Searching for Dark Matter at Collider

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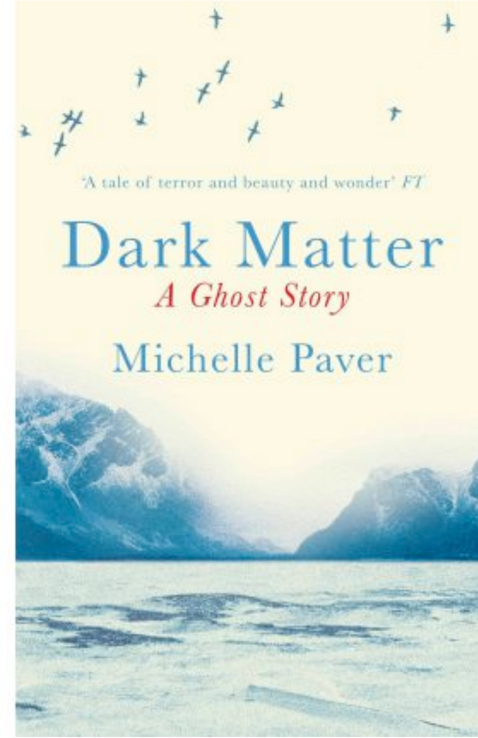
The 2nd International Summer school on TeV Experimental Physics (iSTEP)

Outline

- Dark Matter Introduction
- Collider search at ATLAS
  - DM+jet
  - DM+heavy flavor
  - DM+photon
  - DM+W/Z
  - DM+Higgs
- Prospect

Dark Matter

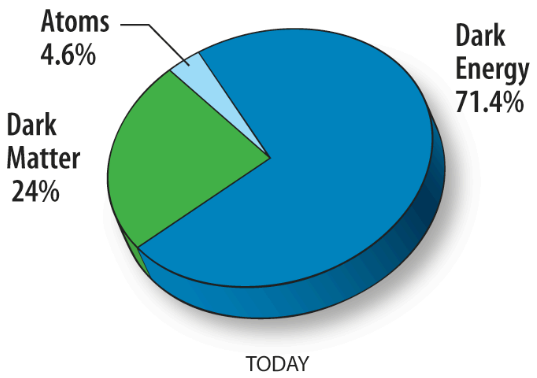

MHP
DARK MATTER
The Ultimate Post Workout Muscle Growth Accelerator

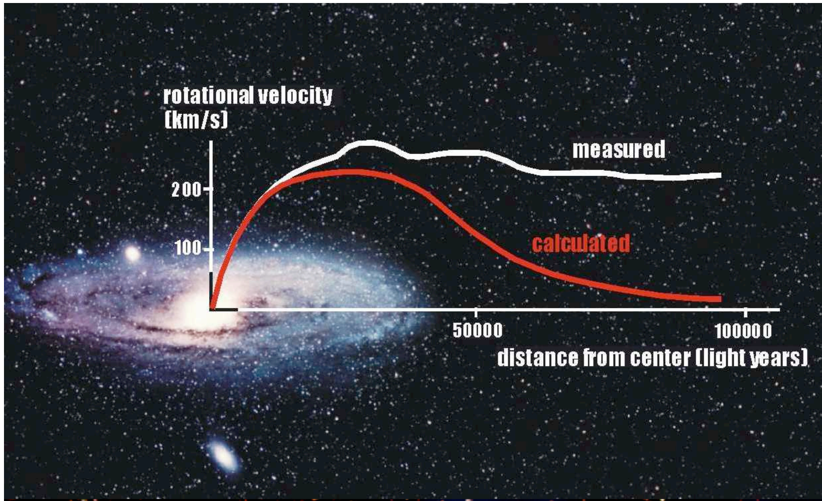

'A tale of terror and beauty and wonder' FT
Dark Matter
A Ghost Story
Michelle Paver

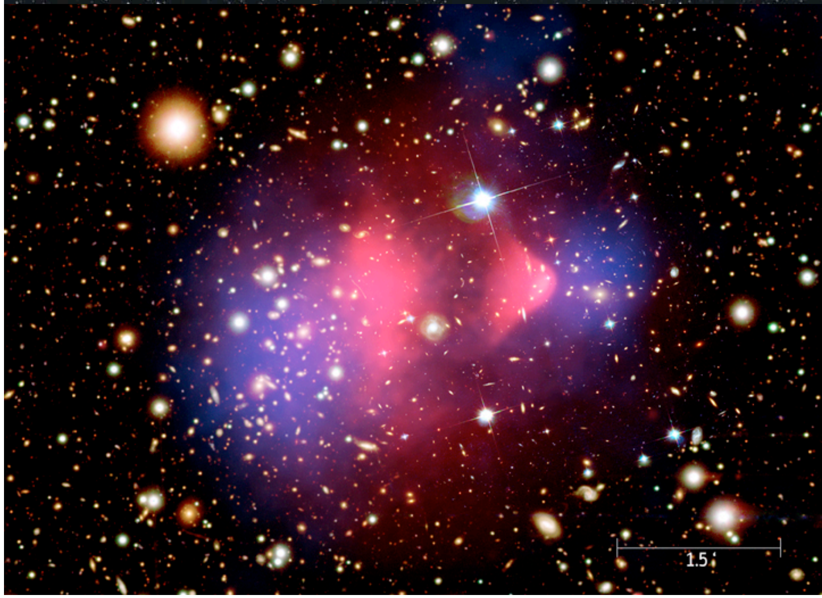

LIU YE AIDAN QUINN MERYL STREEP
DARK MATTER
When he couldn't reach the stars he embraced the darkness
INSPIRED BY A TRUE STORY
THE FAULT IS NOT IN OUR STARS, BUT IN OURSELVES.
- WILLIAM SHAKESPEARE
M
Moderate violence, Infrequent coarse language

Dark Matter

- One of the BSM we are certain of





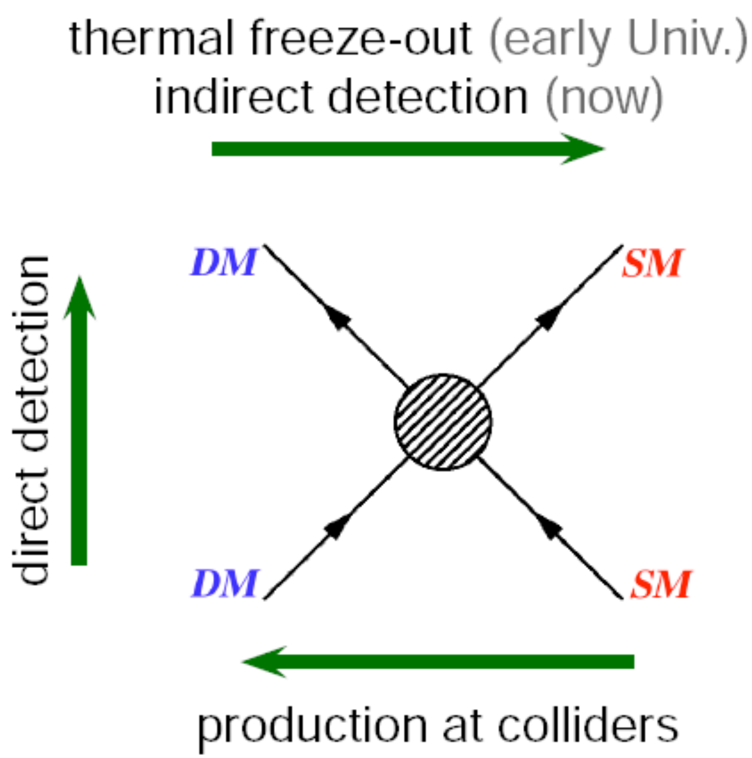


- Its nature remains a mystery

Dark Matter Candidates

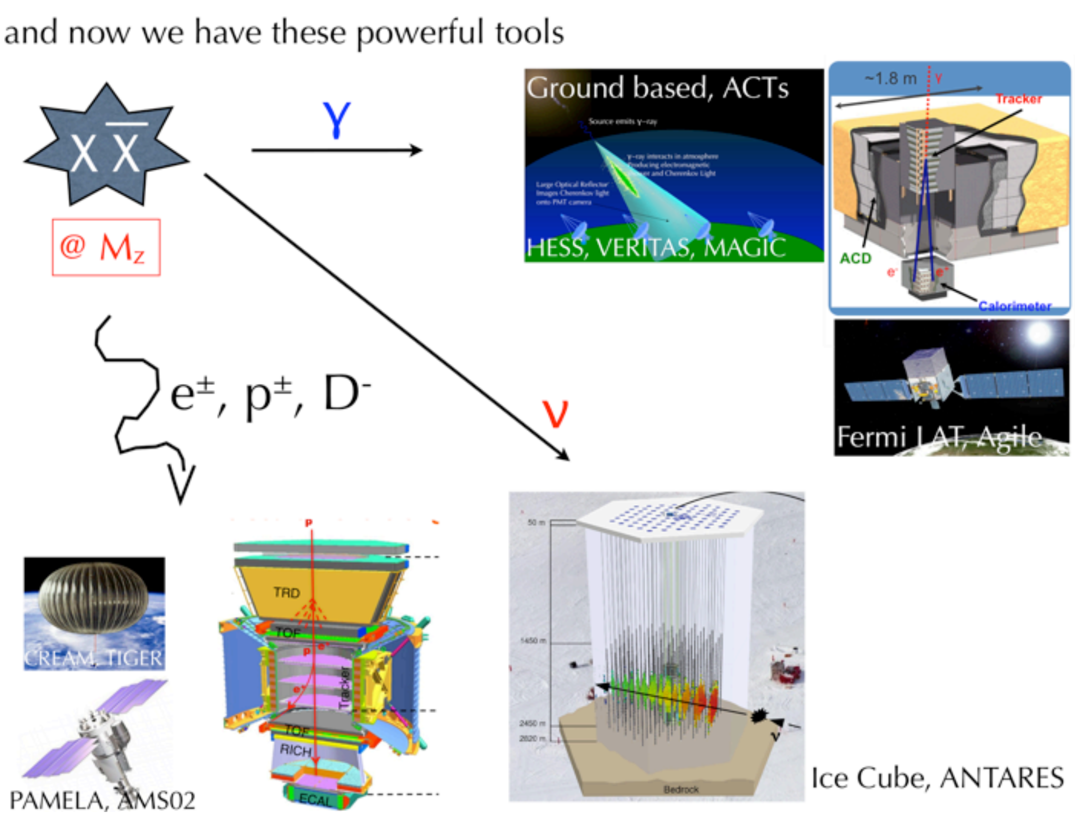
- One possible candidate: **Weakly Interacting Massive Particle (WIMP)**
  - Naturally account for the amount of dark matter we observe in the Universe
  - Occurs in many models of physics beyond the SM
  - We can use particle physics experimental techniques to search for it.

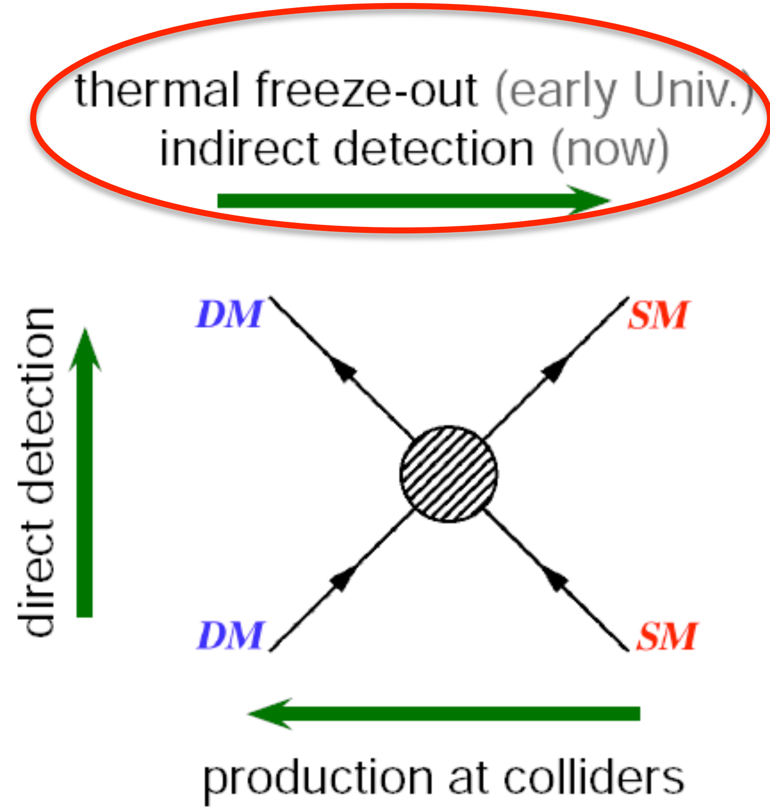
- Three approaches in searching for WIMP
  - Indirect experiments
  - Direct experiments
  - Collider experiments



Searching for WIMP

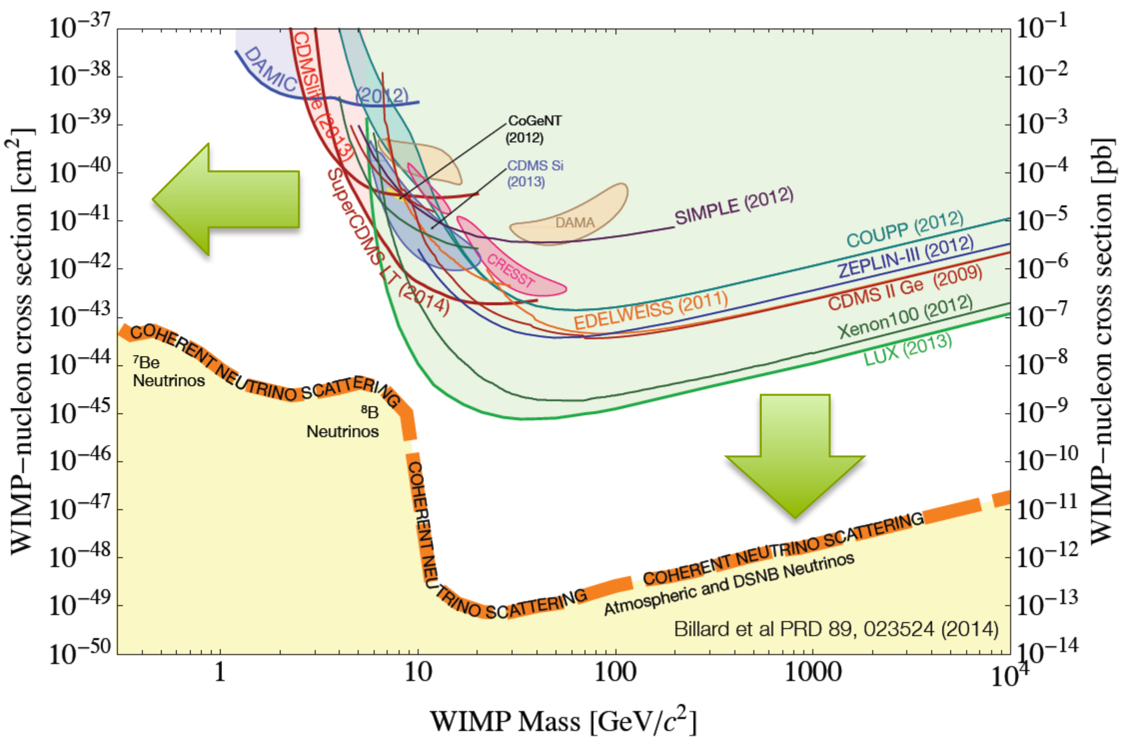
- Indirect detection
  - DM annihilation in nearby galaxies
  - High-energy cosmic-rays, γ-rays, neutrino etc
  - Challenging backgrounds

