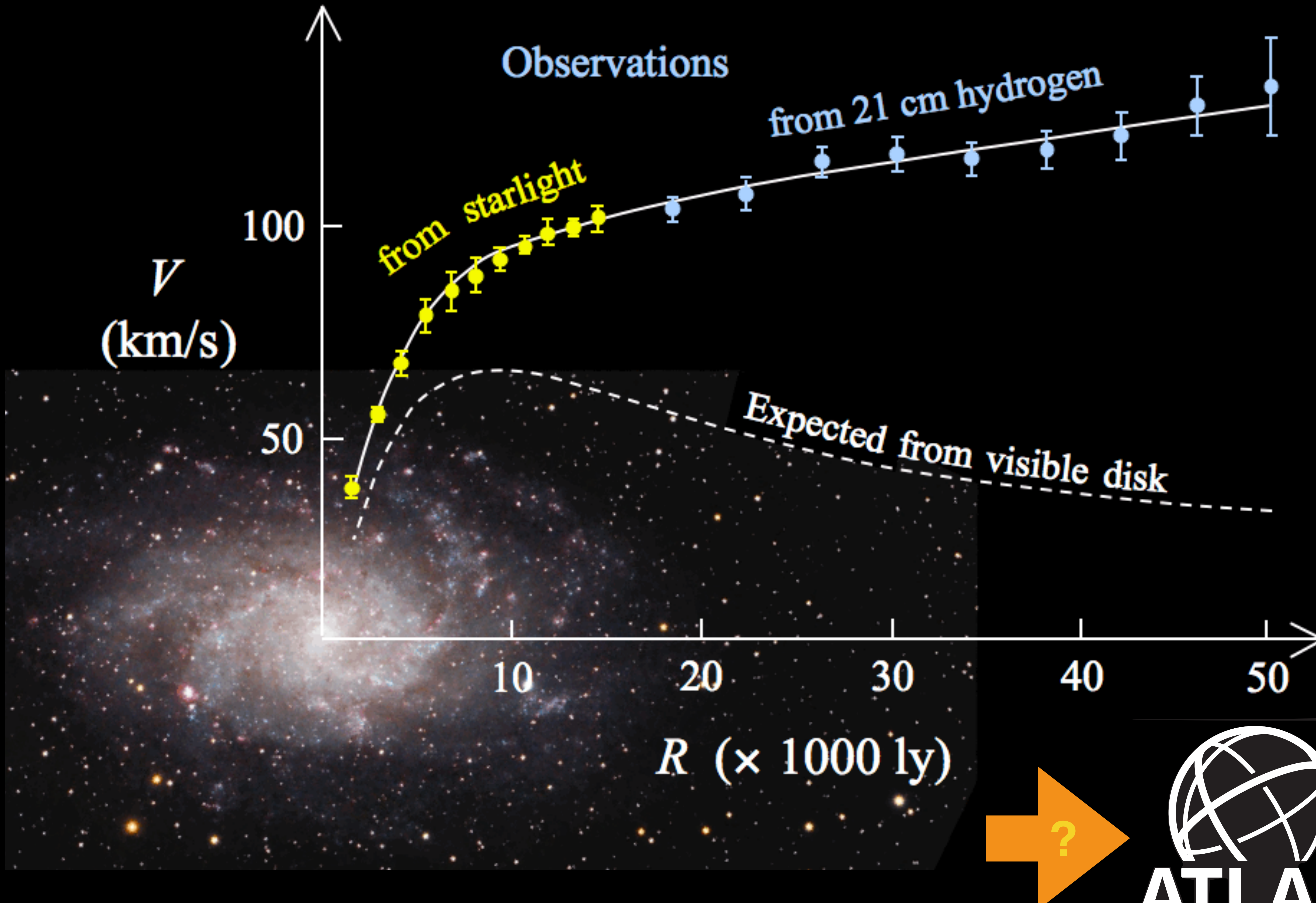
Mono-X @ ATLAS

or, LHC as a Dark Matter factory

Valerio Ippolito

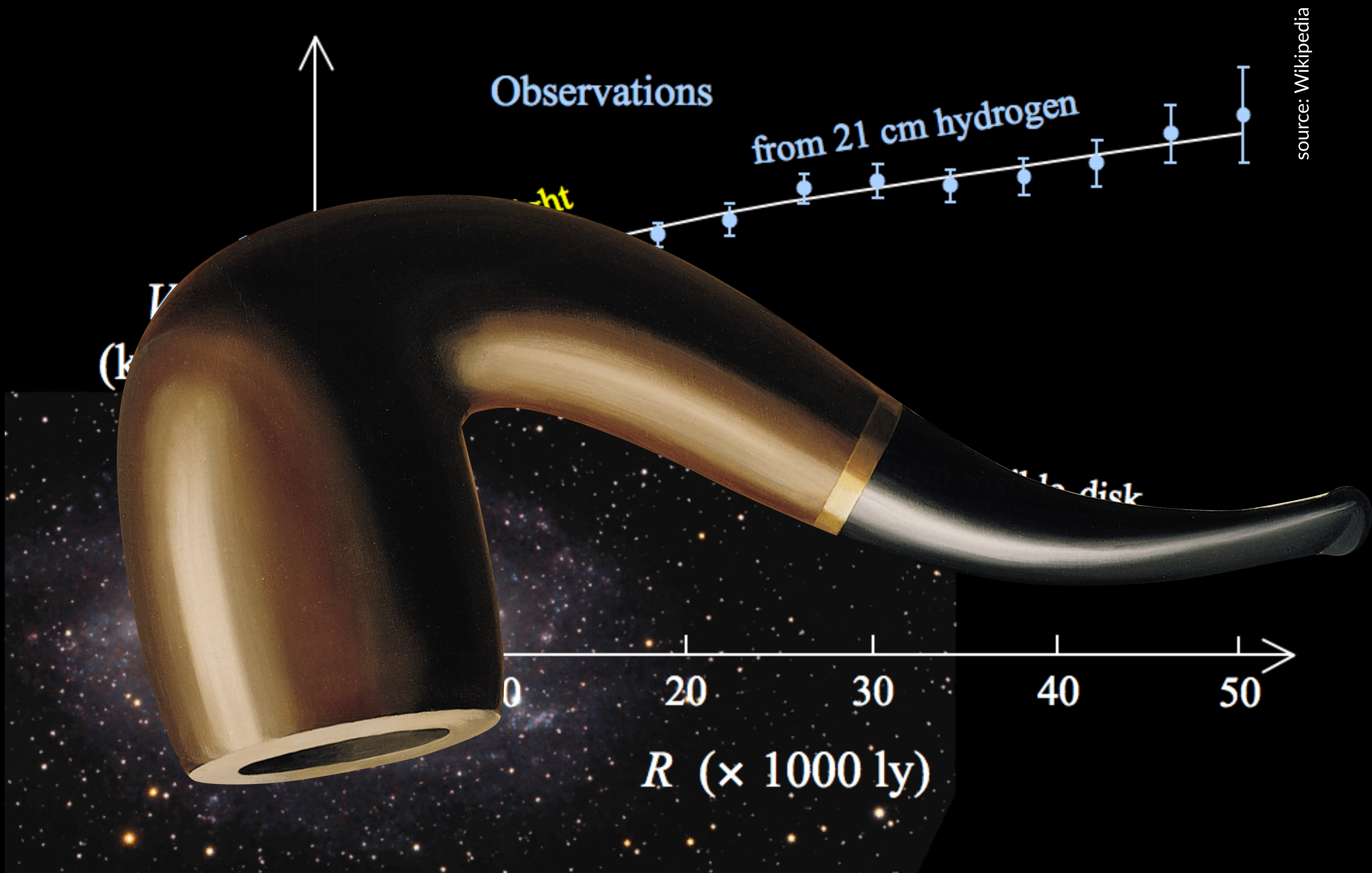
Harvard University

on behalf of the ATLAS collaboration



source: Wikipedia

ATLAS
EXPERIMENT

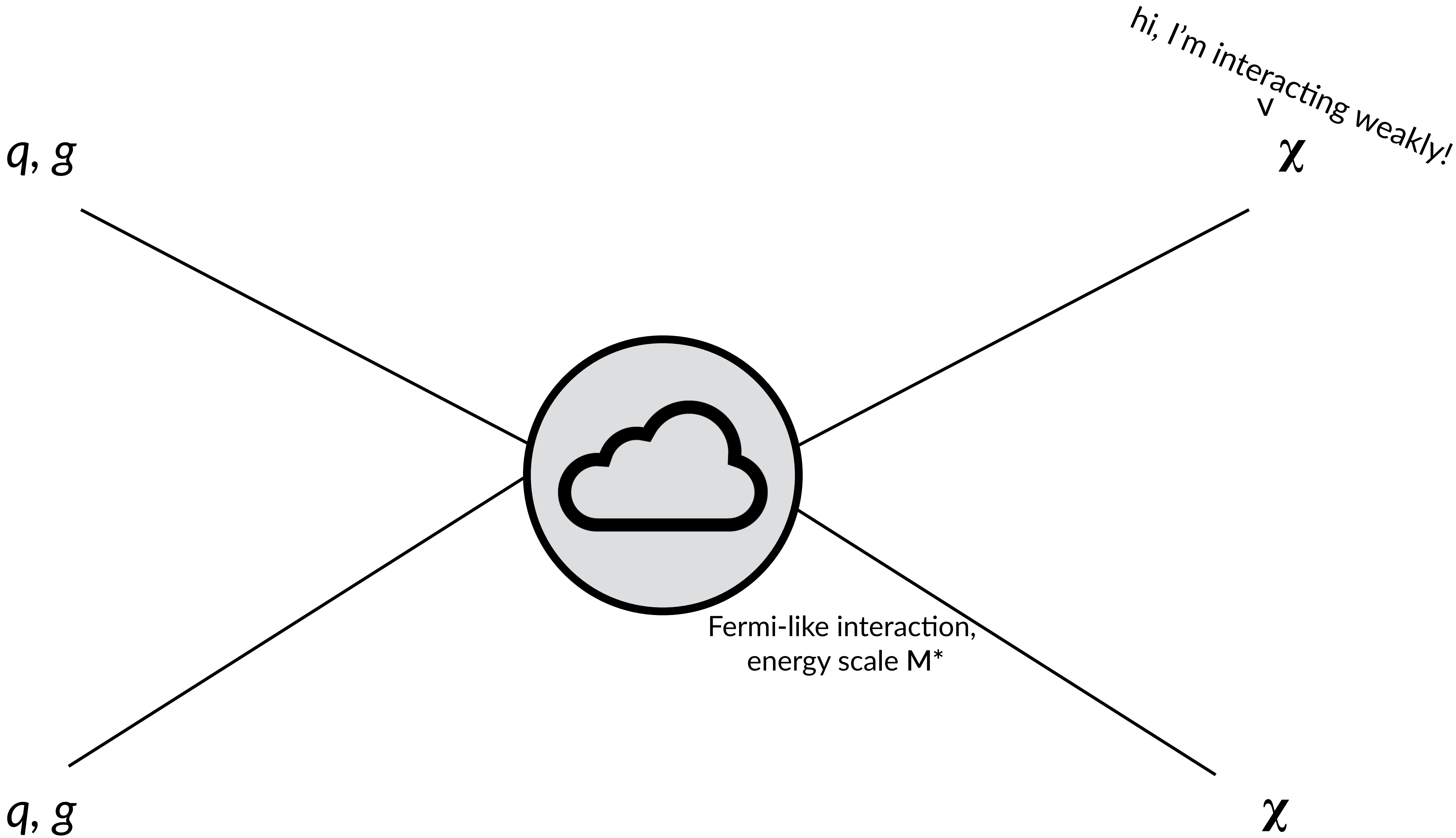


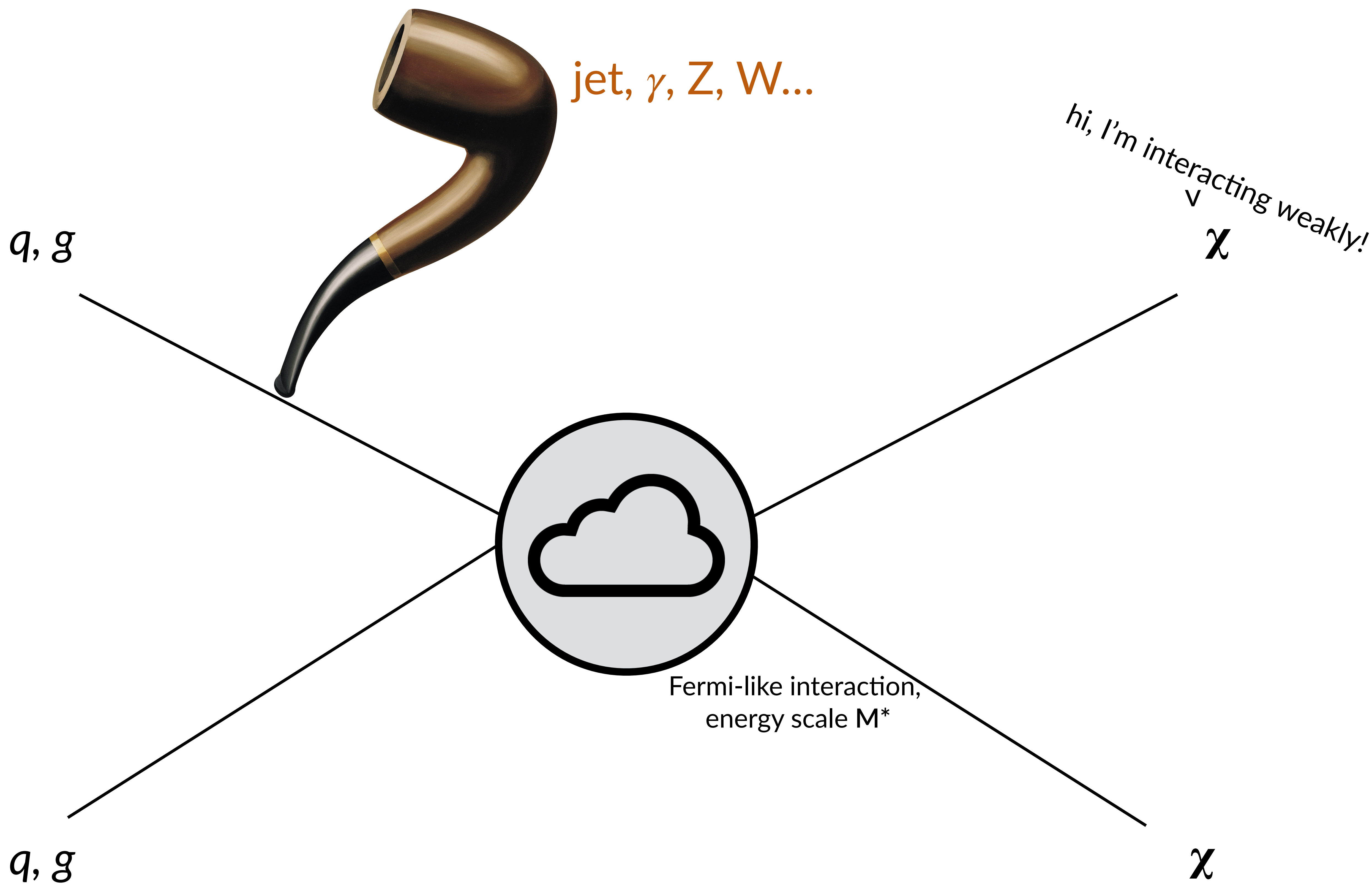
Ceci n'est pas de la matière sombre

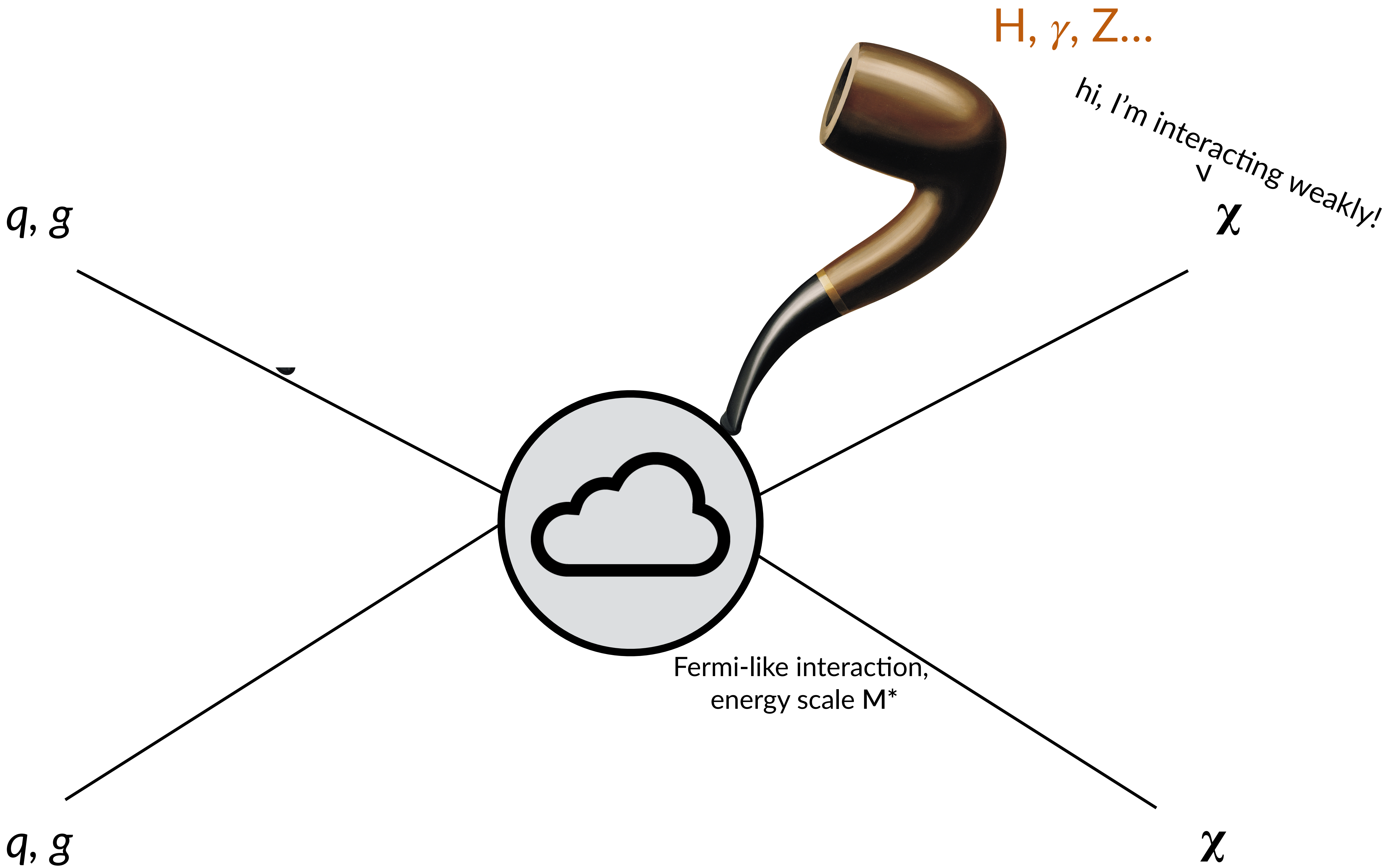
hi, I'm interacting weakly!

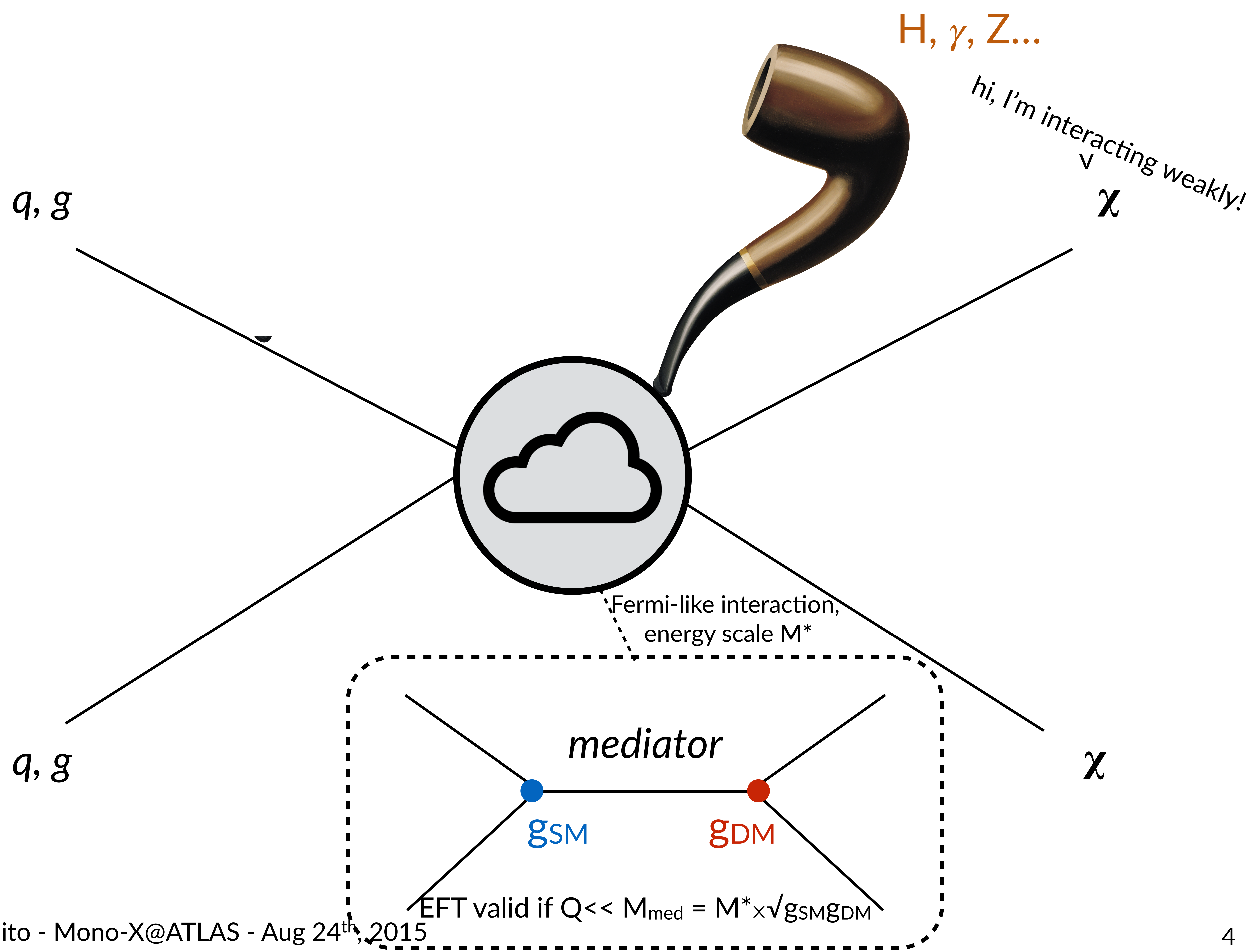
v

χ

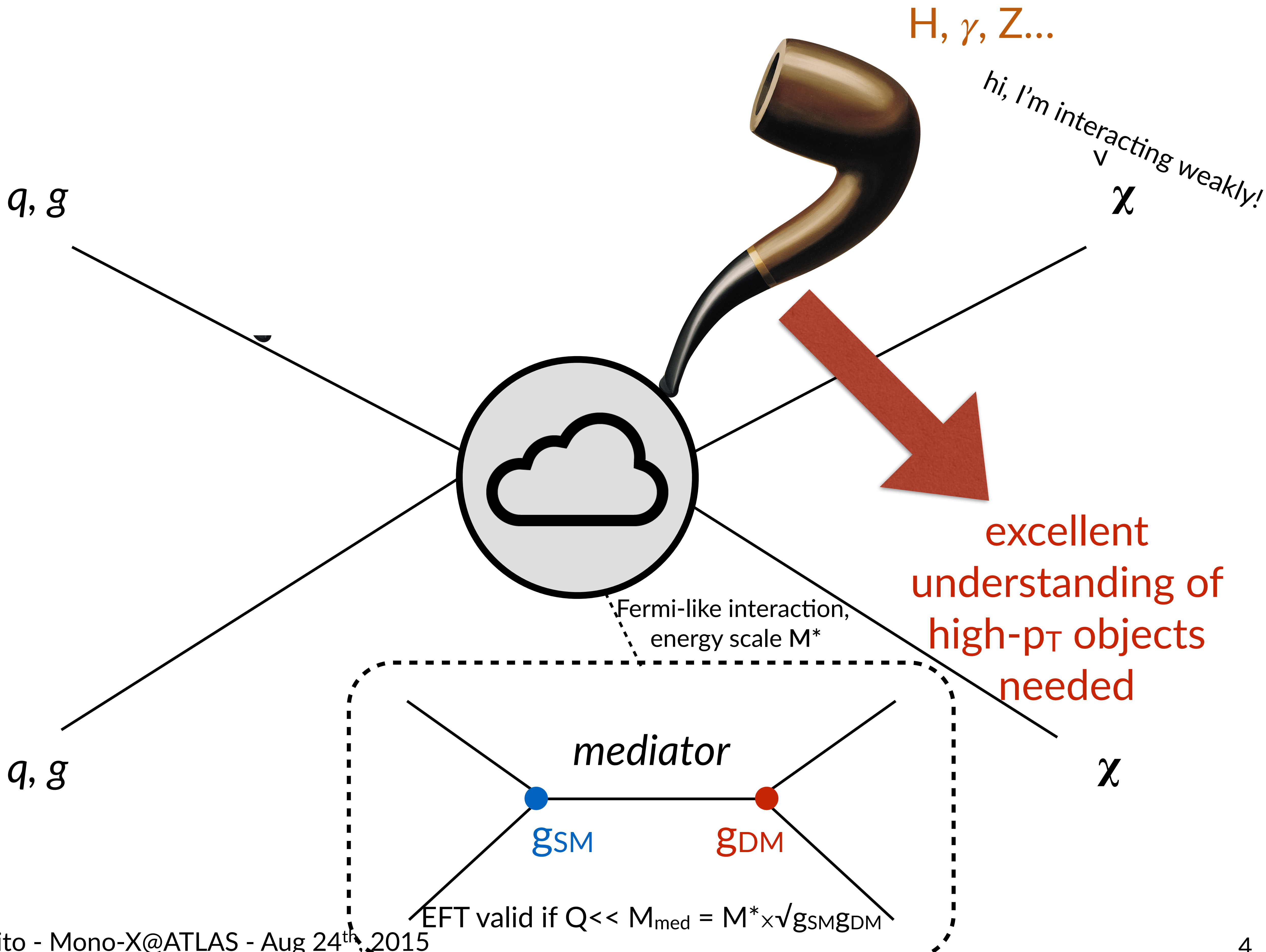

hi, I'm interacting weakly!
v
q, g
χ
Fermi-like interaction,
energy scale M*
q, g
χ


jet, γ, Z, W...
hi, I'm interacting weakly!
v
χ
q, g
Fermi-like interaction,
energy scale M*
q, g
χ

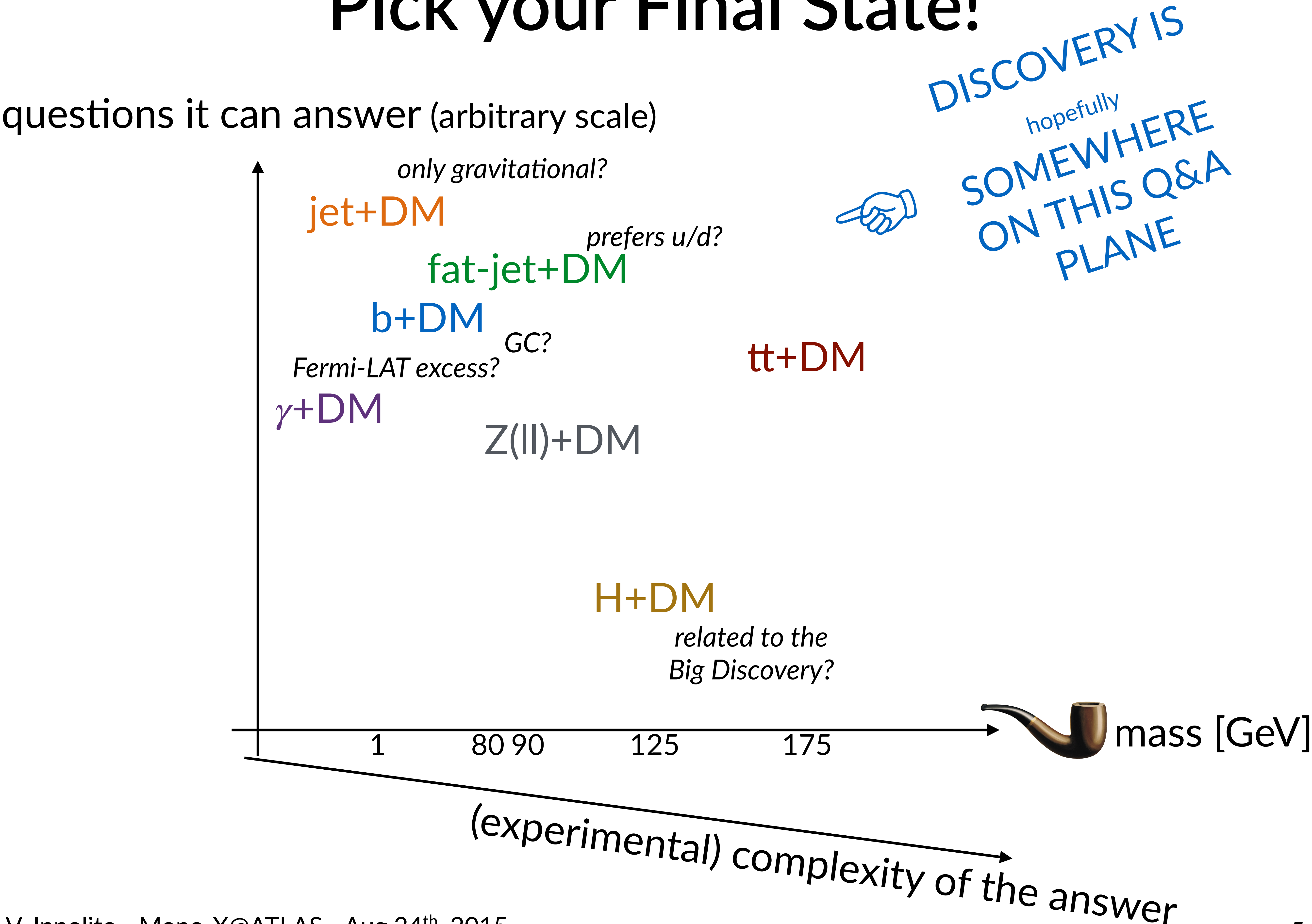

H, γ, Z...
hi, I'm interacting weakly!
q, g
χ
Fermi-like interaction,
energy scale M*
q, g
χ



H, γ, Z...
hi, I'm interacting weakly!
q, g
χ
q, g
χ
Fermi-like interaction, energy scale M*
mediator
gSM
gDM
EFT valid if Q<< Mmed = M*×√gSMgDM


H, γ, Z...
hi, I'm interacting weakly!
q, g
χ
q, g
χ
excellent understanding of high-pT objects needed
Fermi-like interaction, energy scale M*
mediator
gSM
gDM
EFT valid if Q<< Mmed = M*×√gSMgDM

Pick your Final State!



Pick your Final State!

questions it can answer (arbitrary scale)

only gravitational?

jet+DM

prefers u/d?

