Dark Matter Searches

(at the LHC!)

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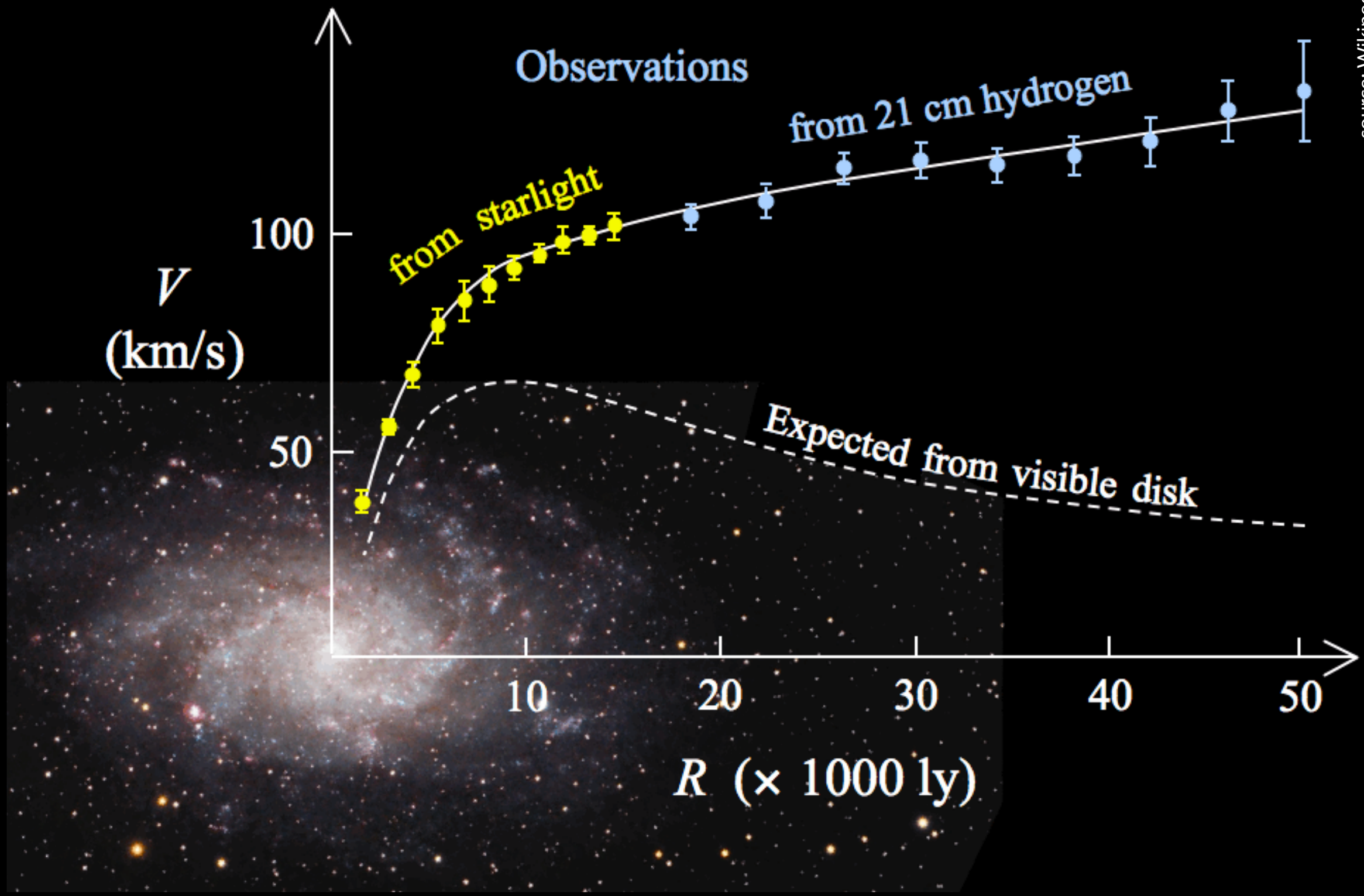
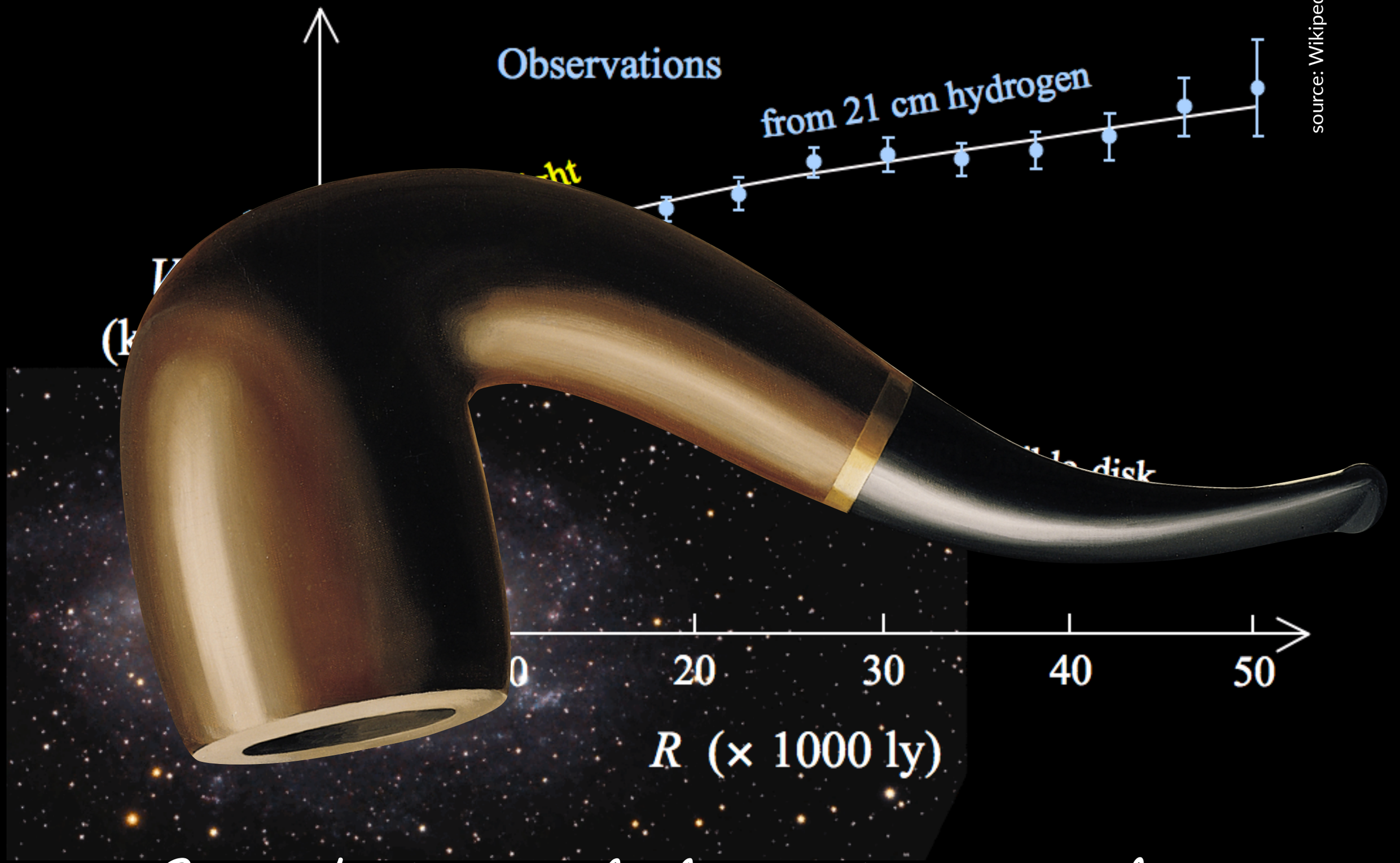
on behalf of the ATLAS and CMS collaborations

rotation velocity curve, M 33 spiral galaxy



source: Wikipedia

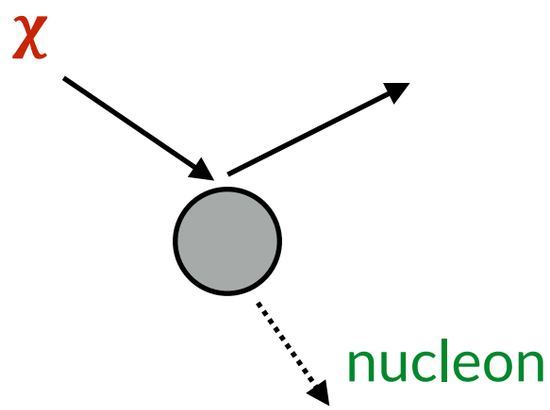
rotation velocity curve, M 33 spiral galaxy

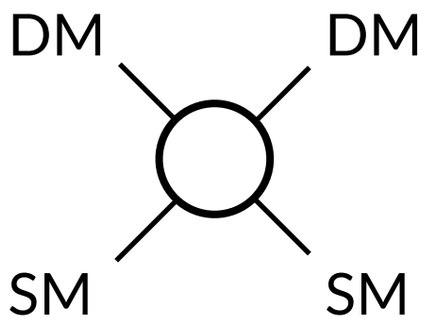


Ceci n'est pas de la matière sombre

Spotting the Invisible

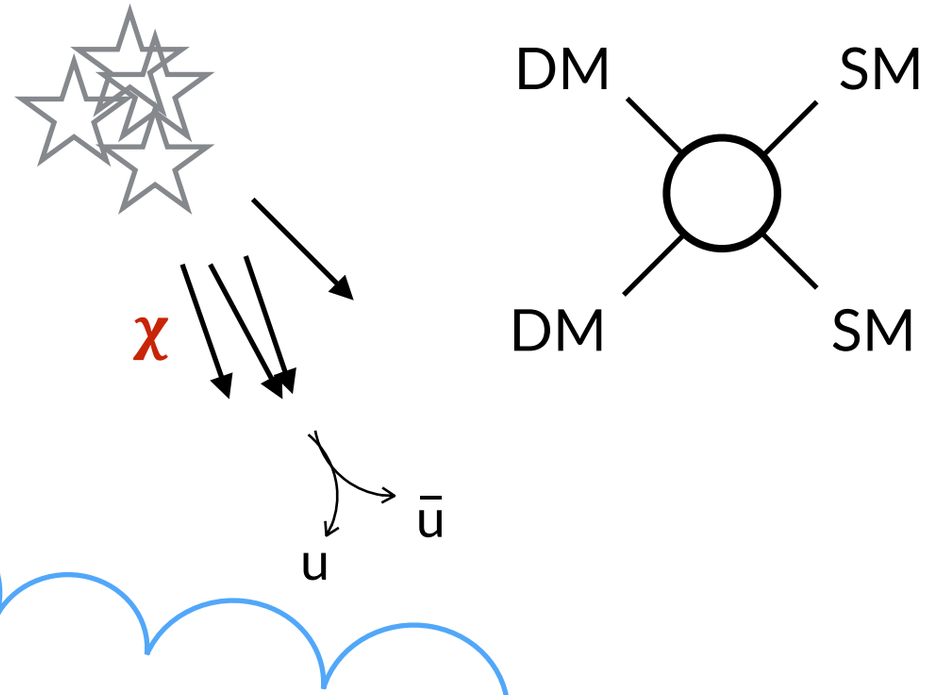
direct detection



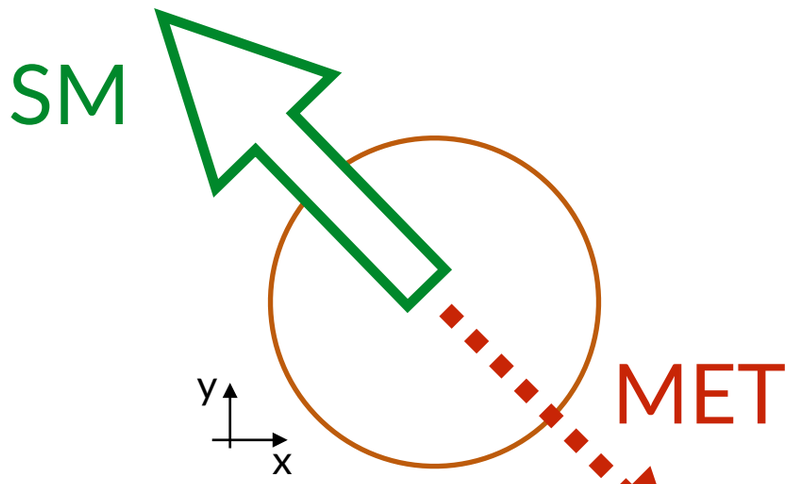


must know: nucleon form factors, DM local density, background levels…

indirect detection

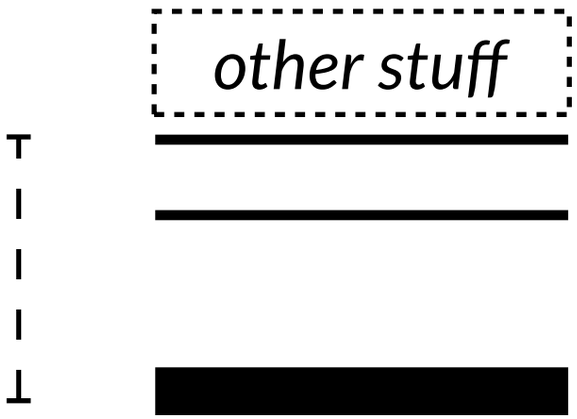


must know: detector, reconstruction, SM backgrounds…



Going Beyond (the Standard Model)

what's there



***Run-1**: assume this Δm is high (**EFT**, not always valid)*

Run-2**: go beyond EFT, with **simplified models

typical degrees of freedom:

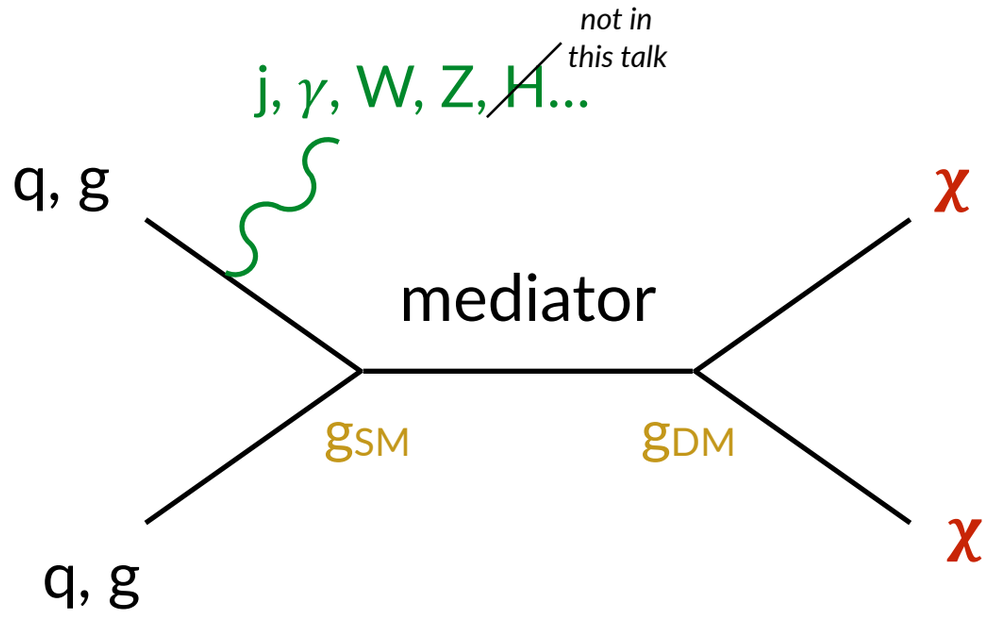
- mediator mass and type (vector, axial-vector…)
- DM mass and type (Dirac fermion…)
- mediator-SM coupling g_{SM}
- mediator-DM coupling g_{DM}

Going Mono (X)

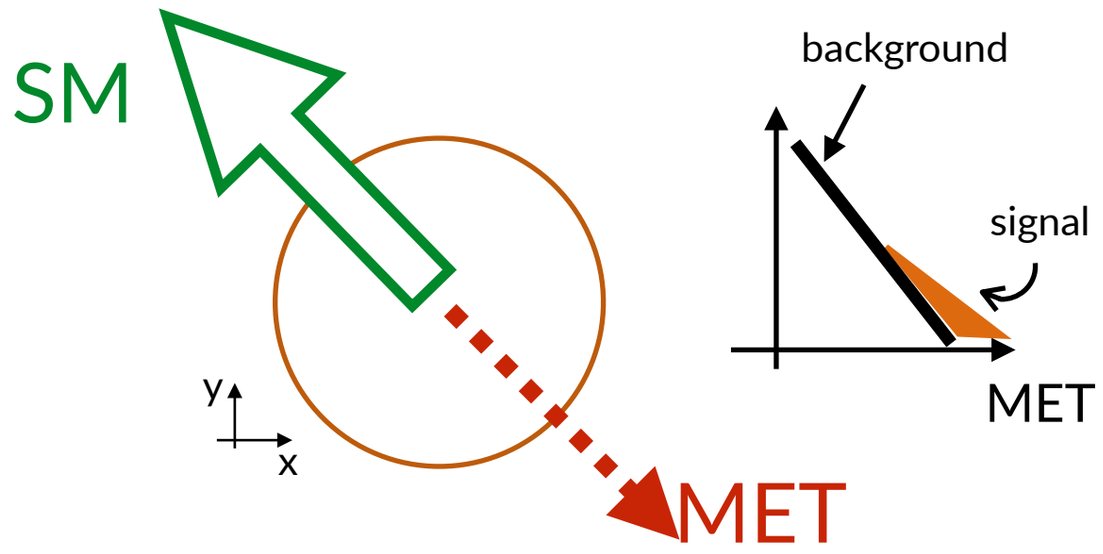
e.g.: Z'-like mediator, s-channel, tagging object from ISR

but also: $\chi\chi$XX interactions, t-channel…

what happens



what we see



theory (see also Andrea's talk)

- extend the SM with sensible **benchmark models**
- ease **re-interpretations**, **not** necessarily **complete**
- 1507.00966, 1603.04156, LHC DM WG

experiment

- cover all signatures
- often a high-p_T challenge (signal shows up in tails)!

The (ATLAS+CMS) Dark Matter Atlas

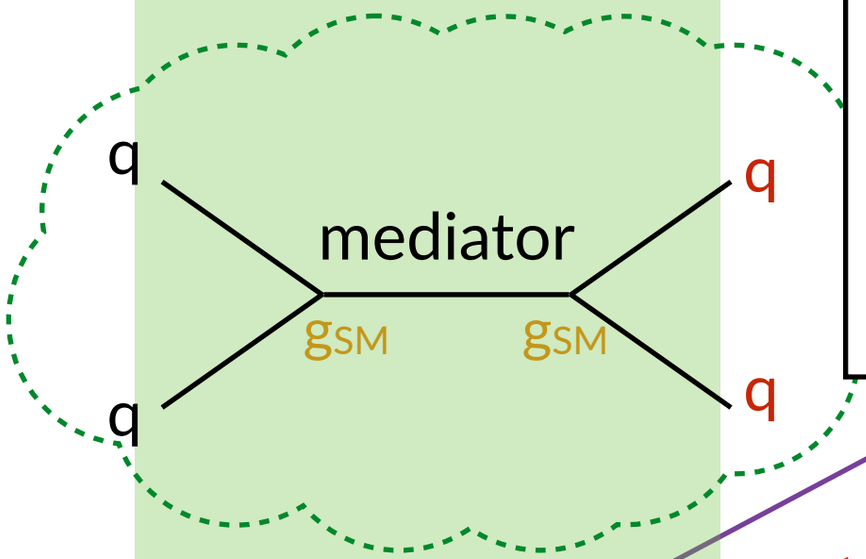
(not to scale!)

"best strategy" (at LHC and outside) depends on mediator type and couplings ☞ no general favourite, need to probe full phase space!

dark matter mass *m*

hic sunt leones

dijet searches



on-shell mediator decay

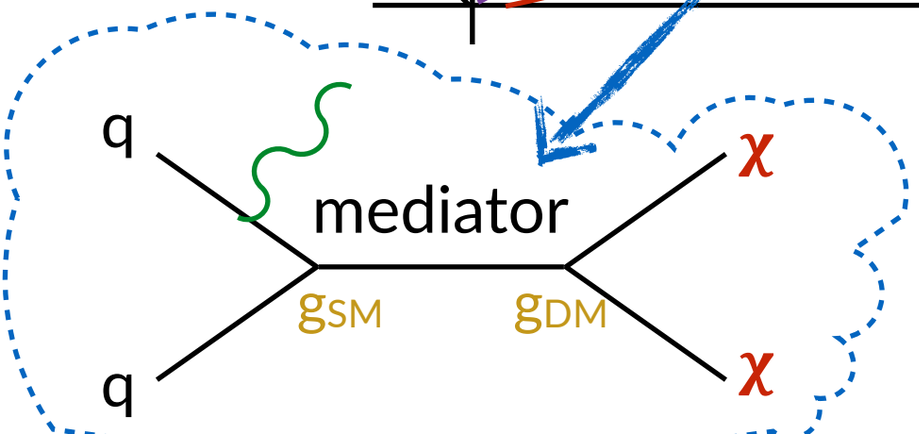
$\Omega > \Omega_{WMAP}$

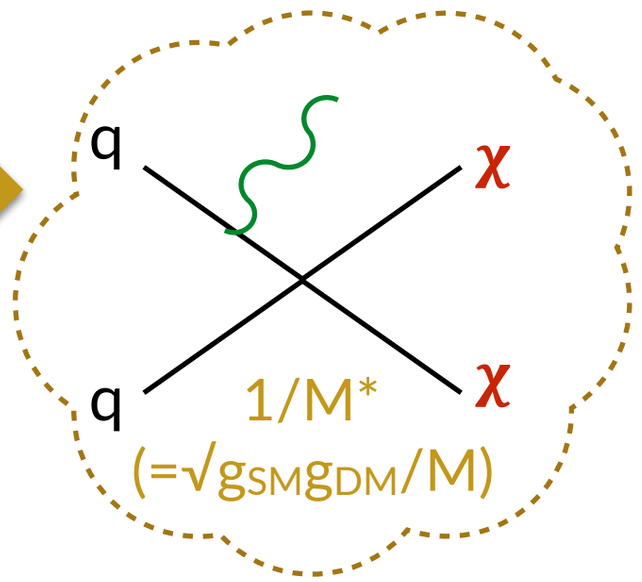
couplings

mono-X

EFT

mediator mass *M*





Relevant Results

italics = 8 TeV, green = 13 TeV

	ATLAS	CMS
monojet	1604.07773	EXO-16-013-pas
mono-W/Z(had)	ATLAS-CONF-2015-080	
razor		*1603.08914v1*
α_T		SUS-15-005 (SUSY analysis)
mono-γ	1604.01306	*PLB 755 102-124*
bb		B2G-15-007
tt (dilepton)	*Eur. Phys. J. C(2015) 75:92*	*B2G-13-004-pas*
tt(single lepton)		*JHEP06(2015)121*
mono-t		*PRL114.101801, B2G-15-001*
mono-W(lv)	*JHEP09(2014)037*	*Phys. Rev. D 91, 092005*
mono-Z(ll)	*PhysRevD.90.012004*	*Phys. Rev. D 93, 052011*
mono-H($\gamma\gamma$)	*PRL 115.131801*	
mono-H(bb)	ATLAS-CONF-2016-019	
dijet	PLB 754 (2016) 302–322	PRL 116, 071801; 1604.08907

see Mario&Francesco's talk

will mostly focus on most sensitive channels, complete interpretations (simplified model vs EFT) and recent results

Complementarity, in a nut-shell

can use bb/tt + MET
(mediator couples à la Yukawa with quark masses)

can use jets + MET

	LHC	DD	ID
scalar	low xsec, soft MET	:|	
pseudo -scalar	low xsec, soft MET	:'((velocity suppressed)	:)
vector	large xsec	:) (spin independent)	
axial-vector	large xsec	:((spin-dependent: experimental issue)	

MET + Jet(s)

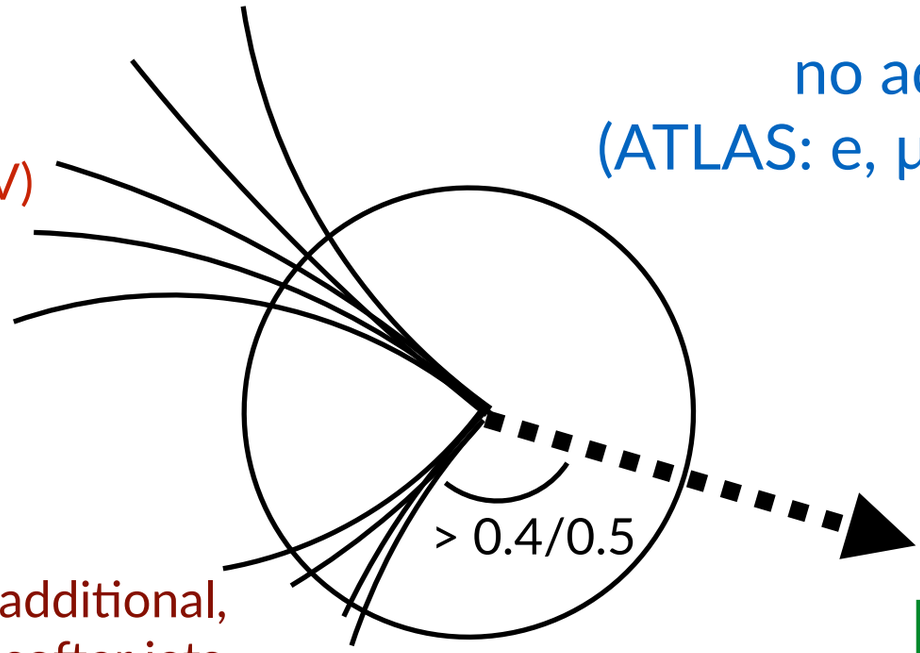
- the narrow
- the large
- the clever

JET + DM

best channel if tagging object comes from ISR! (pay only α_s)

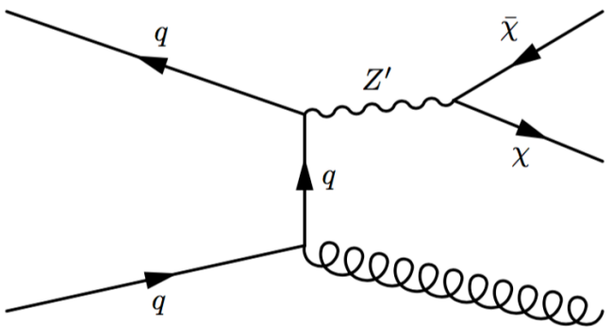
jet

high-pT (100-250 GeV)
central (|η|<~2.4)
tight quality



no additional object
(ATLAS: e, μ; CMS: e, μ, τ, γ, b-jet)

+ trigger
ATLAS: MET > 70 GeV
CMS: MET, H_T^{miss} > 90 GeV

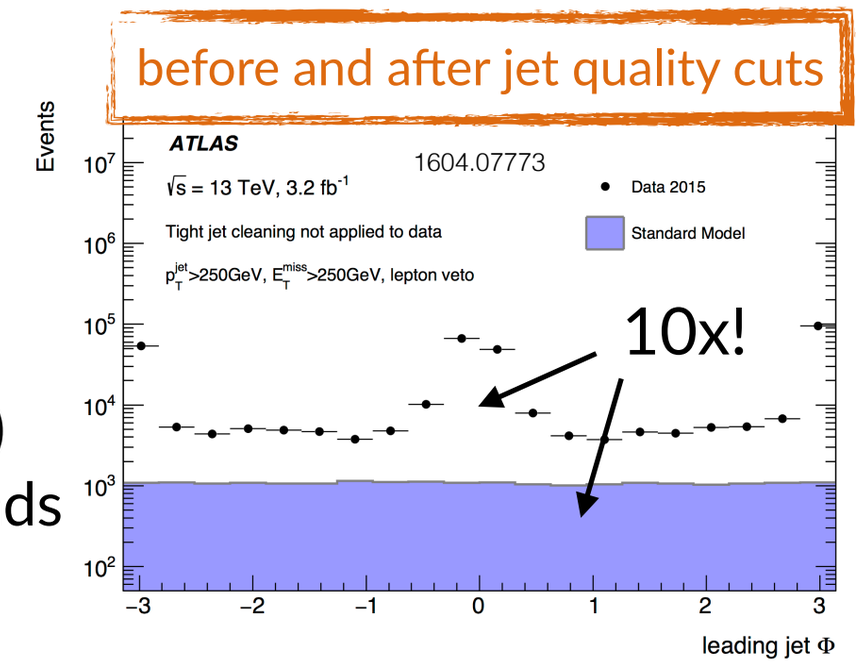


additional,
softer jets
(ATLAS: up to 3;
CMS: any)

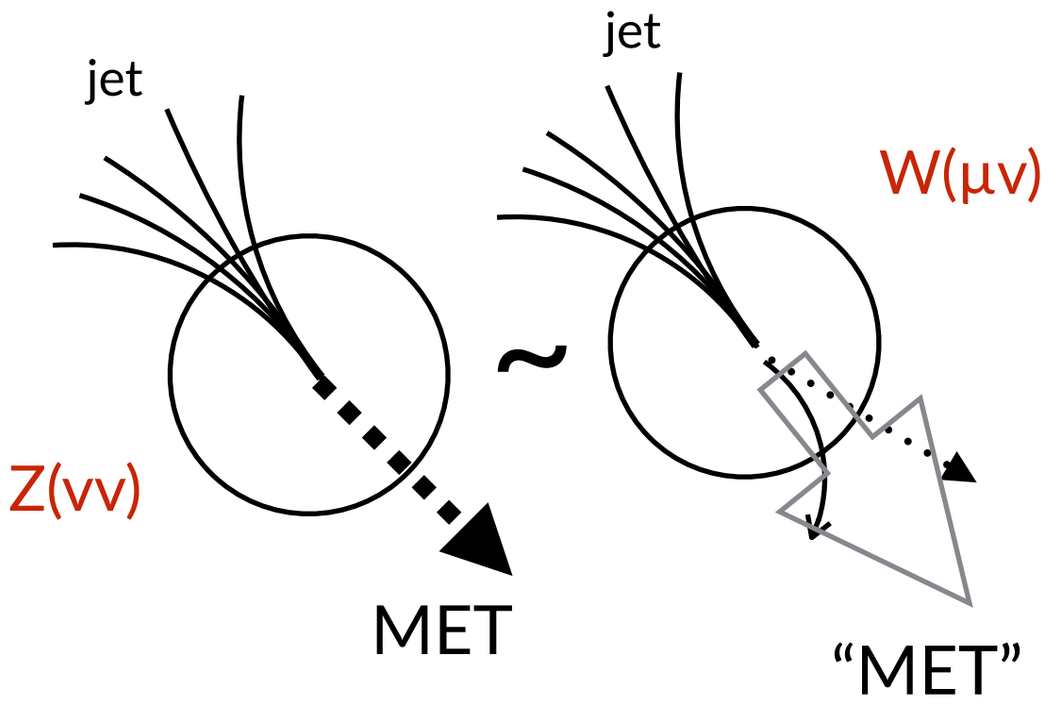
MET
> 200-250 GeV

same signature as
- Z(νν) + jets, W(τ[qq']ν) + jets…
- beam-induced background ☞ jet quality cuts

not really "mono"-jet (higher acceptance in n_{jets})
- cannot rely solely on QCD modeling of backgrounds



How the Z(νν)+jets Was Won



estimate MET in Z(νν) + jets from V recoil pT in V+jets events

- ideally use Z(ll) + jets, but 6 times lower statistics than Z(νν) + jets…
- can use W(lν) + jets
  - but neither W/Z ratio vs pT nor its EW/QCD corrections are flat
  - ☞ systematic uncertainty
- γ + jets even better at high pT

Z(νν)+jet normalisation factor vs MET from simultaneous SR+CR fit

binned shape analysis, with shapes for EW backgrounds constrained from CR data

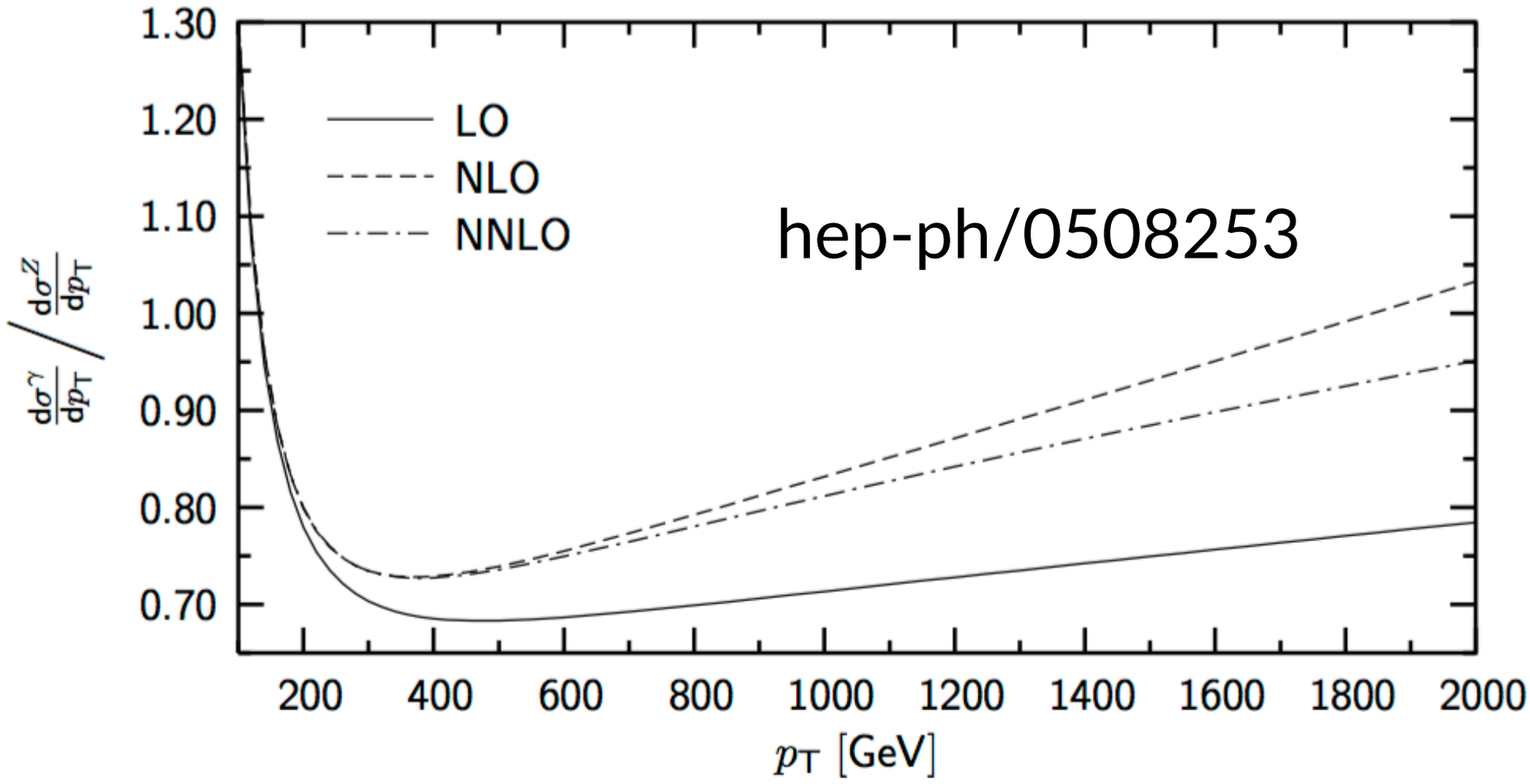
what's used for constraining Z(νν)

	W(μν)	W(eν)	Z(μμ)	Z(ee)	γ+jet
ATLAS	✓				
CMS	✓	✓	✓	✓	✓

dominates at low MET

dominates at high MET

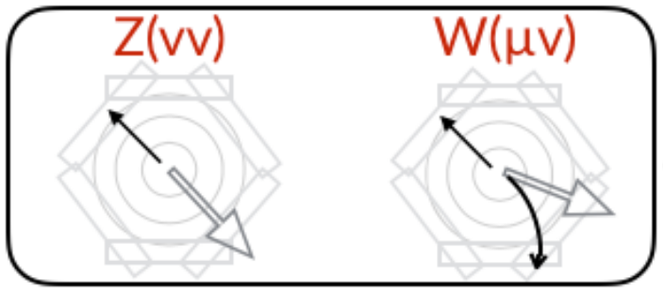
Z(νν) MODELLING UNCERTAINTIES

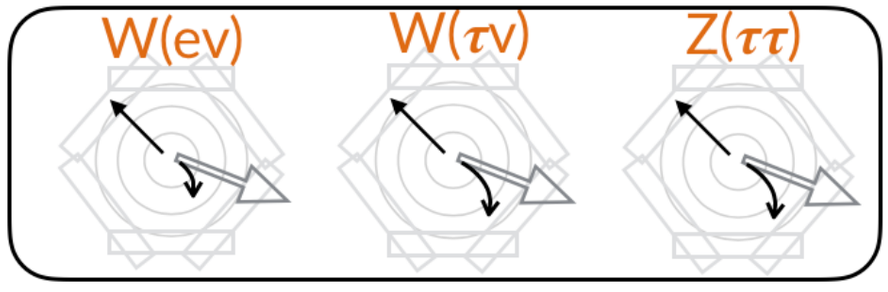


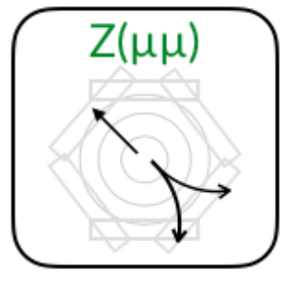
example: gamma/Z pT ratio at 14 TeV isn't flat!

- EW corrections matter!
  - CMS: use full size of EW correction as uncertainty (~scale uncertainties)
- ATLAS uses only W(μν)->Z(νν) with 2-5% transfer uncertainty effect
  - significant contribution to total uncertainty

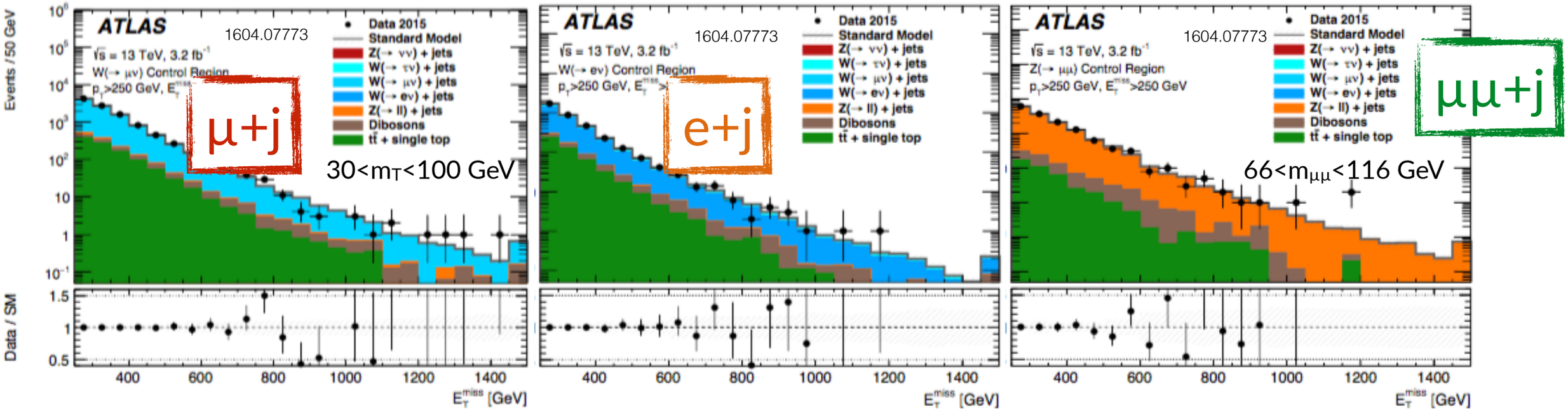
ATLAS: THREE CONTROL REGIONS

$k_{1\mu}$ × 

+ k_{1e} × 

+ $k_{2\mu}$ × 

+ ...



