

Searches for Dark Matter and New Physics with Unconventional Signatures

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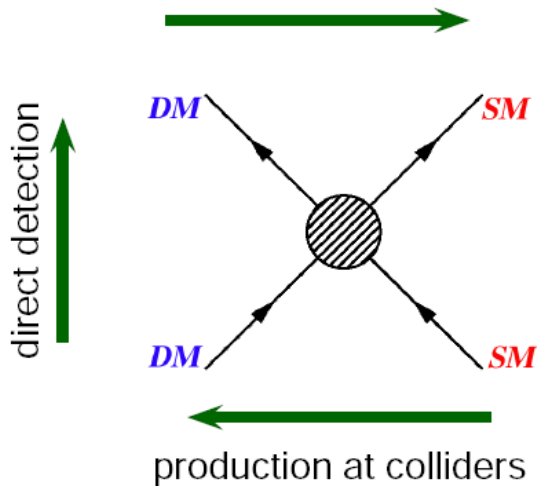
La Thuile, 11 March 2016

Rencontres de Physique de la Vallée d'Aoste



Dark Matter Searches

thermal freeze-out (early Univ.)
indirect detection (now)



Direct: DM-nucleon scattering (LUX, XENON, CDMS, CRESST, ..)

Indirect: DM annihilation (AMS, Fermi, Pamela, IceCube, ...)

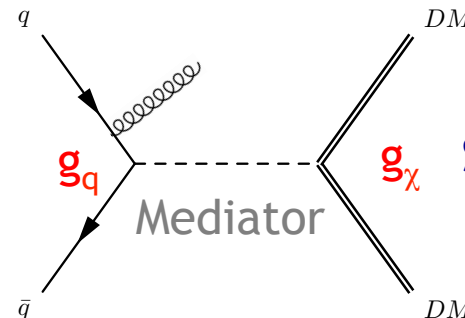
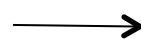
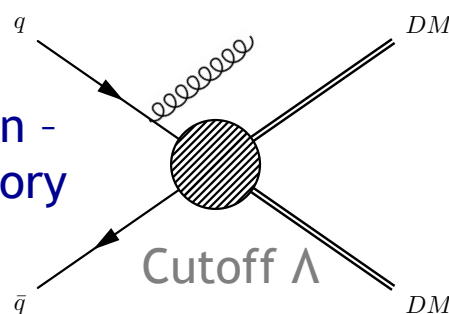
Production: at colliders (ATLAS, CMS, ...)

Best for low DM mass and spin-dependent couplings

Production in decays: SUSY cascades, Higgs portal

Direct production: only detectable as missing transverse momentum in association with additional, visible objects (“mono-X” channels, with $X = q, g, \gamma, W, Z, t, t\bar{t}, b, b\bar{b}$)

Contact interaction -
effective field theory



Simplified models

DM parameters: DM and mediator masses, couplings, type of interaction (scalar, pseudoscalar, vector, axial-vector, tensor)

e.g. *ATLAS/CMS DM Forum, arXiv 1507.0966 (2015)*

Dark Matter Searches - Monojets

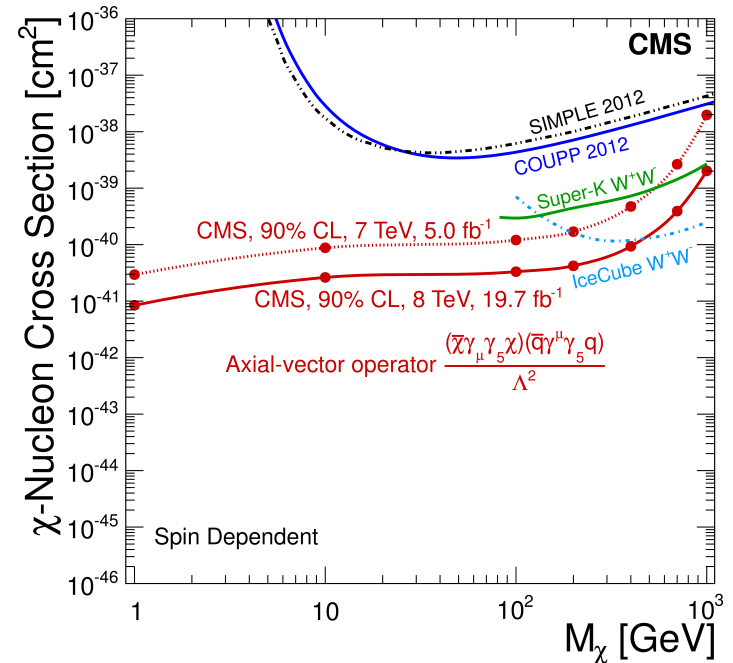
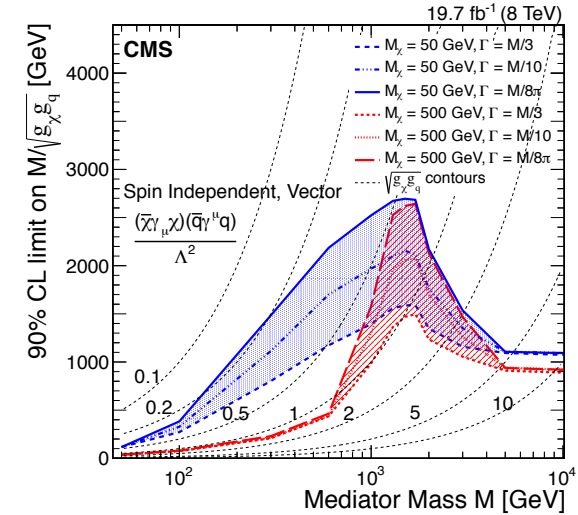
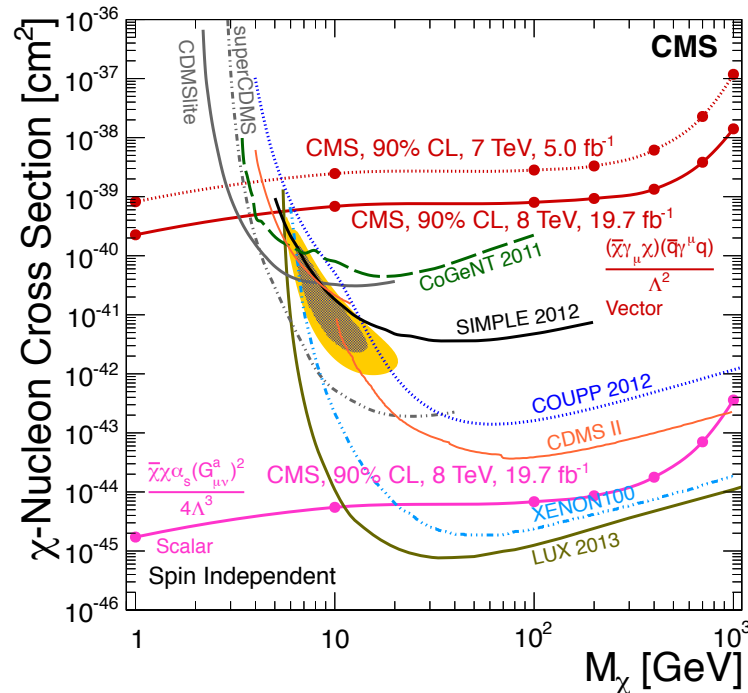
CMS-EXO-12-048, EPJC 75 (2015) 235

Data sample:

19.7 fb⁻¹ at $\sqrt{s} = 8$ TeV, 5.0 fb⁻¹ at $\sqrt{s} = 7$ TeV

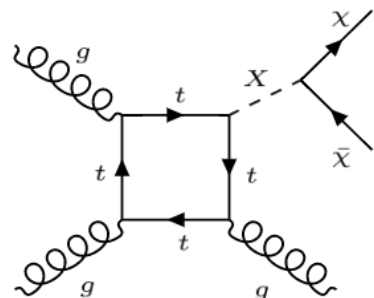
Background:

Z(vv) estimated from Z($\mu\mu$) control sample,
t $\bar{t}$ and QCD multijets removed by excluding
events with more than 2 jets with $p_T > 30$ GeV

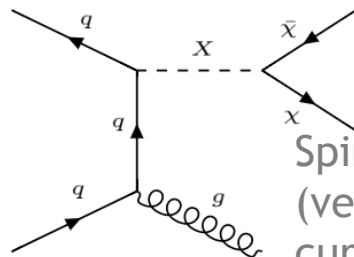




Dark Matter Searches - Monojets



Spin-0 mediator X (scalar or pseudoscalar current)

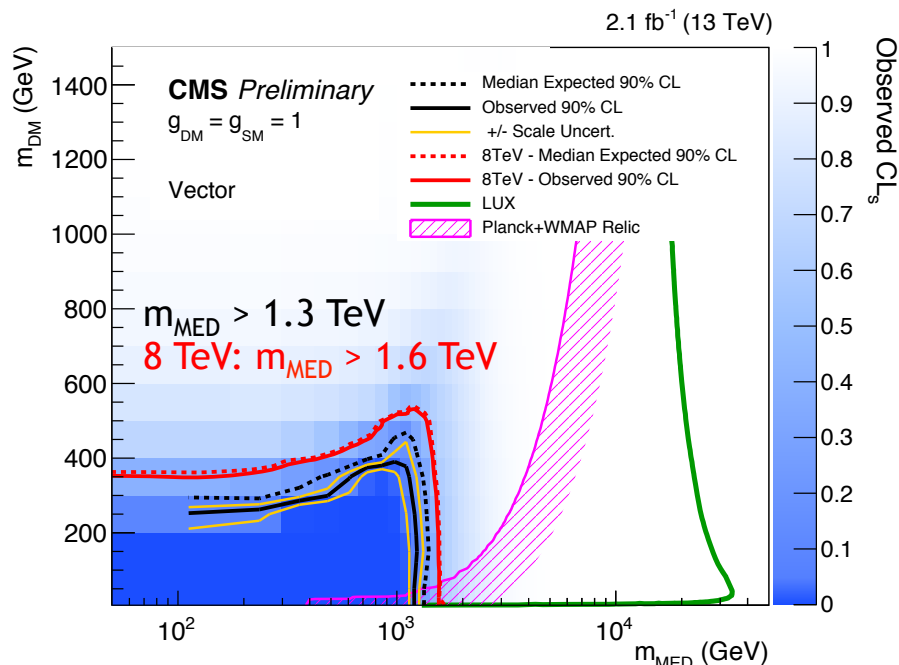
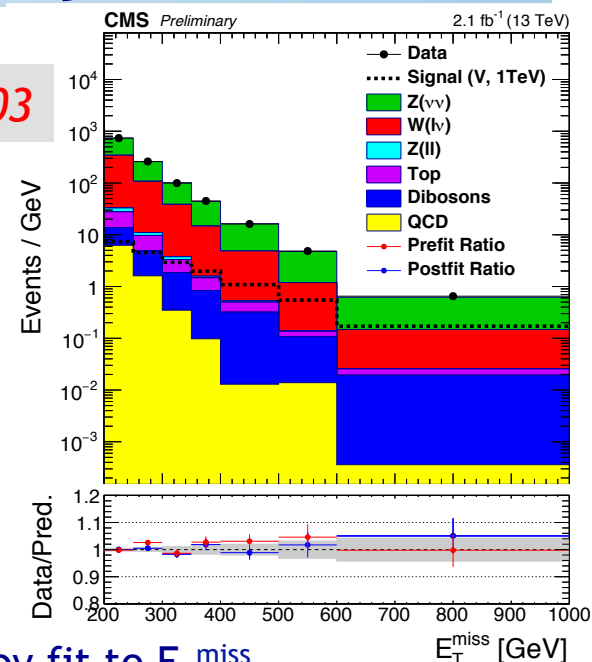


