Dark Matter Searches at CMS

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on behalf of the CMS collaboration

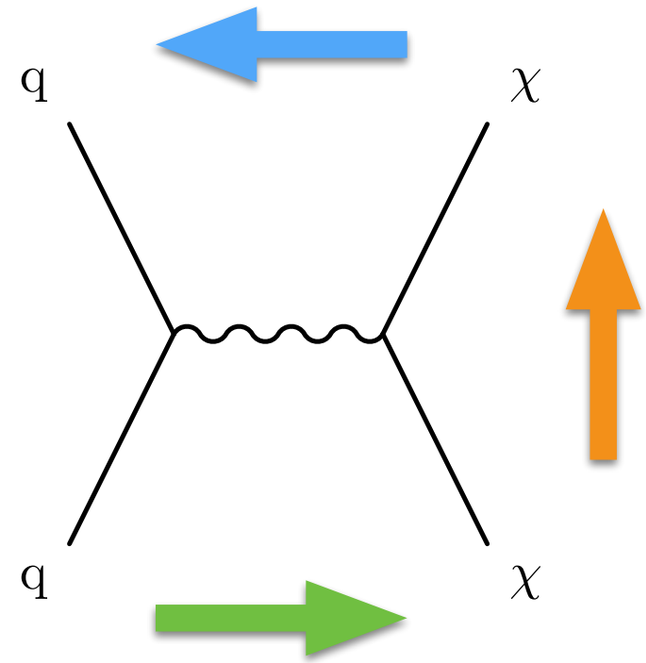
Phenomenology 2016 Symposium

LHC: A powerful probe for dark matter

DM existence well established, identity unknown.
→ One of the most important questions of particle physics today

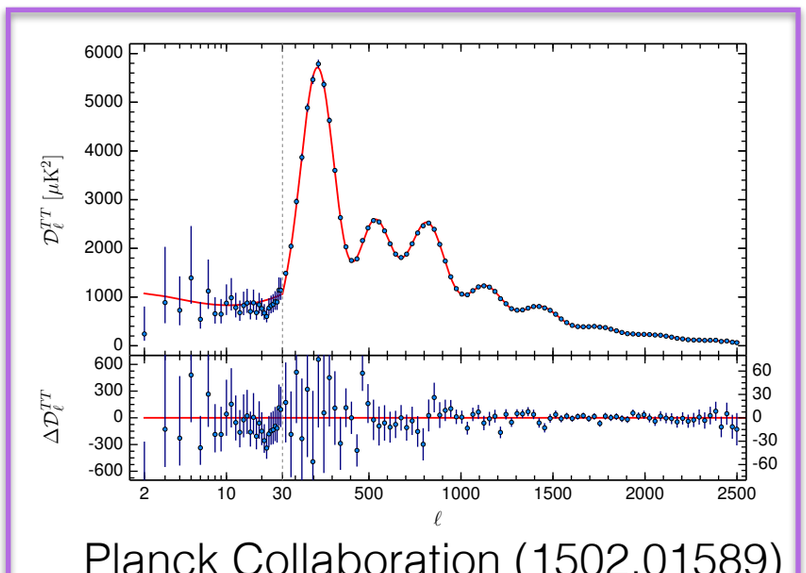
Four probes for dark matter physics:

- Direct search by DM-nucleon scattering
- Indirect search of DM annihilation products
- Production at colliders
- Astrophysical & cosmological observations



Collider searches have

- Competitive sensitivity to direct searches.
- Ability to characterize the DM interaction in detail.
  - Interaction spin/parity, coupling, etc.



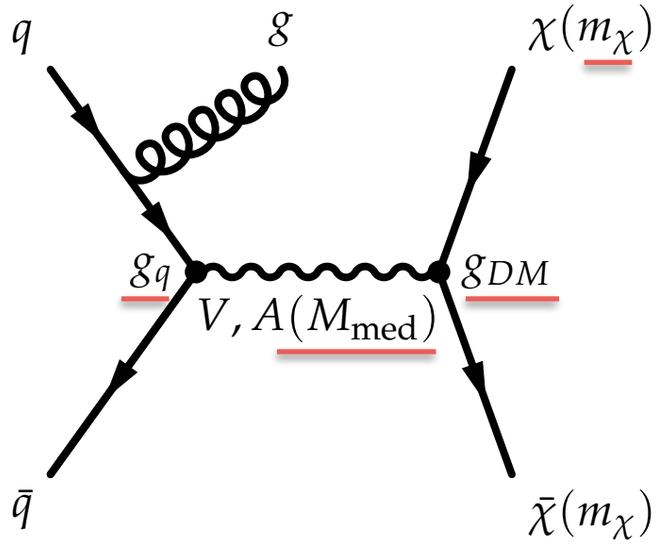
Planck Collaboration (1502.01589)

Common framework for LHC DM searches

LHC DM searches = E_T^{miss} + X (=j, W, Z, γ, H, tt, bb, t, etc.)

ATLAS/CMS Dark Matter Forum recommendations
(July 6, 2015 1507.00966)

- Categorizes physics of E_T^{miss} + X final states.
- Provides common bases for interpreting search results.
- Recommends use of simplified models with minimal particle content wherever applicable.
  → Well-defined set of model parameters.
  Typically M_{DM}, $M_{mediator}$, g_{SM}, g_{DM}
- Focus on Dirac fermion DM, vary spin/parity of mediator



Dark matter searches at CMS

Latest

X	Data set	CMS ID	Available since	Published
Jets, W/Z(qq)	2015	EXO-16-013	Apr 2016	Preliminary
t→μνb	2012	B2G-15-001	Apr 2016	Preliminary
bb	2015	B2G-15-007	Mar 2016	Preliminary
Jets	2012	EXO-14-004	Mar 2016	JHEP, Submitted
Z($\ell\ell$)	2012 (2015)	EXO-12-054 (HIG-16-008)	Nov 2015 (Mar 2016)	PRD, Accepted (Preliminary)
tt (1ℓ)	2012	B2G-14-004	Apr 2015	JHEP 06 (2015) 121
γ	2012	EXO-12-047	Oct 2014	PLB 755 (2016) 102
W($\ell\nu$)	2012	EXO-12-060	Aug 2014	PRD 91 (2015) 092005

Flagship: Jets+E_T^{miss} + mono-W/Z(qq)

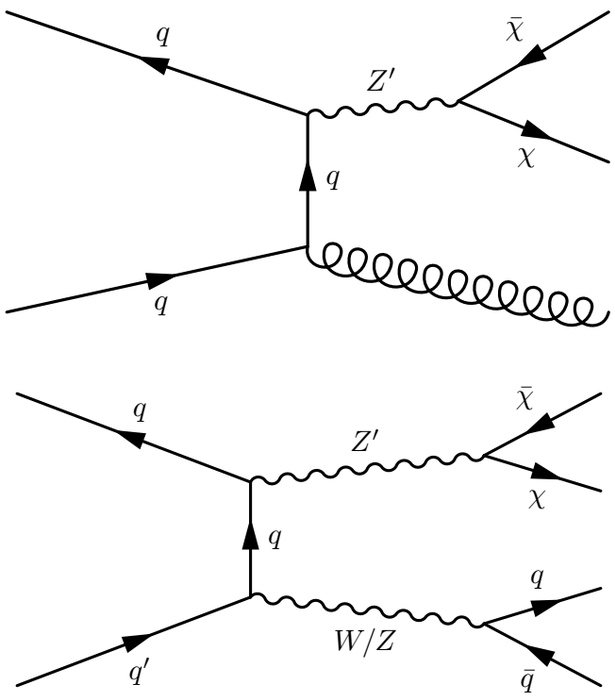
Signature = large E_T^{miss} + high-p_T jets.

Sensitive to most generic class of DM signals. High rate.

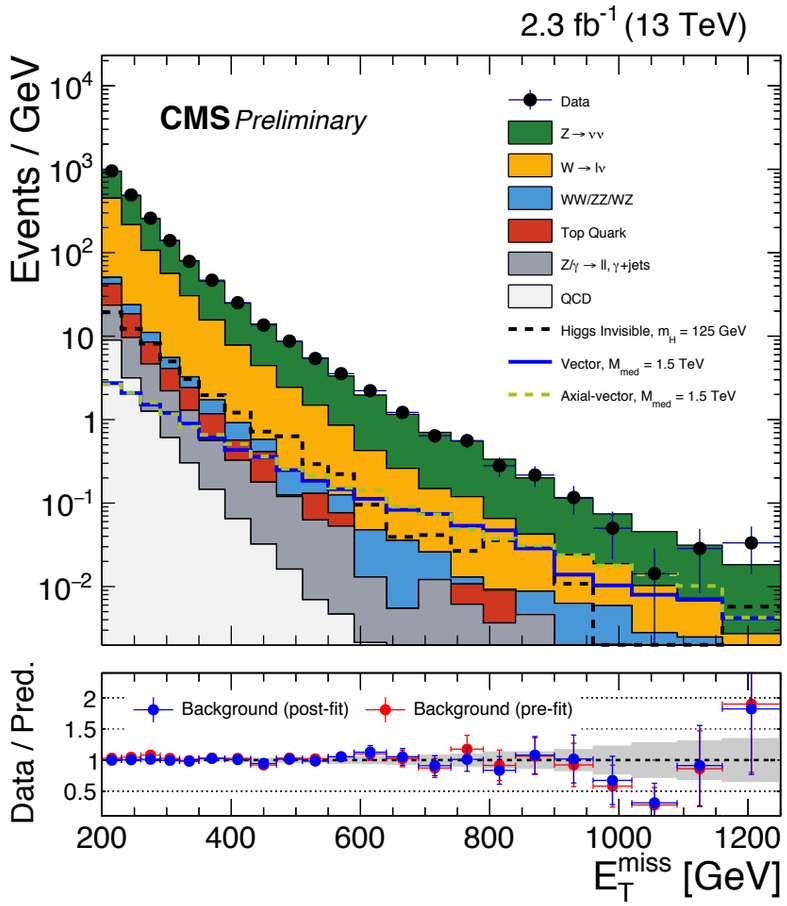
- "Fat jet" category for boosted W/Z(qq): E_T^{miss}, $p_T^{j1} > 250$ GeV.
- Inclusive category: Remaining $E_T^{miss} > 200$ GeV & $p_T^{j1} > 100$ GeV.

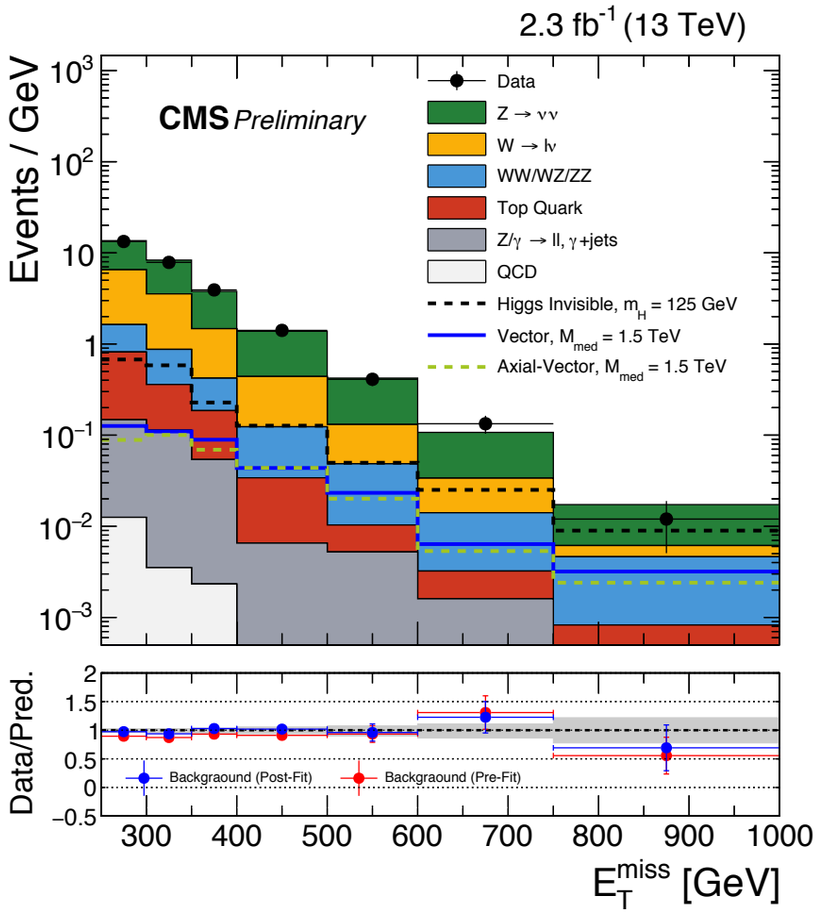
Fit background and signal predictions to data E_T^{miss} distributions.

