Chasing Dark Matter at the LHC

part 2: jets and beyond

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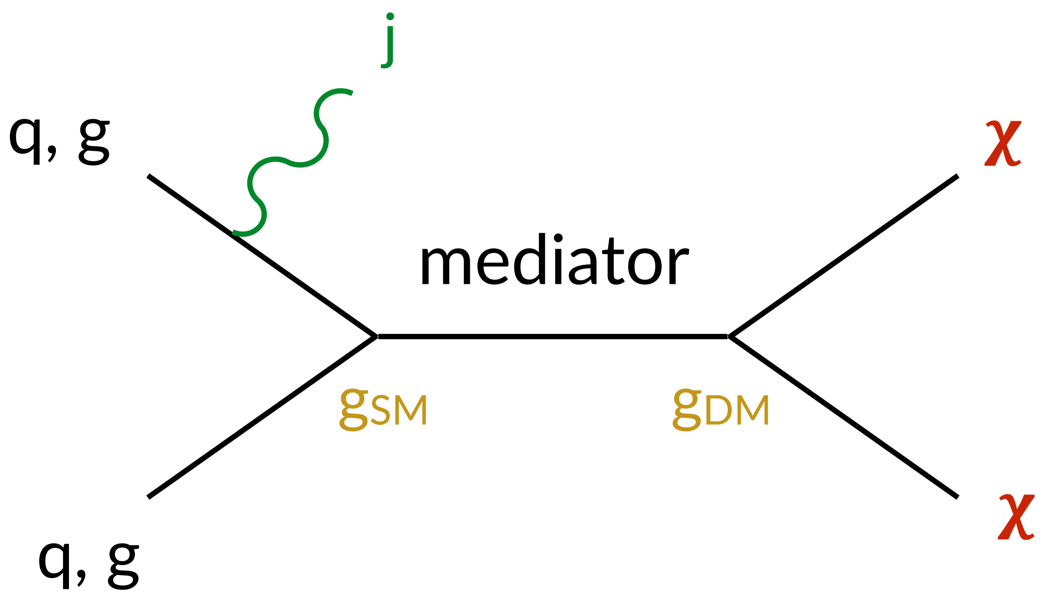
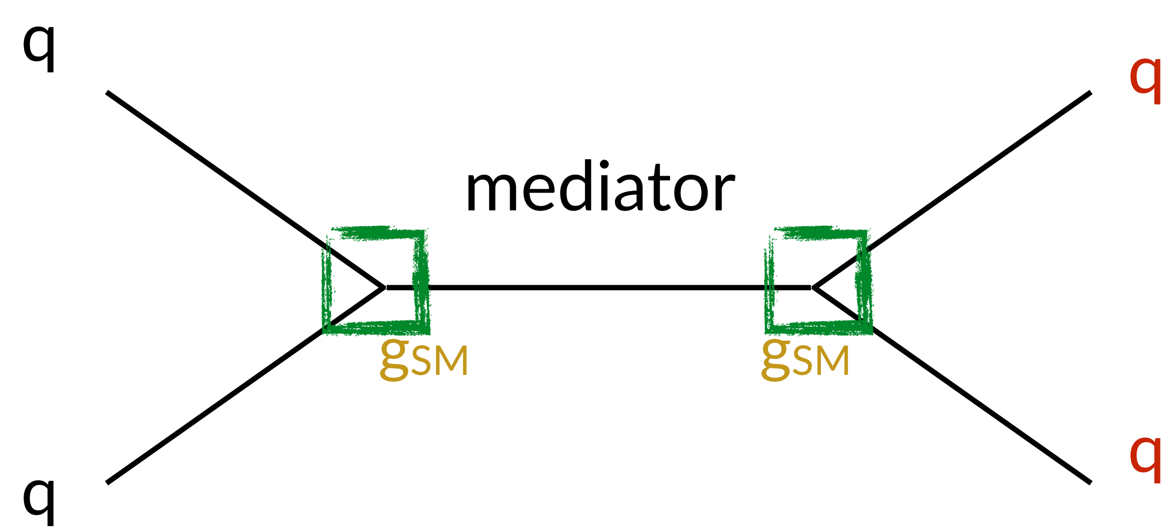
Why Jets?



because $\alpha_s >> \alpha$



because it's convenient to study *both* vertices

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)

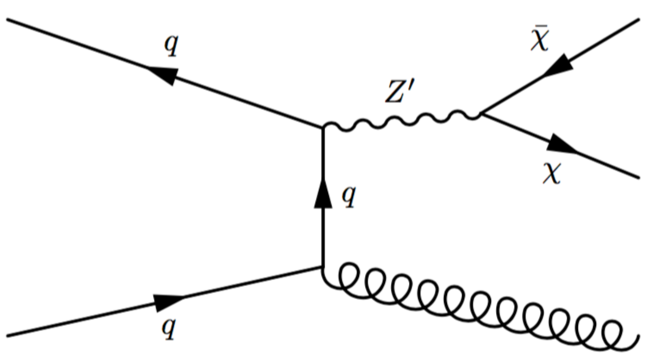
- the narrow
- the large
- (the clever)

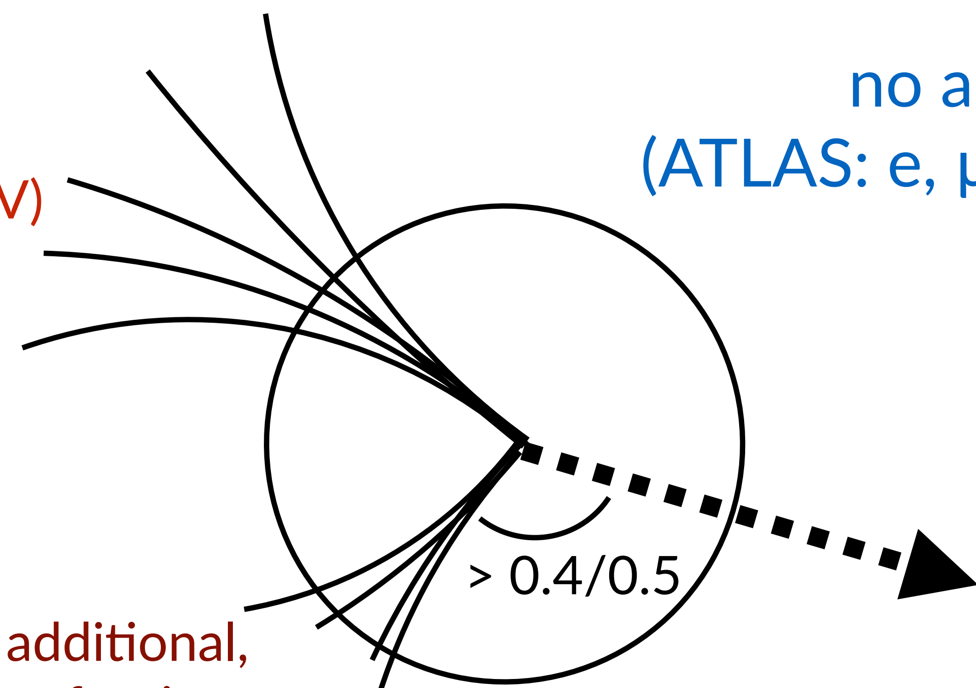
JET + DM

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)





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

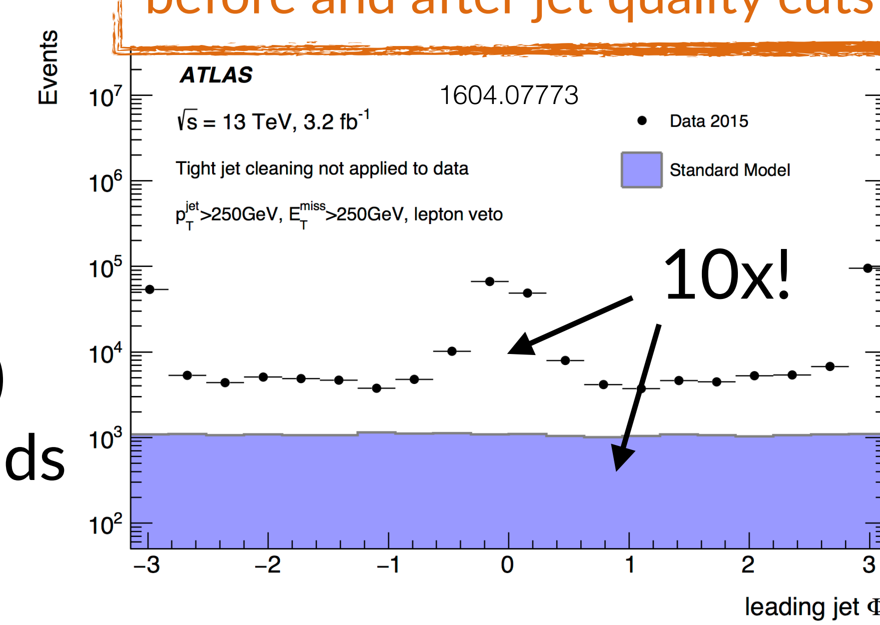
+ trigger
ATLAS: MET > 70 GeV
CMS: MET, H_T^{miss} > 90 GeV

MET
> 200-250 GeV

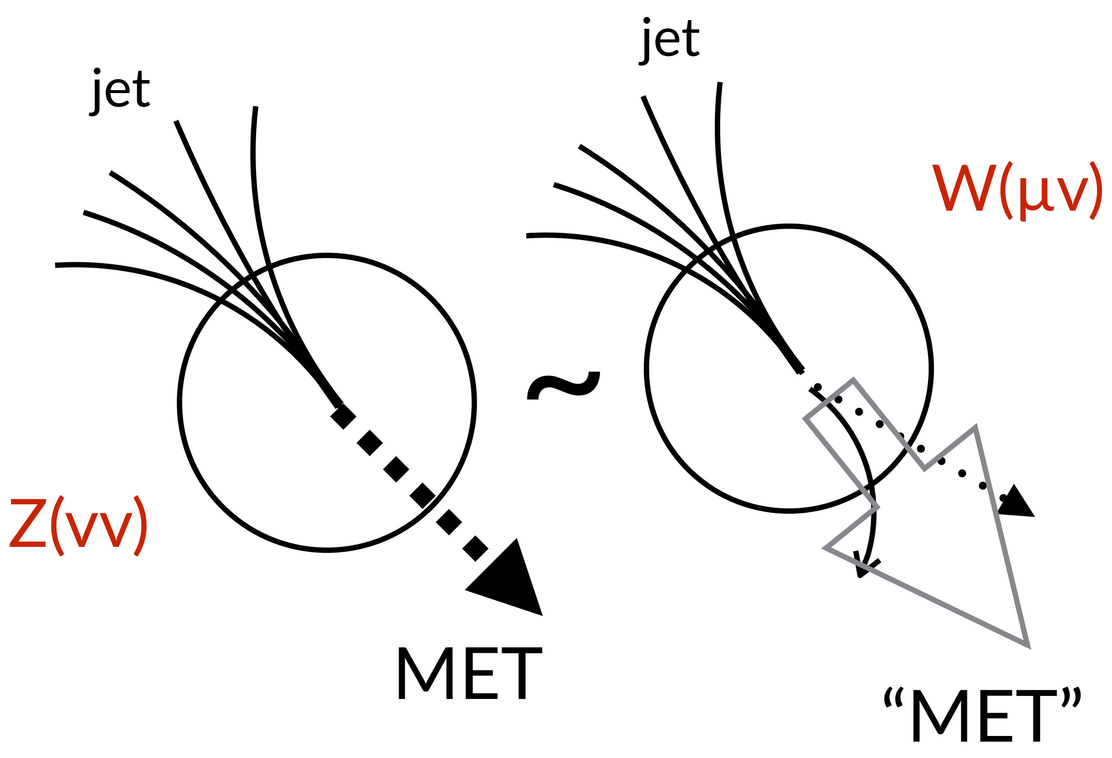
same signature as
- Z(νν) + jets, W(τ[qq']ν) + jets…
- beam-induced background ☞ jet quality cuts

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

before and after jet quality cuts



How the Z(vv)+jets Was Won



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

- ideally use Z(ll) + jets, but 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

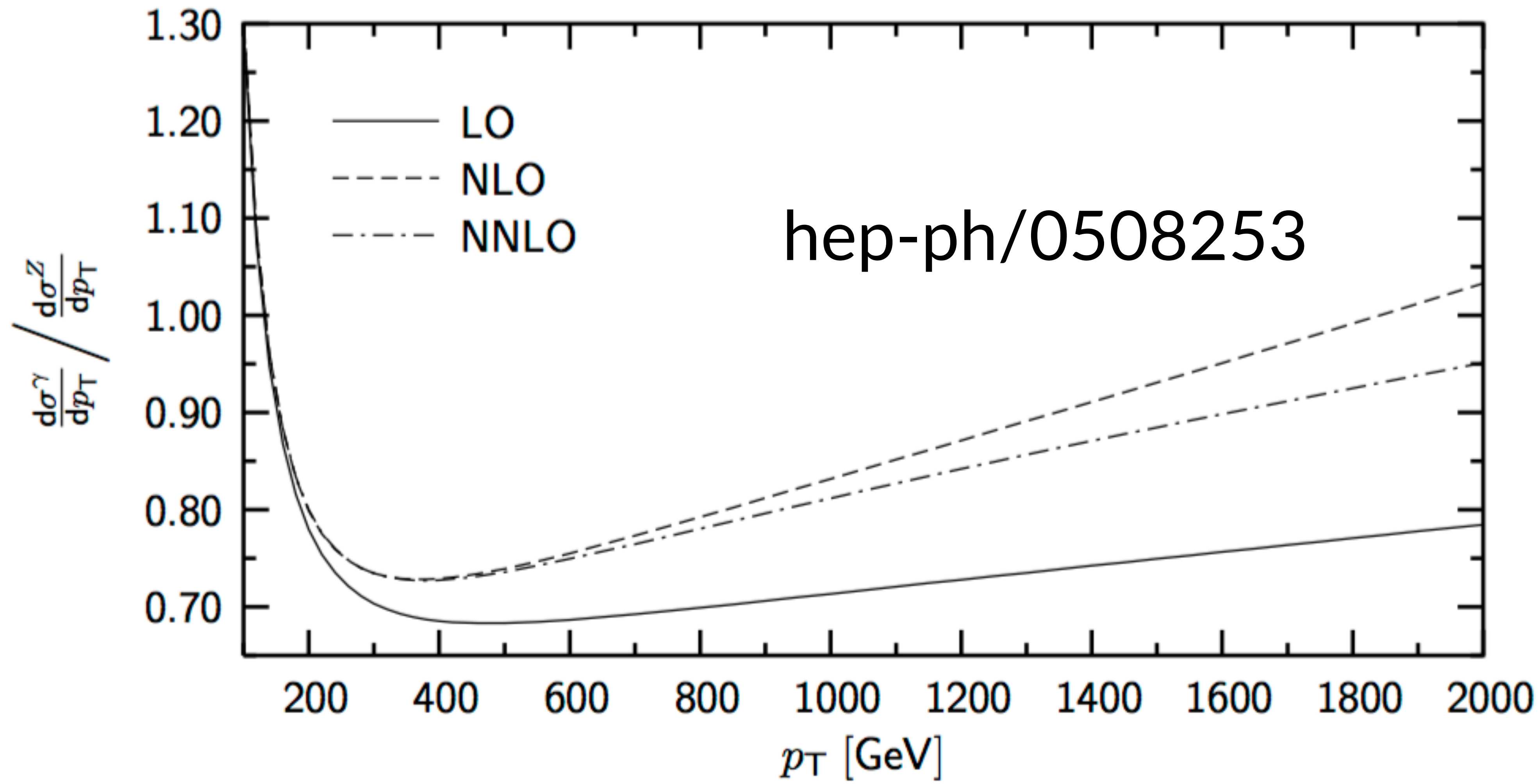
binned shape analysis, with shapes for EW backgrounds constrained from CR data

what's used for constraining Z(νν)

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

dominates at low MET (CMS W(μν)) — dominates at high MET (CMS γ+jet)

Z(νν) modelling uncertainties

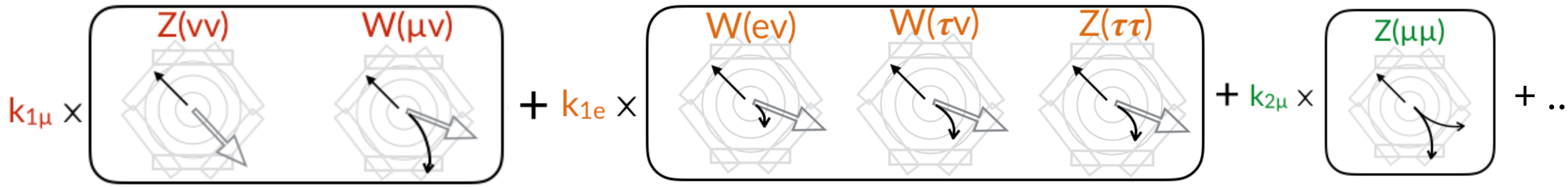


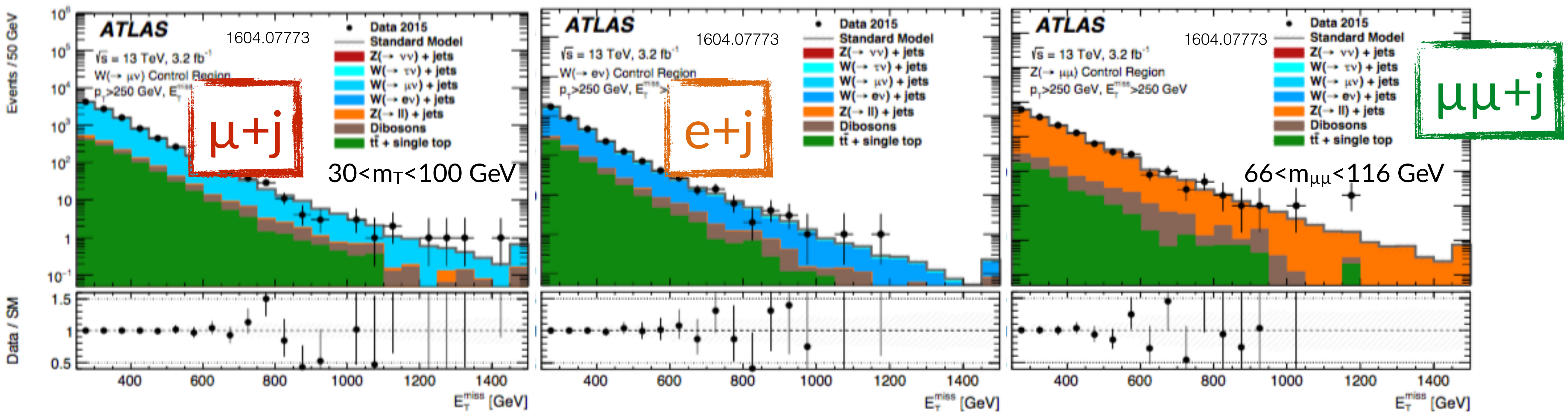
hep-ph/0508253

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





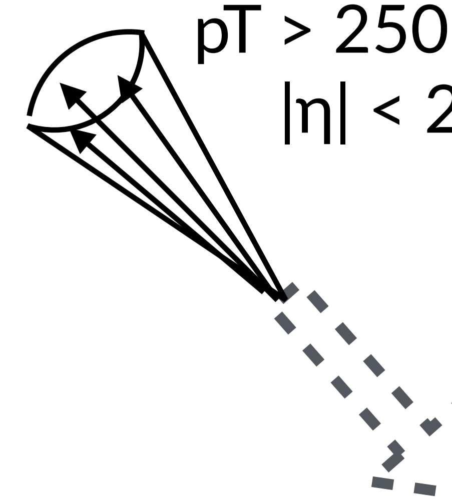
<u>subleading bkg</u>

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

systematics on total bkg

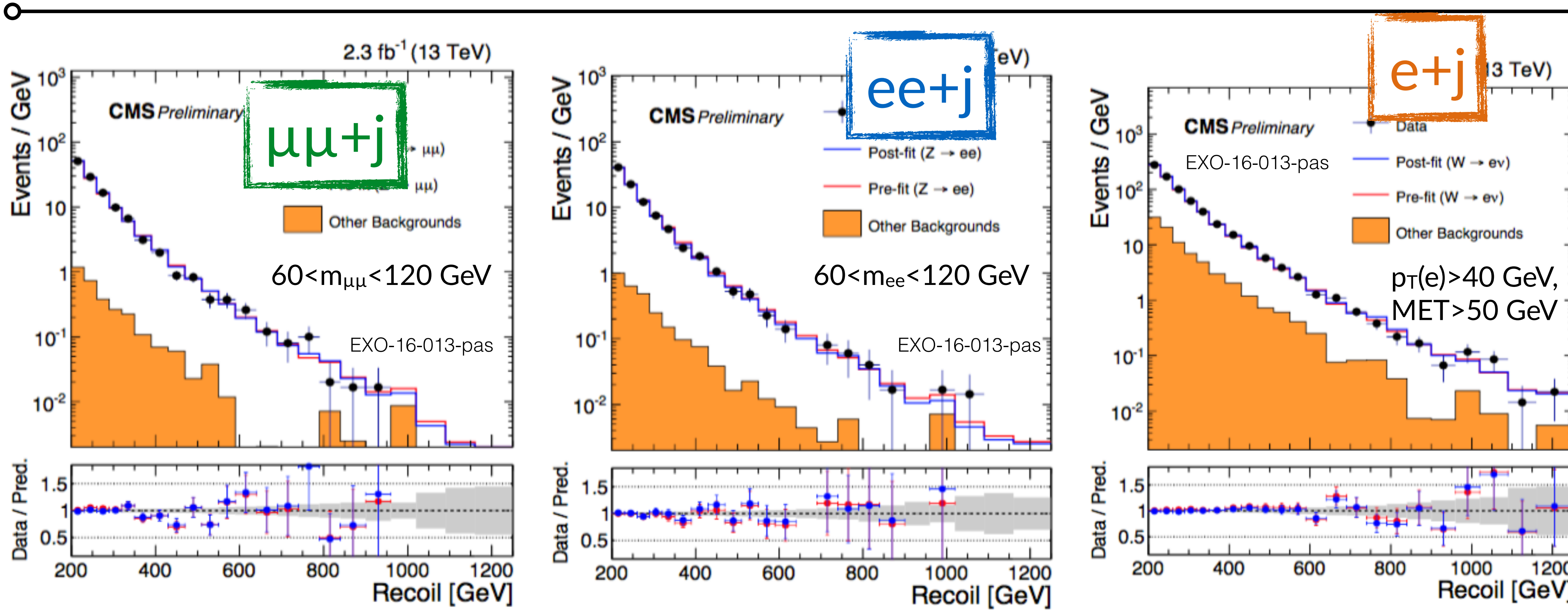
- 2-5% uncertainty for usage of W(μν) for estimation of Z(νν)
- ~3% uncertainty due to ttbar modeling (MC@NLO vs Powheg)
- 4-12% total uncertainty

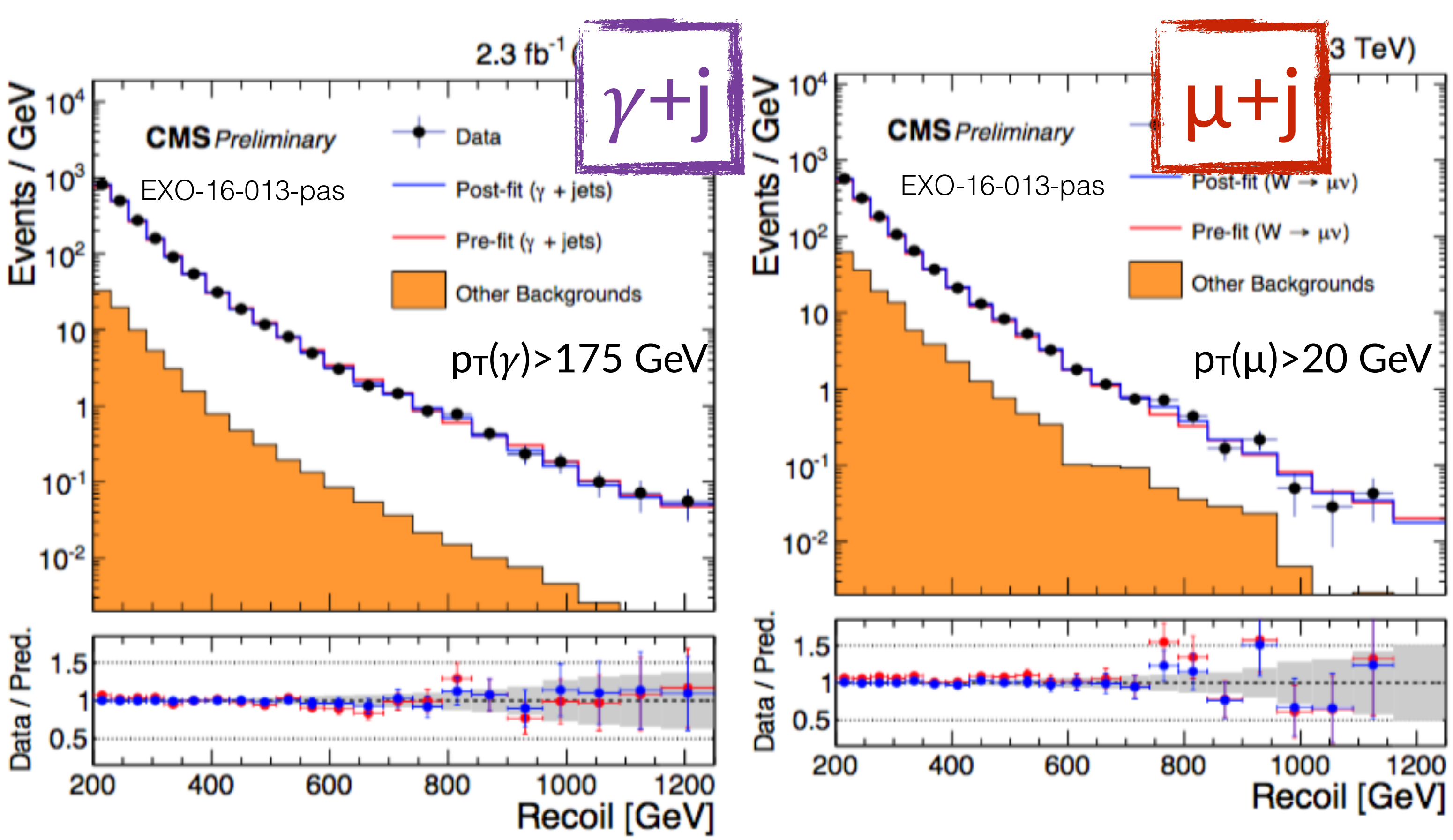
anti-k_t R=0.4, pT > 250 GeV, $|\eta| < 2.5$



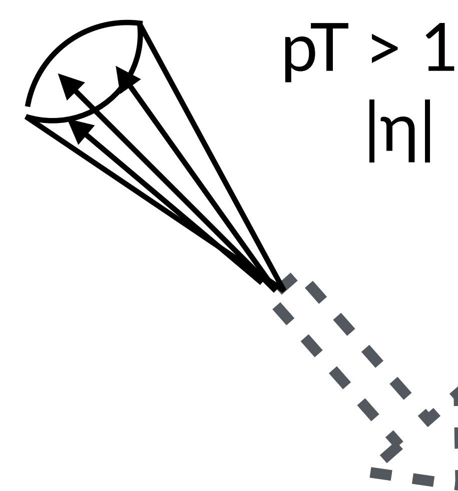
"MET" > 250 GeV

CMS: FIVE CONTROL REGIONS



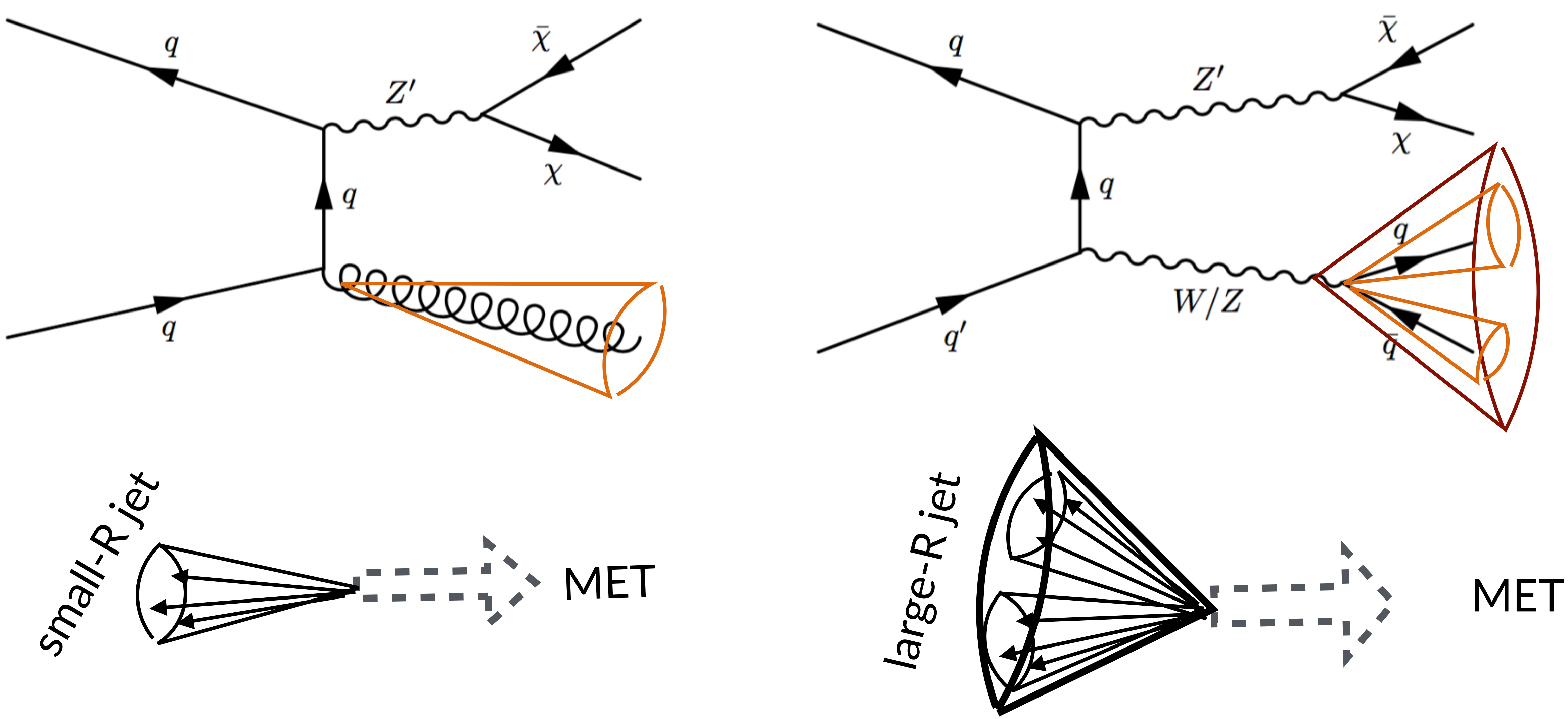


anti-k_t R=0.4,
pT > 100 GeV,
$|\eta|$ < 2.5



“MET” > 200 GeV

Playing with the jet radius parameter



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

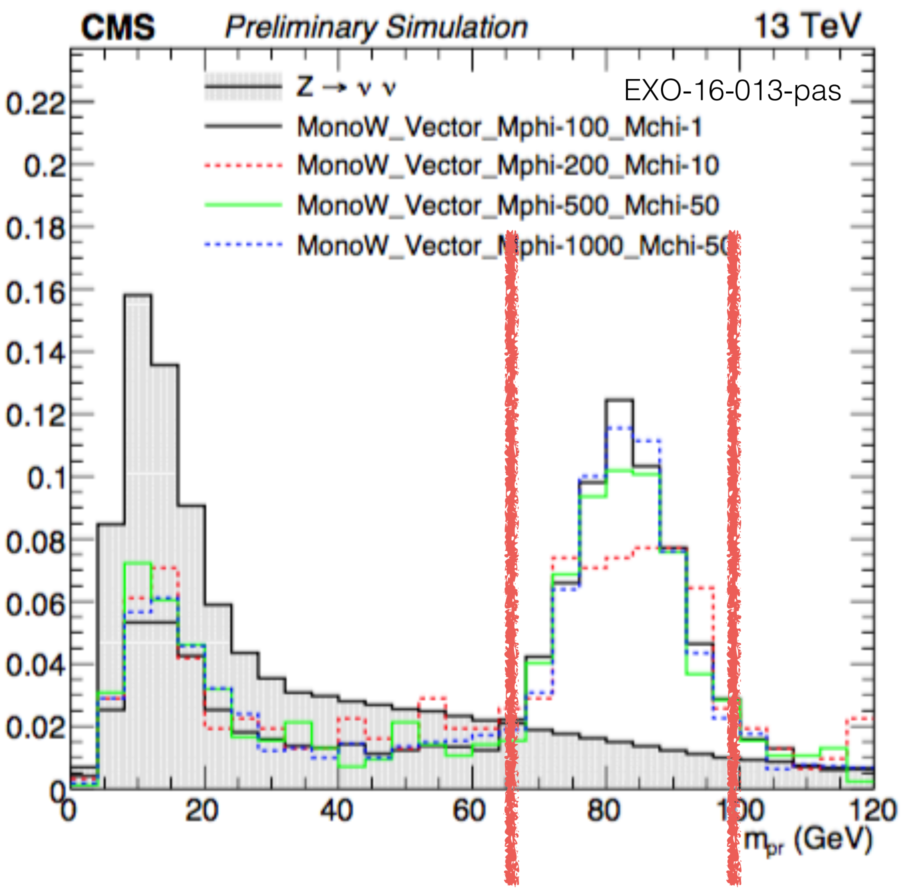
- also helps probing non-universal mediator couplings to u/d quarks (W), DM-V effective vertices

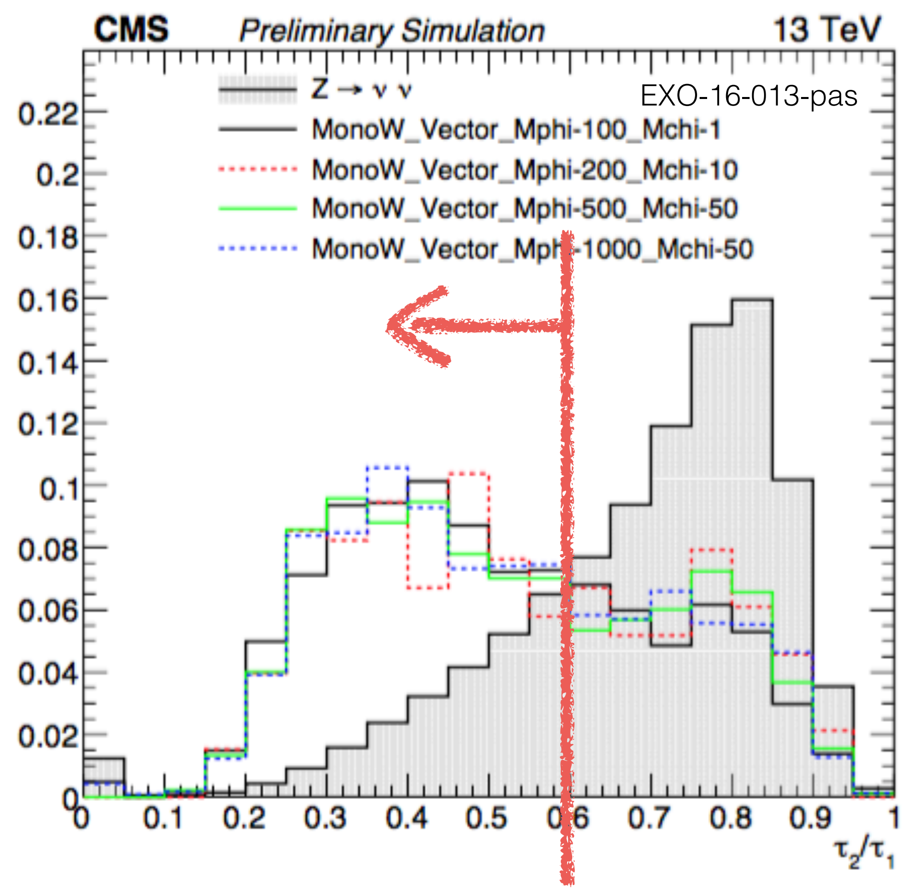
[~same for H->bb!]

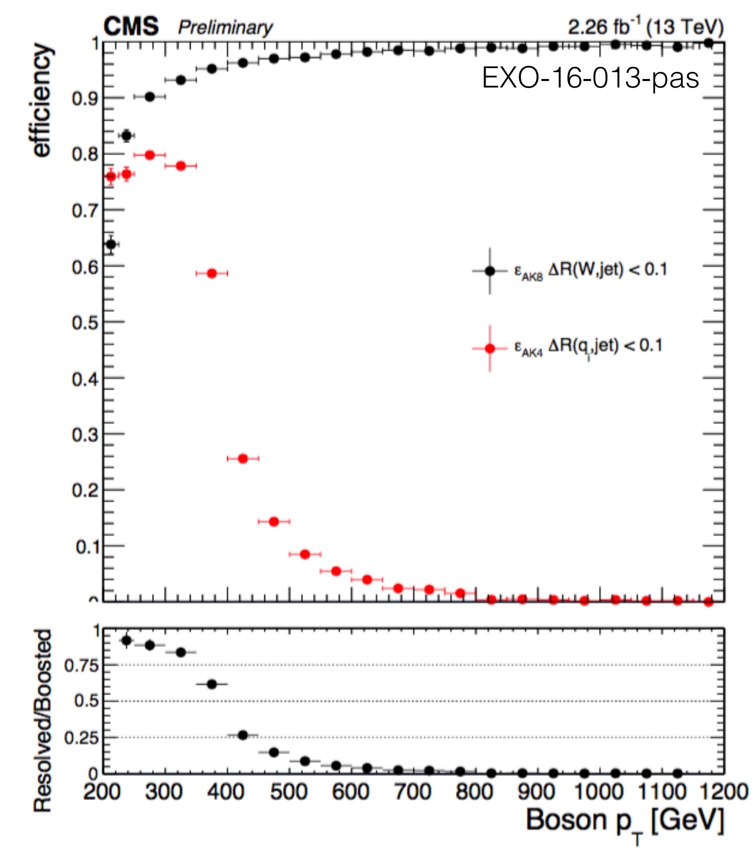
- profit from boosted regime using large-R jets
  - a couple of orders of magnitude lower statistics, though…
- ATLAS: dedicated analysis; CMS: combined with small-R mono-jet

gain by 2-5% on final limits

Getting fat

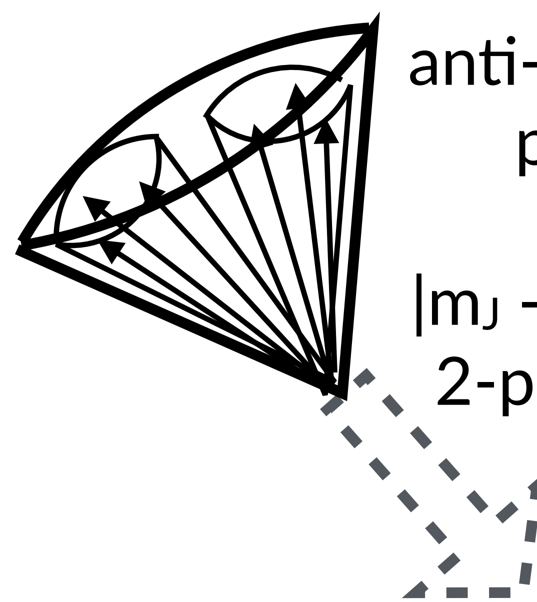






large-R jets help when topology is boosted (pT > ~250 GeV)

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

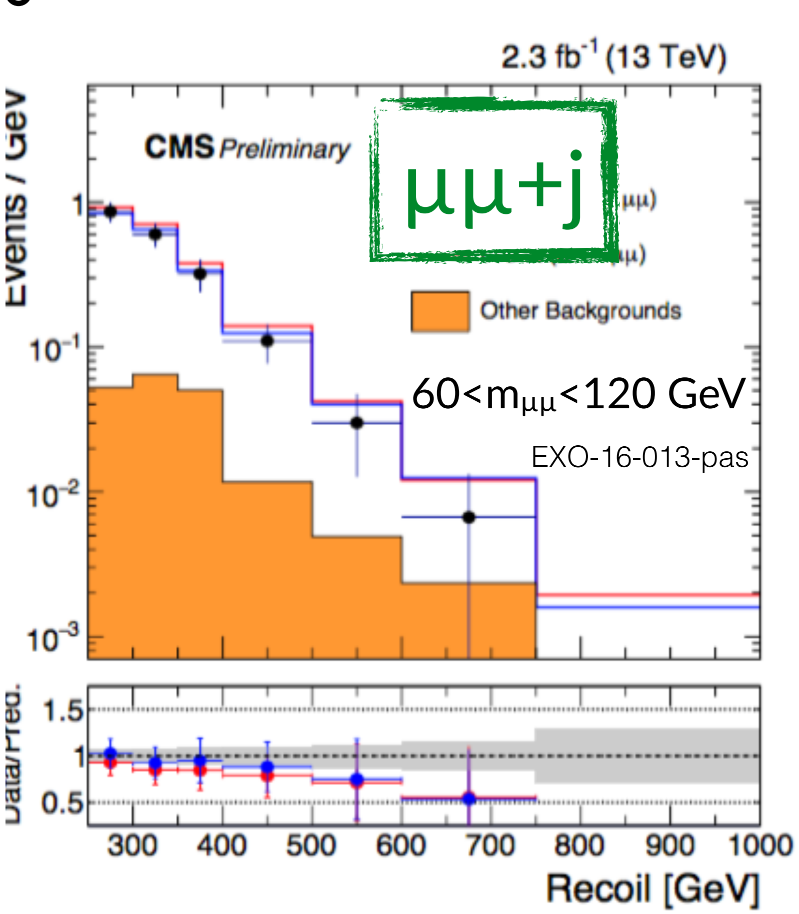


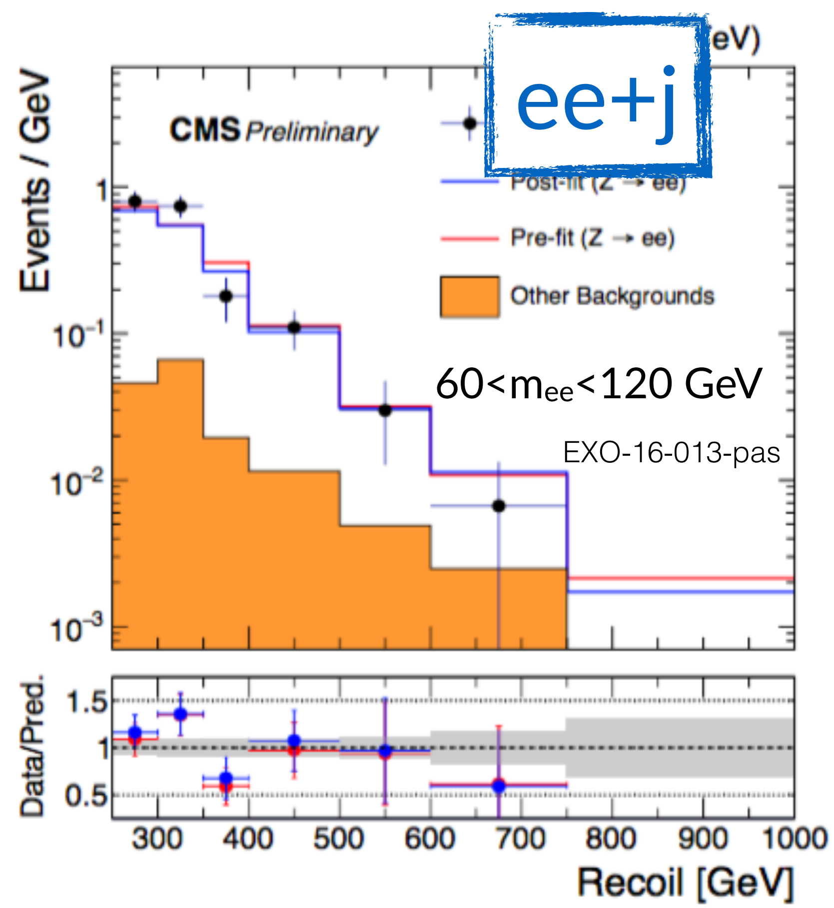
anti-k_t R=0.8 pruned,
pT > 250 GeV,
$|\eta|$ < 2.4,
$|m_J - m_{W/Z}|$ < 15 GeV,
2-prong (τ_2/τ_1<0.6)

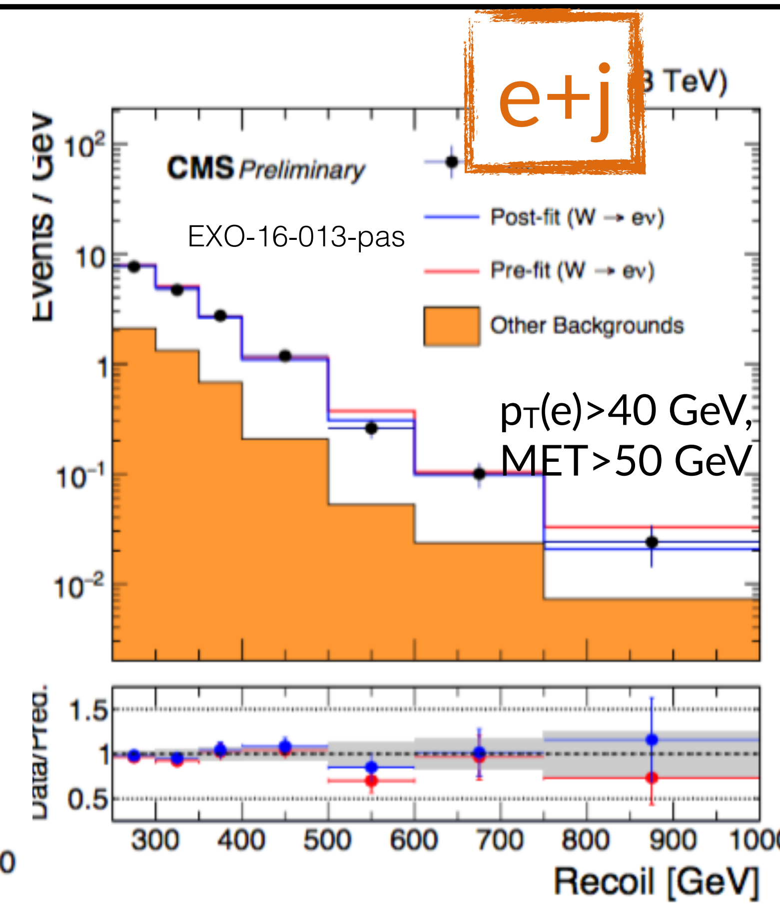
separation power depends on

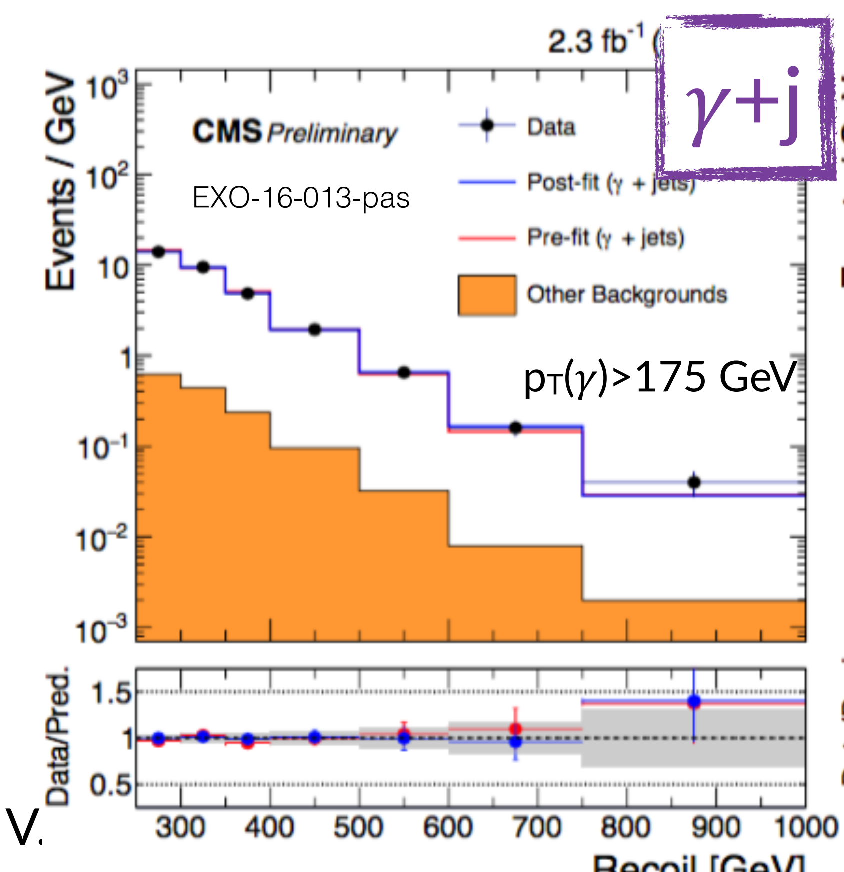
- mDM (~ pT(V))
- mMed (~ V polarisation)
- bkg composition (g/q-jets)

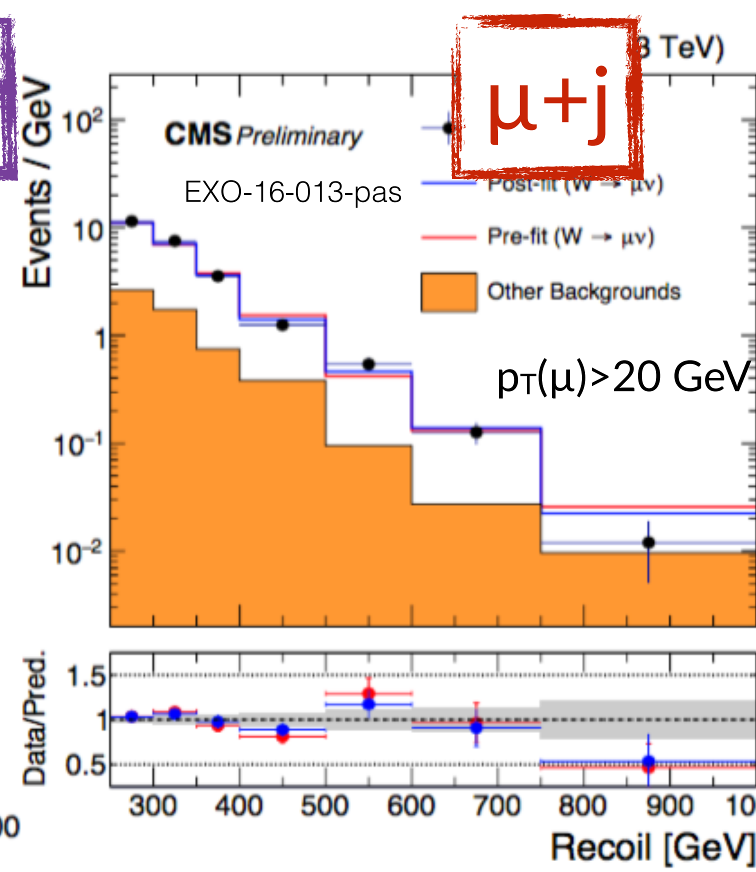
CMS: Five control regions (x2)

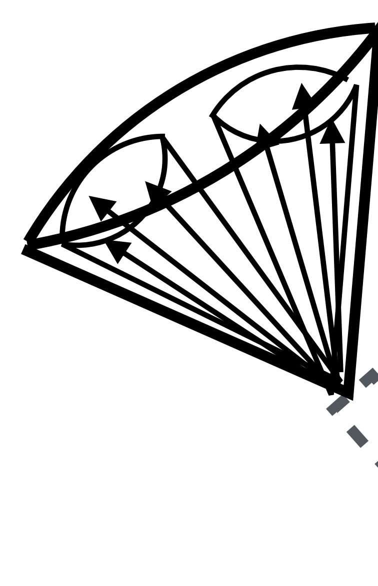








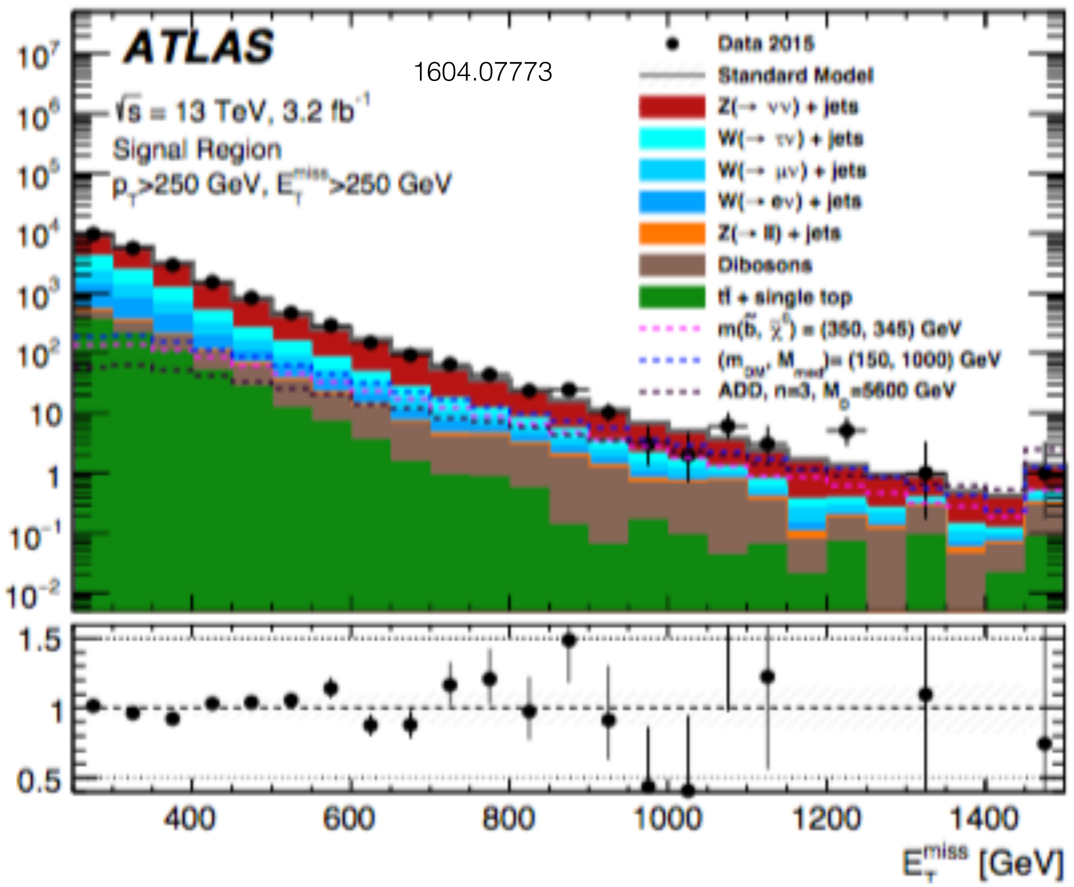




anti-k_t R=0.8 pruned,
pT > 250 GeV,
$|\eta| < 2.4$,
$|m_J - m_{W/Z}| < 15$ GeV,
2-prong ($\tau_2/\tau_1 < 0.6$)

