Searches for DM with CMS

3rd ICTP-SAIFR South American Dark Matter Workshop

ICTP-SAIFR, São Paulo, Brazil
(2-4 December 2020)

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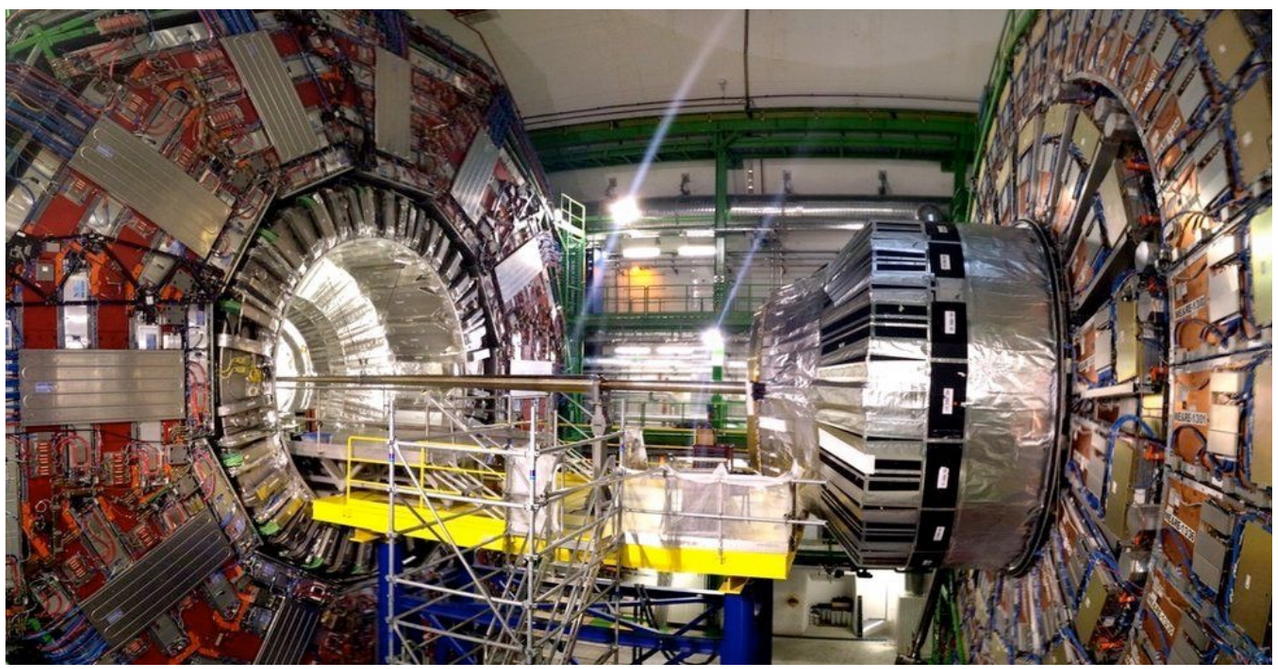
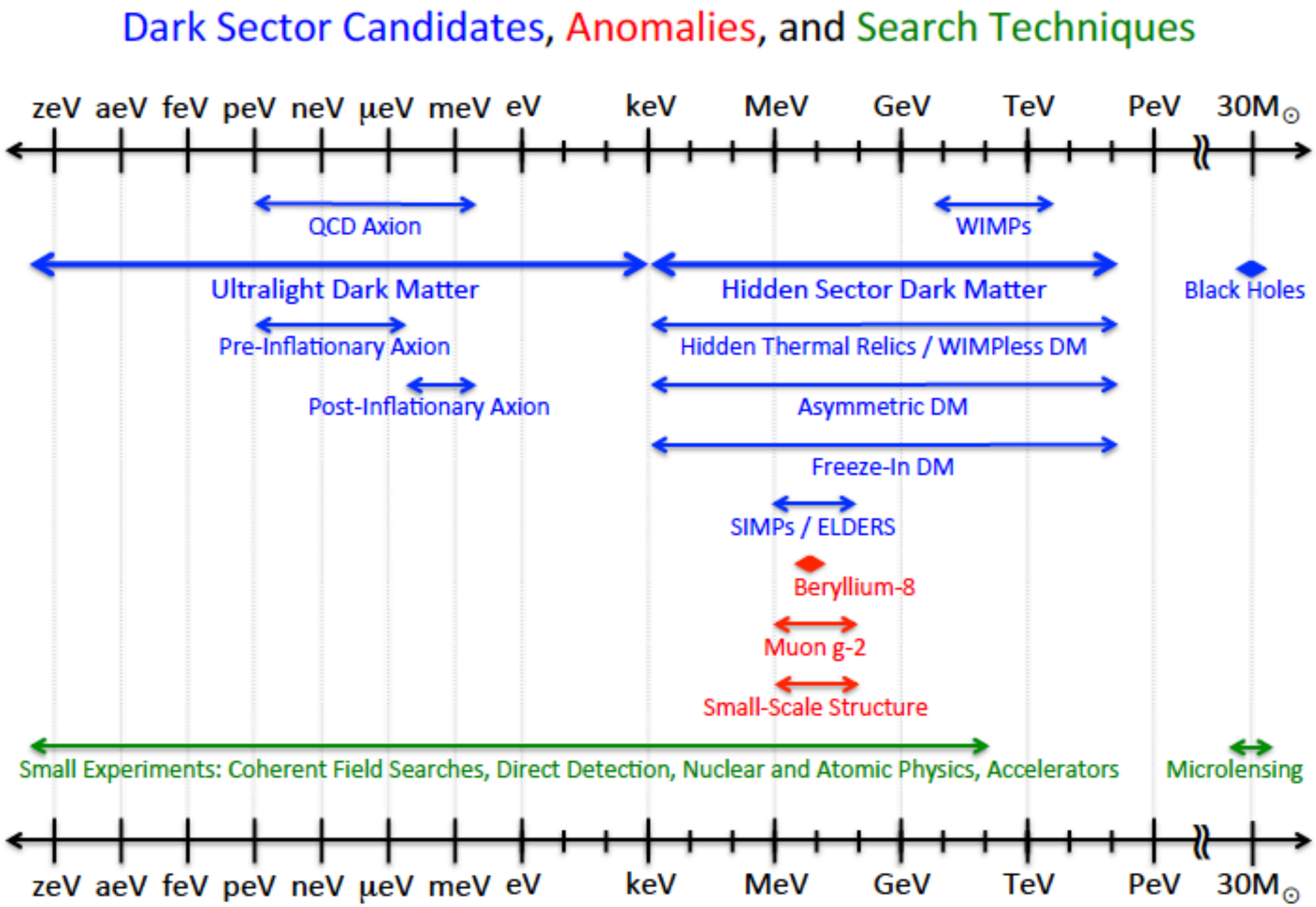
(On behalf of the CMS Collaboration)



Dark Matter Search: Big Picture

From Battagliere et al., arXiv:1707.04591



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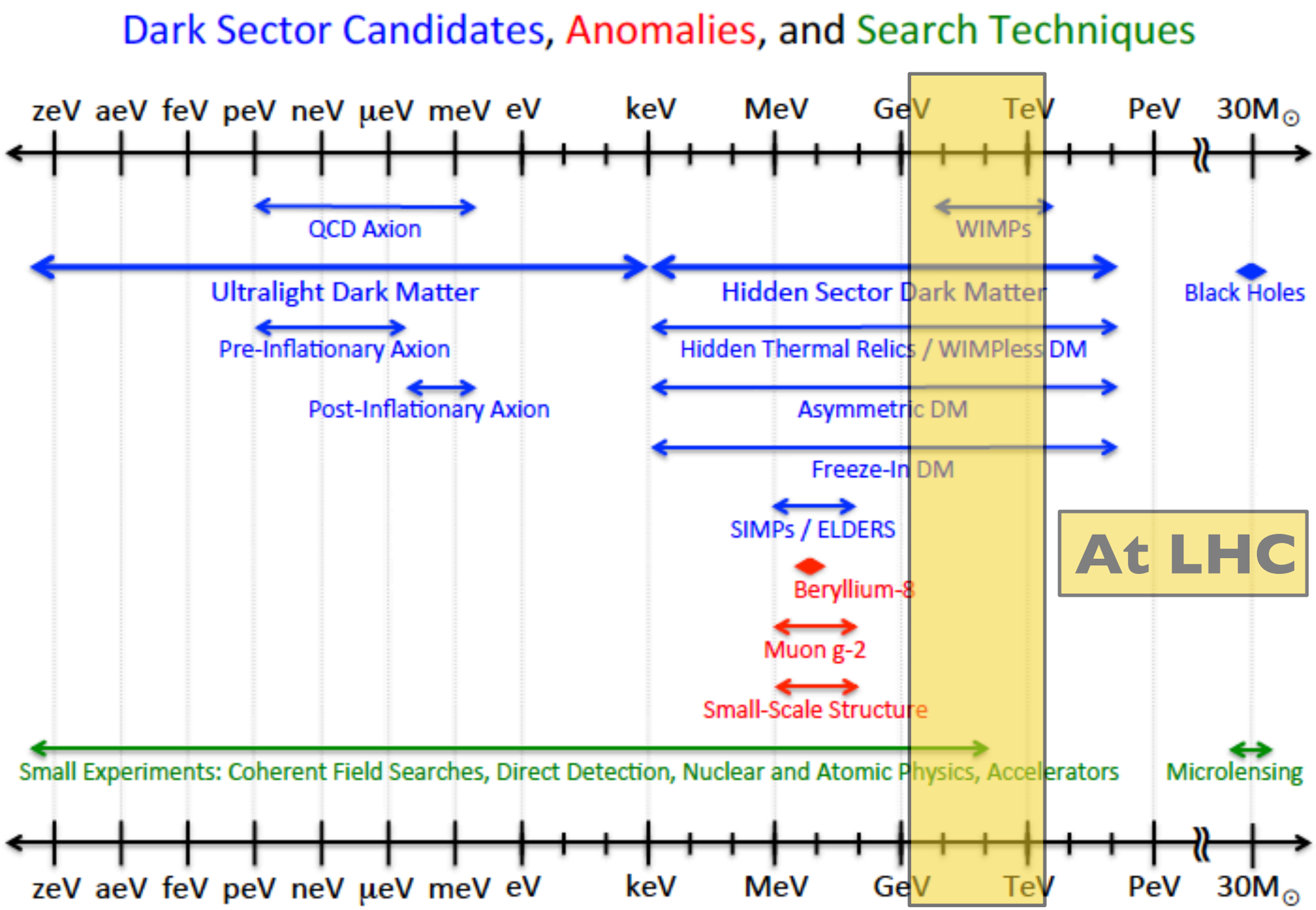
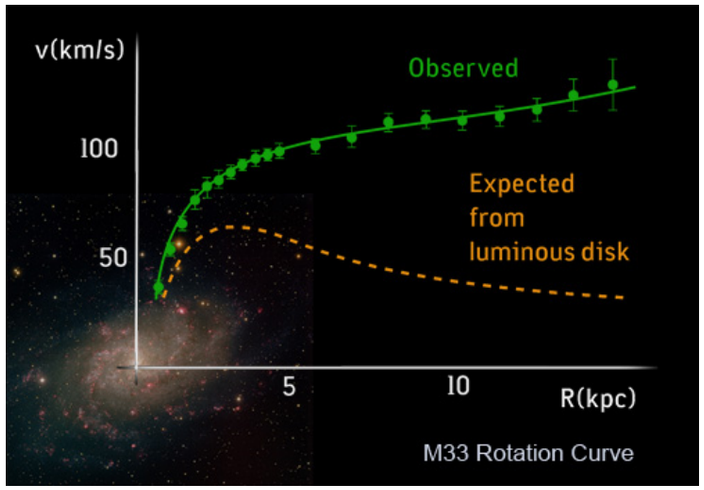
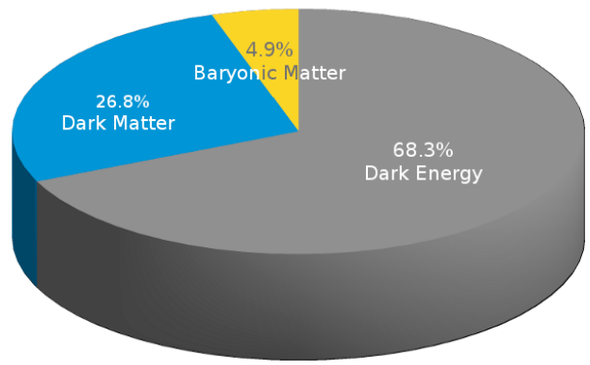


DM Evidence and Different Approaches

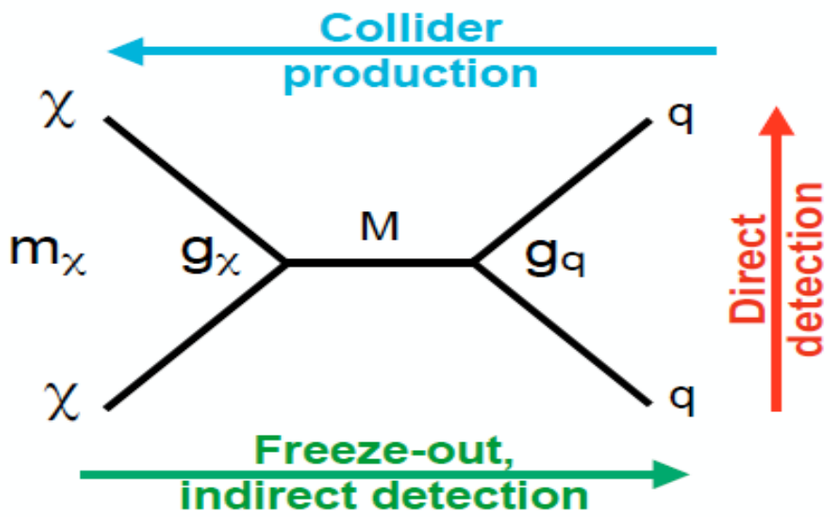
- **Strong astrophysical evidence for the existences of dark matter**
  - **Rotation curve**
  - **CMBR spectrum**
  - **Gravitational lensing**





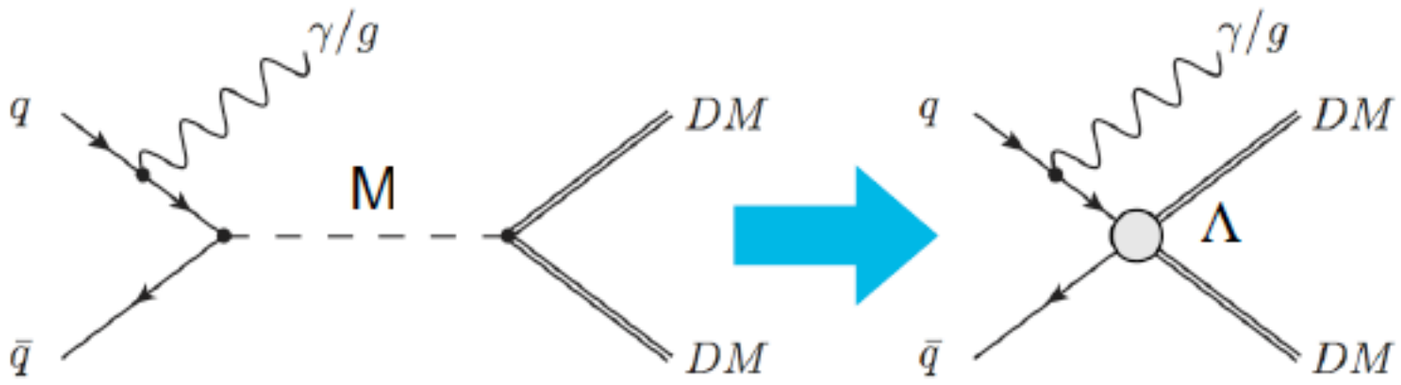
- **Nature of DM is still unknown**
- **No direct observation yet**

- **LHC a prime lab for production of DM in pp collision**
  - **Can probe a variety of DM/SM interactions**



From EFT to Simplified Models

◉ **Very early searches were mostly from EFT**



$$\Lambda = M/\sqrt{g_\chi g_q}$$

◉ **Simplified models to interpret results**

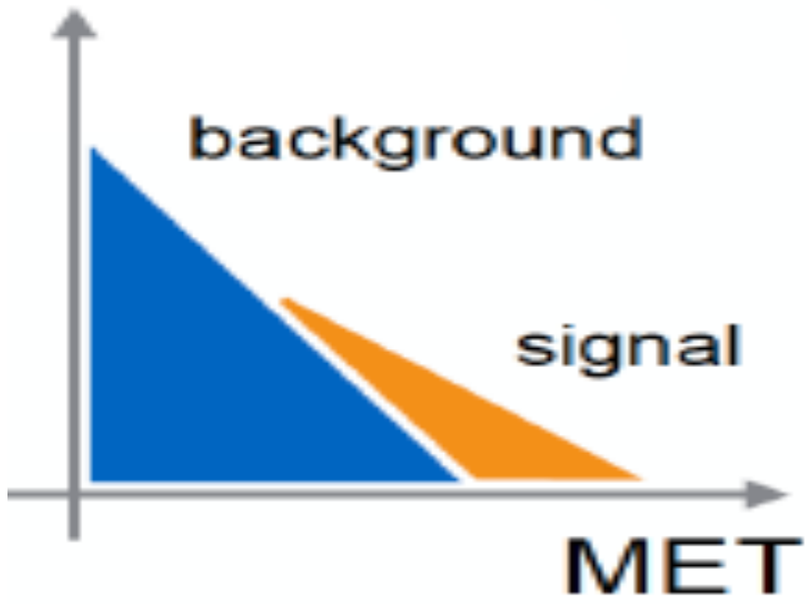
- **DM particle is Dirac fermion**
- **Pair produced via massive mediators (vector, axial-vector, scalar, pseudo-scalars)**
- **Minimal set of parameters: M_{DM}, M_{MED}, g_q, g_{DM}**
- **Mediator has minimal decay width**
- **Complementarity of Direct Detection(DD) vs Collier searches**

