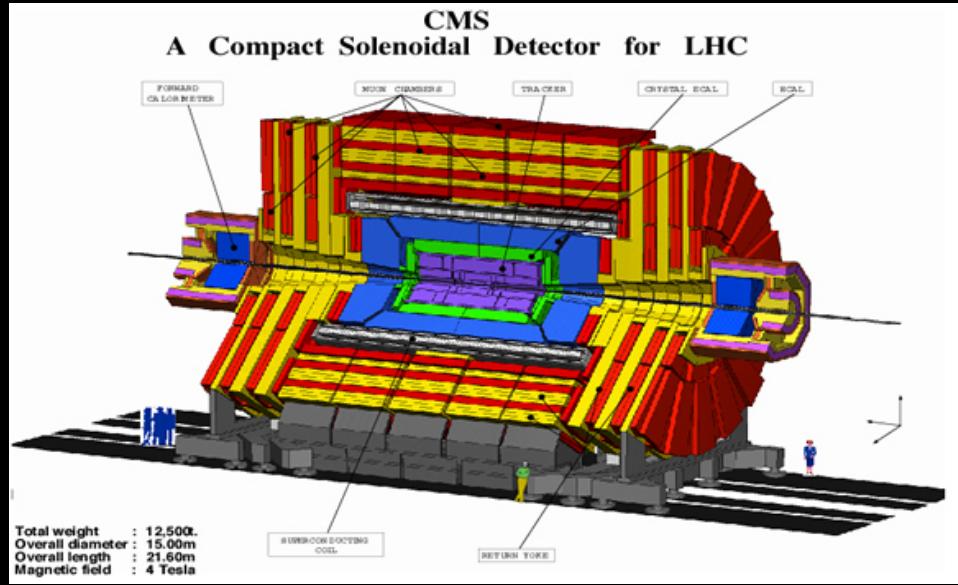
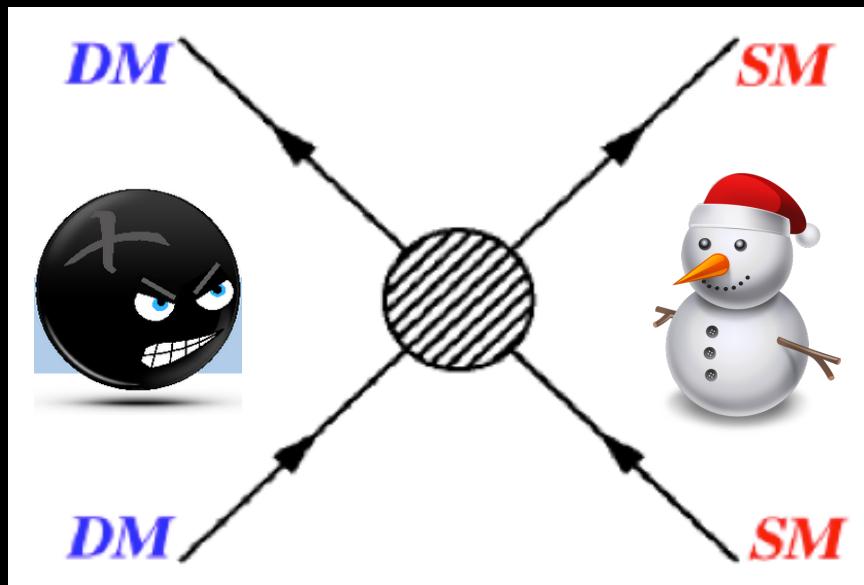


Dark matter searches with CMS



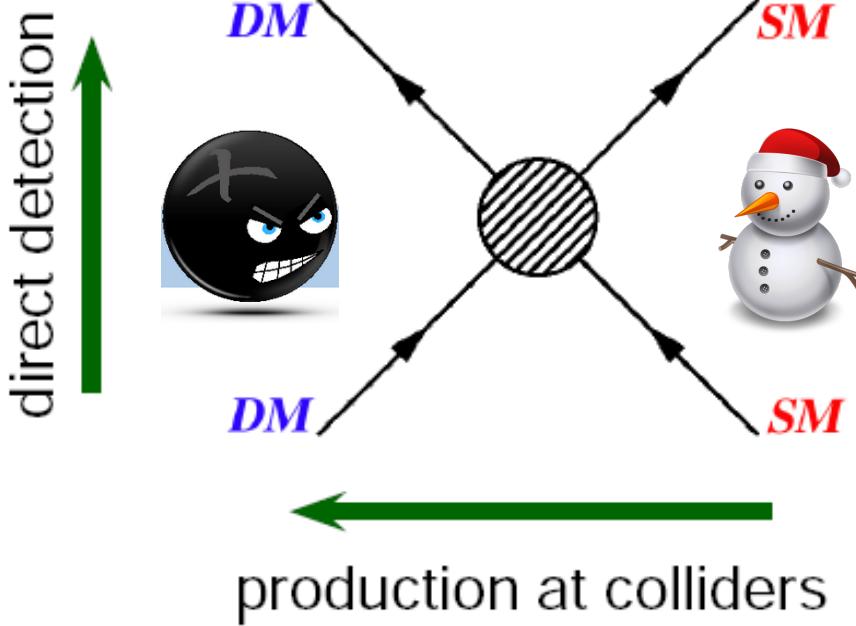
Manfred Jeitler

Institute of High Energy Physics of the Austrian Academy of Sciences

for the CMS collaboration

Ways to look for Dark Matter

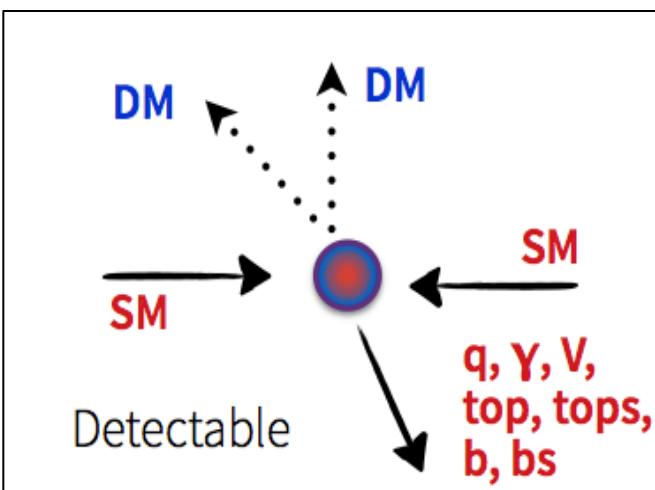
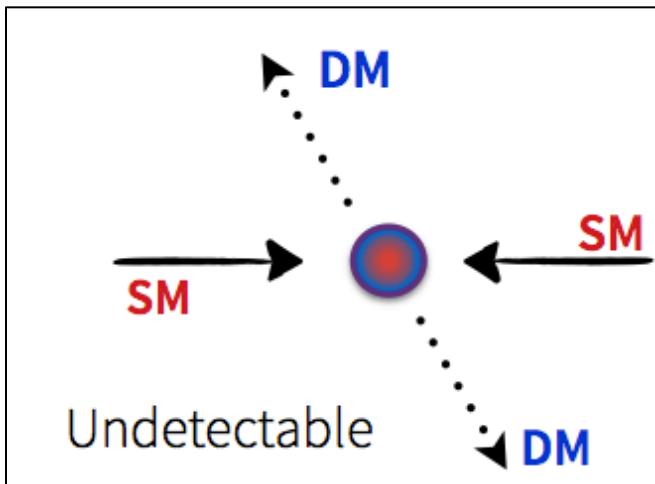
thermal freeze-out (early Univ.)
indirect detection (now)



- indirect: CM annihilation
 - Pamela, Fermi, AMS, IceCube
- direct: DM-nucleon scattering
 - liquid noble-gas detectors
 - cryogenic detectors
- production: at colliders

- how can we get a signal from “invisible” objects?

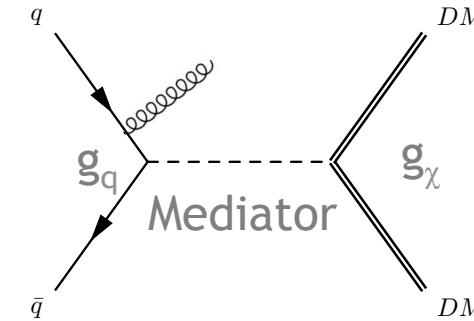
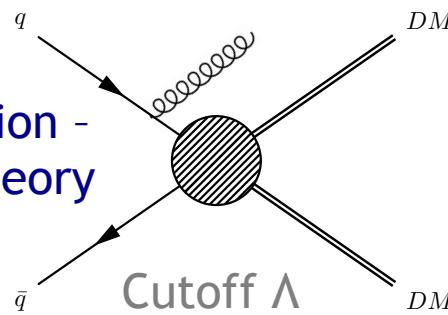
Ways to look for Dark Matter



- select events with visible particles from Initial-State Radiation (ISR)
- look for ISR-object plus missing transverse momentum
 - “ E_T^{miss} ”, “missing ET”, “MET”
 - → “mono-X” searches
 - mono-jet, mono-photon, mono-Z, mono-W
- production in decay chains
 - SUSY cascades
 - Higgs portal

Effective Field Theories vs. Simplified Models

Contact interaction -
effective field theory



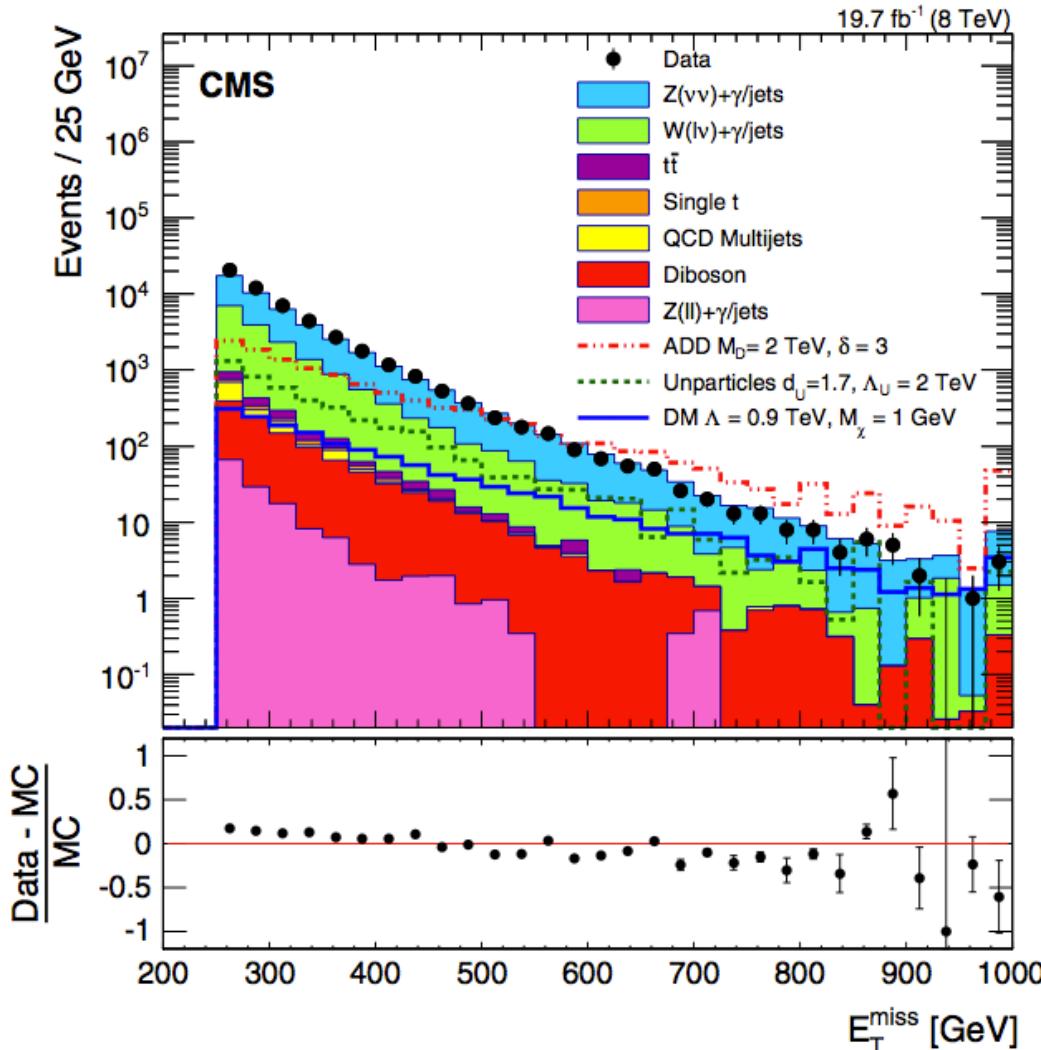
Simplified models

- so far, Dark-Matter search interpretation mostly in terms of Effective Field Theories
 - contact interaction, valid if mediator mass \gg momentum transfer
 - 8 TeV analyses
 - invalid at high energy transfer

