Dark Matter (and Dark Mediators) at the LHC

NIKHEF

GRAPPA
GRavitation AstroParticle Physics Amsterdam

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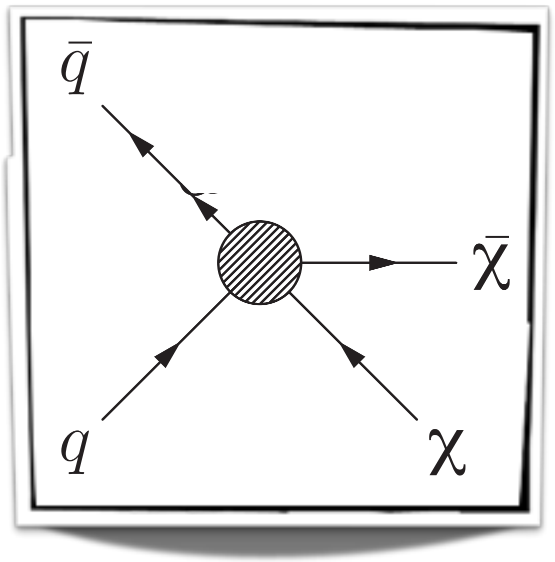
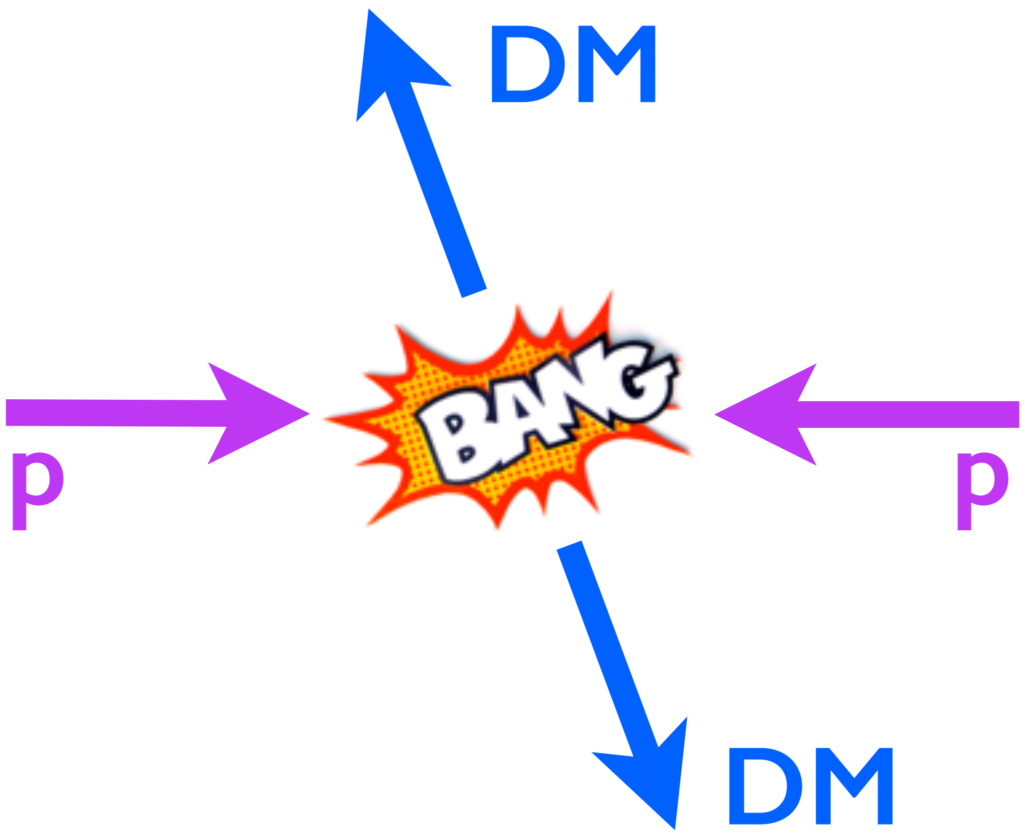
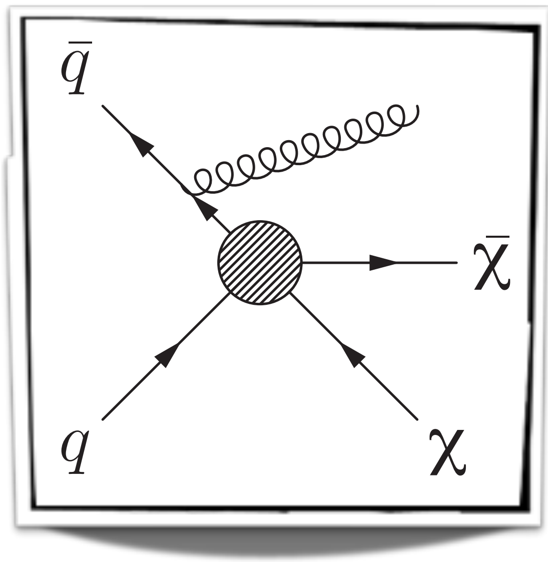
30/11/2015

DM production at the LHC

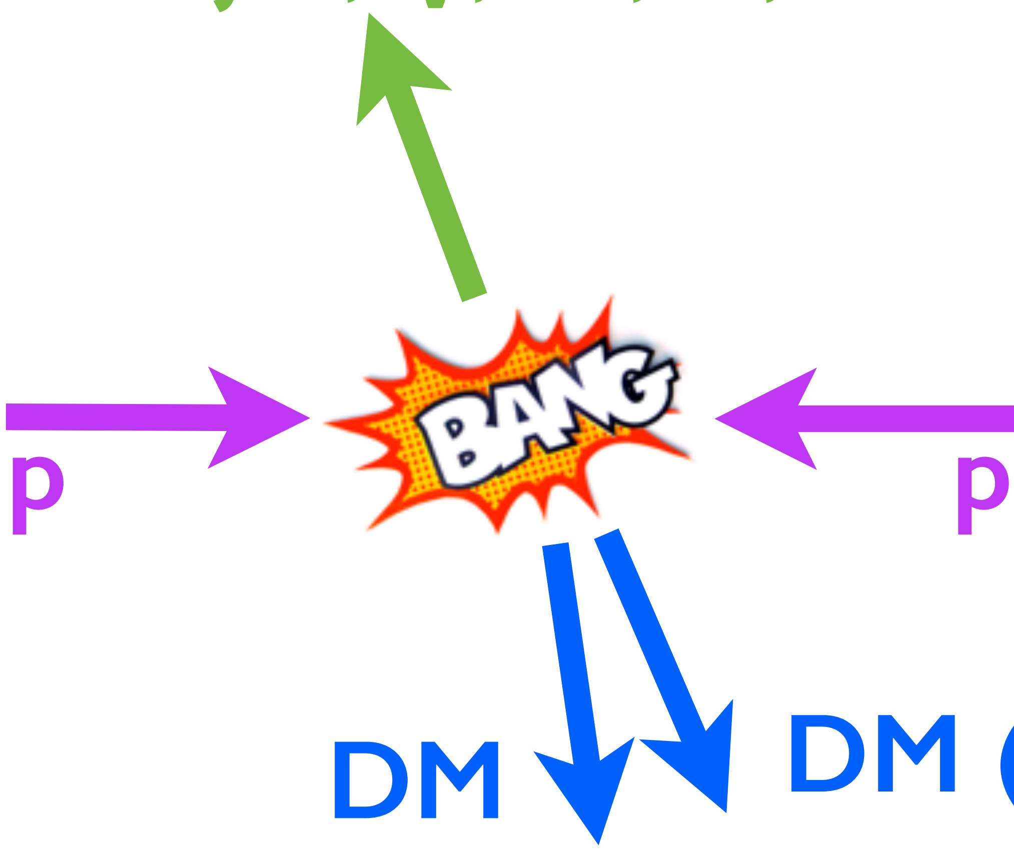




DM production at the LHC

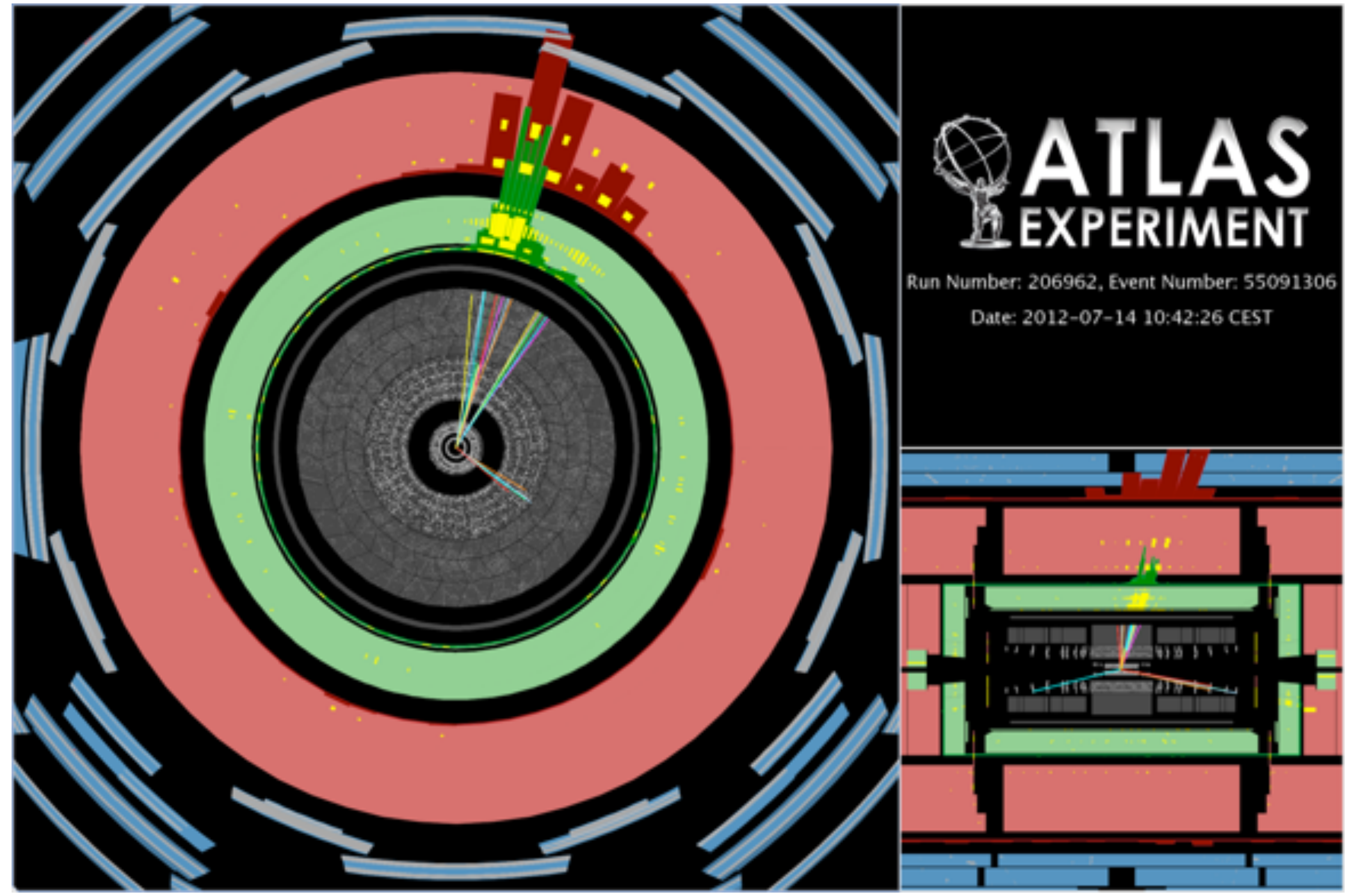


jet, γ, W, Z, ...



p p

DM DM (missing transverse momentum)

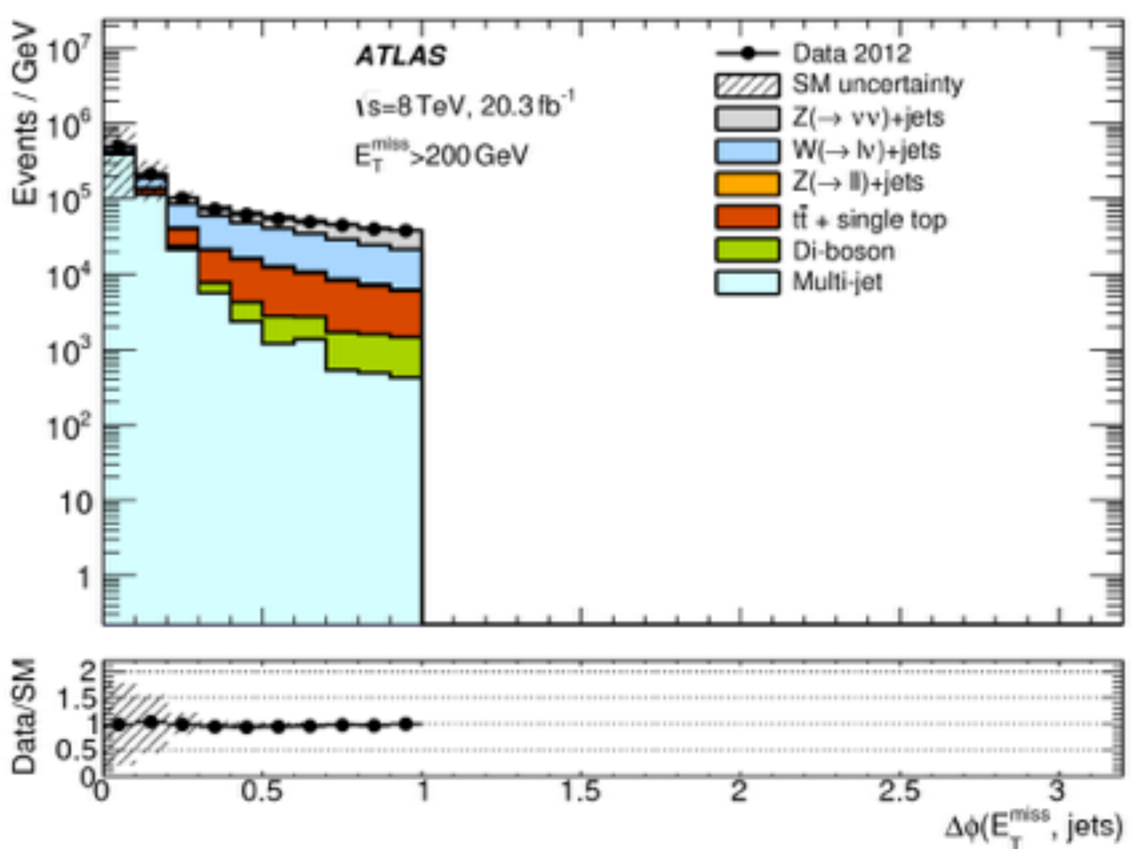


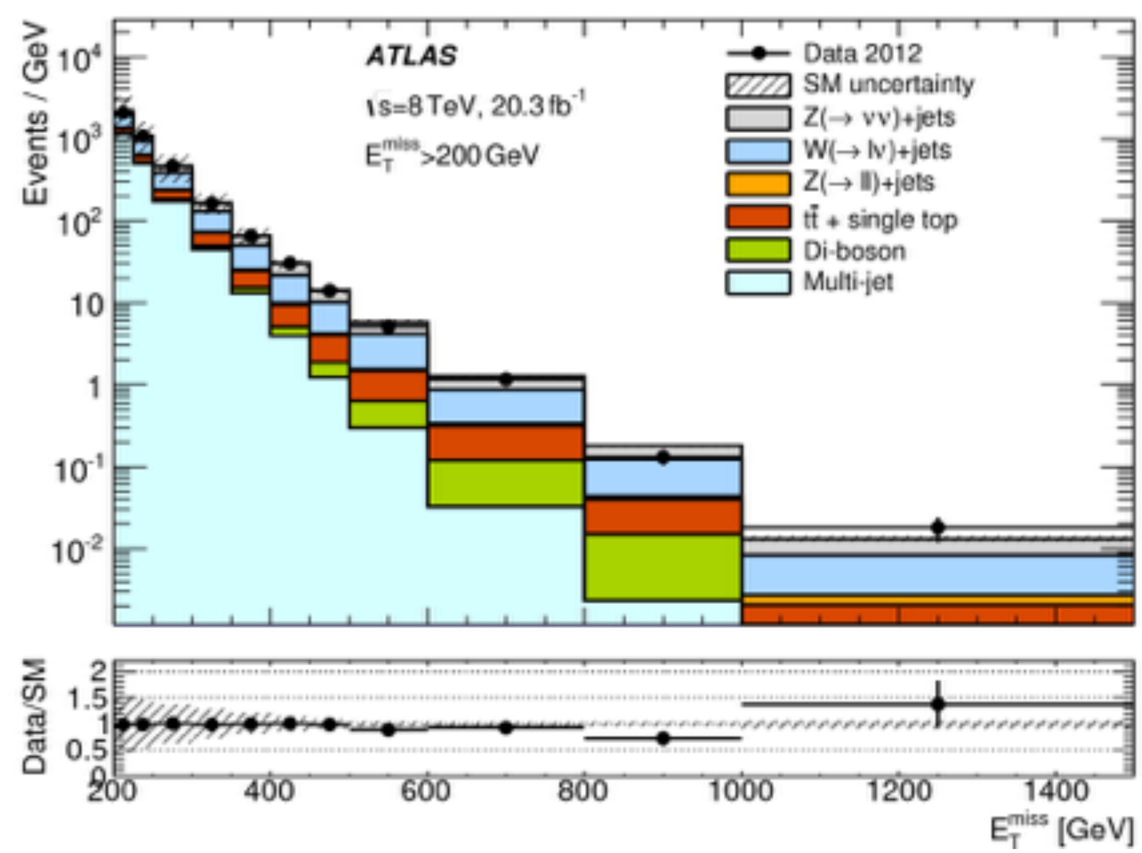
mono-jet event from 7 TeV data
[JHEP 1304 (2013) 075]

multi-jet background

Eur. Phys. J. C (2015) 75:299

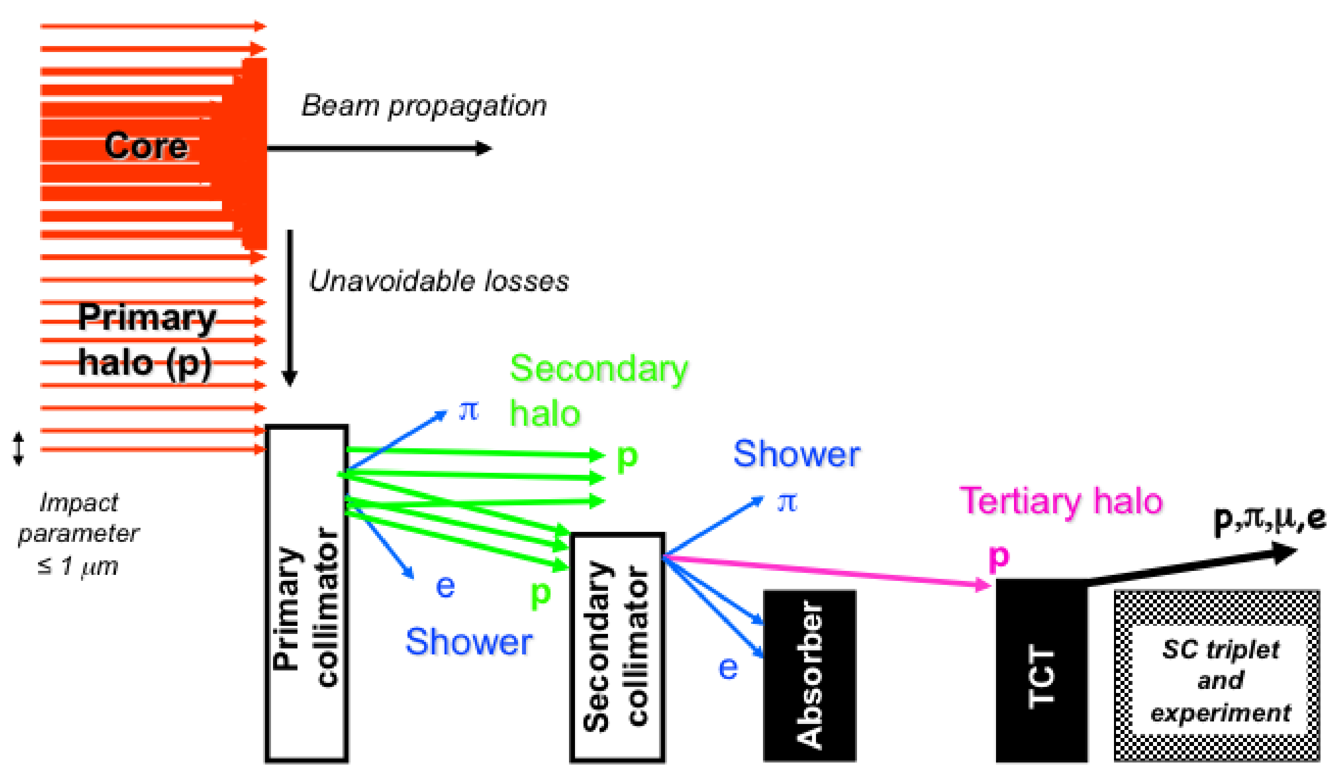
- Multi-jet events are the most abundant processes at the LHC.
- Mis-balanced multi-jet events, where a jet is mis-reconstructed, may lead to MET in the direction of the jet.