◉ **ATLAS-CMS Dark Matter Forum**

– **Recommendations for: couplings, models parameters** **arXiv:1507.00966**

DM Candidate and This talk

- **DM Features (assuming it has *particle origin)***
  - **DM has to be neutral**
  - **Must be stable**
  - **Right abundance is required, sets constraints on its mass and other parameters**
- **Main focus on few benchmark/latest results**
  - **Mono-jet Search (Benchmark Search)**
  - **Higgs Portal for DM**
  - **Dark Photon**
  - **Mediator Searches**
    - **Dijet**
    - **Dijet+ISR γ/jet (boosted/merged)**

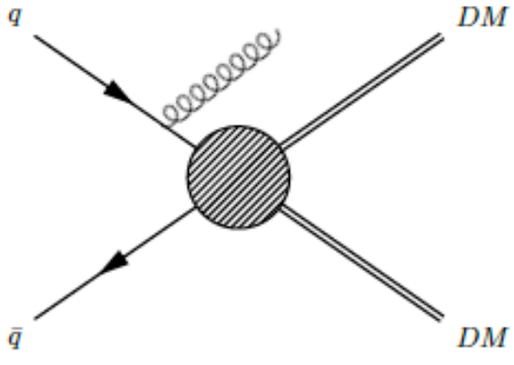


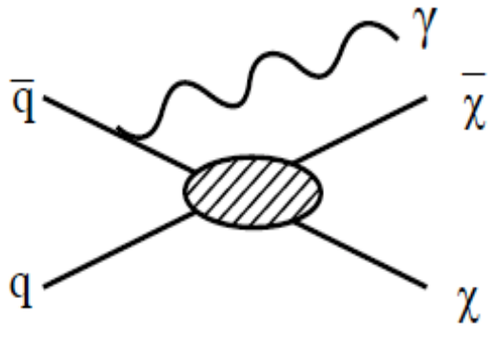
- **A complete list is at:**
  - **https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO**

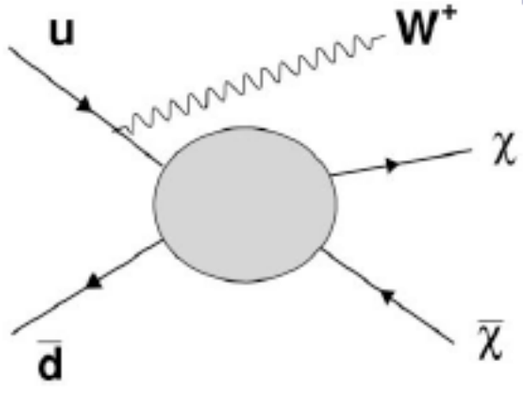
Various DM Searches at LHC

Typical Signature: Large MET+ X

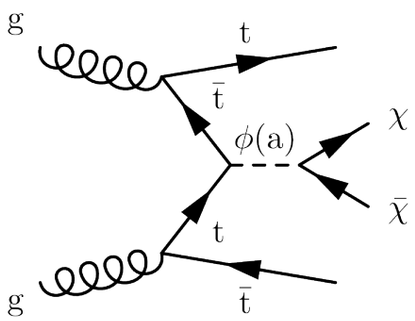
Mono-X(X=γ/jet/W….)

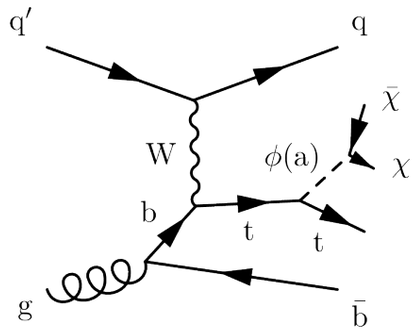


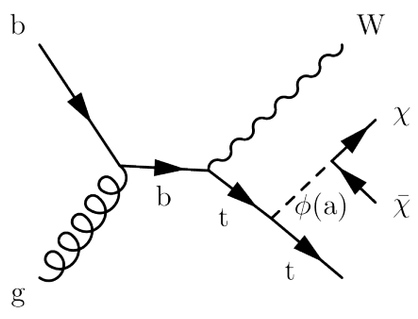


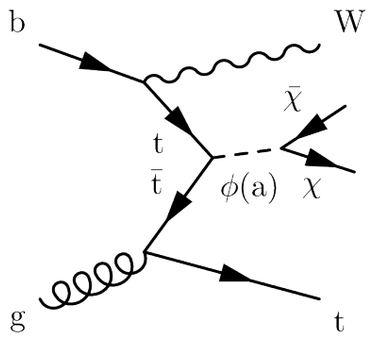


Mediated by virtual t-channel and virtual s-channel

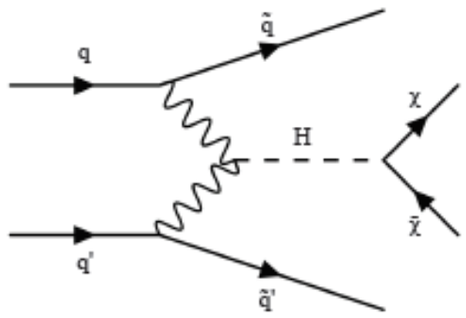


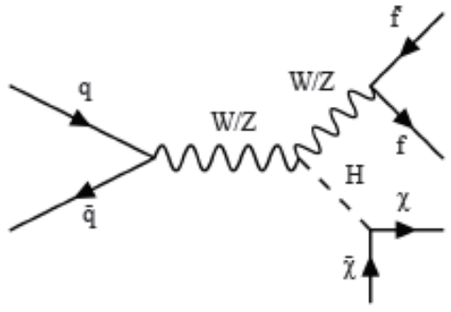




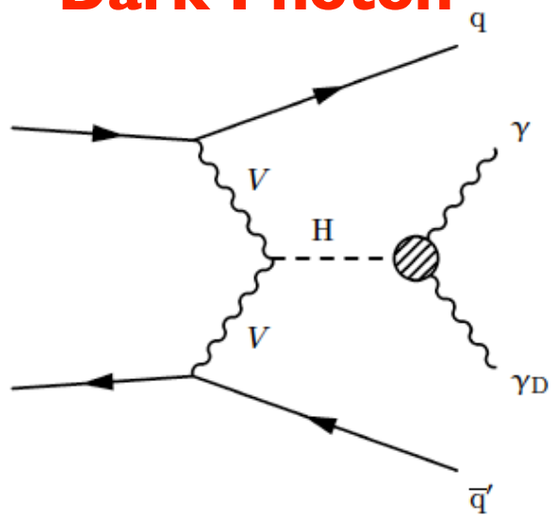


Higgs -> Invisible

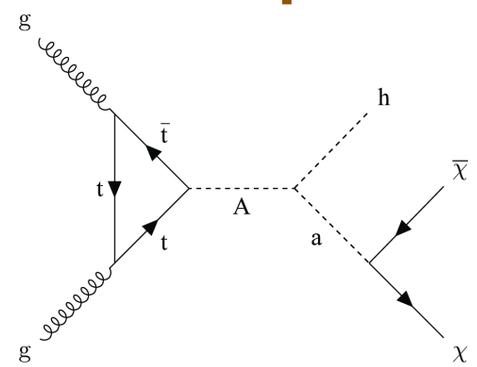




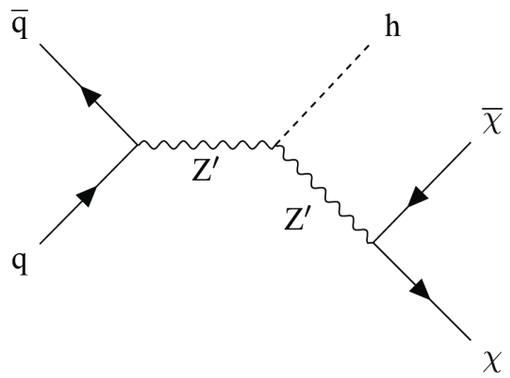
Dark Photon



2HDM + a pseudo-scalar



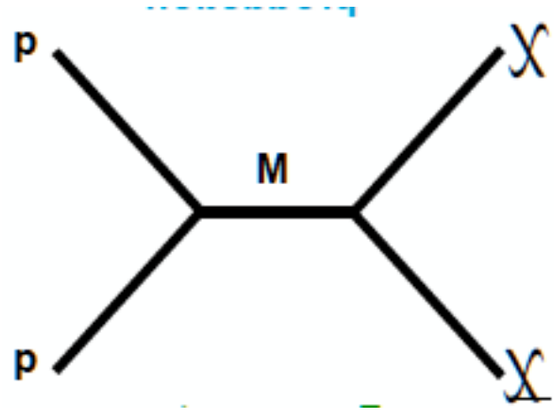
Z' Baryonic production



DM Searches at LHC: Analysis Steps

Trigger on Events:

- DM leave no signature in detector
  - Trigger: On ISR γ/jet, H, W/Z…..



Backgrounds:

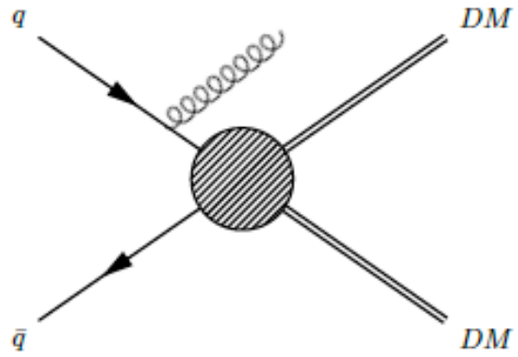
- Specific to channel
  - e.g. Z($\nu\nu$)+jets, W(lν)+jets with lost lepton…many more
- Instrumental
  - faulty detector sector, experimental environment
- SM background with mis-measured missing transverse energy
  - e.g. QCD multi jet, inclusive γ

Control Regions(CRs):

- Similar behaviour of background but negligible signal
- Multiple CRs to targets different background
  - Transfer factors (from simulation) to link different regions
- Simultaneous binned likelihood fit
  - Constrained uncertainties, robust limits/results

Mono-jet/V: Benchmark Analysis at LHC

- Well known backgrounds
  - Z($\nu\nu$)+jets, instrumental, reducible e.g., W+Jets
- A lot of state-of the art theoretical work
  - NLO EW and QCD correction to V+jets
- Advance analysis techniques using SR and CRs simultaneous fits
  - Reduced uncertainties



