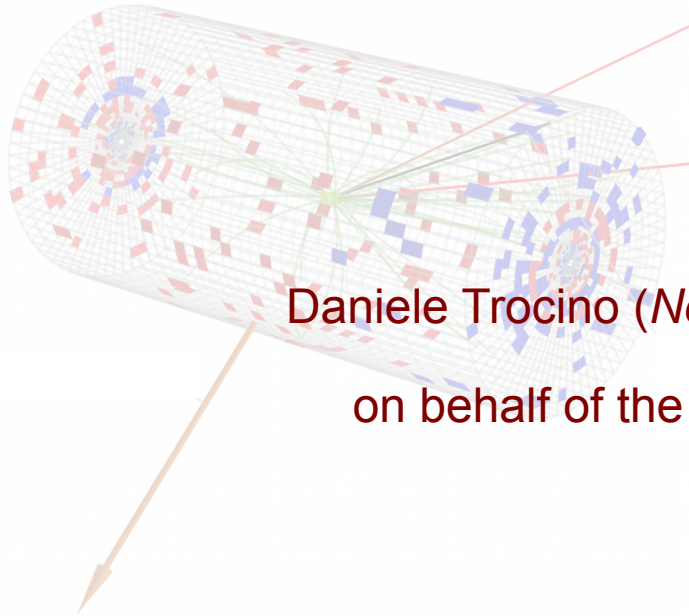
Dark Matter Searches at CMS



Daniele Trocino (*Northeastern University*)

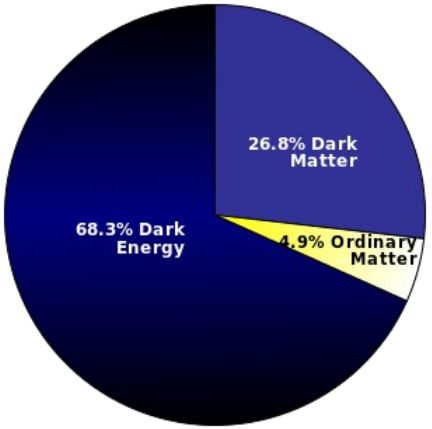
on behalf of the CMS Collaboration

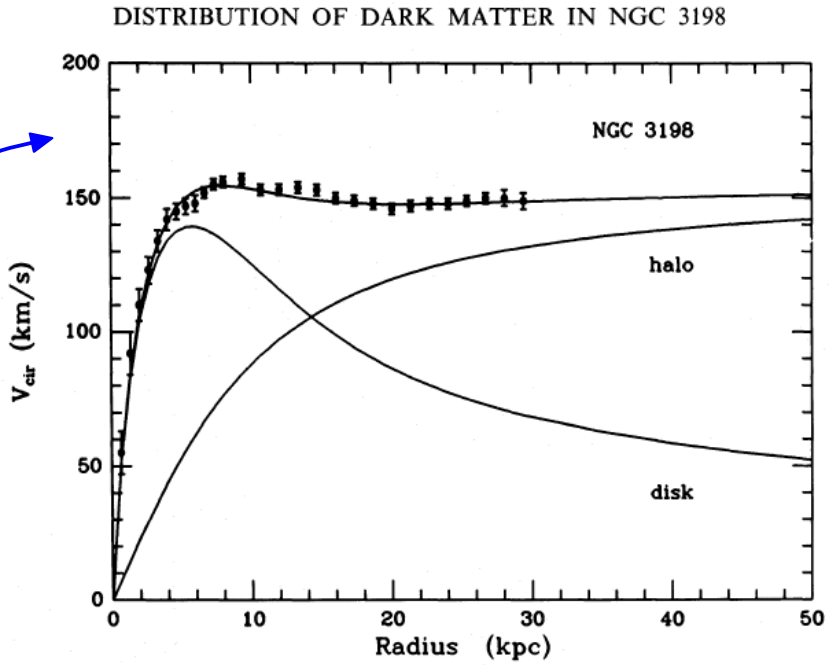
6th International Workshop on High Energy Physics in the LHC Era

Universidad Técnica Federico Santa María, Valparaíso (Chile) — January 9, 2016

Why Dark Matter at the LHC?

- Dark matter (DM) is currently one of the most promising new-physics searches at the LHC
  - its existence is indicated by several astrophysical observations …
    - orbits in galaxy clusters, galaxy rotation curves, gravitational lensing, etc
  - … it is estimated to account for about 27% of all energy-matter in the Universe …





Astrophys. J. Part I, v295
1985, pp 305-313

  - … but it has never been directly observed!

Properties of Dark Matter

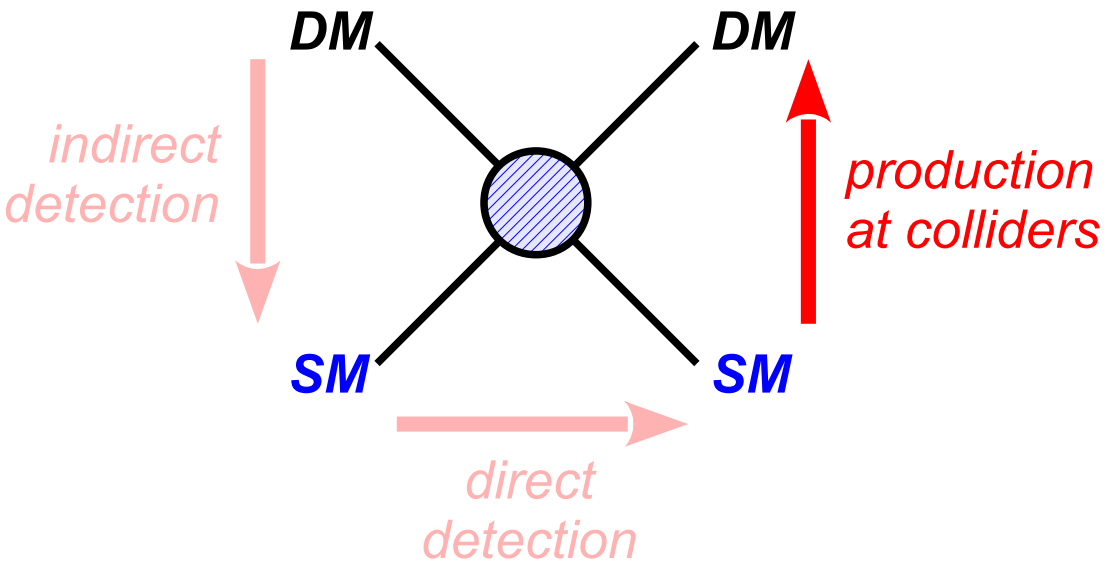
- To be compatible with observations, DM must
  - be stable and massive ⇒ gravitational effects
  - have little interaction with standard model (SM) particles
    - electrically neutral ⇒ "dark"
    - interaction cross sections no higher than the weak scale ⇒ current DM density
  - be cold, i.e. $\langle v \rangle \ll c$ ⇒ galaxy distribution in the Universe

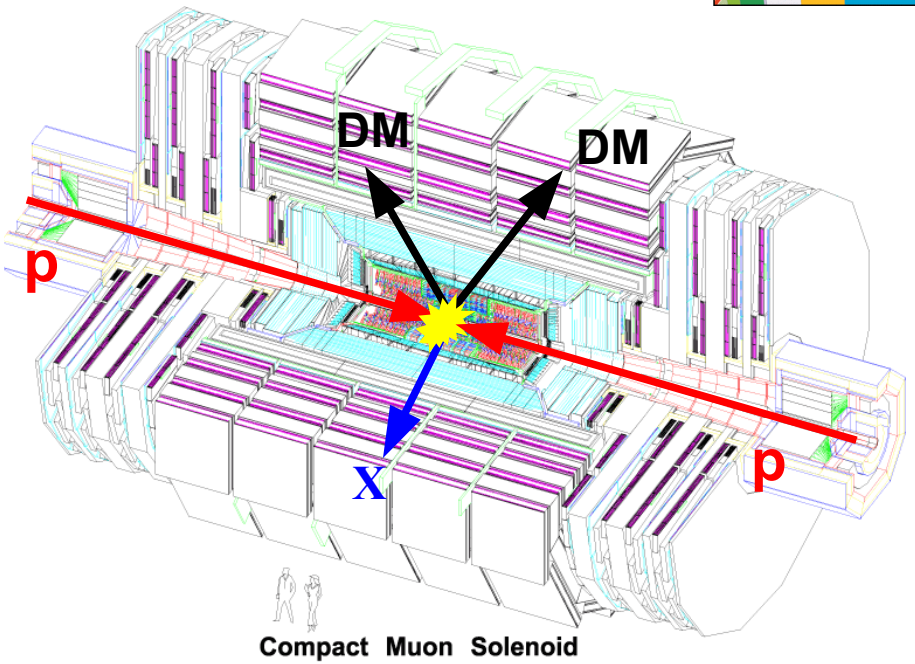
➔ Ideal DM candidate is a weakly-interacting massive particle (WIMP)

- main focus of collider searches

For further details, see talk by A. Nelson on Thursday (and backup slides)

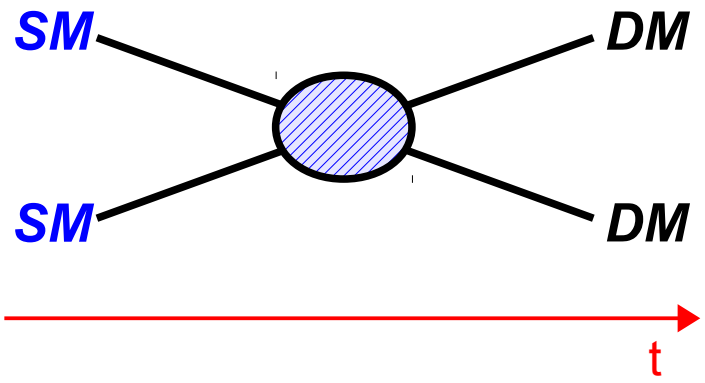
Dark Matter Production & Detection



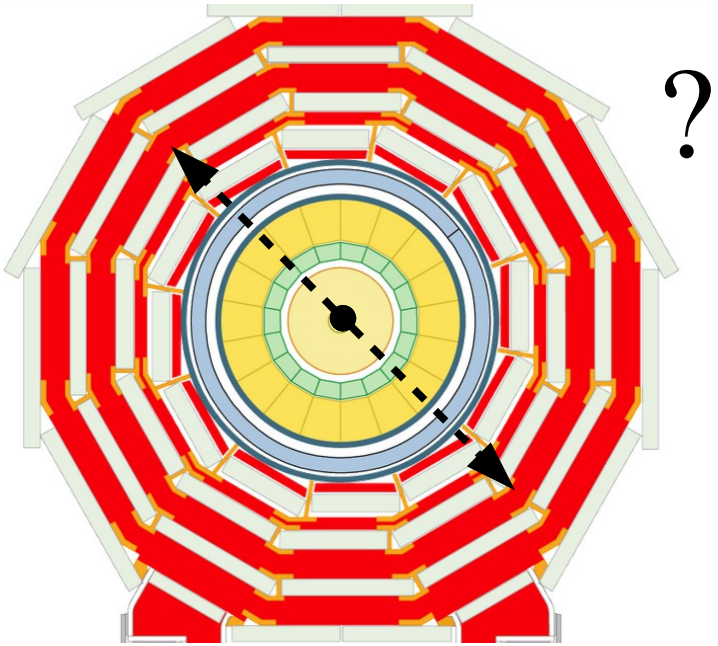


- Hypothetical DM particles may be produced in proton-proton collisions at the LHC
  - rare process, but very high statistics
- However, observing DM in LHC experiments is very challenging
  - DM candidates are not detectable by CMS or ATLAS
    - experimental signature: missing transverse momentum or energy MET or $E_{\mathrm{T}}^{\mathrm{miss}} = \left|\vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right|$
  - DM signals compete with very abundant SM processes involving neutrinos

Dark Matter Signals at the LHC



- Leading-order diagram produces only undetectable particles in the final state
  - ➔ no way to trigger the event!



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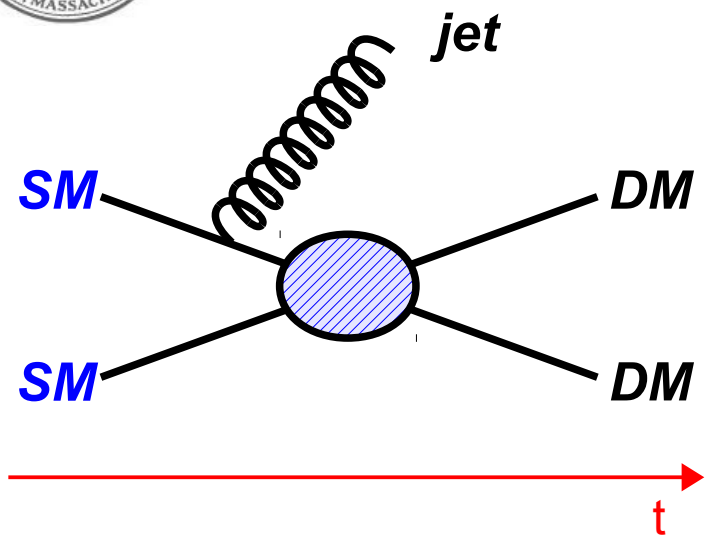
Dark Matter Signals at the LHC



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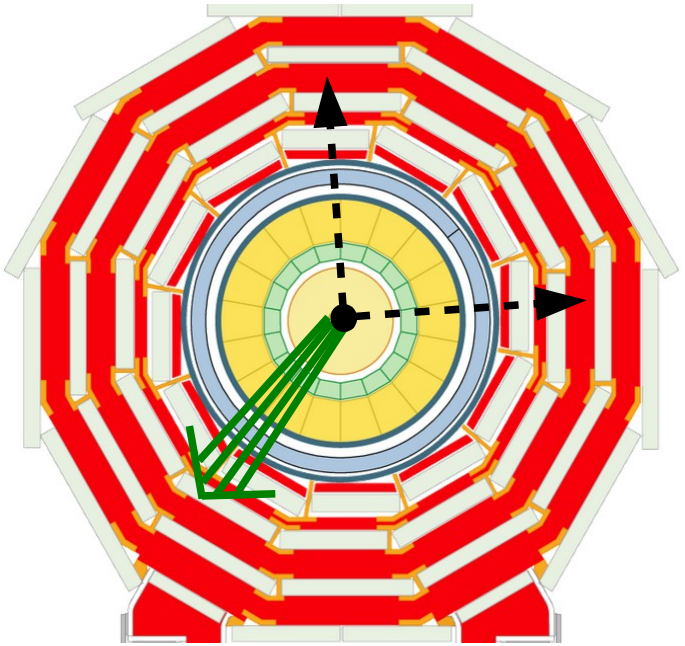
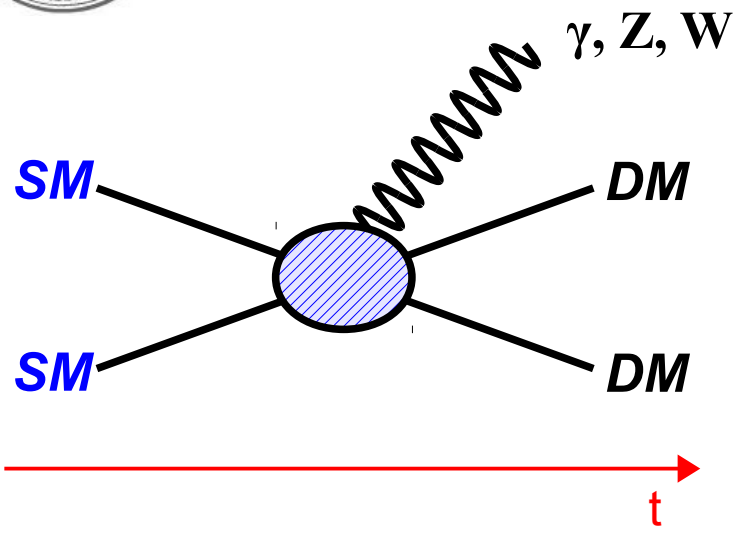
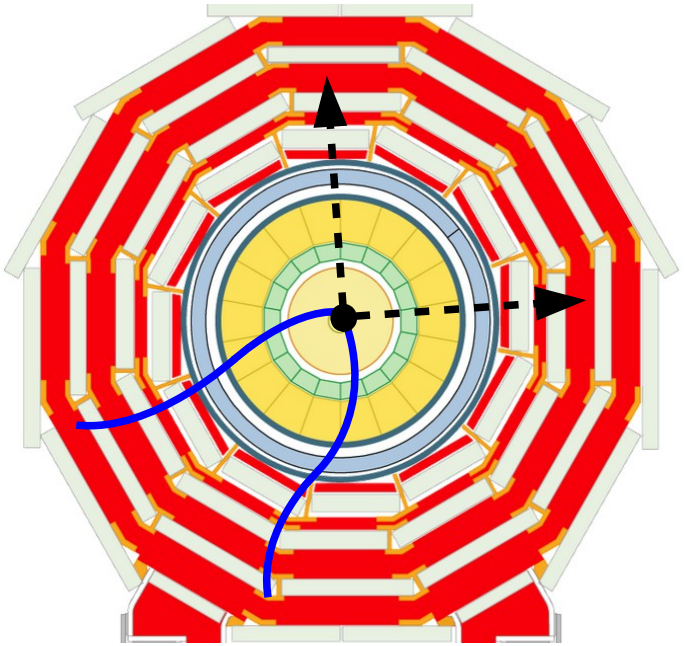
- To be detected, DM can recoil against
  - ➔ initial-state QCD radiation:

    MET + jet(s) (*mono-/multi-jet*)



Dark Matter Signals at the LHC





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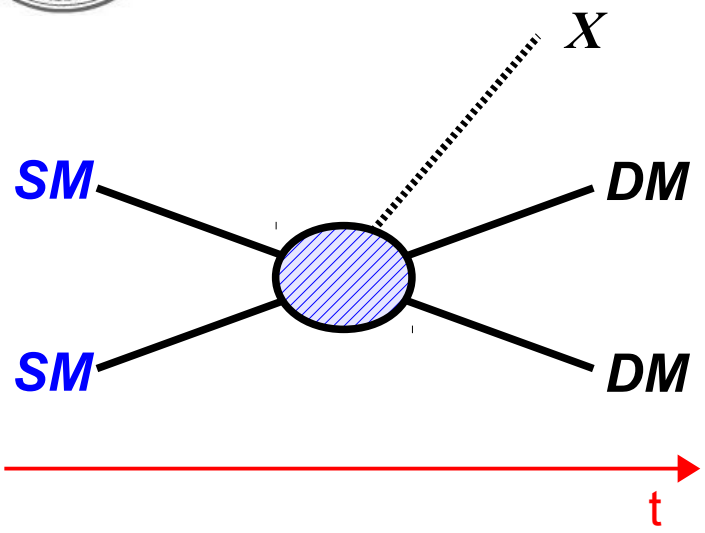
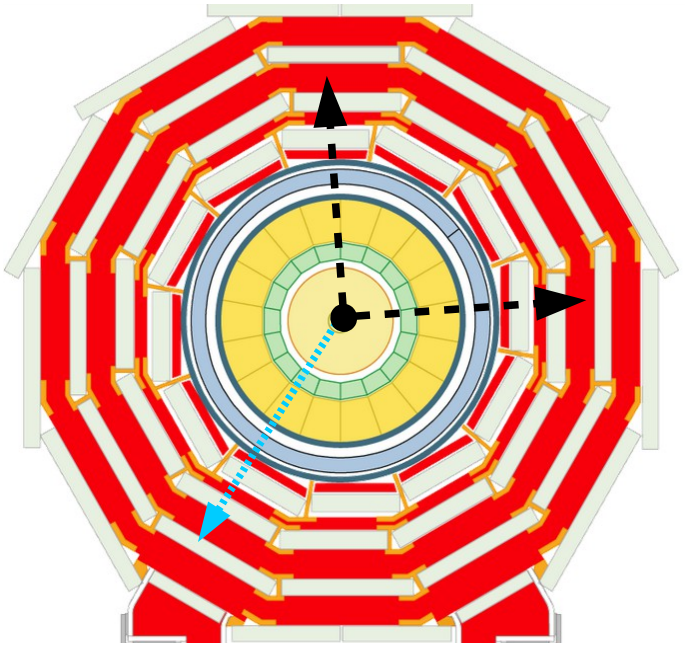
  - ➔ electroweak radiation:
    - MET + photon (*mono-photon*)
    - MET + two jets or a "fat" jet (*mono-W/Z hadronic*)
    - MET + one/two leptons (*mono-W/Z leptonic*)