- now: use Simplified Models
 - for 13 TeV analyses
 - explicit definition of mediator particles
 - benchmark models:
ATLAS/CMS DM Forum
 - » arXiv 1507.0966 (2015), 1603.04156 (2016)

Monojet

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



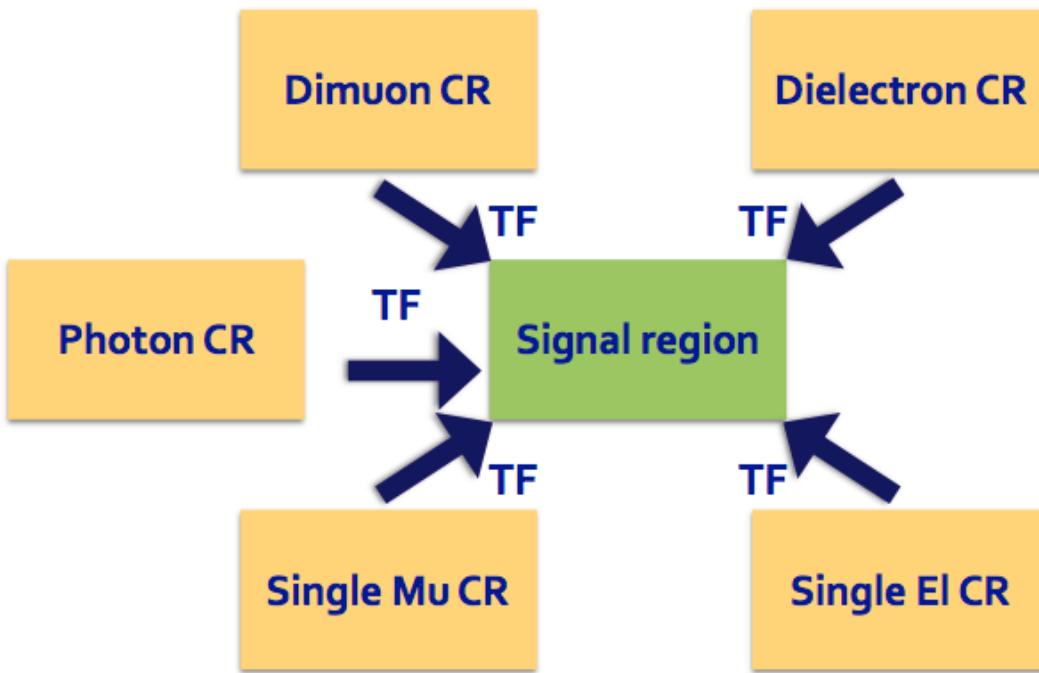
- require jet
- require E_T^{miss}
- veto leptons

dominant backgrounds:

- $Z(vv)+\gamma/\text{jets}$
- $W(lv)+\gamma/\text{jets}$

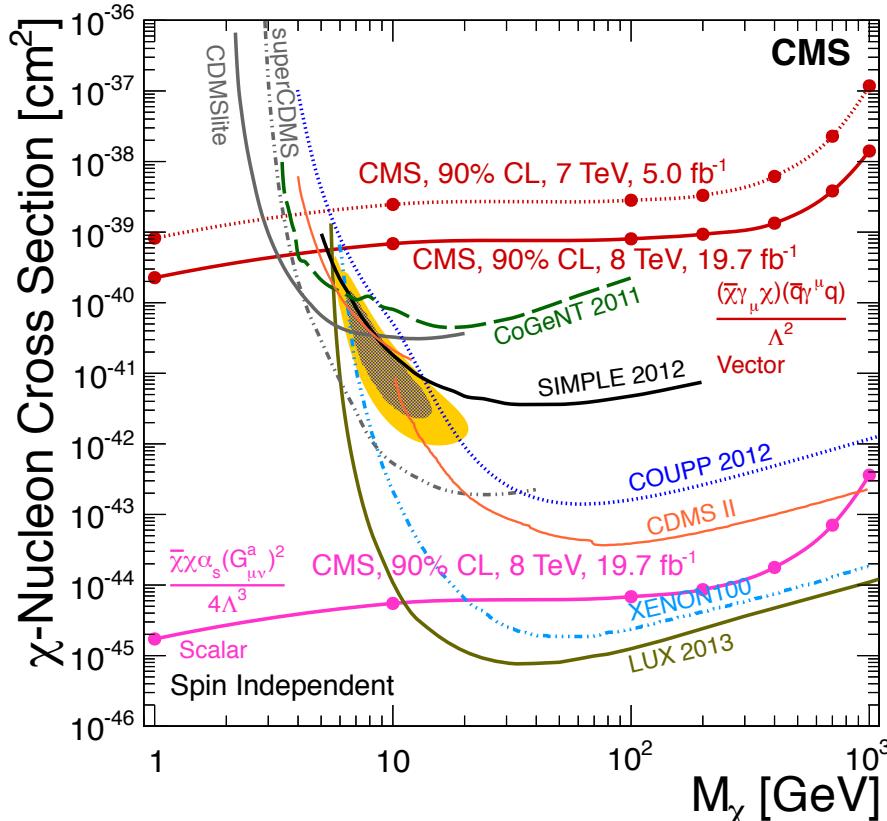
estimate using $Z(\mu\mu)$
and $W(\mu\nu)$ events

Monojet: backgrounds

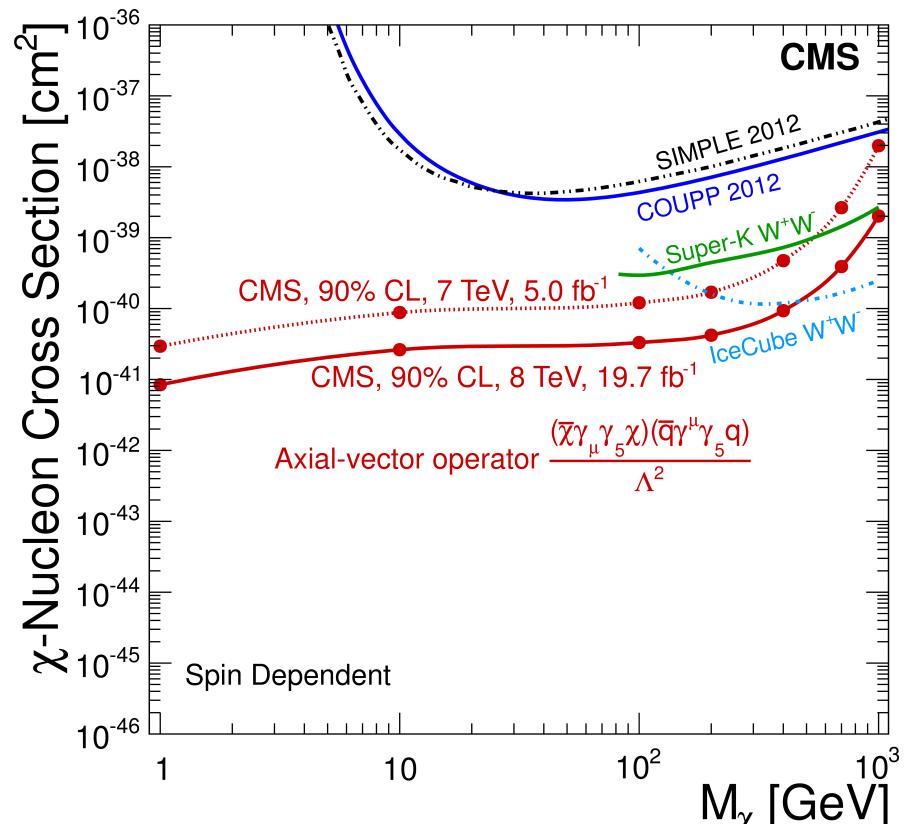


- data-driven analysis
- use specific control regions with enriched backgrounds
- apply to signal region using “Transfer Factors”