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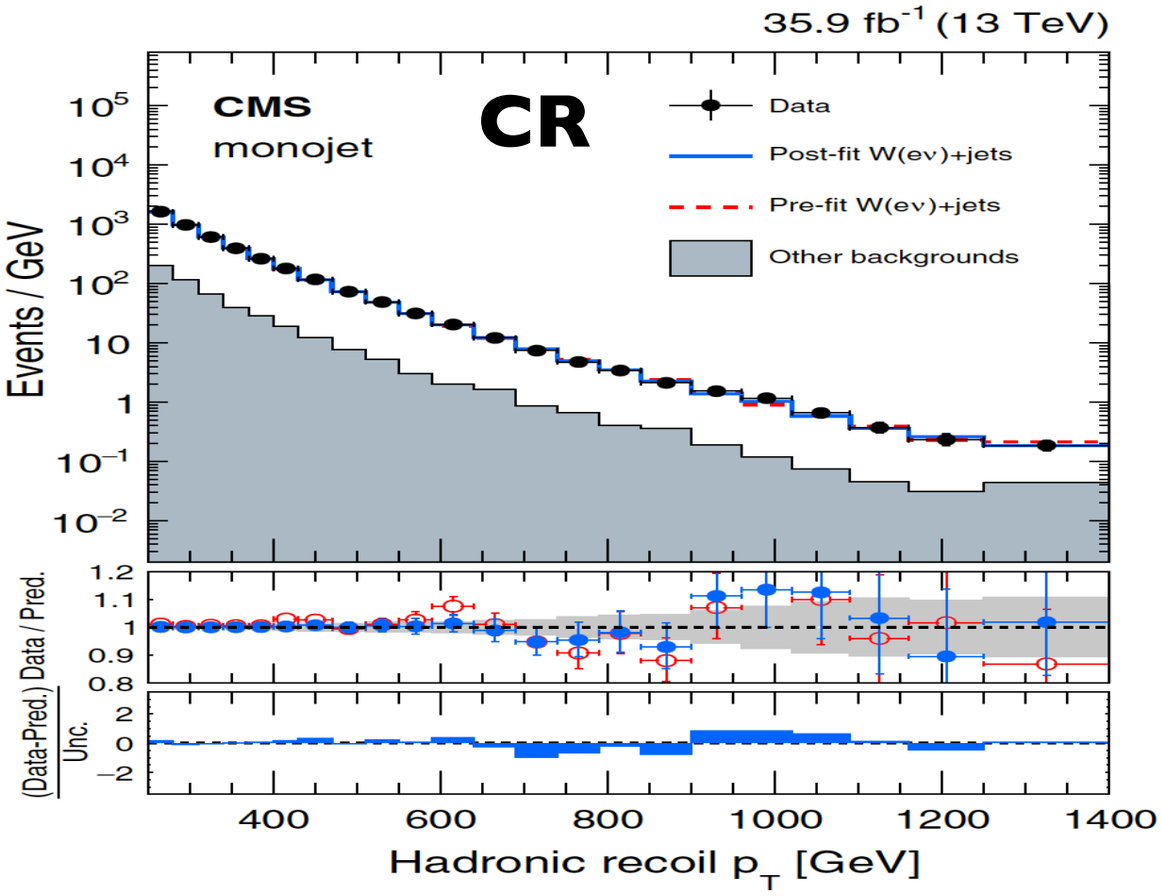
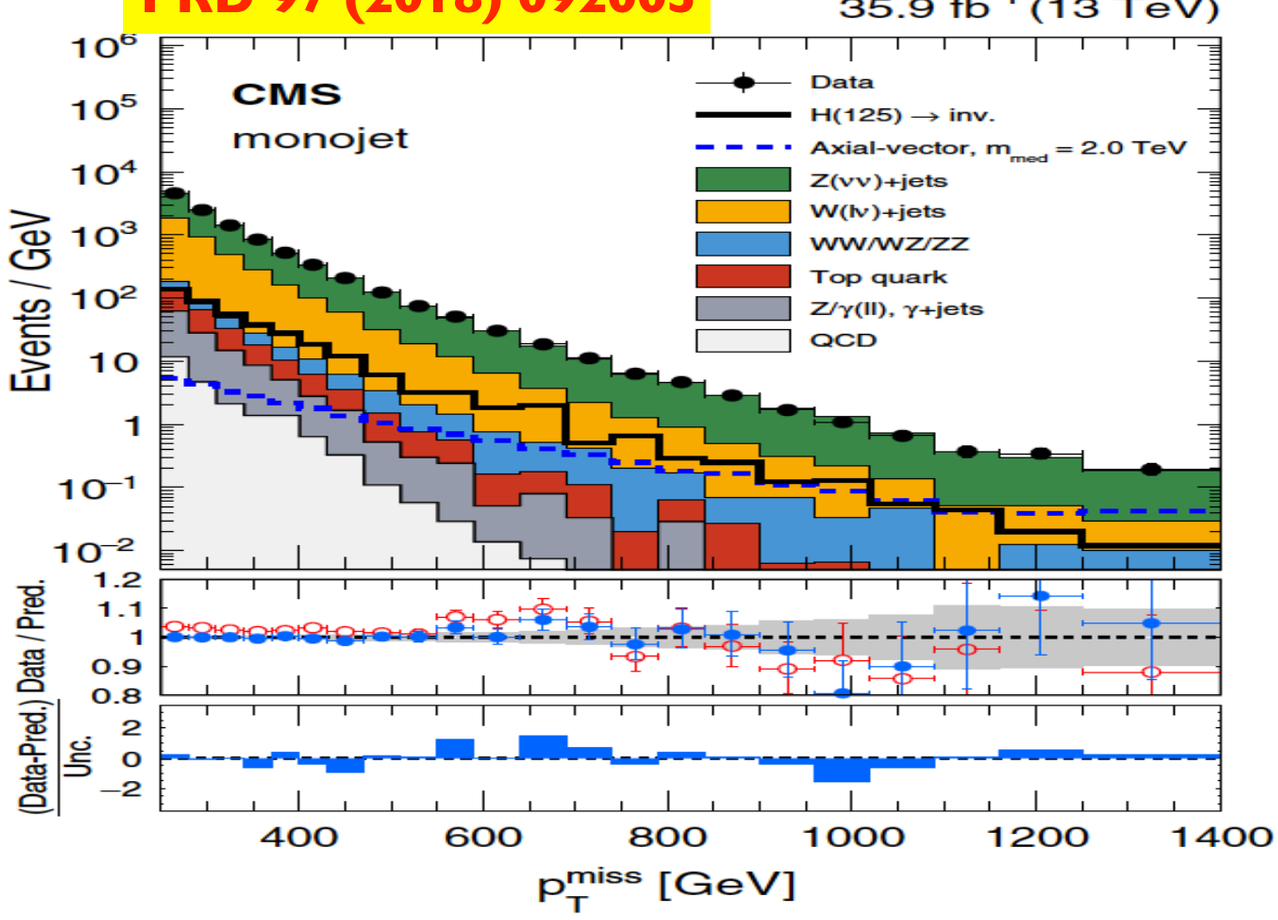
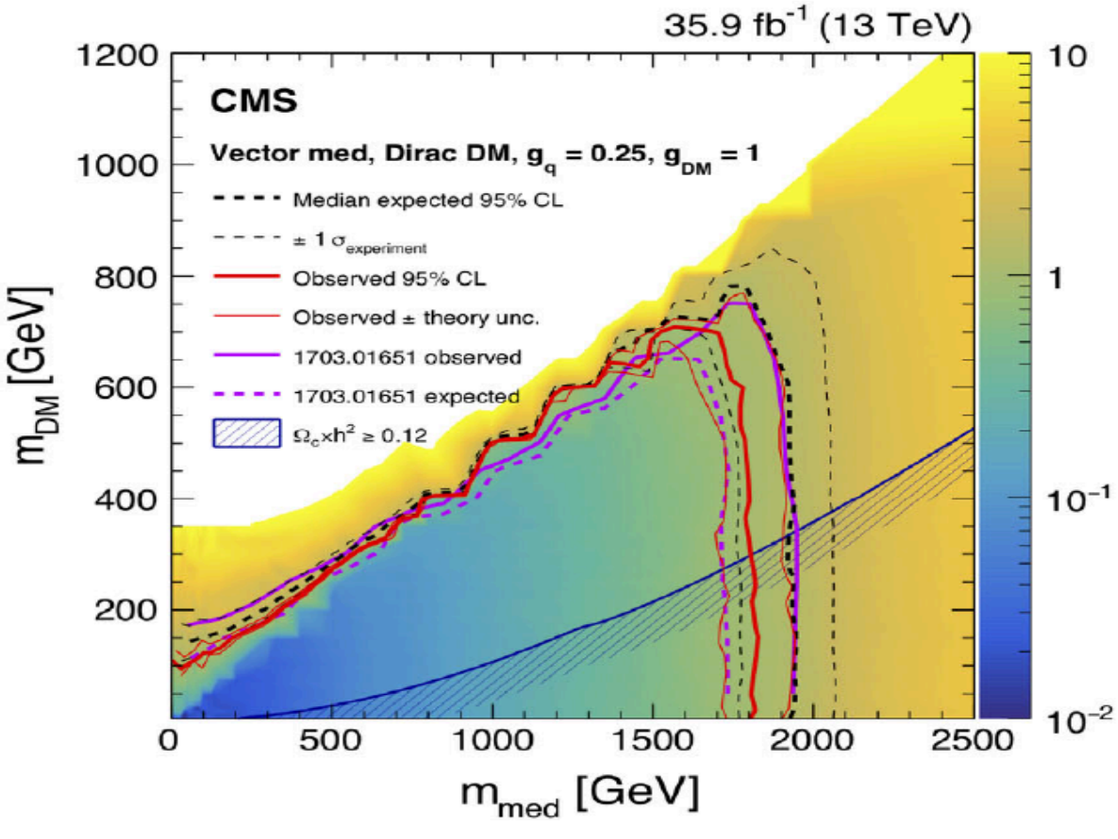
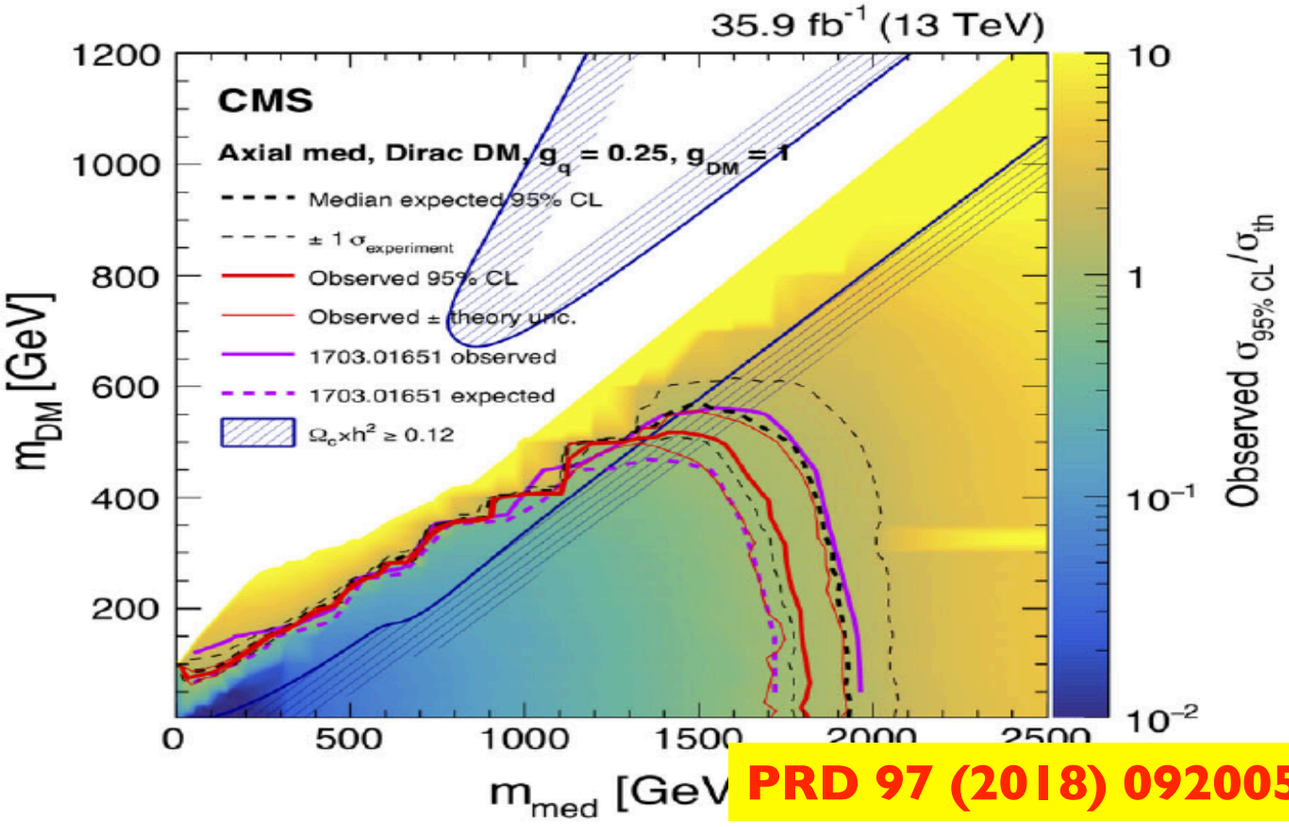




Mono-jet/V Search: Results





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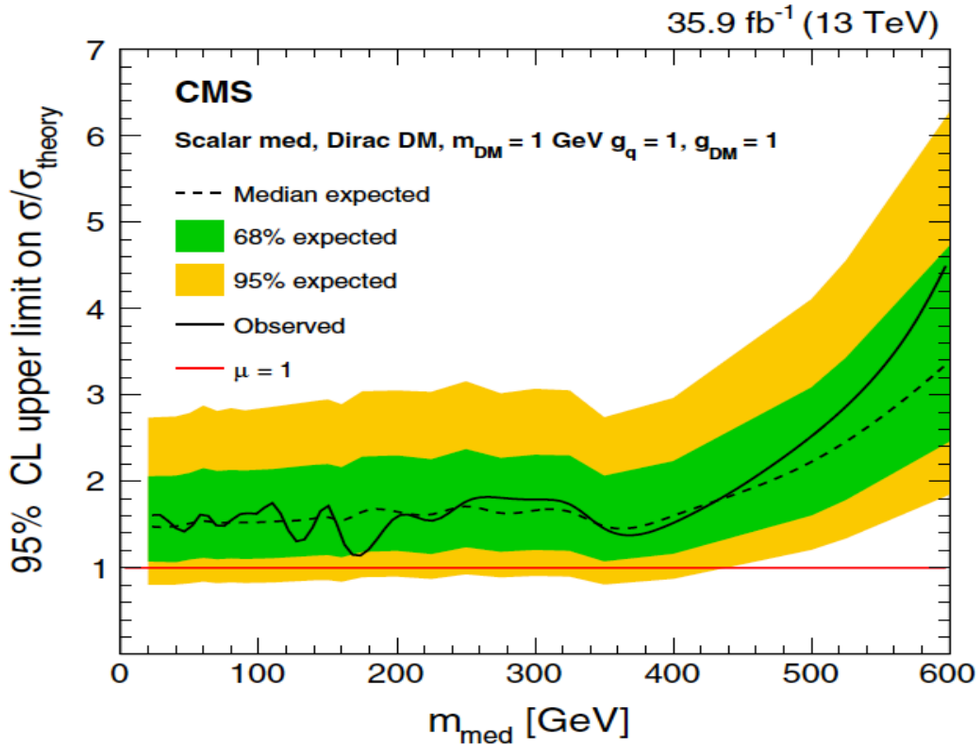
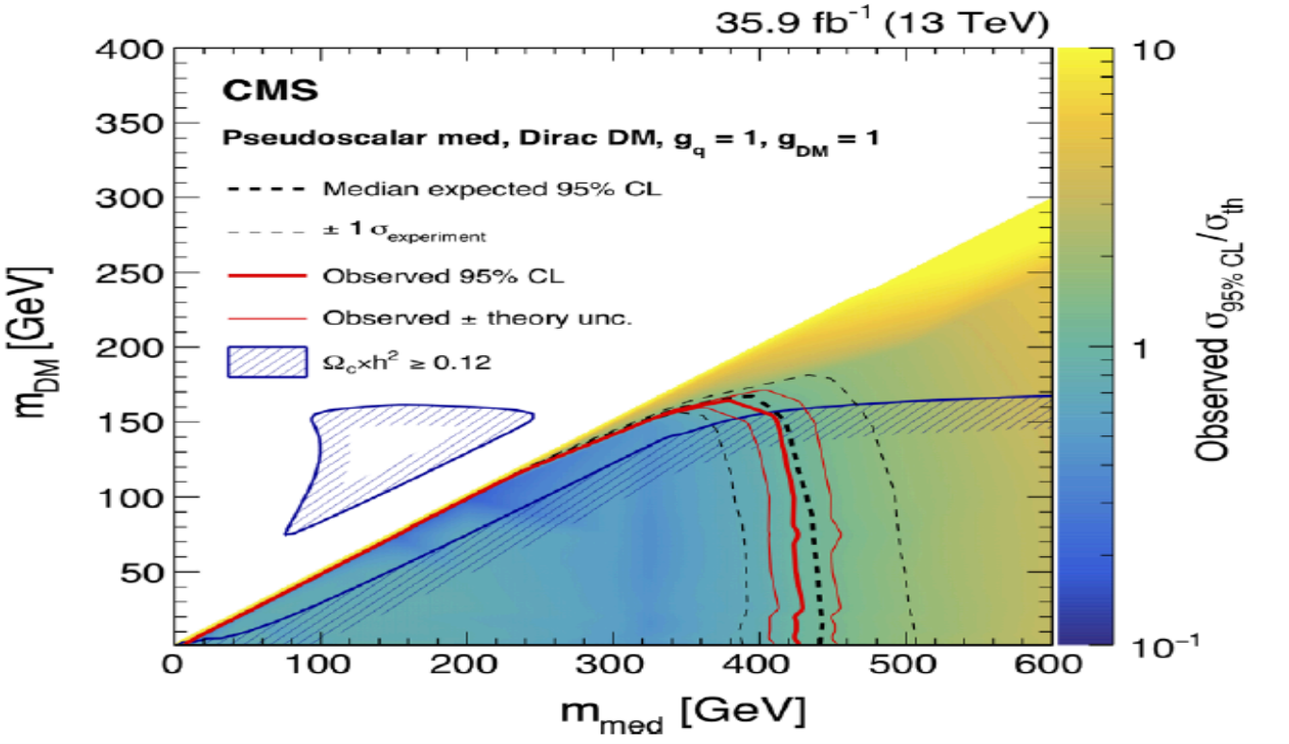
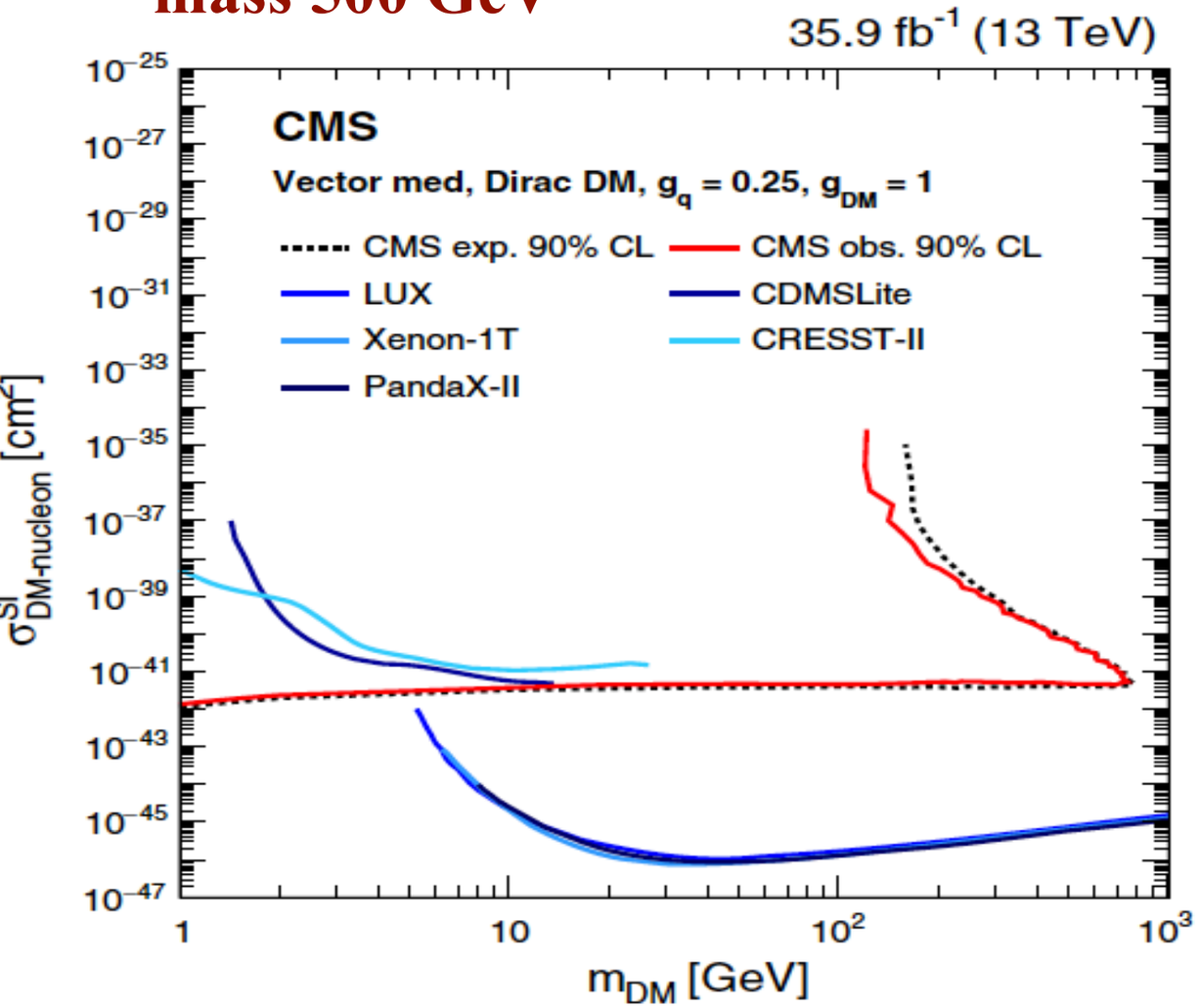




Complementarity with DD and ID

Collider experiment and DD

- SI (Vector mediator) is competitive for DM mass < 5 GeV and
- SD (Axial Vector mediator) is DM mass 500 GeV



