How dark is Dark?

the Dark Matter quest at ATLAS

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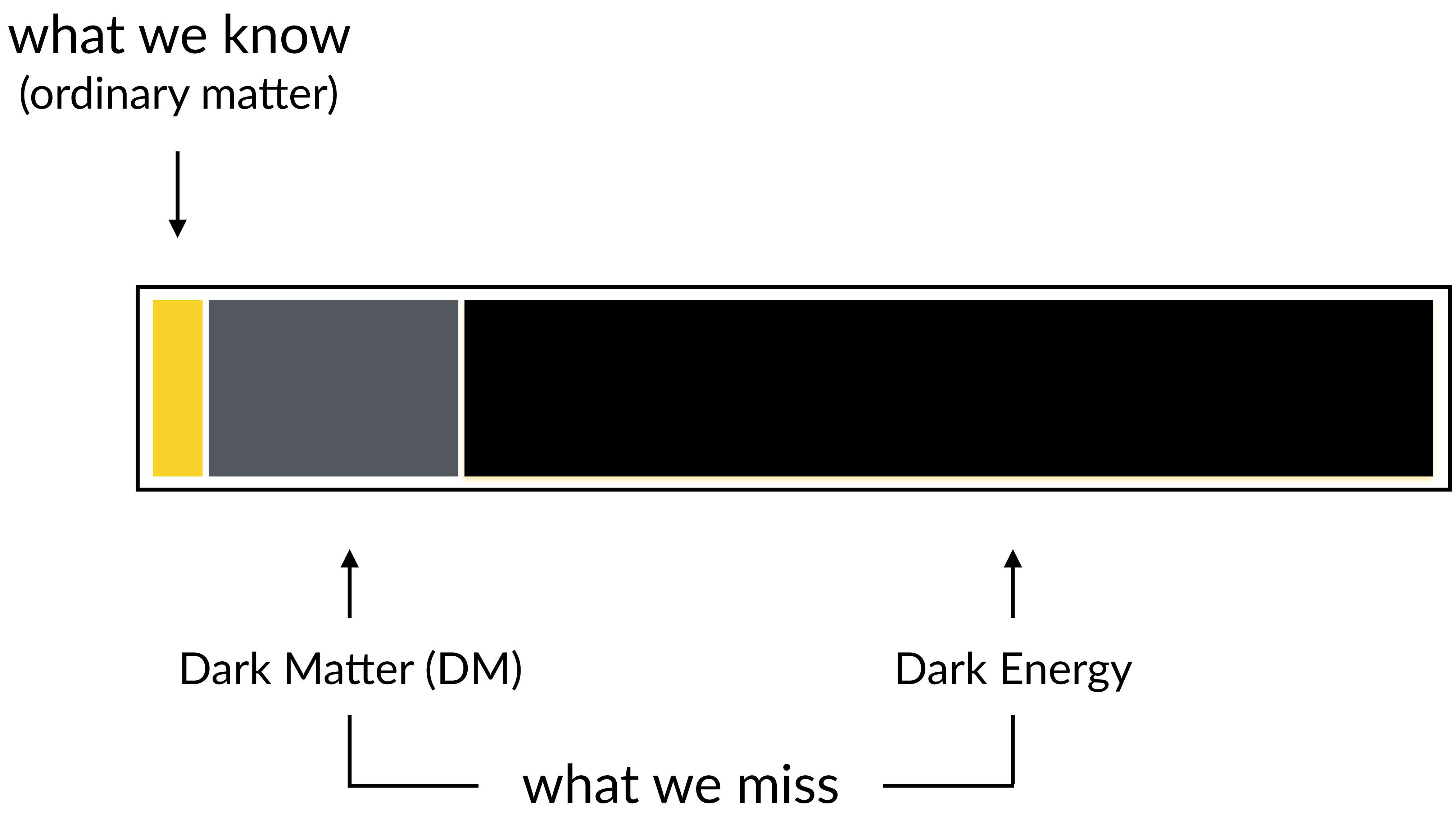
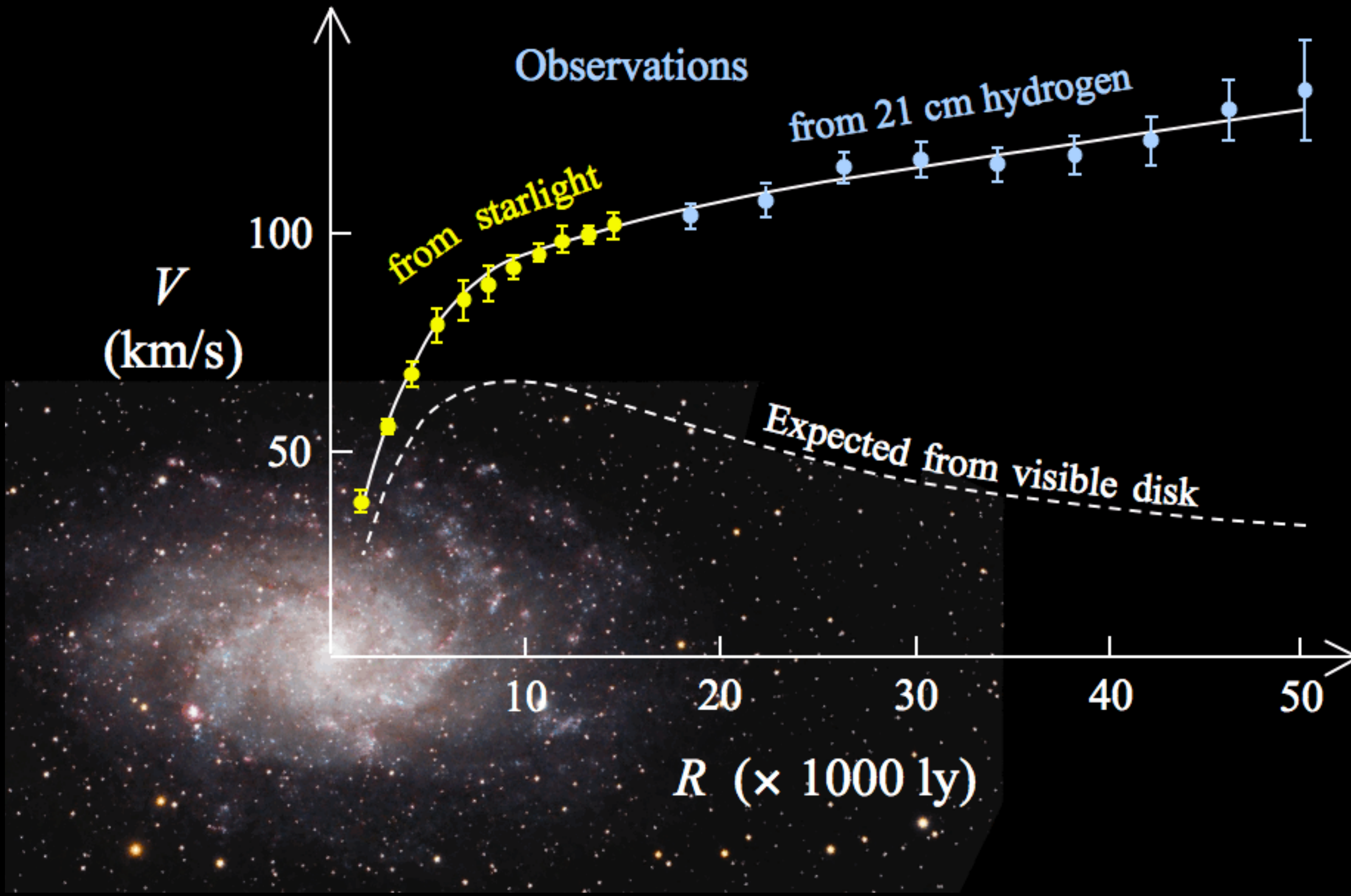
Progress bar

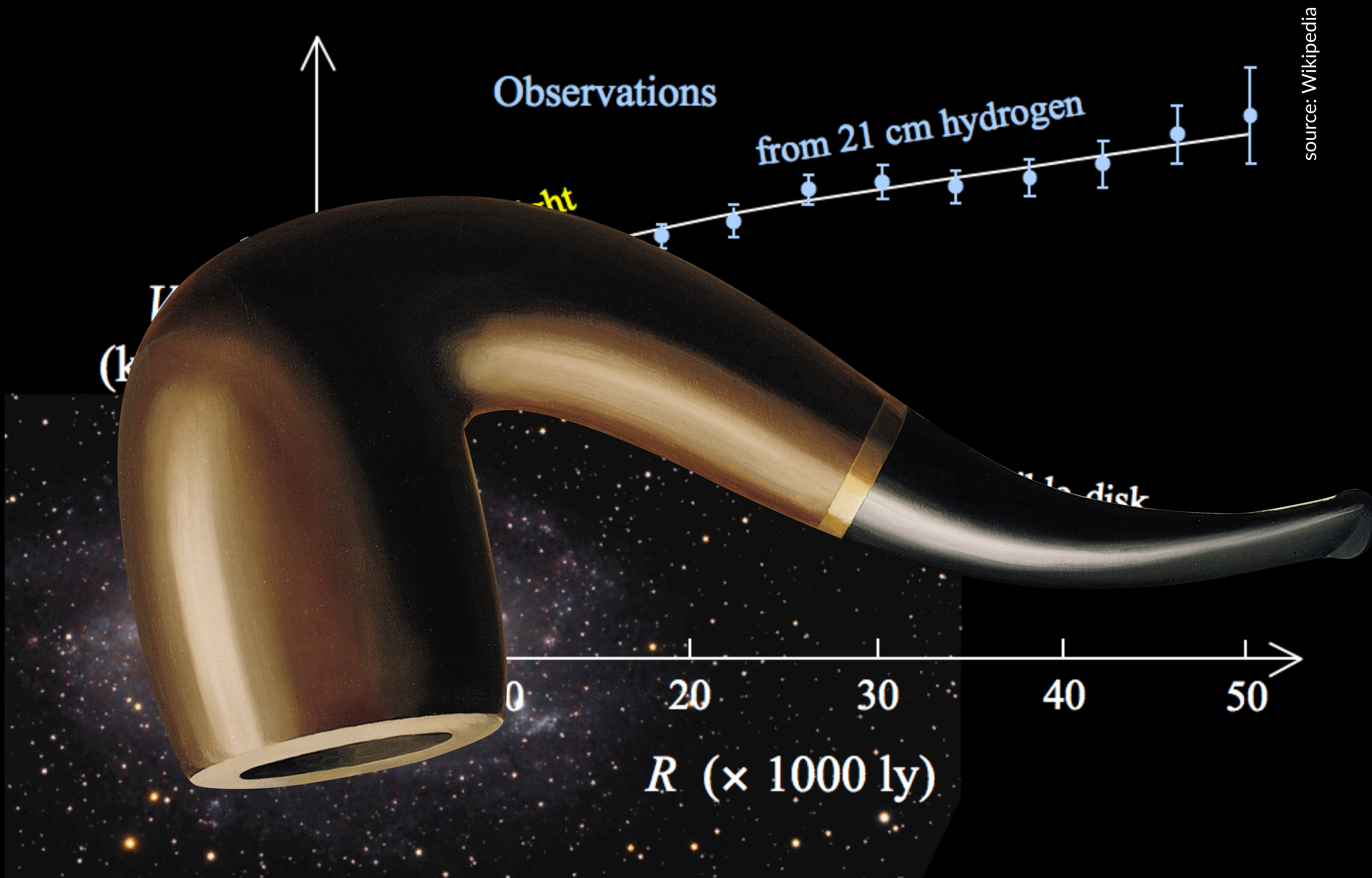


rotation velocity curve, M 33 spiral galaxy



source: Wikipedia

rotation velocity curve, M 33 spiral galaxy

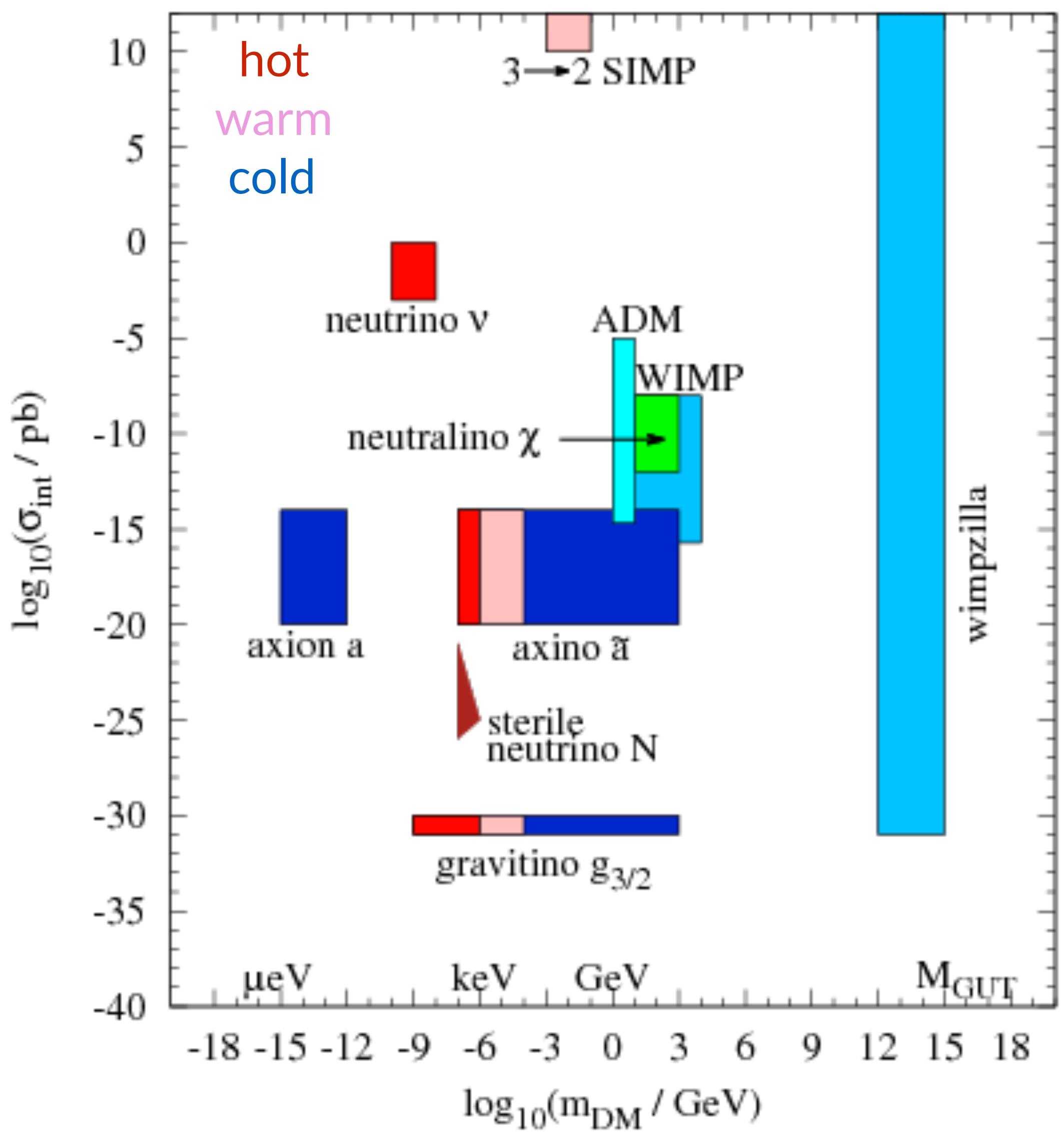


Ceci n'est pas de la matière sombre

Weakly interacting massive particles

Phys.Rept. 555 (2015) 1-60

typical interaction cross-section



DM mass

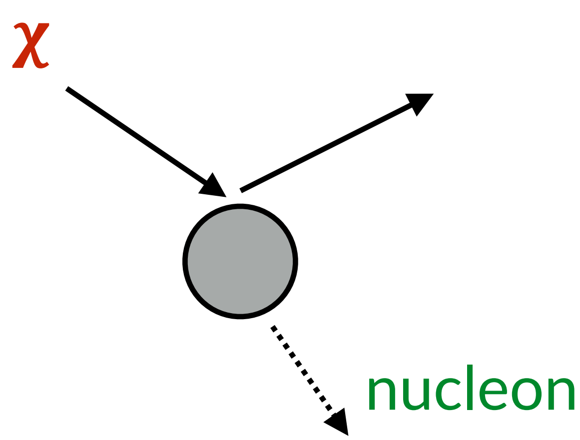
WIMPs: an attractive solution to the DM problem

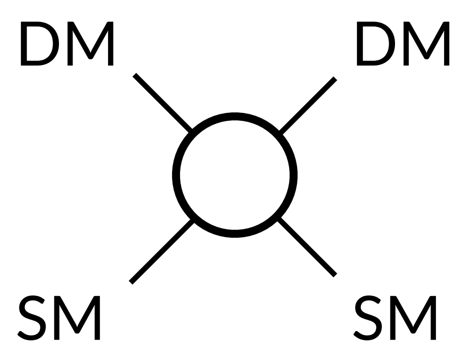
(new physics around the corner?)

Using the available Dark Matter

- build detectors which may detect the existing Dark Matter (DM)
- hope they do
  - experimental challenge set by DM mass and nature of DM-SM interaction

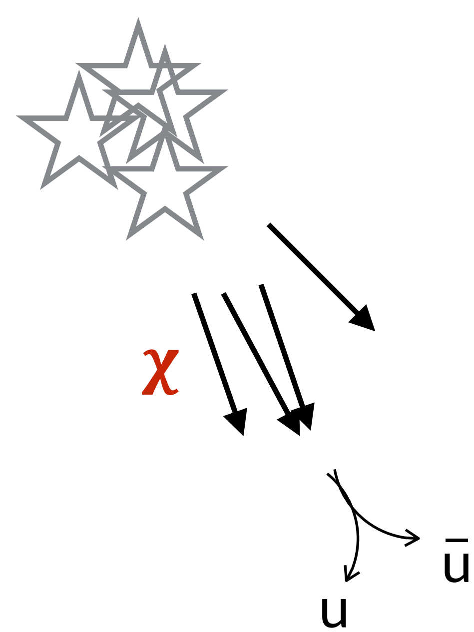
direct detection

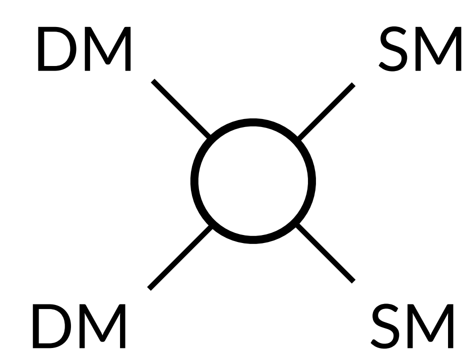




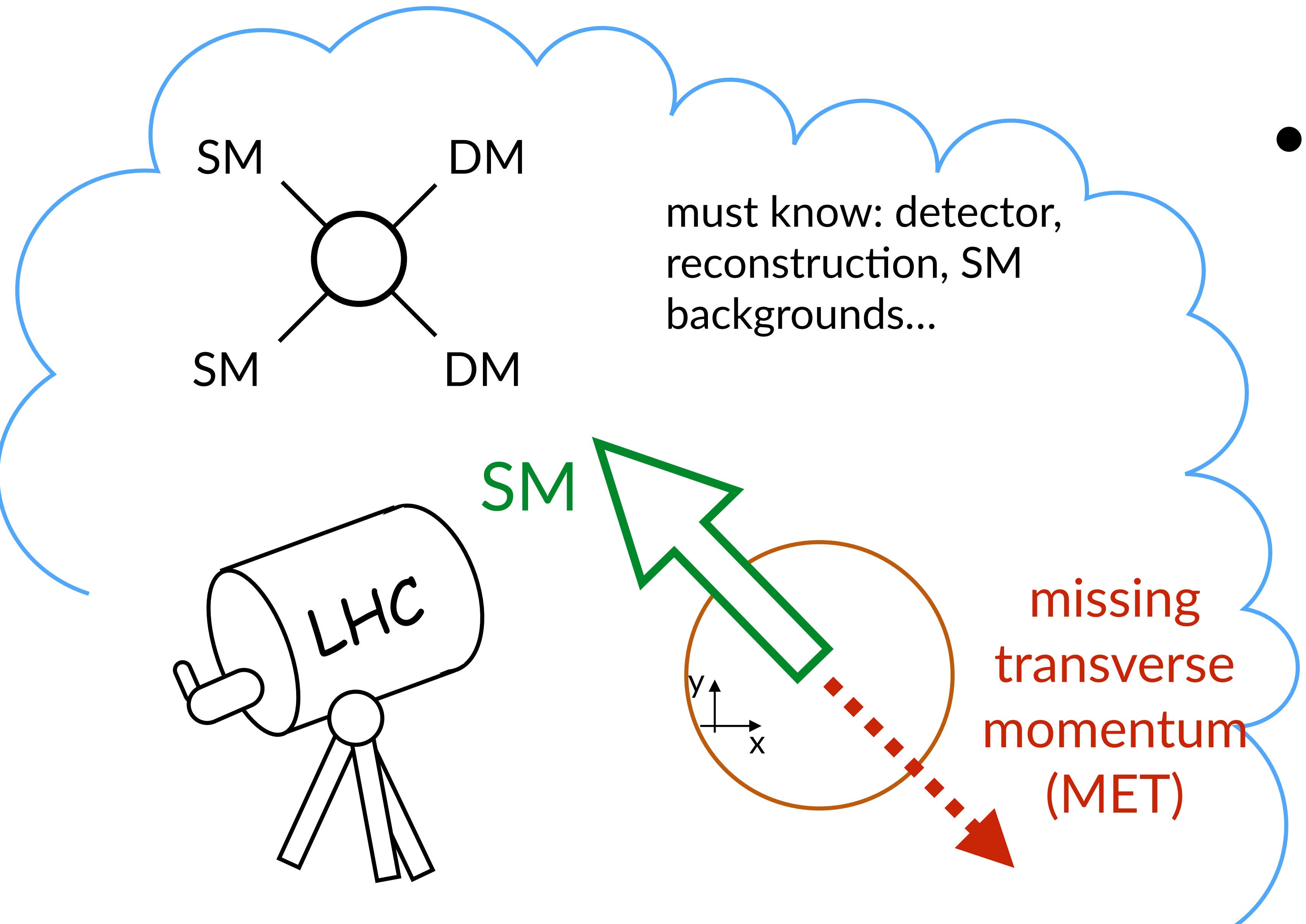
must know: nucleon form factors, DM local density, background levels…

indirect detection

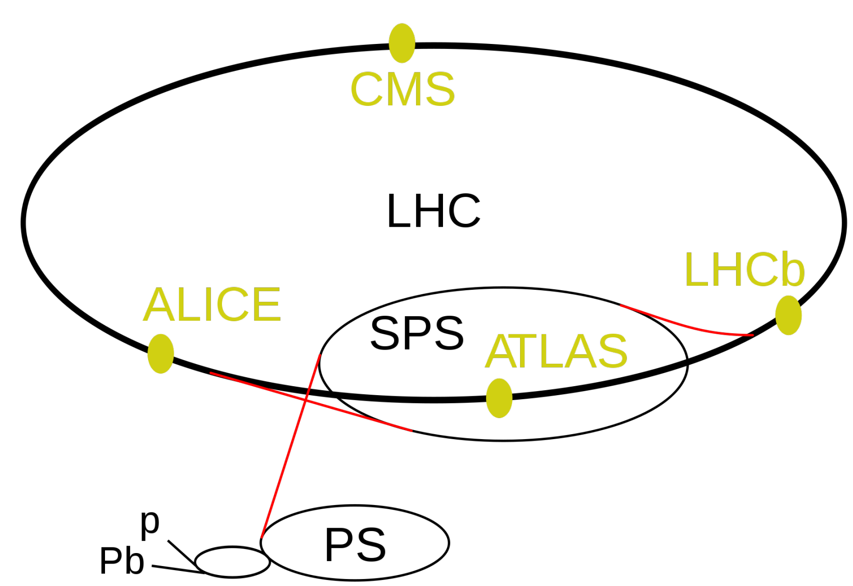




What about producing it?

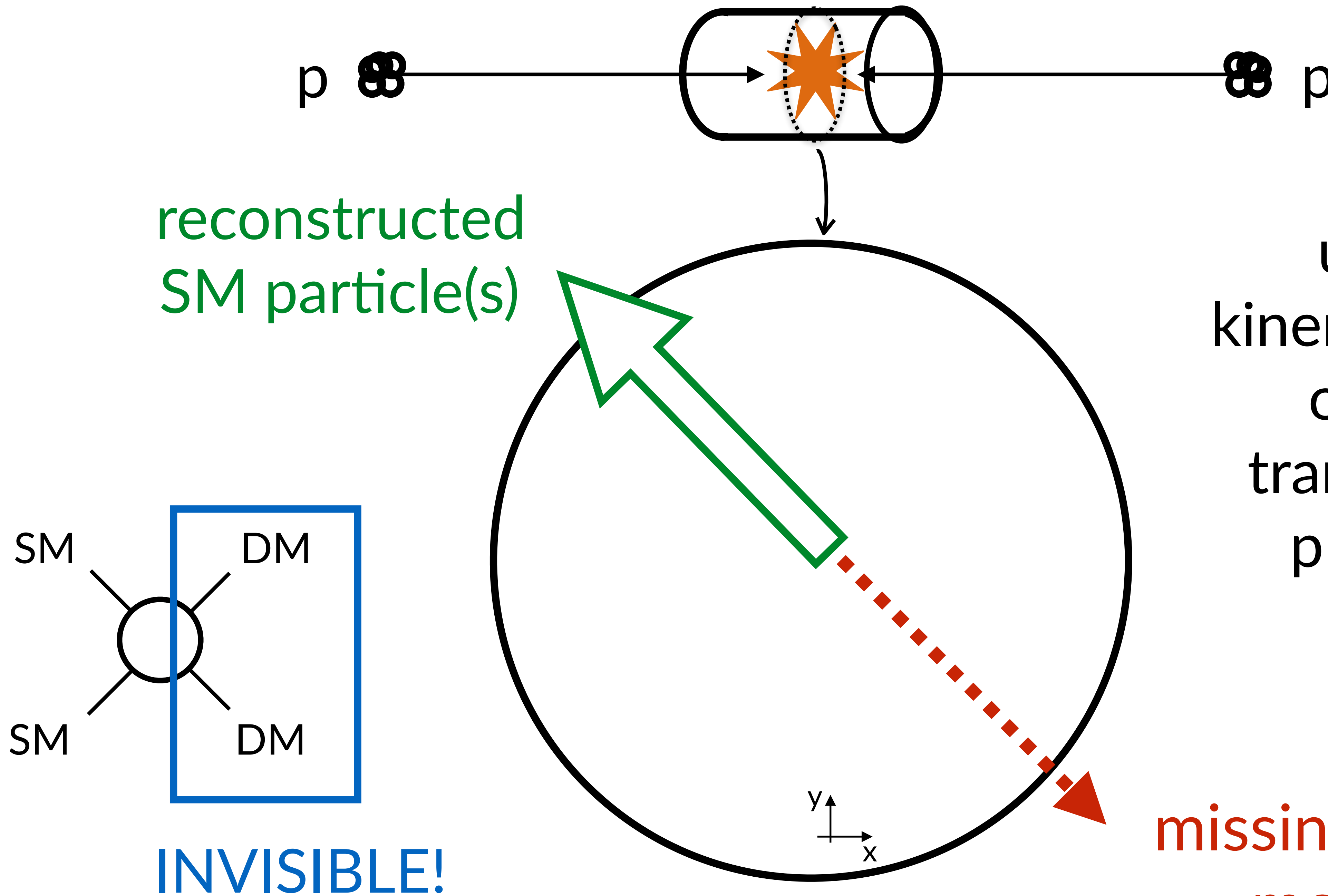


- build a collider which might produce DM
- build detectors which can detect everything else
- hope they do
  - experimental challenge set by needed precision and nature of DM-SM interaction



The invisible, through the visible

pp collisions @ 13 TeV

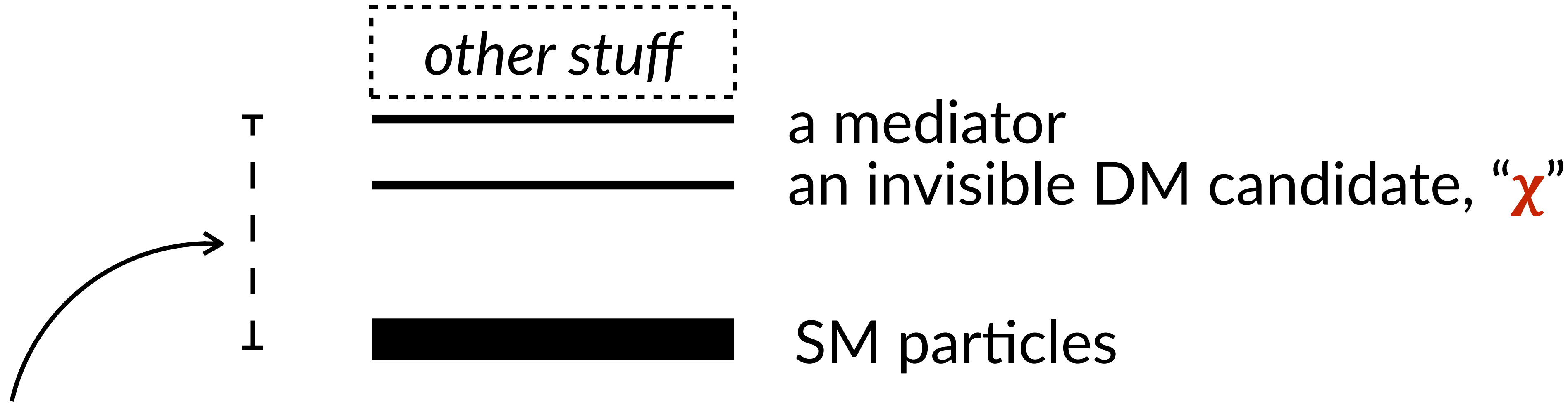


use the fact kinematics is closed on the plane transverse to the proton beams

Who's missing?

Extending the Standard Model

or: what are we all looking for?



