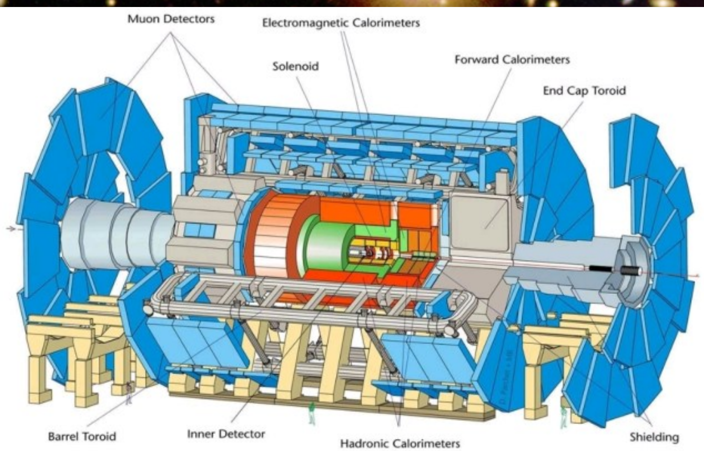
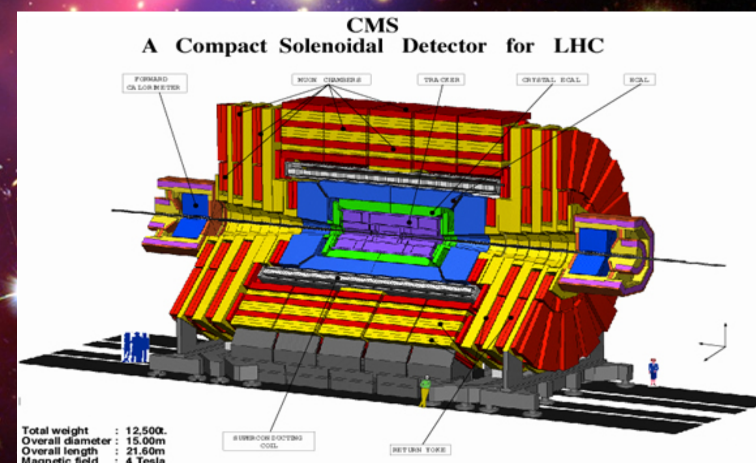
Dark Matter @ the LHC





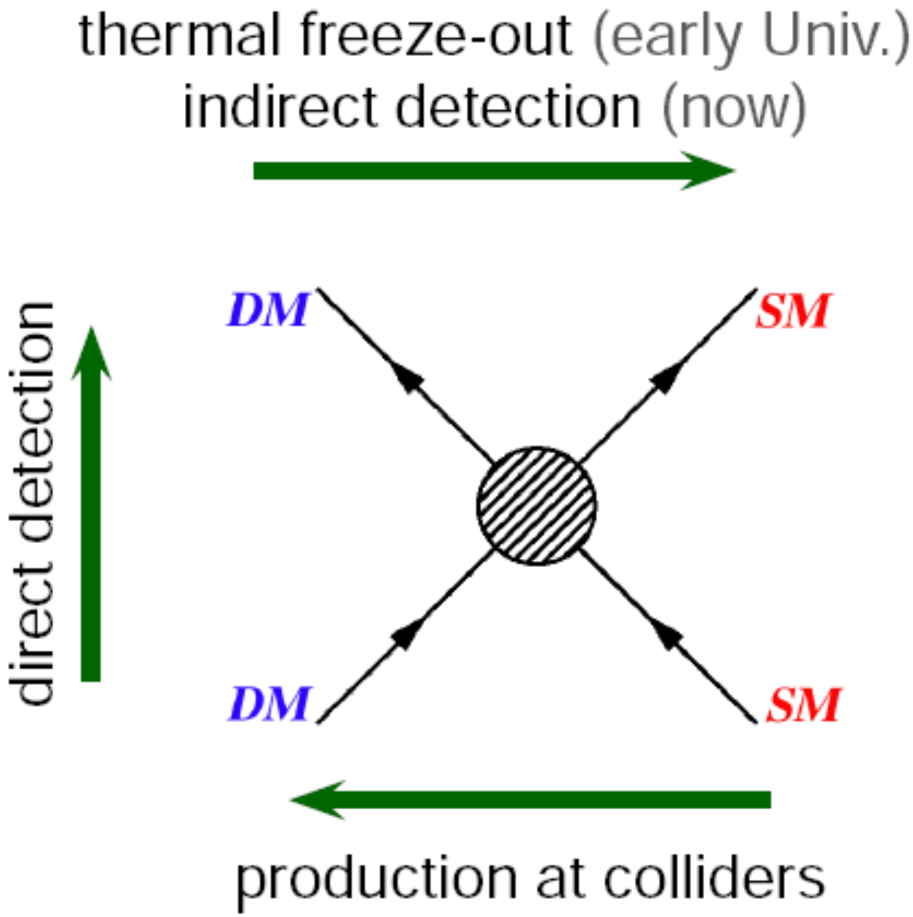
Manfred Jeitler

Institute of High Energy Physics of the Austrian Academy of Sciences

for the ATLAS and CMS collaborations

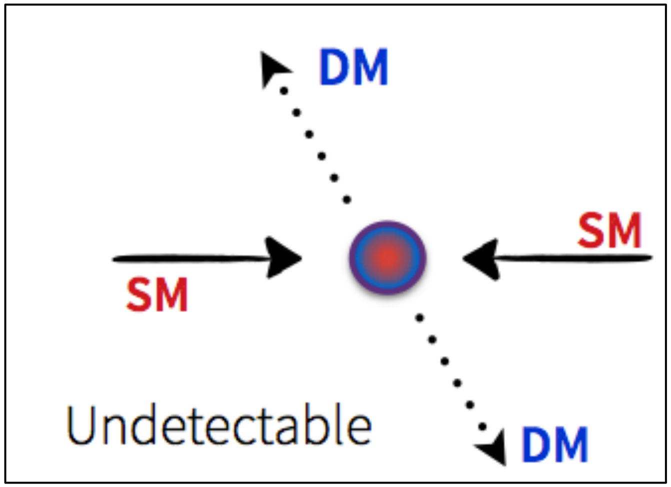
Ways to look for Dark Matter (DM) …

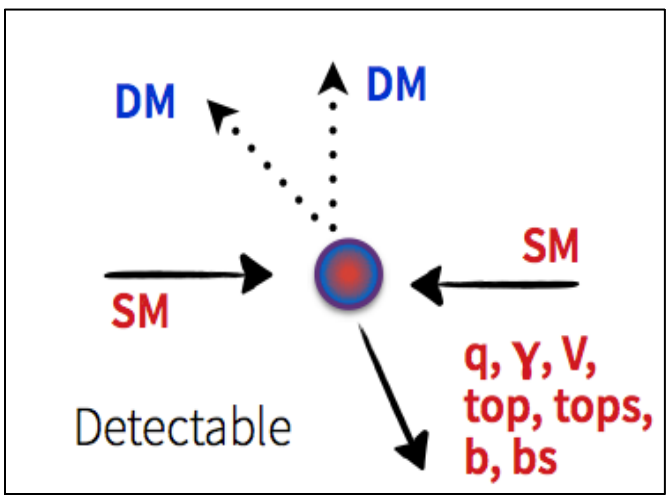
… if it couples at least weakly to Standard Model (SM) particles
(if we are unlucky, it doesn't!)



- indirect: DM annihilation
  - Pamela, Fermi, AMS, IceCube
- direct: DM-nucleon scattering
  - liquid noble-gas detectors
    - LUX, XENON1T
  - solid-state cryogenic detectors
    - SuperCDMS, CRESST- II
- production at colliders
- how can we get a signal from "invisible" objects?

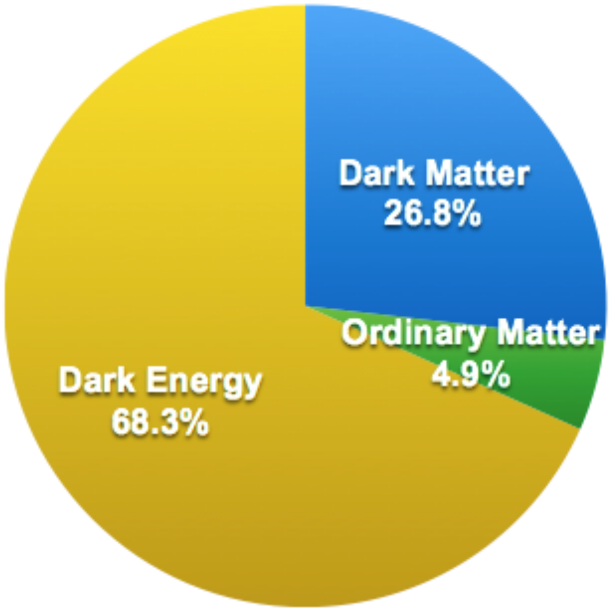
Ways to look for Dark Matter at a hadron collider





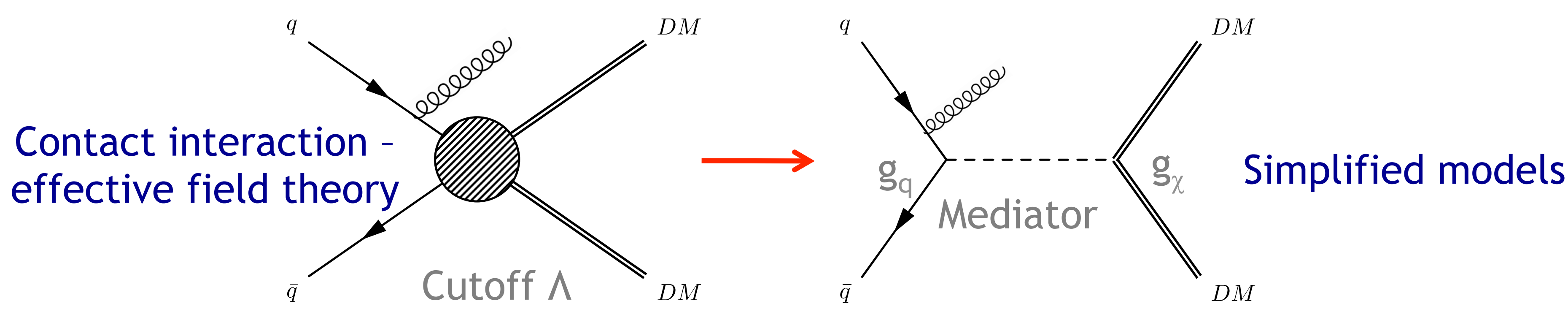
- DM particles invisible in detector
- total transverse momentum conserved
- select events with visible particles from Initial-State Radiation (ISR)
- look for ISR-object plus missing transverse momentum
  - "E_T^{miss}", "missing ET", "MET"
  - → "mono-X" searches
    - "E_T^{miss} +X" analyses: "thing + nothing"
  - mono-jet, mono-photon, mono-Z, mono-W
- production in decay chains
  - SUSY cascades
  - Higgs portal

Grounding assumption



- Dark Matter assumed to be a single particle
  - Dirac fermion WIMP
  - produced in pairs
  - stable on collider timescales
  - non-interacting with the detector
- DM sector has 5 times more mass than SM sector
  - DM sector could be much more complex
  - but one DM particle and one mediator might be dominant in discovery

Effective Field Theories (EFT) vs. Simplified Models



- LHC Run 1 (<=2012): DM interpretation mostly in terms of Effective Field Theories
  - contact interaction, valid if mediator mass >> momentum transfer
  - 7 and 8 TeV collision energy
  - invalid at high energy transfer
- LHC Run 2 (>=2015): use Simplified Models
  - 13 TeV collision energy
    - → higher momentum transfer possible
    - → EFT may become invalid
  - explicit definition of mediator particles
  - benchmark models

Model parameters

Main 4 model parameters:

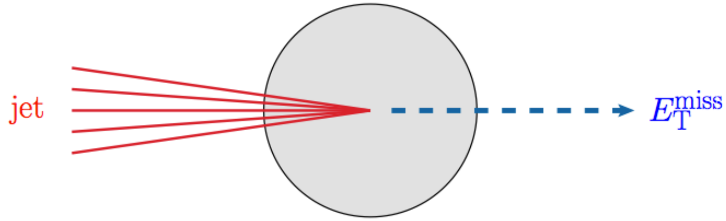
- m_{DM} : mass of Dirac fermion χ
  - "Dark Matter mass", i.e. mass of "Dark Matter particle"
- m_{med} : mass of mediator
- g_q : mediator coupling to quarks
- g_{DM} : mediator coupling to DM

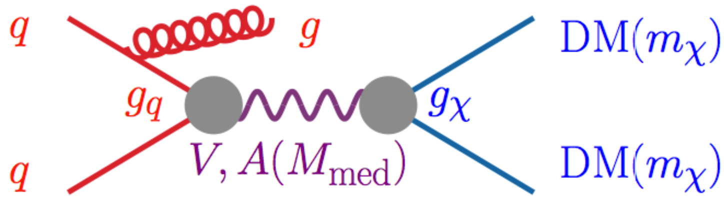
- *Mediator couplings to leptons set to zero*
  - to avoid stringent LHC bounds from di-lepton searches
- *assume minimal flavor violation*
- *assume minimal decay width of mediator*
- ATLAS/CMS DM Forum
  - arXiv 1507.0966 (2015), 1603.04156 (2016)
  - discussions among ATLAS, CMS and theorists

Mediator coupling

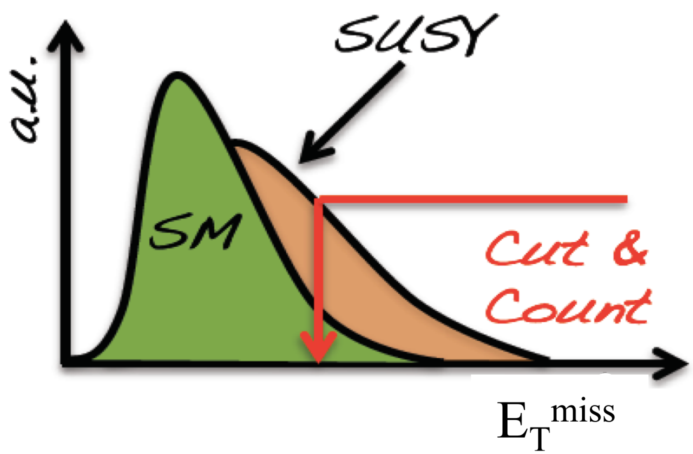
- spin-independent
  - scalar coupling
  - vector coupling
- spin-dependent
  - axial-vector coupling
  - pseudo-scalar coupling
- very different sensitivities in direct-detection experiments

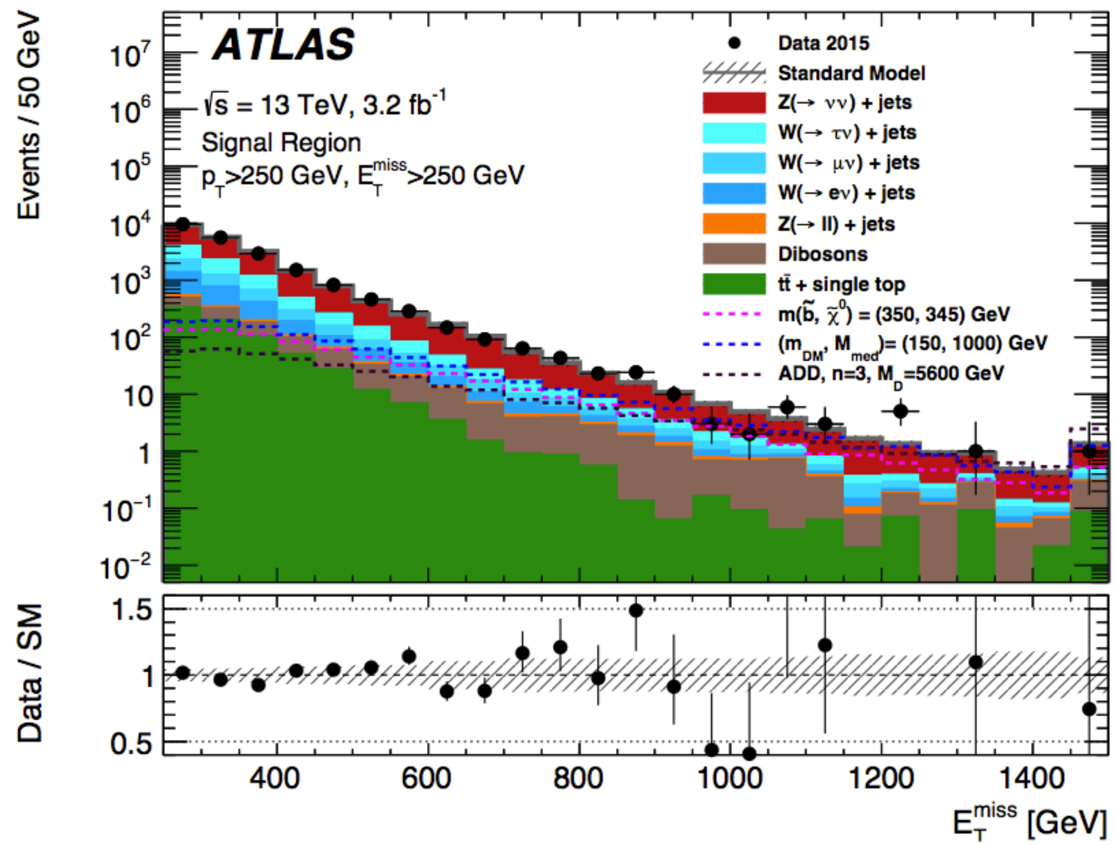
Monojet





ATLAS-EXOT-2015-03





Monojet

analysis:

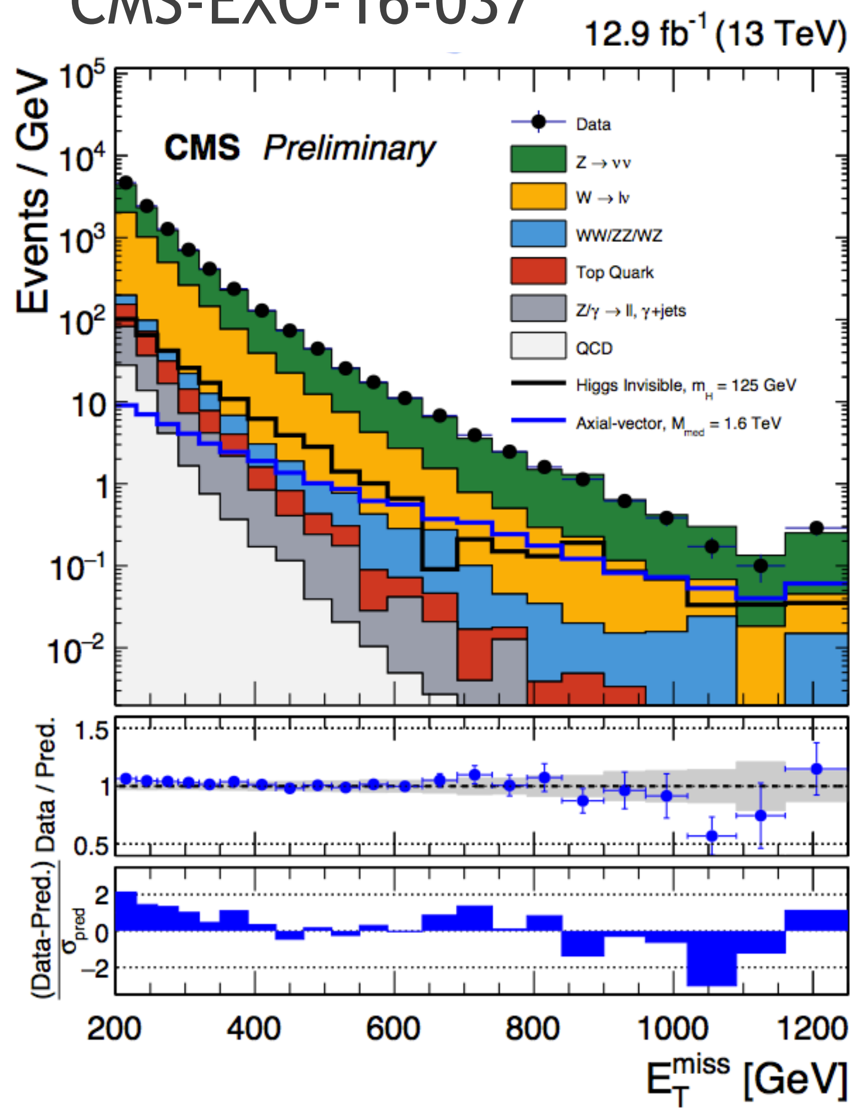
- require jet
- require E_T^{miss}
- veto leptons

dominant backgrounds:

