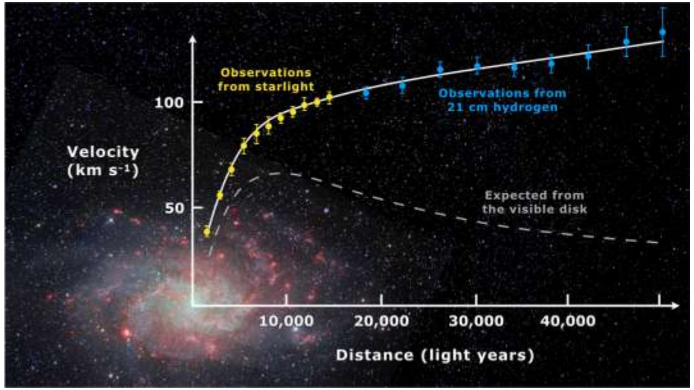
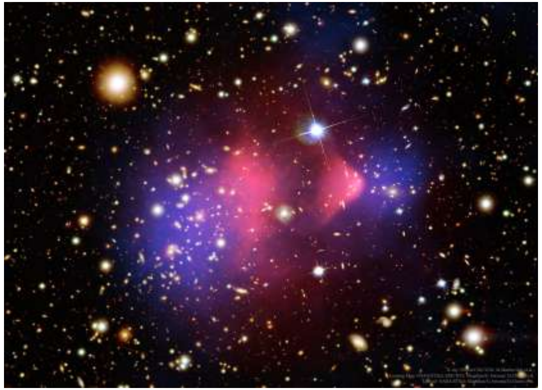
Searches for dark matter at CMS

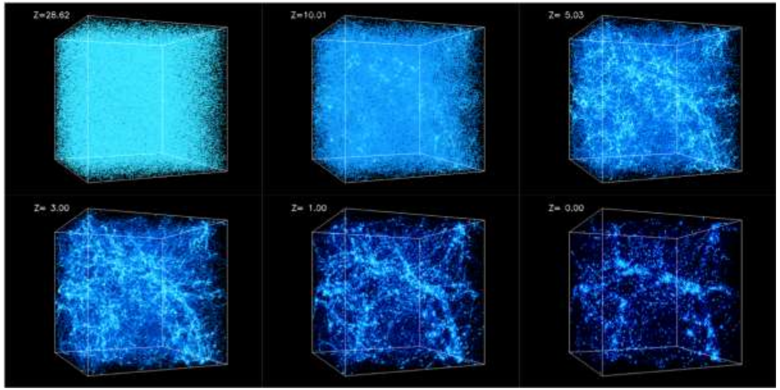
THIAGO TOMEI

SPRACE-Unesp

Gravitational Evidence for Dark Matter

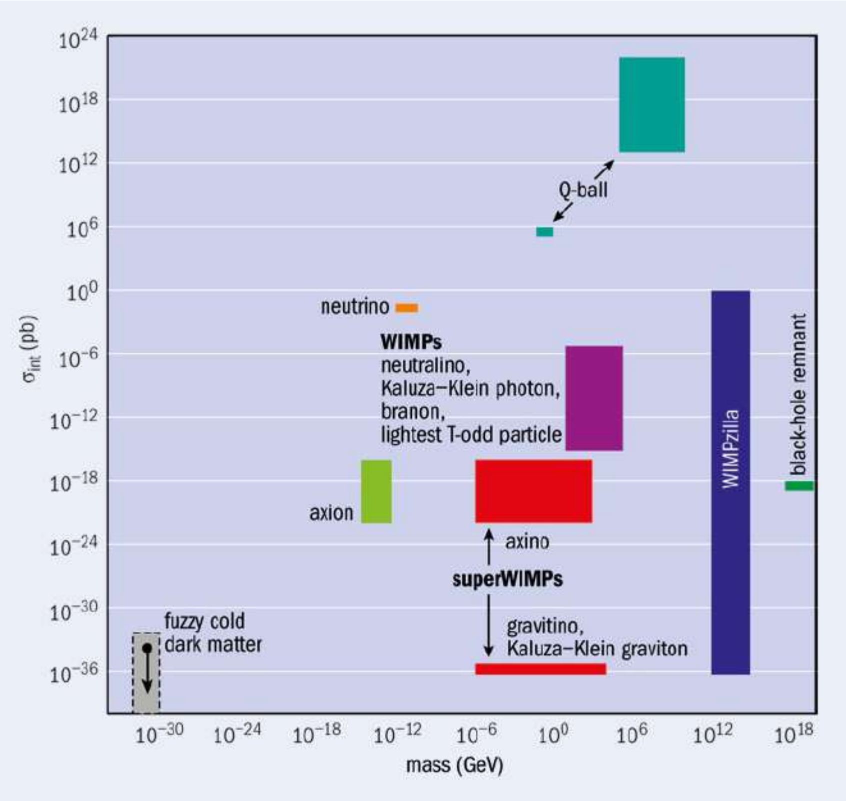






Simulations on NCSA by A. Kravtsov (U.Chicago) and A. Klypin (NMSU); visualization by A. Kravtsov

Dark Matter Candidate: Gross Features



Dark

- ❑ Electrically neutral
  - Limits on charge and electric/magnetic dipole moment

Collisionless

- ❑ Limits on σ_{xx}/m_x

Classical

- ❑ Confined in kpc scale → de Broglie wavelength
  - $m > 10^{-22}$ eV (boson)
  - $m > 25$ eV (spin ½ fermion)

Fluid

- ❑ Stability of bound systems → $m < 10^3\ M_{Sun} \sim 10^{70}$ eV

Stable (or long-lived)

- ❑ Should not have decayed by now

Dark Matter: Hunter's Guide

Direct detection

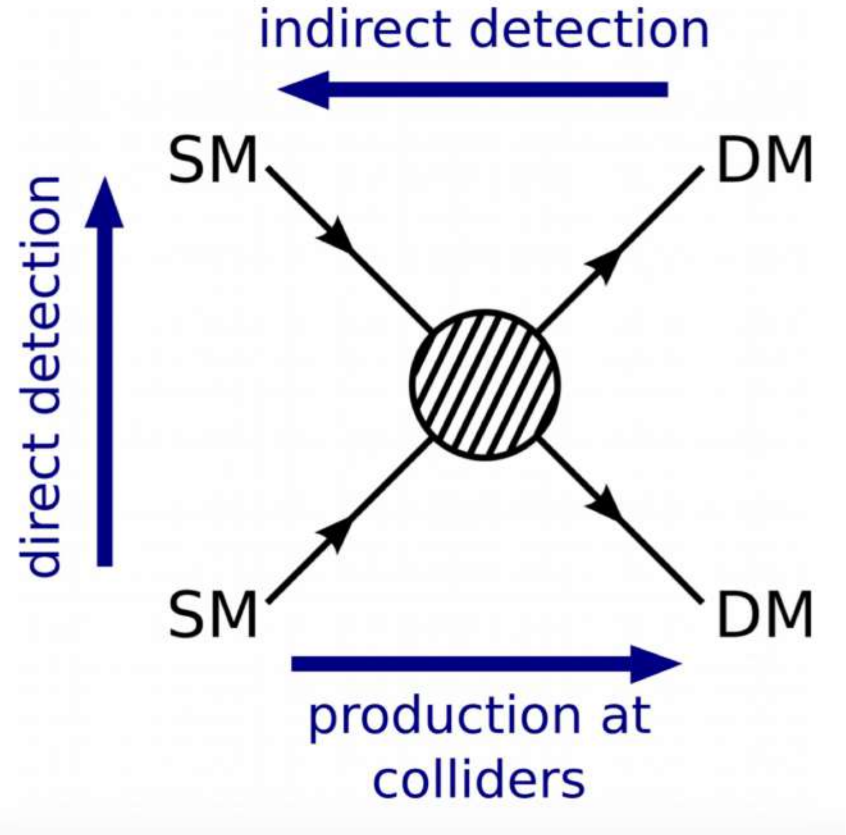
- Scattering between DM particle and nuclei → recoil detection

Indirect detection

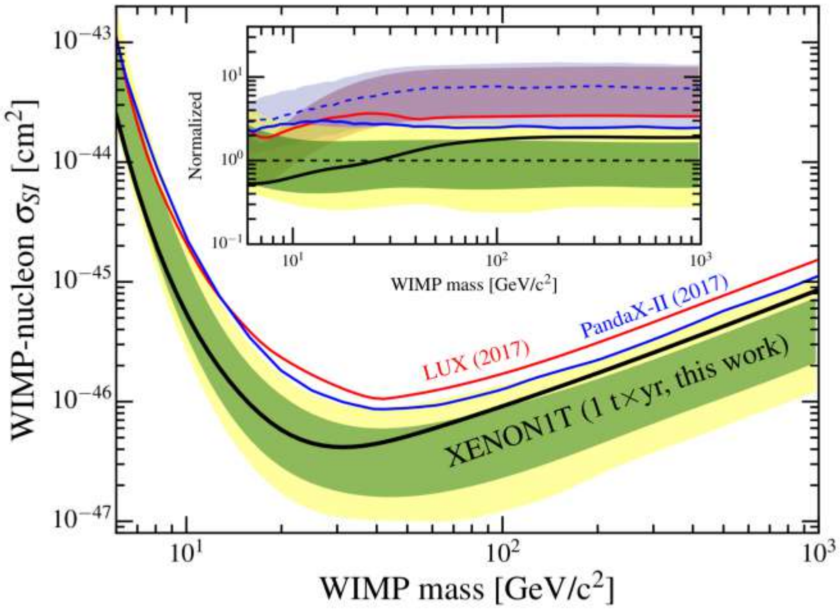
- Annihilation of DM pairs → effects on particle distribution