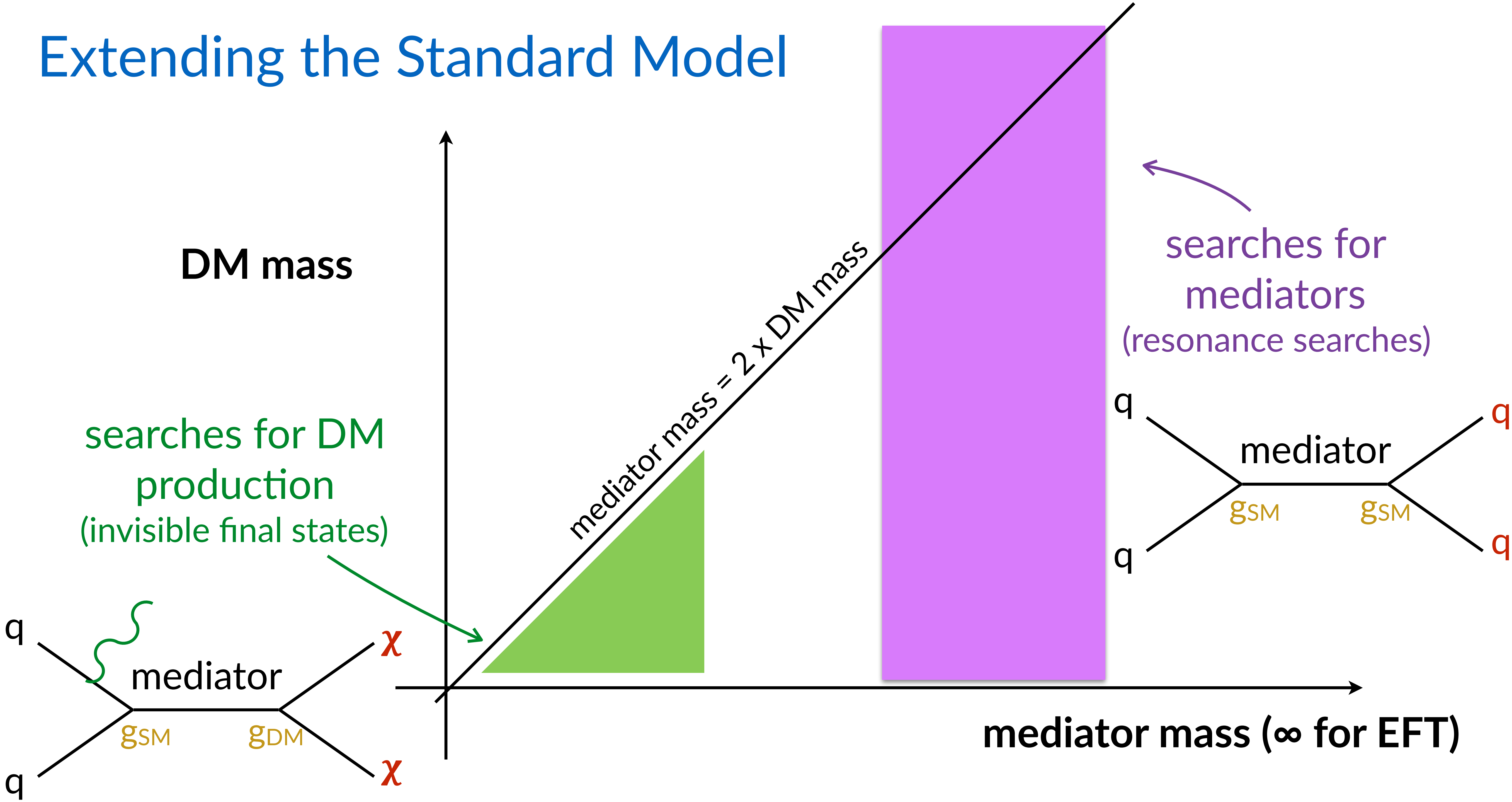
Δm >> q^2: ***effective field theory*** *(like in the case of direct detection)*

Δm <~ q^2: use ***simplified models***

(simplified Lagrangian w.r.t. UV-complete models like SUSY)

	mediator	**DM**	**coupling strength**
direct detection	choice of the target	choice of the technology	reach neutrino bkg
LHC	choice of the final state	almost irrelevant if < O(100 GeV)	background estimation, luminosity

Extending the Standard Model



- once interaction is fixed (e.g. vector), parameter space is (at least) 4-dimensional
  - mediator mass, DM mass, mediator-SM coupling strength, mediator-DM coupling strength
- results often expressed in terms of 2D slices at **fixed couplings**

Complementarity

- LHC may produce DM, and hence characterise a possible discovery
  - strength: synergy of (often non-trivial) final states
  - limitation: “invisible” requires trigger and MET

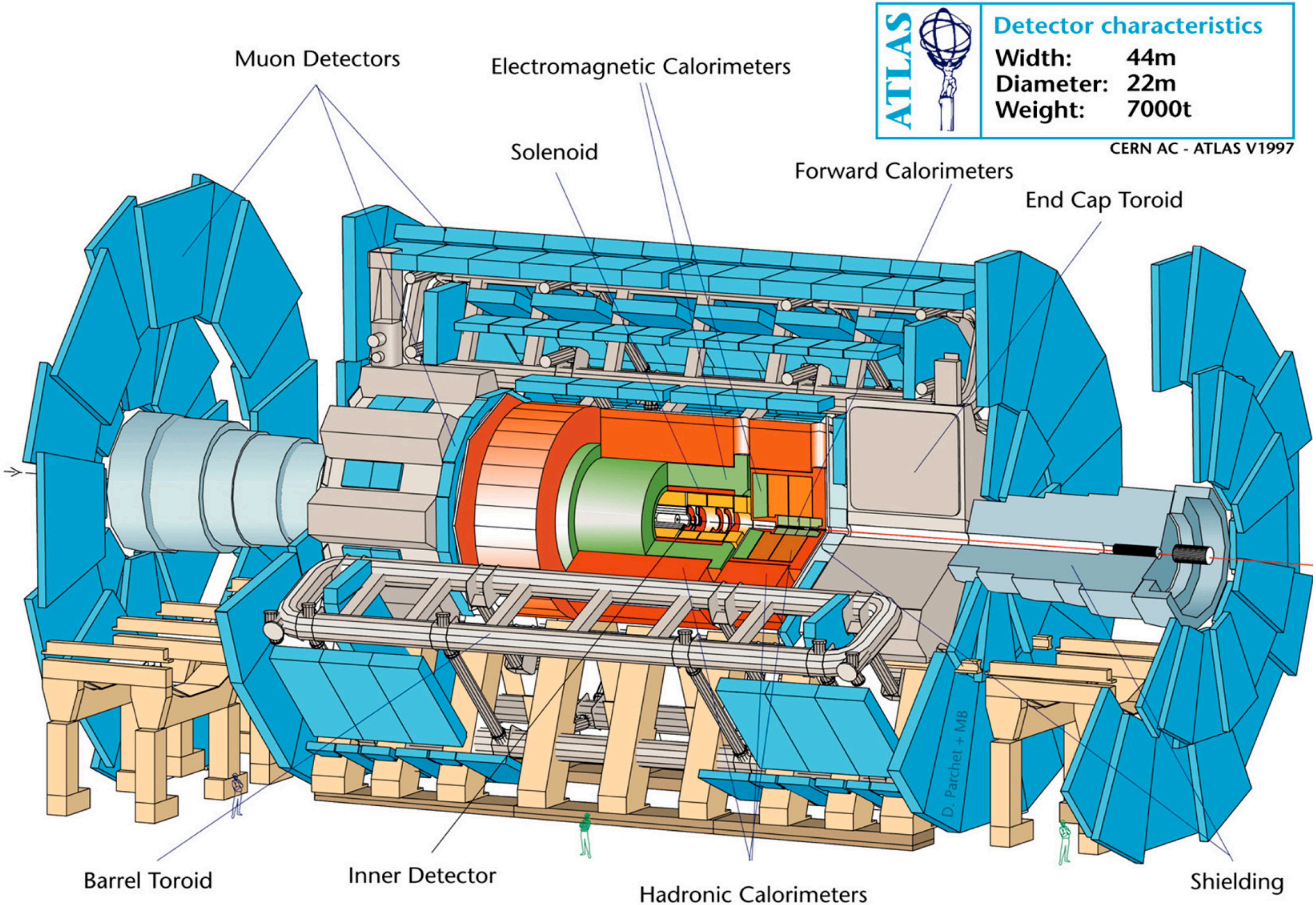
can use bb/tt + MET and multiple signatures
(mediator couples à la Yukawa with quark masses)

can use jets + MET and confirm with mediator searches
& ancillary channels (MET+gamma, MET+W/Z...)

	LHC	direct detection	indirect detection
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)	

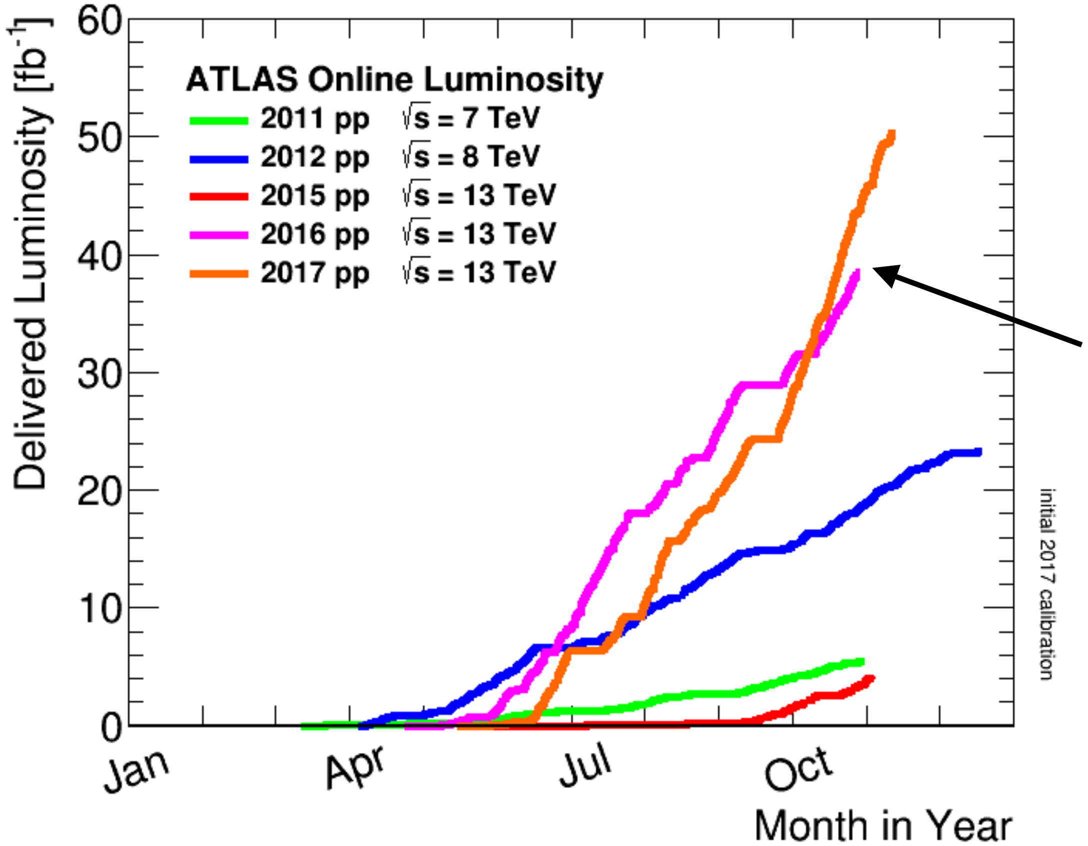
Challenges

The ATLAS detector



How the LHC collects data

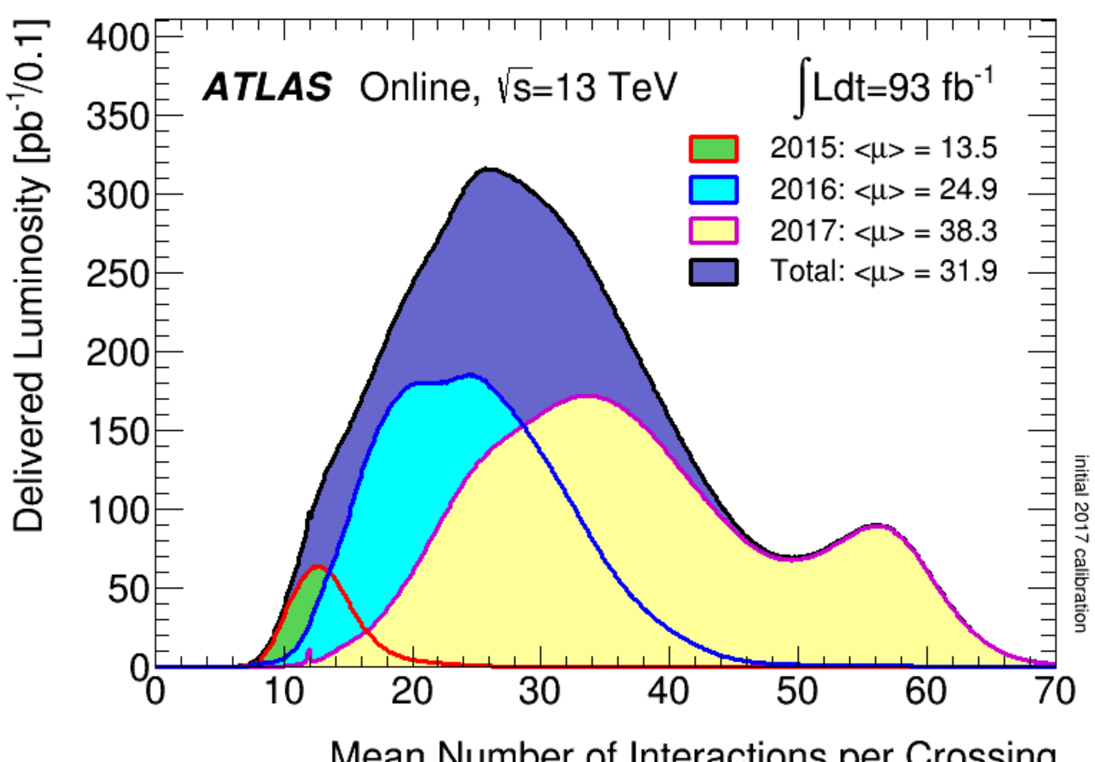
current luminosity goal: 120 fb^{-1} at 13 TeV by end of 2018



impressive increase in slope vs year!

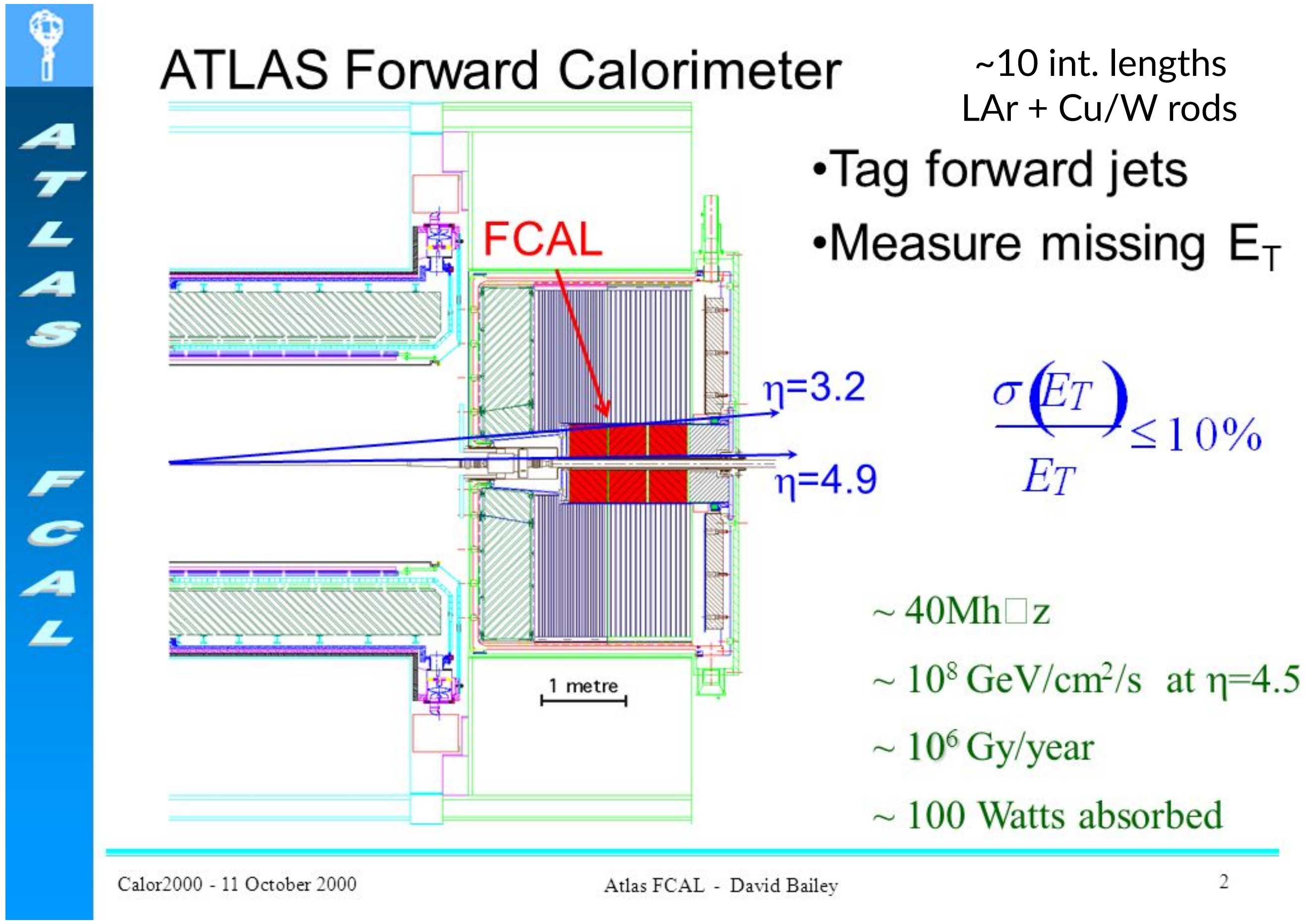
- collision rate: 40 MHz
- after hardware trigger (“L1”): 100 kHz
- after software trigger (“HLT”, ~40k CPUs): 1 kHz

how much does it cost in terms of event pile-up?

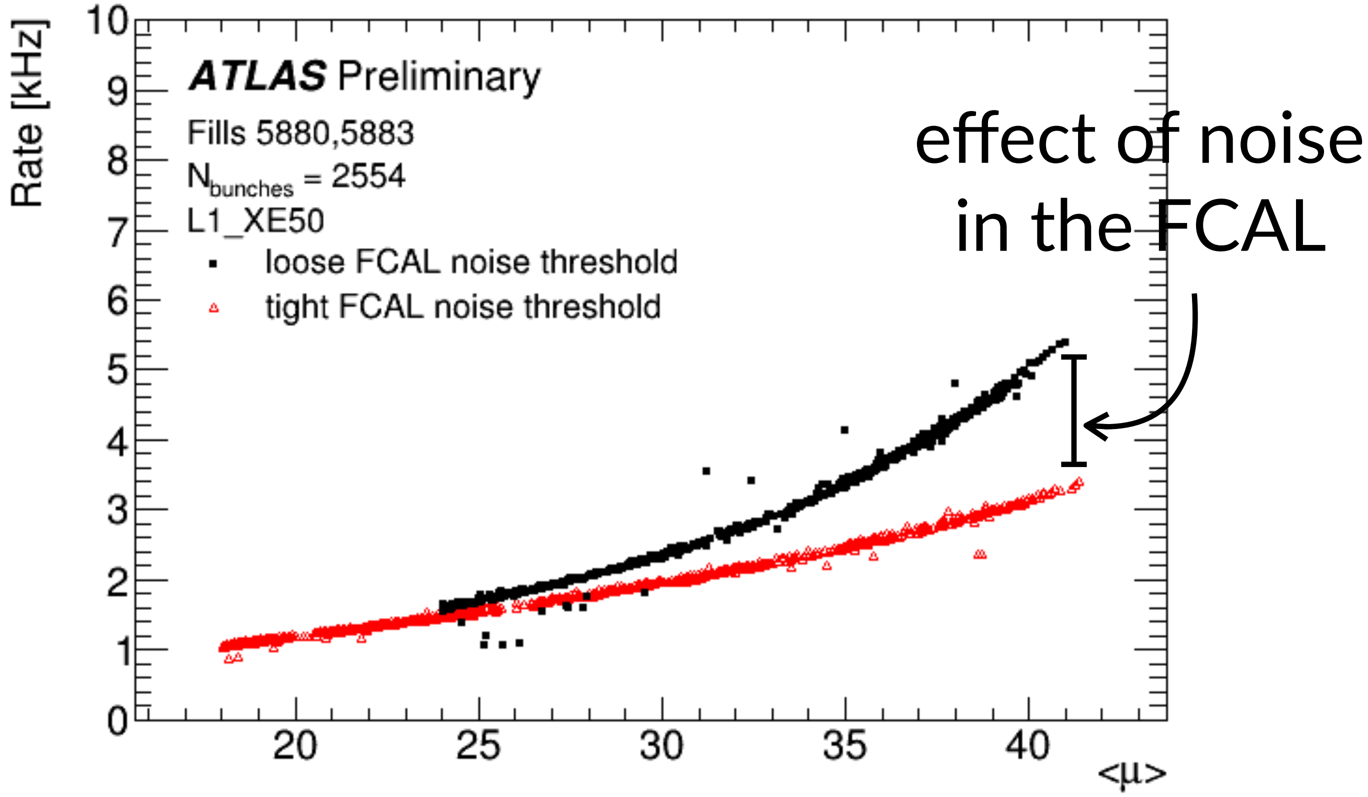


Triggering the invisible

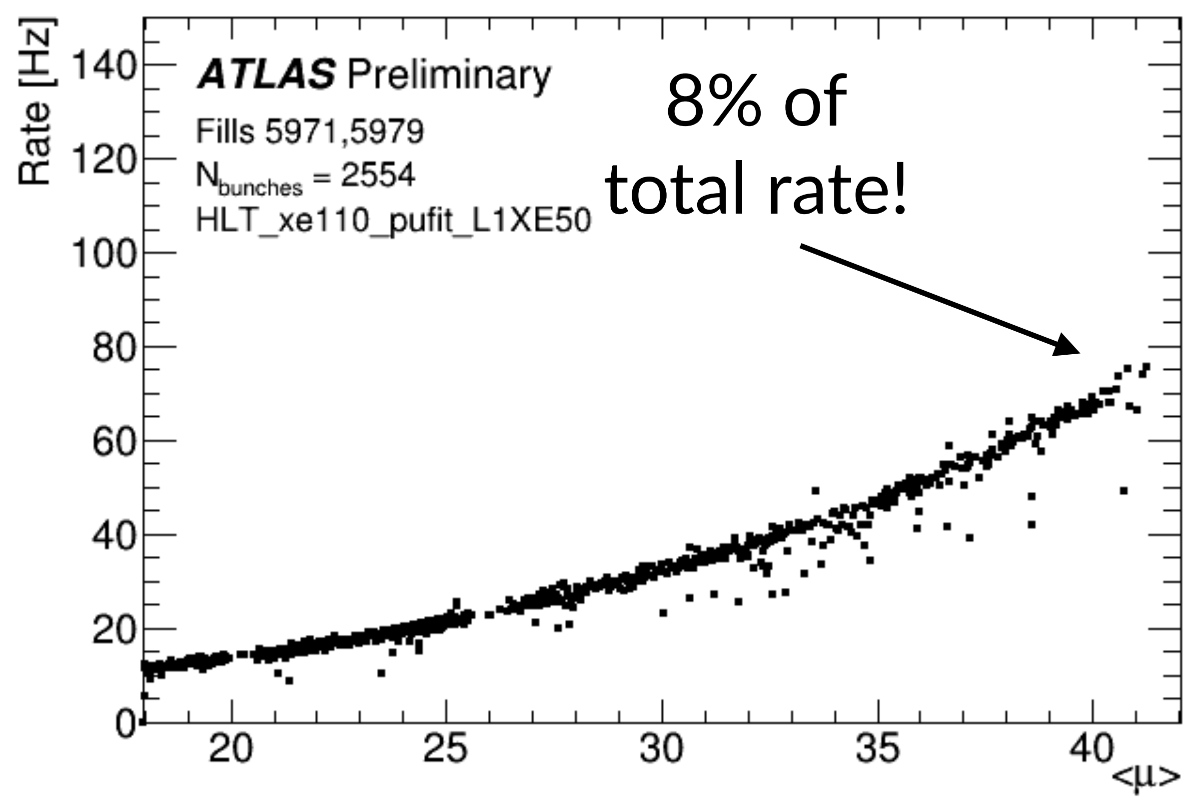
- MET trigger rate naturally dominated by event pile-up, especially in forward region
- must cope with L1 and HLT rate budget



L1 MET trigger rate vs pile-up



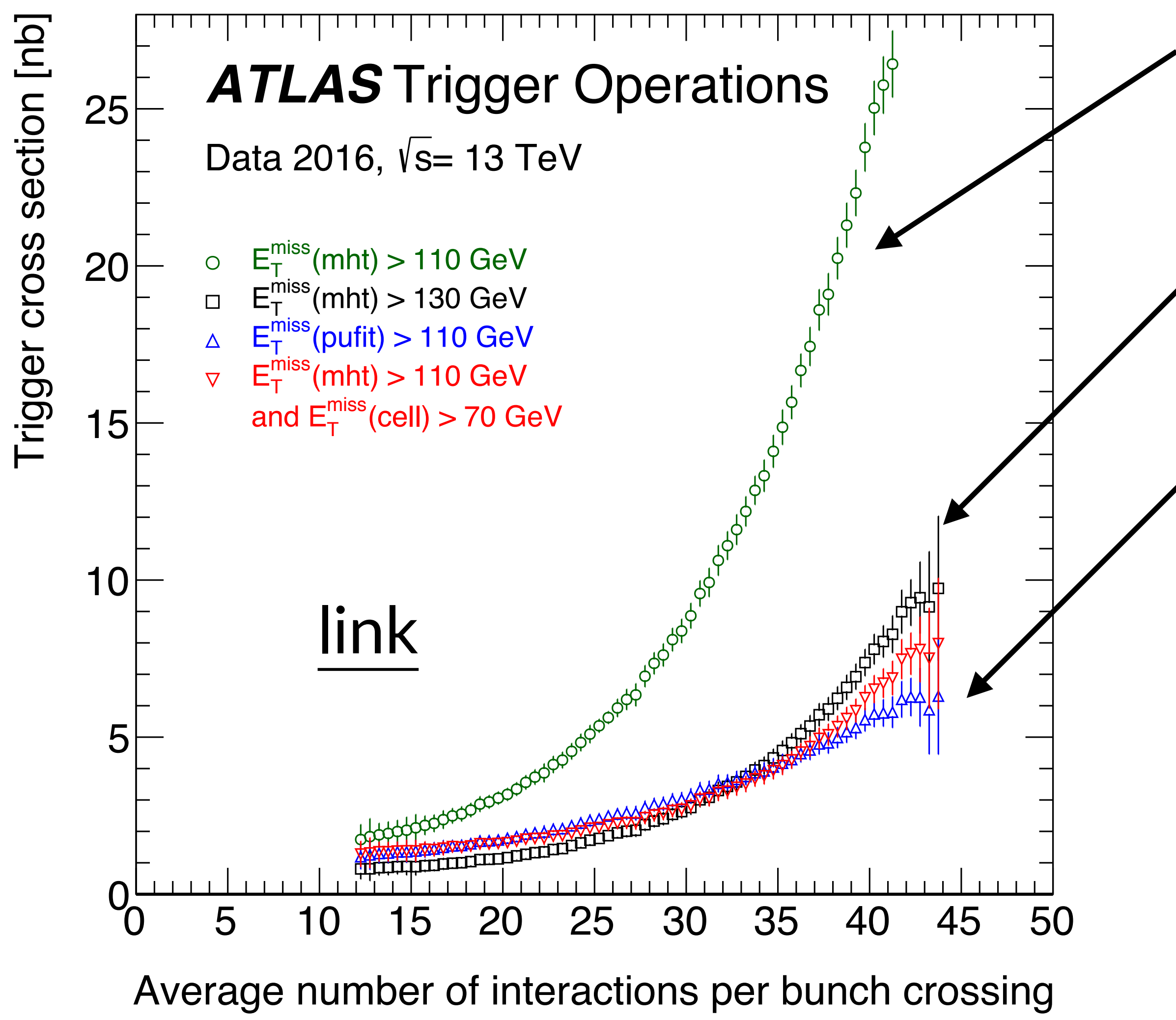
HLT MET trigger rate vs pile-up



Pile-up: the LHC stone guest

a crucial issue both at trigger and reco level

MET trigger cross-section vs pile-up



MET from sum of calorimeter jets calibrated at EM+JES scale **110 GeV** threshold

same but **130 GeV** threshold

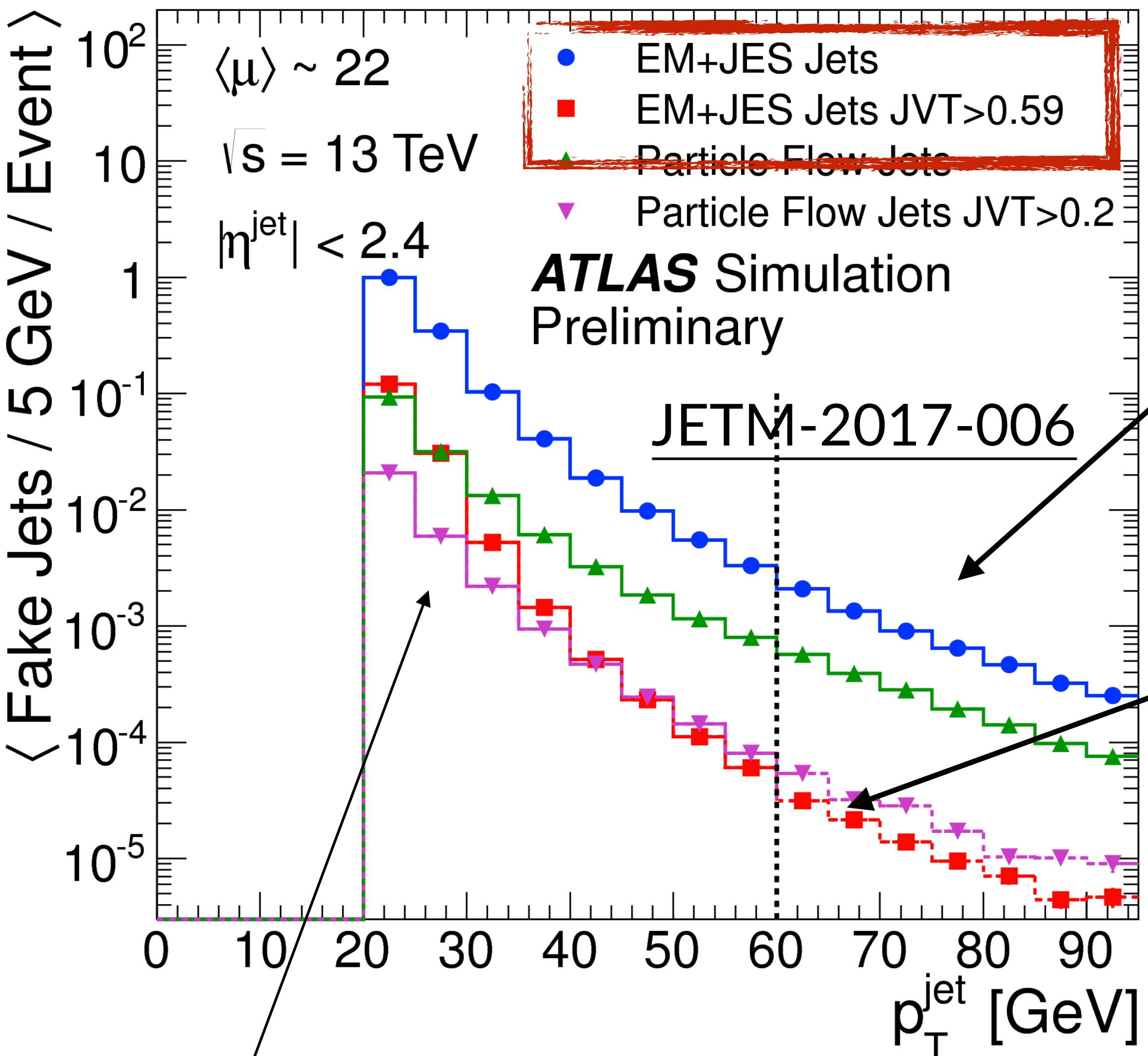
110 GeV threshold, but MET from clusters corrected for pile-up

- fit pile-up transverse energy density on "towers" of calorimeter clusters
- subtract it from clusters-above-threshold

Pile-up: the LHC stone guest

a crucial issue both at trigger and reco level

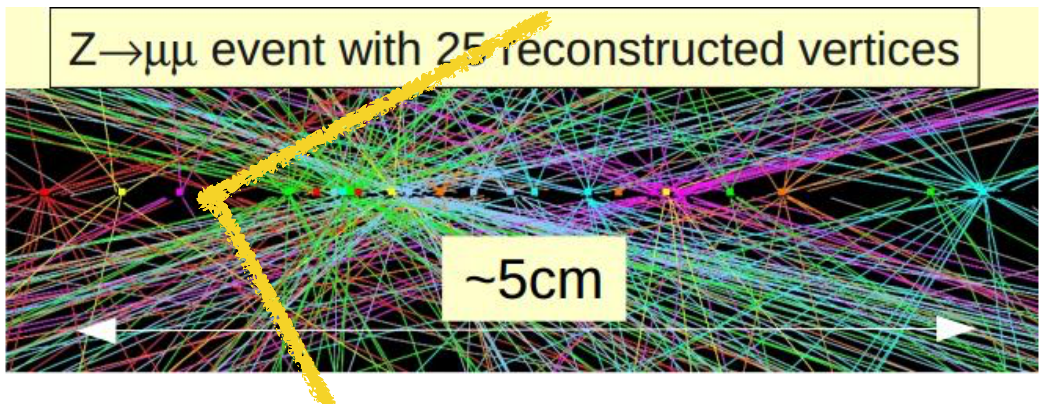
number of pile-up jets rate vs jet pT



calorimeter jets calibrated to EM+JES scale

same after using jet-to-vertex association

particle flow jets (under commissioning)

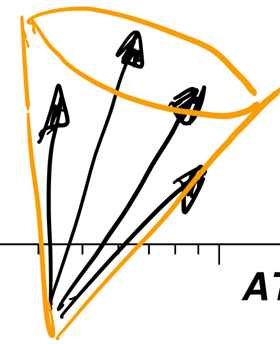


- need sophisticated algorithms to retain sensitivity to softer signals (e.g. spin-0 interactions)
- key issue for beyond-Run-2 performance

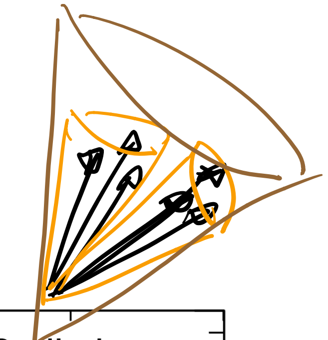
You must know your jets...