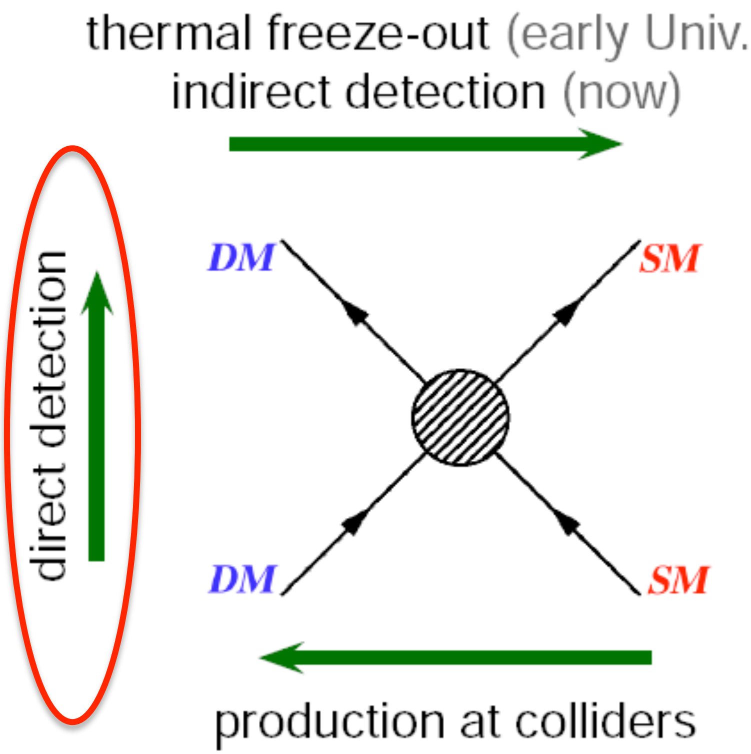




Searching for WIMP

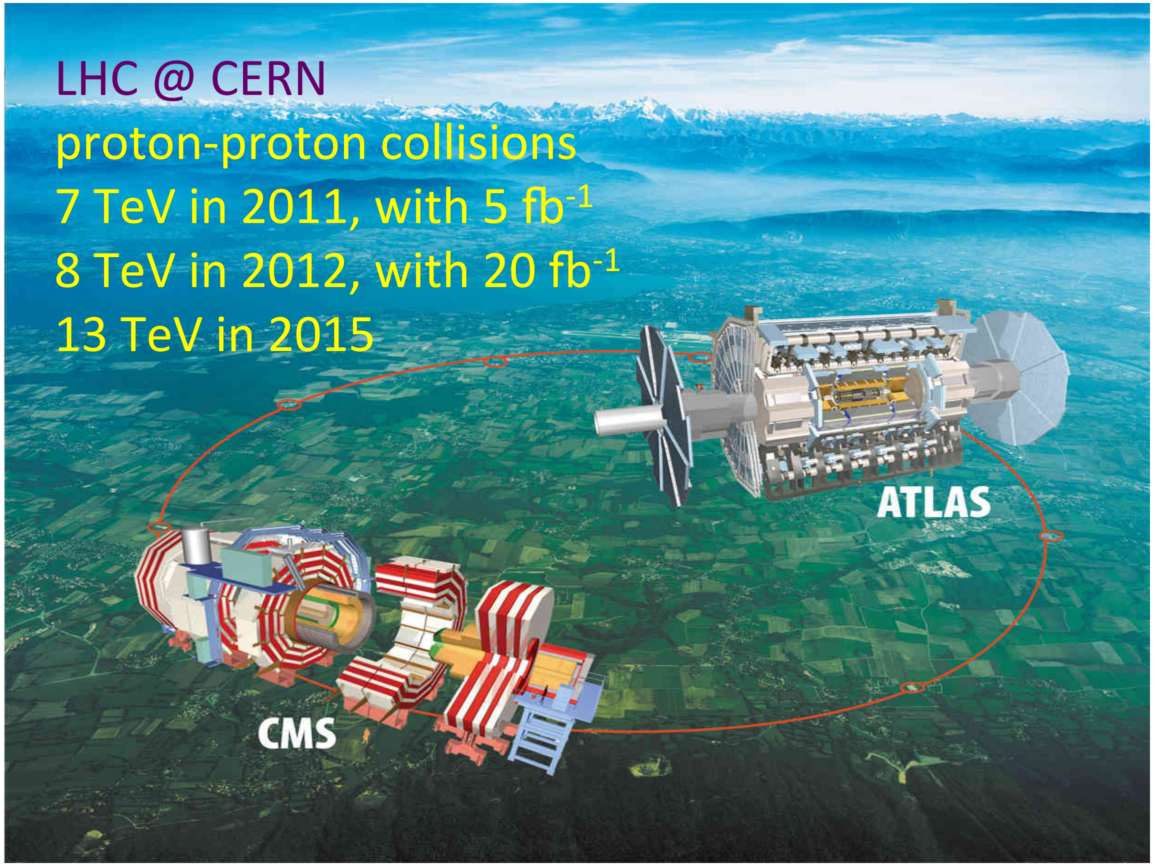
- Direct detection
  - Nuclear (atomic) recoils from scattering
  - Galactic DM in solar system

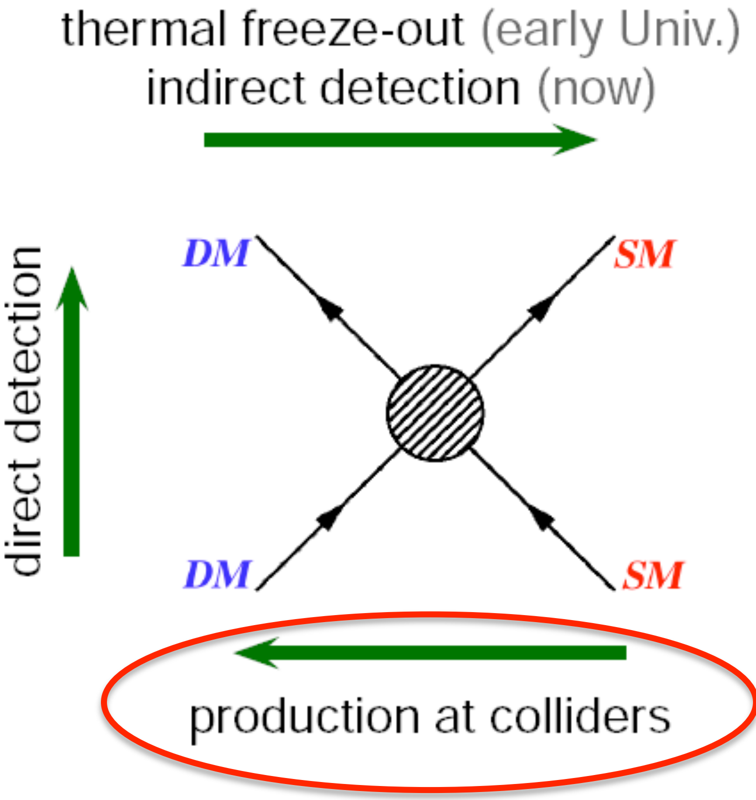




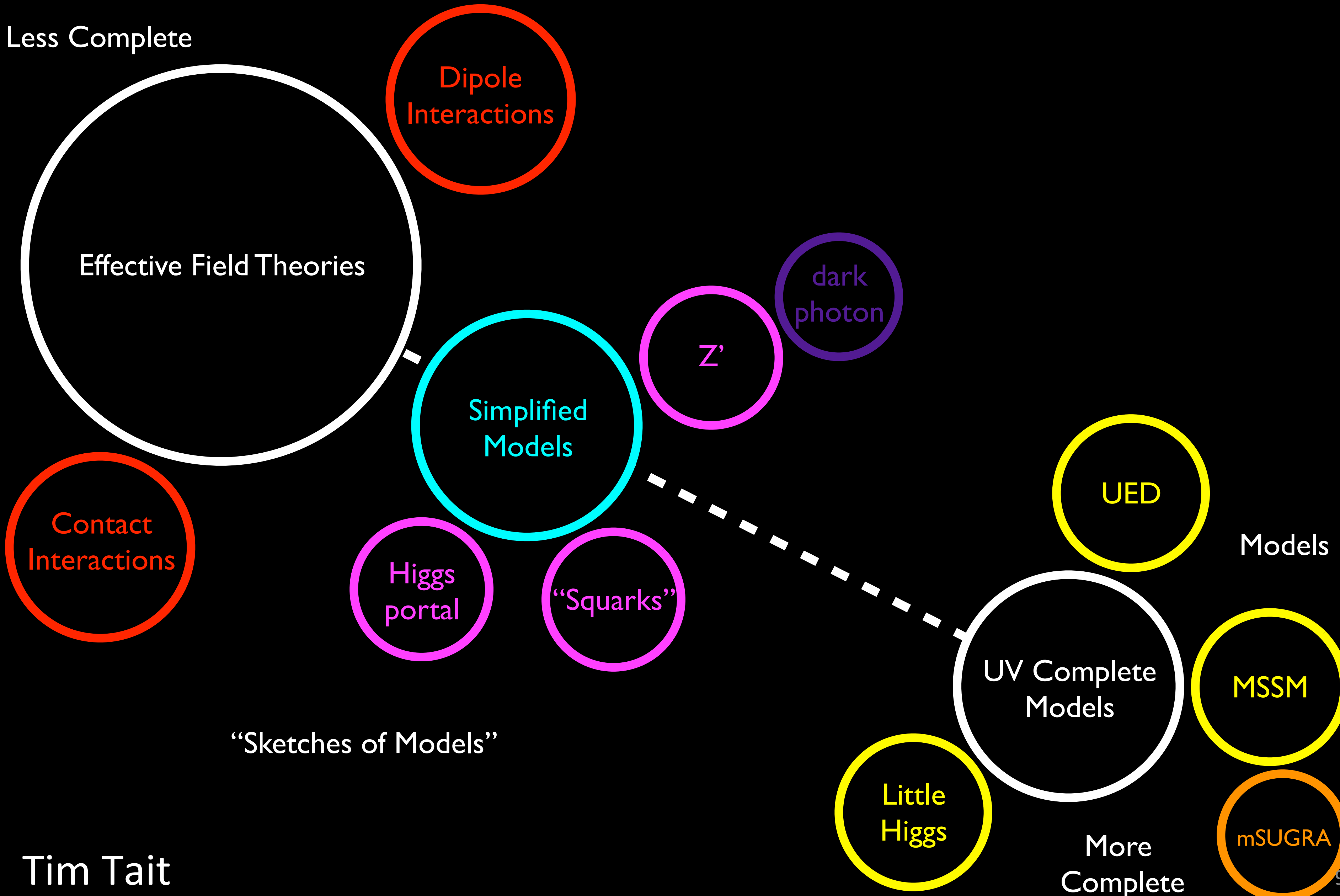
Searching for WIMP

- Collider searches
  - DM production from collisions: independent searches
  - Sensitive to small mass WIMPs
  - May reveal the nature of WIMPs
  - Is the produced new particle a DM?



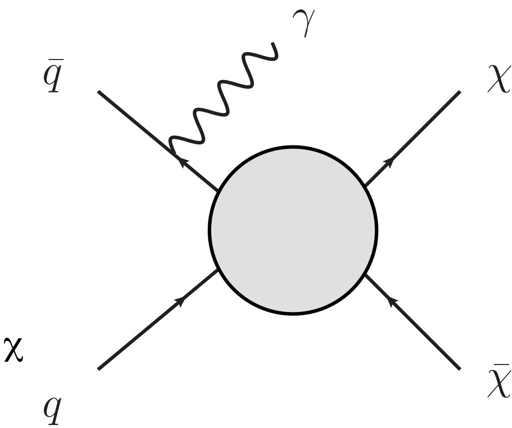


Spectrum of Theory Space

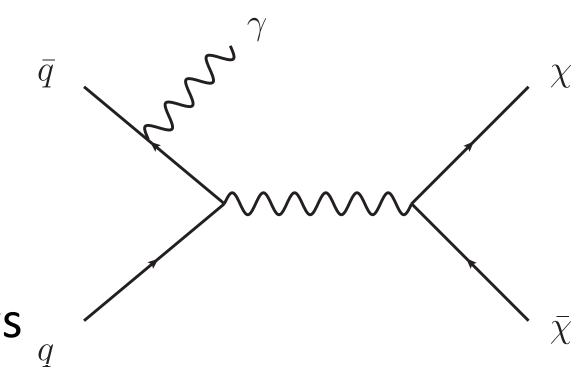


Tim Tait

DM Production

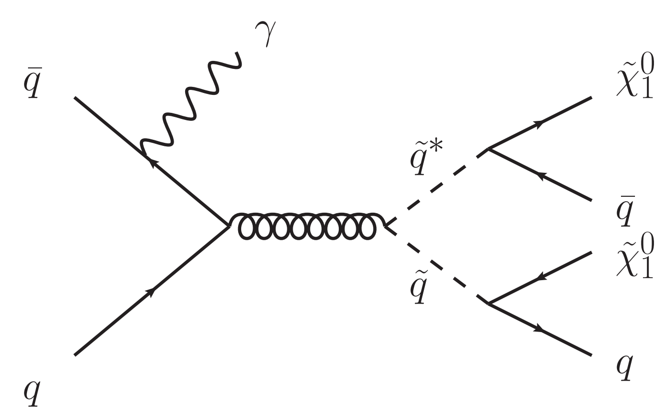


- Effective field theory (EFT)
  - Broad coverage of models by integrating out the details
  - Free parameters: mass scale M* and dark matter mass m_χ
  - Validity concerns



- Simplified model: UltraViolet-complete
  - Keep the information of intermediate state
  - s-channel or t-channel
  - Parameters: Mediator mass M_{med}, width Γ, couplings

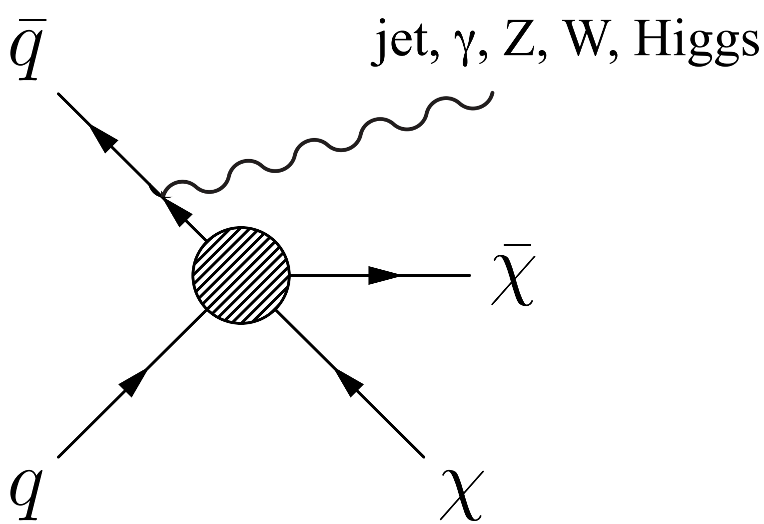
$$\frac{g_f^2 g_\chi^2}{(Q_{tr}^2 - m_V^2)^2} \xrightarrow{Q_{tr} << m_V} \frac{g_f^2 g_\chi^2}{m_V^4} = \frac{1}{M_*^4}$$

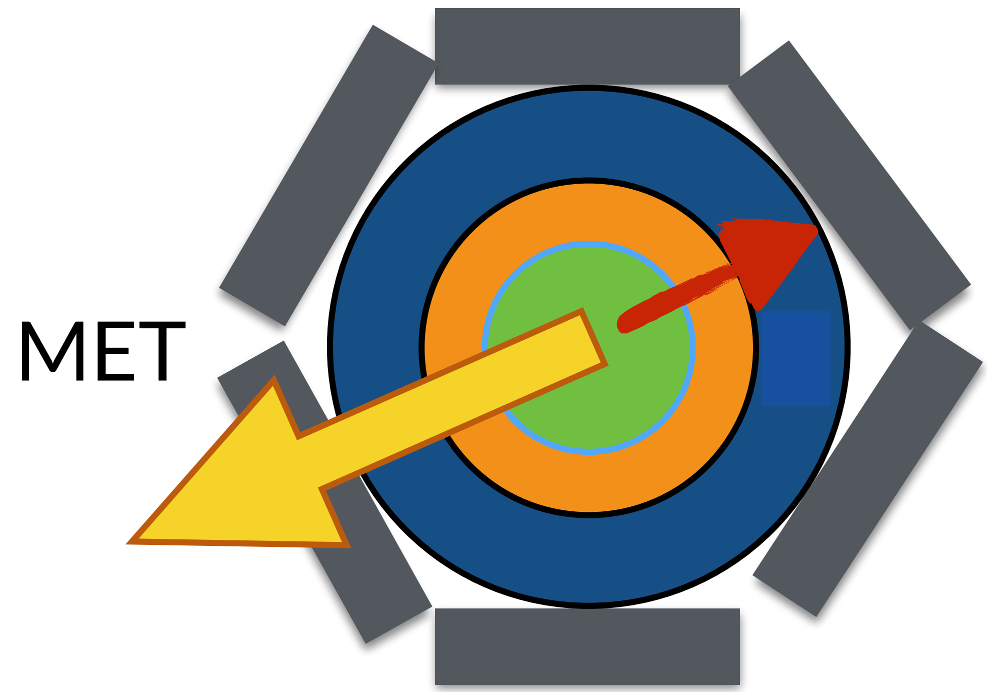


- Full theory model
  - Compressed SUSY

Dark Matter in Detector

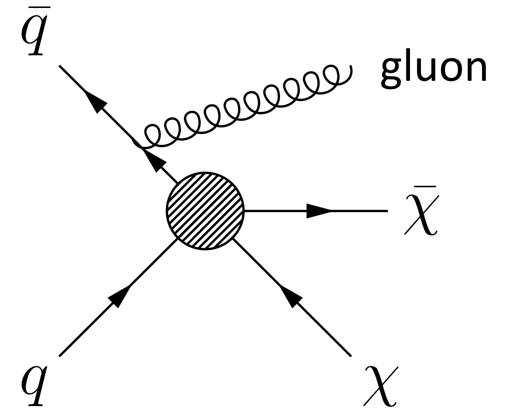
- Colliders may produce small mass DM
- DM is invisible to our detectors
- DM+X processes – co-production of DM and visible particles
  - DM + Jet, photon, Z, W, Higgs
  - Large missing transverse energy (MET)