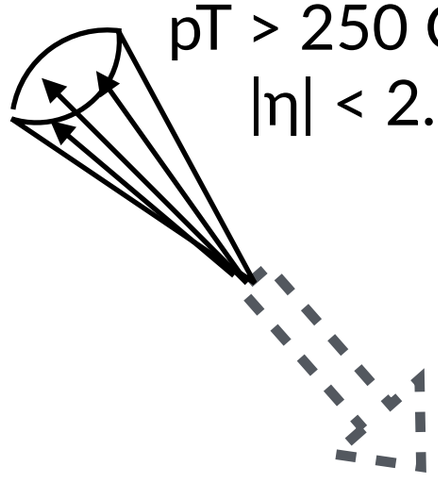
subleading bkg

\+ non-collision bkg (data), multi-jet (data), Zee, top, diboson (MC)

systematics on total bkg

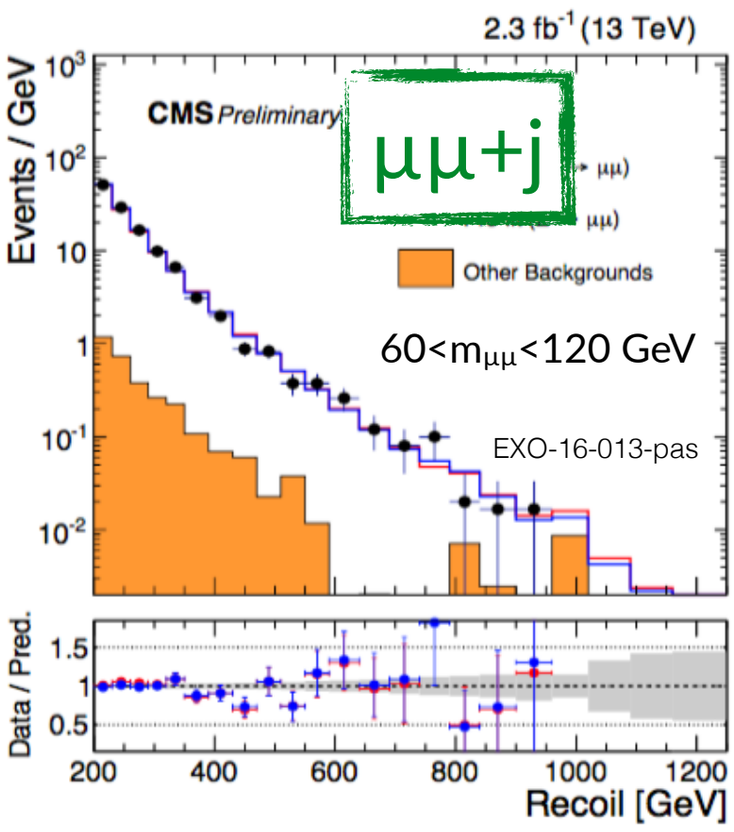
- 2-5% uncertainty for usage of W(μν) for estimation of Z(νν)
- ~3% uncertainty due to ttbar modeling (MC@NLO vs Powheg)
- 4-12% total uncertainty

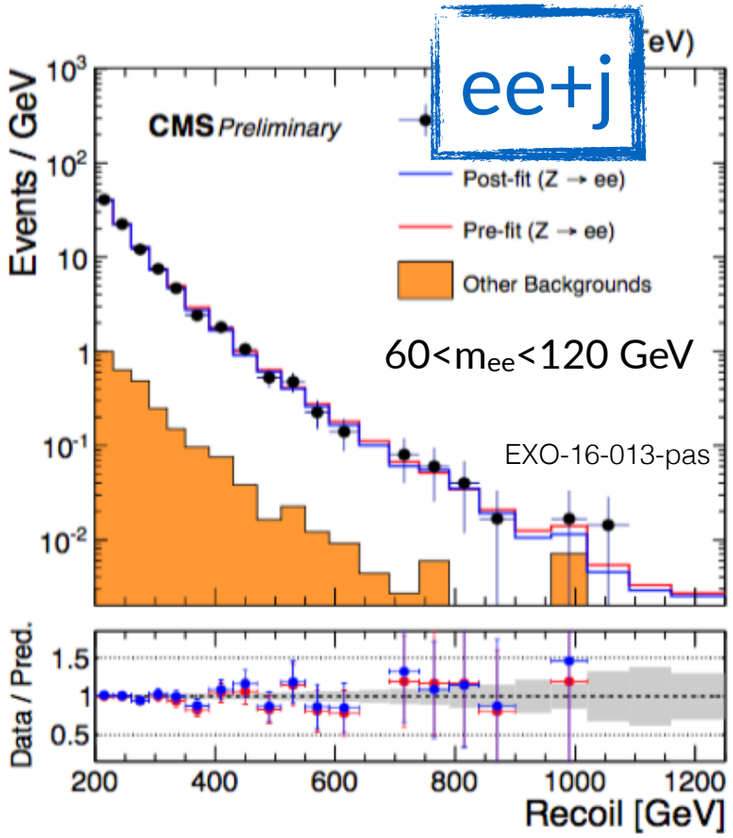
anti-k_t R=0.4,
pT > 250 GeV,
|η| < 2.5

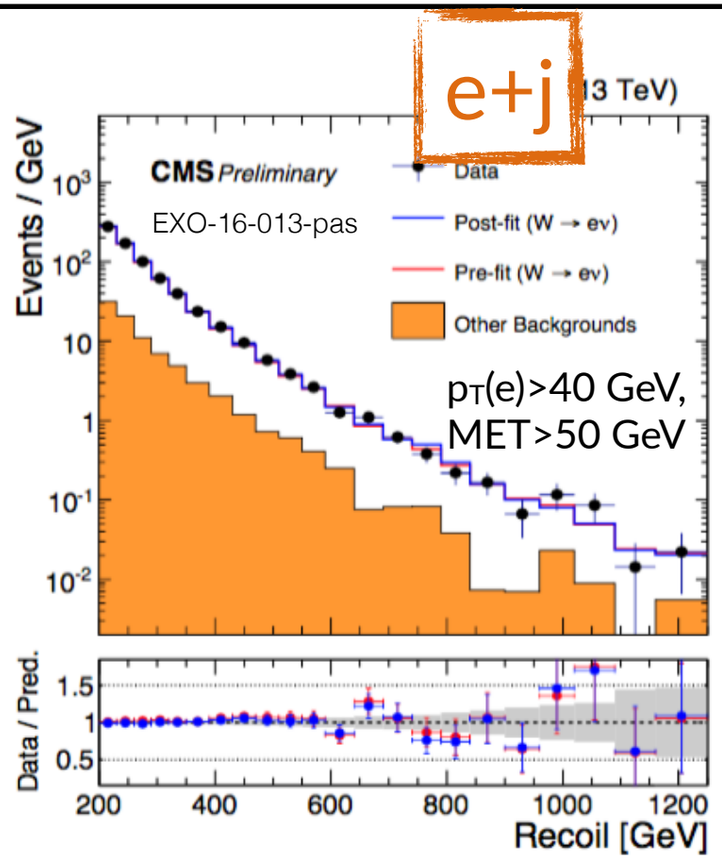


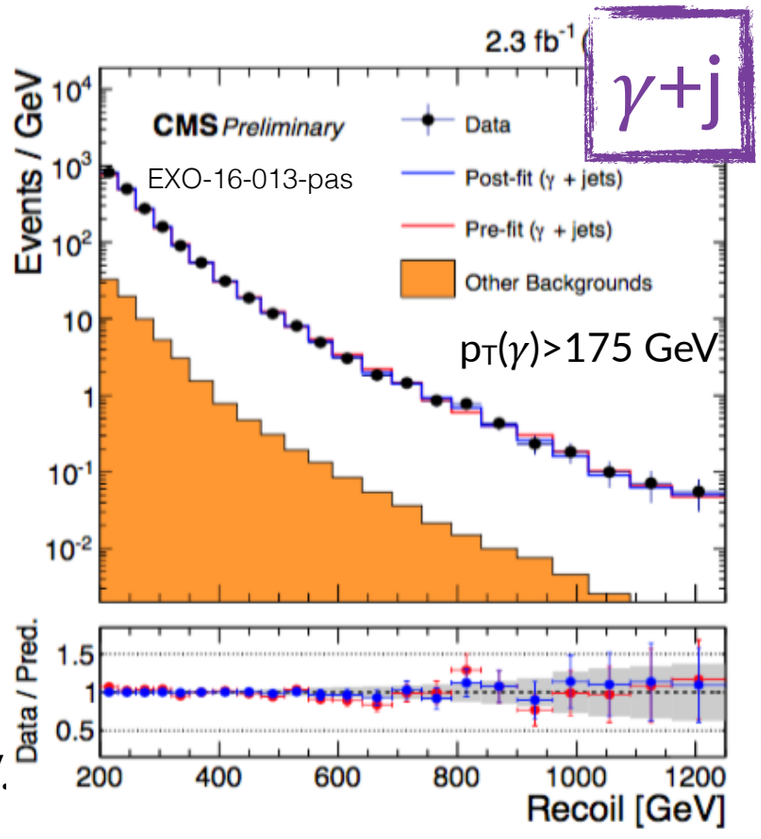
"MET" > 250 GeV

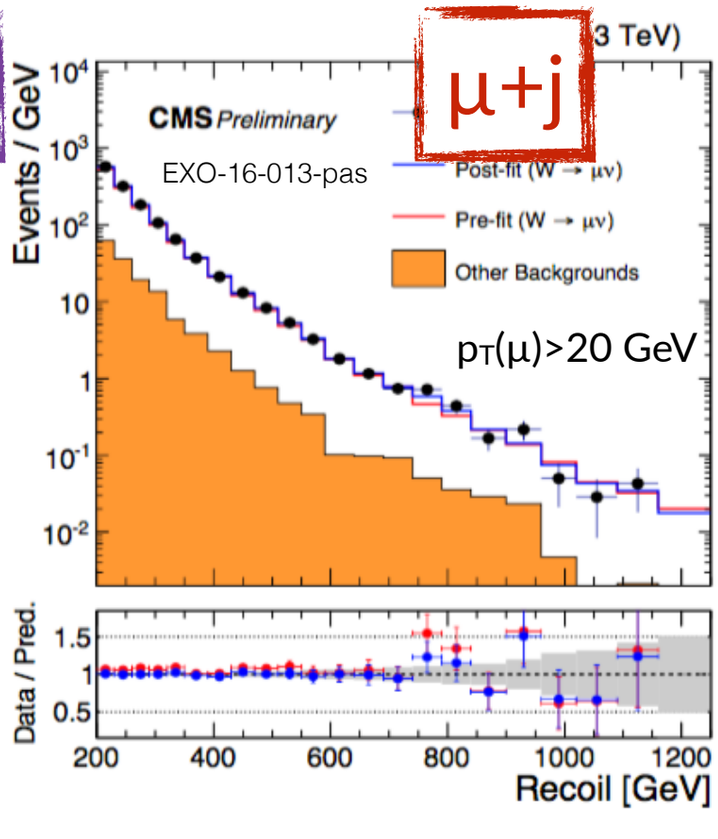
CMS: FIVE CONTROL REGIONS



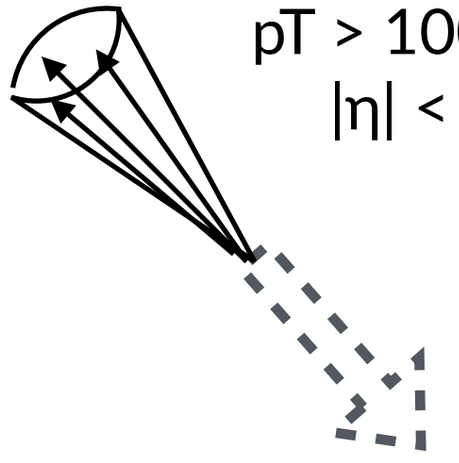






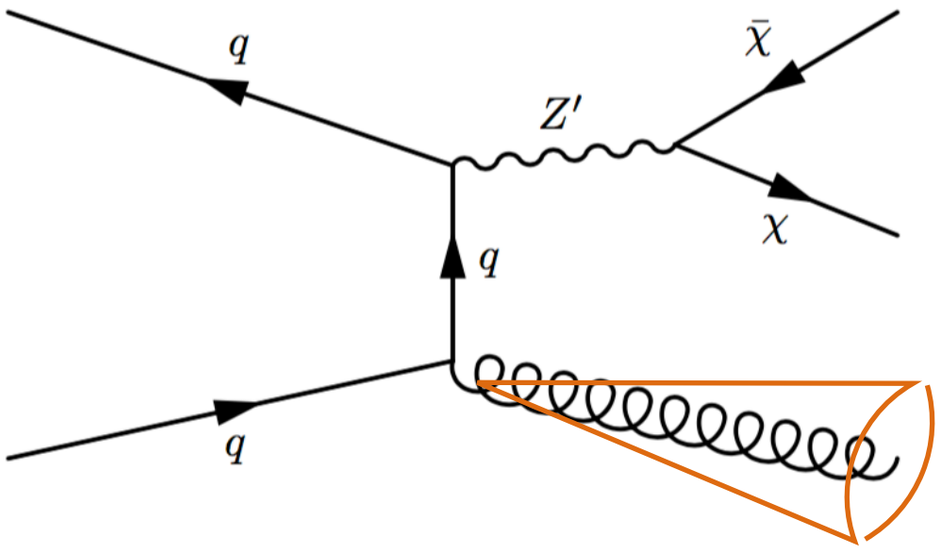


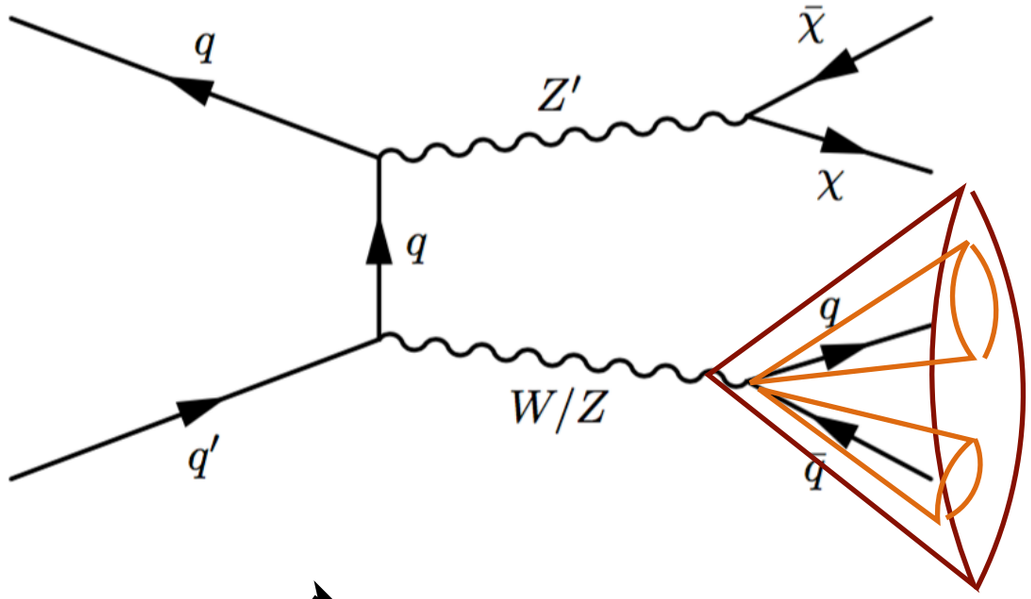
anti-k_t R=0.4,
pT > 100 GeV,
$|\eta| < 2.5$

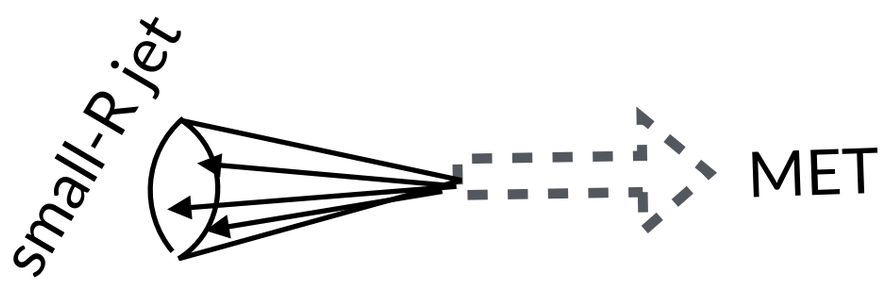


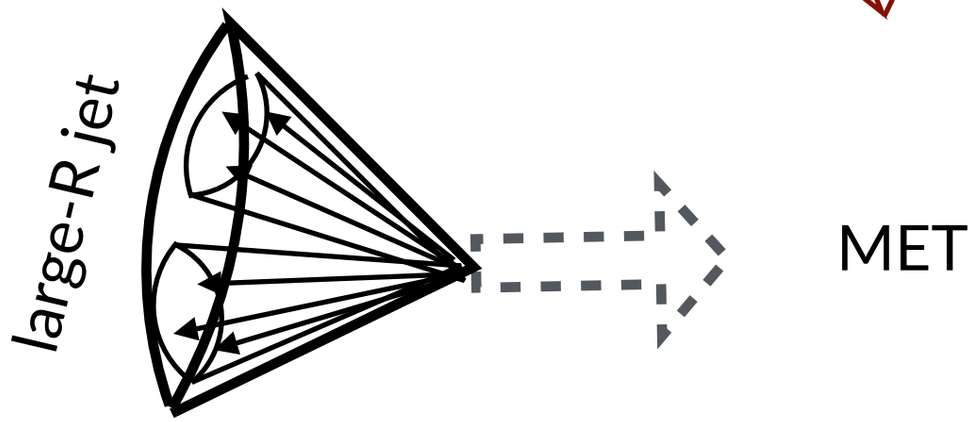
"MET" > 200 GeV

Playing with the jet radius parameter







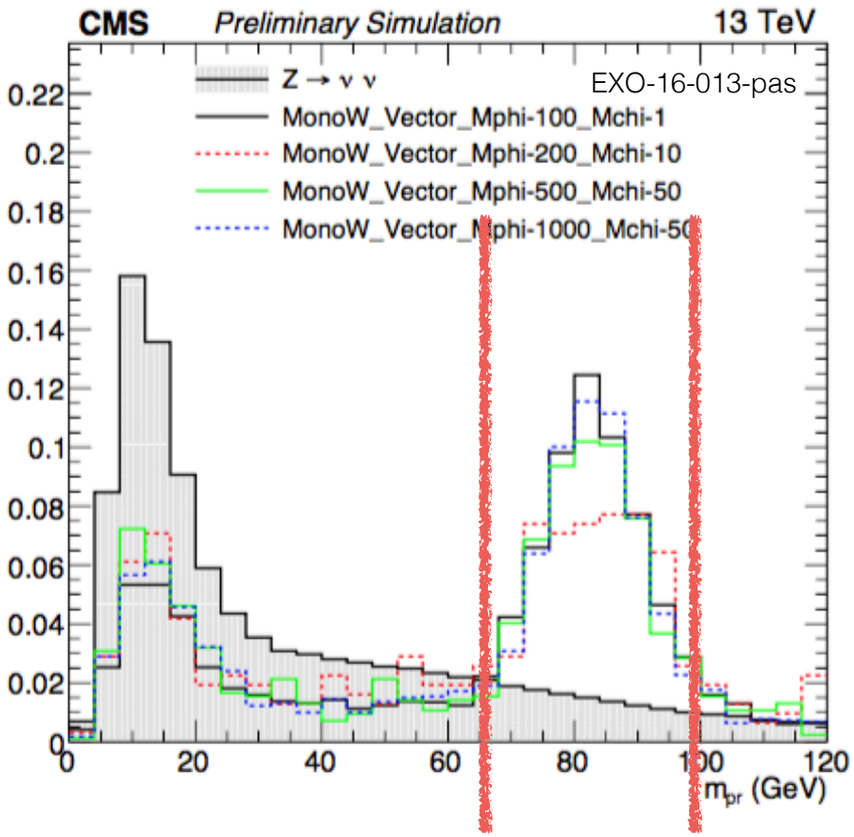


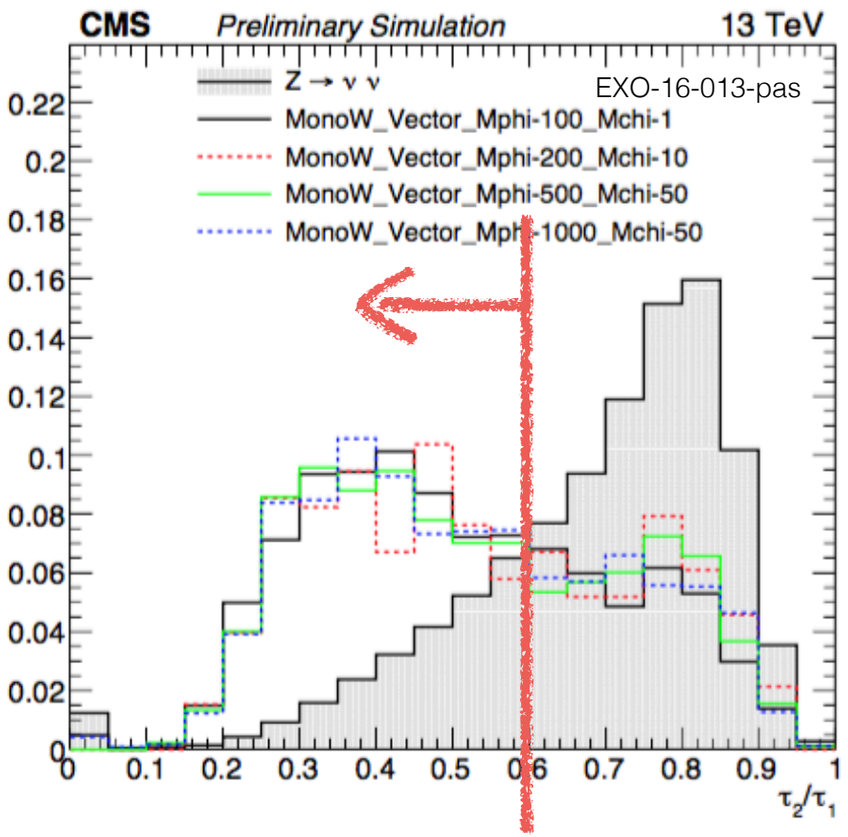
mono-jet and mono-W/Z(had) signatures are similar

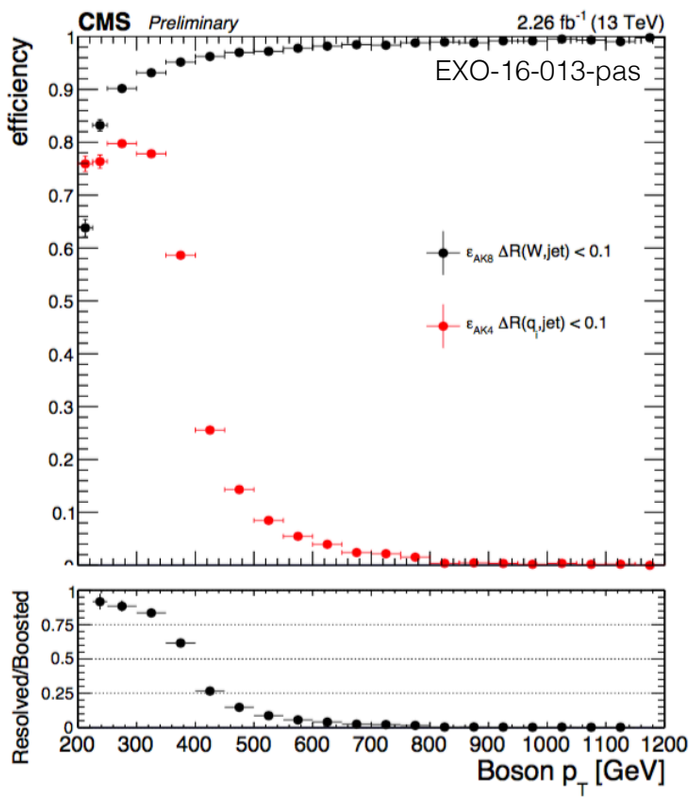
- also helps probing non-universal mediator couplings to u/d quarks (W), DM-V effective vertices
- profit from boosted regime using large-R jets
  - a couple of orders of magnitude lower statistics, though…
- ATLAS: dedicated analysis; CMS: combined with small-R mono-jet

→ gain by 2-5% on final limits

Getting fat







large-R jets help when topology is boosted (pT > ~250 GeV)

- ~60% tagging efficiency (with ~13% uncertainty)

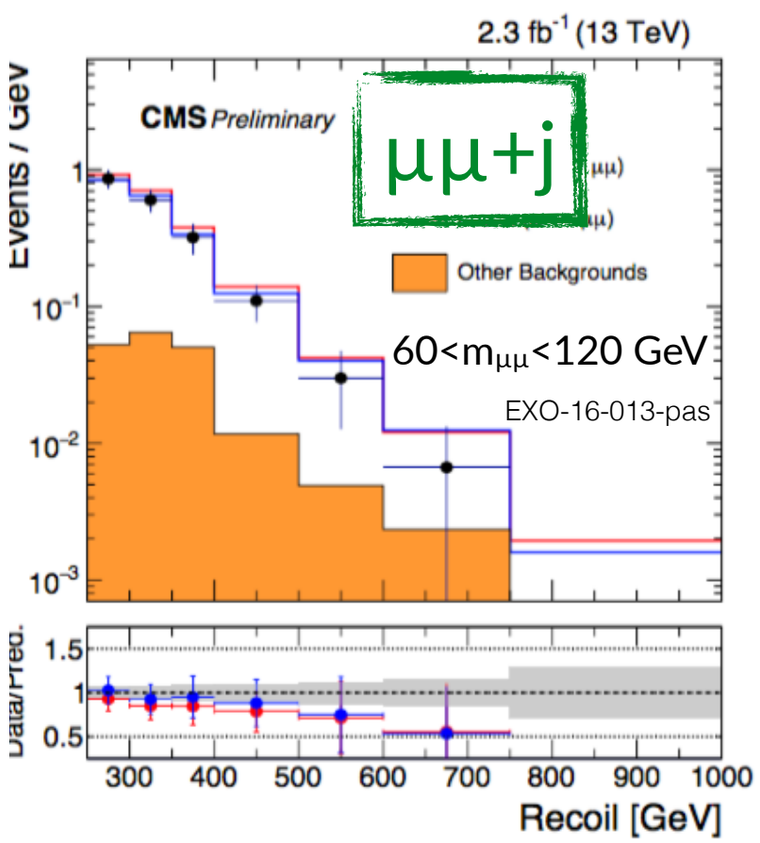
separation power depends on

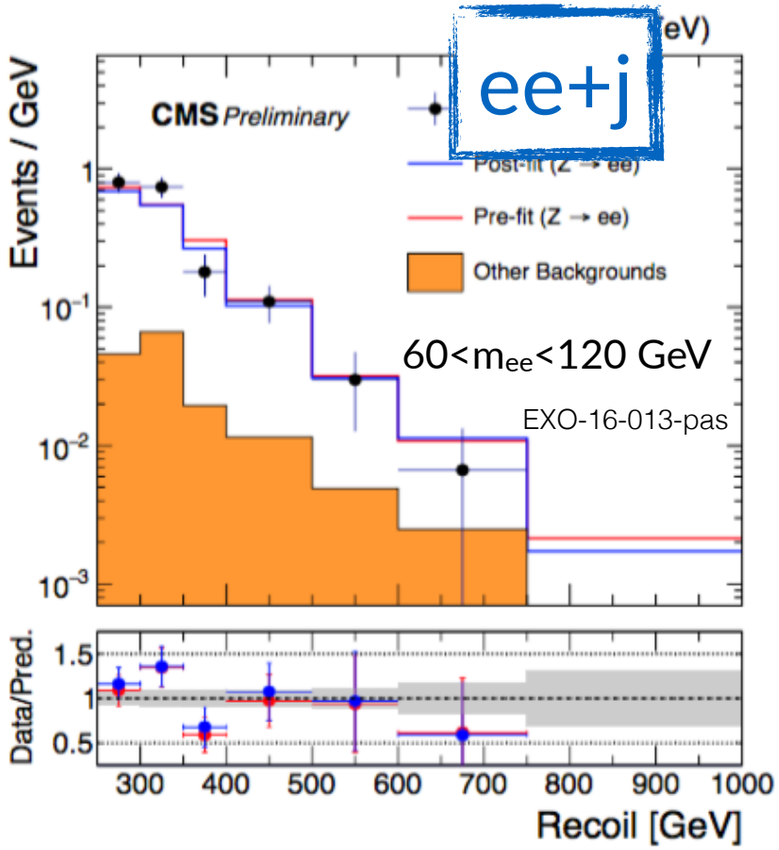
- mDM (~ pT(V))
- mMed (~ V polarisation)
- bkg composition (g/q-jets)

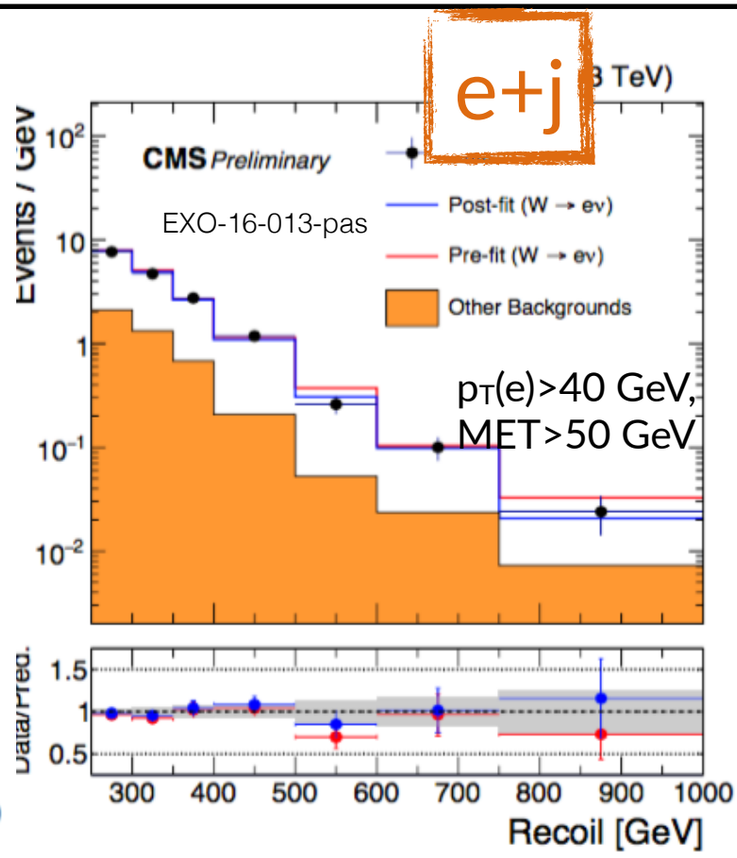
anti-k_t R=0.8 pruned,
pT > 250 GeV,
$|\eta| < 2.4$,
$|m_J - m_{W/Z}| < 15$ GeV,
2-prong (τ_2/τ_1<0.6)

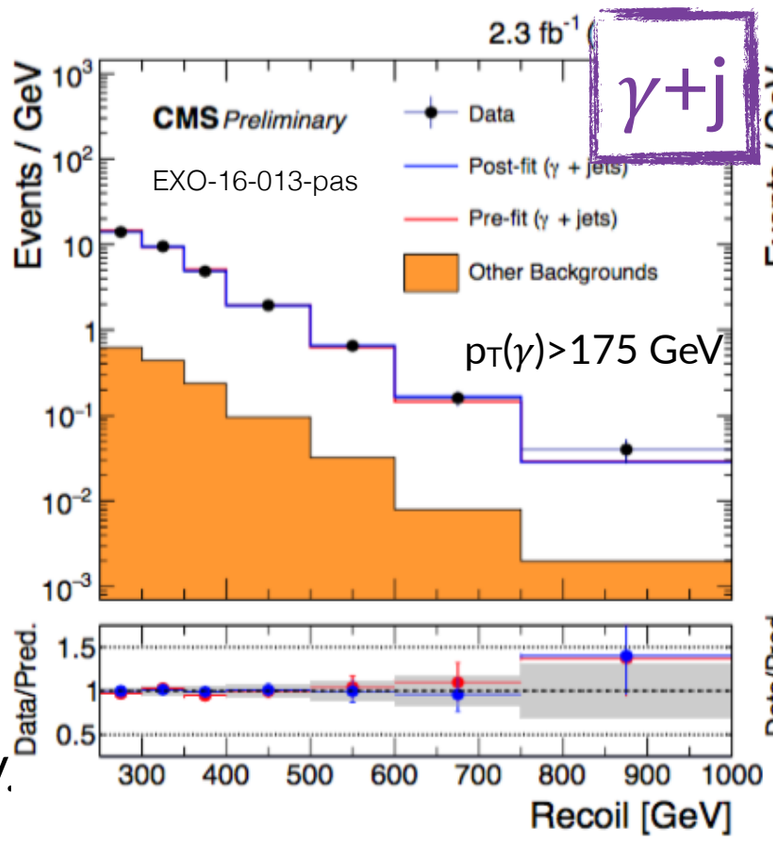
MET

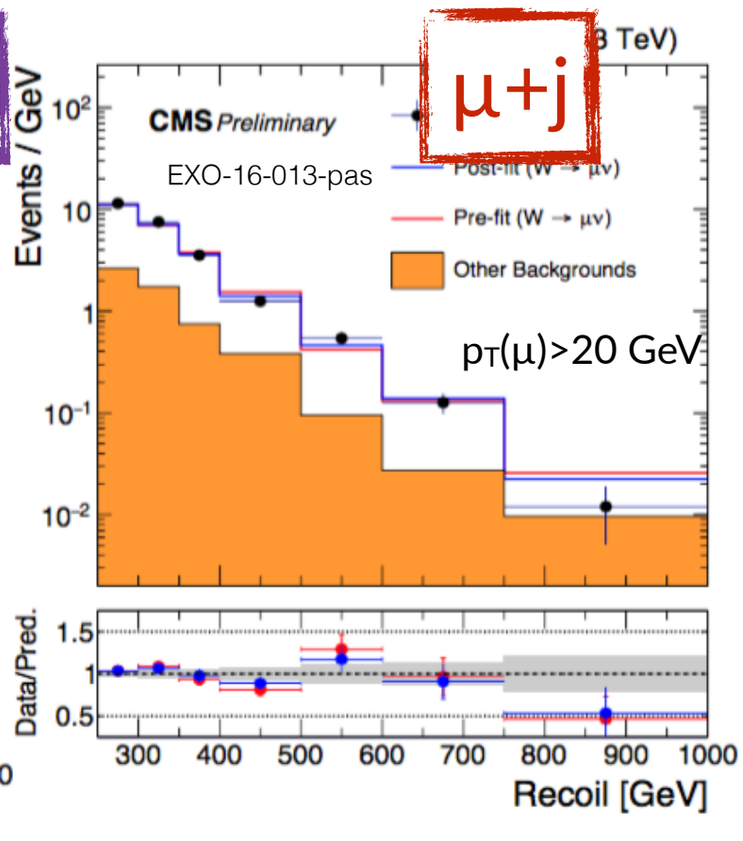
CMS: FIVE CONTROL REGIONS (X2)







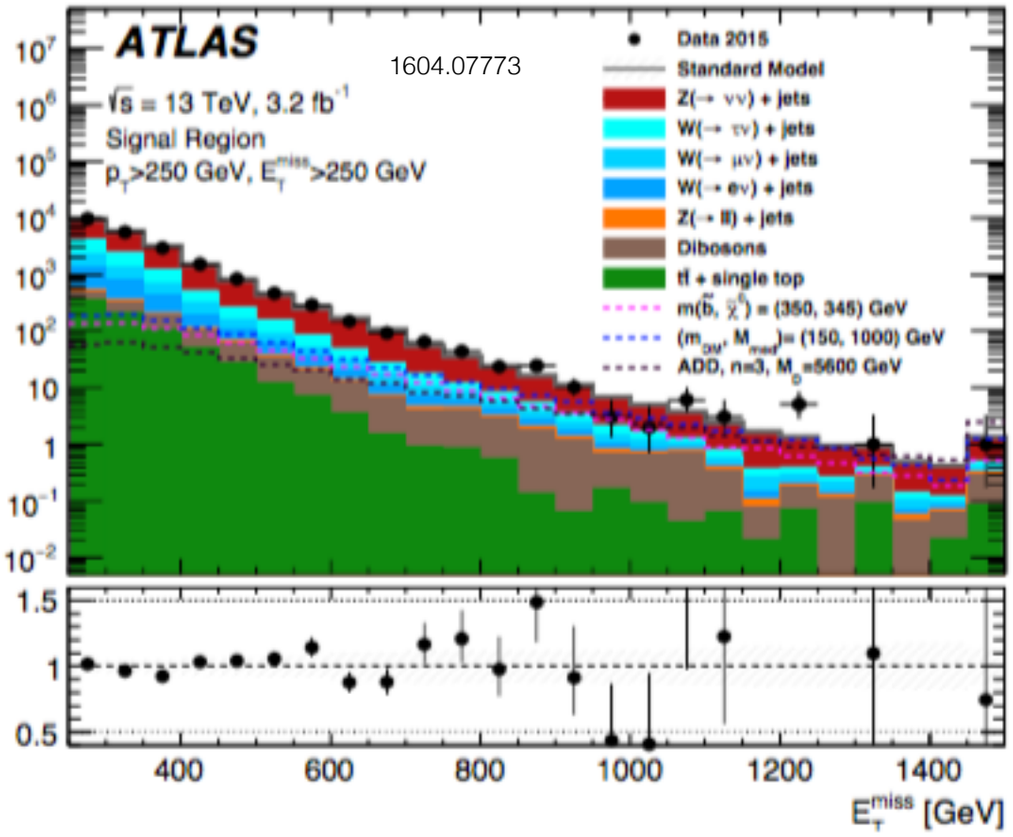




anti-k_t R=0.8 pruned,
pT > 250 GeV,
$|\eta|$ < 2.4,
$|m_J - m_{W/Z}|$ < 15 GeV,
2-prong (τ_2/τ_1<0.6)

"MET" > 250 GeV

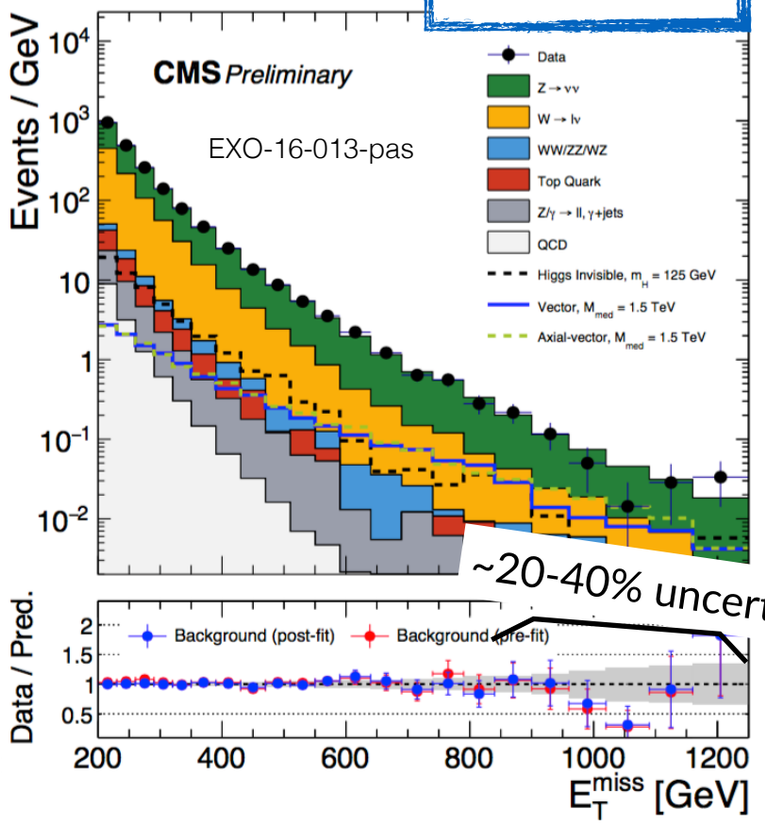
RESULTS



no significant excess observed w.r.t. SM prediction

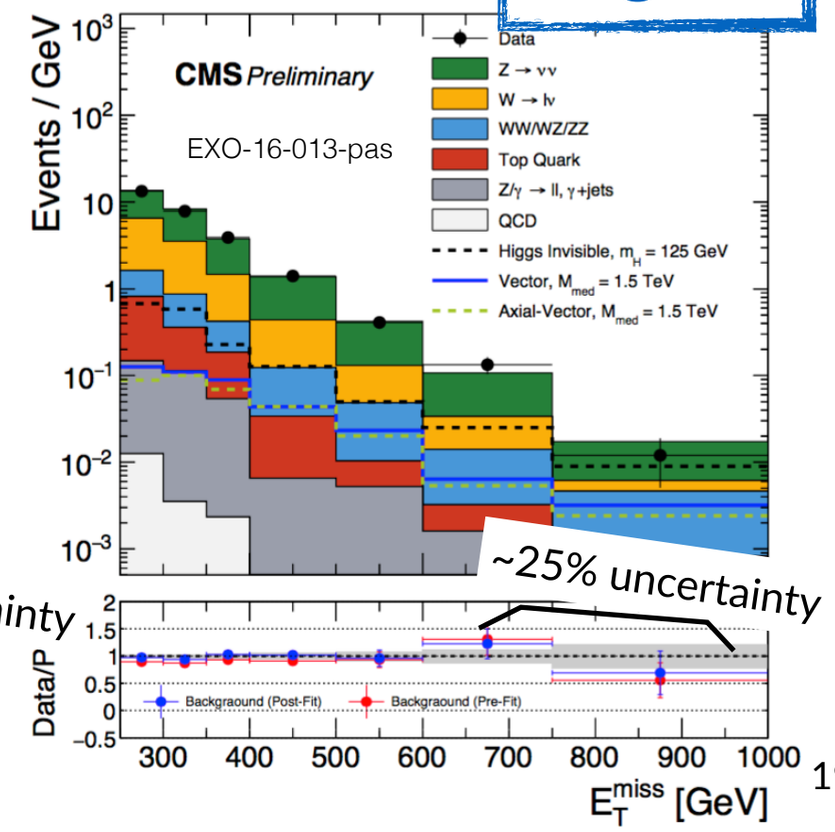
- put limits on signal yield for different tested hypotheses, using MET ("MET") binned shape fit in SR(+CRs)