→ Resolve kinematic differences among DM models.

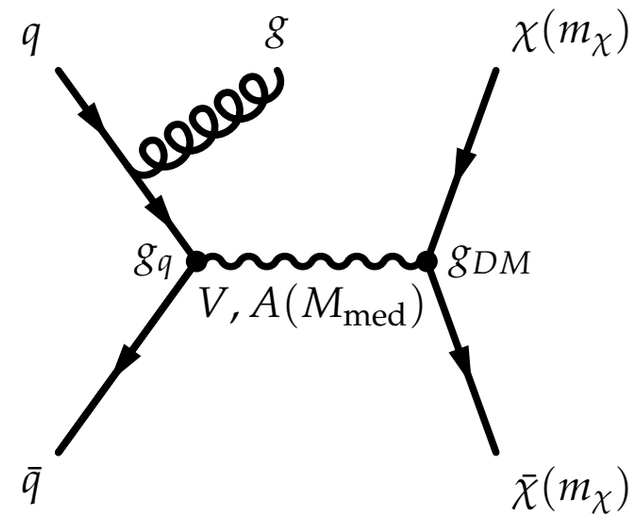


EXO-16-013





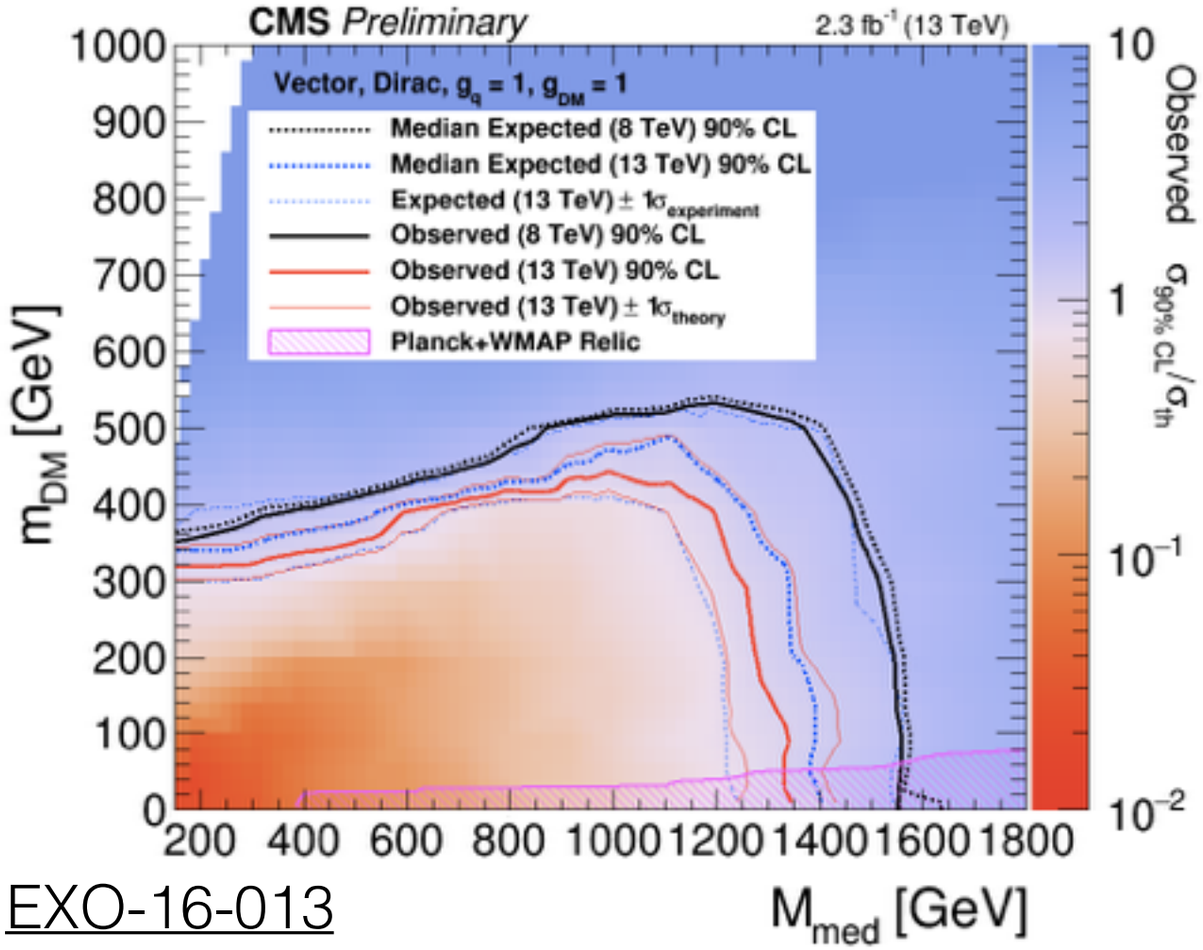
Jets+E_T^{miss} + mono-W/Z(qq) results [13 TeV]

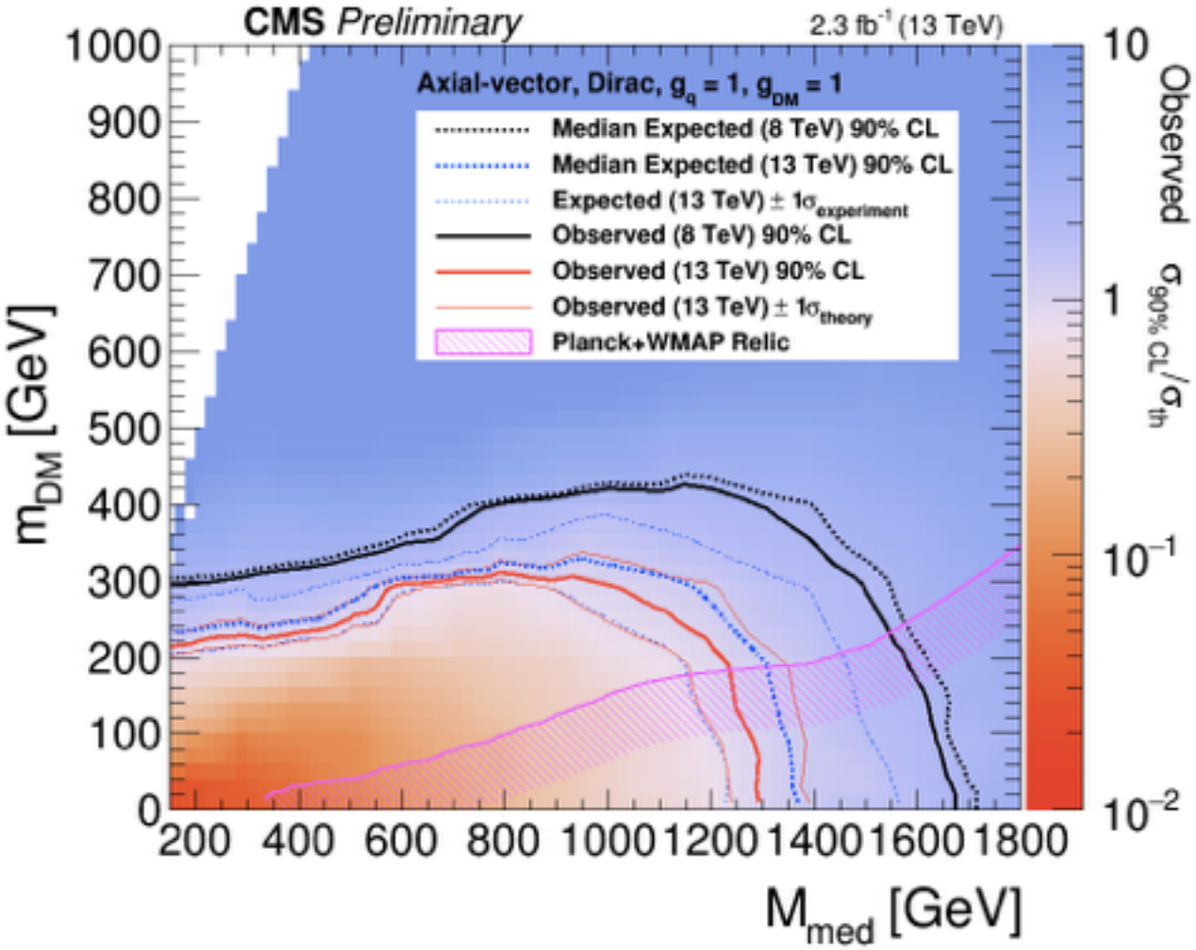


No excess observed. Limits set on cross sections in simplified models.

Fix $g_q = 1 = g_{DM} = 1$, scan in M_{med} & M_{DM}

More 13 TeV data needed to supersede 8 TeV.



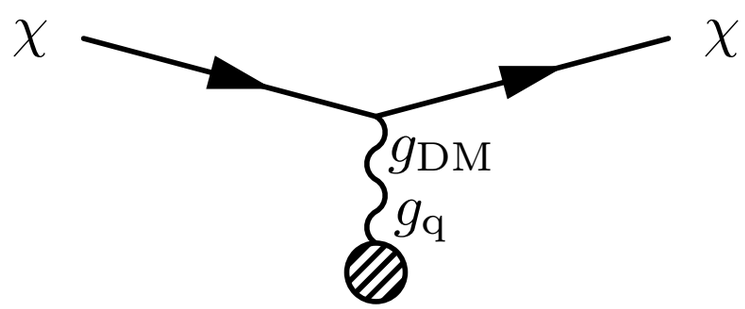


EXO-16-013

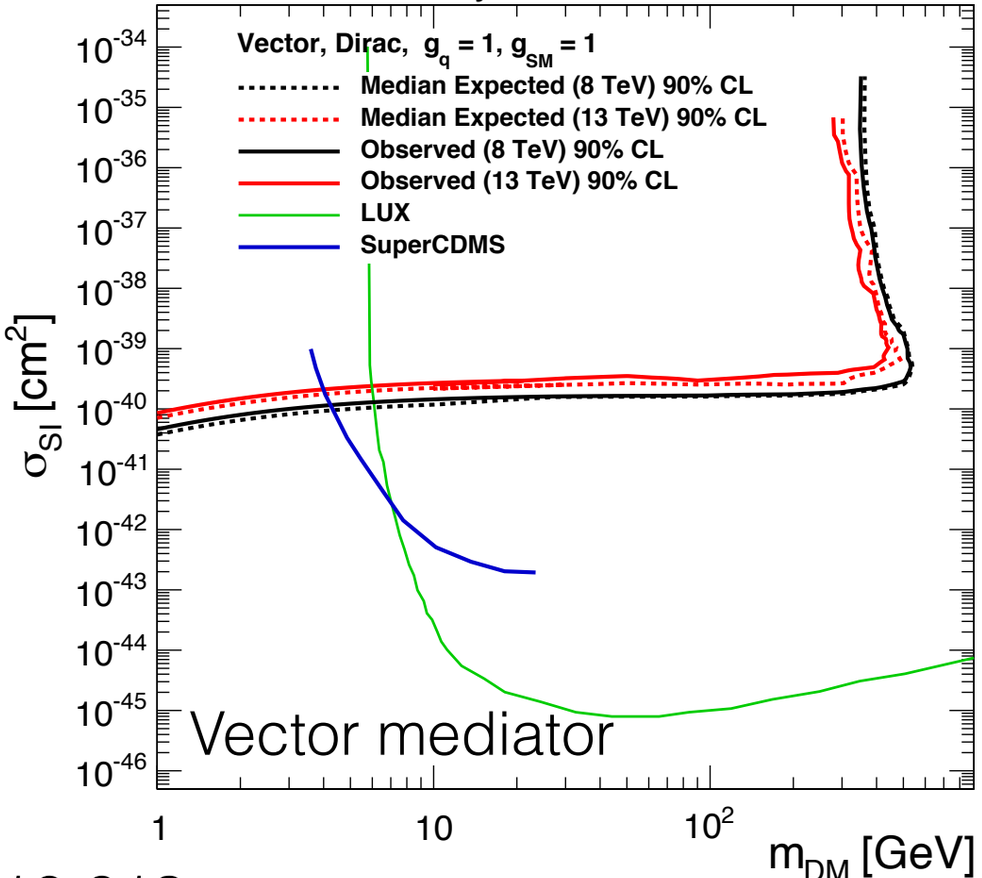
Jets+E_T^{miss} + mono-W/Z(qq) results [13 TeV]

