LDMA'17

Light Dark Matter 2017

24-28 May 2017

La Biodola - Isola d'Elba

SEARCHES FOR DARK MATTER AT ATLAS AND CMS

Rocío Vilar

(for Atlas and CMS collaboration)

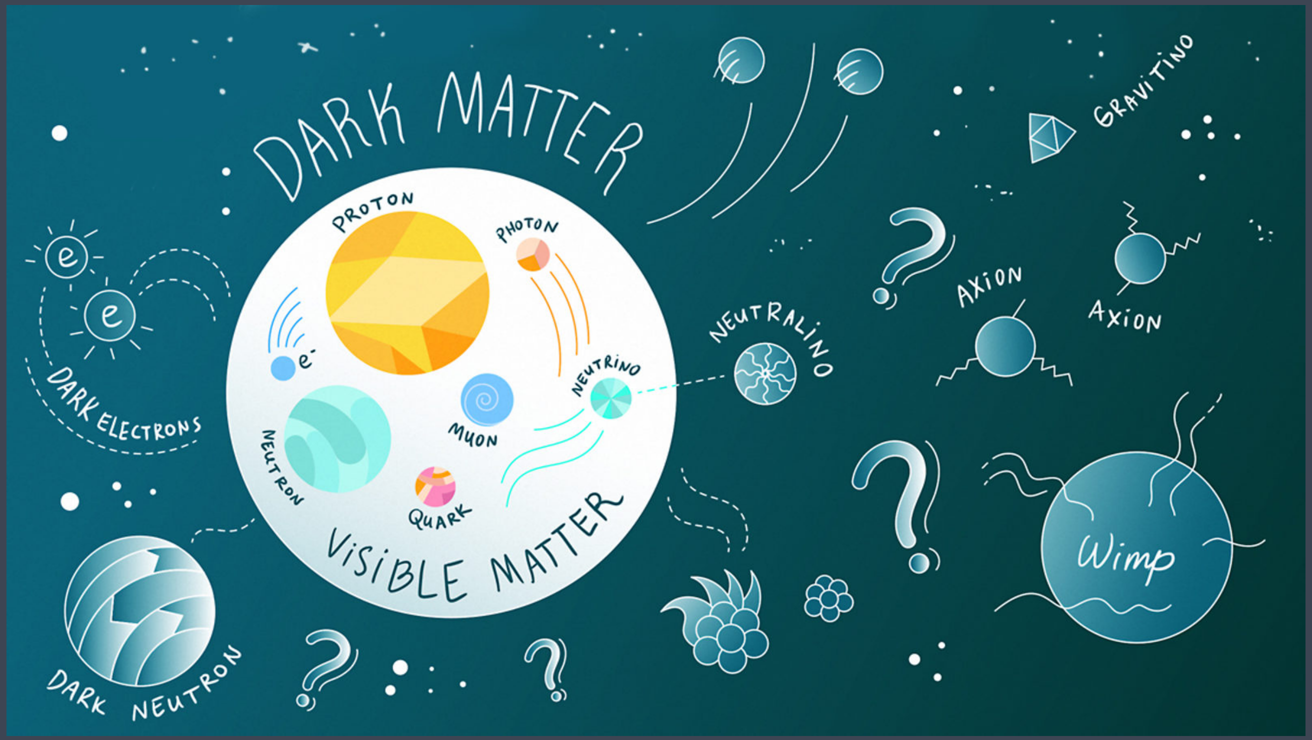
Instituto de Física de Cantabria (IFCA)

OUTLINE

- Introduction
- Experimental apparatus
- Mono-X
  - X=jets, W/Z, γ, Higgs, Top
- Conclusions and Outlook

INTRODUCTION

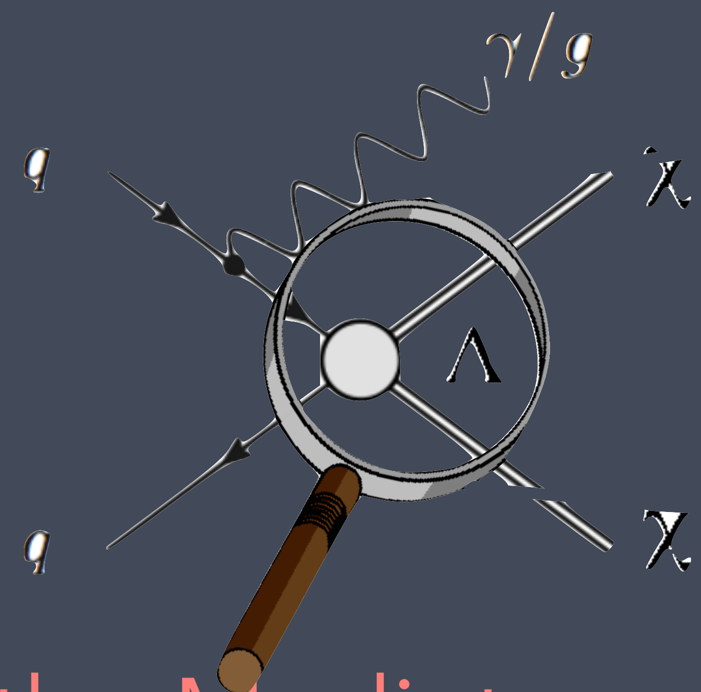
- There are plenty of motives to search for new physics at LHC
  - gauge hierarchy problems, baryon asymmetry, flavour problems, neutrino masses and mixing..etc
  - Dark Energy
  - **Dark Matter.** Evidence that exists → So let´s look for it from all perspectives, including LHC, we expect **new particles** and forces. Also cosmology points out to weak scale, LHC is suited for search this scale



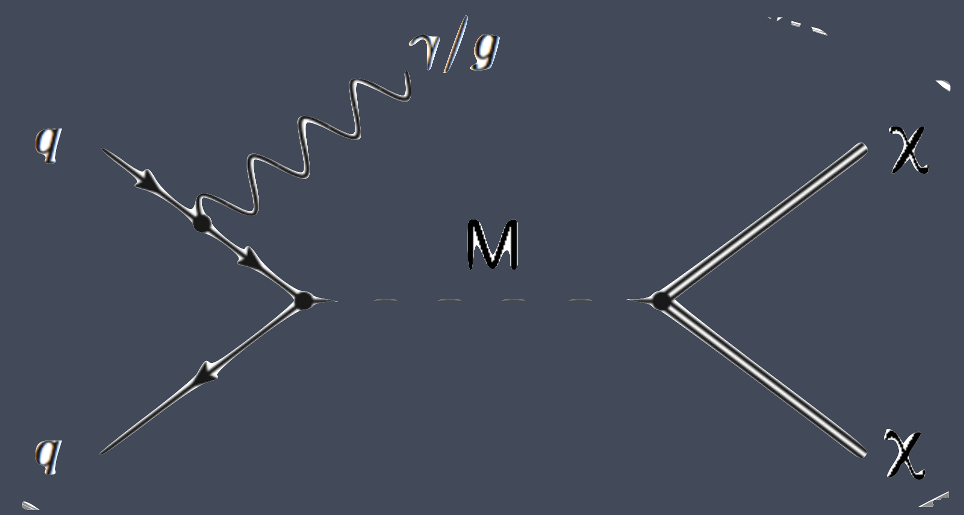
INT.:MODELS AT LHC

- **EFT** theories: Heavy mediators integrated out

$$Q_{Transfer} < M = \sqrt{g_\chi g_q} L < 4\pi\Lambda$$



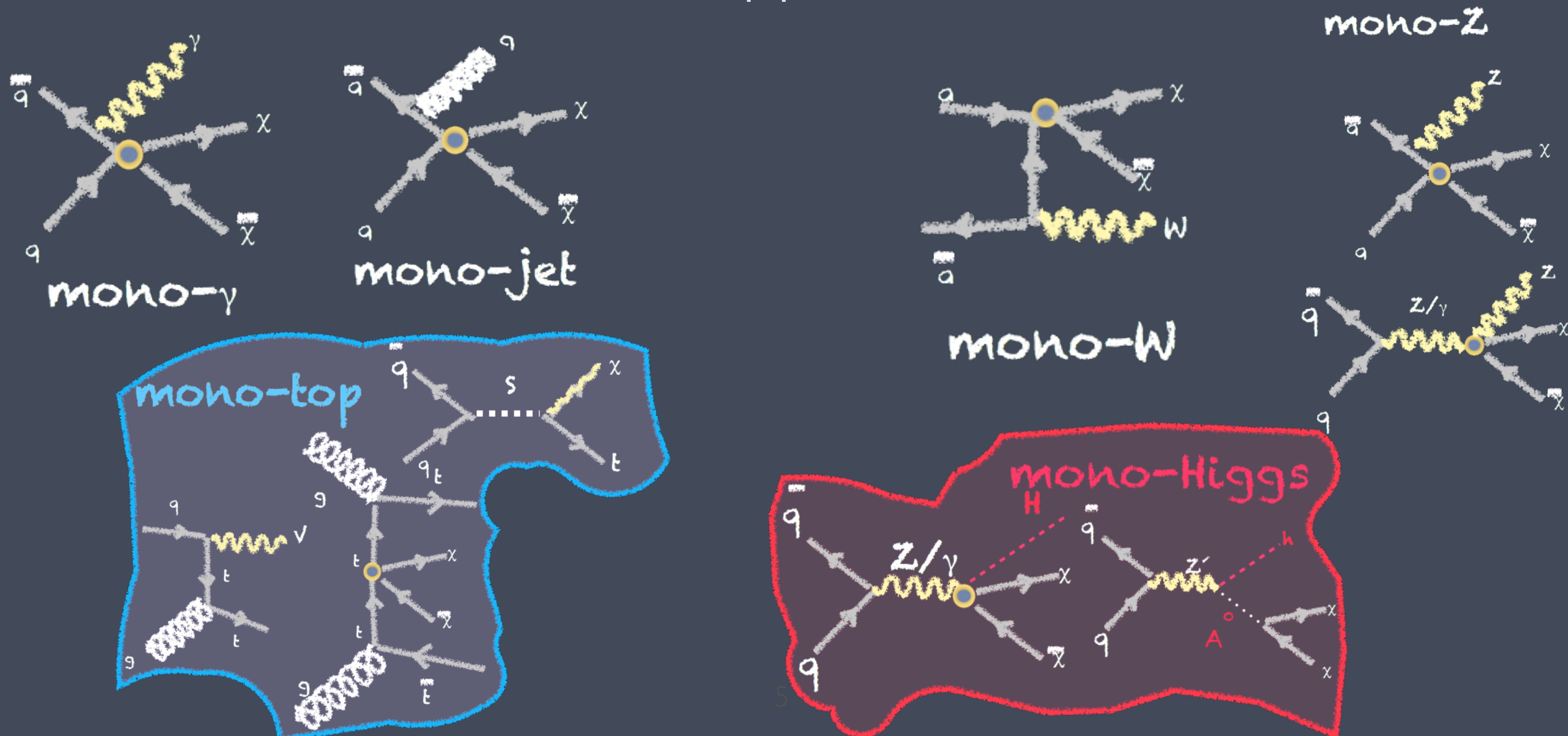
  - model independent
  - Validity issues at LHC energies
- **Simplified** Models: Explicit nature of the Mediator
  - at least 4 parameter:
    - M_{med}, M_x, g_{SM}, g_{DM}
  - valid at all energies



LHC DM Forum: arxiv:1507.00966

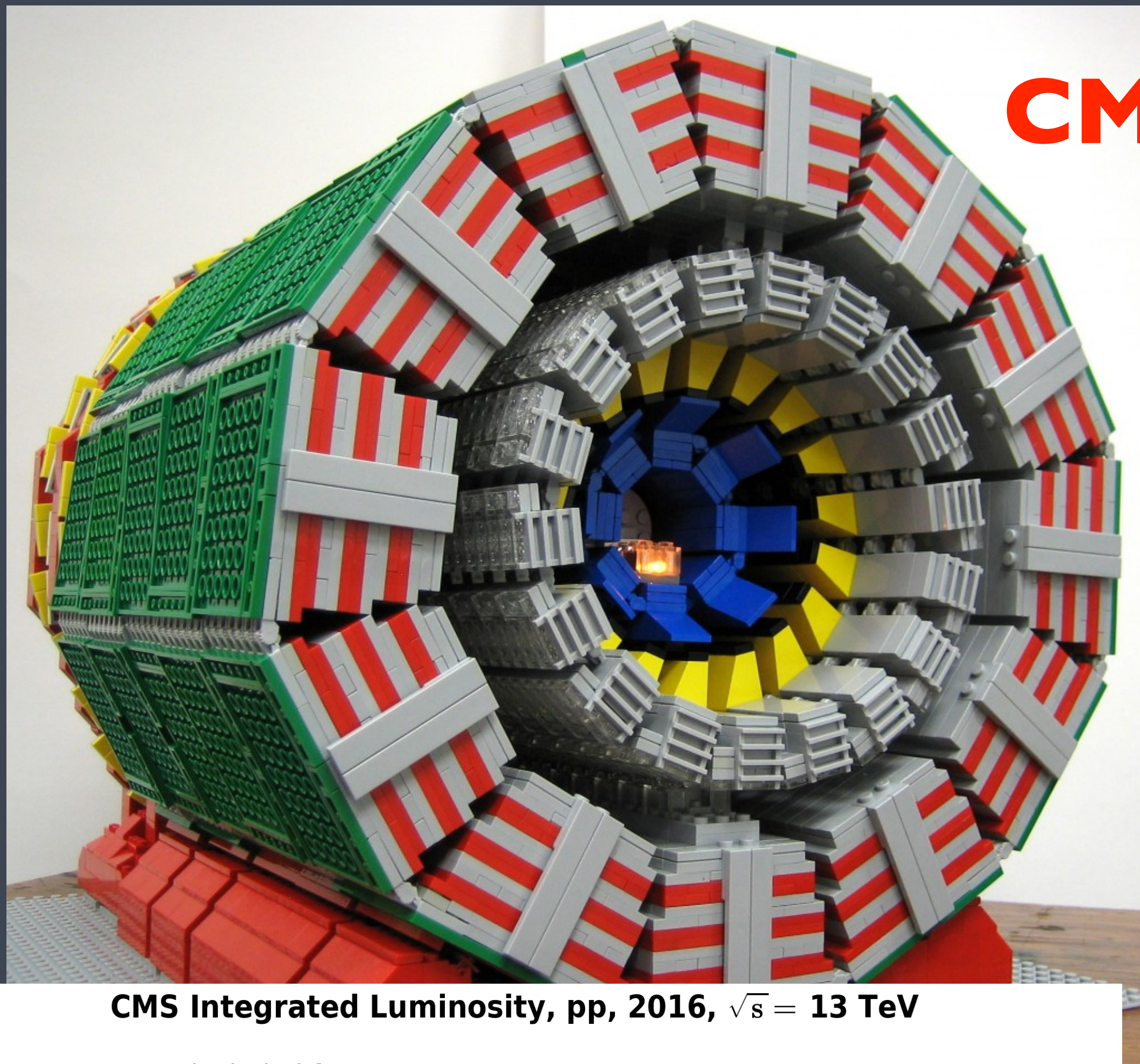
INTRODUCTION

- Look everywhere, wide range and generic signatures
  - Dark Sector: dijets, dileptons, displaced, portals, etc (see M. Vertucci´s talk)
  - **Dark Matter candidates**: pp-> Met + X (**mono-X** search)