small-R



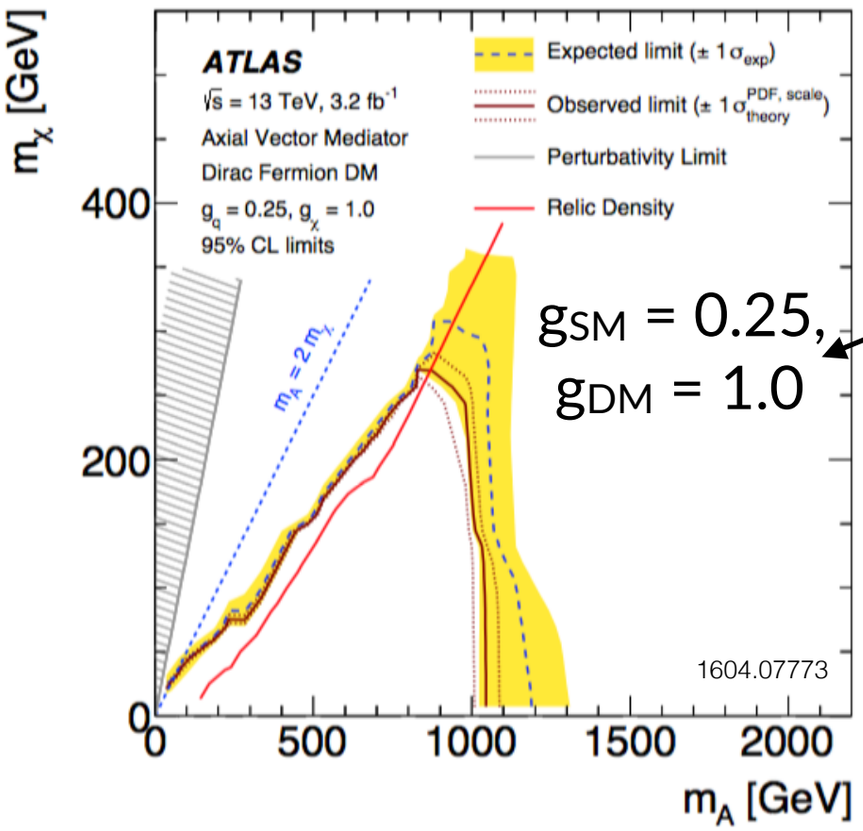
~20-40% uncertainty

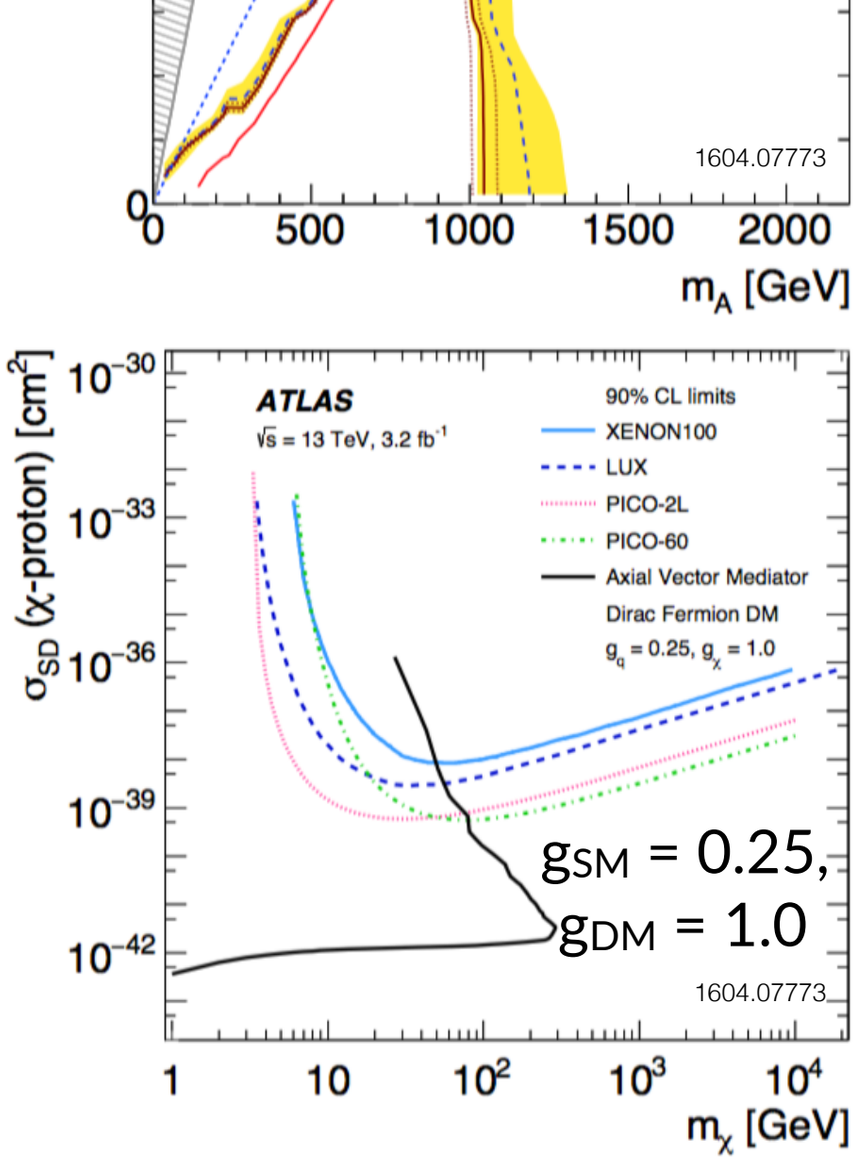
large-R



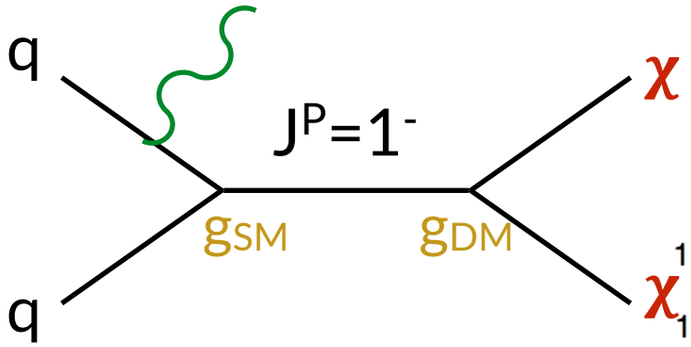
~25% uncertainty

Interpretations: axial-vector mediator, s-channel

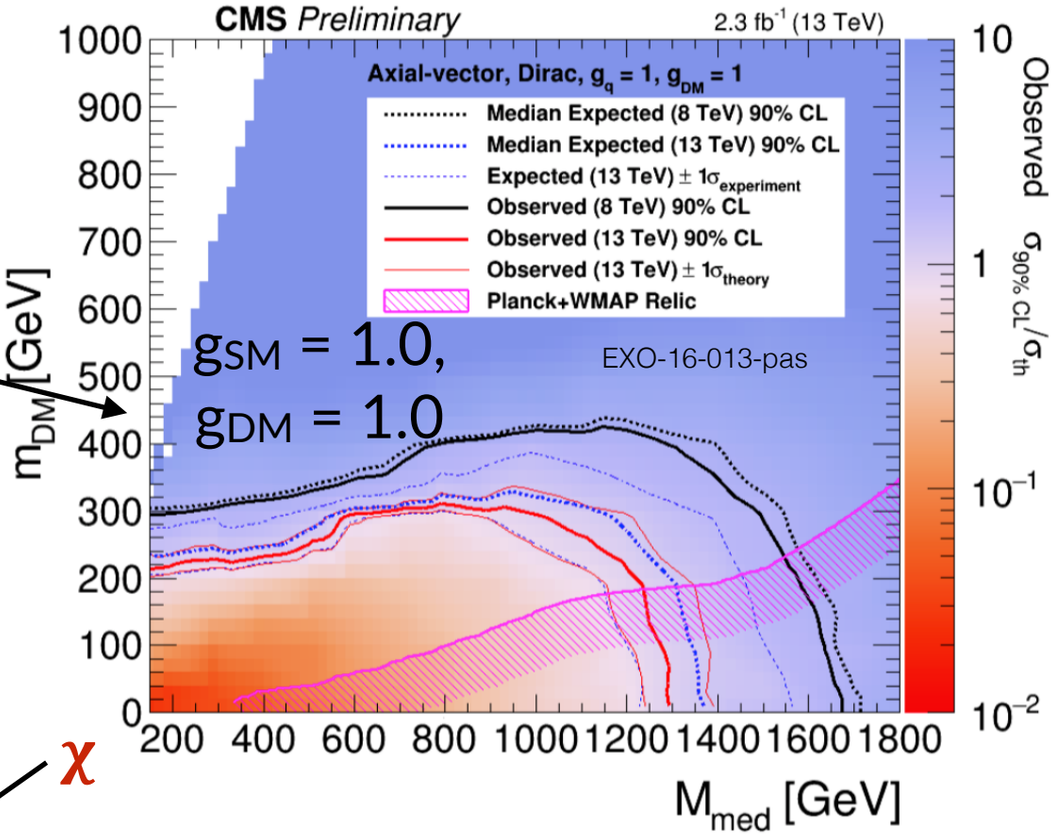


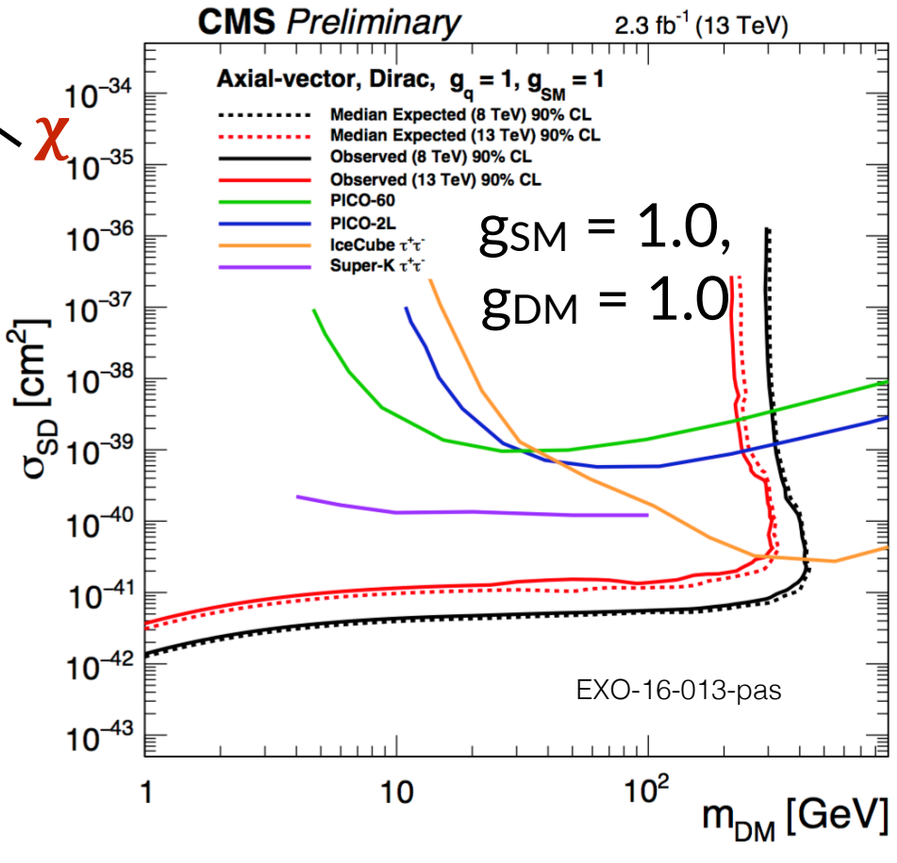


mind the couplings (will be harmonised) and luminosities (CMS: Run2 < Run1)



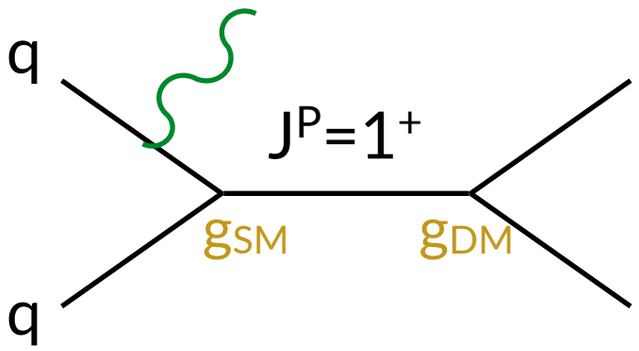
axial vector
=
spin-dependent WIMP-nucleon scattering
=
LHC is better



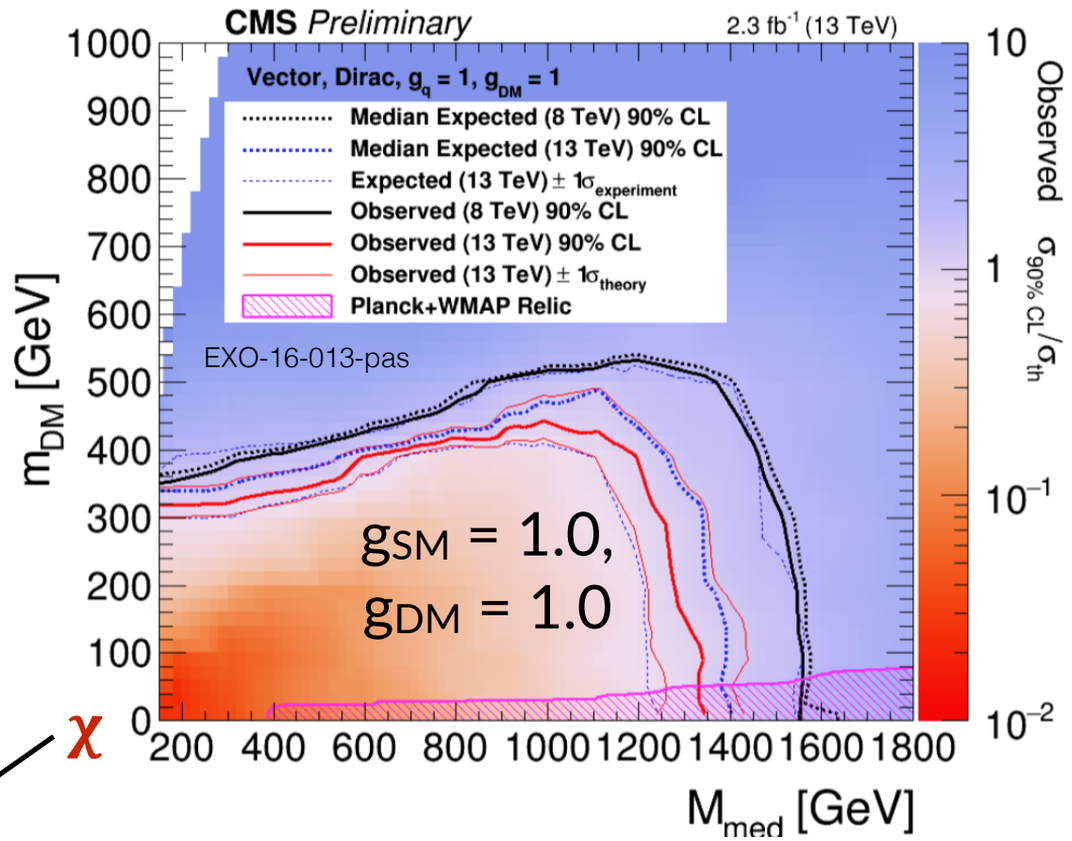


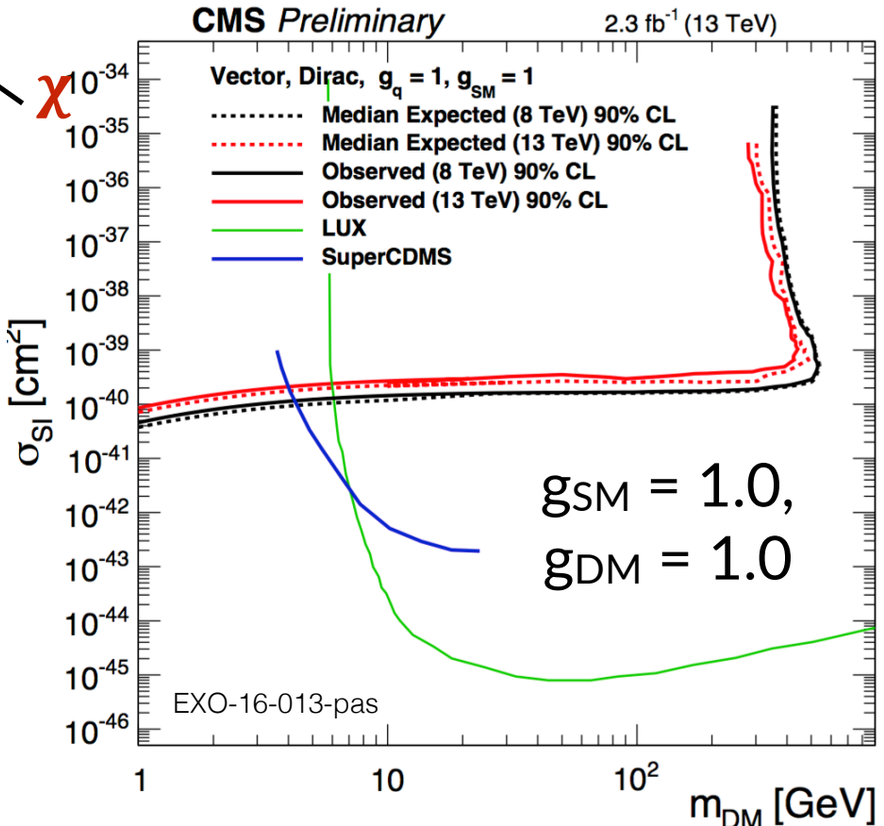
2016

Interpretations: vector mediator, s-channel

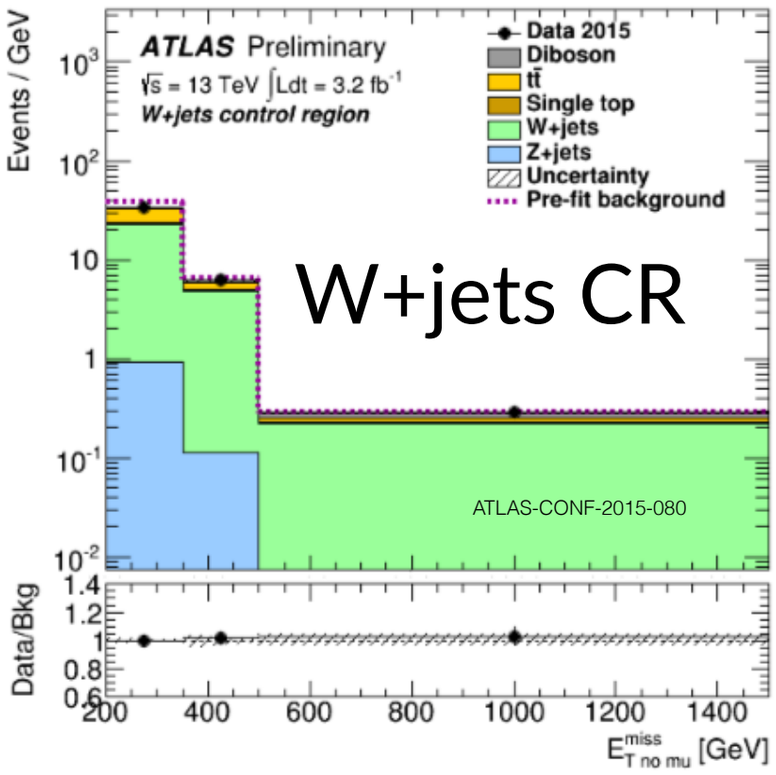


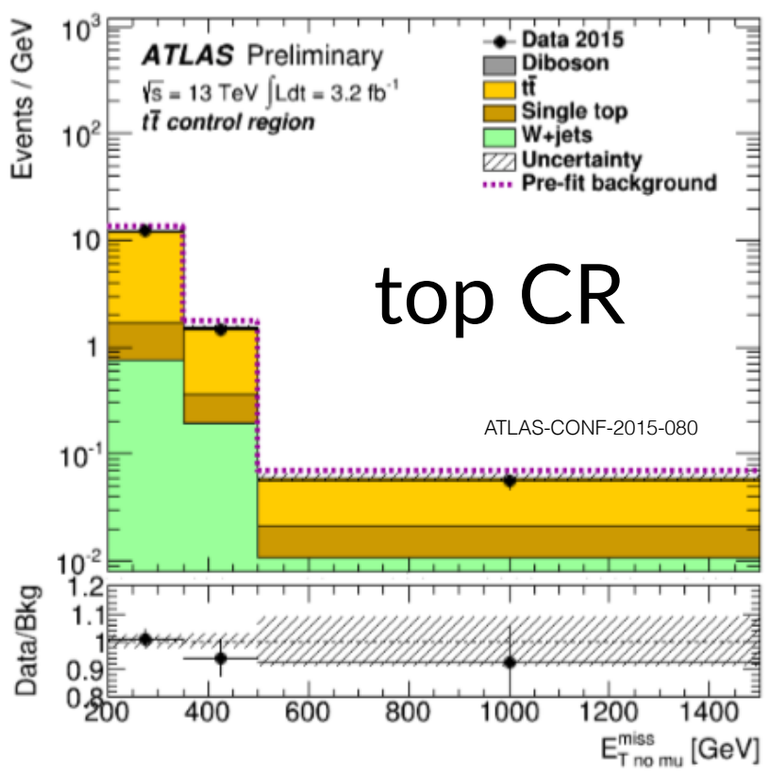
vector
=
spin-independent
WIMP-nucleon
scattering
=
LHC complementary at
low DM mass

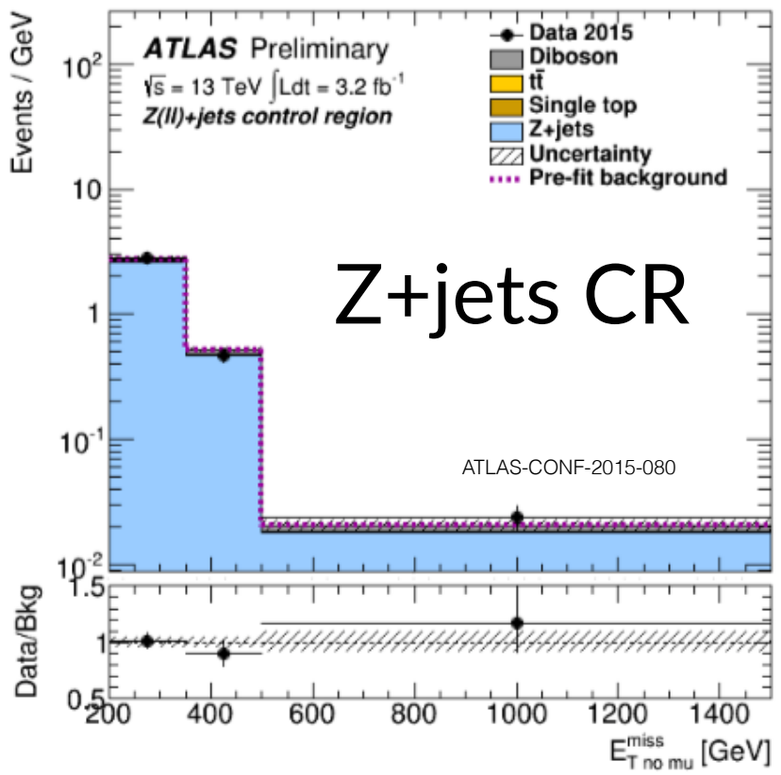




Mono-W/Z at ATLAS



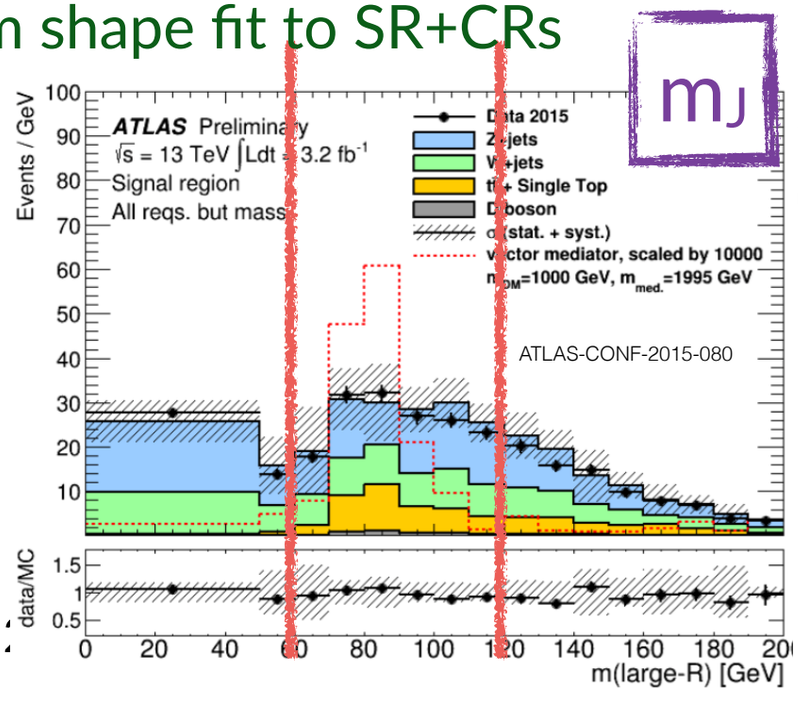


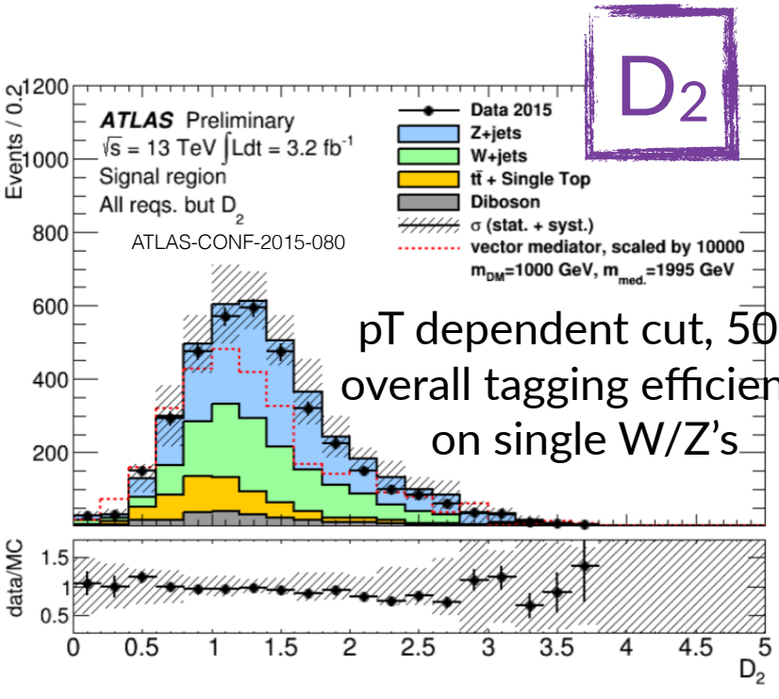


trimmed large-R jet (anti-kT R=1.0), MET > 250 GeV

- CRs: 1μ+0 b-jet (Wμν), 2μ (Zμμ), 1μ+>=1b-jet (ttbar)
  - W, Z, ttbar normalisation from shape fit to SR+CRs

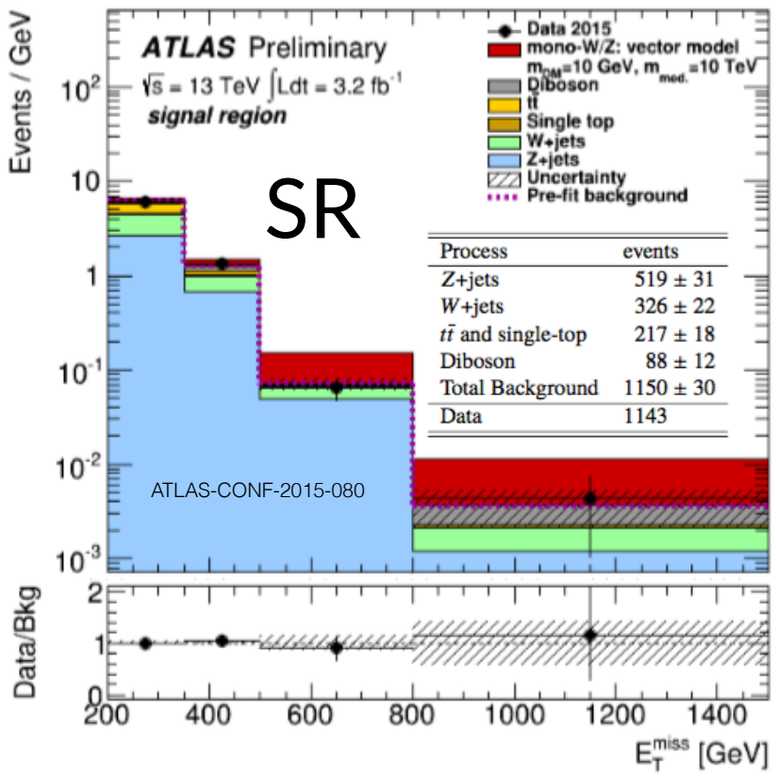
boson tagging based on jet mass and 2-prongness ("D_2"), main uncertainty on total bkg (5-10%)

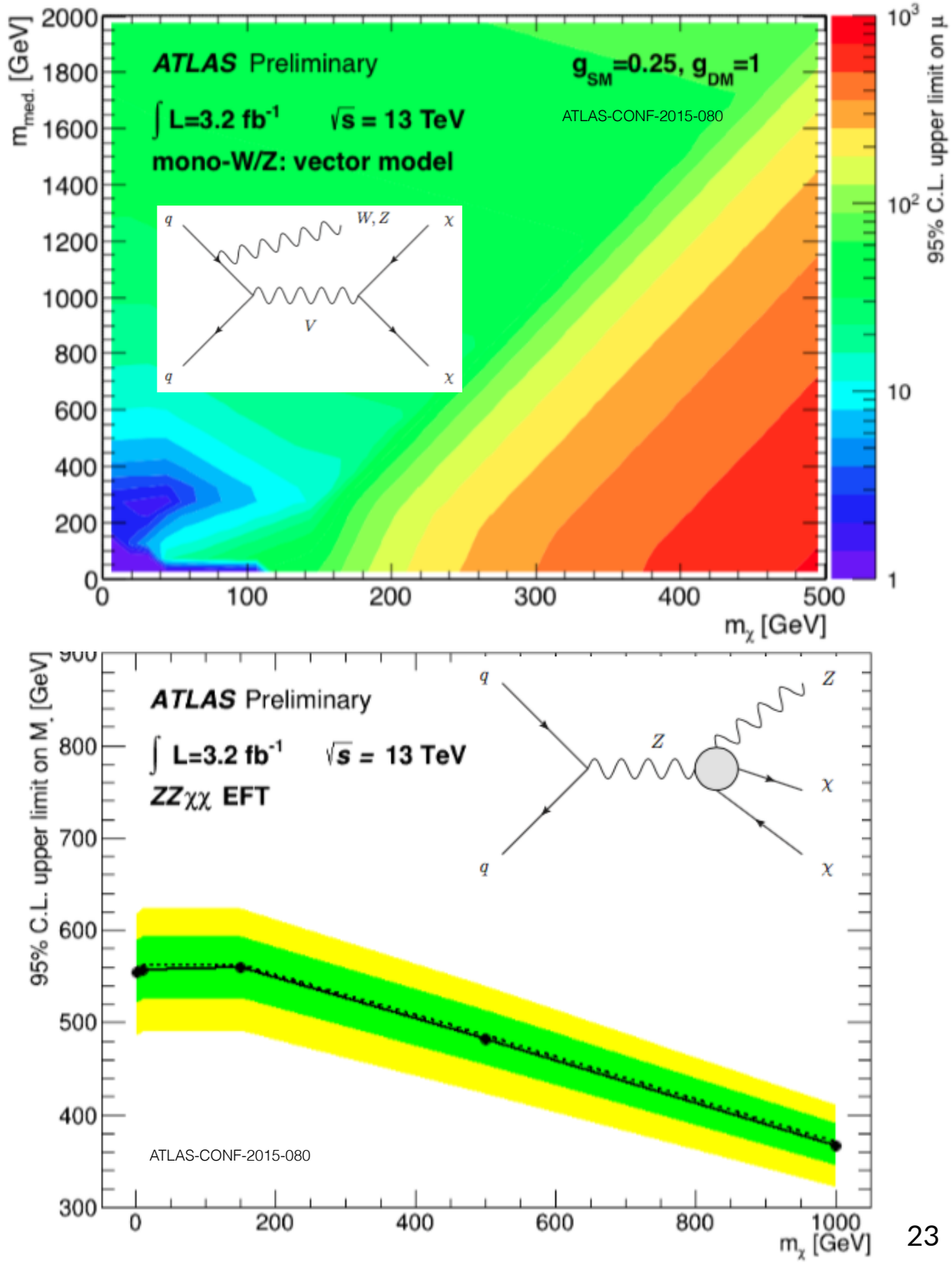




pT dependent cut, 50% overall tagging efficiency on single W/Z's

Mono-W/Z at ATLAS - Results





unique sensitivity to ZZ$\chi\chi$ EFT

- Z' simplified model: less sensitive than mono-jet (almost by construction: ISR!)

Beyond: Razor

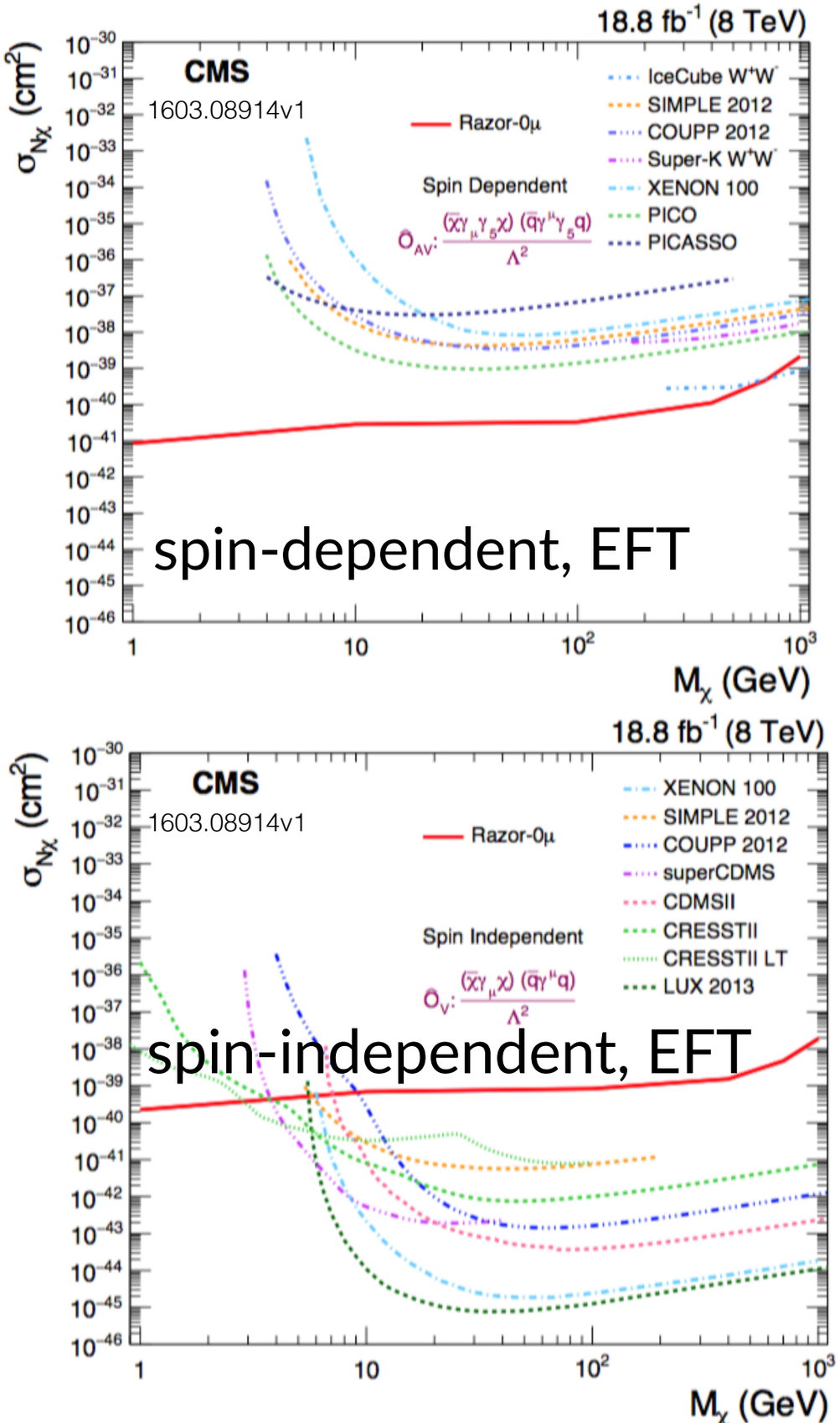
mass scale (e.g. m_{NLSP})

$$M_R = \sqrt{(|\vec{p}^{j_1}| + |\vec{p}^{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2|}$$

$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{p}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

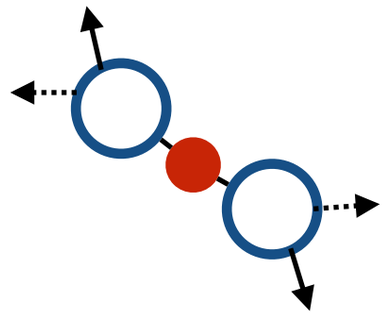
$$R = \frac{M_T^R}{M_R}$$

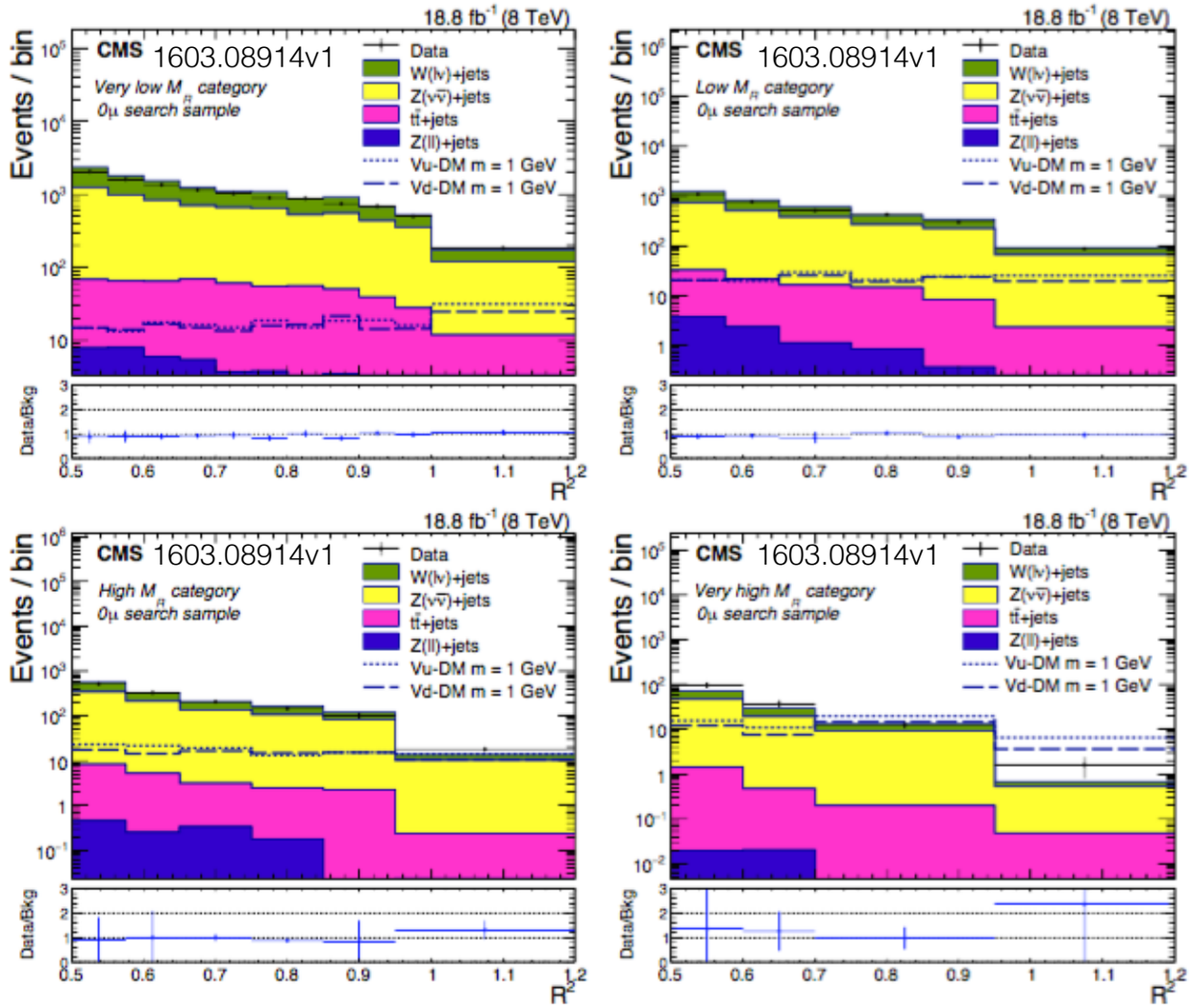
dijet topology (~$\Delta\Phi(j_1,j_2)$)



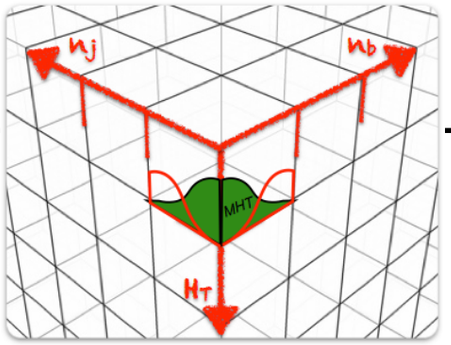
exploit razor variables (N_{jets}>=2)

- born in SUSY (e.g. SUS-15-004)
- access lower pT/MET region
  - particularly relevant for softer signals e.g. scalar mediator





BEYOND: α_T



H_T = scalar sum of jet pTs
H_T^{miss} = "MET" from jet info only
ΔH_T = E_T imbalance of pseudo-jets

$$\alpha_T = \frac{1}{2} \cdot \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - \not{H}_T^2}}$$

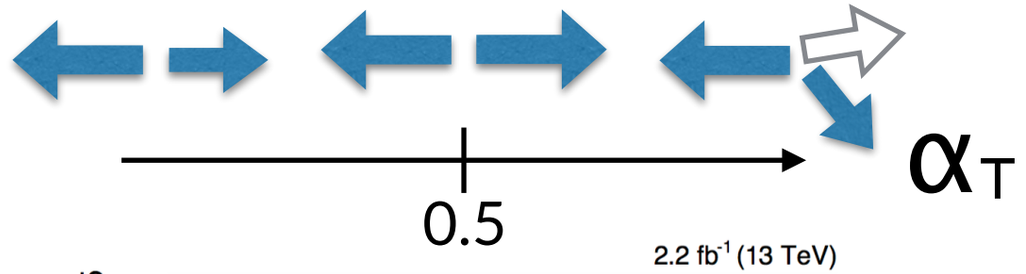
main experimental limitations of monojet-like searches:

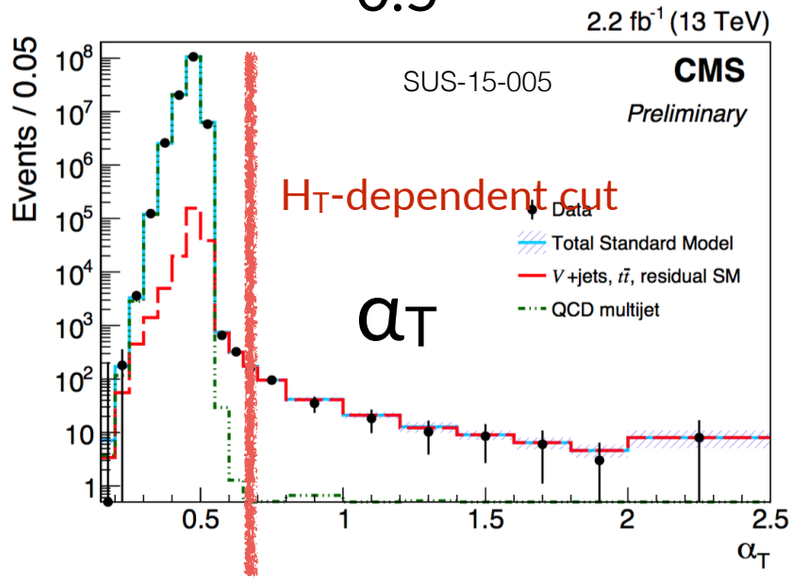
1. need to trigger events

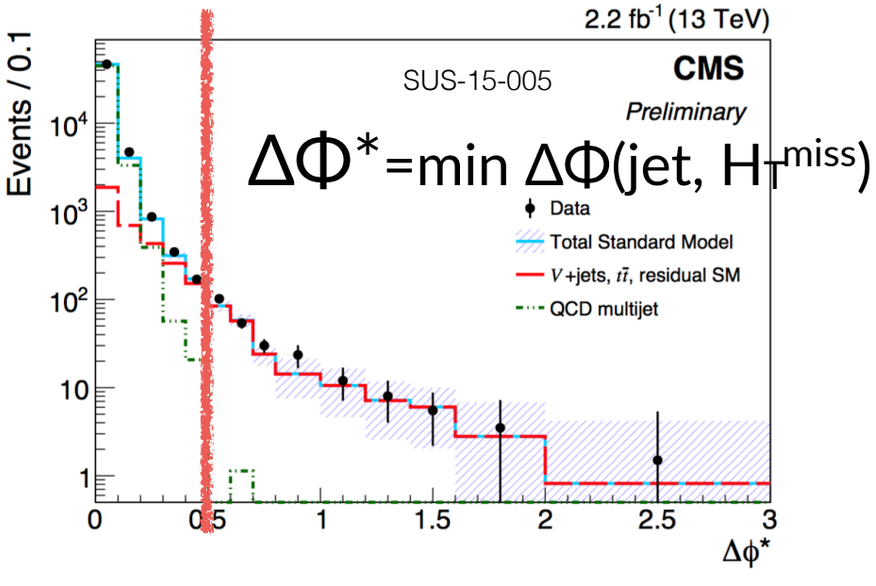
- rely mostly on MET trigger
  - same topology of beam background (which has higher rate)
  - a problem, when signals have low MET (e.g. [pseudo]scalar)
- can exploit (n-)jet+MET for specific searches (e.g. razor for N_{jets}>=2)

2. need to reject multi-jet background (especially for tt+MET)

- a jet is mis-reconstructed/lost and fakes MET -> cut on ΔΦ(jet, MET)
- might use α_T for better rejection
  - form "pseudo-jets" from reco jets
  - trigger on H_T+α_T, cut on ΔΦ*
  - can reach H_T>200 GeV, H_T^{miss}>130 GeV



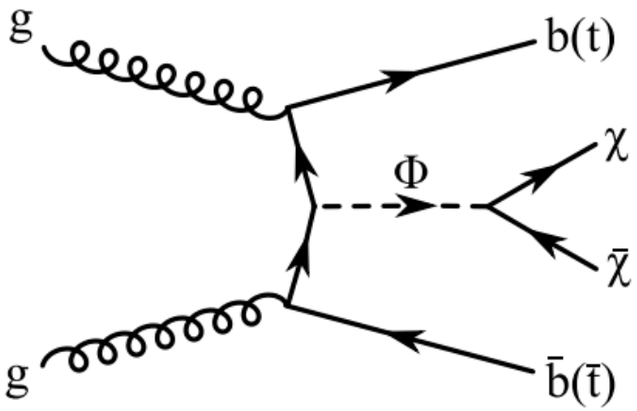


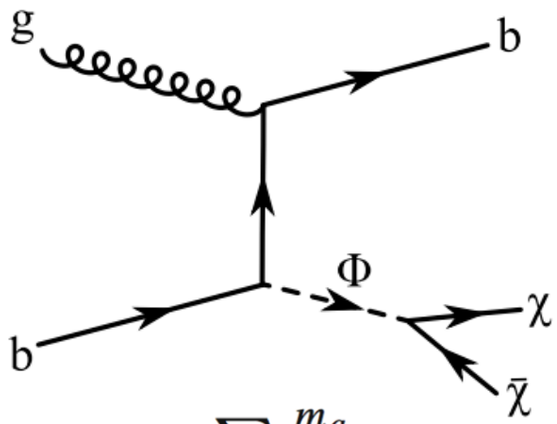


MET + HEAVY QUARKS

(a quest for the elusive)

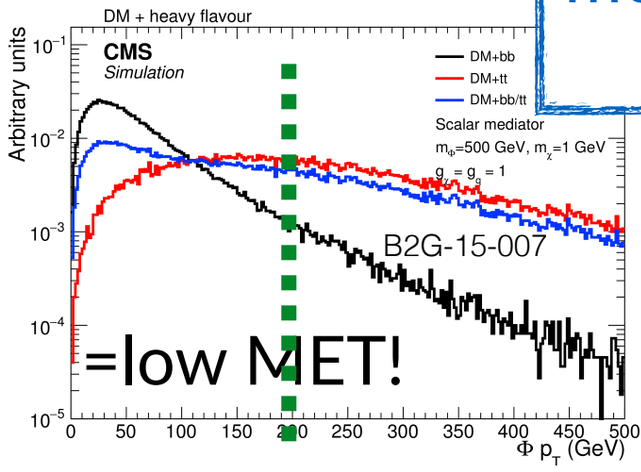
CMS: b(b) + MET @ 13 TeV





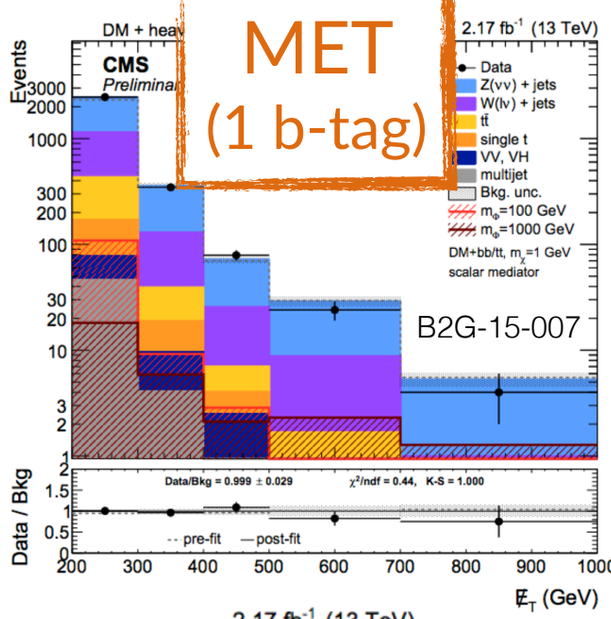
$$\mathcal{O}_{\text{scalar}} = \sum_q \frac{m_q}{M_*^N} \bar{q} q \bar{\chi} \chi$$

mediator pT ("true")

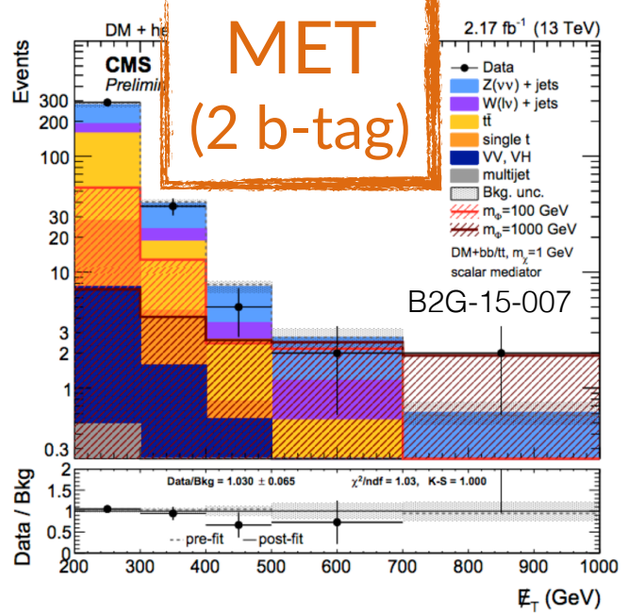


=low MET!