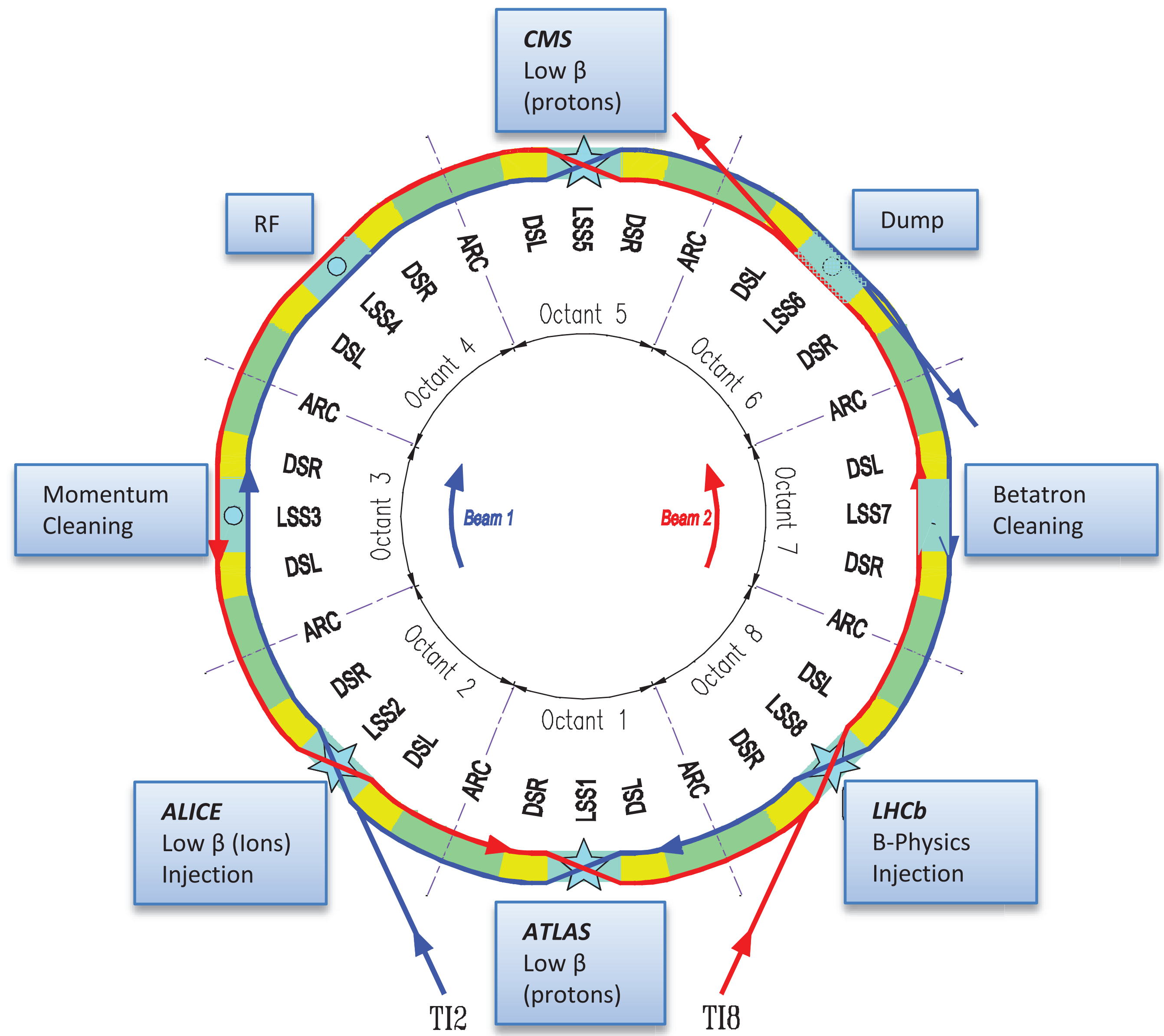




beam-induced backgrounds

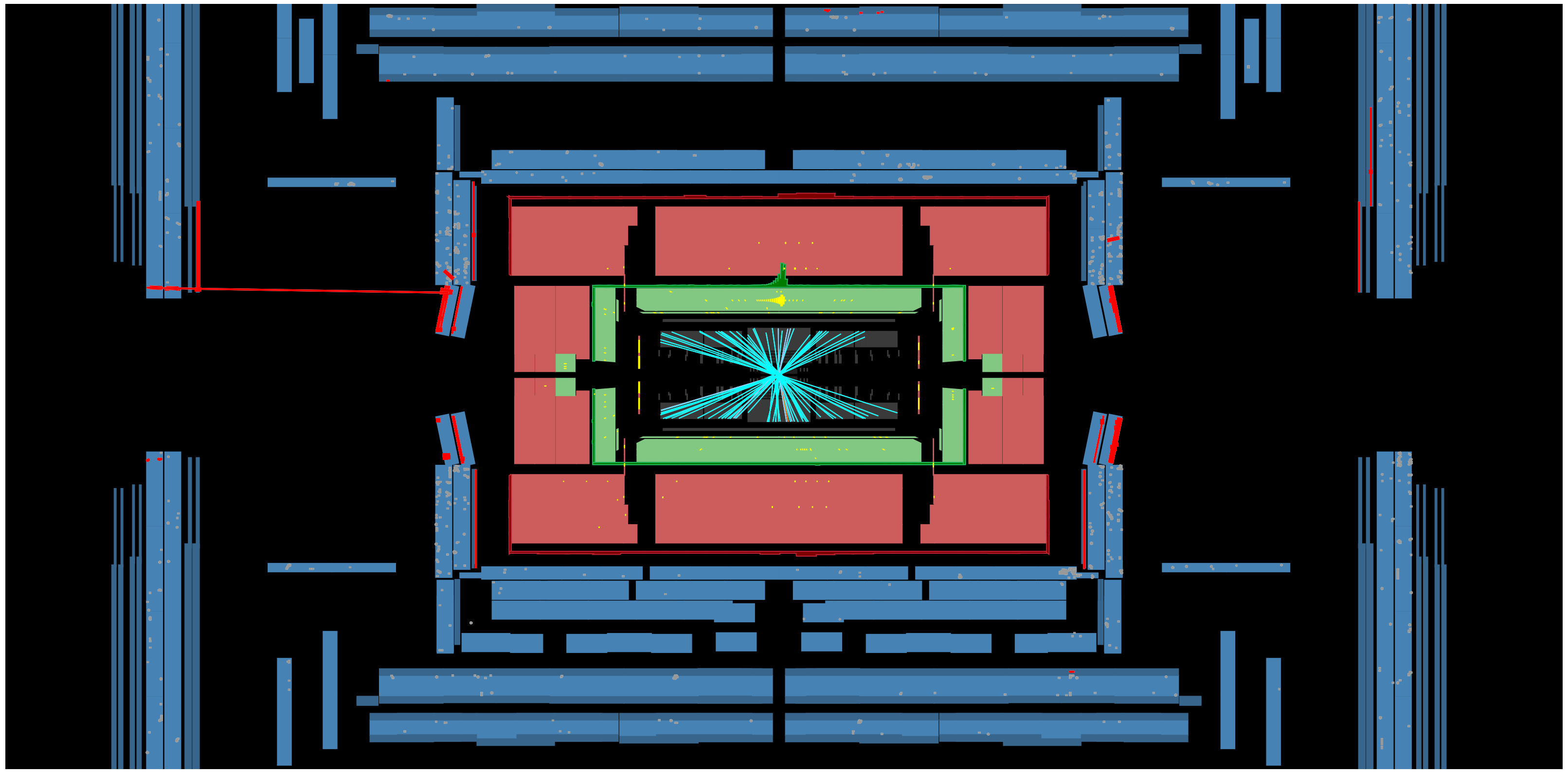
- beam-gas interactions
- beam halo



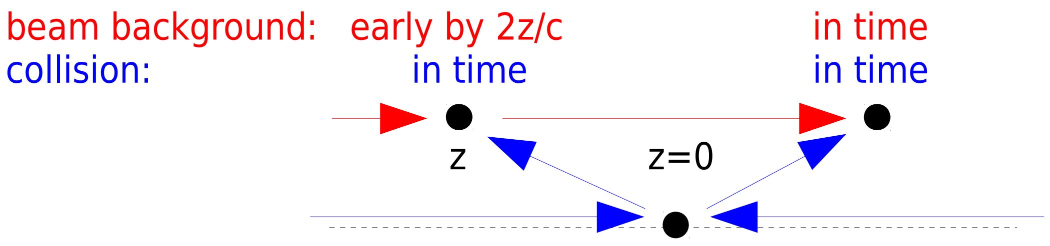


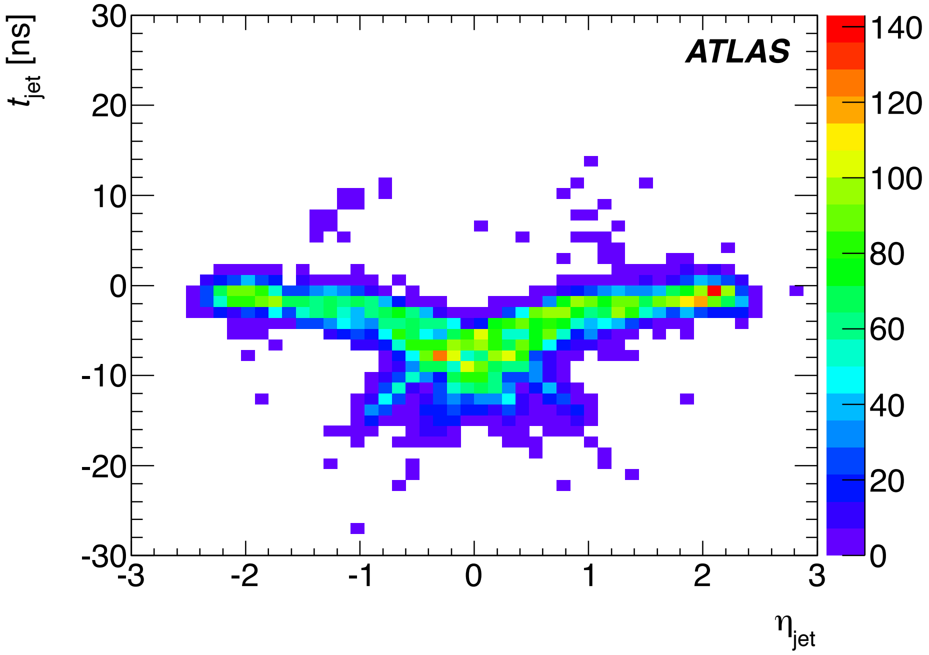
JINST 8 (2013) P07004

beam-induced backgrounds



- Beam-induced muons lead to fake jets balanced by MET.

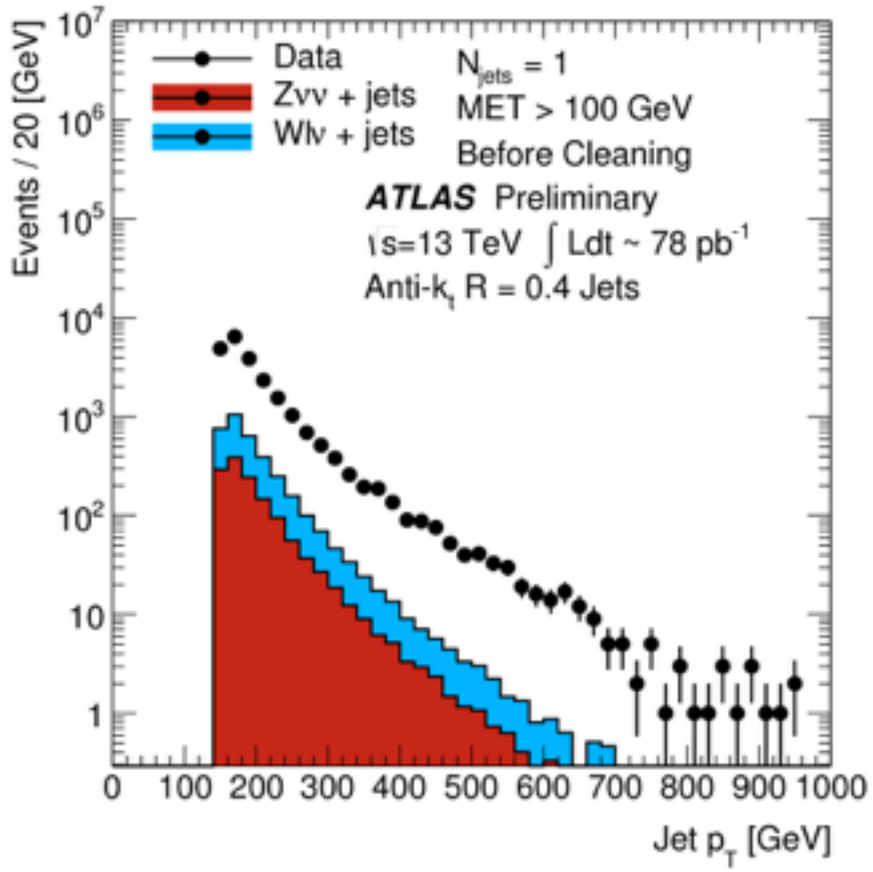


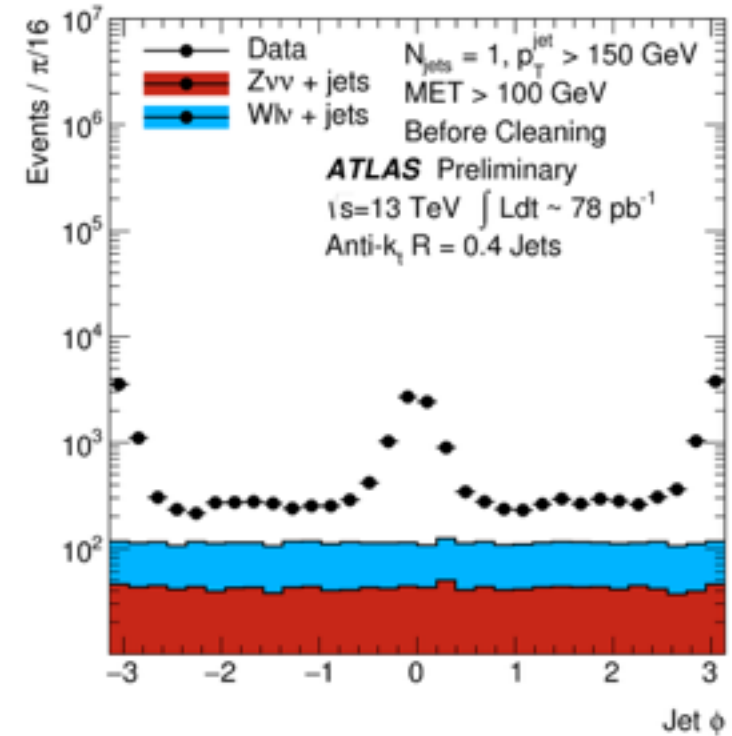


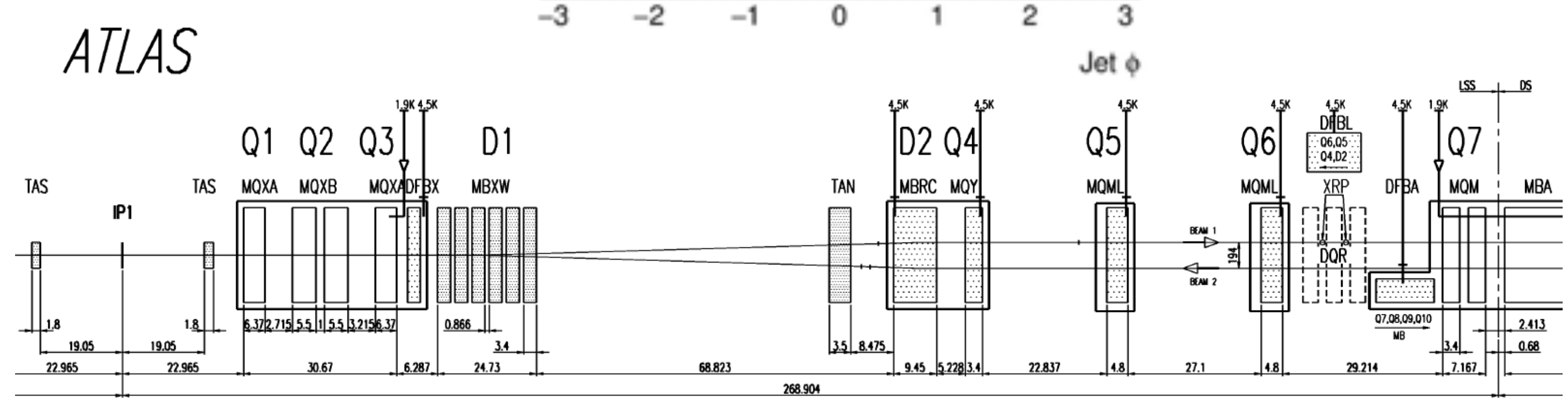
[JINST 8 (2013) P07004]

Non-collision backgrounds

[EXOT-2015-005]







- Non-collision backgrounds are suppressed by jet quality requirements to sub-percent level in the mono-jet analysis.
  - beam-induced backgrounds (with typical azimuthal signature)
  - cosmic muons

ATLAS-CONF-2015-029

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Event selection and backgrounds

Selection criteria									
Preselection									
Primary vertex									
$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV									
Jet quality requirements									
At least one jet with $p_{\mathrm{T}} > 30$ GeV and $\|\eta\| < 4.5$									
Lepton and isolated track vetoes									
Monojet-like selection									
The leading jet with $p_{\mathrm{T}} > 120$ GeV and $\|\eta\| < 2.0$									
Leading jet $p_{\mathrm{T}}/E_{\mathrm{T}}^{\mathrm{miss}} > 0.5$									
$\Delta\phi(\mathrm{jet}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) > 1.0$									
Signal region	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8	SR9
Minimum $E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	150	200	250	300	350	400	500	600	700

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	

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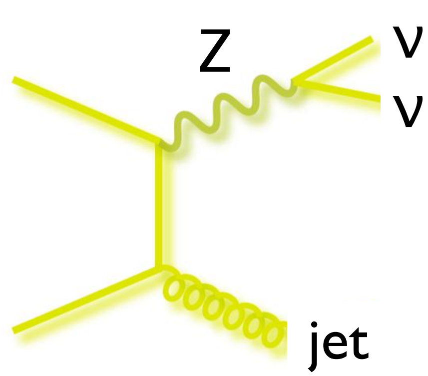
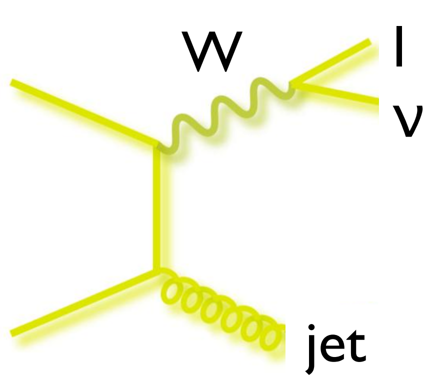
V+jets background

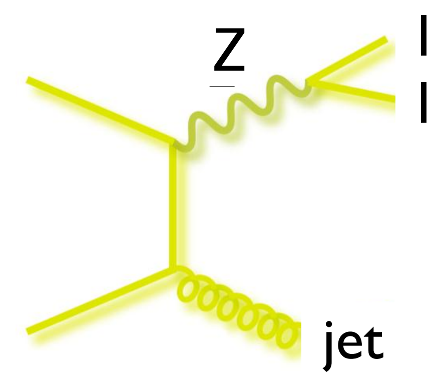
signal region

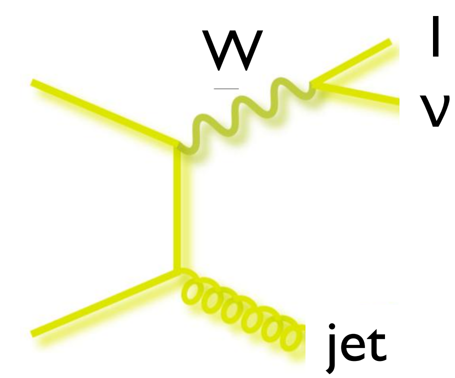




← mis-reconstructed μ or e or outside of the detector acceptance or hadronic τ decay

control region



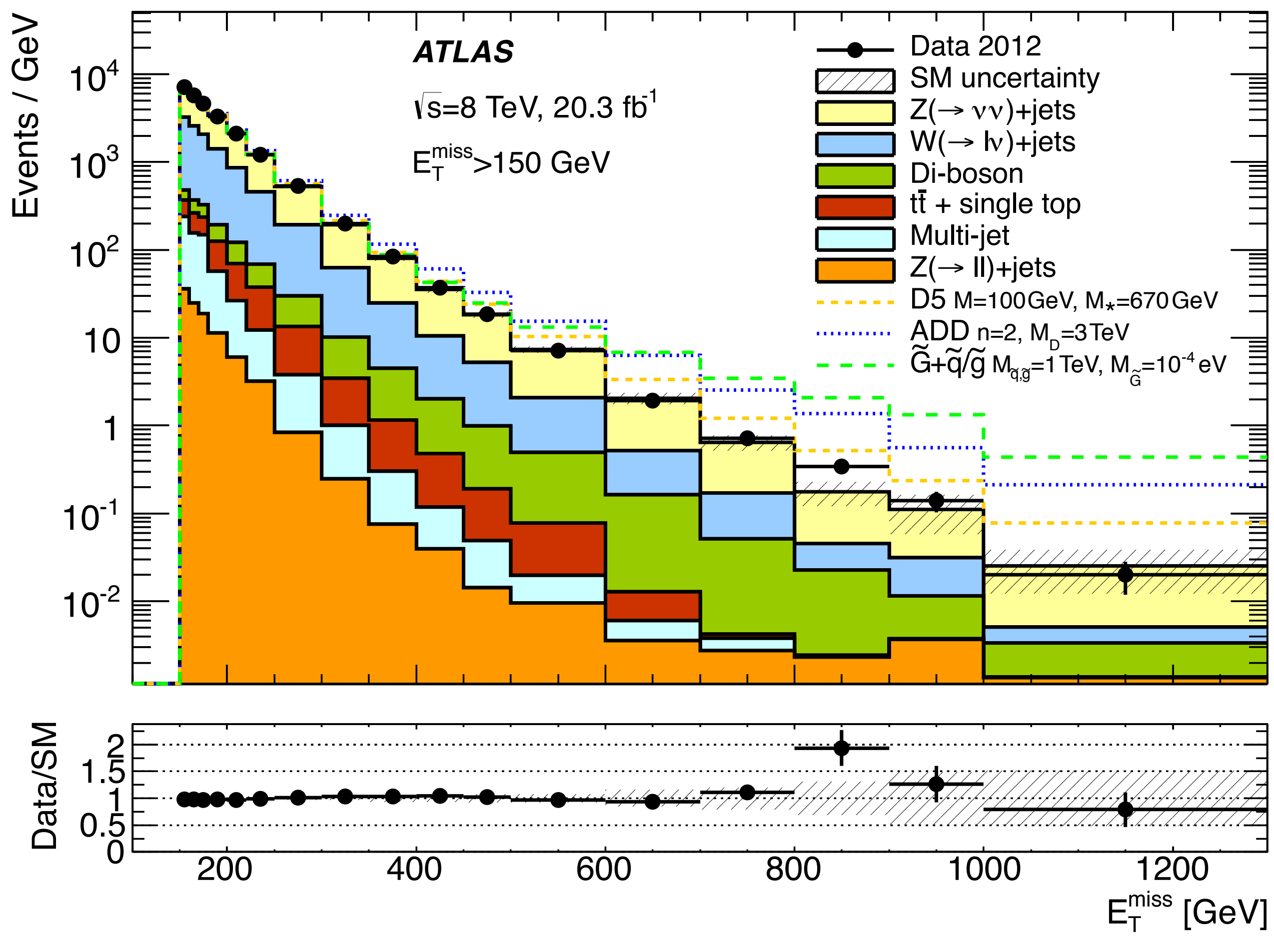


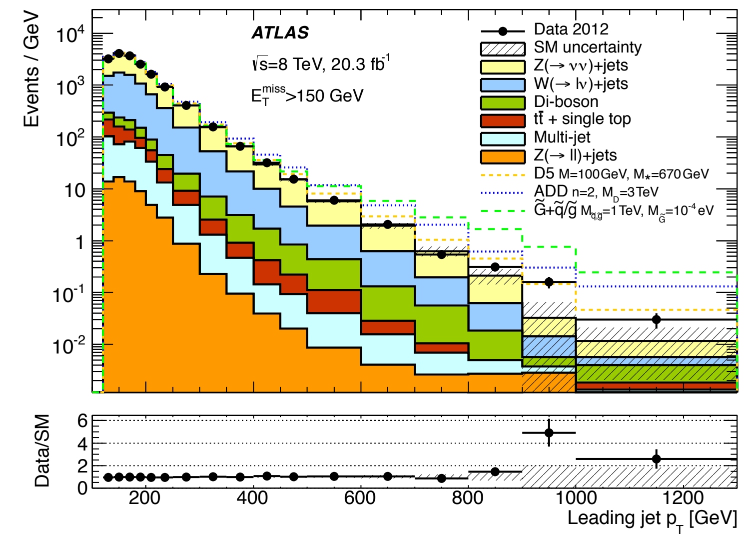
$$N_{\mathrm{signal}}^{Z(\to\nu\bar{\nu})} = \frac{(N_{W(\to\mu\nu),\mathrm{control}}^{\mathrm{data}} - N_{W(\to\mu\nu),\mathrm{control}}^{\mathrm{non}-W/Z})}{N_{W(\to\mu\nu),\mathrm{control}}^{\mathrm{MC}}} \times N_{\mathrm{signal}}^{\mathrm{MC}(Z(\to\nu\bar{\nu}))} \times \xi_{\ell} \times \xi_{\mathrm{trg}}$$

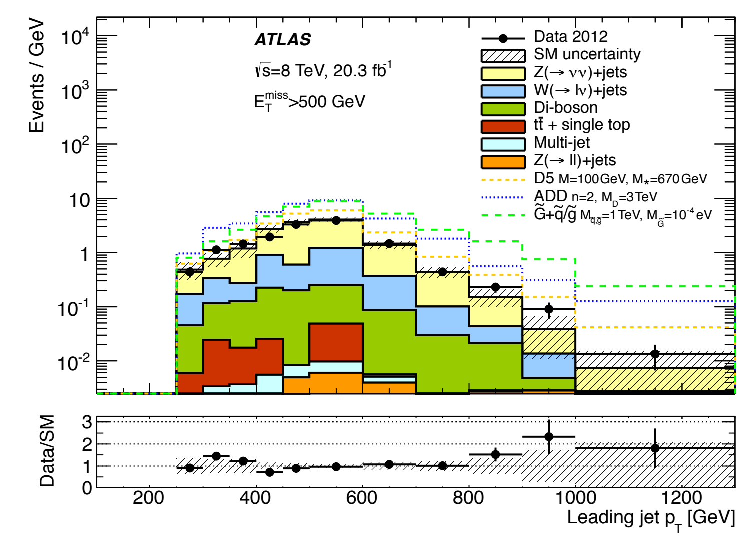
$$N_{\mathrm{signal}}^{W(\to\mu\nu)} = \frac{(N_{W(\to\mu\nu),\mathrm{control}}^{\mathrm{data}} - N_{W(\to\mu\nu),\mathrm{control}}^{\mathrm{non}-W/Z})}{N_{W(\to\mu\nu),\mathrm{control}}^{\mathrm{MC}}} \times N_{\mathrm{signal}}^{\mathrm{MC}(W(\to\mu\nu))} \times \xi_{\ell} \times \xi_{\mathrm{trg}} \times \xi_{\ell}^{\mathrm{veto}}$$

results

8 TeV 20.3 fb^{-1}







MET > 150 GeV

Signal Region	SR1	SR2	SR3	SR4	SR5
Observed events	364378	123228	44715	18020	7988
SM expectation	372100 ± 9900	126000 ± 2900	45300 ± 1100	18000 ± 500	8300 ± 300