Dark Matter Signals at the LHC





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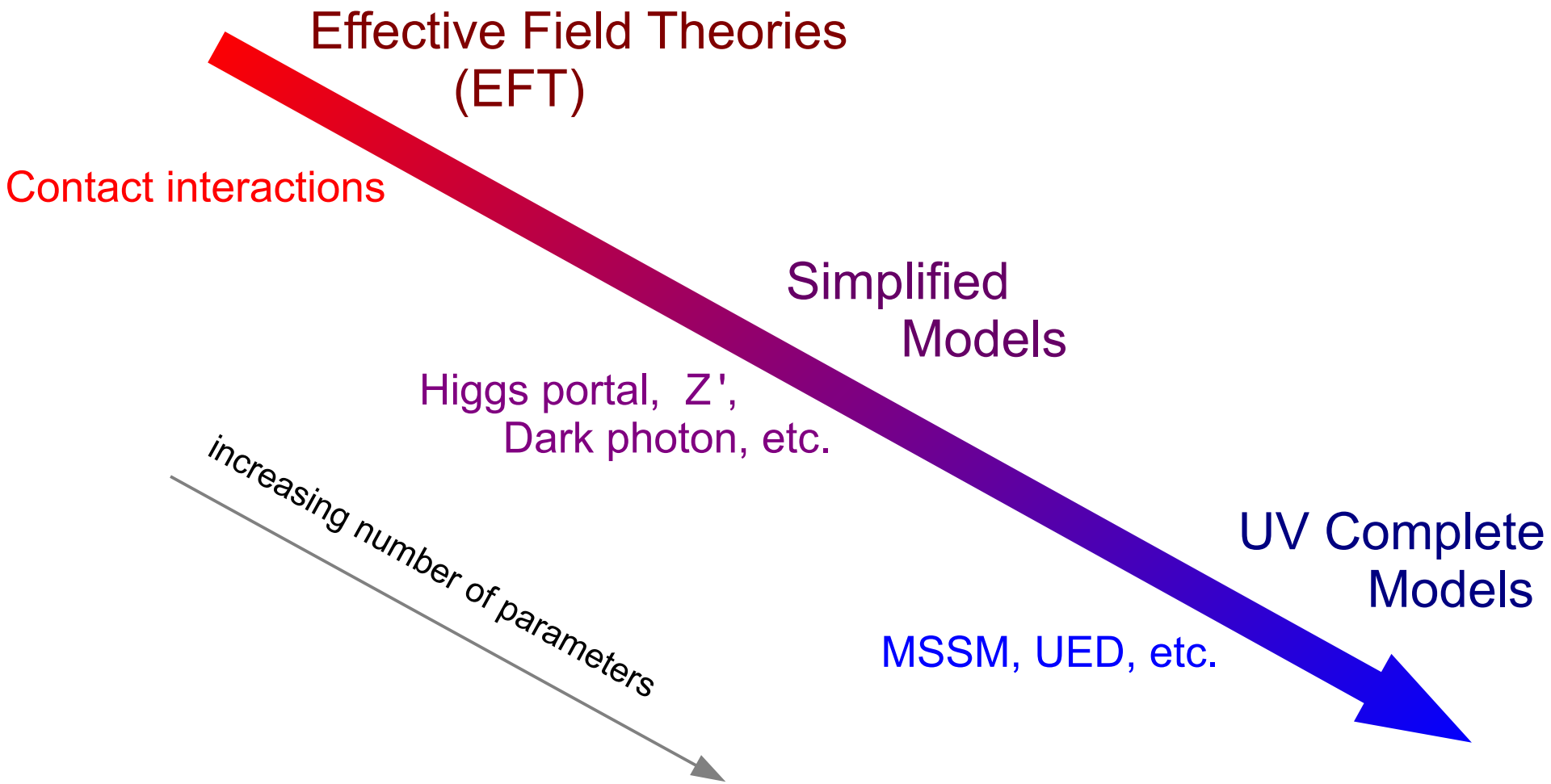
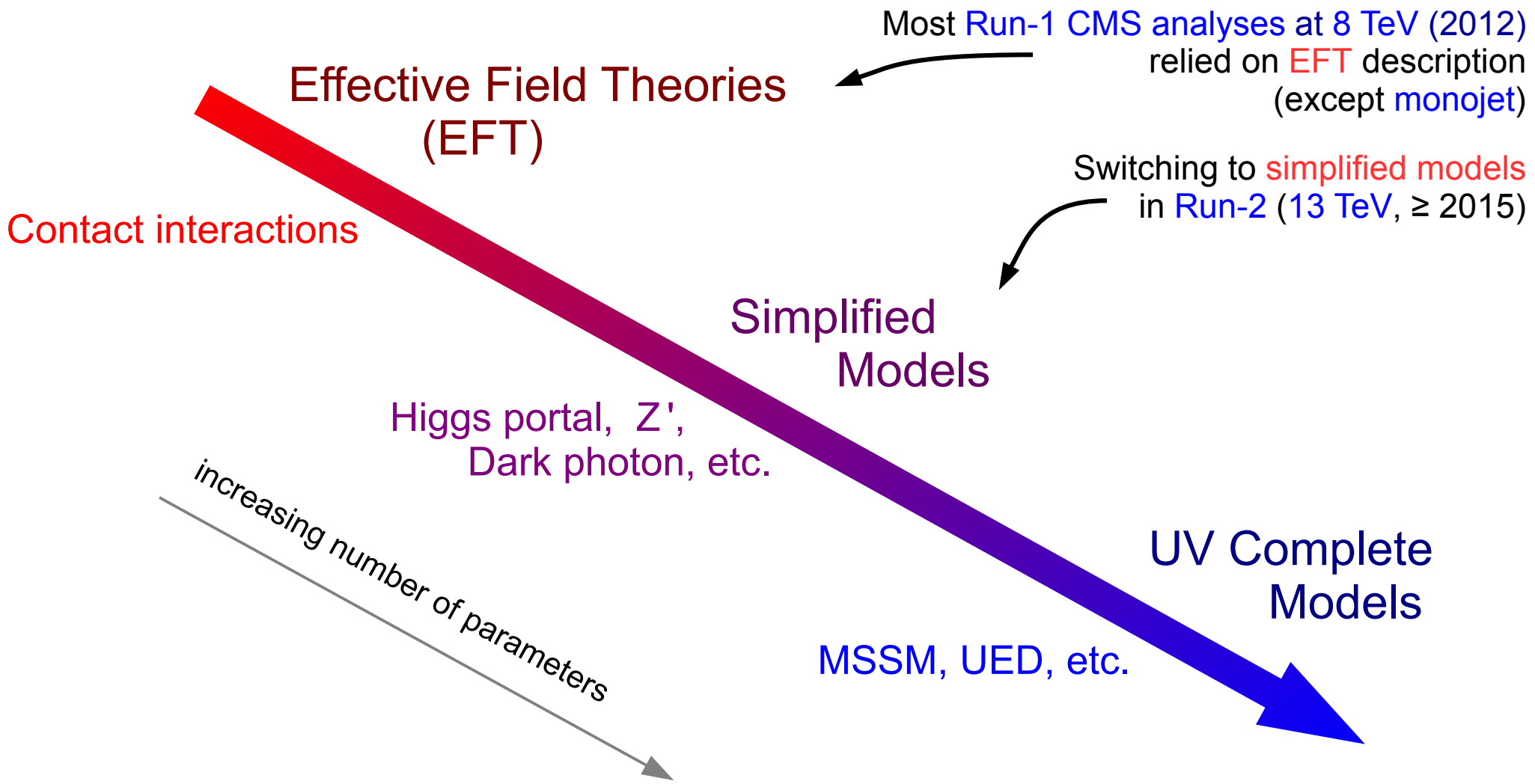
    - MET + one/two leptons (*mono-W/Z leptonic*)
  - ➔ or any other detectable systems:
    - e.g. heavy quarks, Higgs bosons, etc.

Models of Dark Matter



Freely adapted from
T. Tait, Lepton Photon 2013

Models of Dark Matter



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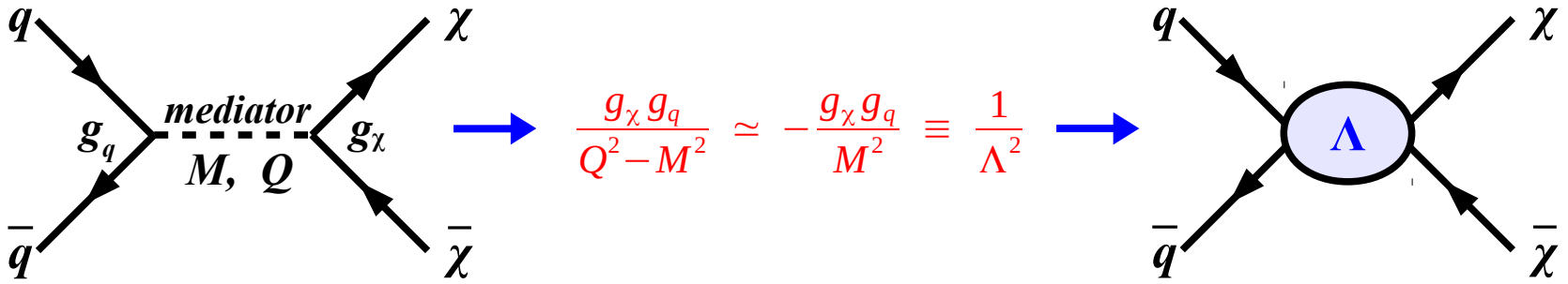
Effective Field Theory and Its Validity

- EFT depend only on two parameters:
  - DM mass m_χ and interaction scale $\Lambda \approx M / \sqrt{g_\chi g_q}$



- EFT are reliable only if $M^2 \gg \langle Q^2 \rangle$ — *not always true at LHC energies!*
  - **Truncation**: remove signal events where $Q > M \sim \Lambda \cdot \sqrt{g_\chi g_q}$

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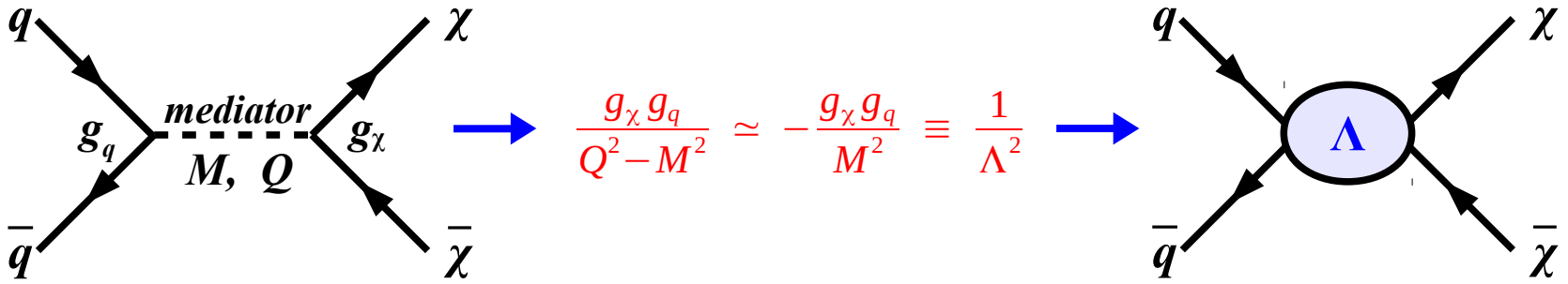


$$\frac{g_\chi g_q}{Q^2 - M^2} \simeq -\frac{g_\chi g_q}{M^2} \equiv \frac{1}{\Lambda^2}$$

- EFT are reliable only if $M^2 \gg \langle Q^2 \rangle$ — *not always true at LHC energies!*
  - **Truncation**: remove signal events where $Q > M \sim \Lambda \cdot \sqrt{g_\chi g_q}$

	Name	Initial state	Type	Operator
spin independent	D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
	D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
spin dependent	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	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$

Used to calculate cross sections

- $q\bar{q} \to \chi\bar{\chi}$ *LHC*
- $q\chi \to q\chi$ *Direct Detection*

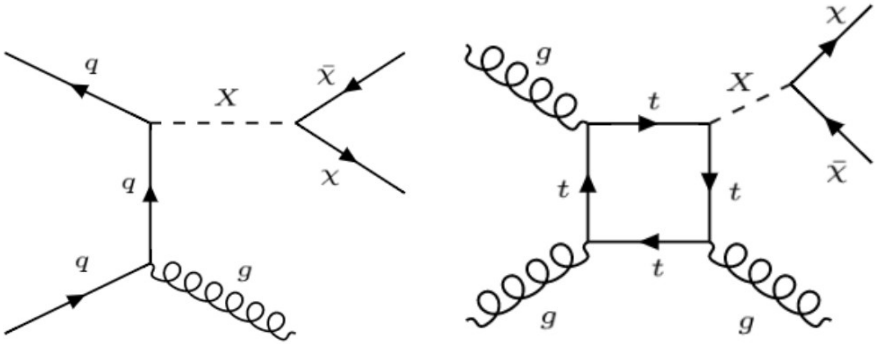
Dark Matter Searches at CMS

- During the LHC Run-1 and first year of Run-2, CMS has conducted numerous searches for DM candidates
  - About 20 fb^{-1} of data at $\sqrt{s}$ = 8 TeV + 2.1 fb^{-1} at $\sqrt{s}$ = 13 TeV (only shown for mono-jet here)
- Main analyses presented here
  - **DM + jets:** mono-jet, W/Z → 2 jets or 1 "fat" jet, di-jet with razor variables
  - **DM + photons:** mono-photon
  - **DM + leptons:** mono-$W(\ell\nu)$, mono-$Z(\ell\ell)$
  - **DM + heavy-flavor quarks:** mono-top, top pairs
  - **DM in Higgs-portal models:** "invisible" Higgs produced with different mechanisms
    - vector boson fusion (VBF), gluon-fusion + jets, $V(had)H$, $Z(2\ell)H$, $Z(b\bar{b})H$

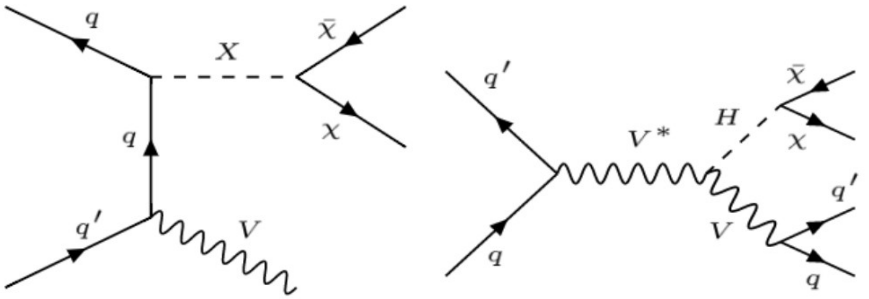
Dark Matter + Jets

Signal modeling

- Jets from initial-state QCD radiation or hadronic decay of V = W/Z
- Simplified models, several mediator types: (axial-)vector, (pseudo-)scalar

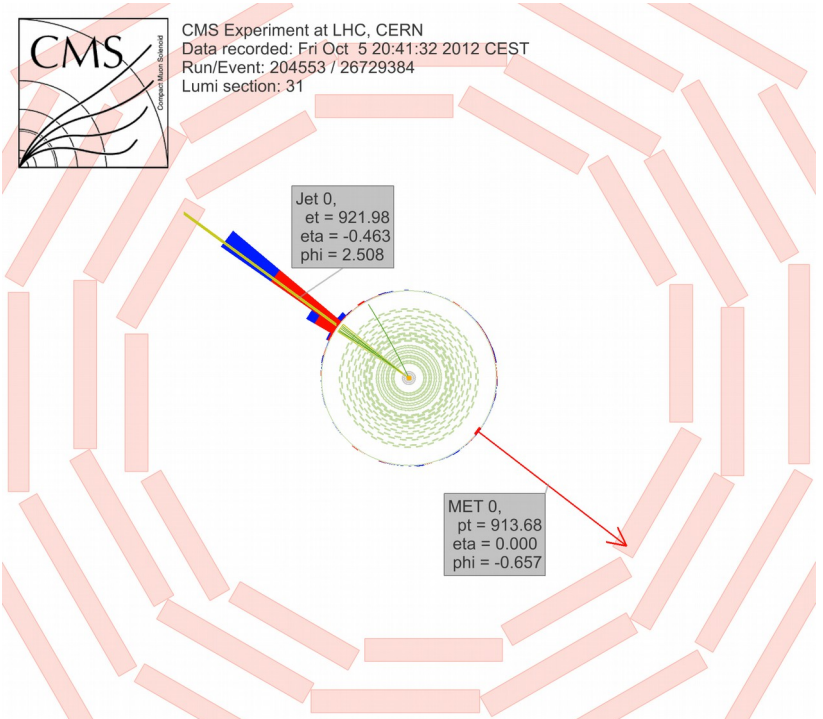


Monojet



Jets from W/Z decay

- Events are characterized by
  - one or two central high-p_T jet(s)
  - high missing transverse energy: E_T^{miss} > 200-250 GeV



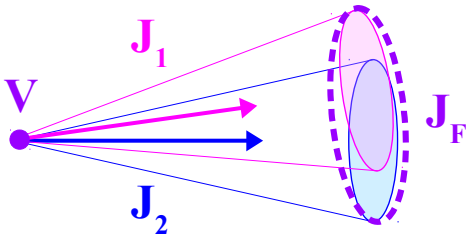
CMS-EXO-12-055
Eur. Phys. J. C 75 (2015) 235

Dark Matter + Jets
Event Categories

- Events are split into 3 exclusive categories

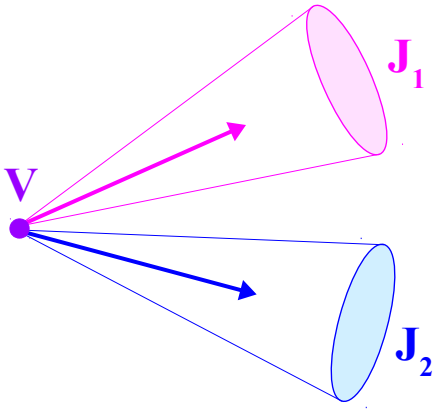
$V \rightarrow jj$

- **Boosted V** → the two jets are reconstructed as a single "fat" jet
  - 1 jet with p_T > 250 GeV and mass = 60-110 GeV
  - jet-substructure techniques → likelihood of originating from 2 jets



- **Resolved V** → low-p_T V, two jets can be fully reconstructed
  - 2 jets with p_T > 30 GeV and mass = 60-110 GeV
  - multivariate techniques using properties of the dijet system:

    jet quark-gluon likelihood, color-flow variables,
    jet and dijet masses and opening angle, etc.

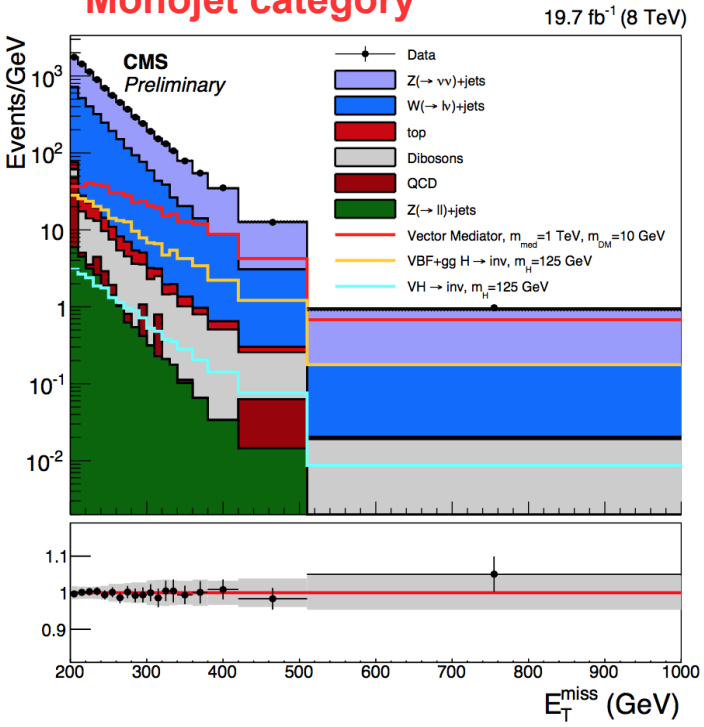


- **Monojet** → all events excluded from the previous categories
  - at least 1 jet with p_T > 150 GeV
  - veto on events containing leptons or photons

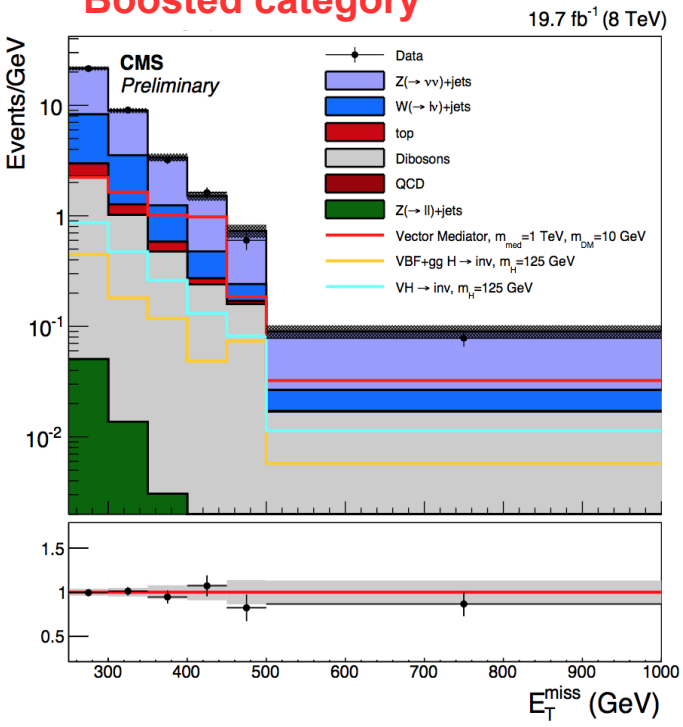
Dark Matter + Jets
Background Estimation

- Dominant backgrounds $Z(\nu\nu)$ + jets and $W(\ell\nu)$ + jets (when ℓ is missed) are estimated from control regions in data
  - **$Z(\mu\mu)$ + jets**, **γ + jets**, **$W(\ell\nu)$ + jets** with **identified ℓ**
- Both normalization and E_T^{miss} shape are corrected