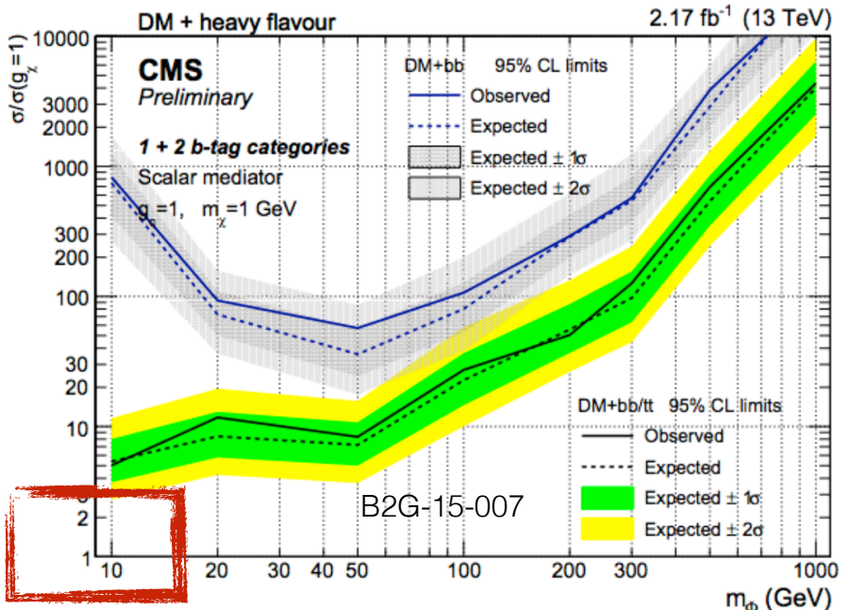
MET (1 b-tag)

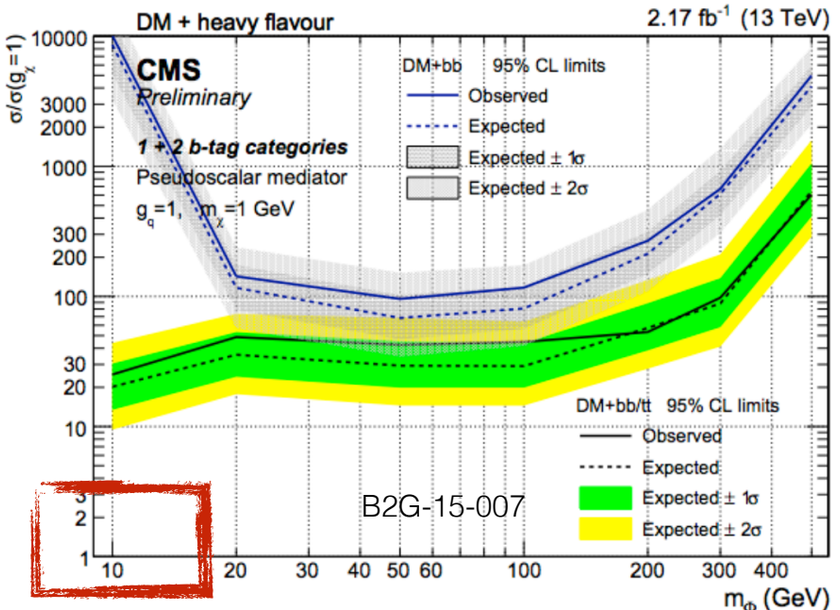


MET (2 b-tag)

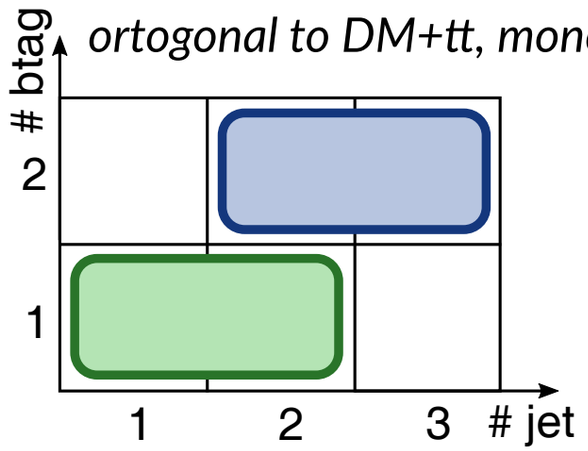


- à-la-monojet, but binned in $N_{b\text{-tags}}$, N_{jets}
- sensitive also to ttbar+DM production
- softer mediator pT -> MET trigger is a challenge!
  - need more luminosity to be fully sensitive





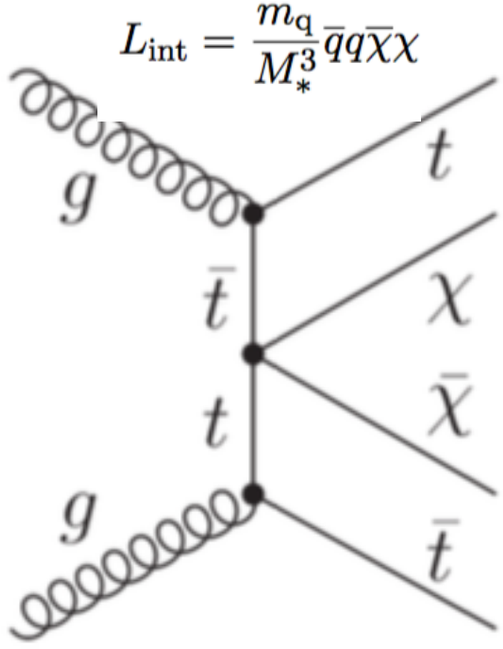
ortogonal to DM+tt, mono-jet

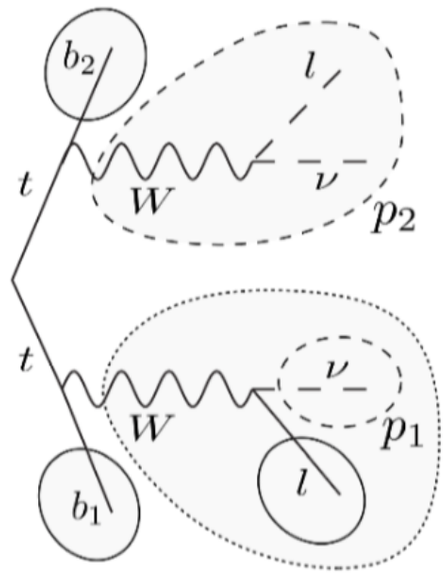


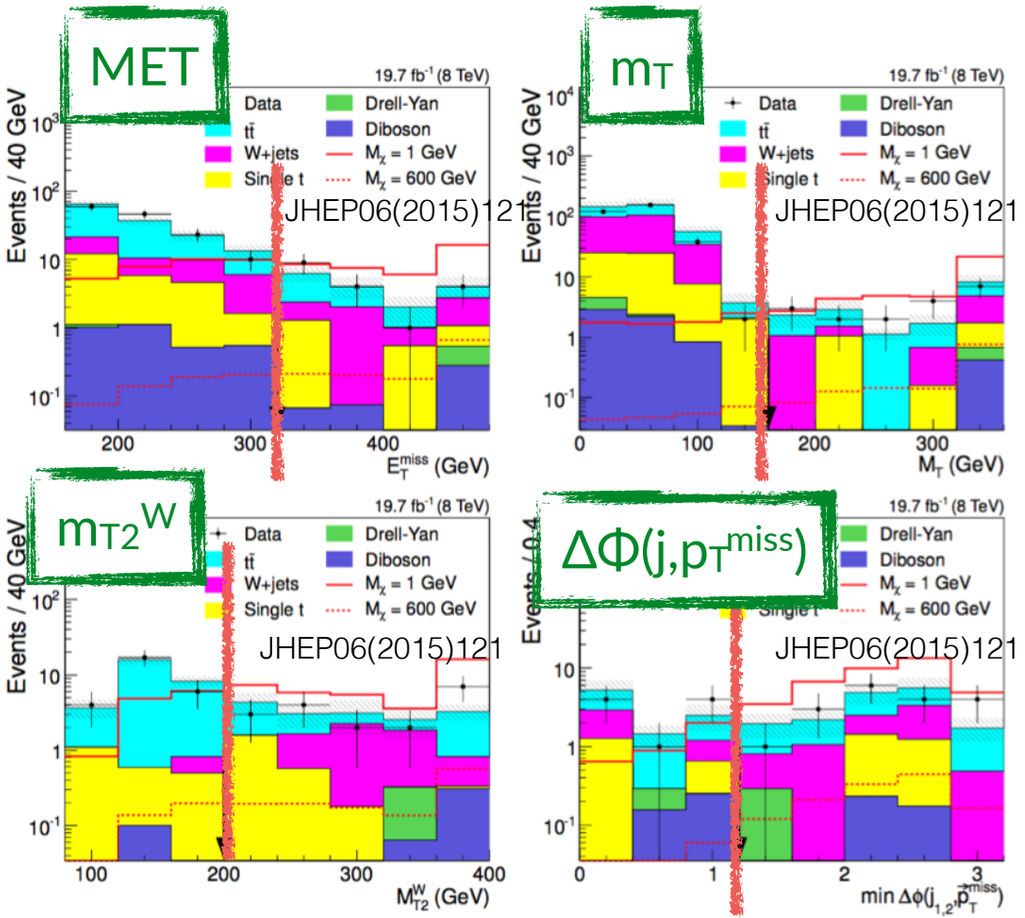
CMS: T(T) + MET @ 8 TeV

similar idea with tt final state

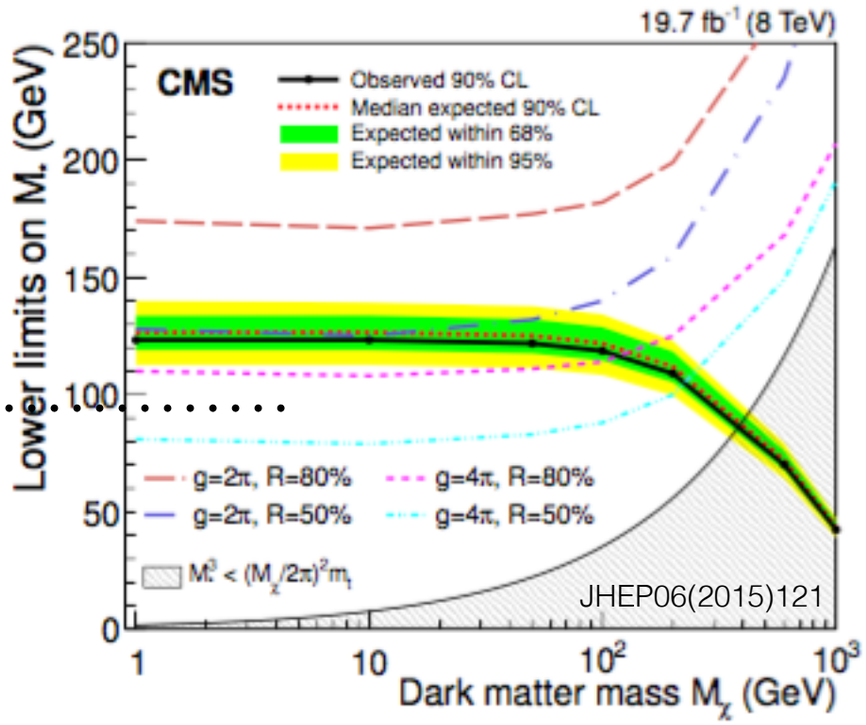
- searched in 1-lepton (better) and 2-lepton channel
- use MET as S/B discriminant
- 13 TeV work in progress!
  - increase in sensitivity from parton luminosity ratios
  - add fully hadronic channel -> significant improvement foreseen!







dilepton channel



V.

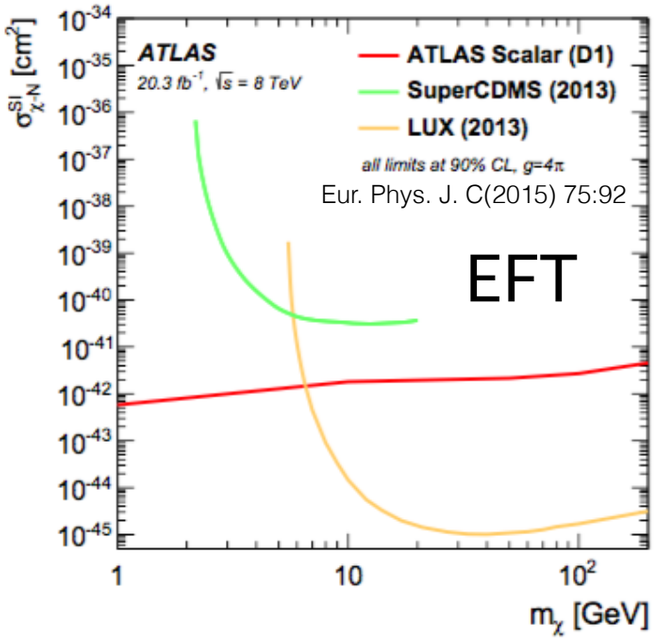
ATLAS: B/BB/TT(HAD,SEMI-LEP) @ 8 TEV

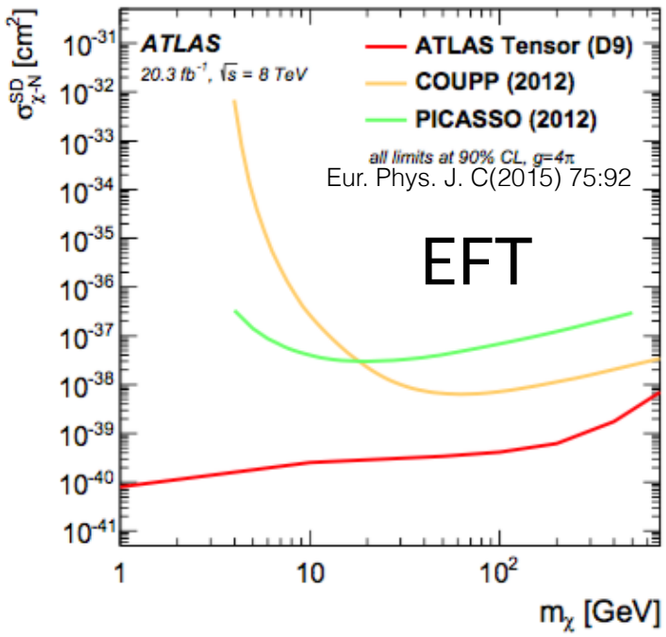
4 SRs: **b**+DM, **bb**+DM, **tt(had)**+DM, **tt(semi-lep)**+DM [~stop]

1/2 **b-tag** + **MET** ⊕ low n_{jet} (SR1,2), **razor** (SR3), 1 **lepton**+m_T/am_{T2}/topness/m_{jjj} (SR4)

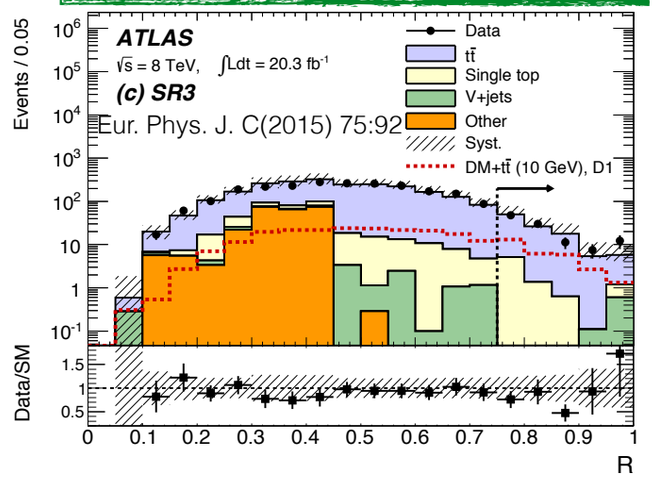
dominant **Z(vv)+jets** (SR1,2, from Z/γ+jets), **ttbar** (SR3,4, from orthogonal semi-lep CRs)

background uncertainty ~10/10/7/20% (flavour, top p_T, showering, stat.)

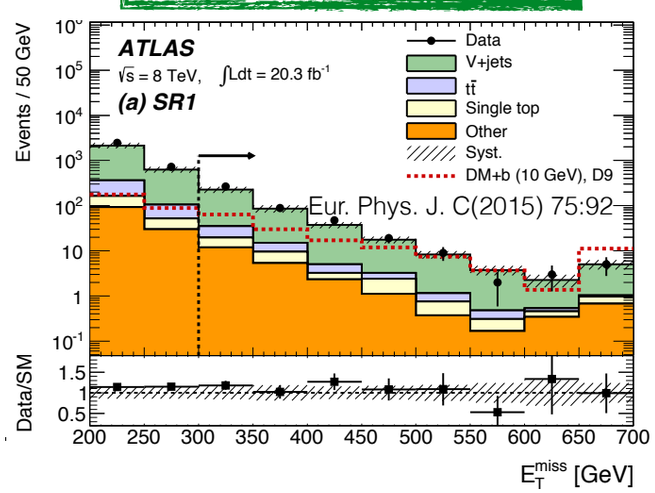




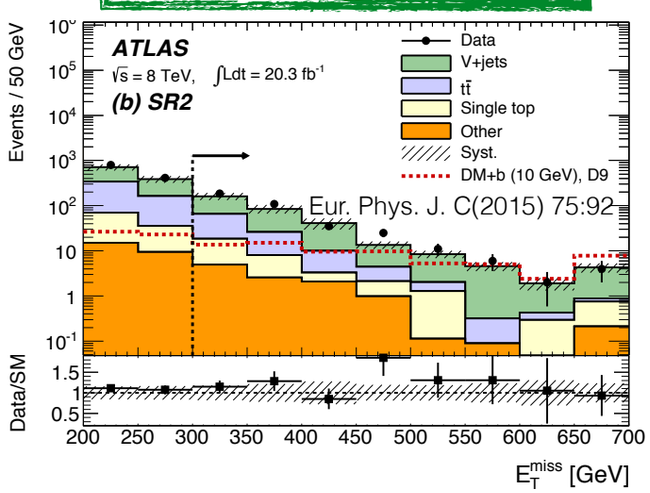
razor in tt(had)+DM SR



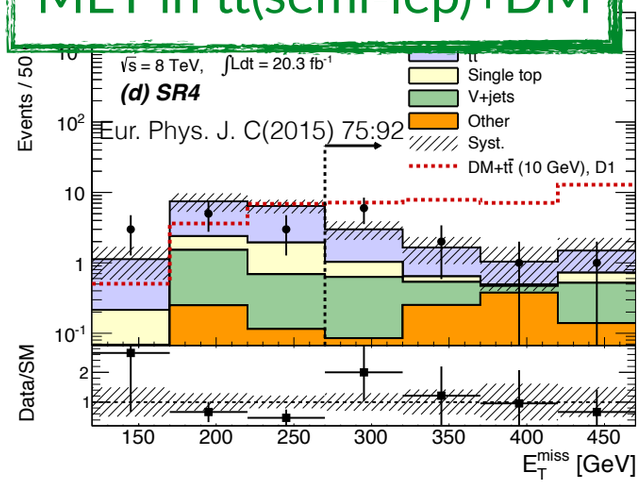
MET in b+DM SR



MET in bb+DM SR



MET in tt(semi-lep)+DM



WORK IN PROGRESS: MONO-TOP

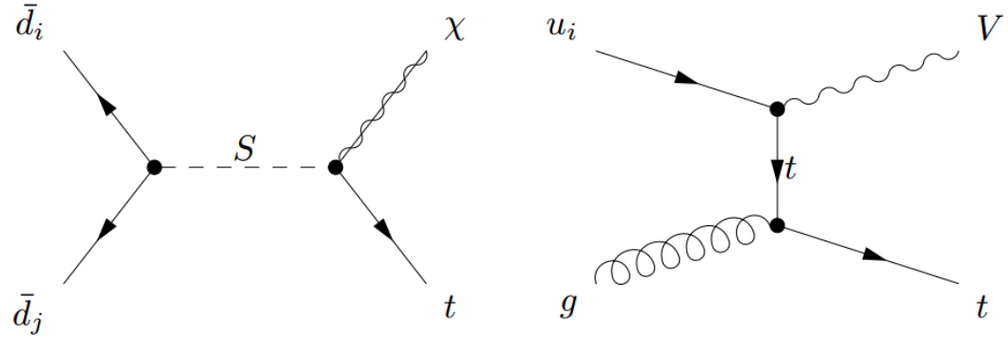
unique sensitivity to specific models not currently probed by other mono-X analyses

- massive mediator decaying into DM + top quark (RPV SUSY, hylogenesis)
- flavor-changing current

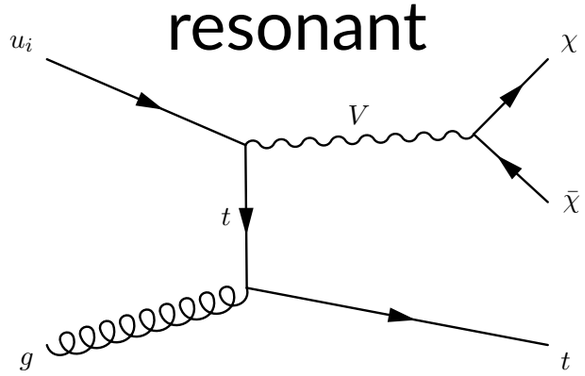
similar experimental idea as mono-W/Z, but with top-tagging (ε~40%)

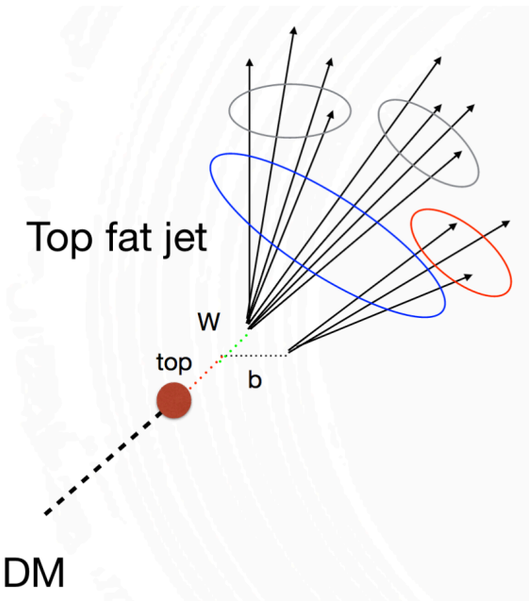
- MET+large-pT,R jet from hadronic top decay
- as in mono-jet, main background from Z(νν)/W(μν)+jets

non-resonant

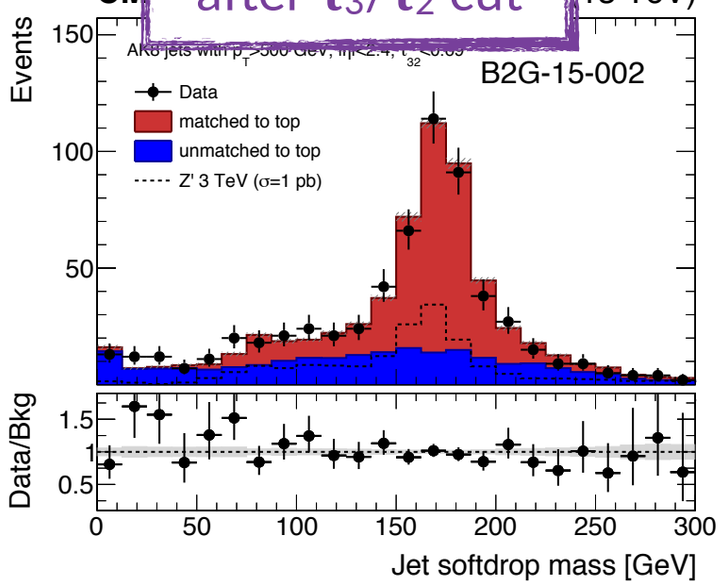


resonant

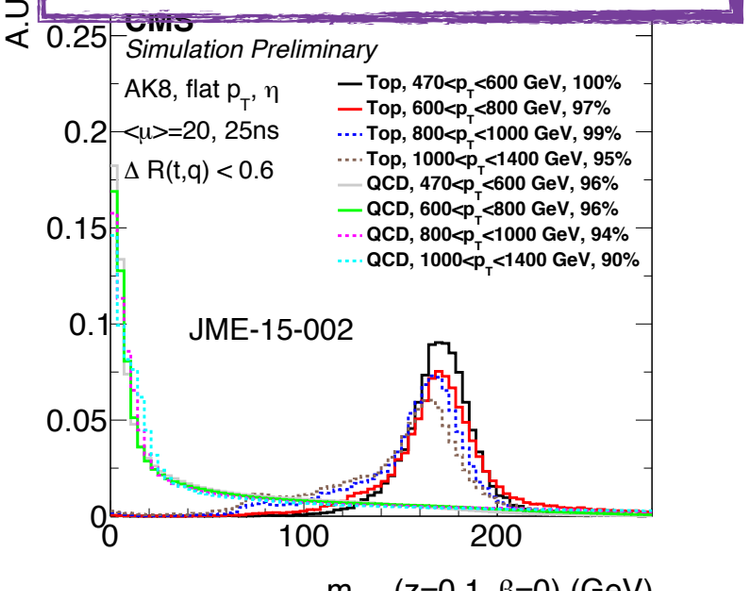




soft-drop mass after τ_3/τ_2 cut

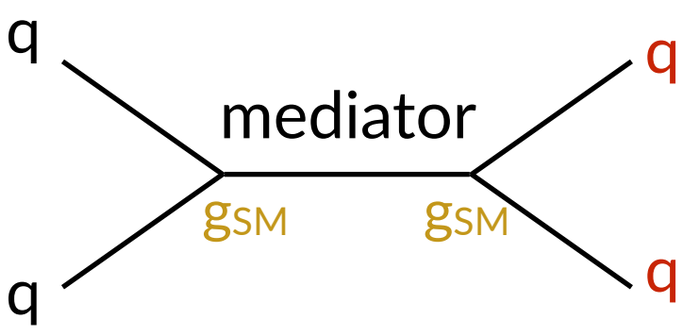


soft-drop mass with merged top requirement

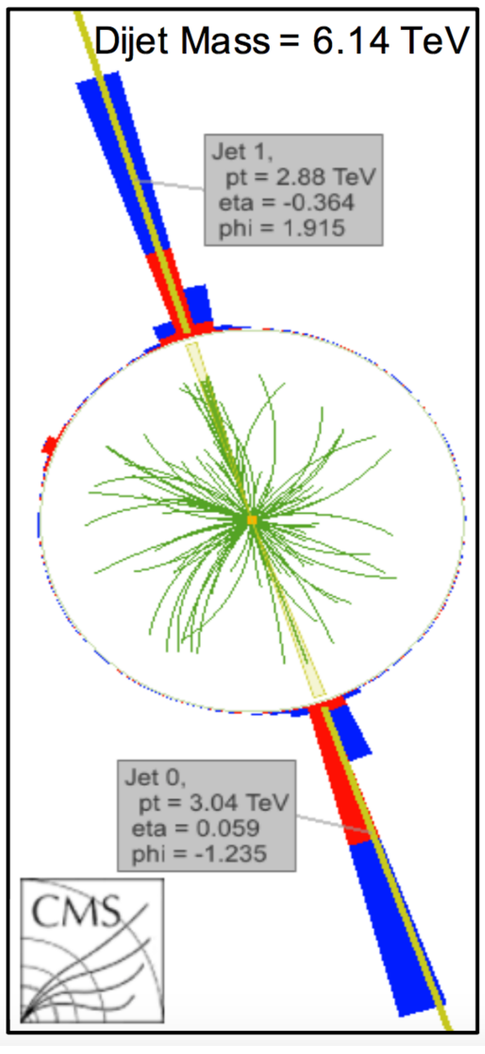


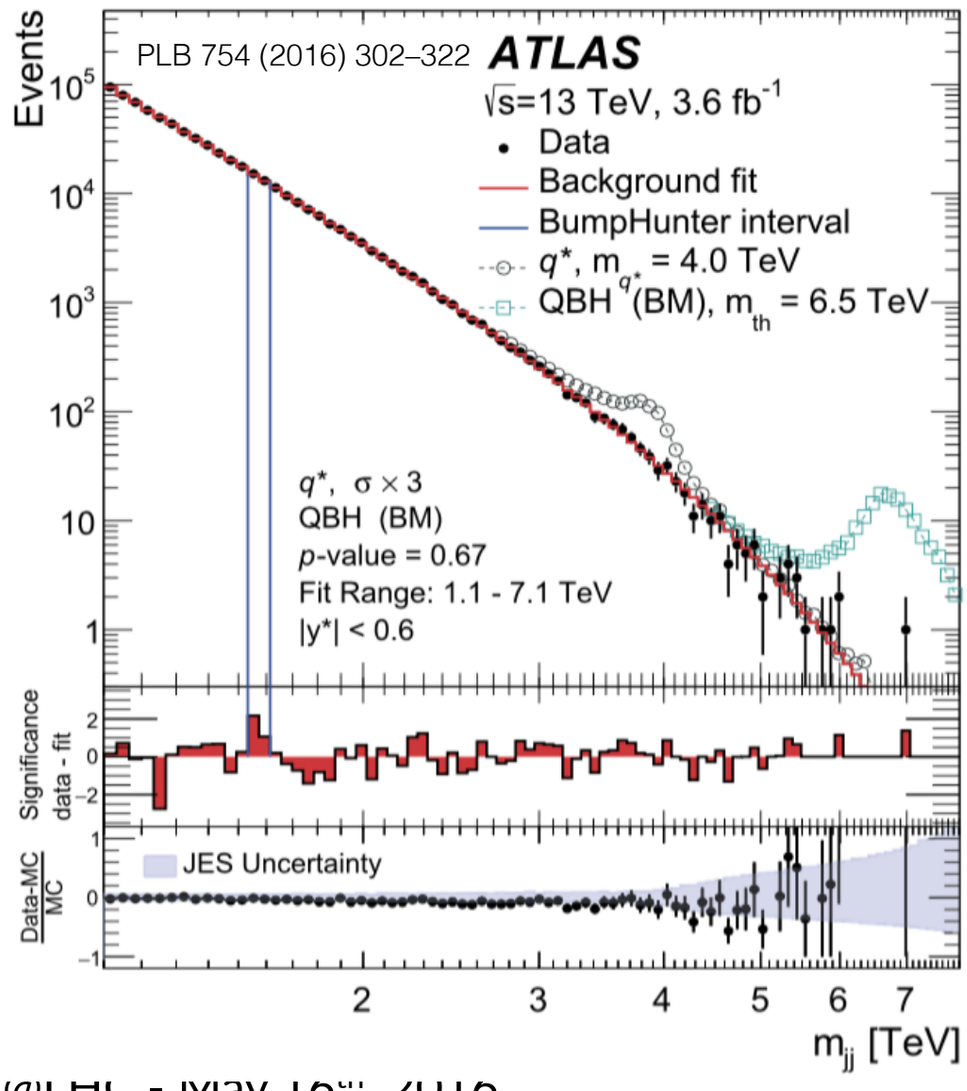
Beyond Mono

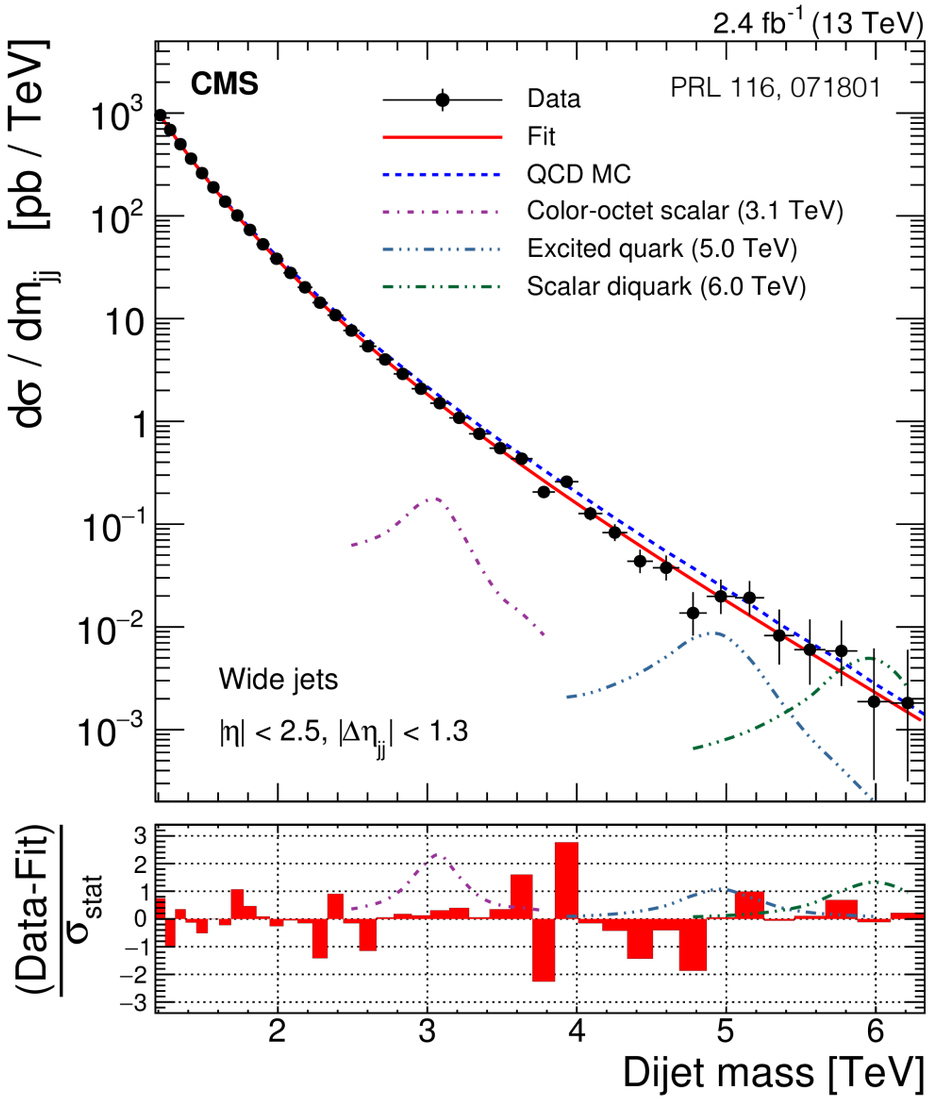
DIJET (OR "IS YOUR SIMPLIFIED MODEL ALREADY EXCLUDED?")



