DM@LHC2016: Workshop Impressions

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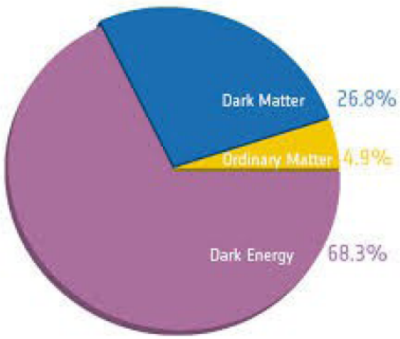
Introduction

Introduction

What do we know?

- How much: $\Omega_{DM} \approx 0.26$
- Likely particle with non-gravitational interactions
- Dark:
  - Electrically neutral - probably
  - Colour neutral – (H-dibaryon...)
- Cold: nonrelativistic during structure formation
- Sufficiently long-lived
- Non-baryonic (from BBN – $\Omega_B \approx 0.04$)



Candidate within the Standard Model of particle physics?

- Neutrinos
  - Correspond to hot DM
  - Cannot account for the observed dark matter density

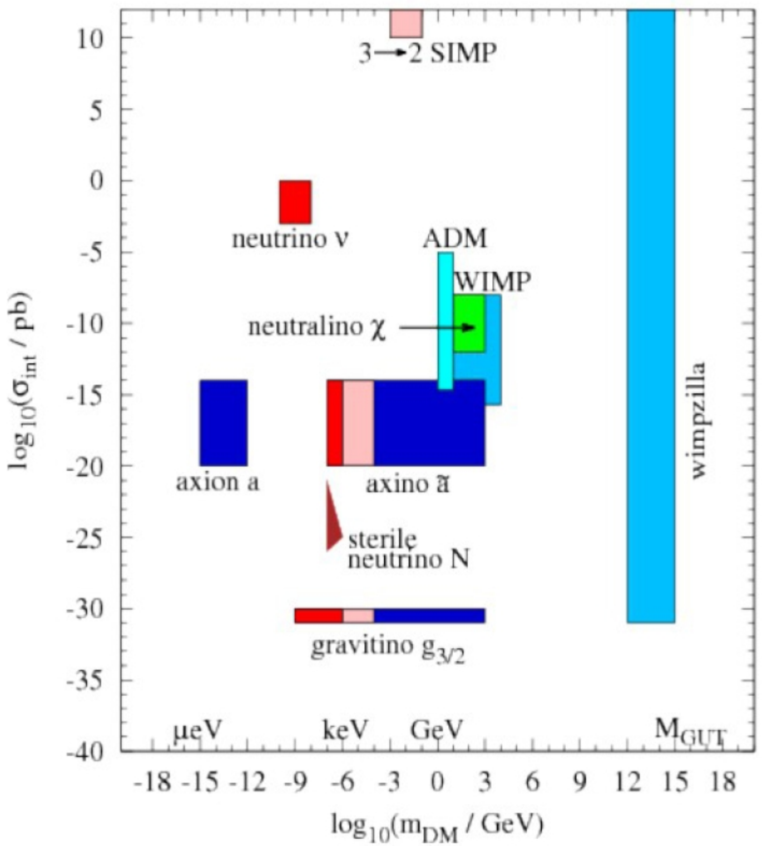
$$\sum \Omega_\nu h^2 \simeq m_{\nu_i}/93\mathrm{eV}$$

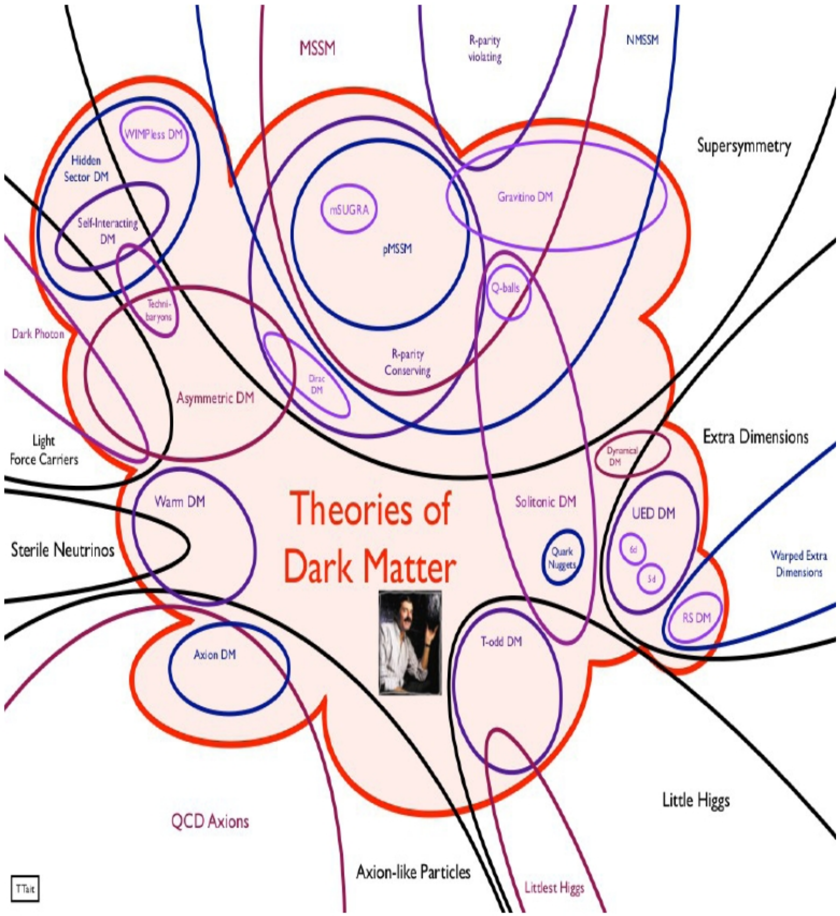
Physics beyond the Standard Model !

Many candidates (theorists are inventive...)

Introduction

Particle physics candidates





Introduction

Freeze out - WIMPs

(1) Assume dark matter X is initially in thermal equilibrium:

$$XX \leftrightarrow SM\ SM$$

(2) Universe cools:

$$XX \longrightarrow SM\ SM$$

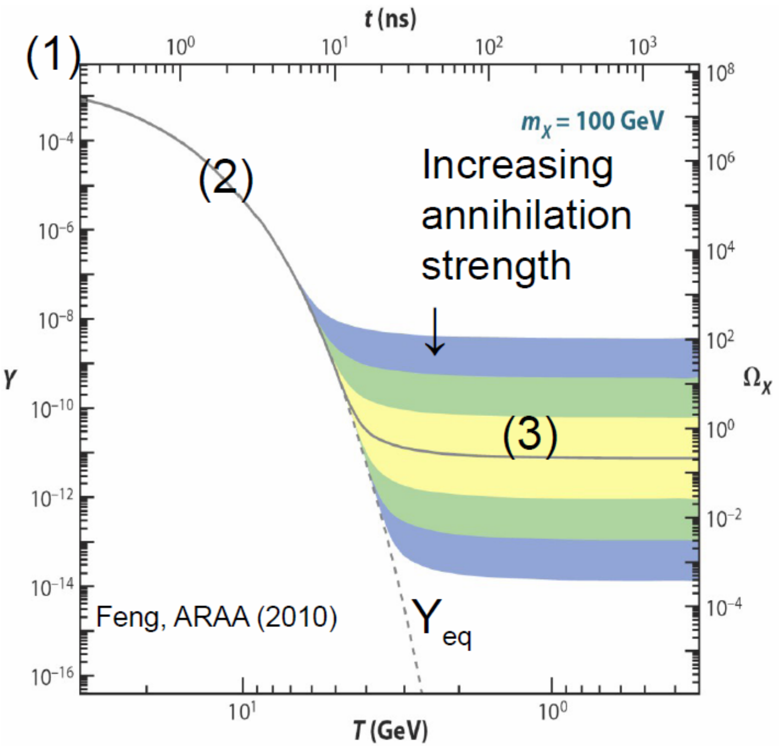
(3) Universe expands:

$$XX \qquad SM\ SM$$

The abundance is determined by the annihilation cross section!

Works just fine for weak scale masses and couplings → WIMP miracle

Unitarity bound: $m_{DM} \lesssim 100$ TeV

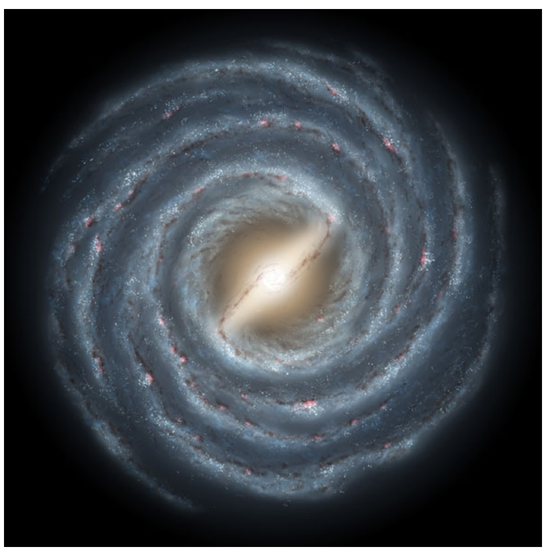


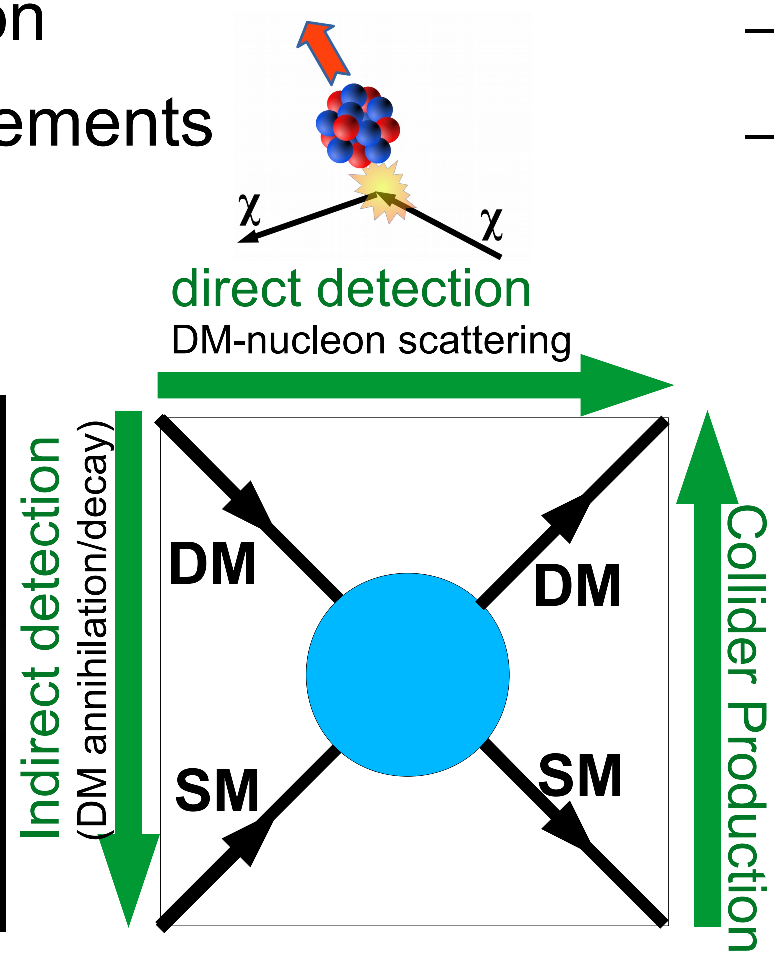
Introduction

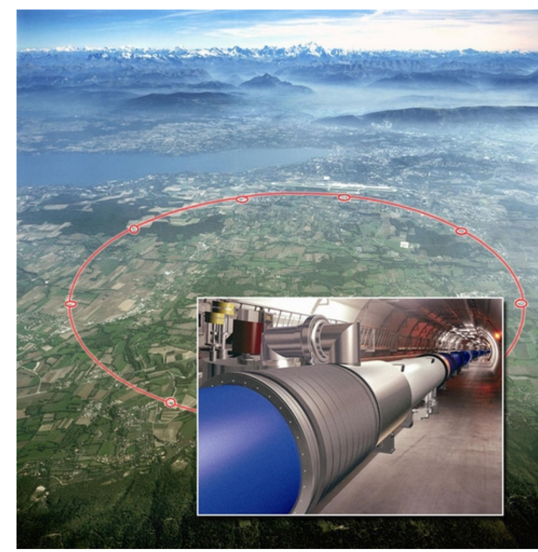
- Dark Matter (DM) well established:
  - Galaxy rotation
  - CMB measurements

- Three detection methods
  - Direct
  - Indirect
  - Production in collisions

  → LHC







Indirect Detection

Indirect Detection: Challenges

Astrophysical backgrounds = Large Systematic Uncertainties

Challenging to model theoretically
(e.g., cosmic ray diffusion)

New surprises as experimental sensitivities continue to improve
(e.g., millisecond pulsars)

How will we ever know that we have discovered dark matter?

Signal detection in more than one target

Correlate gamma-ray signal with large-scale structure that traces the DM signal

ML, Mishra-Sharma, Rodd, Safdi [in progress]

Mariaangela Lisanti

InDirect Detection

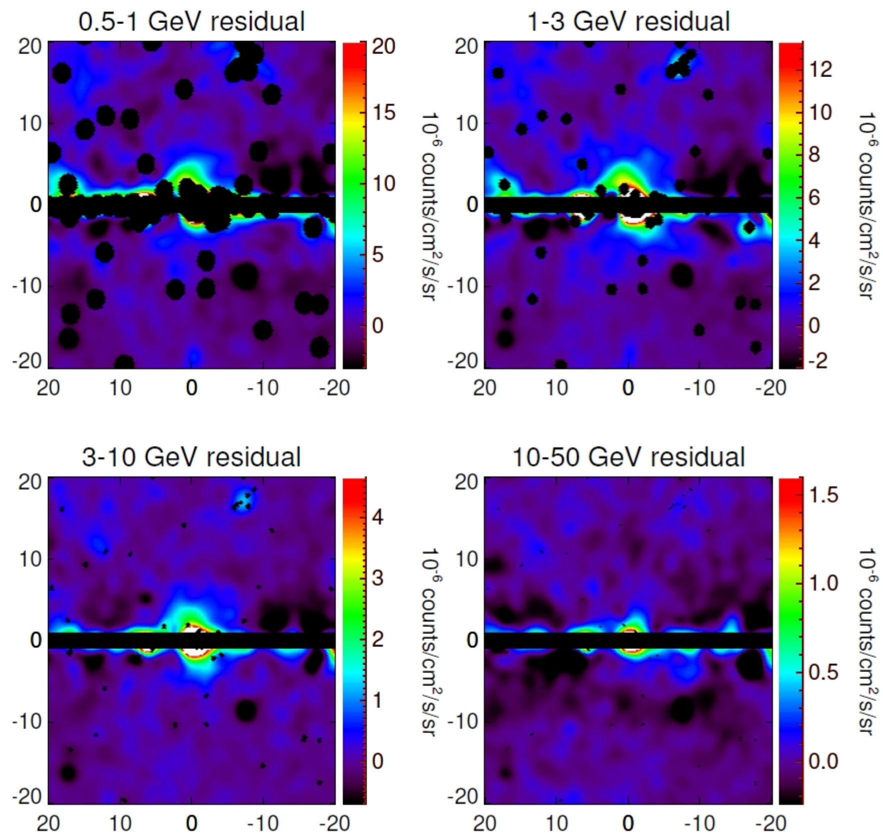
GeV Photon Excess

Observed at the Galactic Center and Inner Galaxy (≲ 10°)

Constitutes ~10% total flux

High statistical significance

Goodenough and Hooper [0910.2998]
Hooper and Goodenough [1010.2752]
Boyarsky, Malyshev, Ruchayskiy [1012.5839]
Hooper and Linden [1110.0006]
Abazajian and Kaplinghat [1207.6047]
Gordon and Macias [1306.5725]
Abazajian *et al.* [1402.4090]
Daylan *et al.* [1402.6703]
Calore, Cholis, and Weniger [1409.0042]
Fermi Collaboration [1511.02938]



Daylan *et al.* [1402.6703]

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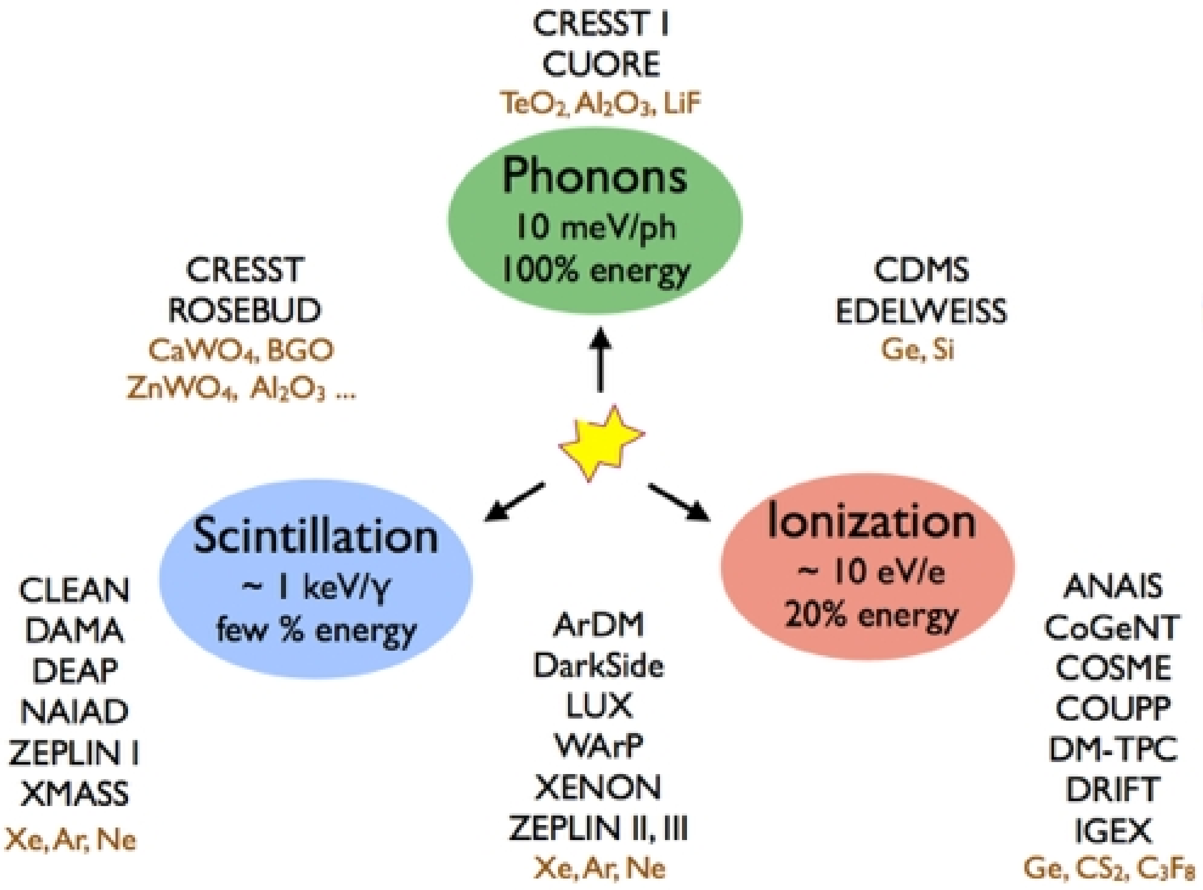
Introduction

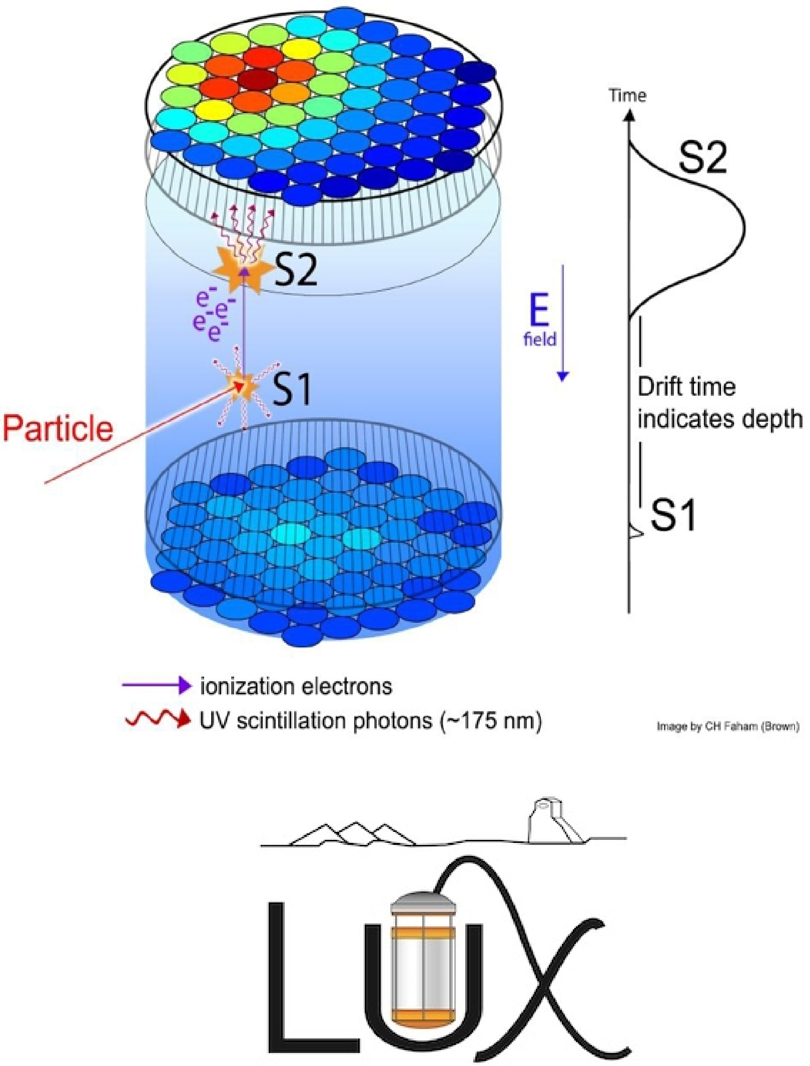
direct detection

- vector(DM)-vector(SM)
  - stringent limits from spin-independent direct detection
  - best limit: $\mathcal{O}(10^{-45}\text{cm}^2)$ by LUX
- axial(DM)-axial(SM)
  - not quite so stringent limits from spin-dependent direct detection
  - best limit neutron $\mathcal{O}(10^{-40}\text{cm}^2)$ by LUX
  - best limit proton $\mathcal{O}(10^{-39}\text{cm}^2)$ by PICO
- vector(DM)-axial(SM)
  - $\sigma \propto v^2$ or q^2 and direct detection very suppressed
  - essentially no limit (see Del Nobile, Cirelli, Panci 1307.5955 for actual limit)
- axial(DM)-vector(SM)
  - $\sigma \propto v^2$ or q^2 and direct detection very suppressed
  - essentially no limit

S. Vogel

Direct Detection





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Direct Detection: Direction!