DISCOVERY IS hopefully SOMEWHERE ON THIS Q&A PLANE

direct answer: limit on $N_{sig} \sim \sigma$

can probe
EFT: suppression scale $M^{*} \sim \sigma^{(-1/n)}$
Simplified models: $g_{SM}g_{DM} \sim \sigma^{(-1/n)}$

can tell
χ-nucleon scattering σ

does need
data-driven bkg estimation to reduce modeling uncertainties (discovery is in tails!)

mass [GeV]

...perimental) complexity of the answer

JET + MET

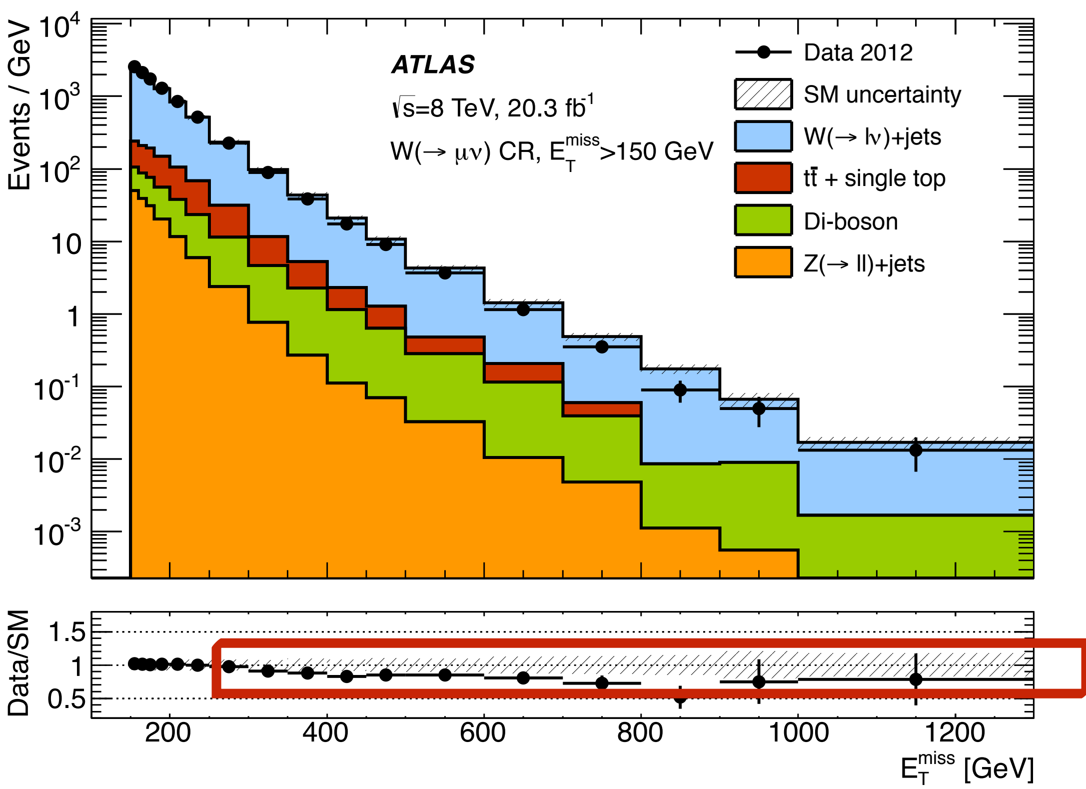
best channel for ISR fans (you pay only α_s > α_{EM})

one antikt(R=0.4) **jet** with p_T>120 GeV, |η| < 2.0, MET > 150÷700 GeV

dominant **Z(νν)+jets**, W(τν)+jets from CRs with leptons

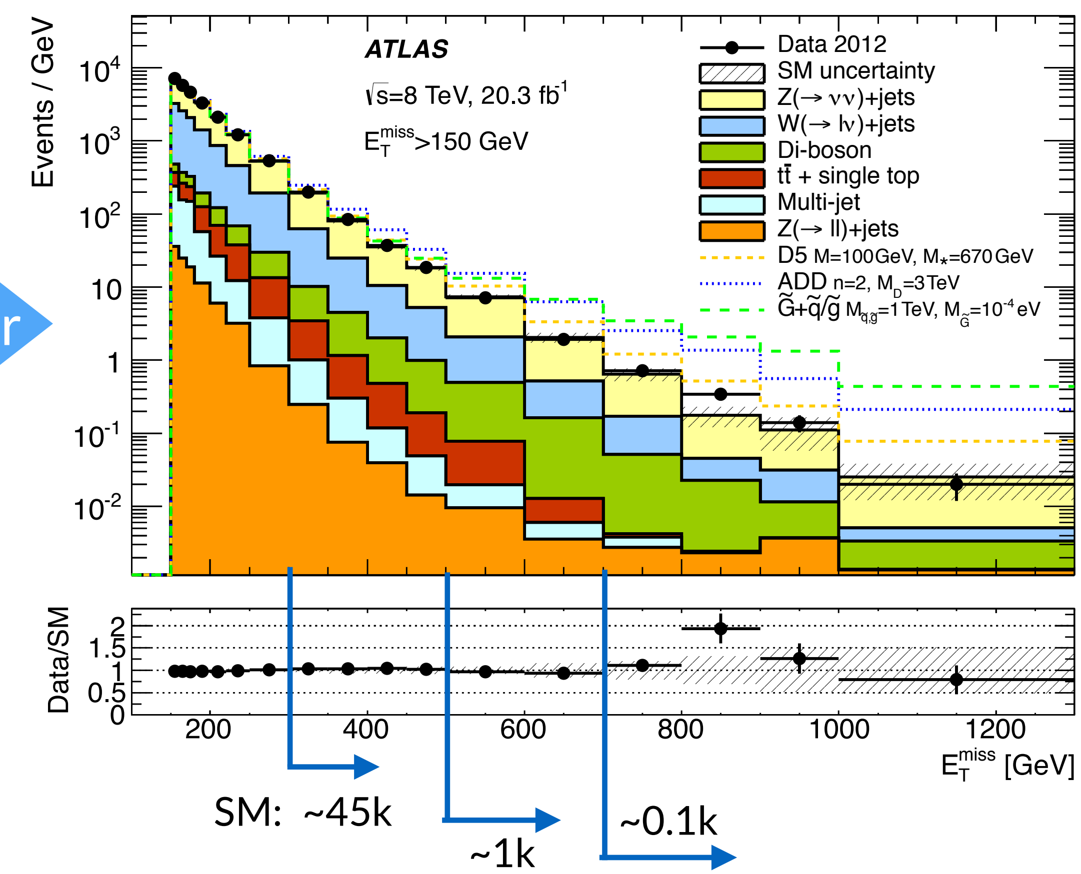
bkg uncertainty ~3÷6÷14% (top, diboson, V p_T modelling, JES/JER…)

"MET" in W(μν)+jet CR [~p_T(W)]



transfer factor

MET in SR (lepton veto)



PRL 112, 041802 (2014)

FAT–JET + MET

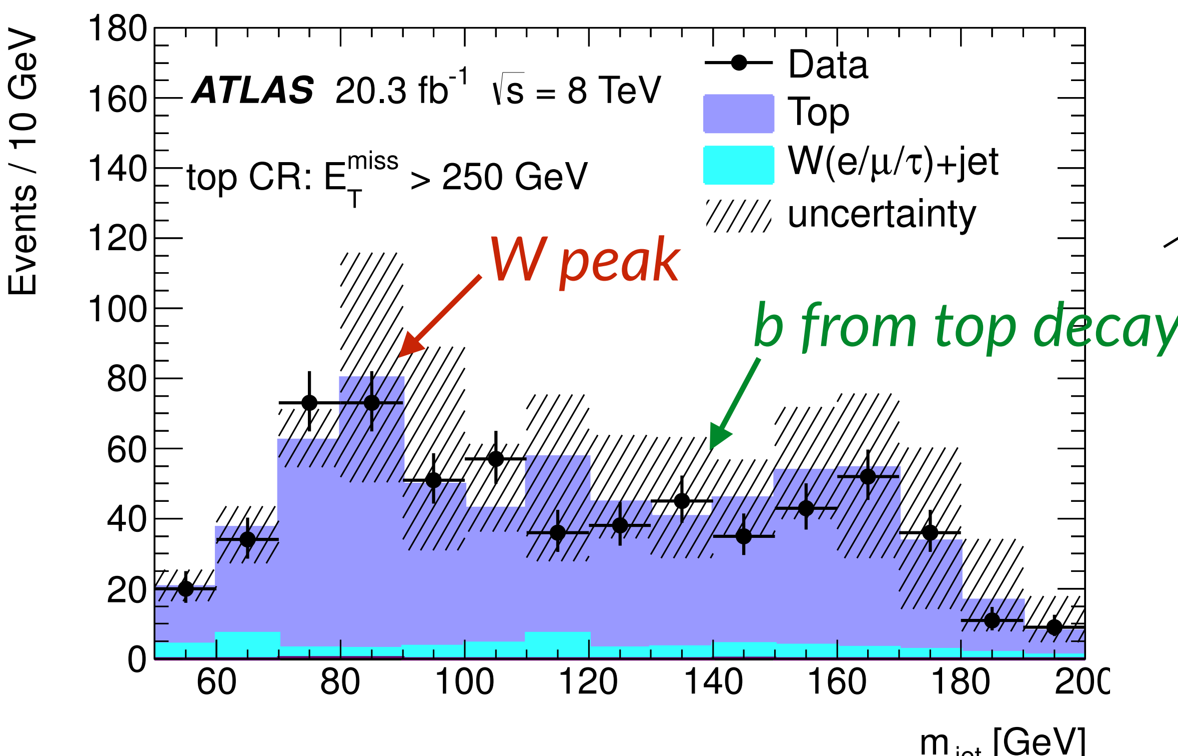
W/Z hadronic decays, unique probe for u vs d quark-DM couplings

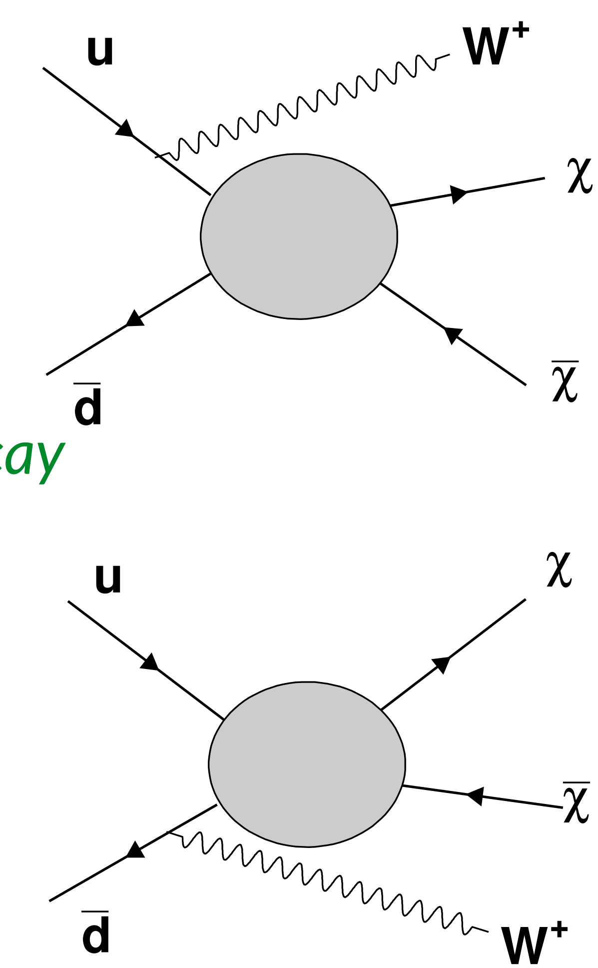
Cambridge-Achen (R=1.2), mass drop filter, 50 < m_{jet} < 120 GeV, MET>350÷500 GeV

dominant Z(νν)+jets, W(lν)+jets from CRs with leptons (SR has lepton veto)

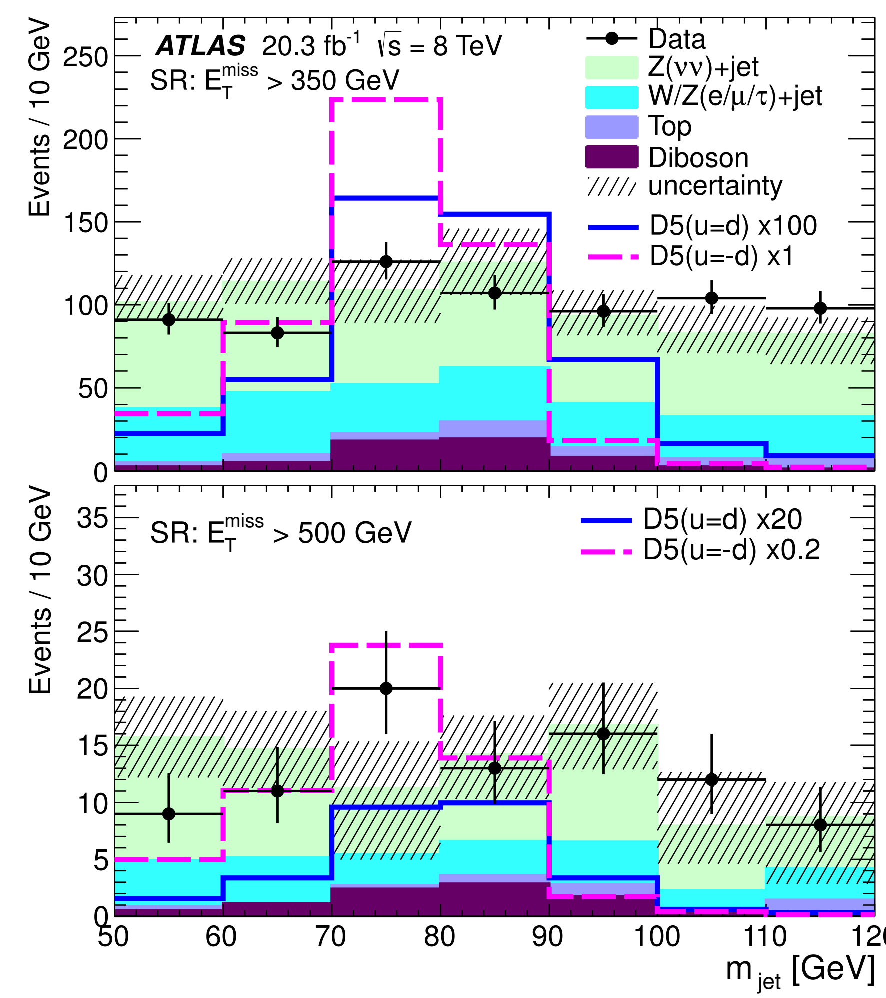
bkg uncertainty ~7÷13% (CR statistics, theory, fat jet calibration)

m_{jet} in top validation region



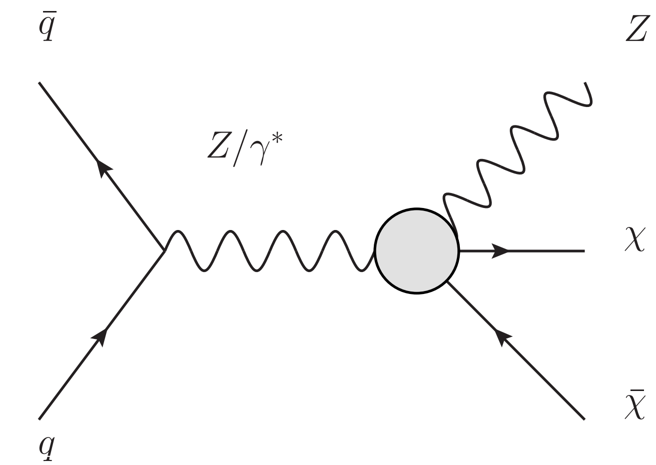


m_{jet} in SR (SM: 700-900 evts)



PRD 90, 012004 (2014)

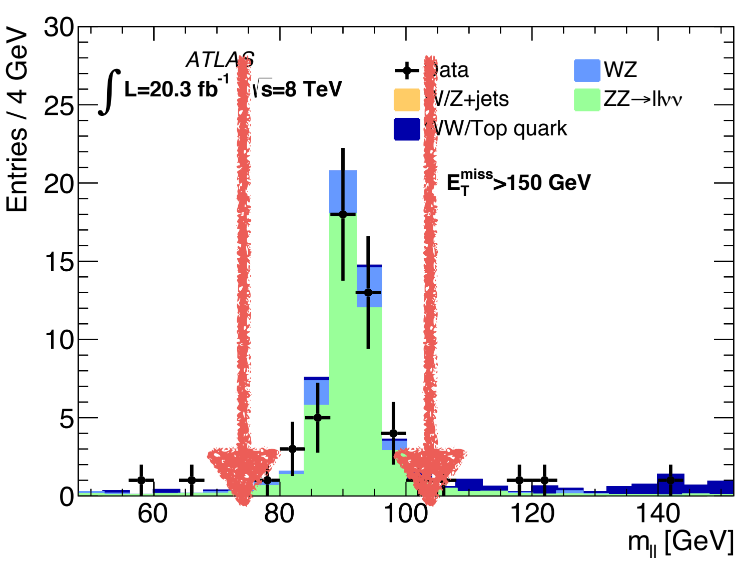
Z + MET



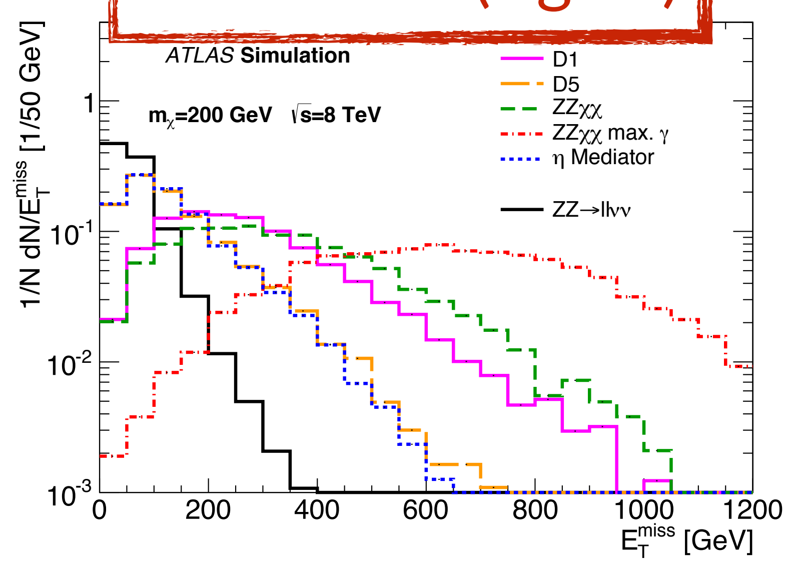
probes also DM/Z coupling using Z leptonic decays

- isolated **electrons/muons**, p_T > 20 GeV, |η| < 2.47/2.5, 76 < m_{ll} < 106 GeV
- **MET** > 150÷450 GeV balanced against Z
- dominant **ZZ(ννll)** (MC), **WW(lνlν)** from eν CR, V+jets from ABCD (MET vs η^{ll}) or ΔΦ/MET fit
- bkg uncertainty ~40% (theo) ⊕ 5% (JES, lepton E scale), validation in 4l/3l/eμ CRs

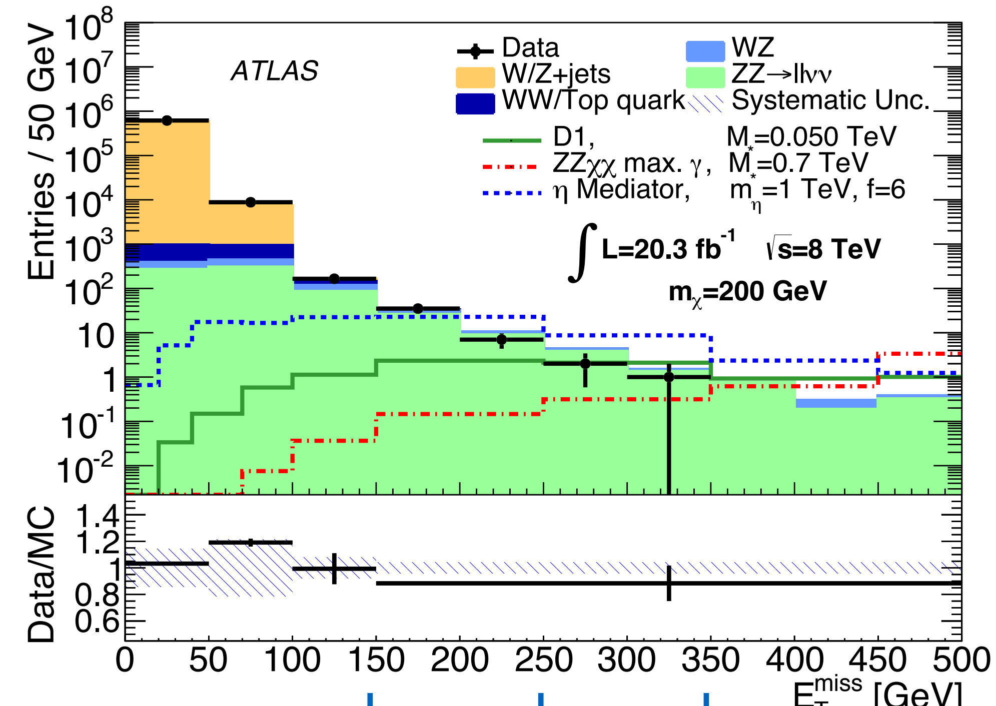
m_{ll} in 2μ CR



MET in SR (signal)



MET in SR



SM: ~45 ~7 ~1

γ + MET

complementary to jet+MET, unique for Fermi-LAT excess @ 130 GeV

tight, isolated **photon** with p_T > 125 GeV, |η| < 1.37, up to 1 jet

MET > 150 GeV (SM ~560 evts)

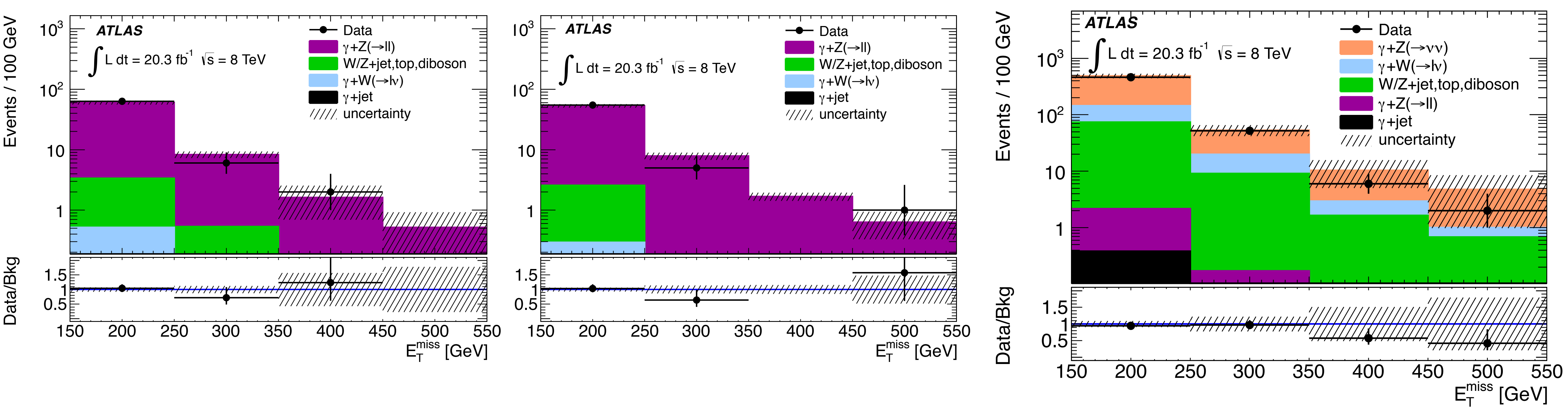
dominant **Z(νν)+γ**, W(lν)+γ from simultaneous fit to dilepton, 1-lepton CRs

bkg uncertainty ~5% (e→γ fake, lepton ID/energy scale), validation at low MET

"MET"[~p_T(Z)] in 2μ CR

"MET"[~p_T(Z)] in 2e CR

MET in SR (lepton veto!)



EPJ C (2015) 75:92

B/T + MET

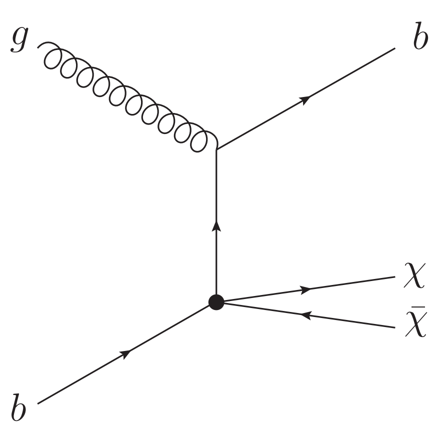
special sensitivity to scalar interactions & Galactic Center excess

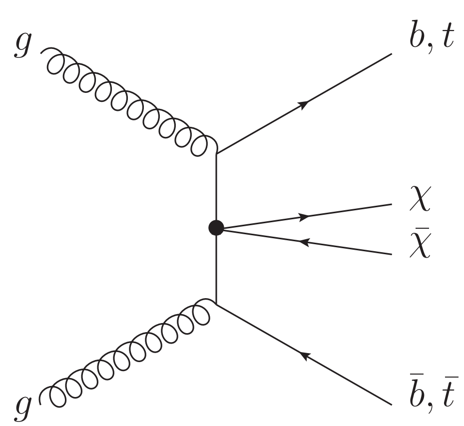
4 SRs: **b+DM**, **bb+DM**, **tt(had)+DM**, **tt(semi-lep)+DM** [~stop]

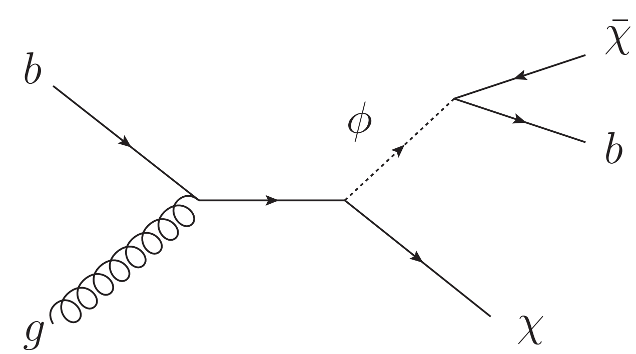
1/2 **b-tag** + **MET** ⊕ low **n_{jet}** (SR1,2), **razor** (SR3), 1 **lepton**+m_T/am_{T2}/topness/m_{jjj} (SR4)

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

bkg unc. ~10/10/7/20% (flavour, top p_T, showering, stat.)

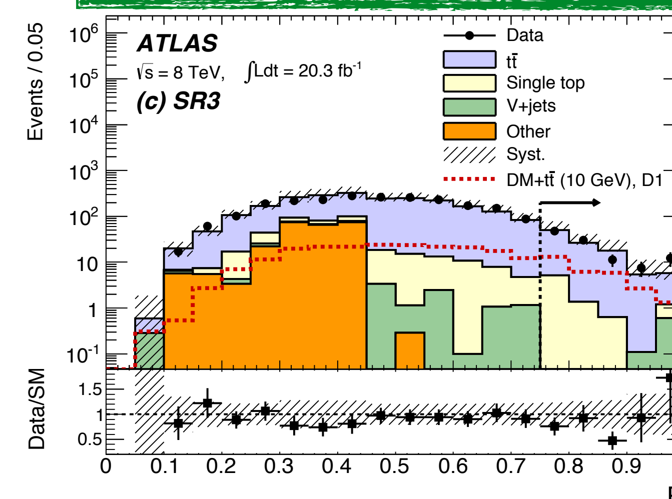




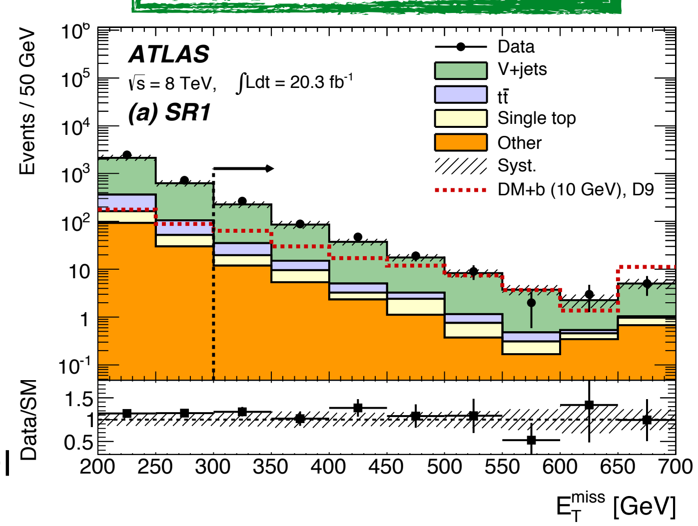


SM: ~390/250/100/7 events

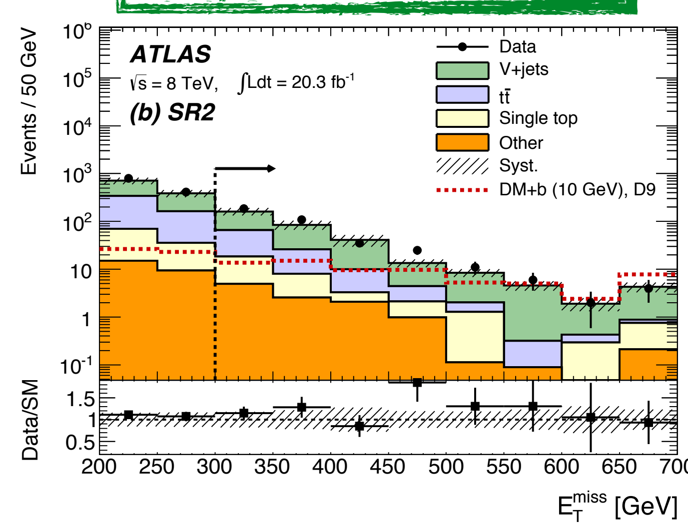
razor in tt(had)+DM SR



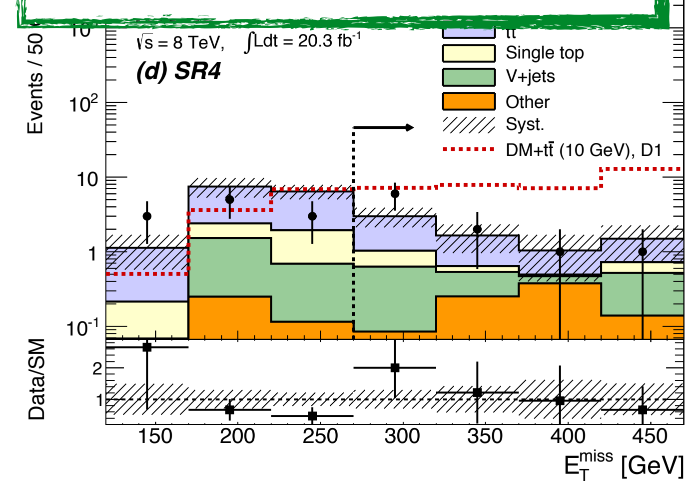
MET in b+DM SR



MET in bb+DM SR



MET in tt(semi-lep)+DM

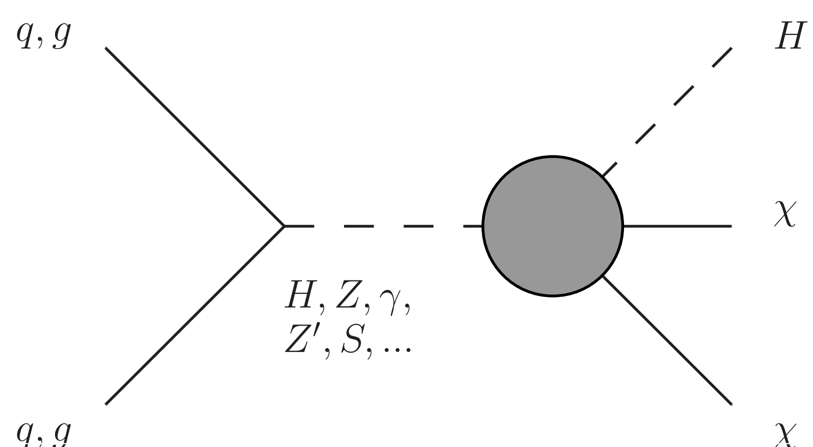


arXiv:1506.01081, subm. PRL

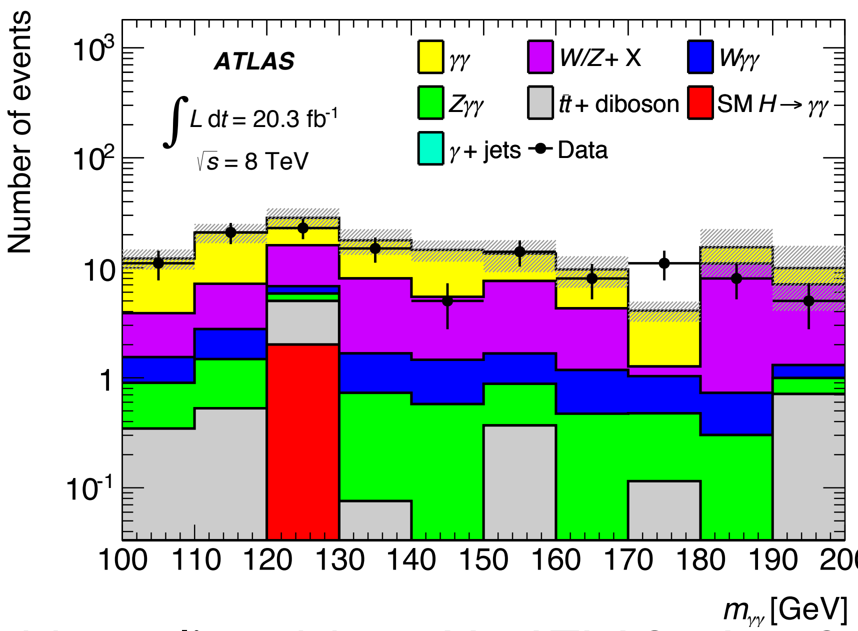
H + MET

trying to relate the Higgs sector to DM (especially for $m_{DM} > m_H$)