Production at colliders

- Complementary to direct and indirect detection
- Rich phenomenology



Status of Direct Detection of Dark Matter



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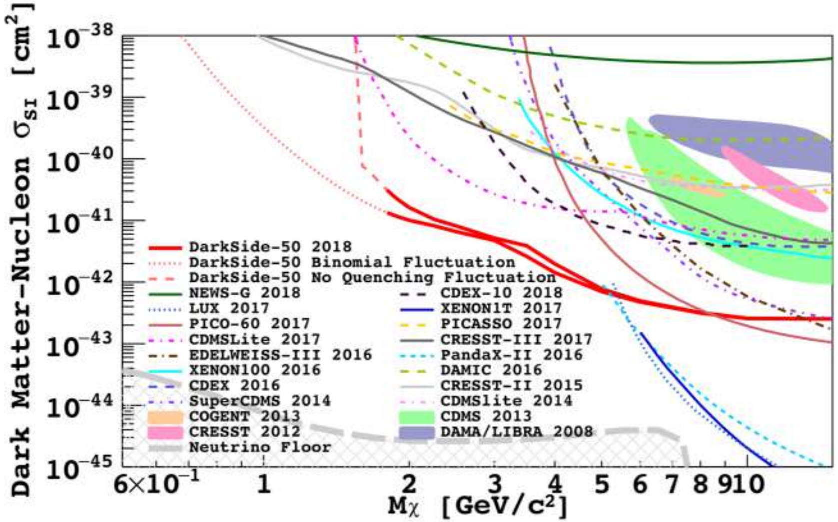
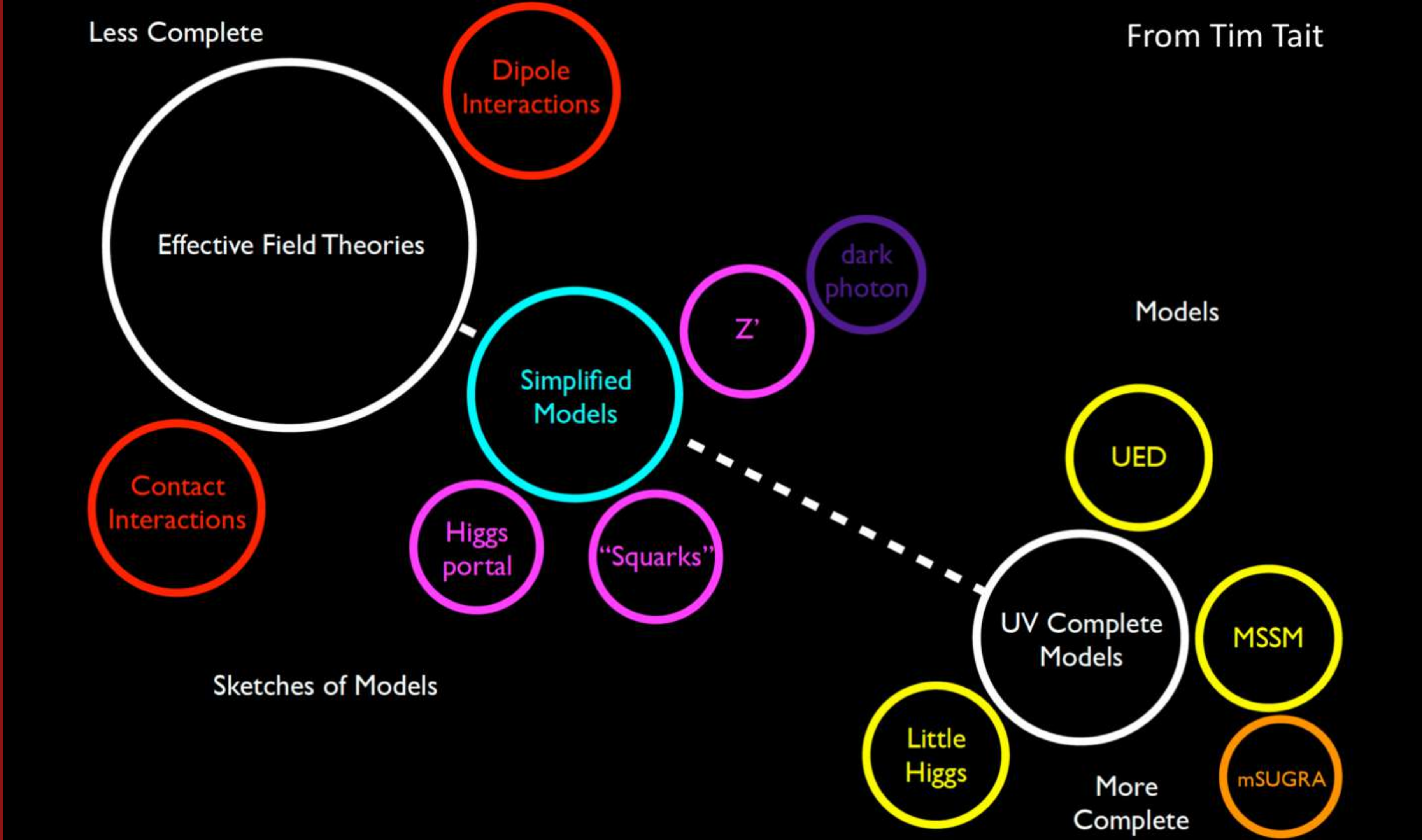


1802.06994

Results for spin-independent (SI) interaction only
– but see later for spin-dependent (SD)



Less Complete
From Tim Tait
Dipole Interactions
Effective Field Theories
dark photon
Z'
Models
Simplified Models
UED
Contact Interactions
Higgs portal
"Squarks"
UV Complete Models
MSSM
Sketches of Models
Little Higgs
More Complete
mSUGRA

Modelling the Dark Matter Production

Direct production of DM pair

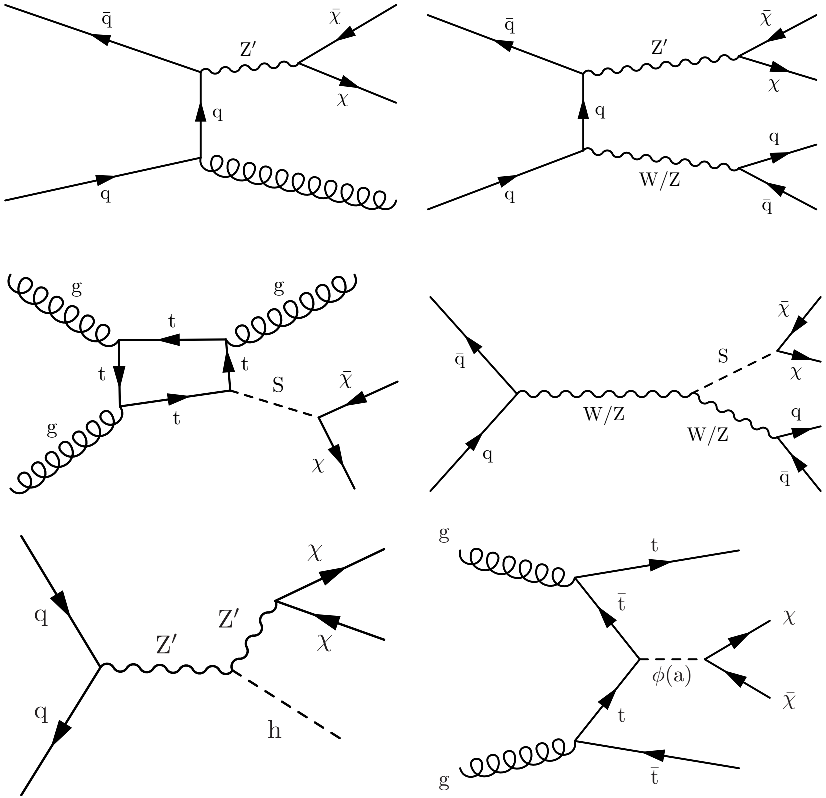
- At LHC energies: explicit mediator

Signature

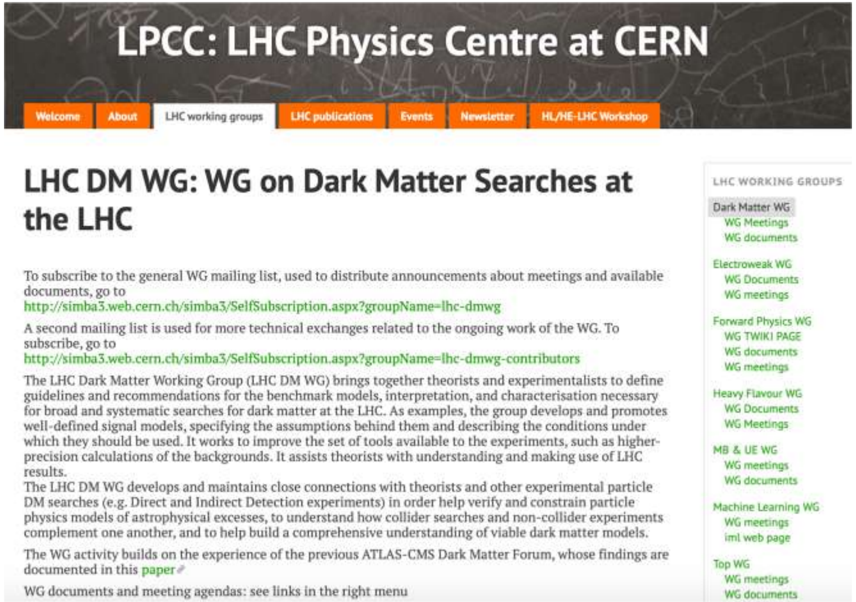
- DM leaves no signal in the detector → transverse momentum imbalance (p_T^{miss})
- Back-to-back DM pair is invisible → trigger on recoiling SM particles → "mono-X" search.

But also...

- Cascade decays (like SUSY)
- Searches with long-lived particles
- Limits on pure mediator production



The LHCC Dark Matter Working Group


LPCC: LHC Physics Centre at CERN

Welcome | About | LHC working groups | LHC publications | Events | Newsletter | HL/HE-LHC Workshop

LHC DM WG: WG on Dark Matter Searches at the LHC

To subscribe to the general WG mailing list, used to distribute announcements about meetings and available documents, go to http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg

A second mailing list is used for more technical exchanges related to the ongoing work of the WG. To subscribe, go to http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg-contributors

The LHC Dark Matter Working Group (LHC DM WG) brings together theorists and experimentalists to define guidelines and recommendations for the benchmark models, interpretation, and characterisation necessary for broad and systematic searches for dark matter at the LHC. As examples, the group develops and promotes well-defined signal models, specifying the assumptions behind them and describing the conditions under which they should be used. It works to improve the set of tools available to the experiments, such as higher-precision calculations of the backgrounds. It assists theorists with understanding and making use of LHC results.
The LHC DM WG develops and maintains close connections with theorists and other experimental particle DM searches (e.g. Direct and Indirect Detection experiments) in order help verify and constrain particle physics models of astrophysical excesses, to understand how collider searches and non-collider experiments complement one another, and to help build a comprehensive understanding of viable dark matter models.