Spin-1 mediator X
(vector or axial-vector current)

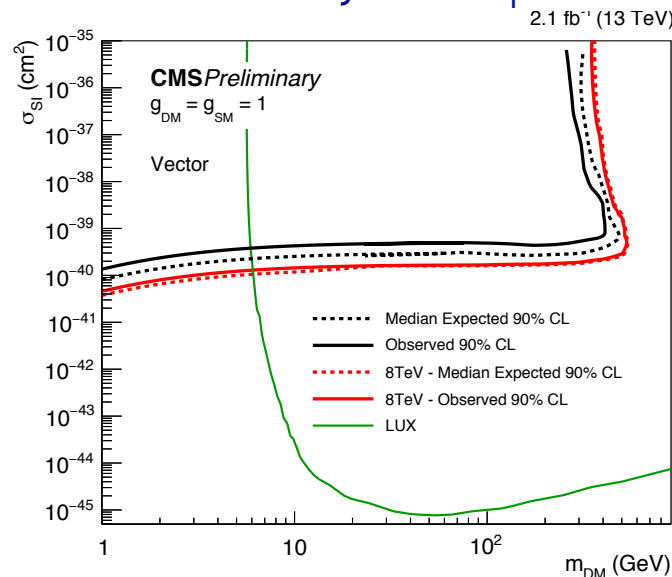
NEW: CMS-EXO-15-003

Event selection: ≥ 1 jets with $E_T > 100$ GeV, $E_T^{\text{miss}} > 200$ GeV

Data sample: 2.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$



DM signal
extracted by fit to E_T^{miss}

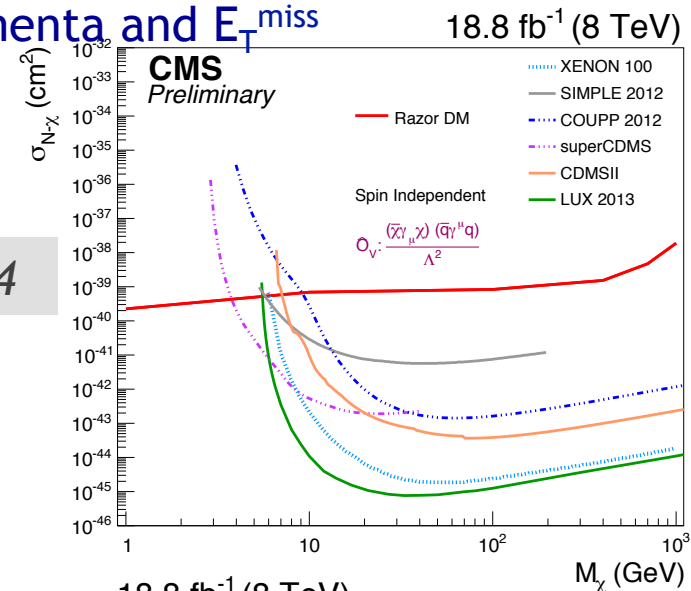
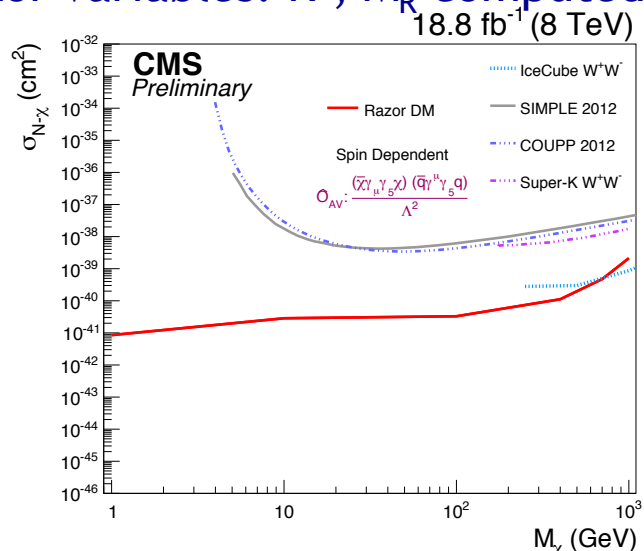




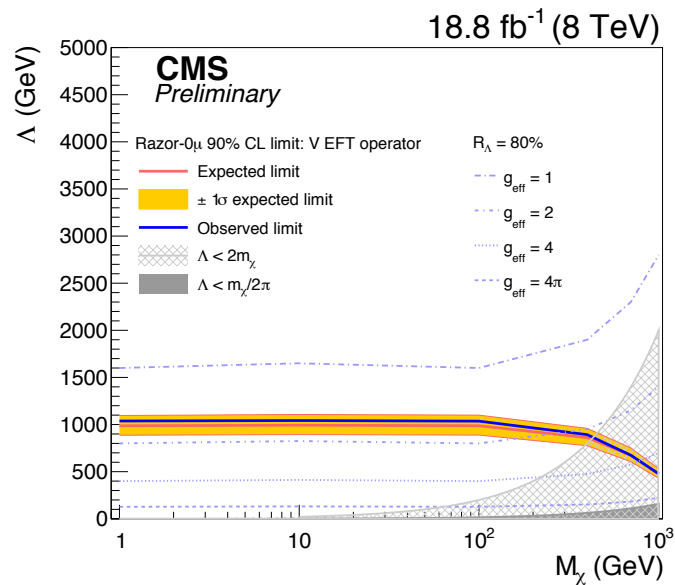
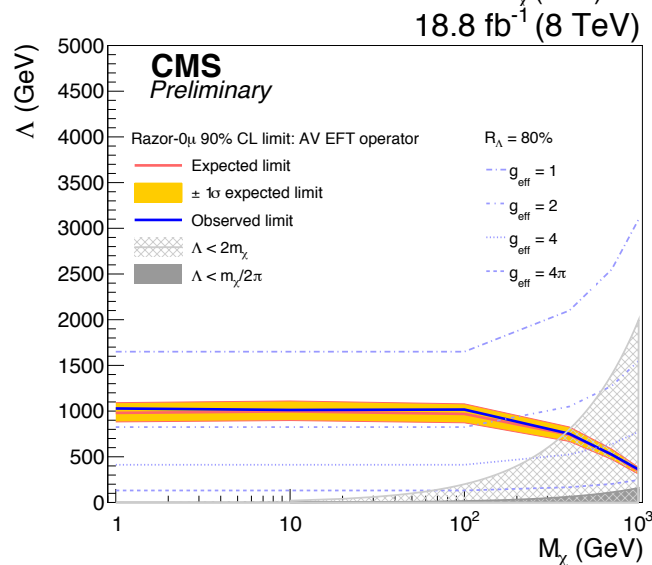
Dark Matter Searches - Razor dijet analysis

Signature: Dijets + E_T^{miss} , no leptons

Razor variables: R^2 , M_R computed from the jet momenta and E_T^{miss}



CMS-EXO-14-004



R_Λ quantifies fraction of events for which EFT hypothesis is still valid

$$g_{\text{eff}} = \sqrt{g_q g_x}$$

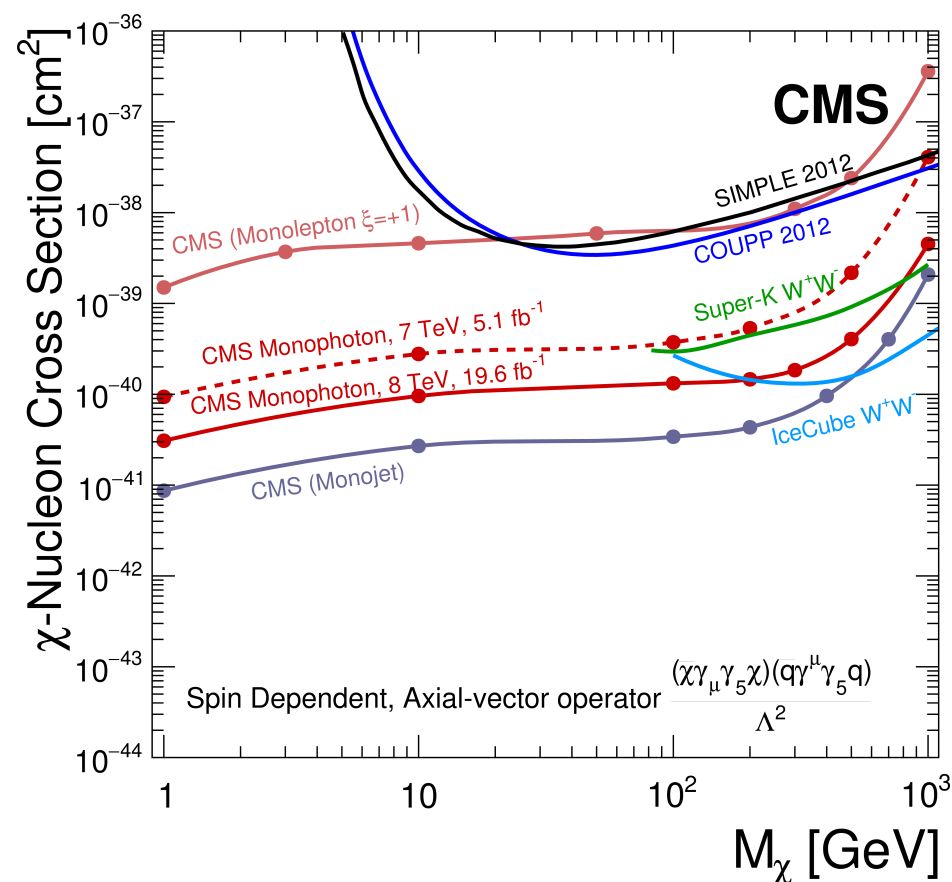
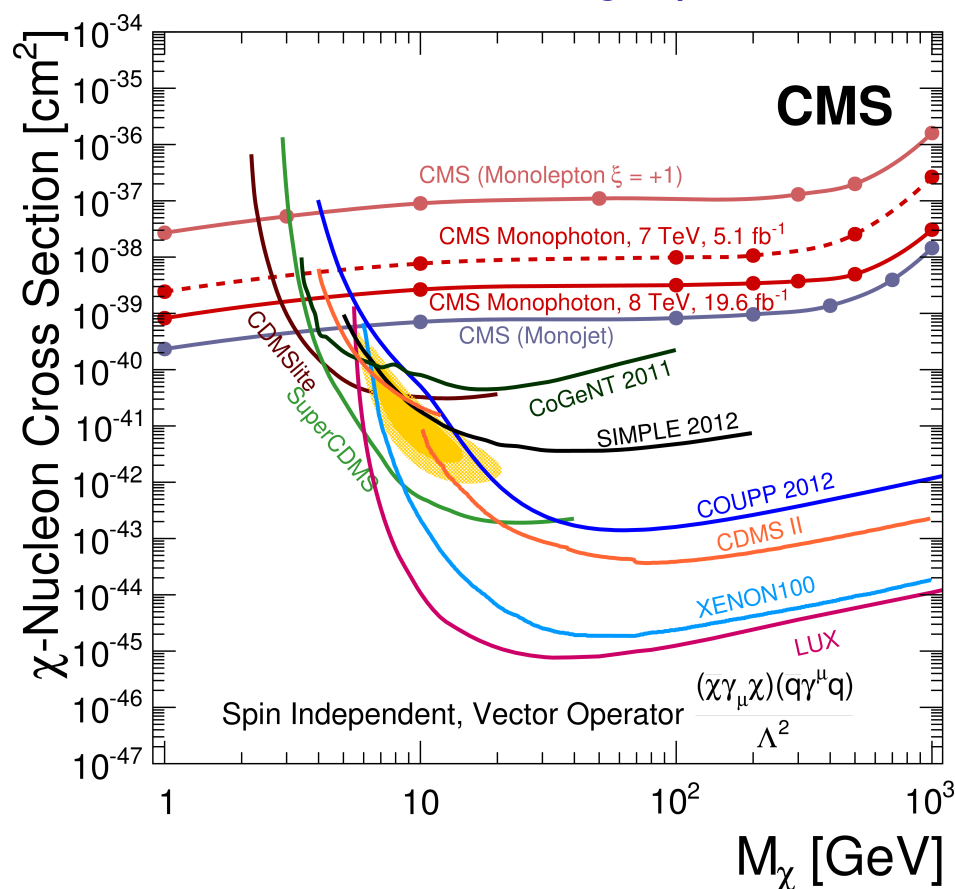


