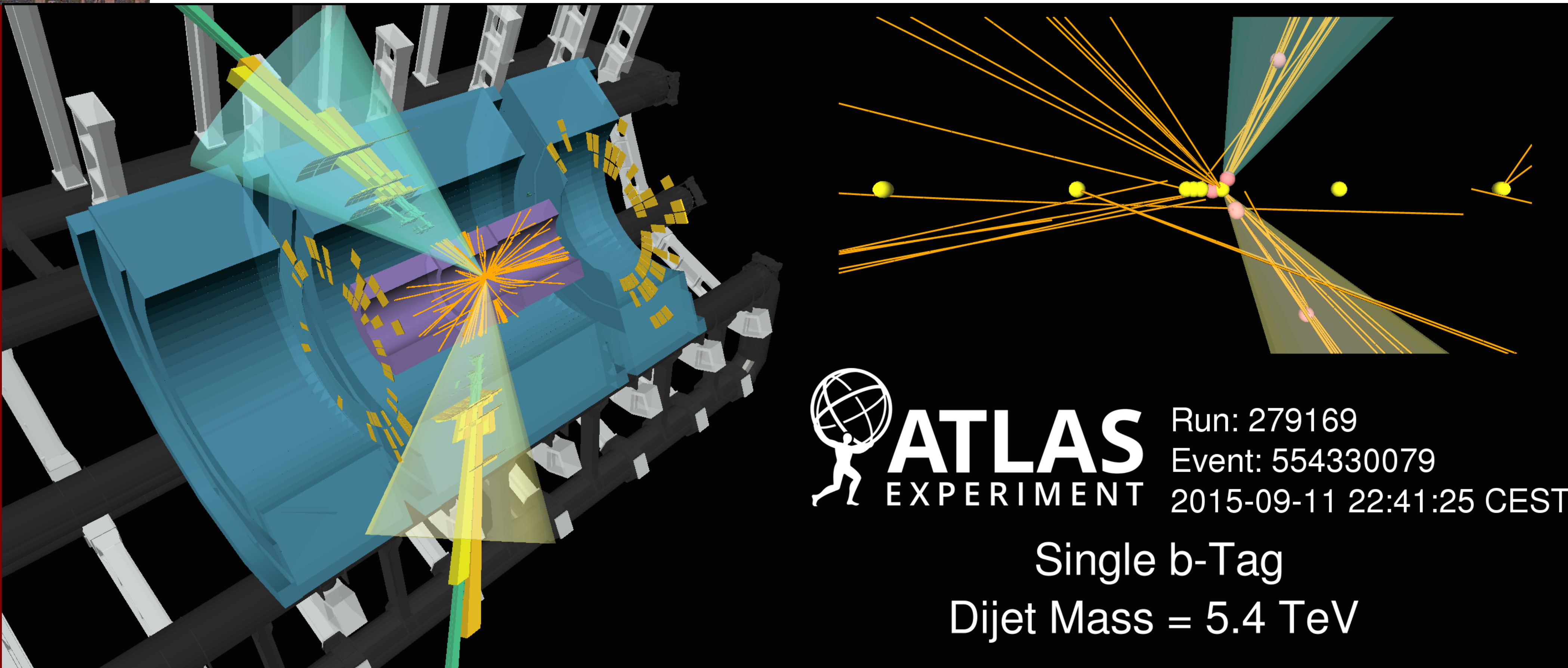


CMS PAS EXO-14-005



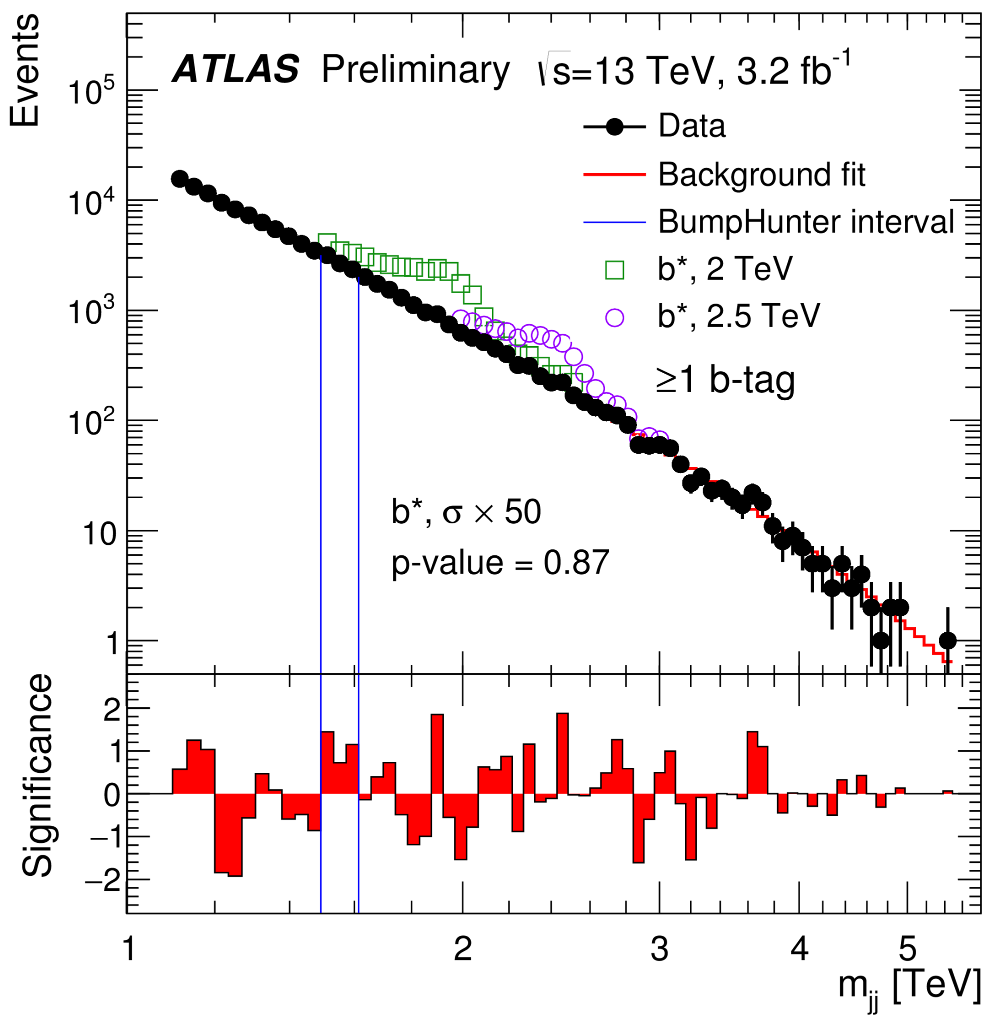


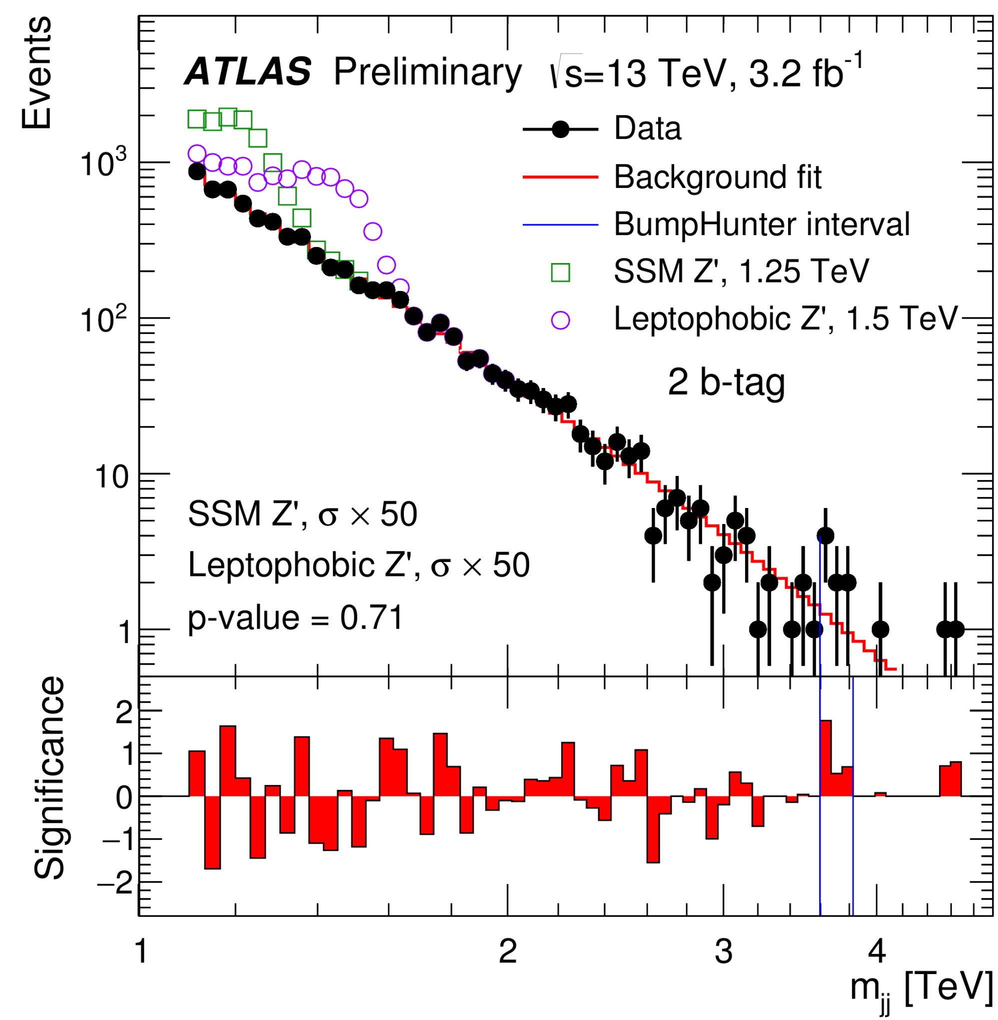
Di-beauty-Jets



- Third Generation (top & bottom) heavy, might be special → investigate couplings to b
- Needs identification of jets containing bottom hadrons → b-tagging
- Depending on decay (bb, bq, bg) → at least 1 or 2 b-tags
