Search for Dark Matter in CMS at the LHC

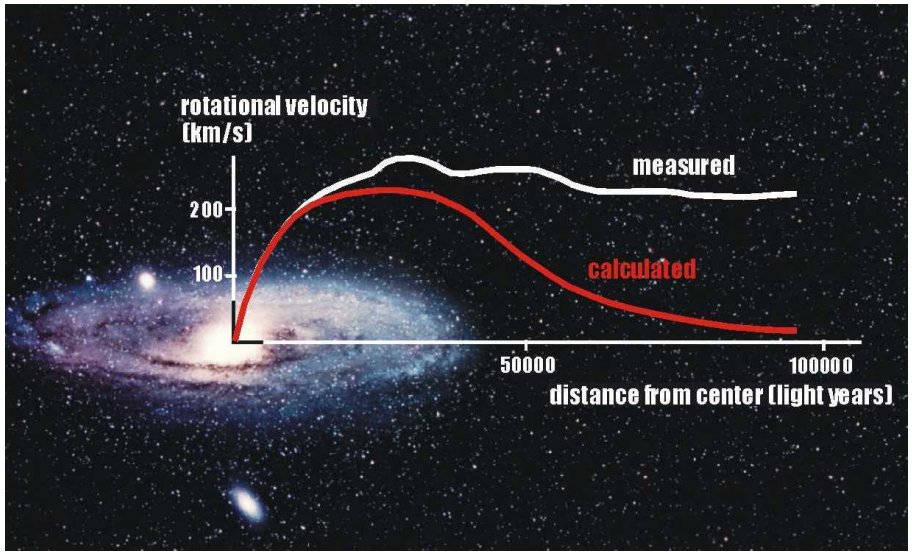
Yong Yang (University of Zurich)
on behalf of CMS collaboration

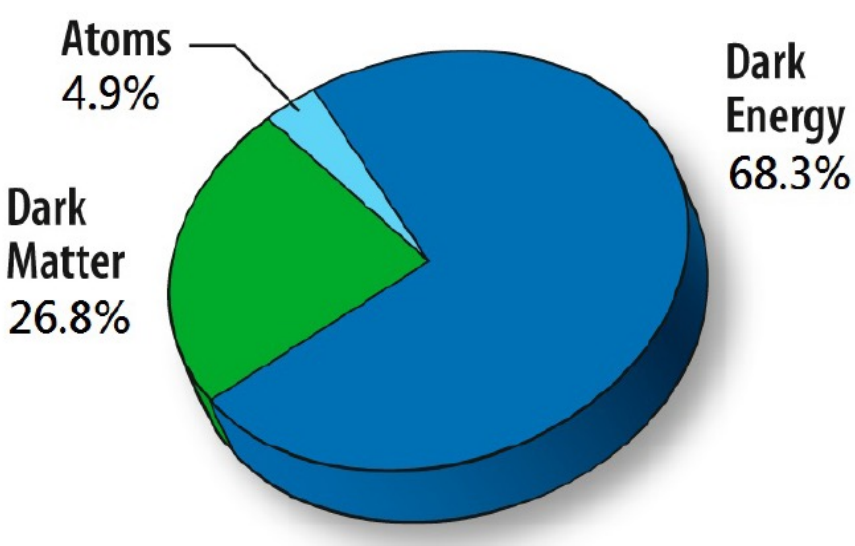
17 Mar 2015, MITP, Mainz
“Effective theories and dark matter”

Outline

- Motivation and Introduction
  - Dark matter and EFT
- CMS detector
- Dark Matter results
  - mono-jet, mono-lepton
  - tops (and relation with mono-jet)
  - Higgs-DM
- Outlook of RunII in CMS

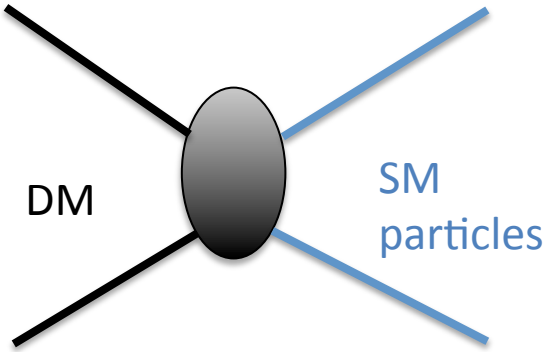
Dark Matter (DM)

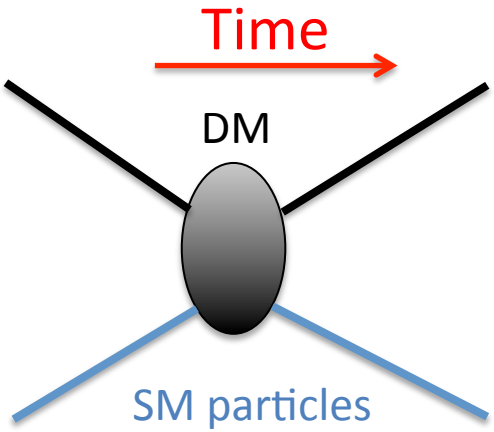


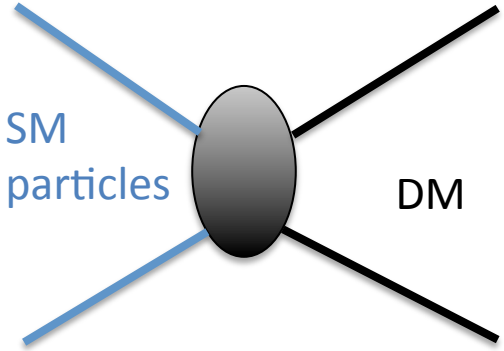


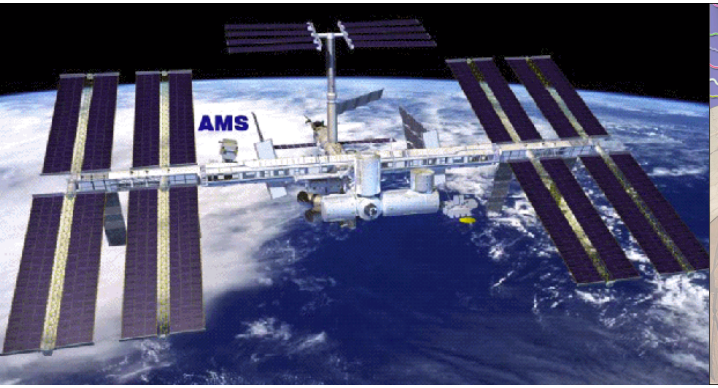
- Many evidence for DM
- One is to explain stars' velocity
  - galaxy must be more massive
  - we can not see the matter → "dark matter"
- DM makes up 27% of our universe

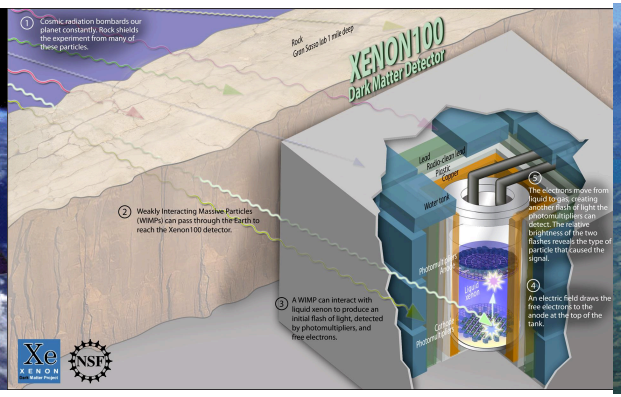
Detecting dark matter

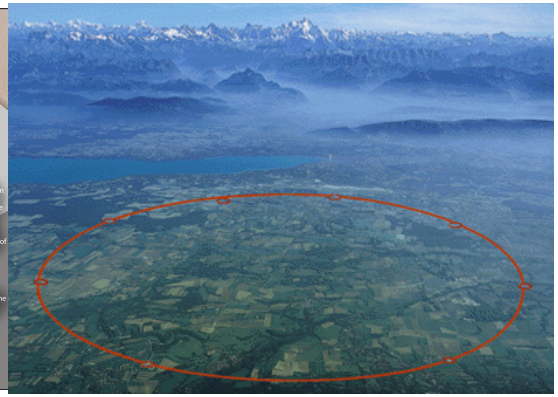












Indirect detection

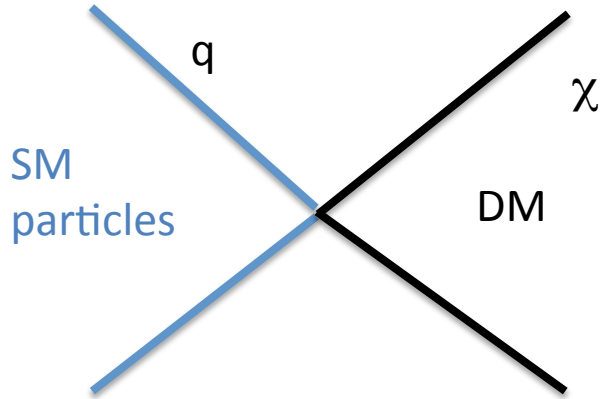
Direct detection

Collider experiment

Key question: How does DM interact with SM particles ?

Effective Field Theory (EFT)

EFT: Contact interaction



$C\,(q\,\Gamma\,q\;\chi\,\Gamma\,\chi)$

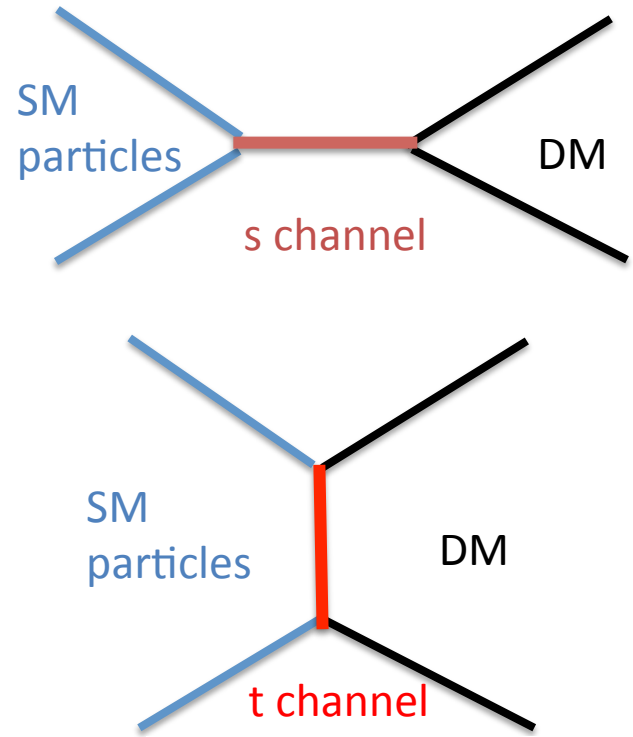
$$\Gamma = \{1, \gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}$$

$$\frac{m_q}{M_*^3}\chi\bar{\chi}q\bar{q} \quad \text{(Scalar)}$$

$$\frac{1}{M_*^2}\chi\gamma^\mu\bar{\chi}q\gamma_\mu\bar{q} \quad \text{(vector)}$$

and many more..