MET > 700 GeV

Signal Region	SR6	SR7	SR8	SR9
Observed events	3813	1028	318	126
SM expectation	4000 ± 160	1030 ± 60	310 ± 30	97 ± 14

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limits on σ×A×ε

Upper limits on $\sigma \times A \times \epsilon$ [fb]		
Signal Region	90% CL Observed (Expected)	95% CL Observed (Expected)
SR1	599 (788)	726 (935)
SR2	158 (229)	194 (271)
SR3	74 (89)	90 (106)
SR4	38 (43)	45 (51)
SR5	17 (24)	21 (29)
SR6	10 (14)	12 (17)
SR7	6.0 (6.0)	7.2 (7.2)
SR8	3.2 (3.0)	3.8 (3.6)
SR9	2.9 (1.5)	3.4 (1.8)

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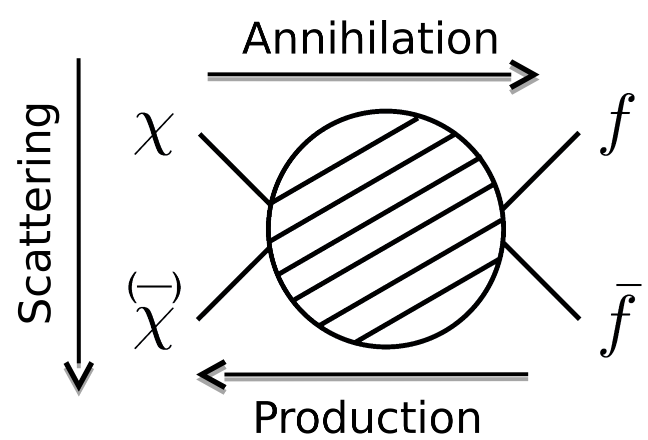
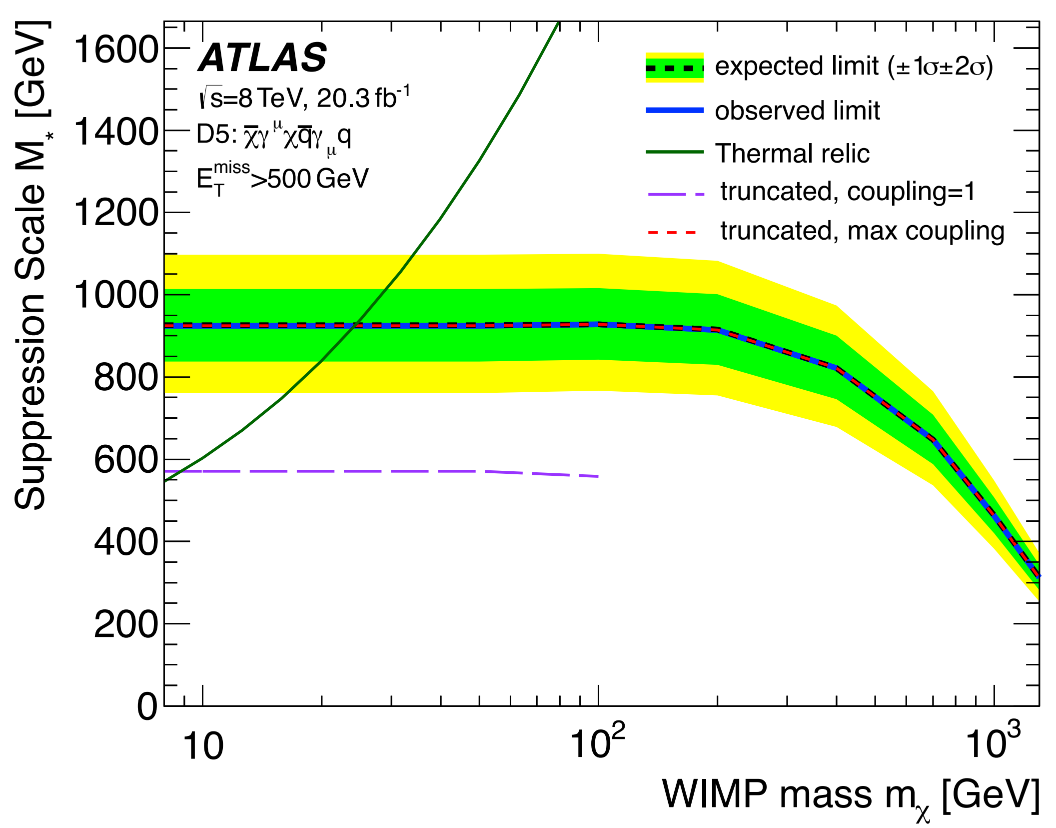
Dark Matter EFT operators

- 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.
- EFT has two parameters (mDM and suppression scale Λ)

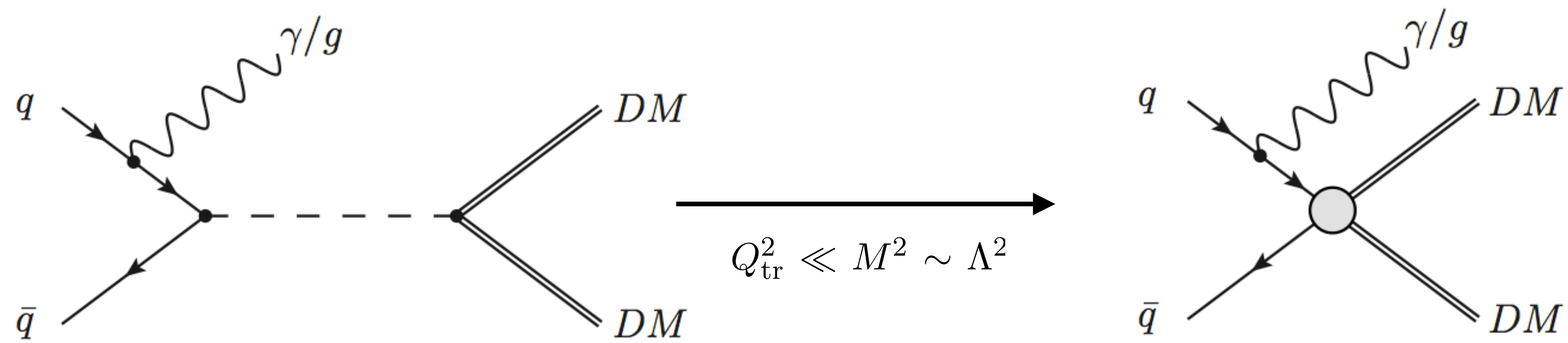


Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
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	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$



1008.1783

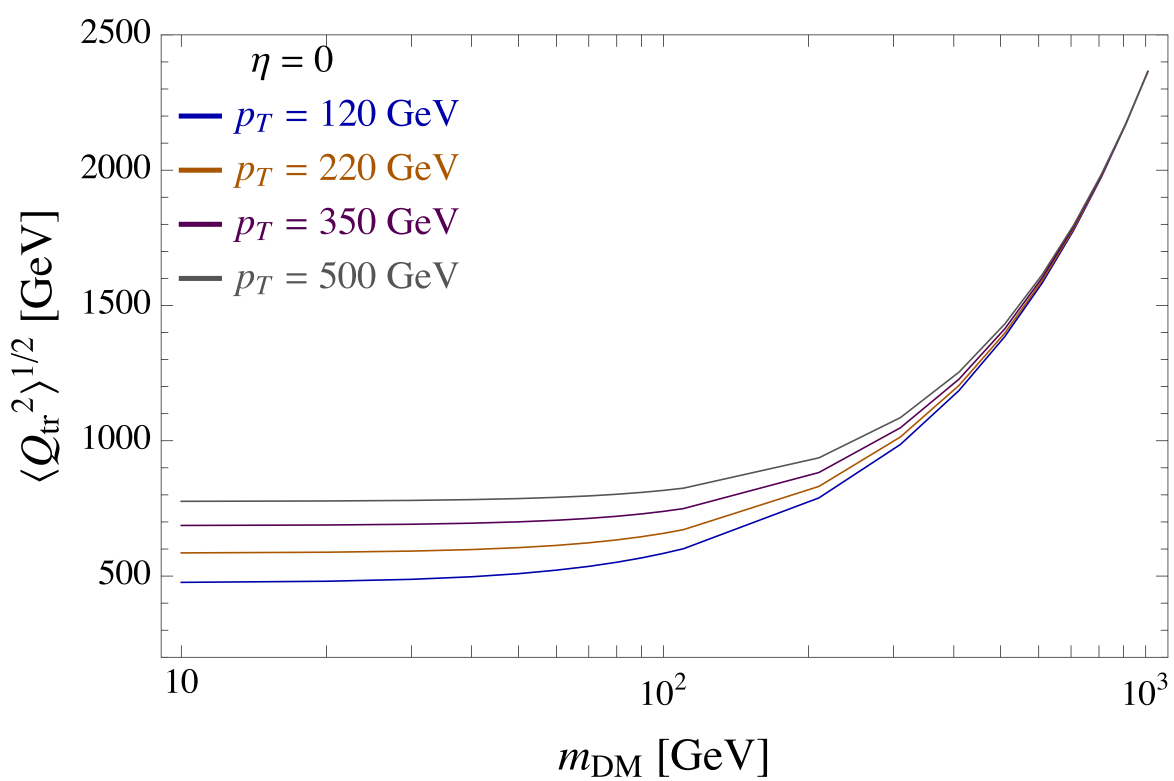
Contact interactions



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

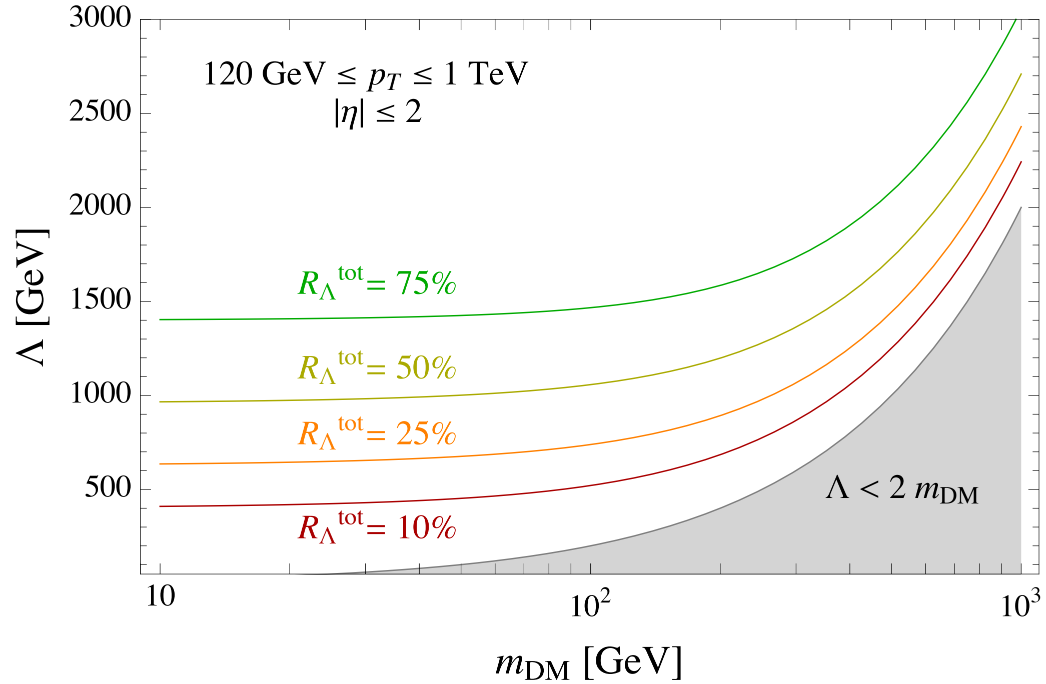
$$\mathcal{O}_S = \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{q}q) \qquad \frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M^2}$$

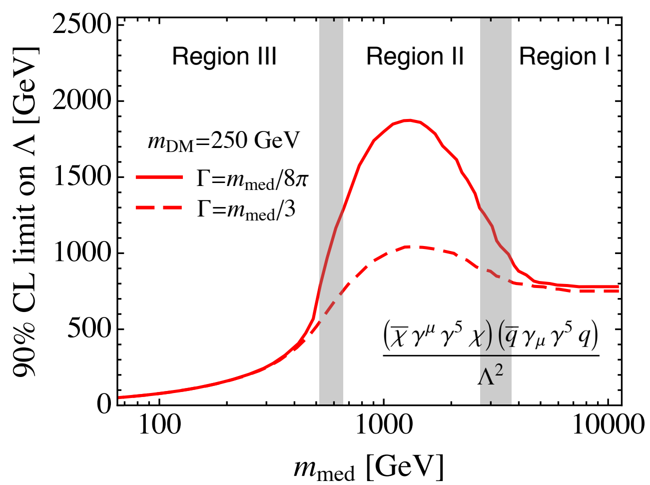
- It is safe to use EFT when the mediator can be integrated out.
- However, at the LHC energies, the limits on the suppression scale are comparable to the momentum transfer!

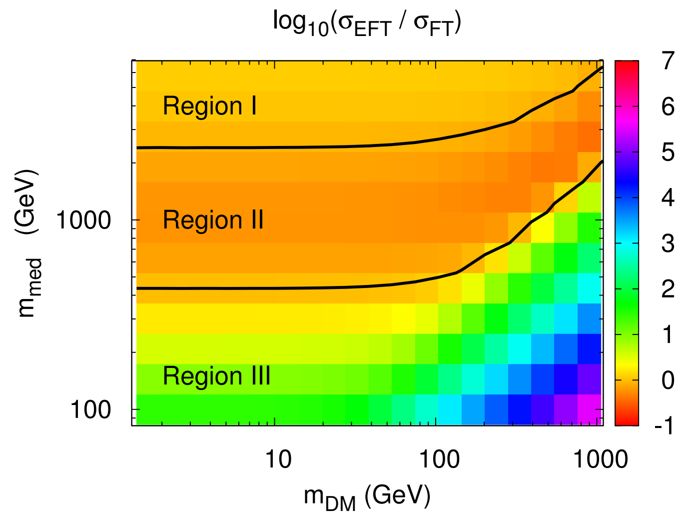


EFT validity

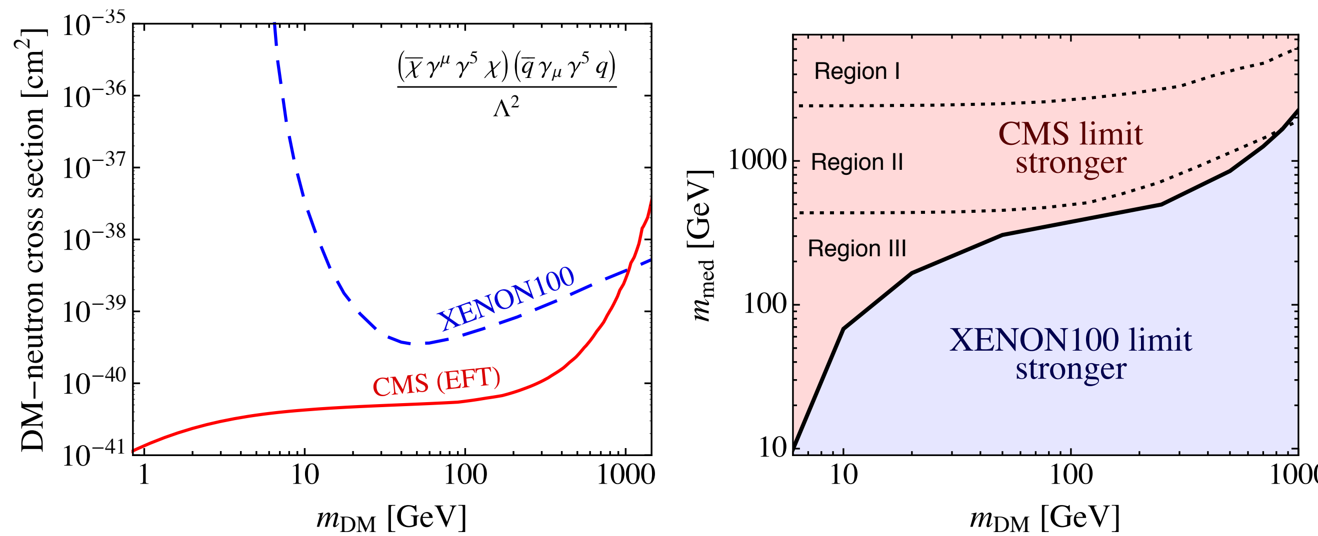
- ratio of valid events $R_\Lambda^{\rm tot} \equiv \frac{\sigma_{\rm eff}|_{Q_{\rm tr}<\Lambda}}{\sigma_{\rm eff}}$
- The collider limits do not satisfy the EFT validity condition.
- How do the EFT limits compare to the limits from s-channel models with light mediators?







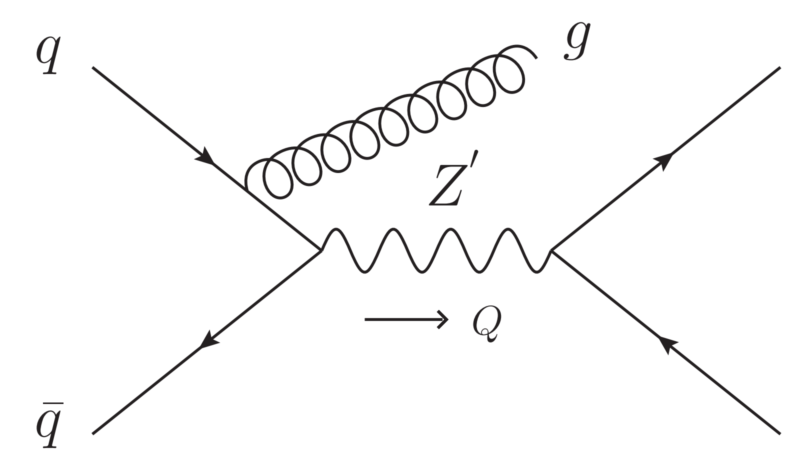
- EFT limits are aggressive in region III, DD limits are stronger at low DM and mediator masses!



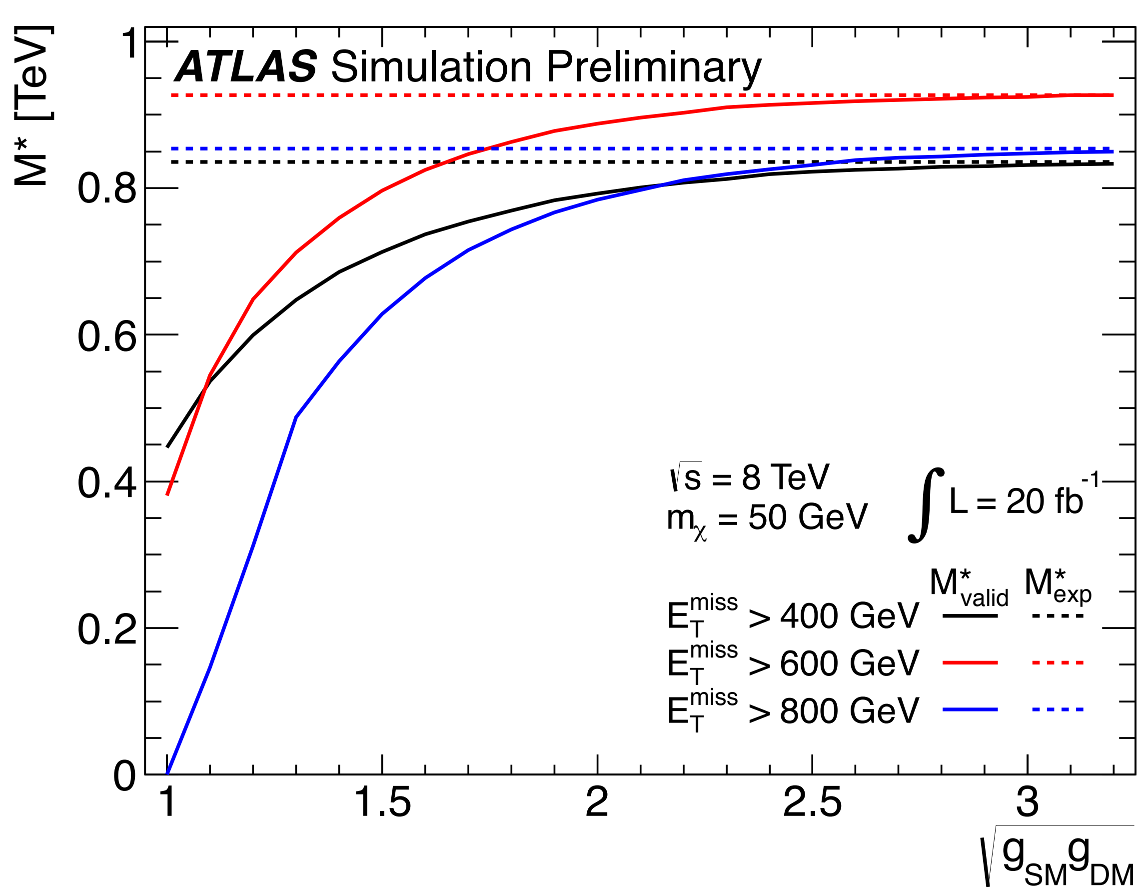
EFT validity

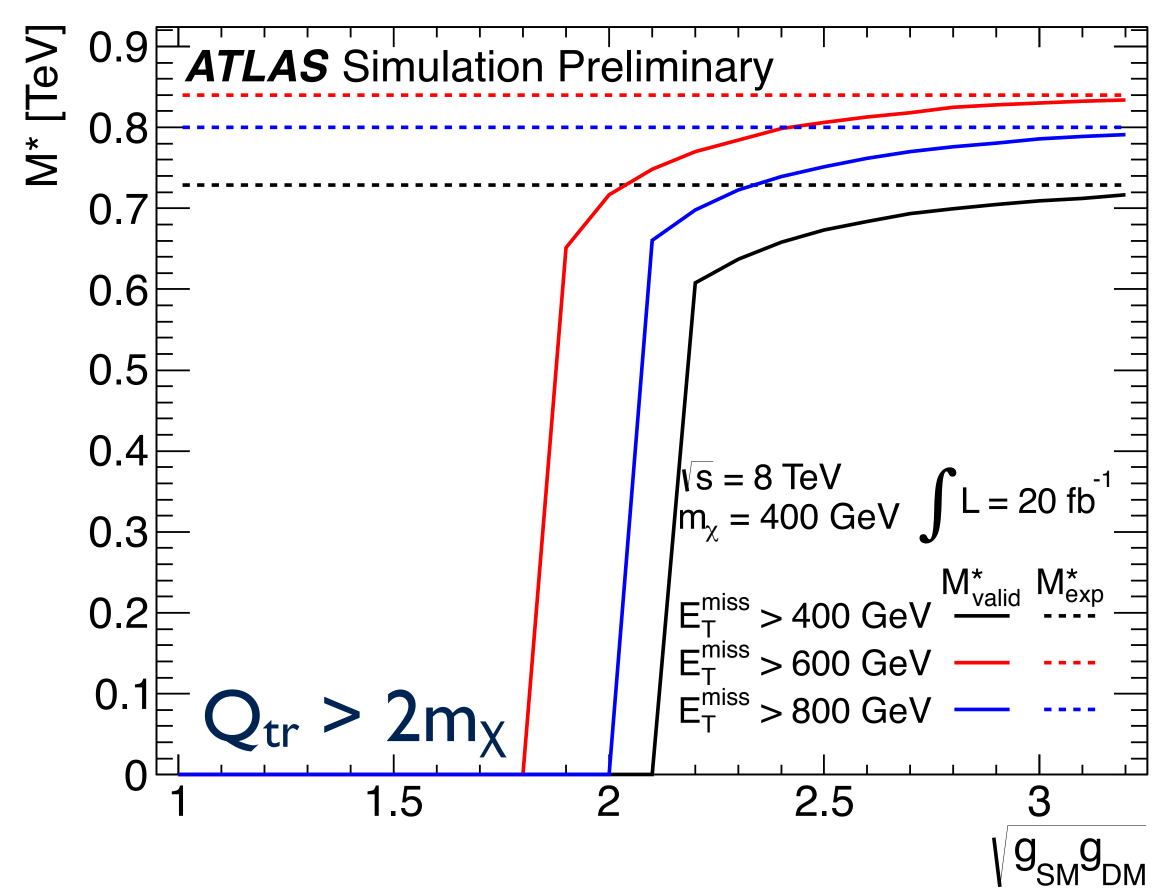
ATL-PHYS-PUB-2014-007

- Minimum requirement for EFT being a valid approximation of UV-complete models is $Q_{tr} < M_{med} = \sqrt{g_q\, g_\chi}\; M^*$.
- Not all events generated in EFT are valid at the LHC energies.
- As a consequence, the M* limits decrease.
- For D5, the EFT approach is fully valid for $\sqrt{g_q\, g_\chi} \gtrsim \pi$.