  - Possible qg background reduction also for X → qq modes

Di-beauty-Jets

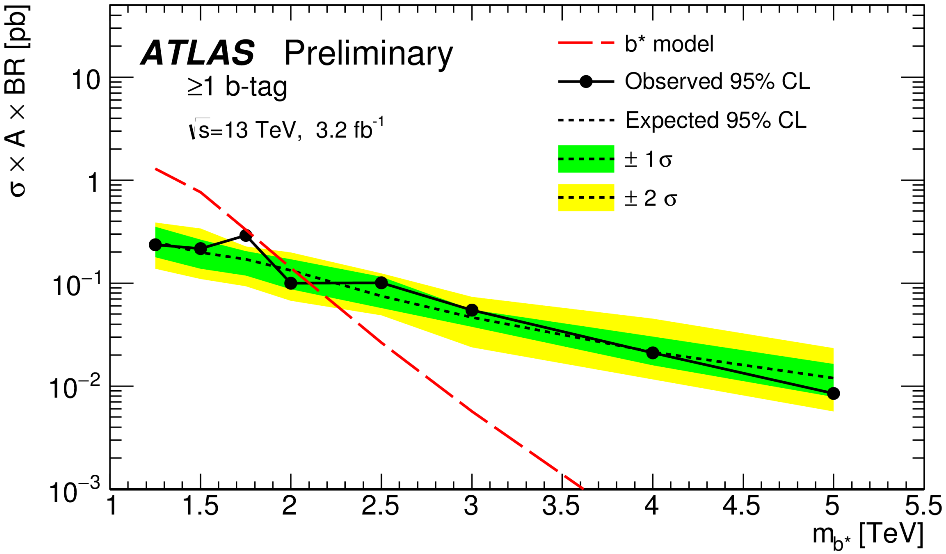


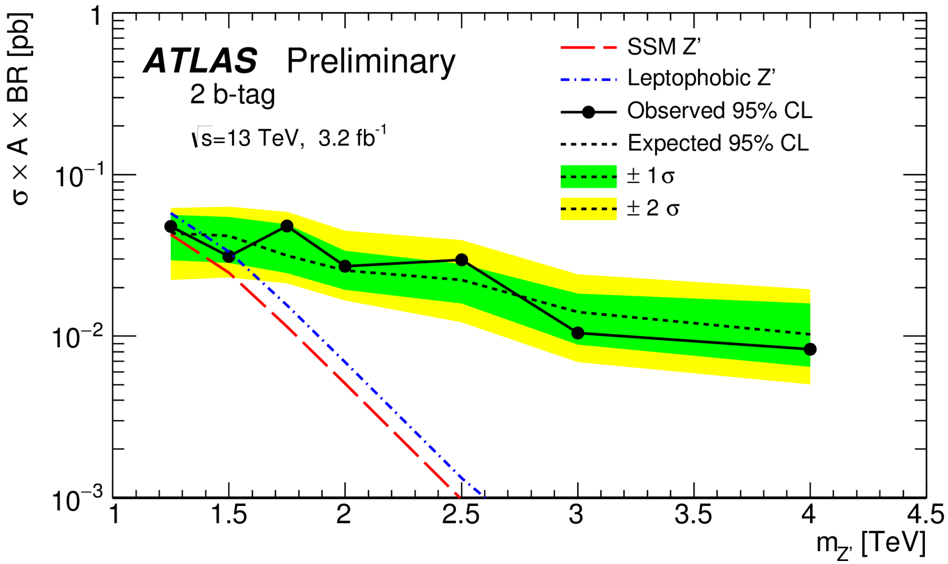


- Same selection as dijets (p_T > 440 GeV, $|y^*| = ½ |y_1 - y_2| < 0.6$)
- Limit $|\eta| < 2.5$, to tracking coverage for b-tagging

arXiv:1603.08791v1 [hep-ex]