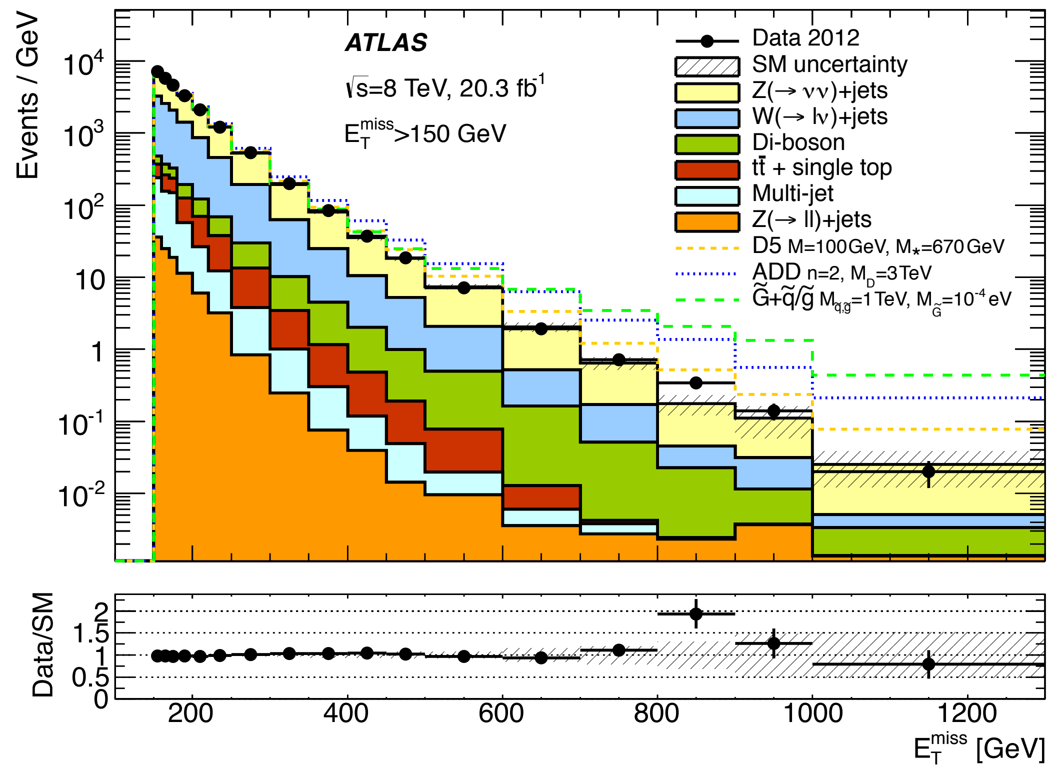


DM + jet

EPJC (2015) 75:299

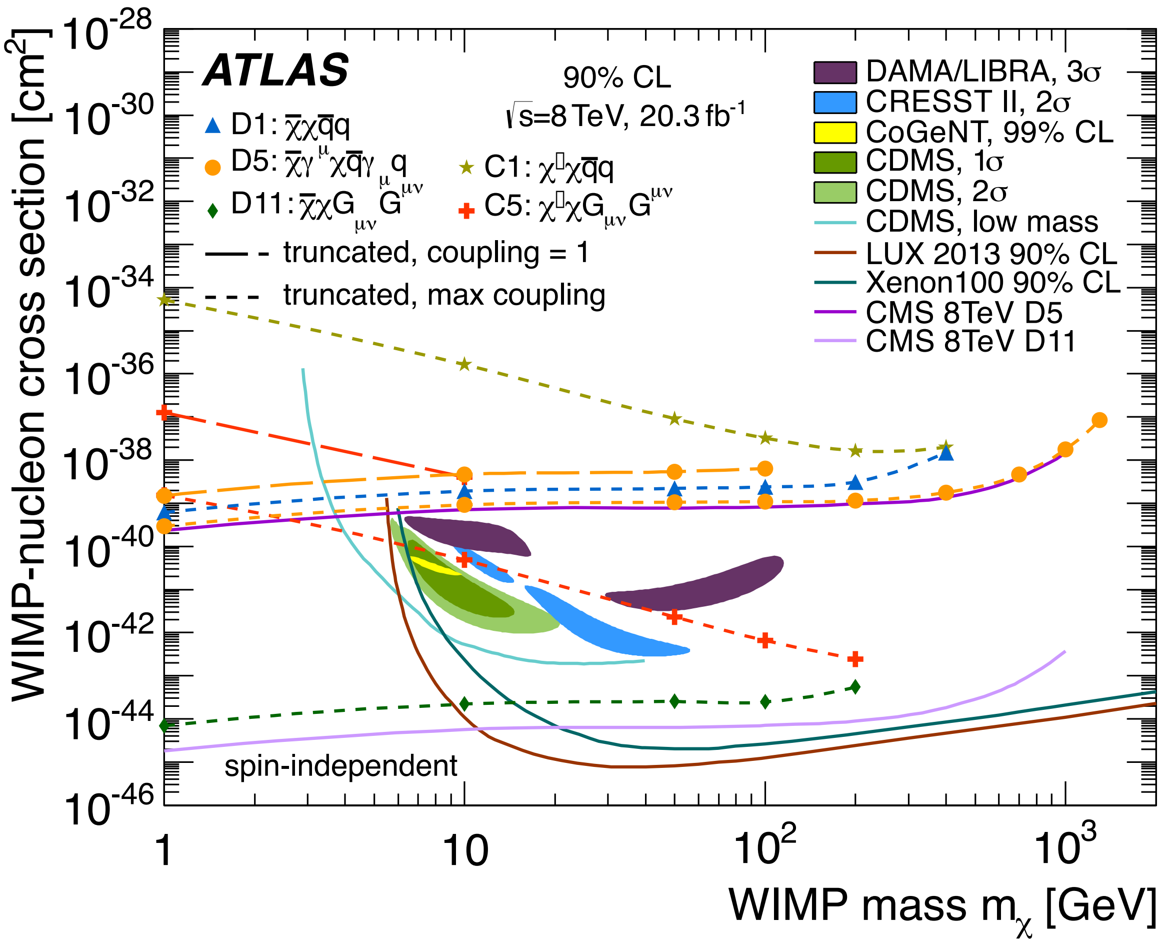


- Jet from ISR gluon
  - Strongest sensitivity for general DM model
- MET > 150 GeV (trigger)
- At least one energetic jet
  - pT > 120 GeV, |η|<2.0
  - pT / MET > 0.5
  - Dphi (jet, MET) > 1.0
- Multiple SR
  - MET > 150 – 700 GeV
- No significant excess



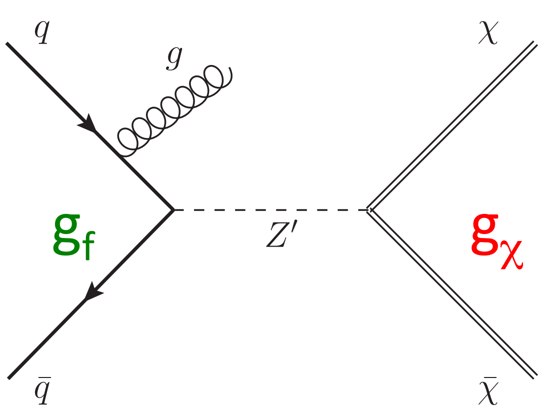
Constraints on Direct Detection

- Via EFT model, derive the constrains on the DM-nucleon scattering cross section
- Sensitive to low mass DM

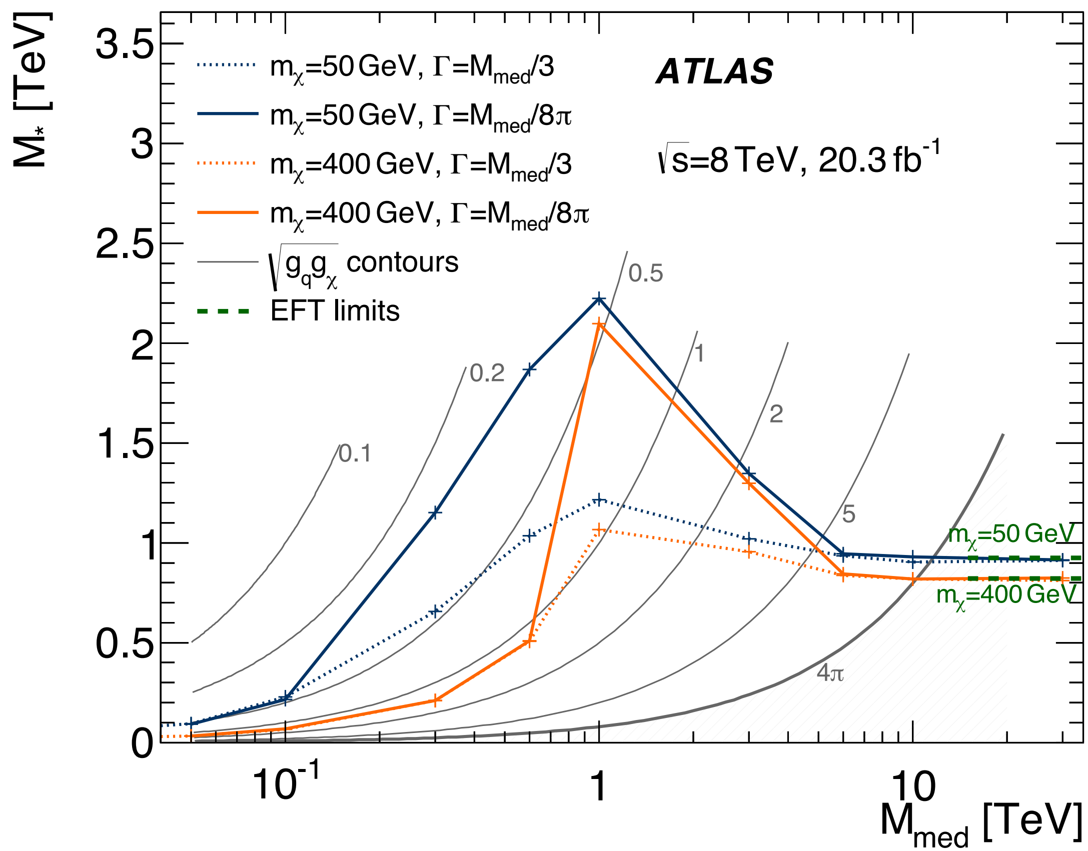


Simplified Model

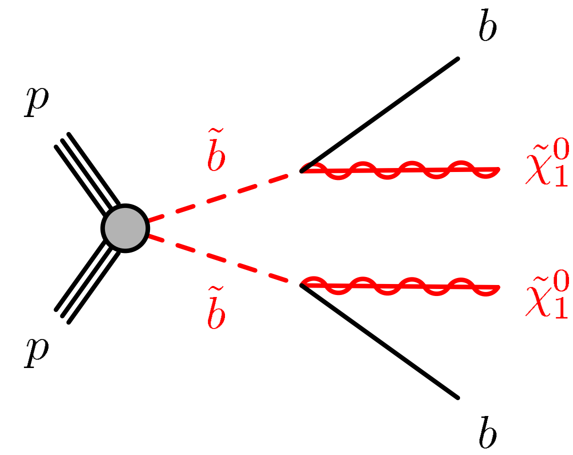
- Go beyond EFT with a UV-complete simplified model
- Z'-like mediator with vector/axial-vector interaction
  - Parameter: mediator mass M_{med}, mediator width Γ, dark matter mass m_χ
- Limits are set on $M^* \equiv M_{med} / \sqrt{g_f g_\chi}$



P. Fox et al. arXiv:1109.4398



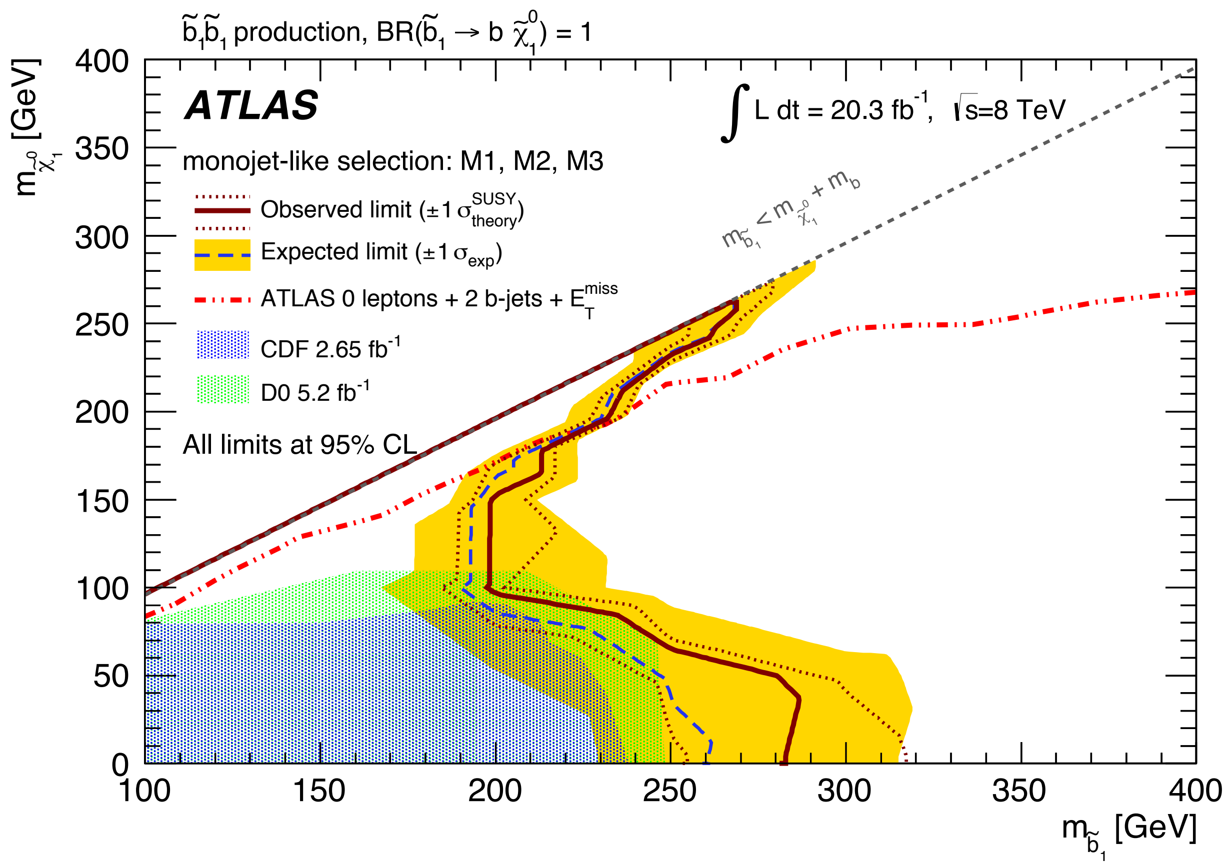
Compressed SUSY



- Small mass splitting between squark and LSP
  - Quarks too soft to be reconstructed as jets

- ISR gluon gives DM + jet signature: complementary to SUSY zero-lepton search

PRD 90, 052008 (2014)

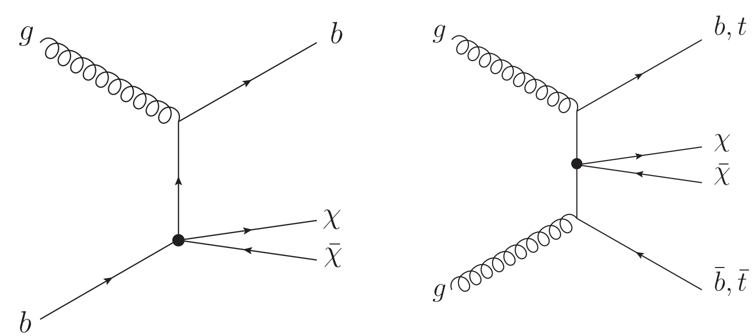


DM + heavy flavor

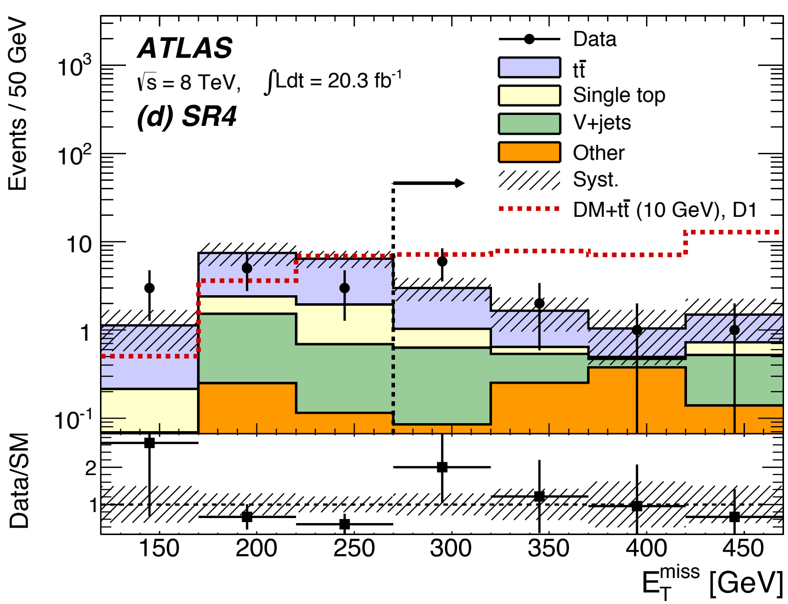
EPJC (2015) 75:92

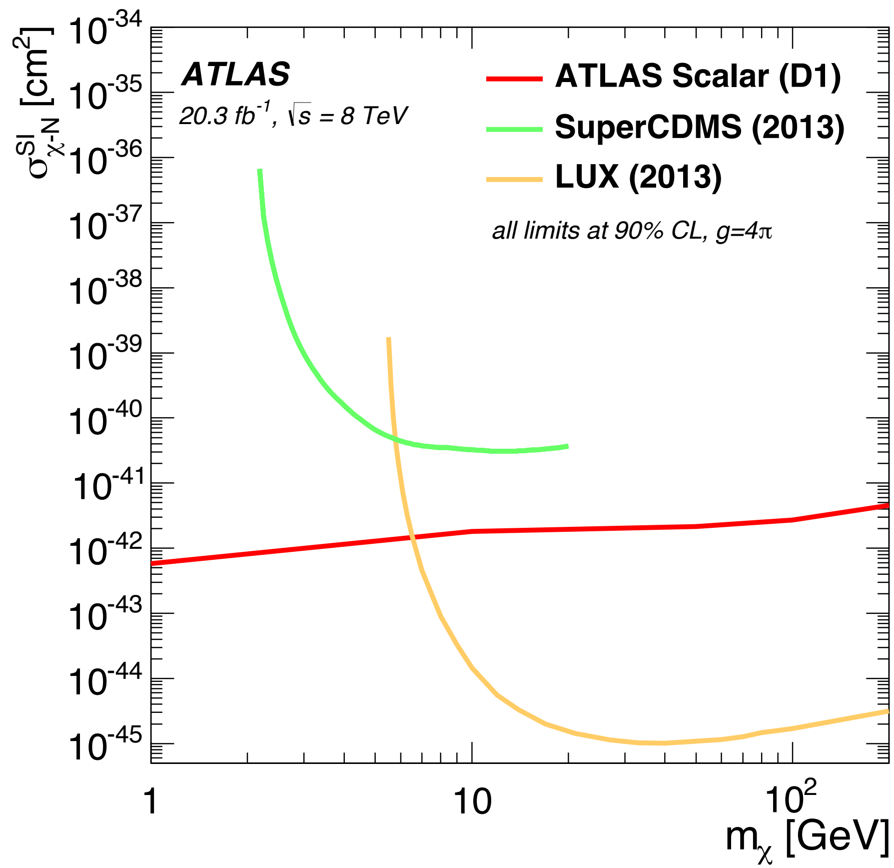
- If DM coupling to SM has a Yukawa term
  - EFT scalar operator