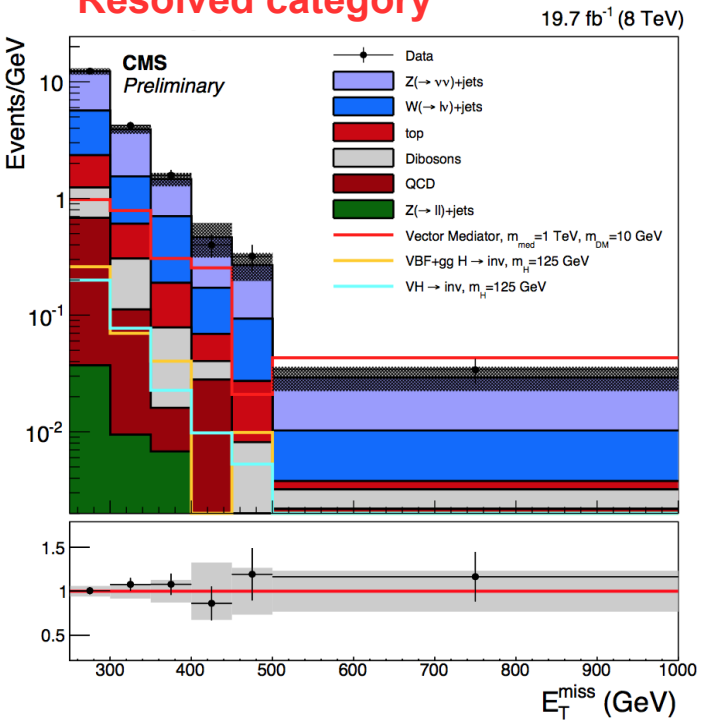
Monojet category



Boosted category



Resolved category

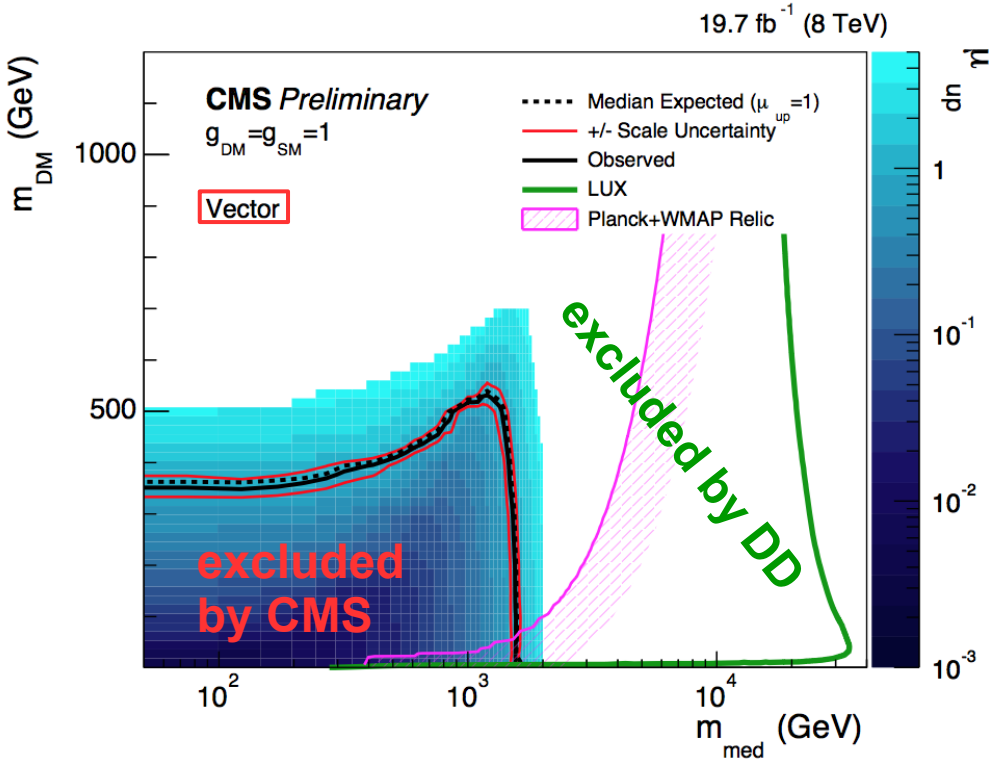


Dark Matter + Jets

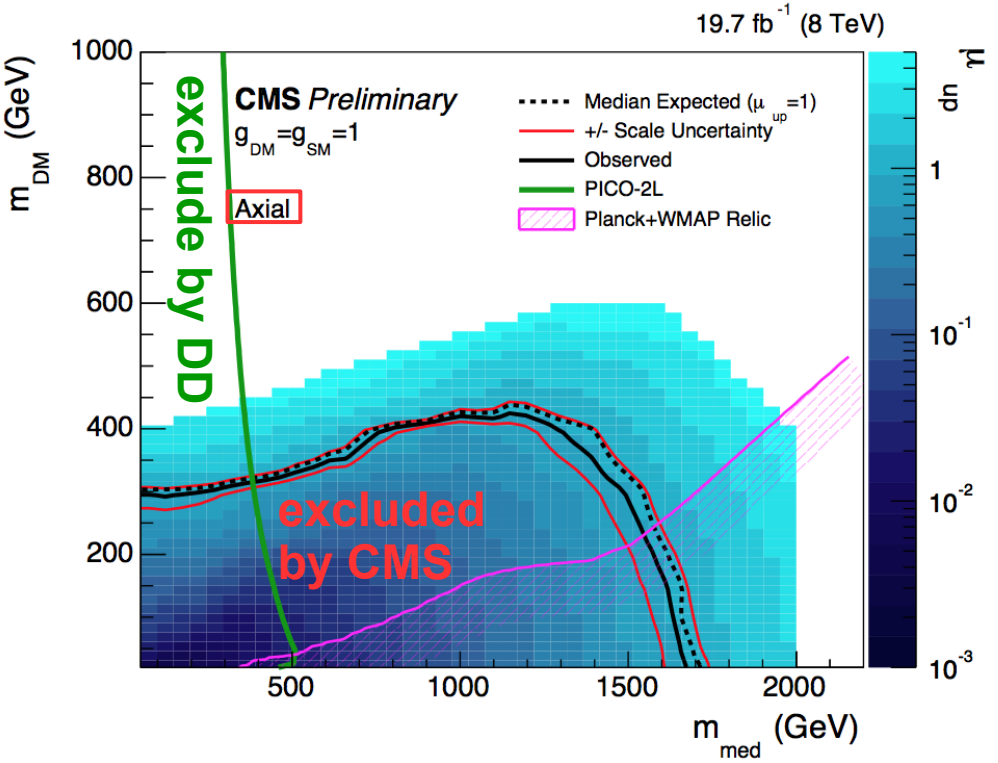
Limits on Model Parameters

- Good agreement between data and SM simulation, no excesses observed
- 90% CL limit contours set in the DM mass vs mediator mass plane for $g_\chi = g_q = 1$
  - Compare with limits derived from direct-detection experiments (LUX) and relic density

Vector mediator, spin independent



Axial-vector mediator, spin dependent

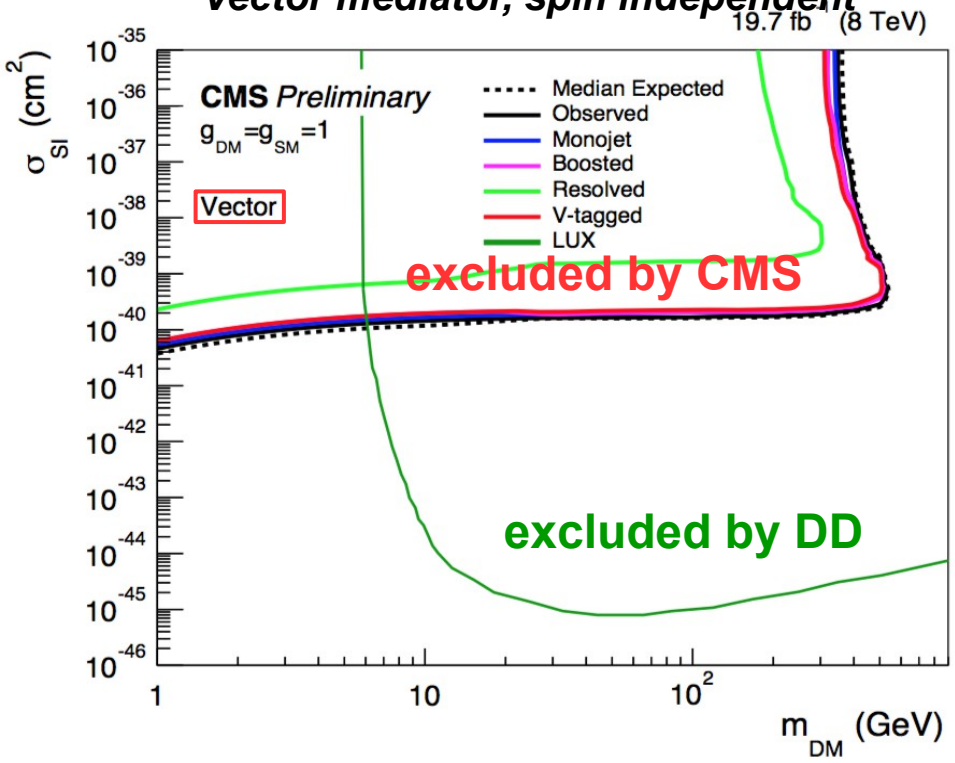


Dark Matter + Jets

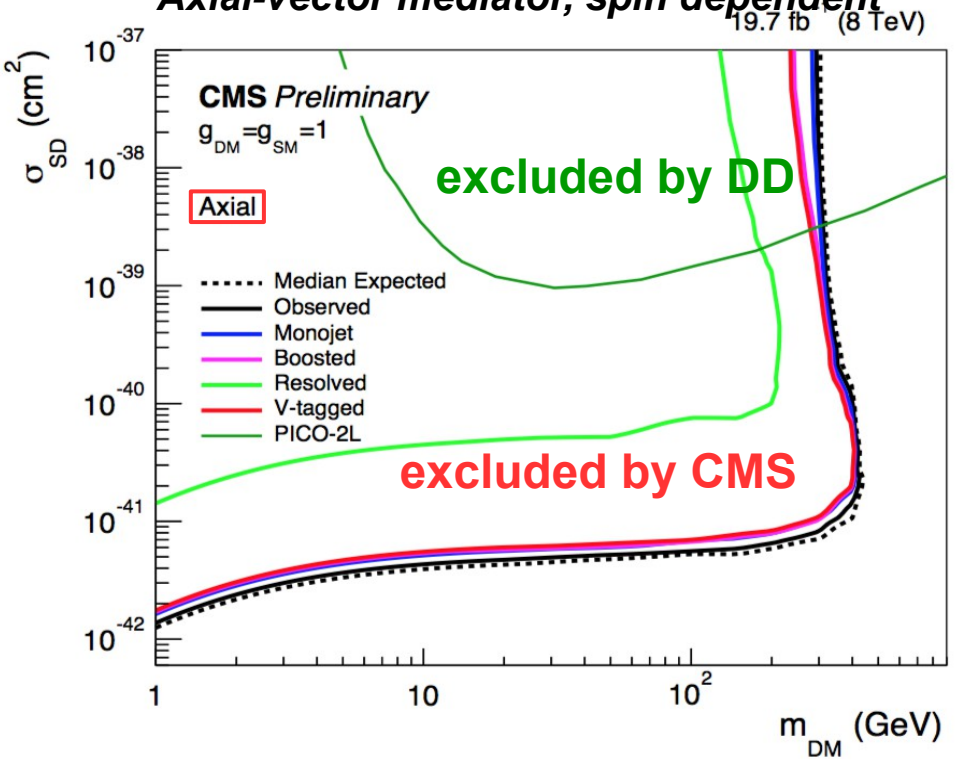
Limits on DM-Nucleon Cross Sections

- Limits on model parameters are translated into 90% CL limits on the DM-nucleon cross section for $g_\chi = g_q = 1$
  - For a vector mediator (spin-independent cross section), CMS extends limits from direct detection experiments to lower DM masses, < ~6 GeV
  - For an axial-vector mediator (spin-dependent cross section), direct-detection experiments lose sensitivity and LHC limits dominate up to DM masses of a few hundred GeV

Vector mediator, spin independent



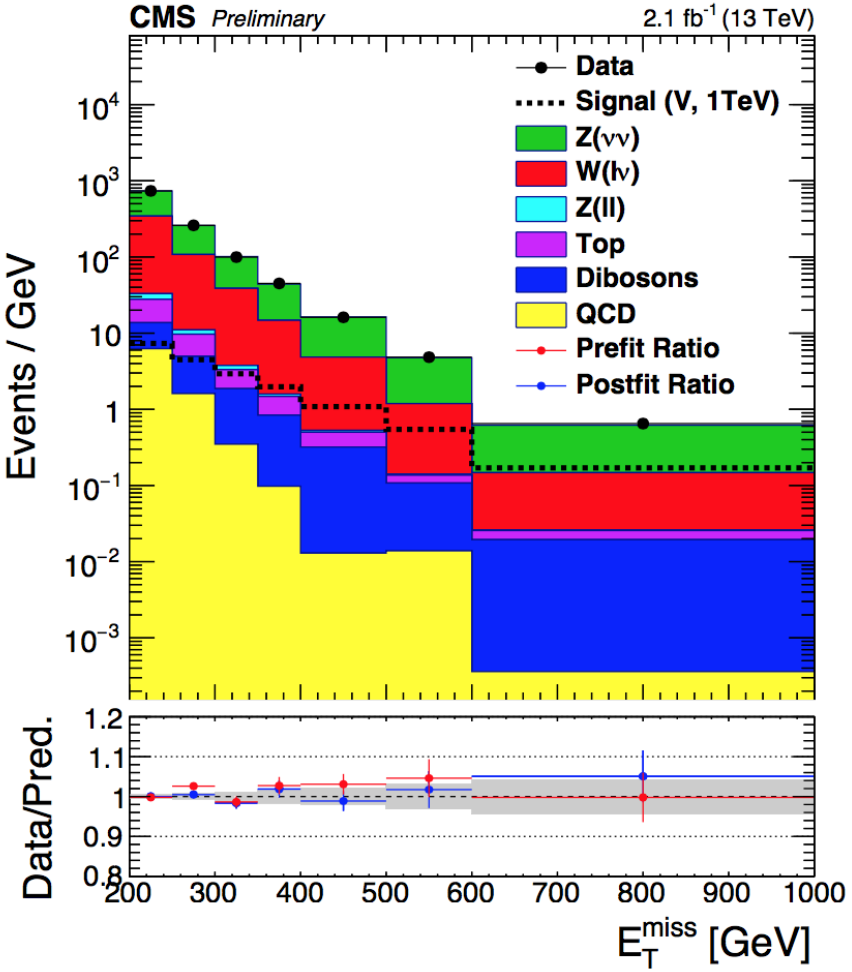
Axial-vector mediator, spin dependent



Monojet
First Results with 13 TeV Data

- The first 2.1 fb^{-1} of CMS data at 13 TeV have been analyzed in search of DM + jets
  - Only results for the monojet category are presented

- No excess is found w.r.t. the SM prediction and limits are computed

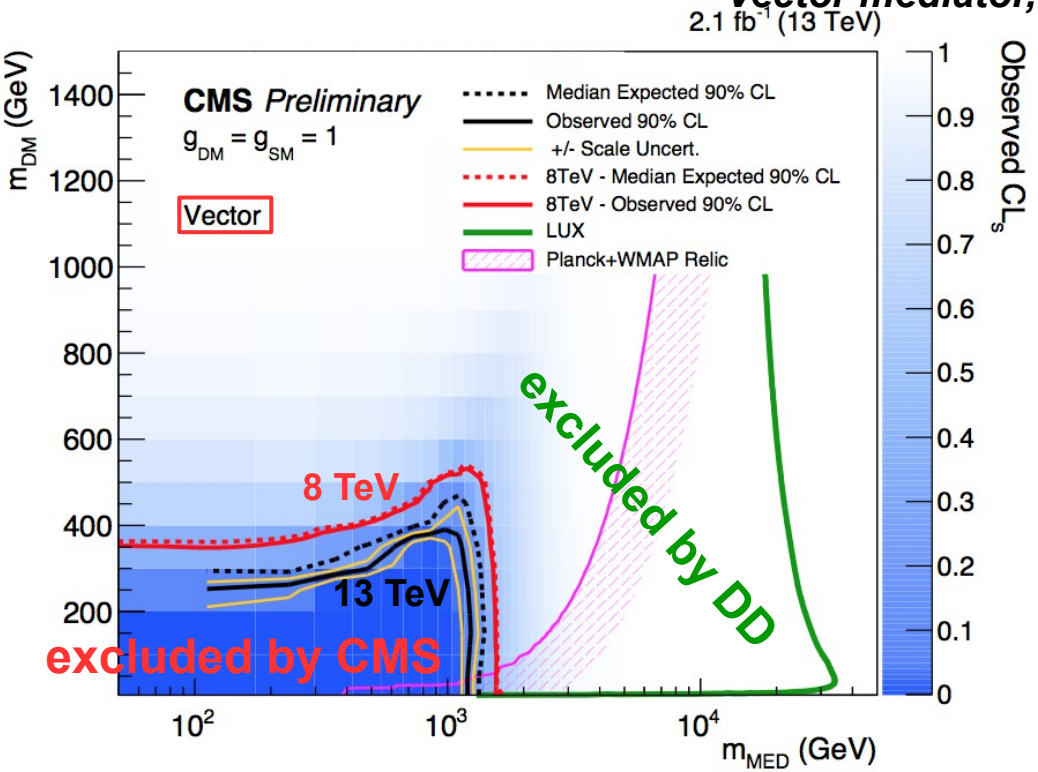


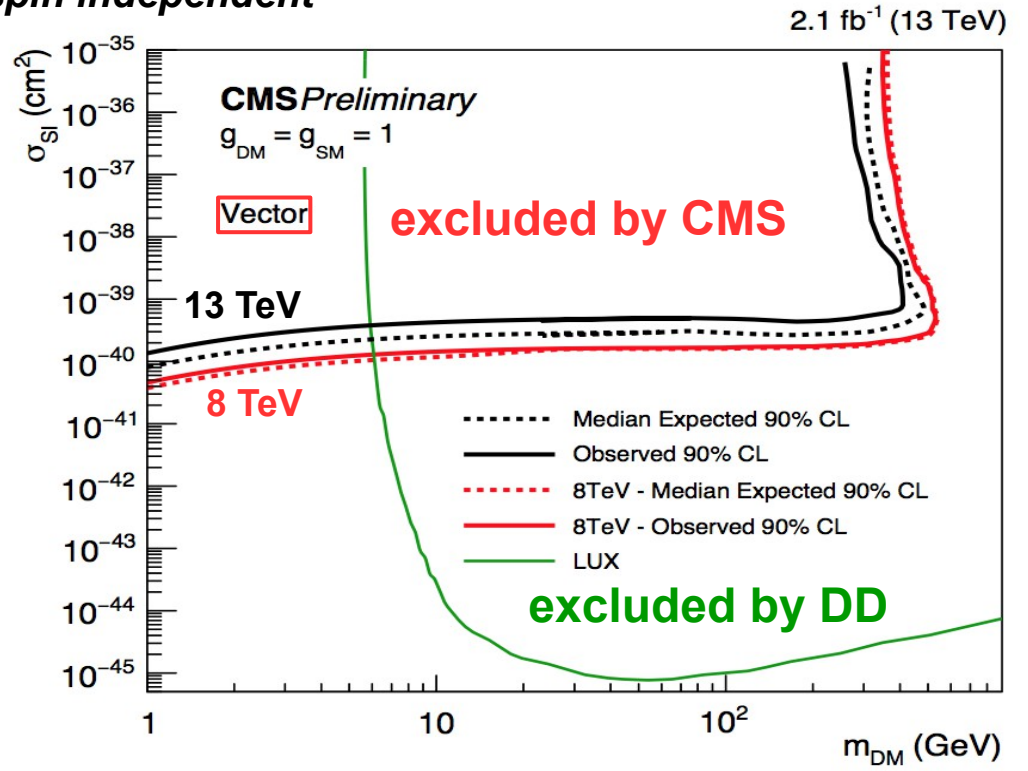
CMS-EXO-15-003

Monojet
First Results with 13 TeV Data

- The first 2.1 fb^{-1} of CMS data at 13 TeV have been analyzed in search of DM + jets
  - Only results for the monojet category are presented
- Limits from 13 TeV data are less stringent than those from 8 TeV data (~20 fb^{-1})
  - Same sensitivity at 13 TeV can be reached with ~5 fb^{-1}

Vector mediator, spin independent





Dark Matter + Dijet
Razor Variables

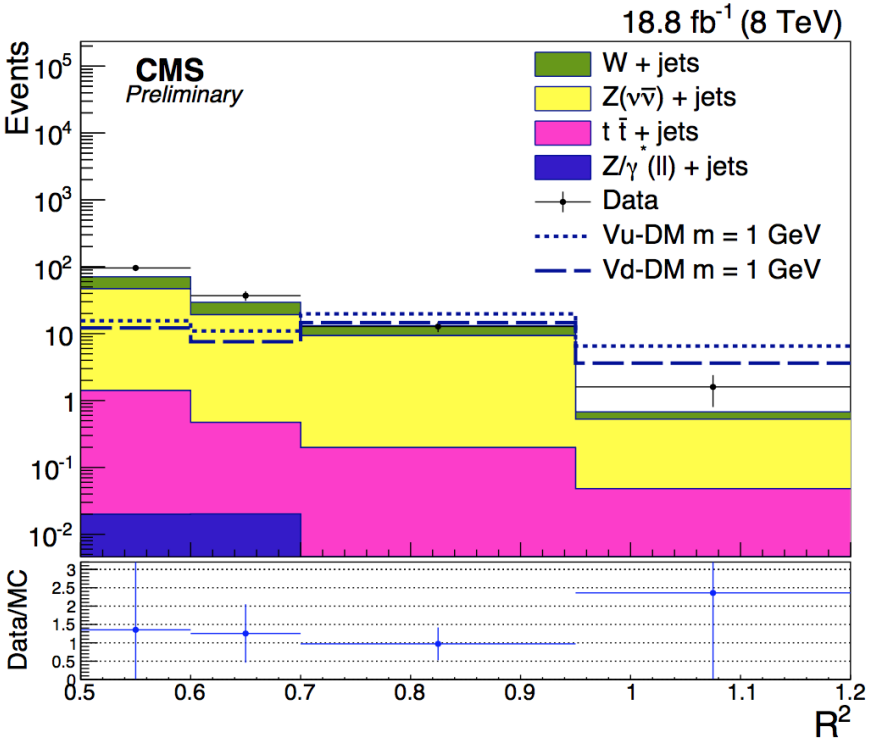
- Selects events with at least two central jets with p_T > 80 GeV and no leptons
  - if more jets are present, force the event into a dijet topology by iteratively clustering around the two highest-p_T jets ("megajets")
  - complementary selection w.r.t. monojet