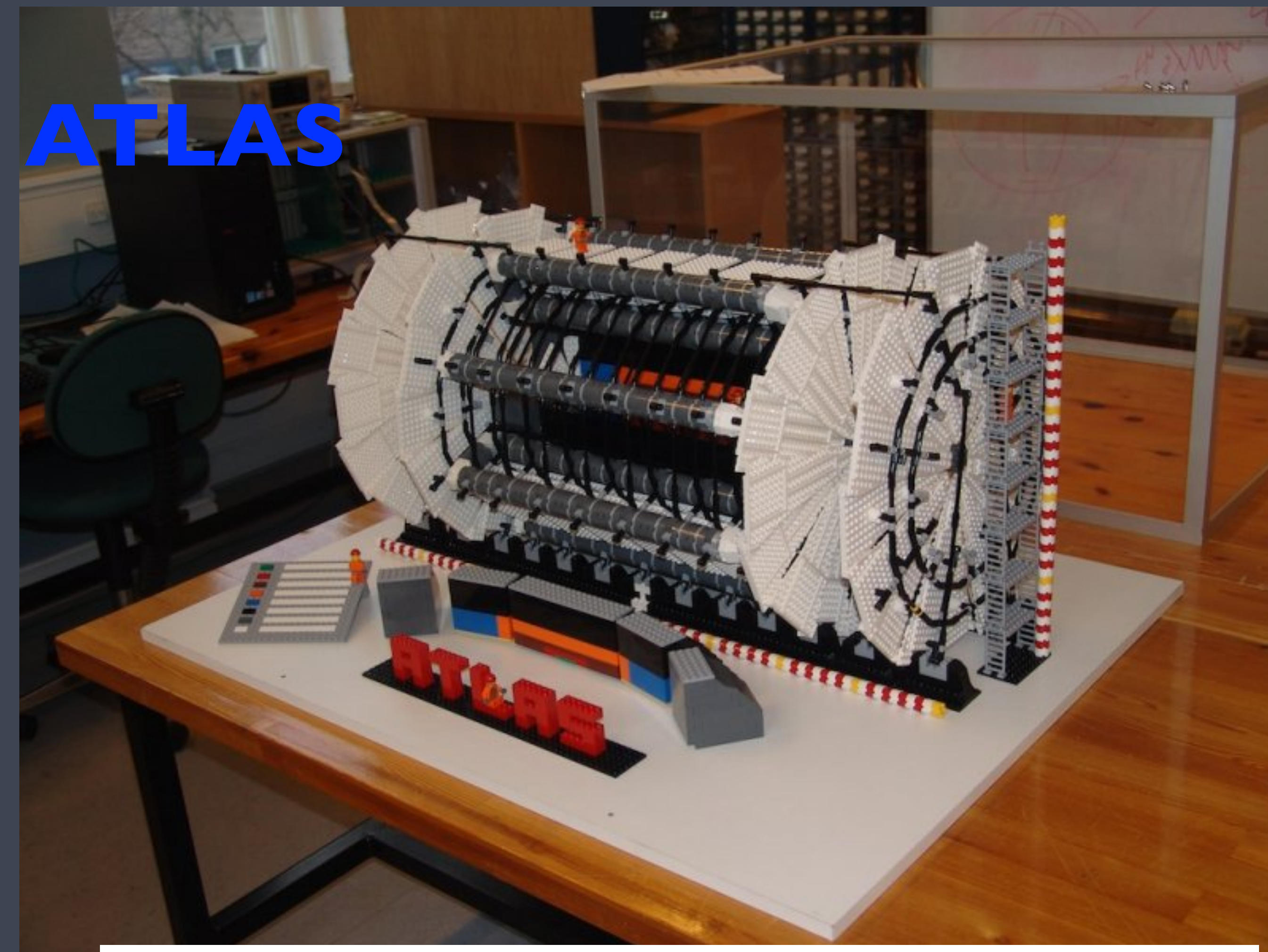


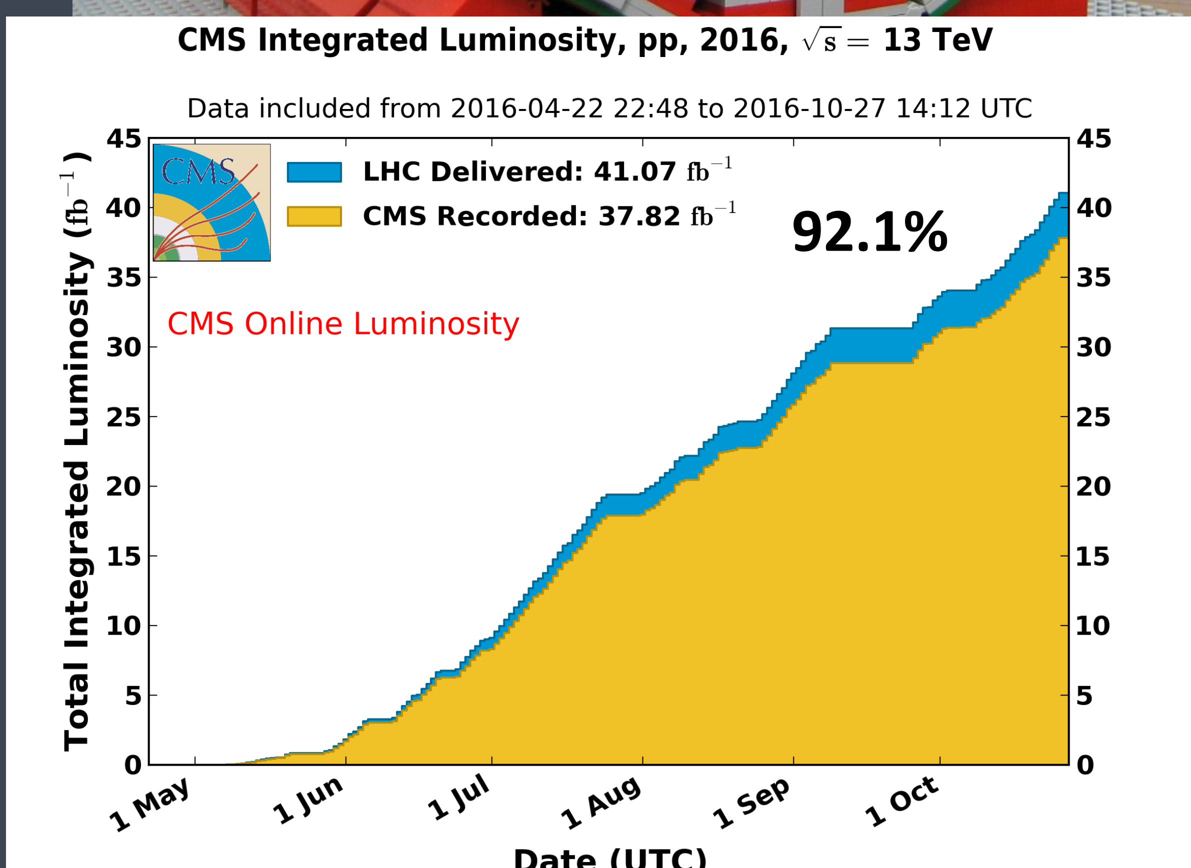
EXPERIMENTAL SETUP

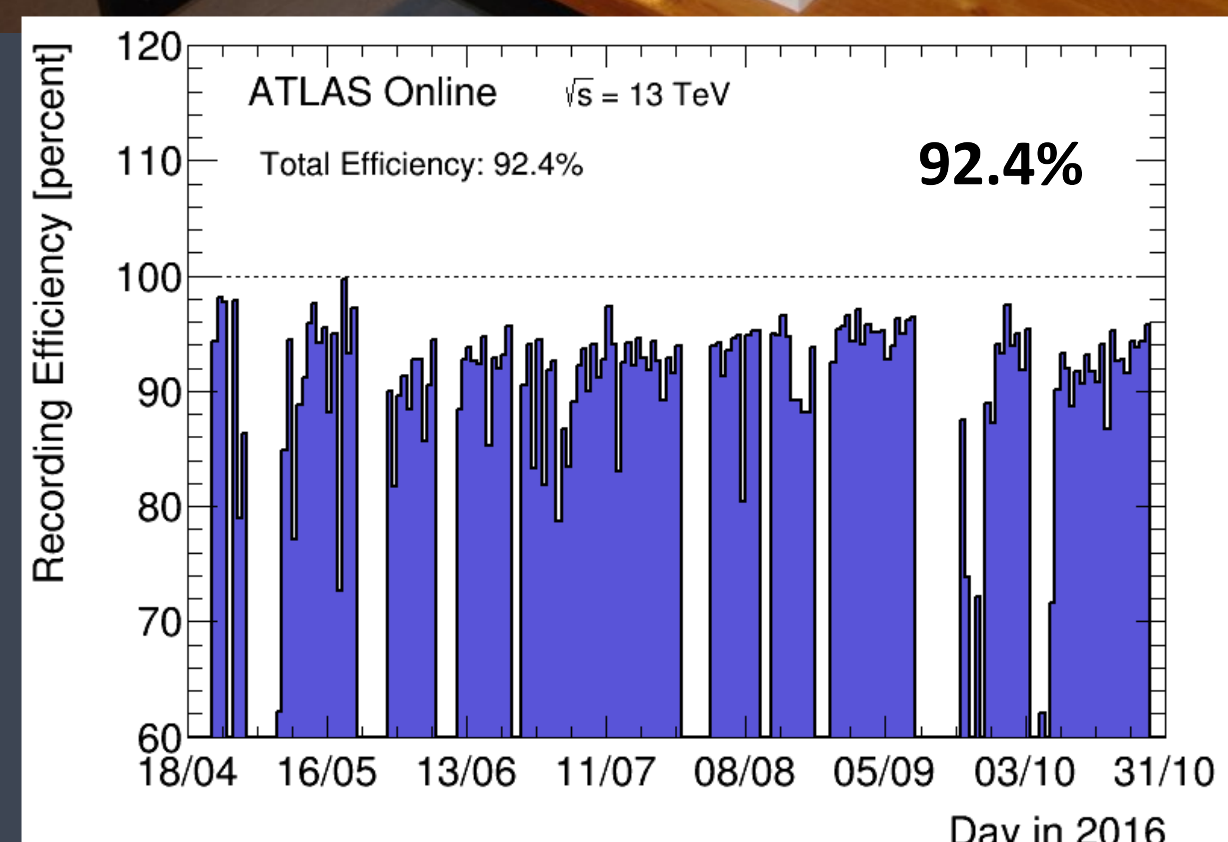
CMS



ATLAS







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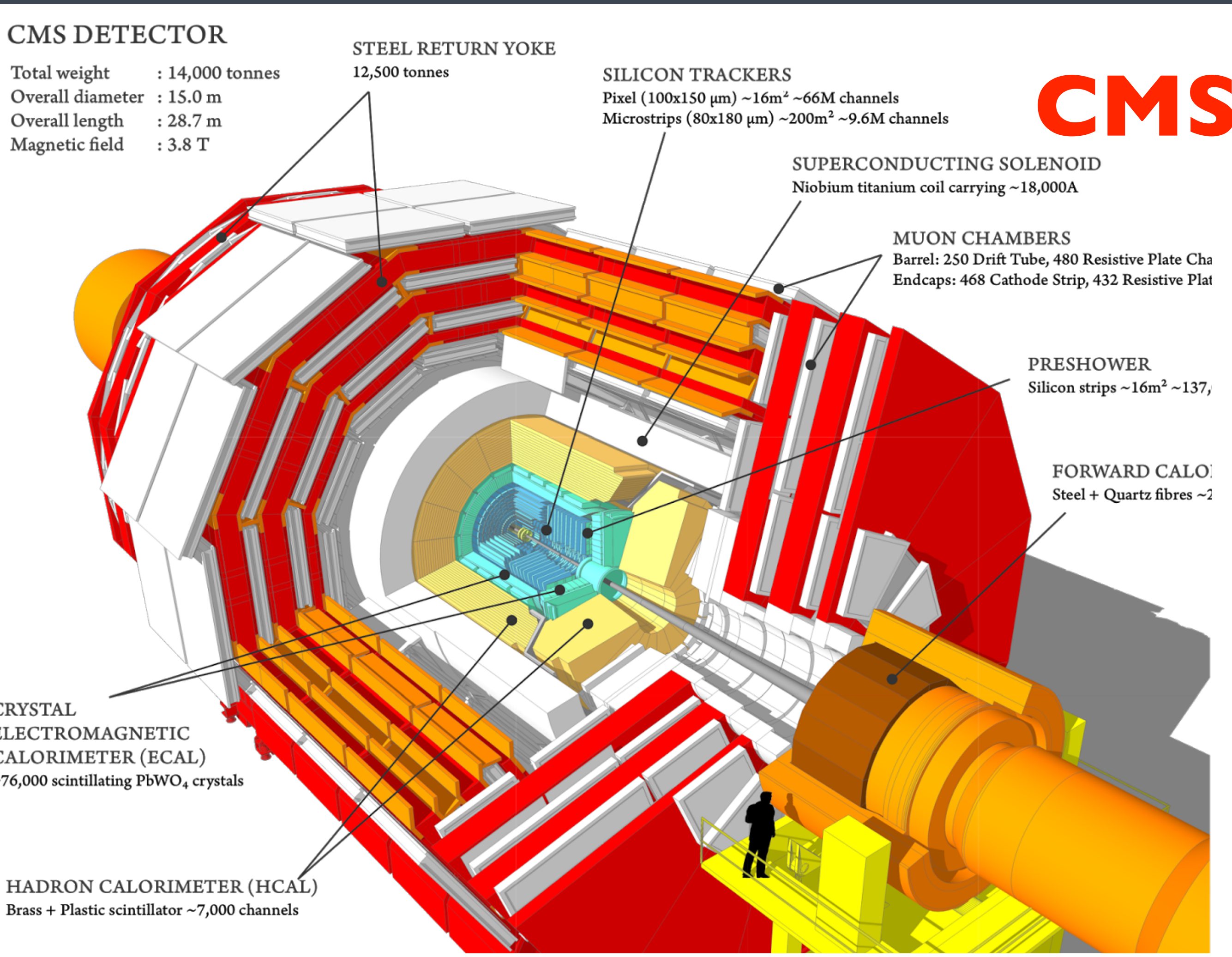
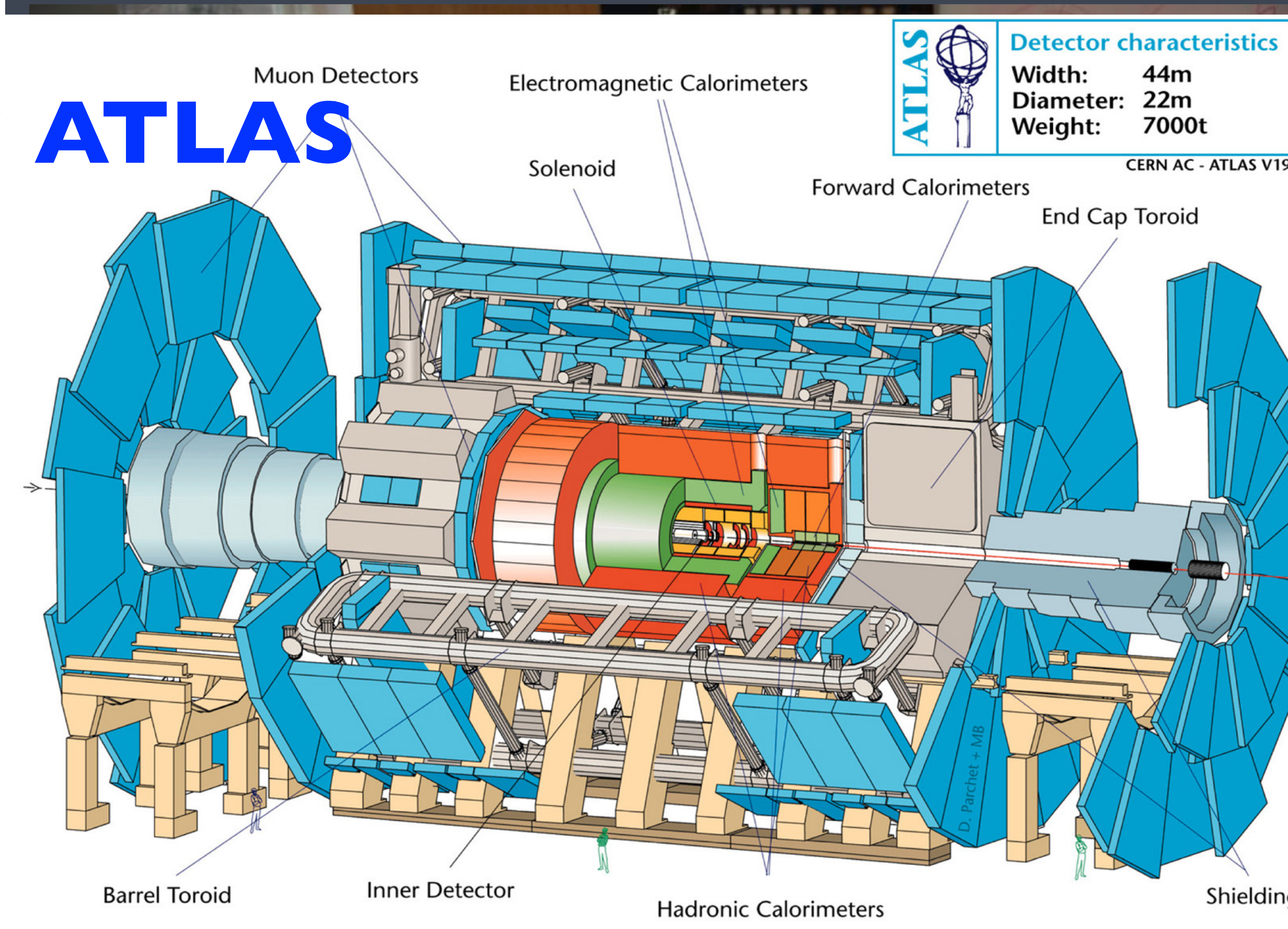
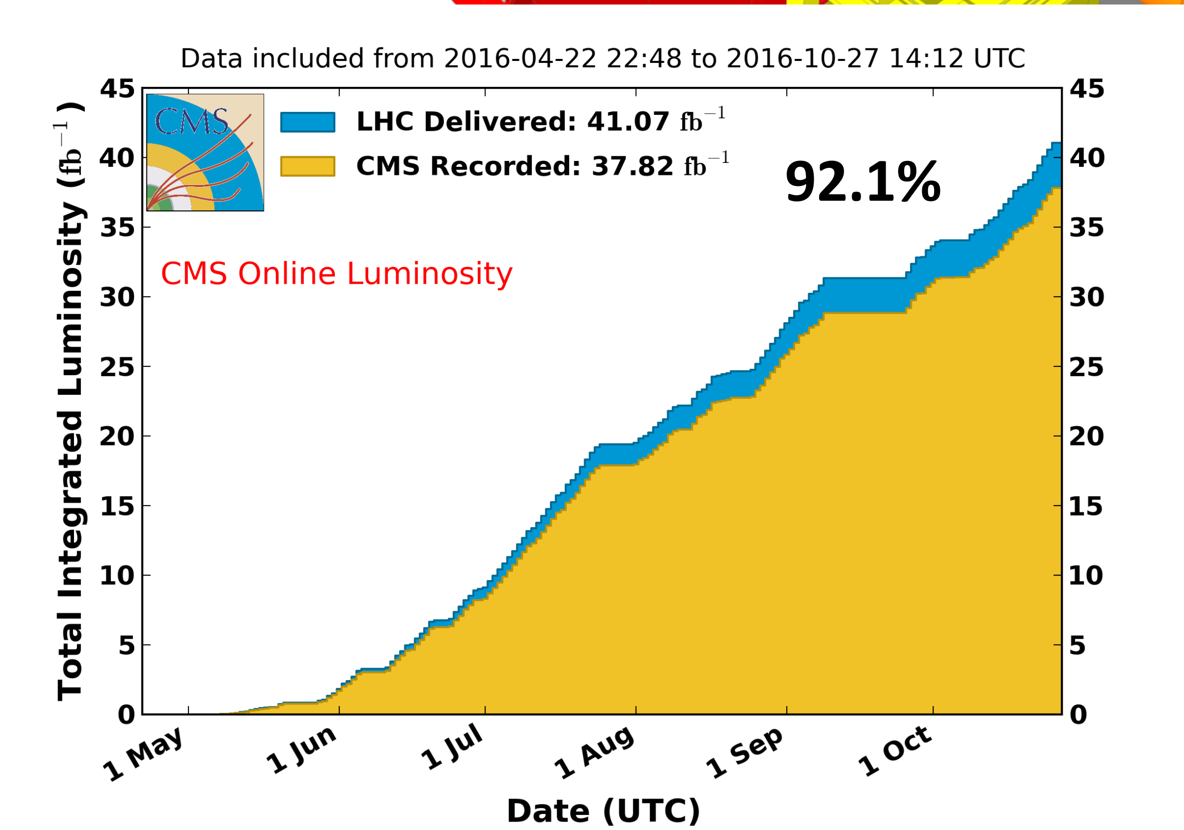
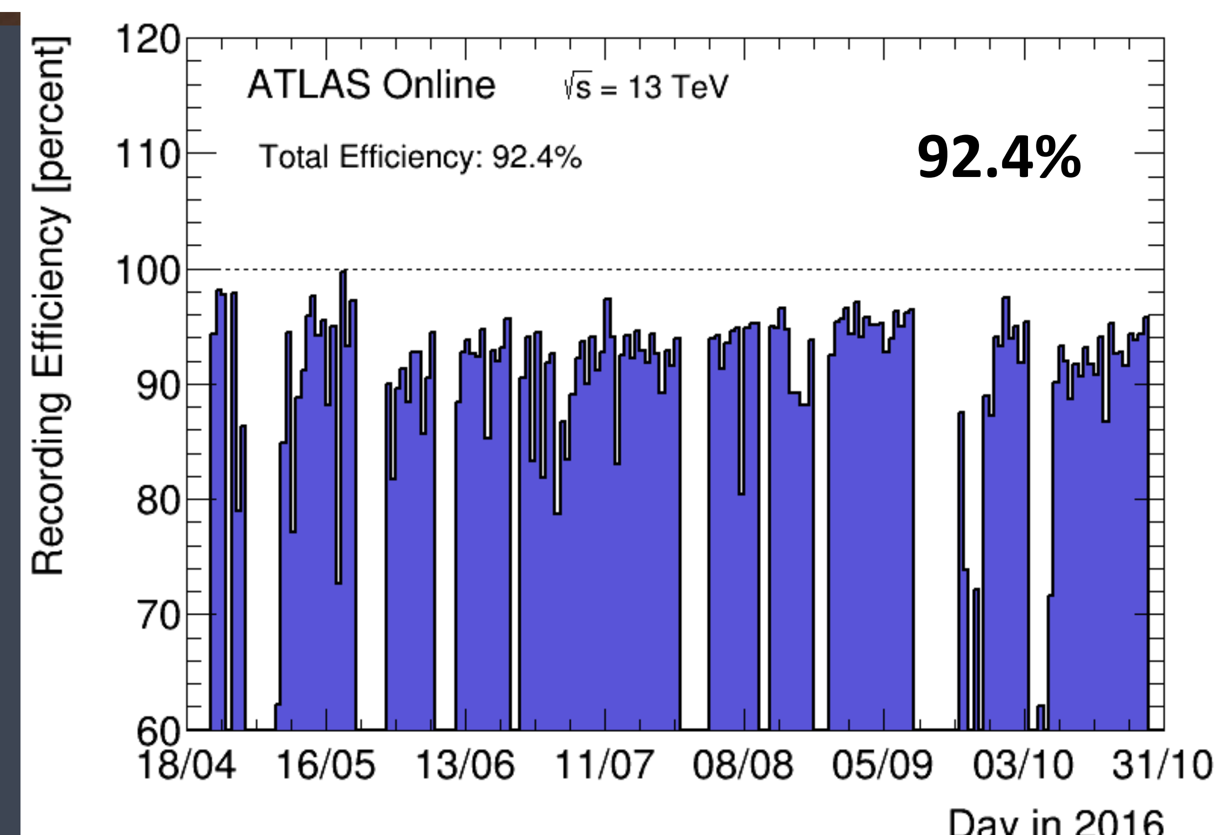




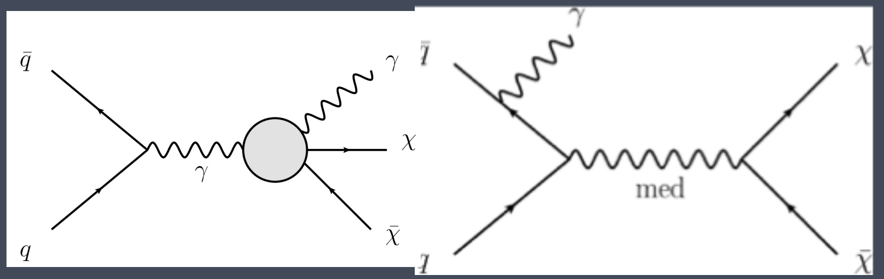




SEARCHES AT LHC

		ATLAS			CMS		
		ref.	data	$L(fb^{-1})$	ref	data	$L(fb^{-1})$
Mono-γ		arxiv: 1704.03848 (new)	2015+2016	36.1	CMS-PAS-EXO-16-039	2016	12.9
Mono-V		Phys. Lett. B 763 (2016) 251	2015	3.2	CMS-PAS-EXO-16-048 (new)	2015+2016	35.9
Mono-jet		PRD 94 (2016) 032005	2015	3.2			
mono-Higgs	bb	ATLAS-CONF-2017-028 (new)	2015+2016	36.1	arXiv: 1703.0[illegible] (new)	2015	2.3
	$\gamma\gamma$	ATLAS-CONF-2017-024 (new)	2015+2016	36.1	CMS-PAS-EXO-17-054	2015+2016	35.9
	ZZ	ATLAS-CONF-2015-059	2015	3.2			
mono-Z		ATLAS-CONF-2016-056	2015+2016	13.3	CMS-PAS-EXO-16-052 (new)	2016	35.9
mono-top					CMS-PAS-EXO-16-040	2015+2016	12.9
mono-tt	had	ATLAS-CONF-2016-077	2015+2016	13.3	CMS-PAS-EXO-16-005	2015	2.2
	semi-l	ATLAS-CONF-2016-050	2015+2016	13.2			
	lep	ATLAS-CONF-2016-076	2015+2016	13.3	CMS-PAS-EXO-16-028	2015	2.2
mono-bb		ATLAS-CONF-2016-086	2015+2016	13.3	CMS-PAS-B2G-15-007	2015	2.17

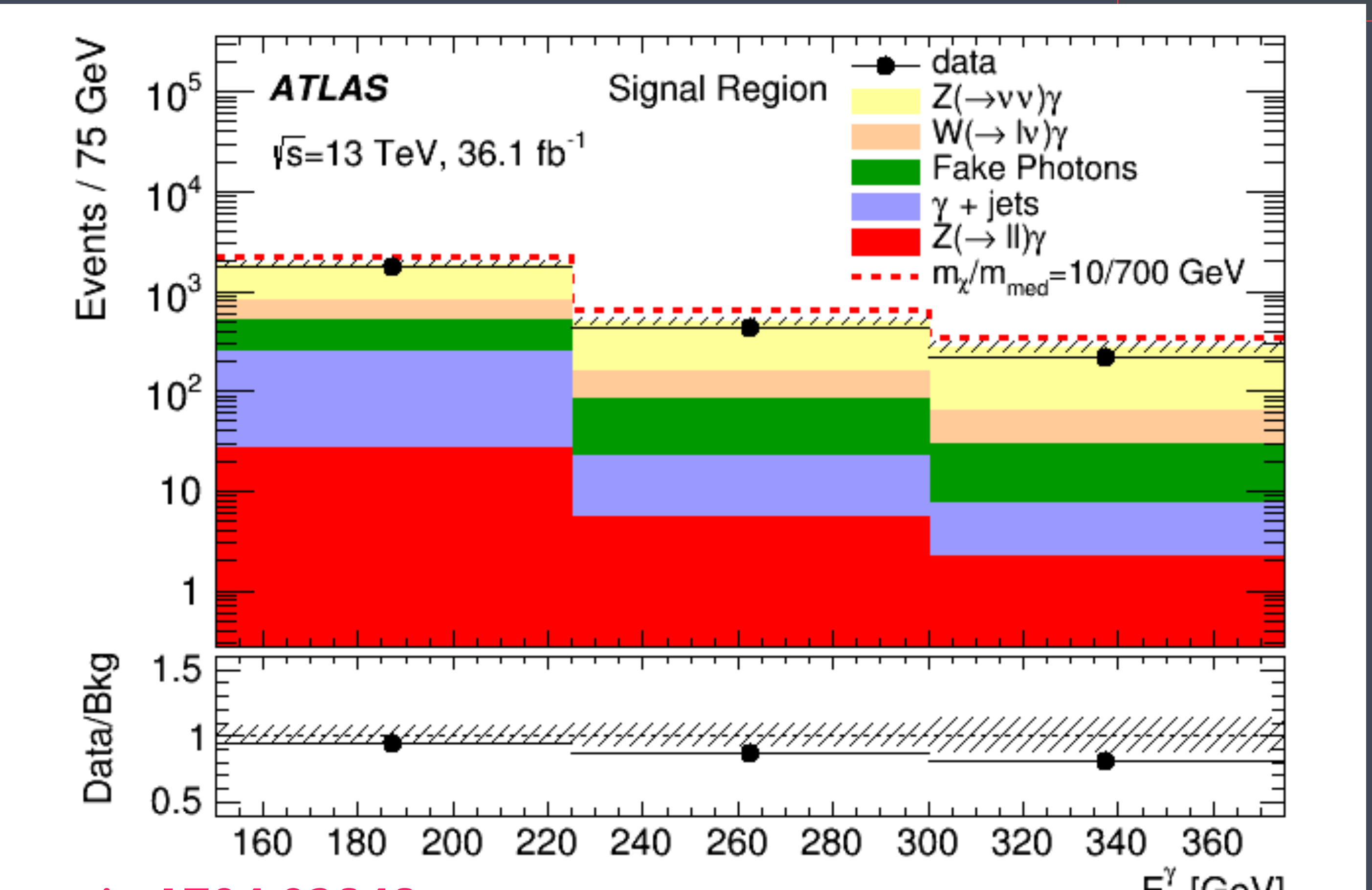
MONO-γ



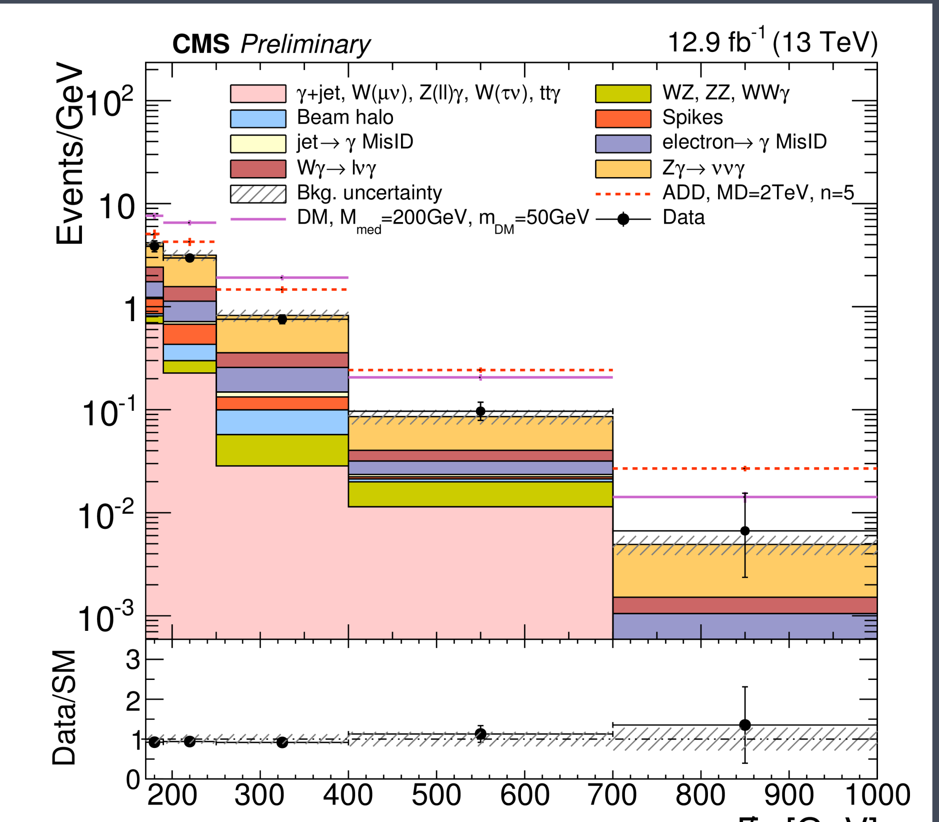
- **SELECTION**
  - Well identified High P_T isolated γ + High missing E_T ($\not{E}_T$)
  - Additional azimuthal requirements between $\not{E}_T$ and jets or leptons
  - lepton veto

BACKGROUNDS

- Main: true photon with EWK productions (~80%):
  - Z (->$\upsilon\upsilon$)+ γ, W(lυ)+ γ
    - also Z (->ll)+ γ, ttγ, VVγ,W(lυ)
- Others are
  - electron fakes and jet fakes,
  - detector backgrounds,
  - γ+jets,

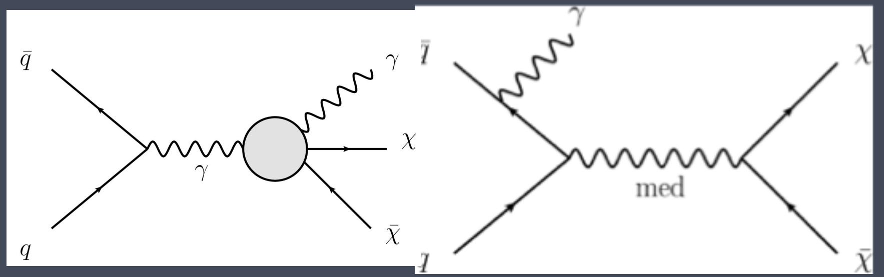


arxiv:1704.03848



CMS-PAS-EXO-16-039

MONO-γ



- **SELECTION**
  - Well identified High P_T isolated γ + High missing E_T ($\not{E}_T$)
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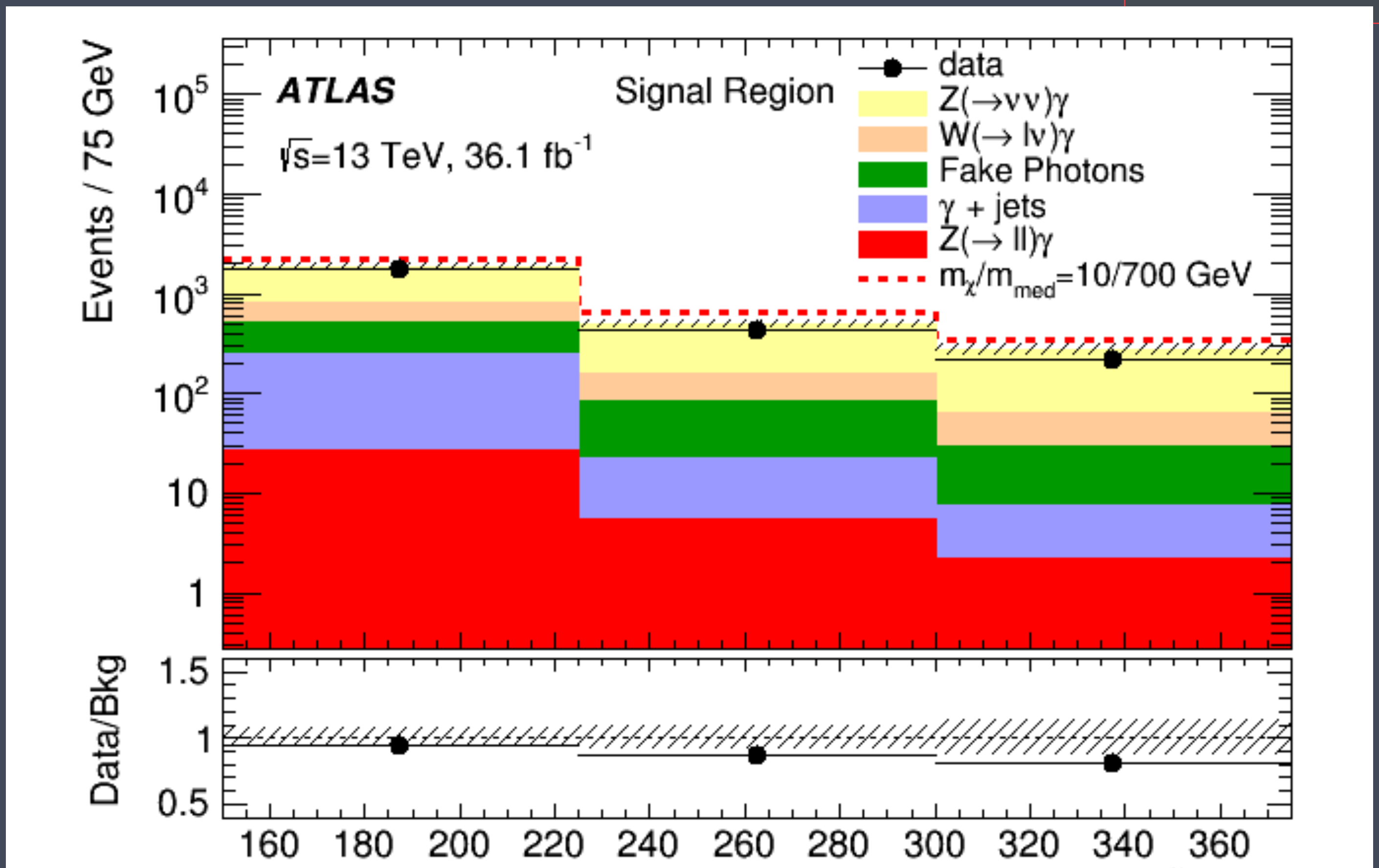
BACKGROUNDS