One step beyond EFT



$$\frac{1}{q_{\rm tr}^2 - M^2} \sim \frac{1}{M^2}$$

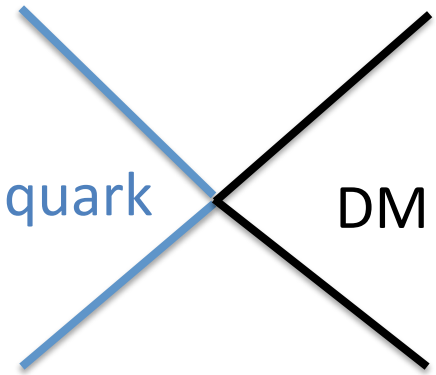
When momentum transfer is << M

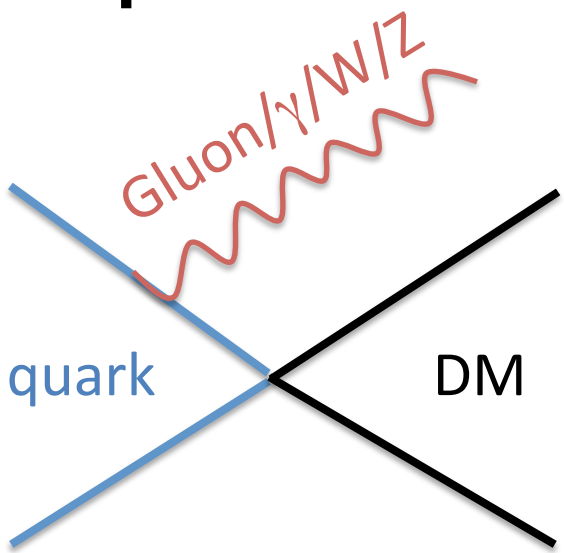
A short list of operators

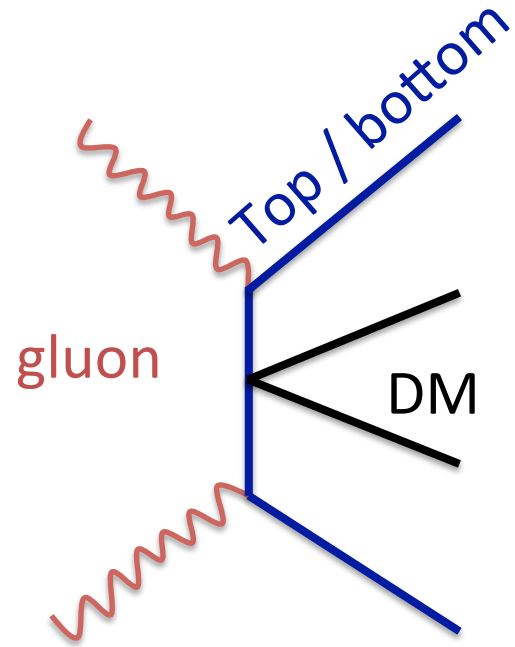
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

- Searches at LHC have been focused on Dirac fermion
  - With the above five representative operators
- Dark matter can be Majorana Fermi, Complex / Real scalar.

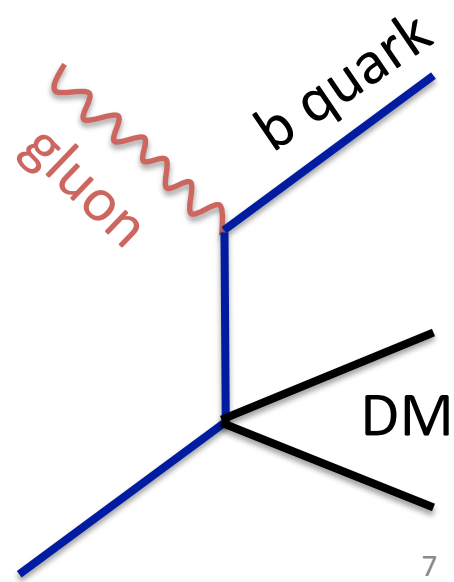
EFT DM production at LHC







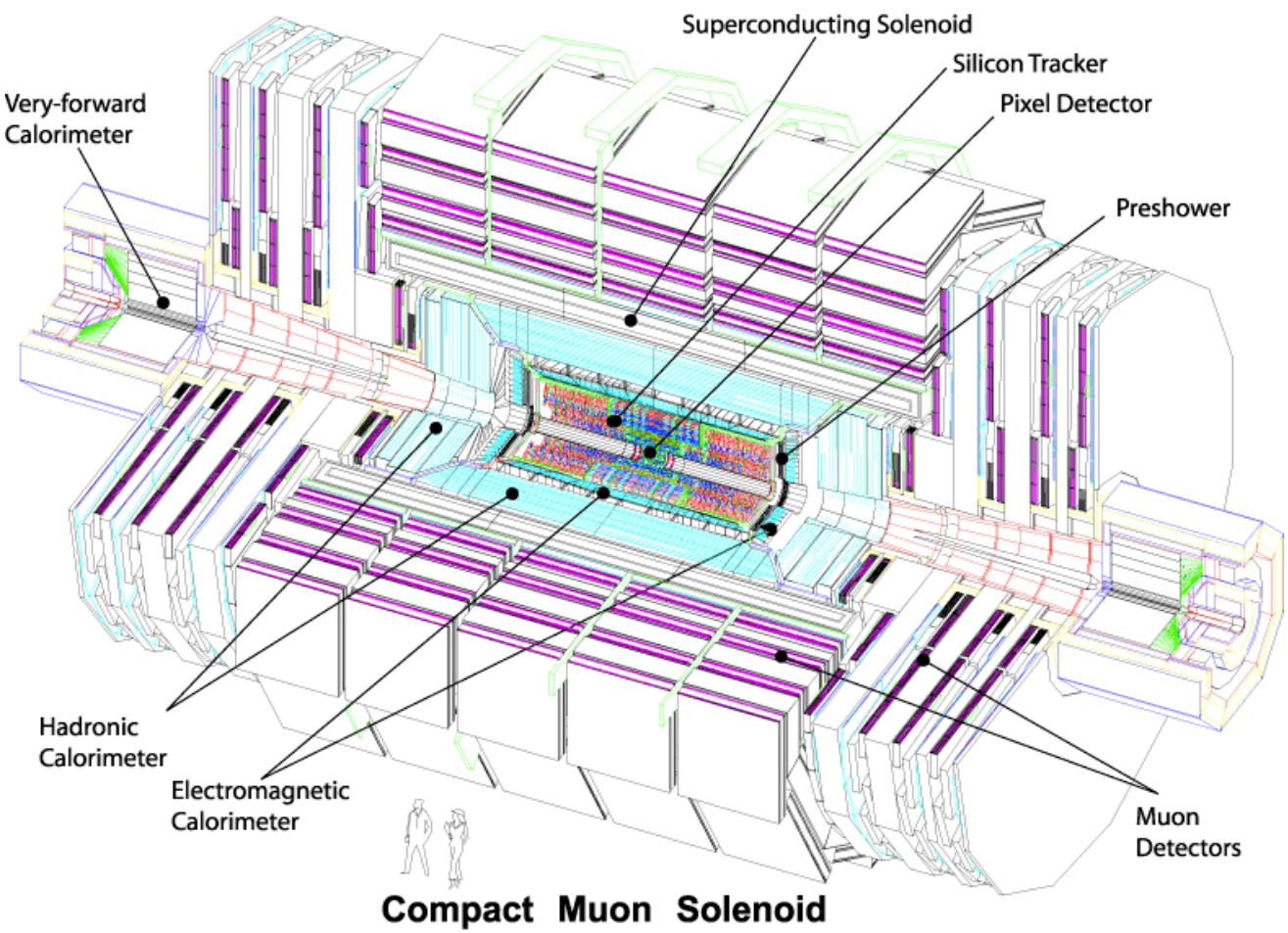
Largest rate, but not detectable



Large MET in DM events
- Mono-jet
- Mono lepton
- Tops (lepton+ jets)

Covered in this talk

The CMS Detector



High Field (3.8 T)

Modular Design

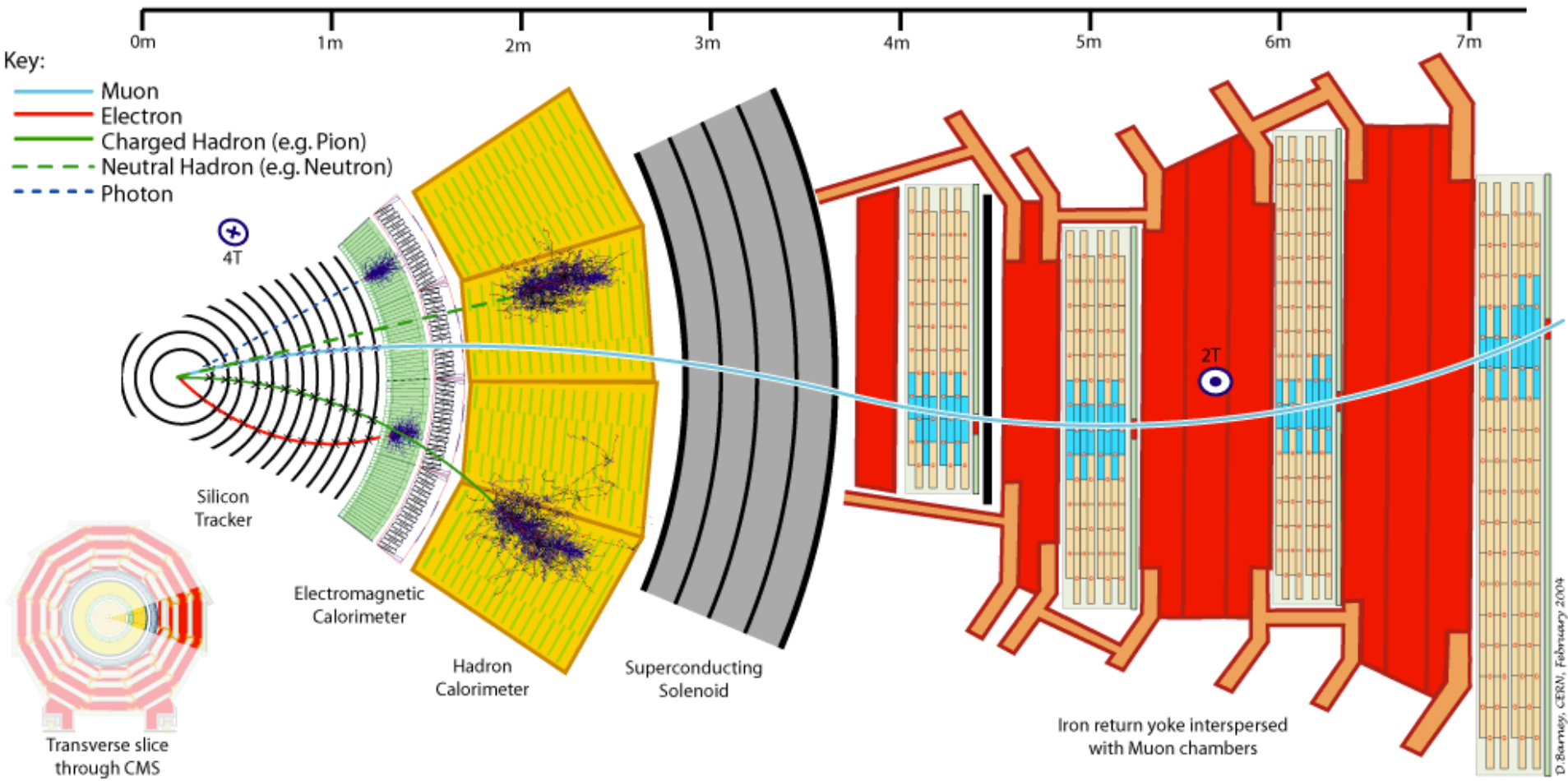
Exceptional Pixel+Track +Crystal ECAL and Muon Systems

Particle Flow based Reconstruction:

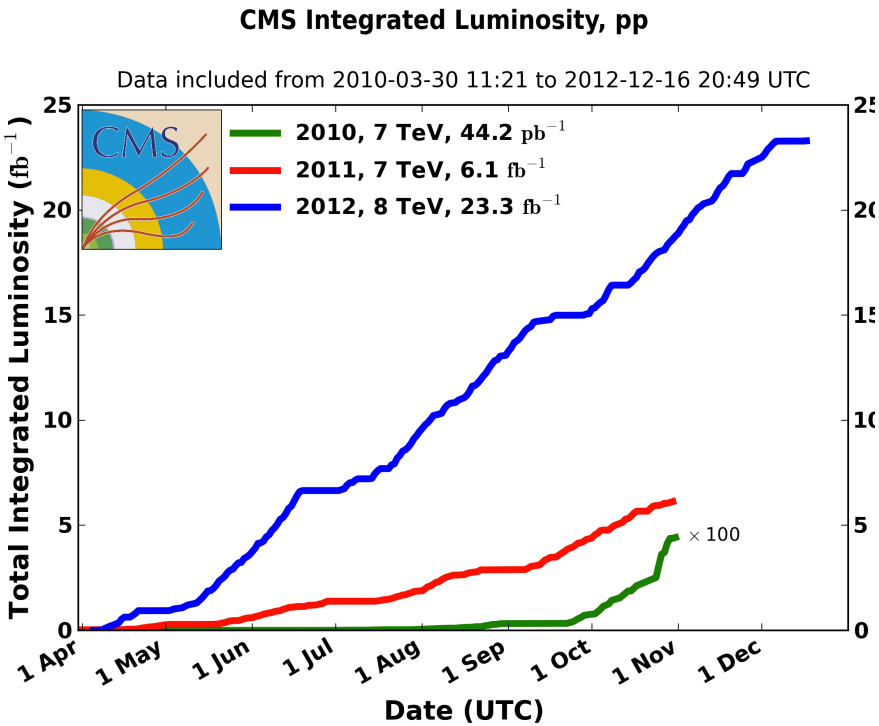
- Electron
- Muon
- Photon
- Jet
- MET

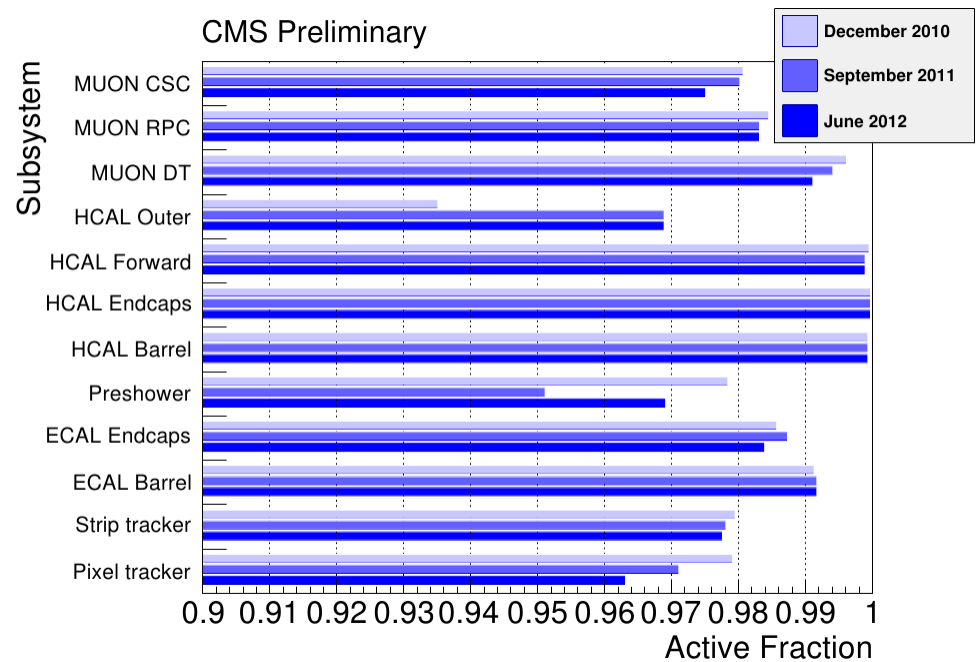
Total weight 14000 tons
Overall diameter 15 m
Overall length 28.7 m

Particles in CMS detector



Collected data and detector performance in Run I

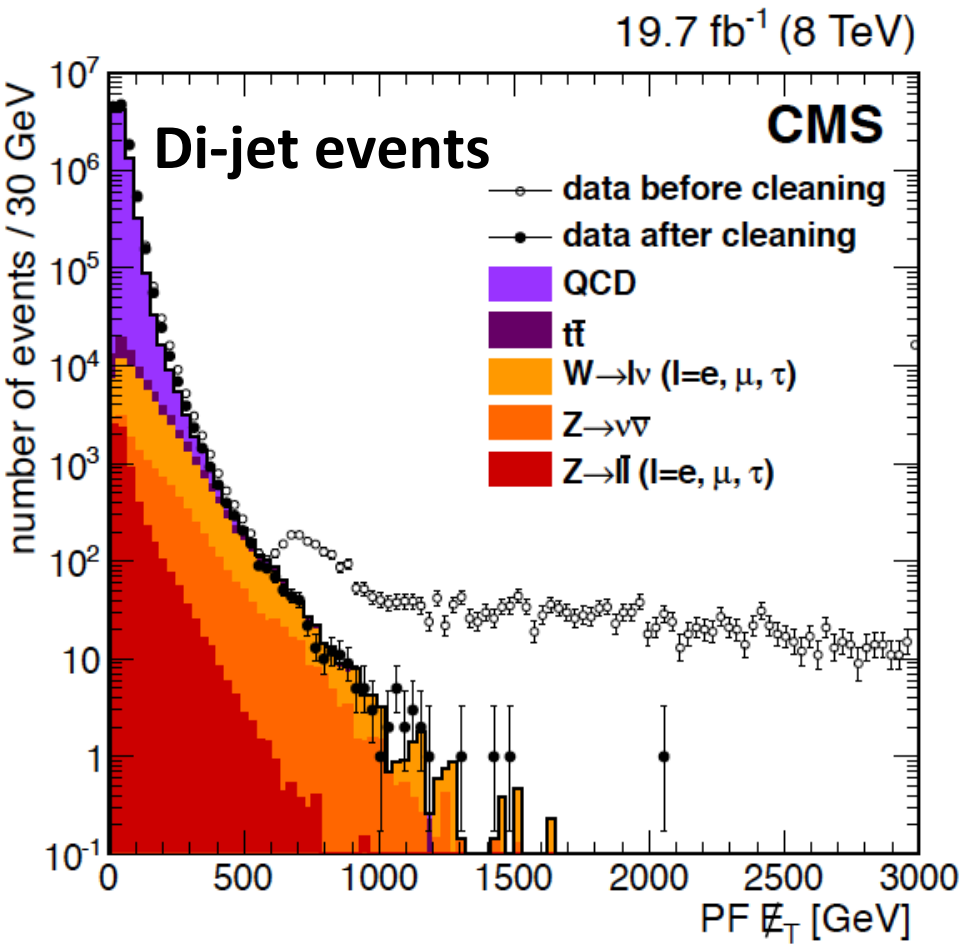




- ~20 fb^{-1} 8 TeV data for searches in this talk
- >96% channels of sub-detectors are good

MET performance

JINST 10 P02006 (2015)

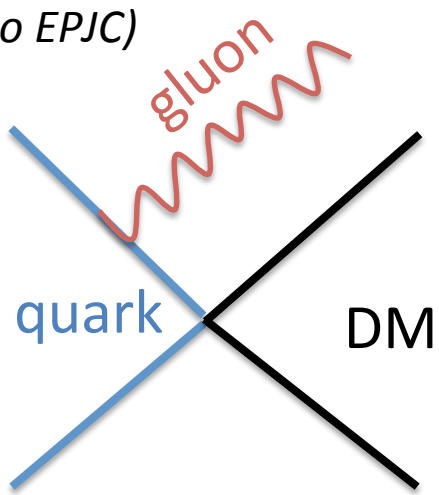


Events above 600 GeV, misfire of HCAL laser calibration. Above 1.5 TeV, electronic noise of HCAL

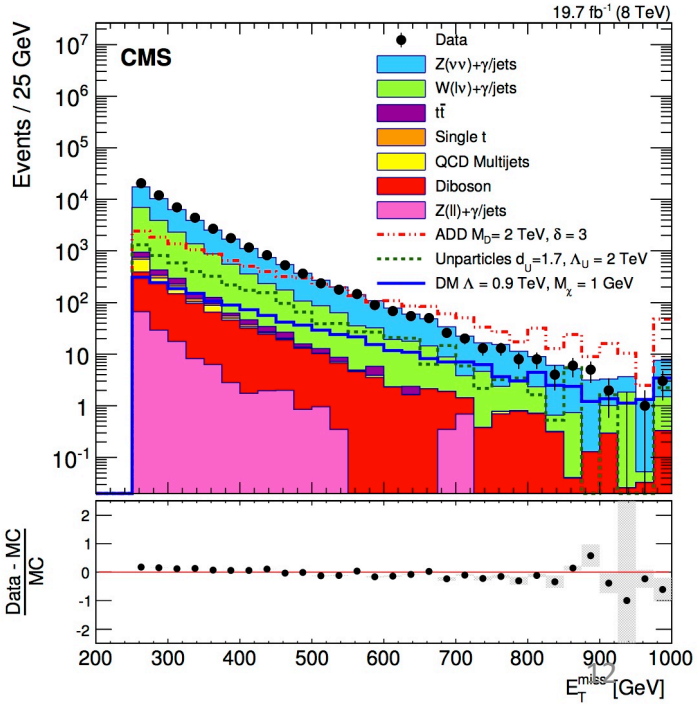
- Event mis-reconstruction can cause large MET
  - Mis-functional detector channels
  - Anomalous signals (not produced by pp collisions)
- Cleaning algorithms are developed to ensure control data is well described by simulation.

CMS monojet + DM search

1408.3583 (submitted to EPJC)

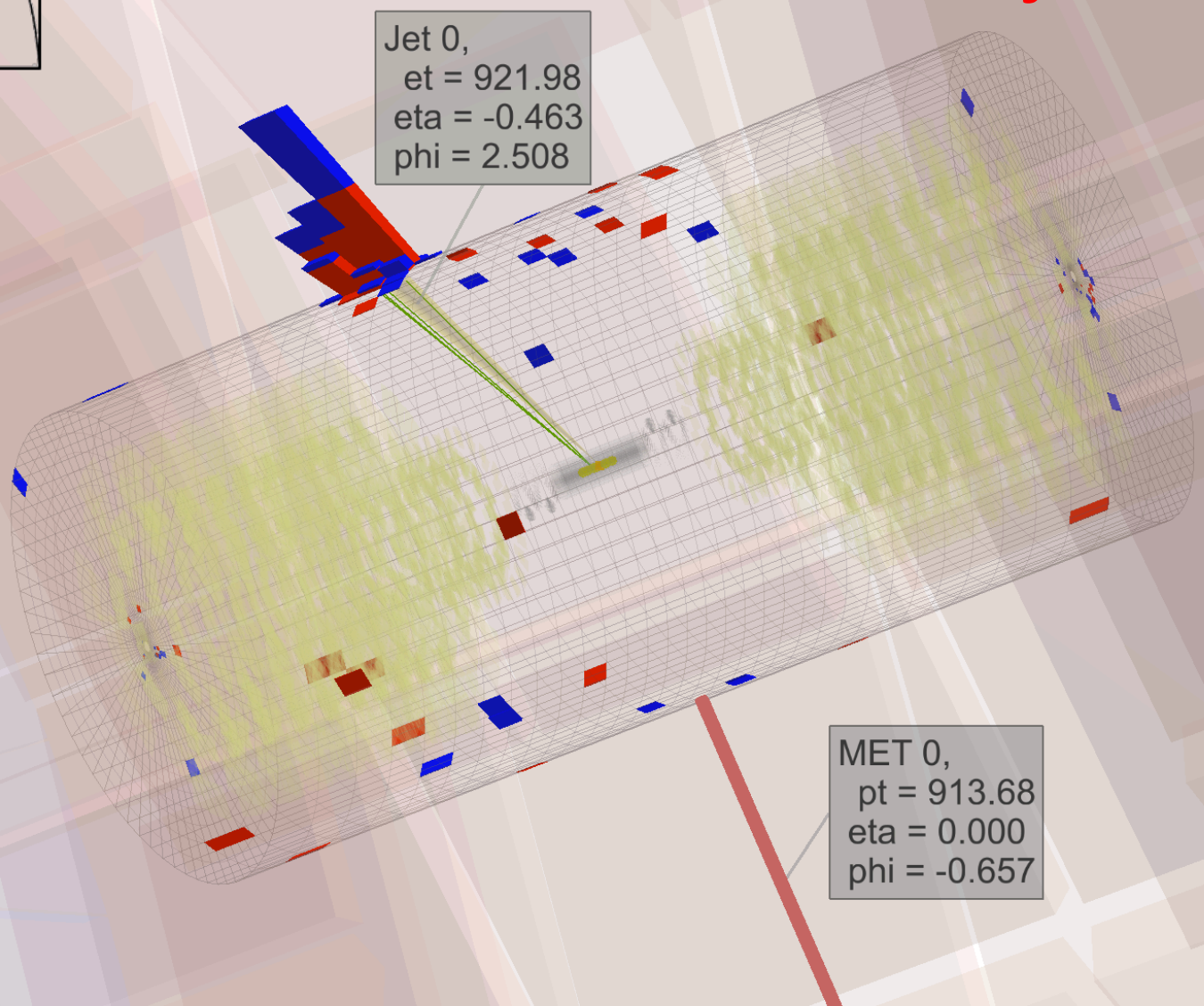


- Event selections:
  - Leading jet p_T > 110 GeV
  - At most one more jet p_T > 30 GeV
  - topological cuts $\Delta\phi(j_1,j_2)$<2.5 to reduce QCD
  - Veto events with isolated leptons
- Primary bkg. estimated from data:
  - $Z(\nu\nu)$+jets from $Z(\mu\mu)$+jets
  - $W(l\nu)$+jets from $W(\mu\nu)$+jets
- Best limits with MET> 500 GeV
- Also sensitive to ADD and unparticle model