"MET" > 250 GeV

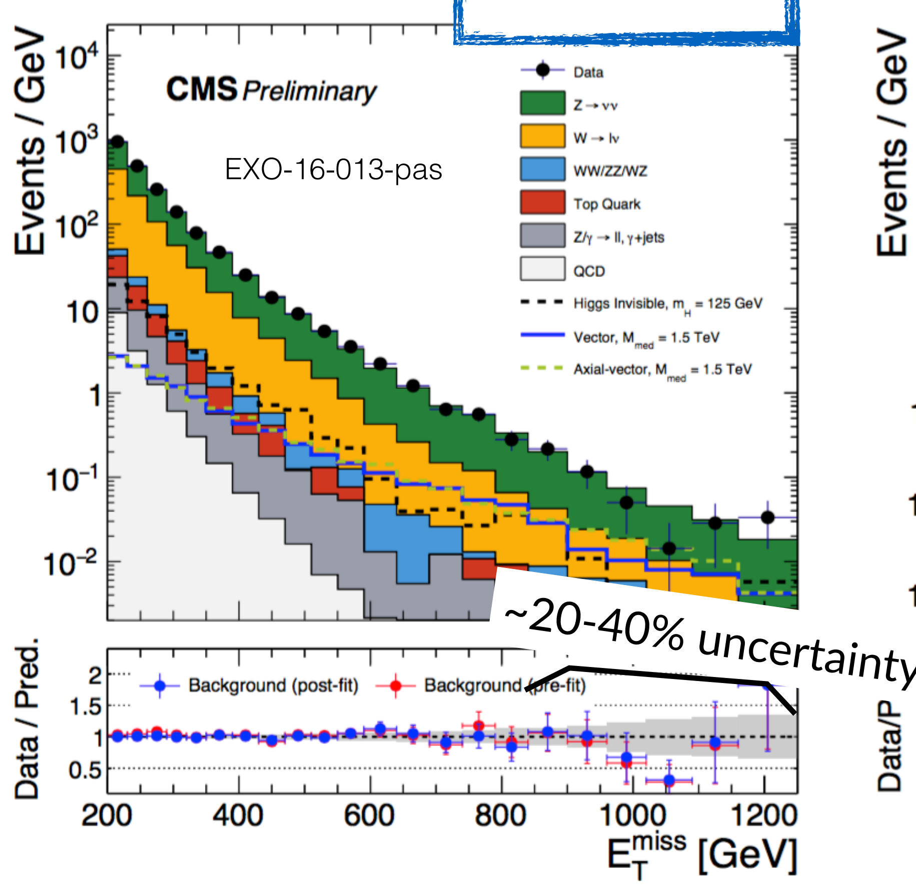
Results



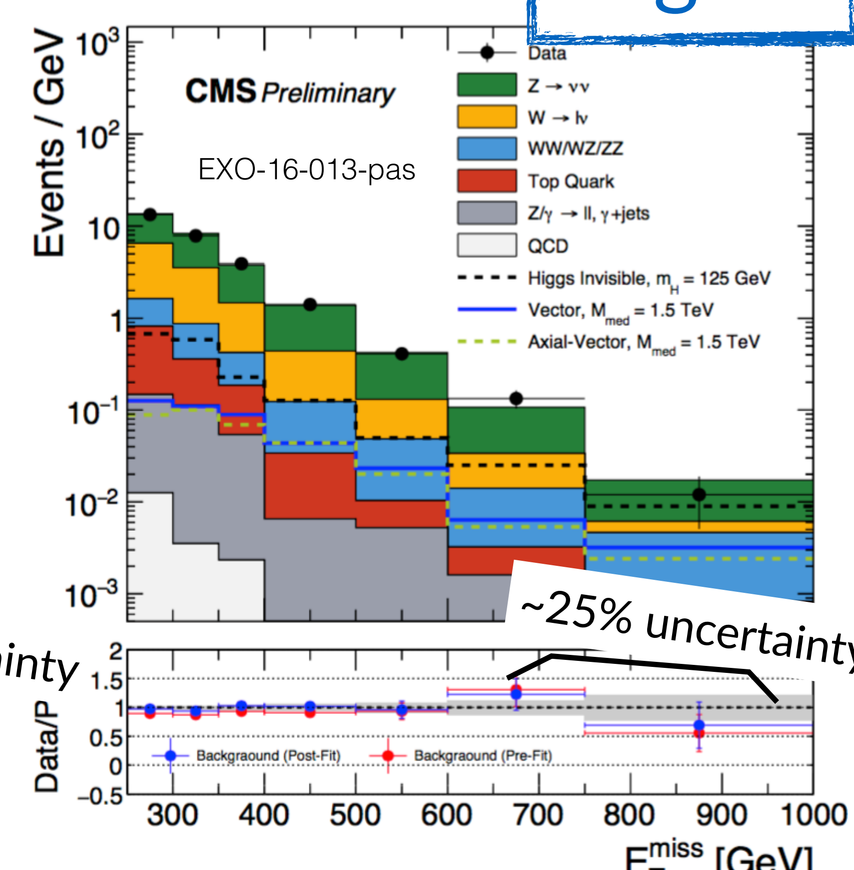
no significant excess observed w.r.t. SM prediction

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

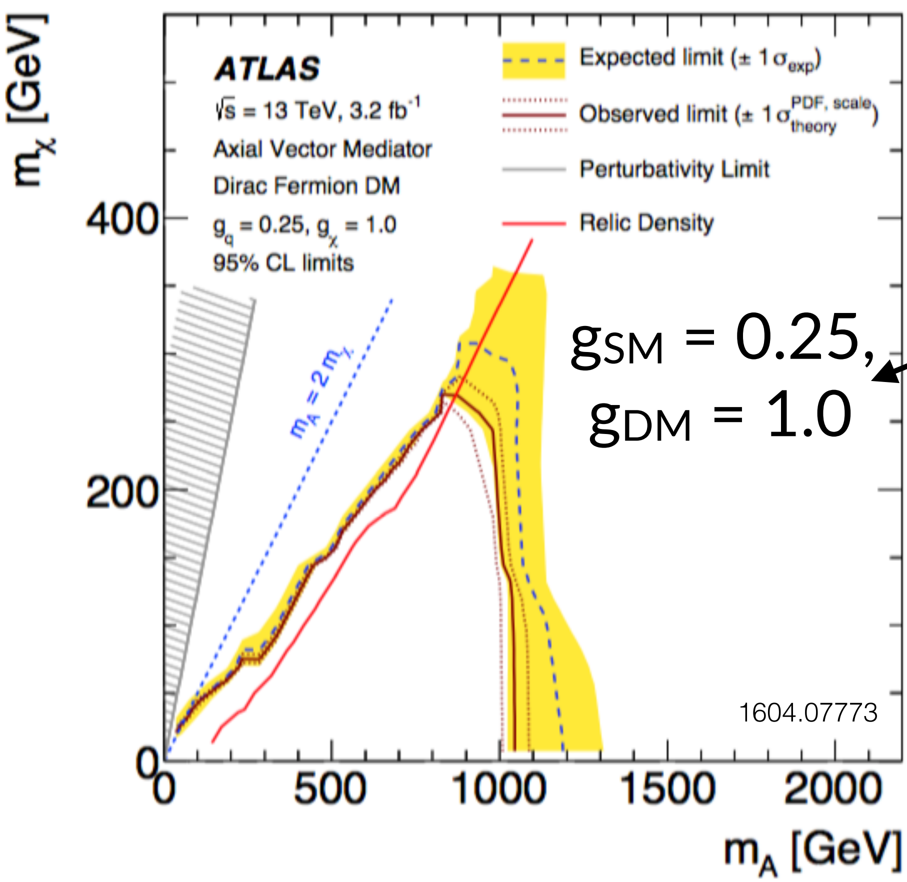
small-R



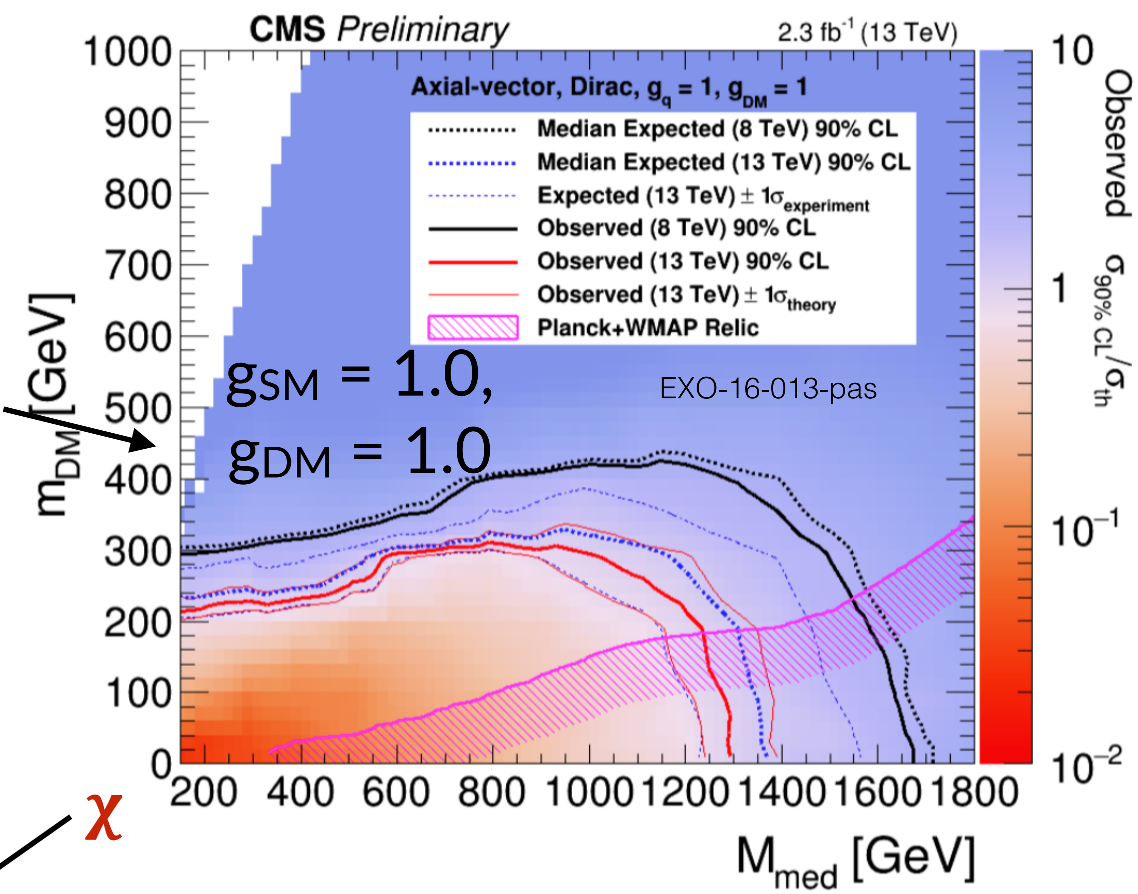
large-R

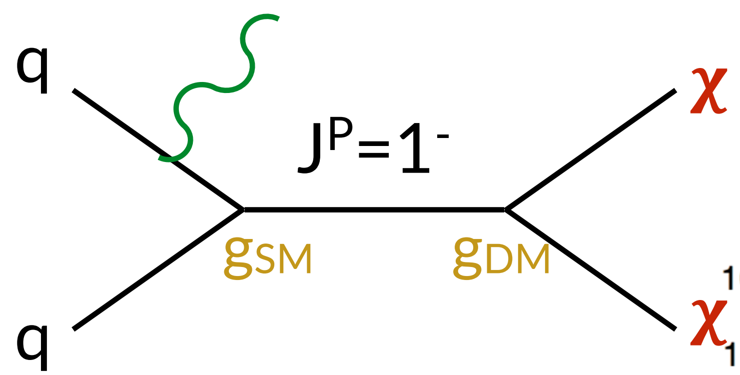


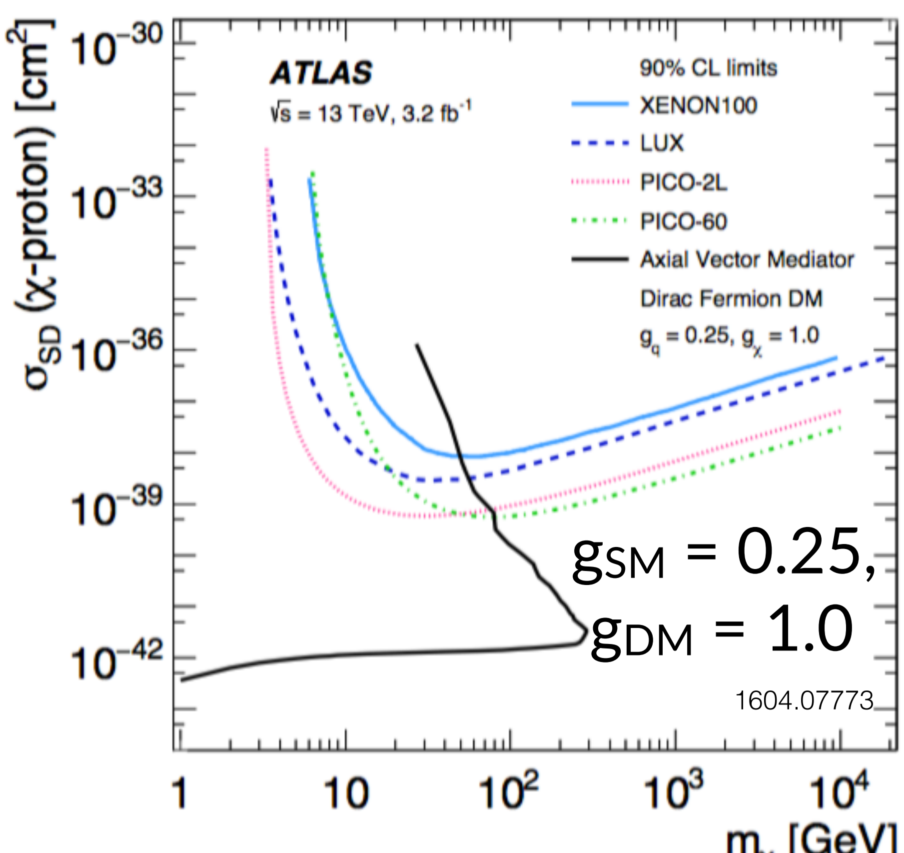
Interpretations: axial-vector mediator, s-channel



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







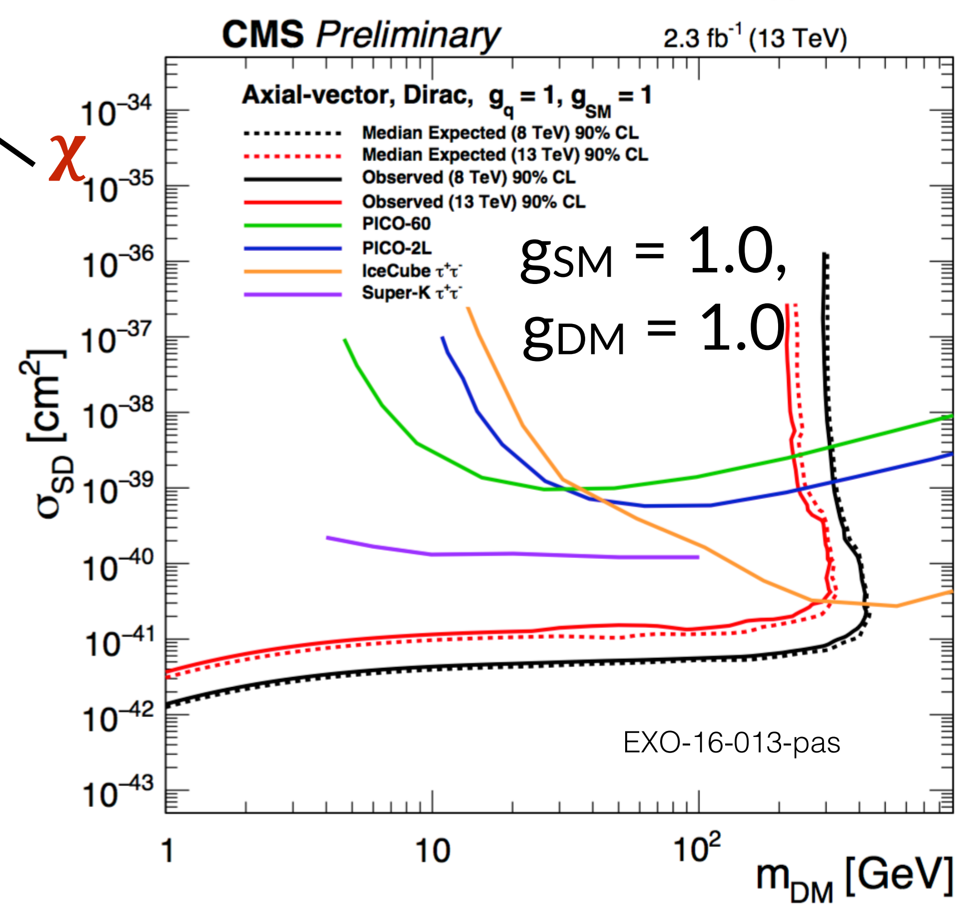
axial vector

=

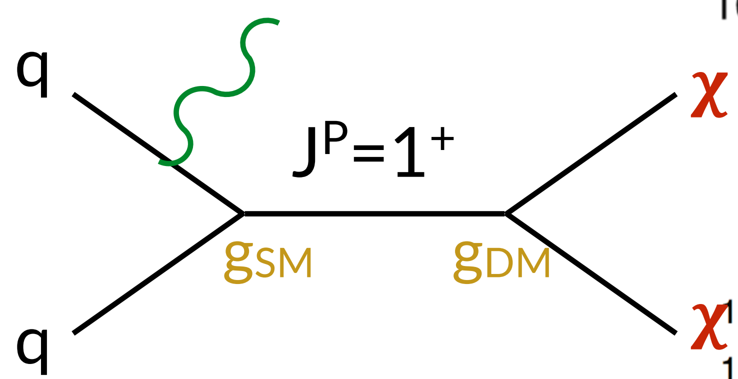
spin-dependent WIMP-nucleon scattering

=

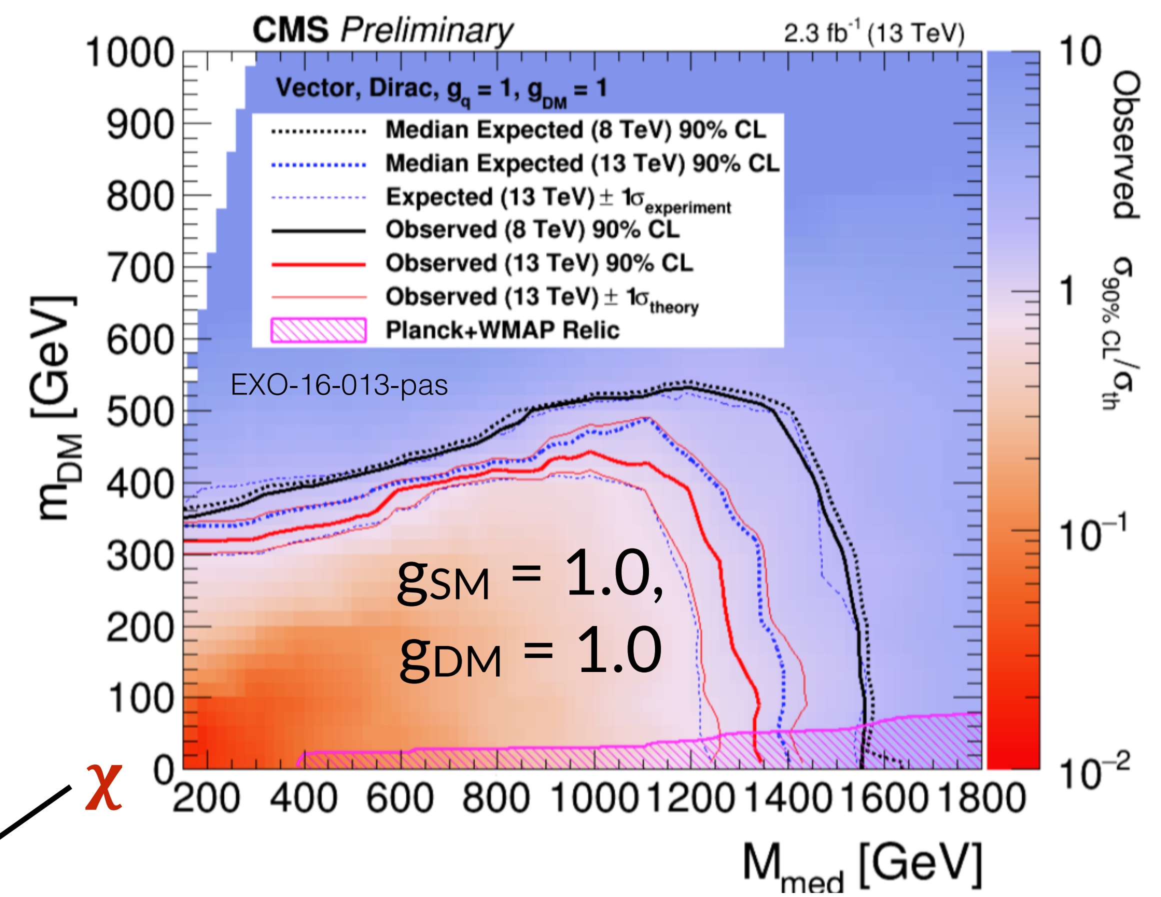
LHC is better

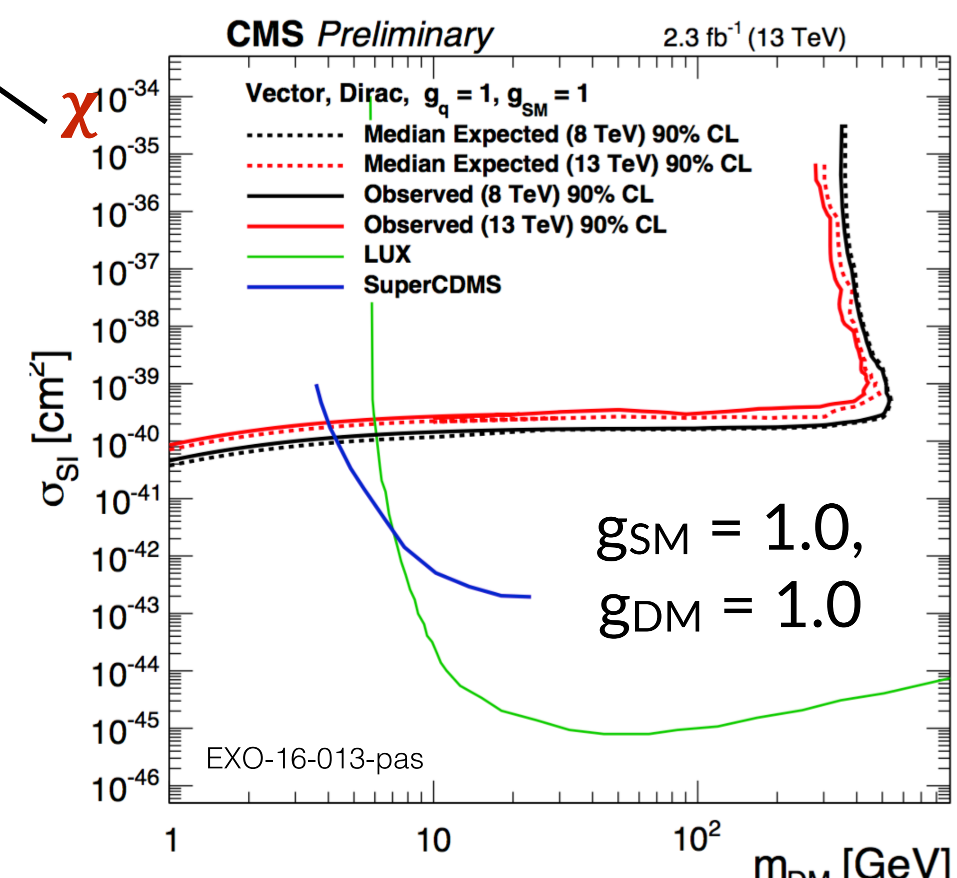


Interpretations: vector mediator, s-channel



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



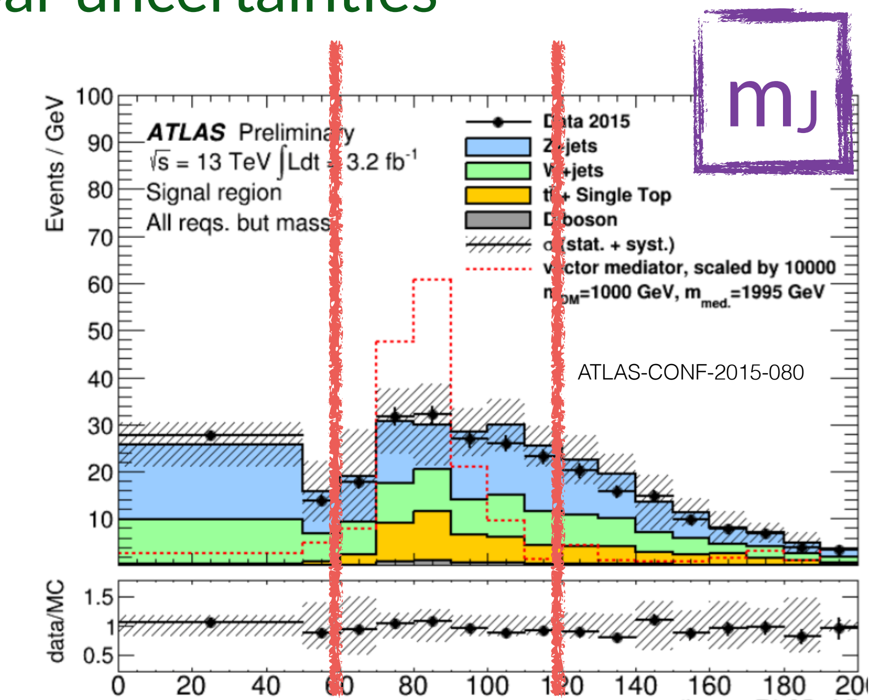


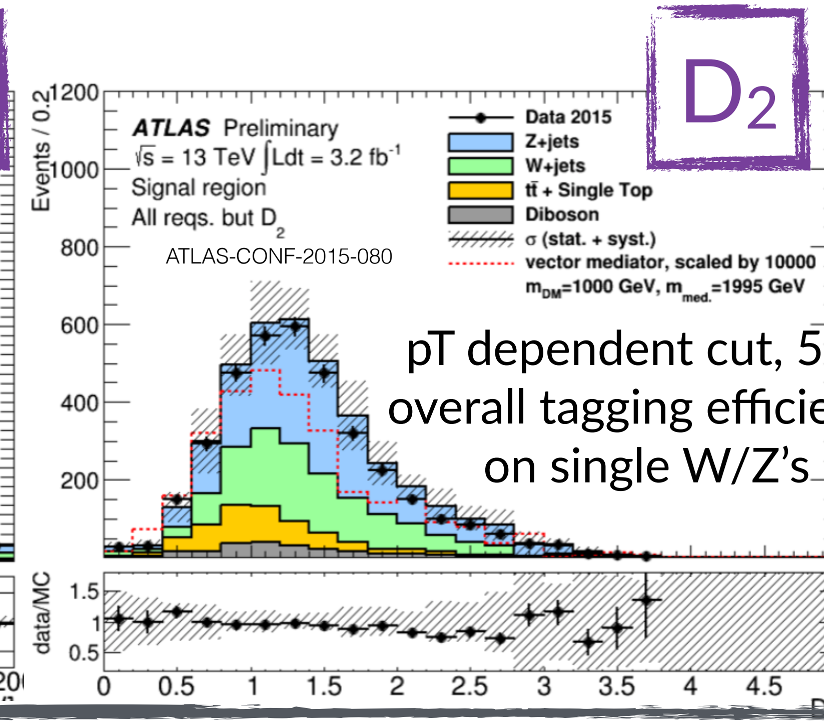
Mono-W/Z at ATLAS

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

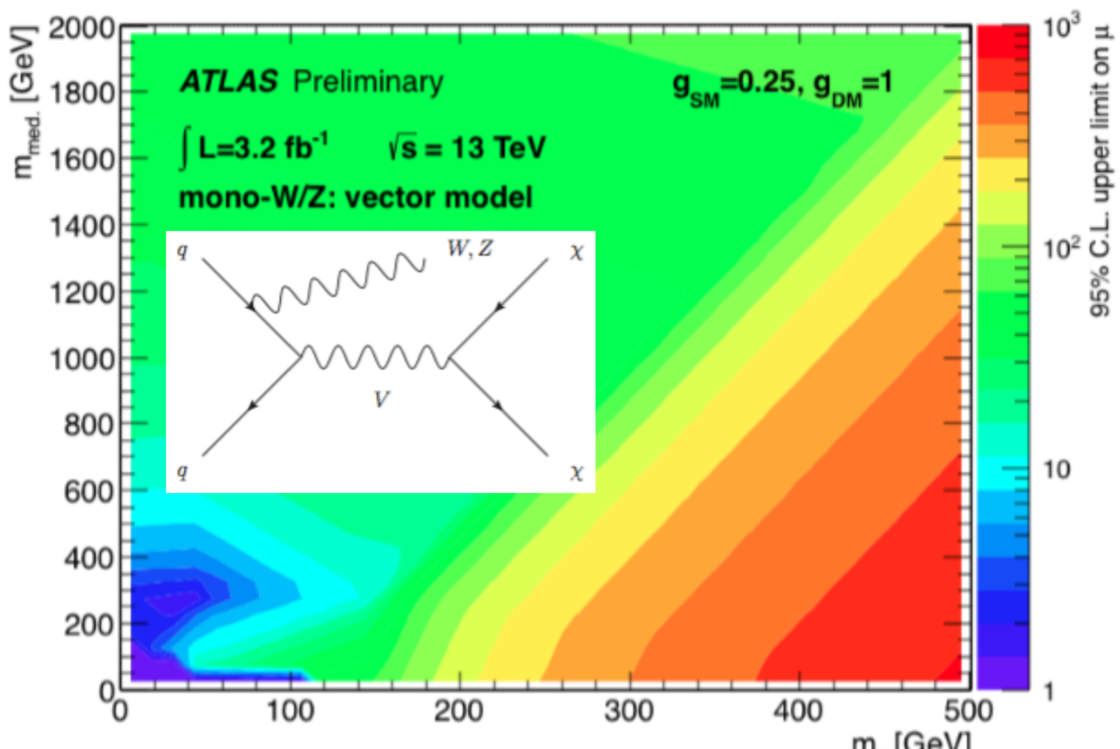
- with 1μ1b CR for reducing ttbar uncertainties

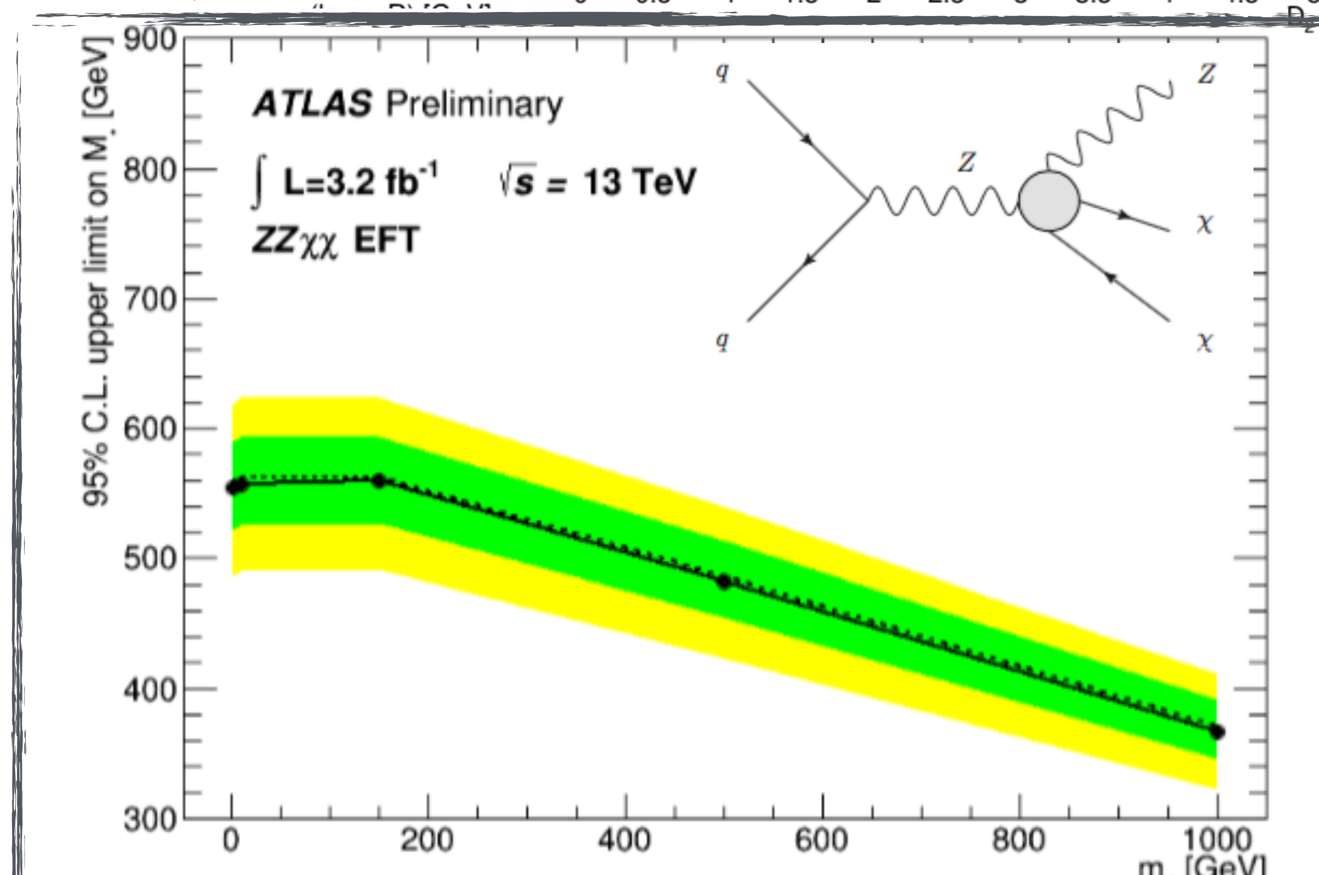
boson tagging based on jet mass and 2-prongness ("D_2"), main uncertainty on total bkg (5-10%)





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



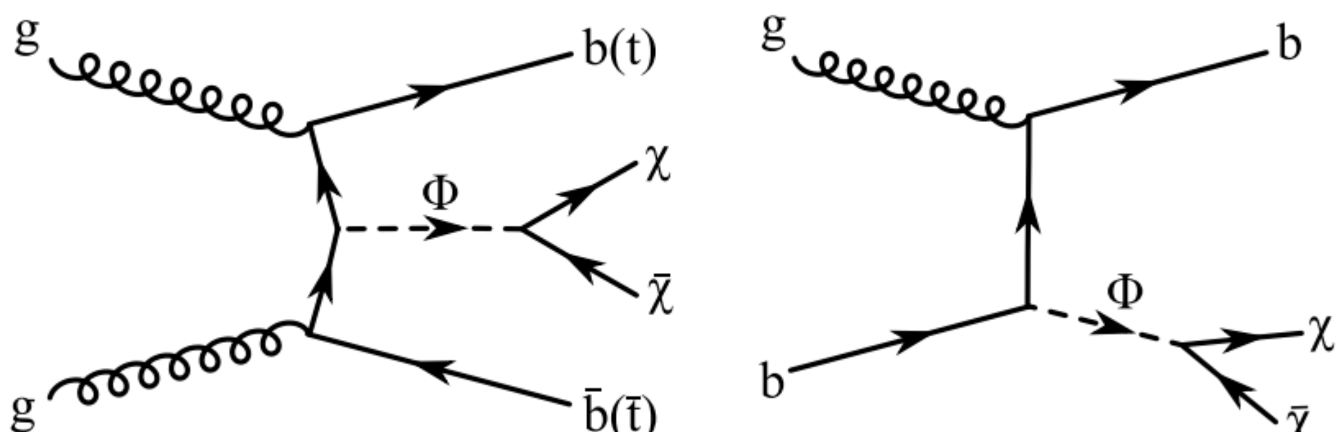


MET + HEAVY QUARKS

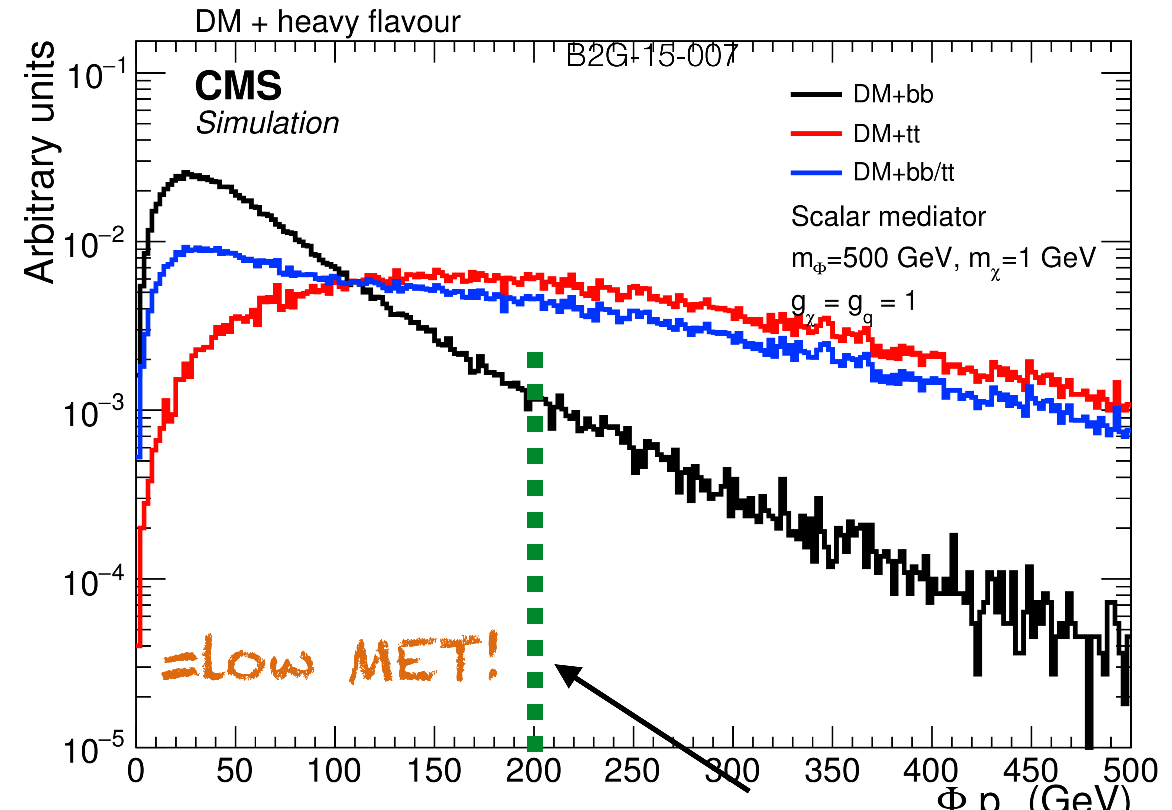
(a quest for the elusive)

CMS: B(B) + MET @ 13 TEV

mediator pT ("true")

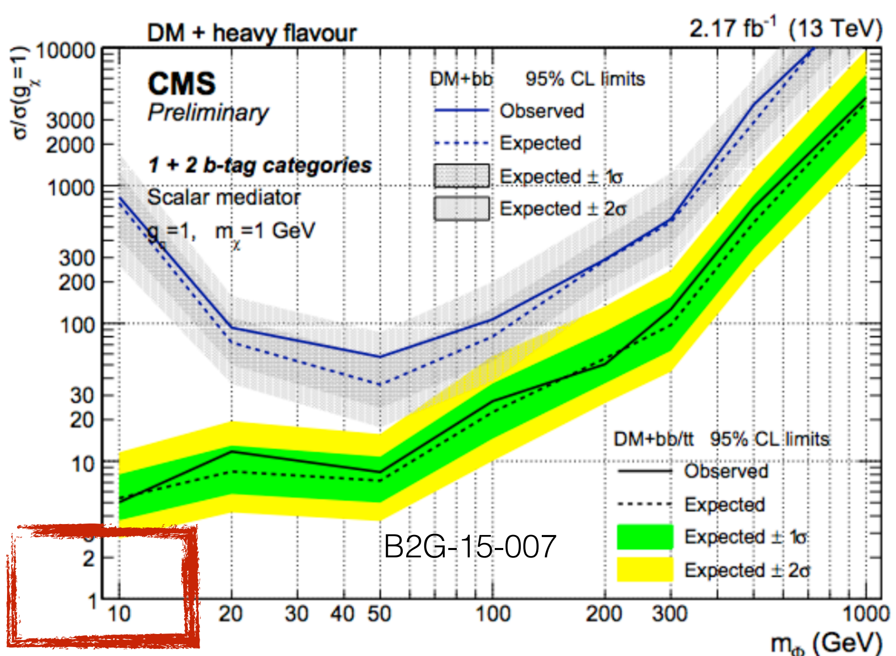


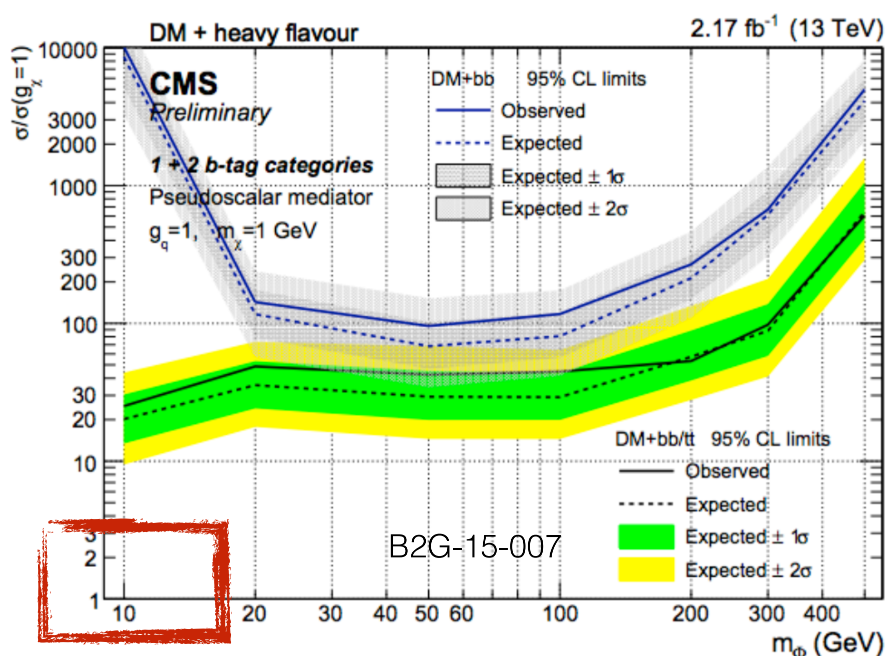
$$\mathcal{O}_{\mathrm{scalar}} = \sum_q \frac{m_q}{M_*^N} \bar{q} q \bar{\chi} \chi$$

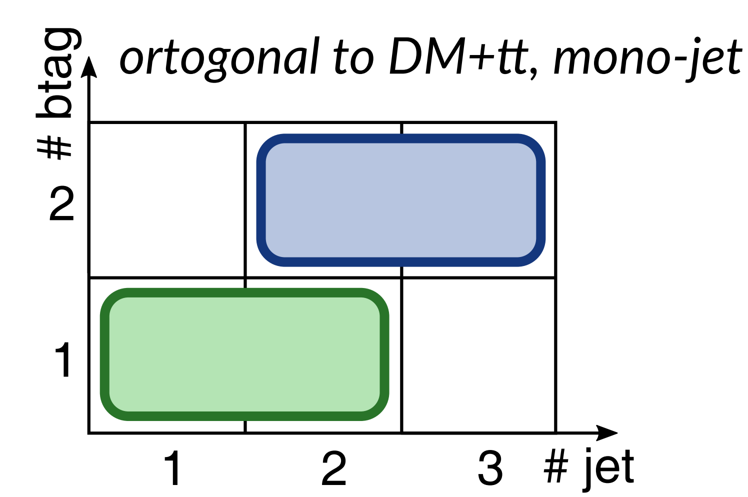


à-la-monojet, but binned in $N_{b\text{-tags}}$, N_{jets}

- sensitive also to ttbar+DM production
- softer mediator pT -> MET trigger is a challenge!
  - need more luminosity to be fully sensitive

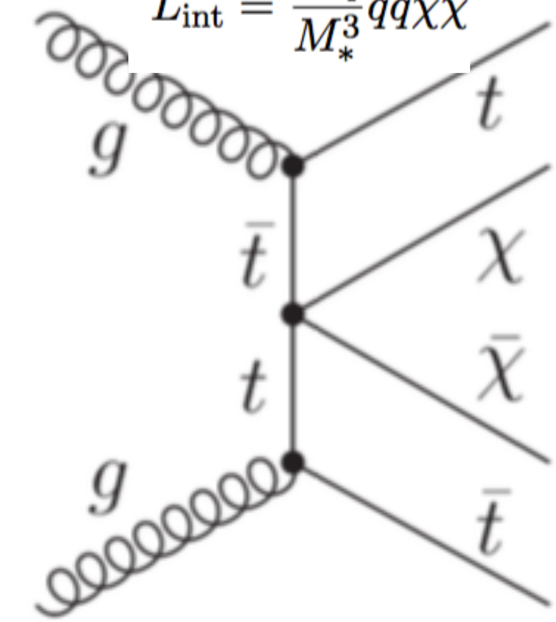






CMS, ATLAS: TT + MET @ 8 TEV

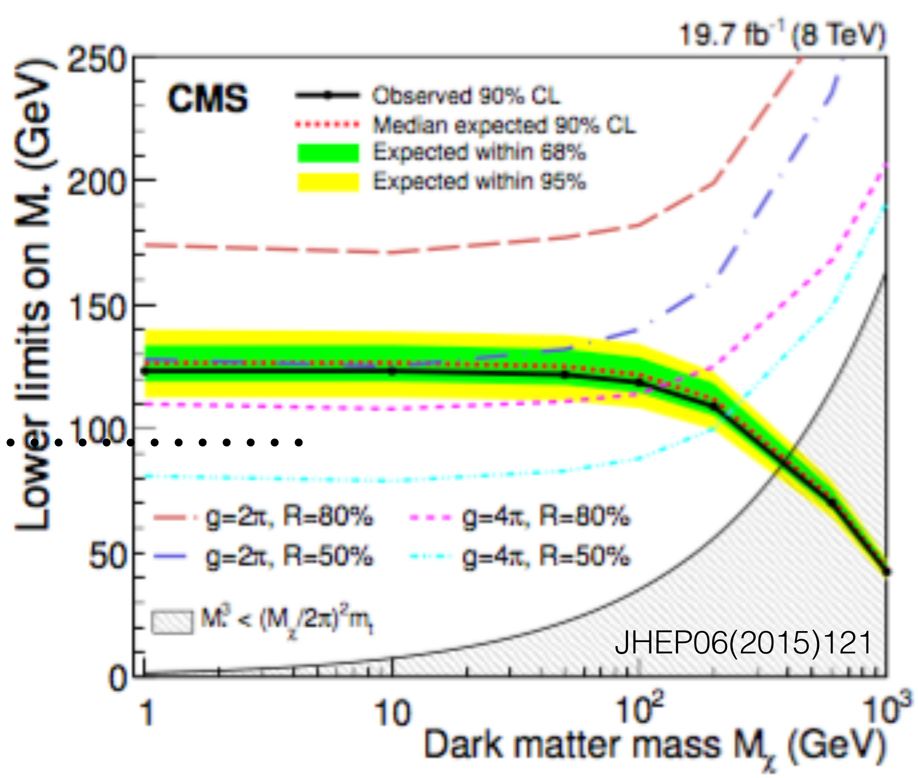
$$L_{\rm int} = \frac{m_q}{M_*^3}\bar{q}q\bar{\chi}\chi$$

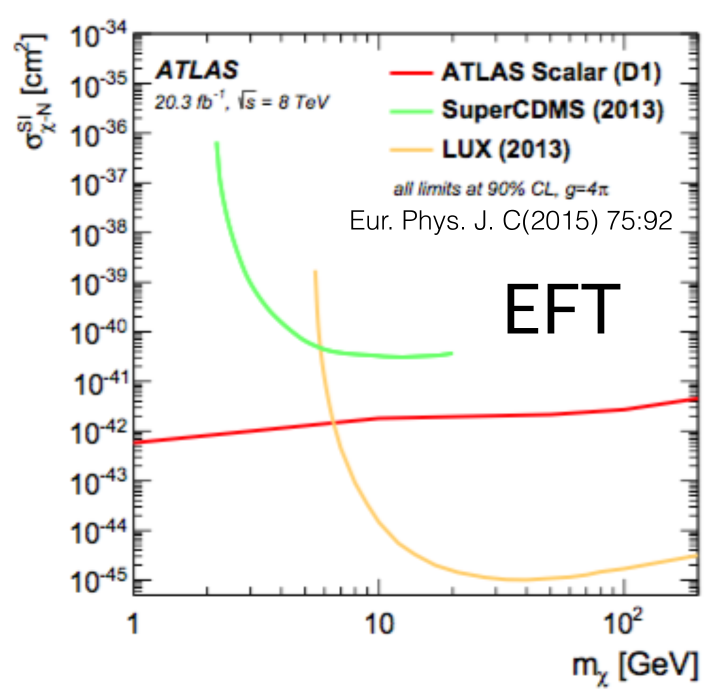


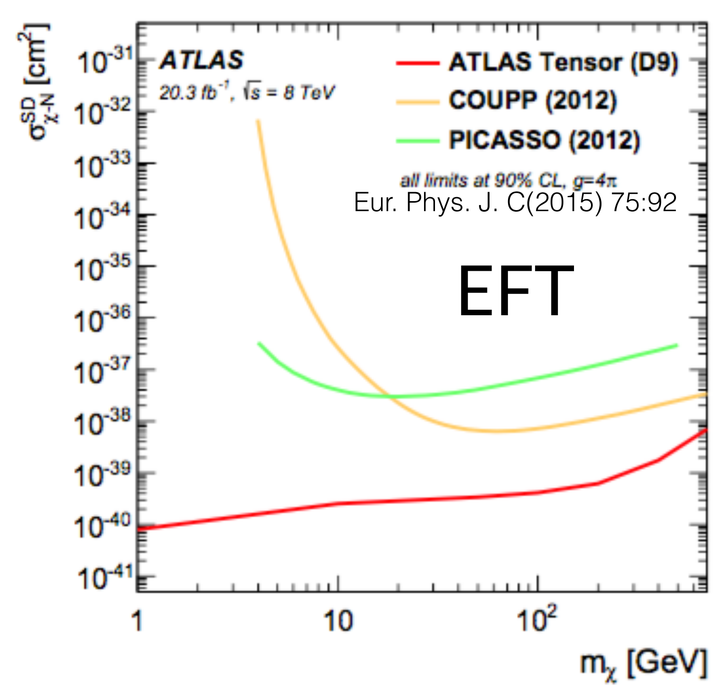
similar idea with tt final state

- 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
  - ATLAS also has fully hadronic channel -> increased sensitivity

dilepton channel





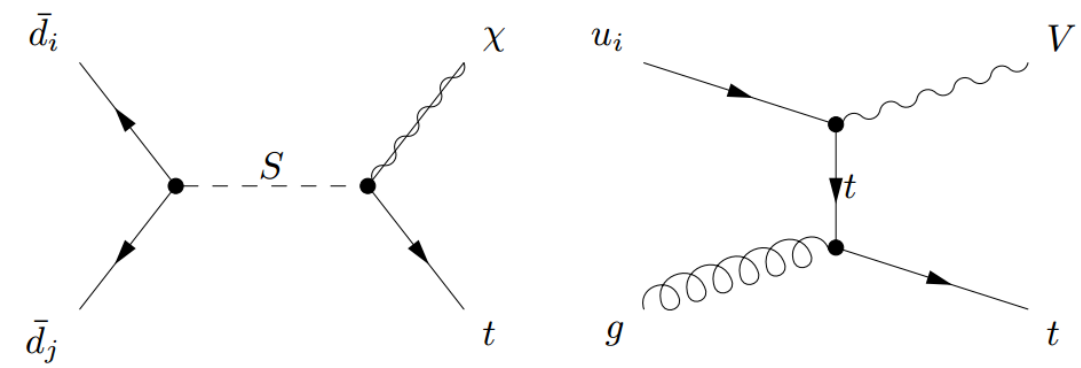


MONO−TOP

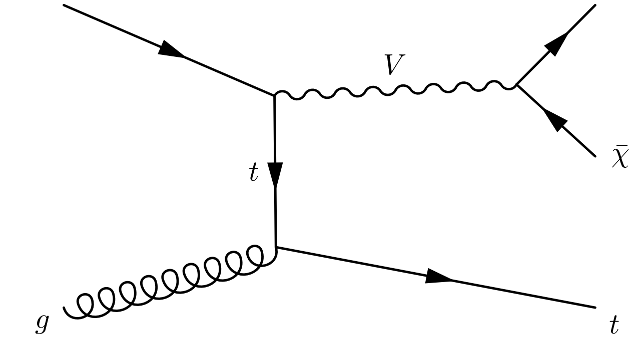
unique sensitivity to specific models not currently probed by other mono-X analyses