- Main: true photon with EWK productions (~80%):
  - Z (->$\nu\nu$)+ γ, W(lν)+ γ — Calculated with MC and normalised in CRs: ll+γ, μ+γ
    - also Z (->ll)+ γ, ttγ, VVγ,W(lν)
- Others are
  - electron fakes and jet fakes,
  - detector backgrounds,
  - γ+jets,

  From data fake ratio for electron, side bands for hadrons



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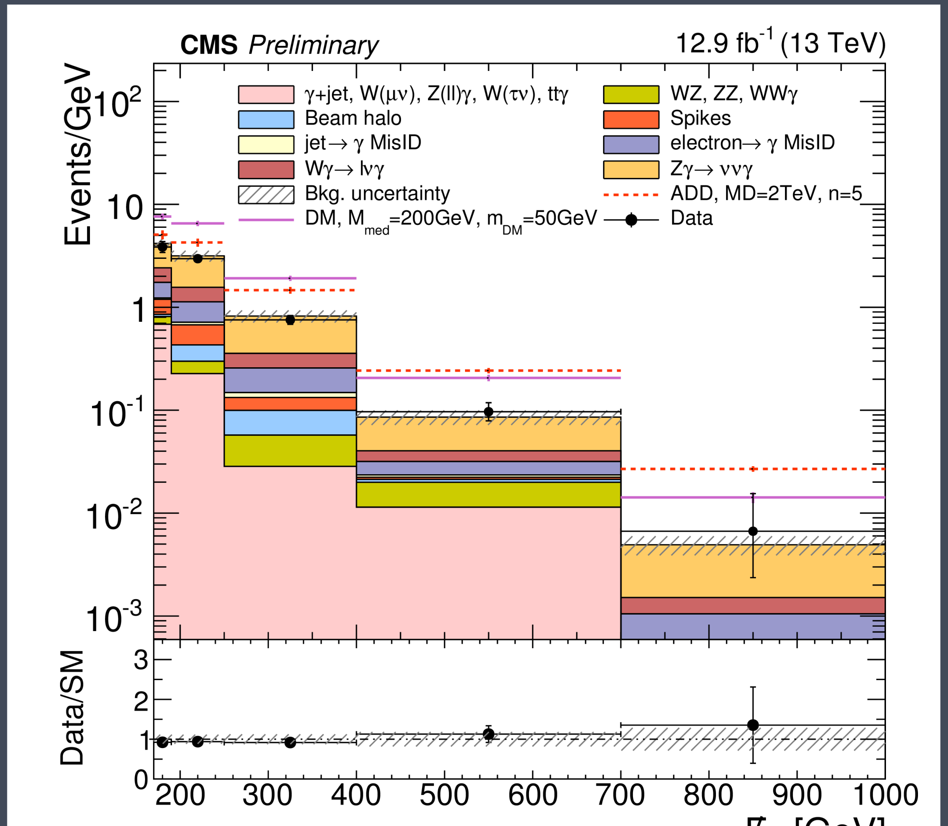
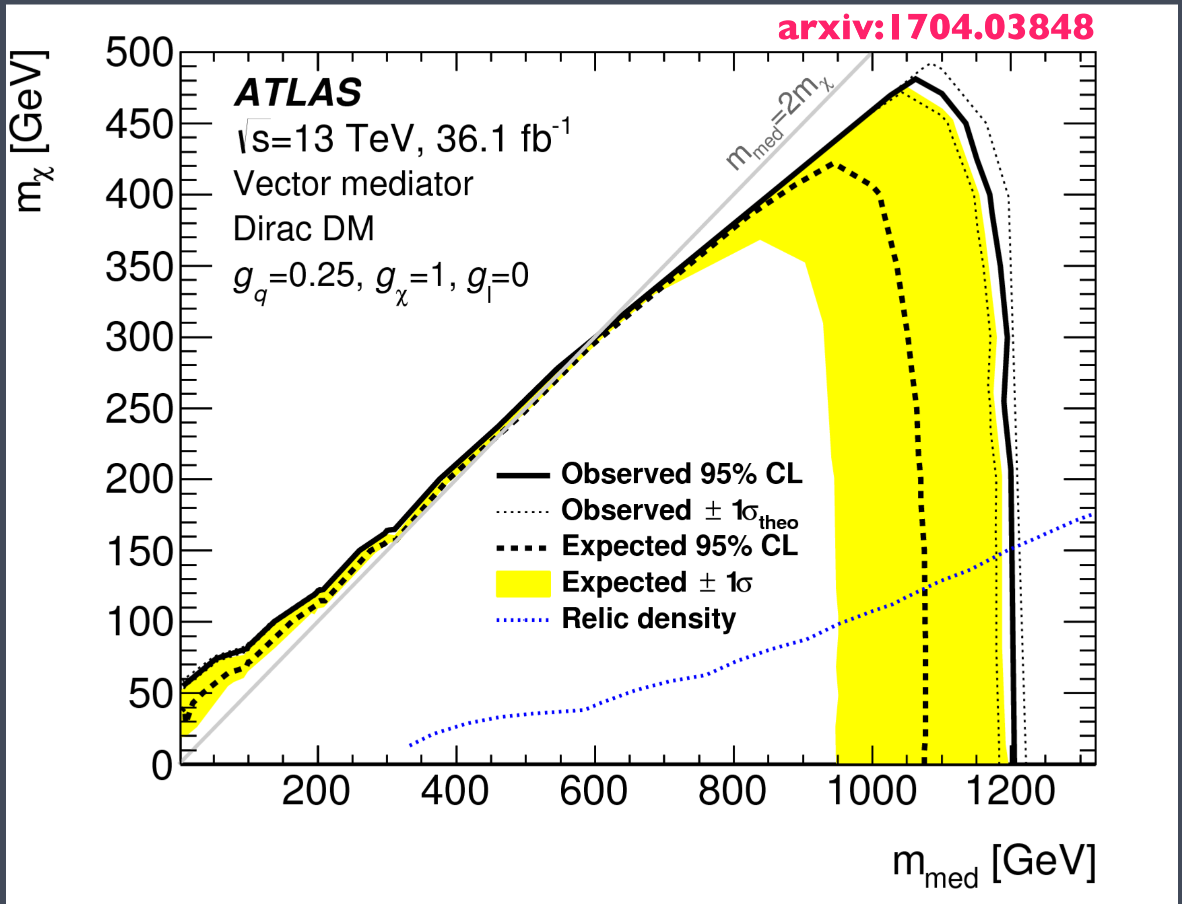


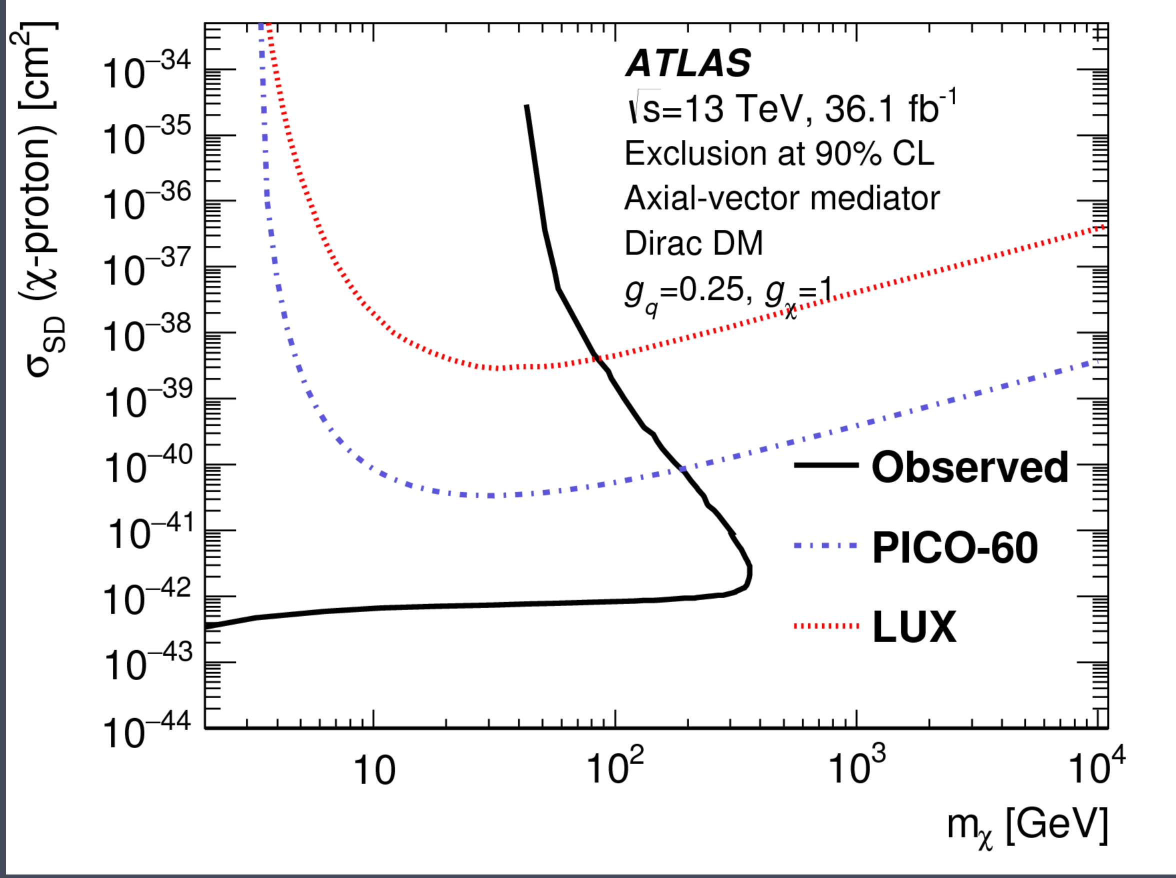
CMS-PAS-EXO-16-039

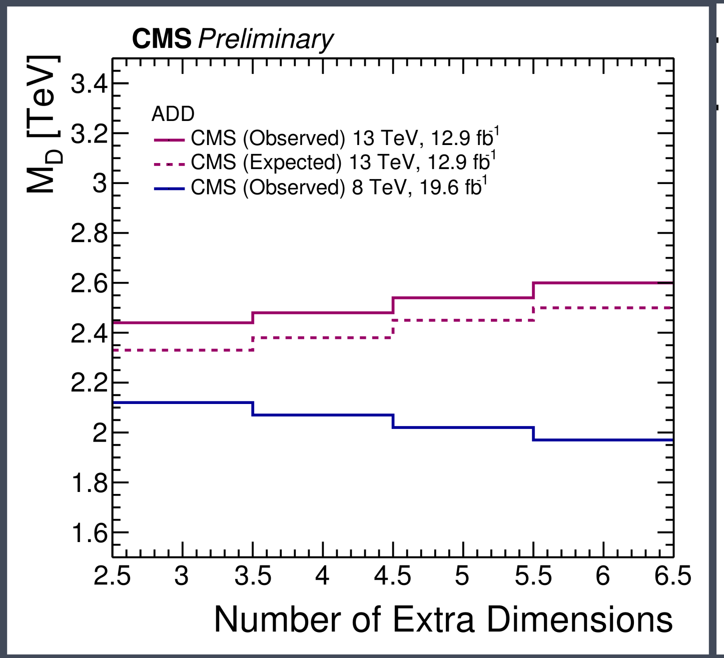
MONO-γ: RESULTS

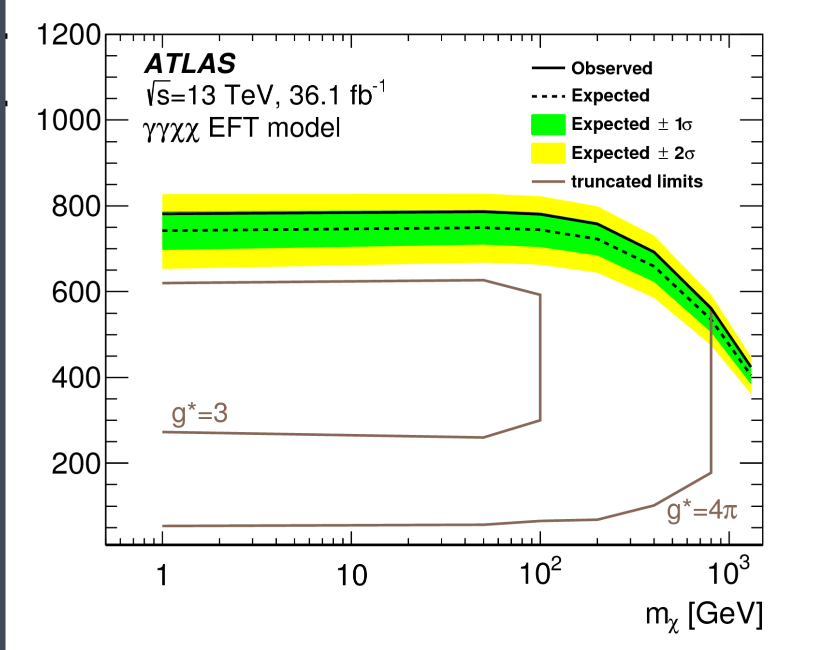
- No excess is found, limits based on the the models proposed by the CMS-ATLAS forum:
  - Limits for vector/axial mediator of 1200 (750) GeV
  - EFT Dim-7 EFT scale up to 620 GeV
- With the Run II data the limits are still dominated by statistics:
  - Main Systematics coming from PDFs, energy scales and resolutions (E_T), backgrounds normalisation. The total background uncertainties could vary up 6-14%.

arxiv:1704.03848

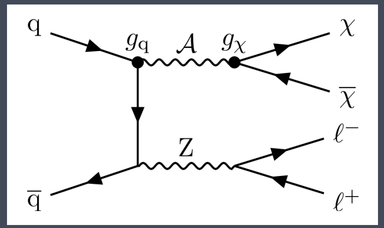


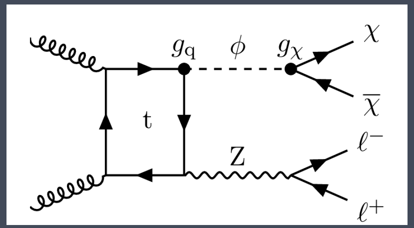






MONO Z(->LL)

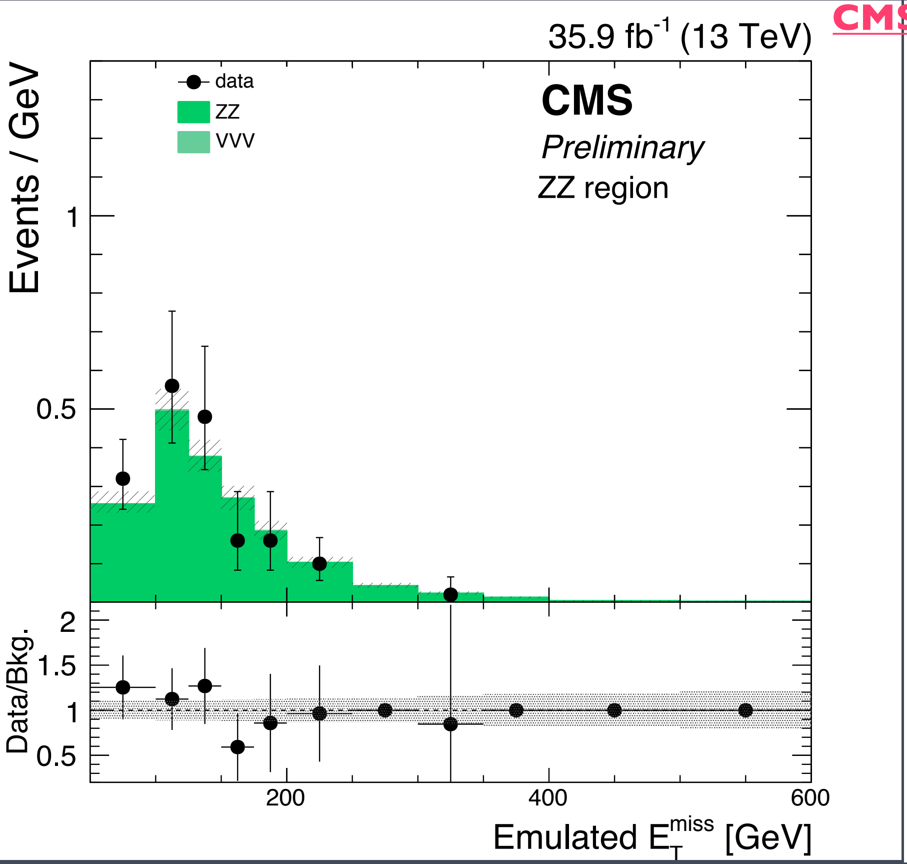


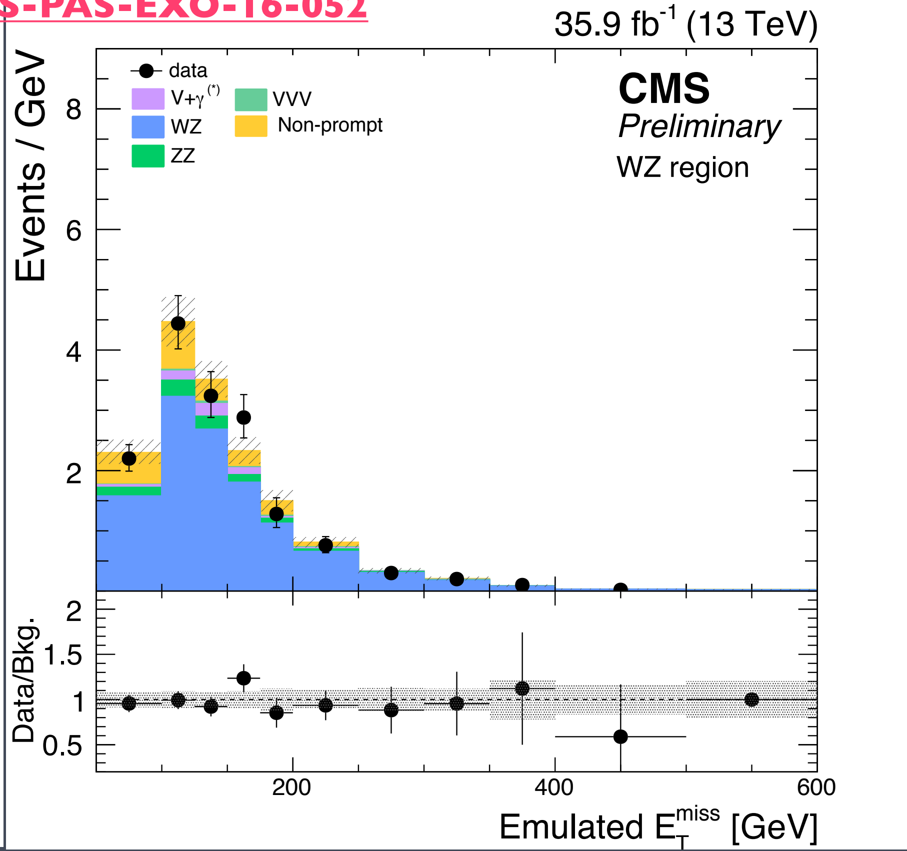


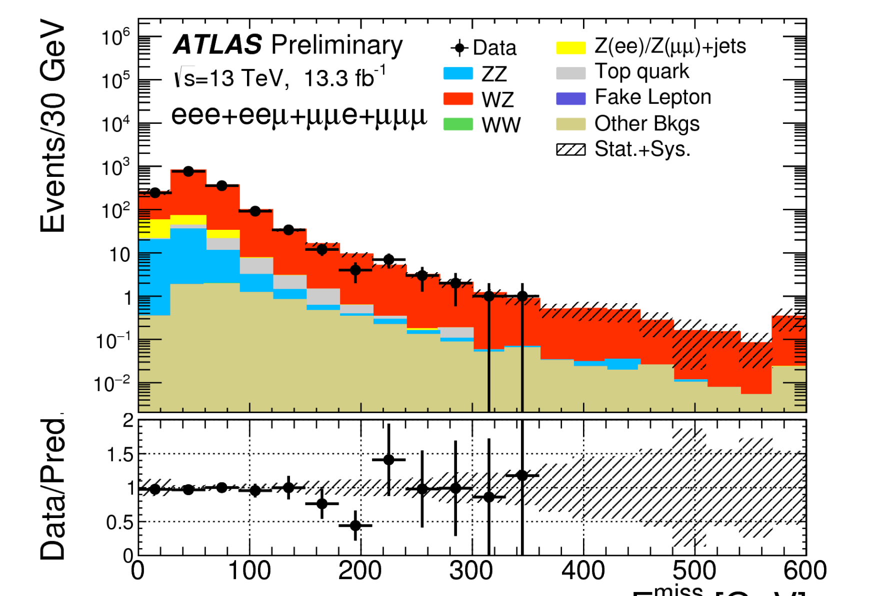
- **Selection**
  - two well defined high Pt isolated leptons with same flavour
  - m_{ll} within the Z mass window
  - large $\not{E}_T$ and requirements of balance ratio, $|\not{E}_T - P_T^{ll}|/P_T^{ll}$
  - $P_T(ll)$ great that 60 GeV and $\Delta R(ll)$
  - ≤1 jet and b-jet veto and extra lepton veto
  - azimuthal angles requirements between leptons and jet and $\not{E}_T$

- **Backgrounds**
  - ZZ, WZ (85%)
    - Calculated with MC and normalised in CRs: 3leptons and 4 leptons
  - WW, top (tt,tW), DY, VVV
    - combination of datadriven, CR and MC
  - W+jet, ZH, H,