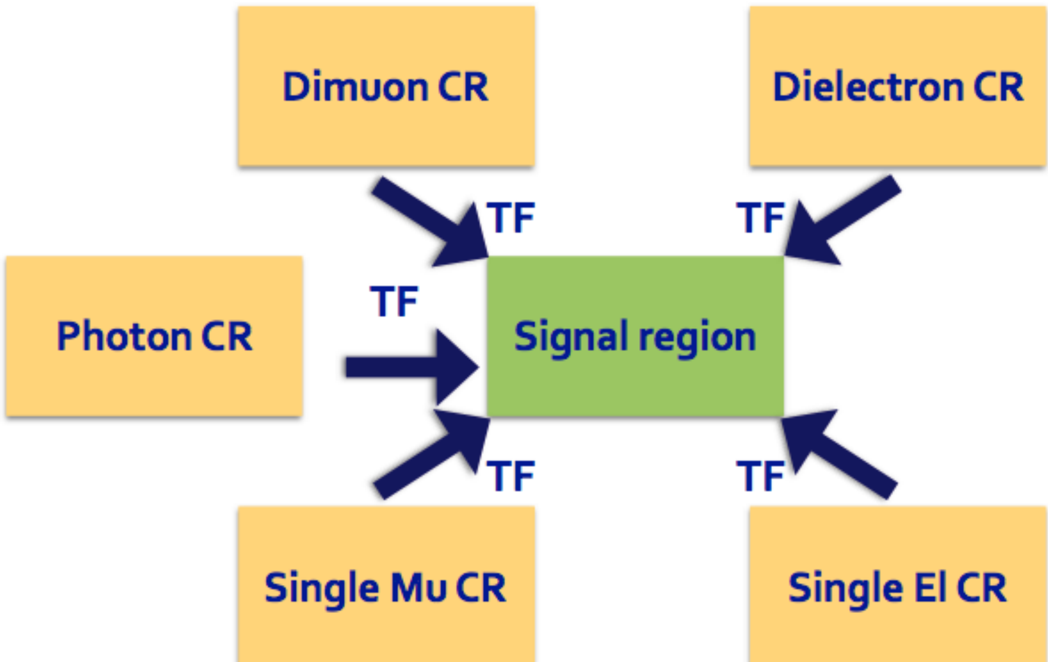
- Z(νν)+γ/jets
  - irreducible
- W(ℓν)+γ/jets

estimate using Z(μμ) and W(μν) events

CMS-EXO-16-037



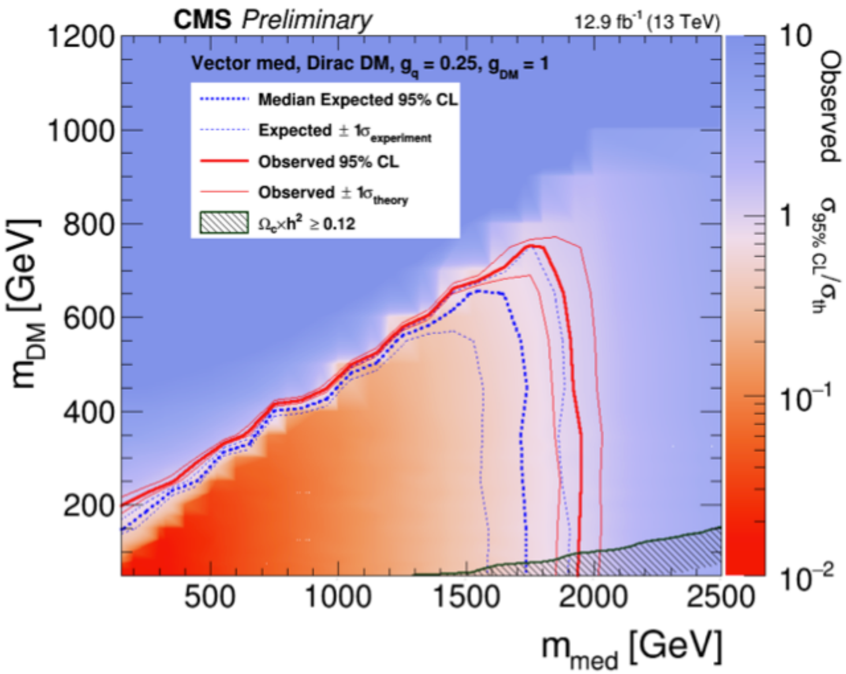
Monojet: backgrounds

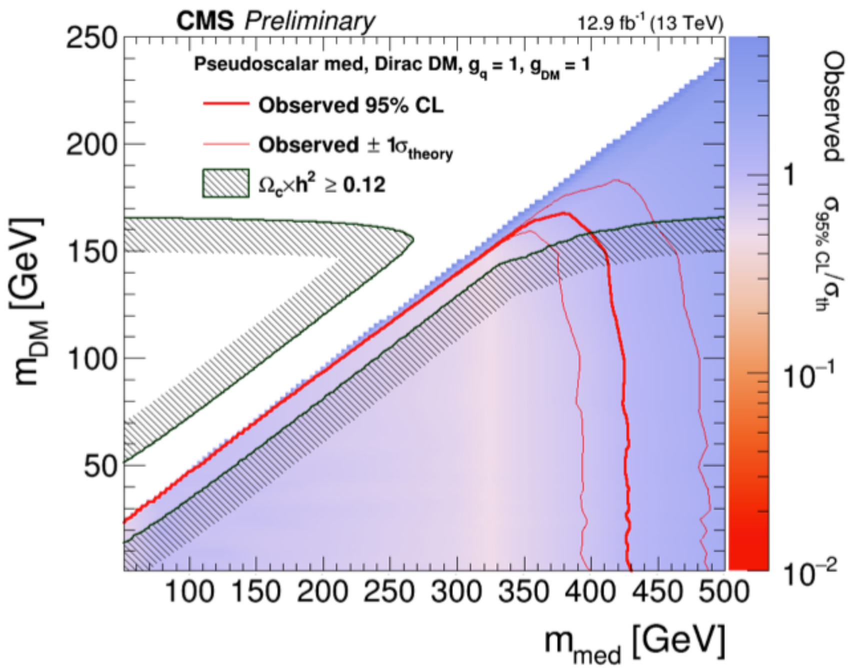


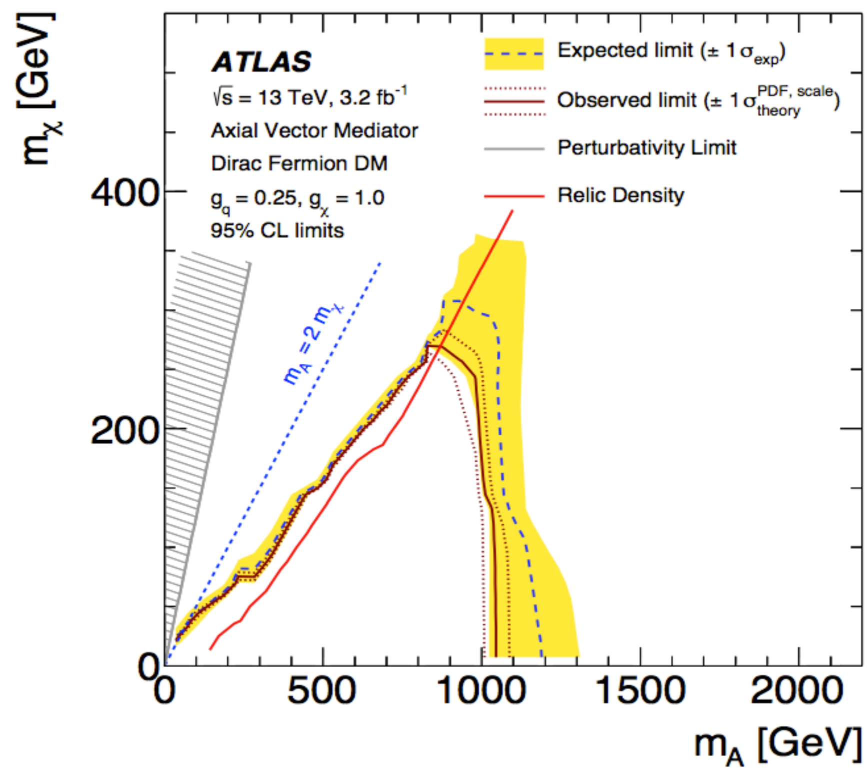
- data-driven analysis
- use specific control regions with enriched backgrounds
- apply to signal region using "Transfer Factors"

Monojet: results

- plot Dark-Matter mass against Mediator mass
- for fixed coupling: $g_q = 0.25$, $g_{DM} = 1$





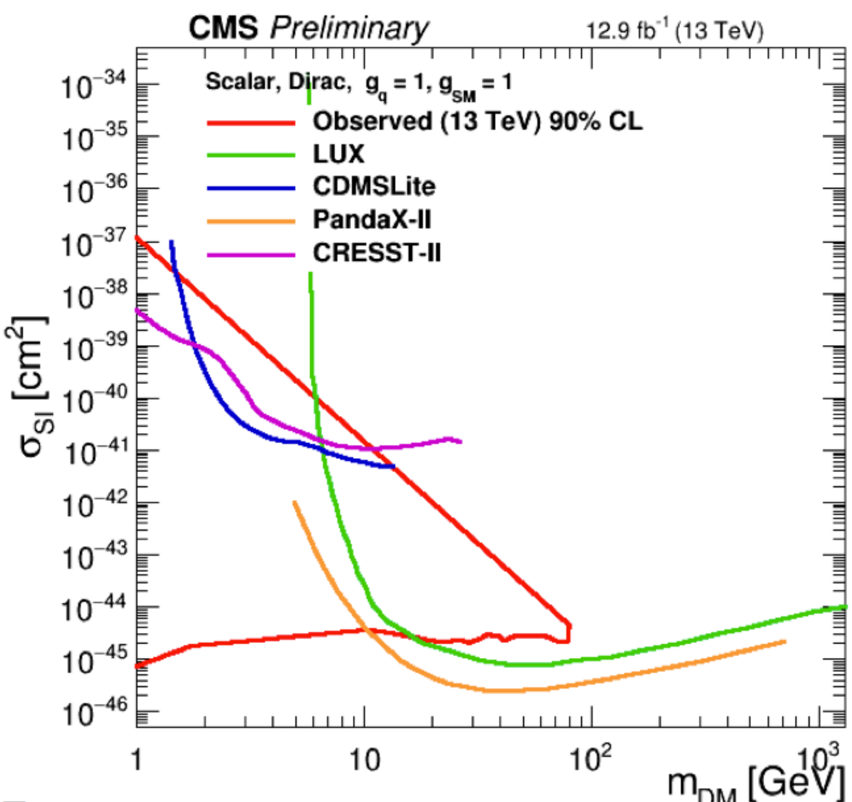


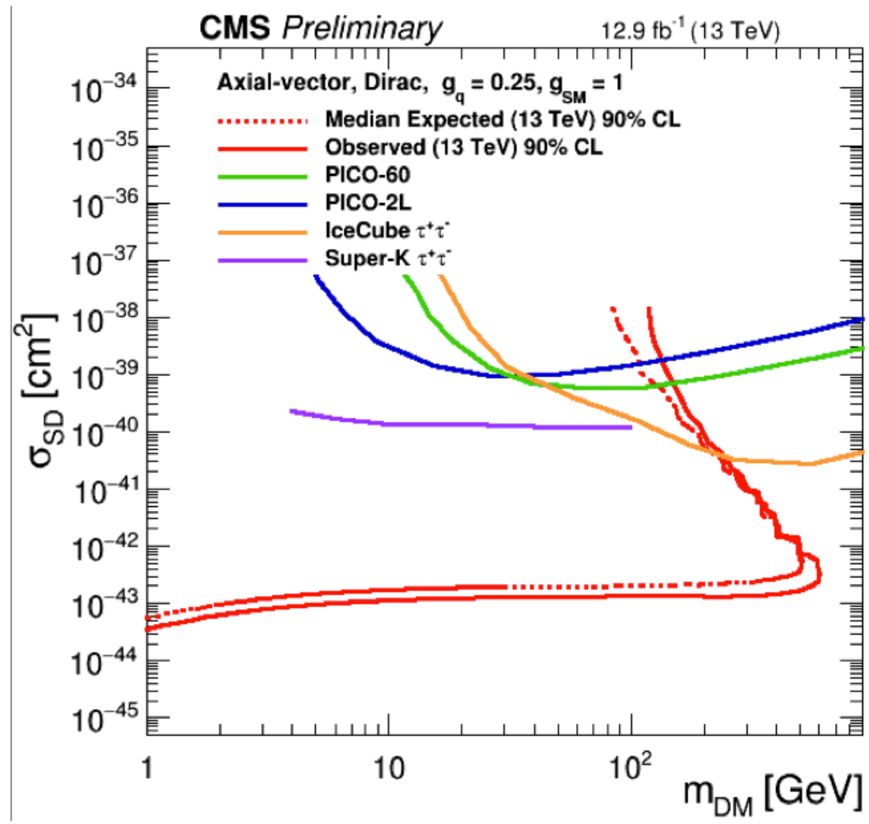
Monojet: results

plot cross section against Dark-Matter mass

- allow comparison with direct/ indirect detection experiments
- for fixed coupling
  - » $g_q = 0.25$, $g_{DM} = 1$

- *spin independent (SI): best limits from direct detection*
- *spin dependent (SD): easier for collider*





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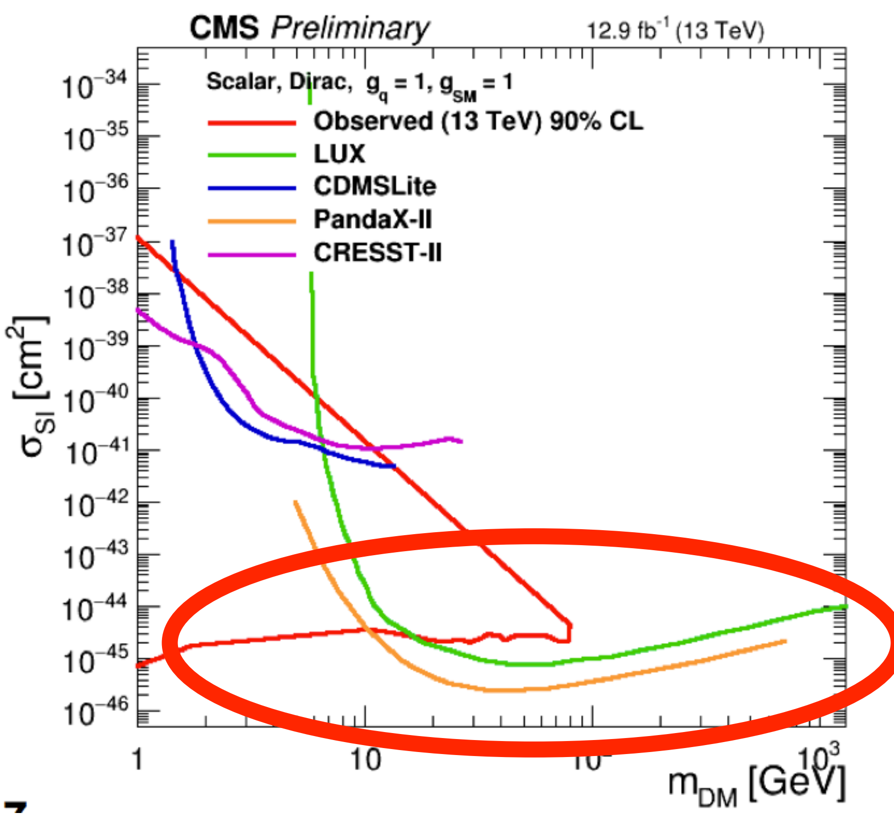

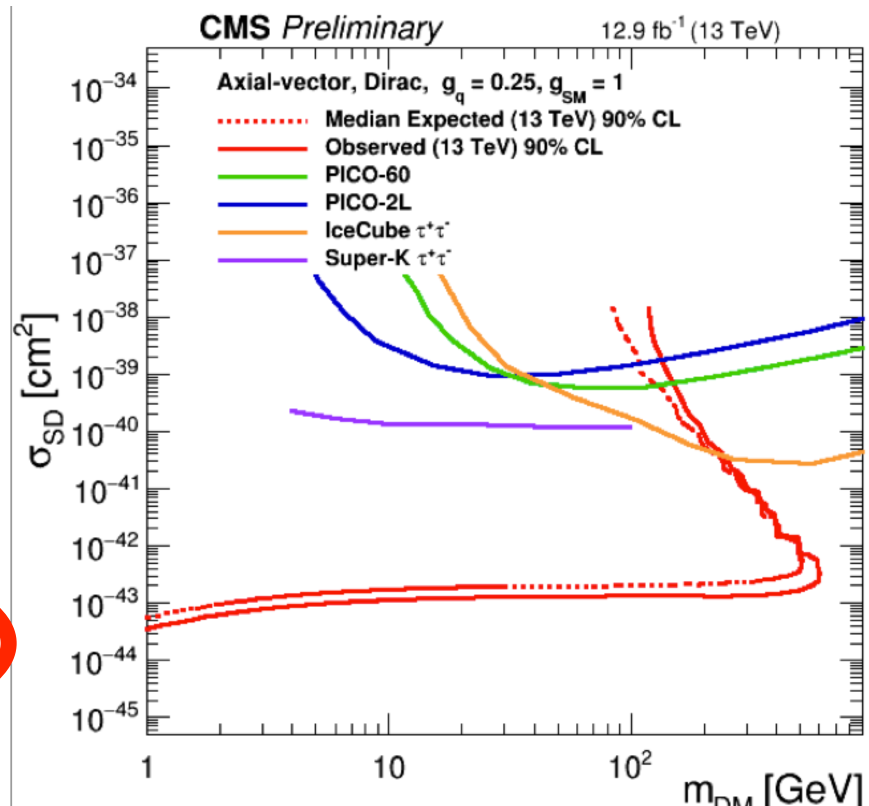

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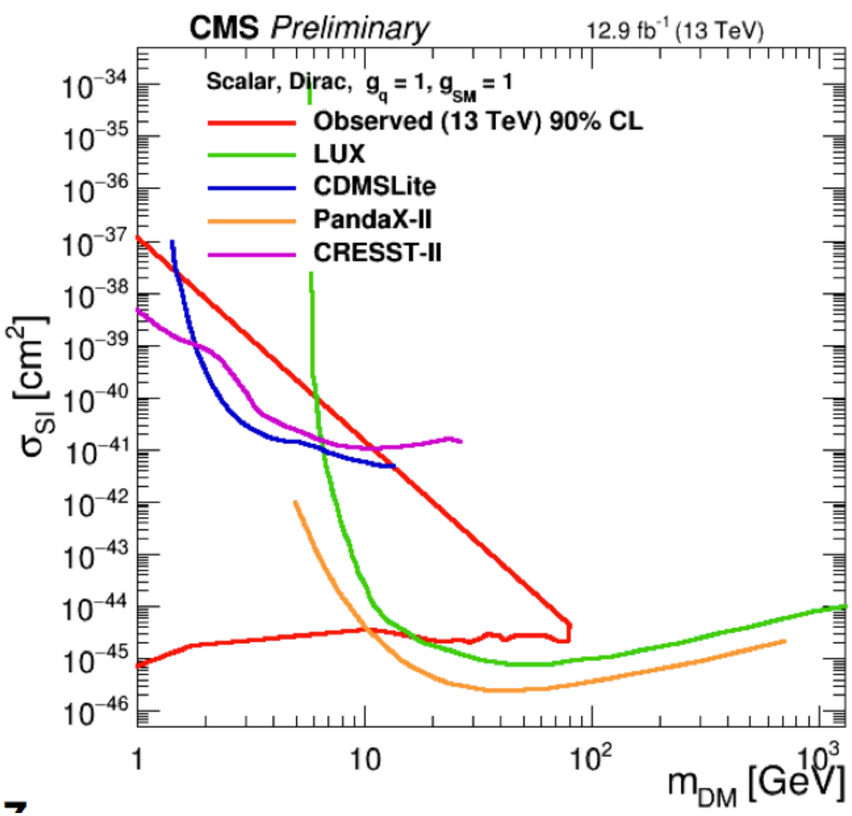
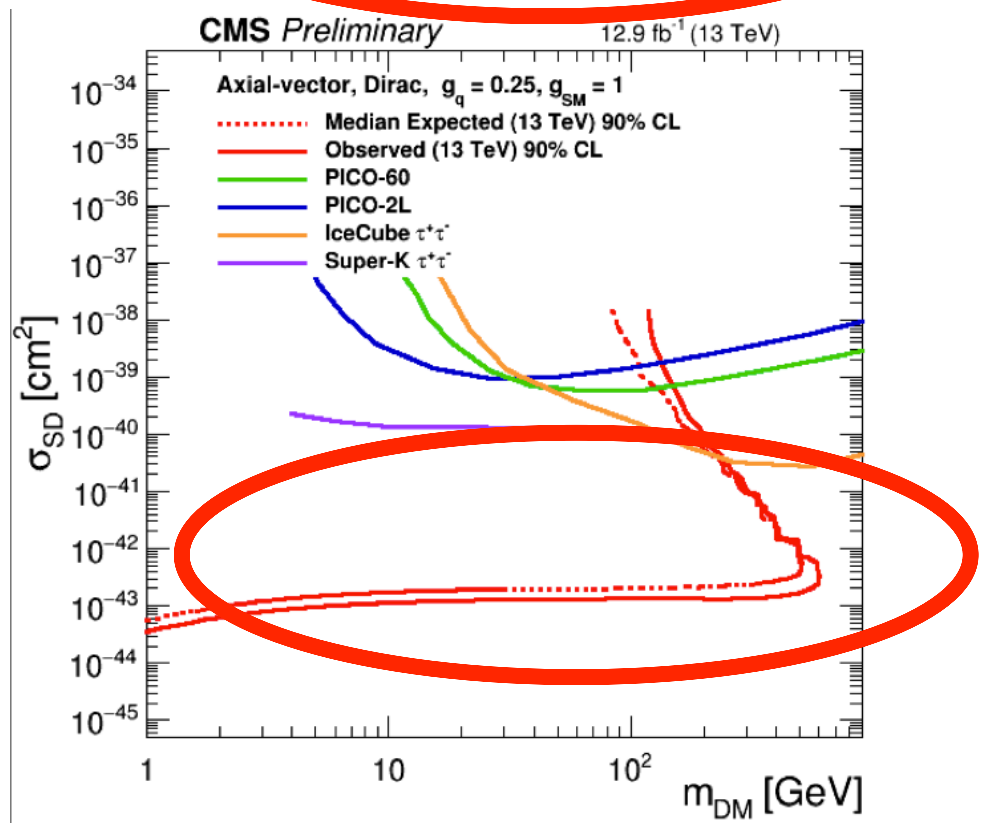
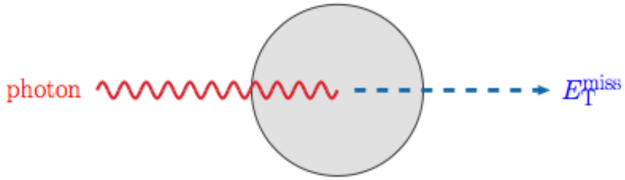
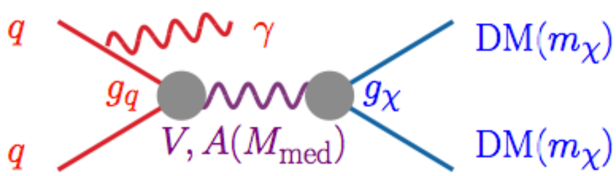