$$\frac{g_q\, g_\chi}{Q^2 - m_{\rm med}^2} \approx -\frac{g_q\, g_\chi}{m_{\rm med}^2}\left(1 + \frac{Q^2}{m_{\rm med}^2} + \mathcal{O}\left(\frac{Q^4}{m_{\rm med}^4}\right)\right)$$





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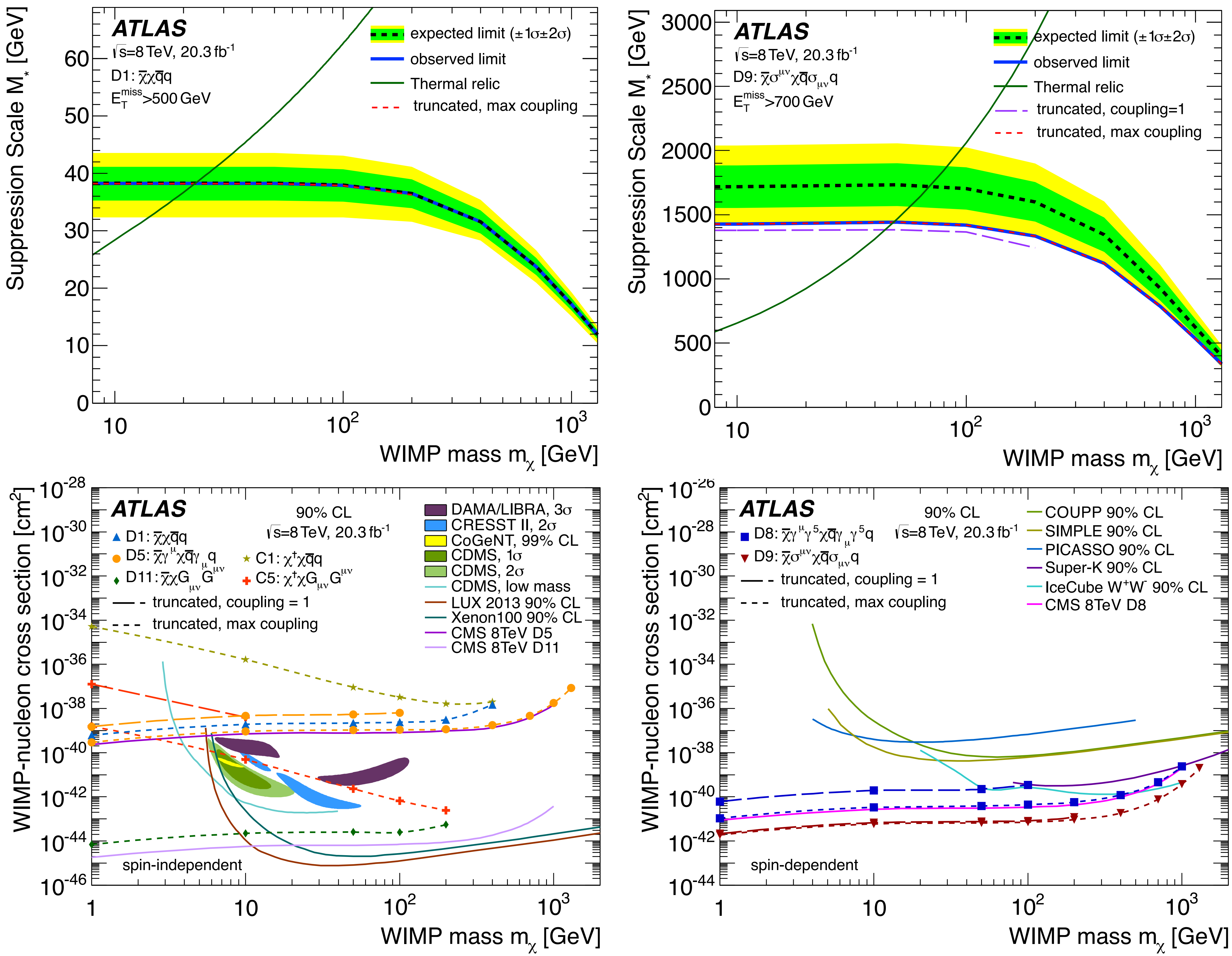
DM interpretation



PRL 112, 041802 (2014)

mono-W/Z(qq)

8 TeV   20.3 fb^{-1}

Event selection

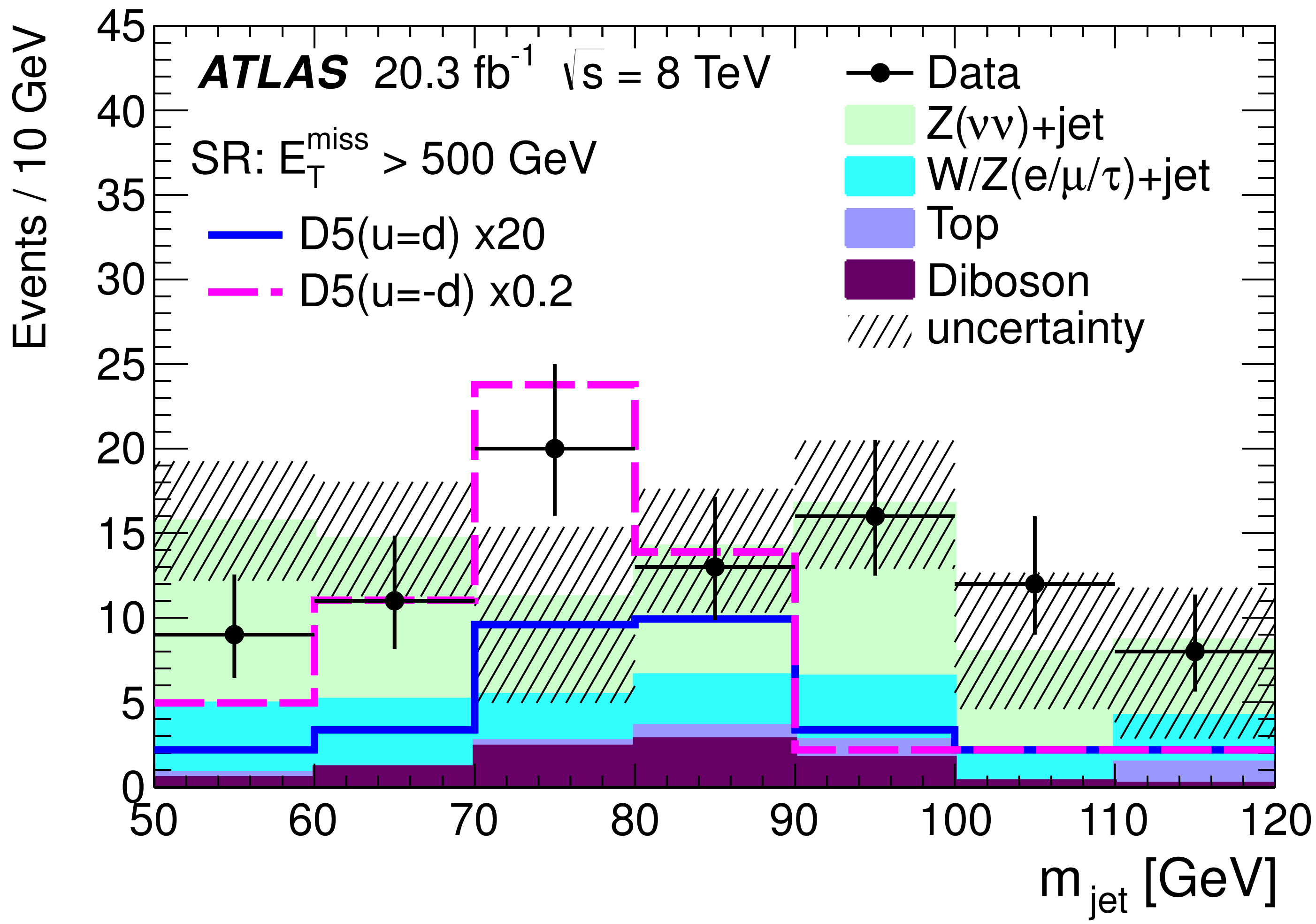
- large R=1.2 Cambridge-Aachen jet
  pT > 250 GeV, |η| < 1.2,
  50 < m < 120 GeV, $\sqrt{y}$ > 0.4
- at most one extra light jet
  pT > 40 GeV, |η| < 4.5
  away from the fat jet (dR > 0.9)
  and MET (dφ > 0.4)
- lepton and photon veto
  (pT > 10 GeV)
- SR defined by
  MET > 350, 500 GeV

Dominant backgrounds

- Zνν+jets, W/Z from CR
  (inverted muon veto)

Uncertainties

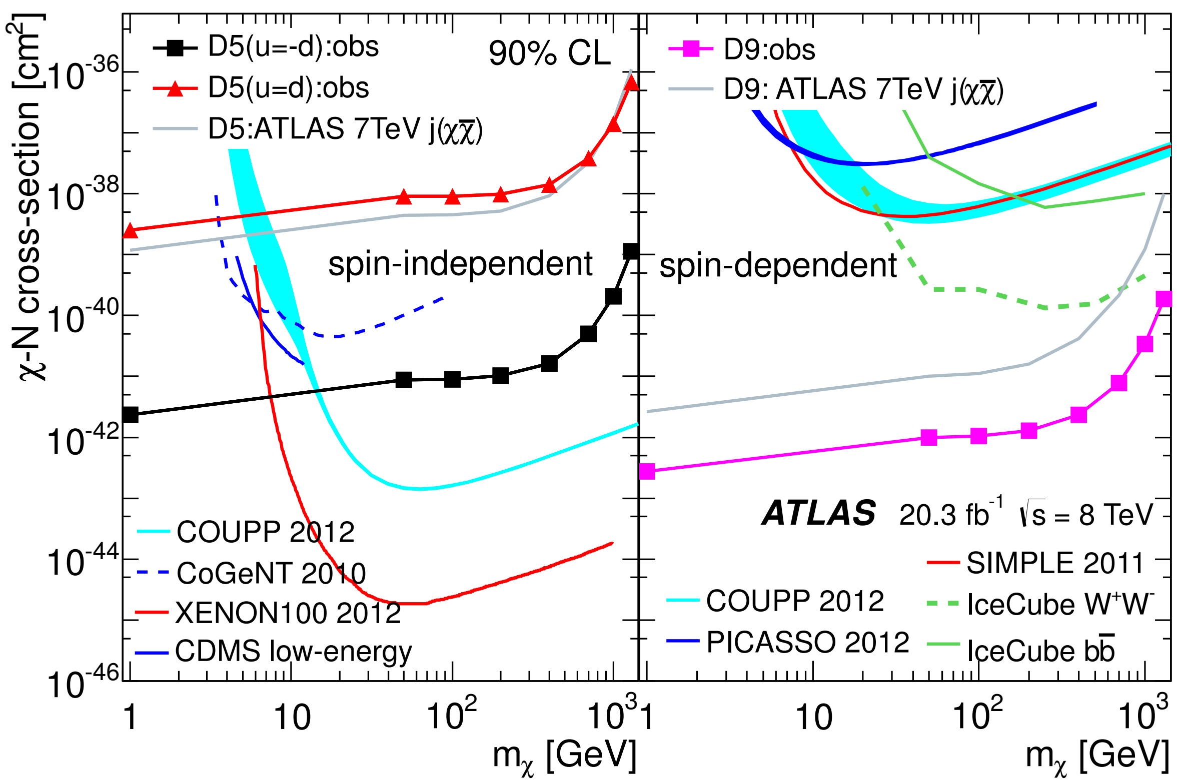
- limited CR statistics
- MC theory uncertainties
- C-A jet energy scale/resolution
- total uncertainty 7-13%

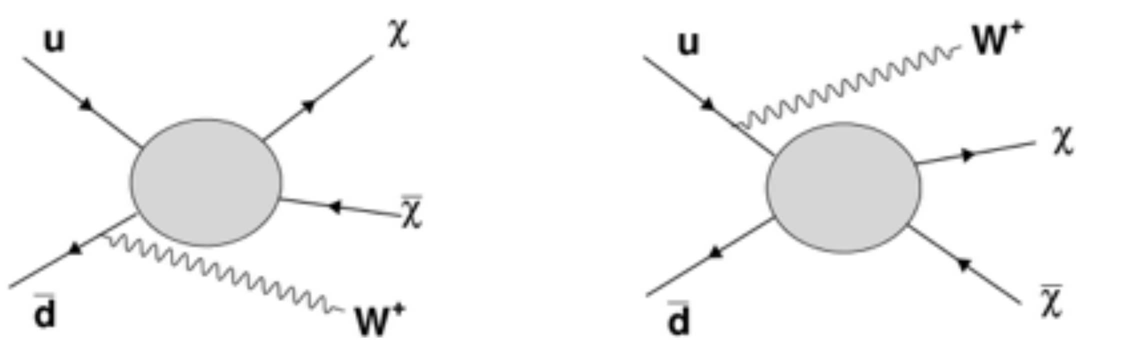


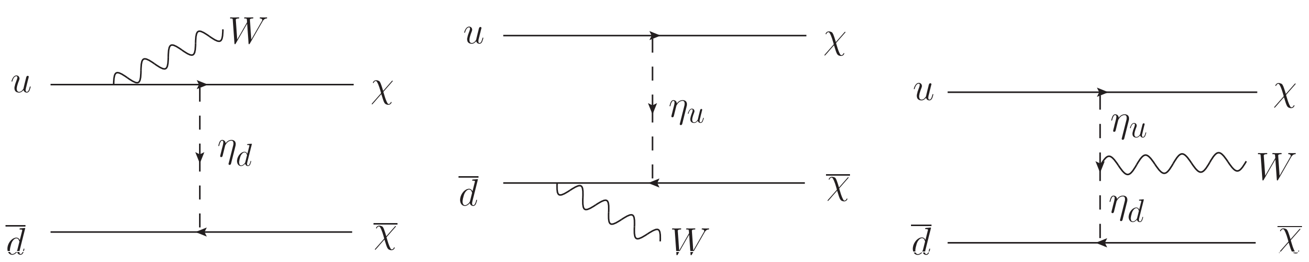
PRL 112, 041802 (2014)

mono-W/Z(qq)

- Sensitive to the sign of the DM couplings to up and down quarks.
  - C(u) = C(d) destructive interference
  - C(u) = -C(d) constructive interference
- Order of magnitude improvement on the WIMP-nucleon cross section limits.
  - M* > ~2 TeV for D5 constructive mode.



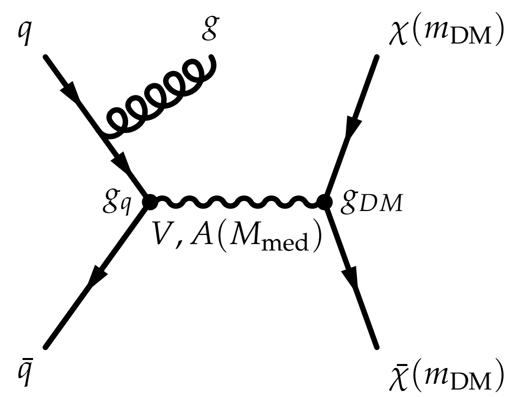


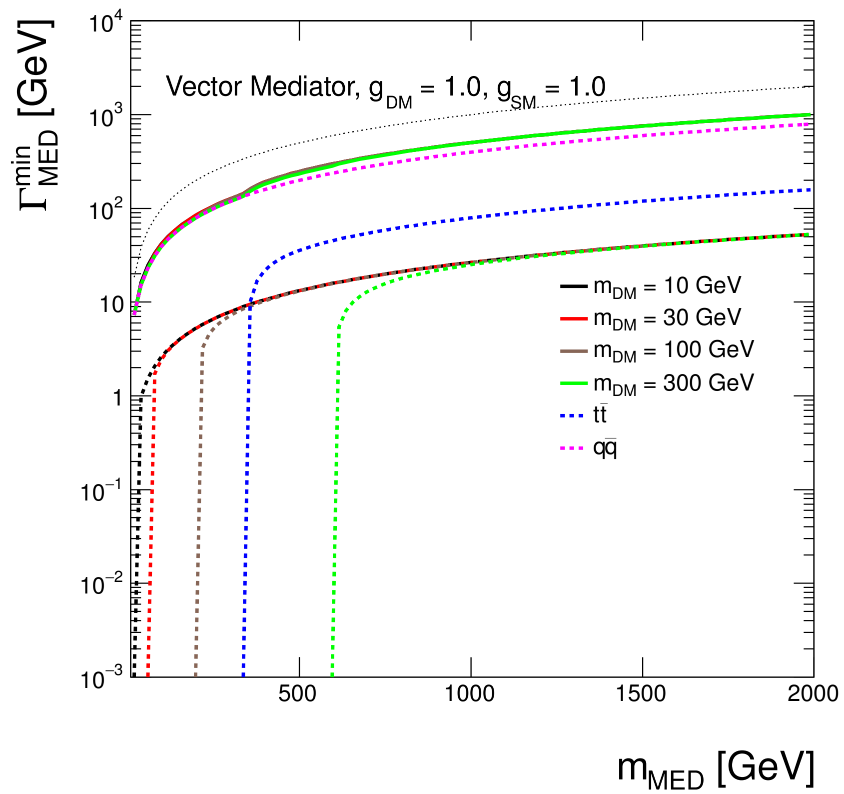


- However, other than C(u) = C(d) violates the gauge invariance.

1503.07874

spin-1 mediator in s-channel





- Dirac Dark Matter
- universal quark coupling
- U(1) gauge symmetry
- minimal mediator width

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

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

$$\Gamma^{\text{V}}_{\text{min}} = \frac{g_\chi^2 M_{\text{med}}}{12\pi}\left(1 + \frac{2m_\chi^2}{M_{\text{med}}^2}\right)\beta_{DM}\theta(M_{\text{med}} - 2m_\chi) + \sum_q \frac{3g_{\text{q}}^2 M_{\text{med}}}{12\pi}\left(1 + \frac{2m_q^2}{M_{\text{med}}^2}\right)\beta_q\theta(M_{\text{med}} - 2m_q),$$

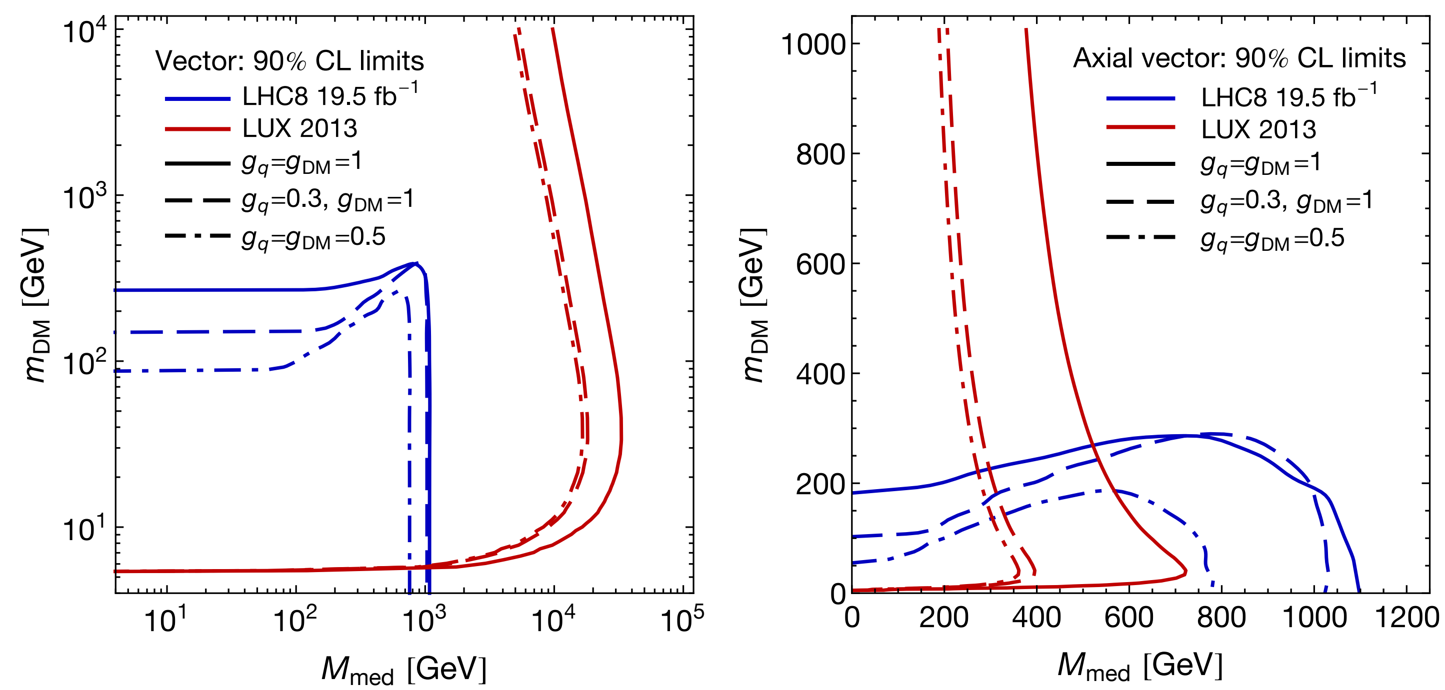
$$\Gamma^{\text{A}}_{\text{min}} = \frac{g_\chi^2 M_{\text{med}}}{12\pi}\beta_{DM}^3\theta(M_{\text{med}} - 2m_\chi) + \sum_q \frac{3g_{\text{q}}^2 M_{\text{med}}}{12\pi}\beta_q^3\theta(M_{\text{med}} - 2m_q)\ .$$

- 4 free parameters $\{\, g_{\text{q}},\ g_\chi,\ m_\chi,\ M_{\text{med}},\}$

[1407.8257](1407.8257)

