Dark Matter
(and Dark Mediators)
at the LHC

David Šálek

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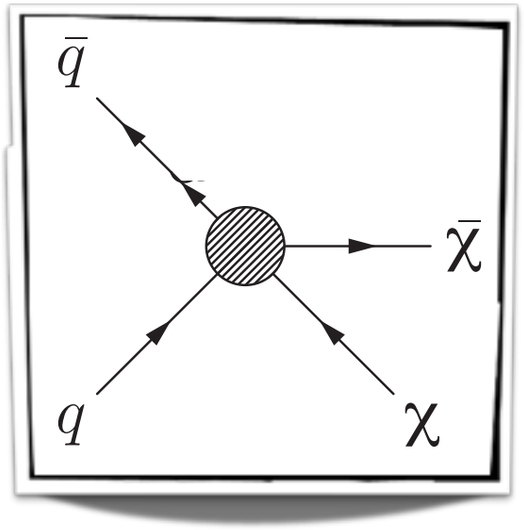
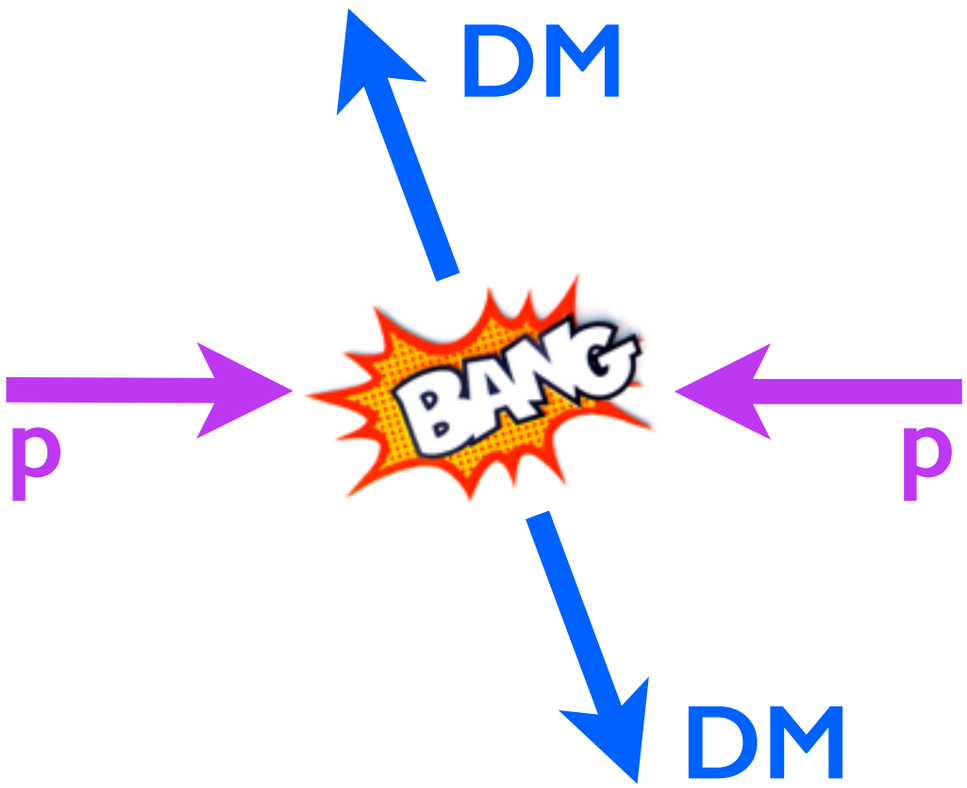
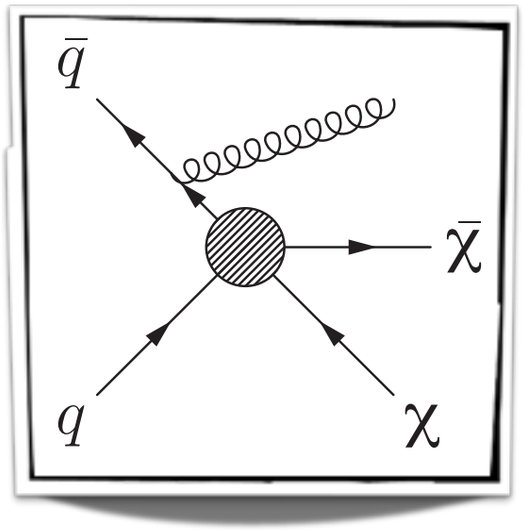
15/12/2015

DM production at the LHC

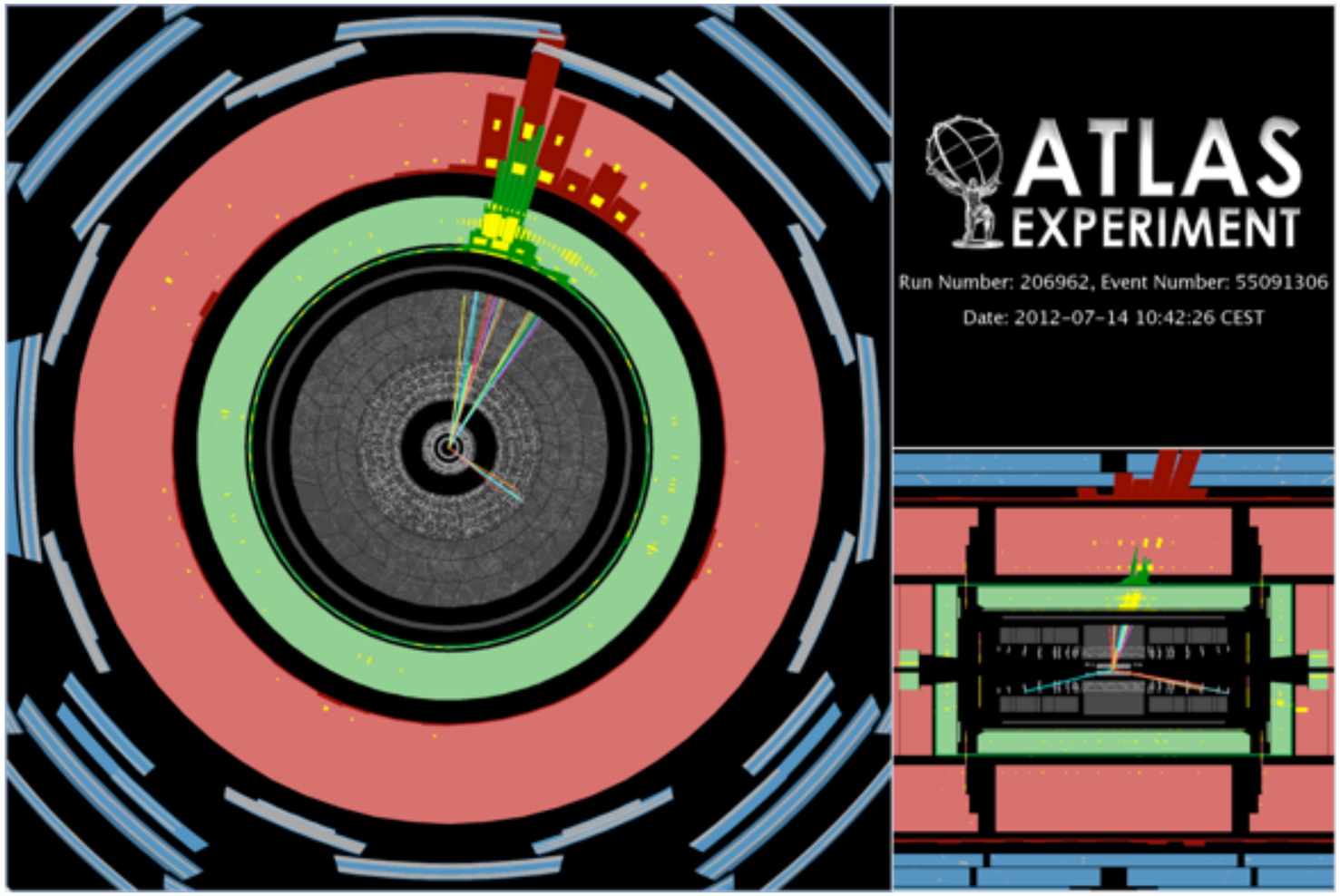




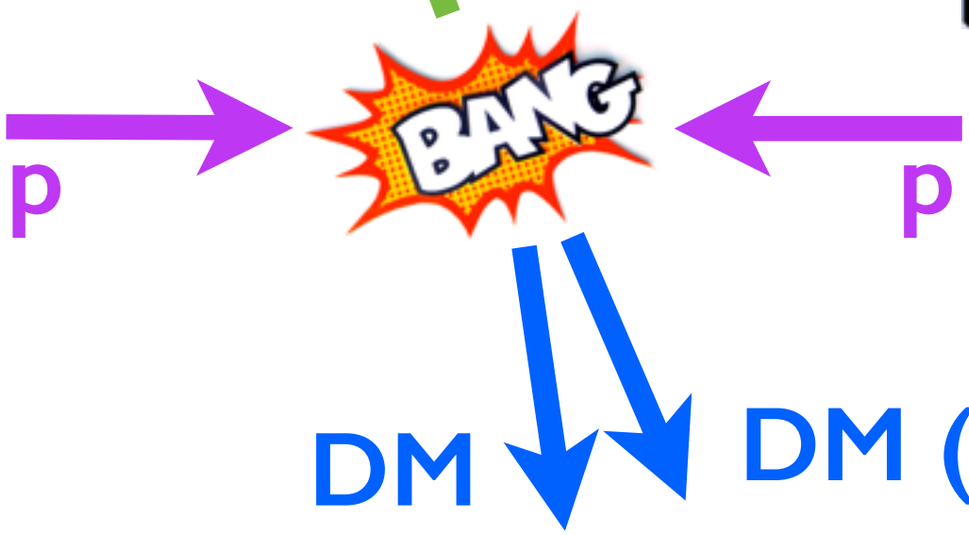
DM production at the LHC



jet, γ, W, Z, ...



mono-jet event from 7 TeV data
JHEP 1304 (2013) 075



experimental signatures

	Run-1 results	Run-2 results
MET signatures		
• mono-jet	Eur. Phys. J. C (2015) 75:299	
• mono-γ	PRD 91, 012008 (2015)	
• mono-W/Z	PRD 90, 012004 (2014) PRL 112, 041802 (2014) HEP 09 (2014) 037	ATLAS-CONF-2015-080
• heavy flavour + DM	EPJC 75 (2015) 79 EPJC 75 (2015) 92	
• mono-H	1510.06218 Phys. Rev. Lett. 115, 131801 (2015)	
• H→invisible	1508.07869 PRL 115, 131801 (2015) PRL 112, 201802 (2014)	
Resonant searches		
• di-jets	PRD 91, 052007 (2015)	1512.01530

