Physics beyond the Standard Model 2

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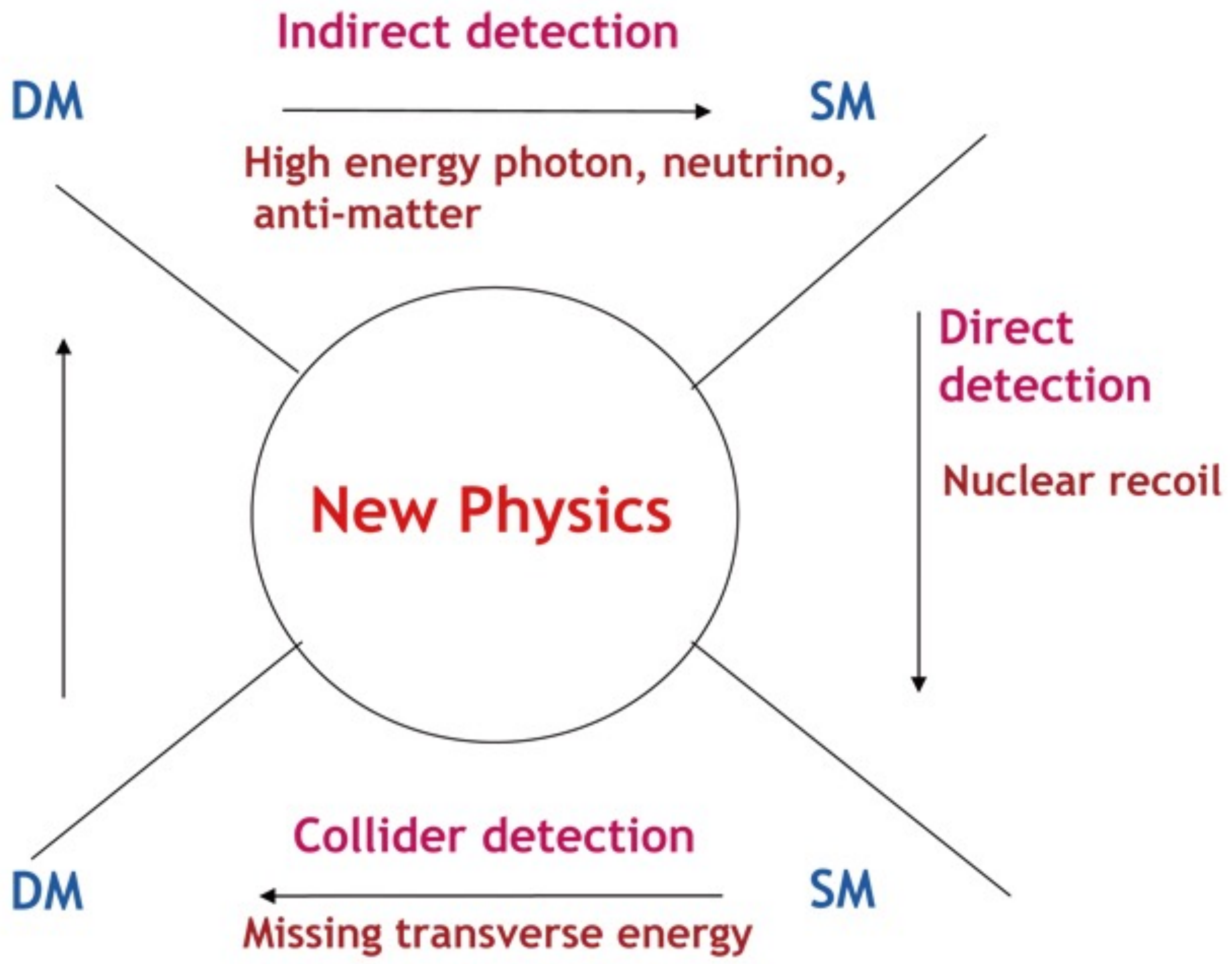
Caveat

Stolen most of my slides from Kerstin Perez, Zhili Weng and others.

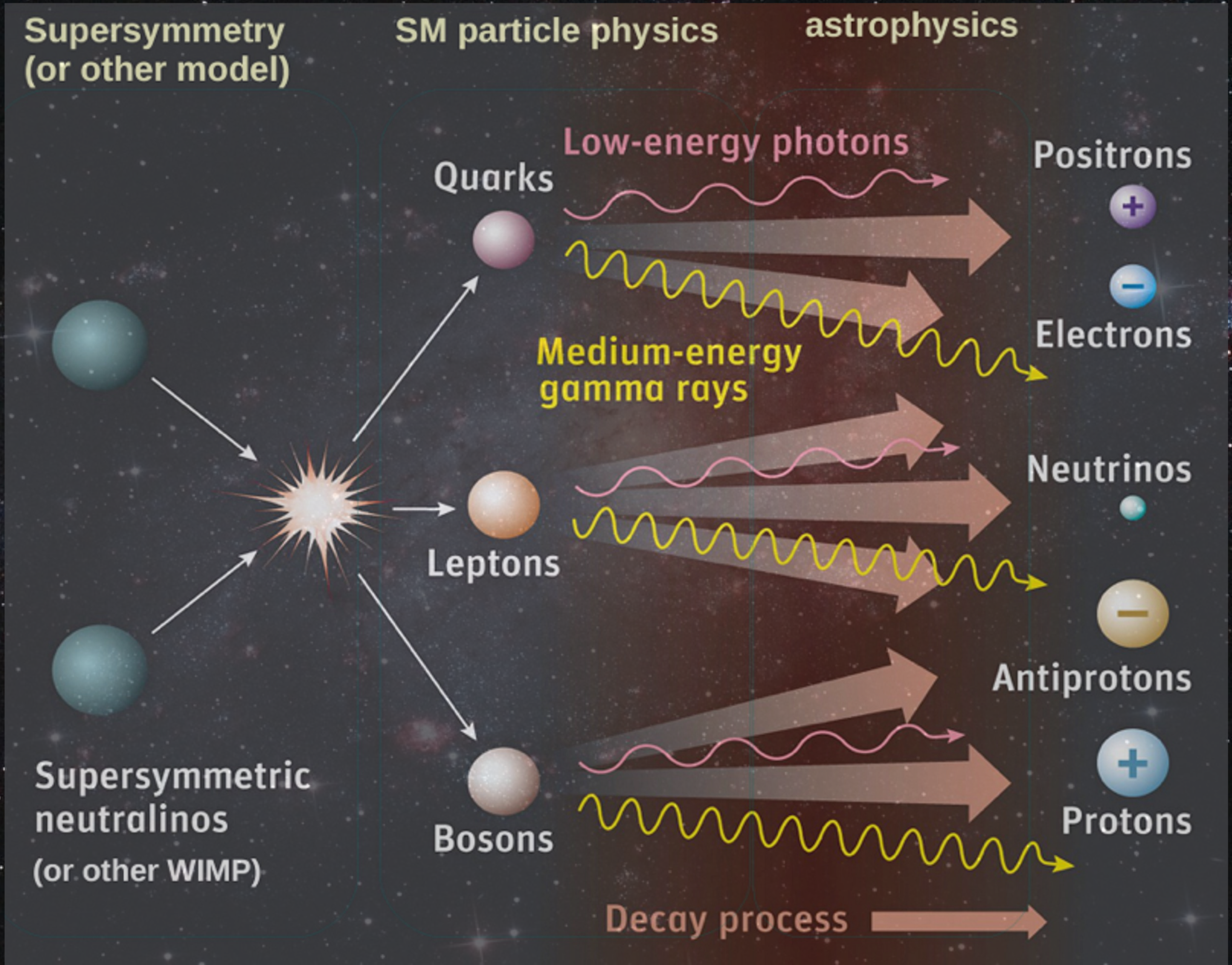
Dark Matter Searches

3 complementary Dark Matter search strategies



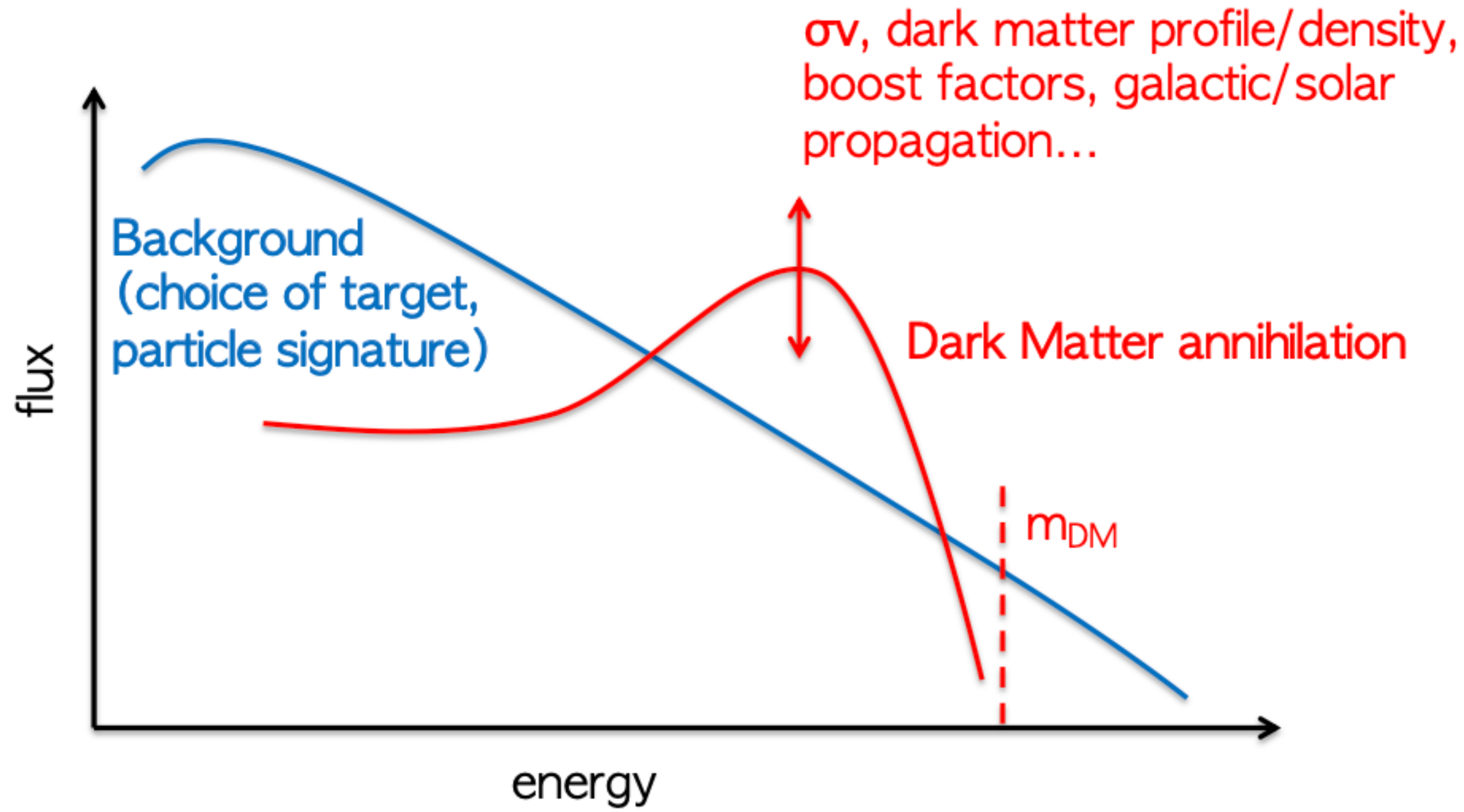
CHANG-SEONG MOON (KNU)

The sky as a laboratory



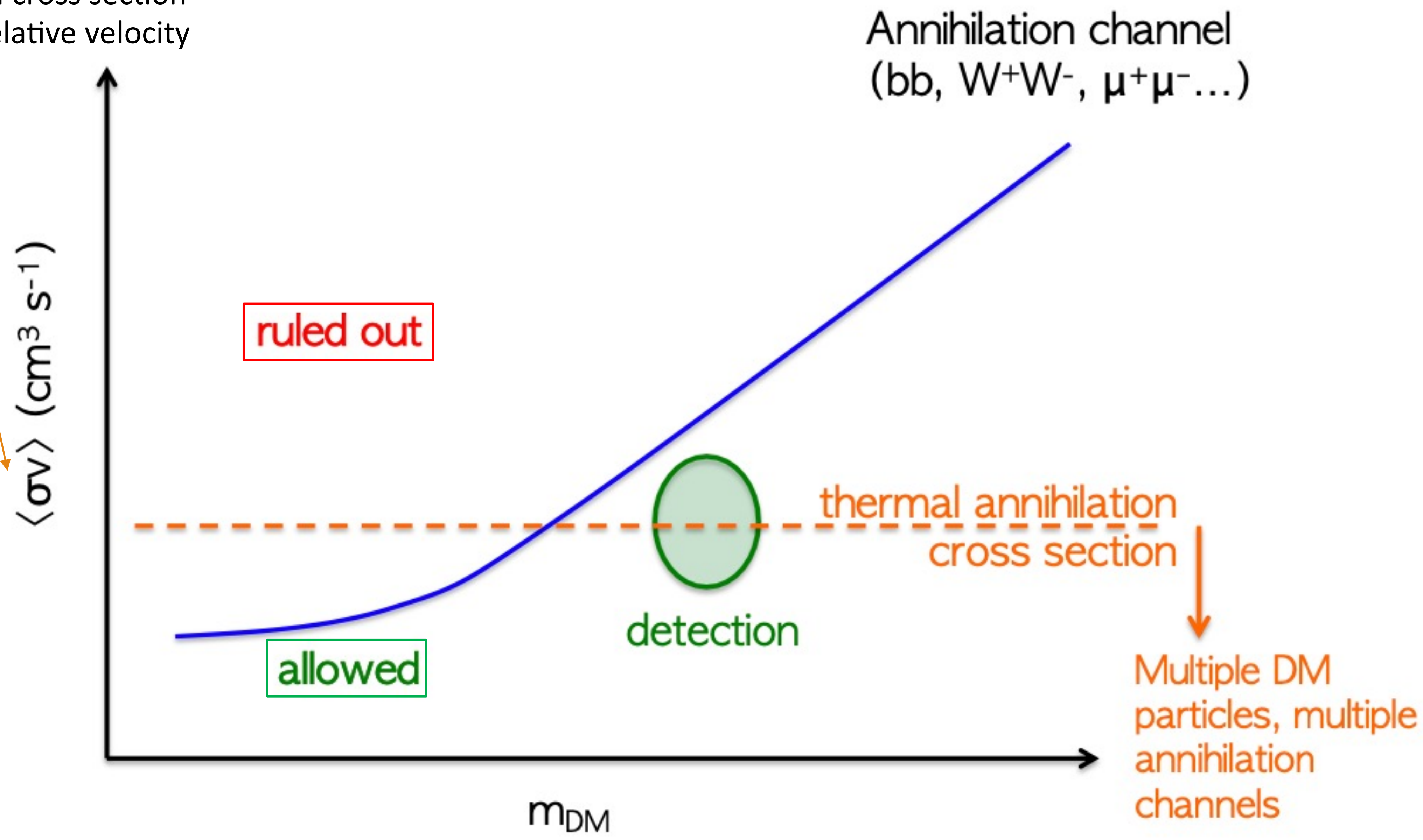
The challenge of astroparticle searches

Common challenge = minimize/constrain astrophysical background, maximize predicted dark matter signal



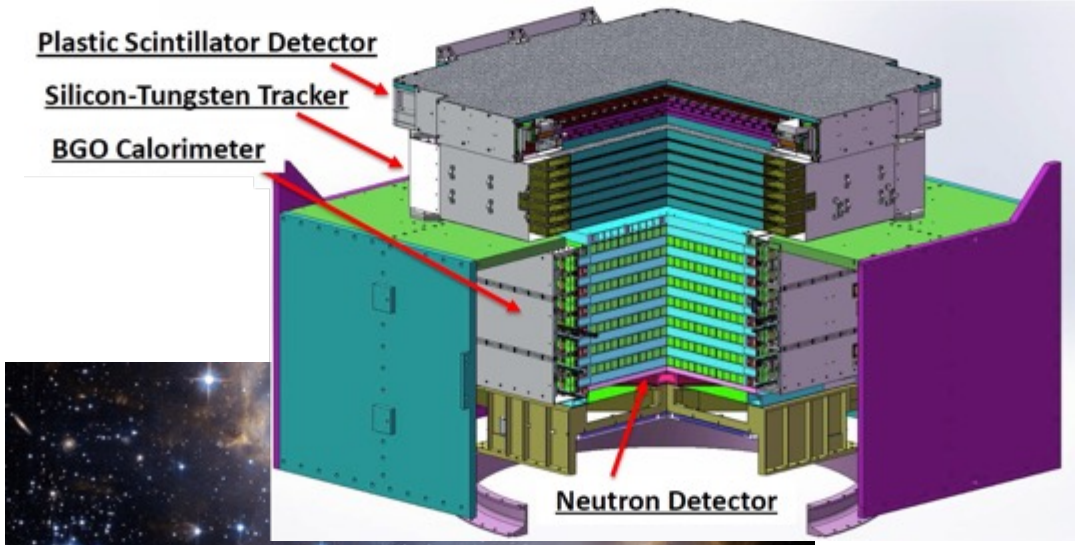
Typical Dark Matter search result

Annihilation cross section
times the relative velocity

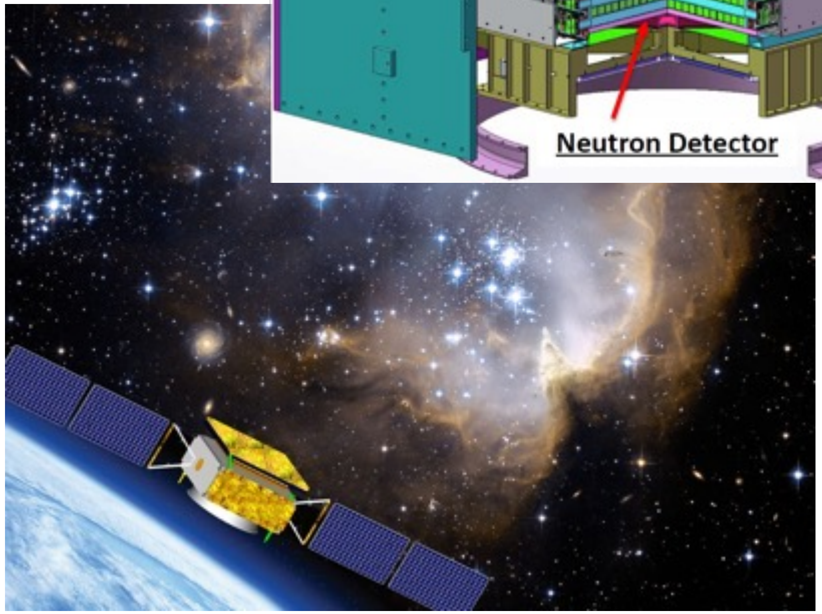


The Dark Matter Particle Explorer (DAMPE)

- Launched into a Sun-synchronous orbit at an altitude of about 500 km on 17 Dec 2015
- High-energy particle detector optimized for studies of CREs and γ-rays up to about 10 TeV
- The DAMPE instrument
  - from top to bottom, consists of a plastic scintillator detector, a silicon–tungsten tracker-converter detector, a bismuth germanium oxide (BGO) imaging calorimeter, and a neutron detector

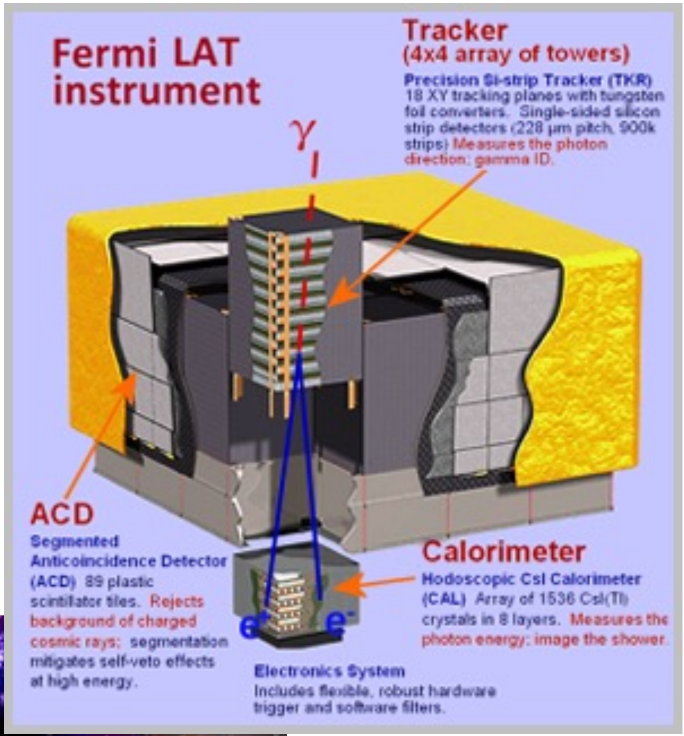


- Detection by the DAMPE space telescope
  - High energy gamma rays, electrons and cosmic ray ions to aid in the search for dark matter
  - Designed to look for the indirect decay signal of a hypothetical dark matter candidate called weakly interacting massive particles (WIMP).

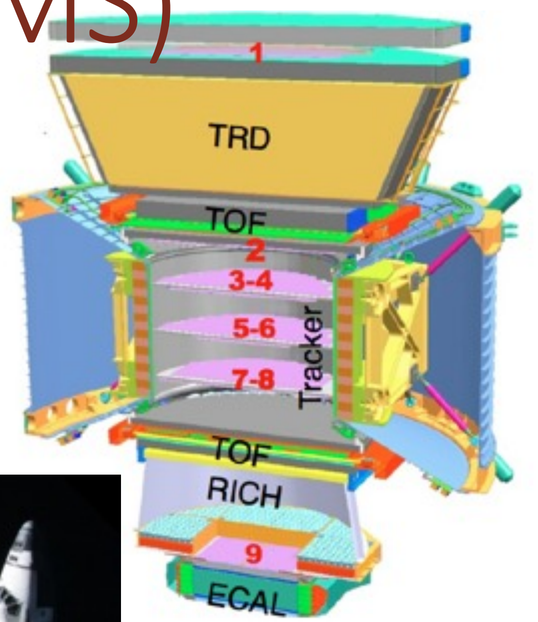


The Fermi Gamma-ray Space Telescope (GLAST)

- Fermi includes two scientific instruments
  - The Large Area Telescope (LAT)
  - The Gamma-ray Burst Monitor (GBM).
- High-energy world to exploration and helping us answer these questions.
  - Study how black holes, notorious for pulling matter in, can accelerate jets of gas outward at fantastic speeds.
  - Study subatomic particles at energies far greater than those seen in ground-based particle accelerators.
  - Gaining valuable information about the birth and early evolution of the Universe.

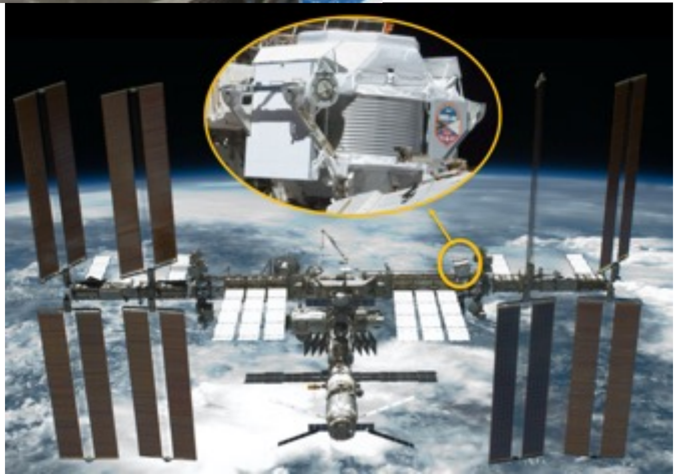


The Alpha Magnetic Spectrometer (AMS)

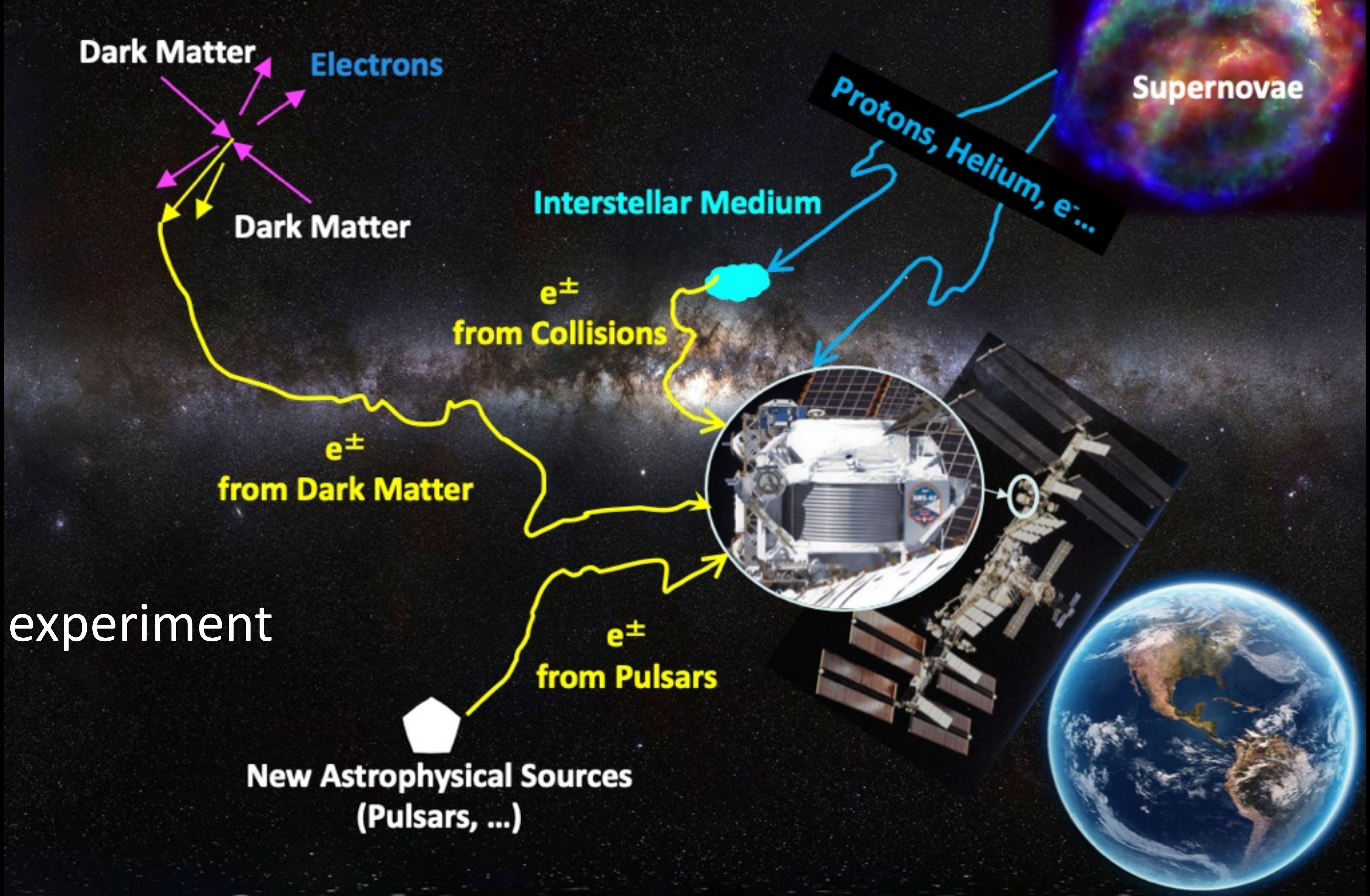


- AMS is a particle physics experiment module that is mounted on the International Space Station (ISS)
- The experiment is a recognized CERN experiment (RE1)
- The module is a detector that measures antimatter in cosmic rays
  - This information is needed to understand the formation of the Universe and search for evidence of dark matter.

우주 정거장(ISS)

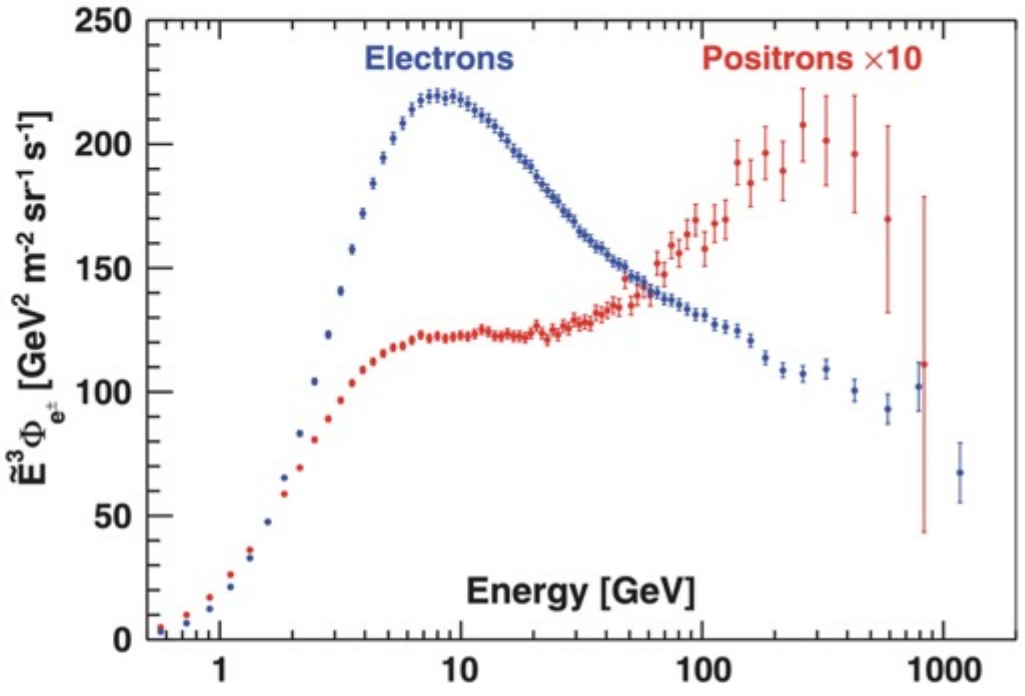


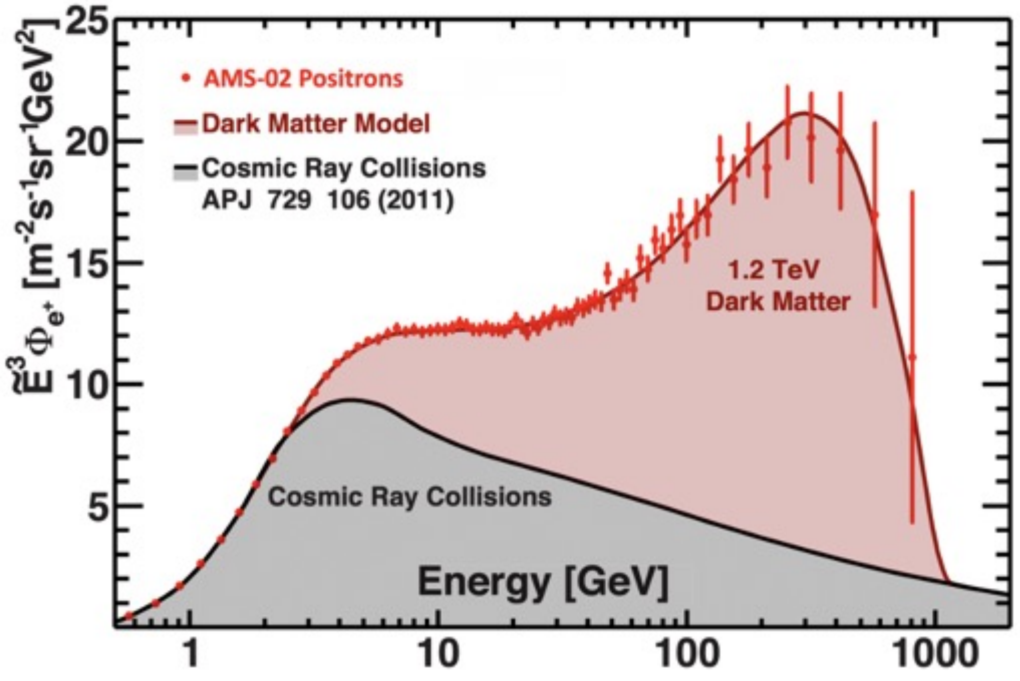
What is the Origin of Cosmic Positrons and Electrons?