Di-beauty-Jets

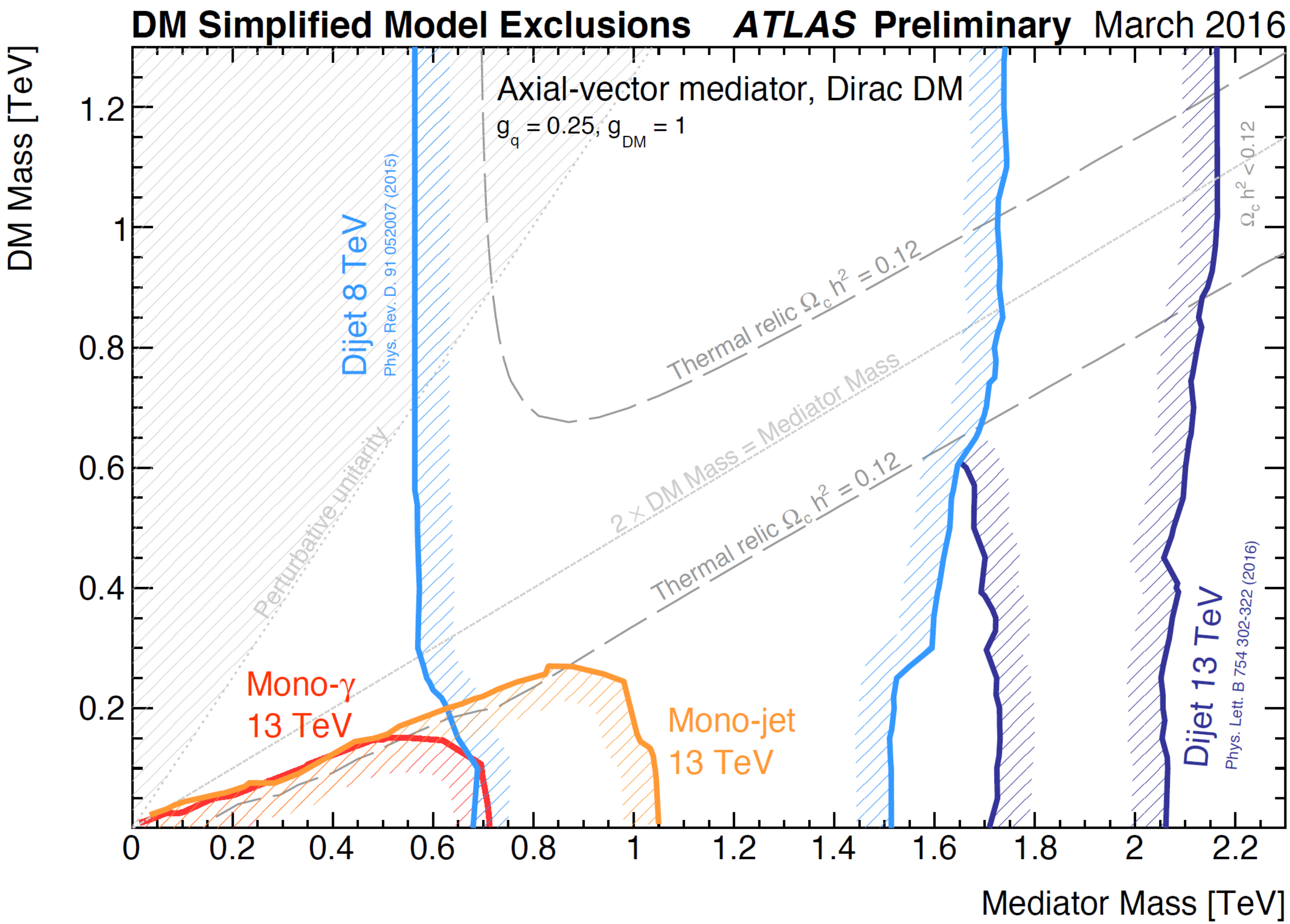




- Limits on benchmark models
- Excited quarks b* → bg
  - >= 1 b-tag
  - Excluded masses 1.1-2.1 TeV
- Extra Gauge Bosons Z'
  - 2 b-tag
  - Leptophobic Z'
  - Excluded masses 1.1-1.5 TeV
  - Sequential Standard Model (SSM) → SM couplings
  - Not enough data to exclude Sequential SM Z'

arXiv:1603.08791v1 [hep-ex]

Summary


DM Simplified Model Exclusions ATLAS Preliminary March 2016
Axial-vector mediator, Dirac DM
g_q = 0.25, g_DM = 1
Dijet 8 TeV
Phys. Rev. D. 91 052007 (2015)
Dijet 13 TeV
Phys. Lett. B 754 302-322 (2016)
Mono-γ 13 TeV
Mono-jet 13 TeV
Perturbative unitarity
Thermal relic Ω_c h² = 0.12
2 × DM Mass = Mediator Mass
Thermal relic Ω_c h² = 0.12
Ω_c h² < 0.12
DM Mass [TeV]
Mediator Mass [TeV]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2

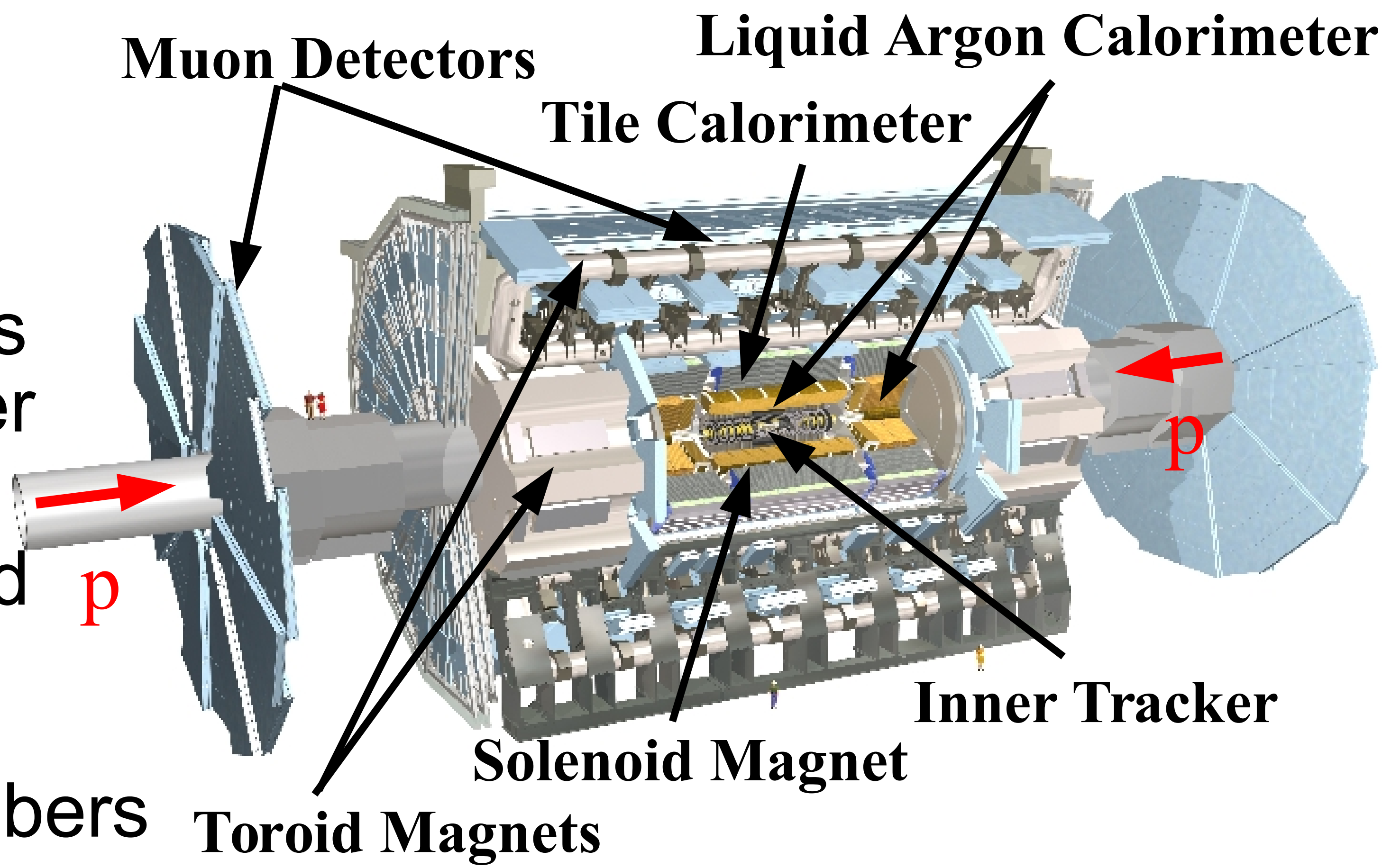
Conclusion

- The hunt for Dark Matter continues
- ATLAS and CMS have new interesting results
- Just the beginning of 13 TeV running ...
- LHC searches complementary to direct searches
- Jet channels are particularly sensitive
- Search for both DM and mediator candidates
- Model dependence in Interpretation
  - LHCDMWG Recommendations should unify approaches and help comparisons

Bonus Slides

ATLAS: a particle detector at the LHC

- Inner tracker
  - 2T solenoid
  - |η|<2.5
  - Silicon pixel
  - Silicon strips
  - straw tracker
- Muon system
  - 0.5-2T toroid
  - |η|<2.7
  - Precision & trigger chambers



- $\sigma_{Pt}/Pt \sim 0.05\% Pt[GeV] \oplus 1.5\%$
- ~ 10 μm impact parameter resolution

Technicalities: narrow width

The narrow-width approximation

width, even for resonances normally considered narrow. The extreme end of this tail due to the PDFs is sometimes suppressed in the searches by requiring the partons to be have mass close to the pole mass, within a few standard deviations on the dijet mass resolution. This is generally a reasonable solution for the shapes, as the QCD background overwhelms the signal at low dijet mass. However, the way that this tail from PDFs is handled can significantly affect the total resonance cross section quoted for specific models, as we discuss in Appendix A

Narrow width approximation:

- Approximate the true resonance shape with a delta function
- This avoids low-mass tails as PDFs will act only in the surrounding of the peak

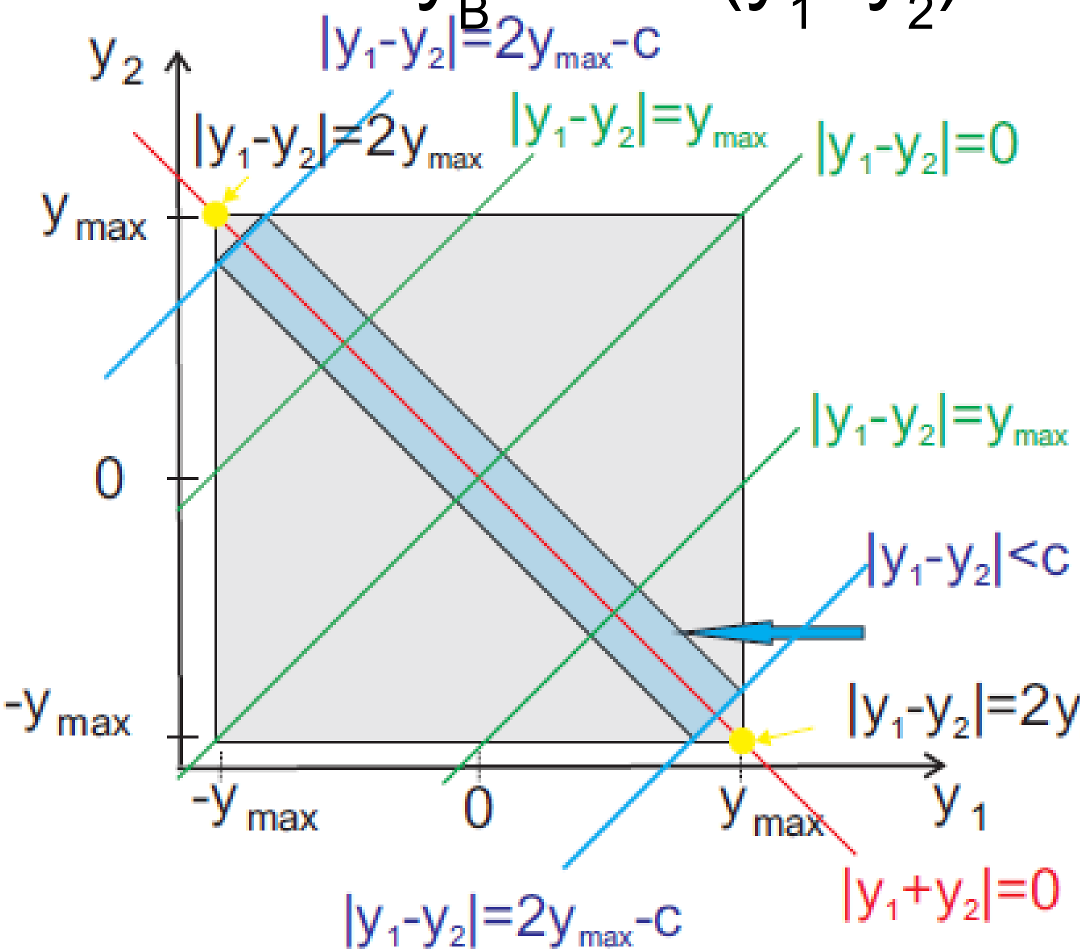
$$\sigma_{had}(m_R) = 16\pi^2 \times \mathcal{N} \times \mathcal{A}_{\cos\theta^*} \times BR \times \left[\frac{1}{s}\frac{dL(\bar{y}_{min},\bar{y}_{max})}{d\tau}\right]_{\tau=m_R^2/s} \times \frac{\Gamma_R}{m_R}, \quad (44)$$

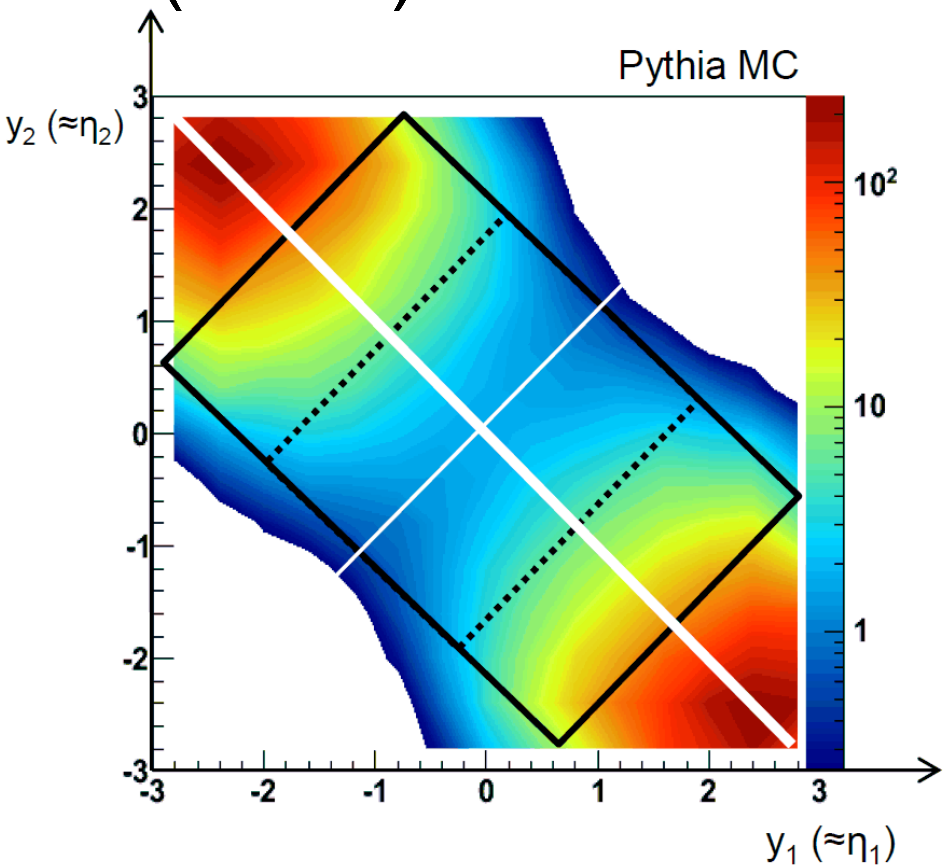
/here the parton luminosity $\frac{dL}{d\tau}$ is calculated at $\tau = m_R^2/s$, and constrained in the inematic range $[\bar{y}_{min}, \bar{y}_{max}]$.

Searches for Dijet Resonances at Hadron Colliders
Robert M. Harris, Konstantinos Kousouris arXiv:1110.5302

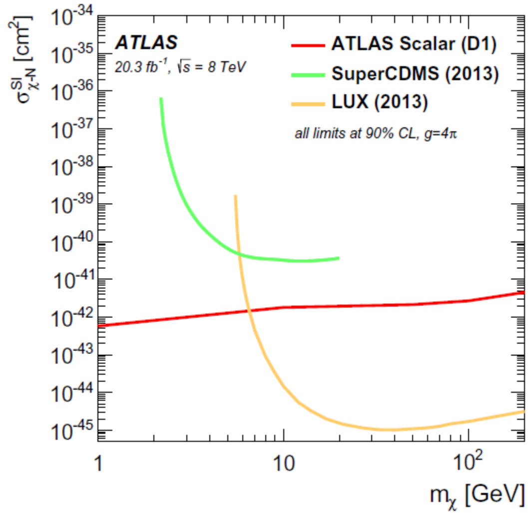
Rapidity distribution, Selection

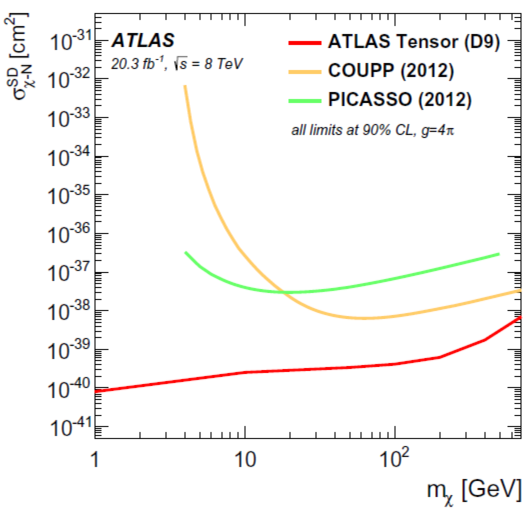
- $|y^*|<1.7$, $|y_B|<1.1$, implied: $|y_{1,2}|<2.8$, $p_T>80$ GeV
  boost $y_B = 0.5*(y_1+y_2) = 0.5\ln(x1/x2)$