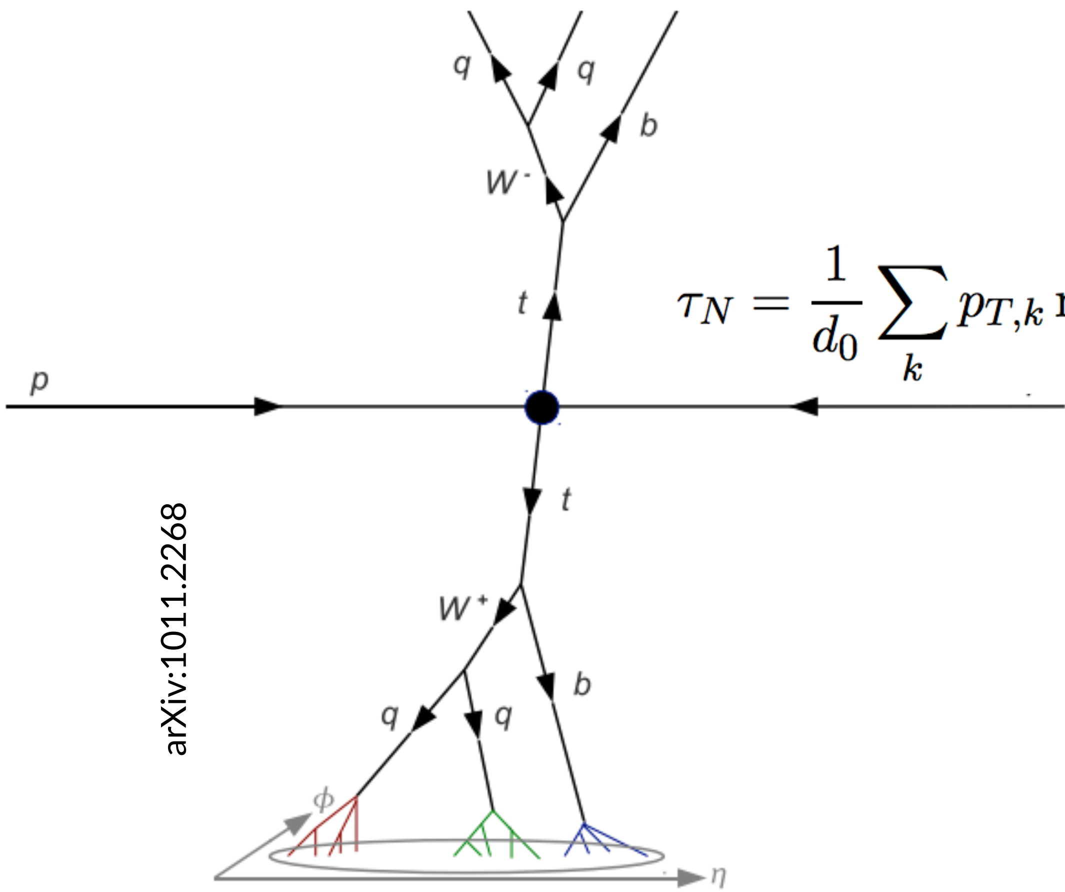
- massive mediator decaying into DM + top quark (RPV SUSY, hylogenesis)
- flavor-changing current

non-resonant



resonant

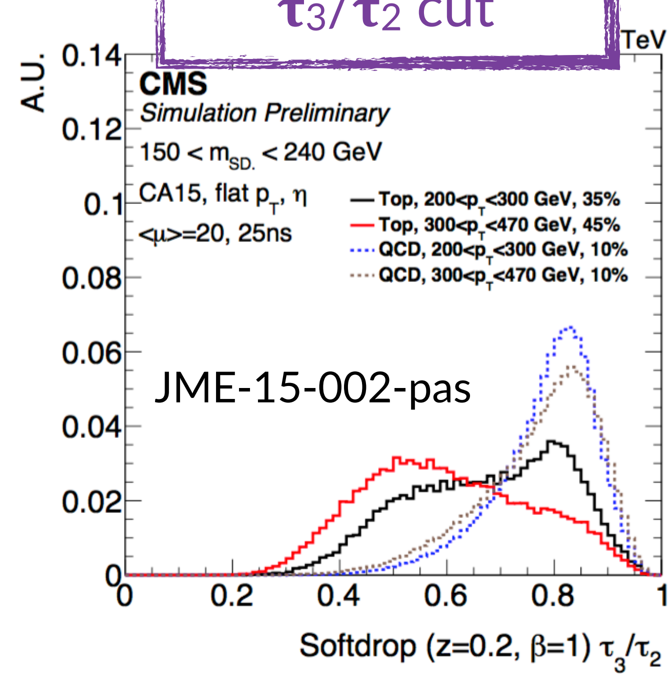




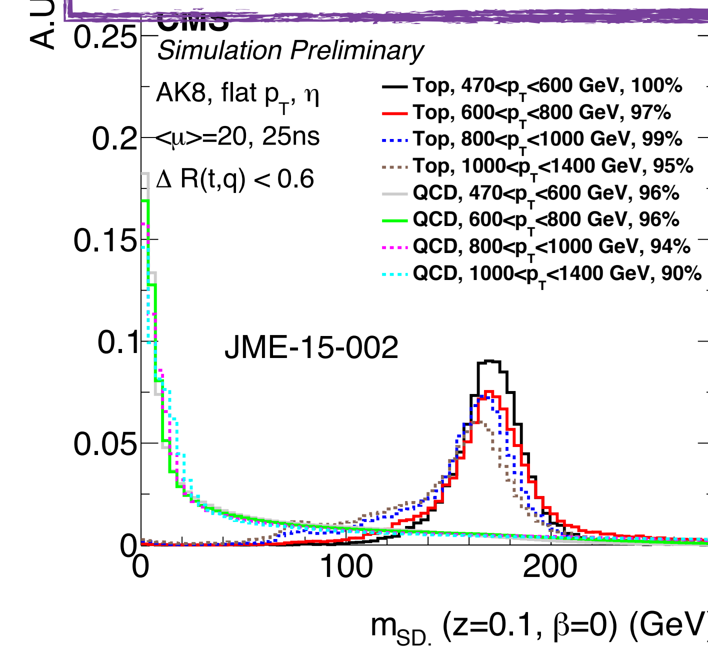
arXiv:1011.2268

$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k}\min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$

τ3/τ2 cut

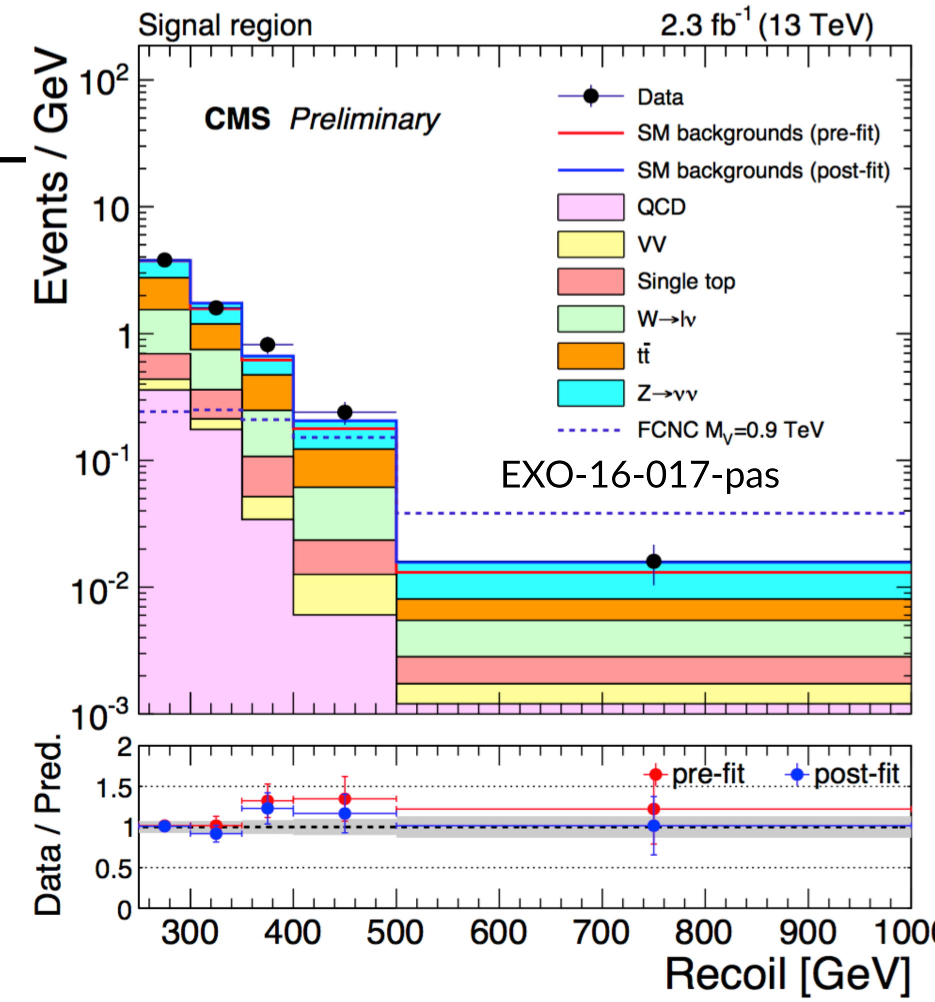


soft-drop mass with merged top requirement



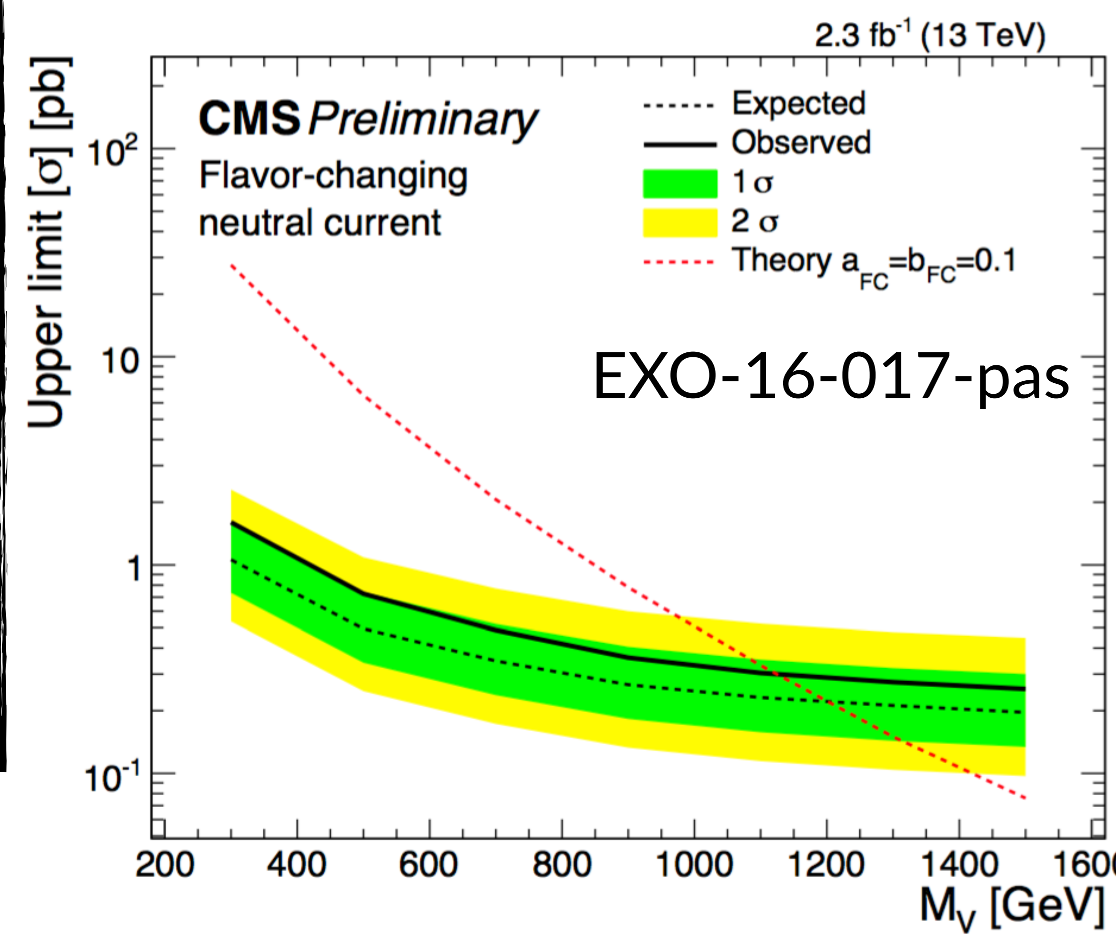
CMS: Mono-top @ 13 TeV

- trigger: MET>90 GeV or MHT>90 GeV
- C/A jet, R=1.5, pT > 250 GeV, |eta|<2.5
  - b-tagging, top mass requirement
  - soft-drop + τ_3/τ_2 cut: 13% top-tagging efficiency
- b-veto against ttbar
- CRs enriched in 1-2 lepton CRs (w/0-1 b-tag) and gamma+jet CR
- HF fraction: 1-4% on V+jets



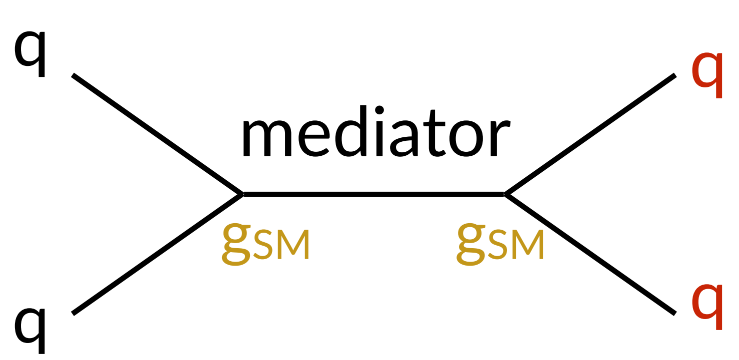
interesting signature, but a lot of work to do

- assumed V-SM coupling can influence interplay with other searches (single-top, ttbar…)
- non-obvious relic density constraints
- fat-jet tagging is always an experimental challenge



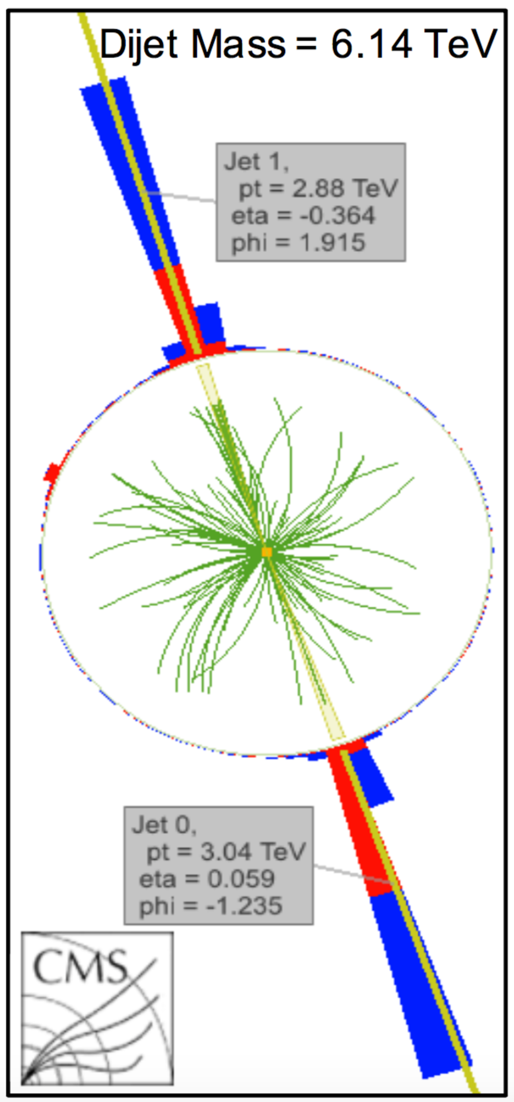
Beyond Mono

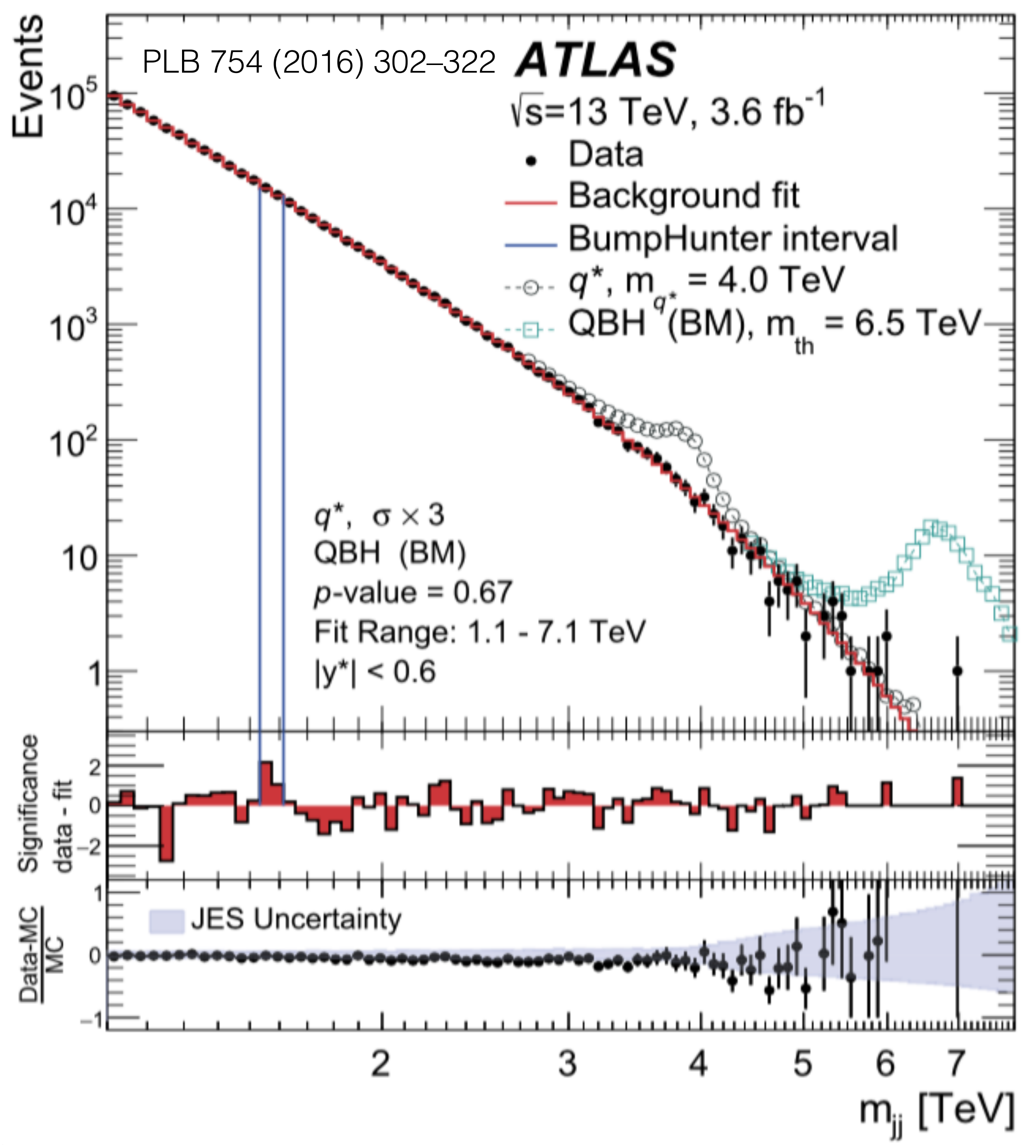
DIJET (OR "IS YOUR SIMPLIFIED MODEL ALREADY EXCLUDED?")

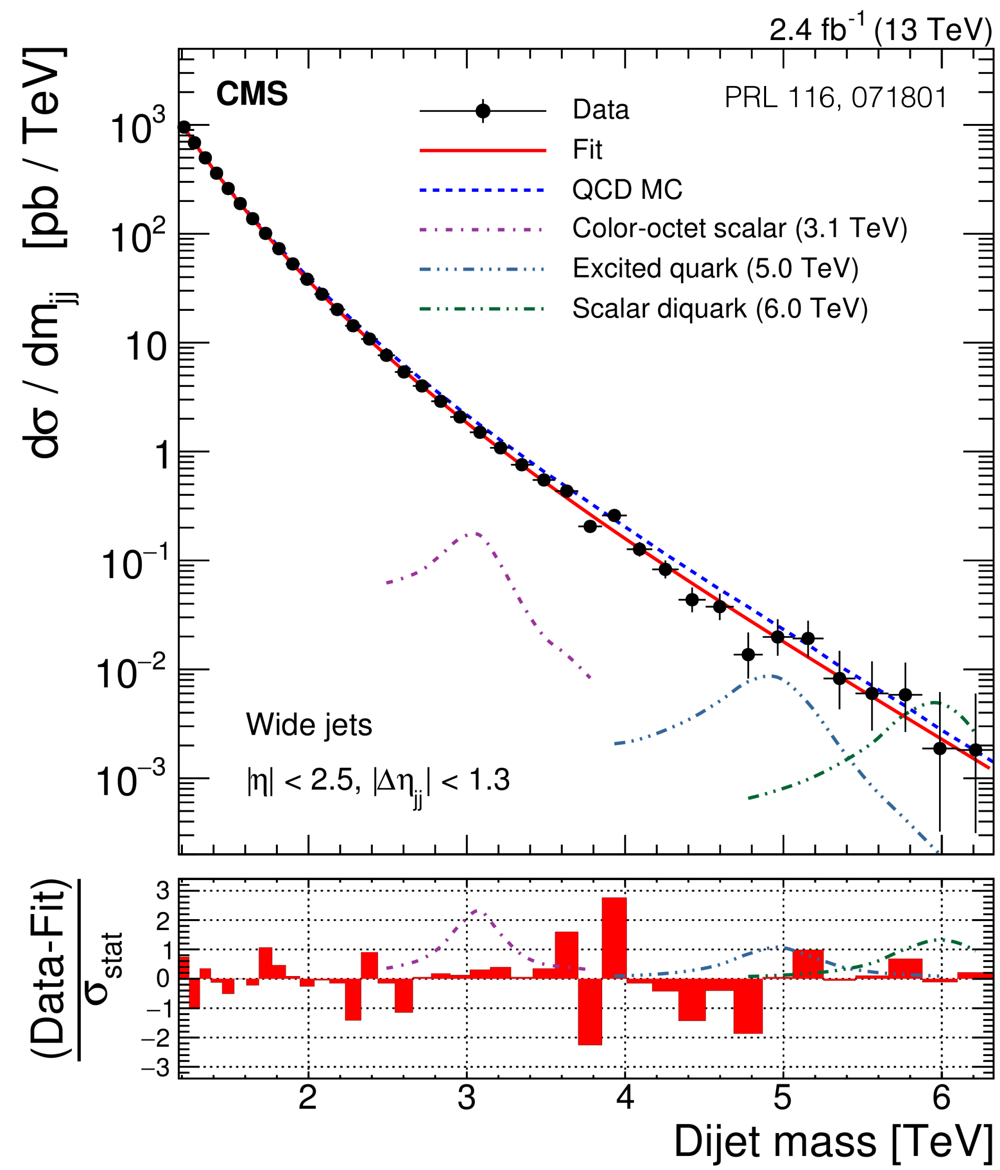


mediator can decay back to quarks

- 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







Data Scouting ("TLA") @ ATLAS

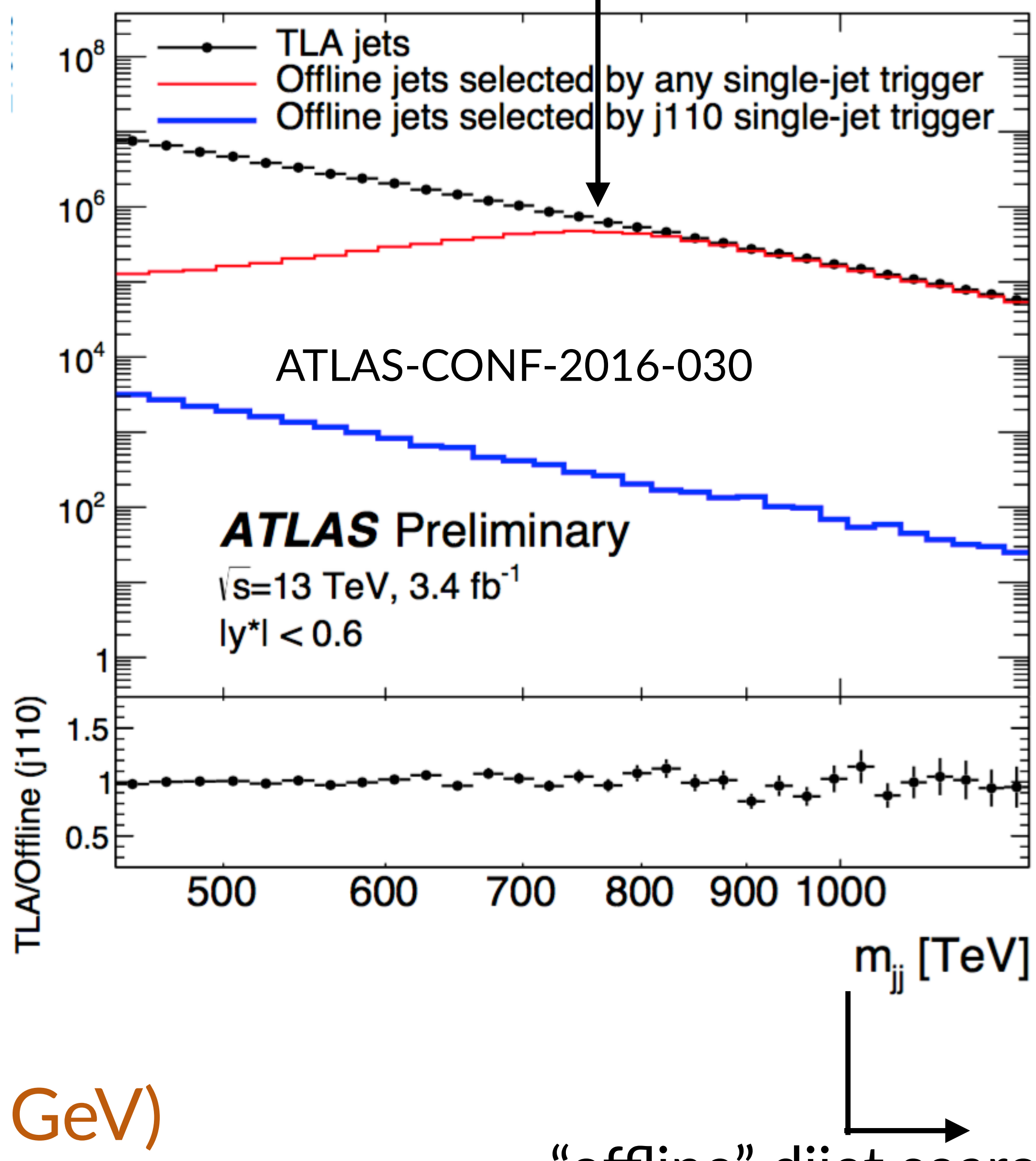
problem: limited trigger rate -> high pT threshold for single jet triggers

- 100 kHz @ L1 -> pT(single jet) > ~400 GeV

first unprescaled single jet trigger at p_T > 400 GeV

solution: store only minimal jet information

- start with 75 GeV L1 trigger (+2 kHz; EM scale)
- save all HLT jets above 4 GeV (~5% of total event size)
- calibrate them using offline jets
  - no tracking info -> 3.5-5% systematics (mostly due to flavour uncertainties)

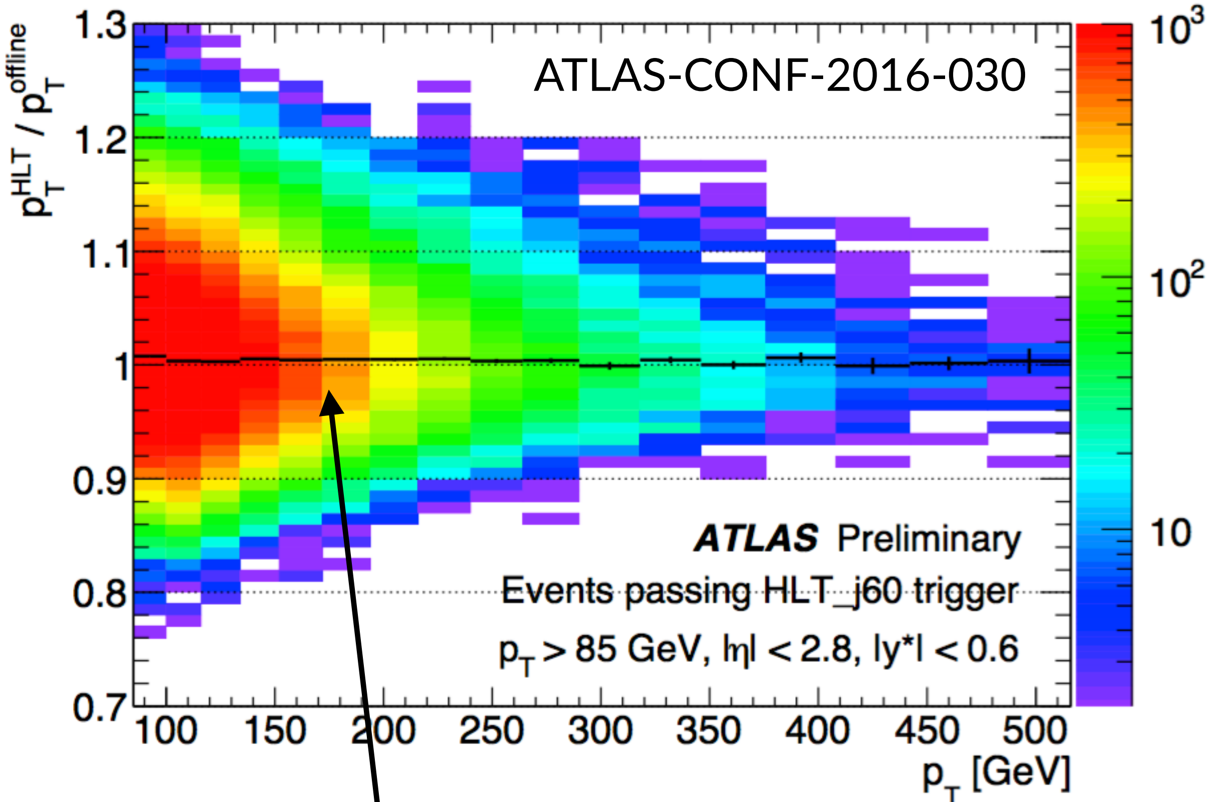


dijet search using trigger-level jets

- pT1>185 GeV, pT2>85 GeV
- |y*|<0.3 (for m_{jj}<550 GeV) or < 0.6 (m_{jj}>550 GeV)

Trigger-level Jets vs Offline Jets

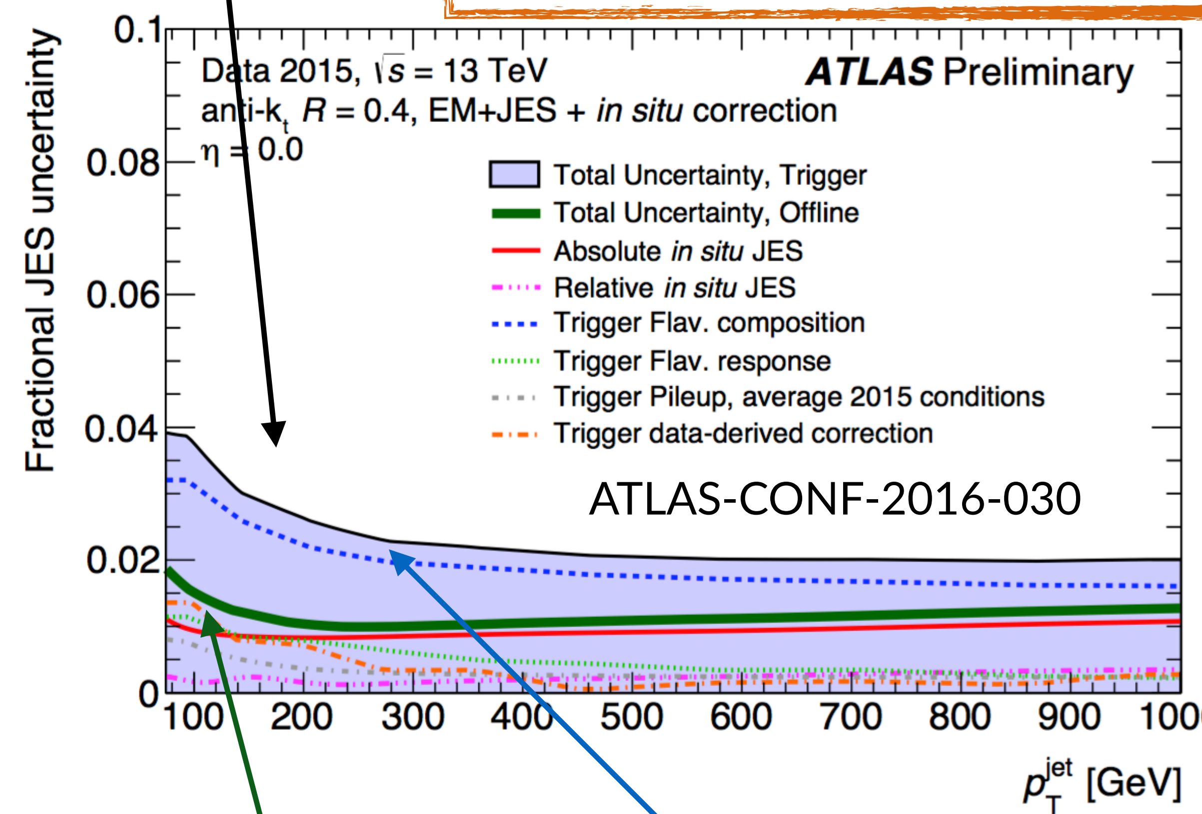
pT(trigger)/pT(offline) vs pT



trigger/offline pT response within ~1%

trigger jet total

energy scale uncertainty



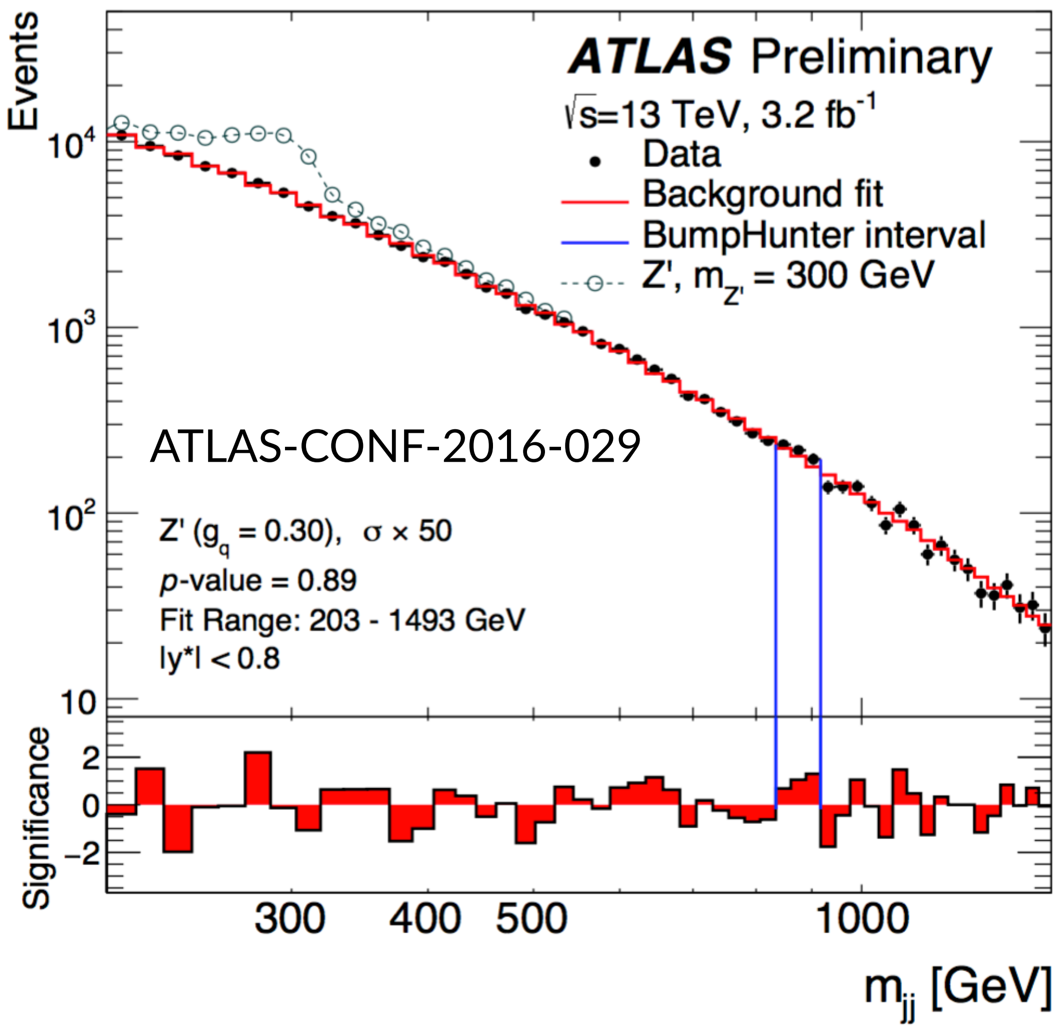
offline jet total

flavour composition (q vs g)

trigger-level tracking/ vertexing info would help!

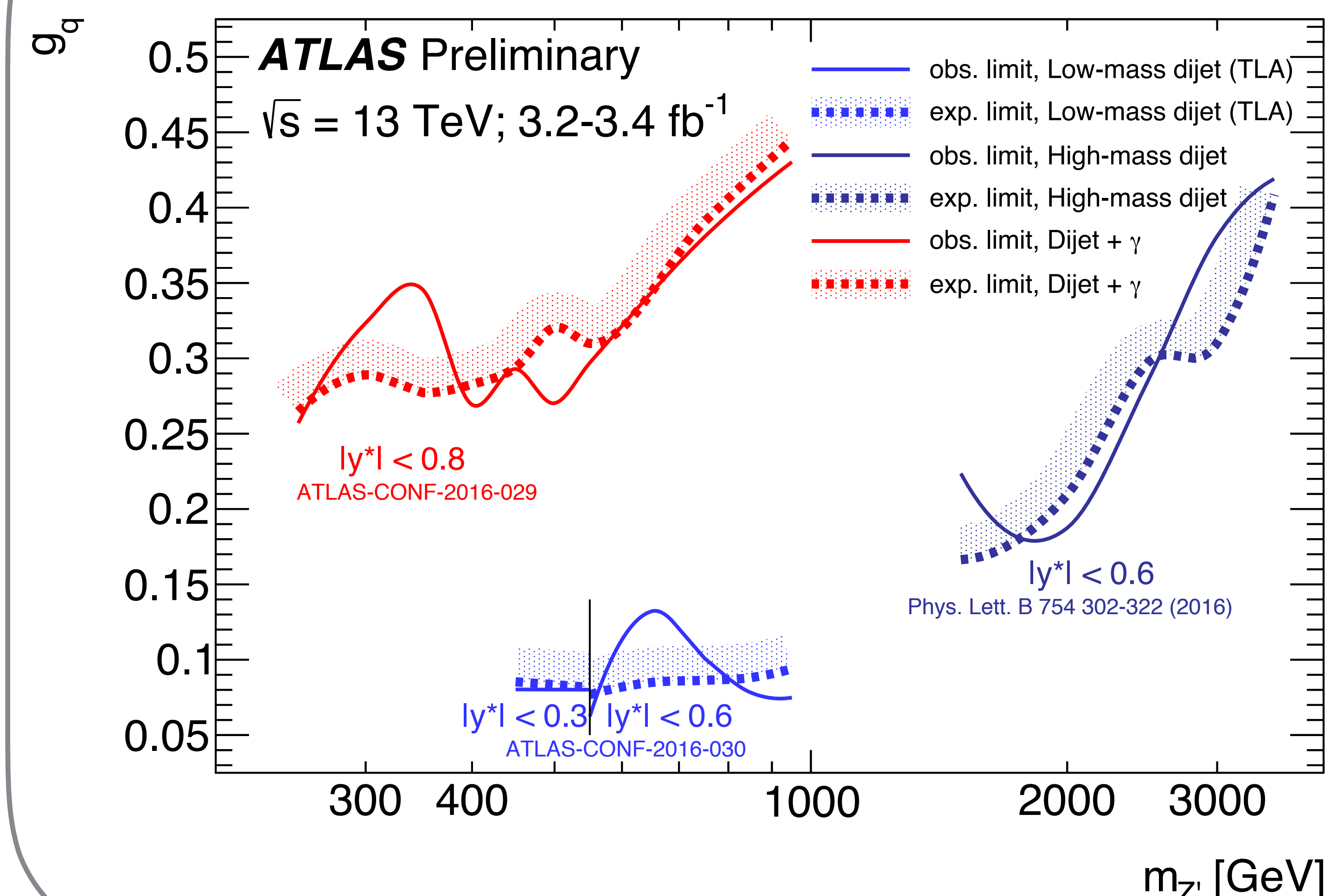
Dijet search strategies, compared

dijet+ISR photon



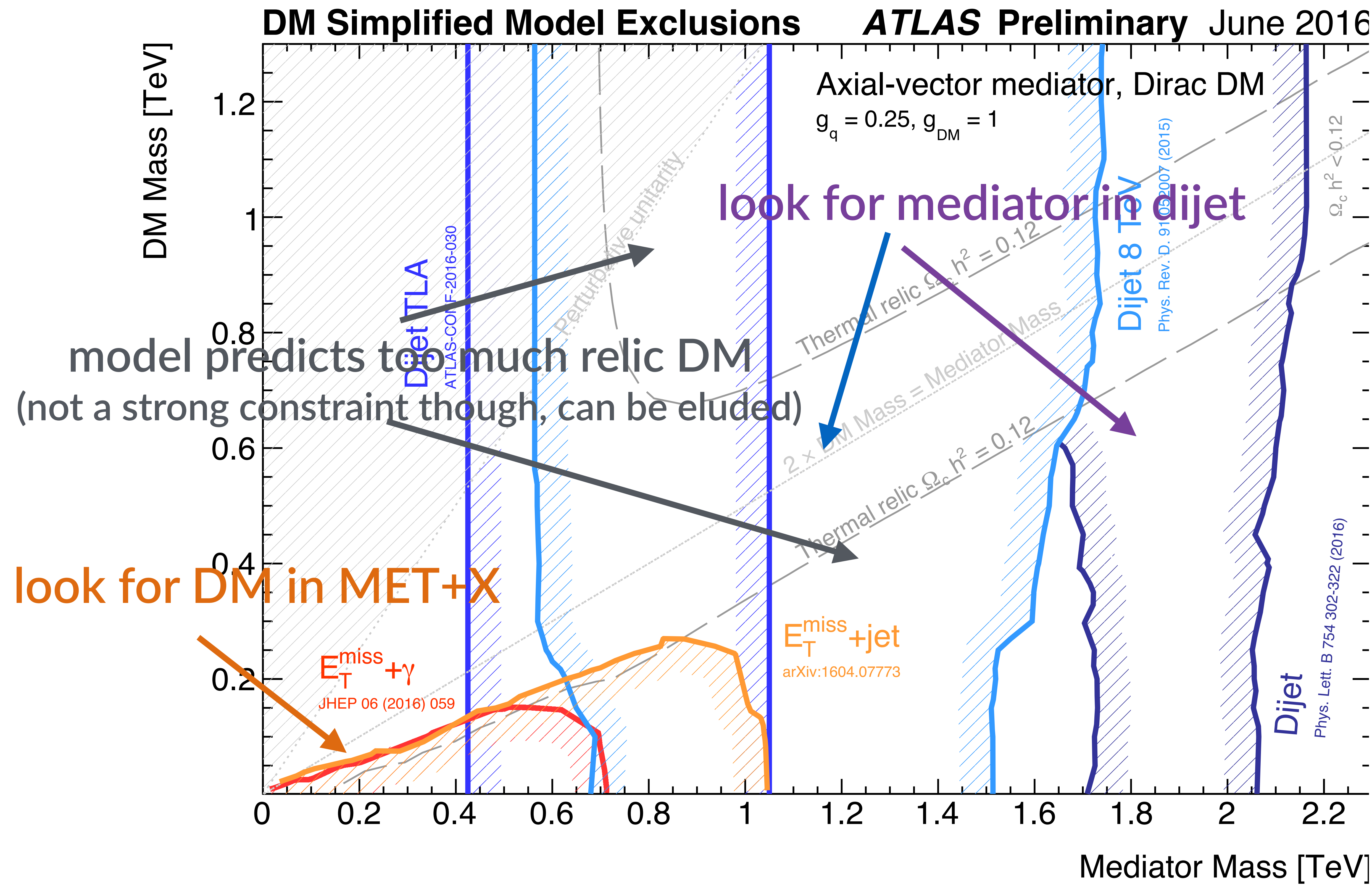
- one photon with pT>130 GeV
- 2 jets with p_T > 25 GeV, |y*|<0.8
- extend range to lower masses

the overall picture



Complementarity

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



mind the couplings!

What's Next?

Preparing for the Unexpected, Part 1

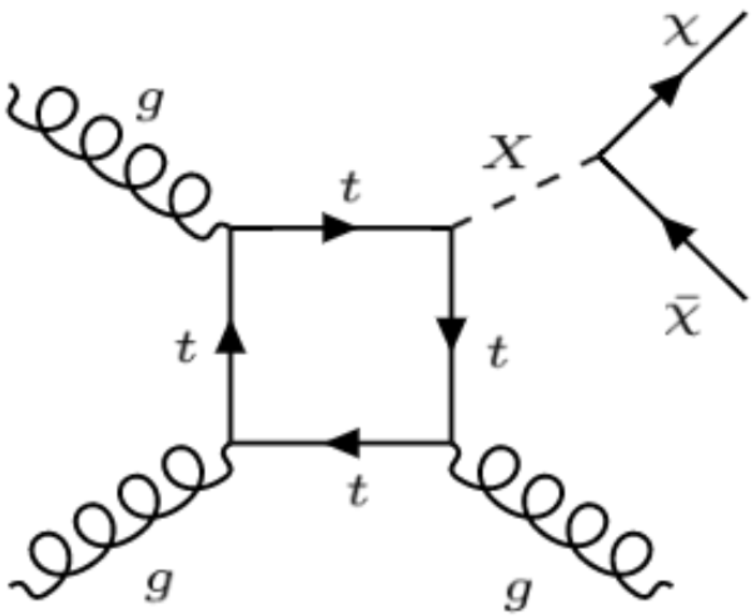
no discovery from the LHC since 1460 days

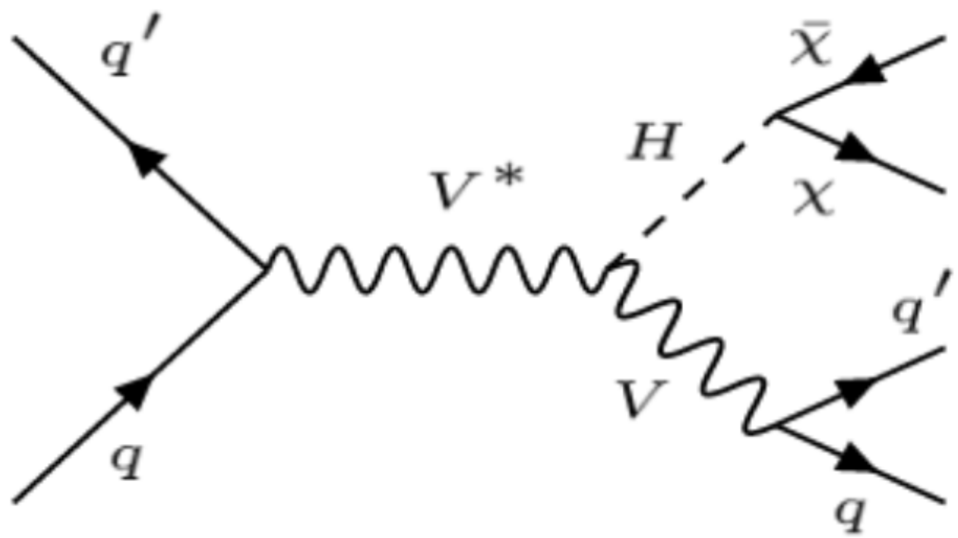
naive question: is there anything beyond the SM?
practical question: are we ready to probe it?

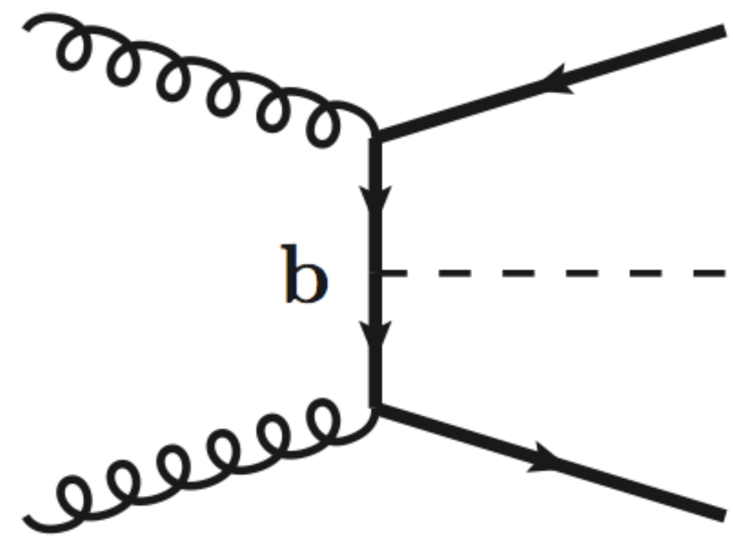
- soft signatures are hard
  - trigger is a limitation (rates, MET resolution)
  - systematics-dominated at low p_T
    - call for N^kLO modelling of SM backgrounds (e.g. W/Z+jets…)
    - data-driven backgrounds, when possible
- hard signatures are challenging
  - need bullet(pileup)-proof jet and MET reconstruction techniques

Tackling the Soft: Combination

ease the difficult: probe scalar/ pseudo-scalar interactions using monojet + Hinv + mono-HF





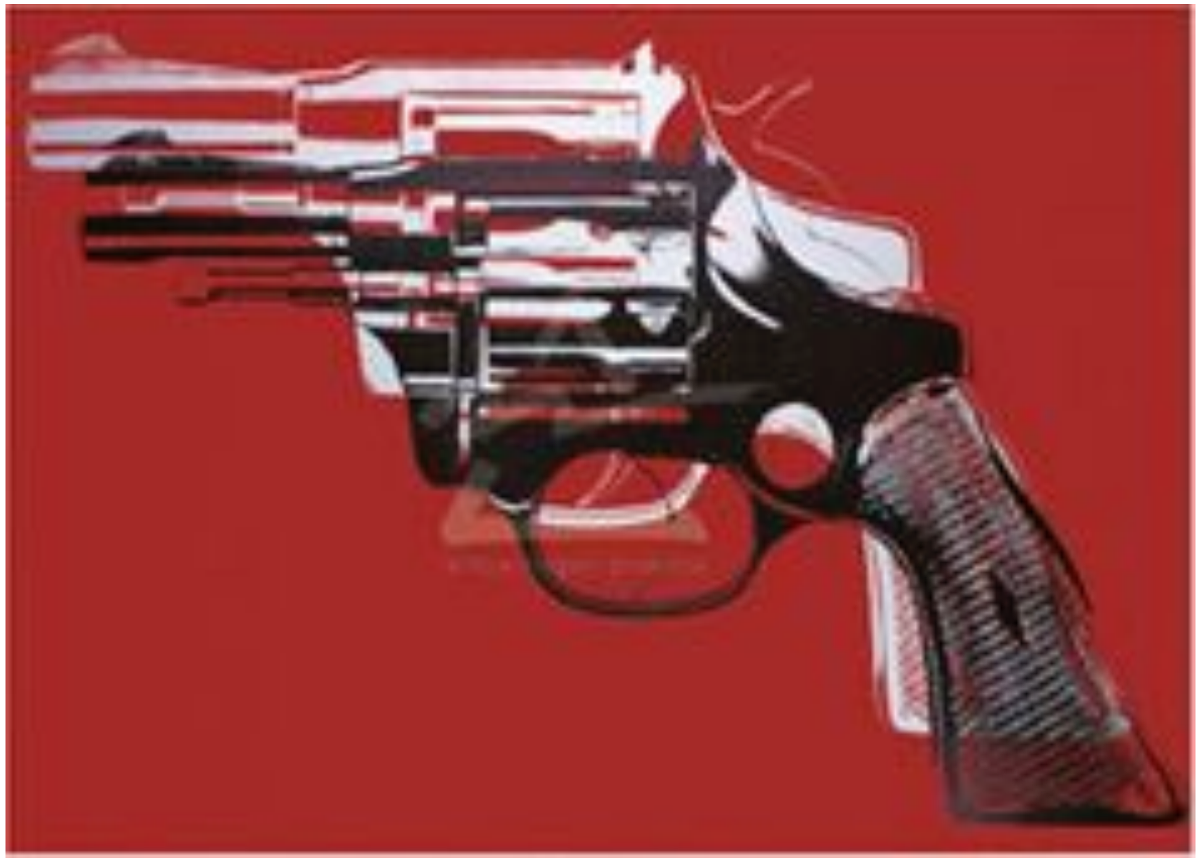


object veto/orthogonality in CMS analyses well designed to allow combination -> stay tuned?