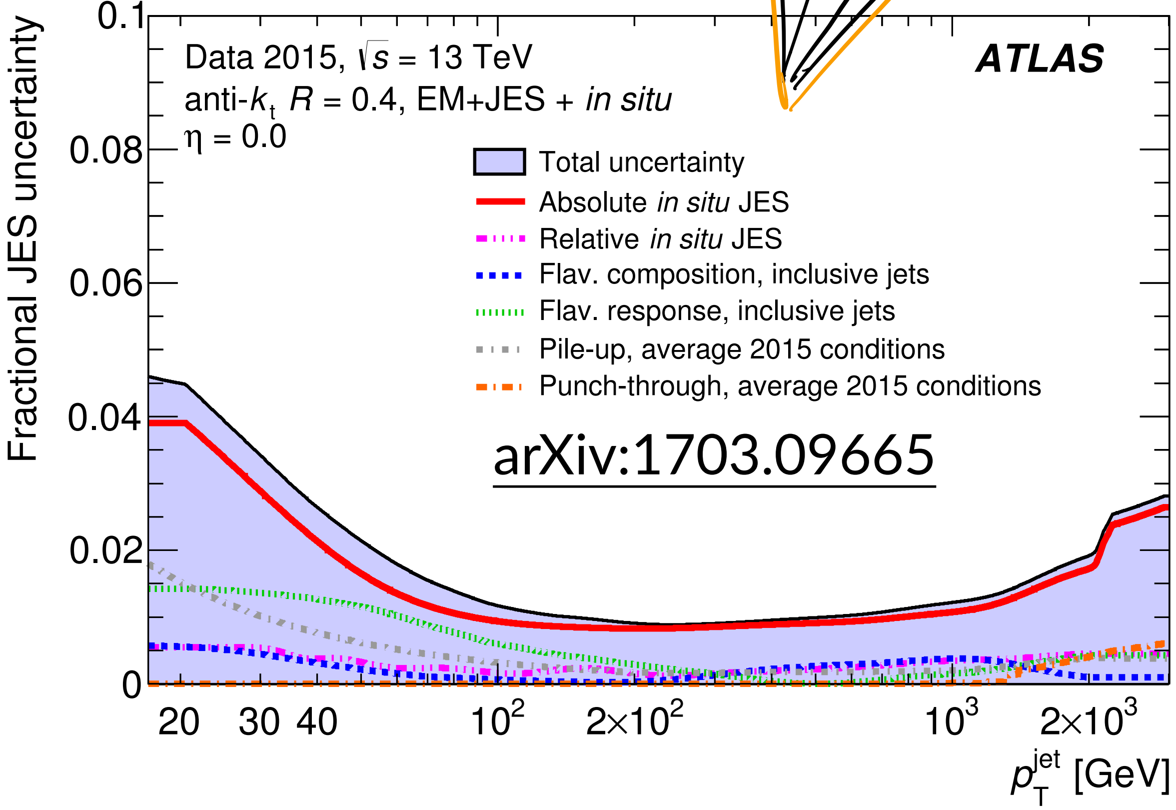
crucial for selection efficiency and systematic uncertainties

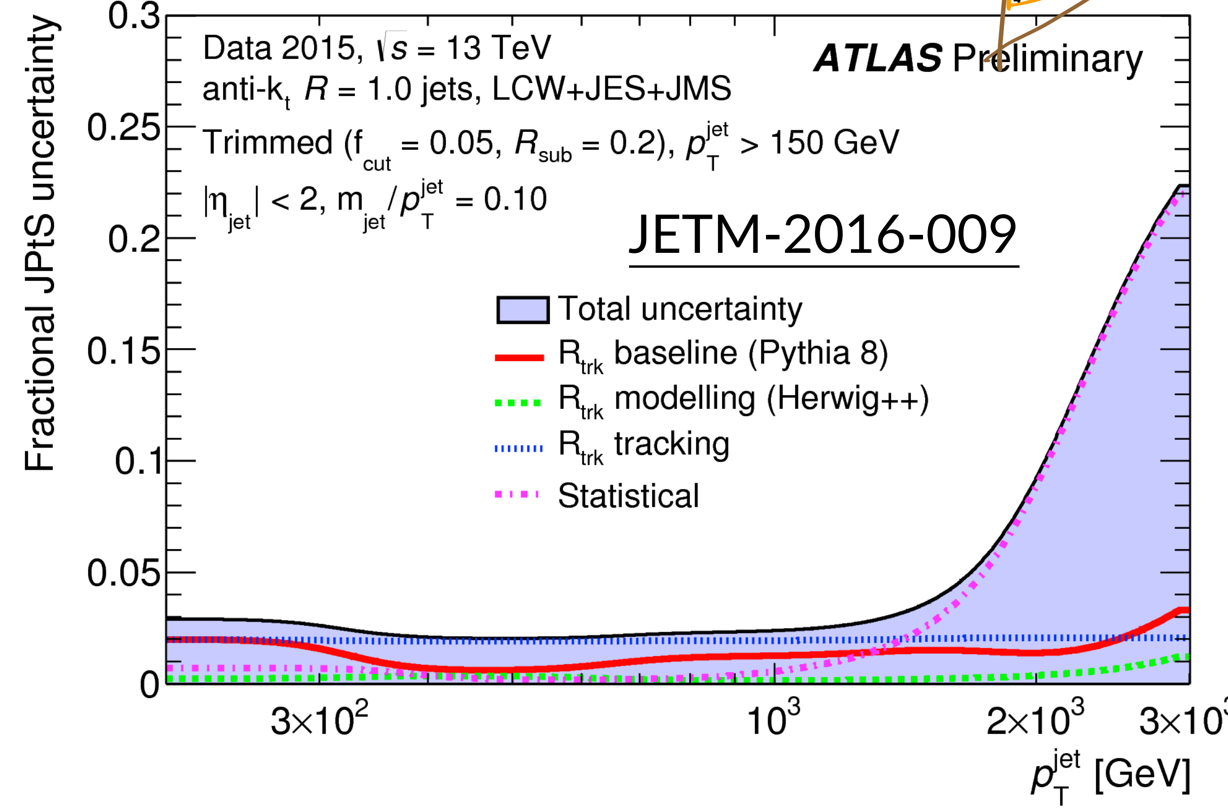
antikt R=0.4 jets



antikt R=1.0 trimmed jets



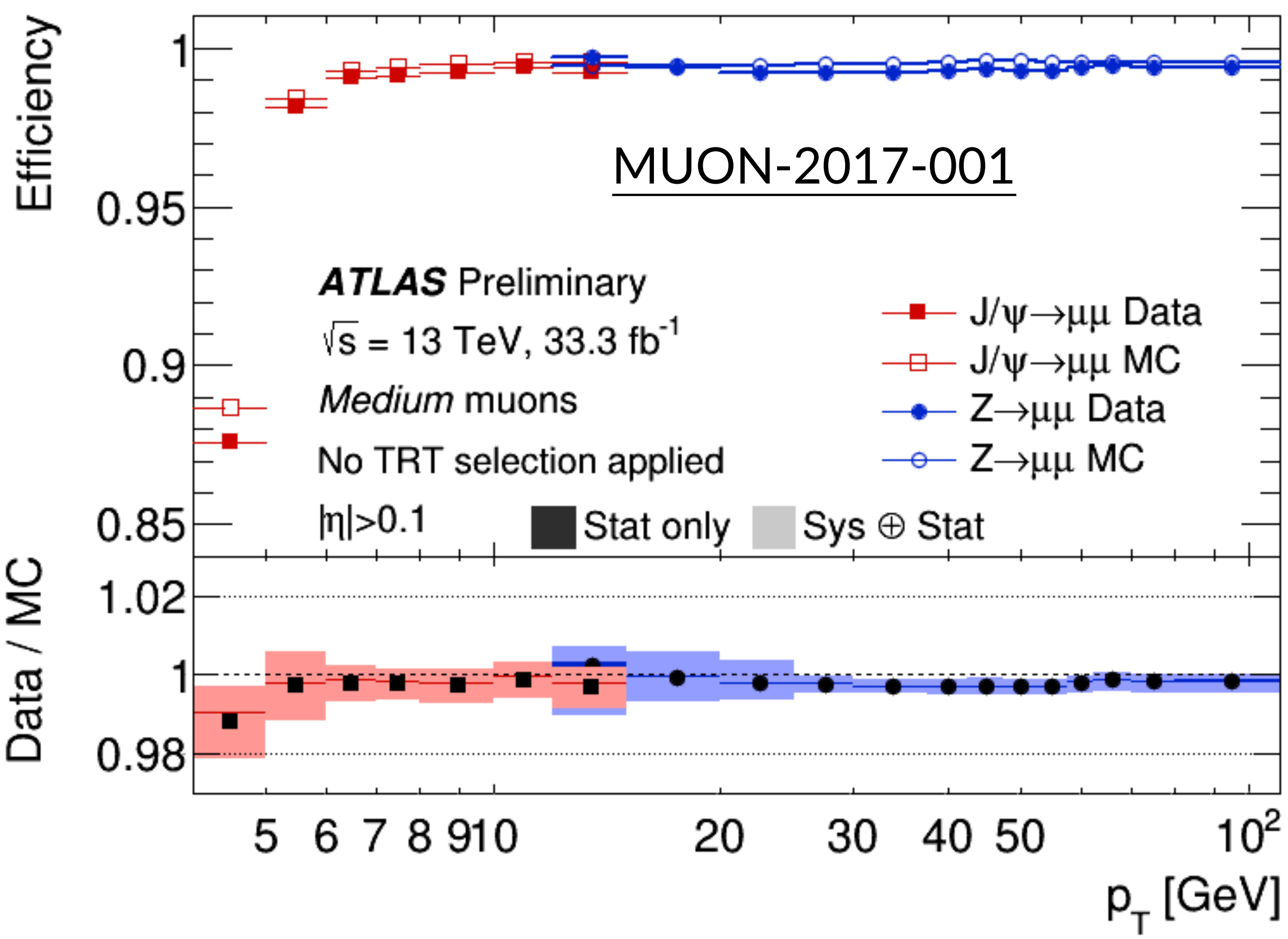


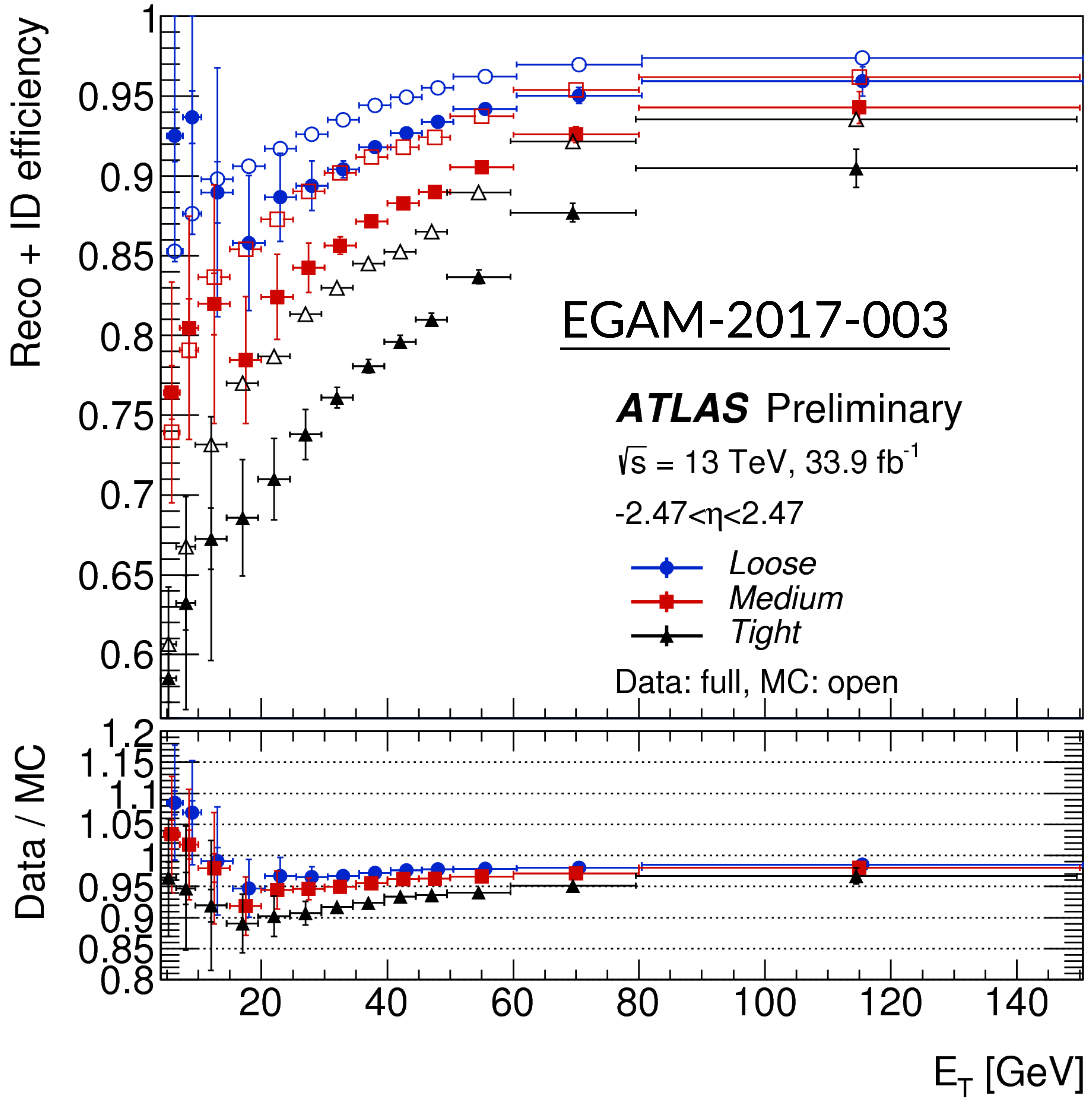


- made of topological energy clusters in calorimeters
  - calibration: MC simulation + data-driven techniques (e.g. dijet, Z+jet, gamma+jet, multi-jet events)
  - inner tracker information for identification and calibration
- very-high-p_T searches demand robust modeling of large-radius jets

… and master your leptons

excellent lepton reconstruction performance

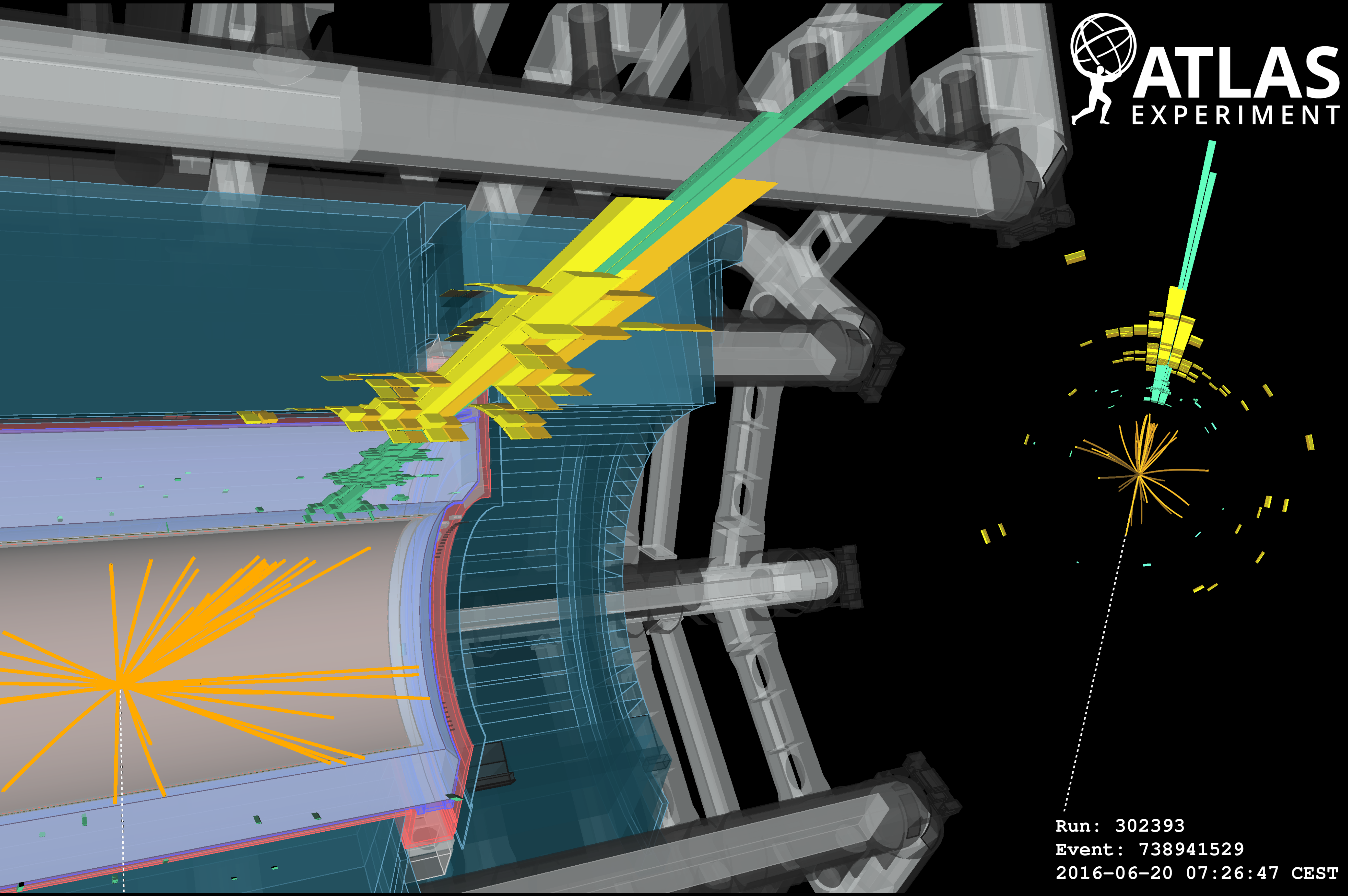




- crucial to exploit W/Z physics at the TeV scale
- you need to trust your lepton reco/ID uncertainty to be able to constrain SM backgrounds from the data (notably Zvv+jets!)

The invisible

mono-jet, mono-W/Z, mono-photon…


ATLAS
EXPERIMENT
Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

MET+jets

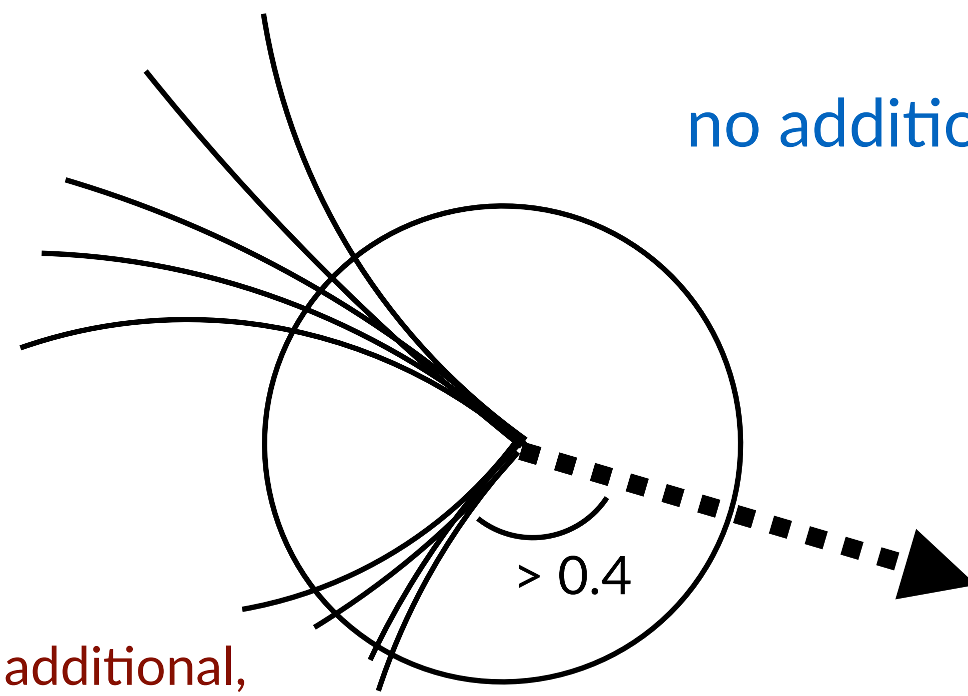
arXiv:1711.03301

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

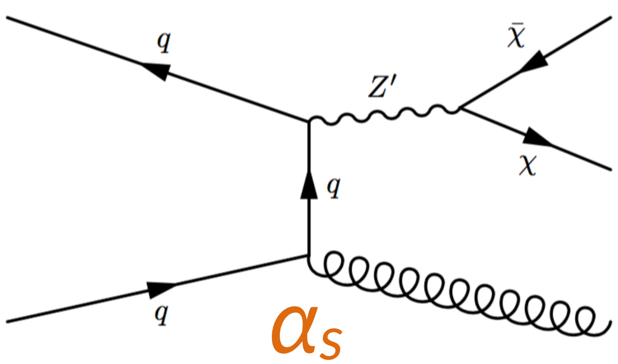
jet

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

no additional electron or muon



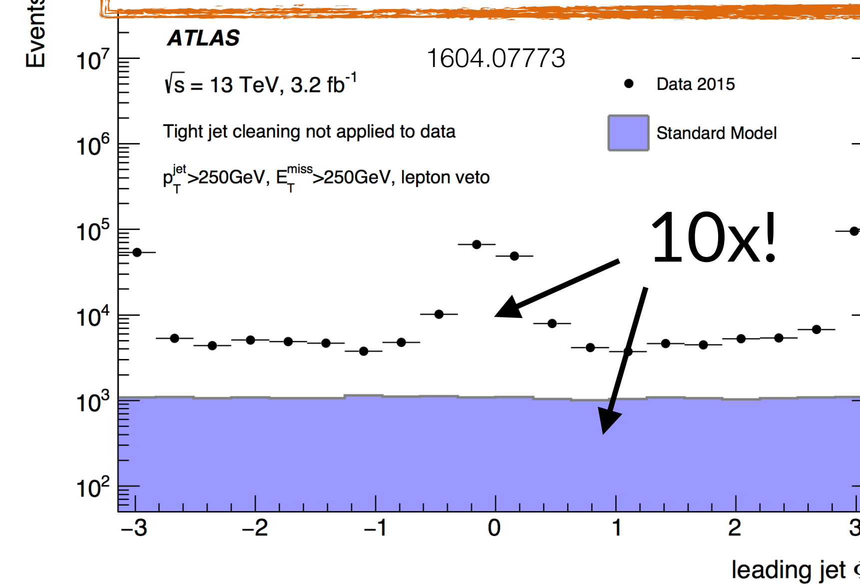
+ trigger
MET > 70 GeV
(fully efficient above 200 GeV)



additional,
softer jets
(up to 3)

MET
> 250 GeV

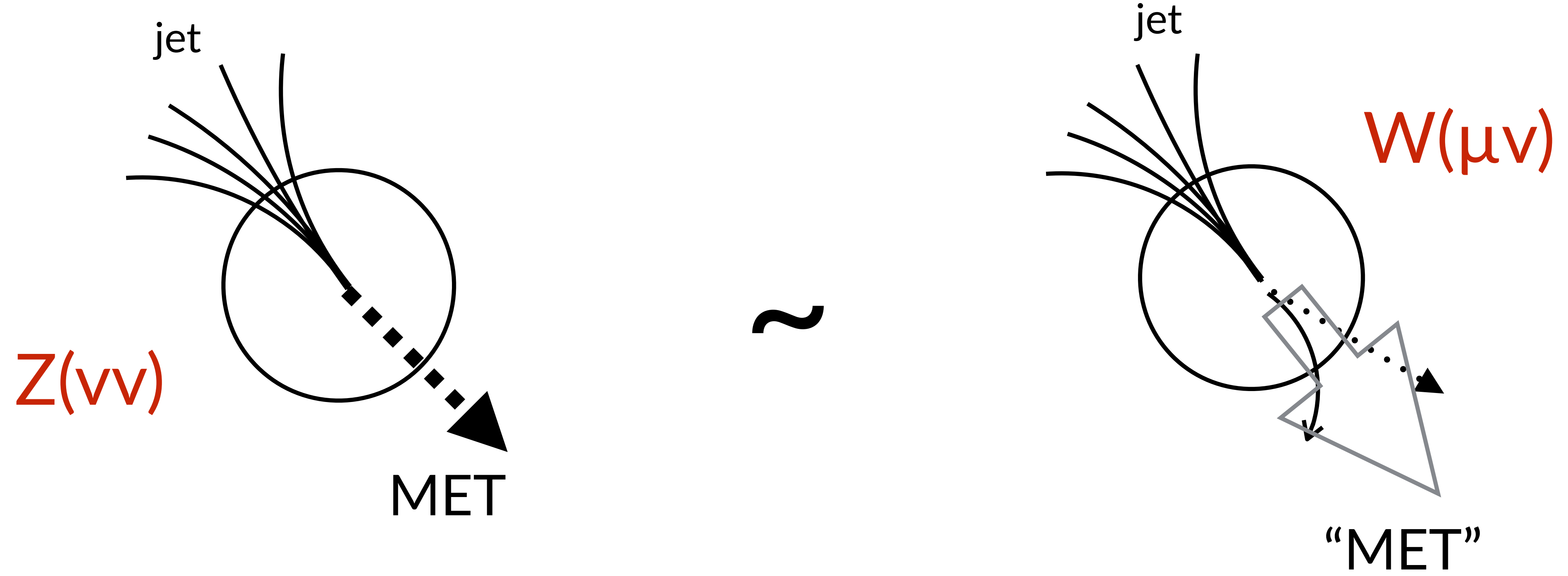
before and after jet quality cuts



same signature as
- Z(νν) + jets, W(τ[qq']ν) + jets…
  - normalisation from simultaneous fit to p_T(W/Z) distributions in lepton control regions
- use calorimeter segmentation to reject beam & instrumental background

Reducing the irreducible: estimating V+jets (V=W or Z)

if we pretend leptons are invisible:



- fully link the Z(νν)+jets cross-section to the W(μν)+jets one

$$N_{meas}(Z\nu\nu) = \mathbf{k} * N_{meas}(W\mu\nu/e\nu) = \mathbf{k} * N_{meas}(Z\mu\mu)$$

from a fit to data enriched in W/Z+jets

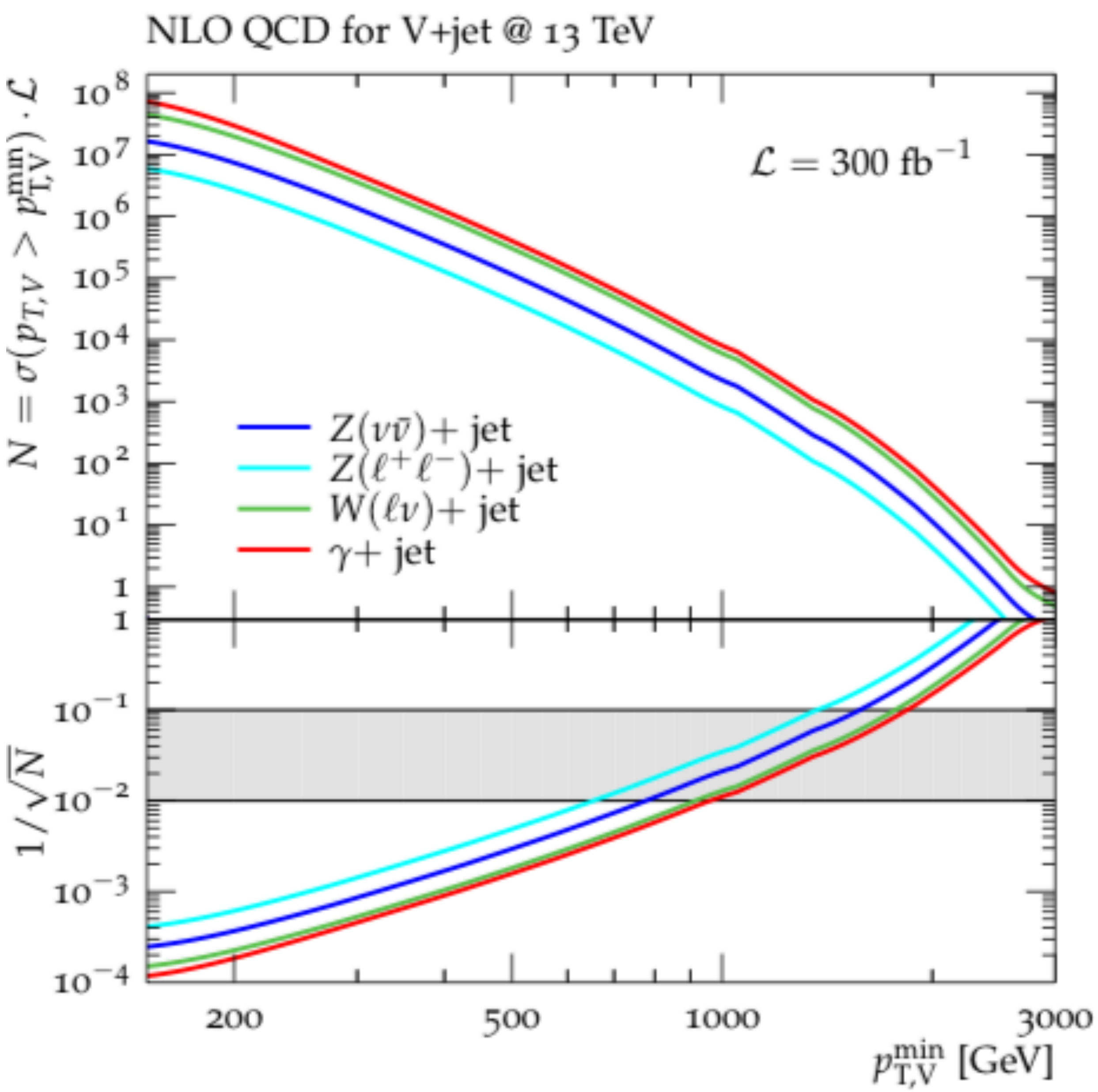
- background uncertainty from residual differences between Z(νν) and the rest (e.g. muon uncertainties)
- do this differentially, as a function of $p_T(V)$ -> why?