Monojet: limits on DM-nucleon cross sections

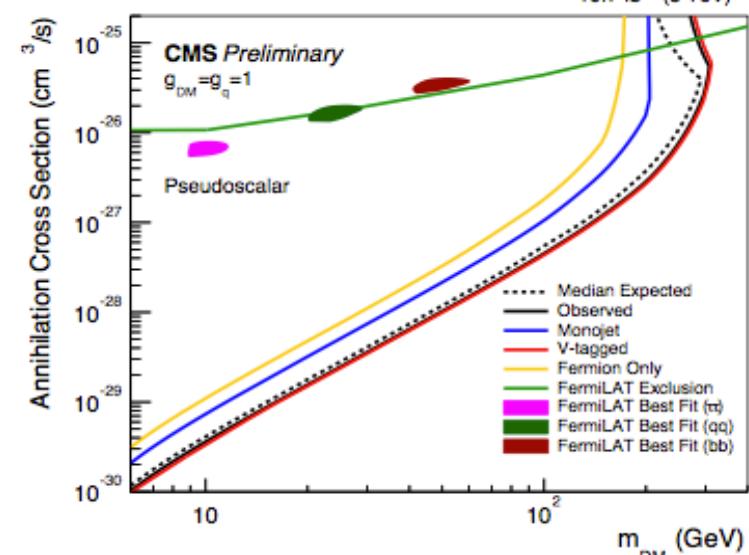
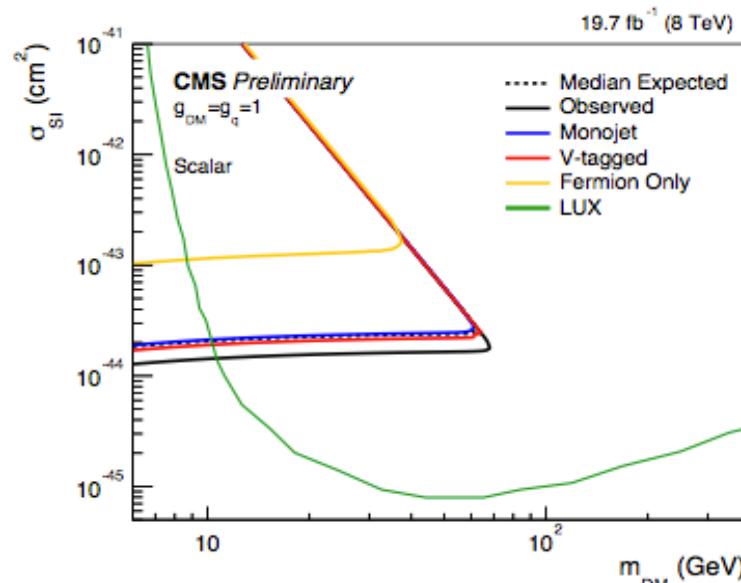
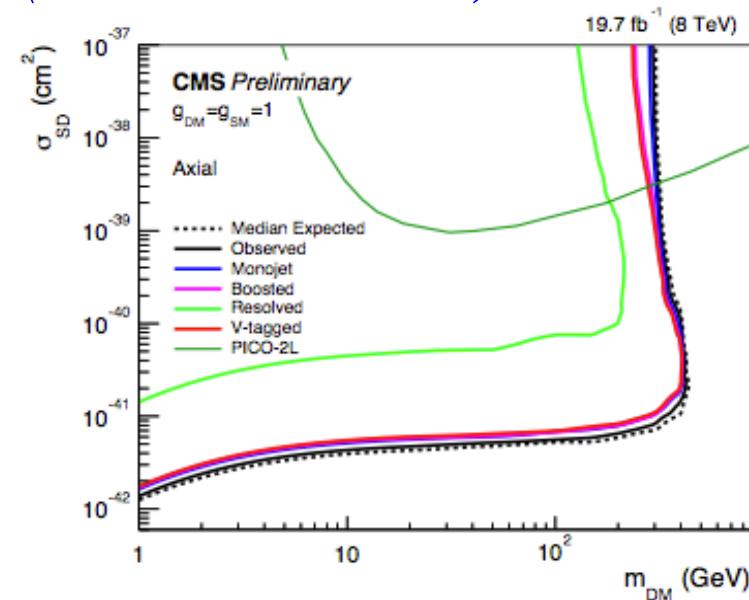
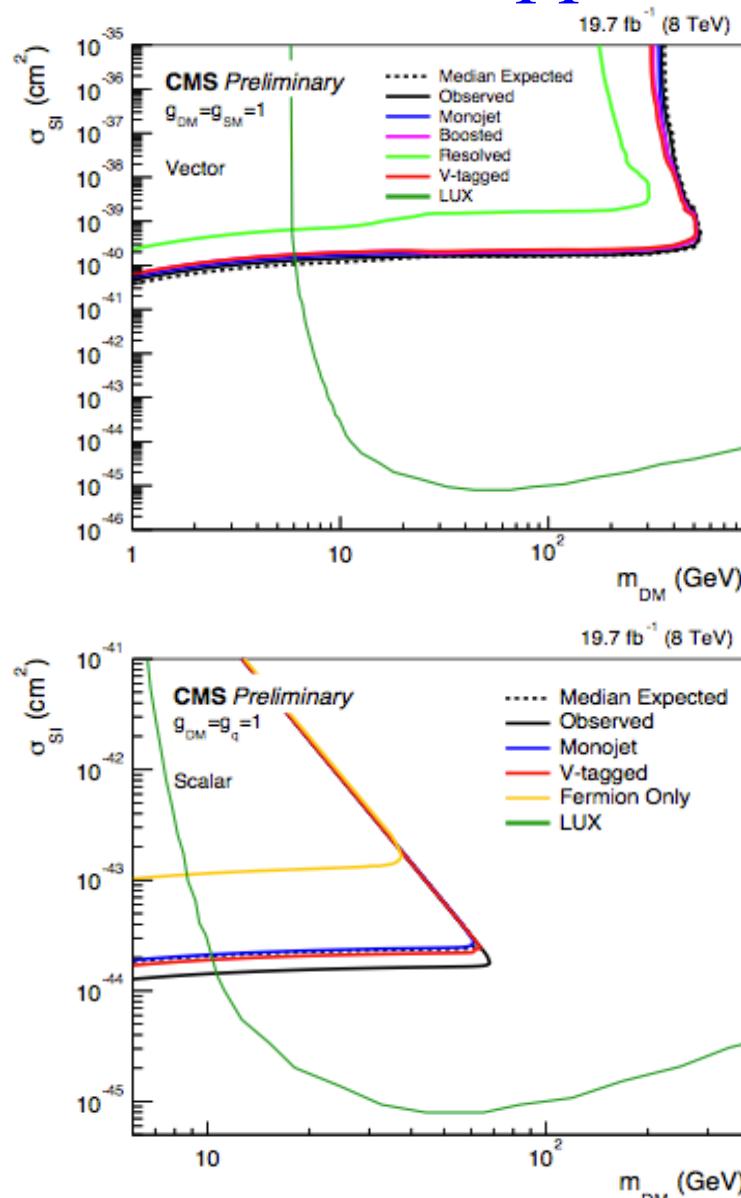


spin independent (vector and scalar)

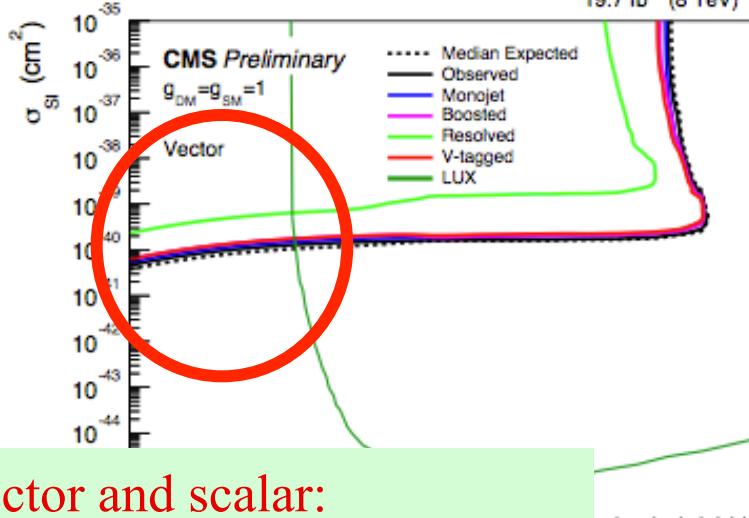


spin dependent (axial-vector)

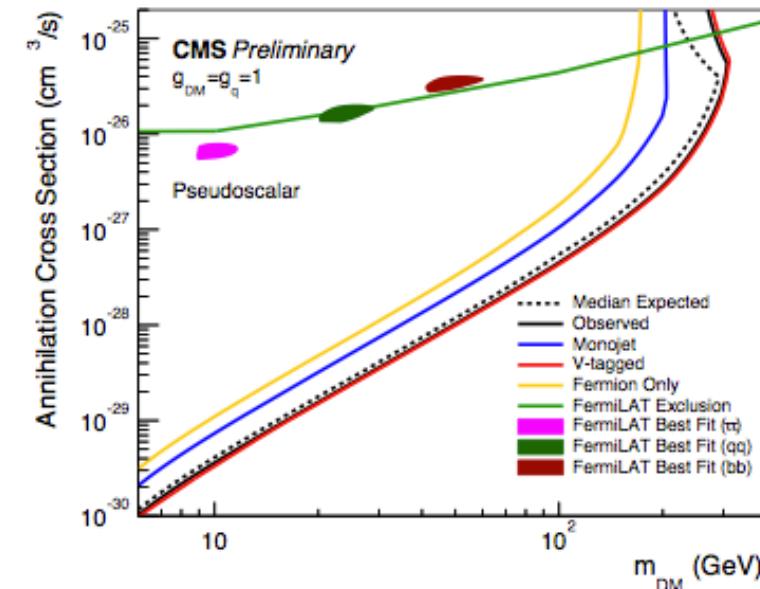
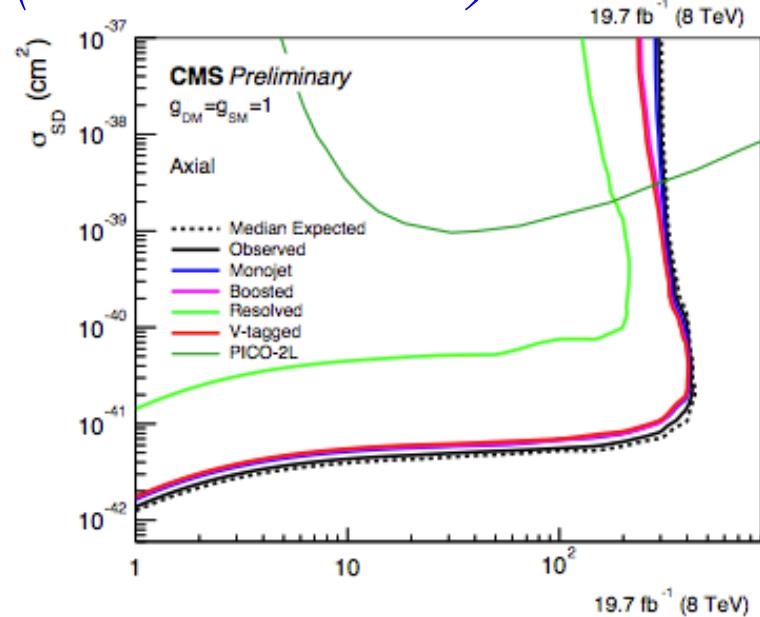
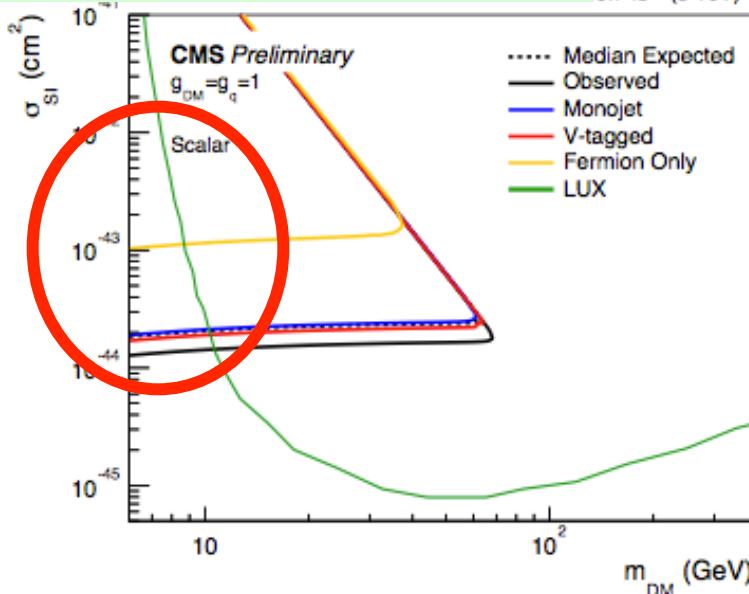
Monojet limits in Simplified Models approach (EXO-12-055)



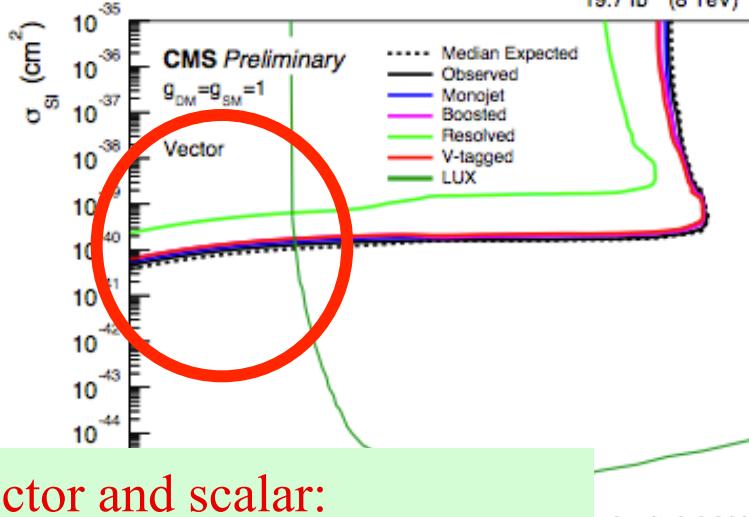
Monojet limits in Simplified Models approach (EXO-12-055)