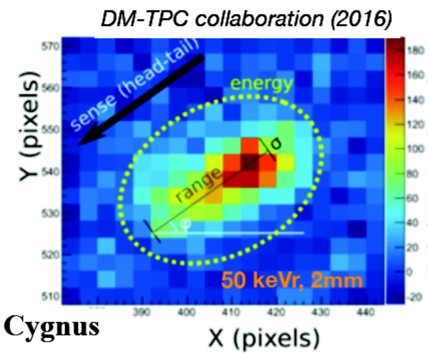
Directional detection

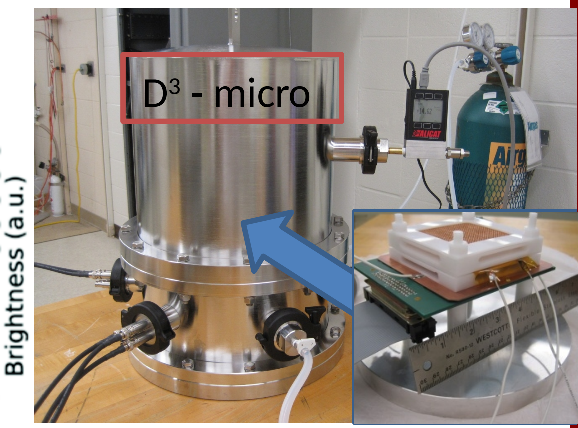
Directional detection aims at measuring both the recoil energy and direction using gas TPC

Leading experiments are: **DRIFT**, **DM-TPC**, **MIMAC** and **Newage**

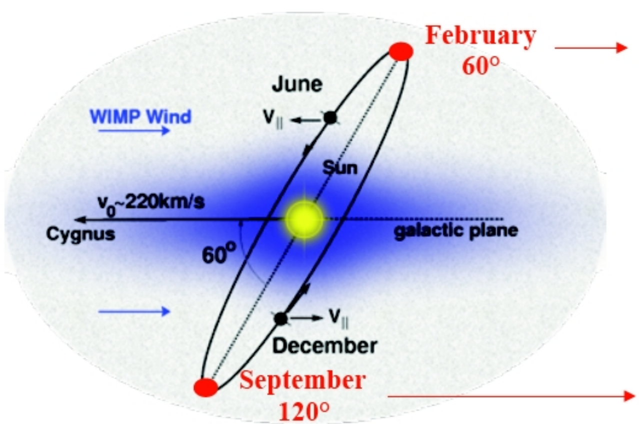
Great experimental challenges:

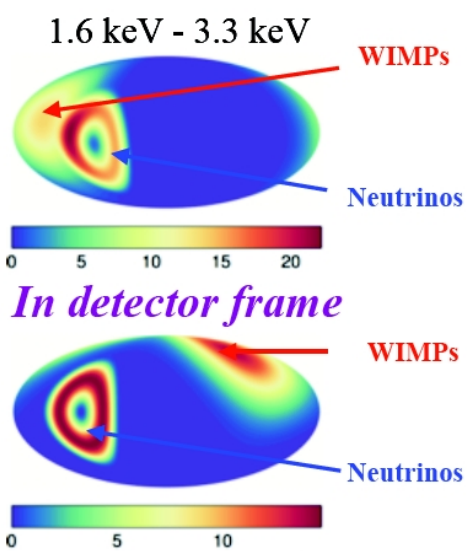
- **Intrinsic angular resolution**: ~20 degrees RMS
- **Thresholds**: 1 keV (energy), 10 keV (directional)
- **Exposure**: ~100 g (DRIFT)
- **Target**: Fluorine (excellent spin-dependent coupling)

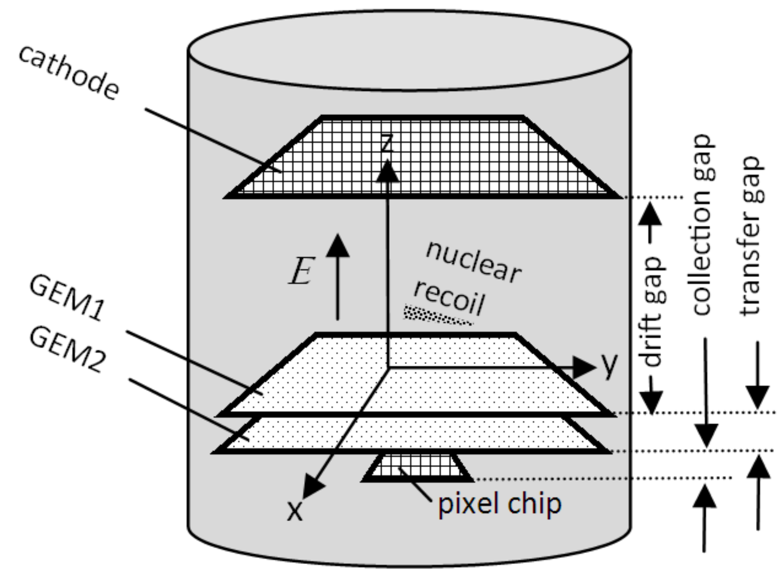




- Thanks to the rotation of Solar System around Galactic Center, WIMPs are coming from **Cygnus**
- Solar neutrinos are coming from … the **Sun**







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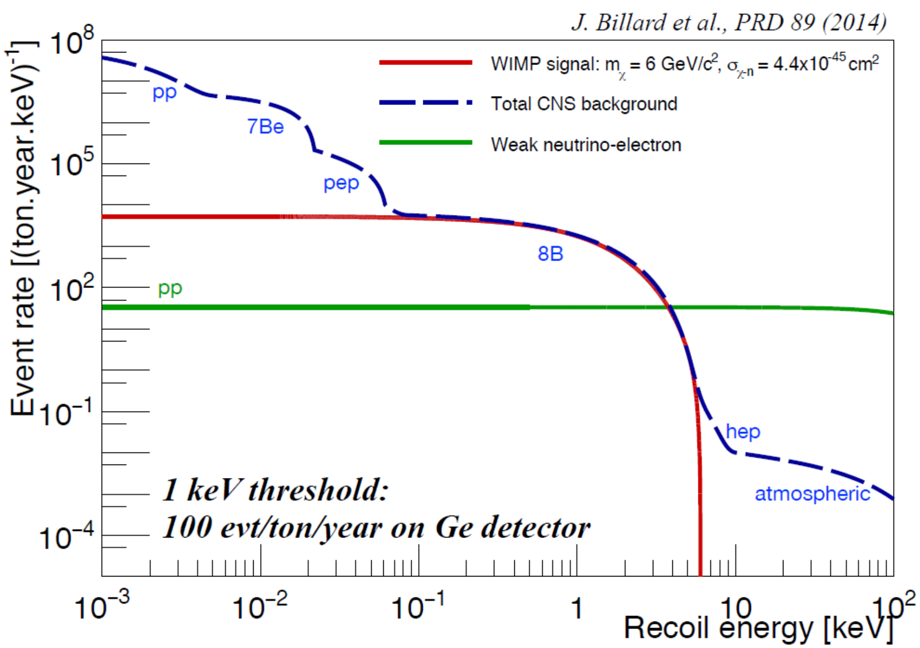
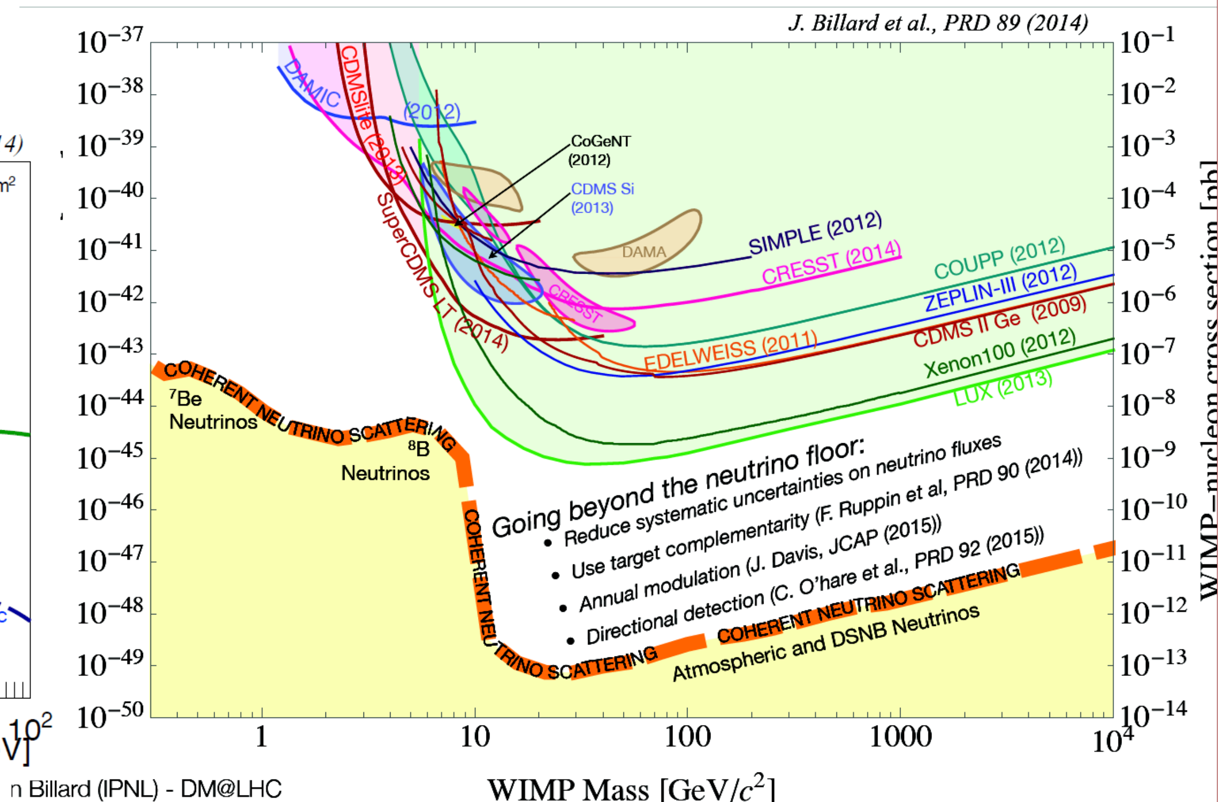
Direct Detection

The neutrino background





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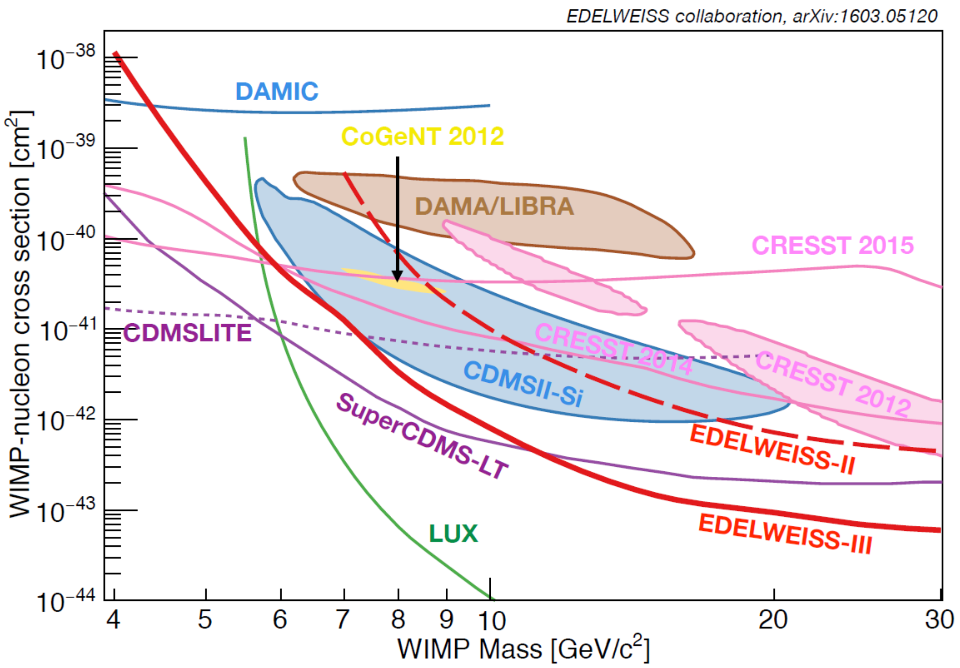
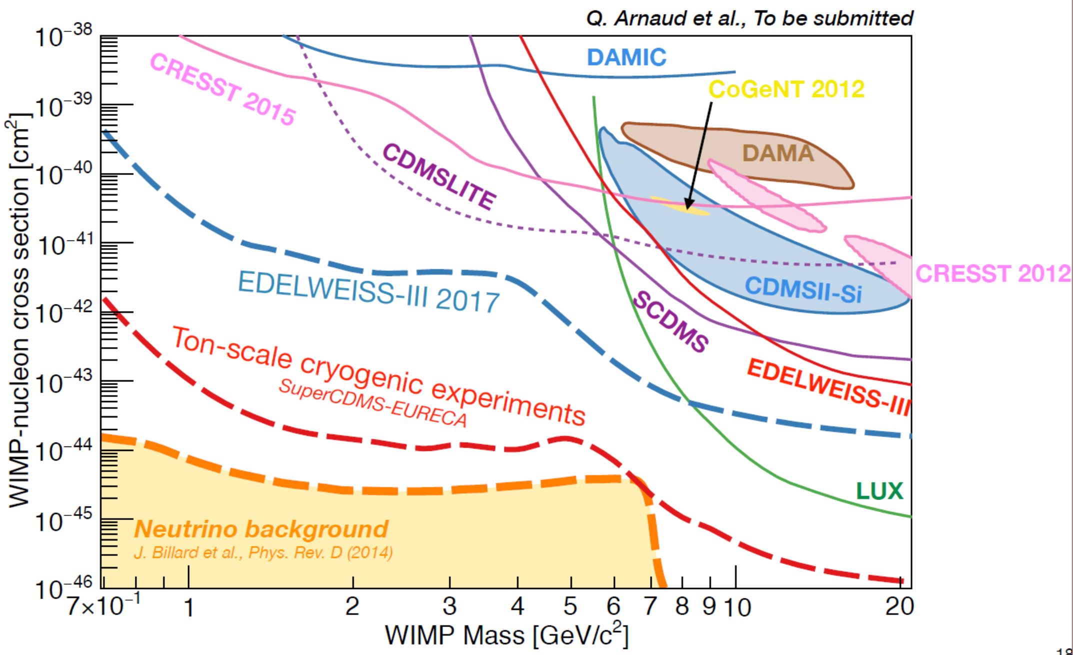
Direct Detection





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DM at the LHC

1. **Monojet**
   - Strategy: reconstruction, analysis & interpretation
2. **Other Mono-X**
   - Mono-V/γ
   - Mono-H
   - DM+HF
   - H→inv
3. **Alice+LHCb**
   - Dark photons
   - Dark sectors
4. **Cosmological constraints**
   - For LHC & FCC
5. **Resonances constraints**

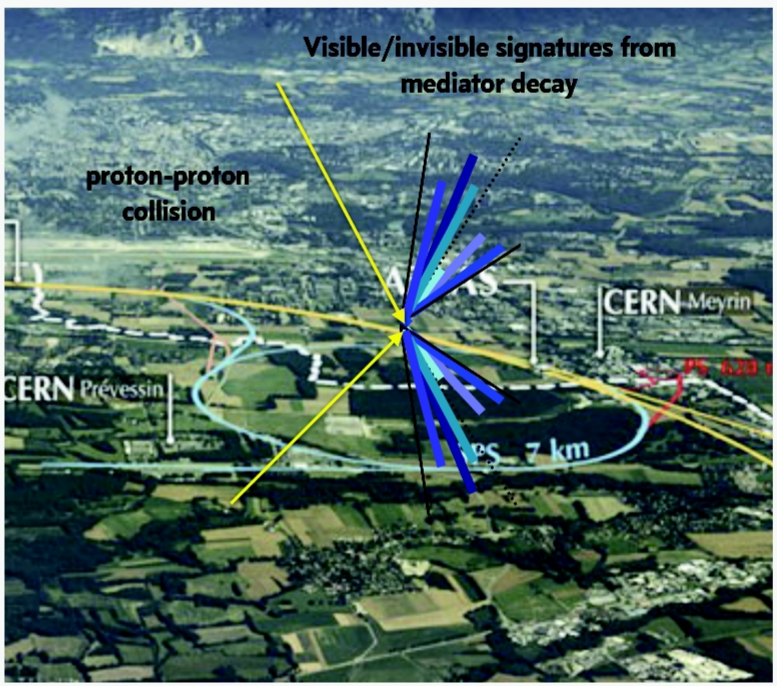
Tristan du Pree

DM at the LHC

Gathering the community for a view of the landscape

ATLAS/CMS Dark Matter Forum (2015)

Determined recommended **benchmark models** for LHC Run 2 searches:
emphasis on **mediators** that could be **produced** and **discovered** in the next few years



Joint ATLAS/CMS/theory discussion forum

- Classify benchmark models (simplified models) according to final state signatures
- Propose a small set of simplified models for early Run-2 LHC searches
- Review tools and implementations, state-of-the-art calculations
- Maintain model repository

A. Boveia/S. Malik

DM at the LHC

LHC Dark Matter Working Group (2015–)

http://lpcc.web.cern.ch/lpcc/index.php?page=dm_wg

The LHC Dark Matter Working Group (LHC DM WG) brings together **theorists** and **experimentalists** to define **guidelines and recommendations for the benchmark models, interpretation**, and **characterisation** necessary for **broad and systematic searches for dark matter at the LHC.**

The LHC DM WG develops and maintains close connections with theorists and other experimental particle DM searches (e.g. Direct and Indirect Detection experiments) in order to help **verify and constrain particle physics models** of **astrophysical excesses**, to understand how collider searches and non-collider experiments **complement** one another, and to help build a **comprehensive understanding** of viable dark matter **models**.

arXiv:1603.04156

CERN-LPCC-2016-001

arXiv:1603.04156v1 [hep-ex] 14 Mar 2016

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

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Pilot effort: translation of LHC simplified model results into DM-nucleon cross-section plane (DD/ID)

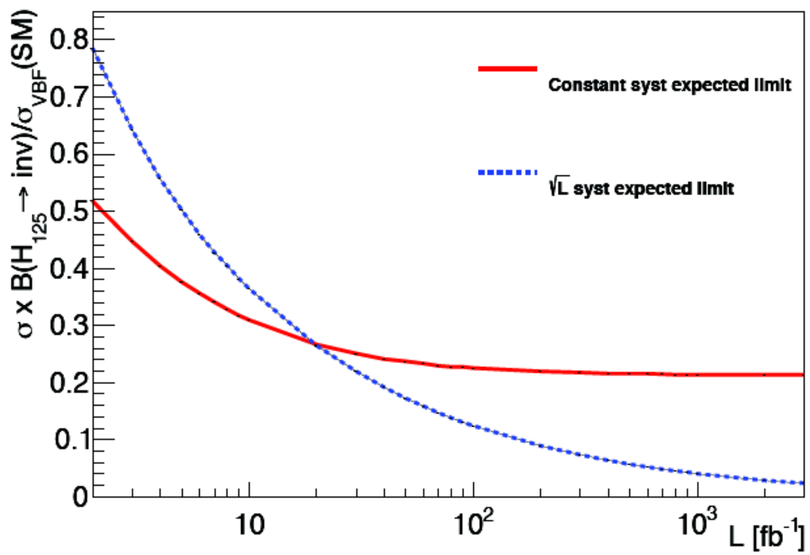
A. Boveia/O. Buchmueller

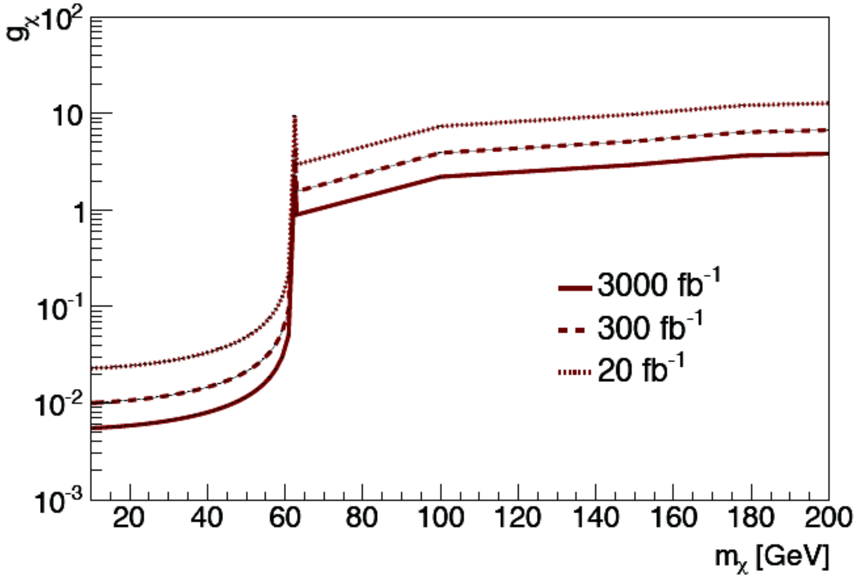
Higgs → invisible

- This Higgs boson thing seems like it could be useful

$$pp \to (h^{(*)} \to \chi\chi) + X$$

  - Or through extra Higgs(es) in non-minimal models
- Combined limit on $\mathrm{BR}(H_{125} \to \text{ inv.}) \lesssim 0.25$





Brooke, Buckley, Dunne, Penning, Tamanas, Zgubic 1603.07739

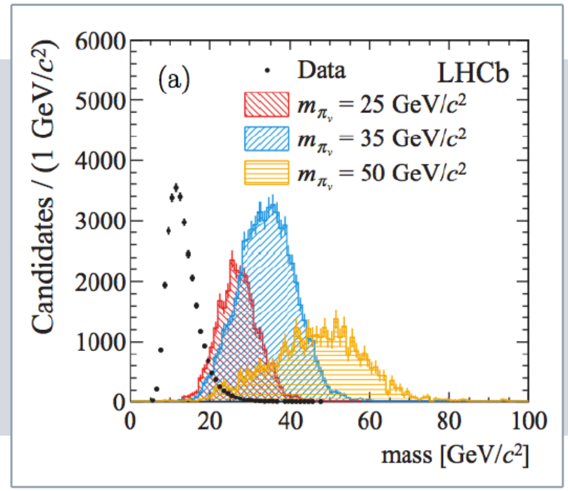
M. Buckley/P.Dunn

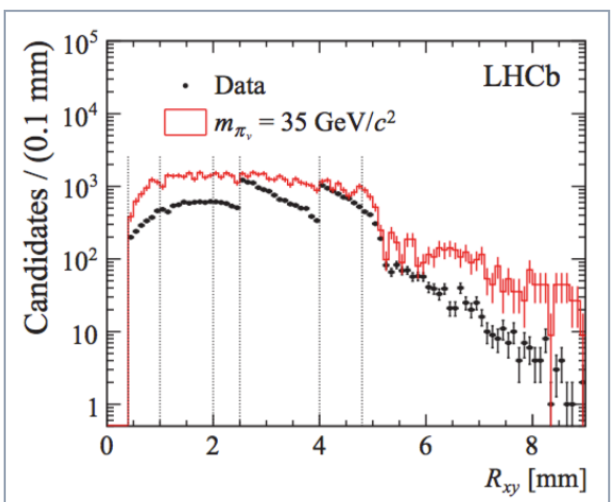
More exotic searches

Eur.Phys.J.C75(2015)152

Displaced jets

- $H \rightarrow \pi_v(bb)\pi_v(bb)$
  - Hidden valley - long-lived particles
- **Low mass**
  - 25 GeV – 50 GeV
- **Displaced bb**
  - 0.4 mm – 4.8 mm





LHCb advantages

- **Triggers**: low-mass&p_T
  - Upgrade: full software trigger
- **Vertex resolution**
  - Critical for displaced searches

DM@LHC: see Swagata Mukherjee for Atlas+CMS long lived

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

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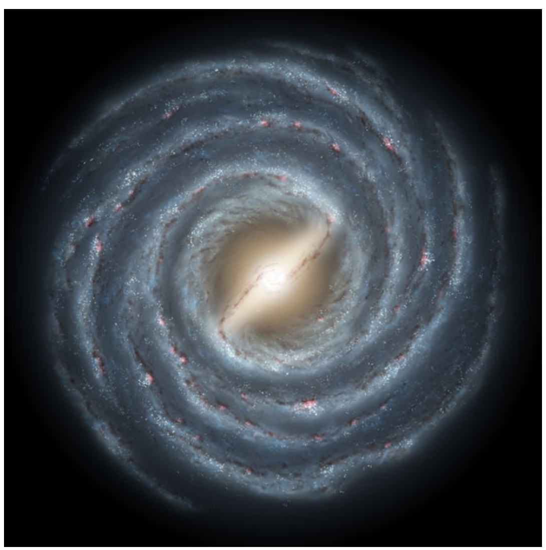
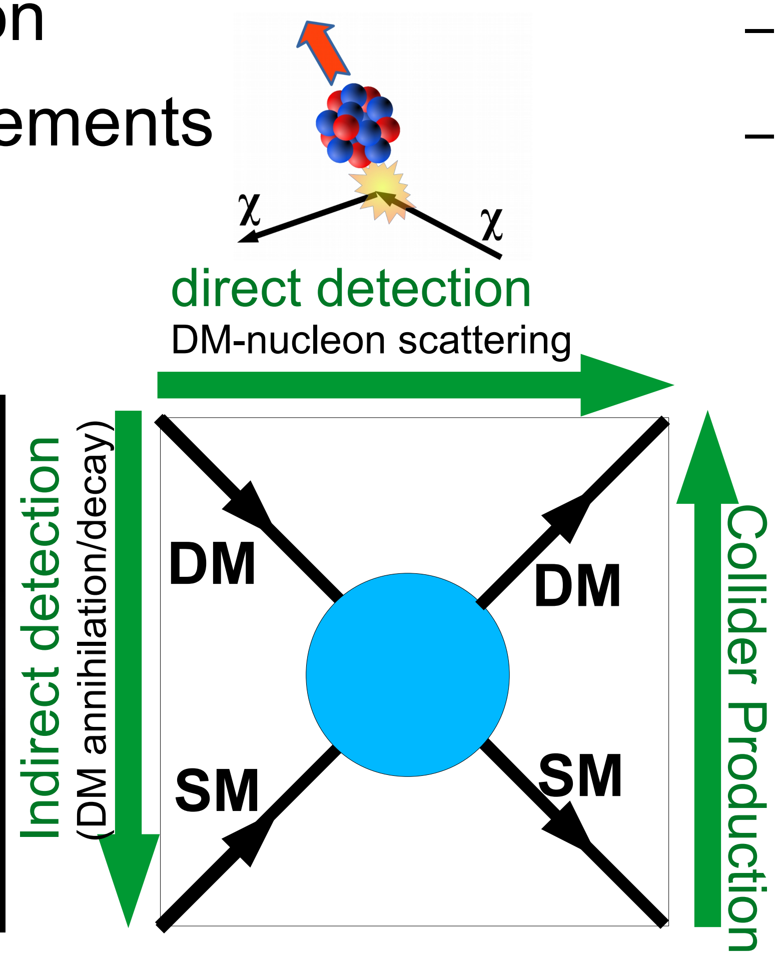
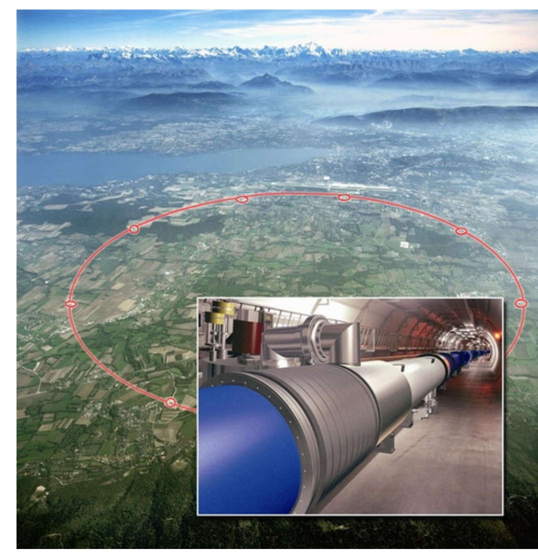
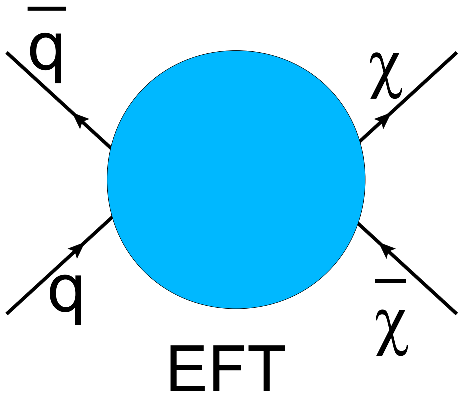