- mediator can decay back to quarks
- look for it in dijet events
- high-mass (>~1 TeV, jet trigger): can recast generic limits on gaussian signals
- low-mass: may exploit data-scouting

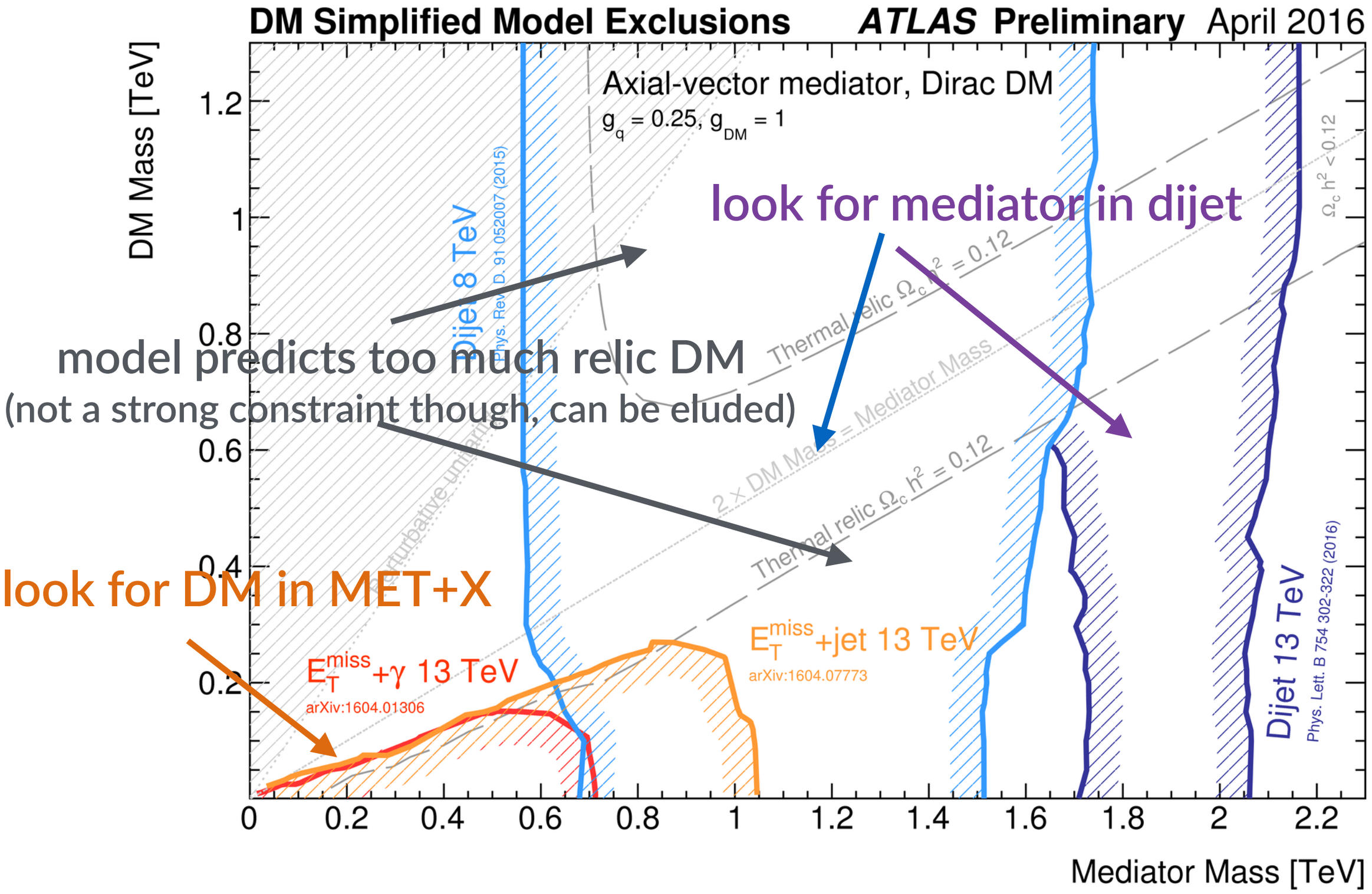






Complementarity

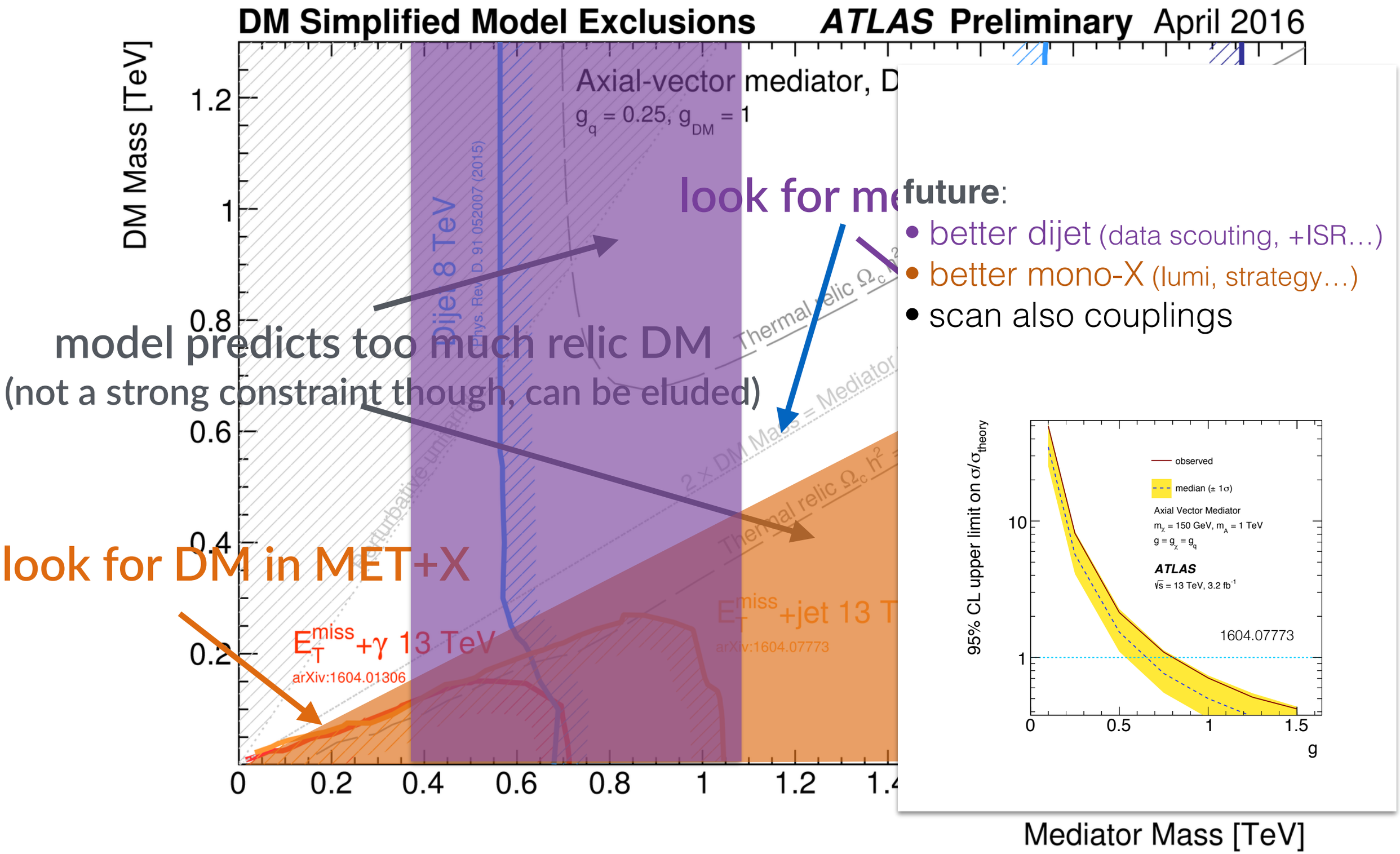
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html



mind the couplings!

Complementarity

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html



future:

- better dijet (data scouting, +ISR…)
- better mono-X (lumi, strategy…)
- scan also couplings

Mediator Mass [TeV]

mind the couplings!

Conclusions

Conclusions

- ATLAS and CMS use similar strategies for DM searches
  - common base for interpretation of results (LHC DM WG et al)
  - consistent techniques in mono-X searches
- experimental work can profit from higher foreseen luminosity
  - improve sensitivity to (pseudo-)scalar models, t-channel models
  - CR statistics may help reducing modeling uncertainties for sub-leading backgrounds (dominant in e.g. mono-jet, mono-γ)
- improved techniques (may) help!
  - "data-scouting" for low mass mediator searches
  - top tagging for mono-top, razor, α_T...
  - multi-channel combination

"nothing is as hard as looking for a black cat in a dark room, especially if there is no cat"

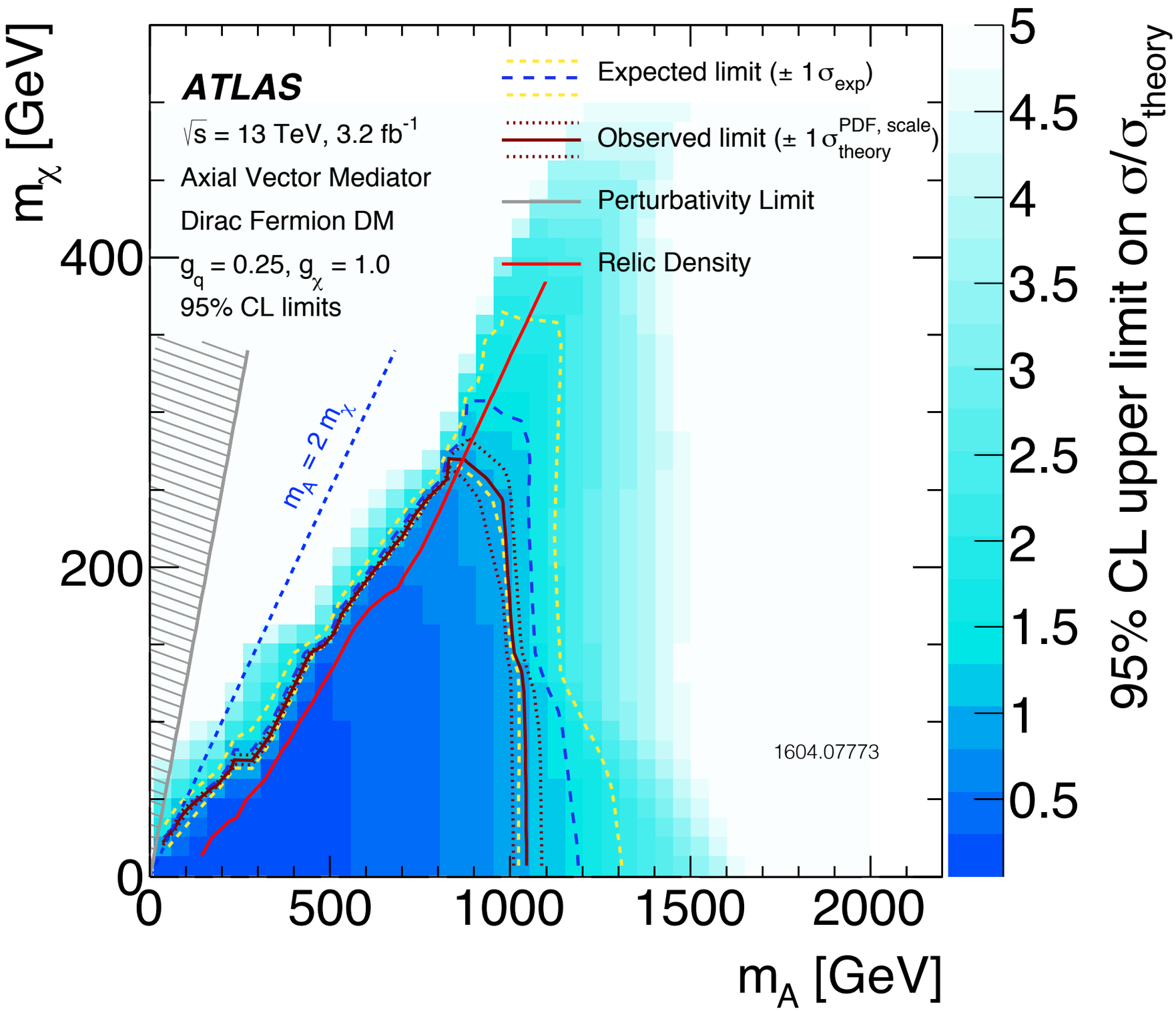
SPARES

Henri Cartier-Bresson, Jean Paul Sartre - MoMA, New York

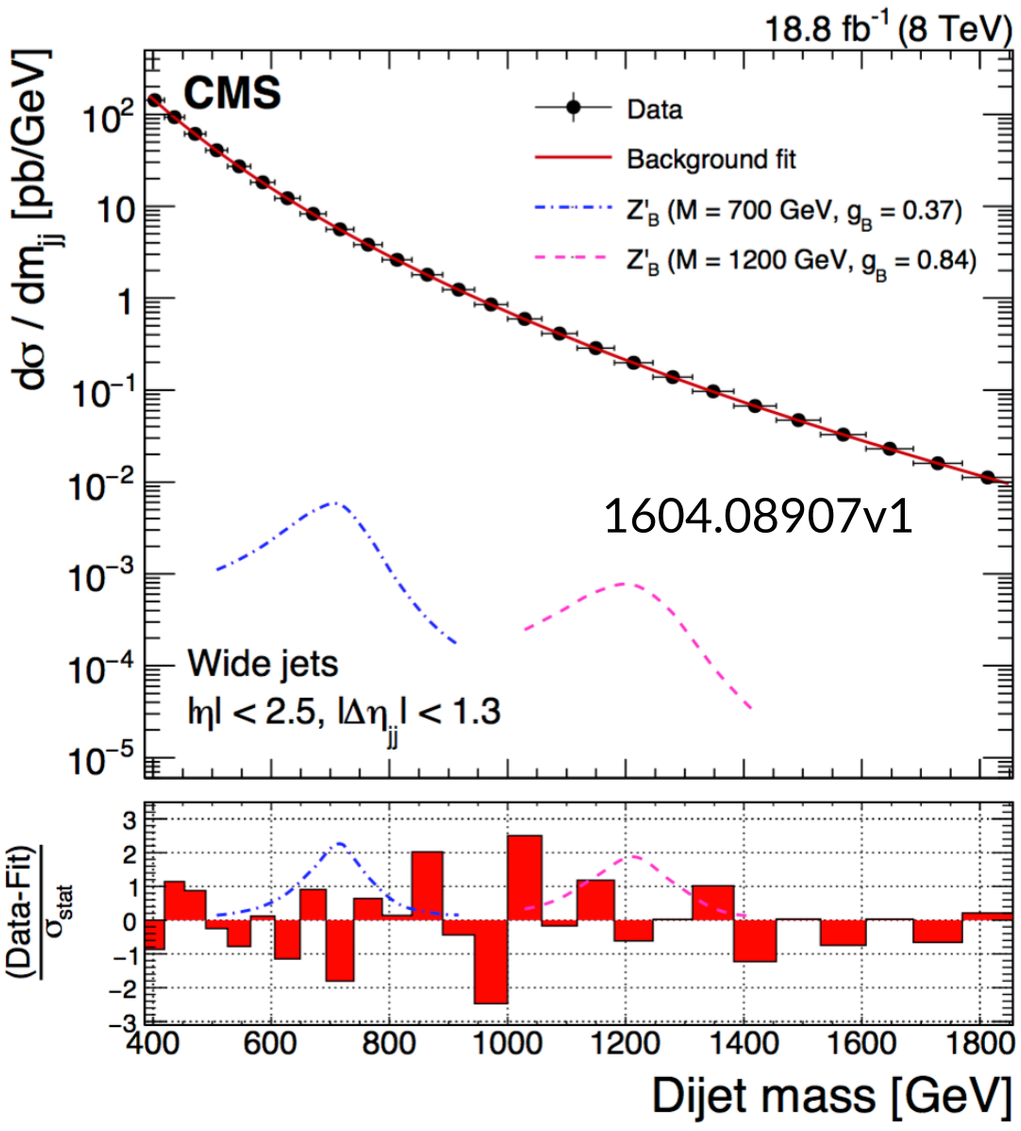
How far are we?

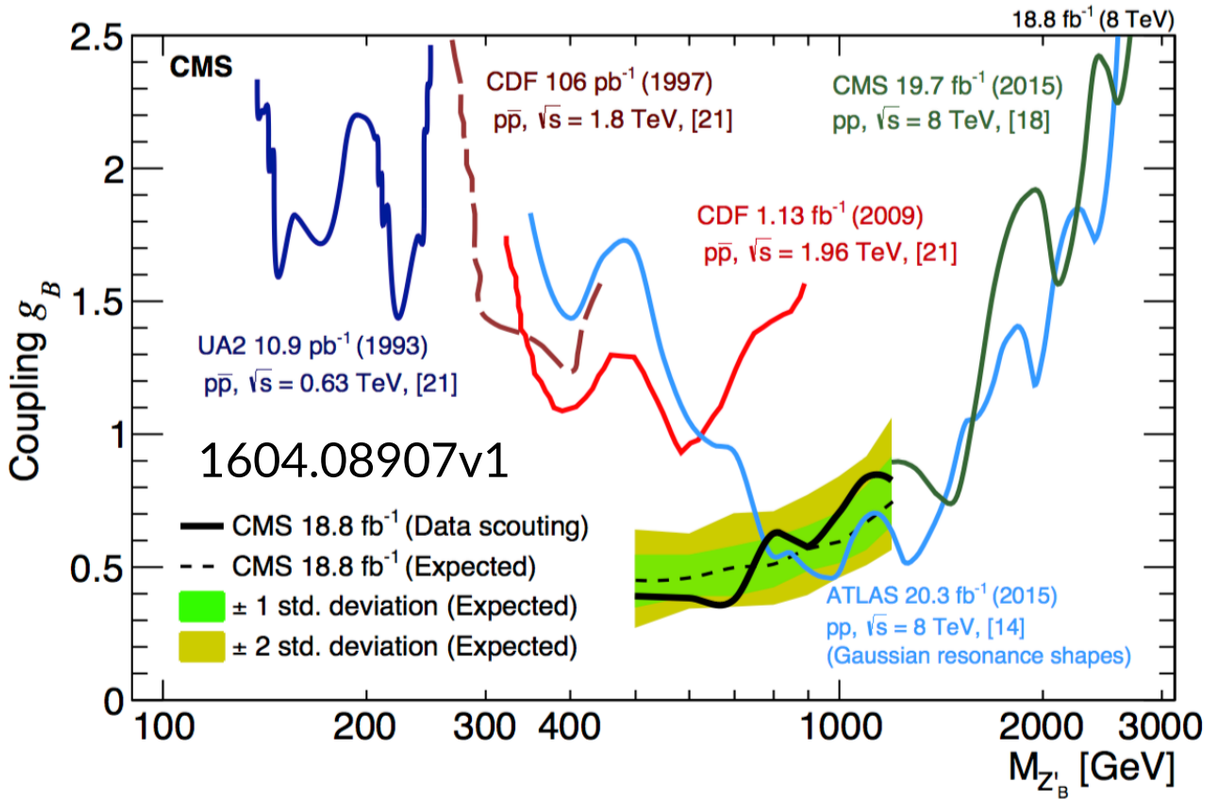
coloured, z axis: signal strength limit

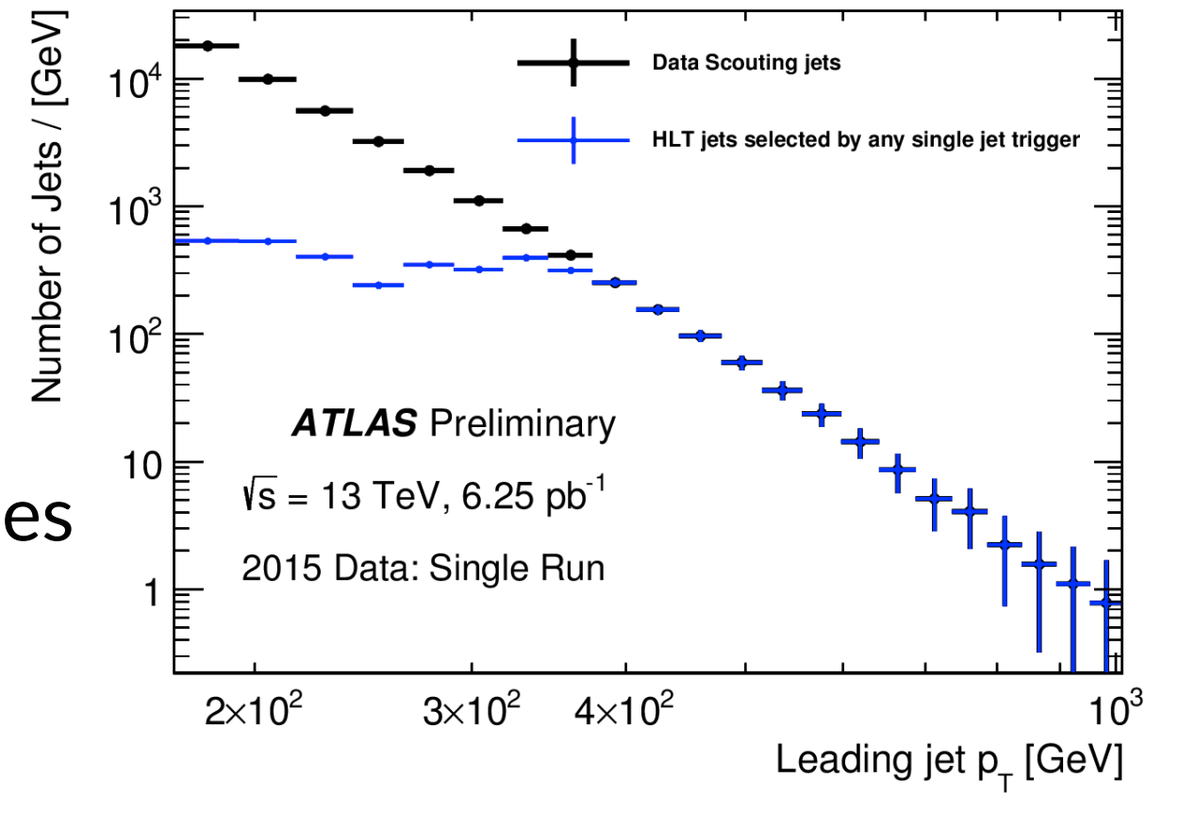
(sensitivity gain with luminosity ~ gradient, if stat. dominated)



Dijet: Data Scouting







show-stopper at low mass: trigger!

- use data scouting to bypass rate issues
- reach the 400-500 GeV region

MET + γ, ET AL.

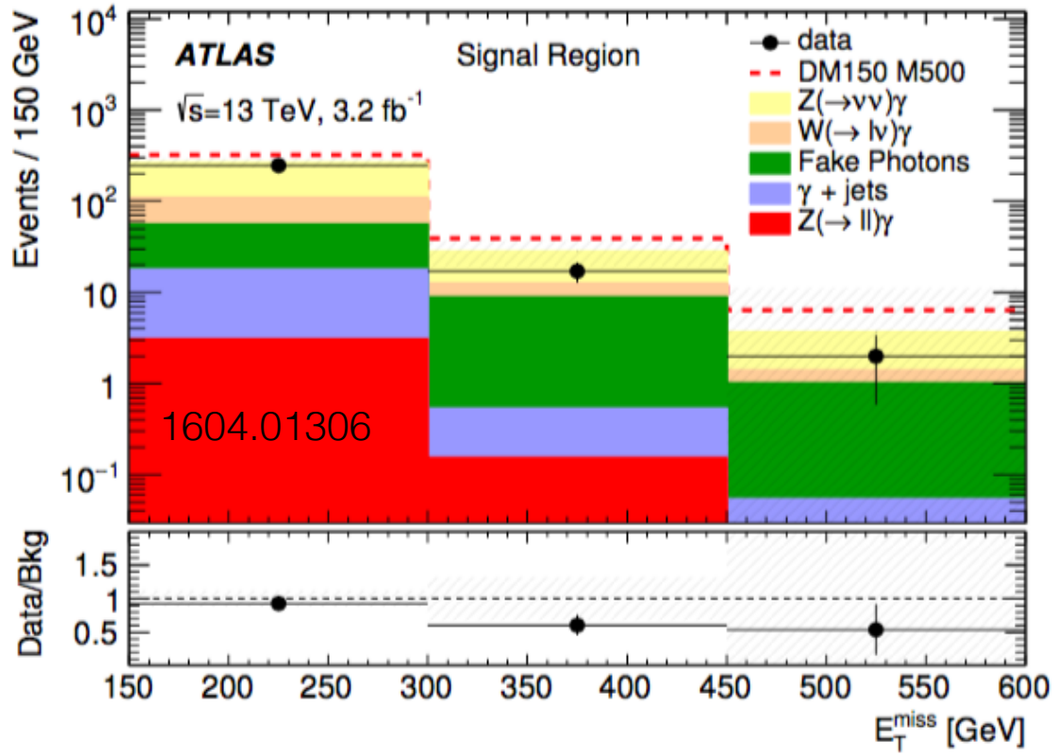
γ + DM

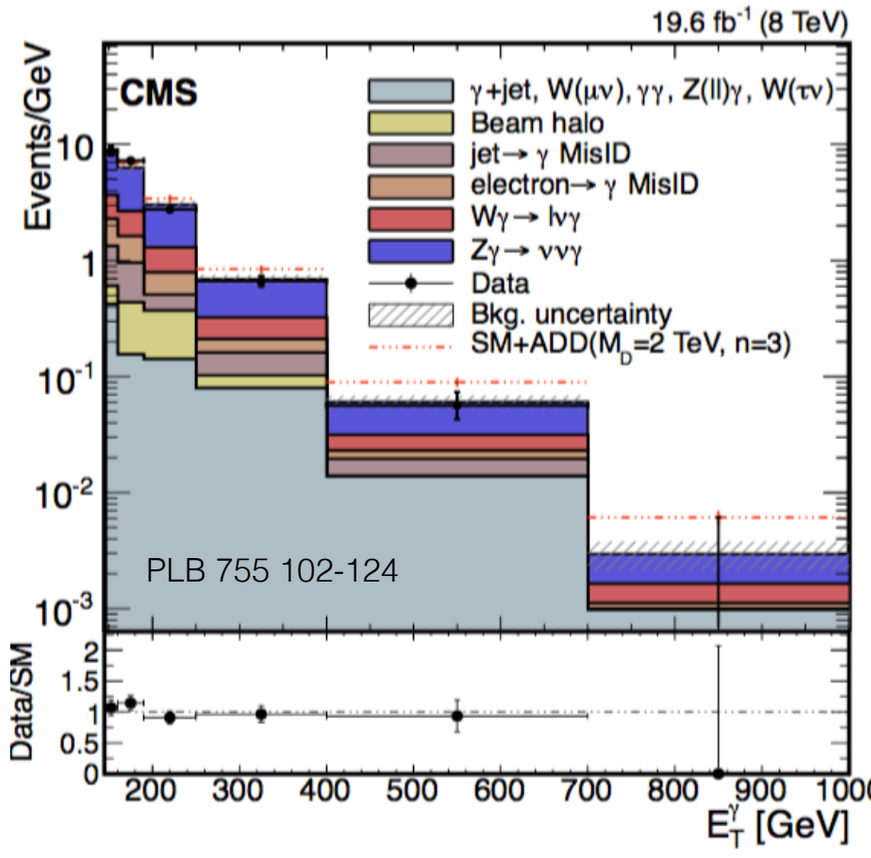
similar strategy as monojet

- Z' simplified model: less sensitive than mono-jet (α vs α_s)
- also sensitive to $\gamma\gamma\chi\chi$ EFT

lower statistics than monojet

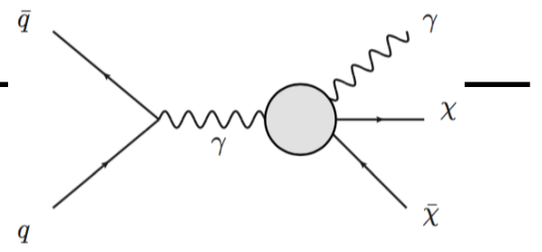
- ATLAS 13 TeV: counting experiment
  - simultaneous fit to SR + CRs
    - W(μν), Z(μμ), Z(ee), W(ev)
  - dominant uncertainty from estimation of e->γ fake factor applied to MET+e events
- CMS 8 TeV: shape analysis

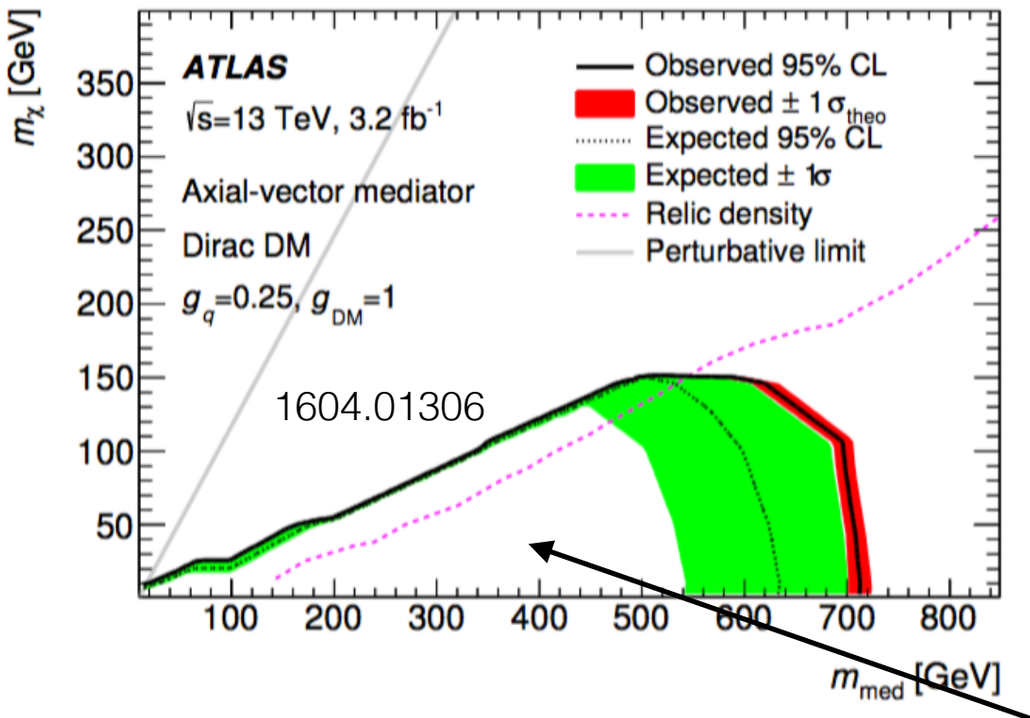


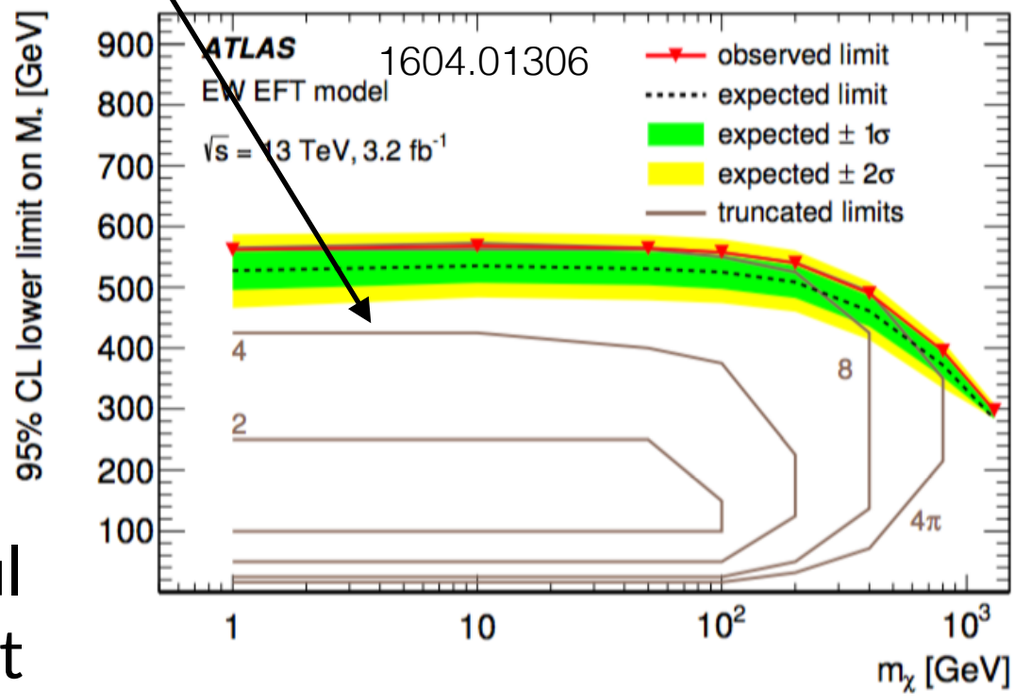


γ + DM: RESULTS

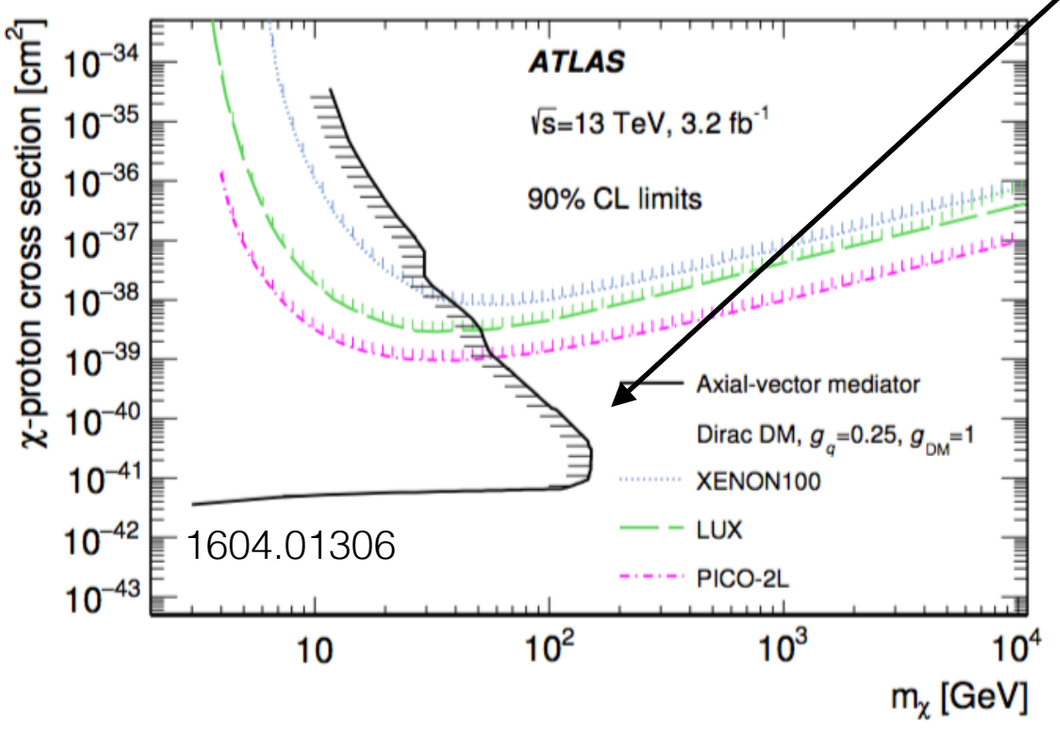
EFT validity (& result) depends on assumed coupling

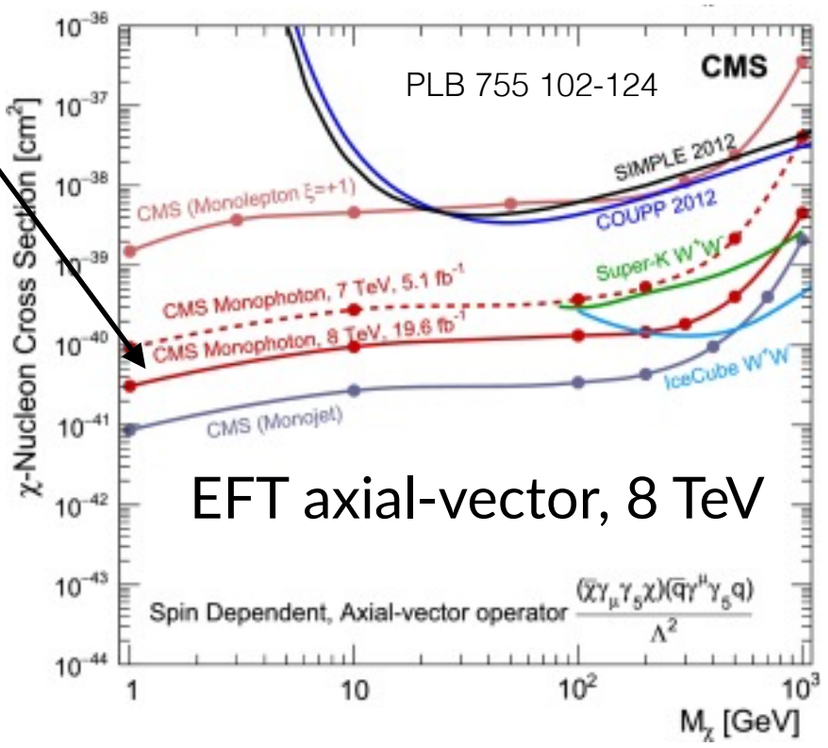






less powerful than monojet



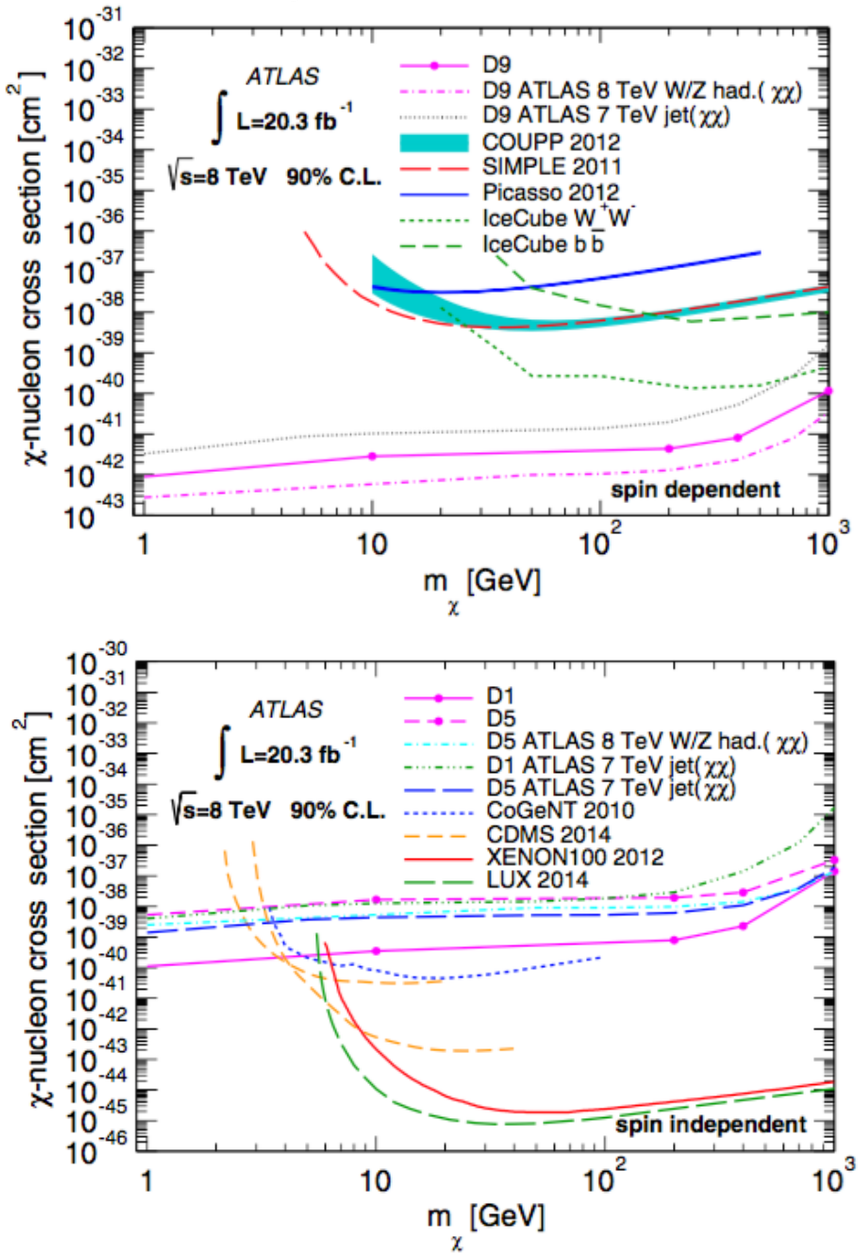


MONO-W,Z -> LEPTONS

same final state as VH(inv), W'(lv) searches

- lower sensitivity than hadronic counterparts

PhysRevD.90.012004



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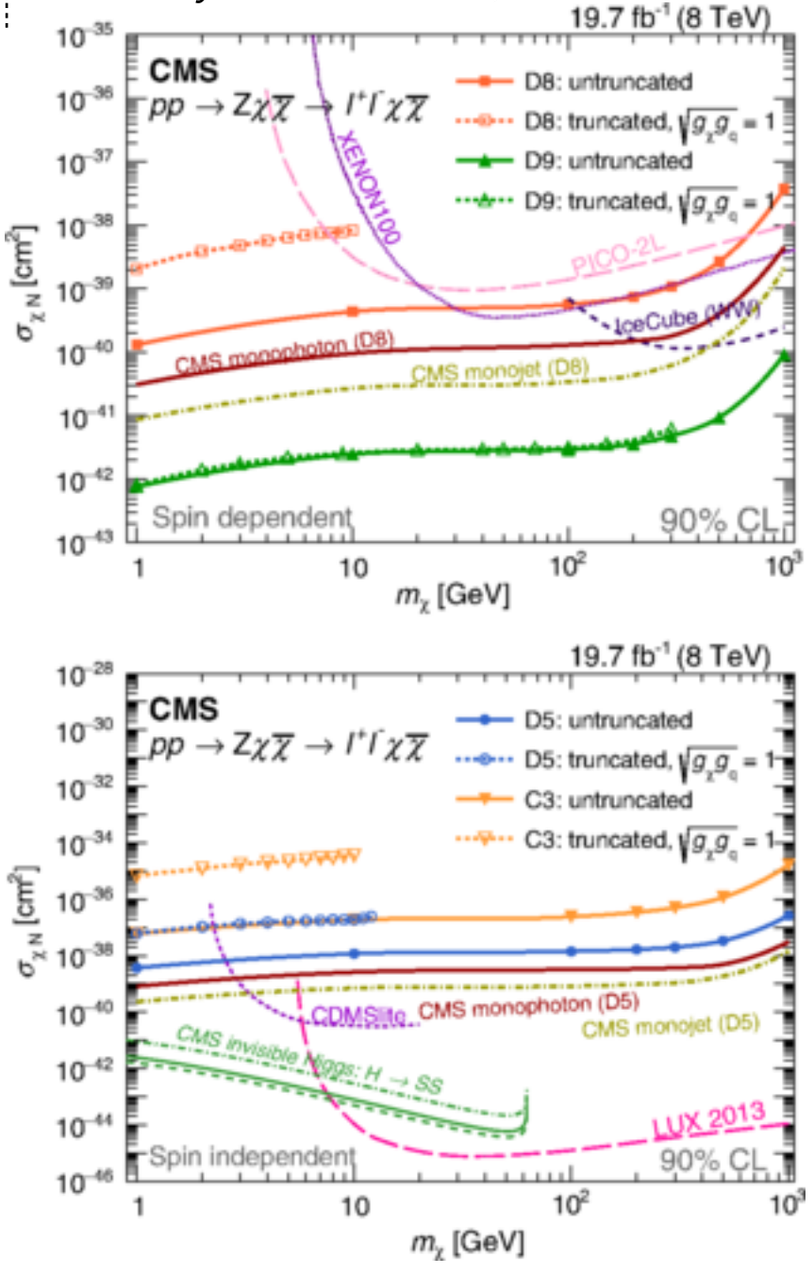
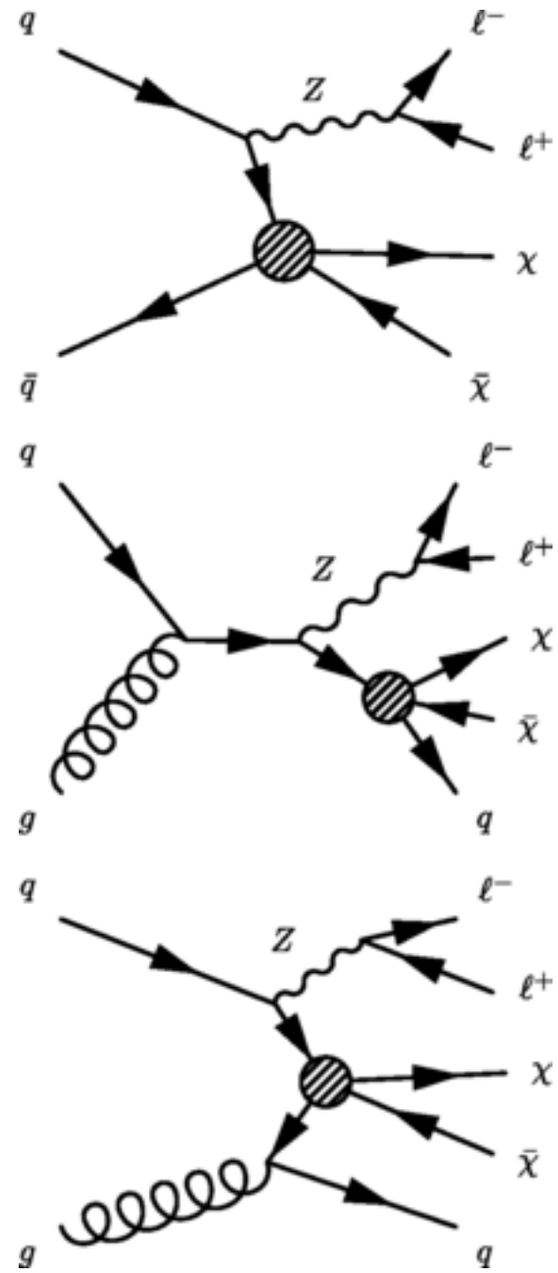
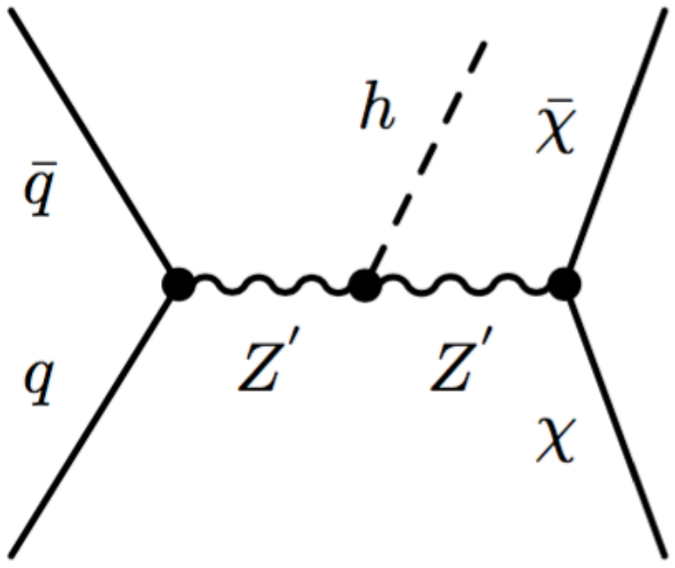
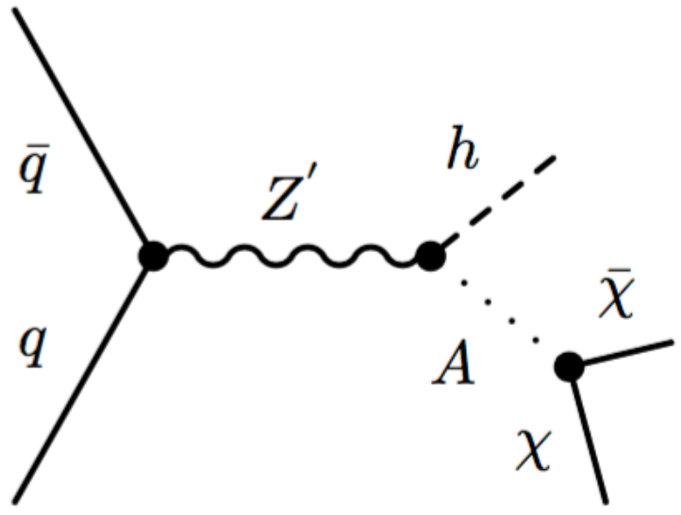
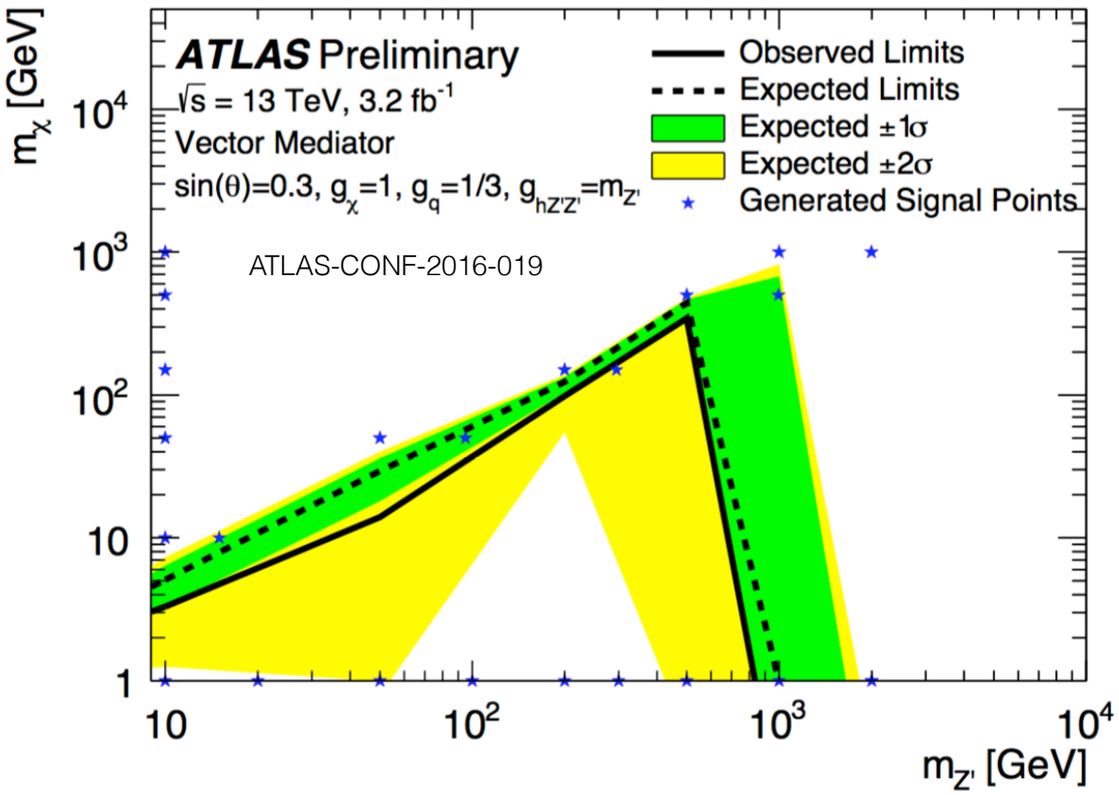




Mono-Higgs







use Higgs as a discovery tool!