Beauty-jets and missing E_T





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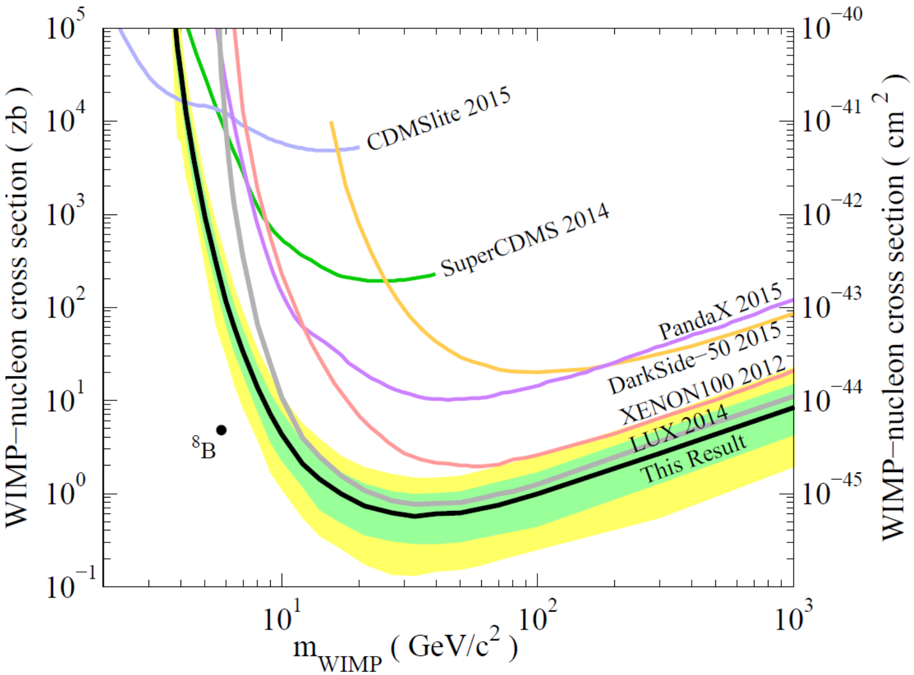
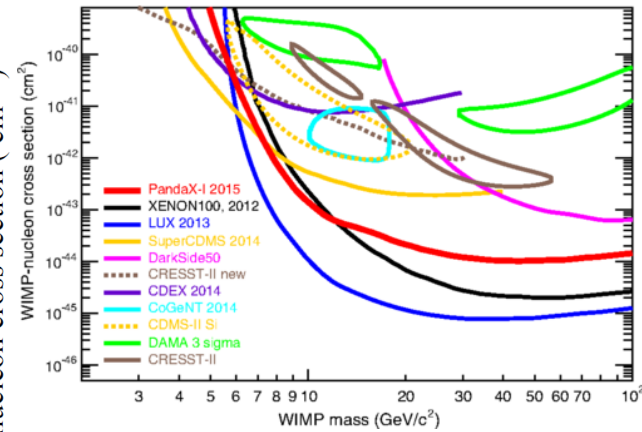
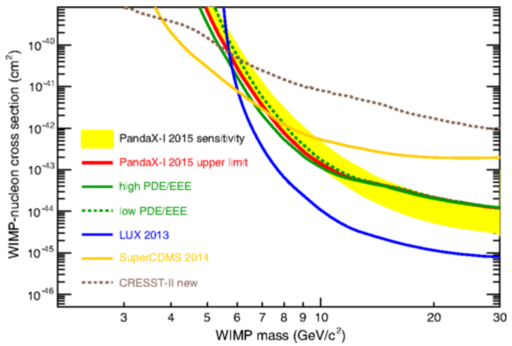
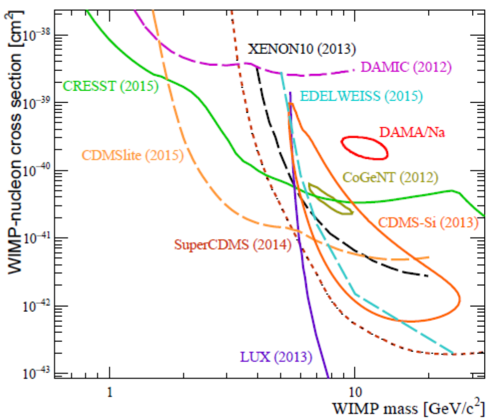
DOI 10.1140/epjc/s10052-015-3306-z

