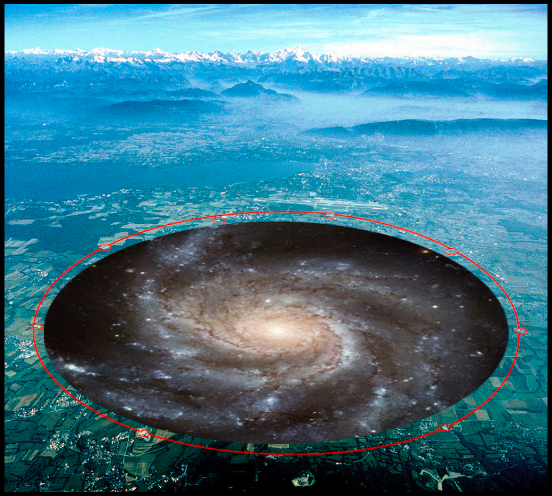
Searching for Dark Matter at the LHC



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March 2017

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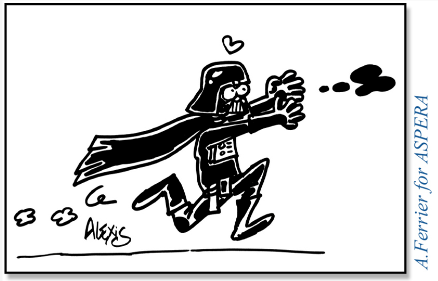
CNRS IN2P3
Les deux infinis



Looking for dark matter

1. The LHC, ATLAS and CMS

2. How to search for dark matter at the LHC – vanilla scenario
    1. What do we expect to see?
    2. An analysis example: the ‘jet+E_T^{miss}’ analysis

3. Interpreting the results:
    1. From EFT to simplified models
    2. Comparison to direct detection searches

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4. The many faces of dark matter at the LHC
    1. Overview of the ‘mono-X’ analyses
    2. The Higgs portal
    3. What about the mediator?
    4. What about more complete models?

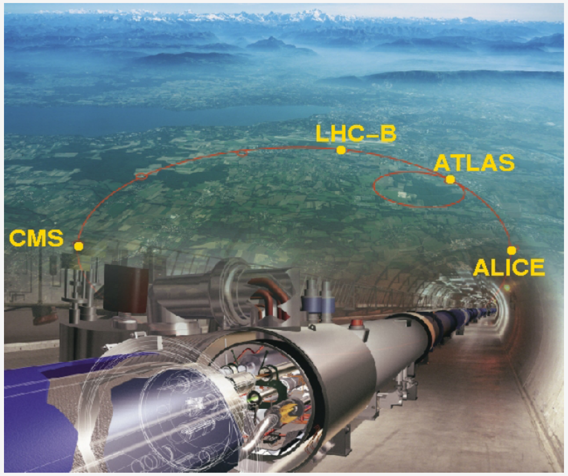
5. The future, a summary and the dream picture

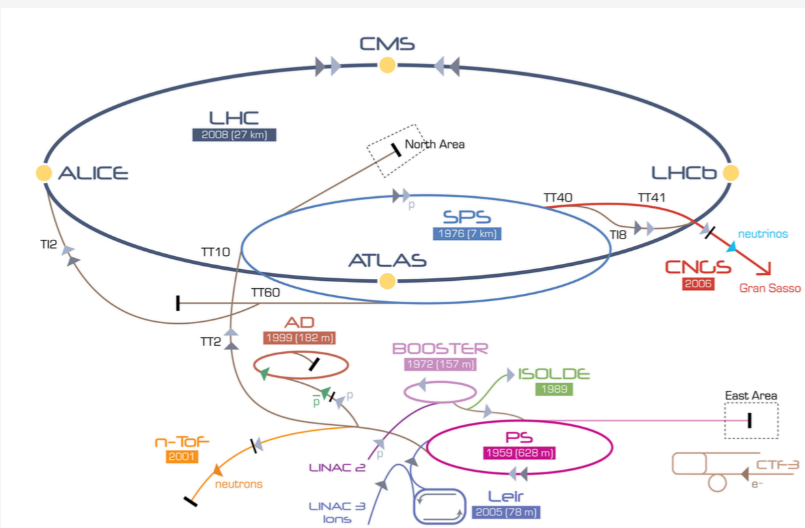
1. The LHC, ATLAS and CMS

"You have to know how to work the machine."

The CERN Large Hadron Collider

Proudly colliding protons*





- Built in the Large Electron Positron (LEP) tunnel:
  - 26.7 km of circumference
  - 100 m underground
- Protons accelerated through a chain before reaching the LHC:

  LINAC (60 MeV) → Booster (1.4 GeV) → PS (25 GeV) → SPS (450 GeV)
- Proton-proton collisions in the LHC :
  - 2009 @ 900 GeV
  - 2010-11 @ 7 TeV
  - 2012 @ 8 TeV
  - 2013-14: Long shutdown 1 (LS1) – machine/detector work
  - 2015-16 @ 13 TeV

**may contain some heavy ions*

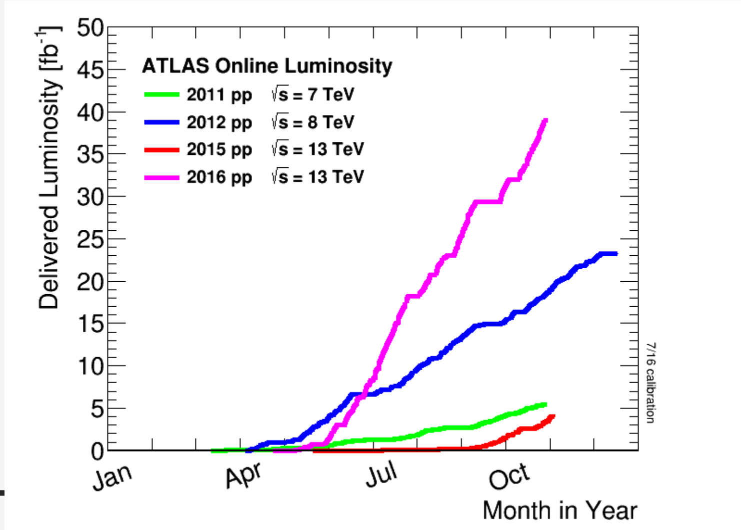
Luminosity

- The luminosity is given by the beam parameters

$$\mathcal{L} = \frac{f_{revolution} N_{bunches} N^2_{protons/bunch}}{A}$$

Design: 10^{34} cm^{-2}s^{-1} (max in 2016: 1.37 x 10^{34} cm^{-2}s^{-1})

- The integrated luminosity : $L = \int \mathcal{L} dt$



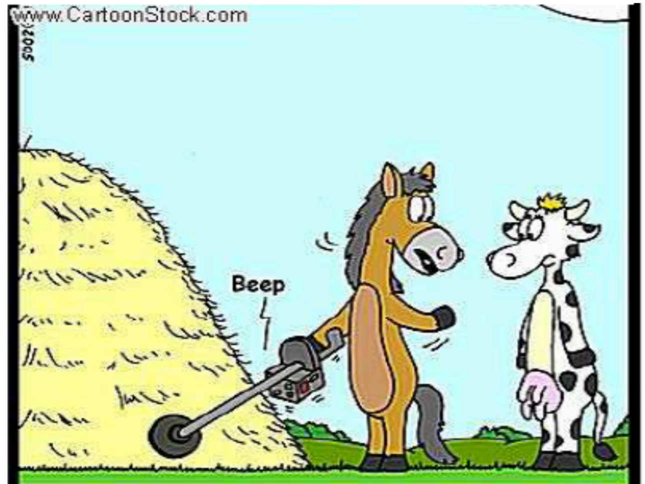
Orders of magnitude

For a process with cross section σ, the number of events for a given integrated luminosity L is simply

$$N_{events} = \sigma L$$

<u>For 40 fb^{-1} of data:</u>

- $\sigma_{inelastic} \sim 80$ mb → $N_{in} \sim O(3 \times 10^{15})$: huge!
  - *Impossible to save everything to disk*
    - *trigger system : save only 'interesting events' 40 MHz→ 1 kHz!*



You were right: There's a needle in this haystack...

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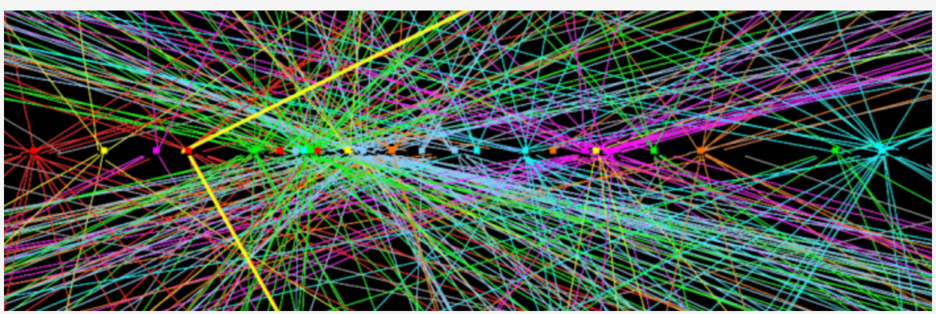
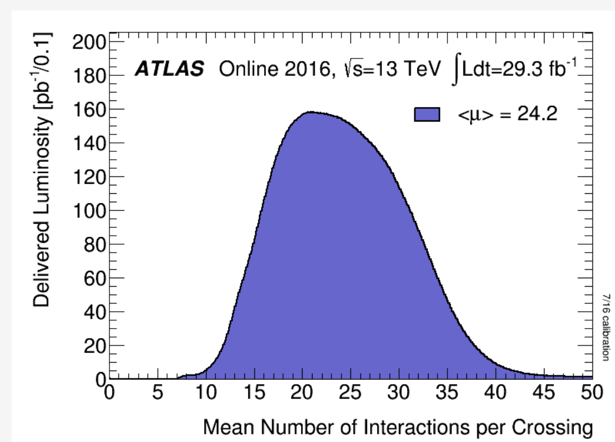
    - *Multiple interactions per bunch crossing (« pile-up »)*





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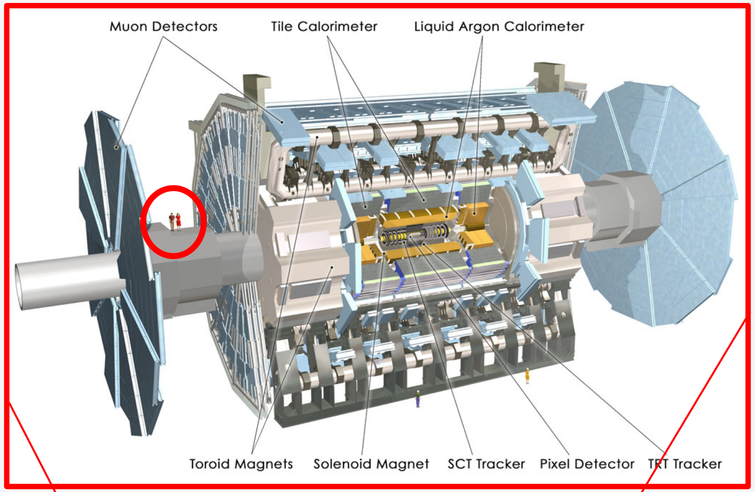
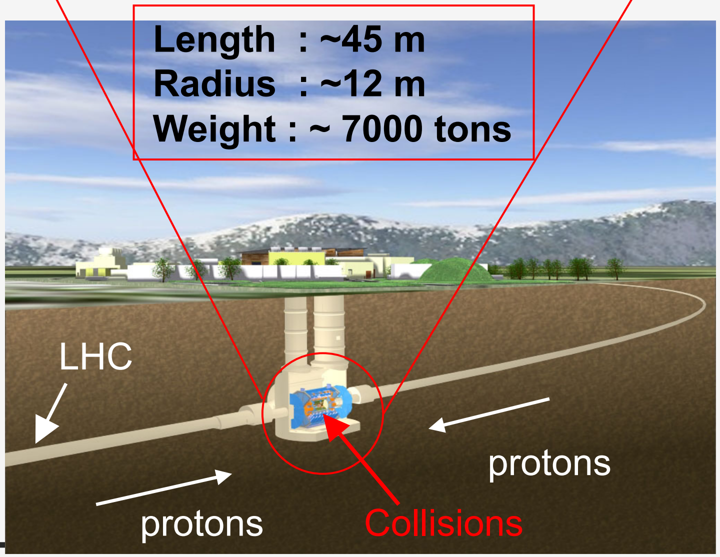
    - *Impossible to save everything to disk*
        - *trigger system : save only 'interesting events' 40 MHz → 1 kHz!*
    - *Multiple interactions per bunch crossing (« pile-up »)*
- $\sigma_{tt} \sim 1$ nb → $N \sim O(4\text{x}10^7)$
    - *Top « factory »!*
- $\sigma_{higgs} \sim 40$ pb → $N \sim O(2\text{x}10^6)$
    - *but most in h→bb… BR(h→γγ) ~ 2x10⁻³ : $N_{h\to\gamma\gamma} \sim O(4k)$*


ALICE
CMS
ATLAS
LHCb

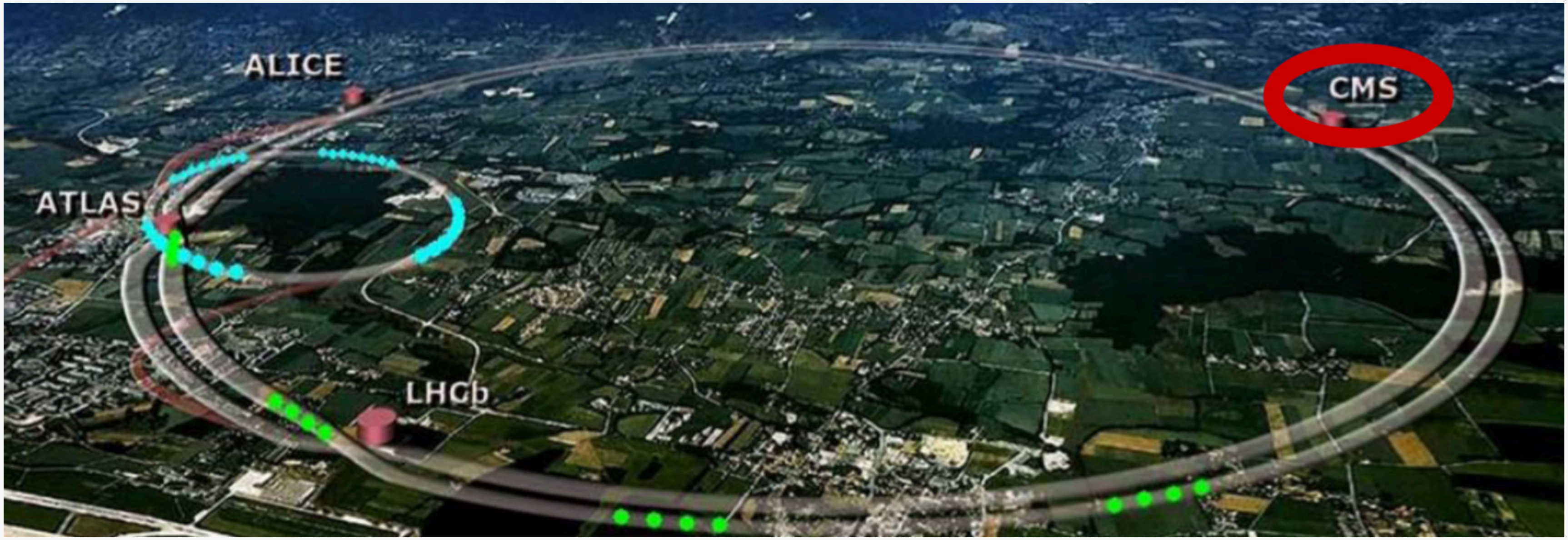
ATLAS: large and 'light'



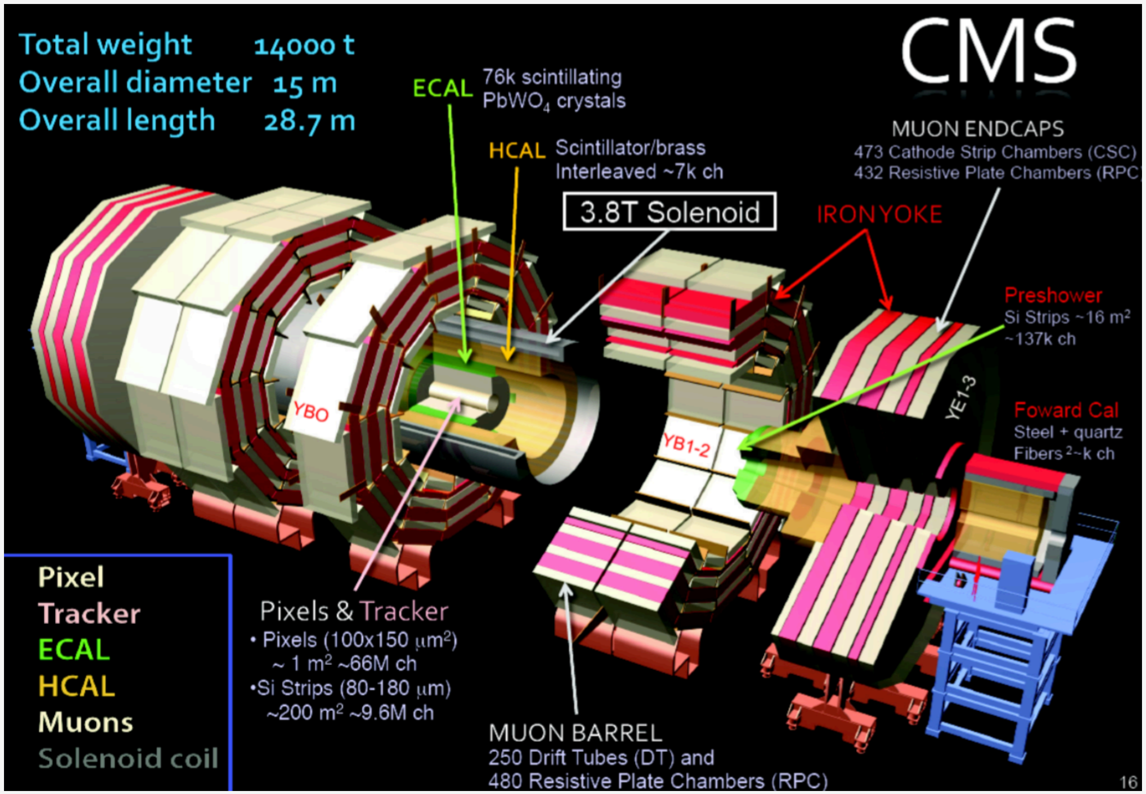


Multi-purpose, high-resolution hermetic detector

- Magnets: 2T central solenoid + 3 toroids
- Tracking: Silicon, transition radiation tracker for electron ID
- Calorimeter: Pb or Cu + LAr and steel/scintillator
- Muons: trigger and precision chambers in ~0.4T toroid field