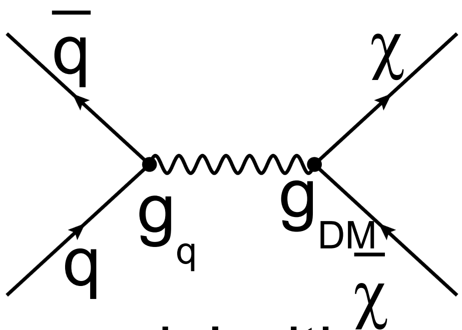




DM at LHC:Models

	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	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$



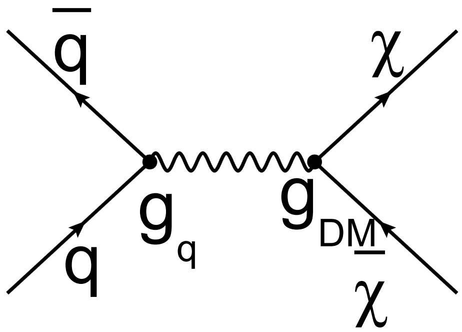


- Common: Effective Field Theory (EFT)
- Limited validity: $m_{mediator} >> E(\chi)$
- Integrate mediator out,
  Fermi constant G_F like coupling:

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

- Now mostly superseeded

DM at LHC:Models



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

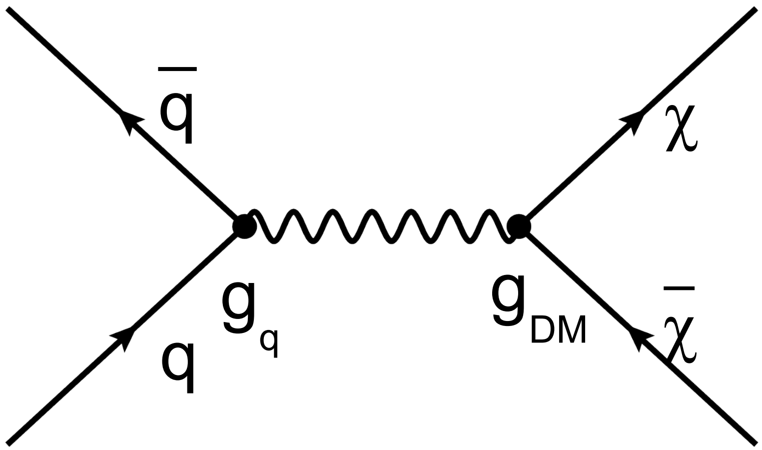
$$\mathcal{L}_{\text{axial-vector}} = g_{\text{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi .$$

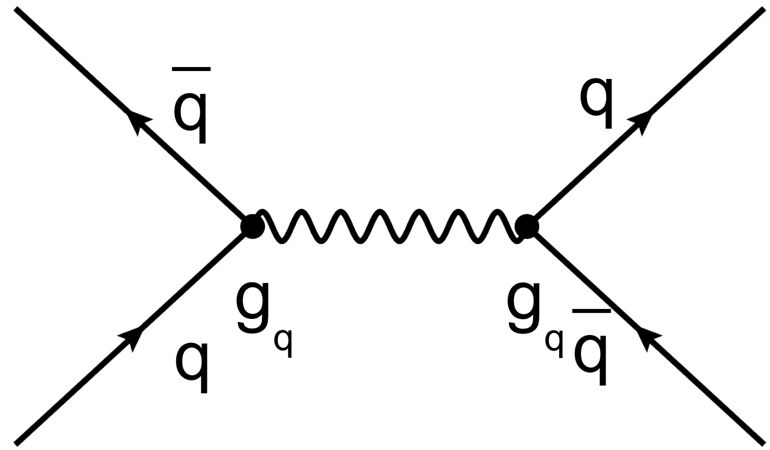
$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}} \phi \bar{\chi} \chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q \, ,$$

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

- 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: $g_{DM} = 1$; $g_q = 1$

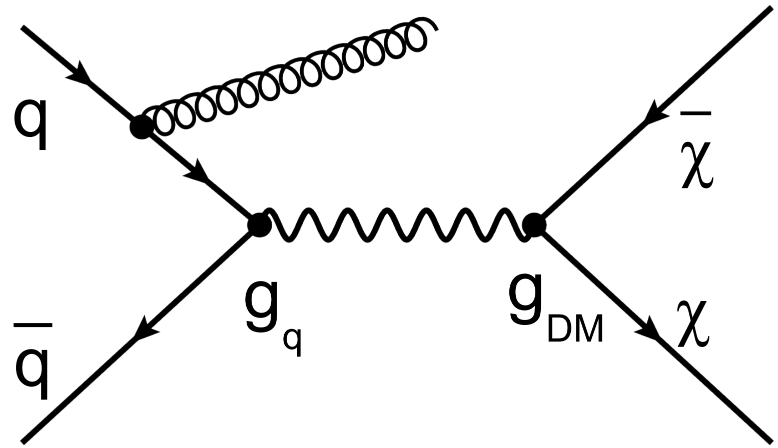
DM at LHC





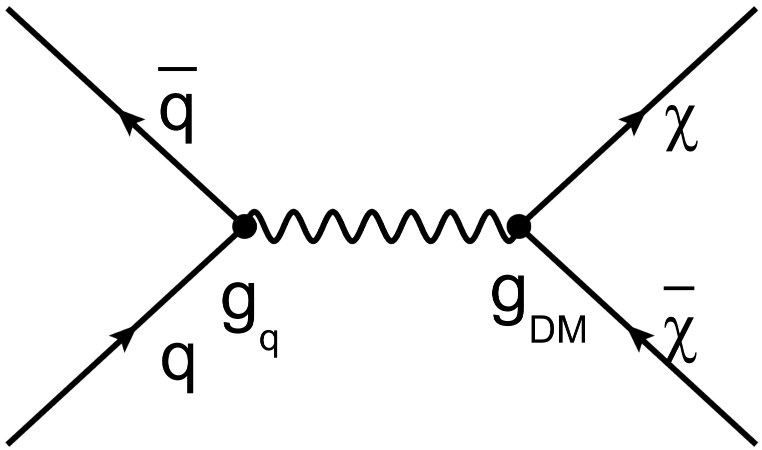
Di-jets

- 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



Mono-jets

DM at LHC



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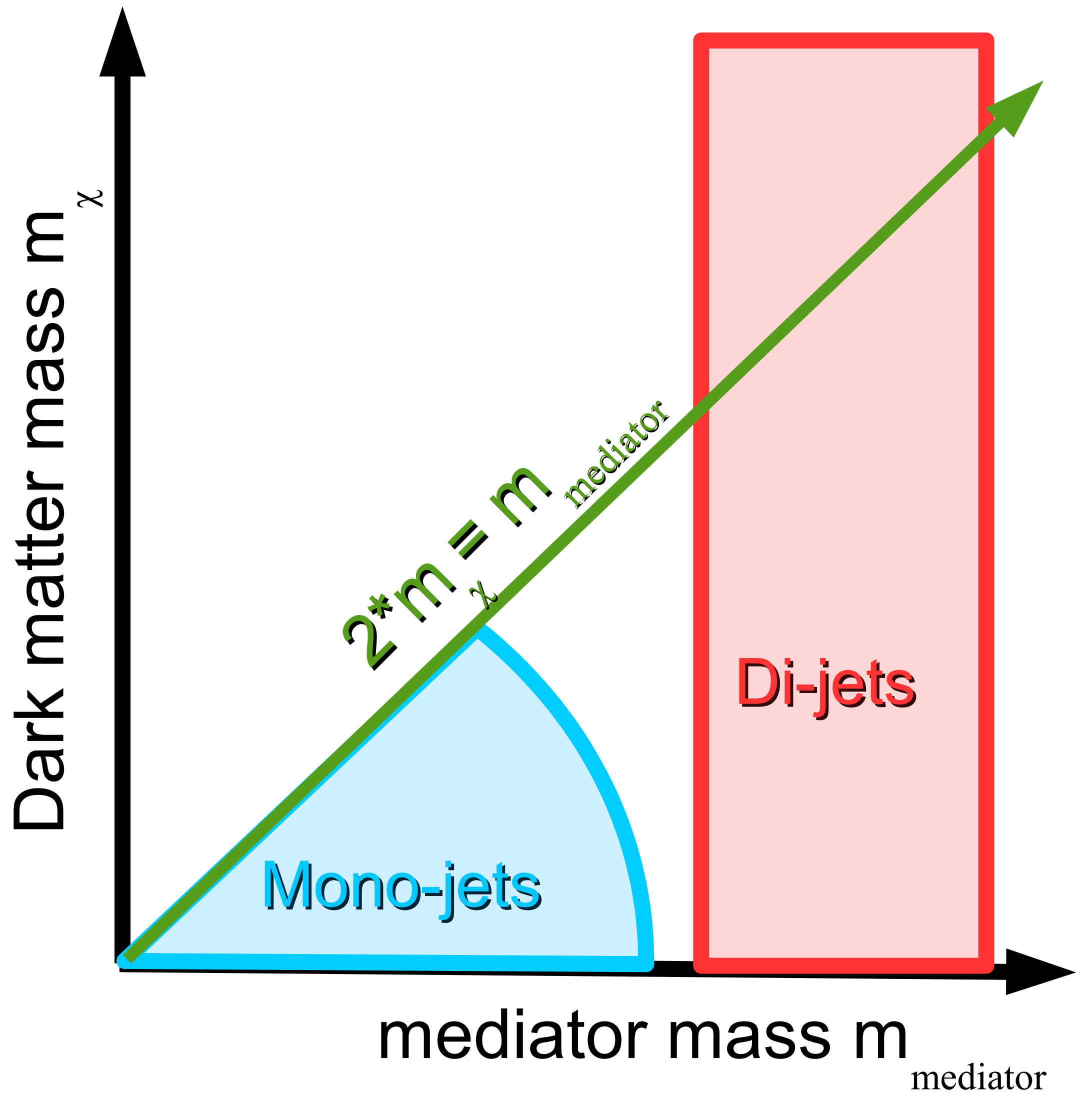
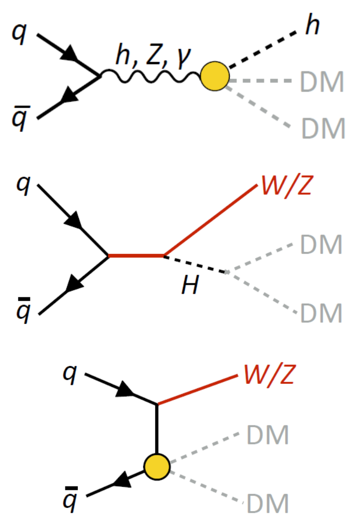
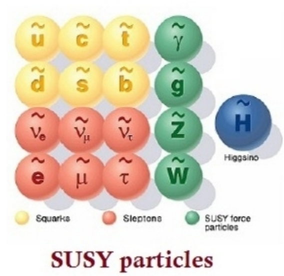


Other DM signals at the LHC

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

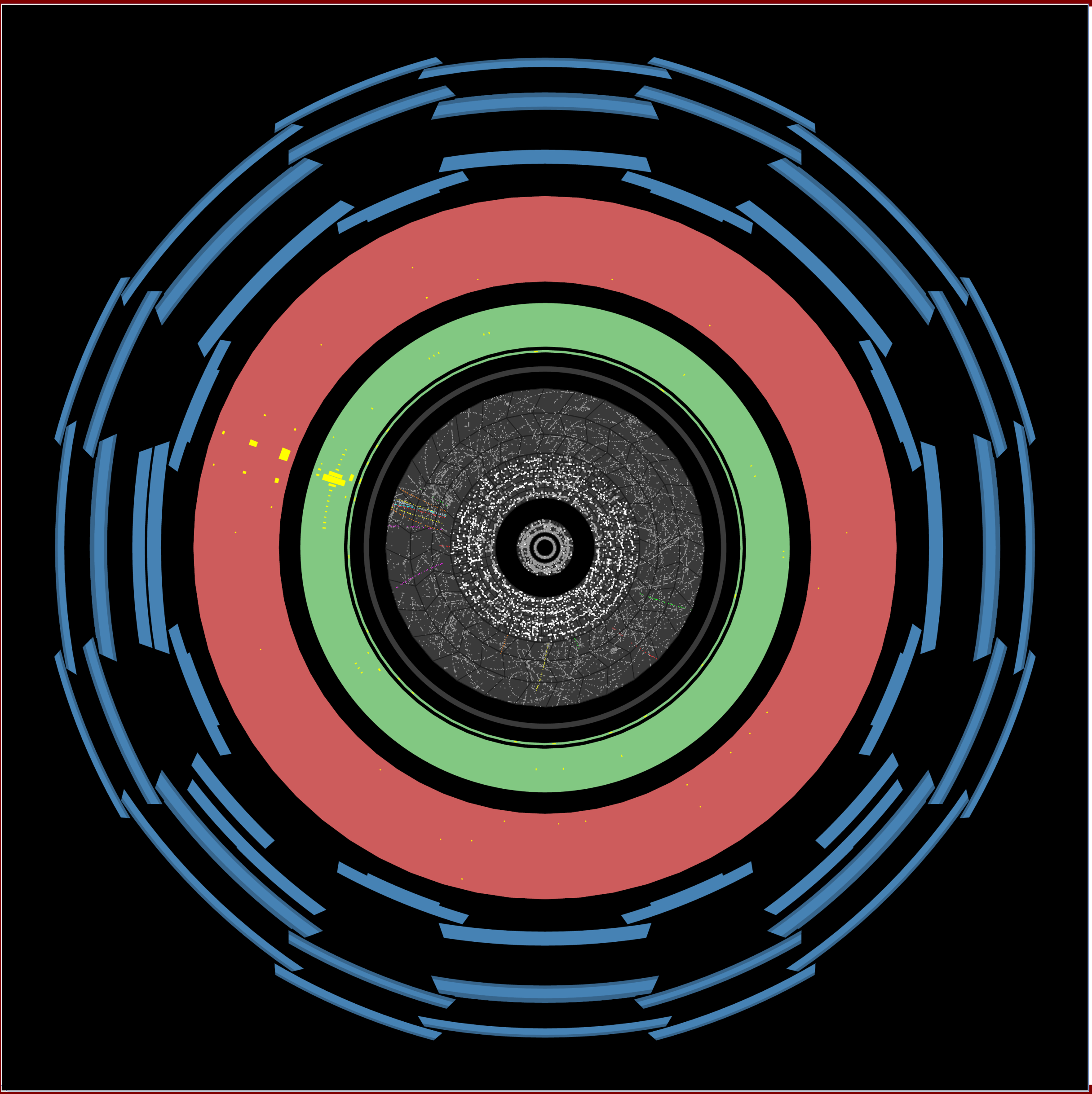


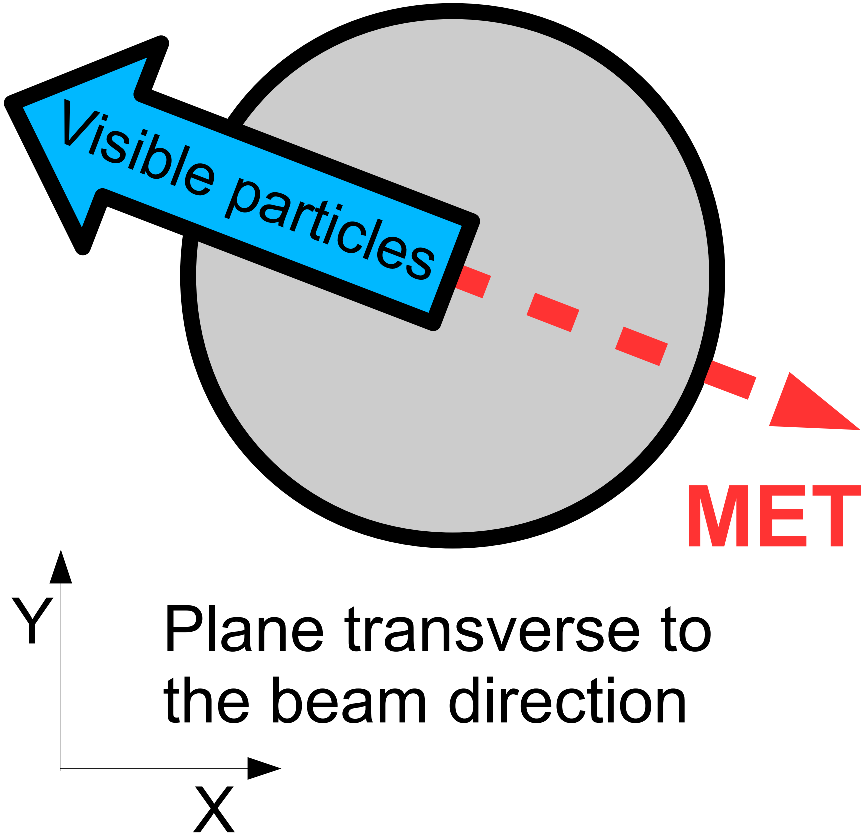
H → jj + MET
Z → jj + MET
W → jj + MET → see Kenji Hamano's talk



SUSY DM candidates → see George Redlingers talk

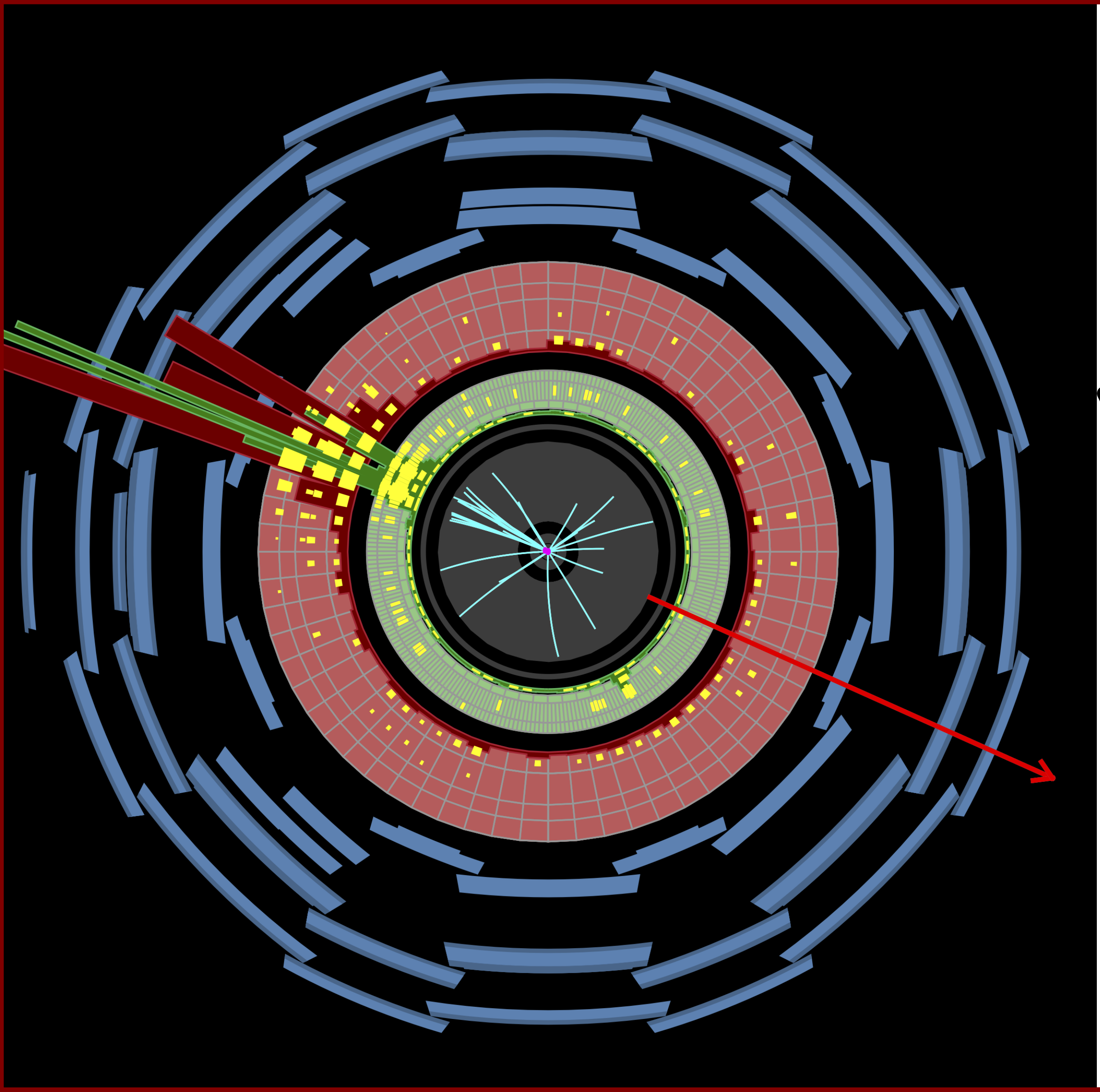
Missing transverse Energy MET

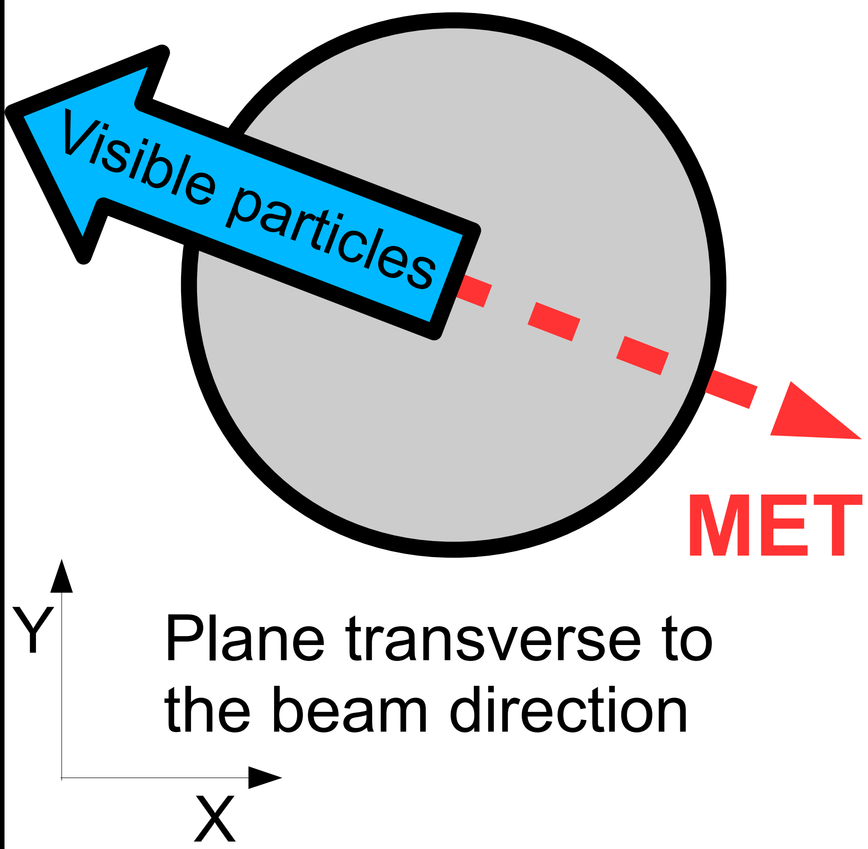




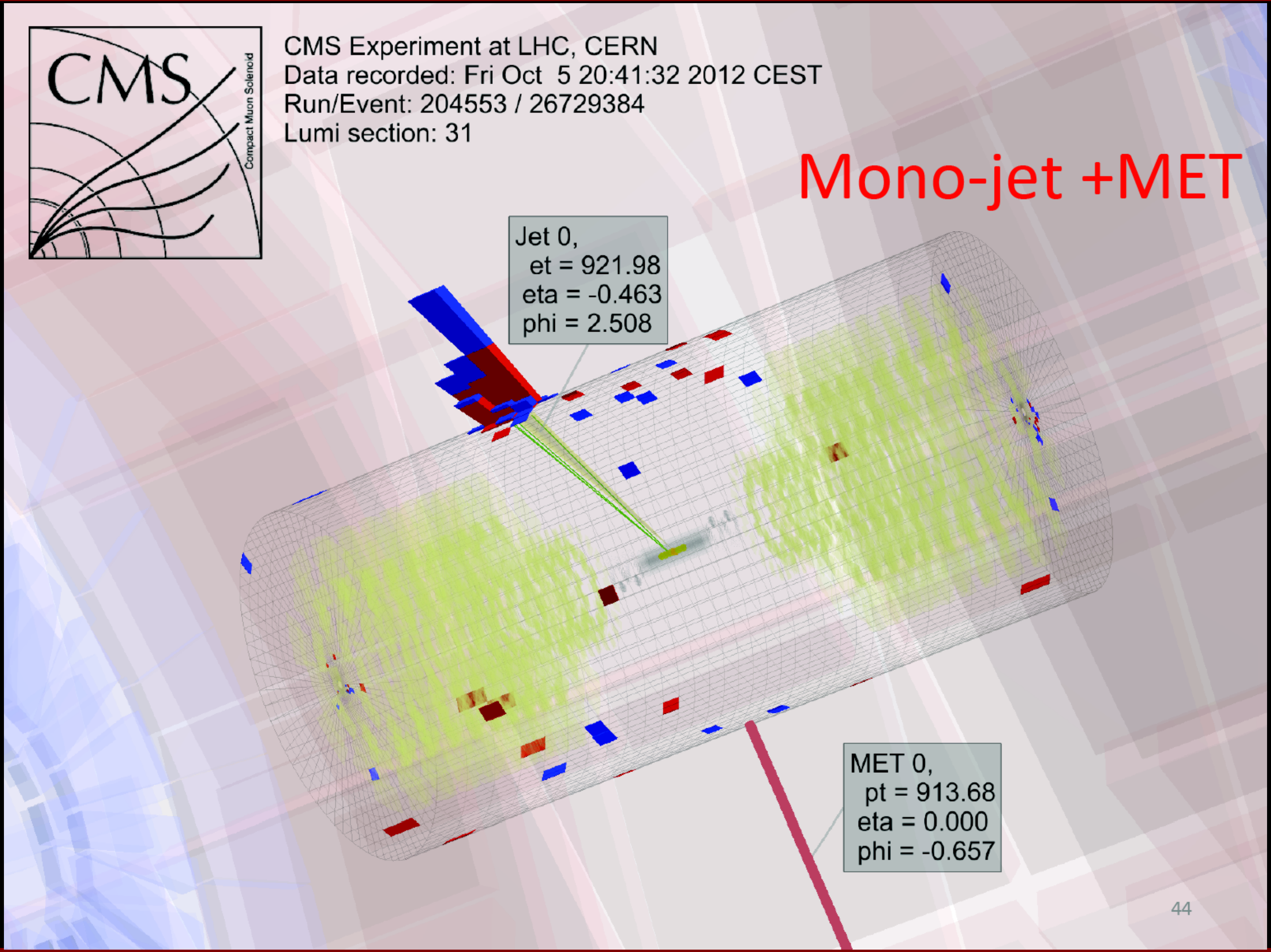
Plane transverse to the beam direction

Missing transverse Energy MET



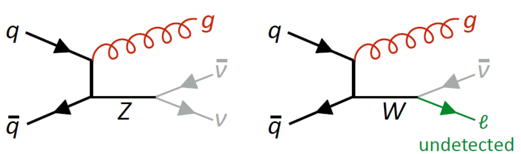


Mono-Jet

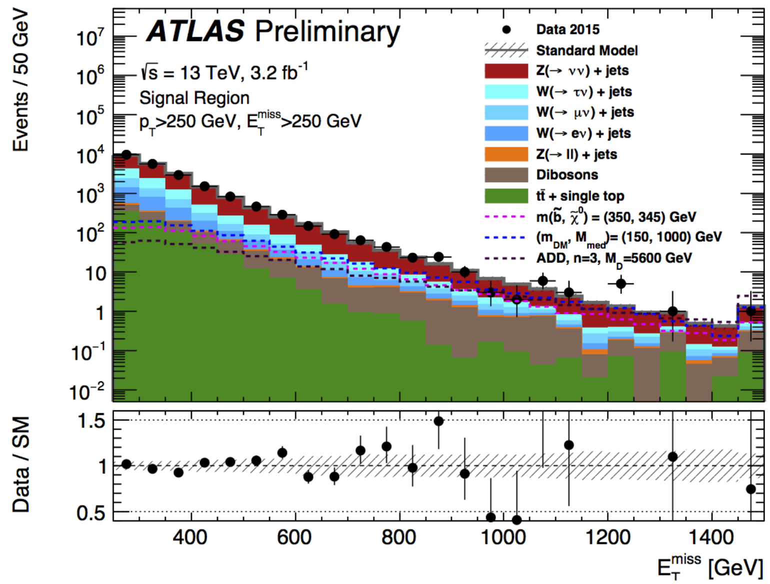

CMS
Compact Muon Solenoid
CMS Experiment at LHC, CERN
Data recorded: Fri Oct 5 20:41:32 2012 CEST
Run/Event: 204553 / 26729384
Lumi section: 31
Mono-jet +MET
Jet 0,
et = 921.98
eta = -0.463
phi = 2.508
MET 0,
pt = 913.68
eta = 0.000
phi = -0.657
44