- probe couplings between a new mediator and Higgs sector
- most sensitive channel is H(bb)+MET
  - use m(bb) as discriminant in boosted and resolved regimes

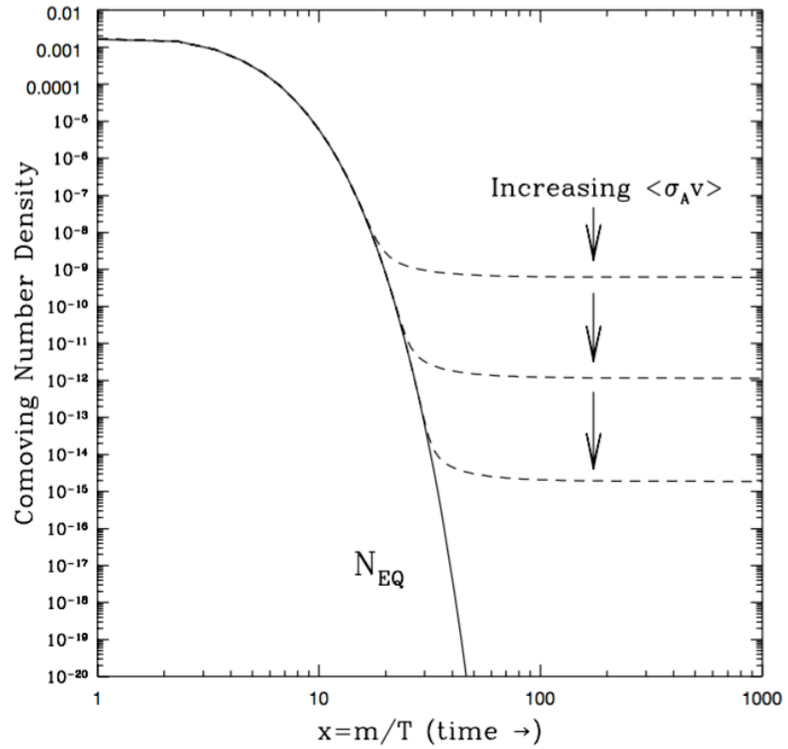
see Francesco&Mario's talk

Looking for Dark Matter

is $F = G\frac{m_{\rm SM} m_{\rm DM}}{r^2}$ the full story?

— *hopefully not*

- can explain current Ωh^2 with weak-scale DM-SM interactions
  - "WIMP miracle"
  - annihilation xsec <σv> determines freeze-out



$$\Omega h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

alternative experimental strategies to look for DM

1. sky: look for its annihilation products
2. underground: see if it scatters
3. LHC: try to produce it

CMS MonoJet @ 13 TeV: Systematics

experimental uncertainties: evaluated as a function of E_T^{miss} (Recoil)
luminosity → 2.7% per muon, 2% per electron
lepton efficiency → 1% per muon, 2% per electron
lepton veto → mainly from tau efficiency → 3%
photon purity → 40% (for QCD in γ+jets)
photon efficiency → 2% per photon
b veto → ~1-2% for light flavors, ~5-6% for b-jets
V-tagging efficiency → 13% on top and di-bosons
anti-correlated among categories
MET → at the level of 5-6% along the full spectrum
(dominated by JEC, JER and unclustered are playing an almost negligible role)

theory uncertainties:
QCD scale: vary renormalization and factorization scales
80% correlation in the Z/γ and Z/W ratios
PDF: NNPDF 3.0 uncertainty
NLO EWK: the size of the correction used as uncertainty

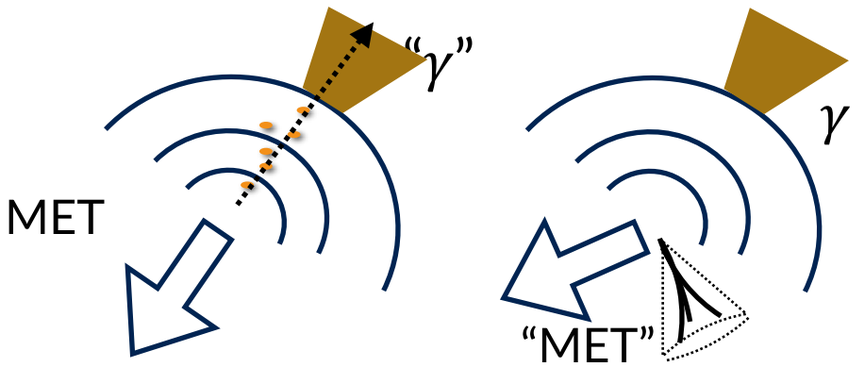
di-bosons, DY and in γ+jets cross-section 20%
top cross-section: 20% →checking data/MC in top CR as well as the effect of top p_T re-weighting

Monophoton @ ATLAS: Background Estimation

simultaneous fit to four inclusive CRs, similar strategy as monojet

- V+γ bkg: 1μ (Wμν), 2μ (Zμμ), 2e (Zee)
- γ+jet: 85 < MET < 110 GeV, ΔΦ(MET, γ)<3.0

fake photon/MET estimation

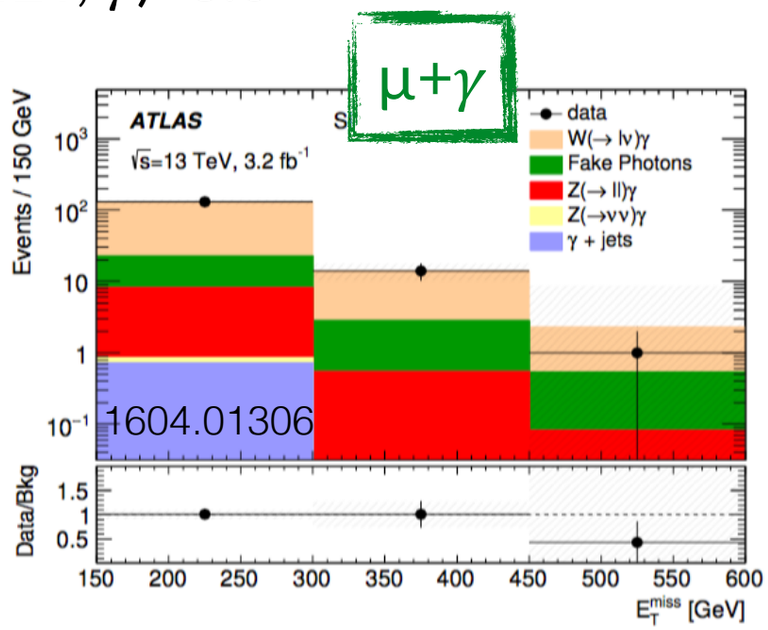


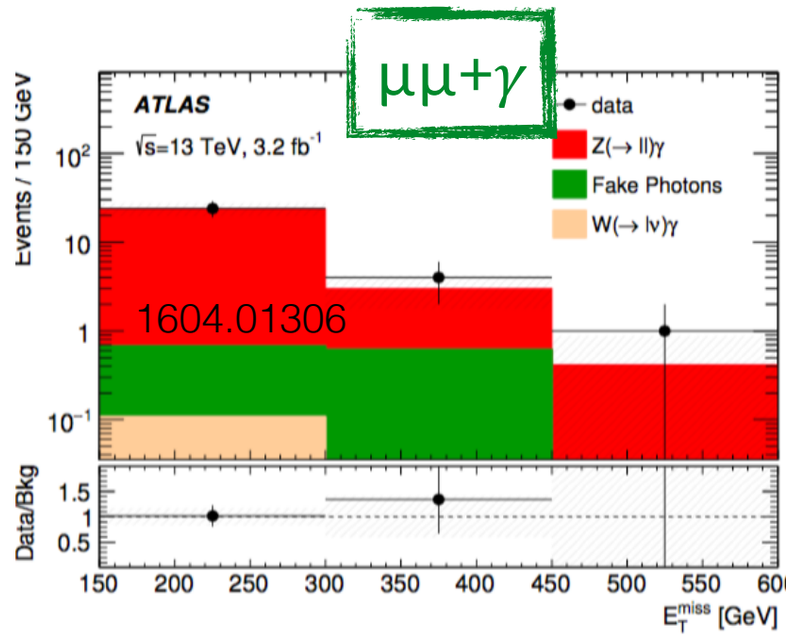
data-driven MET+e

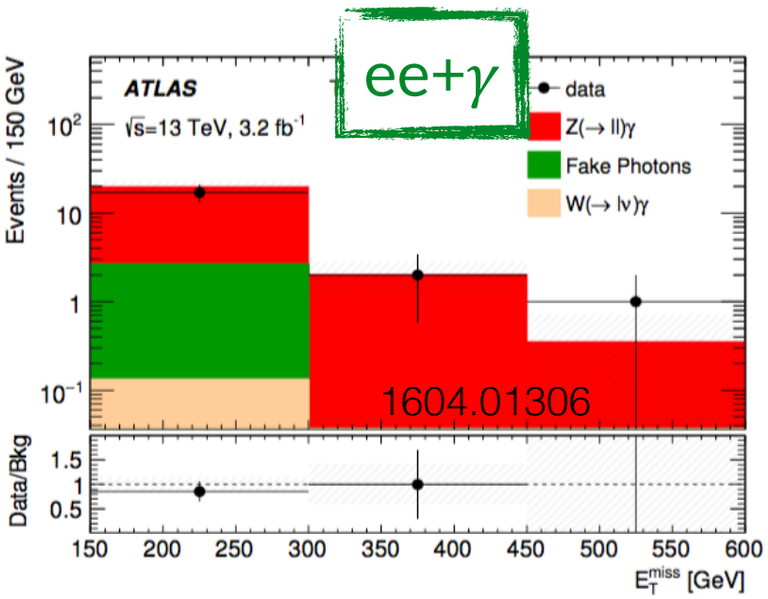
- e->γ fake factor from ee/eγ under Z peak, in pT/eta bins
- applied to event yields in all regions after replacing γ with e
- dominant source of uncertainty from fake factor sample statistics

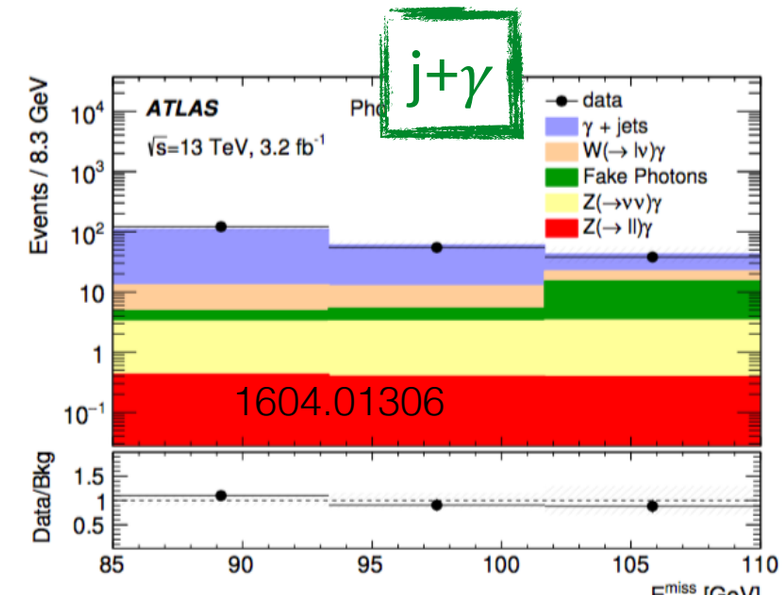
data-driven jet+γ/MET

- jet->γ fake factor from ABCD in photon ID, isolation in each region







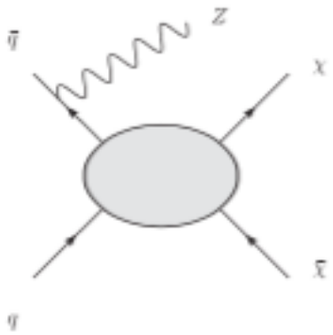


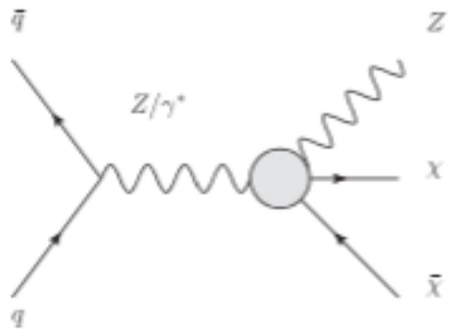
11% bkg uncertainty dominated by statistics (9%), e->γ fake factor (5%)

MonoPhoton – Systematics

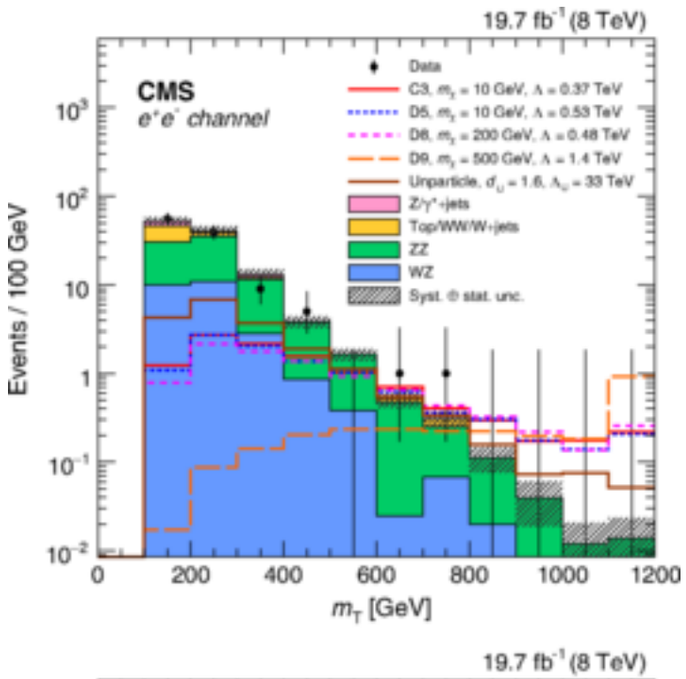
Total background	295
Total background uncertainty	11%
Electron fake rate	5.8%
PDF uncertainties	2.8%
Jet fake rate	2.4%
Muons reconstruction/isolation efficiency	1.5%
Electrons reconstruction/identification/isolation efficiency	1.3%
Jet energy resolution [61]	1.2%
Photon energy scale	0.6%
$\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale and resolution	0.4%
Photon energy resolution	0.2%
Jet energy scale [49]	0.1%

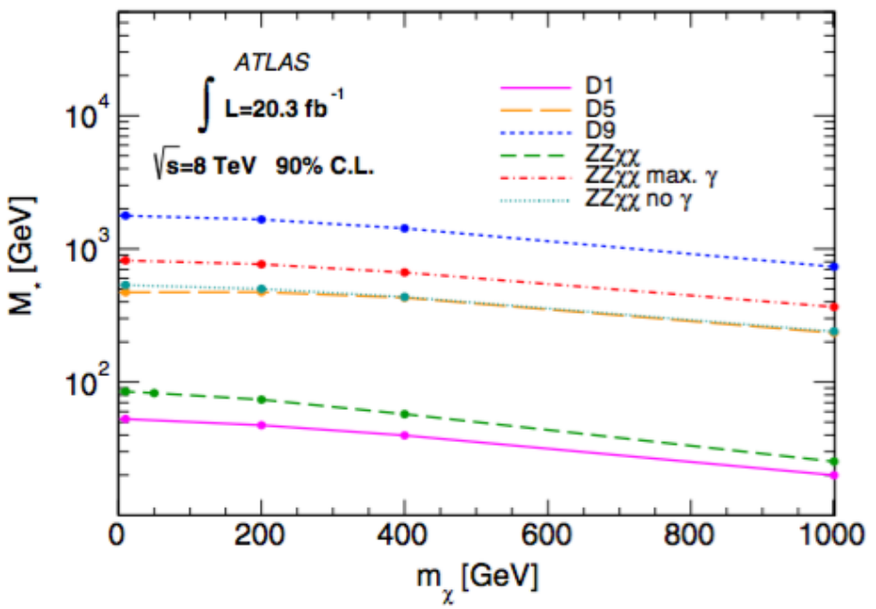
Mono-Z(ll)

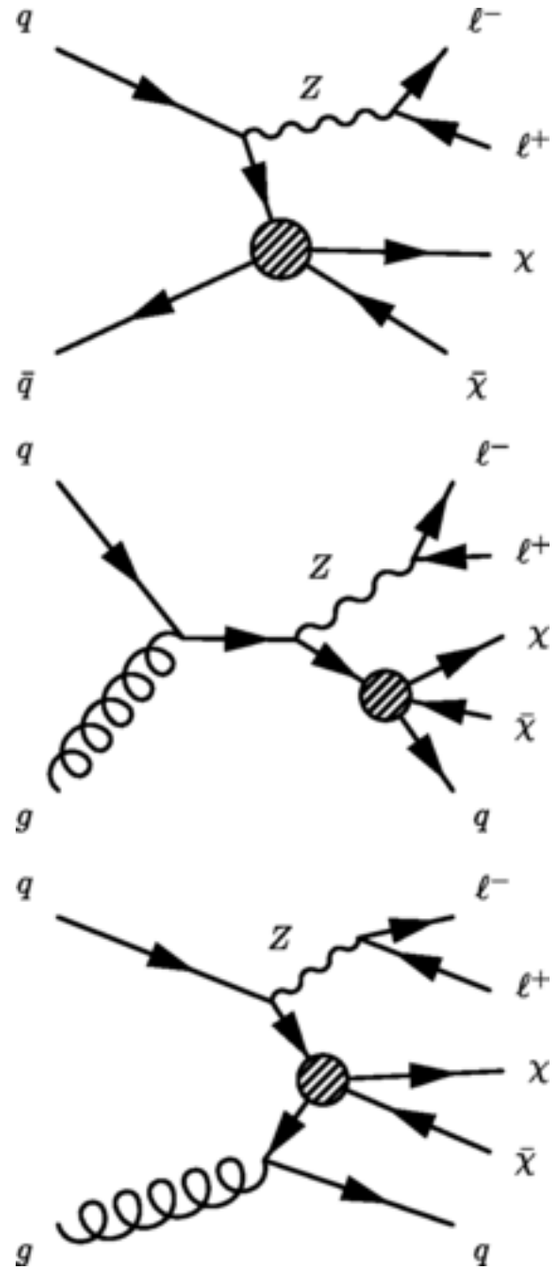


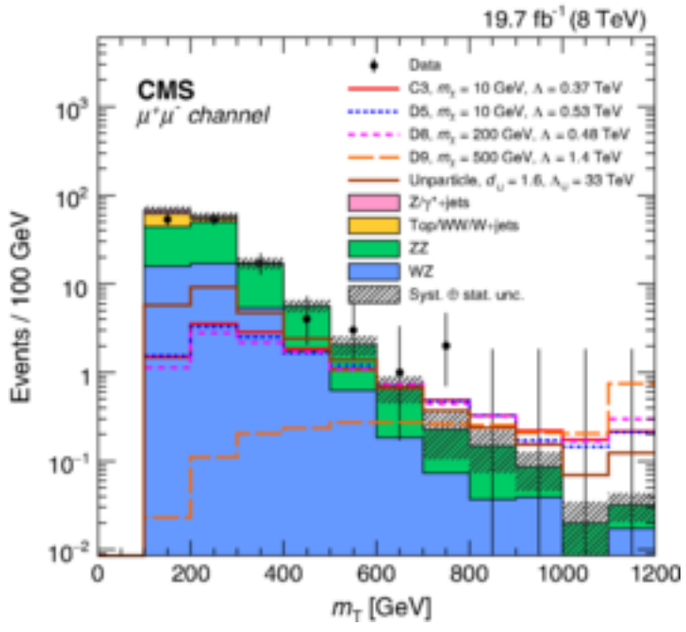


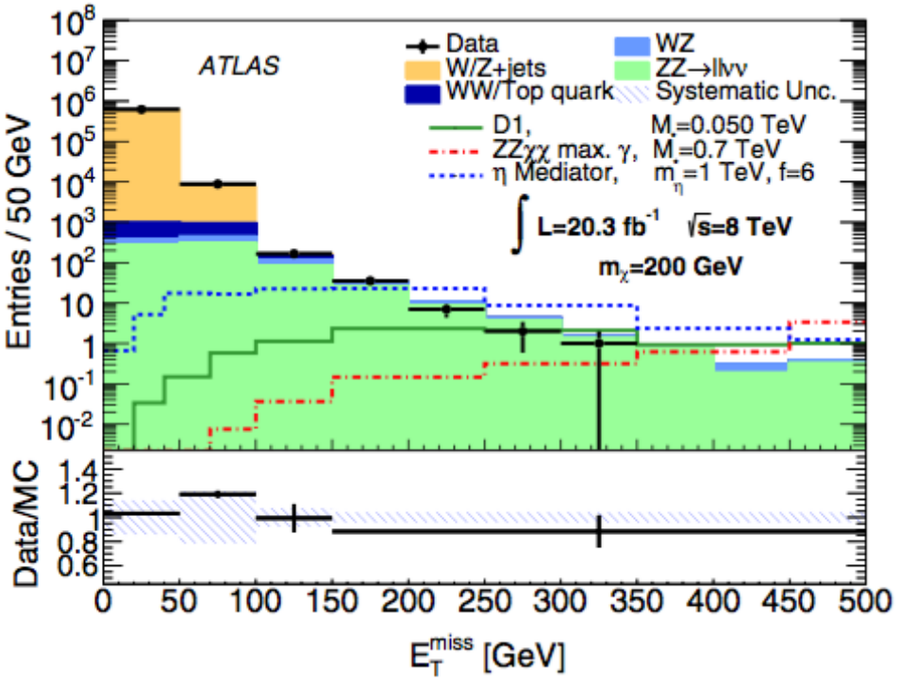
Process	E_T^{miss} threshold [GeV] 150	250	350	450
ZZ	41 ± 15	6.4 ± 2.4	1.3 ± 0.5	0.3 ± 0.1
WZ	8.0 ± 3.1	0.8 ± 0.4	0.2 ± 0.1	0.1 ± 0.1
WW, $t\bar{t}$, $Z \to \tau^+\tau^-$	1.9 ± 1.4	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$
$Z +$ jets	0.1 ± 0.1	...	...	...
$W +$ jets	0.5 ± 0.3	...	...	...
Total	52 ± 18	7.2 ± 2.8	1.4 ± 0.9	$0.4^{+0.7}_{-0.4}$
Data	45	3	0	0