ALICE
CMS
ATLAS
LHCb

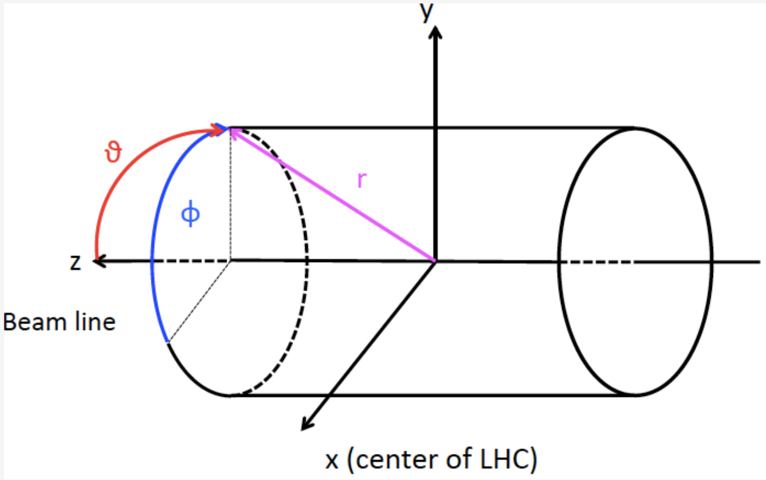
CMS: 'small' and heavy



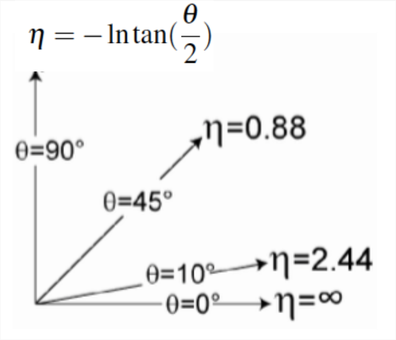
Multi-purpose, high-resolution hermetic detector

- Magnet: 4T central solenoid
- Tracking: Silicon
- Calorimeter: $PbWO_4$ and Fe/scintillator
- Muons: chambers in return yoke

Coordinates



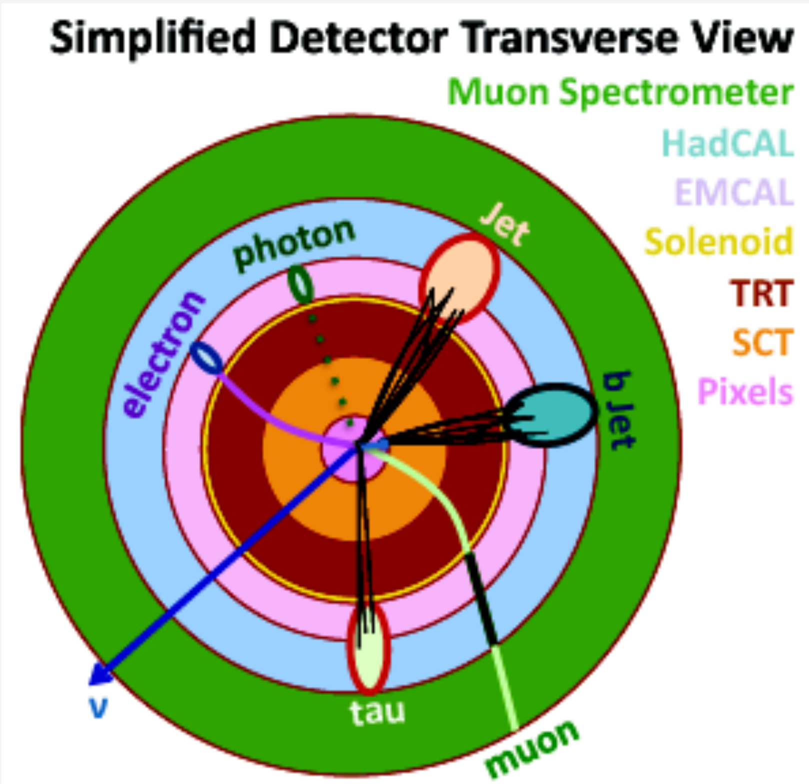
- Azimuthal angle ϕ
- Pseudorapidity η:



- Distance between objects:

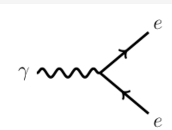
$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

Particle identification



Electron:
- Track
- Shower in EM calo
- Not much in hadronic calorimeter

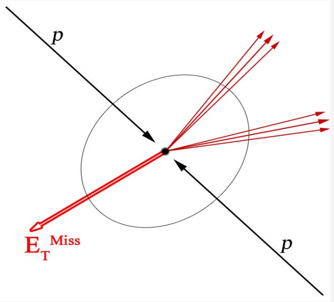
Photon:
- No track (or conversion vertex)
- Shower in EM calo
- Not much in hadronic calorimeter



Hadron (hadronic shower ➔ jet):
- Tracks (from charged components)
- Shower in EM and hadronic calorimeters
- b-jet : displaced vertex from tracks

Muons:
- Track in tracking and muon systems
- Little energy in the calorimeter

Neutrinos (or **dark matter**!): *Finally, we get to it ☺*
- No signal in any detector …
- Sum of momentum in the transverse plane of the pp collision should be 0...
- Imbalance → transverse missing momentum (also called *energy*)

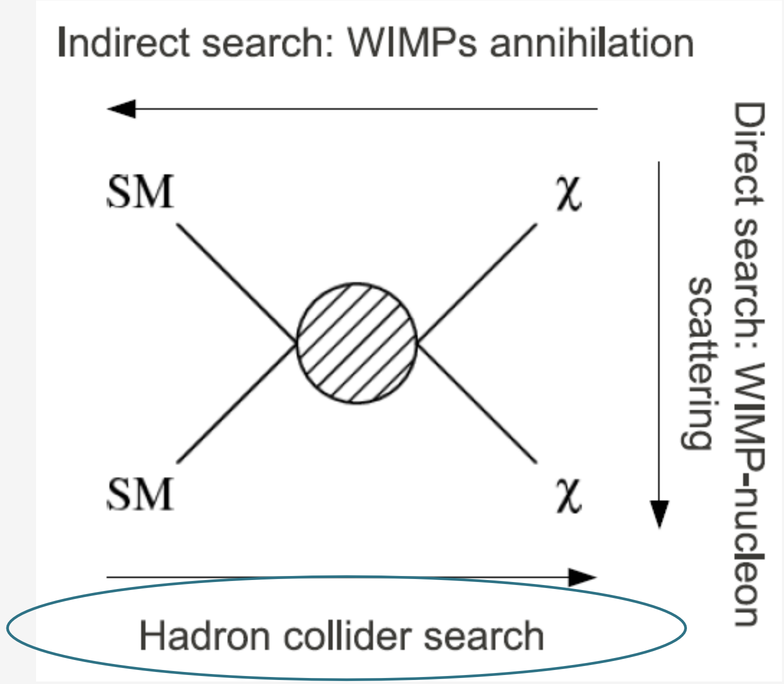


2. How to search for dark matter at the LHC – vanilla scenario

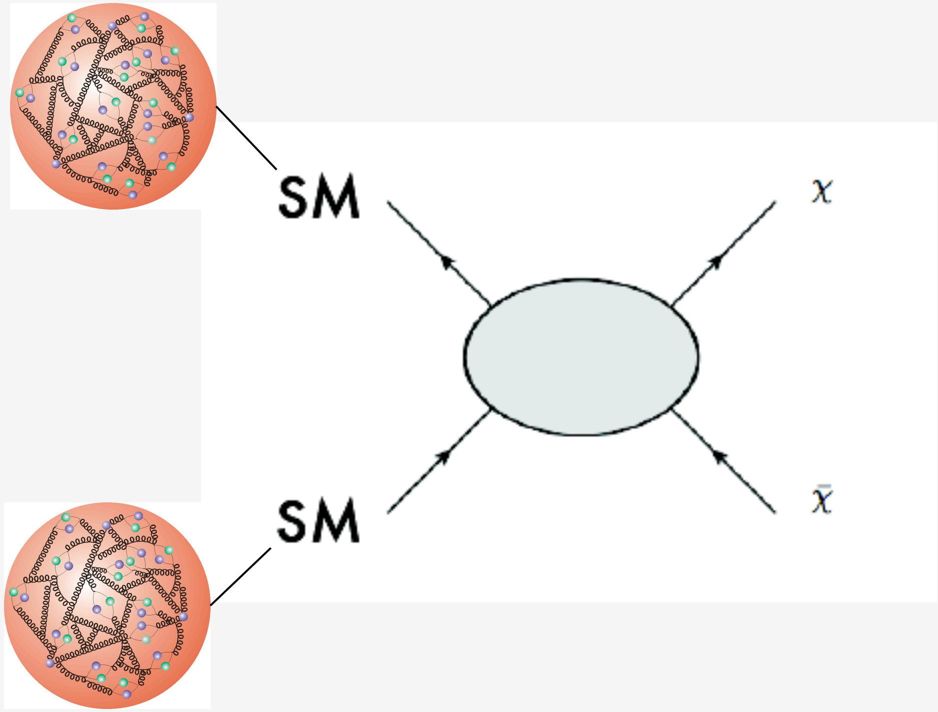
1. What do we expect to see?

Looking for Dark Matter

- Ways to look for dark matter: always need to assume some interaction with the SM obviously!



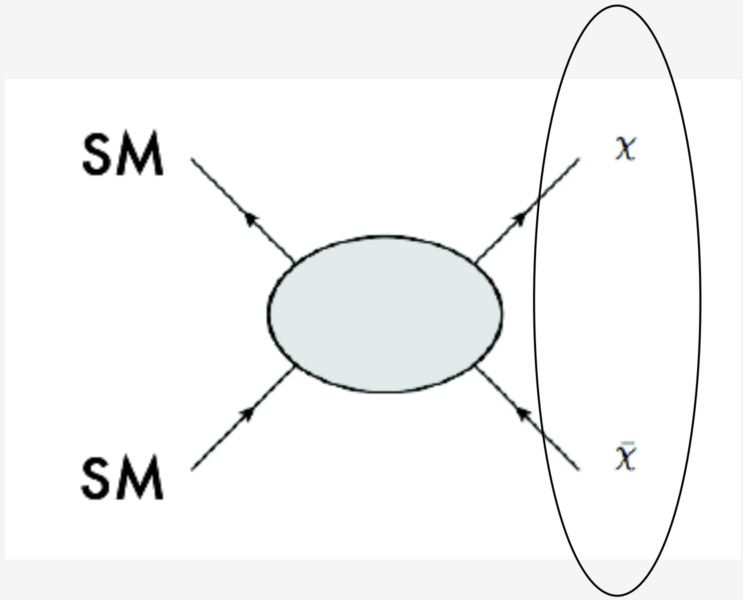
Producing DM at the LHC



Great!

Or is it …? What is the problem here?

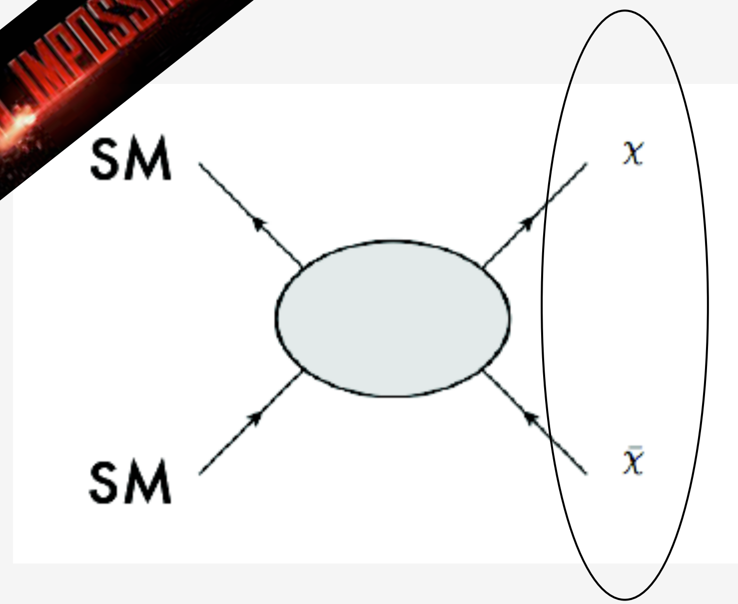
Producing DM at the LHC



What do we see this in the detector?
How do we know this event even occurred?

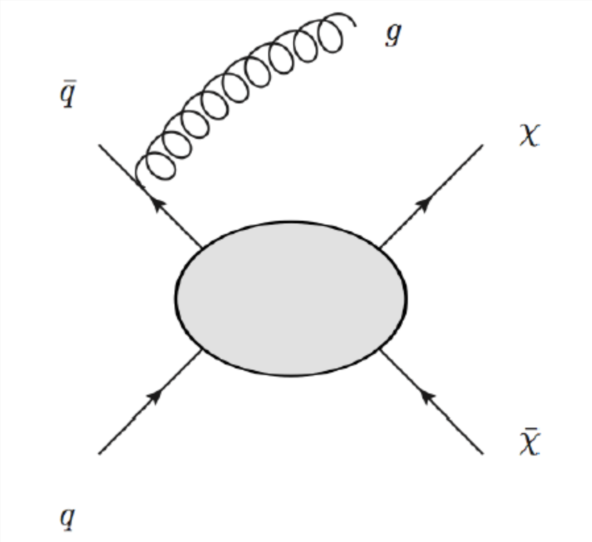
Producing DM at the LHC

?



What do we see this in the detector?
How do we know this event even occurred?

Producing DM at the LHC



Unless there is initial-state radiation, like a high-p_T jet, photon, …

The so-called $X+E_T^{miss}$ analyses* because all we see is this one object accompanied by large missing transverse energy

How do we search for such a signature at the LHC?

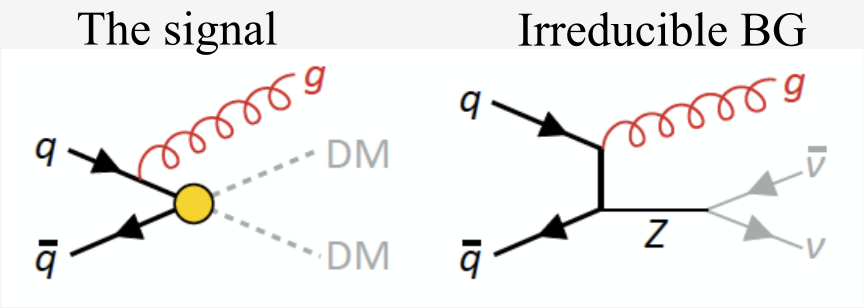
* *Also known as « mono-X » analyses, but this can be misleading…*

2. How to search for dark matter at the LHC – vanilla scenario

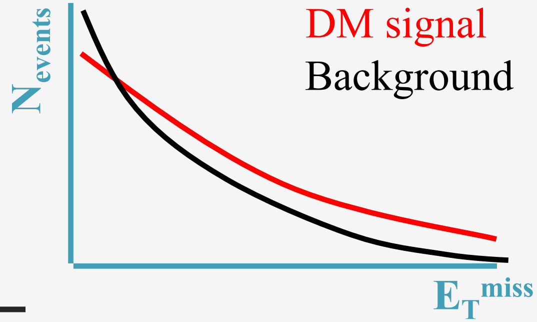
2. The jet+E_T^{miss} analysis

« Irreducible » backgrounds

Well-known standard model processes can also give the same final states:

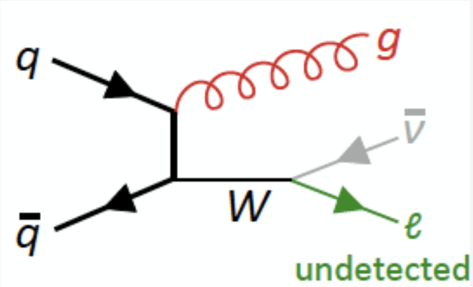


Can exploit 'cut-and-count' (more events in the jet+ E_T^{miss} final state than expected from the background only) and sometimes shape (e.g. harder E_T^{miss} spectrum…)



« *Reducible* » *backgrounds*

This final state can also occur in other processes because of misidentification of objects:



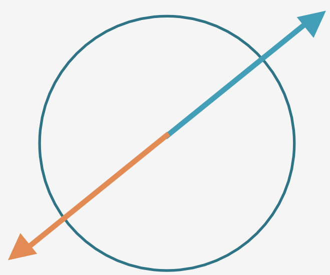
Fails the identification algorithm or
is out of acceptance

Veto against the presence of extra objects... good ID algorithms...

« Reducible » backgrounds

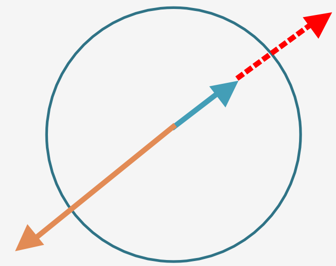
Mono-jet final states can also occur in other processes because of mismeasurements of objects:

Reality:



well-balanced dijet event

Measurement:



Jet(s)+(fake) E_T^{miss} event
(resolution effects, dead material…)

Asking for large E_T^{miss} and a good azimuthal separation between E_T^{miss} and objects helps…

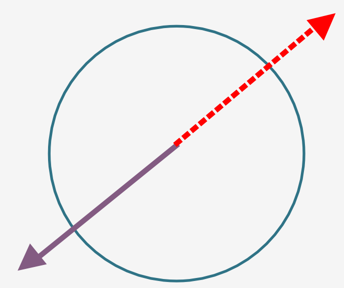
« Reducible » backgrounds

Mono-jet final states can also occur in other processes because of non-collision background:

Reality:

- *Noise in the calorimeter*
- *Jet coming from a pileup interaction*
- *Energy in the calo coming from non-collision beam interactions*

Measurement:



(fake) jet+ E_T^{miss} event

Jet quality requirements:
good response shape / distribution of energy / timing in the calorimeters, requirements on the tracks related to the primary vertex…

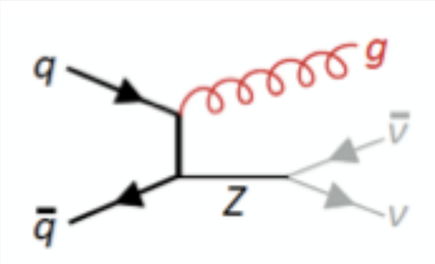
Defining the signal region

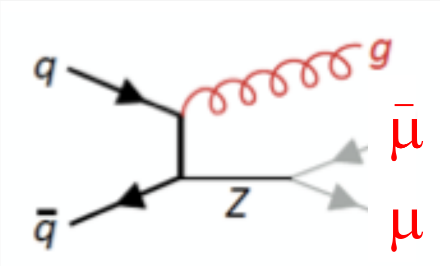
- *Define a signal region (SR) by selecting events such as to get an enhanced signal-over-BG ratio:*
    - *Select events with a high-p_T X and a large E_T^{miss}*
    - *Veto on extra objects*
        - *For example: no lepton in the final state*
    - *Avoid mismeasured objects which could lead to « fakes » (e.g.: no jet pointing in the E_T^{miss} direction, clean against non-collision BG…)*

- ATLAS selection on 13 TeV data (*Phys. Rev. D 94, 032005,2016*):
    - « Event cleaning »
    - Leading central jet within $p_T > 250$ GeV
    - 7 inclusive SRs with E_T^{miss} thresholds from >250 GeV to >700 GeV
    - $\Delta\phi$(sel. jets, E_T^{miss})>0.4
    - Lepton veto and more than 4 central jets

Estimating the BG

- **Need to estimate the BG contribution in the SR:**
  - Avoid relying too much on Monte Carlo simulations (extreme corner of the phase space)
  - Try to use data itself to help in the BG estimation
    - For example, to estimate Z(νν)+jet, select events in data which have Z(μμ)+jet instead (***control region***).