The WG activity builds on the experience of the previous ATLAS-CMS Dark Matter Forum, whose findings are documented in this paper

WG documents and meeting agendas: see links in the right menu

LHC WORKING GROUPS
- Dark Matter WG
  - WG Meetings
  - WG documents
- Electroweak WG
  - WG Documents
  - WG meetings
- Forward Physics WG
  - WG TWIKI PAGE
  - WG documents
  - WG meetings
- Heavy Flavour WG
  - WG Documents
  - WG Meetings
- MB & UE WG
  - WG meetings
  - WG documents
- Machine Learning WG
  - WG meetings
  - iml web page
- Top WG
  - WG meetings
  - WG documents

Guidelines and recommendations

for benchmark models

LHC x Direct and Indirect Detection

DM limits from mediator searches

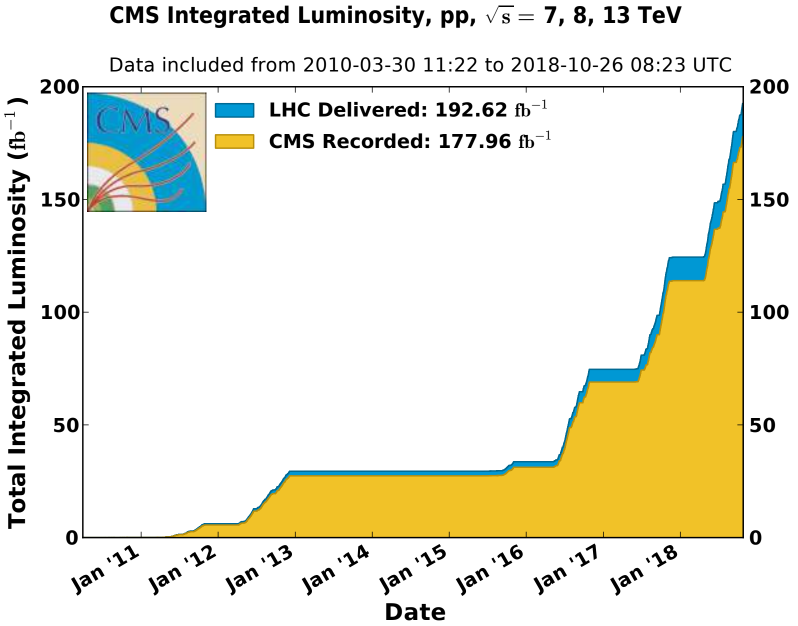
Model evolution:

spin-0 , t-channel

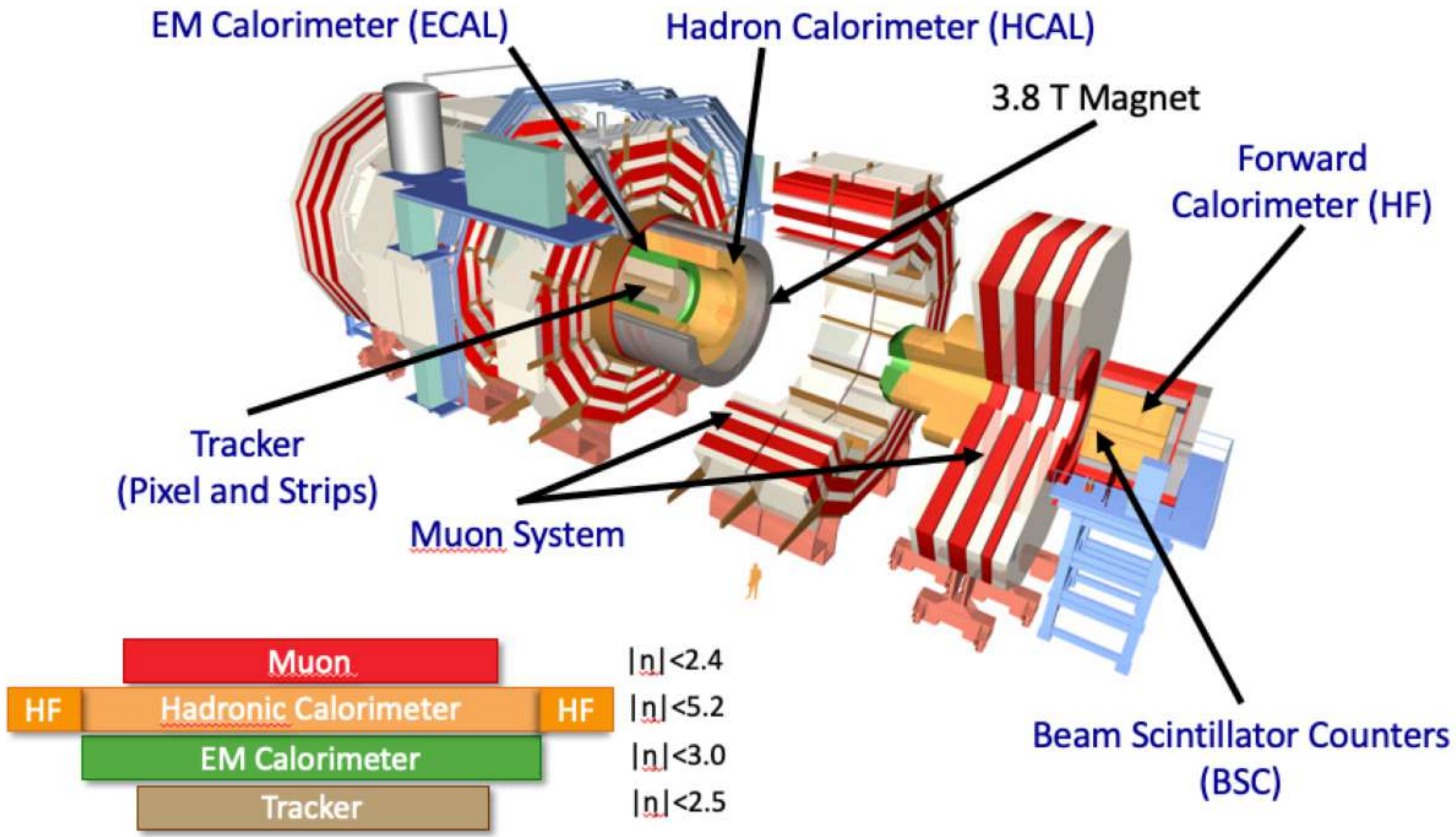
Large Hadron Collider

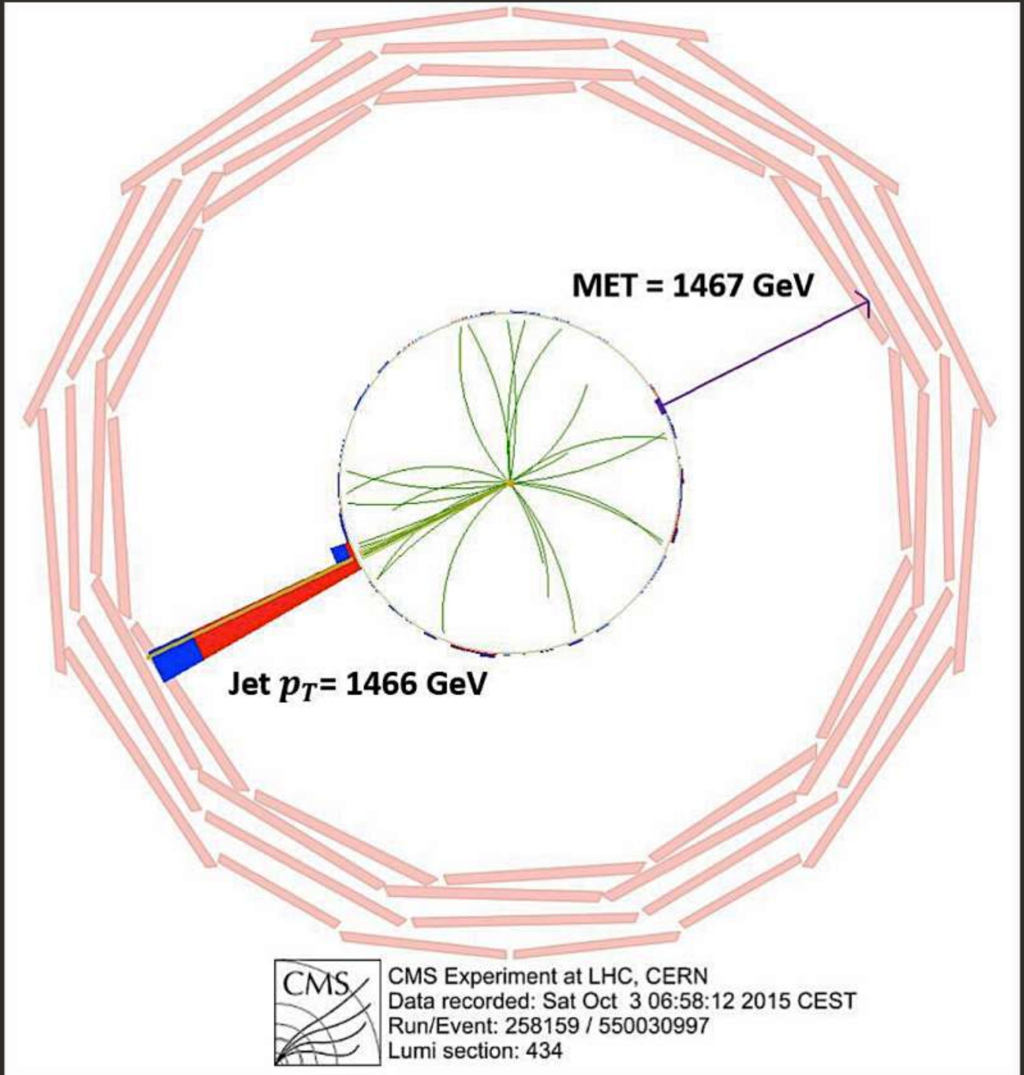
LHC: most powerful particle collider in operation

- Four large experiments: ATLAS, CMS, ALICE, LHCb
- Delivered ~150/fb of pp collisions at √s = 13 TeV to ATLAS and CMS in Run
- Also used for HI studies