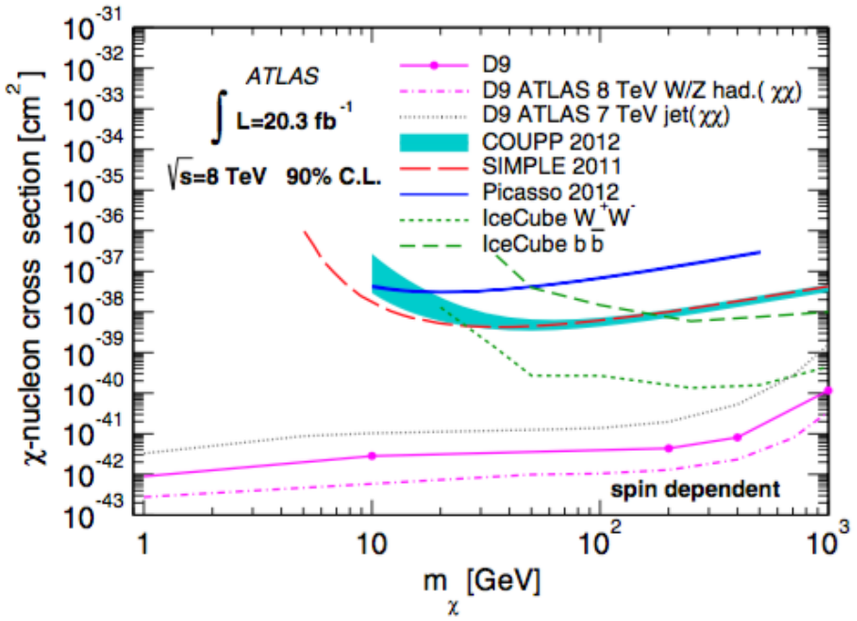


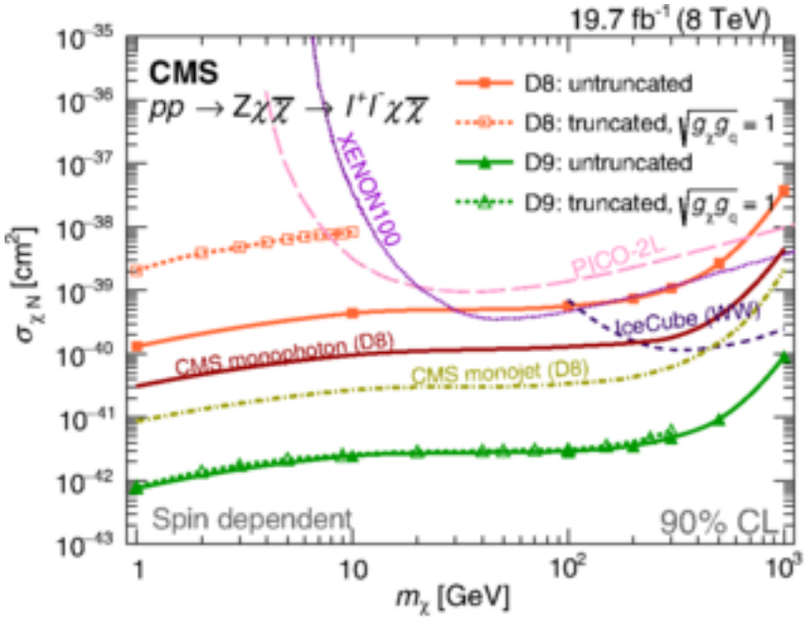


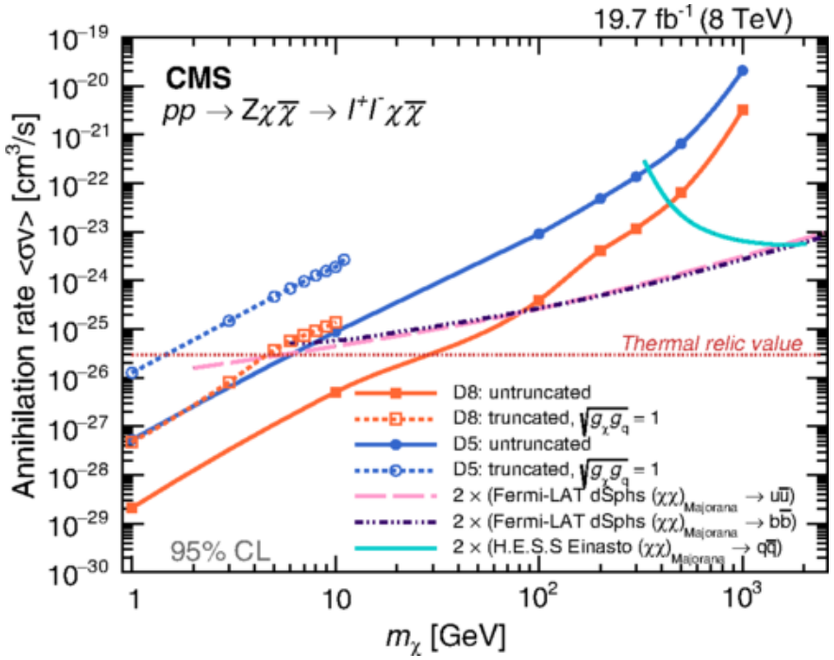


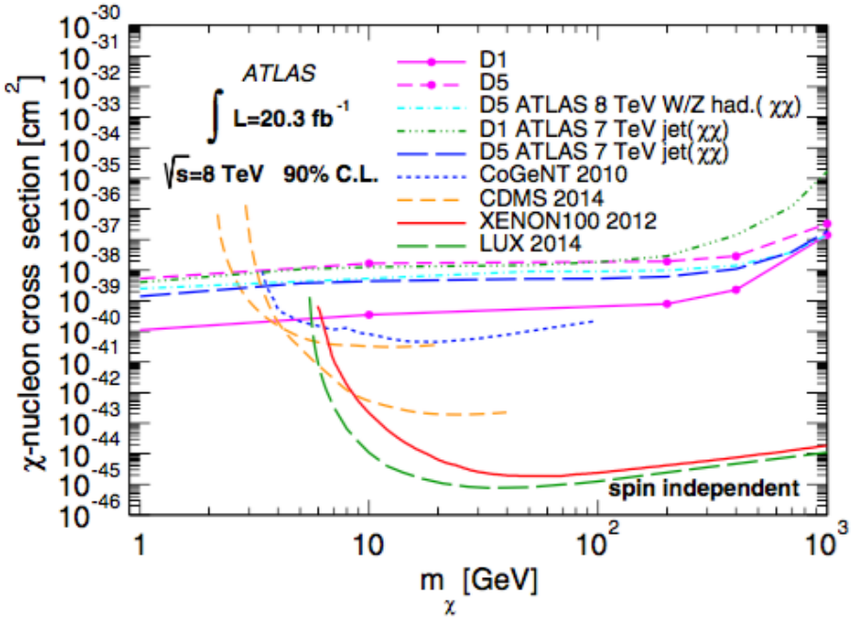


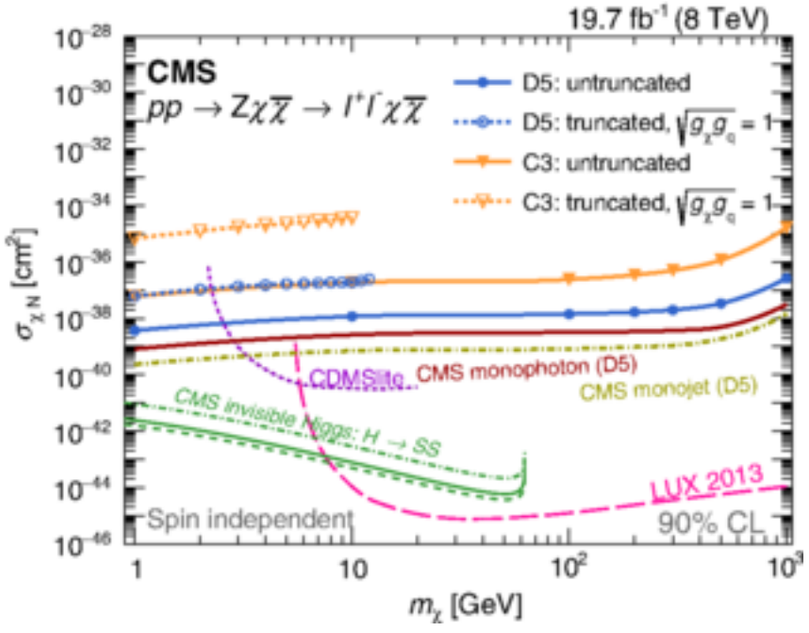
Mono-Z(ll) – Results

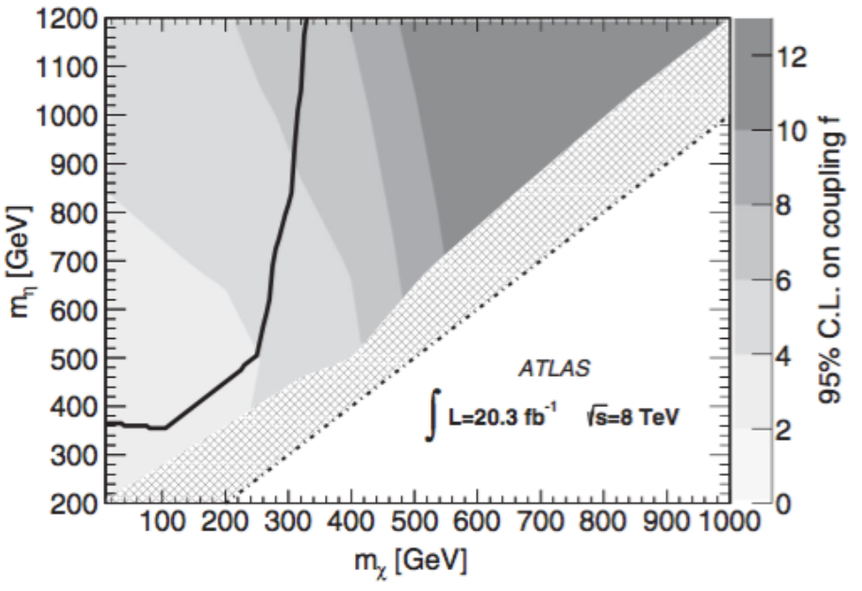




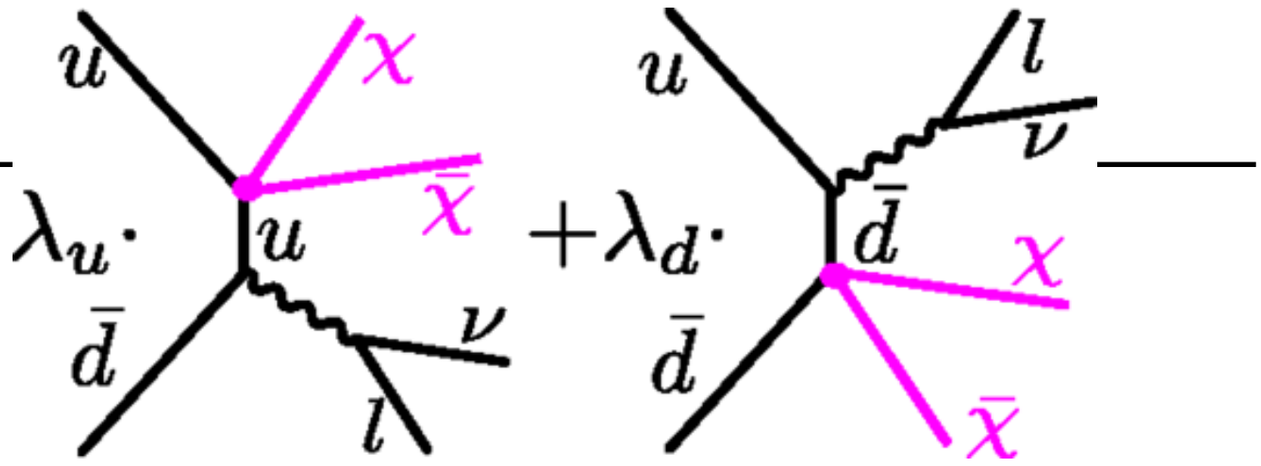








Mono-W(lv)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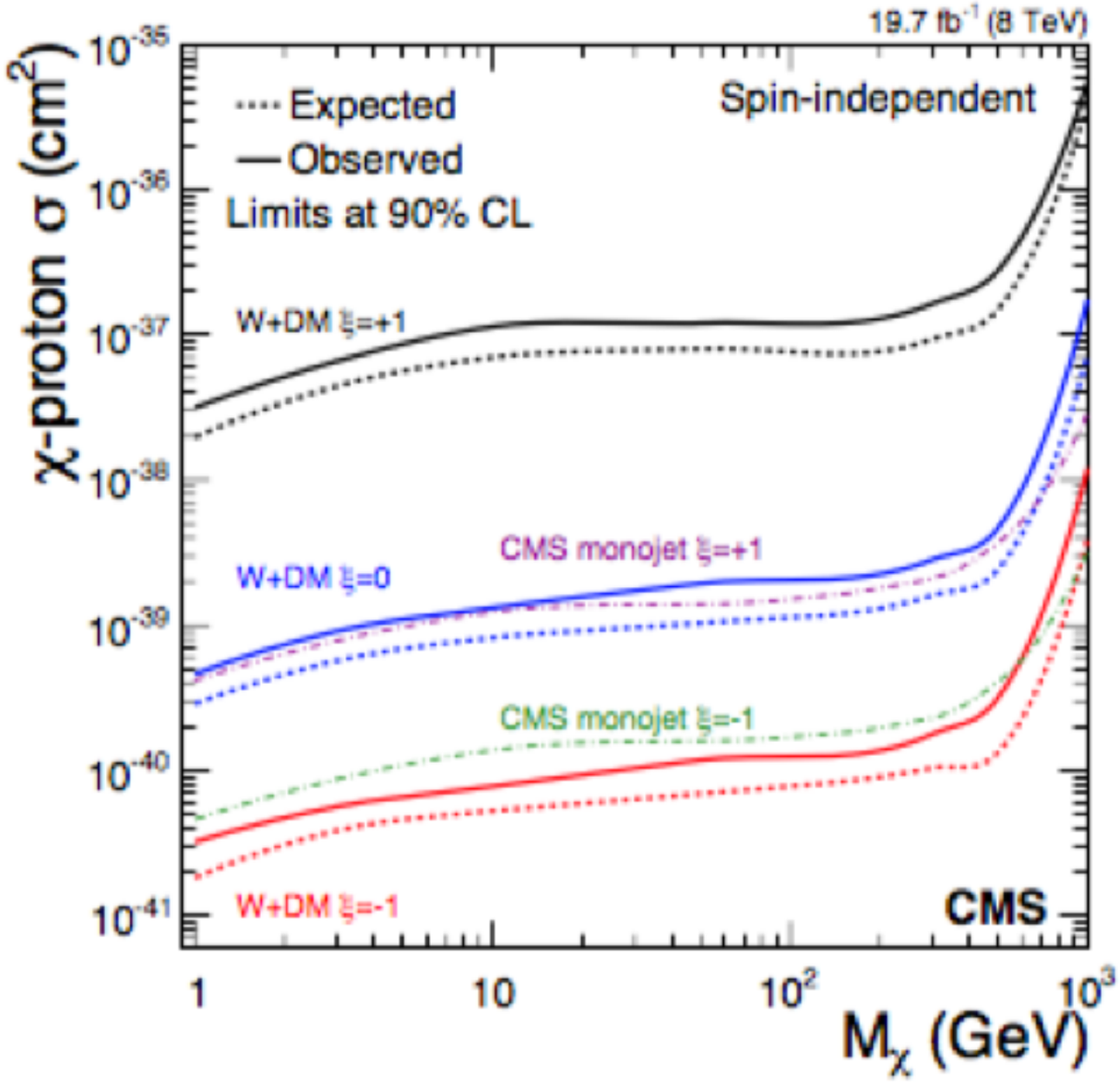
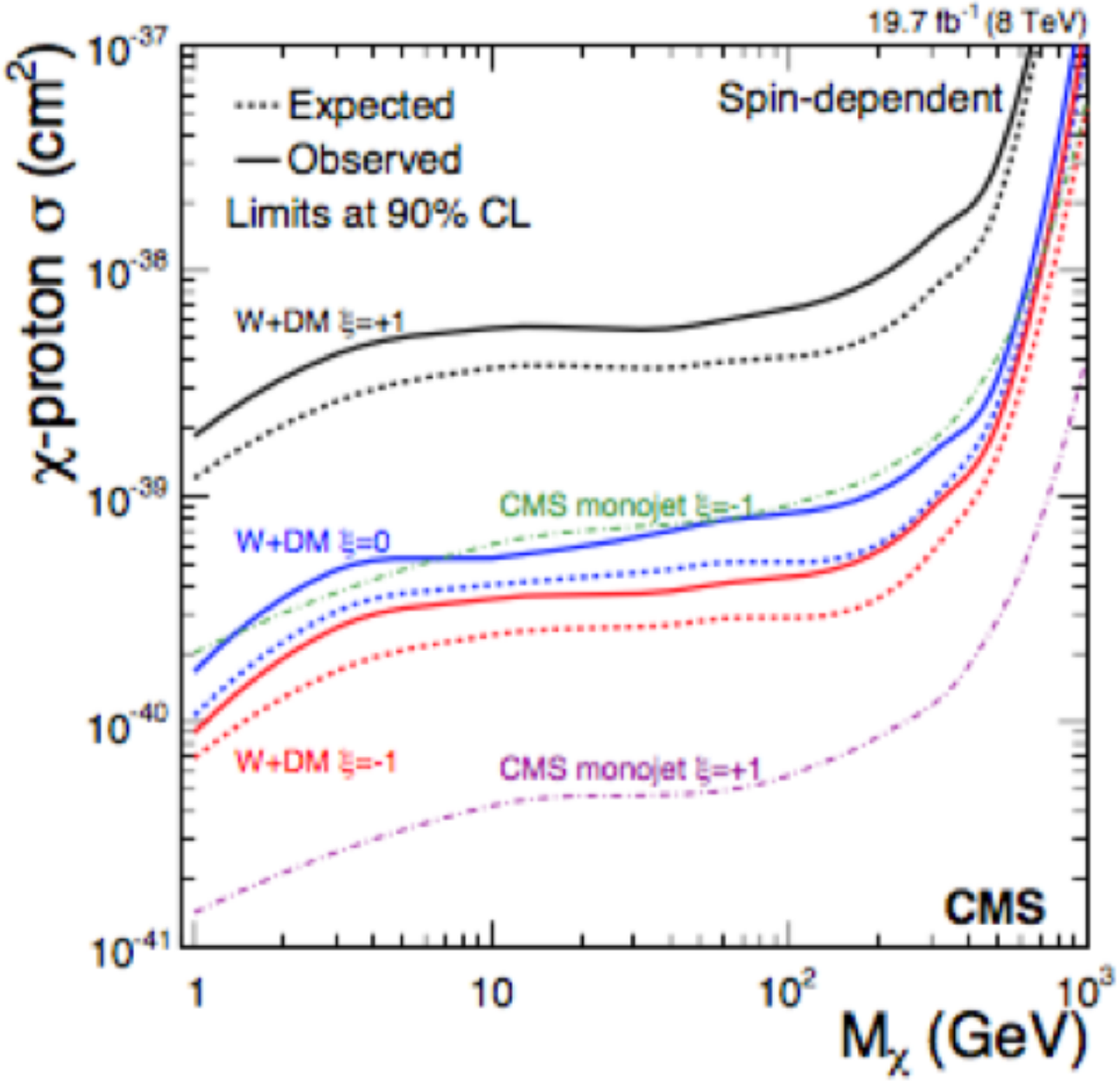
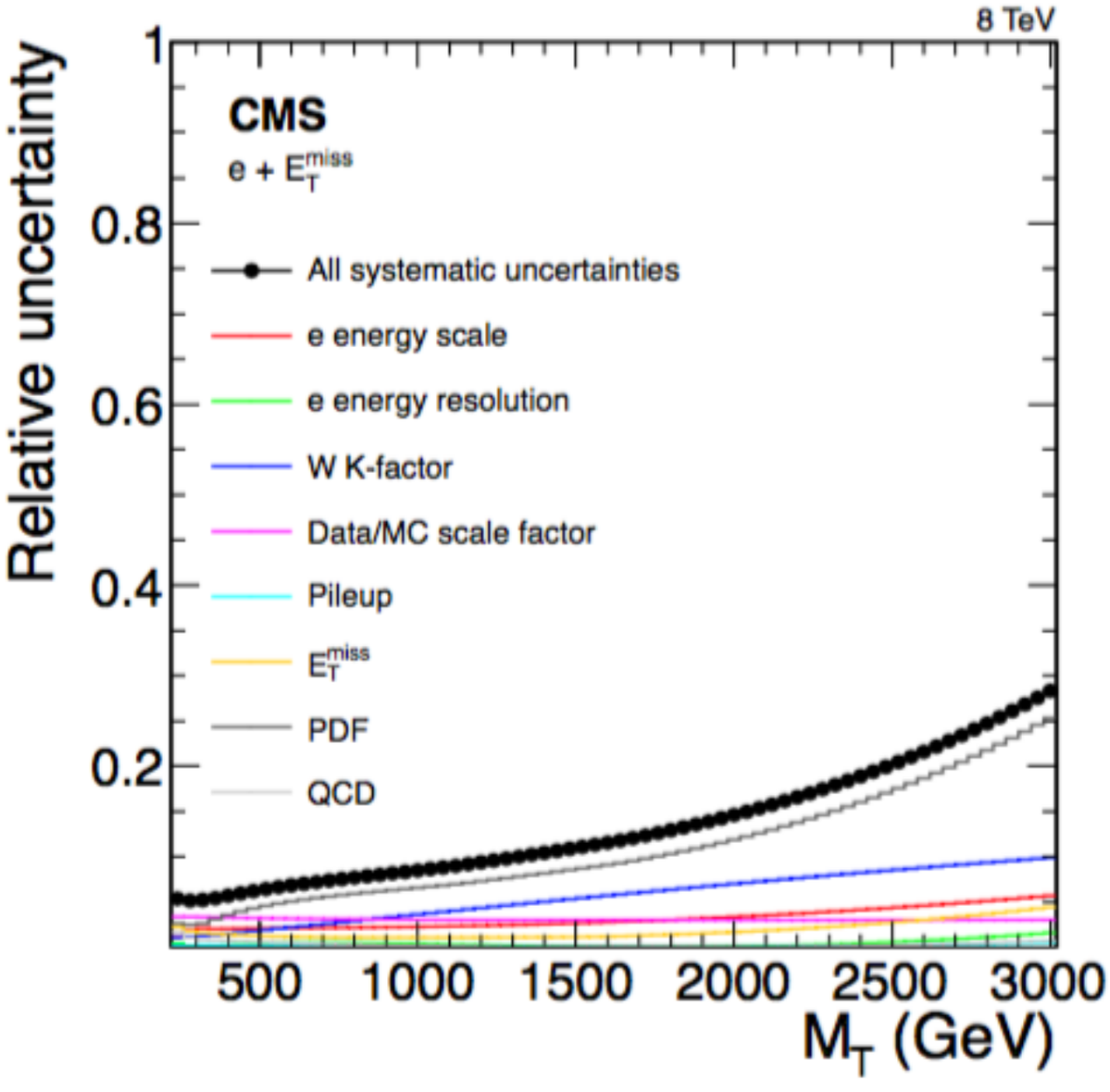
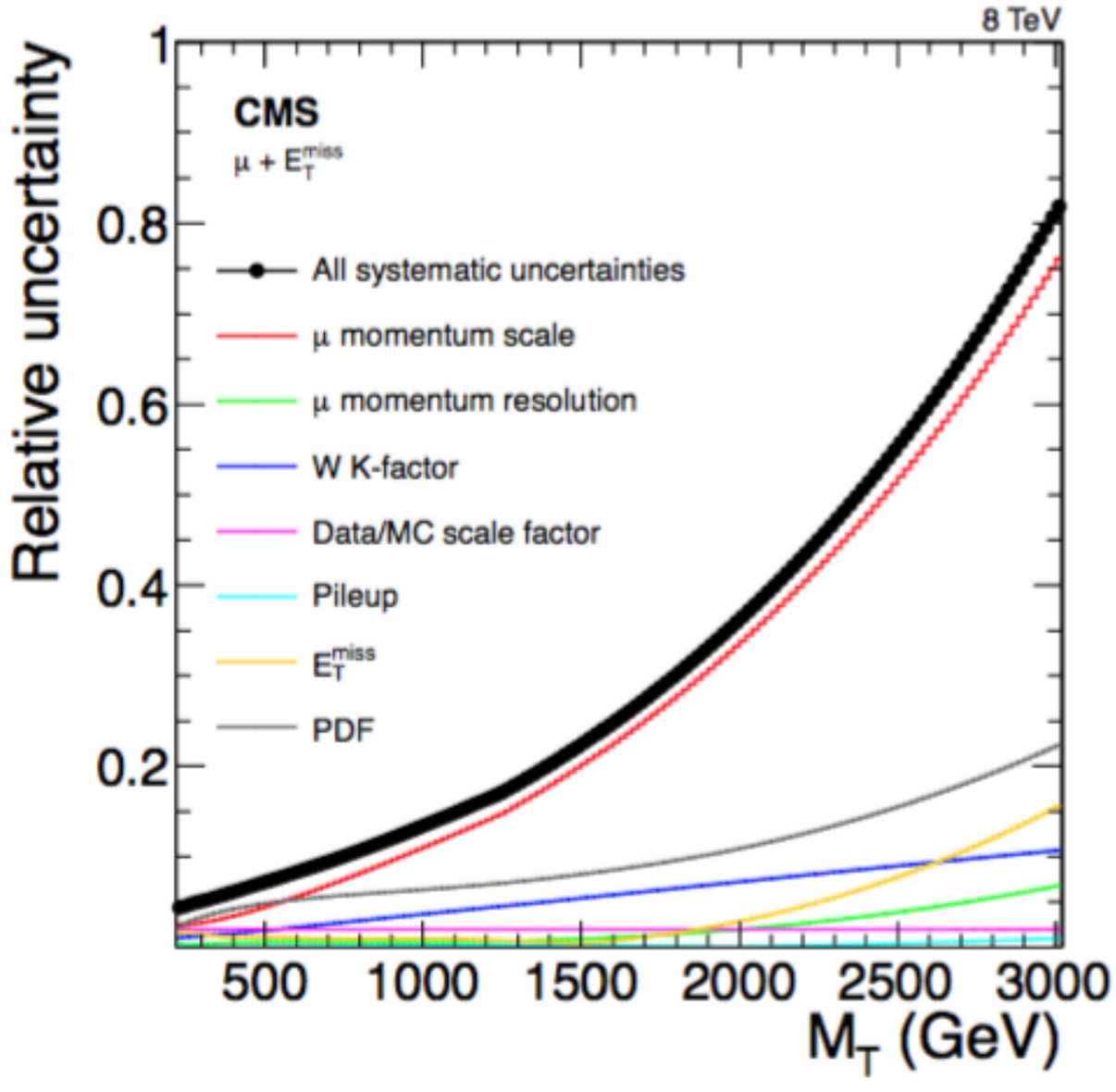

19.7 fb^{-1} (8 TeV)
Spin-independent
Expected
Observed
Limits at 90% CL
W+DM ξ=+1
W+DM ξ=0
CMS monojet ξ=+1
CMS monojet ξ=-1
W+DM ξ=-1
CMS
χ-proton σ (cm^2)
M$_\chi$ (GeV)

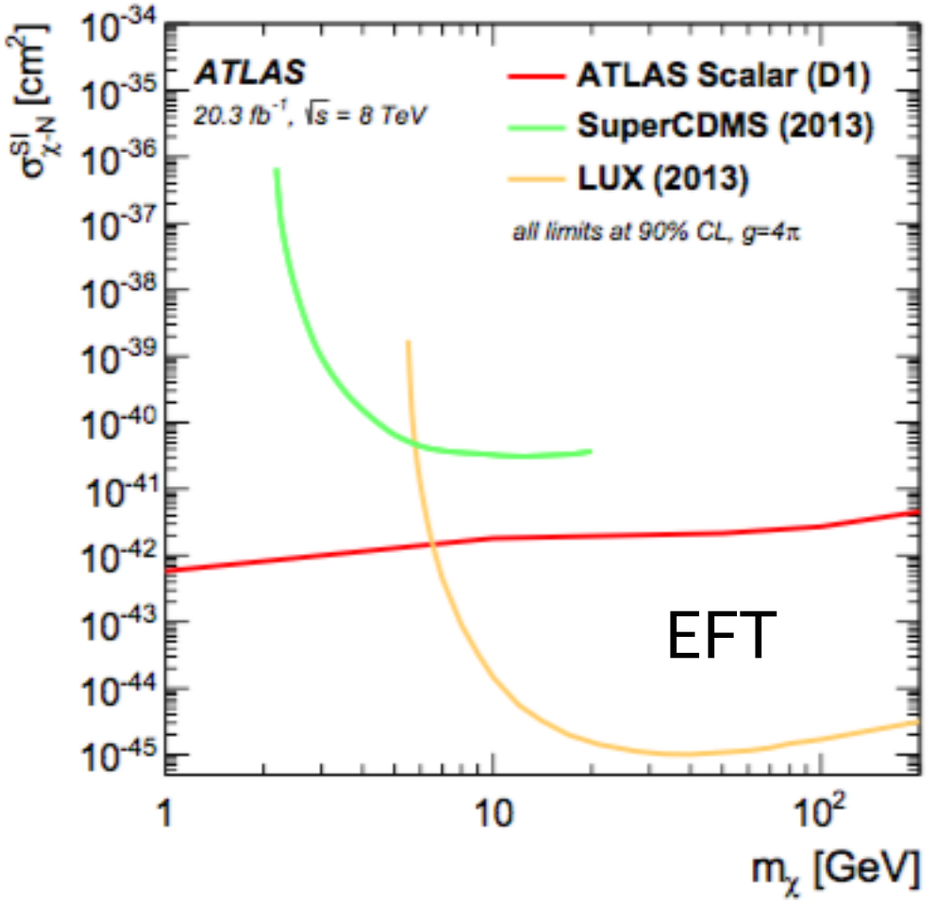

19.7 fb^{-1} (8 TeV)
Spin-dependent
Expected
Observed
Limits at 90% CL
W+DM ξ=+1
CMS monojet ξ=-1
W+DM ξ=0
W+DM ξ=-1
CMS monojet ξ=+1
CMS
χ-proton σ (cm^2)
M$_\chi$ (GeV)

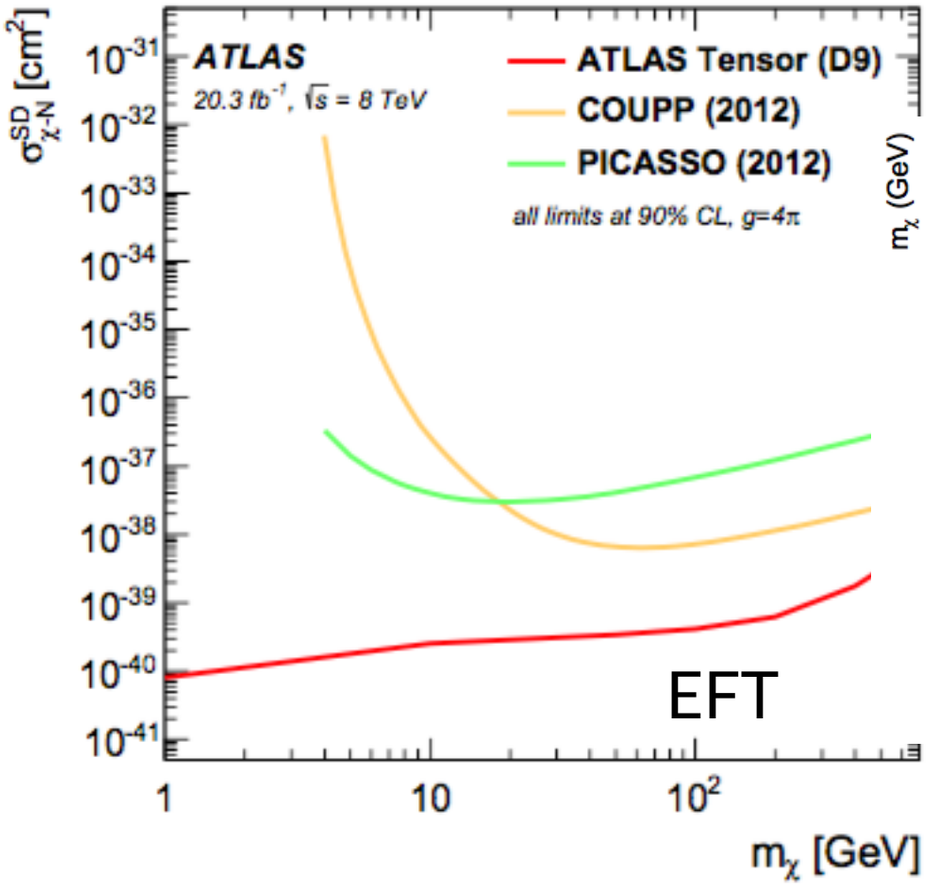
Mono-W(lv)

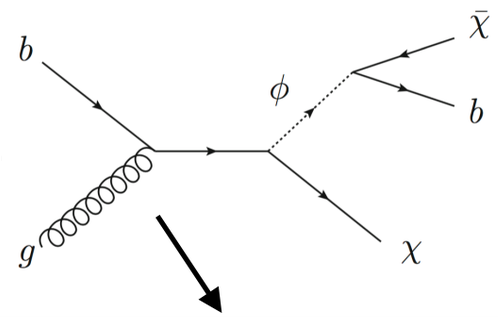

CMS
$e + E_T^{miss}$
8 TeV
All systematic uncertainties
e energy scale
e energy resolution
W K-factor
Data/MC scale factor
Pileup
E_T^{miss}
PDF
QCD
Relative uncertainty
M_T (GeV)

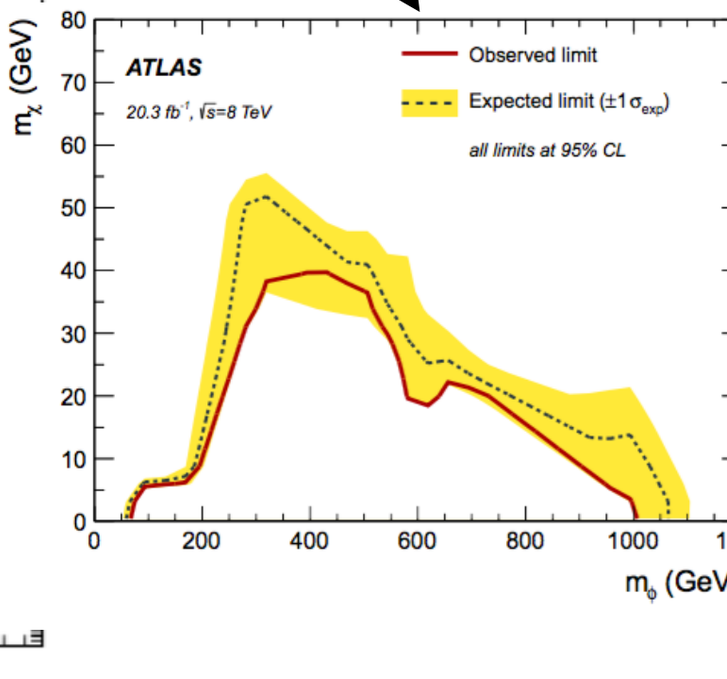

CMS
$\mu + E_T^{miss}$
8 TeV
All systematic uncertainties
μ momentum scale
μ momentum resolution
W K-factor
Data/MC scale factor
Pileup
E_T^{miss}
PDF
Relative uncertainty
M_T (GeV)

ATLAS Mono-HF @ 8 TeV (results)









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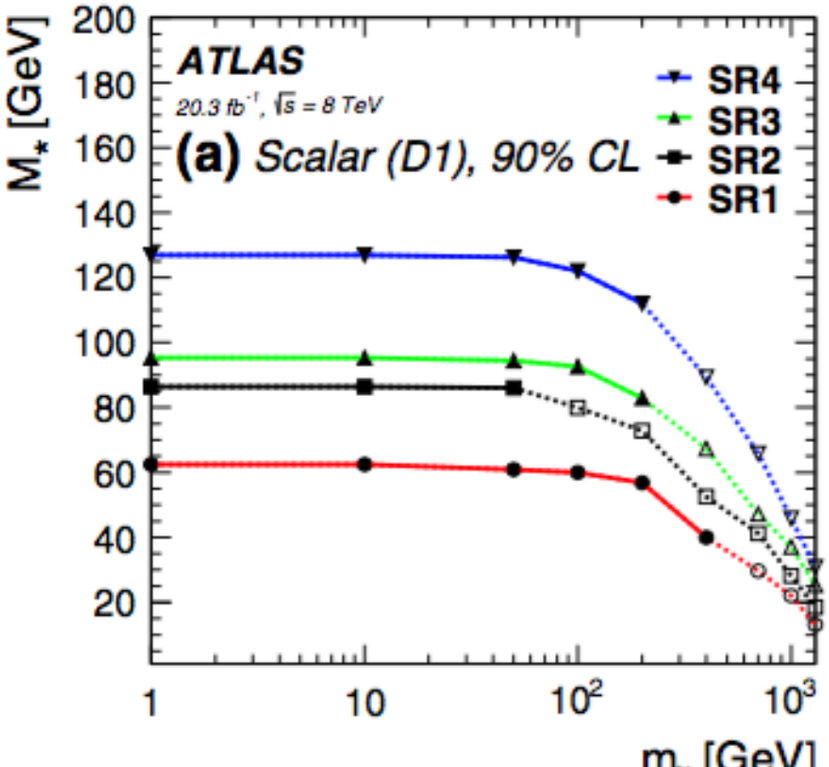
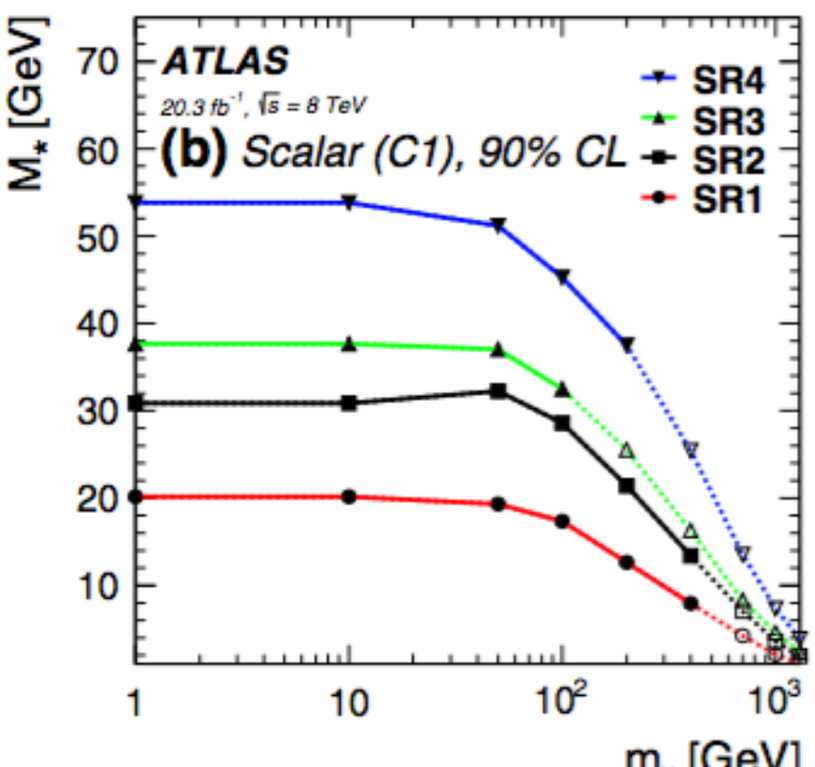
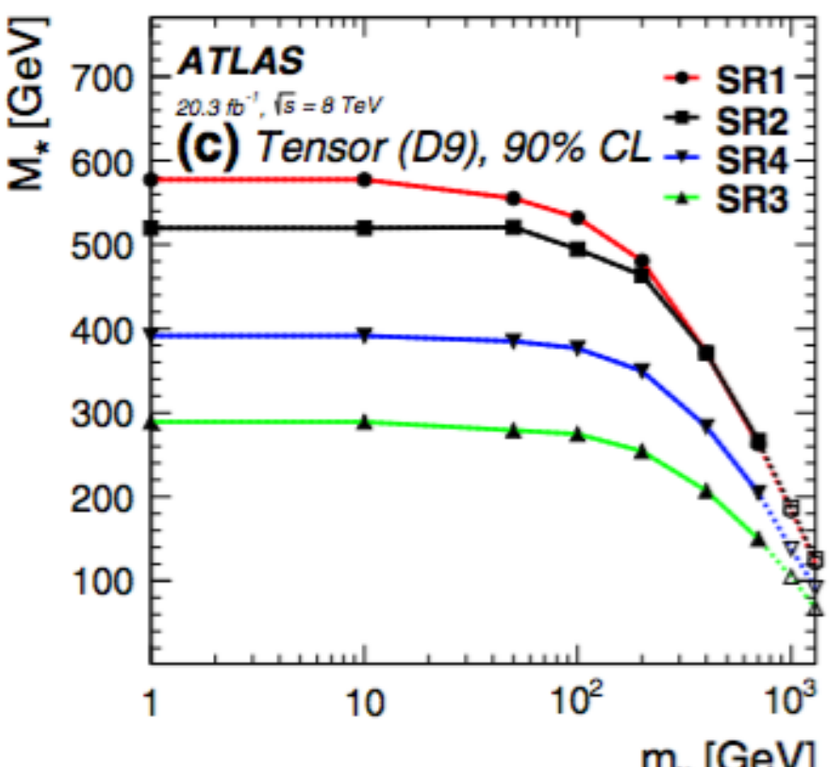
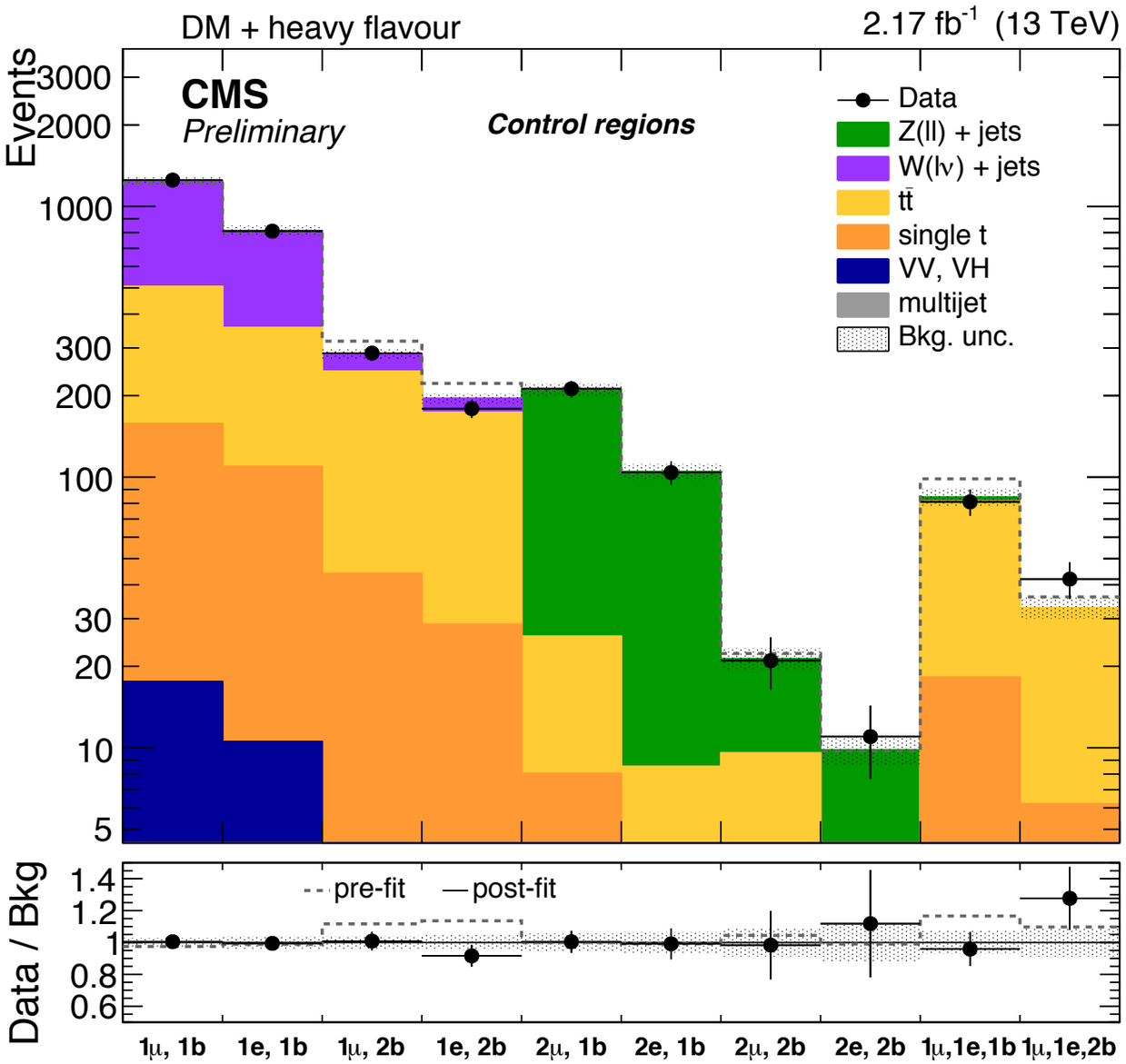




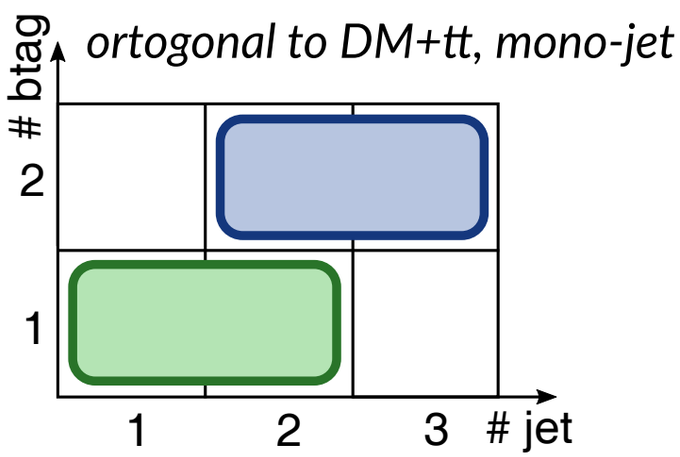


CMS: B(B) + MET @ 13 TeV – BKG & SYST

B2G-15-007



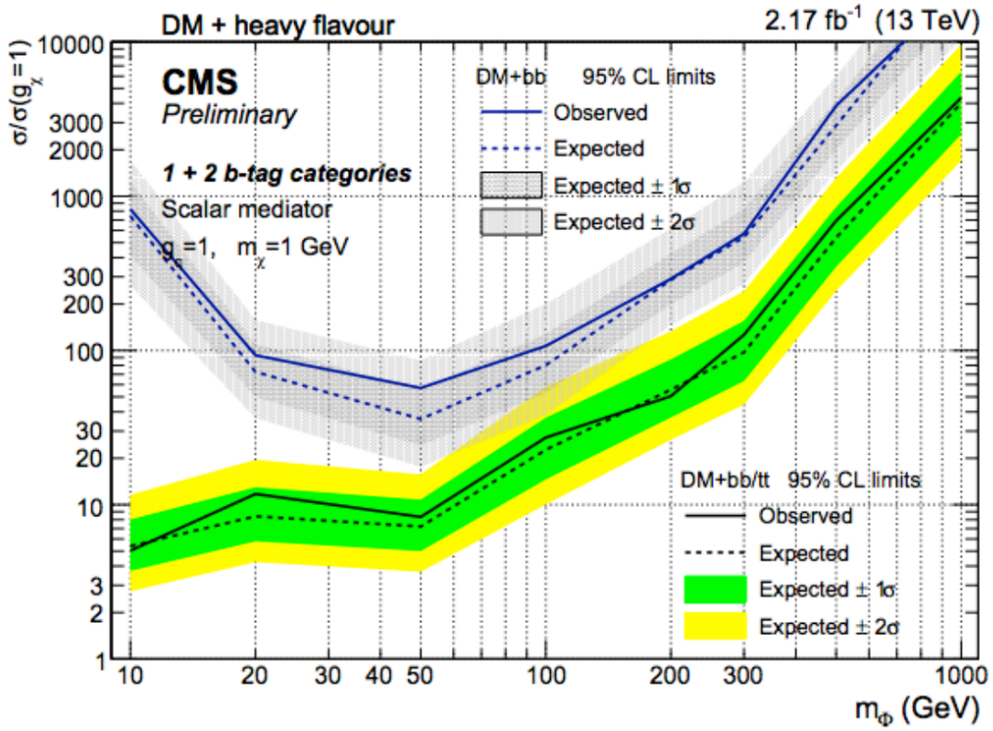
	process	2ℓ	1ℓ	$1\mu, 1e$	SR1	SR2
MET resolution	all	1%	1%	< 1%	1%	1%
MET scale	all	< 1%	< 1%	< 1%	< 1%	< 1%
JES	VV, ST, multijet	1%	1%	2%	< 1%	1%
b-tagging	all	7%	9%	7%	8%	11%
lepton trigger, id, iso	all	4%	3%	3%	3%	3%
trigger	all		< 1%		< 1%	
pile-up	all	2%	1%	1%	1%	< 1%
Fact. scale	all	4%	3%	4%	4%	4%
Ren. scale	all	7%	6%	12%	5%	6%
EWK corr.	V+jets	4%	2%	< 1%	5%	3%
PDF	all	1%	1%	1%	1%	1%
luminosity	VV, ST, multijet			2.7%		
Other bkg cross section	VV, ST			15%		
Multijet cross section	multijet			50%		

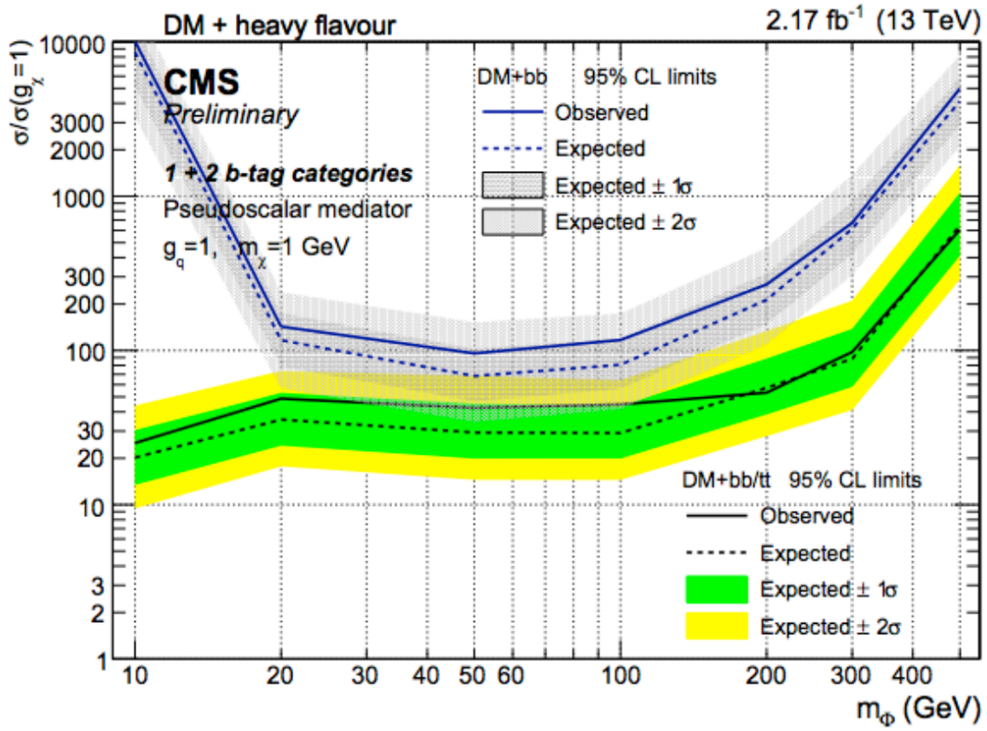


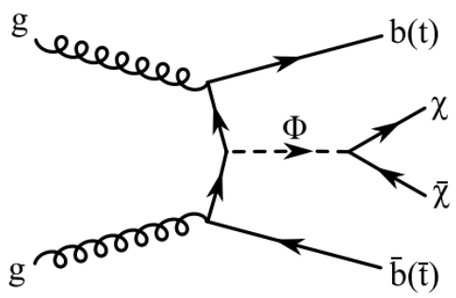
W Z ttbar

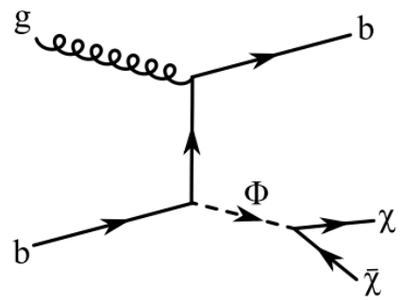
CMS Mono-b(b) @ 8 TeV

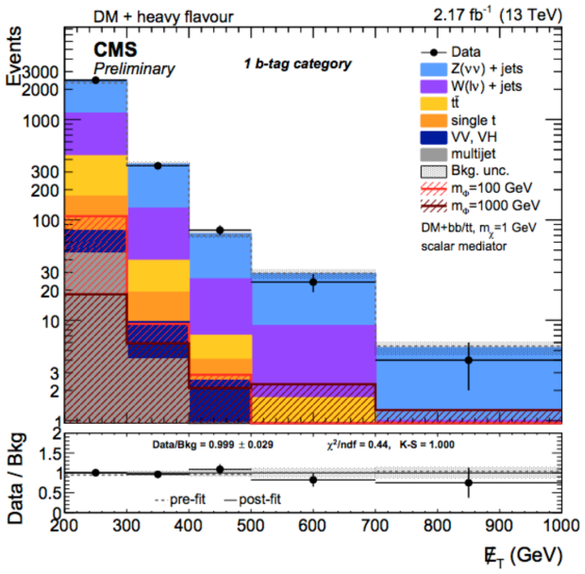
B2G-15-007

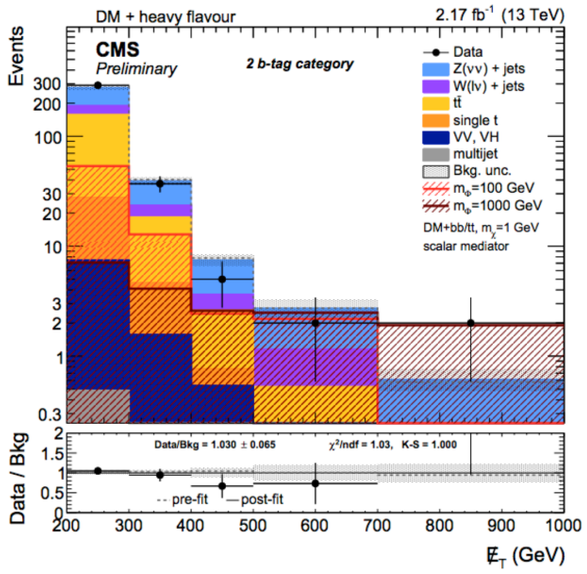






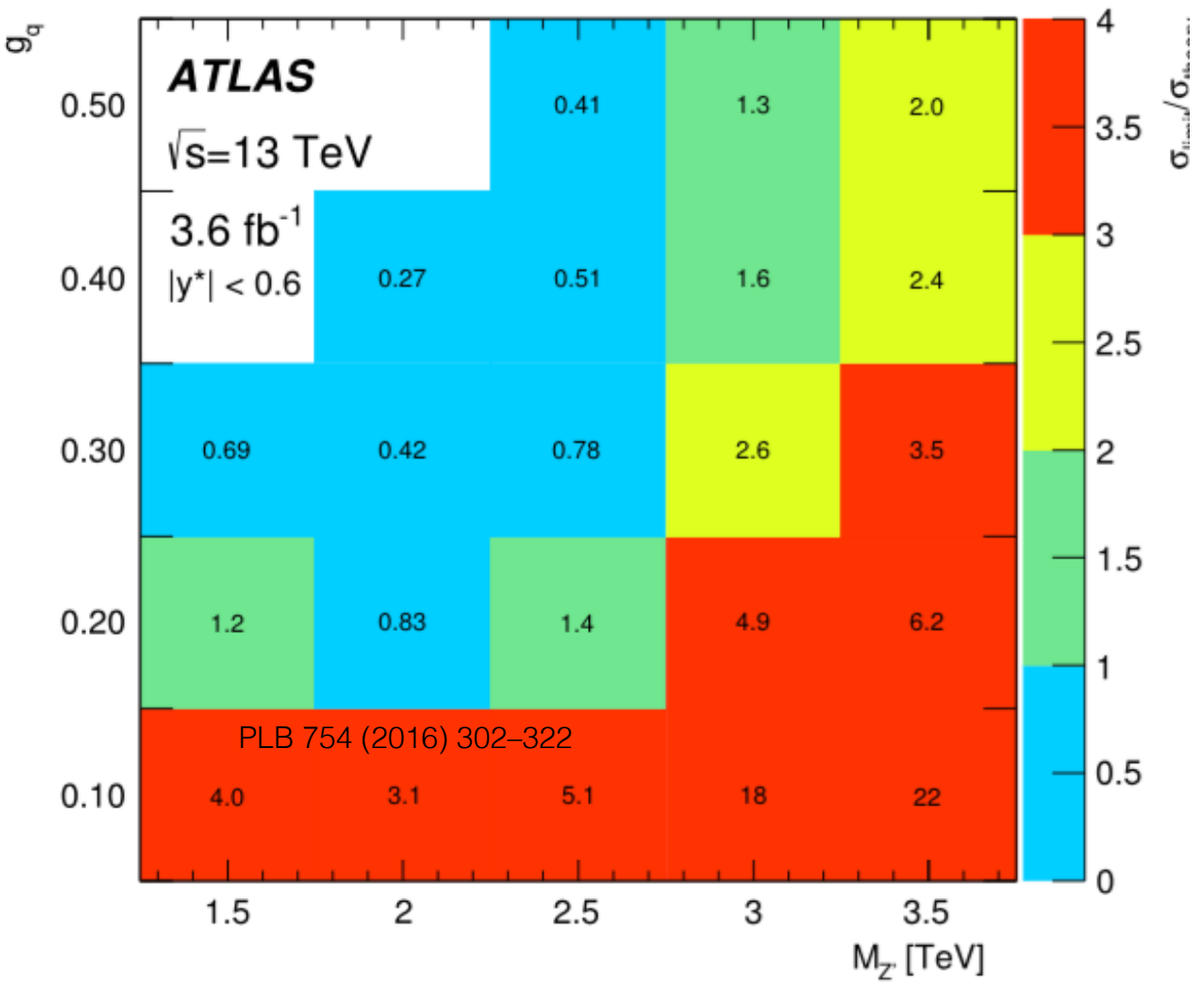


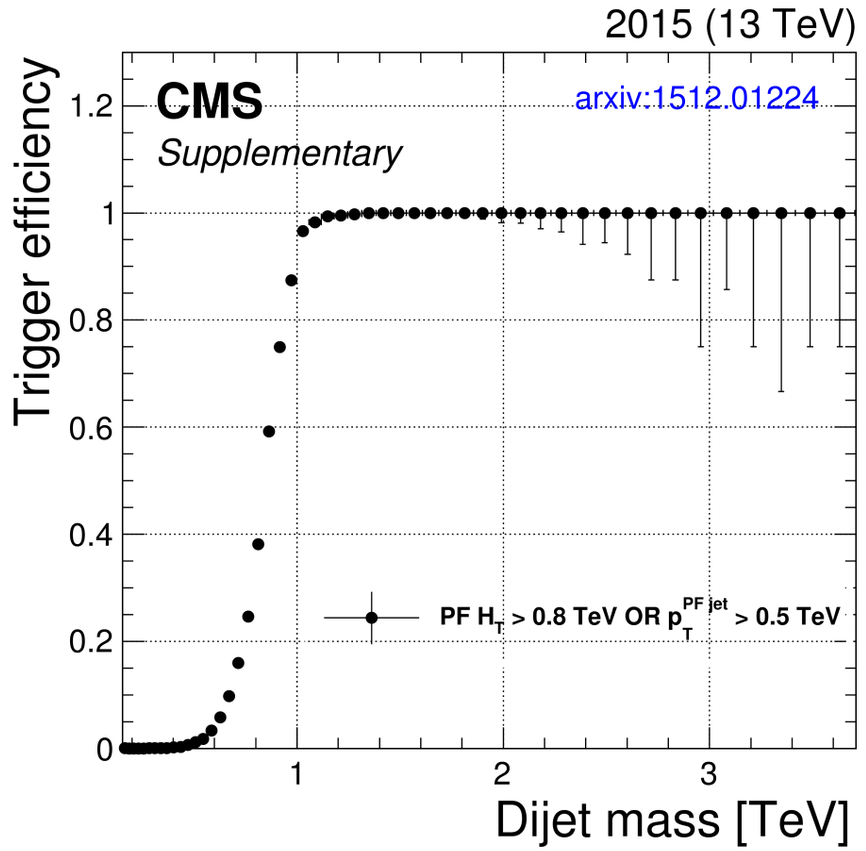




	process	2ℓ	1ℓ	$1\mu, 1e$	SR1	SR2
MET resolution	all	1%	1%	< 1%	1%	1%
MET scale	all	< 1%	< 1%	< 1%	< 1%	< 1%
JES	VV, ST, multijet	1%	1%	2%	< 1%	1%
b-tagging	all	7%	9%	7%	8%	11%
lepton trigger, id, iso	all	4%	3%	3%	3%	3%
trigger	all		< 1%		< 1%	
pile-up	all	2%	1%	1%	1%	< 1%
Fact. scale	all	4%	3%	4%	4%	4%
Ren. scale	all	7%	6%	12%	5%	6%
EWK corr.	V+jets	4%	2%	< 1%	5%	3%
PDF	all	1%	1%	1%	1%	1%
luminosity	VV, ST, multijet			2.7%		
Other bkg cross section	VV, ST			15%		
Multijet cross section	multijet			50%		