- Lower cross section than monojet, but good discrimination against SM processes
  - Razor variables are defined

$$M_R = \sqrt{\left(|\vec{p}^{J1}| + |\vec{p}^{J2}|\right)^2 - \left(p_z^{J1} + p_z^{J2}\right)^2}$$

$$R = \frac{M_T^R}{M_R}, \text{ with}$$

$$M_T^R = \sqrt{\frac{E_T^{miss}\left(p_T^{J1} + p_T^{J2}\right) - \vec{p}_T^{miss}\cdot\left(\vec{p}_T^{J1} + \vec{p}_T^{J2}\right)}{2}}$$



- $Z(\nu\nu)$ + jets and $W(\ell\nu)$ + jets backgrounds constrained using control regions (events with 1 or 2 muons)

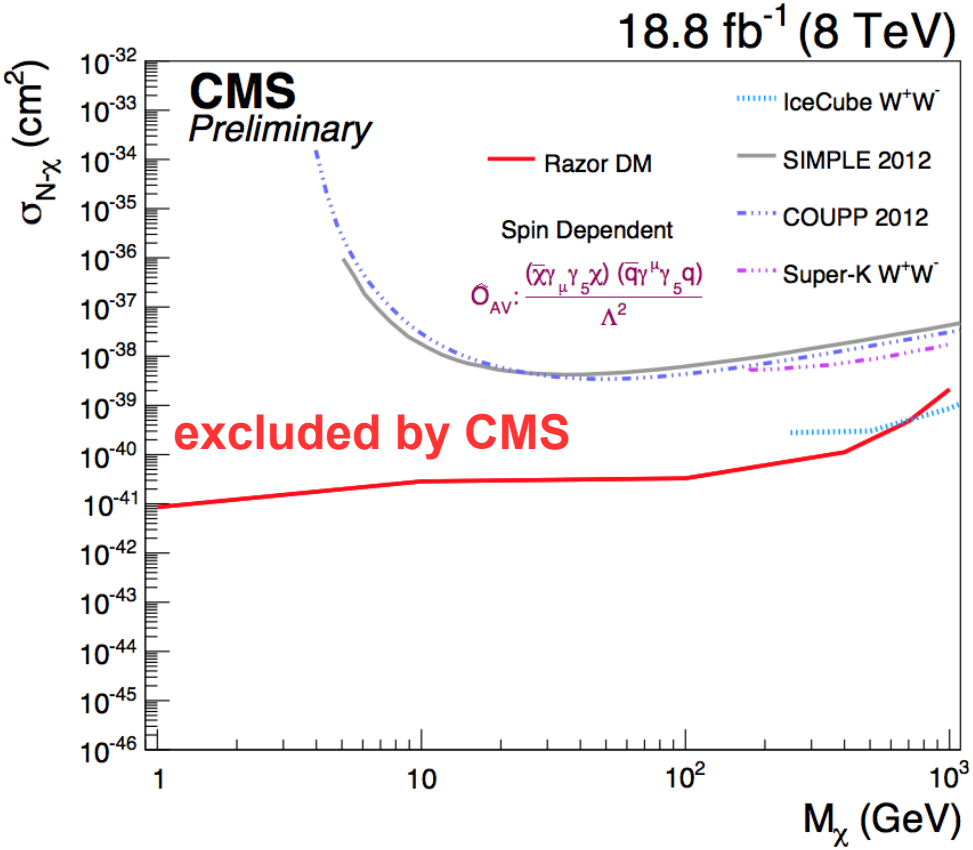
CMS-EXO-14-004

Dark Matter + Dijet

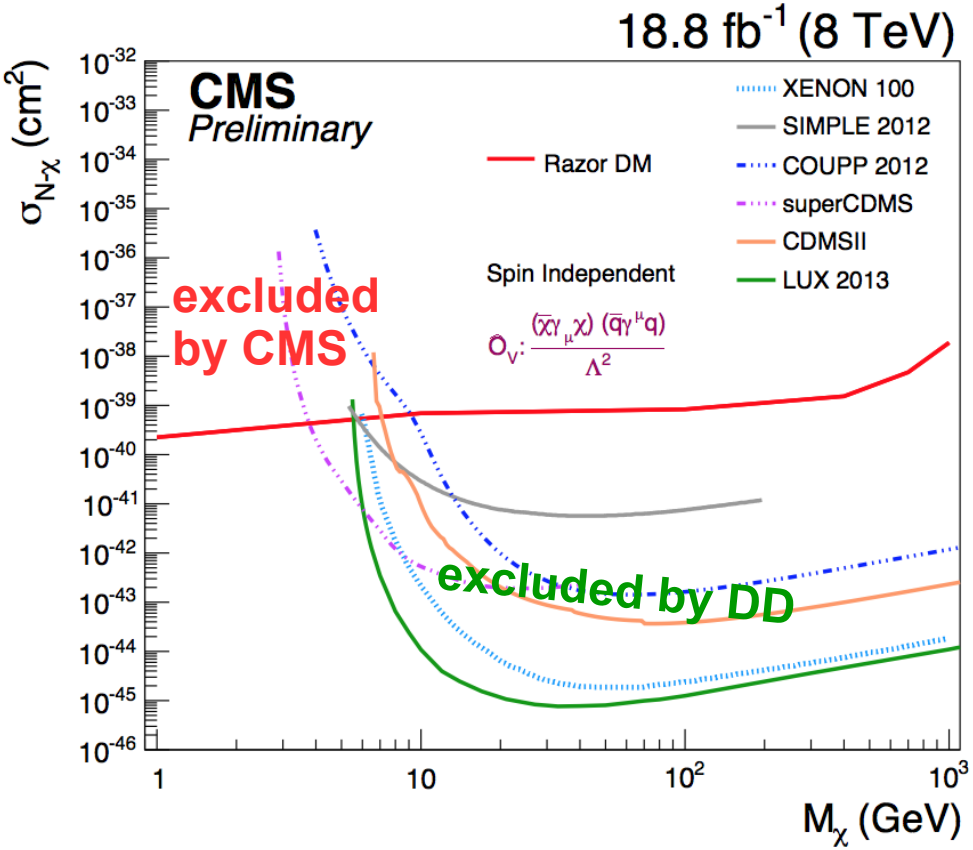
Limits on DM-Nucleon Scattering

- In the context of EFT, limits are set on the cutoff scale Λ and translated into limits on DM-nucleon scattering cross section
  - Sensitivity comparable to that of monojet analysis

Axial-vector mediator, spin dependent



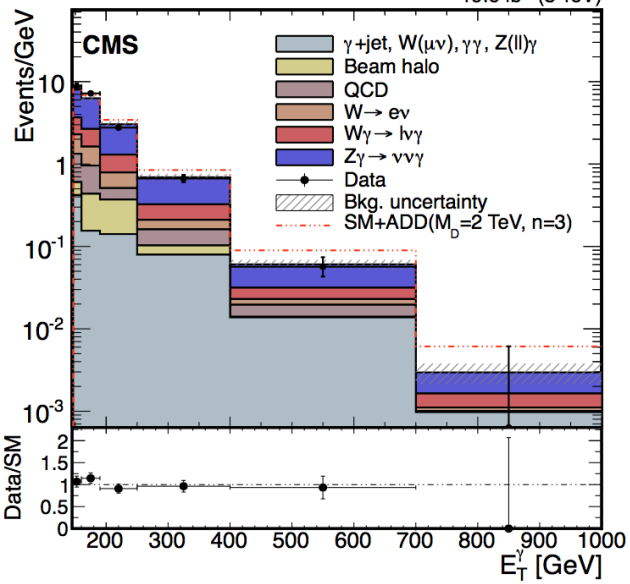
Vector mediator, spin independent

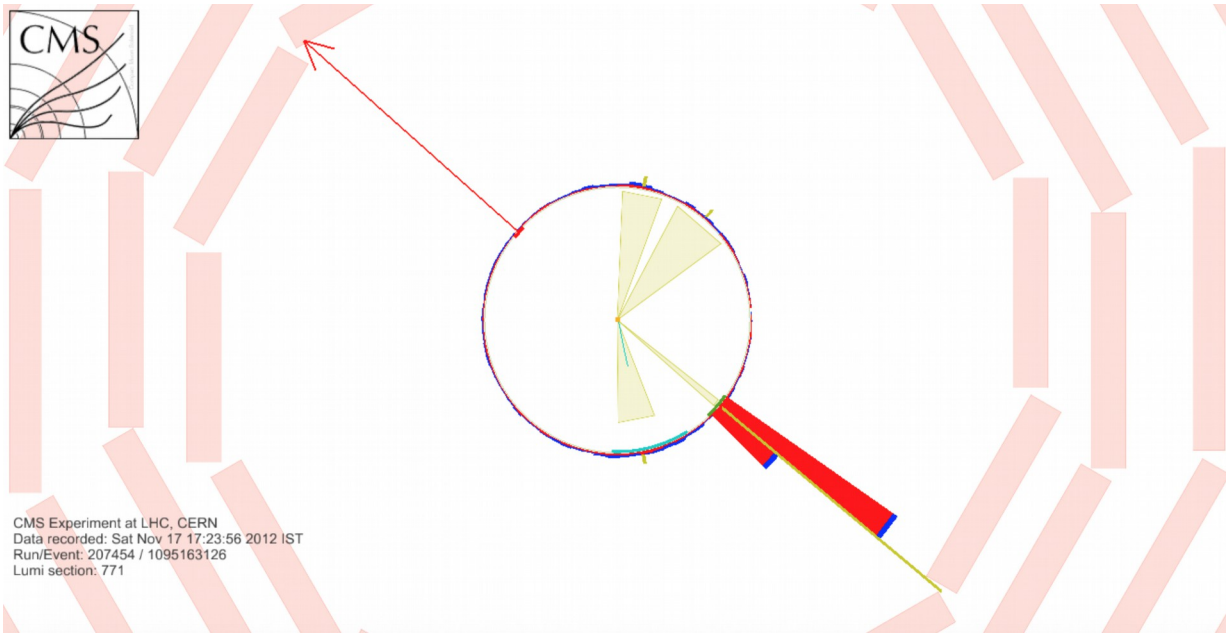


Dark Matter + Photon

Monophoton Analysis

- Similar production mechanism as in monojet, with a photon radiated by the initial-state partons
  - Lower cross section, but also lower backgrounds
  - Select events with
    - photon transverse energy E_T^{γ} > 145 GeV
    - E_T^{miss} > 140 GeV





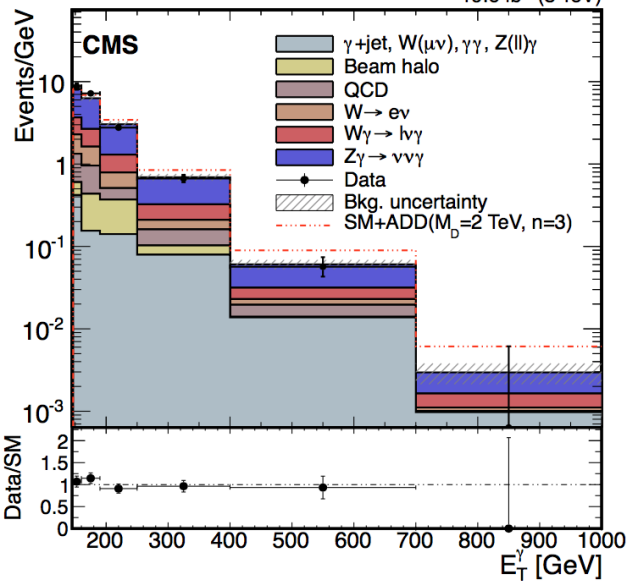
Photon + E_T^{miss} event

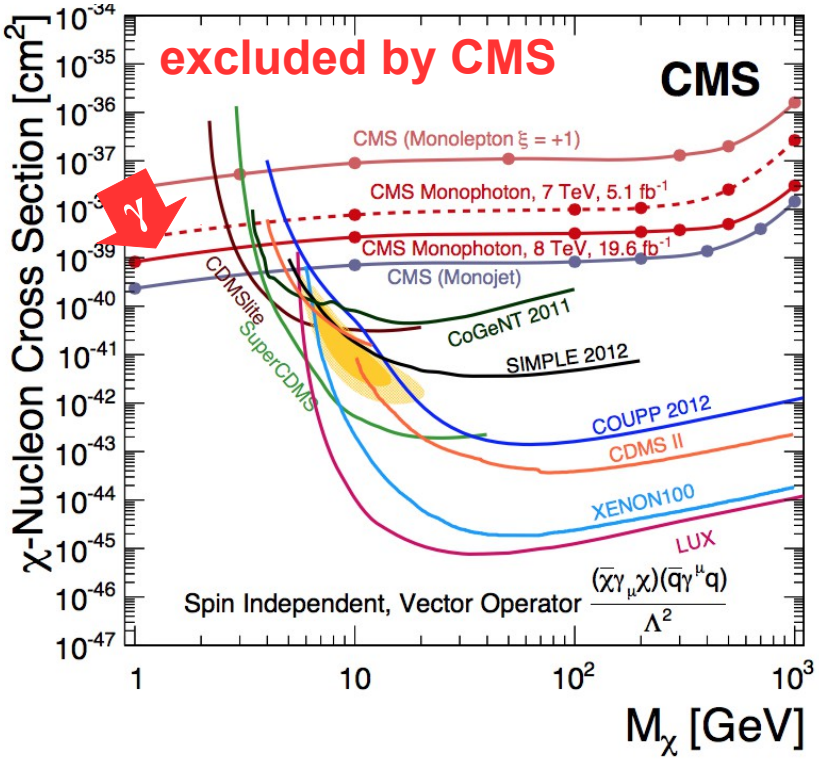
CMS-EXO-12-047

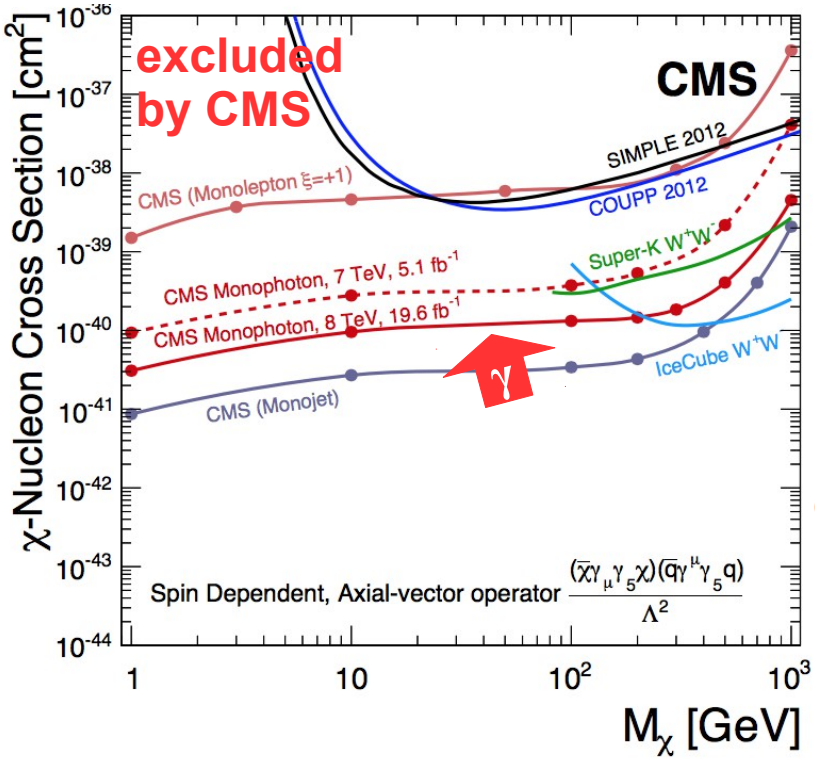
Dark Matter + Photon

Monophoton Analysis

- Similar production mechanism as in monojet, with a photon radiated by the initial-state partons
  - Lower cross section, but also lower backgrounds
  - Select events with
    - photon transverse energy E_T^{γ} > 145 GeV
    - E_T^{miss} > 140 GeV
- Fitting the E_T^{γ} spectrum, upper limits are set on DM production and translated into DM-nucleon scattering







CMS-EXO-12-047

Dark Matter + Leptons

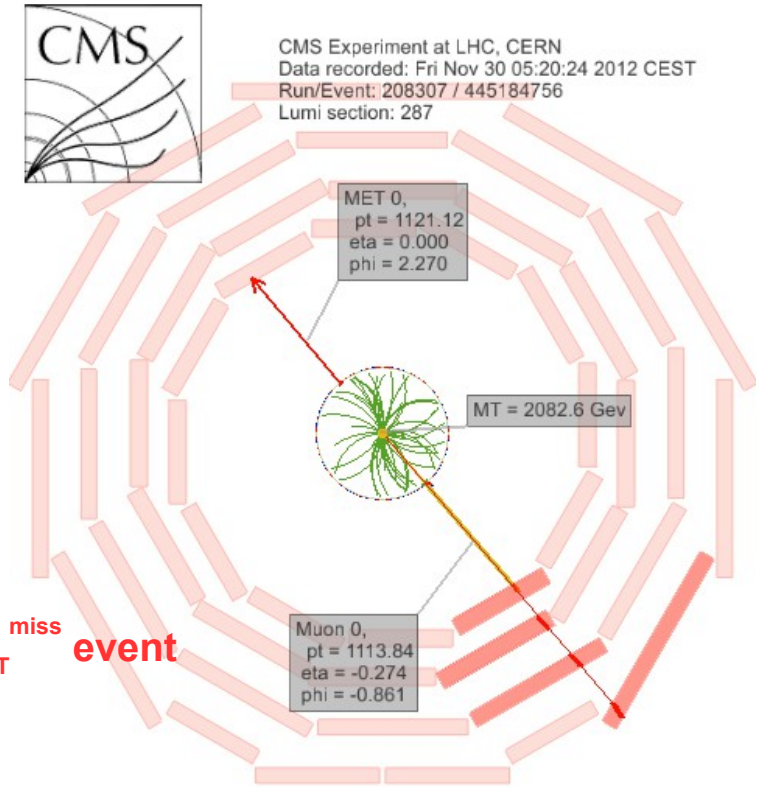
Mono-W($\ell\nu$) and Mono-Z($\ell\ell$)

- Lower rate than hadronic channels, but cleaner signature

PRD 91, 092005 (2015)
CMS-EXO-12-054

DM + W($\ell\nu$)

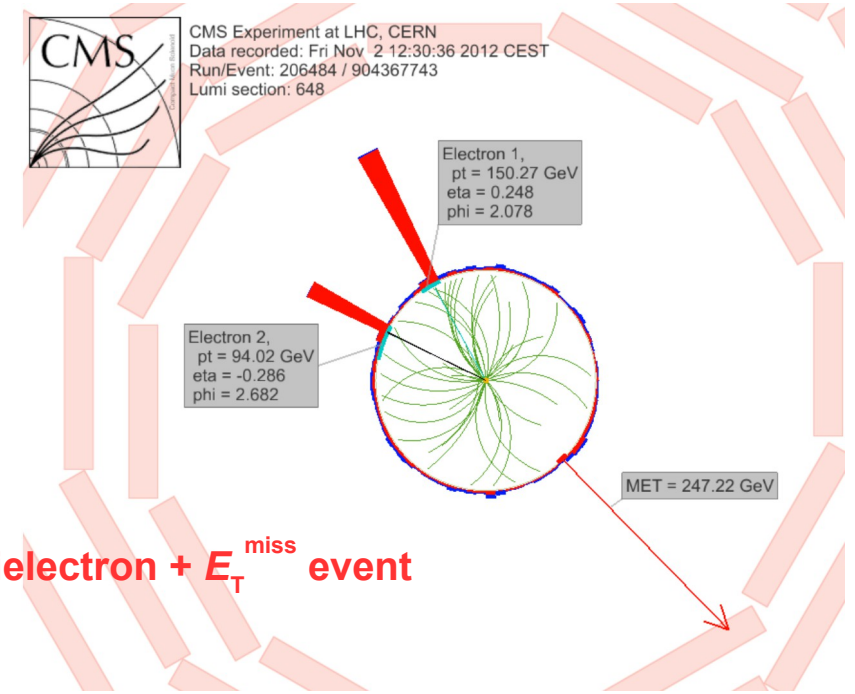
- exactly 1 isolated, high-p_T *e* or μ
- high E_T^{miss} with quality requirements and $E_T^{miss}/p_T(\ell)$ balance
- Main background from tails of $W \to \ell\nu$, estimated from simulation



Muon + E_T^{miss} event

DM + Z($\ell\ell$)

- exactly 2 isolated, opposite-sign *e* or μ with mass in $M_Z \pm 10$ GeV
- high E_T^{miss} with quality requirements and $E_T^{miss}/p_T(\ell\ell)$ balance
- Main background from $ZZ \to 2\ell 2\nu$ and $WZ \to 3\ell\nu$, estimated from simulation