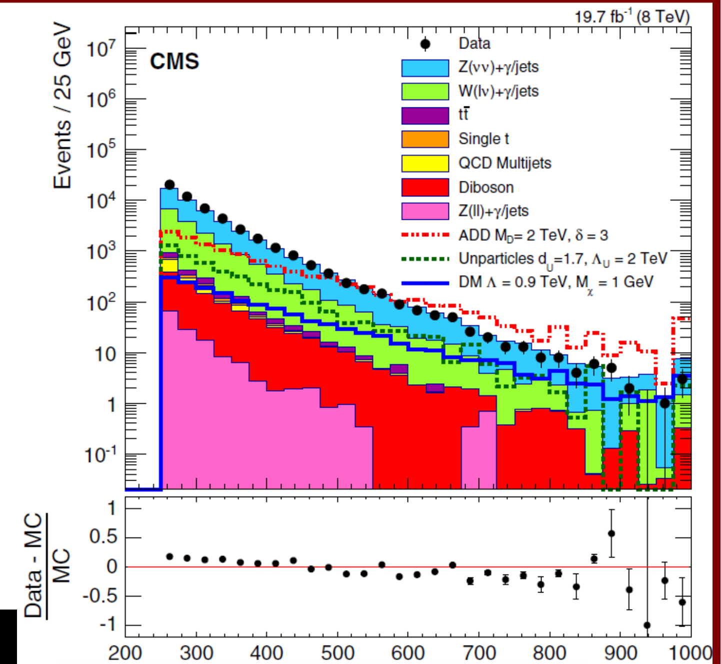
Mono-Jet: Backgrounds

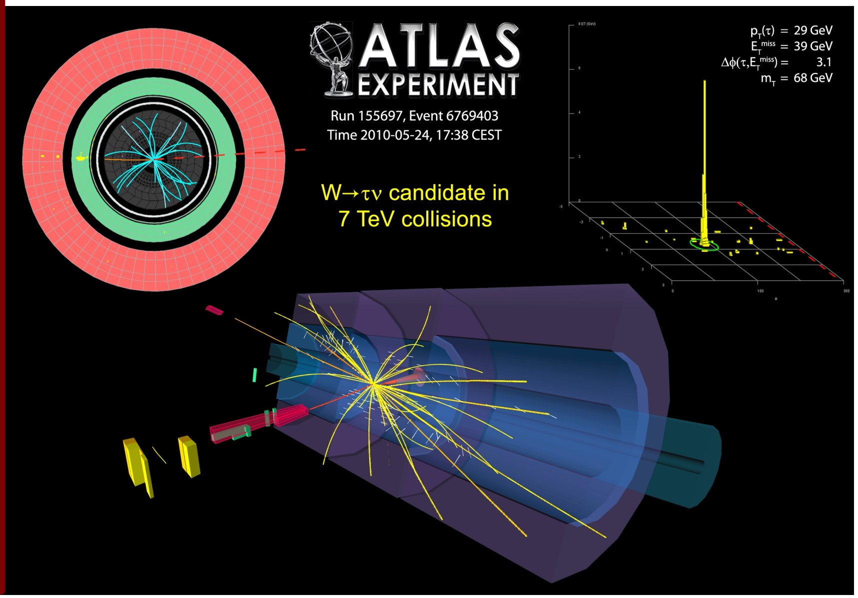
- MET hard to model
- Estimate/measure invisible decays (ν's)

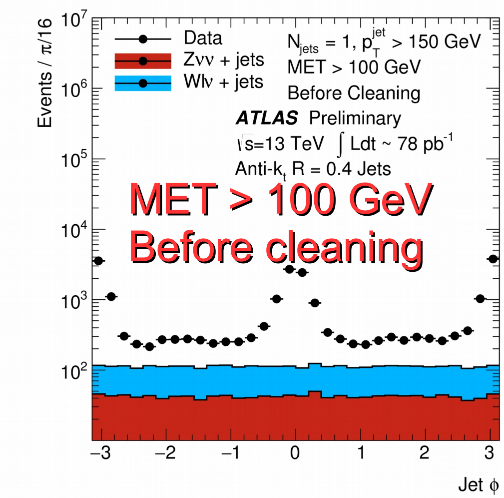


- use Z→ ll & W→ lν to model Z→ νν
- Detector effects & non-collision bkgs are very important too!
- Distributions rather well described

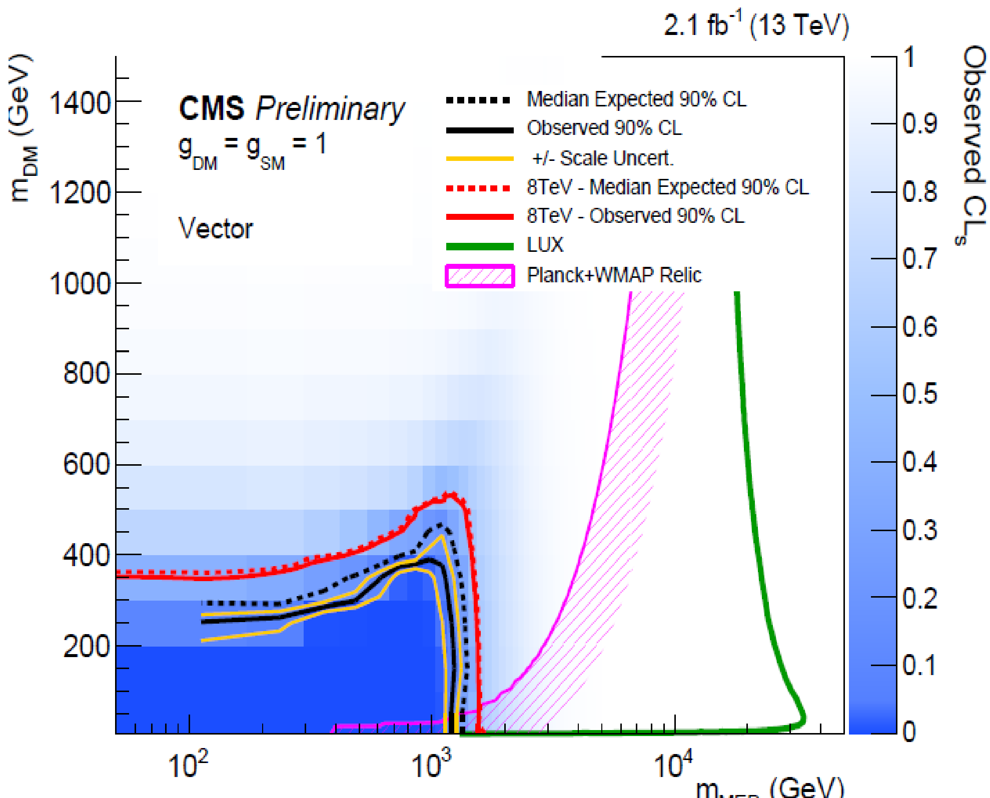


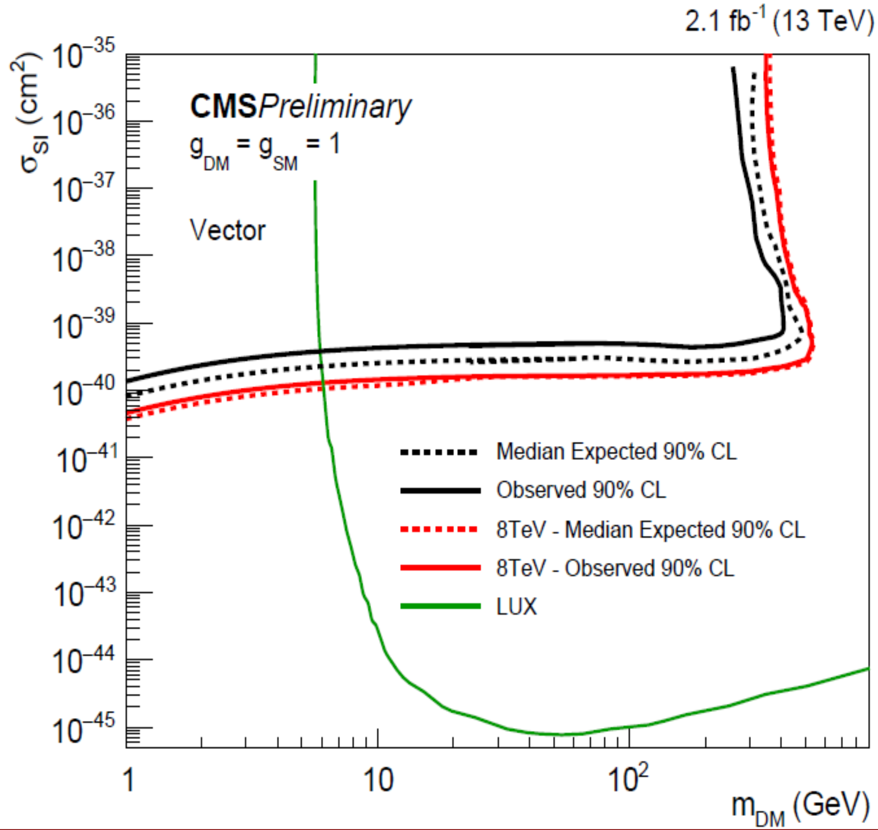






Mono-Jet

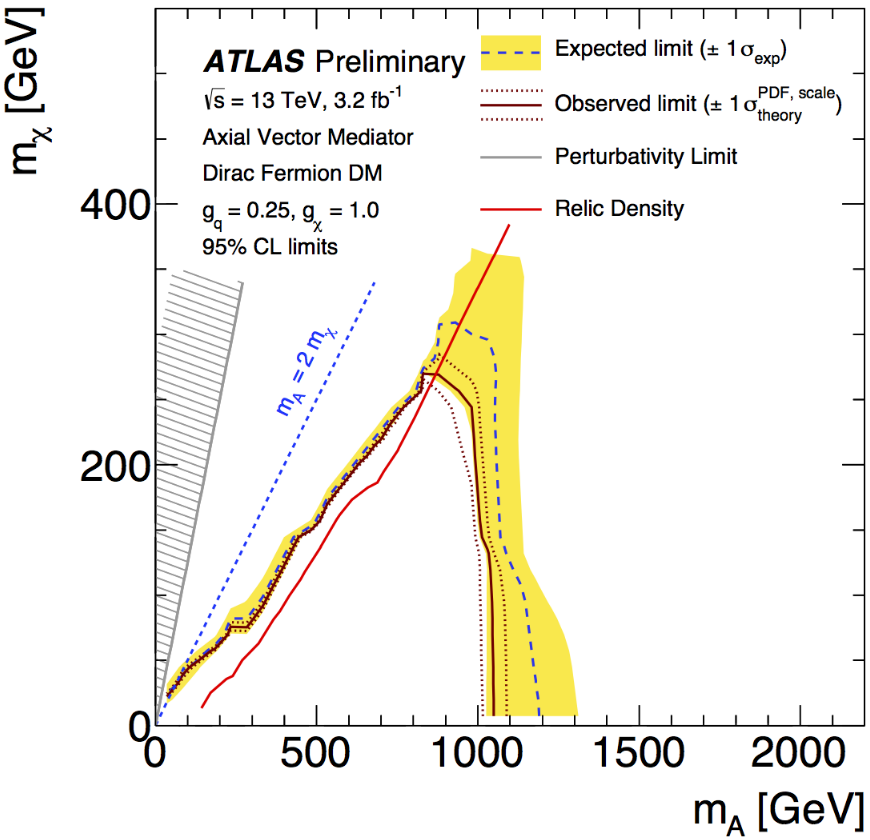


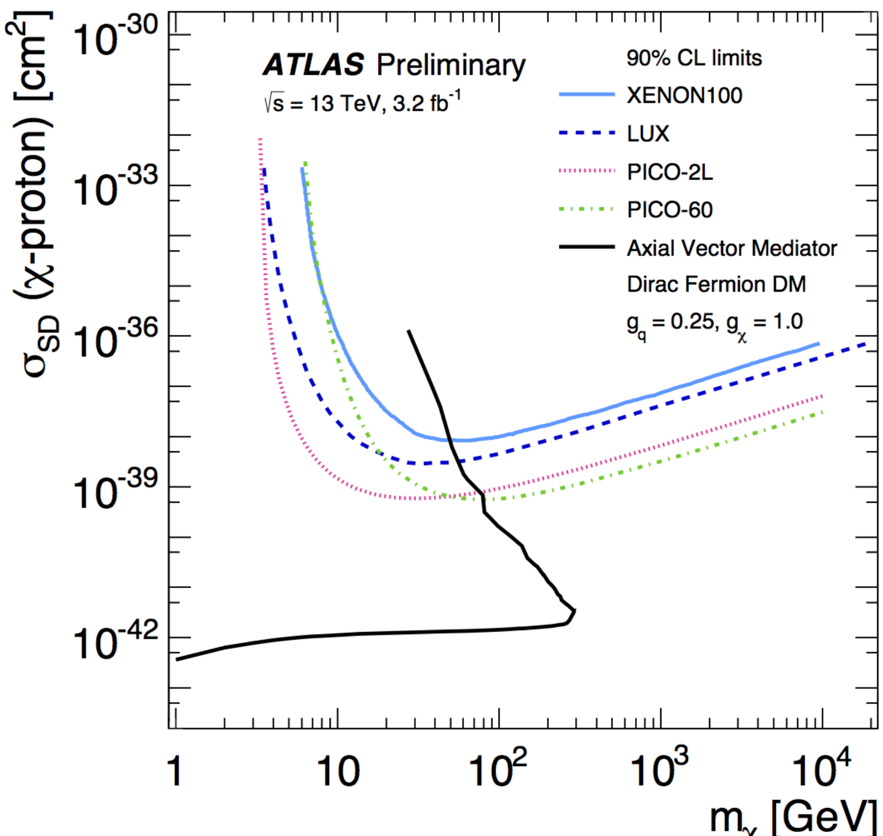


- Vector mediator: $g_{DM} = g_{SM} = 1$
- Selection:
  - Leading jet: $p_T > 100$ GeV; $|\eta| < 2.5$
  - $E_T^{miss} > 200$ GeV, Input Jets: $|\eta| < 5$

CMS PAS EXO-15-003

Mono-Jet



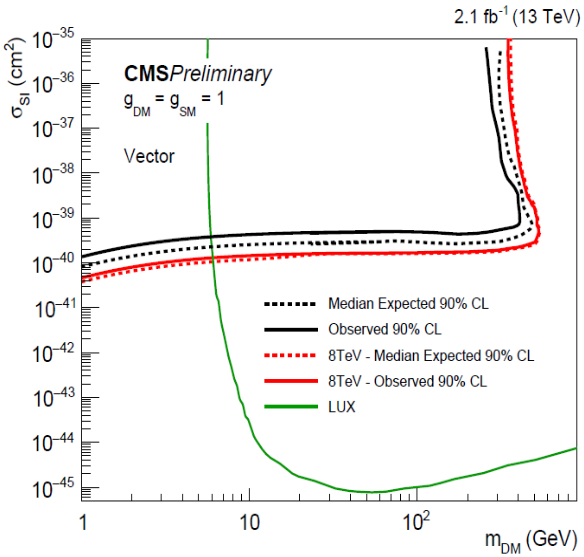


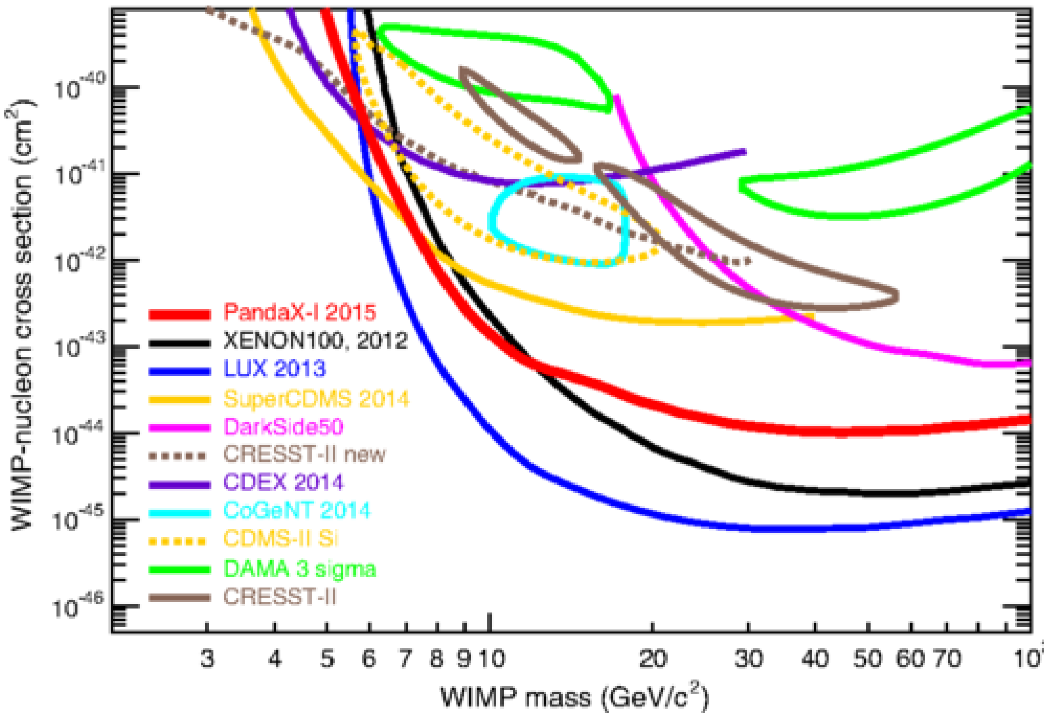
- Axial Vector Mediator: $g_{DM} = 1$ $g_{SM} = 0.25$

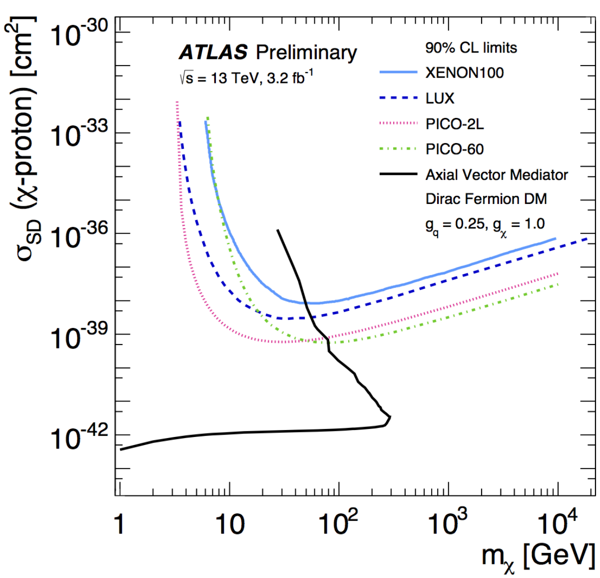
EXOT-2015-03

- 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

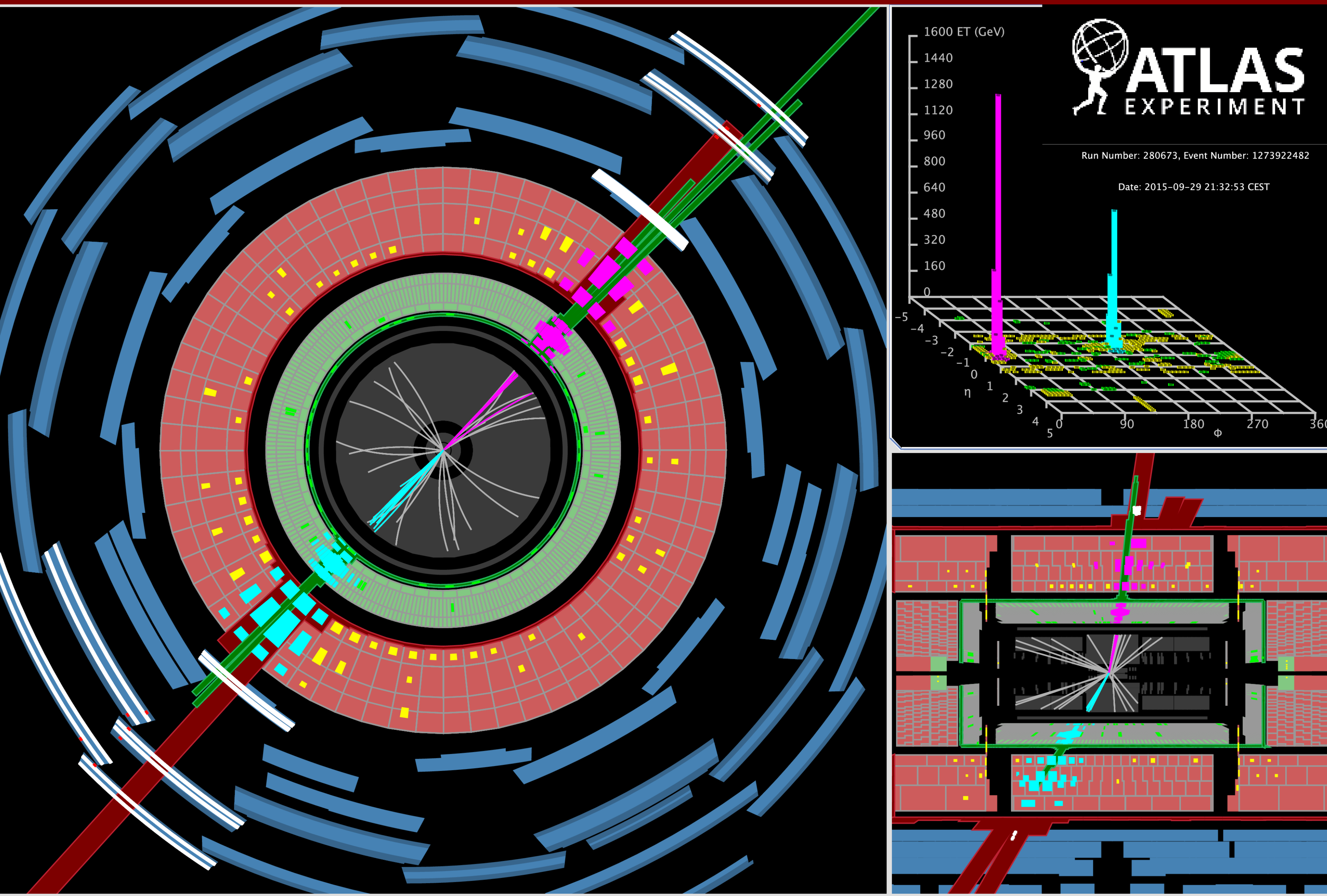






- Translate into DM-nucleon cross sections
- Spin dependent (SD) or independent (SI) according to mediator model used
- Note: Comparisons model dependent!
- LHC experiments provide complementary coverage!