$$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$$



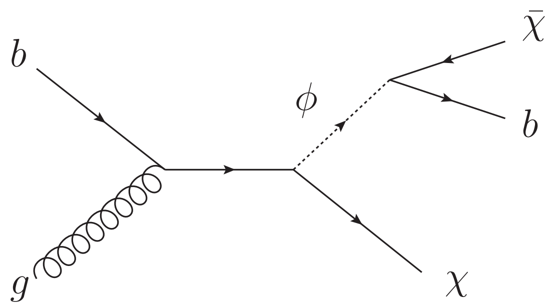
- SR1: DM + b
- SR2: DM + bbbar
- SR3: DM + ttbar (full hadronic)
- SR4: DM + ttbar (semil-leptonic)
  - In collaboration with SUSY stop team



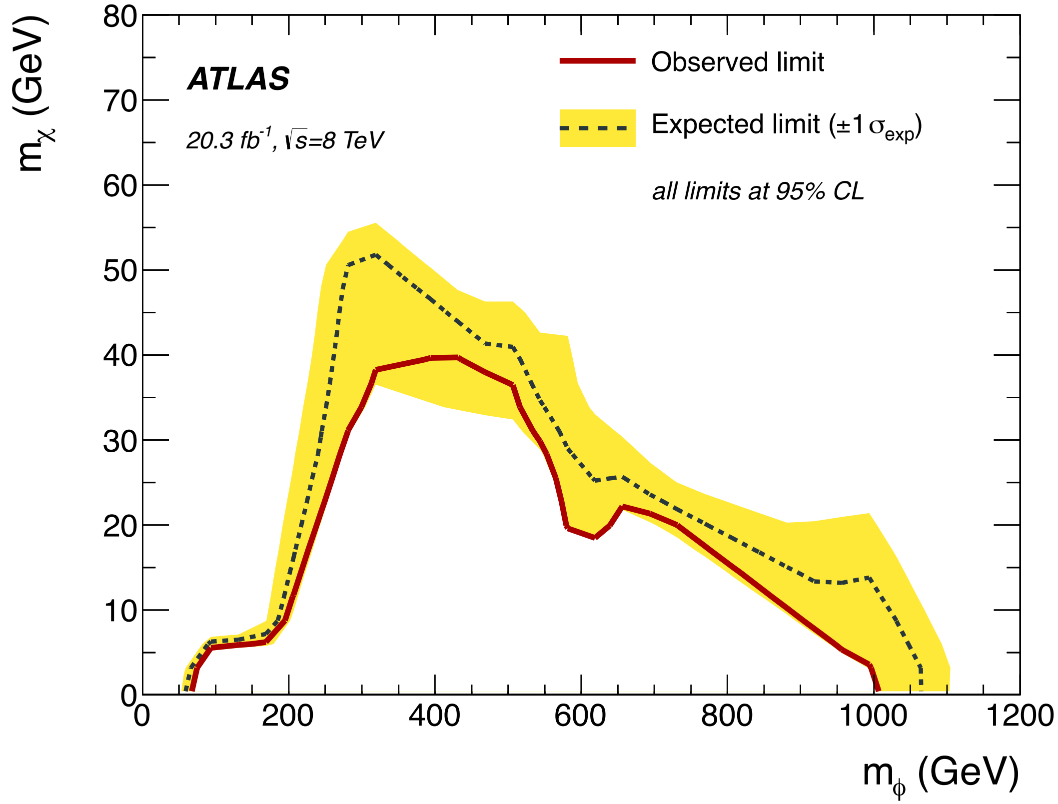


DM + heavy flavor

- b- FDM model: motivated by the Fermi-LAT ~ GeV line (Hooper)



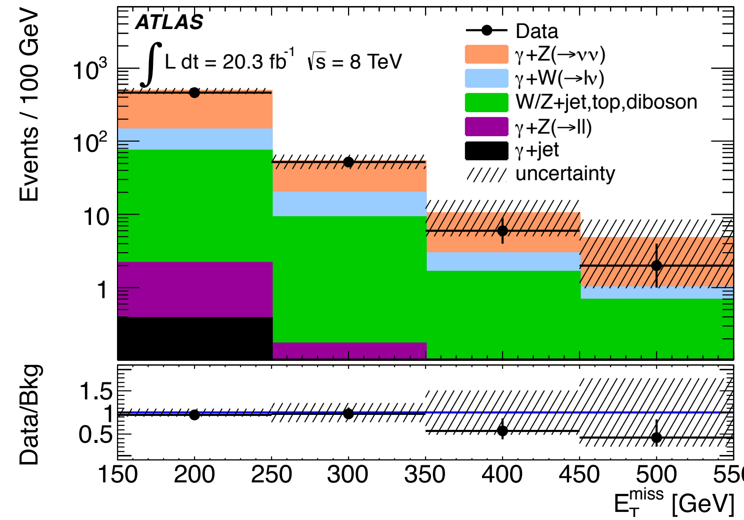
P. Agrawal et al. arXiv:1404.1373



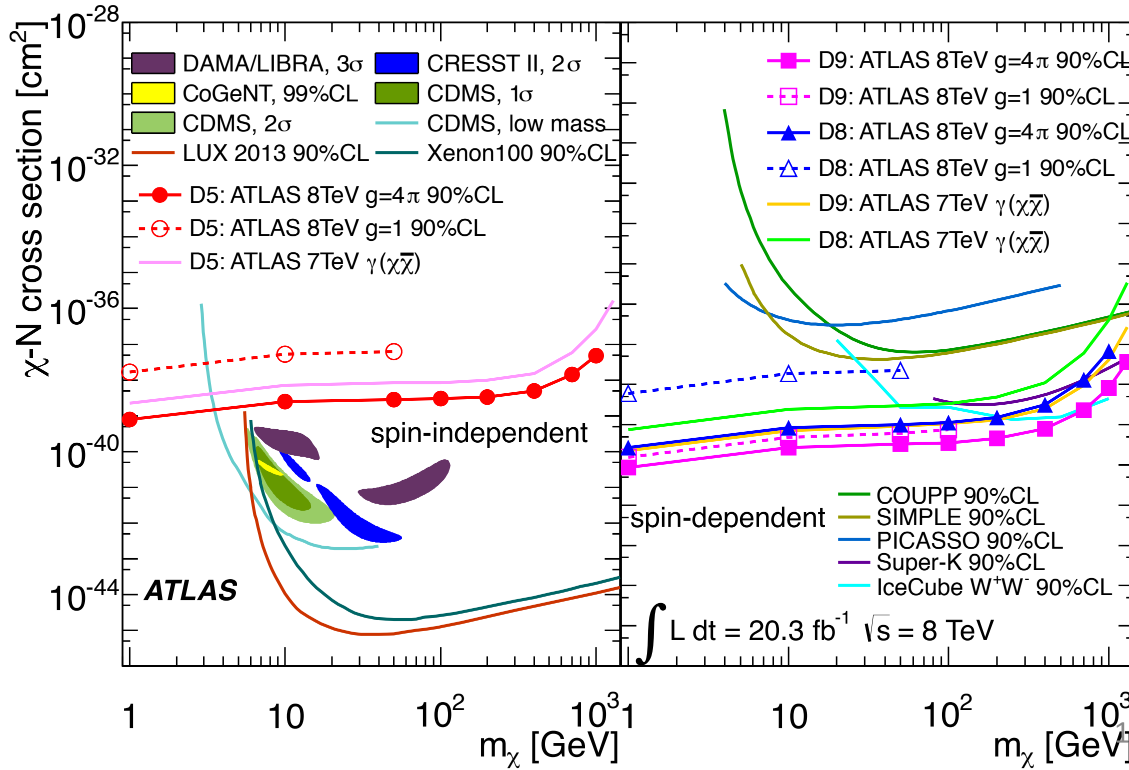
DM + photon

Phys. Rev. D 91, 012008 (2015)

- Good photon, $E_T > 150$ GeV
- 0 or 1 additional jet
- Veto on electron and muon
- SR: $E_T^{miss} > 150$ GeV

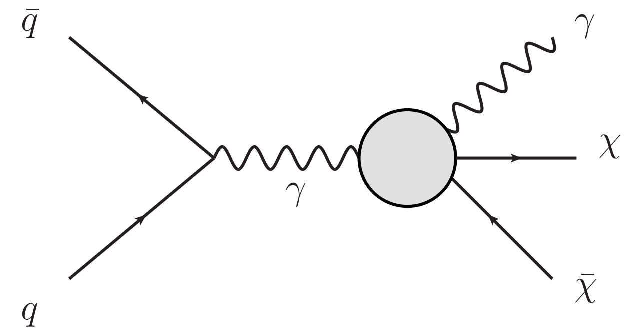


- Complementary to DM+jet channel in terms of EFT model



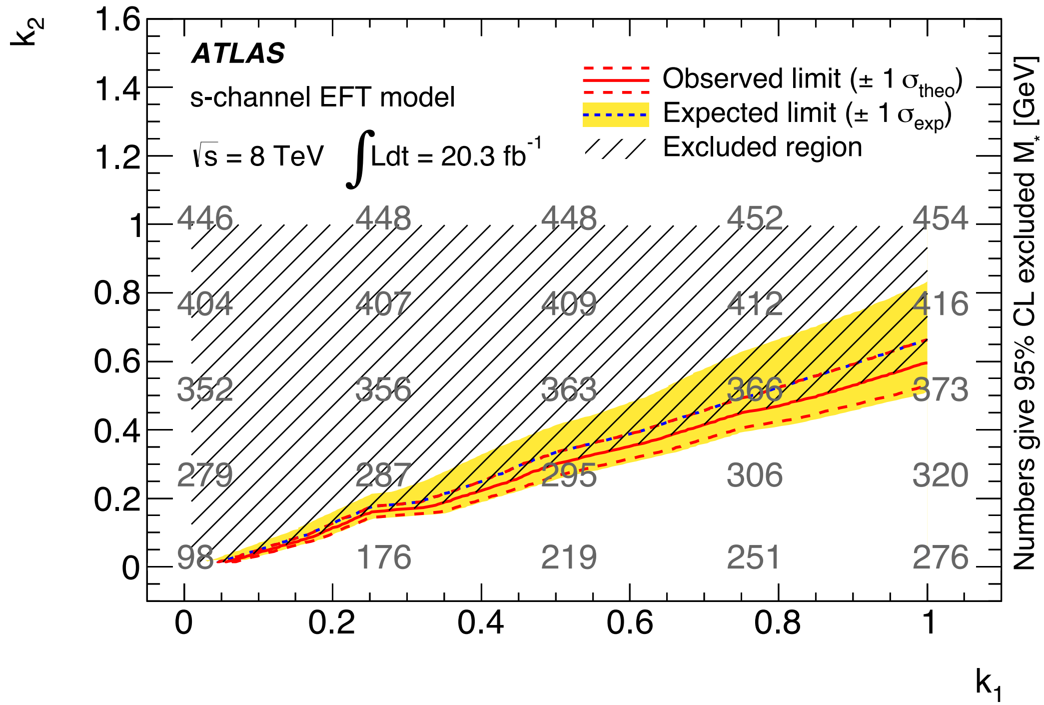
DM + photon

- Sensitive to dark matter direct coupling to photon
- Motivated by the Fermi-LAT
  - DM 130 GeV



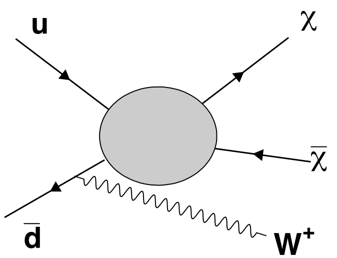
A. Nelson et al. arXiv:1307.5064

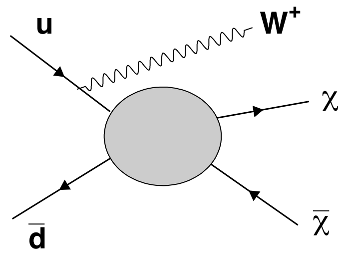
The effective coupling to different bosons is parametrized by the coupling strengths k1 and k2, which control the strength of the coupling to the U(1) and SU(2) gauge sectors of the SM, respectively.



DM + W (qq)

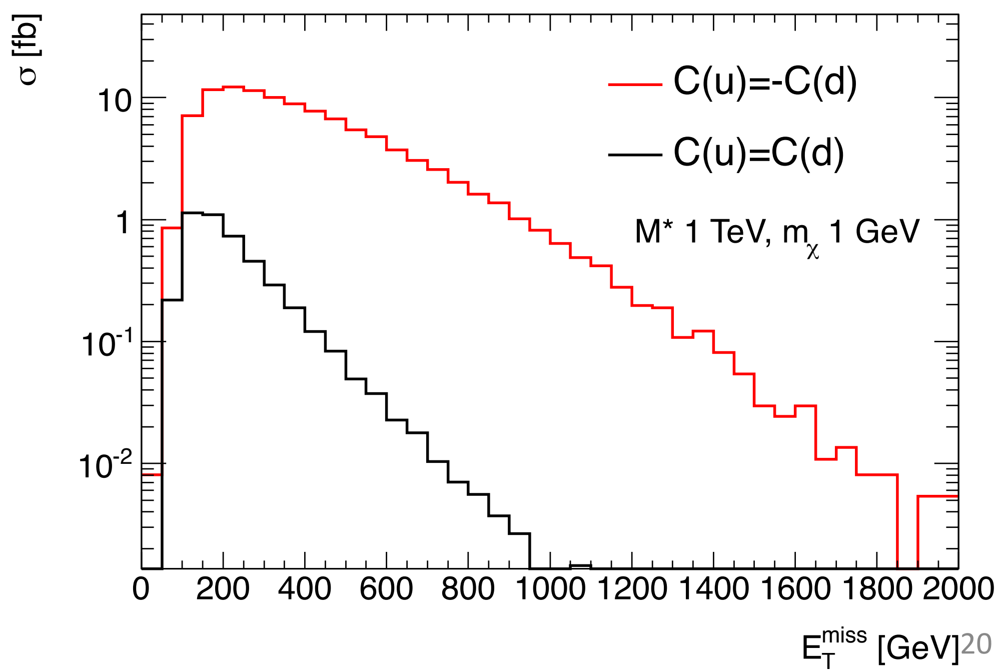
PRL 112, 041802 (2014)