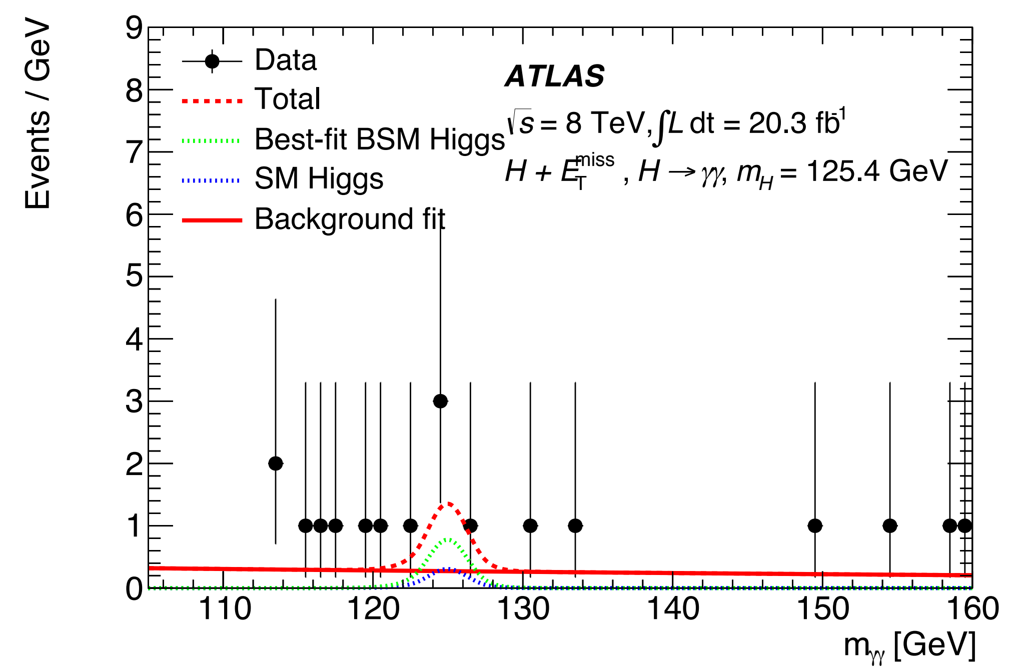
- tight, isolated **photons** (à la H->$\gamma\gamma$), 105 < $m_{\gamma\gamma}$ < 160 GeV
- **MET** > 90 GeV, $p_T(\gamma\gamma)$ > 90 GeV (balanced γ's)
- from **sidebands** (non-resonant), except H+MET (ZH, WH)
- H+MET bkg uncertainty ~6% (theo) ⊕ 4% (γ ID, E scale, JES)



$m_{\gamma\gamma}$ in SR (data vs MC)

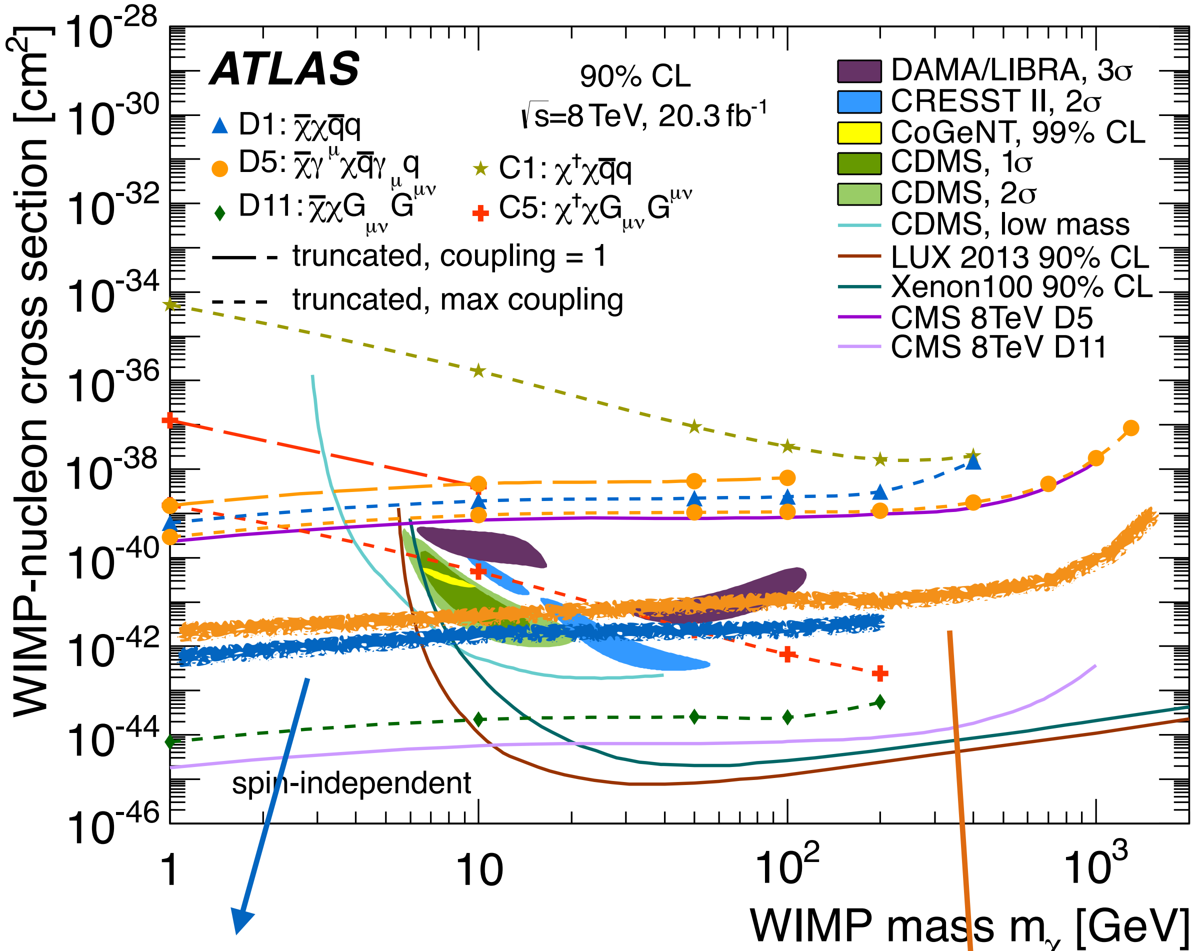


$m_{\gamma\gamma}$ in SR (fit)

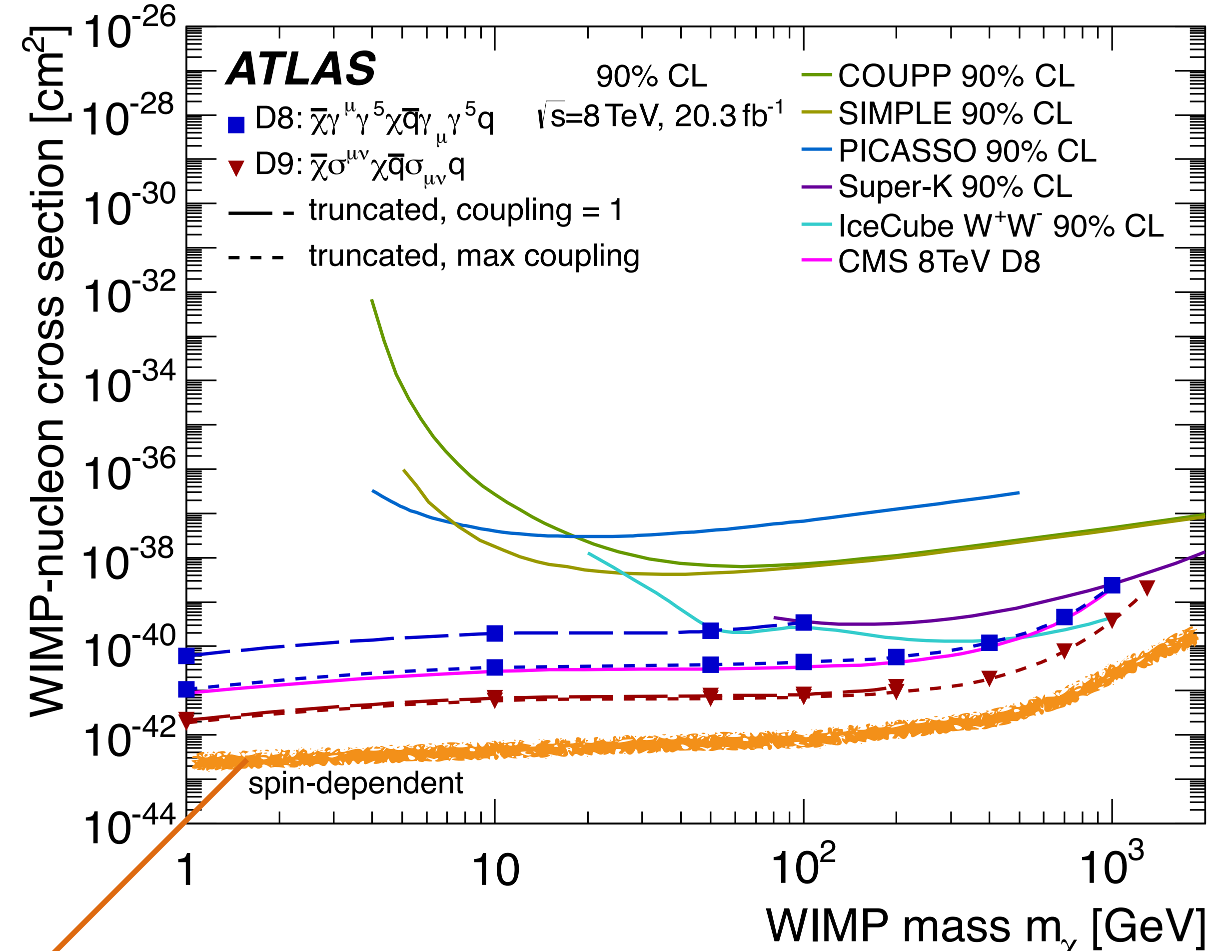


All You Care About...

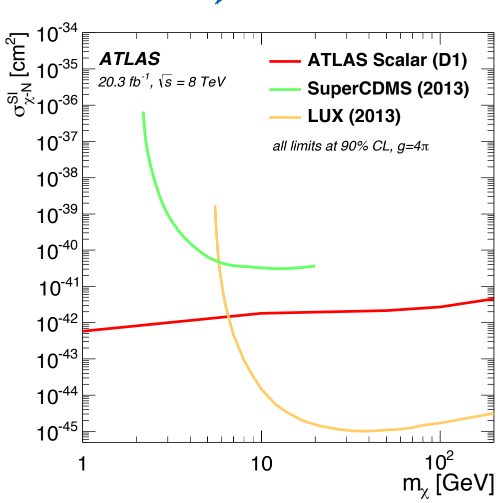
limit on **SI** χ-nucleon interaction xsec



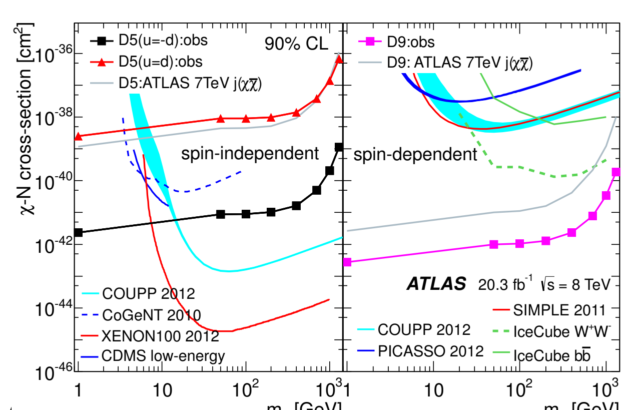
limit on **SD** χ-nucleon interaction xsec



D1, b+DM



D5 (u=-d), D9, fat-jet+DM

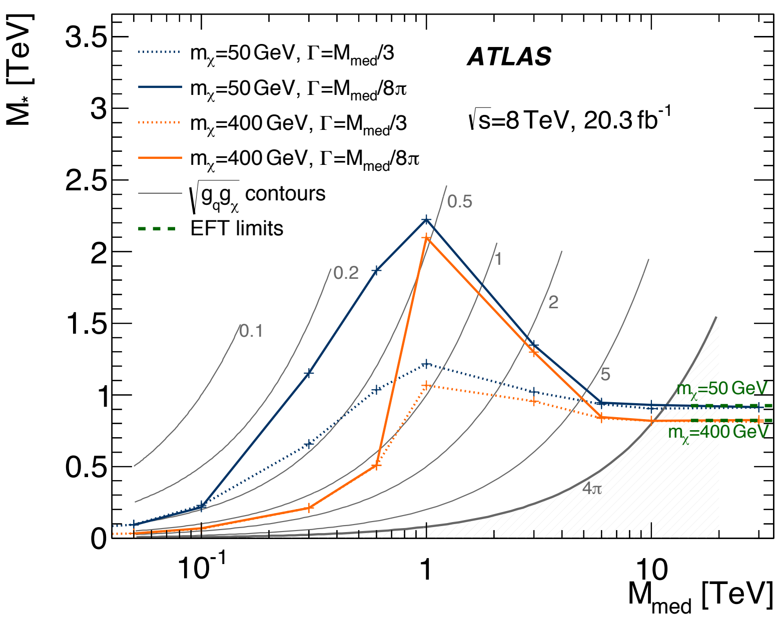


jet+DM best player on the DirDet EFT plane for low m_{DM}, but...

$Q \ll M_{med} = M^* \sqrt{g_{SM} g_{DM}}$ EFT validity requirement makes comparison with DirDet tricky...

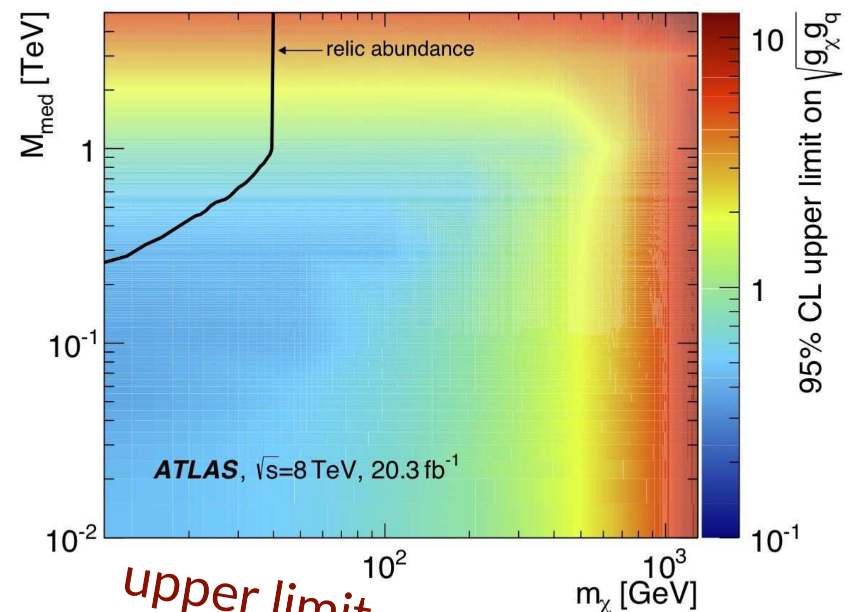
…And Beyond…

jet+DM Z'-like model



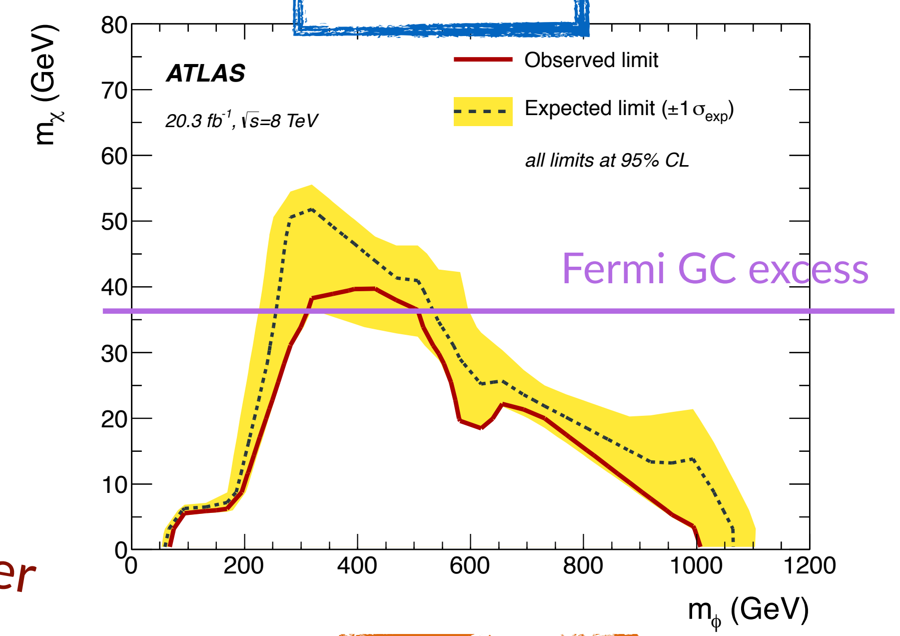
M* limit depends on Q vs M_{med}!

⊕ *plethora of* ***simplified models*** *(being) considered to exploit full LHC reach ☞ we can really say more than simple ISR EFT…*

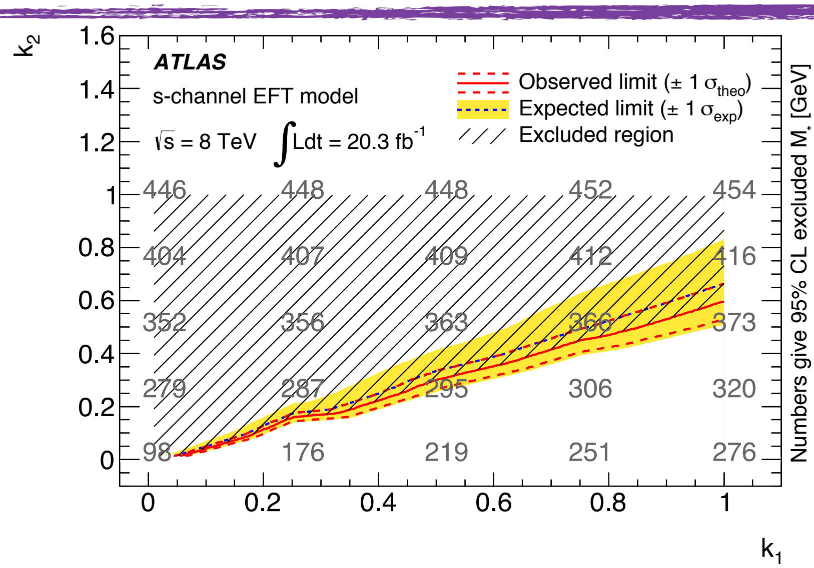


upper limit on couplings vs lower limit from relic abundance

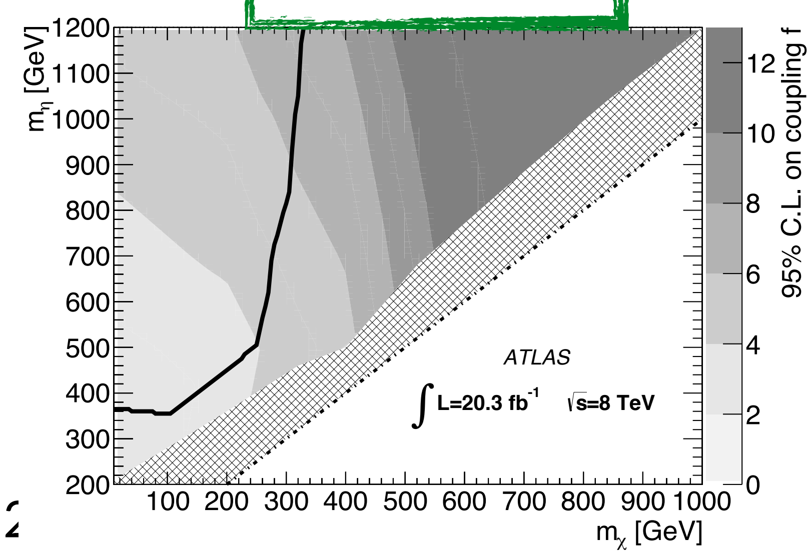
b+DM



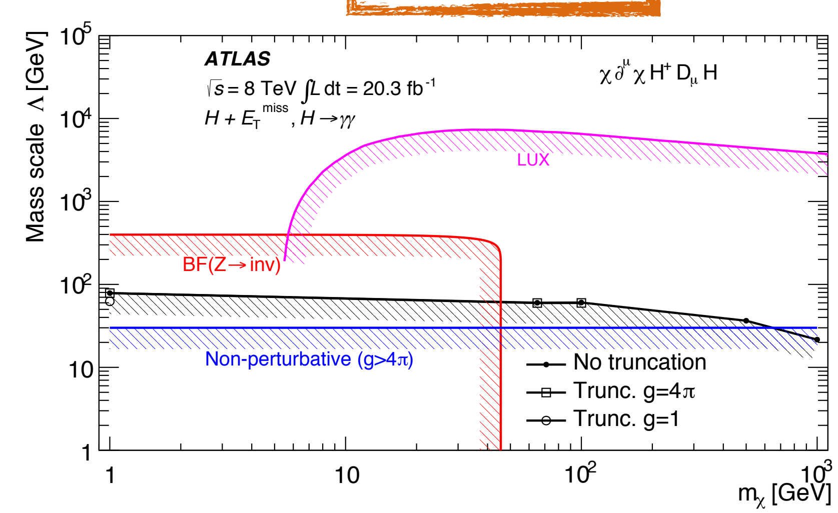
γ+DM (vs Fermi-LAT 130 GeV excess)



Z(ll)+DM



H+DM

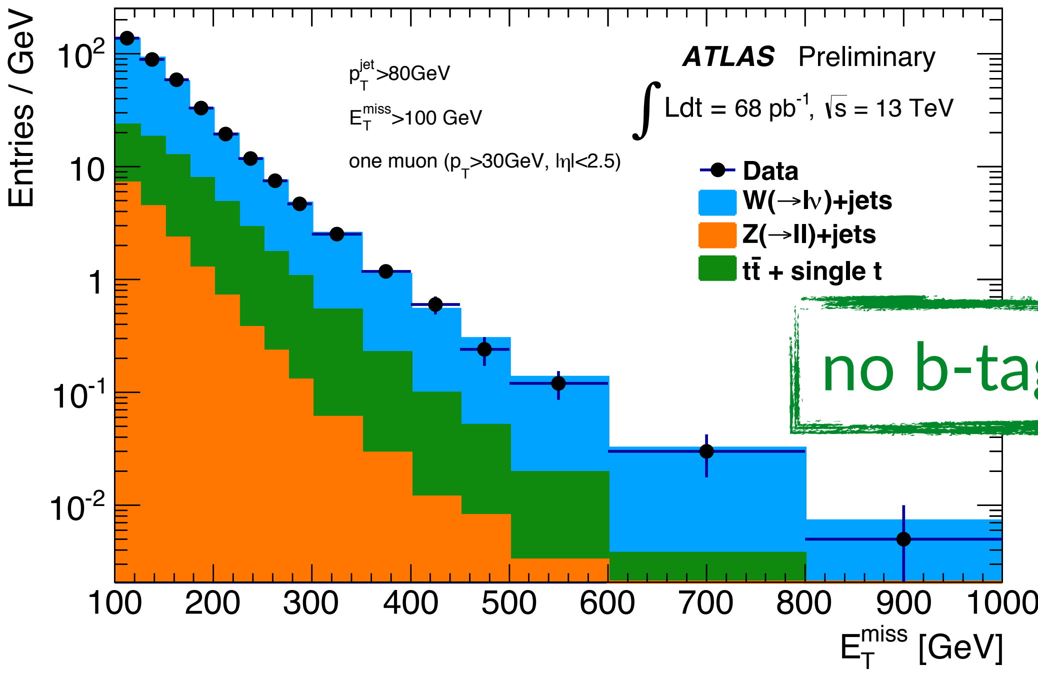


Starting Blocks!

~80 pb^{-1} of intense work to commission detector and analyses

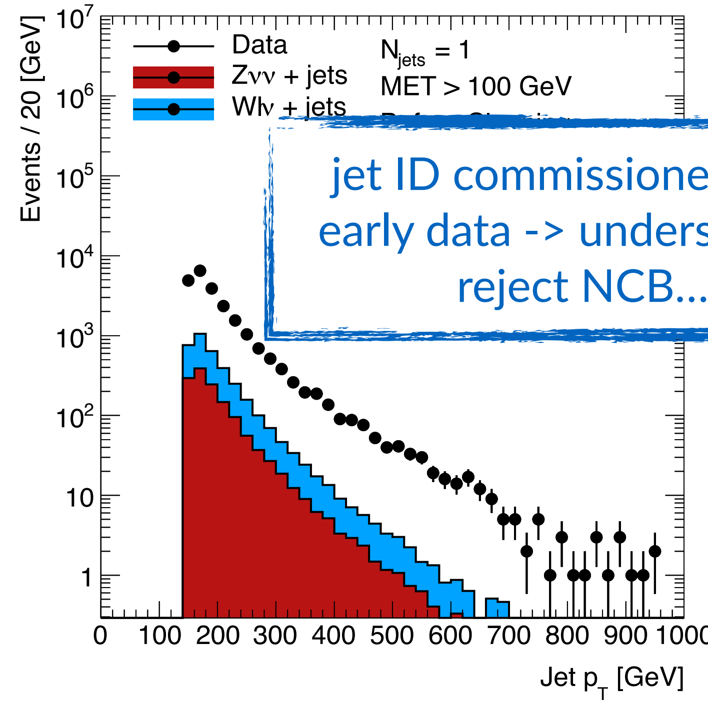
EXOT-2015-005
EXOT-2015-006
EXOT-2015-007

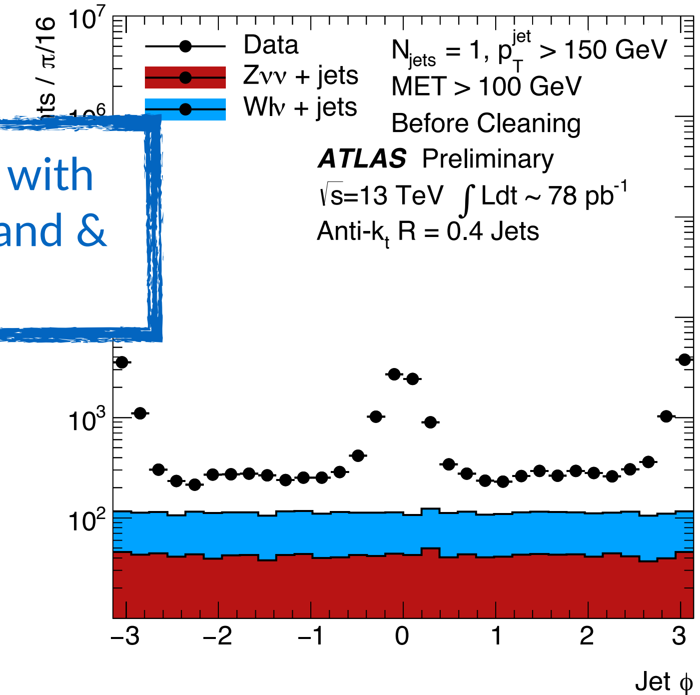
jet+DM ready to go



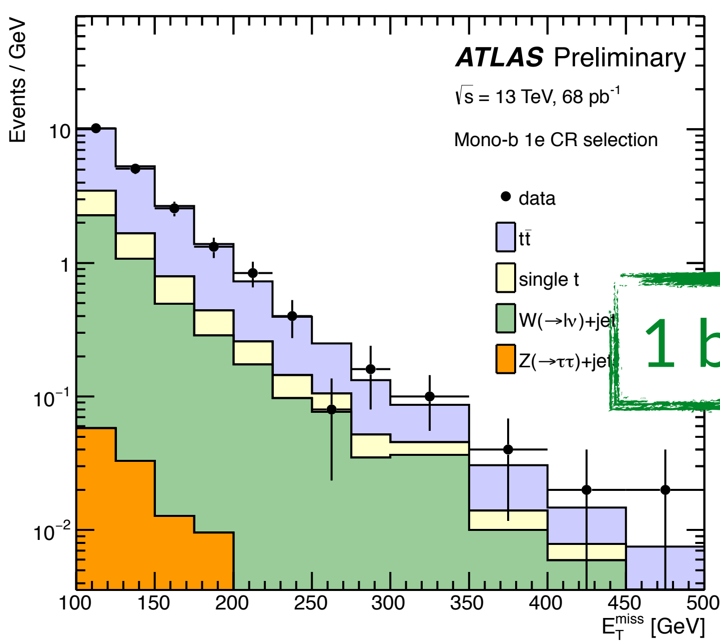
no b-tag

non-collision bkg under control

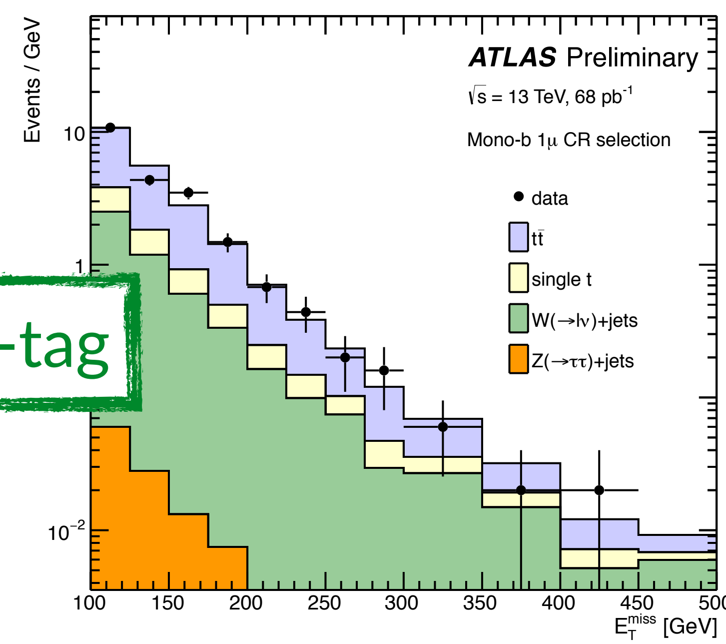




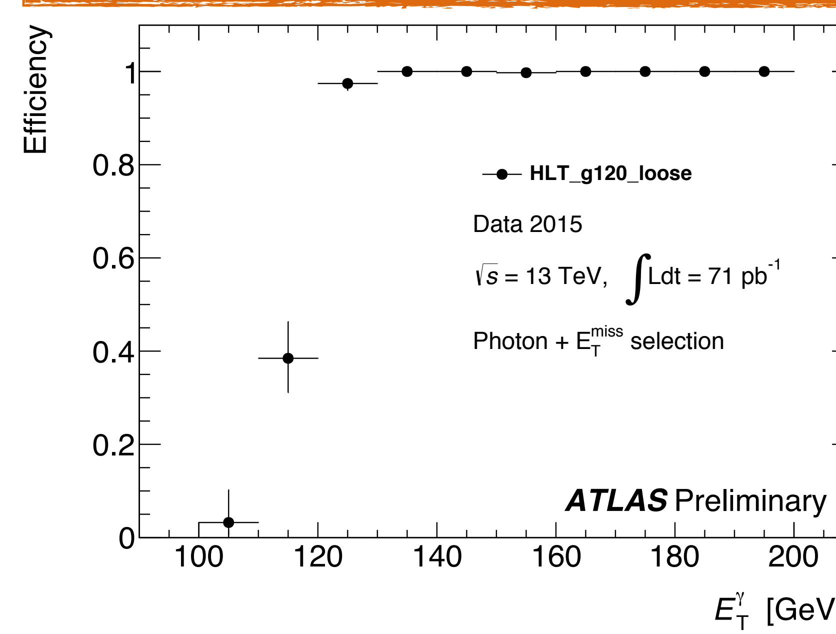
jet ID commissioned with early data -> understand & reject NCB...