AMS experiment

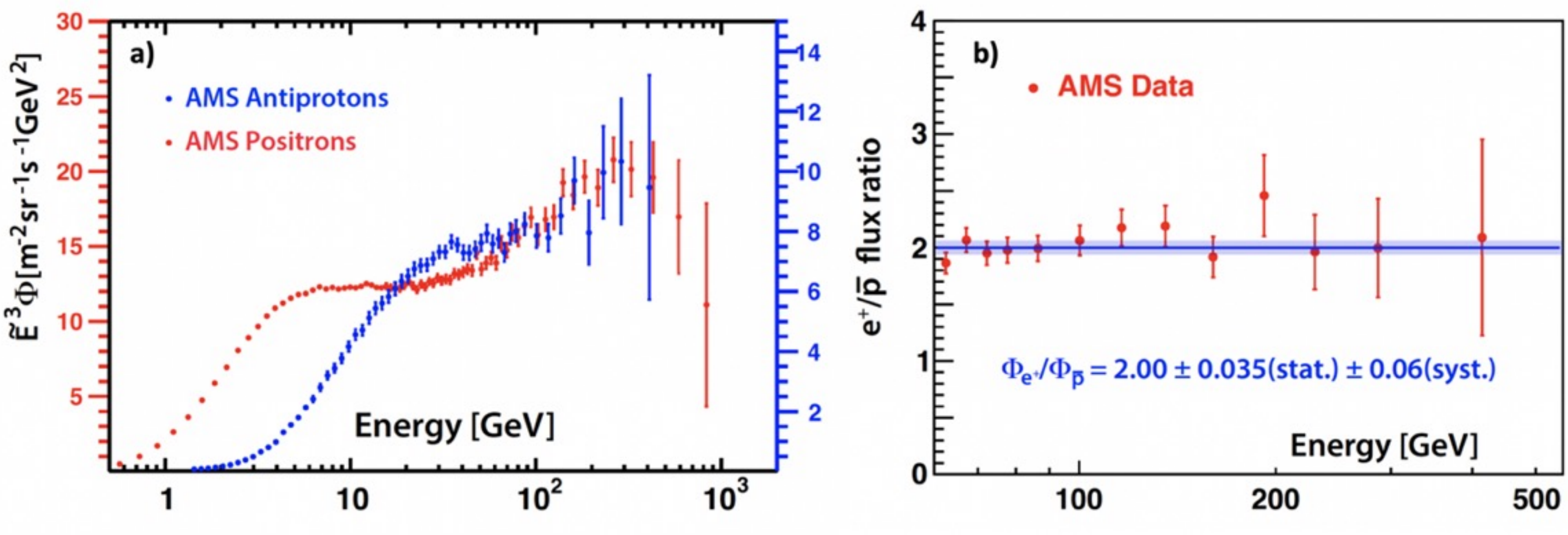
Origins of Cosmic Positrons and Electrons





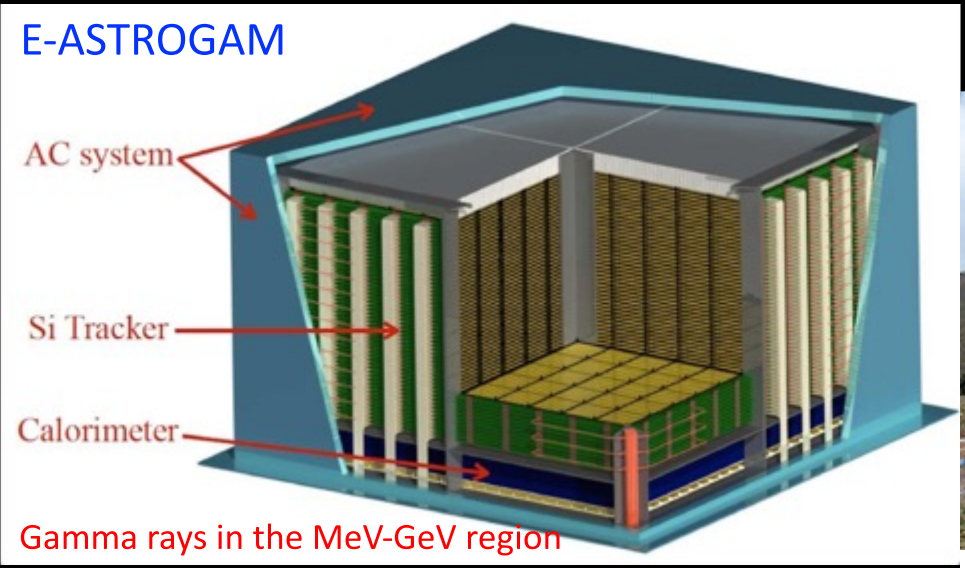
- The AMS positron spectrum (red data points) and electron spectrum (blue data points). The electron spectrum and the positron spectrum have distinctly different magnitudes and energy dependences.
- Comparison of the AMS data with predictions of a dark matter model. More statistics at high energies are required to verify the agreement and to understand the behavior of the positron spectrum beyond the cutoff energy.

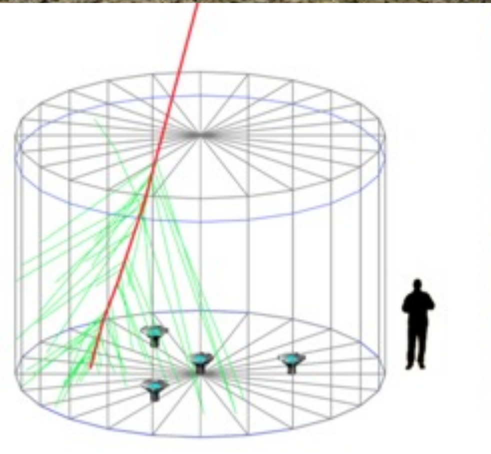
Origins of Cosmic Positrons and Electrons



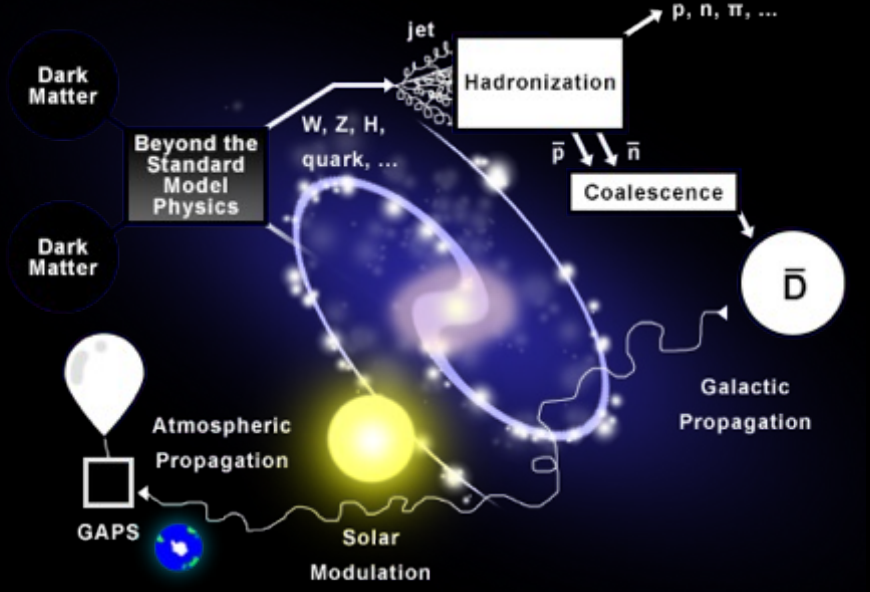
- Comparison of the AMS positron spectrum ($\tilde{E}^3_{e+}\Phi_{e+}$, red data points, left axis) and antiproton spectrum ($\tilde{E}^3_{e+}\Phi_{\bar{p}}$, blue data points, right axis). They exhibit striking similarity at high energy.
- The positron-to-antiproton flux ratio in the range [60 – 525] GeV with the result of the fit with a constant value.

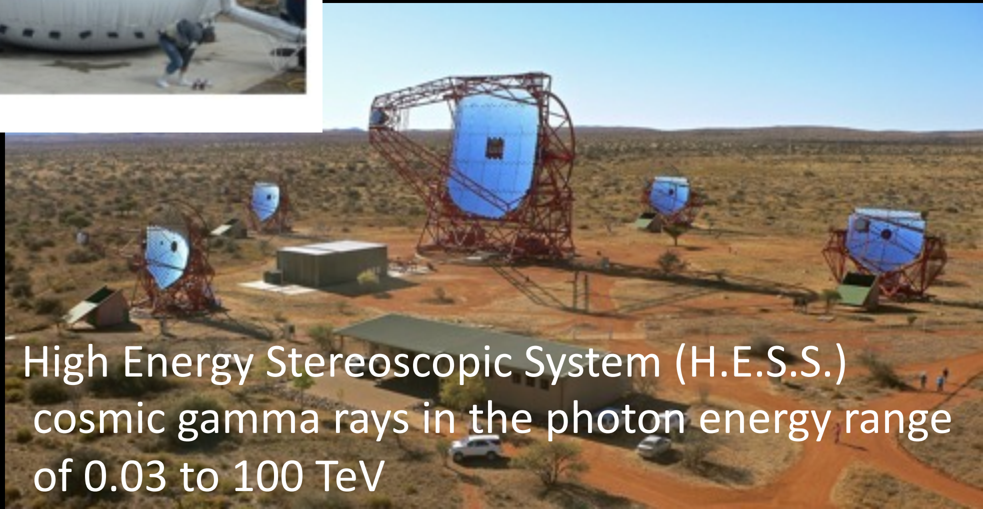
More experiments for Dark Matter Searches





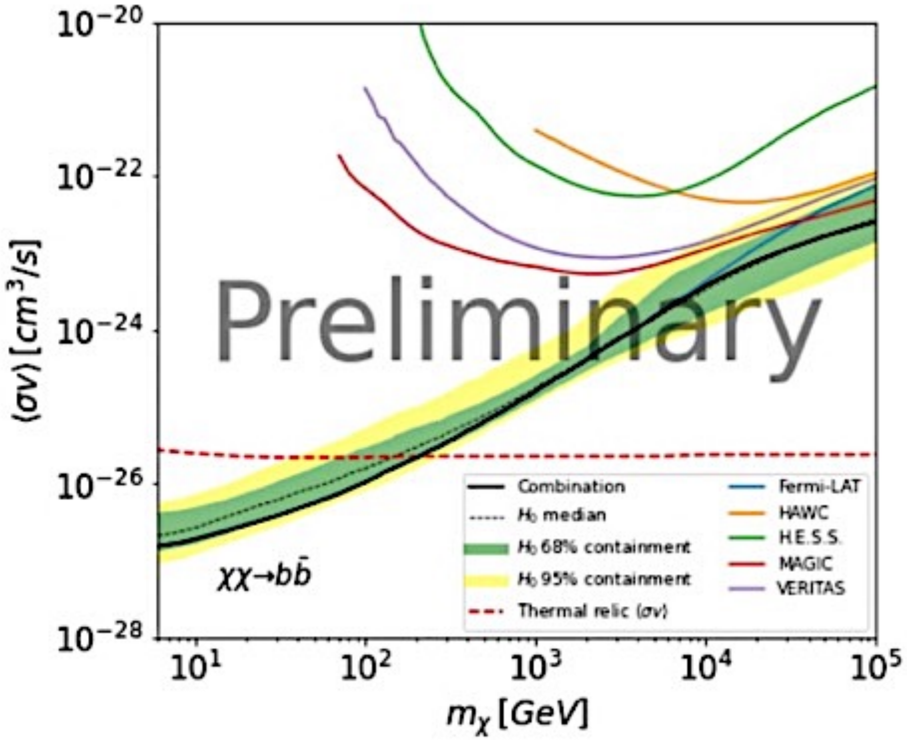
GAPS (General AntiParticle Spectrometer)
Antarctic balloon mission searching for low-energy (< 0.25 GeV/n) cosmic-ray antinuclei





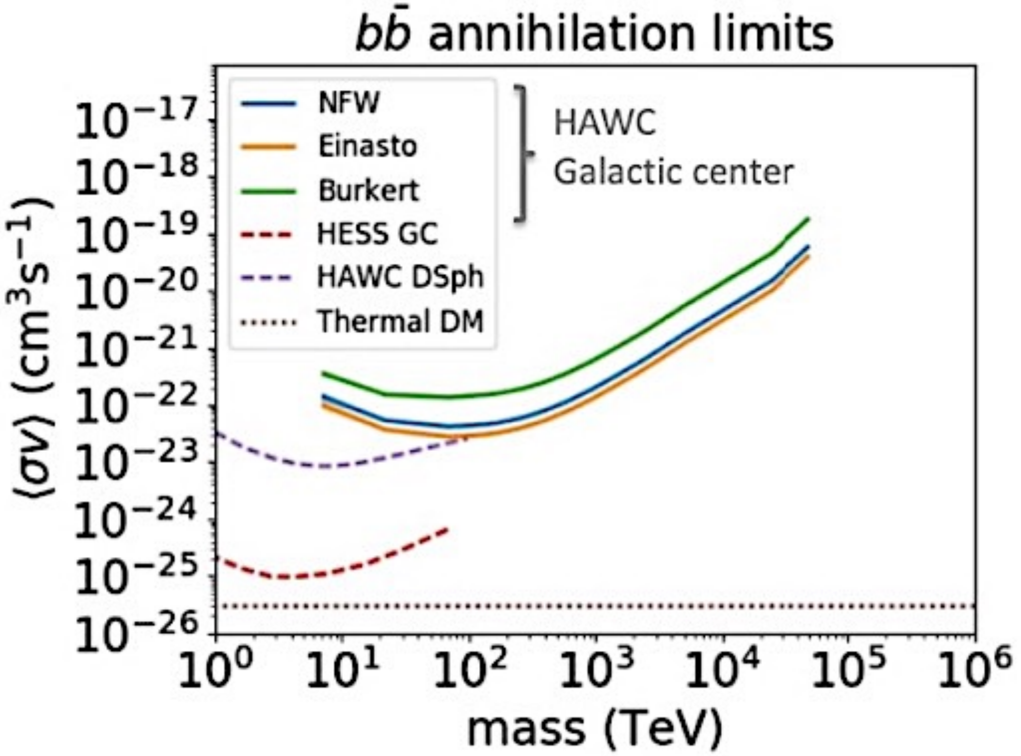
Gamma-rays: non-detection limits

Armand+ (ICRC 2021) 2108.13646



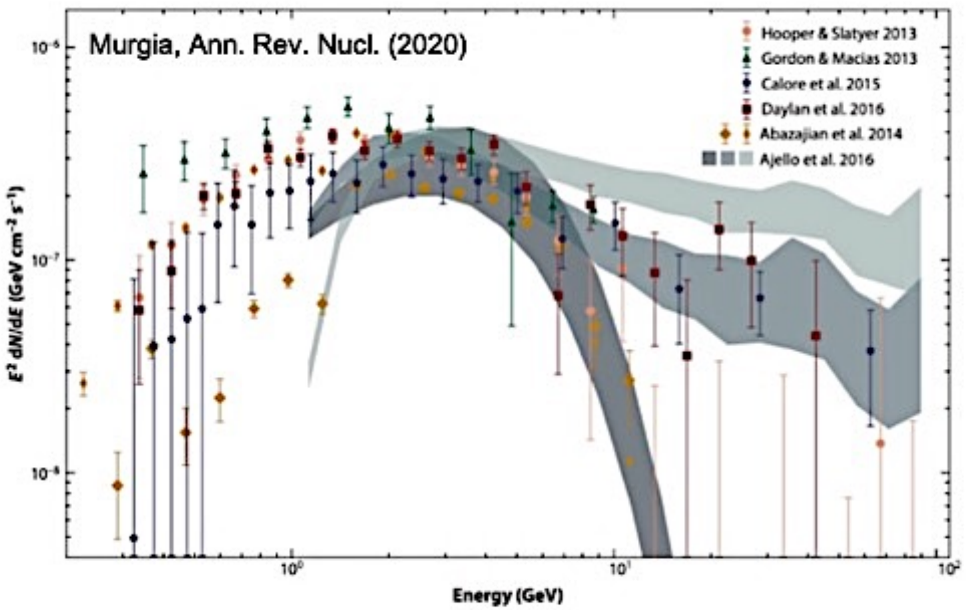
Fermi-LAT, HAWC, H.E.S.S., MAGIC, VERITAS observations of **dwarf spheroidal galaxies** give leading constraints from ~1-100s of GeV gamma-rays

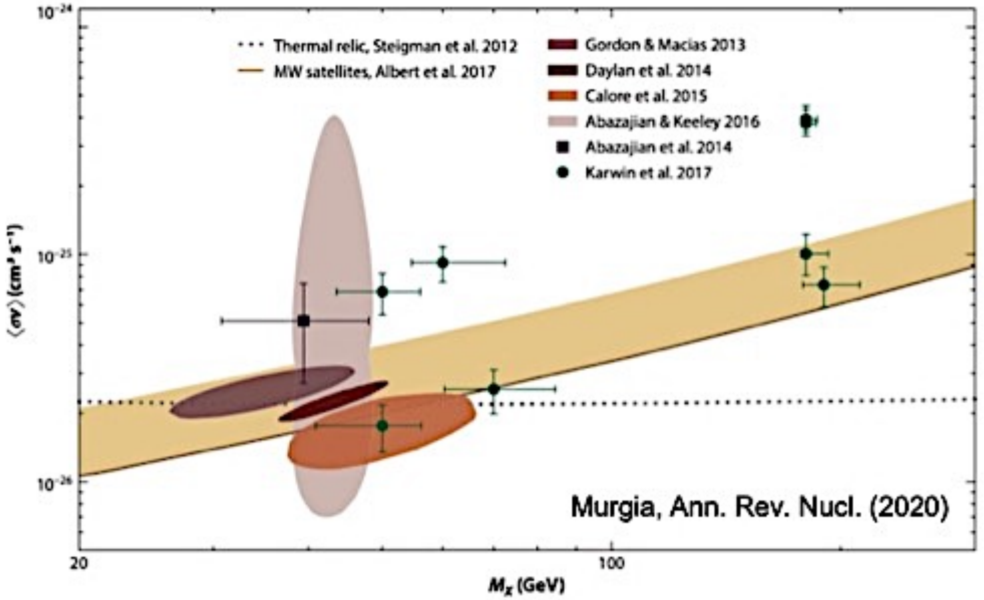
A.Abeseykara+ (2018) 1710.10288



HAWC and HESS observations of our **Galactic center** give leading constraints from TeV gamma-rays

The Galactic Center “GeV excess”





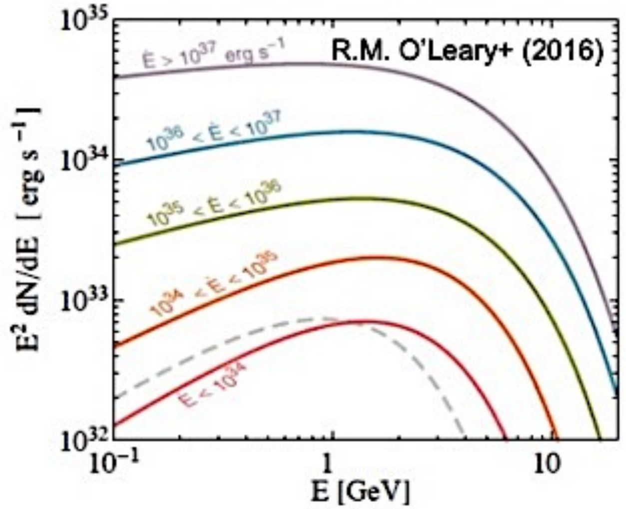
- An excess of gamma-rays at the Galactic Center, with **spectrum, morphology, intensity consistent with annihilating dark matter**

e.g. Hooper, Linden (2011), Abazajian, Kaplinghat (2012), Gordon, Macias (2013), Daylan, et al. (2014), Calore, Cholis, Weniger (2014), Murgia, et al. (2015), Ackermann et al. (2017), Cholis et al. (2021)ç

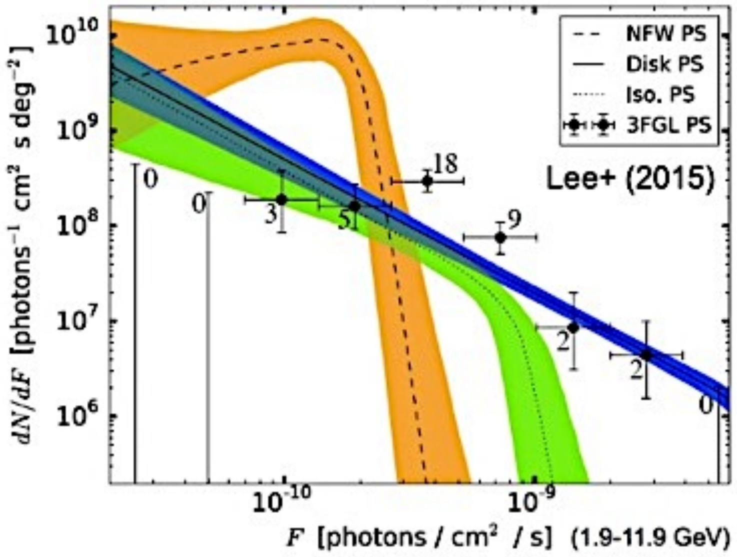
- Consistent with non-detection limits from dwarf galaxies, considering uncertainties due to Galactic and dwarf halo profiles, astrophysical background modeling

e.g. Agrawal+ 1411.2592, Karwin+ 1612.05687, Hayashi+ 1603.08046, Klop+ 1609.03509, Abazajian+ 1510.06424, Benito+ 1612.02010, Linden 1905.11992, Ando+ 2002.11956

The Galactic Center "GeV excess"



- Spectrum also consistent with **millisecond pulsars (MSPs)**
- Could indicates a population of pulsars with a luminosity function and binary progenitor population quite different from those in the Milky Way disk or globular clusters
- **Statistical methods: population of faint sources shows more hot/cold pixels than a flat dark matter signal**

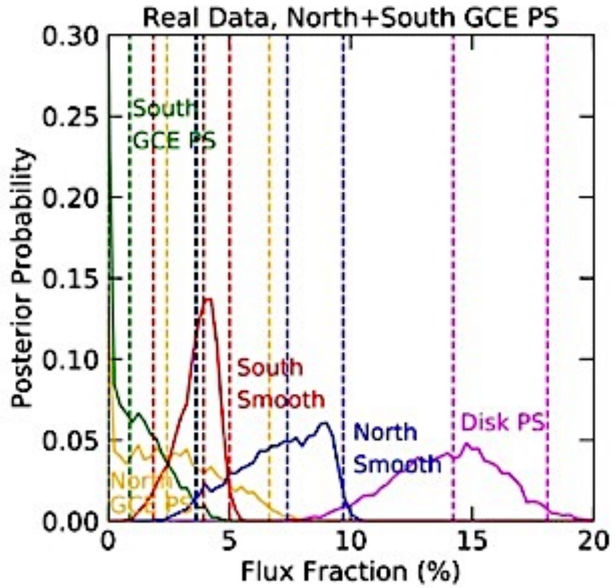


← Full excess can be due unresolved point sources

Lee+ (2015) 1506.05124
Bartels+ (2015) 1506.05104
Buschmann+ (2020) 2002.12373

Allowing north-south asymmetry renews possible DM component→

Leane, Slatyer (2019) 1904.08430
Leane, Slatyer (2020) 2002.12371

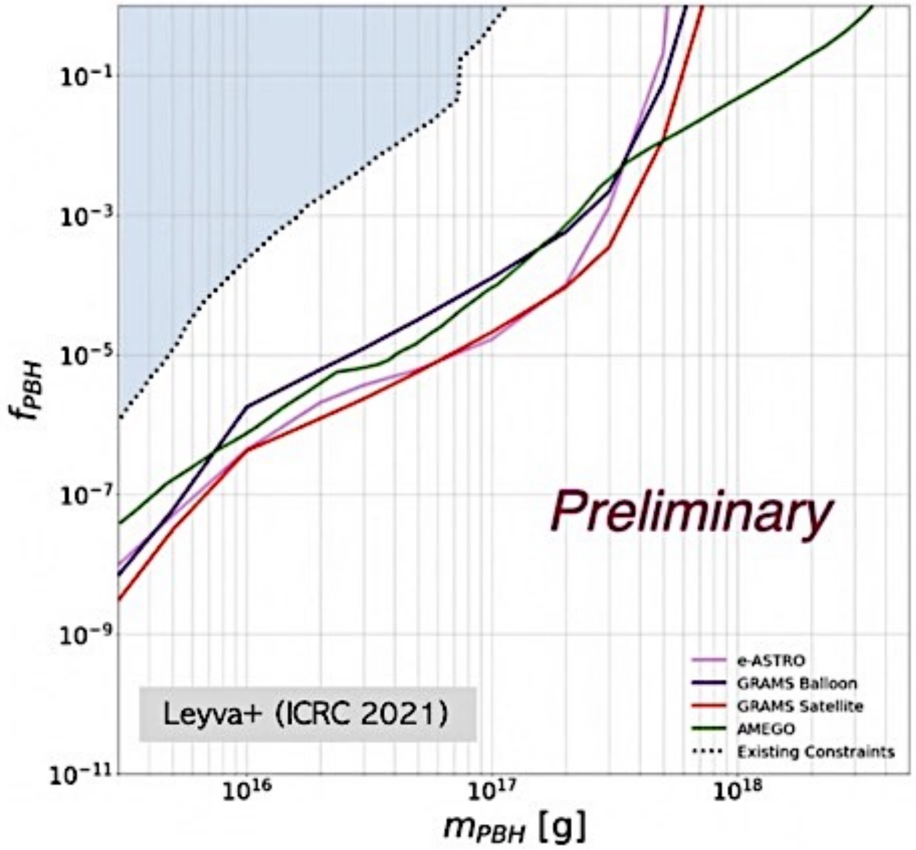


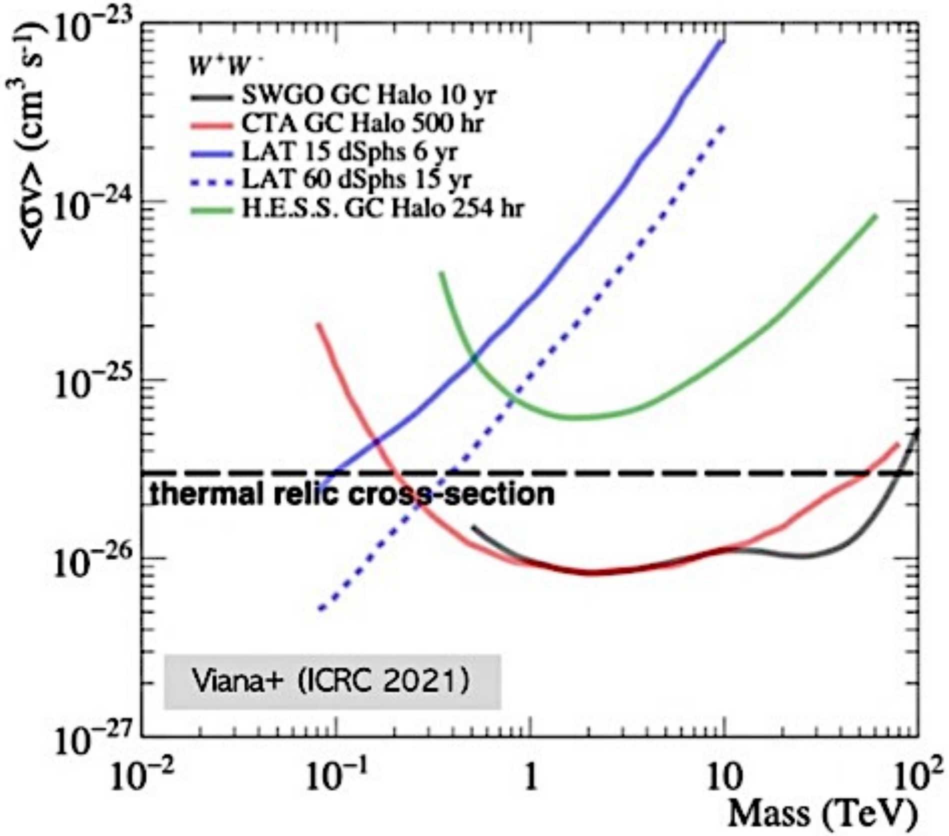
Interpretation depends on poorly-understood Galactic diffuse & pulsar population

MeV and TeV gamma-rays for future

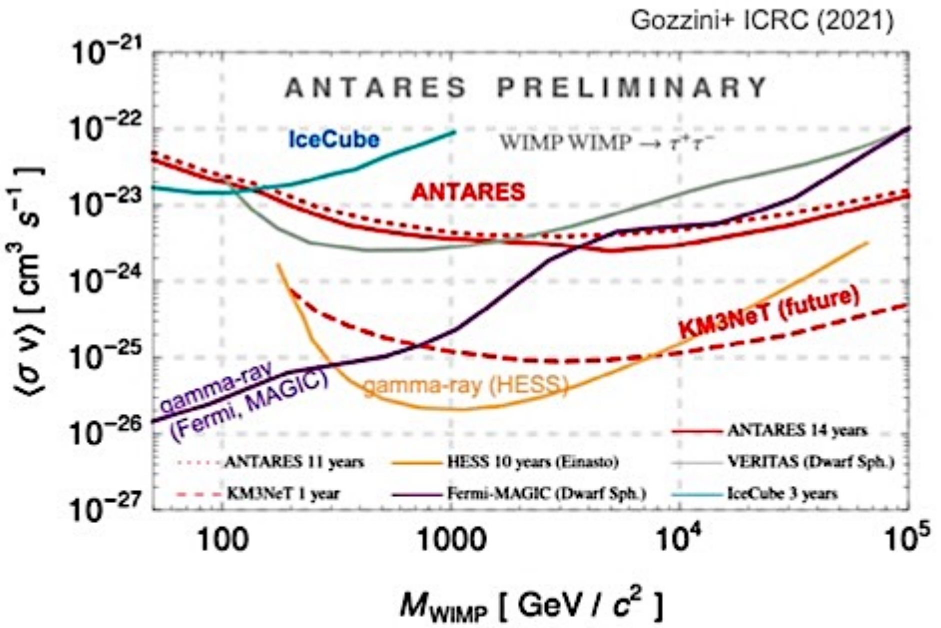
- New instruments opening the **“MeV gap”** sensitive to **primordial black hole** evaporation
  e.g. COSI, GRAMS, Amego, GECCO, e-ASTROGRAM

- Future/ongoing **TeV gamma-ray** instruments improve sensitivity to TeV+ mass dark matter
  e.g. HAWC, LHAASO, CTA, SWGO, Tibet ASg

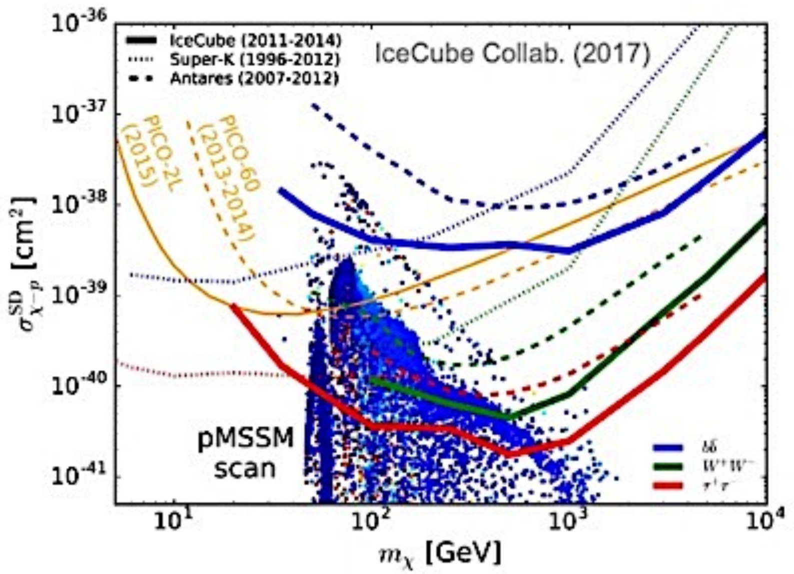




Neutrinos : non-detection limits, future prospects

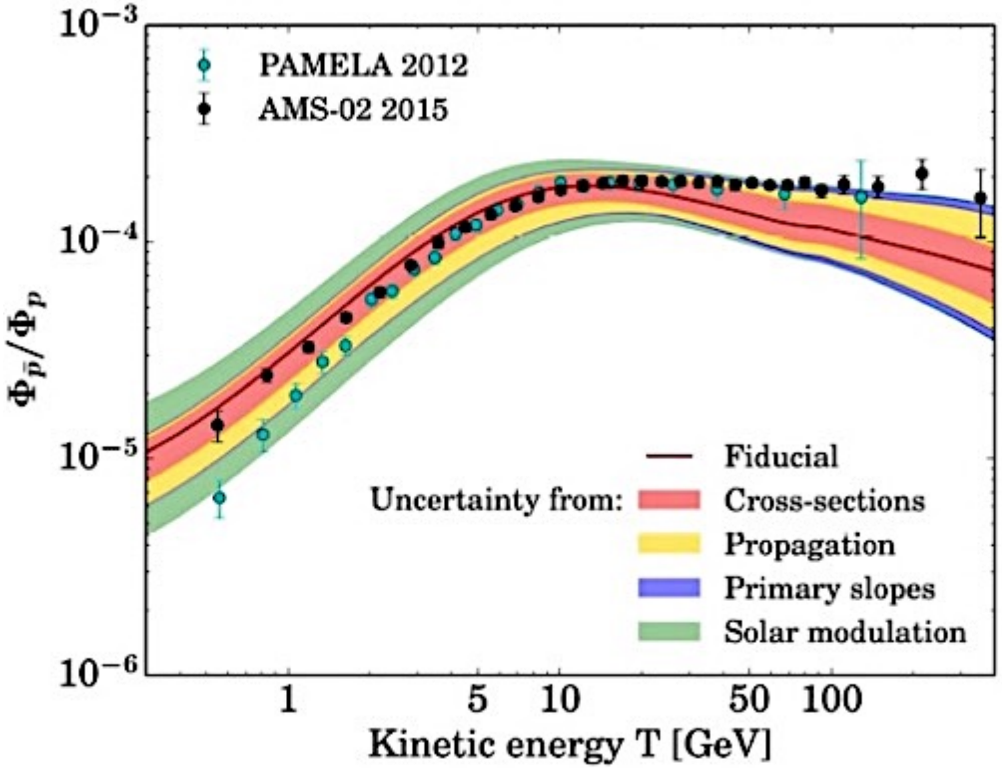


- Current neutrino DM **annihilation limits** not yet competitive with gamma-ray bounds
- Future high-energy/ultra-high energy neutrino detectors promising for high-mass dark matter searches
  e.g. POEMMA, IceCube-Gen2, KM3NeT