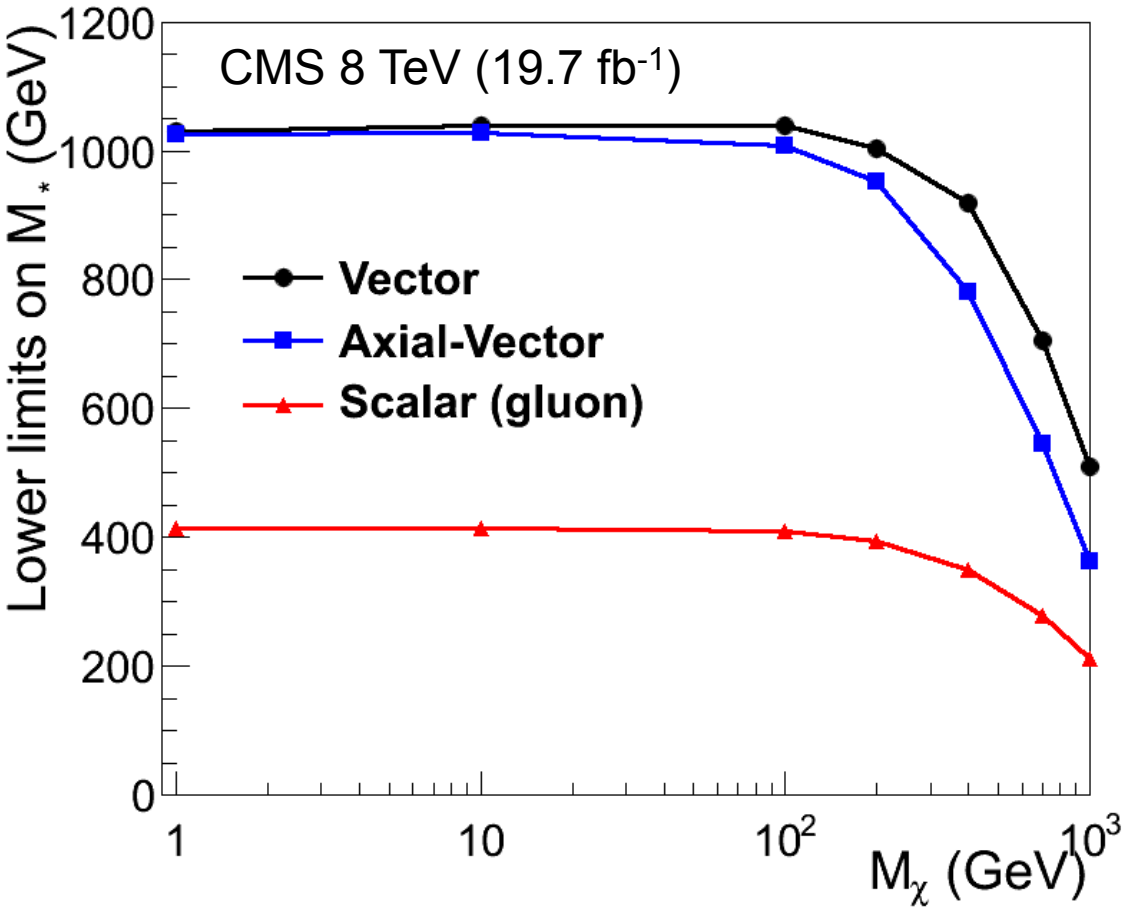


CMS Experiment at LHC, CERN
Data recorded: Fri Oct 5 20:41:32 2012 CEST
Run/Event: 204553 / 26729384
Lumi section: 31

Mono-jet +MET



Limits on M_* from DM+monojet



Vector

$$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

Axial-Vector

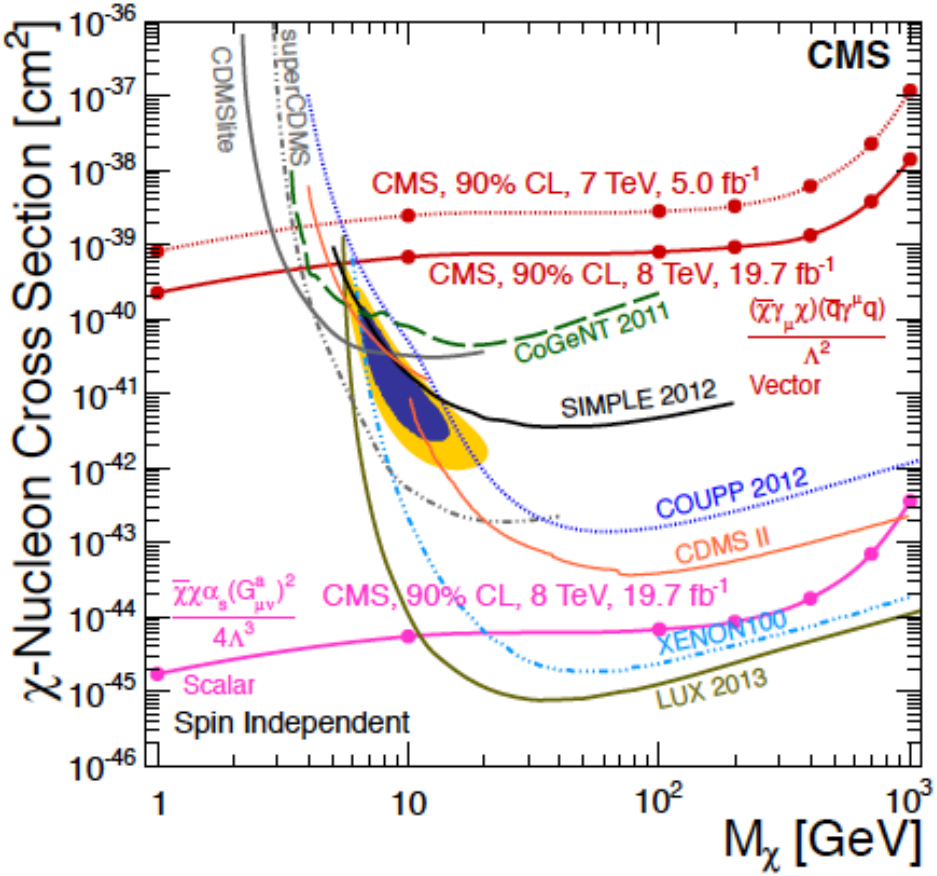
$$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$$

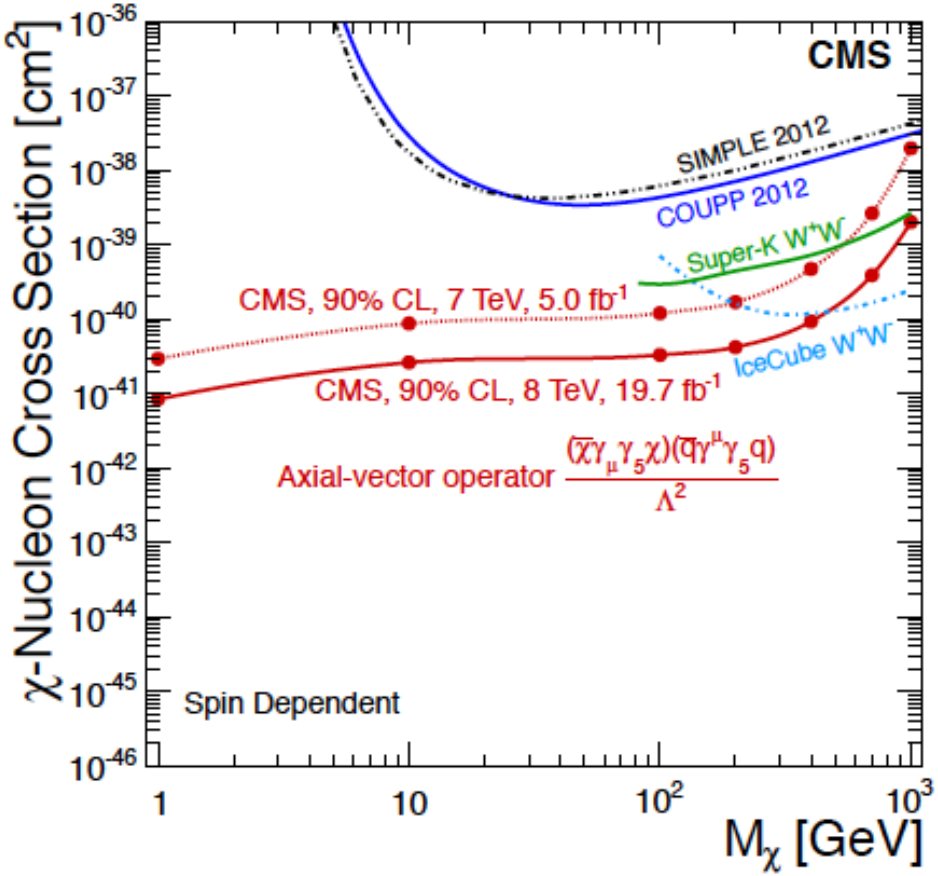
Scalar

$$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$$

Set 90% CL limits on effective operator scale M* for 3 couplings for different DM mass hypotheses

DM-nucleon cross section limits from DM+monojet

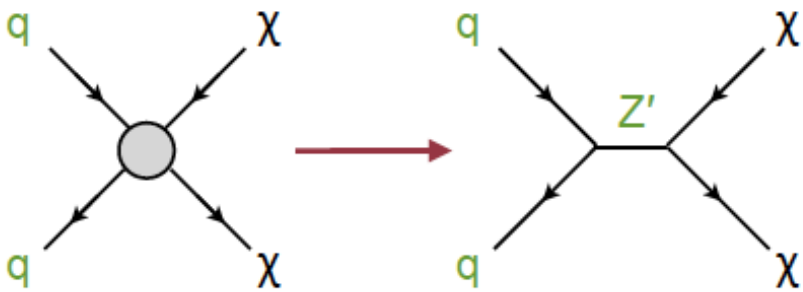




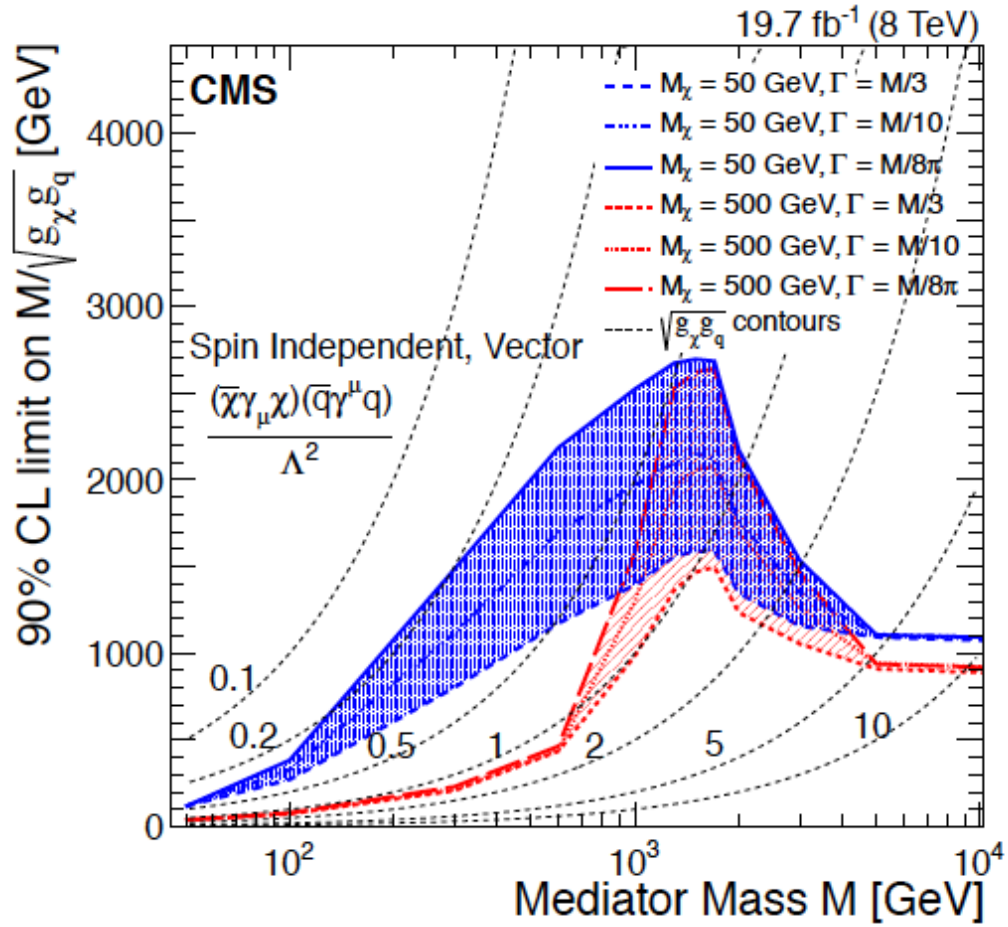
- Very strong limits for low DM mass scenarios for SI and SD operators