Dark Matter Searches - Monophotons

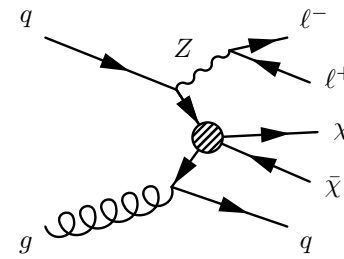
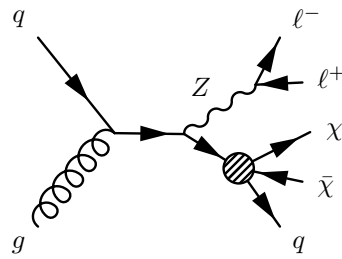
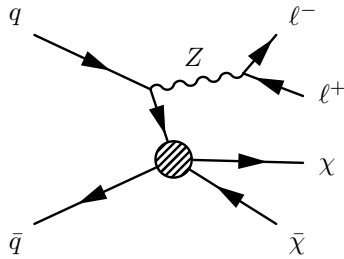
CMS-EXO-12-047, PLB 755 (2016)102

Data sample: 19.6 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$, 5.1 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$

Event selection: single photon with $E_T > 145 \text{ GeV}$ and $|\eta| \leq 1.44$, $E_T^{\text{miss}} > 140 \text{ GeV}$



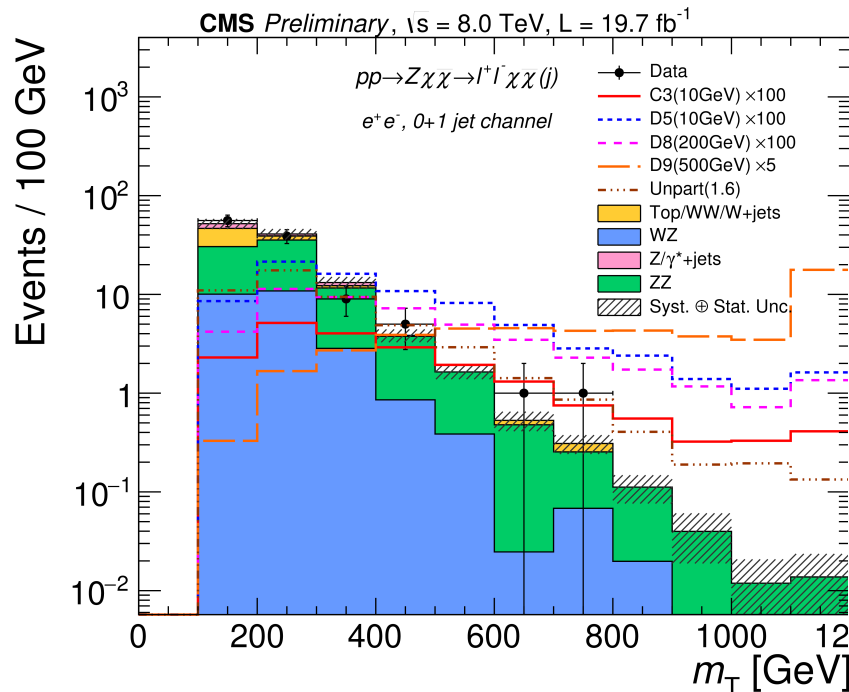
Dark Matter Searches - Mono-Z



Data sample: 19.7 fb⁻¹ at $\sqrt{s} = 8$ TeV

Event selection: 2 isolated, opposite-charge e/ μ each with $p_T > 20$ GeV and invariant mass compatible with Z, no additional e/ μ with $p_T > 20$ GeV, dilepton $p_T > 50$ GeV, no b-tagged jet

CMS-EXO-12-054



Operators for Dirac fermion (D) or complex scalar (C) DM coupling to SM quarks, Λ being the coupling scale of interactions between DM and quarks:

Vector coupling, spin-independent (D5): $\frac{\bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q}{\Lambda^2}$

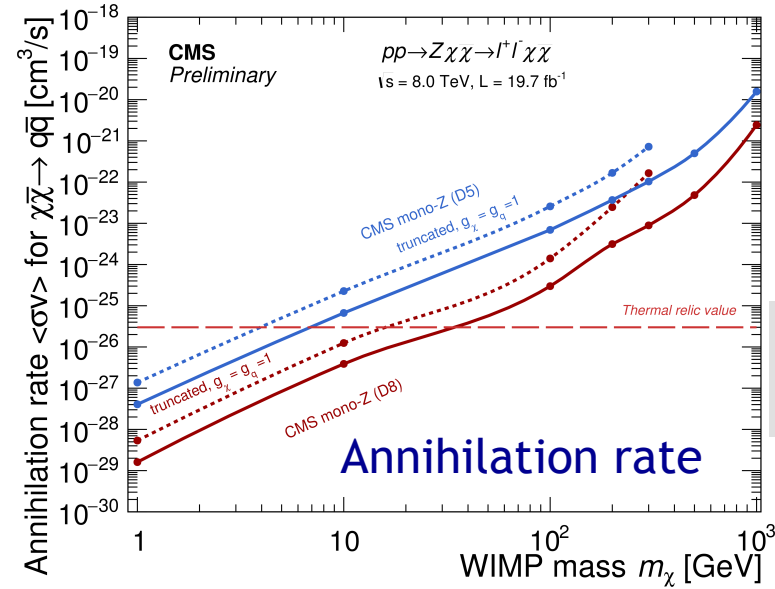
Axial-Vector coupling, spin-dependent (D8): $\frac{\bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q}{\Lambda^2}$

Tensor coupling, spin-dependent (D9): $\frac{\bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q}{\Lambda^2}$

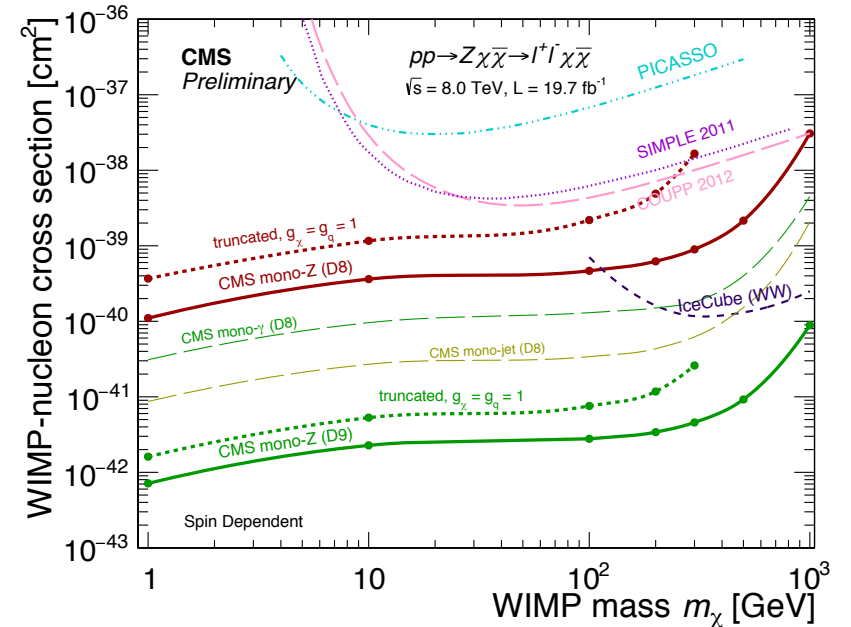
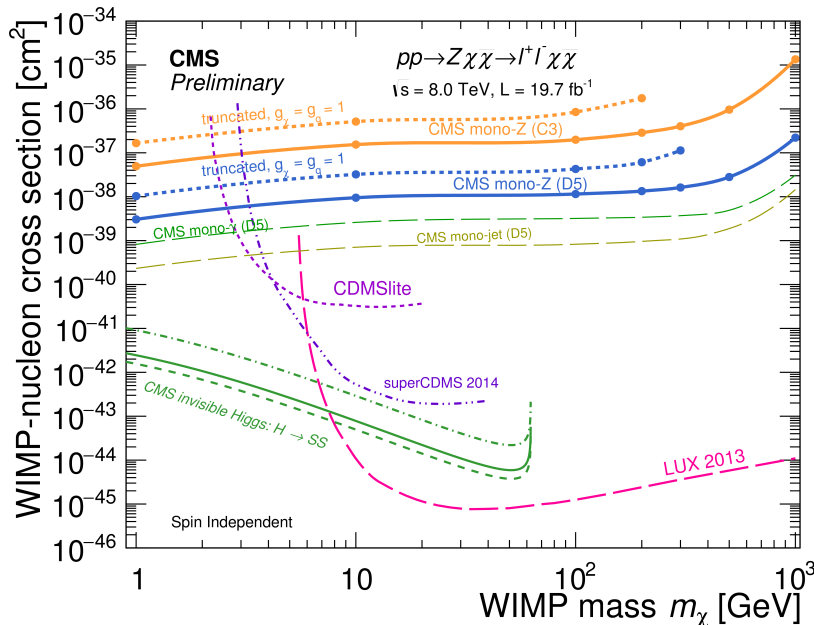
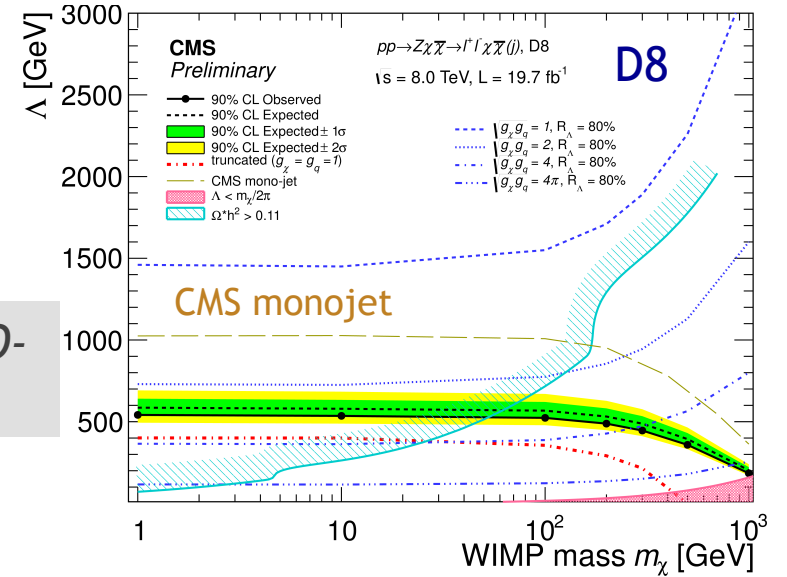
Vector coupling, spin-independent (C3): $\frac{\chi^\dagger \partial_\mu \chi \bar{q} \gamma^\mu q}{\Lambda^2}$