1 b-tag



ready for triggering γ+DM



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EXOT-2015-005
EXOT-2015-006
EXOT-2015-007

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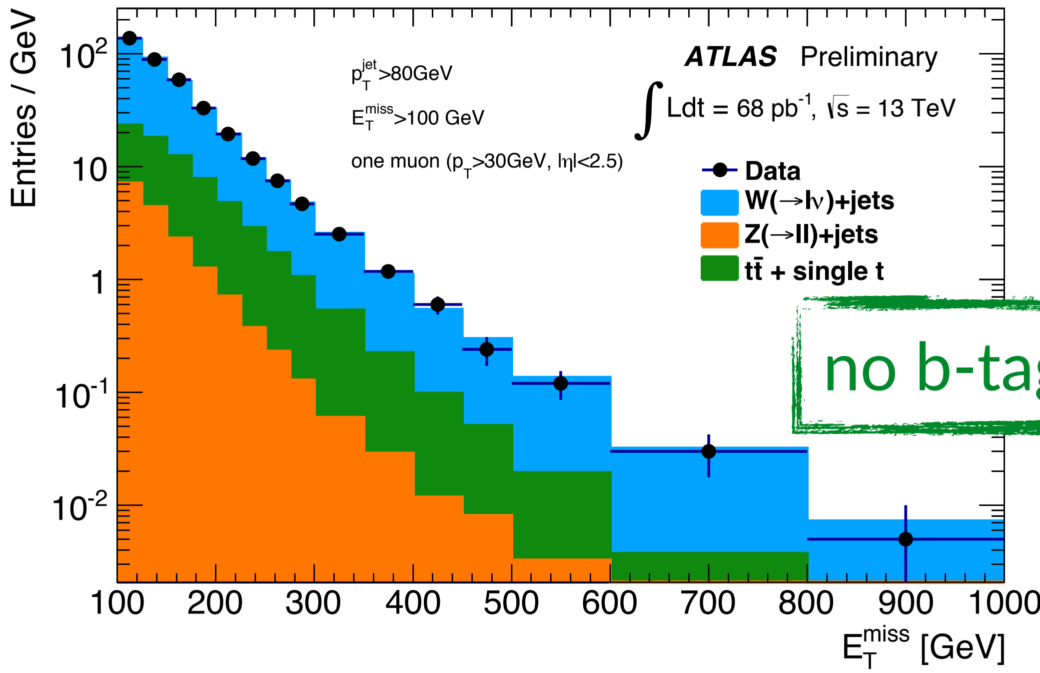

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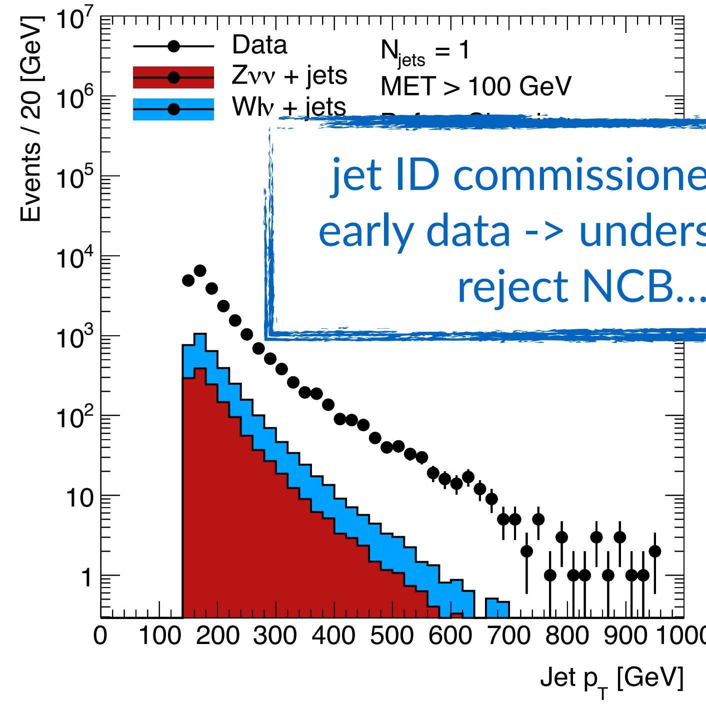

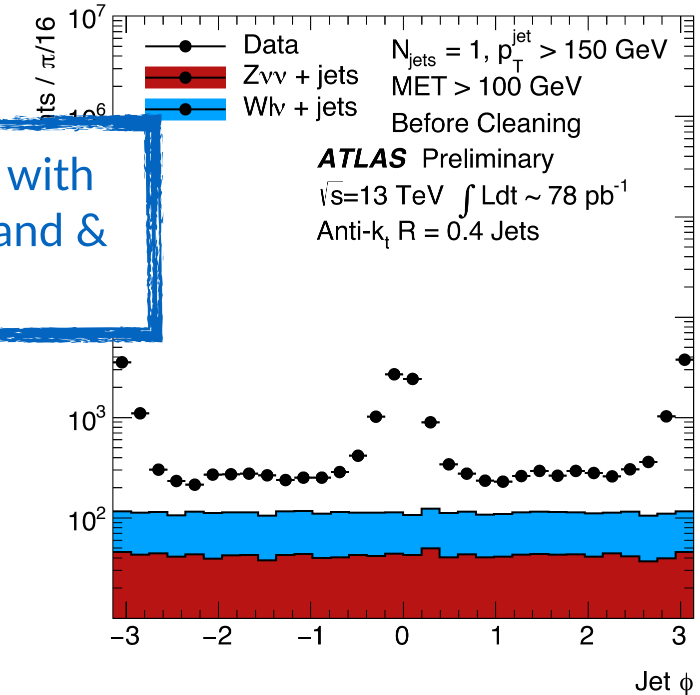

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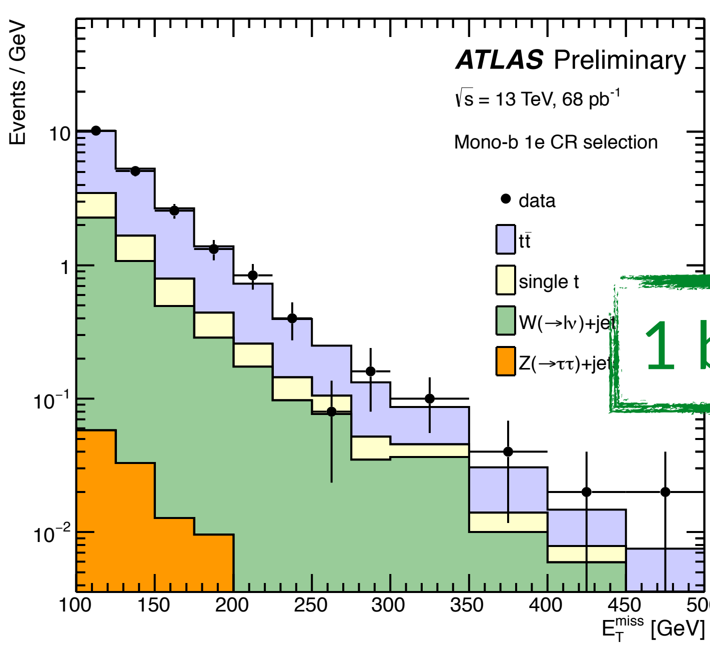
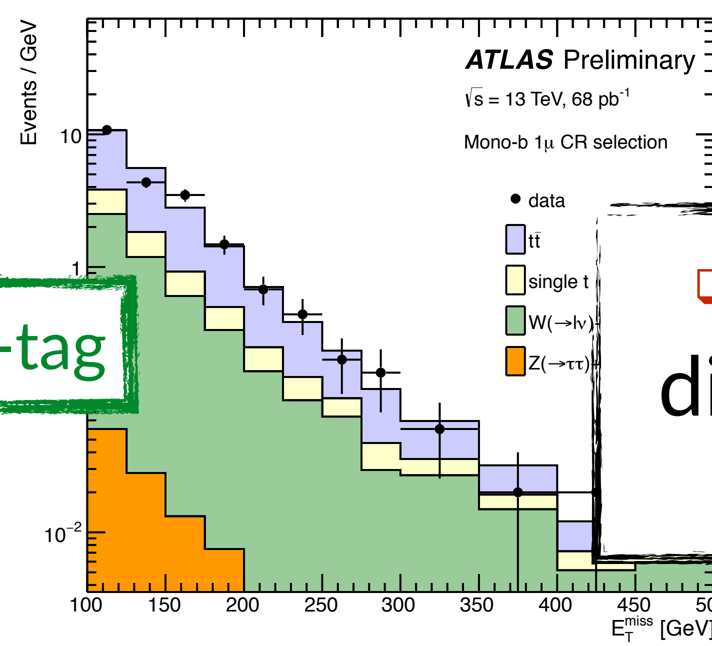


1 b-tag



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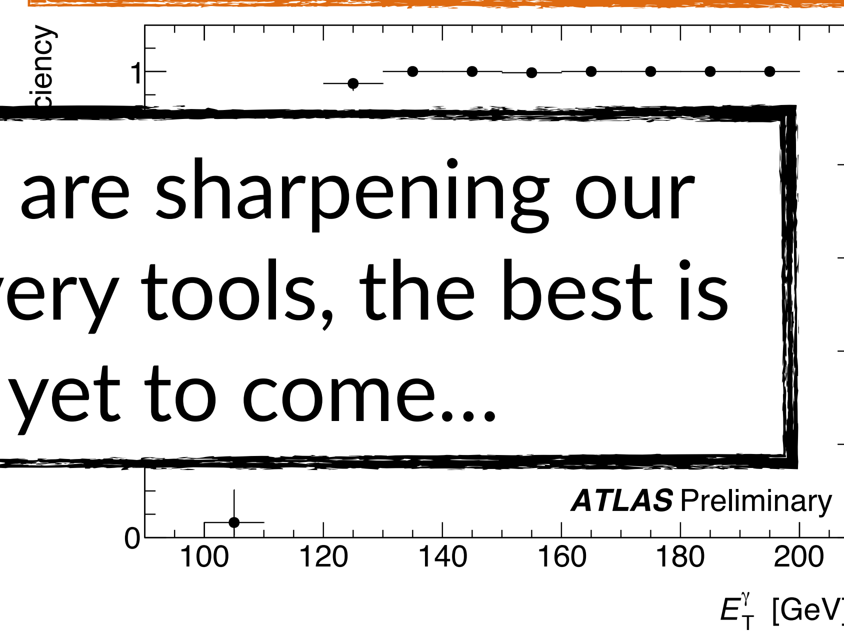


➪ we are sharpening our discovery tools, the best is yet to come...

SURPRISES

<intentionally left blank>

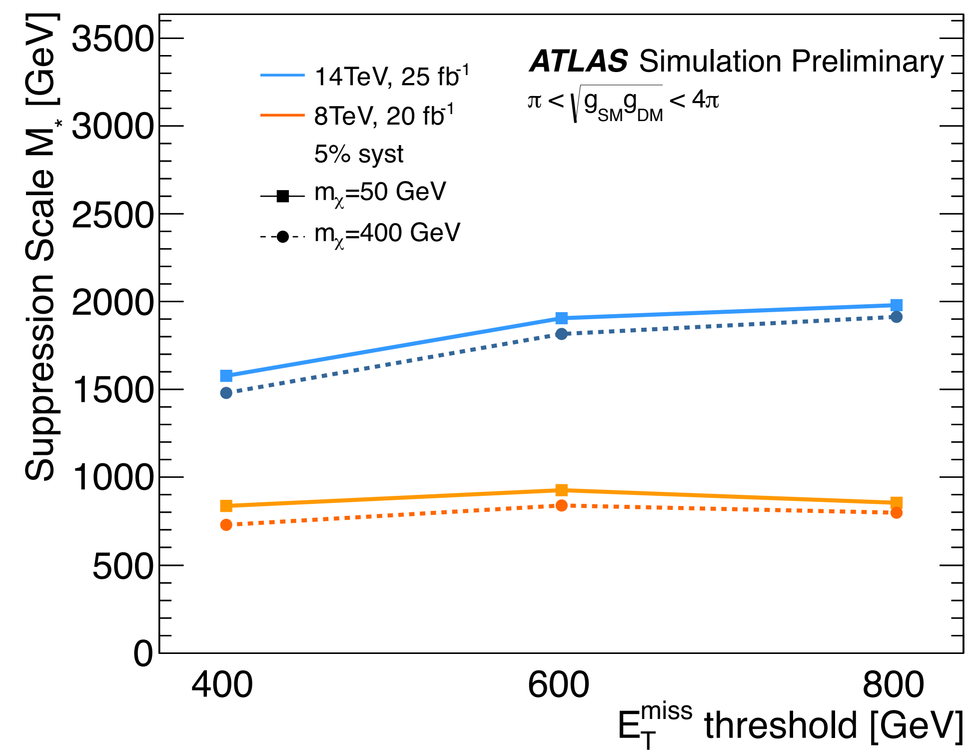
~~Tommy~~ ATLAS EXPERIMENT, can you see me?

our **telescope**: LHC as a probe for DM

ATLAS can be **competitive** with DirDet

- extend reach to <u>low mass</u> WIMPS
- probe different simplified scenarios
- ultimately, *produce&study* DM

jet+DM: √s is gonna matter!



ATL-PHYS-PUB-2014-007

our **sky**: Run-2!

look *everywhere*: beyond **EFT**,
X+inv w/**simplified models**, dijet (look for mediators directly)…

joint ATLAS+CMS strategy on simplified models (arXiv:1507.00966)

look *carefully*: optimise detector and techniques for high p_T regime

new data will tell us!

Backup

poorlydrawnlines.com

Q&A

Question	Typical Answer Provider	Mr. X
is it really only about gravitation?	jet + MET	fermion, scalar
explain Fermi-LAT excess?	γ + MET	fermion
explain Galactic Center excess?	b-jet + MET	fermion, complex scalar
related to the Big Discovery?	H($\gamma\gamma$) + MET	fermion, scalar

OPERATOR, PLEASE?

x = sensitive, v = best observed limit

EFT ——— SimMod

DM-SM interaction	C1	C5	D1	D5	D8	D9	D11	H	$Z\chi\chi$	$\gamma\chi\chi$	Z'	b-FDM
channel / interaction	SI				SD		SI					
jet + DM	X	V	X	V	V	X	V				V	
fat-jet + DM	X		X	x/v*		V		X				
b/bb/tt+DM	V		V			X						V
Z(ll) + DM			X	X		X			V			
γ + DM				X	X	X				V	X	
H($\gamma\gamma$) + DM								V				

* unique for u/d coupling interference

Operator, Please!

Name	Initial state	Type	Operator
C1	qq	Scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	Scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	Scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	Vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	Axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	Tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	Scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

MonoJet (Sel, Bkg)

Background process	Method	Control sample
$Z(\rightarrow \nu\bar{\nu})$+jets	MC and control samples in data	$Z/\gamma^*(\rightarrow \ell^+\ell^-)$, $W(\rightarrow \ell\nu)$ ($\ell = e, \mu$)
$W(\rightarrow e\nu)$+jets	MC and control samples in data	$W(\rightarrow e\nu)$ (loose)
$W(\rightarrow \tau\nu)$+jets	MC and control samples in data	$W(\rightarrow e\nu)$ (loose)
$W(\rightarrow \mu\nu)$+jets	MC and control samples in data	$W(\rightarrow \mu\nu)$
$Z/\gamma^*(\rightarrow \ell^+\ell^-)$+jets ($\ell = e, \mu, \tau$)	MC-only	
$t\bar{t}$, single top	MC-only	
Diboson	MC-only	
Multijets	Data-driven	
Non-collision	Data-driven	

Selection criteria									
Preselection									
Primary vertex									
$E_T^{miss} > 150$ GeV									
Jet quality requirements									
At least one jet with $p_T > 30$ GeV and $\|\eta\| < 4.5$									
Lepton and isolated track vetoes									
Monojet-like selection									
The leading jet with $p_T > 120$ GeV and $\|\eta\| < 2.0$									
Leading jet $p_T/E_T^{miss} > 0.5$									
$\Delta\phi(\text{jet}, \mathbf{p}_T^{miss}) > 1.0$									
Signal region	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8	SR9
Minimum E_T^{miss} (GeV)	150	200	250	300	350	400	500	600	700

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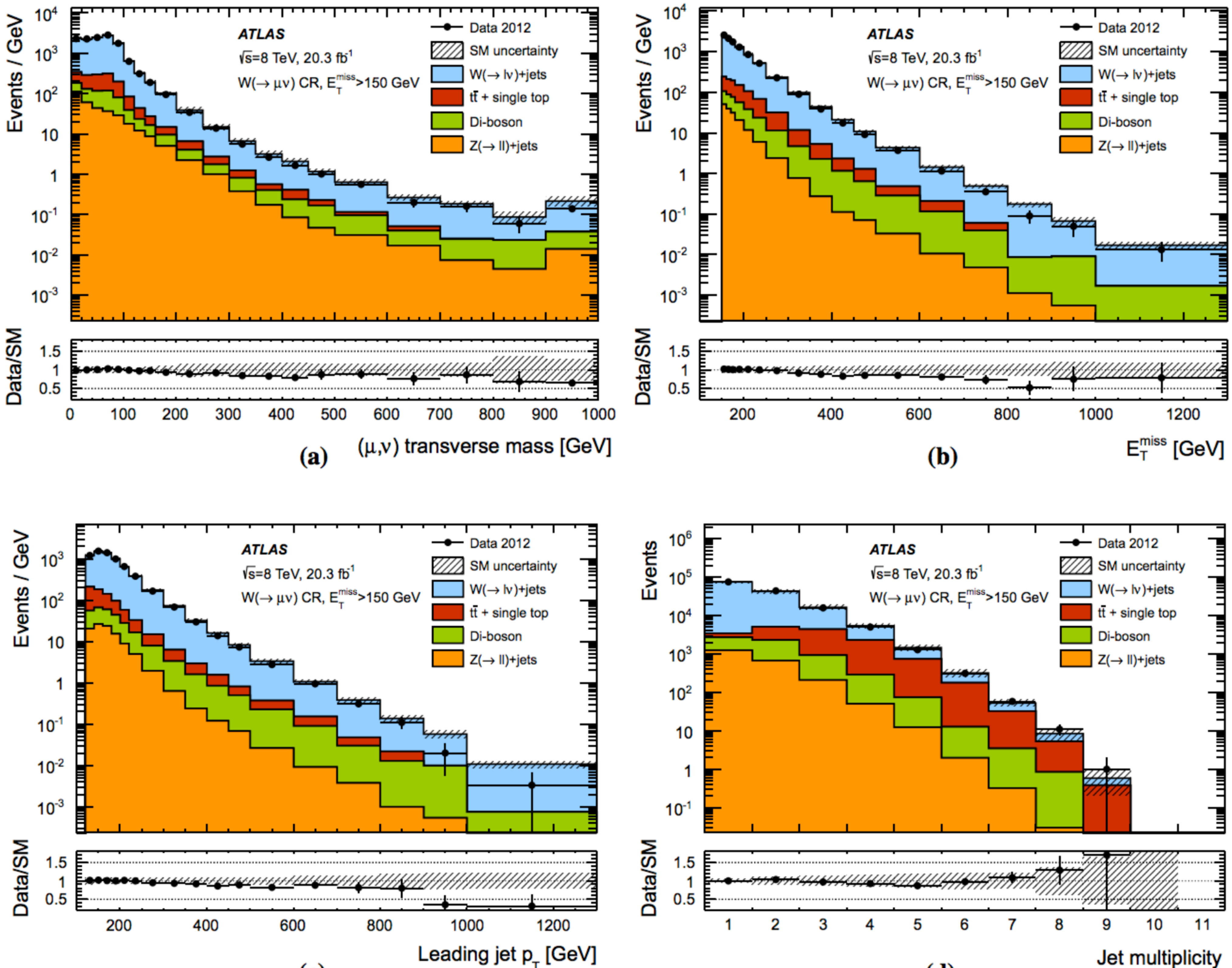
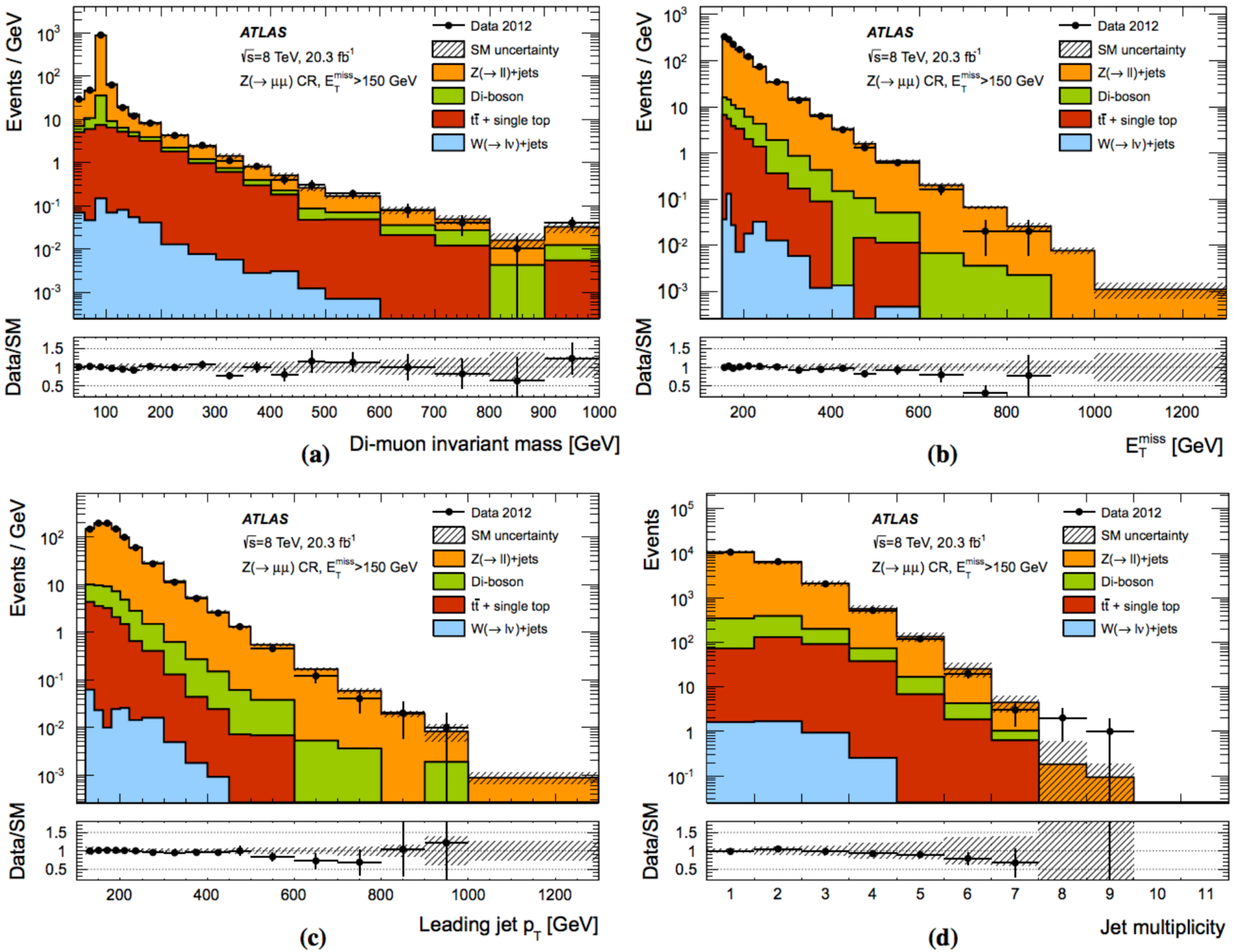
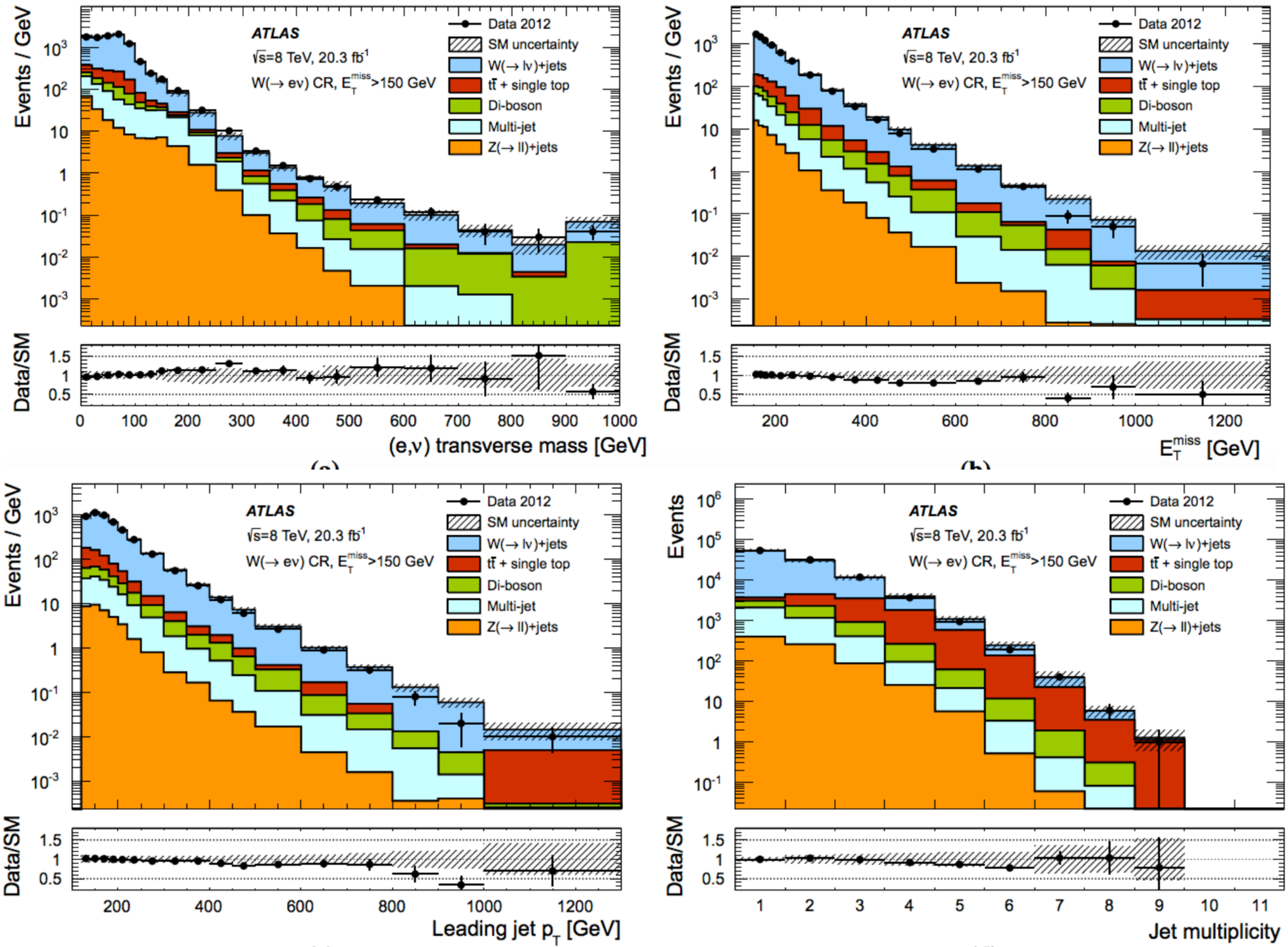
MonoJet (CR1μ)



MonoJet (CR2μ)



MonoJet (CR1e)



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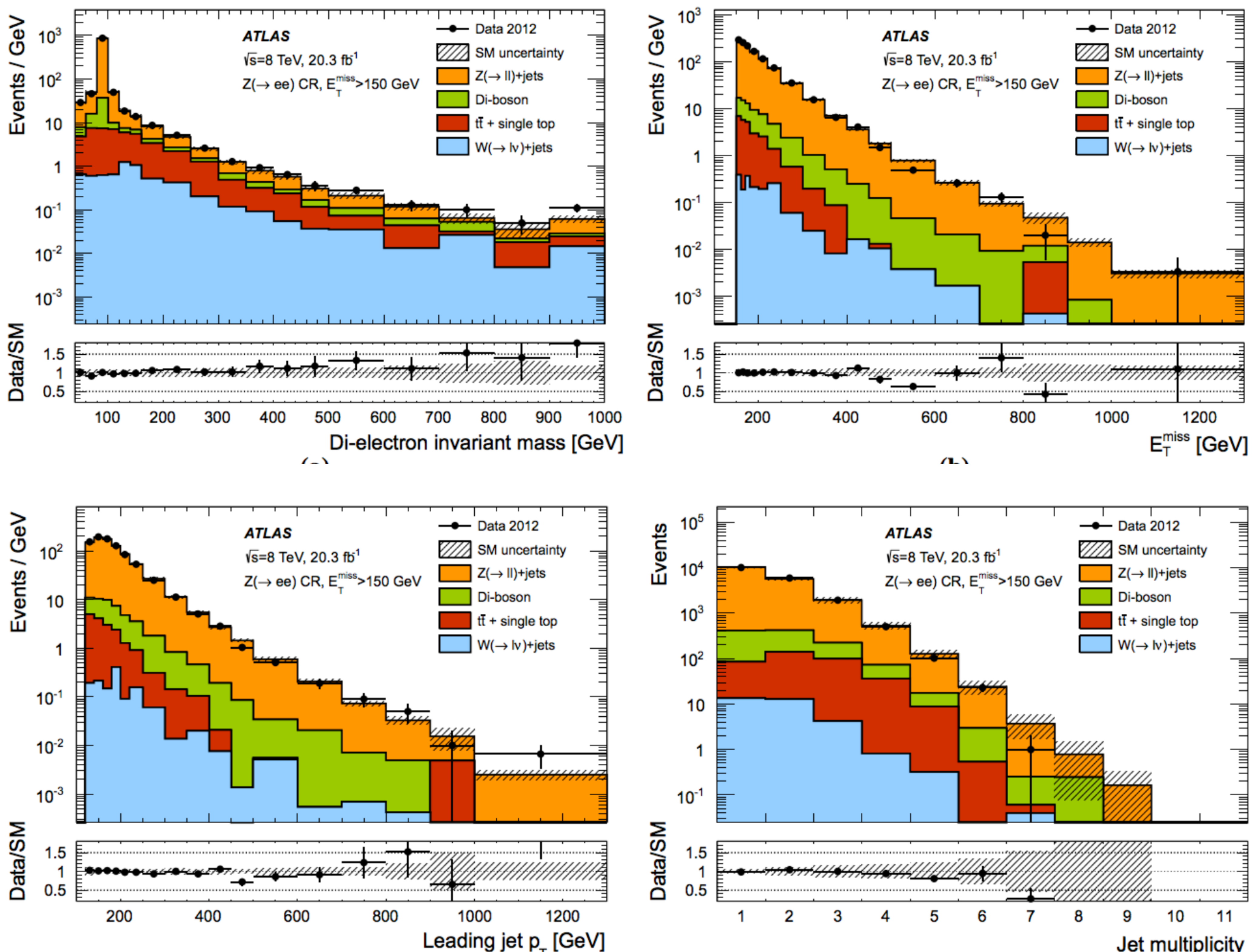
MonoJet (CR2e)