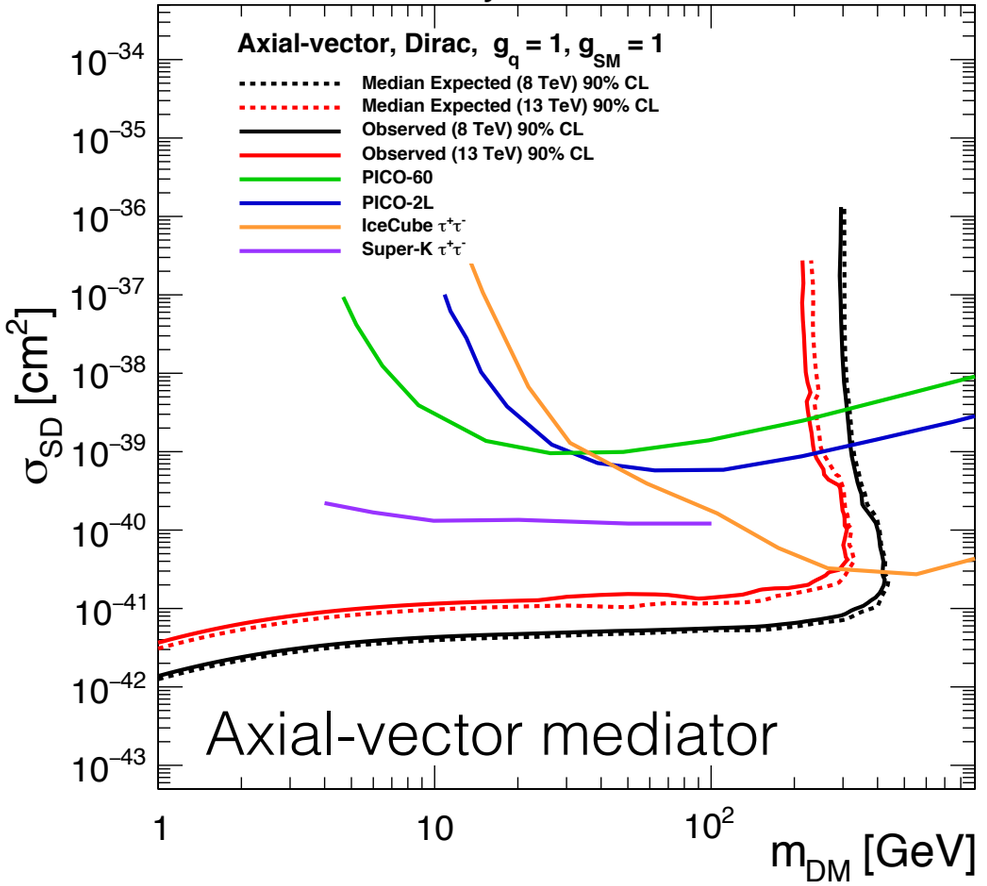
Recast simplified model cross sections
to DM-nucleon scattering cross section.

Vector mediator → spin-independent
Axial-vector mediator → spin-dependent



Sensitivity complementary to / better than direct searches.



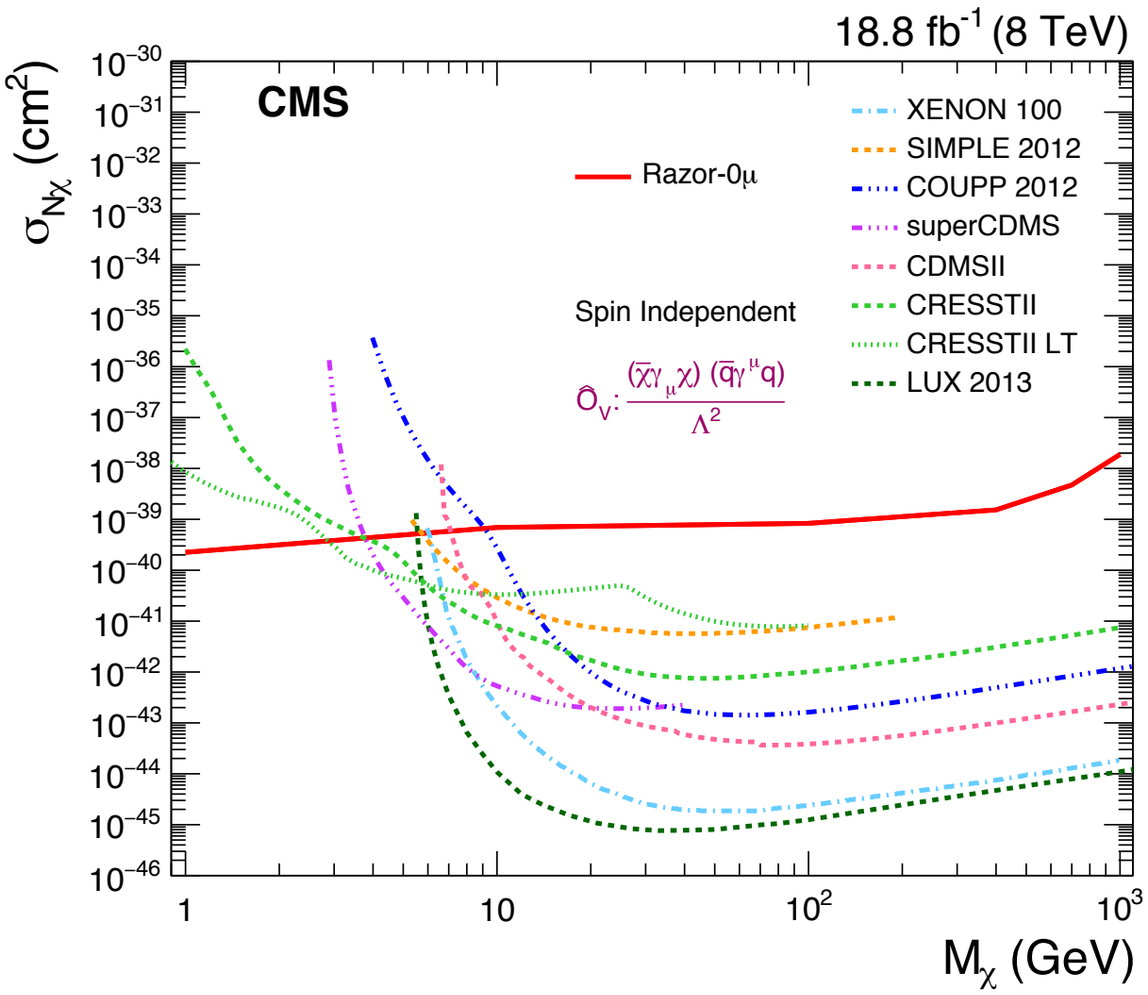


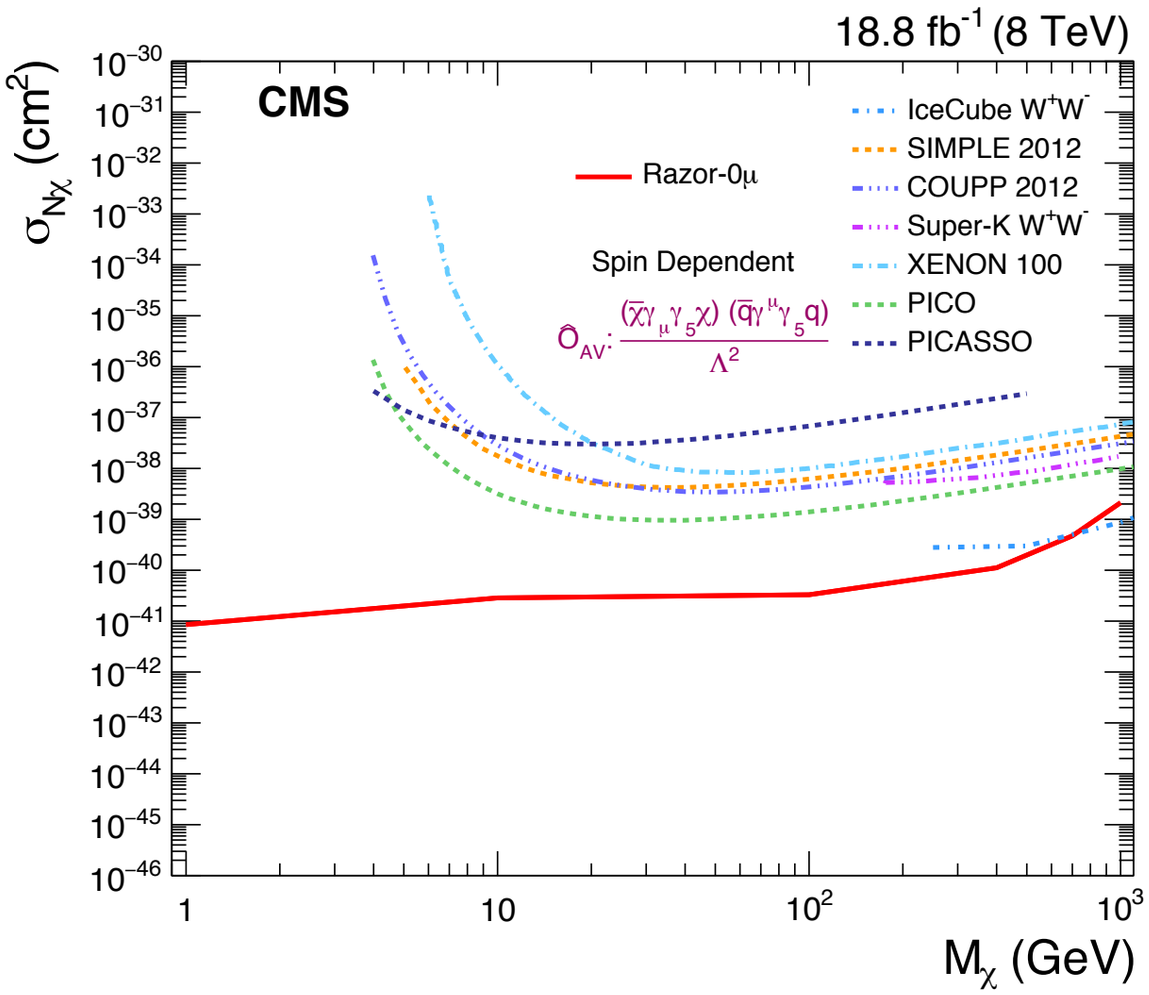
EXO-16-013

Jets + E_T^{miss} with razor variables [8 TeV]

Another approach for ≥2 jets + E_T^{miss}
Use razor R^2 (~E_T^{miss} wrt event transverse mass)

Similar sensitivity* to jets+E_T^{miss}





EXO-14-004

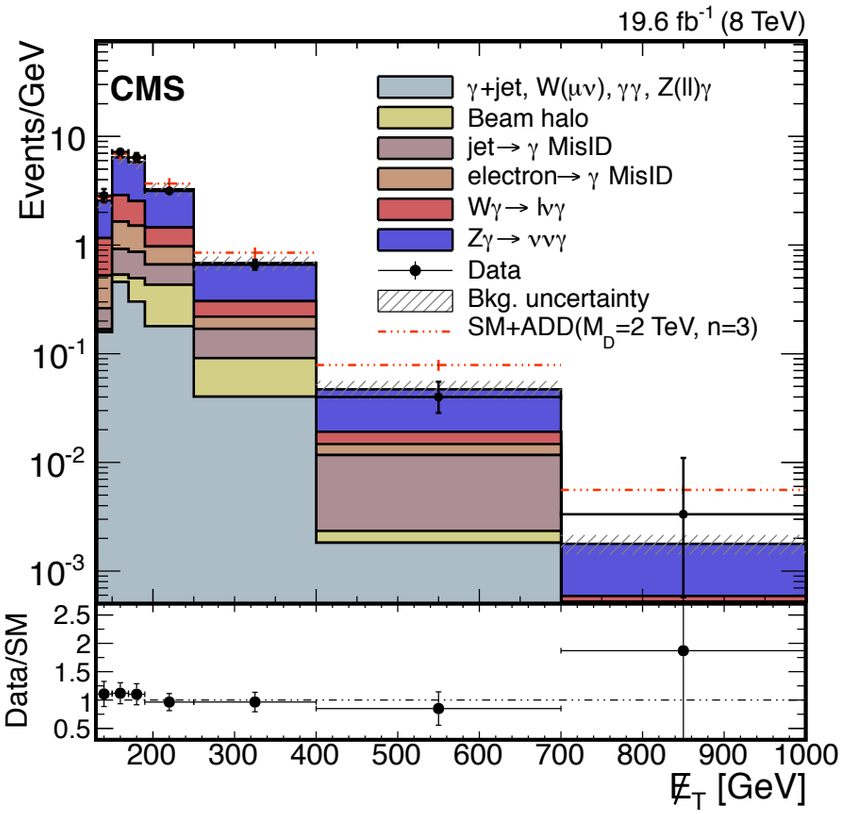
* Interpreted on EFT ($M_{med} \gg \sqrt{s}$) - should not compare directly