DiJet Events

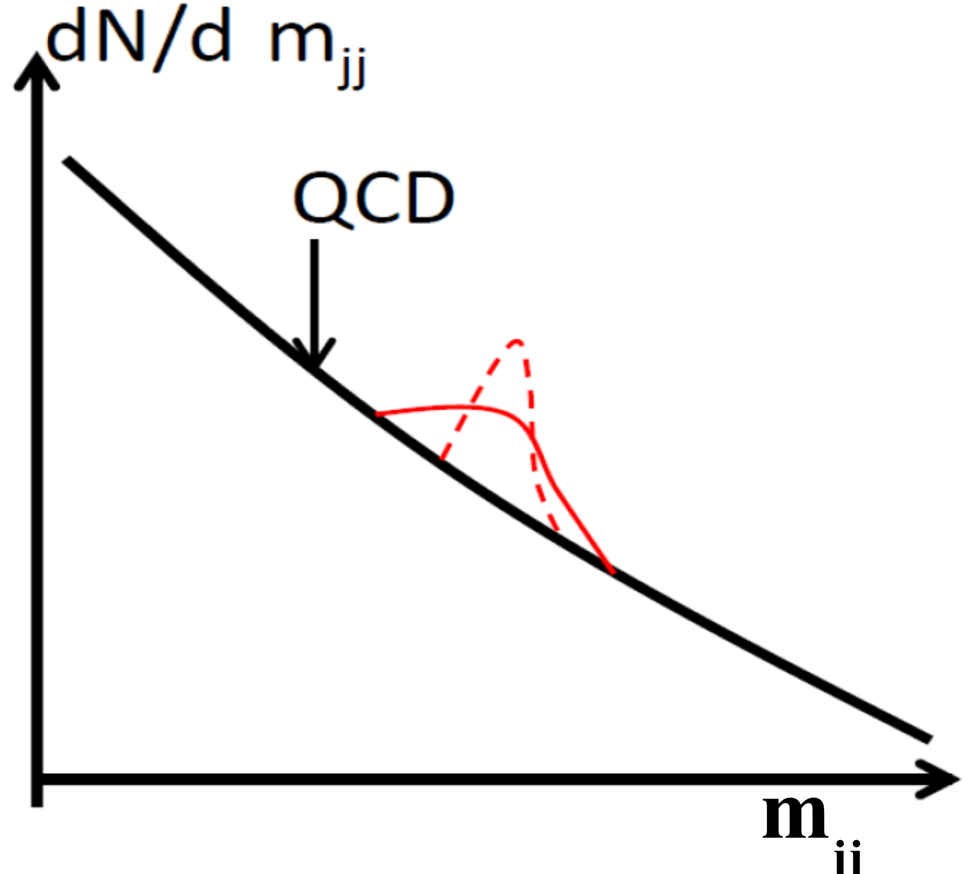


Introduction: Dijet resonances

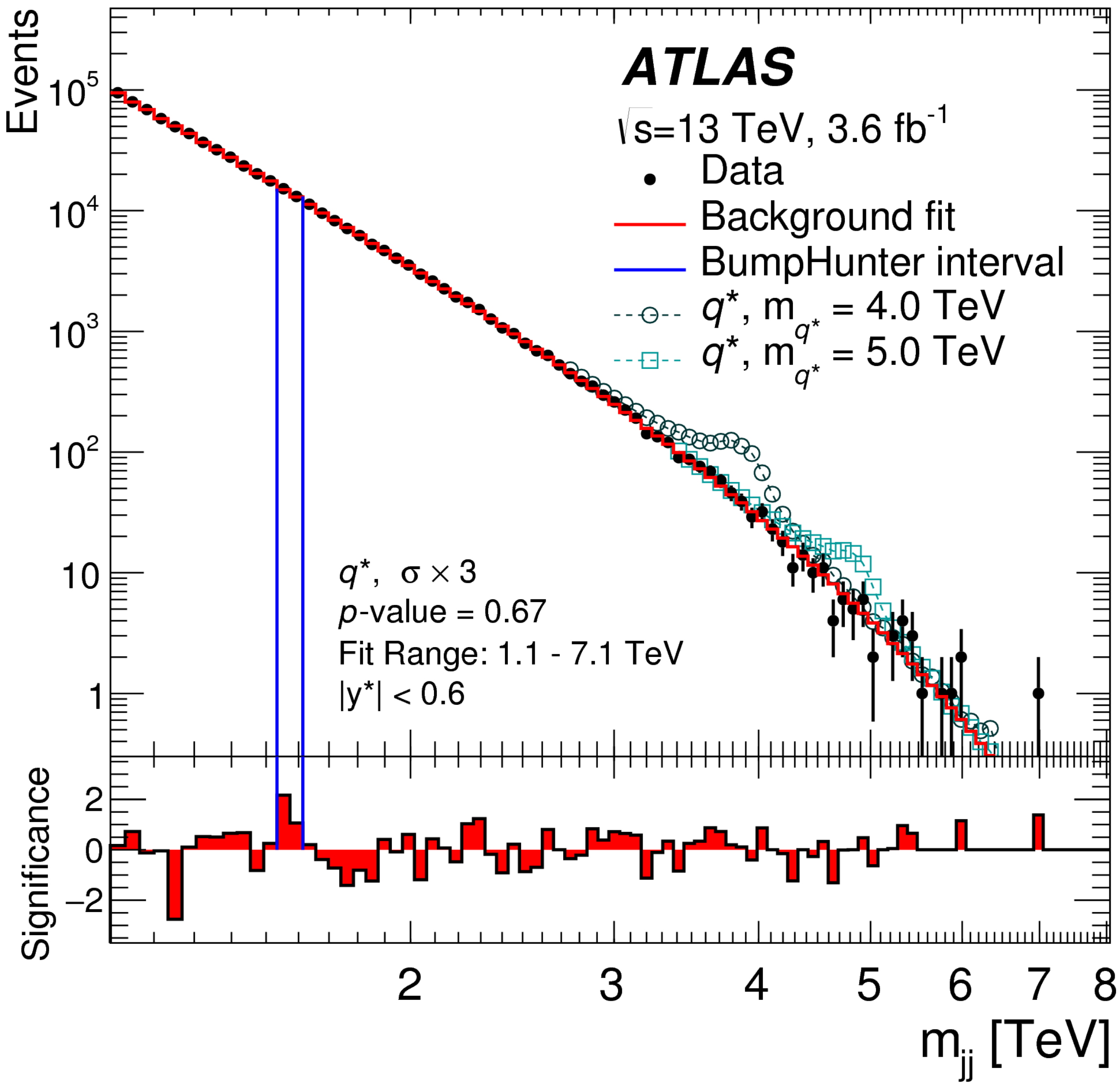
- Look for resonant qq, gq and gg states
- Benchmark search for new physics
- Construct dijet mass
- Fit smooth spectrum

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

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



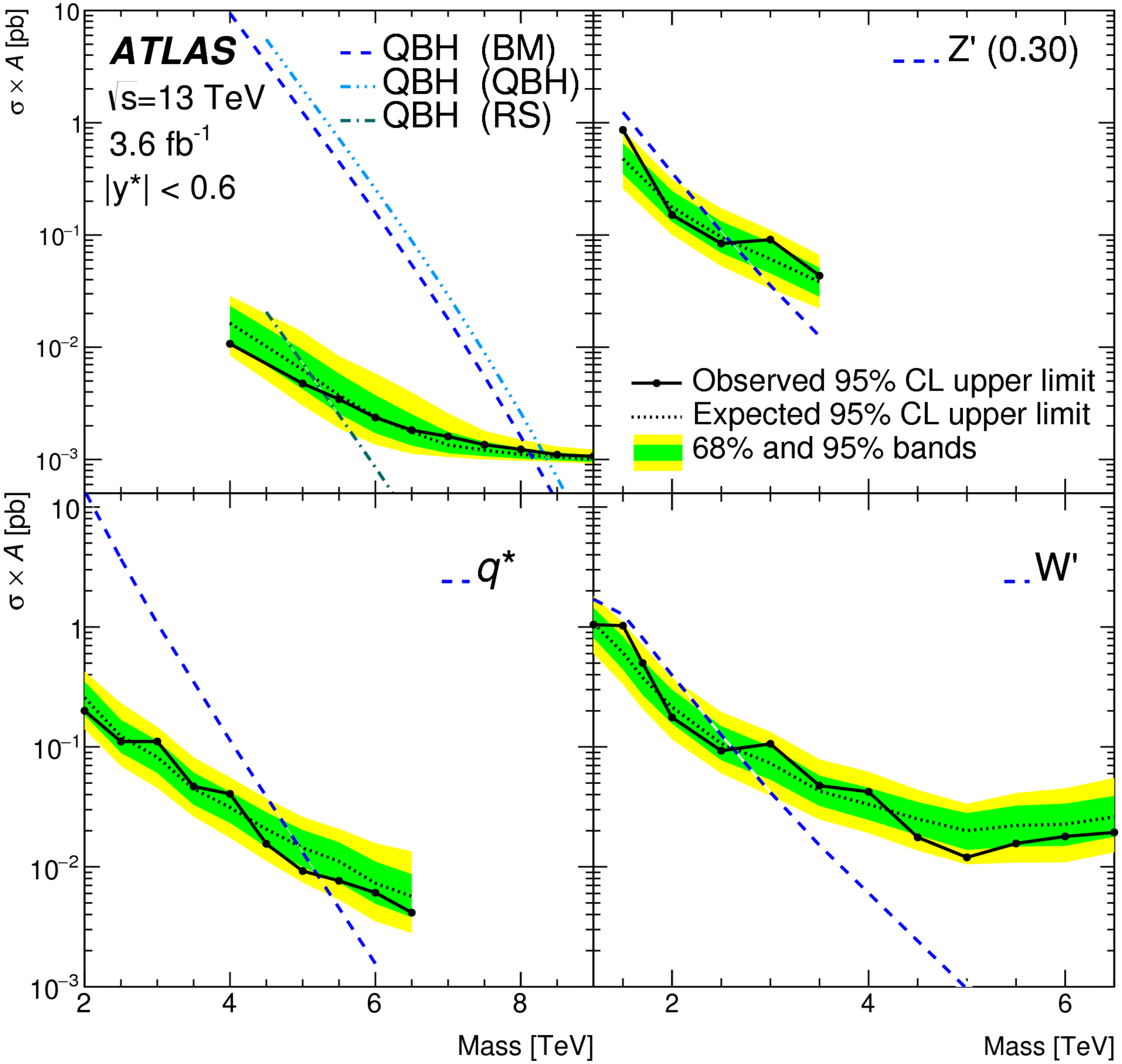
Dijet resonances



- 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

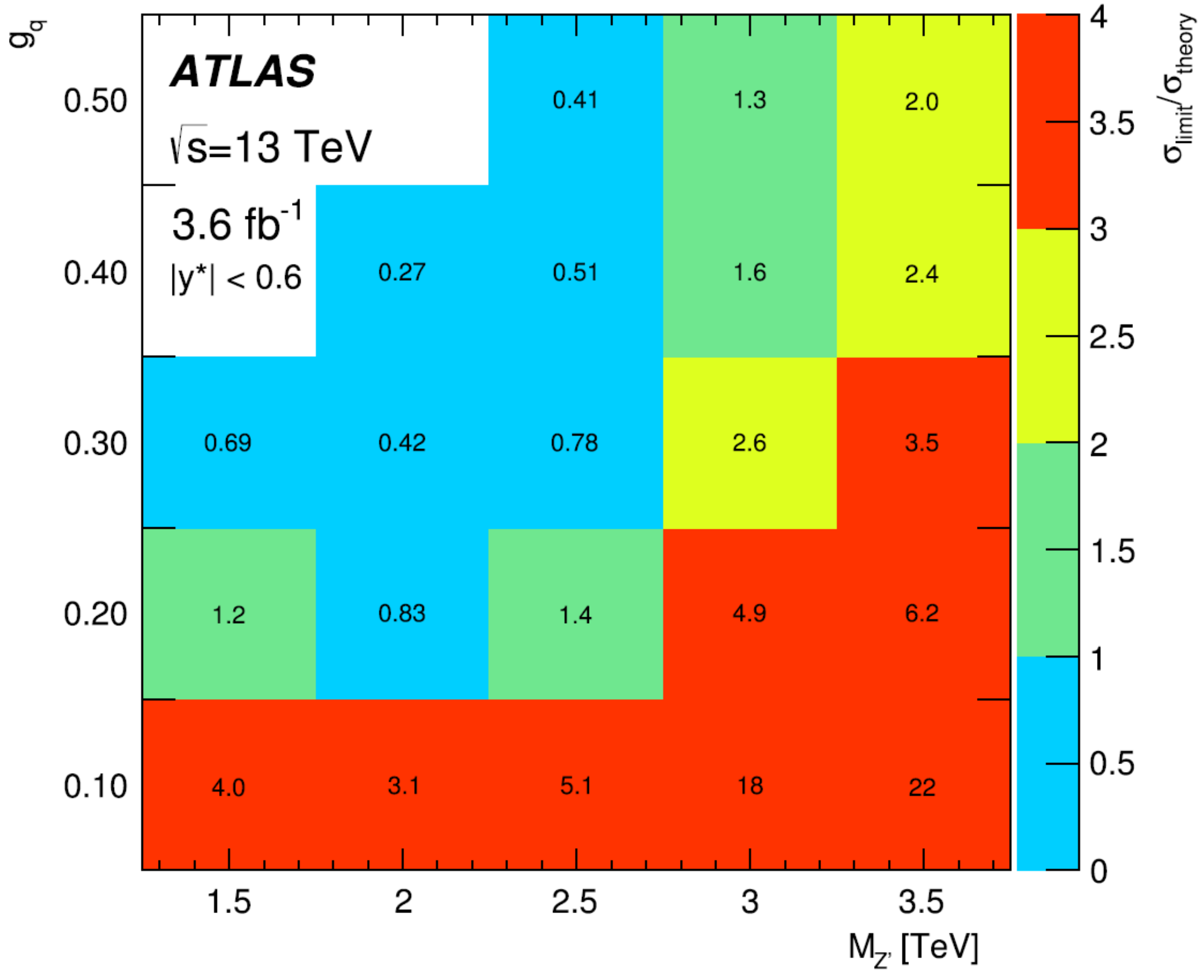
Limits on Dijet resonances



- 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)

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

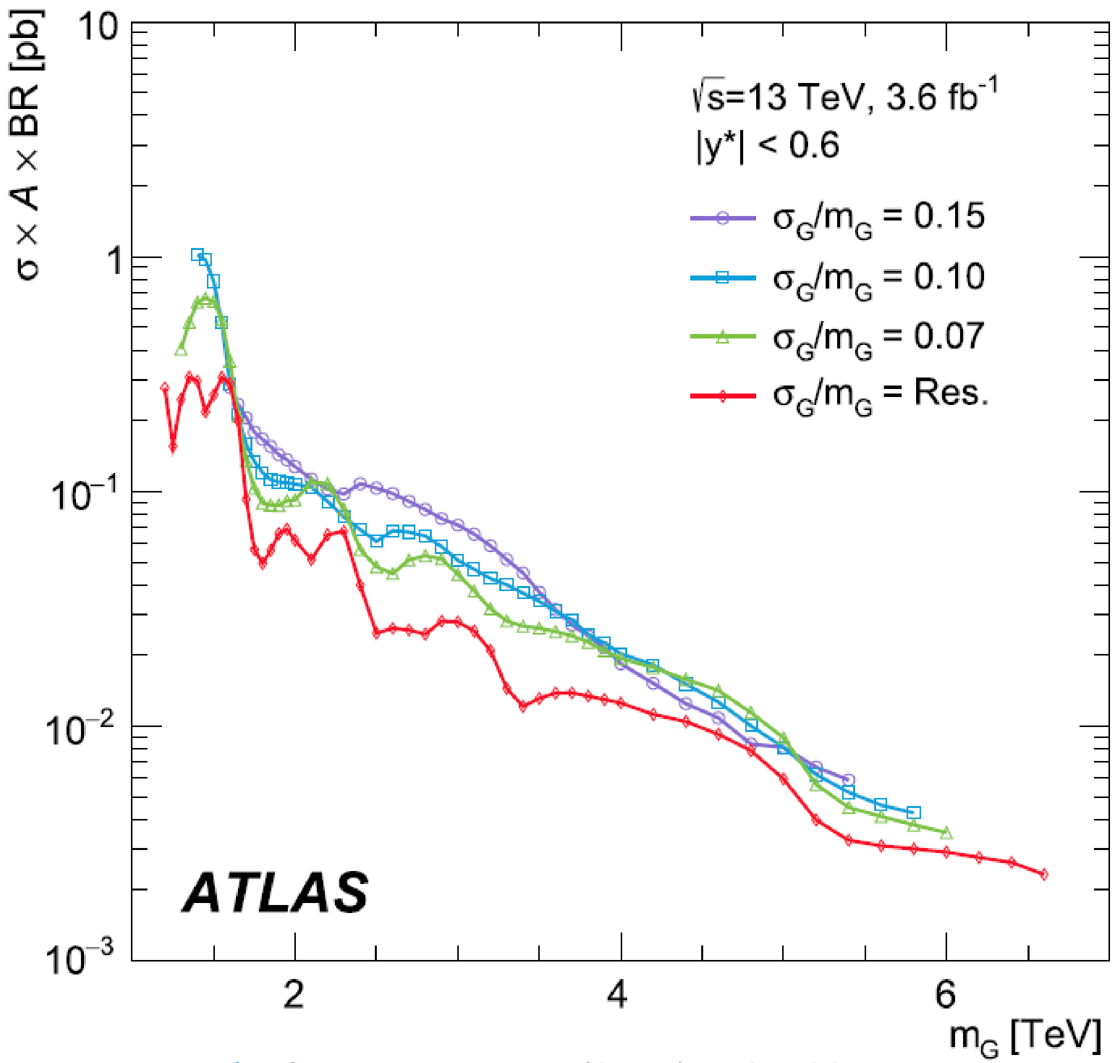
Limits on Dijet resonances



- Limits on benchmark models
  - 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
http://dx.doi.org/10.1016/j.physletb.2016.01.032

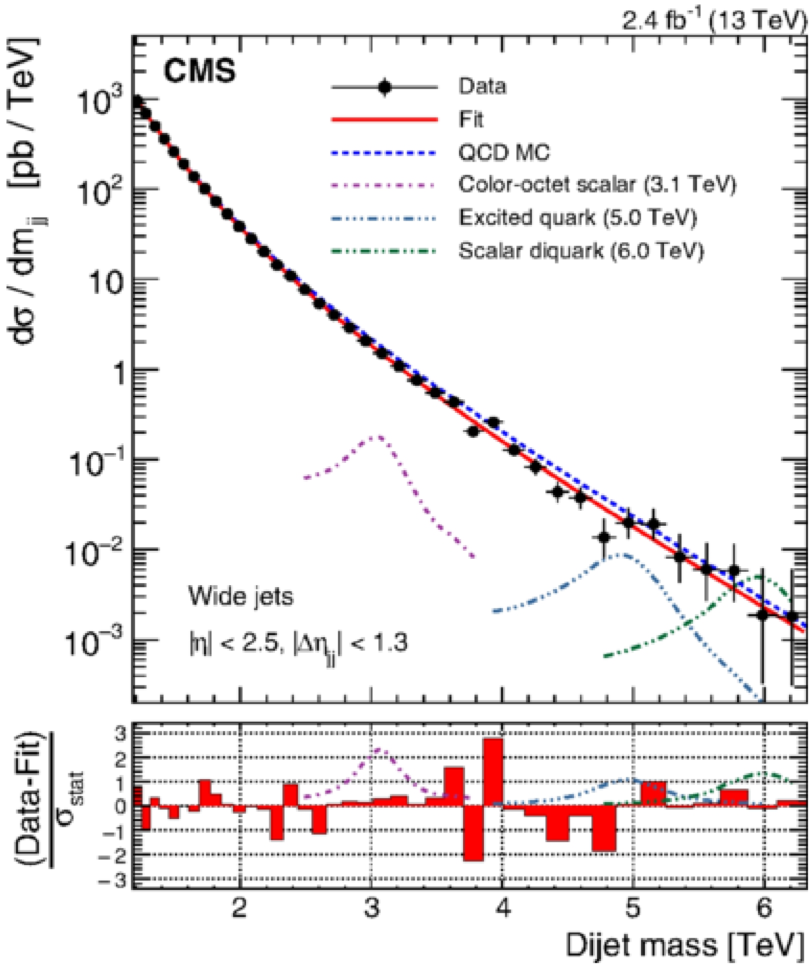
Limits on Dijet resonances

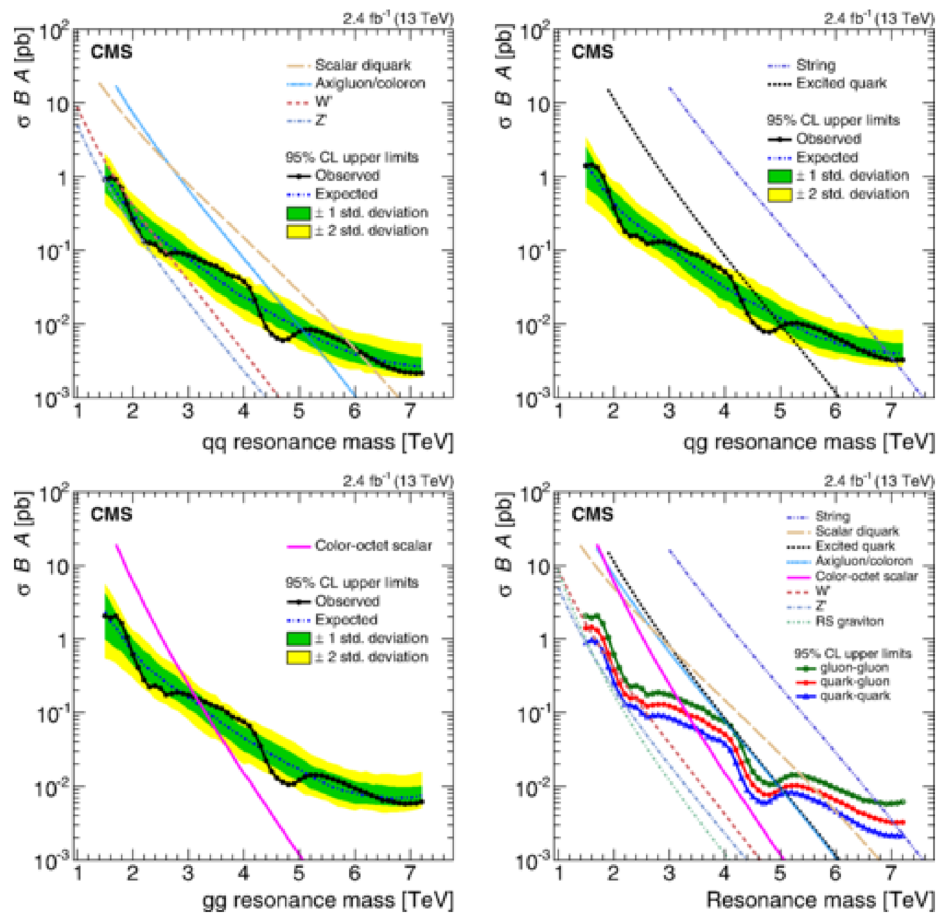


Physics Letters B 754 (2016) 302–322
http://dx.doi.org/10.1016/j.physletb.2016.01.032

- 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



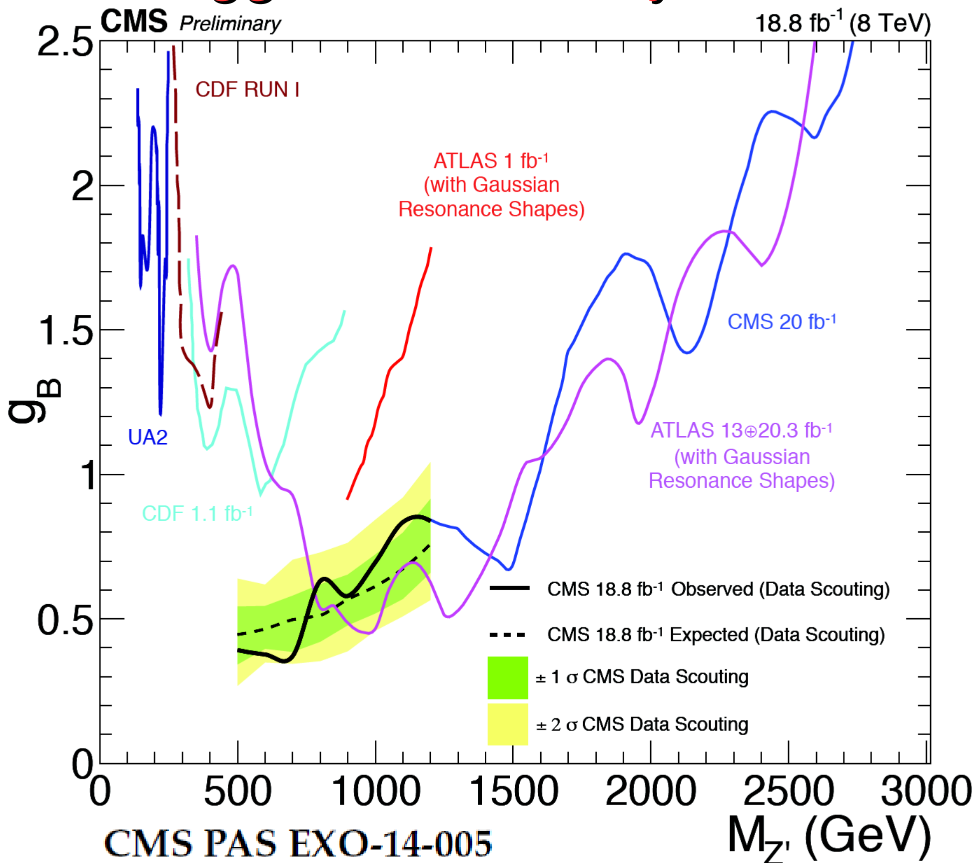


PRL **116,** 071801 (2016)
DOI: 10.1103/PhysRevLett.116.071801

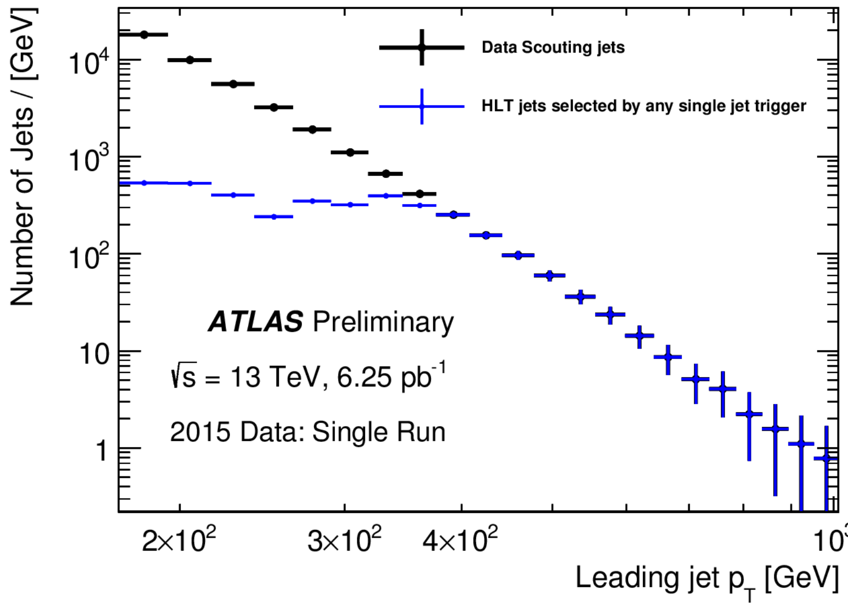
- Excluded masses: String resonance (7.0 TeV) , scalar di-quark (6.0 TeV), axigluon (5.1 TeV), excited quark q* (5.0 TeV), Heavy W' (2.6 TeV)