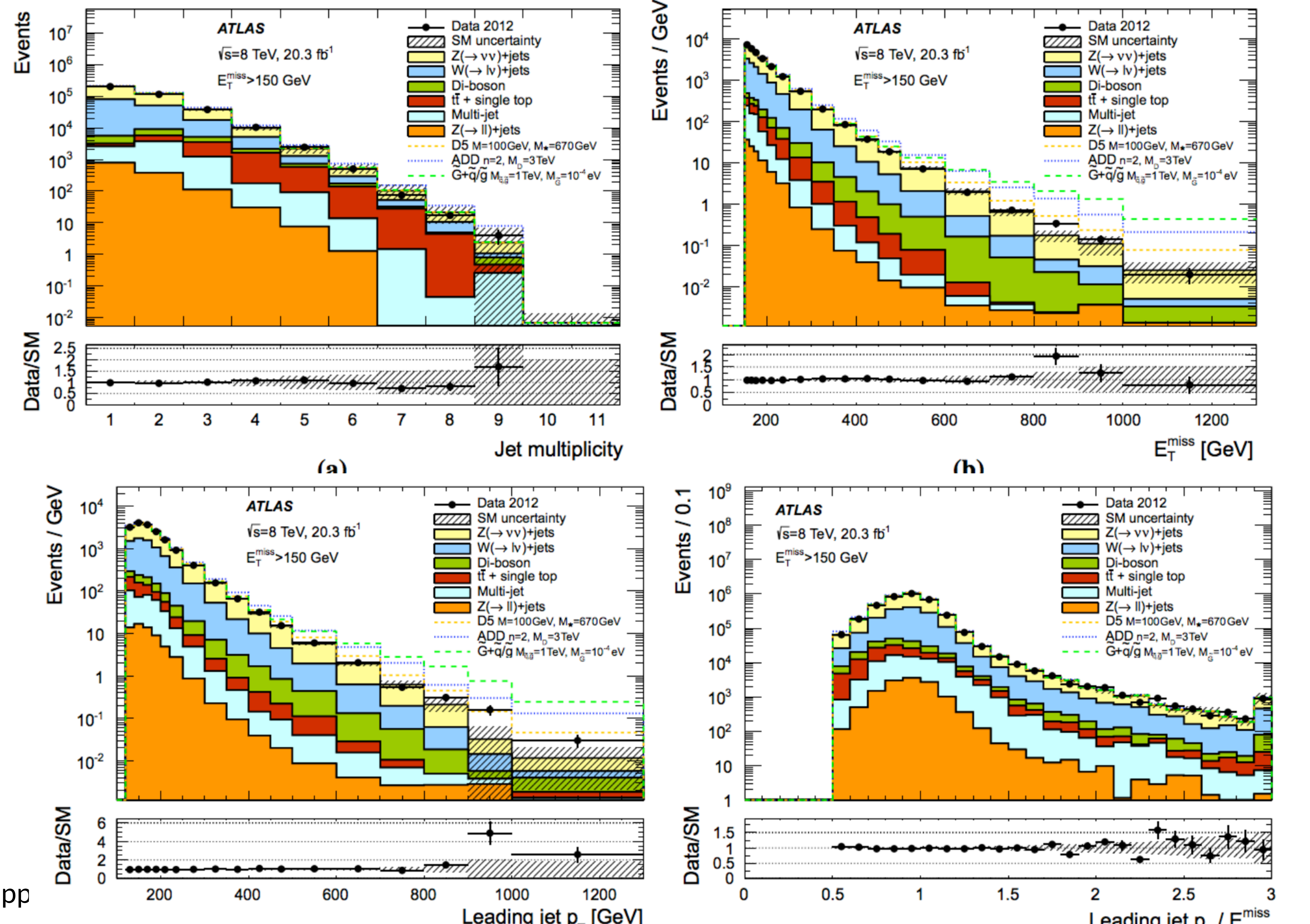


MonoJet (Yields)

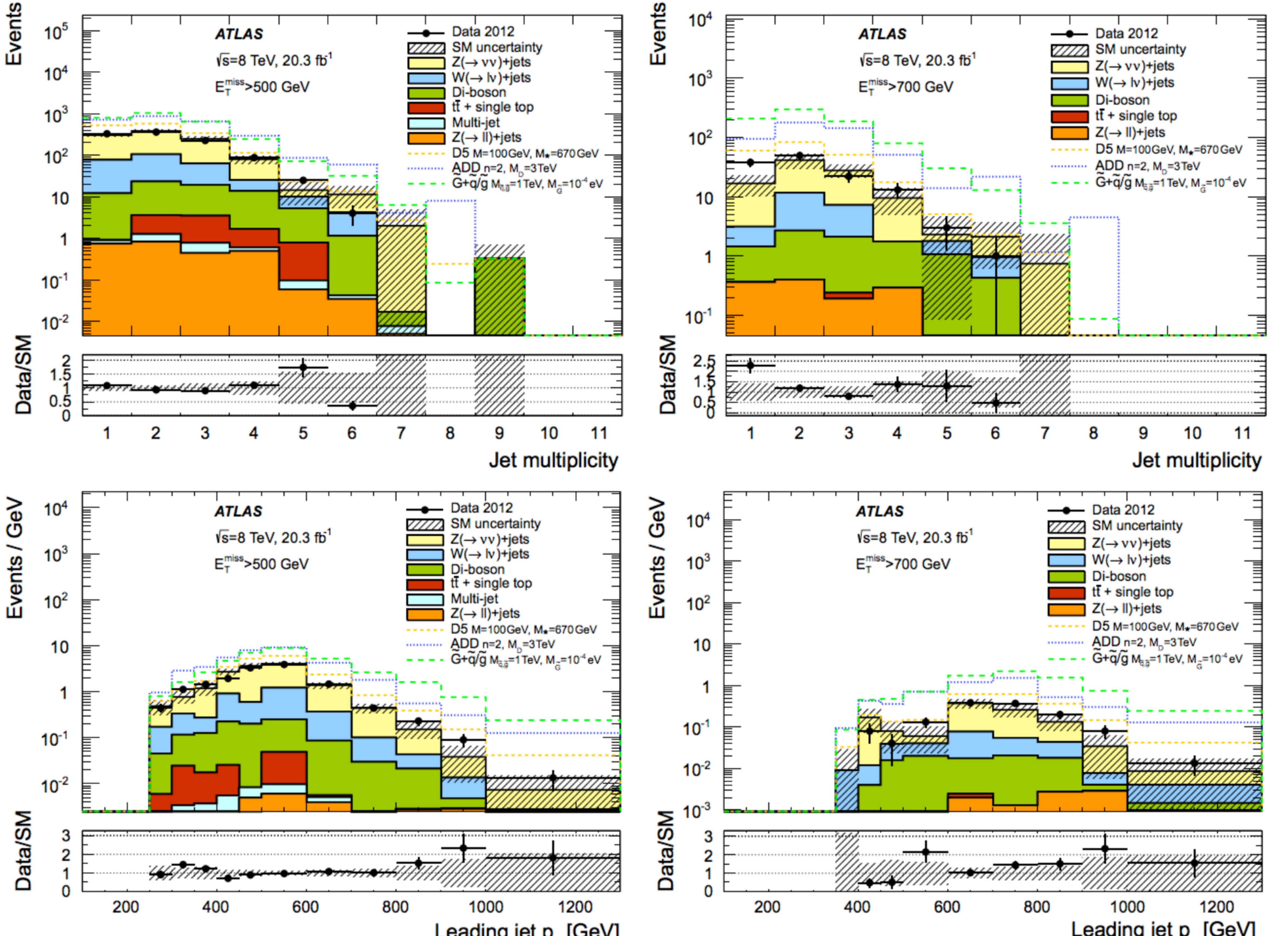
Signal region	SR1	SR2	SR3	SR4	SR5
Observed events	364378	123228	44715	18020	7988
SM expectation	372100 ± 9900	126000 ± 2900	45300 ± 1100	18000 ± 500	8300 ± 300
$Z(\rightarrow \nu\bar{\nu})$	217800 ± 3900	80000 ± 1700	30000 ± 800	12800 ± 410	6000 ± 240
$W(\rightarrow \tau\nu)$	79300 ± 3300	24000 ± 1200	7700 ± 500	2800 ± 200	1200 ± 110
$W(\rightarrow e\nu)$	23500 ± 1700	7100 ± 560	2400 ± 200	880 ± 80	370 ± 40
$W(\rightarrow \mu\nu)$	28300 ± 1600	8200 ± 500	2500 ± 200	850 ± 80	330 ± 40
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$	530 ± 220	97 ± 42	19 ± 8	7 ± 3	4 ± 2
$Z/\gamma^*(\rightarrow \tau^+\tau^-)$	780 ± 320	190 ± 80	45 ± 19	14 ± 6	5 ± 2
$t\bar{t}$, single top	6900 ± 1400	2300 ± 500	700 ± 160	200 ± 70	80 ± 40
Dibosons	8000 ± 1700	3500 ± 800	1500 ± 400	690 ± 200	350 ± 120
Multijets	6500 ± 6500	800 ± 800	200 ± 200	44 ± 44	15 ± 15

Signal region	SR6	SR7	SR8	SR9
Observed events	3813	1028	318	126
SM expectation	4000 ± 160	1030 ± 60	310 ± 30	97 ± 14
$Z(\rightarrow \nu\bar{\nu})$	3000 ± 150	740 ± 60	240 ± 30	71 ± 13
$W(\rightarrow \tau\nu)$	540 ± 60	130 ± 20	34 ± 8	11 ± 3
$W(\rightarrow e\nu)$	170 ± 20	43 ± 7	9 ± 3	3 ± 1
$W(\rightarrow \mu\nu)$	140 ± 20	35 ± 6	10 ± 2	2 ± 1
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$	3 ± 1	2 ± 1	1 ± 1	1 ± 1
$Z/\gamma^*(\rightarrow \tau^+\tau^-)$	2 ± 1	0 ± 0	0 ± 0	0 ± 0
$t\bar{t}$, single top	30 ± 20	7 ± 7	1 ± 1	0 ± 0
Dibosons	183 ± 70	65 ± 35	23 ± 16	8 ± 7
Multijets	6 ± 6	1 ± 1	0 ± 0	0 ± 0

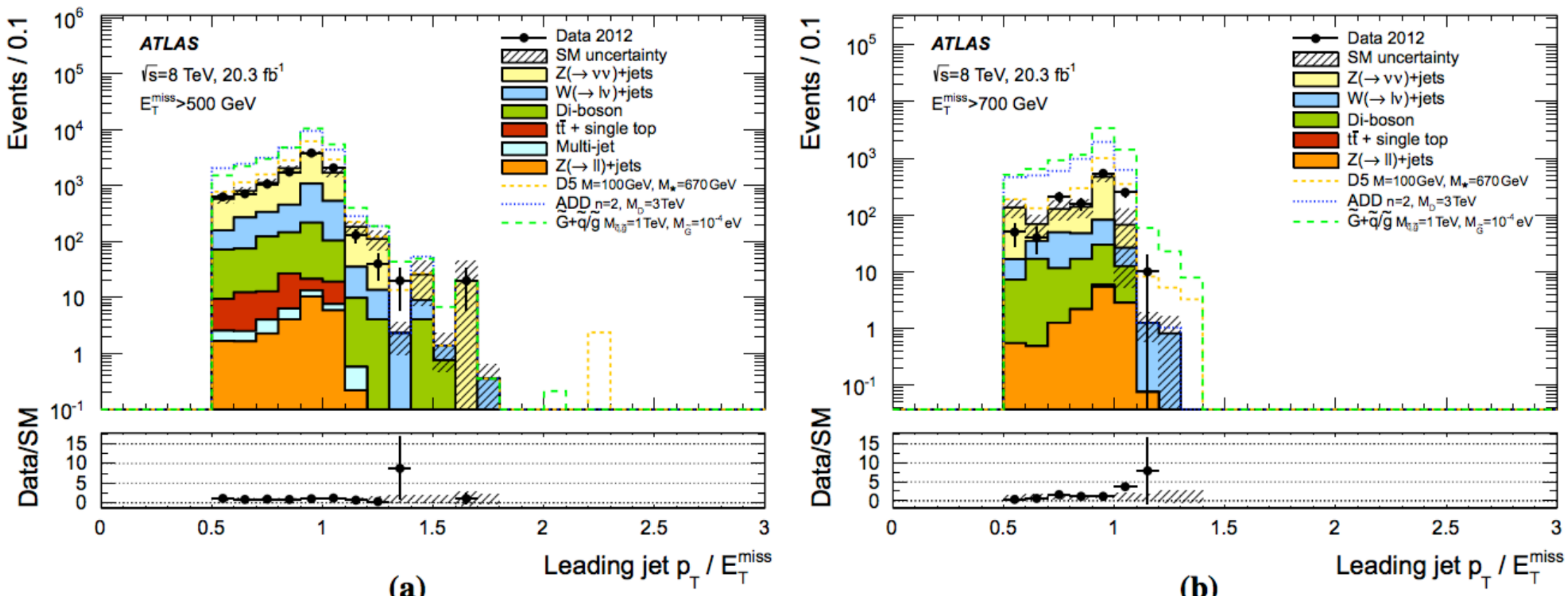
MonoJet (SR)

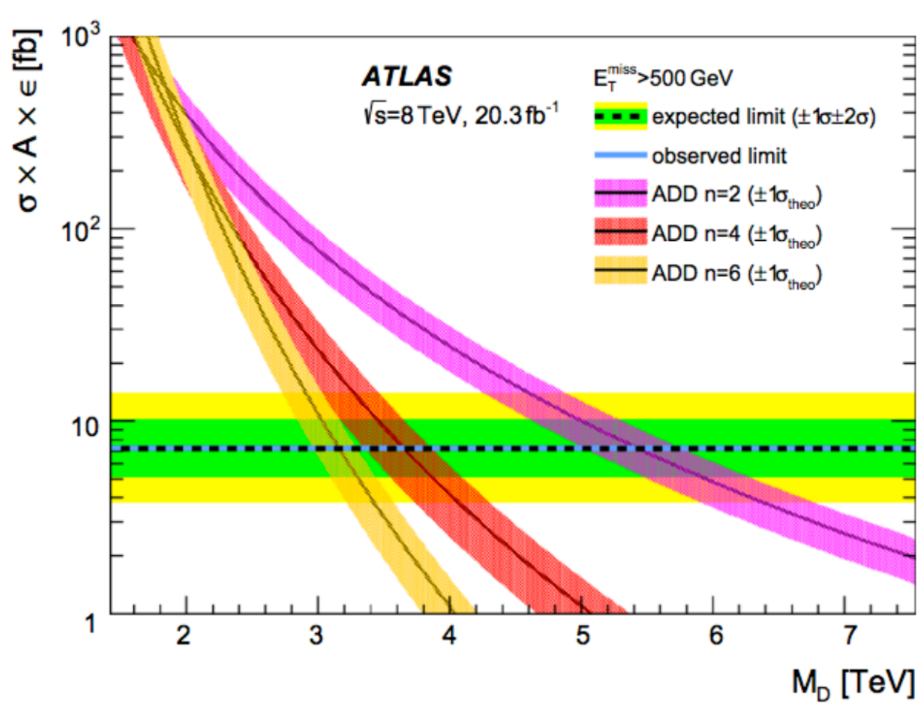

ATLAS
√s=8 TeV, 20.3 fb-1
E_T^{miss}>150 GeV
Data 2012
SM uncertainty
Z(→ νν)+jets
W(→ lν)+jets
Di-boson
tt̄ + single top
Multi-jet
Z(→ ll)+jets
D5 M=100GeV, M*=670GeV
ADD n=2, M_D=3TeV
G+q̃/g̃ M_q̃,g̃=1TeV, M_G̃=10^-4 eV
Events
Events / GeV
Events / 0.1
Data/SM
Jet multiplicity
E_T^{miss} [GeV]
Leading jet p_T [GeV]
Leading jet p_T / E_T^{miss}
(a)
(b)

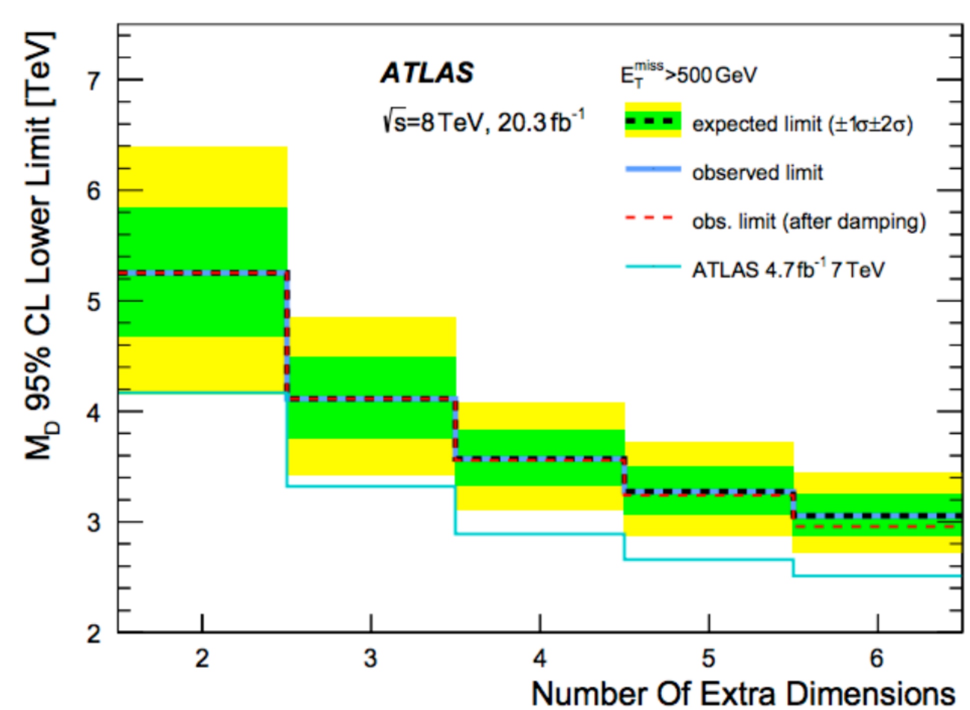
MonoJet (SR, MET > 500 GeV)



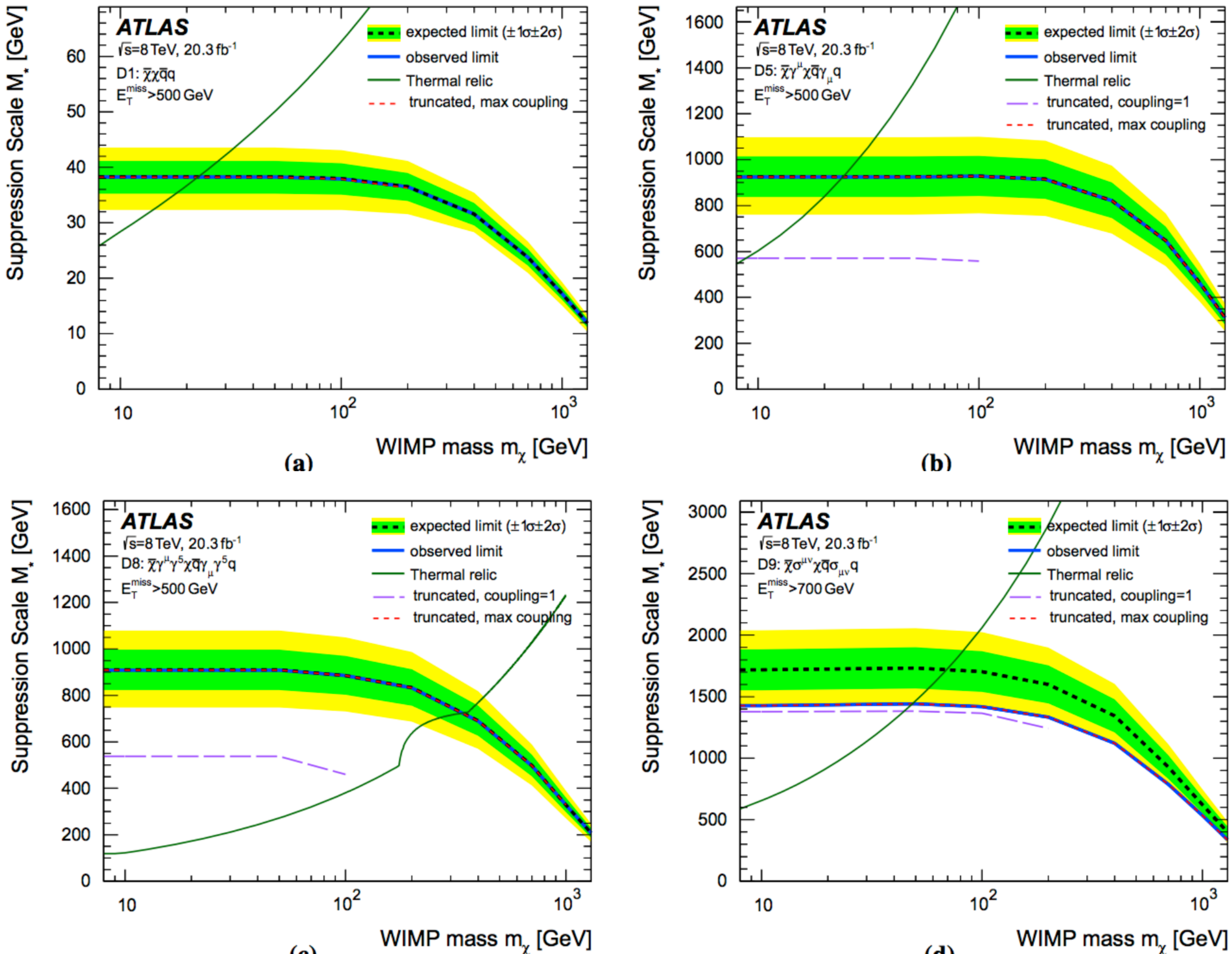
MONOJET (SR > 500 GEV & ADD)







MonoJet (M*)


ATLAS
√s=8 TeV, 20.3 fb-1
D1: χ̄χq̄q
E_T^miss>500 GeV
expected limit (±1σ±2σ)
observed limit
Thermal relic
truncated, max coupling
Suppression Scale M* [GeV]
WIMP mass mχ [GeV]
(a)
ATLAS
√s=8 TeV, 20.3 fb-1
D5: χ̄γ^μχq̄γ_μq
E_T^miss>500 GeV
expected limit (±1σ±2σ)
observed limit
Thermal relic
truncated, coupling=1
truncated, max coupling
Suppression Scale M* [GeV]
WIMP mass mχ [GeV]
(b)
ATLAS
√s=8 TeV, 20.3 fb-1
D8: χ̄γ^μγ^5χq̄γ_μγ^5q
E_T^miss>500 GeV
expected limit (±1σ±2σ)
observed limit
Thermal relic
truncated, coupling=1
truncated, max coupling
Suppression Scale M* [GeV]
WIMP mass mχ [GeV]
ATLAS
√s=8 TeV, 20.3 fb-1
D9: χ̄σ^μνχq̄σ_μνq
E_T^miss>700 GeV
expected limit (±1σ±2σ)
observed limit
Thermal relic
truncated, coupling=1
truncated, max coupling
Suppression Scale M* [GeV]
WIMP mass mχ [GeV]

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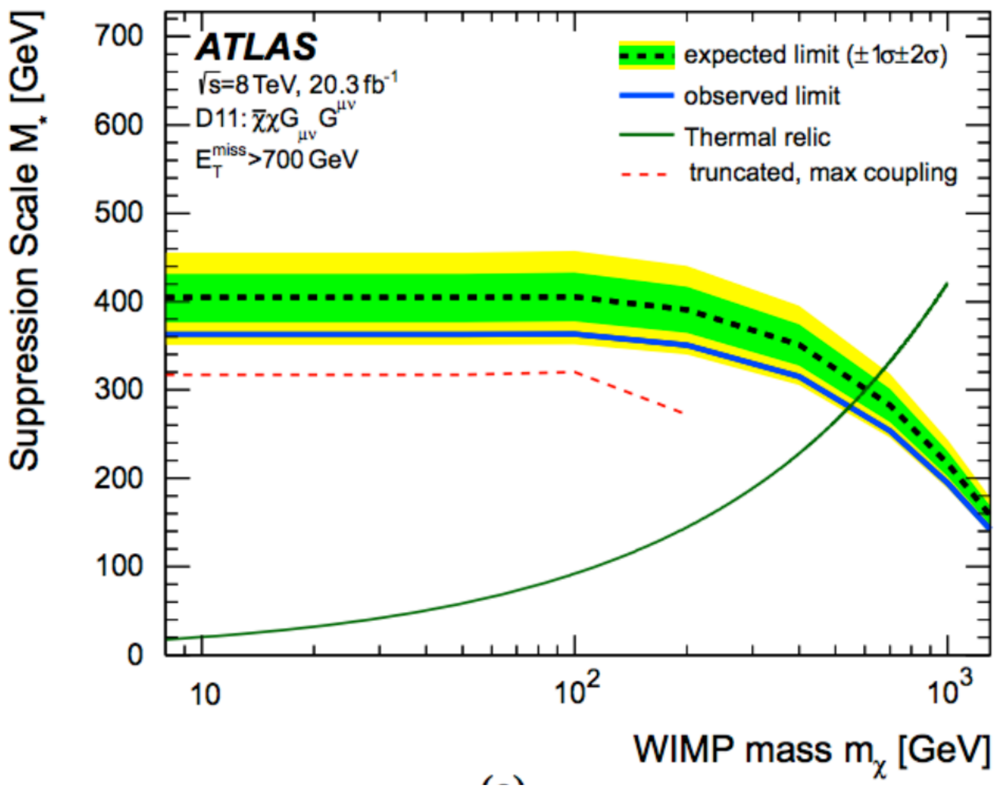
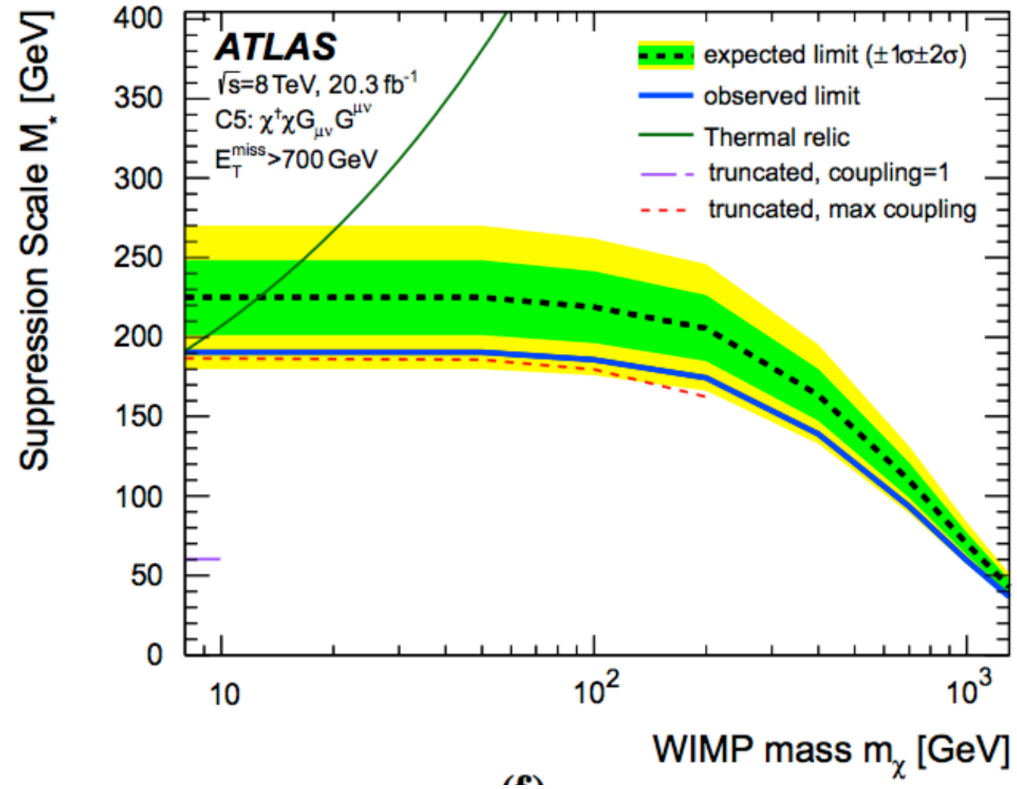
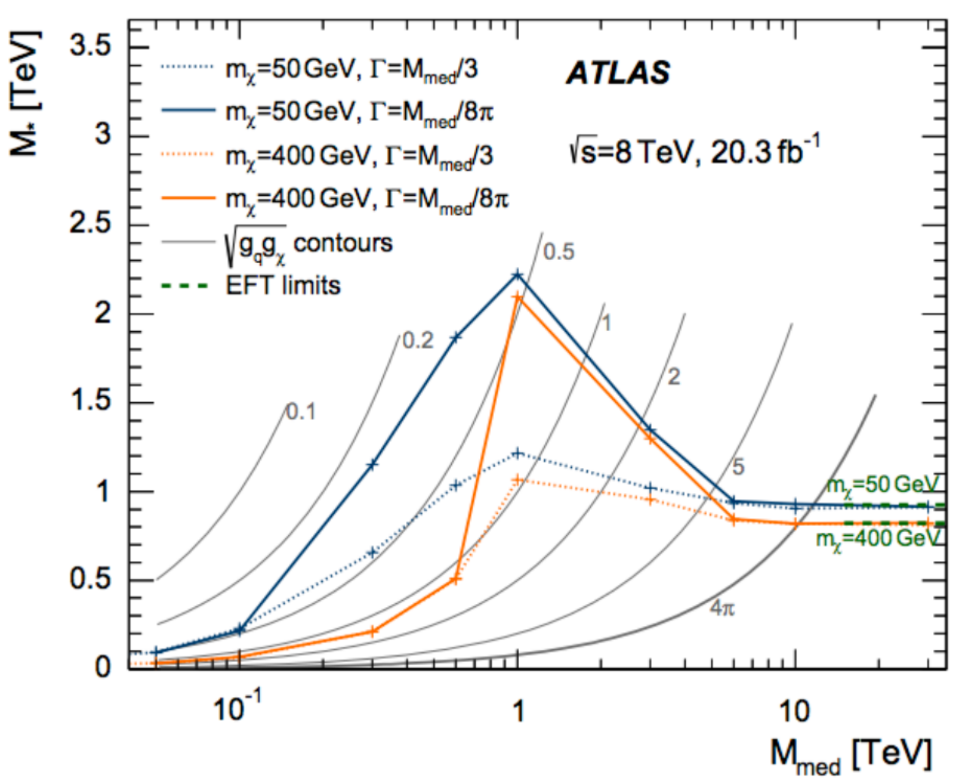
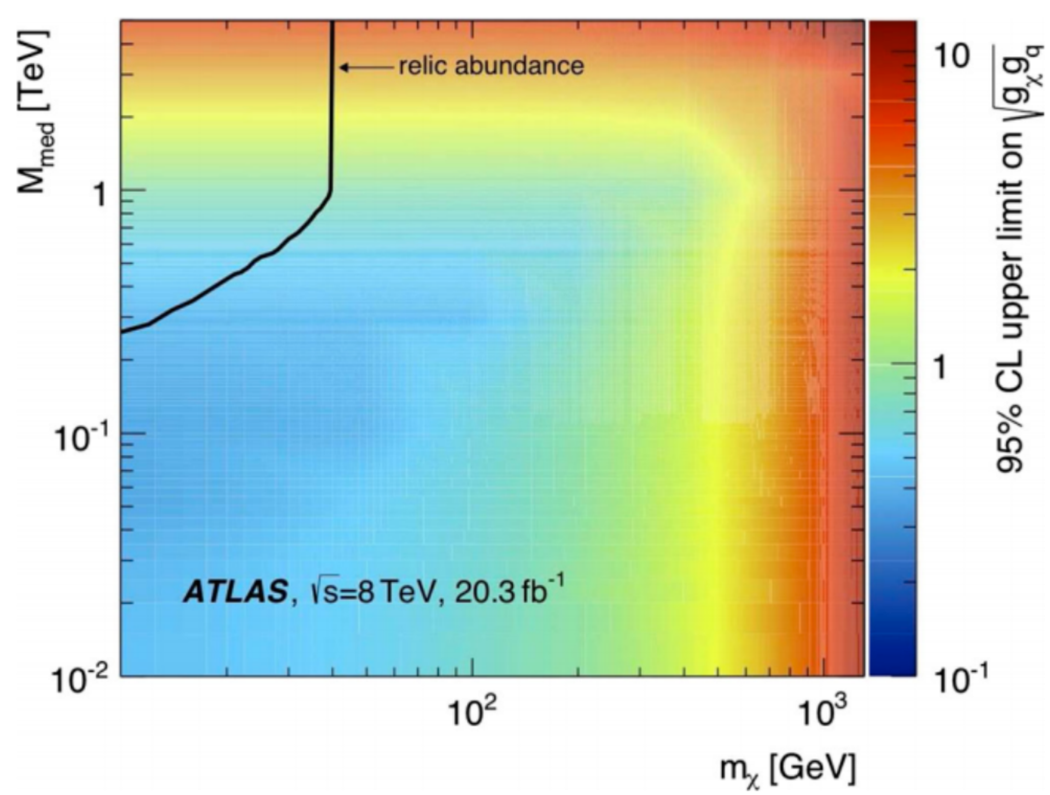
MonoJet (M* and SimMod)