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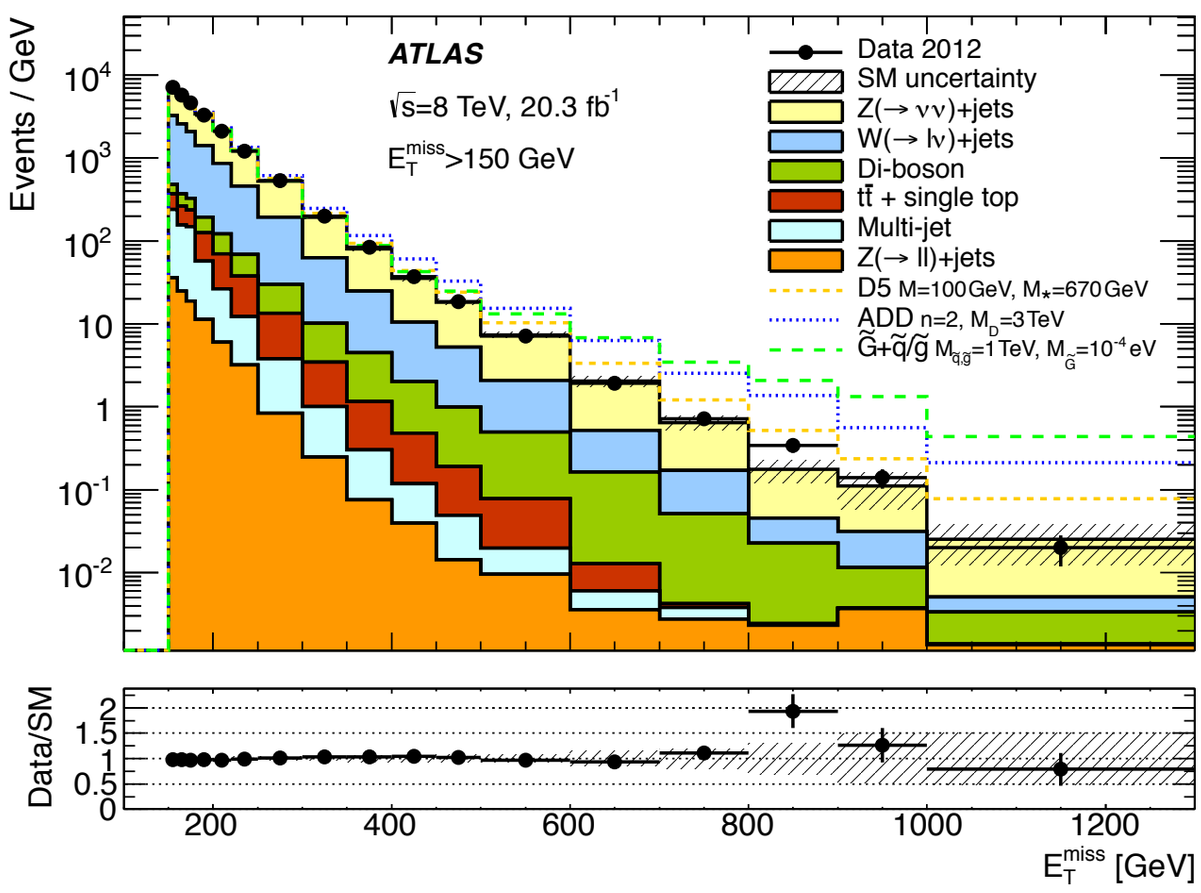
mono-jet

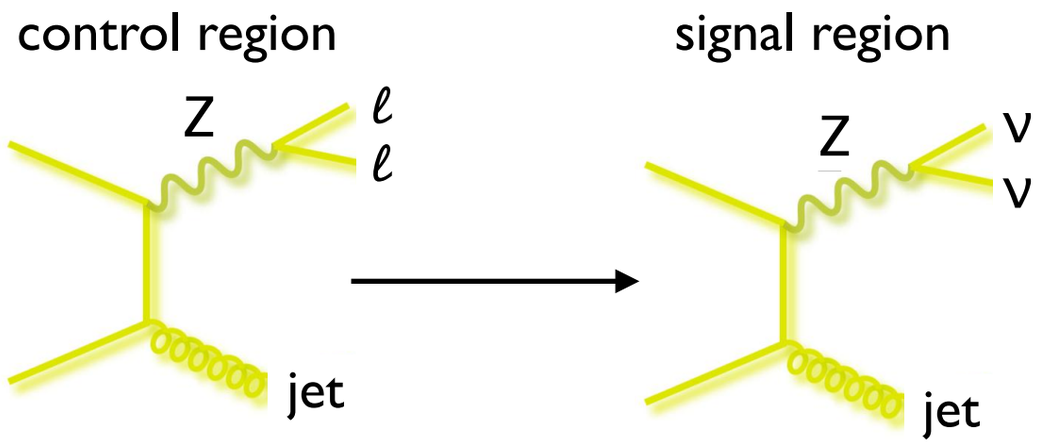
8 TeV 20.3 fb^{-1}

Event selection

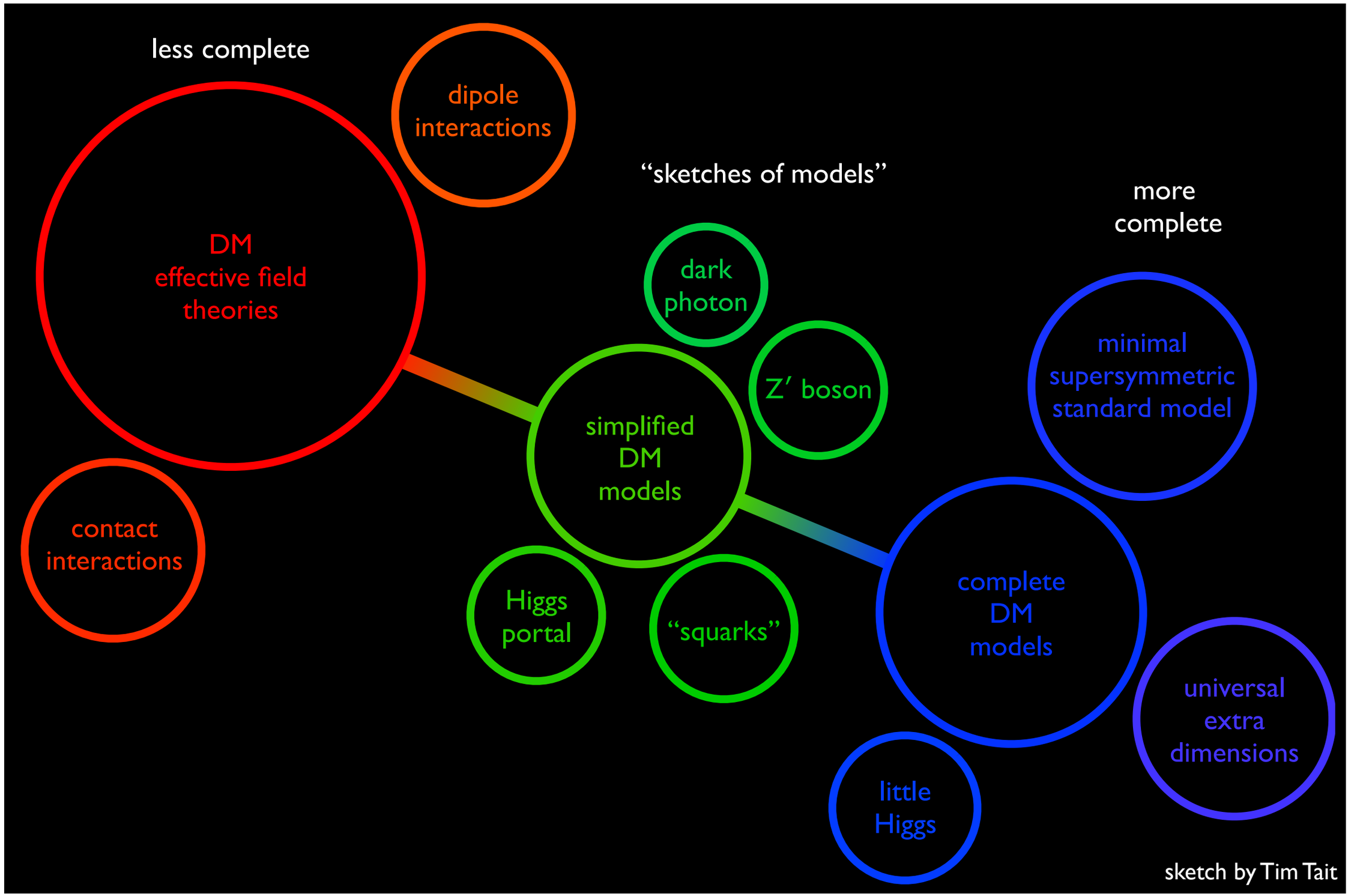
- MET trigger
- jet pT > 120 GeV
- MET > 150 GeV
- lepton veto

Background process	Method	Control sample
$Z(\to \nu\bar{\nu})$+jets	MC and control samples in data	$Z/\gamma^*(\to \ell^+\ell^-)$, $W(\to \ell\nu)$ $(\ell = e, \mu)$
$W(\to e\nu)$+jets	MC and control samples in data	$W(\to e\nu)$ (loose)
$W(\to \tau\nu)$+jets	MC and control samples in data	$W(\to e\nu)$ (loose)
$W(\to \mu\nu)$+jets	MC and control samples in data	$W(\to \mu\nu)$
$Z/\gamma^*(\to \ell^+\ell^-)$+jets $(\ell = e, \mu, \tau)$	MC-only	
$t\bar{t}$, single top	MC-only	
Diboson	MC-only	
Multijets	Data-driven	
Non-collision	Data-driven	

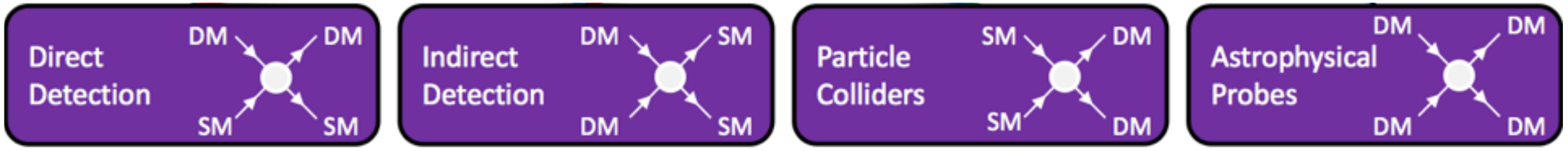




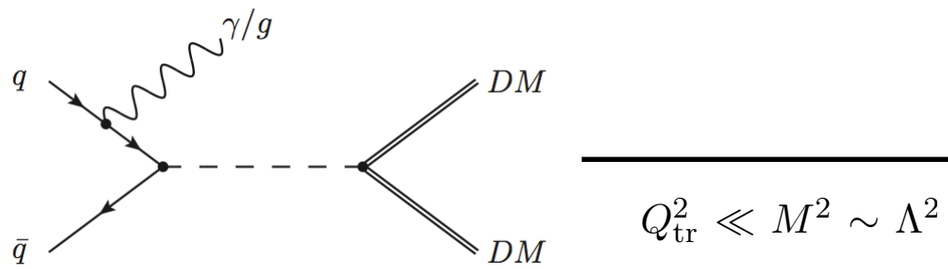
DM interpretations



contact interactions



- Contact interactions (dimension-6 operator) form a simple framework for the description of the collider and astro-particle experimental results and were widely used in Run-1 by both ATLAS and CMS.