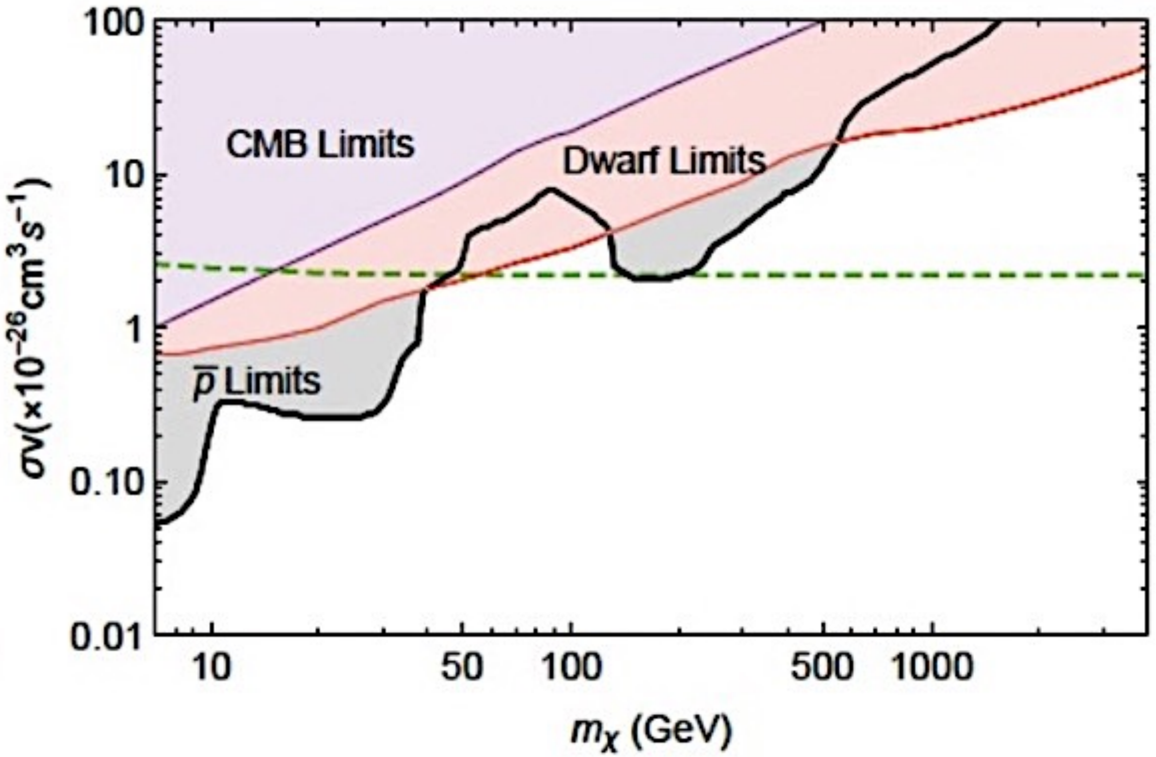


- DM loses energy due to scattering, becomes trapped in Sun's core, then annihilates into GeV neutrinos
- Neutrinos competitive with leading **limits on *spin-dependent* nuclear scattering** cross sections (compared to direct detection)

Antiprotons: dark matter limits



G. Giesen+(2015)



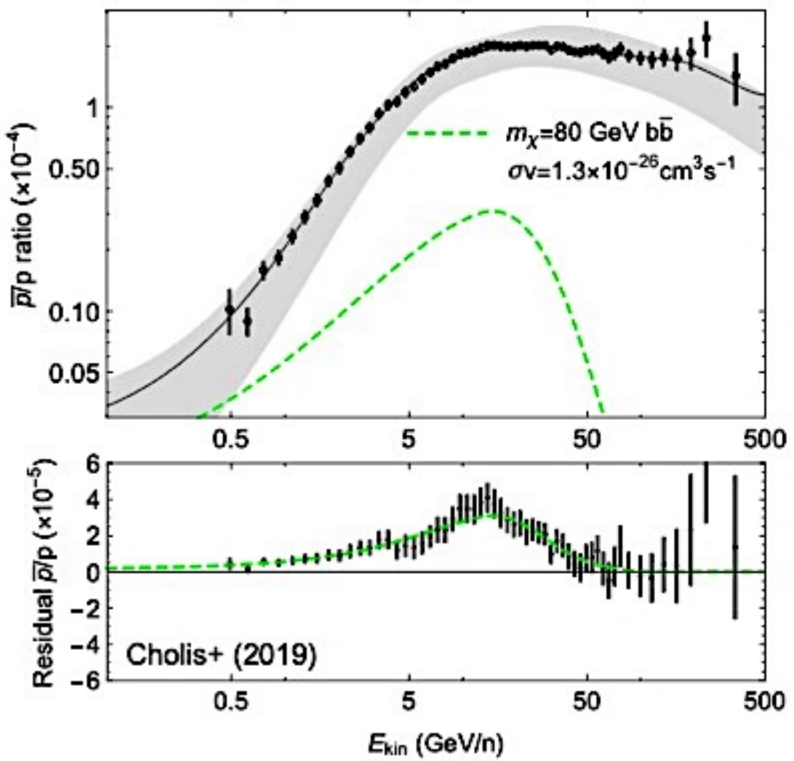
I. Cholis+(2019)

- High-precision AMS measurement prompts improved modeling of production cross-sections and propagation
- Strong constraints on dark matter annihilation (to bb) below 40 GeV

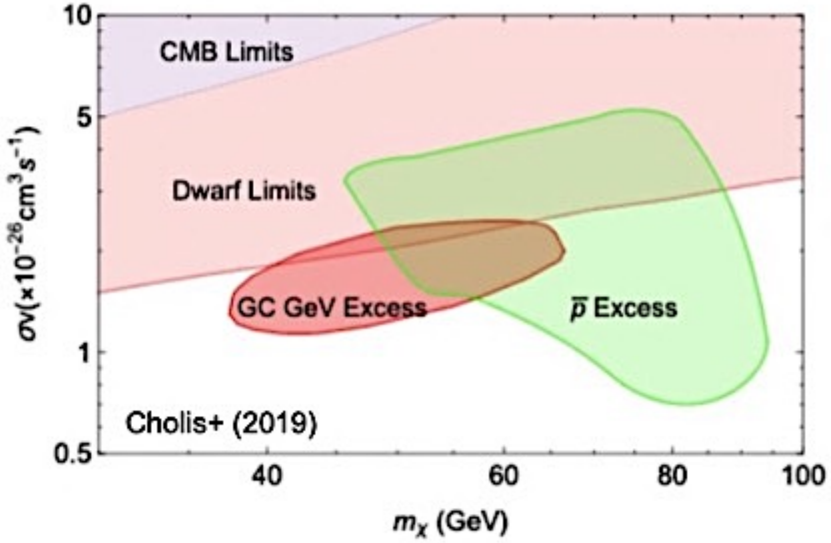
Antiproton excess?

- Possible excess in ~5-20 GeV antiprotons, at level of few % of total flux

Cuoco+(2016), Cui+(2016), Cui+ (2018), A. Cuoco+ (2019), Cholis+ (2019)



- Signal consistent with ~50-100 GeV dark matter
- Consistent properties as source of Galactic center GeV excess



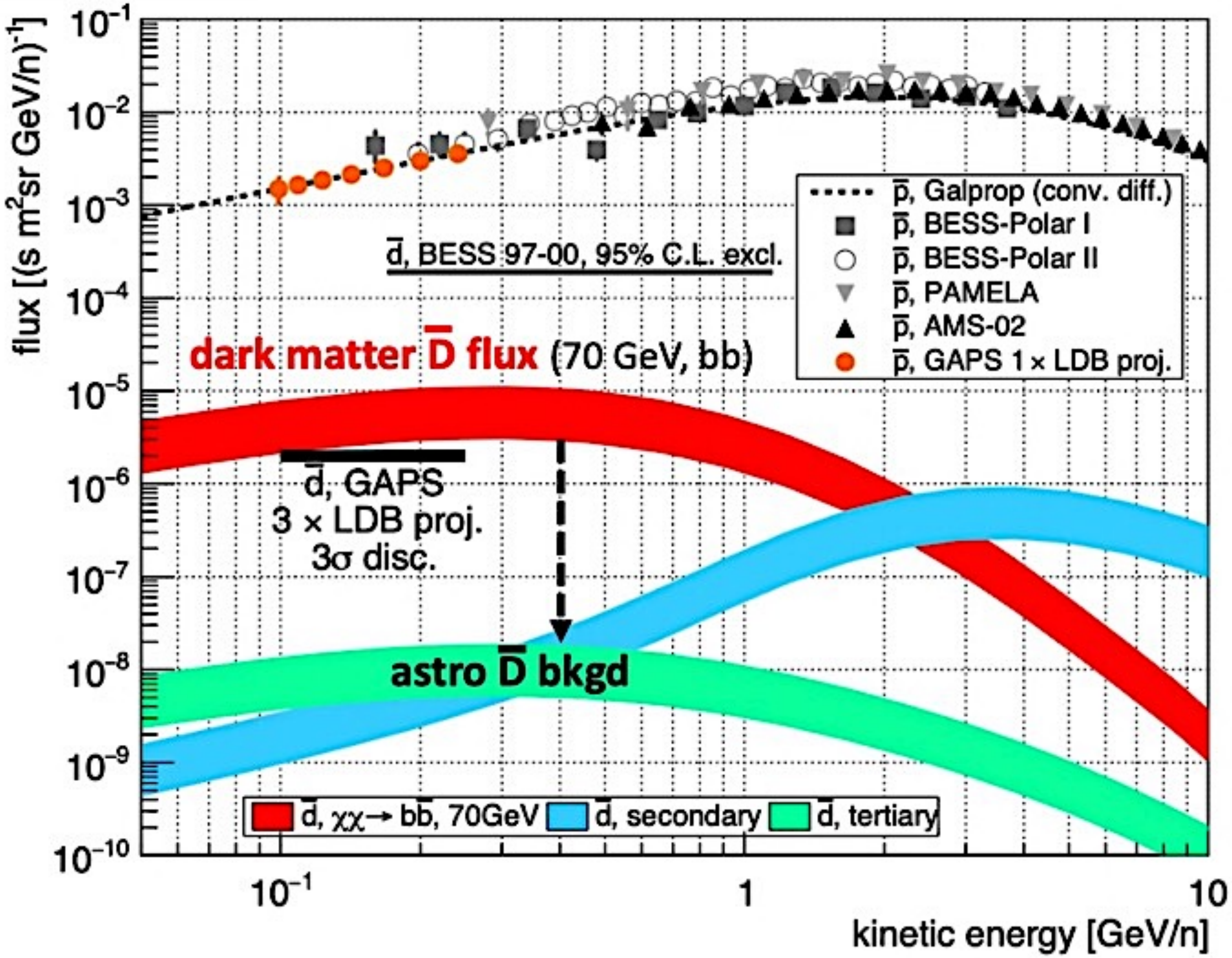
…But significance possibly weakened by uncertainties, in particular on absorption in AMS

Hesig+ (2020) 2005.04237, Reinert+Winkler (2018), Boudad+ (2020)

Interpretation depends on Galactic and Solar propagation, antiproton production uncertainties, ***possible correlated systematic uncertainties from AMS***

New physics in cosmic antideuterons for future

A generic ***new physics*** signature with *essentially zero* conventional astrophysical background

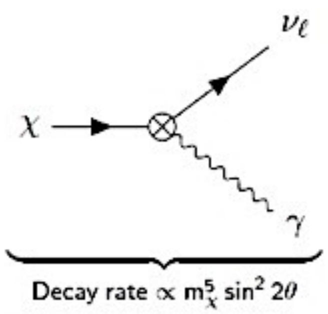


- **GAPS** first experiment optimized specifically for *low-energy antinuclei* ($\bar{p}$,$\bar{D}$,$\overline{He}$) signatures
- **First Antarctic balloon flight 2022/2023**

Review of Cosmic Antinuclei Searches for Dark Matter:
von Doetinchem, Perez+
JCAP (2020)

X-ray searches: narrowing window for sterile neutrinos

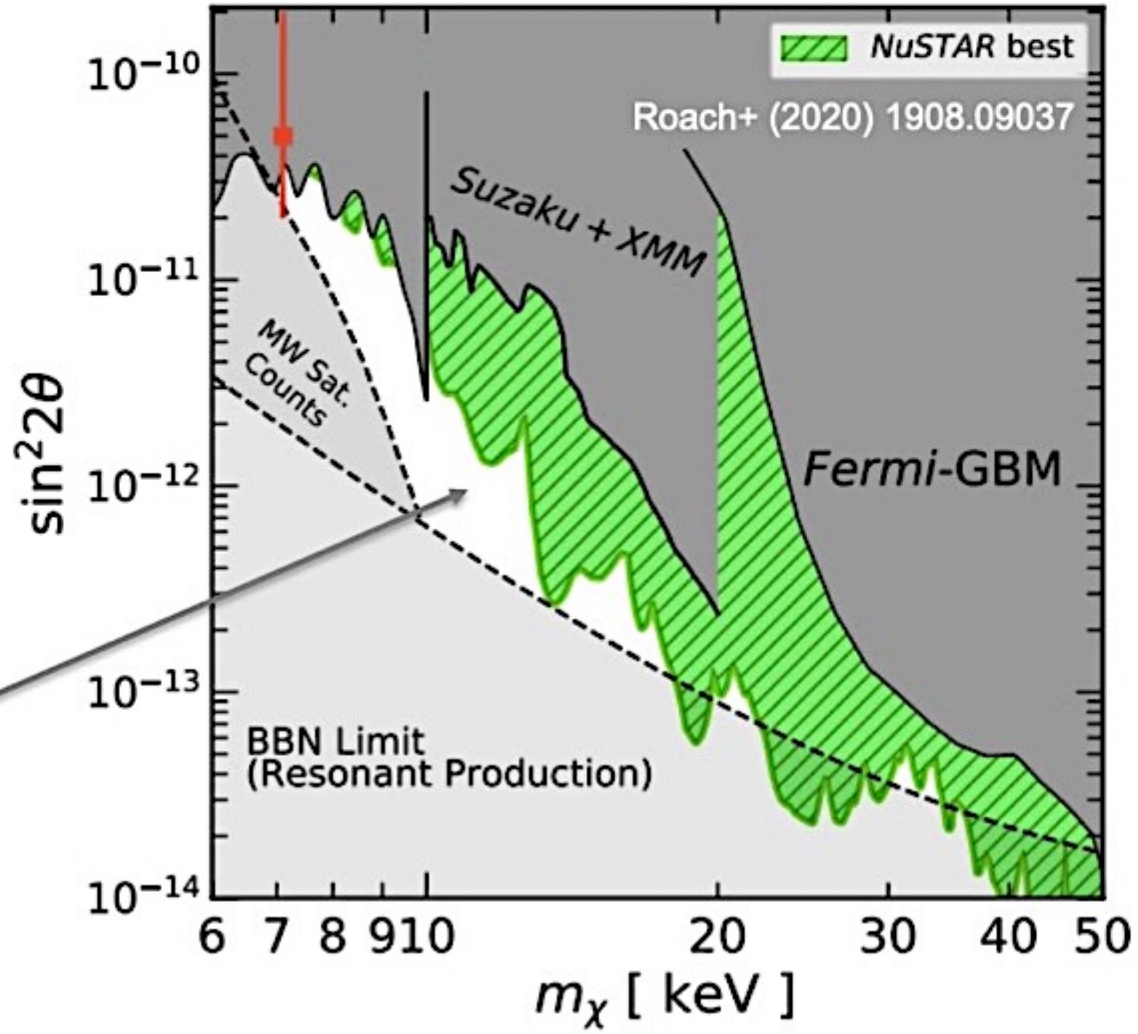
- **Sterile neutrinos** are a candidate for **keV-mass dark matter**, motivated by neutrino mass and mixing
- Can decay to a neutrino and a photon with $E_{photon} = m_{DM} / 2$



→ ***Astro X-ray line searches give leading sensitivity***

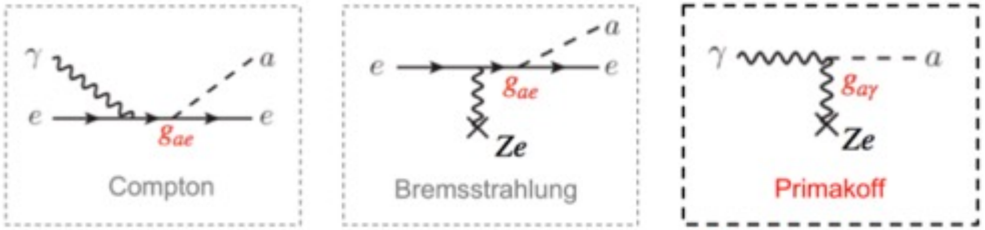
- Finite parameter space for sterile neutrinos to be all of dark matter in the simplest models
- Ongoing/future missions can cover full parameter space

  e.g. NuSTAR, eROSITA, ATHENA



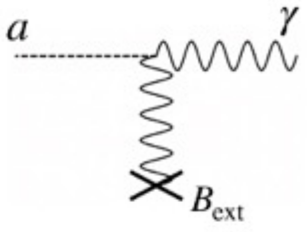
Probing axion-like particles with astrophysics

(1) Axions can participate in the analog of many astrophysical processes
→Axions produced in stars / alter stellar properties



Most relevant process for stars!

(2) Axion-photon conversions can occur **in interstellar magnetic fields**



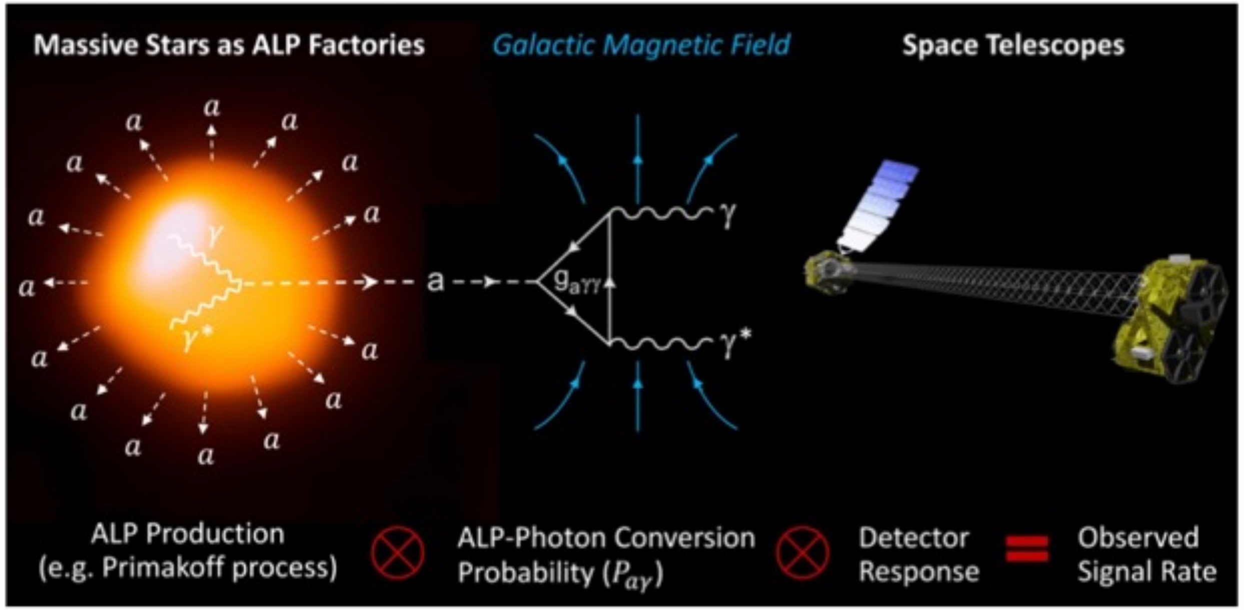


Image credit: Mengjiao Xiao, see also

Probing axion-like particles with astrophysics

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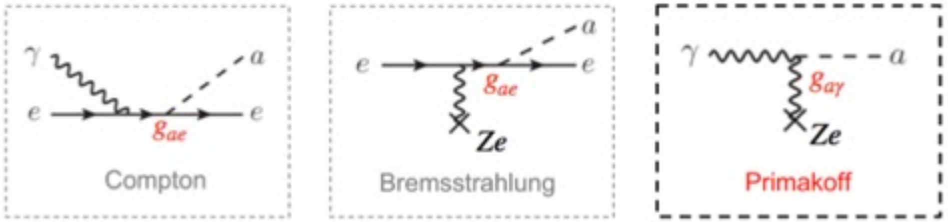

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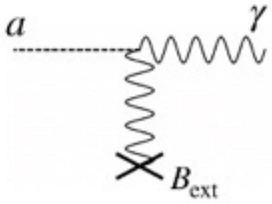
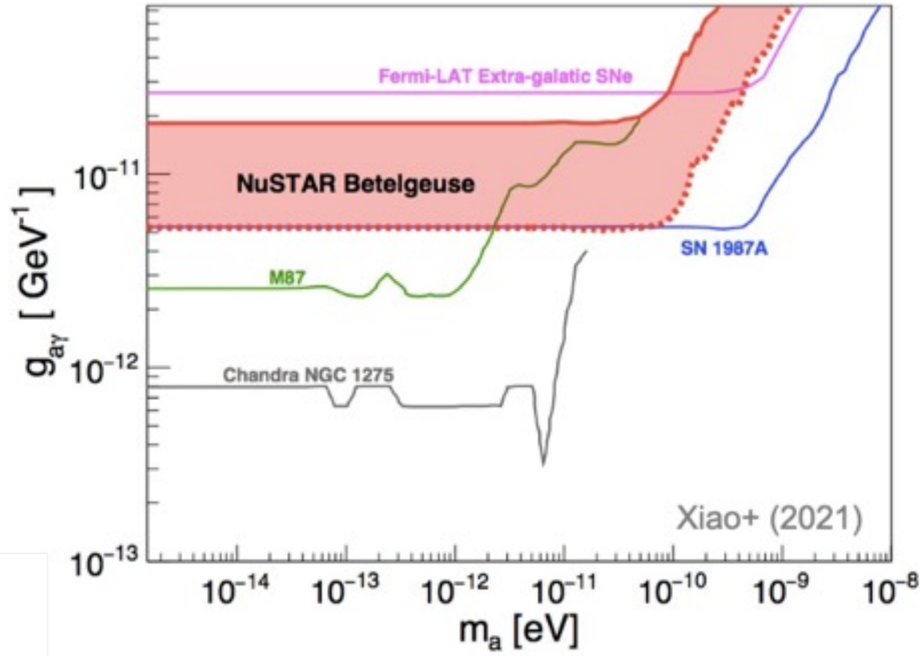
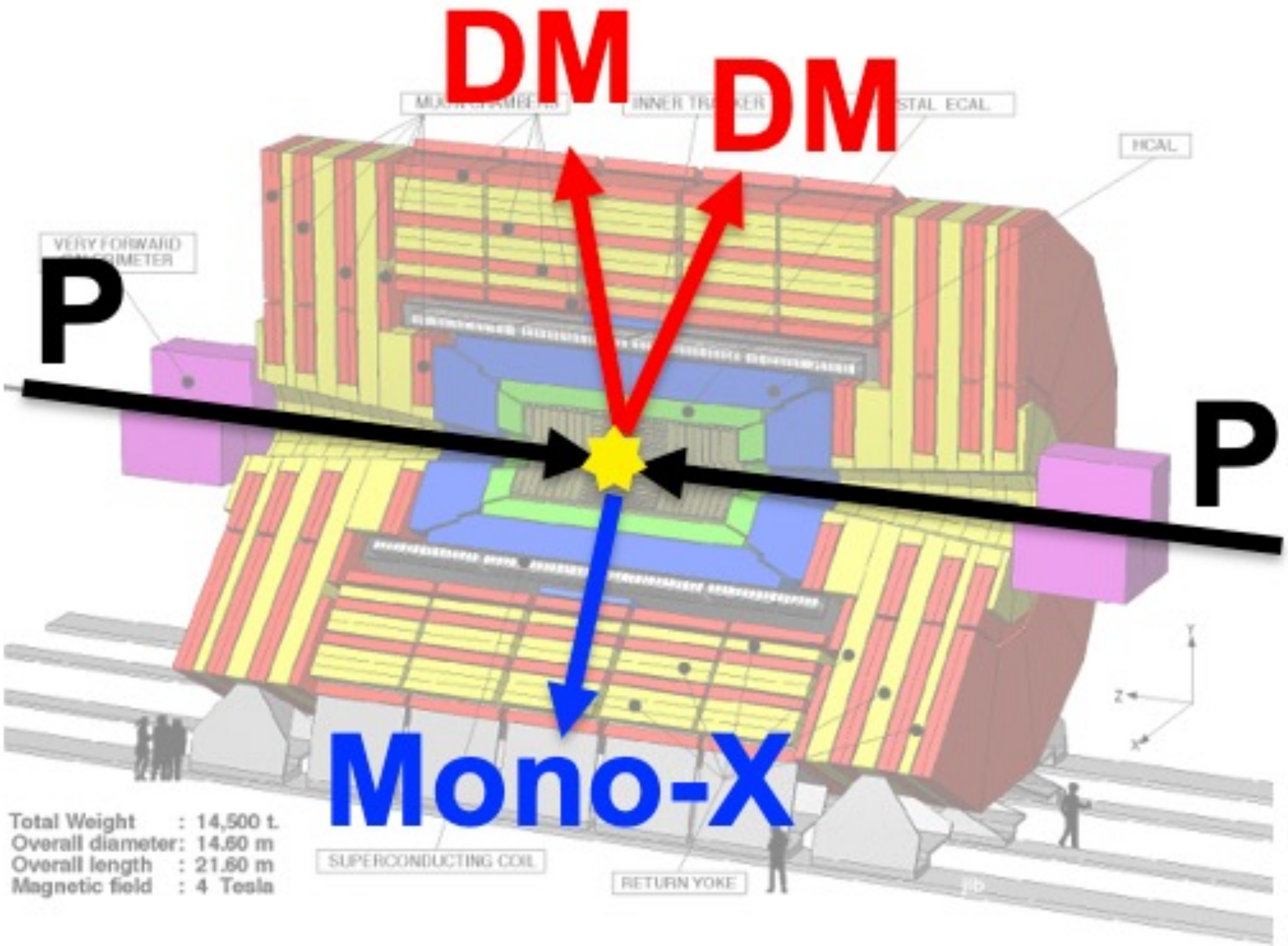


- Astrophysical limits from these searches give **low-mass axion limits** at least ~3x deeper than CAST
- **Comparable to next-generation axion experiments** ALPS-II and Baby-IAXO

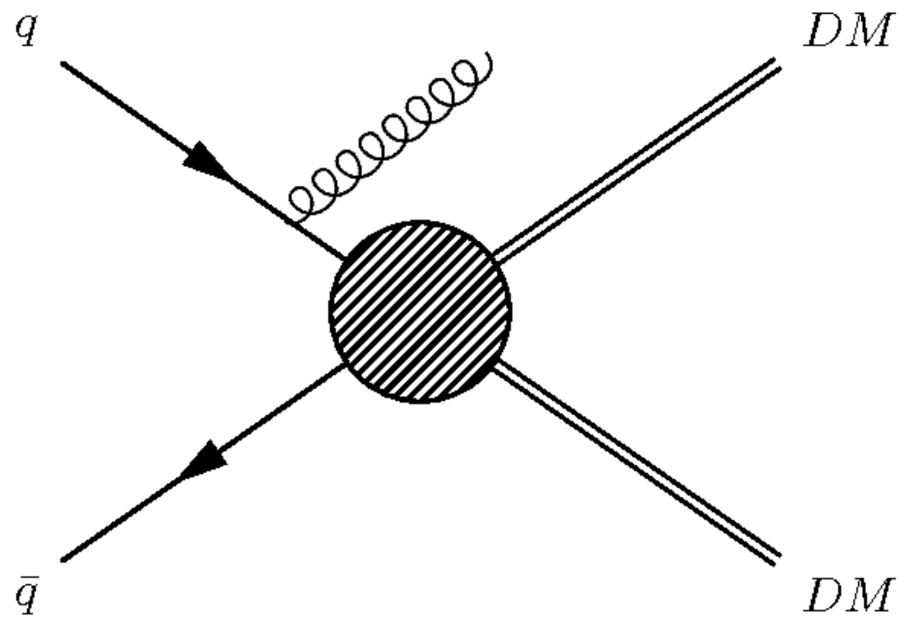
e.g. Xiao+ (2021), Dessert+ (2020), Payez+ (2015), Meyer+ (2020), Marsh+ (2017), Reynolds+ (2019),



Dark Matter at CERN LHC



DM models at ATLAS/CMS in RUN1 (7-8 TeV)



Run1 (7-8 TeV) : Effective Field Theories (EFT)

- Contact Interactions between DM and SM
- DM is pair-produced and light new particle
- Mediators are very heavy
  - Invalid if mediator light enough to be resolved
- 2 parameters: Dark Matter mass & interaction strength

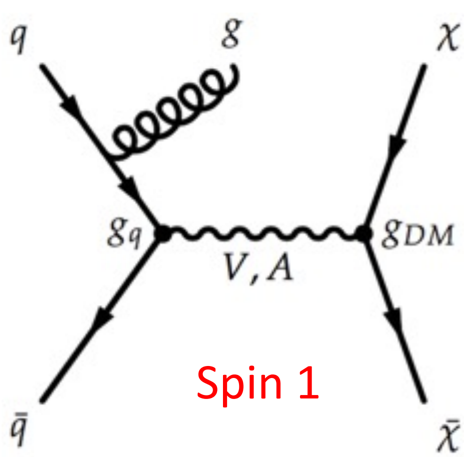
DM models at ATLAS/CMS in RUN2 (13 TeV)

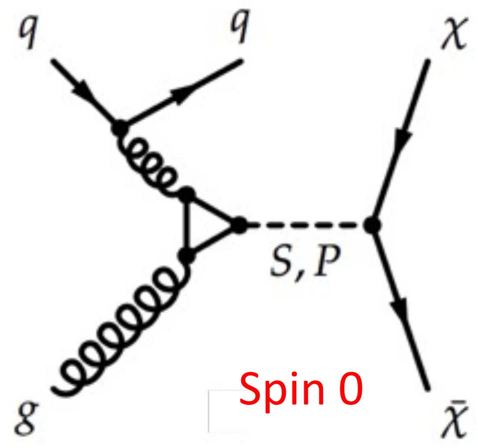
Run2 (13 TeV): Simplified Models

- Suggested by ATLAS/CMS Dark Matter Forum
- Fermionic DM particles interact a mediator
- Bosonic mediator
  - ❑ Spin 0: scalar (S) / pseudo-scalar (PS)
  - ❑ Spin 1: vector (V) / axial-vector (AV)
  - ❑ Coupling to both SM and DM particles

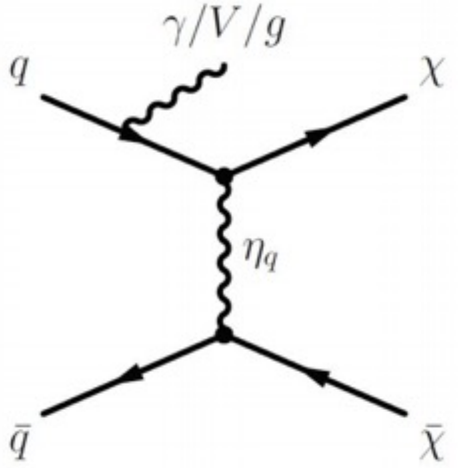
- More parameters
  - ❑ Mediator mass (m_{med}) and width
  - ❑ DM mass (m_{DM})
  - ❑ Mediator coupling to SM (g_q)
  - ❑ Mediator coupling to DM (g_{SM})

s-channel

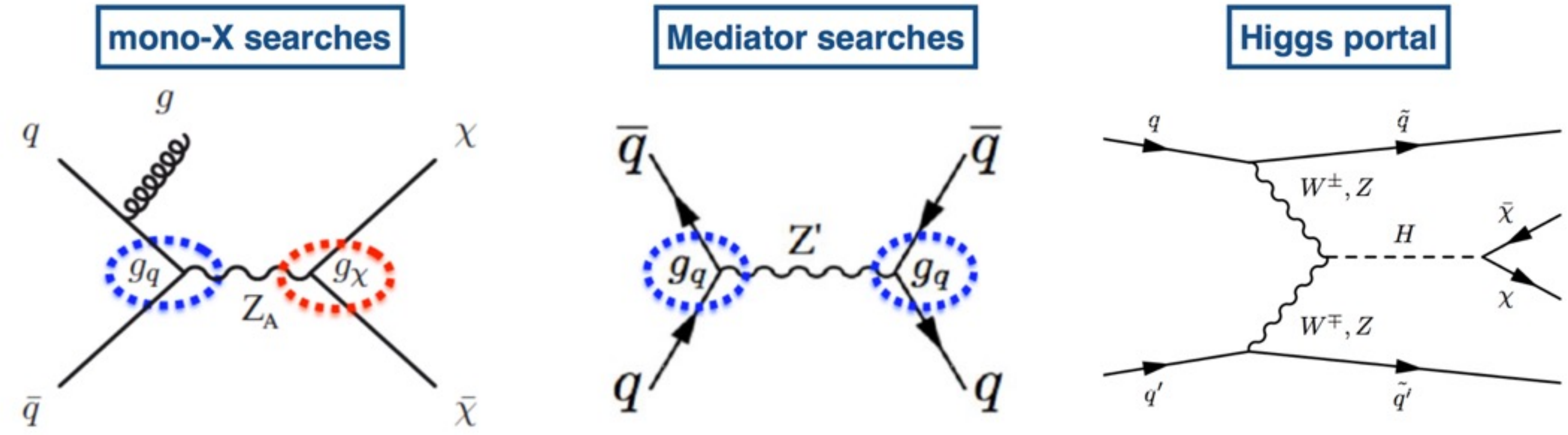




t-channel



Three main strategies for DM at ATLAS/CMS



Mono-X : DM particles are produced together with Standard Model particles

- Look for an energetic SM particle recoiling against the invisible DM system

DM mediators are produced and decay to pair of SM particles, typically quarks

- Search for bumps in the m_{jj} spectrum

DM production through the Higgs portal

- Higgs Boson can decay into DM particles

Mono-X strategies for DM search

Search for weakly-interacting massive particle (WIMP) as a DM pair at LHC

DM particles cannot be detected by ATLAS, CMS and LHCb detectors.