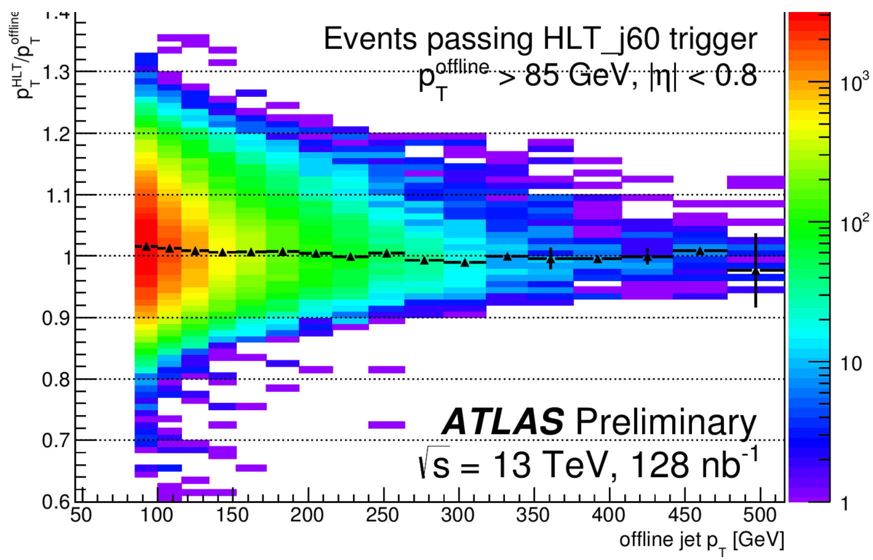
Dijet Events at low mass

- At low mass → low jet pT threshold
- Data rate to high to write out
  → Online data scouting
  Trigger Level Analysis

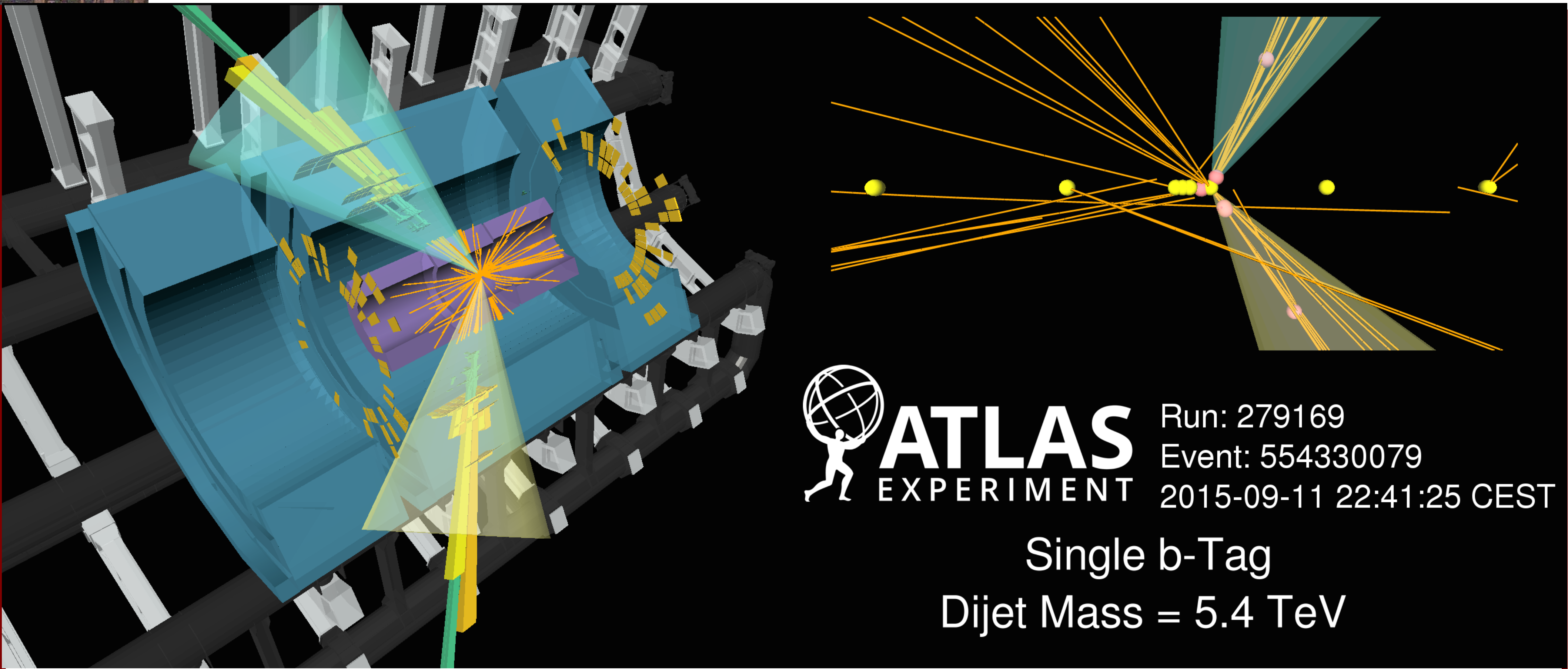


CMS PAS EXO-14-005



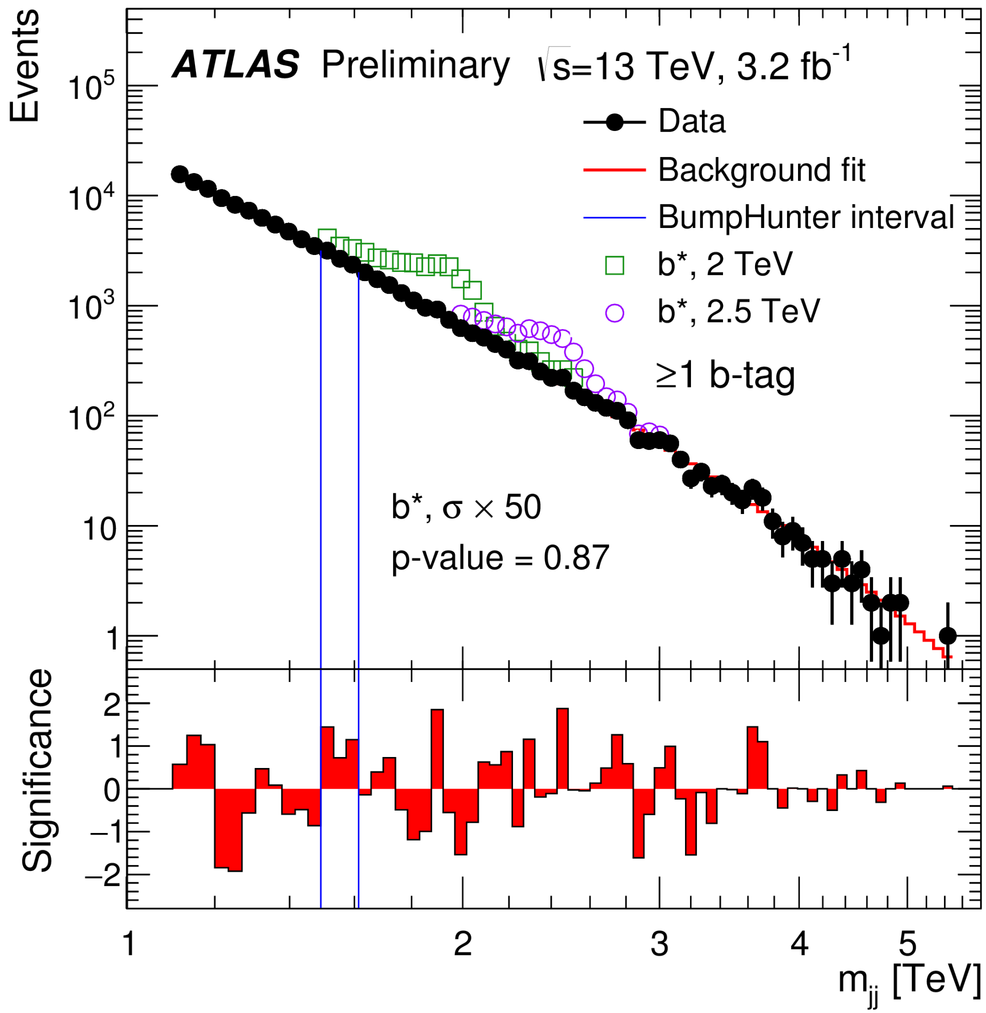


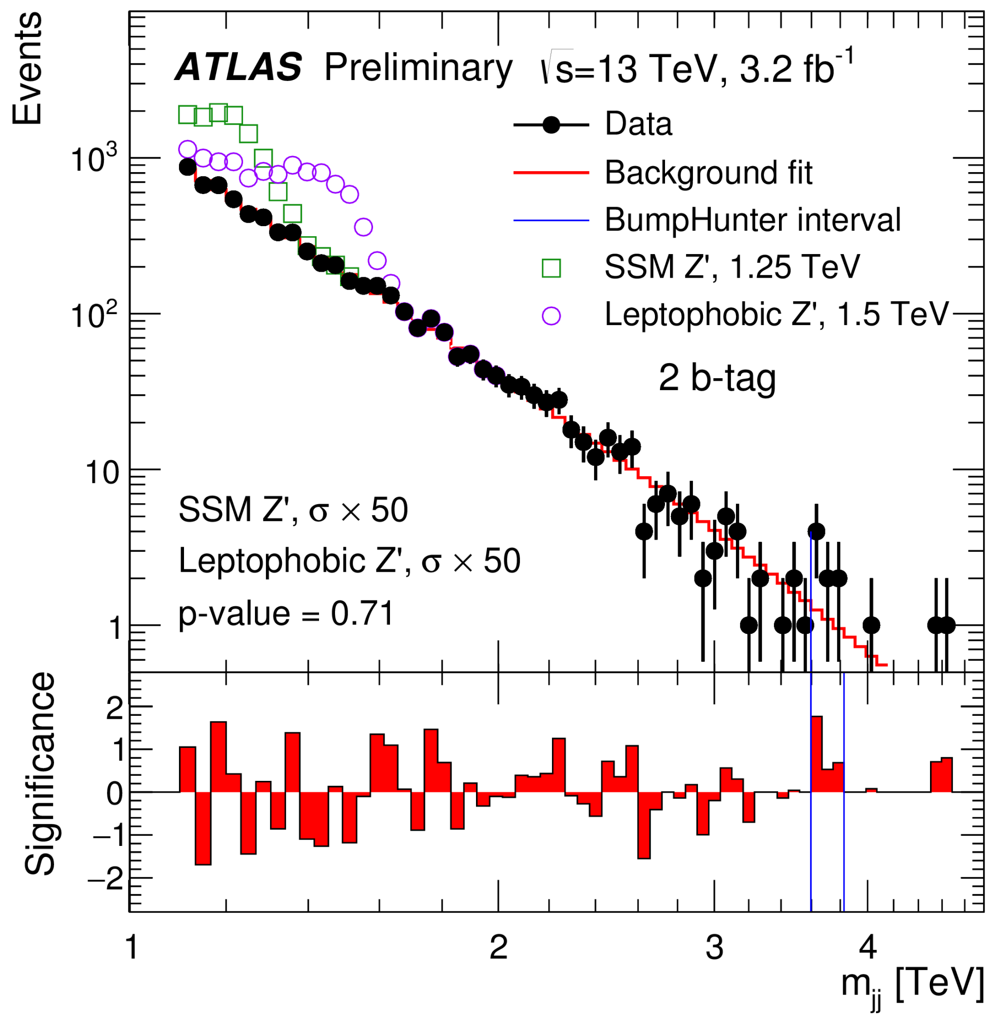
Di-beauty-Jets



- 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

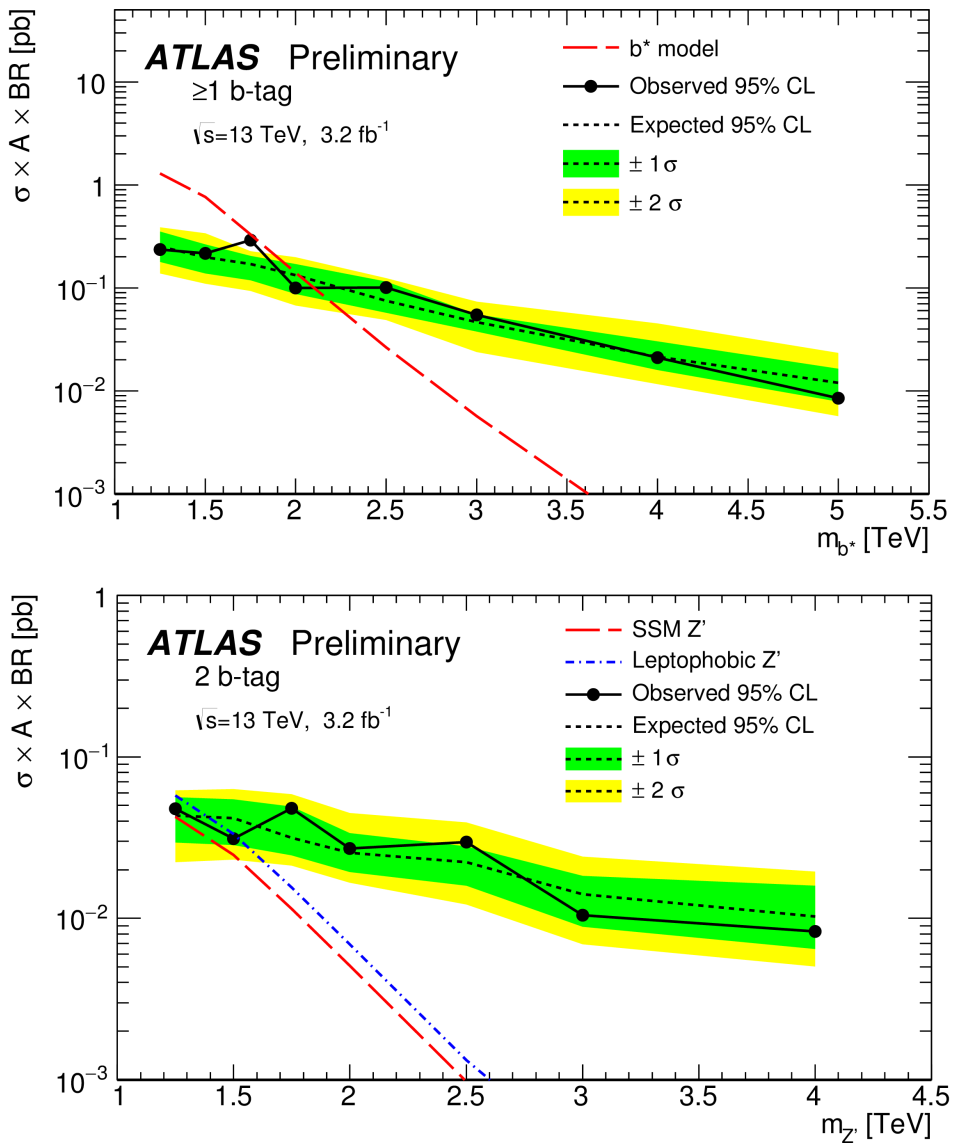




- Same selection as dijets (p_T > 440 GeV, $|y^*| = ½ |y_1-y_2|<0.6$)
- Limit $|\eta|$ < 2.5, to tracking coverage for b-tagging

arXiv:1603.08791v1 [hep-ex]

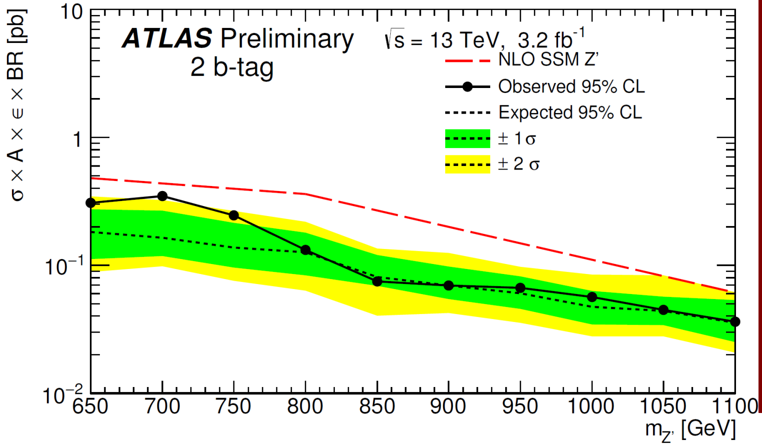
Di-beauty-Jets



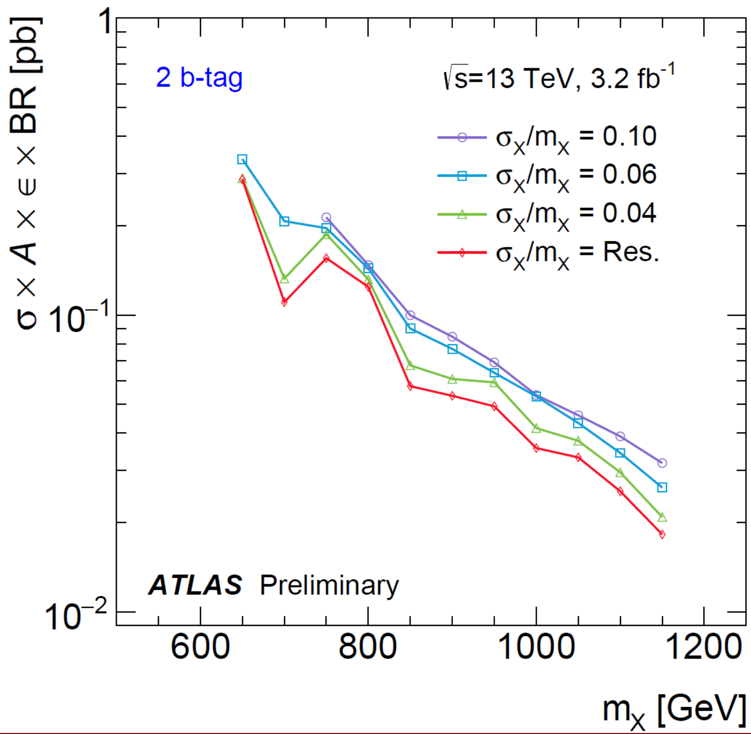
- Limits on benchmark models
- Excited quarks b* → bg
  - >= 1 b-tag
  - Excluded masses 1.1-2.1 TeV
- Extra Gauge Bosons Z'
  - 2 b-tag
  - Leptophobic Z'
  - Excluded masses 1.1-1.5 TeV
  - Sequential Standard Model (SSM) → SM couplings
  - Not enough data to exclude Sequential SM Z'

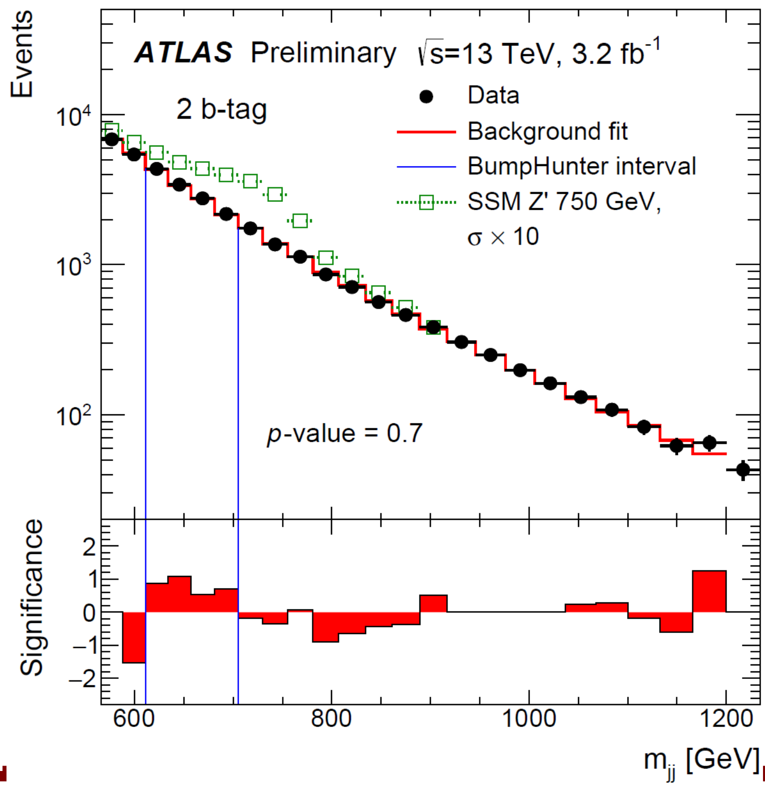
arXiv:1603.08791v1 [hep-ex]

Di-b-Jets: what about 750 GeV ?



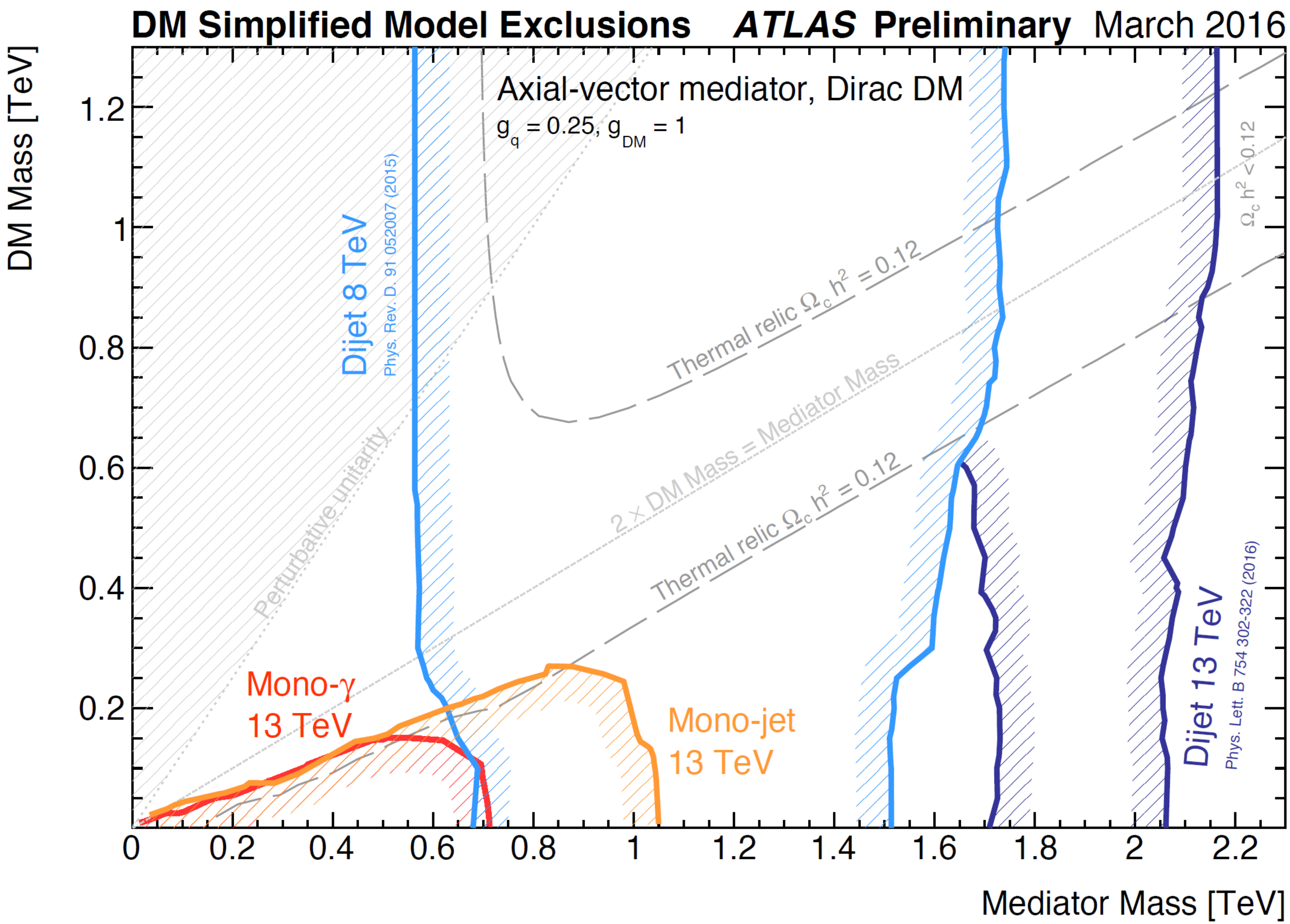
- Needs different trigger strategy
- Di-b-jet trigger p_T >175 GeV & p_T > 60 GeV
- Limits on benchmark model Extra Gauge Bosons Z'
  - Sequential Standard Model (SSM) → SM couplings
- Exclude 0.3-0.02 pb in the mass range 0.65-1.15 TeV





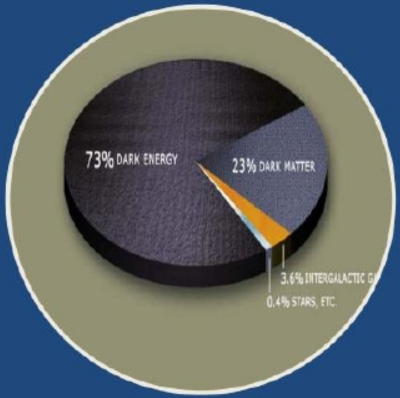
ATLAS-CONF-2016-031

Summary



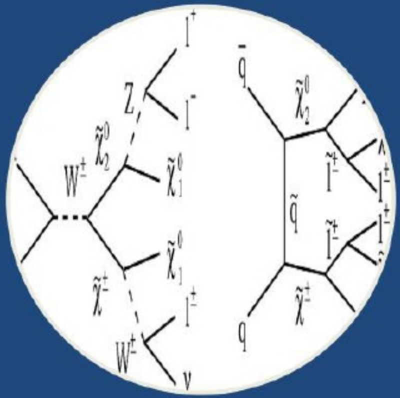
DM Simplified Model Exclusions *ATLAS* Preliminary March 2016
Axial-vector mediator, Dirac DM
$g_q = 0.25, g_{DM} = 1$
Dijet 8 TeV
Phys. Rev. D. 91 052007 (2015)
Perturbative unitarity
Thermal relic $\Omega_c h^2 = 0.12$
2 × DM Mass = Mediator Mass
Thermal relic $\Omega_c h^2 = 0.12$
$\Omega_c h^2 < 0.12$
Mono-γ
13 TeV
Mono-jet
13 TeV
Dijet 13 TeV
Phys. Lett. B 754 302-322 (2016)
DM Mass [TeV]
Mediator Mass [TeV]

Putting it together: Global Fits!