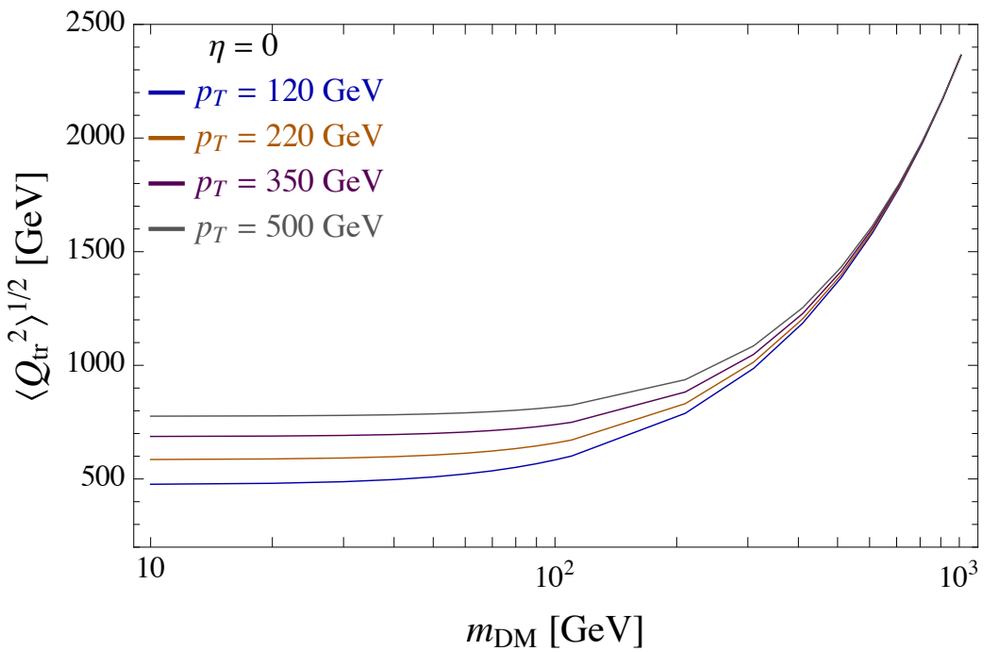


$$\frac{1}{Q_{\rm tr}^2 - M^2} = -\frac{1}{M^2}\left(1 + \frac{Q_{\rm tr}^2}{M^2} + \mathcal{O}\left(\frac{Q_{\rm tr}^4}{M^4}\right)\right)$$

EFT has two parameters (m_{DM} and suppression scale Λ)

$$\mathcal{O}_S = \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{q}q) \qquad \frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M^2}$$

- It is safe to use EFT when the mediator can be integrated out.
- However, at the LHC energies, the limits on the suppression scale are comparable to the momentum transfer!



mono-jet

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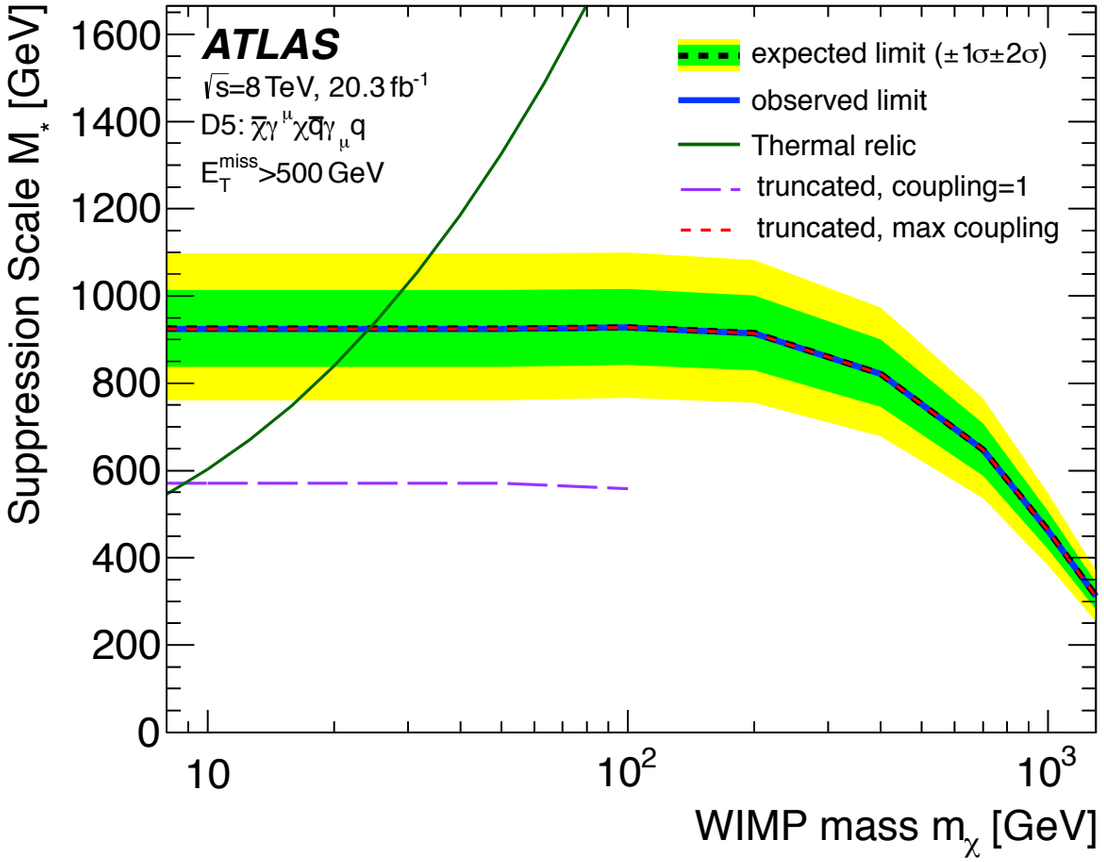
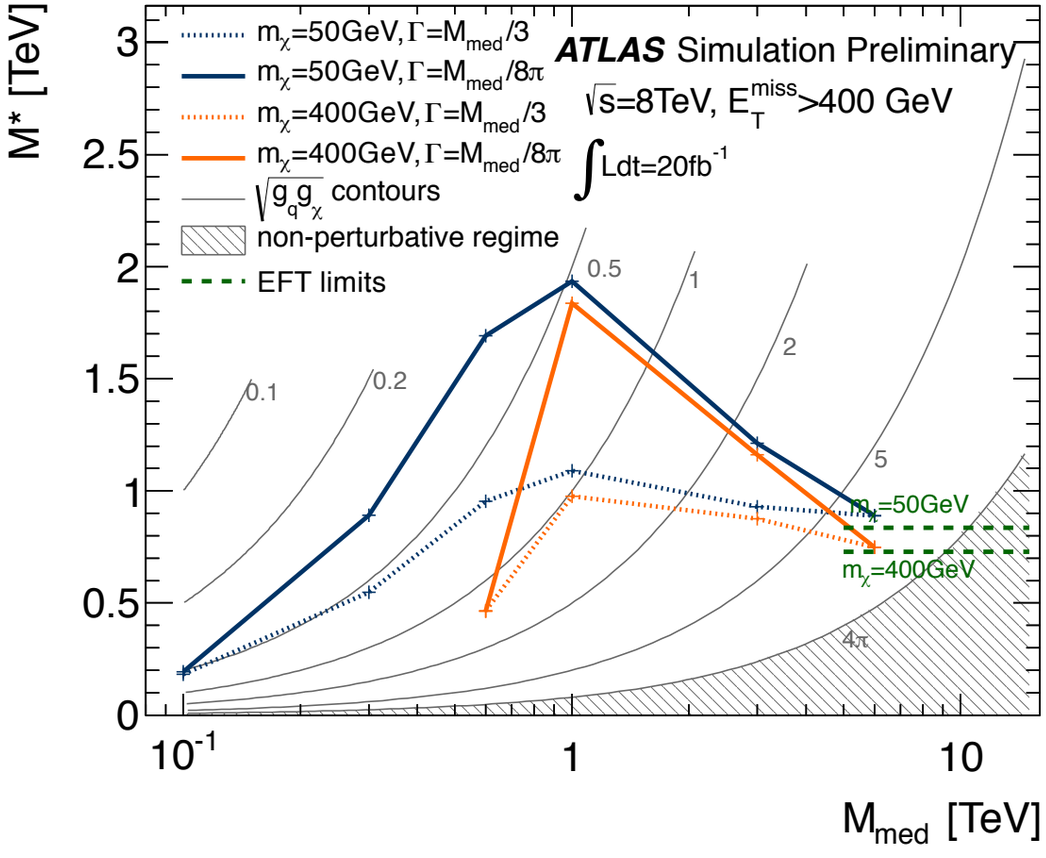
ATL-PHYS-PUB-2014-007

- Limits on the suppression scale of the EFT operators are set assuming full EFT validity.



- Simplified models with Z'-like mediators reveal that
  - EFT limits are conservative in the resonant region.
  - EFT limits are not valid for light mediators.



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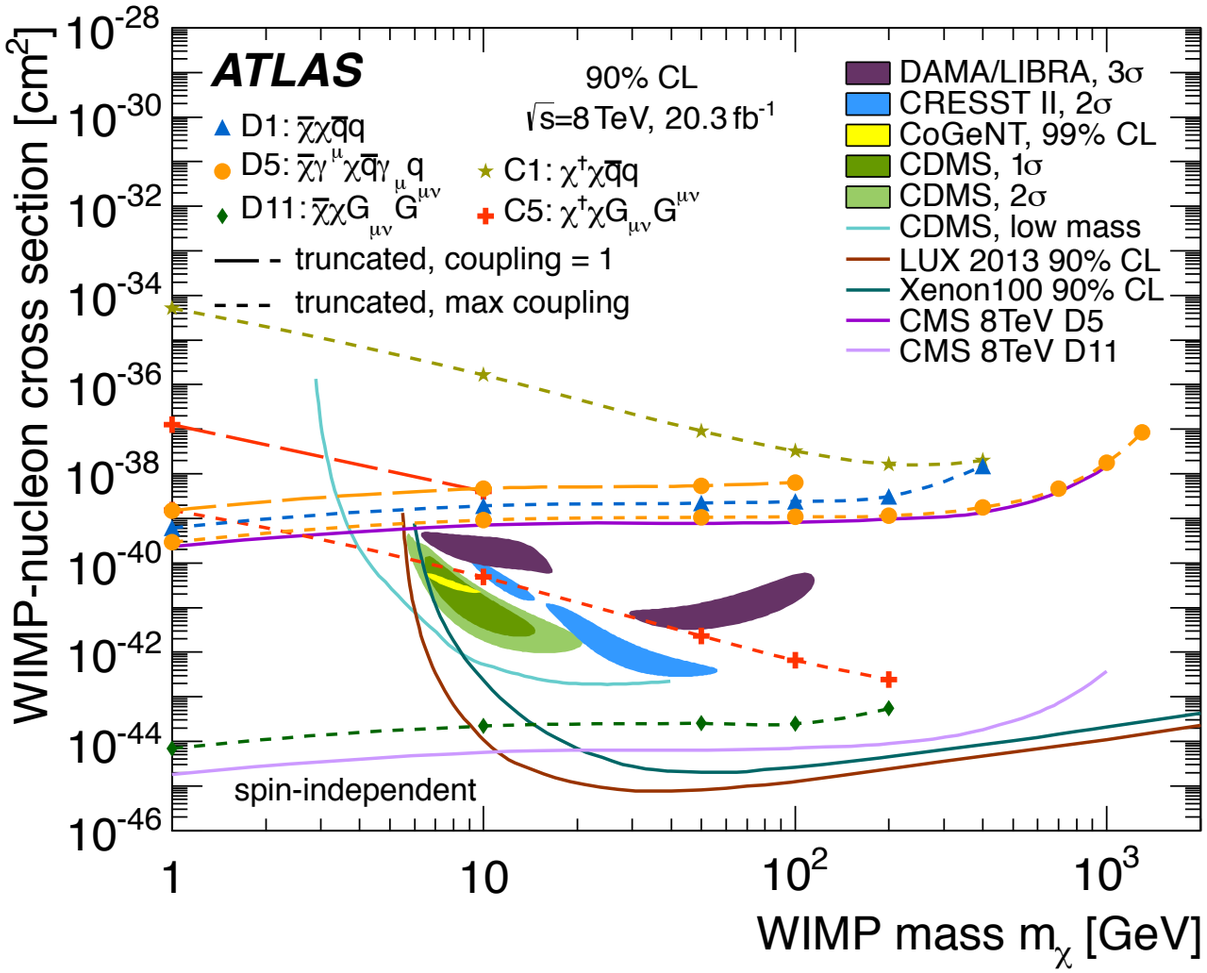
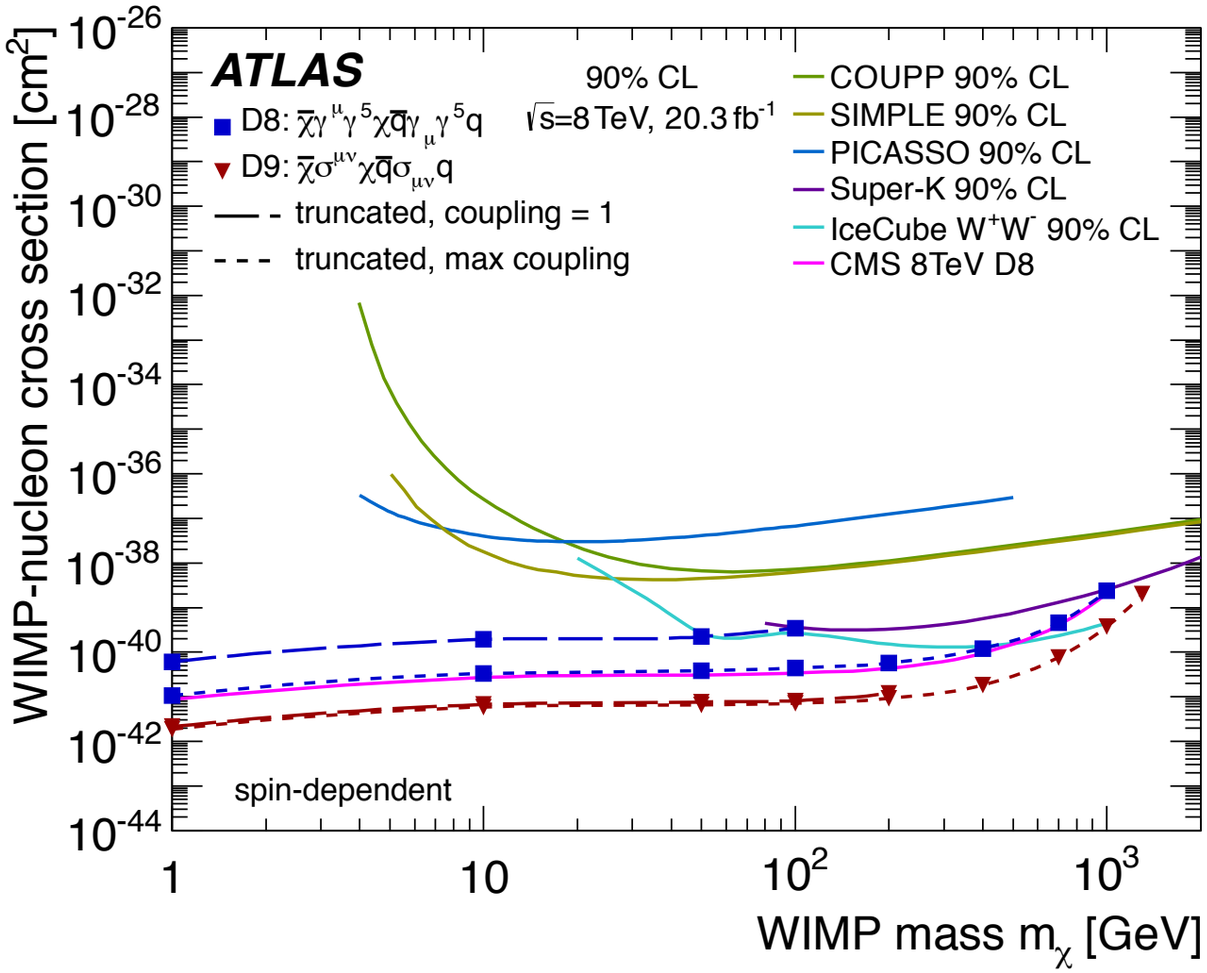
DM interpretation