Dark Matter Searches - Mono-Z



CMS-EXO-12-054



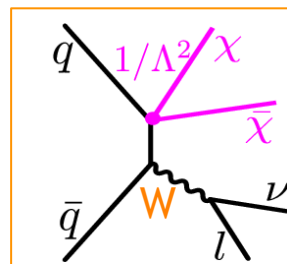
Dark Matter Searches - Mono-W

Dark matter interpretation of W' analysis

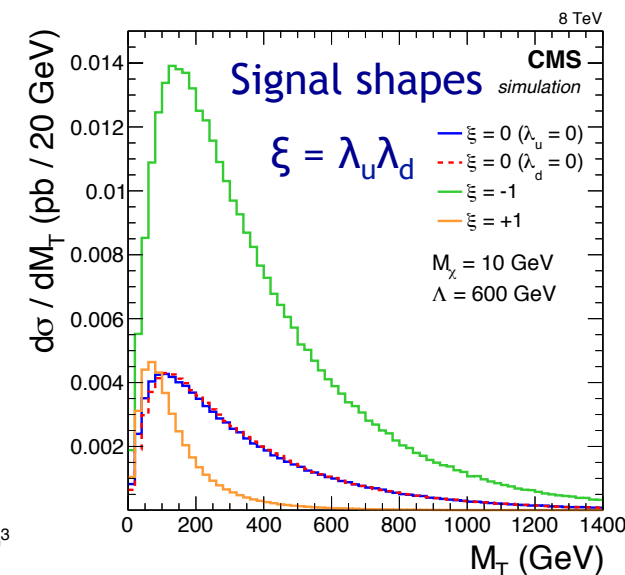
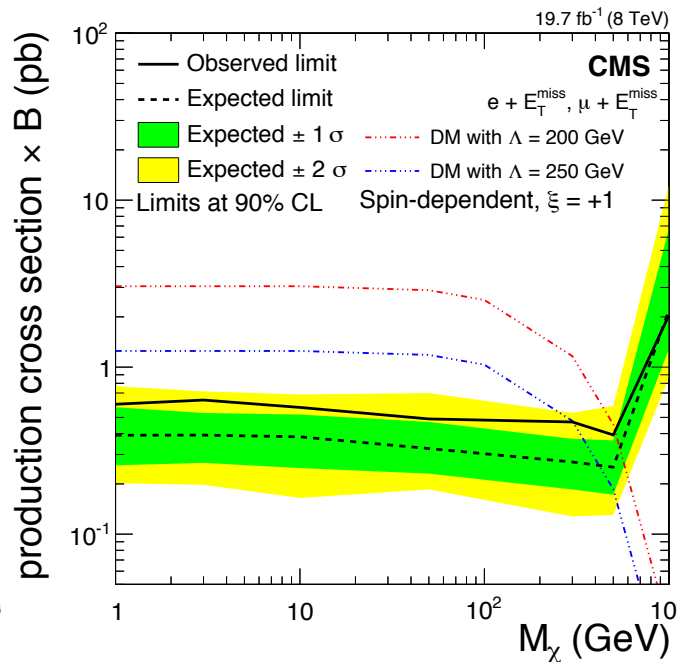
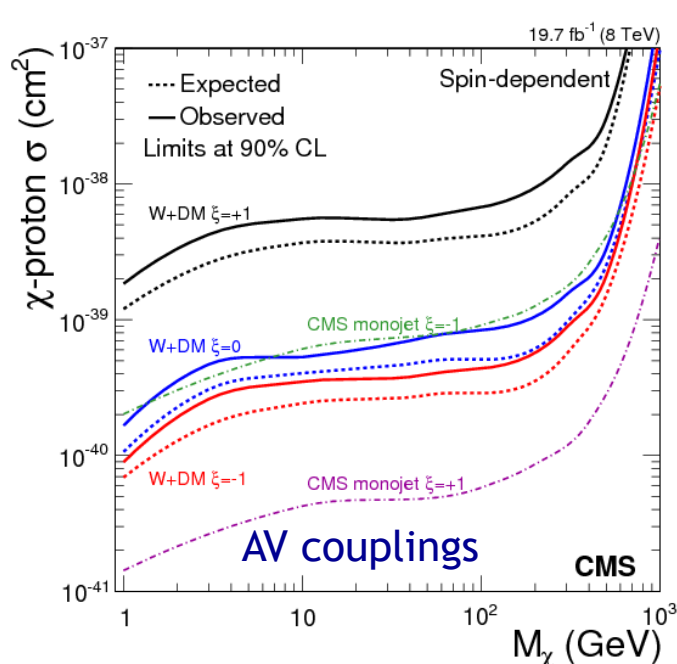
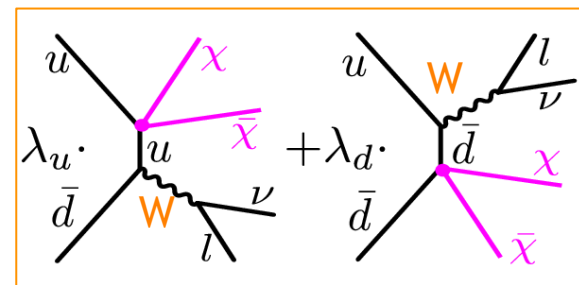
Data sample: 19.7 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$

Event selection: prompt or non-prompt
(from τ) single e or μ and E_T^{miss}

Advantages over monojet and mono- γ channels:
lower SM background and trigger lepton



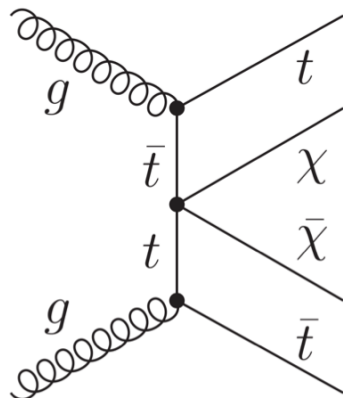
DM interference



CMS-EXO-12-060, PRD 91 (2015) 092005

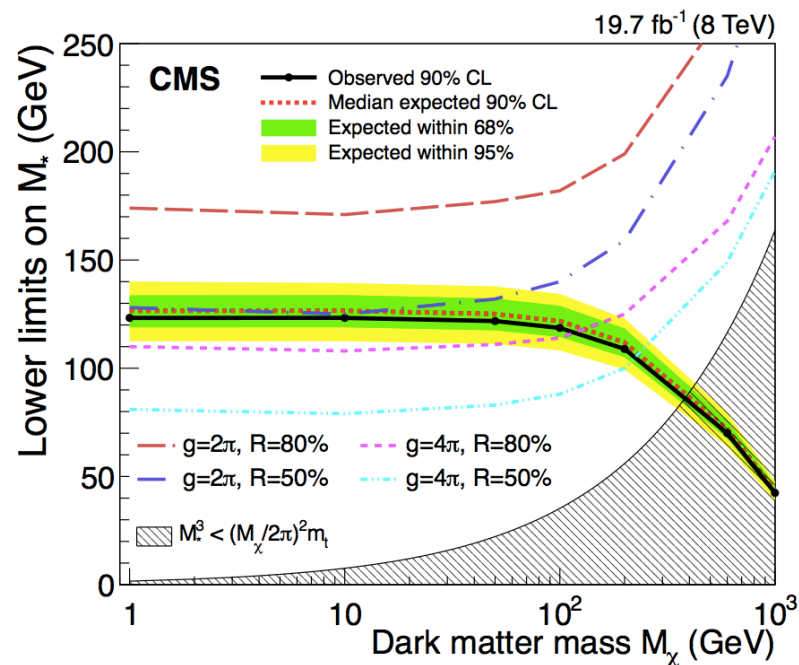
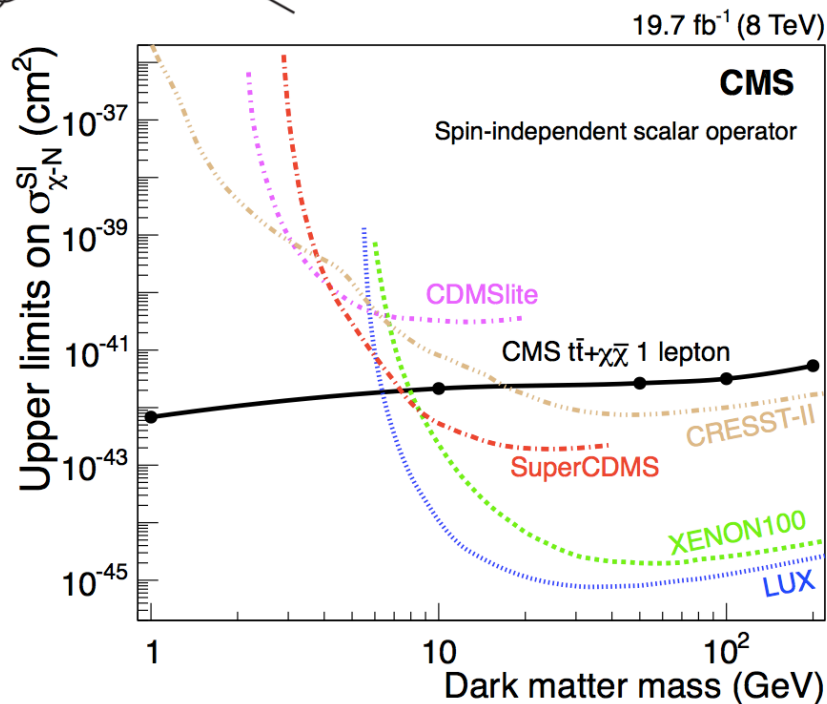
Dark Matter Searches - Top Pairs

$q\text{-}\chi$ couplings for heavy flavors enhanced in scalar interactions



$t\bar{t} + E_t^{\text{miss}}$ signature:
single lepton with jets, at least 1 b-tagged