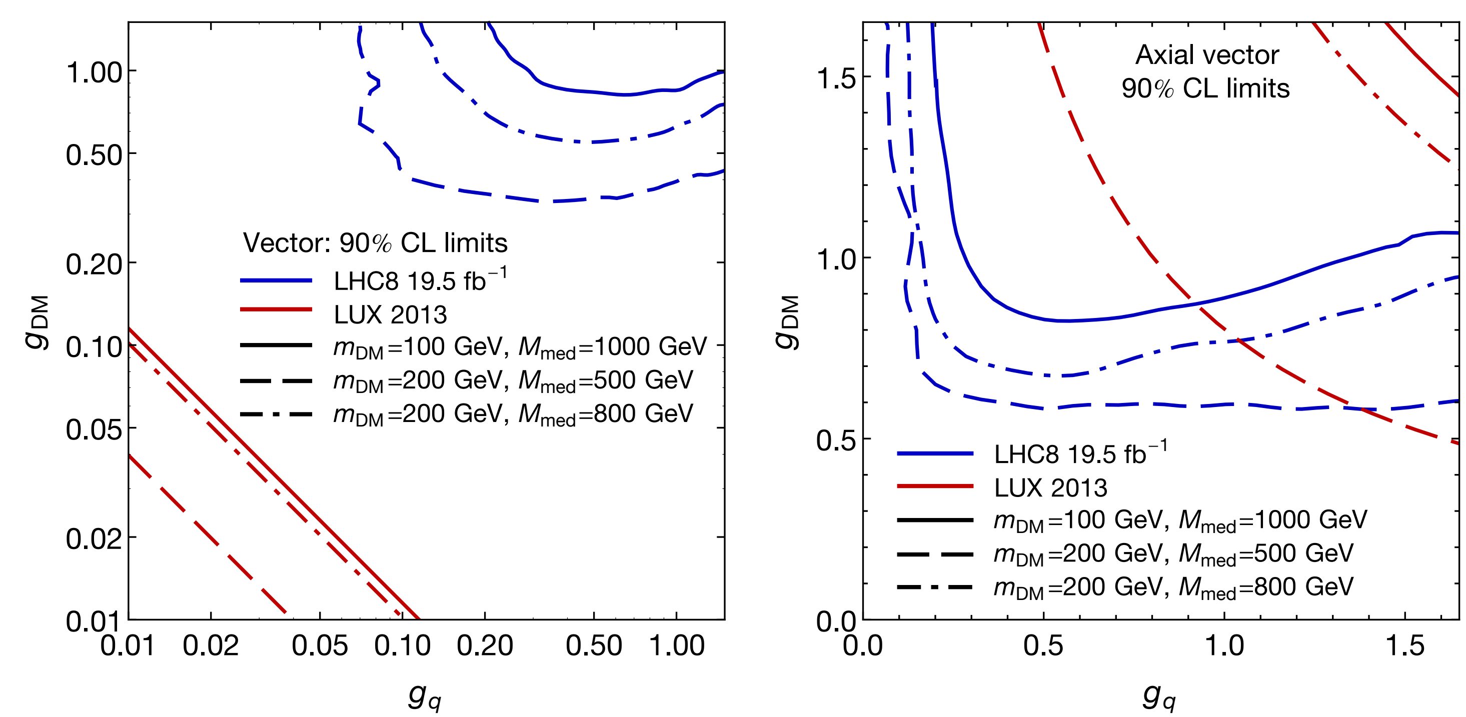
Minimal Simplified Dark Matter models

- SI cross-section is enhanced by A^2 for a vector mediator.
- Cross section for DD scales by $g_q^2 g_{DM}^2 / M_{med}^4$



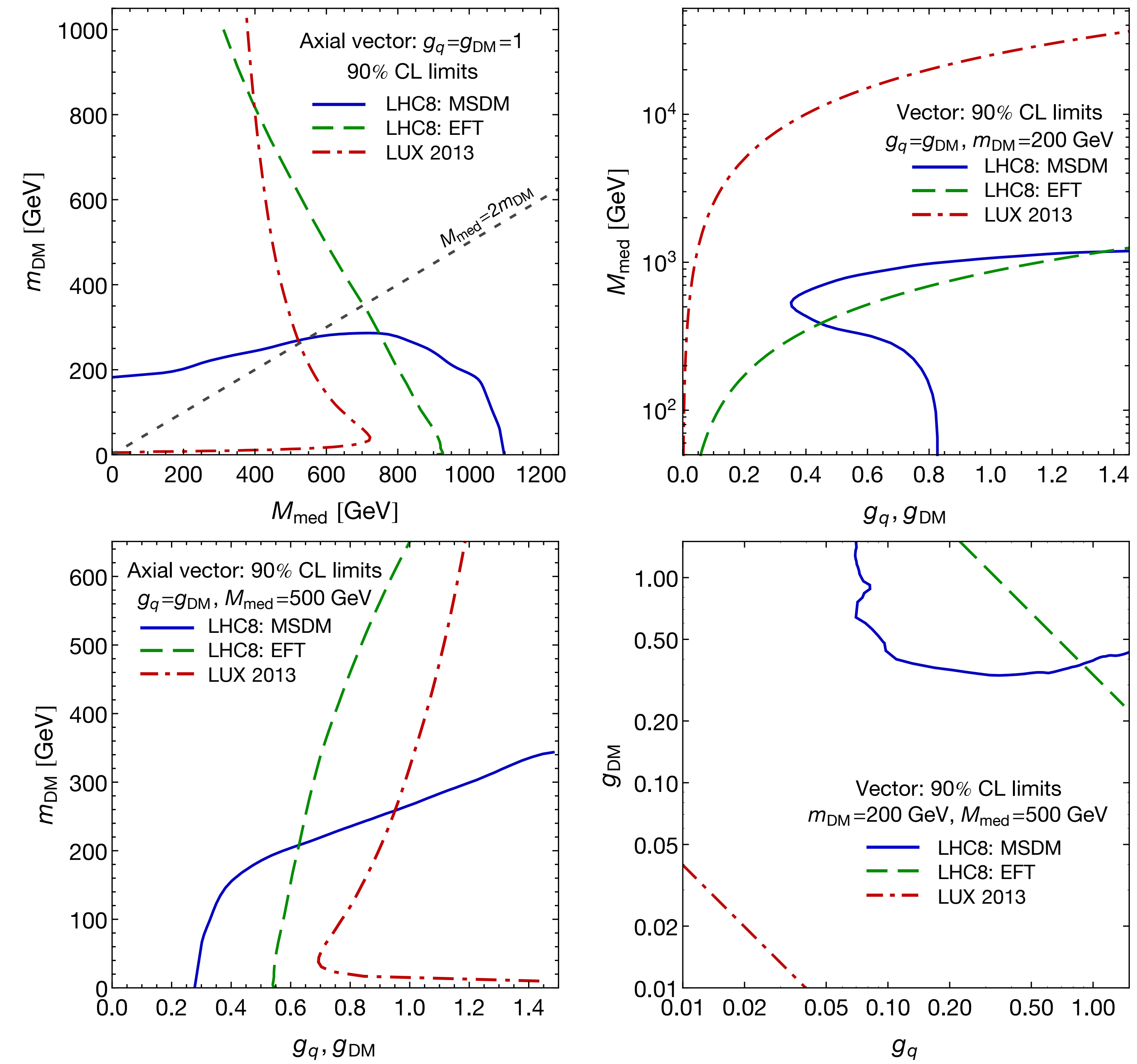
- DD limits are fully symmetric in this plane.
- Mono-jet search is able to break this degeneracy, since the mediator width is not symmetric in g_q and g_{DM}

$$\Gamma_{\text{med}} \propto 18 g_q^2 + g_{\text{DM}}^2$$



EFT limitations

- EFT overstates the limit at low M_{med} or large m_{DM} as the suppressed off-shell mediator production is not taken into account.
- The underlying coupling structure is not resolved by EFT.



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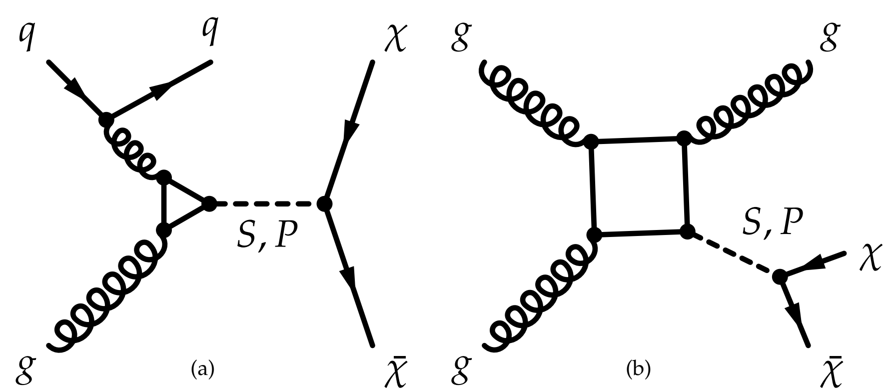
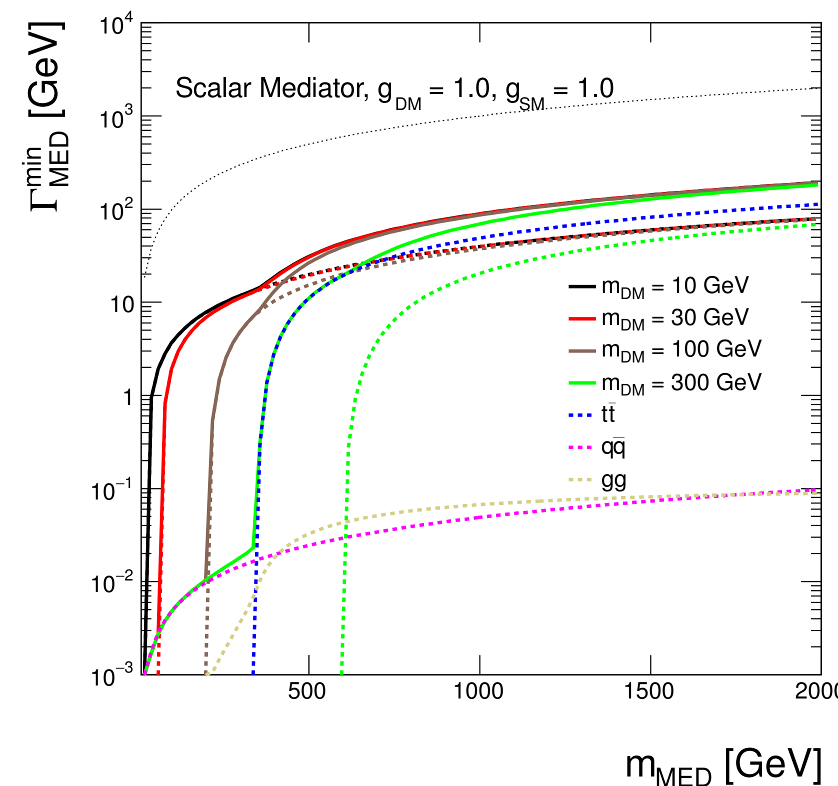
spin-0 mediator in s-channel



$$\Gamma_{\phi,a} = \sum_f N_c \frac{y_f^2 g_q^2 m_{\phi,a}}{16\pi}\left(1-\frac{4m_f^2}{m_{\phi,a}^2}\right)^{x/2} + \frac{g_\chi^2 m_{\phi,a}}{8\pi}\left(1-\frac{4m_\chi^2}{m_{\phi,a}^2}\right)^{x/2} + \frac{\alpha_s^2 y_t^2 g_q^2 m_{\phi,a}^3}{32\pi^3 v^2}\left|f_{\phi,a}\left(\frac{4m_t^2}{m_{\phi,a}^2}\right)\right|^2$$

- Dirac Dark Matter
- Minimal Flavour Violation
- mediator is pure singlet → not invariant under SU(2)L
  → one could add mixing with H sector
  (but this is beyond the scope of the DM Forum)
- minimal mediator width



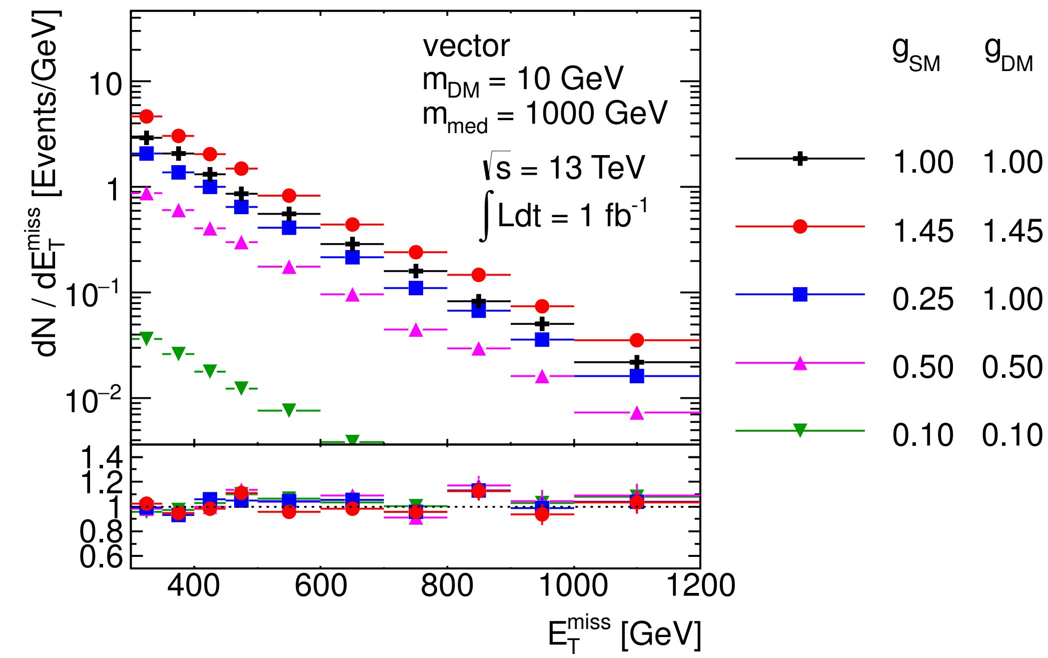
$$\mathcal{L}_\phi = g_\chi \phi \bar{\chi}\chi + \frac{\phi}{\sqrt{2}}\sum_i \left(g_u y_i^u \bar{u}_i u_i + g_d y_i^d \bar{d}_i d_i + g_\ell y_i^\ell \bar{\ell}_i \ell_i\right),$$

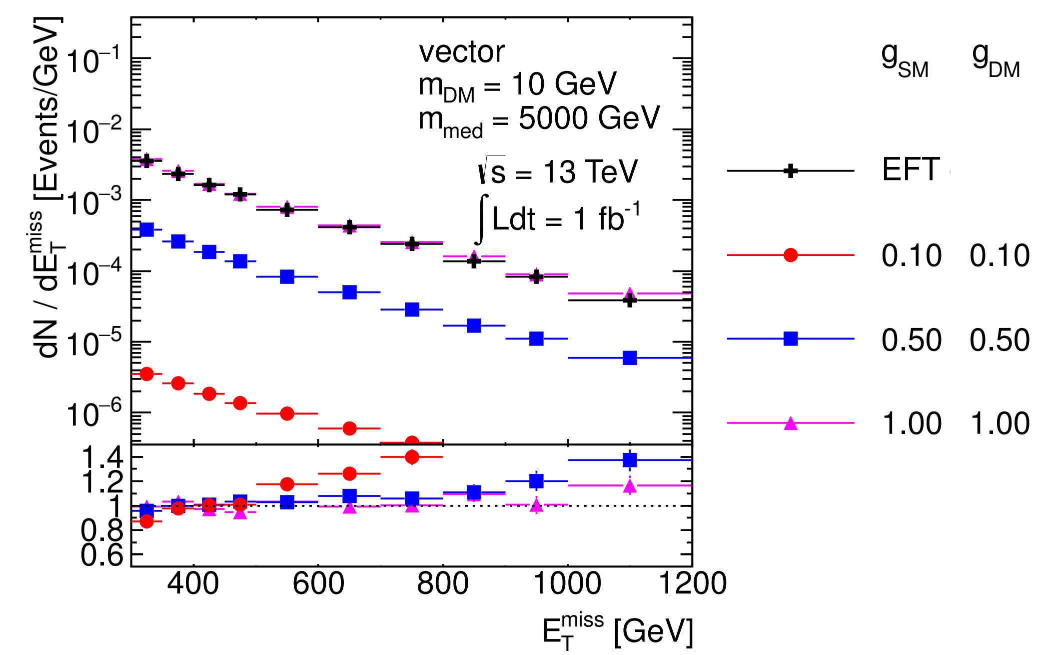
$$\mathcal{L}_a = i g_\chi a \bar{\chi}\gamma_5\chi + \frac{ia}{\sqrt{2}}\sum_i \left(g_u y_i^u \bar{u}_i \gamma_5 u_i + g_d y_i^d \bar{d}_i \gamma_5 d_i + g_\ell y_i^\ell \bar{\ell}_i \gamma_5 \ell_i\right).$$

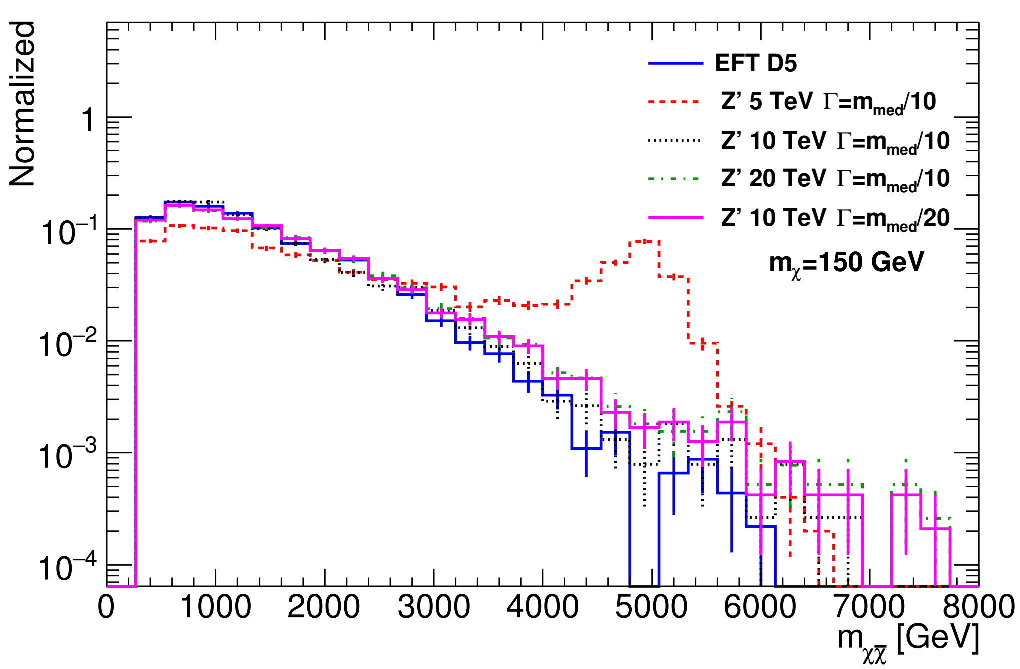
- 4 free parameters
  $\{m_\chi,\ m_{\phi/a} = M_{\rm med},\ g_\chi,\ g_q\}$

scan over couplings

- The shapes of kinematic distributions do not depend on the mediator width (couplings), only the cross section changes.
- The PDF suppression at low Bjorken x has an impact only for heavy narrow mediators that are beyond the sensitivity of early Run-2 data.
- We introduce one heavy mediator mass point to allow for reinterpretation as EFT
→ care has to be taken to make sure the DM-pair invariant masses are similar.



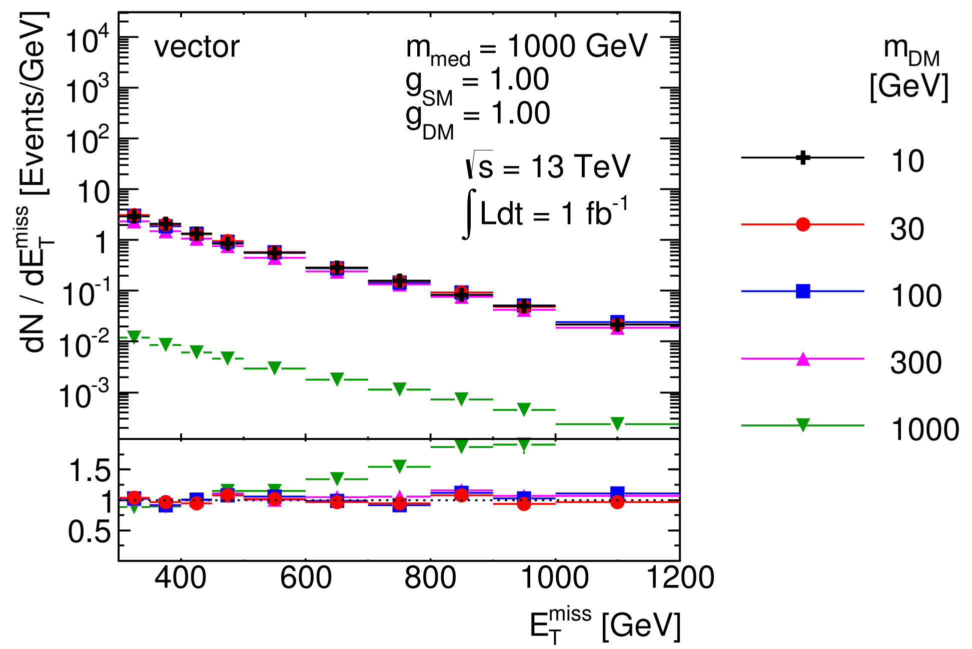


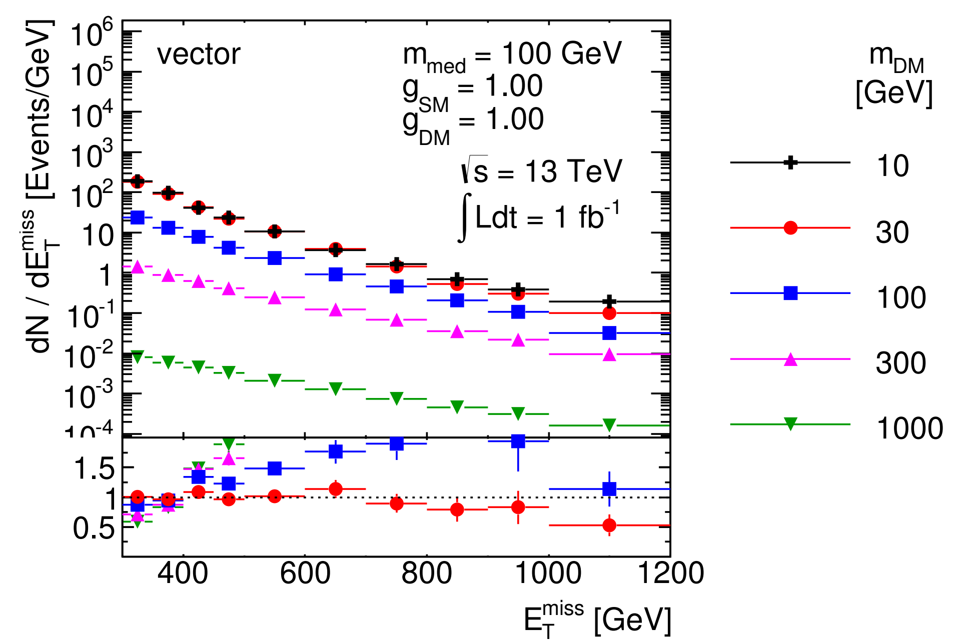


1507.00966

scan over DM mass

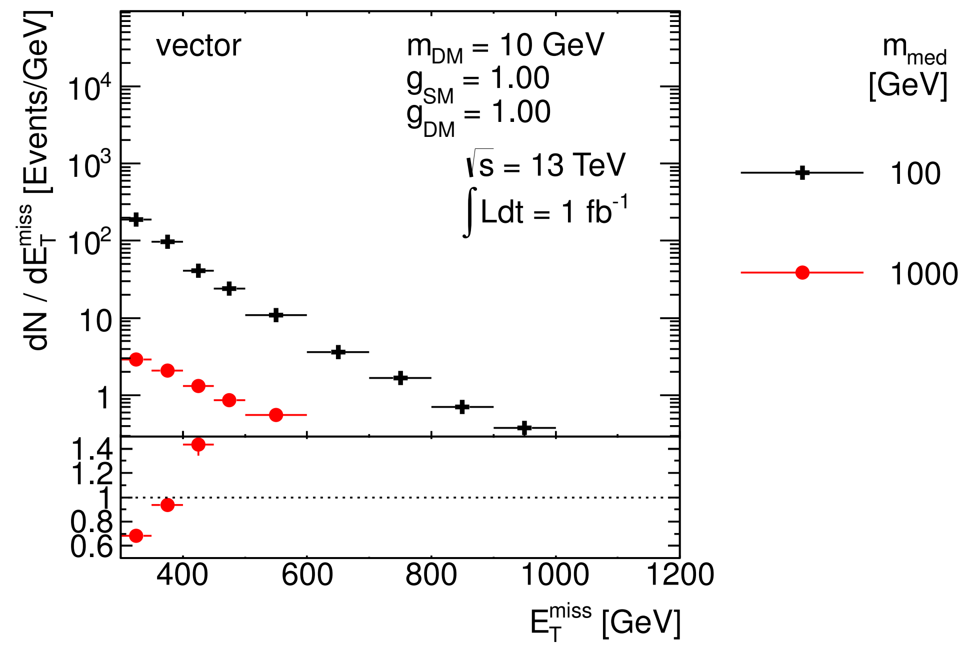
- on-shell (2mDM << mMed):
  - Kinematic distributions do not strongly depend on the DM mass.
- threshold (2mDM ~ mMed):
  - The production is resonantly enhanced and both cross section and kinematic shapes change rapidly. → finer granularity needed
- off-shell (2mDM >> mDM):
  - MET spectrum hardens with increasing DM mass and the cross section is suppressed.