direct detection

- model assumptions
- kinematic limitation at low mass

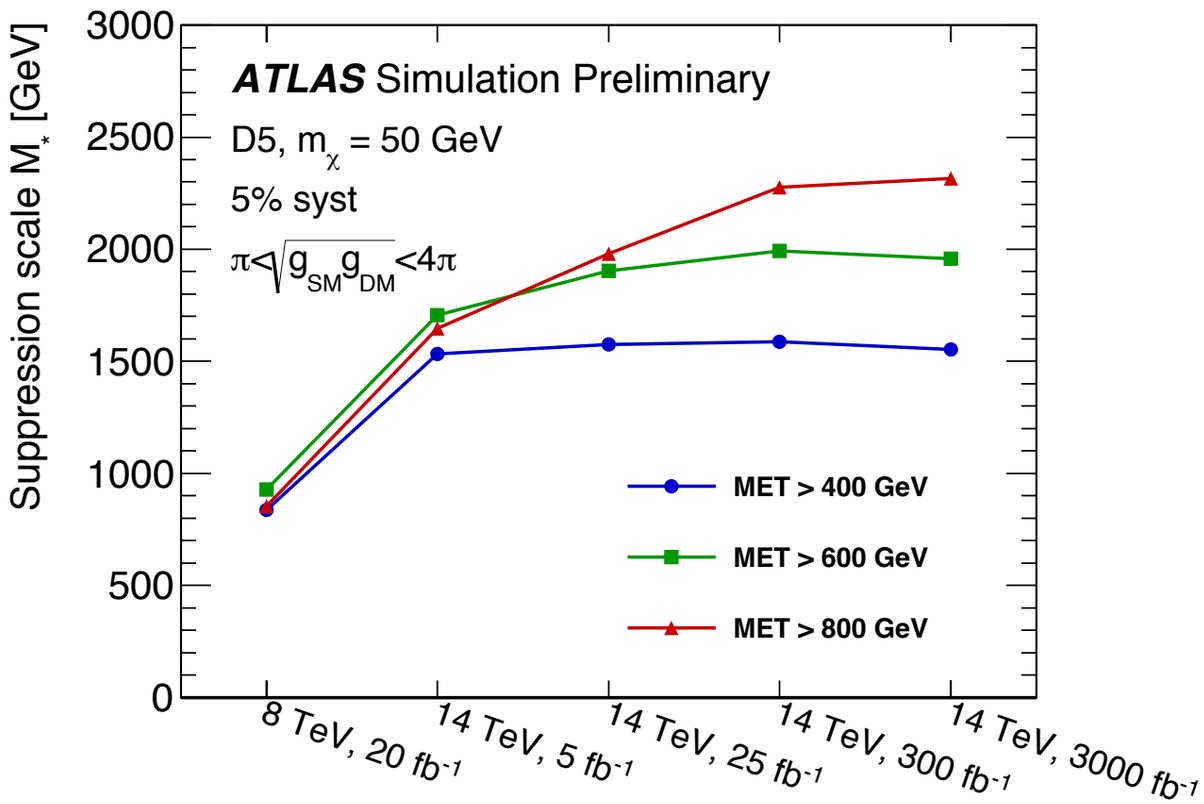
DM production at the LHC

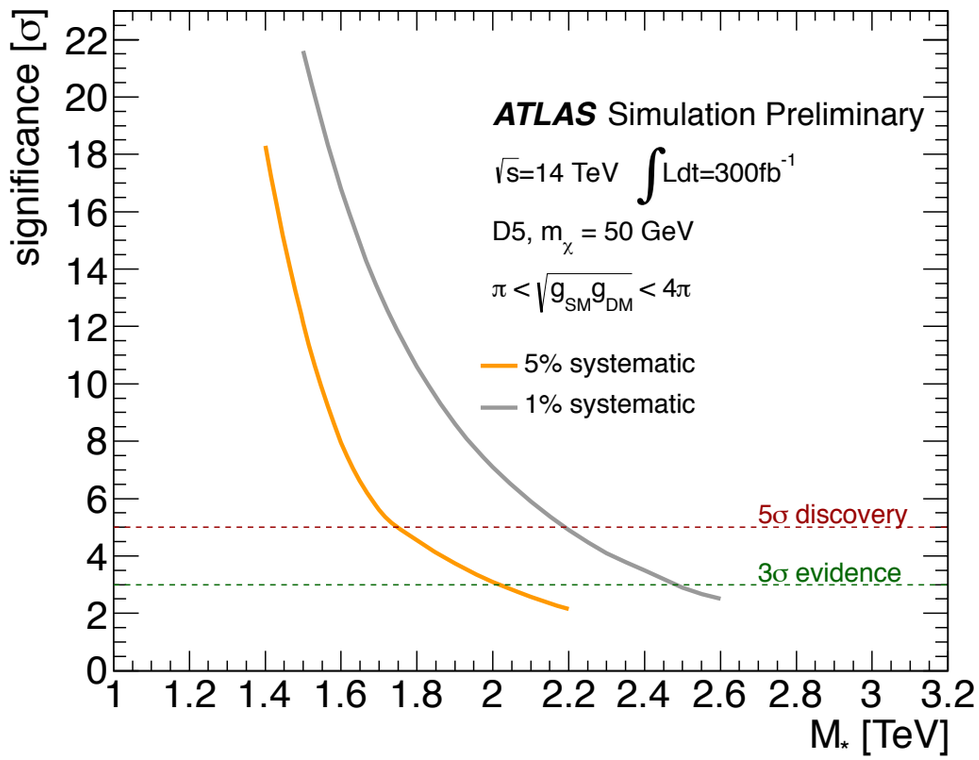
- no astrophysical assumptions
- EFT validity
- sensitive at low mass

mono-jet prospects @ 14 TeV

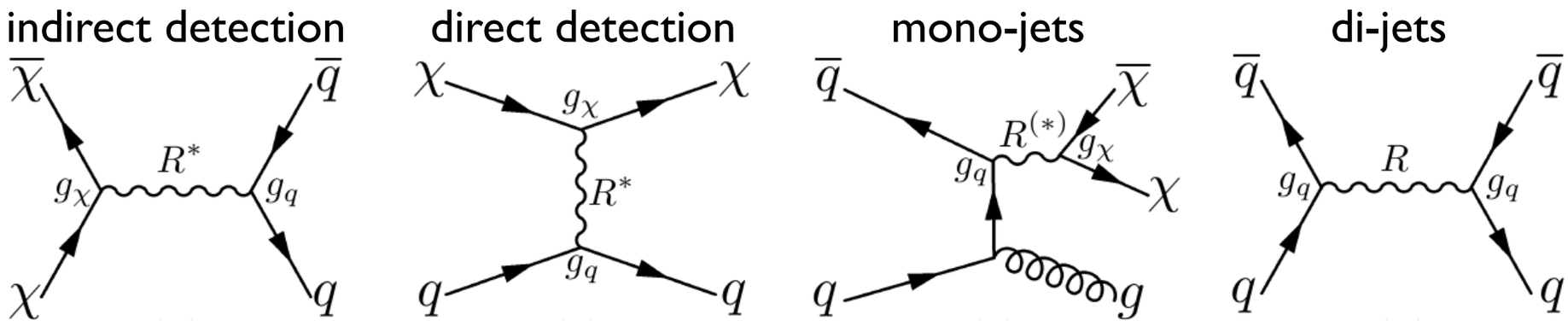
ATL-PHYS-PUB-2014-007

- Already first data from Run-2 may bring improvements in sensitivity to DM.
  - Exclusion limits may be improved by factor of 2 with first few fb^{-1}.
  - 5σ discovery potential for $M^* \sim 1.7$ TeV with 300 fb^{-1}.