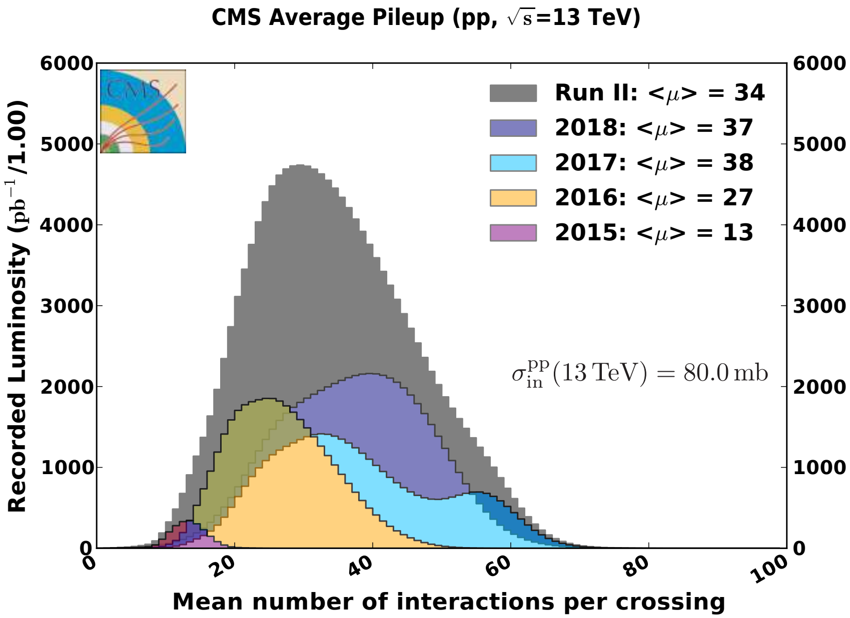
Compact Muon Solenoid

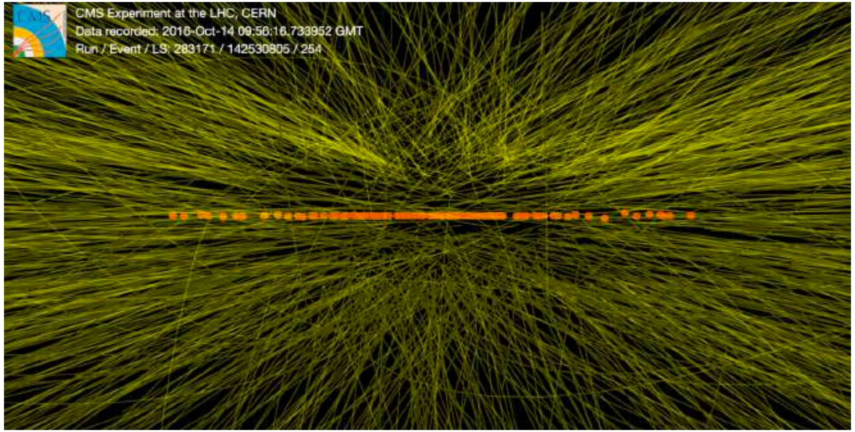




MET = 1467 GeV
Jet p_T= 1466 GeV
CMS
CMS Experiment at LHC, CERN
Data recorded: Sat Oct 3 06:58:12 2015 CEST
Run/Event: 258159 / 550030997
Lumi section: 434

LHC @ 13 TeV – A Harsh Environment



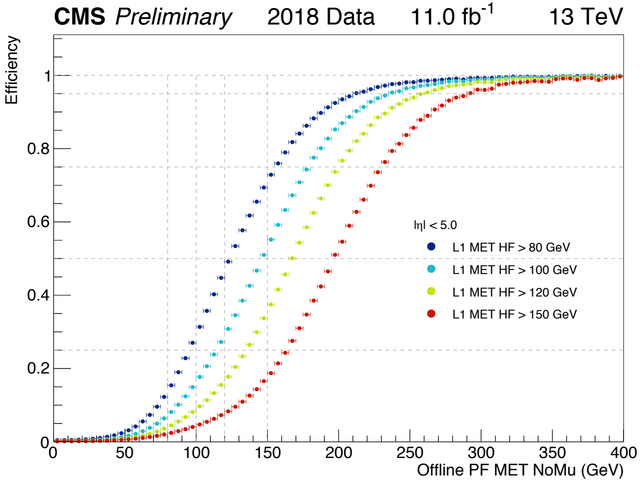


Searching for DM at Collider Experiments

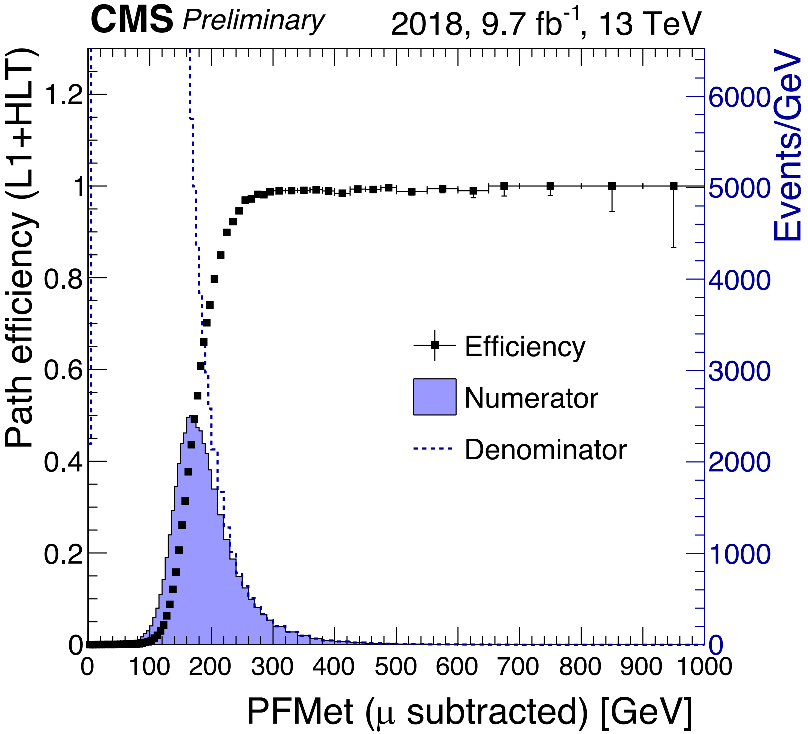
p_T^{miss} signature

Standard trigger:

- ❑ p_T^{miss}, H_T^{miss} > 120 GeV; H_T > 60 GeV
- ❑ No muons in the computation
  - Control regions