Weapons of Z(vv) destruction

arXiv:1705.04664v1

v2 goes to NNLO in QCD,
work-in-progress @ ATLAS

V+jets xsec x BR, as a function of p_T



produce more W+jets than Z(ll)+jets: use both to reduce statistical uncertainties

$$\mathcal{L}(K) = \prod_{\text{region } i} \text{Pois}\left(N_{OBS}^{(i)} \,\middle|\, K \times N_{MC}^{(i)}\right)$$

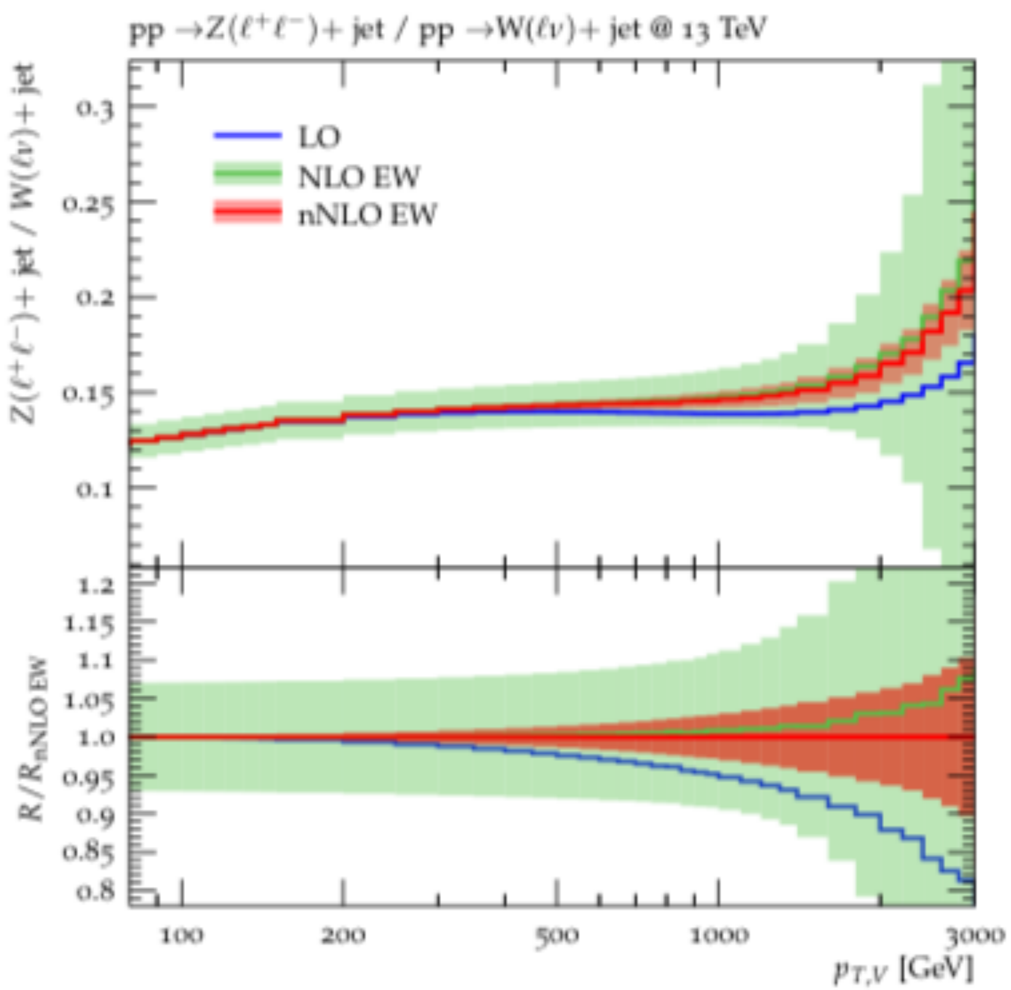
- fit from data a common, global scale factor to W and Z normalisation

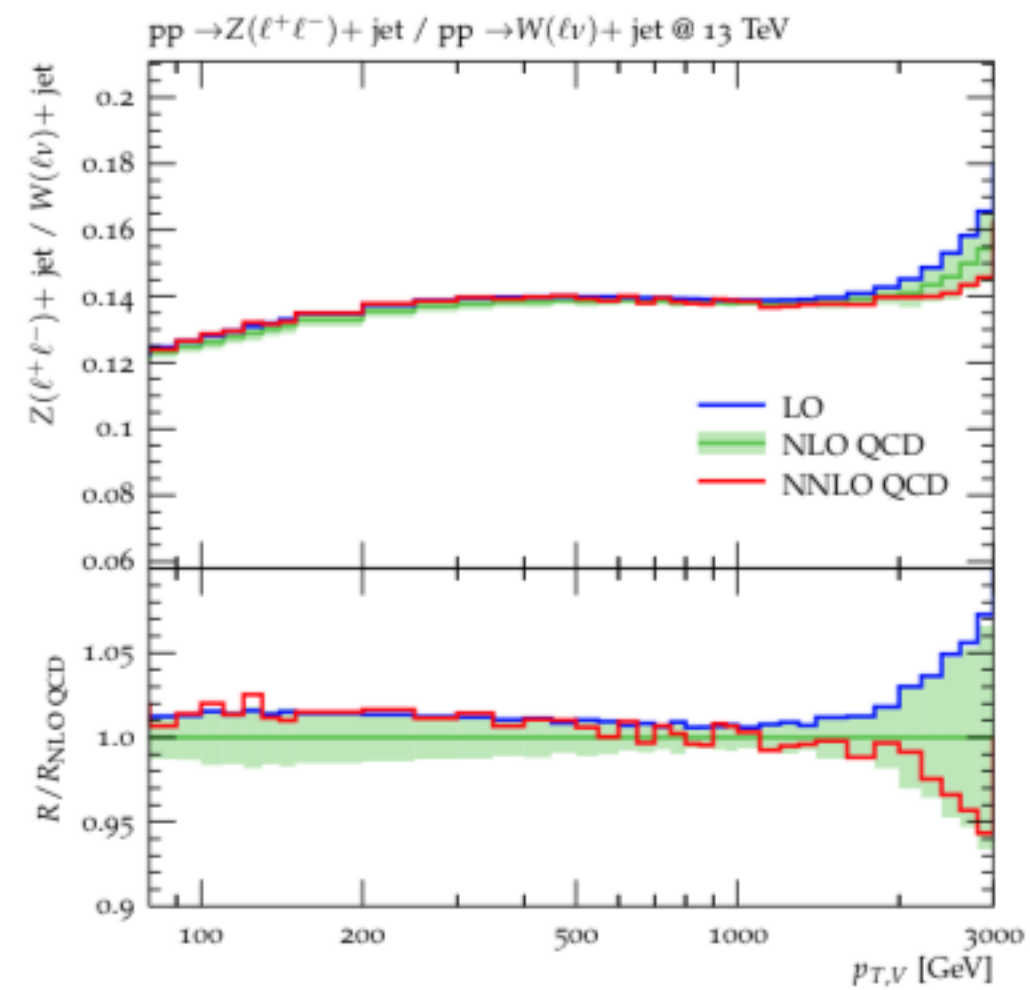
- assume the W/Z cross-section ratio is known to a given precision

(ATLAS MC accuracy: Sherpa NLO up to 2 partons, LO up to 4 partons)

Z(ll)/W(ll) cross-section ratio at higher order

EW uncertainties >> QCD uncertainties





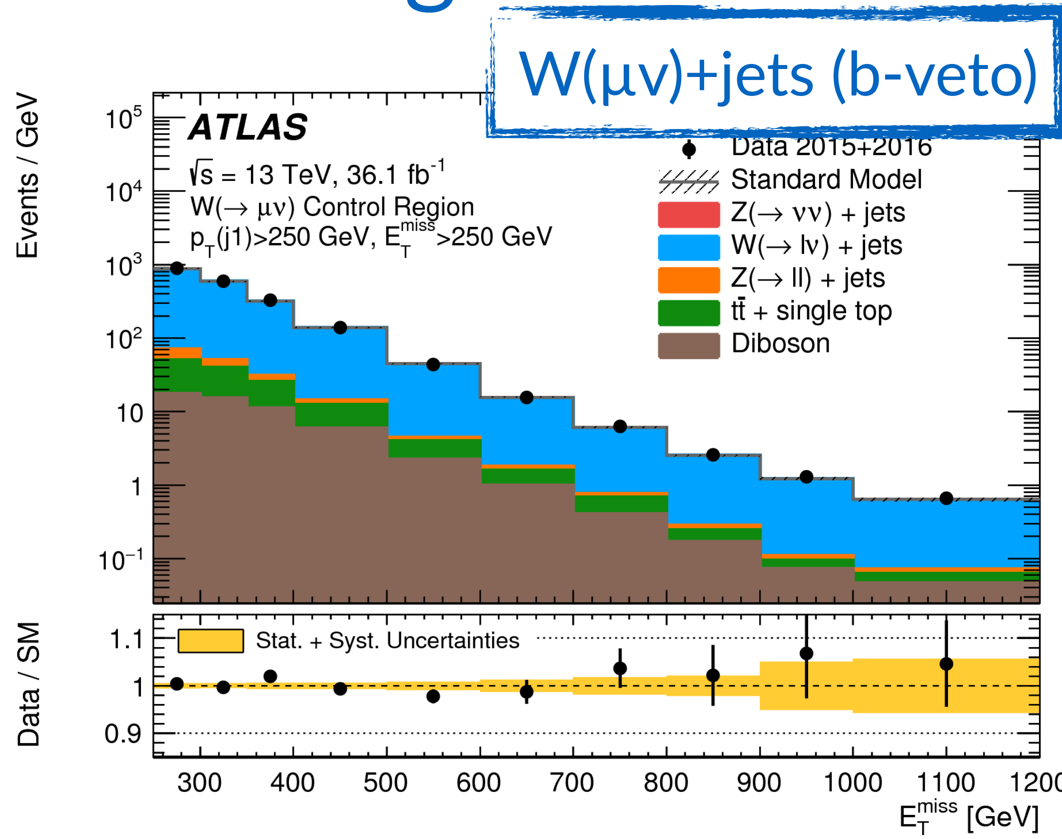
key points:

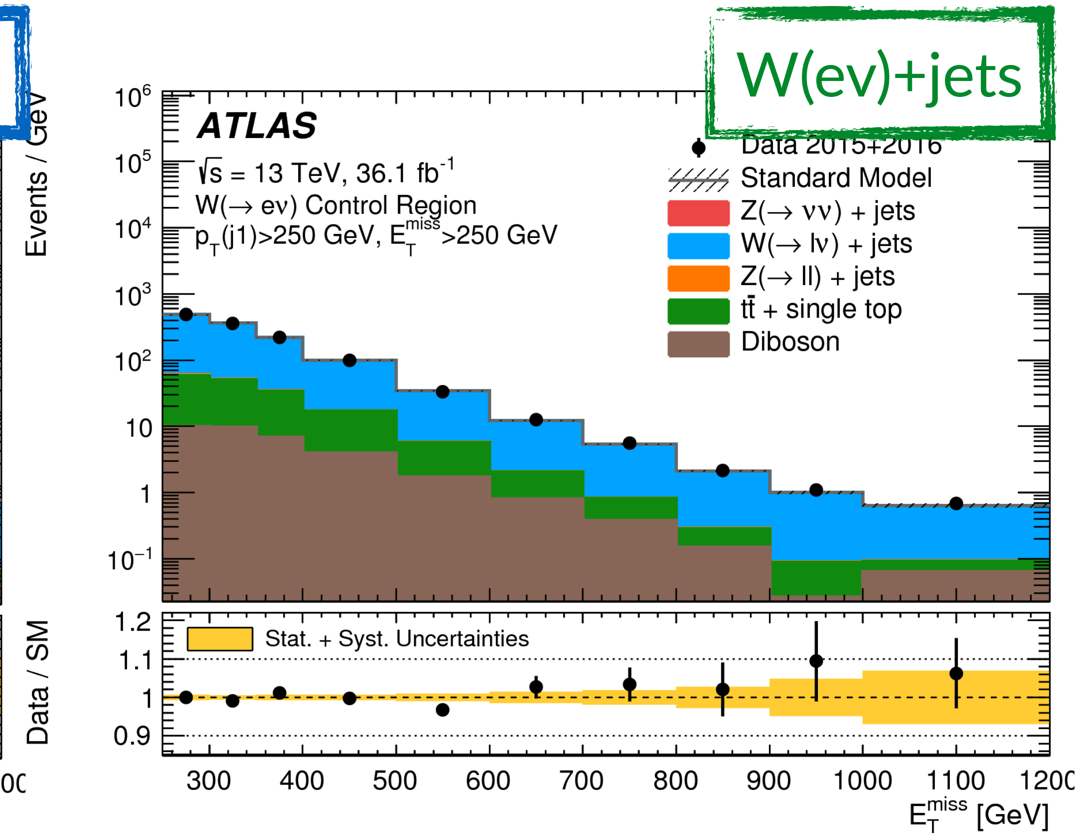
- shape and normalisation uncertainties on the W/Z cross-section ratio
  - correlation scheme from state-of-the-art theory calculations
- fit an overall correction factor common to W and Z

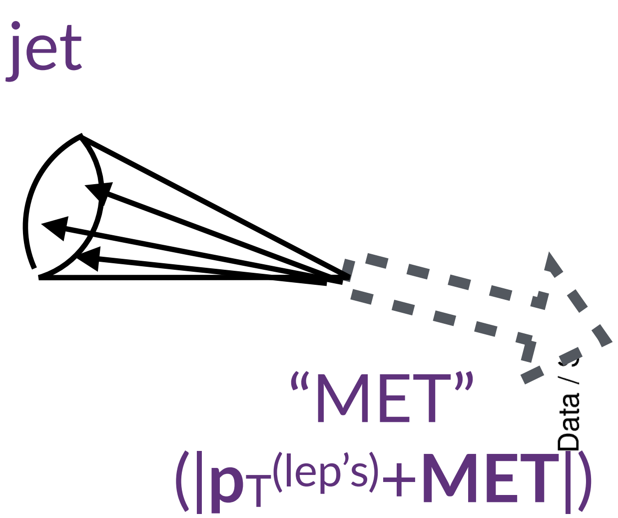
p_T(W/Z) in control regions

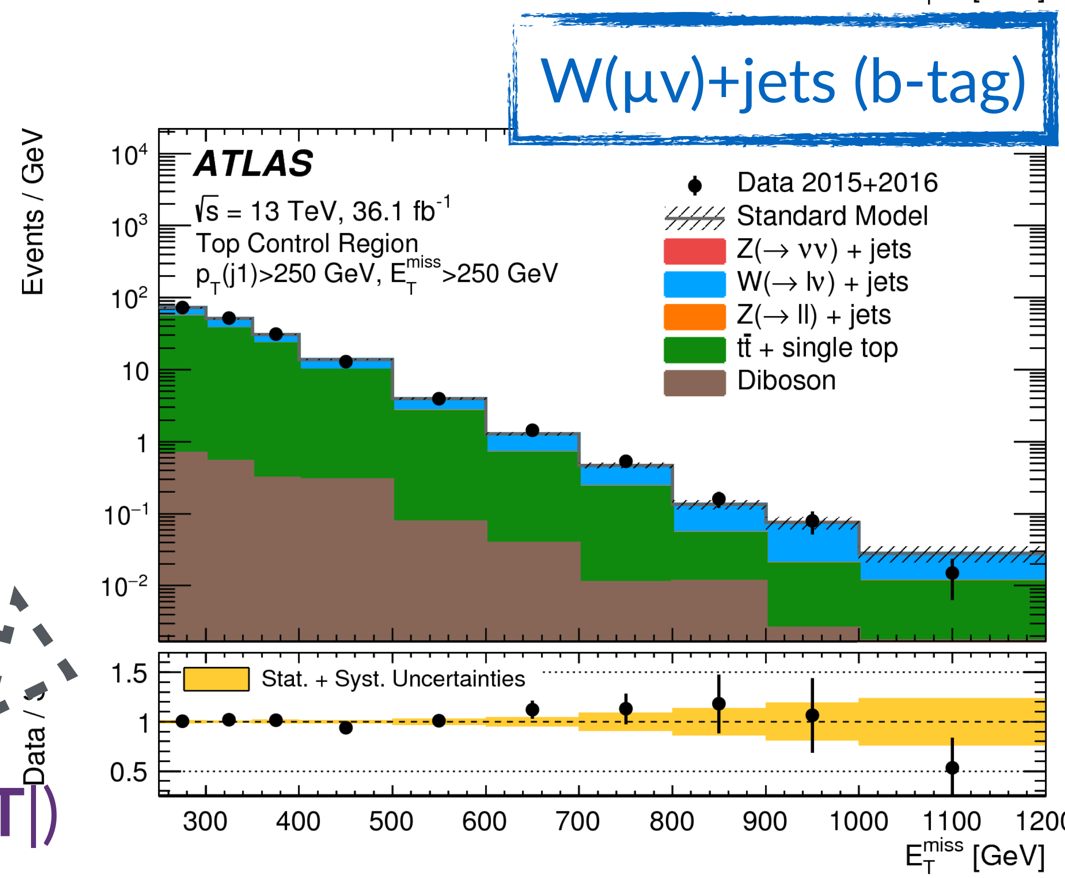
fit parameters:

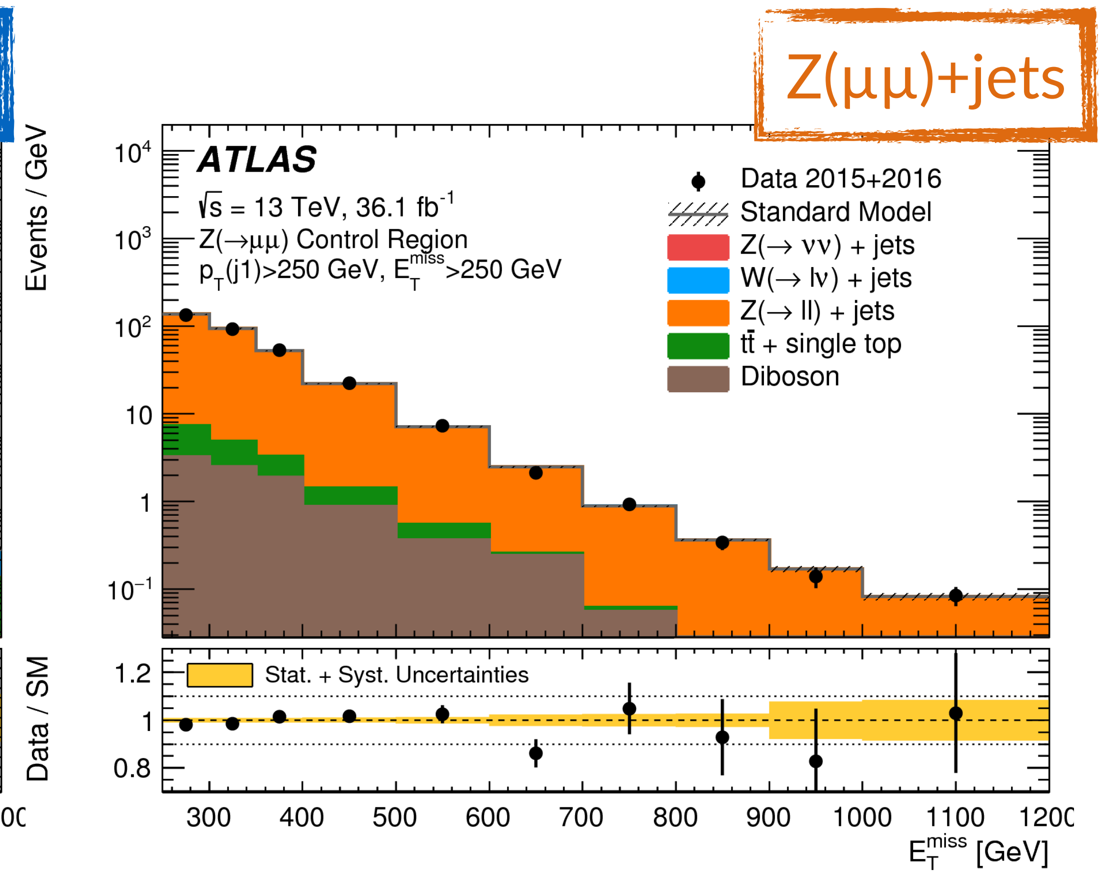
- W/Z normalisation (free, common also to Z(νν)+jets)
- ttbar/single-t normalisation
- shape/ normalisation uncertainties (constrained)



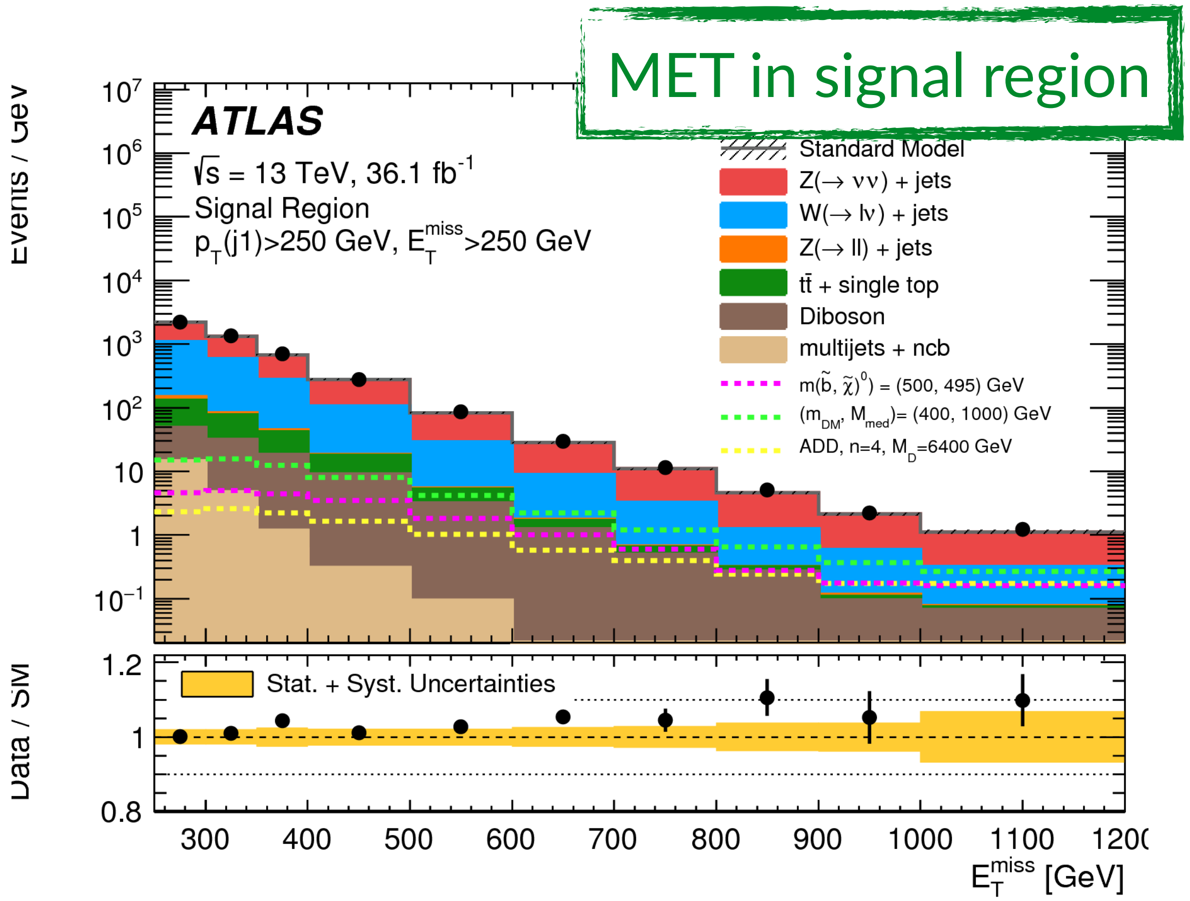








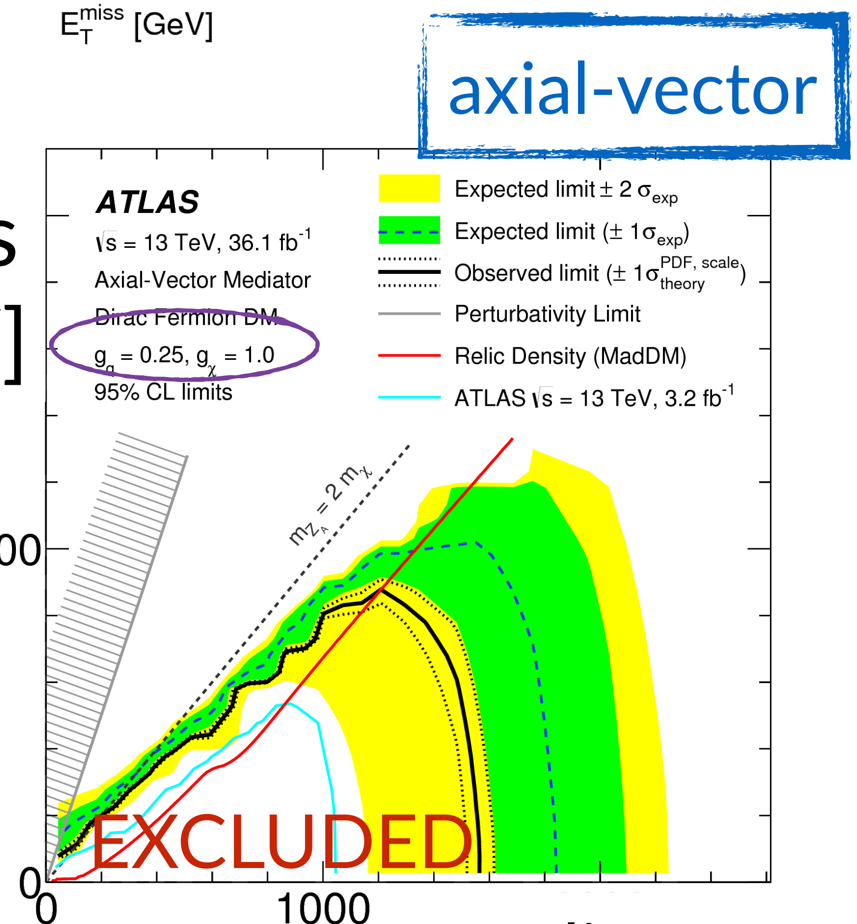
MET+jets: results

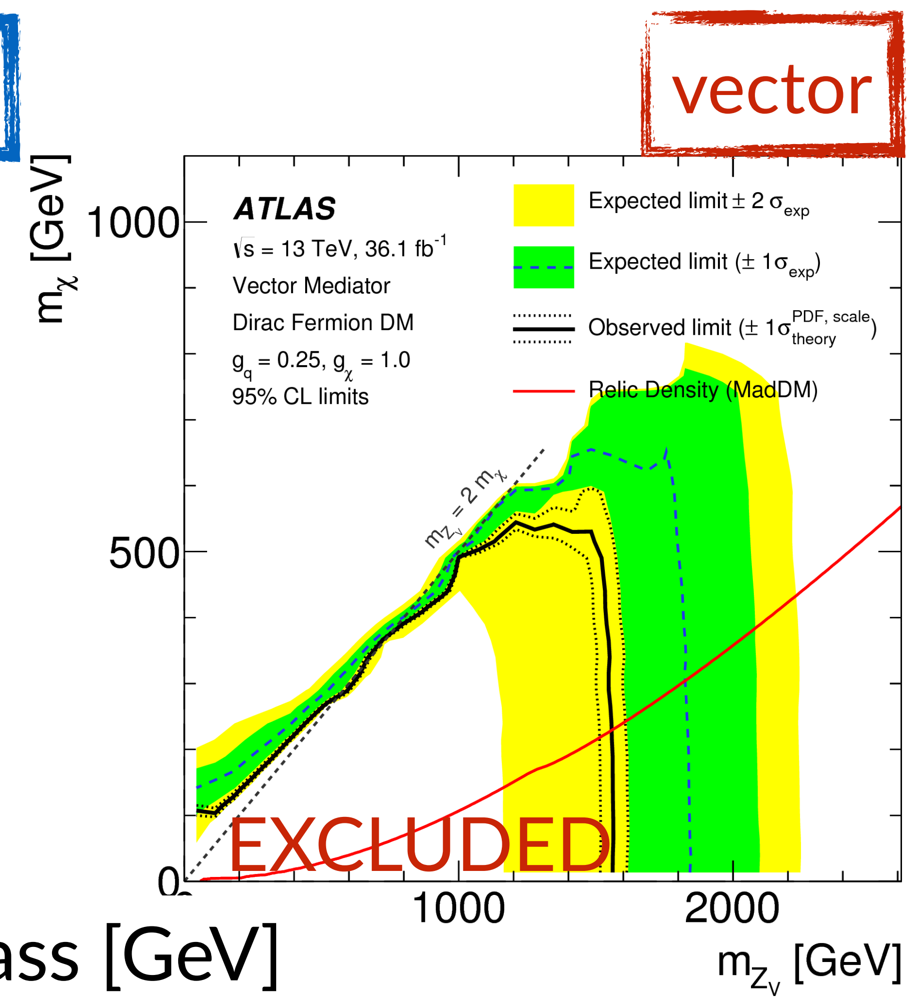


- 2-7% uncertainty on signal region background
  - theo: 0.7-1% for the W(lv)/Z(ll)->Z(vv) extrapolation
  - exp: electron/muon efficiency, jet energy scale/reso
- probing s-channel ($J^P=0^-, 1^+, 1^-$) and t-channel DM-SM interactions
  - pseudoscalar: cannot yet exclude model with g=1

discovery potential depends on assumed interaction and couplings!

DM mass [GeV]





mediator mass [GeV]

MET+W/Z(had)

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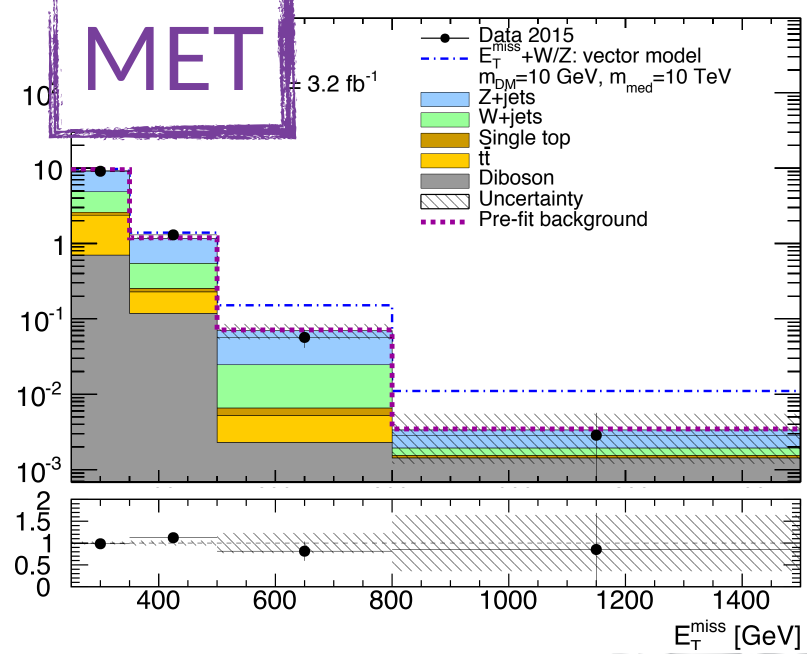
trimmed large-R jet (anti-kT R=1.0), MET > 250 GeV

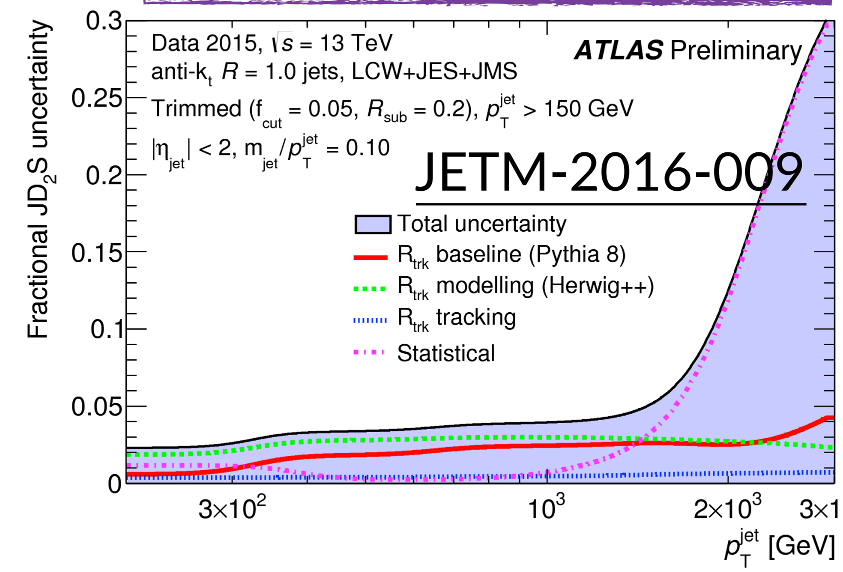
- with 1μ1b CR for reducing ttbar uncertainties

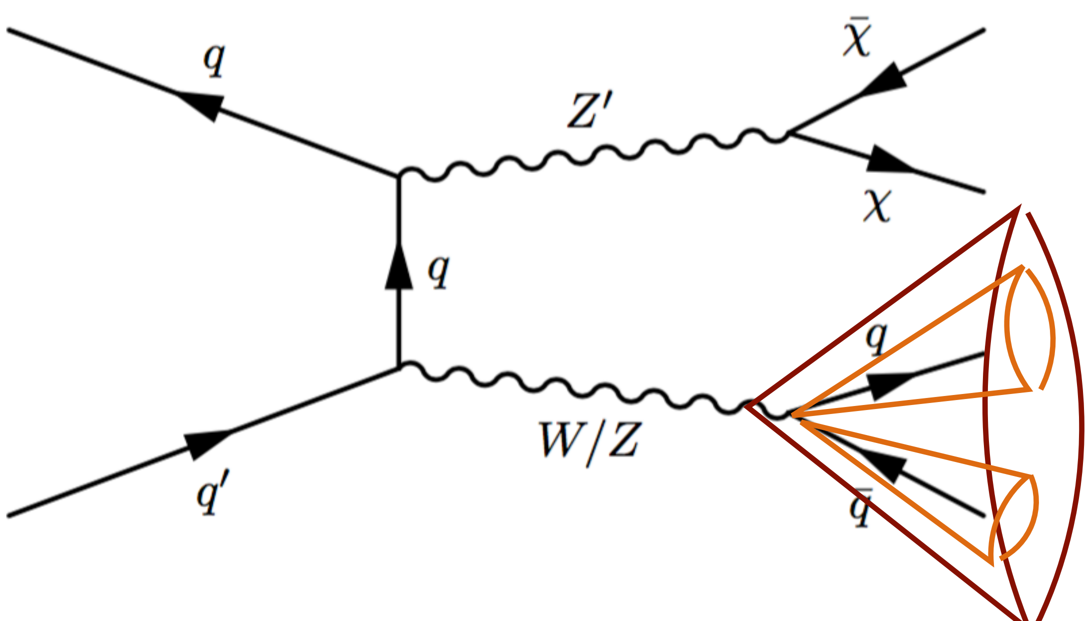
boson tagging based on jet mass and p_T-dependent cut on 2-prongness ("D_2", ε~50%), main uncertainty on total bkg (5-13%)