SR 

 CR

- This is the same production process, but a different Z decay…
- The events in the CR are orthogonal to the ones in the SR
- No signal event is expected in the CR
- One can then mimic E_T^{miss} by removing the muons from the transverse momentum imbalance computation.
- Usually have one control region for each of the main backgrounds

Estimating the BG from data

- The number of events in the control region is compared to the number of events predicted by the Monte Carlo simulation to derive a normalisation factor:

$$k = \frac{N_{data}^{CR}}{N_{Monte\ Carlo}^{CR}}$$

- The normalisation factor can then be applied to the number of Monte Carlo simulation events for the background in the signal region:

$$N_{data}^{SR} = k \times N_{Monte\ Carlo}^{SR}$$

$$= N_{data}^{CR} \times \frac{N_{Monte\ Carlo}^{SR}}{N_{Monte\ Carlo}^{CR}}$$

Any uncertainty affecting the background prediction in the same way in the control and signal regions will cancel out in the ratio (e.g. integrated luminosity)

E_T^{miss} + jet in ATLAS: backgrounds

- The main BG is Z(νν)+jet
  - As said before, one could use a Z(μμ)+jet CR, however:
    - In the SR(E_T^{miss}>700 GeV) ~100 Z(νν)+jet events expected
    - Given that BR(Z→νν)~20% and BR(Z→μμ)~3.4%, we would have ~17 events in the Z(μμ)+jet CR
      - 1/sqrt(17)~24% statistical uncertainty on the normalisation!
  - **<u>Idea:</u>** use a CR enriched in W(μν)+jet instead:
    - Larger W production cross section and BR(W→μν)~10.6%
      - Gain a factor ~7 in number of events with respect to Z→μμ
    - But, need to add an uncertainty on the predicted ratio between Z and W productions.

$$N_{data}^{Z\to\upsilon\upsilon,SR} = N_{data}^{W\to\mu\upsilon,CR} \times \frac{N_{Monte\ Carlo}^{Z\to\upsilon\upsilon,SR}}{N_{Monte\ Carlo}^{W\to\mu\upsilon,CR}}$$

E_T^{miss} + jet in ATLAS: backgrounds

- The second largest background is W(lν)+jet , where the charged lepton is missed in the reconstruction

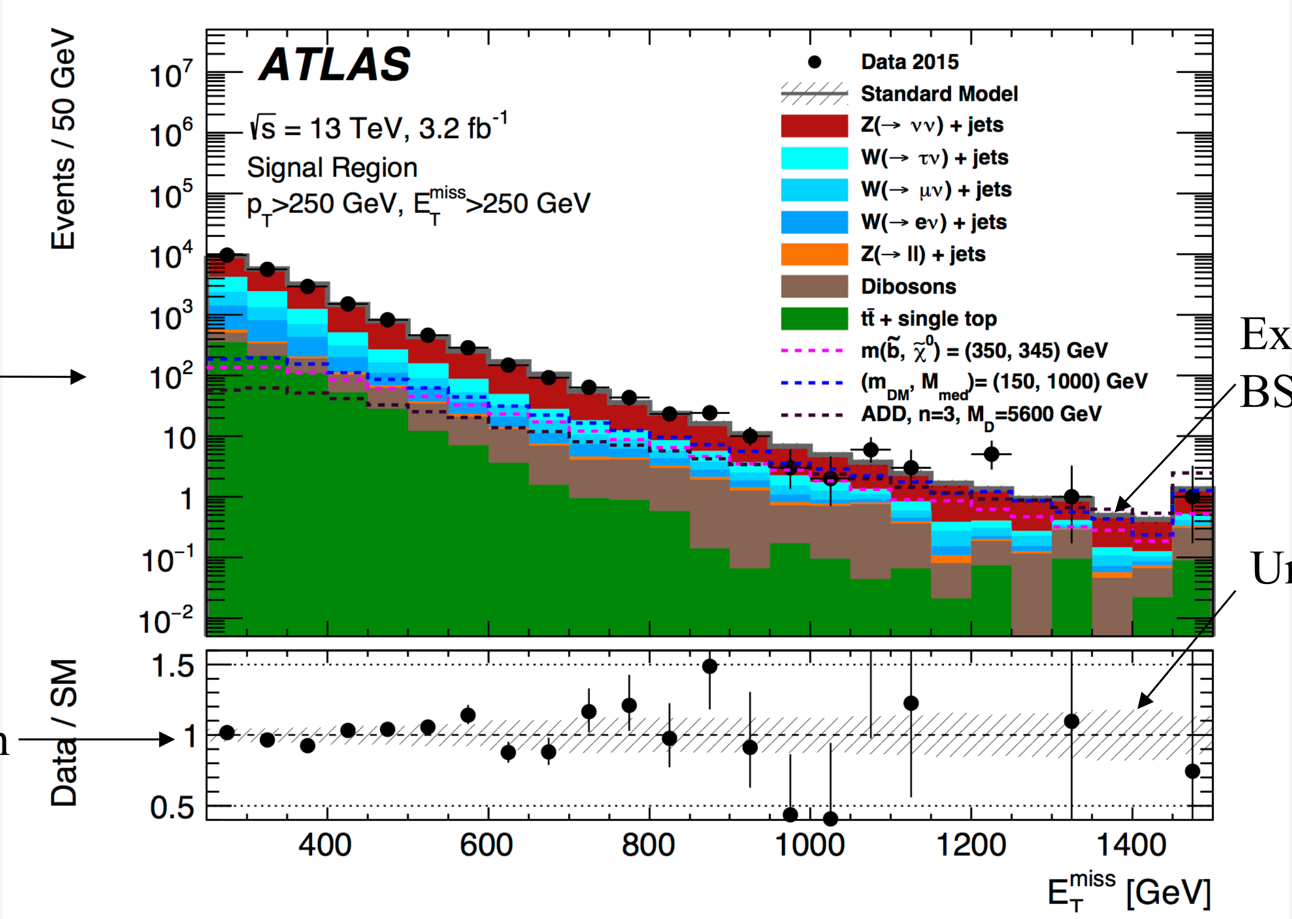
    - **Idea:** Again, use a CR enriched in W(μν)+jet

- Backgrounds which are expected to contribute very little to the event count in the signal region are taken from Monte Carlo simulation directly (top pair production, diboson production,…)
    - can live with large uncertainties on very small backgrounds!

- Very small rate (<<0.5%) from dijet and non-collision background due to the good cleaning cuts applied.
    - Residual (or upper limits on their) contributions can also be obtained by involved estimation methods using the data itself.

E_T^{miss} + jet in ATLAS

Data vs expectation



Examples of BSM signals

Uncertainty

Data/expectation

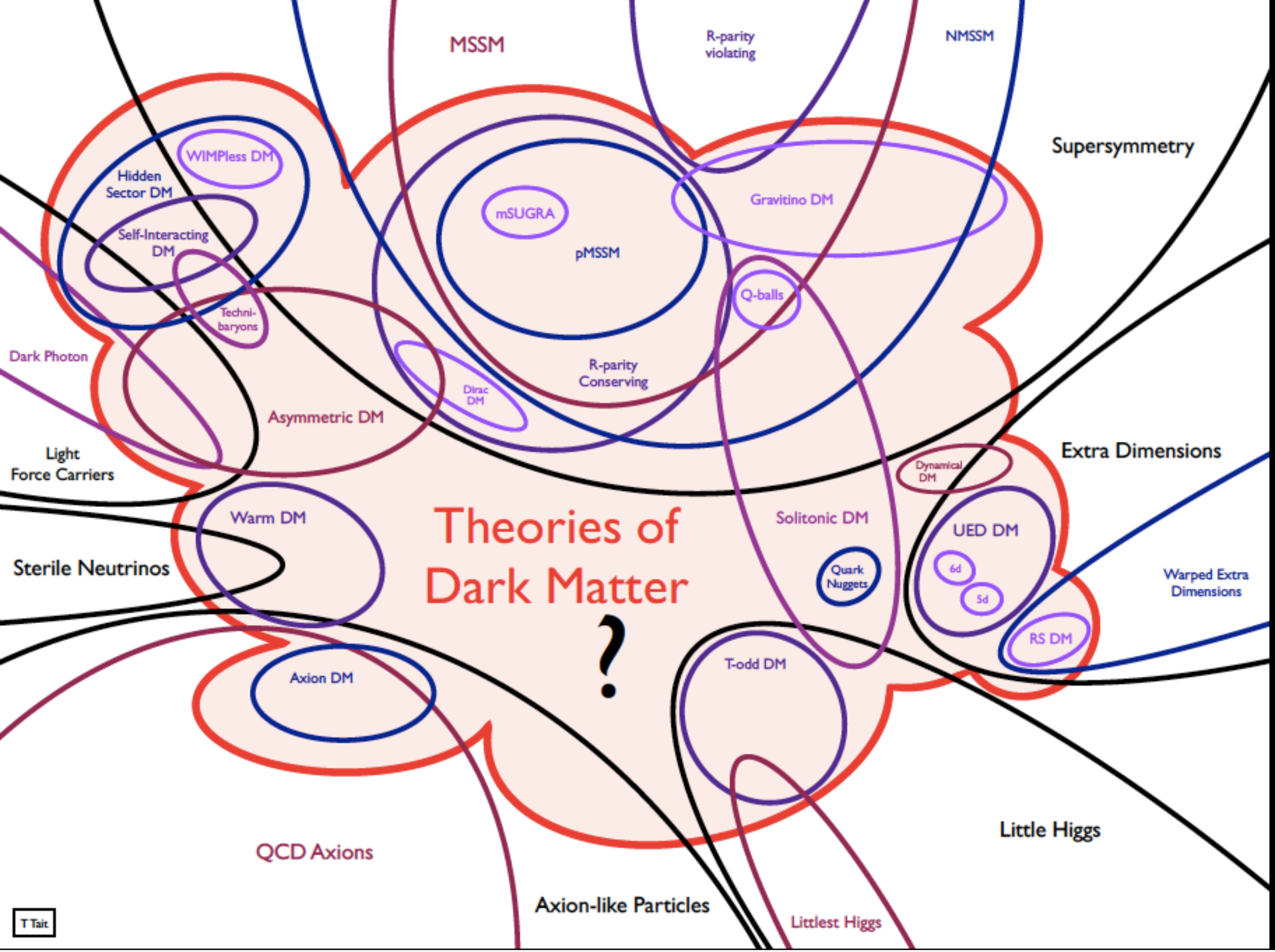
No significant excess

3. Interpreting the results

1. From EFT to simplified models

If there is no excess in the data, we can simply constrain the dark matter models, right?

Ok… which model?


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
6d
5d
Quark Nuggets
Sterile Neutrinos
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
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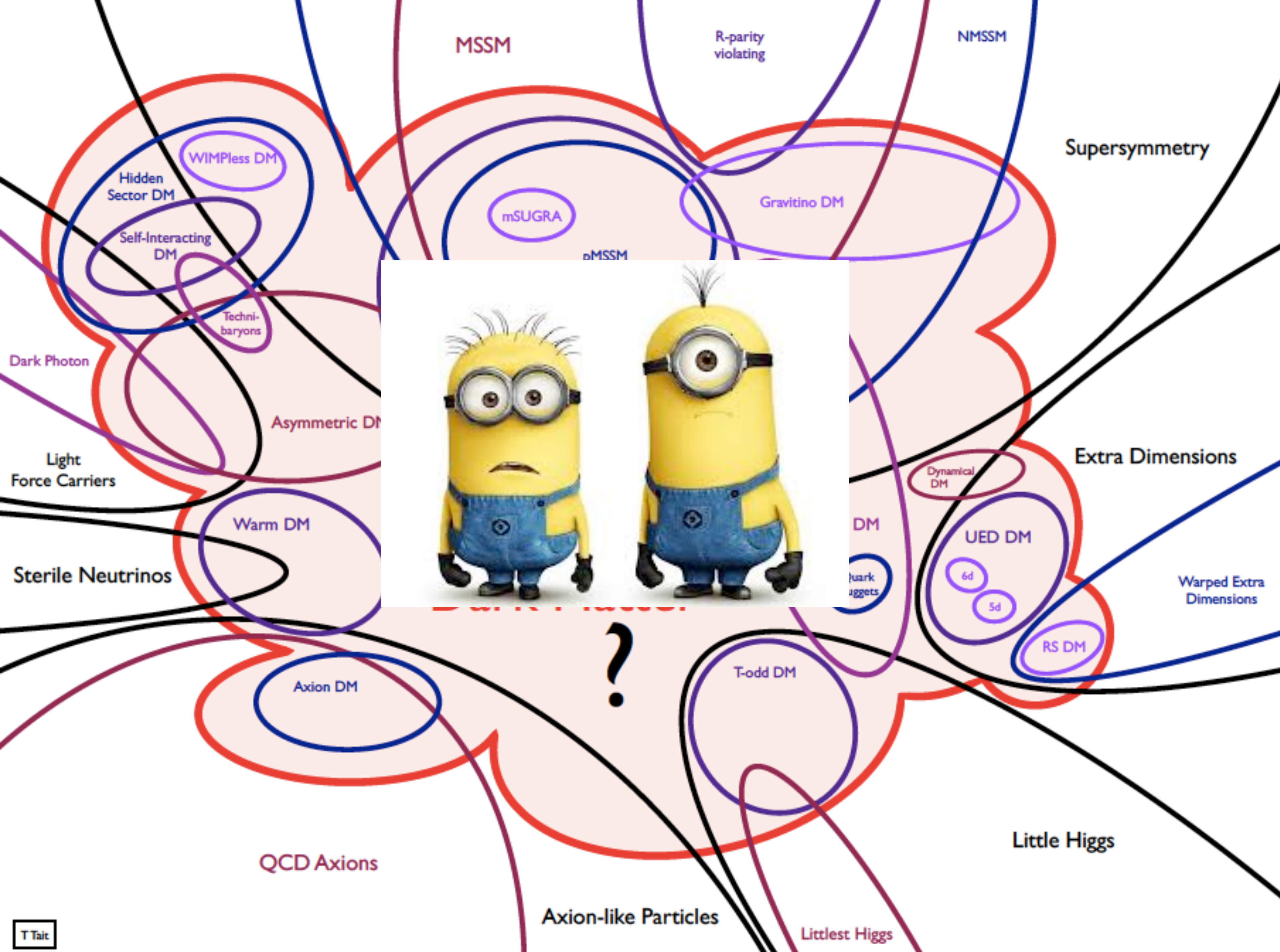

MSSM
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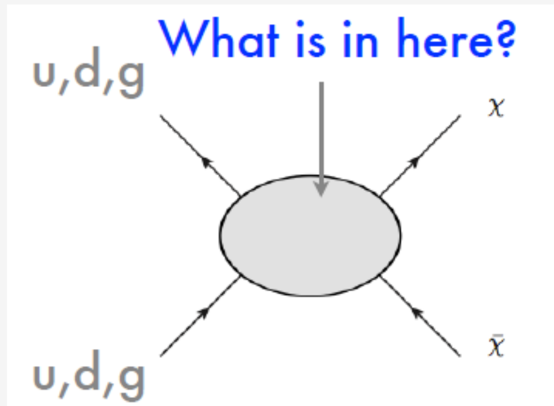
UED DM
6d
5d
Warped Extra Dimensions
RS DM
Warm DM
Sterile Neutrinos
DM
?
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

Let's start simple…
What about an effective field theory?

The "run-1 strategy"

aka contact interactions



(we don't care!)

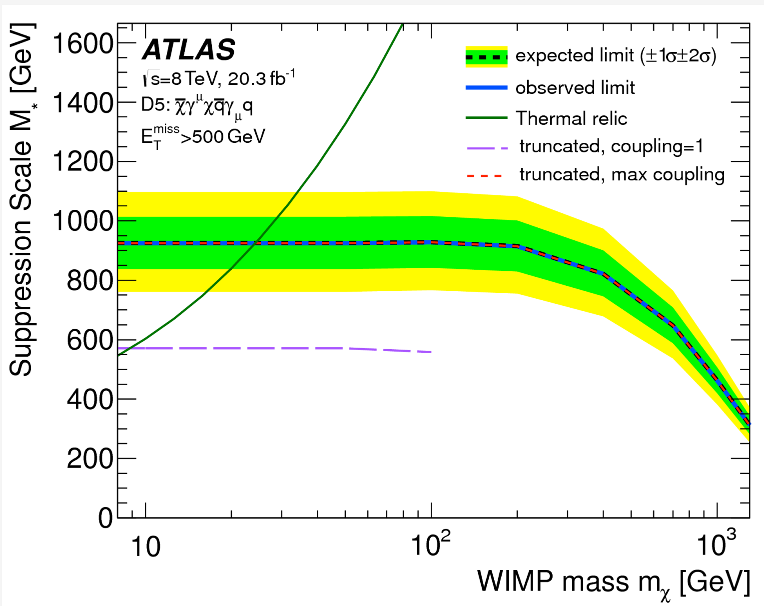
Need some **assumptions**:

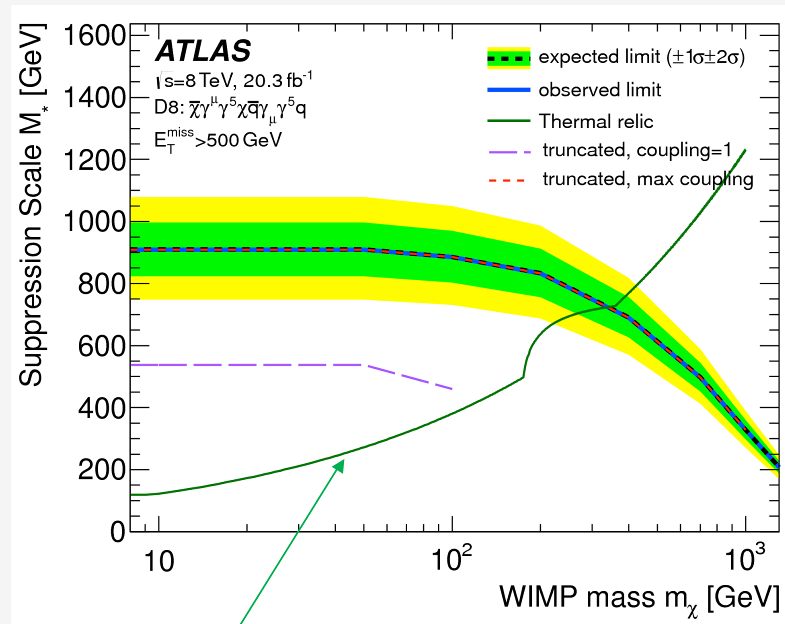
- Heavy mediator which is integrated out
- Assume one interaction type at a time, with M* parameterizing the strenght of the interaction
- Dirac DM

Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

Setting limits - effective theory

Take D5 (vector) and D8 (axial-vector) as examples:





Thermal relic abundance is equal to the one measured in Cosmic Microwave Background anisotropies, in the absence of any interaction other than the one considered (over-abundant above the line, under-abundant below).