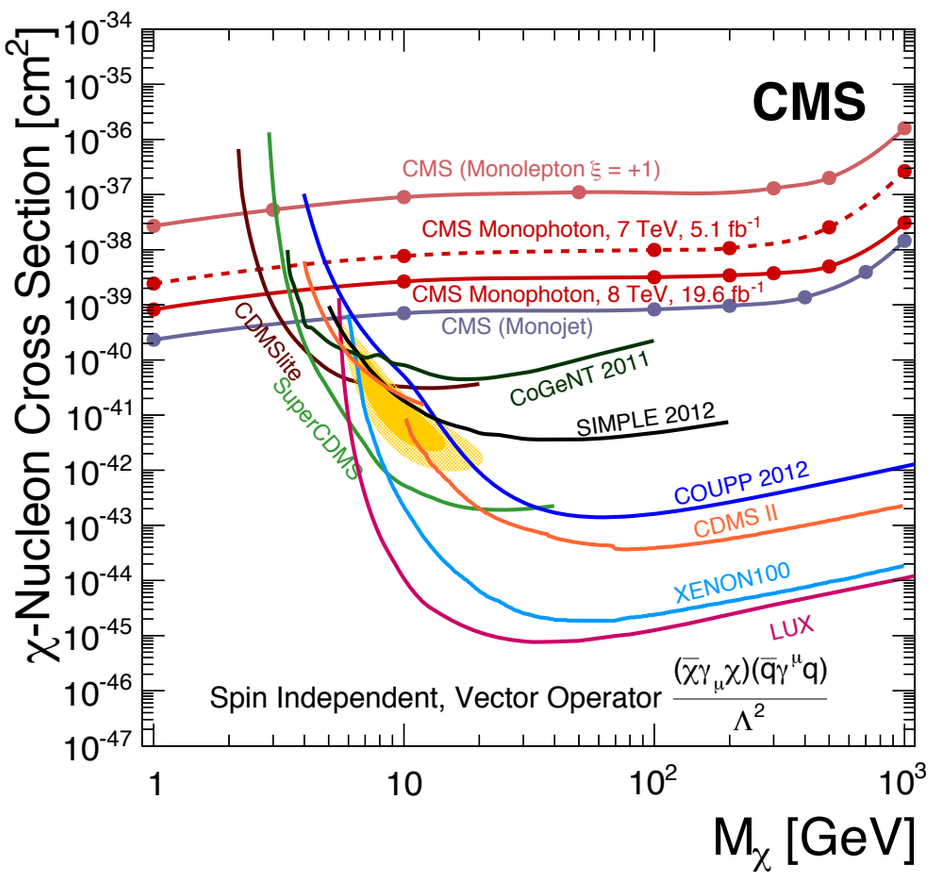
Monophoton [8 TeV]

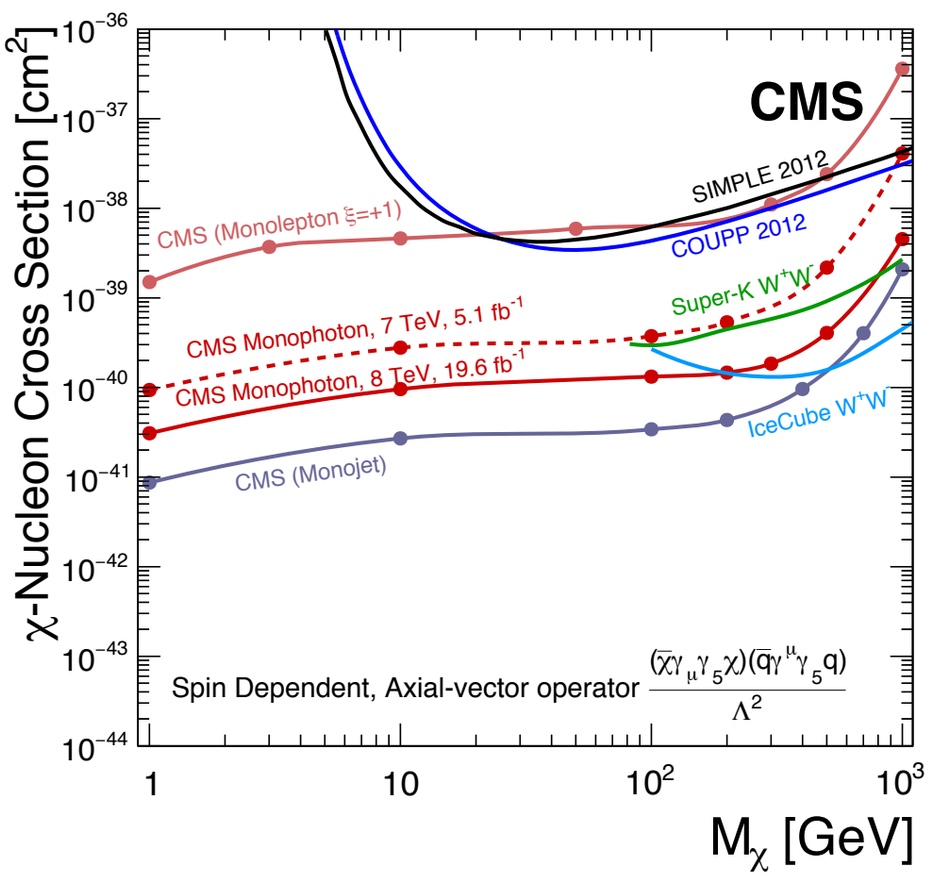
E_T^{miss} > 140 GeV & γ p_T > 145 GeV.

Fit bkgd and signal predictions to data p_T^{γ} distribution.

Less sensitive than jets+E_T^{miss}, but an important cross check when DM is found.







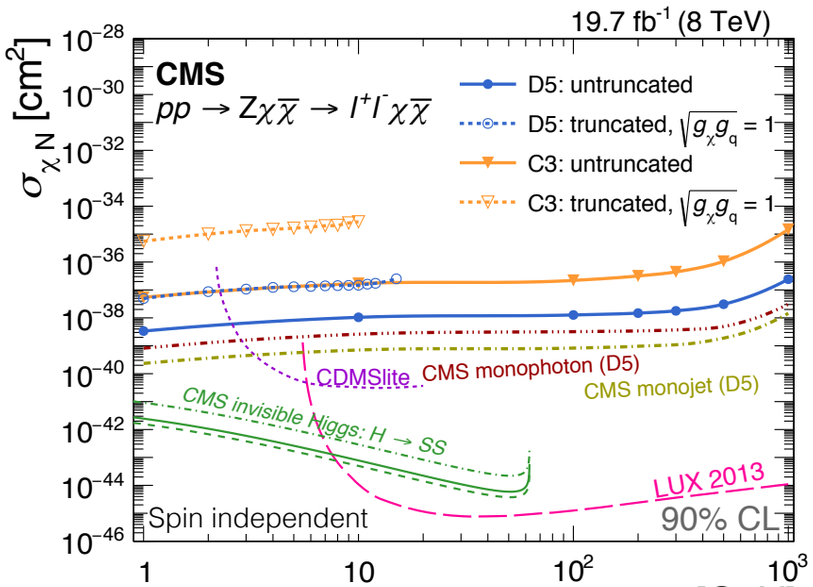
EXO-12-047

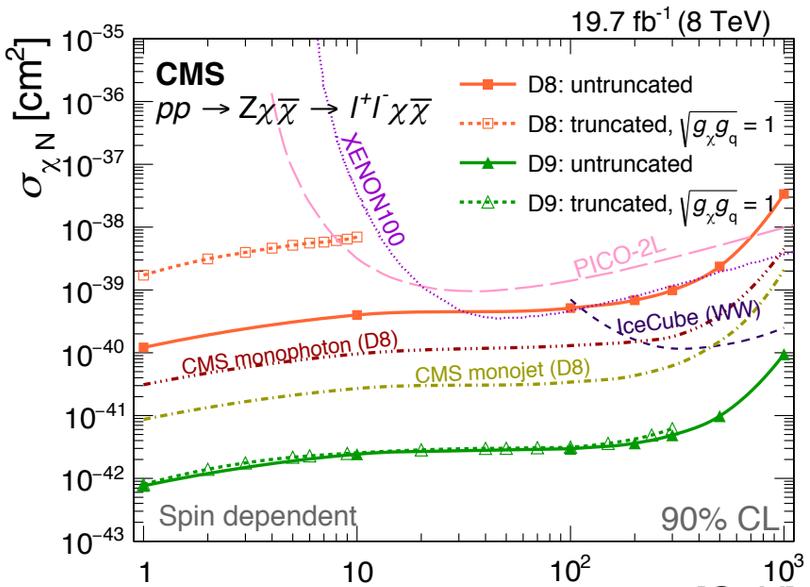
*EFT limits. Monojet reference outdated.

Mono-Z(ℓℓ), W(ℓν) [8 TeV]

Z(ℓℓ)

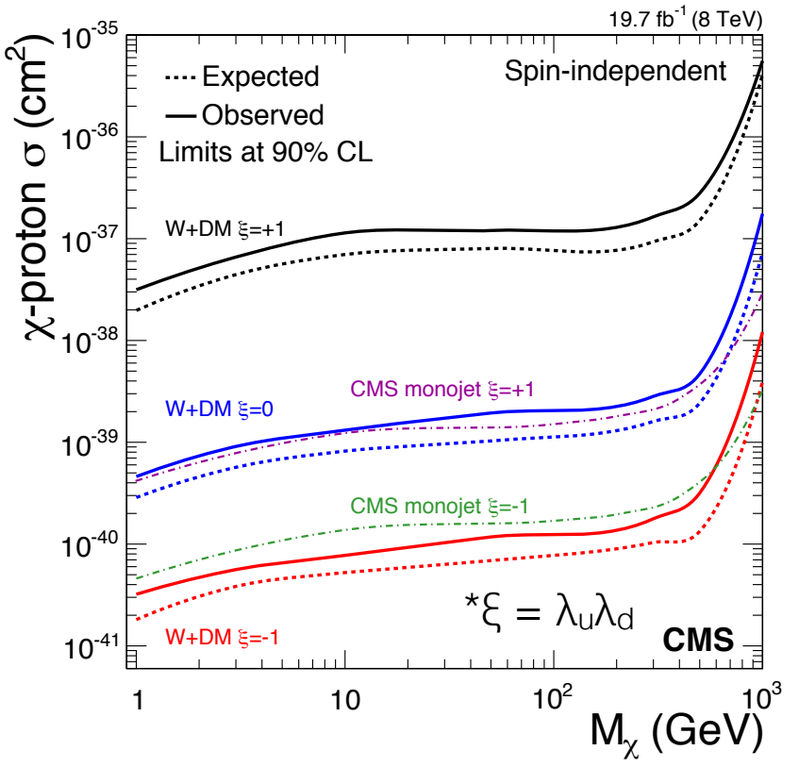
- e^+e^- or $\mu^+\mu^-$
- $|M_{\ell\ell}-M_Z| < 10$ GeV
- $E_T^{miss} > 80$ GeV
- Fit to $M_T^{\ell\ell}$ distribution