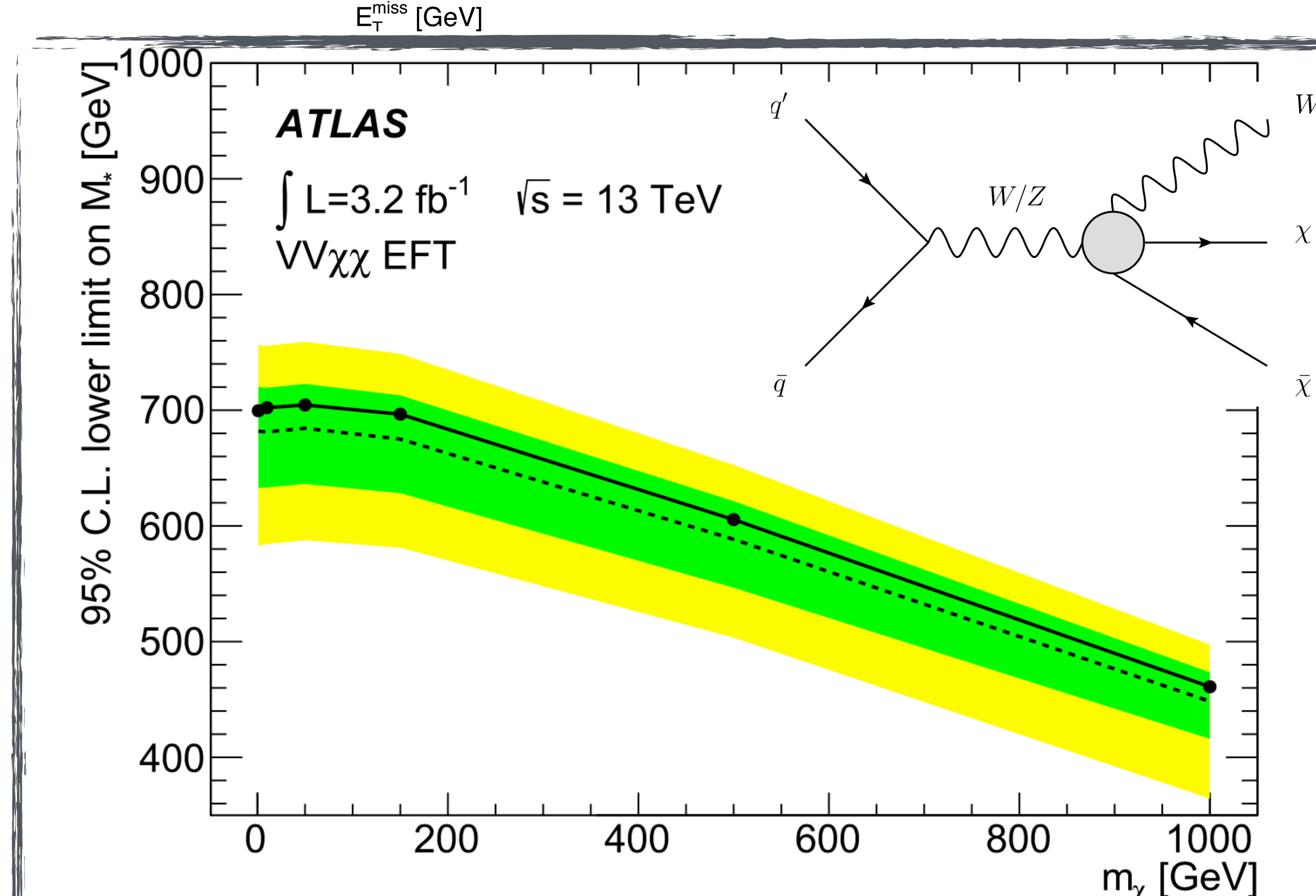
MET



D2 scale uncertainty





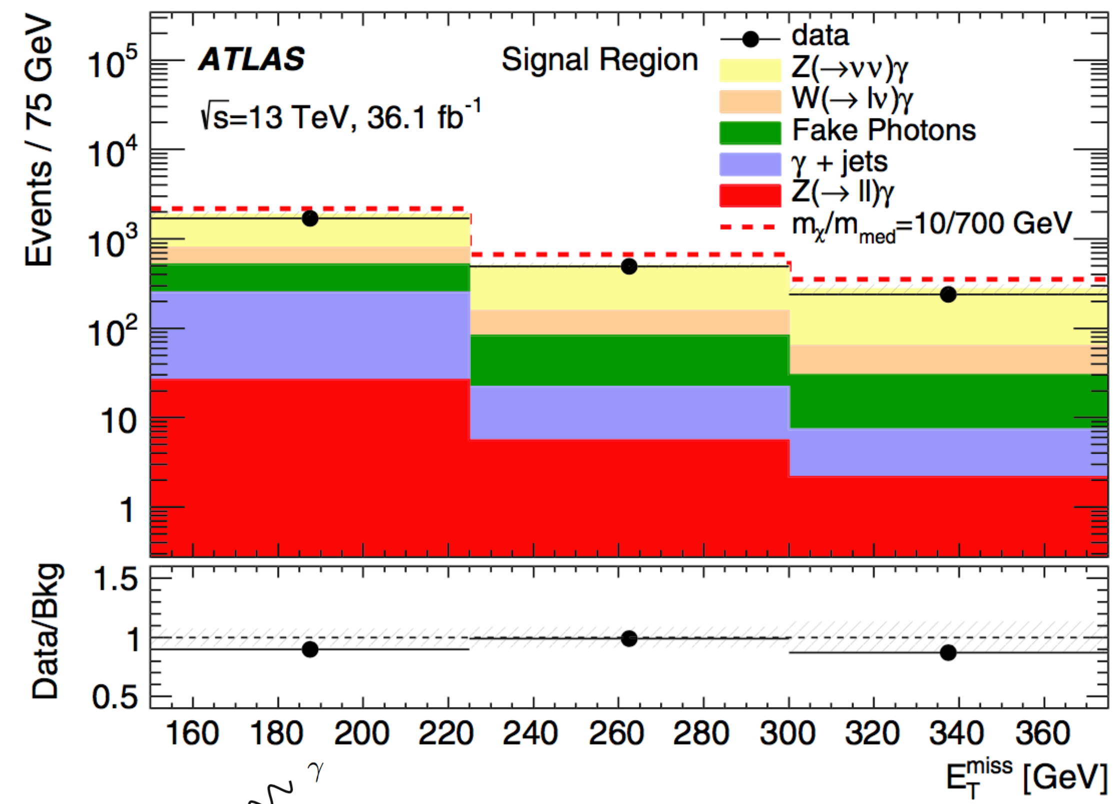


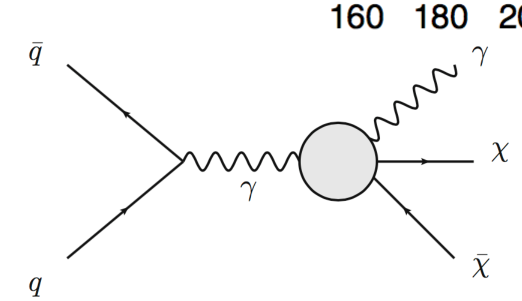
MET+photon

Eur. Phys. J. C 77 , 6 (2017) 393

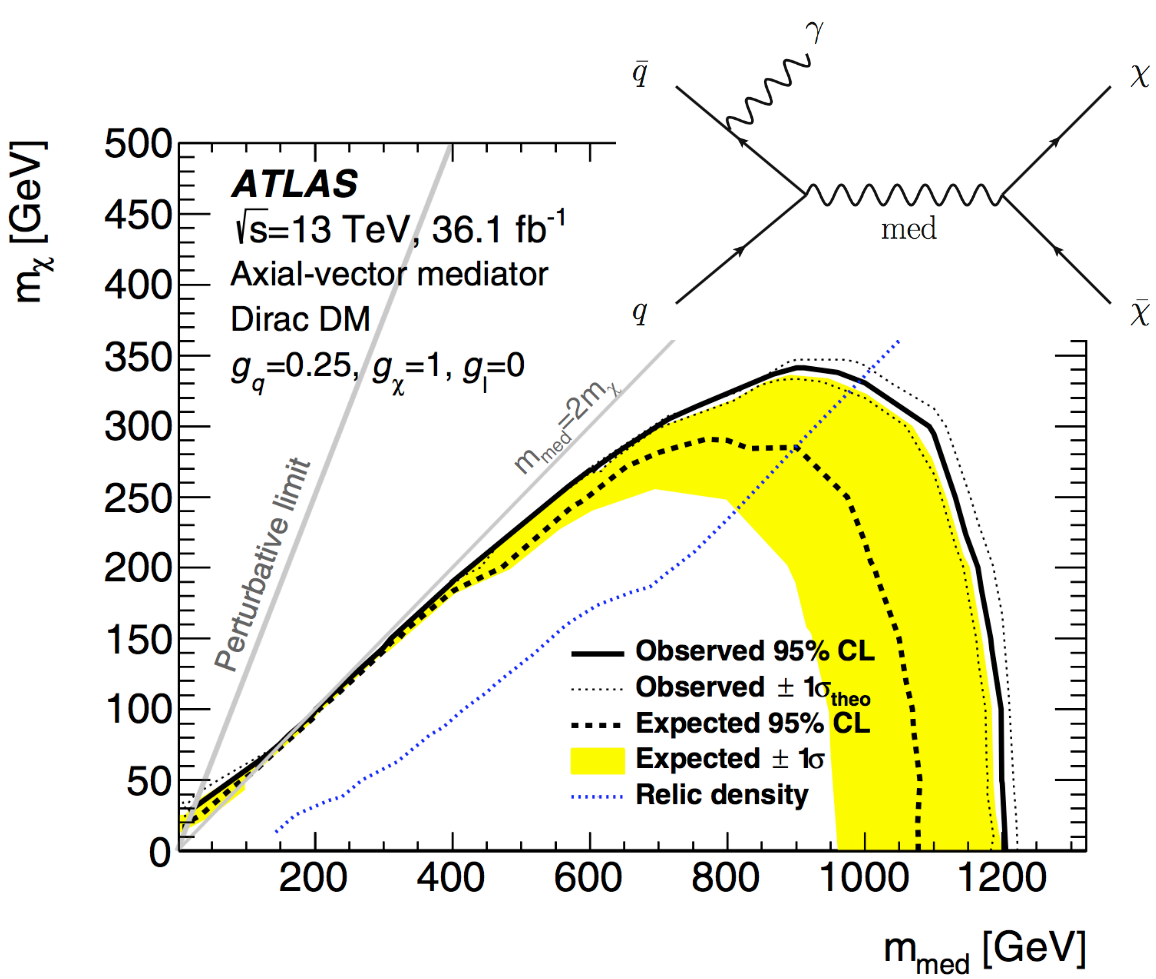
similar strategy as monojet

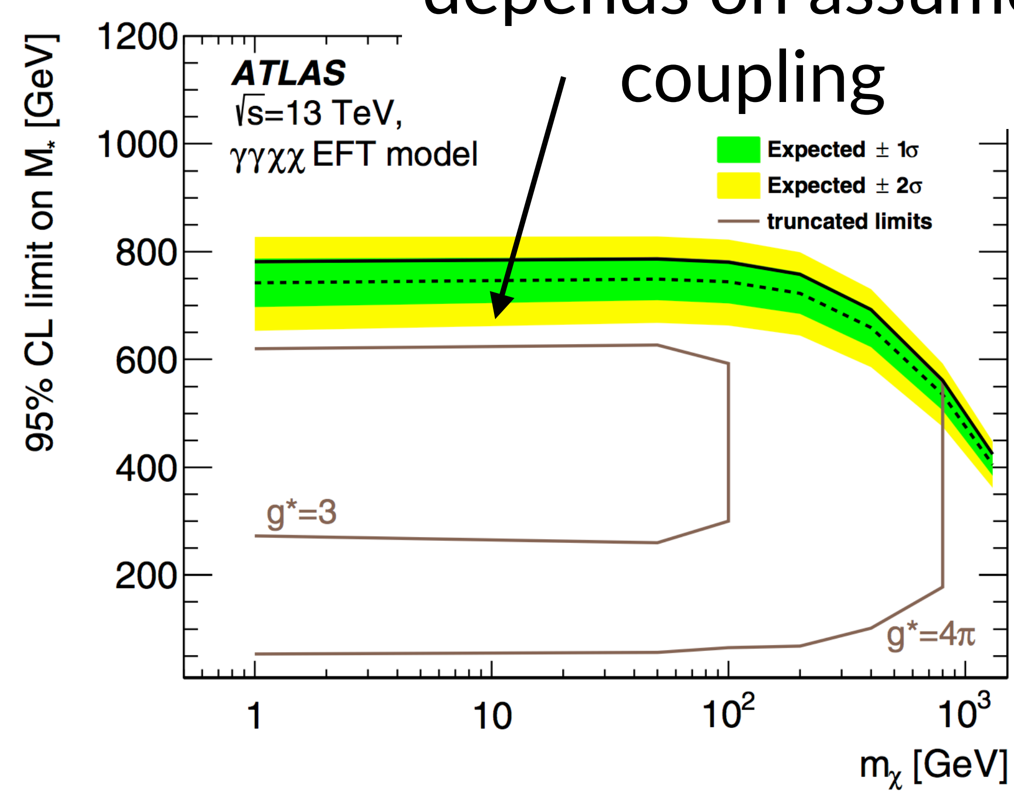
- statistical uncertainties still dominant
- main systematics from jet->γ fake factor (ABCD method, 1-5%)
- e->γ fake factor applied to MET+e events (1.5%)
- jet energy scale (6-1%)
- also sensitive to $\gamma\gamma\chi\chi$ EFT

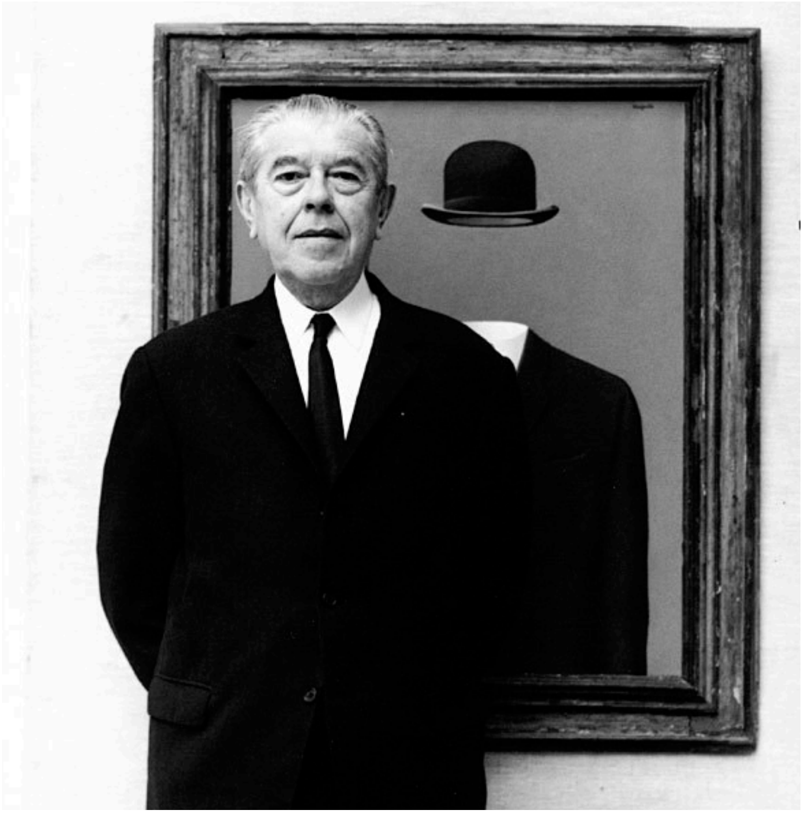




EFT validity (& result) depends on assumed coupling



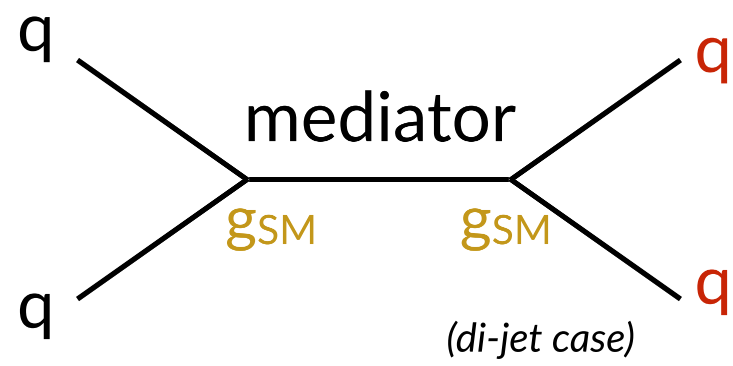




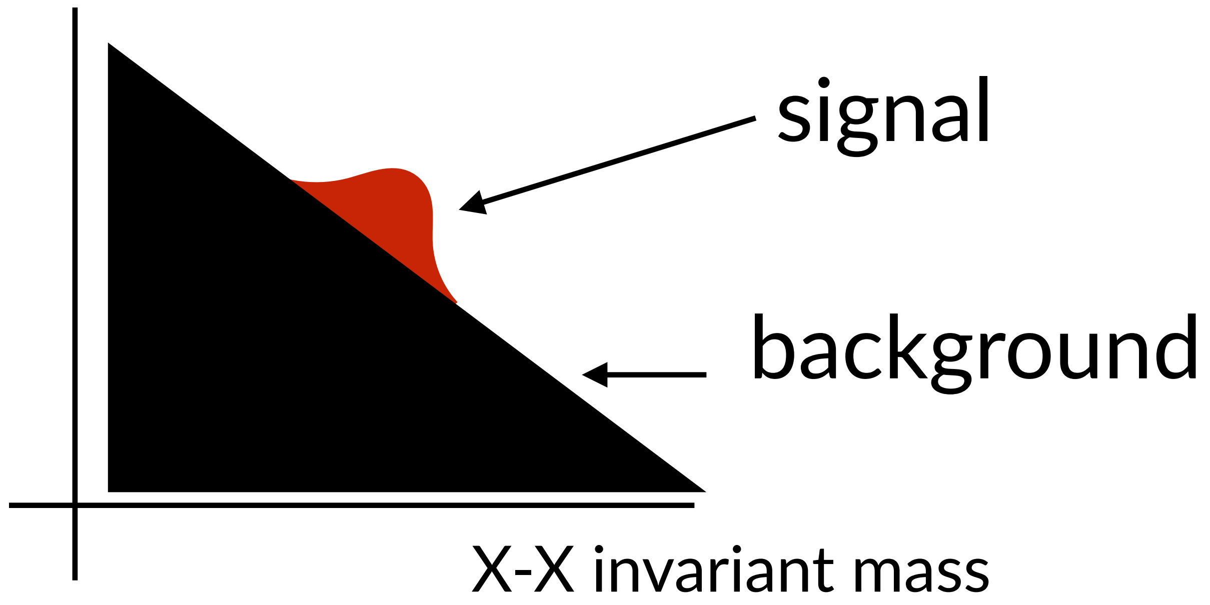
The visible

di-jet, di-lepton, di-top…

Di-X: resonance searches



look for the mediator



<u>Ye Olde Resonance Discovery Algorithm</u>

1. collect the events
2. discriminate signal from background

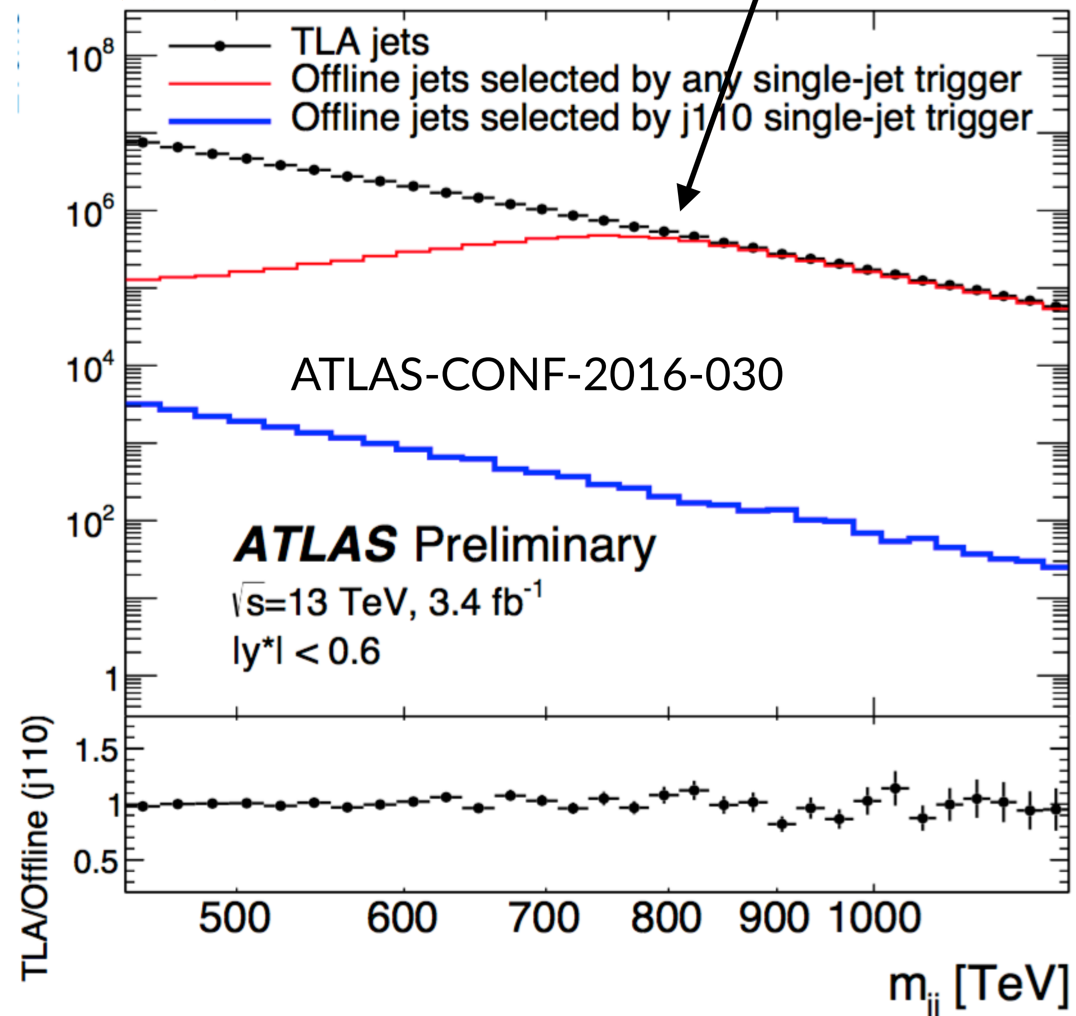
let's take di-jet as an example

Challenge #1: collect the events

L1 trigger rate limited to 100 kHz -> high p_T threshold for single jet triggers bounds mediator mass reach from below

dijet mass spectrum

first unprescaled single jet trigger at p_T > 400 GeV



"offline" dijet search

solution #1: store only minimal jet information ("data scouting")

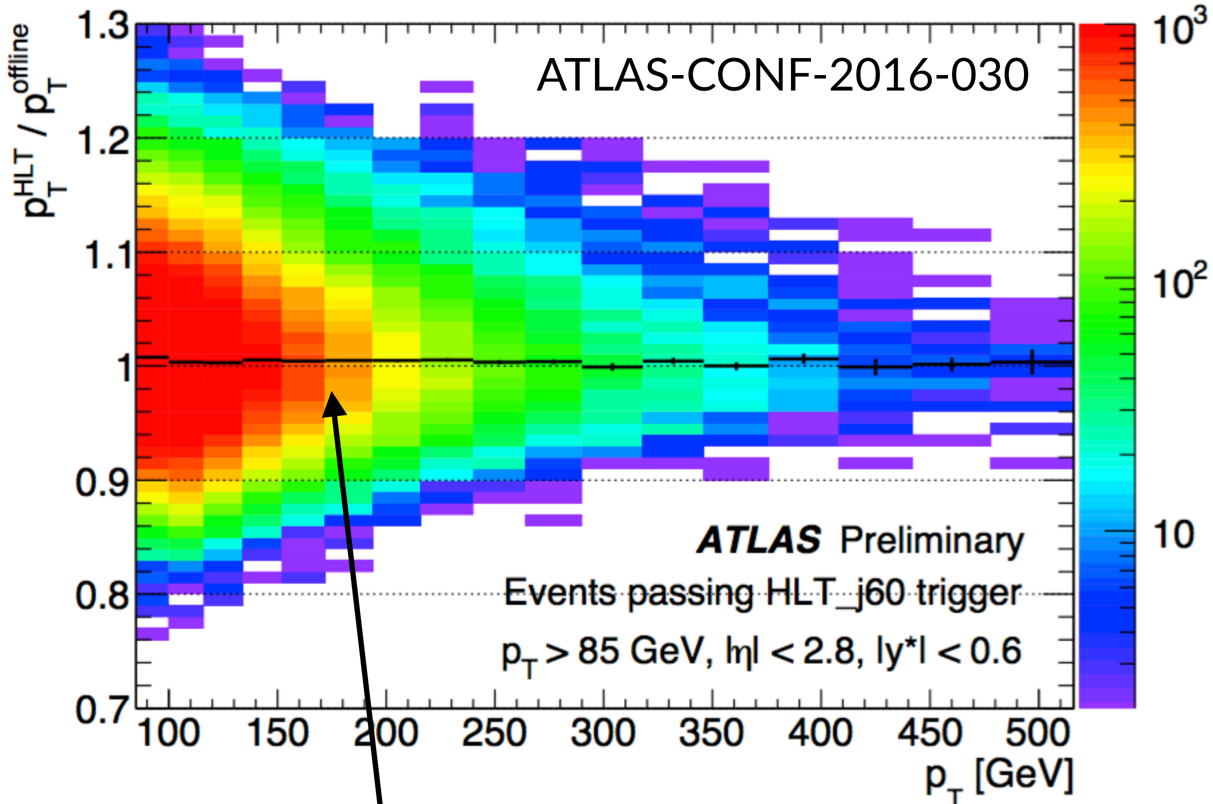
- start with 75 GeV L1 trigger (+2 kHz; EM scale)
- save all HLT jets above 4 GeV (~5% of total event size)
- calibrate them using offline jets
  - no tracking info -> 3.5-5% systematics (mostly due to flavour uncertainties)

solution #2: trigger on an ISR object

solution #3: use boosted boson tagging

Trigger-level vs offline jets

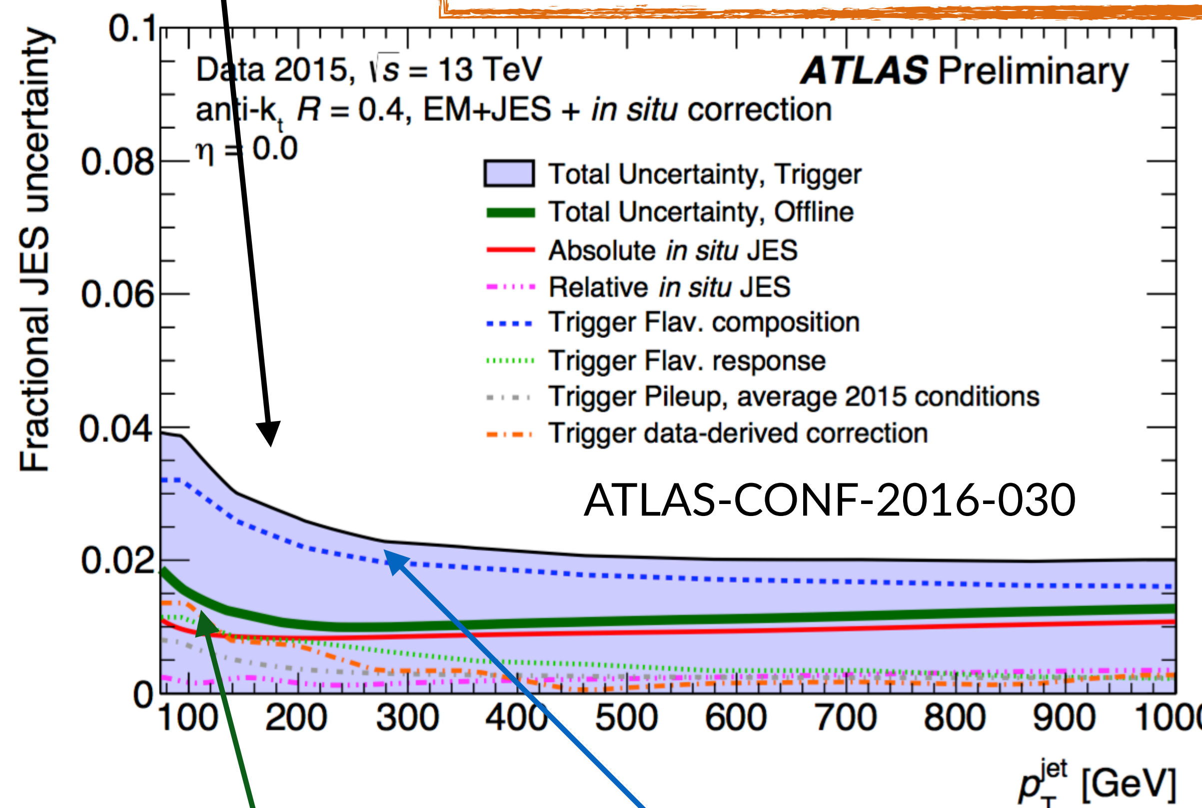
pT(trigger)/pT(offline) vs pT



trigger/offline pT response within ~1%

trigger jet total

energy scale uncertainty



offline jet total

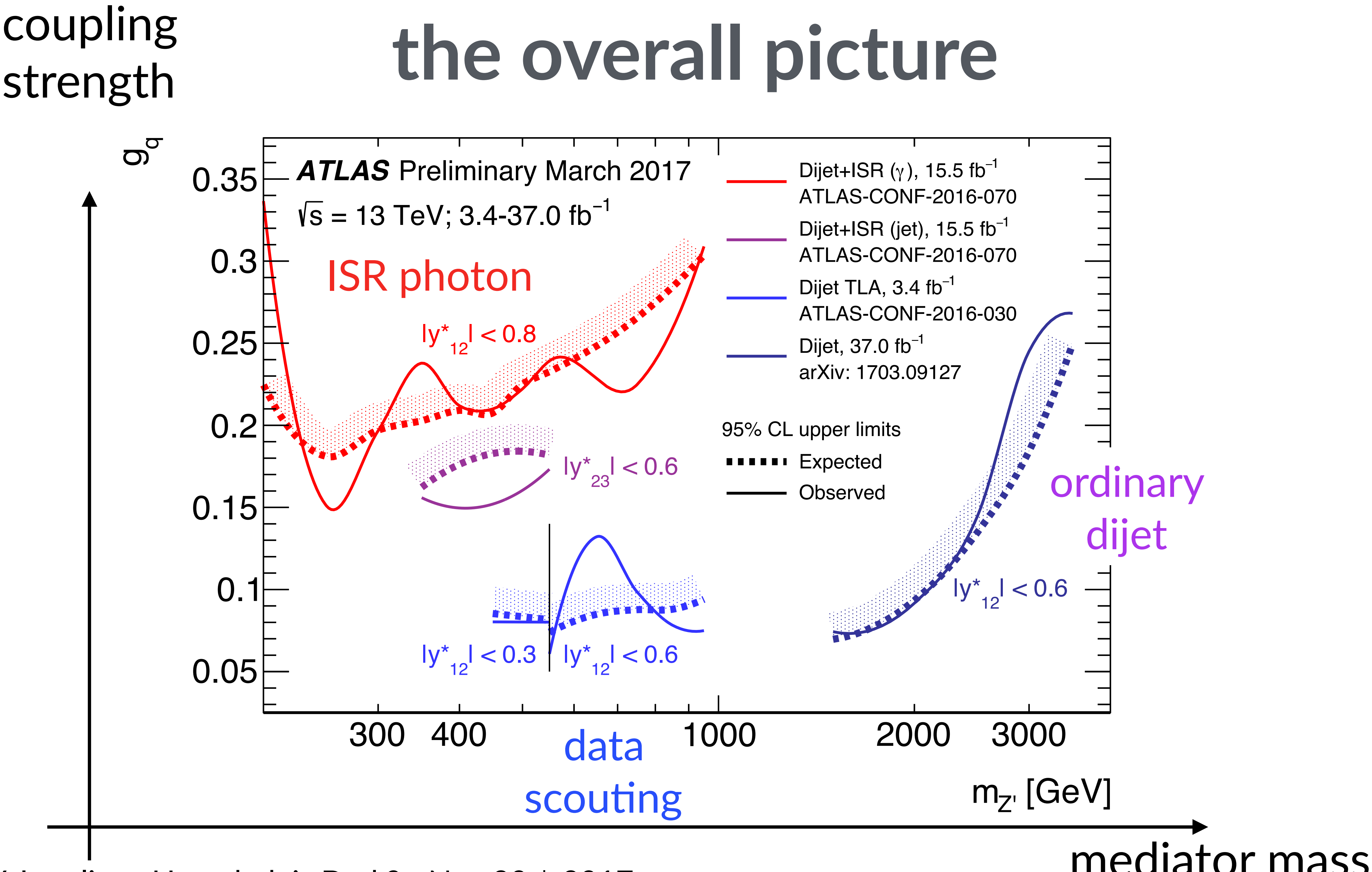
flavour composition (q vs g)

trigger-level tracking information would help...