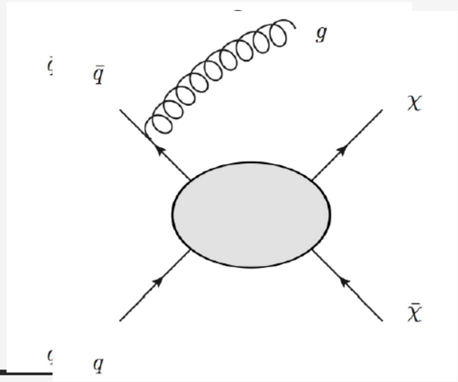
But are EFTs a valid approach?

The bounds we place on M* are at the TeV level or less, but the momentum transfer in LHC collisions can be higher…

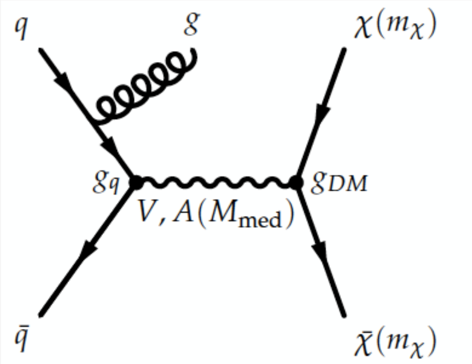
→ one of the hypotheses for EFT to be valid is that the mediator is so heavy it can be integrated out, this is *not* the case if we are able to produce the mediator on shell in a large fraction of the events!

→ Are the limits set then too optimistic? Too pessimistic?

→ Say we have an s-channel process:



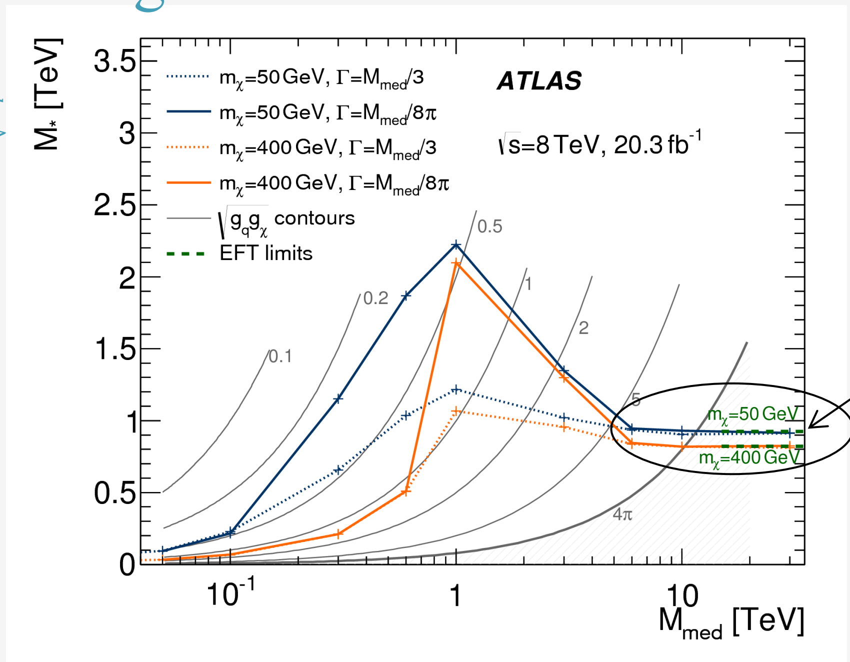
$$M^* = \frac{M_{med}}{\sqrt{g_q g_{DM}}}$$



But are EFTs a valid approach?

Putting limits on this s-channel model instead and comparing:

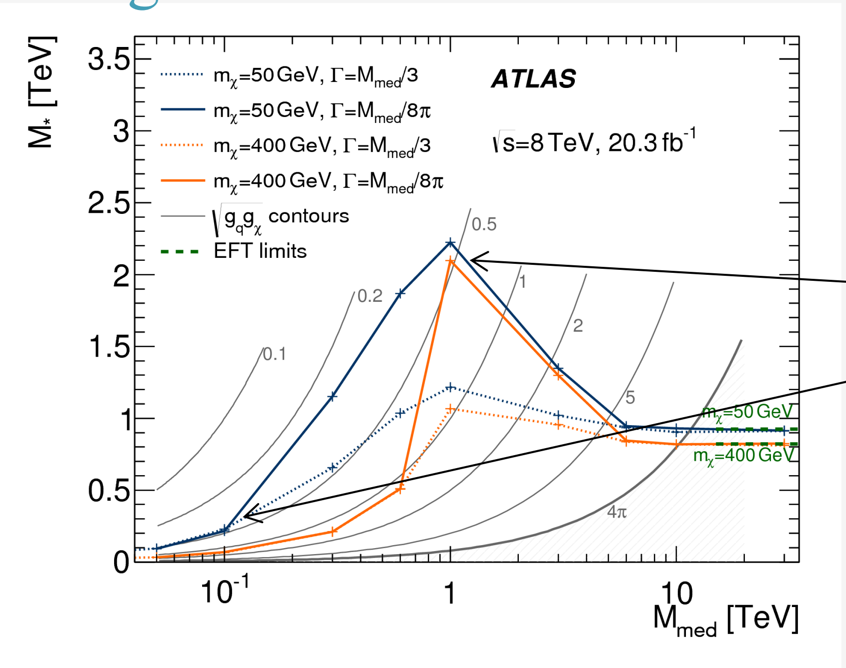
$$M^* = \frac{M_{med}}{\sqrt{g_q g_{DM}}}$$



Recovering the EFT limits at large mediator masses
(expected, this is where the EFT is valid…)

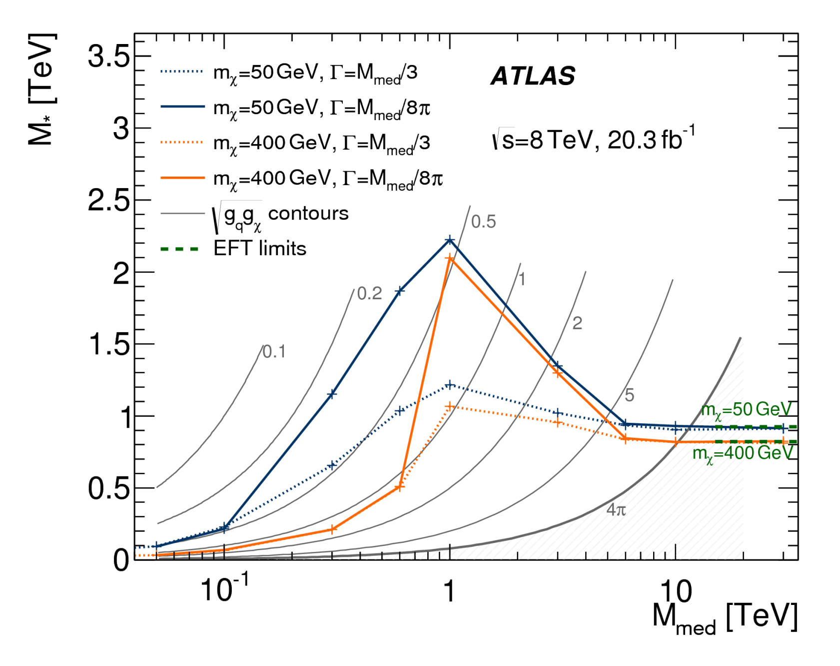
But are EFTs a valid approach?

Putting limits on this s-channel model instead and comparing:



But the EFT misses the features of the ‘real’ underlying model if the mediator mass is not heavy enough

But are EFTs a valid approach?



$$M_{med} = M^* \times \sqrt{g_q g_{DM}}$$

The ~ 1 TeV EFT limit on M* is only always valid in the case of very large couplings:

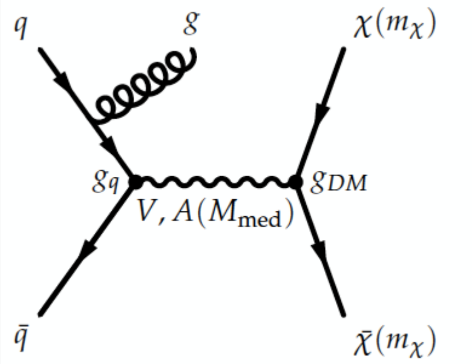
- for $g_q g_{DM} \sim (4\pi)^2$, M*>1 TeV means M_{med}>12.6 TeV

But there is no reason to expect these large couplings!

Defining new benchmarks for run-2

- The ATLAS/CMS Dark Matter Forum was formed before the start of Run-2:
  - Collaboration between experimentalists and theorists
  - Aim: identify sets of models to use for optimization and interpretations of the searches
  - Ended with recommendations published in 2015: http://arxiv.org/abs/1507.00966

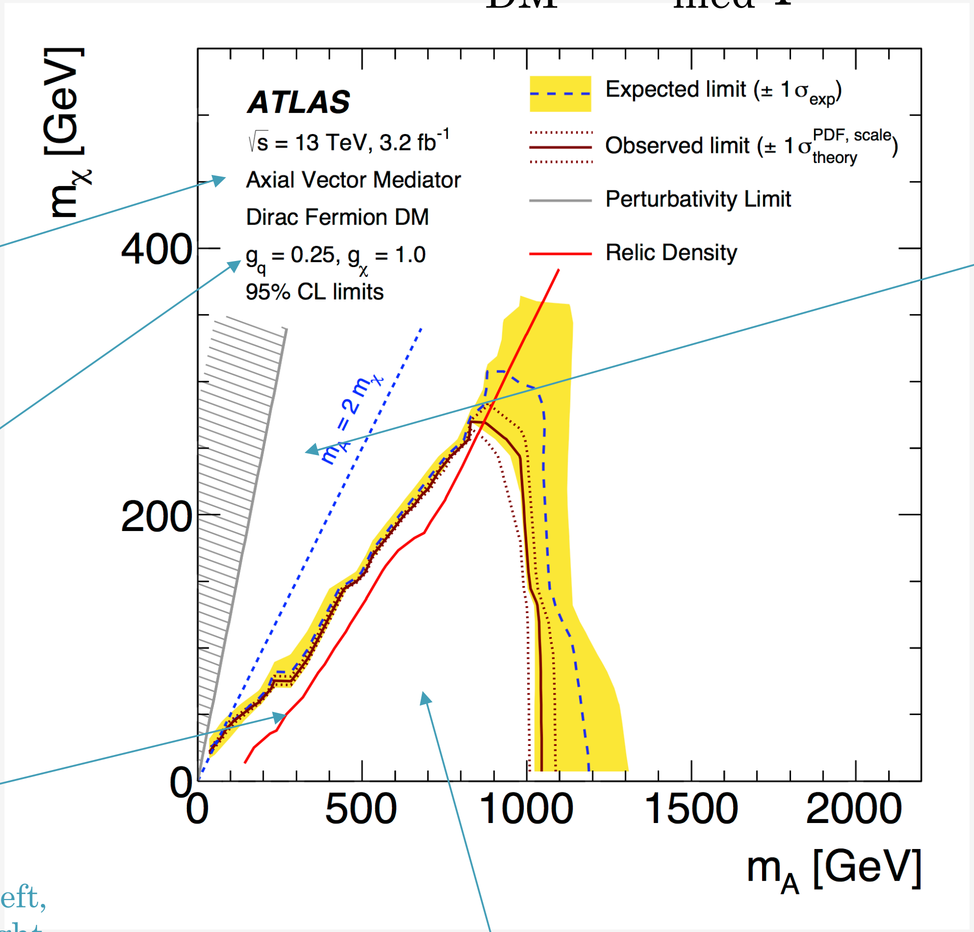
- Main point: drop the EFT, focus on the ***simplified models*** when possible
  - s-channel simplified model with different mediator types



Free parameters:
m_{DM}, M_{med}, g_{DM}, g_q
Γ_{med} is a function of the other parameters (assuming no other coupling)

E_T^{miss} + jet in ATLAS: limits

Limits presented in the m_{DM} / M_{med} plane:



For a given mediator type

For given couplings

Much smaller production rate for $M_{med} < 2\ m_{DM}$: difficult to set limits there

DM relic density: underabundant on the left, overabundant on the right (for this simplified model)

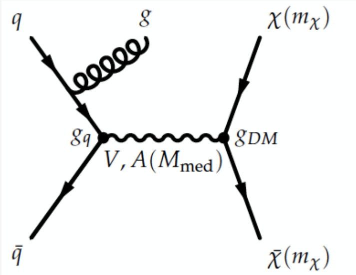
Excluded region

3. Interpreting the results

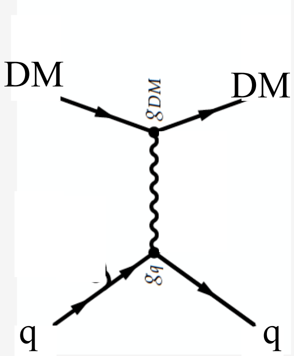
2. Comparison to direct detection

We’re both looking for the same thing, no?

Comparison to direct detection



- We have a simplified model describing the production, through a mediator, of DM particles from quarks
- The same model can also be used to describe the interaction between a DM particle bouncing off a quark ➔ direct detection mechanism!



- Non-relativistic plane wave expansion:
  - Scalar and vector mediators would lead to spin-independent interactions:

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

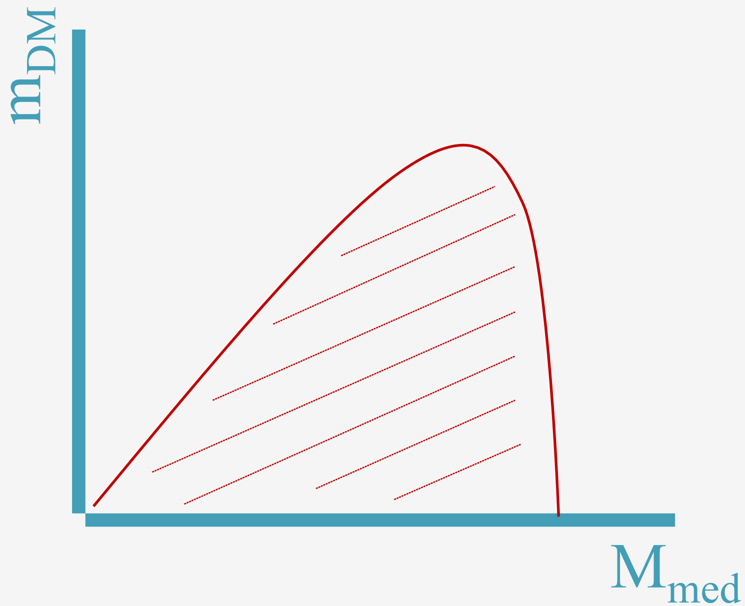
  - Pseudo-scalar and axial-vector mediators would lead to spin-dependent interactions:

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

f and f_s: factors to translate quark interaction into nucleon interaction

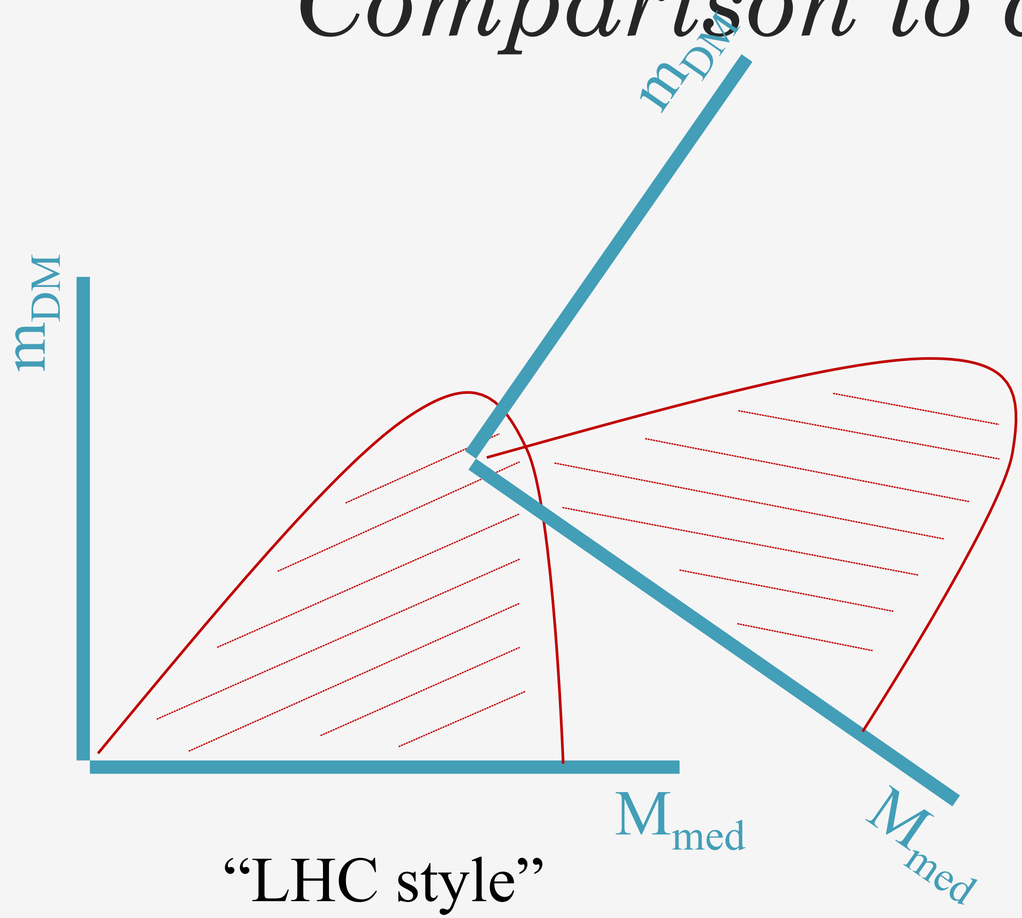
$\mu_{n\chi} = m_n m_{\rm DM}/(m_n + m_{\rm DM})$