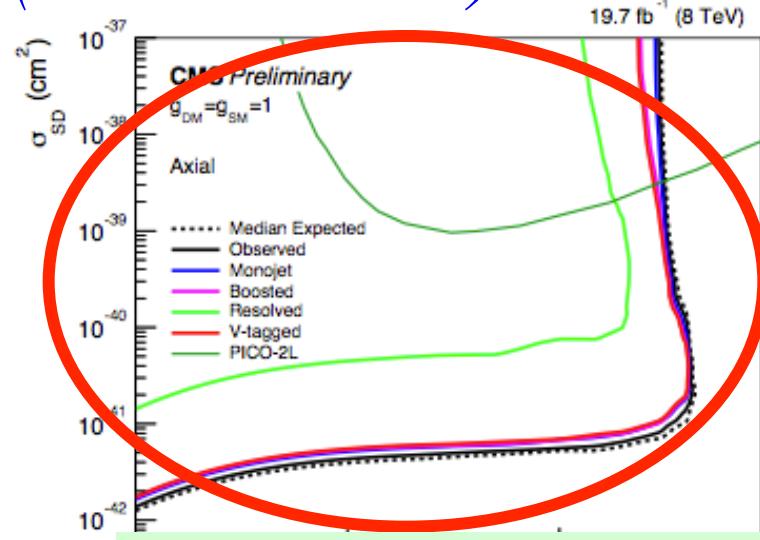
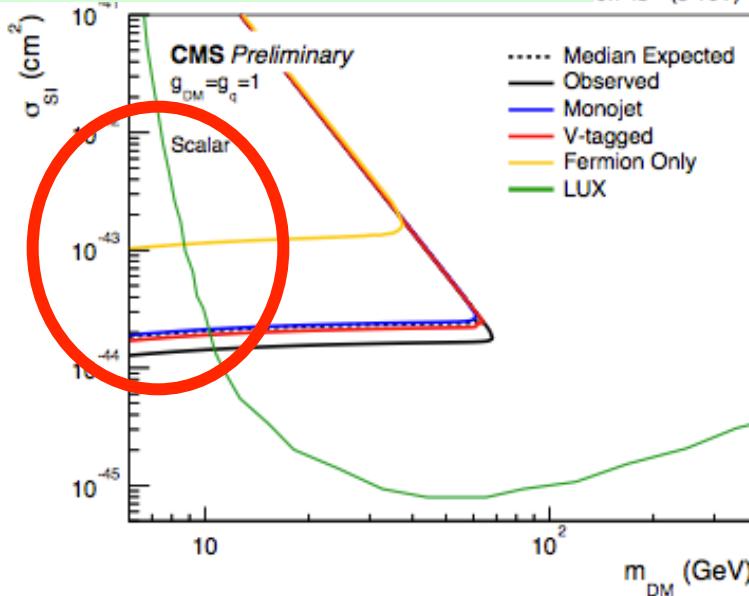
vector and scalar:
LHC contributes at low m_{DM}



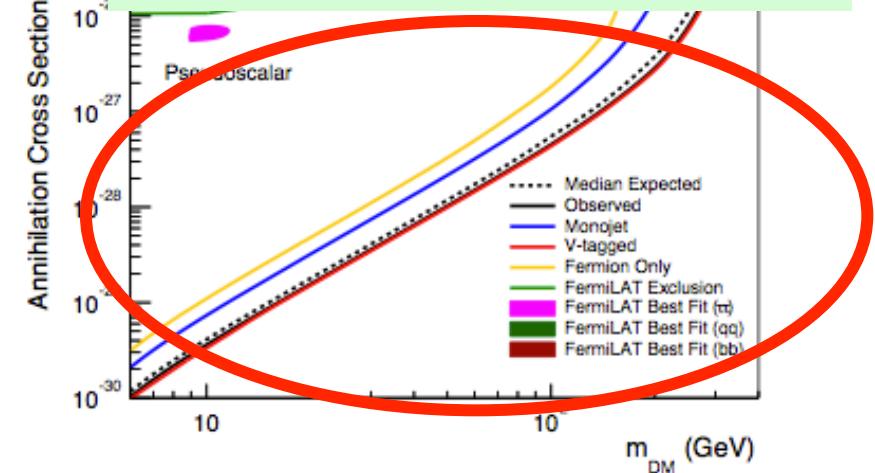
Monojet limits in Simplified Models approach (EXO-12-055)



vector and scalar:
LHC contributes at low m_{DM}



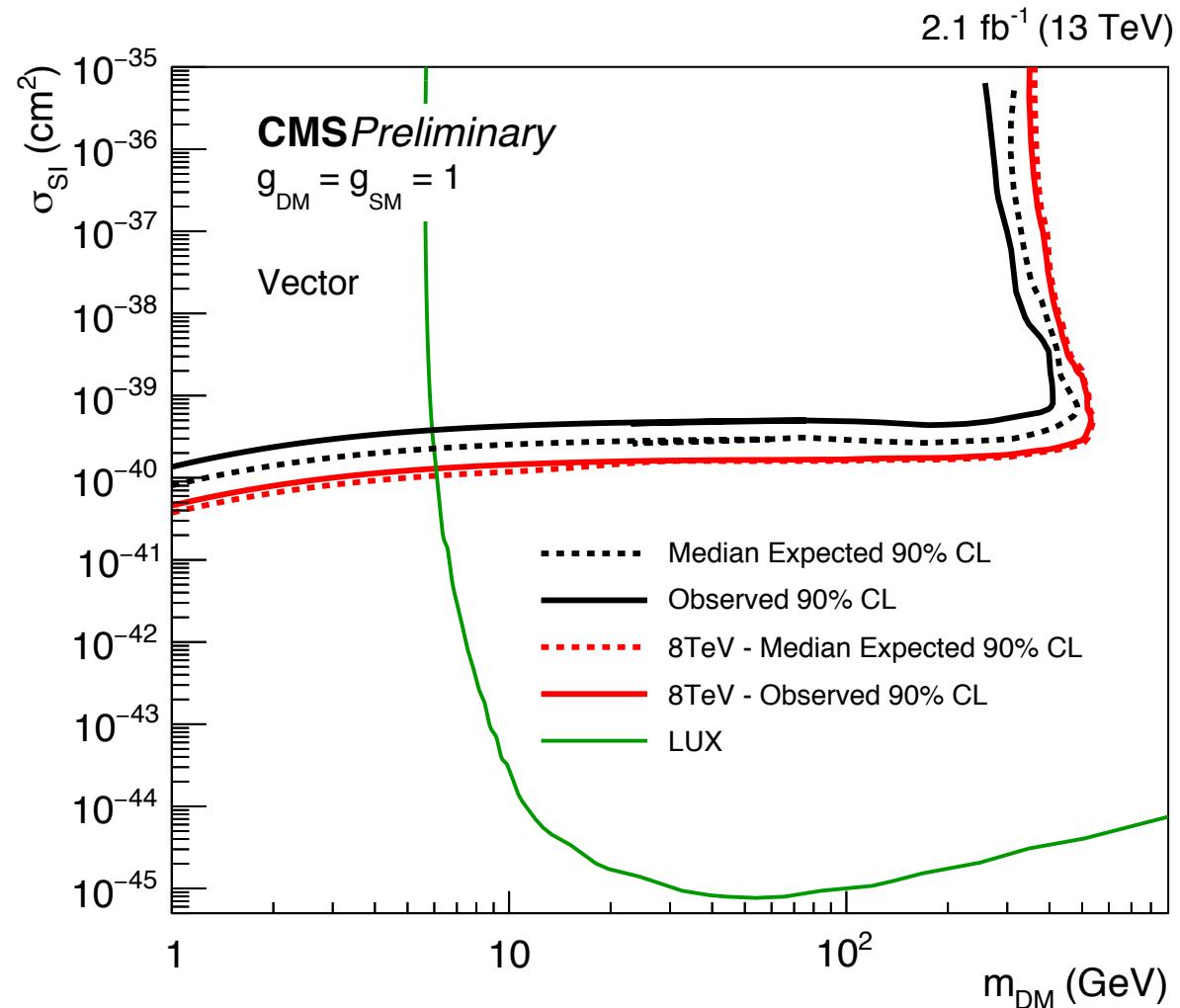
axial and pseudoscalar:
LHC yields strongest constraints over wide range



Monojet: first results at 13 TeV

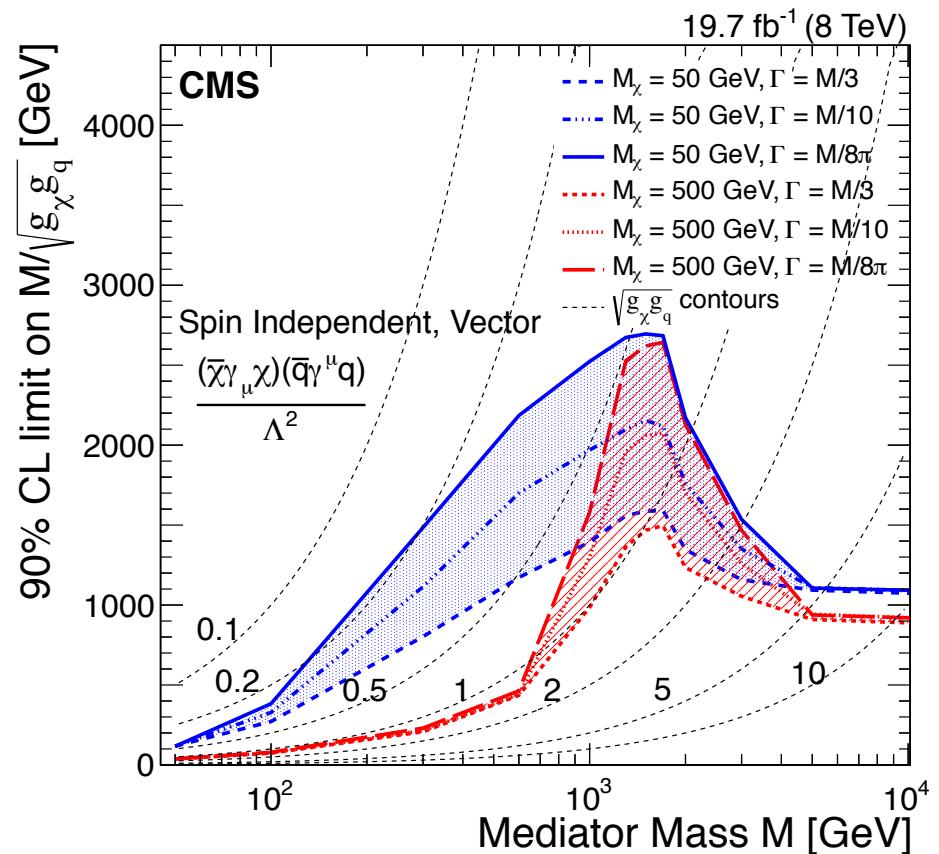
- update with 13-TeV data: CMS-EXO-15-003

will reach Run-1
(8 TeV)
sensitivity at
 5 fb^{-1}



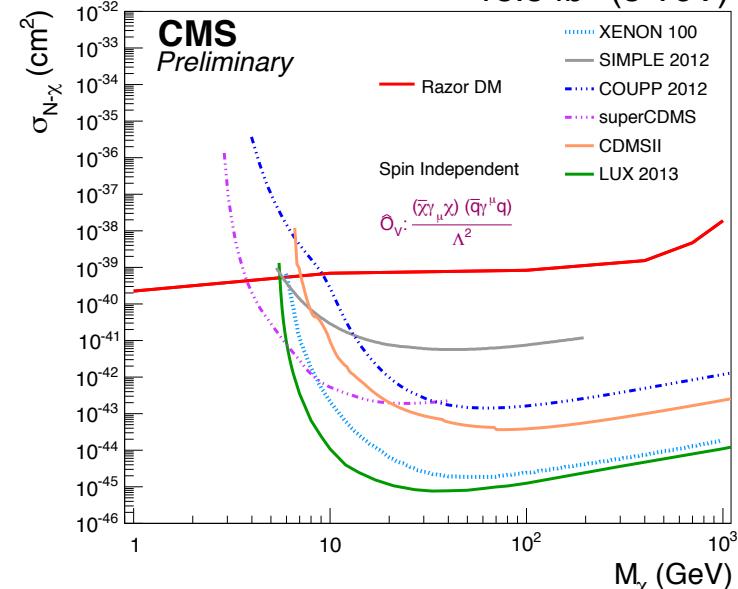
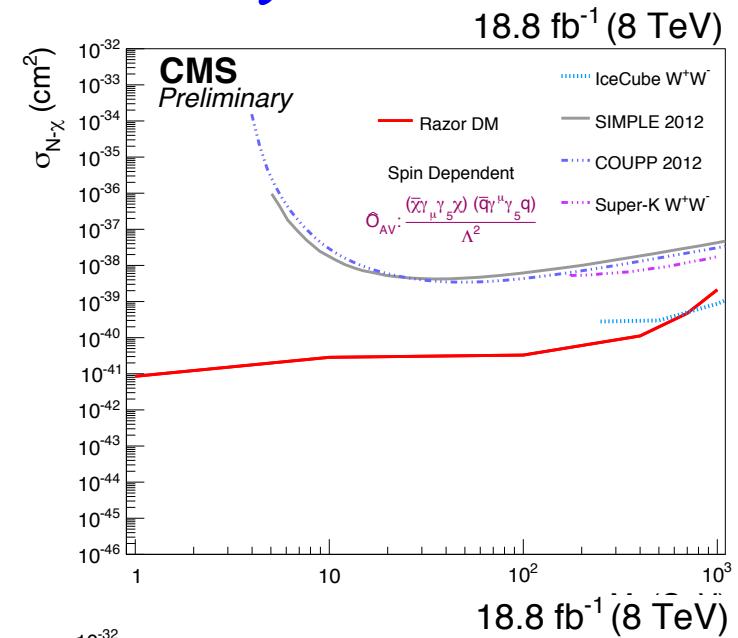
Monojet: analysis using Simplified Models