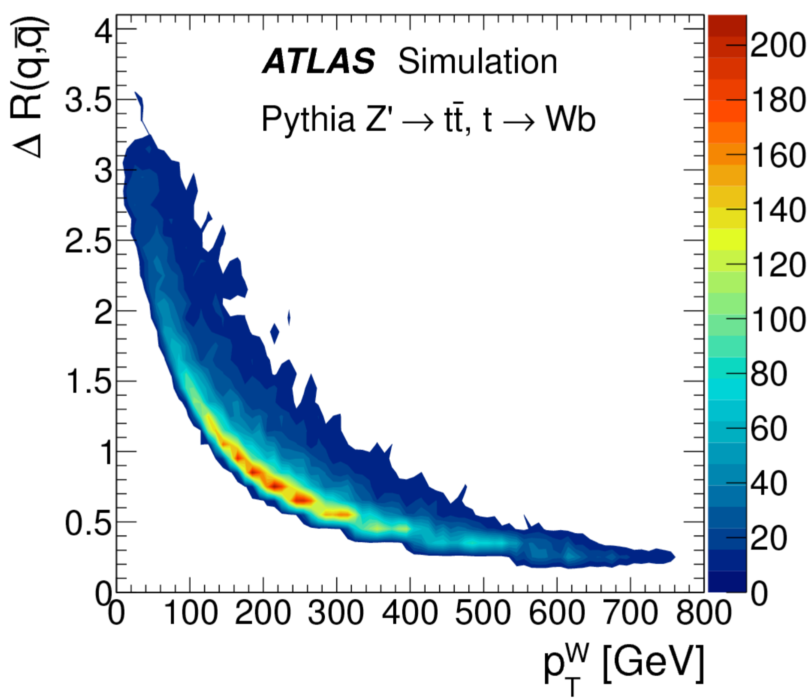
Sensitive to the sign of DM couplings to up and down quarks

- C(u) = - C(d): constructive interference
- C(u) = C(d): destructive interference



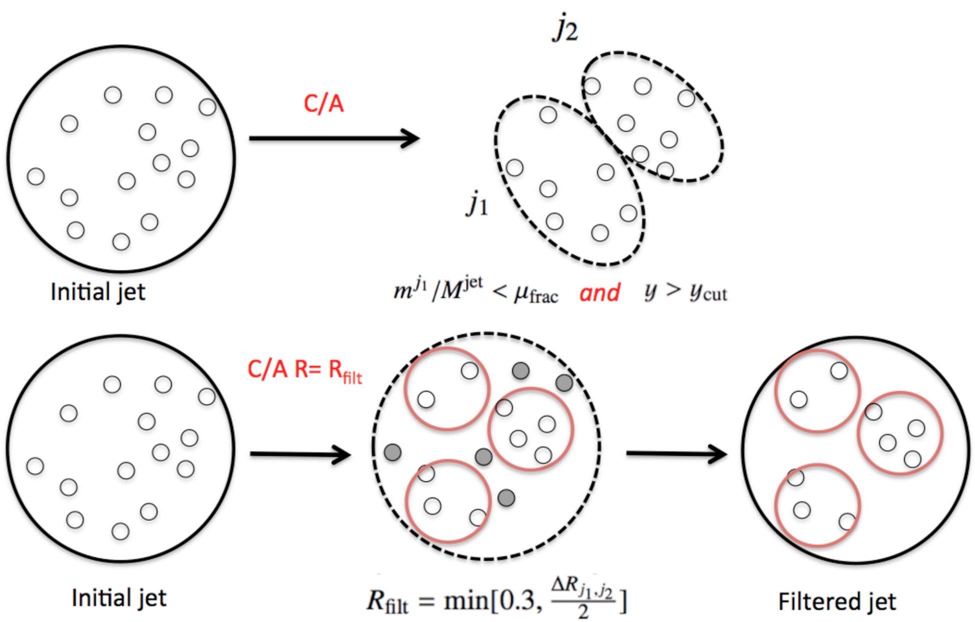
Searching Strategy

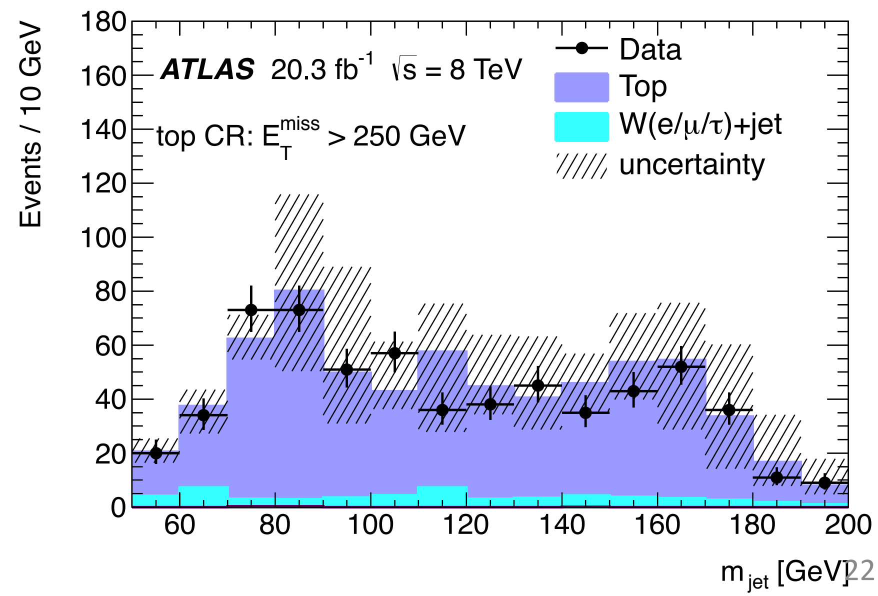
- **Signature:**
  - Missing transverse energy (MET), single W or Z with hadronic decay
- **Strategy:**
  - Large MET
  - Quarks from boosted W or Z tend to be close and merge as one jet
  - Single large-radius jet to identify boosted W or Z
  - Signals will show a W or Z peak in jet mass spectrum



Jet Substructure (1)

- Large-radius jet:
  - Cambridge-Aachen (C/A) jet with radius of 1.2
- Mass-drop/filtering:
  - Identifying relatively symmetric sub-jets
- This groomed jet is able to reconstruct the W boson, as shown in control region.
  - It includes a W peak and a tail due to the inclusion of (part of) the b jet from top decay $t\bar{t}$

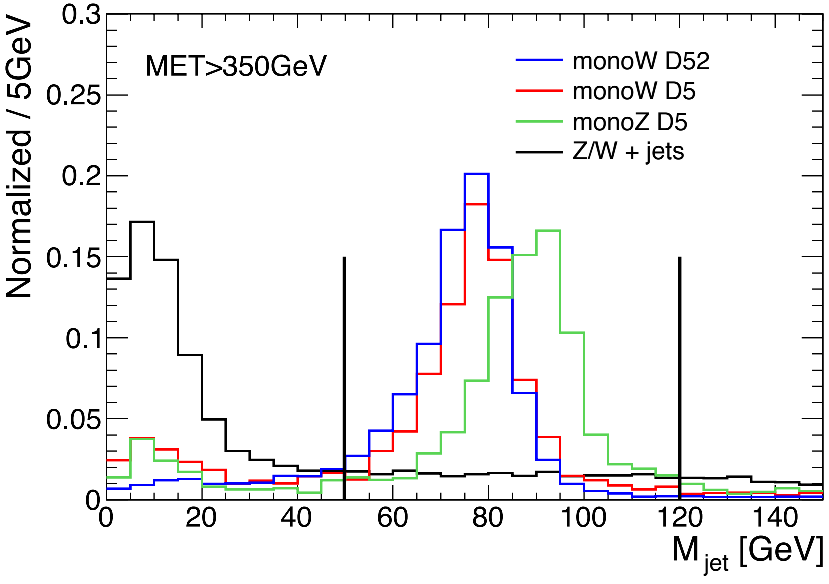




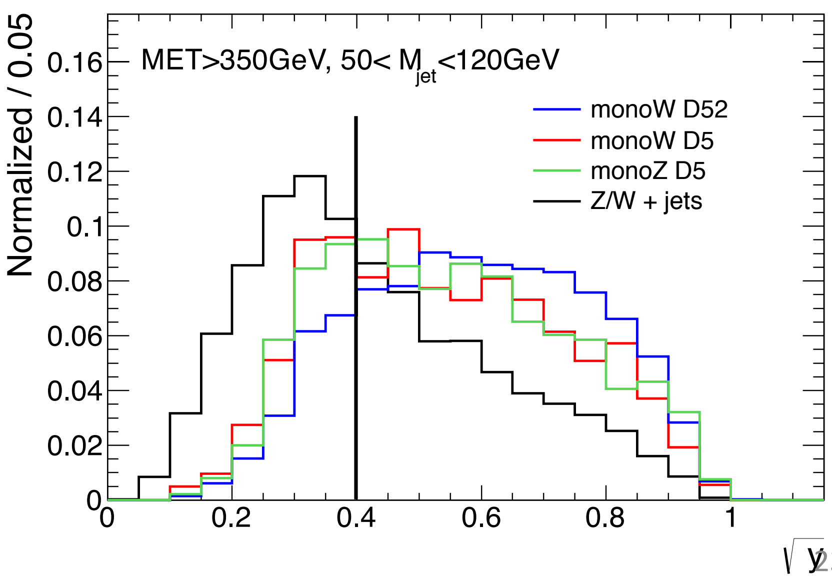
Jet Substructure (2)

- Discriminants against jets not from W/Z decay.
  - Jet mass: m_{jet}
  - Two sub-jets momentum balance: $\sqrt{y} = \min(p_{T1}, p_{T2}) \times dR_{12} / m_{jet}$
- There are other boson-tagging techniques under development. Not used here yet.

Jet mass

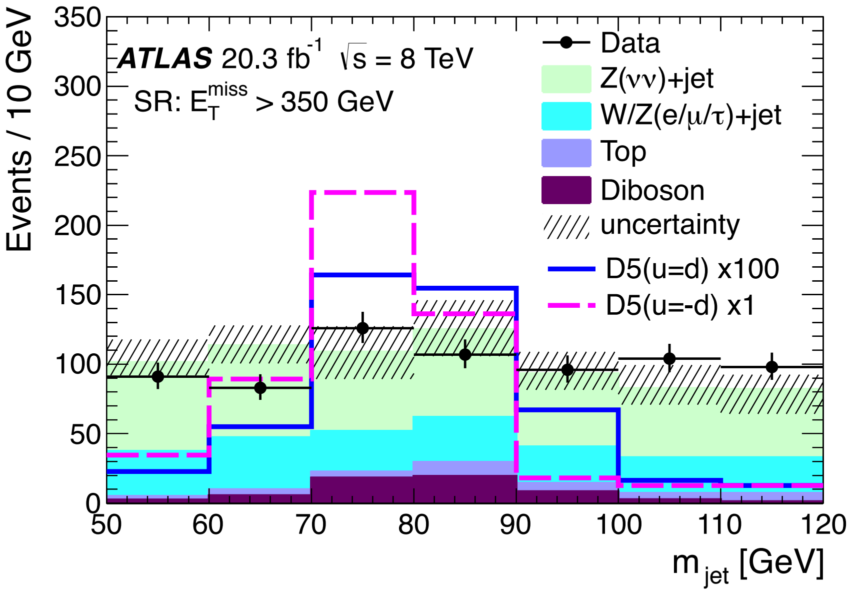


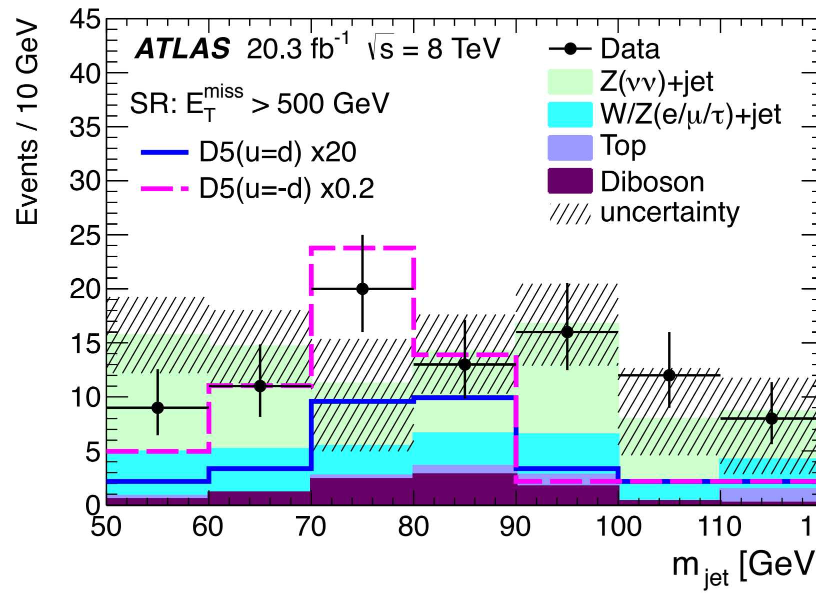
Momentum balance



DM + W (qq)

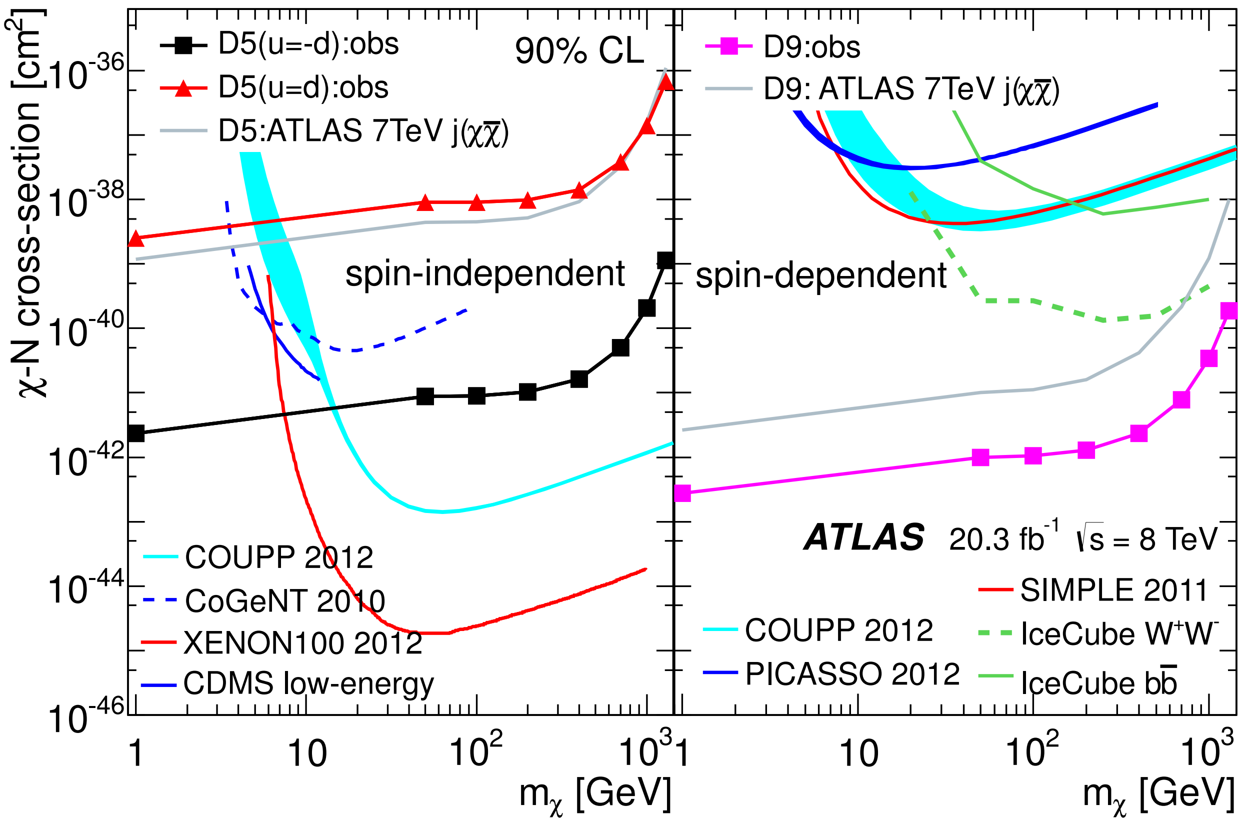
- Reconstruct W/Z with central large-R jet
  - $p_T > 250$ GeV, m_{jet} [50, 120]GeV
- 0 or 1 extra small-R jet, veto lepton/γ
- SR1 and SR2: $E_T^{miss} > 350, 500$ GeV





DM + W (qq)

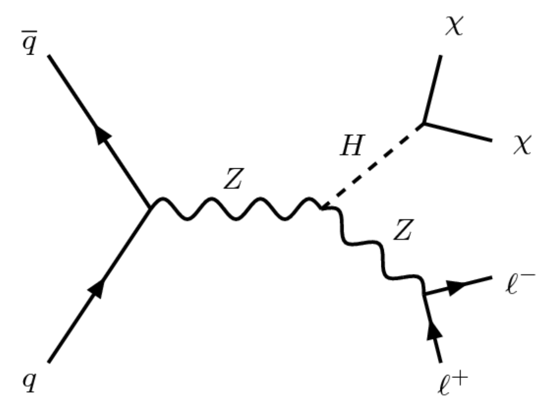
- Improve the collider constraints on WIMP-nucleon cross section at low m_χ by one order of magnitude