CMS-PAS-EXO-16-052



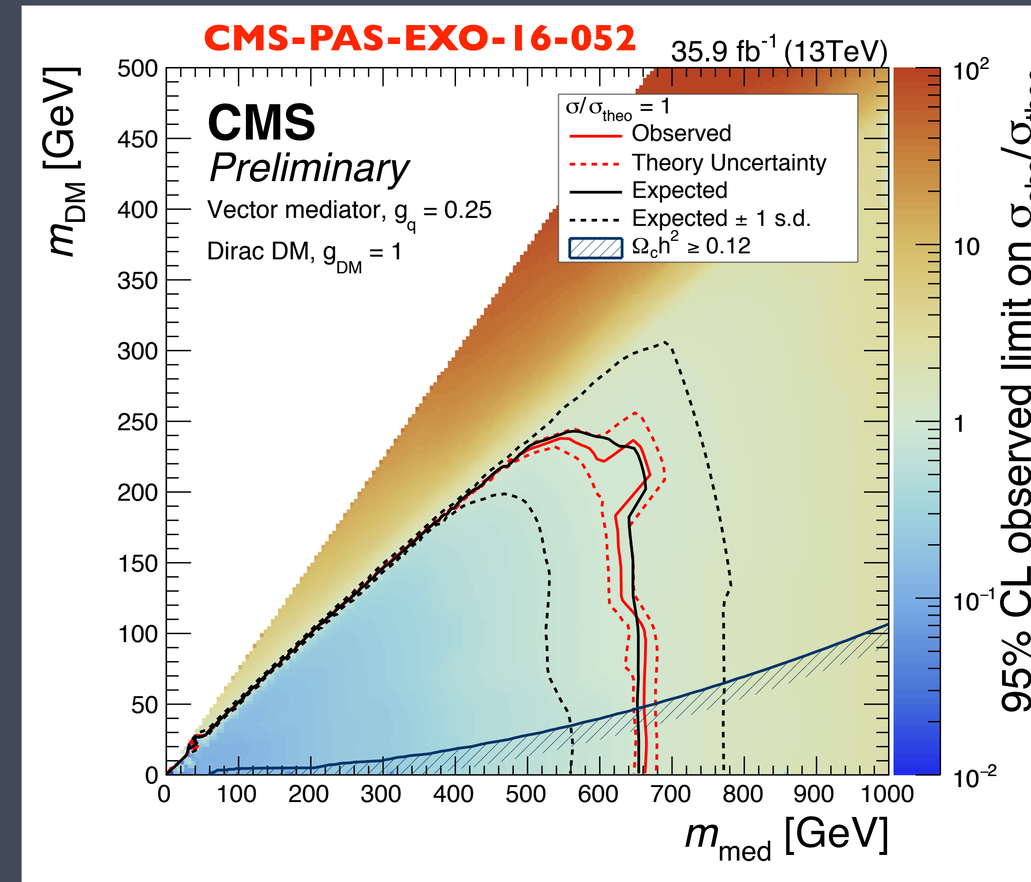


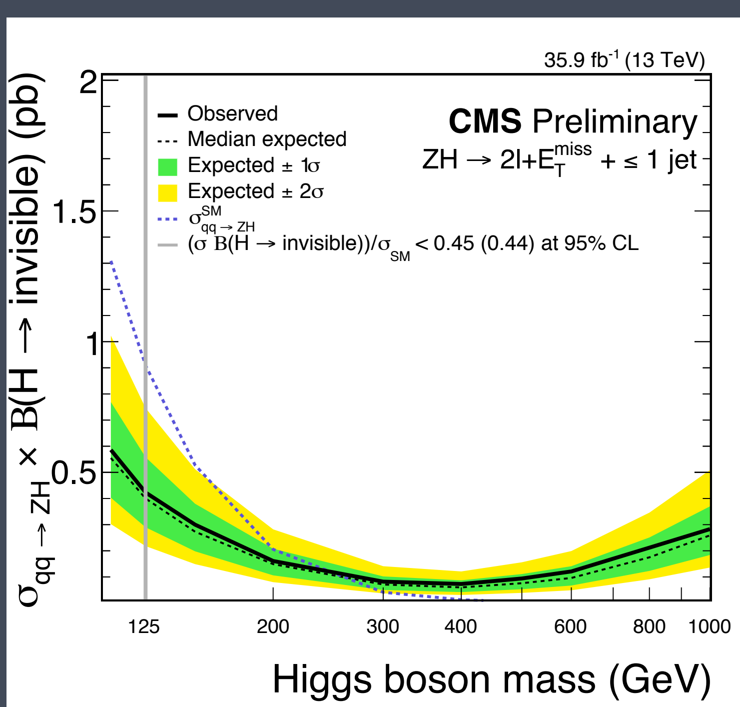


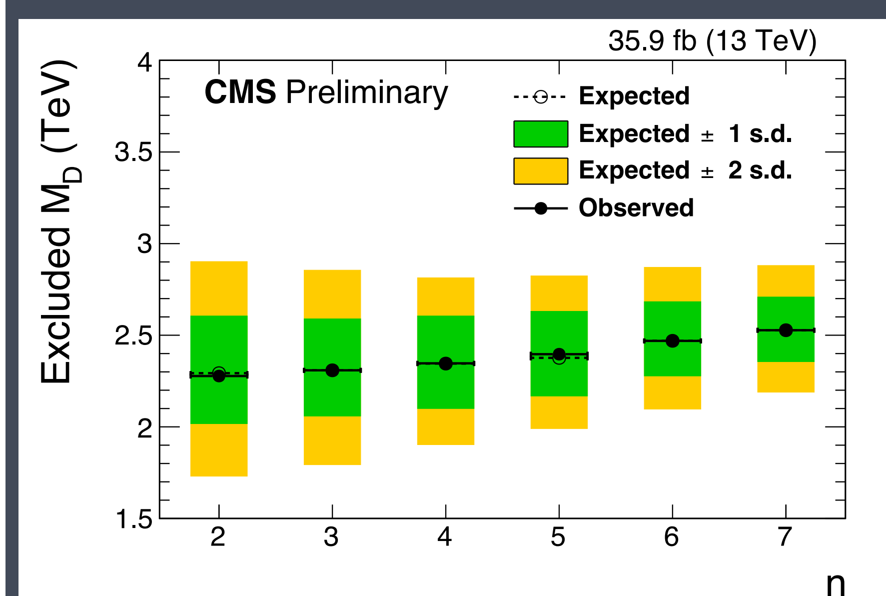
ATLAS-CONF-2016-056

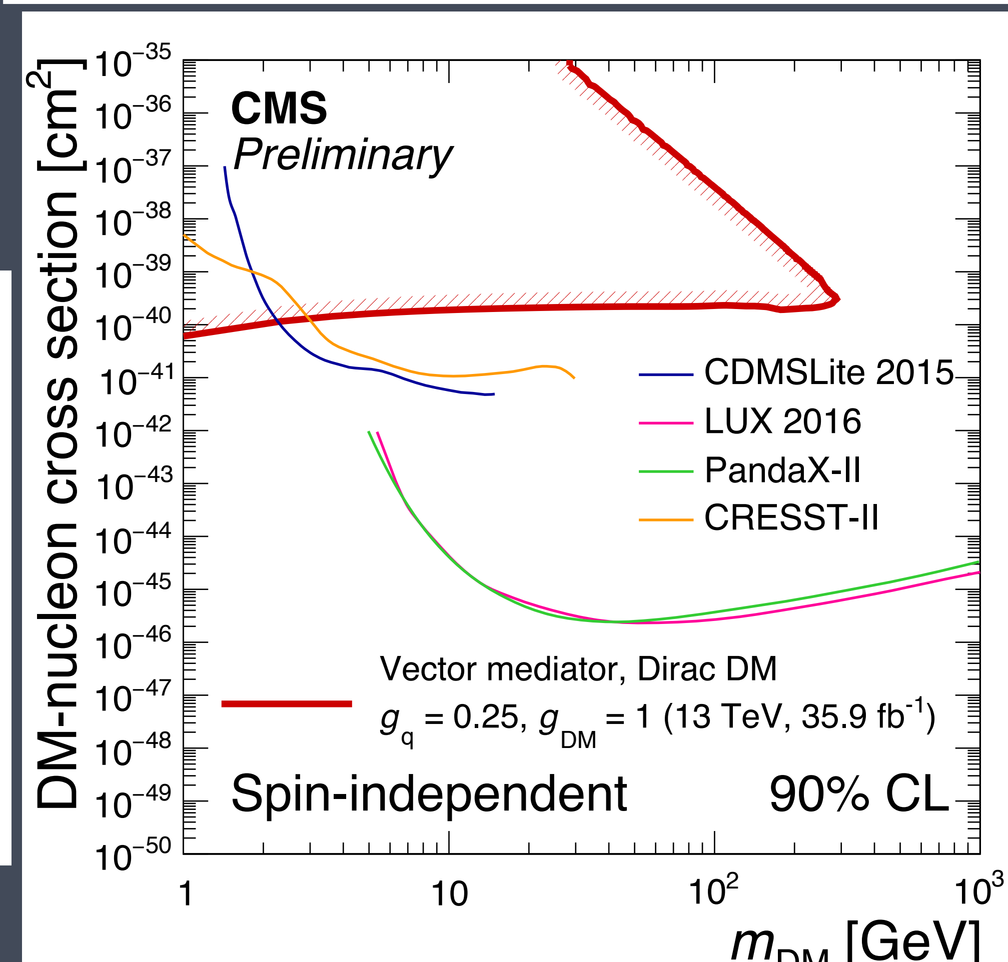
MONO Z(->LL)

- **No excess** is found, **limits** are set
    - Simplified Models of DM (vector/axial, scalar/pseudoscalar)
        - vector/axial: M_{med} >680 GeV and M_{DM} up to 240 (150) GeV
    - Invisible Higgs, ADD
- Systematic Uncertainties
    - Theoretical uncertainties are missing higher order corrections, PDFs (5% in signal), plus EWK corrections for the backgrounds (14%)
    - Experimental uncertainties includes luminosity, leptons related, energy scales, resolutions and modelling (jet and $\not\!\!E_T$) (around 3%)

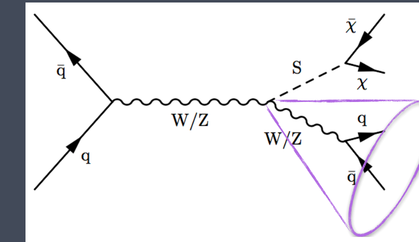
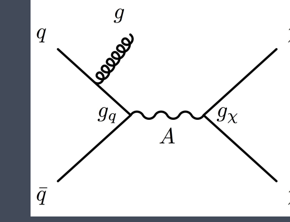
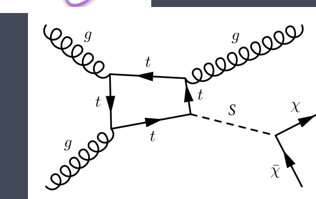
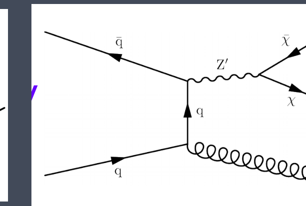








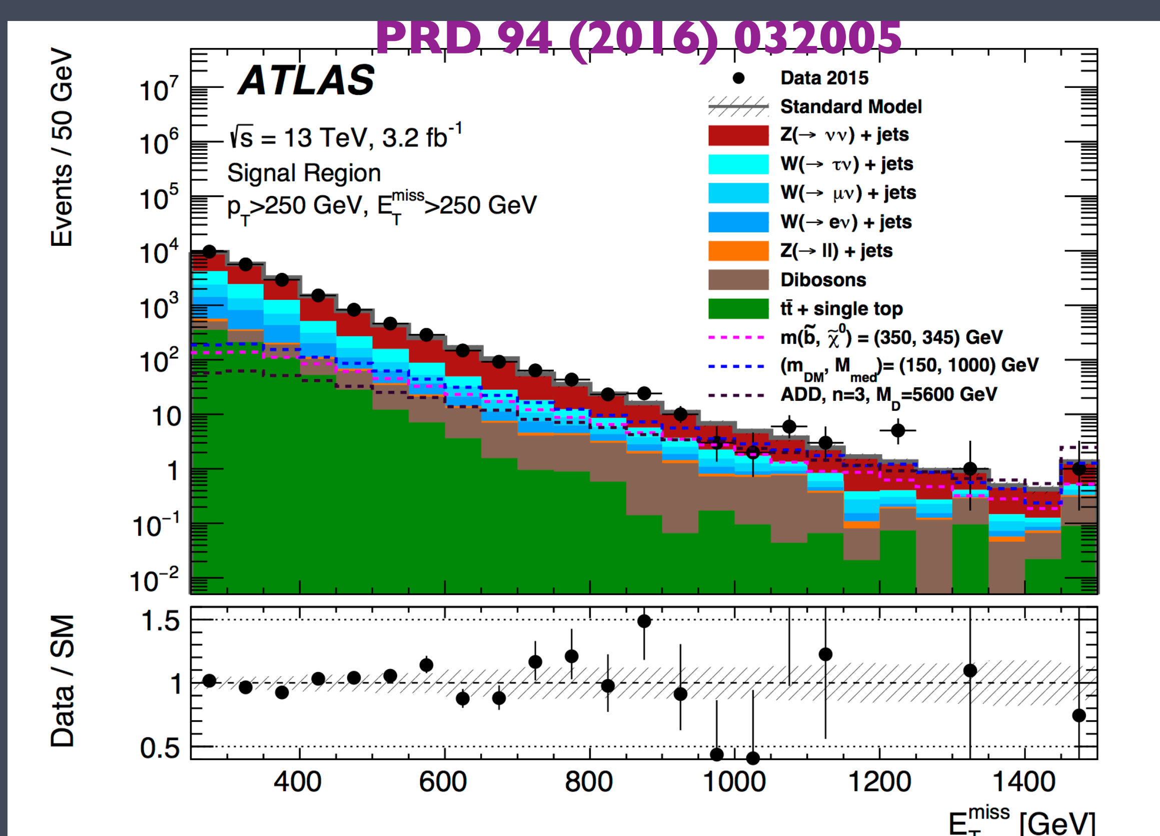
MONO-JET/V

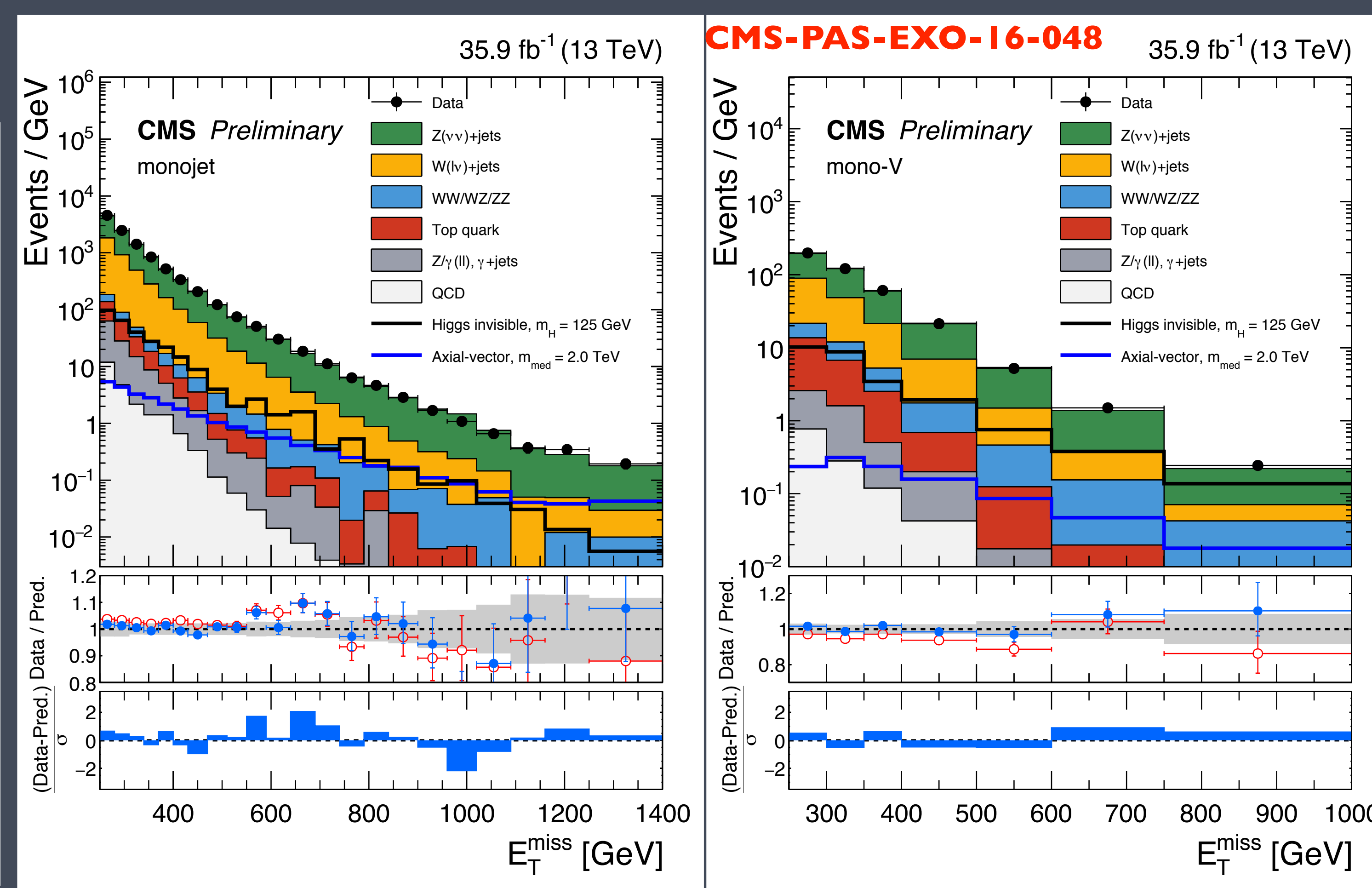





- **SELECTION**
  - >1 High P_T Jet, separate from the $\not{E}_T$
  - large $\not{E}_T$
  - No leptons
  - CMS includes mono-V
    - large R jet (0.8) with very high P_T
    - very high $\not{E}_T$
    - V-tagging w/N-subjettines variables
    - m_{jj} requirement

- **BACKGROUNDS**
  - Z ($\to \nu\nu$)+ jets, W($l\nu$)+ jets (90%)
  - others: QCD multi jet events, VV, top, DY+jets, γ+jets

Estimates in CR, using $\mu\mu$, ee, μ,e and γ+jets data samples. Extract from a simultaneous fit to signal and CR regions. CMS used Transfer Functions

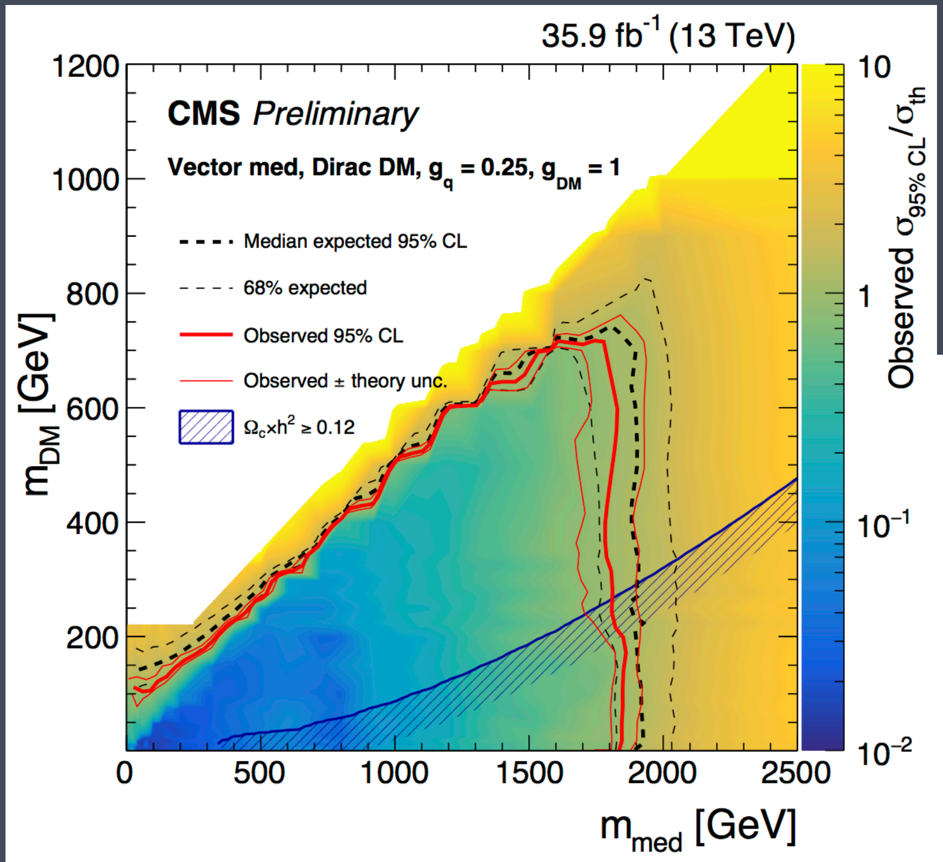


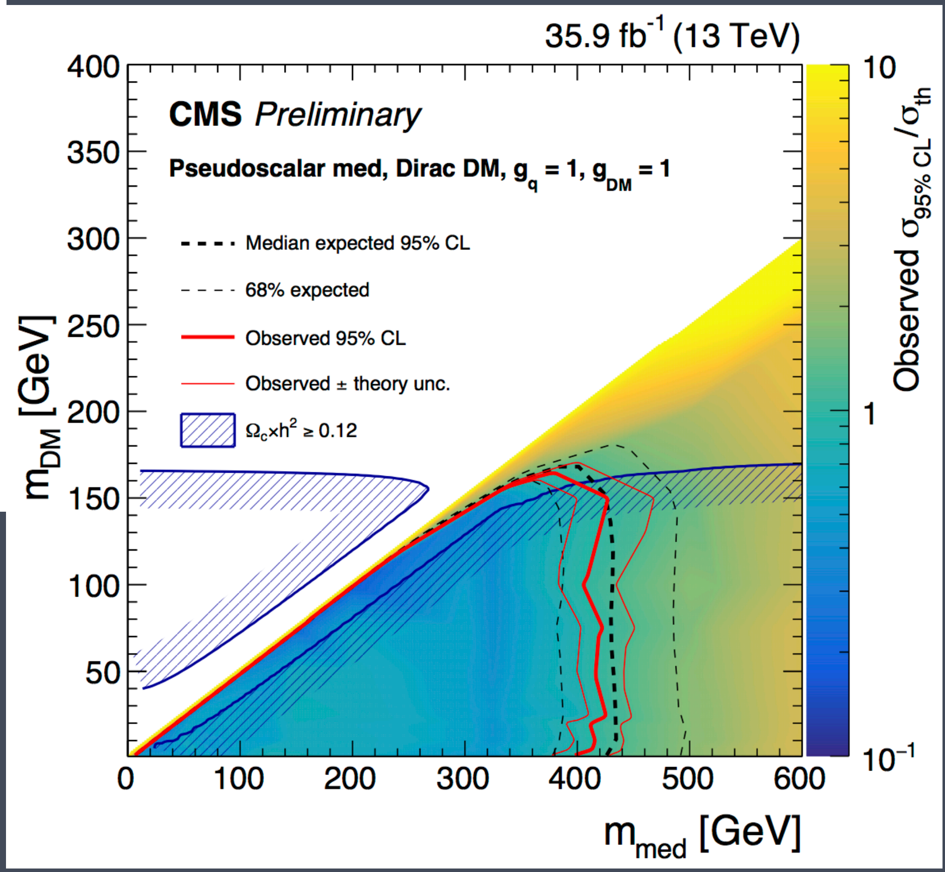


MONO-JET/V

CMS-PAS-EXO-16-048

- No excess found, limits on both spin 1 and 0 mediators
- Main Systematic uncertainties:
  - Background theoretical uncertainties: Normalisation and factorisations scales, PS-ME matching, W/Z +jets modelling
  - Experimental uncertainties: lepton ID, $\not{E}_T$





CMS (35.9 fb^{-1}) mono Jet/V	
Pseudo(Scalar)	Mmed < 400(100) GeV M_{DM}<175(35) GeV
Vector/Axial	*Mmed* < 1.8 TeV M_{DM}<750(550) GeV
H(Inv)BR	< 0.53(0.4)

ATLAS (3.2 fb^{-1}) mono Jet	
ADD LED	M_D< 6.58 TeV at n = 2 M_D< 4.31 TeV at n = 6
Axial -vector	1 TeV

MONO-JET/V

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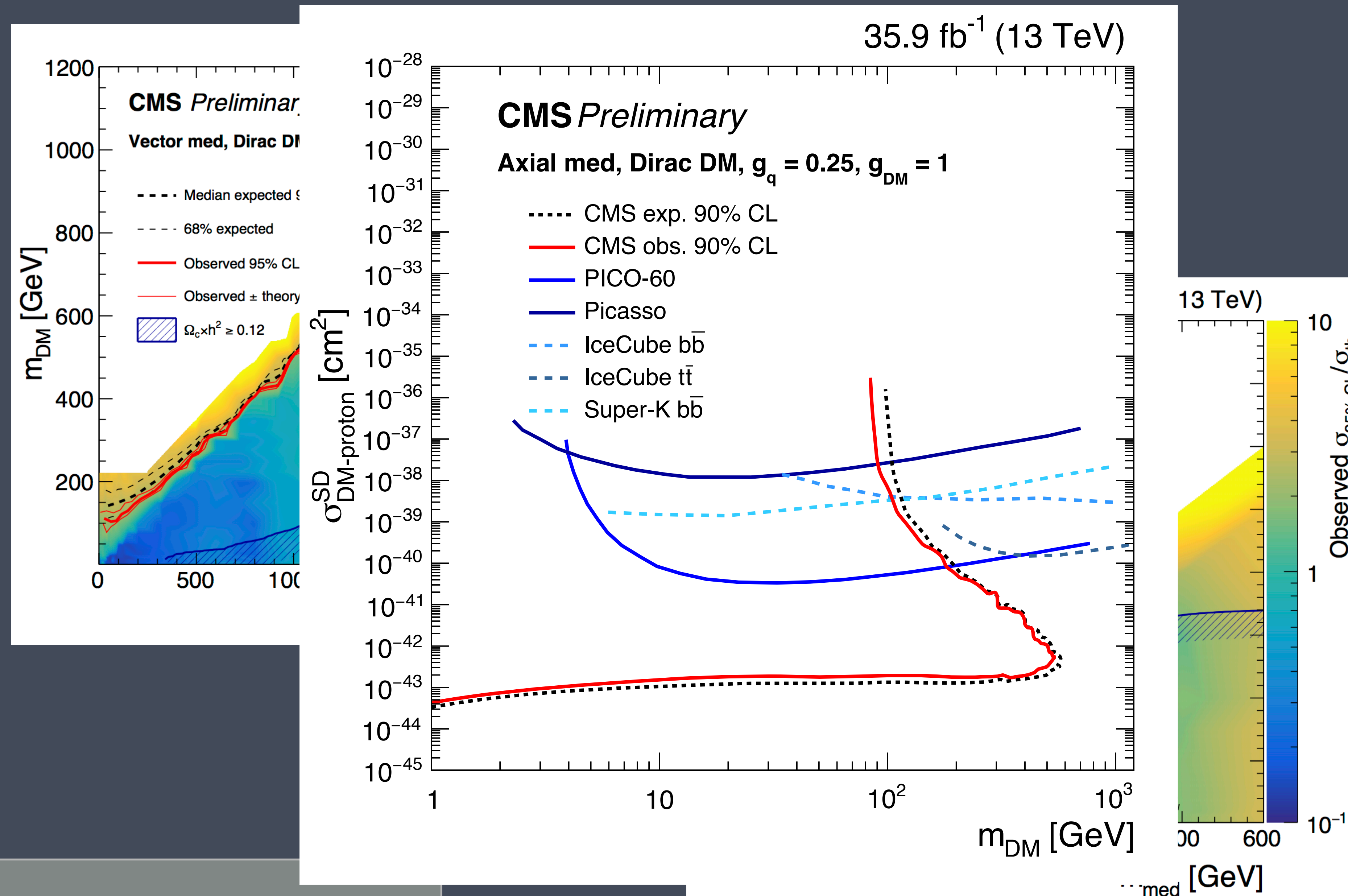

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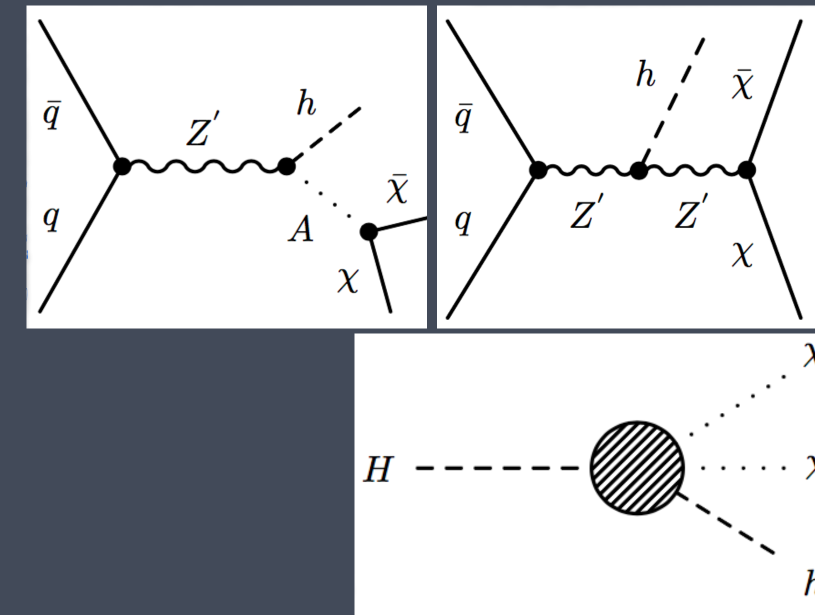
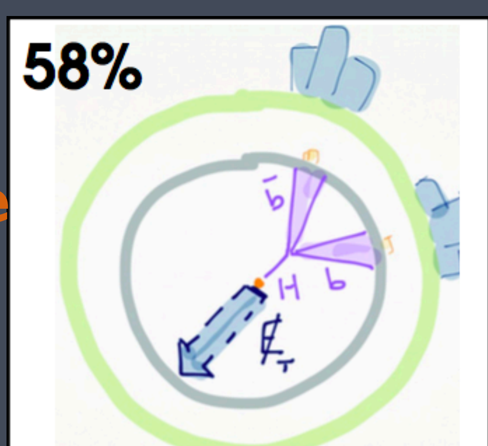
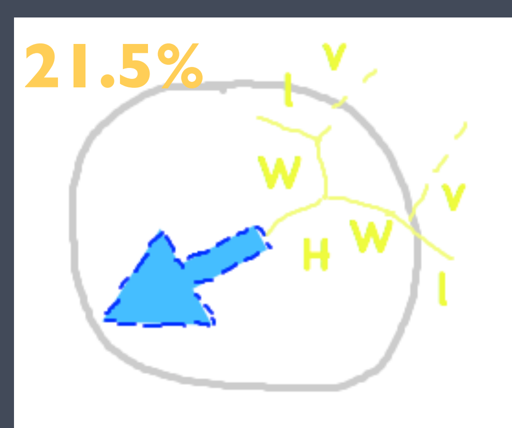
MONO-H