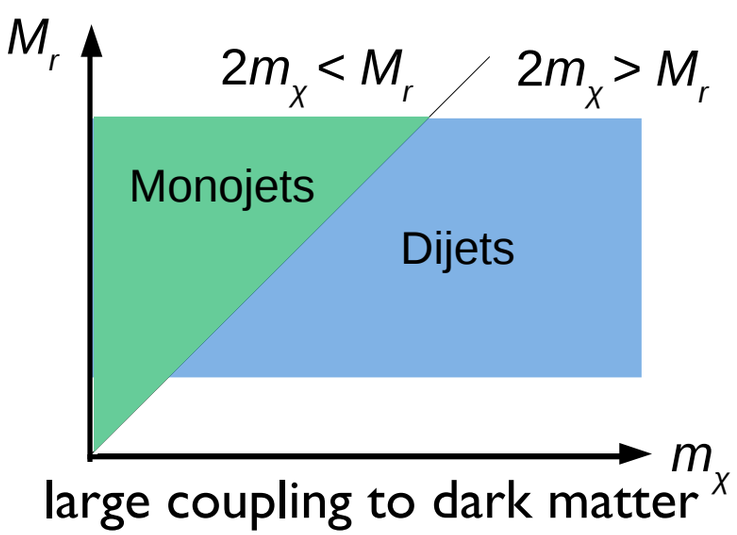


searching for new mediators

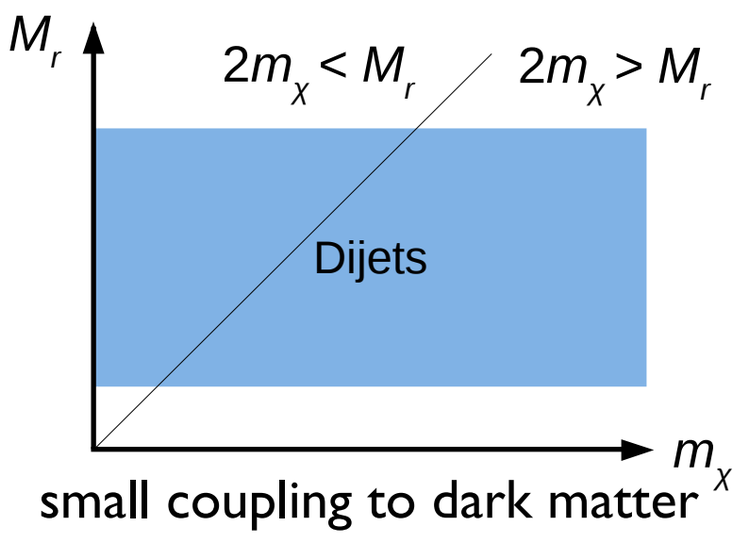


- Simplified models (4 free parameters: m_χ, M_R, g_q, g_χ)
- Basic set of simplified models for the early Run-2 ATLAS and CMS searches was recommended by the DM Forum [1507.00966]

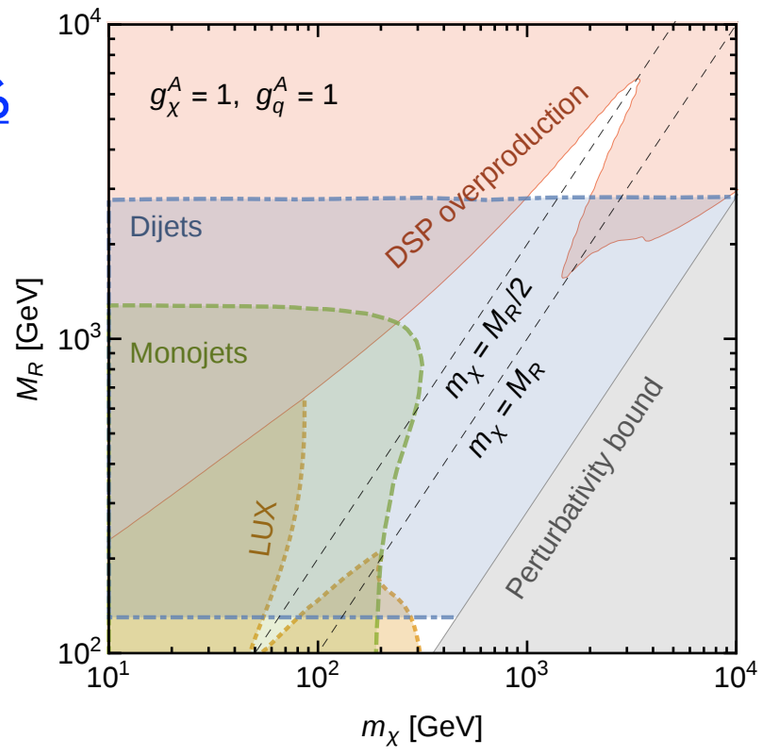
- Simplified models allow for a richer phenomenology and more complex interpretations
  → e.g. complementarity of mono-jets and di-jets [1503.05916]



large coupling to dark matter



small coupling to dark matter

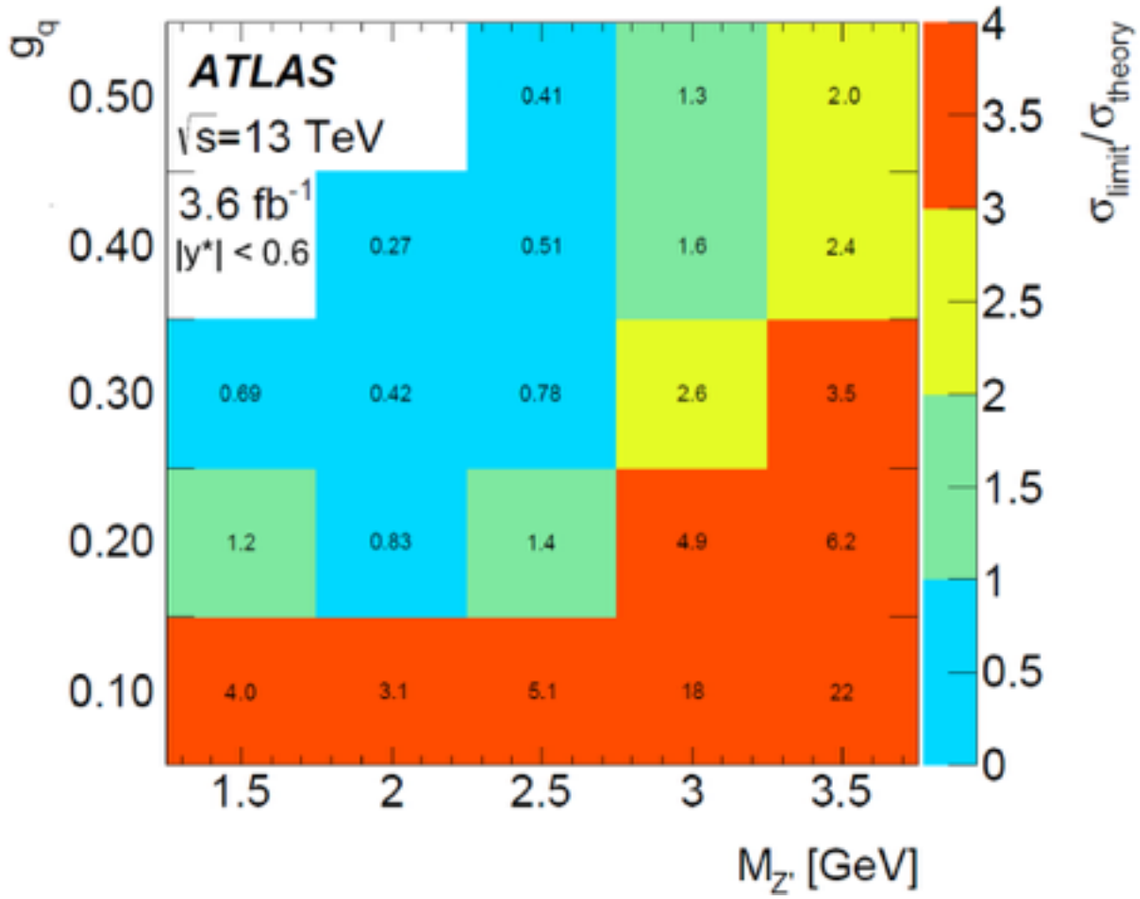


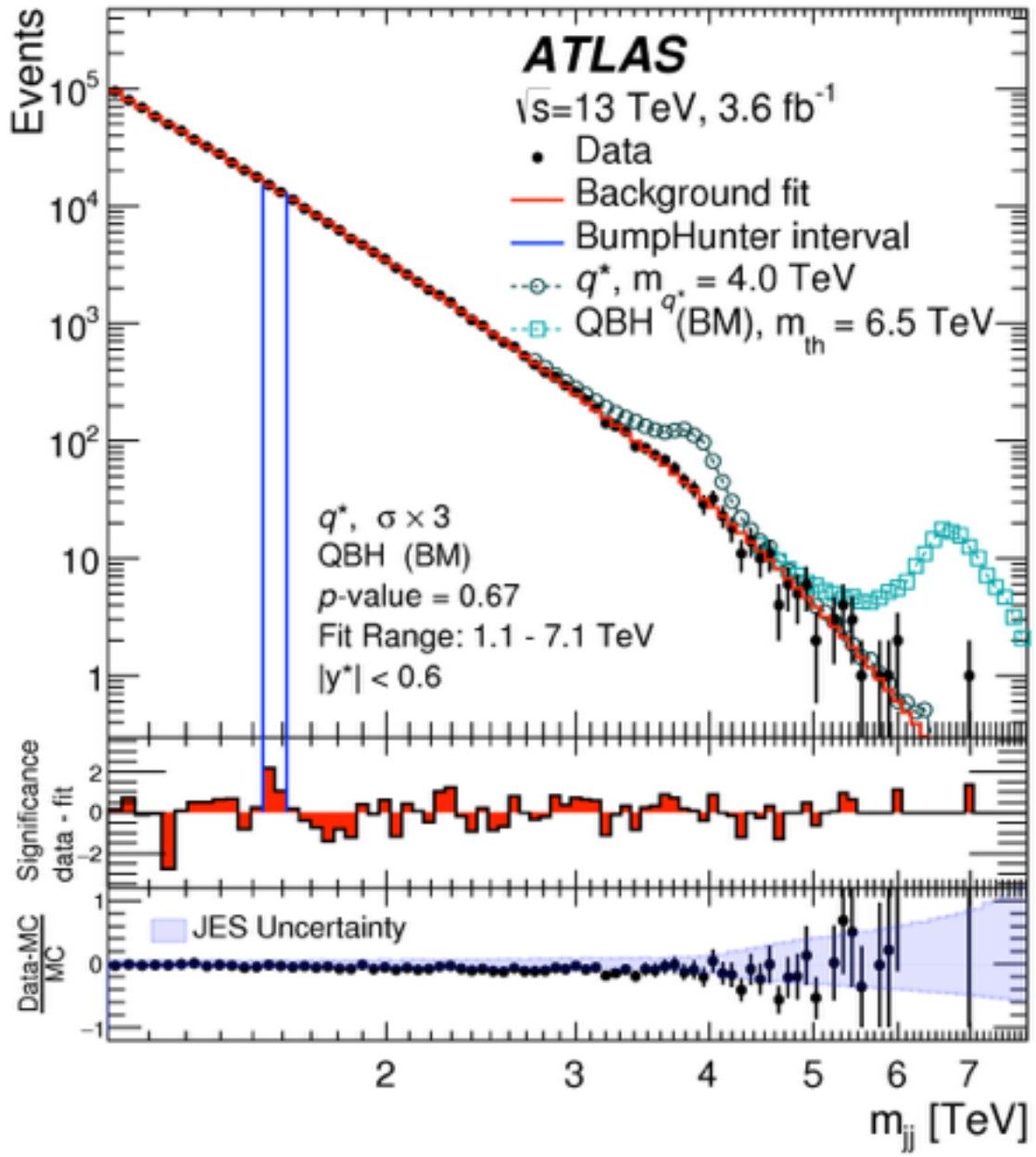
di-jets @ 13 TeV

13 TeV 3.3 fb^{-1}

Event selection

- jet trigger (pT > 360 GeV)
- 2 jets (pT > 440 GeV and 50 GeV)
- rapidity |y*| < 0.6