TRIGGER!

main limitation for accessing the soft phase space

- be clever (use new kinematic variables)
- be smart (exploit specific topologies)



Jet+MET, v2: Razor

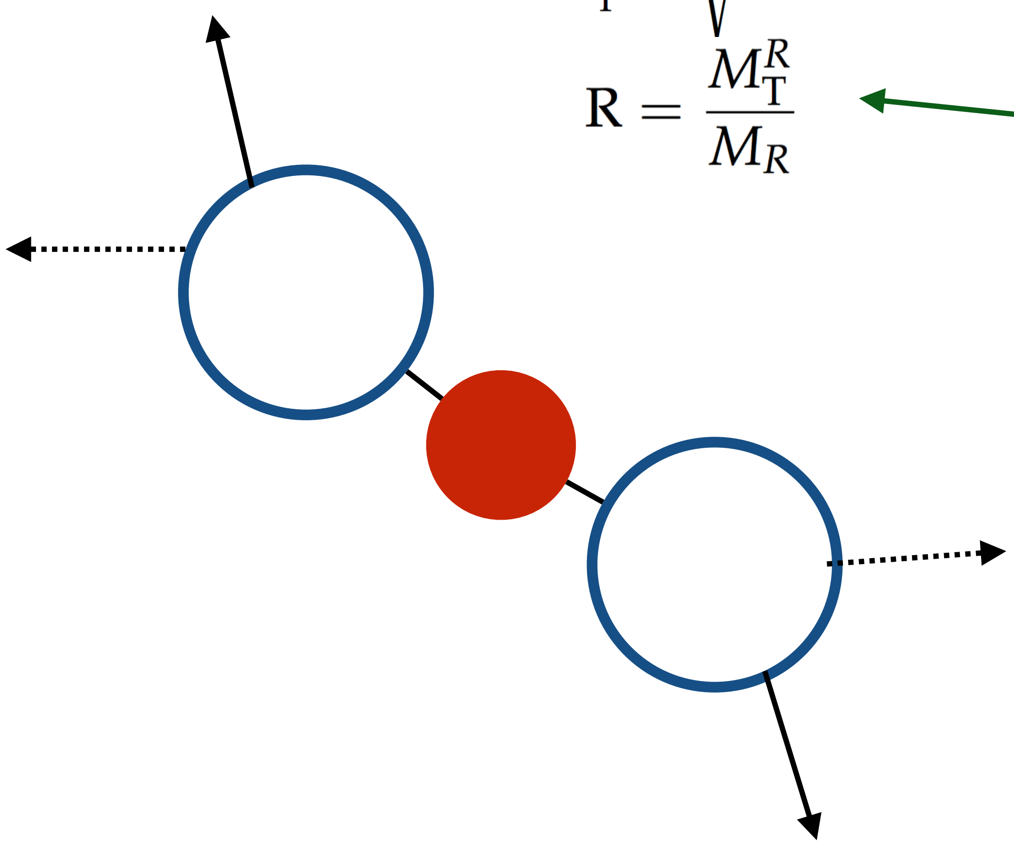
mass scale (e.g. m_{NLSP})

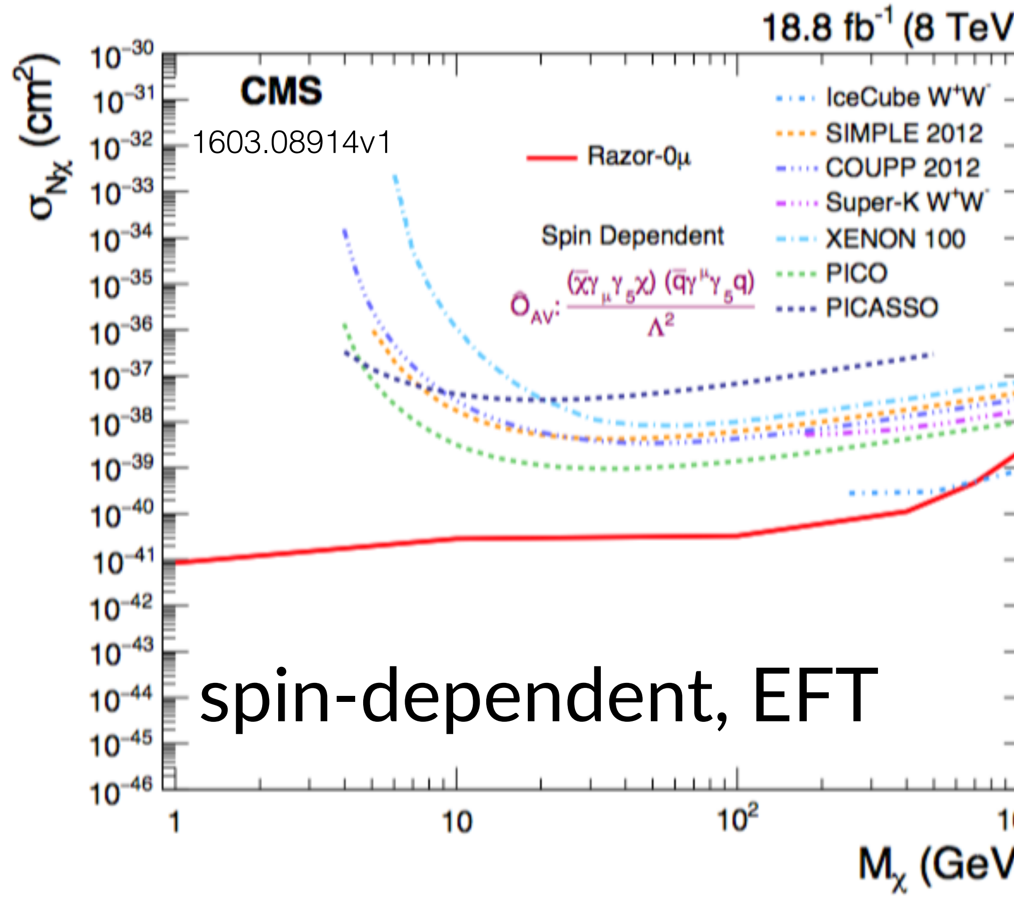
$$M_R = \sqrt{(|\vec{p}^{j_1}| + |\vec{p}^{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2|}$$

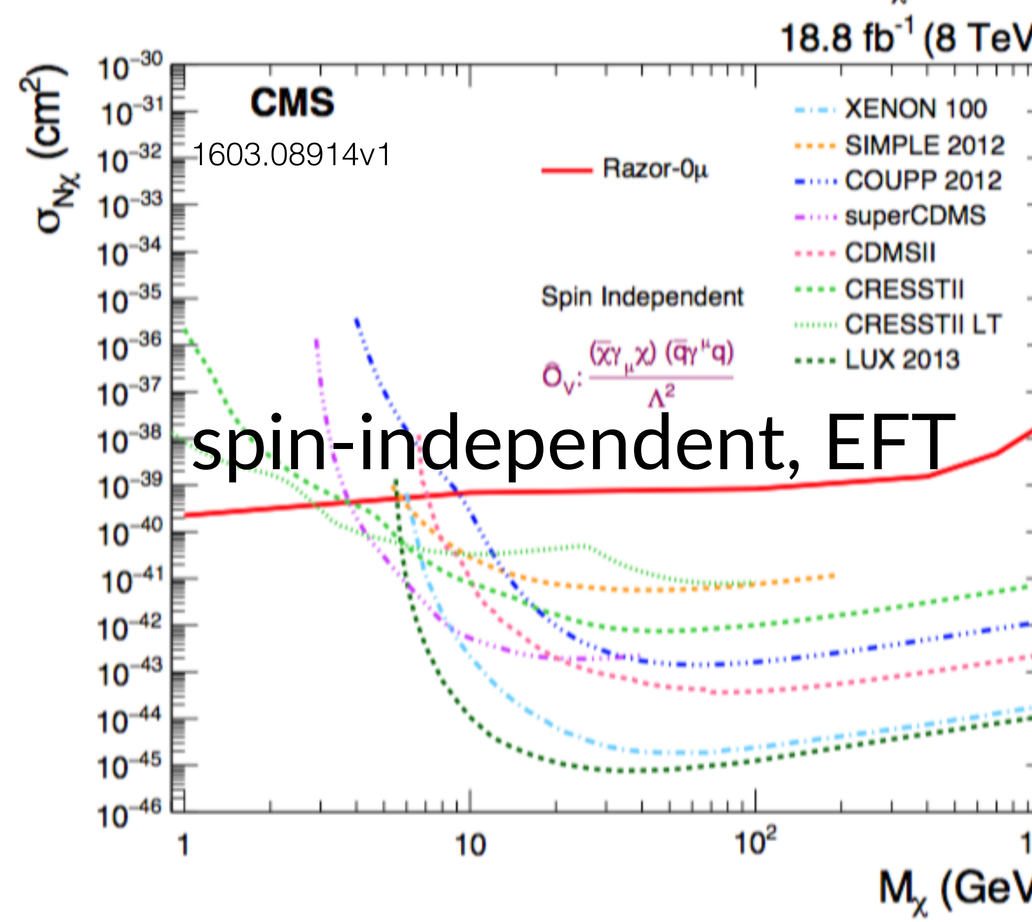
$$M_T^R = \sqrt{\frac{E_T^{miss}(p_T^{j_1} + p_T^{j_2}) - \vec{p}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

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

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





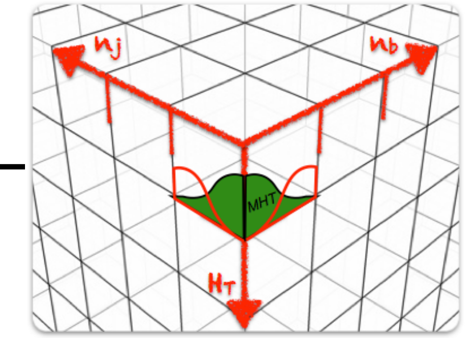


exploit razor variables (N_{jets}>=2)

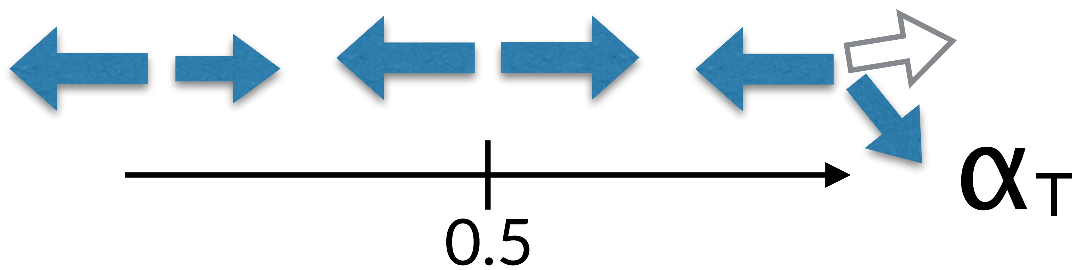
- born in SUSY (e.g. SUS-15-004)
- access lower pT/MET region
  - particularly relevant for softer signals e.g. scalar mediator

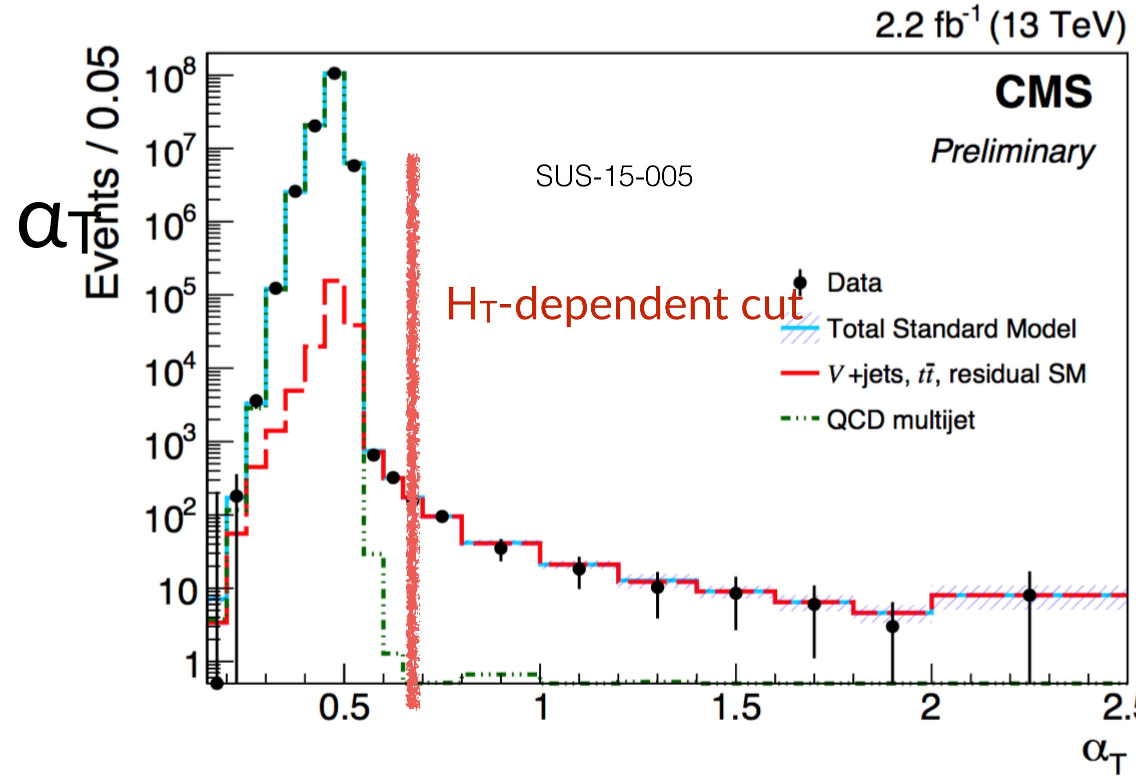
JET + MET, V3? α_T

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



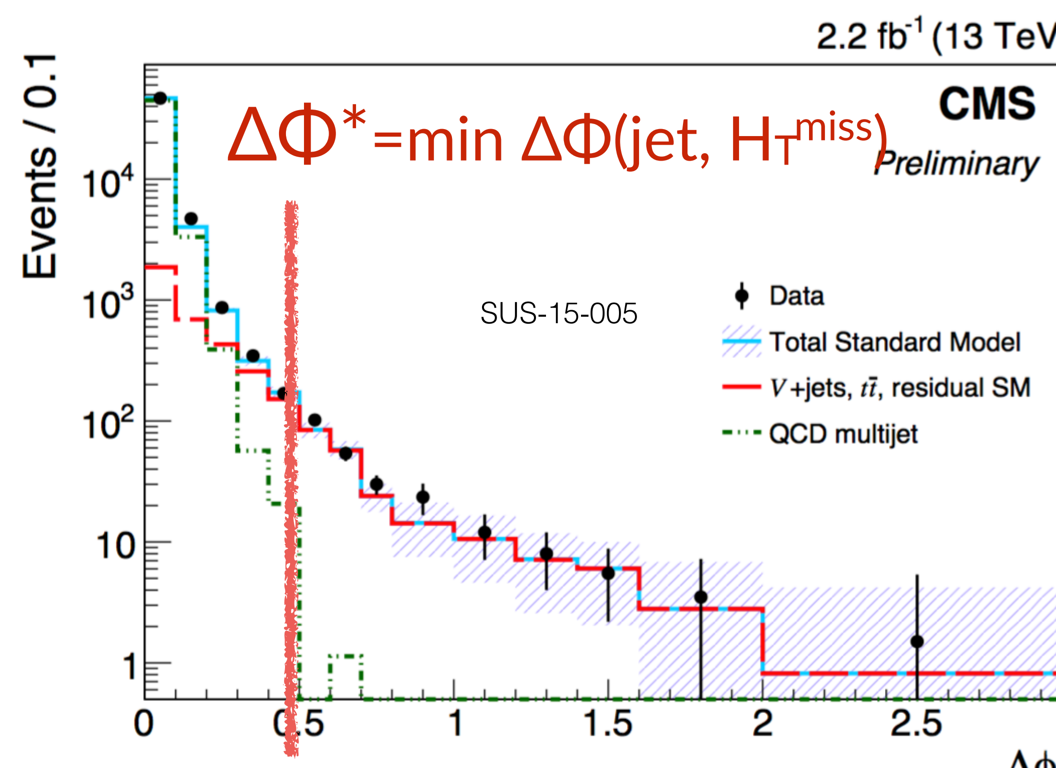
$$\alpha_T = \frac{1}{2} \cdot \frac{H_T - \Delta H_T}{\sqrt{{H_T}^2 - {\not{H}_T}^2}}$$





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

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

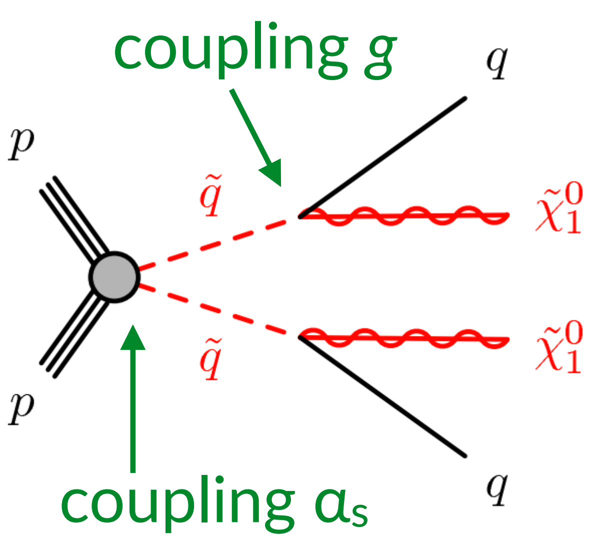


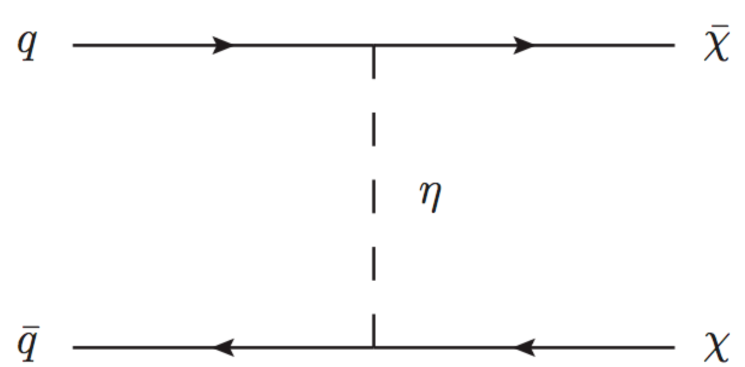
Preparing for the Unexpected, Part 2

“where should I look?”

- theoretical input = guide to cover all sensible signatures
- benchmark signal = an instrument to communicate results, not to fully explain reality
- a way to identify experimental challenges!

example: t-channel





how complementary can mono-jet be w.r.t. SUSY searches?

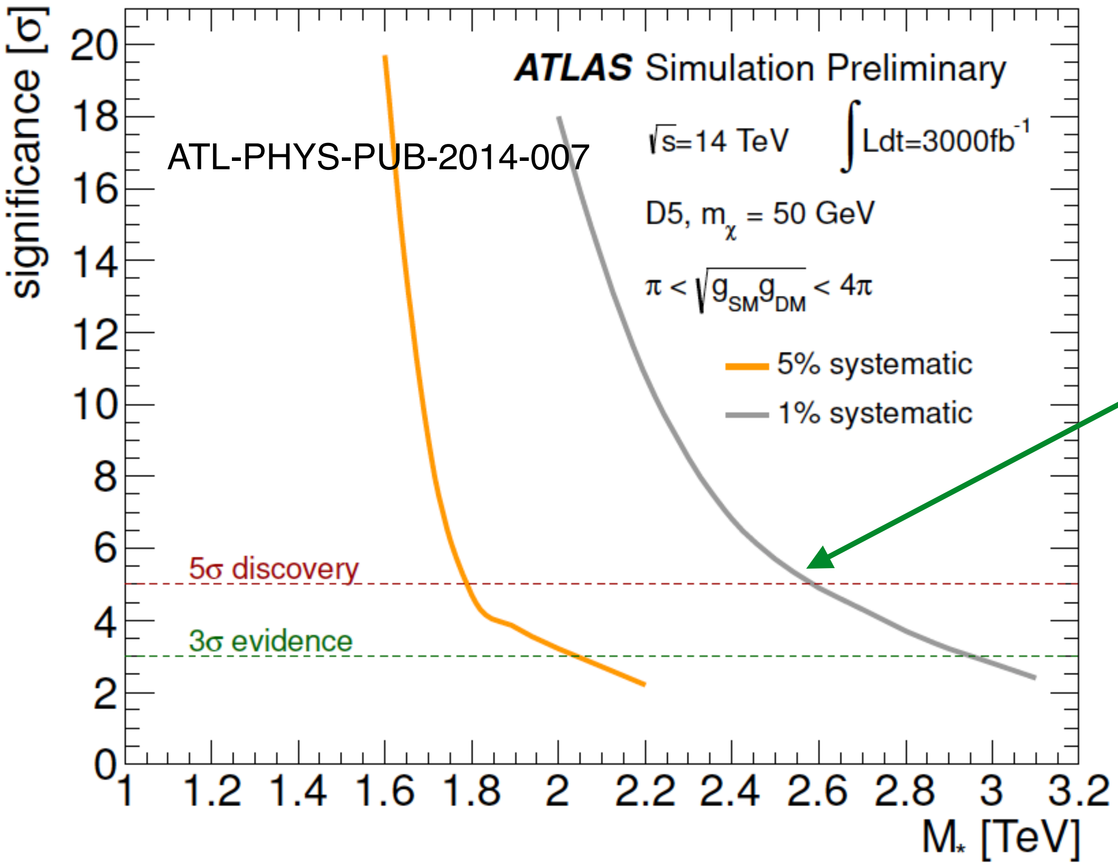
example: LLPs

how much can searches of displaced particles help us? (e.g. compressed spectra)

e.g. arXiv:1402.2285, 1605.07058…

Welcome to the Machine

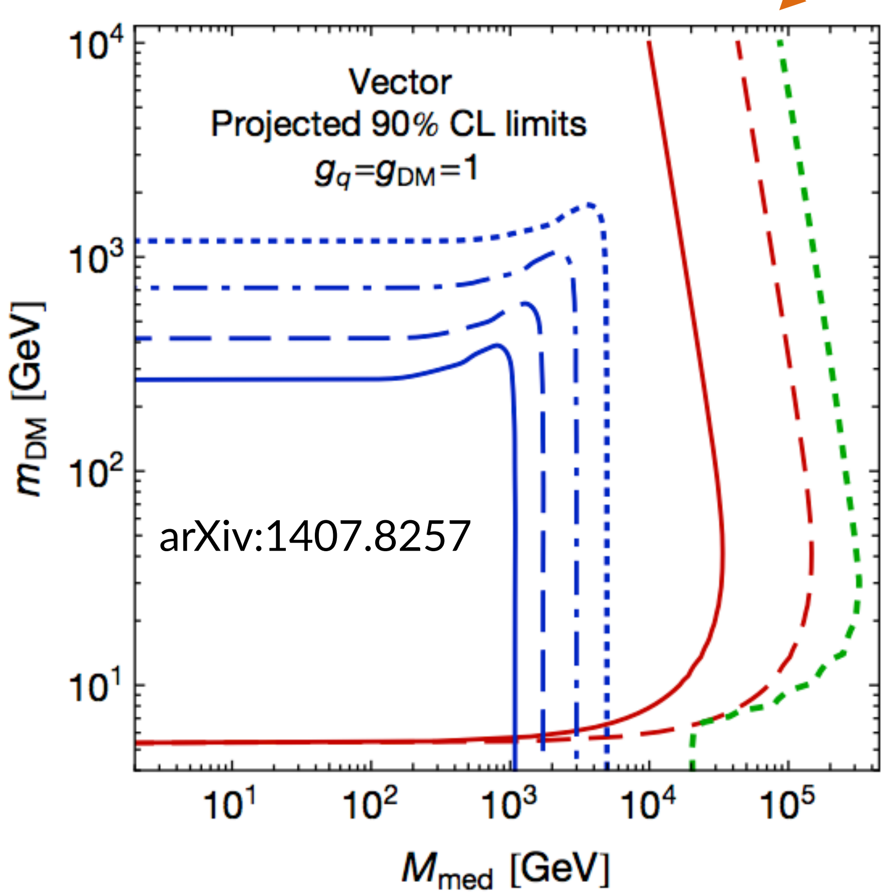
see also https://indico.cern.ch/event/539266

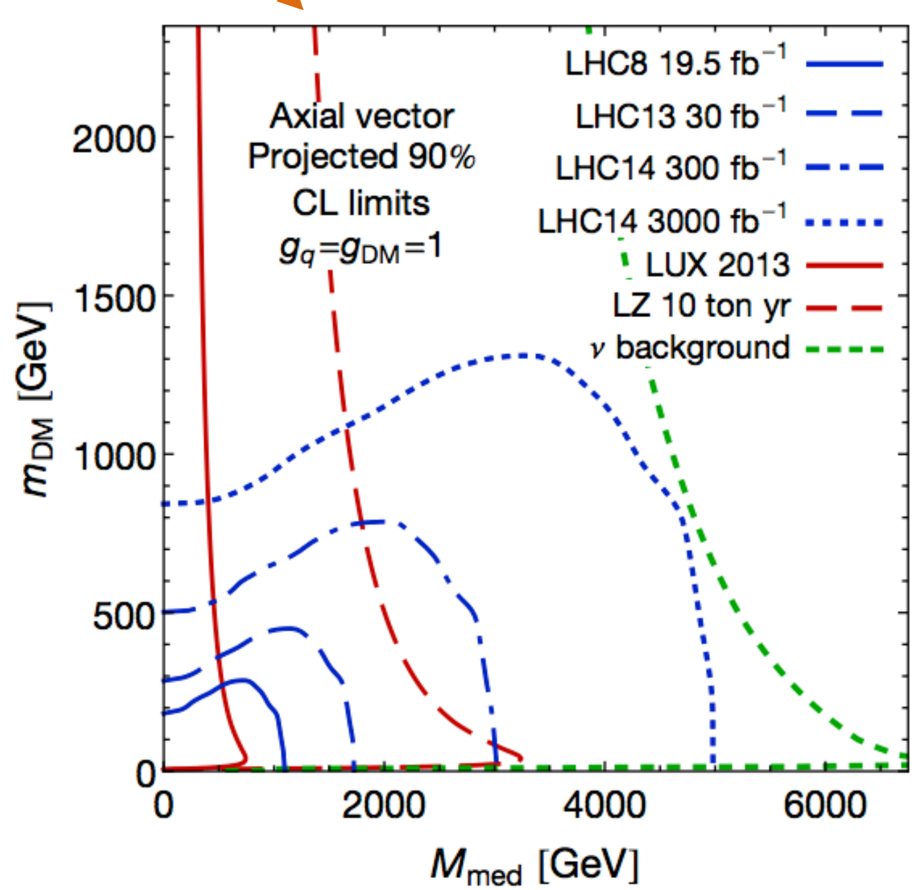


key point: need to reduce systematics

key point: low dependence on mDM at low mDM, complementary to DD for axial-vector interactions (right)

these are projections from ~2014: more to follow (with realistic detector simul.) for ECFA 2016!





Conclusions

- is LHC complementary to dedicated experiments? short answer: *yes*
  - but: need to avoid being systematics-dominated
  - main challenges: background uncertainties, trigger, particle reconstruction
  - main strength: ~no m_{DM} dependence, complementary strategies
- ultimate goal: use LHC as a telescope for DM
  - requires experimental work to look for it in a comprehensive way
  - work already started - stay tuned!

"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 DO OUR SIMPLIFIED MODELS TALK TO DIRECT DETECTION?

DD looks for non-relativistic nucleus-DM scattering

- 90% CL limits on σ_{SI} and σ_{SD}, vs m_{DM}
  - SI ($J^{PC}=0^+, 1^+$) usually shown assuming $\sigma^p=\sigma^n$

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

0^+ $\sigma_{\rm SI} \approx 1.1 \times 10^{-39}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$

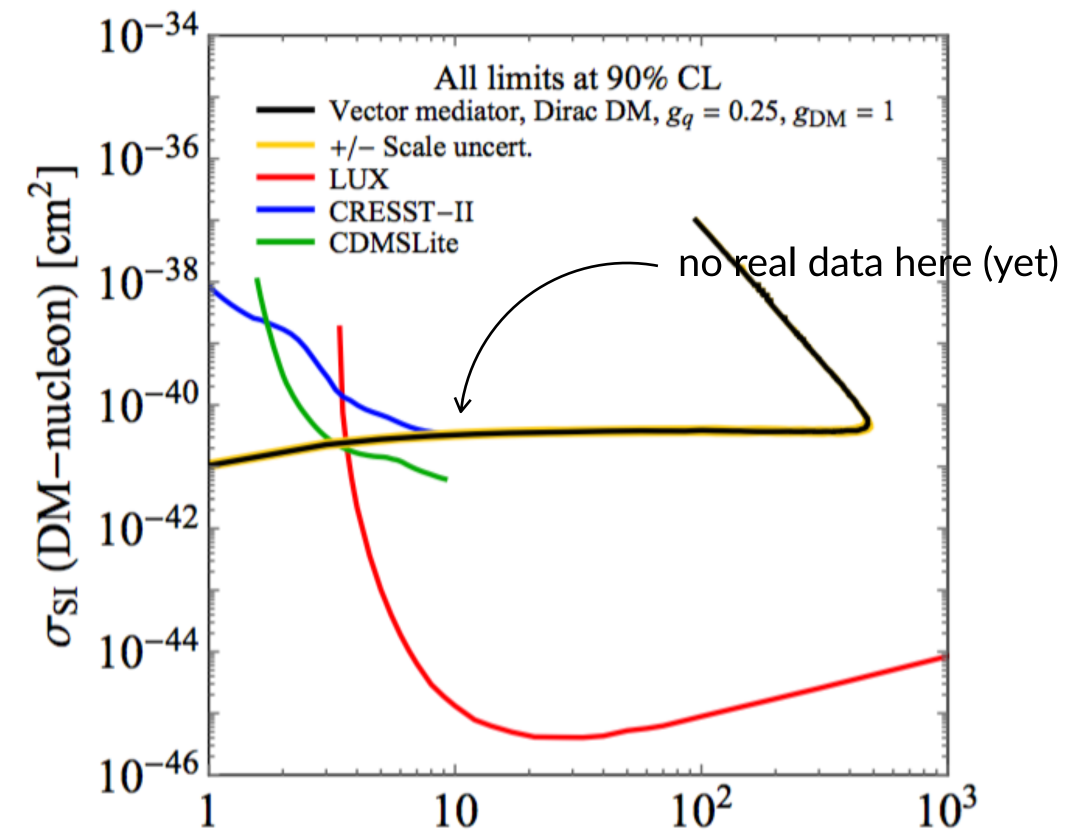
0^- $\sigma_{\rm SI} \approx 0$ (suppressed by velocity dependent terms)

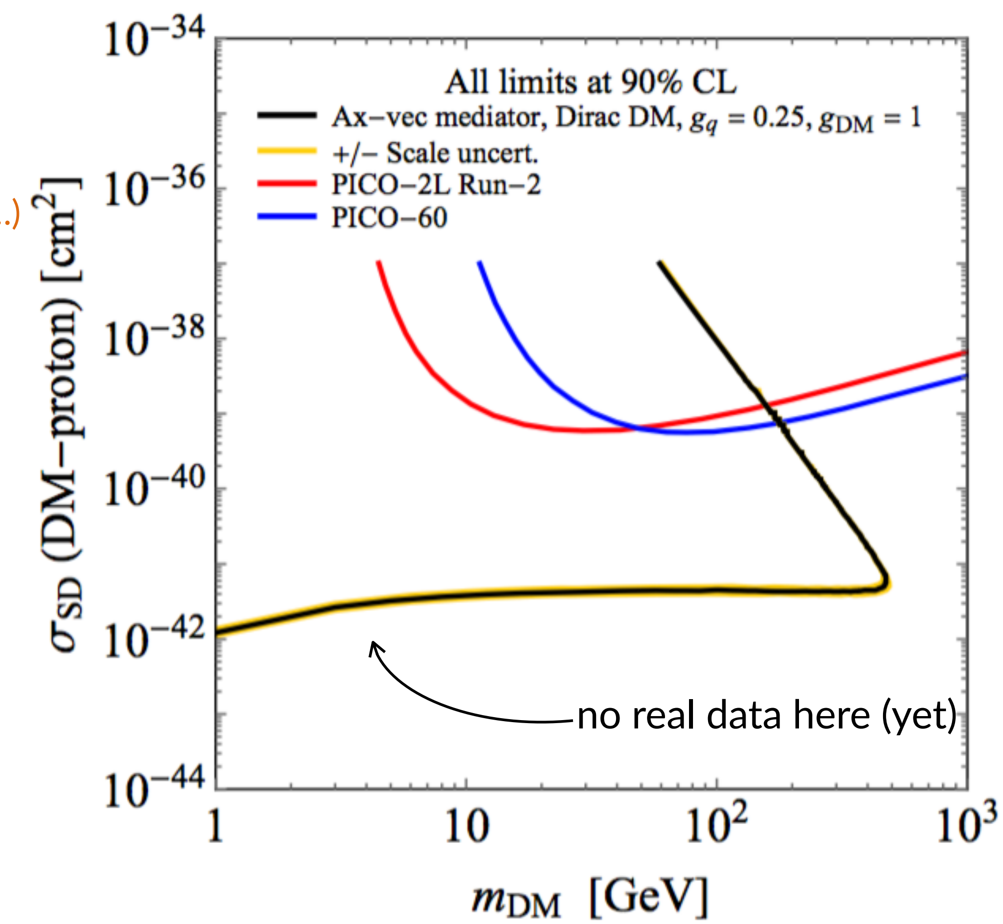
1^+ $\sigma_{\rm SI} \approx 6.9 \times 10^{-43}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{125\ {\rm GeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$

  - SD ($J^{PC}= 1^-$) sensitive to either p (PICO, ...) or n (LUX, XENON100, ...), through isotope spin (σ^p more difficult, need odd #p...)
    - LHC result is the same for p and n
    - Ice-cube limit depends on assumed annihilation channel - weak for qq, no comparison possible for WW/ll which we exclude from our models ☞ not to be shown

$$\sigma_{\rm SD} = \frac{3\, f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}$$

1^- $\sigma^{\rm SD} \approx 3.8 \times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$





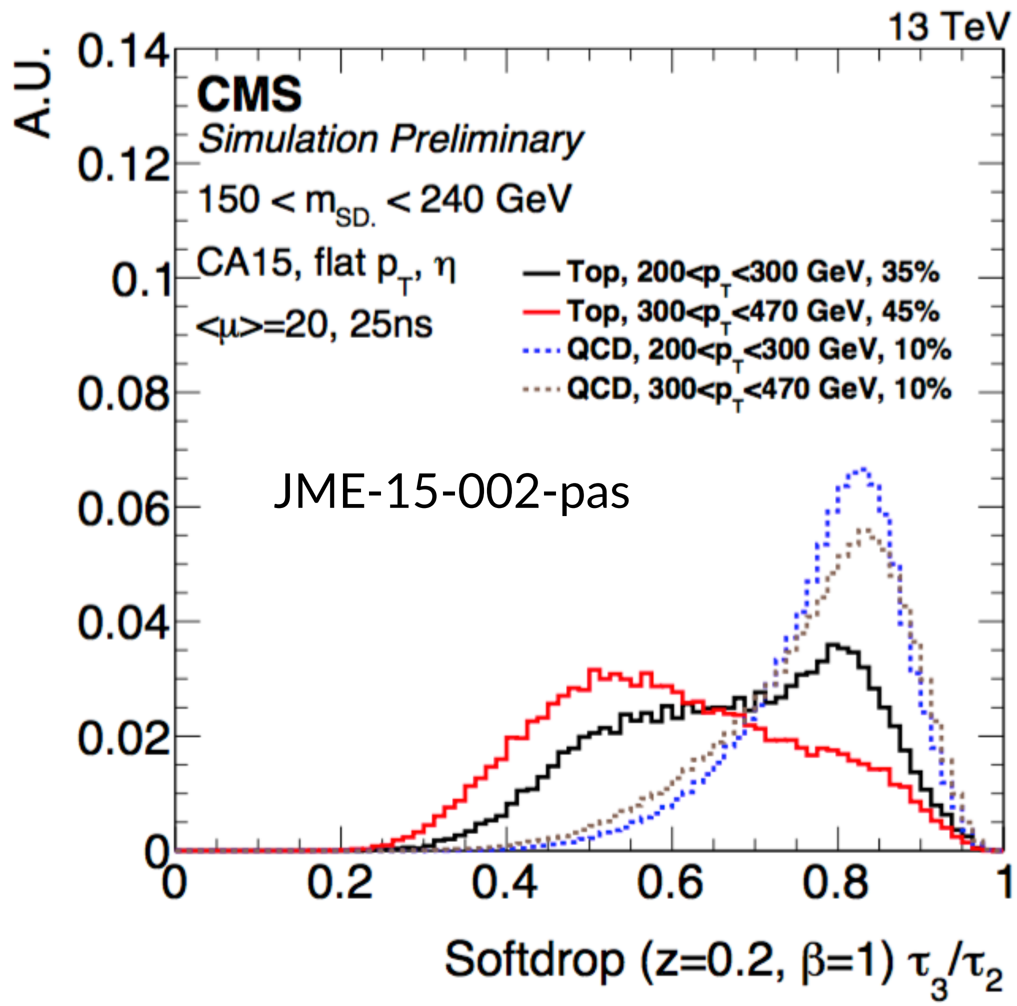
Boosted Top Tagging

n-subjettiness

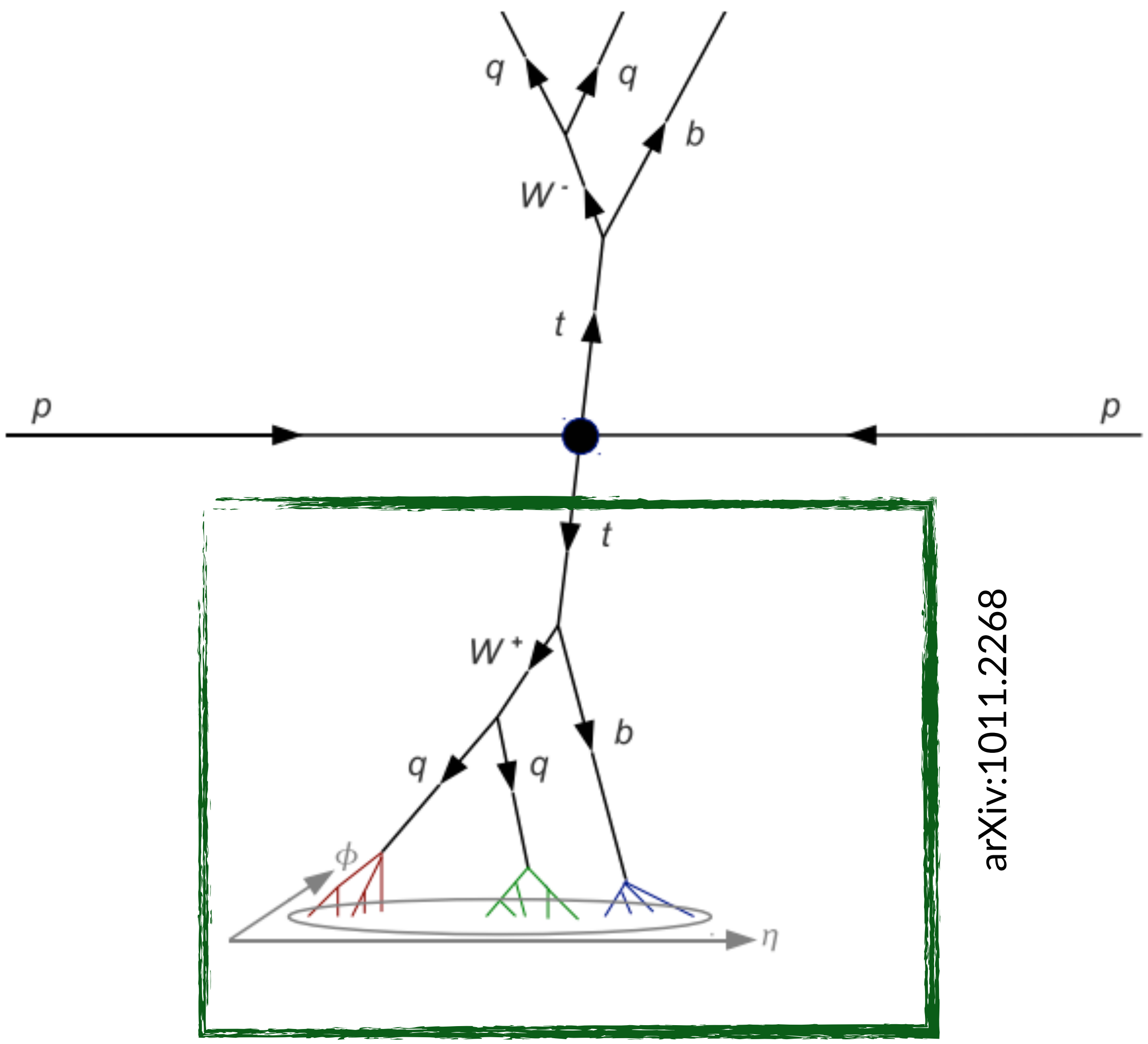
angular distance between sub-jet k and the rest

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$

$$d_0 = \sum_k p_{T,k} R_0$$



JME-15-002-pas



arXiv:1011.2268

How You Kill Multi-Jet

n-subjettiness

angular distance between sub-jet k and the rest

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$

$$d_0 = \sum_k p_{T,k} R_0$$

D2

similar performance, choice depends on optimisation

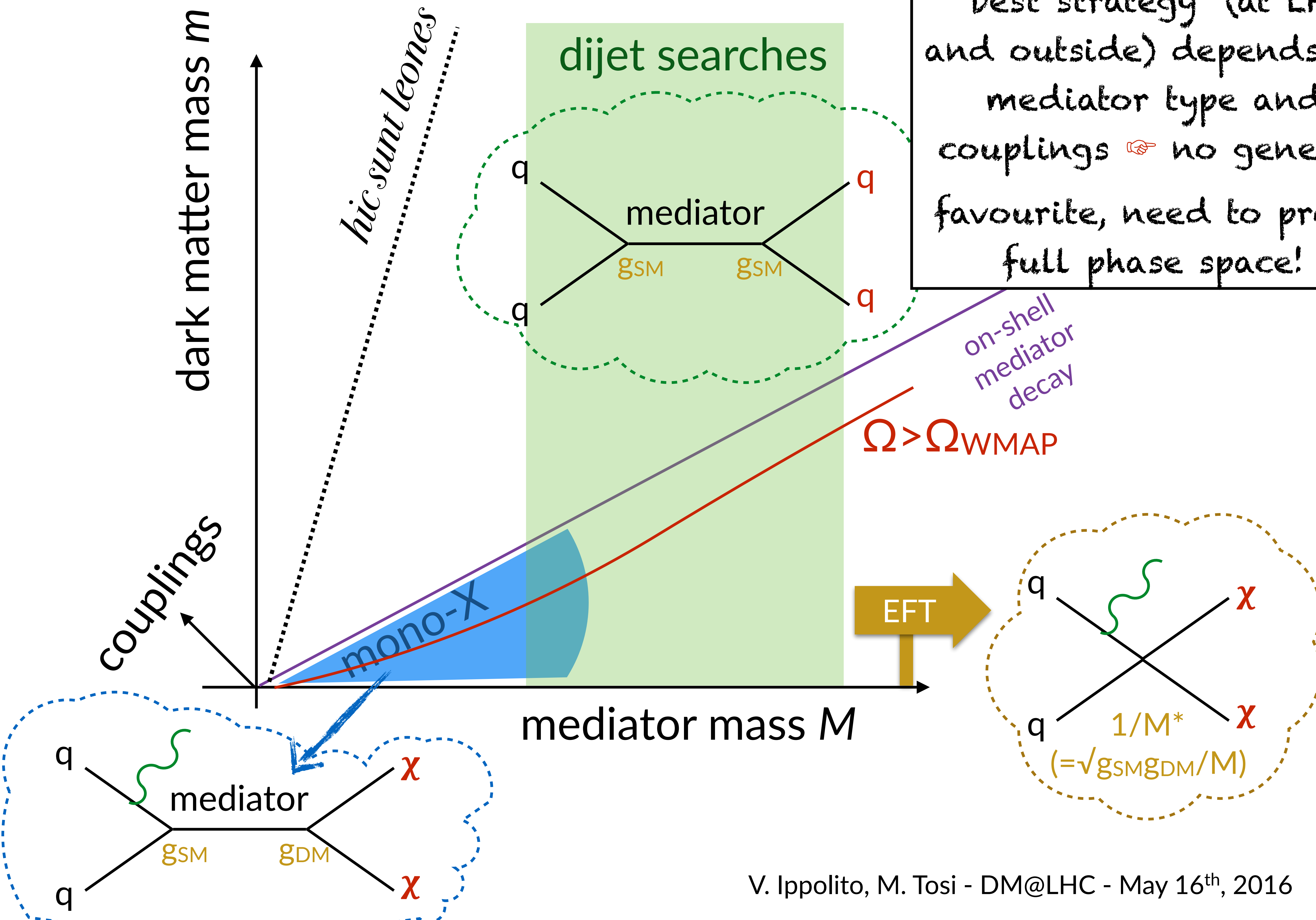
$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$$

$$e_2^{(\beta)} = \frac{1}{p_{TJ}^2} \sum_{1 \le i < j \le n_J} p_{Ti} p_{Tj} R_{ij}^{\beta} \,,$$

$$e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{1 \le i < j < k \le n_J} p_{Ti} p_{Tj} p_{Tk} R_{ij}^{\beta} R_{ik}^{\beta} R_{jk}^{\beta} \,,$$

The (ATLAS+CMS) Dark Matter Atlas

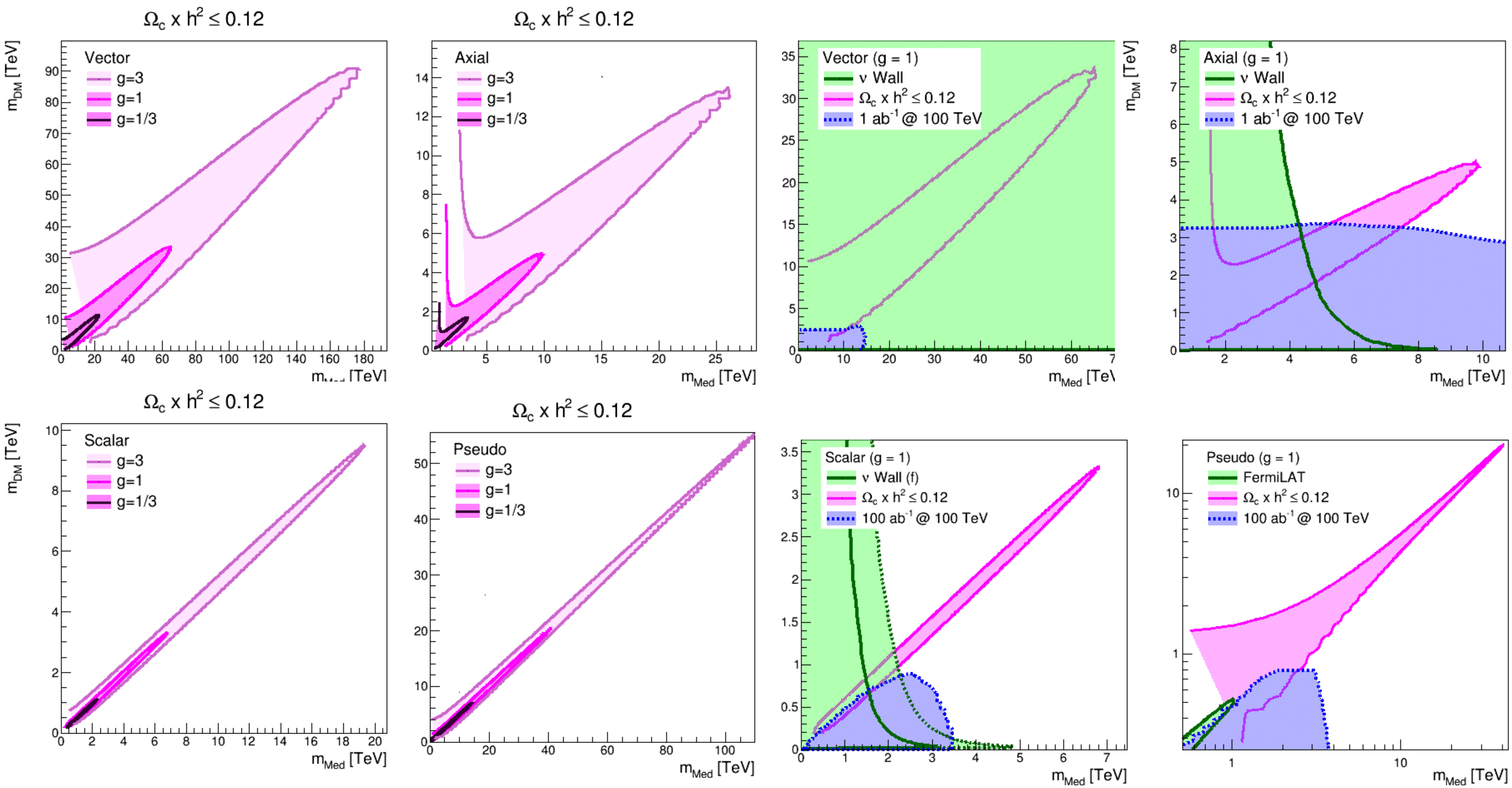
(not to scale!)



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

FCC

arXiv:1603.08525



- pseudo-scalar hard to constrain
  - may use mediator decay (e.g. $\gamma\gamma$)
- FCC can explore large fraction of what's allowed by relic density

Relevant Results

italics = 8 TeV, **green** = 13 TeV

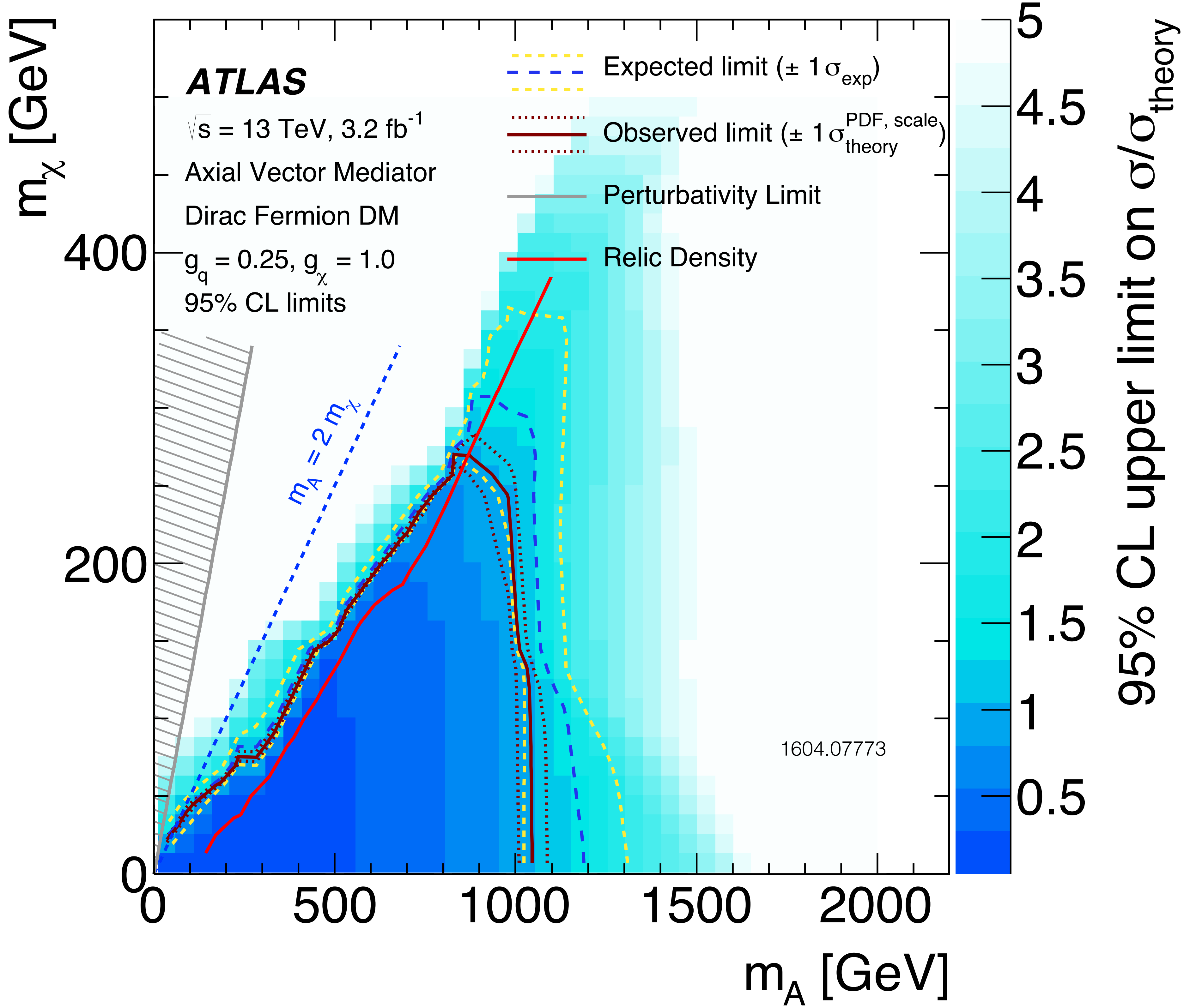
	ATLAS	CMS
monojet	**1604.07773**	**EXO-16-013-pas**
mono-W/Z(had)	**ATLAS-CONF-2015-080**	
razor		*1603.08914v1*
α_T		SUS-15-005 (SUSY analysis)
mono-γ	**1604.01306**	*PLB 755 102-124*
bb	*Eur. Phys. J. C(2015) 75:92*	**B2G-15-007**
tt (dilepton)		*B2G-13-004-pas*
tt(single lepton)		*JHEP06(2015)121*
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**

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

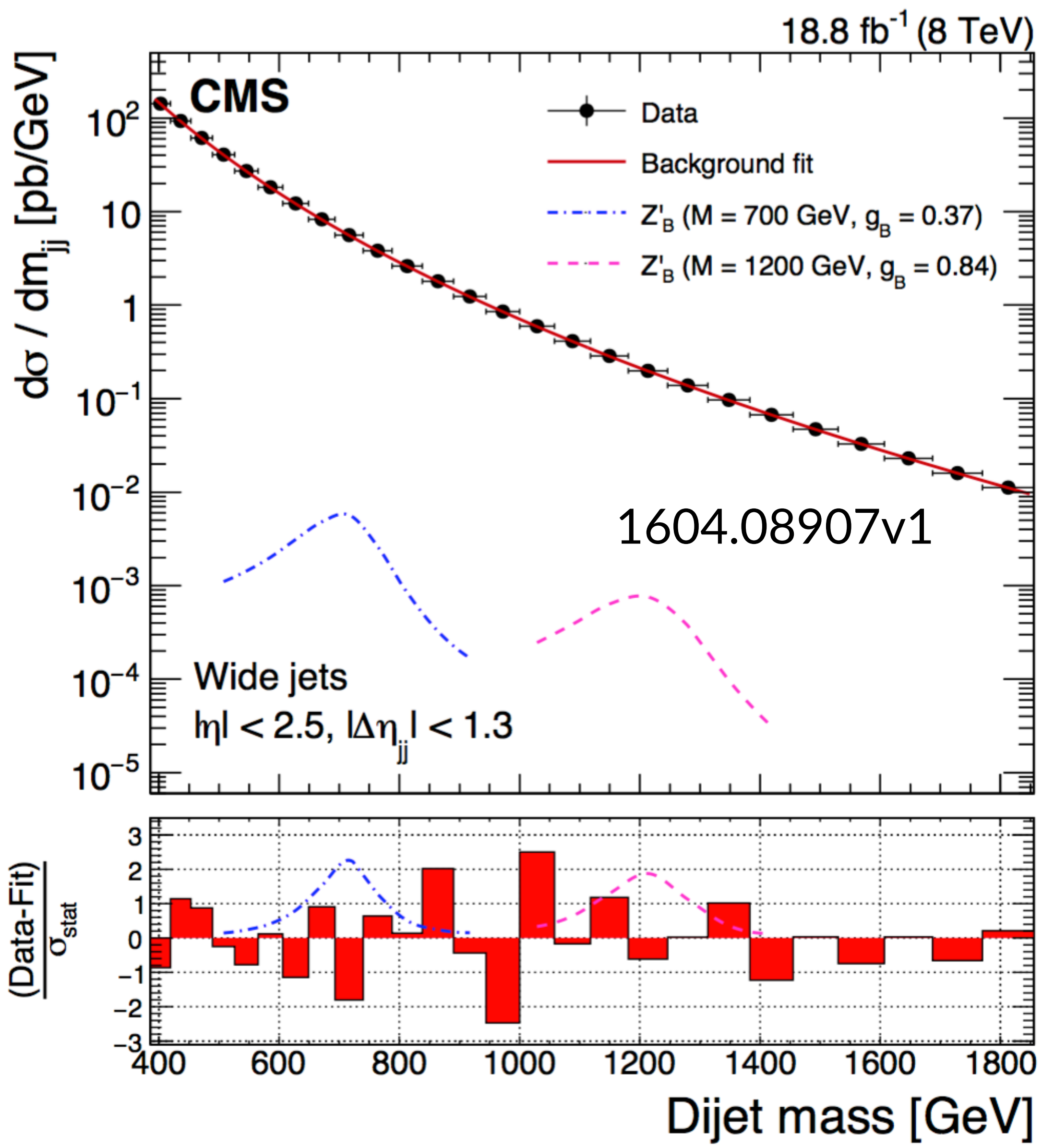
How far are we?