JHEP 06 (2015) 121
CMS-B2G-14-004



M_* : scale of the interaction



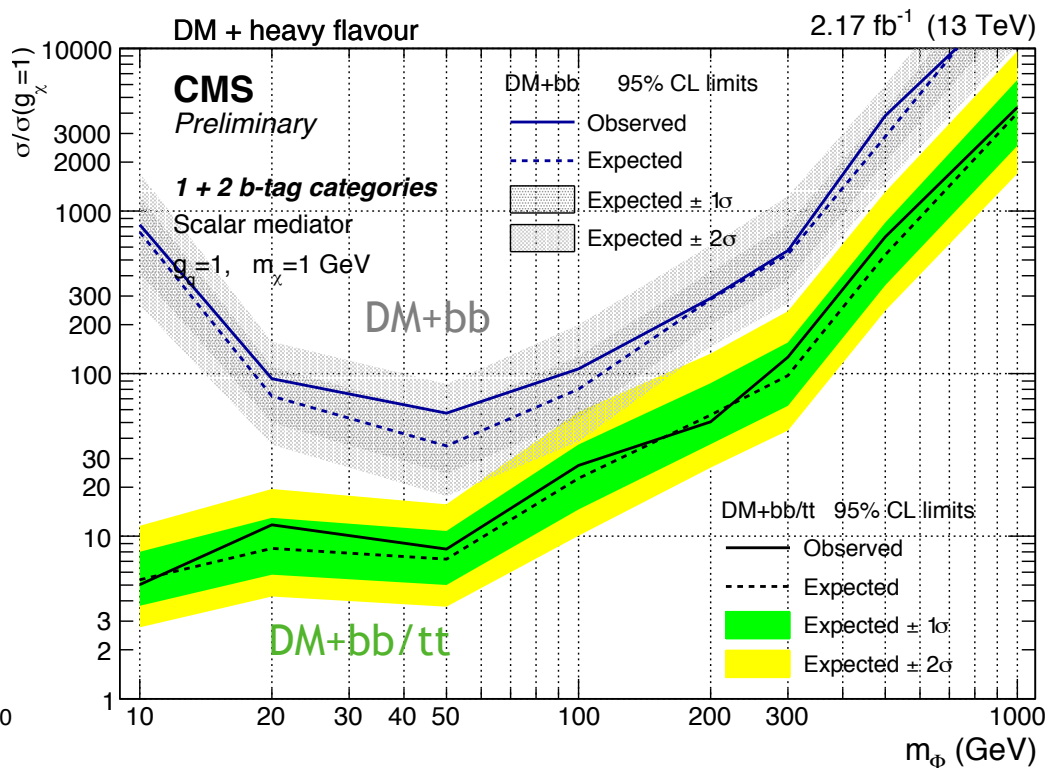
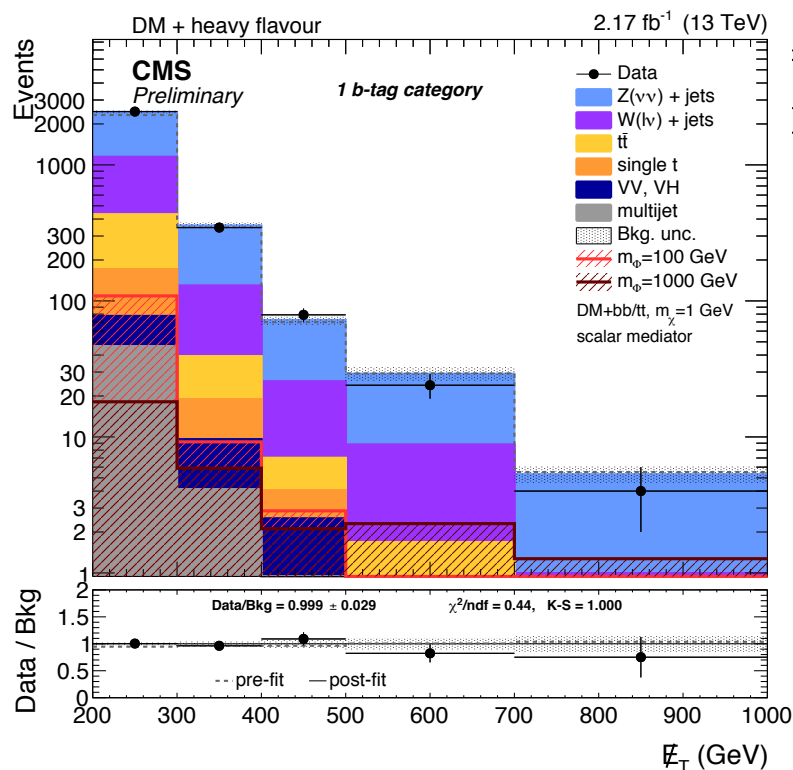
Dark Matter in association with b quarks

Data sample: 2.17 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$

Signature: $b \text{ (1 or 2)} + E_T^{\text{miss}}$

This analysis is sensitive also to DM production processes in association with t quarks, which decay to b's.

NEW: CMS-EXO-B2G-15-007

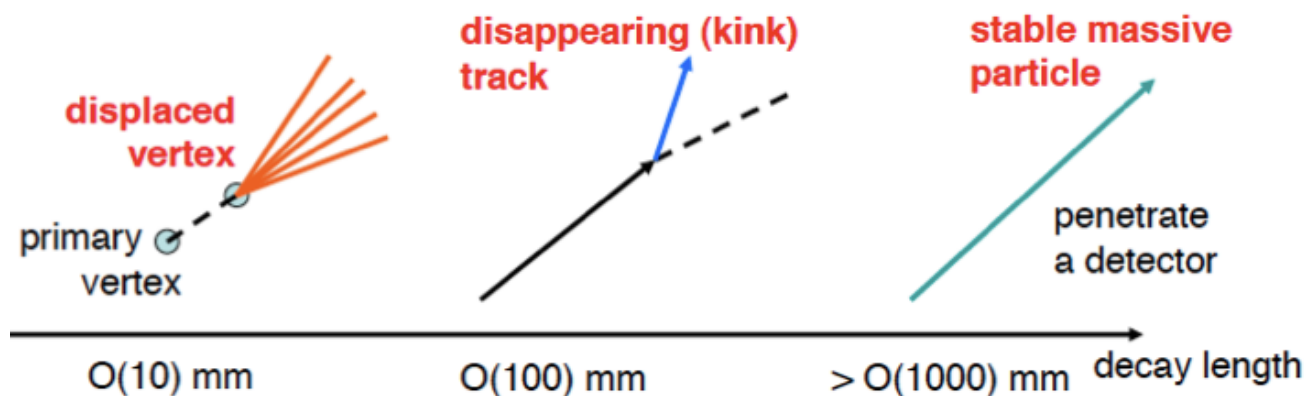


Mediator-DM couplings up to $5 \times \sigma/\sigma_{g_{\text{DM}}=1}$ are excluded.

Unconventional Signatures

Signatures:

- Displaced objects
- Disappearing or kinked tracks
- Delayed objects
- Stopped particles
- Lepton jets



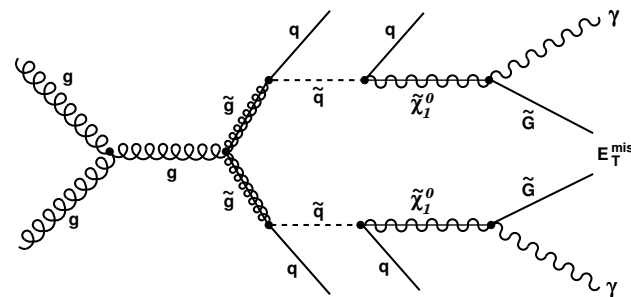
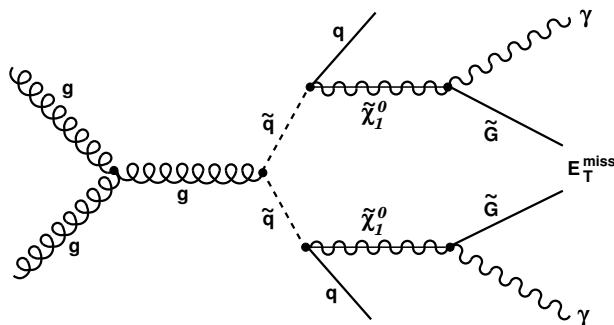
Long-lived particles are predicted in many BSM scenarios

- SUSY: GMSB, AMSB, split SUSY, RPV SUSY
- Hidden valley scenarios

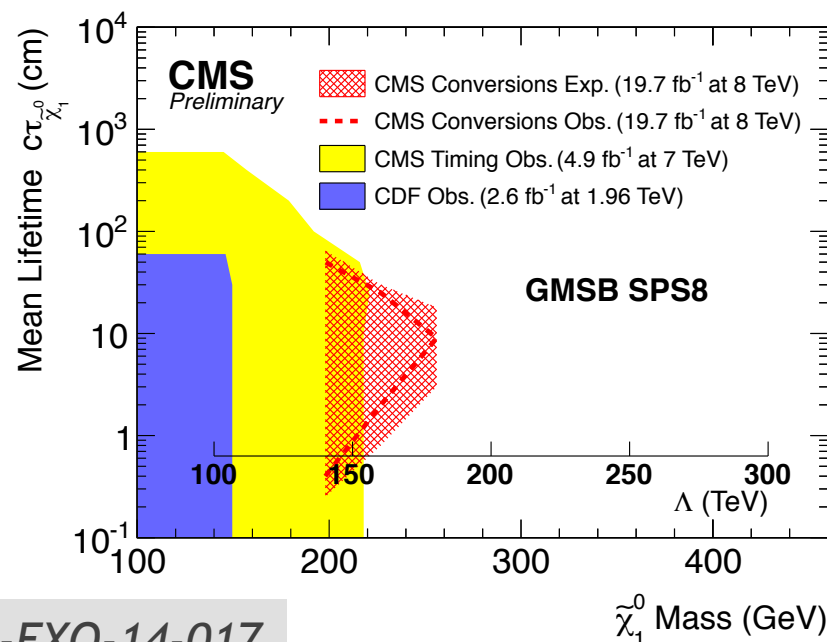
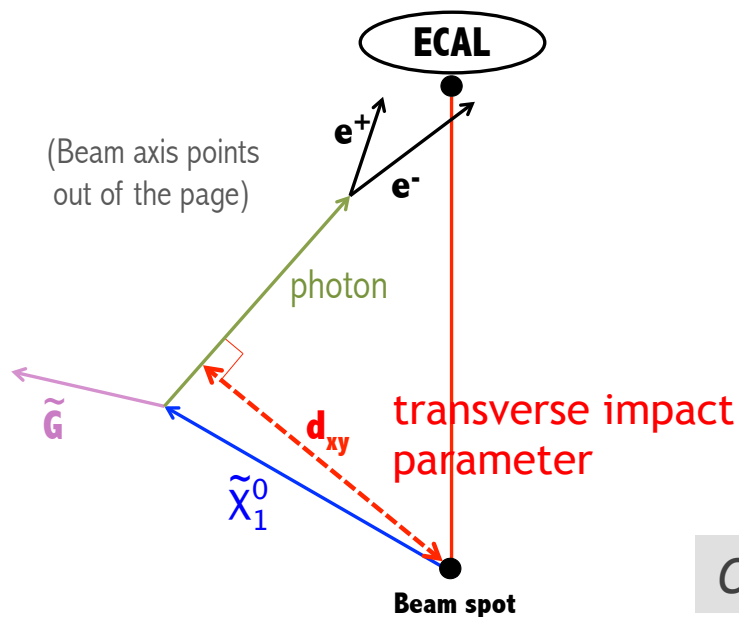


Long-lived Neutral Particles Decaying to Photons

Model with GMSB: long-lived lightest neutralino decays to gravitino and photon



Event selection: 2γ , with one converting to e^+e^- , at least 2 jets, and E_T^{miss}
 Scenario: $0.4 \text{ cm} \leq c\tau \leq 100 \text{ cm}$



CMS-EXO-14-017



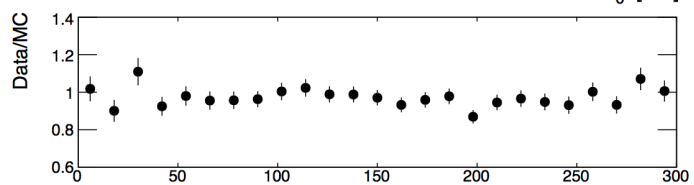
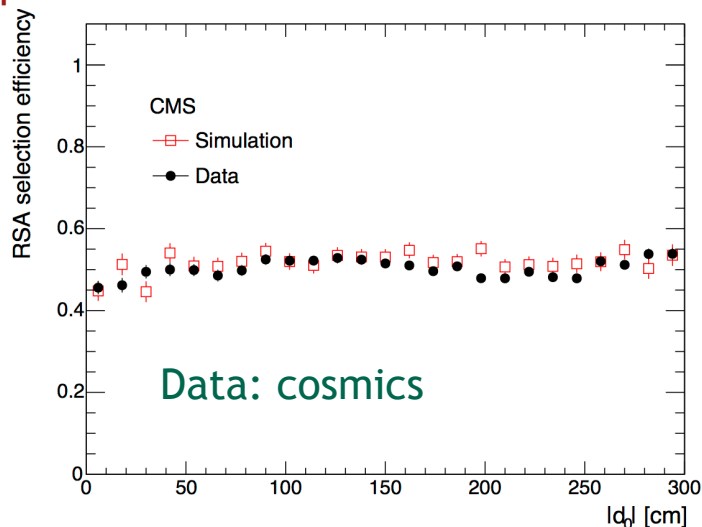
Long-lived Neutral Particles Decaying to Muons

Topology: Two muons originating from displaced secondary vertex, detected in muon chambers only

Limits derived for two specific models:

- 1) $H^0 \rightarrow XX \rightarrow 4\mu$ (H^0 ... non-SM Higgs boson, X ... long-lived boson with spin 0)
- 2) 2 squark pairs, with $\tilde{q} \rightarrow q\tilde{\chi}^0$, long-lived $\tilde{\chi}^0 \rightarrow \mu\mu\nu$ (R-parity violated)