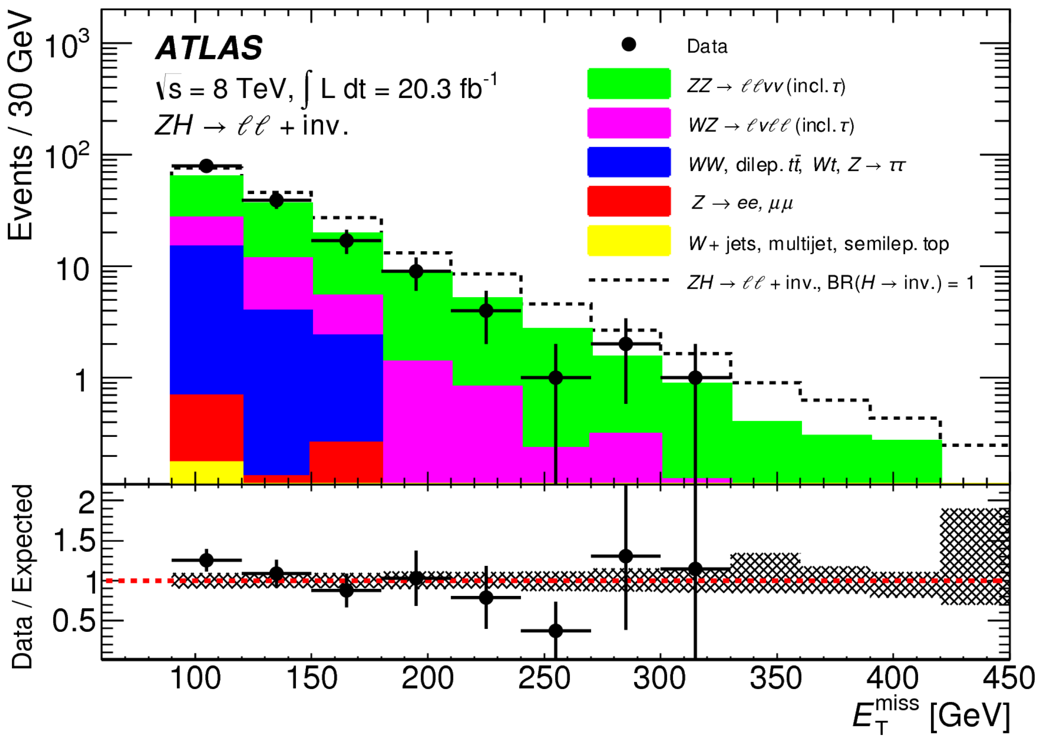


DM + Z(ll)

PRL 112, 201802 (2014)

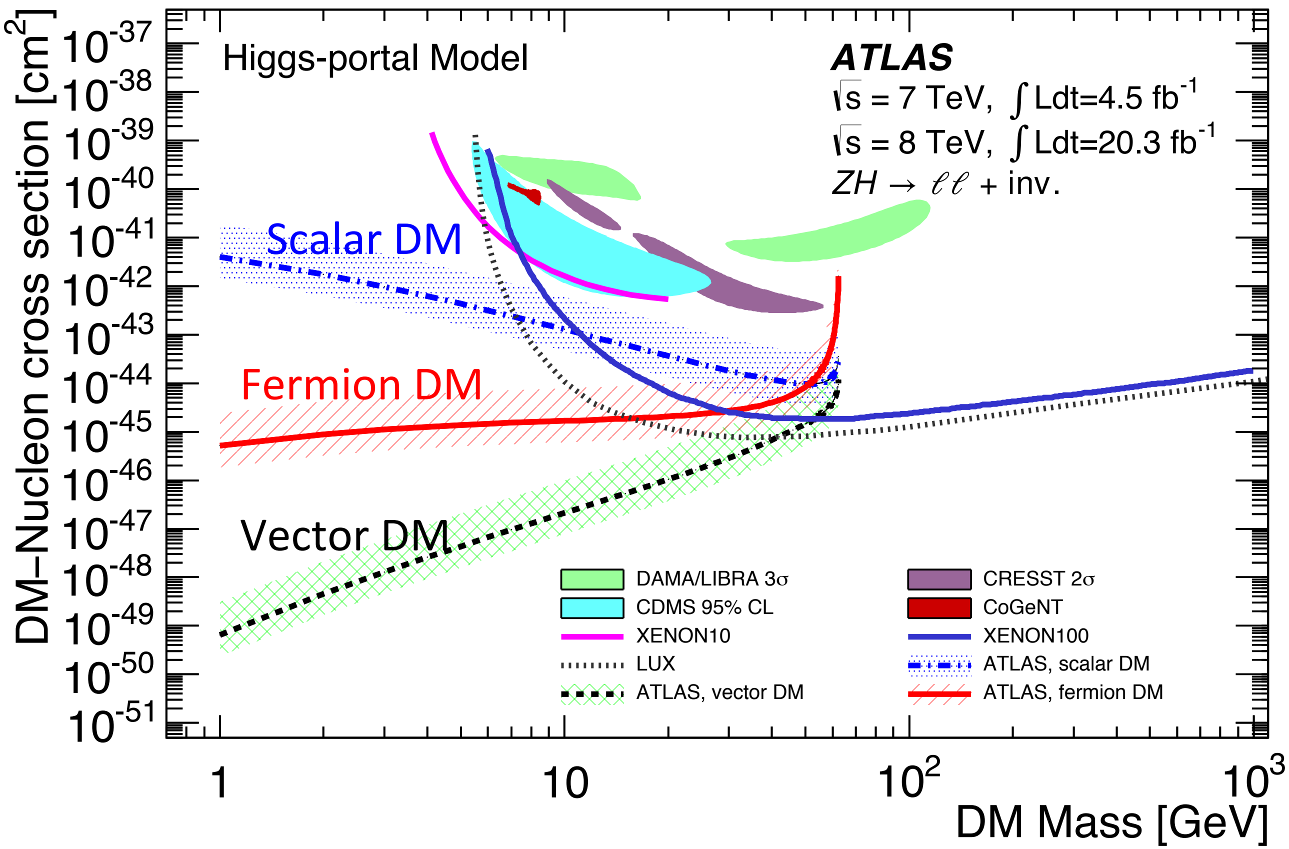
- $Z(\ell\ell)+E_T^{miss}$
  - $E_T^{miss} > 90$ GeV, $\Delta\phi(E_T^{miss}, p_T^{miss}) < 0.2$
- Sensitive to Higgs-portal DM
  - Higgs invisible BR





DM + Z(ll)

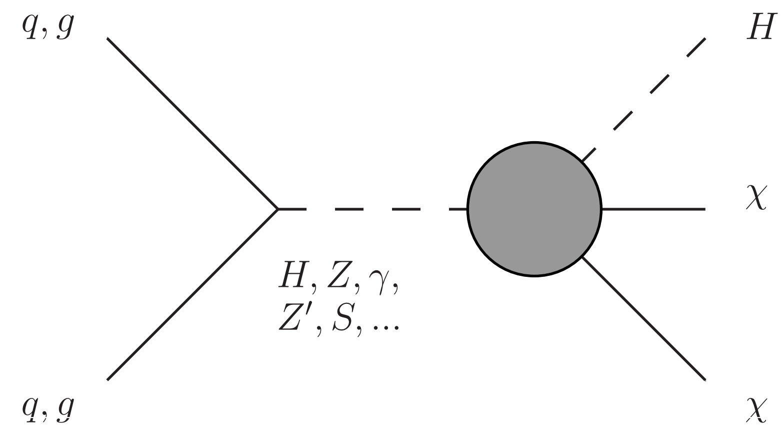
- Derive limits on DM-nucleon scattering cross section.
  - Vector, scalar, fermion DM particles
  - Sensitive to DM with $m_\chi < m_H/2$

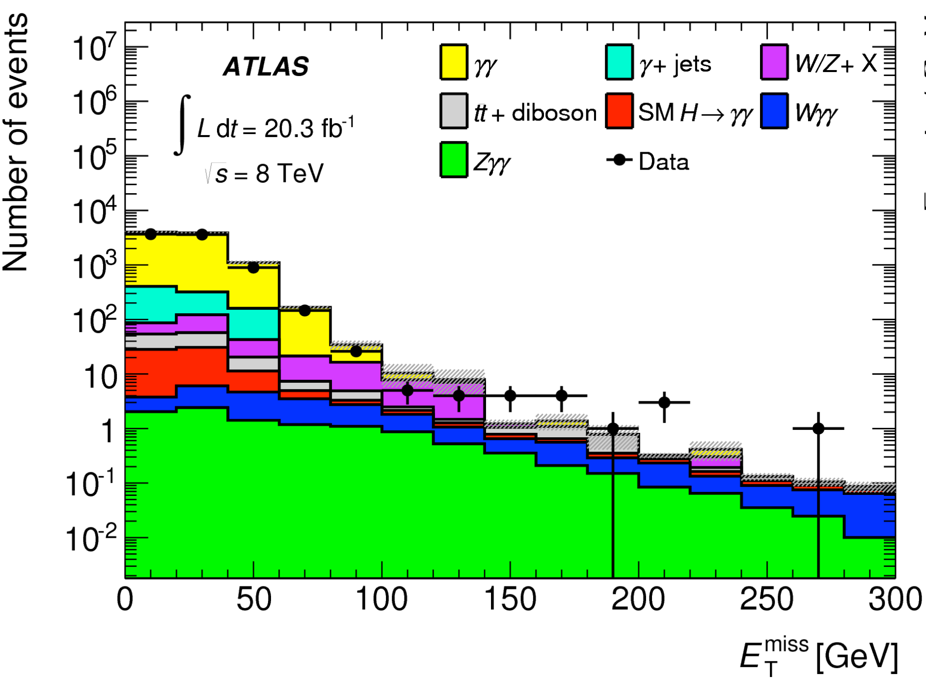


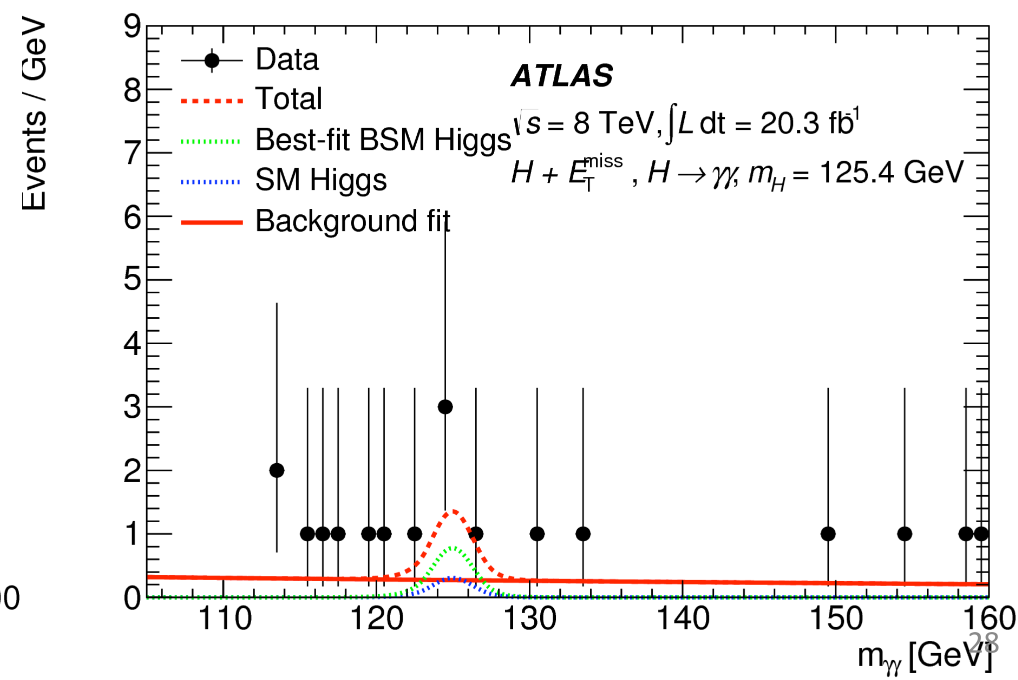
DM + Higgs

Submitted to PRL
arXiv:1506.01081

- Higgs discovery: new window to DM search
- Two isolated tight photons
  - pT > $0.35m_{\gamma\gamma}$, $0.25m_{\gamma\gamma}$
  - 105 GeV < $m_{\gamma\gamma}$ < 160 GeV
  - MET > 90 GeV
  - pT ($\gamma\gamma$) > 90 GeV

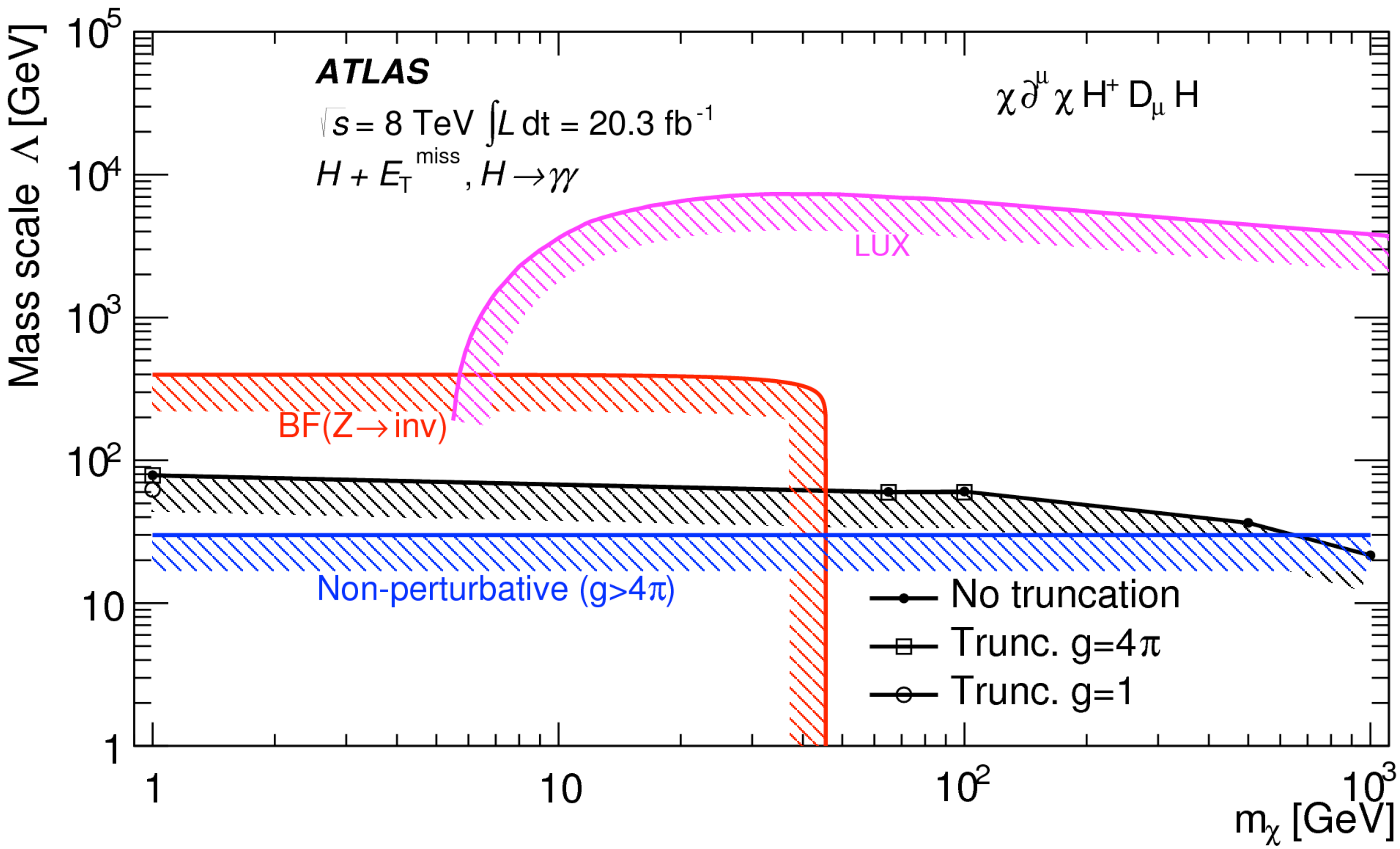






DM + Higgs

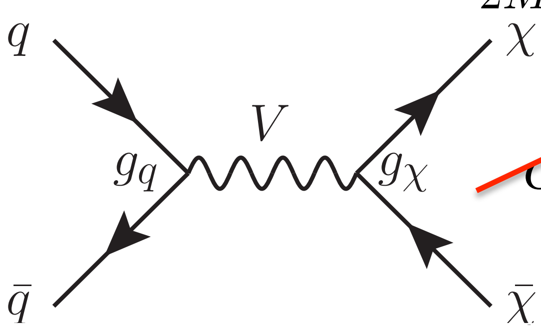
- Derive limits for both EFT and simplified models



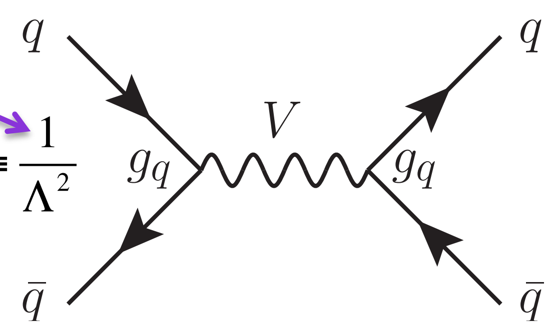
Di-jet Channel

- Search for DM production mechanism directly

$$
\begin{aligned}
\mathscr{L}_{\rm eff} = {} & \bar{q}(i\partial\!\!\!/ - M_q)q + \bar{\chi}(i\partial\!\!\!/ - M_\chi)\chi \\
& - \frac{g_q^2}{2M_V^2}\bar{q}_L\gamma^\mu q_L \bar{q}_L \gamma_\mu q_L - \frac{g_q g_\chi}{M_V^2}\bar{q}_L\gamma^\mu q_L \bar{\chi}_L \gamma_\mu \chi_L \\
& - \frac{g_\chi^2}{2M_V^2}\bar{\chi}_L\gamma^\mu \chi_L \bar{\chi}_L \gamma_\mu \chi_L ; \qquad (
\end{aligned}
$$



$$G_\chi \equiv \frac{g_q g_\chi}{M_V^2} \qquad G_q \equiv \frac{g_q^2}{M_V^2} \equiv \frac{1}{\Lambda^2}$$