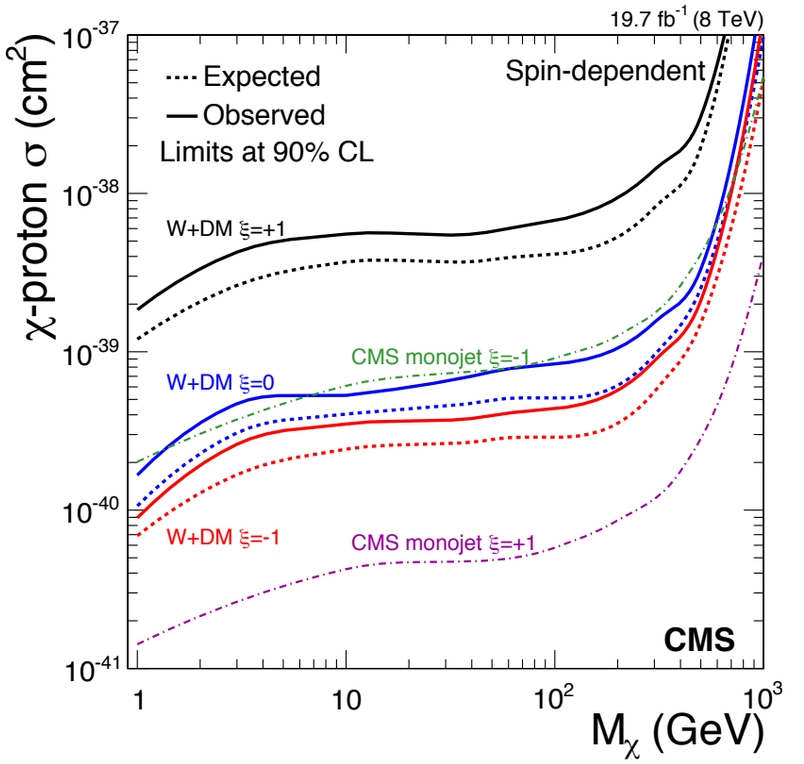




W(ℓν)

- 1 μ $p_T > 45$ GeV or 1 e $p_T > 100$ GeV
- $0.4 < p_T^{\ell}/E_T^{miss} < 1.5$
- Fit to M_T^{ℓ} distribution





EXO-12-054
EXO-12-060

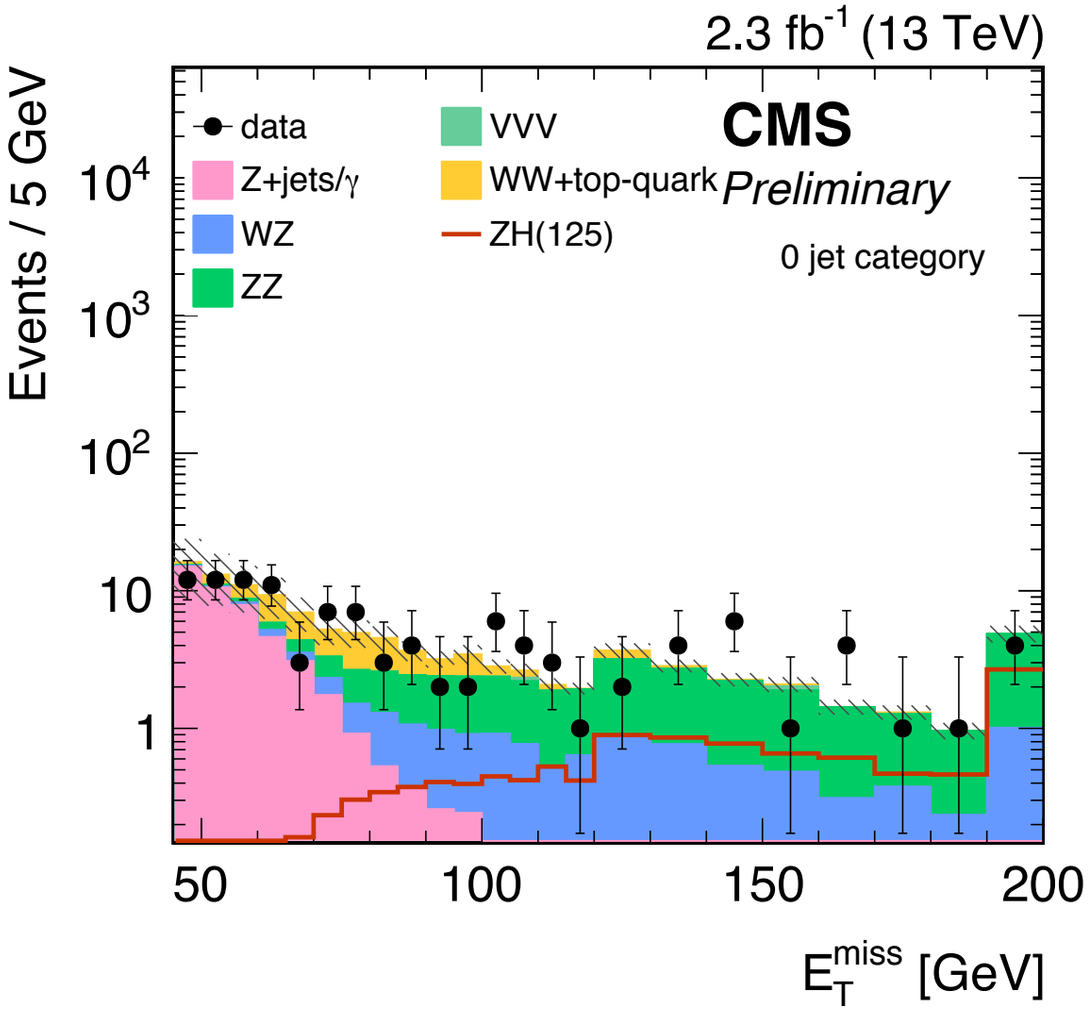
*EFT limits. Monojet reference outdated.

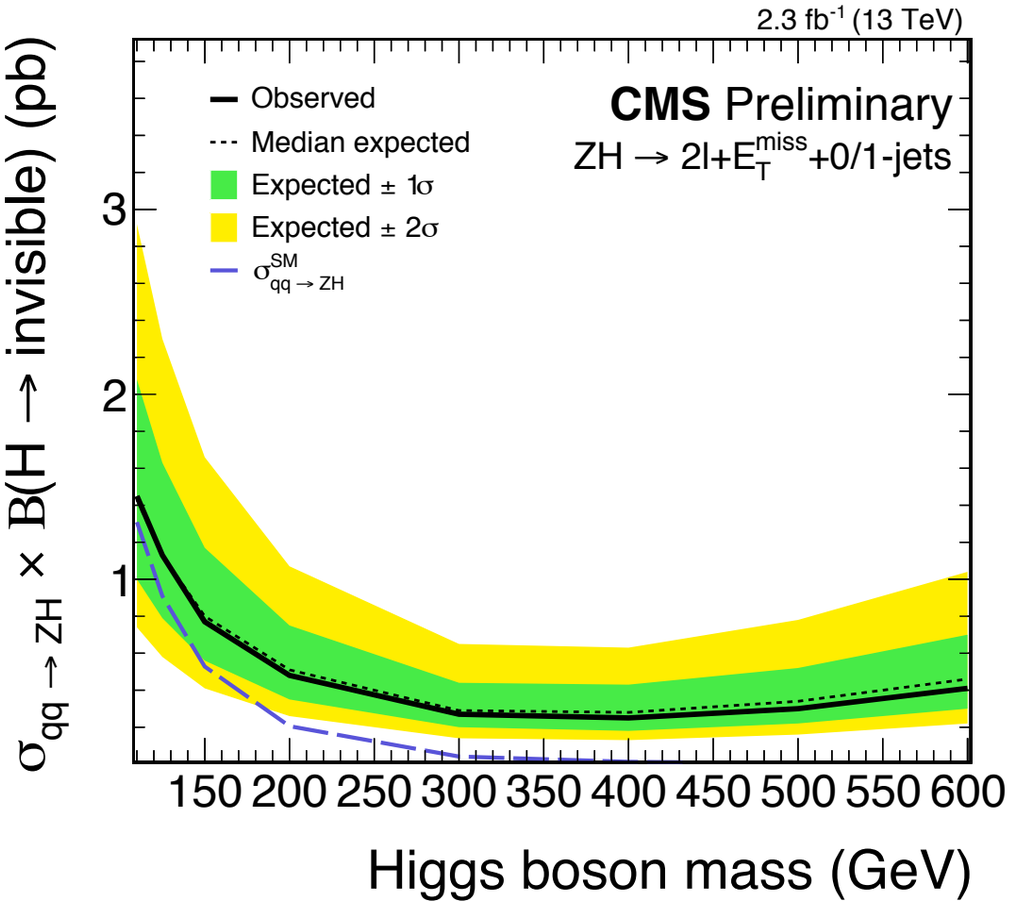
$Z(\ell\ell)+E_T^{miss}$ ZH interpretation [13 TeV]

Probing spin-0 mediator with SM Higgs-like couplings.

Strategy similar to 8 TeV $Z(\ell\ell)+E_T^{miss}$.

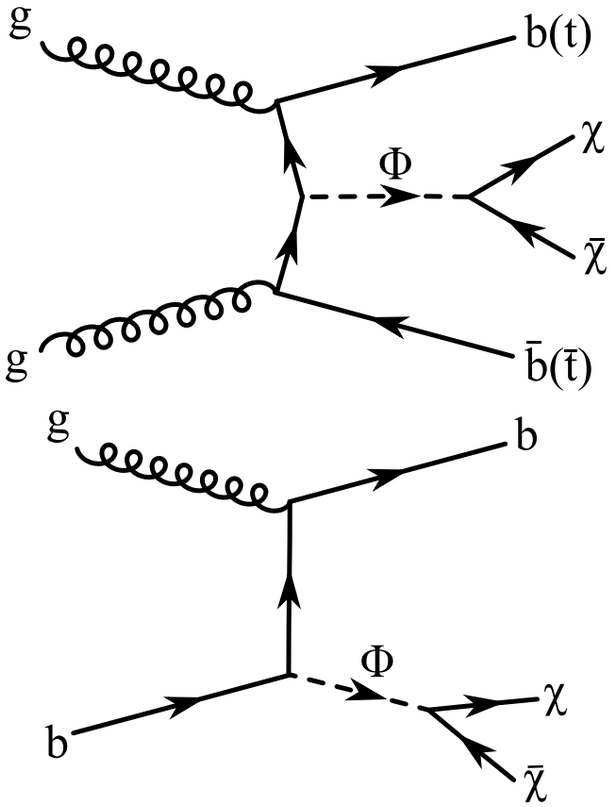
Sensitive down to $\sigma \times BR \sim \sigma^{SM}_{ZH(125)}$.





HIG-16-008

bb/tt + E_T^{miss} [13/8 TeV]