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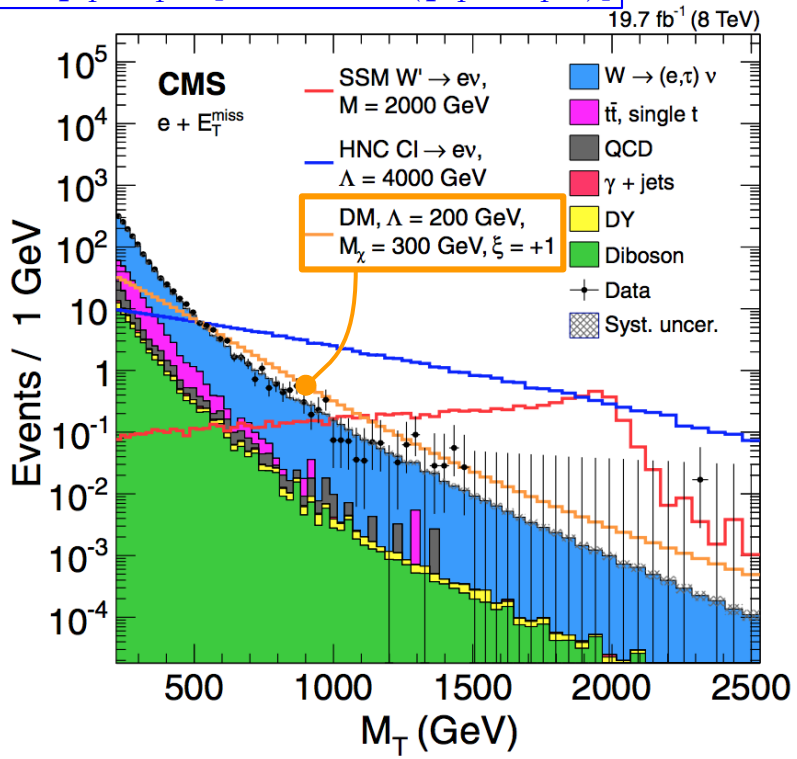
$$m_T = \sqrt{2\, p_T^{l(l)}\, E_T^{miss}\, [1-\cos\Delta\phi(p_T^{l(l)}, E_T^{miss})]}$$



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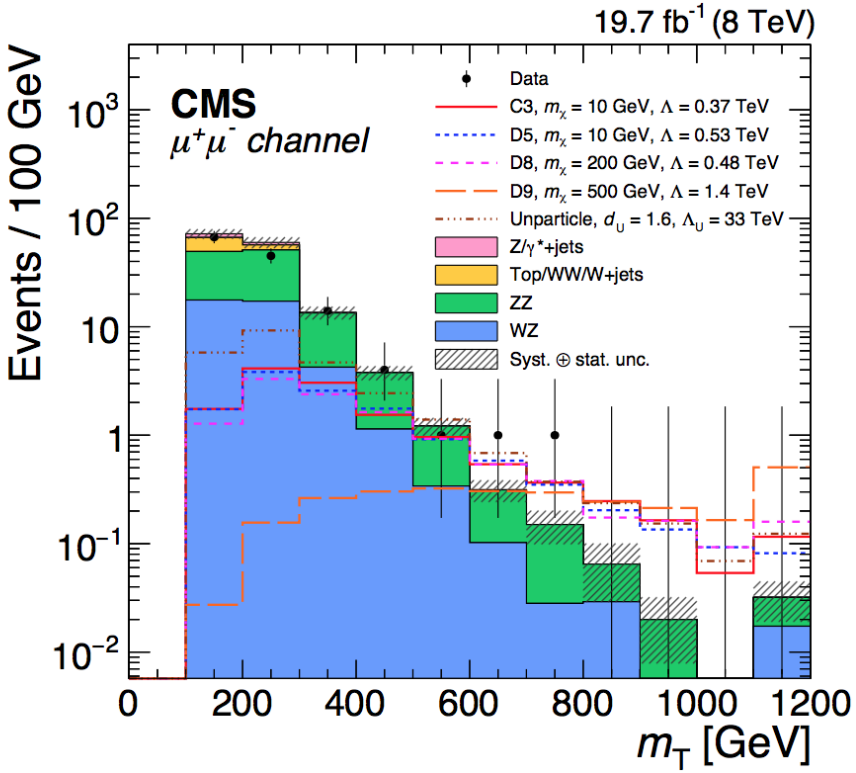
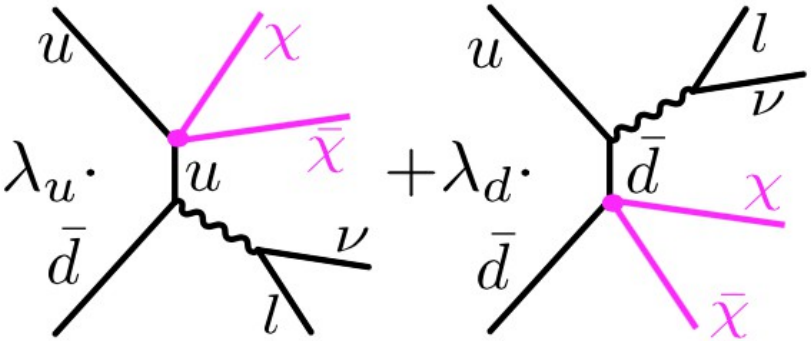


Dark Matter + Leptons

Interpretation of Results: Mono-W($\ell\nu$)

- The mono-W cross section is significantly affected by the interference between diagrams with DM-*u* and DM-*d* coupling
- Different interference scenarios are considered:

$$\xi = \lambda_u \cdot \lambda_d = -1,\ 0,\ +1$$



Dark Matter + Leptons

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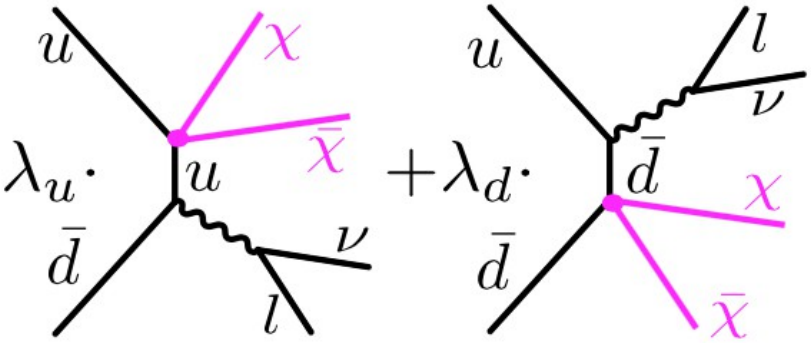
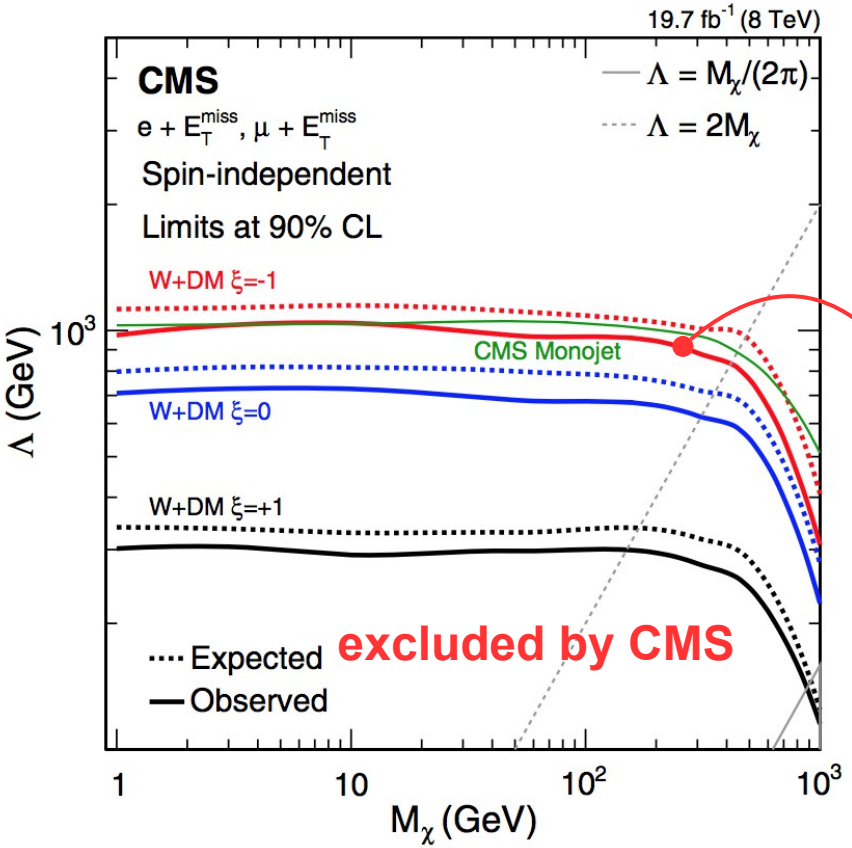
- Limits are set on the EFT parameter Λ for different signal models



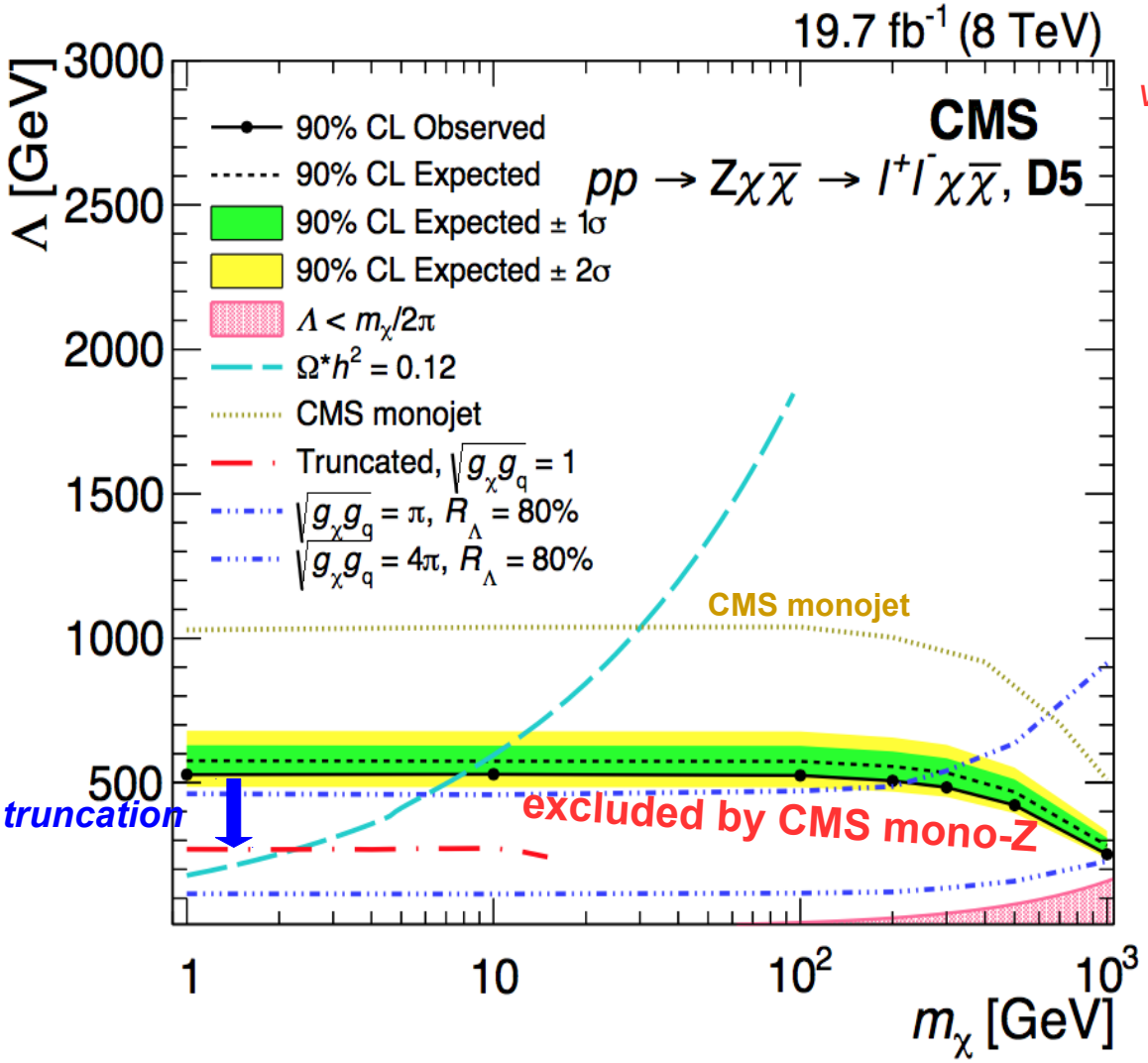


For constructive interference ($\xi = -1$) exclusion limits comparable with those from monojet

Dark Matter + Leptons

Interpretation of Results: Mono-Z($\ell\ell$)

- Limits on the EFT parameter Λ and the DM-nucleon cross section are computed for different mono-Z models



vector, spin-independent coupling

Truncated limits *(red dashed line)*

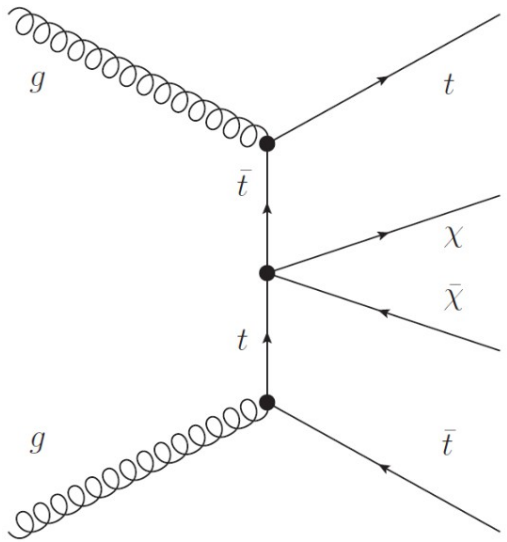
→ *significant reduction in sensitivity*

Dark Matter + Top Quarks

Top-Quark Pairs

- DM + top pair production dominates in case of scalar coupling ~ $\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$

- Select semi-leptonic events: $t\bar{t} \rightarrow b\ell\nu + \bar{b}q\bar{q}$
  - exactly 1 lepton
  - ≥ 3 jets, at least 1 b-tagged
  - E_T^{miss} > 320 GeV
  - specific kinematic cuts to suppress $t\bar{t}$ events



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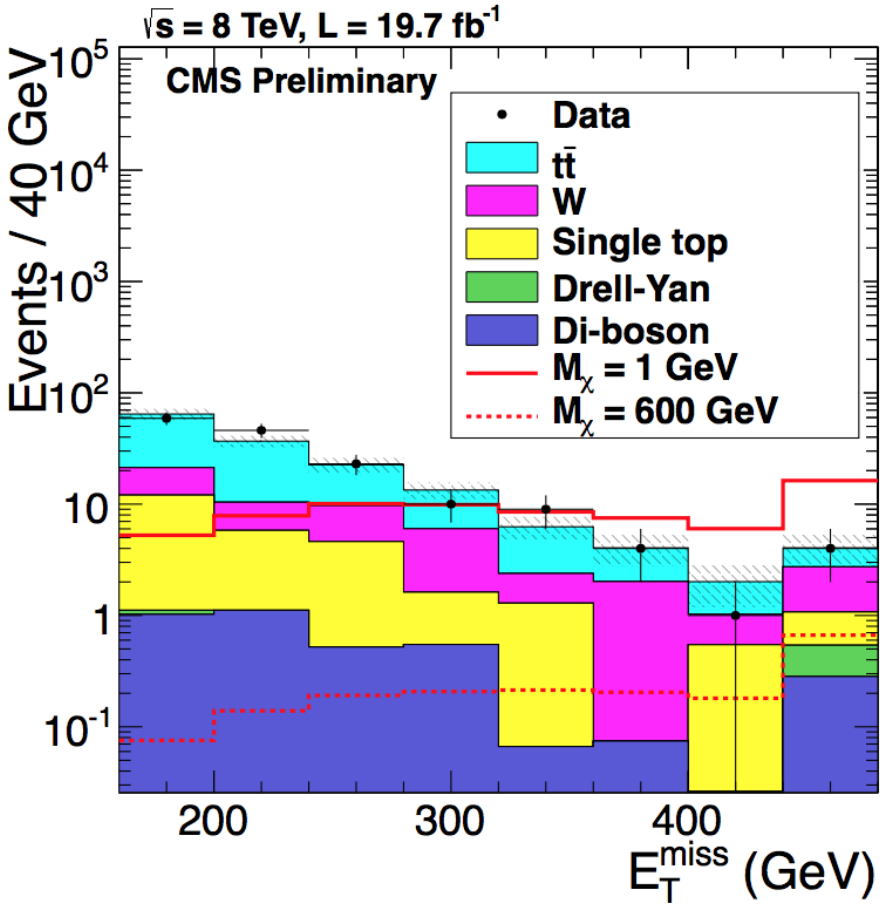


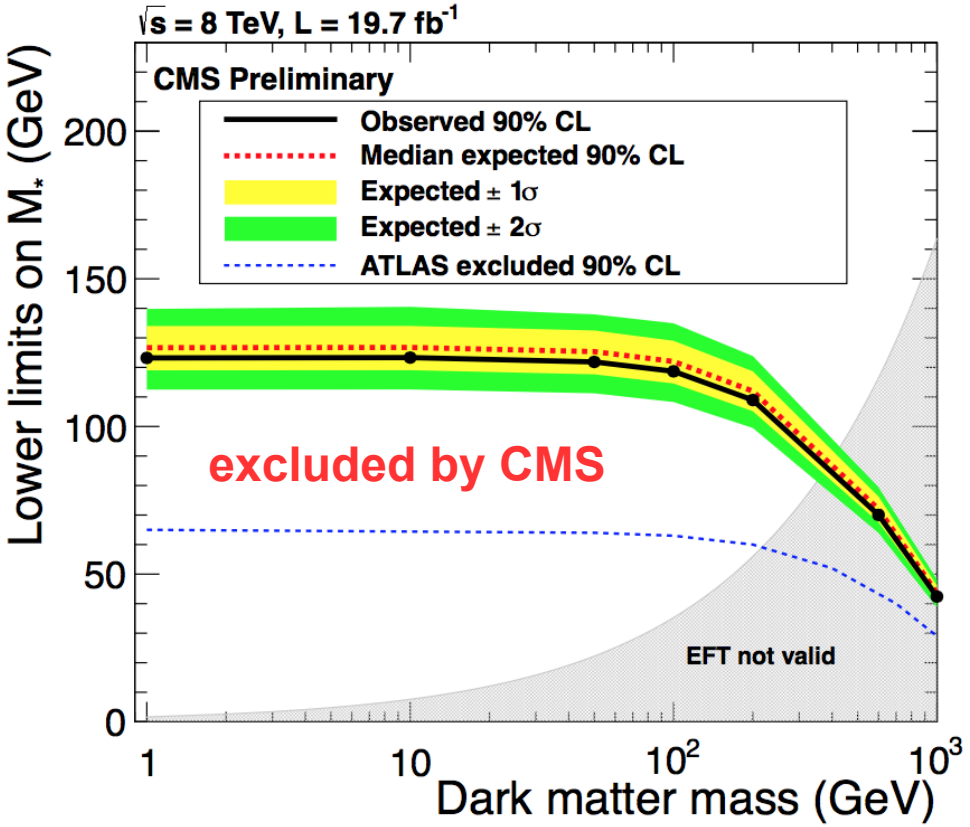
Dark Matter + Top Quarks

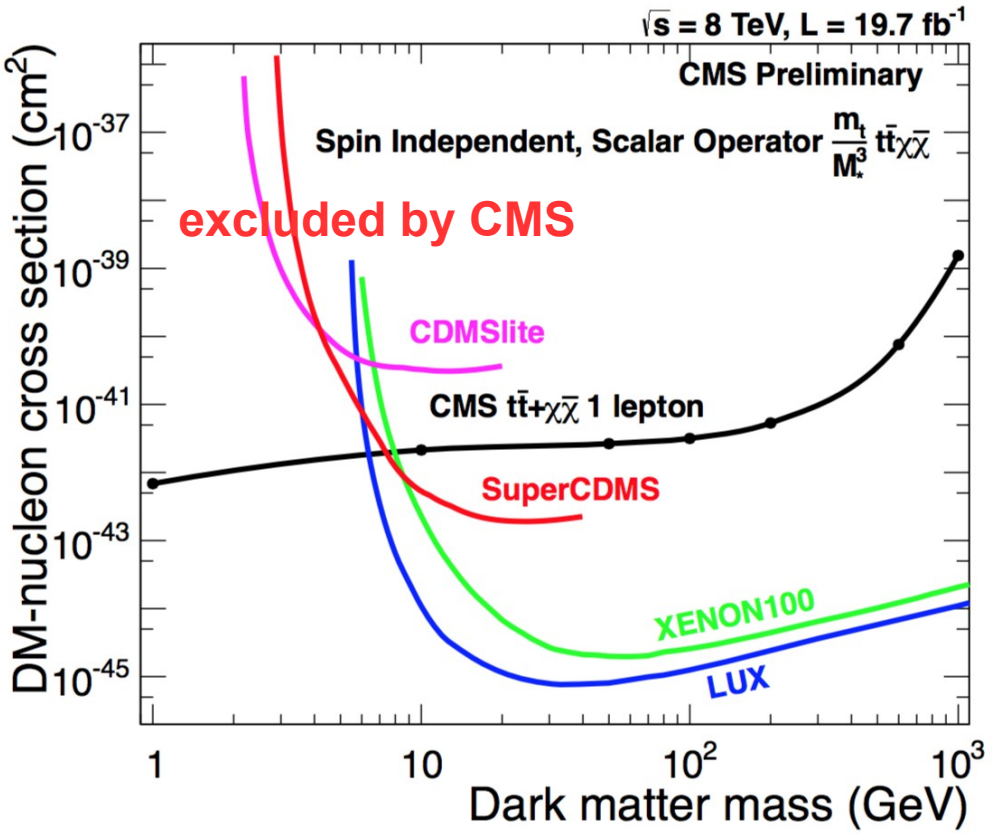
Top-Quark Pairs: Interpretation

- Results are interpreted in the context of EFT with scalar coupling: then translated into DM-nucleon cross section limits