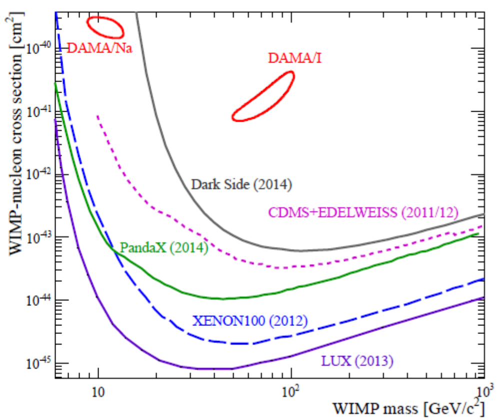
Direct Detection

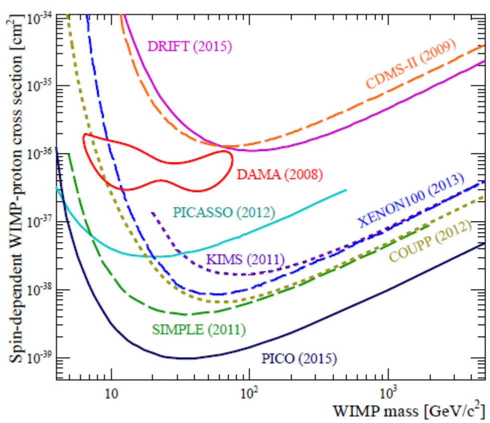


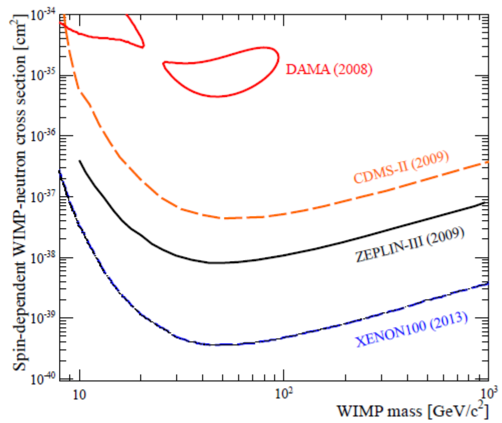




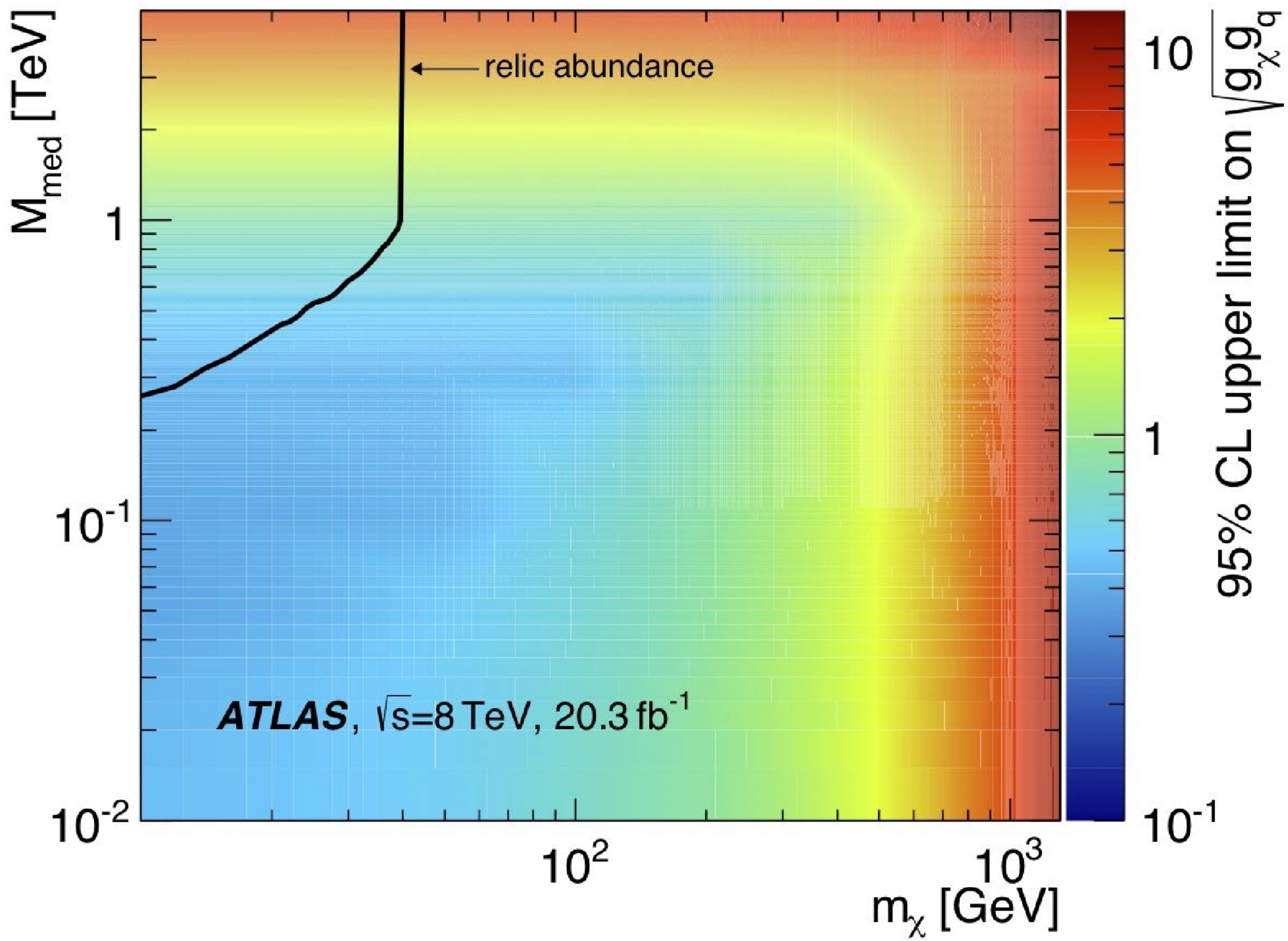








Mono-Jet



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DOI 10.1140/epjc/s10052-015-3517-3

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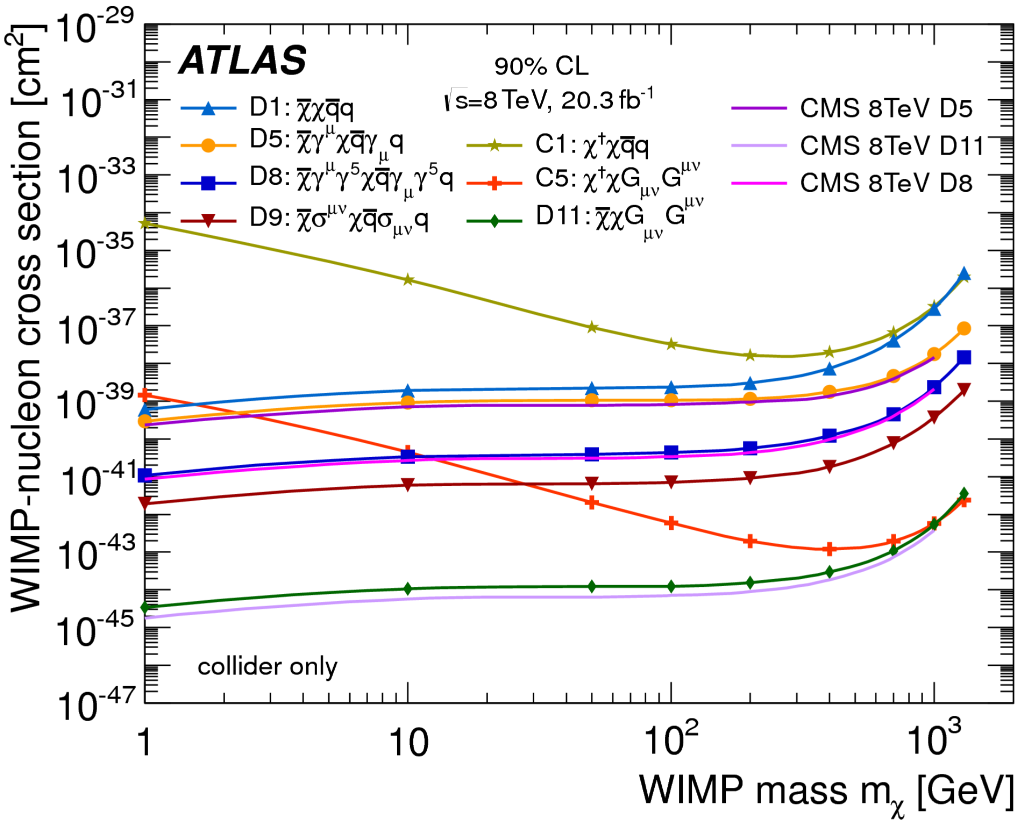

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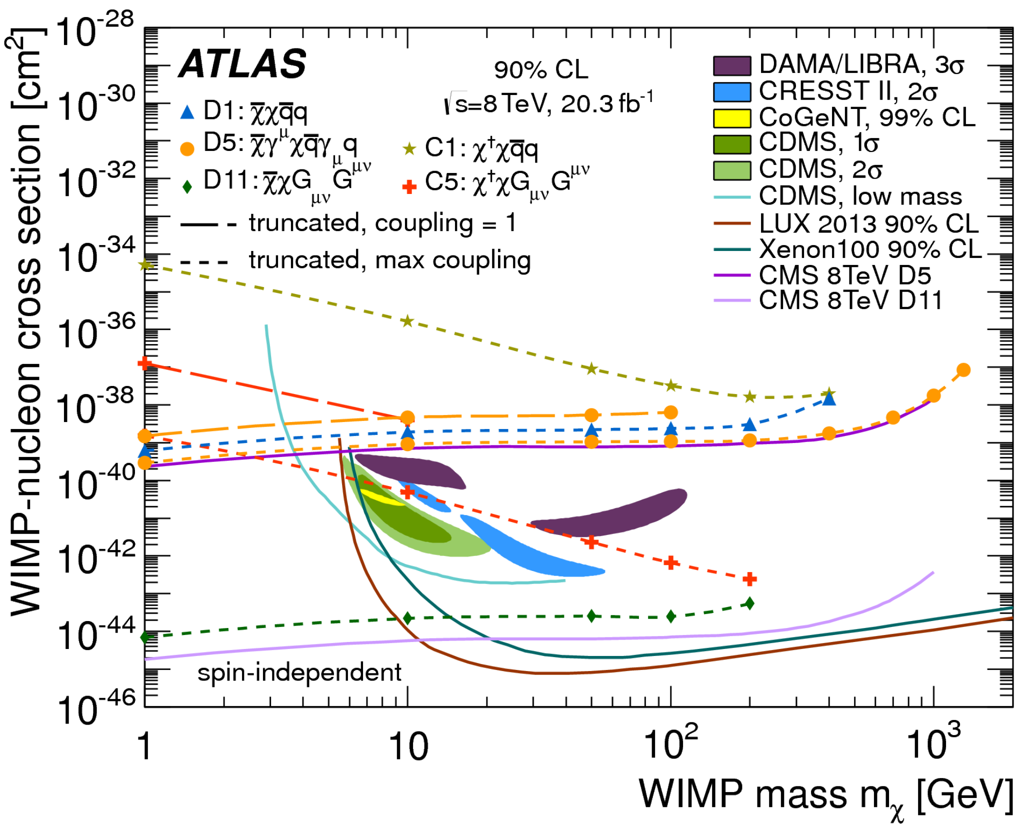