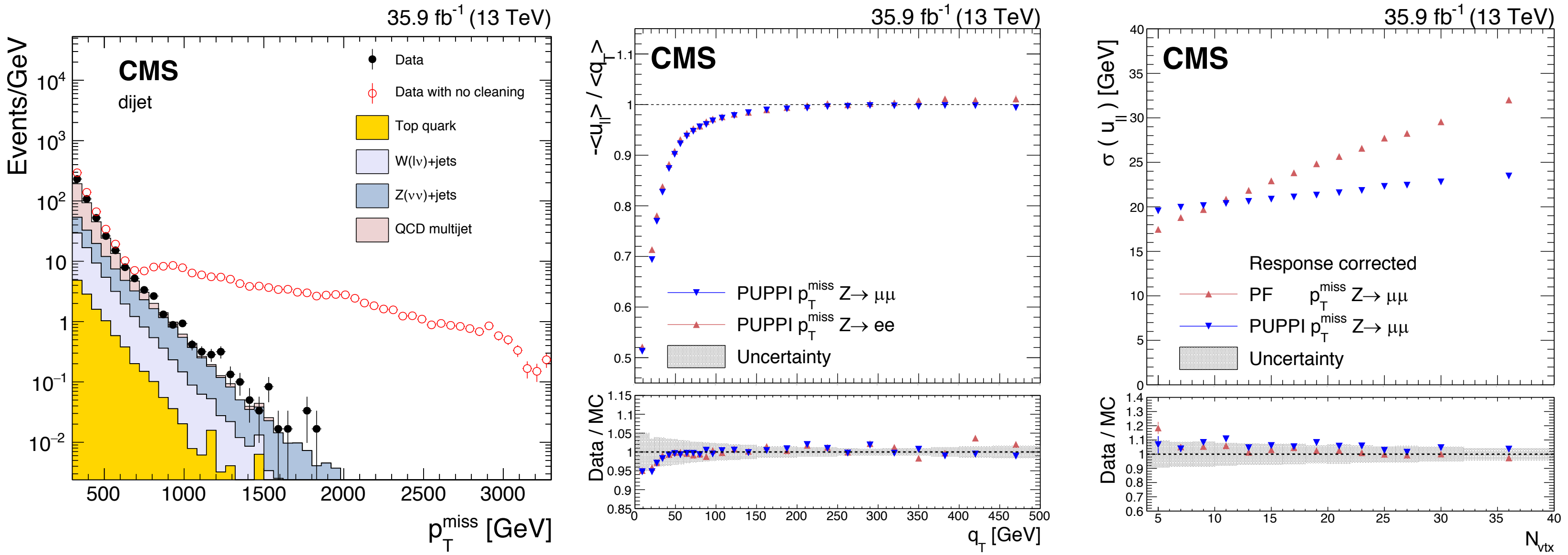


http://cds.cern.ch/record/2629372



http://cds.cern.ch/record/2631527

Missing p_T Reconstruction



Extensive cleaning needed for sensible p_T^{miss} distribution

Dominated by Z(vv) + jets at higher values

Pileup per particle identification

- ❑ Smaller pileup dependence

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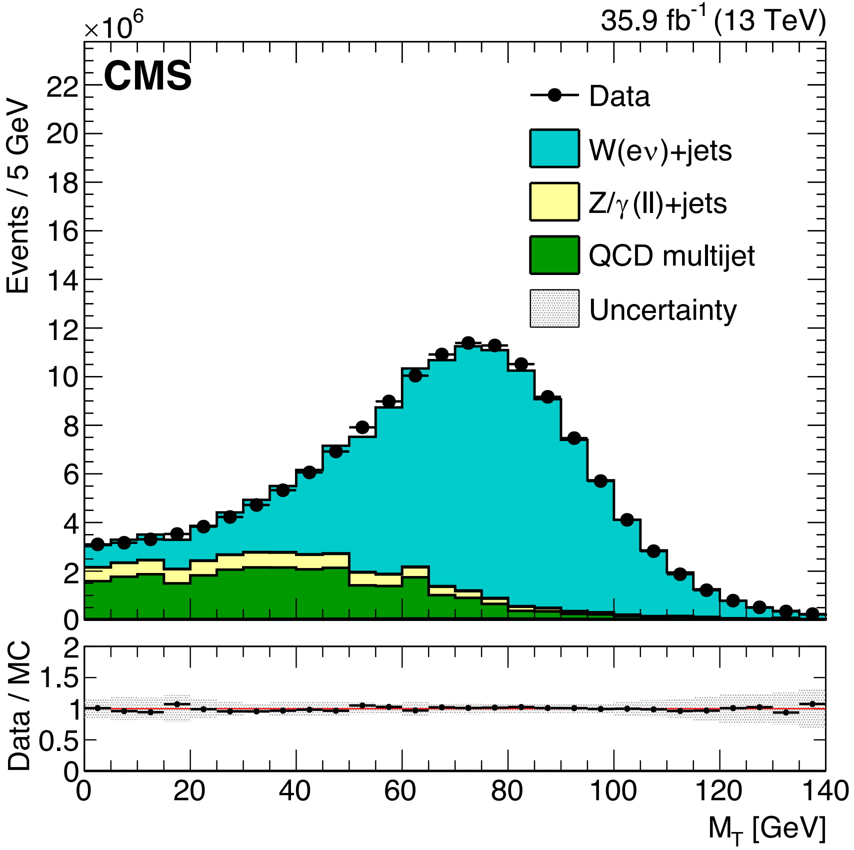
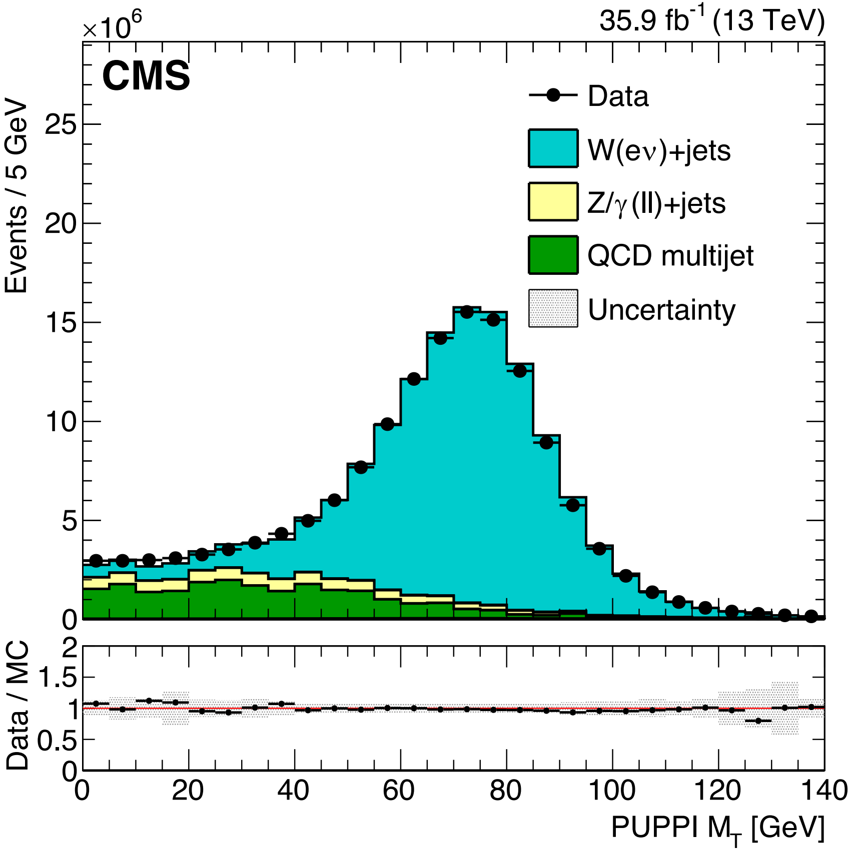


M_T with regular PF p_T^{miss}

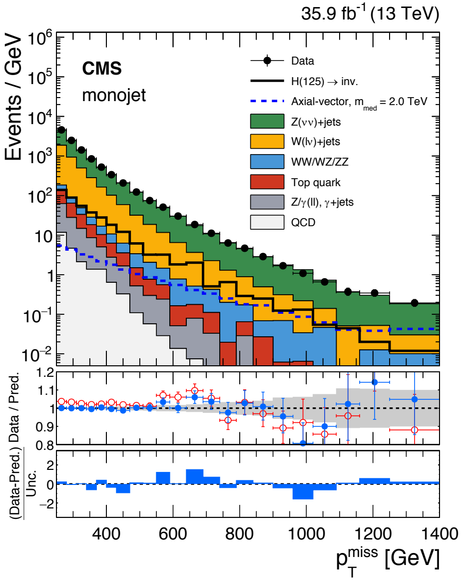


M_T with PUPPI PF p_T^{miss}

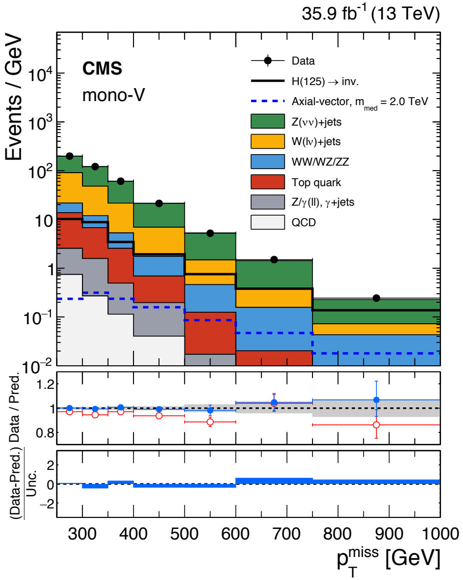
JINST 14 (2019) P07004

EXO-16-048: DM + jet (1)

Monojet

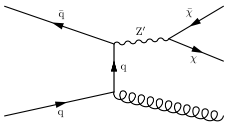


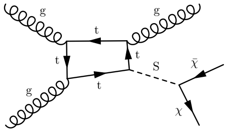
Mono-V

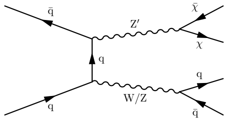


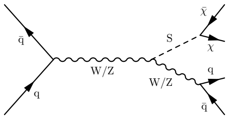
Baseline DM search analysis

- Standard trigger (no HT threshold)
- Monojet selection
  - $p_T^{miss} > 250$ GeV
  - AK4 jet, $p_T > 100$ GeV, $|\eta| < 2.4$
  - Mono-V category
    - AK8 jet, $p_T > 250$ GeV, $|\eta| < 2.4$
    - $\tau_2/\tau_1 < 0.6$
    - m_{jet} in [65, 105] GeV range
- Vetos
  - p_T^{miss} close to jet
  - B-tagged jets
  - Isolated leptons and photons
- Surviving SM backgrounds
  - Z (νν), W(lν) + jets
    - Lost lepton in the W case
- Control regions:
  - 1 & 2 ele/mu single photon









EXO-16-048: DM + jet (2)

Low p_T^{miss}

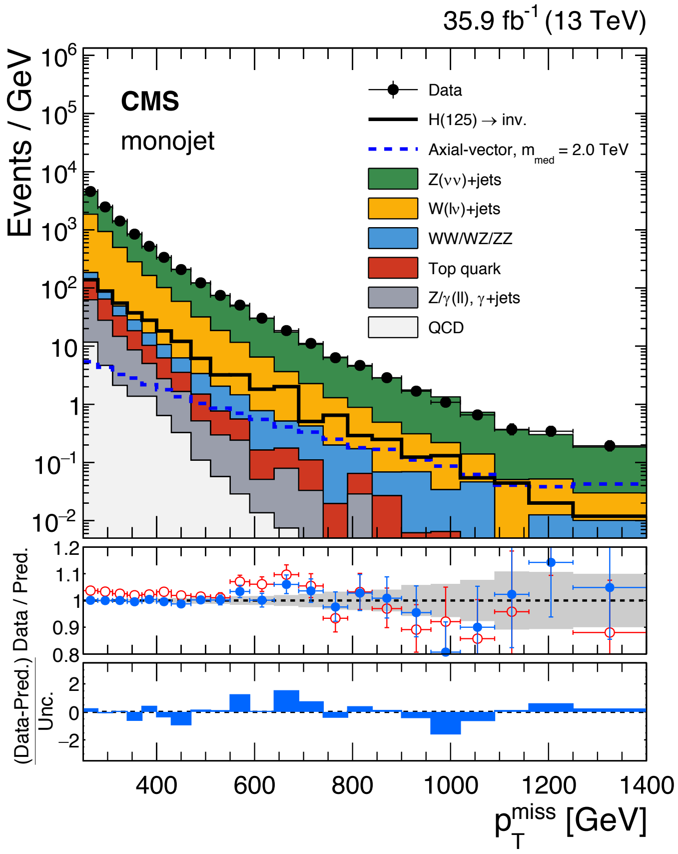
- Systematically limited
- Lots of effort to model V+jets background
- Challenge increases with pileup

High p_T^{miss}

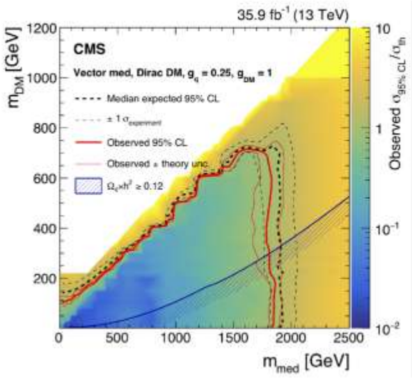
- Statistically limited
- Improve slowly with luminosity

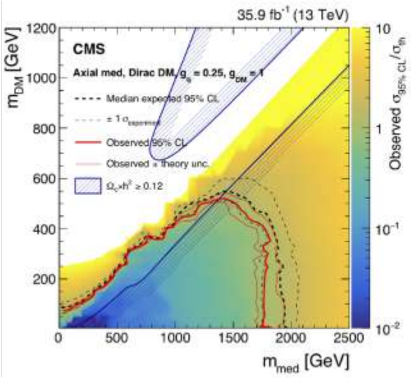
Precise predictions needed for both regimes!