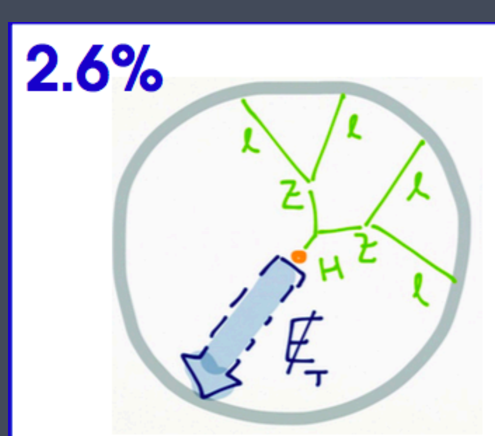


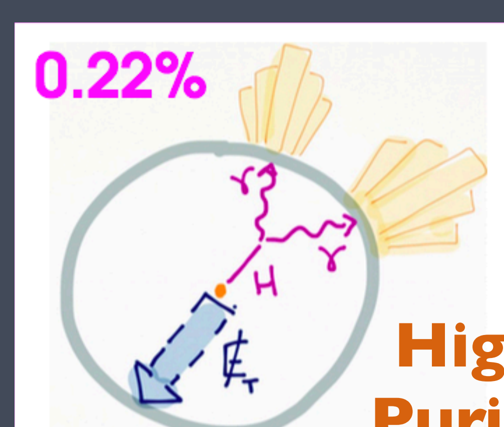
- ISR suppressed by the small mass couplings to quarks
  - preferentially emitted as part of the effective vertex itself.
  - positive mono-Higgs signal would probe directly the structure of the effective DM-SM coupling
- Signal involved Higgs in the BSM models responsible for producing DM
  - Signatures are Higgs signal (ZZ, $\gamma\gamma$, bb,etc) plus large $\not{E}_T$

Large BR

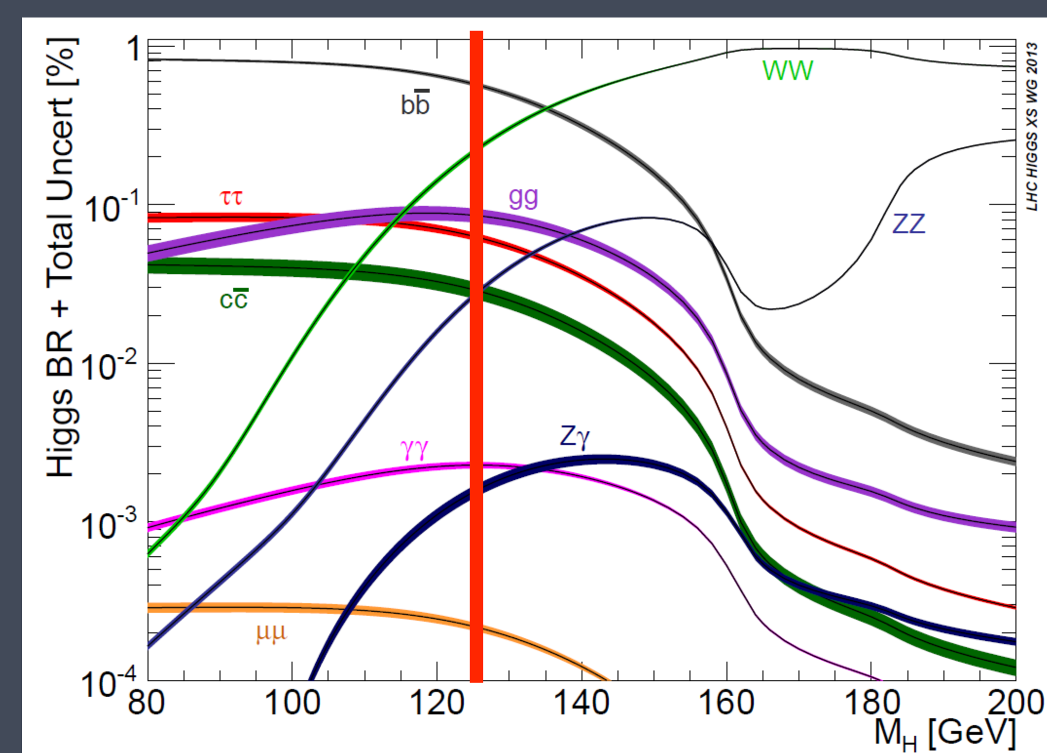








High Purity



MONO-H

- H (bb)
  - **Selection**
    - b-jets, lepton veto and $m_{H,reco}$ consistent with H_{mass} and large $\not{E}_T$
    - azimuthal angle requirements between $\not{E}_T$ and jets, and $\not{E}_T$ and P_T^{miss}
    - **Resolved**: two b-jets, large P_T^H, separation between Higgs and $\not{E}_T$, energetic activity coming from jets in the Higgs
    - **Boosted:** large R-jet consistent with H_{mass}, veto τ leptons within large jet, and additional b-jets and small hadron activity outside the large jet
  - Background
    - Z+bb(30/60%) ,W+jets(10/25%) and tt(15/50%) depending on SR
      - Constrain from control regions (1μ or 2 l)
    - others: VV, VH, tW or multijets are from MC predictions.
  - Systematics uncertainties coming mainly from background modelling and b-tagging. Stats dominates the measurements

- H ($\gamma\gamma$)
  - **Selection**
    - two high Pt γs, $m_{\gamma\gamma}$ >95 GeV, $P_T^{\gamma}/m_{\gamma\gamma}$ >1/3. If photons are two close, no iso requirements
    - large $P_T^{\gamma\gamma}$ and P_T^{miss} and less than 3 high P_T jets
    - azimuthal angle requirements between 2 photons and $P_T^{miss,}$ and an energetic jet and $P_T^{miss,}$
  - Background
    - resonant: SM H(H and VH) to photons;
      - estimated from MC
    - non resonant QCD, EWK.
      - Background estimated from data driven fitting the data
  - Systematics coming mainly from theory in the Higgs background and experimental uncertainties in the $P_T^{miss,}$, thought the systematics accounts less than 1%. Dominated by the stats

MONO-H

- **H (bb)**
  - **Selection**
    - b-jets, lepton veto and $m_{H,reco}$ consistent with H_{mass} and large $\not{E}_T$
    - azimuthal angle requirements between $\not{E}_T$ and jets, and $\not{E}_T$ and P_T^{miss}
    - **Resolved**: two b-jets, large P_T^H, separation between Higgs and $\not{E}_T$, energetic activity

- **H ($\gamma\gamma$)**
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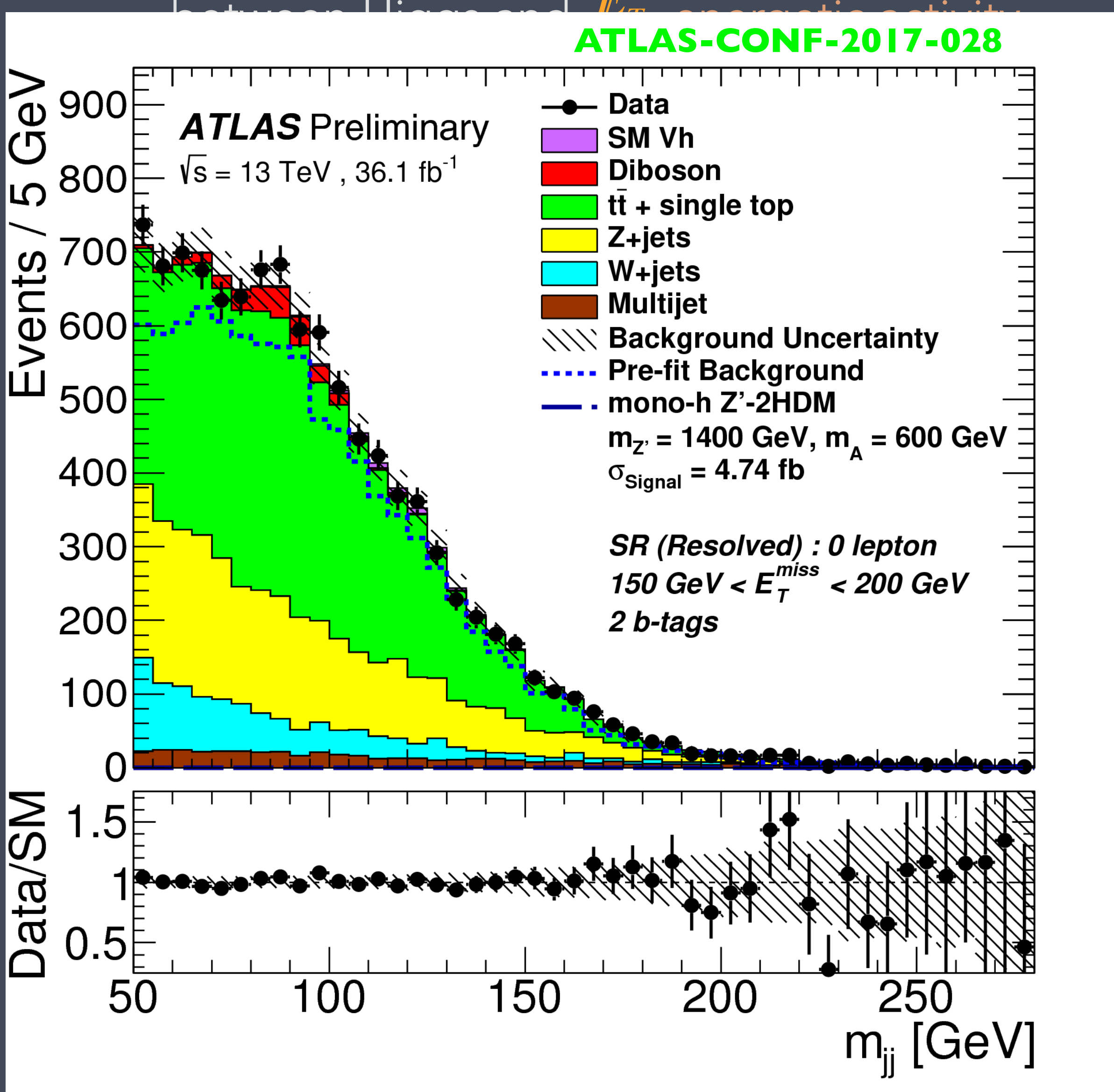
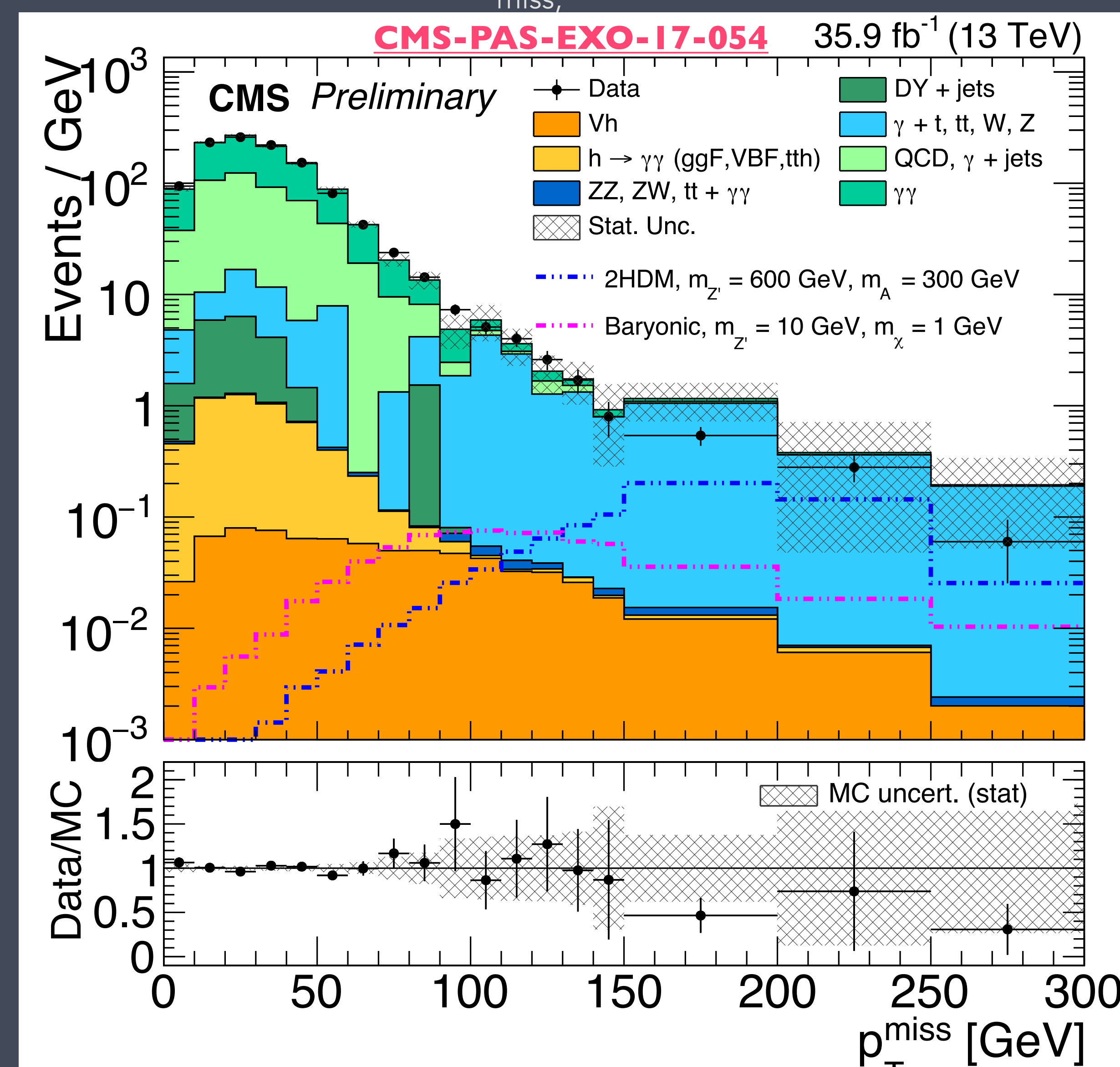
    - two high Pt γs, $m_{\gamma\gamma}$ >95 GeV, $P_T^{\gamma}/m_{\gamma\gamma}$ >1/3. If photons are two close, no iso requirements
    - large $P_T^{\gamma\gamma}$ and P_T^{miss} and less than 3 high P_T jets
    - azimuthal angle requirements between 2 miss,



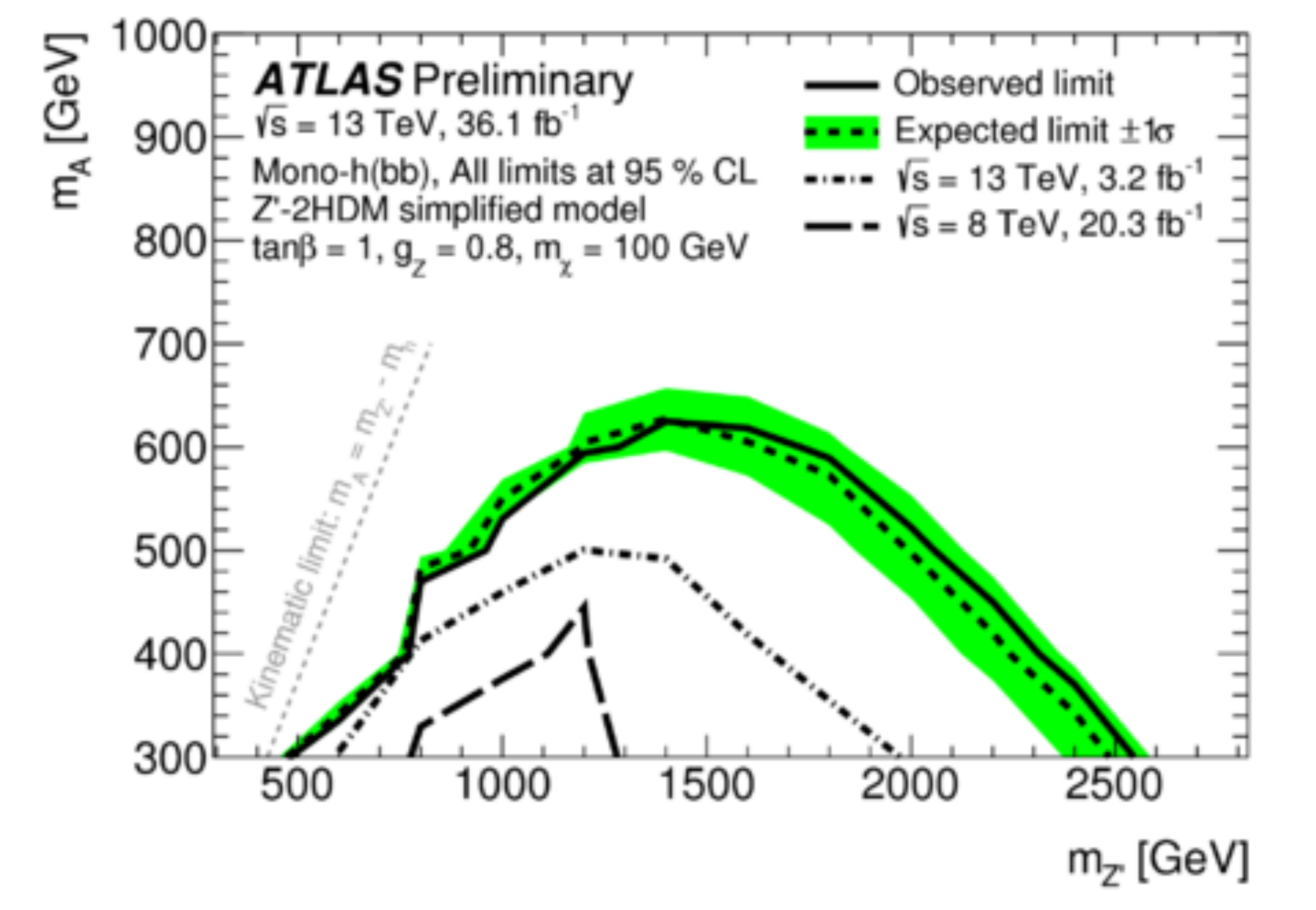


MONO-H

- No excess found, limits set in
  - Vector mediator or 2HDM model
    - 2HDM, 500 GeV< Mz´ < 2500 GeV
    - Z´ baryonic. Mz´>800 GeV