Comparison to direct detection



"LHC style"

Comparison to direct detection



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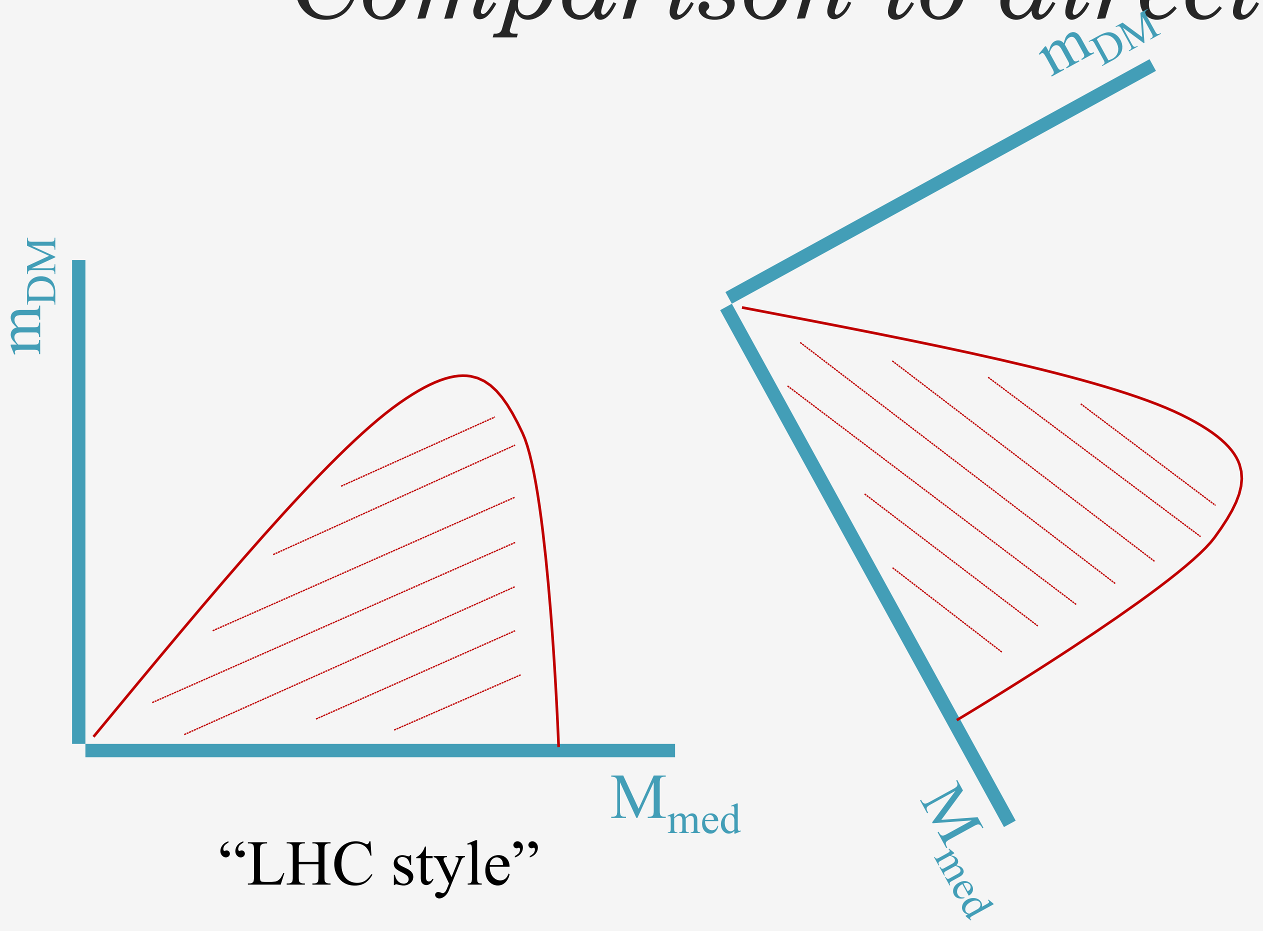
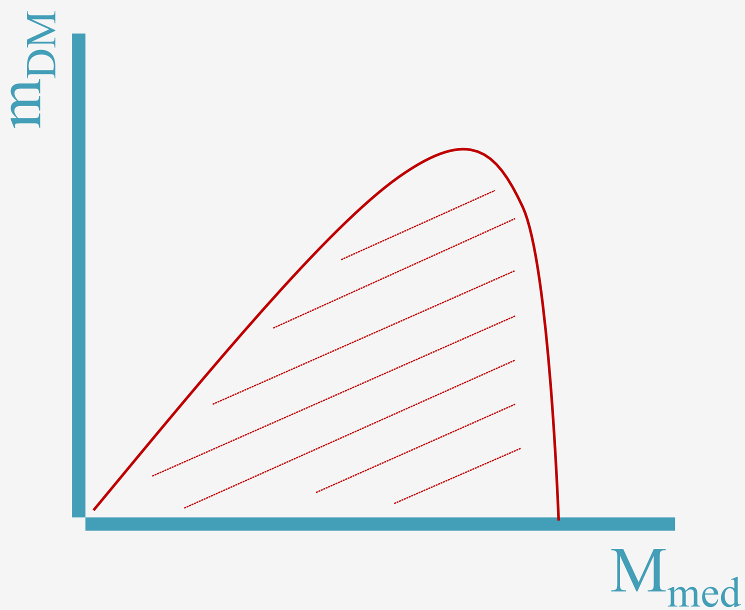
Comparison to direct detection

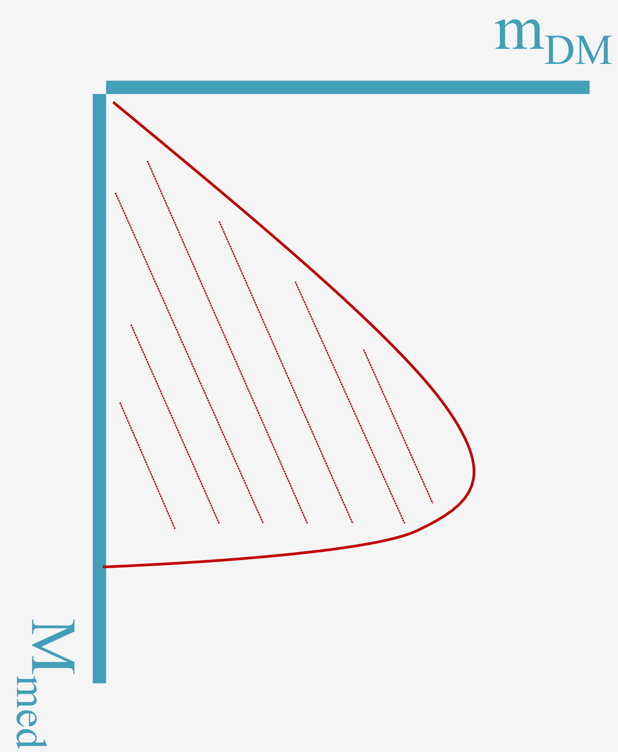


"LHC style"

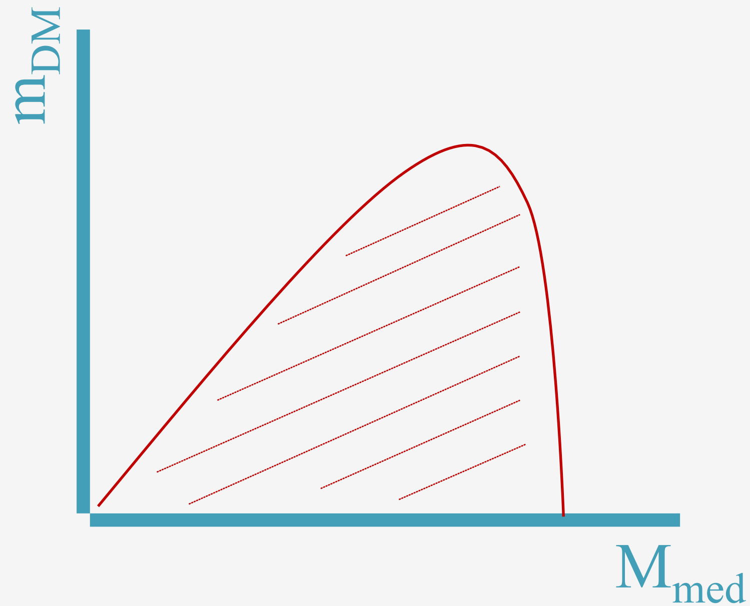
Comparison to direct detection



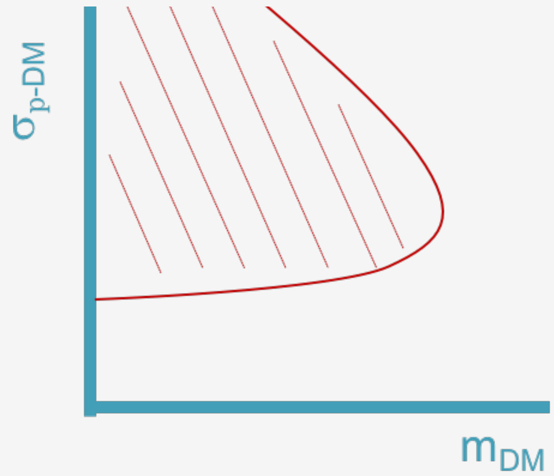
"LHC style"



Comparison to direct detection

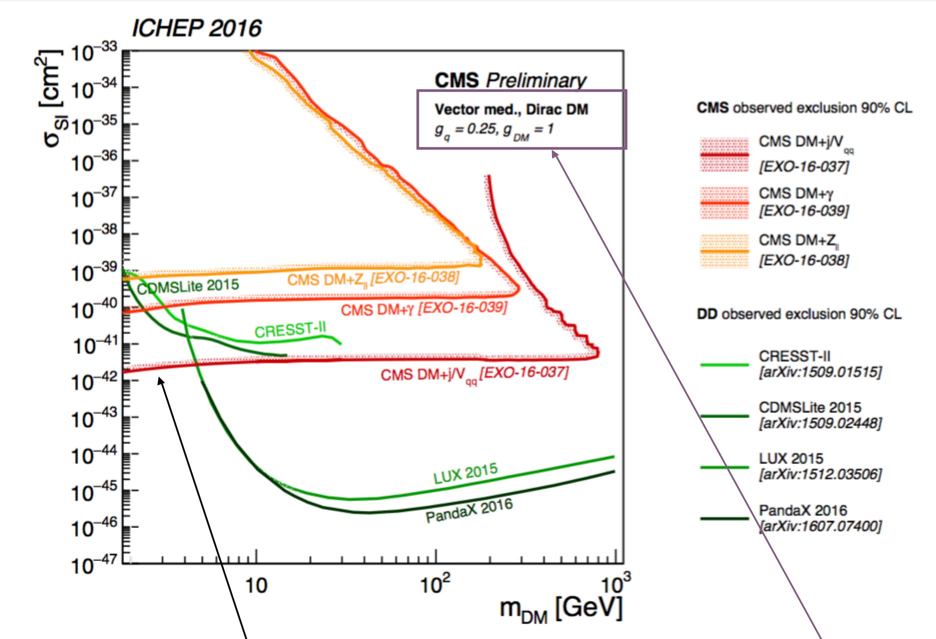


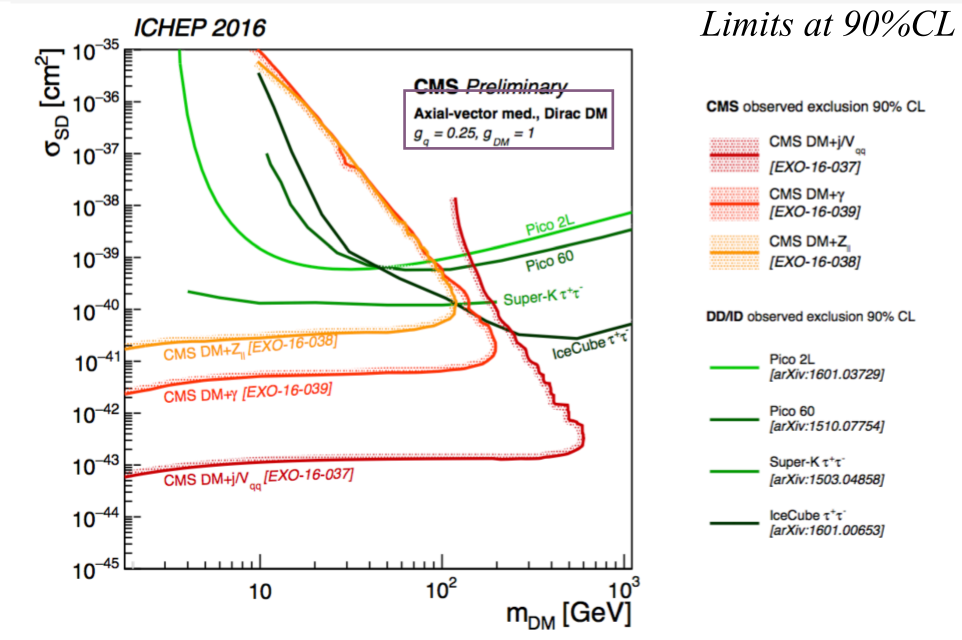
"LHC style"



"Direct dection style"

Comparison to direct detection

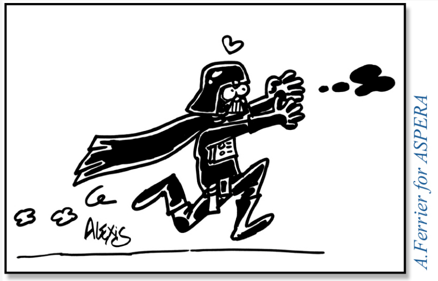




The LHC is able to probe the low masses

The LHC is particularly relevant in SD

But one must remember the **assumption of the model** considered.
It's not a competition with direct detection: we are complementary!



Looking for dark matter

1. The LHC, ATLAS and CMS

2. How to search for dark matter at the LHC – vanilla scenario
    1. What do we expect to see?
    2. An analysis example: the ‘jet+E_T^{miss}’ analysis

3. Interpreting the results:
    1. From EFT to simplified models
    2. Comparison to direct detection searches

4. The many faces of dark matter at the LHC
    1. Overview of the ‘mono-X’ analyses
    2. The Higgs portal
    3. What about the mediator?
    4. What about more complete models?

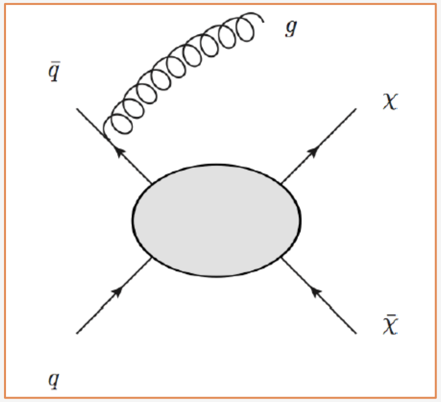
5. The future, a summary and the dream picture

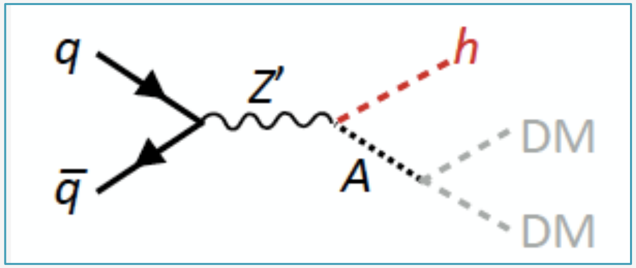
4. The many faces of dark matter at the LHC

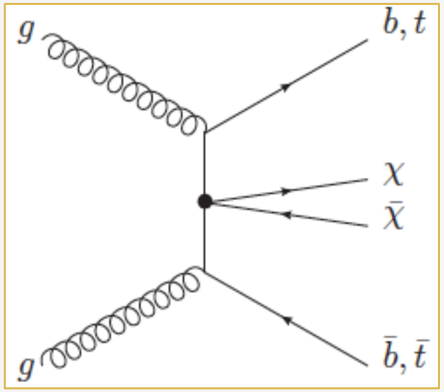
1.Overview of the ‘E_T^{miss}+X’ analyses

The E_T^{miss}+X searches

- All we see is the X, accompanied by large missing transverse energy from the DM production
- X can come from ISR (as we saw before), or from a more complicated interaction involving more than one new states
- X can be a single object (*mono-X searches*), or a more complex final state (e.g. at top-quark pair)







The E_T^{miss}+X searches in Run-2

X	ATLAS	CMS
Jet	Phys. Rev. D 94, 032005 (2016)	**CMS-PAS-EXO-16-037**
W or Z (qq)	arXiv:1608.02372 (subm. to PLB)	
Z(ll)	**ATLAS-CONF-2016-056**	**CMS-PAS-EXO-16-038**
Photon	JHEP 1606 (2016) 059	**CMS-PAS-EXO-16-039**
b quark(s)	**ATLAS-CONF-2016-086**	CMS-PAS-B2G-15-007
Top quark(s)	**ATLAS-CONF-2016-050 (1-lepton)** **ATLAS-CONF-2016-076 (2-lepton)** **ATLAS-CONF-2016-077 (0-lepton)**	CMS-PAS-EXO-16-005 (0/1-lepton tt) CMS-PAS-EXO-16-028 (2-lepton tt) **CMP PAS EXO-16-040** (1 boosted top)
$H(\gamma\gamma)$	**ATLAS-CONF-2016-087**	CMS-PAS-EXO-16-011
H(bb)	arXiv:1609.04572 (subm. to PLB)	CMS-PAS-EXO-16-012
H(4l)	ATLAS-CONF-2015-059	

2015 dataset or **ICHEP 2016 dataset**

Probably more results to come out for the Moriond conference next week!

The E_T^{miss}+X searches in Run-2

X	ATLAS	CMS
Jet	Phys. Rev. D 94, 032005 (2016)	CMS-PAS-EXO-16-037
W or Z (qq)	arXiv:1608.02372 (subm. to PLB)	
Z(ll)	**ATLAS-CONF-2016-056**	**CMS-PAS-EXO-16-038**
Photo		
b quar		
Top qu		) p)
H(γγ)		
H(bb)	arXiv:1609.04572 (subm. to PLB)	CMS-PAS-EXO-16-012
H(4l)	ATLAS-CONF-2015-059	

2015 dataset or **ICHEP 2016 dataset**

We will now go through the E_T^{miss}+X list together…
The idea is not that you recall all details of every analysis, but that you get a flavour of all that's possible.