Collider experiment and ID

- For pseudoscalar limits are competitive below ~150 GeV

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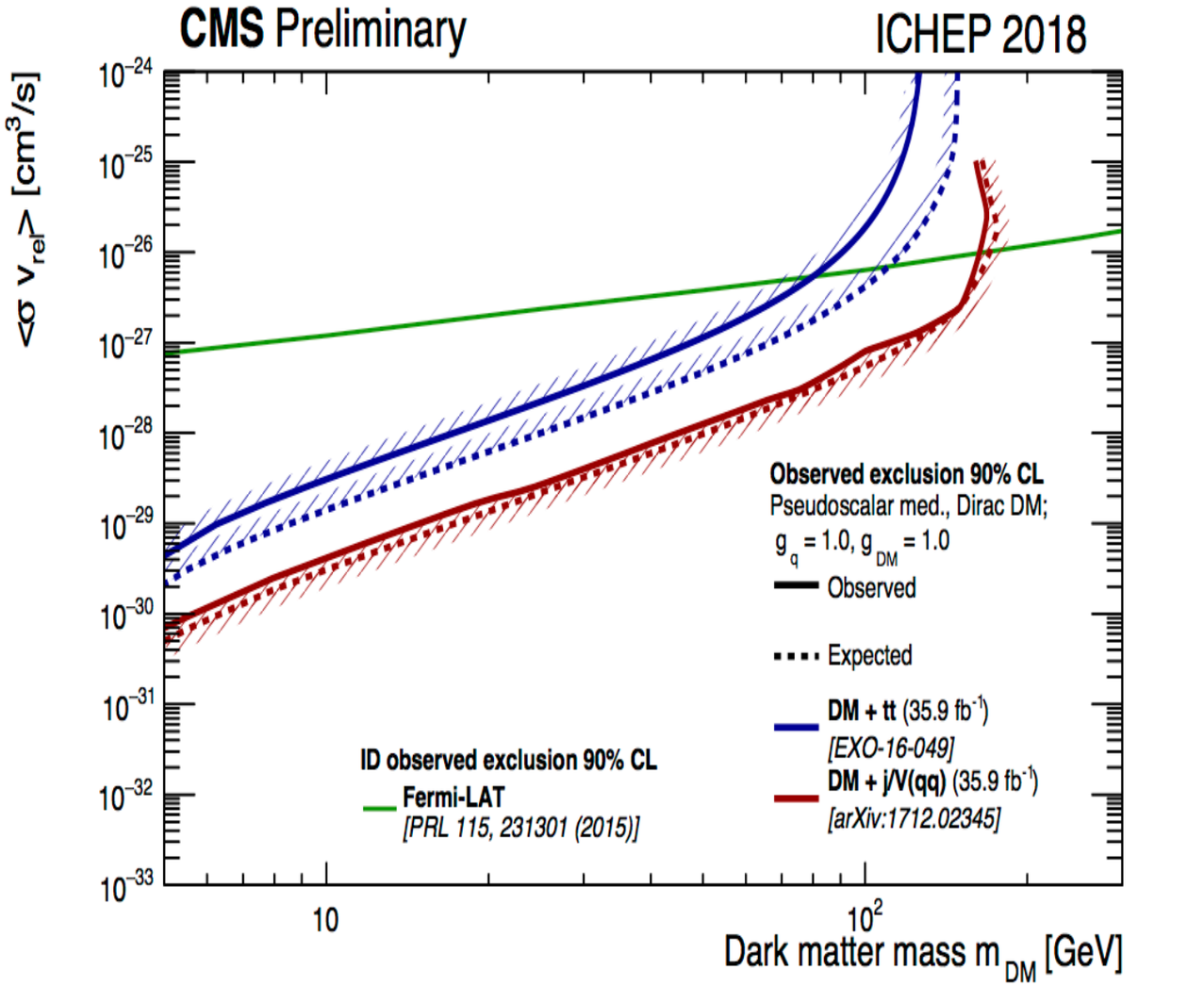

t/tt +MET: Simplified HF + DM Model

- **Search strategy is to look for excess in MET spectrum in All Hadronic (AH) and Single Lepton (SL) signal region**
  - Events are categorised based on N_b= 1 (t+DM), >1 (tt+DM)
  - MET > 250 (AH), 160 (SL)
  - N_{jet} >= 3 (AH), 2 (SL)
  - >=1 forward jets
- **Six SRs: Simultaneous optimisation of various variables in these regions**

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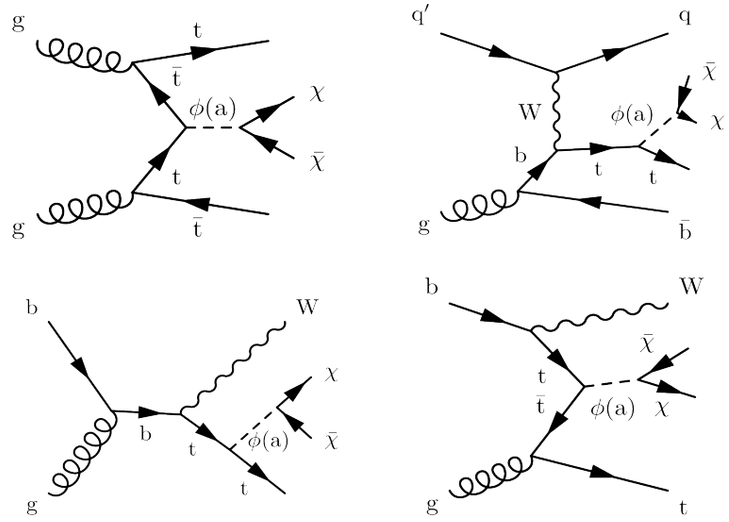
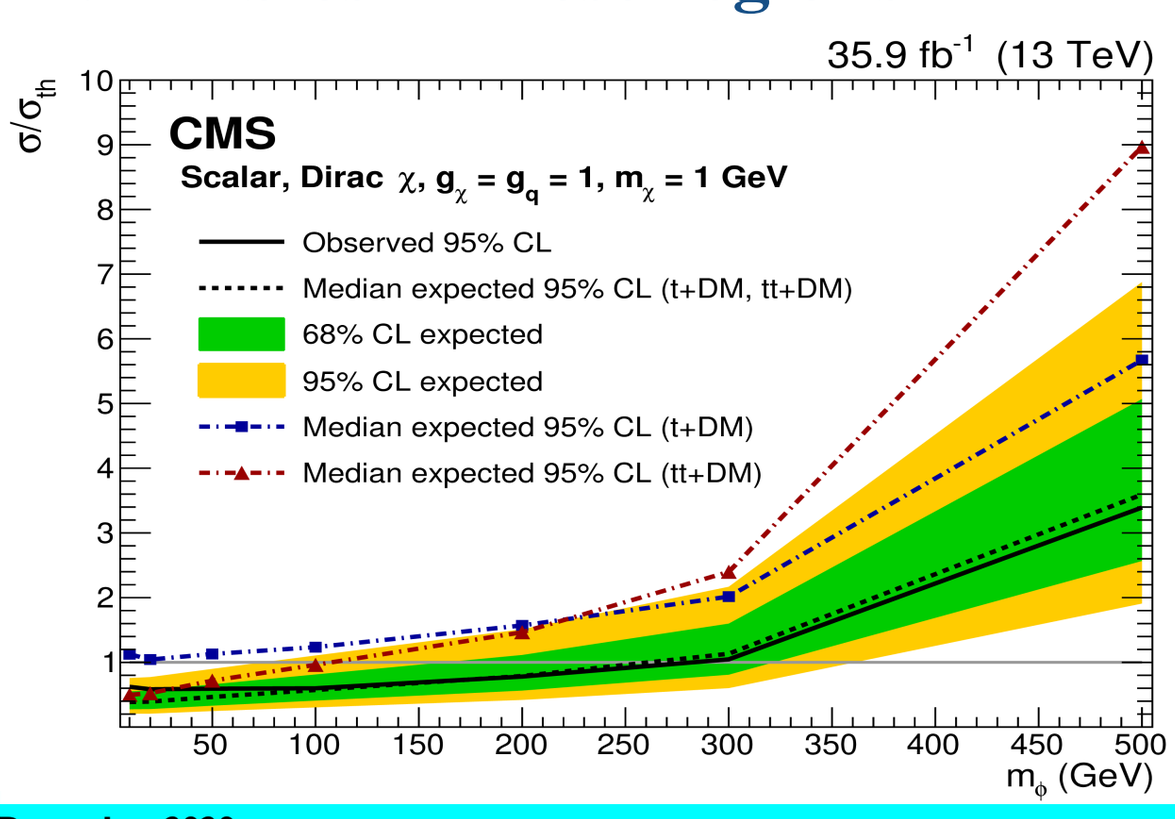
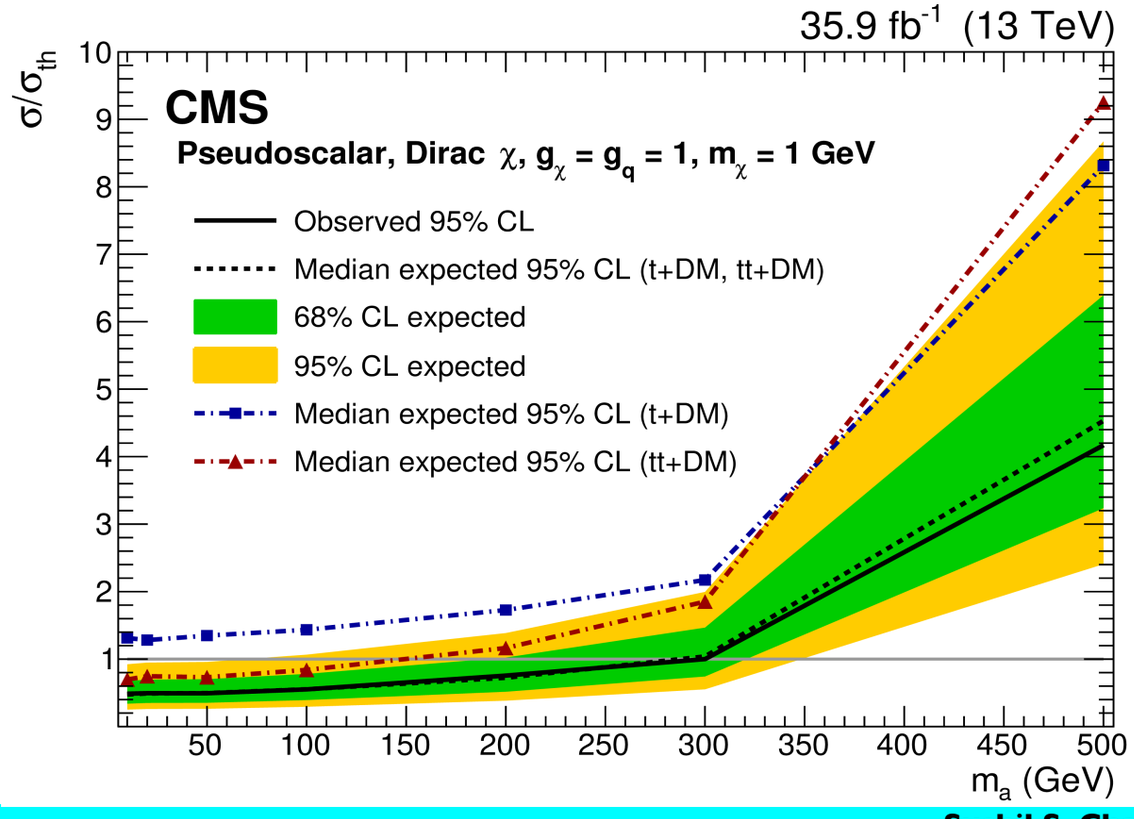
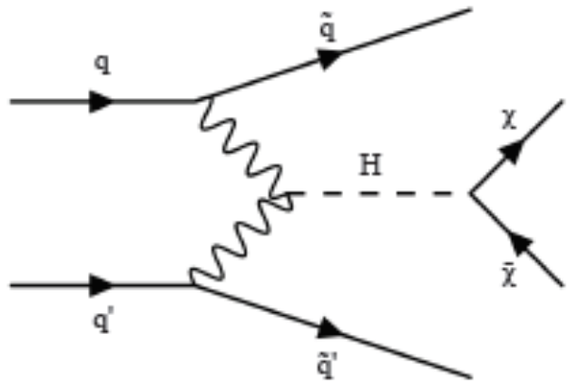






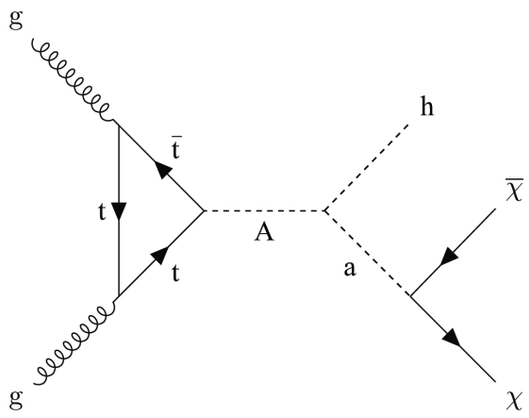
DM Search: Higgs Extended Sector and Invisible Decay

- **Higgs can decay directly to DM particles**
  - **in association of W/Z**
  - **VBF channel**

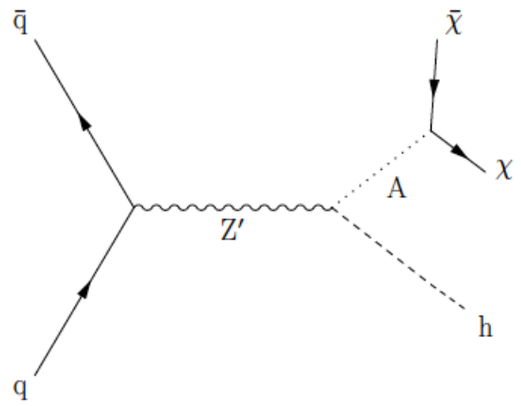


- **Mono-Higgs Searches**
  - **bb/$\gamma\gamma$/$\tau\tau$+MET**
  - **ZZ/WW +MET**

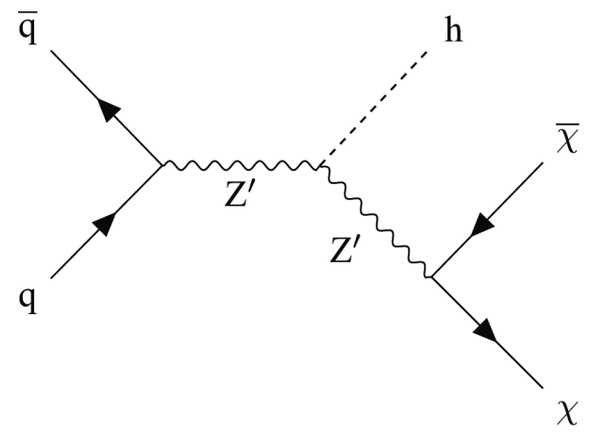
- **Three different model focussed here:**
  - **2HDM, 2HDM+a and Baryonic Z'**