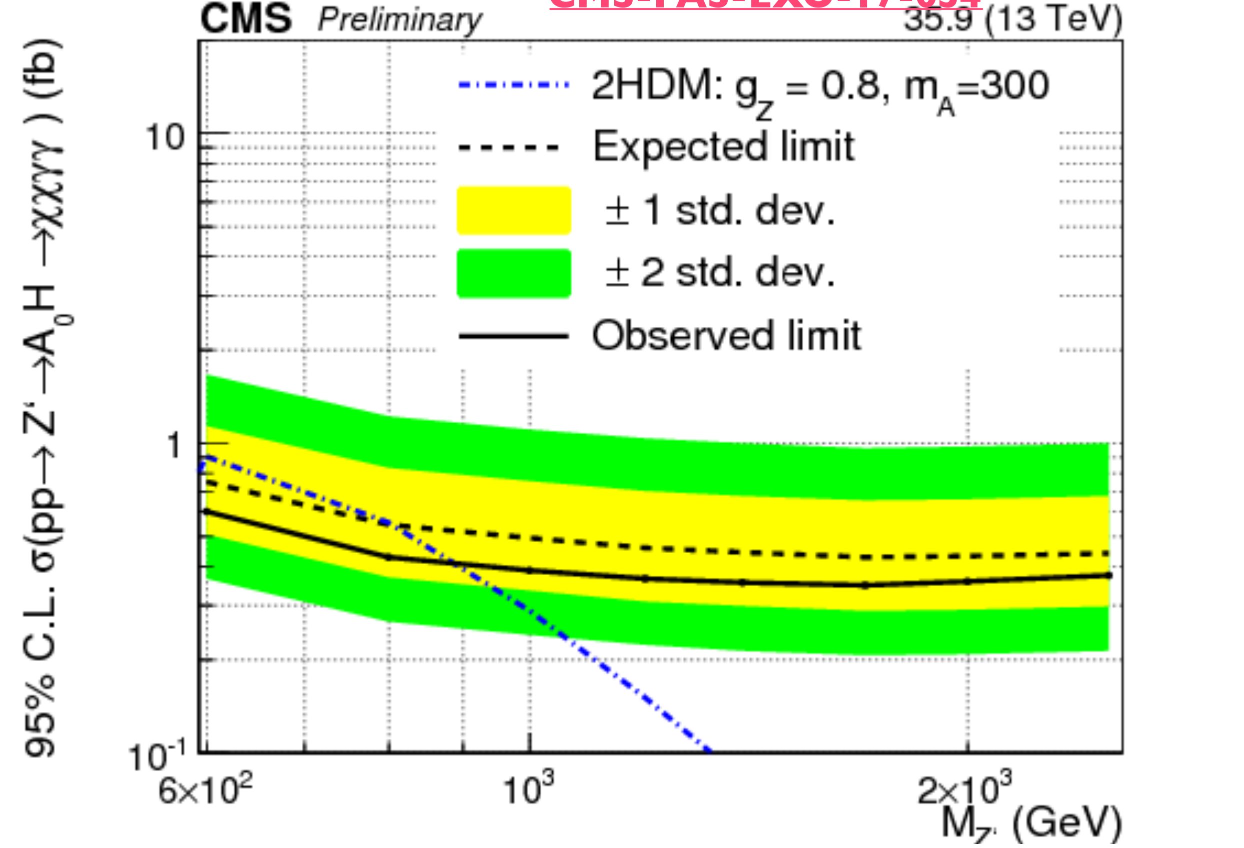
- **H (bb)**

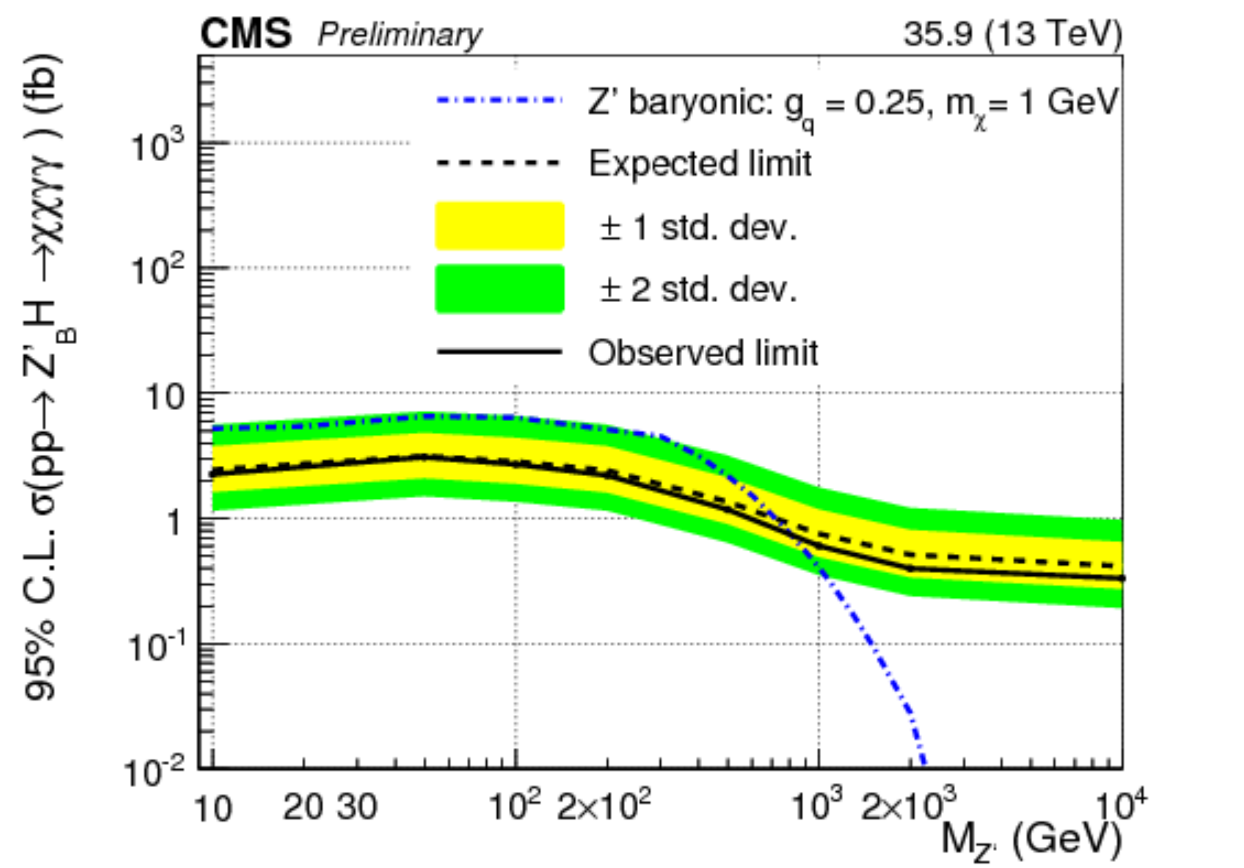
ATLAS-CONF-2017-028



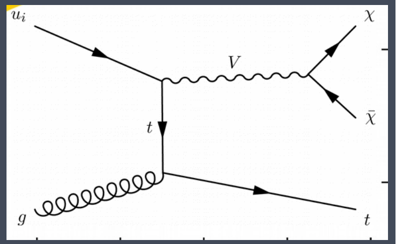
- **H (γγ)**

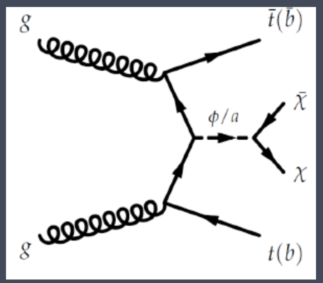
CMS-PAS-EXO-17-054





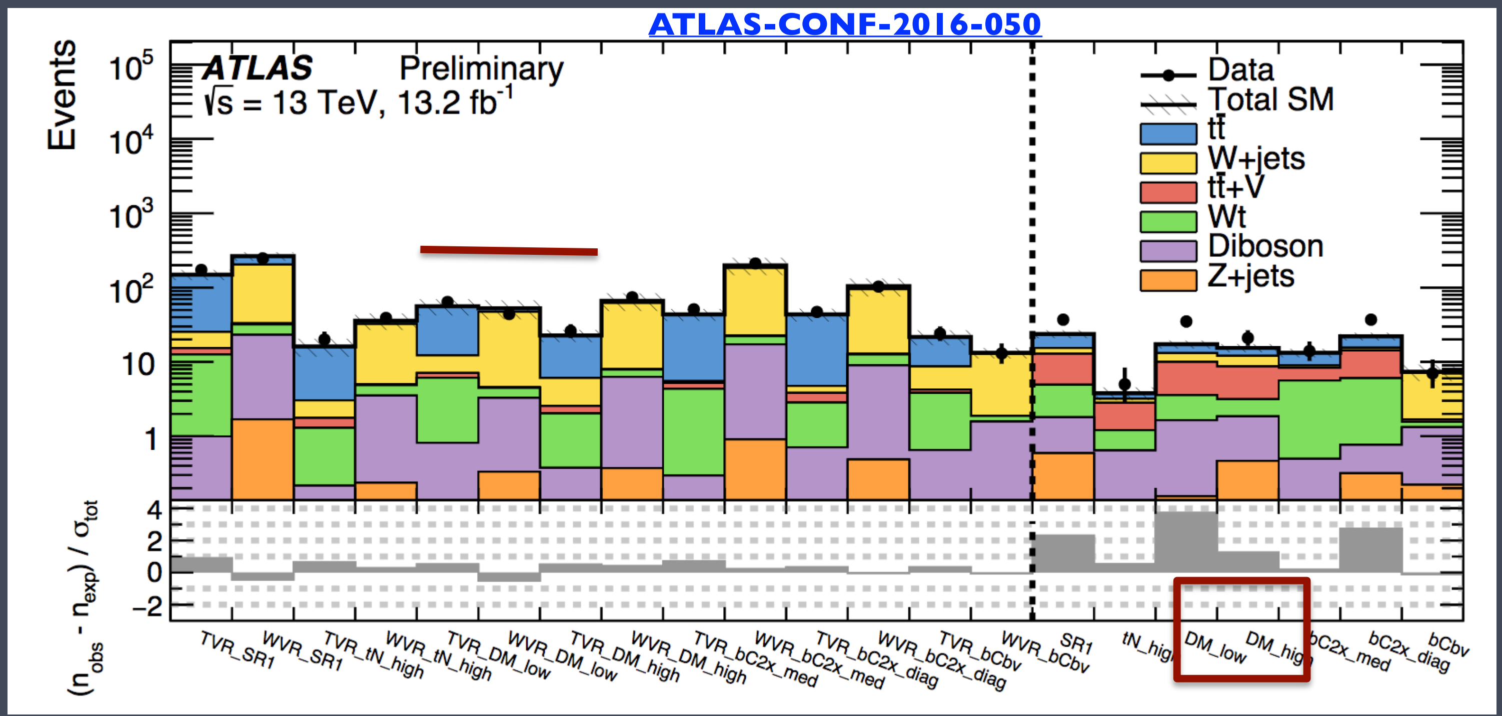
DM+TOP

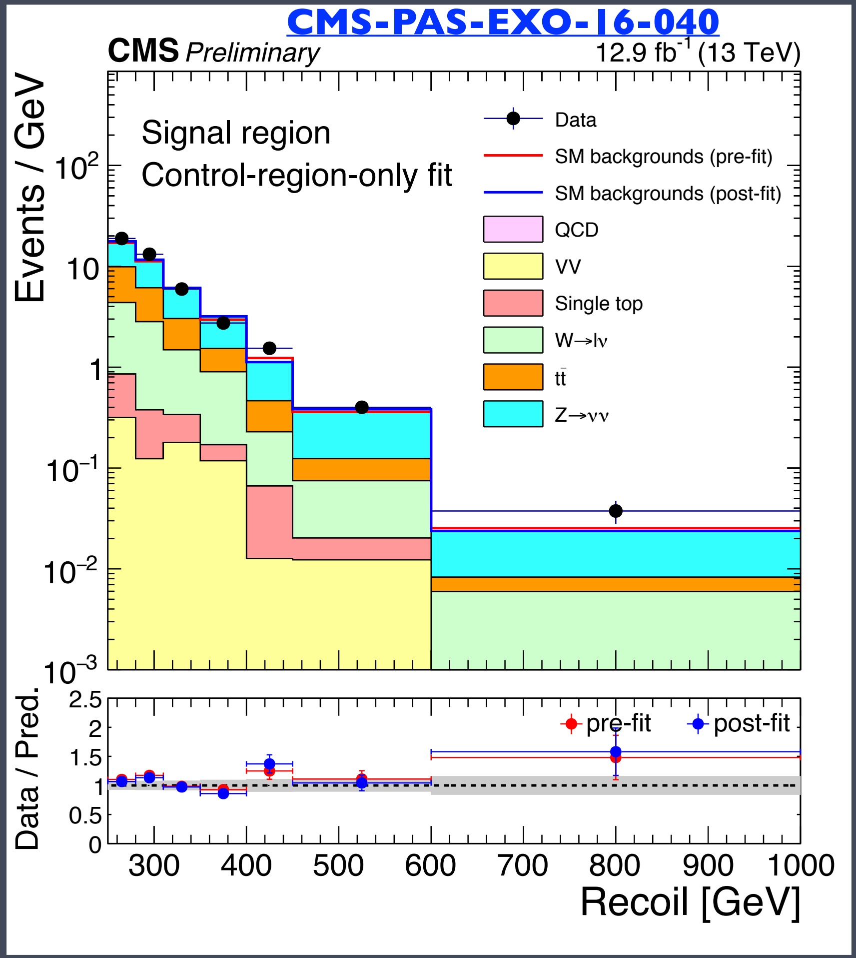




- Probes the Yukawa coupling for scalar mediators
- DM+tt
  - Signature:
    - tt +$\not{E}_T$ in hadronic, semileptonic and dilepton.
    - jets and b-tag requirements, kinematical and topological cuts
    - fat-jets for boosted regions.
- DM+top (mono-top)
  - Signature:
    - fully hadronic top decay in boosted top
    - large $\not{E}_T$ and large hadronic activity, very hight P_T fat jet with a b-jet, with N-subjetttines compatible with top
    - veto leptons and additional b-jets outside

- **DM+tt**
  - **background**: top (top pairs, single top, ttV), W+jets, Z+jets
    - constraint in CR at simultaneous fit
- **DM+top (mono-top)**
  - **backgrounds: Top pairs, Z(->$\nu\nu$) +jets, W(->νl) +jets**
    - constraint in CR in simultaneous fit

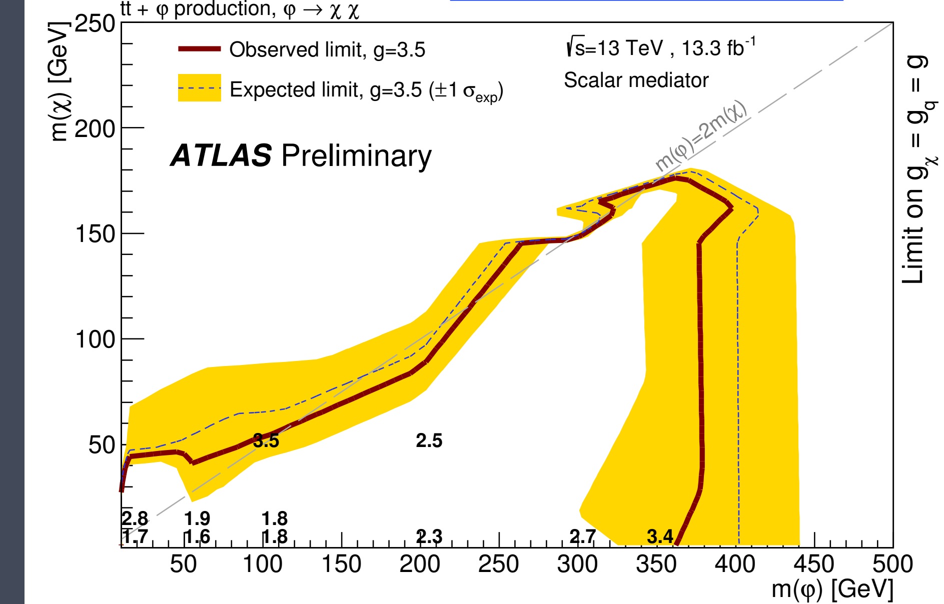


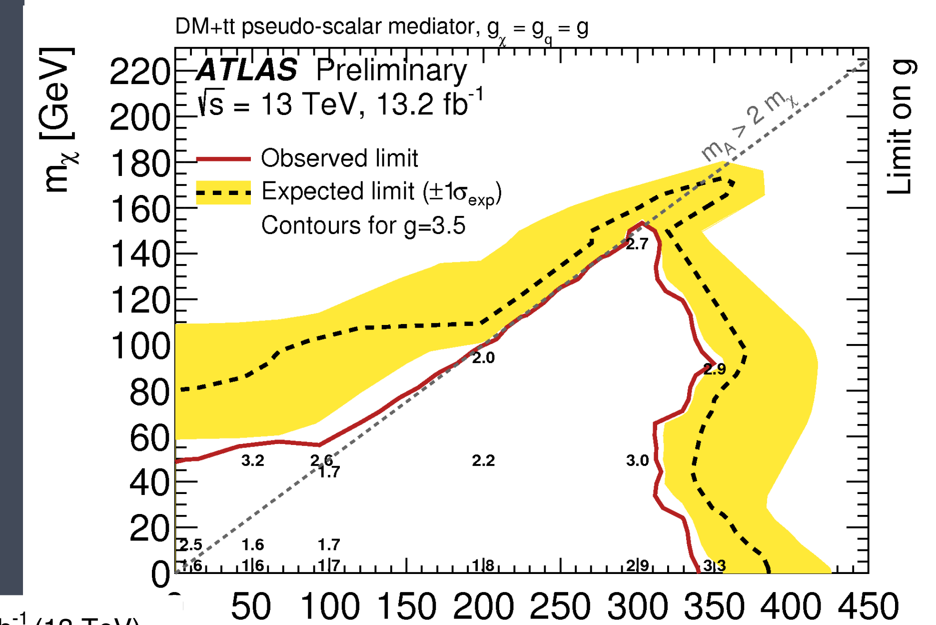


DM+TOP

- No Excess, set limits on scalar-pseudoscalar mediators
  - **tt+DM**
    - semileptonic channel ATLAS sees a local excess of 3.3 σ in one the SR regions no seen any where else
  - **t+DM**
    - M_{med} <2.7 TeV for M_{χ} =100GeV, for a non resonant model with FNCN M_{med} <1.5 TeV for M_{χ} =10GeV
- Main systematics includes Theoretical uncertainties in background modelling (renormalization and factorizations, HF , EWK corrections) and Experimental (b-tagging, top-tagging, objects ID), luminosity.

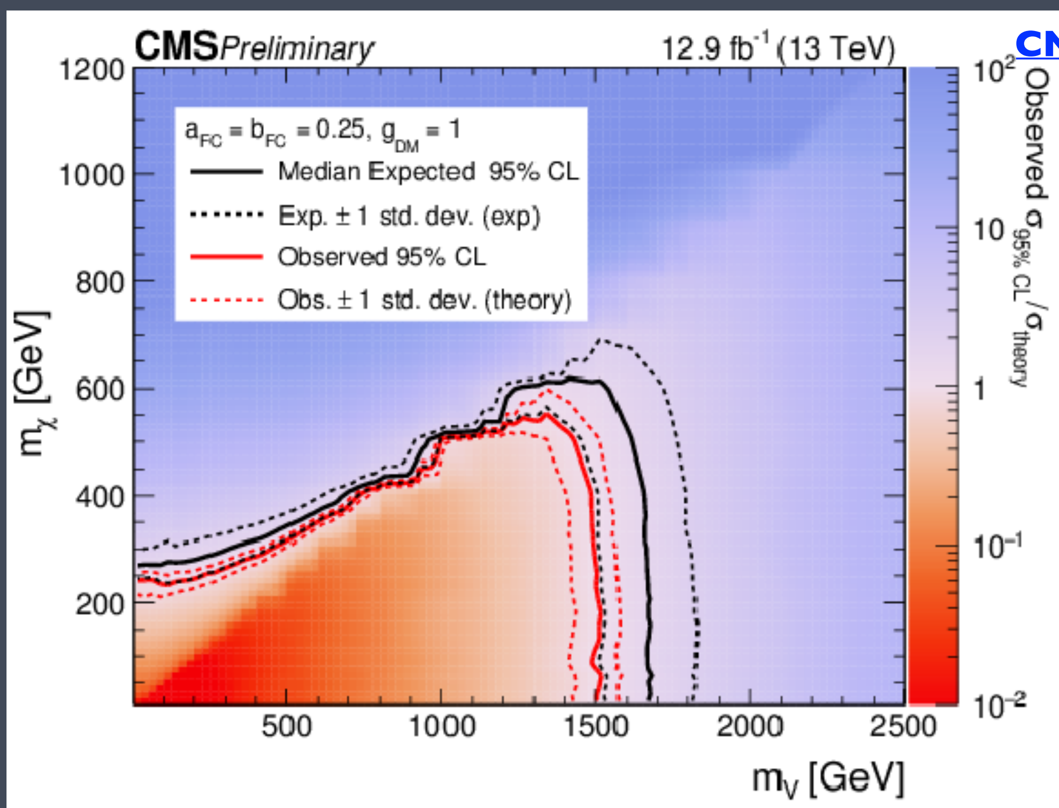
ATLAS-CONF-2016-077

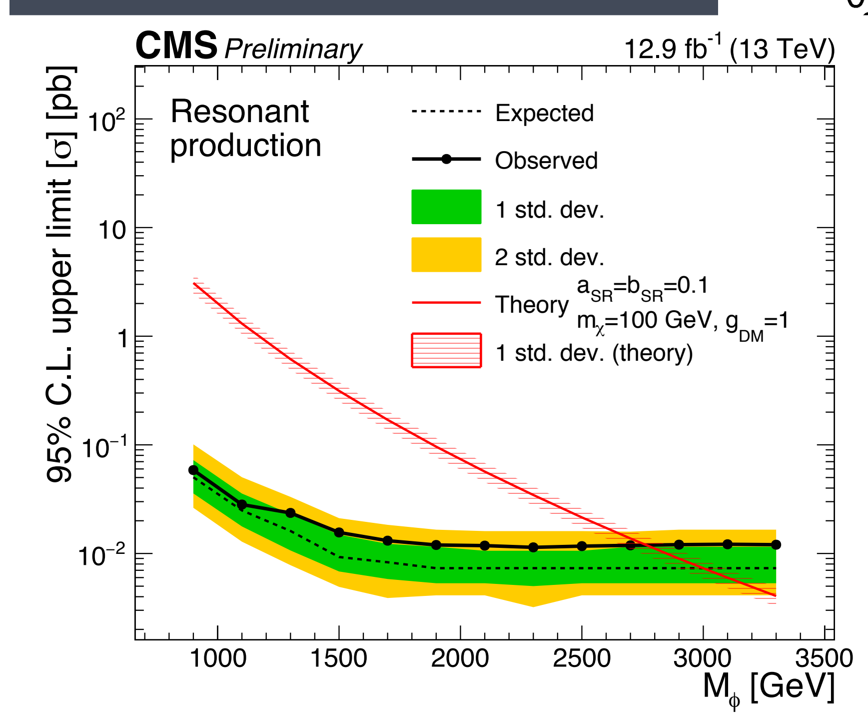




ATLAS-CONF-2016-050

CMS-PAS-EXO-16-040





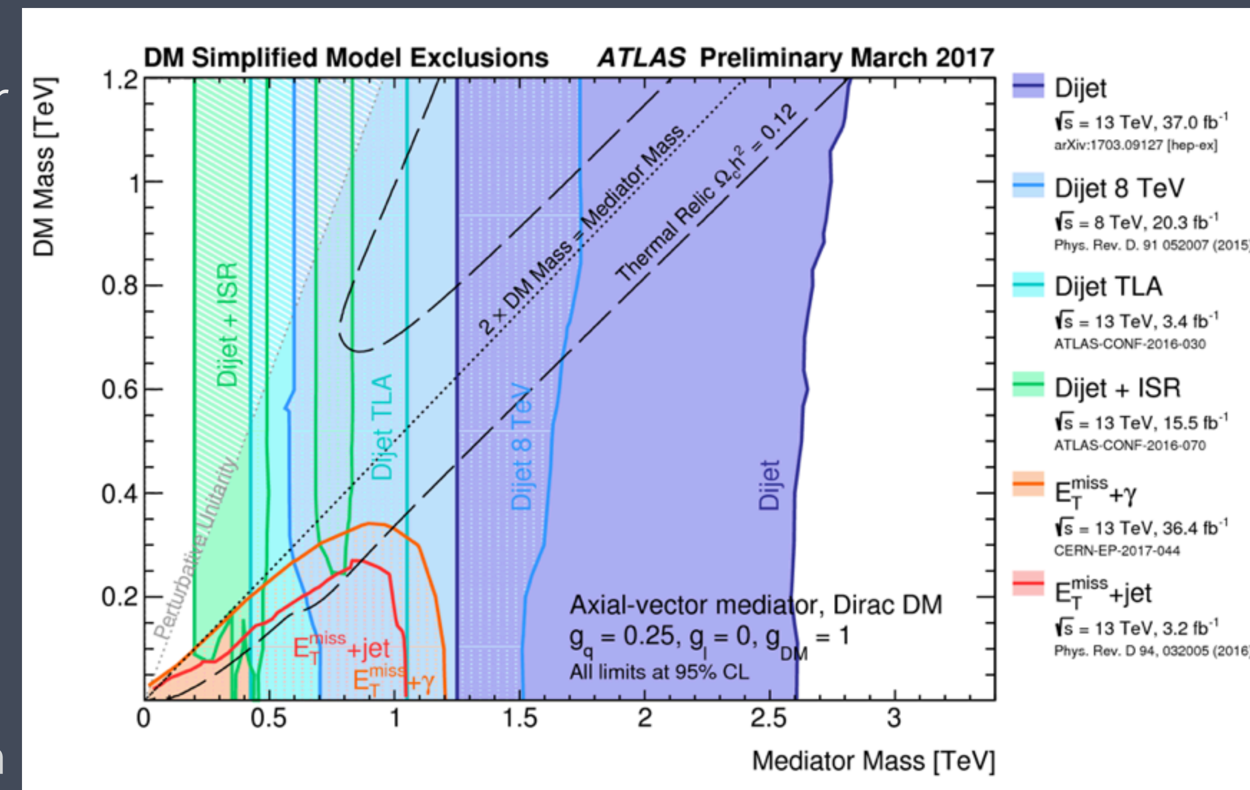
SUMMARY OF DM +X SEARCH

95% CL exclusion region in the mediator- DM mass plane for different MET+X searches for spin-1/0 mediators with couplings

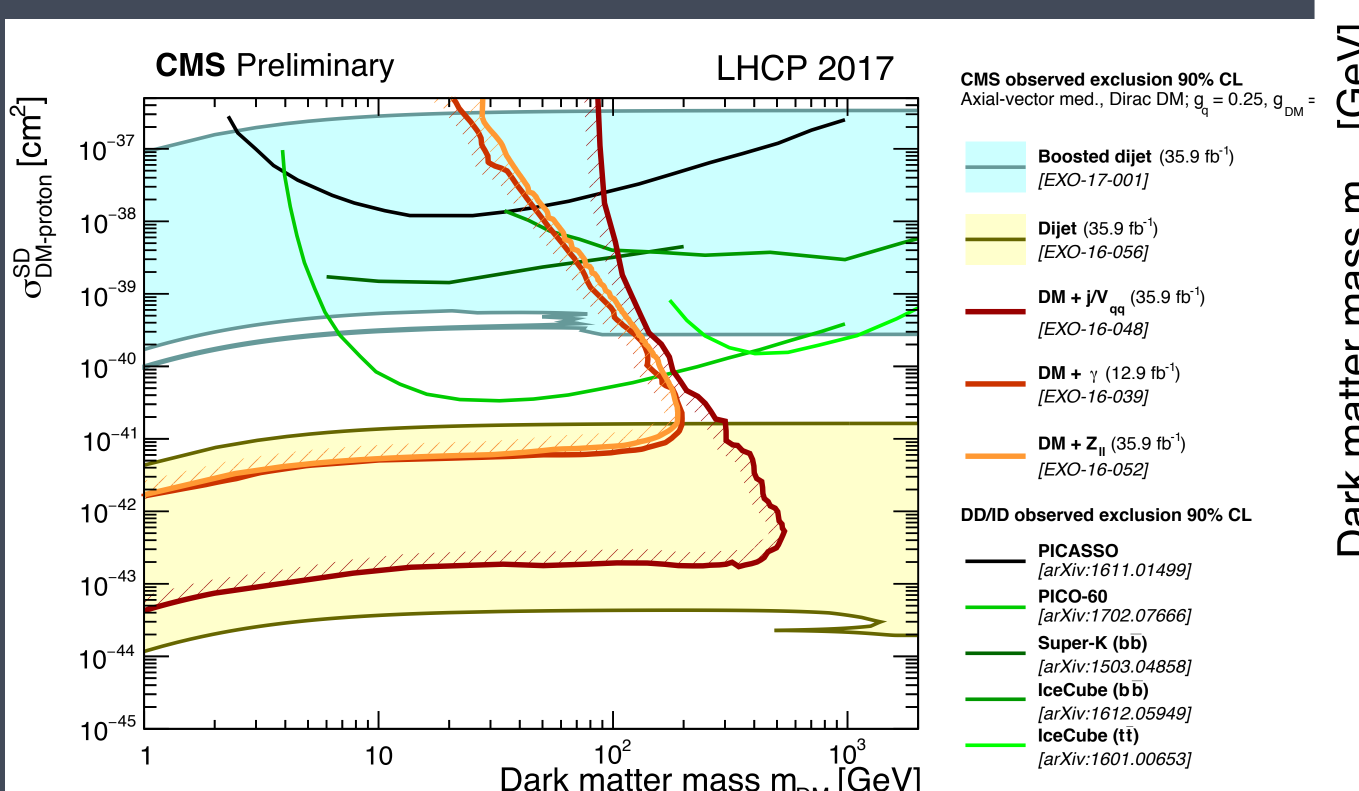
- $g_q = 0.25, g_l = 0, g_{DM} = 1$ or $g_q = 0.1, g_l = 0.1, g_{DM} = 1$

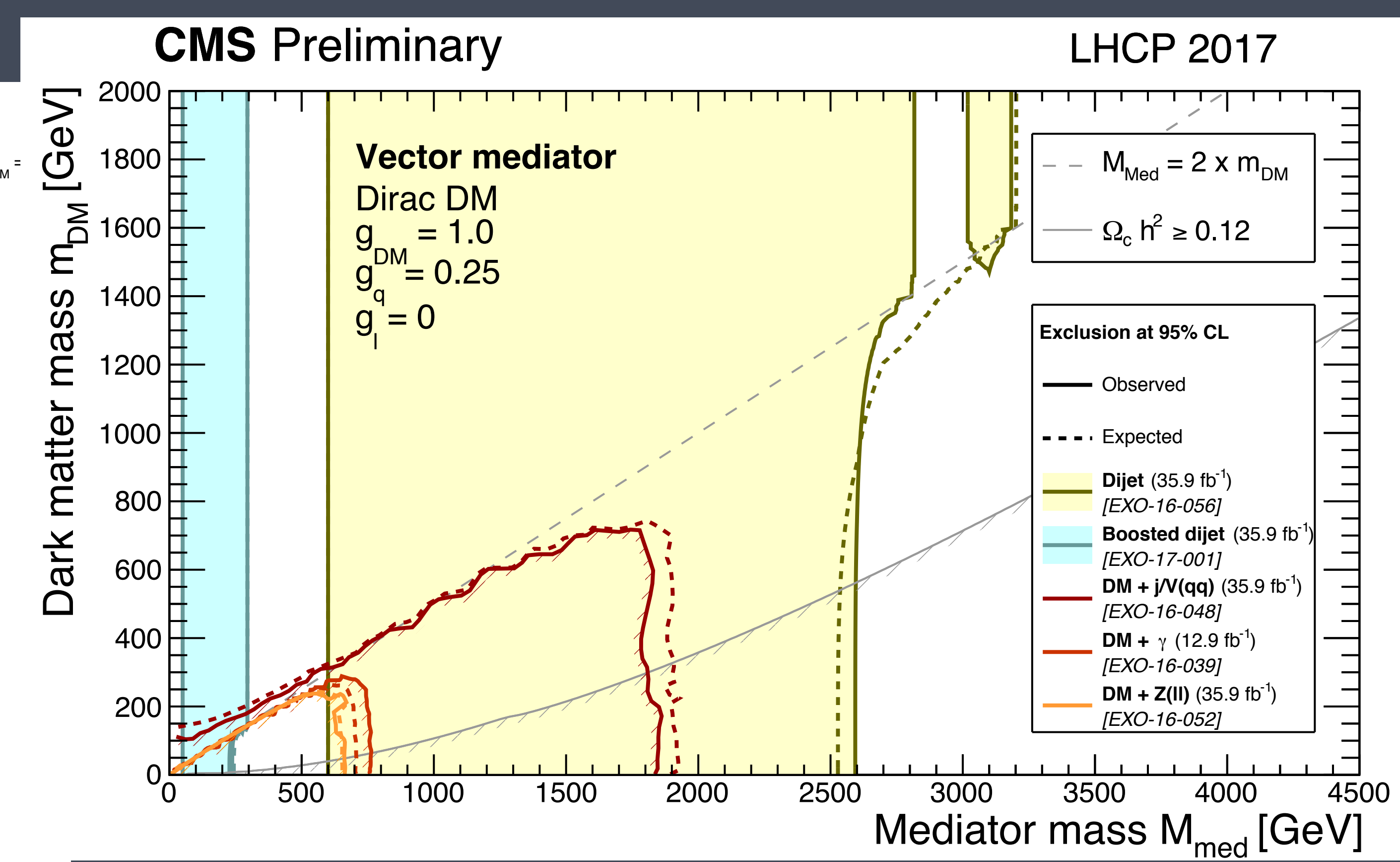
The mono-jet has better sensitivity with full 2016+2015 lumi.
Recast of MET+X analysis to set DM-nucleon limits:

- SD the strongest
- SI the strongest below 5.5 GeV
- this is only valid for the coupling and models chosen



CMS-LHCP-2017





CONCLUSIONS

- Searches at different **MET +X final** states have been presented
- **No excess** has been observed yet -> 95% C.L upper limits were set in several Simplified Models using Run II data:
    - limits at low mass spin 0 mediators
    - multi-TeV mass spin 1 mediators
- Searches at Dark Matter at LHC are **complementary** to other searches
    - **Re-interpretation** in terms of **DM-nucleon** cross sections