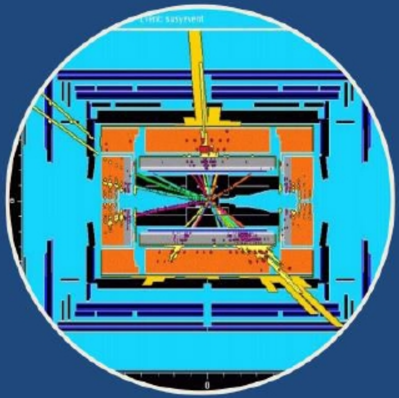
Evidence from Astroparticle physics

- Dark Matter
- Assumptions



Theoretical connections

- Supersymmetry
- Extra Dimensions
- … , ??



Consequences for LHC

- LHC phenomenology
- Model testing

S. Caron

Putting it together: Global Fits!

GAMBIT: a *second-generation* global fit code

GAMBIT: The Global And Modular BSM Inference Tool

Overriding principles of GAMBIT: flexibility and modularity

- General enough to allow fast definition of new datasets and theoretical models
- Plug and play scanning, physics and likelihood packages
- Extensive model database – not just small modifications to constrained MSSM (NUHM, etc), and not just SUSY!
- Extensive observable/data libraries (likelihood modules)
- Many statistical options – Bayesian/frequentist, likelihood definitions, scanning algorithms
- A smart and *fast* LHC likelihood calculator
- Massively parallel
- Full open-source code release

Pat Scott

The Future of Simplified Models

Tables, tables, tables

Joachim Kopp

ID	X	$\alpha+\beta$	M_s	Spin	$(SM_1\ SM_2)$	X–DM–SM_3	M_s–X–X
SU1	$(1, N, \alpha)$	0	$(1,1,0)$	B	$(u_R\,\overline{u_R}), (d_R\,\overline{d_R}), (\ell_R\,\overline{\ell_R})$ $(Q_L\,\overline{Q_L}), (L_L\,\overline{L_L}), (H\,H^\dagger)$	H1	✓
SU2				F	$(L_L\,H)$		
SU3			$(1,3,0)^{N\geq 2}$	B	$(Q_L\,\overline{Q_L}), (L_L\,\overline{L_L}), (H\,H^\dagger)$	H1	✓
SU4				F	$(L_L\,H)$		
SU5			[illegible]	B	$(d_R\,\overline{u_R}), (H^\dagger\,H^\dagger), (L_L\,L_L)$		✓
SU12		-3	$(1,2,-3)$	B	$(L_L\,\ell_R)$		
SU13				F	$(\ell_R\,H^\dagger)$		
SU14	$(1, N\pm 2, \alpha)$	0	$(1,3,0)$	B	$(Q_L\,\overline{Q_L}), (L_L\,\overline{L_L}), (H\,H^\dagger)$		✓$(\alpha=0)$
SU15				F	$(L_L\,H)$		
SU16		-2	$(1,3,-2)$	B	$(H^\dagger\,H^\dagger), (L_L\,L_L)$		✓$(\alpha=\pm 1)$
SU17				F	$(L_L\,H^\dagger)$		

Tally

In total 161 simplified models (defined by representations of DM, X and M)

49 *s*-channel, 105 *t*-channel, 7 hybrid

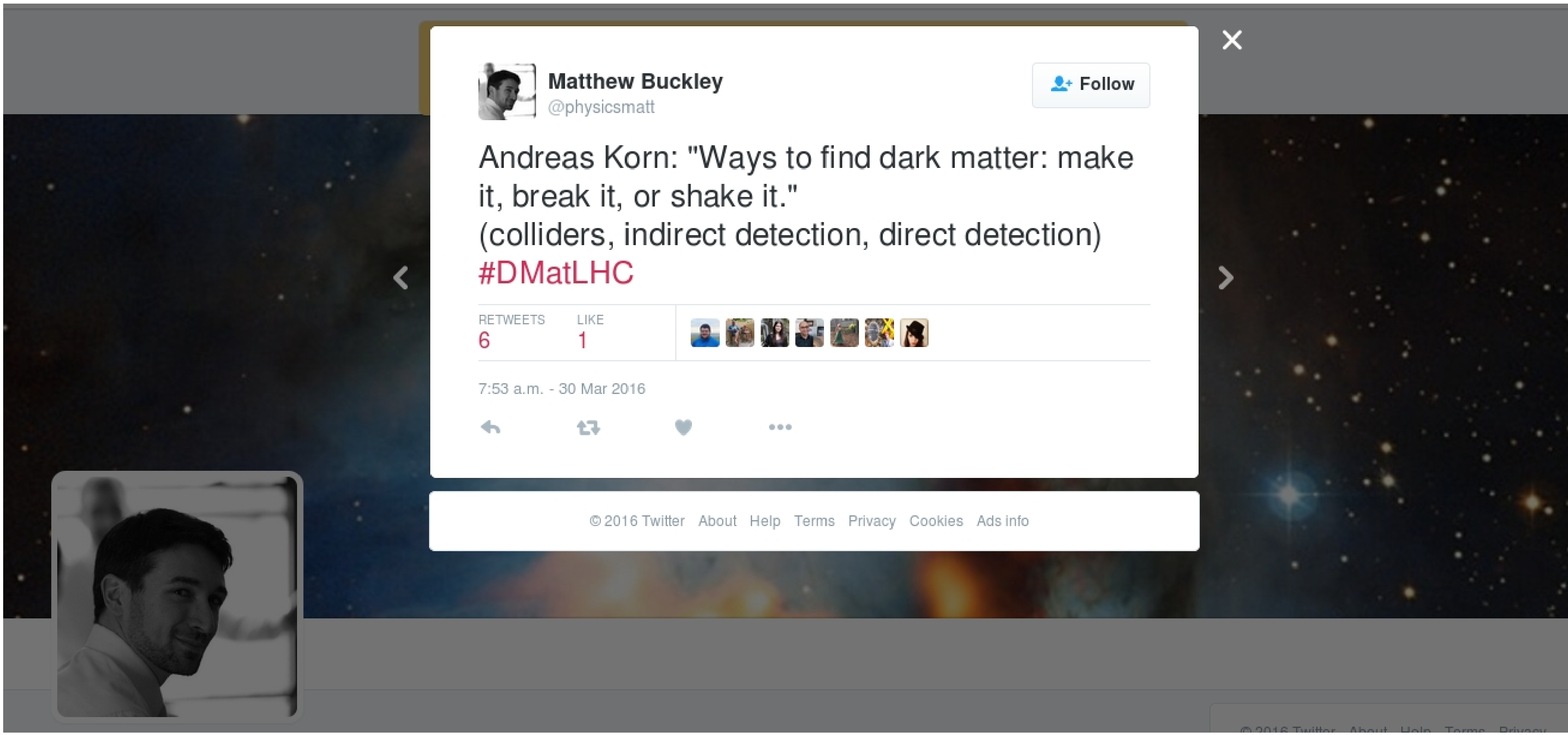
DM	in $(1, N, \beta)$ representation of $SU(3)\times SU(2)\times U(1)$
X	coannihilation partner
M_s	*s*-channel mediator
SM_1, SM_2	SM particles in coannihilation DM + X $\to SM_1 SM_2$
SM_3	Possible additional vertex DM–X–SM_3

Joachim Kopp

Conclusion

- The hunt for Dark Matter continues
- Very nice and constructive workshop
  https://indico.cern.ch/event/342623
- 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
- Hope presenting hard work on LHC measurements has the right consequences ….

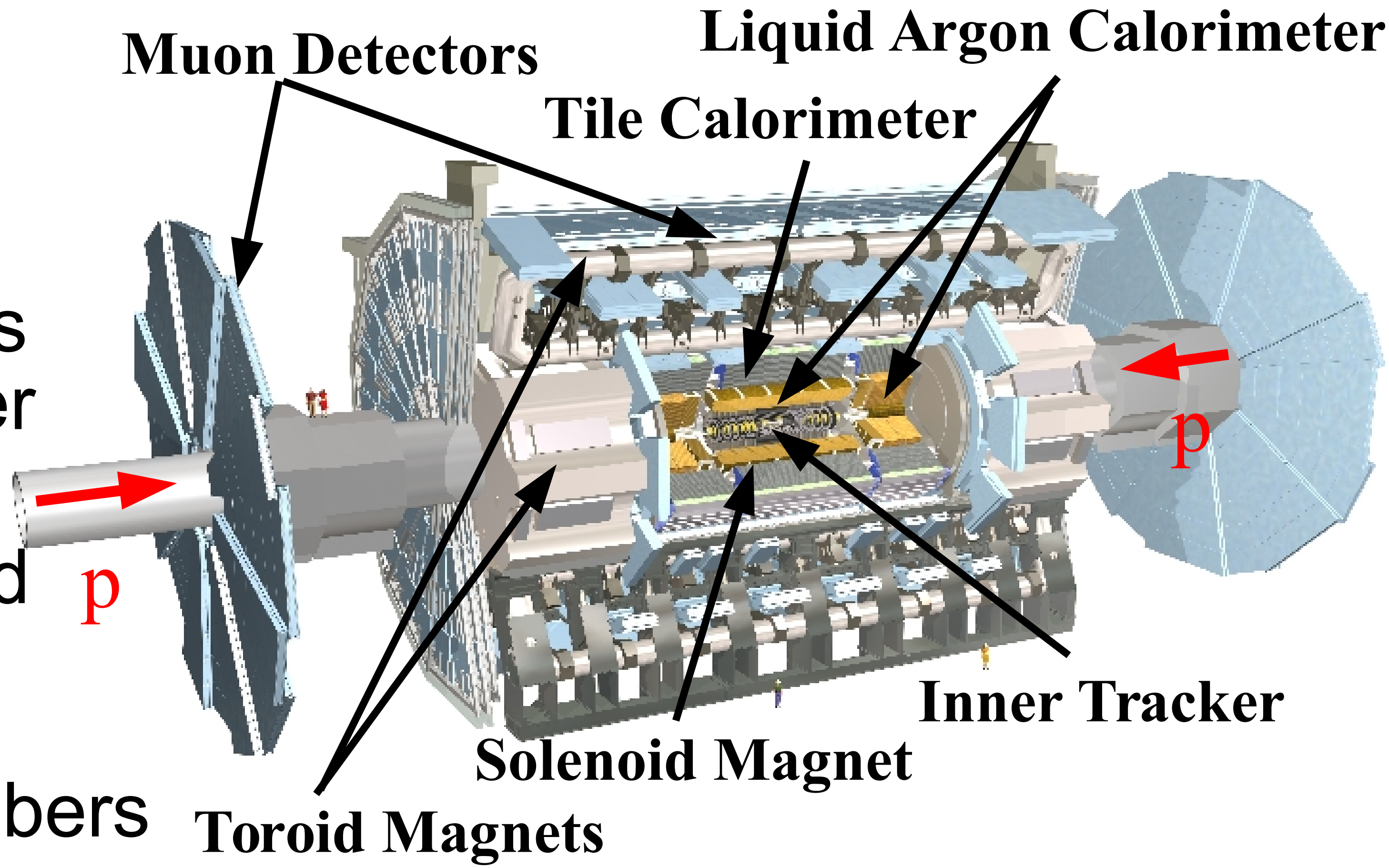
Consequences



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

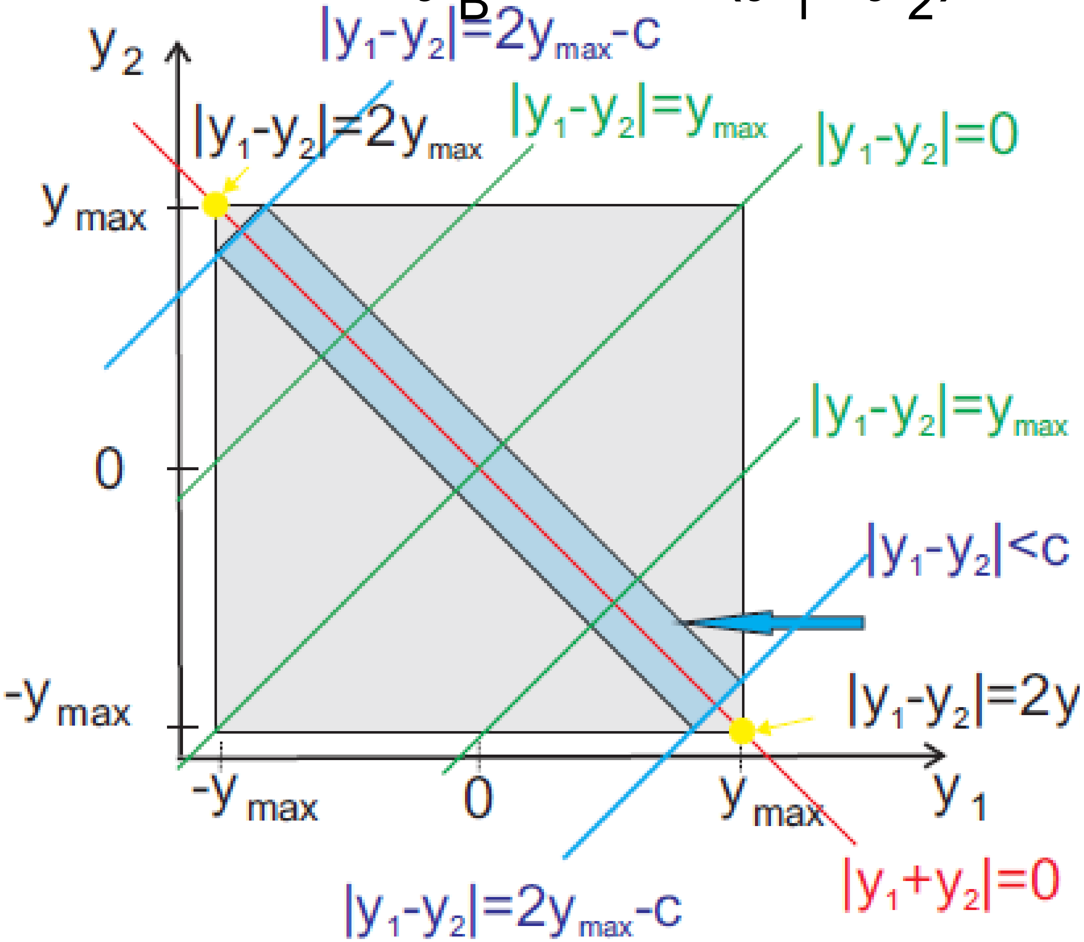
$$\sigma_{had}(m_R) = 16\pi^2 \times \mathcal{N} \times \mathcal{A}_{\cos\theta^*} \times BR \times \left[\frac{1}{s}\frac{dL(\bar{y}_{min}, \bar{y}_{max})}{d\tau}\right]_{\tau=m_R^2/s} \times \frac{\Gamma_R}{m_R}, \quad (44)$$

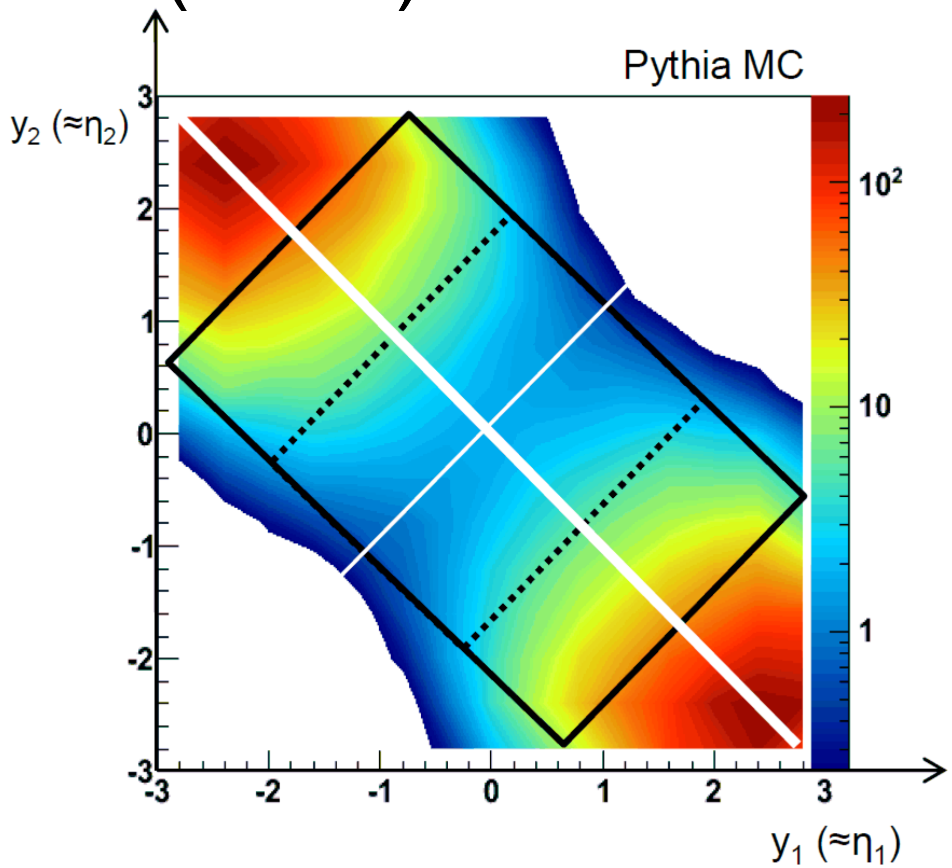
vhere the parton luminosity $\frac{dL}{d\tau}$ is calculated at $\tau = m_R^2/s$, and constrained in the inematic range $[\bar{y}_{min}, \bar{y}_{max}]$.

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

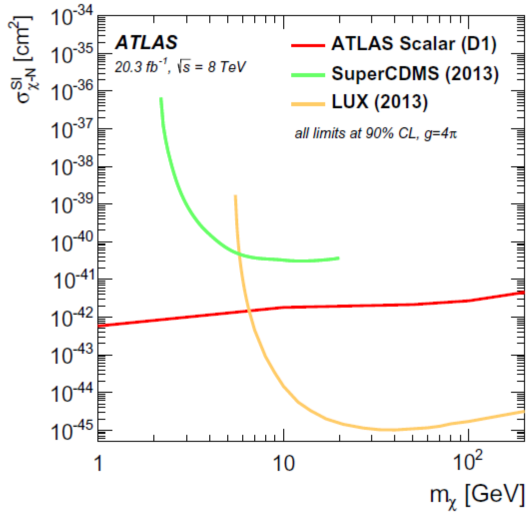
Rapidity distribution, Selection

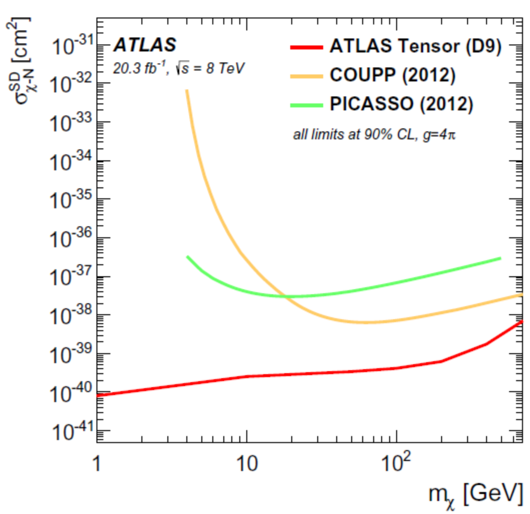
- $|y^*|<1.7$, $|y_B|<1.1$, implied: $|y_{1,2}|<2.8$, $p_T>80$ GeV
  boost $y_B = 0.5*(y_1+y_2) = 0.5\ln(x1/x2)$





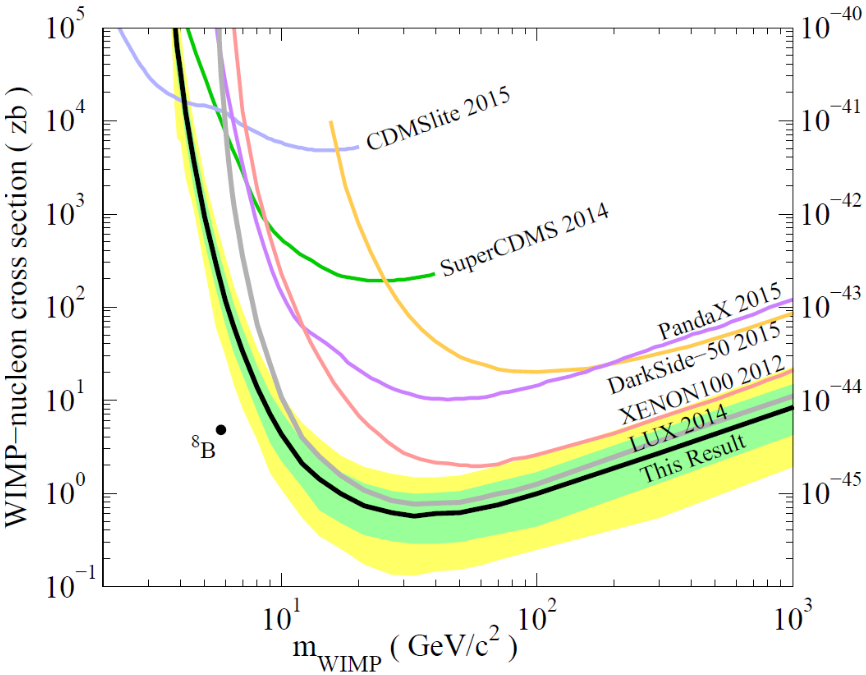
Beauty-jets and missing E_T

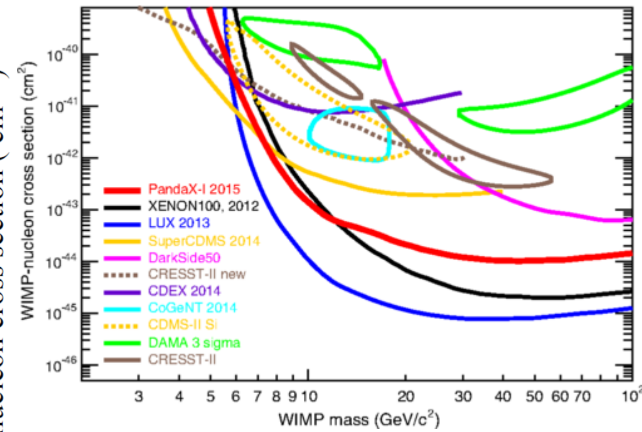


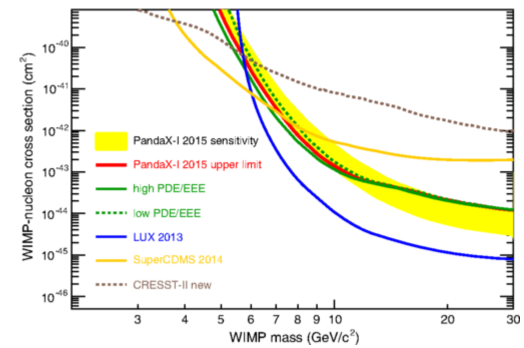


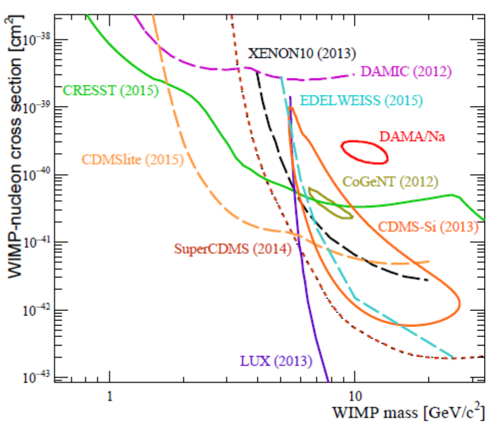
Eur. Phys. J. C (2015) 75:92
DOI 10.1140/epjc/s10052-015-3306-z