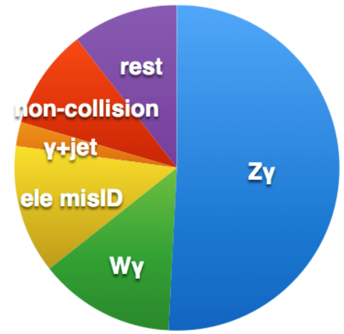






ATLAS-EXOT-2015-05

CMS-EXO-16-039

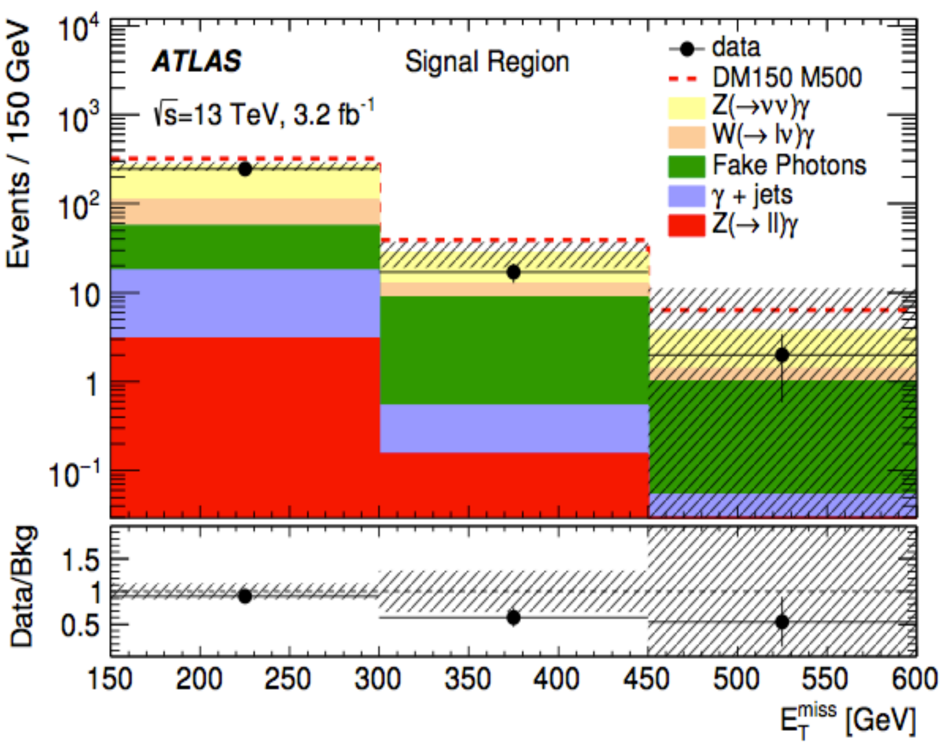


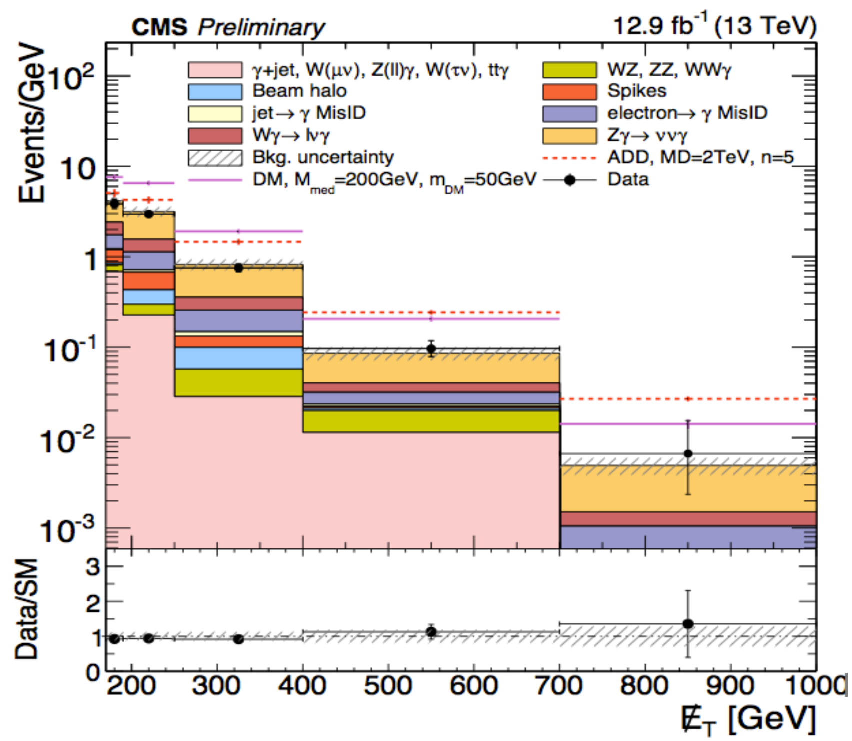
Monophoton

- cleaner than monojet
  - cross-section smaller

dominant backgrounds:

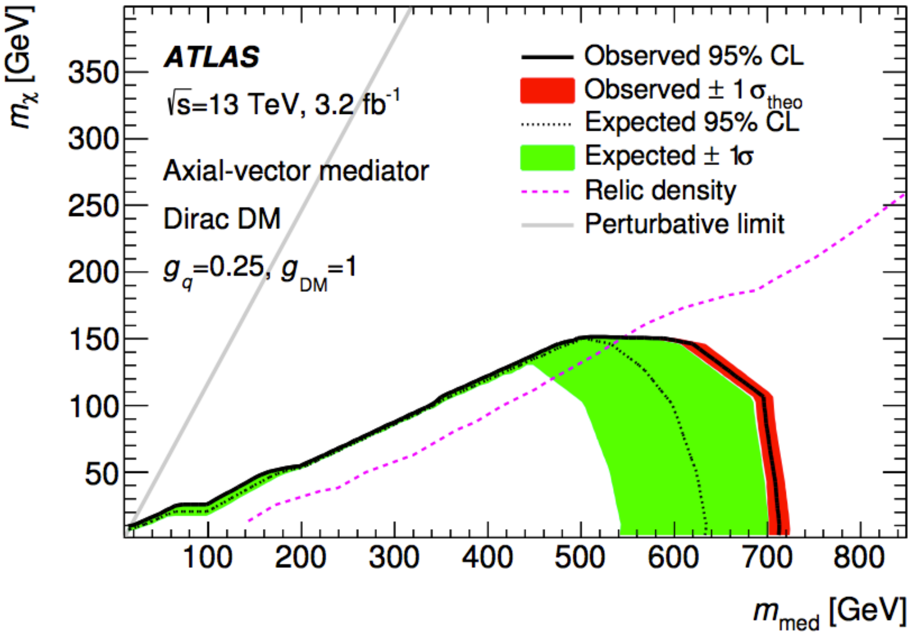
- Z(νν)+γ
  - irreducible
- W(ℓν)+γ

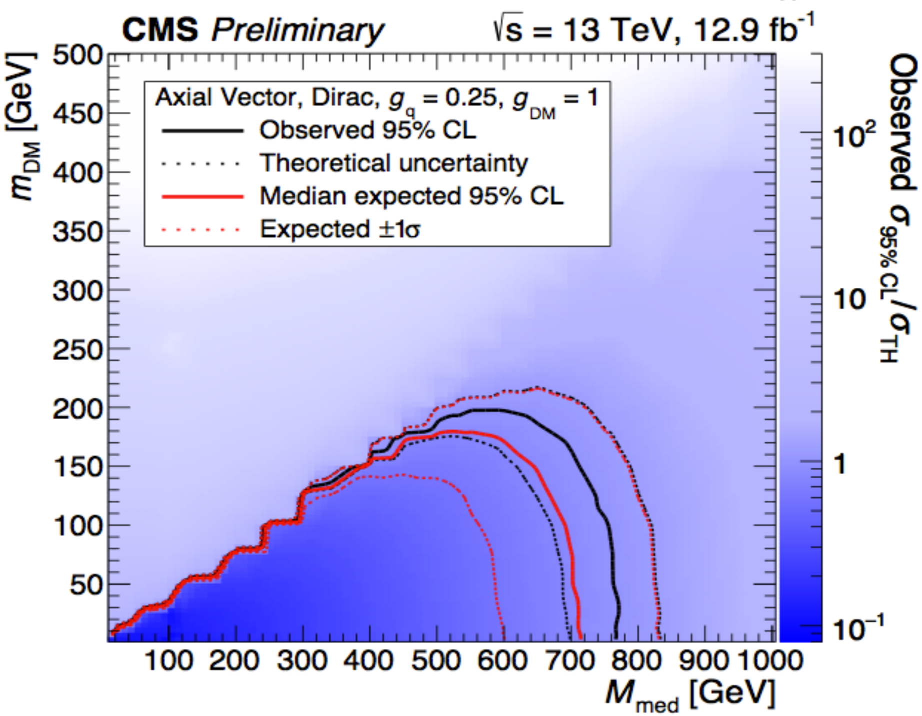


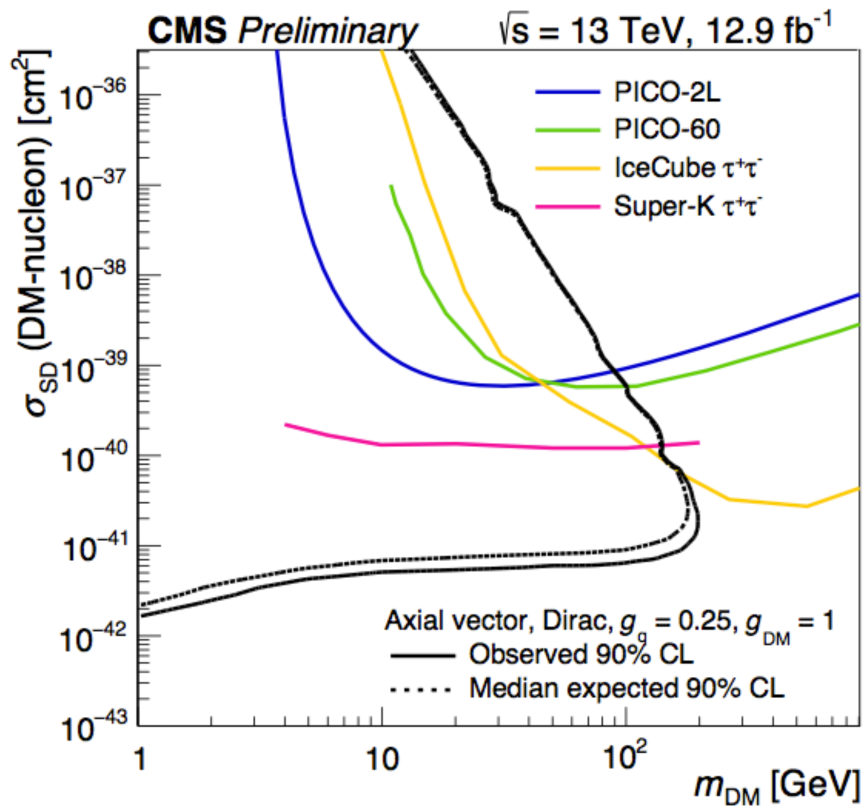


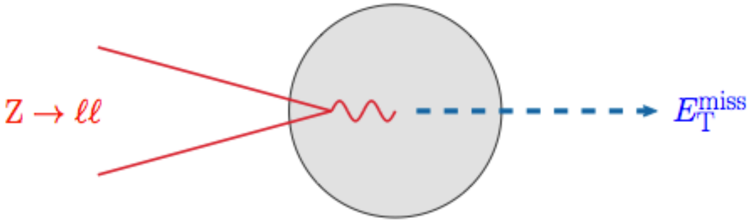
Monophoton

exclude mediator < 760 GeV
for vector / axial-vector



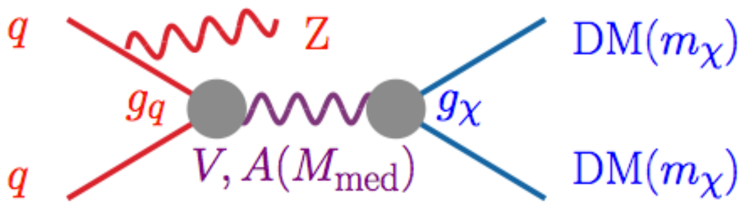






Mono-Z

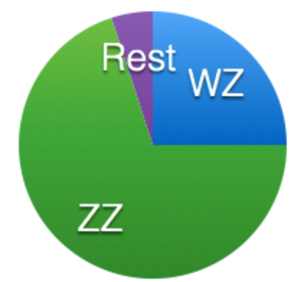
$E_T^{miss} + Z(\to \ell^+\ell^-)$

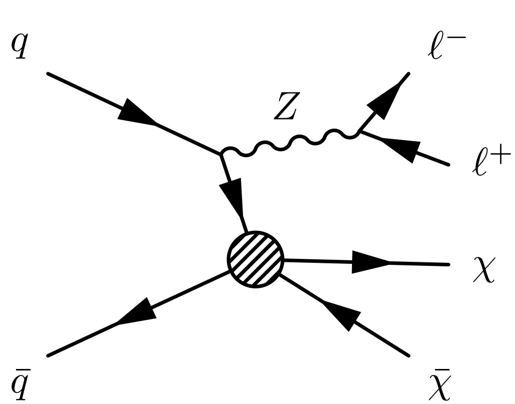


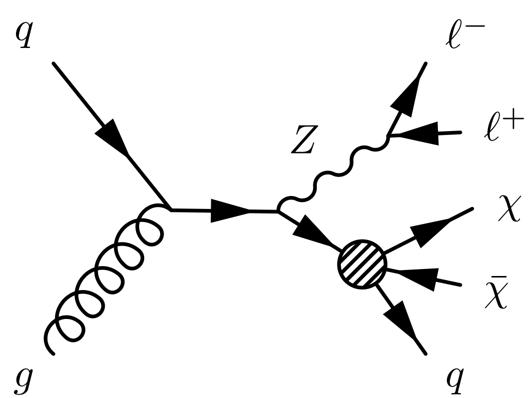
ATLAS-CONF-2016-056

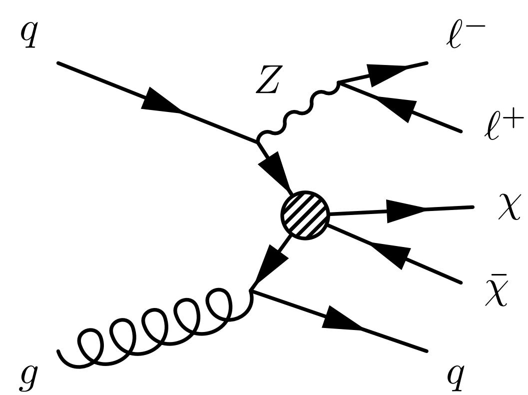
CMS-EXO-16-038

- $Z \rightarrow \mu\mu$ or $Z \rightarrow ee$
- still cleaner but less statistics
- main background: ZZ, WW
  - $ZZ \to \nu\nu + \ell^+\ell^-$ is irreducible