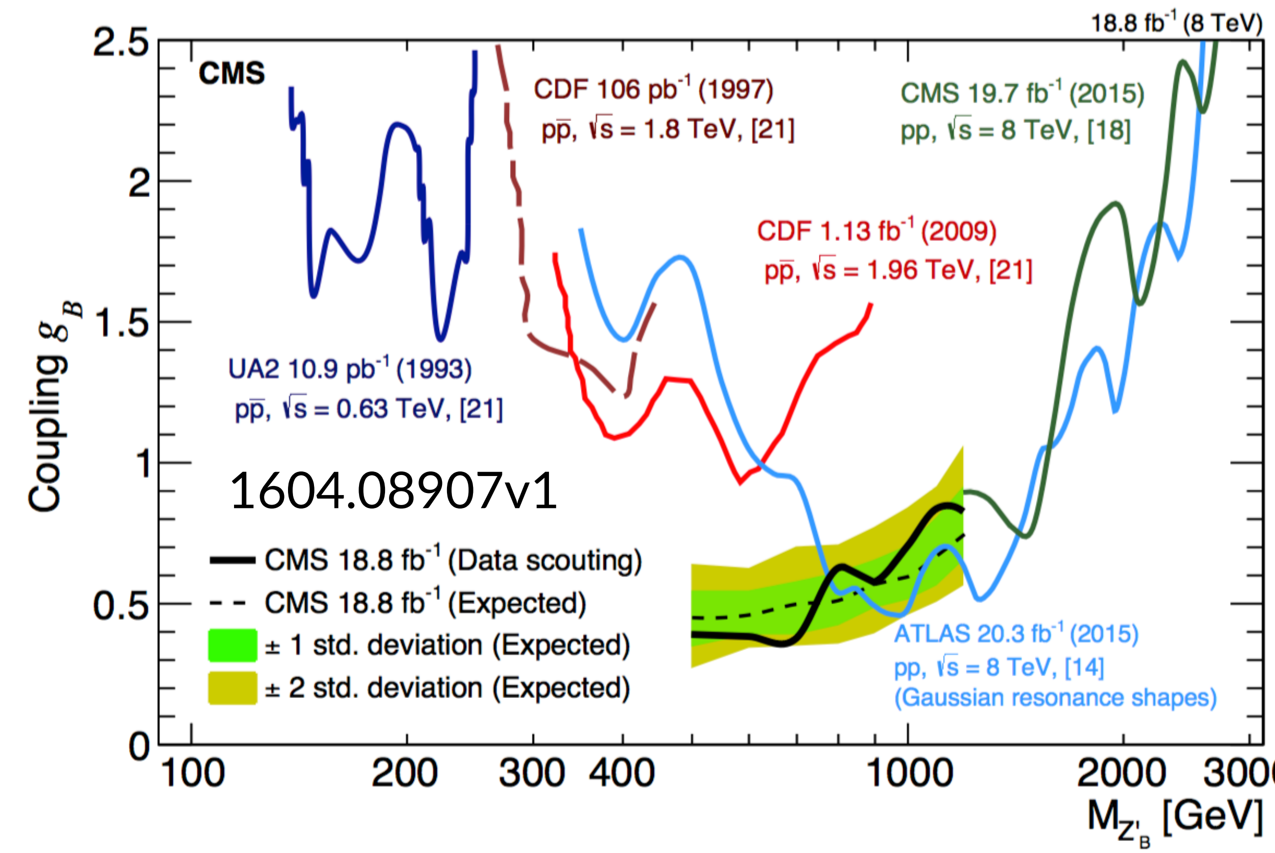
coloured, z axis: signal strength limit

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



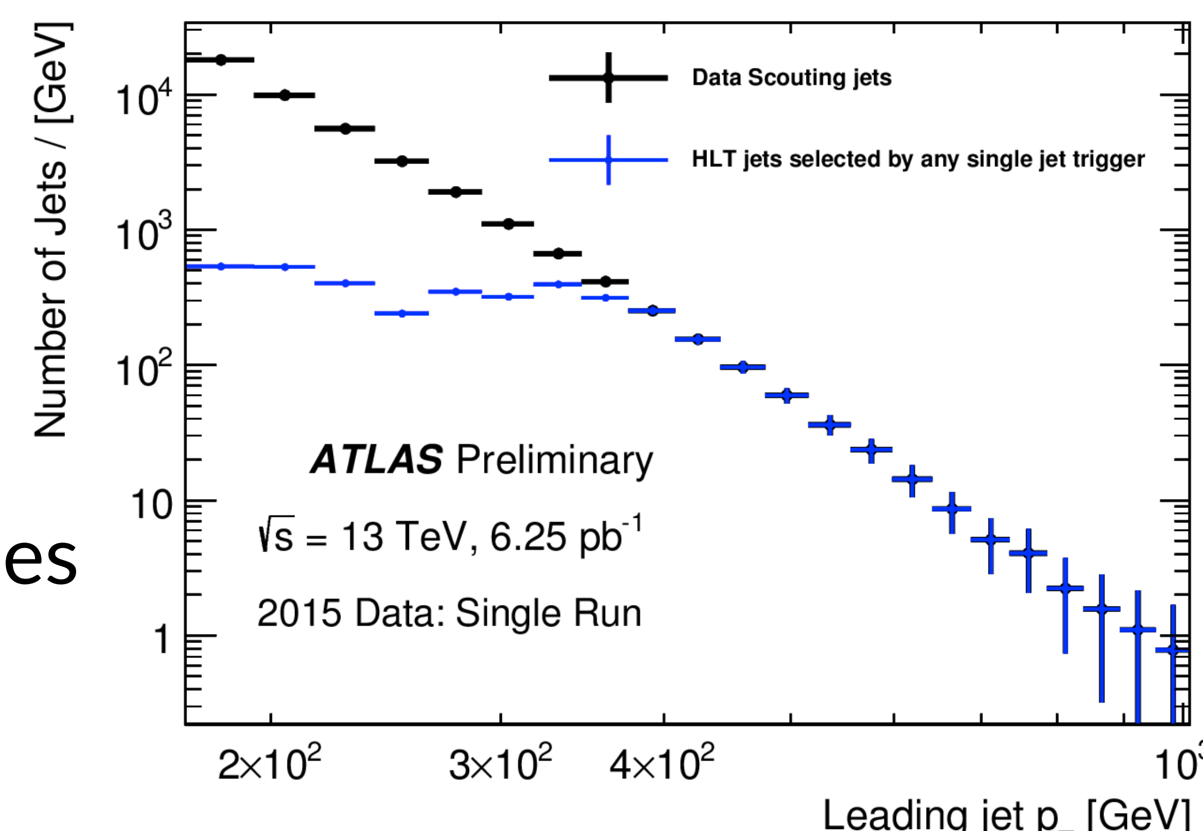
Dijet: Data Scouting



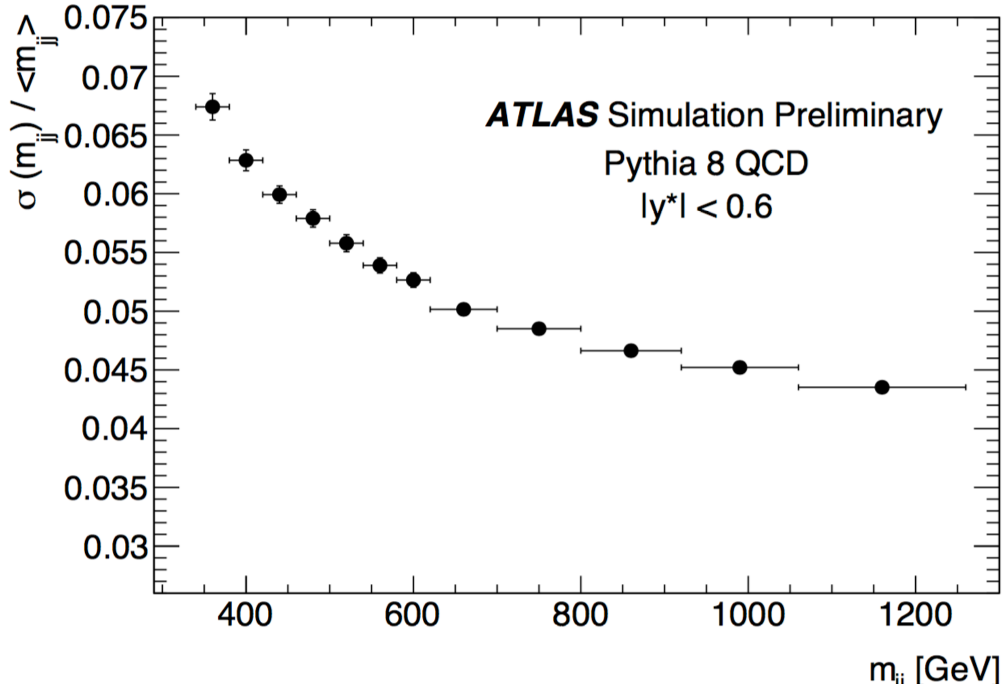


show-stopper at low mass: trigger!

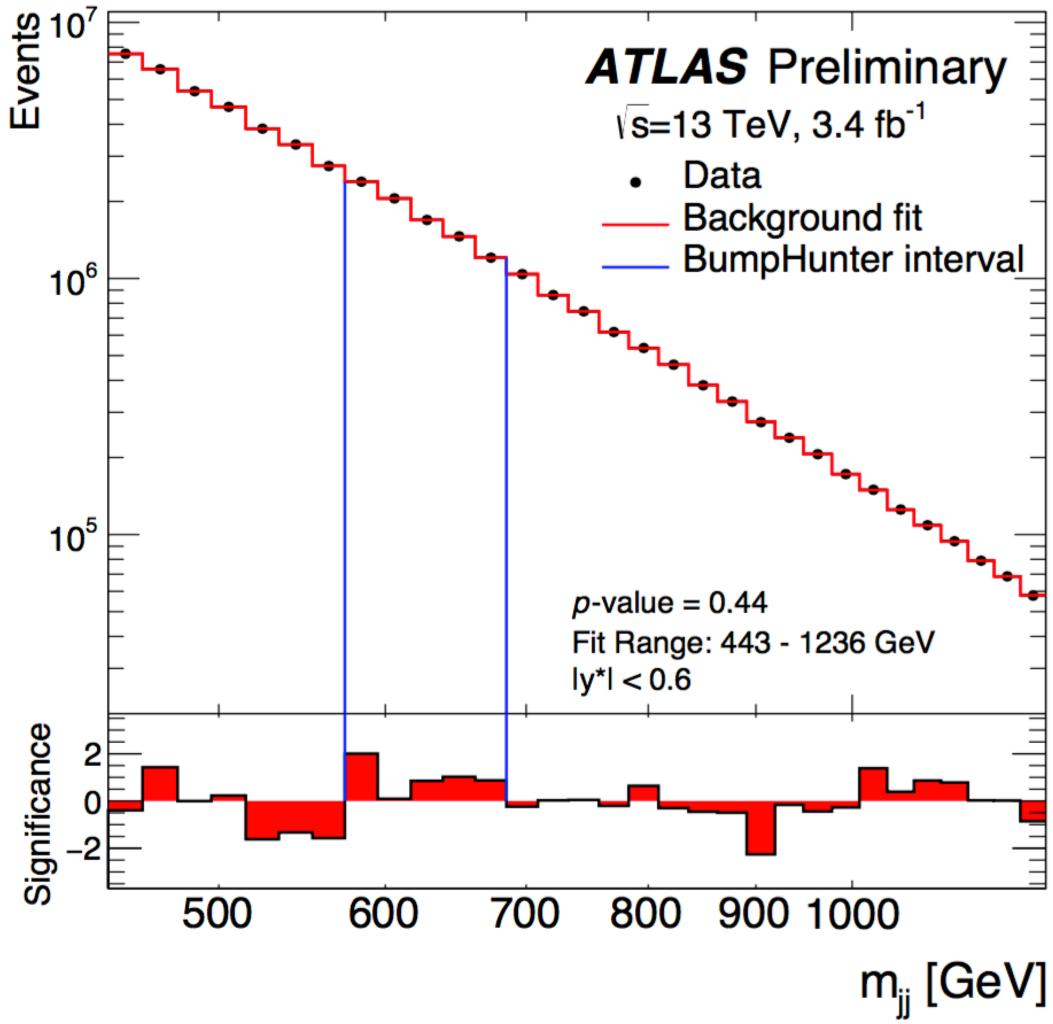
- use data scouting to bypass rate issues
- reach the 400-500 GeV region



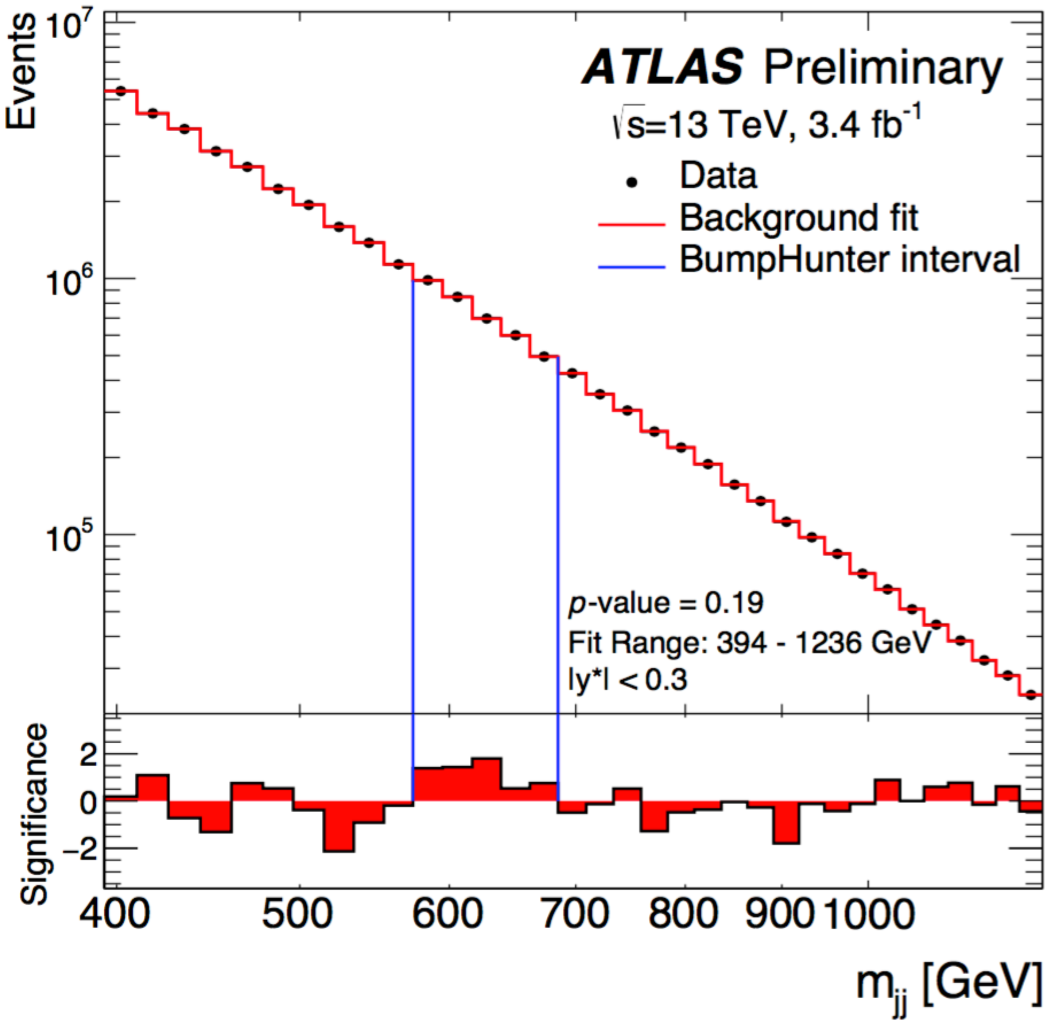
TLA: Results



ATLAS Simulation Preliminary
Pythia 8 QCD
|y*| < 0.6
σ (m_jj) / <m_jj>
m_jj [GeV]

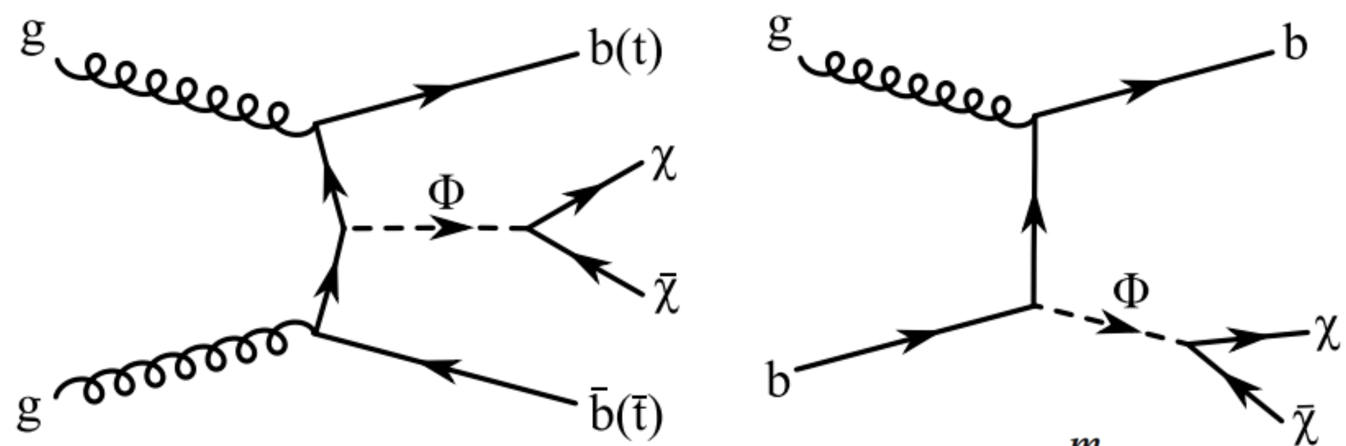


ATLAS Preliminary
√s=13 TeV, 3.4 fb-1
Data
Background fit
BumpHunter interval
p-value = 0.44
Fit Range: 443 - 1236 GeV
|y*| < 0.6
Events
Significance
m_jj [GeV]

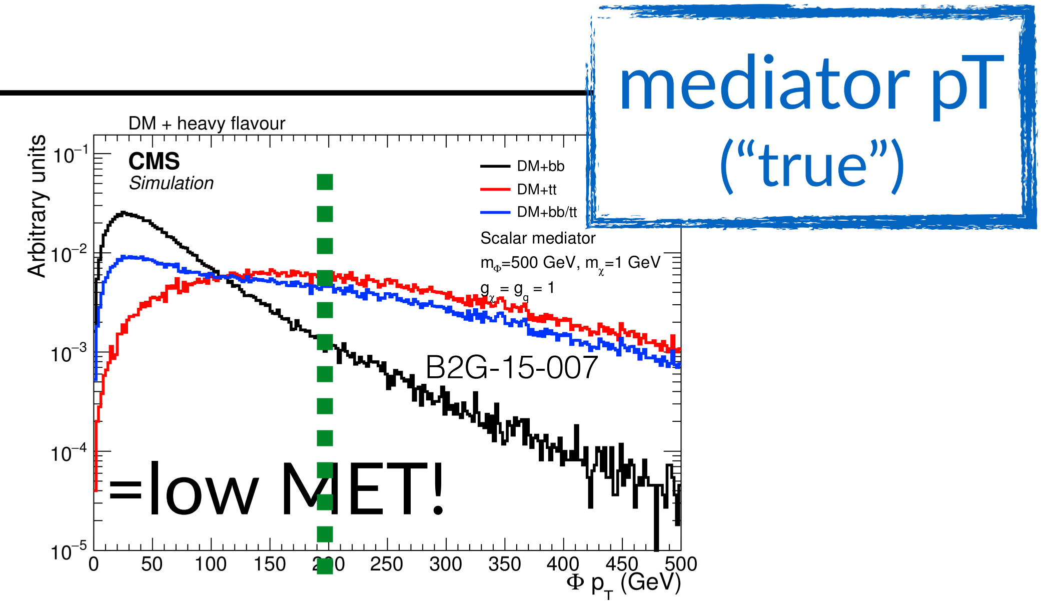


ATLAS Preliminary
√s=13 TeV, 3.4 fb-1
Data
Background fit
BumpHunter interval
p-value = 0.19
Fit Range: 394 - 1236 GeV
|y*| < 0.3
Events
Significance
m_jj [GeV]

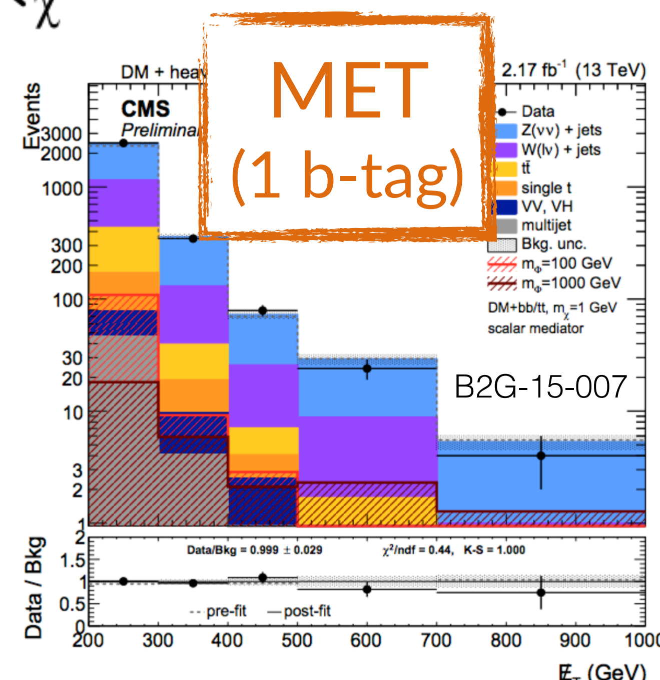
CMS: B(B) + MET @ 13 TEV

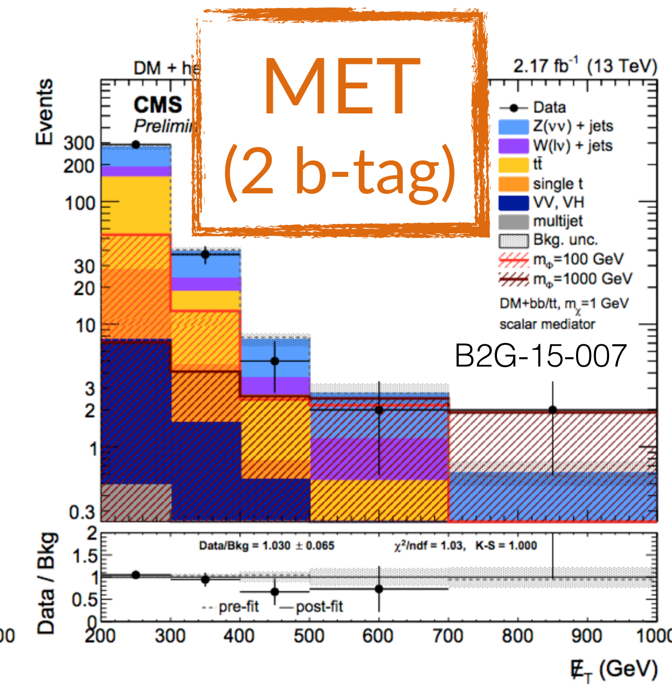


$$\mathcal{O}_{\text{scalar}} = \sum_q \frac{m_q}{M_*^N}\bar{q}q\bar{\chi}\chi$$

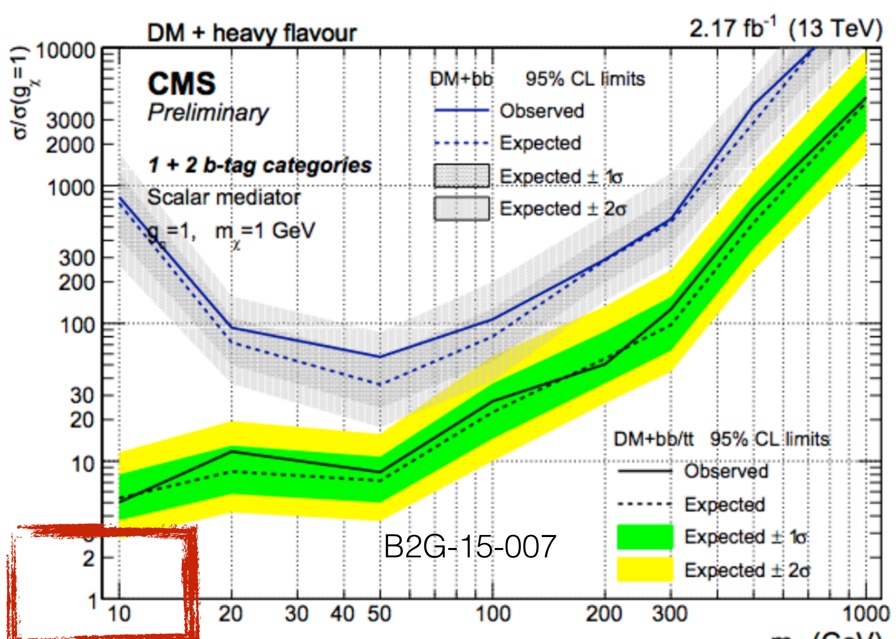


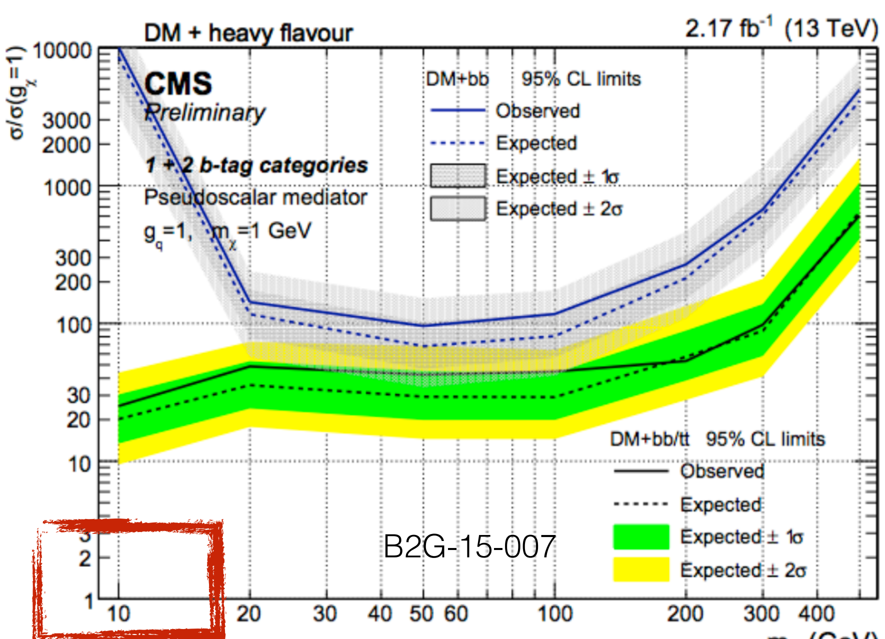
à-la-monojet, but binned in $N_{\text{b-tags}}$, N_{jets}

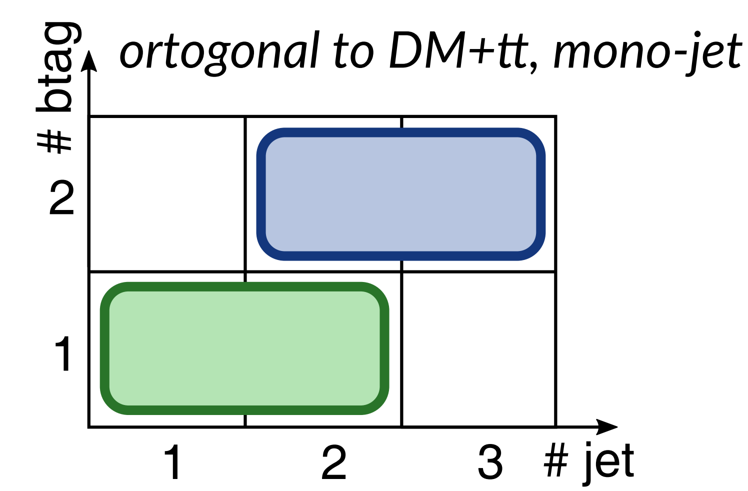




- sensitive also to ttbar+DM production
- softer mediator pT -> MET trigger is a challenge!
  - need more luminosity to be fully sensitive







MET+γ, ET AL.

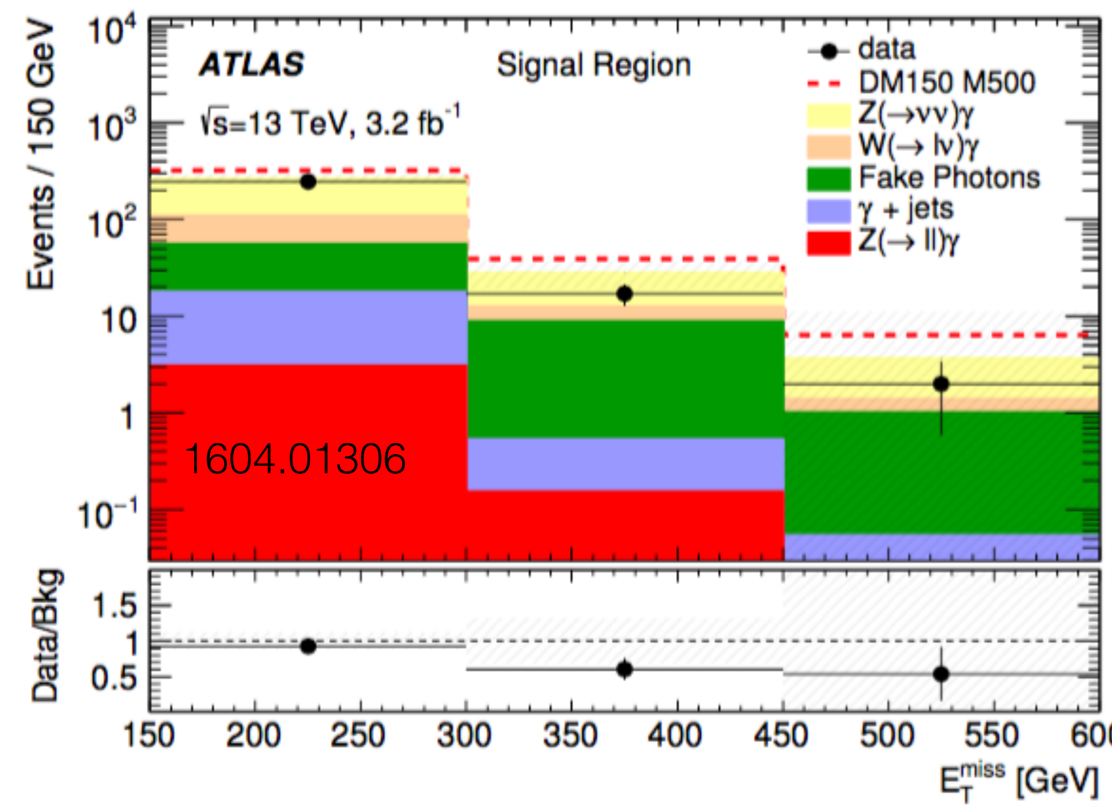
γ + DM

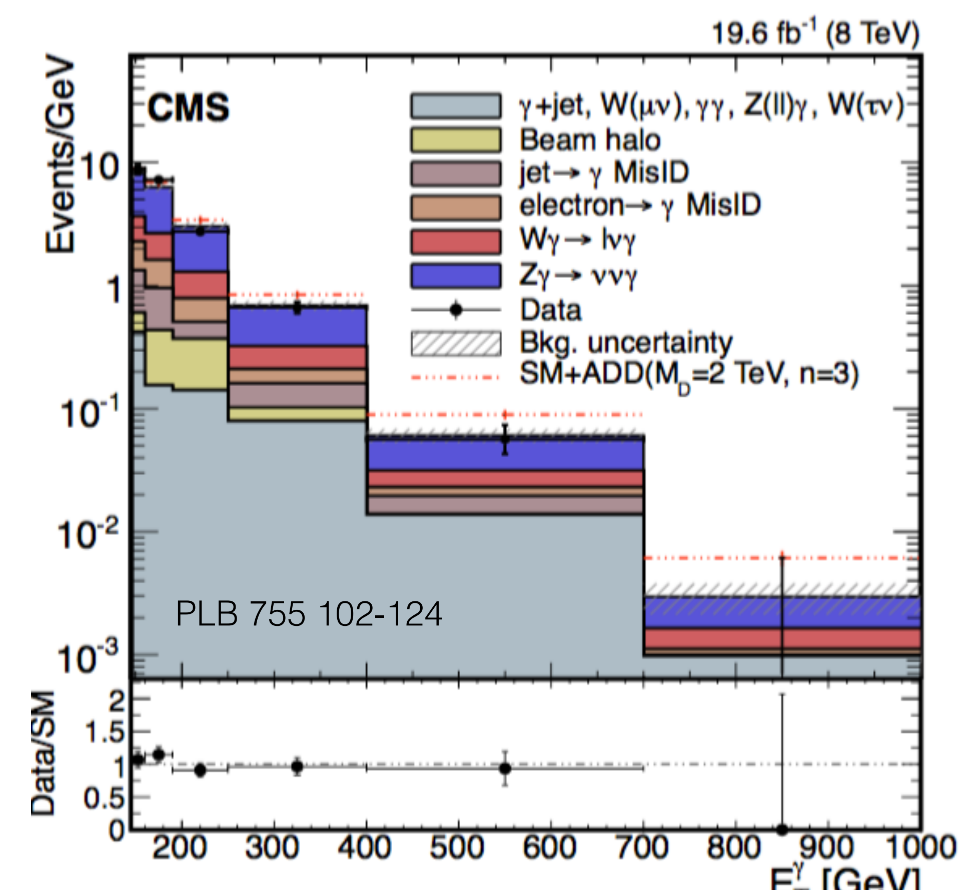
similar strategy as monojet

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

lower statistics than monojet

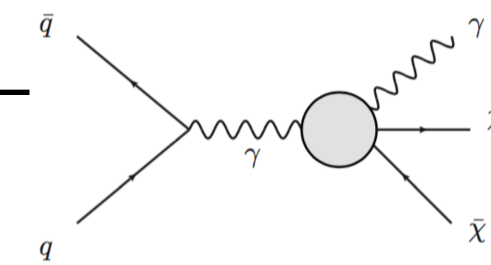
- ATLAS 13 TeV: counting experiment
  - simultaneous fit to SR + CRs
    - W(μν), Z(μμ), Z(ee), W(ev)
  - dominant uncertainty from estimation of e->γ fake factor applied to MET+e events
- CMS 8 TeV: shape analysis

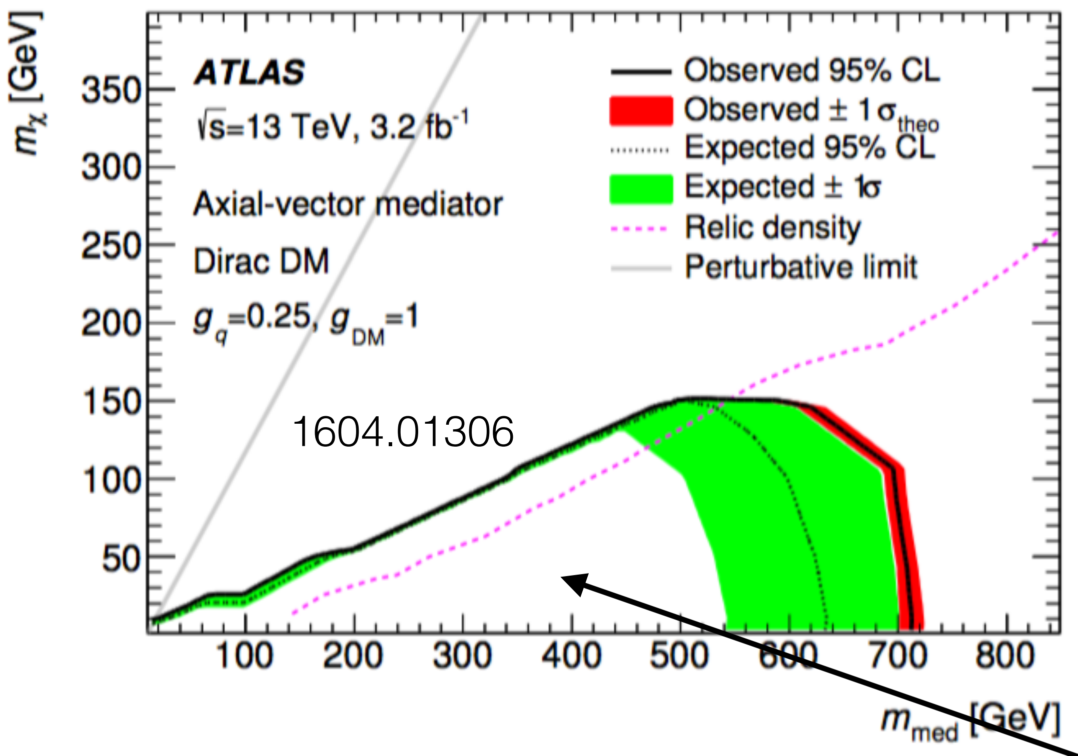


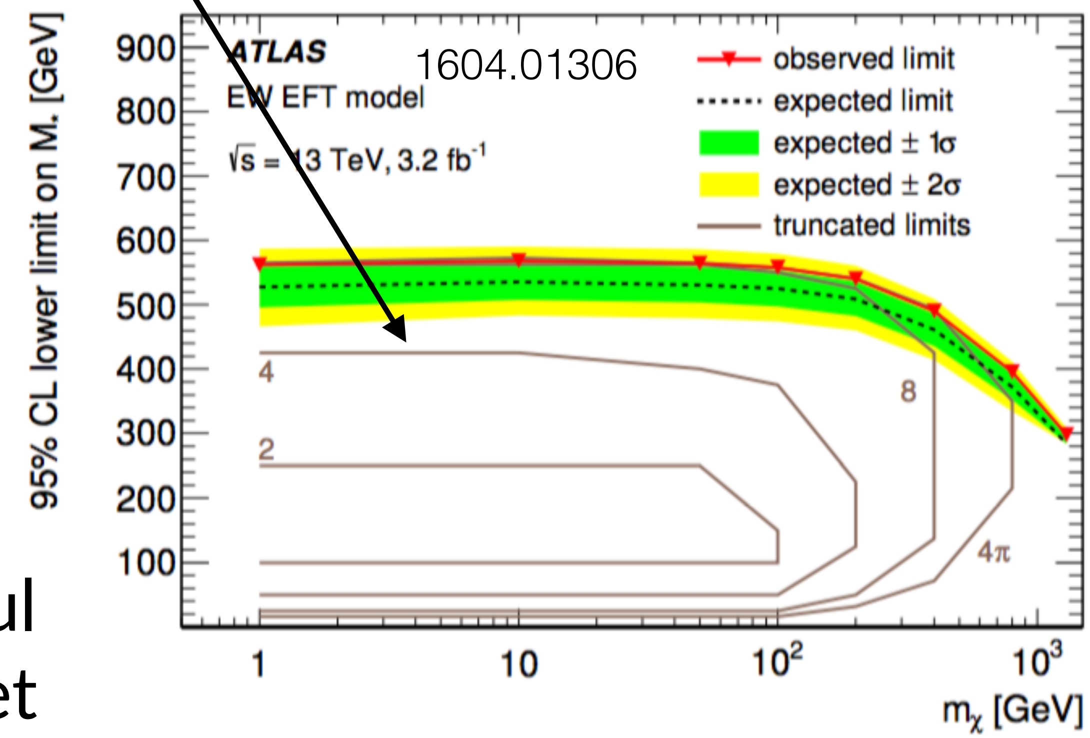


γ+DM: RESULTS

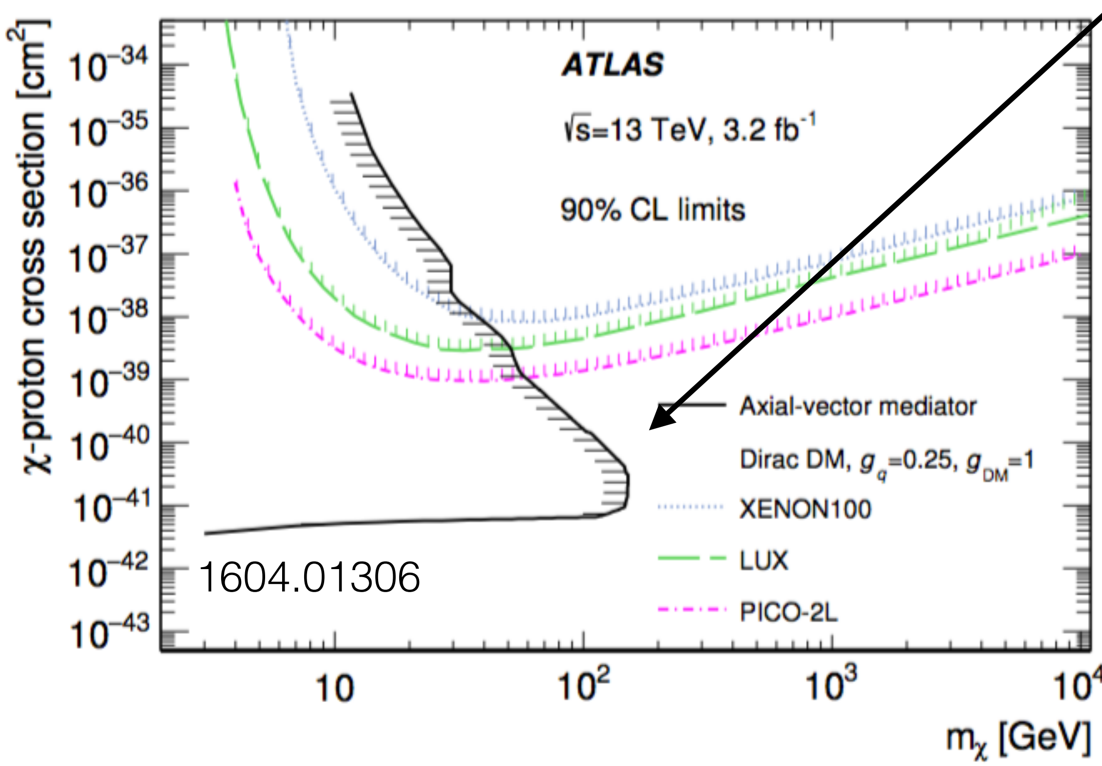
EFT validity (& result) depends on assumed coupling

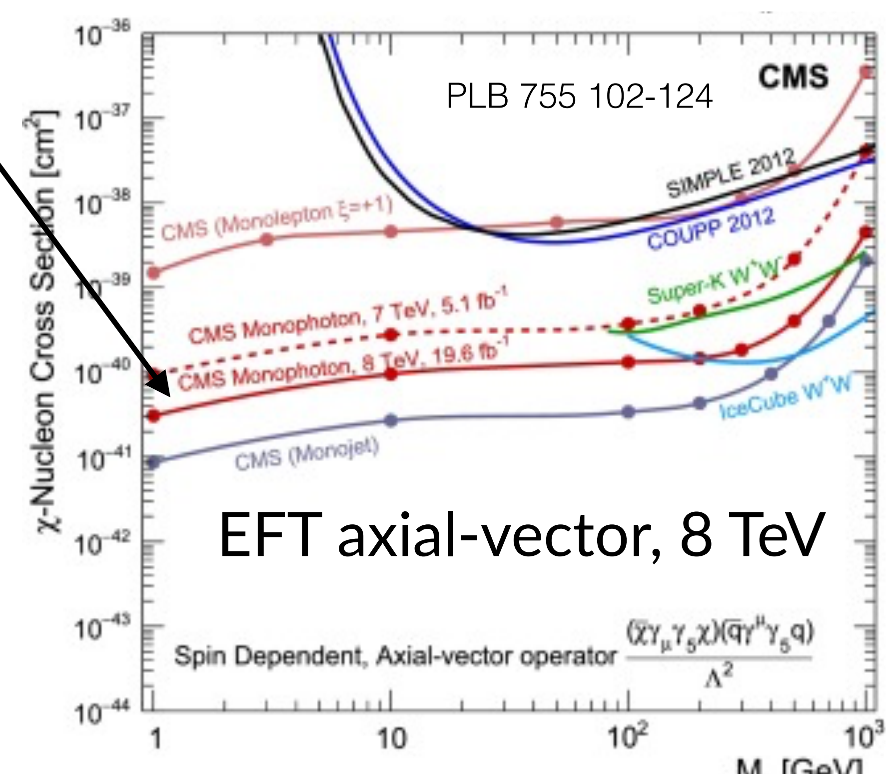






less powerful than monojet



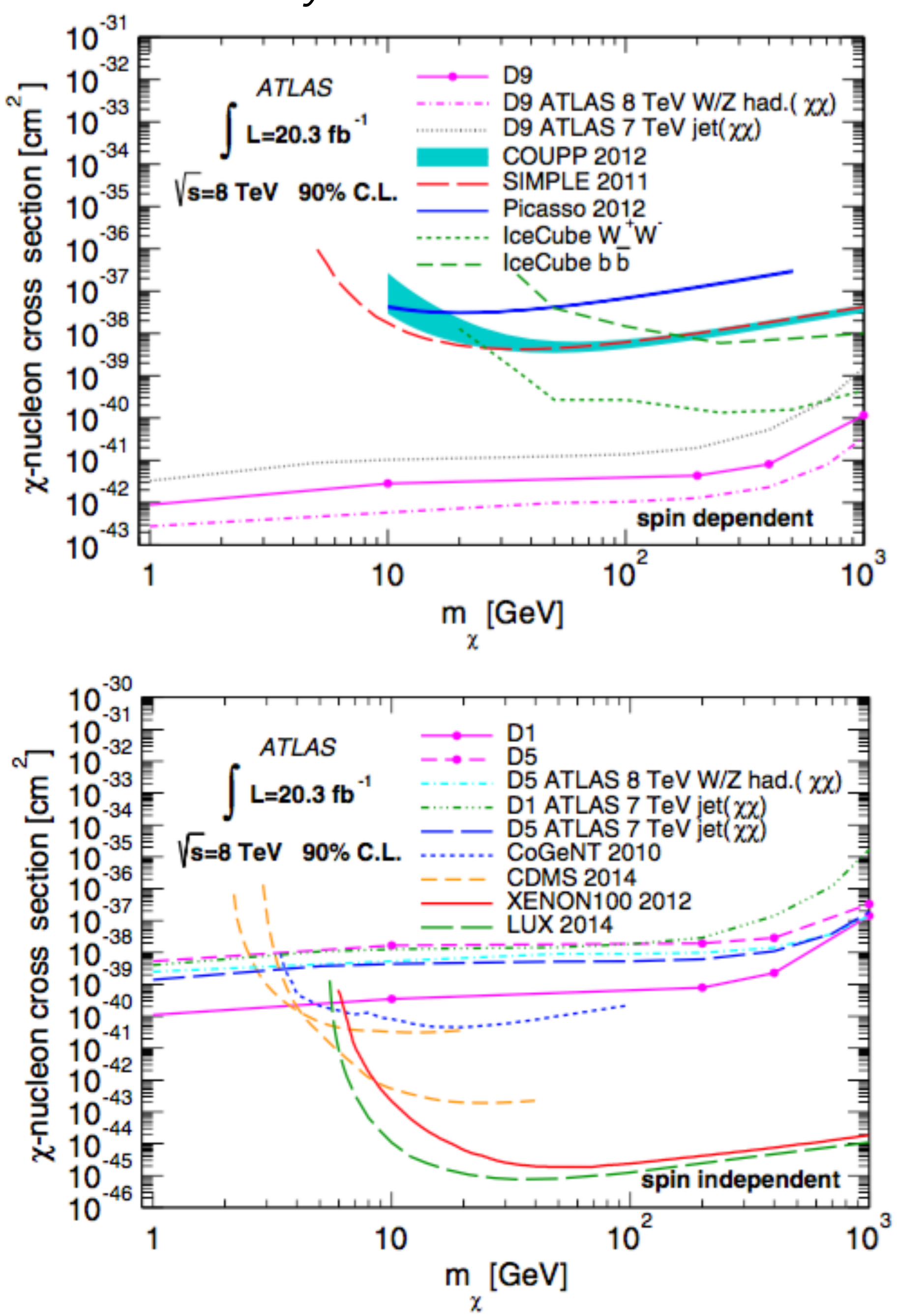


MONO-W,Z -> LEPTONS

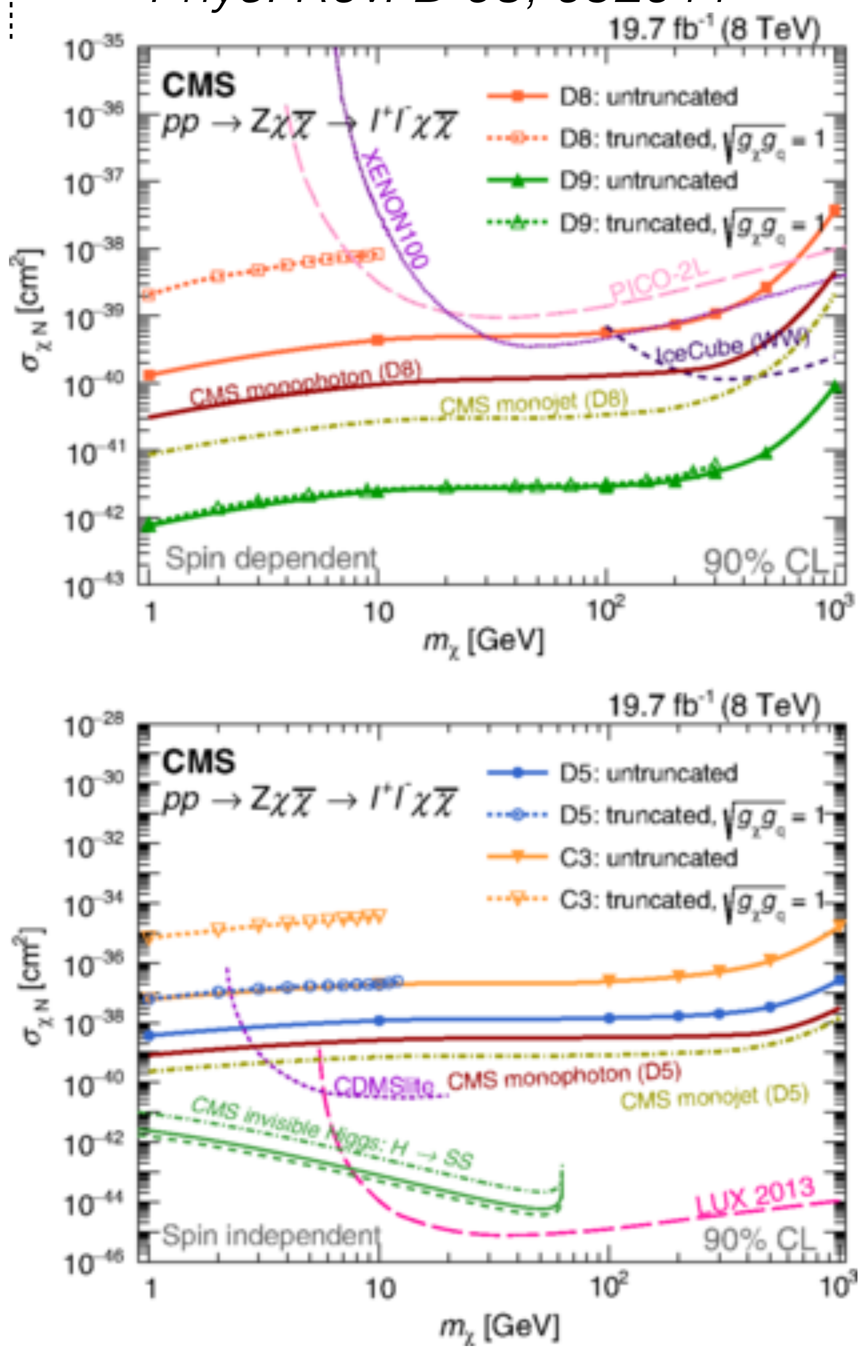
same final state as VH(inv), W'(lv) searches

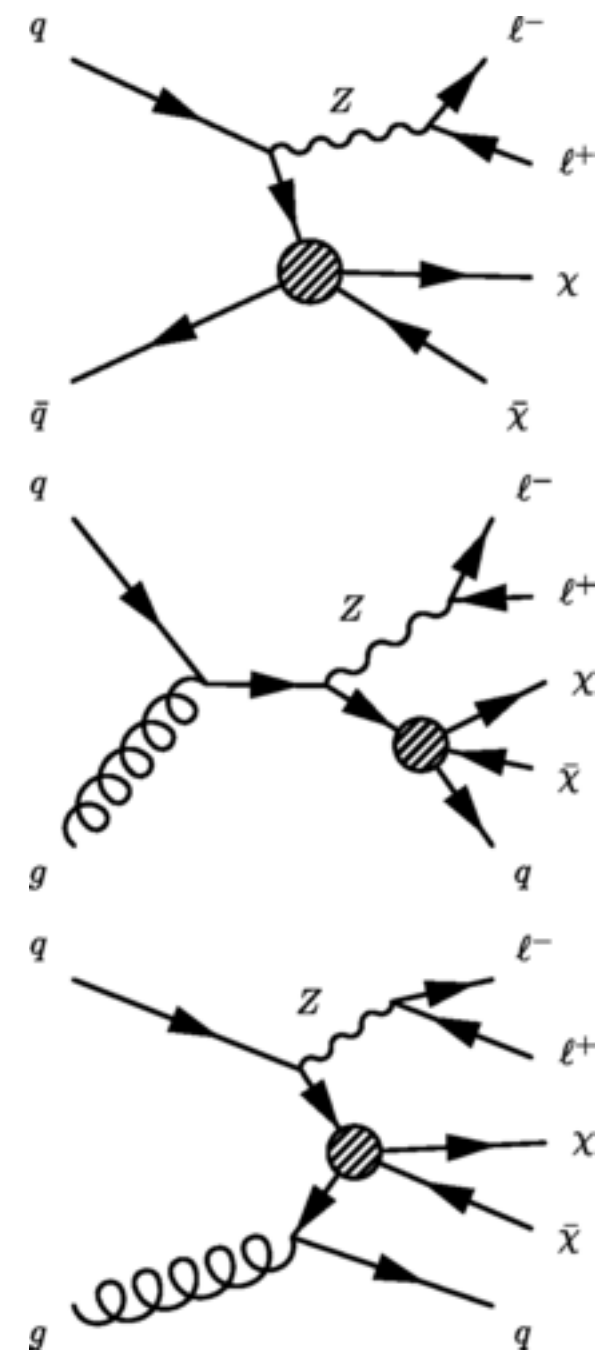
- lower sensitivity than hadronic counterparts

PhysRevD.90.012004

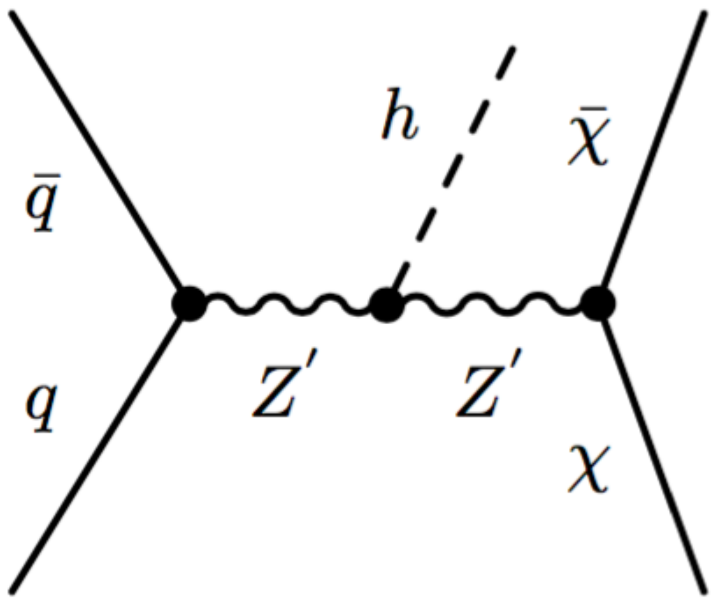


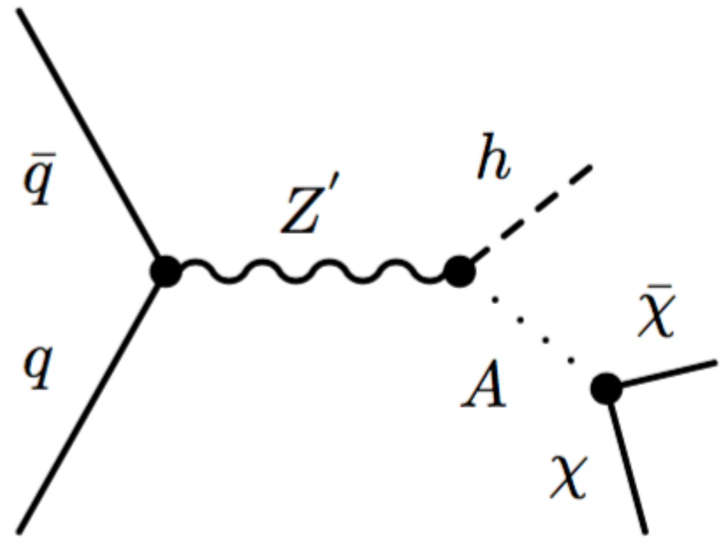
Phys. Rev. D 93, 052011

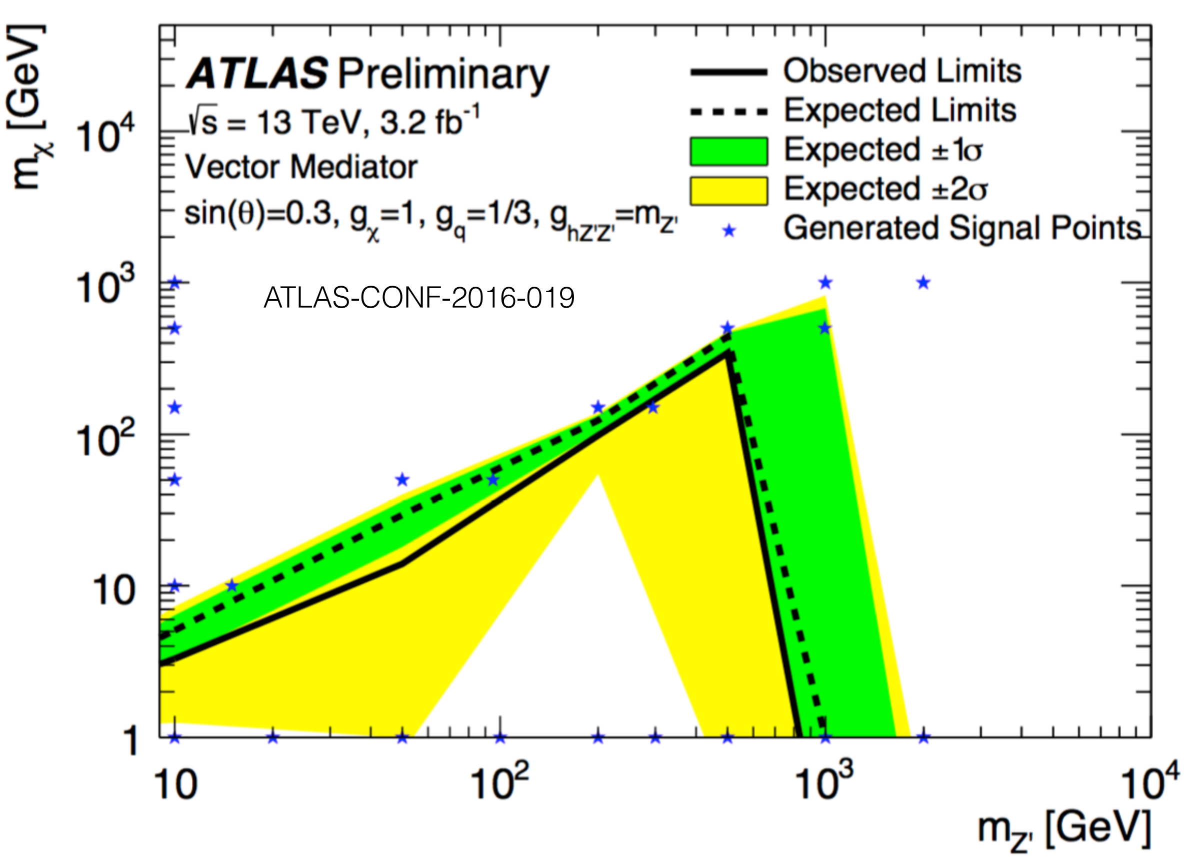




Mono-Higgs







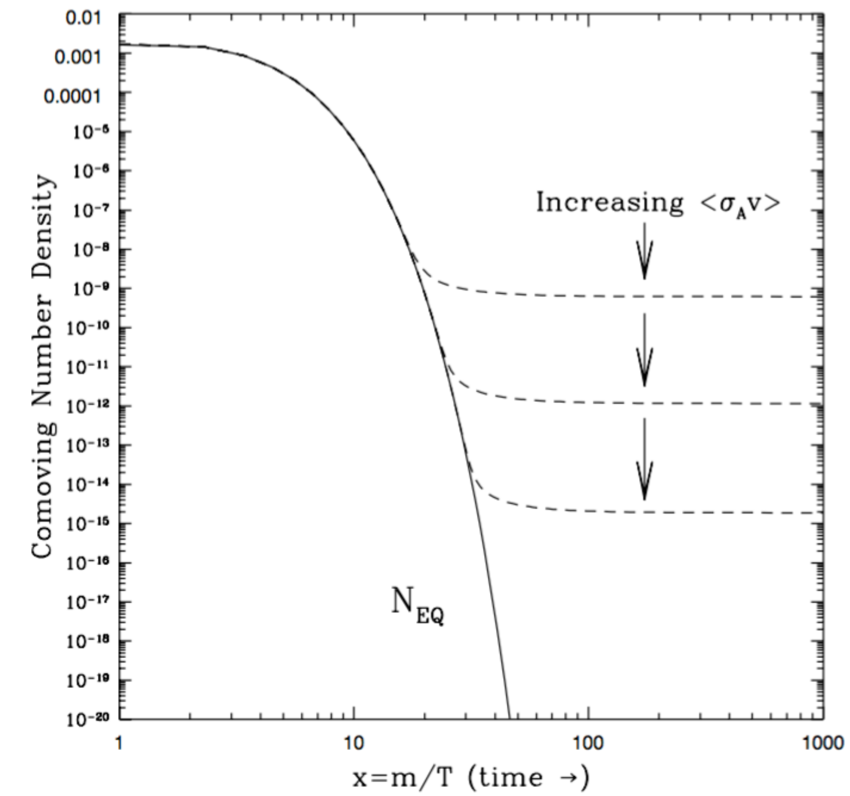
use Higgs as a discovery tool!