One step beyond EFT

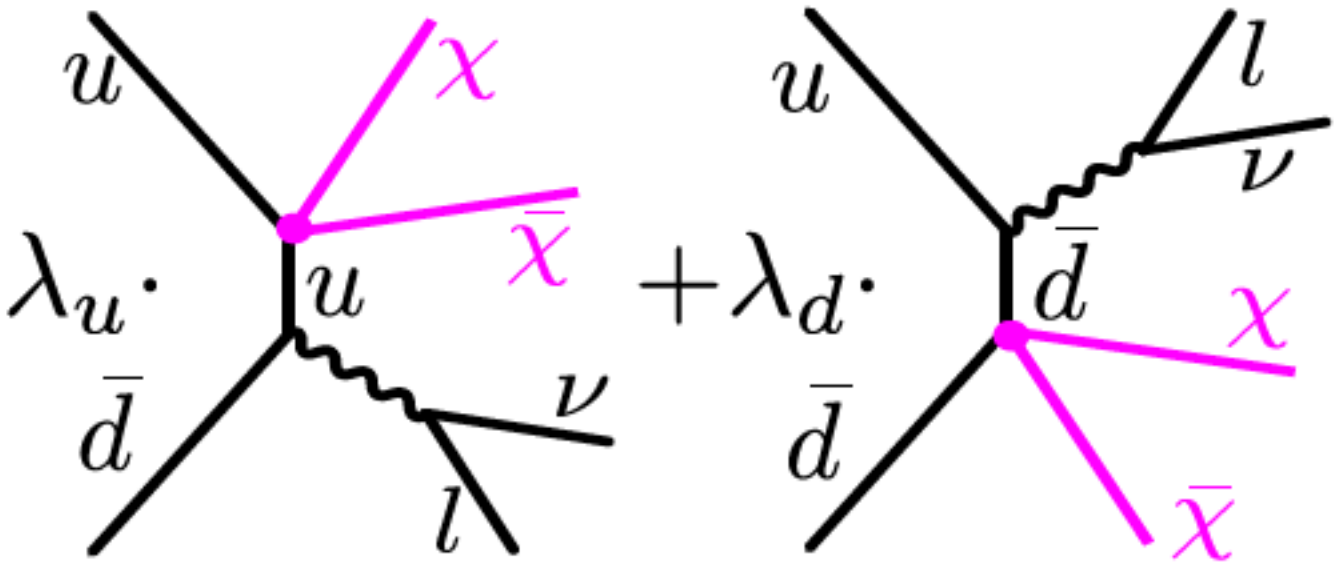
- Assume a mediating particle, s-channel Z'



- Re-derive limits vs Z' mass
- Very high mass Z' approximates EFT
- Above few hundred GeV, EFT gives conservative results



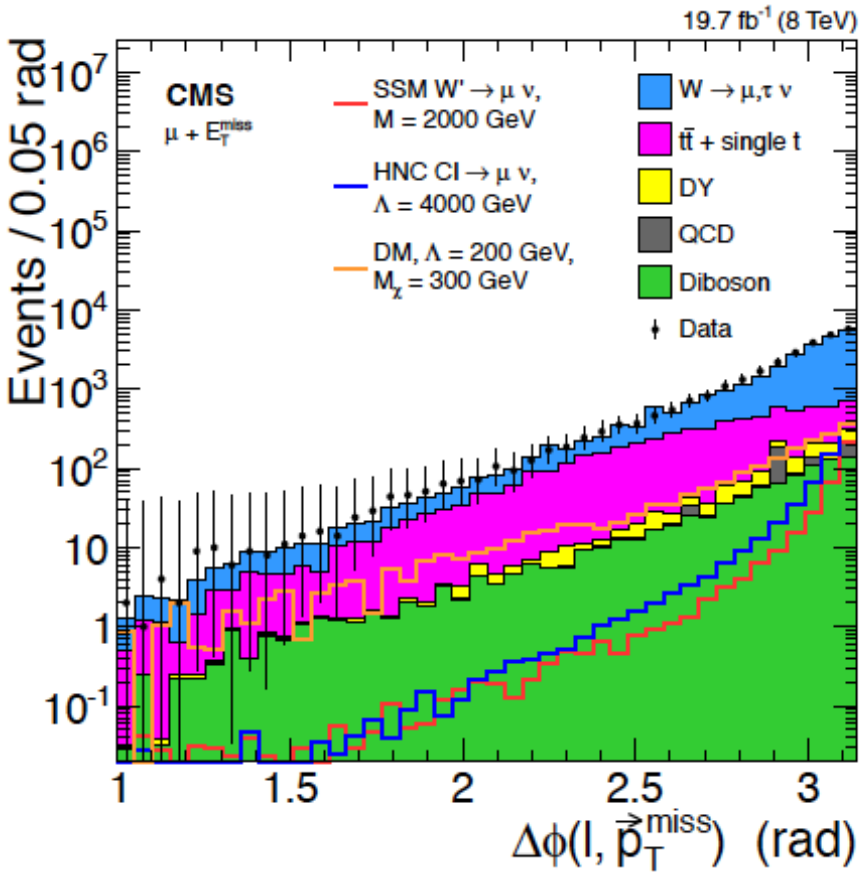
DM+ monolepton

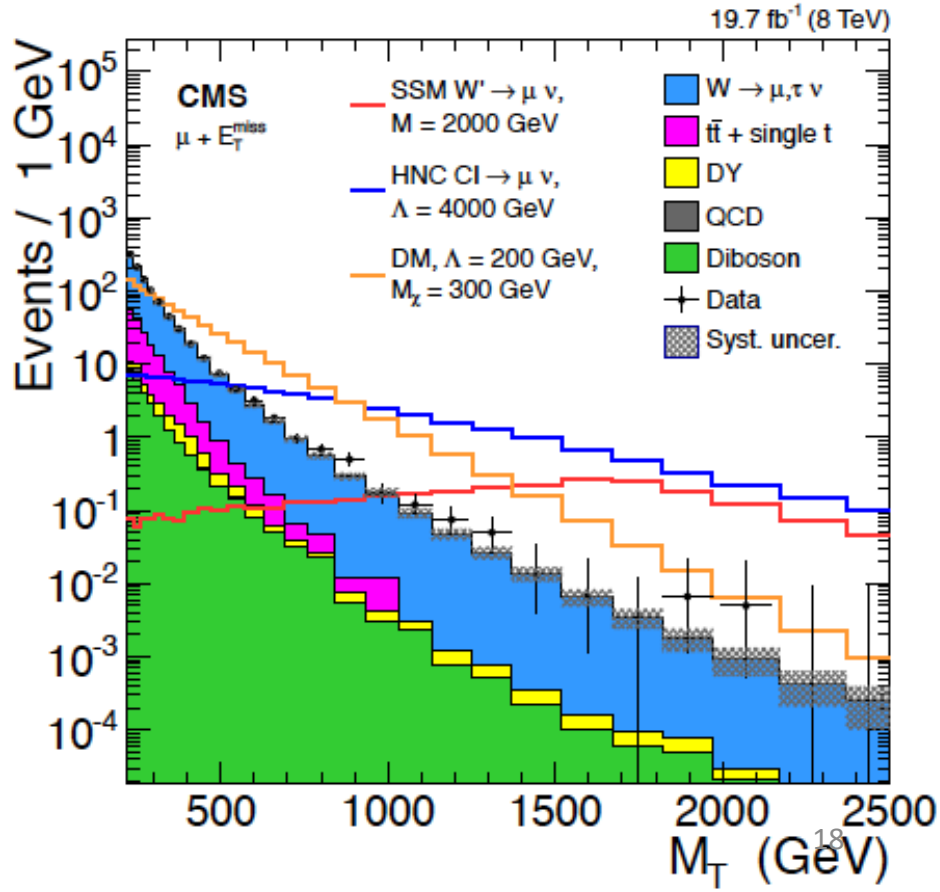


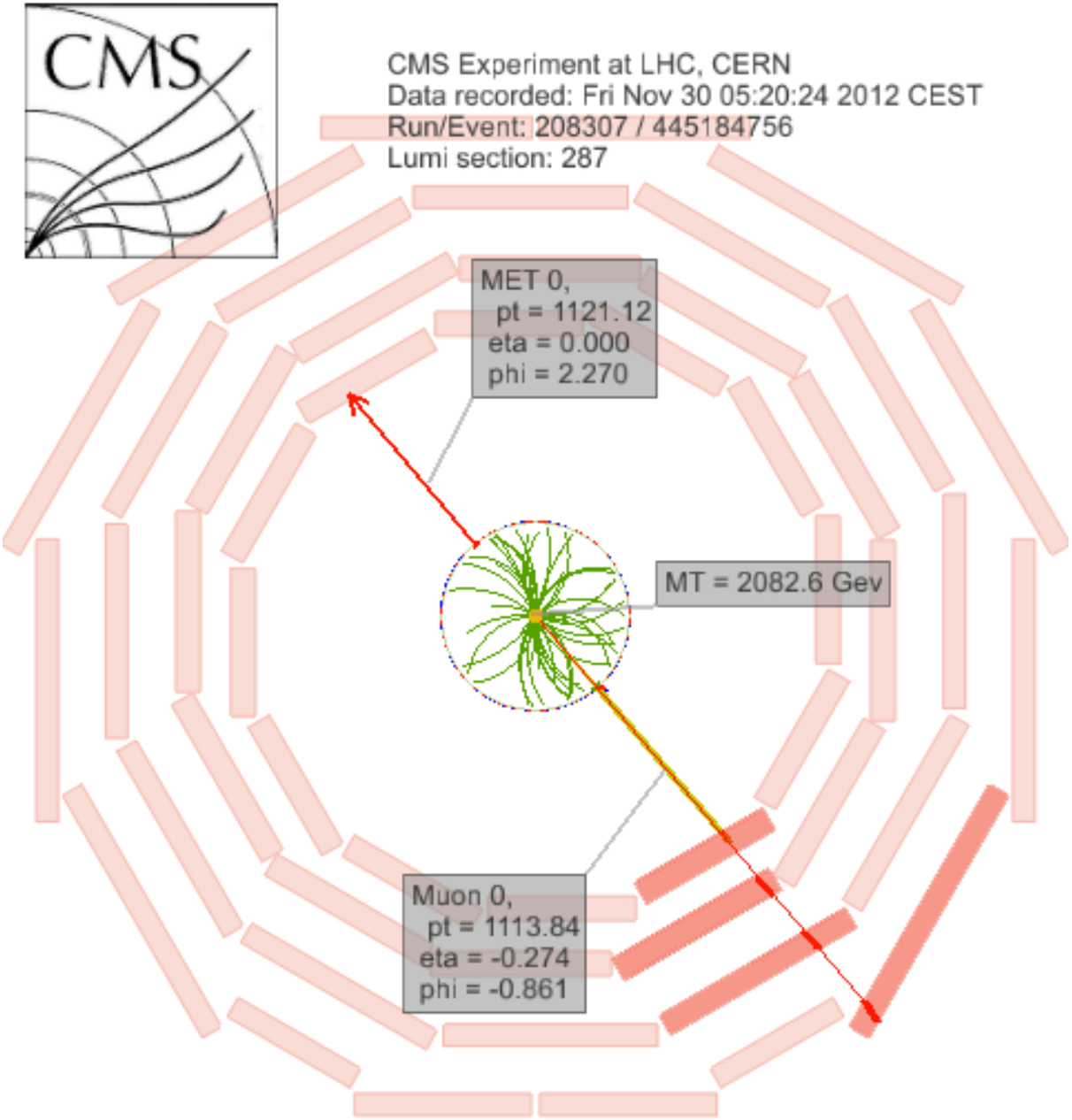
- DM can couple to up and down-type quark
- Different $\zeta = \lambda_u \lambda_d$ are considered:
  - $=\pm 1$ maximizing interference
  - $=0$, only up or only down-type coupling