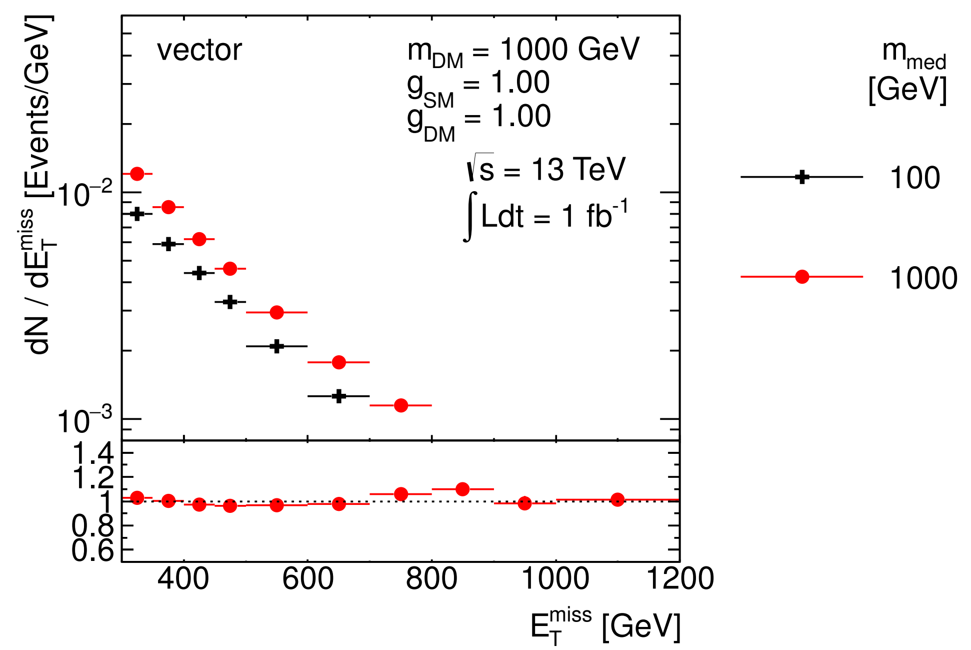


scan over mediator mass

- At fixed DM mass, the mediator mass has a significant impact on kinematics and cross section for the on-shell DM production region.

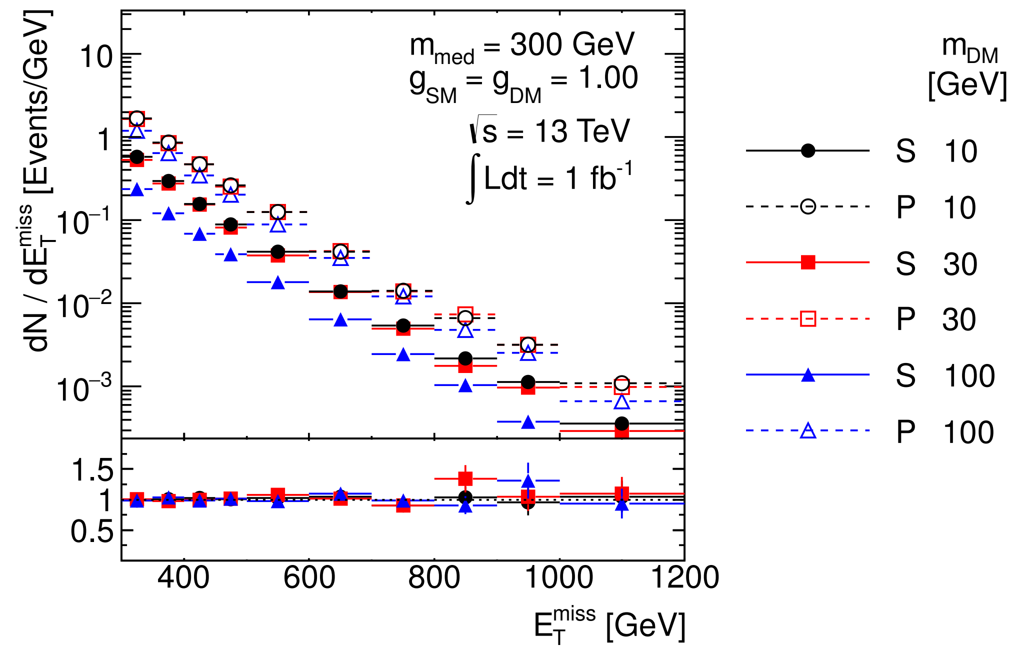


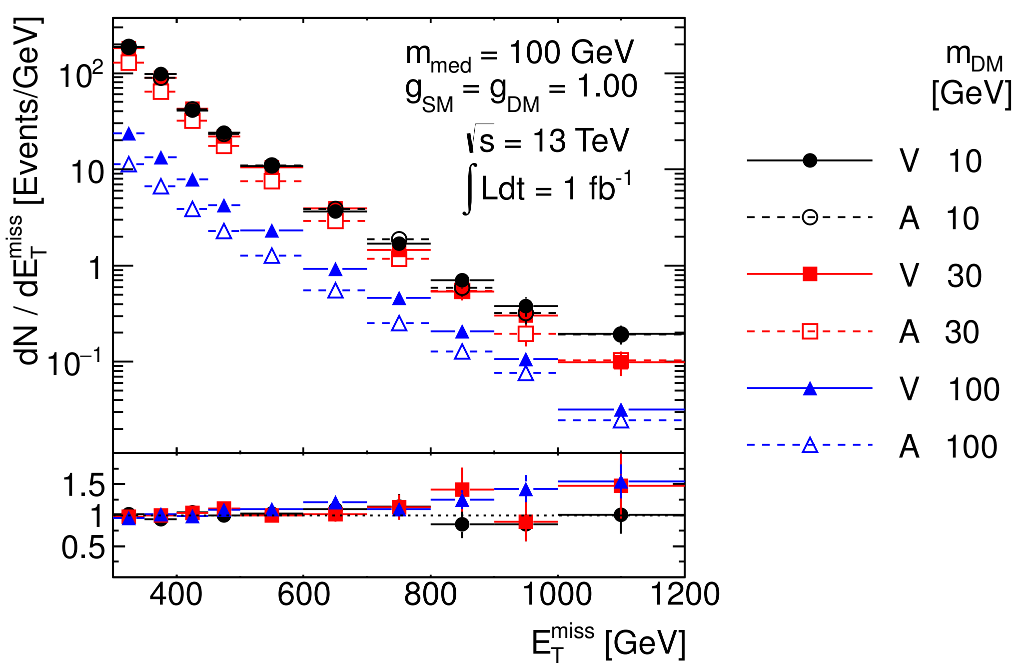
- Shapes of kinematic distributions do not change in the off-shell regime.

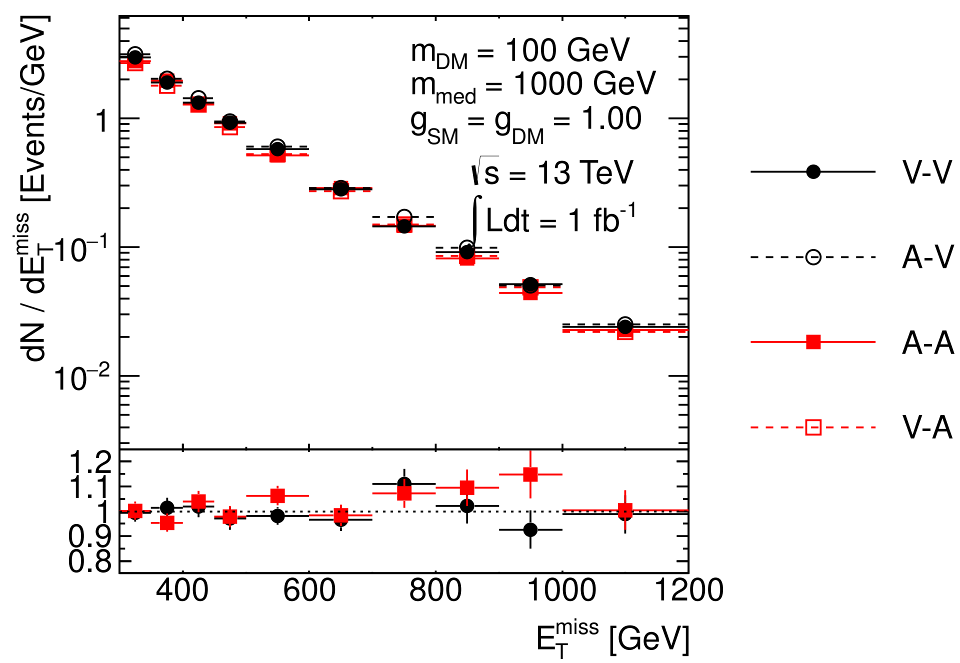


spin structure

- No significant differences are observed between V and A mediators and S and P mediators.
- Differences appear close to the 2mDM=mMed threshold.







proposed mass grids

- We choose gSM=0.25 and gDM=1 for V and A in order to suppress interplay between mono-jet and di-jet constraints. → Such coupling choice leads to Γ/M < 0.06 (contrary to Γ/M ~ 0.5 for gSM=gDM=1)
- For S and P, di-jet signatures come from 2-loop diagrams, therefore we stay with gSM=gDM=1. → Such coupling choice leads to Γ/M < 0.1

- Choice of the highest mediator mass is motivated by the sensitivity of the early Run-2 data.
- 10 TeV mediator is added to resemble EFT.
- The grid is optimised based on the dependencies studied in the scans over the couplings presented in the DM Forum writeup (and on previous slides).

vector and axial-vector

m_χ / GeV	M_{med} / GeV									
1	10	20	50	100	200	300	500	1000	2000	10000
10	10	15	50	100						10000
50	10		50	95	200	300				10000
150	10				200	295	500	1000		10000
500	10						500	995	2000	10000
1000	10							1000	1995	10000

scalar and pseudo-scalar

m_χ (GeV)	M_{med} (GeV)								
1	10	20	50	100	200	300	500	1000	10000
10	10	15	50	100					10000
50	10		50	95	200	300			10000
150	10				200	295	500	1000	10000
500	10						500	995	10000
1000	10							1000	10000

cross-section scaling

- Kinematic distributions do not change for different couplings (mediator widths).

➡ In principle, only the sample cross sections need to be rescaled.

- In the narrow width approximation:

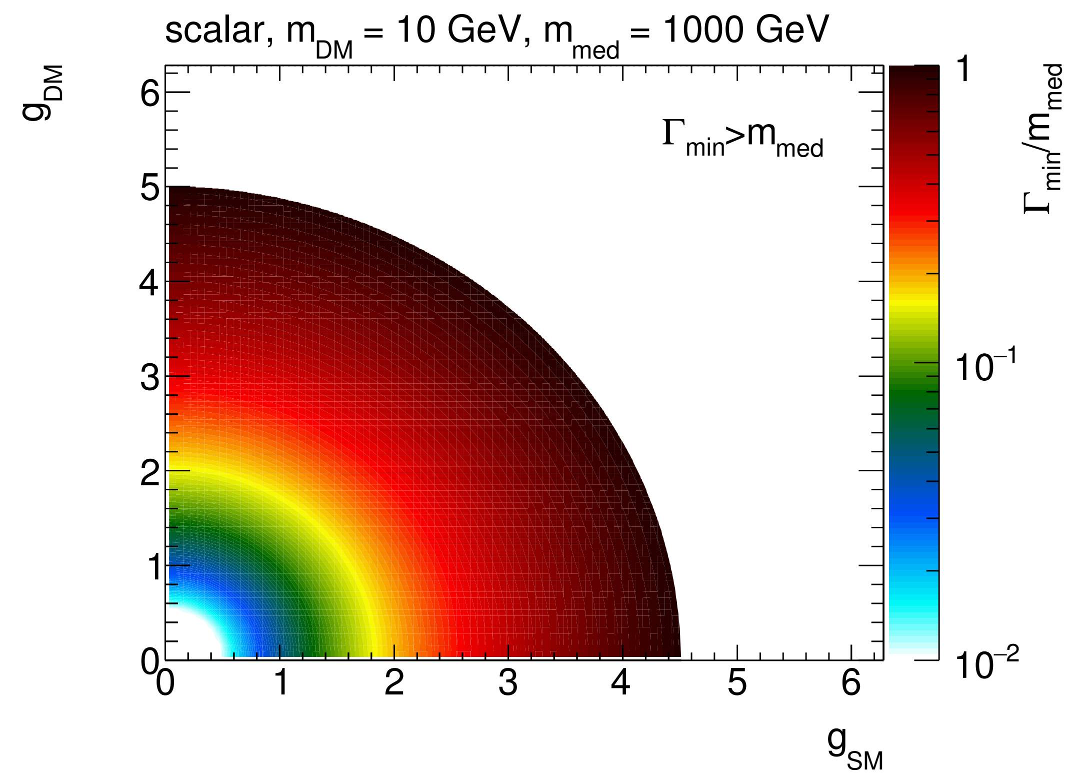
$$\int \frac{ds}{(s - M_{\rm med}^2)^2 + M_{\rm med}^2 \Gamma^2} = \frac{\pi}{M_{\rm med}\Gamma}$$

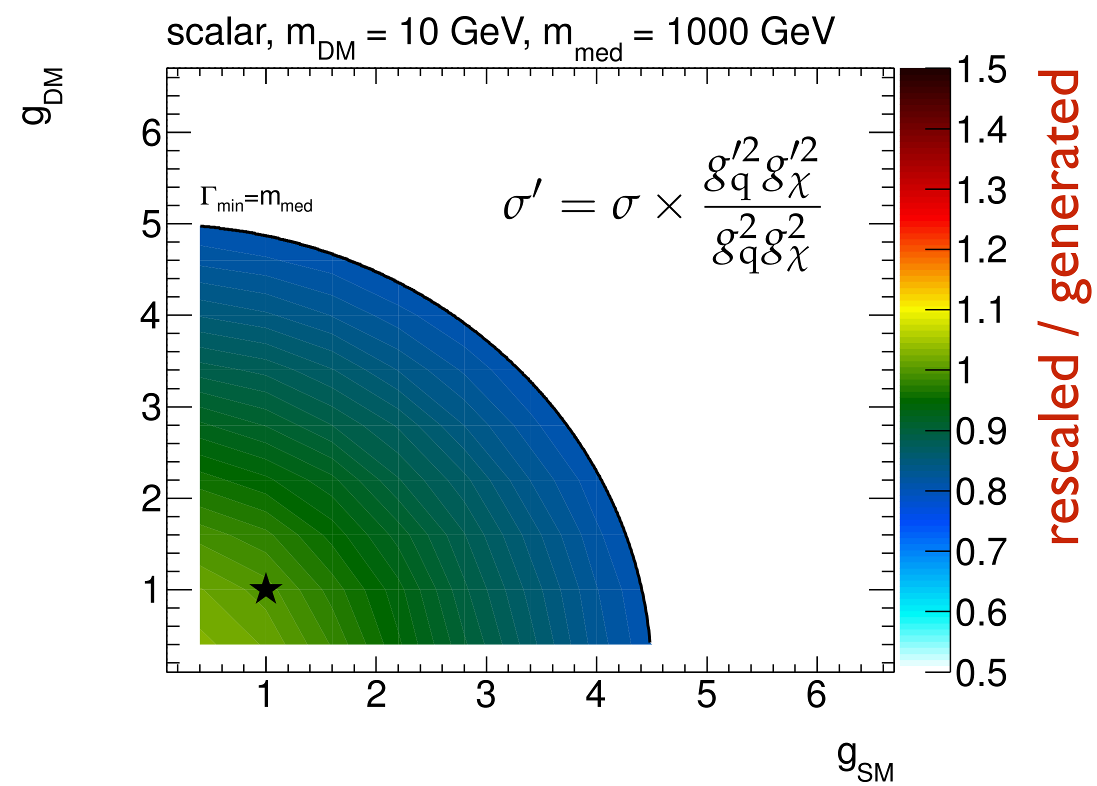
➡ which suggests cross section scaling (ignoring the PDF effects):

$$\sigma \propto \frac{g_q^2 g_{\rm DM}^2}{\Gamma}$$

- This scaling works well along the lines of constant width.

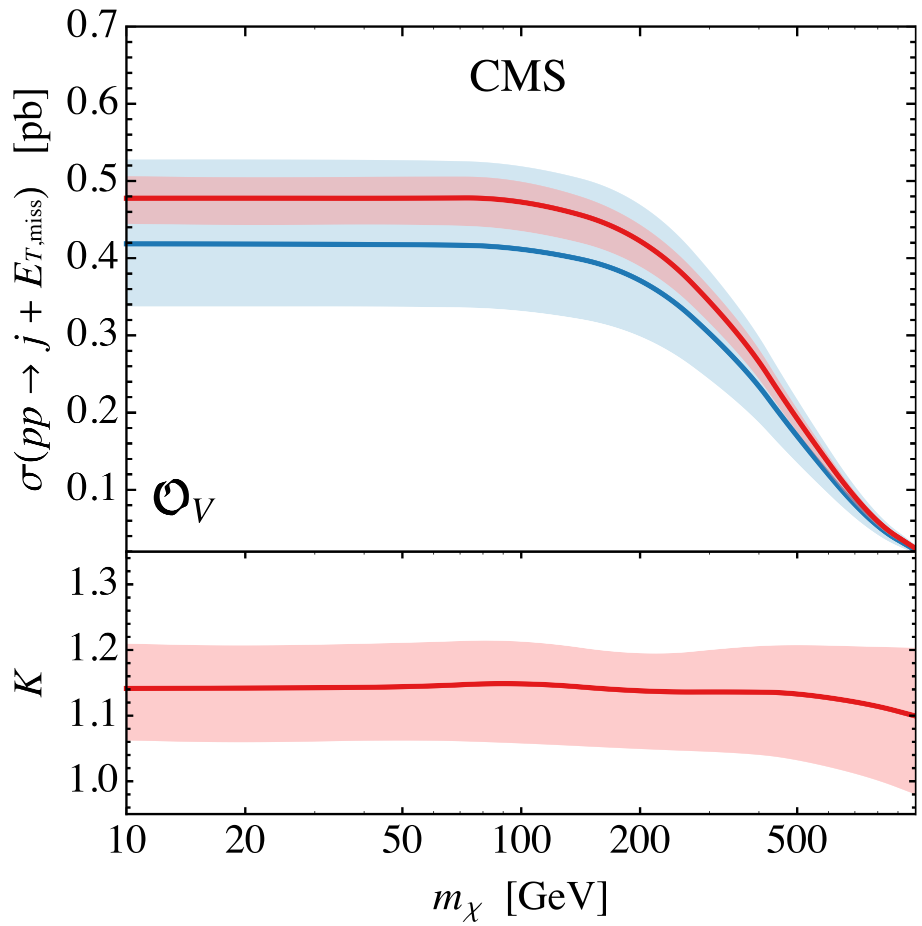
- We can present results in the gSM-gDM plane using only the following points:
  - g = 0.1, 0.25, 0.5, 0.75, 1, 1.25, 1.5 for V/A
  - g = 0.1, 1, 2, 3 for S/P





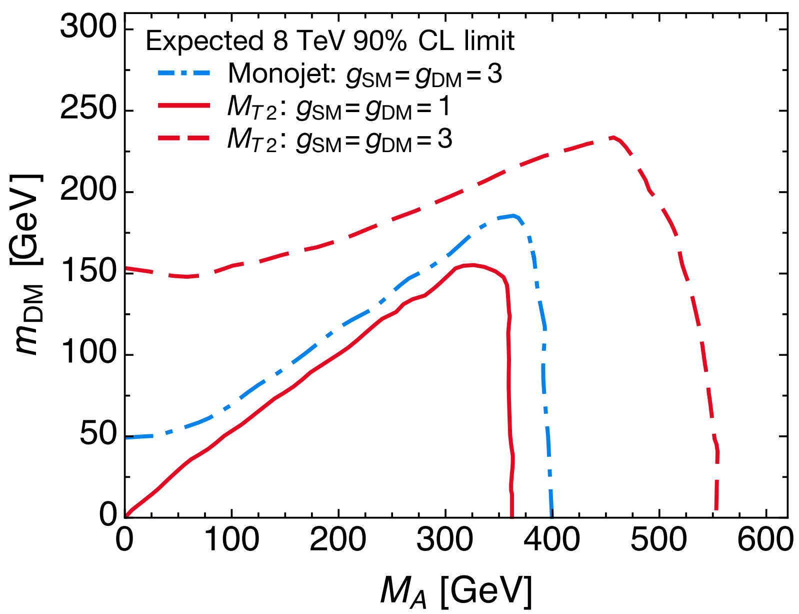
LO and NLO

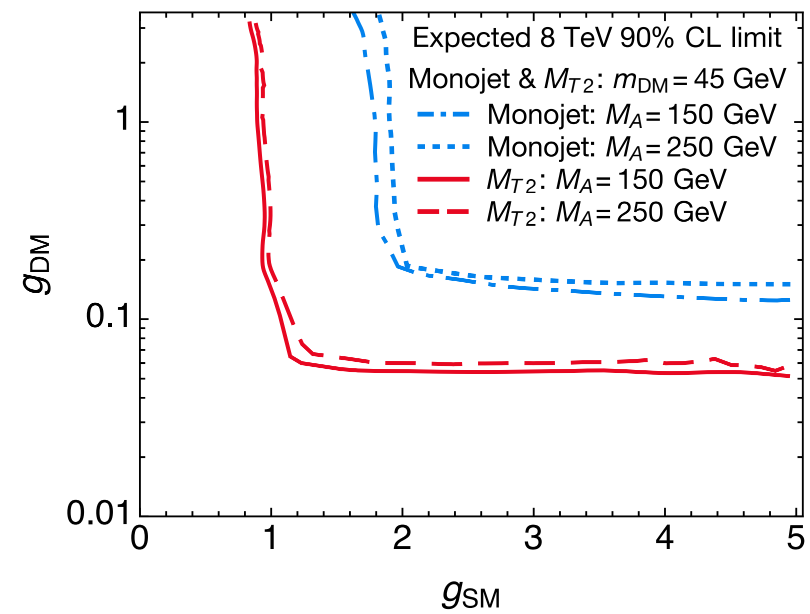
- Including NLO corrections results in a small enhancement of the cross-section compared to LO.
- dynamic scale $H_T = \sqrt{m^2_{\bar{\chi}\chi} + p^2_{T,j_1}} + p_{T,j_1}$ $\mu = \xi H_T/2 = \mu_R = \mu_F$
- It also leads to substantial reduction in the dependence on the choice of the renormalisation and factorisation scales.



$$K = \frac{\sigma(pp \to j + E_{T,\mathrm{miss}})^{\xi=[1/2,2]}_{\mathrm{NLO}}}{\sigma(pp \to j + E_{T,\mathrm{miss}})^{\xi=1}_{\mathrm{LO}}}$$

higher jet multiplicities





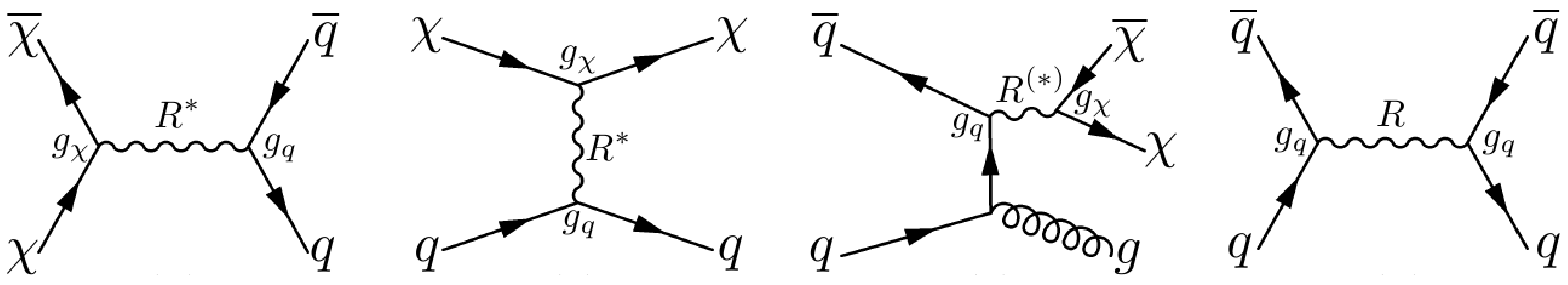
$$\mathcal{L}_{\rm int} = i g_{\rm DM} A \bar{\chi} \gamma^5 \chi + i g_{\rm SM} \sum_q \frac{m_q}{v} A\, \bar{q} \gamma^5 q$$

- Multi-jet searches, such as MT2 search, may have stronger sensitivity to pseudo-scalar mediators than mono-jet.