- 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 $F = G\frac{m_{\mathrm{SM}} m_{\mathrm{DM}}}{r^2}$ 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

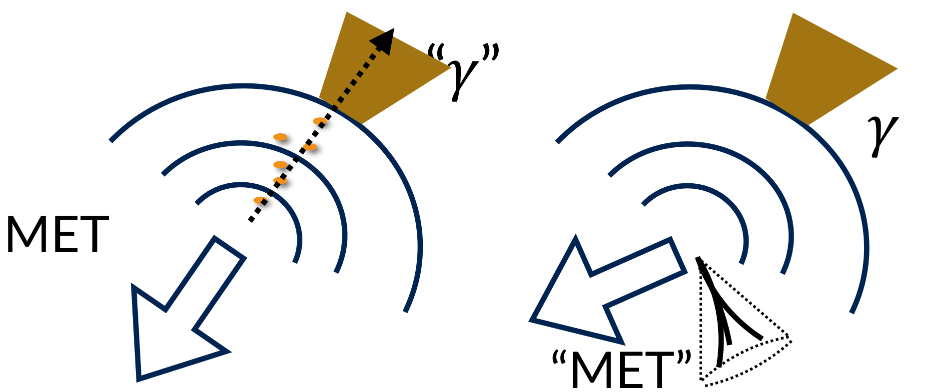
di-bosons, DY and in γ+jets cross-section 20%
top cross-section: 20% →checking data/MC in top CR as well as the effect of top p_T re-weighting

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

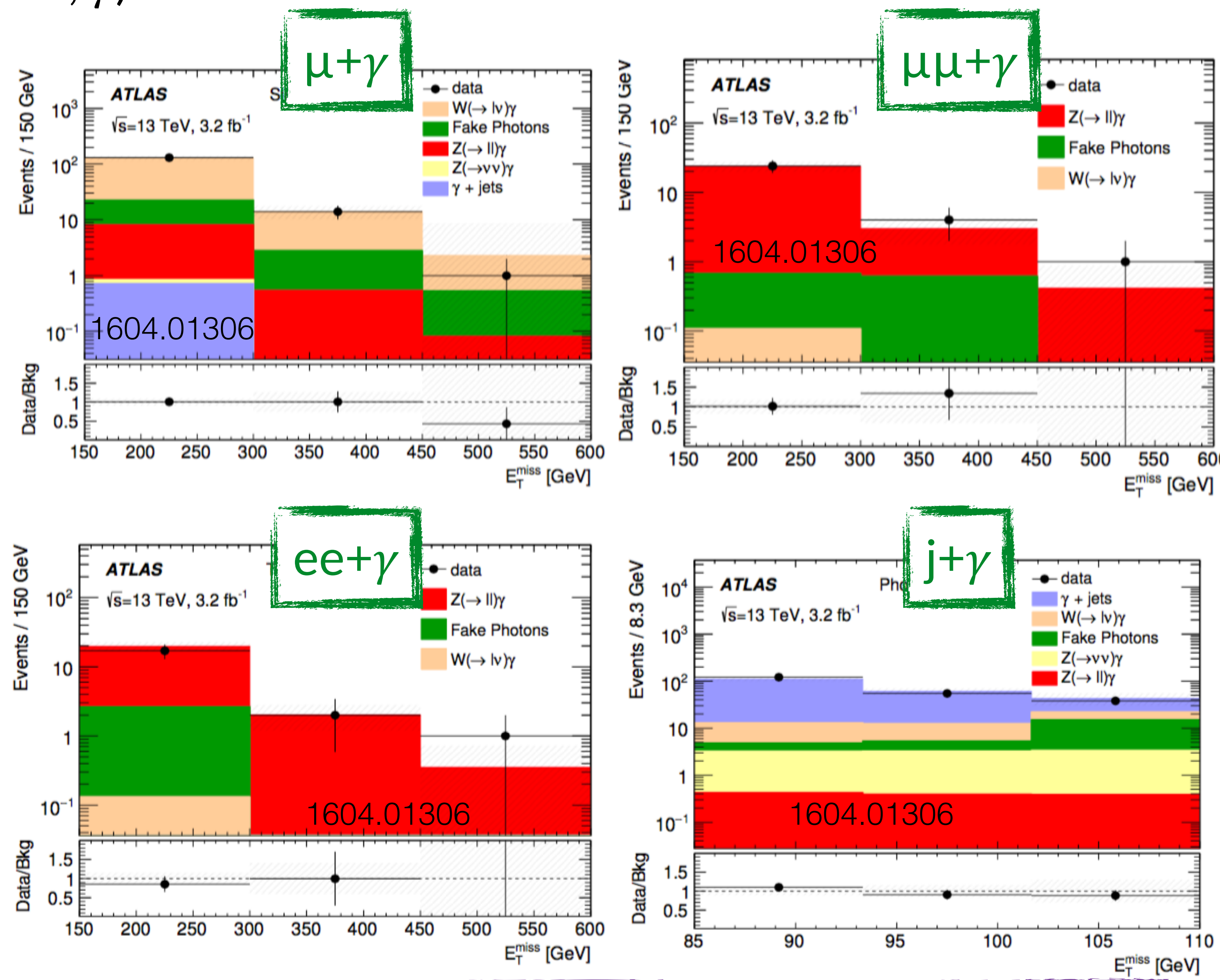


data-driven MET+e

- 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

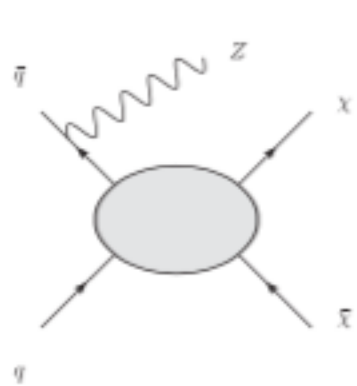


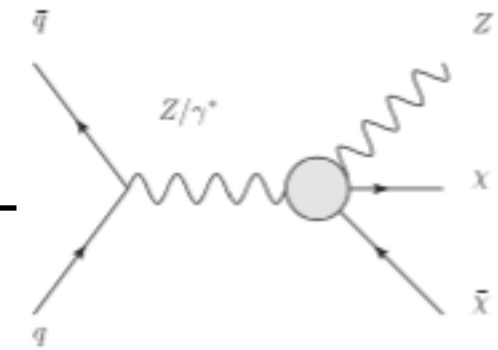
11% bkg uncertainty dominated by statistics (9%), e->γ fake factor (5%)

MonoPhoton – Systematics

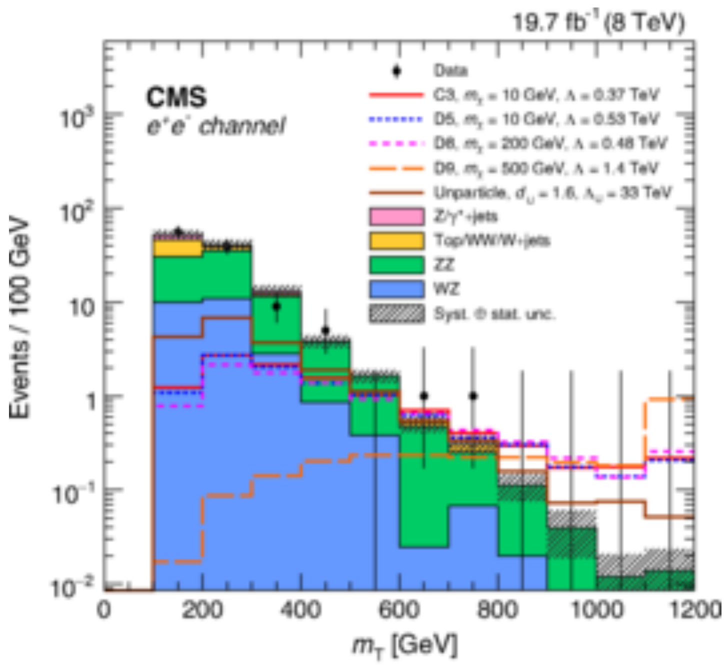
Total background	295
Total background uncertainty	11%
Electron fake rate	5.8%
PDF uncertainties	2.8%
Jet fake rate	2.4%
Muons reconstruction/isolation efficiency	1.5%
Electrons reconstruction/identification/isolation efficiency	1.3%
Jet energy resolution [61]	1.2%
Photon energy scale	0.6%
$E_{\mathrm{T}}^{\mathrm{miss}}$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

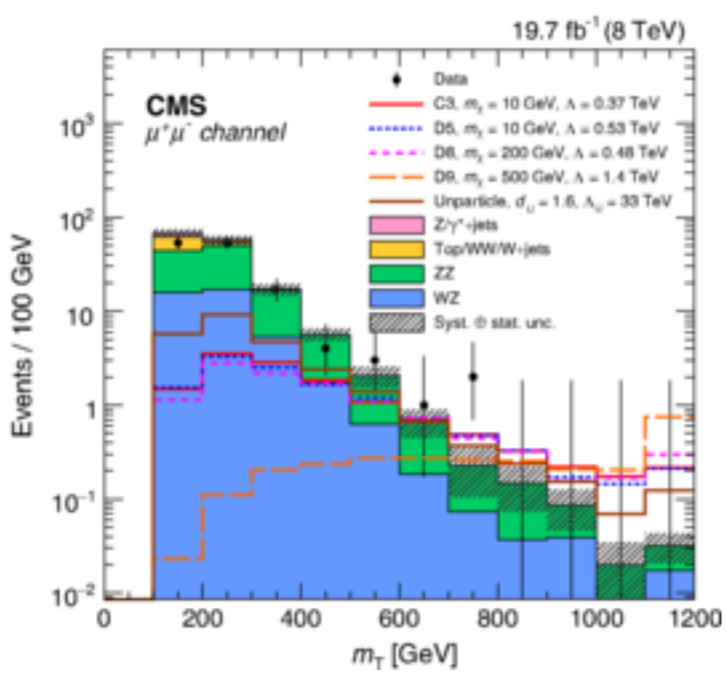
MONO-Z(LL)

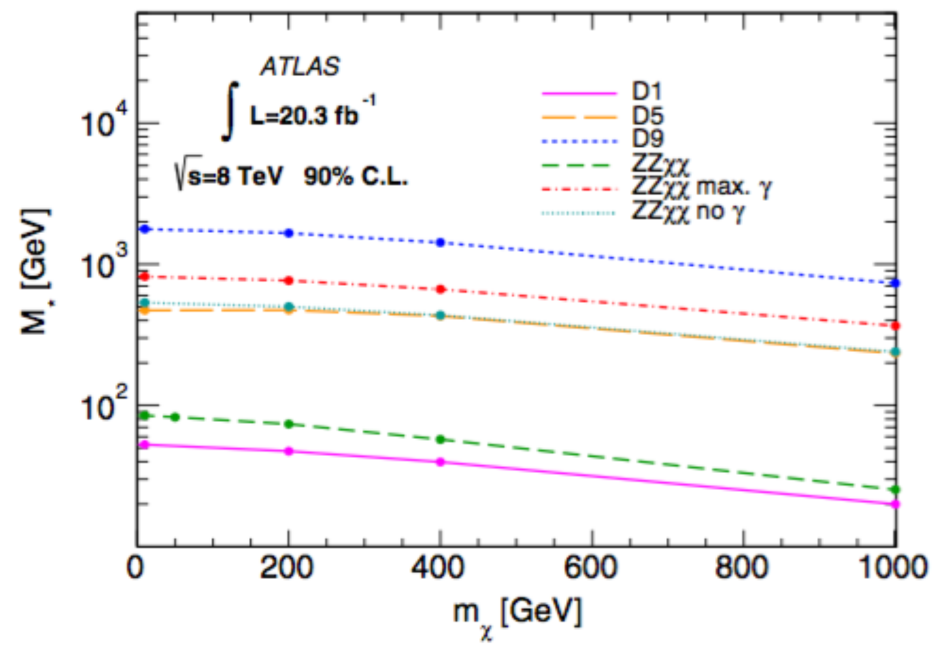


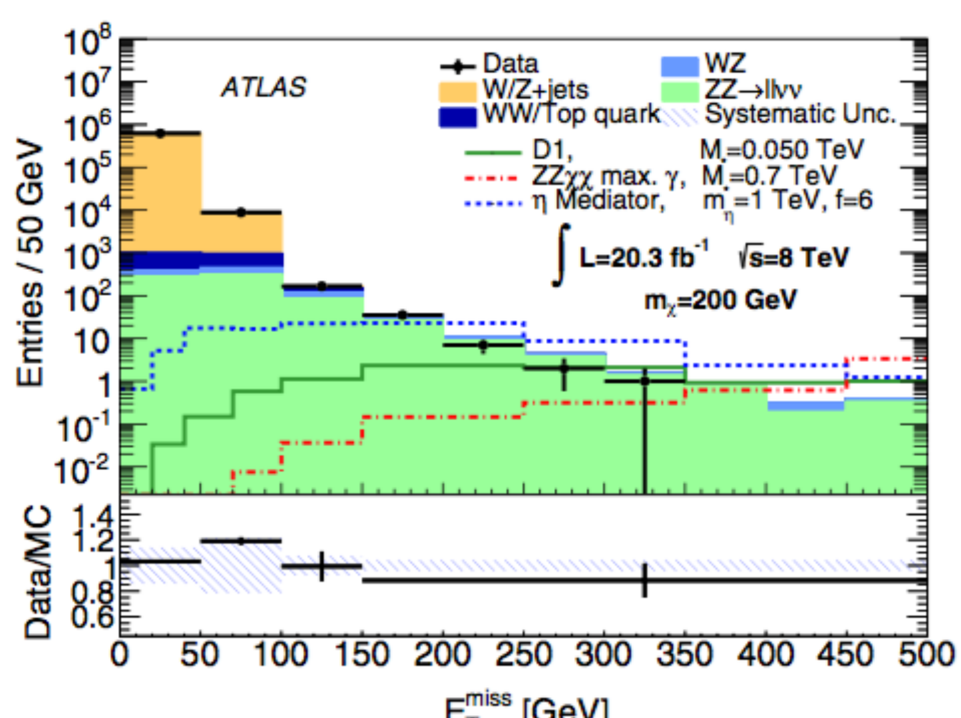


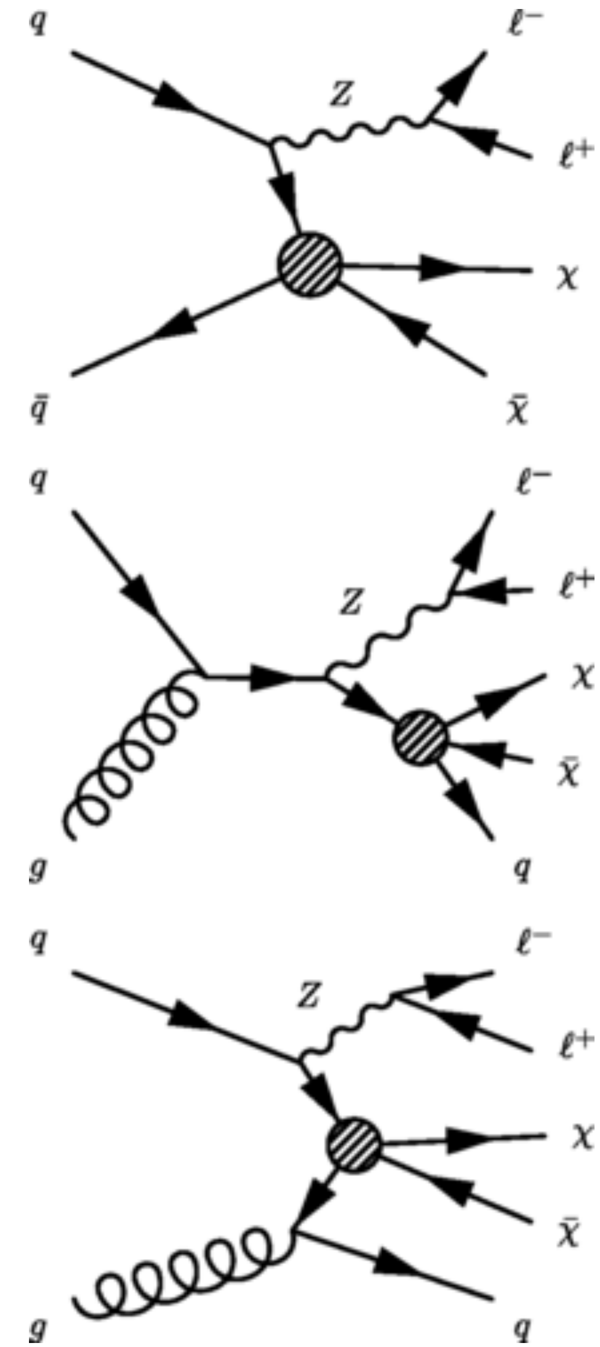
	E_T^{miss} threshold [GeV]			
Process	150	250	350	450
ZZ	41 ± 15	6.4 ± 2.4	1.3 ± 0.5	0.3 ± 0.1
WZ	8.0 ± 3.1	0.8 ± 0.4	0.2 ± 0.1	0.1 ± 0.1
WW, $t\bar{t}$, $Z \to \tau^+\tau^-$	1.9 ± 1.4	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$
Z + jets	0.1 ± 0.1	...	...	...
W + jets	0.5 ± 0.3	...	...	...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



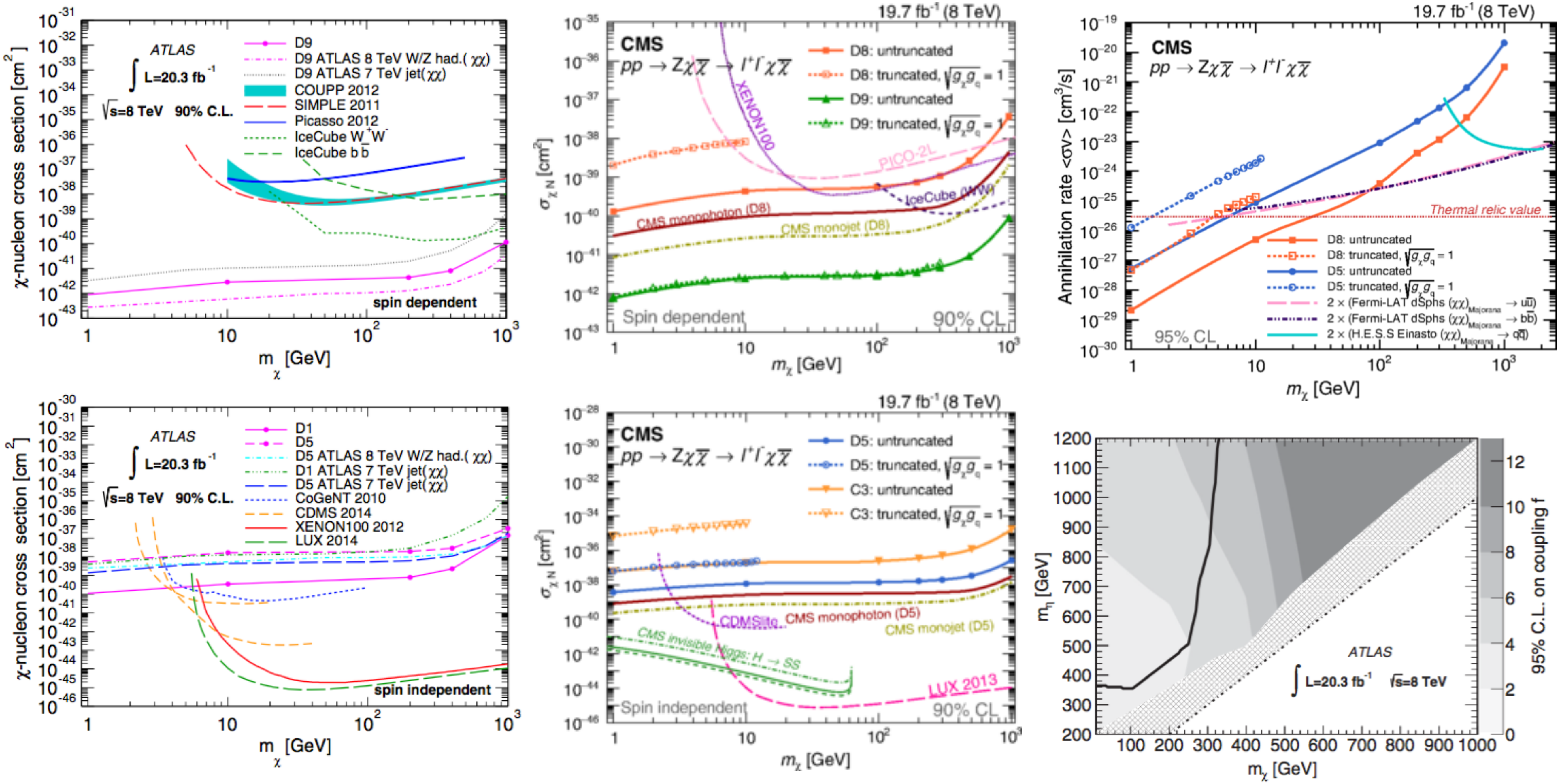




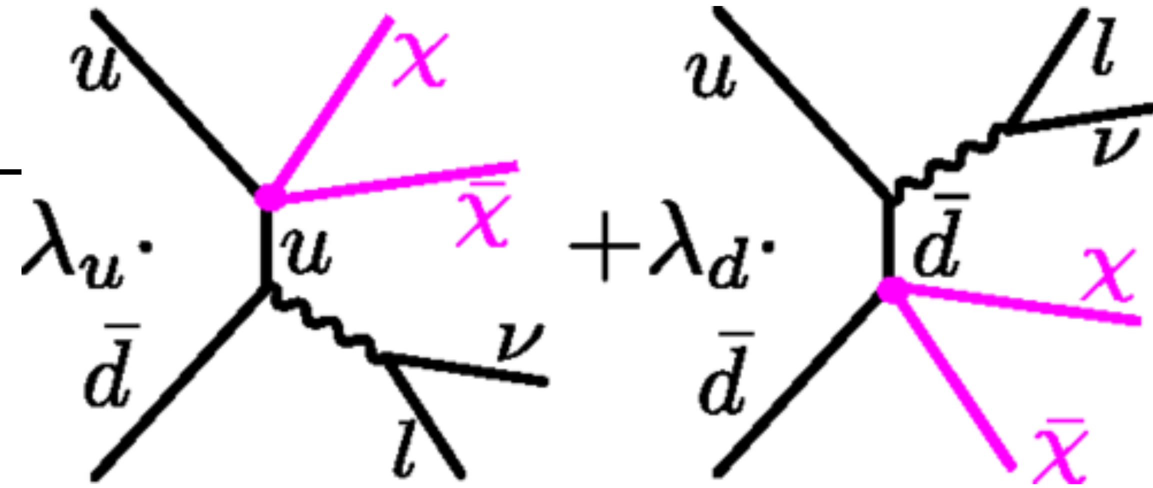




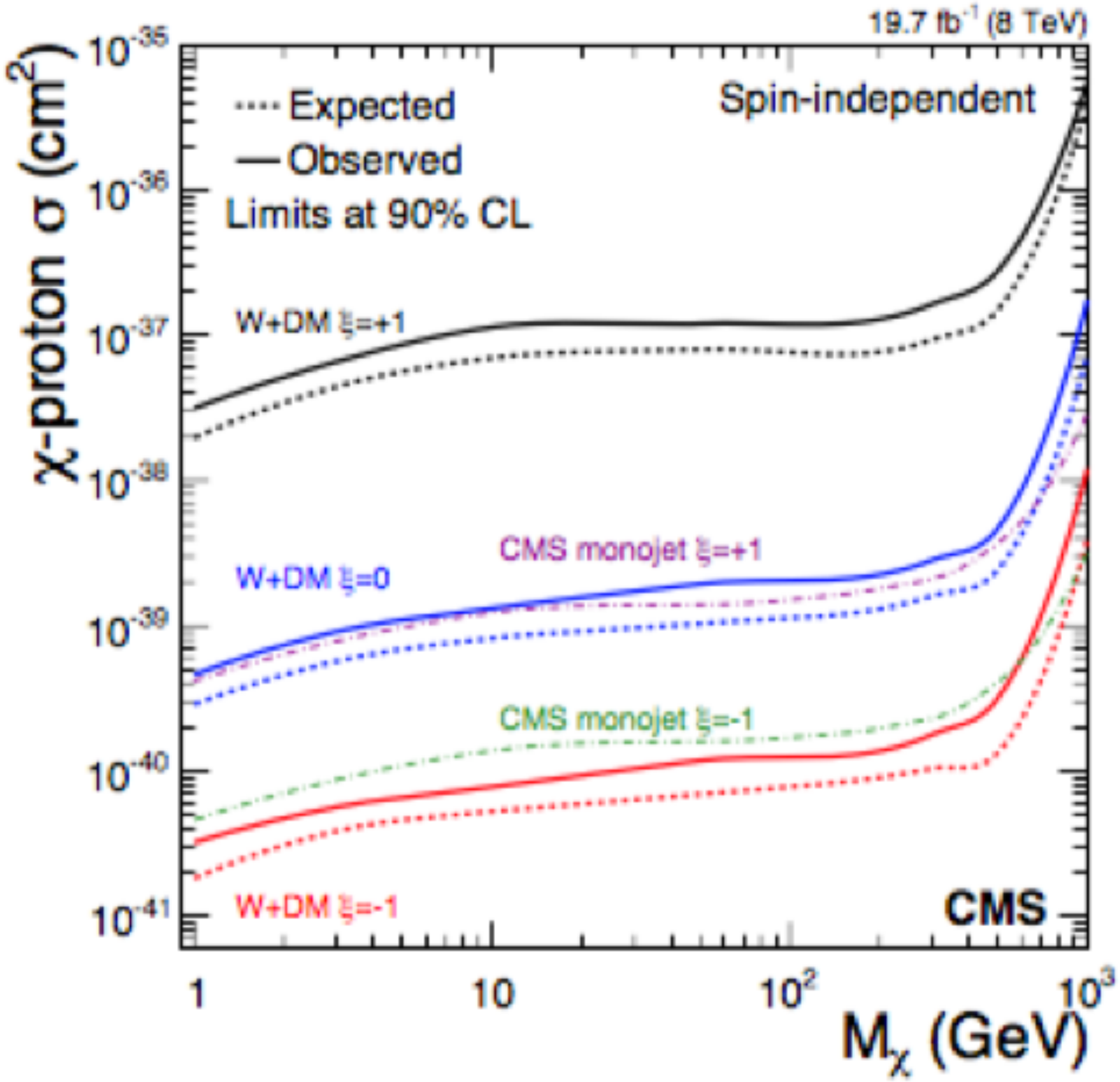
Mono-Z(ll) - Results



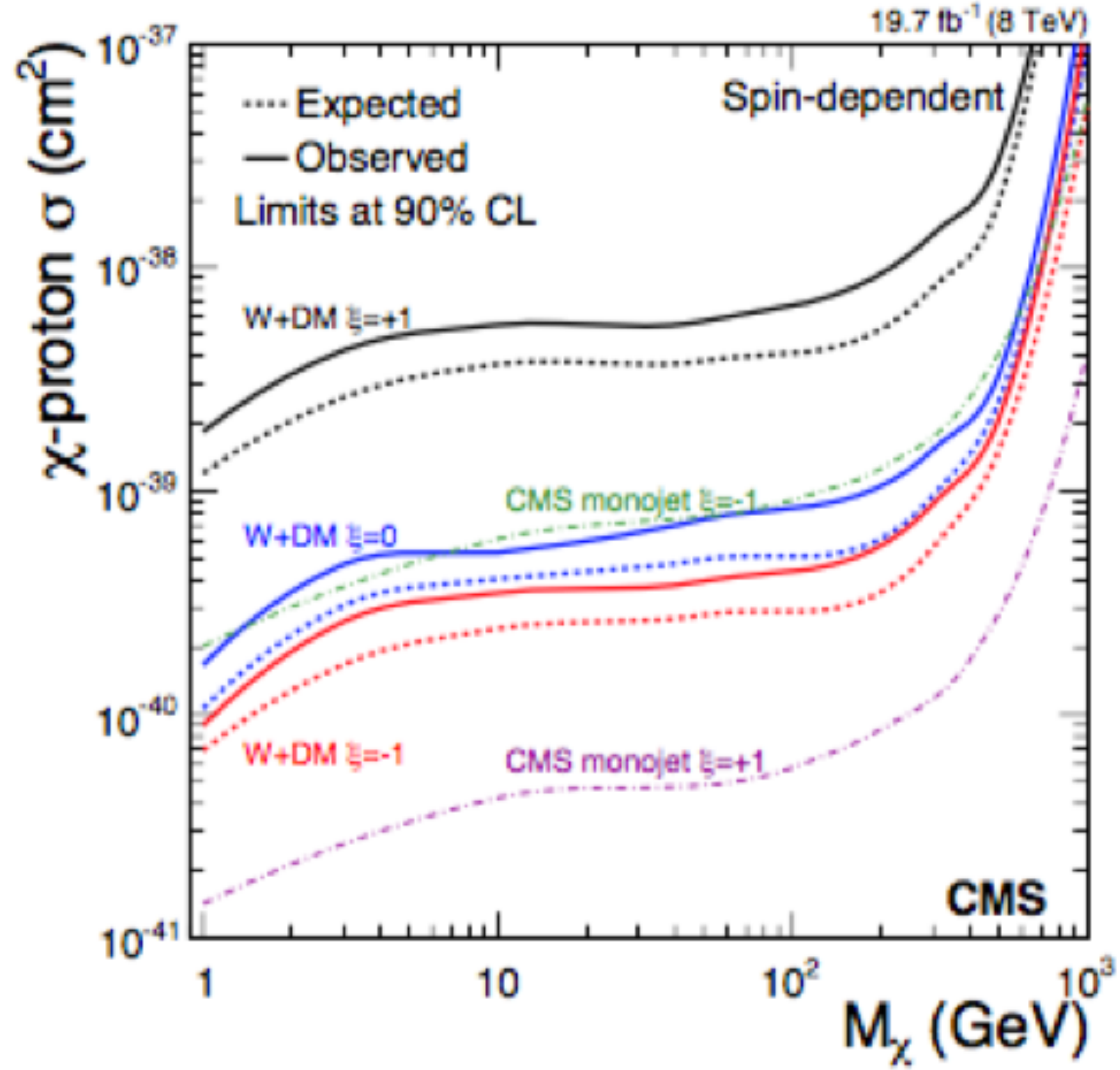
Mono-W(lν)



$\lambda_u \cdot$ + $\lambda_d \cdot$

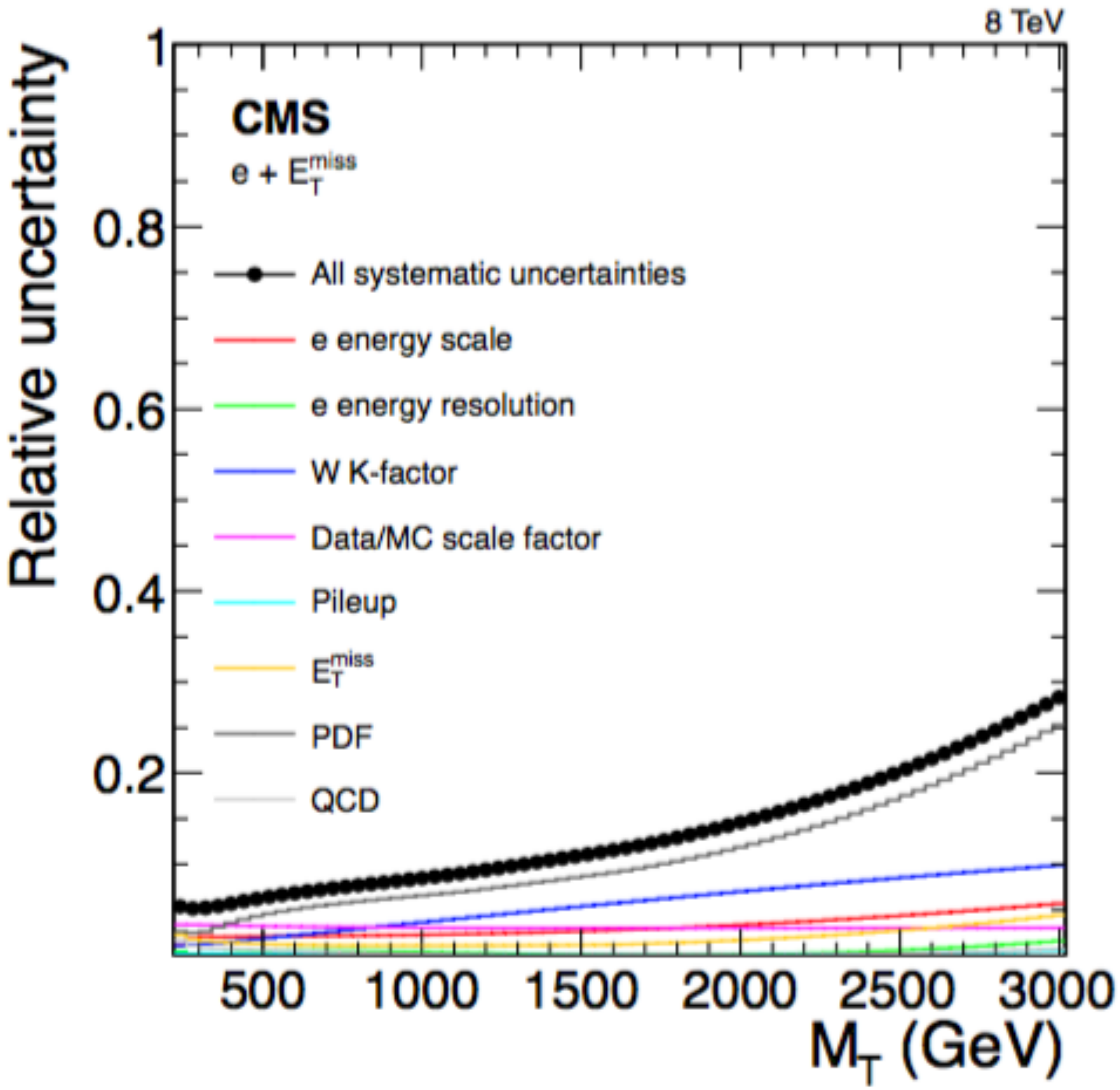


19.7 fb⁻¹ (8 TeV)
Expected
Observed
Limits at 90% CL
Spin-independent
W+DM ξ=+1
W+DM ξ=0
CMS monojet ξ=+1
CMS monojet ξ=-1
W+DM ξ=-1
CMS
χ-proton σ (cm²)
M_χ (GeV)

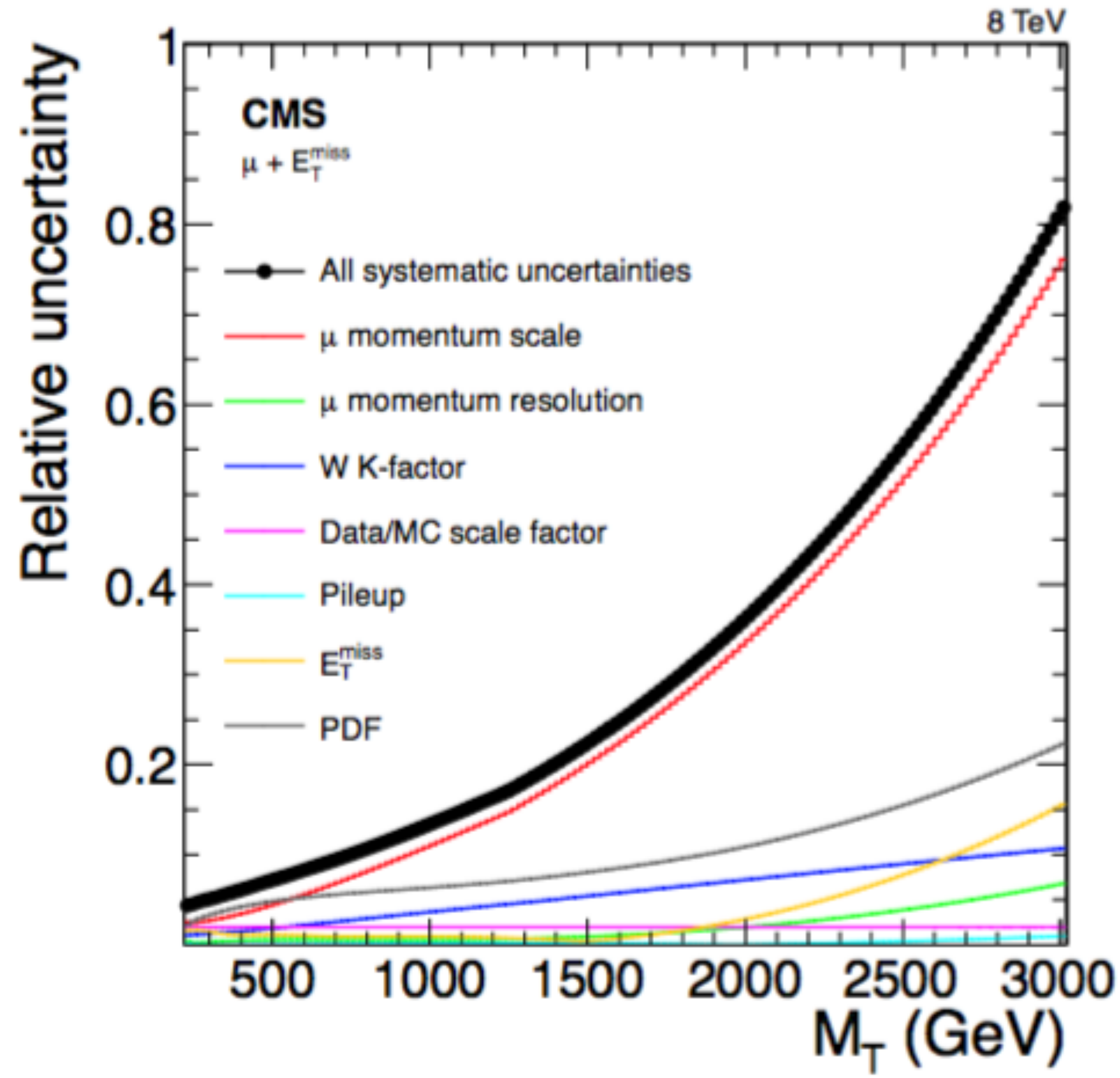


19.7 fb⁻¹ (8 TeV)
Expected
Observed
Limits at 90% CL
Spin-dependent
W+DM ξ=+1
CMS monojet ξ=-1
W+DM ξ=0
W+DM ξ=-1
CMS monojet ξ=+1
CMS
χ-proton σ (cm²)
M_χ (GeV)

Mono-W(lν)

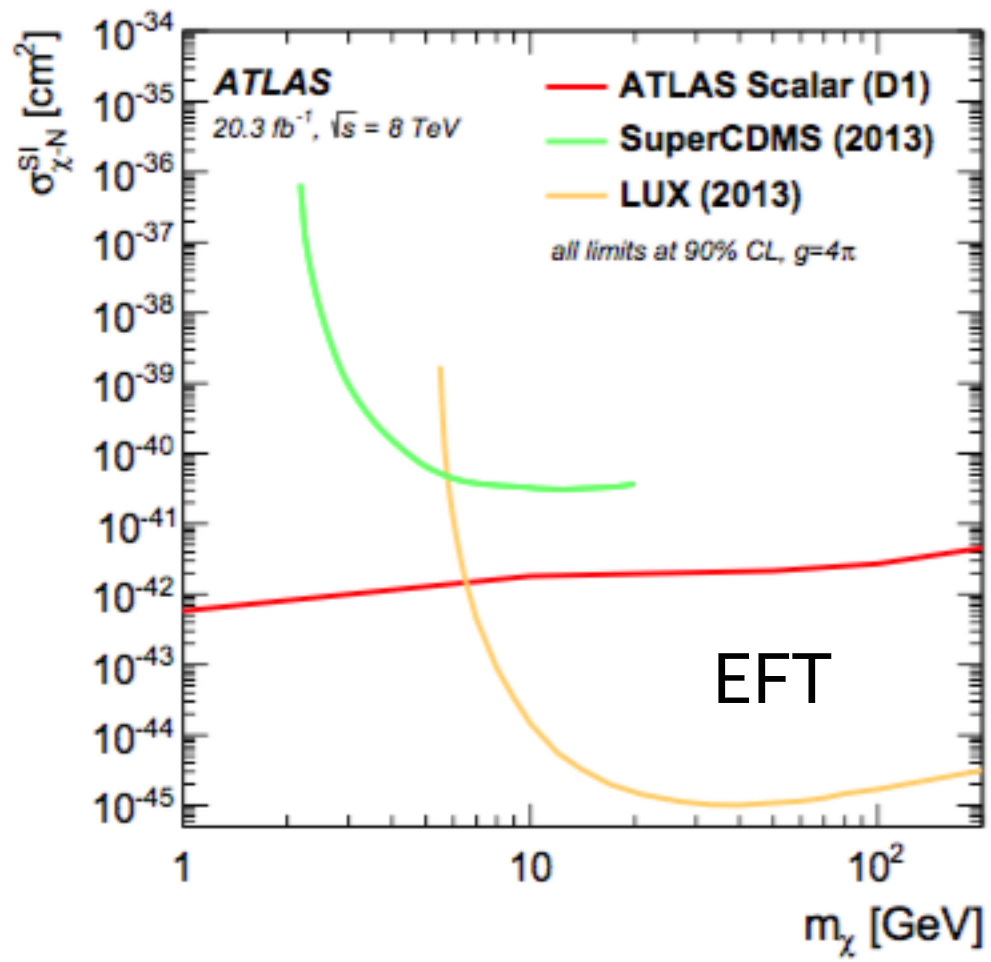


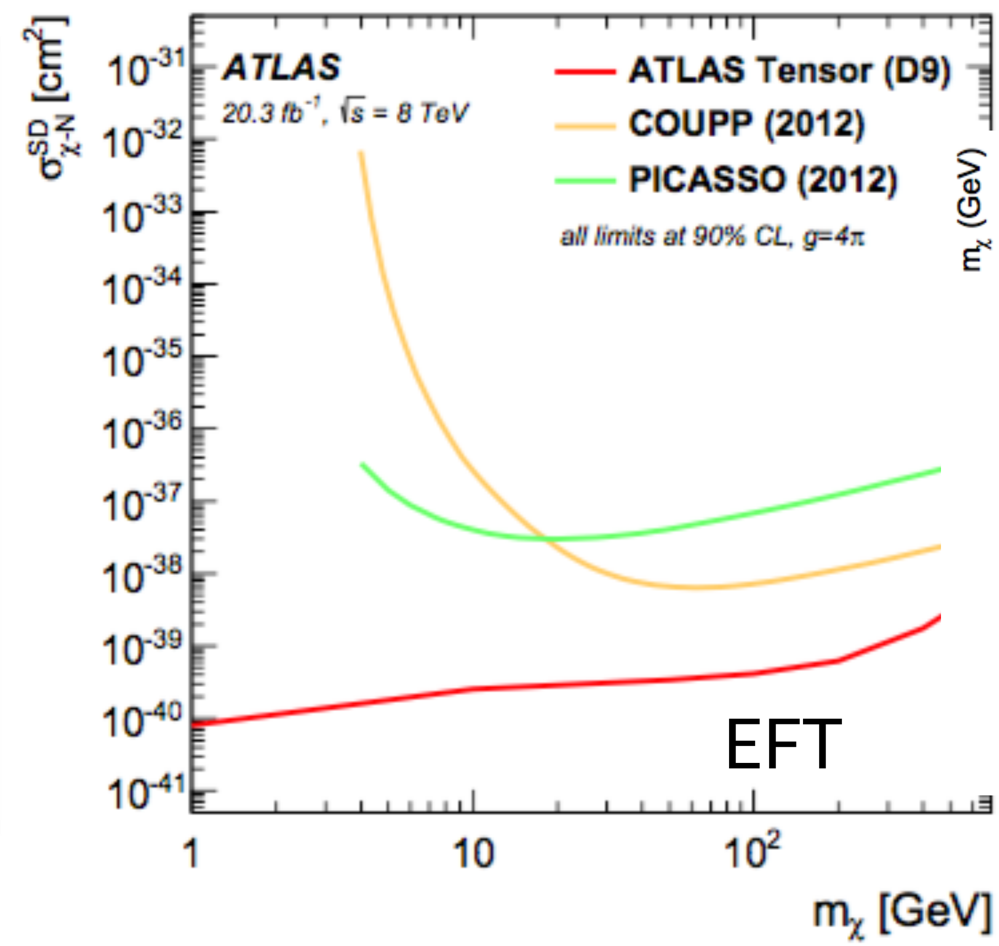
8 TeV
CMS
e + E_T^{miss}
All systematic uncertainties
e energy scale
e energy resolution
W K-factor
Data/MC scale factor
Pileup
E_T^{miss}
PDF
QCD
Relative uncertainty
M_T (GeV)

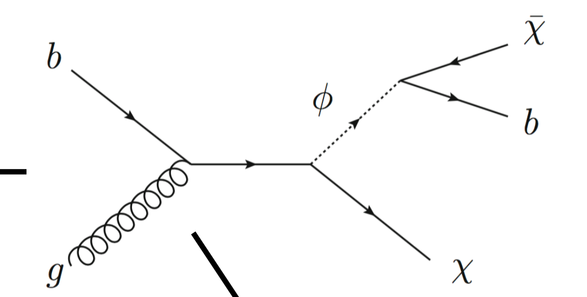


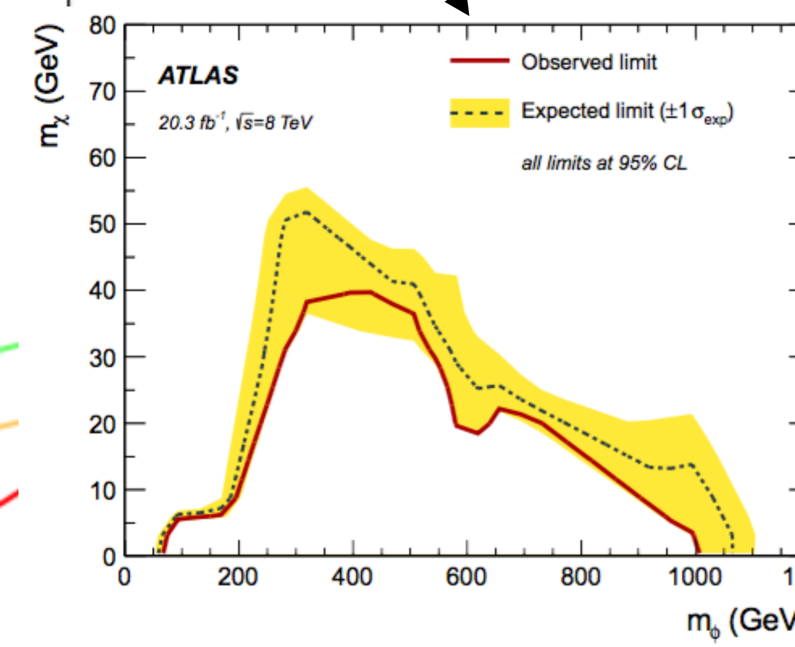
8 TeV
CMS
μ + E_T^{miss}
All systematic uncertainties
μ momentum scale
μ momentum resolution
W K-factor
Data/MC scale factor
Pileup
E_T^{miss}
PDF
Relative uncertainty
M_T (GeV)

ATLAS Mono-HF @ 8 TeV (results)