$$L_{\text{int}} = \frac{m_q}{\Lambda^3} \bar{\chi}\chi\bar{q}q$$

  - strong cross section limits owing to the Λ^3 dependence

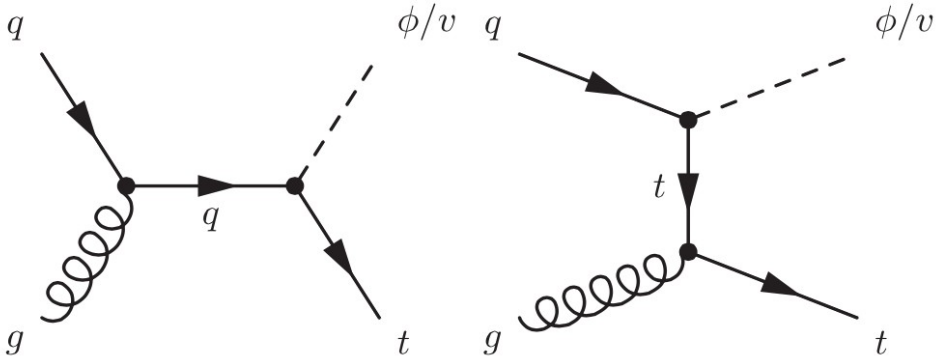


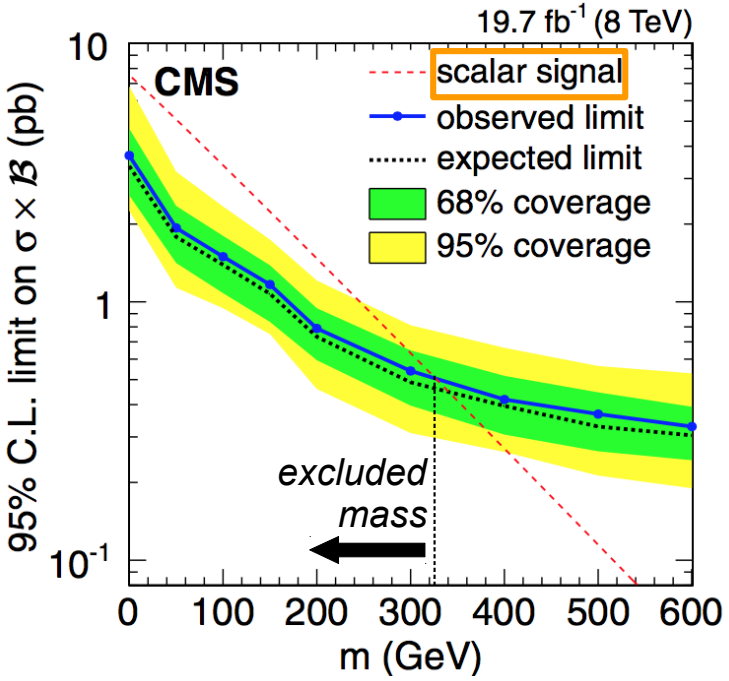


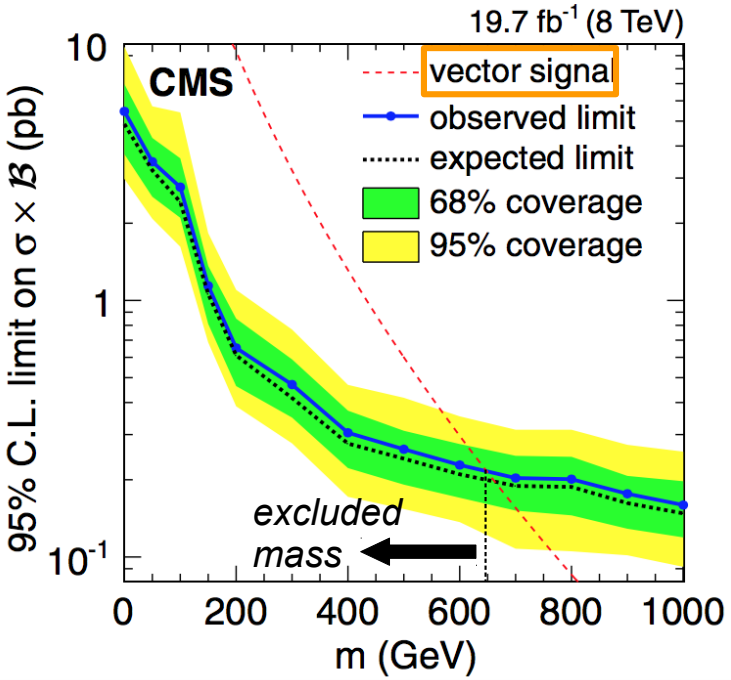
Dark Matter + Top Quarks

Mono-Top

- Single top + E_T^{miss} signatures predicted by several models
- Focus on a model with a flavor-changing interaction mediated by an invisible boson
- Selection hadronic final states
  - three jets, no isolated leptons, E_T^{miss} > 350 GeV
- Invisible bosons excluded for masses below 330 GeV (scalar) or 650 GeV (vector)





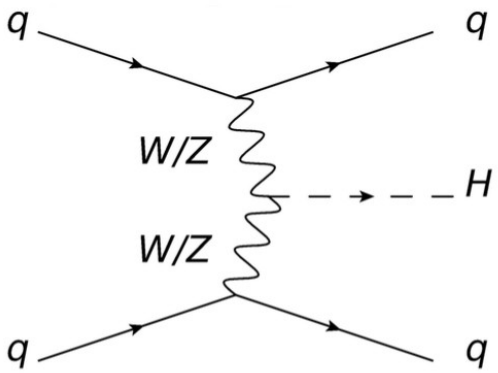


PRL 114, 101801 (2015)

Dark Matter in Higgs-Portal Models

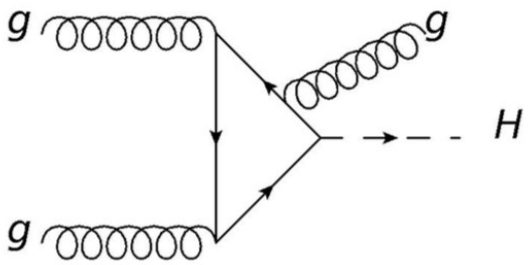
- In Higgs-portal models of DM, a Higgs boson is the only mediator between DM and SM sectors
  - the Higgs can be produced with SM cross section, but have a significant branching fraction to DM particles (B_{inv})

- The Higgs must be produced in association with a visible system
  - several channels considered and combined

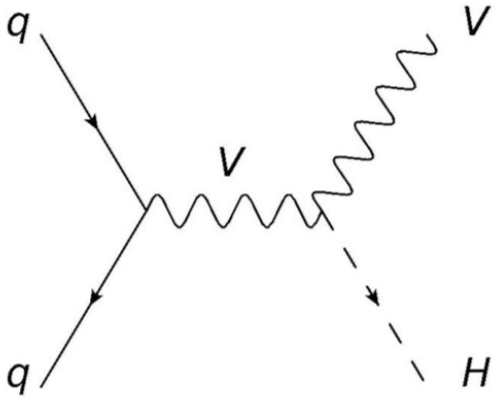


Vector Boson Fusion (VBF)

2 forward jets with large η separation and invariant mass



Monojet



"Higgs-strahlung"

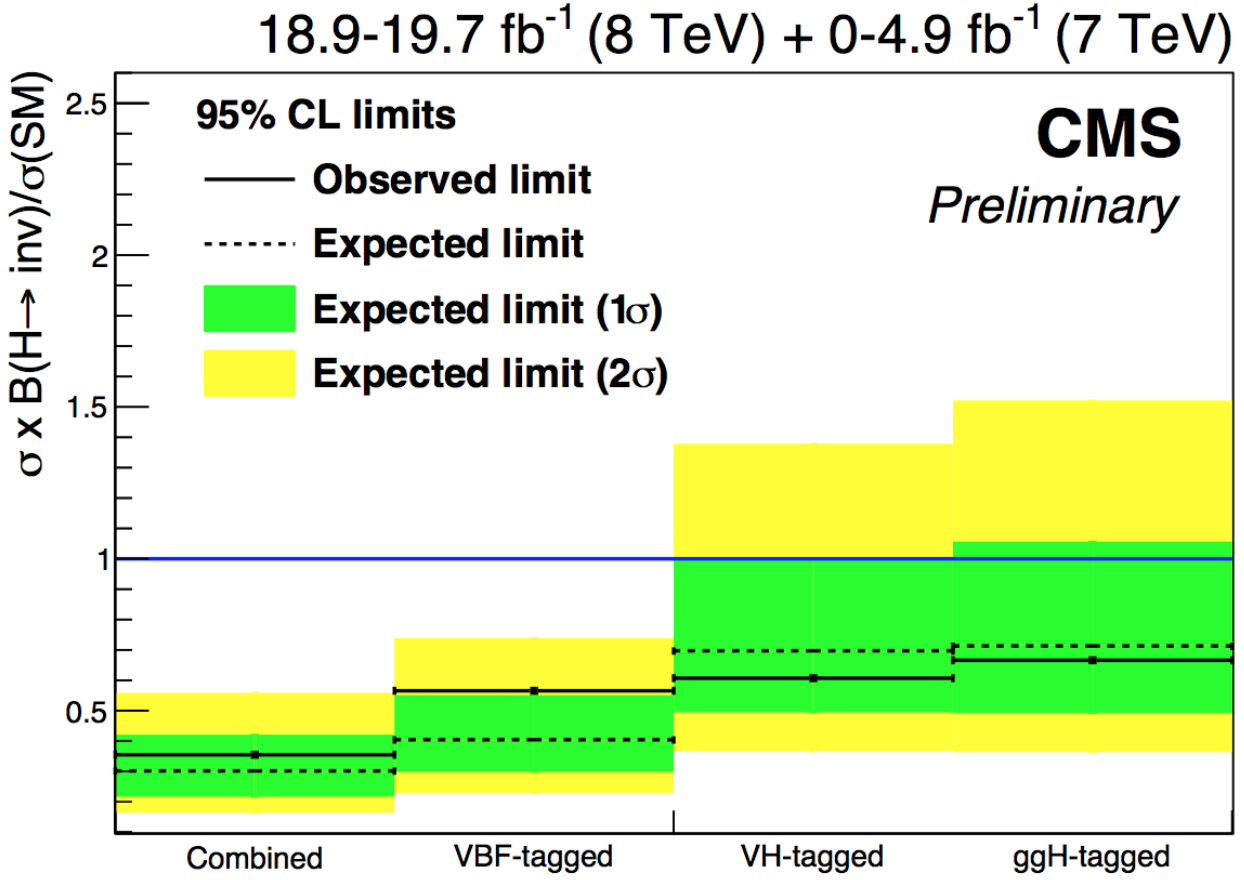
$W \to q\bar{q}'$, $Z \to q\bar{q} / \ell^+\ell^- / b\bar{b}$

EPJC 74, 2980 (2014)

CMS-PAS-HIG-15-012

Dark Matter in Higgs-Portal Models

- With no deviations from SM expectations, upper limits can be set on $\sigma \cdot B_{inv}/\sigma_{SM}$
  - If the Higgs boson is produced with SM cross section, these can be interpreted as limits on the invisible branching fraction B_{inv}



m_H = 125 GeV

B_{inv} < 0.36

Summary and Prospects

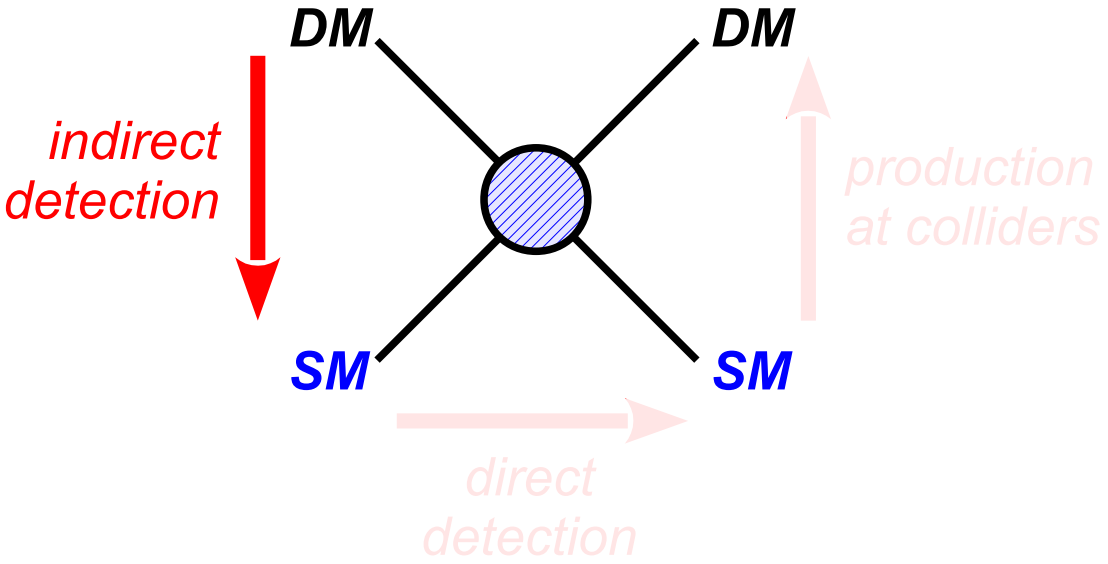
- *CMS has performed a variety of searches for signals of DM in Run-1 data*
  - X + E_T^{miss}, where X can be 1 or more jets, photons, W or Z bosons, top quarks, etc.
  - Advanced techniques used for signal selections and background control (razor variables, jet substructure, multivariate analyses, etc.)
  - No indications of DM so far
- *Interpretation of the data has relied mainly on EFT models*
  - Analyses are now switching to simplified models for Run-2, according to the recommendations of the LHC DM Forum
  - Monojet and V(had)-tagged analyses used simplified models also in Run-1
- *CMS results were compared with direct-detection experiments and proved complementary, especially improving at low DM masses and in spin-dependent scenarios*
- *Run-2 is already here!*
  - CMS collected about 2.1 fb^{-1} good collision data in 2015
  - About 5 fb^{-1} are necessary to reach the same sensitivity as in Run-1

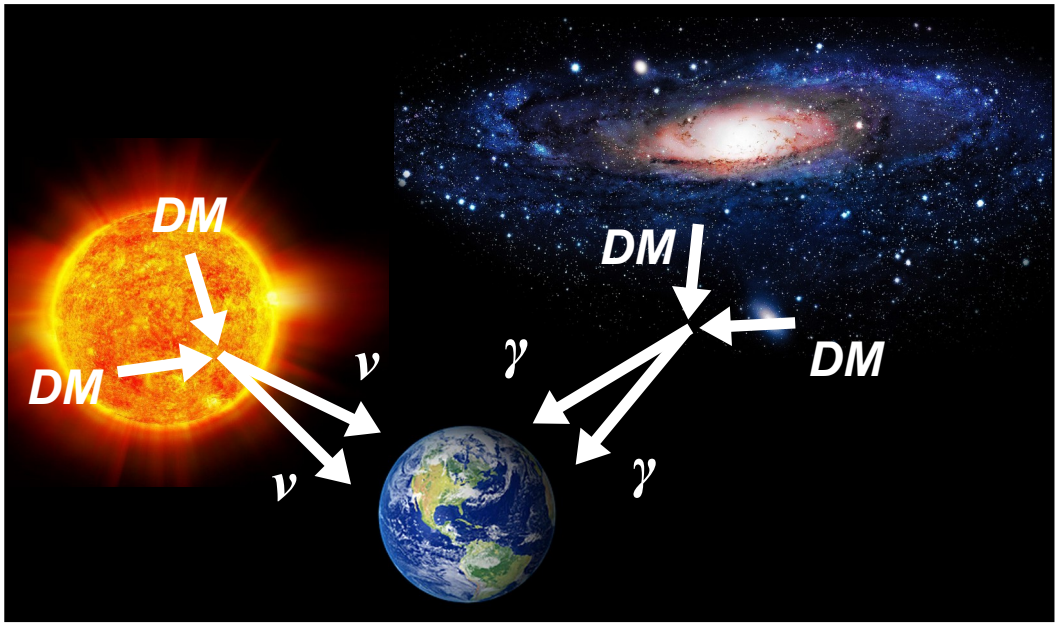
Backup

Outline

- Introduction
  - Motivations
  - Dark Matter at the LHC
- Dark Matter Searches at CMS
  - Channels with jets
  - Channels with photons
  - Channels with leptons (from W or Z bosons)
  - Channels with heavy-flavor quarks
  - Dark matter through “Higgs-portal”
- Future prospects and conclusions

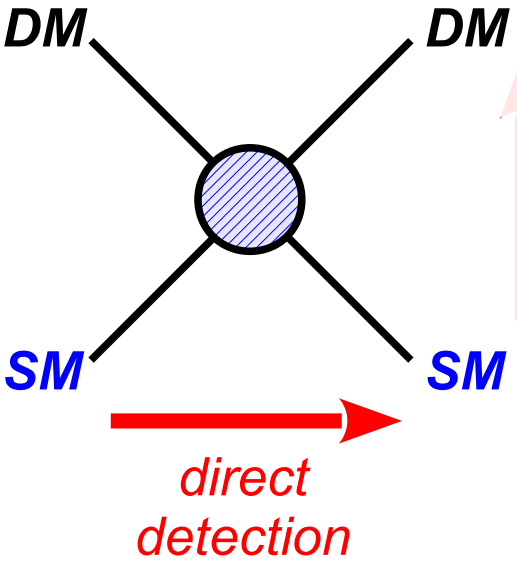
Dark Matter detection (I)

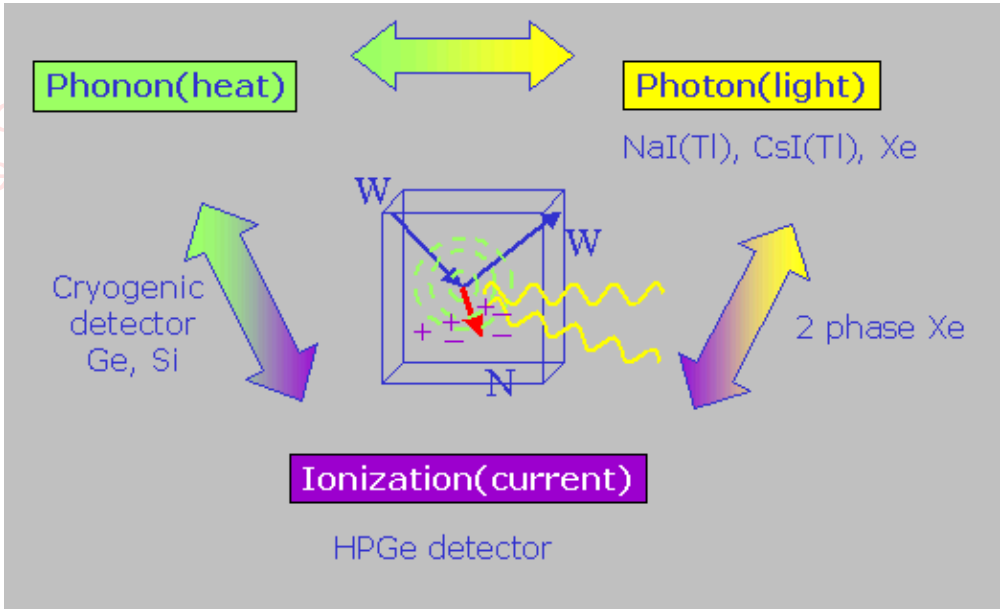




- Indirect detection
  - look for WIMP-annihilation decay products from far-away locations where DM is expected to accumulate (e.g. center of galaxies, Sun)
    - excess gamma rays, neutrinos
  - large backgrounds, difficult estimation

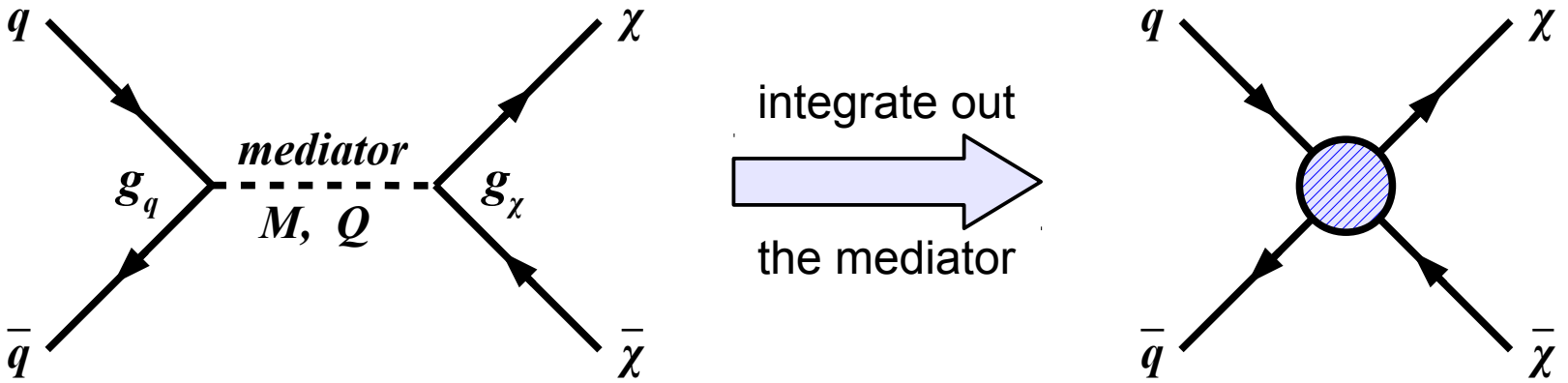
Dark Matter detection (II)