- dependence of mediator mass divided by coupling on mediator mass
- approximate Λ at high mediator mass
- higher limits in region where mediator can be produced at LHC



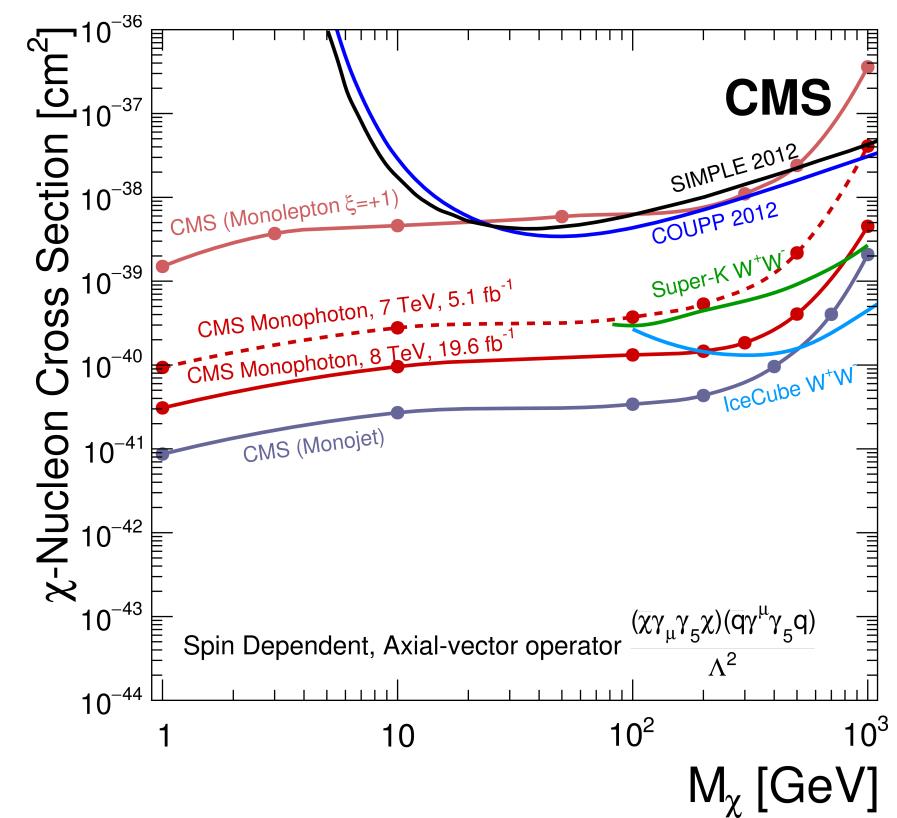
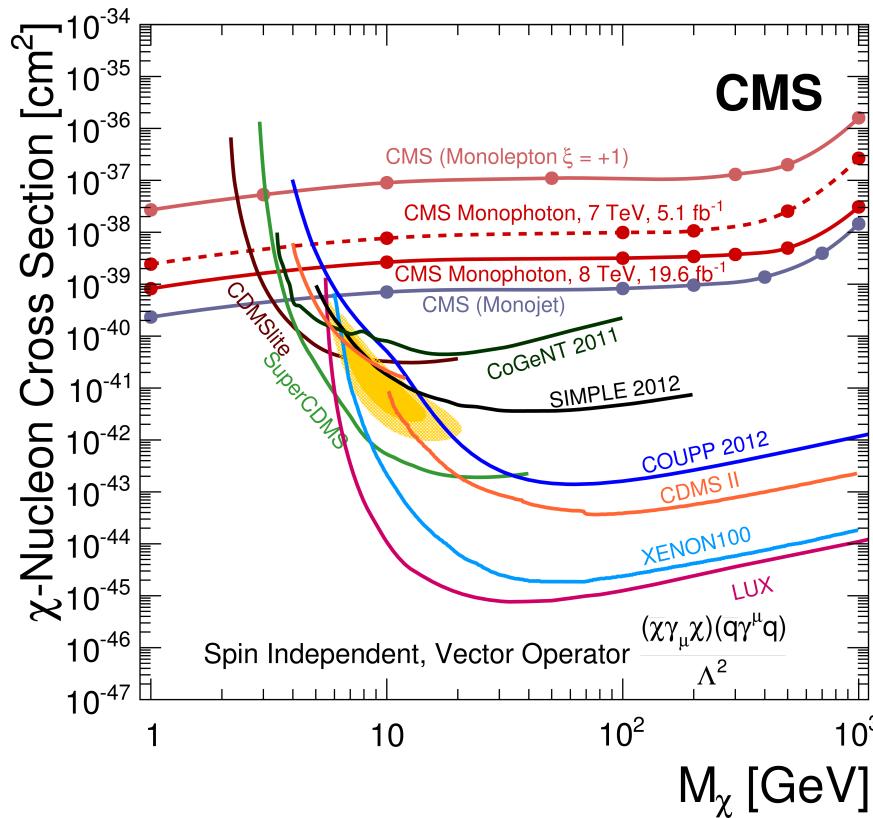
Razor dijet analysis

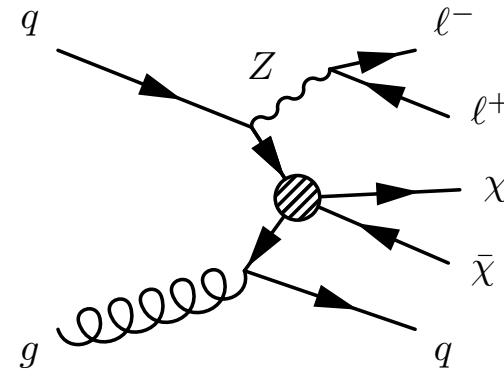
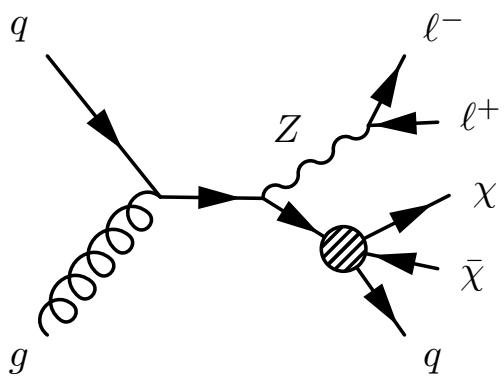
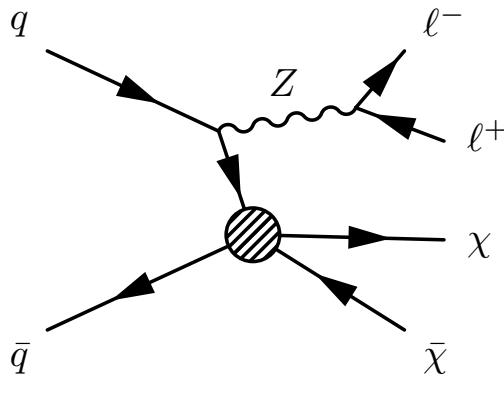
- CMS-PAS-EXO-14-004
- event selection: ≥ 2 jets, E_T^{miss} , no (isolated) leptons
- “razor” variables used to quantify transverse balance of jet momenta
- separate analyses with / without b-jets
- dijet topology: good discrimination against SM backgrounds
 - compensates for less statistics due to more required jets



Monophoton

- CMS-EXO-12-047, PLB 755 (2016)102
- single photon ($E > 145$ GeV, barrel only), $E_T^{\text{miss}} > 140$ GeV
- dominant background: $Z\gamma \rightarrow v\bar{v}\gamma$, $W\gamma \rightarrow l\bar{v}\gamma$