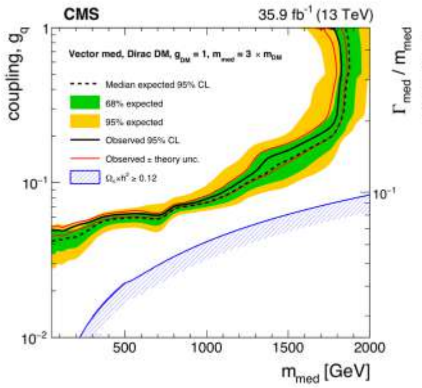
- NLO QCD + EWK: https://arxiv.org/abs/1705.04664

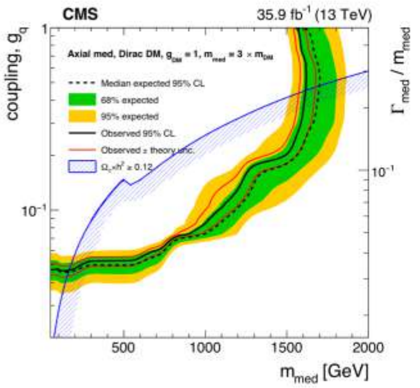


EXO-16-048: DM + jet (3)



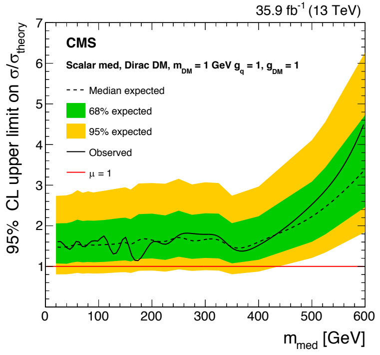




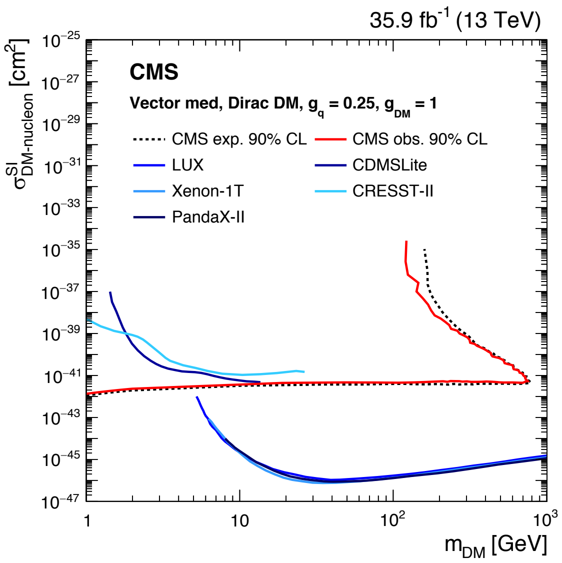


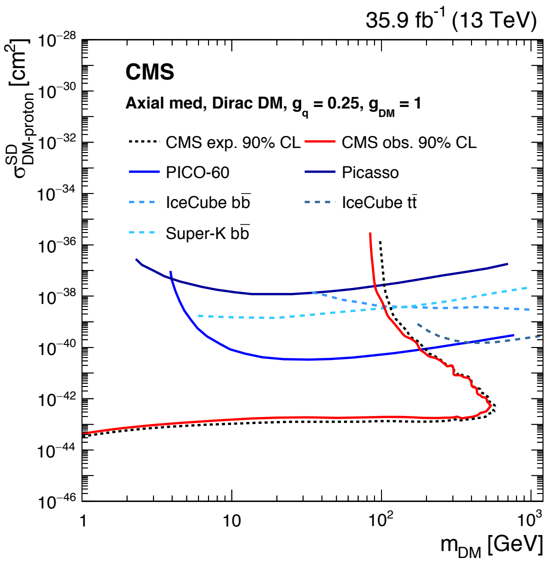
Interpretation in different planes

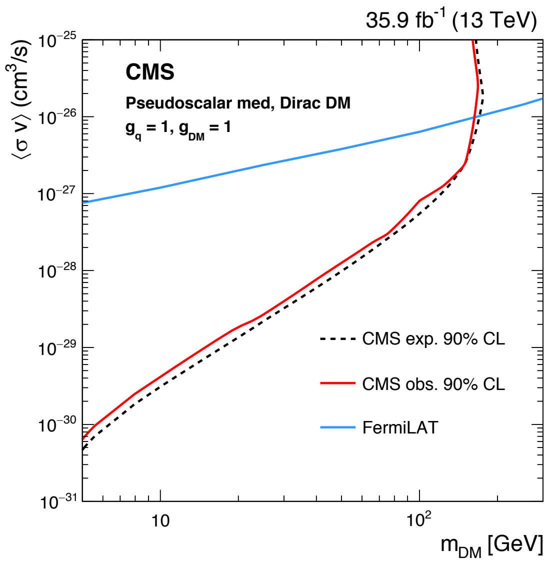
- m_{DM} x m_{med}, fixed couplings
- g_q x m_{med}, fixed m_{med}/m_{DM} ratio
- σ x m_{DM}, fixed coupling
  - Cast to σ(DM-nucleon) or <σv>



EXO-16-048: Compare with DD / ID



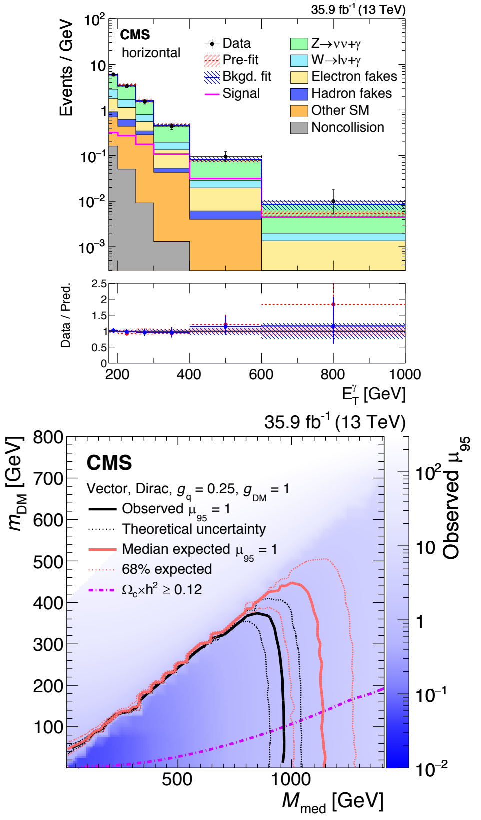




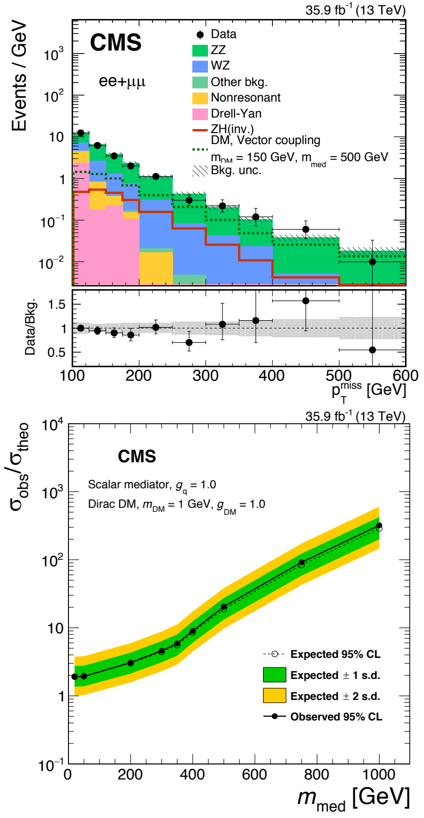
Collider search probes low-mass DM and pseudoscalar/axial mediators.

Dark Matter with …

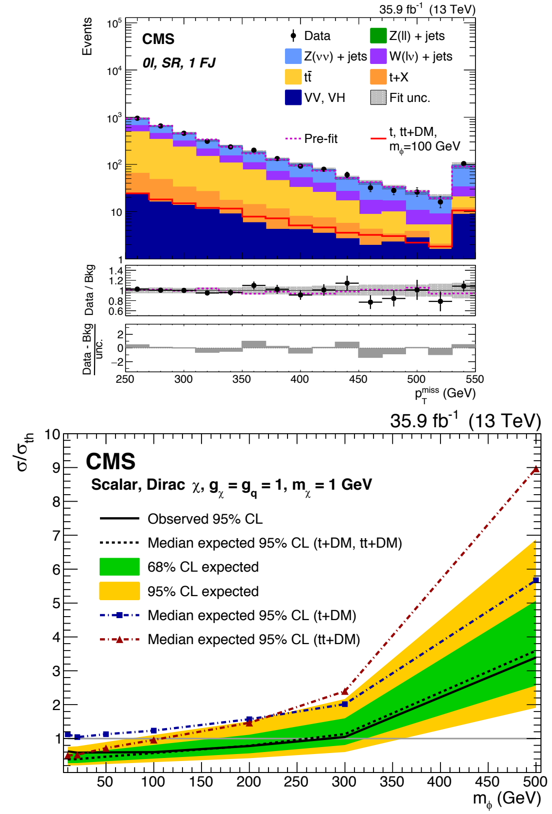
Photon



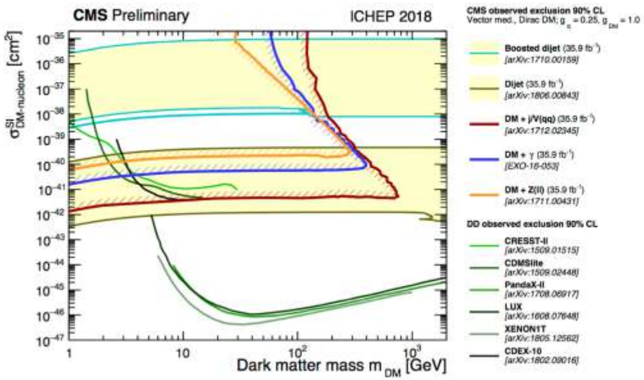
Z (ll)