- Direct detection
  - measure nucleus recoil from DM-nucleus collisions when DM "flows" through the detector
    - most experiments detect scintillation light or temperature variations
    - ionization current helps separate the backgrounds
  - very low signal rate (few events/kg/year) and collision energy (~10 keV)

Effective Field Theories of DM



- If $M^2 \gg Q^2$, the cross section does not depend on Q/M:

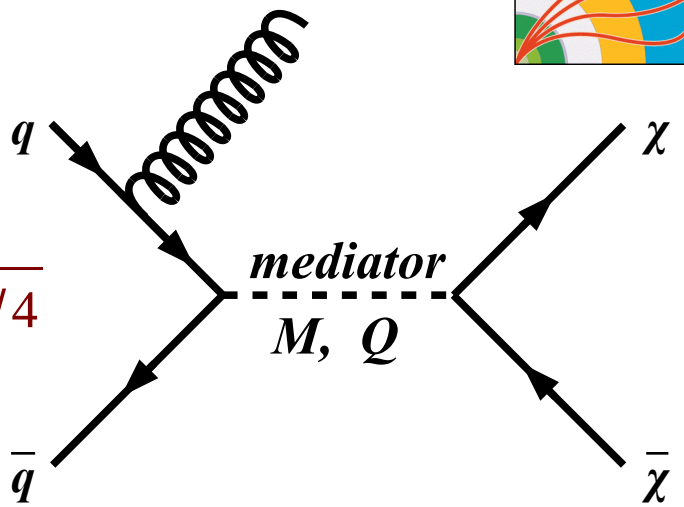
$$\frac{g_\chi g_q}{Q^2 - M^2} = -\frac{g_\chi g_q}{M^2}\left(1 + \frac{Q^2}{M^2} + O\left(\frac{Q^4}{M^4}\right)\right) \simeq -\frac{g_\chi g_q}{M^2} = \frac{1}{M_*^2}$$

- The EFT is determined by
  - DM candidate mass: m_χ
  - cut-off scale of the model: $M_* = \dfrac{M}{\sqrt{g_\chi g_q}}$
  - nature of the coupling

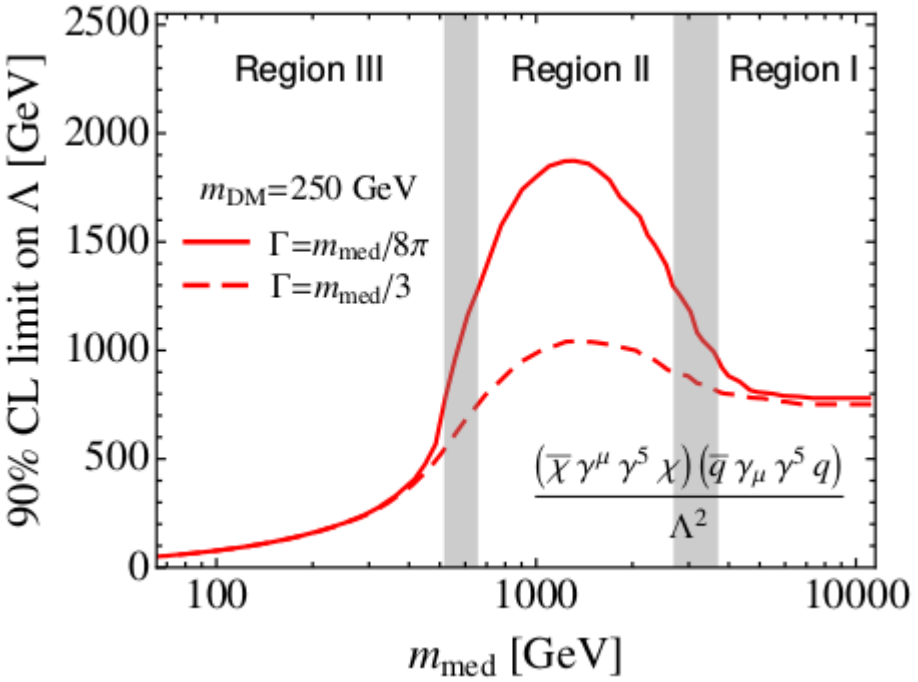
Validity of EFT

- EFT are valid if $M^2 \gg Q^2$
- What happens elsewhere?

$$\frac{g_\chi^2 g_q^2}{\left(Q^2 - M^2\right)^2 + \Gamma^2/4}$$



arXiv:1308.6799



Three regions of mediator mass M

- **Region I:** heavy M

  EFT results consistent with simplified model with mediator

- **Region II:** medium M ($M^2 \sim Q^2$)

  EFT has smaller cross section than simplified model ⇒ conservative limits

- **Region III:** light M ($M \lesssim 2m_\chi$)

  EFT has larger cross section than simplified model ⇒ limits too optimistic

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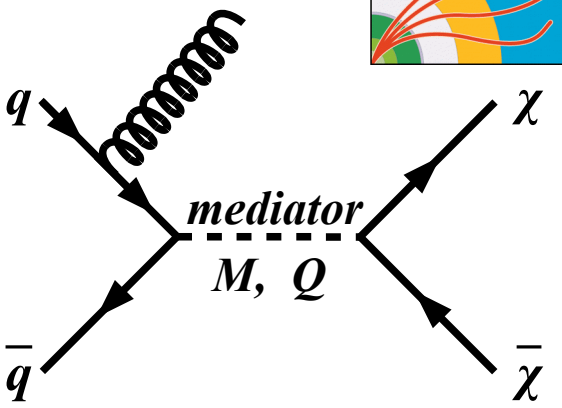
- What happens elsewhere?

$$\frac{g_\chi g_q}{Q^2 - M^2} \simeq -\frac{g_\chi g_q}{M^2} \equiv \frac{1}{\Lambda^2}$$



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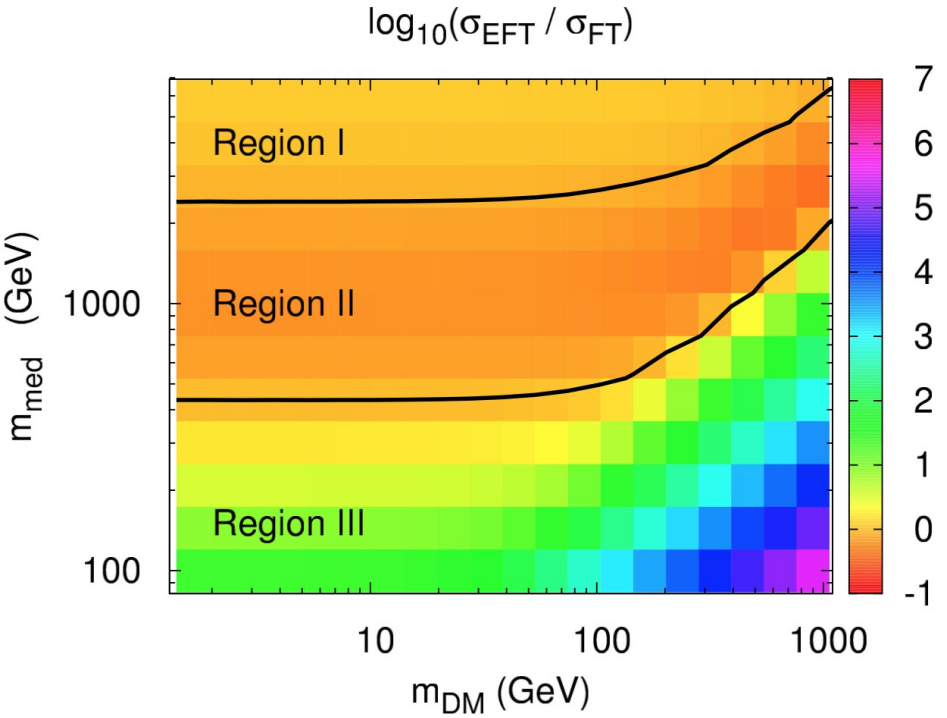

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EFT Accuracy and Truncation

- Kinematic and perturbativity requirements lead to a minimal constraint on the cutoff scale of the EFT:

$$\Lambda > m_\chi / (2\pi) \quad \rightarrow \textit{necessary, but not sufficient condition}$$

- More realistic requirements can be imposed on the transferred momentum:

$$Q_{\mathrm{tr}} < M_{\mathrm{med}} \sim \Lambda \cdot \sqrt{g_\chi g_q}$$

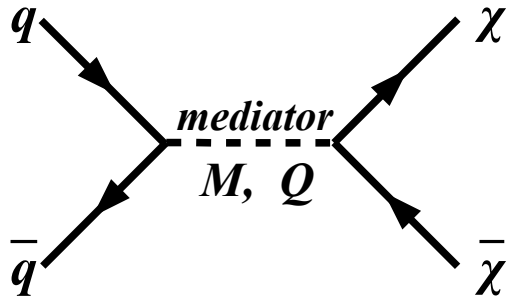
- Two possible approaches:
  - Define regions of accuracy of the EFT based on the fraction of events satisfying the condition above, R_Λ (e.g. $R_\Lambda > 80\%$):

$$R_\Lambda = \frac{\int_{p_{\mathrm{T}}^{\mathrm{min}}}^{p_{\mathrm{T}}^{\mathrm{max}}} \mathrm{d}p_{\mathrm{T}} \int_{\eta^{\mathrm{min}}}^{\eta^{\mathrm{max}}} \mathrm{d}\eta \frac{\mathrm{d}^2\sigma_{\mathrm{eff}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}\Big|_{Q_{\mathrm{tr}} < \sqrt{g_q g_\chi}\Lambda}}{\int_{p_{\mathrm{T}}^{\mathrm{min}}}^{p_{\mathrm{T}}^{\mathrm{max}}} \mathrm{d}p_{\mathrm{T}} \int_{\eta^{\mathrm{min}}}^{\eta^{\mathrm{max}}} \mathrm{d}\eta \frac{\mathrm{d}^2\sigma_{\mathrm{eff}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}}$$

  - In computing limits on EFT, remove signal events that do not satisfy the condition (for a given value of $\sqrt{g_\chi g_q} < 4\pi$, e.g. $\sqrt{g_\chi g_q} = 1$) $\rightarrow$ *truncated limits*, more conservative

EFT Validity and Truncation

- EFT are reliable only if $M^2 \gg Q^2$



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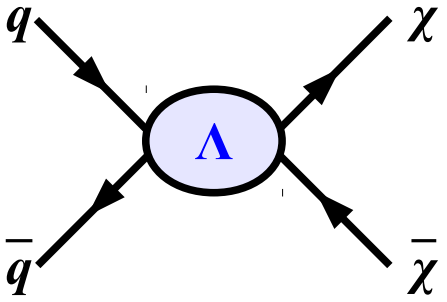


- This is not always true at LHC energies!
- To assess the accuracy of the EFT description, we can impose $Q < M \sim \Lambda \cdot \sqrt{g_\chi g_q}$
- Two possible approaches:

(1) Define regions of EFT accuracy based on the fraction of events satisfying the condition above, R_Λ

$$R_\Lambda = \frac{\int_{p_T^{min}}^{p_T^{max}} dp_T \int_{\eta^{min}}^{\eta^{max}} d\eta \frac{d^2\sigma_{eff}}{dp_T d\eta}\Big|_{Q_{tr} < \sqrt{g_q g_\chi}\Lambda}}{\int_{p_T^{min}}^{p_T^{max}} dp_T \int_{\eta^{min}}^{\eta^{max}} d\eta \frac{d^2\sigma_{eff}}{dp_T d\eta}}$$

(2) When computing limits, remove signal events that do not satisfy the condition → *truncated limits*

Effective Field Theories of DM

- Examples of EFT operators (assuming DM particle χ is a Dirac fermion)
  - spin-independent: scalar (D1) $\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$ vector (D5) $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
  - spin-dependent: axial vector (D8) $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$ tensor (D9) $\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$

- These operators can be translated into DM-nucleon cross sections for comparison with results from direct-detection experiments, e.g.

$$\sigma^{D5} = \frac{\mu^2}{\pi\Lambda^4}\sum_q \left(f_q^N\right)^2 \qquad \sigma^{D9} = \frac{3\mu^2}{\pi\Lambda^4}\sum_q \left(\Delta_q^N\right)^2$$

Δ_q^N $\left(f_q^N\right)$: spin-(in)dependent nucleon form factors

- Similarly, they can be translated into annihilation rates $\langle\sigma v_{rel}\rangle$ for comparison with indirect-detection experiments

Dark Matter + Jets

Event Categories

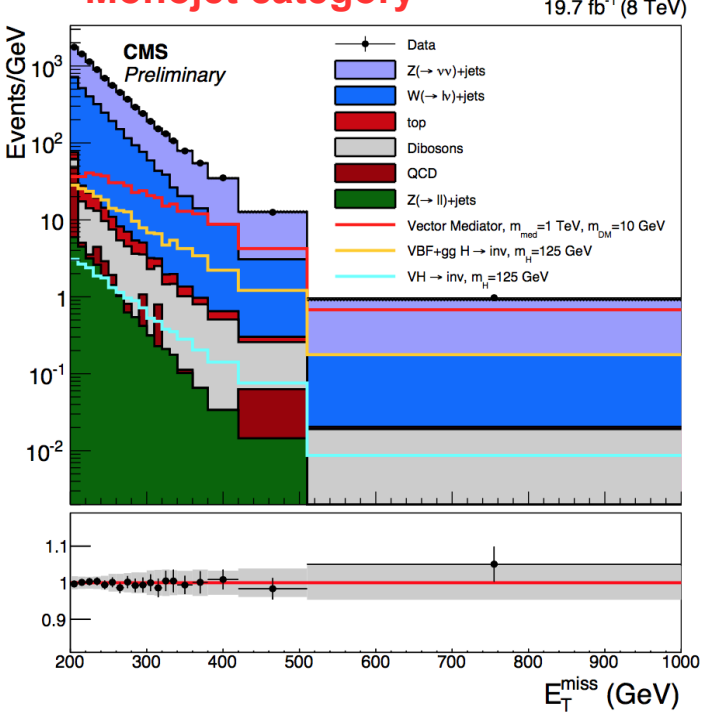
- Events are split into 3 exclusive categories
  - Boosted V → the two jets are reconstructed as a single “fat” jet
    - 1 central jet with p_T > 250 GeV and mass = 60-110 GeV
    - jet-substructure techniques → likelihood of originating from 2 jets
  - Resolved V → low-p_T V boson, the two jets can be fully reconstructed
    - 2 central jets with p_T > 30 GeV and mass = 60-110 GeV
    - multivariate techniques using properties of the jets and dijet system:
      jet quark-gluon likelihood, color-flow variables, jet and dijet masses and opening angle, etc.
  - Monojet → all events excluded from the previous categories
    - at least 1 central jet with p_T > 150 GeV
    - veto on events containing leptons or photons

Dark Matter + Jets
Background Estimation

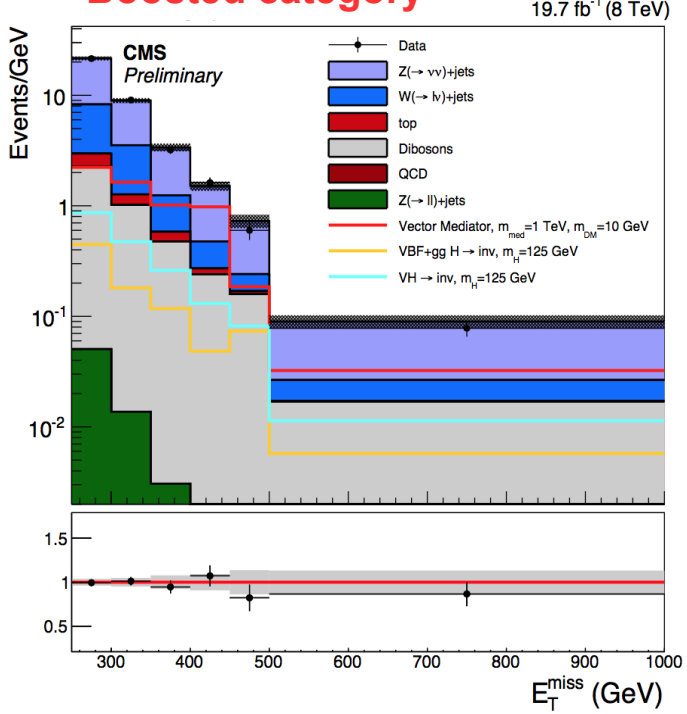
- Dominant backgrounds $Z(\nu\nu)$ + jets and $W(\ell\nu)$ + jets (when ℓ is missed) are estimated from control regions in data
  - **$Z(\nu\nu)$ + jets:** from **$Z(\mu\mu)$ + jets** and **γ + jets** samples
  - **$W(\ell\nu)$ + jets (lost ℓ):** from a **$W(\ell\nu)$ + jets** with **identified ℓ**

- Transfer factors from control regions to signal regions are estimated in simulation
- Corrections to $Z(\nu\nu)$ and $W(\ell\nu)$ are computed in E_T^{miss} bins
  - both normalization and shape are corrected!

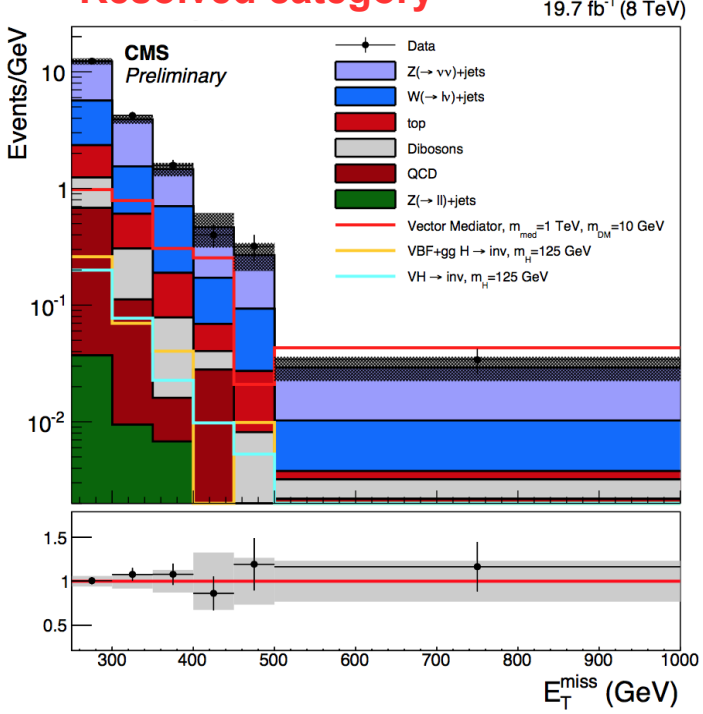
Monojet category



Boosted category



Resolved category



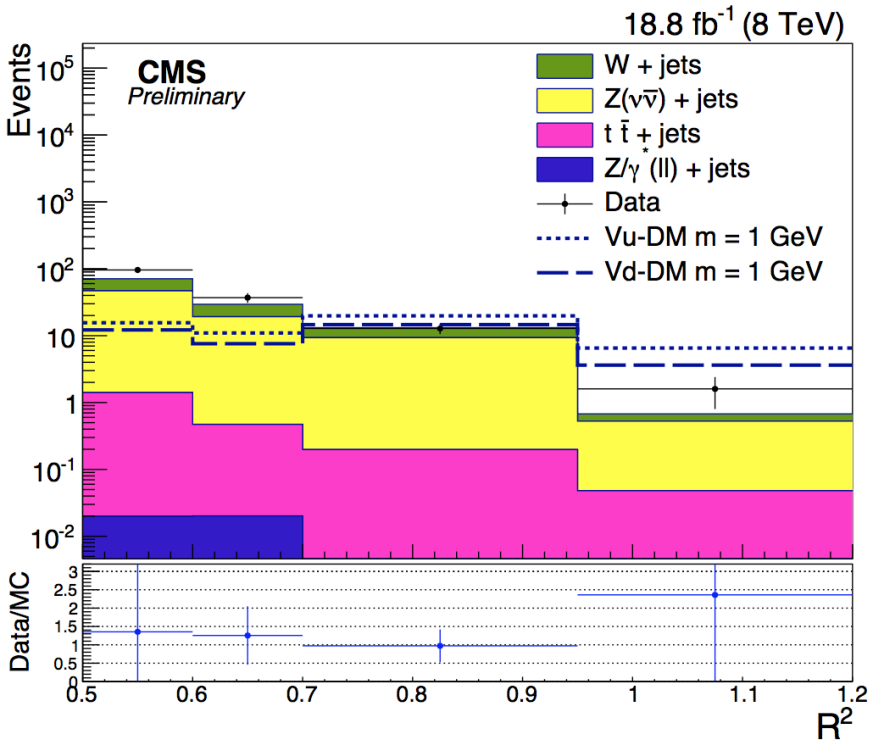
Dark Matter + Dijet
Razor Variables

- Selects events with at least two central jets with p_T > 80 GeV and no leptons
  - if more jets are present, force the event into a dijet topology by iteratively clustering around the two highest-p_T jets ("megajets")
  - complementary selection w.r.t. monojet
- Lower cross section than monojet, but good discrimination against SM processes
  - Razor variables are defined

$$M_R = \sqrt{\left(|\vec{p}^{J1}| + |\vec{p}^{J2}|\right)^2 - \left(p_z^{J1} + p_z^{J2}\right)^2}$$

$$R = \frac{M_T^R}{M_R}, \text{ with}$$

$$M_T^R = \sqrt{\frac{E_T^{miss}\left(p_T^{J1} + p_T^{J2}\right) - \vec{p}_T^{miss}\cdot\left(\vec{p}_T^{J1} + \vec{p}_T^{J2}\right)}{2}}$$