Angular Distribution

- Mediator too heavy to be produced on shell
- New physics process
  - Contact interaction

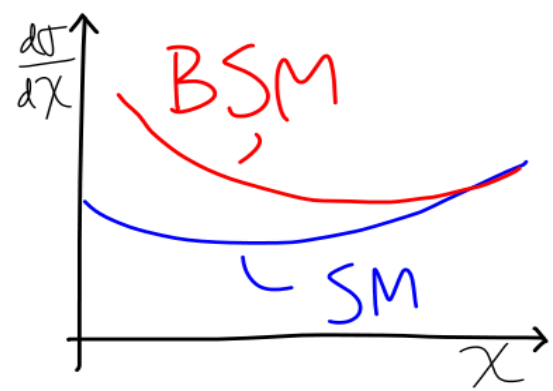
$$L_{qq} = \frac{2\pi}{\Lambda^2}\left[\eta_{LL}(\overline{q}_L\gamma^\mu q_L)(\overline{q}_L\gamma_\mu q_L) + \eta_{RR}(\overline{q}_R\gamma^\mu q_R)(\overline{q}_R\gamma_\mu q_R) + 2\eta_{RL}(\overline{q}_R\gamma^\mu q_R)(\overline{q}_L\gamma_\mu q_L)\right],$$

- Large difference in angular distribution

y_1 - rapidity of leading jet

$y^* = \frac{y_1 - y_2}{2}$

$\chi = e^{2|y^*|}$



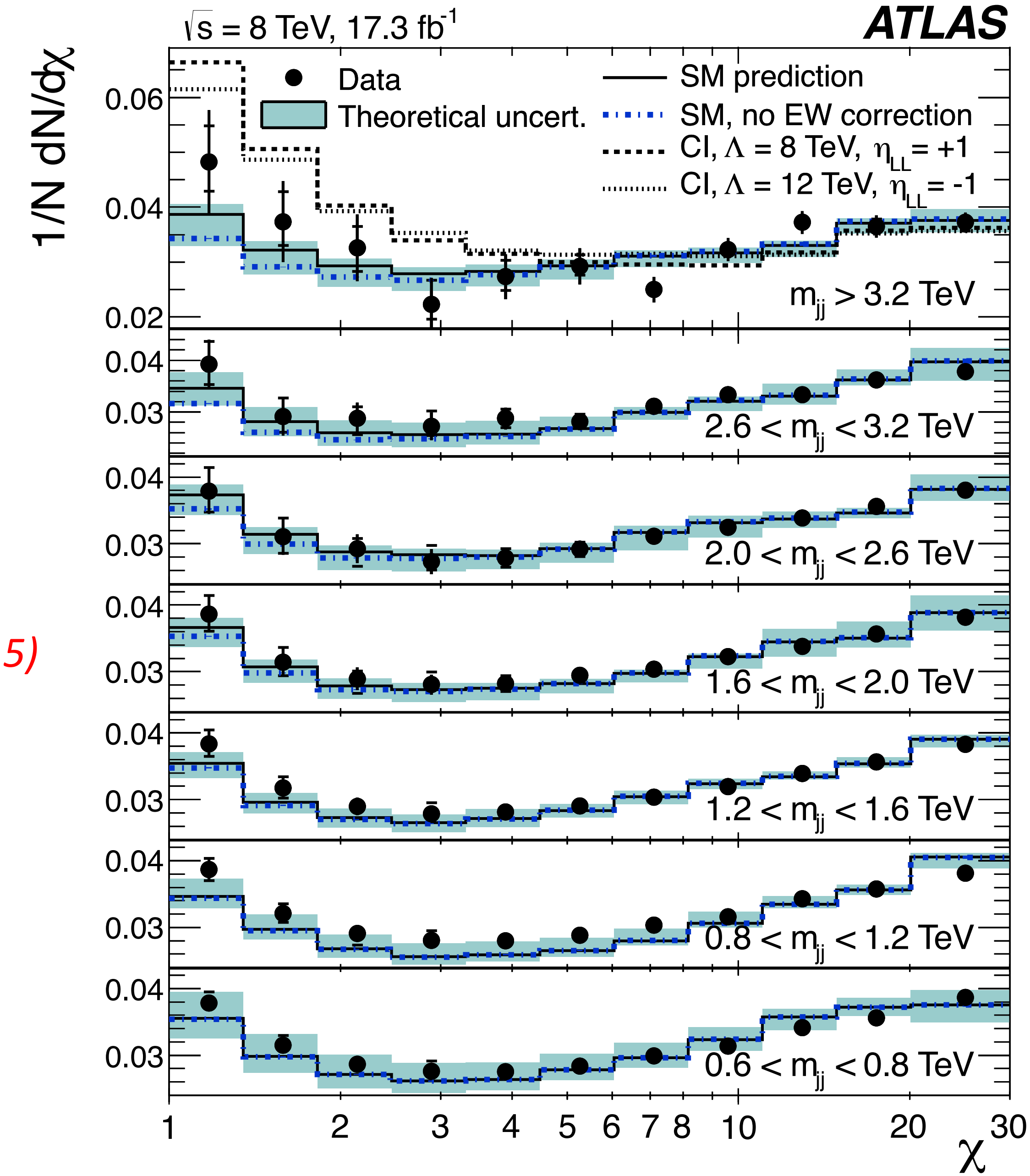
At high dijet mass

Run I Data

- Searching for angular distribution deviation in high mass region

- No significant excess

Phys. Rev. Lett. 114, 221802 (2015)

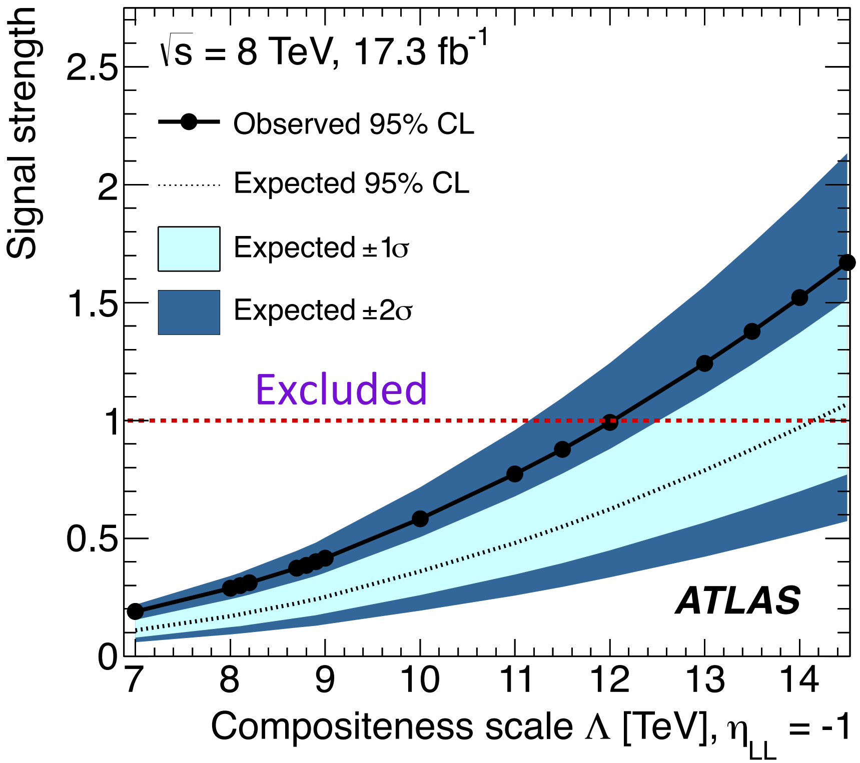


Results

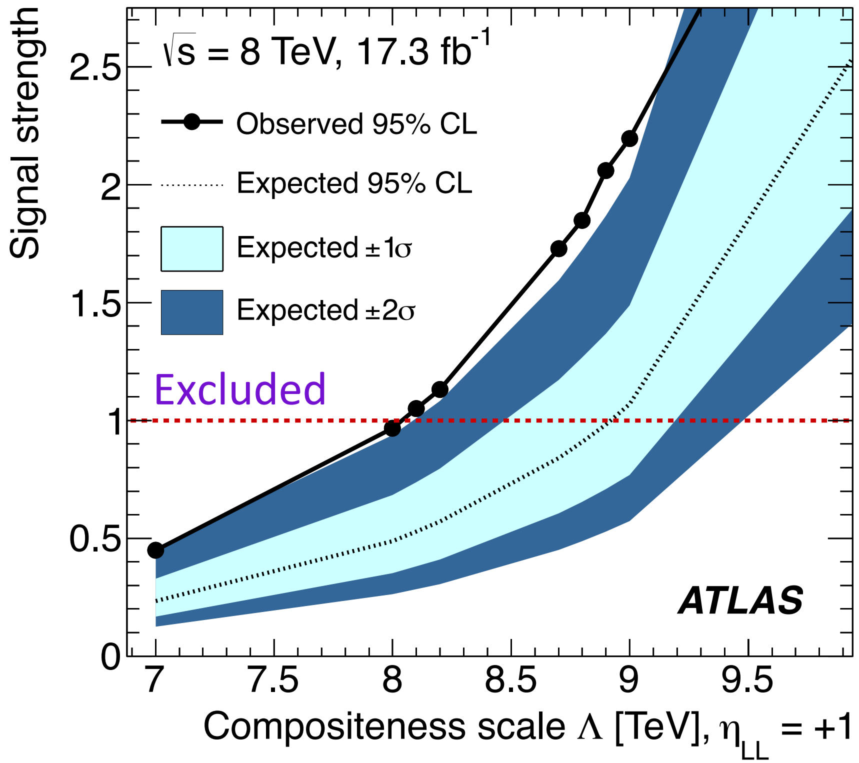
- Convert the cross section limits into the lower limits on energy scale of contact interaction.

$$G_q \equiv \frac{g_q^2}{M_V^2} \equiv \frac{1}{\Lambda^2}$$

Positive interference

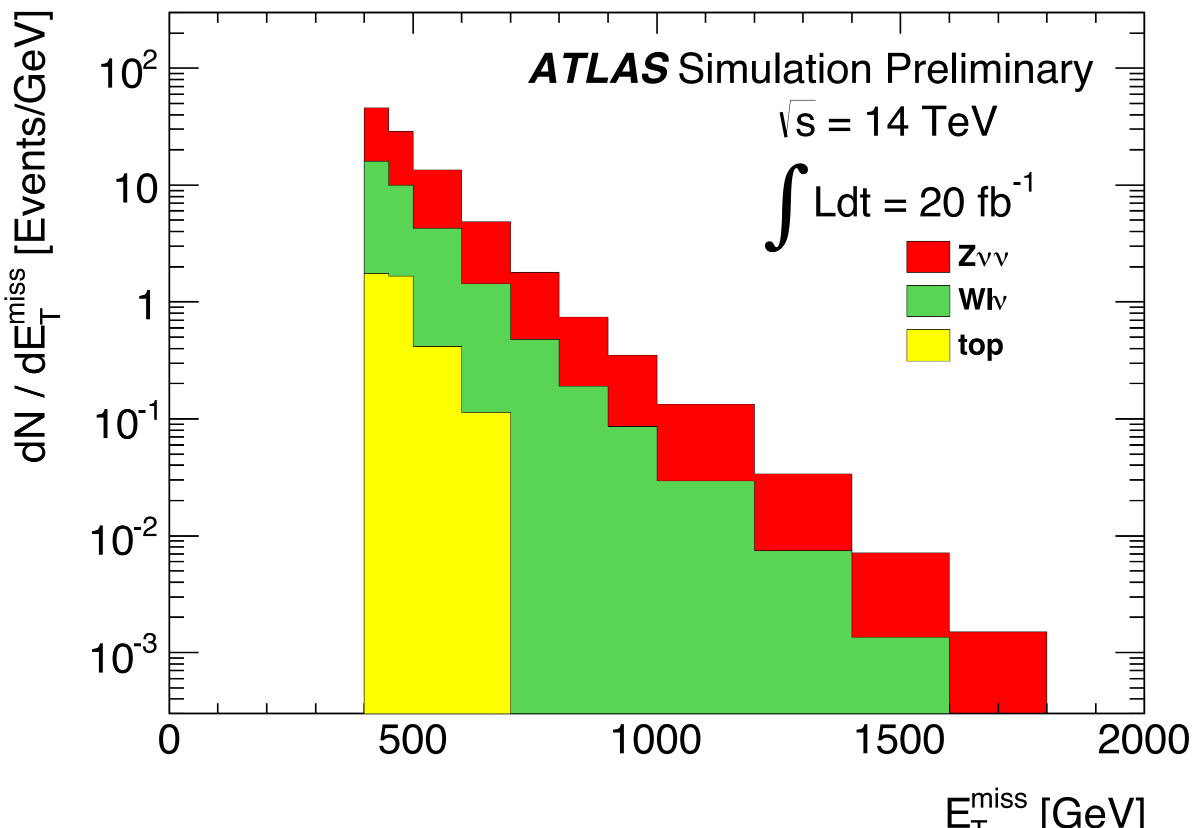


Negative interference



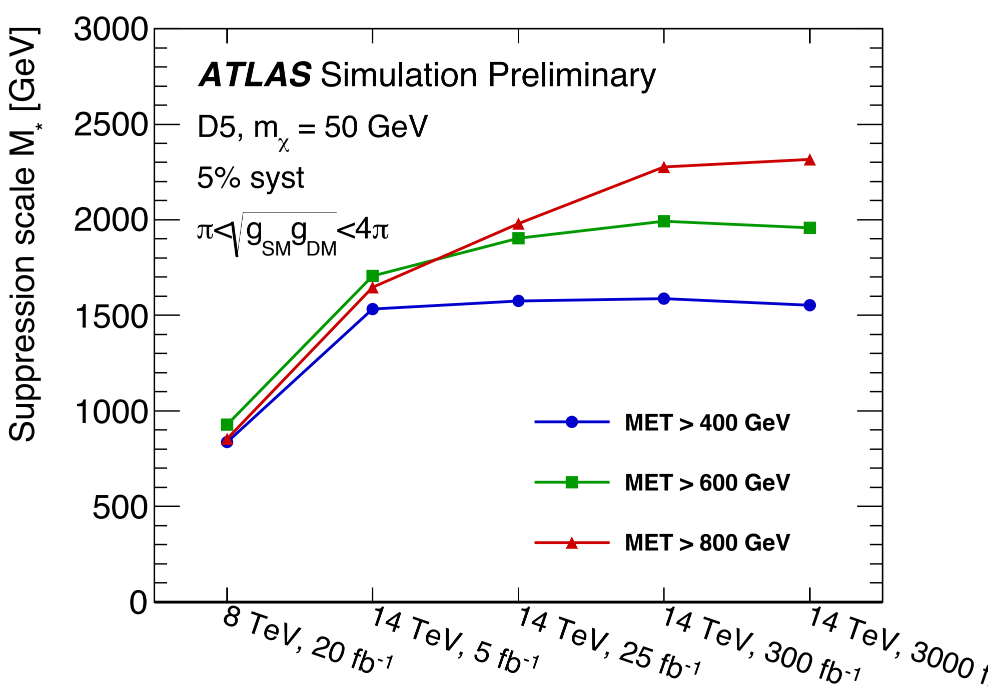
DM + jet (14 TeV)

- LHC has restarted: 7/8 TeV => 13/14 TeV *ATL-PHYS-PUB-2014-007*
- Various milestones of 14 TeV data-taking:
  - 25 fb^{-1} (1st year), 300 fb^{-1} (end of Run-II), 3000 fb^{-1} (HL-LHC)

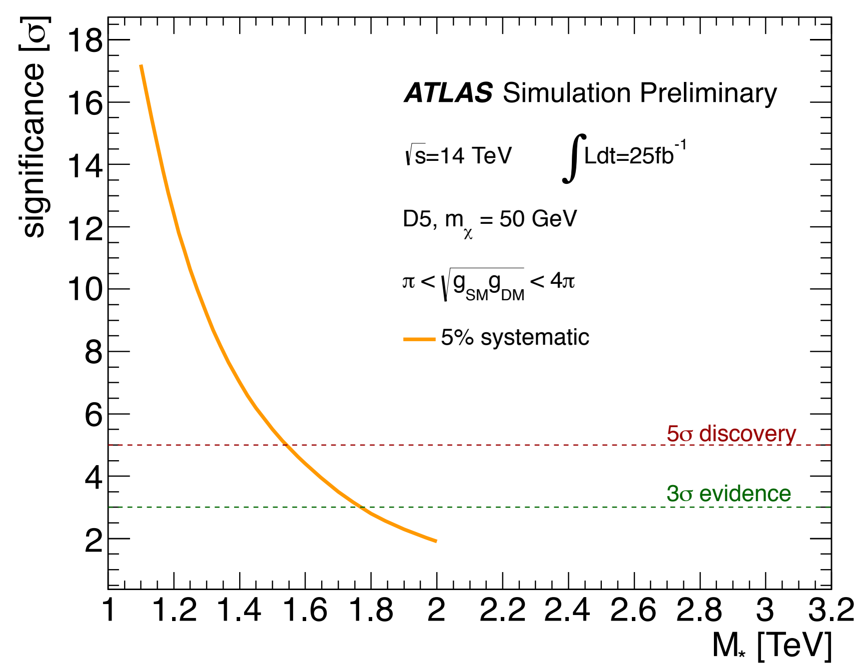


DM + jet (14 TeV)

- Significantly enhance the signal sensitivity



Exclusion



Discovery

Summary

- LHC may be able to produce DM and detect it.
- Advantages on small mass DM candidates
- From ATLAS Run-I intensive dark matter searches (including SUSY dark matter candidates), we have not discovered a dark matter candidate yet.
- LHC Run-II data with unprecedented collision energy open a new window!