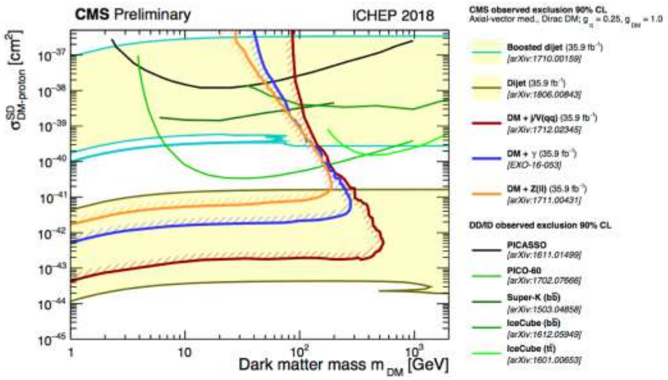


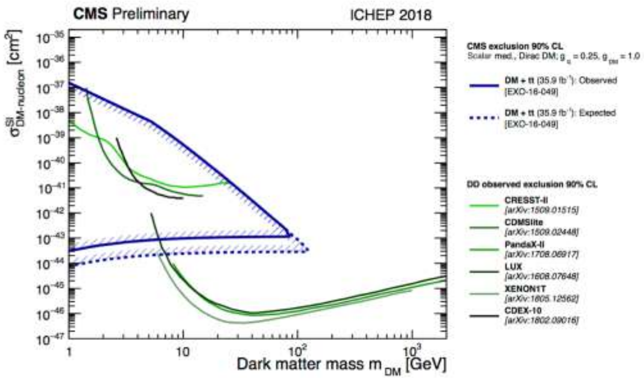
Top and ttbar

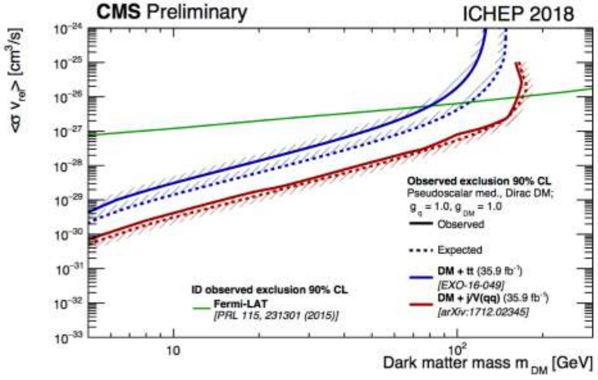


Dark Matter Summary Plots

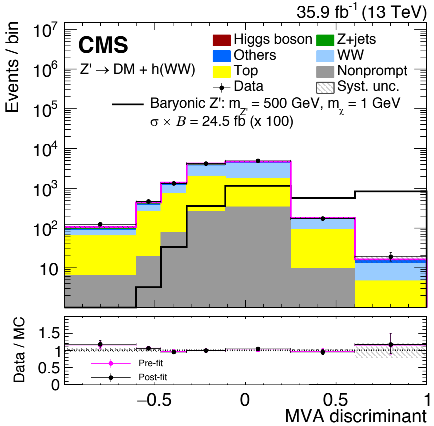


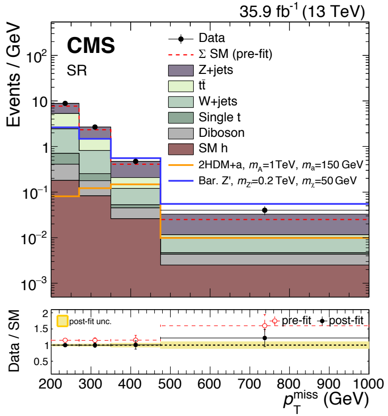






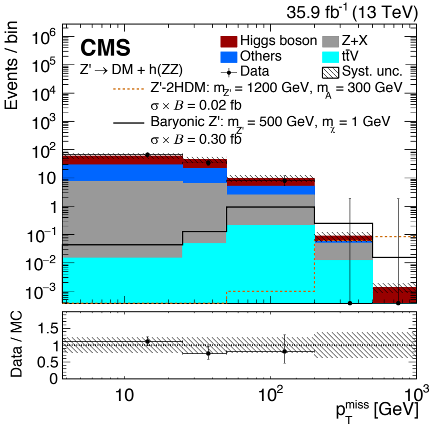
Dark Matter + Higgs Boson (1)

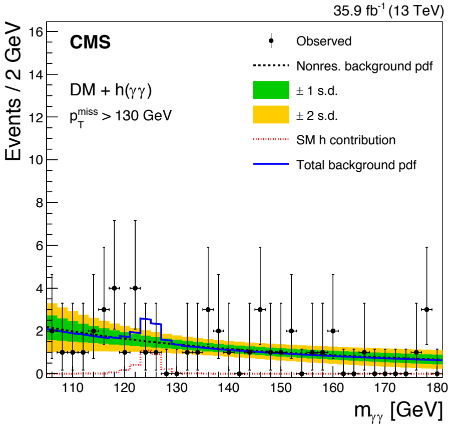


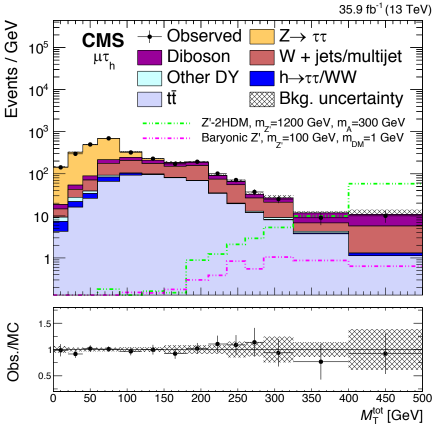


All different H decay channels

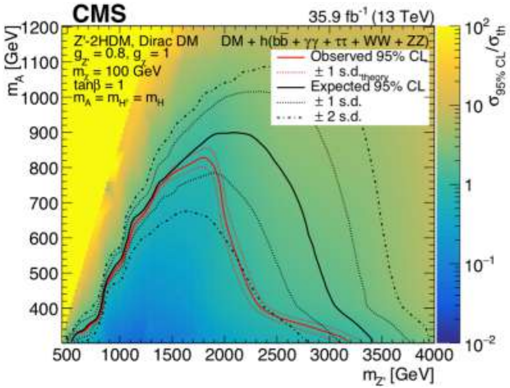
- bbbar, with AK8 and CA15 jets
- $\gamma\gamma$, in bins of p_T^{miss}
- $\tau\tau$, with both 1 and 2 τ_h
- WW and ZZ
  - WW in eνμν channel only
  - ZZ in 4e, 4μ and 2e2μ channels

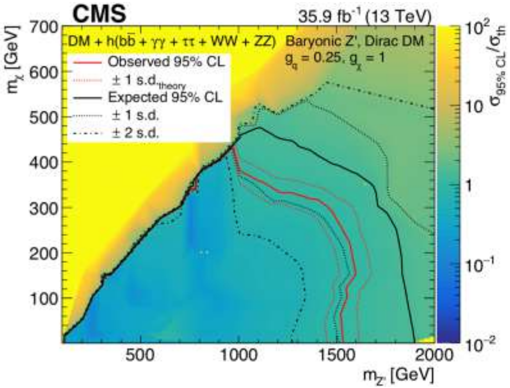


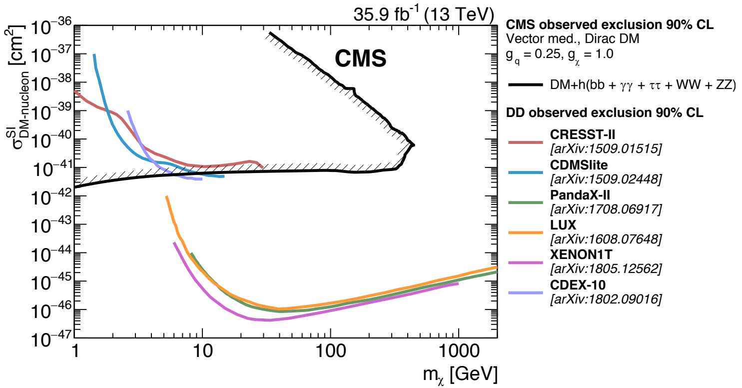




Dark Matter + Higgs Boson (2)







Interpretations in terms of different benchmark models

- Z' + 2HDM: Z' + pseudoscalar A + Dirac DM
- Baryonic Z': Z' + baryonic Higgs h_B (mixes with H)

Competitiveness with DD: m_{DM} in [1, 5] GeV range

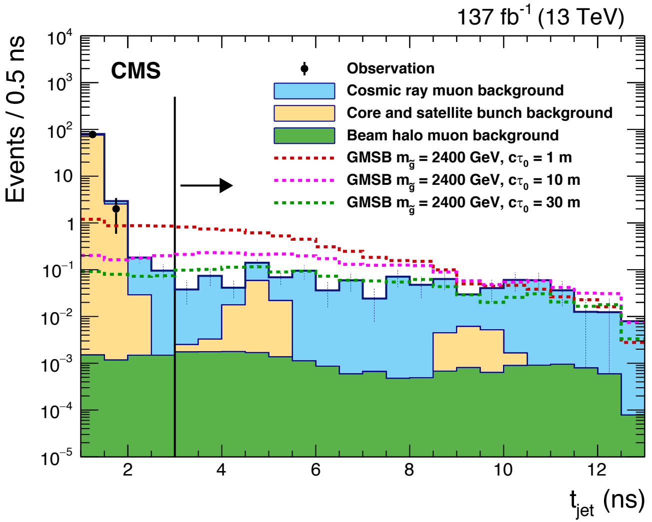
Dark Matter and Nonprompt Jets (1)

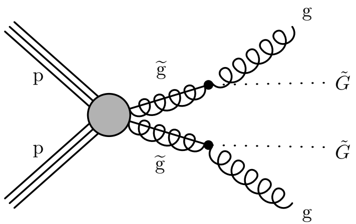
Full Run 2

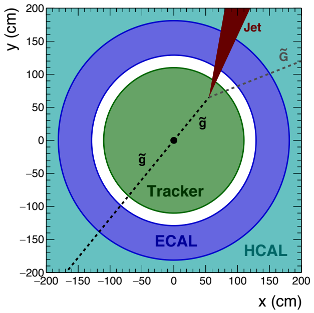
Long-lived particle decaying to DM + q/g

- ❑ Signature: displaced, nonprompt jet + p_T^{miss}
- ❑ Measure delay with ECAL timing
- ❑ Backgrounds are purely instrumental

Baseline jet selection	
$\lvert\eta\rvert < 1.48$	Barrel has better timing
$p_T > 30\,\mathrm{GeV}$	
Signal jet selection	
$E_{\mathrm{ECAL}} > 20\,\mathrm{GeV}$	
$N_{\mathrm{ECAL}}^{\mathrm{cell}} > 25$	Avoid noise and APD hits
$\mathrm{HEF} > 0.2$ and $E_{\mathrm{HCAL}} > 50\,\mathrm{GeV}$	
$t_{\mathrm{jet}}^{\mathrm{RMS}} / t_{\mathrm{jet}} < 0.4$ and $t_{\mathrm{jet}}^{\mathrm{RMS}} < 2.5\,\mathrm{ns}$	
$\mathrm{PV}_{\mathrm{track}}^{\mathrm{fraction}} < 0.08$	Avoid prompt jets and jets satellite bunches
$E_{\mathrm{ECAL}}^{\mathrm{CSC}} / E_{\mathrm{ECAL}} < 0.8$	Avoid beam halo
$t_{\mathrm{jet}} > 3\,\mathrm{ns}$	
Event level selection	
At least one signal jet	
$p_T^{\mathrm{miss}} > 300\,\mathrm{GeV}$	
Quality filters	
$\max(\Delta\phi_{\mathrm{DT}}) < \pi/2$	Avoid noise and APD hits
$\max(\Delta\phi_{\mathrm{RPC}}) < \pi/2$	