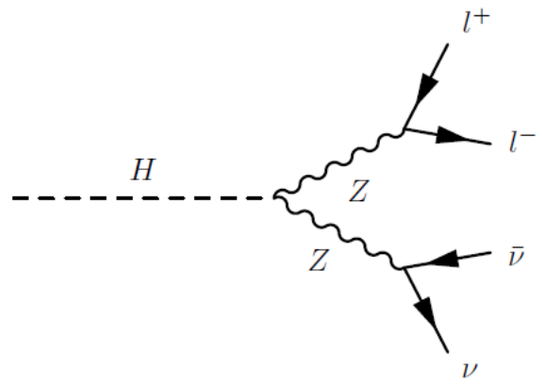




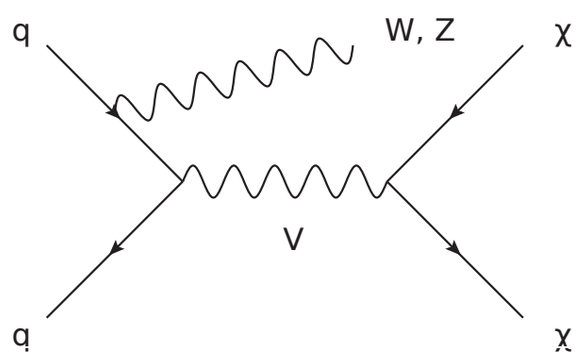
Phys. Rev. D. 90, 012004 (2014)
PRL 112, 201802 (2014)

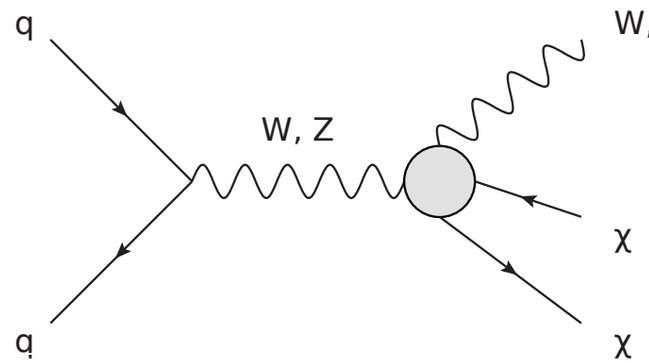
$\ell\ell$+MET final state

- search for heavy Higgs boson

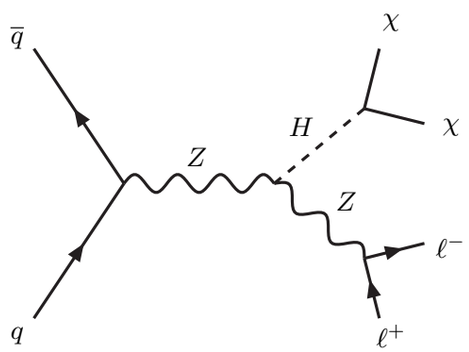


- mono-Z
  - simplified models
  - dimension-7 EFT operators





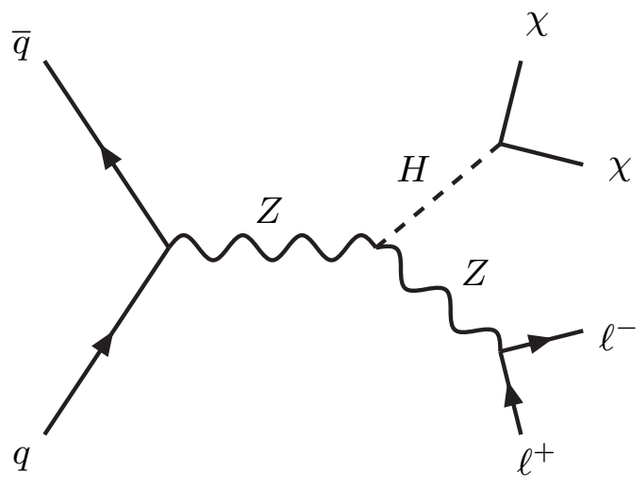
- search for invisibly decaying Higgs boson
  - SM Higgs decay has BR(H→ZZ→inv.) ~ 0.1%
  - many BSM models predict large BR(H→inv.)

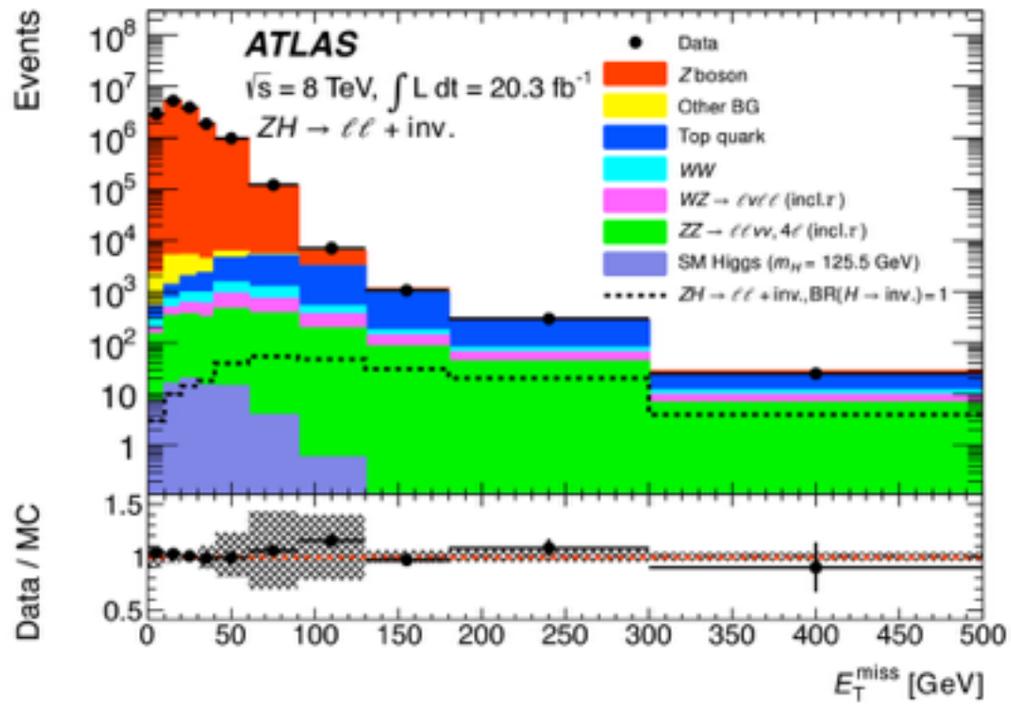


ZH(→invisible)

7 TeV 4.5 fb^{-1}
8 TeV 20.3 fb^{-1}

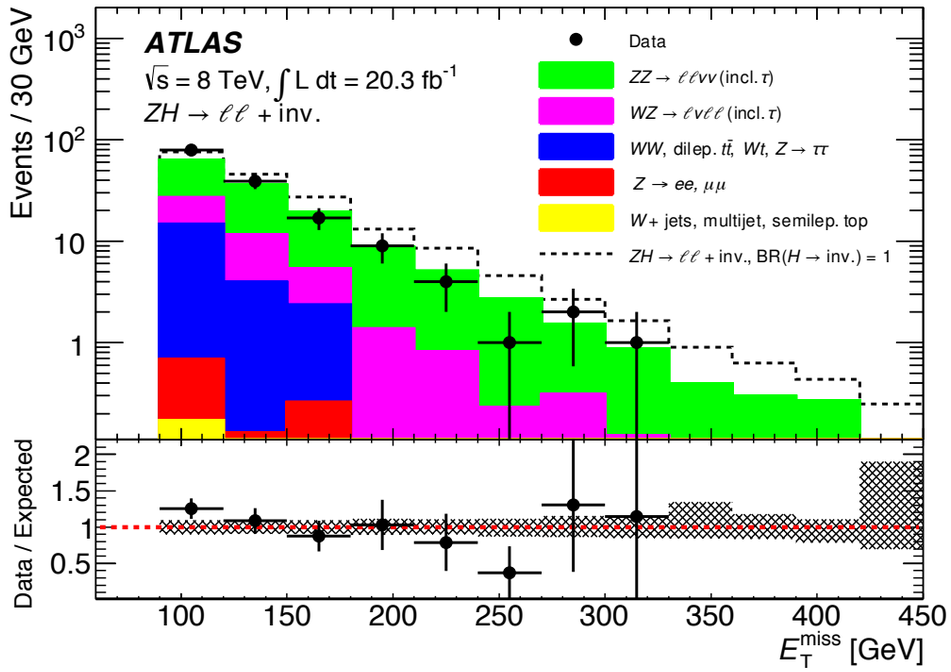
PRL 112, 201802 (2014)