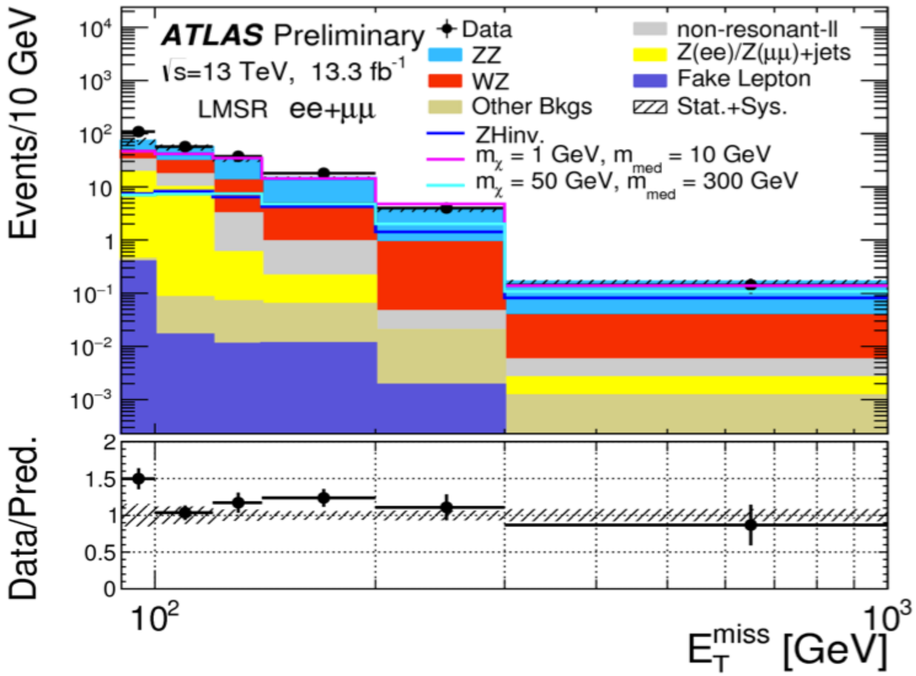


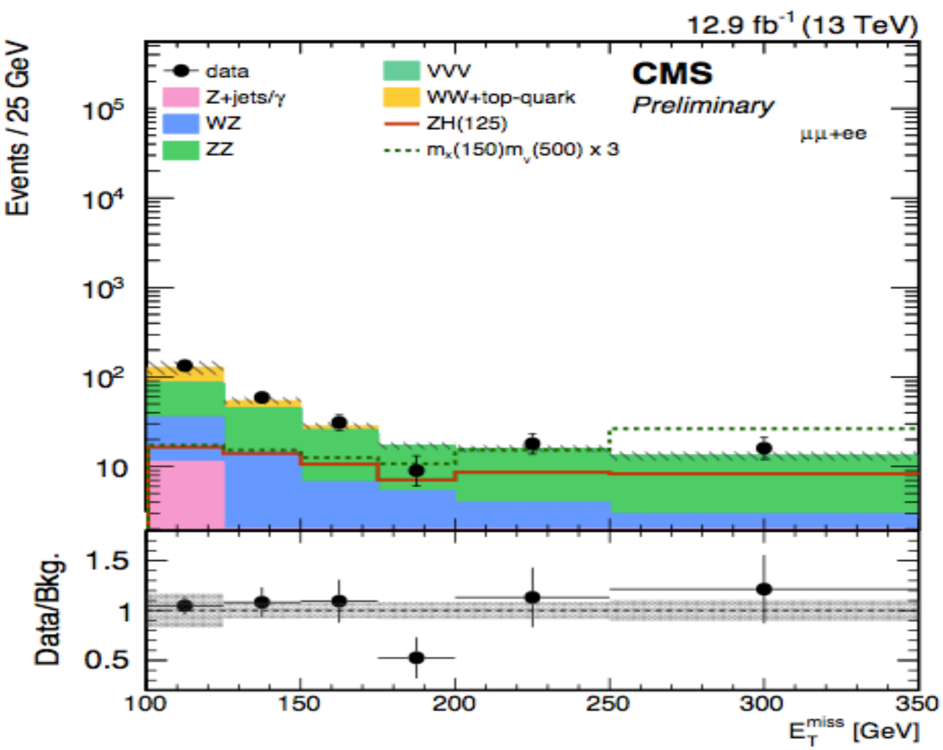




Mono-Z

$E_T^{miss} + Z(\rightarrow \ell^+\ell^-)$





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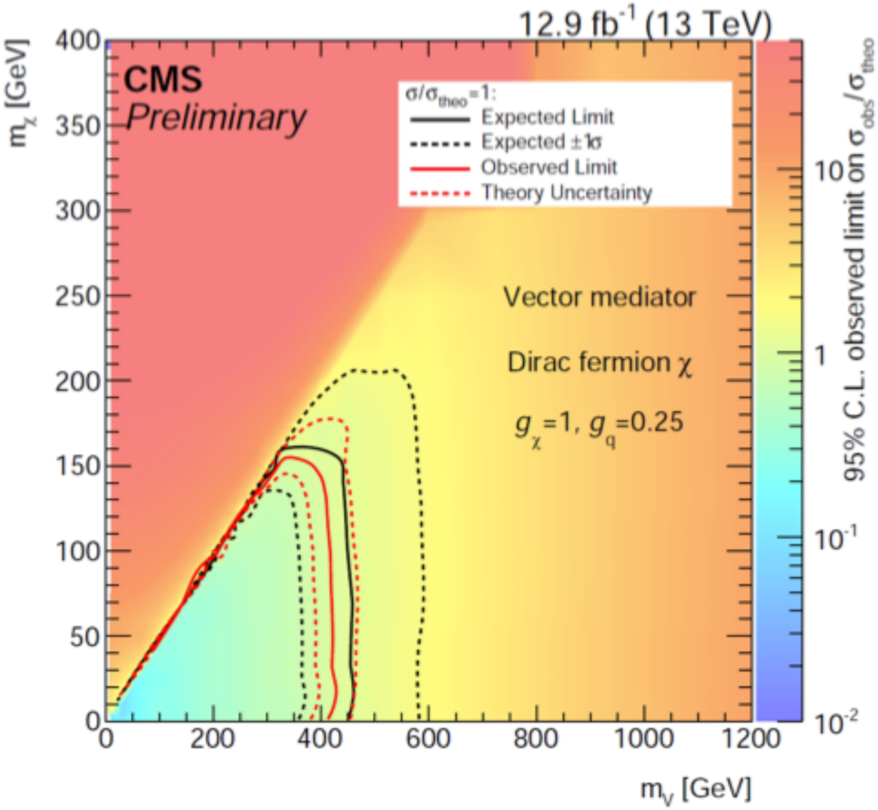
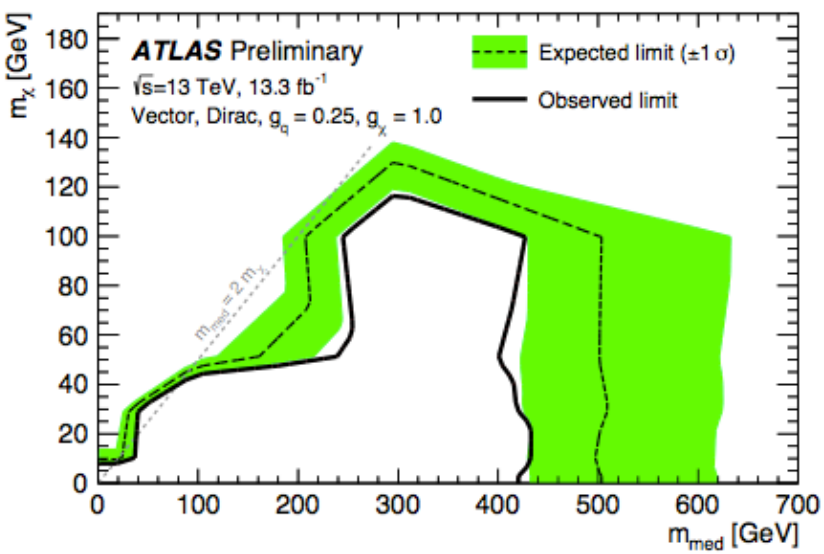
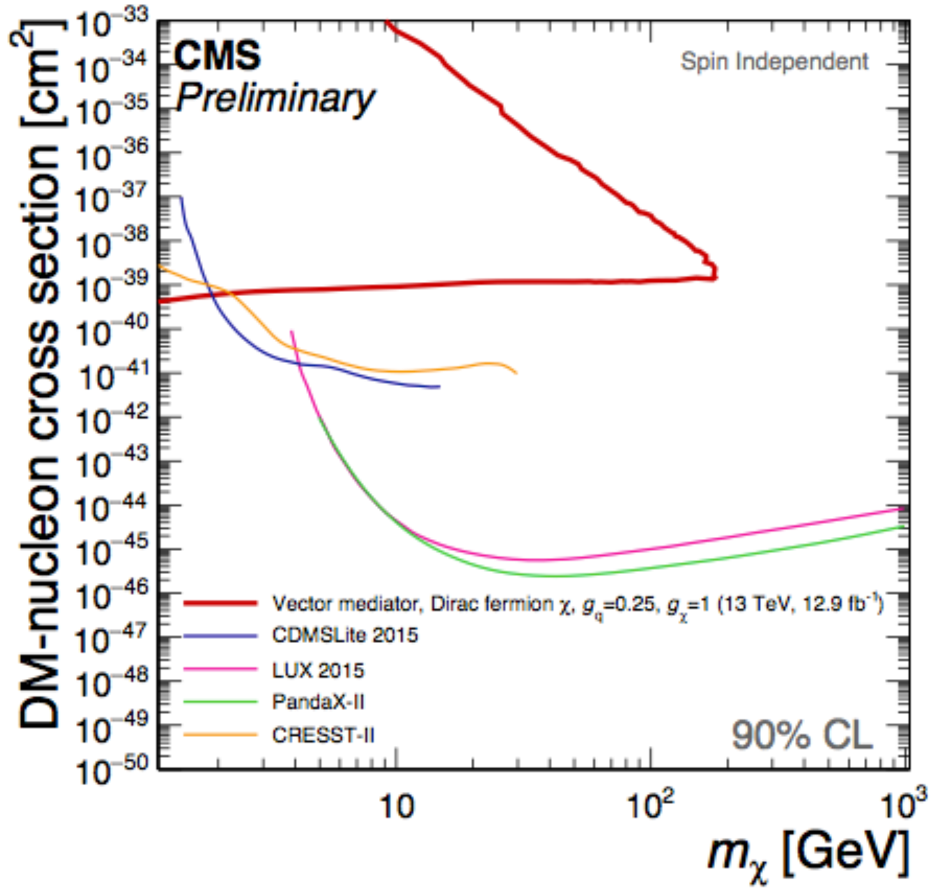
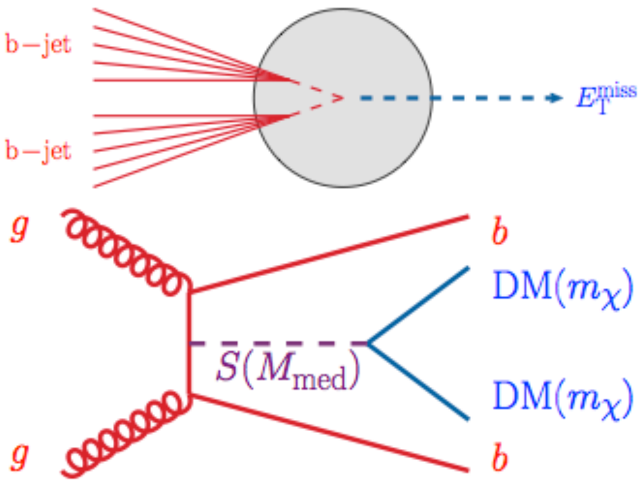




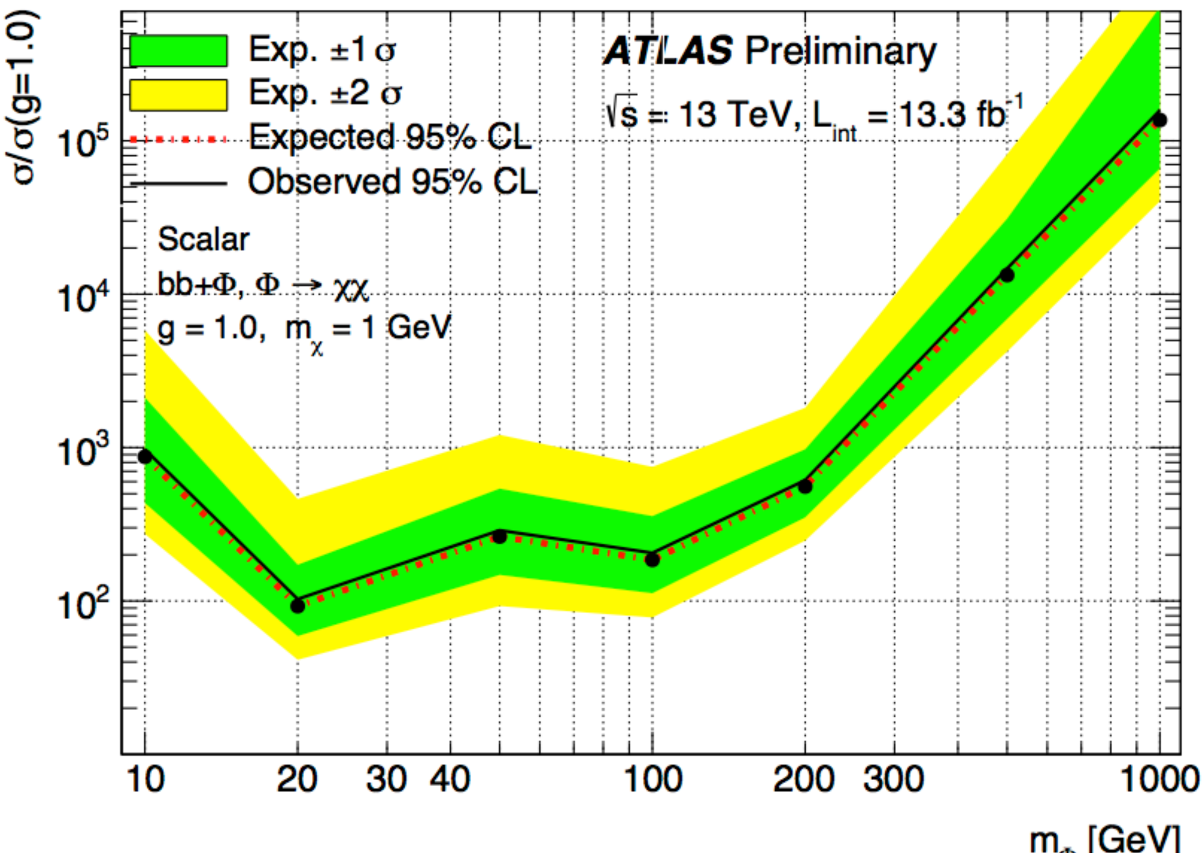




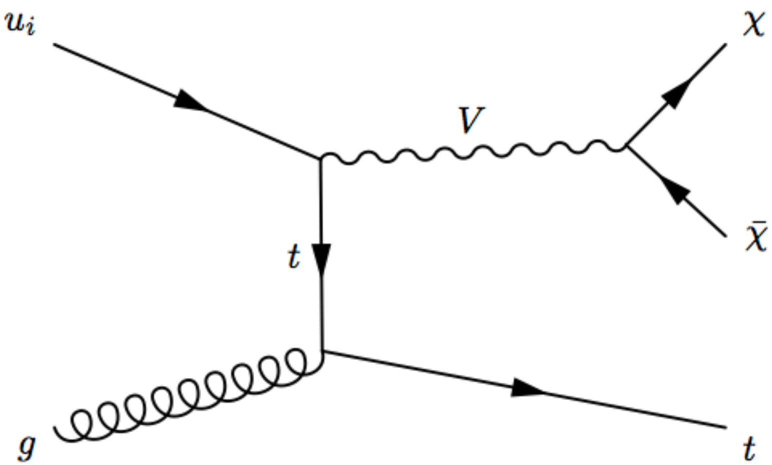
heavy flavor:
E_T^{miss} +b-jets

- sensitive to scalar mediator
- di-b-jet diagram dominates at LHC
- background: top, V+jets

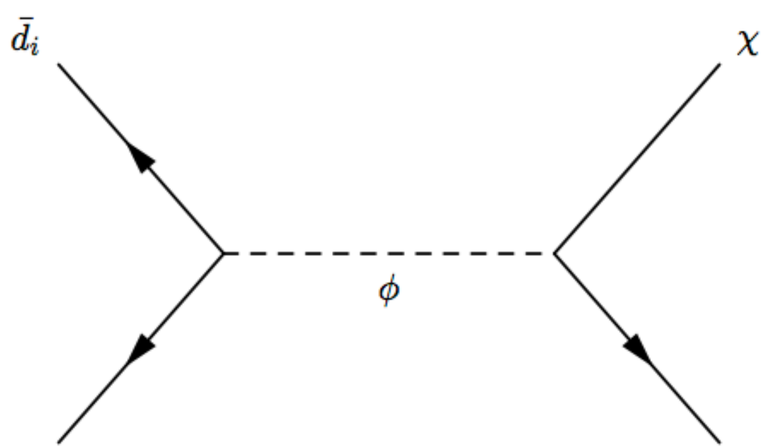
ATLAS-CONF-2016-086
CMS-B2G-15-007



mono-top

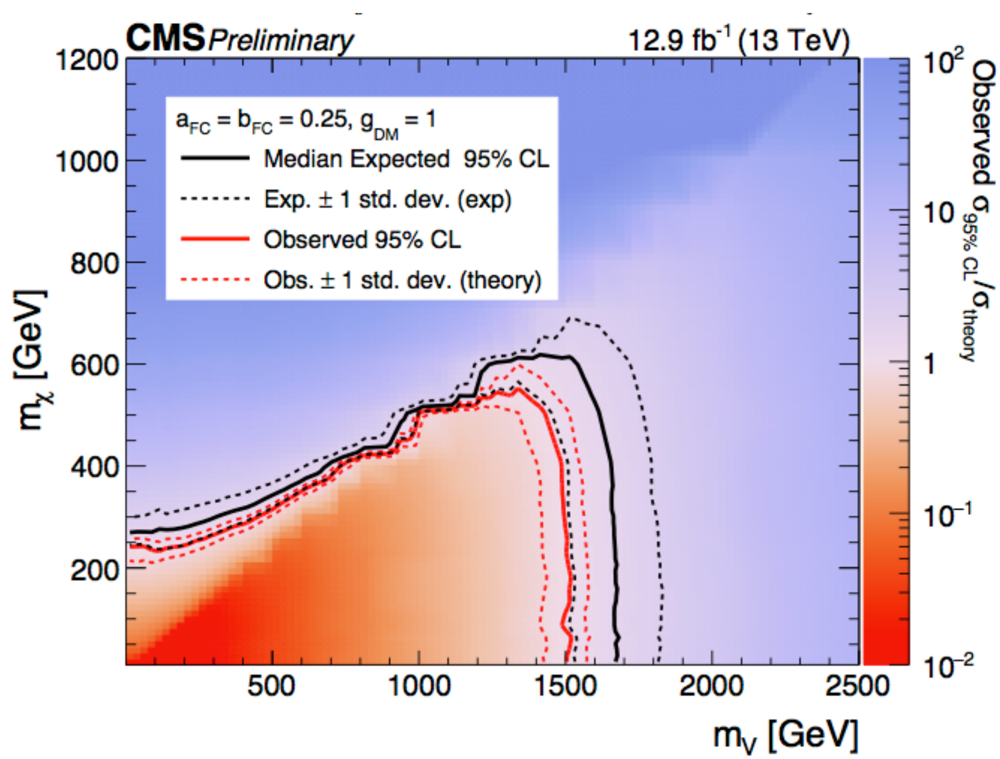


Flavor-changing neutral current (FCNC)



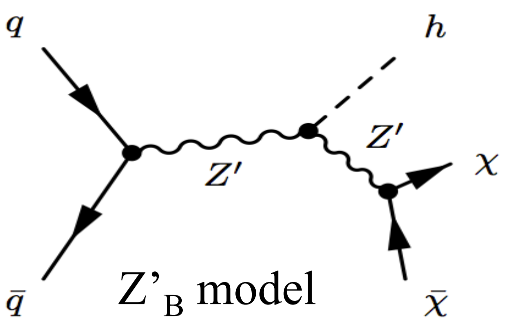
Color-charged scalar

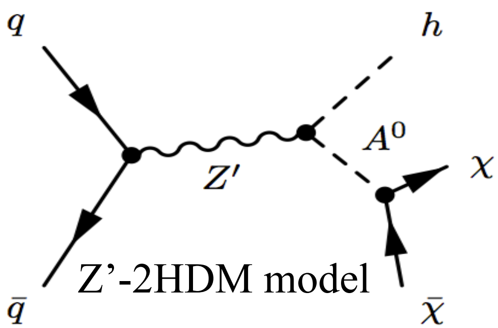
- “wide” jet and $E_T^{miss} > 250$ GeV
- mass 110-210 GeV
- subjet b-tag
- FCNC vector <1.5 TeV excluded
- charged scalar 0.9-2.7 TeV excluded

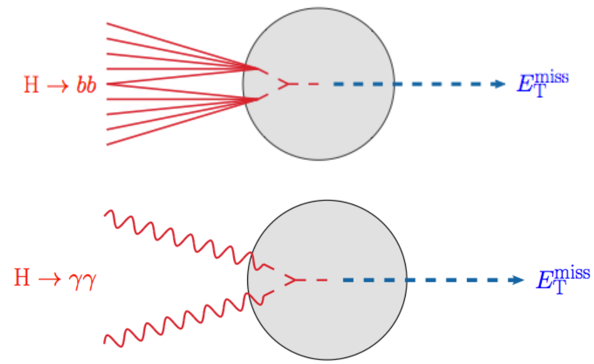


ATLAS-CONF-2015-79

CMS-EXO-16-040







Mono-Higgs

$E_T^{miss} + H\ (\rightarrow bb)$

$E_T^{miss} + H\ (\rightarrow \gamma\gamma)$

ATLAS-CONF-2016-019

ATLAS-CONF-2016-087

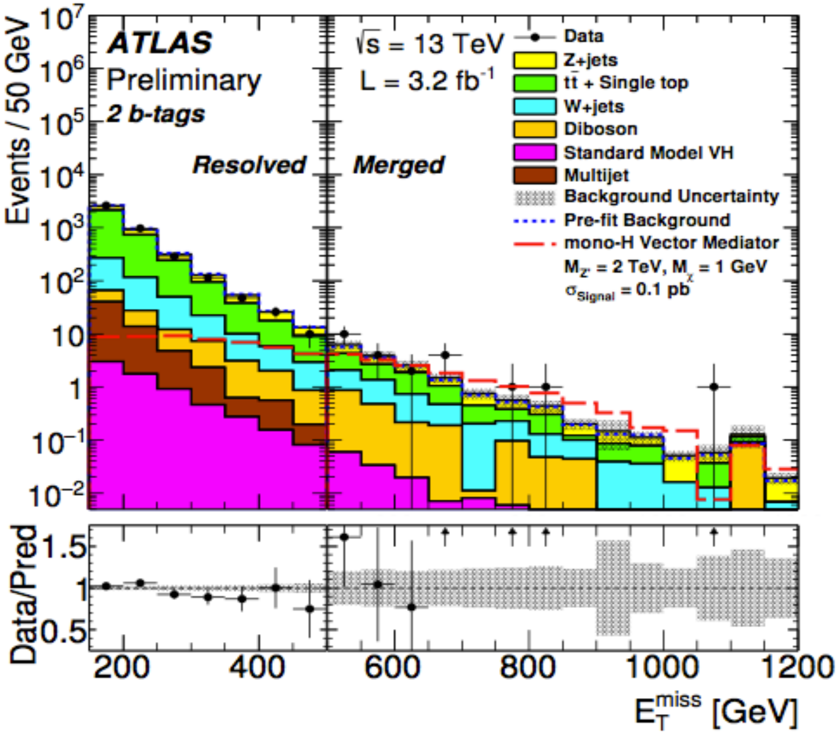
CMS-EXO-16-012

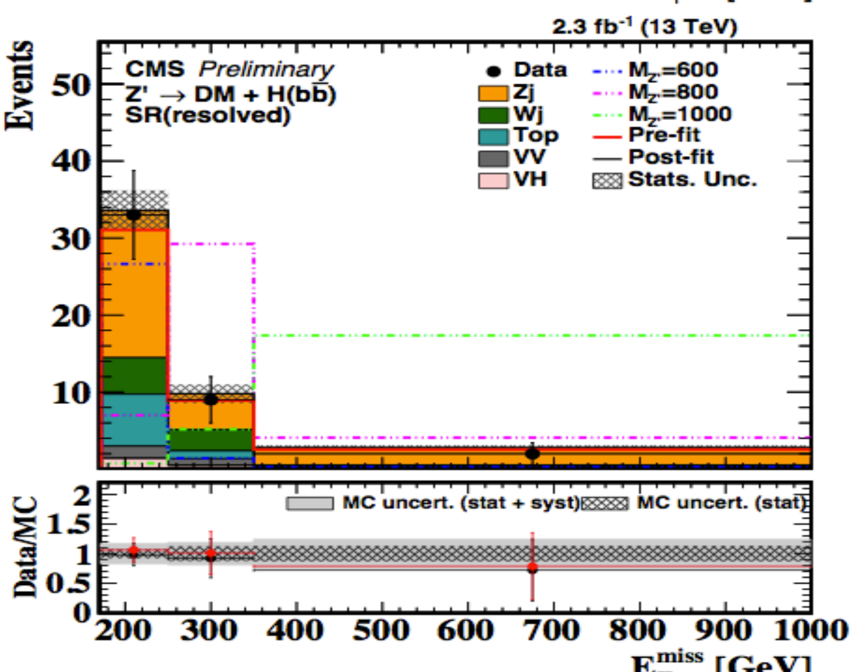
CMS-EXO-16-011

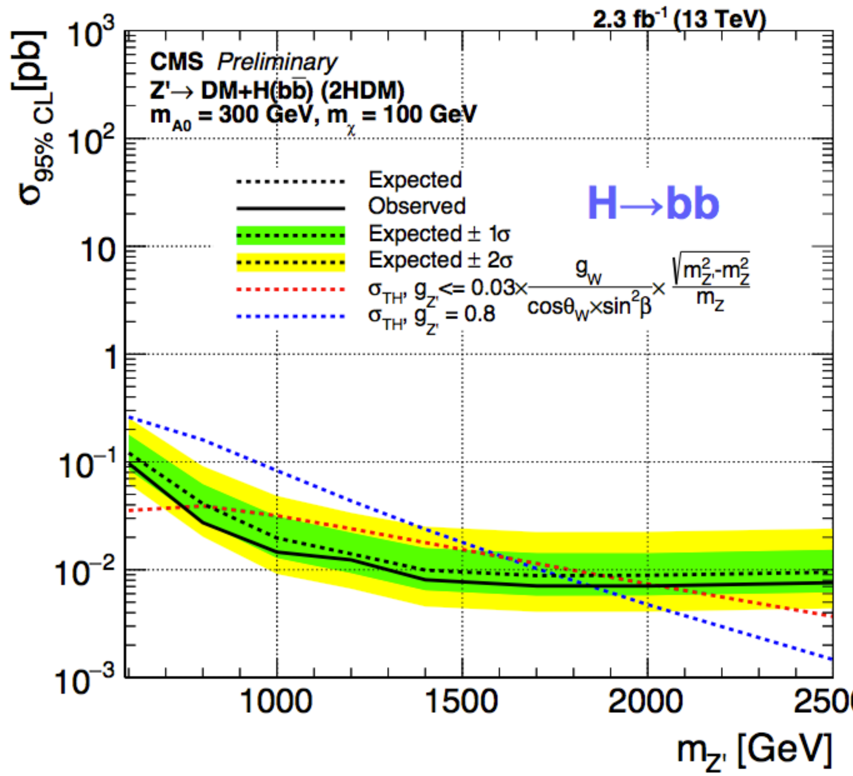
- Higgs might couple to mediator
- H→ bb   largest cross-section
  - two analyses: “resolved” and “boosted” jets
    - two b-jets or one “wide” jet with b-tagged sub-jets
  - backgrounds: V+jets, top
- H→ γγ   clean final state
  - backgrounds: SM γγ, γ + jet