Monolepton selections

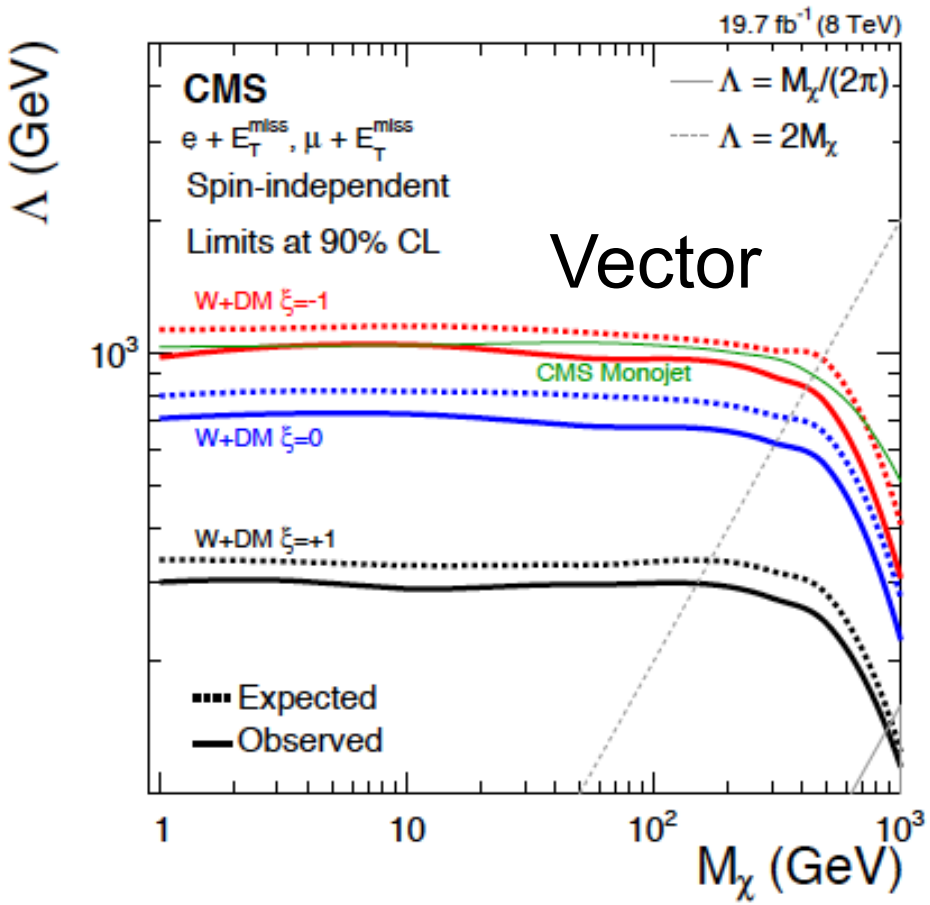
- Event selections:
  - One electron(muon) with p_T > 100 (45) GeV
  - $\Delta\phi$(l,MET) > 0.8 π
  - 0.4< p_T / MET < 1.5

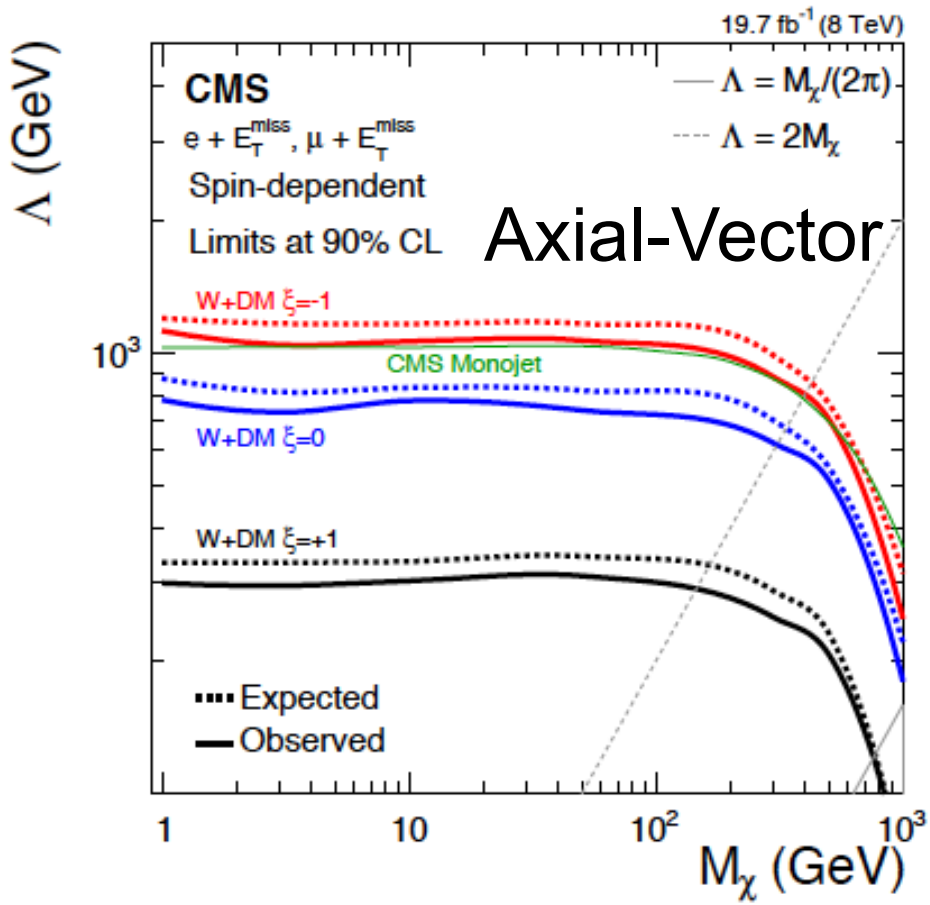





CMS Experiment at LHC, CERN
Data recorded: Fri Nov 30 05:20:24 2012 CEST
Run/Event: 208307 / 445184756
Lumi section: 287
MET 0,
pt = 1121.12
eta = 0.000
phi = 2.270
MT = 2082.6 Gev
Muon 0,
pt = 1113.84
eta = -0.274
phi = -0.861

Limits on $\Lambda(M_*)$ from DM+ monolepton



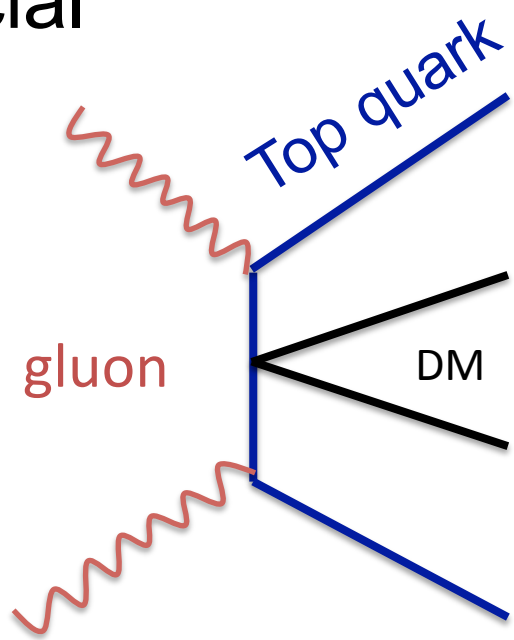


- Results depends strongly on $\zeta = \lambda_u \lambda_d$
- Comparable limits to monojet search for $\zeta = 1$

Dark matter + top-quark pairs

- For (pseudo)scalar mediator, DM couples stronger to heavier quarks.

- Search for DM + top-quark pairs can be beneficial

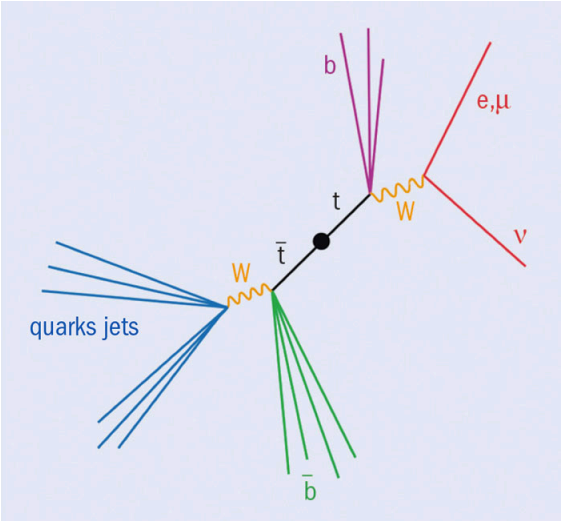


$$\frac{m_q}{M_*^3}\chi\bar{\chi}q\bar{q}$$

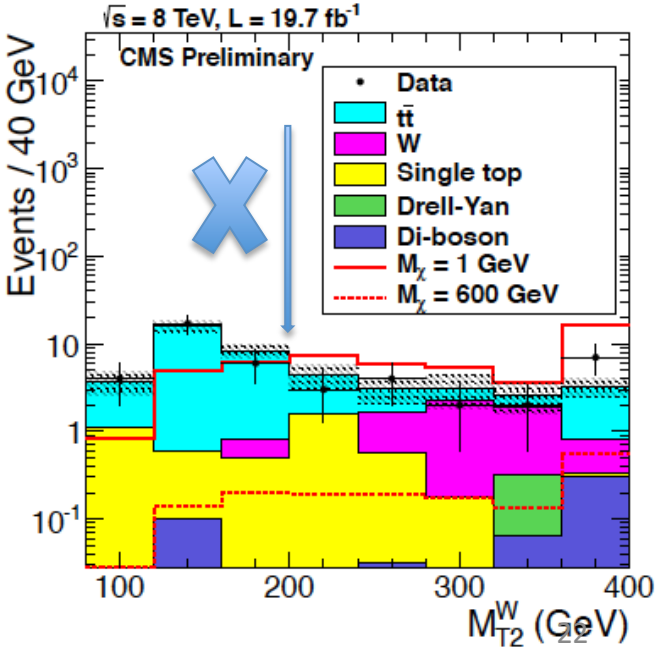
CMS top pair + DM (single-lepton)

CMS-PAS-B2G-14-004

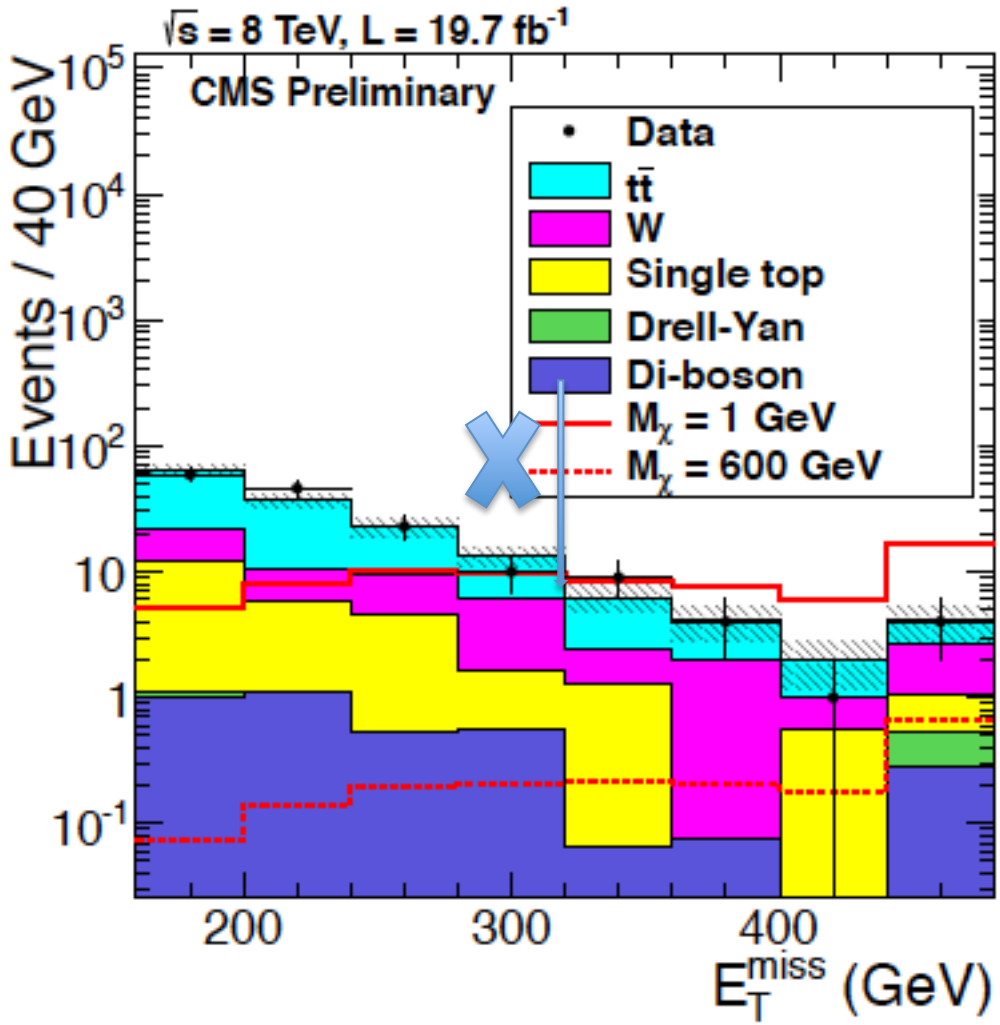
- Event selections:
  - One isolated lepton (electron or muon)
  - $N_{jet} \geq 3$, at least one b-tagged
  - MET > 320 GeV
  - Transverse mass M_T > 160 GeV
  - min $\Delta\phi(j_{1,2}\,\mathrm{MET})$ >2.0
  - M_{T2}^{W} > 200 GeV to reduce remaining tt→2l background