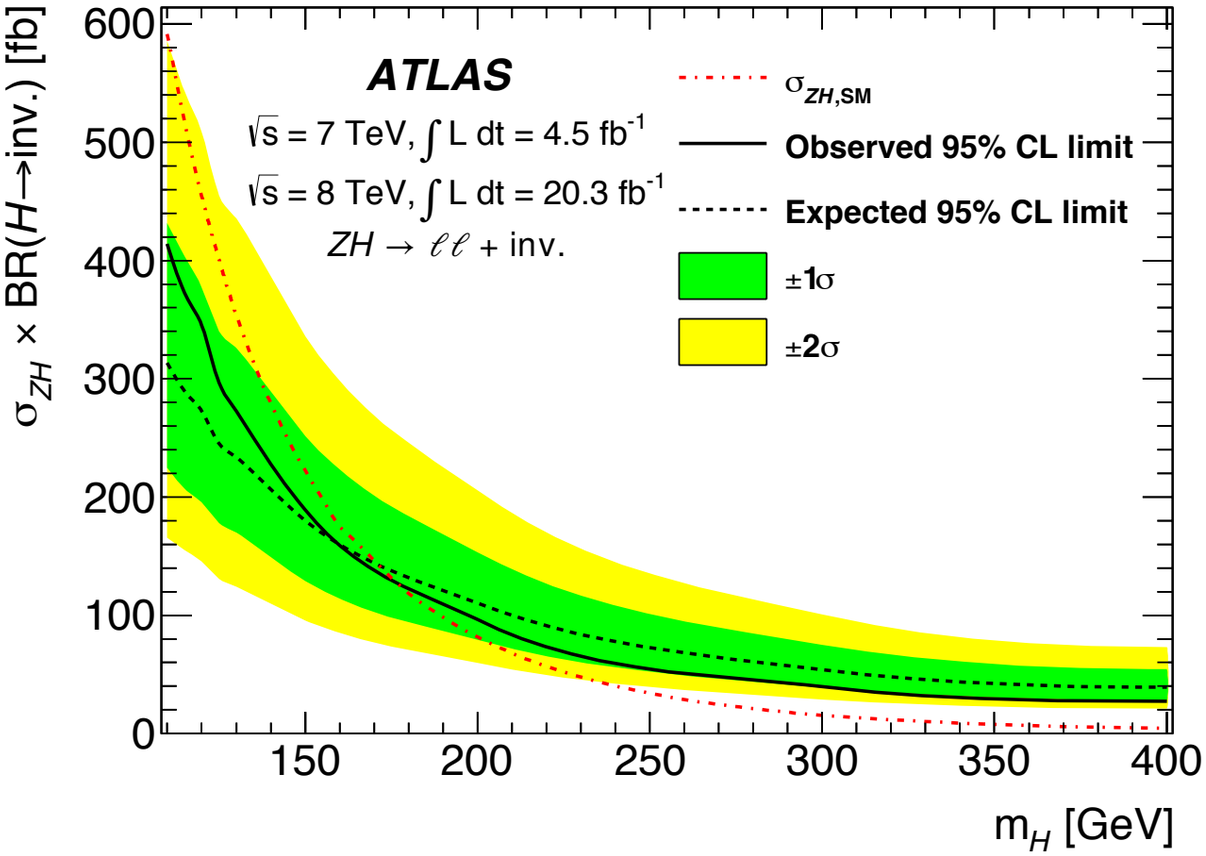
Event selection

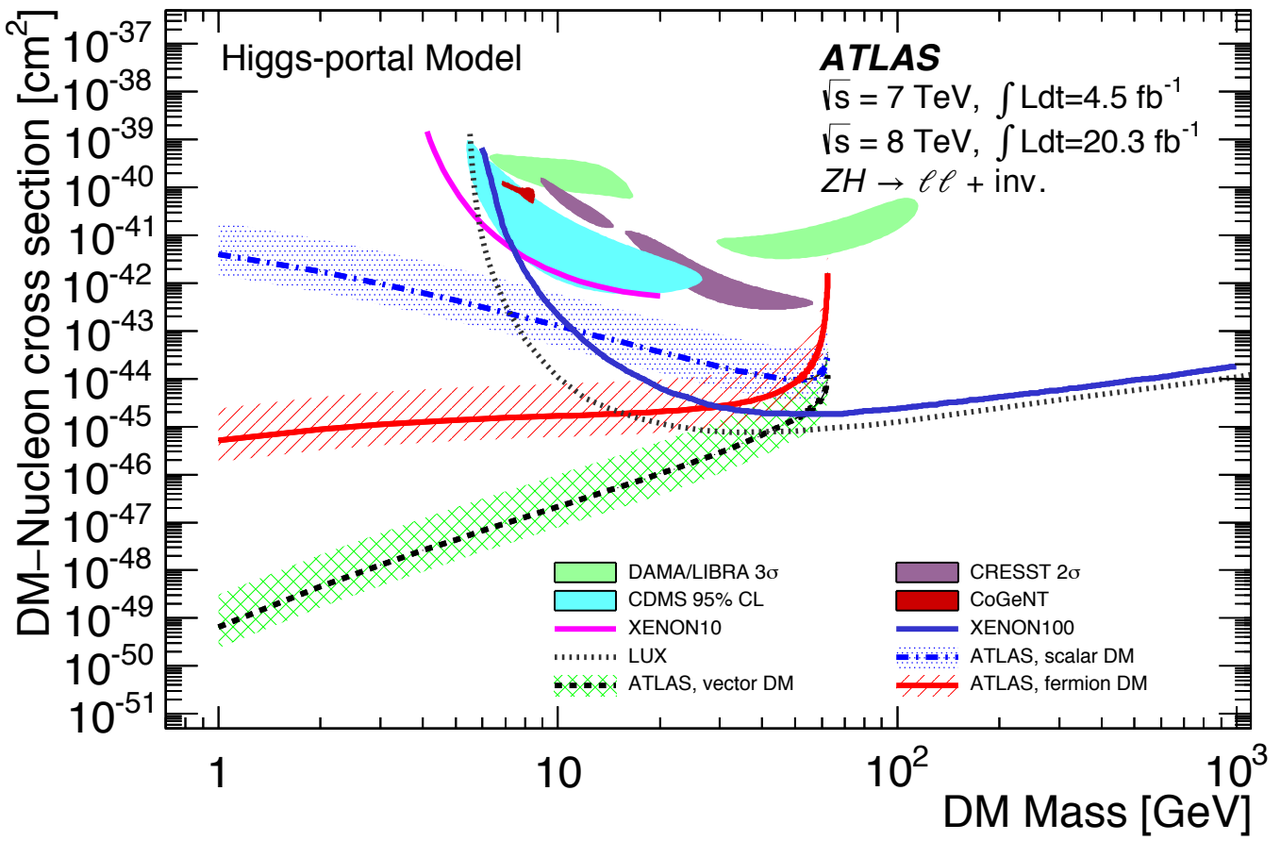
- two opposite sign leptons, 67 < mℓℓ < 106 GeV
- 3rd lepton veto (pT > 7 GeV)
- |MET - pTℓℓ| / pTℓℓ < 0.2
- Δφ(MET, pTmiss) < 0.2
- Δφℓℓ < 1.7
- Δφ(Z, MET) > 2.6
- jet veto (pT > 25 GeV)
- MET > 90 GeV



ZH(→invisible)

PRL 112, 201802 (2014)

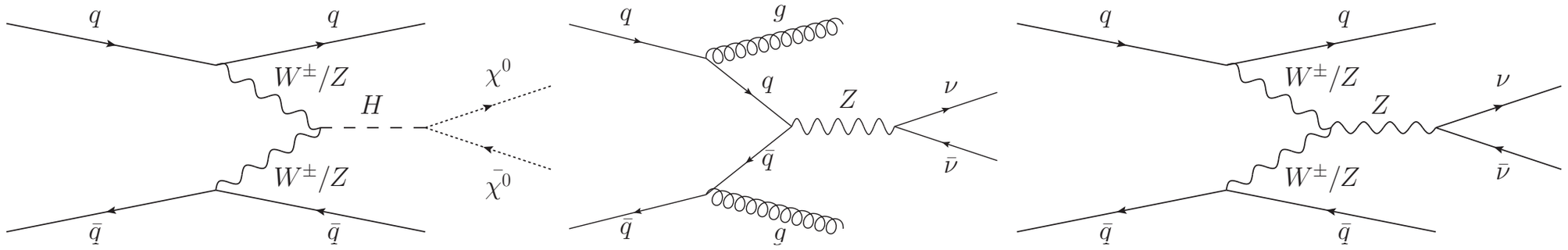


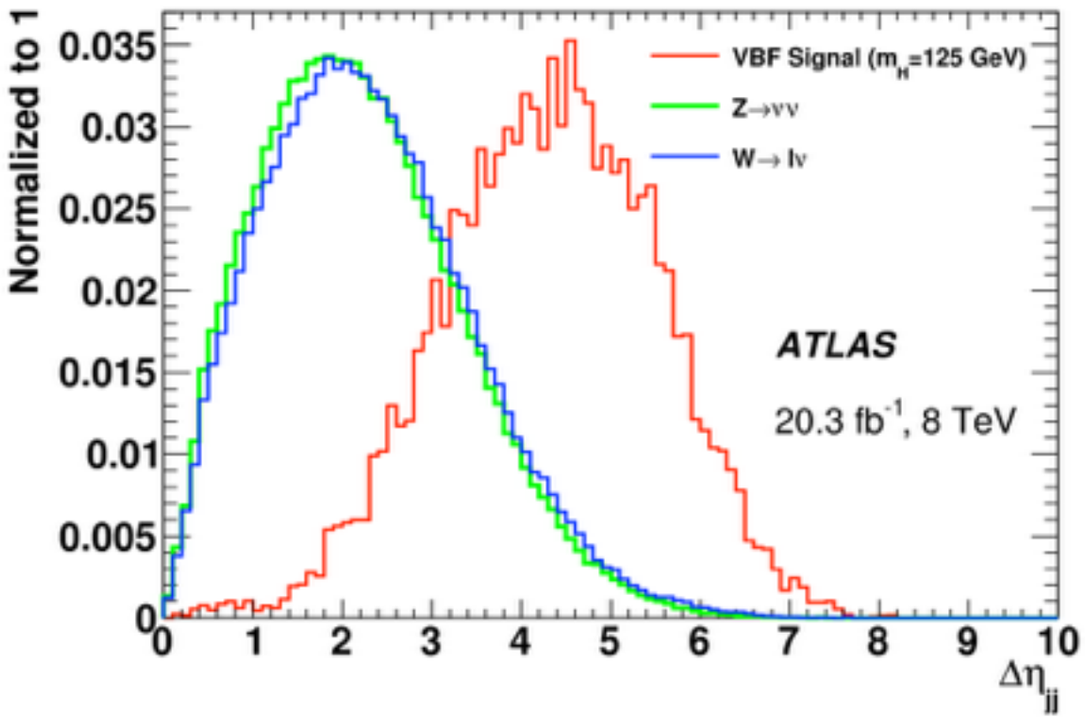


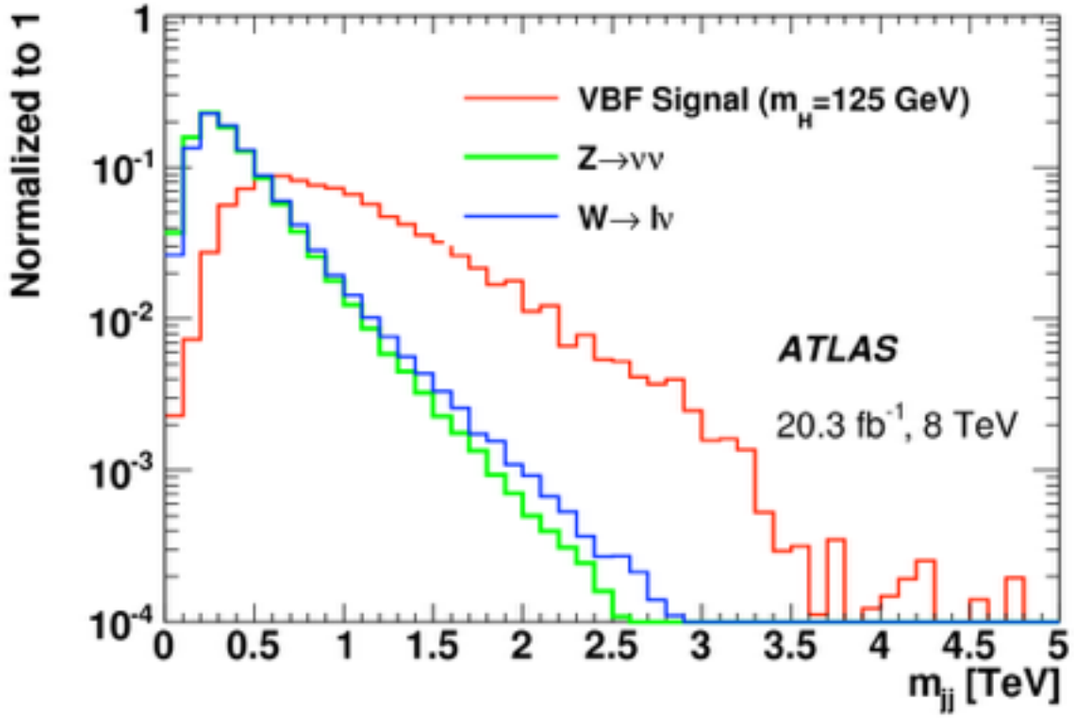
- BR(H→inv.) = 75% observed (63% expected)
- Higgs portal Dark Matter interpretation
  - scalar, vector and fermion DM
  - sensitive to DM with $m_\chi < m_H/2$

1508.07869

VBF H→invisible







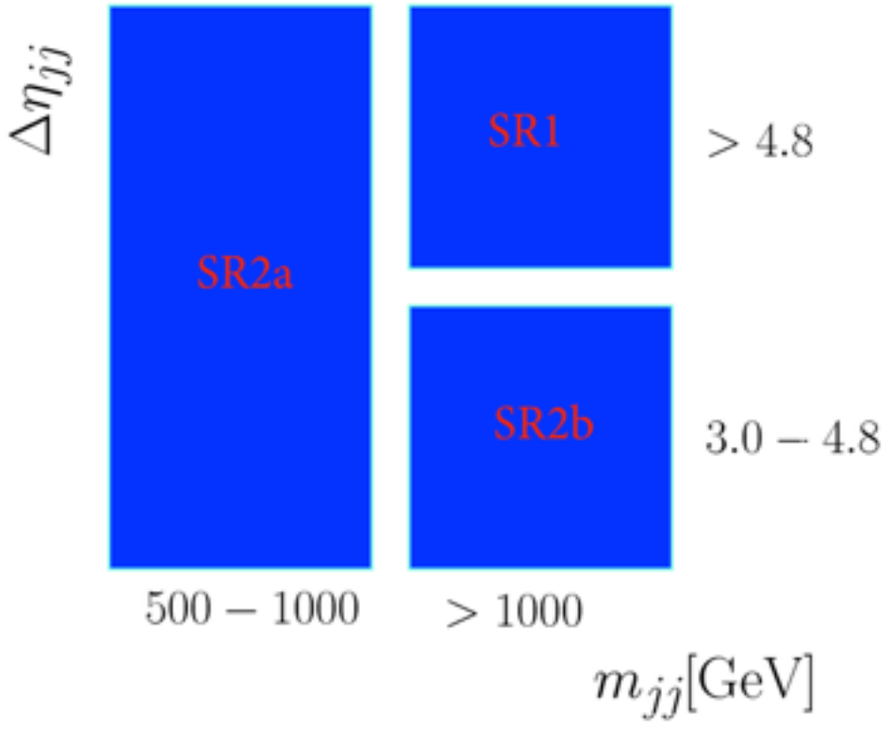
➡ VBF events have distinct topology that allows for efficient signal sensitivity optimisations.