Dijet – Results



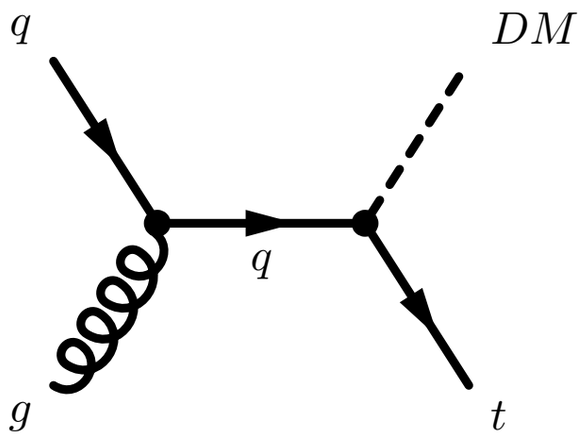


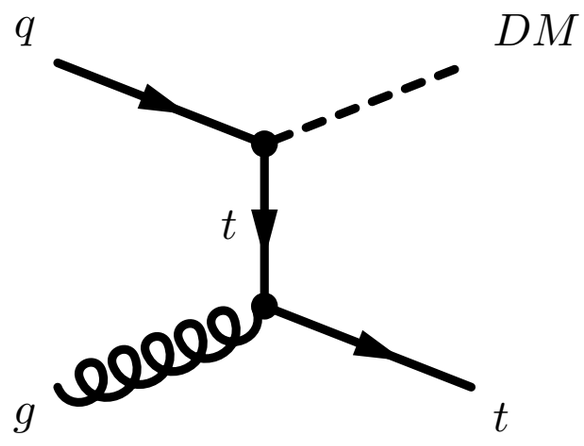
CMS MONO-TOP (HAD) @ 8 TeV

PRL114.101801

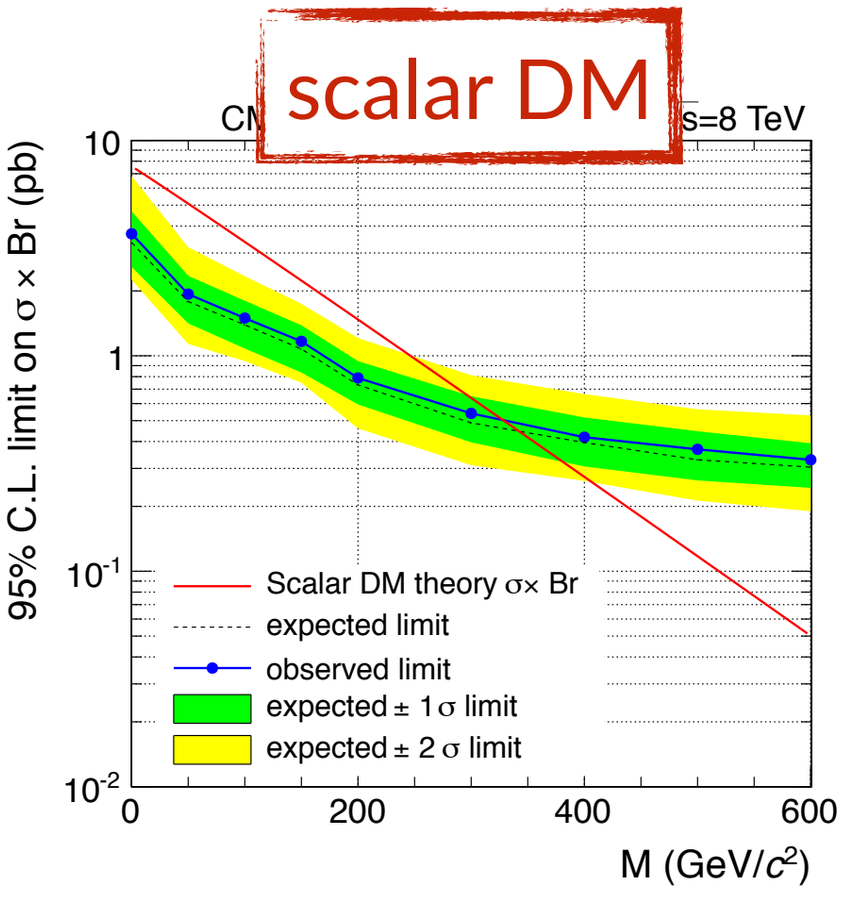
resolved monojet-like selection criteria

- MET > 350 GeV
- 3 jets (60, 60, 40 GeV), 1 b-tagged
  - no additional jet with pT > 35 GeV
- isolated lepton veto (suppress ttbar)
- dominant background from ttbar and Z+jets

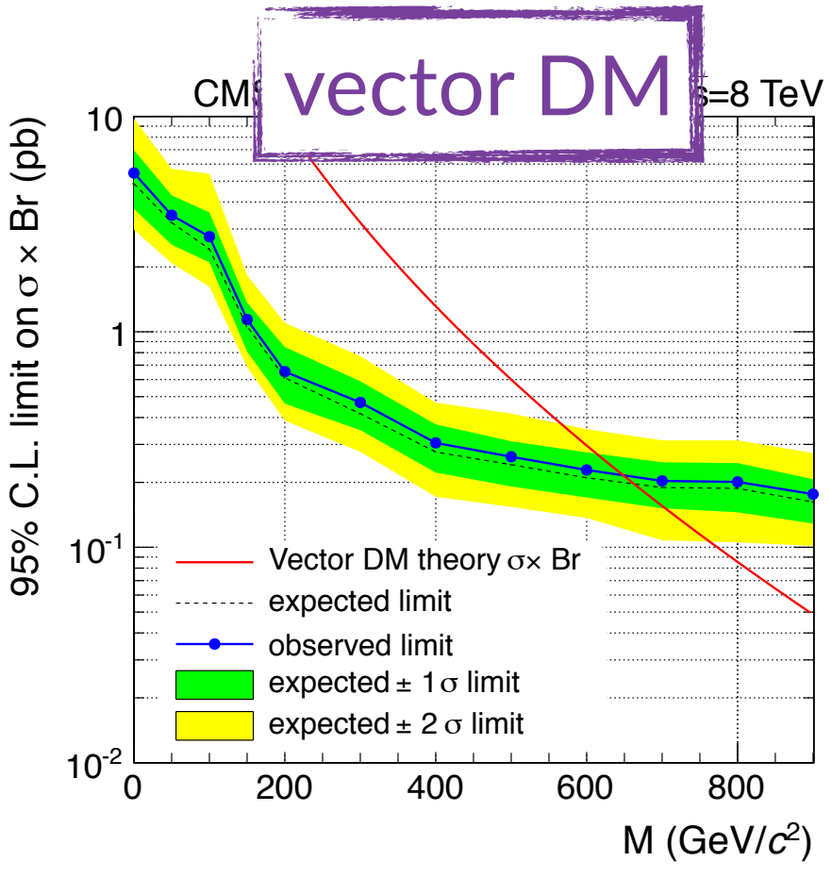




scalar DM



vector DM

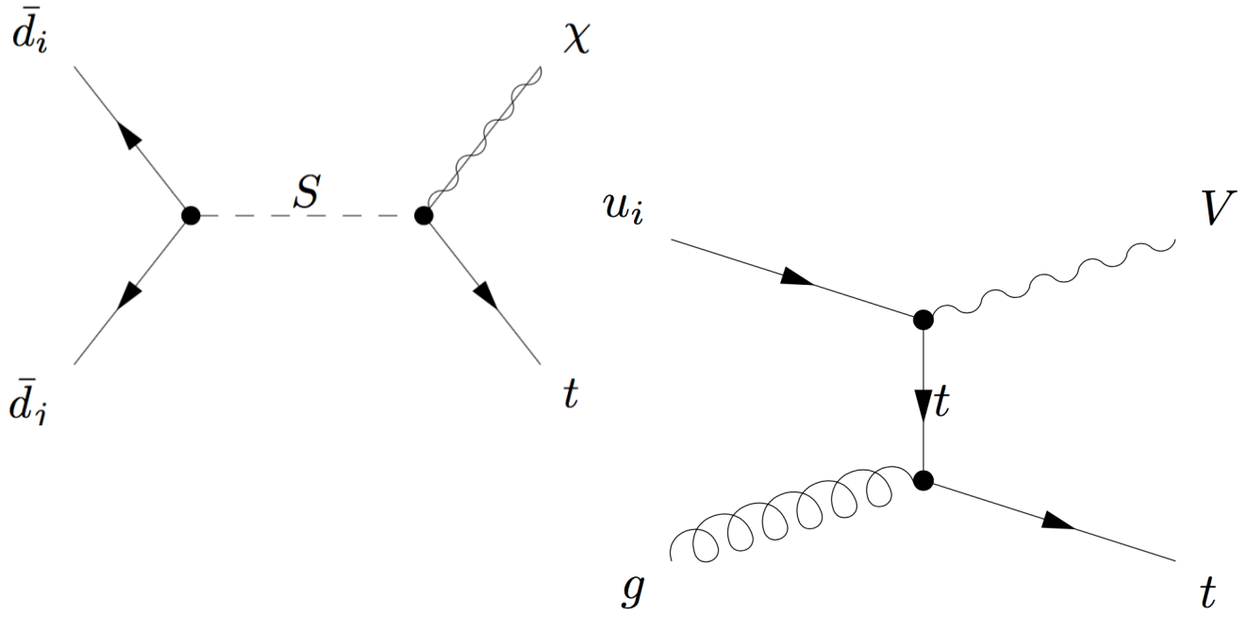


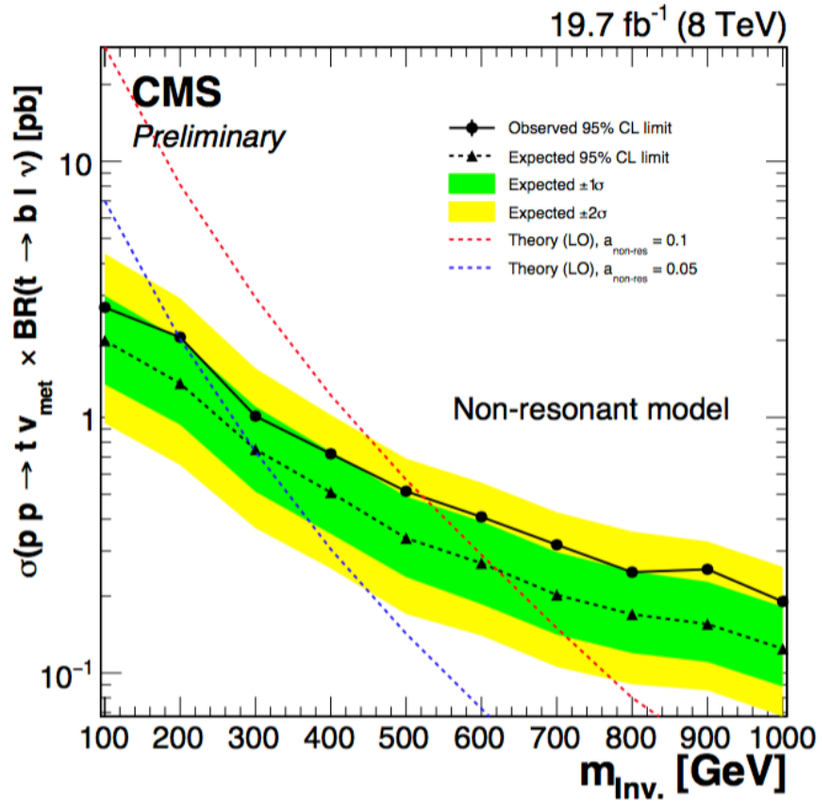
CMS MONO-TOP (LEP) @ 8 TeV

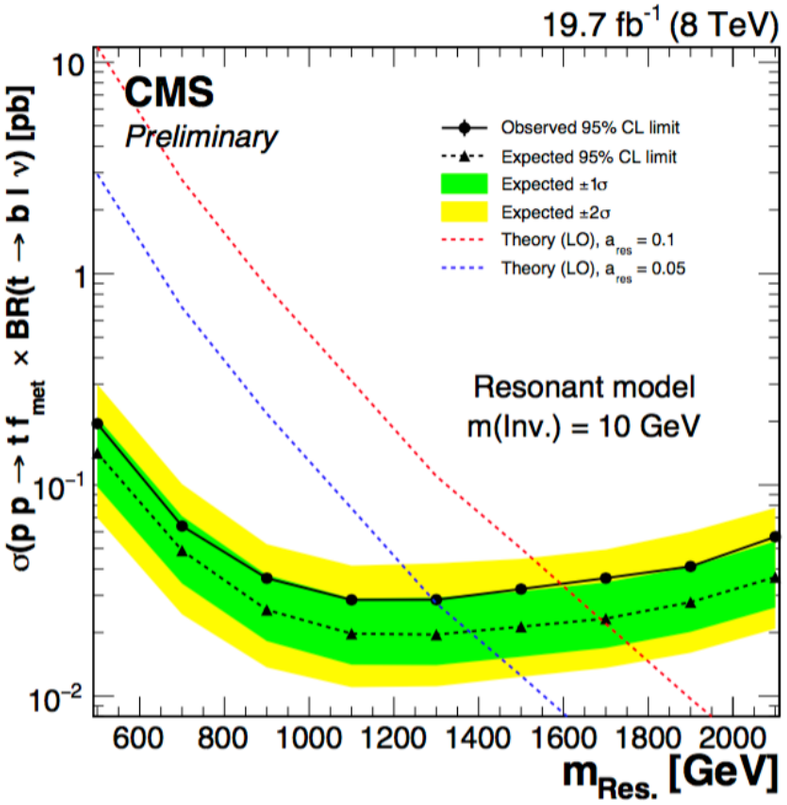
B2G-15-001

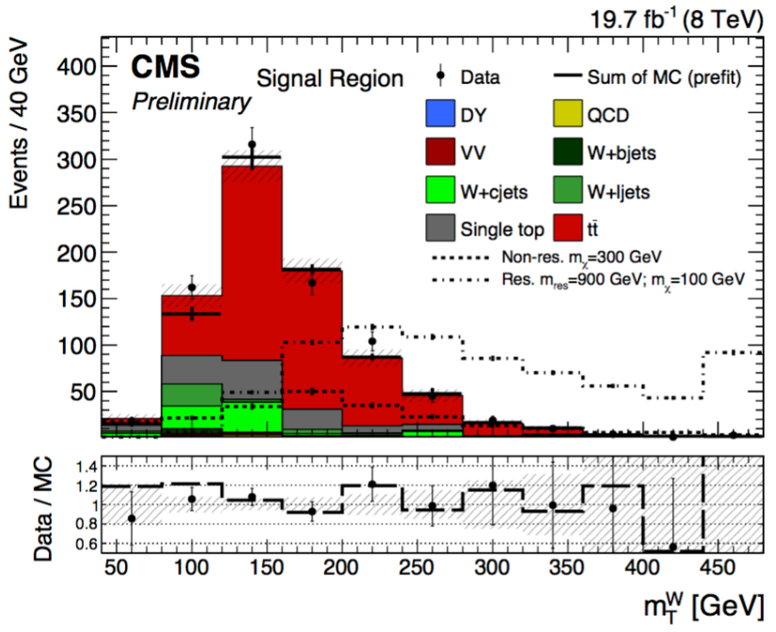
muon+b-jet+MET

- MET > 100 GeV, pT(j) > 70 GeV, pT(μ) > 33 GeV (ΔΦ(jet,μ) < 1.7), pT(W) > 70 GeV, μ trigger
  - 60% efficiency b-tagging (reject W+jets)
  - no additional jet with pT > 30 GeV, |η| < 2.5 (reduce ttbar)
- use m_T(W) as discriminant
- CRs from 0 (W+jets) or 2 b-tag (ttbar)



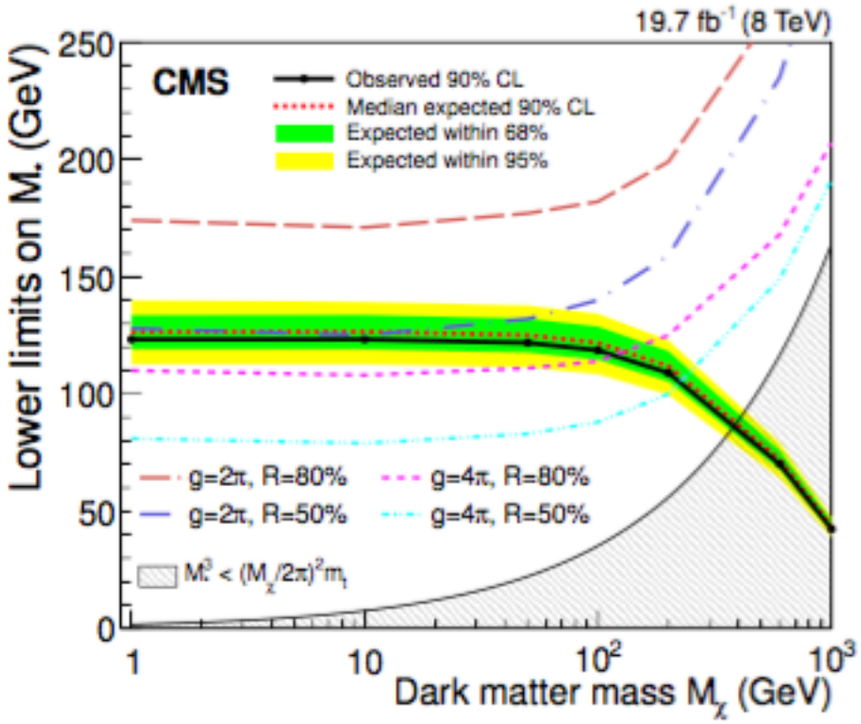


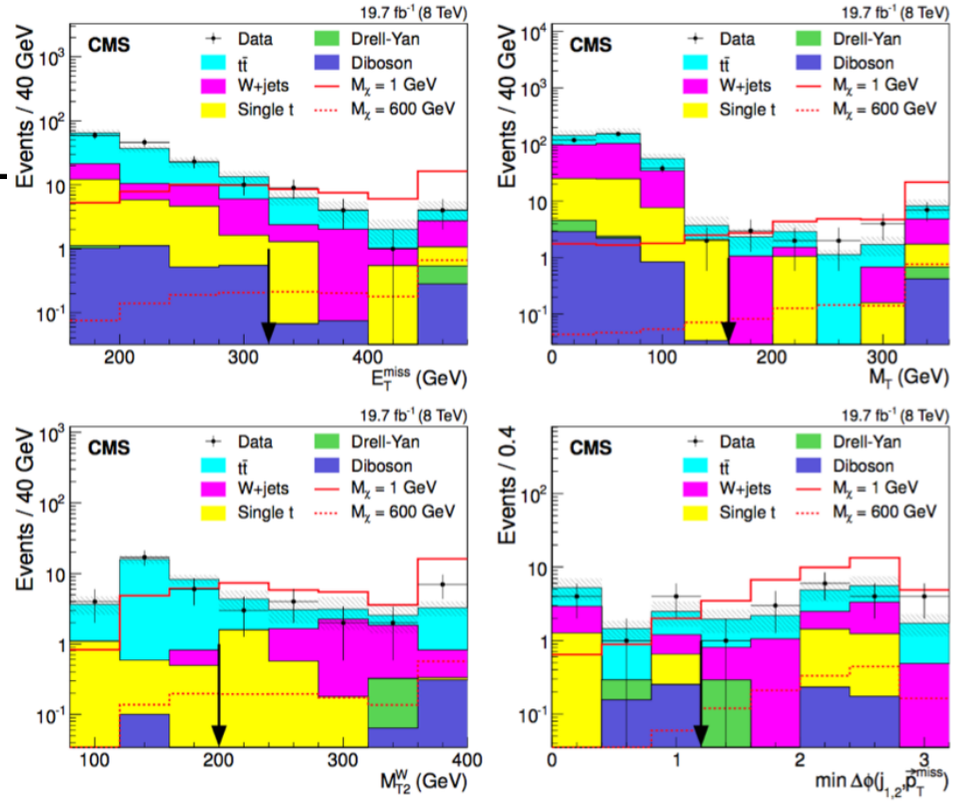


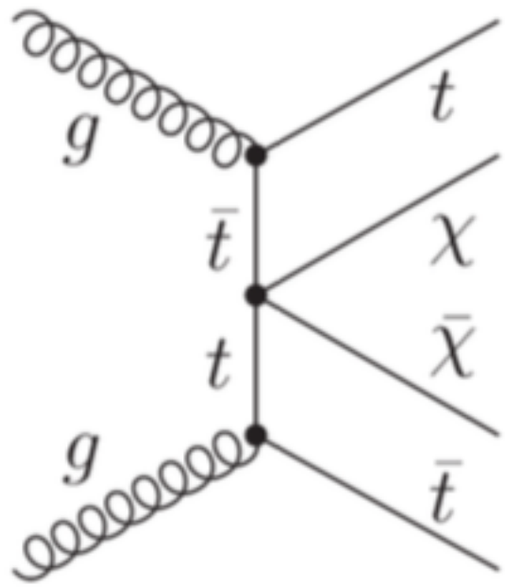


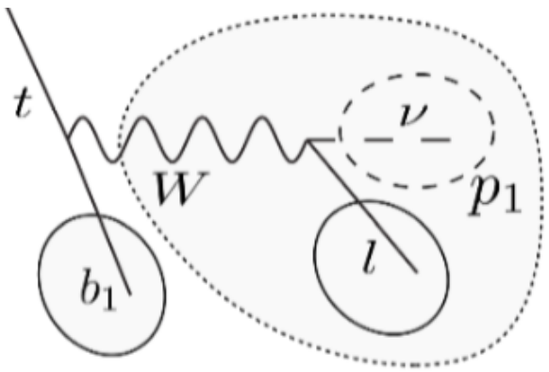
Mono-tt (l)

JHEP06(2015)121





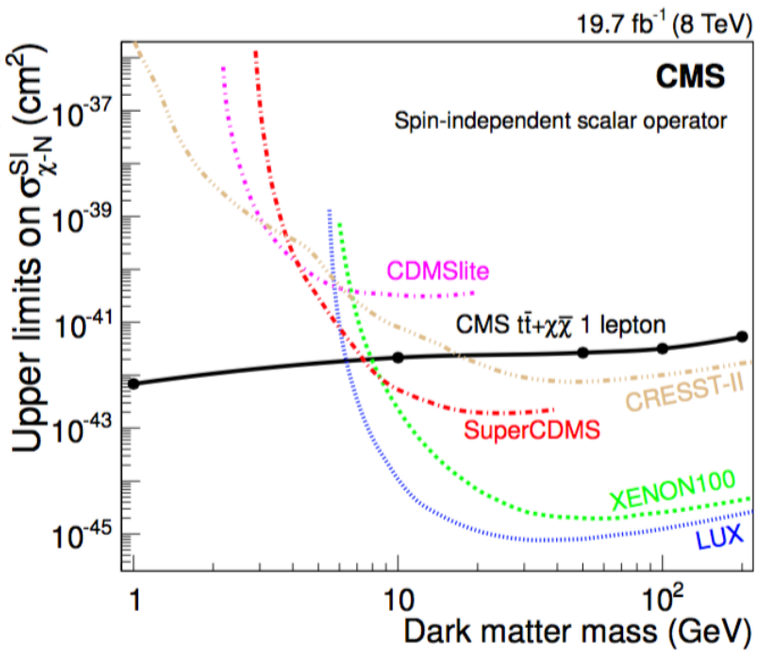




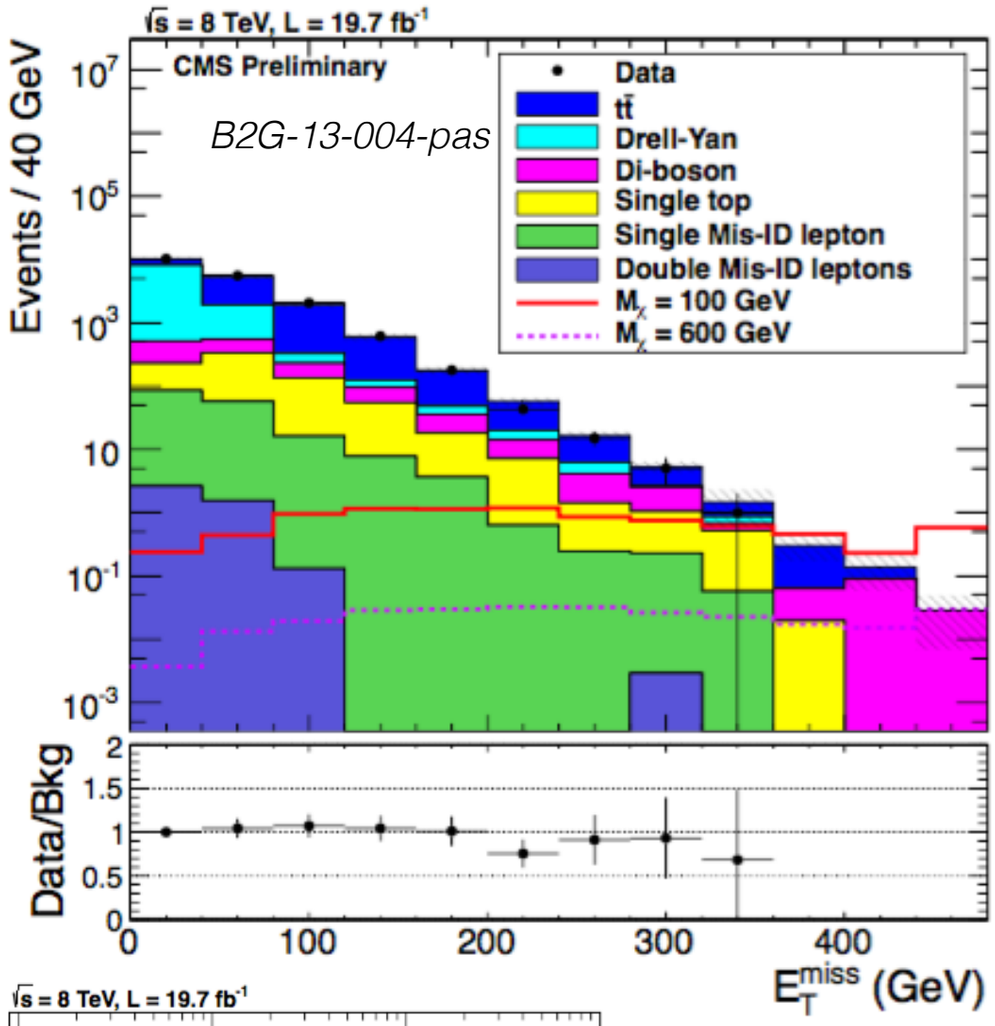
$$L_{\text{int}} = \frac{m_q}{M_*^3}\bar{q}q\bar{\chi}\chi$$

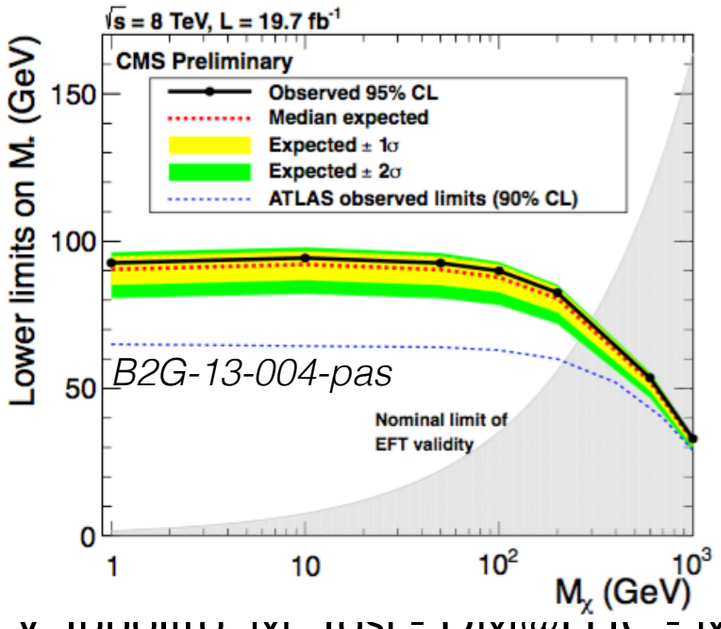
Source of systematic uncertainties	Relative uncertainty on total background (%)
50% normalization uncert. of other bkg in deriving SFs	10
SF_{W+jets} (CR tests)	13
$t\bar{t}$+jets top-quark p_T reweighting	3.9
Jet energy scale	4.0
Jet energy resolution	3.0
b-tagging correction factor (heavy flavour)	1.0
b-tagging correction factor (light flavour)	1.8
Pileup model	2.0
PDF	2.6

Source	Yield (±stat ±syst)
$t\bar{t}$	$8.2 \pm 0.6 \pm 1.9$
W	$5.2 \pm 1.8 \pm 2.1$
Single top	$2.3 \pm 1.1 \pm 1.1$
Diboson	$0.5 \pm 0.2 \pm 0.2$
Drell-Yan	$0.3 \pm 0.3 \pm 0.1$
Total Bkg	$16.4 \pm 2.2 \pm 2.9$
Data	18



Mono-tt (ll)

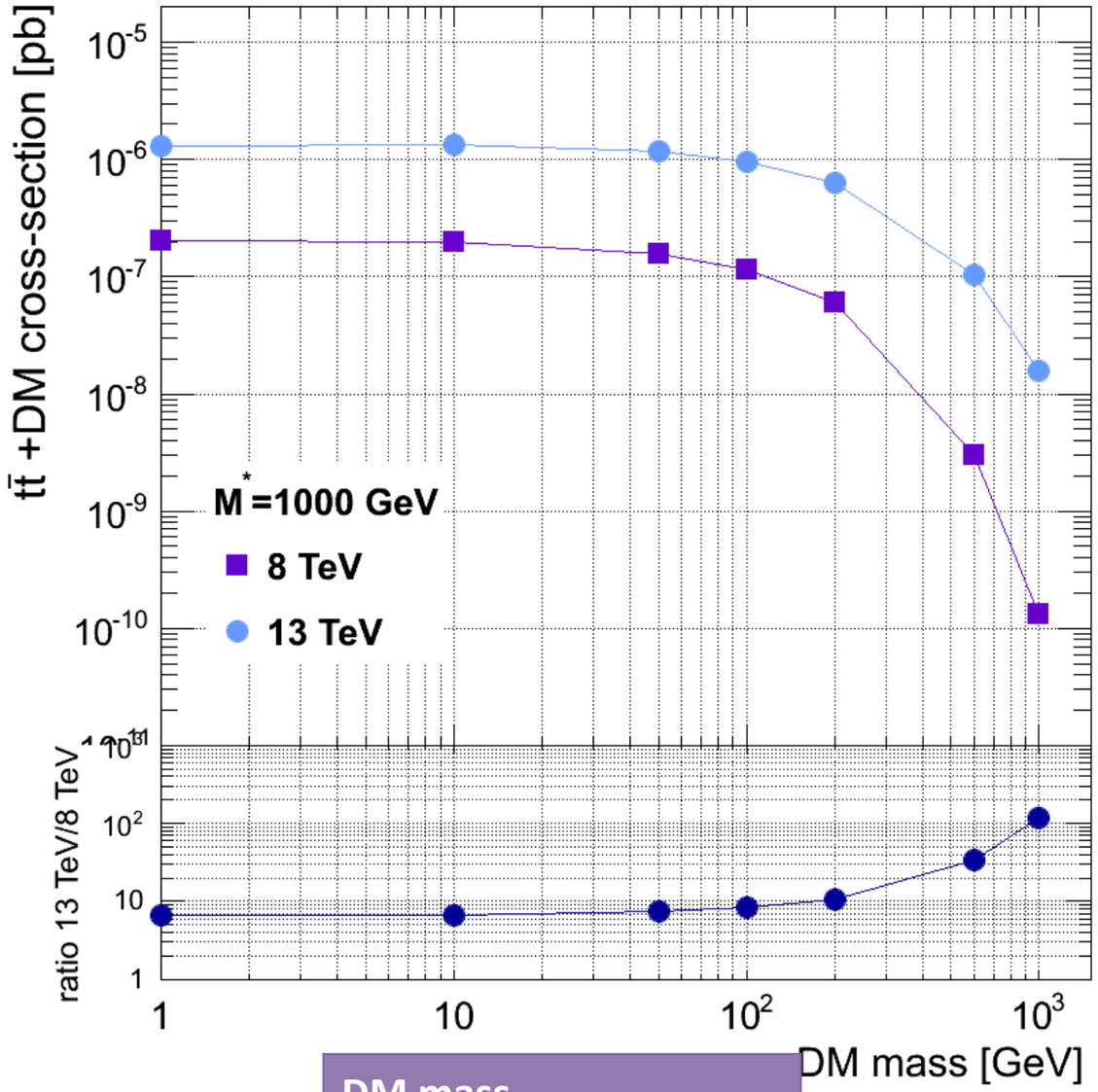




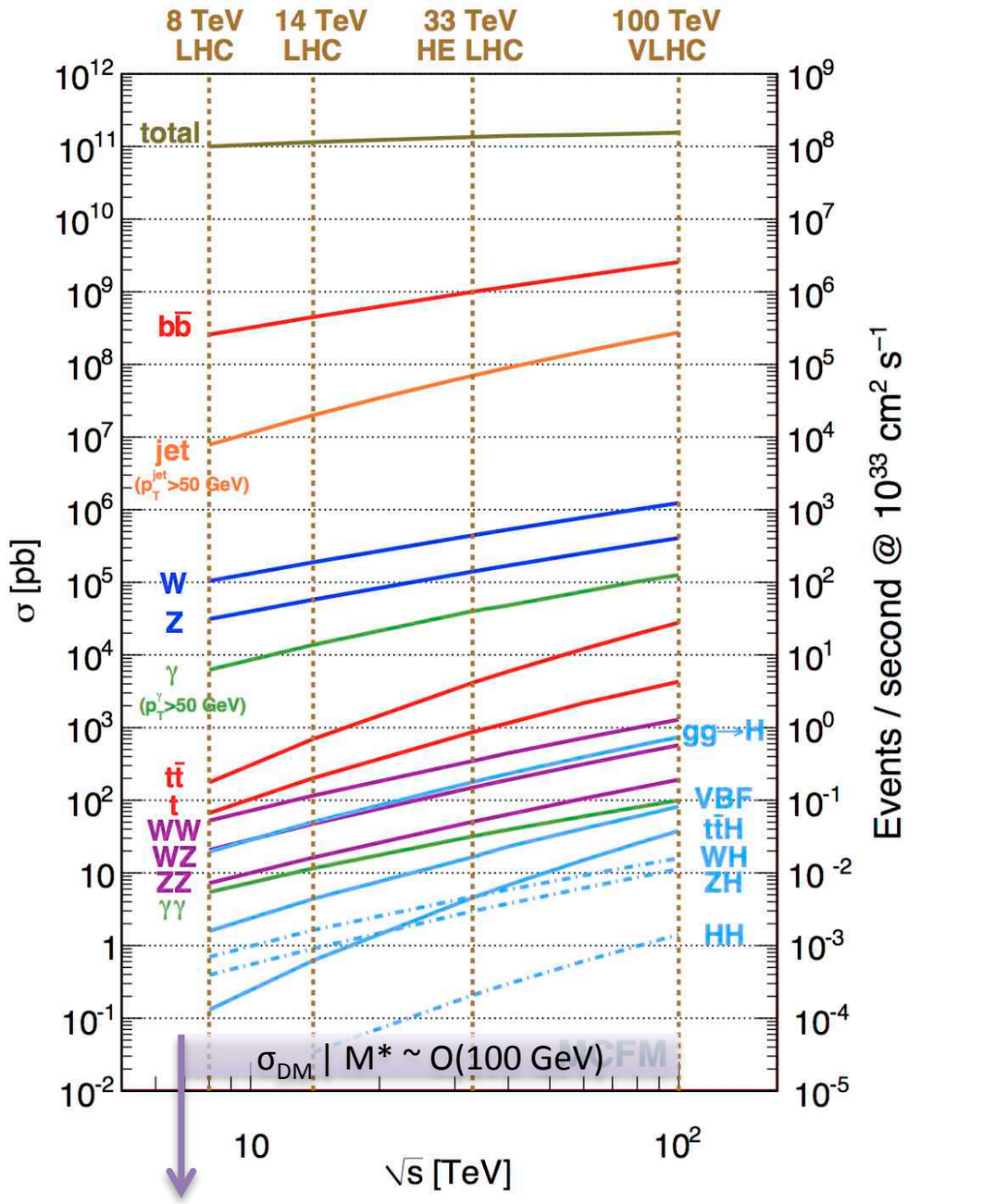
Source of systematic uncertainties	Relative error on total background (%)
Jet energy scale	15
$t\bar{t}$+jets top p_T reweighting	11
Jet energy resolution	5.3
$t\bar{t}$+jets Q^2	3.7
Pileup model	3.1
$t\bar{t}$+jets jet-parton matching	3.0
Cross section	2.7
Integrated luminosity	2.6
Electron energy scale	1.3
Misidentified lepton	1.3
Lepton identification efficiency	1.0
Trigger efficiency	0.3
Muon energy scale	0.2
Unclustered energy scale	0.2

Background Source	Yield
$t\bar{t}$	$0.87 \pm 0.18 \pm 0.27$
Single top	$0.48 \pm 0.46 \pm 0.09$
Di-boson	$0.32 \pm 0.09 \pm 0.05$
Drell-Yan	$0.19 \pm 0.14 \pm 0.03$
One Mis-ID lepton	$0.02 \pm 0.07 \pm 0.02$
Double Mis-ID leptons	$0.00 \pm 0.00 \pm 0.00$
Total Bkg	$1.89 \pm 0.53 \pm 0.39$
Data	1
Signal	$1.88 \pm 0.11 \pm 0.07$

MONO-TT: 8 VS 13 TEV



DM mass [GeV]	$\sigma_{13\ TeV} / \sigma_{8\ TeV}$
1	**8.7**
100	**11.4**
200	**15**
600	**44**
1000	**140**



process	$\sigma_{13\ TeV} / \sigma_{8\ TeV}$
ttbar	**3.3**
W+jets	**1.7**
single top (tW)	**3.1**