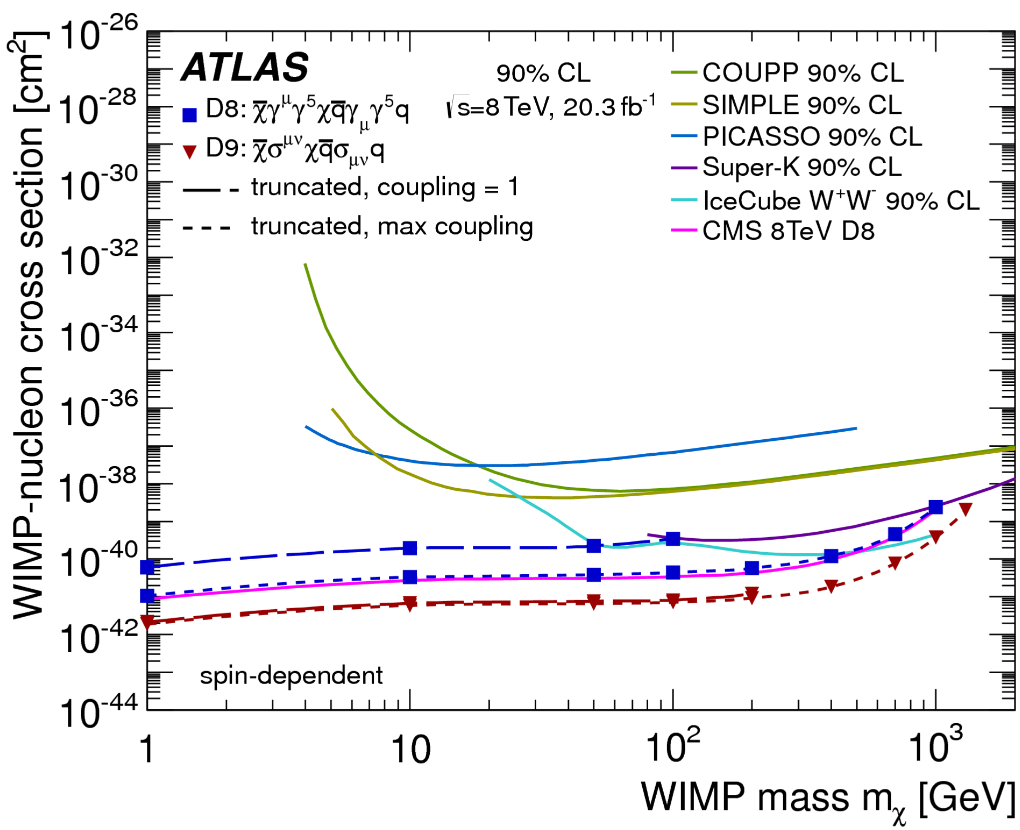

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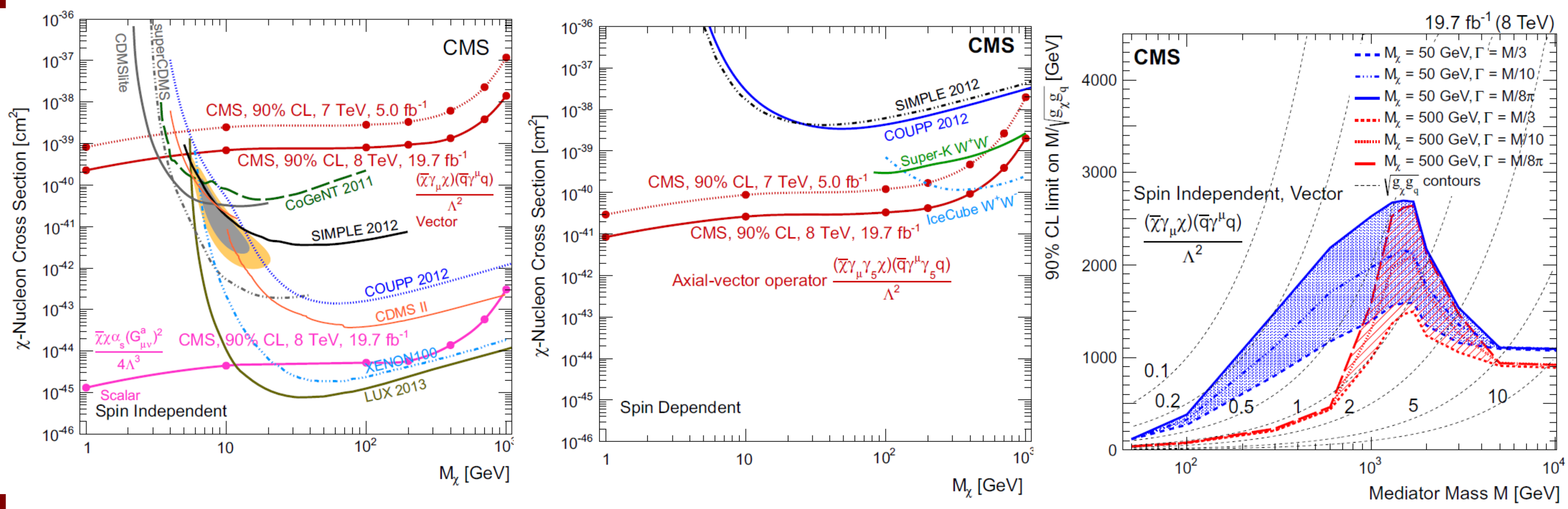