Di-jet search strategies, compared

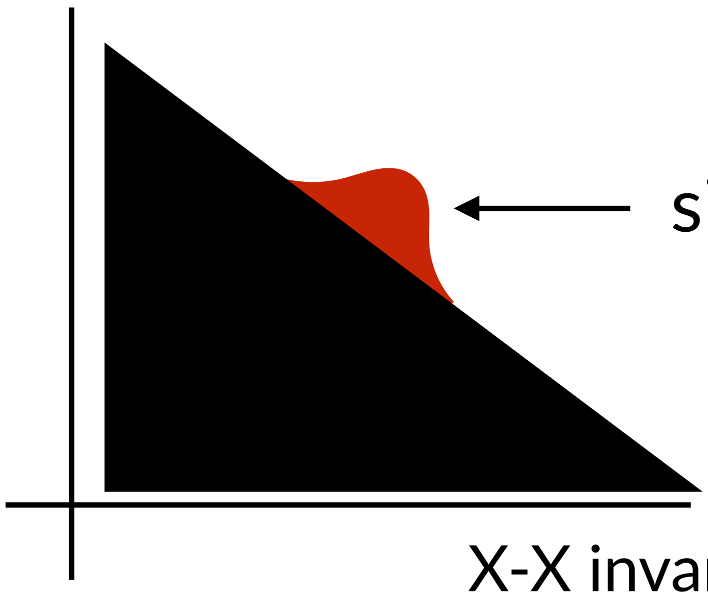
- ISR photon
  - one photon with pT>150 GeV
  - 2 jets with p_T > 25 GeV, |y*|<0.8
- ISR jet
  - one jet with pT > 430 GeV
  - 2 jets with pT > 25 GeV, |y*|<0.6
- extend range to lower masses

the overall picture



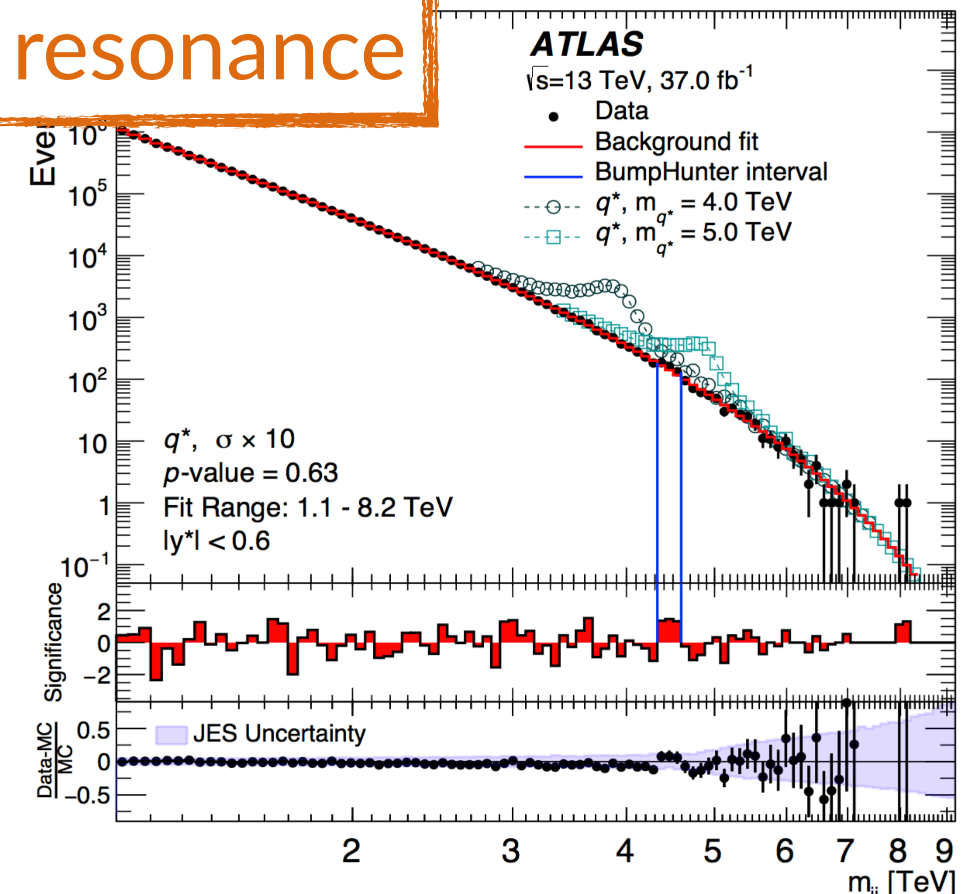
Challenge #2: signal-to-background discrimination

small width/mass

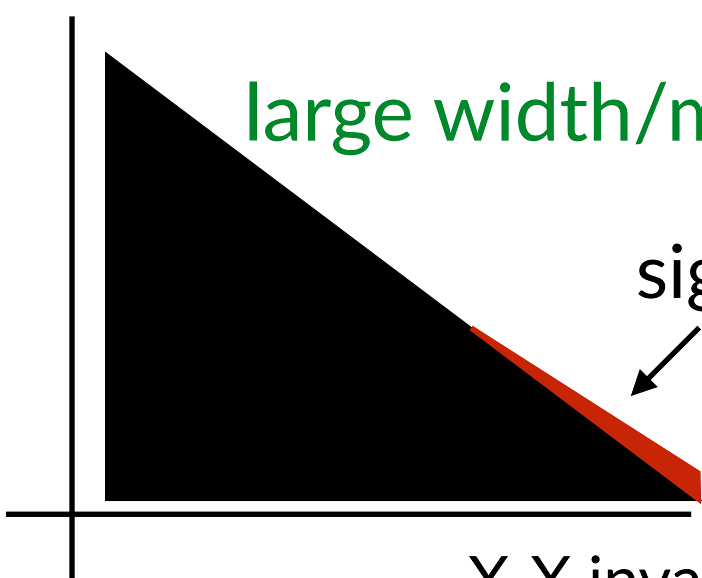


mediator-SM/DM coupling sets event rate and peak width

di-jet resonance



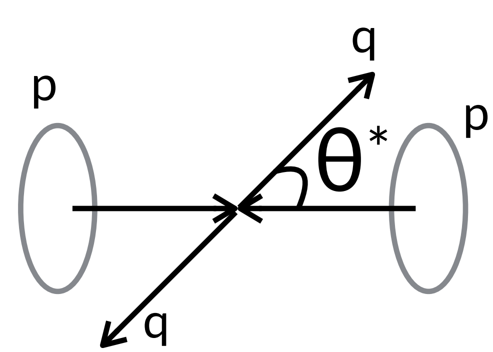
large width/mass



di-jet angular

use instead:

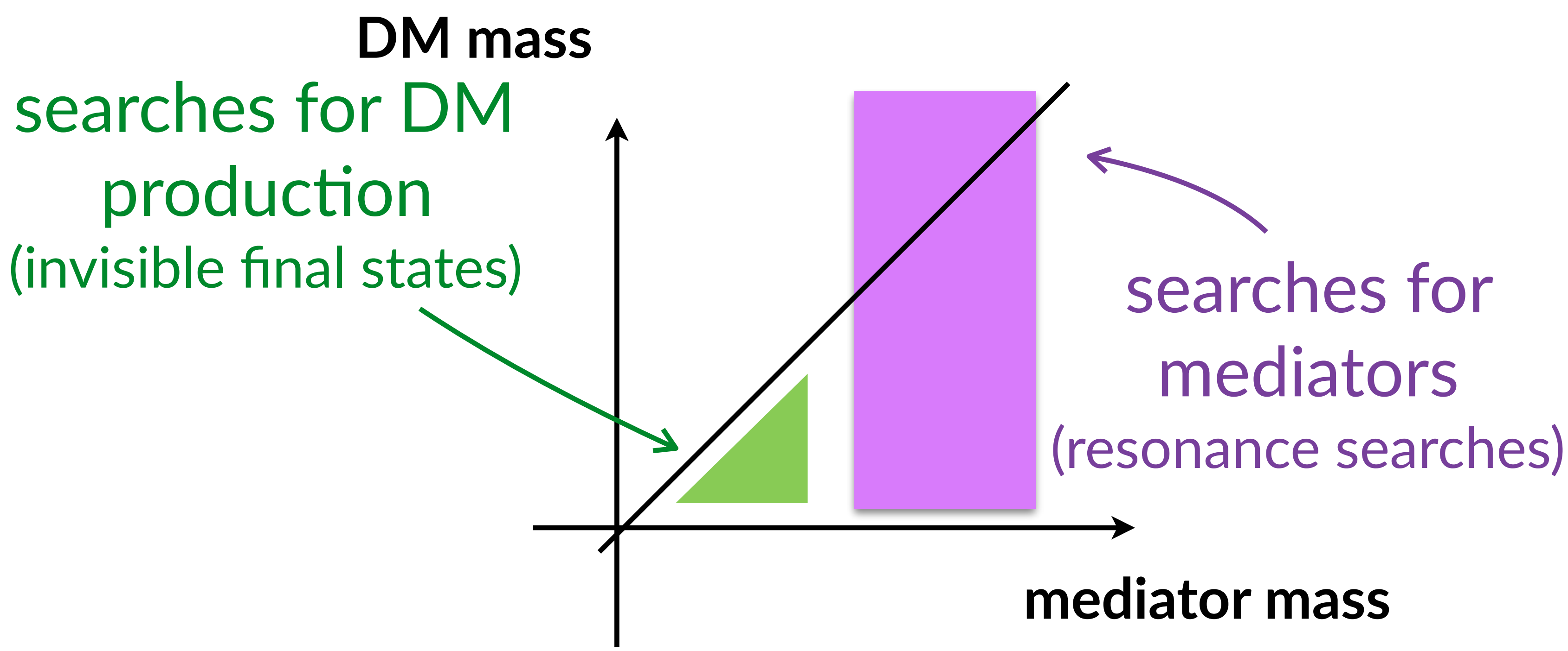
$$\chi_{dijet} = e^{|y_1 - y_2|} \sim \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$



extends searches at higher masses (~3-4 TeV) and couplings

Implications for direct detection

1. take LHC results (high Q^2) at fixed values of the couplings



focus on spin-1 due to available luminosity

2. extrapolate to low Q^2 of direct detection (EFT)

caveat: 1605.04917

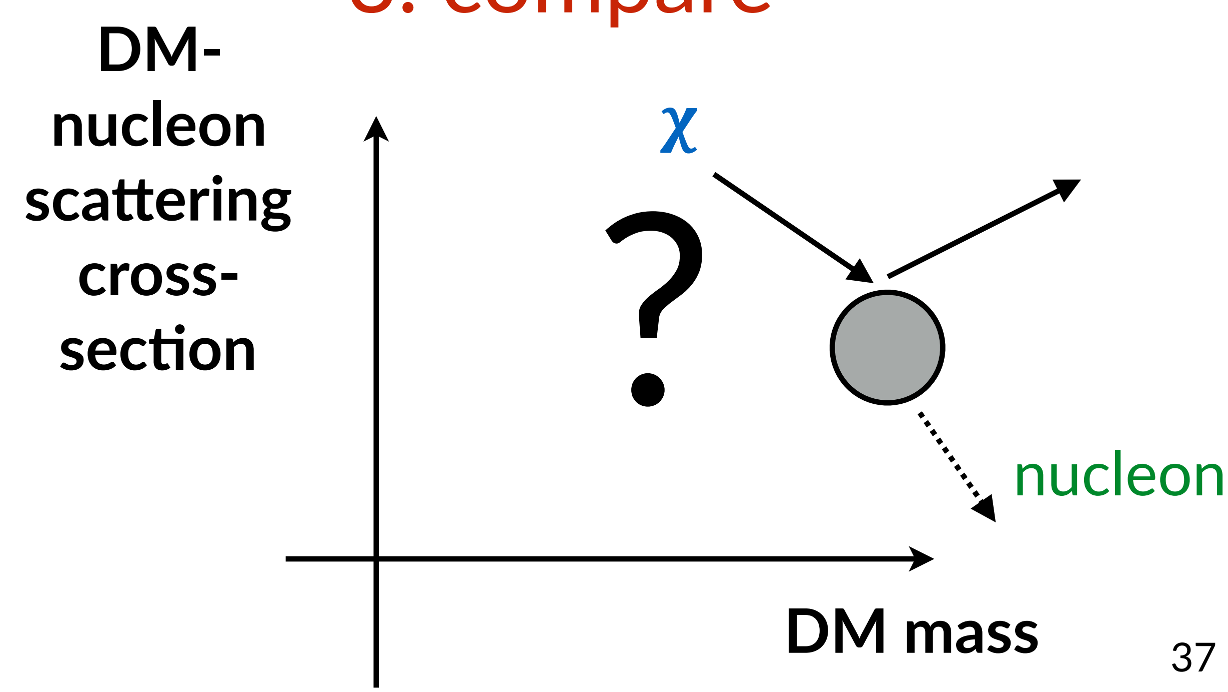
0^+ $\sigma_{SI} \approx 1.1 \times 10^{-39}\ \mathrm{cm}^2 \cdot \left(\frac{g_{DM}\, g_q}{1}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$

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

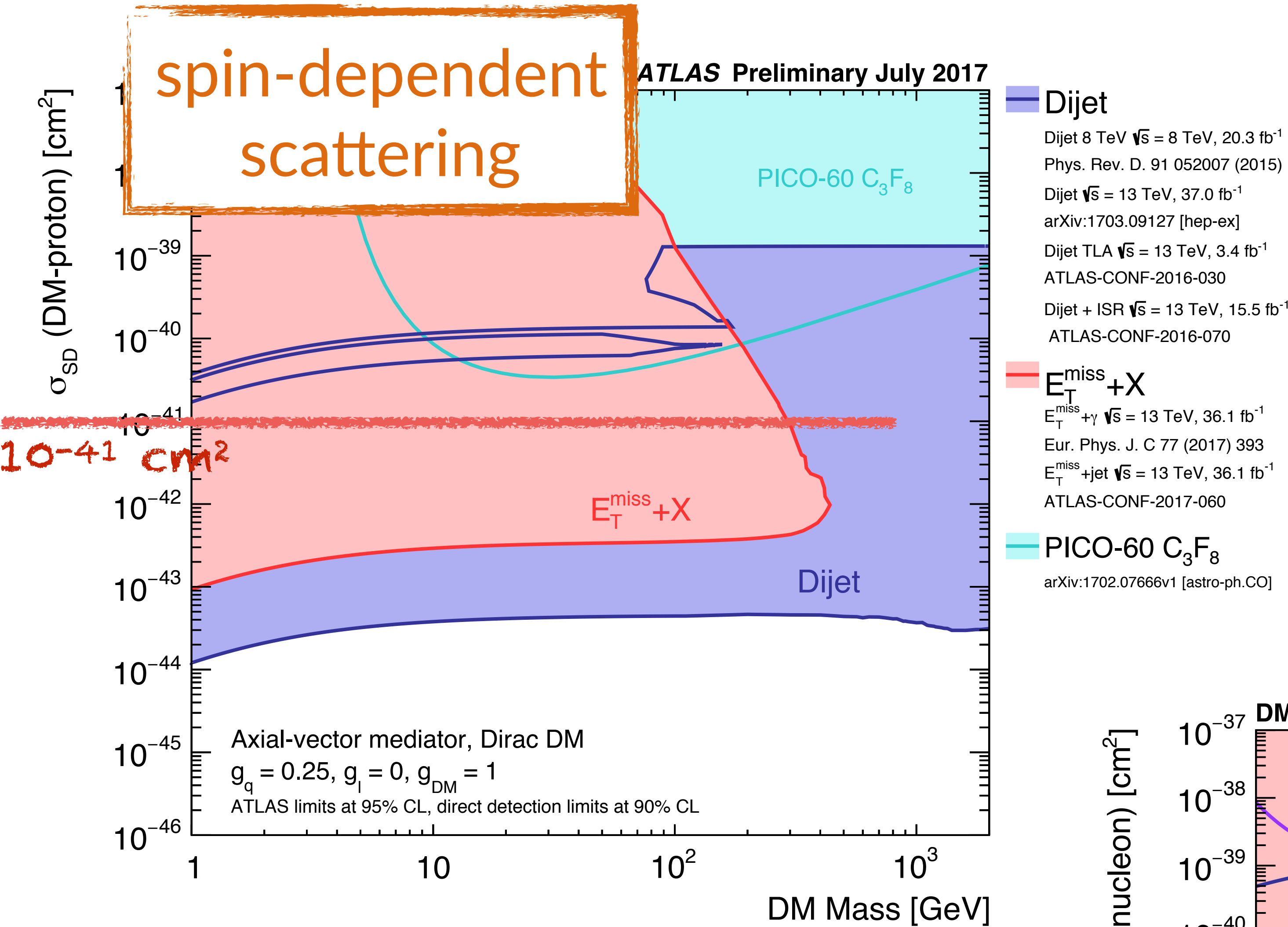
1^+ $\sigma_{SI} \approx 6.9 \times 10^{-43}\ \mathrm{cm}^2 \cdot \left(\frac{g_{DM}\, g_q}{1}\right)^2 \left(\frac{125\ \mathrm{GeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$

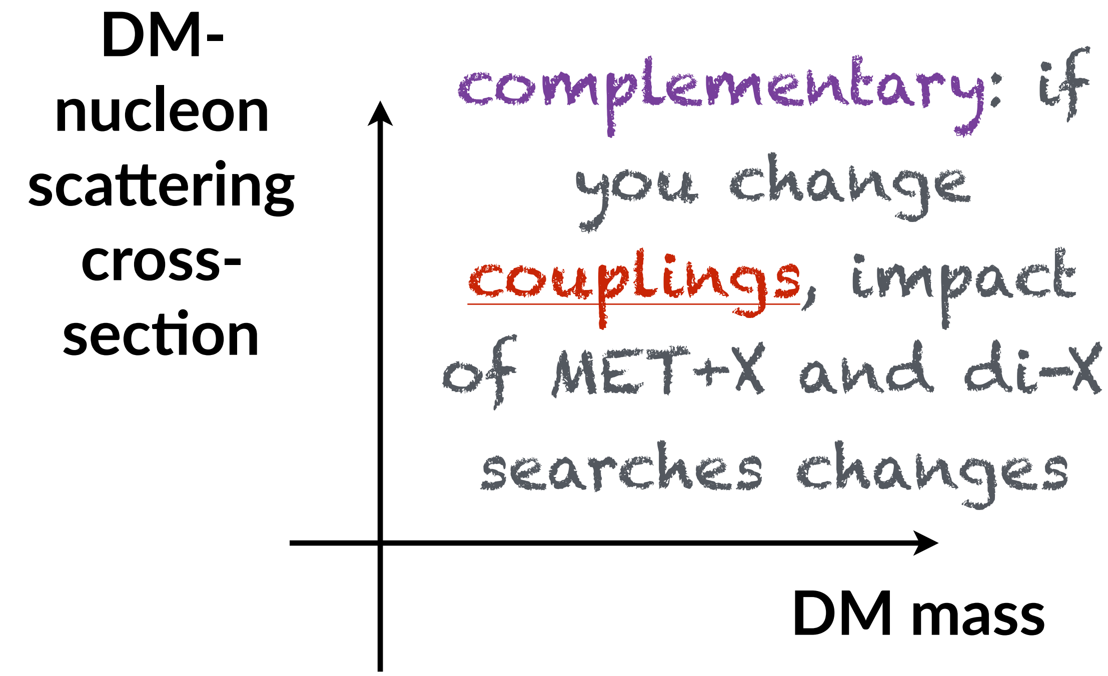
1^- $\sigma^{SD} \approx 3.8 \times 10^{-41}\ \mathrm{cm}^2 \cdot \left(\frac{g_{DM}\, g_q}{1}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$

3. compare



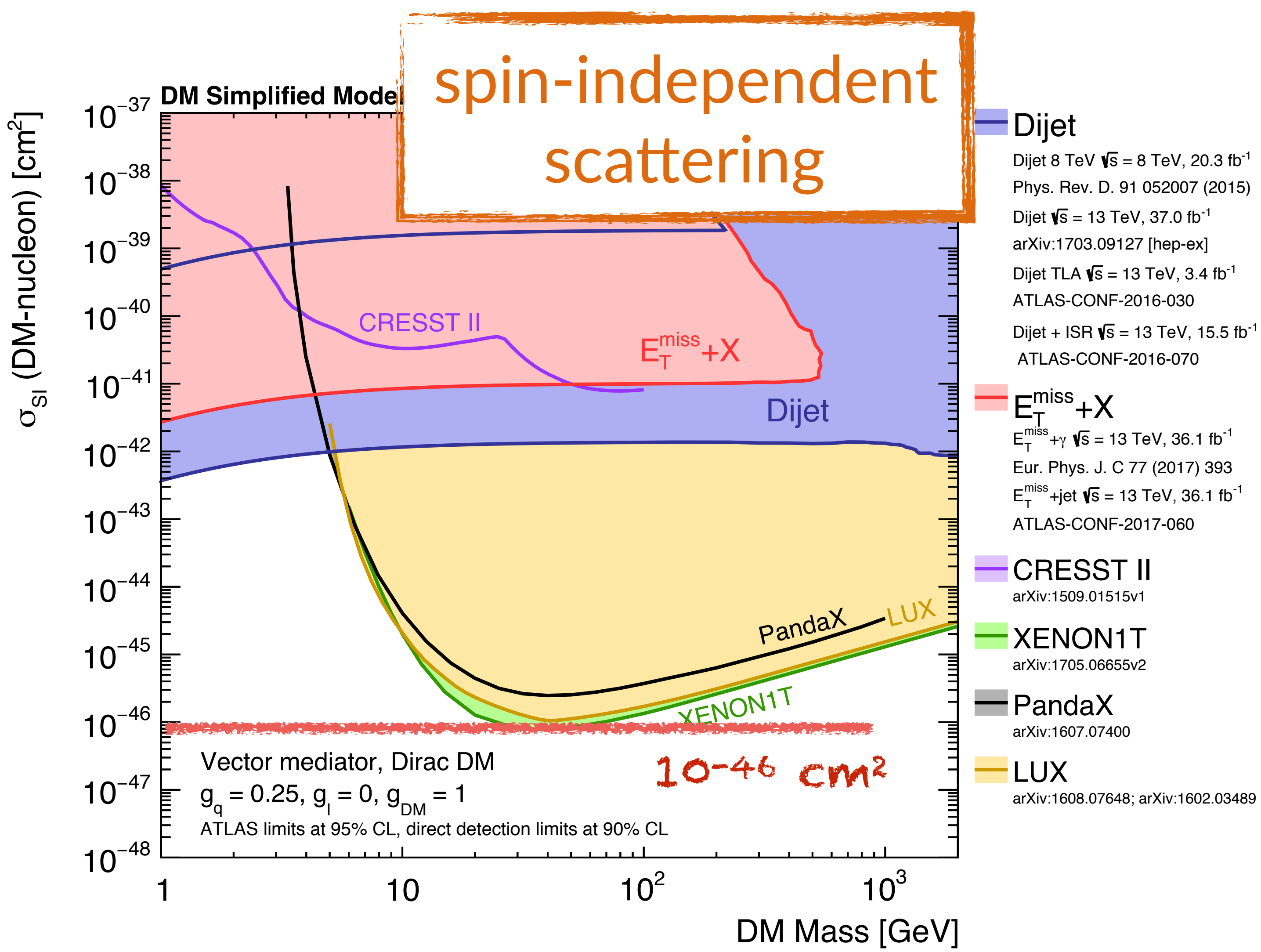
MET+X vs di-X





:-(need to **explore** the parameter space

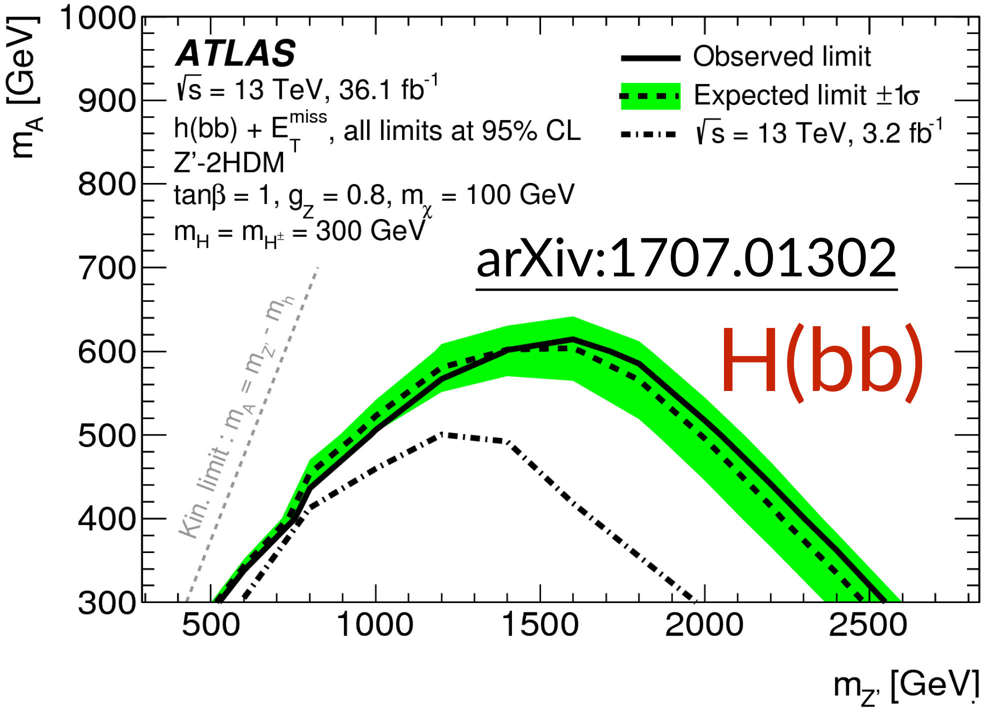
:-) multi-signature: could **characterise** a discovery

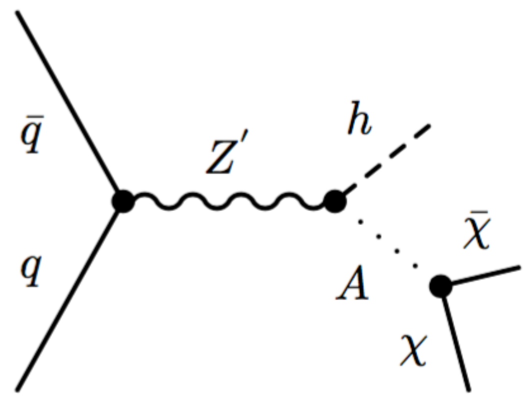


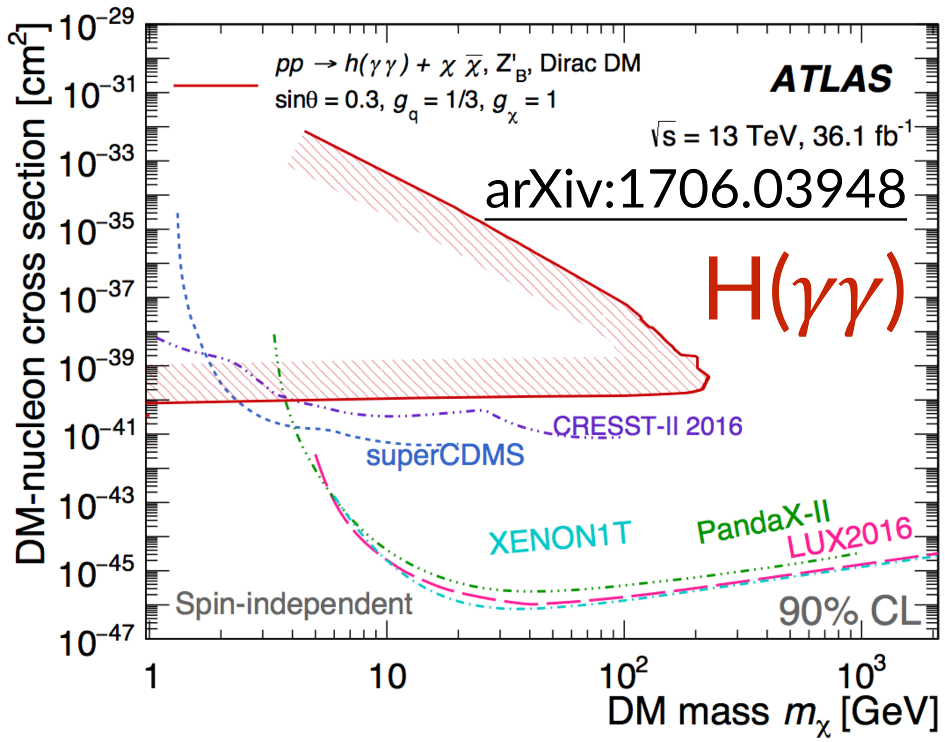
The non-trivial

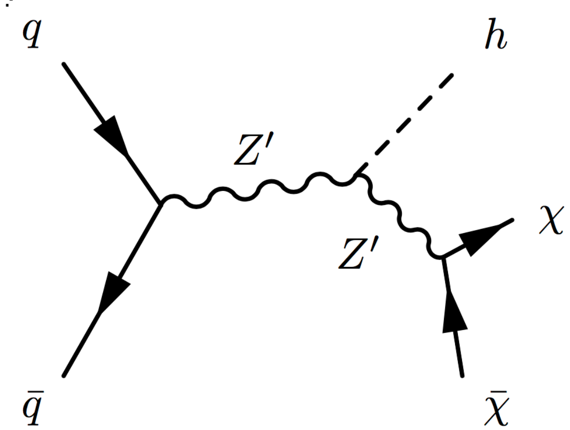
spin-zero interactions, SUSY and beyond

MET+H









Higgs boson as a discovery tool!

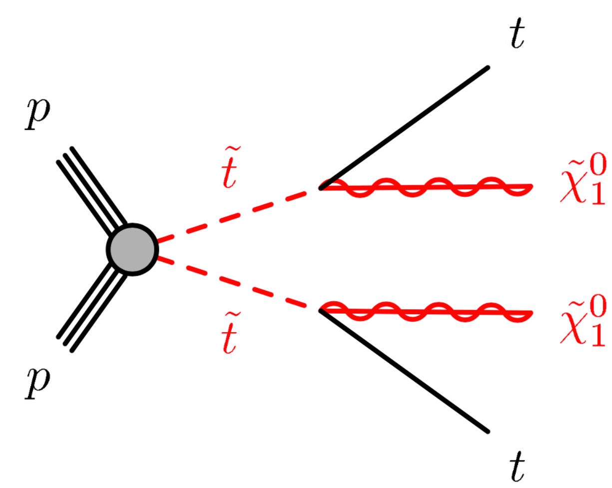
- probe couplings between a new mediator and Higgs sector
- most sensitive channel is H(bb)+MET
  - use m(bb) as discriminant in resolved and boosted regimes (MET </> 500 GeV)
  - bkg from Z(vv)+jet, W+jet and ttbar, 1μ and 2μ/2e CRs

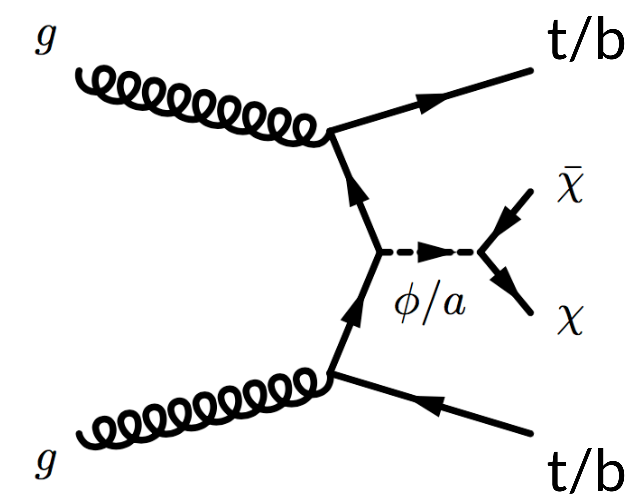
also MET+H(4l) (ATLAS-CONF-2015-059)

theory work ongoing to highlight contribution to spin-0 scenarios
(e.g. https://arxiv.org/abs/1701.07427)

Spin-0: MET+HF

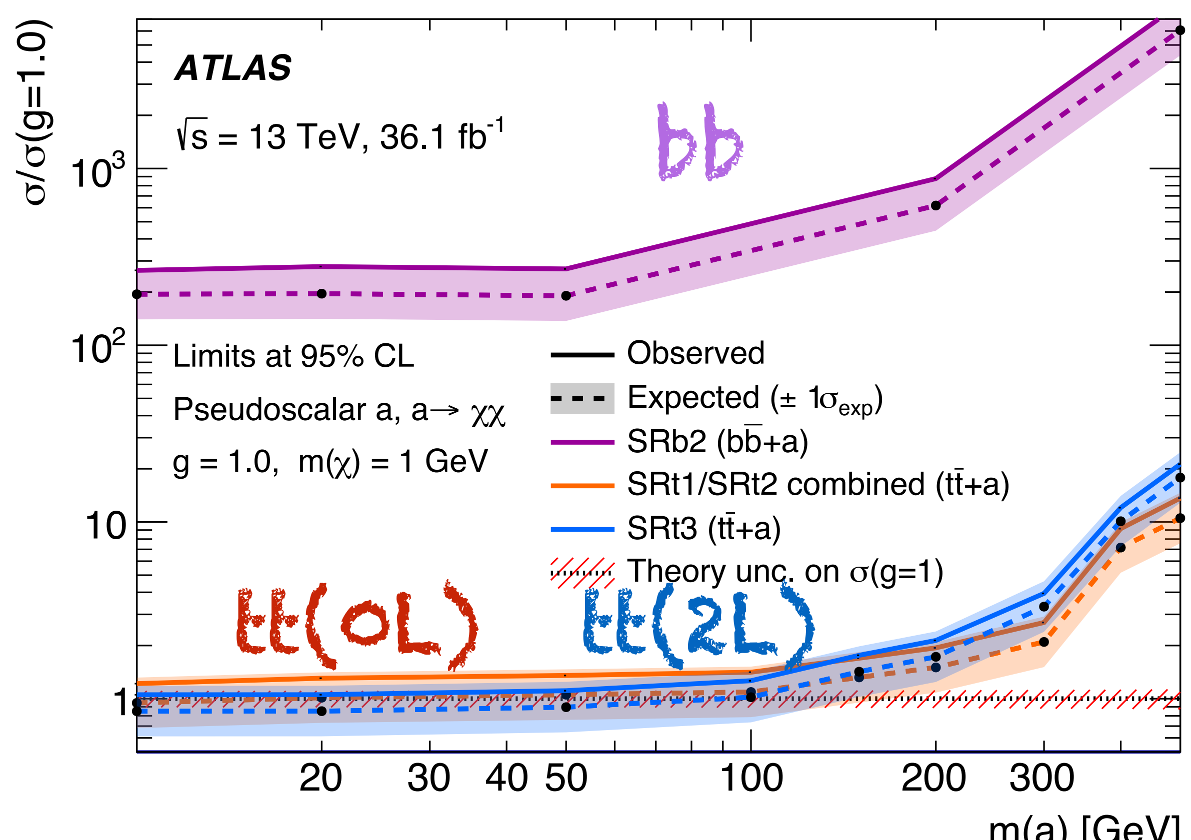
- scalar mediator would couple preferentially to heavy quarks
  - tt+MET (had, 1L, 2L), bb+MET
- same final state as SUSY searches
- sensitivity still limited by low statistics