2HDM + a pseudo-scalar



Z'- 2HDM



Z' Baryonic production

DM Search: 2HDM+ a

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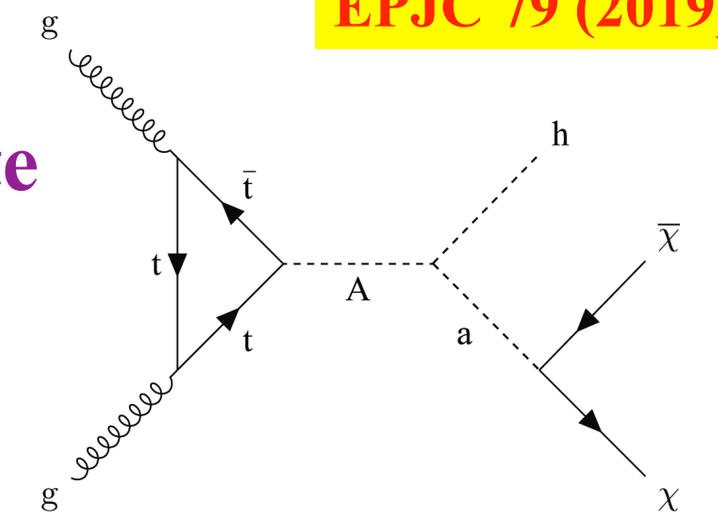
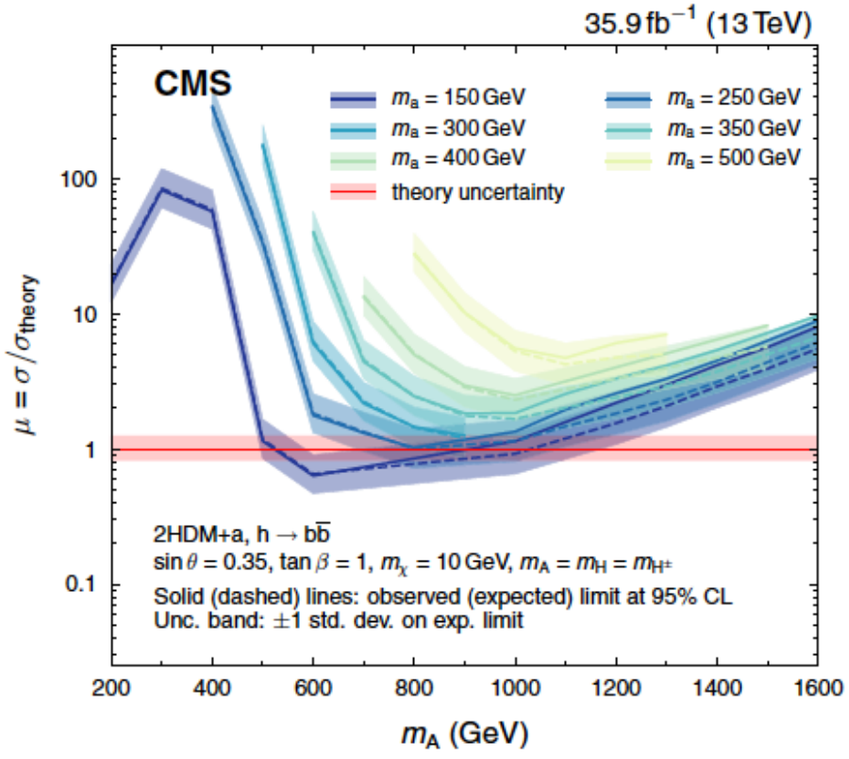
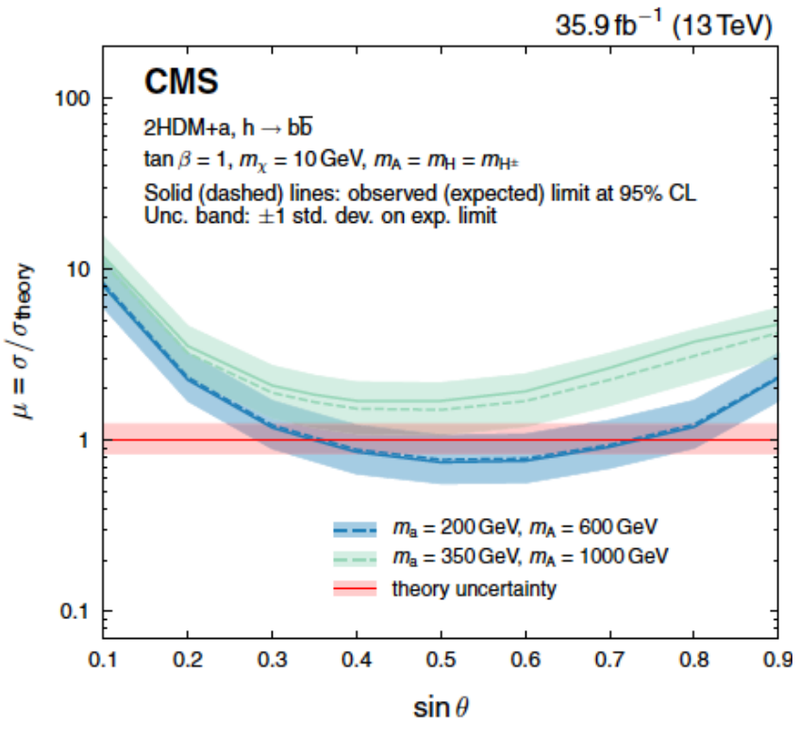
- **Extension of 2HDM model**
  - **Analysis based on h(bb)+MET final state**

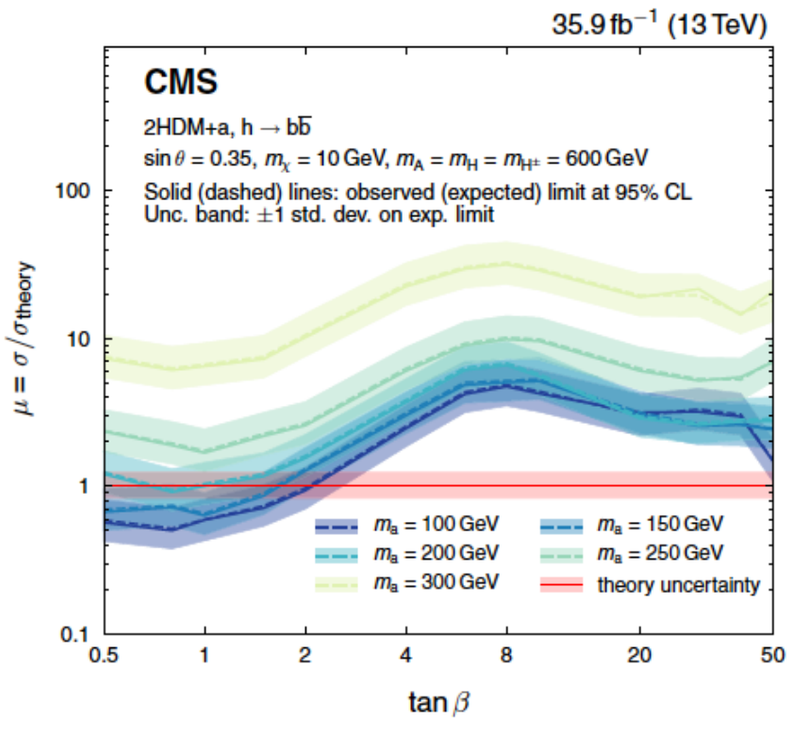
- **Main Backgrounds:**
  - **VH, Z→νν**
  - **W+jets, ttbar, single top**



0.5 TeV< $M_{z'}$<1.09 TeV
for M_a = 150 GeV







DM Search: Z'-2HDM

- **Combination of h decays channels:**
  - **bb, γγ, ττ, WW, ZZ**
- **h(bb)+MET dominate above 800 GeV**
- **h(γγ) +MET dominate below 800 GeV**

H(bb)+MET

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Combination

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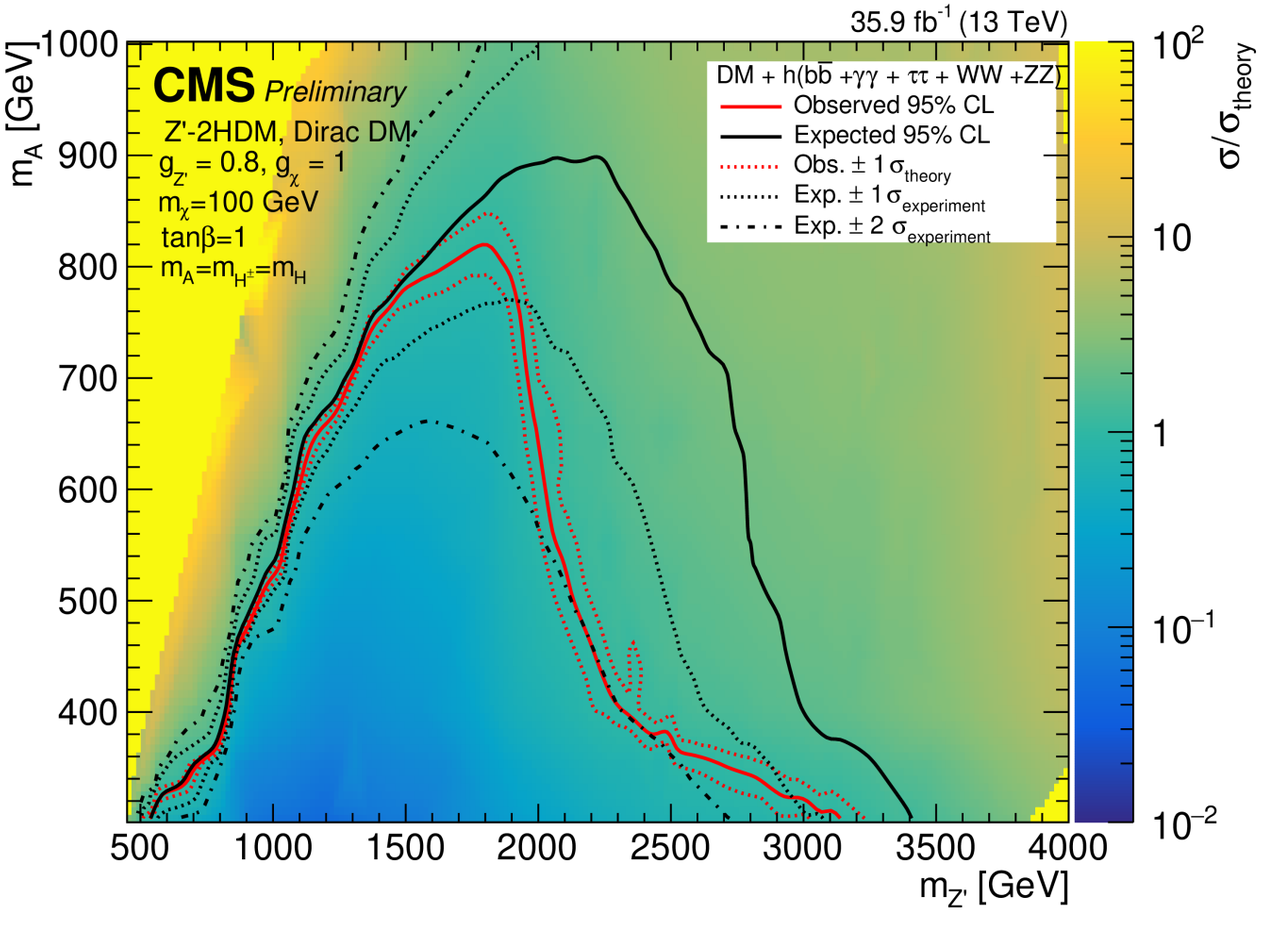
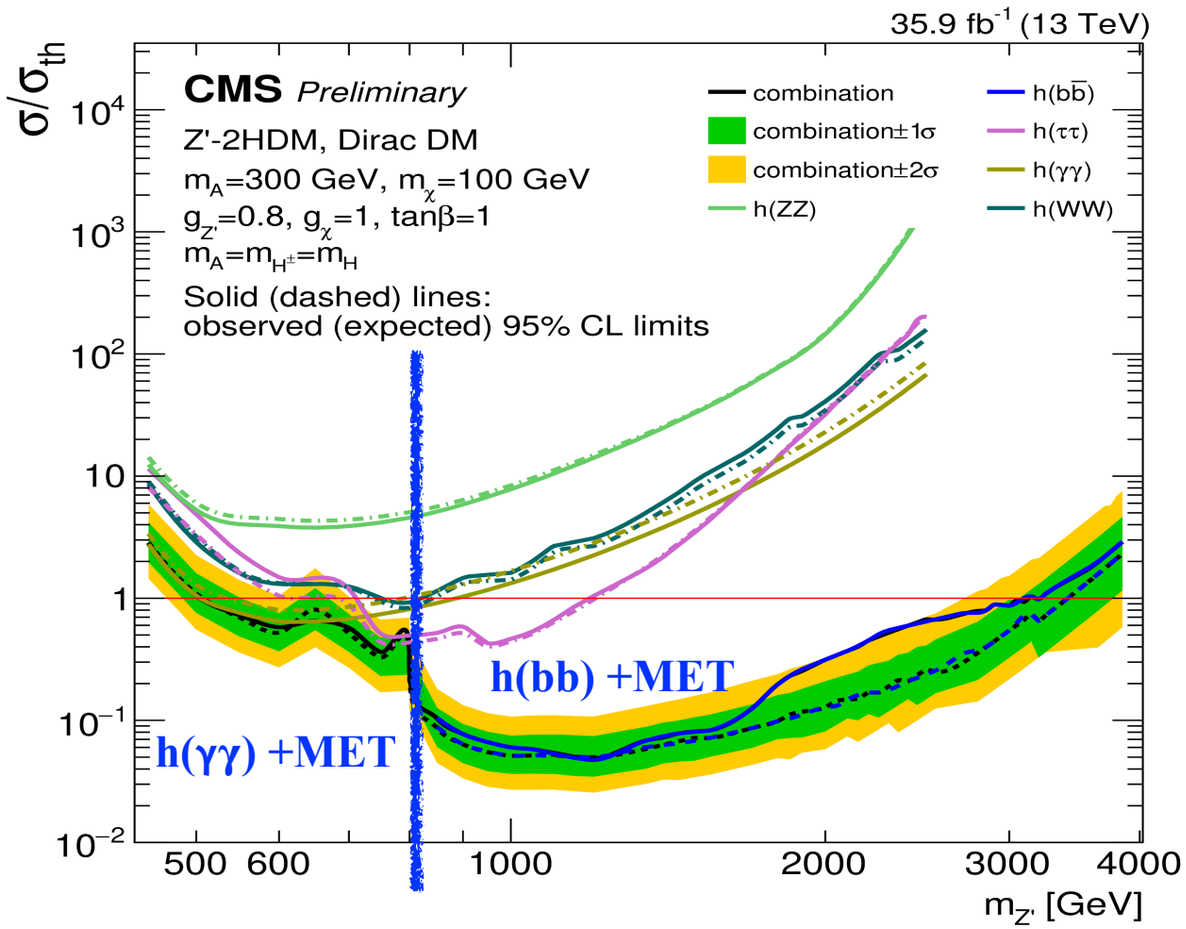
0.6 TeV< $M_{Z'}$<3.2TeV
for M_A= 300 GeV