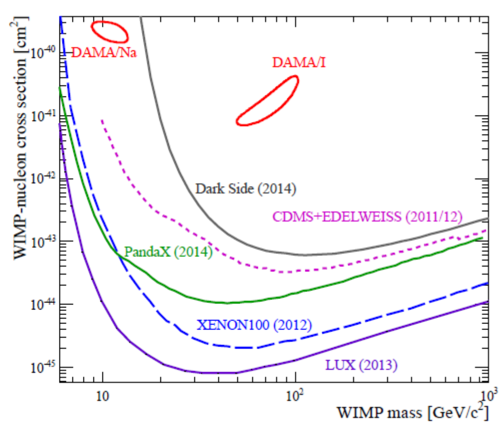
Direct Detection

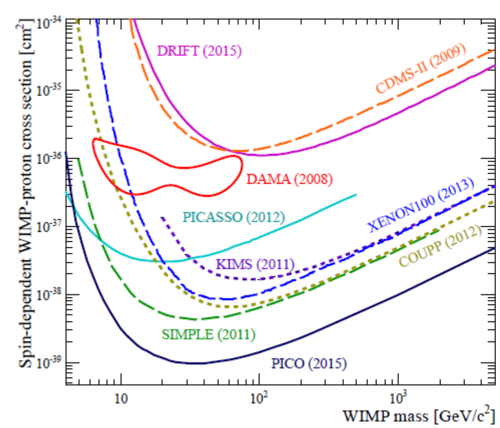


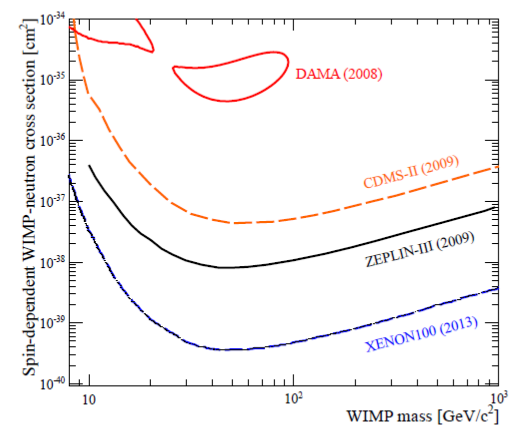












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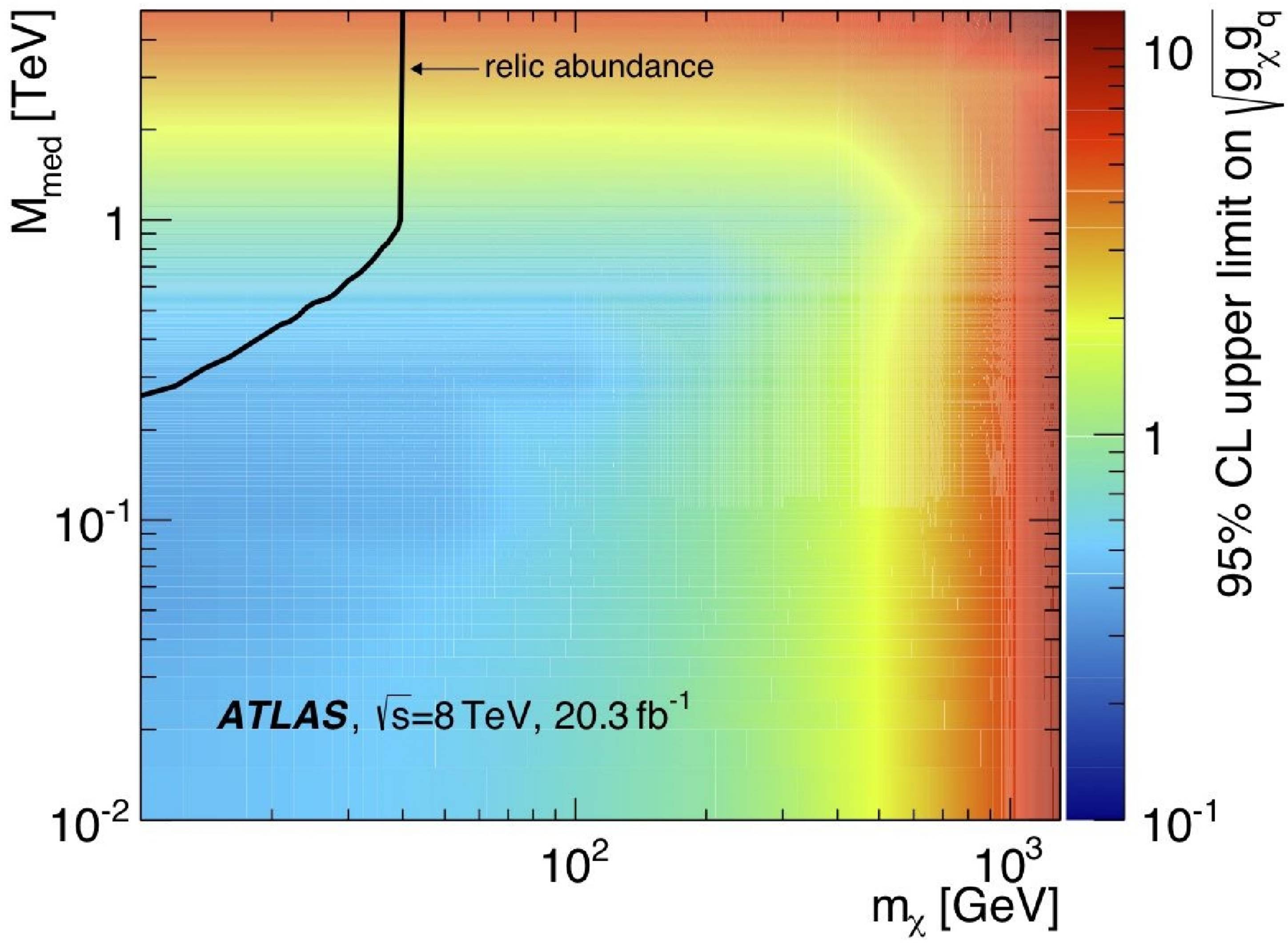

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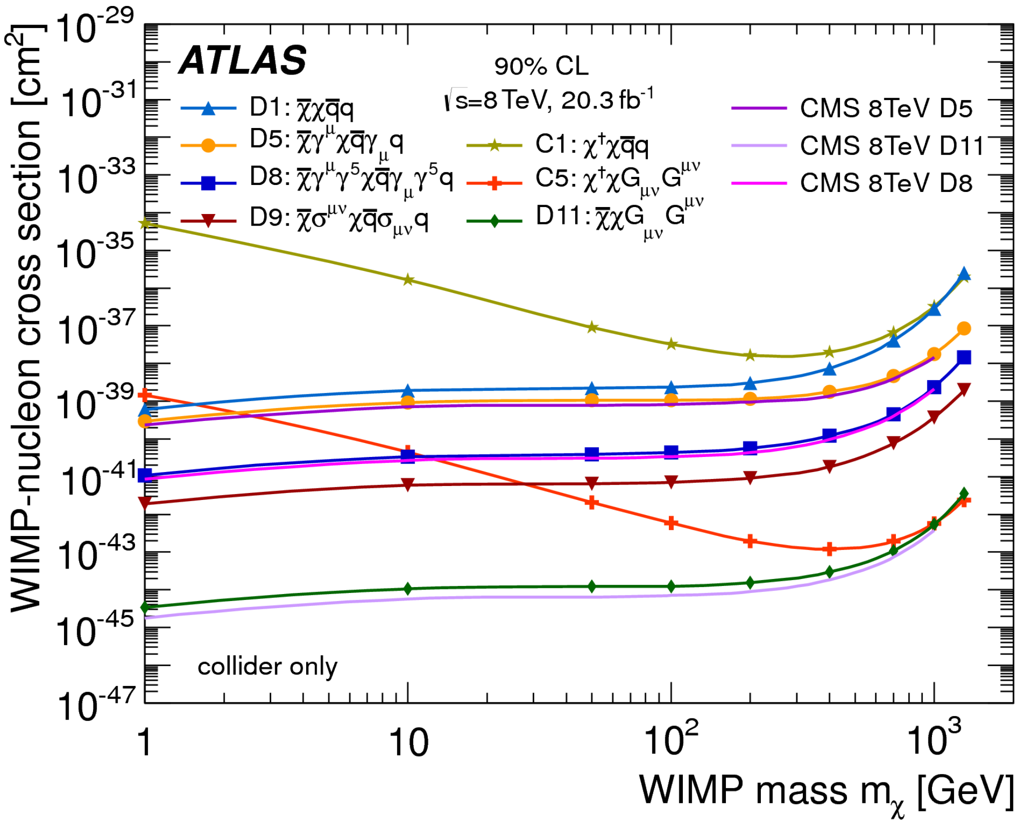

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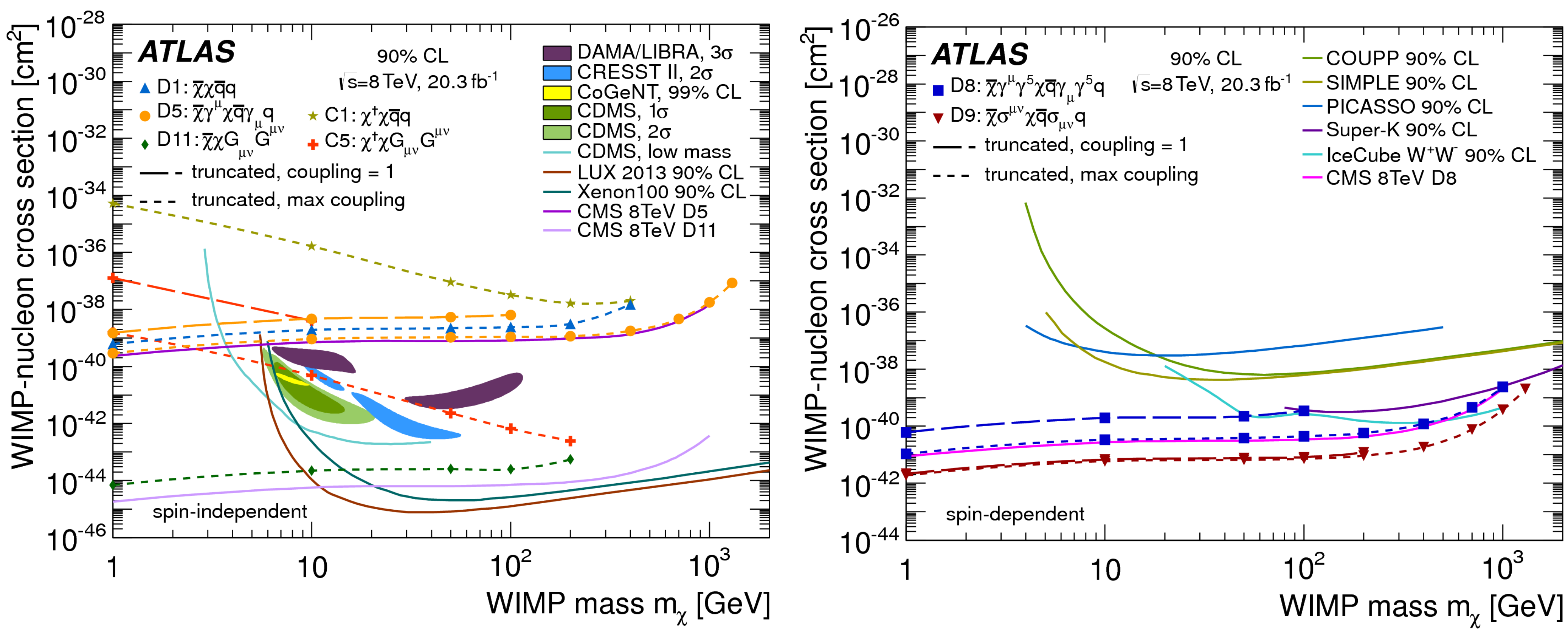

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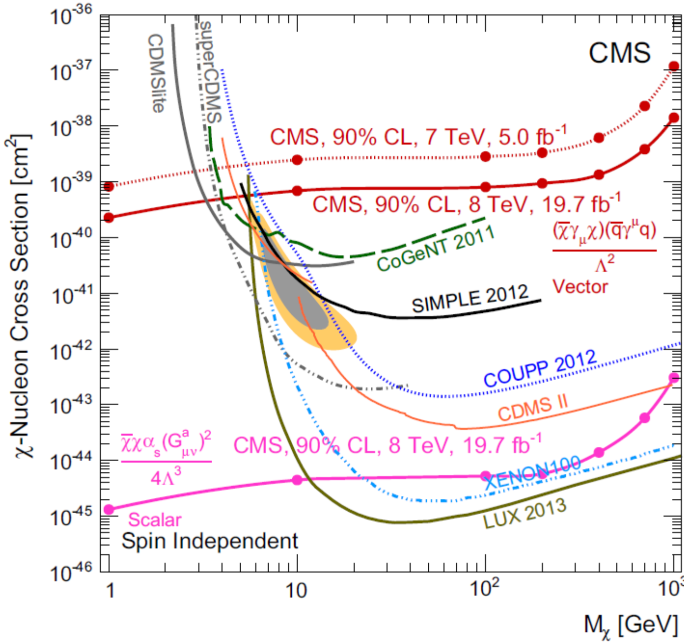

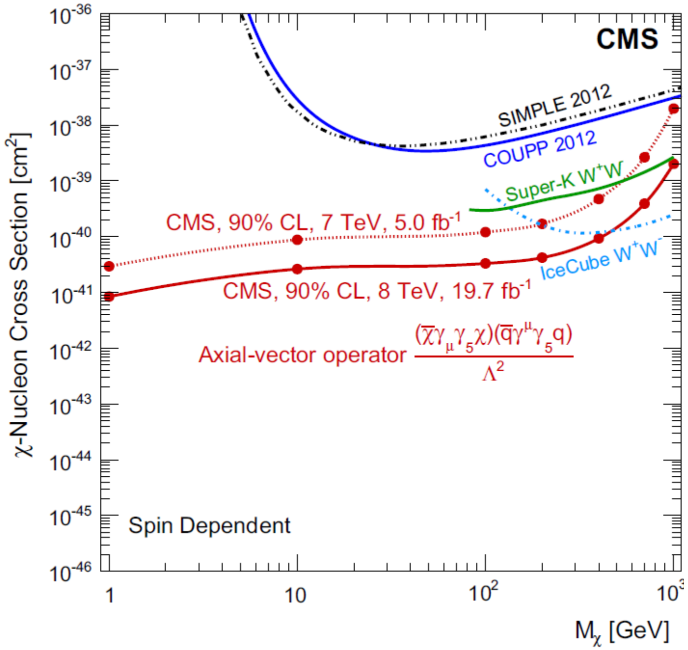

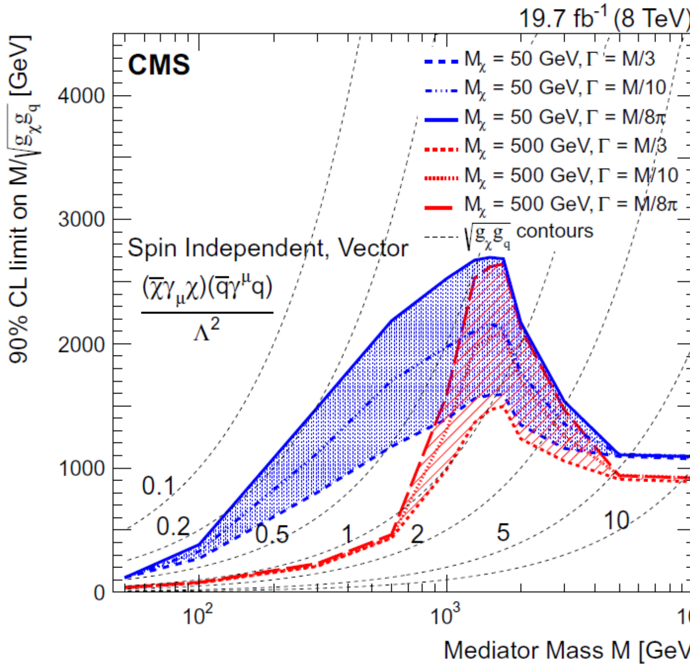

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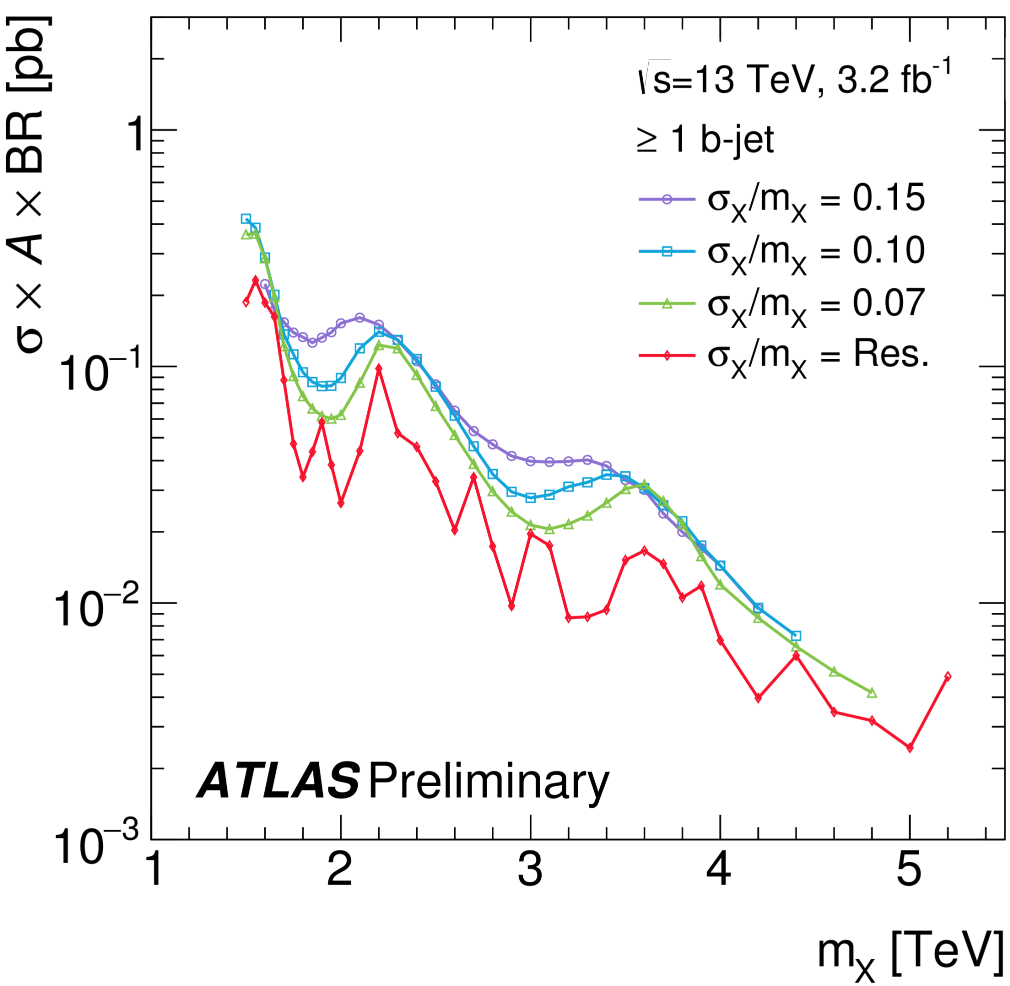
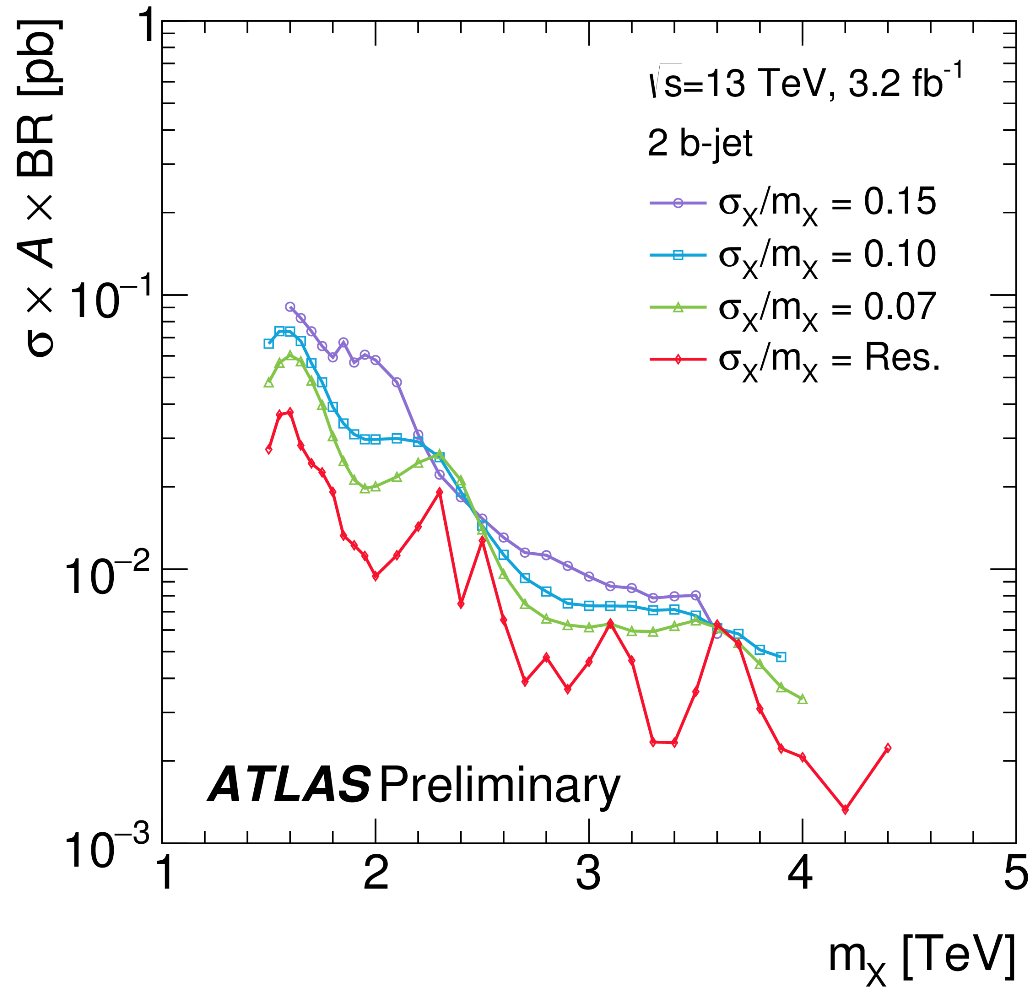
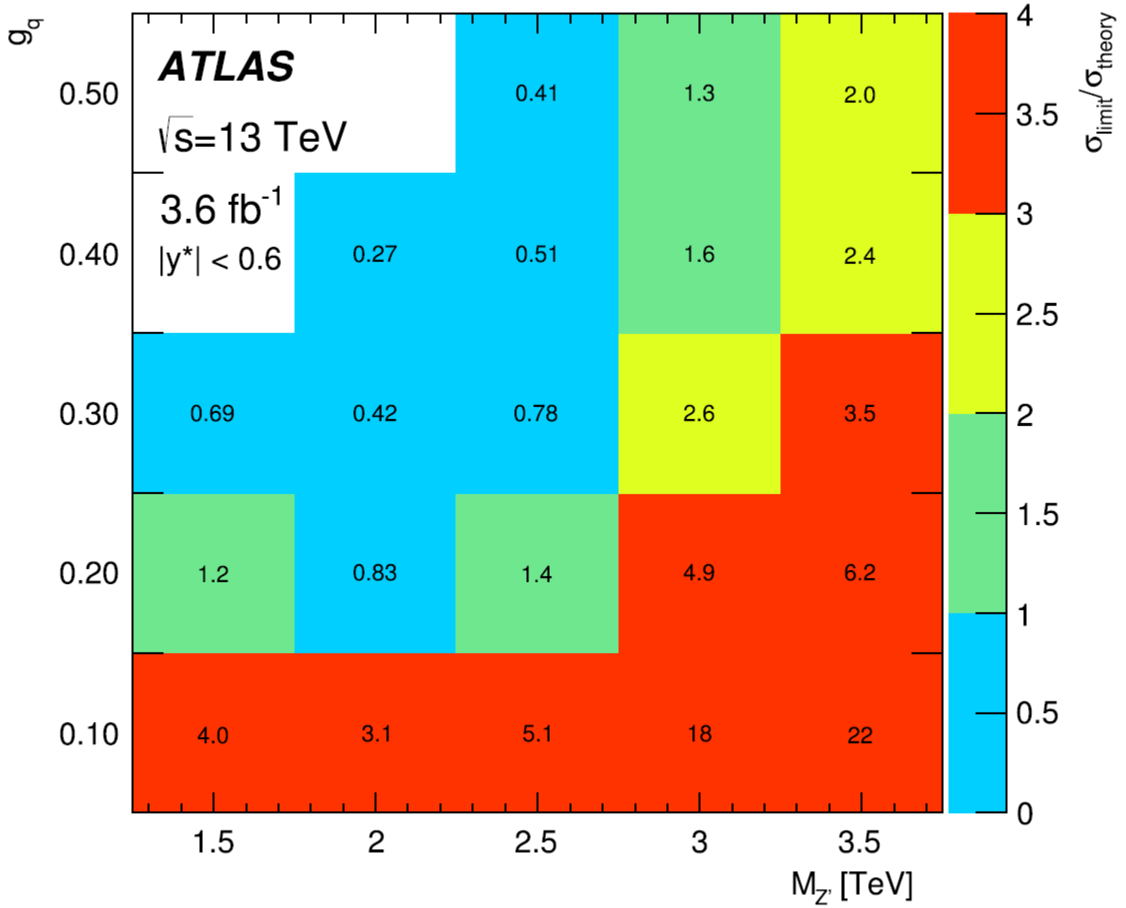




- Gaussian limits: model independent approach

Di-Jet



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