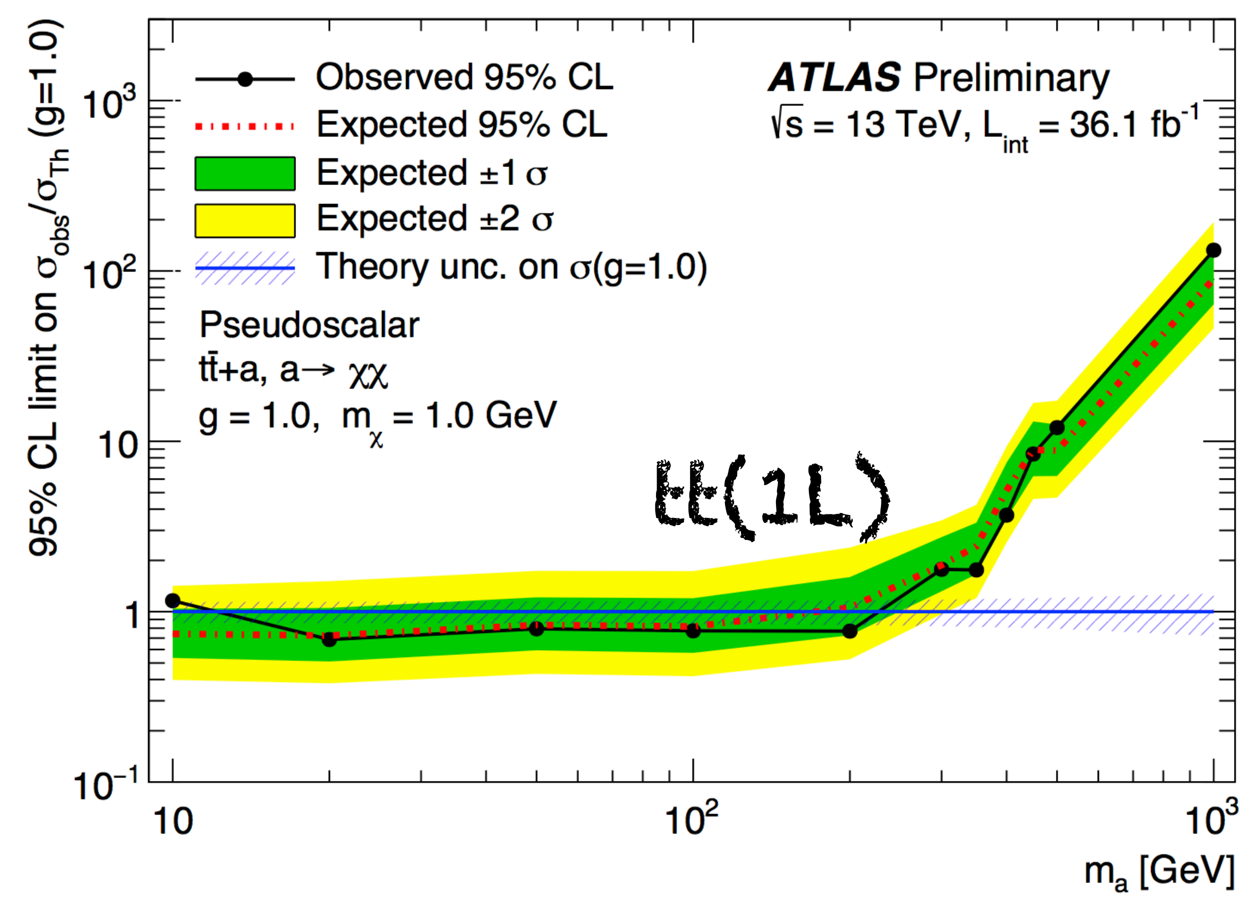




tt(1L): ATL-CONF-2017-037
tt(0L/2L), bb: arXiv:1710.11412

signal strength limit vs mediator mass, for m_{DM} = 1 GeV





Supersymmetry

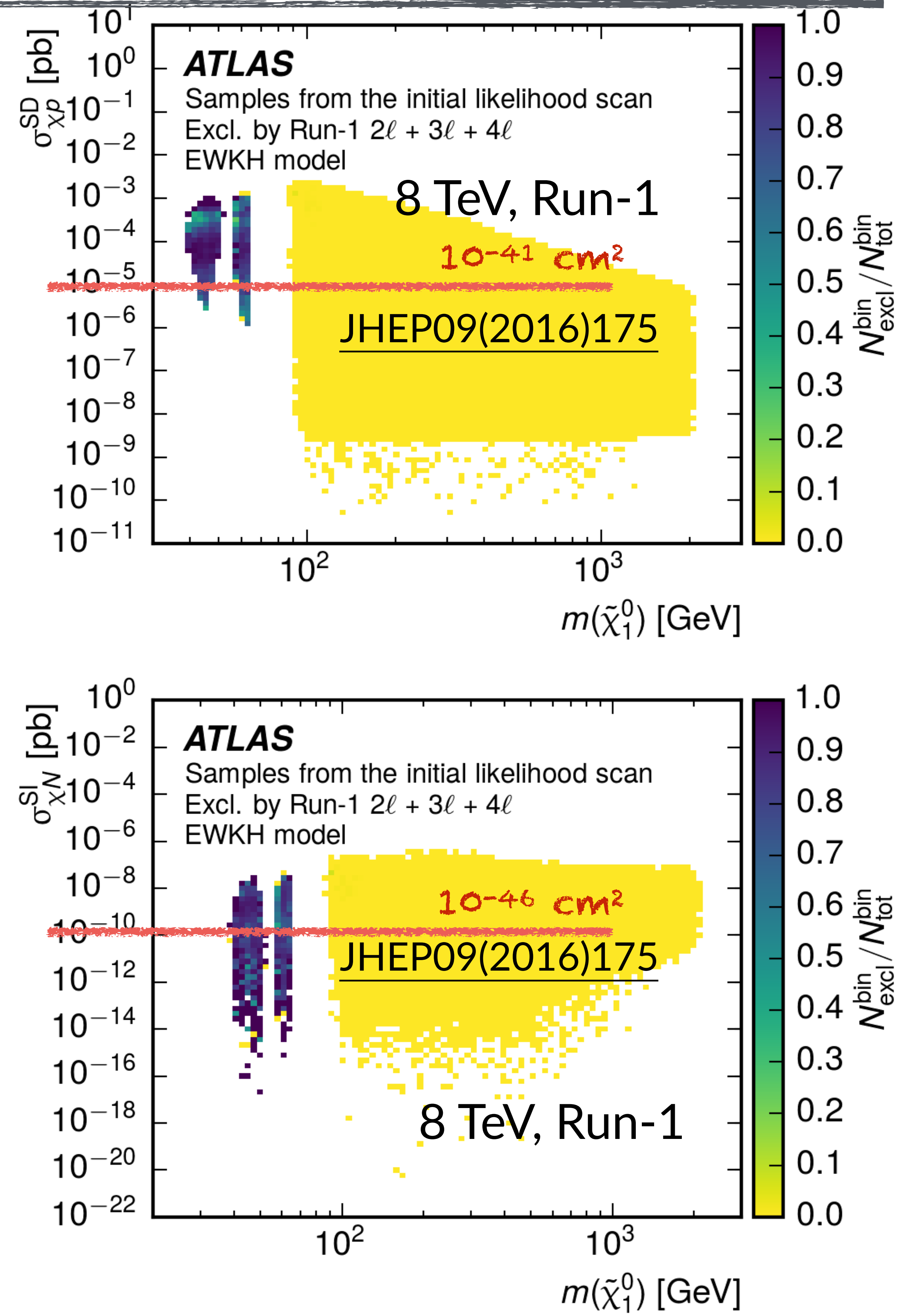
a UV-complete approach to the DM problem

- can investigate impact of EW search results on DM constraints
  - example on the right: 8 TeV results of 2-3-4L with DD, relic density and flavour constraints
    - 13 TeV searches: ATLAS-CONF-2017-035, ATLAS-CONF-2017-039

naturally extends searches to richer signatures

- broader experimental challenges in long-lived scenarios
  - see e.g. ATLAS-CONF-2017-017

scattering cross-section vs DM mass

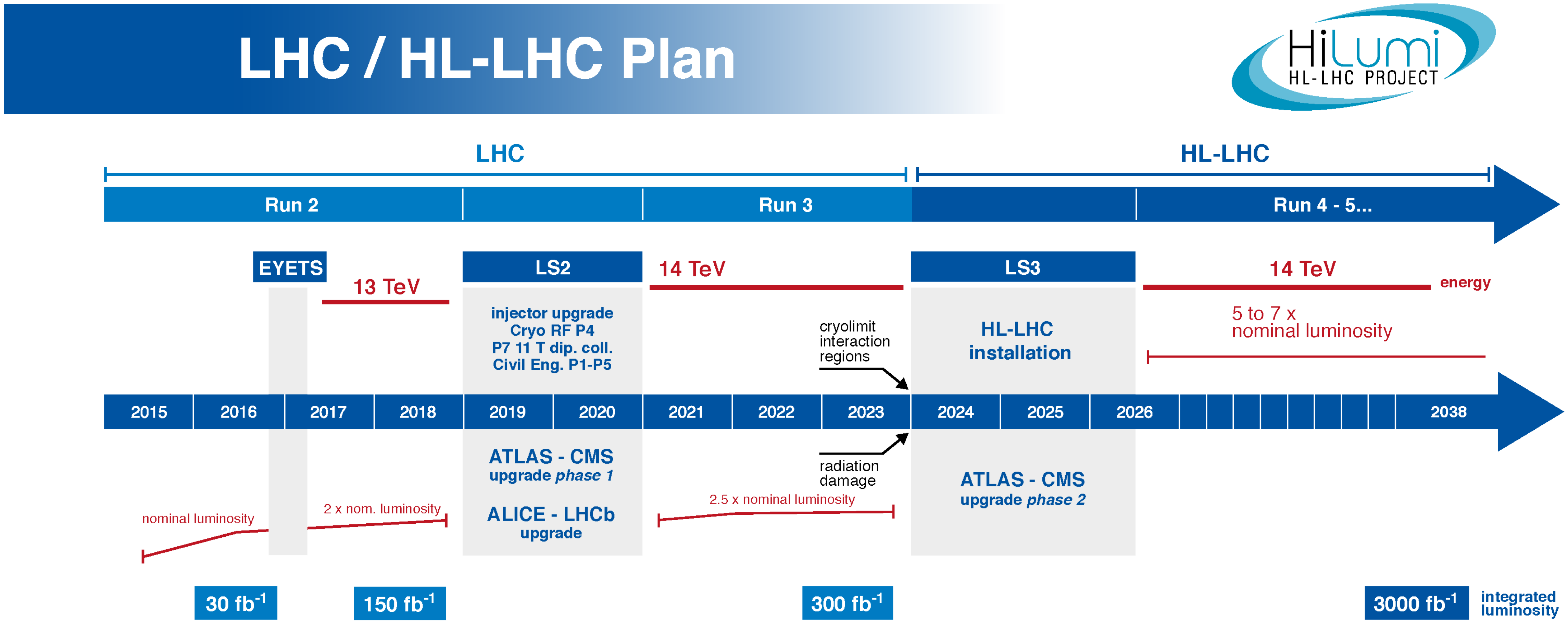


What's Next?

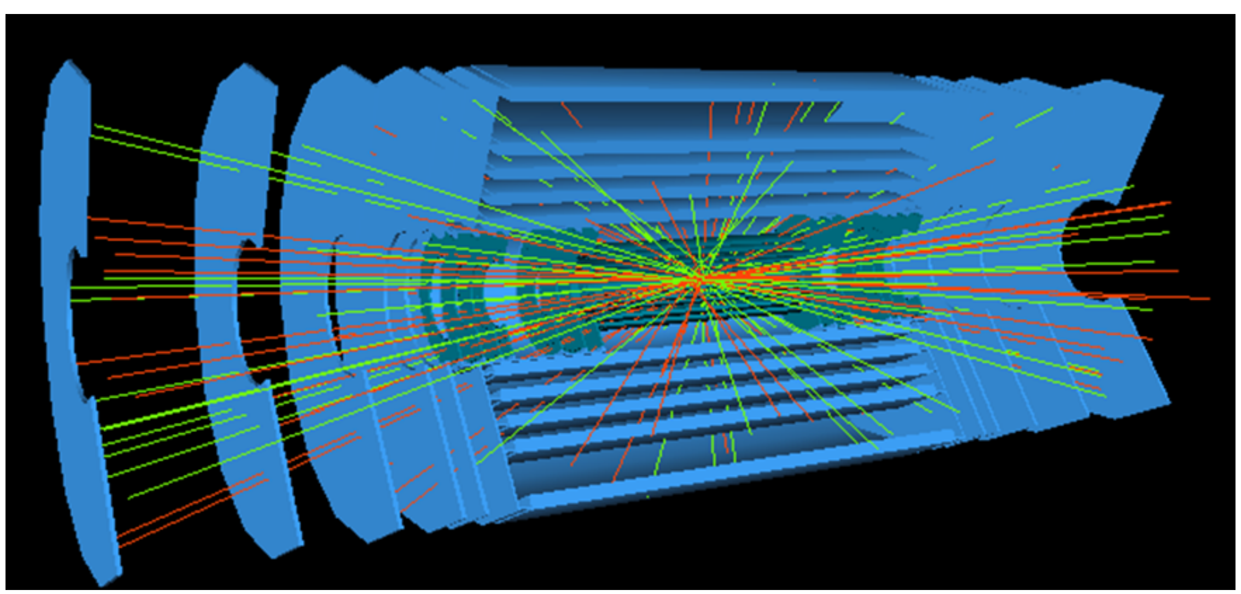

I HAVE AN IDEA.
A GOOD ONE?
LET'S NOT GET AHEAD OF OURSELVES.
poorlydrawnlines.com

Towards High Luminosity

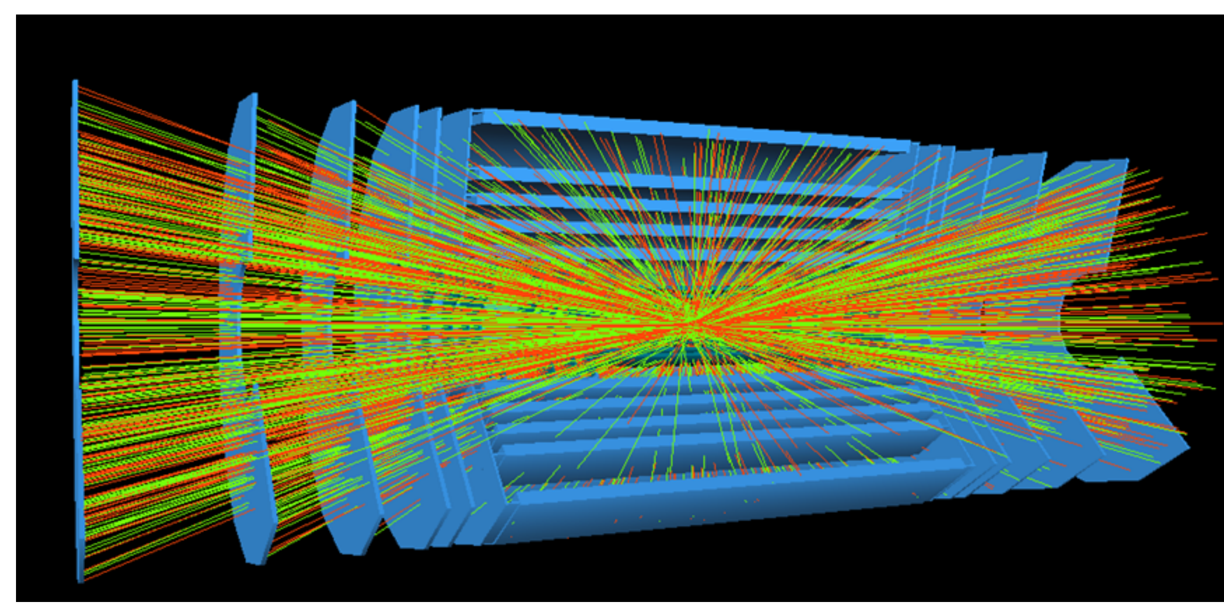
design luminosity: 1×10^{34} cm^{-2} s^{-1}



23 pile-up vertices



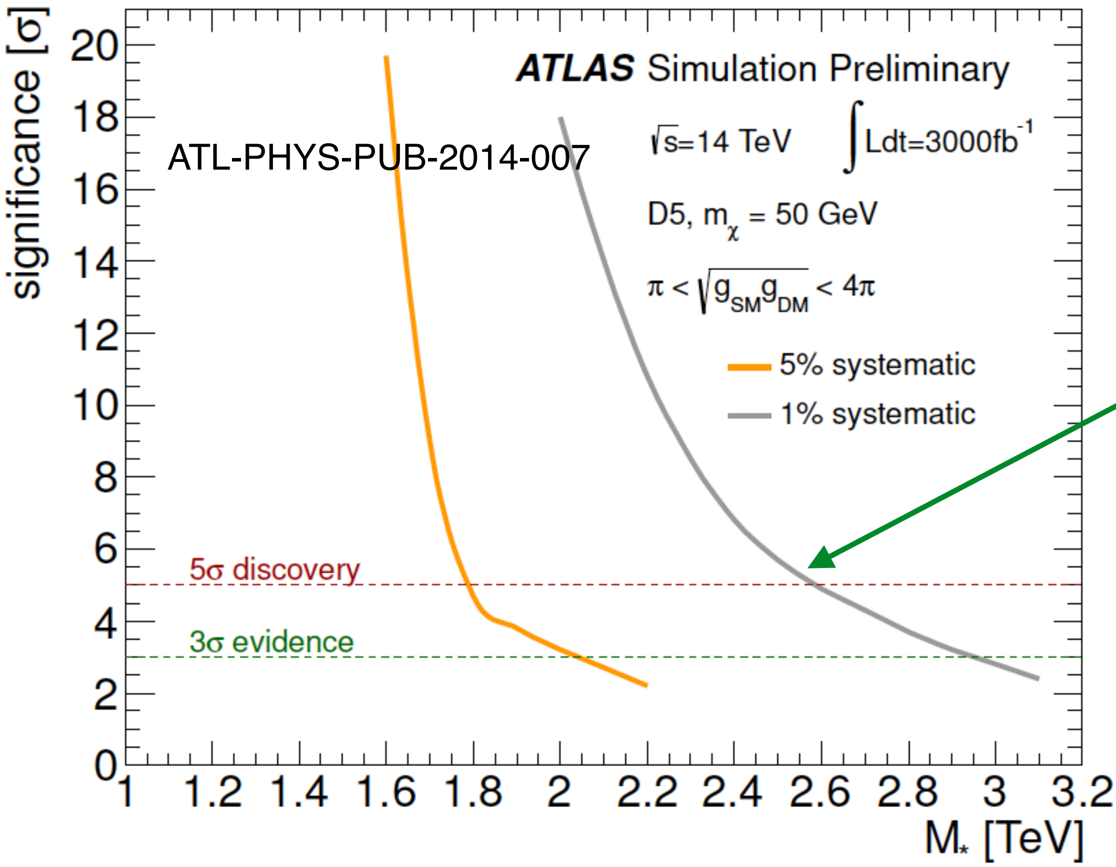
230 pile-up vertices



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

The % challenge

jet+MET: reach in scale of new physics (EFT) for 3 ab^{-1}



you need this level of precision…

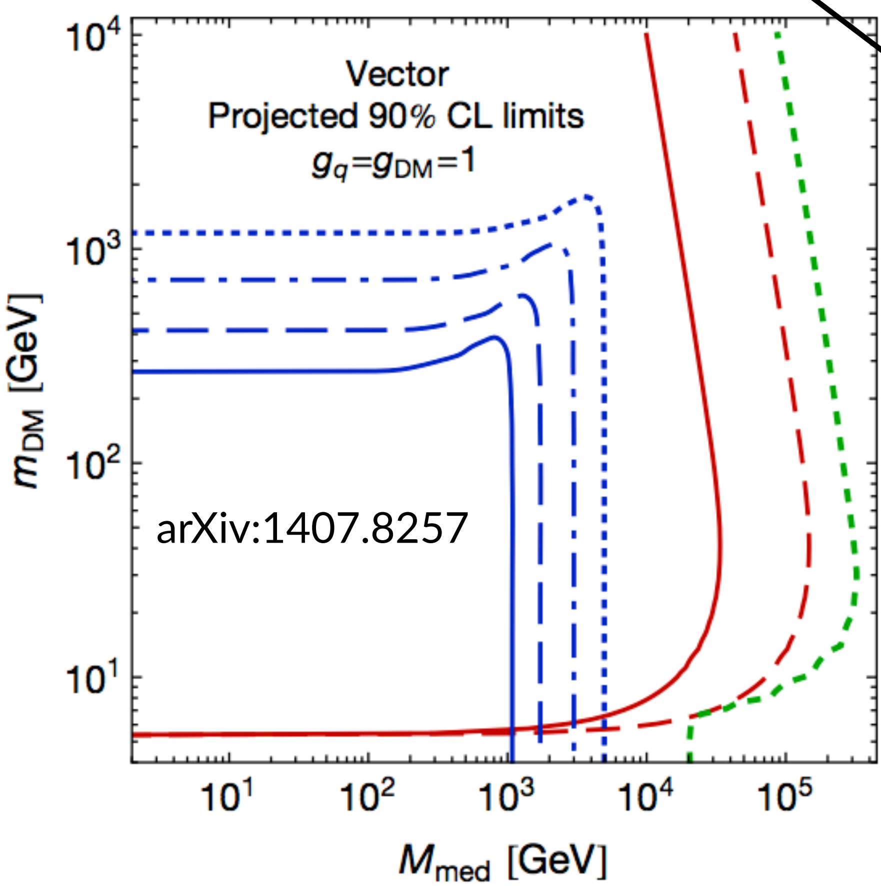
- higher pileup, less room for MET triggers
  - spin-0 becomes more and more challenging
  - must exploit trigger tracking info also at L1
    - ➡ data scouting?
- “precision search”: need %-level systematics
  - lepton and jet uncertainties
  - theory work needed!
    - ➡ use SM V+jets measurements?

The complementarity challenge

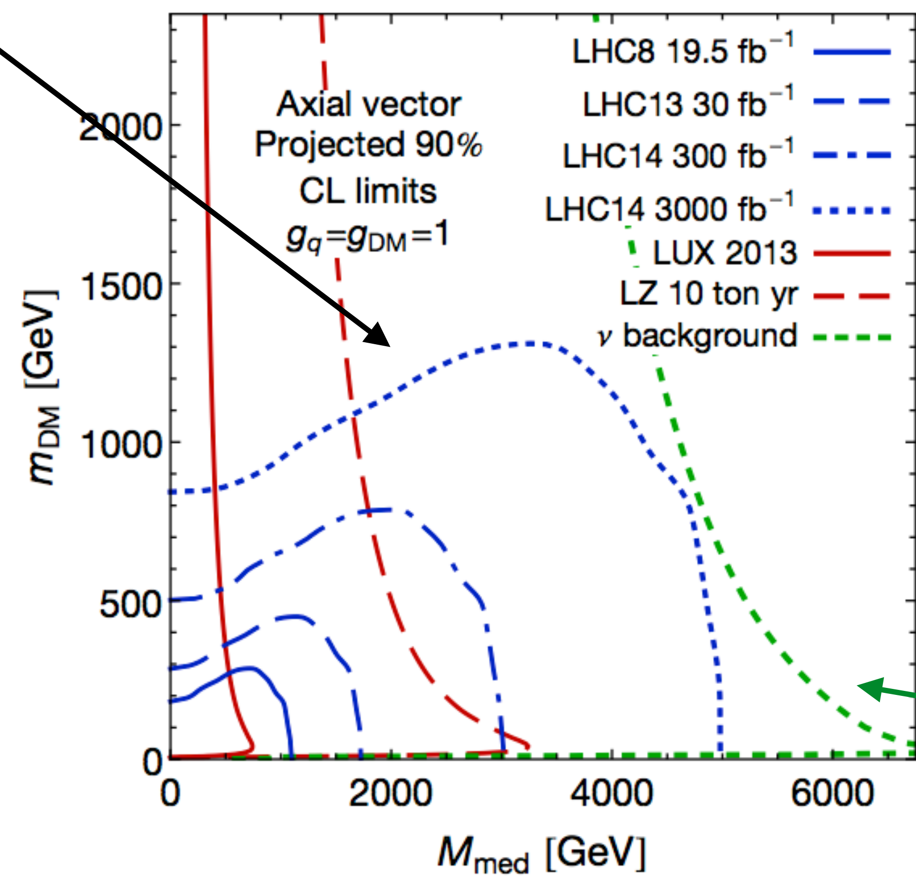
- high-lumi LHC can beat direct detection up to neutrino background
- explore lower-cross-section extensions of the SM (SUSY, long-lived particles (e.g. 1707.05326)…)

region to the left of each curve is expected exclusion; LHC := "mono-jet"

vector



axial-vector

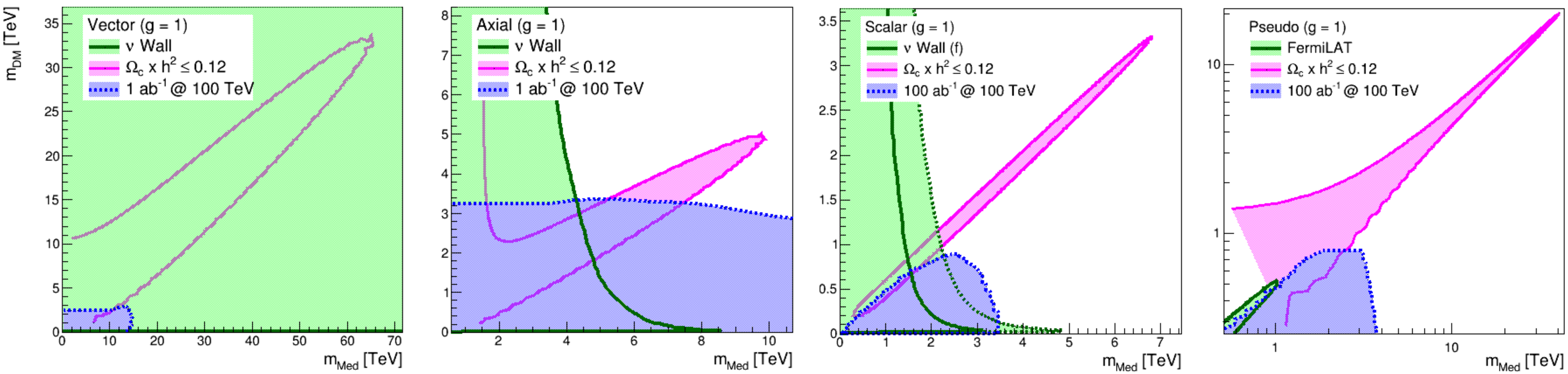


could extend the m_{DM} sensitivity up to 0.5 TeV in ~6 years (mind the couplings!)

neutrino "wall"

What about higher energy?

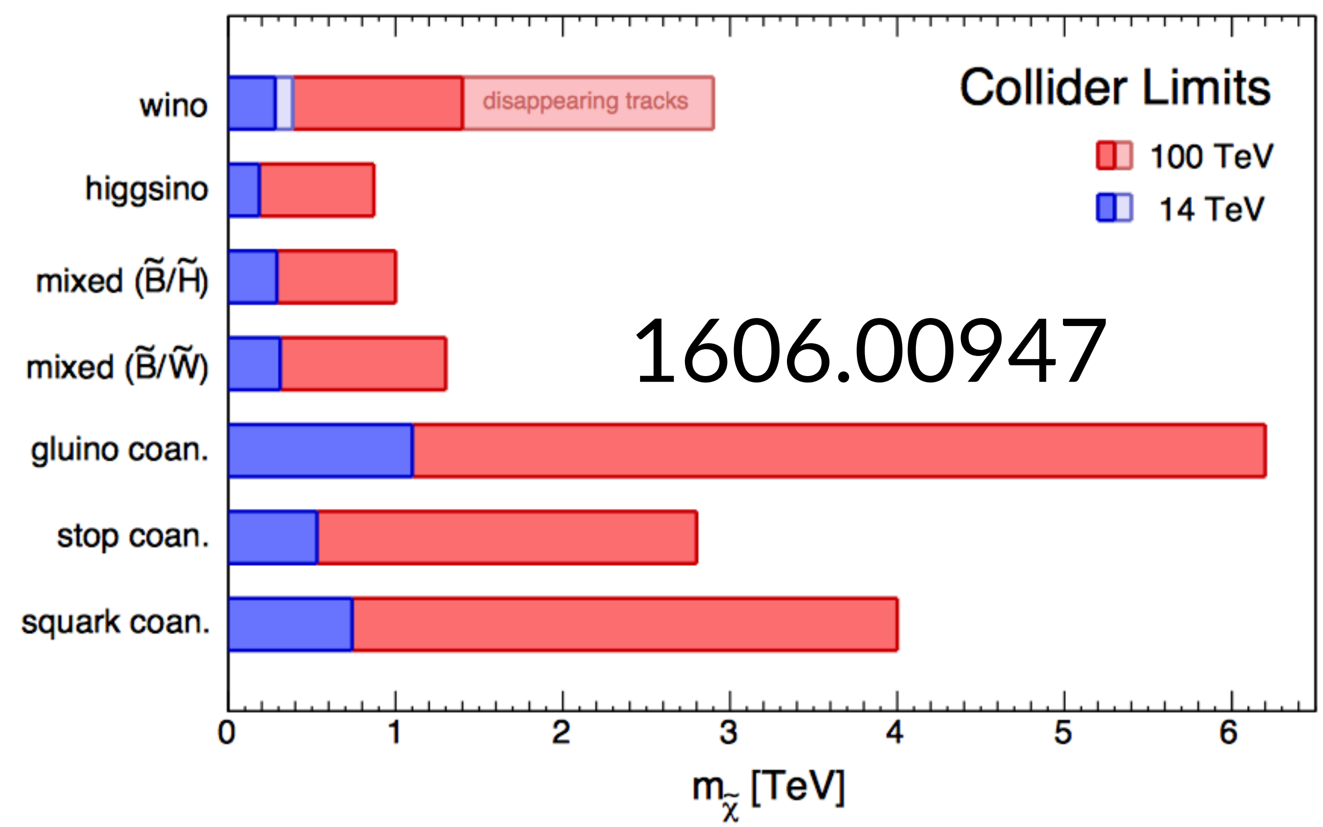
vector | axial-vector | scalar | pseudo-scalar



green: xsec <= neutrino bkg
blue: 1000 fb^{-1} @ 100 TeV
purple: compatible with measured relic density

(for some choice of the couplings)

a higher-energy circular collider may push sensitivity to the TeV scale



Conclusions

extensive DM search programme at ATLAS

- complementary to dedicated experiments for m_{DM} <~ 100 GeV
- ATLAS is a telescope for new physics in multiple final states

expected luminosity

now:	36 fb^{-1}
end of 2018:	120 fb^{-1}
end of 2023:	300 fb^{-1}
HL-LHC (~2038):	3000 fb^{-1}

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

more data, new challenges

- balance between sensitivity to low-momentum signals (e.g. spin-zero) and robustness at very high energy
  - trigger & detector performance are crucial!
- explore lower-cross-section extensions of the SM (SUSY, long-lived particles…)
- may extend LHC reach to m_{DM} ~ 500 GeV in the next ~6 years…

stay finetuned!