μ reconstruction and selection efficiency



d^0 : transverse impact parameter

CMS-EXO-14-012

Signal systematic errors	Source	Uncertainty
	Pileup modelling	2%
	Tracking efficiency from cosmoics	3%
	Trigger efficiency	15%
	Parton distribution functions	< 1%
	Renormalisation and factorisation scales	< 0.5%
	NLO effects	5 – 7%

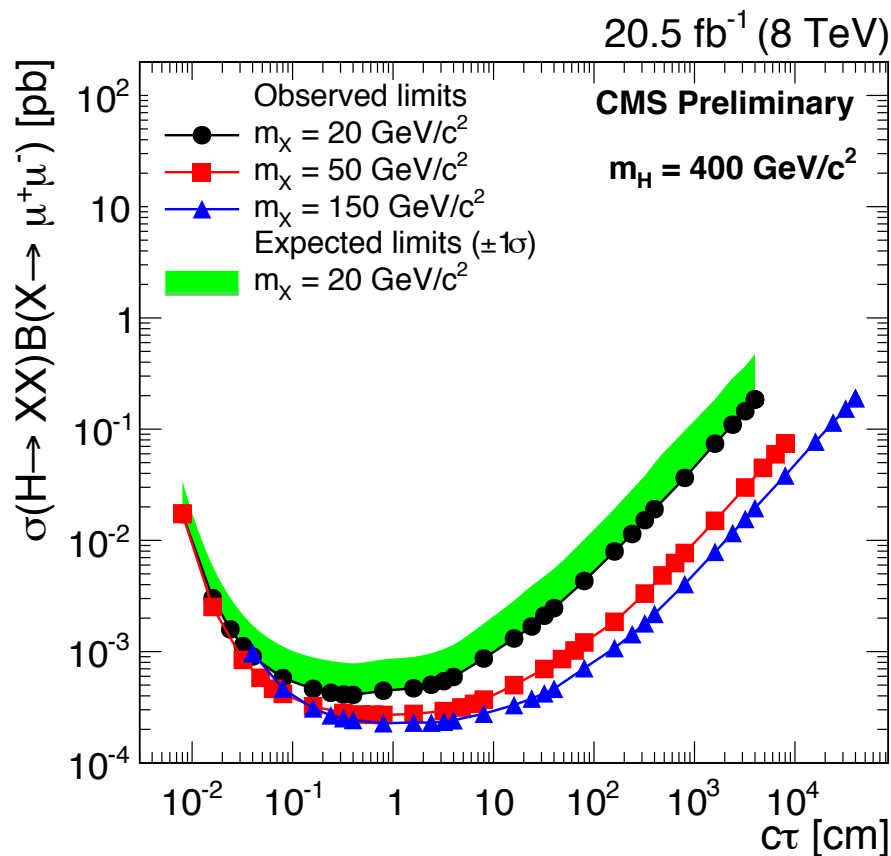
This analysis is orthogonal to a previous one that used only the tracker (arXiv: 1411.6977) - the two analyses have been combined to improve limits



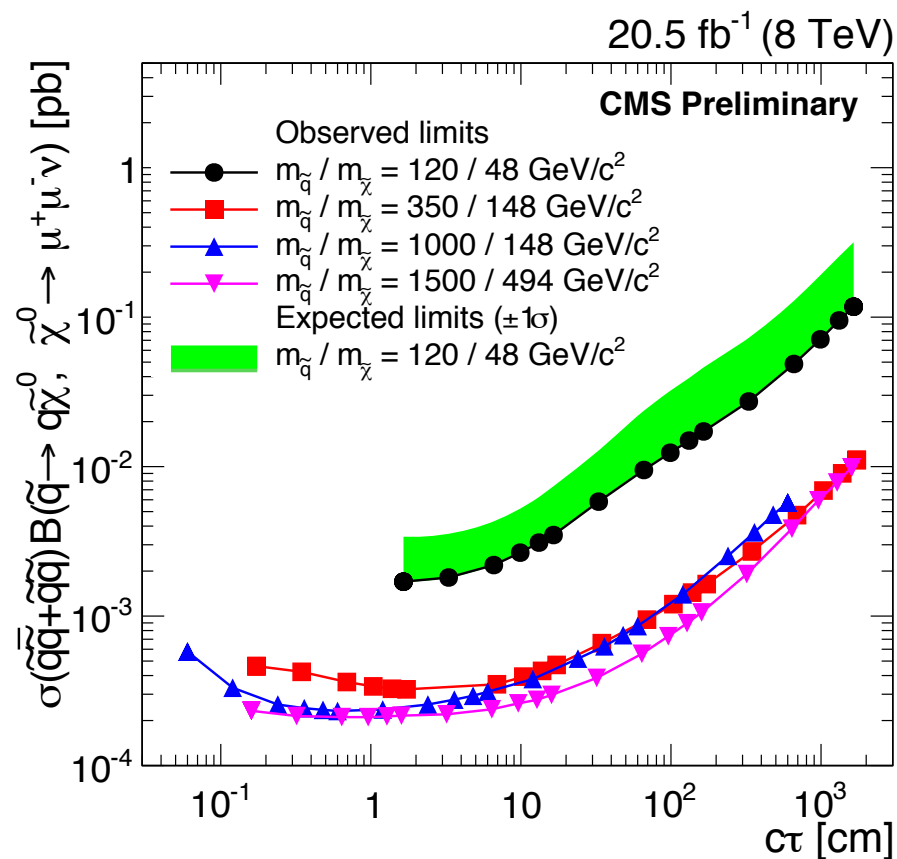
Long-lived Neutral Particles Decaying to Muons

Combined 95% CL upper limits for muon chamber and tracker analyses

$H^0 \rightarrow XX \rightarrow 4\mu$



$\tilde{q} \rightarrow q\tilde{\chi}^0, \tilde{\chi}^0 \rightarrow \mu\mu\nu$

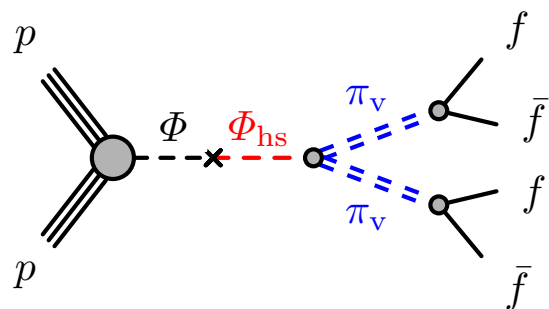


Displaced Jets

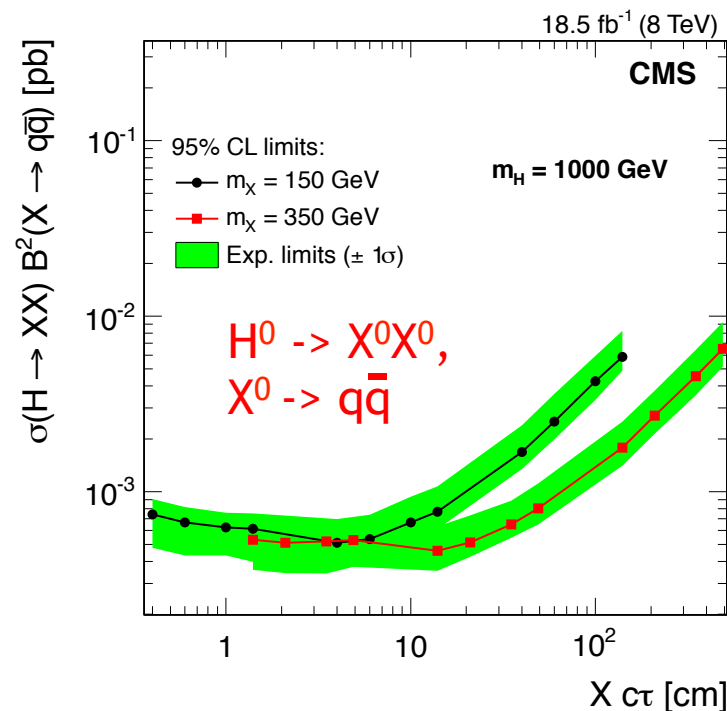
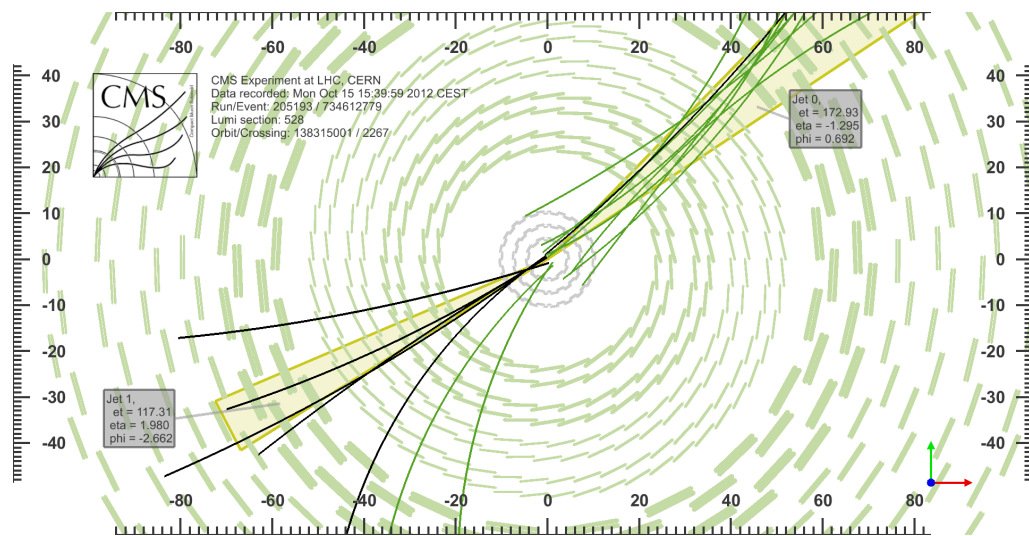
Hidden valley benchmark model: $H/\Phi \rightarrow \Phi_{hs} \rightarrow \pi_v \pi_v$ with $\pi_v \rightarrow jj/\ell\ell$

Decays of v -particles must occur via hidden sector mediator as they do not couple directly to SM particles.

Topology studied: 2 hadronic jets originating from same displaced vertex.