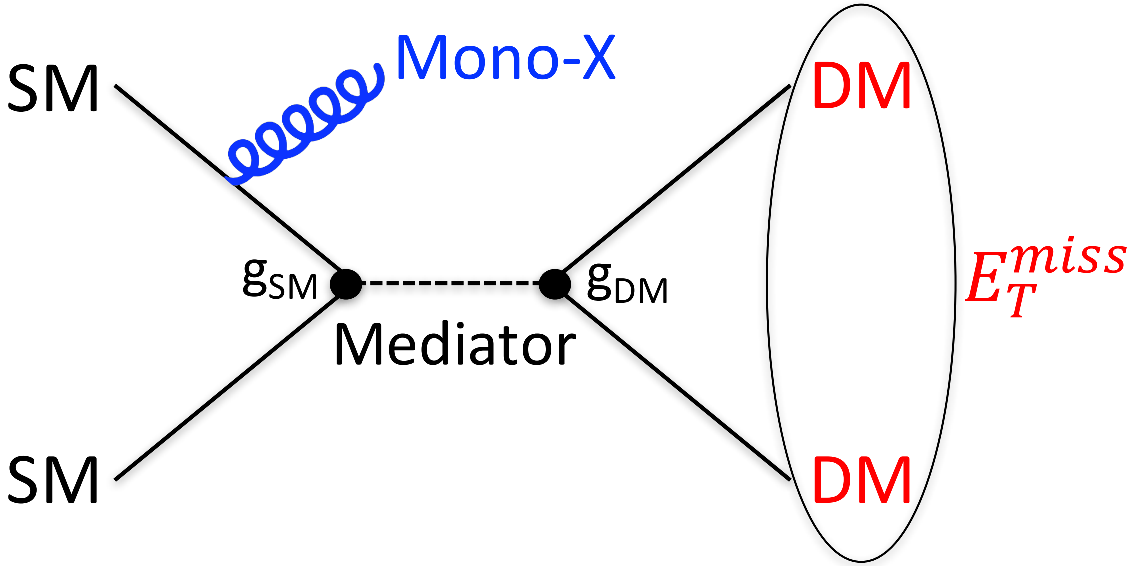
- Large missing transverse energy (E_T^{miss})

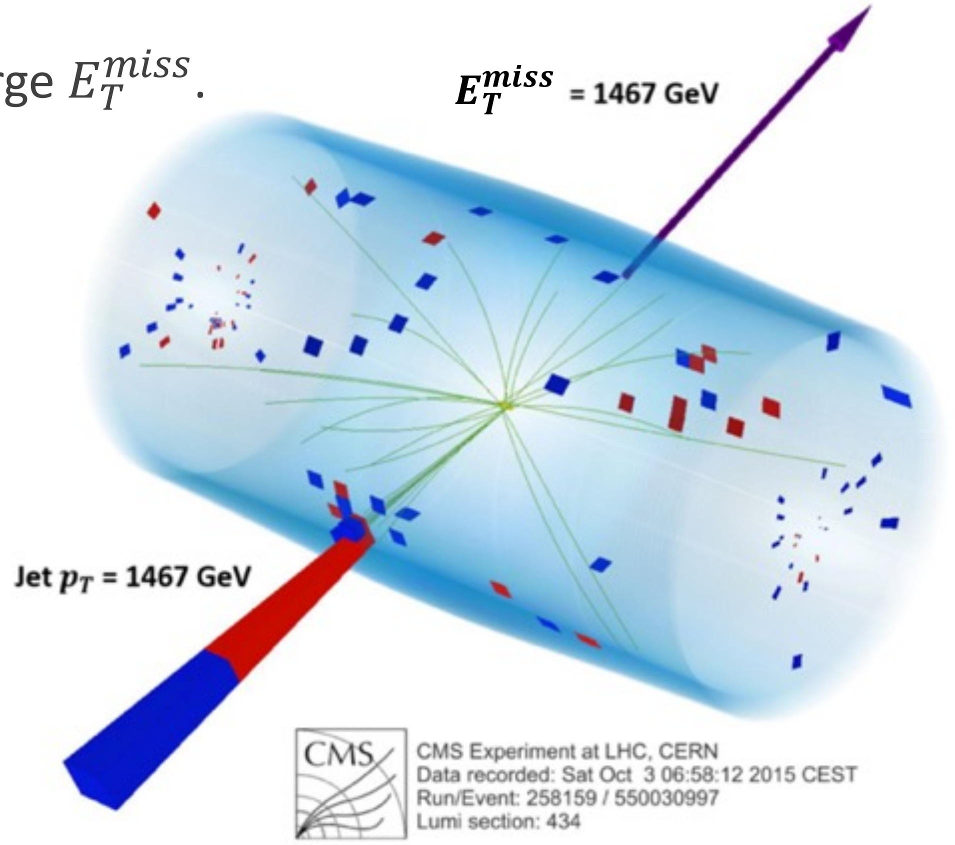
SM particle recoiling against DM particles

- Mono-X signature:
  - jet (g/q), heavy quarks (b/t), higgs or vector bosons (γ/W/Z)

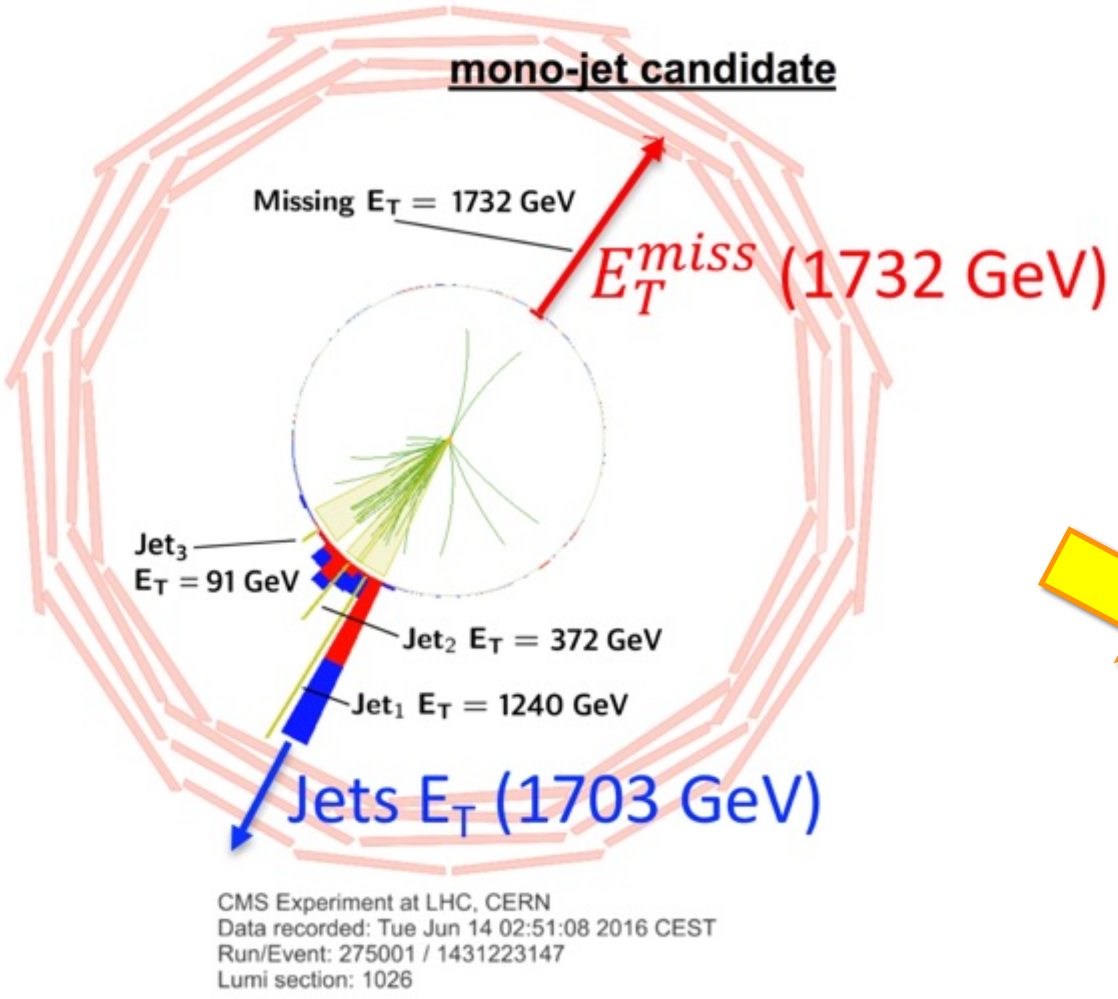
LHC searches focus on events with a SM particle(s) (Mono-X) with large E_T^{miss}.

- E_T^{miss} + Mono-X

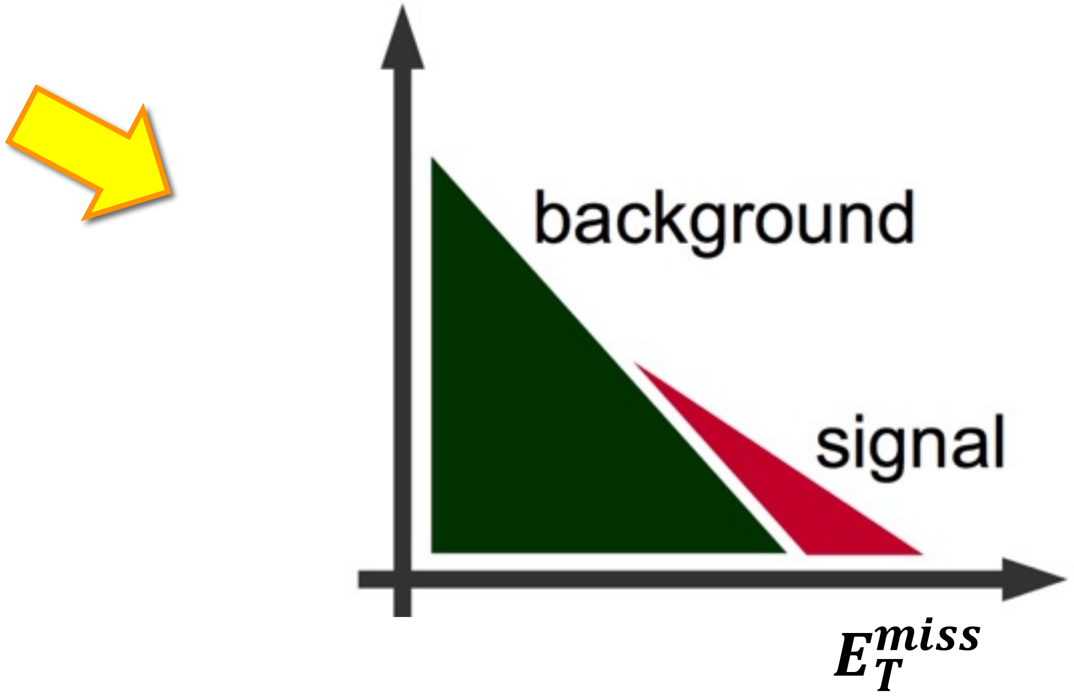




Mono-X strategies for DM search



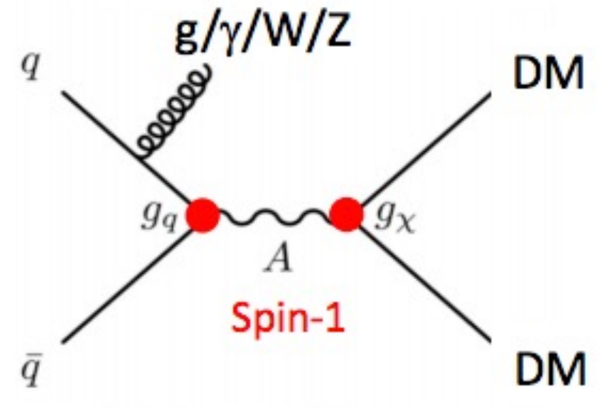
$$E_T^{miss} = -\Sigma_{All\ particles}\, p_T$$



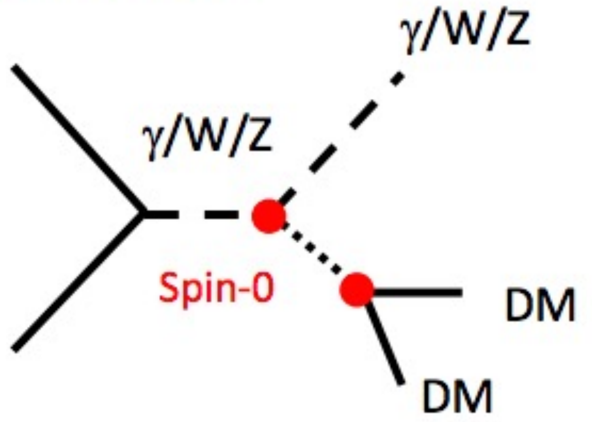
DM Production at ATLAS and CMS

Spin-1 and Spin-0 mediators coupling with DM and SM particles in simplified models.

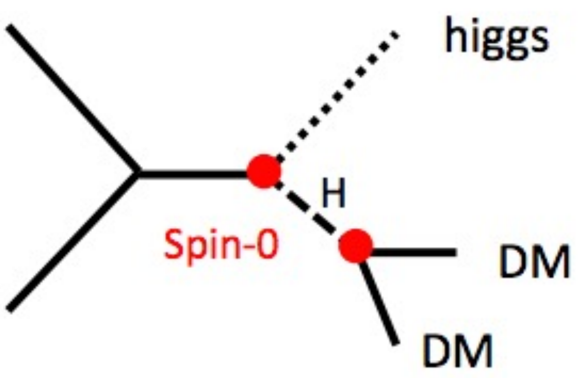
with light quarks



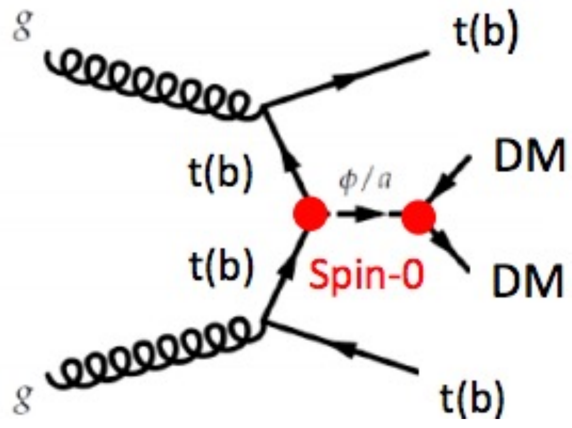
with γ/W/Z



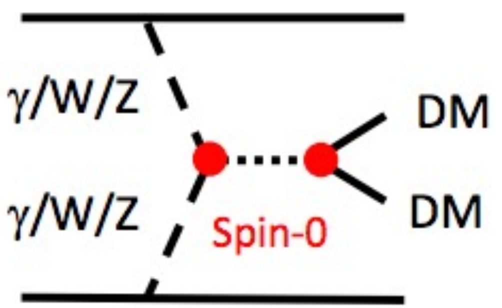
associate with higgs



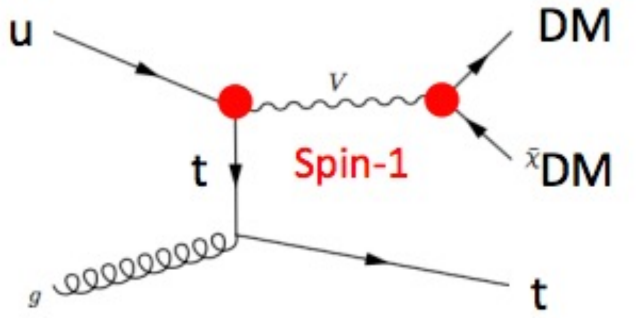
with heavy quarks



VBF



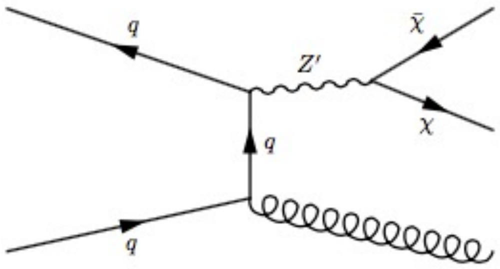
FCN



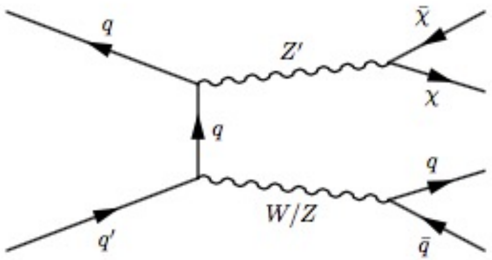
CMS Mono-jet & Mono-W/Z (hadronic)

Largest E_T^{miss}+X cross-section at LHC

spin-1 mediator (vector/axial-vector)

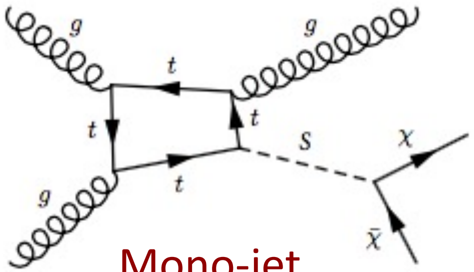


Mono-jet

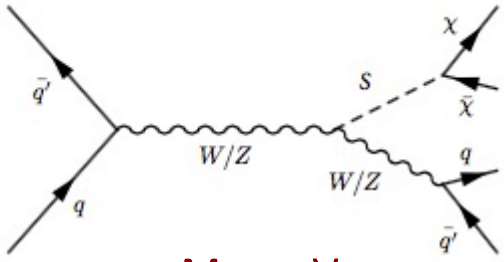


Mono-V

spin-0 mediator (scalar/pseudo-scalar)



Mono-jet



Mono-V

Experimental signature

- Large E_T^{miss} from a spin 0 or 1 mediator decaying into DM particles
- At least one high p_T jet from either QCD radiation or hadronically decaying W/Z-boson
  - Mono-jet channel: E_T^{miss} > 200 GeV, leading jet p_T > 100 GeV
  - Mono-V channel: highly boosted “fat jets” from W/Z: E_T^{miss} and leading jet p_T > 250 GeV
- No leptons (μ, e, τ) or photons (γ)
- Dominant SM backgrounds: Z($\nu\nu$)+jets and W($\ell\nu$)+jets

Typical Mono-jet Strategy

Main Backgrounds (~90%)
- **Z→νν** is the ***main*** background and is ***irreducible***
- **W→lν** when one lepton out of acceptance or not identified

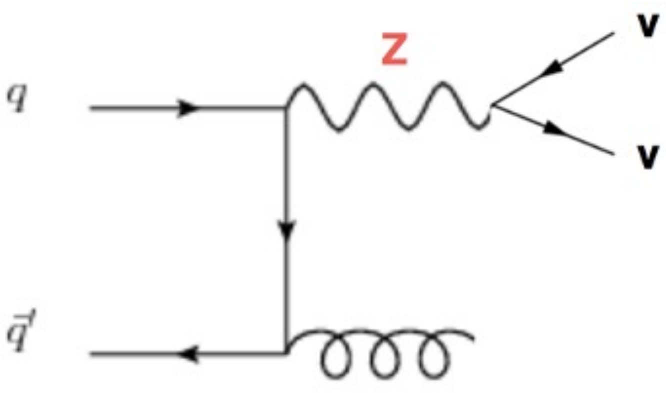
Minor Backgrounds (~10%)
- **Top:** mainly from semi-leptonic tt̄
- **Di-boson:** WZ and ZZ production mainly
- **DY+jets:** when both leptons are lost
- **QCD multi-jet, γ+jets**

Main backgrounds estimated by data-driven method in 5 control regions

Z→νν
- Di-muon events (Z→μμ enriched)
- Di-electron events (Z→ee enriched)
- Photon+jets events

W+jets
- Single muon (W→μν enriched)
- Single electron (W→eν enriched)

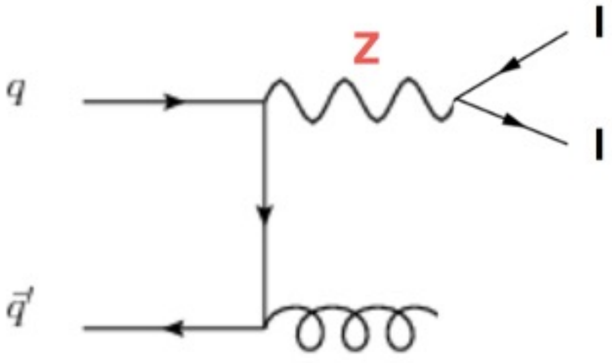
Monojet leading background estimation (1)



Z(vv)+jets: Irreducible background and makes up **50-80%** of the total background estimation!

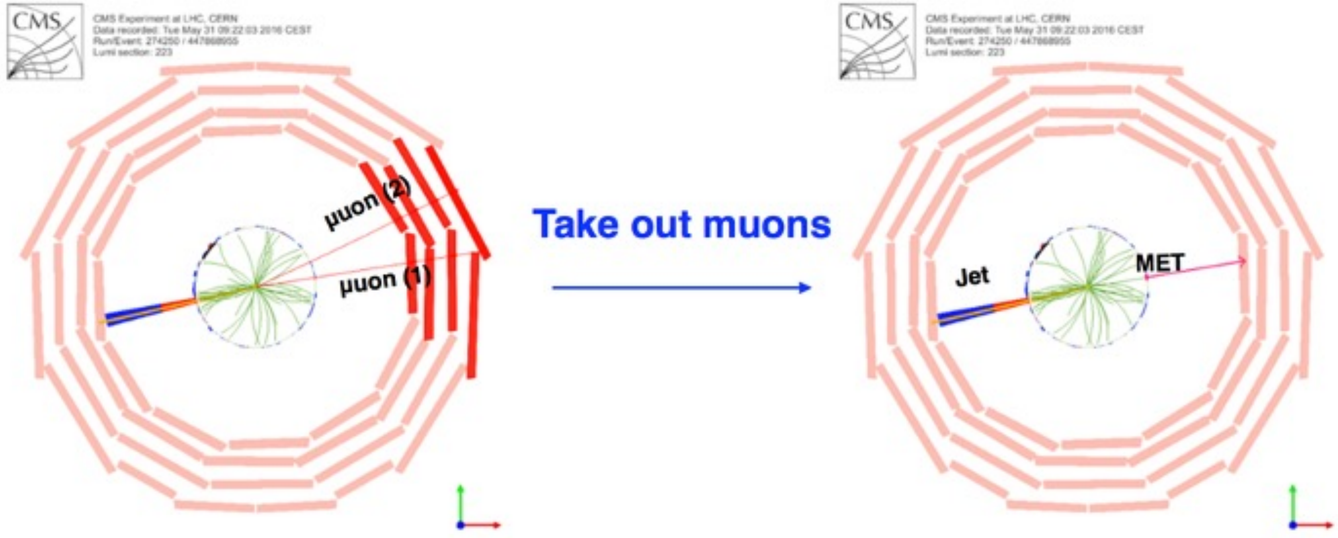
Question: What other standard model processes can we use to estimate the leading background more precisely?

If we remove the muons from a Z→μμ event, it mimics a Z→vv event

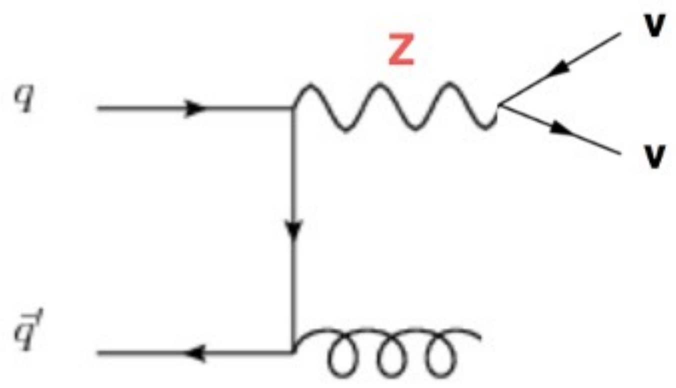


statistically limited

~no theory uncertainties



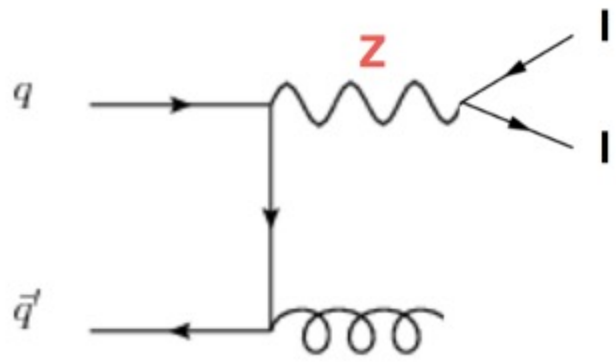
Monojet leading background estimation (2)



Z(vv)+jets: Irreducible background and makes up **50-80%** of the total background estimation!

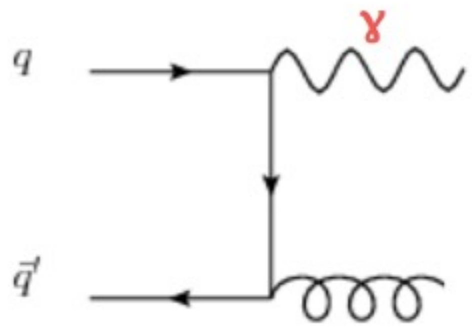
- Estimated **multiple orthogonal control regions**.
- Leading to precision measurement to test the standard model

State of the art differential predictions, uncertainties and the correlation schema on the ratios



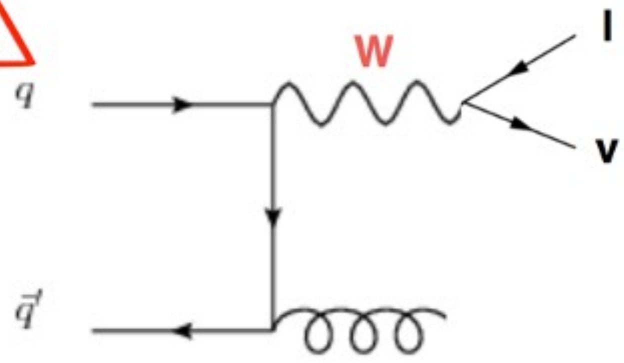
statistically limited

~no theory uncertainties



statistically rich!