Further reading

- MET+γ: Eur. Phys. J. C 77 , 6 (2017) 393
- MET+tt(1-L): ATL-CONF-2017-037
- MET+Z(ll): ATL-CONF-2017-040
- MET+W/Z(had): Phys. Lett. B 763 (2016) 251
- MET+jet: ATLAS-CONF-2017-060
- Z(vv)/Z(ll) cross-section ratio: arXiv:1707.03263
- MET+H(bb): arXiv:1707.01302
- MET+H(gg): arXiv:1706.03948
- MET+H(4l): ATLAS-CONF-2015-059
- MET+tt(0-L, 2-L), MET+bb: arXiv:1710.11412
- di-jet: http://arxiv.org/abs/arXiv:1703.09127
- di-jet TLA: ATLAS-CONF-2016-030
- di-jet ISR: ATLAS-CONF-2016-070
- dilepton: ATLAS-CONF-2017-027
- ttbar resonance: ATLAS-CONF-2016-014
- summary plots: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html
- SUSY EW 2-3l: ATLAS-CONF-2017-039
- chargino/neutralino tau: ATLAS-CONF-2017-035
- chargino long-lived (disapp track): ATLAS-CONF-2017-017
- SUSY pMSSM scan: JHEP09(2016)175

SPARES

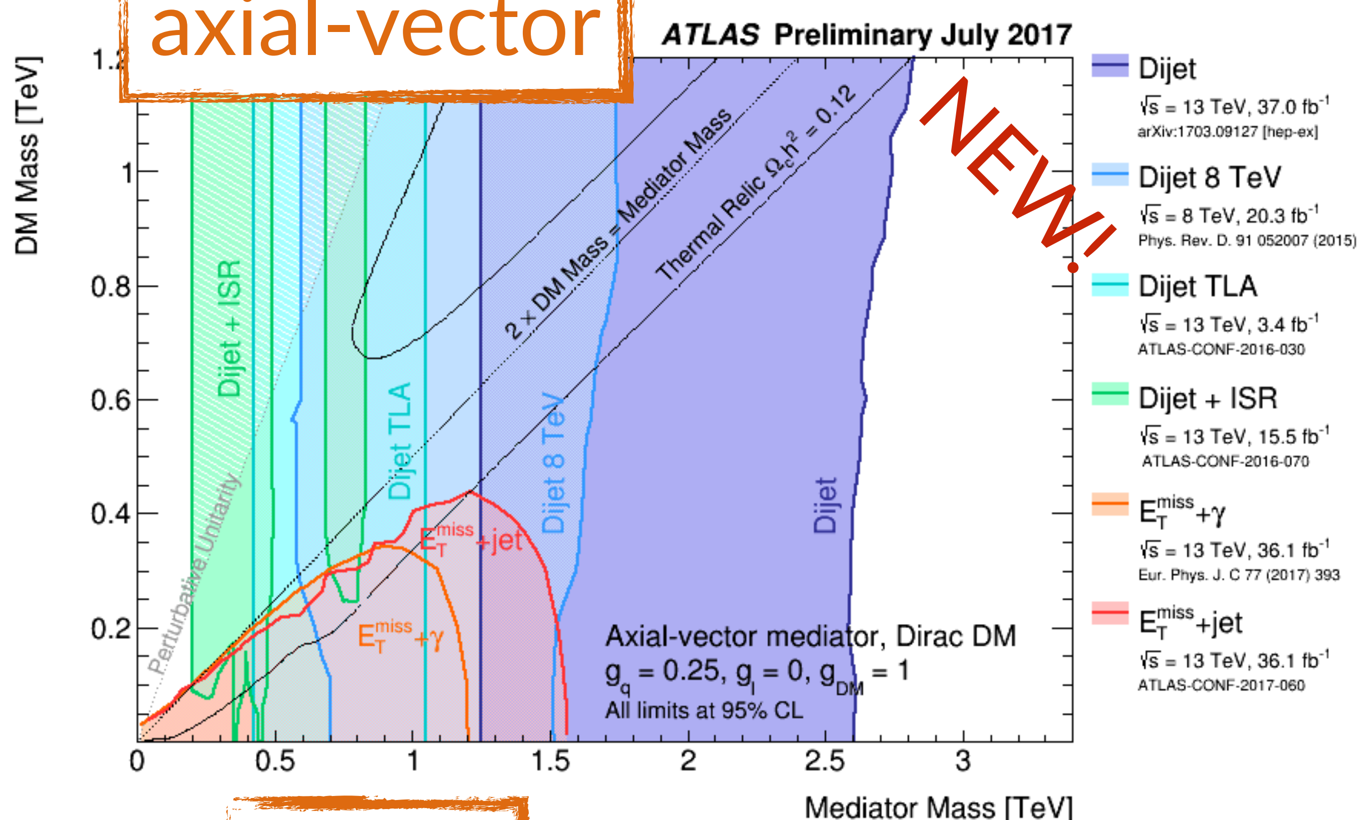
Henri Cartier-Bresson, Jean Paul Sartre - MoMA, New York

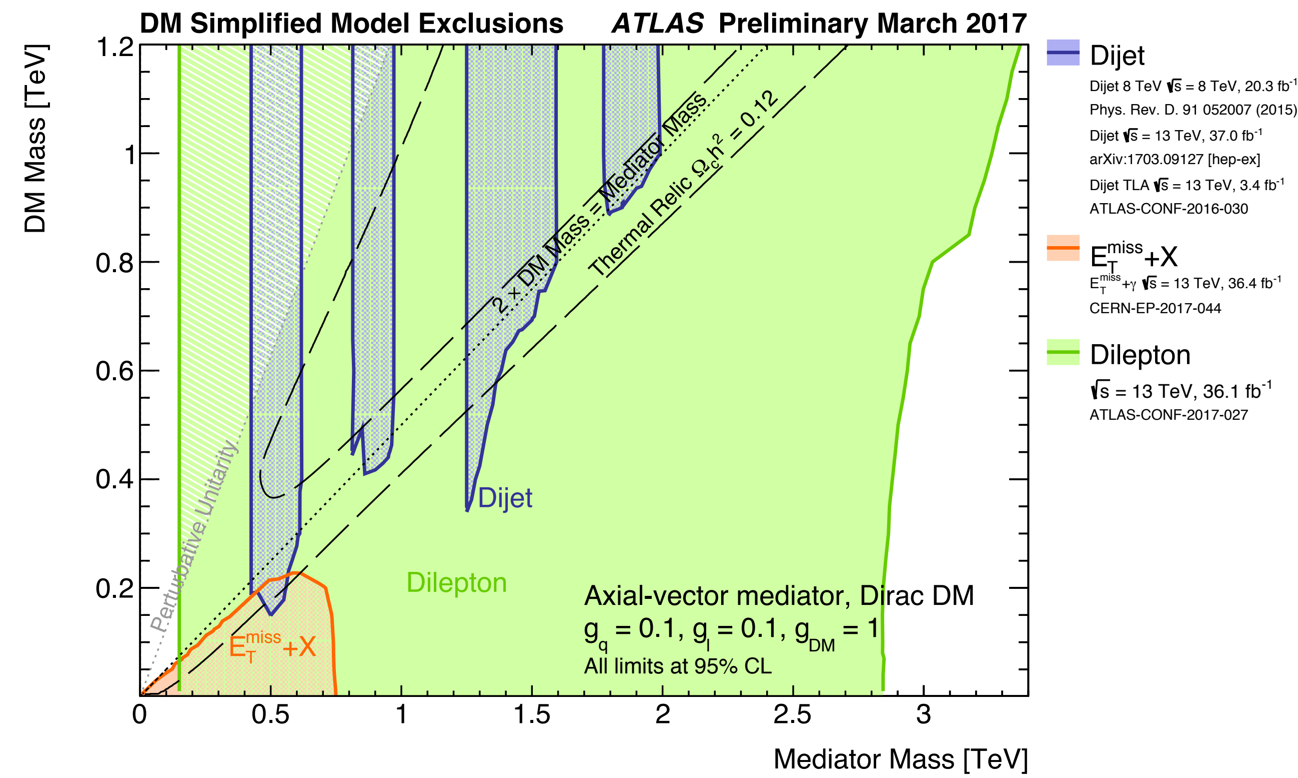
Leptophobic vs leptophilic

$\sigma_{monojet} \sim g_q g_{DM}$
$\sigma_{dijet} \sim g_q^2$

axial-vector

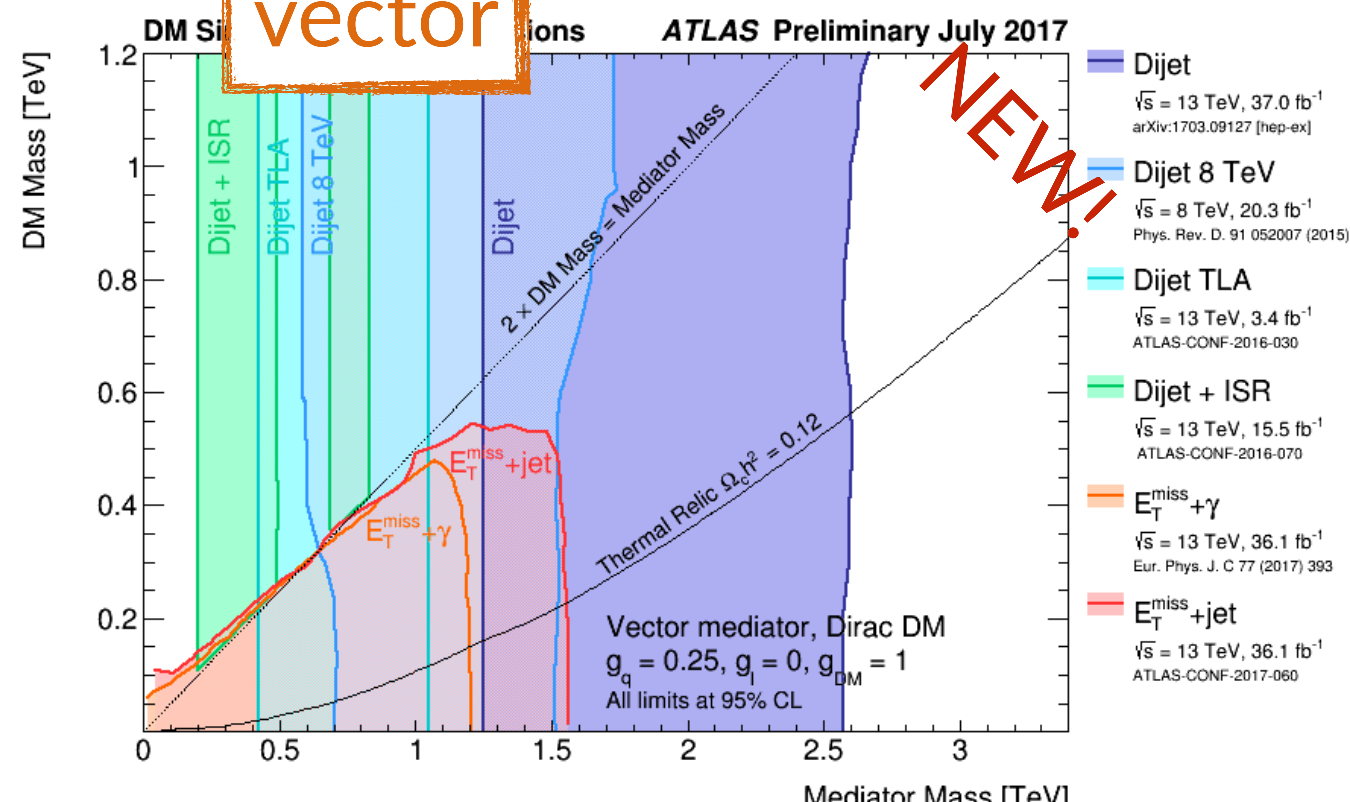
NEW!

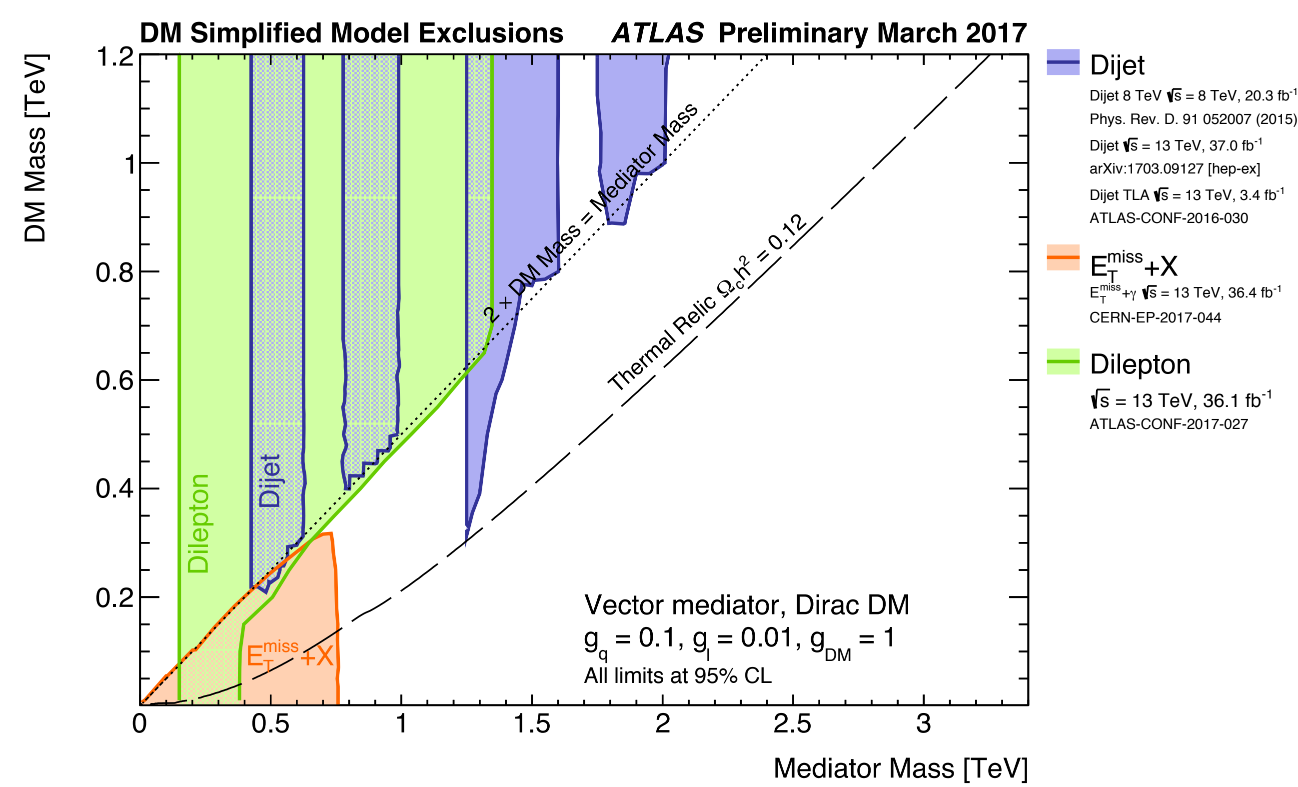




vector

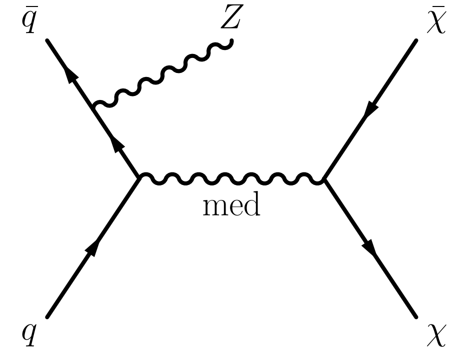
NEW!



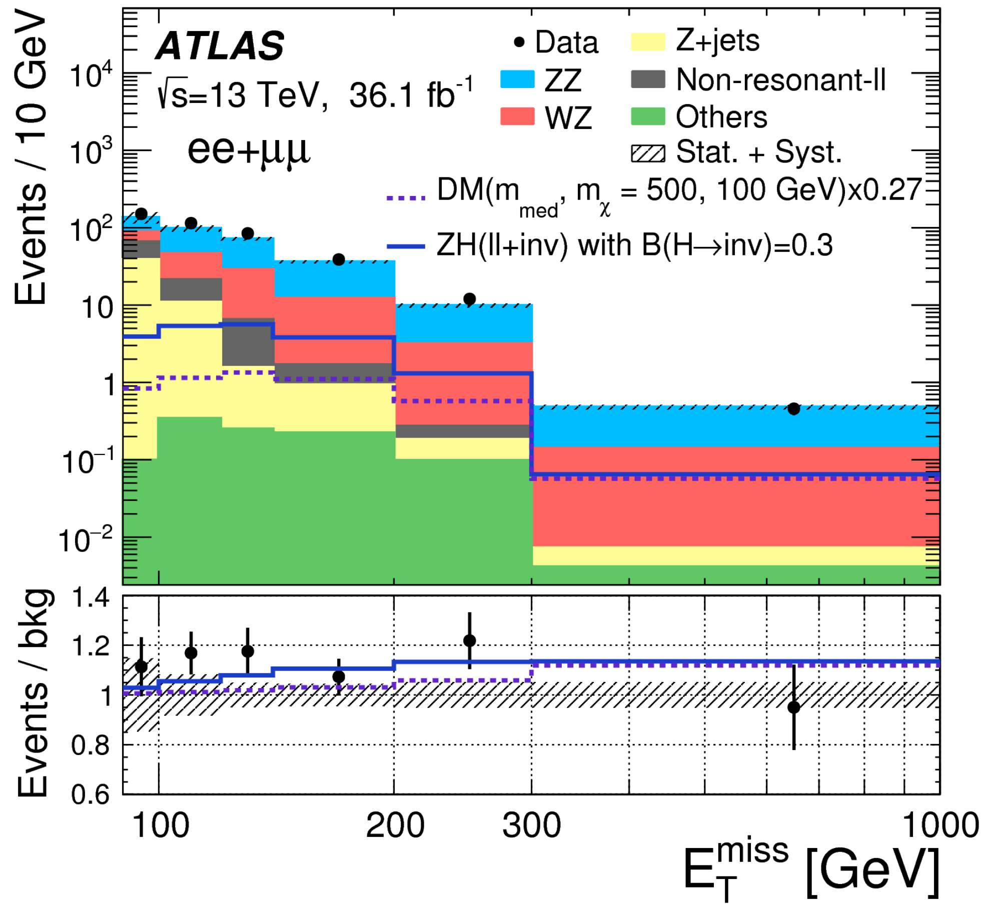


note: results on the right don't have MET+jet

MET+Z(ll)

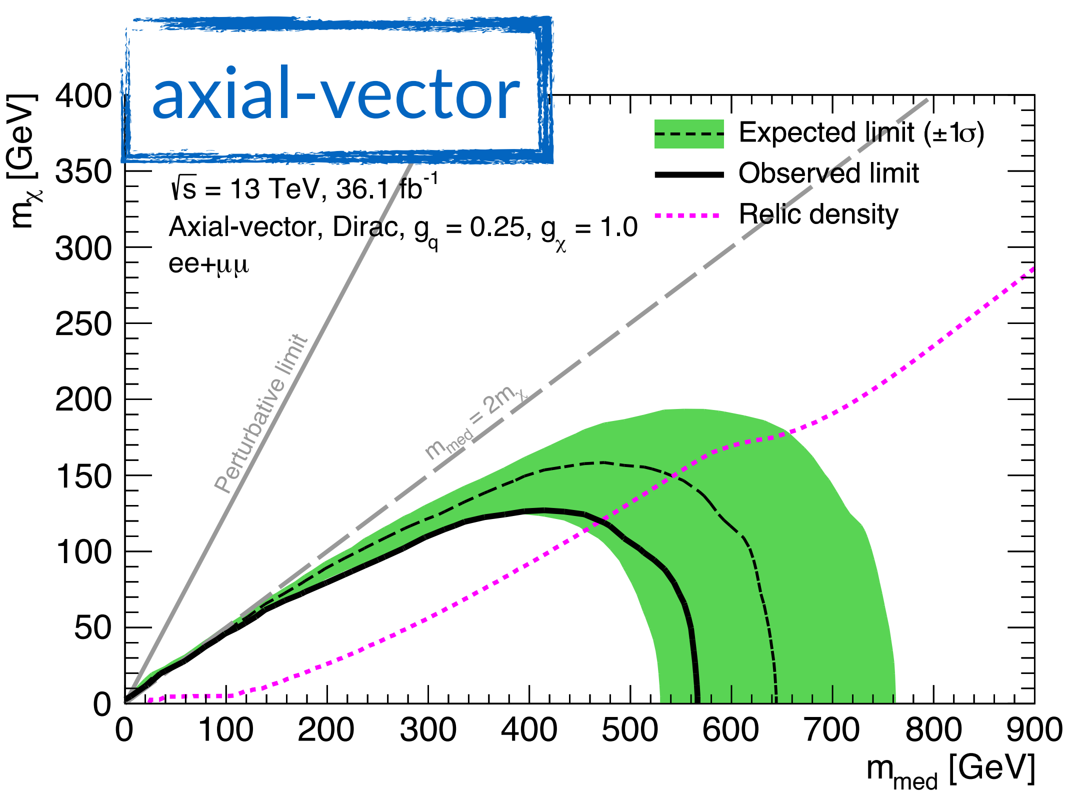


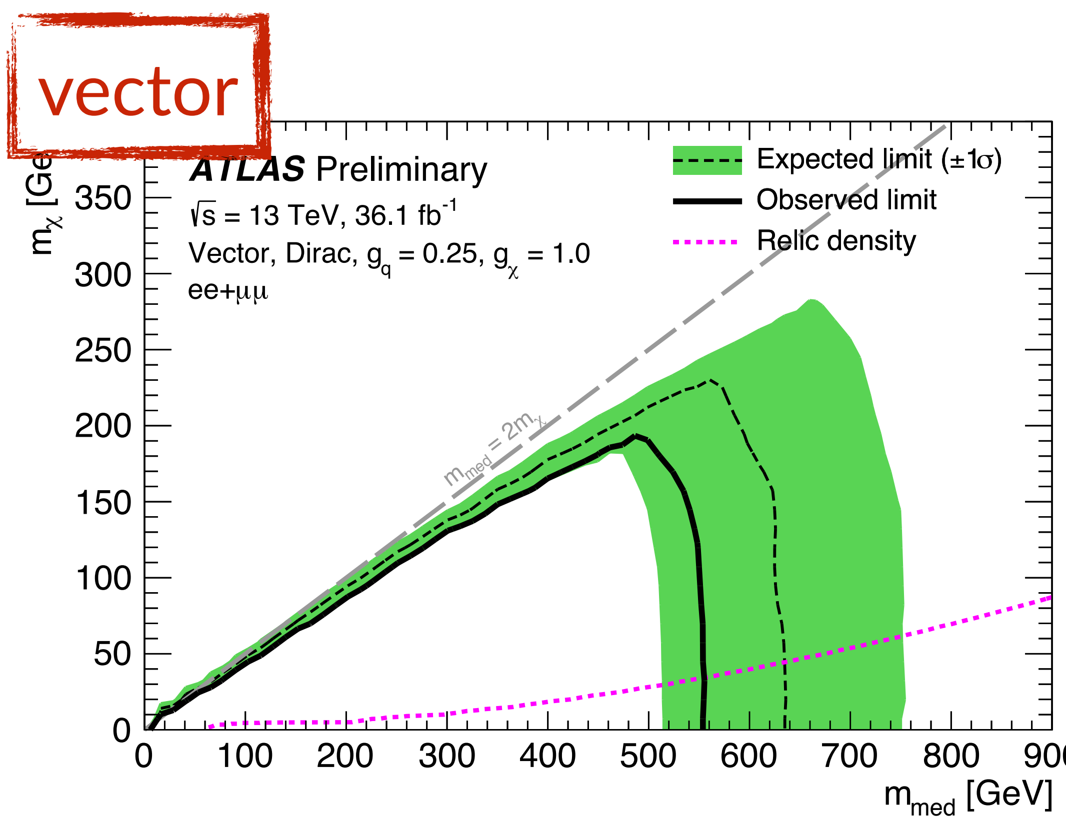
arXiv:1708.09624



- $e^+e^-/\mu^+\mu^-$ pair compatible with a Z
- MET > 90 GeV, MET/H_T>0.6
- $\Delta\Phi$(Z, MET) > 2.7, ΔR(ll) < 1.8, b-veto
- ZZ from simulation, WZ from 3-lepton CR

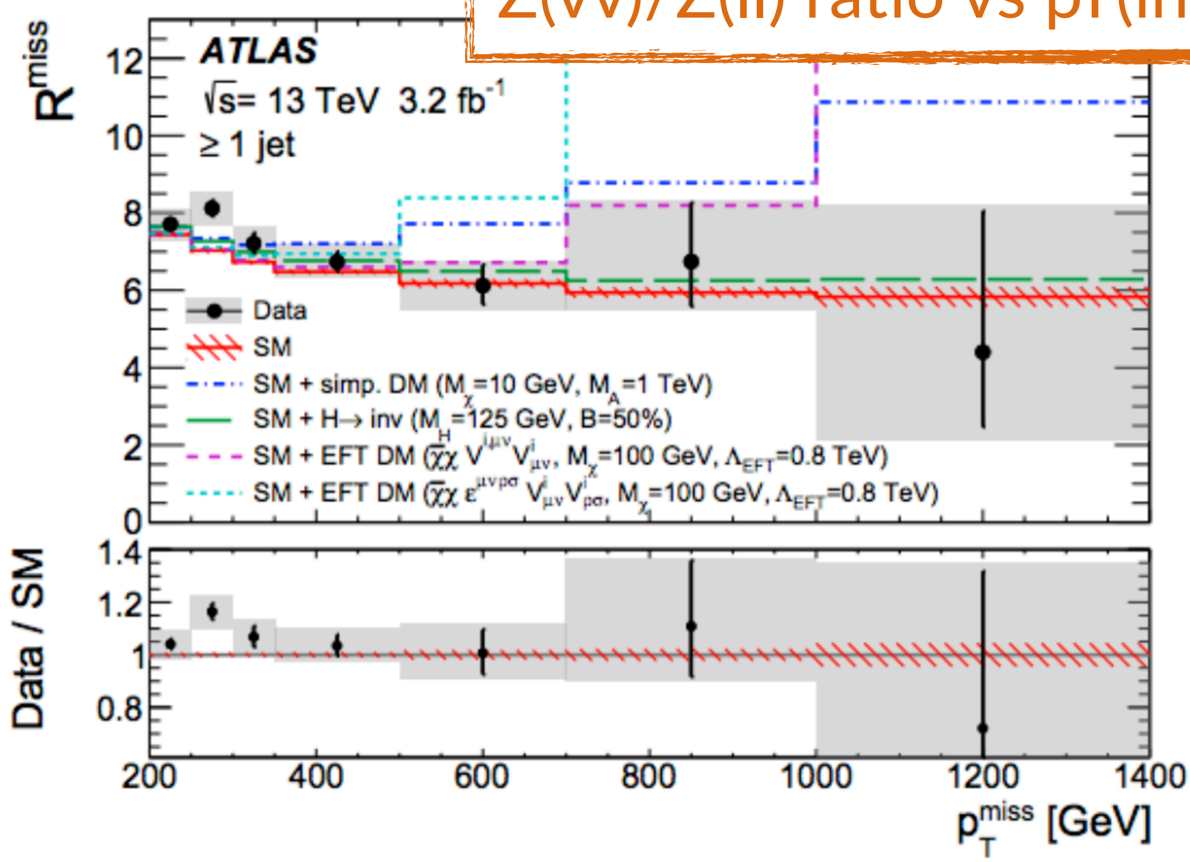
main uncertainties from ZZ modelling, lepton momentum scale/reso and reco/ID efficiency uncertainties, JES





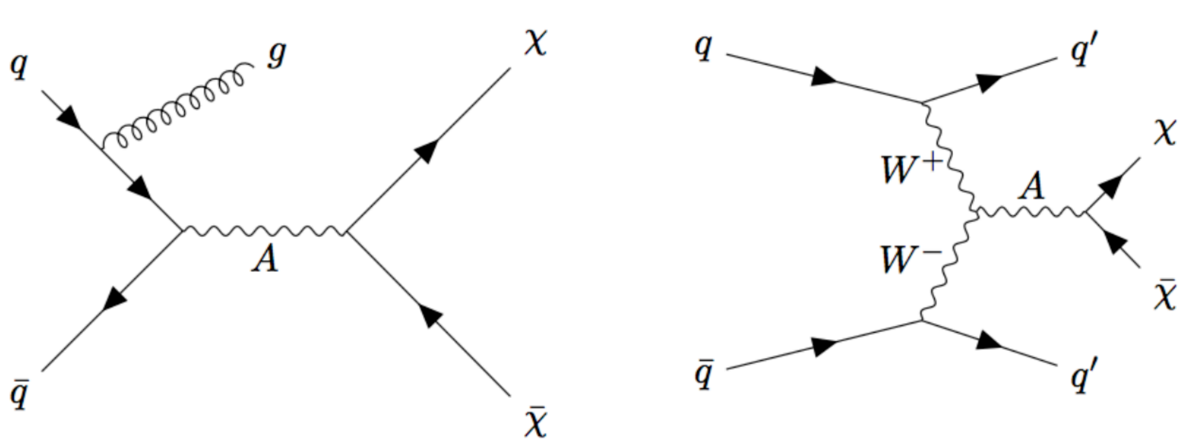
Measurement: the new search?

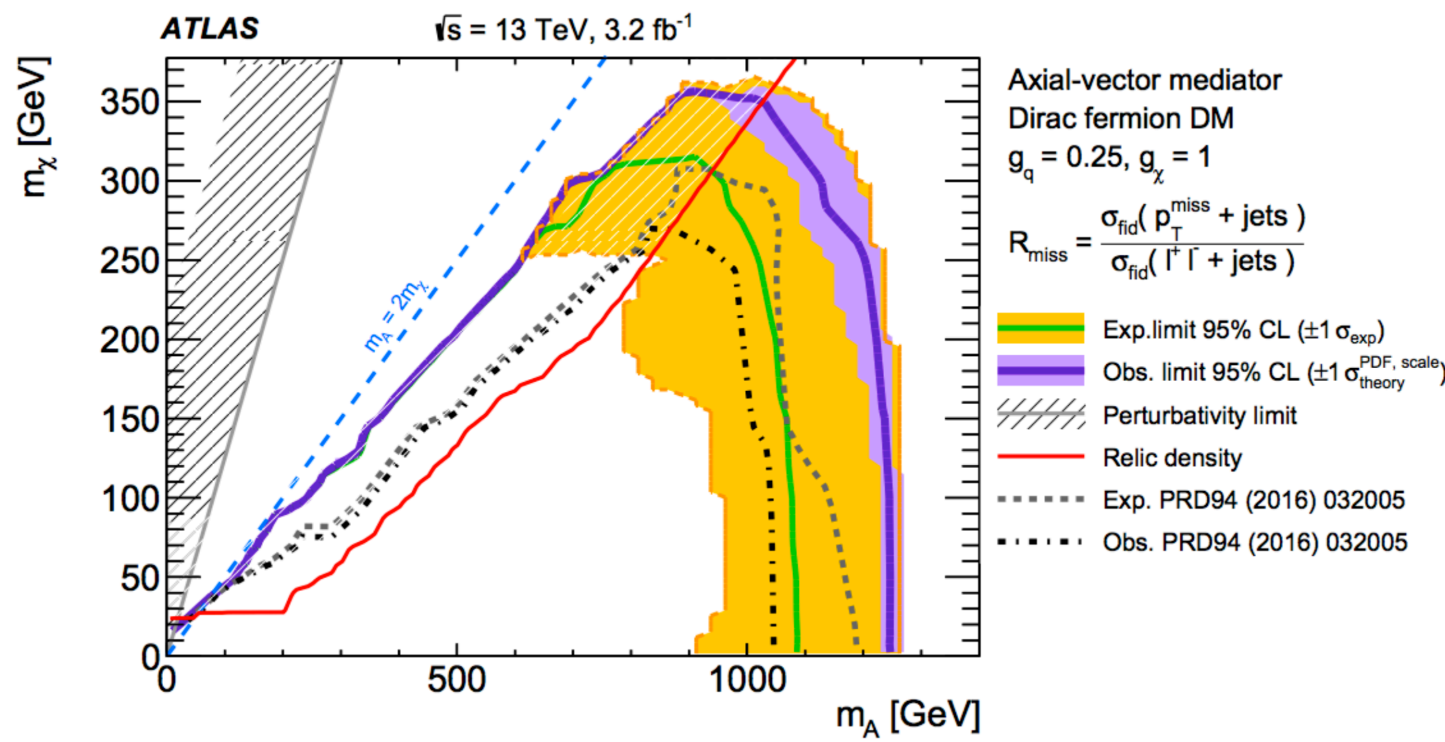
Z(vv)/Z(ll) ratio vs pT(inv)



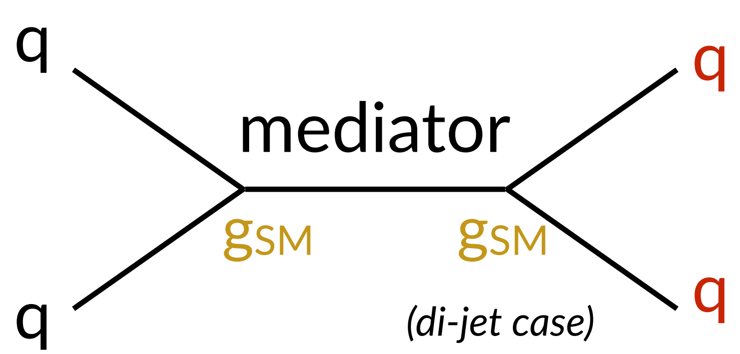
- measure unfolded differential Z(vv)/Z(ll) cross-section ratios
  - “mono-jet” and VBF topologies
  - vs MET/m_{jj}/ΔΦ(jj)
- may be reinterpreted to constrain BSM models
  - e.g. MET+jet simplified models, VBF EFT, H(inv)…
  - s-channel axial-vector: slightly better sensitivity than “standard” search with 3.2 fb^{-1}

arXiv:1707.03263





Di-X



- look directly for the mediator of the SM-DM interaction
  - limited by trigger thresholds and calibration/identification performance
- if mediator couples to leptons, strong constraints from di-lepton searches
  - ttbar resonance searches may also contribute in spin-0 scenarios