Mono-Higgs

$E_T^{miss} + H (\to bb)$

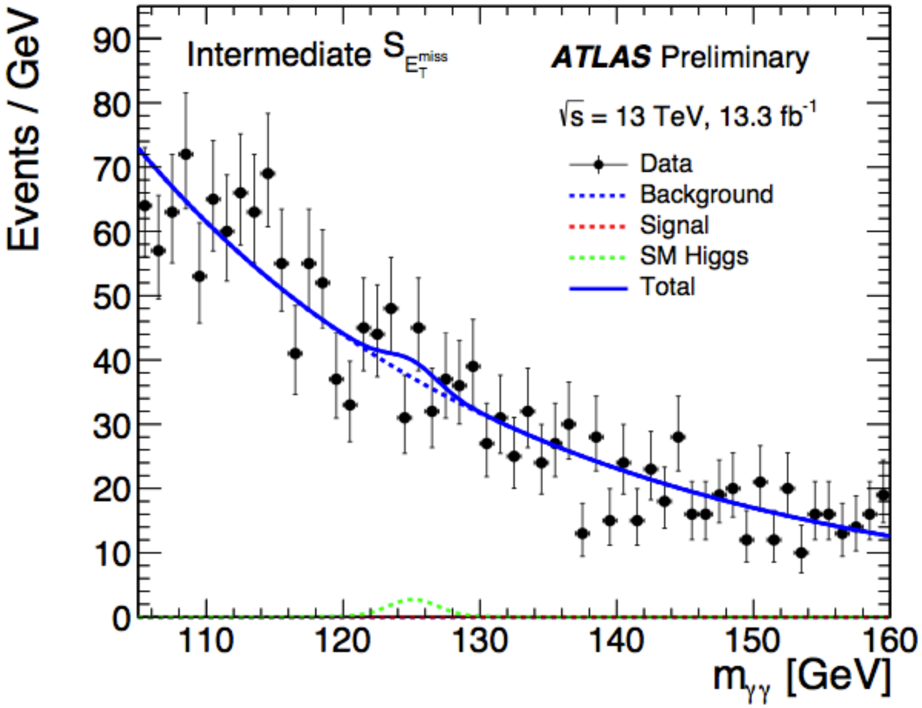


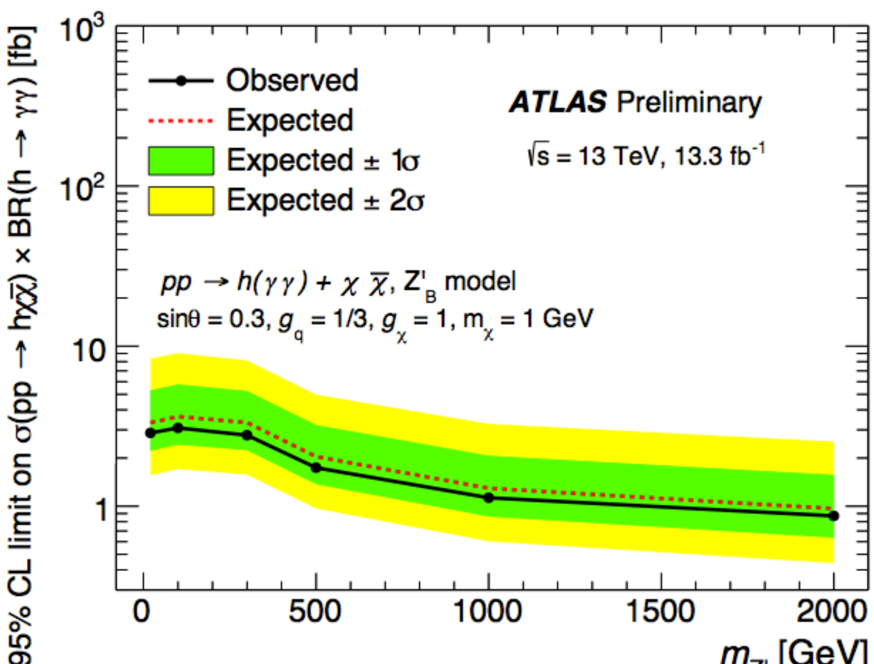


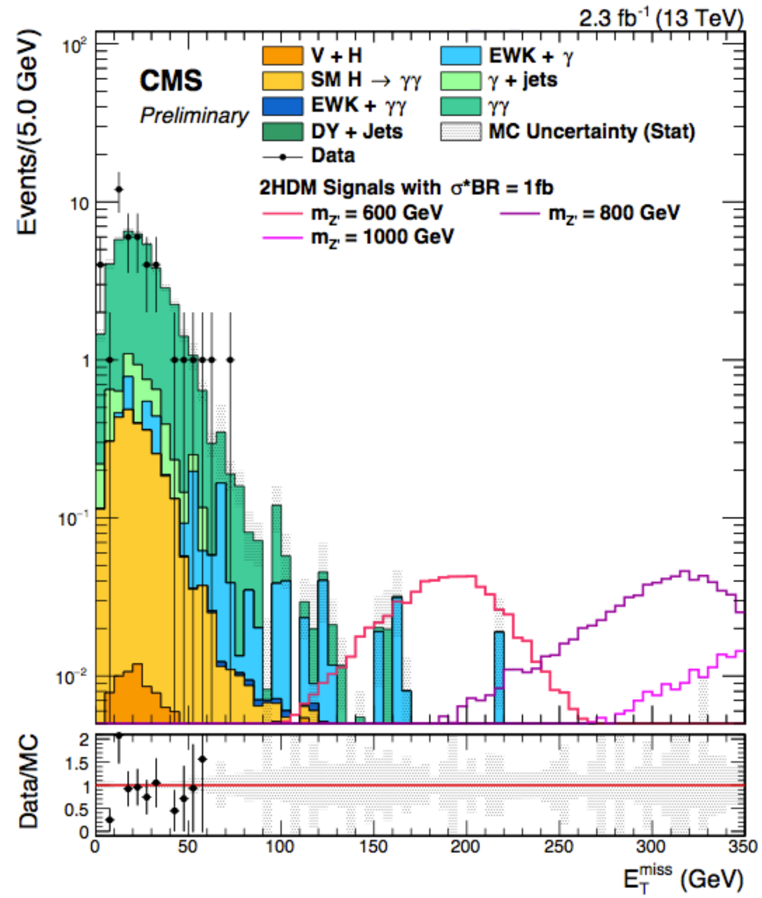


Mono-Higgs

$E_T^{miss} + H\ (\to \gamma\gamma)$

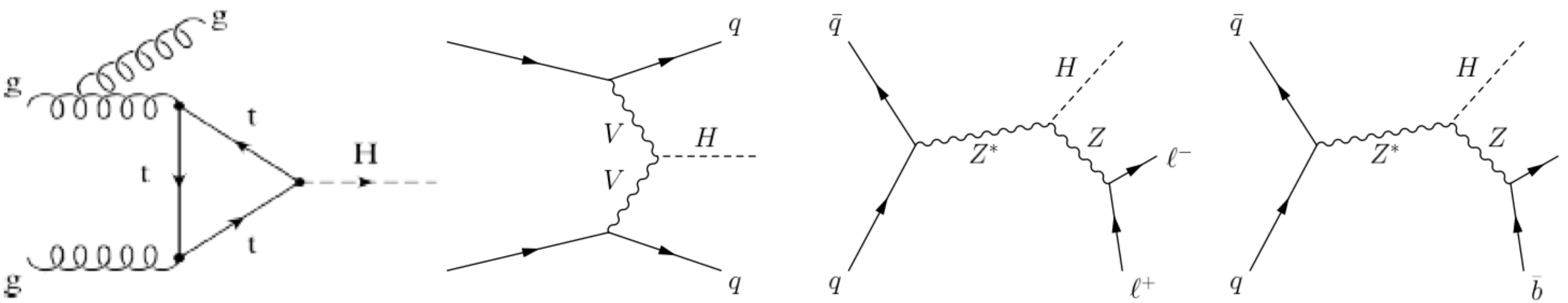






sin θ: mixing angle between baryonic Higgs boson and SM Higgs boson

Invisible Higgs decays



- Higgs width not strongly constrained
- "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

production modes:

- gluon-gluon fusion
  - tag with ISR jet → monojet search
- vector boson fusion
- associated ZH production
  - Z→ℓℓ, Z→bb

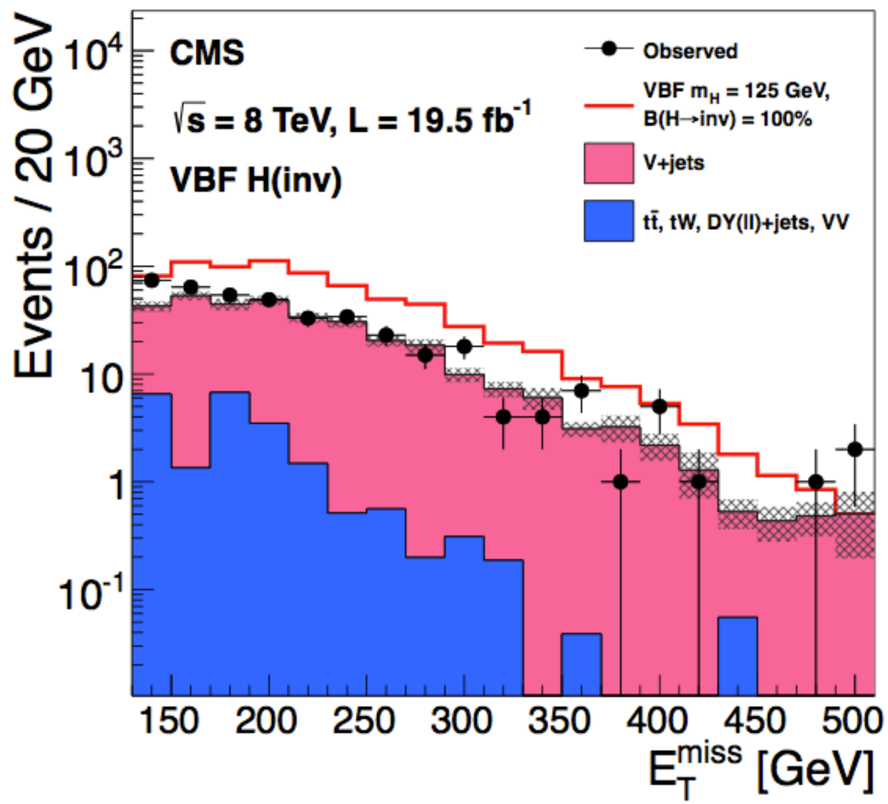
ATLAS CERN-PH-EP-2015-186, 191
CMS-EXO-16-008, 009, 016

Invisible Higgs decays

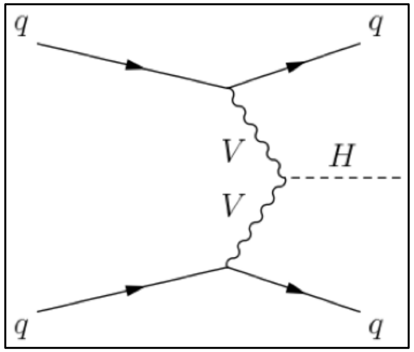
"E_T^{miss}" distribution for Vector Boson Fusion after optimized selection

dominant background: Z / W + jets

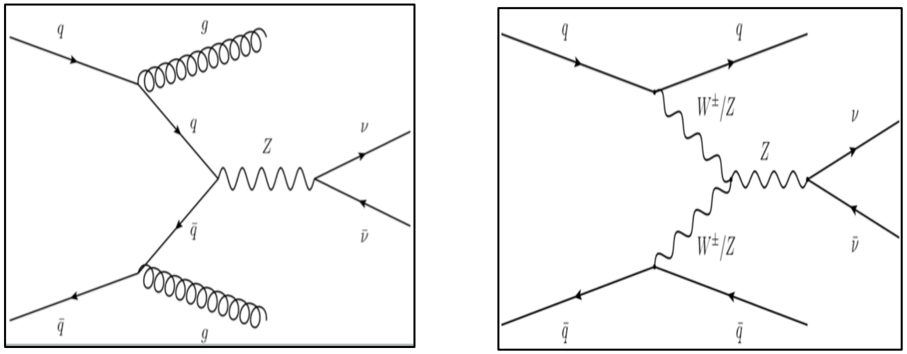
data described well by background



VBF signal



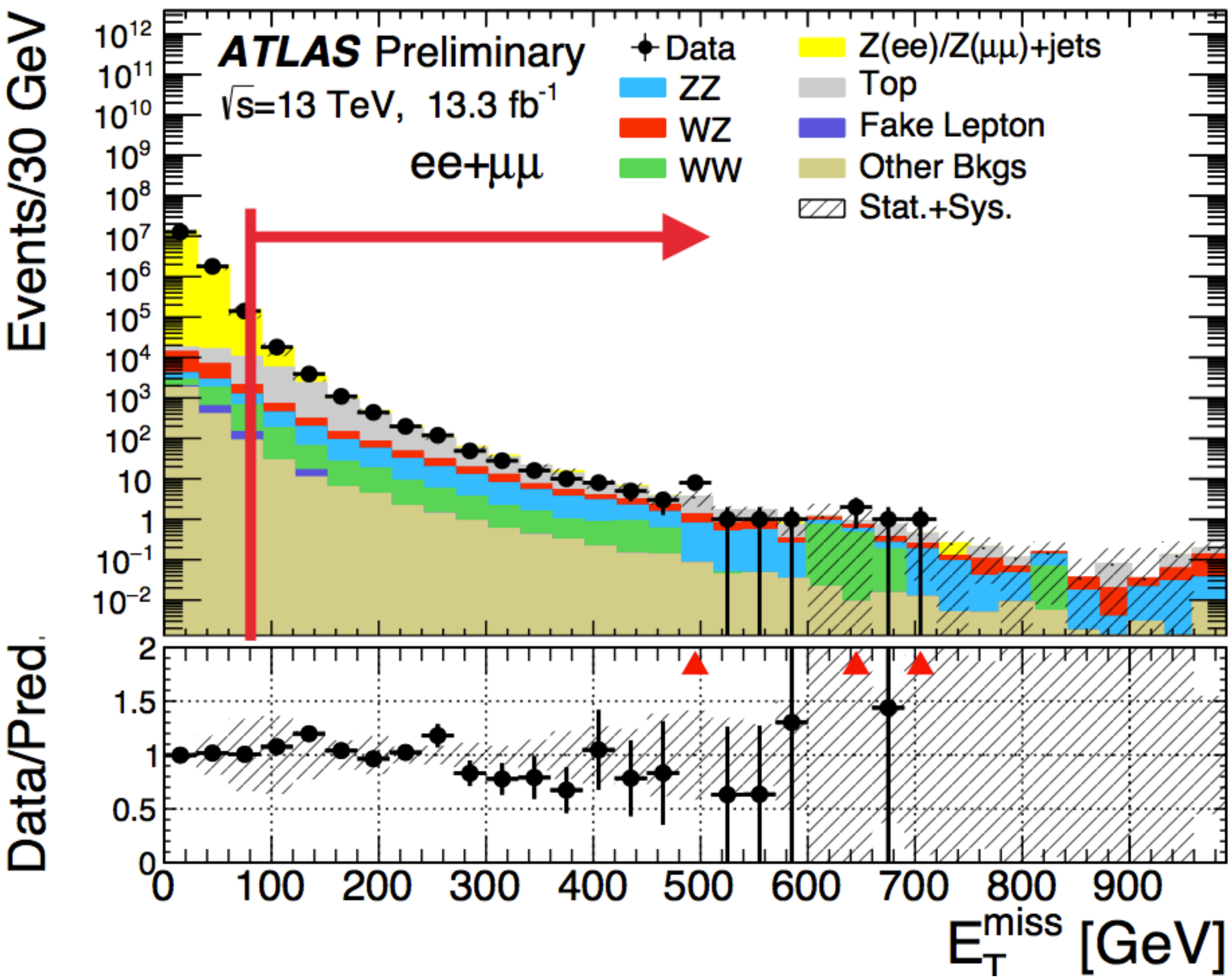
Z→νν background



Invisible Higgs decays:
associated ZH (Z→ℓℓ) production

- clean final state
- low sensitivity

- single-lepton trigger
- ee or μμ pair
- $|M_{\ell\ell} - M_Z| < 15$ GeV
- no b-jets
- 2015+2016 data