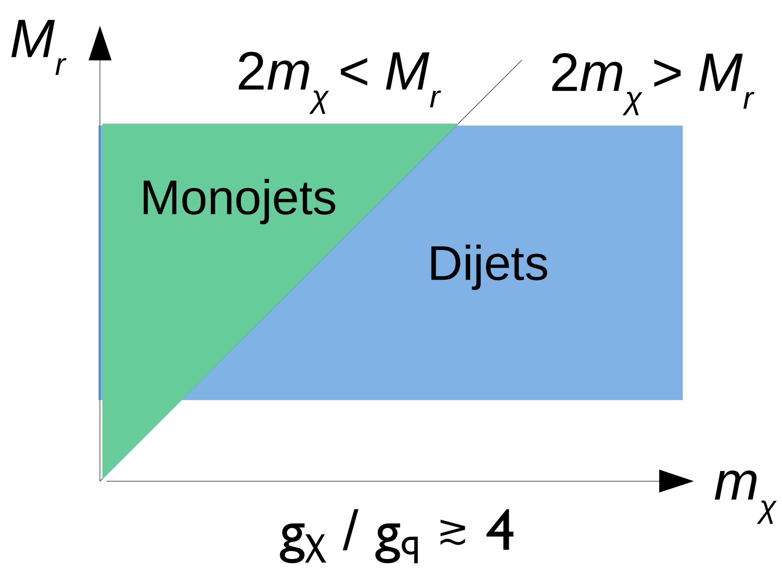
$$M_{T2}^2 \equiv \min_{\not{\mathbf{p}}_1 + \not{\mathbf{p}}_2 = \not{\mathbf{p}}_T} \left[\max\left\{ m_T^2(\mathbf{p}_{Tl^-}, \not{\mathbf{p}}_1), m_T^2(\mathbf{p}_{Tl^+}, \not{\mathbf{p}}_2) \right\} \right]$$

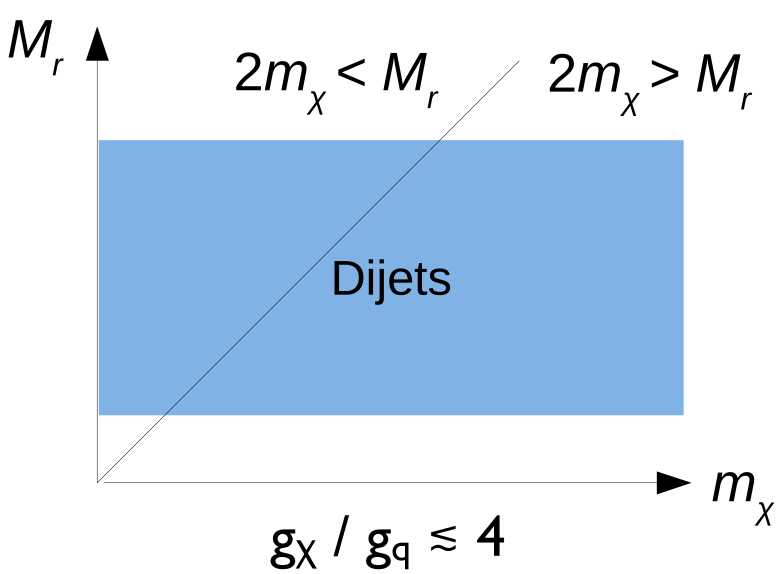
hep-ph/9906349
1502.04358

Searching for new mediators



- DM annihilation
- spin-dependent or spin-independent DM-nucleon scattering
- mono-jet production at the LHC
- di-jet production at the LHC

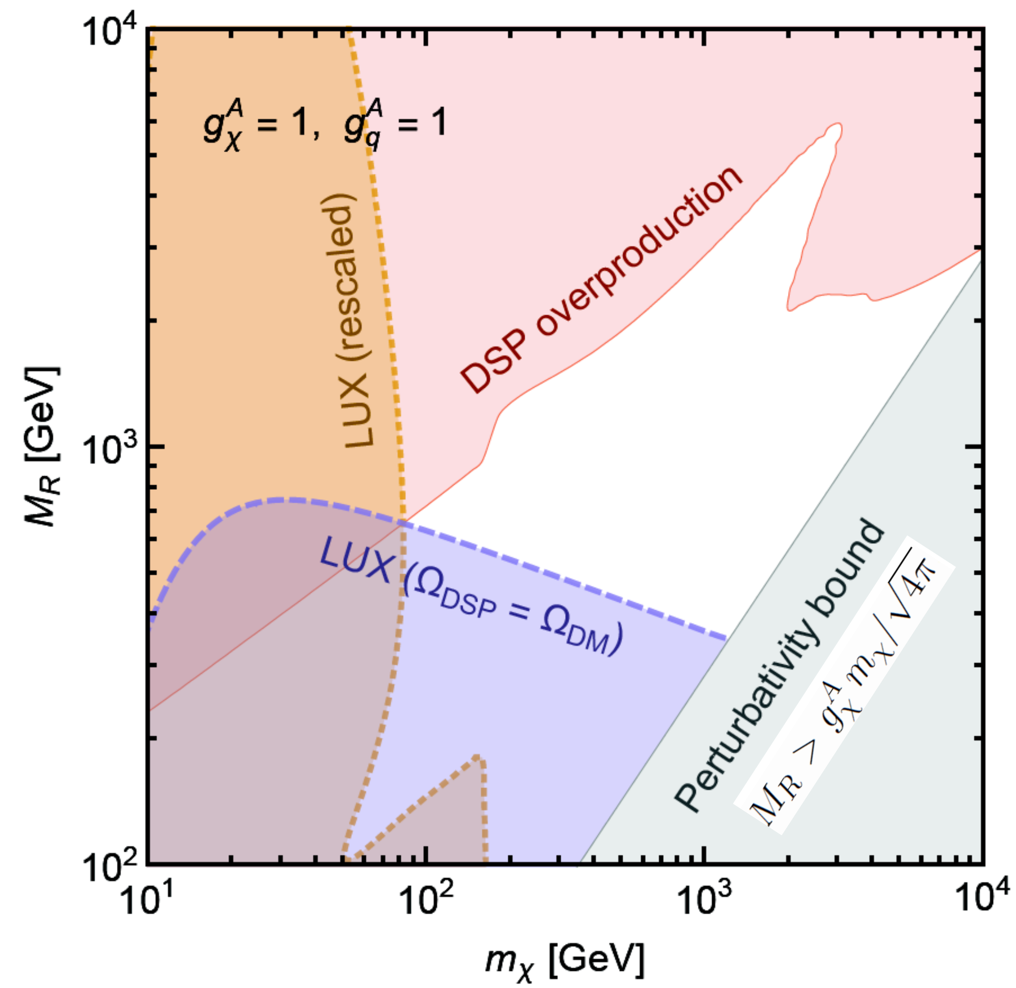




Complementarity

- The region where DM is under-produced is allowed (other DM candidates from the dark sector can contribute).
- Local density ρ scales with the relic abundance, which scales with the inverse of the annihilation cross section.

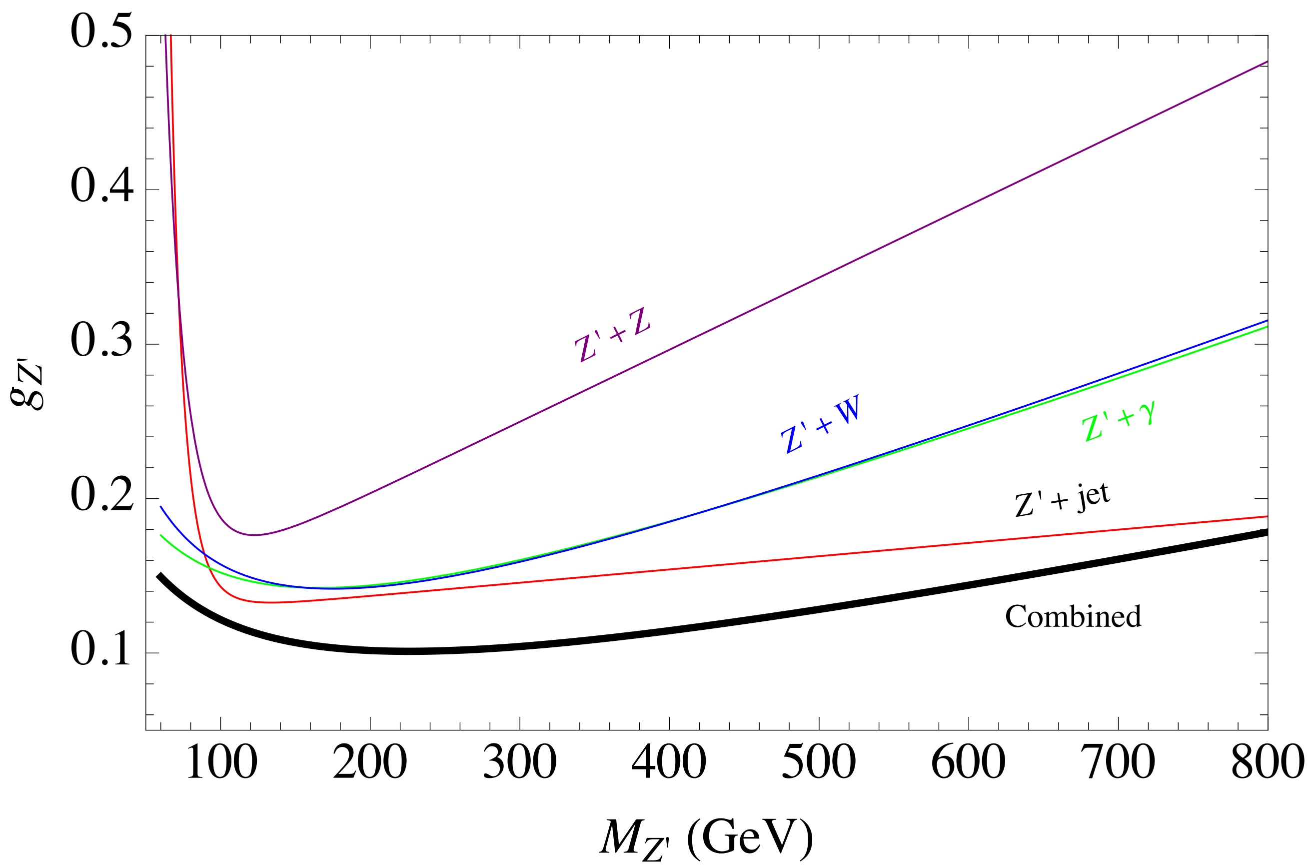
$$\Omega_{\rm DSP} \propto \frac{1}{\langle \sigma v \rangle} \propto g^{-4}$$

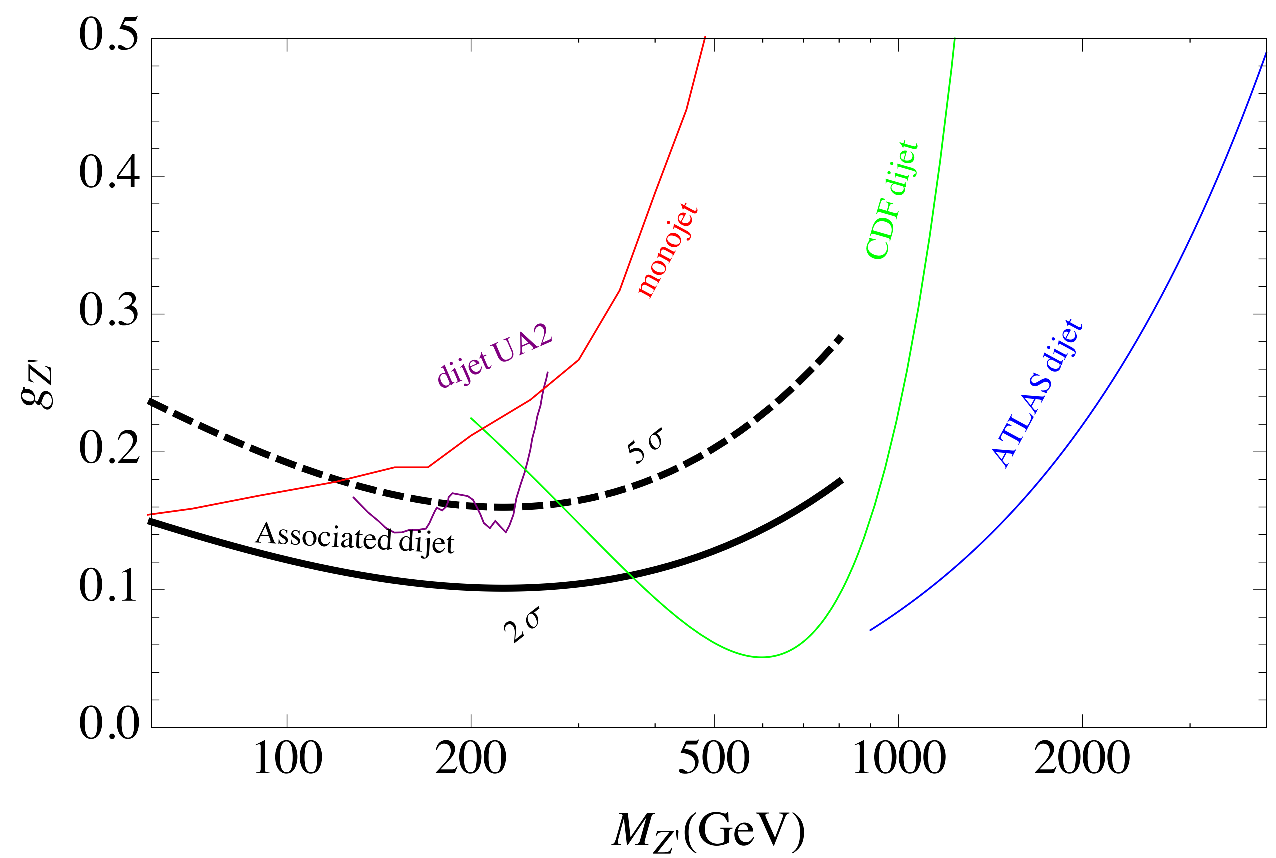


- Collider searches for missing energy: Rate $\propto \sigma \propto g^4$.
- Direct detection: Rate $\propto (\sigma \times \rho) \propto g^0$.
- Indirect detection: Rate $\propto (\sigma \times \rho^2) \propto g^{-4}$.

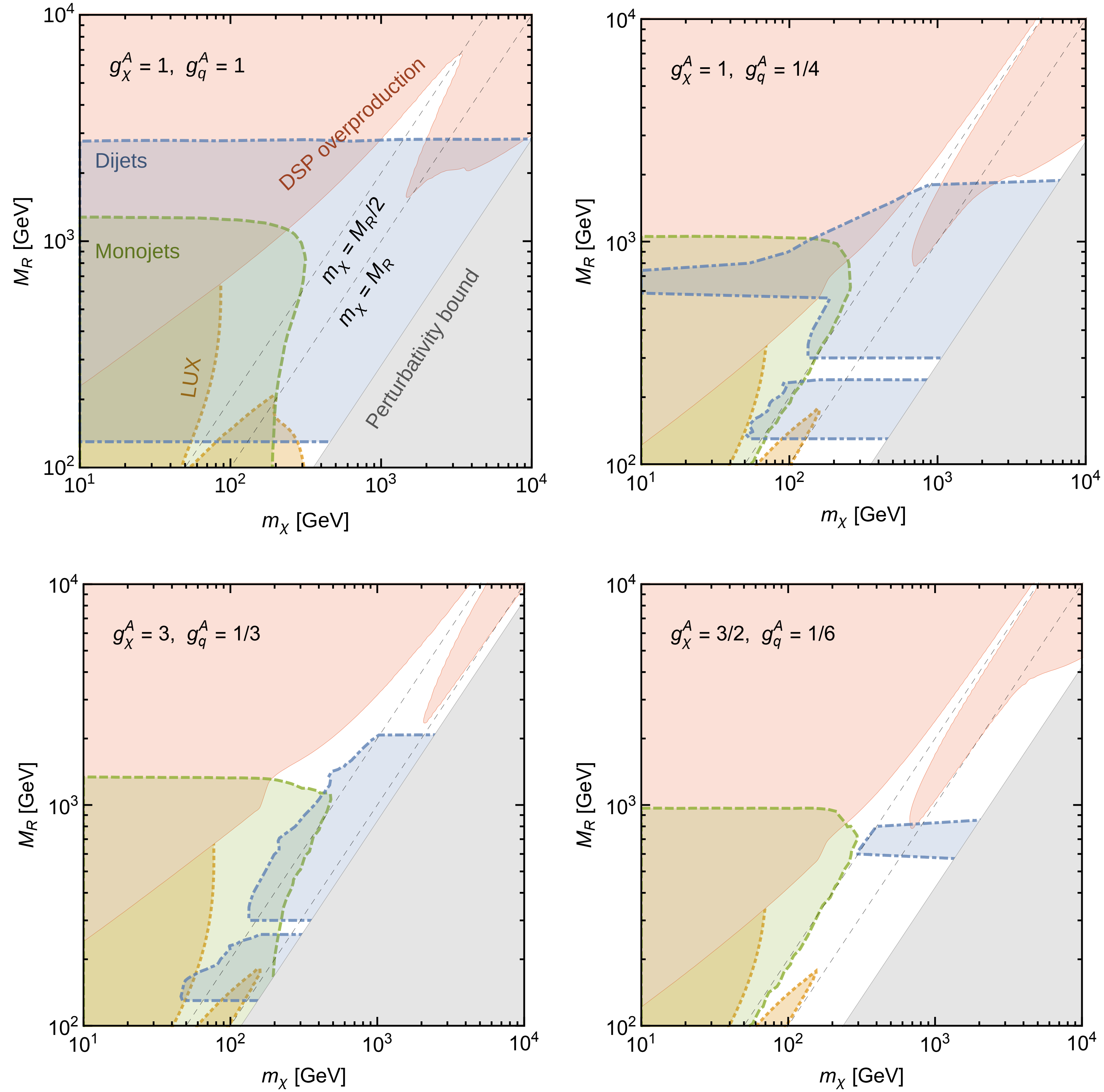
(associated) di-jet analysis

- For large couplings, the usual searches for narrow resonances no longer apply.
- The multi-jet background limits the LHC searches for mediators below 1 TeV.
  - associated di-jet production
  - trigger-level analysis

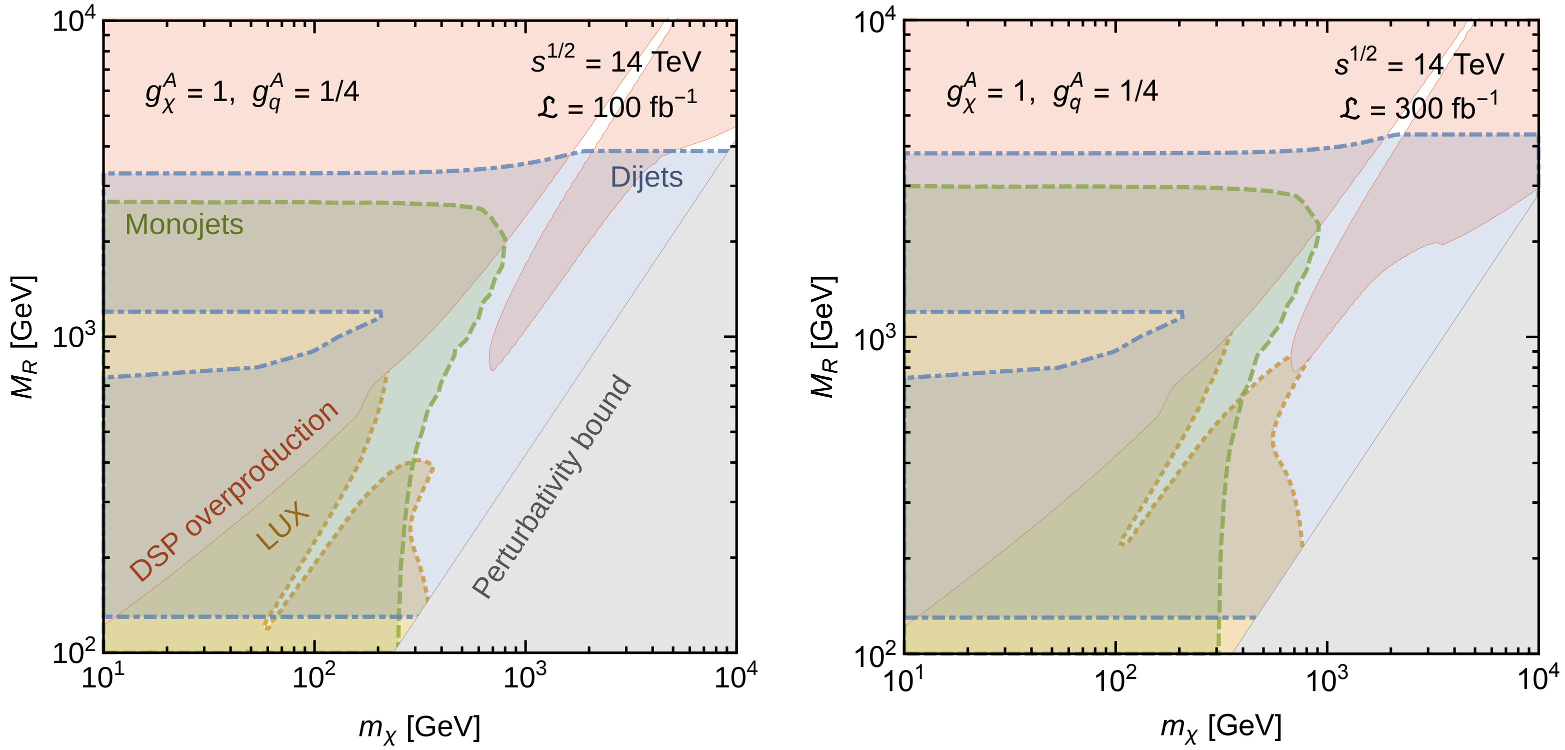




mono-jet and di-jet @ 8 TeV



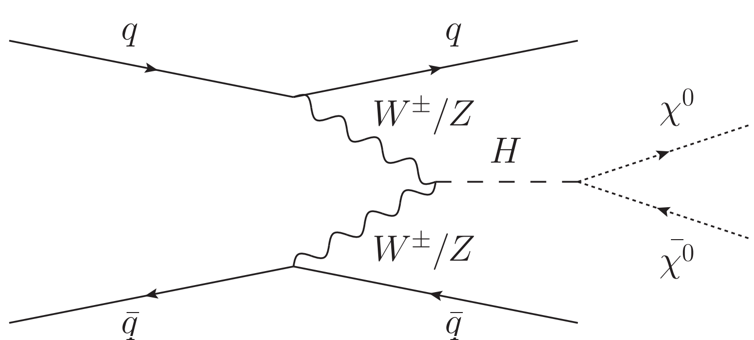
future prospects

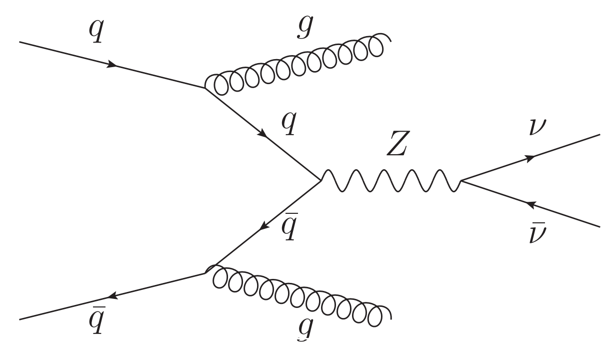


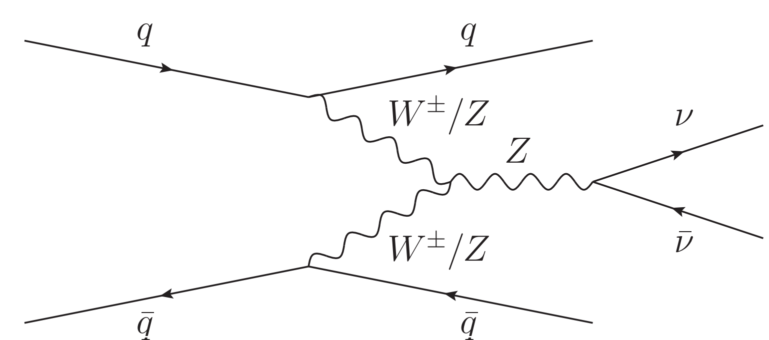
- LHC will probe mediator masses up to 4 TeV and DM masses up to 1 TeV.
- Searches for dijet resonances in association with SM gauge bosons will significantly gain in sensitivity.
- XENON1T and LZ will improve the sensitivity of the direct detection.