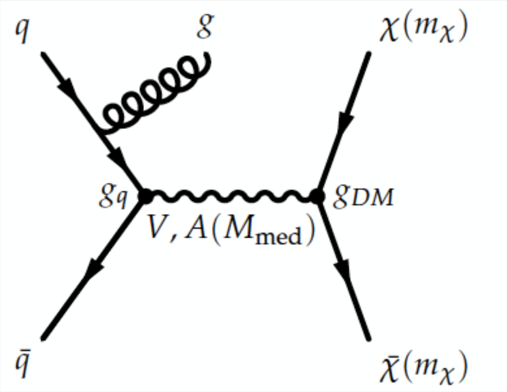
Probably more results to come out for the Moriond conference next week!

General strategy - reminder

- Define a signal region (SR) by selecting events such as to get an enhanced signal-over-BG ratio:
  - Select events with a high-p_T X and a large E_T^{miss}
  - Veto extra objects (e.g.: no e or μ in mono-γ)
  - Avoid mismeasured objects which could lead to fake E_T^{miss} (e.g.: no jet pointing in the E_T^{miss} direction, clean against non-collision BG…)

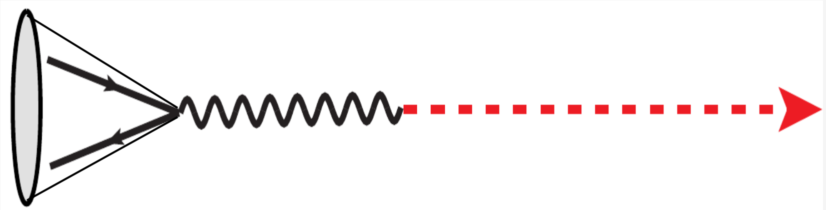
- Estimate the BG contribution in the SR (data-driven or using MC)

- If no excess in the SR: show the limits on models, following the recommendations of the ATLAS/CMS Dark Matter Forum (**arXiv:1507.00966**) and of the LHC DM WG (arXiv:1603.04156)
  - Favours the use of simplified models
  - Benchmarks with specific couplings
  - Limits in the m_{DM}/m_{Med} plane

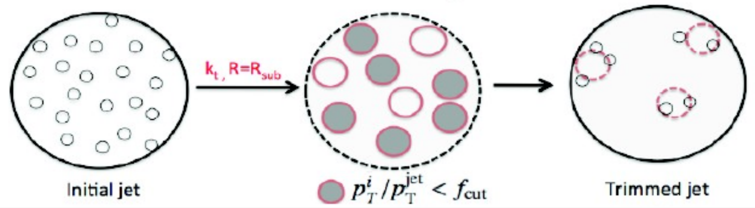


$E_T^{miss} + W/Z(hadronic)$

For highly boosted W/Z, the decay products will not be resolved into two jets, but will be merged in a 'fat' jet ($\Delta R \sim 2m/p_T$)

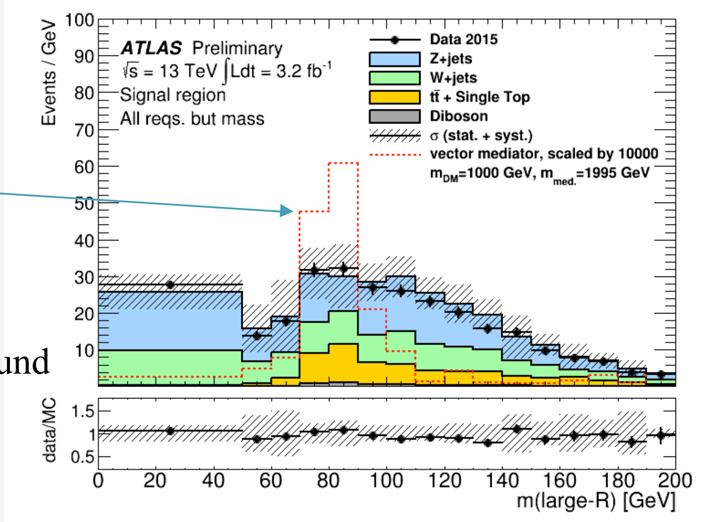


The problem with « fat jet » is that they integrate over more 'unwanted' energy (from pileup jets, underlying event …); use a cleaning procedure, such as trimming:



The large jet can be tagged as W/Z boson with cuts based on:

- its mass must be compatible with the W/Z mass
- using 'substructure variables'
    - Look at how the energy is deposited inside the fat jet
        - Is it more compatible with:
            - 1 'lump' : looks like a single-jet background
            - 2 'lumps' : looks like a W/Z→qq
            - 3 'lumps' : looks like a t→Wb→qqb



$E_T{}^{miss}$ + W/Z(hadronic) in ATLAS

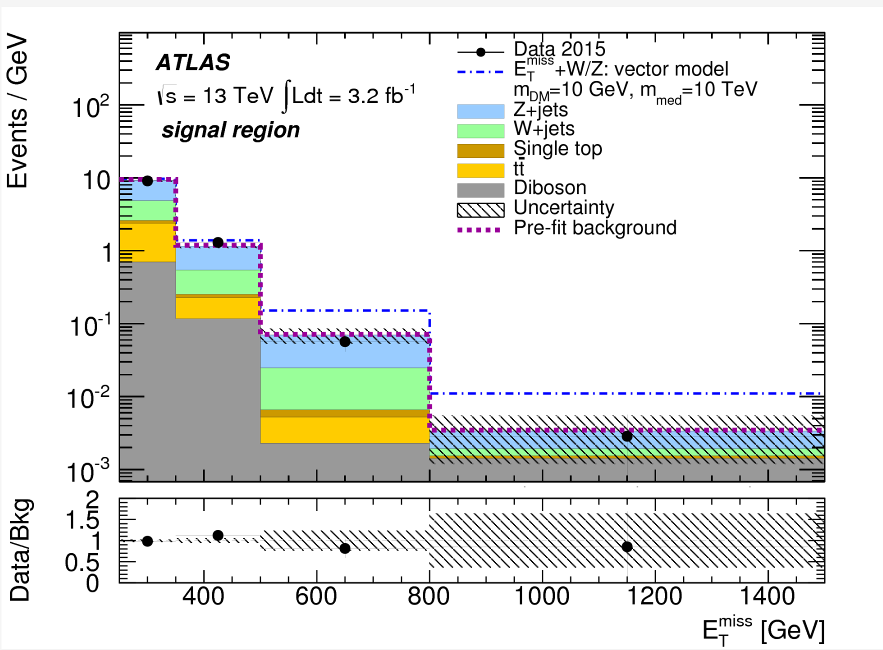
Computed from tracks only

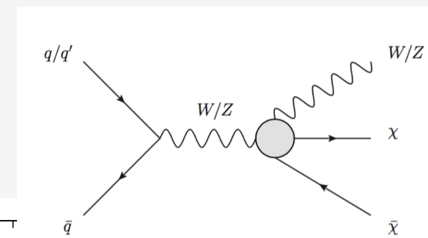
Selection:

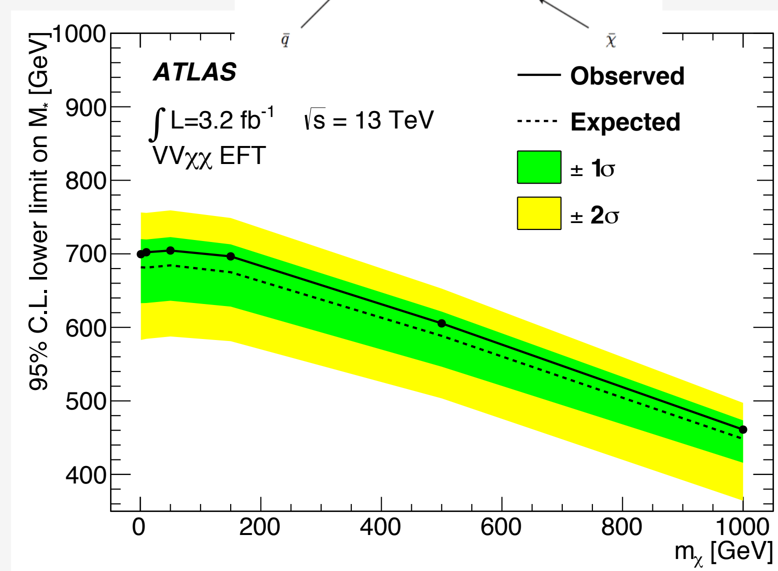
- $E_T{}^{miss}$ >250 GeV, $p_T{}^{miss}$ > 30 GeV and $\Delta\phi(p_T{}^{miss}, E_T{}^{miss})<\pi/2$, $\Delta\phi(\text{jet}, E_T{}^{miss})>0.6$
- Veto on leptons
- Central, p_T>200 GeV large-R trimmed jet tagged as a W/Z *(mass + substructure)*

BG estimation via leptonic CRs

(2μ for Z, 1μ + b-jet/no b-jet for top/W)







Bear in mind the EFT validity issues…

E_T^{miss} + jet/Z/W(hadronic) in CMS

Mono-V:

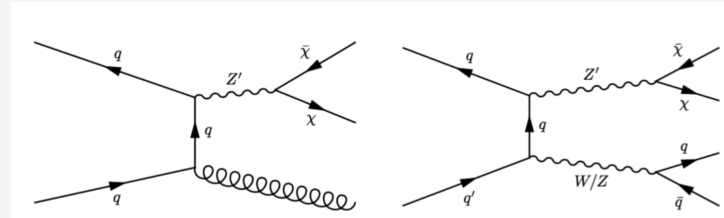
- Fat jet with $p_T > 250$ GeV, $E_T^{miss} > 250$ GeV, tagged as a W/Z (mass and substructure)

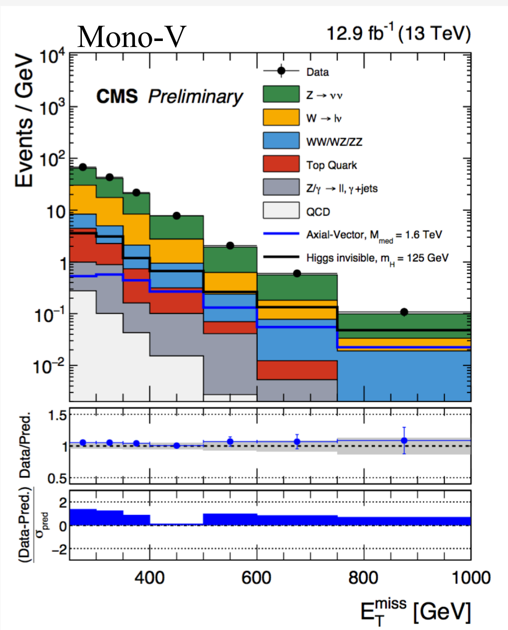
Mono-jet selects remaining events with:

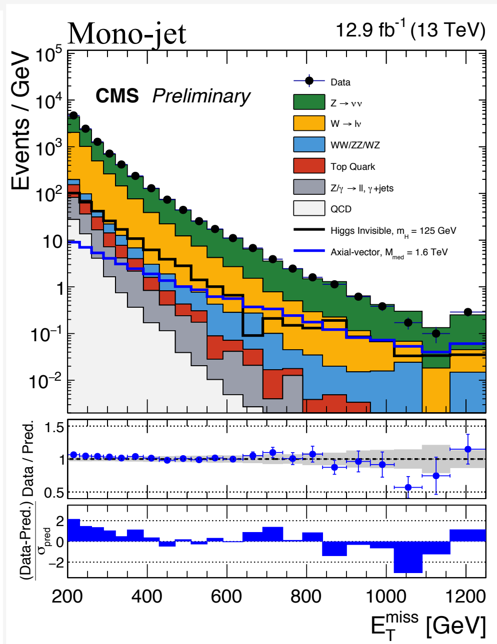
- 'Normal' jet with $p_T > 100$ GeV, $E_T^{miss} > 200$ GeV

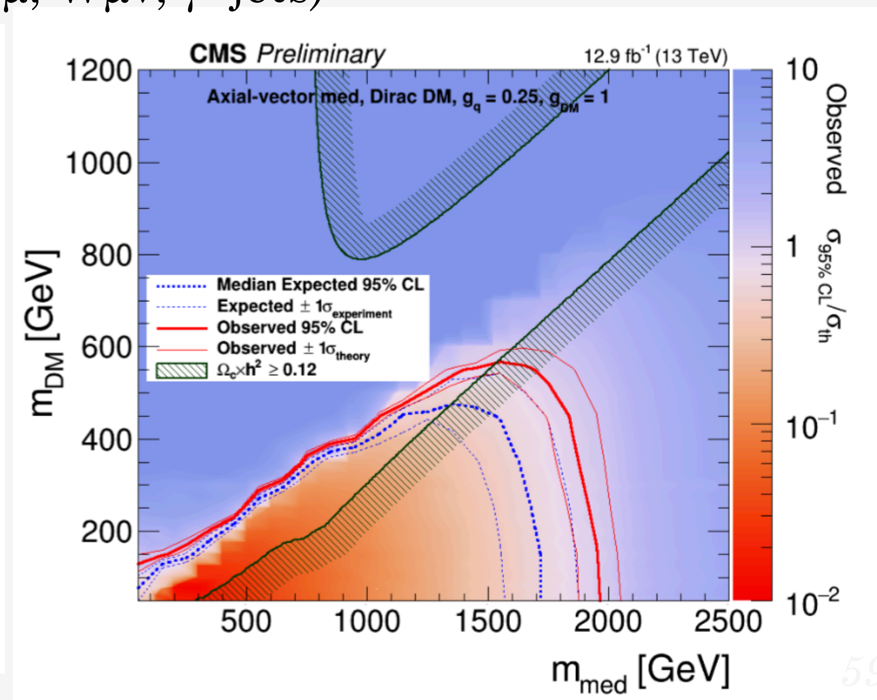
BG estimation via 5 CRs (Zee, Weν, Zμμ, Wμν, γ+jets)

Can mimic Z+jets when m_Z can be neglected









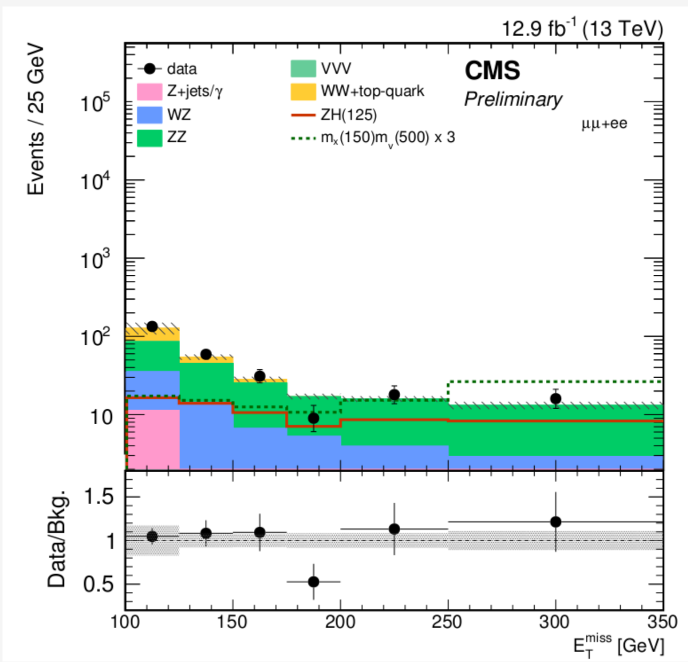
$E_T^{miss} + Z(ll)$

Selection:

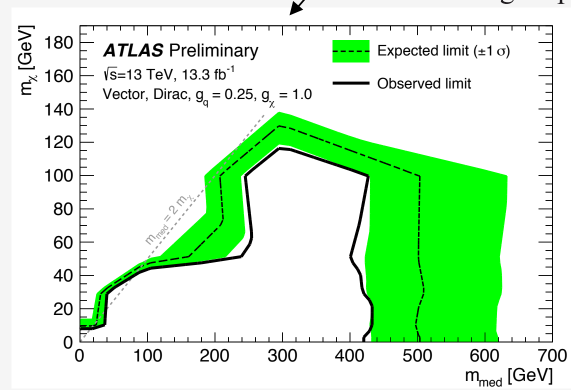
- ee or μμ pairs compatible with the Z mass, away from E_T^{miss} and whose p_T is well balanced with the large E_t^{miss}
- jet/E_T^{miss} separation, no b-jet (*CMS: no extra jet, no hadronic tau*)

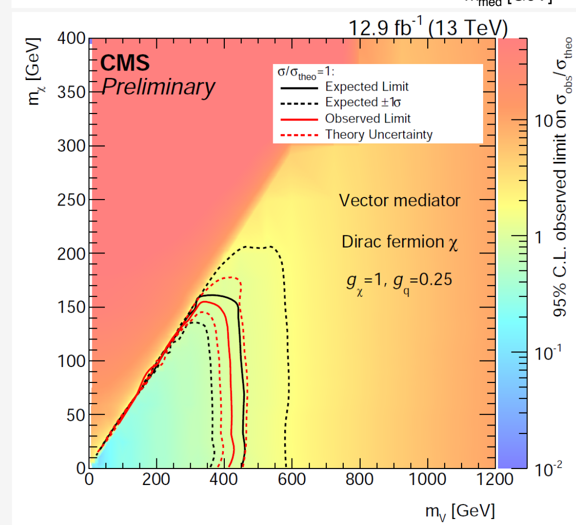
BG estimation:

ZZ (and WZ in CMS) from NNLO-corrected MC
WZ from 3-lepton CR in ATLAS



Sometimes limits can look ‘funky’ due e.g. to a limit grid of simulated signal points



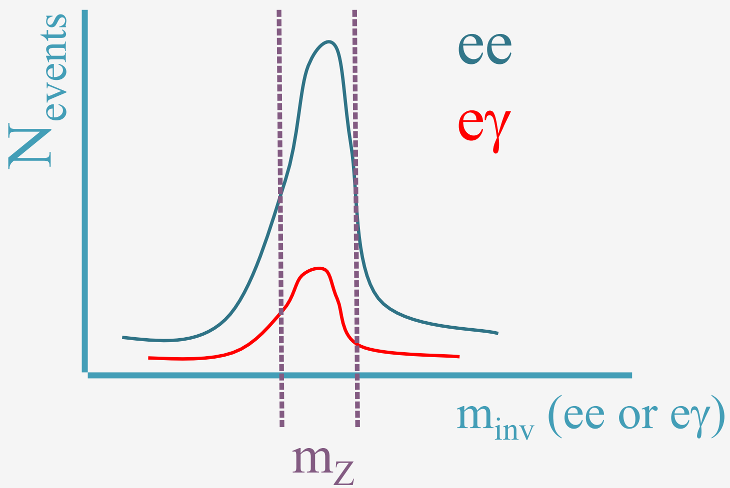


E_T^{miss} + *photon*

Selection:
- High-p_T central photon (ATLAS: 150 GeV, CMS: 175 GeV)
- Large E_T^{miss} (ATLAS: 150 GeV, CMS: 170 GeV) separated from the jets and the γ
- Lepton veto (+ veto on more than 1 jet in ATLAS)