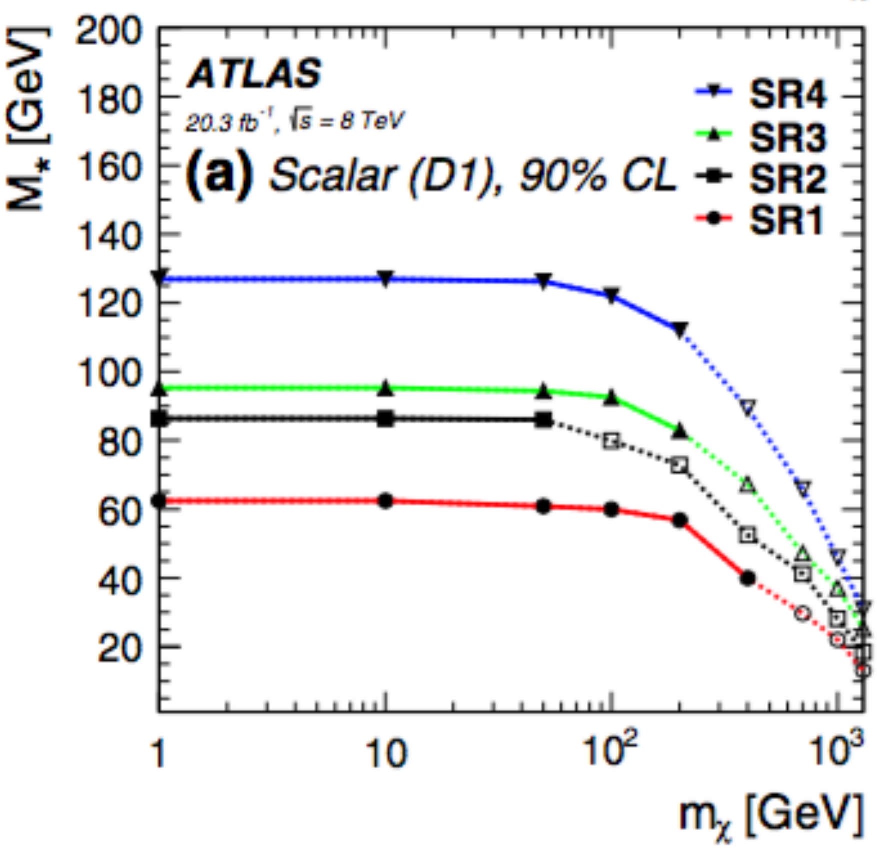


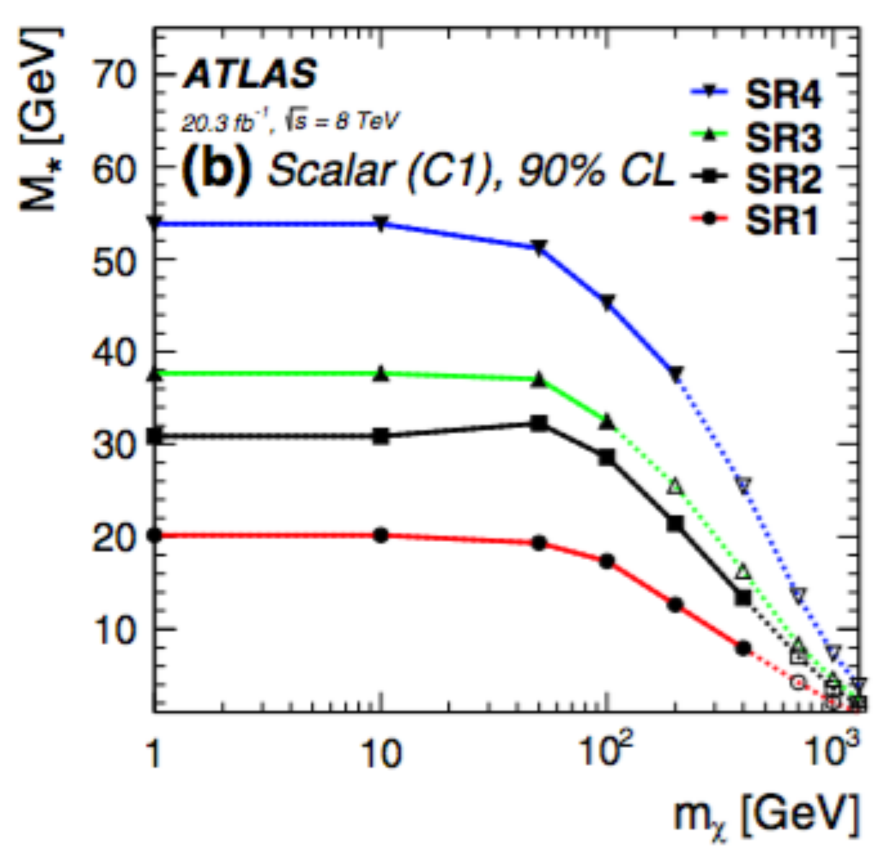


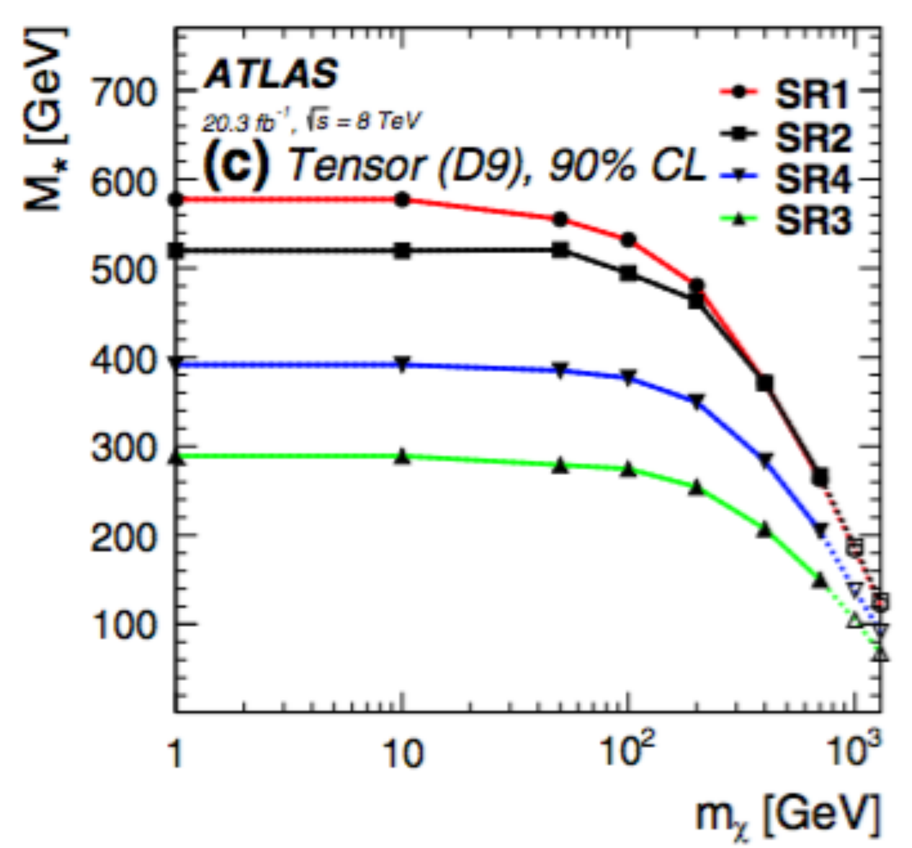




Eur. Phys. J. C(2015) 75:92

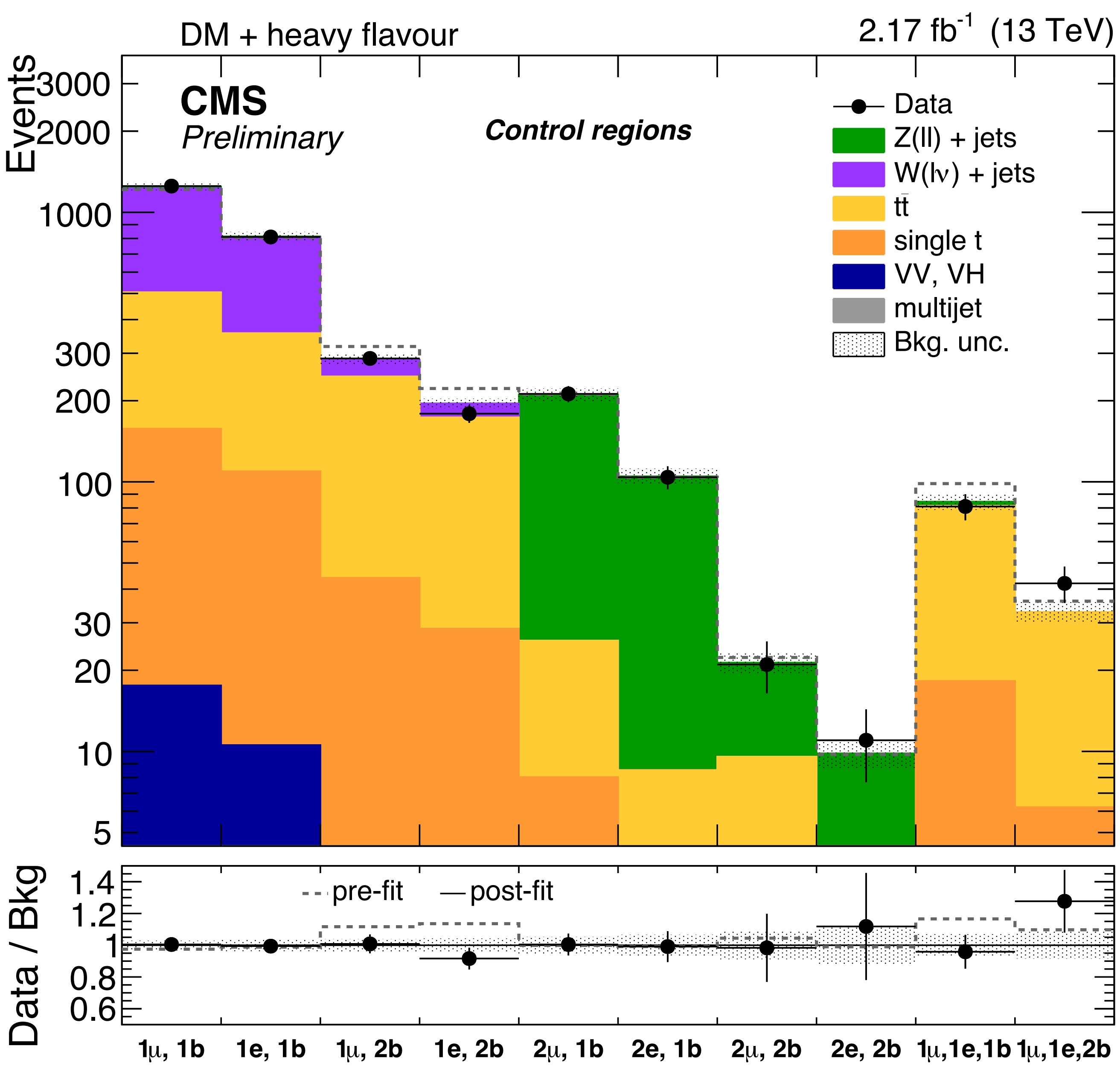






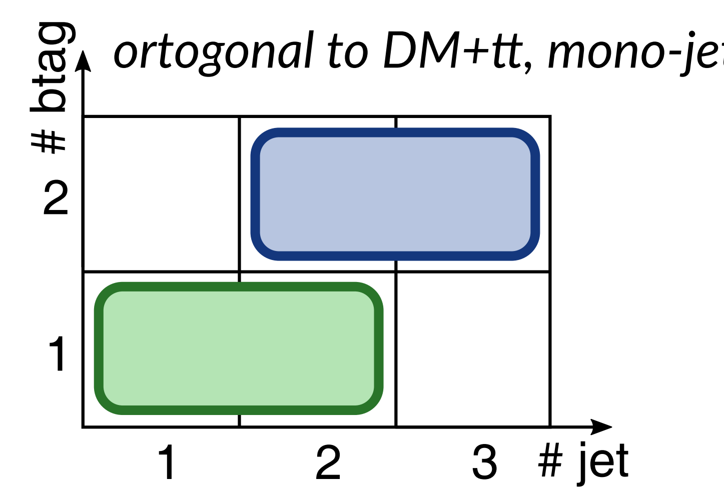
CMS: b(b) + MET @ 13 TeV – bkg & syst

B2G-15-007



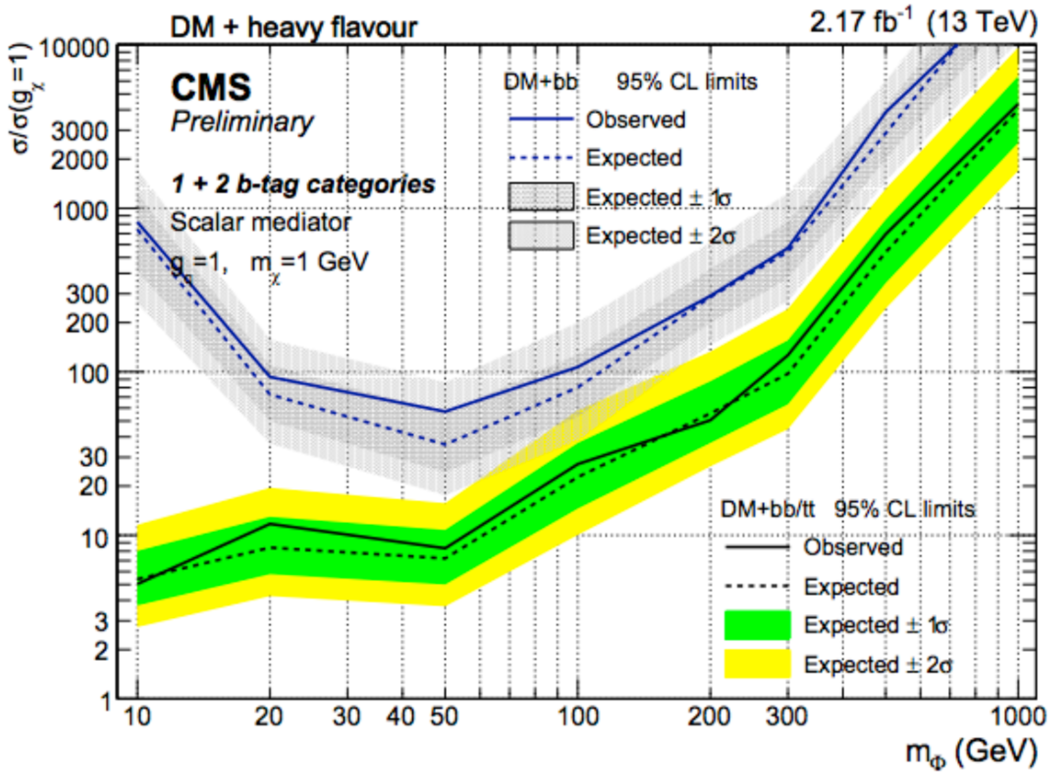
W Z ttbar

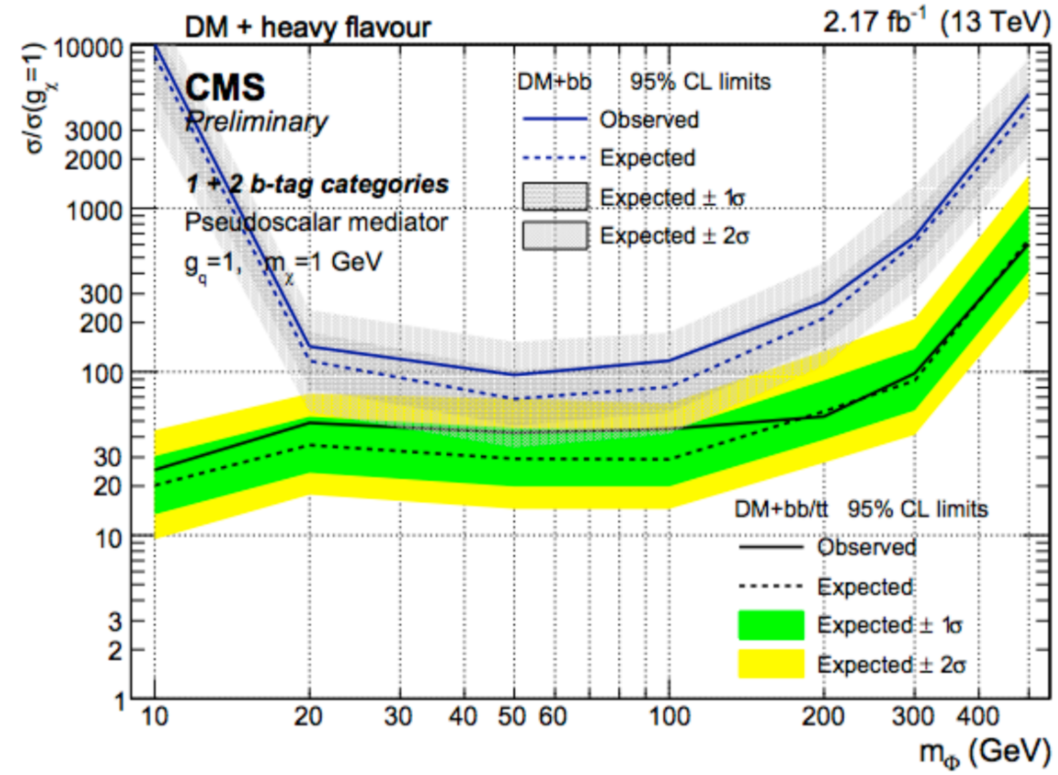
	process	2ℓ	1ℓ	$1\mu, 1e$	SR1	SR2
MET resolution	all	1%	1%	< 1%	1%	1%
MET scale	all	< 1%	< 1%	< 1%	< 1%	< 1%
JES	VV, ST, multijet	1%	1%	2%	< 1%	1%
b-tagging	all	7%	9%	7%	8%	11%
lepton trigger, id, iso	all	4%	3%	3%	3%	3%
trigger	all		< 1%		< 1%	
pile-up	all	2%	1%	1%	1%	< 1%
Fact. scale	all	4%	3%	4%	4%	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%		

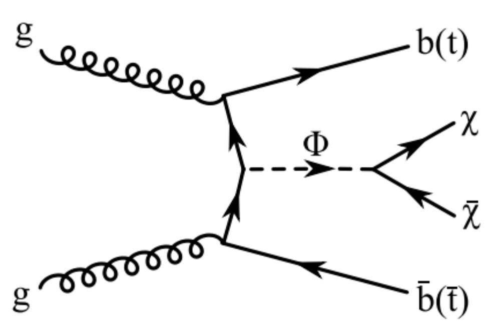


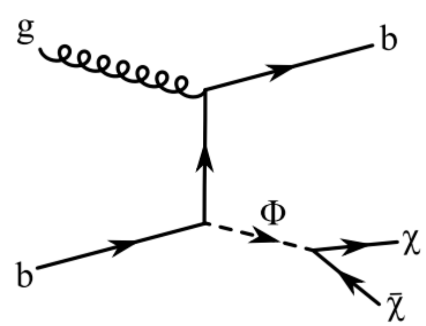
CMS Mono-b(b) @ 8 TeV

B2G-15-007

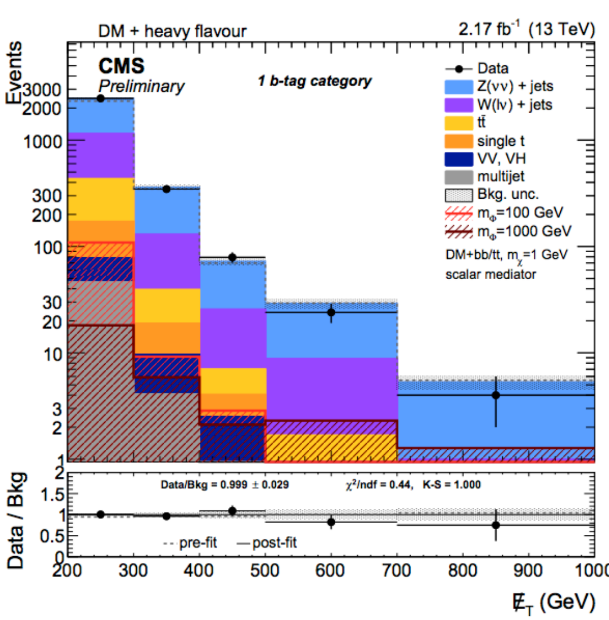


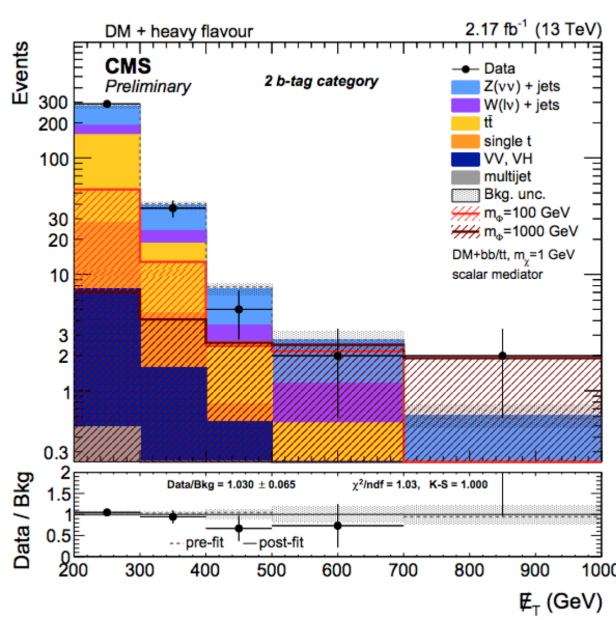




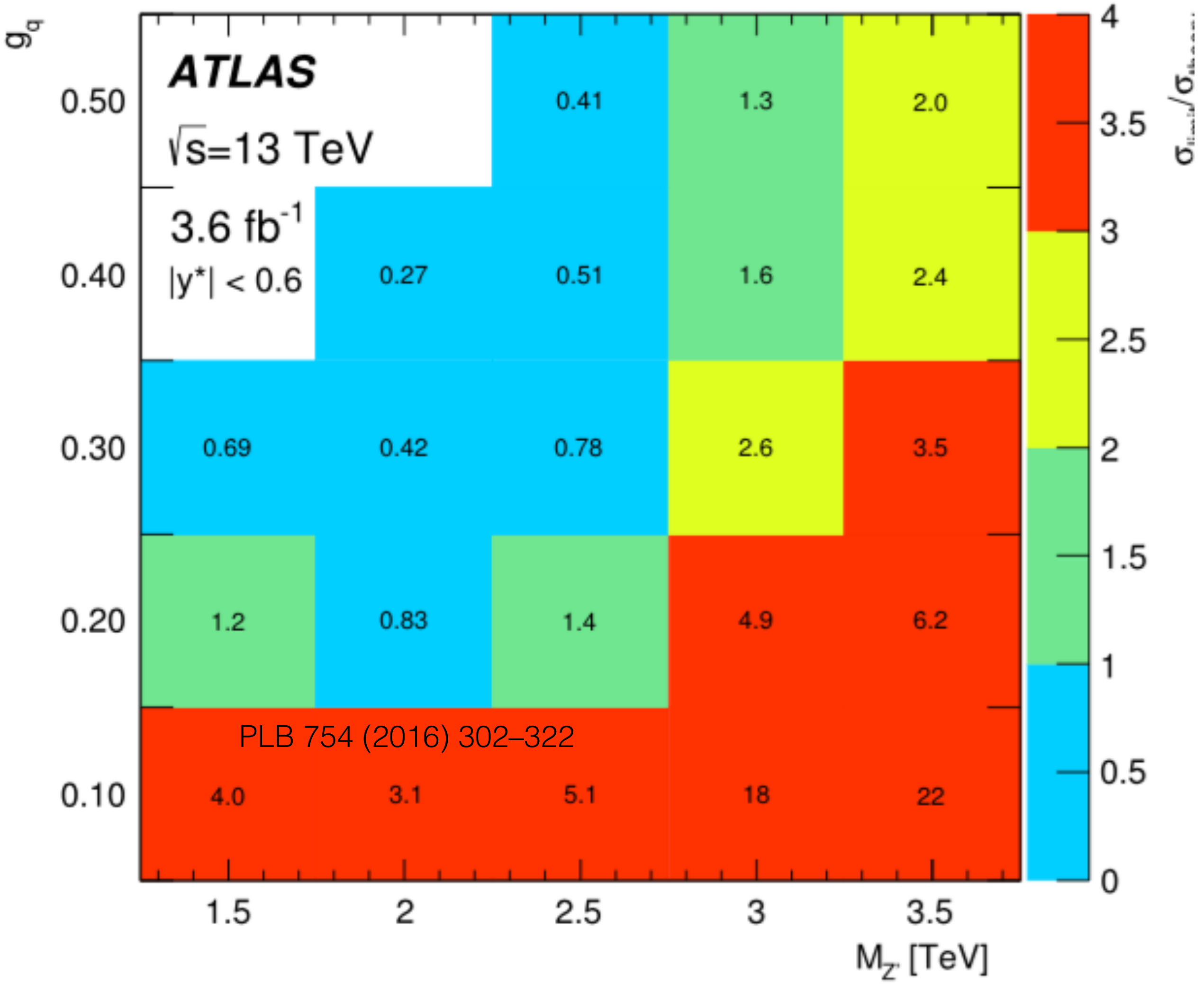


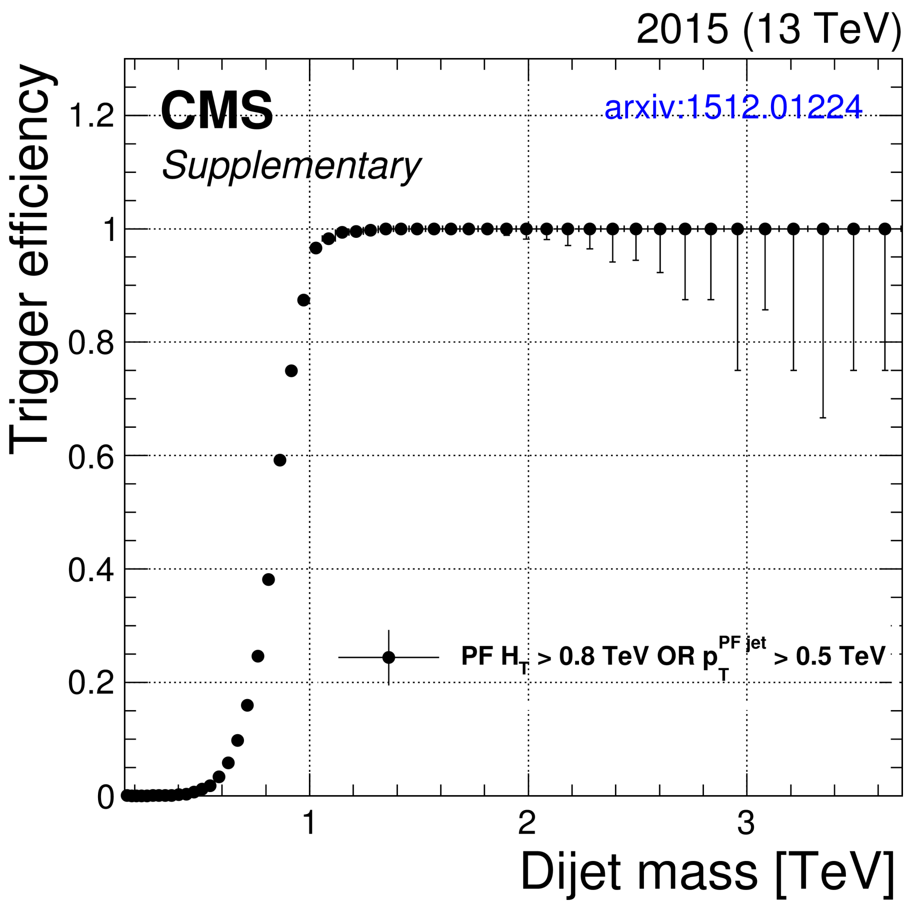
	process	2ℓ	1ℓ	$1\mu, 1e$	SR1	SR2
MET resolution	all	1%	1%	< 1%	1%	1%
MET scale	all	< 1%	< 1%	< 1%	< 1%	< 1%
JES	VV, ST, multijet	1%	1%	2%	< 1%	1%
b-tagging	all	7%	9%	7%	8%	11%
lepton trigger, id, iso	all	4%	3%	3%	3%	3%
trigger	all		< 1%		< 1%	
pile-up	all	2%	1%	1%	1%	< 1%
Fact. scale	all	4%	3%	4%	4%	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

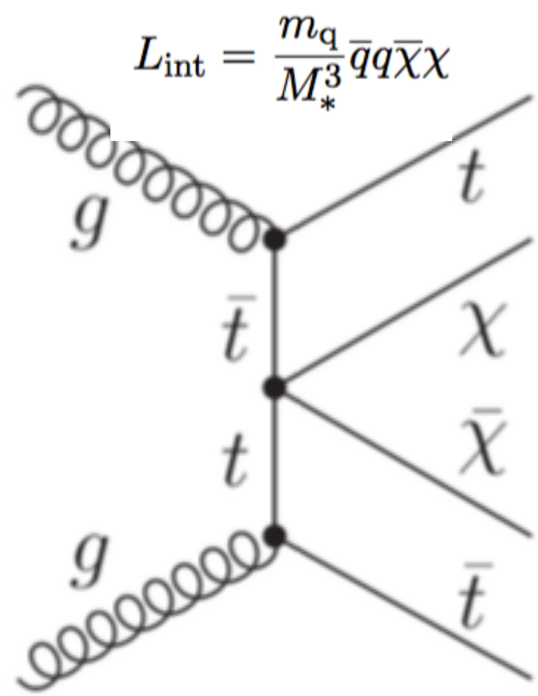


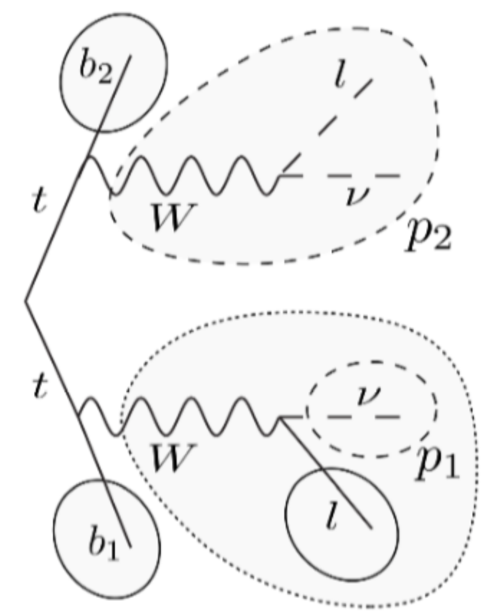


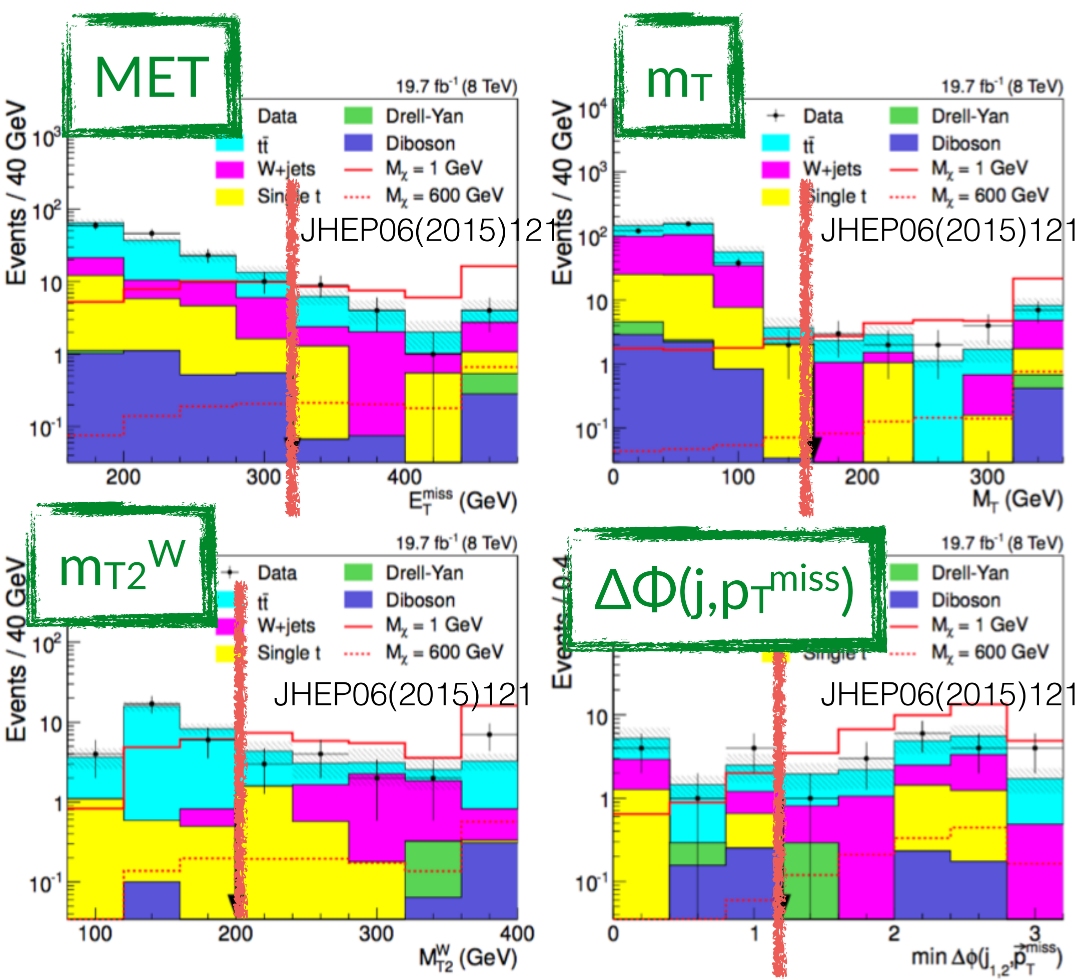
CMS: tt + MET @ 8 TeV

similar idea with tt final state

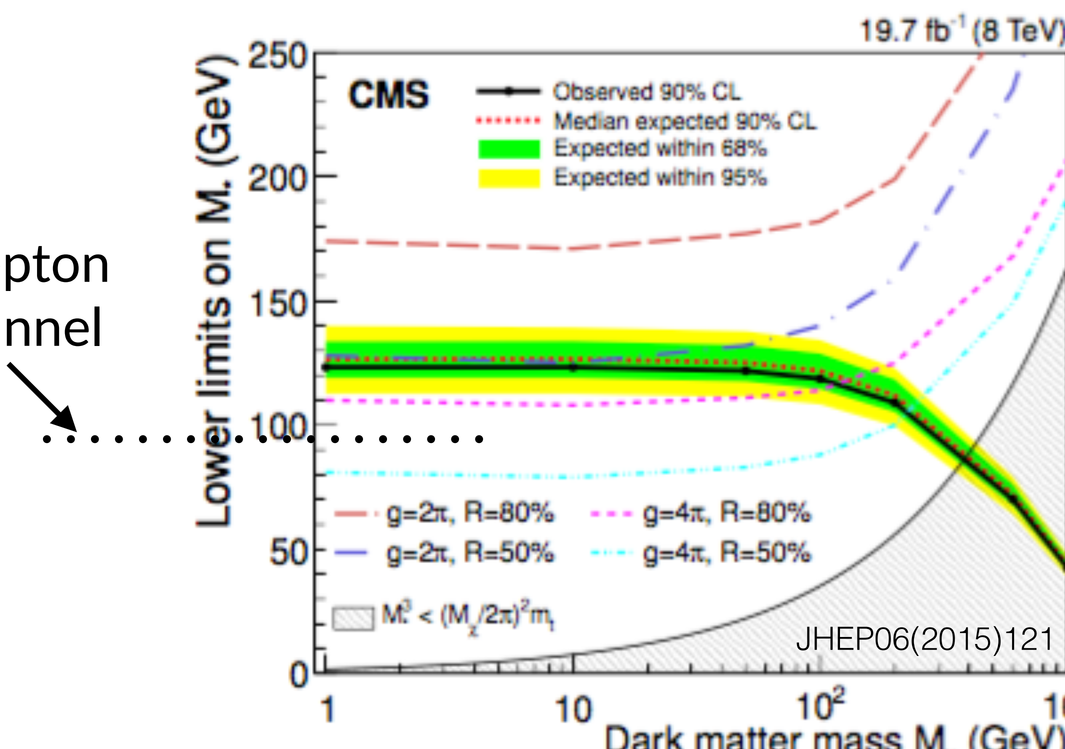
- searched in 1-lepton (better) and 2-lepton channel
- use MET as S/B discriminant
- 13 TeV work in progress!
  - increase in sensitivity from parton luminosity ratios
  - add fully hadronic channel -> significant improvement foreseen!







dilepton channel



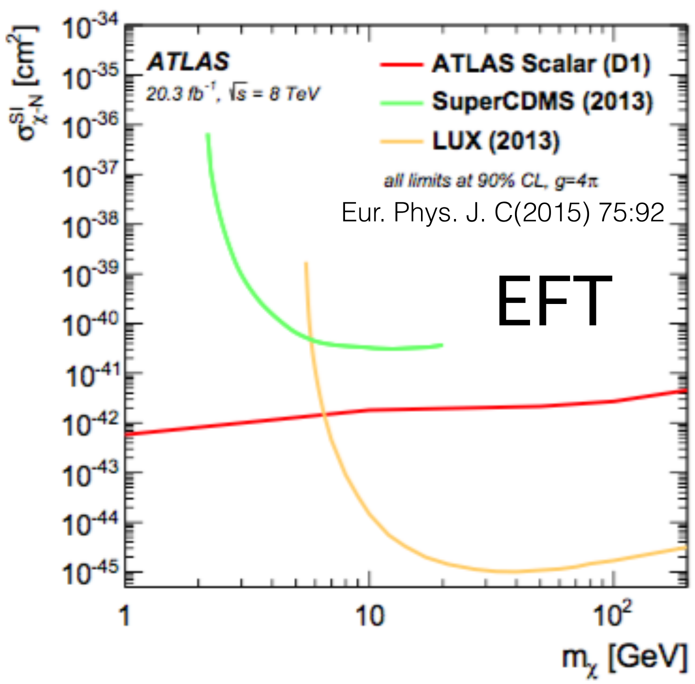
ATLAS: b/bb/tt(had,semi-lep) @ 8 TeV

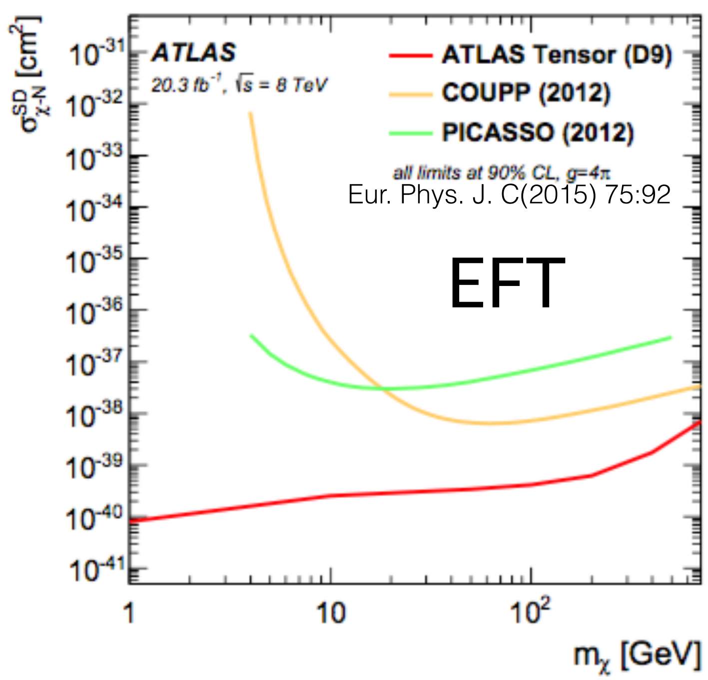
4 SRs: **b+DM**, **bb+DM**, **tt(had)**+DM, **tt(semi-lep)**+DM [~stop]

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

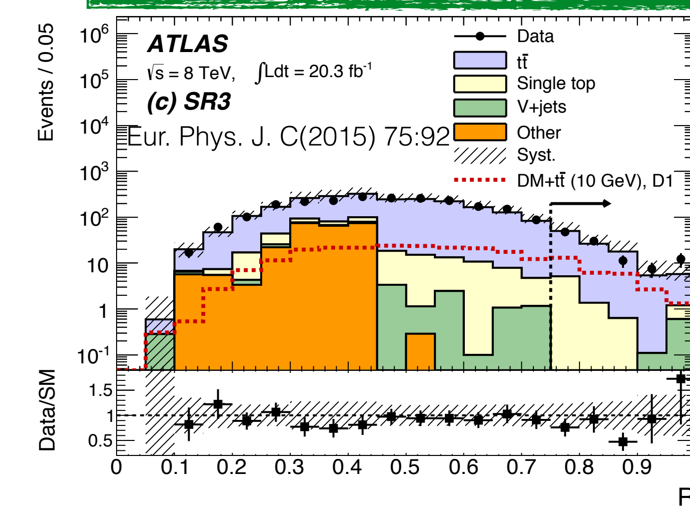
dominant **Z(vv)+jets** (SR1,2, from Z/γ+jets), **ttbar** (SR3,4, from orthogonal semi-lep CRs)

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

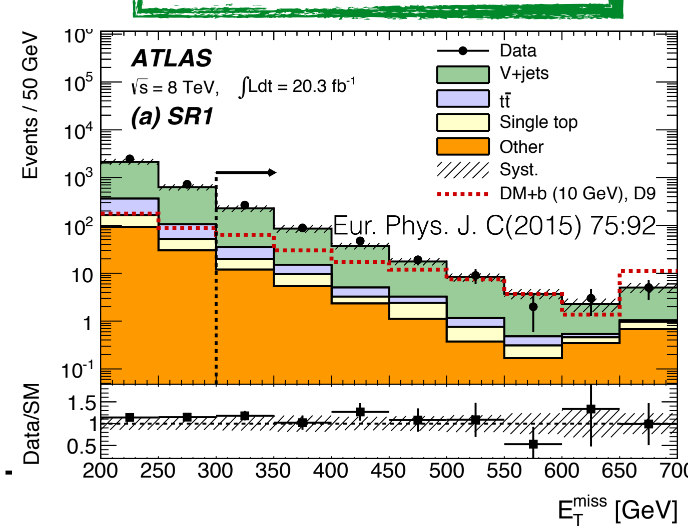




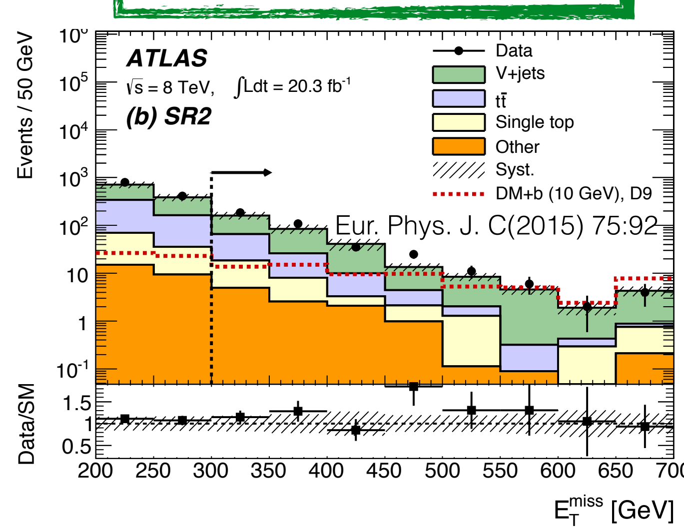
razor in tt(had)+DM SR



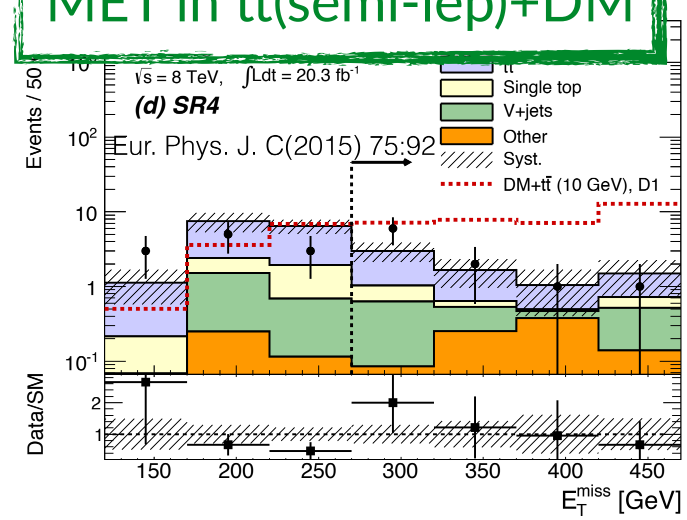
MET in b+DM SR



MET in bb+DM SR



MET in tt(semi-lep)+DM

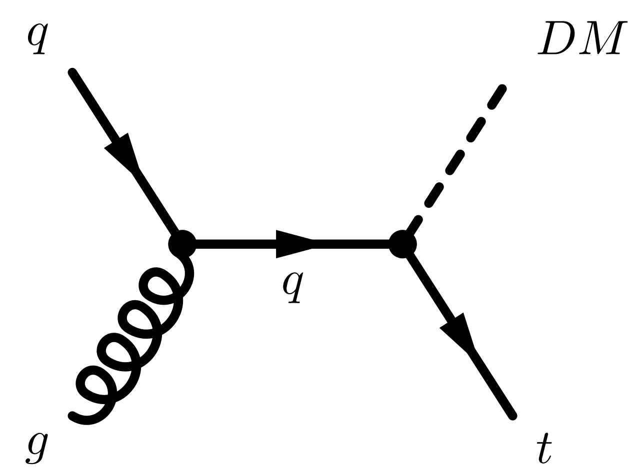


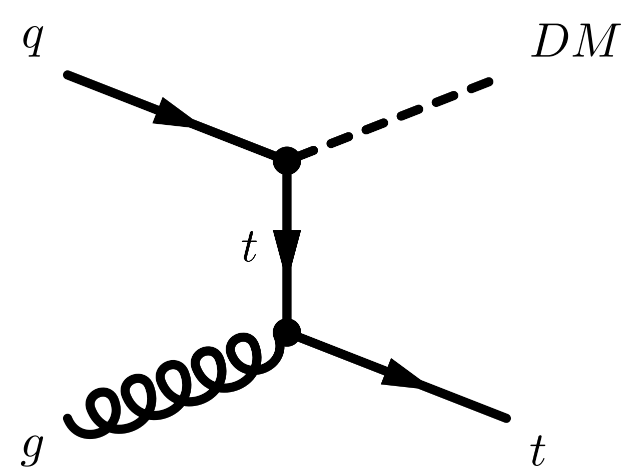
CMS MONO-TOP (HAD) @ 8 TEV

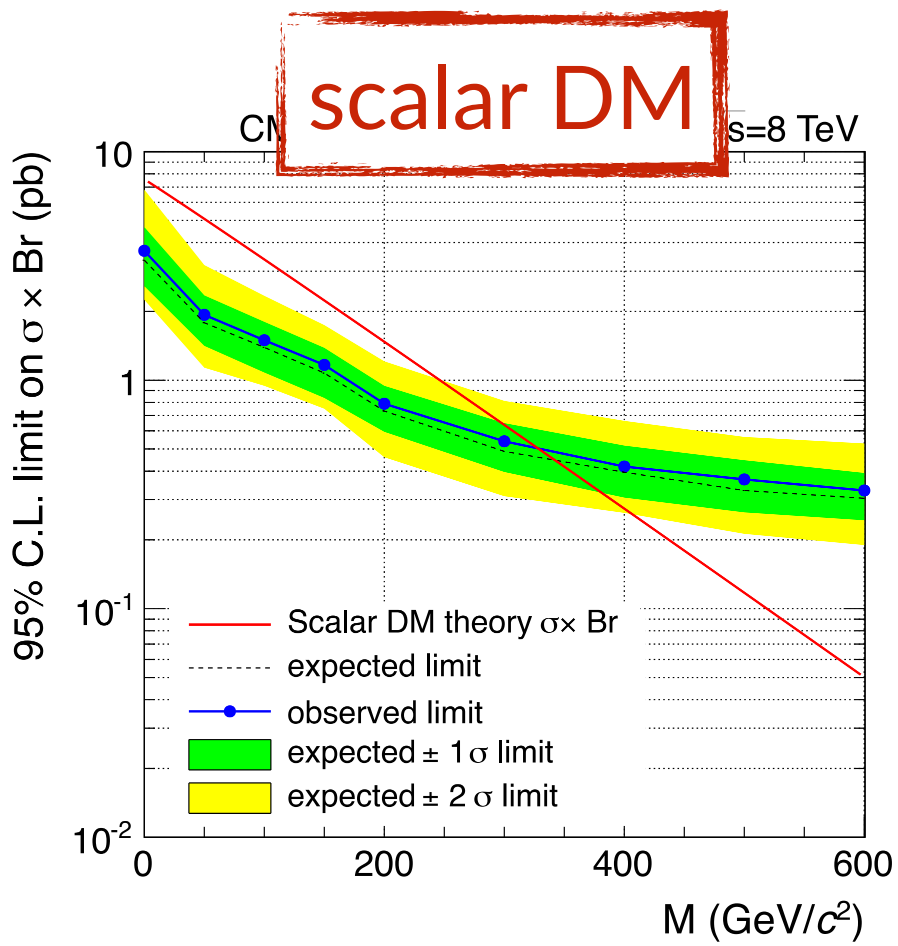
PRL114.101801

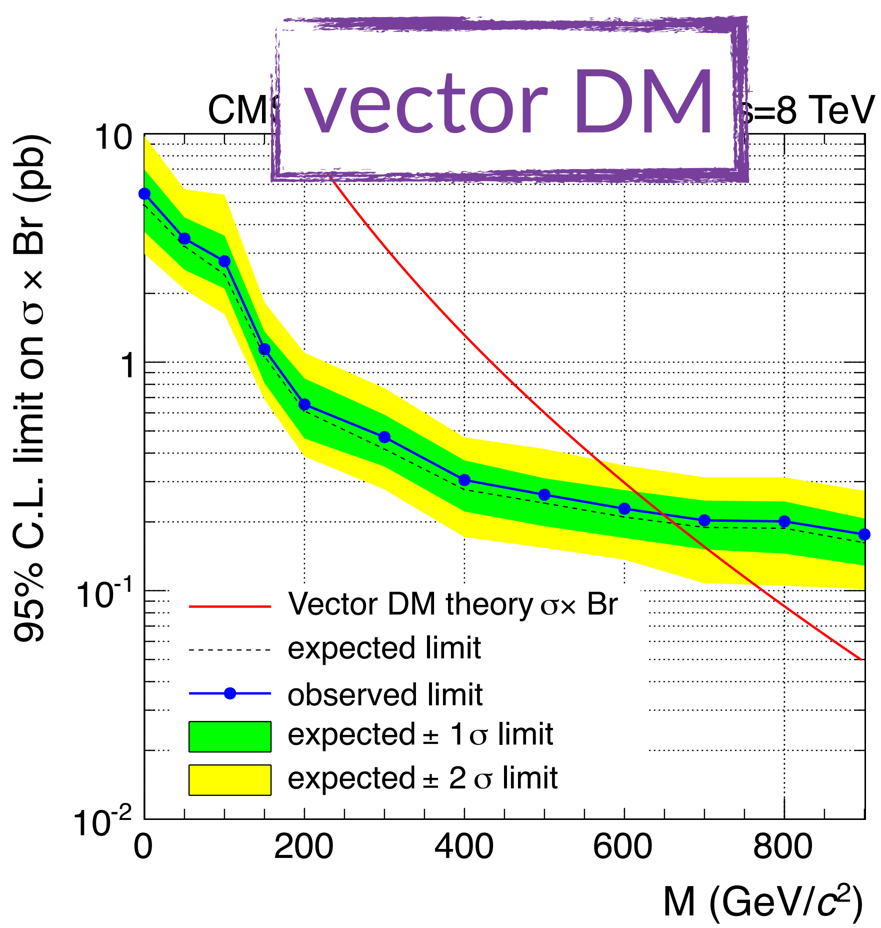
resolved monojet-like selection criteria

- 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







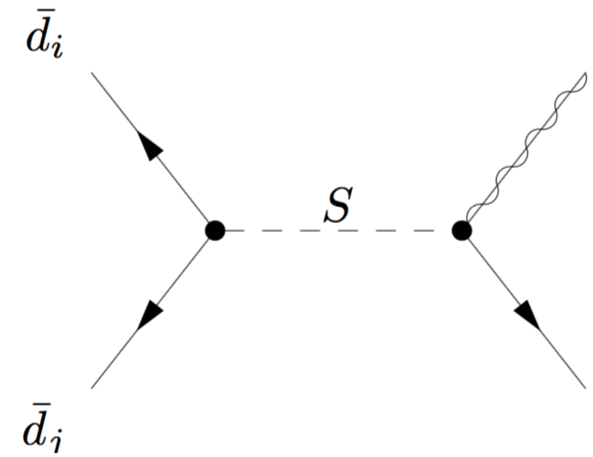


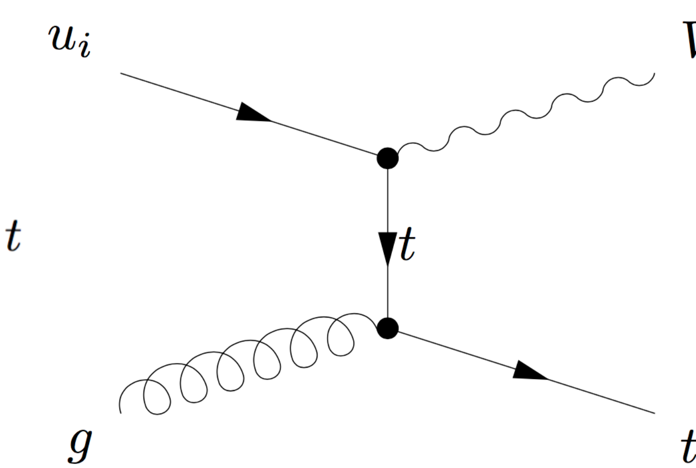
CMS mono-top (lep) @ 8 TeV

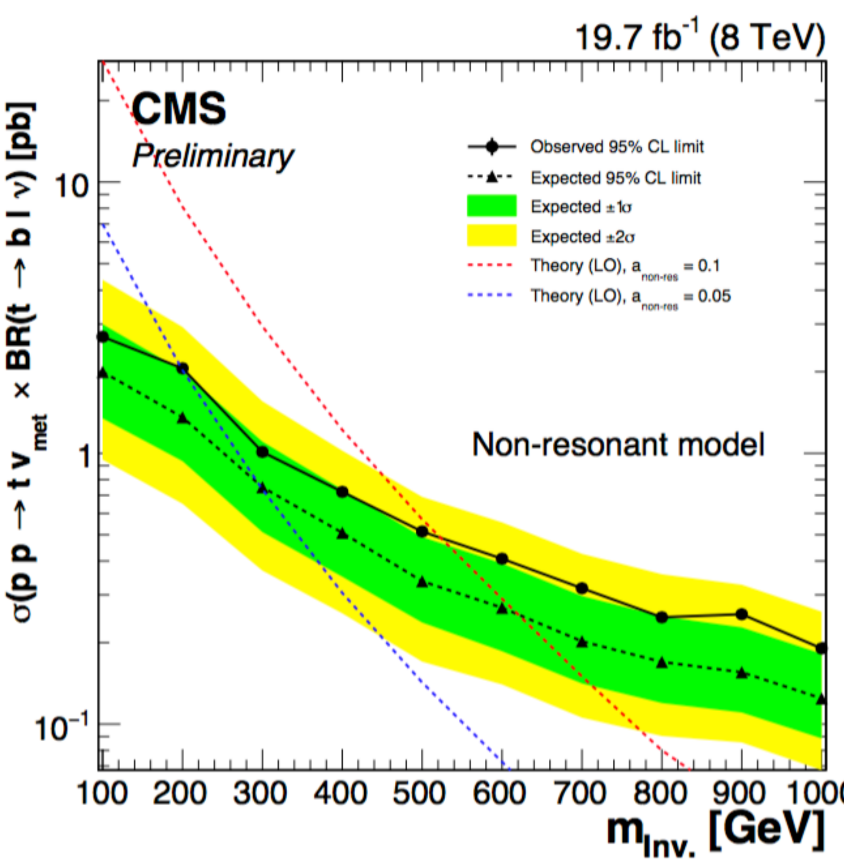
B2G-15-001

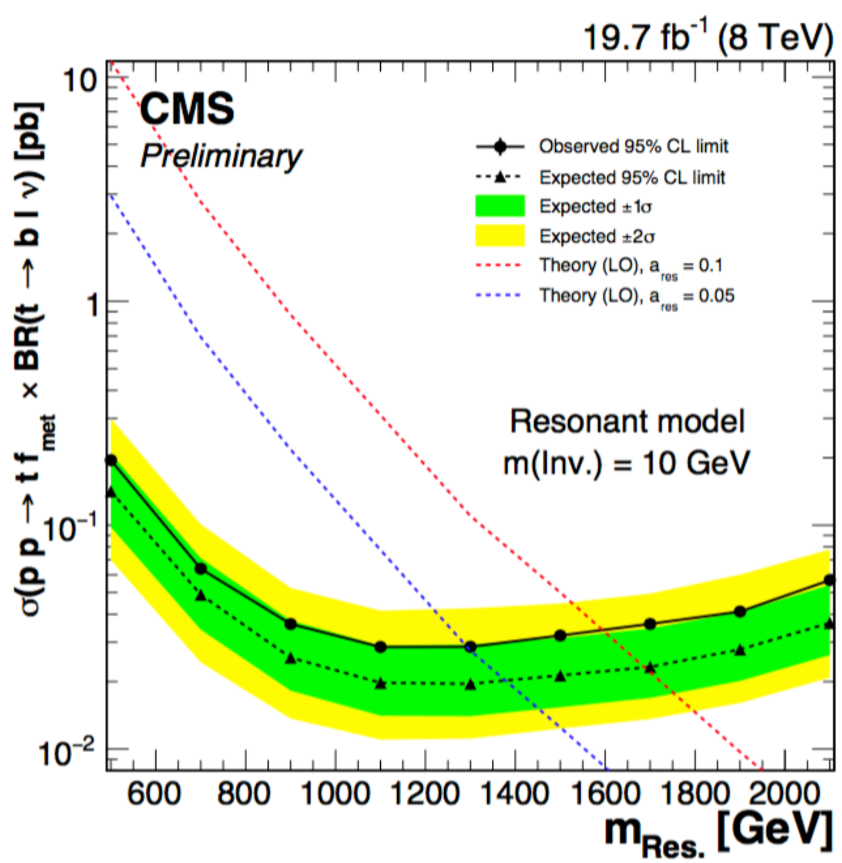
muon+b-jet+MET

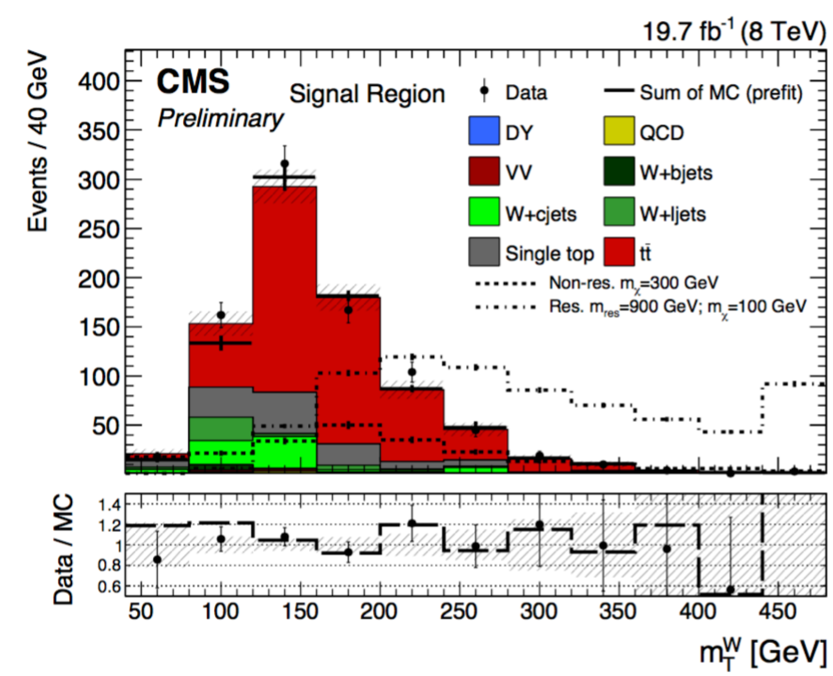
- MET > 100 GeV, pT(j) > 70 GeV, pT(μ) > 33 GeV (ΔΦ(jet,μ) < 1.7), pT(W) > 70 GeV, μ trigger
  - 60% efficiency b-tagging (reject W+jets)
  - no additional jet with pT > 30 GeV, |η| < 2.5 (reduce ttbar)
- use $m_T(W)$ as discriminant
- CRs from 0 (W+jets) or 2 b-tag (ttbar)