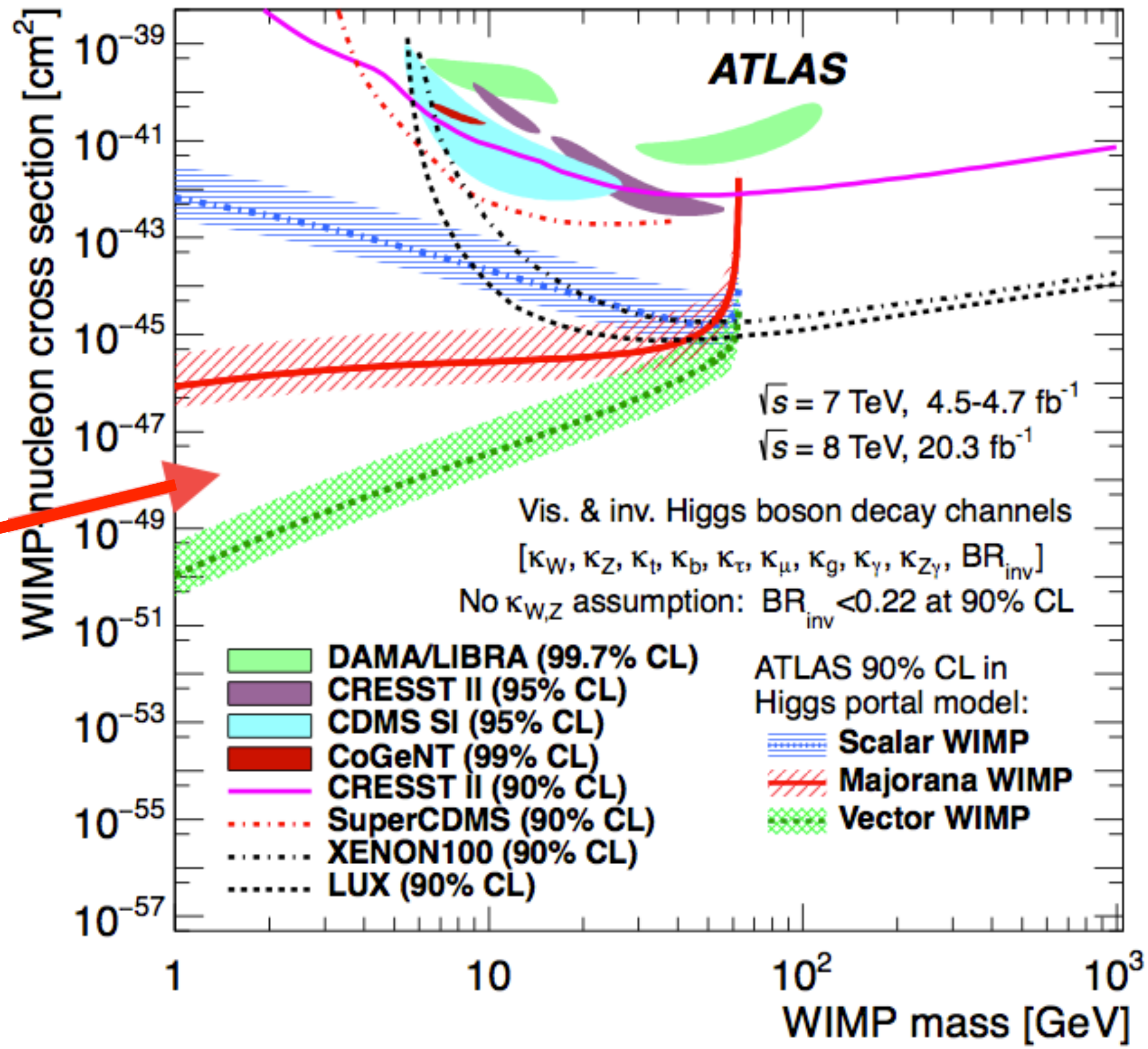


Invisible Higgs decays

combination of ATLAS Run-1 data:

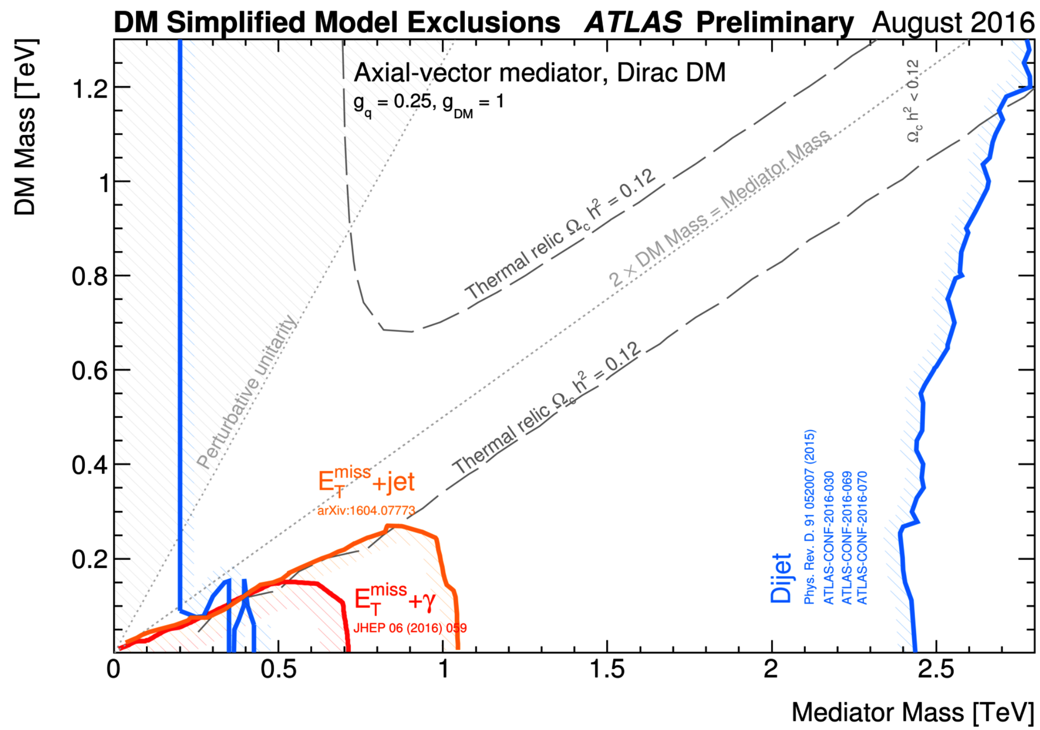
$Br(H \rightarrow inv) < 0.22$

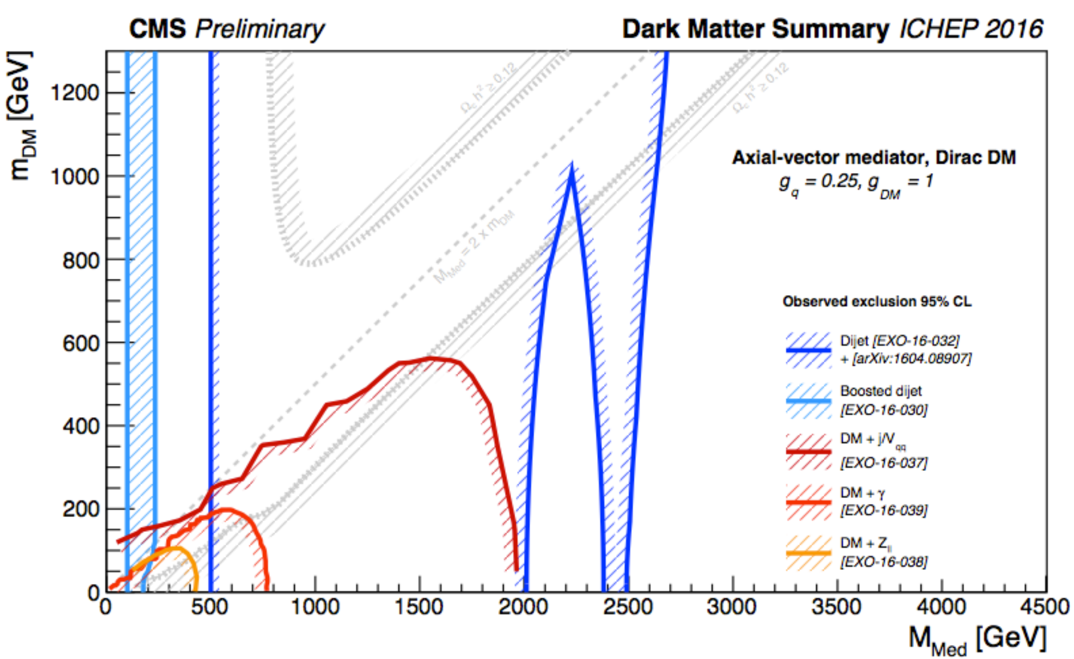
best sensitivity in low-mass region



LHC exclusion based on hypothesis that Dark Matter couples to Higgs sector !

(assumption not needed by direct / indirect detection experiments)



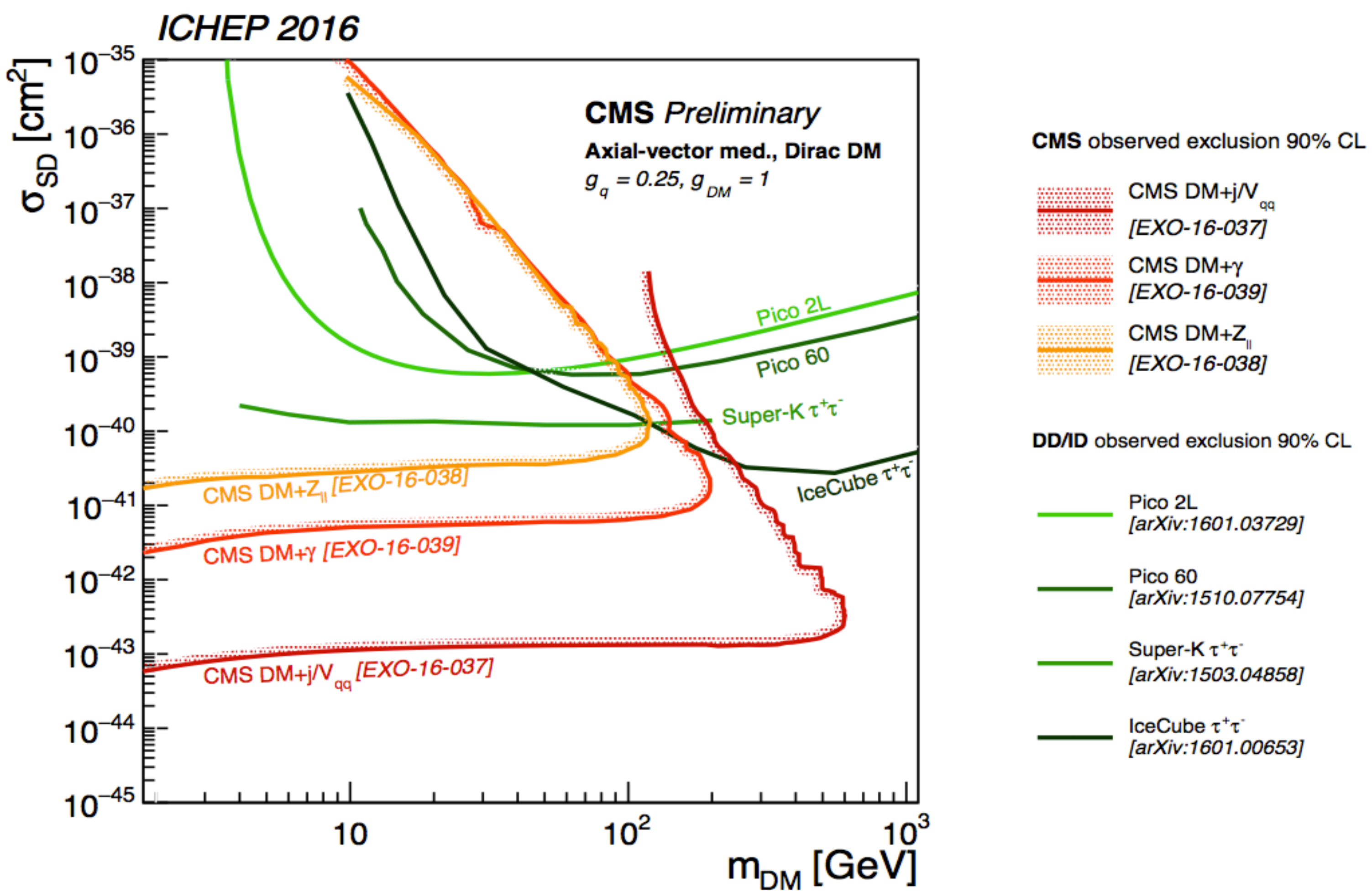


Di-jet searches

- if $2m_{DM} > M_{med}$ → DM cannot be produced on-shell
- mediator decays back to SM
- cover off-shell region by looking at dijets
  - combine close-by jets into "wide jets"
  - challenging because of high events rates
  - keep only minimum of event information
    - "data scouting" (CMS)
    - "trigger-object level analysis (ATLAS)

ATLAS-CONF-2016-030, 069, 070
CMS-EXO-16-032

summary on mono-X search results

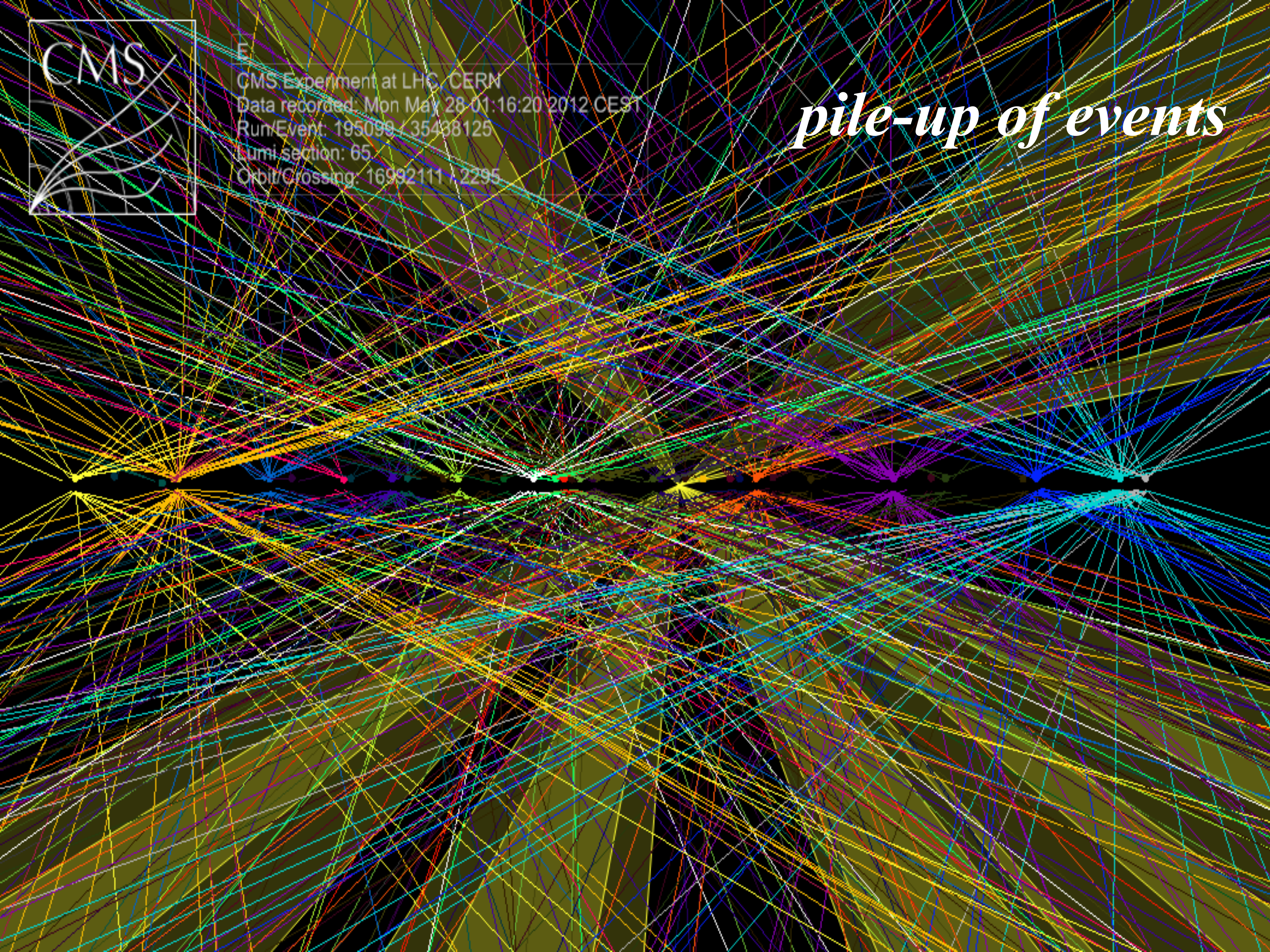


Summary

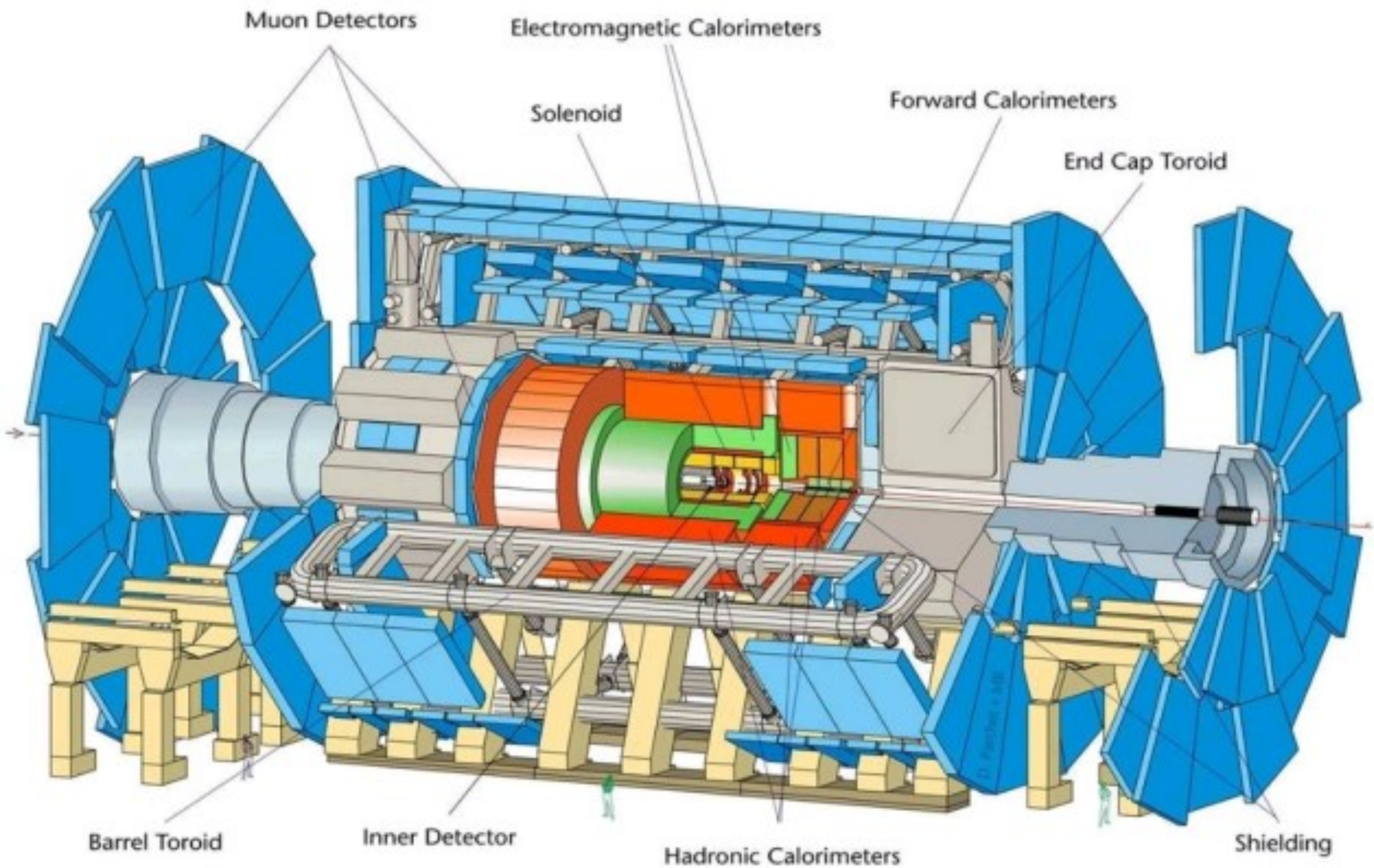
- Data-based techniques employed to estimate background contamination
- With rising LHC energy and momentum transfer, important to complement Effective Field Theory approach by “Simplified Models”, taking into account the mediator particle
- meaningful comparison with direct and indirect observation experiments is essential
- so far, no evidence for Dark Matter (or other BSM physics) at collision energies of $\sqrt{s}$ = 7, 8 and 13 TeV
  - LHC will accumulate much more luminosity than available so far, allowing us to set more stringent limits for Dark-Matter searches

Only a complementary approach of direct and indirect detection experiments and of collider production may throw light on Dark Matter!