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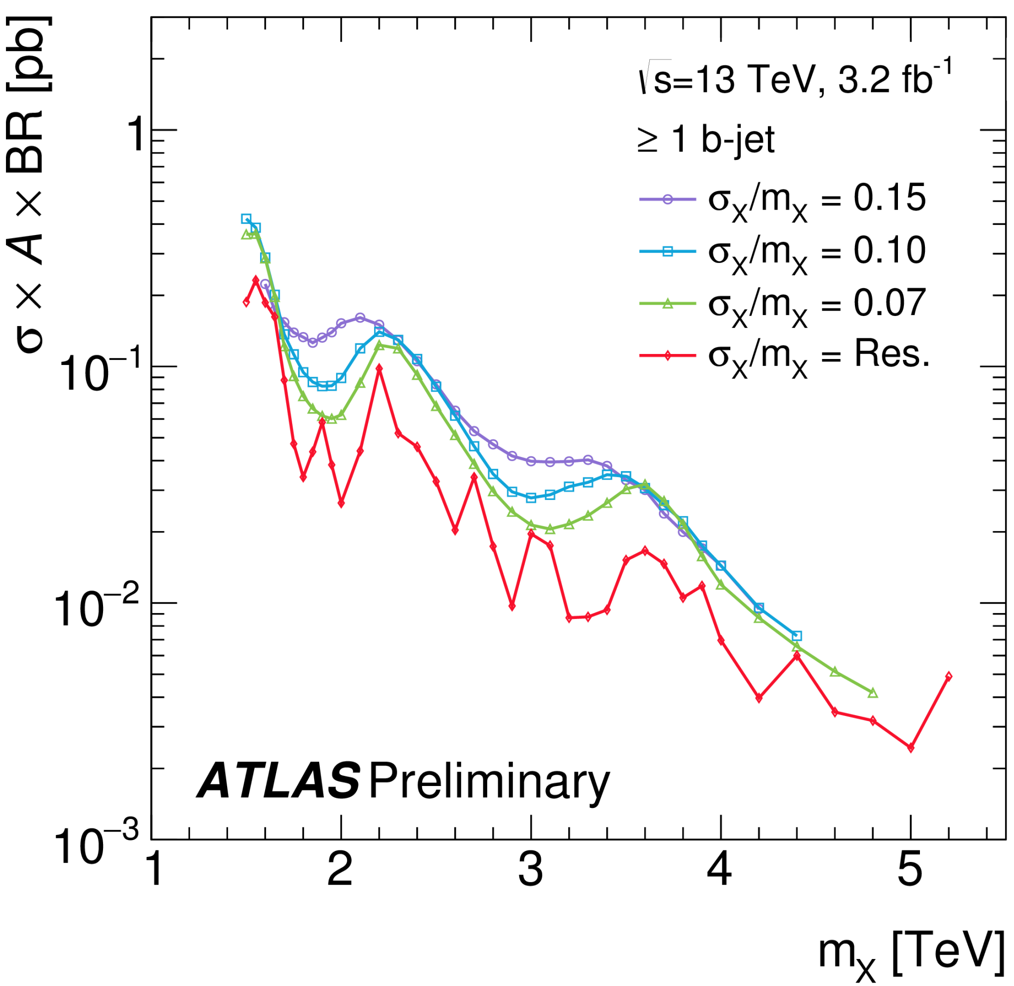
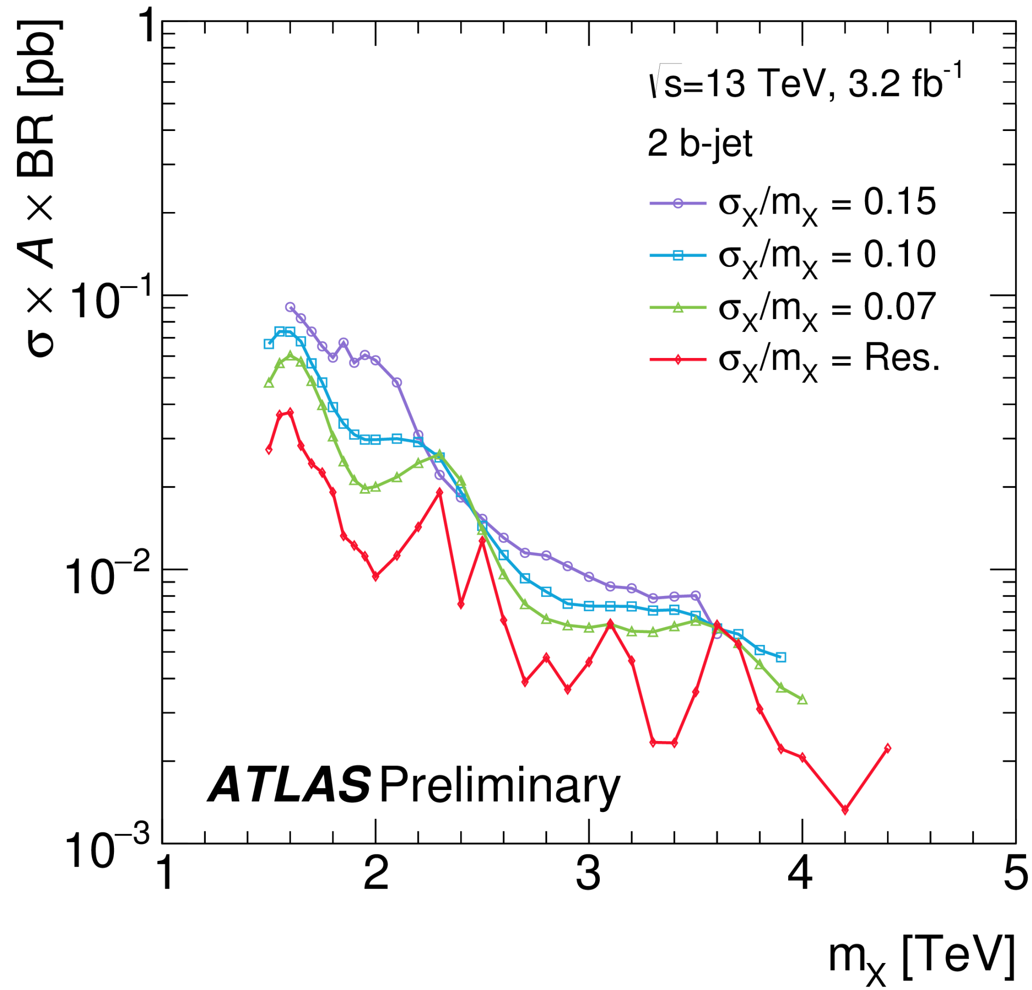
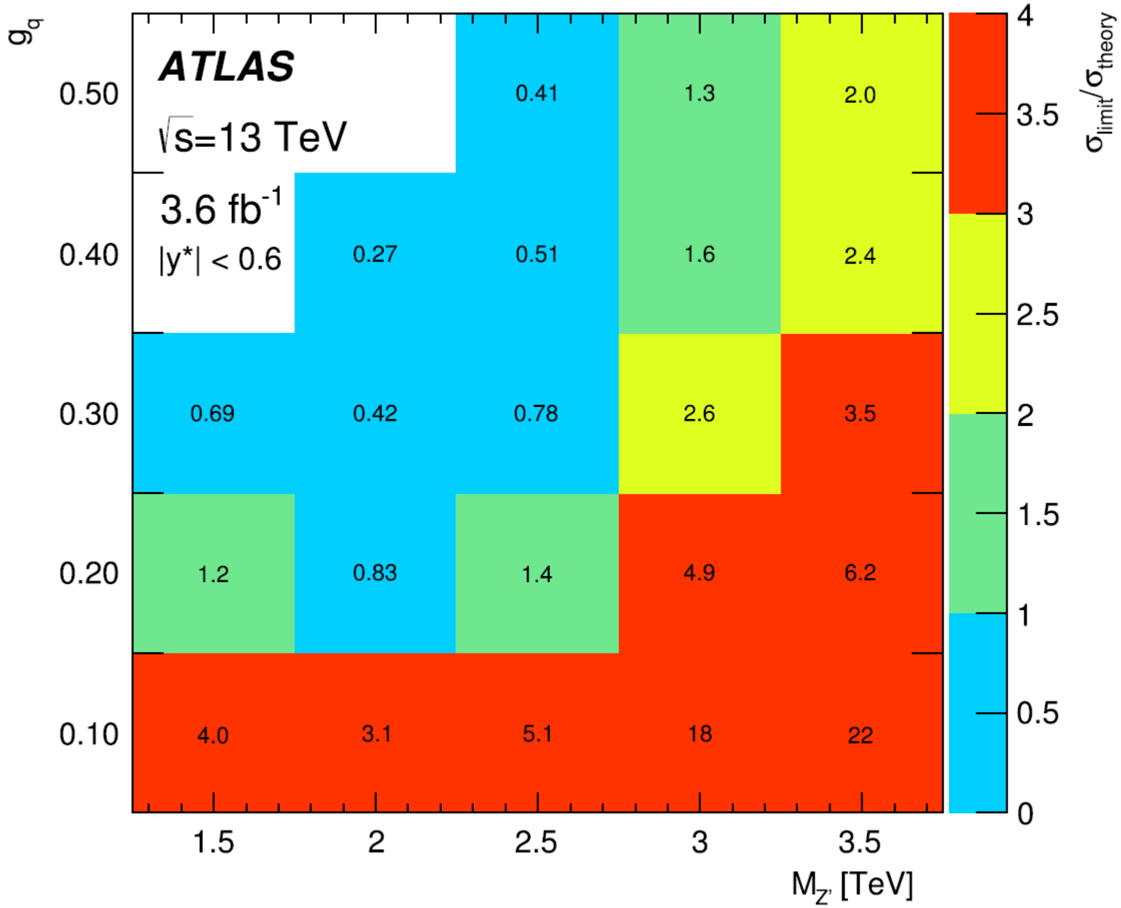
Di-beauty-Jets





- Gaussian limits: model independent approach

Di-Jet



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