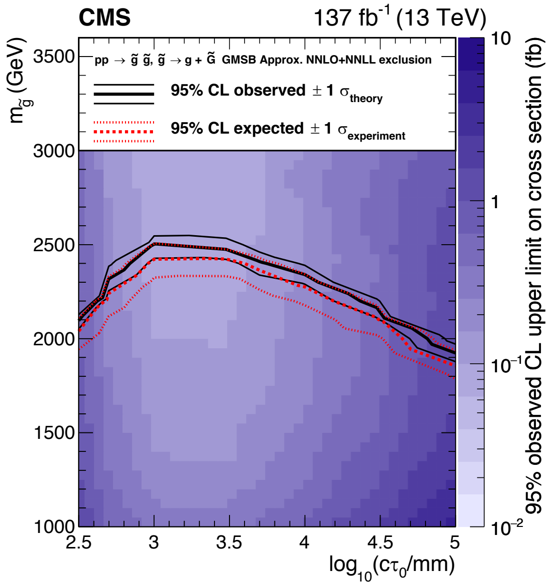
https://arxiv.org/abs/1908.02699

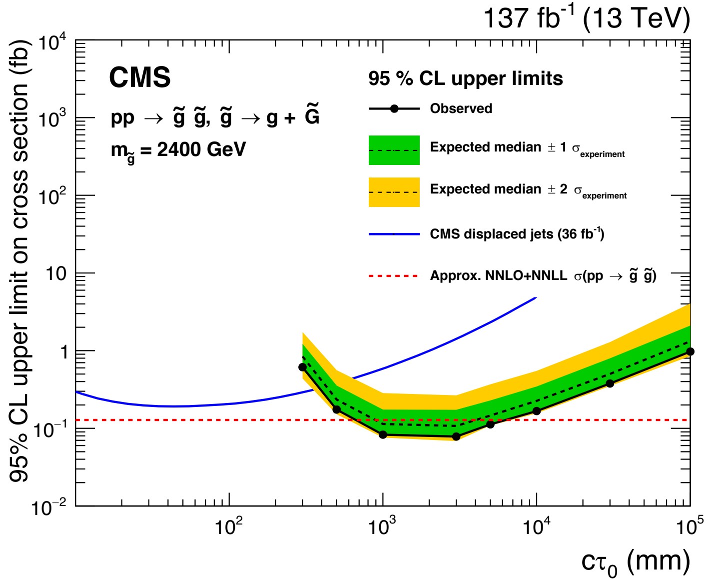
Dark Matter and Nonprompt jets (2)

Full Run 2

Interpretation in terms of GMSB model (gluino + gravitino only)

- Efficiency up to 35% for 2.4 TeV gluino, $1 < c\tau_0 < 10$m





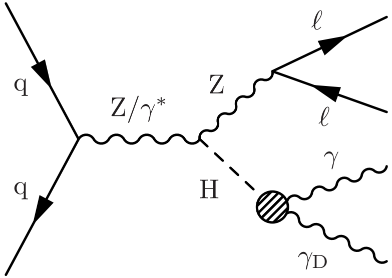
Missing p_T + Z(ll) γ

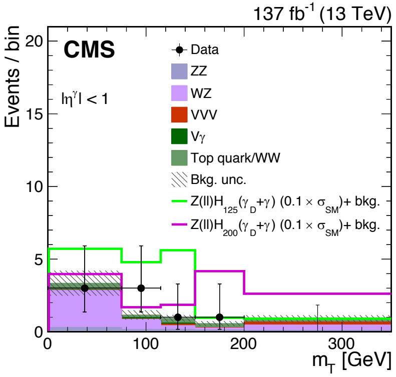
Full Run 2

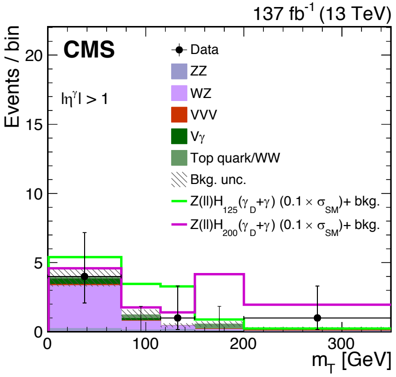
Benchmark model with massless γ_D
- New U(1) symmetry
- Dark photon X photon mixing
- Could be recast in terms of dark matter model

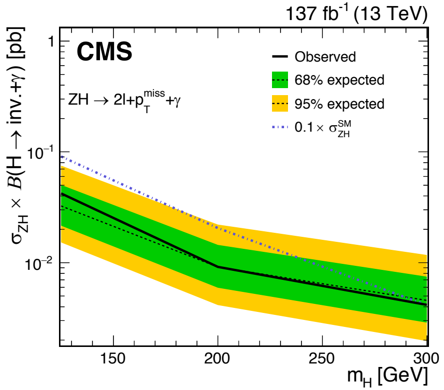
Main background is WZ
- Control regions: eμ, WZ and ZZ

Event selection
- $p_T^{miss} > 110$ GeV
- $p_T^{ll} > 60$ GeV
- $p_T^{\gamma} > 25$ GeV
- $m_{ll\gamma} > 100$ GeV
  - Reject resonant Z γ
- $m_T < 350$ GeV
  - Reject WW background





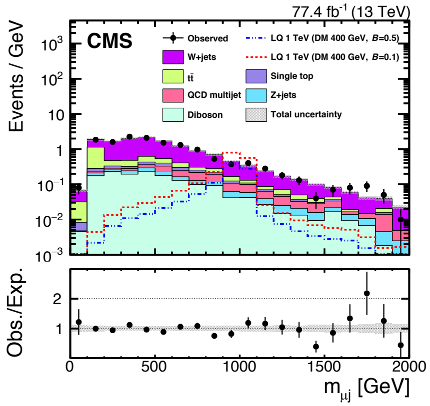


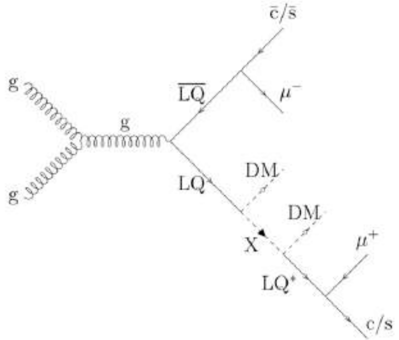


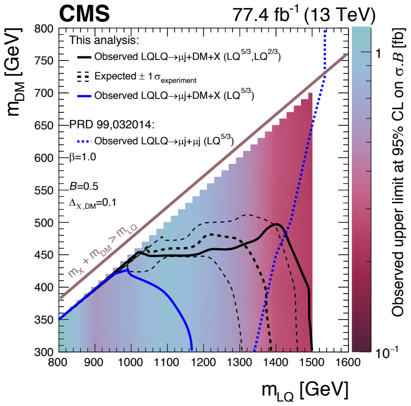
https://arxiv.org/abs/1908.02699

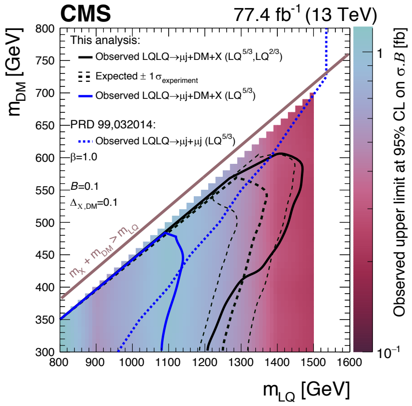
Dark Matter and Leptoquarks

2016+2017









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Benchmark model with LQ pair production

- Coannihilation paradigm – Naker at al. (2015)
- LQ → c(s) + μ, LQ → DM + X

Search in $m_{\mu j}$ distribution

- p_T (jet), p_T^{miss} > 100 GeV
- p_T (μ) > 60 GeV
- m_T > 500 GeV
- Veto b-jets, e, τ_h
- Main backgrounds: inclusive W and ttbar production

Dependency on B(LQ -> c(s) + μ)

Conclusions…

The quest for dark matter is one of the next goals of the LHC

- Complementarity between collider and direct and indirect detection

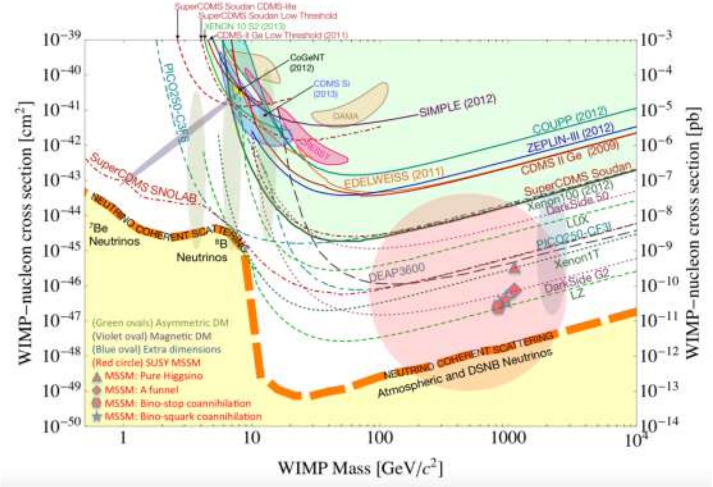
The LHC DM WG: guidelines and recommendations

- Benchmark models
- LHC results together with other experiments
- Comparison with visible mediator searches

CMS is well underway on its analysis of the Run 2 data

- Different channels considered
- Techniques under continuous refinement
- Reinterpretations and new ideas

… and Outlook



LHC Run 3 will bring ~ additional 150/fb.

HL-LHC in the horizon…

- … with all the challenges of PU 200.

Direct detection experiments reaching the neutrino floor soon.

Exciting times ahead!

Thank You!