- Events with 1 or 2 b-tagged jets are analyzed separately (*sensitive to scalar interactions*)
- Control regions with 1 or 2 muons are used to constrain the Z(νν) + jets and W(ℓν) + jets backgrounds

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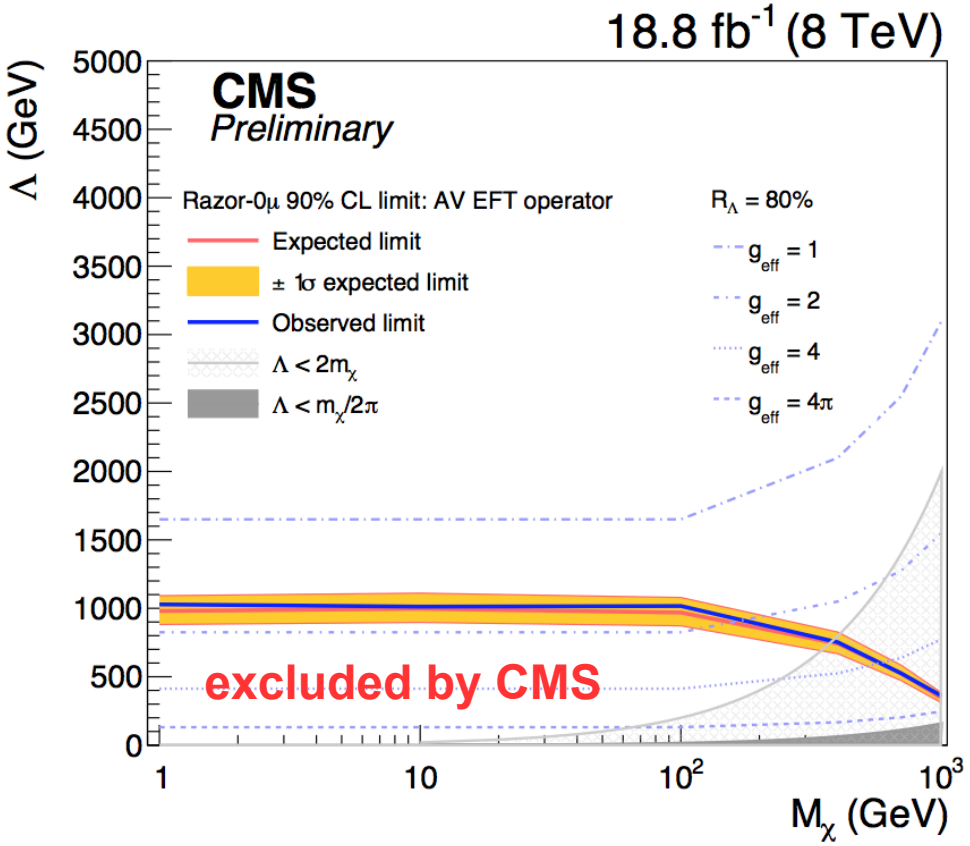
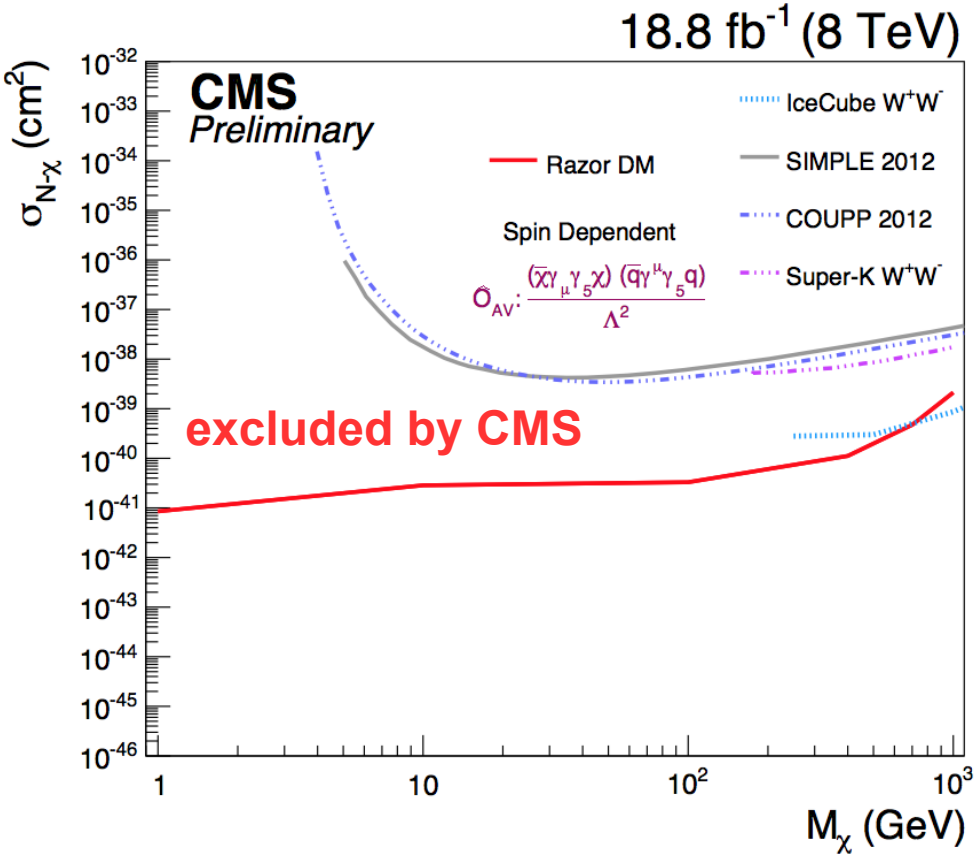
Dark Matter + Dijet

Limits on Axial-Vector Interactions

- In the context of EFT, limits are set on the cutoff scale Λ and translated into limits on DM-nucleon scattering cross section
  - Here shown in the 0 b-jet category, for vector and axial-vector currents
  - Accuracy of the EFT description is quantified by R_Λ contours $\rightarrow$ $R_\Lambda > 80\%$ for $\sqrt{g_\chi g_q} > \sim 2$

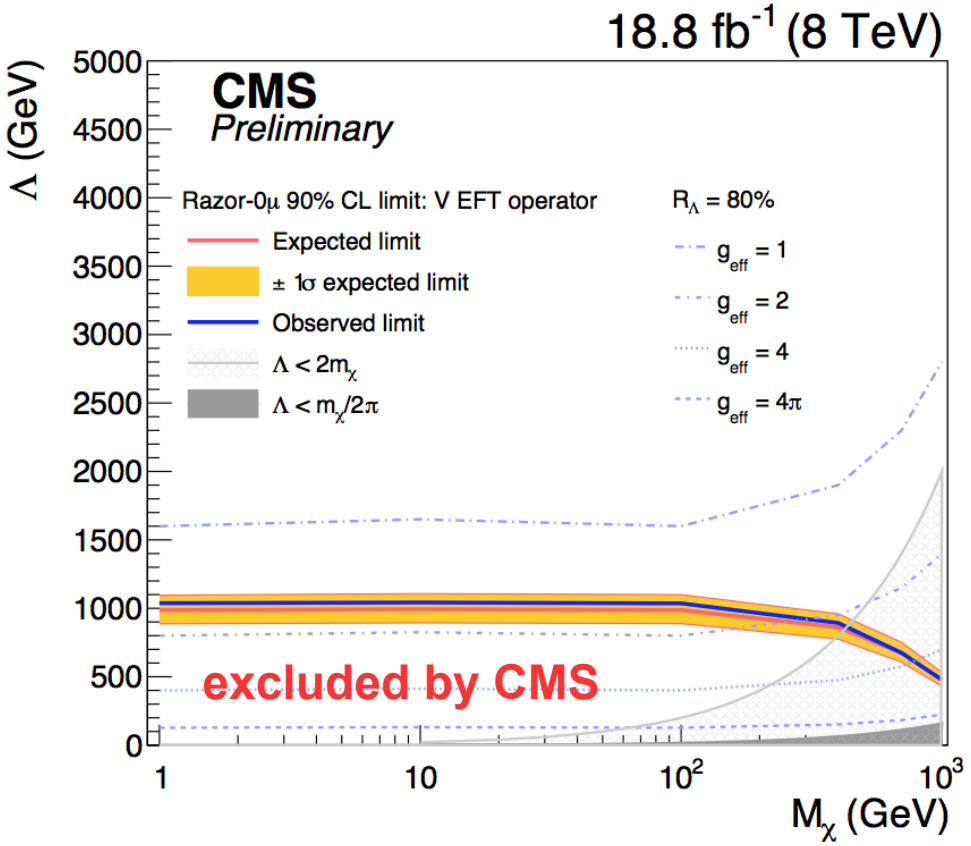


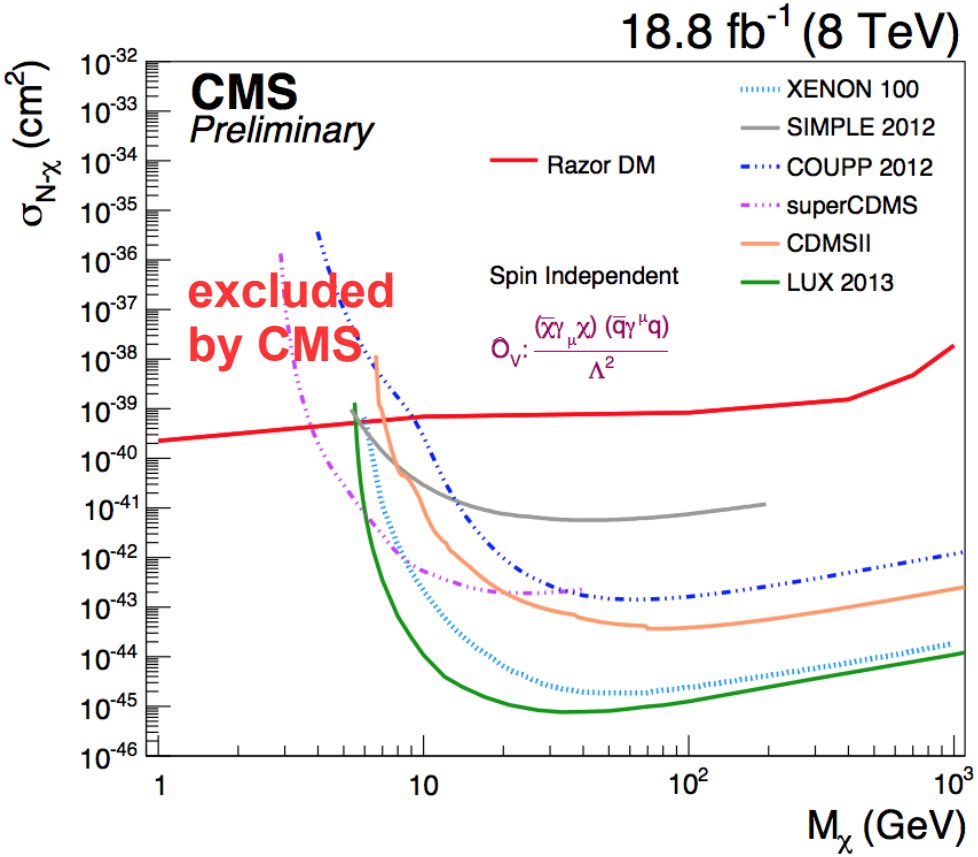


Dark Matter + Dijet

Limits on Vector Interactions

- In the context of EFT, limits are set on the cutoff scale Λ and translated into limits on DM-nucleon scattering cross section
  - Here shown in the 0 b-jet category, for vector and axial-vector currents
  - Accuracy of the EFT description is quantified by R_Λ contours $\rightarrow$ $R_\Lambda > 80\%$ for $\sqrt{g_\chi g_q} > \sim 2$

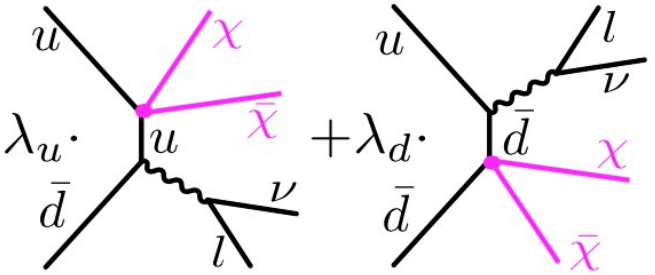


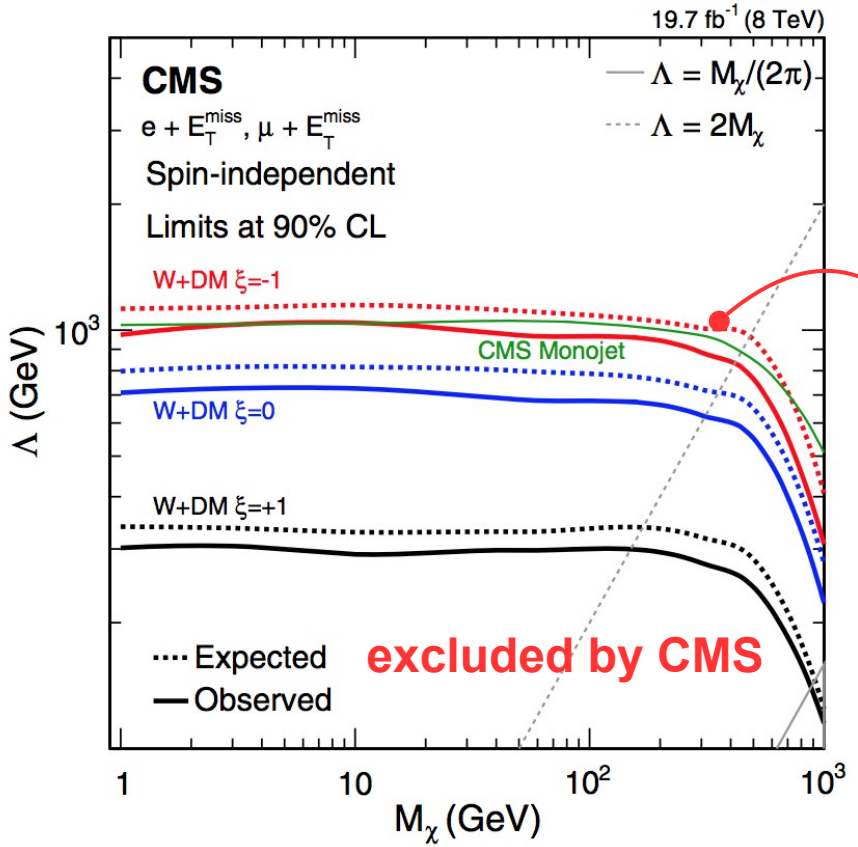


Dark Matter + Leptons

Interpretation of Results: Mono-W($\ell\nu$)

- Limits are set on the EFT parameter Λ for different signal models
  - If the DM couples differently to up- and down-type quarks, the mono-W cross section is significantly affected through the interference between the two main diagrams
  - Different interference scenarios are considered:
    $\xi = \lambda_u \cdot \lambda_d = -1, 0, +1$

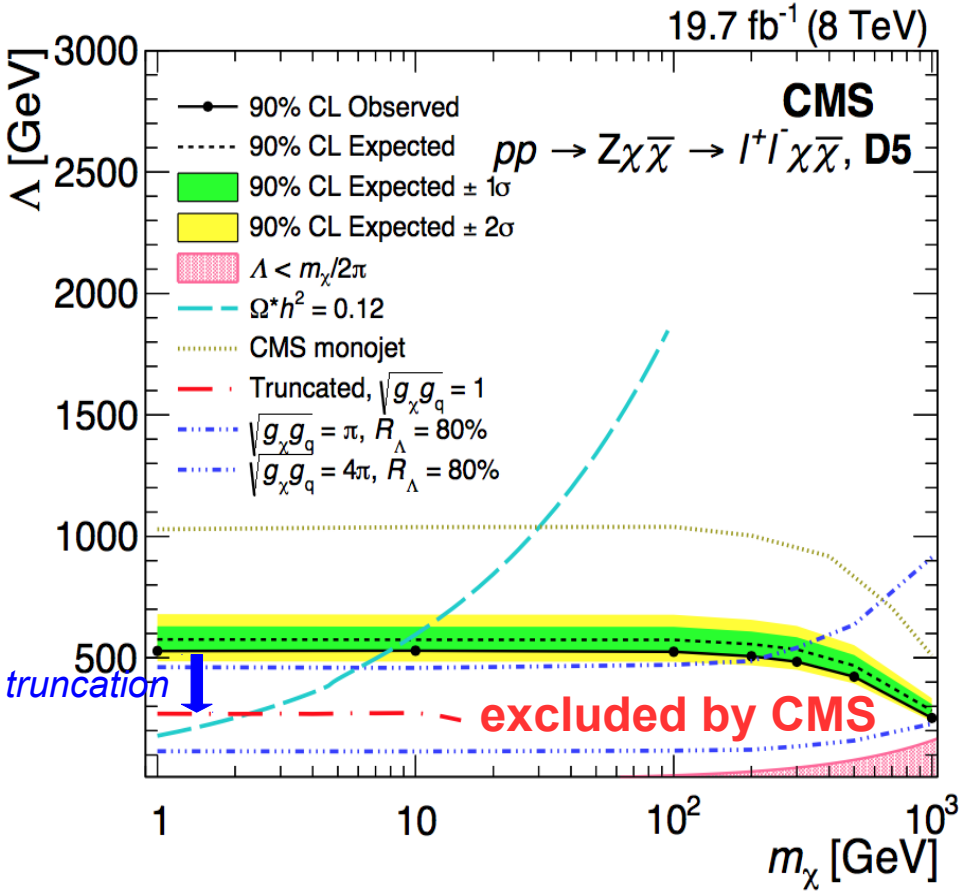
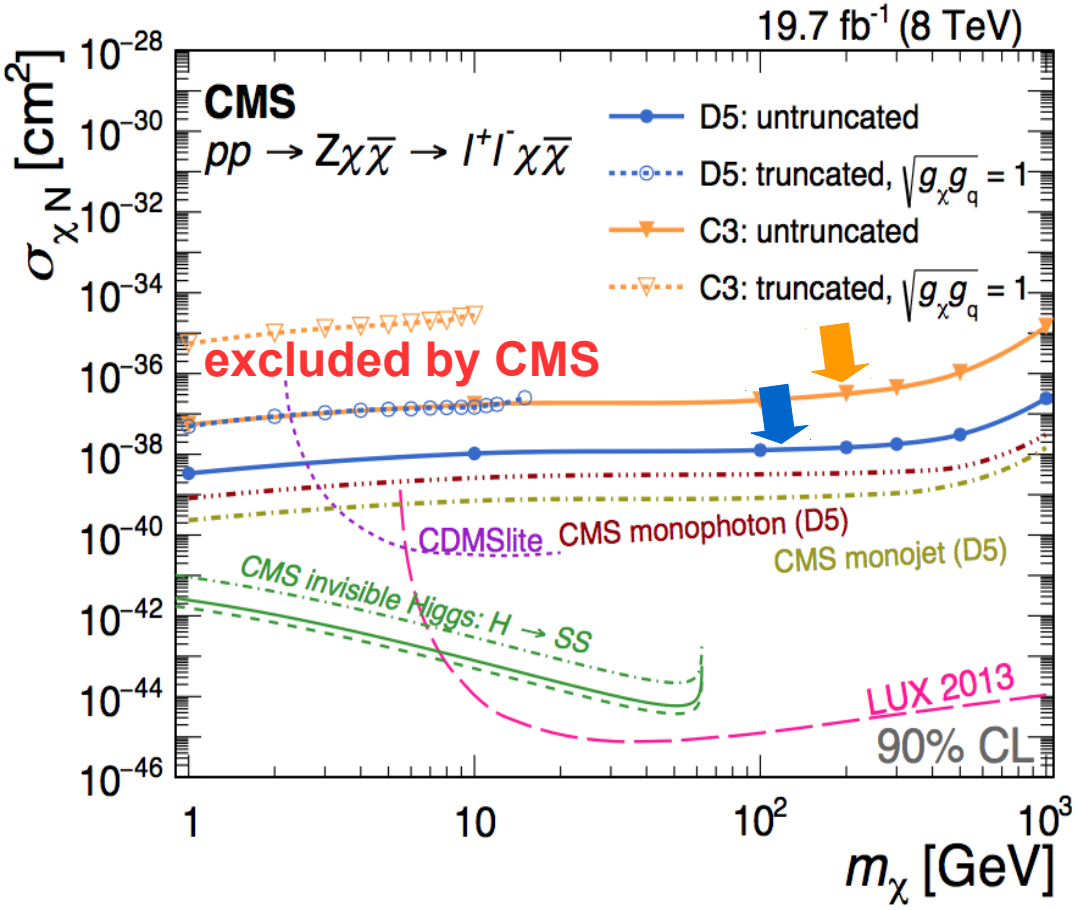




For constructive interference ($\xi = -1$) exclusion limits comparable with those from monojet

Dark Matter + Leptons

Interpretation of Results: Mono-Z($\ell\ell$)

- Limits on the EFT parameter Λ and the DM-nucleon cross section are computed for different mono-Z models
  - truncated limits are also provided

vector coupling, spin-independent cross sections