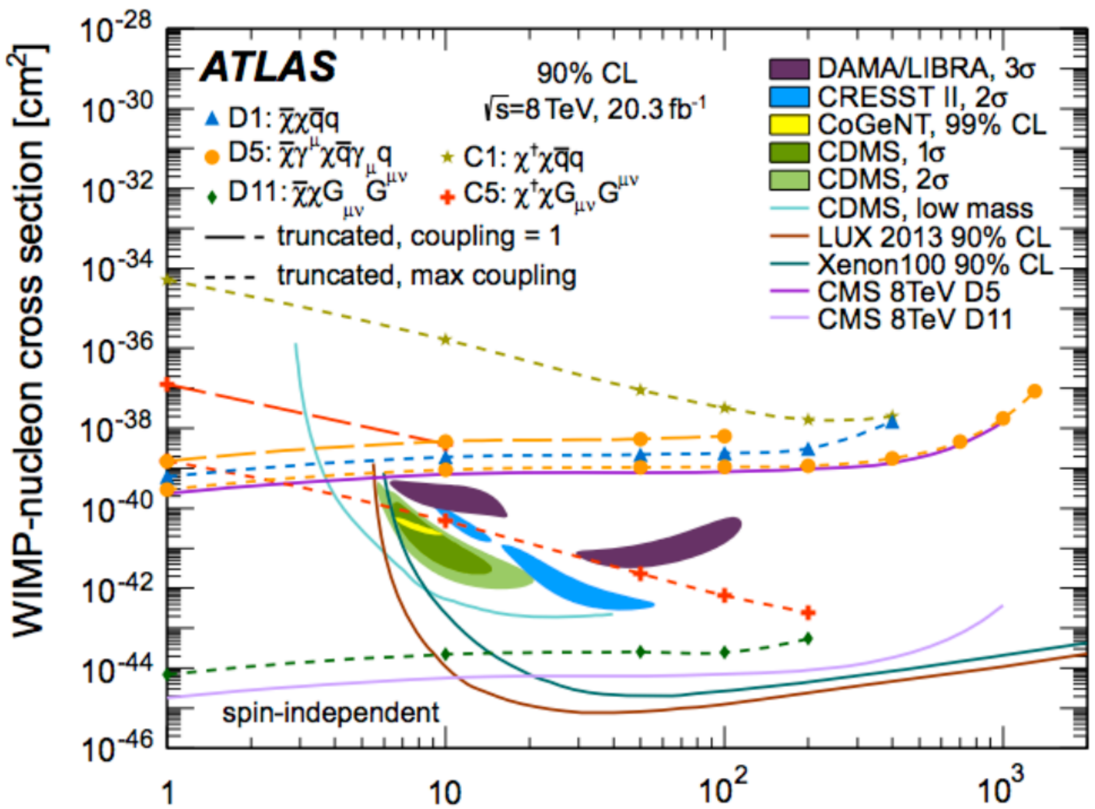


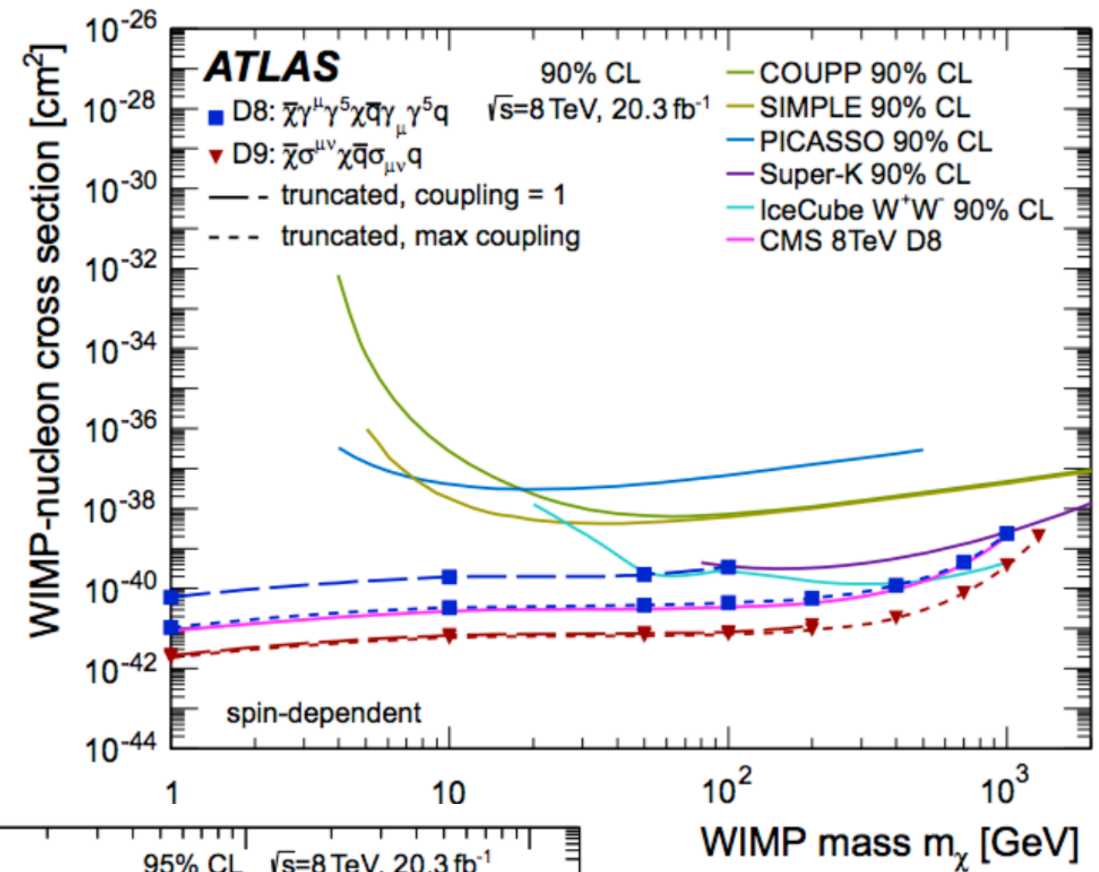




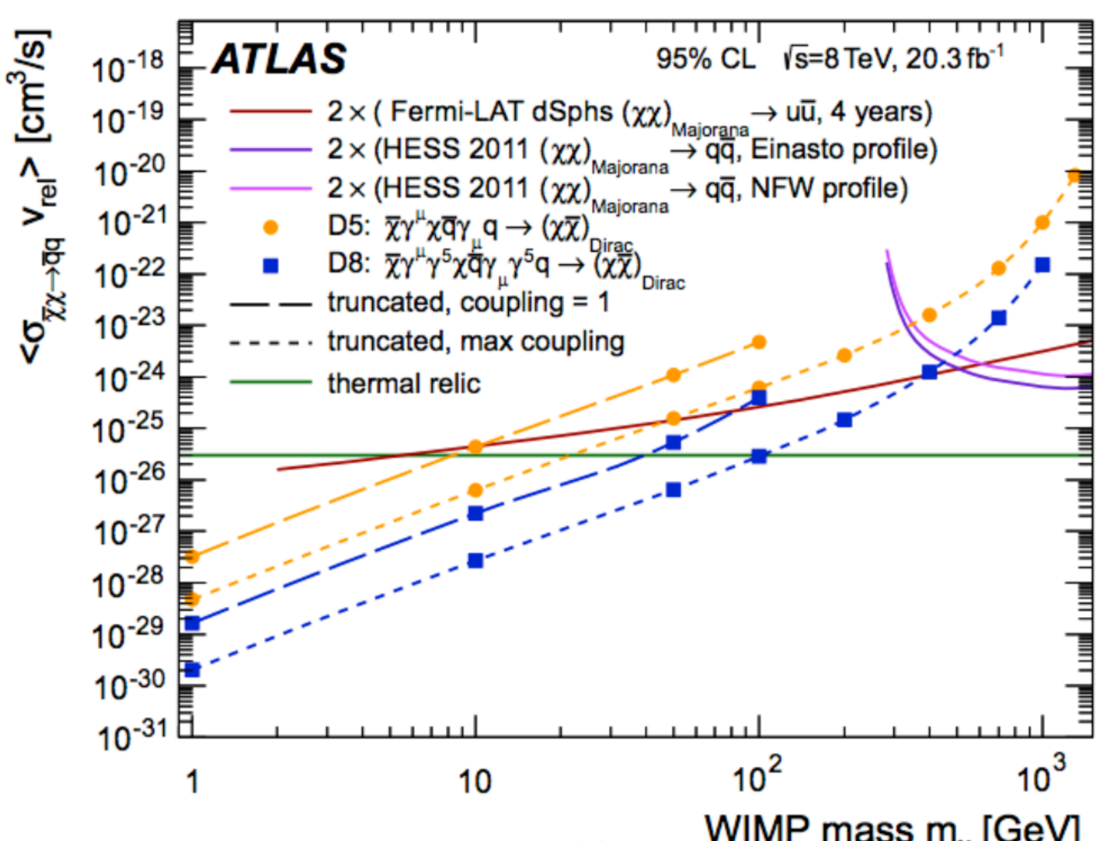


MONOJET (DIRDET LIMITS)



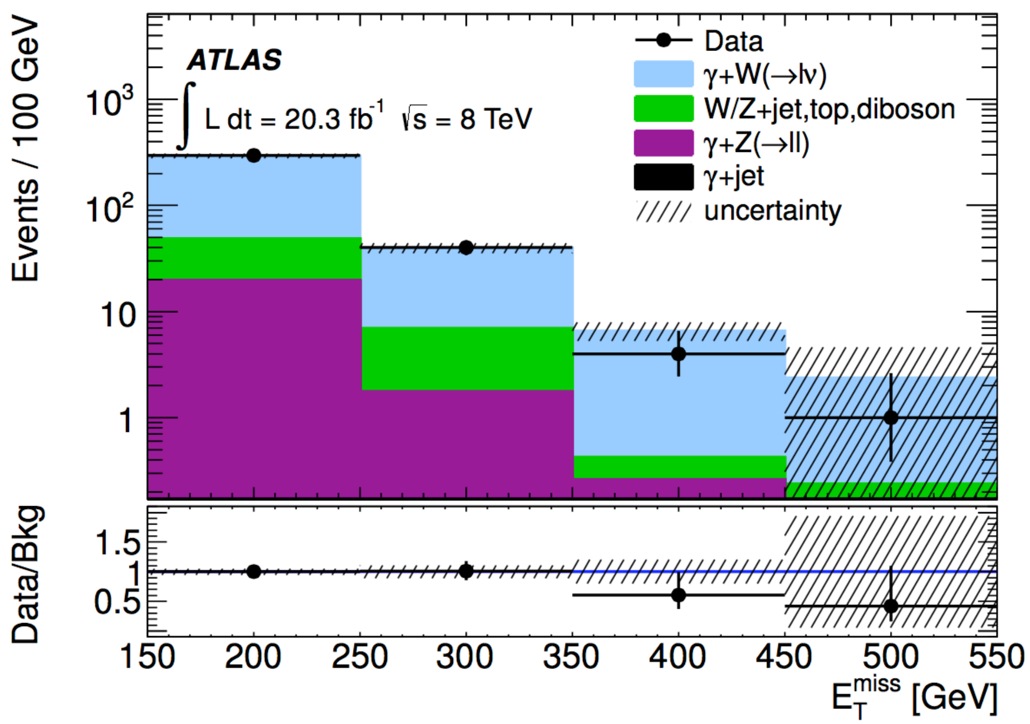


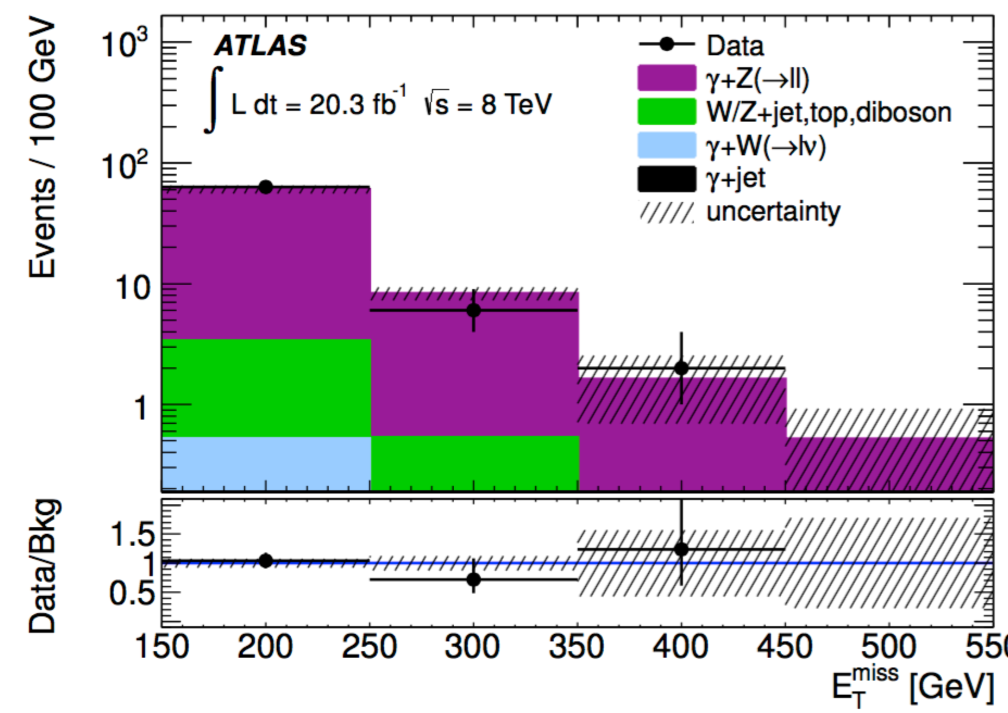
(a)

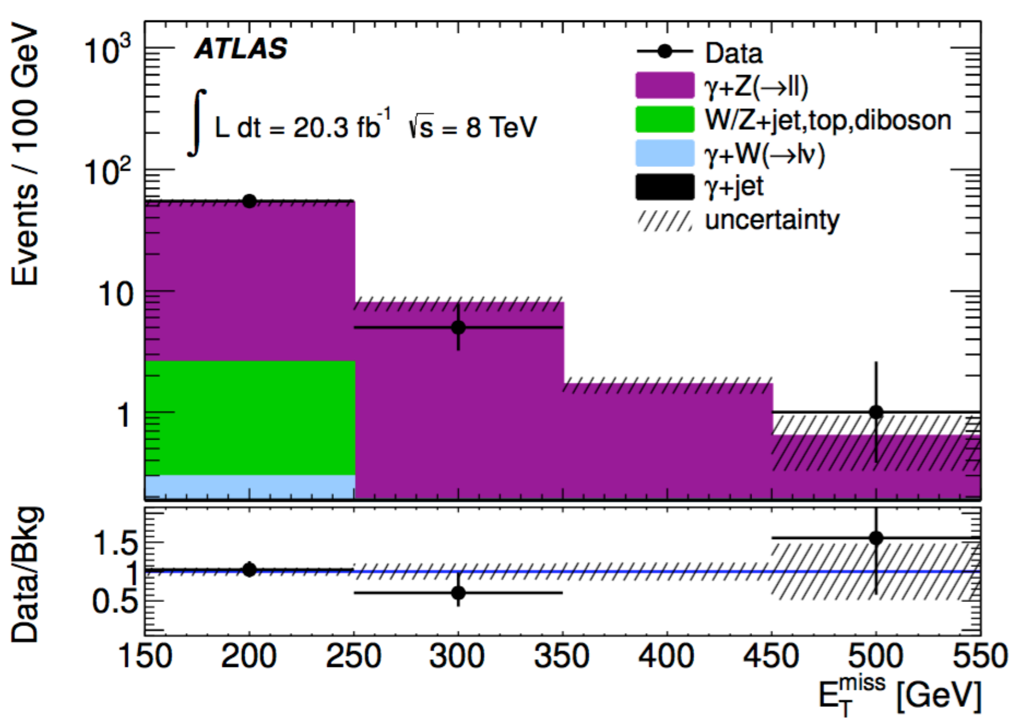


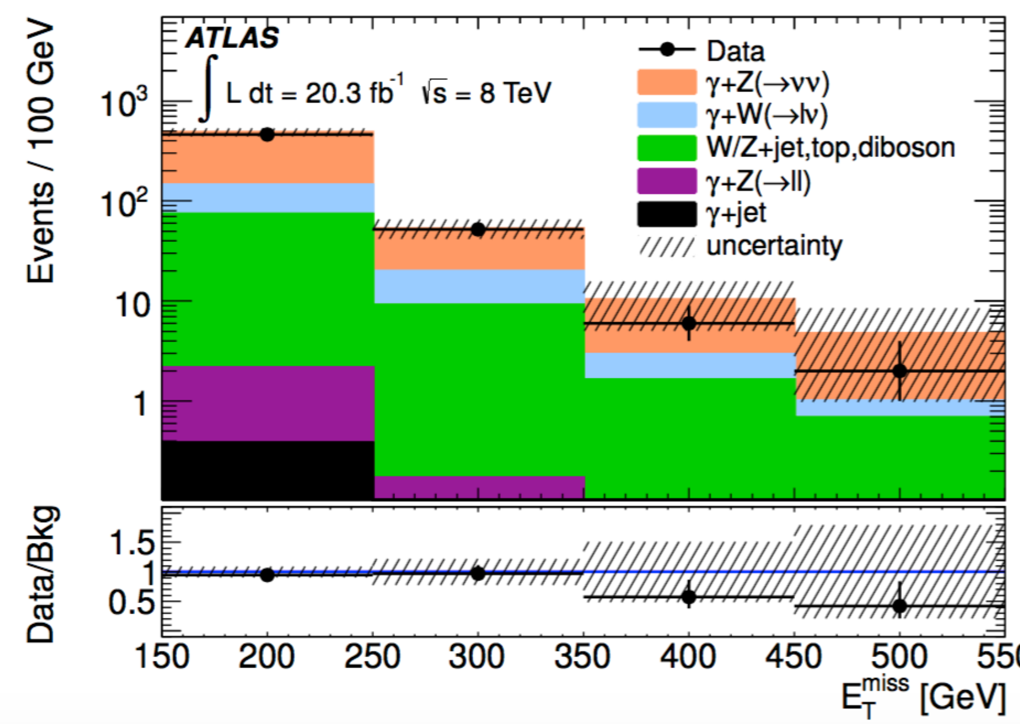
PRD 91, 012008 (2015)

MonoPhoton





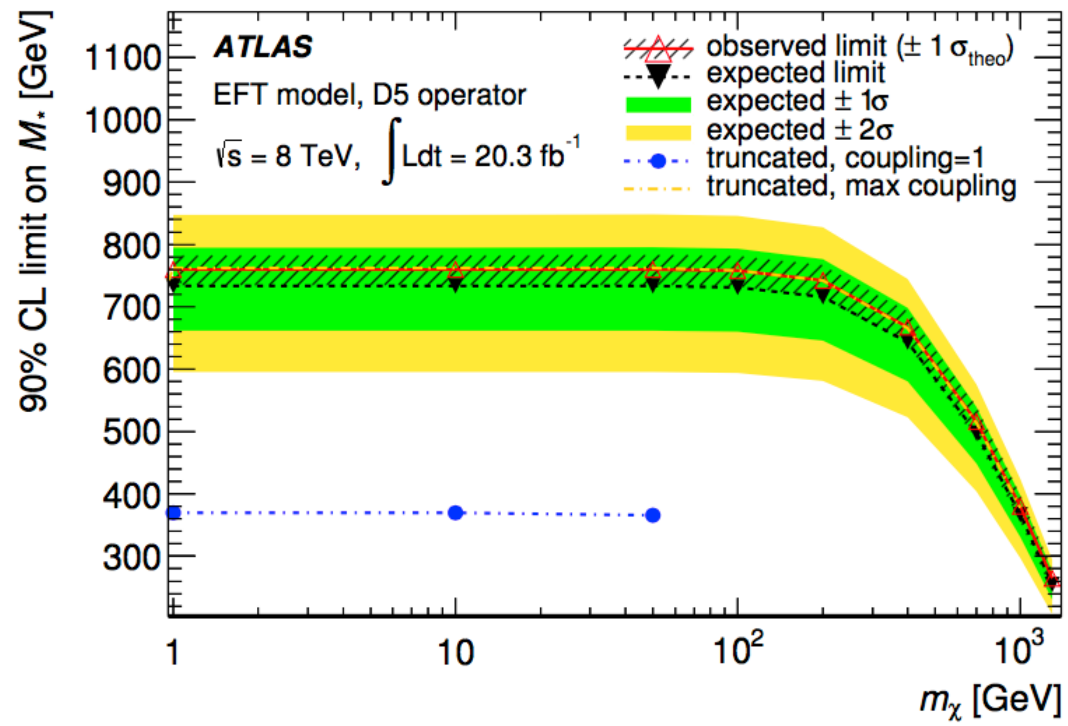


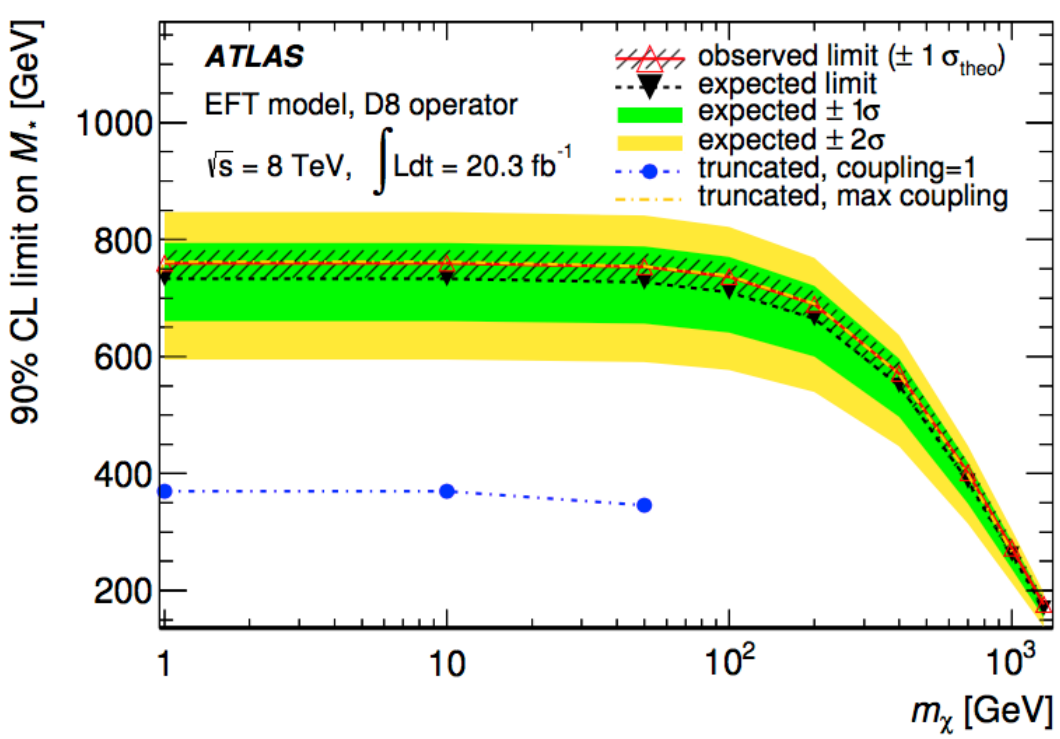


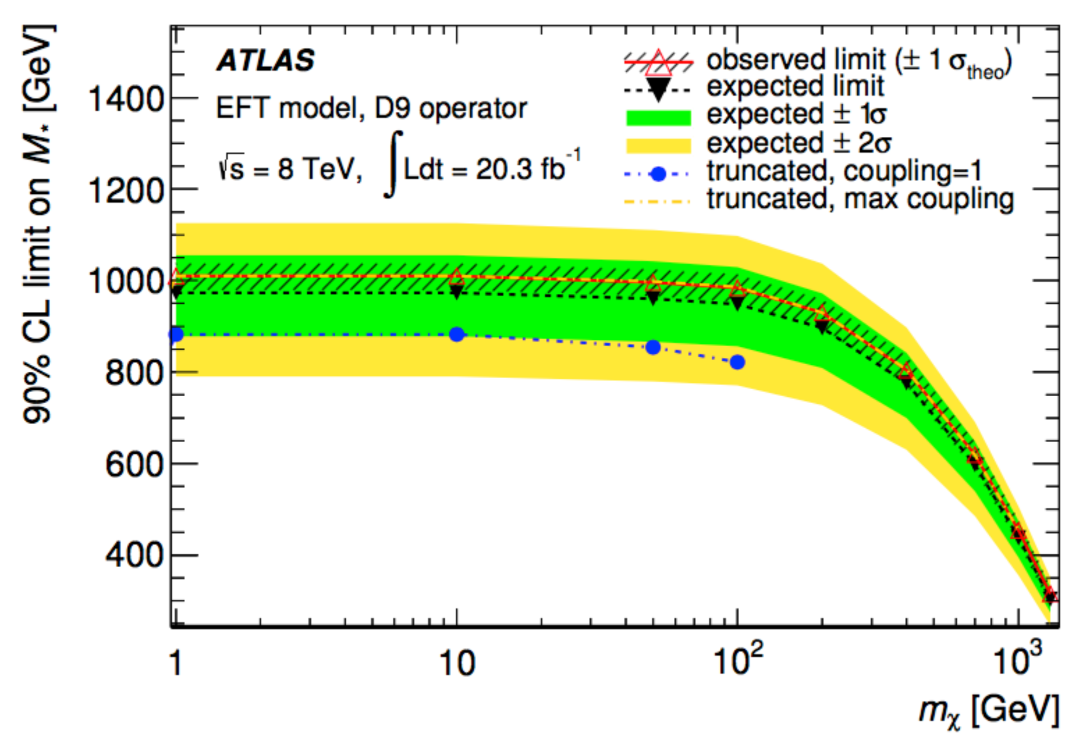
PRD 91, 012008 (2015)

MonoPhoton (M* limits)

Process	Event yield (SR)	Event yield (VR)
$Z(\to \nu\nu) + \gamma$	$389 \pm 36 \pm 10$	$153 \pm 16 \pm 10$
$W(\to \ell\nu) + \gamma$	$82.5 \pm 5.3 \pm 3.4$	$67 \pm 5 \pm 5$
W/Z + jet, $t\bar{t}$, diboson	$83 \pm 2 \pm 28$	$47 \pm 2 \pm 14$
$Z(\to \ell\ell) + \gamma$	$2.0 \pm 0.2 \pm 0.6$	$2.9 \pm 0.3 \pm 0.6$
γ + jet	$0.4^{+0.3}_{-0.4}$	$2.5^{+4.0}_{-2.5}$
Total background	$557 \pm 36 \pm 27$	$272 \pm 17 \pm 14$
Data	521	307