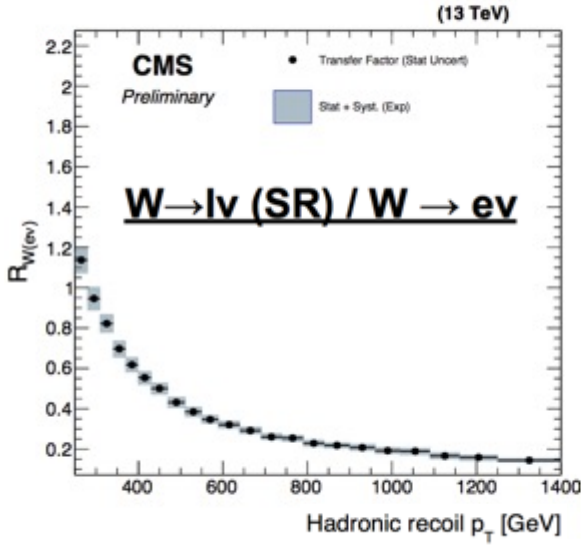
large theory uncertainties

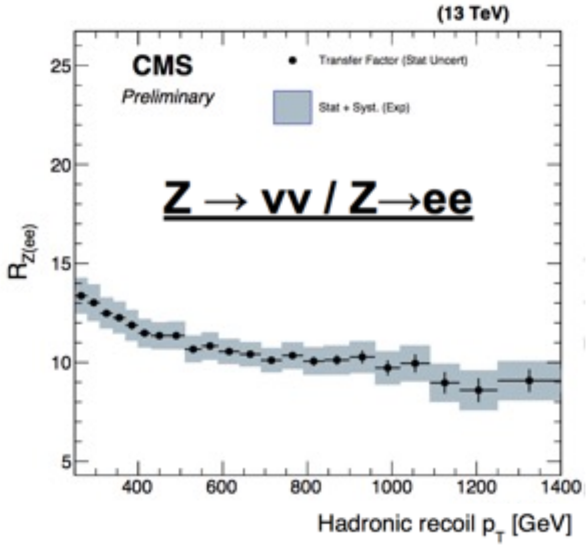


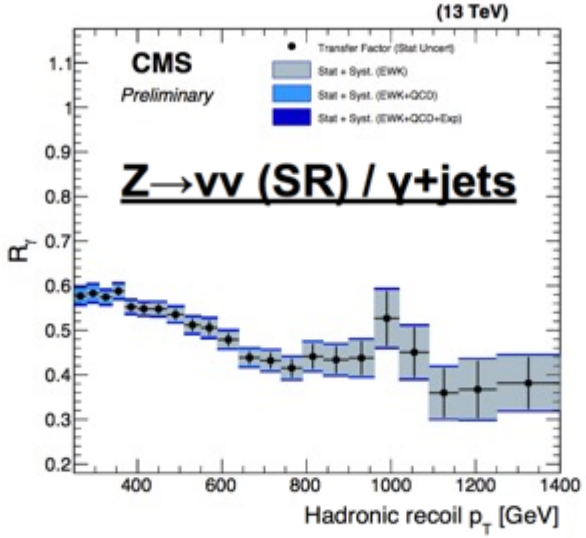
statistically ~ Z (vv)

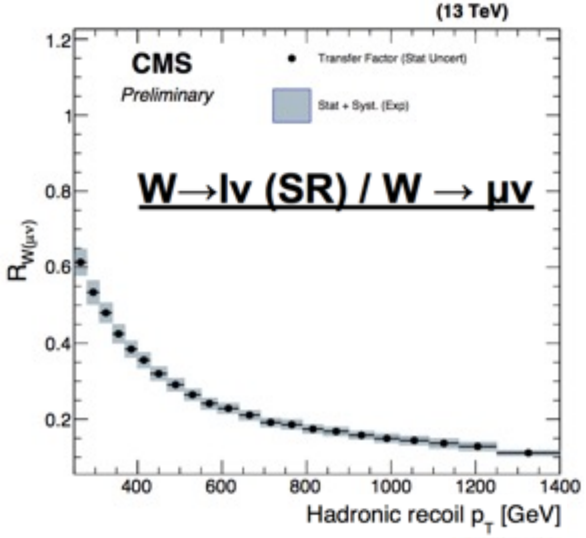
large theory uncertainties

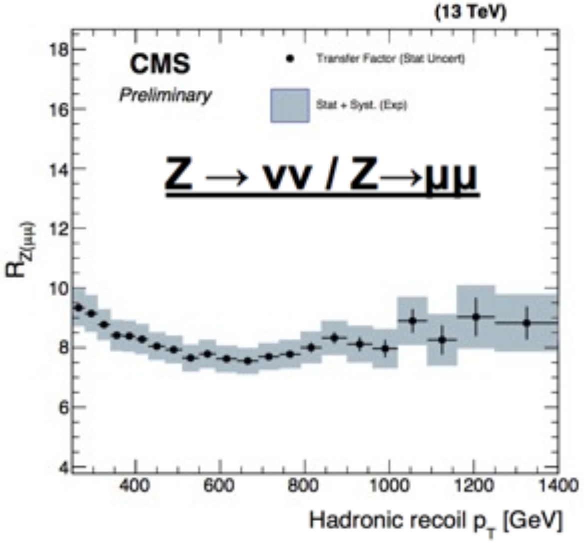
Transfer factors ($R^{\gamma/W/Z}$)

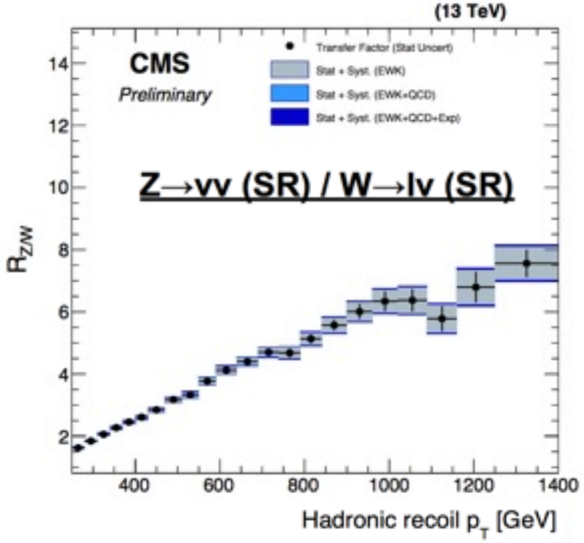






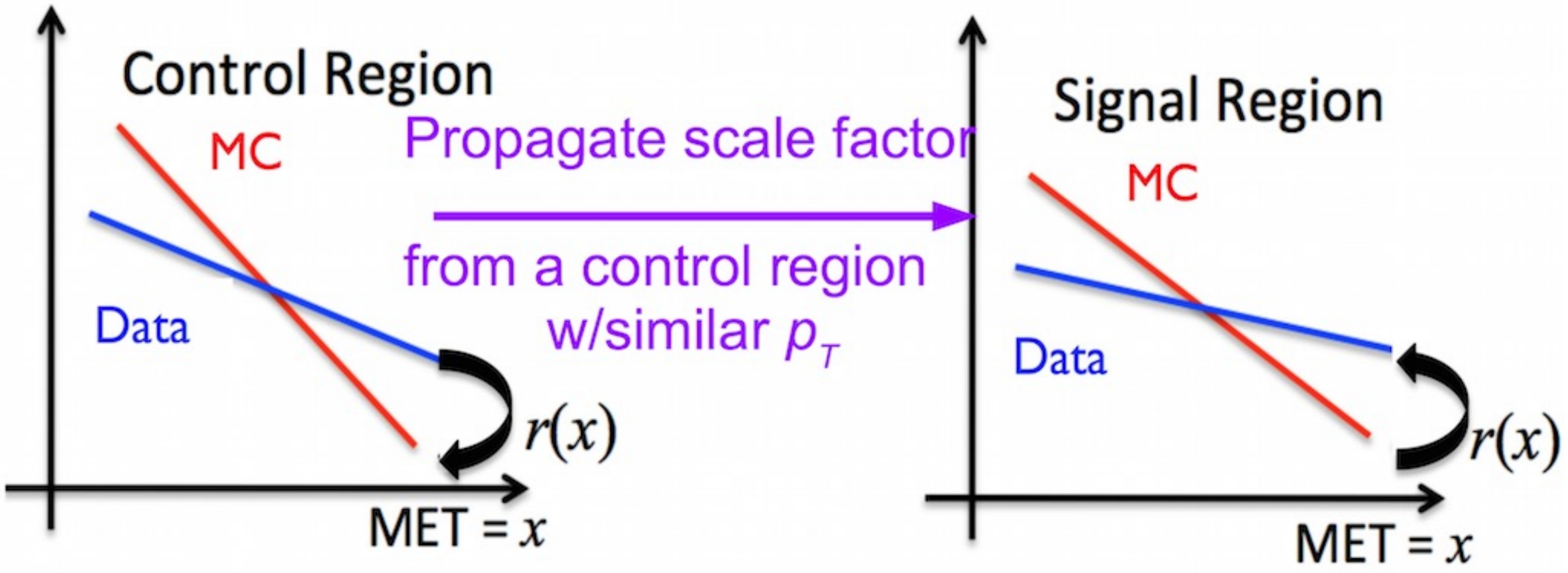






Typical Mono-jet Strategy (2)

- Monojet analyses rely on multiple "signal-free"-ish control regions to model effects



Background estimation

- **Binned transfer factors (TF)** from **MC** are used to translate yields from **CRs** to **SR**
  - **Theoretical** and **experimental uncertainties** on **TF** added as **nuisance parameters** in the final fit

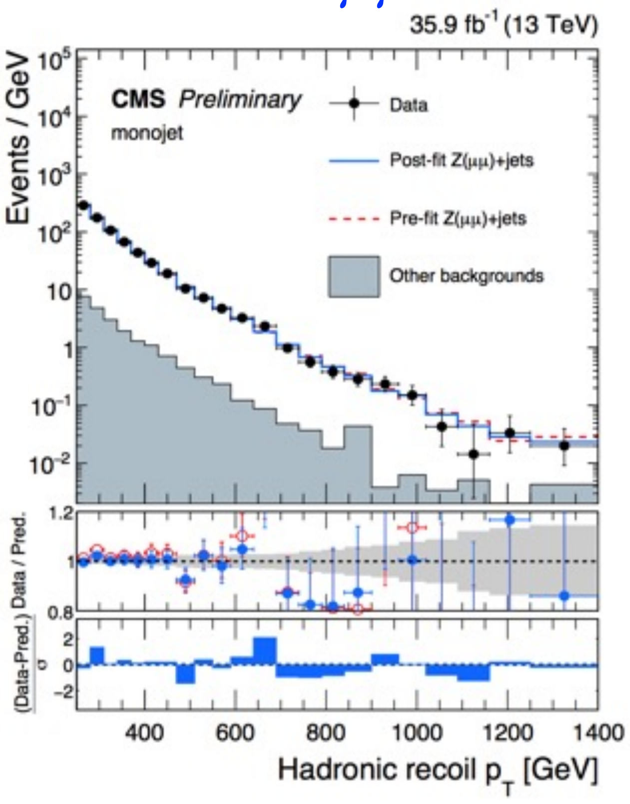
Likelihood model

$$
\begin{aligned}
\mathcal{L}_c(\mu^{Z\to\nu\nu},\mu,\theta) = & \prod_i \mathrm{Poisson}\left(d_i^{\gamma}\,\Big|\,B_i^{\gamma}(\theta) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^{\gamma}(\theta)}\right) \\
\times & \prod_i \mathrm{Poisson}\left(d_i^{Z}\,\Big|\,B_i^{Z}(\theta) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^{Z}(\theta)}\right) \\
\times & \prod_i \mathrm{Poisson}\left(d_i^{W}\,\Big|\,B_i^{W}(\theta) + \frac{f_i(\theta)\mu_i^{Z\to\nu\nu}}{R_i^{W}(\theta)}\right) \\
\times & \prod_i \mathrm{Poisson}\left(d_i\,|\,B_i(\theta) + (1+f_i(\theta))\mu_i^{Z\to\nu\nu} + \mu S_i(\theta)\right)
\end{aligned}
$$

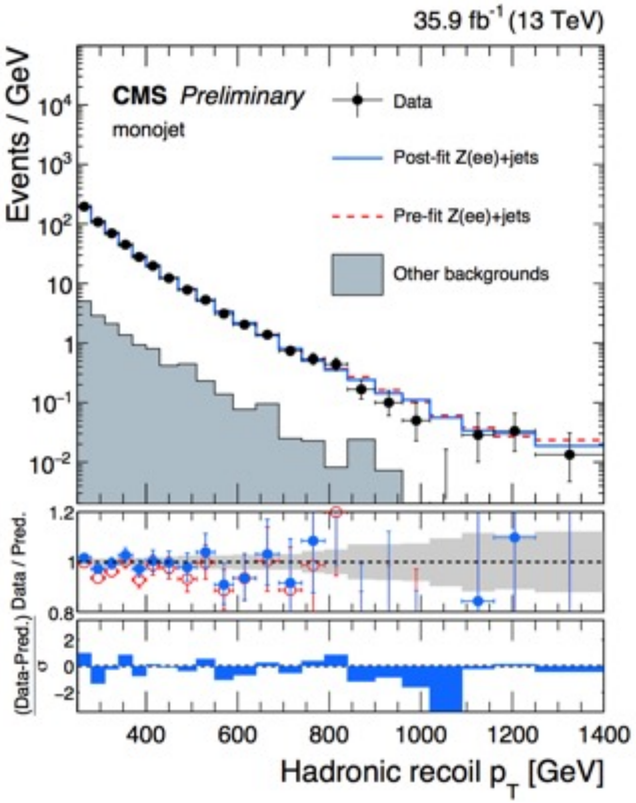
- $S_i(\theta)$ = expected signal
- $B_i(\theta)$ = expected minor backgrounds
- θ = exp. and theory nuisance parameters
- $\mu_i^{Z\to\nu\nu}$ = $Z\to\nu\nu$ rate in the i-bin, free to float
- $\mu_i^{Z\to\nu\nu} \times f_i(\theta)$ = W+jets rate
- $R_i^{\gamma/W/Z}$ = binned transfer factors vs E_T^{miss}

Likelihood Fitting (prefit & postfit)

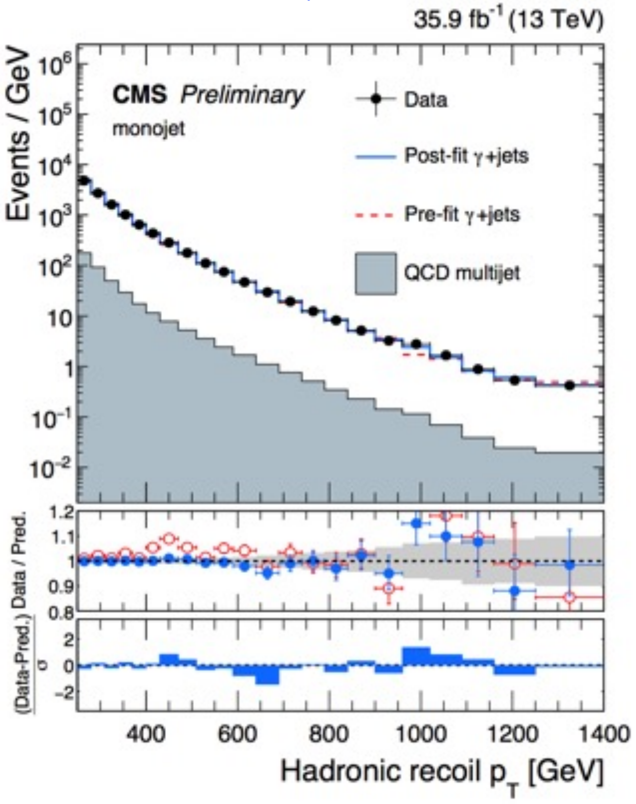
$Z \rightarrow \mu\mu$



$Z \rightarrow ee$



γ+jets

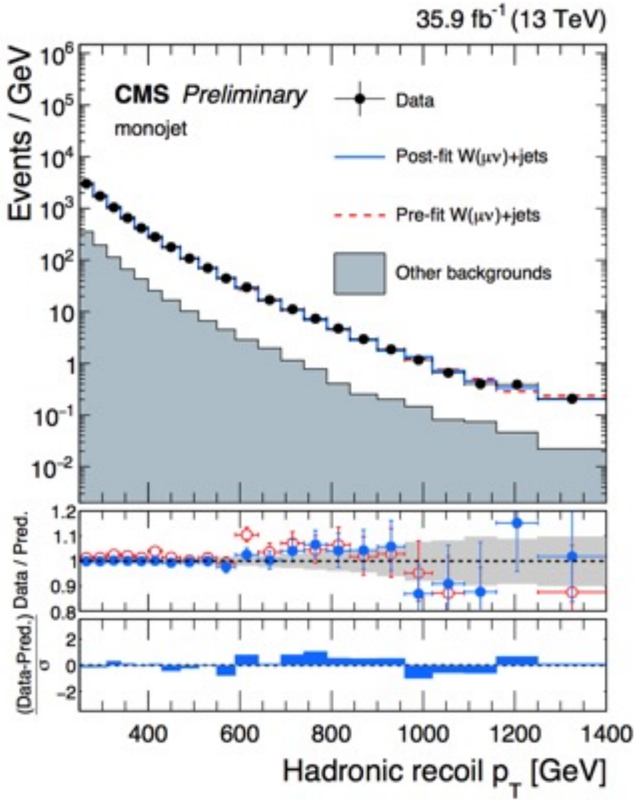


Post-fit γ+jet match well data in the tail → γ+jet statistically dominates the combined fit

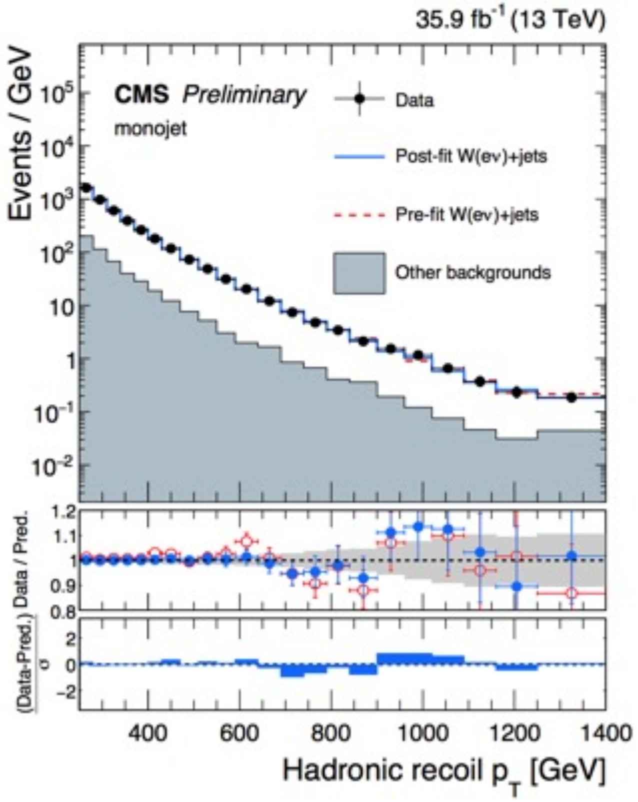
Post-fit uncertainty in the high E_T^{miss} bins around 15%

Likelihood Fitting (prefit & postfit)

$W \rightarrow \mu\nu$



$W \rightarrow e\nu$



Post-fit predictions match well data in all control regions

Post-fit uncertainty in the high E_T^{miss} bins around 15%

CMS Mono-jet & Mono-W/Z : E_T^{miss}

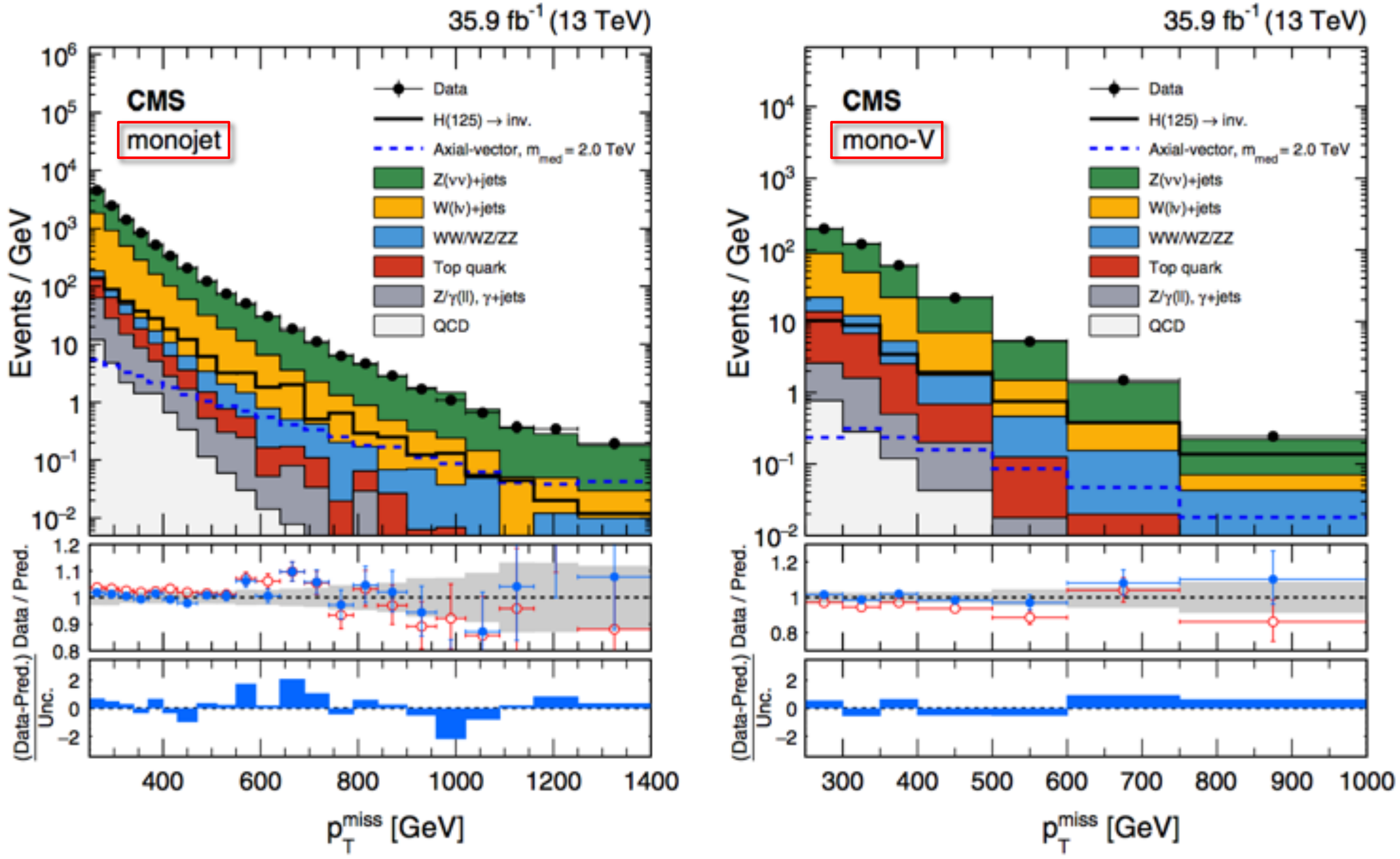
E_T^{miss} distributions in the mono-jet and mono-V signal regions

- Compared with the fitted (post-fit) background expectations for various SM processes.
- No significant excess

Paper: PRD 97 (2018) 092005

Data/MC

Significance



CMS Mono-jet & Mono-W/Z : Limits

Scan parameters in m_{med} and m_{DM} plane.

- Fixed $g_q = 0.25$, $g_{DM} = 1$

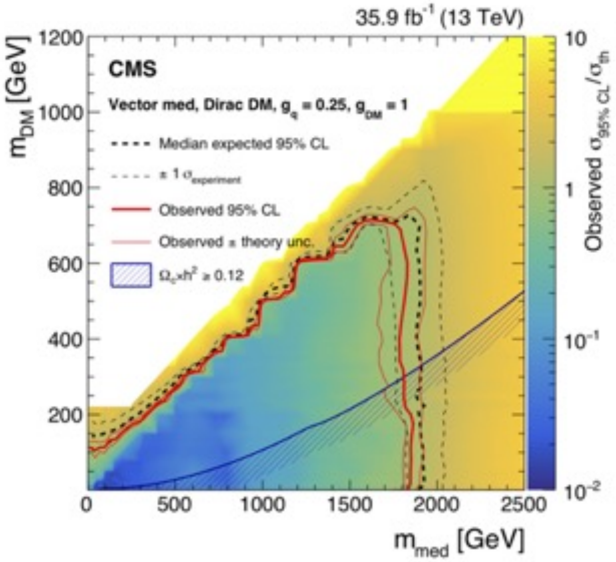
Exclusion limits at 95% CL on the $\mu = \sigma/\sigma_{th}$ in the m_{med}-m_{DM} plane assuming V/AV and S/PS mediators.

Red line: contour for the observed exclusion.

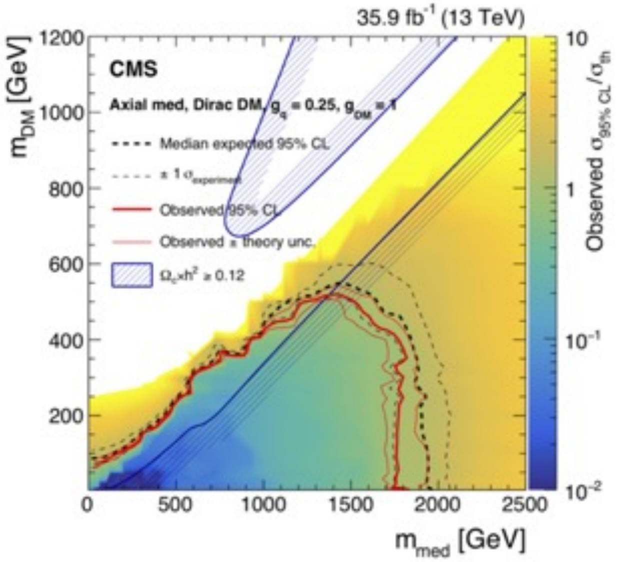
- Excludes models with V/AV mediators for m_{med} < 1.8 TeV
- PS mediator mass up to 400 GeV

Blue line: cosmological constraints from the WMAP and Planck experiments

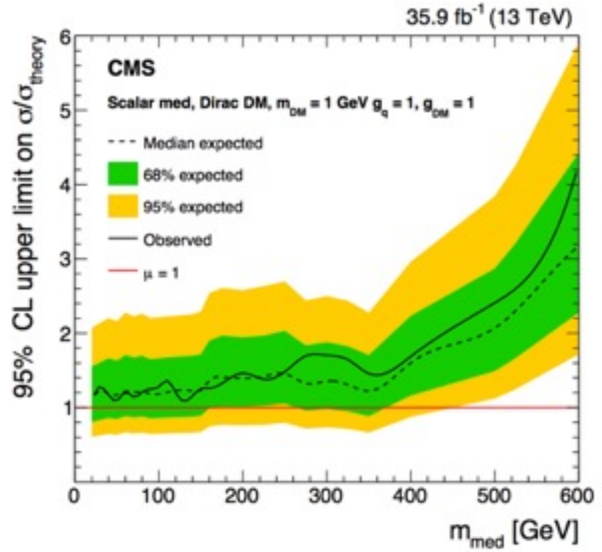
Vector



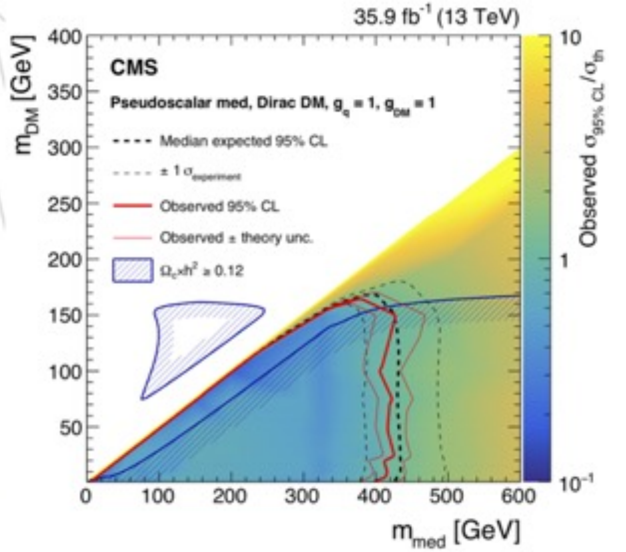
Axial-vector



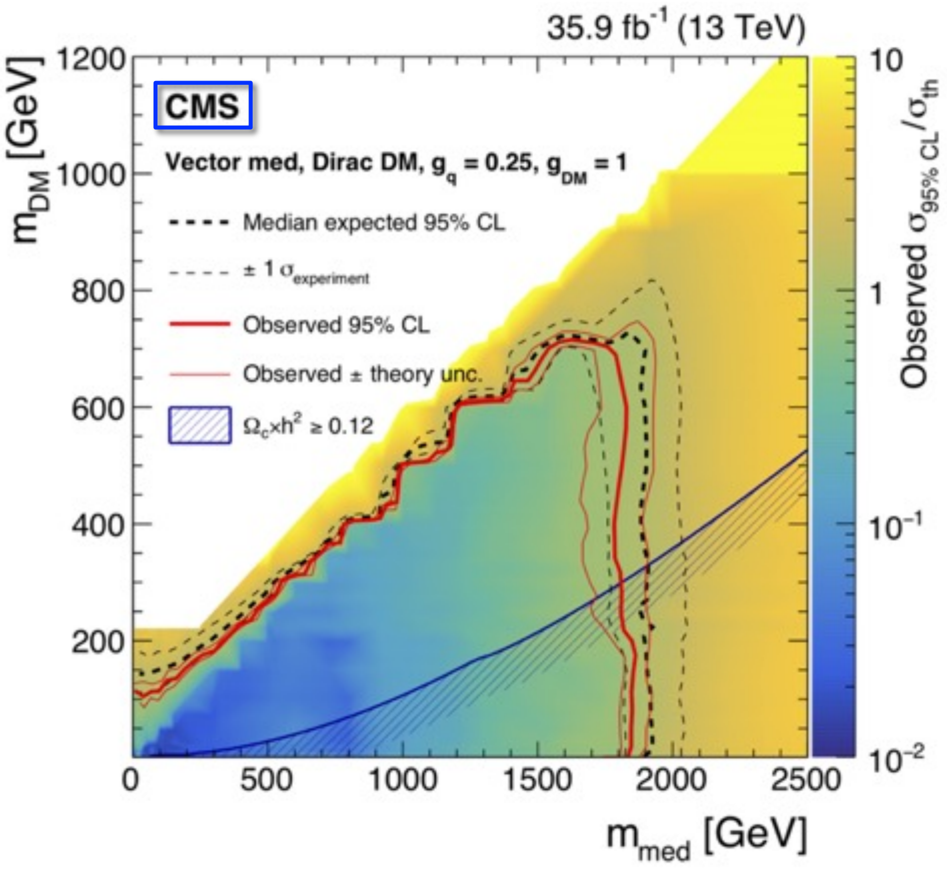
Scalar

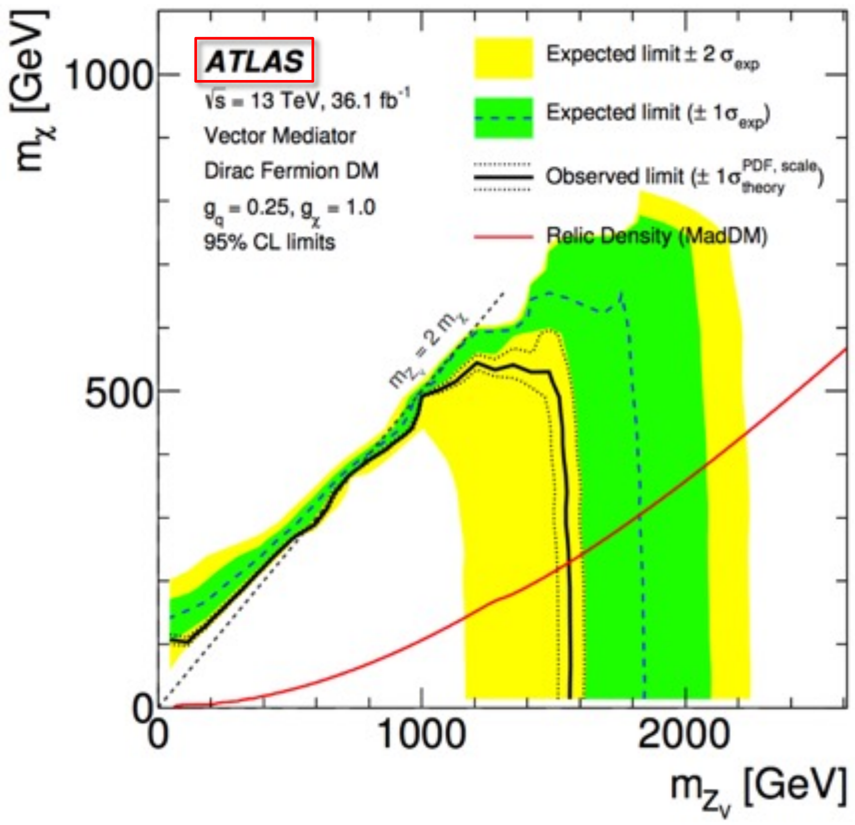


Pseudo-scalar



Comparison between ATLAS and CMS





Vector models in CMS and ATLAS are excluded for mediator masses up to 1.55 TeV to 1.8 TeV respectively for very low DM masses.