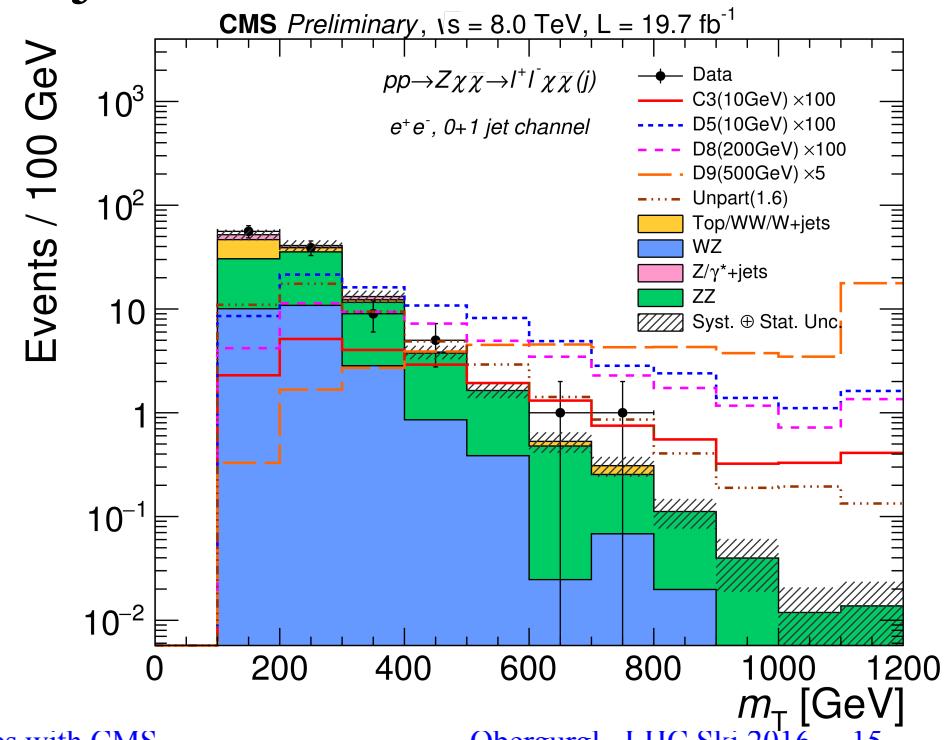
■ CMS-EXO-12-054

■ $Z \rightarrow \mu\mu$ or $Z \rightarrow ee$

■ $E_T^{\text{miss}} > 80 \text{ GeV}$

— back-to-back with leptons

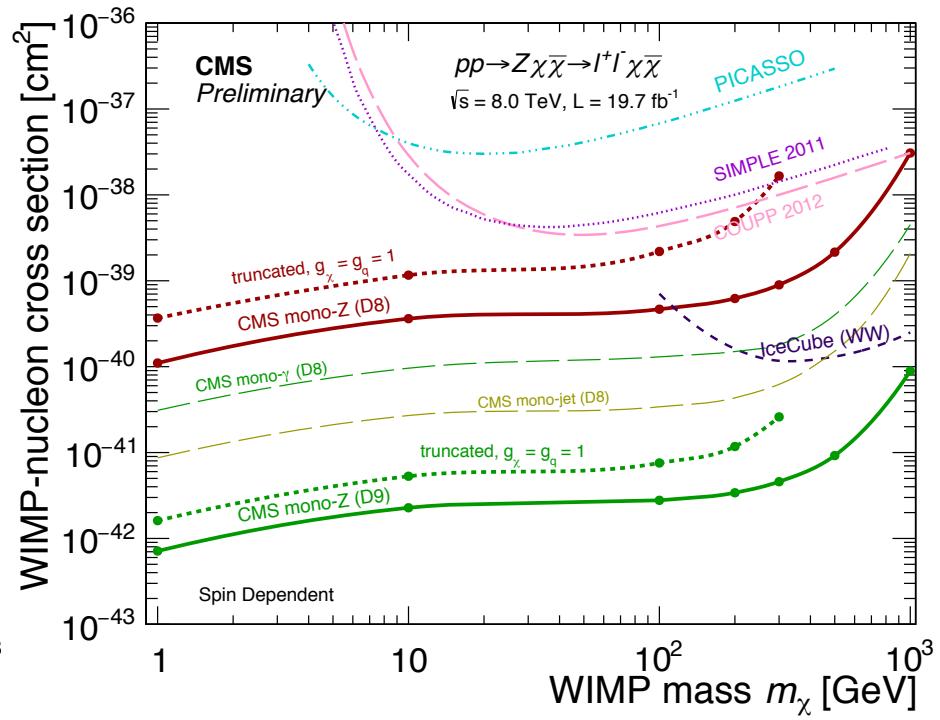
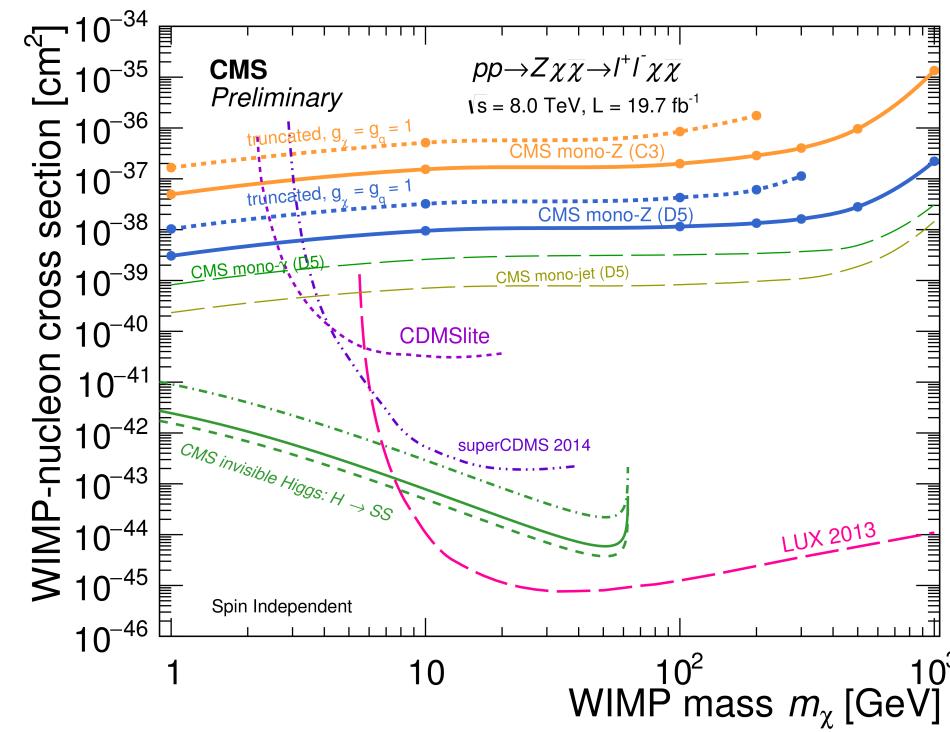
■ $\leq 1 \text{ jet}$



Mono-Z

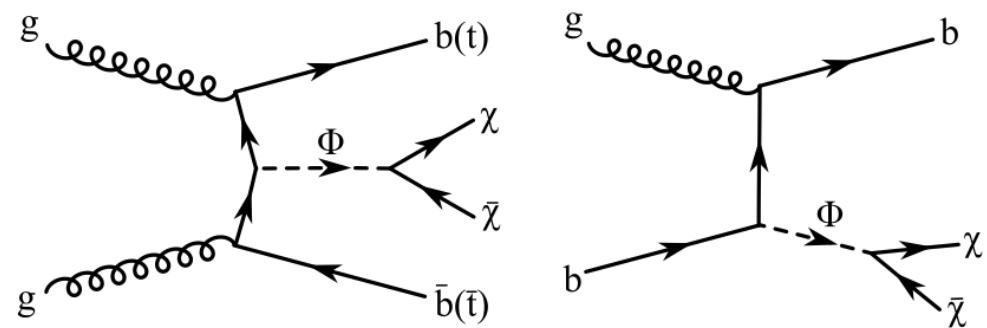
■ DM-nucleon interaction cross section limits

- “truncated” limits: removing events with too high momentum transfer ($Q > \sqrt{g_q g_\chi} \Lambda$)
- also showing mono-photon and mono-jet limits

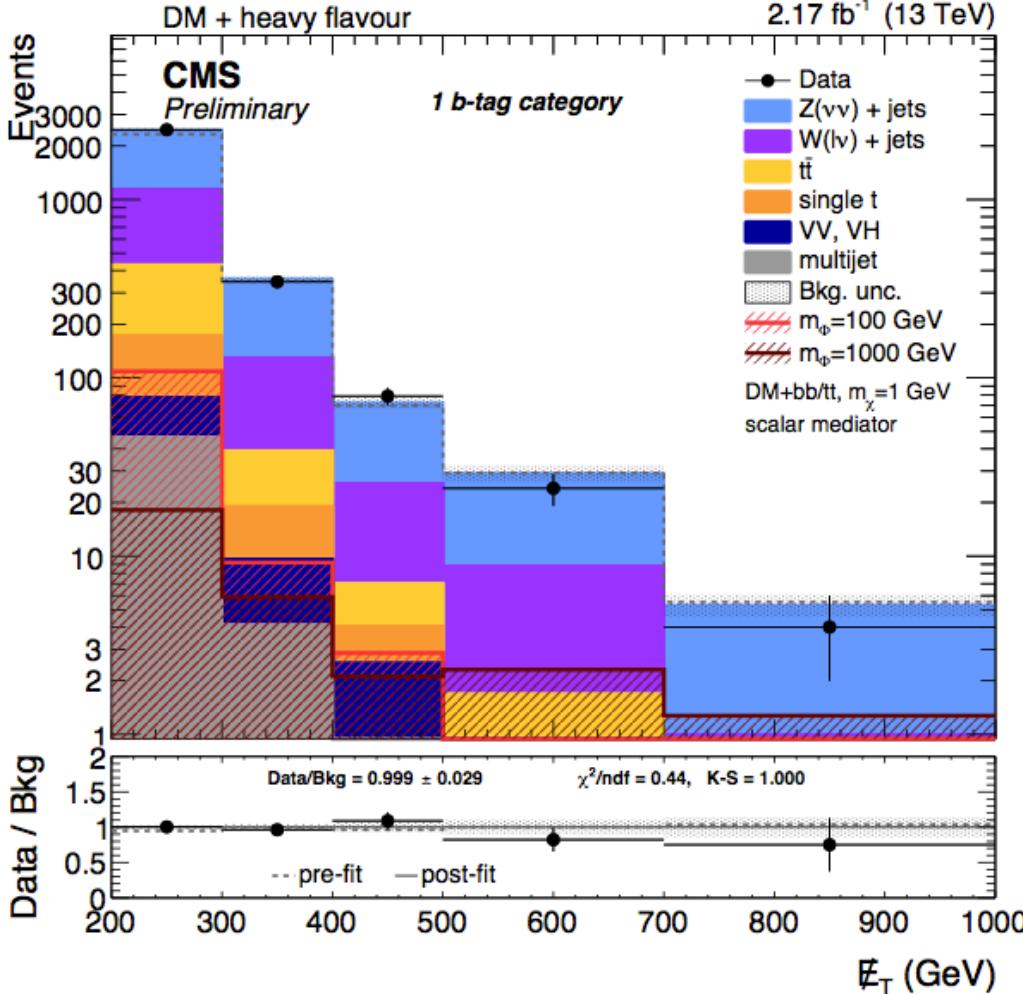


Heavy flavor

- CMS PAS B2G-15-007
- heavy-flavor quarks could strongly couple to scalar and pseudoscalar mediators
 - Yukawa coupling
- look for E_T^{miss} and one or two jets
 - b-tagged jets
 - even in $bb\Phi$ topology often only 1 jet reconstructed
 - also sensitive to top decays