Thou shall not forget: the LHC was <u>not</u> build to produce limits. The LHC is a discovery machine !

LHC Run II

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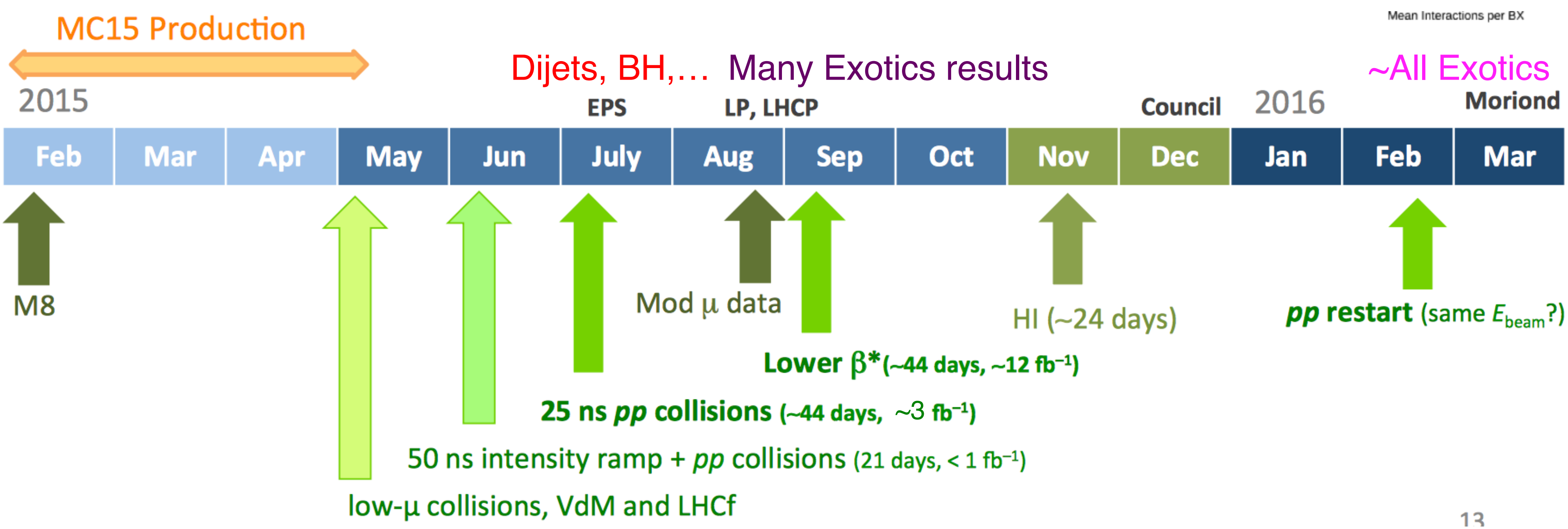
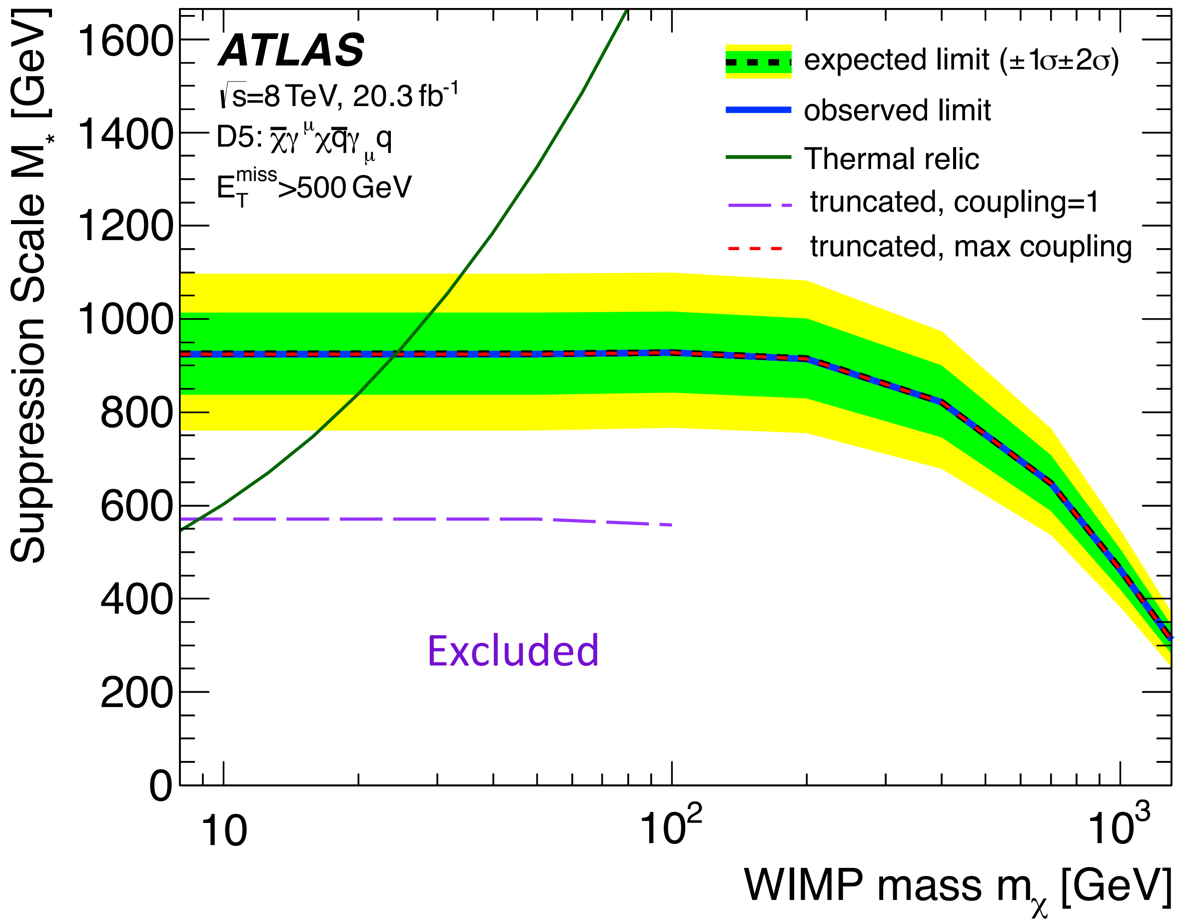


Mean Interactions per BX
MC15 Production
Dijets, BH,… Many Exotics results
~All Exotics
2015
EPS
LP, LHCP
Council
2016
Moriond
Feb
Mar
Apr
May
Jun
July
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
M8
Mod μ data
HI (~24 days)
pp restart (same E beam?)
Lower β*(~44 days, ~12 fb⁻¹)
25 ns pp collisions (~44 days, ~3 fb⁻¹)
50 ns intensity ramp + pp collisions (21 days, < 1 fb⁻¹)
low-μ collisions, VdM and LHCf
13

Run I Results

- Convert the cross section limits into the lower limits on M* for different DM mass m_χ.



EFT validity

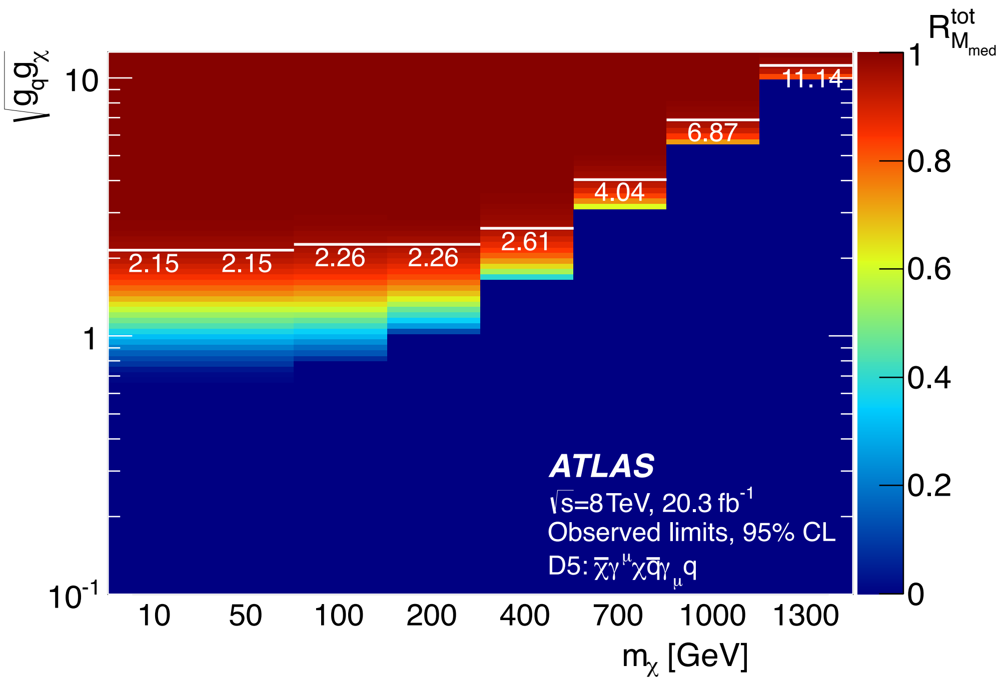
- EFT being a valid approximation requires $Q_{tr} < m_V$ (mediator)
  - Not all the events generated from EFT are valid.
  - cut off those invalid events (truncation)
  - Depending on the couplings and DM mass

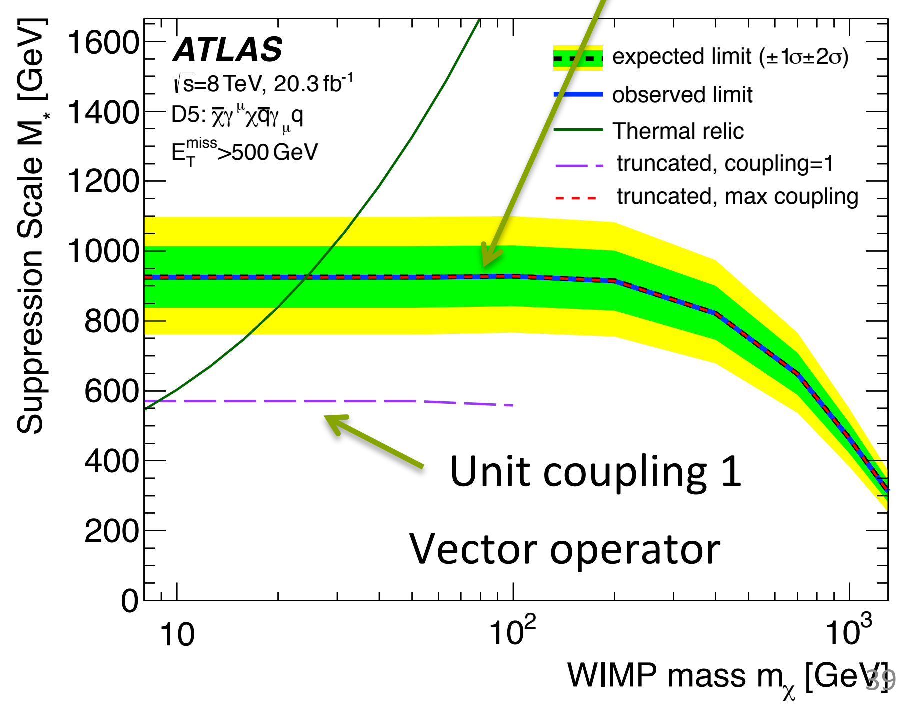
$$\frac{g_f^2 g_\chi^2}{(Q_{tr}^2 - m_V^2)^2} \xrightarrow{Q_{tr} << m_V} \frac{g_f^2 g_\chi^2}{m_V^4} = \frac{1}{M_*^4}$$

$$M_* = m_V / \sqrt{g_f g_\chi}$$

$$\sqrt{g_f g_\chi} \in [0, 4\pi)$$

Maximum coupling 4π





Constraints on Direct Detection

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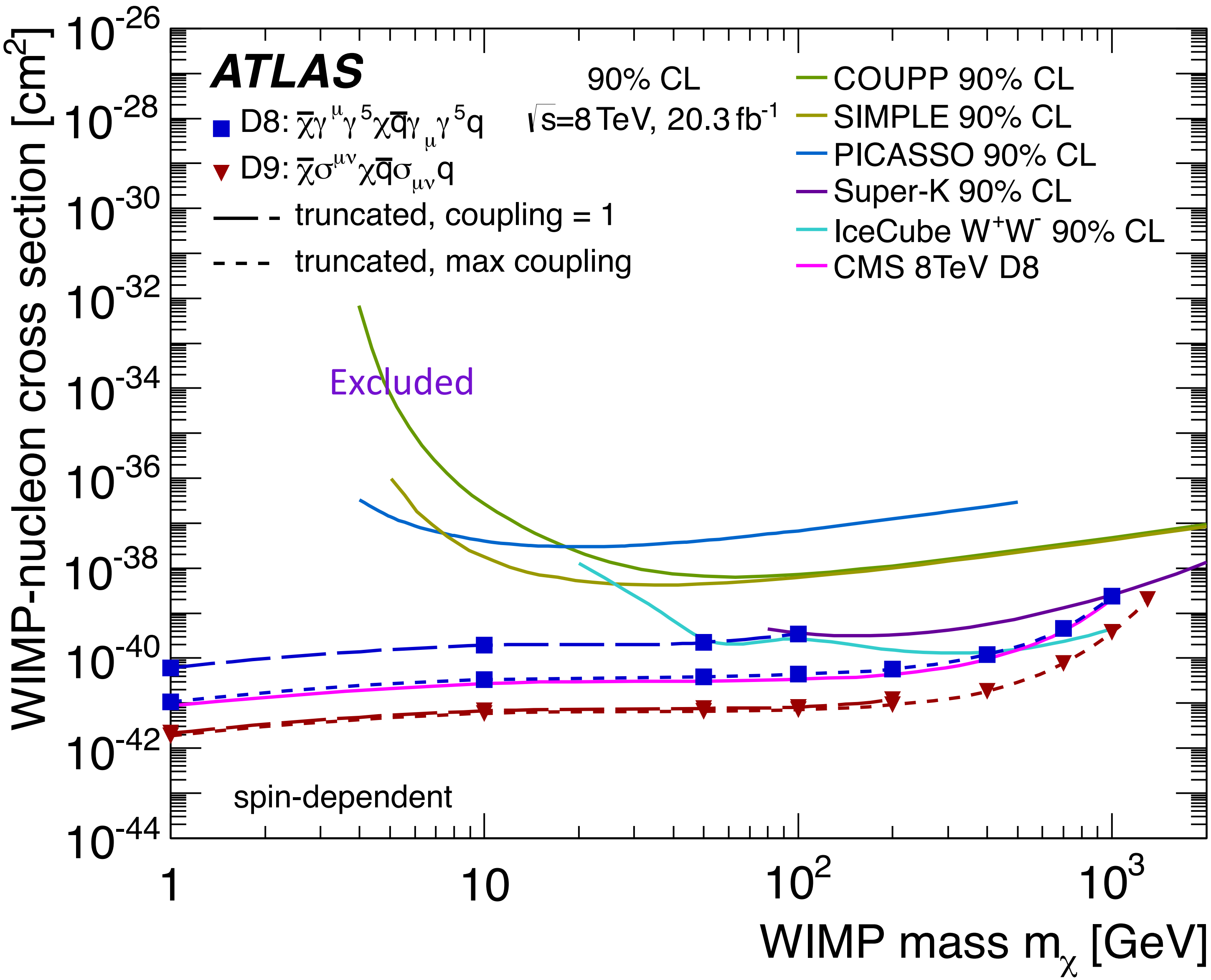

Contact Interaction (CI)

- Here flavor-diagonal color-singlet couplings between quarks are considered

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

$$\begin{aligned}
\Lambda &= \Lambda^{\pm}_{LL} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (\pm 1, 0, 0),\\
\Lambda &= \Lambda^{\pm}_{RR} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (0, \pm 1, 0),\\
\Lambda &= \Lambda^{\pm}_{VV} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (\pm 1, \pm 1, \pm 1),\\
\Lambda &= \Lambda^{\pm}_{AA} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (\pm 1, \pm 1, \mp 1),\\
\Lambda &= \Lambda^{\pm}_{(V-A)} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (0, 0, \pm 1).
\end{aligned}$$

- For Λ_{LL}, positive value results in destructive interference between QCD and CI, while negative value gives constructive interference.

Di-jet Channel

- Mediator mass too large to be produced on-shell
  - Non-resonance signature
  - Change di-jet angular distribution