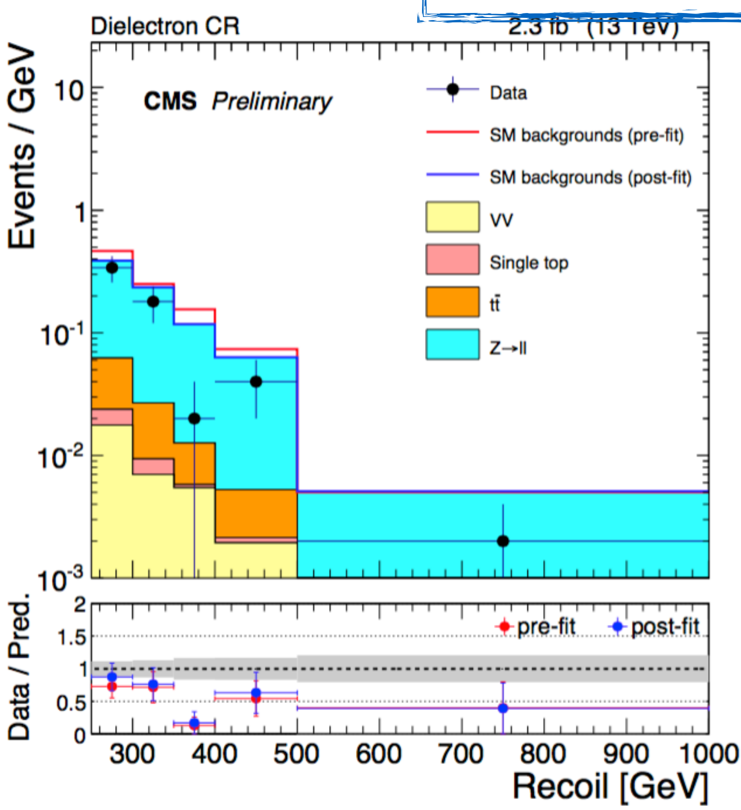


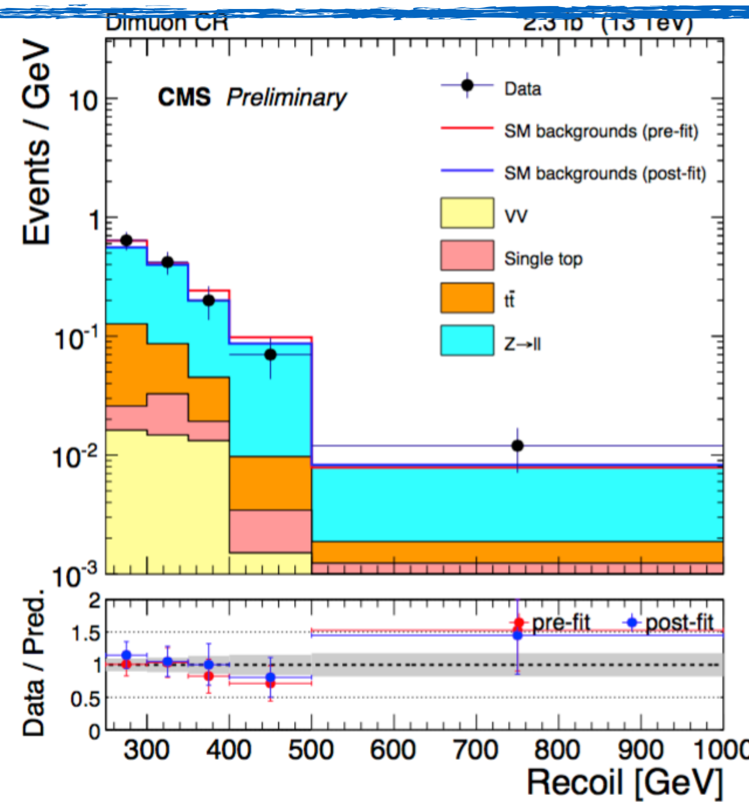


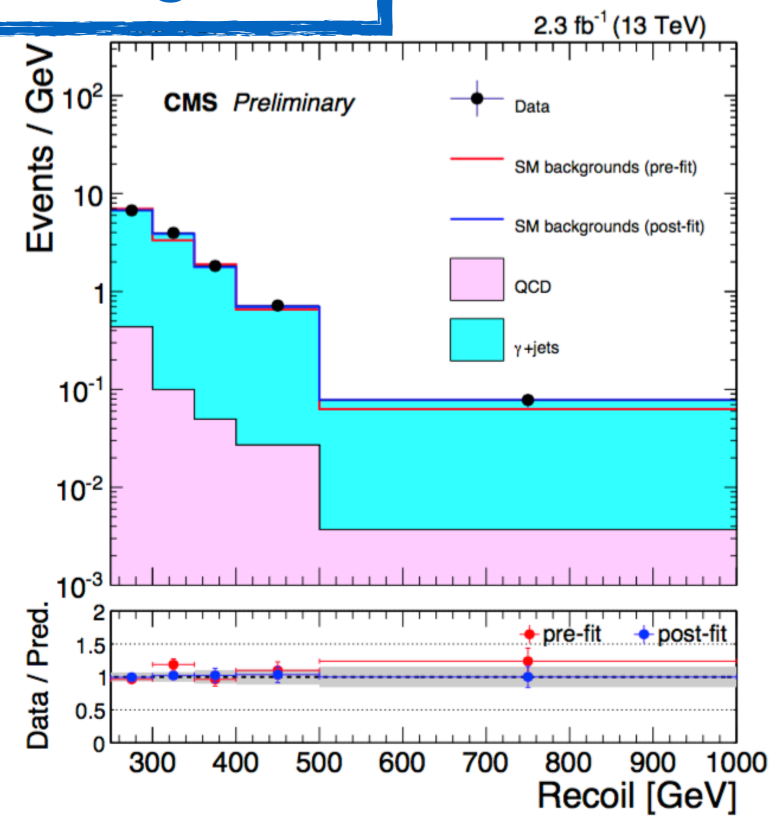


CMS: Mono-top @ 13 TeV CRs

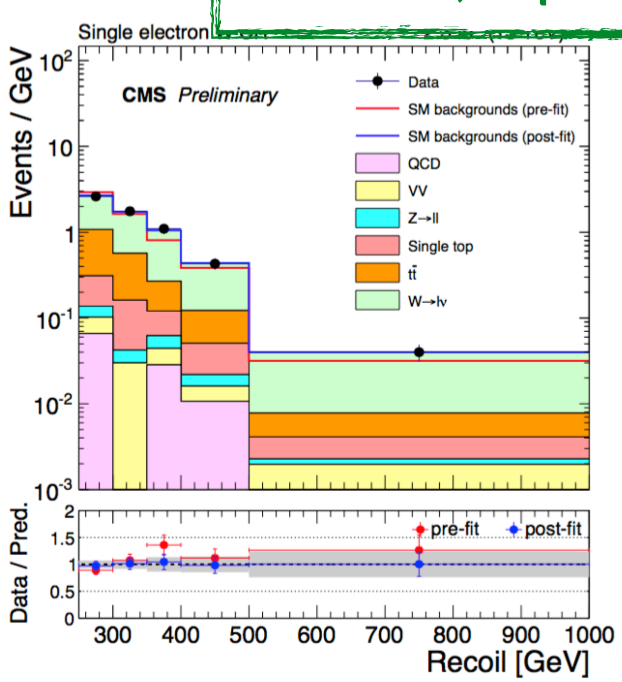
2e, 2μ, gamma+jet used for constraining Z(νν)

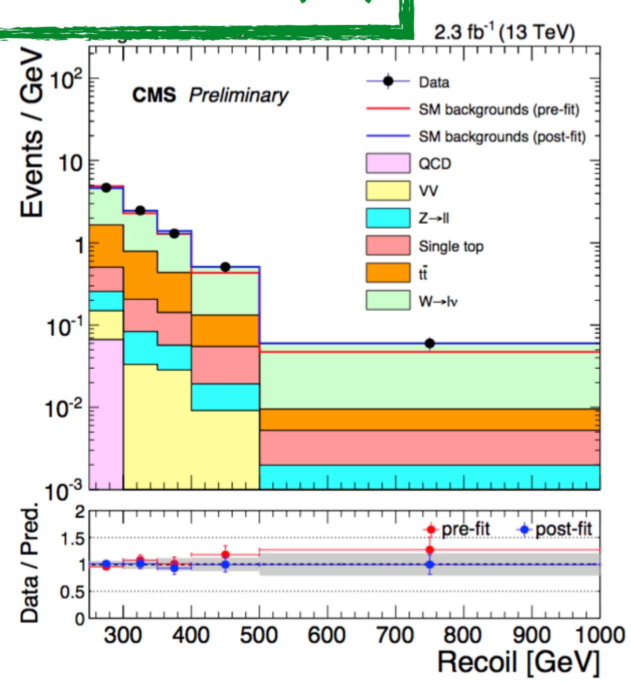




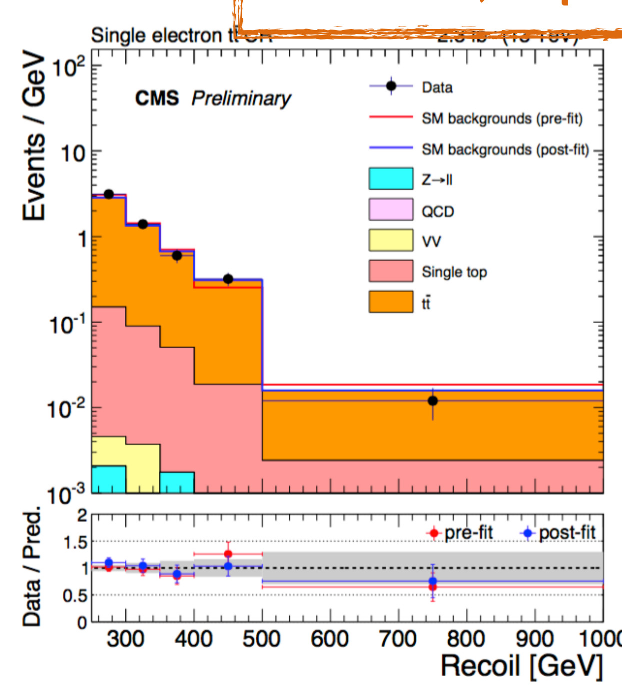


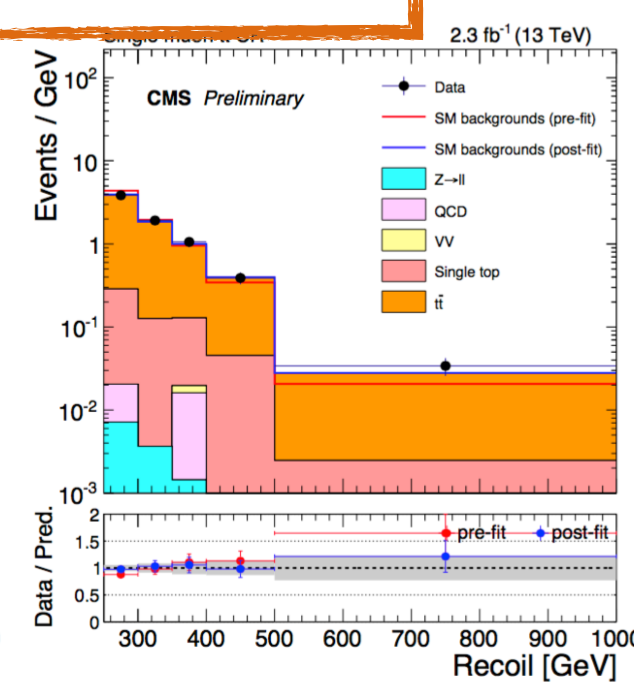
1e+0b, 1μ+0b for W(lν)





1e+1b, 1μ+1b for ttbar

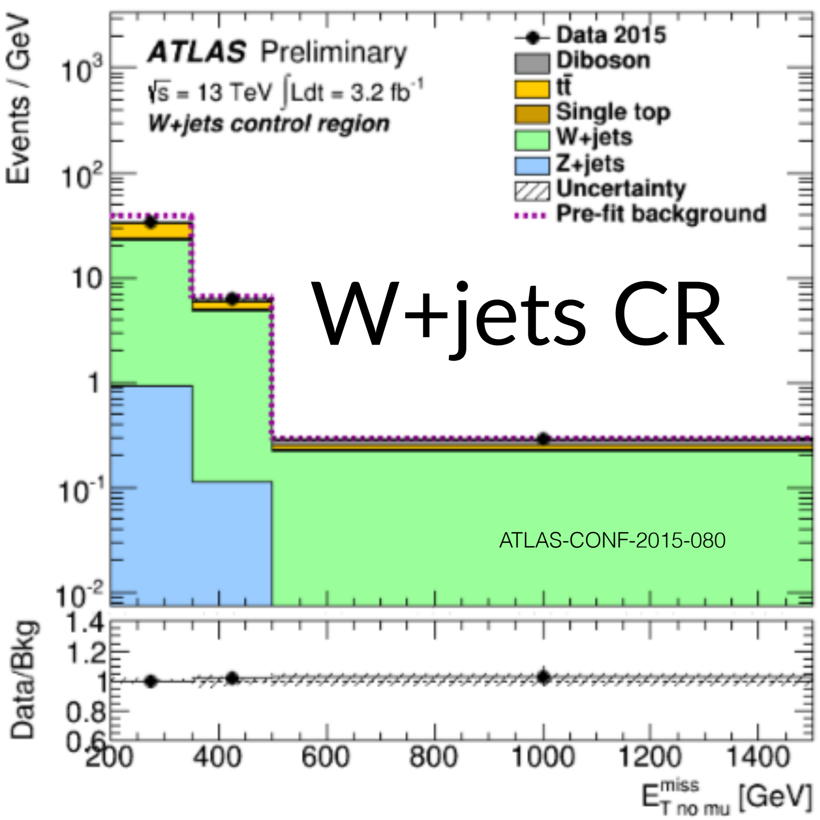


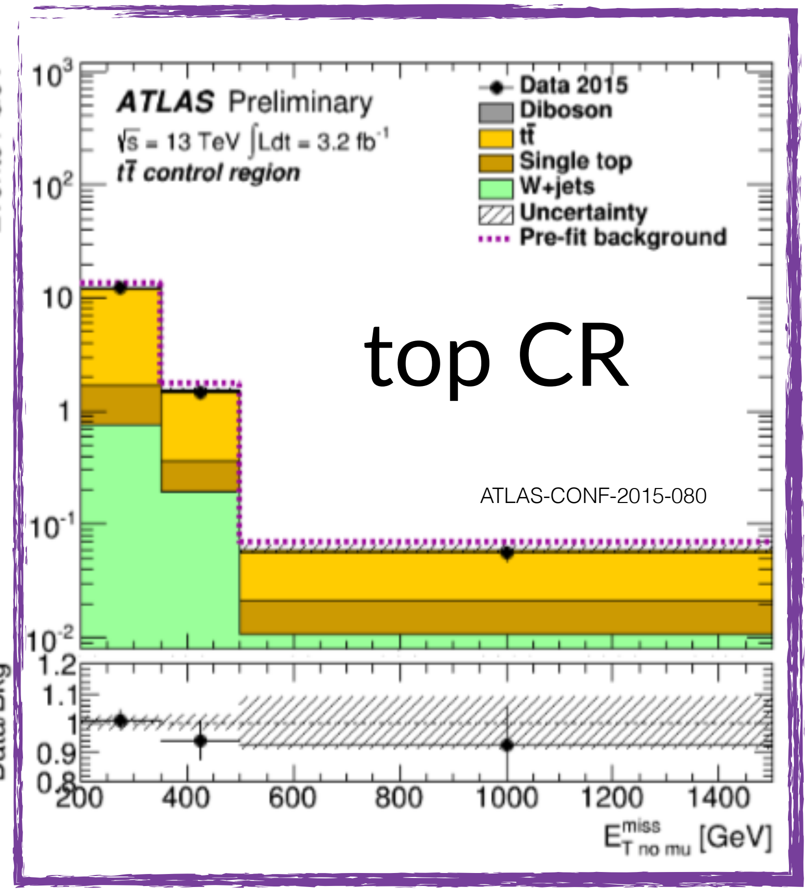


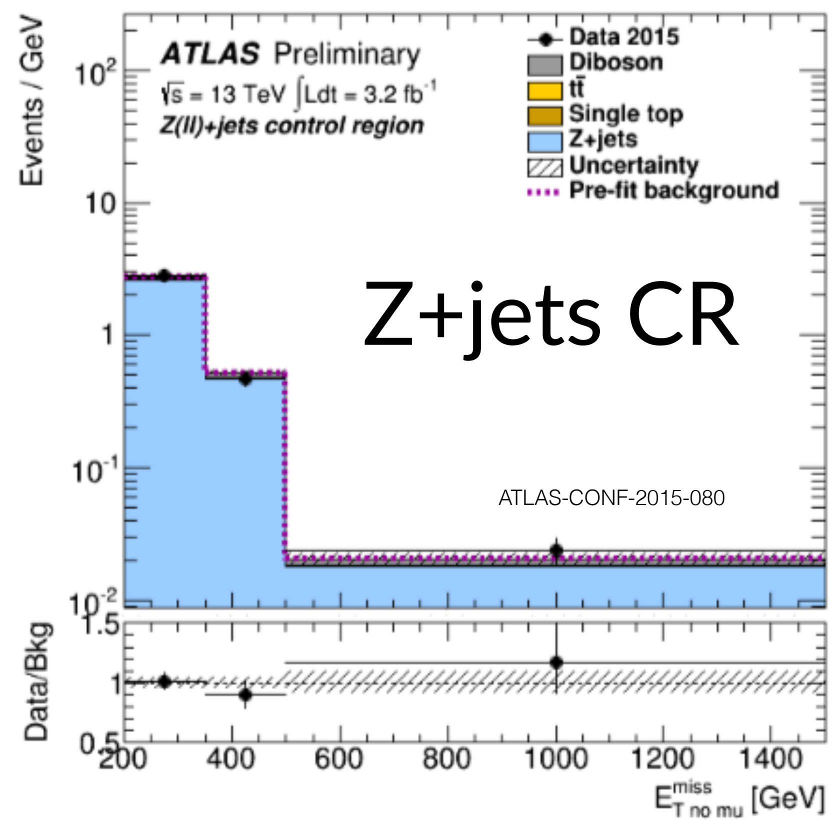
Fat Jet Tagging Techniques

- grooming: remove ISR, UE, pile-up
  - filtering
    - re-cluster constituents with smaller R algorithm
    - consider only the hardest *n* sub-jets
  - trimming
    - re-cluster constituents with smaller R algorithm
    - consider only the sub-jets carrying at least X% of the pT
  - pruning
    - re-cluster i,j constituents into p only if
      - min(pTi, pTj)/pTp < zcut [remove soft radiation]
      - DeltaRij> rcut
    - discard the lower pT consistuent otherwise
  - soft-drop
    - undo clustering step-by-step
    - keep jet if
      - min(pT1+pT2)/sum > zcut * (DeltaR/R)^beta
    - otherwise, keep only sub-jet #1

Mono-W/Z at ATLAS



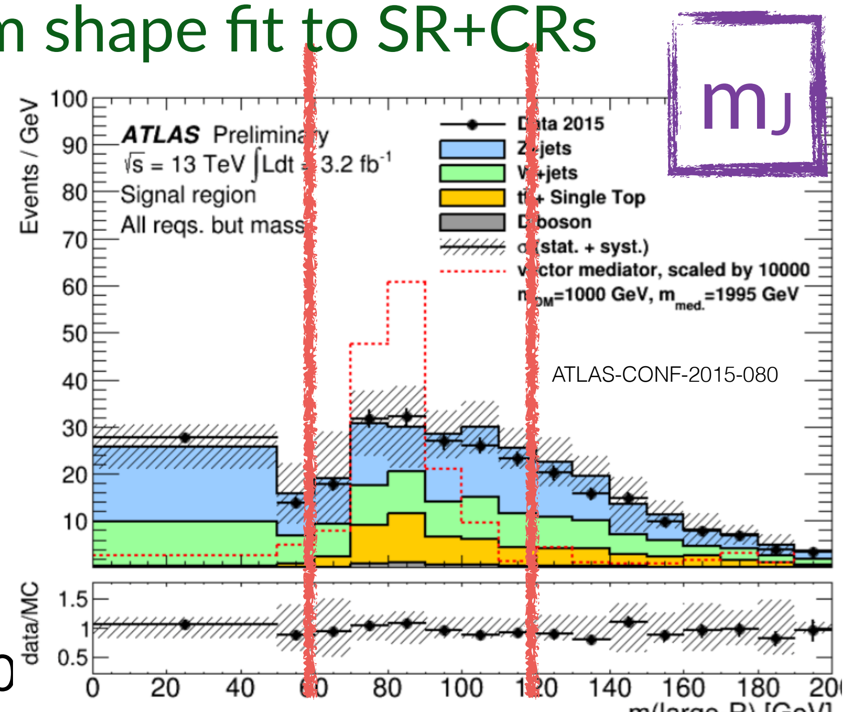


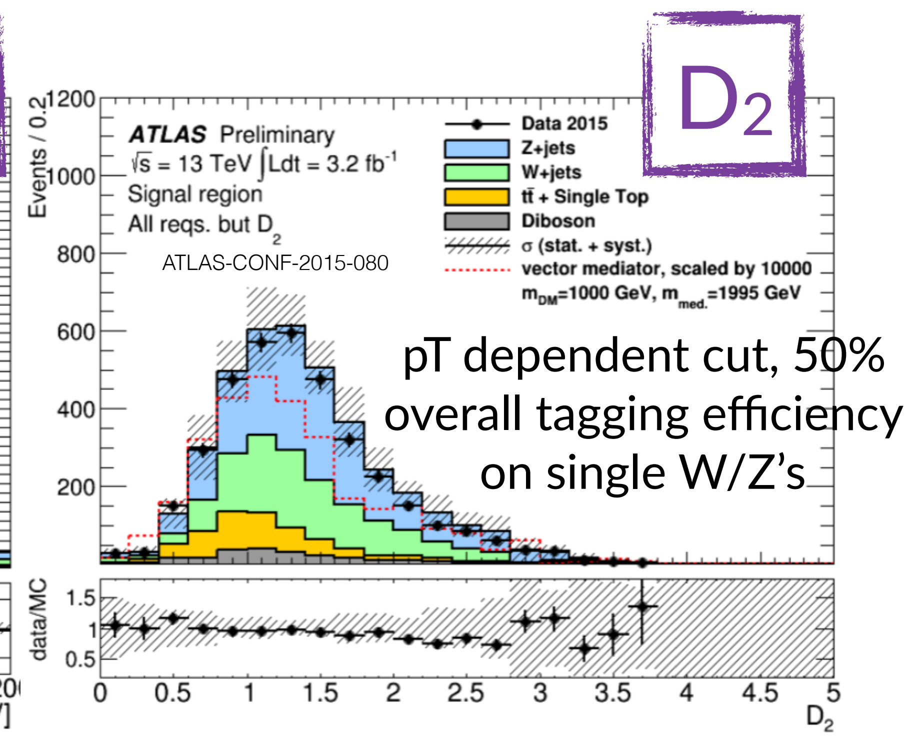


trimmed large-R jet (anti-kT R=1.0), MET > 250 GeV

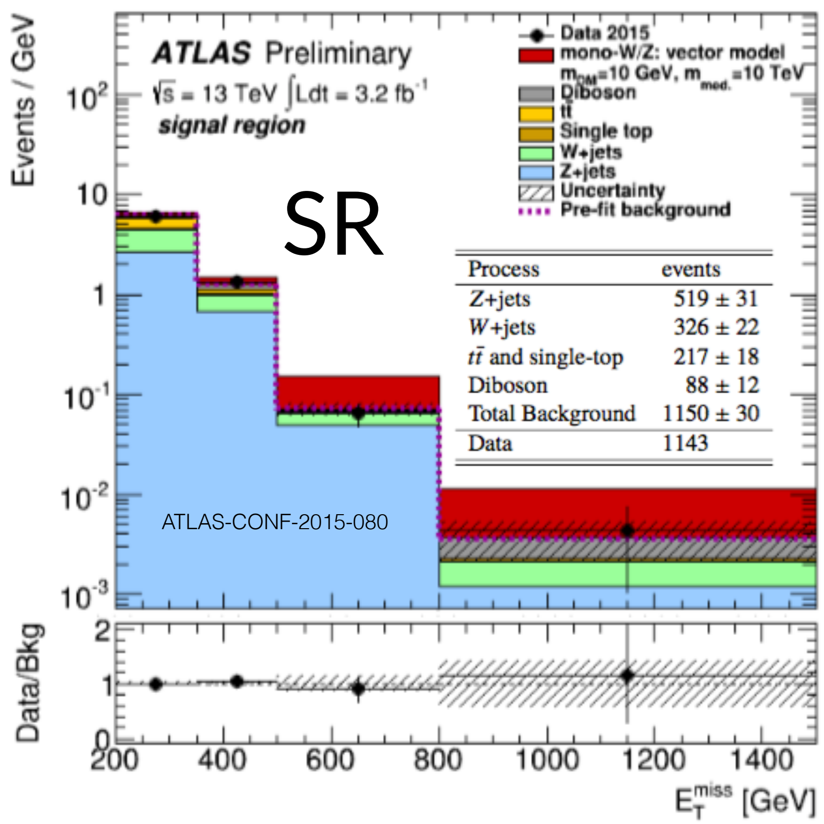
- CRs: 1μ+0 b-jet (Wμν), 2μ (Zμμ), 1μ+>=1b-jet (ttbar)
  - W, Z, ttbar normalisation from shape fit to SR+CRs

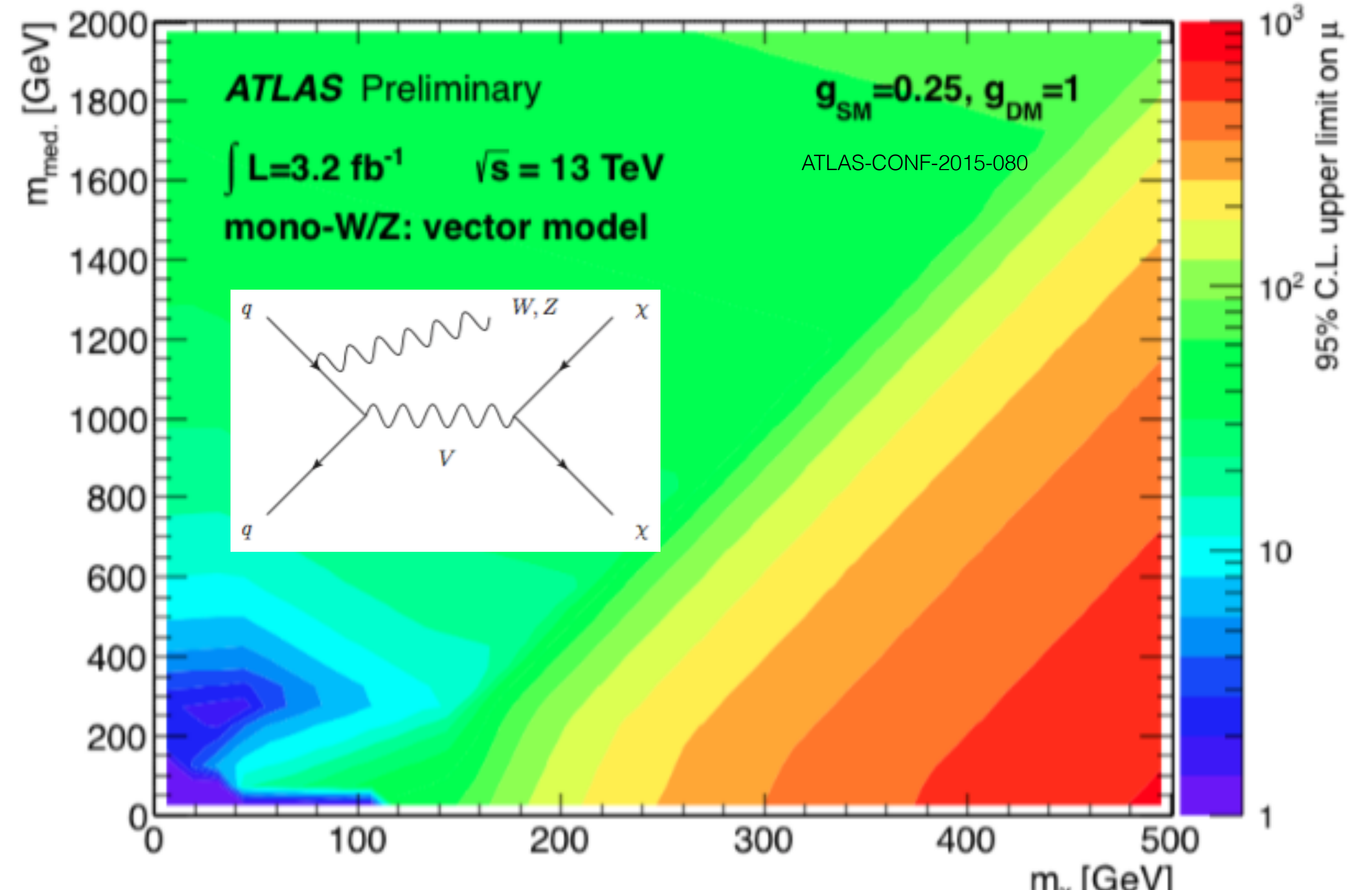
boson tagging based on jet mass and 2-prongness (“D_2”), main uncertainty on total bkg (5-10%)





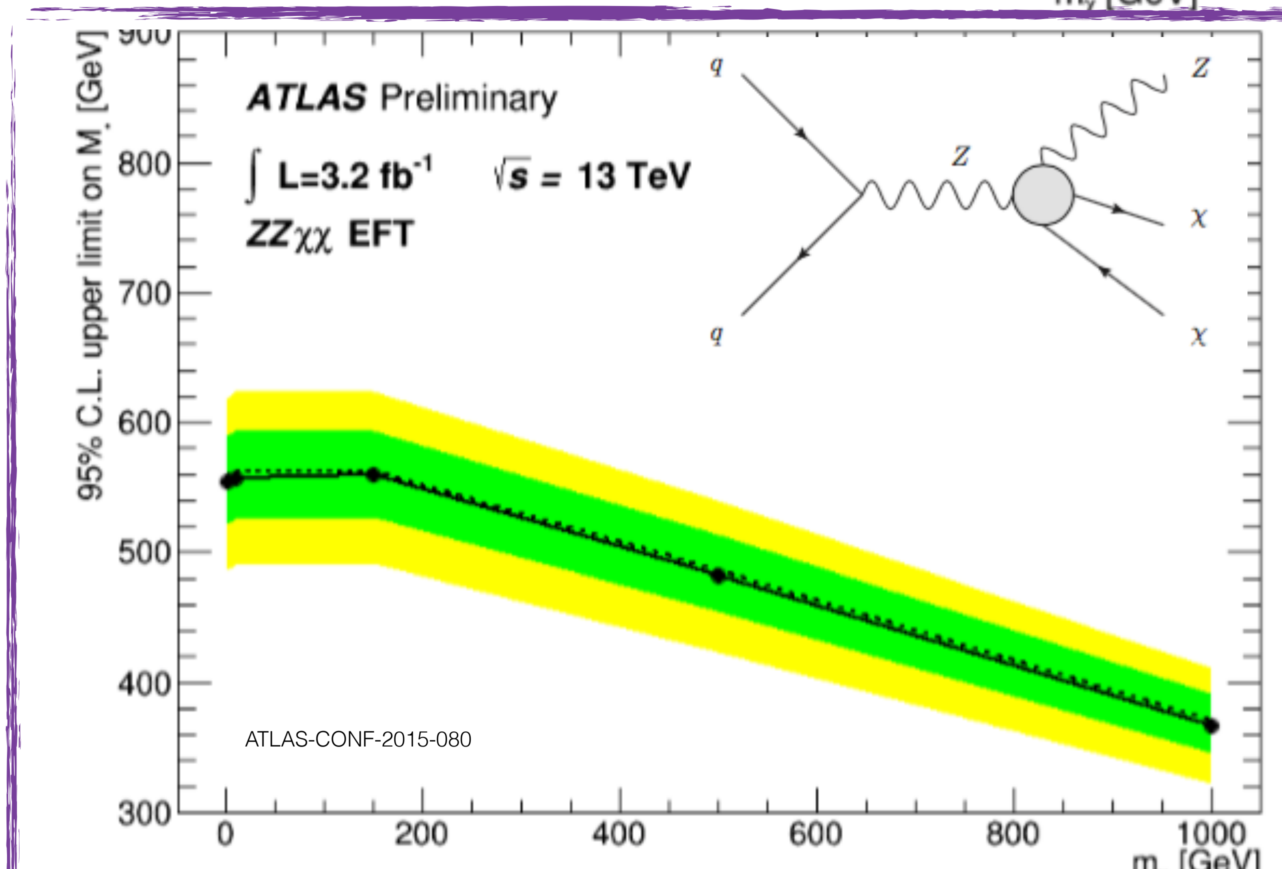
Mono-W/Z at ATLAS – Results





unique sensitivity to ZZ$\chi\chi$ EFT

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



Mono-tt (L)

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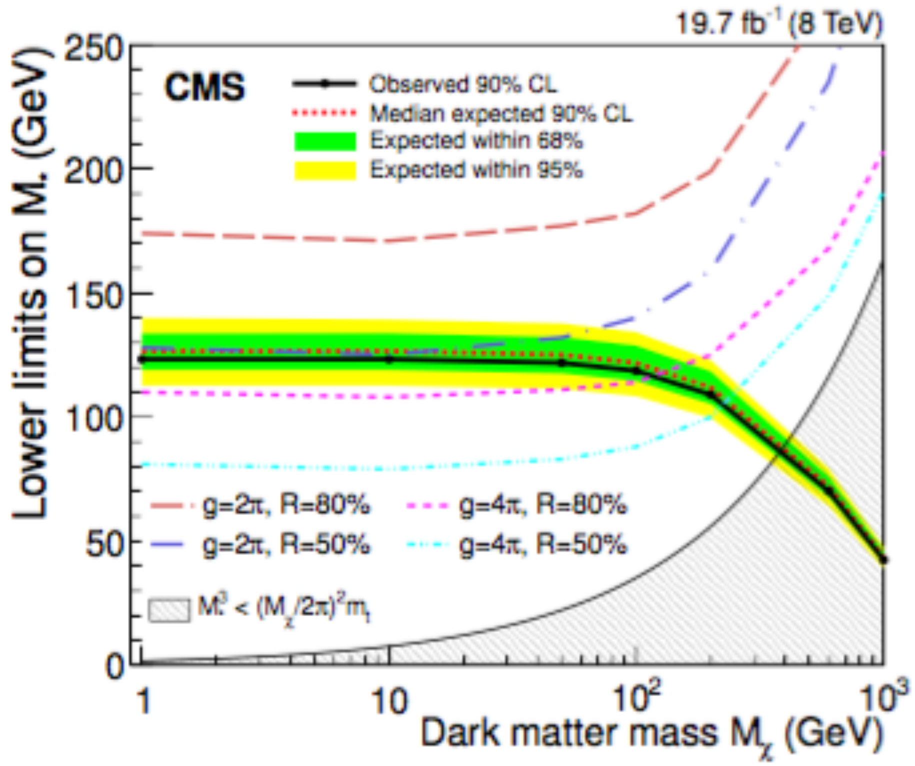
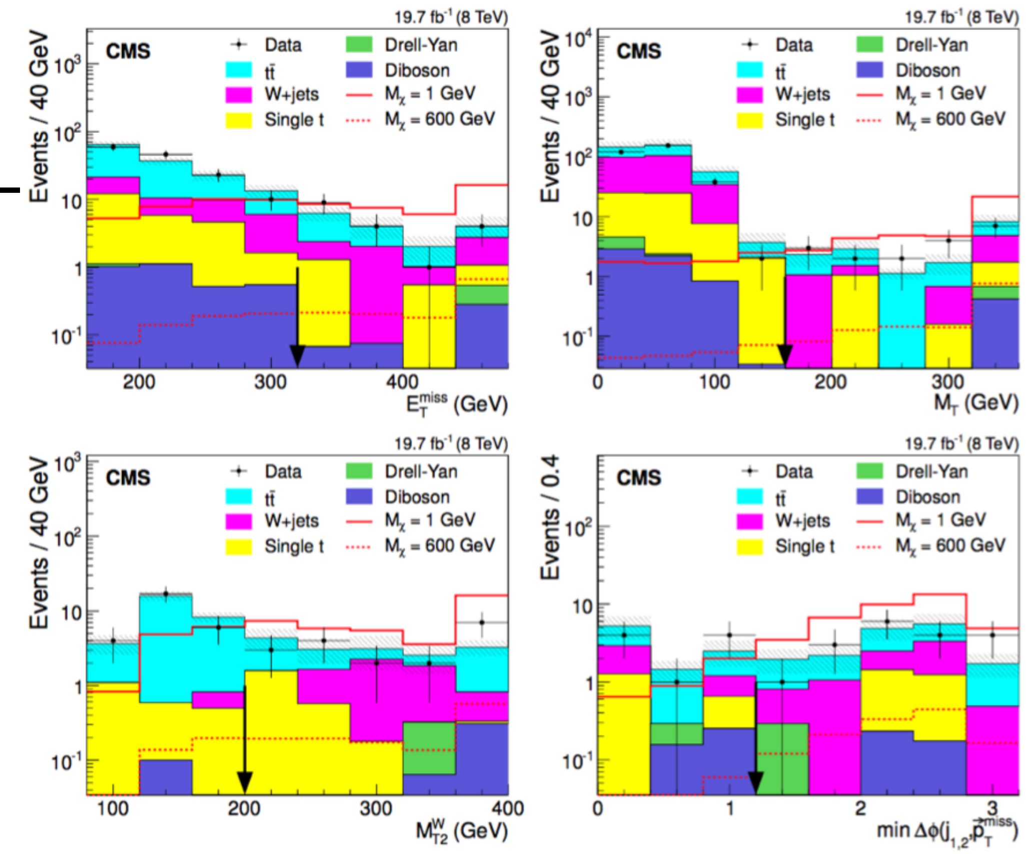
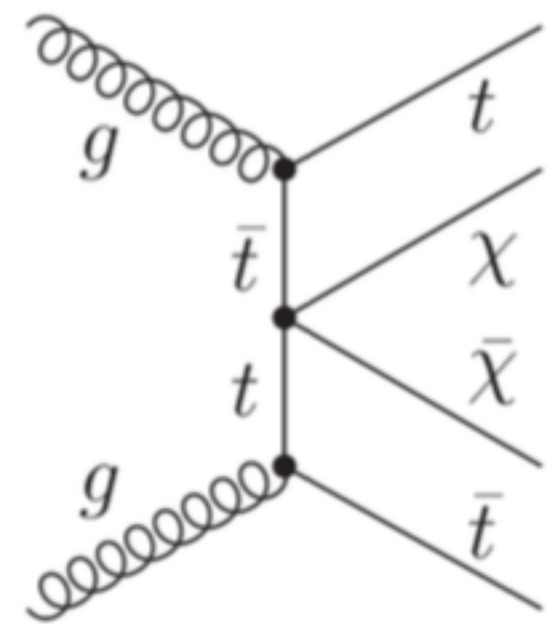
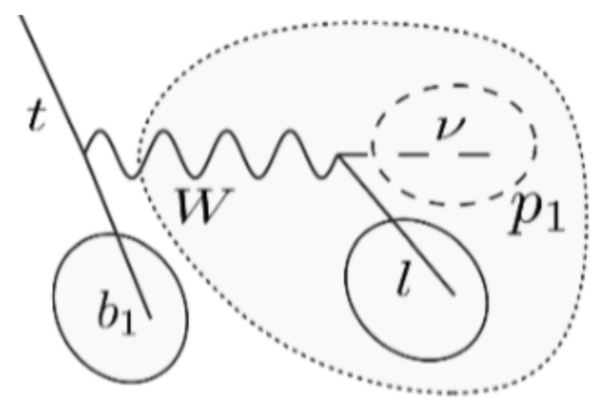




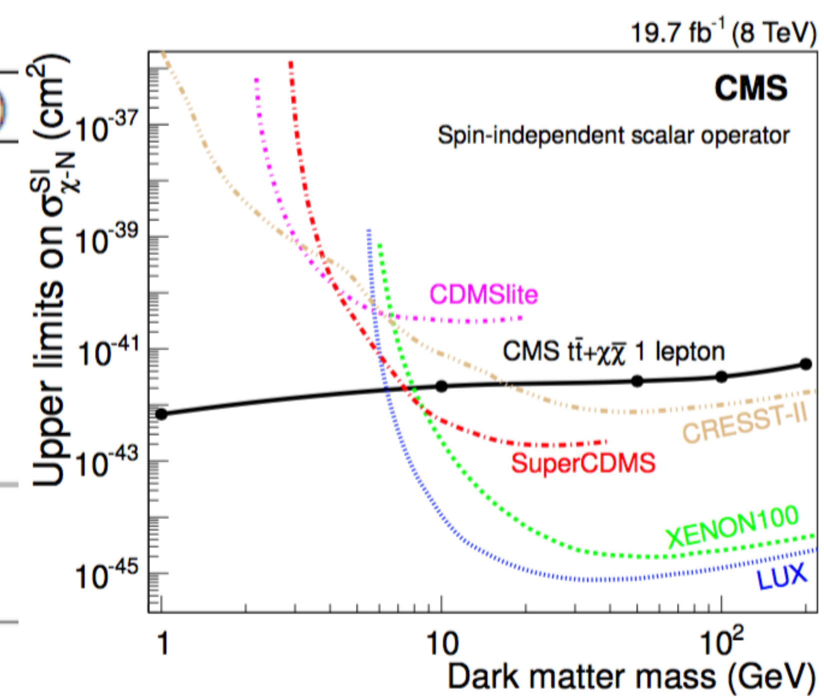




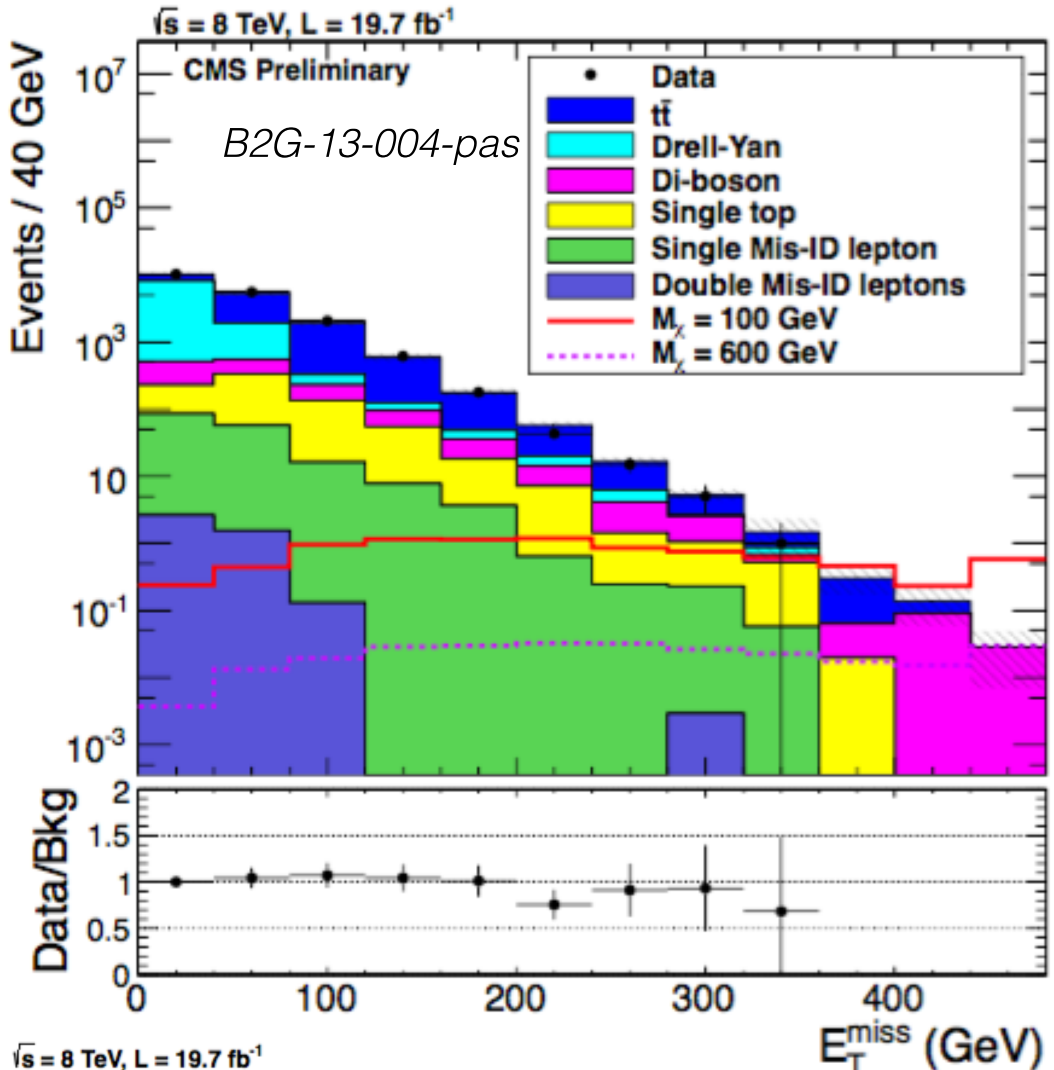
$$L_{\text{int}} = \frac{m_q}{M_*^3}\bar{q}q\bar{\chi}\chi$$

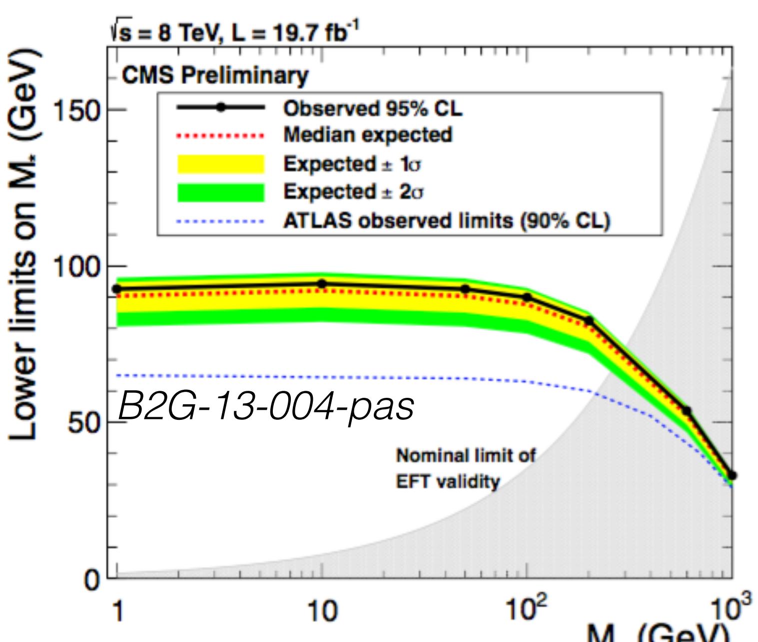
Source of systematic uncertainties	Relative uncertainty on total background (%)
50% normalization uncert. of other bkg in deriving SFs	10
SF_{W+jets} (CR tests)	13
$t\bar{t}$+jets top-quark p_T reweighting	3.9
Jet energy scale	4.0
Jet energy resolution	3.0
b-tagging correction factor (heavy flavour)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

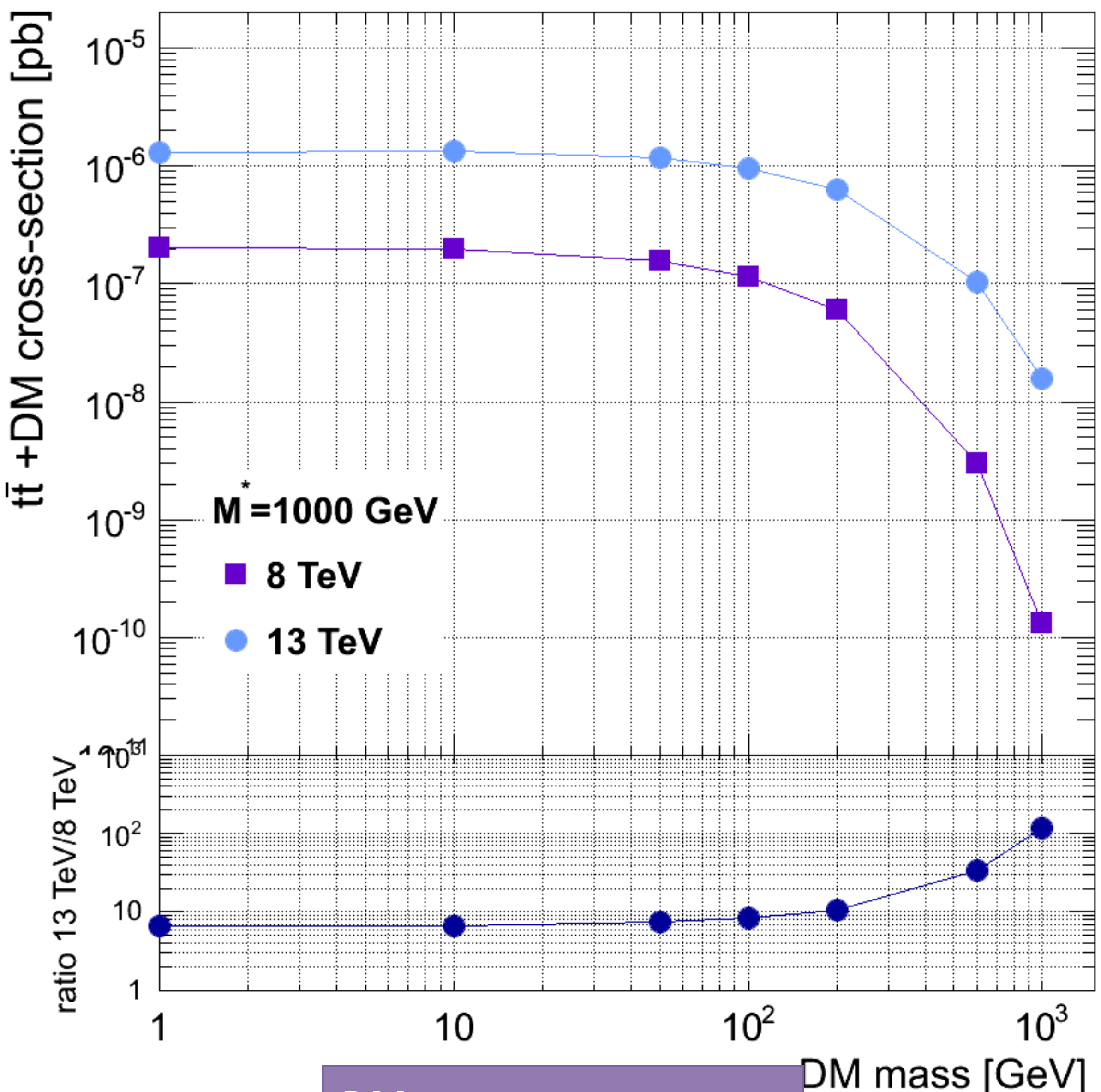




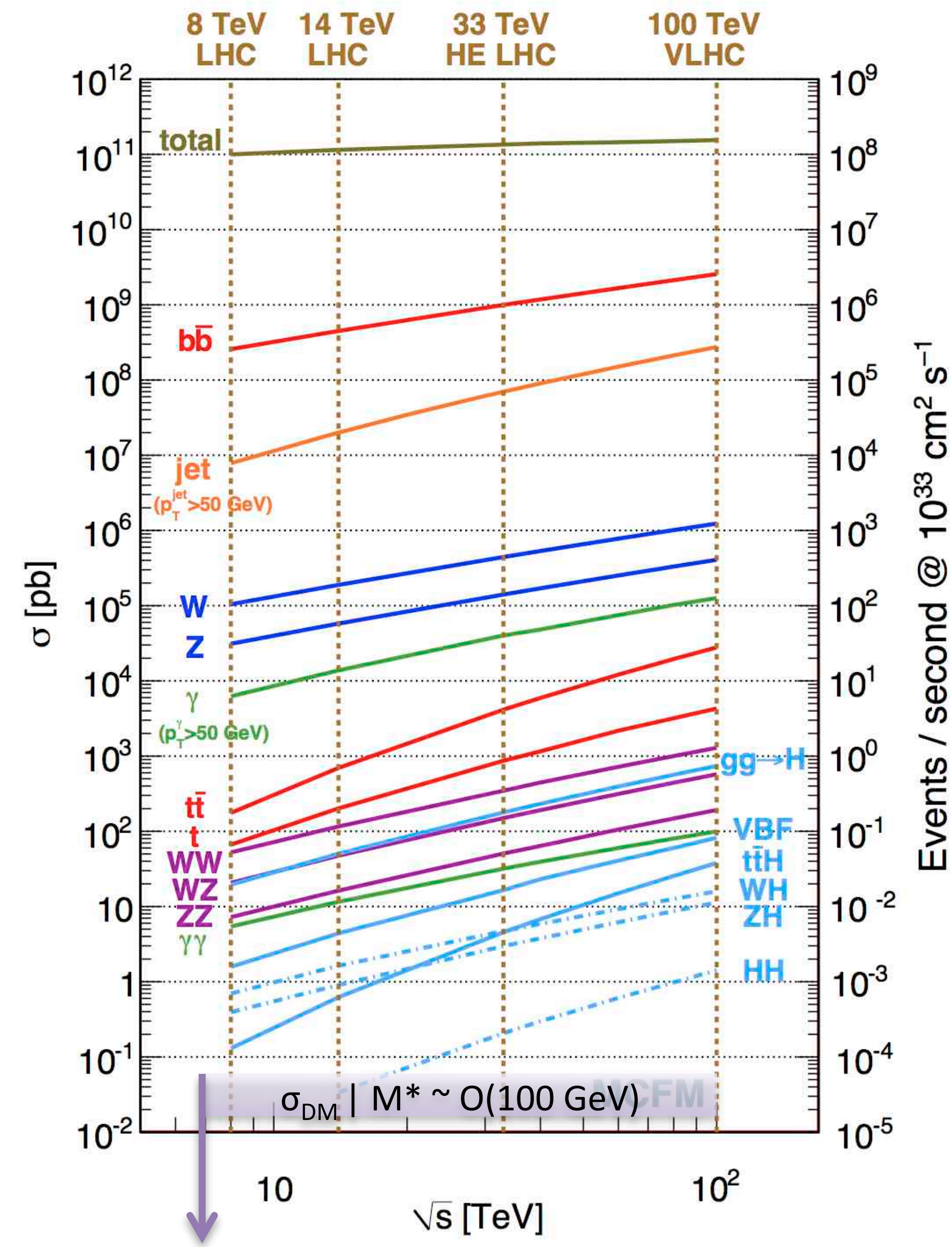
Source of systematic uncertainties	Relative error on total background (%)
Jet energy scale	15
$t\bar{t}$+jets top p_T reweighting	11
Jet energy resolution	5.3
$t\bar{t}$+jets Q^2	3.7
Pileup model	3.1
$t\bar{t}$+jets jet-parton matching	3.0
Cross section	2.7
Integrated luminosity	2.6
Electron energy scale	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**