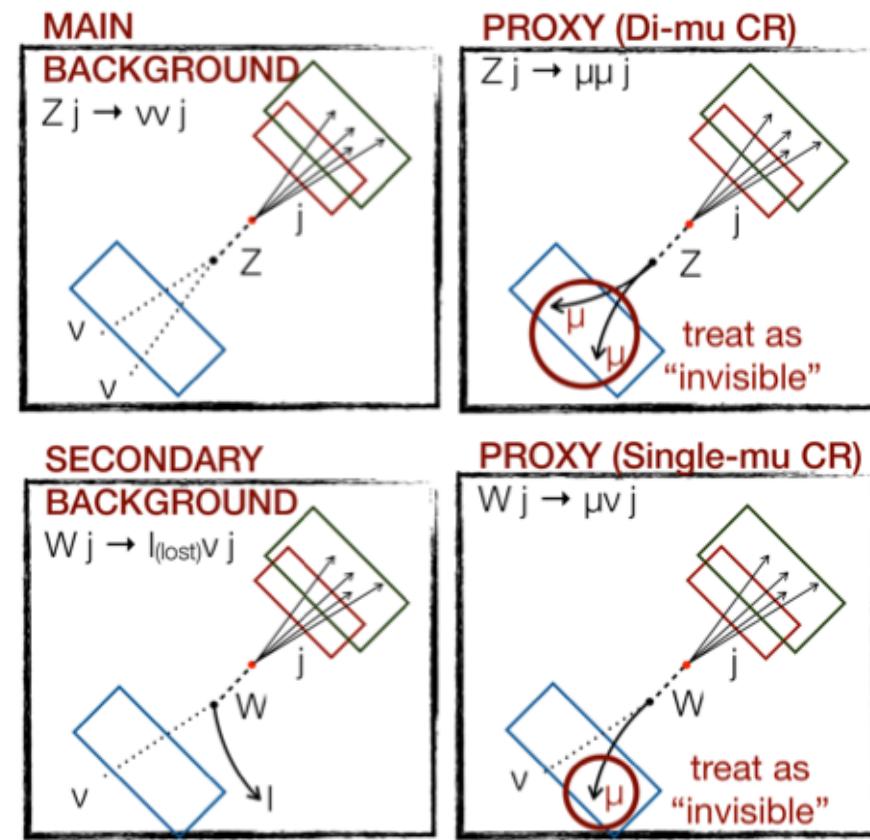
Heavy flavor



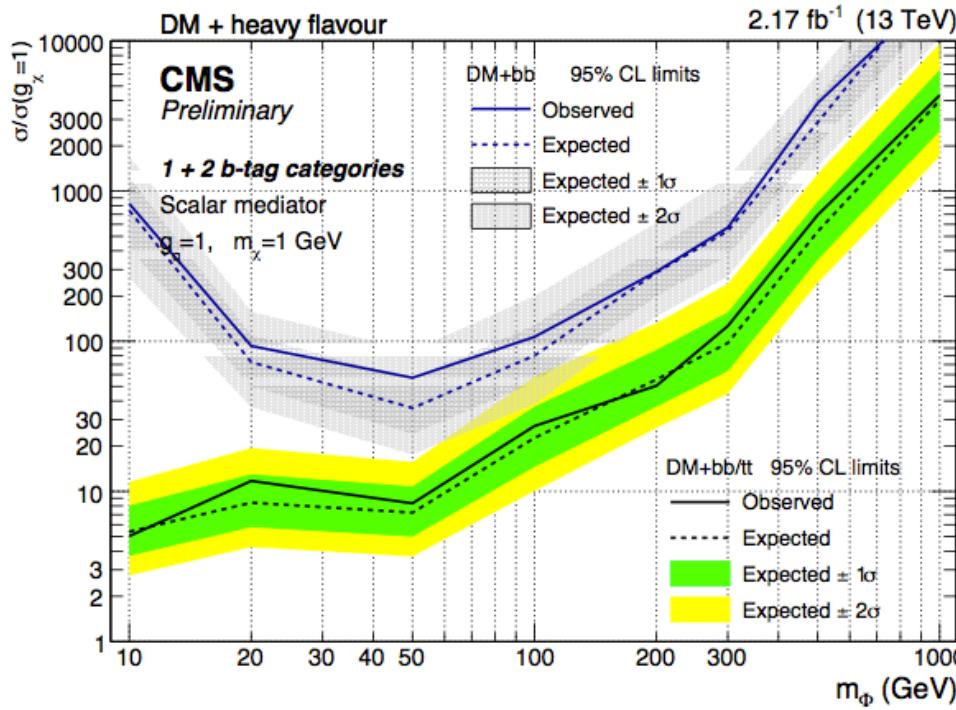
Dominant backgrounds:

- Z(vv) + jets (50%)
- W(lv) + jets (40%)

Control Regions:

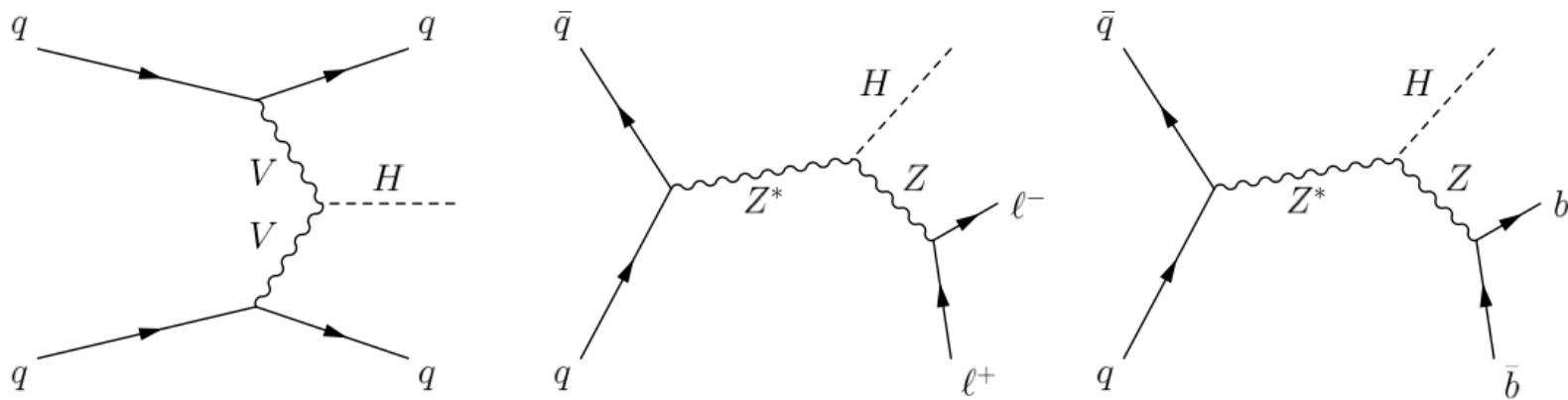


Heavy flavor



- Exclusion limit for heavy flavor vs. mediator mass
 - bb (top)
 - bb/tt (bottom)
- DM candidate mass assumed as 1 GeV

Invisible Higgs decays



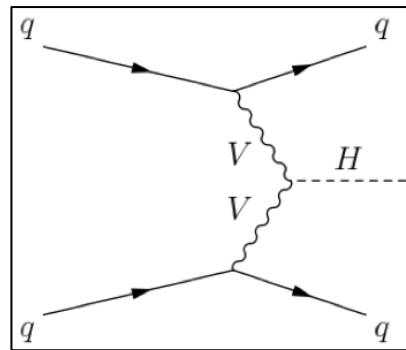
- CMS-HIG-13-030
- production modes:
 - vector boson fusion
 - associated ZH
 - » $Z \rightarrow \ell\ell, Z \rightarrow bb$
- “Higgs-Portal” models of DM
 - Higgs boson is mediator between SM and DM particles
- set limits on additional (invisible) Higgs particles and on invisible branching fraction of 125-GeV Higgs

Invisible Higgs decays

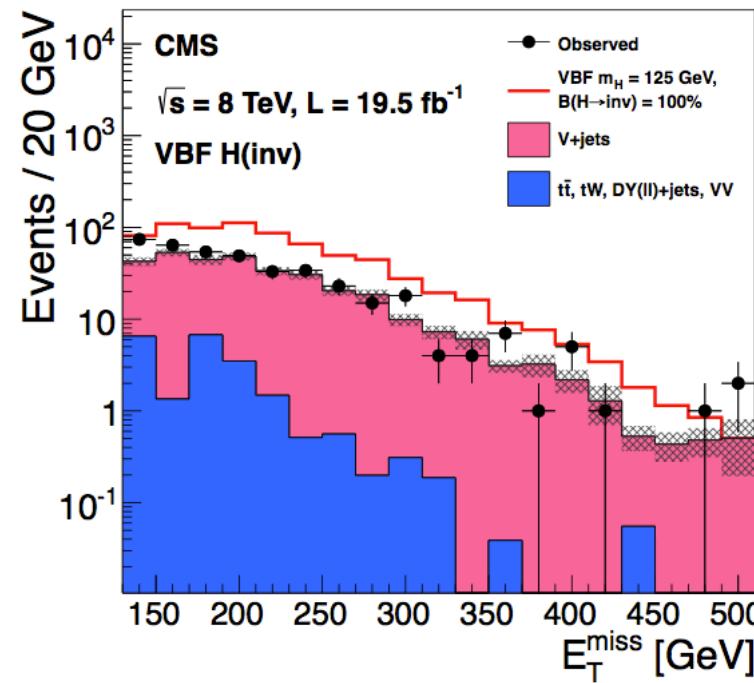
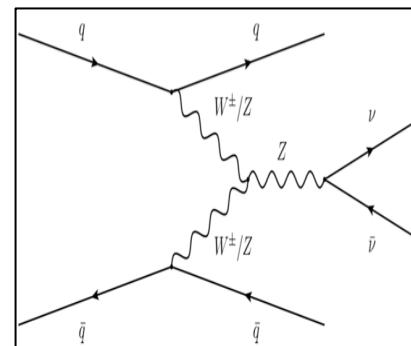
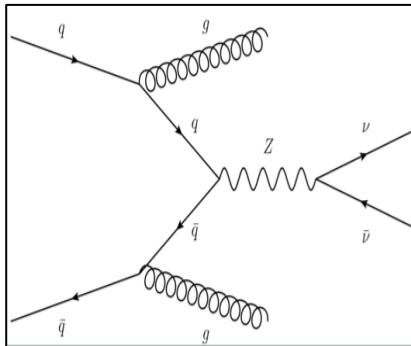
“ E_T^{miss} ” distribution for Vector Boson Fusion after optimized selection

dominant background: $Z / W + \text{jets}$
data described well by background

VBF signal

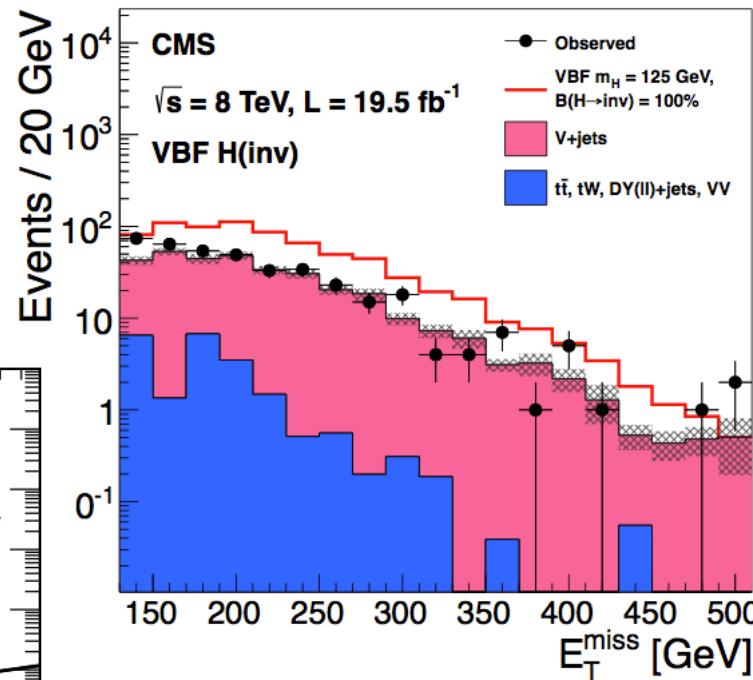
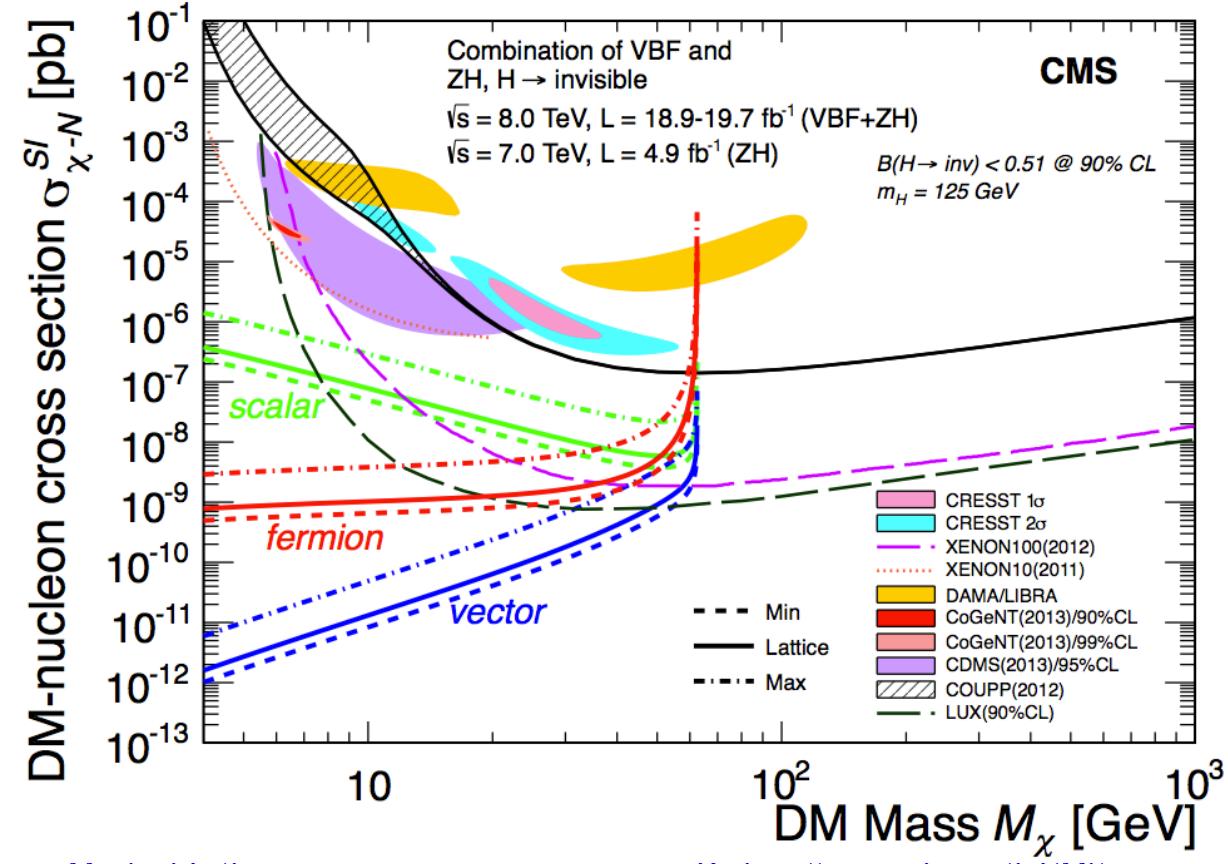