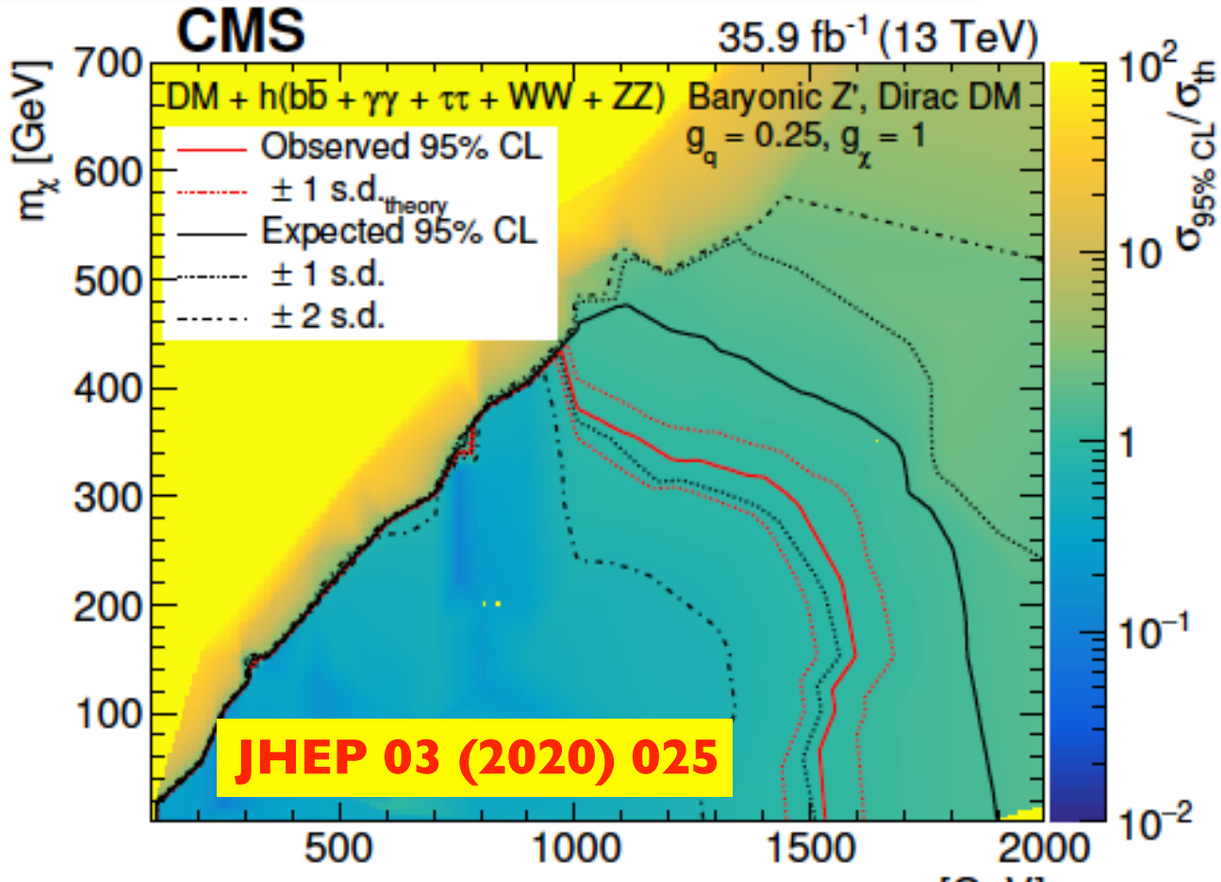


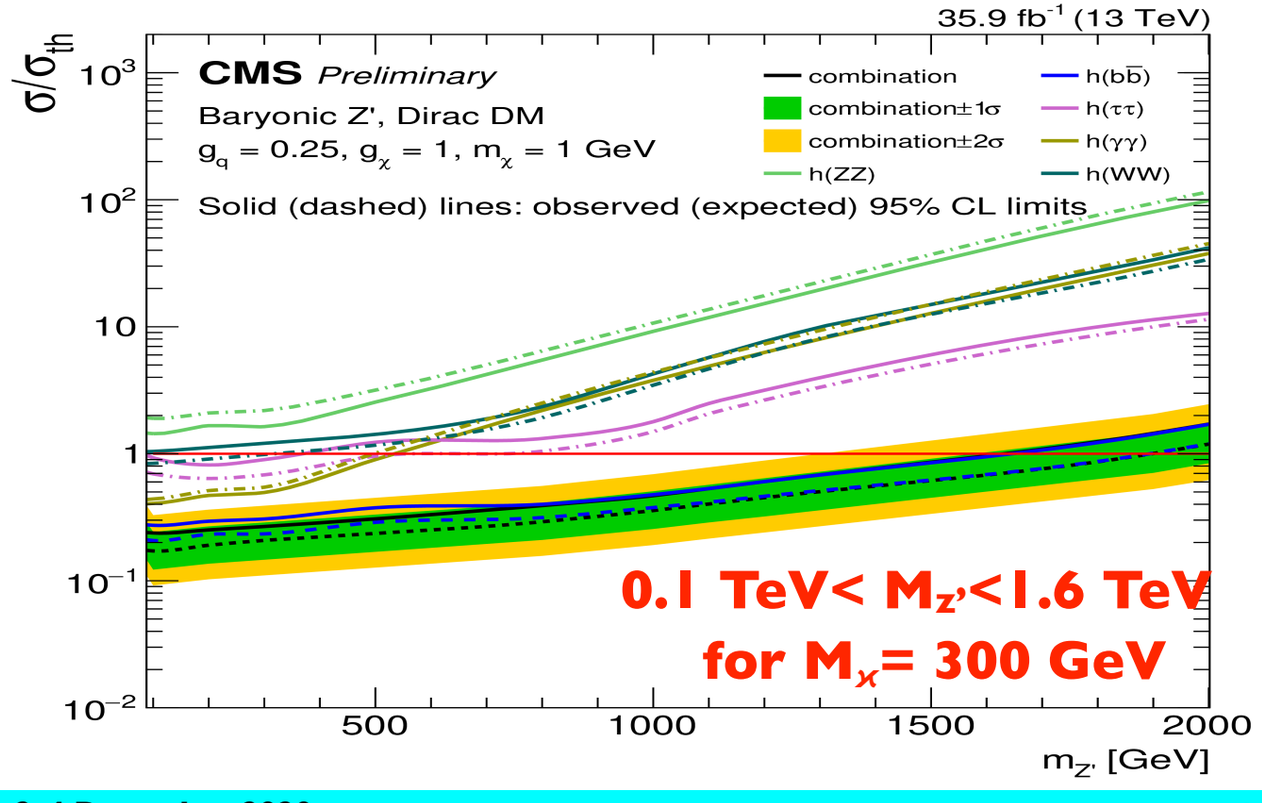


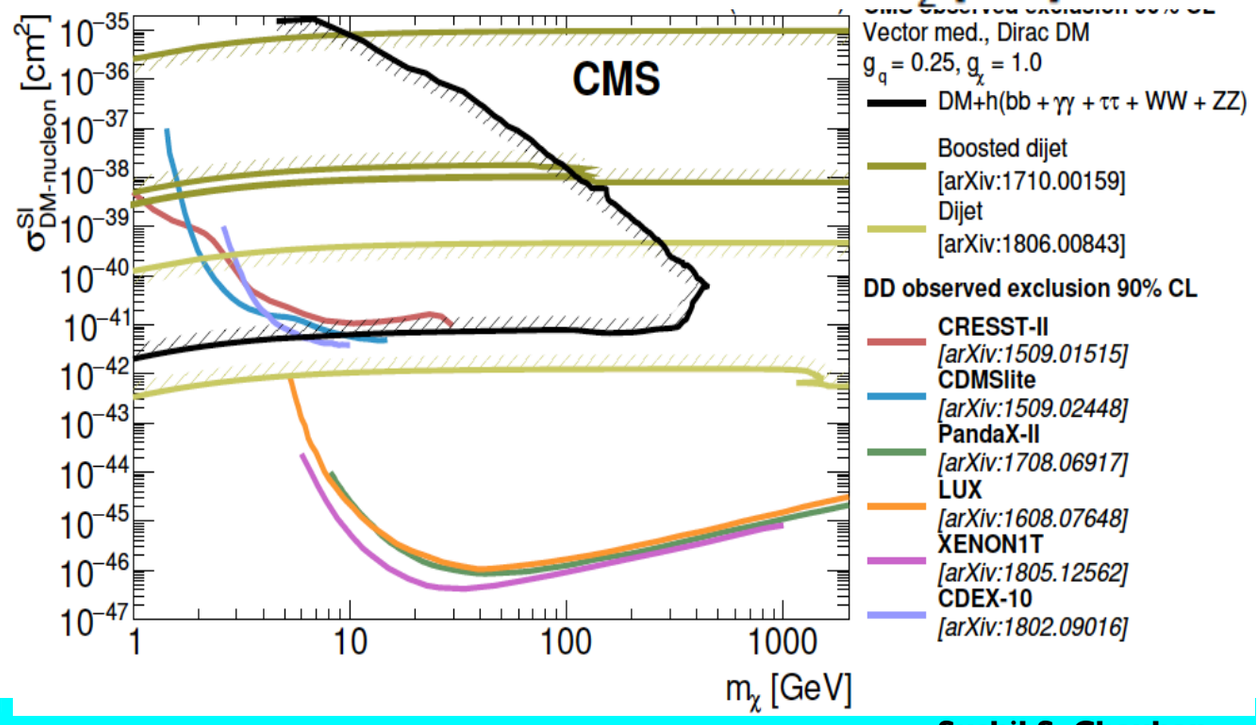
DM Search: Z' Baryonic

- **Combination of h decays**
  - **bb, γγ, ττ, WW, ZZ**
  - **Orthogonality of analyses make combination feasible**

- **h(bb)+MET dominates in search region**







DM Search: Higgs → Invisible

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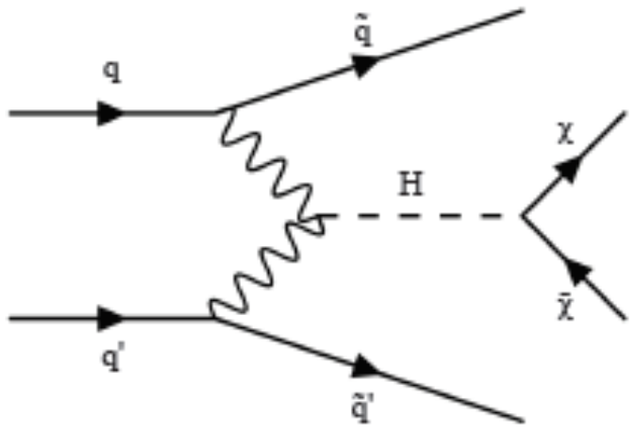
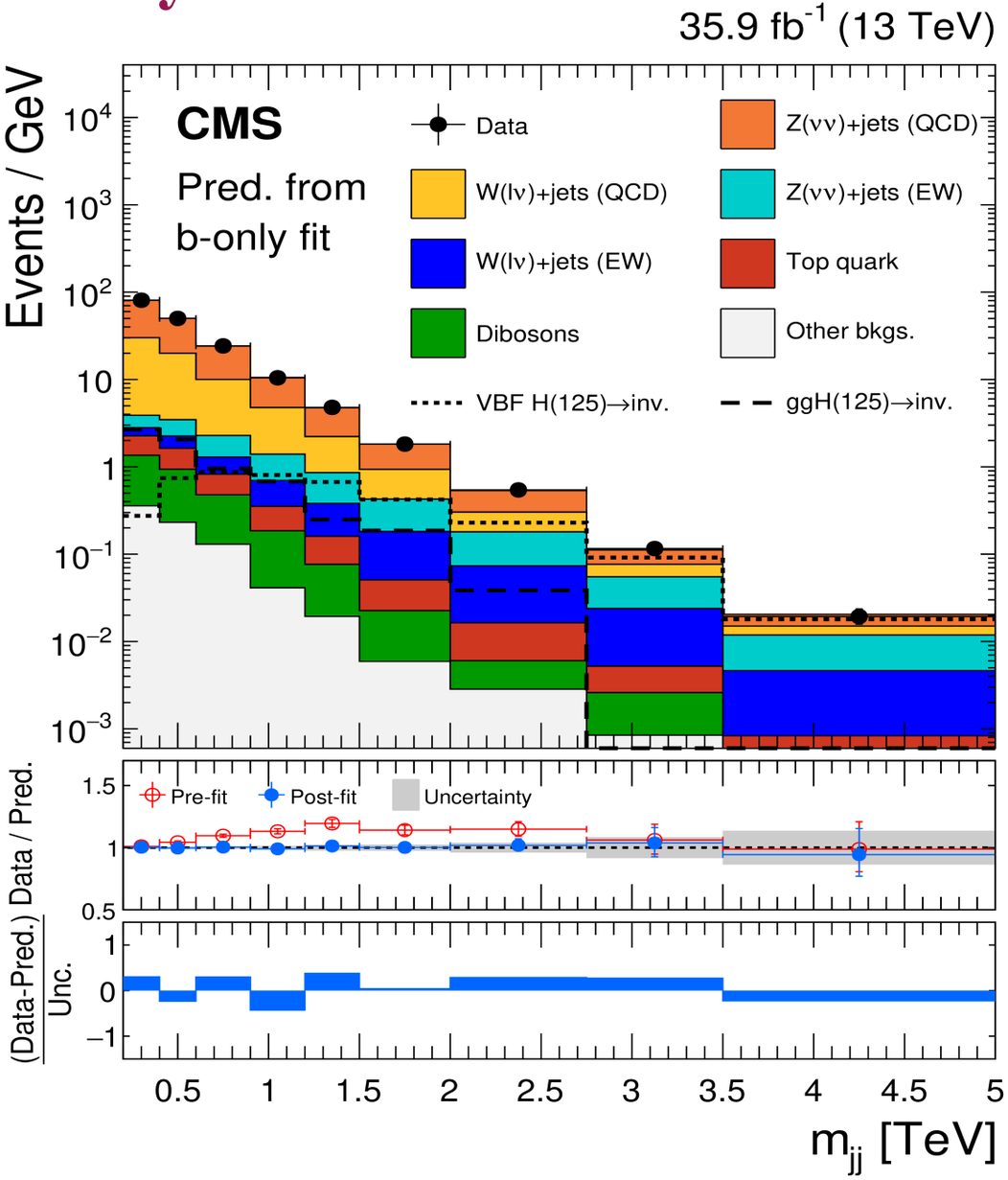


Higgs decay to DM directly

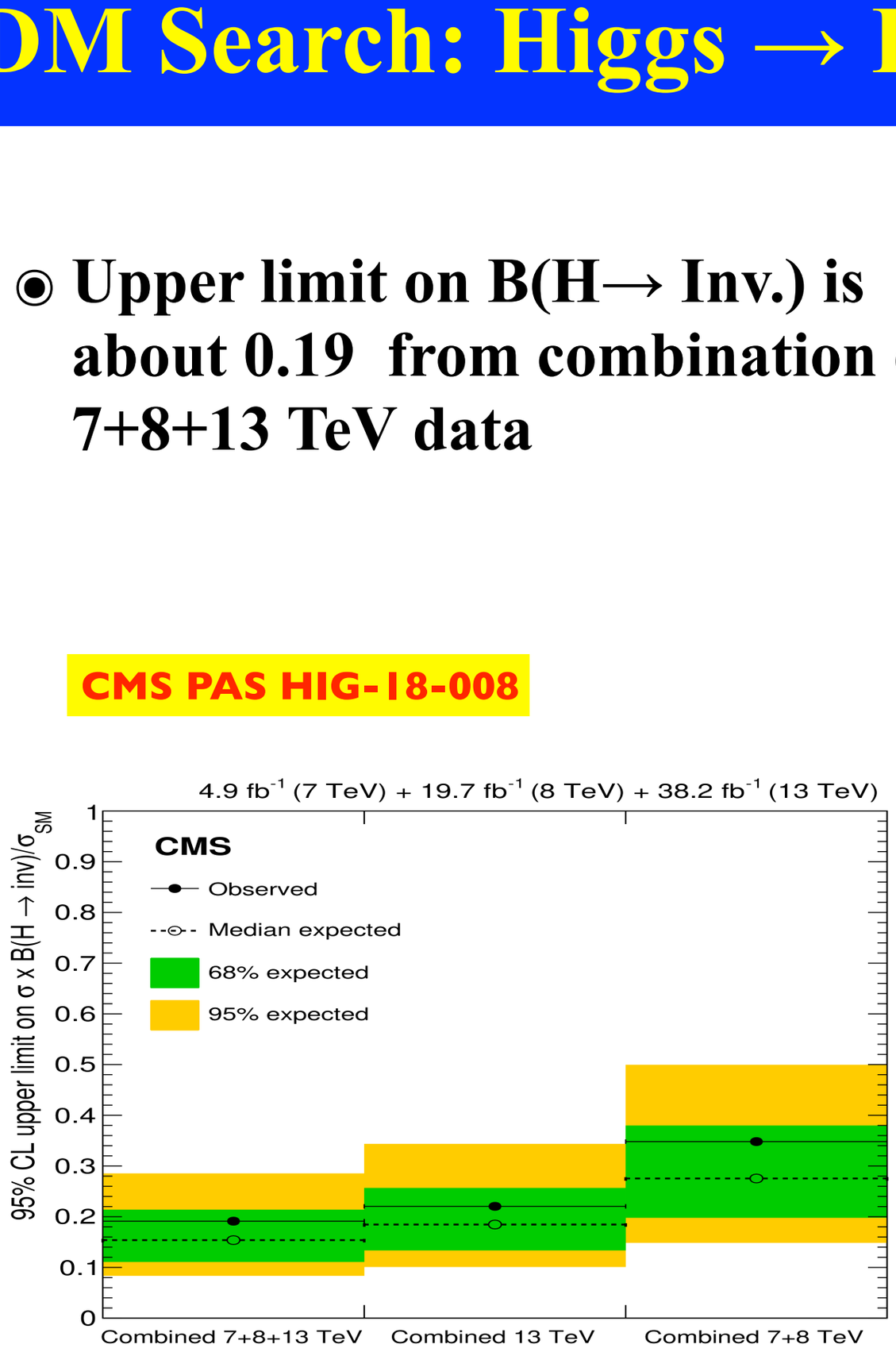
- **Search exploits M_{jj} and $\Delta\eta(jj)$ that characterised VBF Higgs boson productio**
- **Main backgrounds for VBF**
  - **Z(vv)+jets, W(lv)+Jets**
- **2016 data analysis of ZH and ggH channel are combined with VBF**
- **Fit to M_{jj} distribution is performed including SRs**

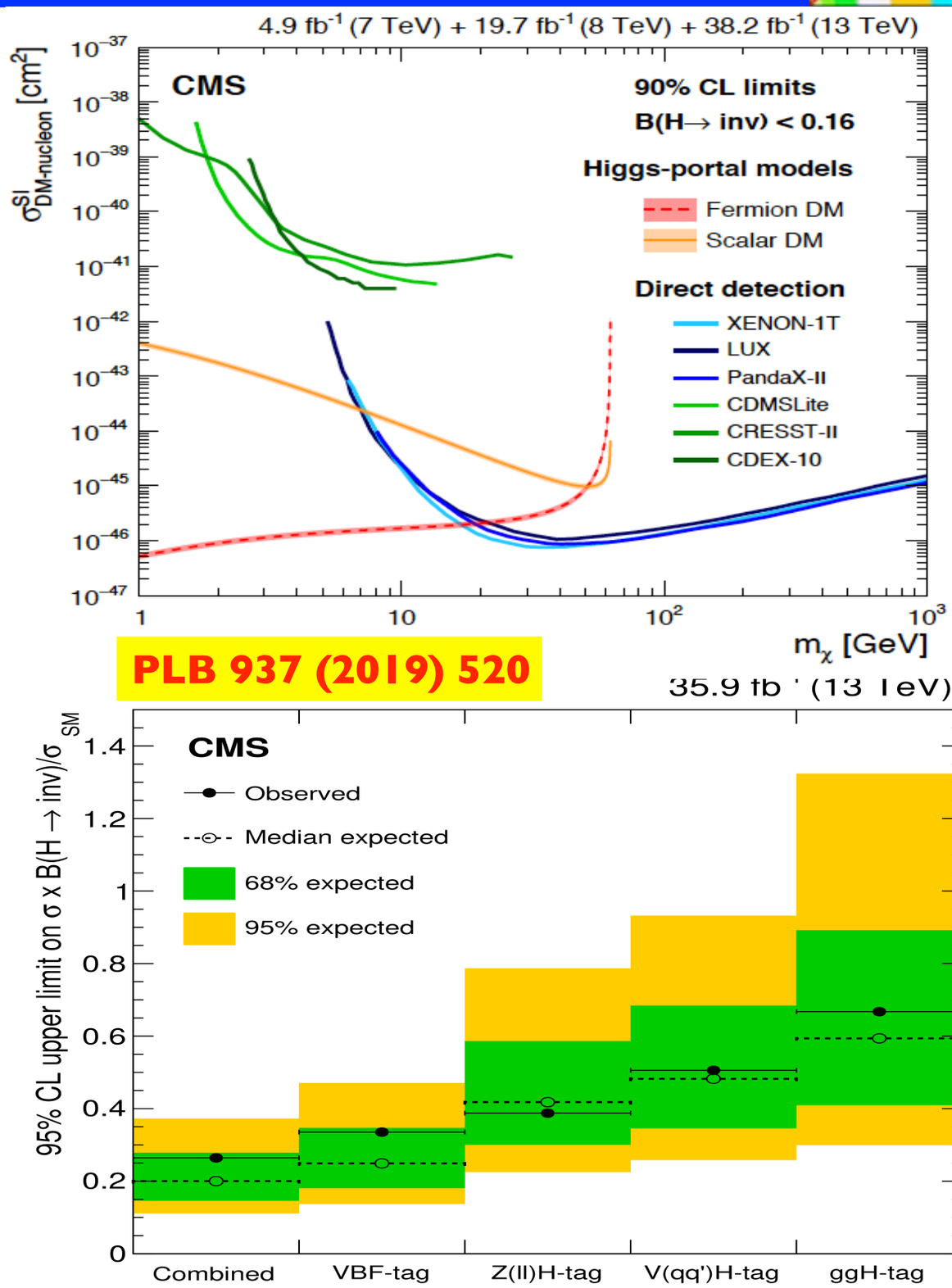


DM Search: Higgs → Invisible

- **Upper limit on B(H→ Inv.) is about 0.19 from combination of 7+8+13 TeV data**