- Backgrounds estimated from simulation
  - Primary backgrounds of tt+jets and w +jets adjusted to match data in control regions



CMS top pair + DM (single-lepton) selection results



SR: MET >320 GeV

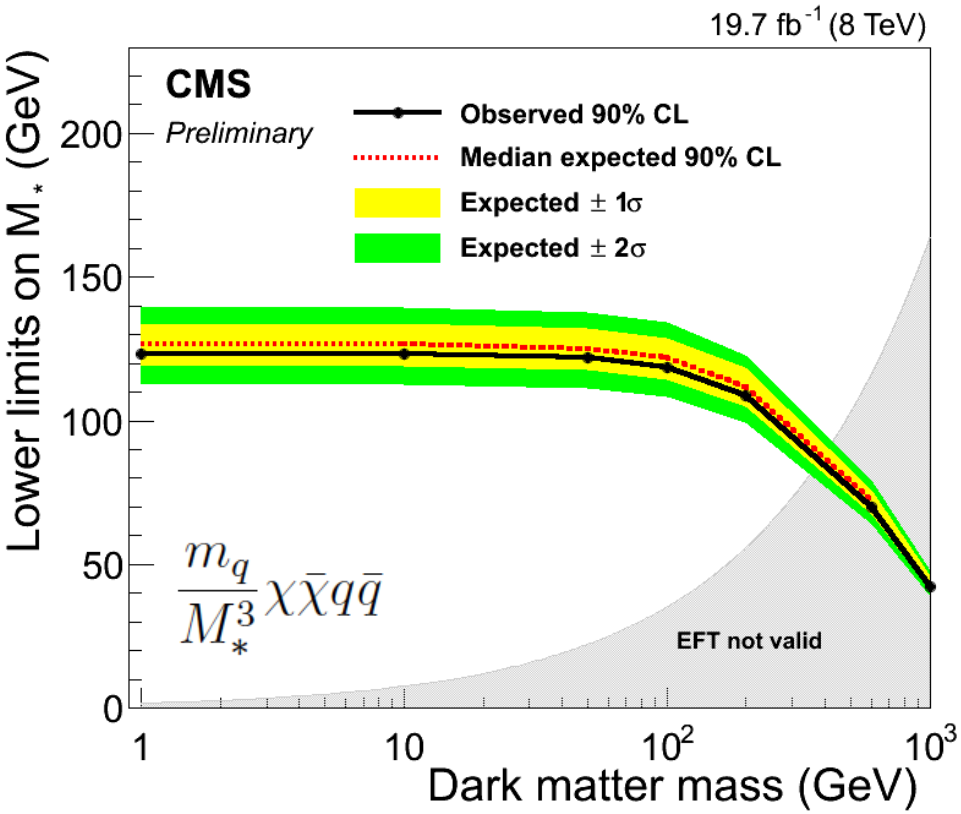
Background Source	Yield
$t\bar{t}$	$8.2 \pm 0.6 \pm 1.9$
W	$5.2 \pm 1.7 \pm 0.6$
Single top	$2.3 \pm 1.1 \pm 1.1$
Di-boson	$0.5 \pm 0.2 \pm 0.2$
Drell-Yan	$0.3 \pm 0.3 \pm 0.1$
Total Bkg	$16.4 \pm 2.2 \pm 2.7$
Data	18
Signal	$38.3 \pm 0.7 \pm 2.1$

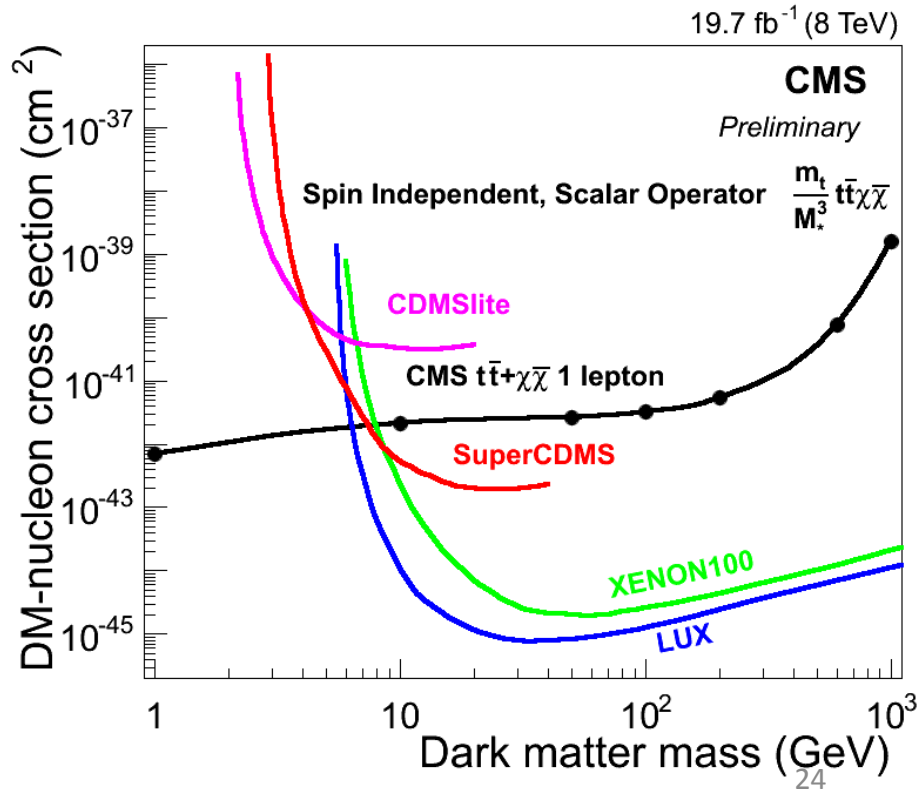
(Signal: $M\chi$ = 1 GeV, M_* = 100 GeV)

Data agrees with expected background

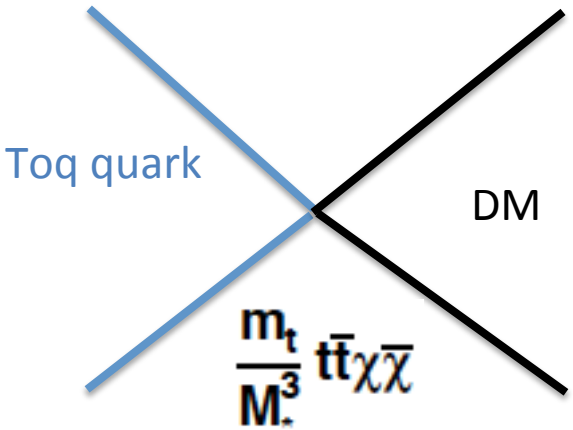
CMS top pair + DM: Limits

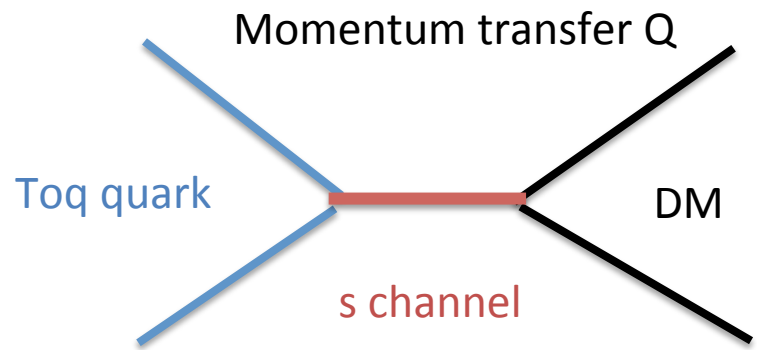
- First limit from CMS on scalar (quark) operator
- Significant improvement compared to other type of search on the same operator
  - 30 (65) GeV for low mass DM from ATLAS monojet (W/Z) search





EFT validity



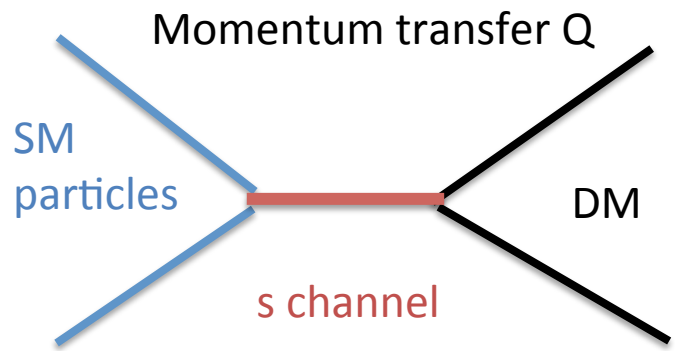


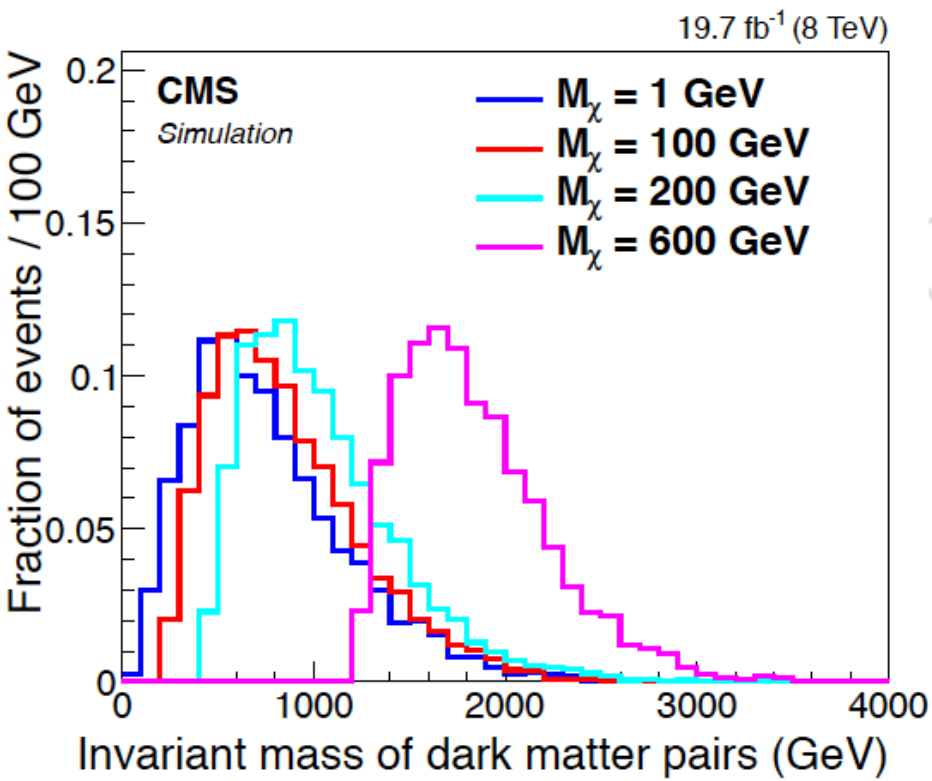
- EFT is valid given Q << M (mediator mass)
  - Depends on details of new physics: the mediator(s), the couplings between mediator(s) and SM/DM particles