Mono-$Z(\rightarrow \ell\ell)$ at CMS

Events with E_T^{miss} > 100 GeV and lepton p_T > 25/20 GeV (electrons), > 20 GeV (muons)

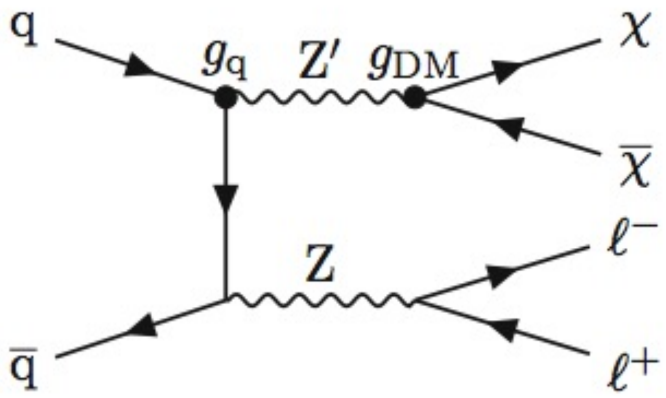
Main background

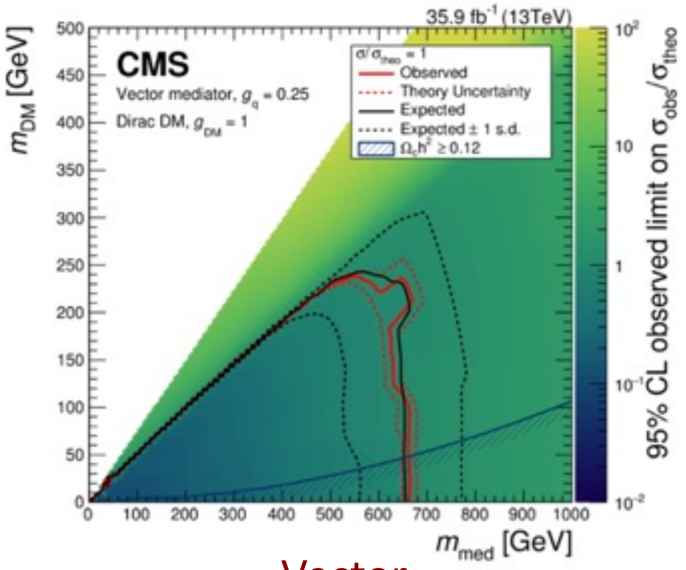
- $ZZ \rightarrow \nu\nu + \ell\ell$ irreducible

Vector/axial-vector mediator decays to DM particles

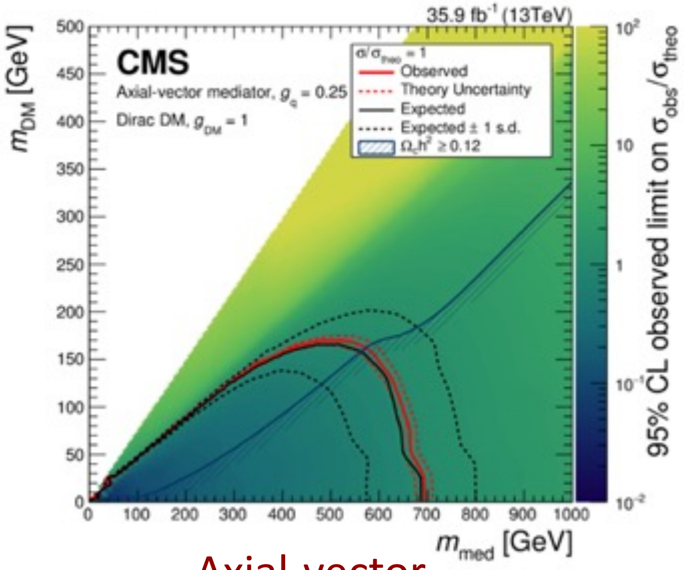
- Excluded the V/AV mediators for m_{med} < 700 GeV

Paper: Eur. Phys. J. C (2018) 78:291

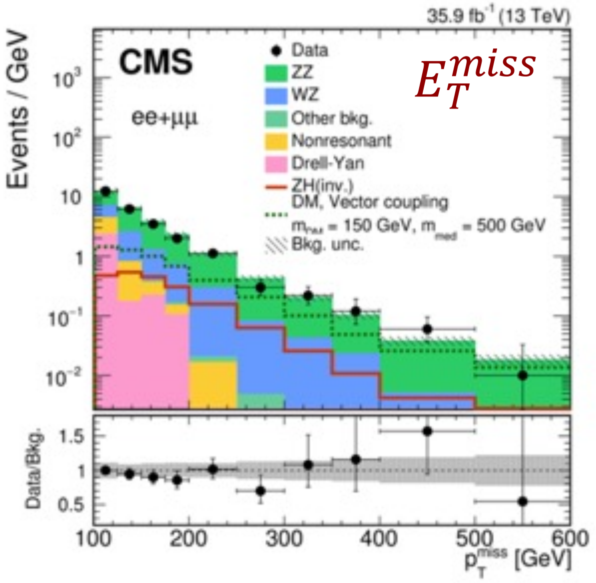




Vector



Axial-vector



Mono-photon at CMS

Events with E_T^{miss} > 170 GeV and at least one photon with p_T > 175 GeV

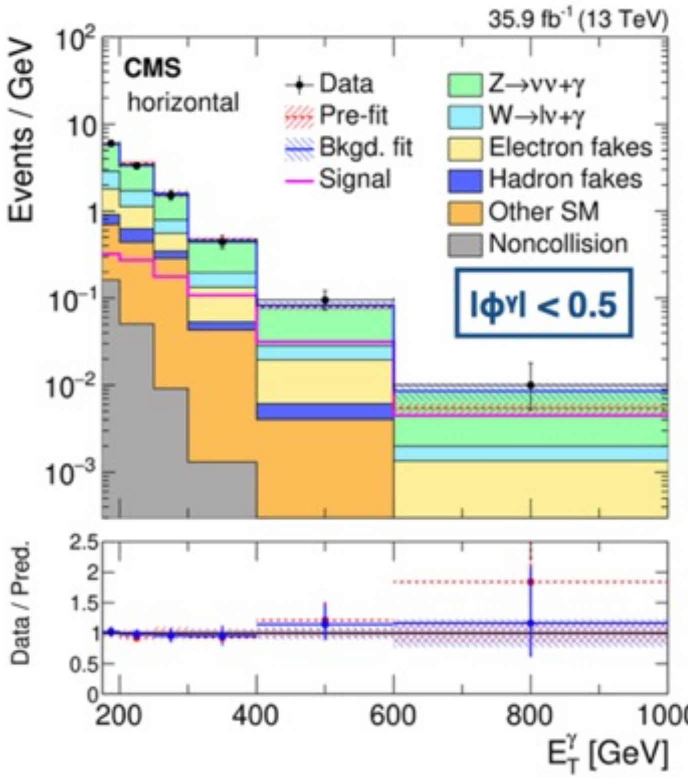
-> No electron or muon to reject $W(\ell\nu)+\gamma$ process

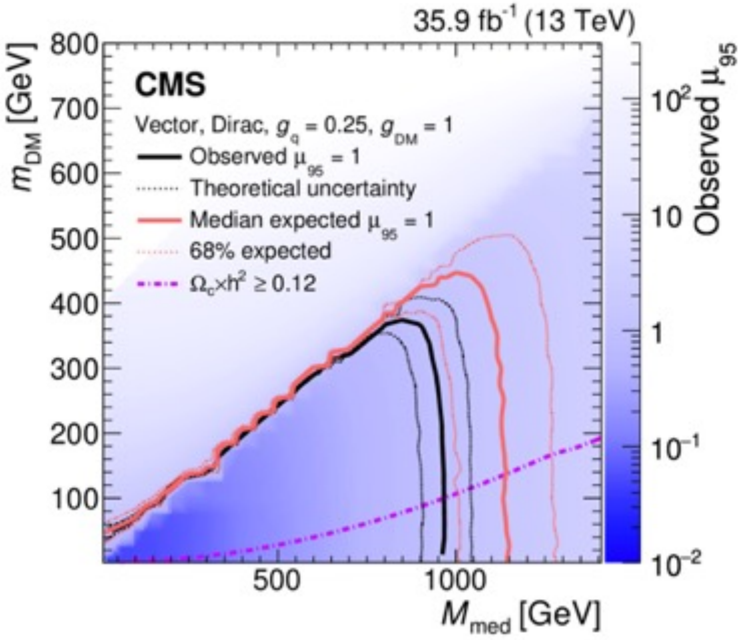
Dominant SM backgrounds:

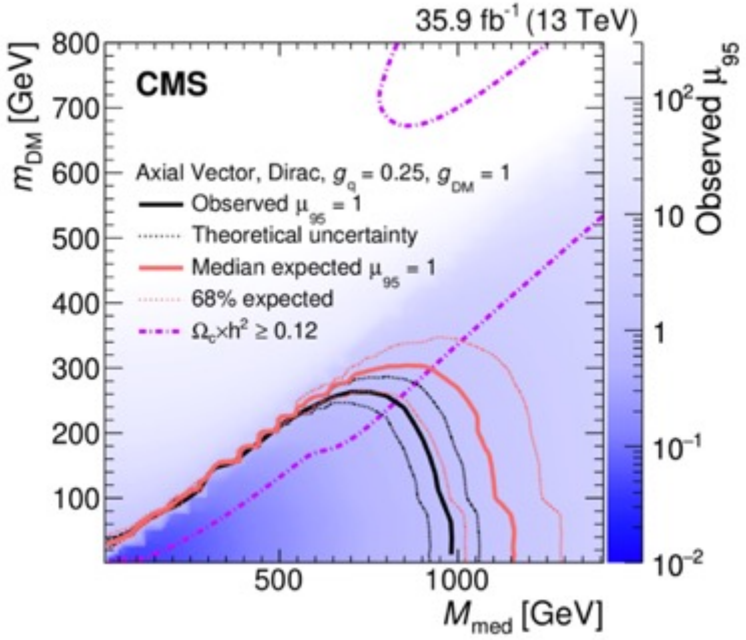
- $Z(\nu\nu)+\gamma$ and $W(\ell\nu)+\gamma$

Vector/axial-vector mediator m_{med} < 900 GeV excluded

Paper: [JHEP02(2019)074]

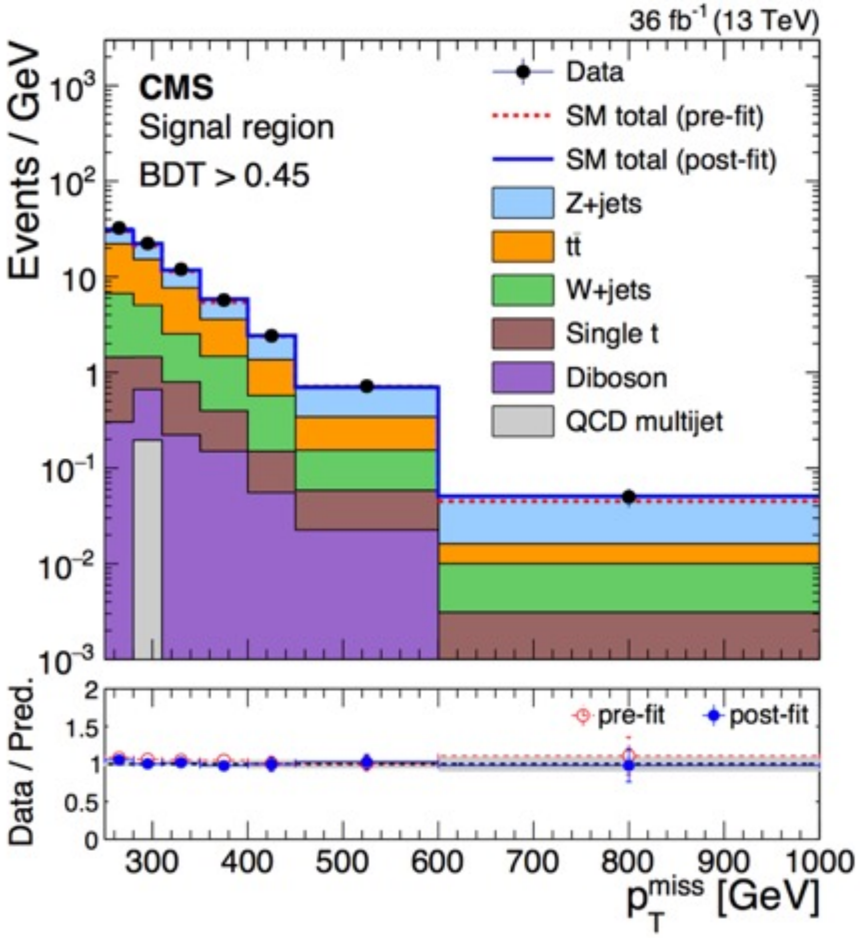




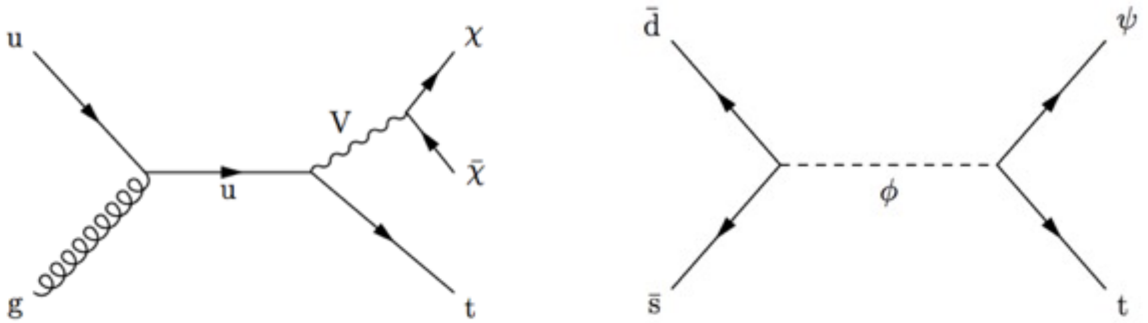


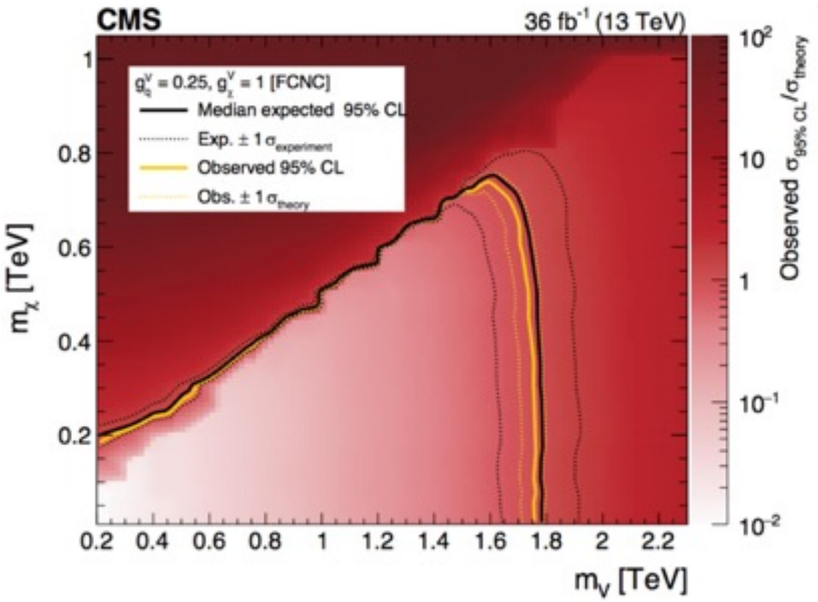
Mono-top (hadronic) at CMS

Simultaneous fit in two signal exclusions regions and 14 control regions



- Two DM models considered:
  - FCNC mediator (V)
    - Decays to DM pair
  - Colored, charged scalar (ϕ)
    - Decays to DM+top
- Augments other searches that assume flavor conservation





Dark matter + $t\bar{t}(b\bar{b})$ at ATLAS/CMS

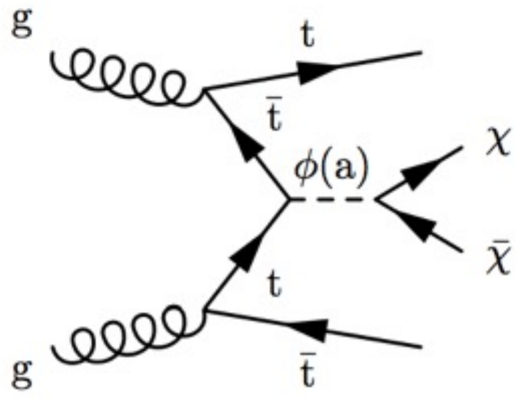
- Scalar/pseudoscalar mediators with Yukawa-like couplings to SM fermions
  - top couplings dominate

scalar

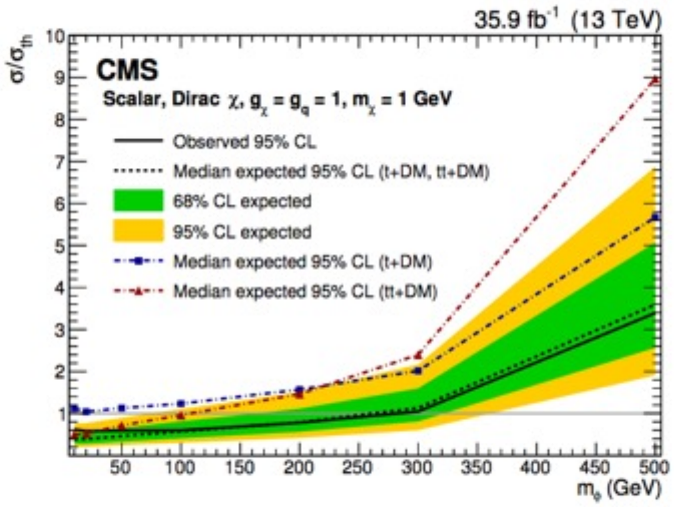
$$\mathcal{L}_\phi \supset g_\chi \phi \bar{\chi}\chi + \frac{g_q \phi}{\sqrt{2}} \sum_f (y_f \bar{f} f),$$

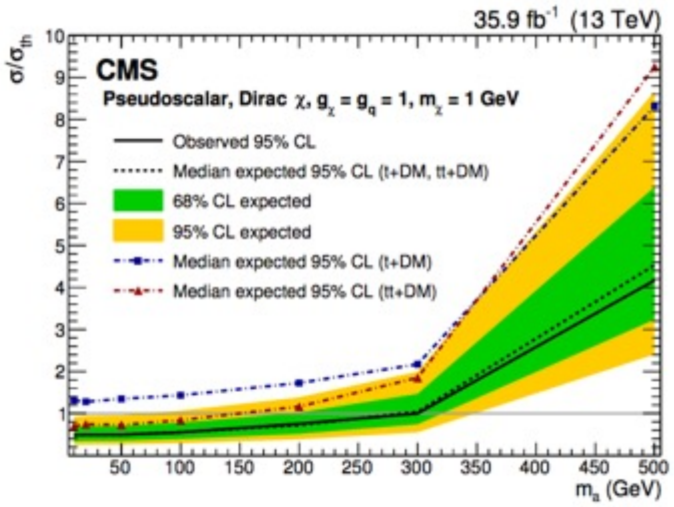
pseudoscalar

$$\mathcal{L}_a \supset i g_\chi a \bar{\chi}\gamma^5\chi + \frac{i g_q a}{\sqrt{2}} \sum_f (y_f \bar{f}\gamma^5 f),$$

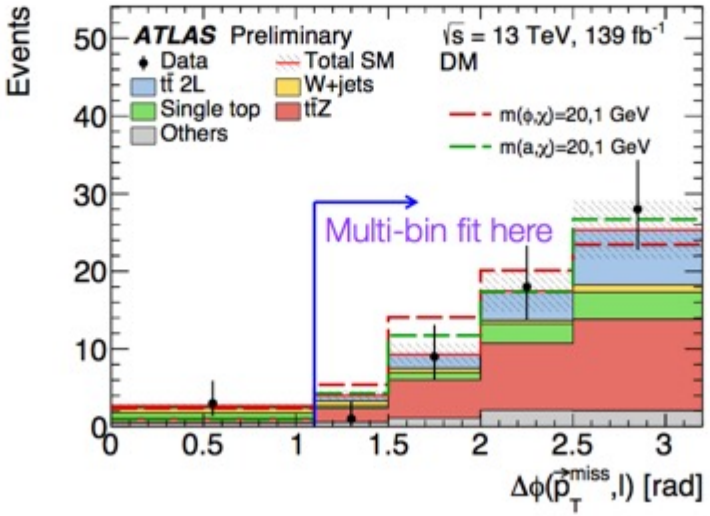


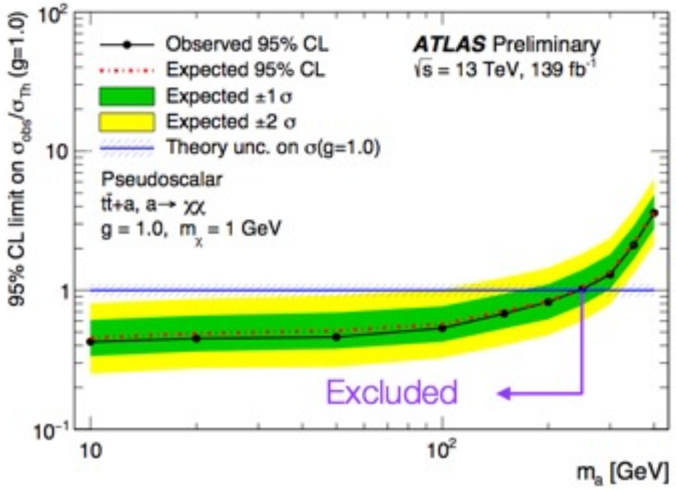
JHEP 03 (2019) 141





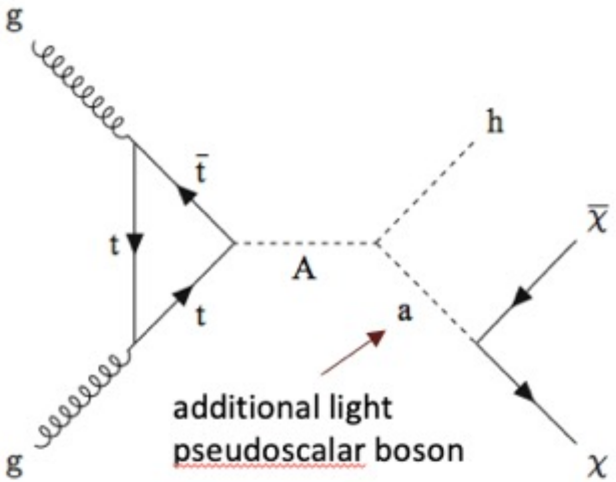
ATLAS-CONF-2020-003

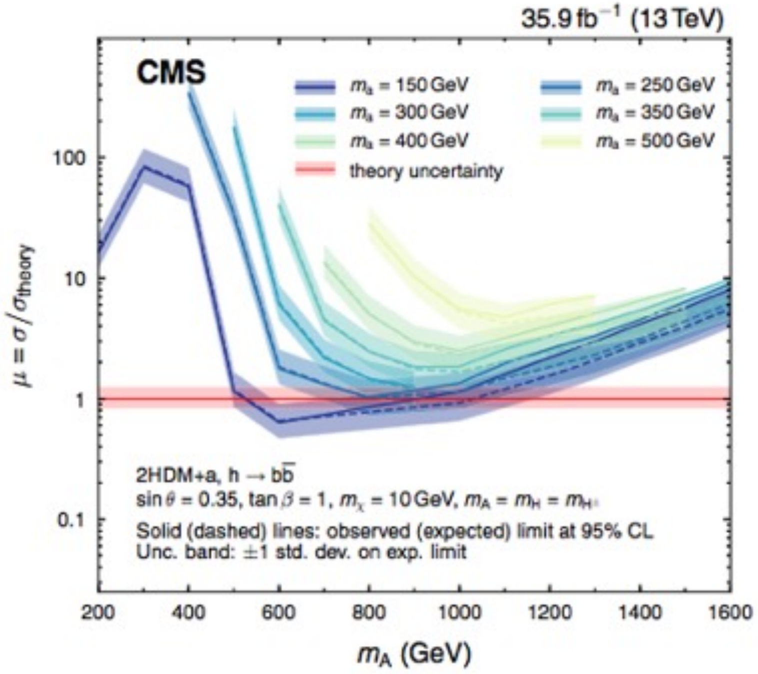




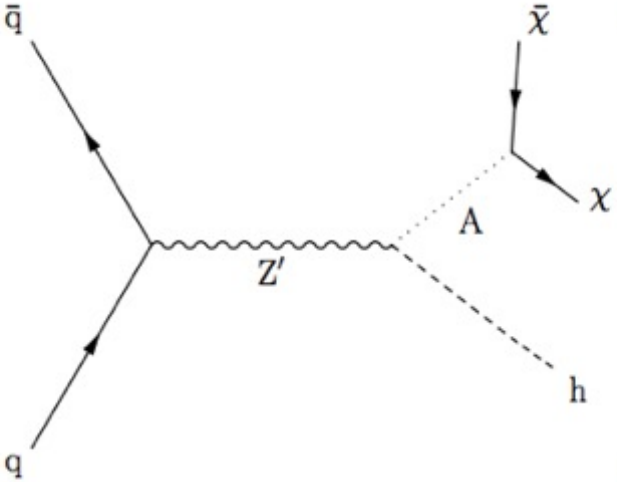
Mono-H at CMS

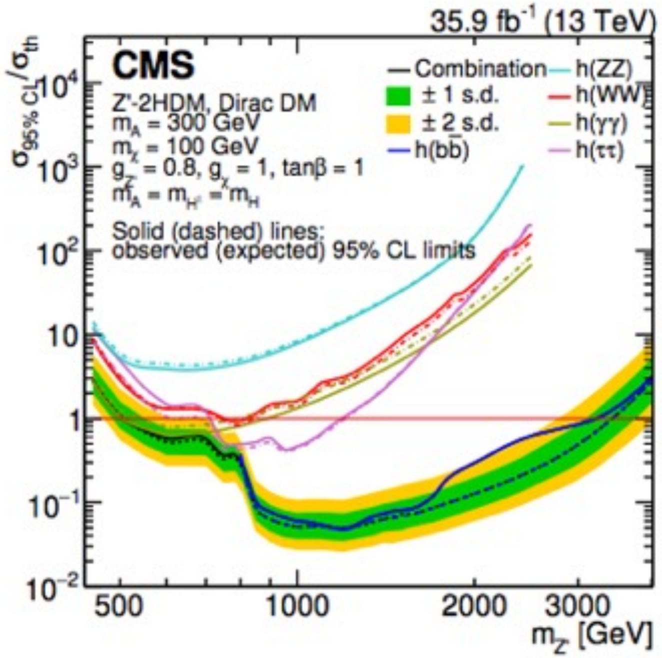
2HDM+a mode



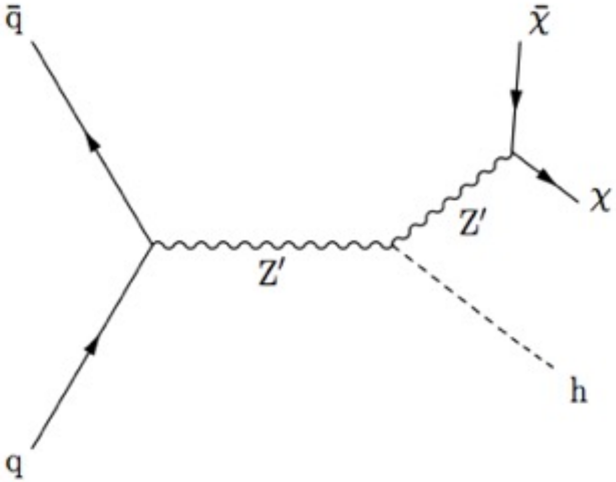


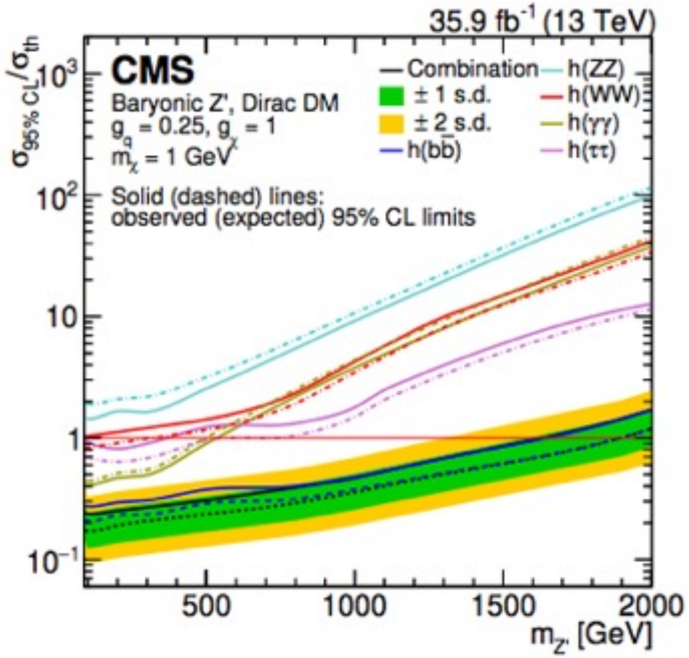
Z' - 2HDM





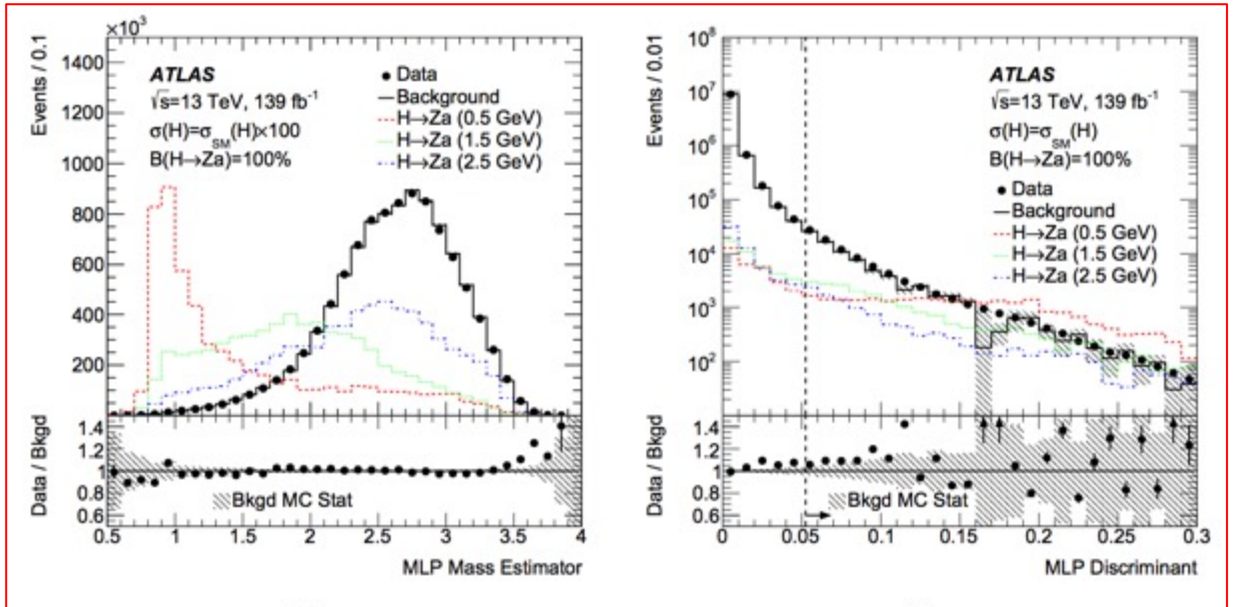
Baryonic Z' model





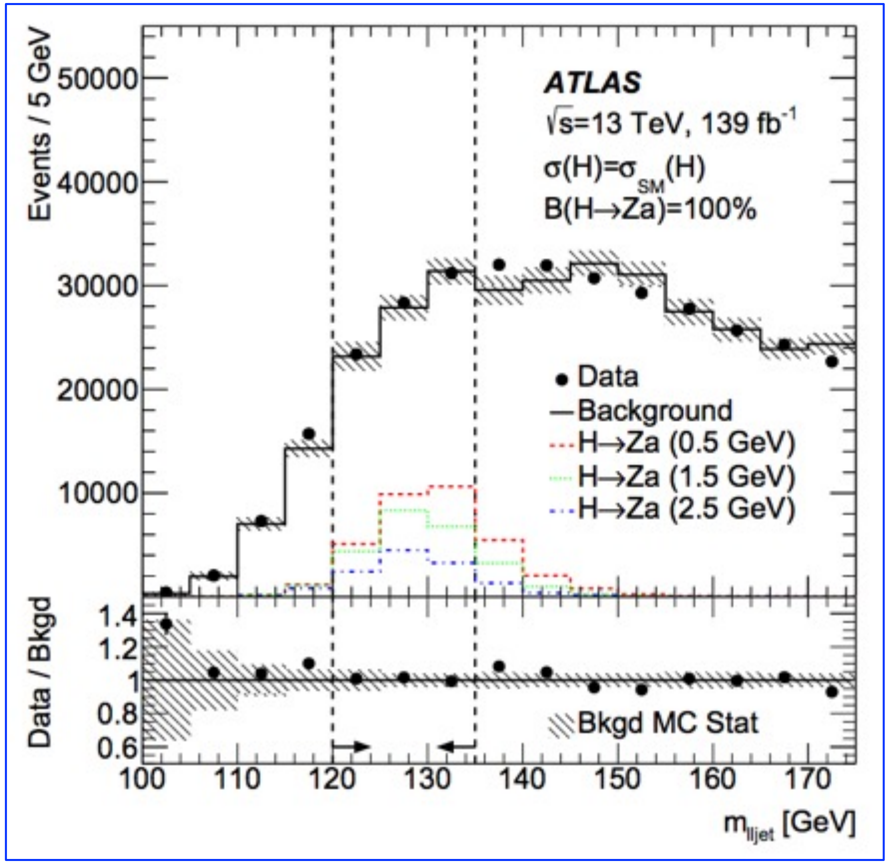
Higgs decays into visible at ATLAS

Higgs decays into a Z boson and a light resonance



(a) (b)

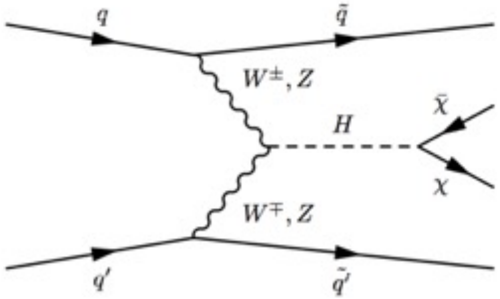
Signal region : Higgs mass window



Output of (a) the regression and (b) the classification by multi layer perceptron (MLPs)

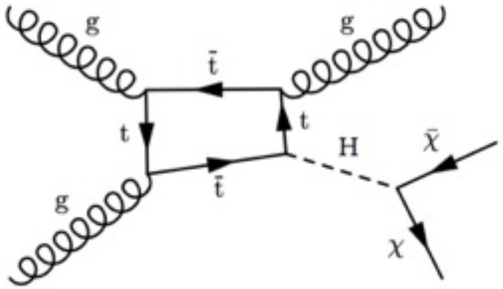
Invisible Higgs decays at CMS

Several ways of tagging invisible Higgs production

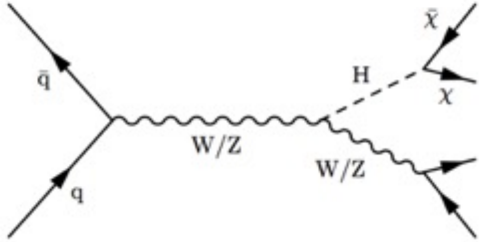


Most sensitive channel

Vector Boson Fusion (VBF) tag – forward jets



Mono-jet



Mono Z(ll) or W/Z (had)