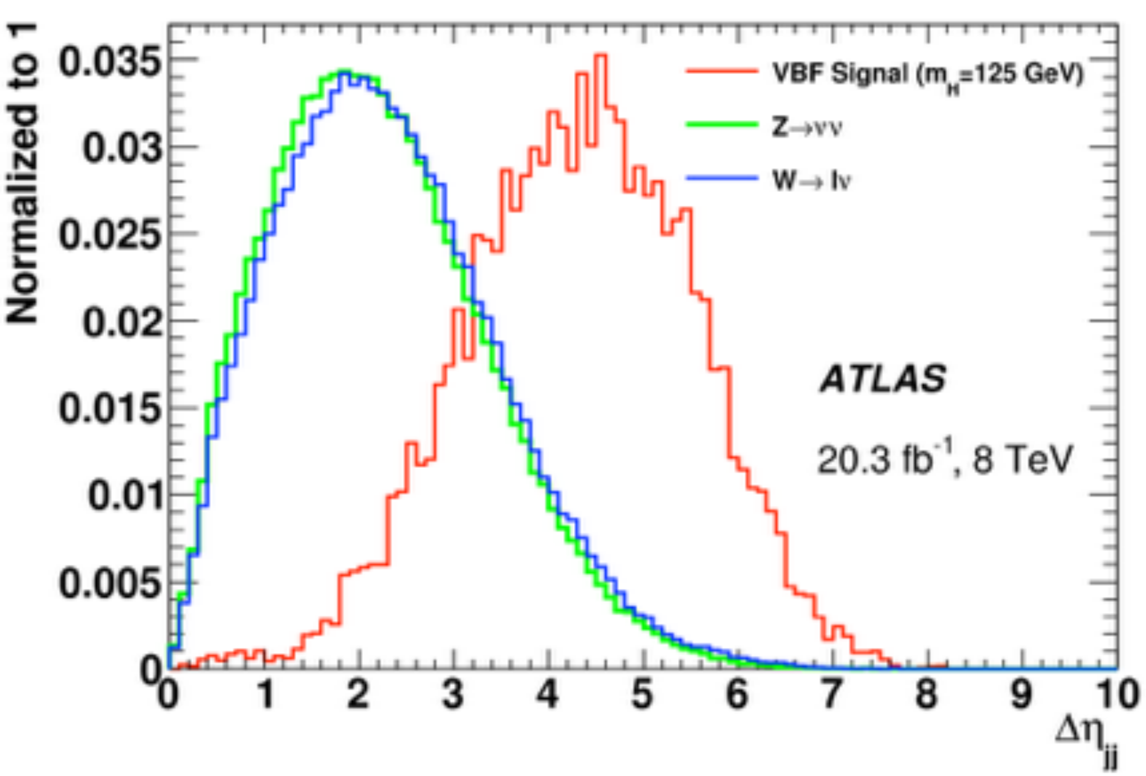
[1508.07869](https://arxiv.org/abs/1508.07869)

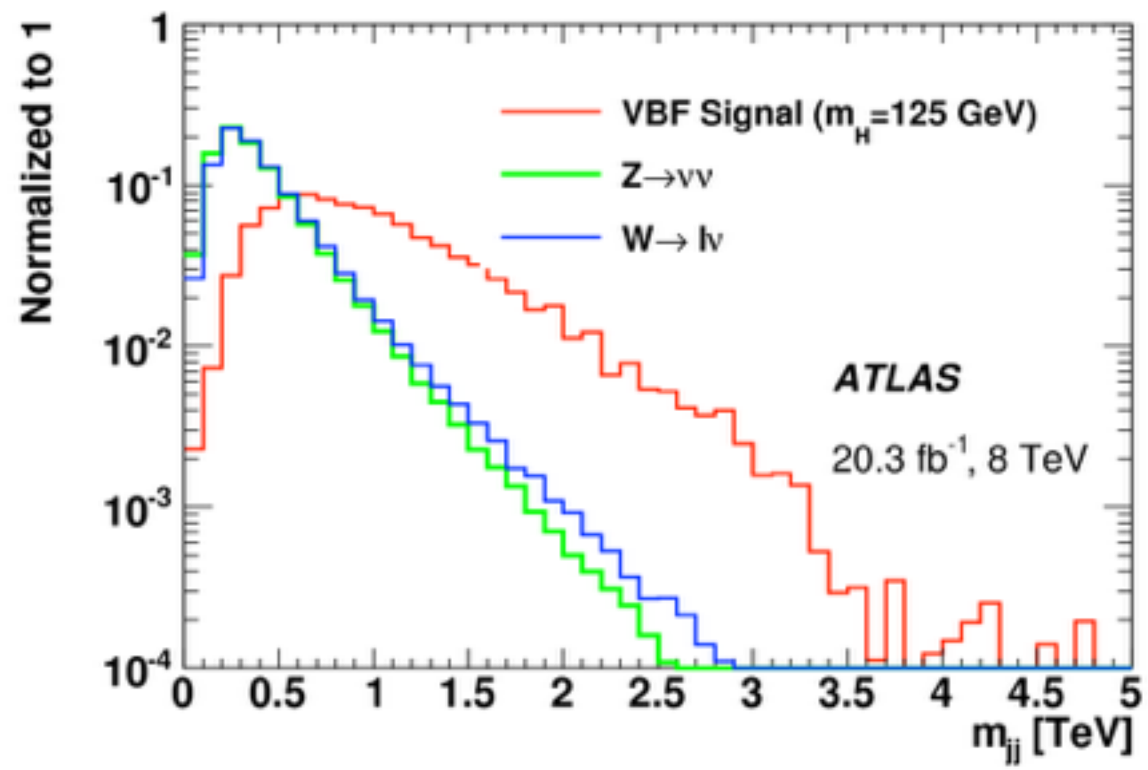
VBF H→invisible







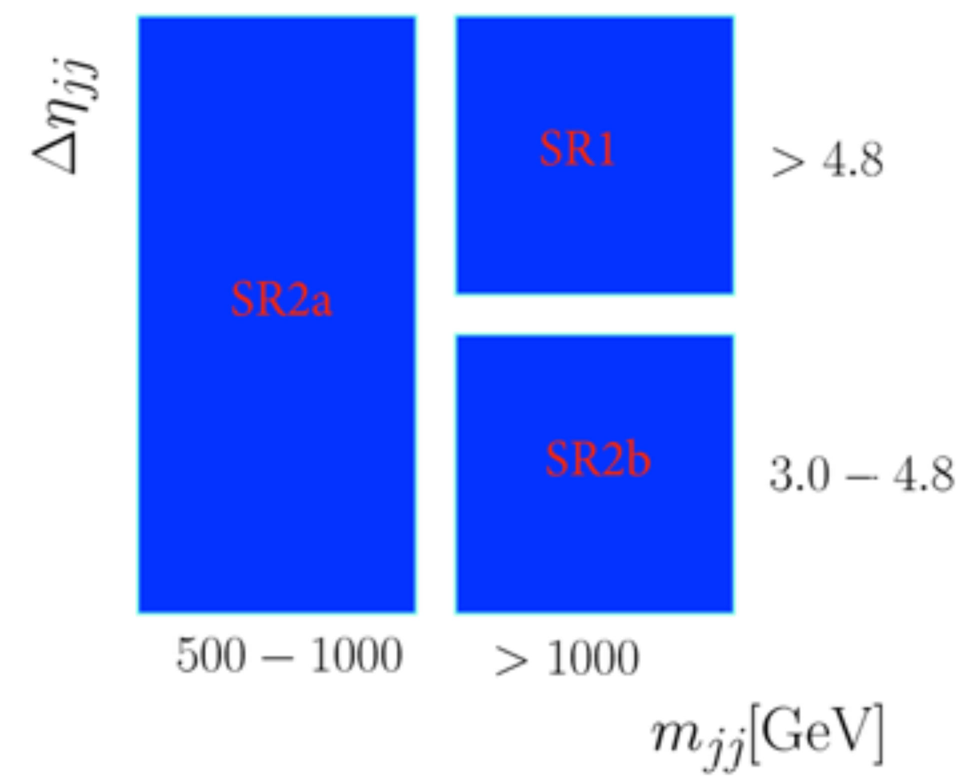




VBF H→invisible

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	



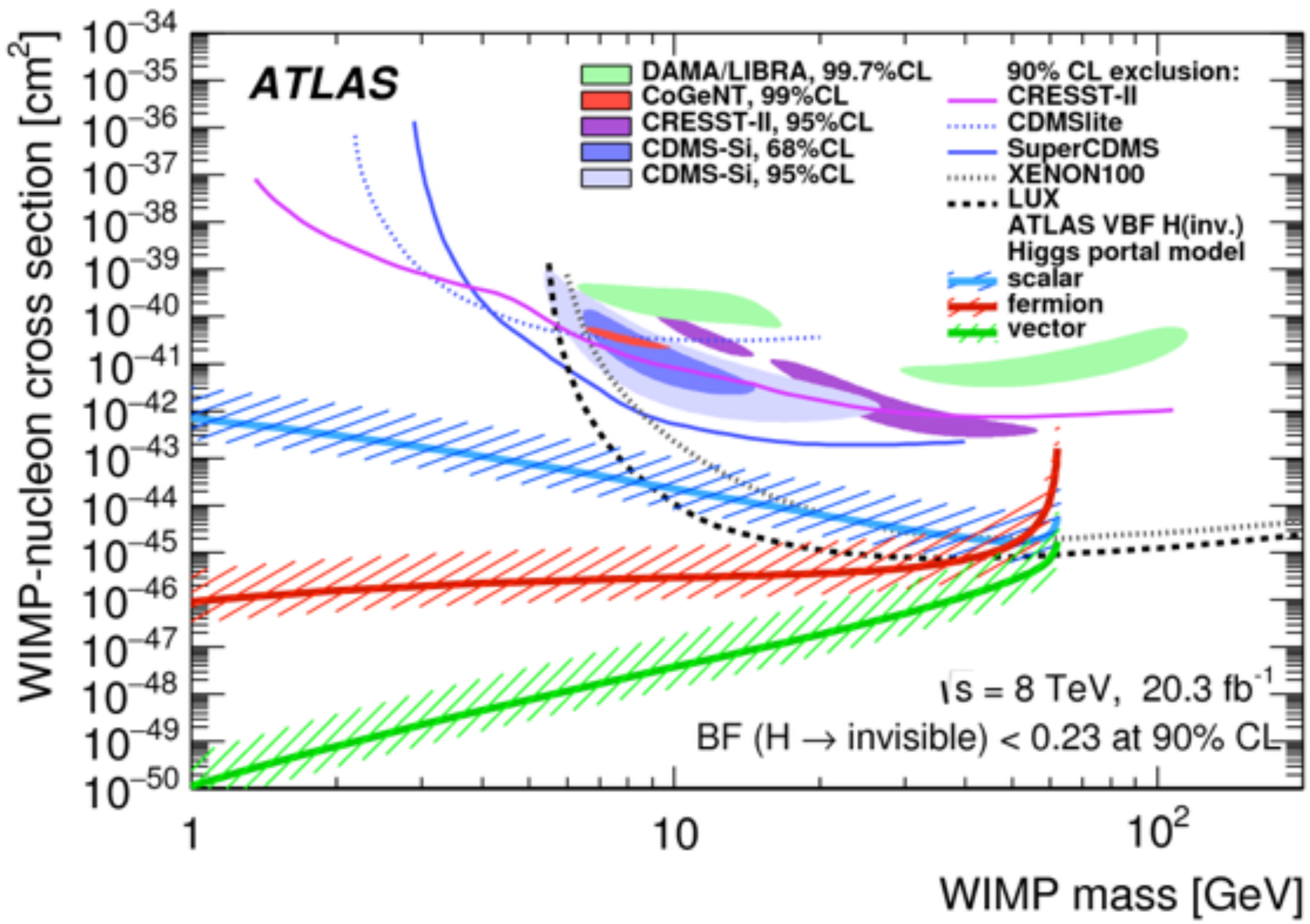
Signal region Process	SR1	SR2a	SR2b
ggF signal	20± 15	58± 22	19± 8
VBF signal	286± 57	182± 19	105±15
$Z(\to \nu\nu)$+jets	339± 37	1580± 90	335±23
$W(\to \ell\nu)$+jets	235± 42	1010± 50	225±16
Multijet	2± 2	20± 20	4± 4
Other backgrounds	1±0.4	64± 9	19± 6
Total background	577± 62	2680±130	583±34
Data	539	2654	636

$$\Gamma_H^{inv} = \frac{BF(H \to \text{invisible})}{1 - BF(H \to \text{invisible})} \times \Gamma_H$$

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

[1508.07869](https://arxiv.org/abs/1508.07869)
[1112.3299](https://arxiv.org/abs/1112.3299)

Higgs portal DM



$$\Gamma^{\text{inv}}_{H\to SS} = \frac{\lambda^2_{HSS} v^2 \beta_S}{64\pi m_H},$$

$$\Gamma^{\text{inv}}_{H\to VV} = \frac{\lambda^2_{HVV} v^2 m_H^3 \beta_V}{256\pi m_V^4}\left(1 - 4\frac{m_V^2}{m_H^2} + 12\frac{m_V^4}{m_H^4}\right)$$

$$\Gamma^{\text{inv}}_{H\to ff} = \frac{\lambda^2_{Hff} v^2 m_H \beta_f^3}{32\pi\Lambda^2},$$

$$\sigma^{\text{SI}}_{SN} = \frac{\lambda^2_{HSS}}{16\pi m_H^4}\frac{m_N^4 f_N^2}{(m_S + m_N)^2},$$

$$\sigma^{\text{SI}}_{VN} = \frac{\lambda^2_{HVV}}{16\pi m_H^4}\frac{m_N^4 f_N^2}{(m_V + m_N)^2},$$

$$\sigma^{\text{SI}}_{fN} = \frac{\lambda^2_{Hff}}{4\pi\Lambda^2 m_H^4}\frac{m_N^4 m_f^2 f_N^2}{(m_f + m_N)^2},$$

summary

- EFT was chosen to interpret DM searches in Run-1
- DM Forum prepared recommendations for simplified models for early Run-2 analyses [1507.00966](1507.00966)
- Recent developments in generators allow for more precise modelling.

➡ richer phenomenology, complementarity, new interpretations

- DM working group under LPCC https://lpcc.web.cern.ch/lpcc/index.php?page=dm_wg

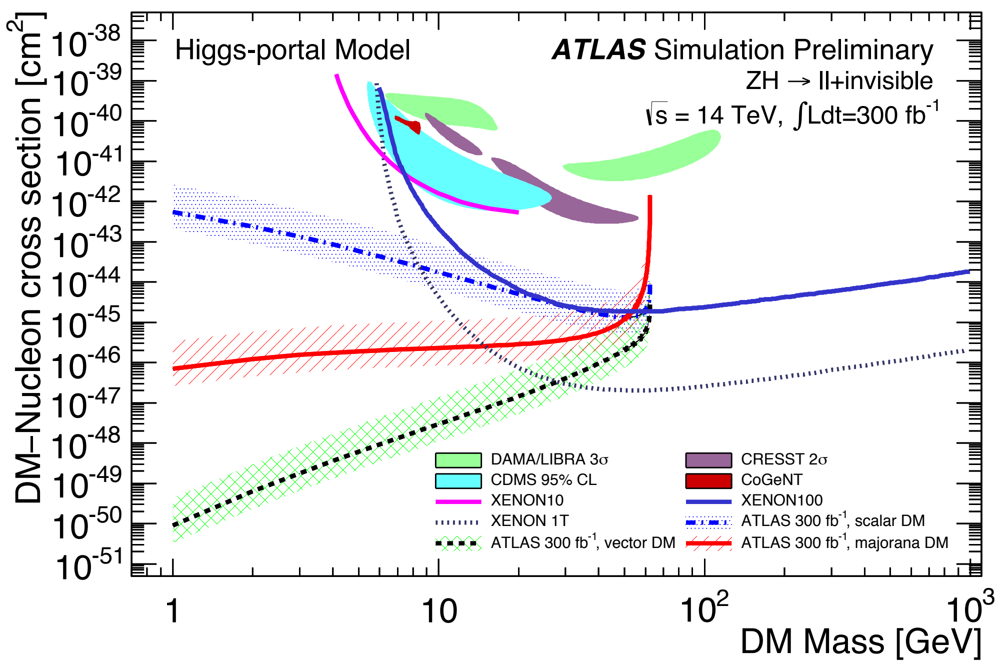
- DM@LHC workshop in Amsterdam, 30/03 - 01/04 (to be announced soon)
  - new Run-2 results
  - complementarity of DM searches

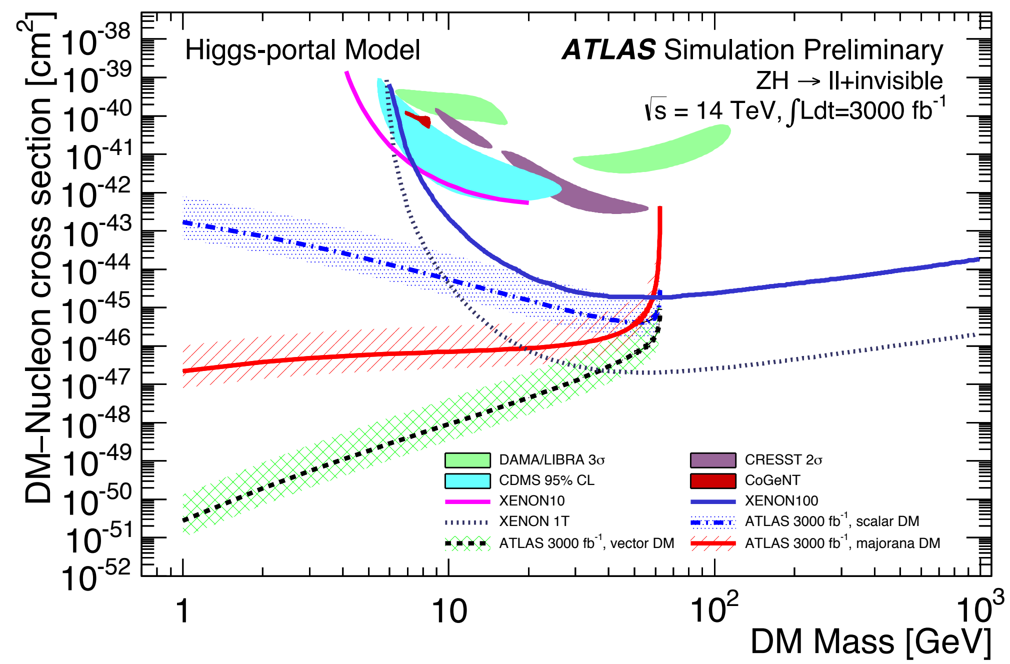
extra material

14 TeV projections

- Zh → ll + MET analysis

BR($H \to$inv.) limits at 95% (90%) CL	300 fb^{-1}	3000 fb^{-1}
Realistic scenario	23% (19%)	8.0% (6.7%)
Conservative scenario	32% (27%)	16% (13%)





- coupling fit
(without Zh → ll + MET)

Nr.	Parameter	300 fb^{-1} Theory unc.:			3000 fb^{-1} Theory unc.:		
		All	Half	None	All	Half	None
1	κ_g	7.5%	5.9%	5.2%	3.5%	2.9%	2.6%
	κ_γ	9.3%	6.2%	4.8%	5.2%	3.0%	1.7%
	$\kappa_{Z\gamma}$	78%	78%	78%	30%	29%	29%
	$BR_{i,u}$	<28%	<26%	<25%	<15%	<13%	<12%

mono-jet prospects @ 14 TeV

ATL-PHYS-PUB-2014-007

Event selection

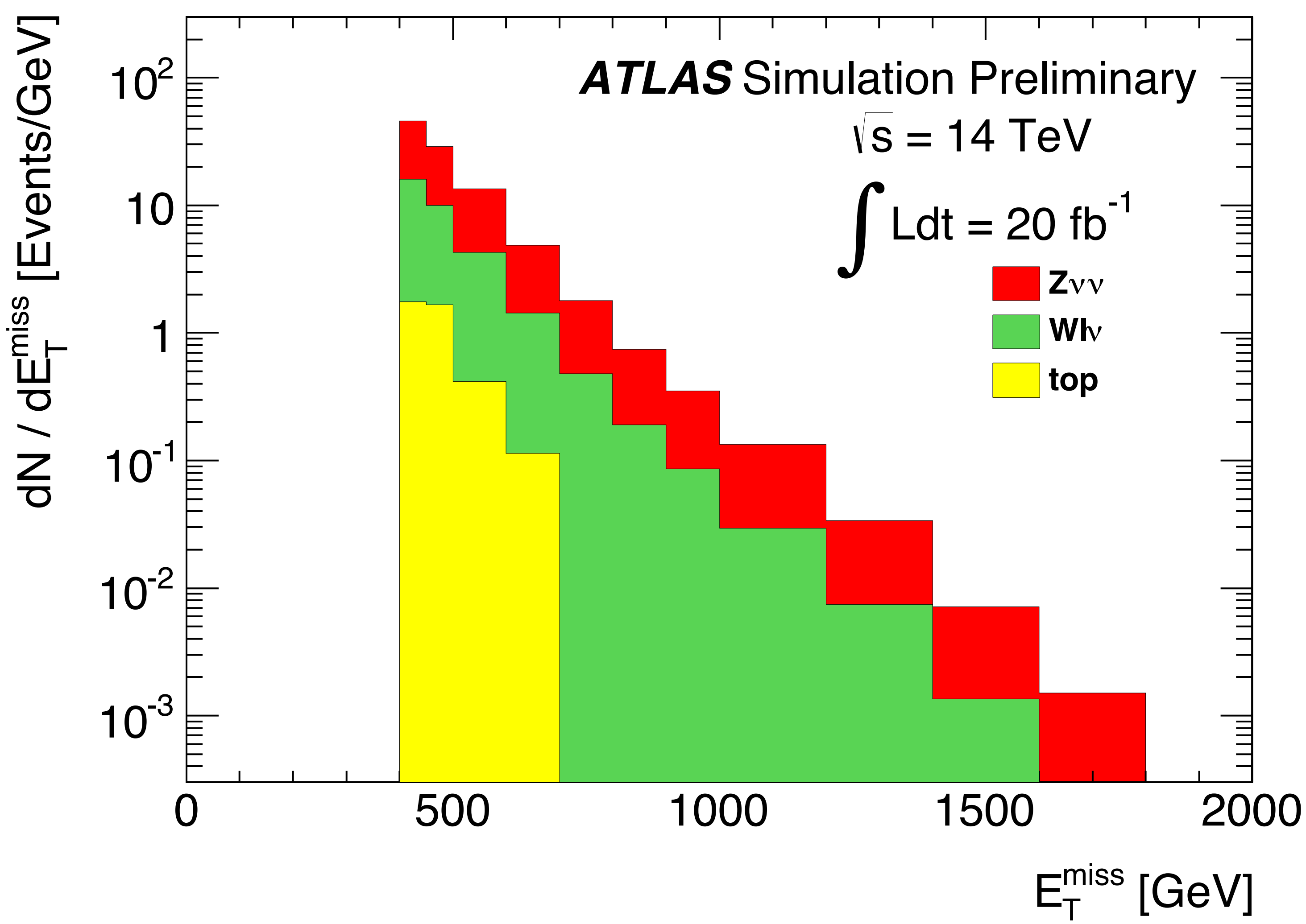
- leading jet pT > 300 GeV
- Δφ(jet, MET) > 0.5
- electron and muon veto
- at most two jets
  - pT > 30 GeV @ 8 TeV
  - pT > 50 GeV @ 14 TeV
- SR defined by
  MET > 400, 600, 800 GeV

Backgrounds

- pure MC study

Systematic uncertainties

- 5% reasonable expectation for early Run-II
- 1% ultimate goal for HL-LHC



mono-jet prospects @ 14 TeV

ATL-PHYS-PUB-2014-007

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