BACKUP


CMS
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

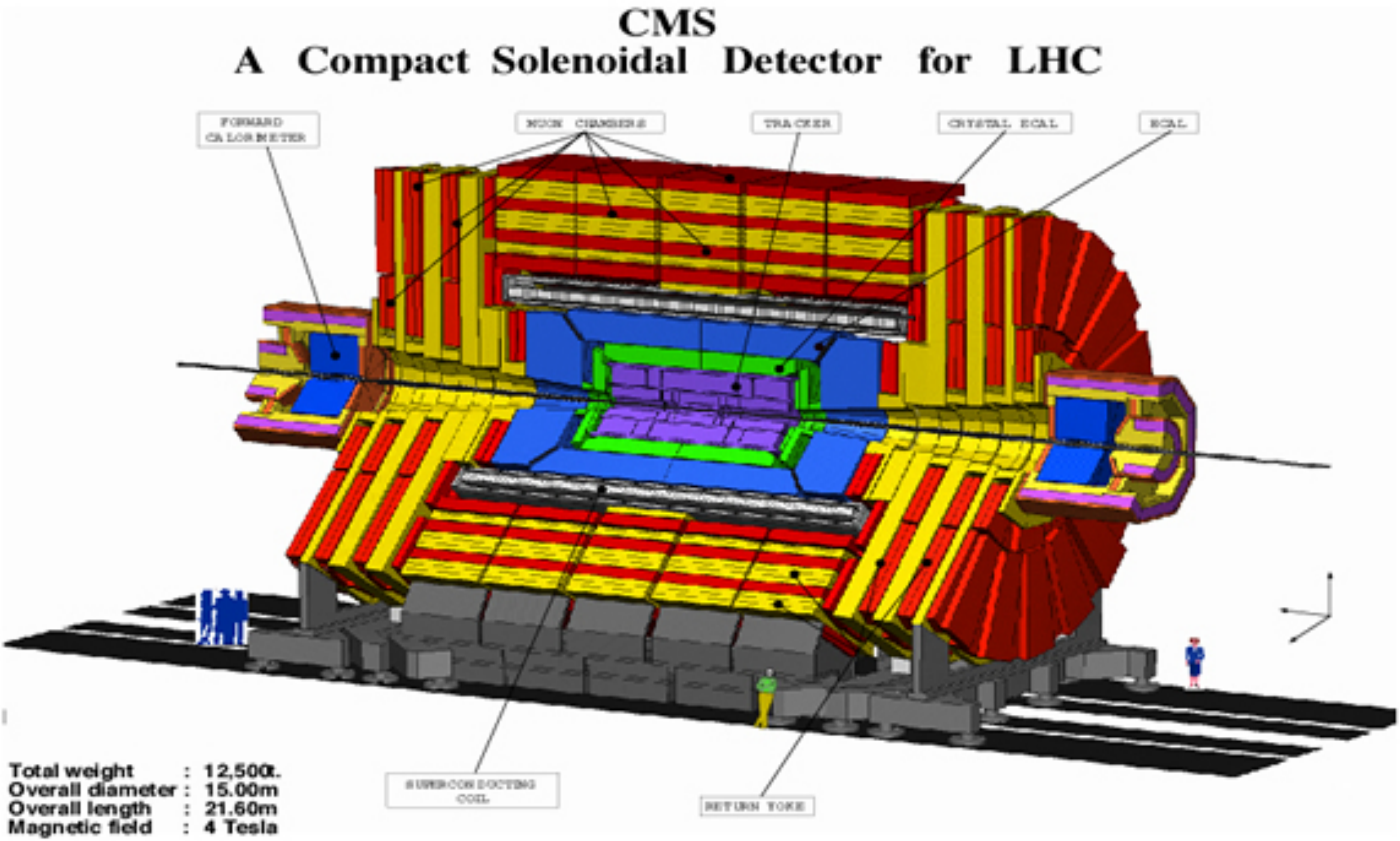
The ATLAS detector



ATLAS analyses

Analysis	Dataset	Public link		
Production search:				
E_T^{miss}+jet	2015	Paper:	EXOT-2015-03	
$E_T^{miss}+\gamma$	2015	Paper:	EXOT-2015-05	
$E_T^{miss}+Z(\rightarrow \ell\ell)$	2015+2016	Note:	ATLAS-CONF-2016-056	new!
$E_T^{miss}+W/Z(\rightarrow qq)$	2015	Paper:	EXOT-2015-08	new!
$E_T^{miss}+H(\rightarrow bb)$	2015	Note:	ATLAS-CONF-2016-019	
$E_T^{miss}+H(\rightarrow \gamma\gamma)$	2015+2016	Note:	ATLAS-CONF-2016-087	new!
$E_T^{miss}+H(\rightarrow \ell\ell\ell\ell)$	2015	Note:	ATLAS-CONF-2015-059	
E_T^{miss}+b-jets	2015+2016	Note:	ATLAS-CONF-2016-086	new!
$E_T^{miss}+t\bar{t}$ (0ℓ)	2015+2016	Note:	ATLAS-CONF-2016-077	new!
$E_T^{miss}+t\bar{t}$ (1ℓ)	2015+2016	Note:	ATLAS-CONF-2016-050	new!
$E_T^{miss}+t\bar{t}$ (2ℓ)	2015+2016	Note:	ATLAS-CONF-2016-076	new!
Mediator search:				
Dijet	2015+2016	Note:	ATLAS-CONF-2016-069	new!
Trigger-level dijet	2015	Note:	ATLAS-CONF-2016-030	
Dijet+ISR	2015+2016	Note:	ATLAS-CONF-2016-070	new!
Summary plots:				
Mediator searches	2015+2016	Plot:	Summary plot page	new!
Search combination	2015+2016	Plot:	Summary plot page	new!

The Compact MUON Solenoid detector



CMS 13 TeV Searches For Dark Matter

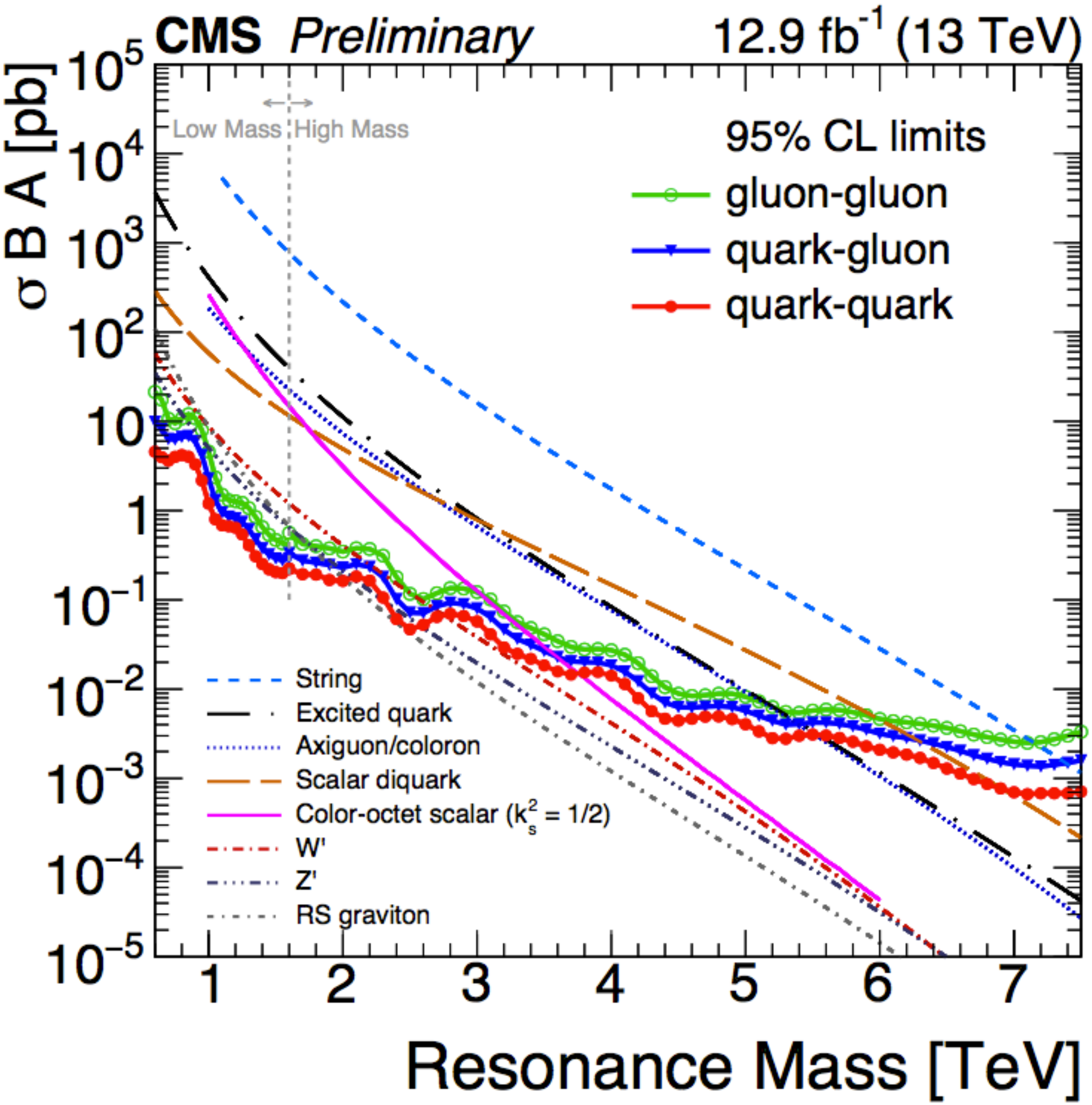
Focus of this talk

X	Dataset	CMS Documentation
jet or V (hadronic)	2016, 12.9 fb	EXO-16-037
photon	2016, 12.9 fb	EXO-16-039
Z (ll)	2015, 2.3 fb	EXO-16-010
Z (ll)	2016, 12.9 fb	EXO-16-038
Higgs (bb)	2015, 2.3 fb	EXO-16-012
Higgs (γγ)	2015, 2.3 fb	EXO-16-011
tt (semilep+had)	2015, 2.2 fb	EXO-16-005
t (hadronic)	2016, 12.9 fb	EXO-16-040

Previous Results

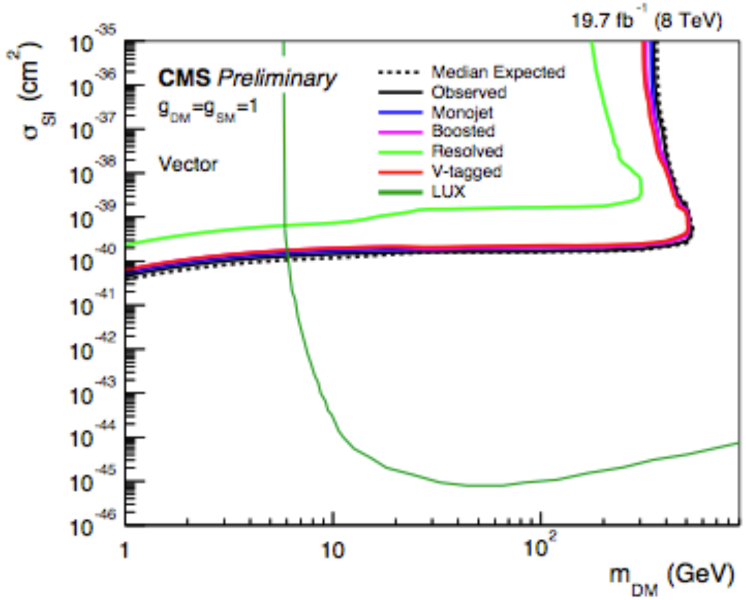
X	Dataset	CMS Documentation
jet or V (hadronic)	2015, 2.3 fb	EXO-16-013
photon	2015, 2.3 fb	EXO-16-014
bb and tt	2015, 2.2 fb	B2G-15-007
t (hadronic)	2015, 2.3 fb	EXO-16-017

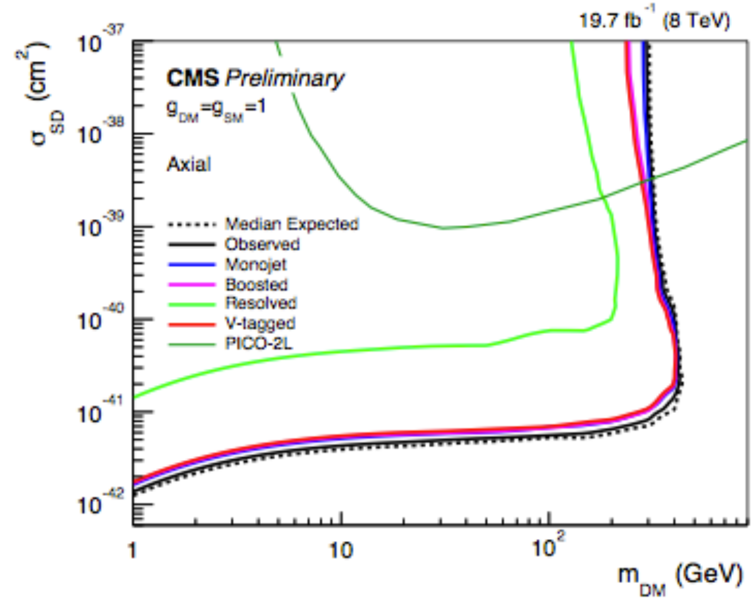
Di-jet resonance mass

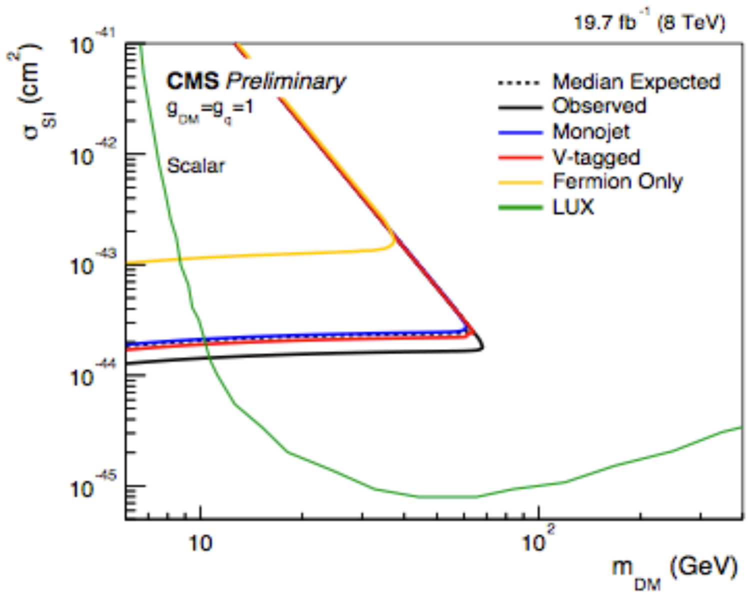


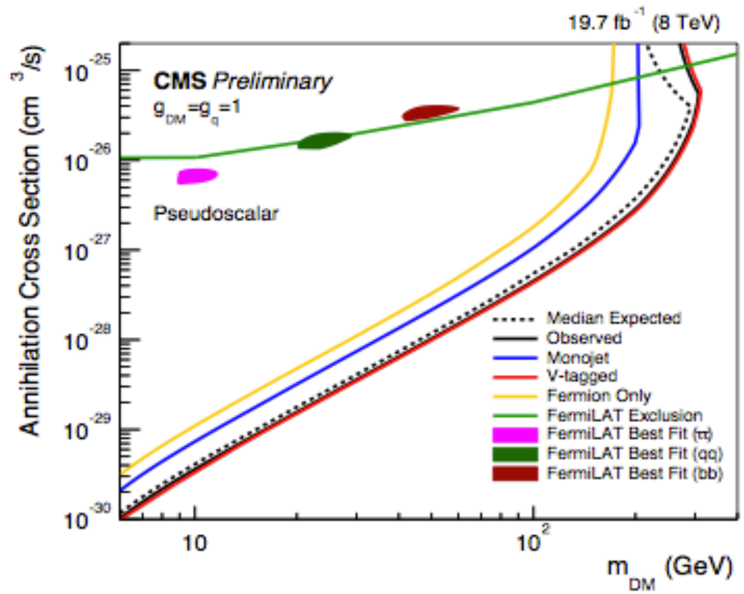
- Limits from both the low-mass and high-mass search. The observed 95% CL upper limits on the product of the cross section, branching fraction, and acceptance for quark-quark, quark-gluon, and gluon-gluon type dijet resonances. The observed limits (solid) are presented from the low mass search, for resonance masses between 0.6 TeV and 1.6 TeV, and from the high mass search for resonance masses greater than or equal to 1.6 TeV. Limits are compared to the predicted cross sections of string resonances [18, 19], excited quarks [24, 25], axigluons [21], colorons [23], scalar diquarks [20], color-octet scalars [26], new gauge bosons W′ and Z′ [27], and RS gravitons [28].

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



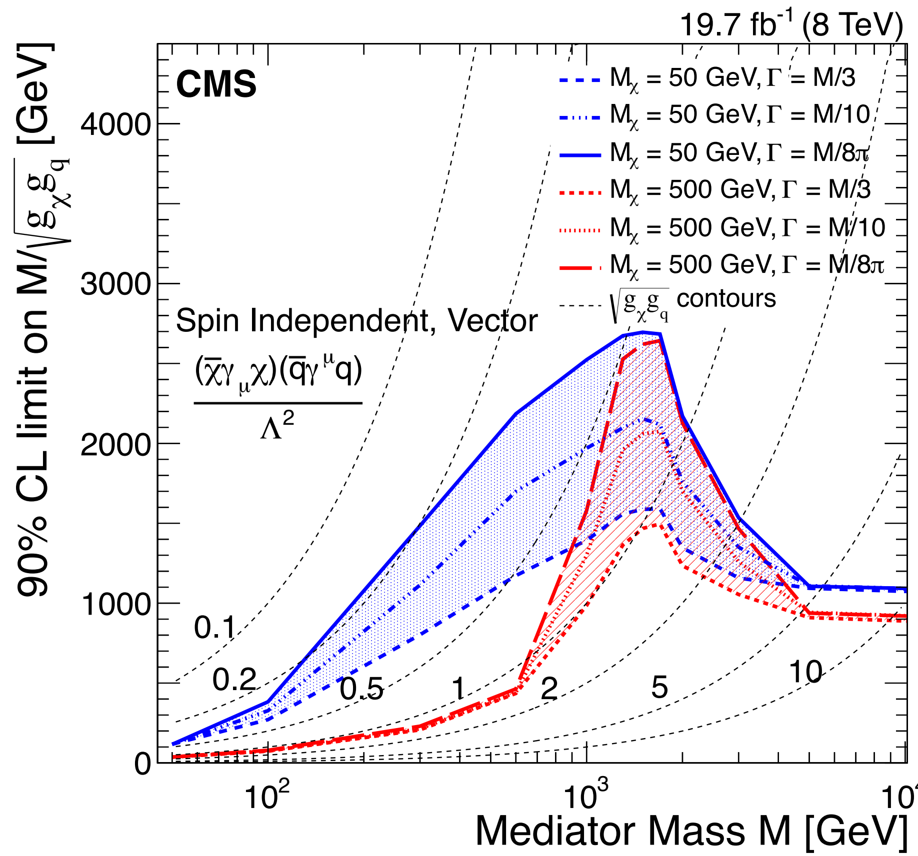






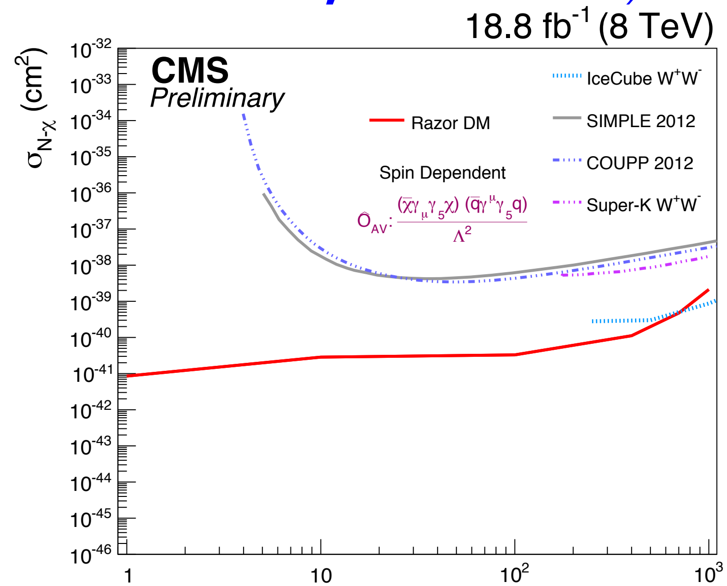
Monojet: analysis using Simplified Models

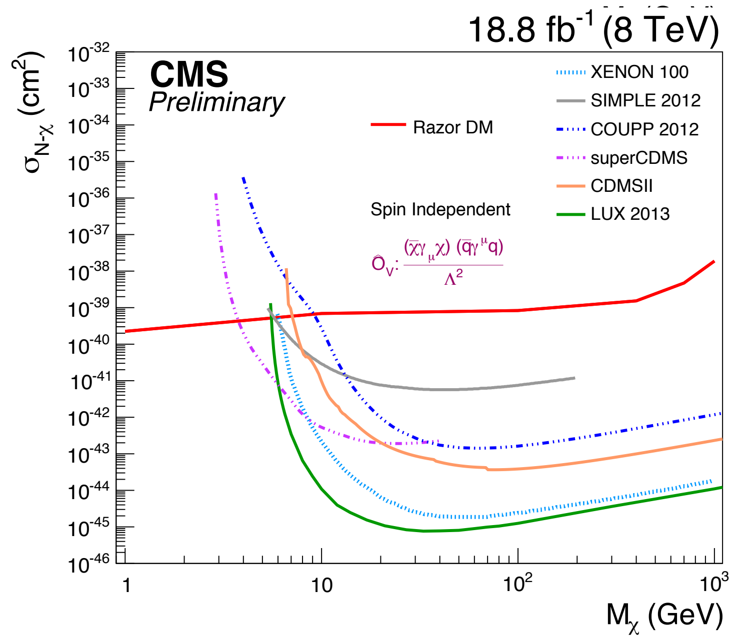
- dependence of mediator mass divided by coupling on mediator mass
- approximate Λ at high mediator mass
- higher limits in region where mediator can be produced at LHC