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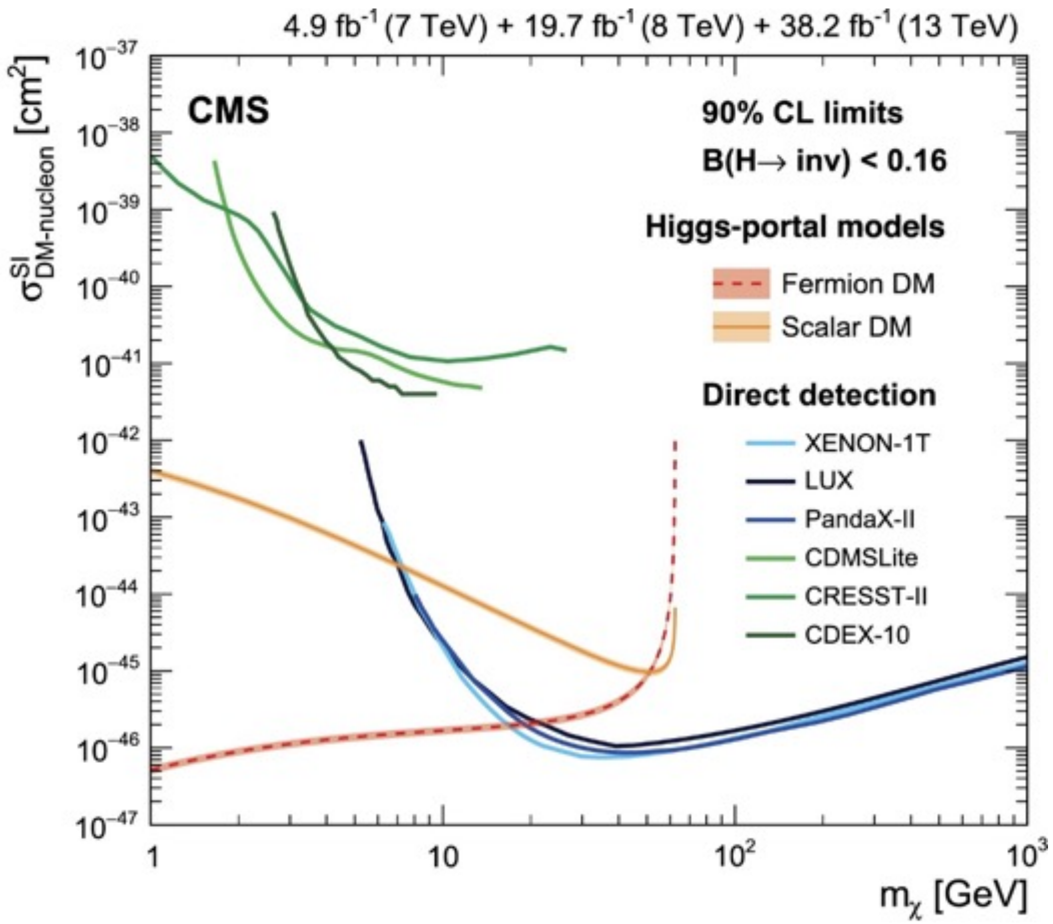
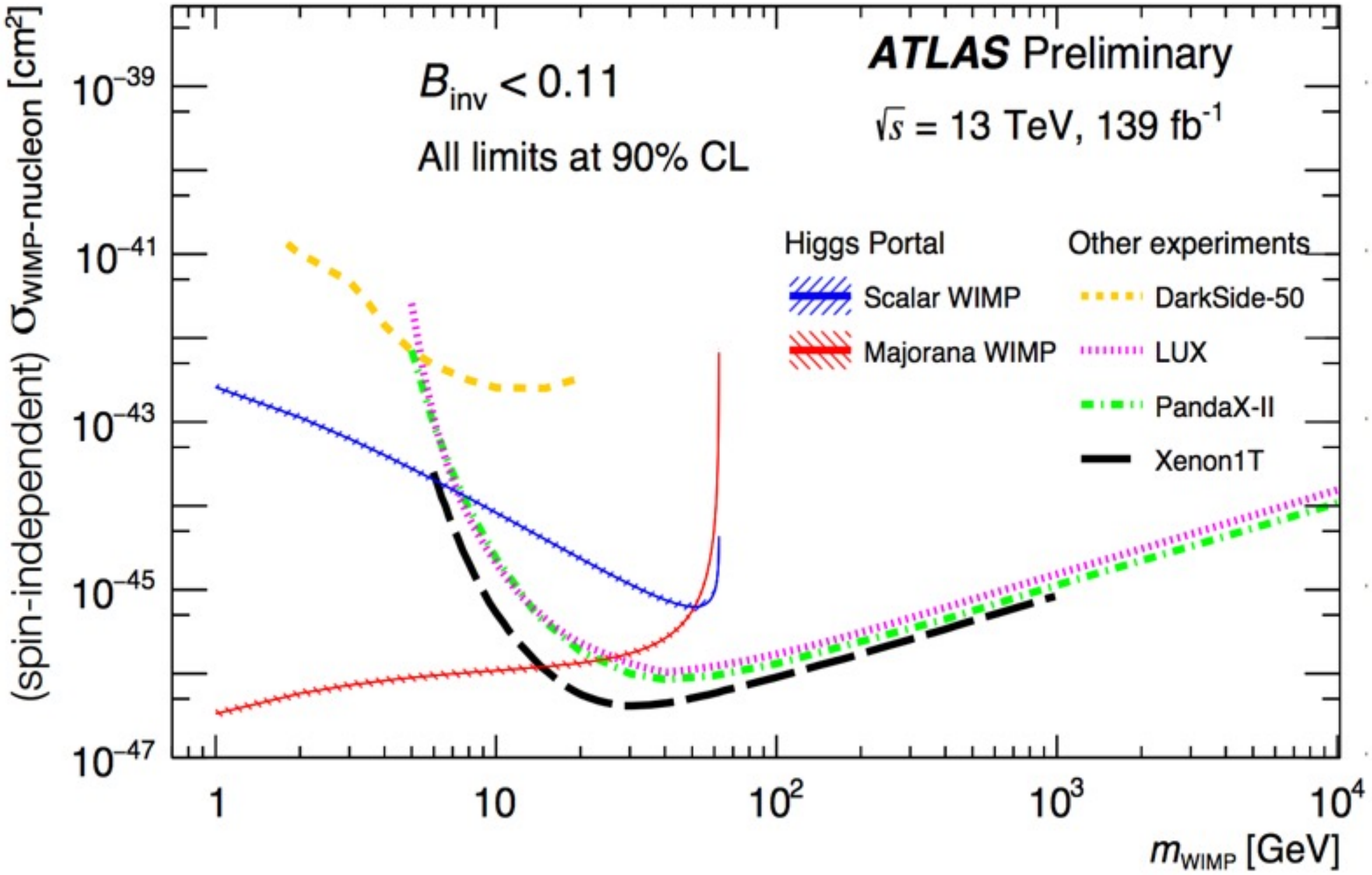
95% CL upper limit : Obs (Exp)
VBF 13 TeV, 36 fb^{-1} : 0.33 (0.25)
Combination : 0.19 (0.15)



CHANG-SEONG MOON (KNU)

Invisible Higgs decays at ATLAS

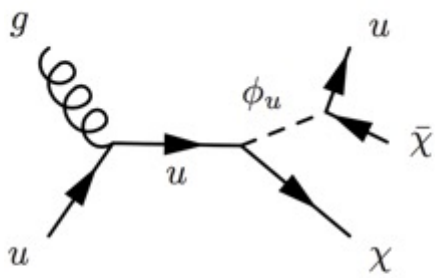
- Fermion DM search provide the best limit below 20 GeV
- Only sensitive for $m_\chi < m_h/2$ $\longrightarrow$ competitive bounds for low DM mass



t-channel mediator at ATLAS/CMS

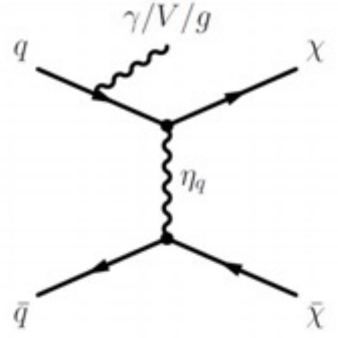
Fermion Portal DM model

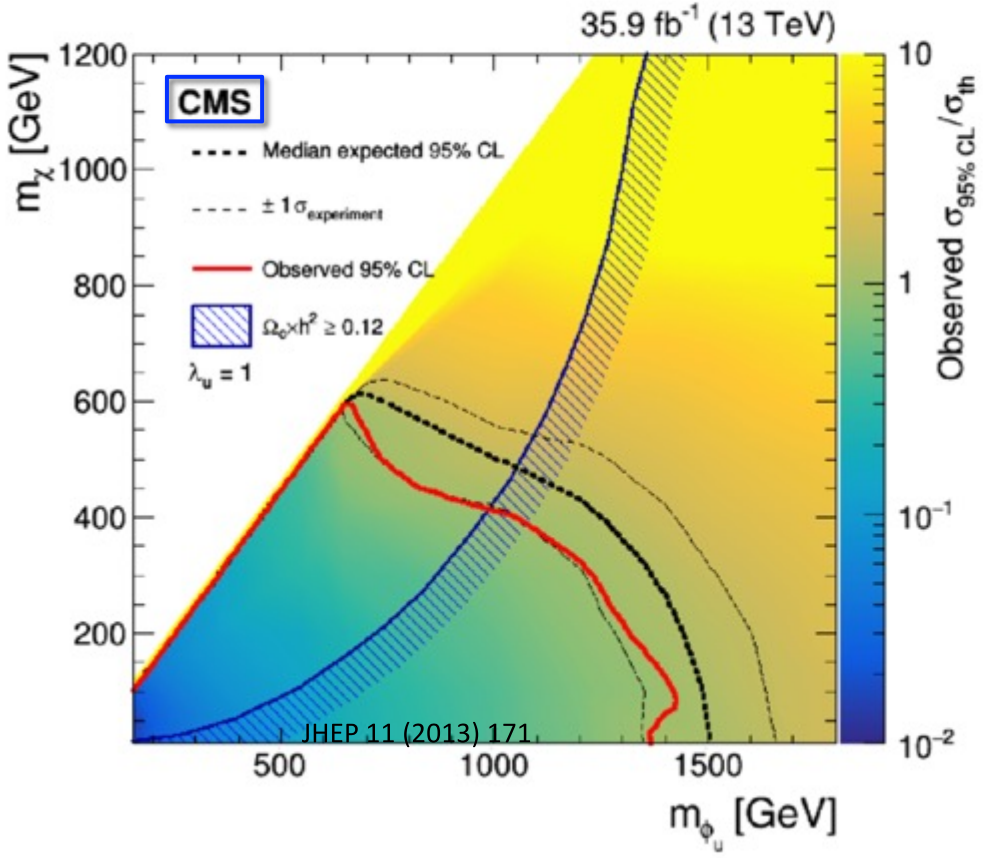
- color-triplet scalar mediator (ϕ_u) couples to DM and up-type quark



Scalar Colour-Charged mediator

- Mediator masses up to 1.67 TeV excluded for m_χ = 50 GeV
- In the case of $m_\chi = m_\eta$, masses up to 620 GeV are excluded.





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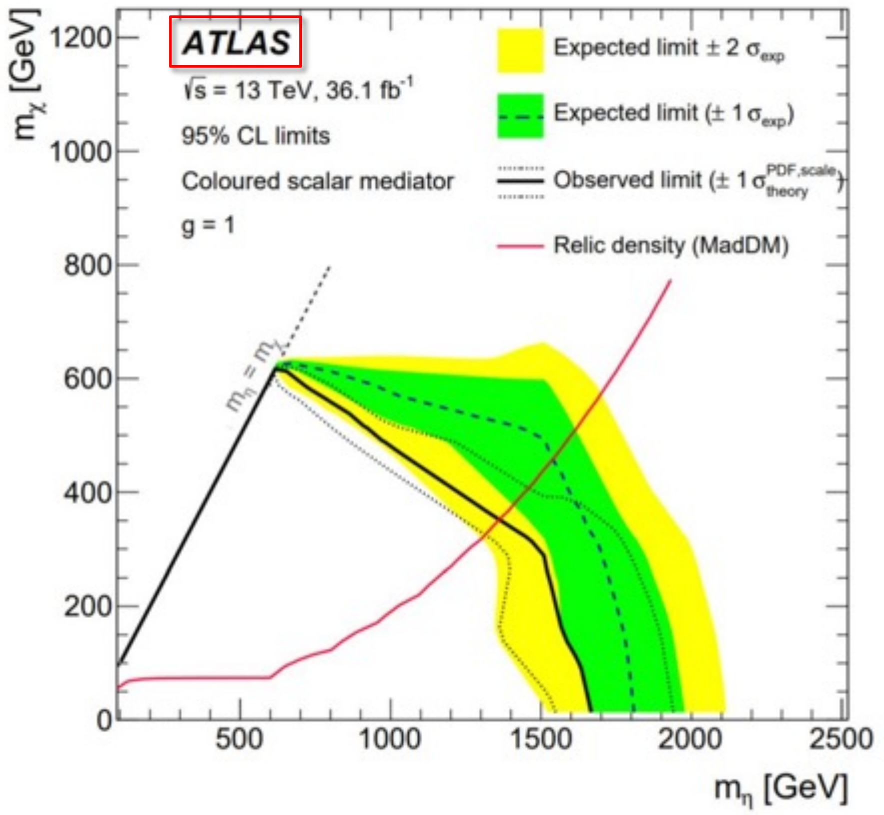
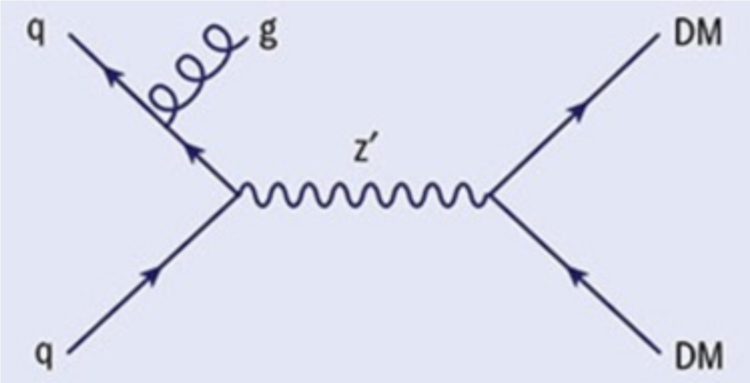
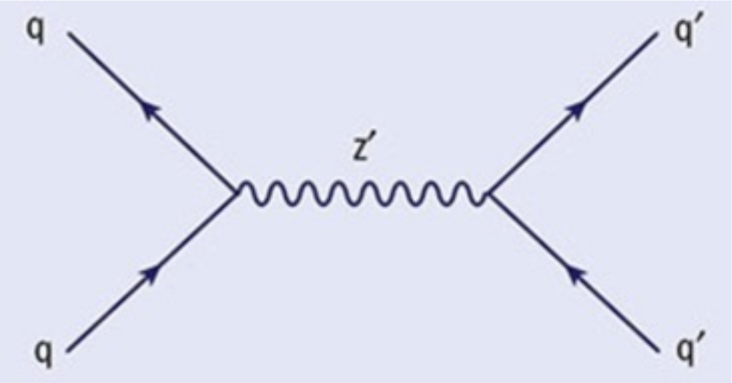


Dark matter mediator search with di-jet events

- Resonance searches complementary to the direct search for WIMPs using mono-X signatures
- New mediator produced at the LHC and decaying to WIMPs can also decay back to partons



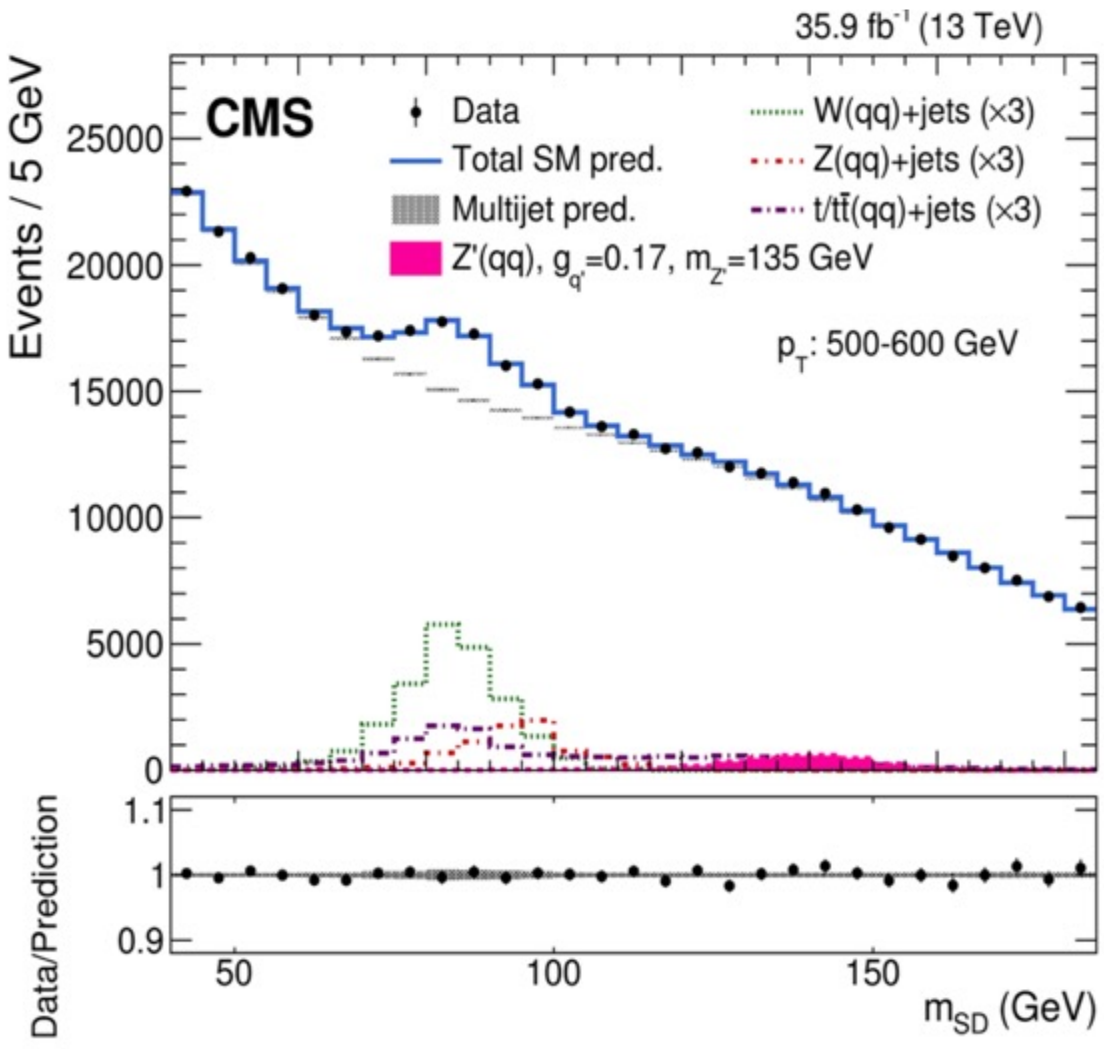


- If accessible to LHC energies, the cross-talk between the DM searches and the resonance searches will be key to establishing the characteristics of interaction.

- One of key strengths of the collider approach

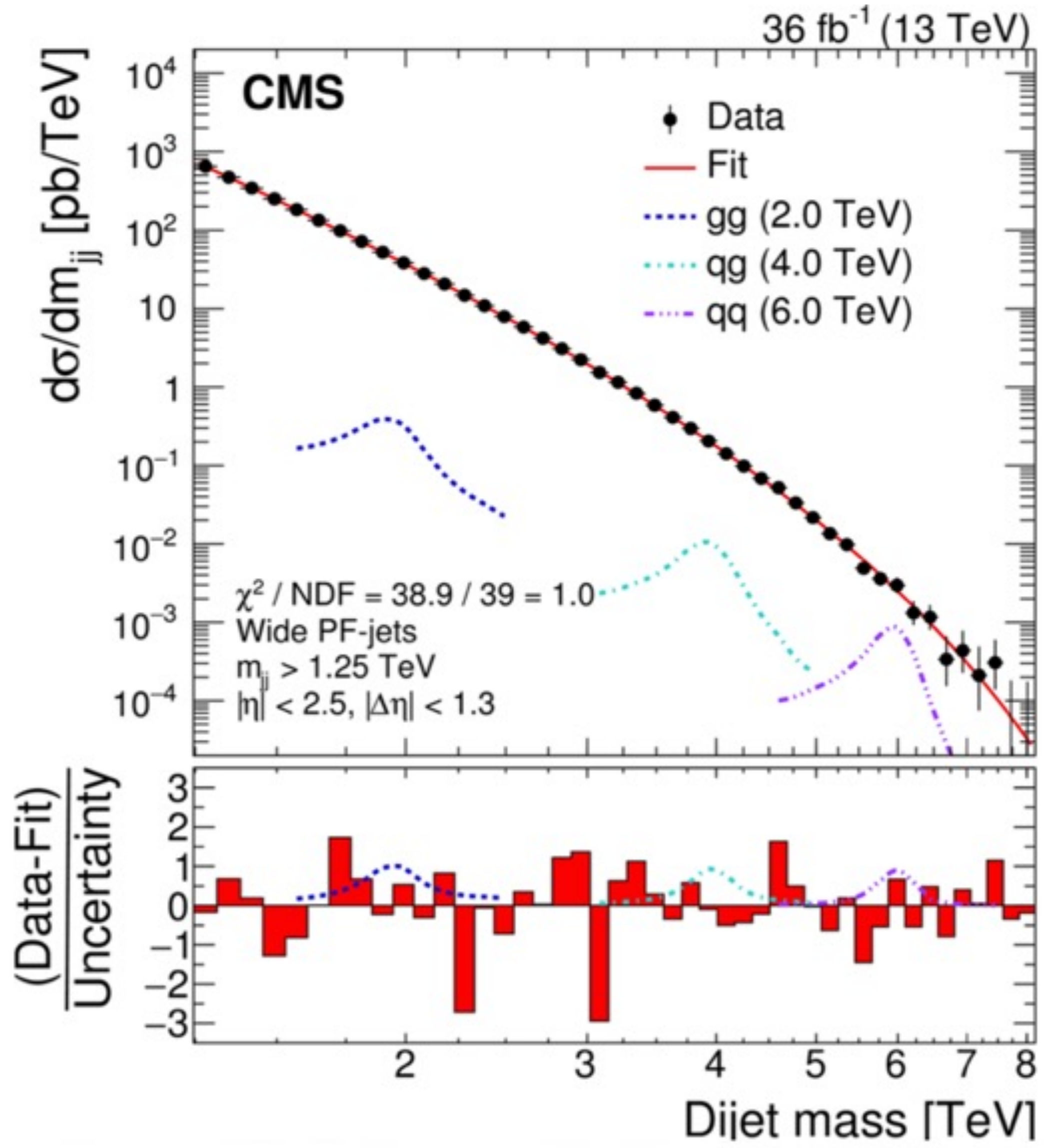
Mediator search with di-jet at CMS

low mass mediator

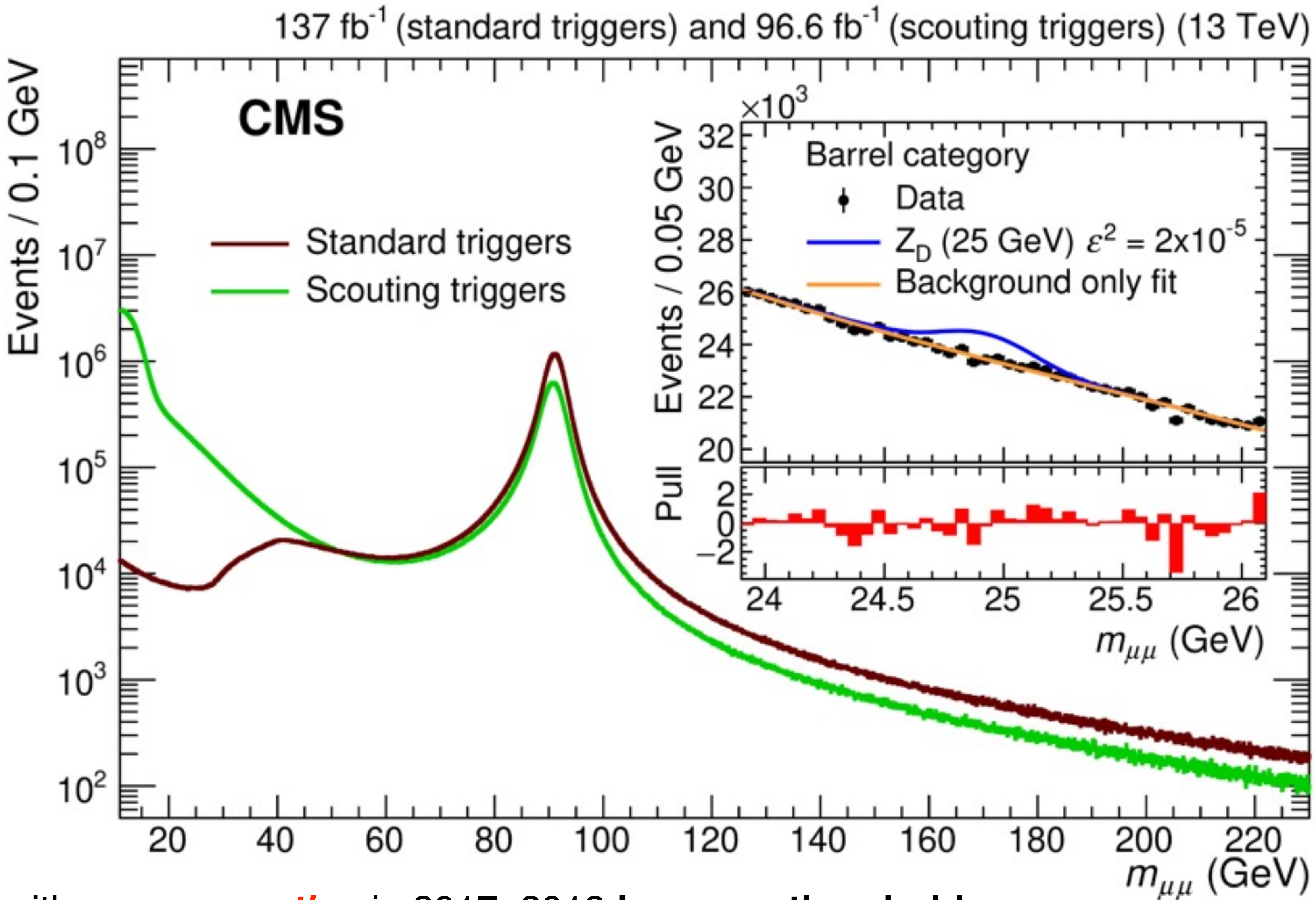


ISR-recoil analysis: 50 GeV < m_{jj} < 300 GeV

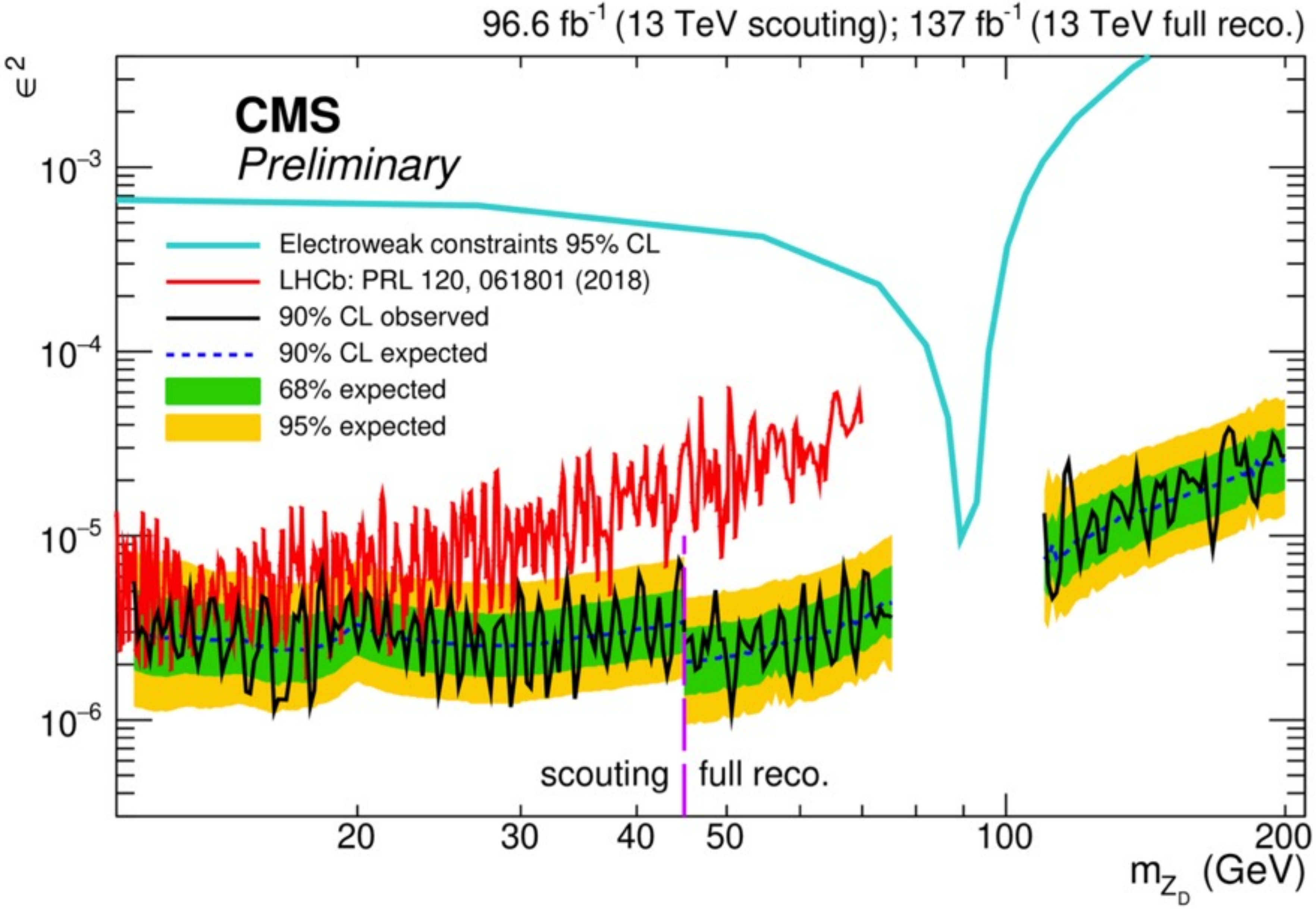
high mass mediator



Dark Photon Search at CMS



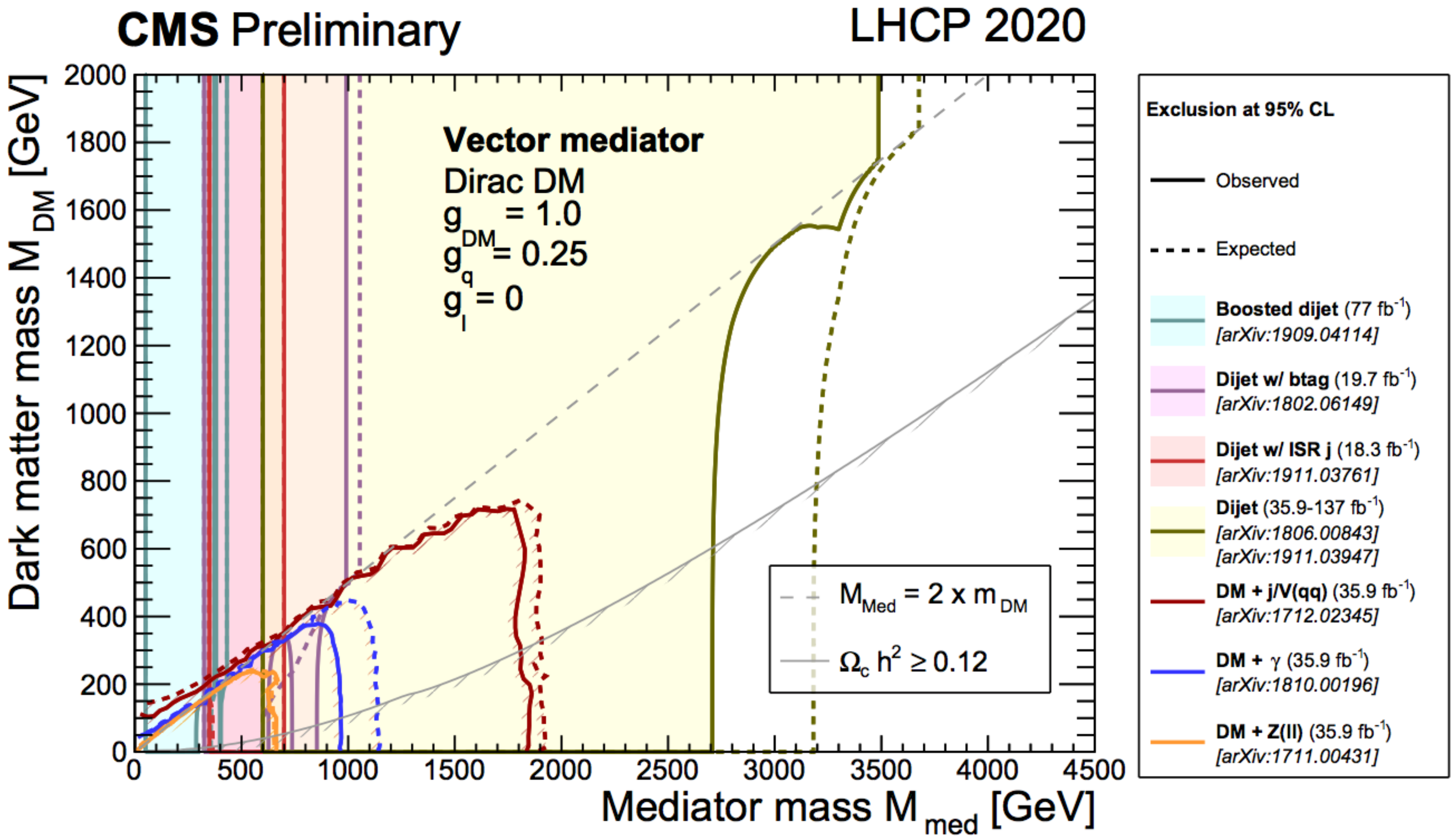
Data collected with ***muon scouting*** in 2017, 2018 **Lower p_T thresholds** on muons
But **save only trigger-level information** about the muons