CMS PAS HIG-18-008





PLB 937 (2019) 520

Dark Photon: ZH Channel

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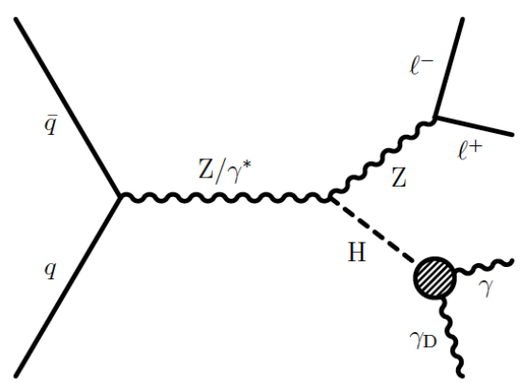
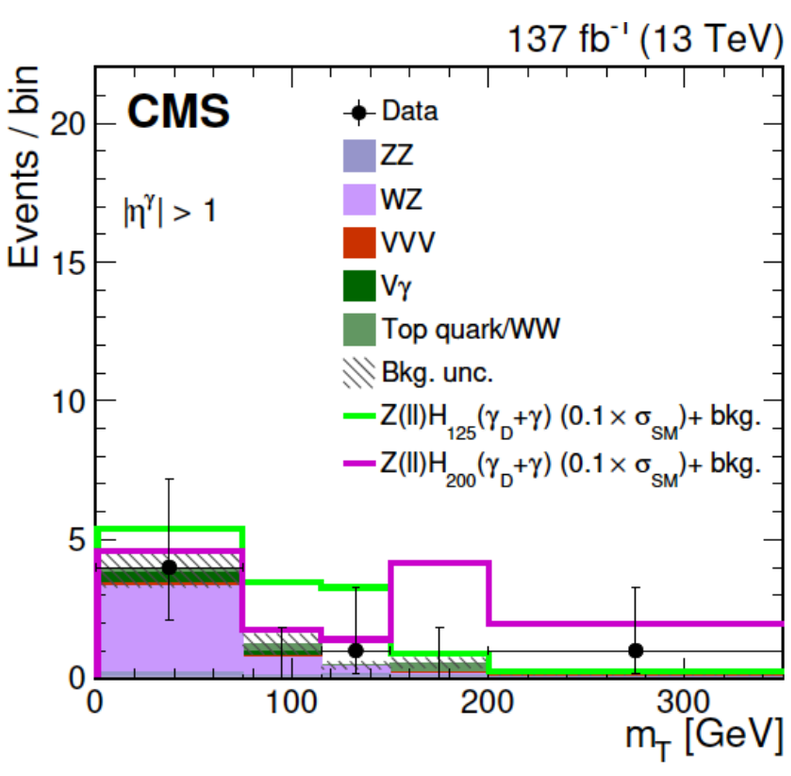
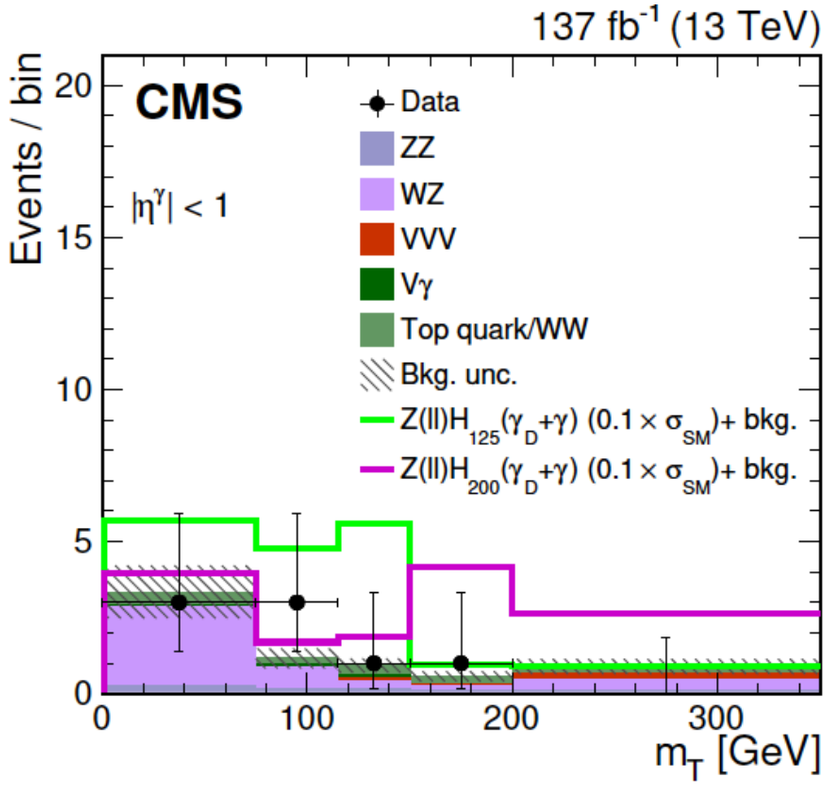
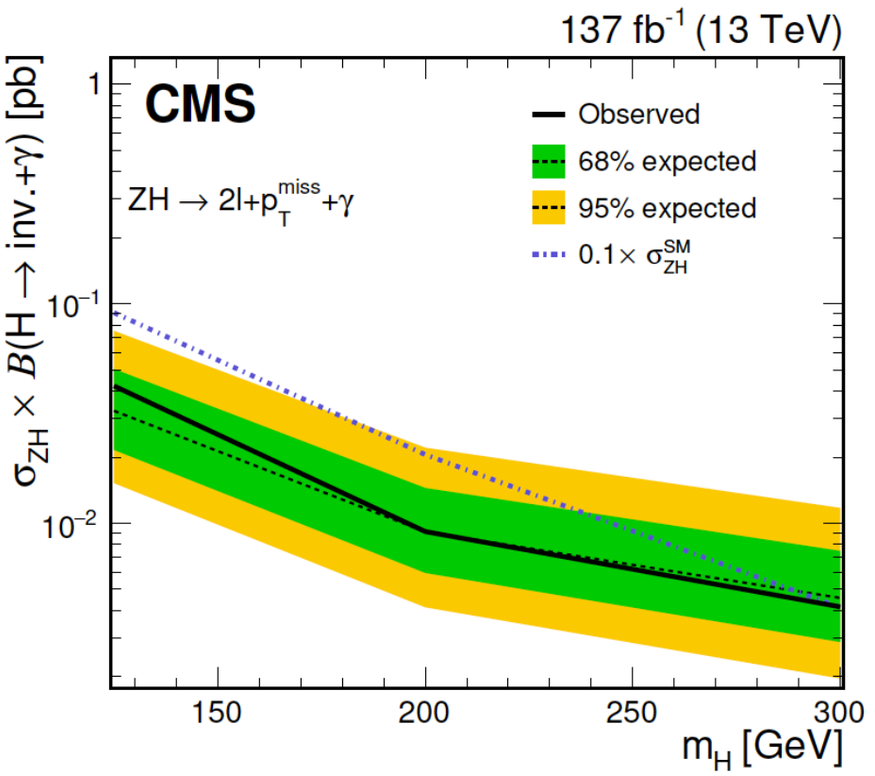
- **Probing a Higgs portal model with Dark Sector**
  - $H \rightarrow \gamma\gamma_d$ where γ_d is massless dark photon
  - M_T of photon-MET system is used as discriminating variable
    - Relatively clean state



Limit on BR < 4.6% at 95% CL for SM H(γ+ Inv.) Channel



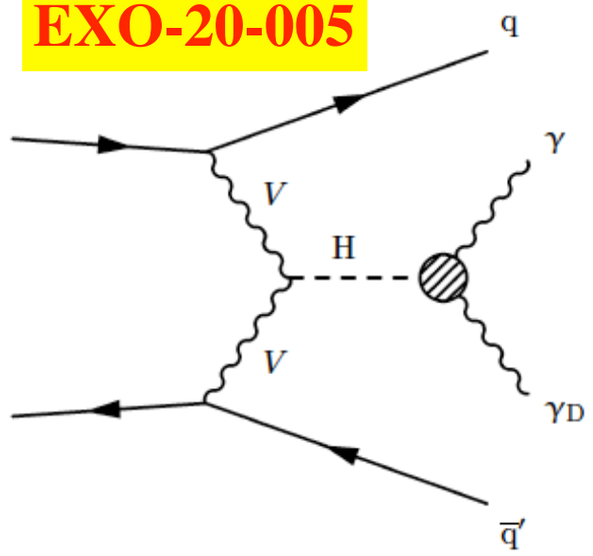




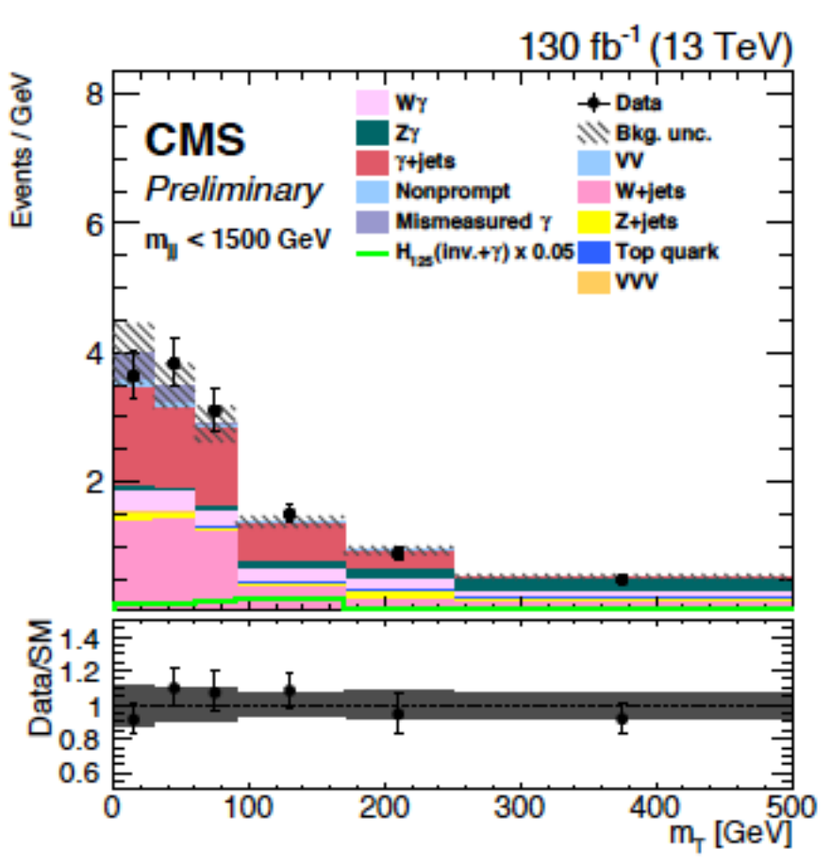
Dark Photon: Higgs VBF Channel

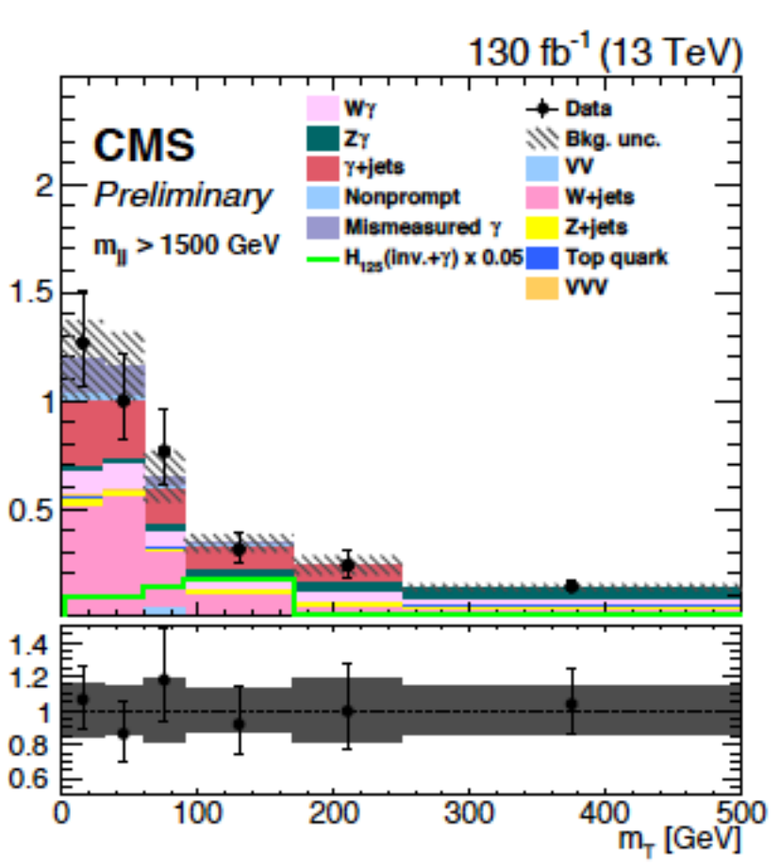
- Isolated single photon
- Two high pT VBF jets with high mass(> 500 GeV)
- Large MET
- Backgrounds: W(lν)+γ , Z($\nu\nu$)+γ, γ+jet are the largest
- Fit to m_T distribution for discrimination

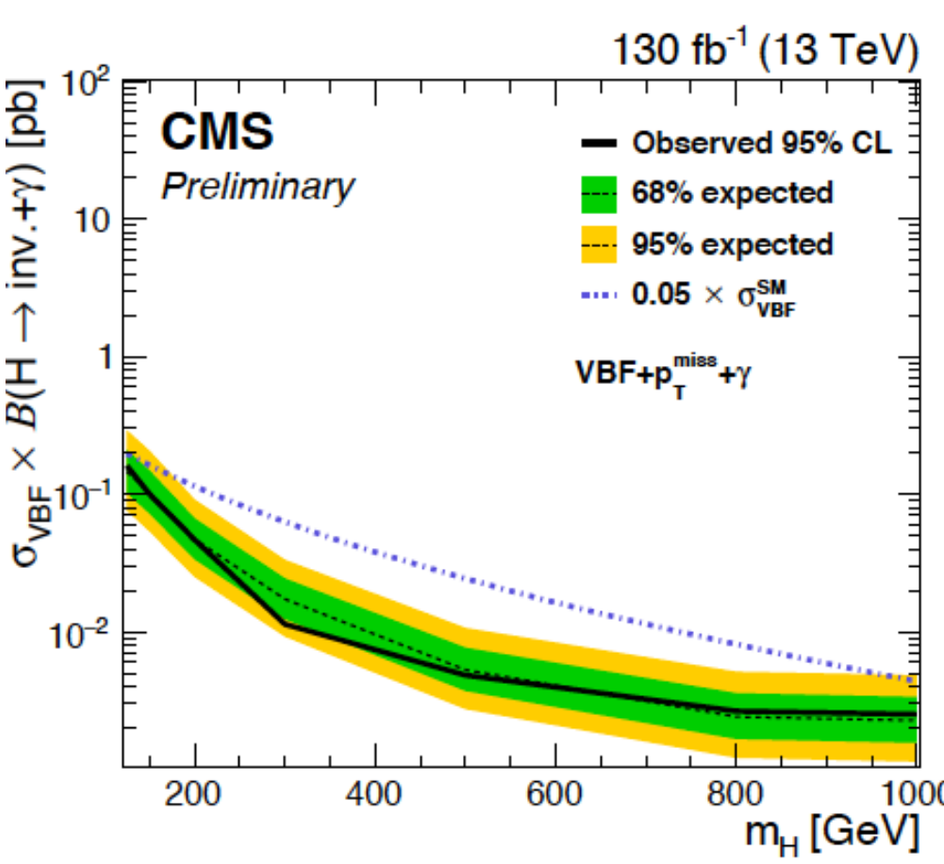
arXiv:2009.14009
EXO-20-005



Limit on BR < 3.4%(2.9%) at 95% CL for VBF(VBF+ZH) channel







Mediator Search: Dijet Resonance Search

- **Mediator can be looked without DM production**
  - Mediator coupled to initial states
  - Constrained on couplings(g_q) for a given DM mass
    - *Dilepton searches are also possible if mediator couples to leptons*
- **Re-interpretation of Dijet resonance search for new physics**