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NEW SEARCHES ARE IN PREPARATION
SO STAY TUNE!!!
(WE´LL KEEP LOOKING)

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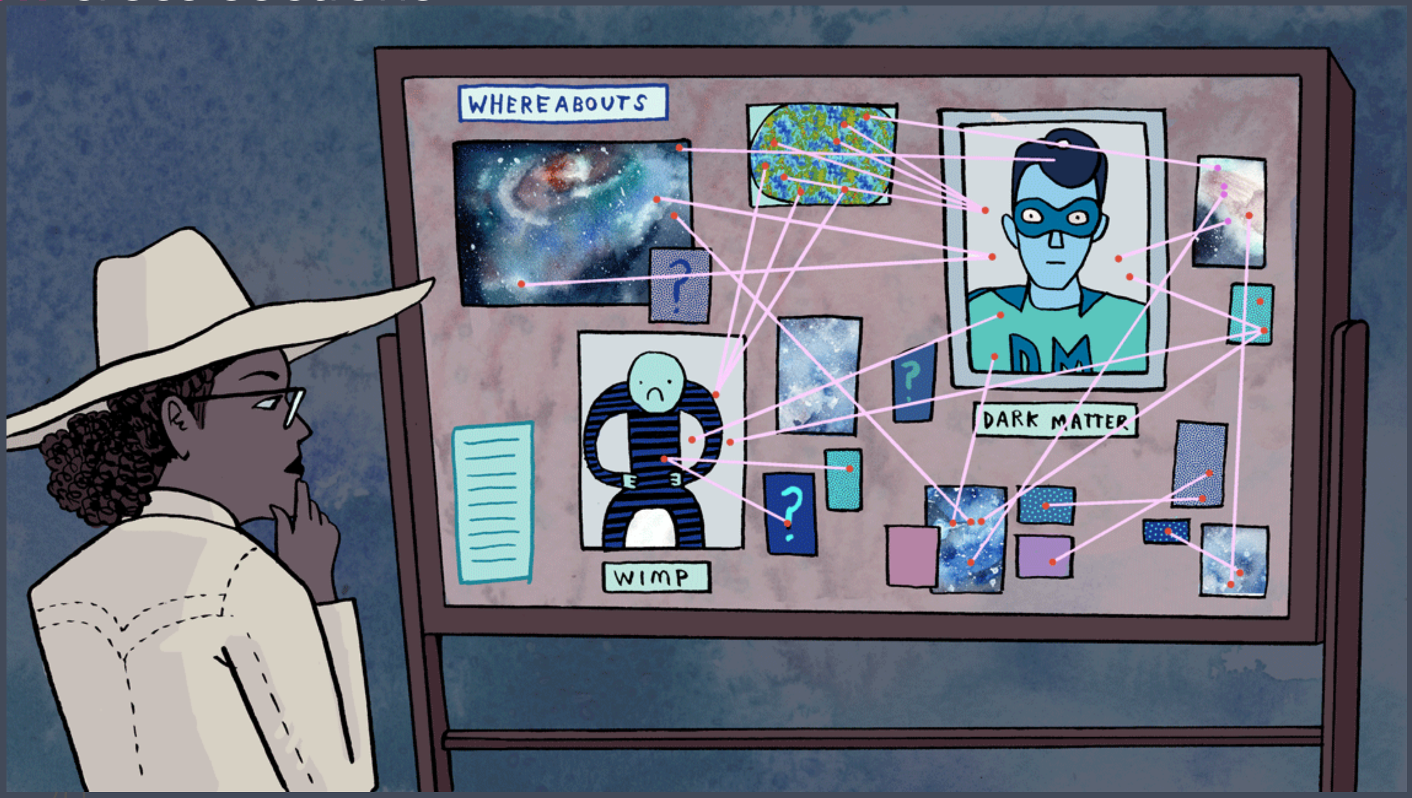
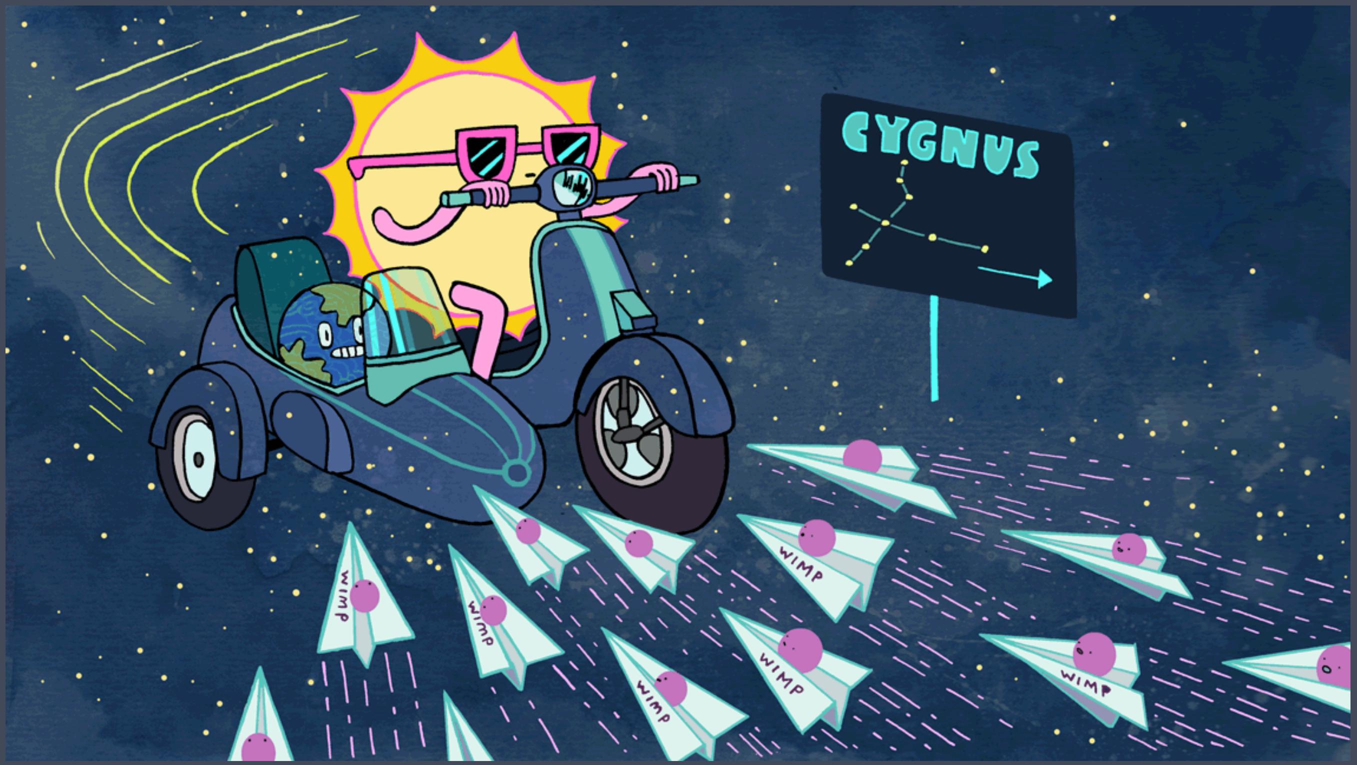


Illustration by Sandbox Studio, Chicago by Corinne Mucha

THANKS!!!

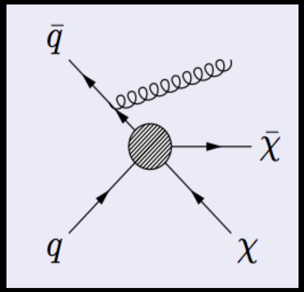
- ¿ANY QUESTIONS?



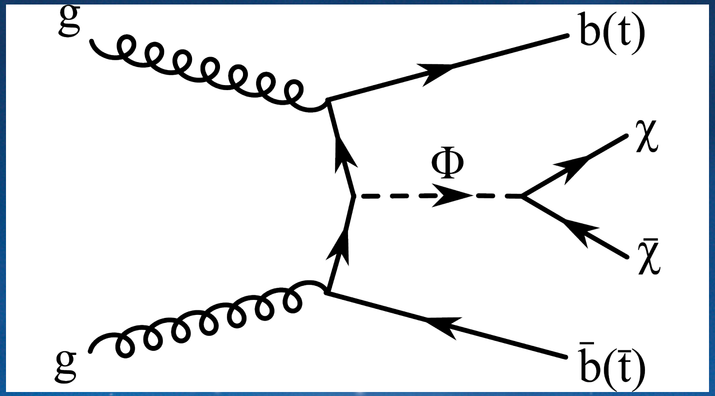
BACK-UP SLIDES(stolen from others)

Benchmark Models

In Run II the ATLAS and CMS experiments moved away from the use of EFT inspired models with questionable validity at high-Q^2

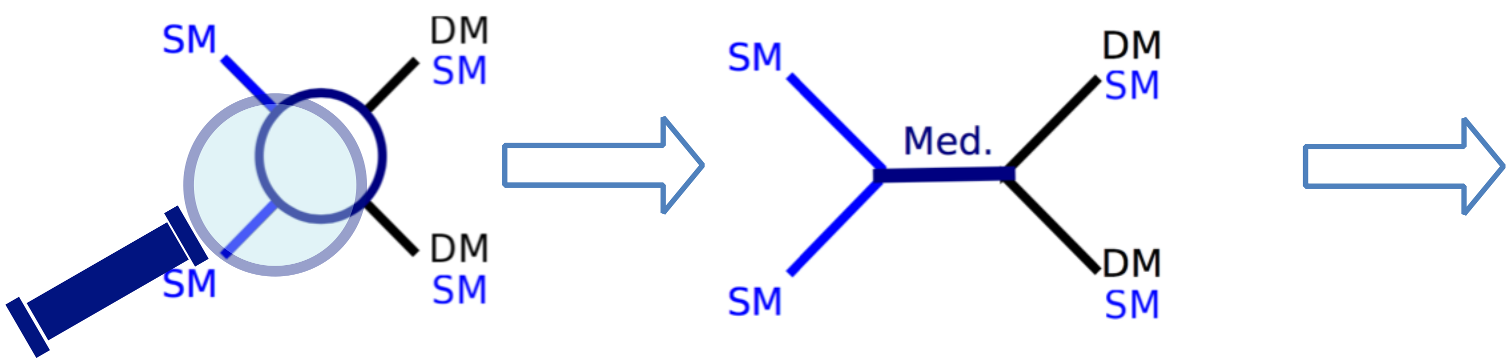


A set of well-defined simplified diagrams with heavy mediators is now considered motivated by a number of different considerations (DM Forum: arXiv:1507.00966)



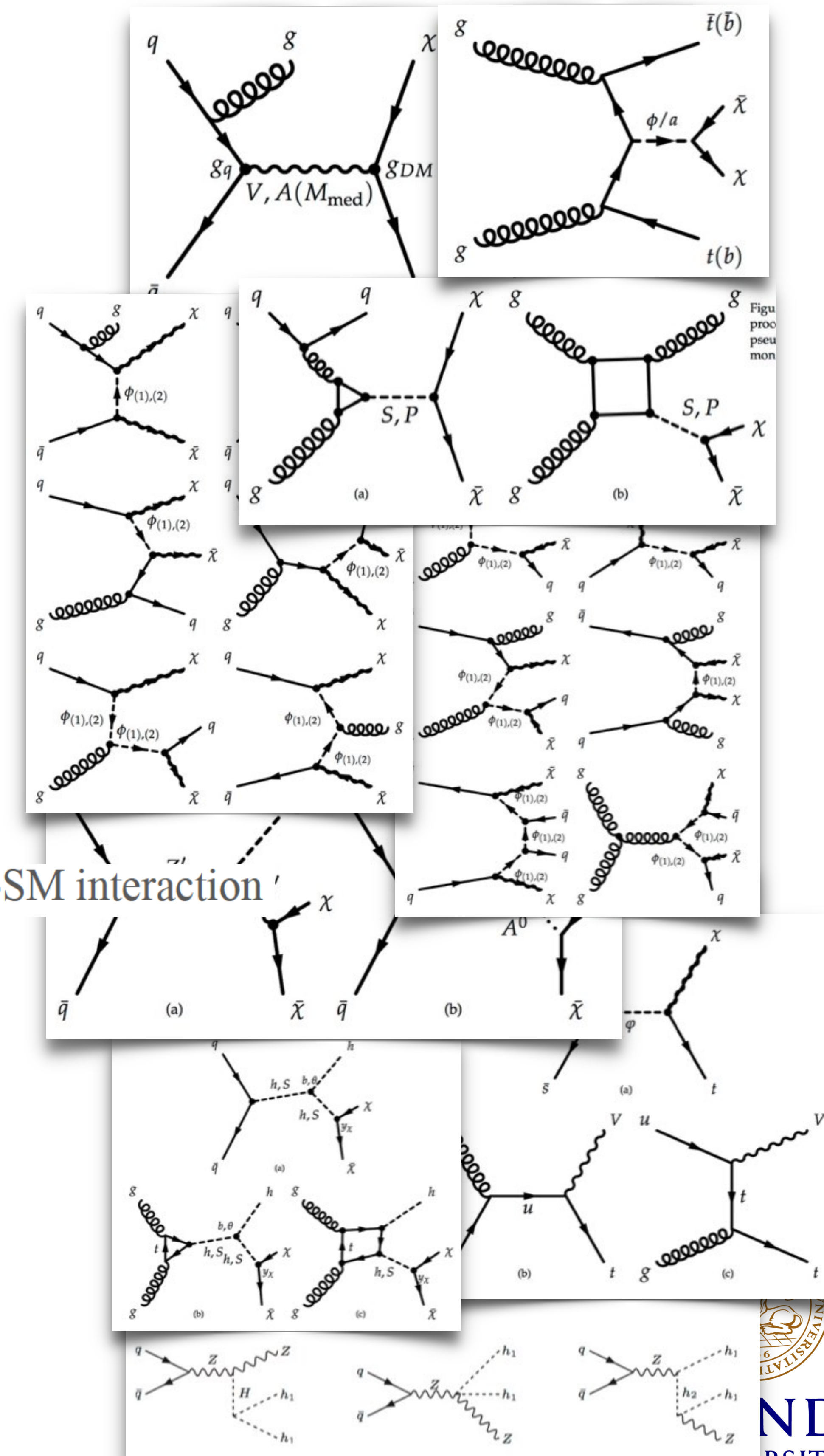
- **Simple extensions of SM symmetries**
- **Minimal Flavor Violation**
- **Assuming Yukawa couplings → favor 3rd generation**
- **Some models inspired by satellite "hints"**

Simplified models for early Run-2 searches



Colliders (Effective Field Theory)

Colliders (Simplified Models)



Motivation and goal of Dark Matter Forum effort:

- Define a basis of simplified models with distinct kinematic distributions
- Aid design of generic LHC Run-2 searches

Grounding assumptions:

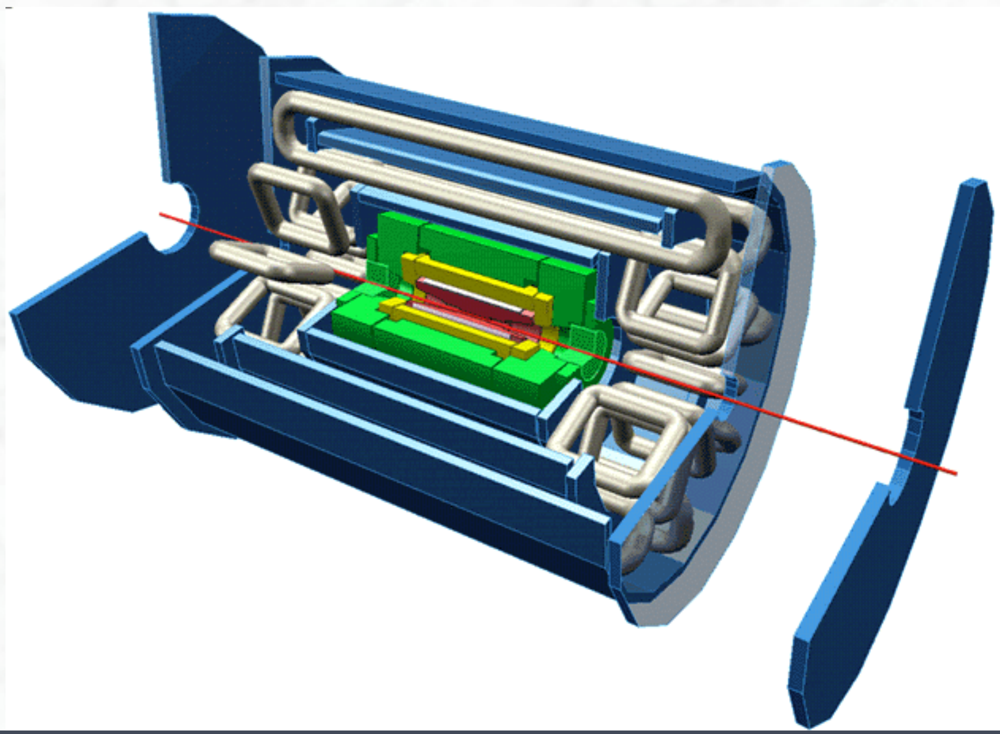
- Dirac DM
- Minimal Flavor Violation
- ...but not necessarily gauge invariance

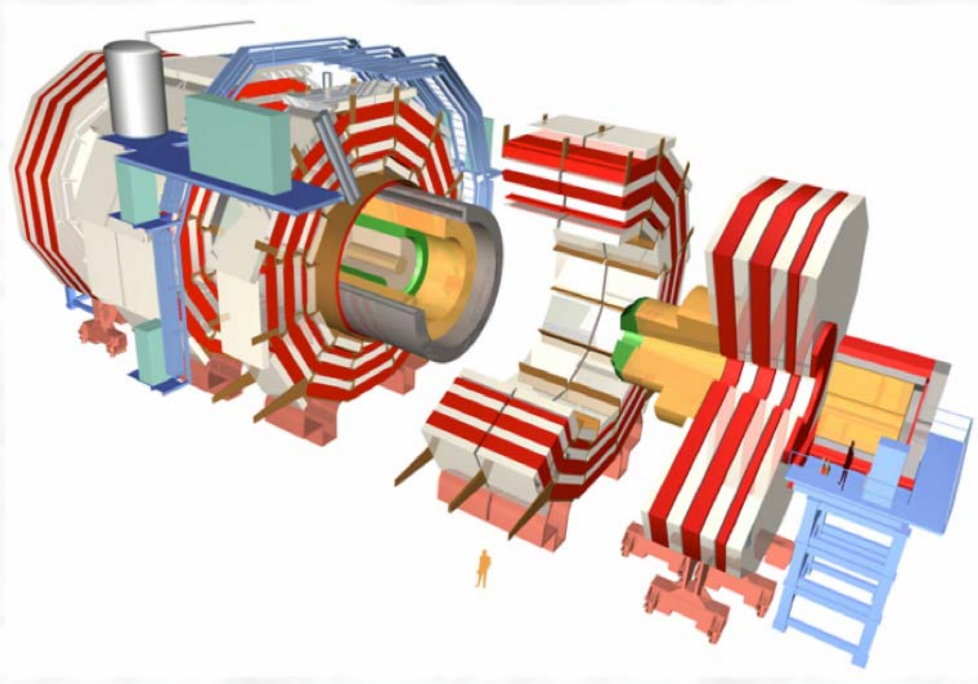
- Mediator has minimal decay width
- A new massive particle mediates the DM-SM interaction
- DM particles are pair-produced

Dirac WIMP mediators:
s- and t-channel exchange
vector/axial-vector/scalar/pseudo-scalar (MFV)
MET+heavy flavour, W, Z, and Higgs

ATLAS EXPERIMENT erc European Commission Horizon 2020 European Union funding for Research & Innovation

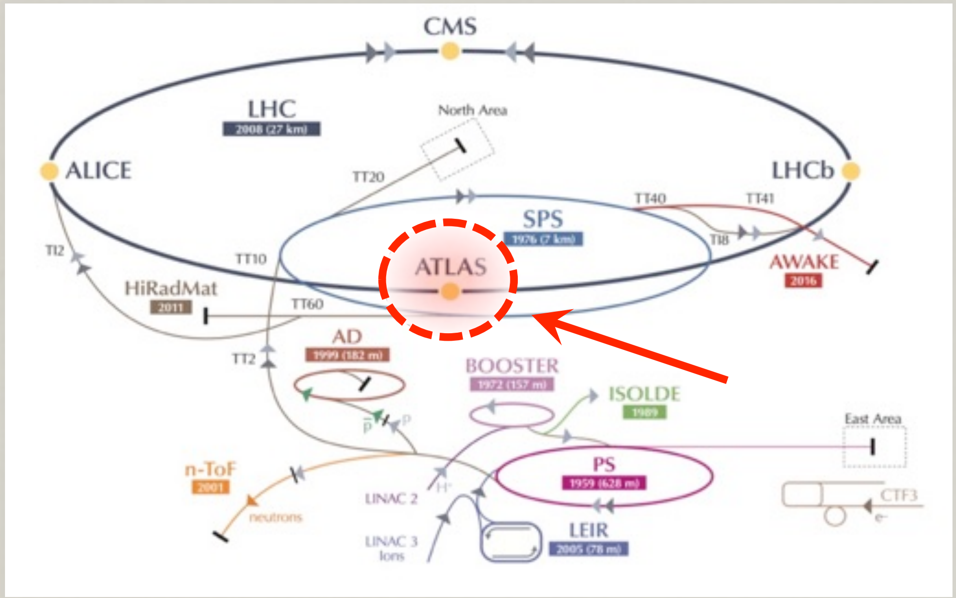
	ATLAS	CMS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)	4 T solenoid + return yoke
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$	Silicon pixels and strips (full silicon tracker) $\sigma/p_T \approx 1.5 \cdot 10^{-4} p_T + 0.005$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	$PbWO_4$ crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Brass + scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)	$\sigma/p_T \approx 1\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)	L1 + HLT (L2 + L3)

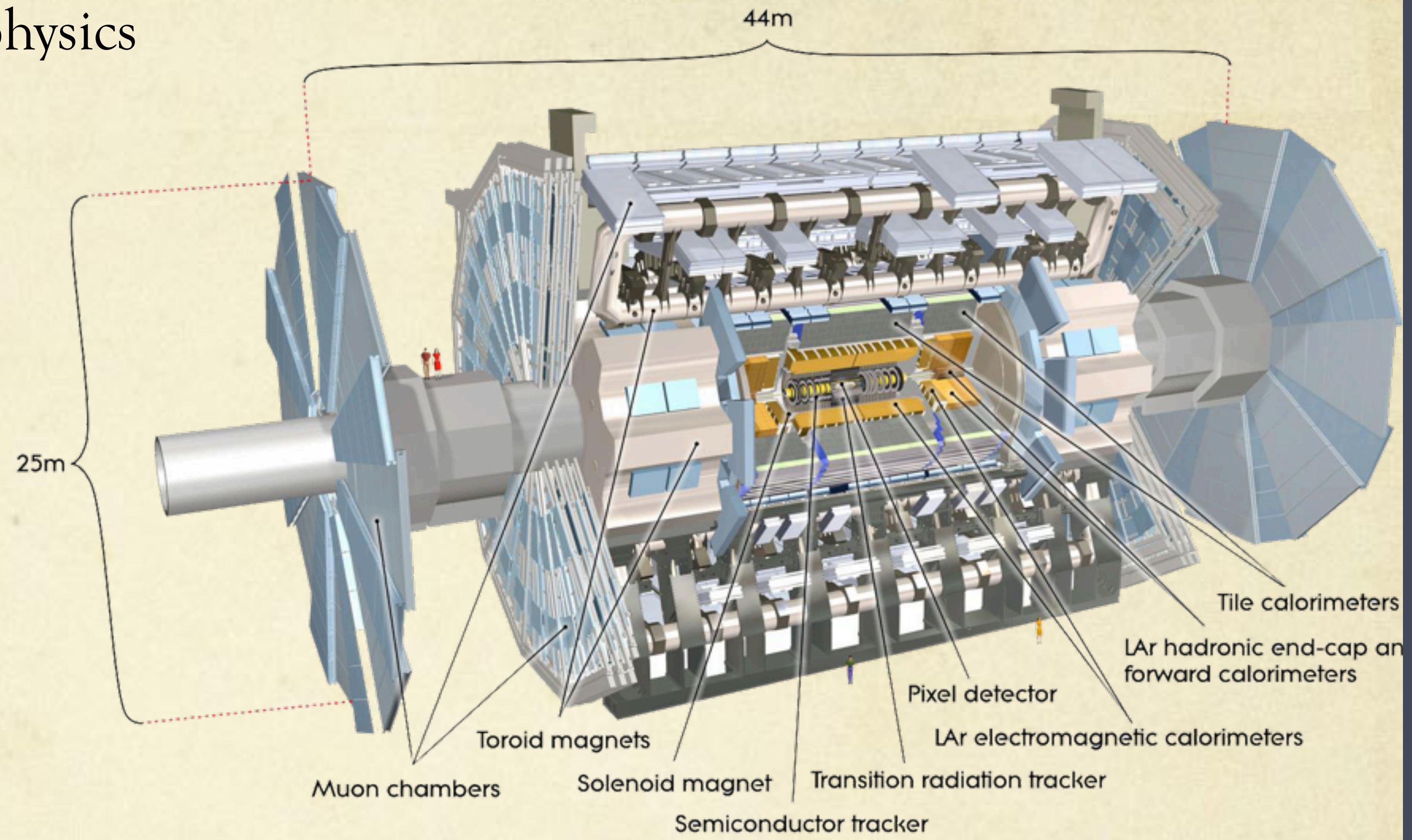




The ATLAS Experiment

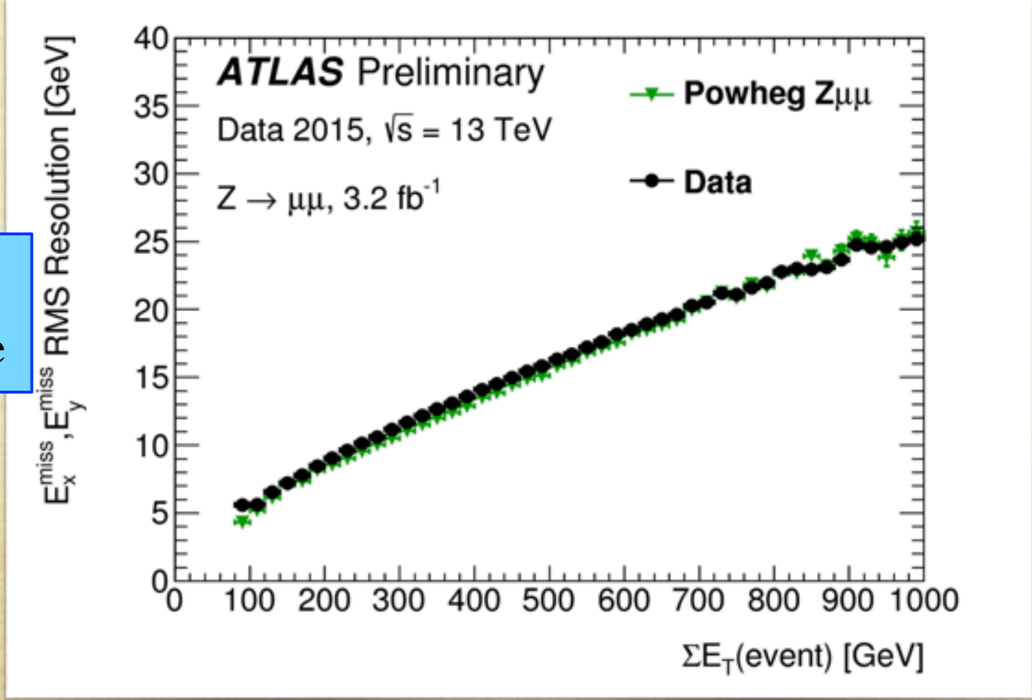
➢ ATLAS is a multipurpose experiment designed to achieve the highest possible flexibility in different sectors of the high energy physics