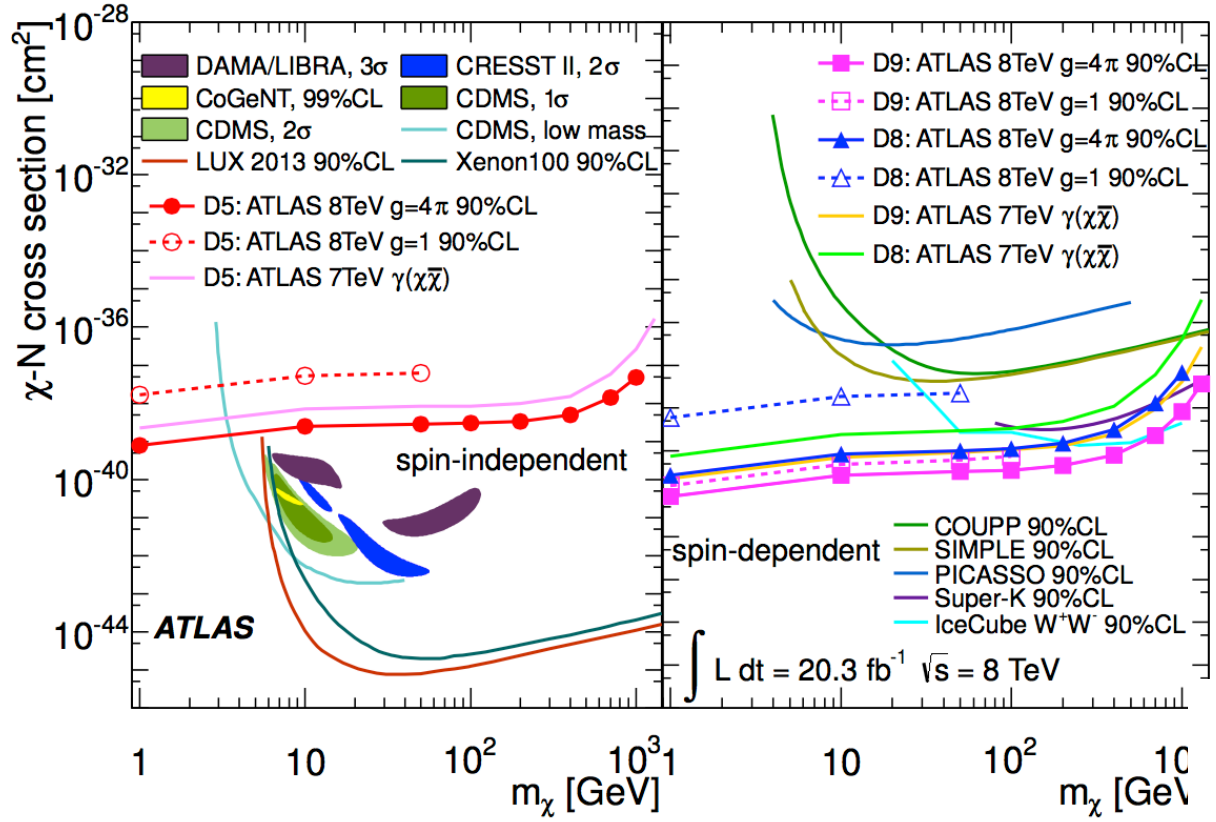


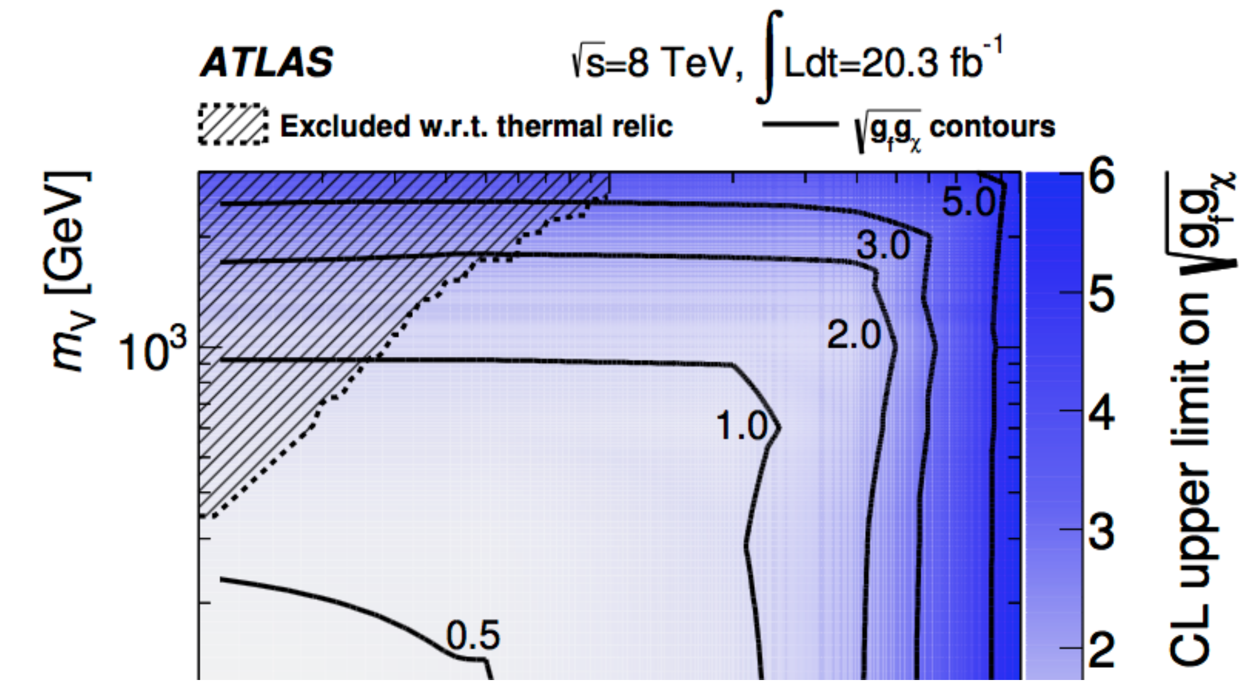


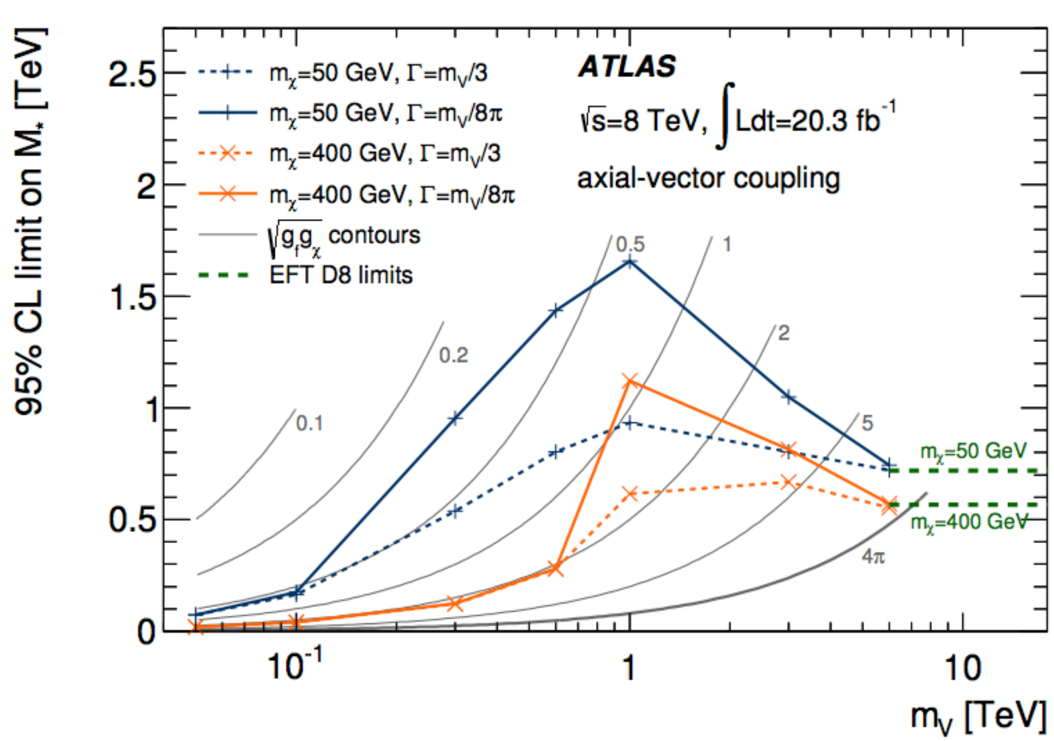


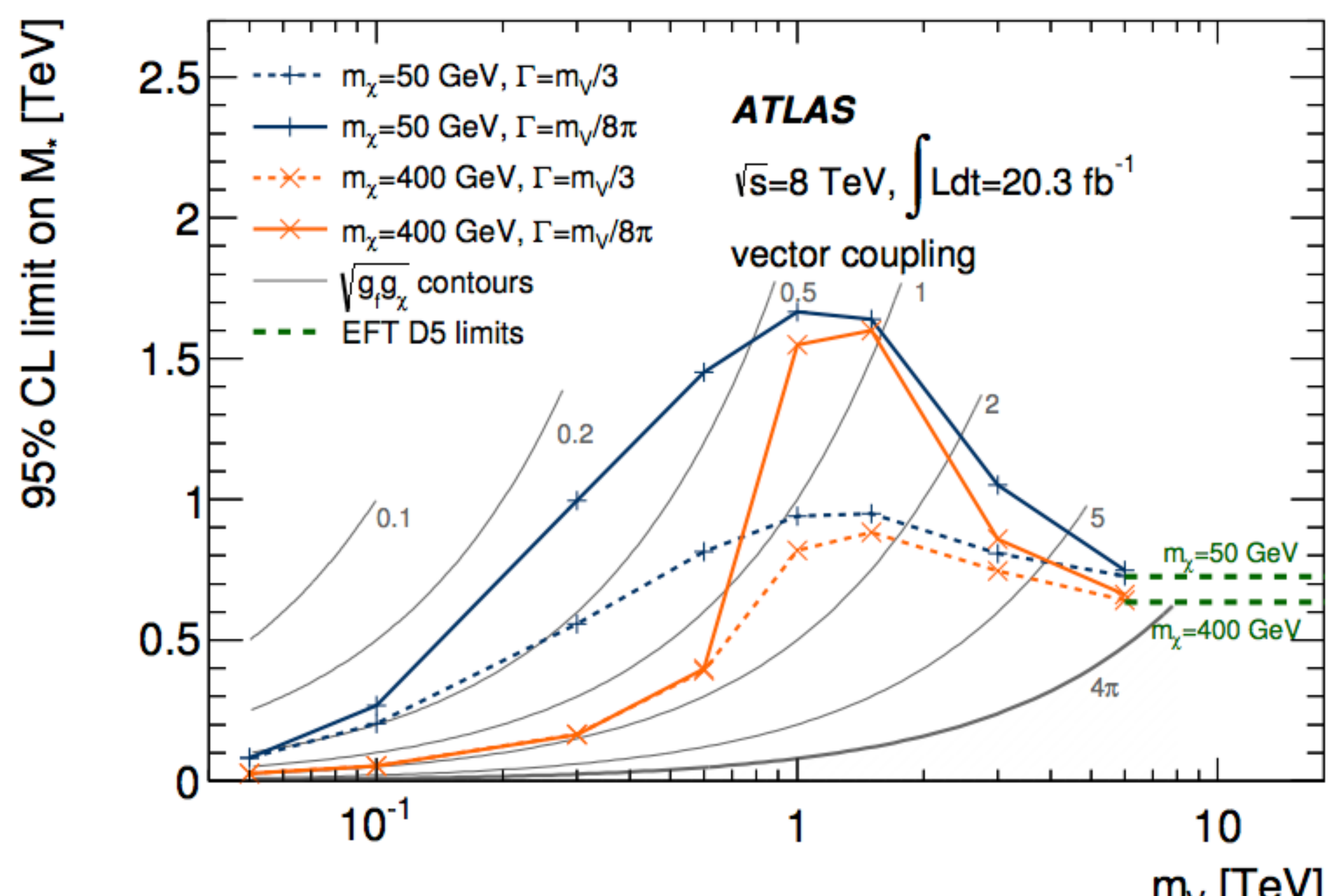
PRD 91, 012008 (2015)

MonoPhoton (DirDet&SimMod)



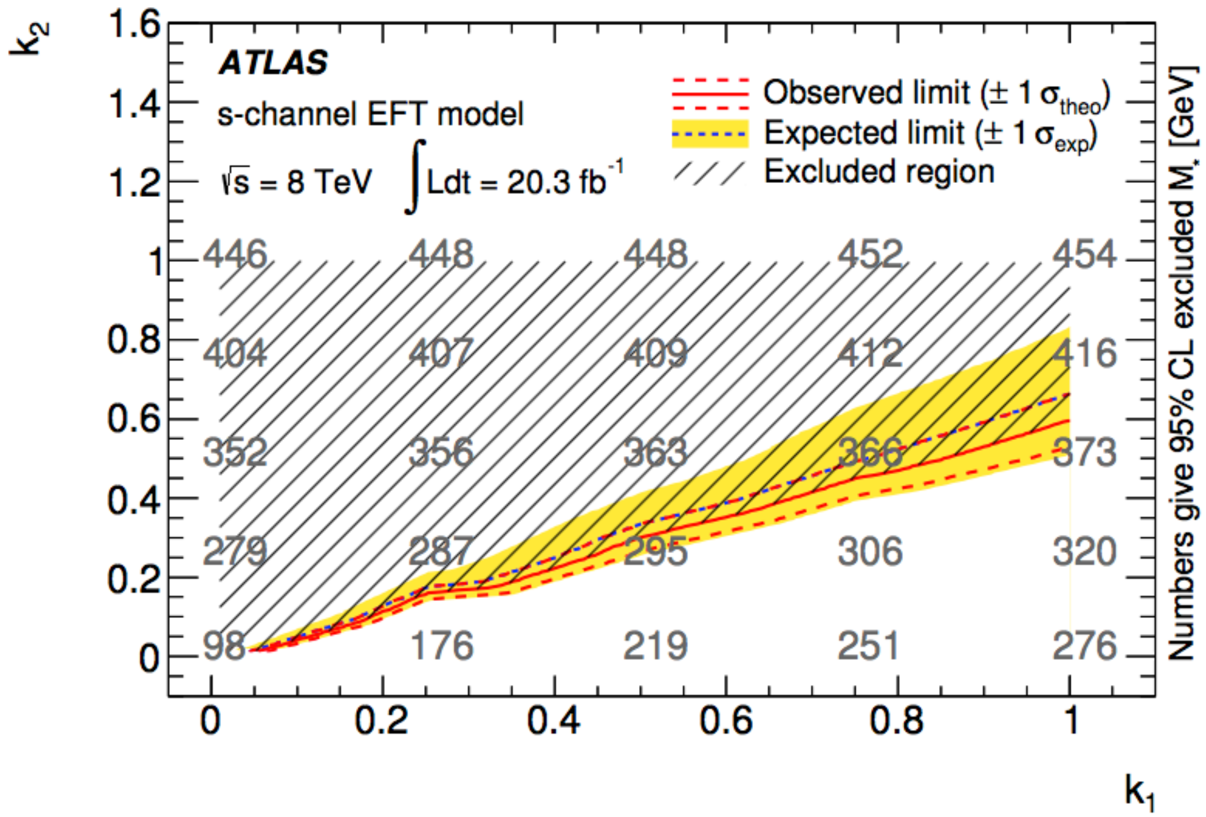


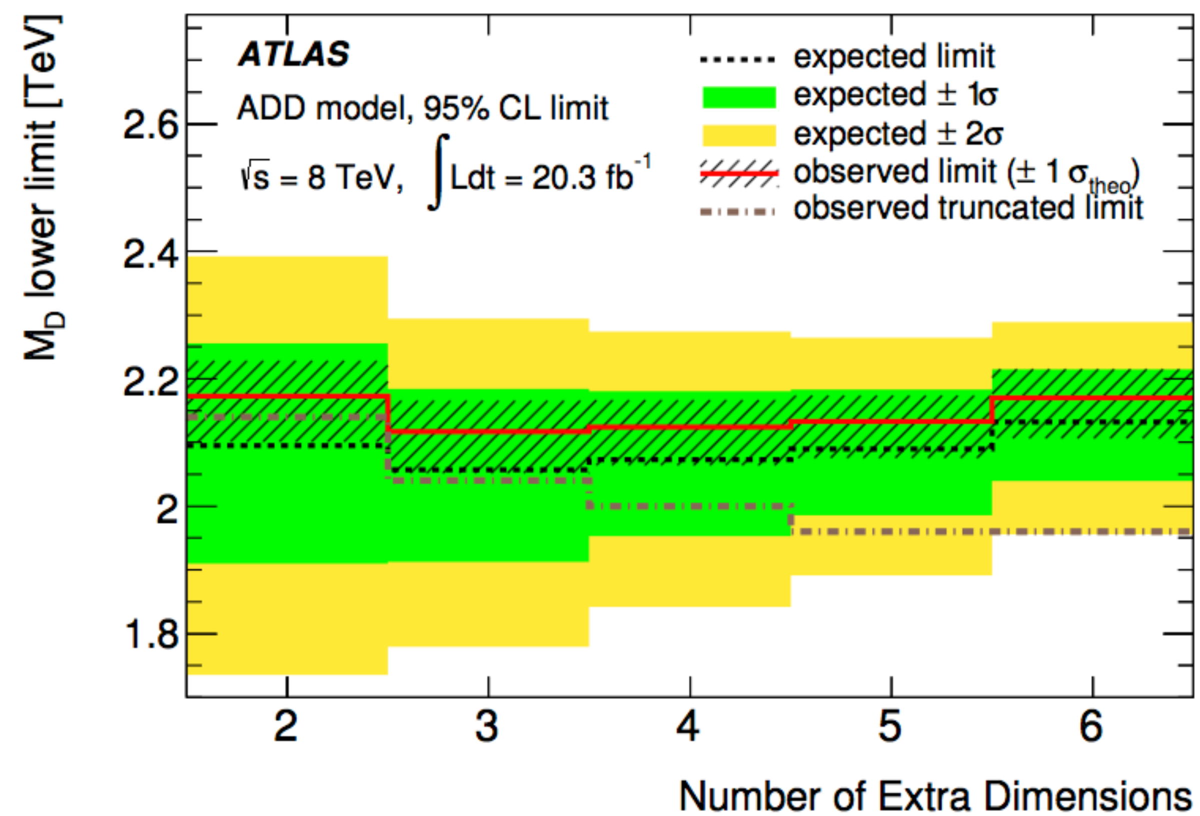


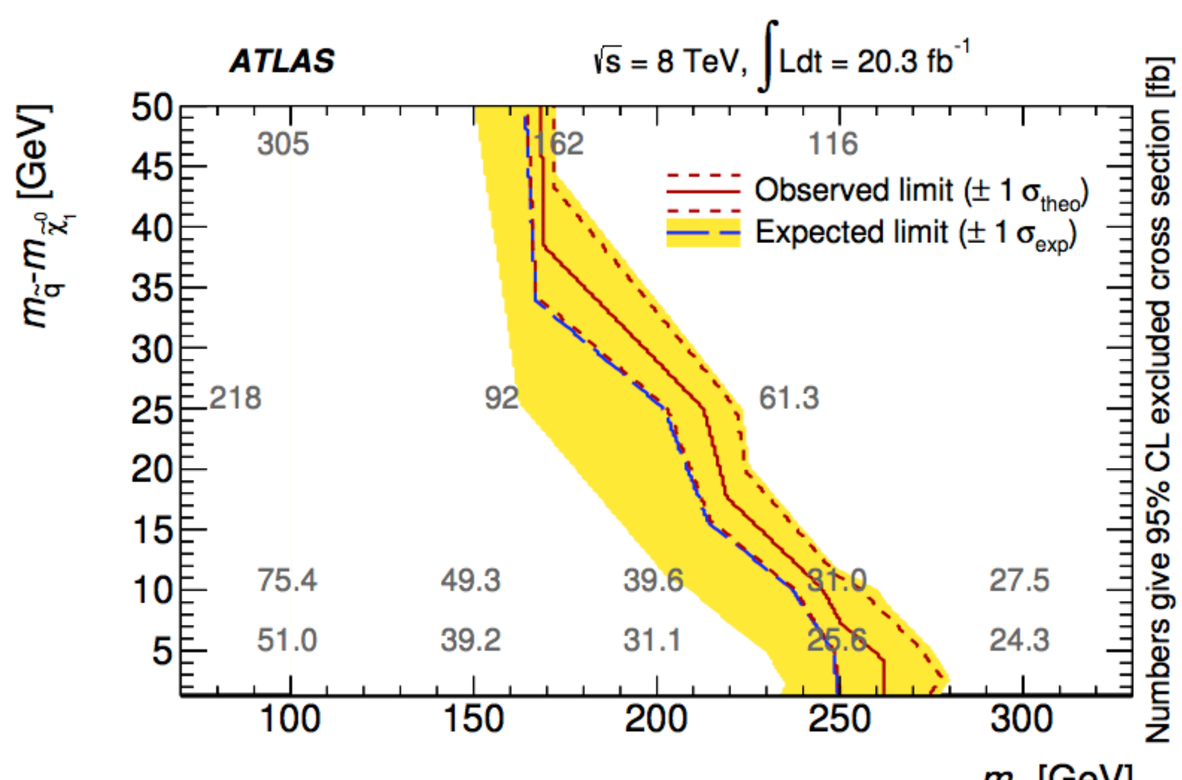


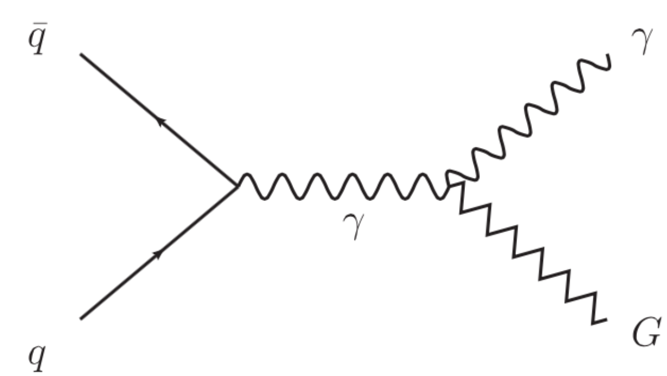
PRD 91, 012008 (2015)

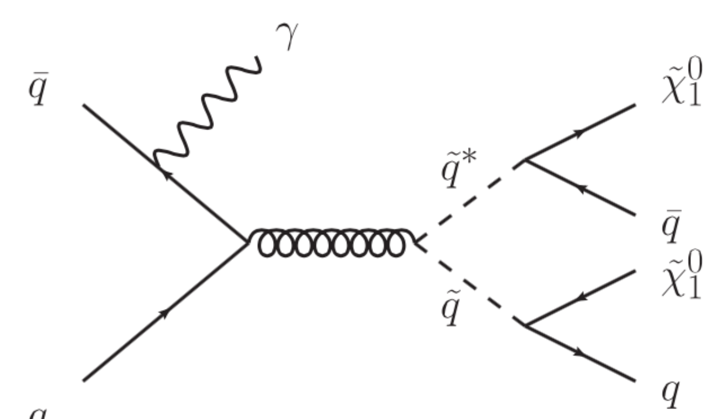
MonoPhoton (EFT, ADD, compressed squarks)





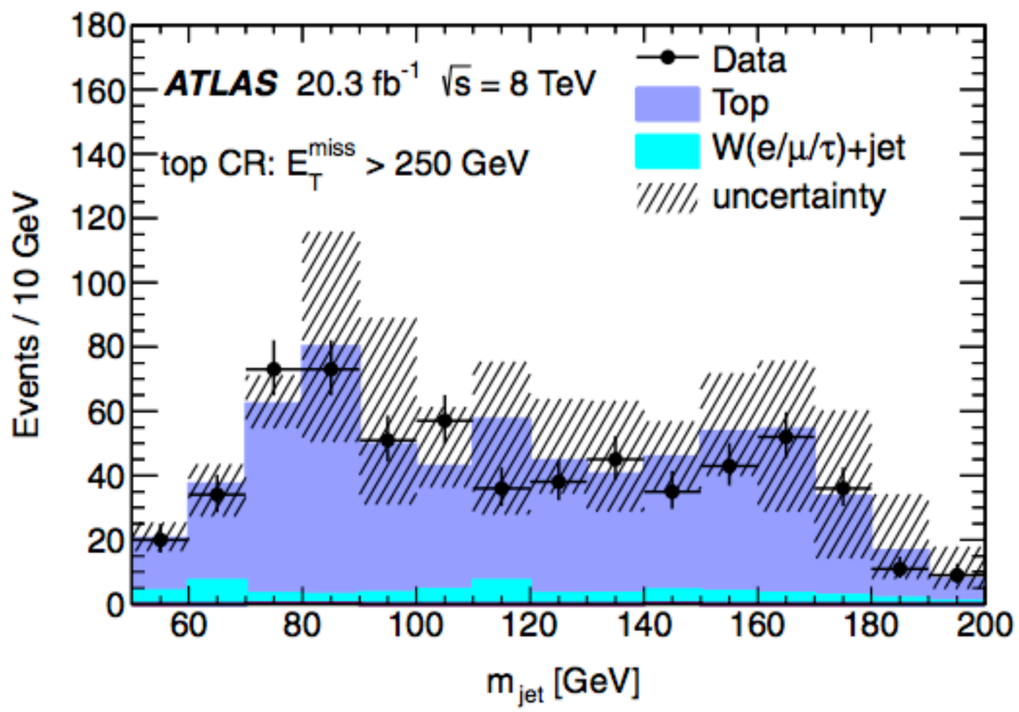




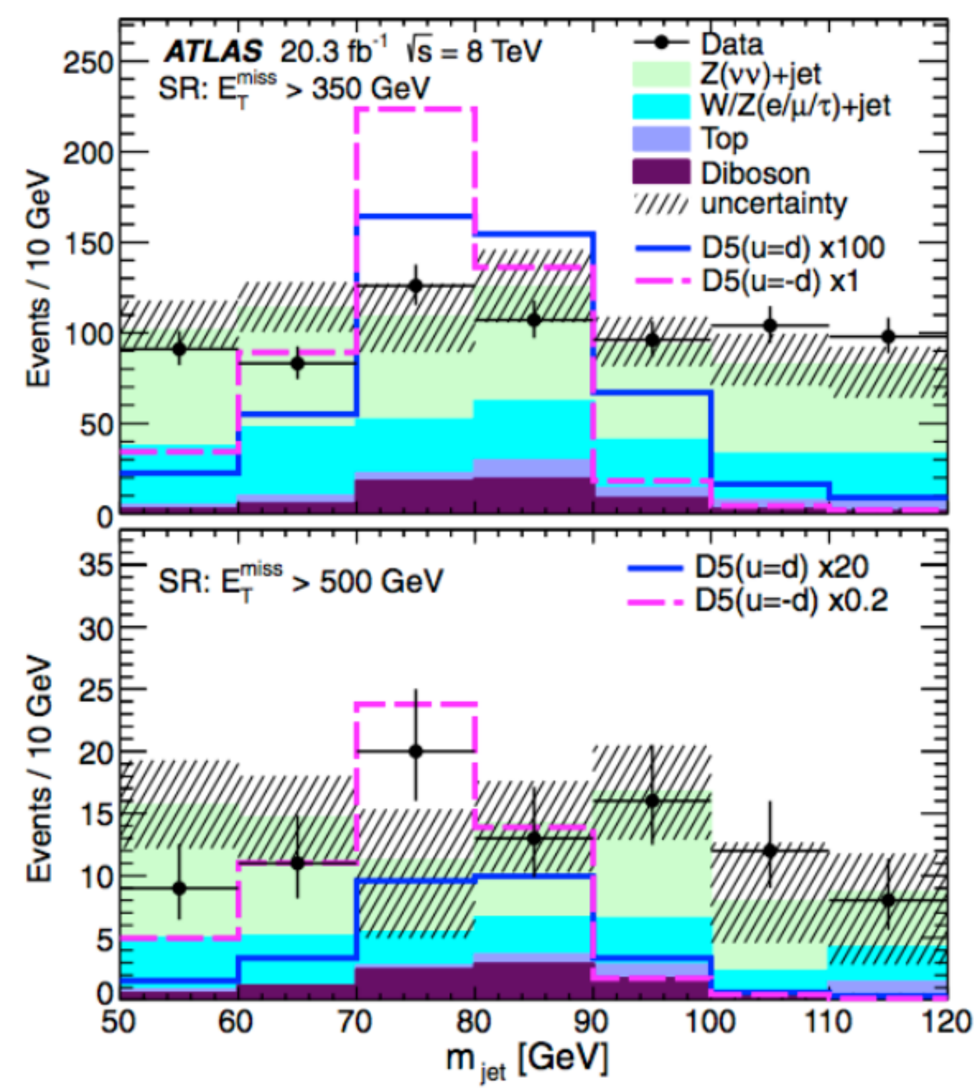


V.

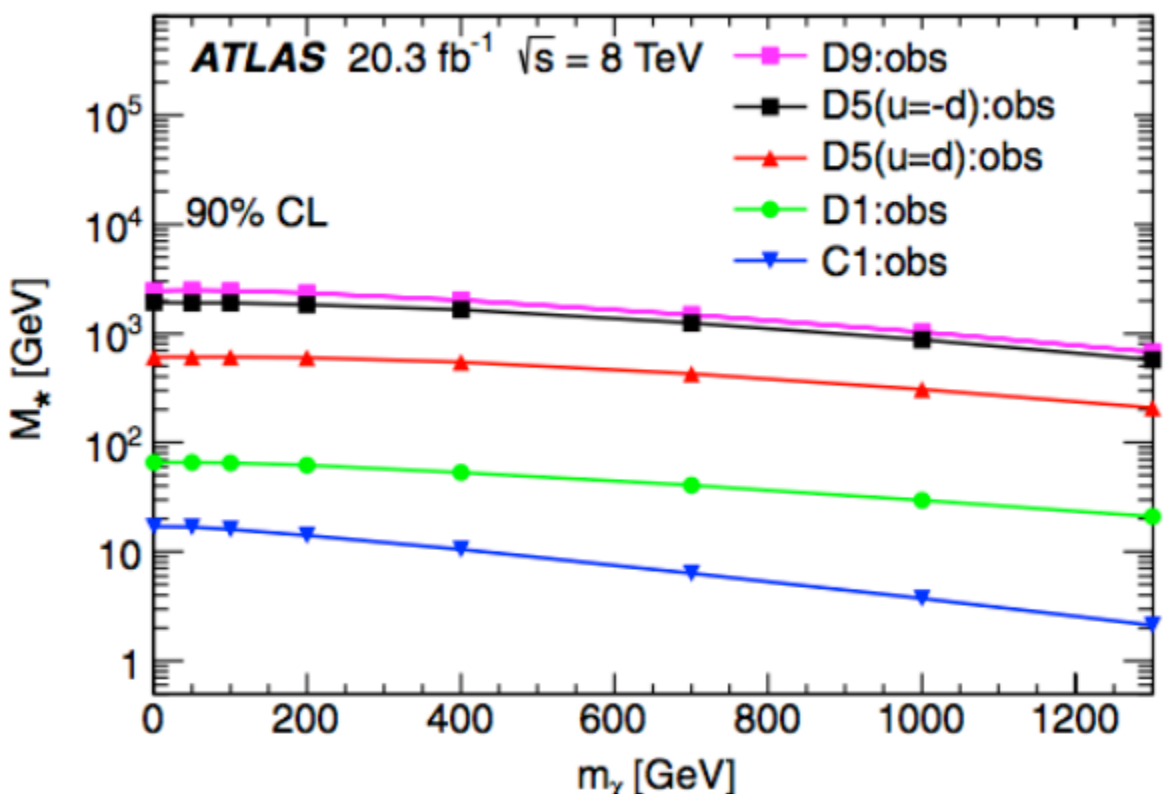
MONO-W/Z HADRONIC

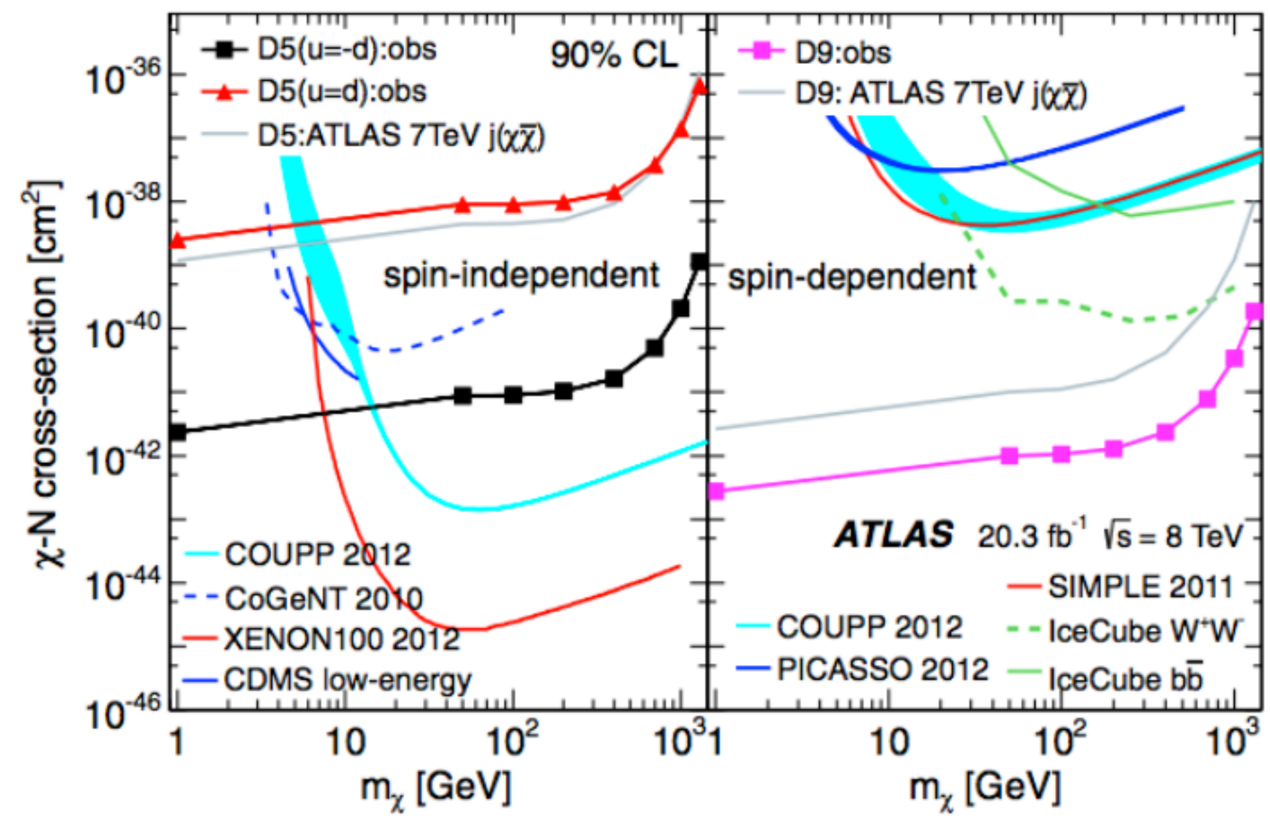


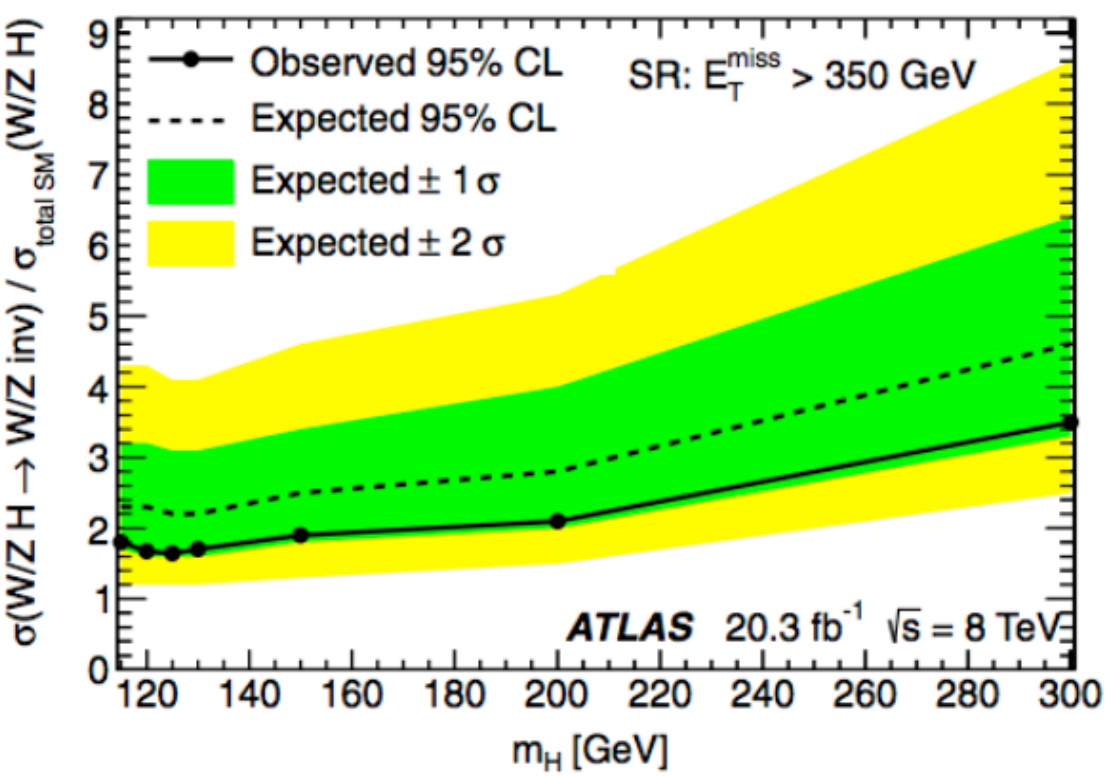
Process	$E_T^{miss} > 350$ GeV	$E_T^{miss} > 500$ GeV
$Z \to \nu\bar{\nu}$	402^{+39}_{-34}	54^{+8}_{-10}
$W \to \ell^{\pm}\nu$, $Z \to \ell^{\pm}\ell^{\mp}$	210^{+20}_{-18}	22^{+4}_{-5}
WW, WZ, ZZ	57^{+11}_{-8}	$9.1^{+1.3}_{-1.1}$
$t\bar{t}$, single t	39^{+10}_{-4}	$3.7^{+1.7}_{-1.3}$
Total	707^{+48}_{-38}	89^{+9}_{-12}
Data	705	89