- one s-channel mediator
- largest allowed couplings (4π)

$$\sqrt{M_*^3/m_t} > M_\chi/2\pi$$

EFT validity



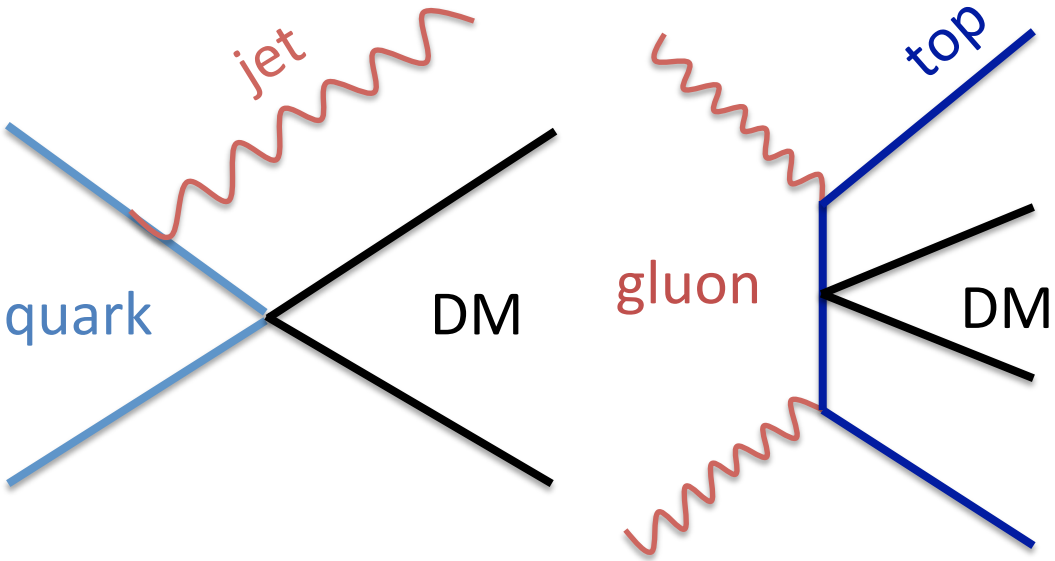


- Under assumption of one s-channel mediator
  - Q = M(χ,χ)
- Minimal requirement on EFT validity (maximal coupling = 4π):

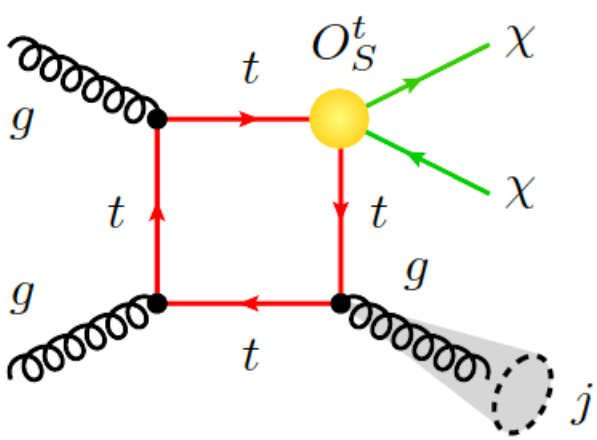
$$M_{\chi\chi} < 4\pi\sqrt{M_*^3/m_t}$$

- 90% low-mass DM (<10 GeV) events meet this.
- Results are more applicable to large couplings

Monojet and tops + DM



Two processes focuses differently: light vs top quark

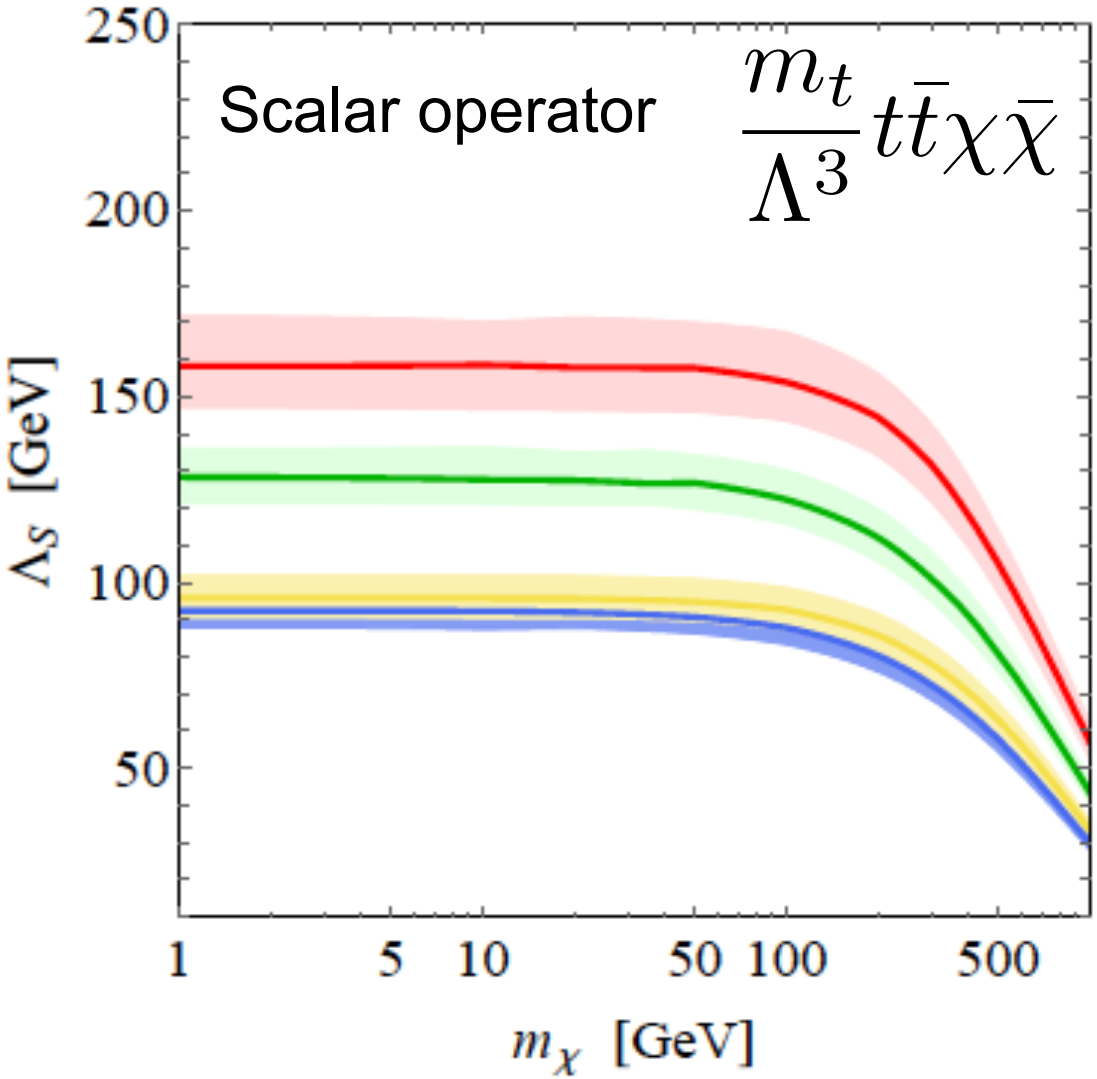


Adding top box : monojet +DM can probe the same coupling as tops + DMs

1503.00691 (Ulrich Haisch, Emanuele Re)

Monojet and tops

1503.00691 (Ulrich Haisch, Emanuele Re)



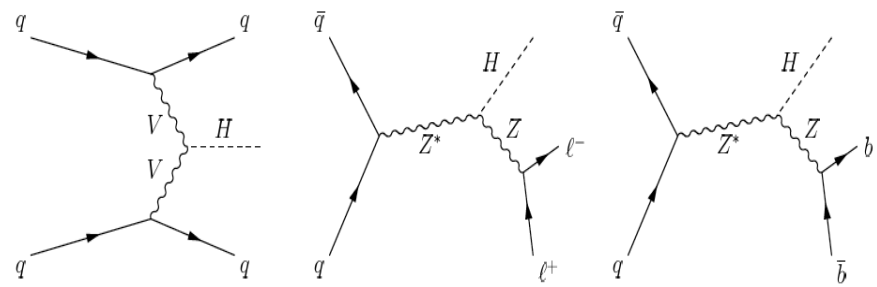
Monojet
Tops (single-lepton)
Tops (di-lepton)
Tops (all hadronic)

Mono-jet is actually more restrictive than tops.

Higgs-portal dark matter

1404.1344 (EPJC)

- Consider Higgs boson mediating ordinary and DM particles

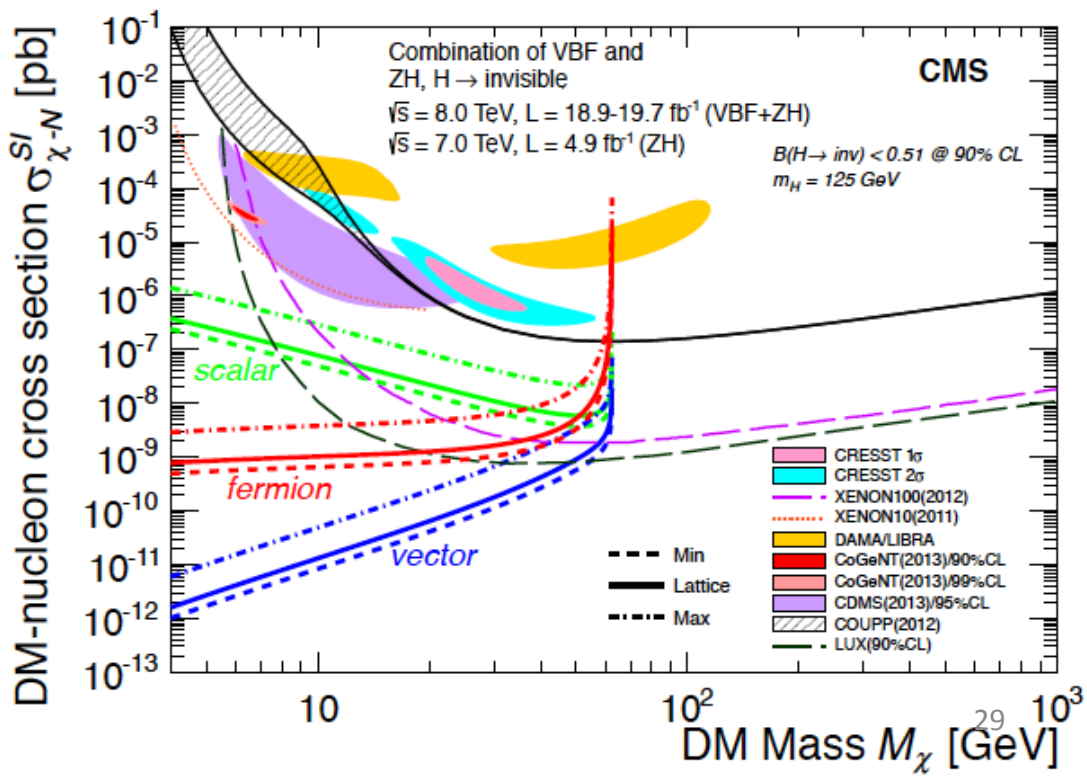


- Exploit VBF and associated ZH
  - 2 jets with high M_{jj} + MET
  - Z→ (ll, or bb) + MET

95% CL BR(H→inv) Obs(Exp)

VBF	0.65(0.49)
ZH	0.81(0.83)
VBF+ZH	0.58(0.44)

for m_H=125 GeV



Outlook for RunII

- EFT will be serving as benchmark for dark matter search.
  - Two parameters: M_* and $M\chi$
  - Need to consider improved treatment of DM production (e.g the box-diagram in monojet)
  - Issue of validity of EFT remains.

- A list of simplified models are being proposed by the ATLAS/CMS dark matter forum, with lots of input from theory communities.
  - New parameters: M_{med} , $W_{med,}$ $M\chi$ and couplings

Summary

- Presented a selected lists of dark matter searches in CMS

- EFT plays important roles
  - Greatly simplifies the DM production
  - Allow easy comparison with direct searches
  - However, caveat on EFT validity

- Dark matter continues to be an important new physics program at the LHC