Spin-0 mediator (Φ) with minimal flavor violation

→ g(SM-Φ)∝Yukawa

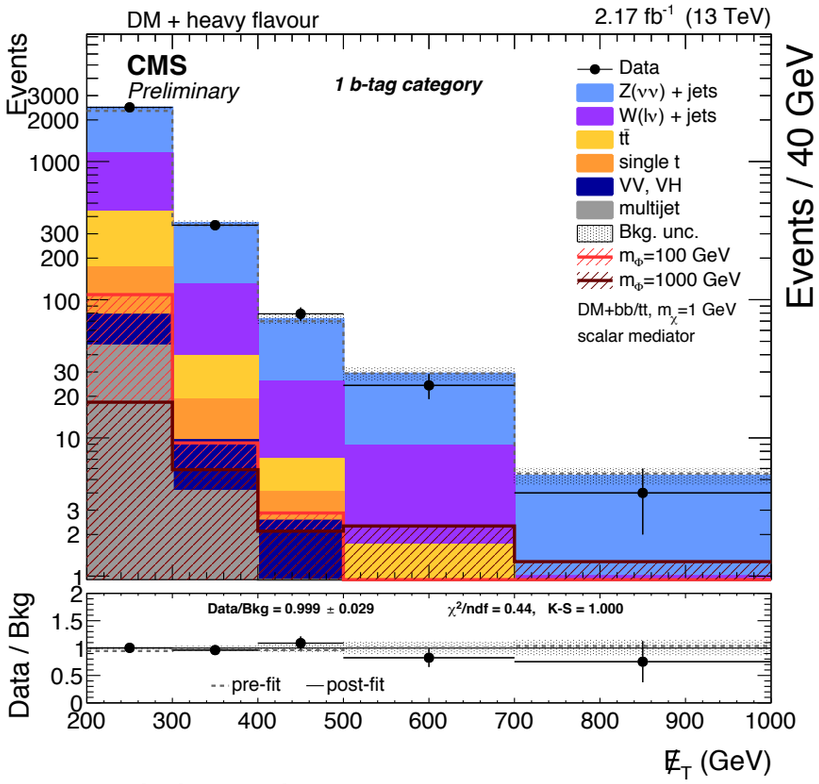
→Enhanced bb/tt-DM associated production

bb+E_T^{miss}

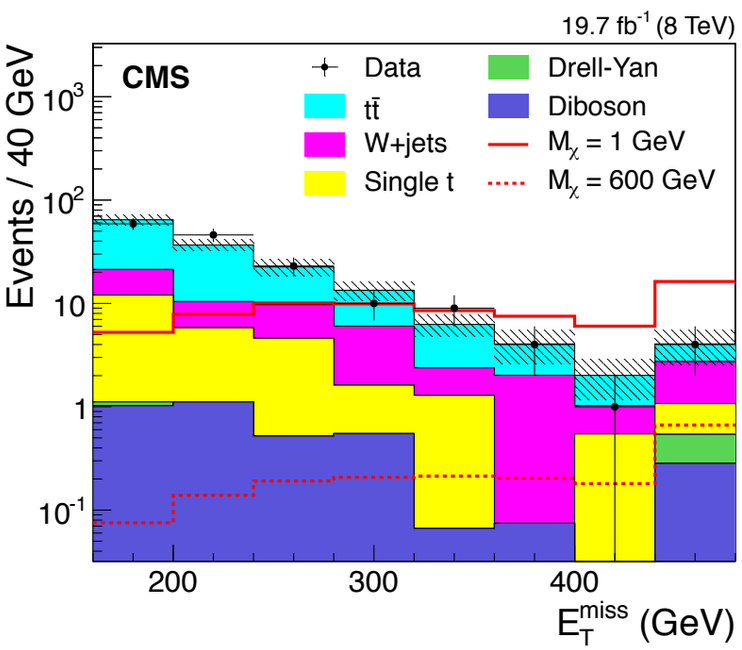
- 1 or 2 b-tagged jets p_T > 50 GeV
- E_T^{miss} > 200 GeV

tt+E_T^{miss}

- ≥3 jets, ≥1 b-tagged
- E_T^{miss} > 320 GeV
- M_T^{ℓ} > 160 GeV
- M^{W}_{T2} > 200 GeV



bb 1 b-tag category



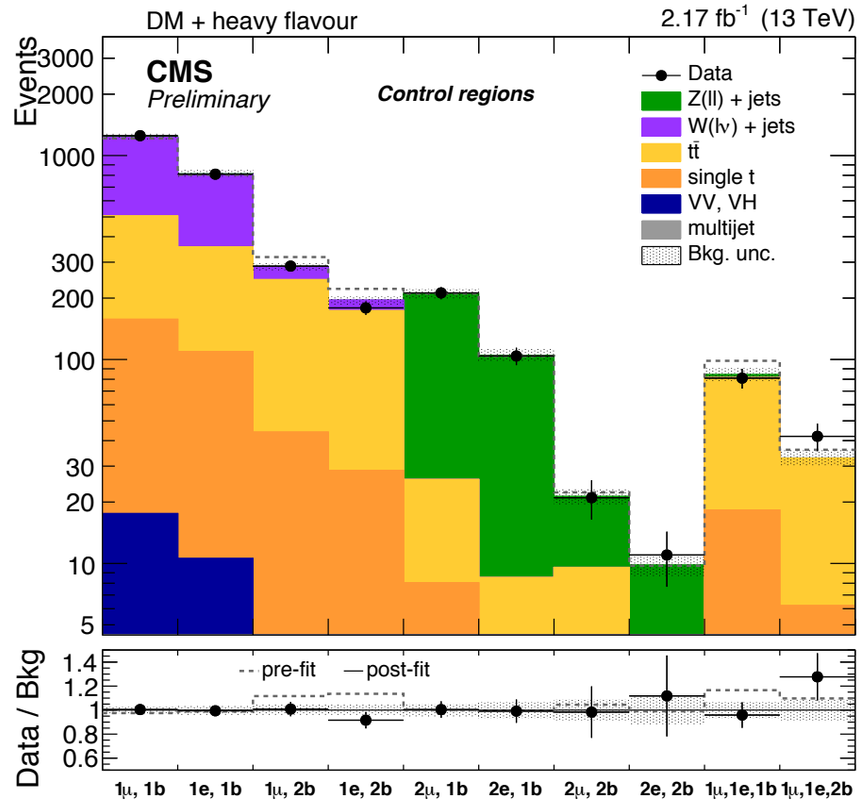
tt signal region

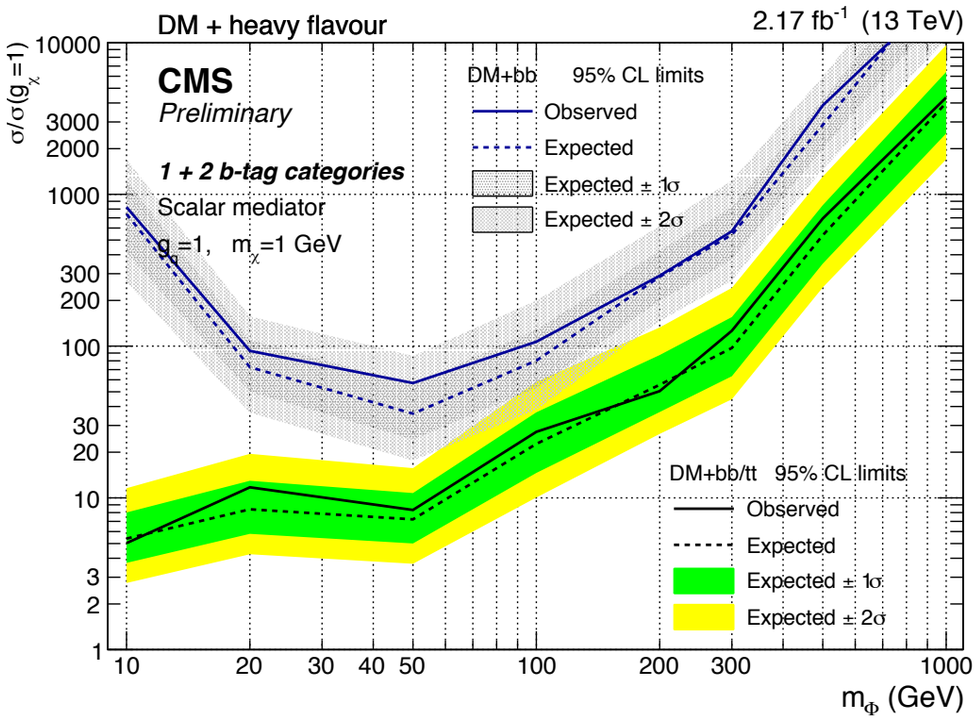
EXO-15-007
EXO-14-004

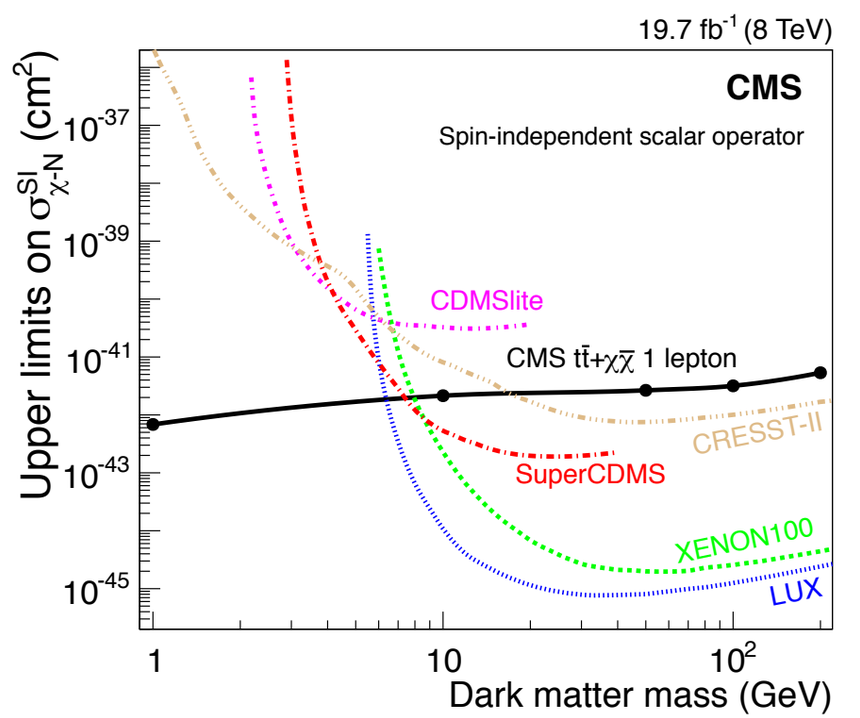
bb/tt + E_T^{miss} results [13/8 TeV]

bb+E_T^{miss}:
Bkgd + signal fit to multiple control regions + signal region.
Results cast in terms of simplified model σ as a function of mediator mass.

tt+E_T^{miss}:
Counting experiment.
Presented as EFT limits.







EXO-15-007
EXO-14-004

Summary and prospects

- CMS dark matter search is in full swing.
- Result interpretation scheme standardized.
  → Easier comparison among collider searches
  AND with direct searches to
  - Establish complementarity.
  - Identify uncovered territories.
- Collider DM searches has competitive sensitivity to direct searches even for generic models.
- Many more 13 TeV results in the pipeline.
  Updates, combinations, etc.