Mono-W/Z hadronic

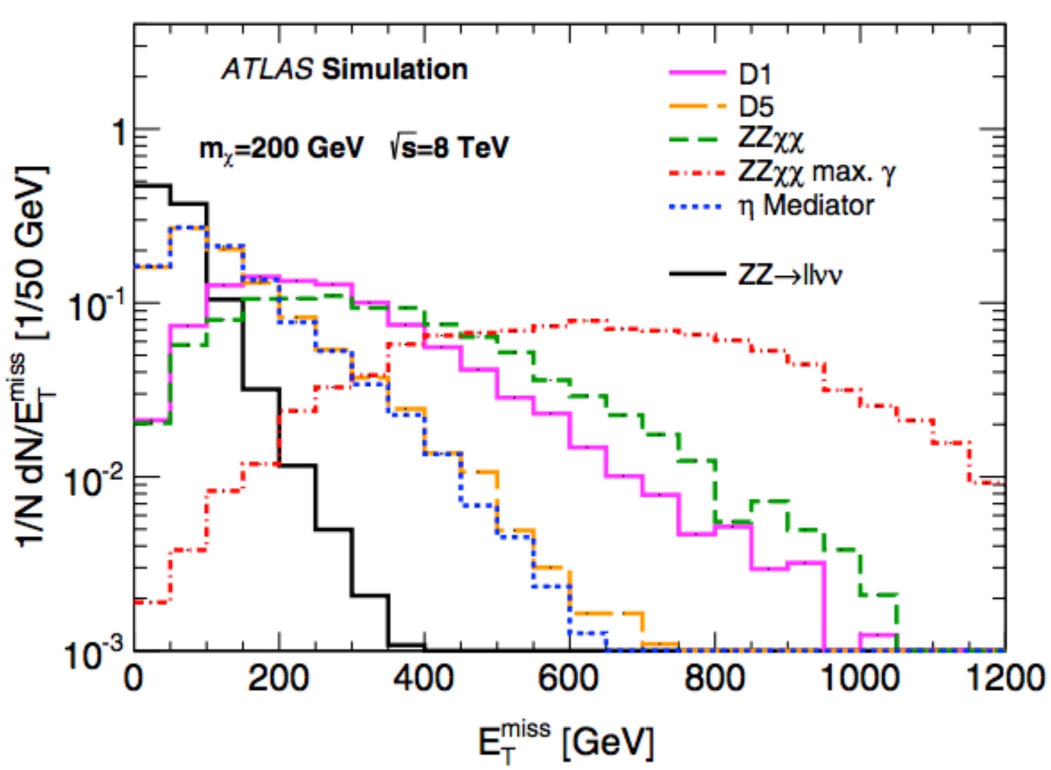


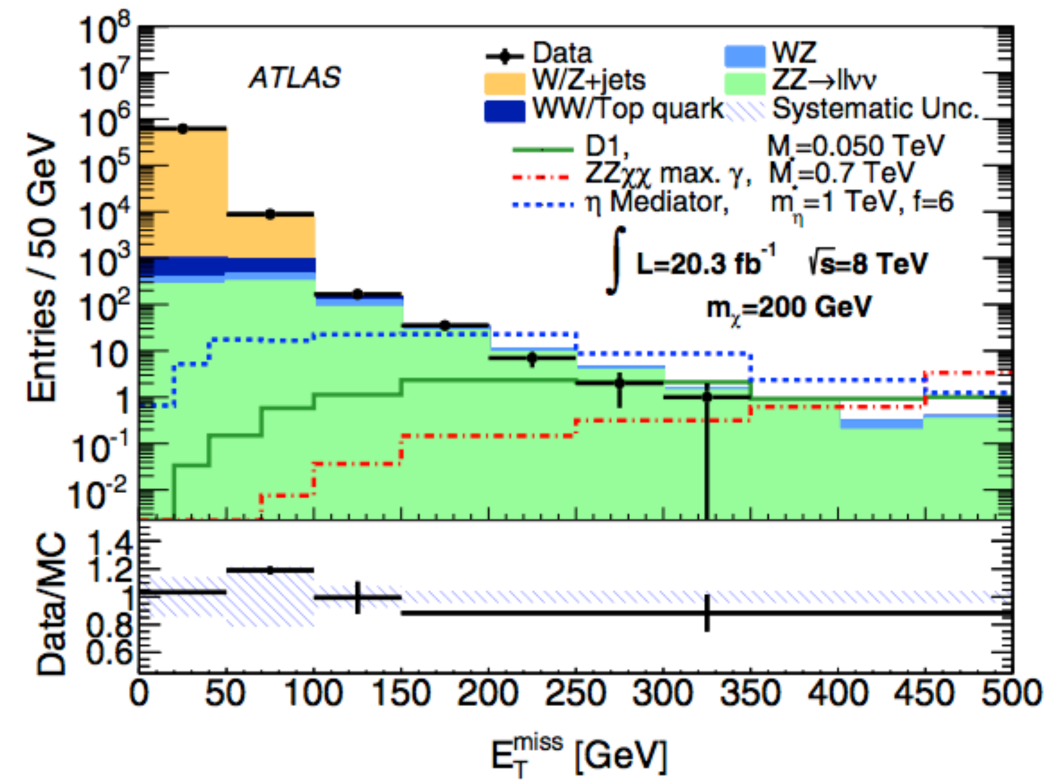


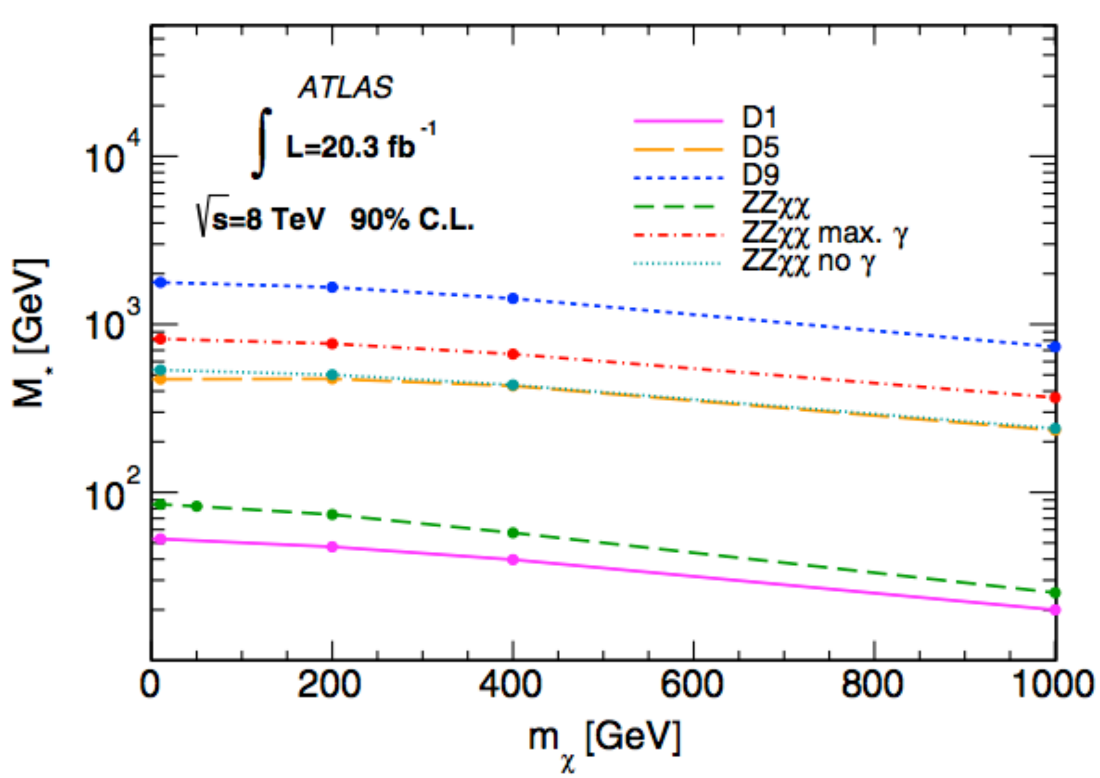


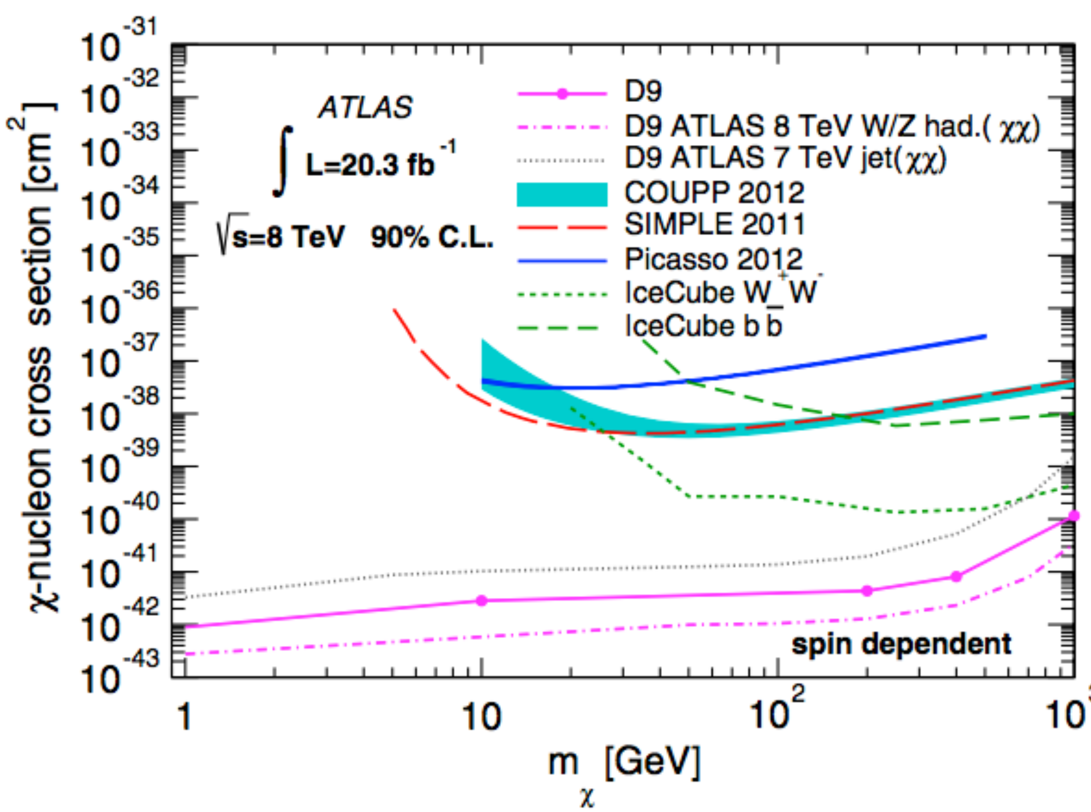
PhysRevD.90.012004

Mono-Z leptonic



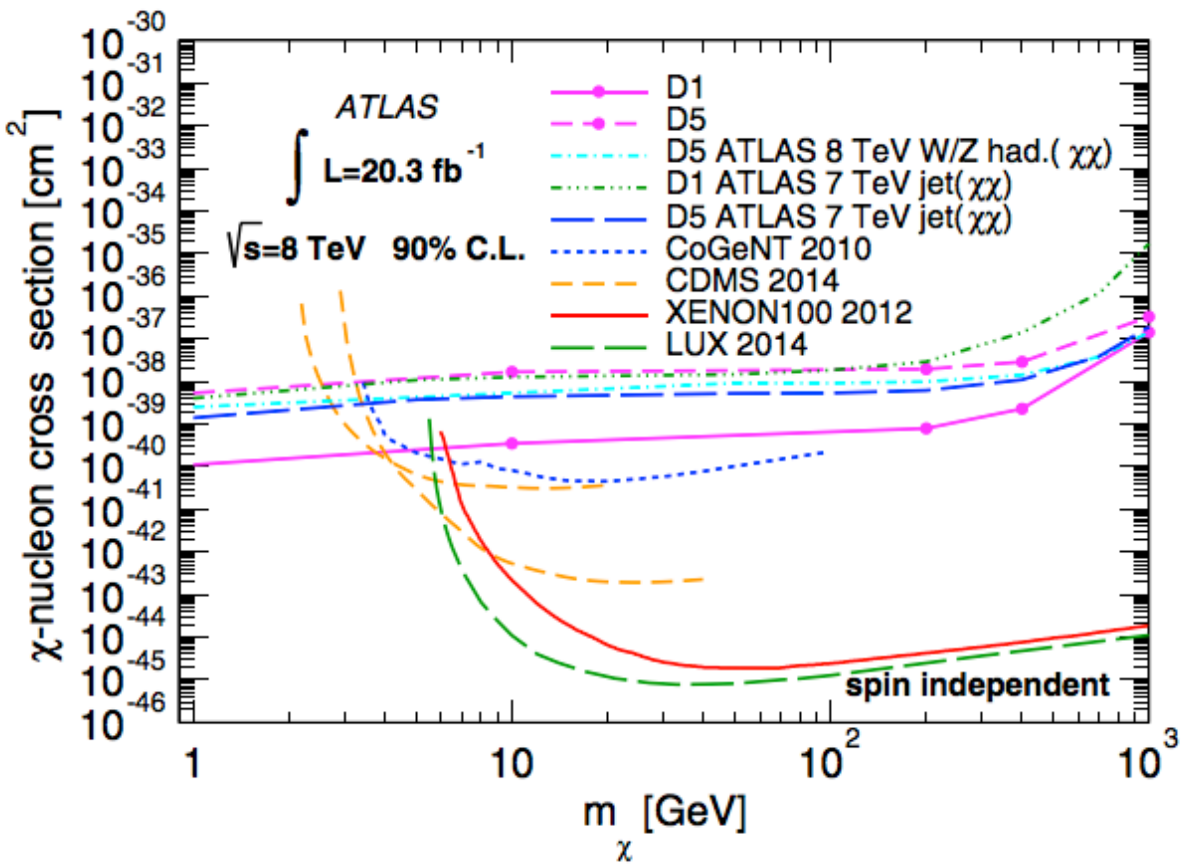


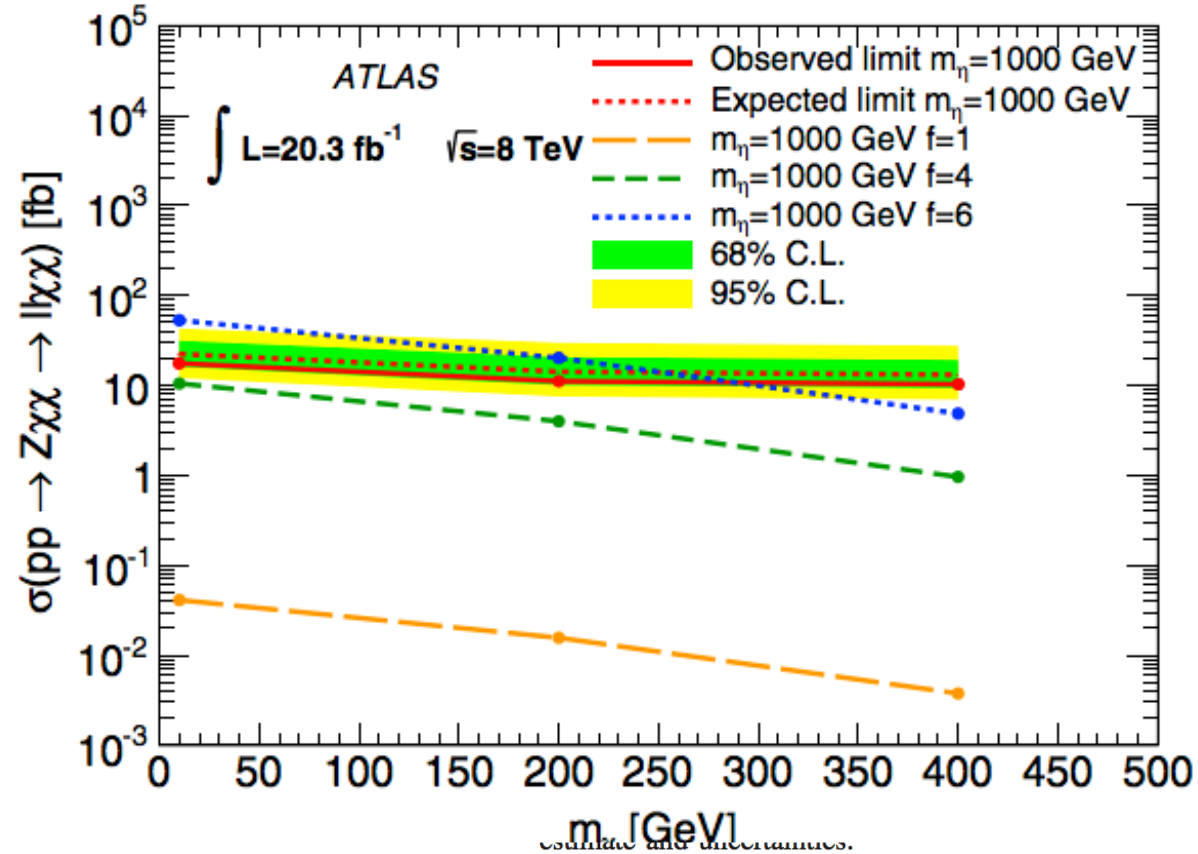




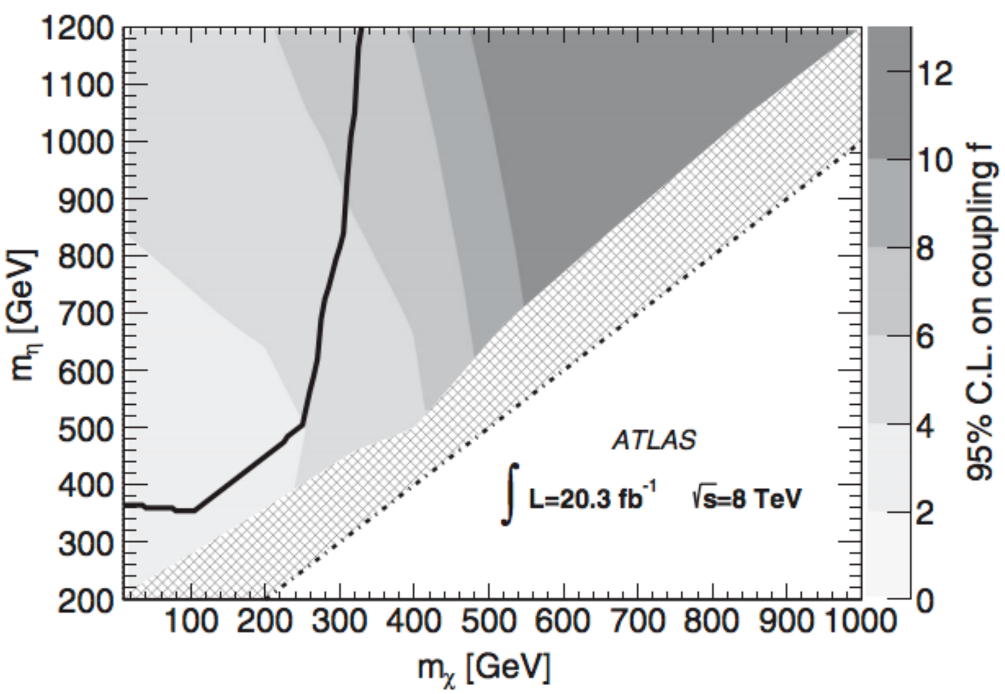
PhysRevD.90.012004

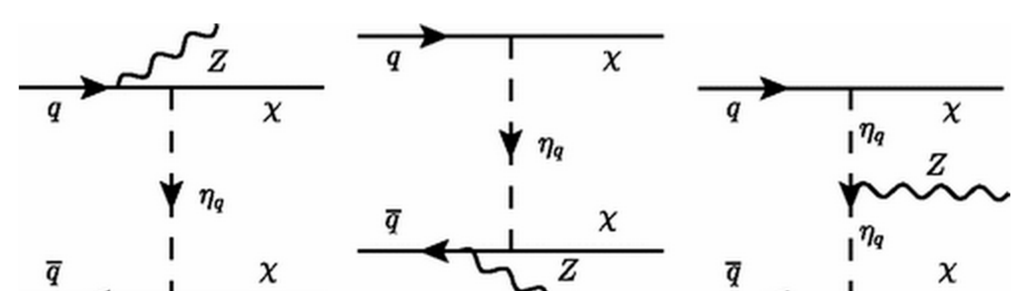
Mono-Z leptonic





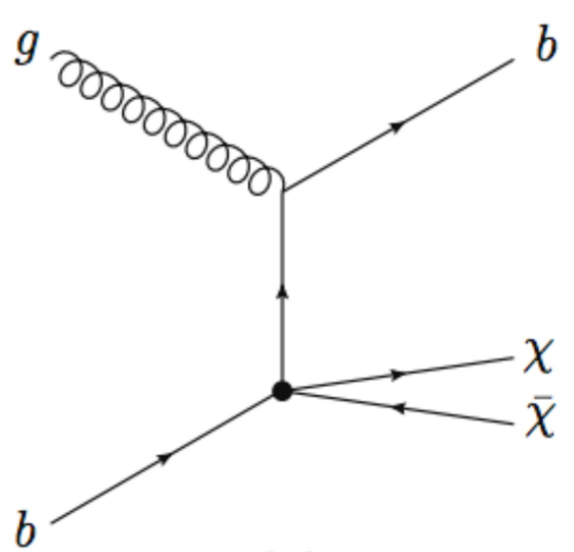
Process	E_T^{miss} threshold [GeV] 150	250	350	450
ZZ	41 ± 15	6.4 ± 2.4	1.3 ± 0.5	0.3 ± 0.1
WZ	8.0 ± 3.1	0.8 ± 0.4	0.2 ± 0.1	0.1 ± 0.1
WW, $t\bar{t}$, $Z \to \tau^+\tau^-$	1.9 ± 1.4	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$
Z + jets	0.1 ± 0.1	...	...	...
W + jets	0.5 ± 0.3	...	...	...
Total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

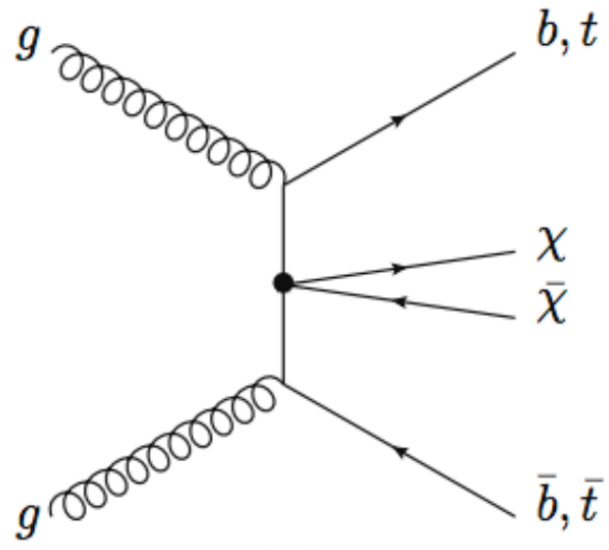


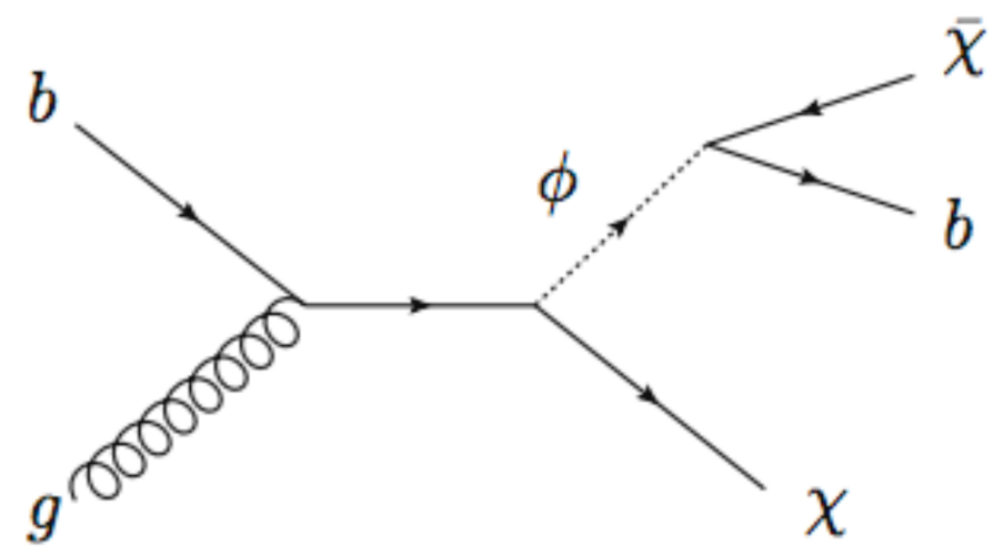


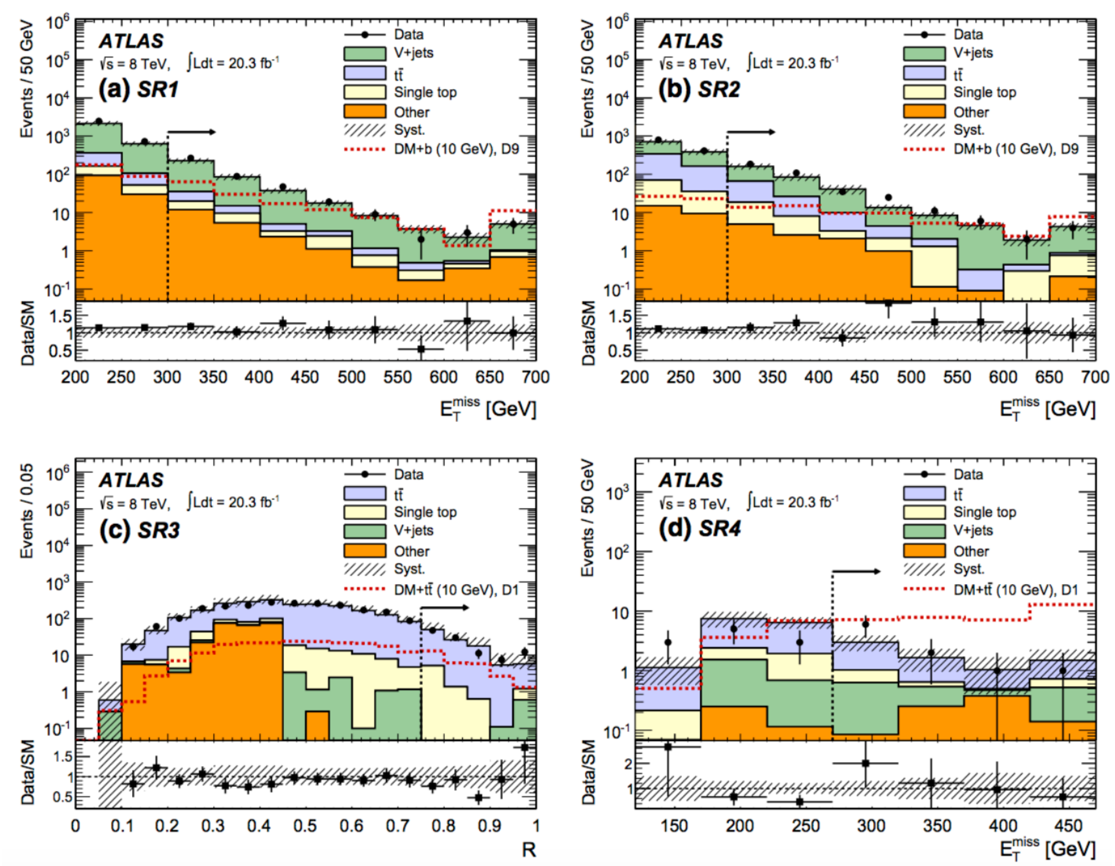
PhysRevD.86.096011

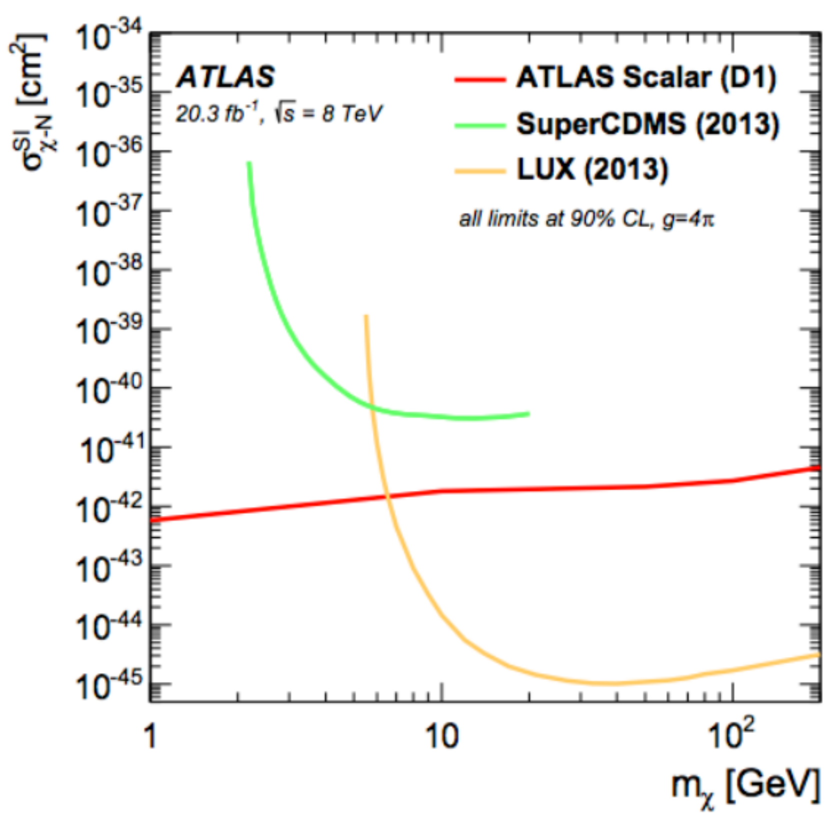
Mono-B


g
b
χ
χ̄
b


g
b, t
χ
χ̄
g
b̄, t̄


b
χ̄
ϕ
b
g
χ


ATLAS
√s = 8 TeV, ∫Ldt = 20.3 fb⁻¹
(a) SR1
(b) SR2
(c) SR3
(d) SR4
Data
V+jets
tt̄
Single top
Other
Syst.
DM+b (10 GeV), D9
DM+tt̄ (10 GeV), D1
Events / 50 GeV
Events / 0.05
Data/SM
E_T^miss [GeV]
R


ATLAS
20.3 fb⁻¹, √s = 8 TeV
ATLAS Scalar (D1)
SuperCDMS (2013)
LUX (2013)
all limits at 90% CL, g=4π
σ^SI_χ-N [cm²]
m_χ [GeV]

Mono-B

Background source	SR1	SR2	SR3	SR4
$Z(\nu\bar{\nu})$+jets	190 ± 26	90 ± 25	1^{+6}_{-1}	–
$W(\ell\nu)$+jets	133 ± 23	75 ± 13		1.3 ± 0.3
$t\bar{t}$	39 ± 5	71 ± 9	87 ± 11	2.9 ± 0.6
Single top			8 ± 3	0.7 ± 0.3
$t\bar{t}$+Z/W	–	–	–	1.4 ± 0.4
Diboson	22 ± 4	8 ± 1	–	0.8 ± 0.4
Total expected background	385 ± 35	245 ± 30	96 ± 13	7 ± 1
Data	440	264	107	10
Expected signal–D1	10 ± 2	49 ± 8	28 ± 2	35 ± 5
Expected signal–C1	17 ± 2	61 ± 9	45 ± 4	51 ± 12
Expected signal–D9	147 ± 25	69 ± 12	2 ± 1	2 ± 1
Expected signal–b-FDM	192 ± 24	61 ± 8	1.0 ± 0.2	–
p value	0.09	0.29	0.24	0.18
Allowed non SM events–Obs.	124	79	41	10
Allowed non SM events–Exp.	81	67	33	7

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Mono-B