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





"Razor" variables

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

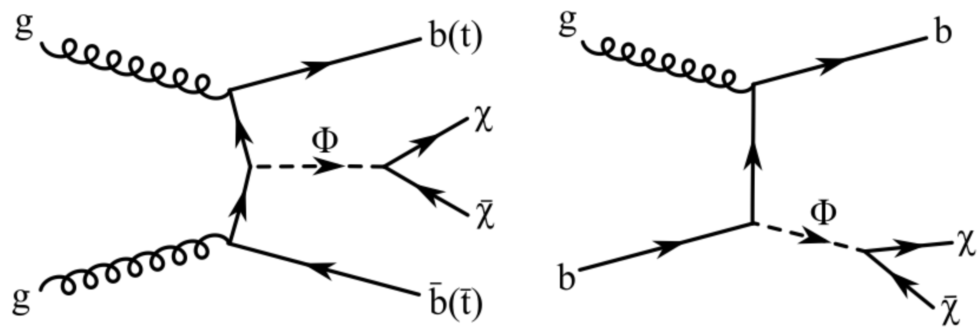
$$R \equiv \frac{M_T^R}{M_R},$$

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

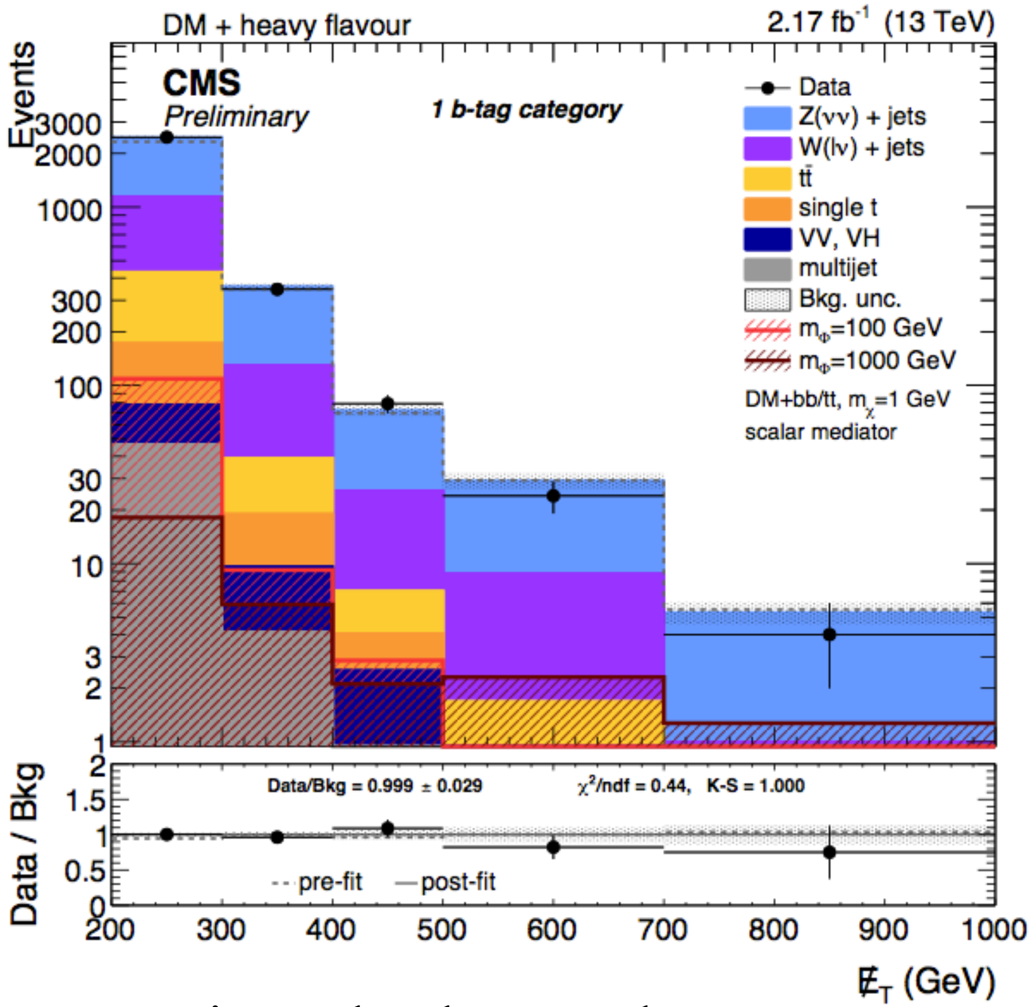
Unlike the razor SUSY searches, which focus on events with large values of M_R, this study considers events with low values of M_R, using R^2 as the discriminating variables between signal and background

Heavy flavor

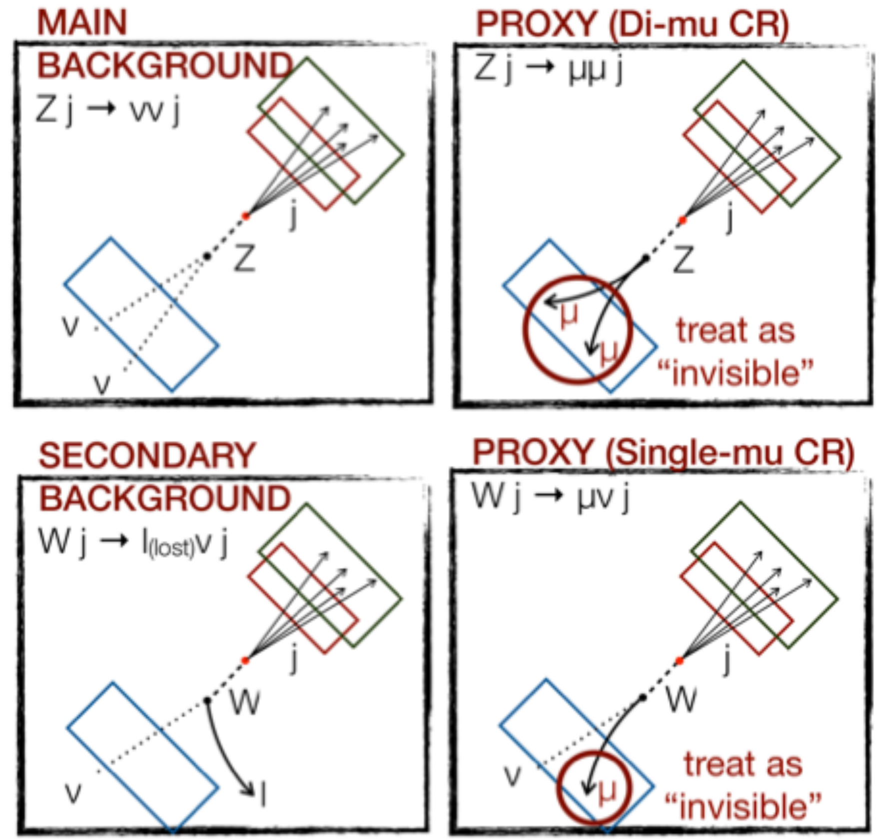
- CMS PAS B2G-15-007
- heavy-flavor quarks could strongly couple to scalar and pseudoscalar mediators
  - Yukawa coupling
- look for E_T^{miss} and one or two jets
  - b-tagged jets
  - even in bbΦ topology often only 1 jet reconstructed
  - also sensitive to top decays



Heavy flavor



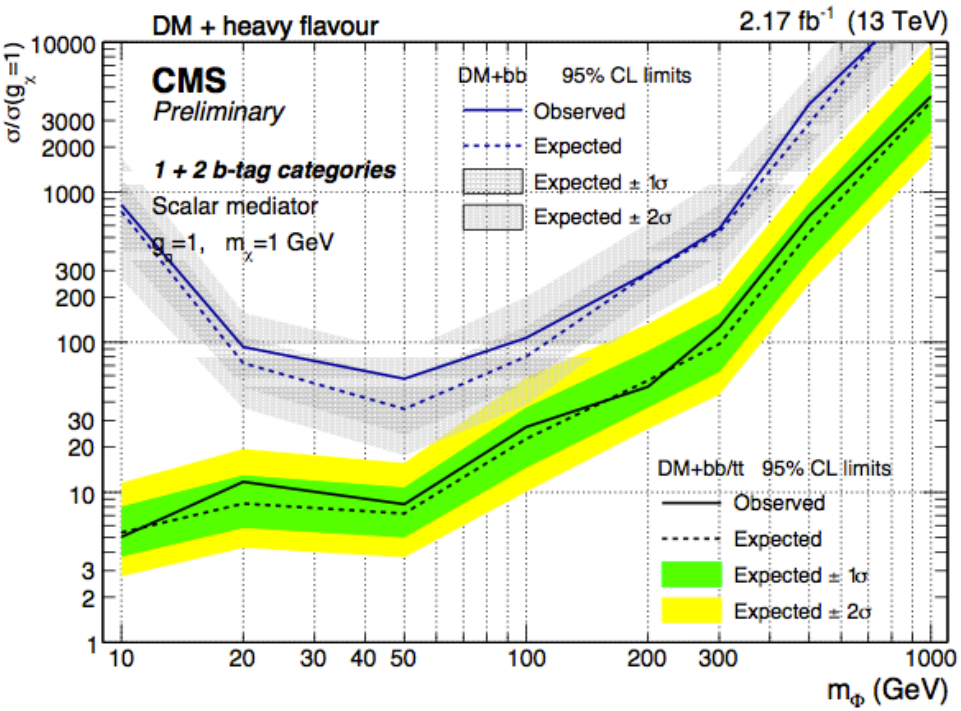
Control Regions:



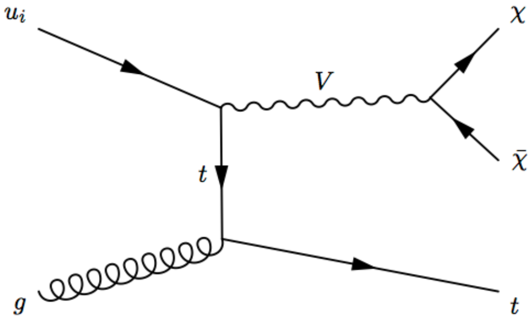
Dominant backgrounds:

- Z(νν) + jets (50%)
- W(ℓν) + jets (40%)

Heavy flavor



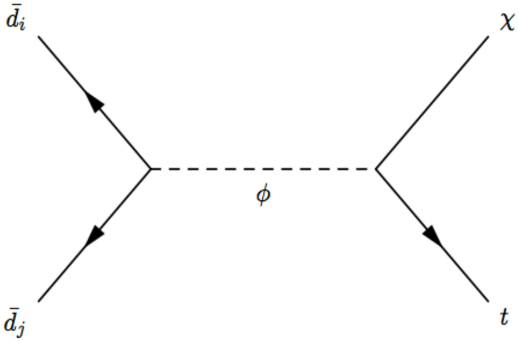
- Exclusion limit for heavy flavor vs. mediator mass
  - bb (top)
  - bb/tt (bottom)
- DM candidate mass assumed as 1 GeV



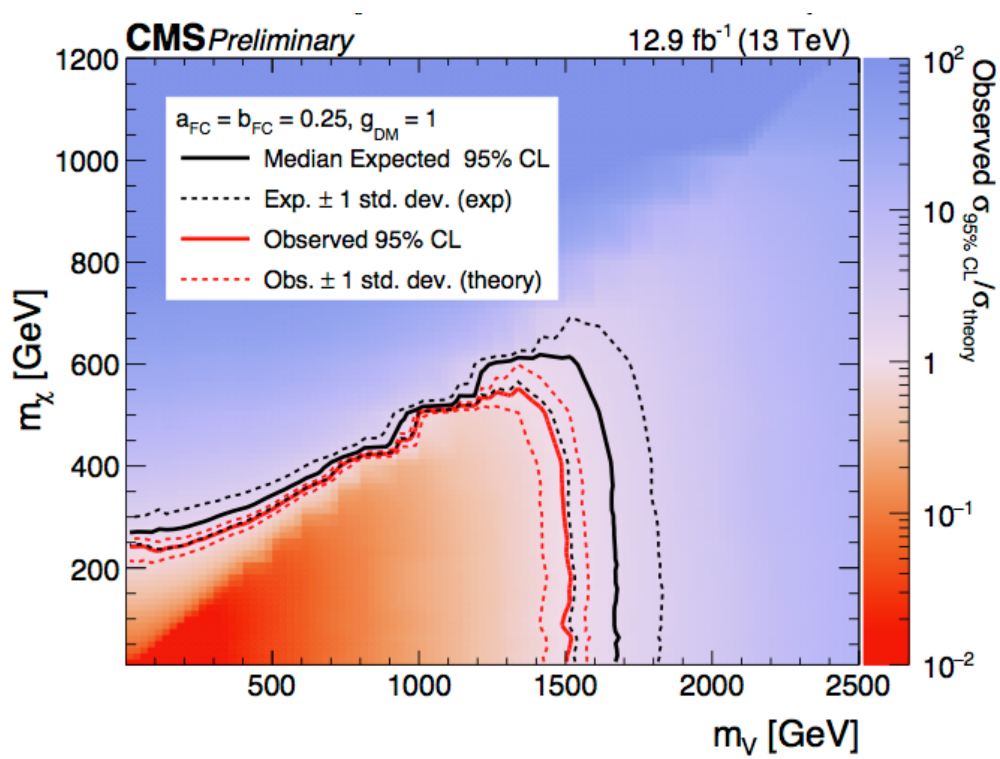
Flavor-changing neutral current (FCNC)

mono-top

- "wide" jet and $E_T^{miss} > 250$ GeV
- mass 110-210 GeV
- subjet b-tag
- FCNC vector <1.5 TeV excluded
- charged scalar 0.9-2.7 TeV excluded



Color-charged scalar



$$a_{FC} = (a_R + a_L)/2$$

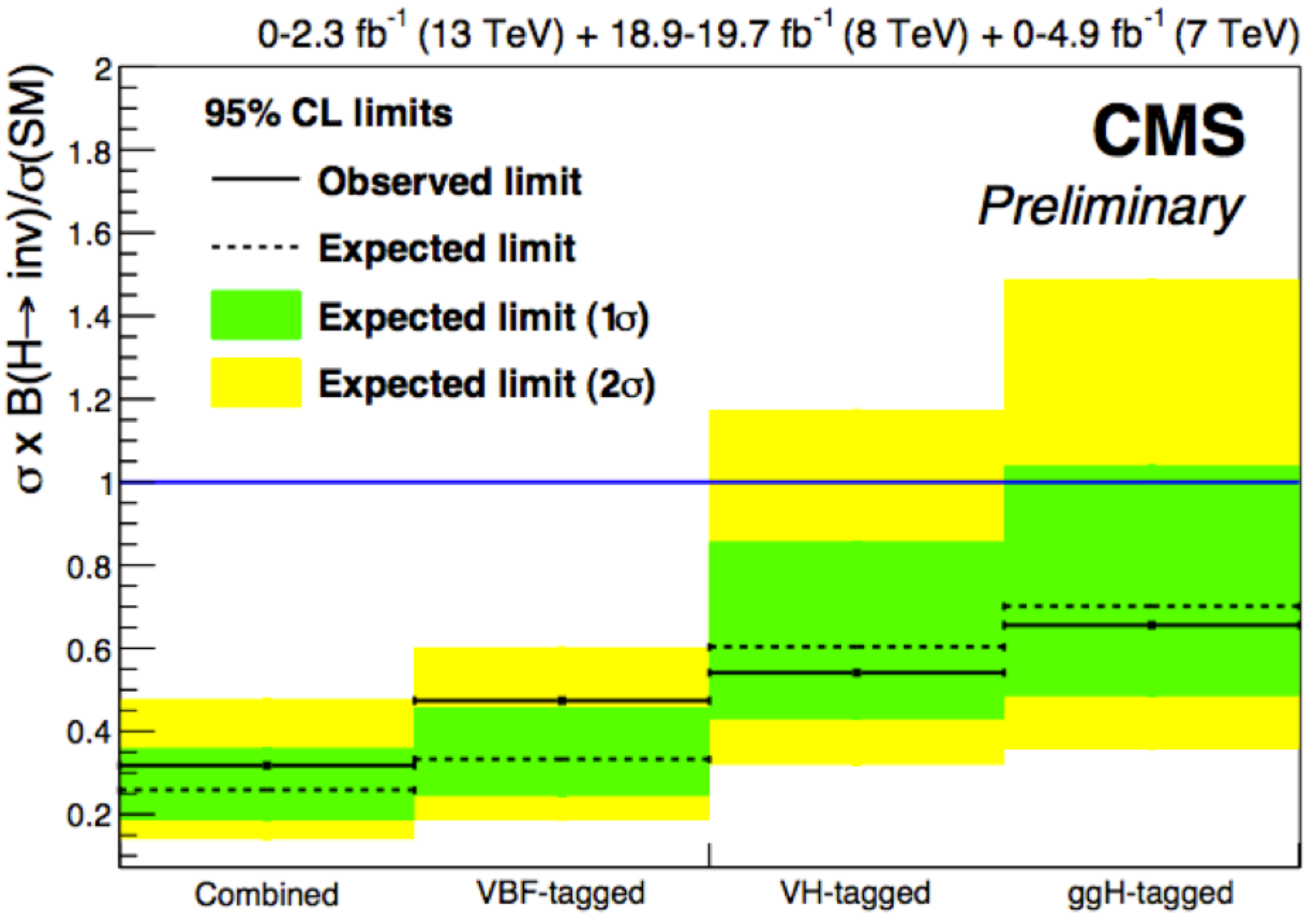
$$b_{FC} = (a_R - a_L)/2$$

a_L, a_R : *left / right-handed coupling of V field to quarks*

ATLAS-CONF-2015-79

CMS-EXO-16-040

Invisible Higgs decays

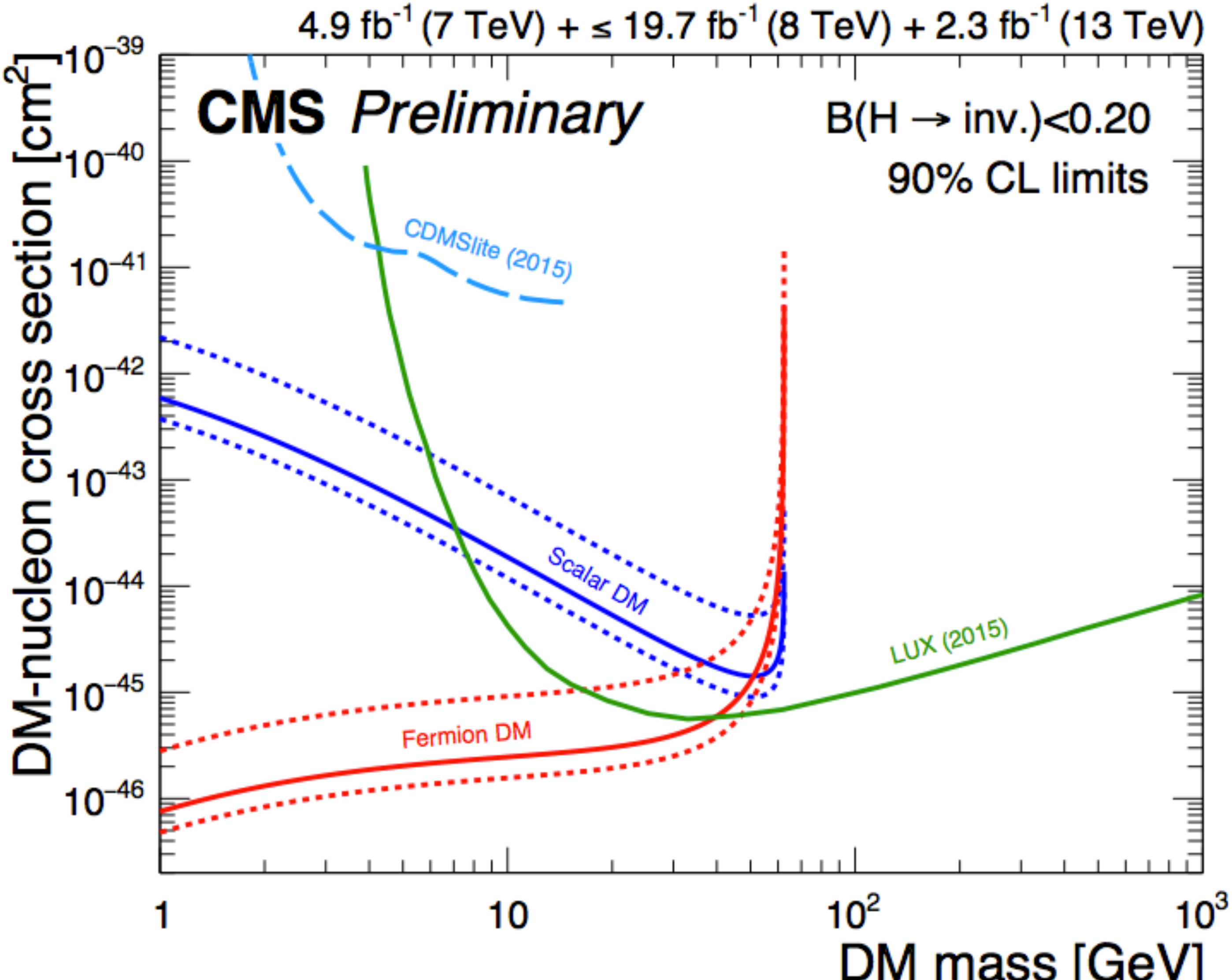


Combination of Run 1 and Run 2 results

CMS PAS HIG-16-009

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

Invisible Higgs decays



Combination of Run 1 and Run 2 (2015) results

CMS PAS HIG-16-016