BACKUPS

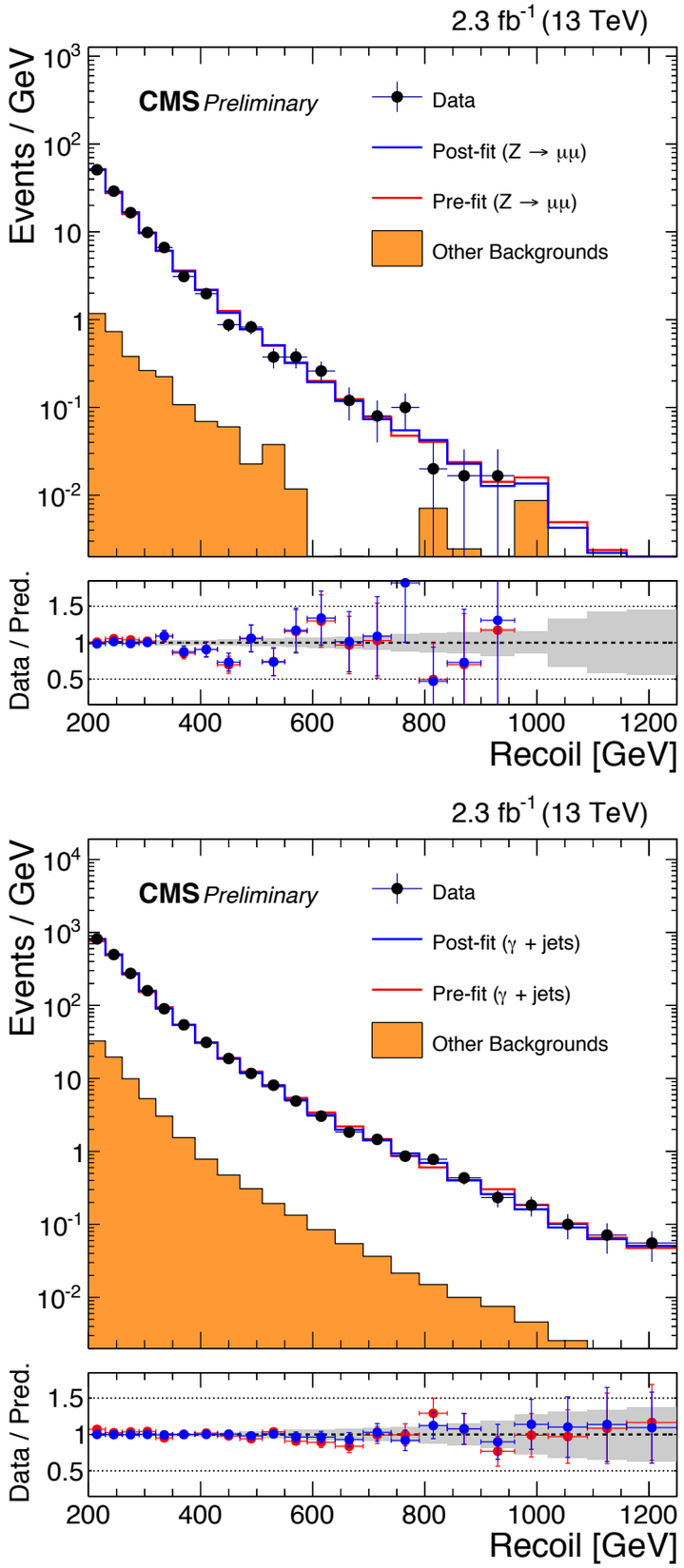
Jets+E_T^{miss} control regions

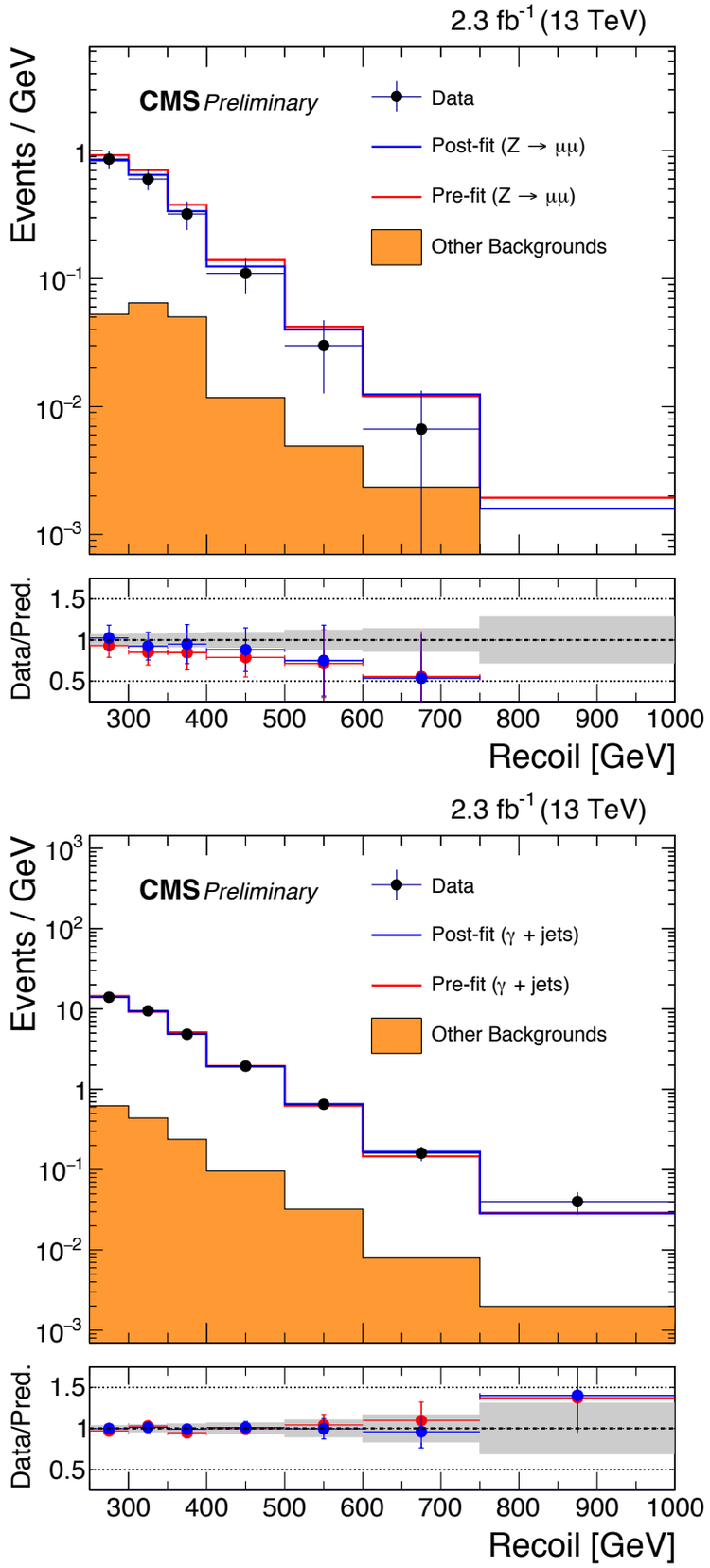
CRs: 2μ/e, 1μ/e, γ.

Remove ℓ/γ from event as E_T^{miss} proxy.

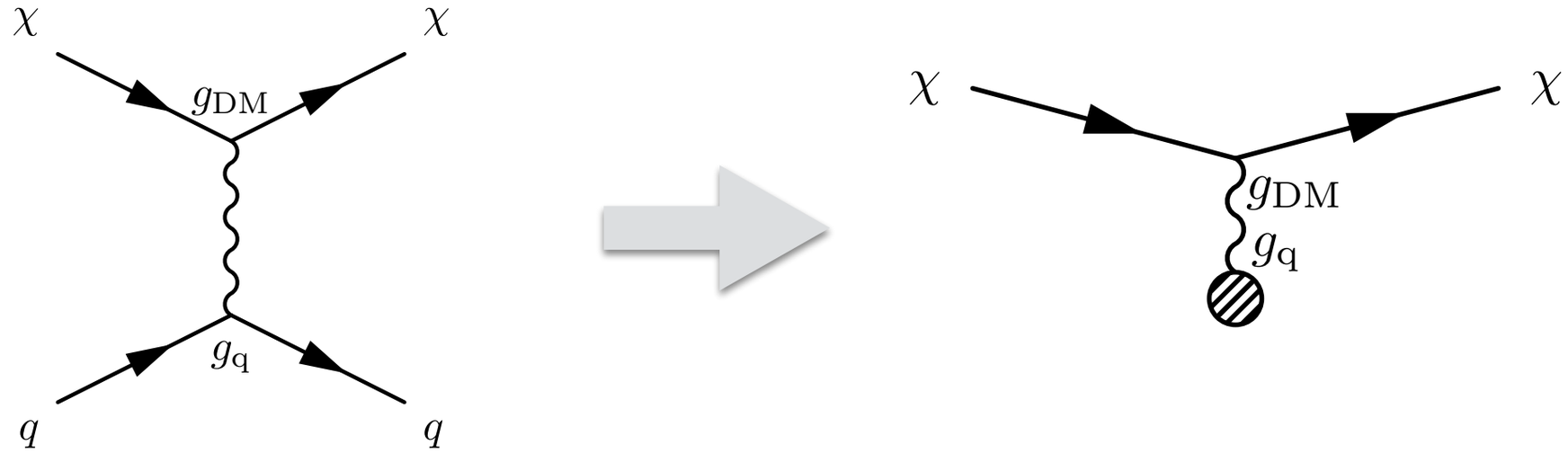
Bkgd estimations connected between CRs and SR

→ Simultaneous fit to constrain SR bkgd.





Nonrelativistic limit for t-channel DM-quark scattering



From Buchmueller, Dolan, Malik, and McCabe (1407.8257)

$$\sigma_{\mathrm{SI}} = \frac{9 g_{\mathrm{DM}}^2 g_{\mathrm{q}}^2 \mu_{n\chi}}{\pi M_{\mathrm{med}}^4}$$

$$\sigma_{\mathrm{SD}} = \frac{3 g_{\mathrm{DM}}^2 g_{\mathrm{q}}^2 (\Delta_u + \Delta_d + \Delta_s)^2 \mu_{n\chi}^2}{\pi M_{\mathrm{med}}^4}$$

$\mu_{n\chi}$: nucleon-DM reduced mass

$\Delta_u = -0.42$, $\Delta_d = 0.85$, $\Delta_s = -0.08$

Razor variables

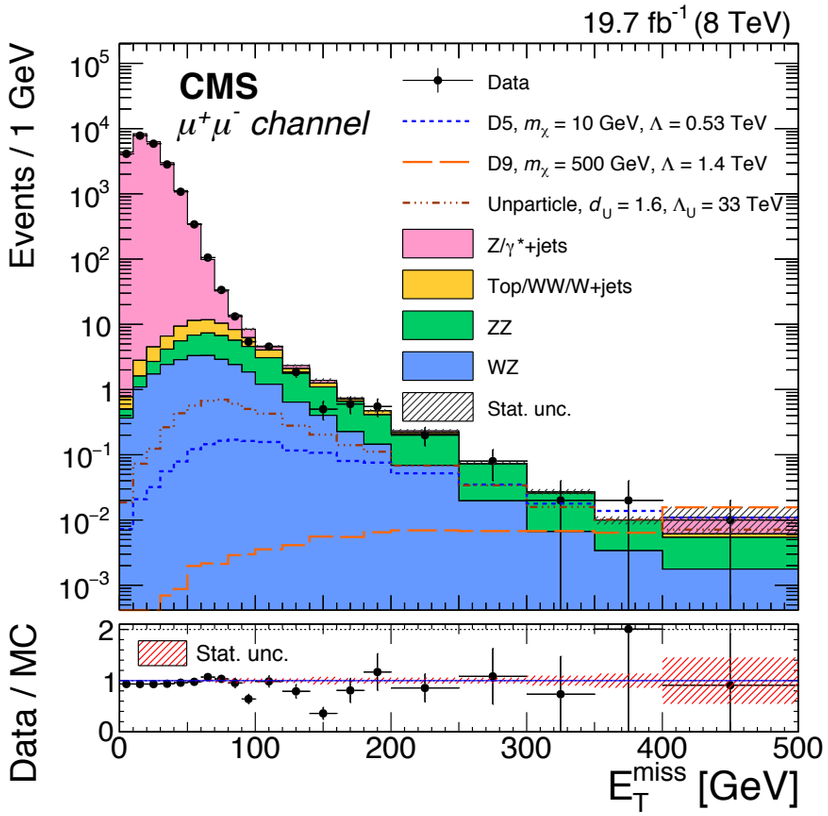
Clusterize all visible objects in the event into two “megajets” j1 and j2.

$$M_{\mathrm{R}} = \sqrt{(|\vec{p}^{\,j1}| + |\vec{p}^{\,j2}|)^2 - (p_z^{j1} + p_z^{j2})^2}$$

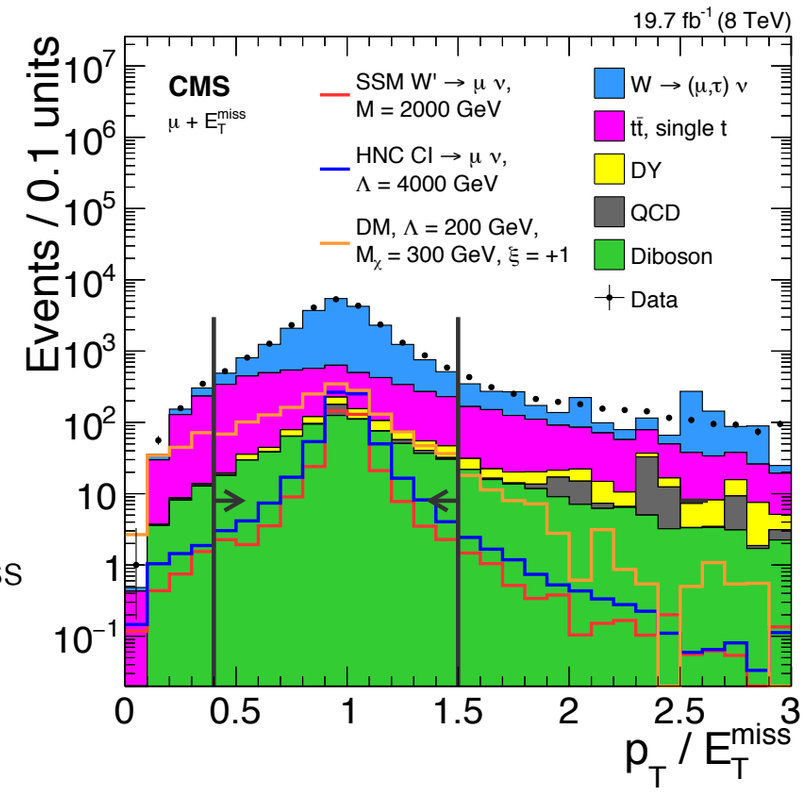
$$M_{\mathrm{T}}^{\mathrm{R}} = \sqrt{\frac{E_{\mathrm{T}}^{\mathrm{miss}}(p_{\mathrm{T}}^{j1} + p_{\mathrm{T}}^{j2}) - \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} \cdot (\vec{p}_{\mathrm{T}}^{\,j1} + \vec{p}_{\mathrm{T}}^{\,j2})}{2}}$$