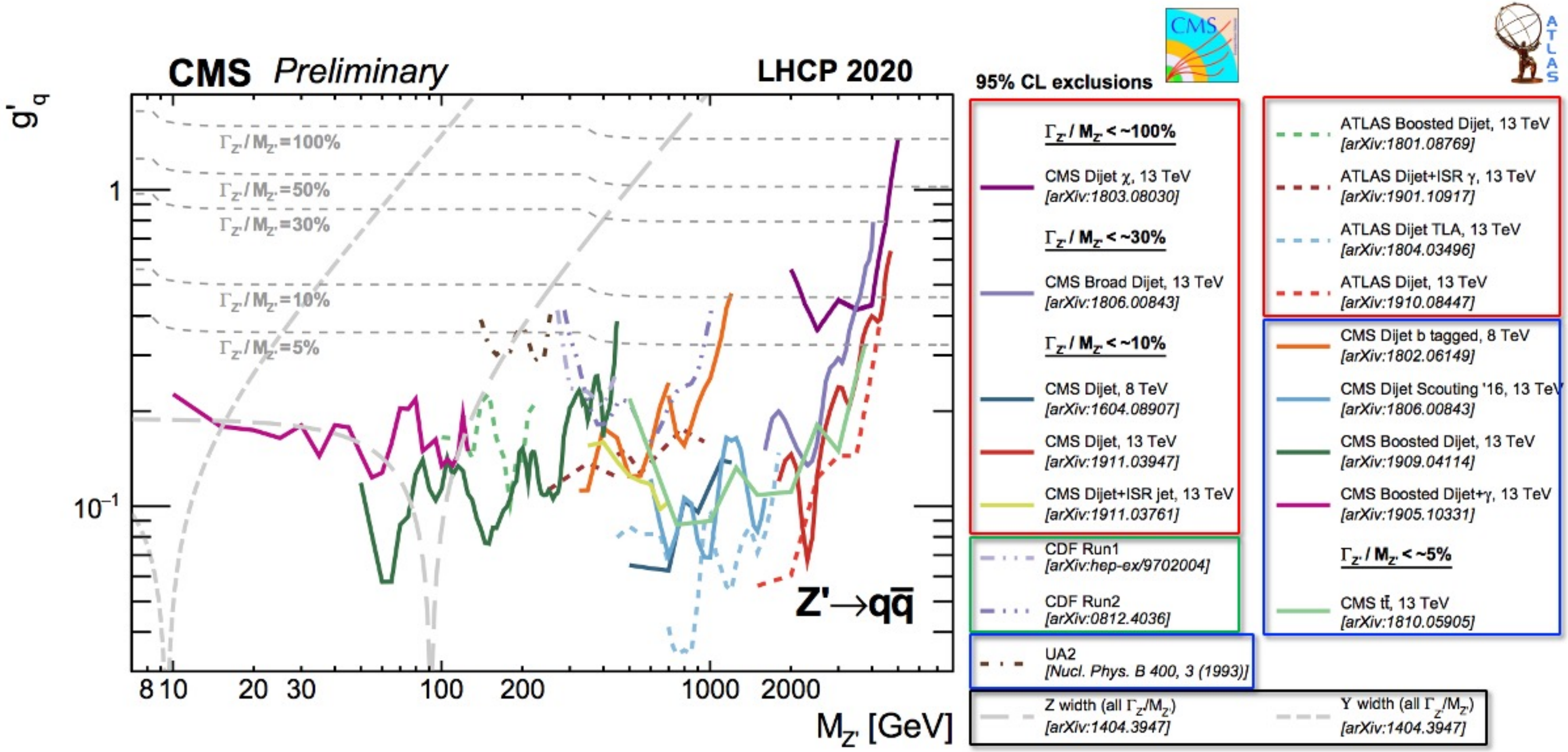
Search for dark photons heavier than 11.5 GeV

For masses below Z peak, 90% CL upper limit on $\epsilon^2 \sim 3 \times 10^{-6}$

Limits on Dark matter and Mediator at CMS



Limits on the universal coupling (g'q)

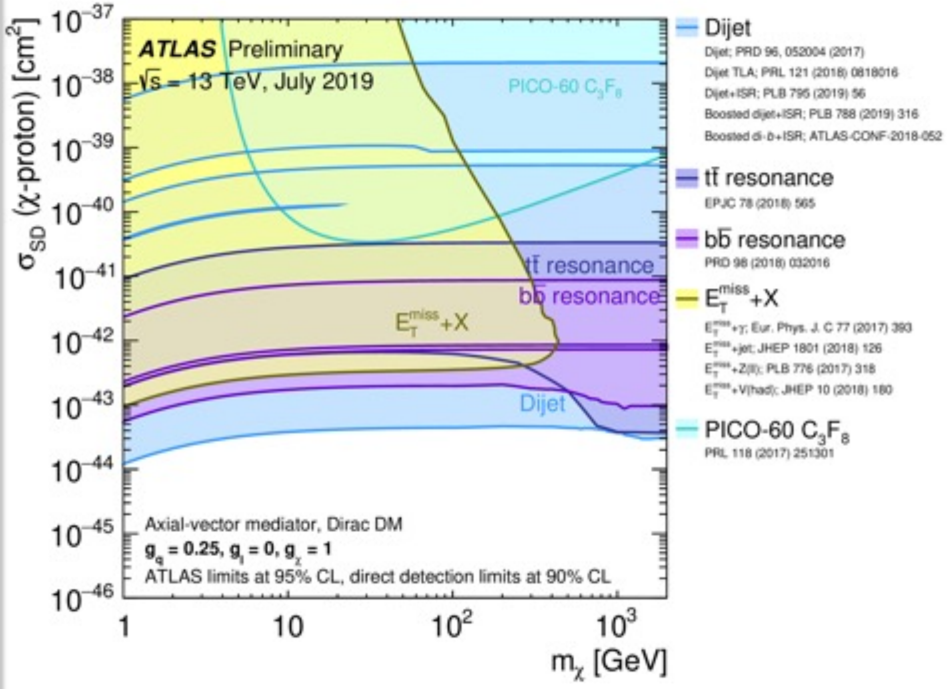


Comparison of Limits on the universal coupling g'_q between a Z′ boson and quarks from various di-jet results from ATLAS, CMS, CDF and UA2 experiments.

Comparisons to direct detection experiments

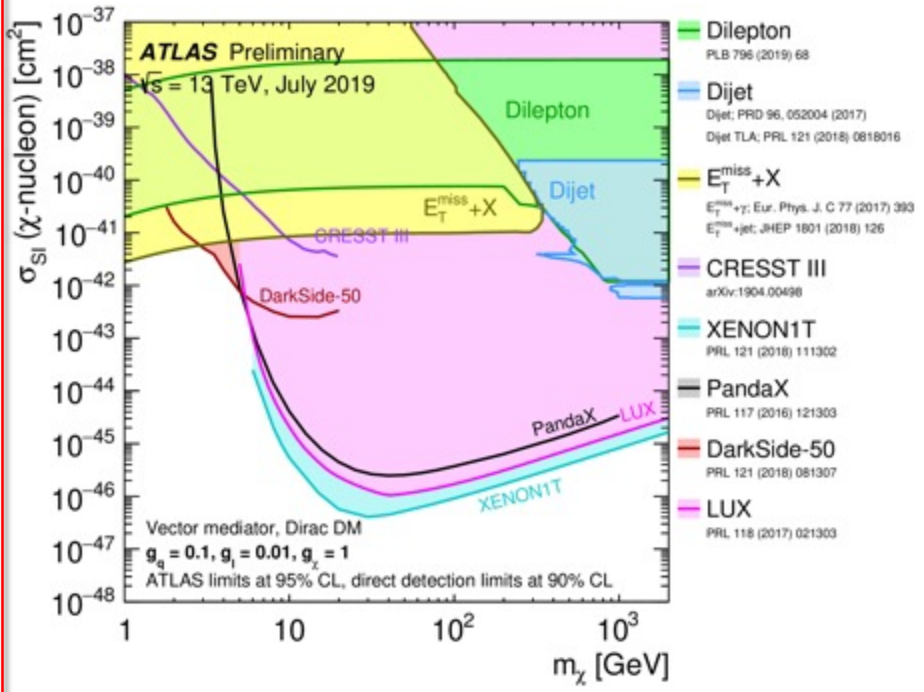
Spin dependent Axial-vector

$g_q = 0.25,\ g_l = 0,\ g_\chi = 1$



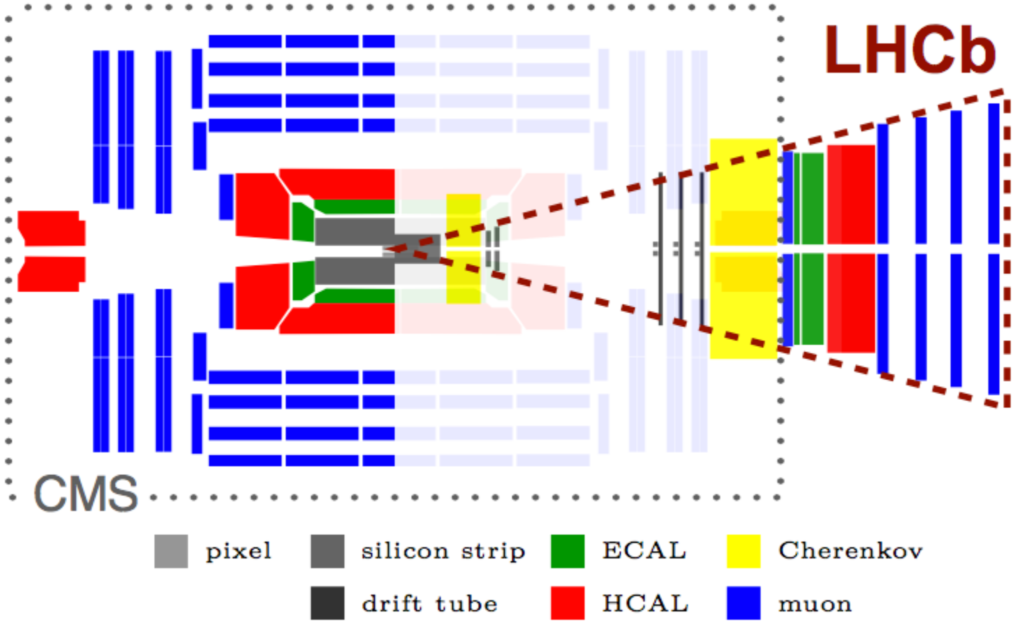
Spin independent Vector

$g_q = 0.1,\ g_l = 0.01,\ g_\chi = 1$



- Comparison of the inferred limits with the constraints from direct-detection
  - Spin dependent WIMP-proton cross-section for axial-vector couplings (left)
  - Spin independent WIMP-nucleon cross-section for vector couplings (right)

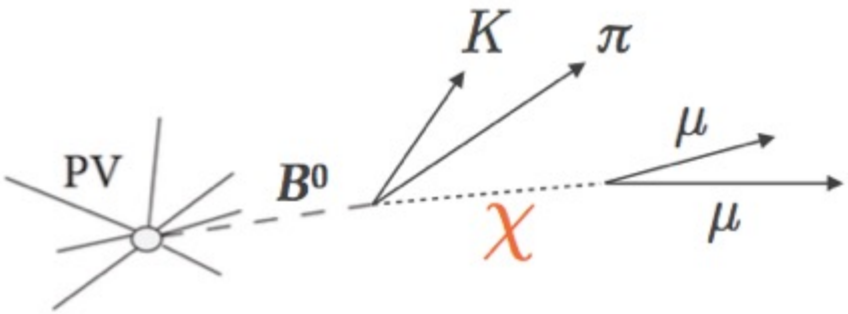
Dark matter at LHCb



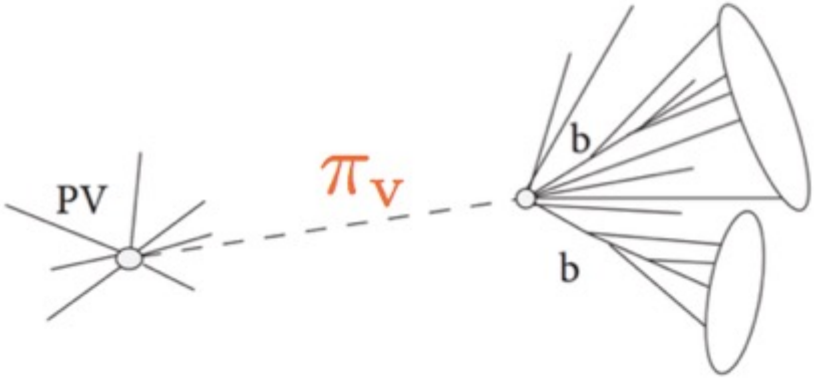
- Unique coverage (2<η<5)
- Soft trigger and forward acceptance :
  - Lighter masses of DM
- Larger forward boost and excellent secondary/tertiary vertex resolution :
  - Short lifetimes (1 ps) of DM
- Very good track momentum resolution

- Two main research

1. Production in Heavy Flavor decays (prompt / displaced)

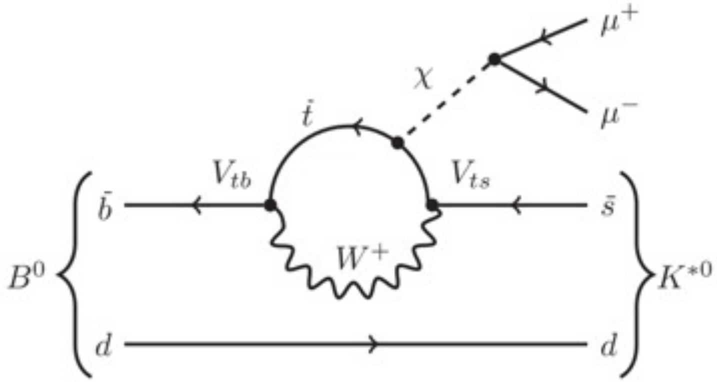


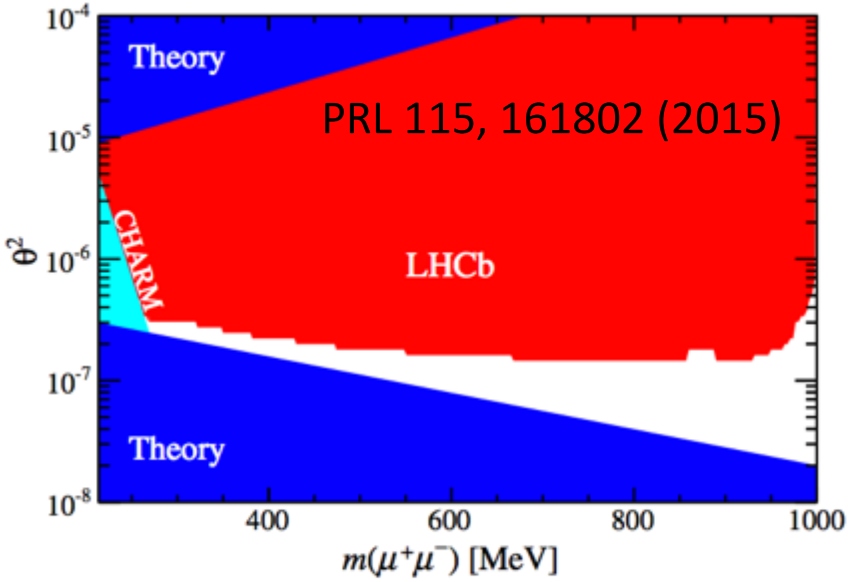
2. Production in pp collision (prompt / displaced)



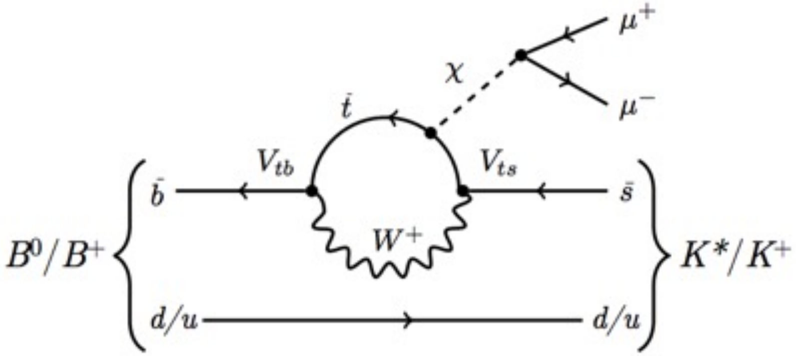
DM searches in B decays at LHCb

- Search for Hidden-Sector Bosons in $B^0 \to K^{*0}\mu^+\mu^-$ Decays





- Search for long-lived scalar particles in $B^+ \to K^+\chi(\mu^+\mu^-)$ decays



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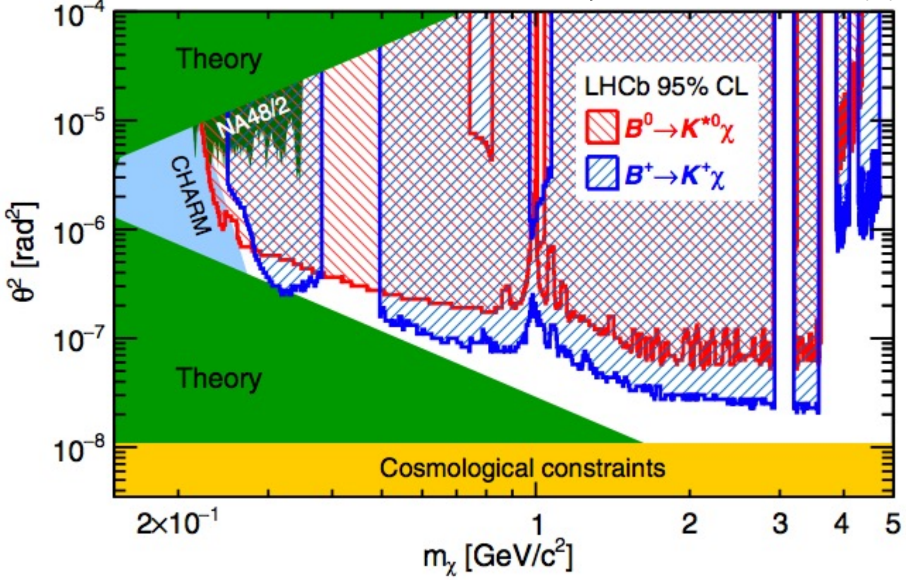
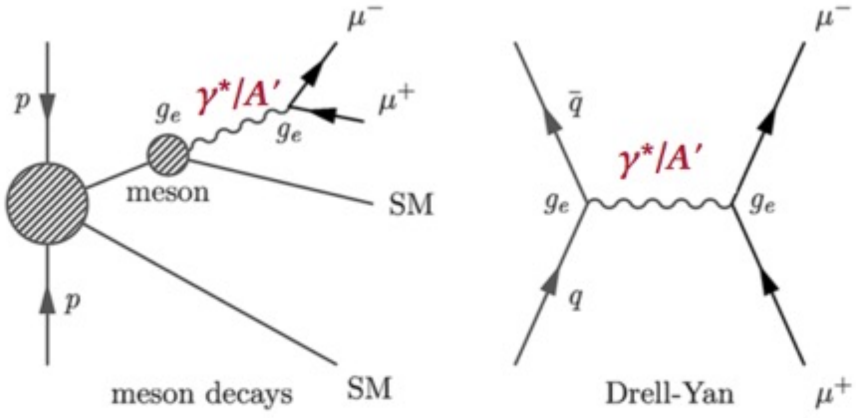
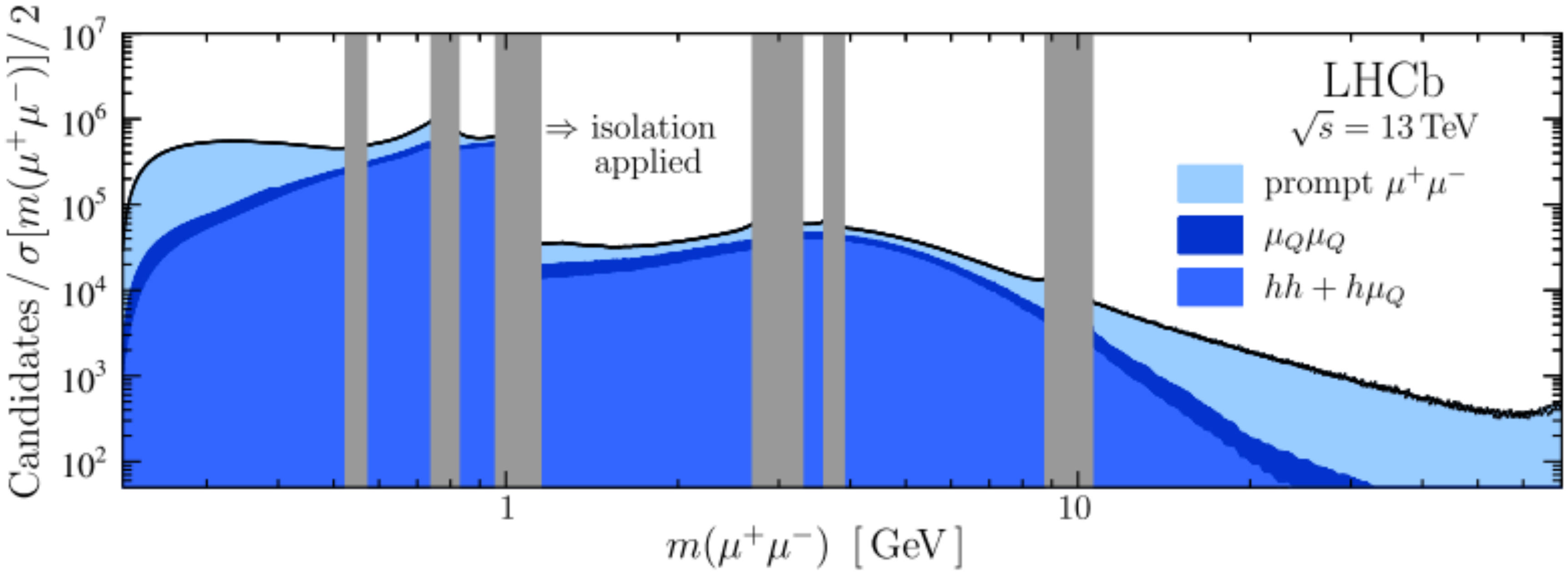


Dark photon in dileption at LHCb

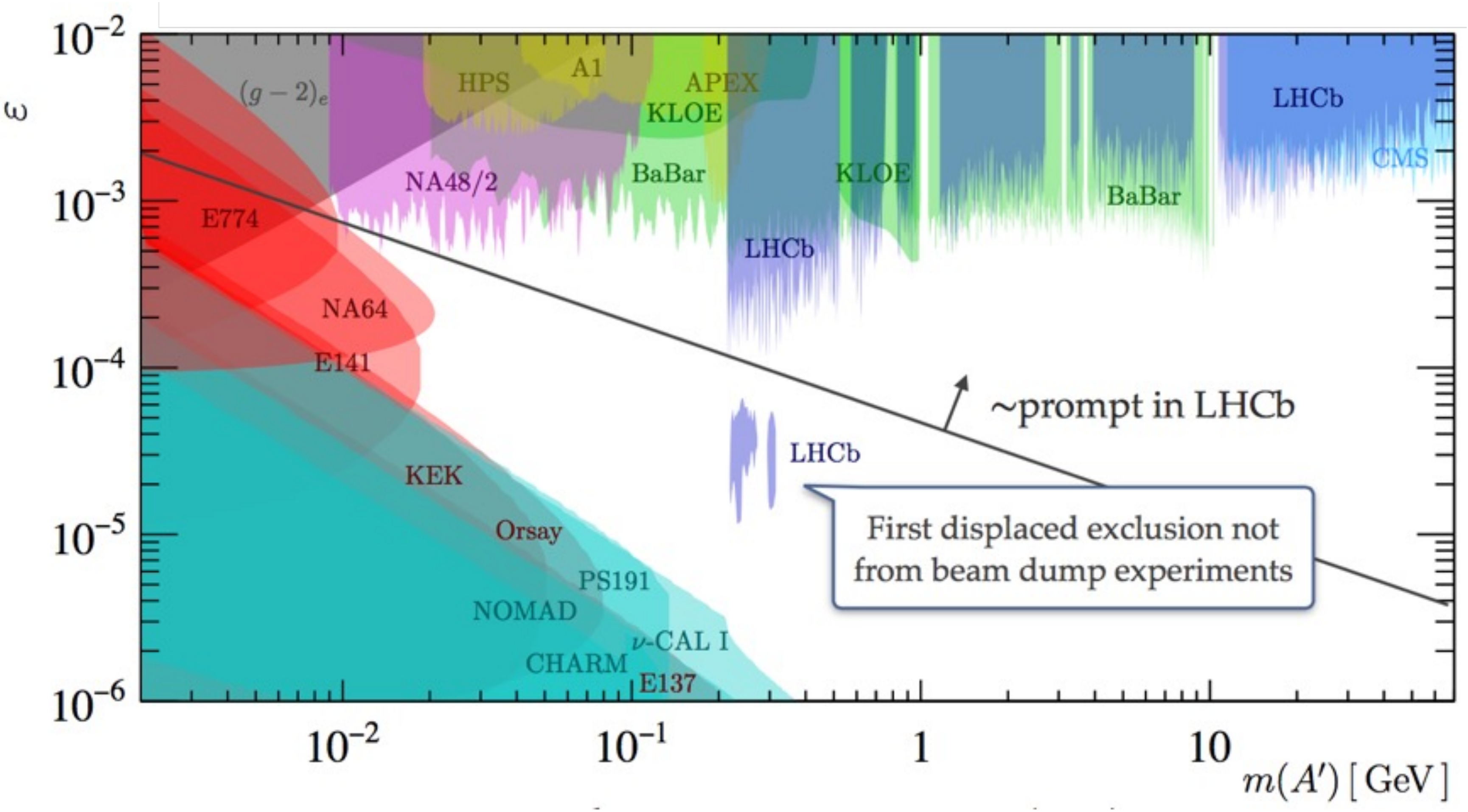
Search for $A' \rightarrow \mu^+\mu^-$ Decays

- Excellent mass resolution is essential for background estimation.
- Soft trigger on μ p_T



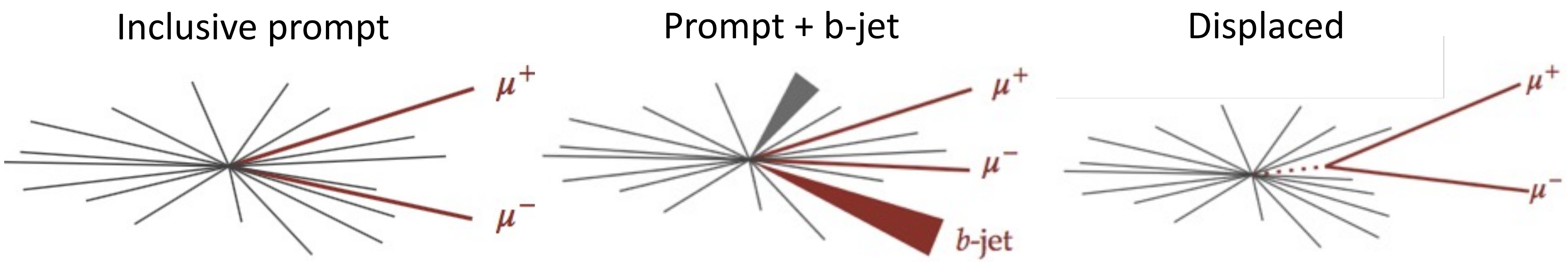


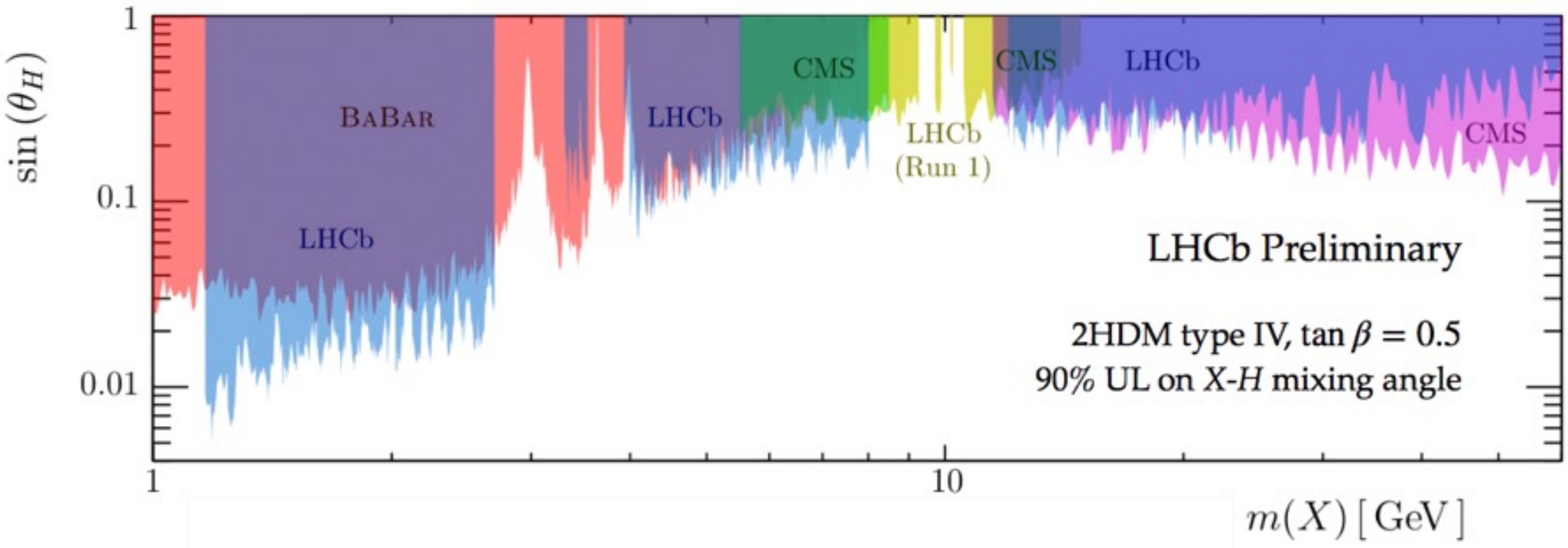
Limits on Dark photon



$D^{*} \rightarrow D^{0}A'(e^{+}e^{-})$ channel can be analysed in Run 3 thanks to upgrade to a triggerless-readout system at LHCb

Inclusive $X \to \mu^+\mu^-$ search





- World best upper limit from LHCb results on mixing angle with Higgs $\sin(\theta_H)$

Concluding remarks

DM search is one of key physics programs at ATLAS, CMS and LHCb.

LHC DM analyses focused on the WIMP search based on the simplified models.

- Mono-X strategy : large E_T^{miss} by DM and SM particle recoiling against DM
  - Mono-X: Jet, γ/ W / Z, top, $b\bar{b}$, $t\bar{t}$, $Higgs$
- Mediator searches
- LHCb results : Production in HF and direct from pp collision

No significant excess yet over the SM background and set limit on the m_{med} and m_{DM}

- Most analysis based on data set up to full Run 2 data at 13 TeV.
- **Provided an important complementary check with DD and ID experiments.**

Run3 data will be taken soon.

- **Stay tuned for the new updates on DM searches at ATLAS, CMS and LHCb.**