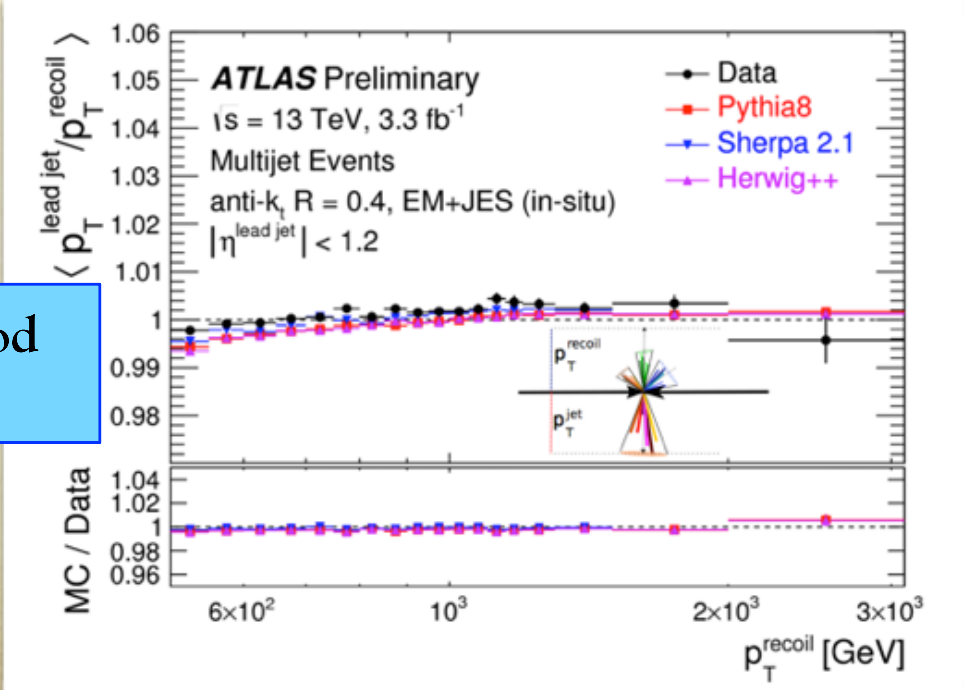


➢ Key ingredients for DM searches

Great MET performance



Well understood jet calibration

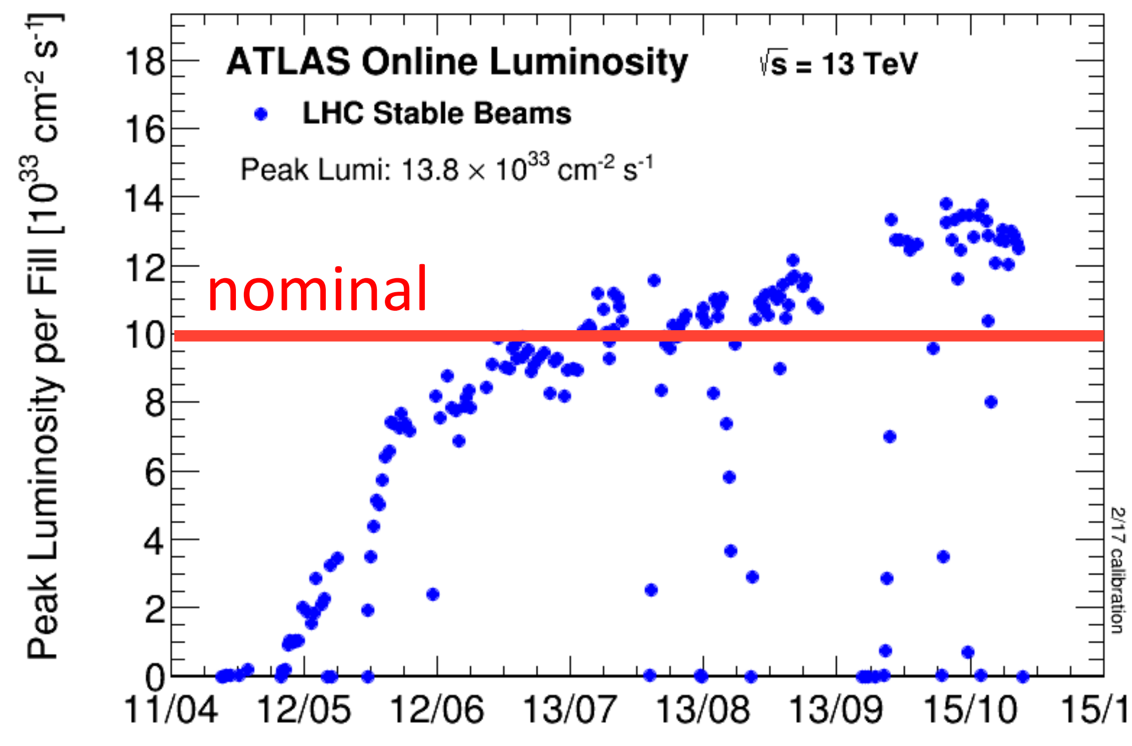


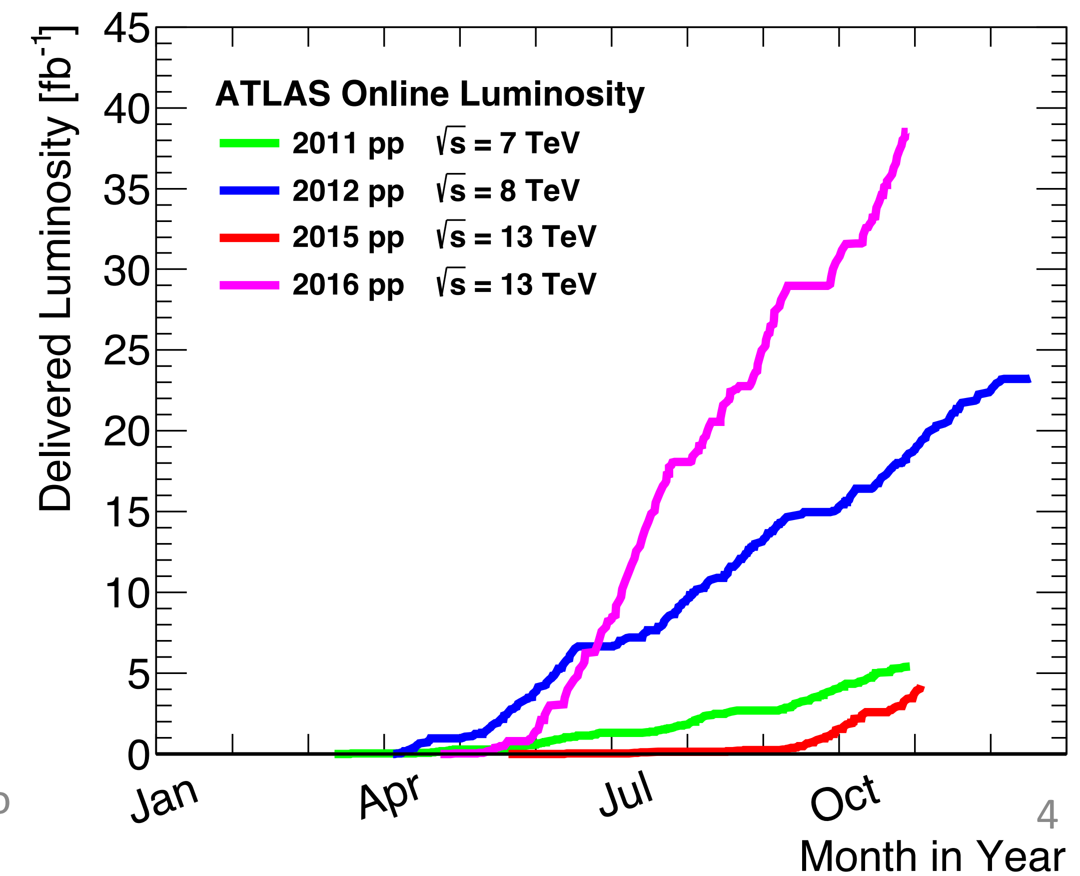
CMS in 2016

- New Capabilities
  - Forward Proton tagging
    - CMS Totem – Precision Proton Spectrometer CT-PPS
      - Tags forward protons to identify double diffractive scattering and Central Exclusive Production of high mass states
  - New Level 1 Muon trigger
  - New Level 1 Calorimeter trigger
  - Endcap Muon Detectors had been upgraded in 2013/14
- Cryogenic System (a.k.a. COLD BOX) for CMS solenoid performed superbly
  - Repair/refurbishment plan succeeded to avoid problems encountered in 2015
- **Big challenge – to deal with even higher pileup than Run 1**

LHC performance in 2016

- Excellent performance of LHC in 2016:
  - Record instantaneous luminosity for p-p interactions $1.4 \times 10^{34}\ cm^{-2}\ s^{-1}$
  - Record delivered luminosity in one year ~ 40 fb^{-1}
  - Excellent p-Pb run:
    - p-Pb Data taken at 5 and 8 TeV
    - Data taken with Pb beams circulating clockwise and anti-clockwise





Many thanks from ATLAS to the LHC team

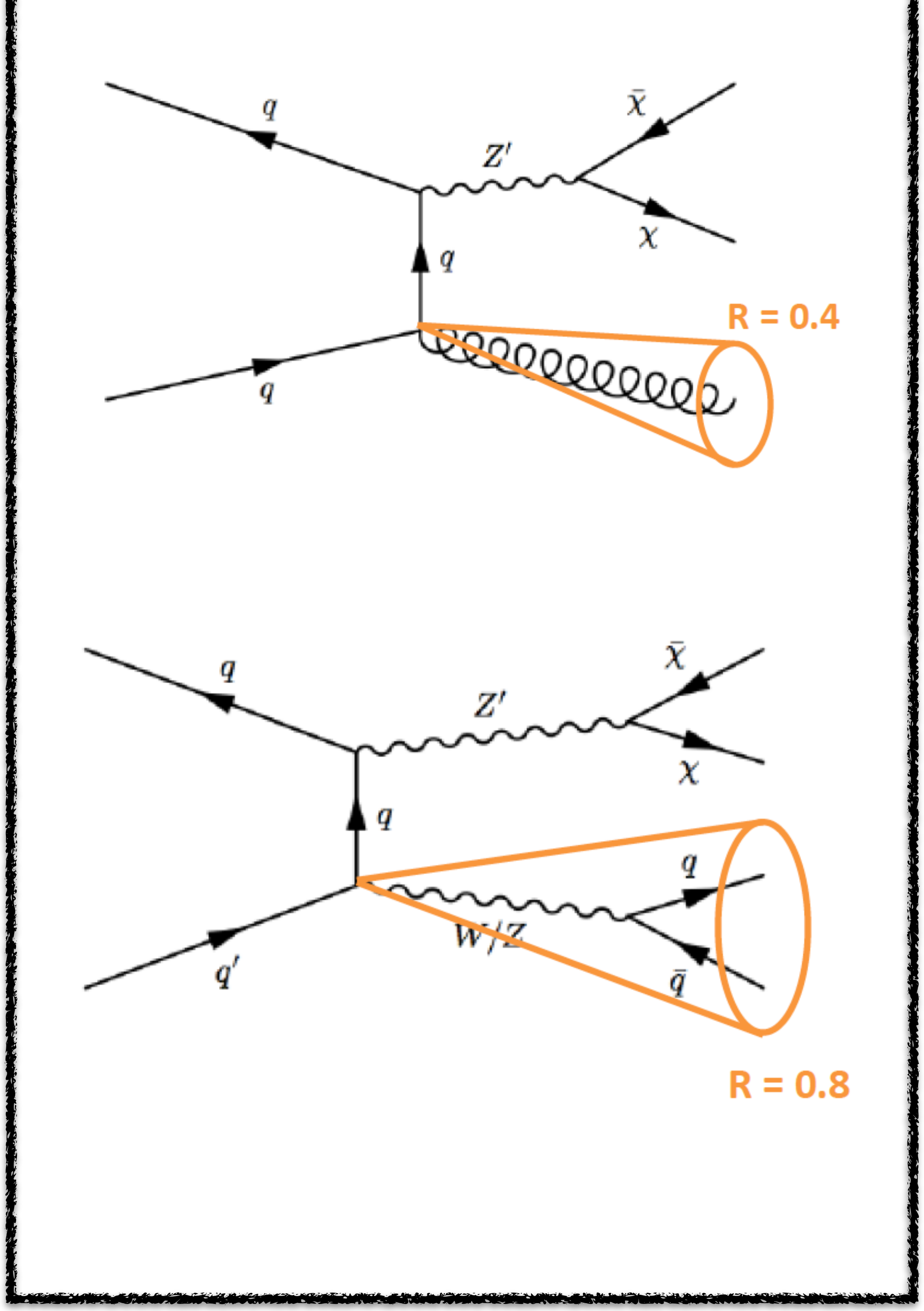
Event Selection and Background

Events are primarily selected with MET cuts on exponentially dumping MET spectra.
Major remaining background are events with $Z(\nu\nu)$ or $W(l\nu)$ with lost lepton.

	Mono-γ	**Mono-Z(ee,$\mu\mu$)**	**Mono-V(had)**
ATLAS	MET > 150 GeV	MET > 90 GeV	MET > 250 GeV
CMS	MET > 170 GeV	MET > 100 GeV	MET > 250 GeV
Major background:			
	$Z(\nu\nu)\gamma$ 55 %	$ZZ(\nu\nu)+WZ(\nu\nu)$	$Z(\nu\nu)$+jets 55 %
	$W(l\nu)\gamma$ 15 %	75 %	$W(l\nu)$+jets 30 %

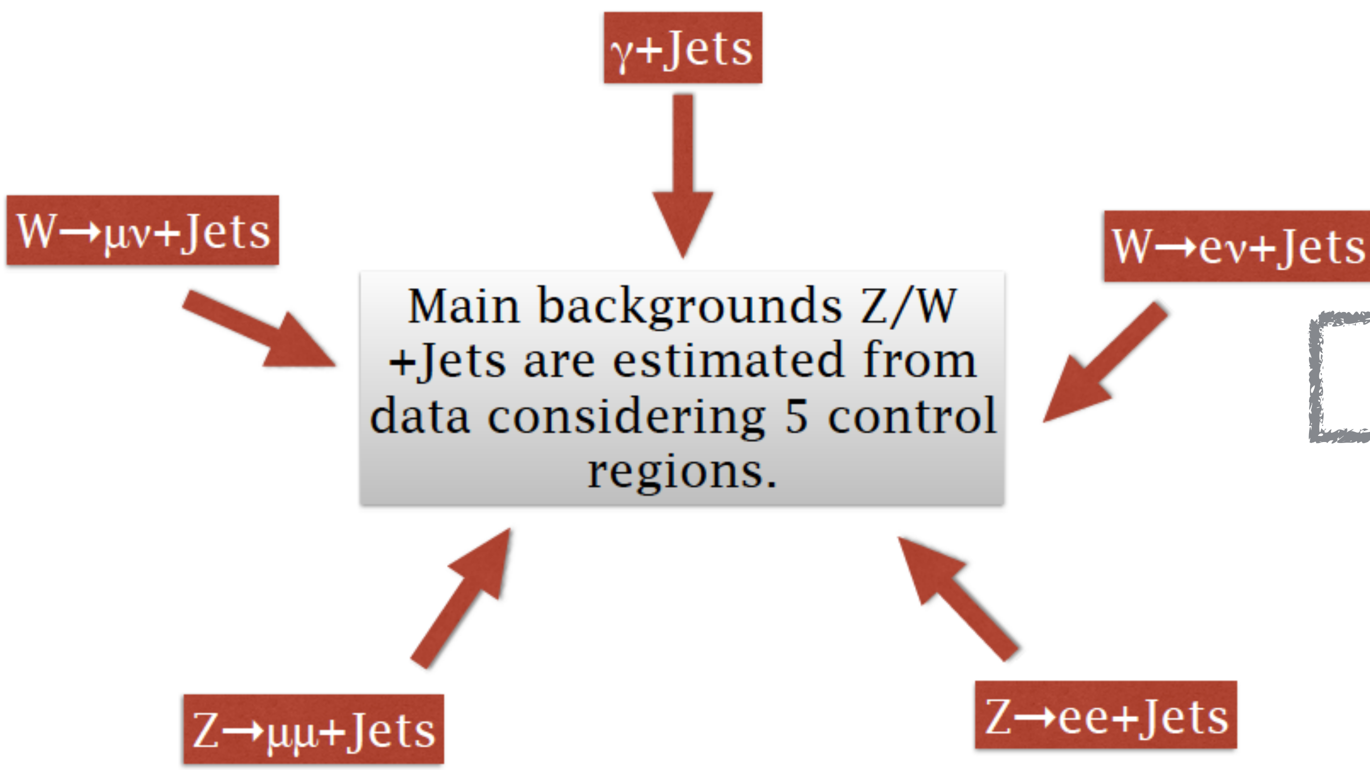
(Percentages are very approximate and rounded to numbers nearest to those in 5 % step. More details in the following.)

- Look for large MET, atleast one high p_T jet and veto leptons, photons, b-jets
- mono-jet:
  - MET>250 GeV,
  - $p_T^{leading}$(ak4 jet) > 100 GeV
- mono-V:
  - MET>250 GeV,
  - $p_T^{leading}$(ak8 jet) > 250 GeV
  - mass: [m_W-15, m_Z+15],
  - Nsubjettiness (τ_2/τ_1) < 0.6



- Need precise estimation of dominant backgrounds
  - ☑ $Z(\nu\nu)$+Jets (60%)) and W+Jets (30%)
  - ☑ Five control region in data
    - $Z(\mu\mu)$+Jets, Z(ee)+Jets, γ+Jets to estimate Z
    - $W(\mu\nu)$+Jets, $W(e\nu)$+Jets to estimate W
  - Extrapolating from control region to signal region by means of precise theoretical prediction.

Estimate background and extract signal strength by performing a simultaneous fit of all mono-jet and mono-V control and signal regions.



Improved theoretical uncertainty

Analysis strategy in CMS

- Transfer factor to translate recoil (in CR) to missing E_T (in SR)
- Global likelihood fit simultaneously to **SR+5CR** regions in all E_T^{miss} bins

$$\mathcal{L}_k(\mu^{Z(\nu\bar{\nu})}, \mu, \theta) = \prod_i \text{Poisson}\left(d_i^{\gamma} | B_i^{\gamma}(\theta) + \frac{\mu_i^{Z(\nu\bar{\nu})}}{R_i^{\gamma}(\theta)}\right)$$ γ + jets CR

$$\times \prod_i \text{Poisson}\left(d_i^{\mu\mu} | B_i^{\mu\mu}(\theta) + \frac{\mu_i^{Z(\nu\bar{\nu})}}{R_i^{\mu\mu}(\theta)}\right)$$

$$\times \prod_i \text{Poisson}\left(d_i^{ee} | B_i^{ee}(\theta) + \frac{\mu_i^{Z(\nu\bar{\nu})}}{R_i^{ee}(\theta)}\right)$$ $Z(ll)$ + jets CR

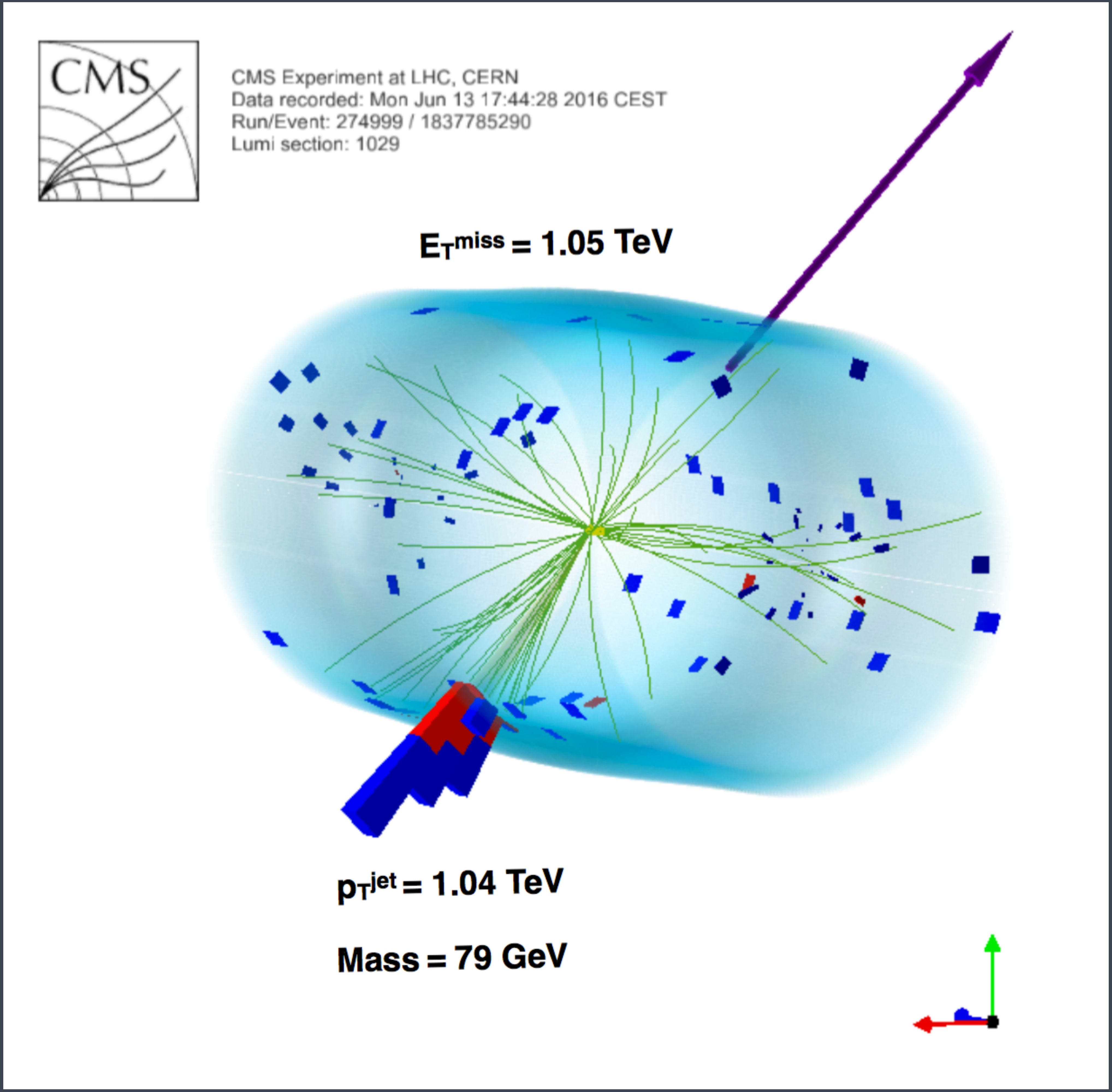
$$\times \prod_i \text{Poisson}\left(d_i^{\mu} | B_i^{\mu}(\theta) + \frac{f_i(\theta)\mu_i^{Z(\nu\bar{\nu})}}{R_i^{\mu}(\theta)}\right)$$

$$\times \prod_i \text{Poisson}\left(d_i^{e} | B_i^{e}(\theta) + \frac{f_i(\theta)\mu_i^{Z(\nu\bar{\nu})}}{R_i^{e}(\theta)}\right)$$ $W(l\nu)$ + jets CR

$$\times \prod_i \text{Poisson}\left(d_i | B_i(\theta) + (1 + f_i(\theta))\mu_i^{Z(\nu\bar{\nu})} + \mu S_i(\theta)\right)$$ SR

$\mu_i^{W\to l\nu} \to f_i(\theta)\cdot\mu_i^{Z\to\nu\nu}$ μ_i : yields R_i : transfer factor

constraints from transfer factors, only one free parameter to fit


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Jun 13 17:44:28 2016 CEST
Run/Event: 274999 / 1837785290
Lumi section: 1029
E_T^{miss} = 1.05 TeV
p_T^{jet} = 1.04 TeV
Mass = 79 GeV

Mono-H(bb) background normalizations

	CMS (resolved)	CMS (boosted)	ATLAS
Z+jets	Mass sideband		Mass shape fit and 2l CR
W+jets	1l+0j CR	1l CR	1mu CR
Top	1l+1j CR		

Recast (M_{MED}, $M\chi$) to nucleon-DM xsec (*arXiv:1603.04156*)

$$\sigma_{\rm SI} = \frac{f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4} \,,$$

Vector

$$f(g_q) = 3 g_q \,,$$

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2 .$$

Scalar

$$f(g_q) = 1.16 \cdot 10^{-3}\, g_q \,,$$

and therefore the size of a typical cross section is

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-43}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{1}\right)^2 \left(\frac{125\,{\rm GeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2 .$$

Recast (M_{MED}, $M\chi$) to nucleon-DM xsec (arXiv:1603.04156)

$$\sigma_{\rm SD} = \frac{3\, f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4} \,. \qquad f^{p,n}(g_q) = \Delta_u^{(p,n)}\, g_u + \Delta_d^{(p,n)}\, g_d + \Delta_s^{(p,n)}\, g_s$$

Under the assumption that the coupling g_q is equal for all quarks, one finds

$$f(g_q) = 0.32 g_q \,,$$

and thus

$$\sigma^{\rm SD} \simeq 2.4 \times 10^{-42}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2 \,.$$

Axial-vector