$$R = \frac{M_{\mathrm{T}}^{\mathrm{R}}}{M_{\mathrm{R}}}$$

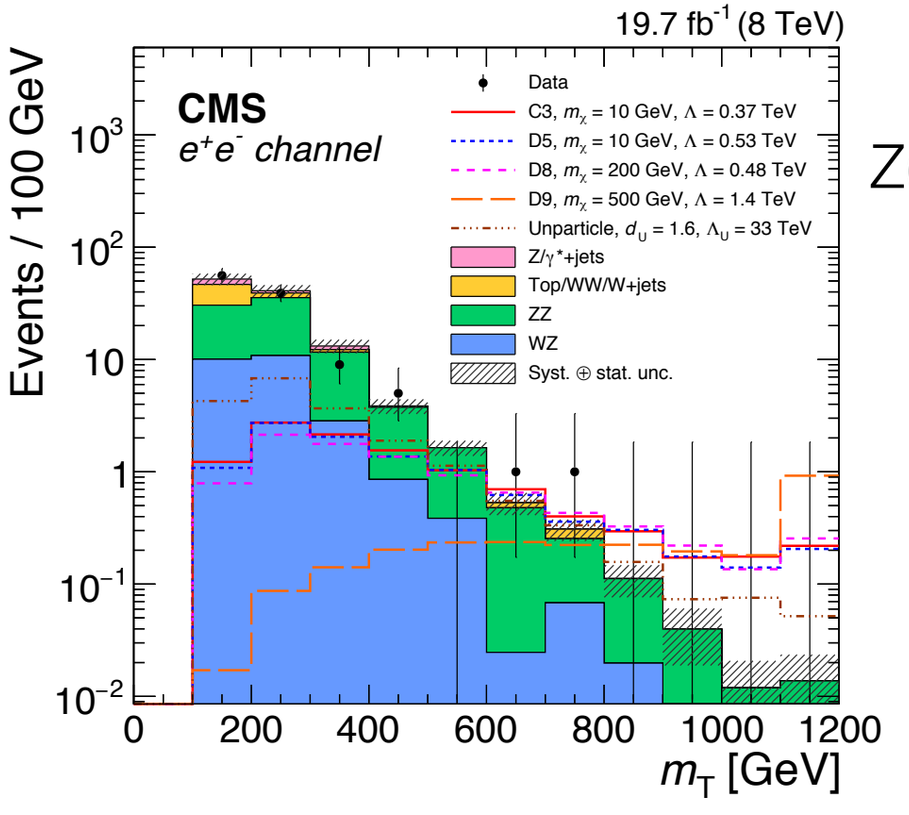
Mono-Z(ℓℓ), W(ℓν)



Z(μμ) E_T^{miss}

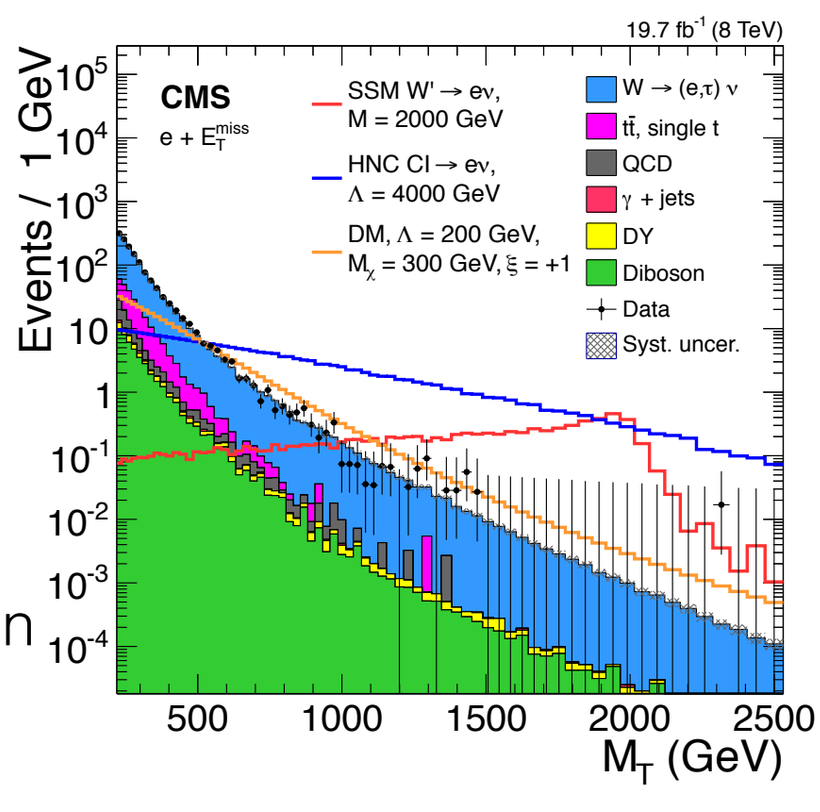


W(μν) p_T^{μ} / E_T^{miss}



Z(μμ) $M_T^{\mu\mu}$, final selection

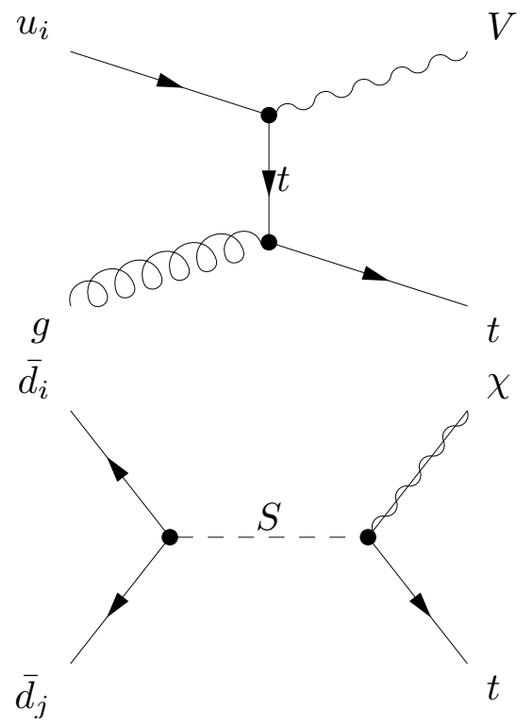
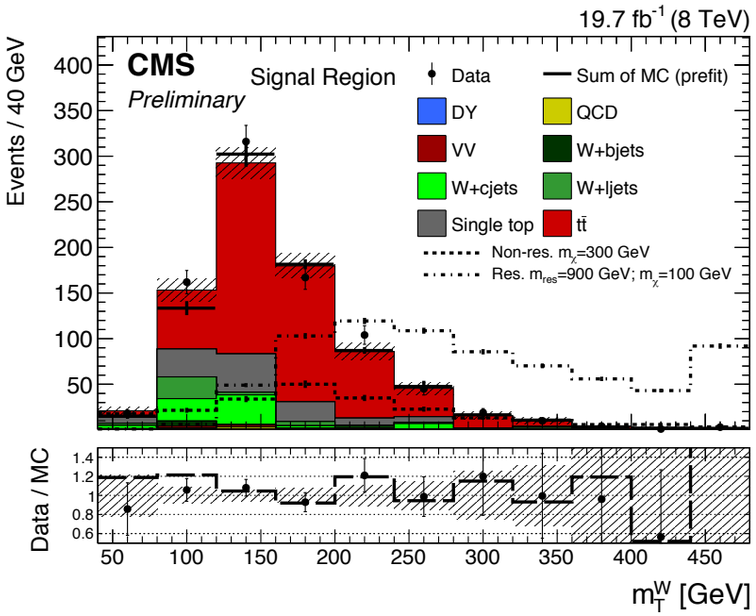
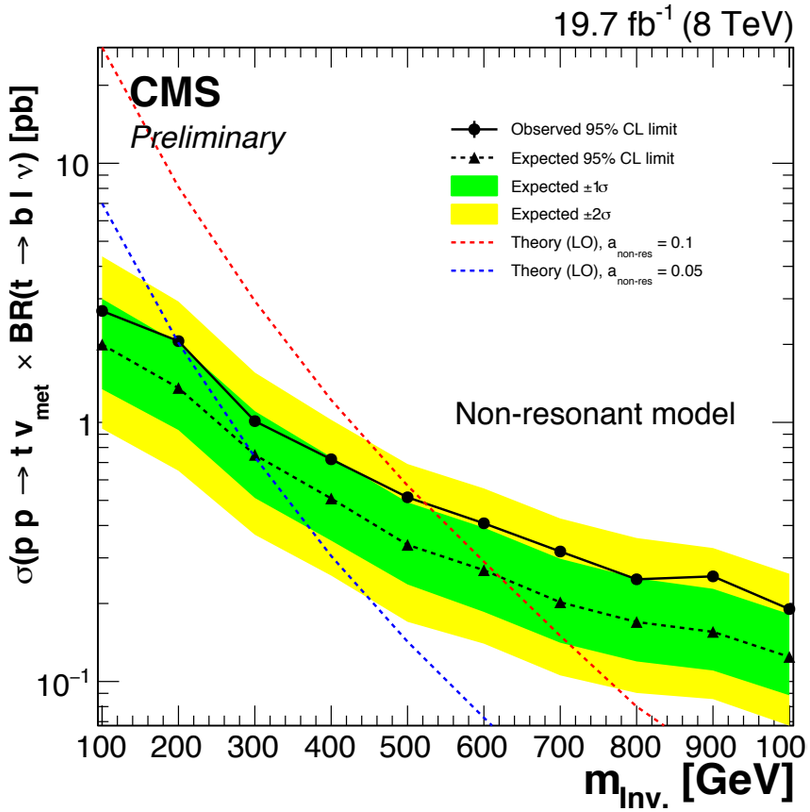
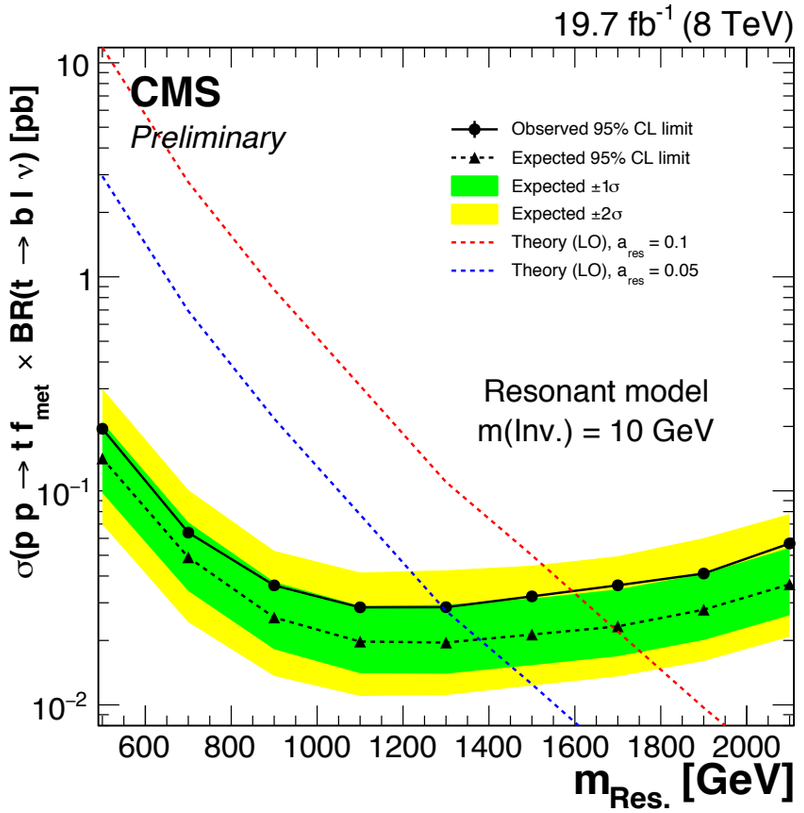
W(μν) M_T^{μ}, final selection



Monotop

Probes FCNC and new colored, charged resonance.

1 μ, 1 b-tagged jet p_T > 70 GeV, E_T^{miss} > 100 GeV.

Signal extraction from fit to M_T^{μ} distribution.

Limits set on σ×BR for invisible mass (FCNC case) and resonance mass.