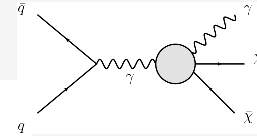
BG estimation:
- Z/W+γ from leptonic CRs (ATLAS) or from NLO-corrected MC (CMS)
- ***Fake photons from data-driven methods***
- Non-collision BG negligible (ATLAS) or estimated with data (CMS)

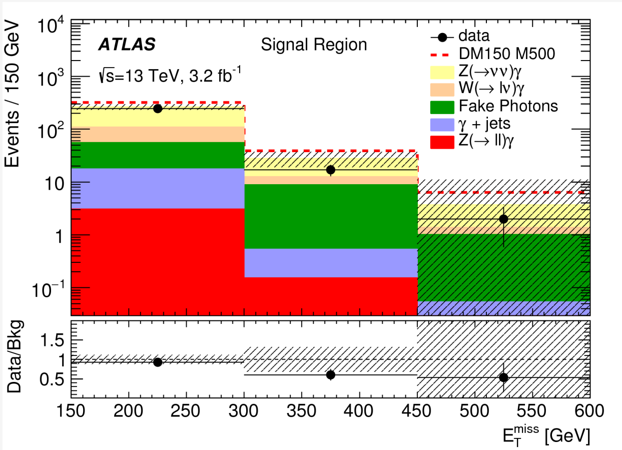
Example: electrons faking photons

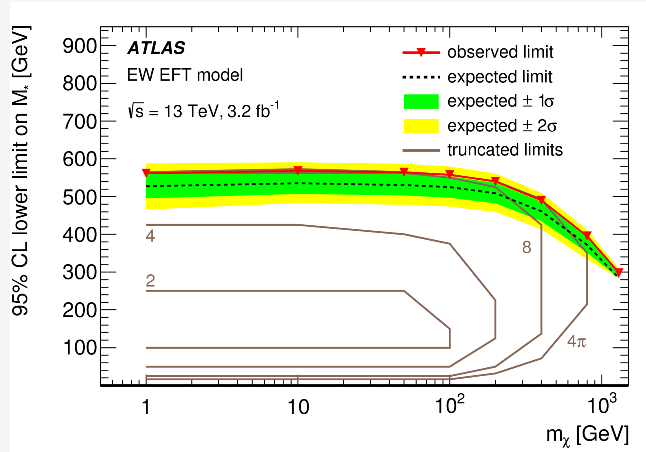


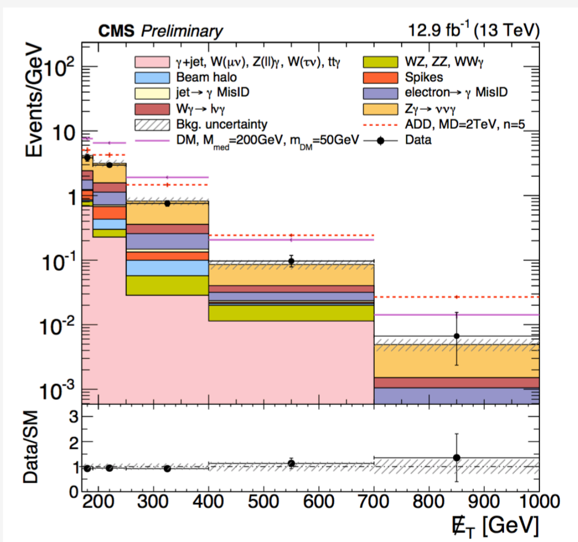
1. Measure the rate at which an electron is misidentified as a photon by making the ratio of eγ to ee events compatible with the Z mass
2. Apply this rate to a sample of e+E_T^{miss} events to know how many events are expected in the SR

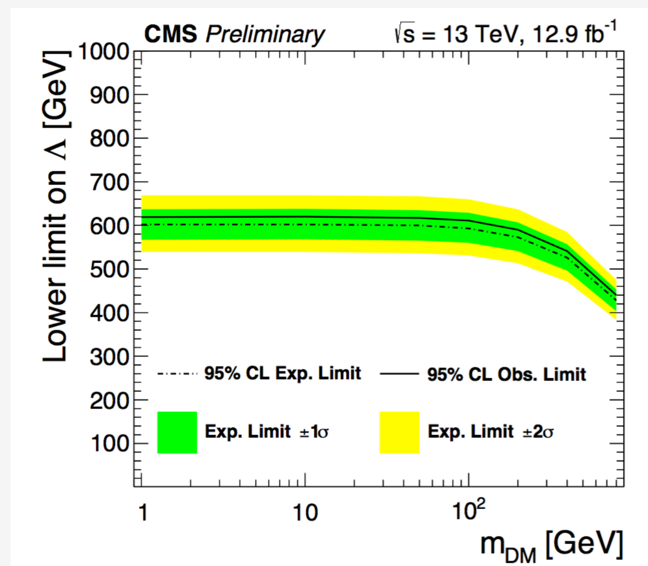
E_T^{miss} + photon



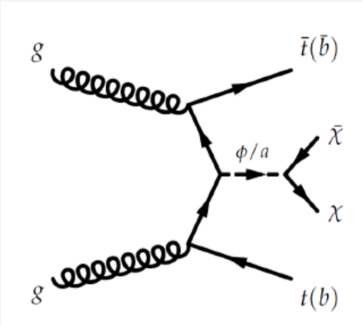








E_T^{miss} + b quark(s)



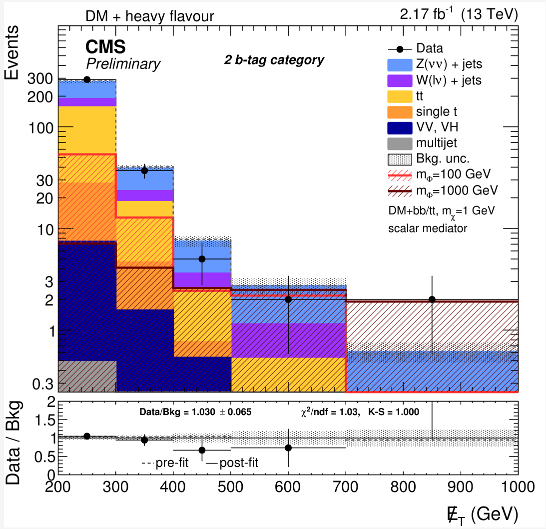
If the production of DM goes through a scalar interaction, one could enhance the coupling to heavy quarks

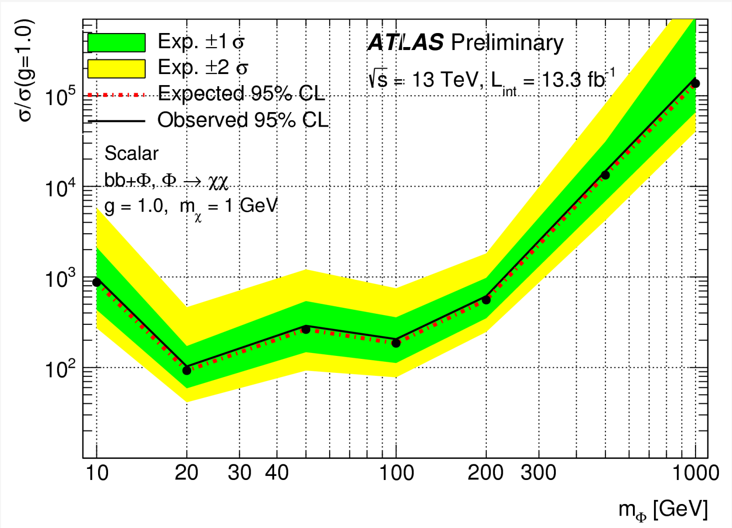
Selection:

Large E_T^{miss} separated from the jets, b-jet(s) (ATLAS: 2, CMS: 1 or 2), lepton veto
ATLAS: angular separation of the jets, momentum imbalance of the two b-jets

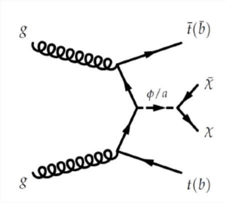
BG estimation:

Through leptonic CRs





E_T^{miss} + *top quarks in ATLAS*

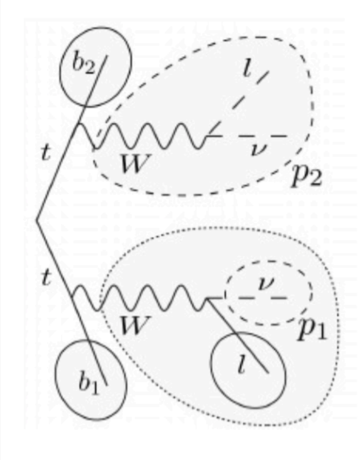


- Start to *diverge seriously from 'mono-X'*, as each top will decay to Wb, with the W decaying either leptonically or hadronically
    - Three different final states for the DM+tt production :
        - **Fully hadronic**: MET + W(qq')b + W(qq')b
        - **Semi-leptonic**: MET + W(lν)b + W(qq')b
        - **Di-leptonic**: MET + W(lν)b + W(lν)b

- Must eliminate the top-antitop SM BG…
    - Fully hadronic: no real E_T^{miss} in the fully-hadronic tt BG
        - Reduce tt BG by requiring large E_T^{miss} and large E_T^{miss} 'significance' E_T^{miss}/sqrt(SumE_T)
            - the E_T^{miss} resolution scales as sqrt(SumE_T) …
        - *Unless it's a semi/di-leptonic tt BG!*
            - Veto on leptons
            - Ask for the minimum transverse mass of (b, E_T^{miss}) to be larger than the top mass
    - Semi-leptonic and di-leptonic: tt BG has real E_T^{miss} …
        - Cutting on E_T^{miss} or E_T^{miss} significance alone isn't enough
        - Use some *clever mass variables* to remove the tt BG…

E_T^{miss} + *top quarks in ATLAS*

Example: dileptonic tt BG in the semi-leptonic channel



1. Identify the objects: 2 b-jets, 1 lepton, E_T^{miss}
2. Assume that it's a dileptonic tt BG in which one lepton is not identified – this lepton will thus be part of the E_T^{miss}
3. Reconstruct the mass of the "top" with all object permutations compatible with the assumption – take the permutation giving the minimal mass

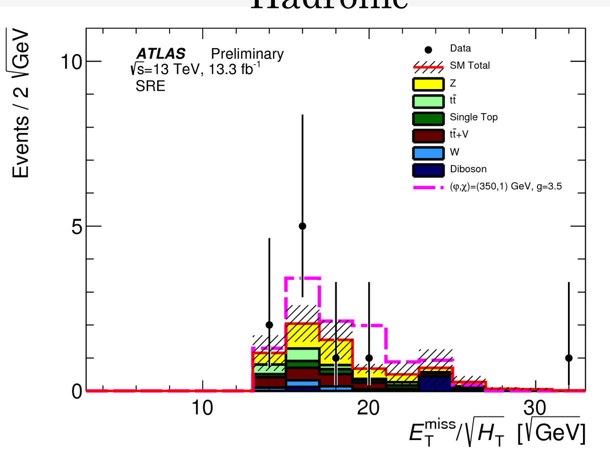
$$M_{T2}^{W} = \min \left\{ m_y \text{ consistent with: } \left[\begin{array}{r} \vec{p}_1^{\,T} + \vec{p}_2^{\,T} = \vec{E}_T^{\text{miss}}\,,\ p_1^2 = 0\,,\ (p_1 + p_\ell)^2 = p_2^2 = M_W^2\,, \\ (p_1 + p_\ell + p_{b_1})^2 = (p_2 + p_{b_2})^2 = m_y^2 \end{array} \right] \right\}$$

Requiring $m_{T2} > m_{top}$ removes this BG without affecting the signal too much

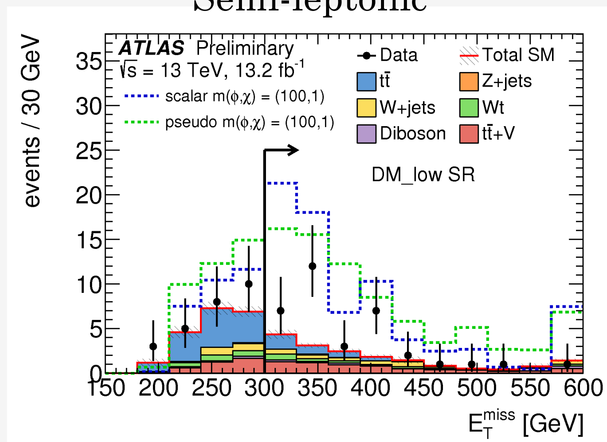
BG estimation using dedicated CRs which reverse one or the other cut in order to be enriched in specific BGs

E_T^{miss} + top quarks in ATLAS

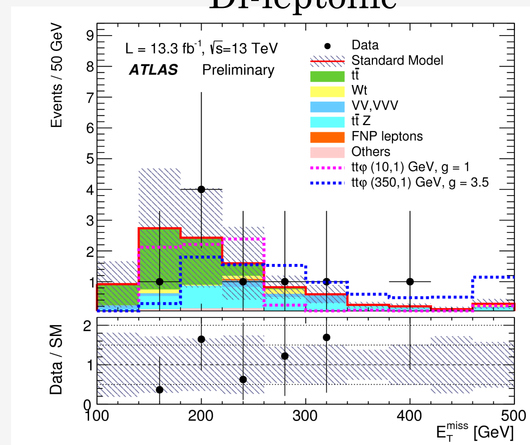
Hadronic

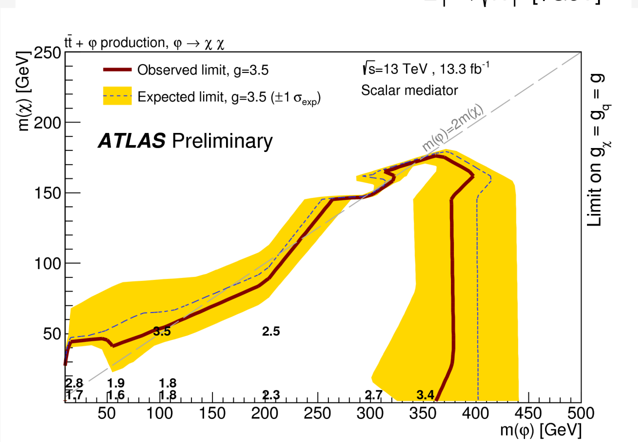


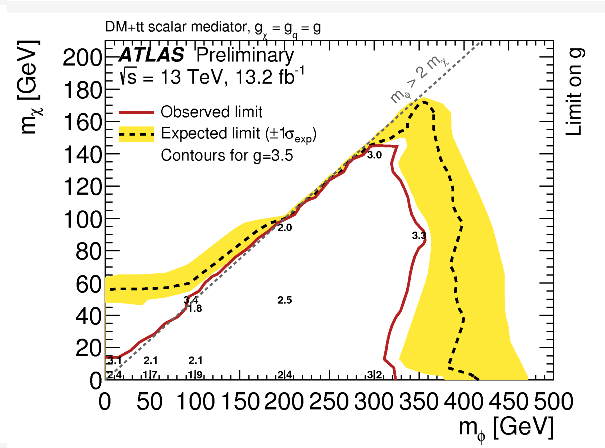
Semi-leptonic

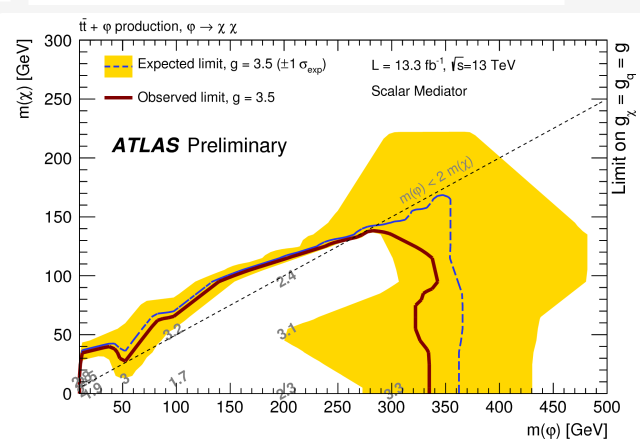


Di-leptonic



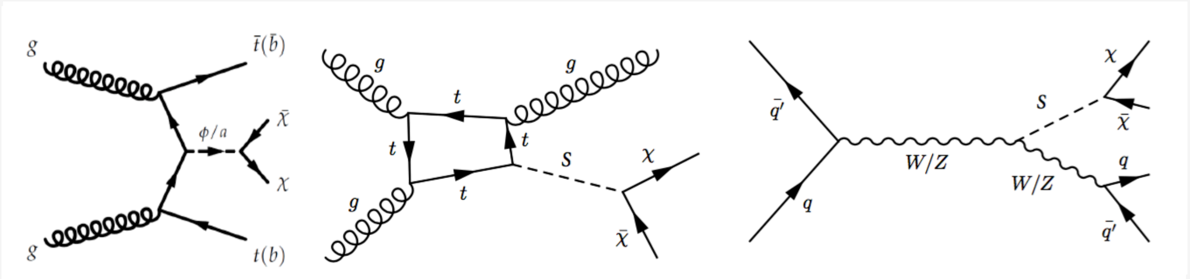


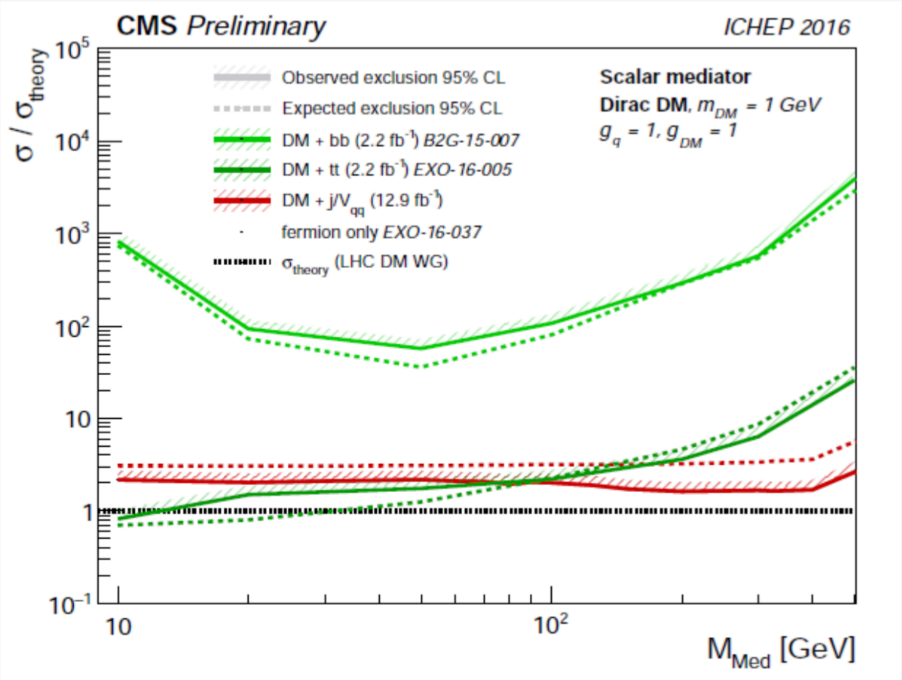




Very similar sensitivity in the three channels: it would be interesting to combine them
→ CMS does the combination of these three channels in their search