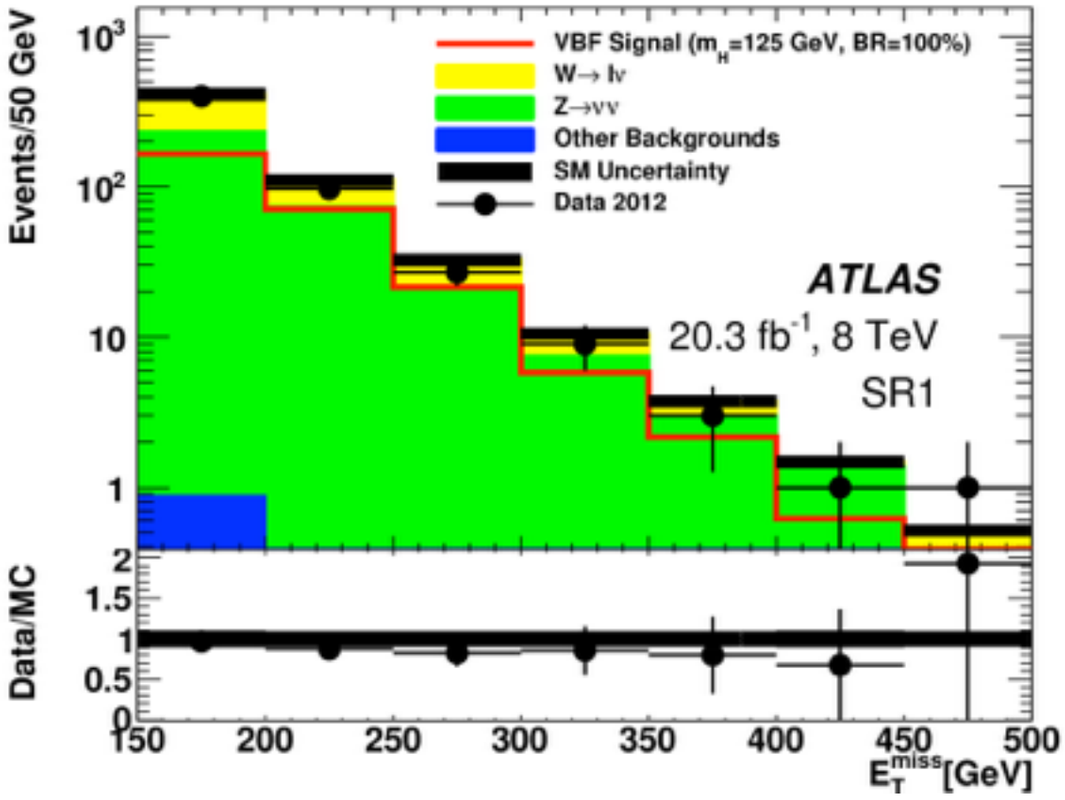
1508.07869

VBF H→invisible

8 TeV 20.3 fb^{-1}

Requirement	SR1	SR2a	SR2b
Leading Jet p_T	>75 GeV	>120 GeV	>120 GeV
Leading Jet Charge Fraction	N/A	>10%	>10%
Second Jet p_T	>50 GeV	>35 GeV	>35 GeV
m_{jj}	>1 TeV	$0.5 < m_{jj} < 1$ TeV	> 1 TeV
$\eta_{j1} \times \eta_{j2}$	<0		
$\lvert\Delta\eta_{jj}\rvert$	>4.8	>3	$3 < \lvert\Delta\eta_{jj}\rvert < 4.8$
$\lvert\Delta\phi_{jj}\rvert$	<2.5	N/A	
Third Jet Veto p_T Threshold	30 GeV		
$\lvert\Delta\phi_{j,E_T^{miss}}\rvert$	>1.6 for j_1, >1 otherwise	>0.5	
E_T^{miss}	>150 GeV	>200 GeV	





95% CL upper limits on BR(H→inv.)

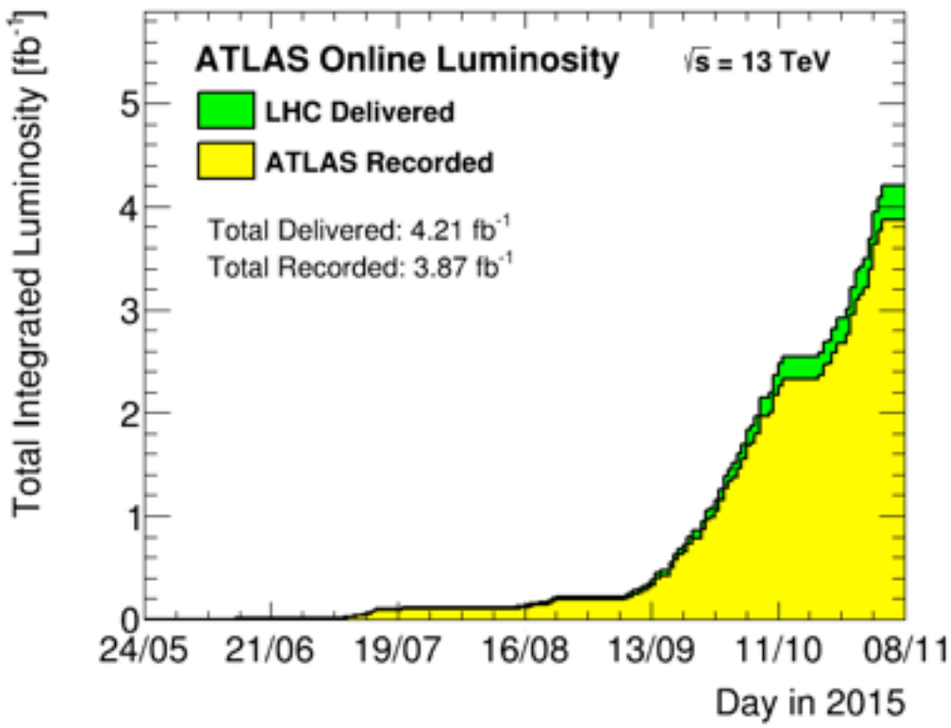
Results	Expected	$+1\sigma$	-1σ	$+2\sigma$	-2σ	Observed
SR1	0.35	0.49	0.25	0.67	0.19	0.30
SR2	0.60	0.85	0.43	1.18	0.32	0.83
Combined Results	0.31	0.44	0.23	0.60	0.17	0.28

→ the most stringent result from LHC Run-1

summary

- Many searches for Dark Matter using MET signatures were developed in Run-1
- EFT models were widely used in Run-1 → validity concerns
- Basic set of simplified models was recommended by the DM Forum
- Close collaboration of the experimental and theory communities continues in the new DM working group within LPCC → focus on the complementarity of experimental results and new models

- Stay tuned for the first Run-2 results!



NEW! released today

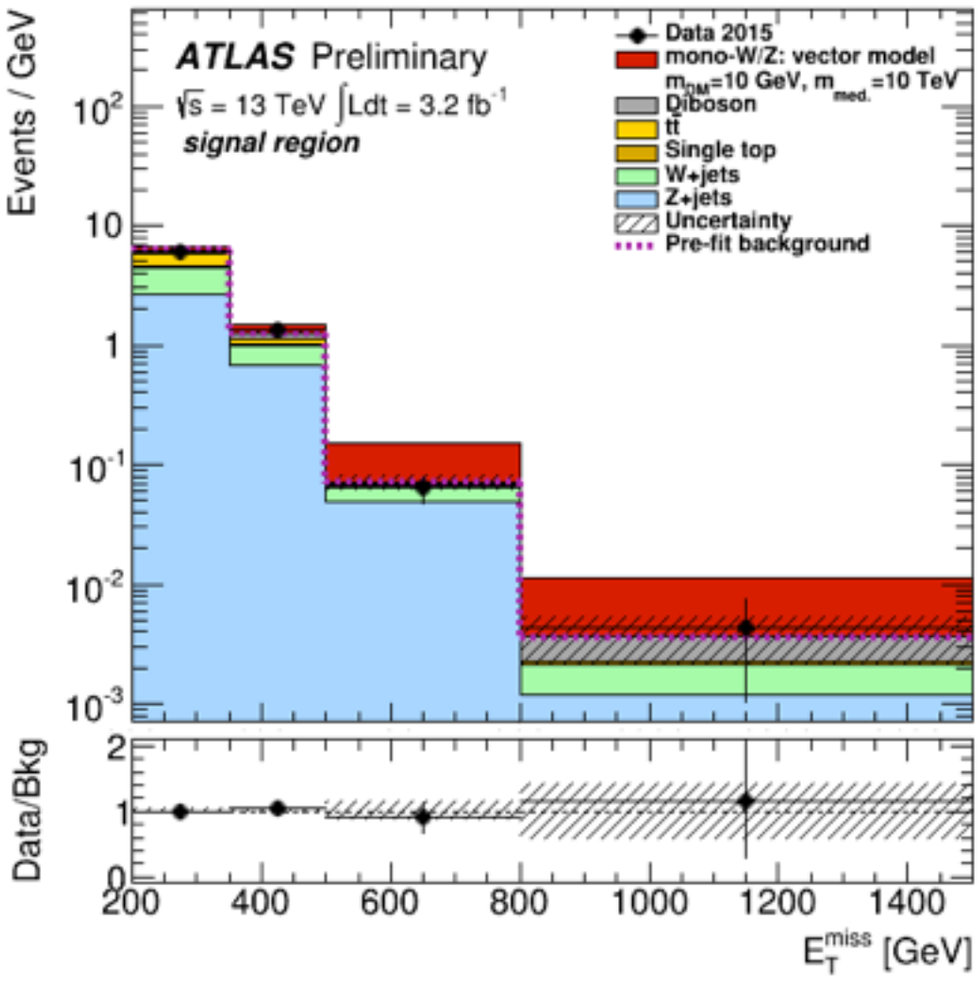
mono-W/Z(qq)

ATLAS-CONF-2015-080

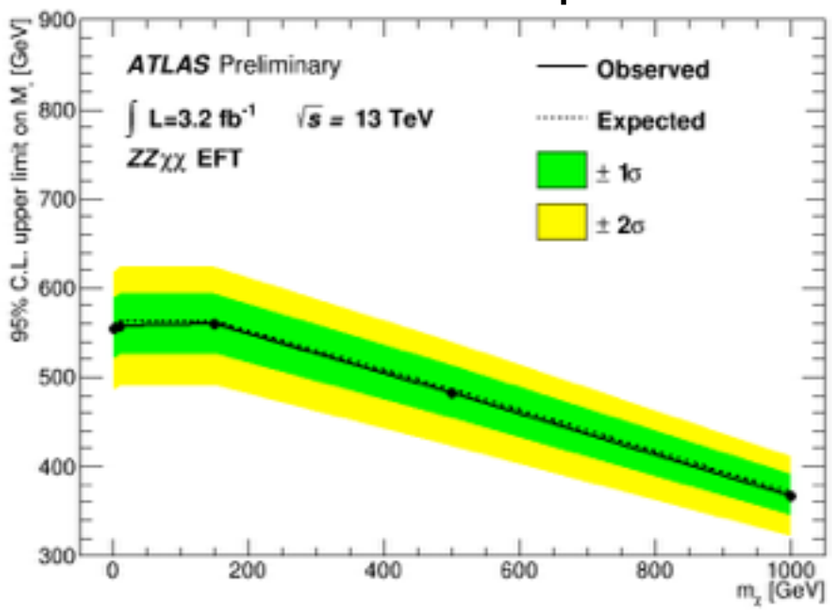
13 TeV 3.3 fb^{-1}

Event selection

- MET trigger
- MET > 250 GeV
- at least one large-R jet



dimension-7 EFT operator



simplified models