CMS-EXO-12-038, PRD 91 (2015) 012007



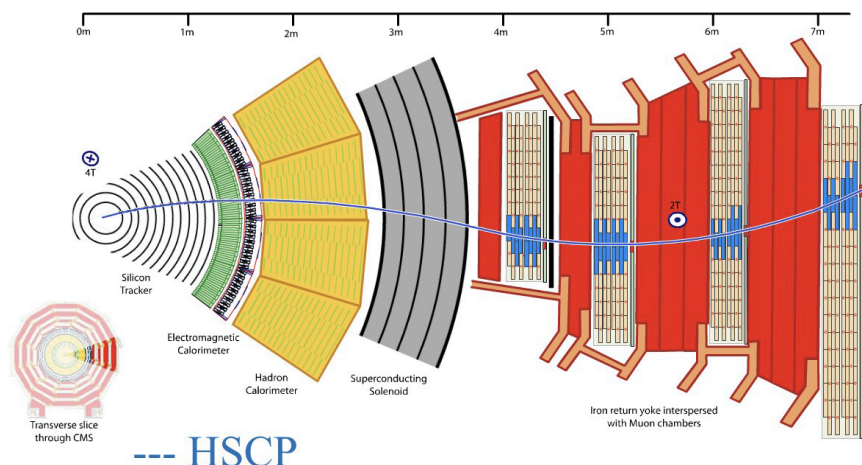
Long-lived Heavy Charged Particles

R-hadrons: long-lived gluinos could hadronize to e.g. $\tilde{g}$ -qqq states

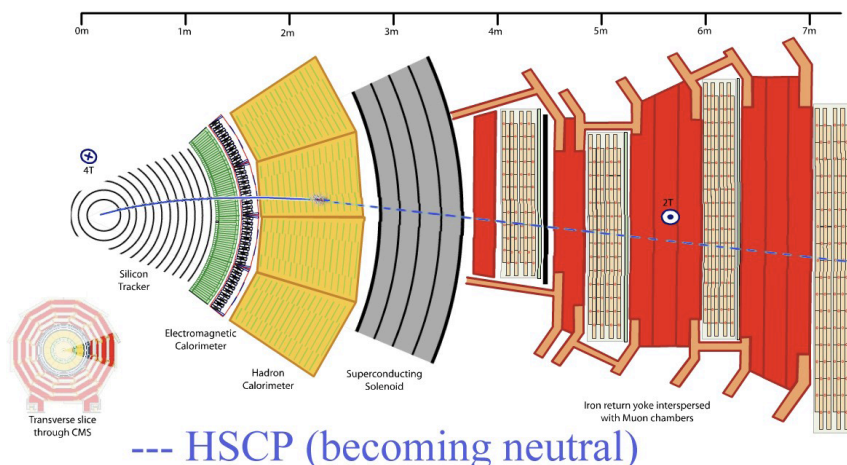
Stable chargino or stau, etc.

If mass greater than about 100 GeV: $\beta < 0.9$.

Nuclear interactions may lead to charge exchange.



Tracker (high dE/dx) + μ system (long TOF)



Tracker only (charge exchange)
-> disappearing track

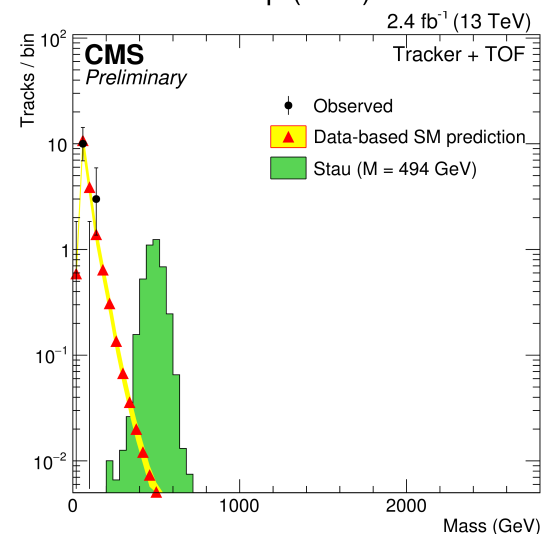
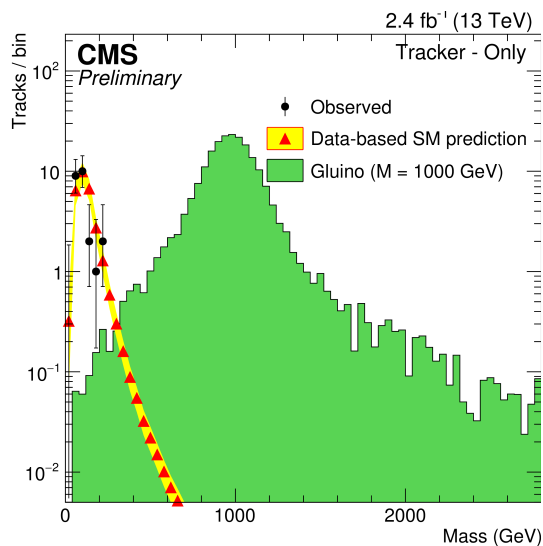
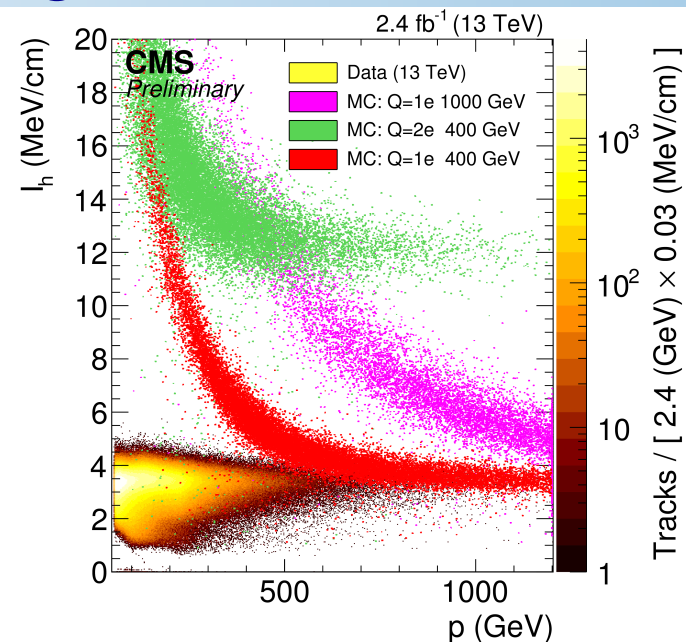
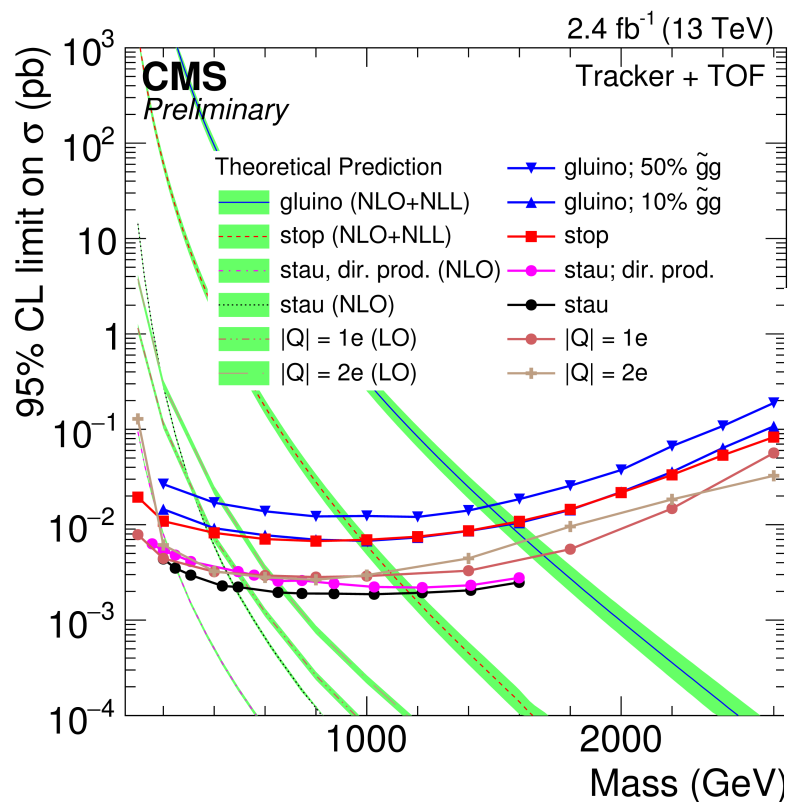


Long-lived Heavy Charged Particles

Data sample: 2.4 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$

Signature: anomalously high energy deposit in tracker and long TOF to muon detectors

NEW: CMS-EXO-15-010



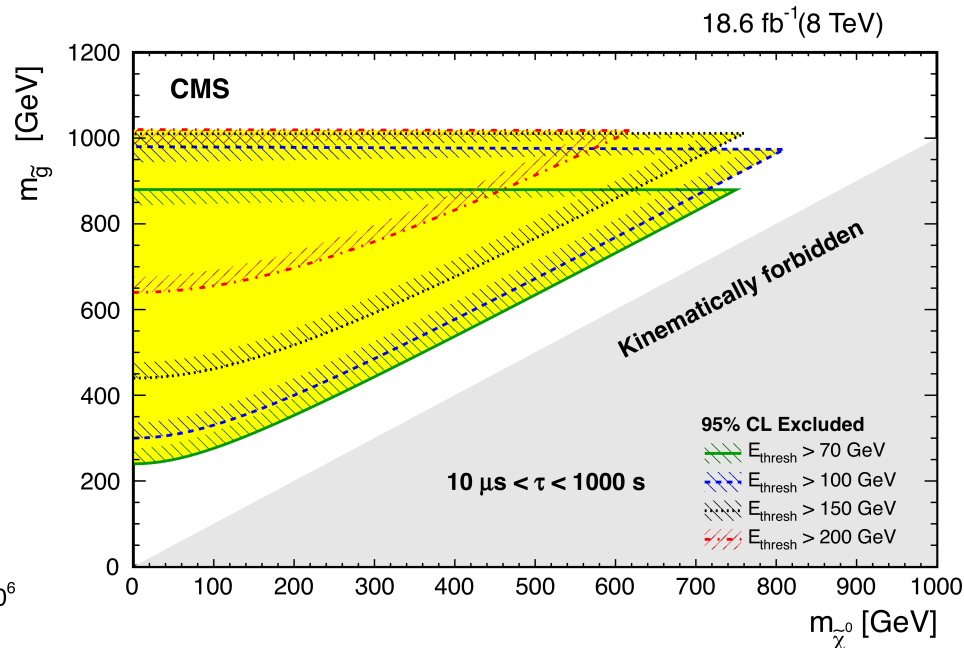
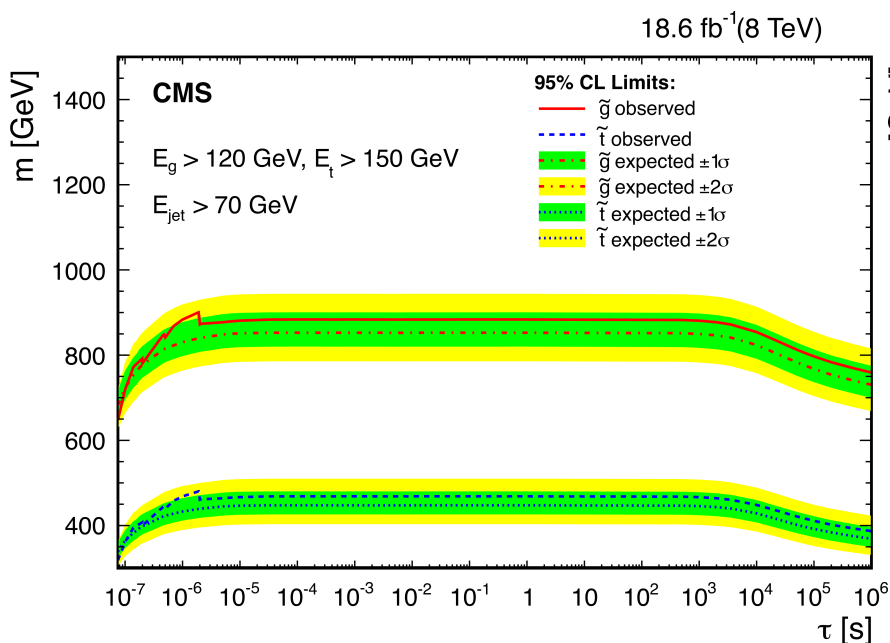
Stopped Particles

Strategy: search for decays of particles with kinetic energies so low that they come to rest in the detector. As $E_{\text{kin}} \sim v^2$, $dE/dx \sim 1/v^2$, for $v < 0.45c$ R-hadrons could come to rest inside the calorimeter. Signature assuming decays to at least one SM particle: randomly timed large energy response in a few channels, most easily observed between pp collisions. Background: cosmic rays, beam halo, instrumental noise.

Data sample: 18.6 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$, with 281 h of dedicated trigger.