- **Scouting analysis (in recent times)**
  - Low level trigger threshold
  - Only limited information about event

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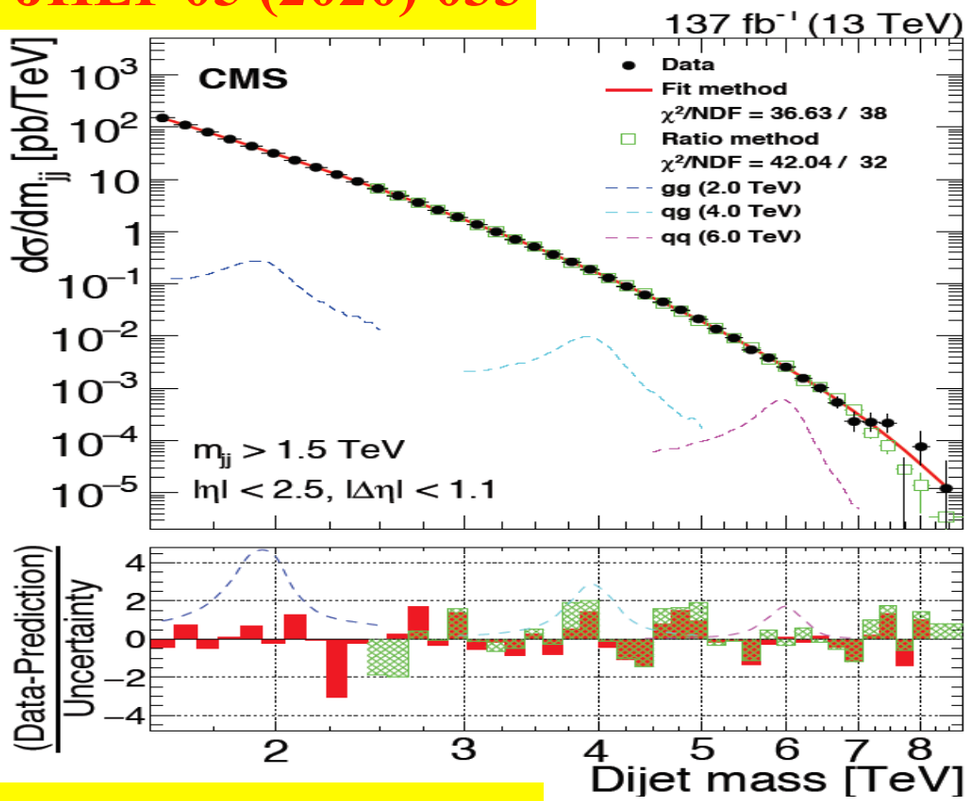

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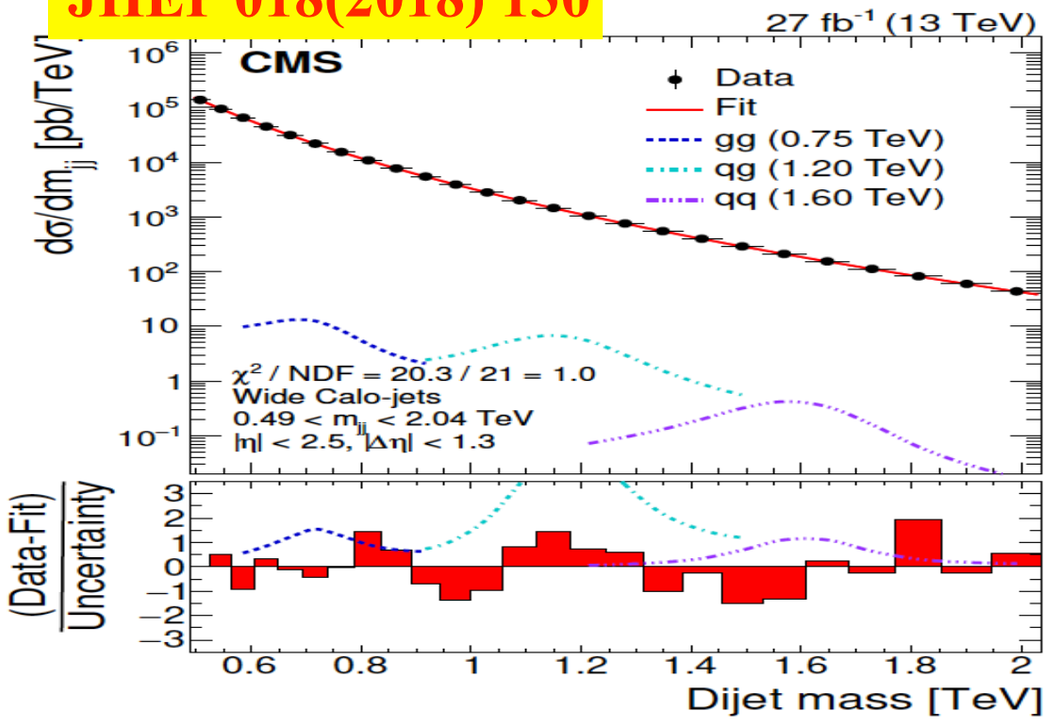
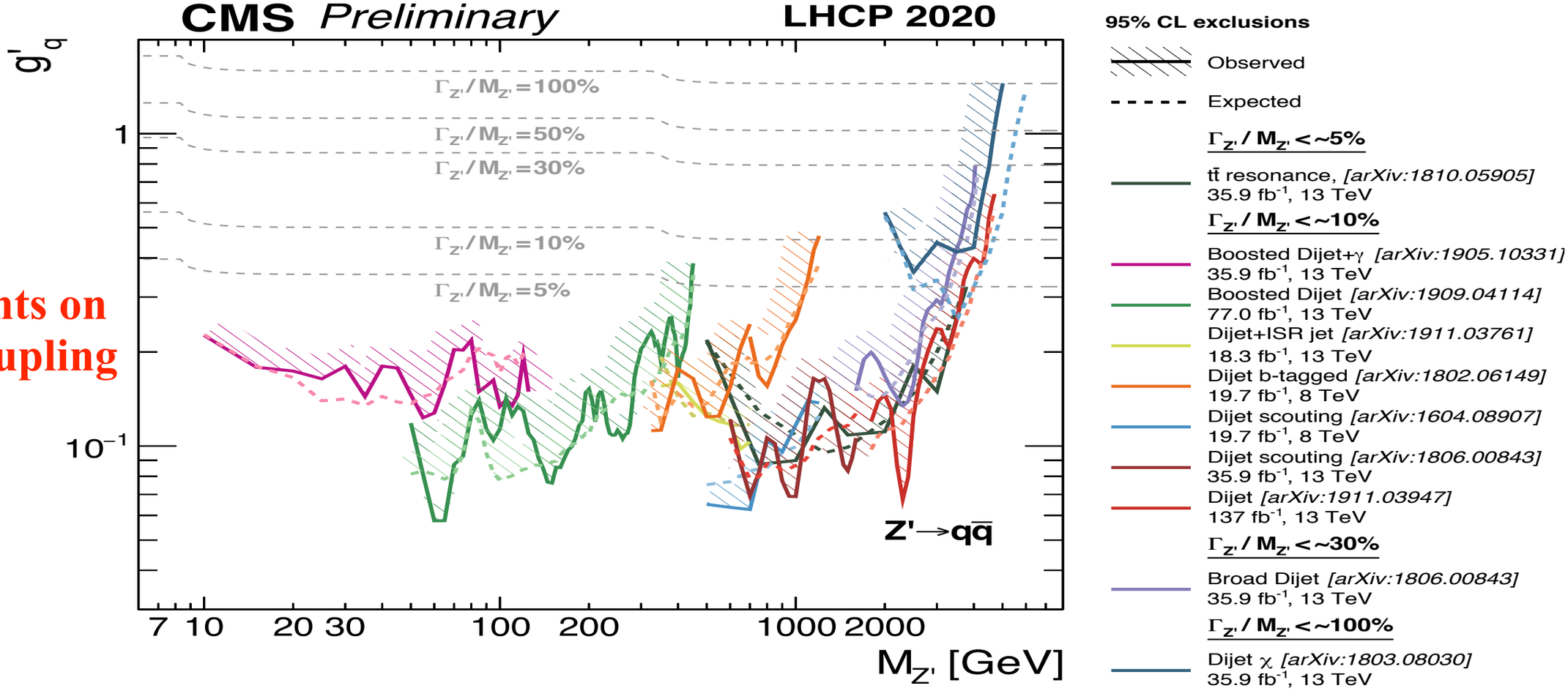


Low and High Mass Diet Searches

CMS Summary Plots

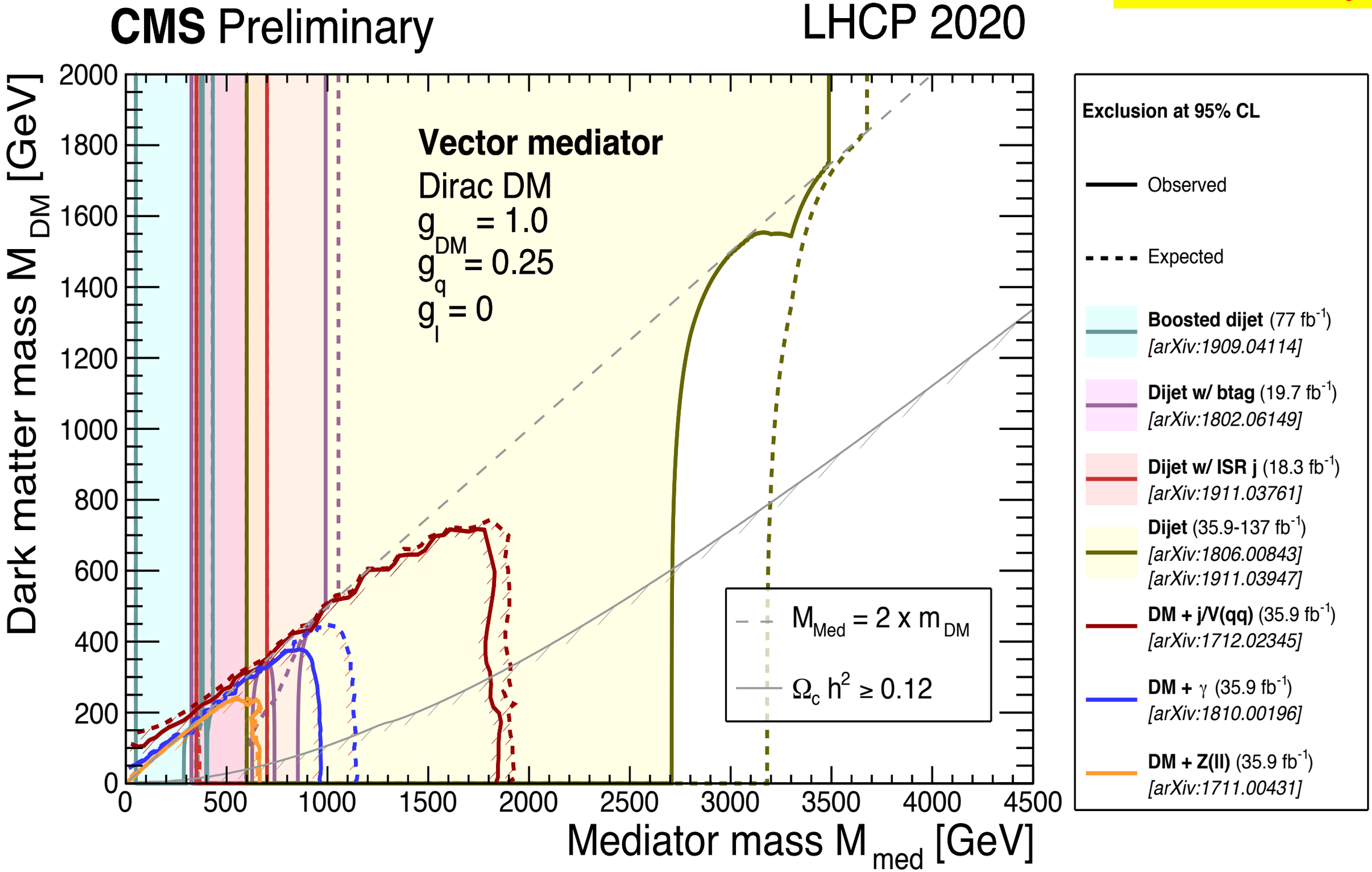
- ISR jet/γ allows to search low mass region
- Typical trigger threshold on ISR jet is few hundred GeV
- Scouting further allows us to go lower masses,
  - Typically boosted regime
- A lot of theoretical and experimental work on jet substructure techniques

Constraints on quark coupling



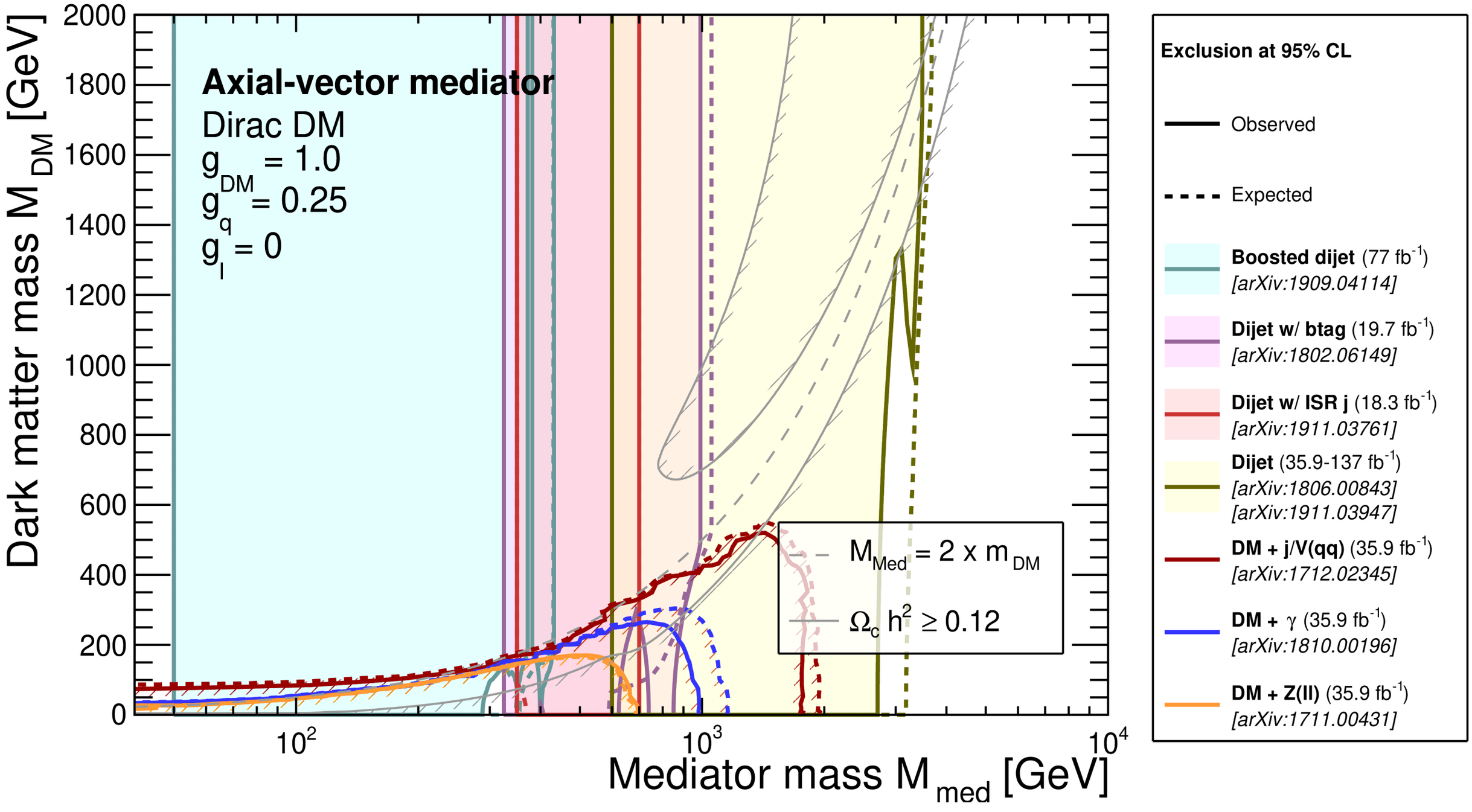
Spin-0 Mediator: Search Summary

CMS Summary Plots



Spin-1 Mediator: Search Summary

CMS Summary Plots



Summary

- **Extensive and broad DM search program at the CMS experiment**
  - **Apart from conventional search channels (like mono-jet, mono-photon, mono-Z etc.) CMS has also looked new interpretation and new combination from various channel**
    - **Top and Higgs are being explored in association with DM production**
    - **Dark Photon and t-channel searches taking shape**
  - **New DM search channels in events with Leptoquark production (not covered here)**

- **No evidence of DM at LHC yet but stay tuned for:**
  - **➡more new results of full Run-2 data, and**
  - **➡near future from Run-3!!**


Thank You!!