$Z \rightarrow vv$ background



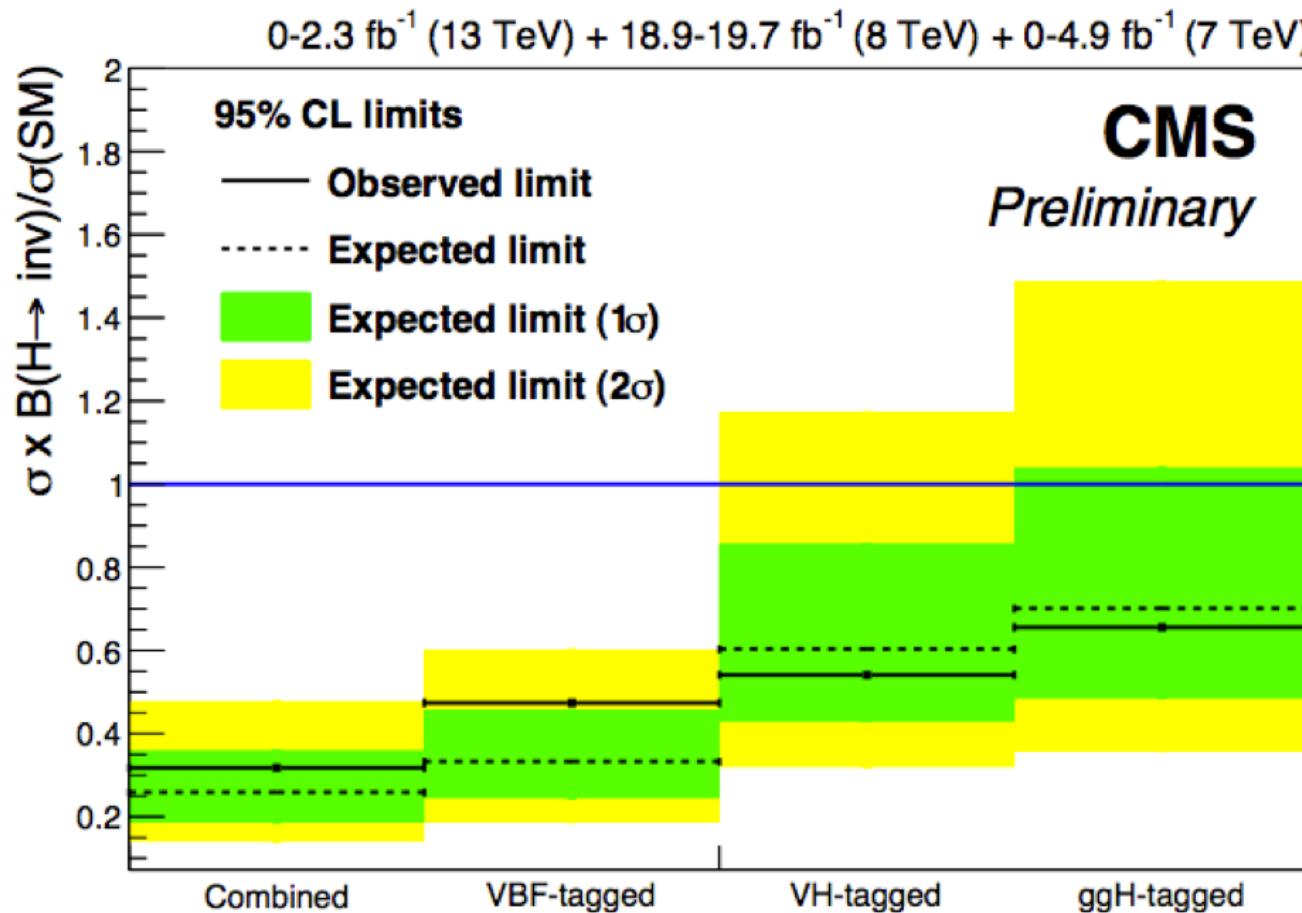
Invisible Higgs decays

“ E_T^{miss} ” distribution for Vector Boson Fusion after optimized selection
 dominant background: Z / W + jets
 data described well by background



Upper limits on the spin-independent DM-nucleon cross section in Higgs-portal models (derived for Higgs mass of 125 GeV and $\text{Br}(H \rightarrow \text{inv}) < 0.51$)

Invisible Higgs decays



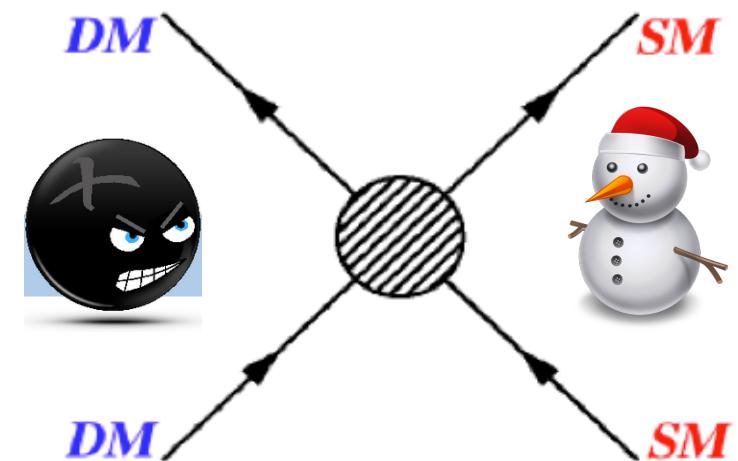
Combination of
Run 1 and Run 2
results

CMS PAS HIG-16-009

Combined limit from
VBF-, VH- and ggH-
tagged analyses on
invisible branching
fraction of 125-GeV
Higgs: < 32%

Summary

- Data-based techniques employed to estimate background contamination
- With rising LHC energy and momentum transfer, important to complement Effective Field Theory approach by “Simplified Models”, taking into account the mediator particle
- ☹ So far, no evidence for Dark Matter (or other BSM physics) at $\sqrt{s} = 7$ and 8 TeV
- ☺ For $\sqrt{s} = 13$ TeV we are expecting significant luminosity only starting this year – stay tuned!



BACKUP

- Dark matter

- Monojets: CMS-PAS-EXO-15-003 ($\sqrt{s} = 13 \text{ TeV}$), EXO-12-048 ($\sqrt{s} = 8 \text{ TeV}$)
 - *EPJC 75 (2015) 235*
- 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)
- Invisible Higgs: CMS-HIG-13-030

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

“Razor” variables

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

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

Unlike the razor SUSY searches, which focus on events with large values of M_R , this study considers events with low values of M_R , using R^2 as the discriminating variables between signal and background



E

CMS Experiment at LHC CERN

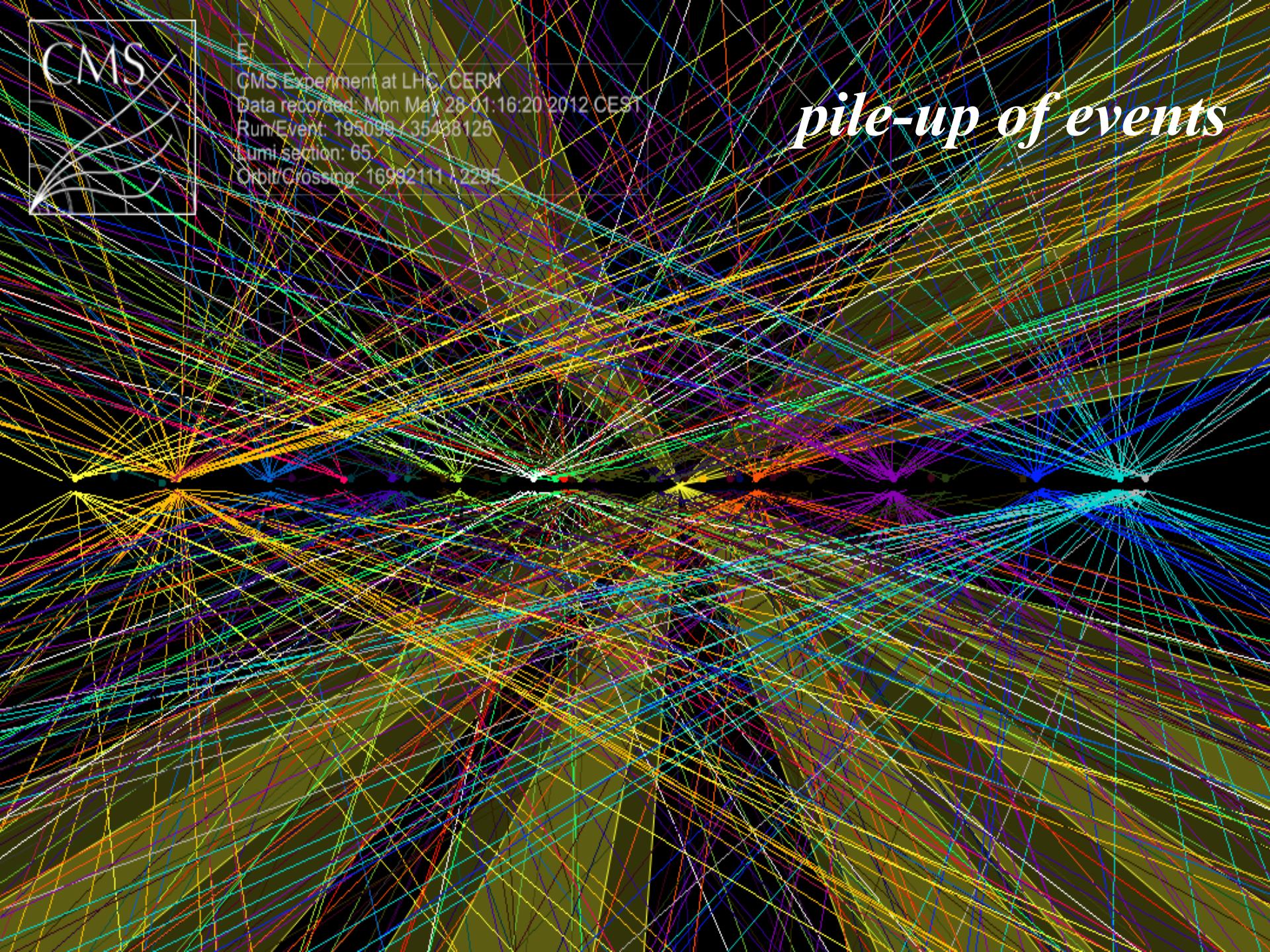
Data recorded: Mon May 28 01:16:20 2012 CEST

Run/Event: 195099 / 35438125

Lumi section: 65

Orbit/Crossing: 16992111 / 2295

pile-up of events



The Compact MUON Solenoid

CMS A Compact Solenoidal Detector for LHC