Assumption: $B(\tilde{g} \rightarrow g\chi^0) = 100\%$, $B(\tilde{t} \rightarrow t\chi^0) = 100\%$

CMS-EXO-12-036





Bibliography

- Dark matter

- Monojets: CMS-PAS-EXO-15-003 ($\sqrt{s} = 13$ TeV), EXO-12-048 ($\sqrt{s} = 8$ TeV)
- Razor dijets: EXO-14-004 (8 TeV)
- Monophotons: EXO-12-047 (8 TeV)
- Mono-Z: EXO-12-054 (8 TeV)
- Mono-W: EXO-12-060 (8 TeV)
- Mono-top: B2G-14-004, B2G-13-004, B2G-12-022 (8 TeV)
- Associated b quarks: B2G-15-007 (13 TeV)

- Unconventional signatures

- Heavy stable charged particles (HSCP):
EXO-15-010 ($\sqrt{s} = 13$ TeV), EXO-13-006, EXO-12-026 ($\sqrt{s} = 8$ TeV)
- Long-lived neutral particles: EXO-12-038, EXO-12-035, EXO-14-017 (8 TeV)
- Stopped long-lived particles: EXO-12-036 (8 TeV)
- Disappearing tracks: EXO-12-034 (8 TeV)
- Displaced lepton pairs: EXO-12-037, EXO-14-012 (8 TeV)

<http://cms-results.web.cern.ch/cms-results/public-results/publications>

Dark Matter

- CMS has studied dark matter signatures with $\sqrt{s} = 7, 8$ and 13 TeV data and has derived limits.
- Simplified models are replacing EFT approach for Run 2 searches.

Unconventional signatures

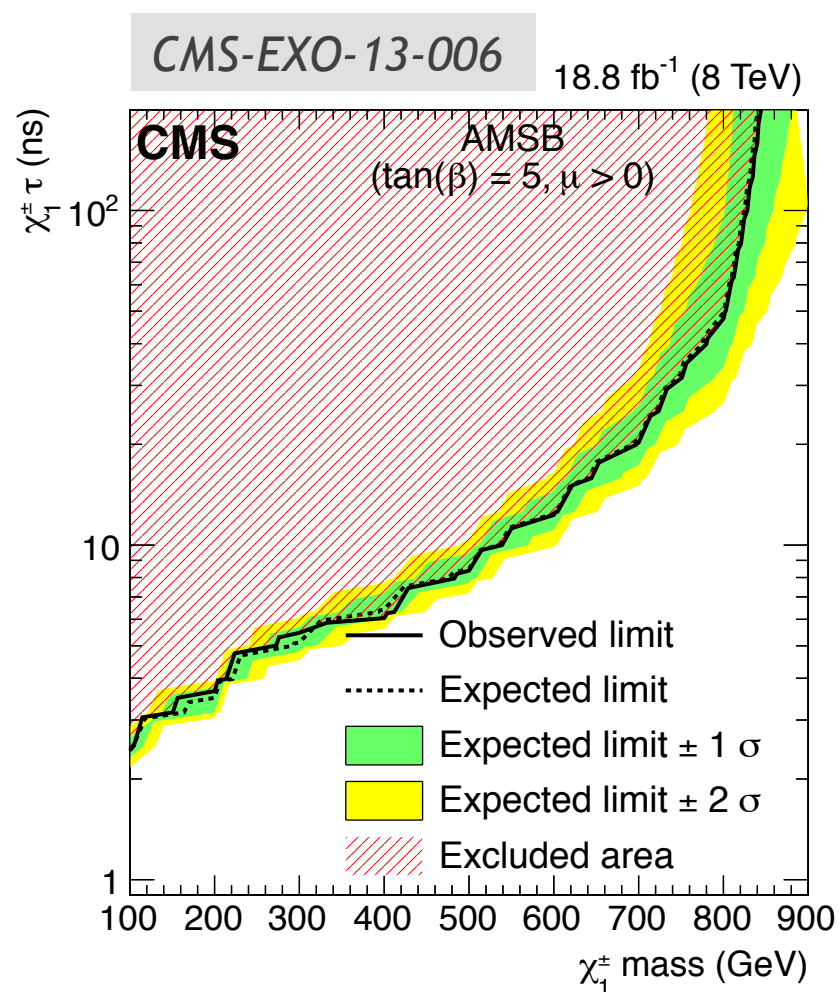
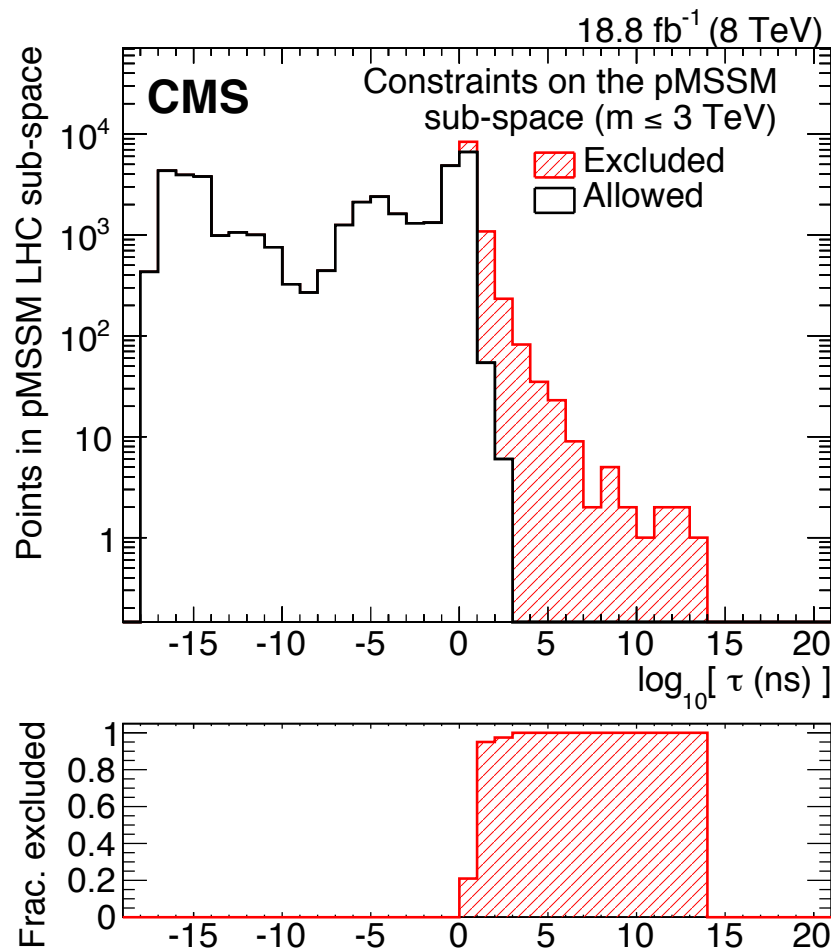
- Several searches for unconventional signatures have been performed.
- Special triggers and analysis techniques have been developed.



BACKUP

Long-lived Heavy Charged Particles

Reinterpretation of previous results on long-lived chargino production [JHEP 07 (2013) 122] in context of pMSSM (first constraints at the LHC) and AMSB models, based on highly-ionizing and penetrating particles



Razor variables

CMS-EXO-14-004

$$M_R \equiv \sqrt{(|\vec{p}_{J_1}| + |\vec{p}_{J_2}|)^2 - (p_z^{J_1} + p_z^{J_2})^2},$$
$$R \equiv \frac{M_T^R}{M_R},$$

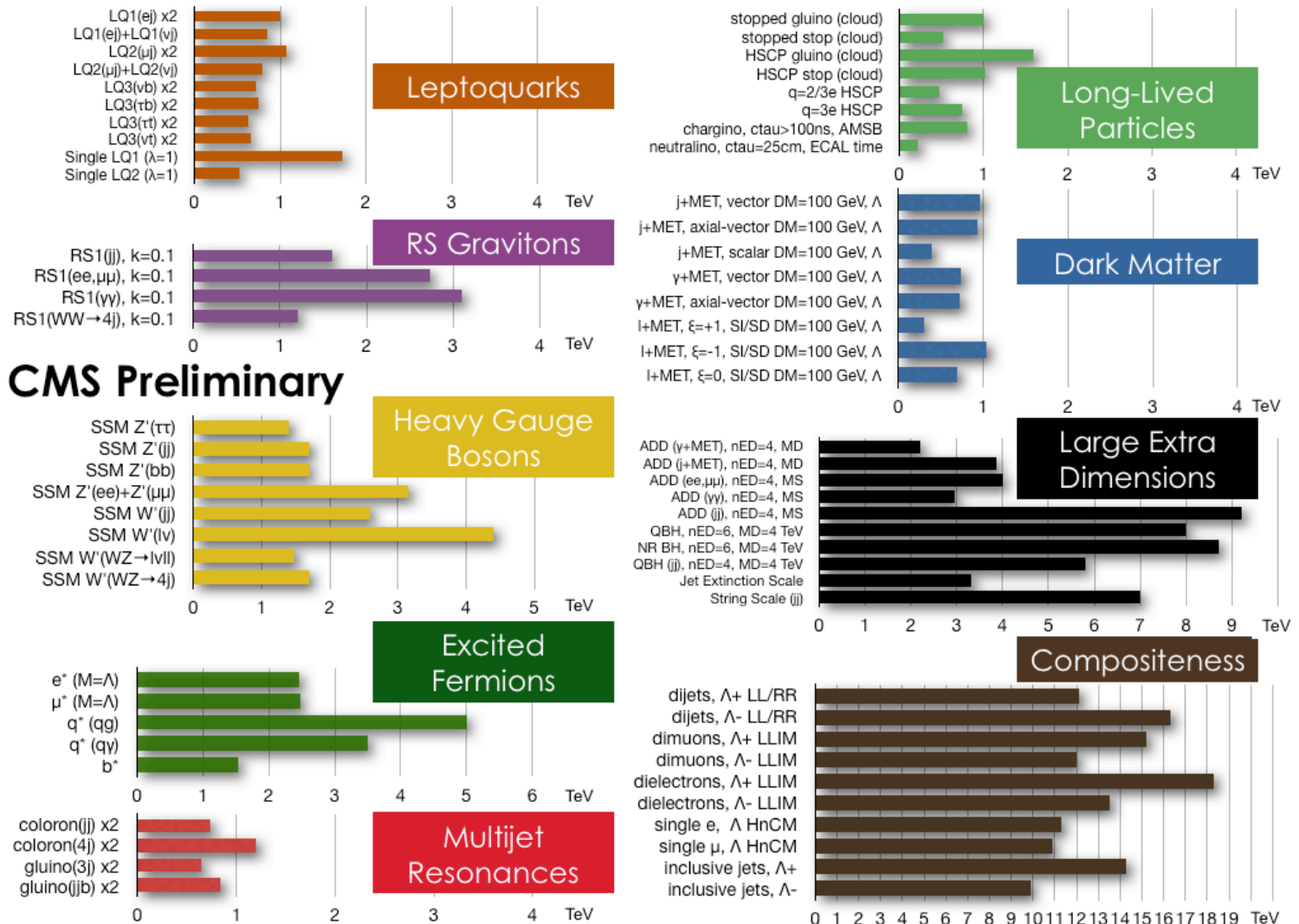
with

$$M_T^R \equiv \sqrt{\frac{E_T^{\text{miss}}(p_T^{J_1} + p_T^{J_2}) - \vec{E}_T^{\text{miss}} \cdot (\vec{p}_T^{J_1} + \vec{p}_T^{J_2})}{2}}$$



Exotica Limits

December 2015



CMS Exotica Physics Group Summary – Dec Jamboree, 2015

Beyond Two Generations Limits

CMS Searches for New Physics Beyond Two Generations (B2G)

95% CL Exclusions (TeV)