Summary: scalar mediator

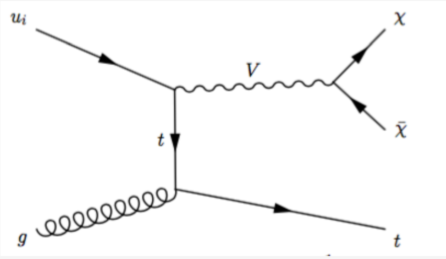




E_T^{miss} + top quark searches competitive with mono-jet/V at low M_{Med}
Future combination possible

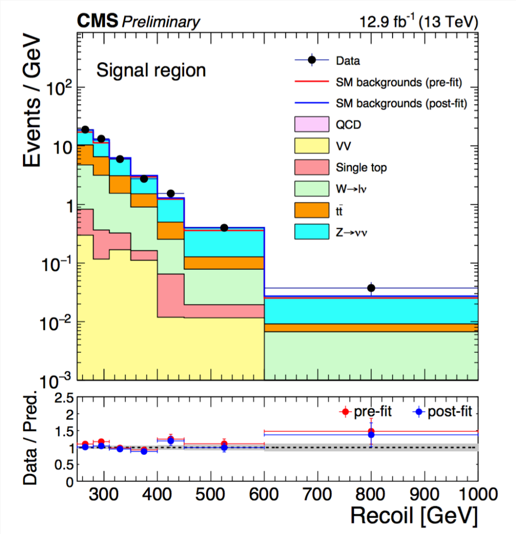
E_T^{miss} + boosted top quark

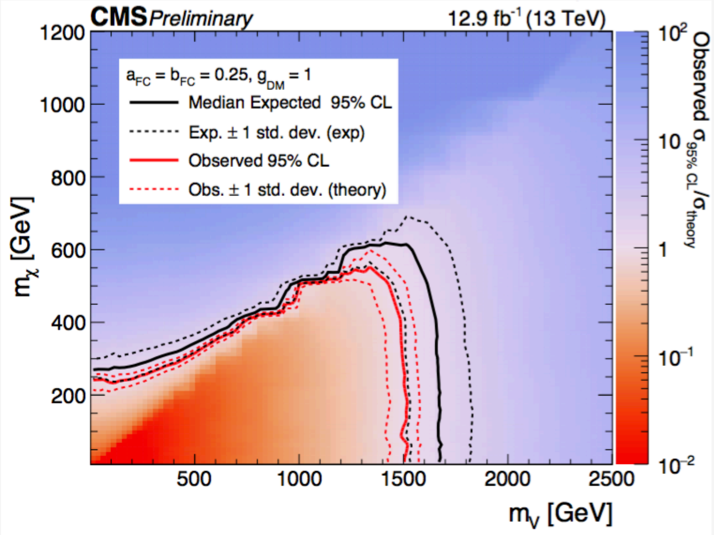
Can also probe more exotic models producing one top in the final state, e.g. this FCNC process:

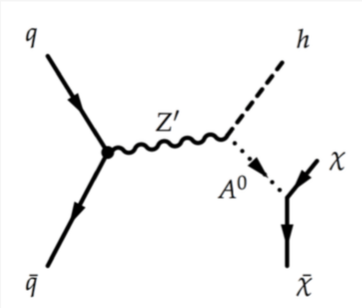


Selection:
E_T^{miss} > 250 GeV
High-p_T (>250 GeV) fat jet tagged as a top (mass and substructure)
Veto b-jets which are far away from the large jet and leptons (incl. τ)

BG estimation from leptonic CRs







$h \to \gamma\gamma$: low BR but clean signal

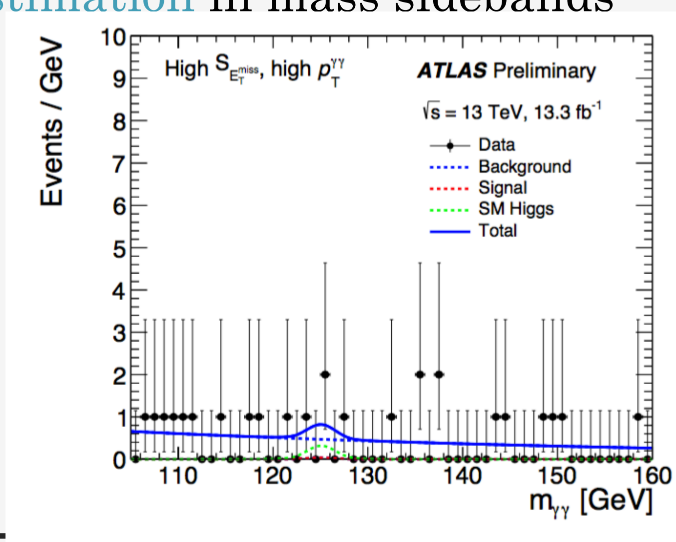
E_T^{miss} + Higgs

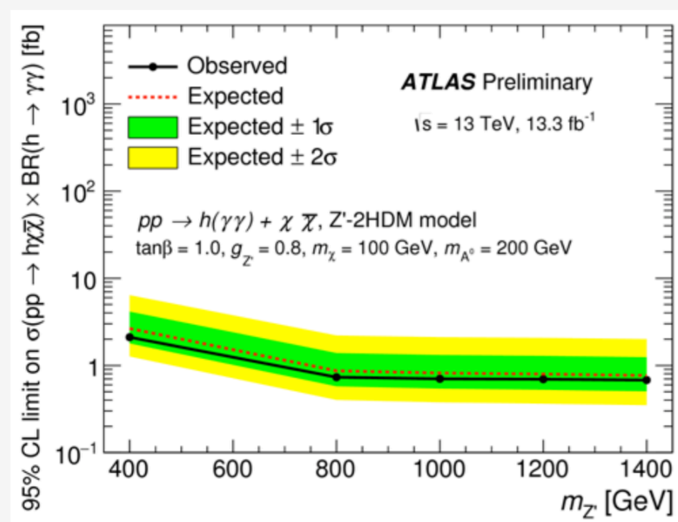
Look for a Higgs-compatible diphoton bump in events with large E_T^{miss}

Selection :

- $p_{T,\gamma 1}/m_{\gamma\gamma} > 0.35$ (CMS: > 0.5), $p_{T,\gamma 12}/m_{\gamma\gamma} > 0.25$
- $105 < m_{\gamma\gamma} < 160$ GeV (CMS: $120 < m_{\gamma\gamma} < 130$ GeV)
- E_T^{miss} significance $> 7\ \mathrm{GeV}^{1/2}$ (CMS: $E_T^{miss} > 105$ GeV)
- $p_{T,\gamma\gamma} > 90$ GeV

BG estimation in mass sidebands





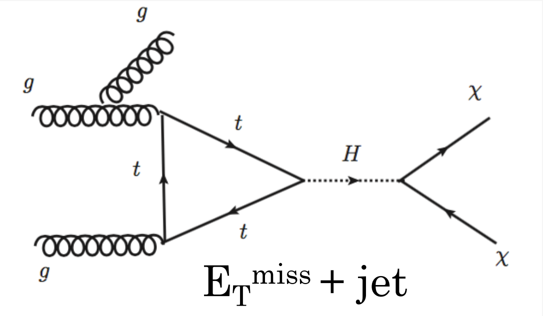
4. The many faces of dark matter at the LHC

2.The Higgs portal

But if the Higgs is able to connect to DM (maybe preferentially) and if DM is light enough…
couldn't the Higgs decay into DM?

Higgs portal?

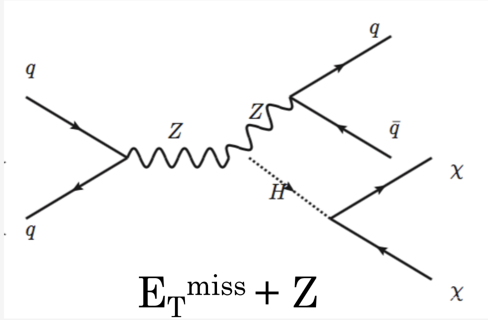
- Let's check for an invisible Higgs!
- Multiple topologies can be used:



Wait a minute…
haven't we done that search before?

Higgs portal?

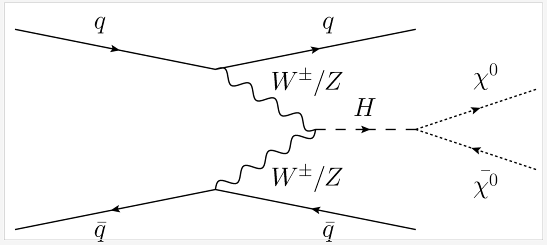
- Let's check for an invisible Higgs!
- Multiple topologies can be used:



Huh, and this one too?

Higgs portal?

- Let's check for an invisible Higgs!
- Multiple topologies can be used:



Vector-boson fusion (VBF) + E_T^{miss}

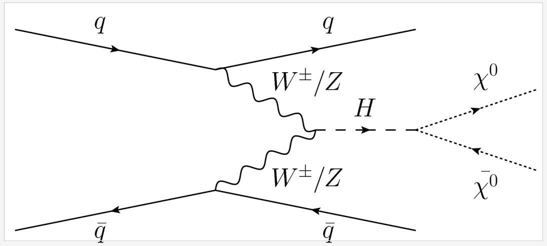
Finally, something new!

E_T^{miss} + VBF in CMS

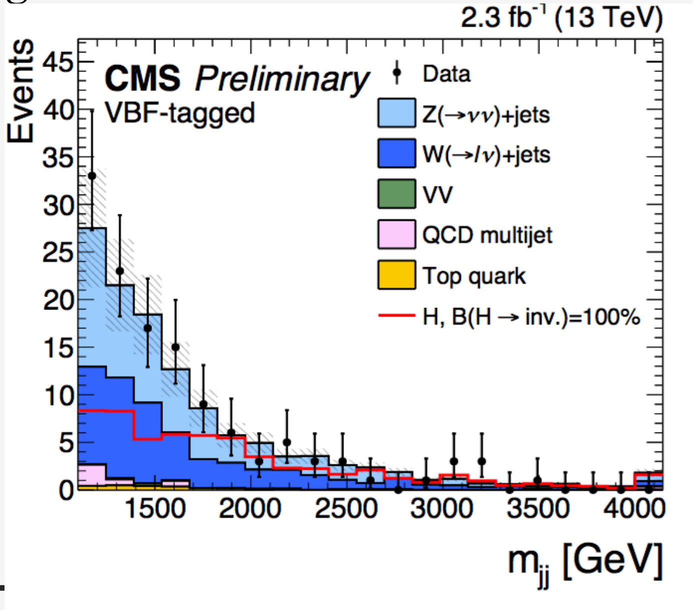
CMS-PAS-HIG-16-016

Selection:

- 2 high-p_T forward jets, in opposite hemisphere, with large dijet mass:
  - $p_{T,j1(j2)} > 80$ (70) GeV, $\Delta\eta(j_1,j_2)>3.6$, $m_{jj} > 1.1$ TeV
- Large E_T^{miss} away from jets:
  - $E_T^{miss} > 200$ GeV and $\Delta\phi(\mathrm{jet},E_T^{miss}) > 2.3$



BG estimation through W/Z CRs



Higgs portal: BR(H→invisible)

The partial width for Higgs decays to a pair of dark matter particles will change the total width of the Higgs:

$$\Gamma_H \longrightarrow \Gamma_H + \Gamma_H^{inv}$$

Γ_H : SM Higgs decay width: 4 MeV

$$\Gamma_H^{inv} = BF_{H(inv)}(\Gamma_H + \Gamma_H^{inv})$$

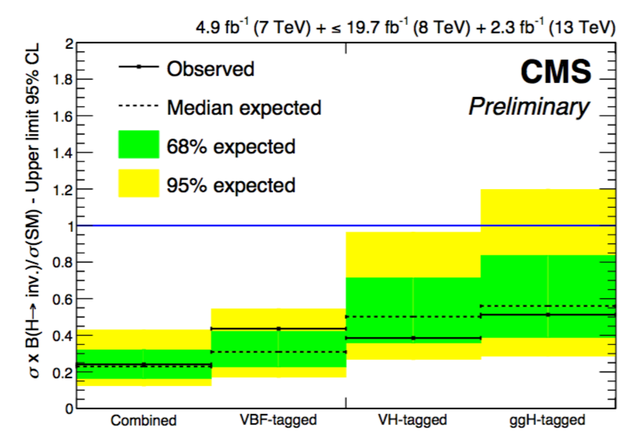
$$\Gamma_H^{inv}(1 - BF_{H(inv)}) = BR_{H(inv)}\Gamma_H$$

$$\boxed{\Gamma_H^{\mathrm{inv}} = \frac{\mathrm{BF}(H \to \mathrm{invisible})}{1 - \mathrm{BF}(H \to \mathrm{invisible})} \times \Gamma_H}$$

Combining the results

CMS Run-1 + 2015 data (arXiv:1610.09218)
If SM production is assumed:

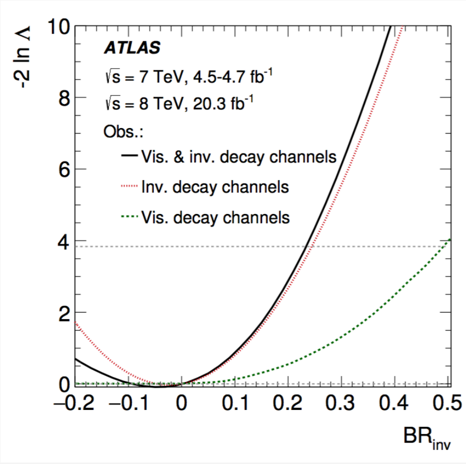
- **BF(h→inv) < 0.24**



ATLAS Run-1 (JHEP 01 (2016) 172):

Channel	Expected	Observed
VBF	0.31	0.28
V(jj)H	0.86	0.78
$Z(\ell\ell)H$	0.62	0.75
Combine	0.27	0.25

- incl. visible decay rate measurements:
    - **BF(h→inv) < 0.23**



Higgs portal: comparison to DD

The partial width for Higgs decays to a pair of dark matter particles depends on the spin of the dark matter particle:

$$\Gamma^{\text{inv}}_{H\to SS} = \frac{\lambda^2_{HSS} v^2 \beta_S}{64\pi m_H}$$

$$\Gamma^{\text{inv}}_{H\to ff} = \frac{\lambda^2_{Hff} v^2 m_H \beta^3_f}{32\pi \Lambda^2}$$

where:

- v is the vacuum expectation value (246 GeV)
- $\beta_\chi = \sqrt{1 - 4m^2_\chi / m^2_H}$
- the λ's are the coupling constants on which we set limits at the LHC

Higgs portal: comparison to DD

And so will the direct detection cross section through a Higgs mediator:

$$\text{scalar } S: \quad \sigma_{S-N} = \lambda_{hSS}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_S + m_N)^2}$$

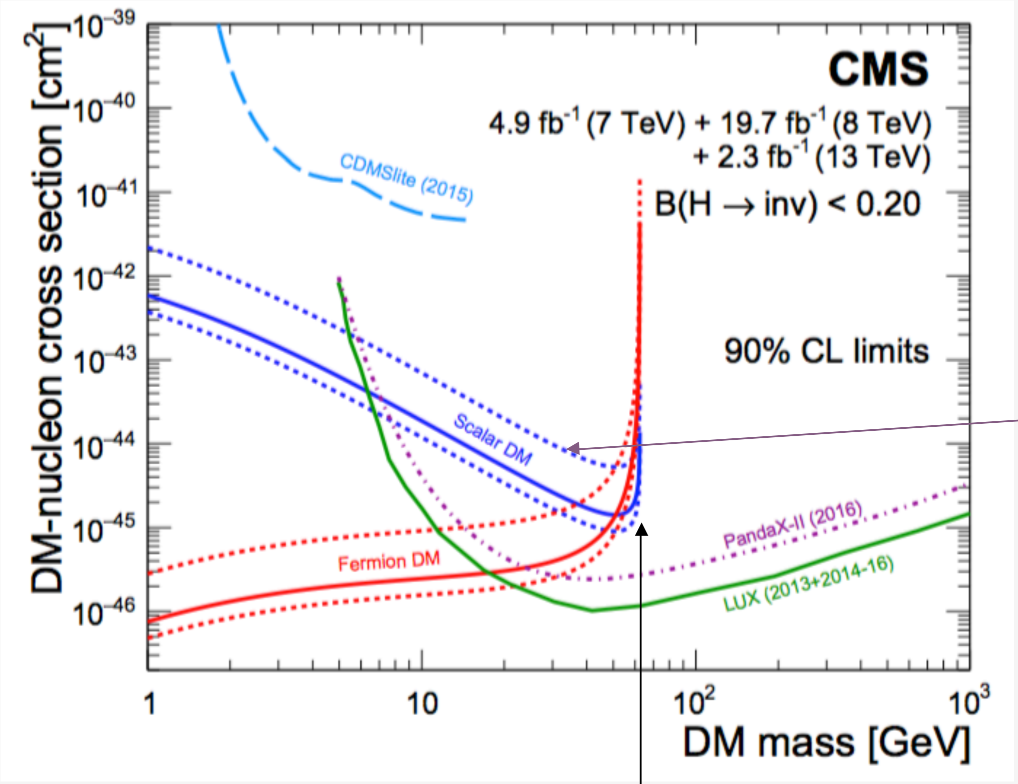
$$\text{fermion } f: \quad \sigma_{f-N} = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{m_N^4 f_N^2 m_f^2}{4\pi m_h^4 (m_f + m_N)^2}$$

where:

- $m_N \sim 0.94$ GeV is the nucleon mass
- $f_N = 0.33^{+0.30}_{-0.07}$ is the form factor associated with the Higgs-nucleon coupling and is computed using lattice QCD
- the λ's are still the coupling constants on which we set limits at the LHC.

Higgs portal: comparison to DD

Considering a higgs mediator model

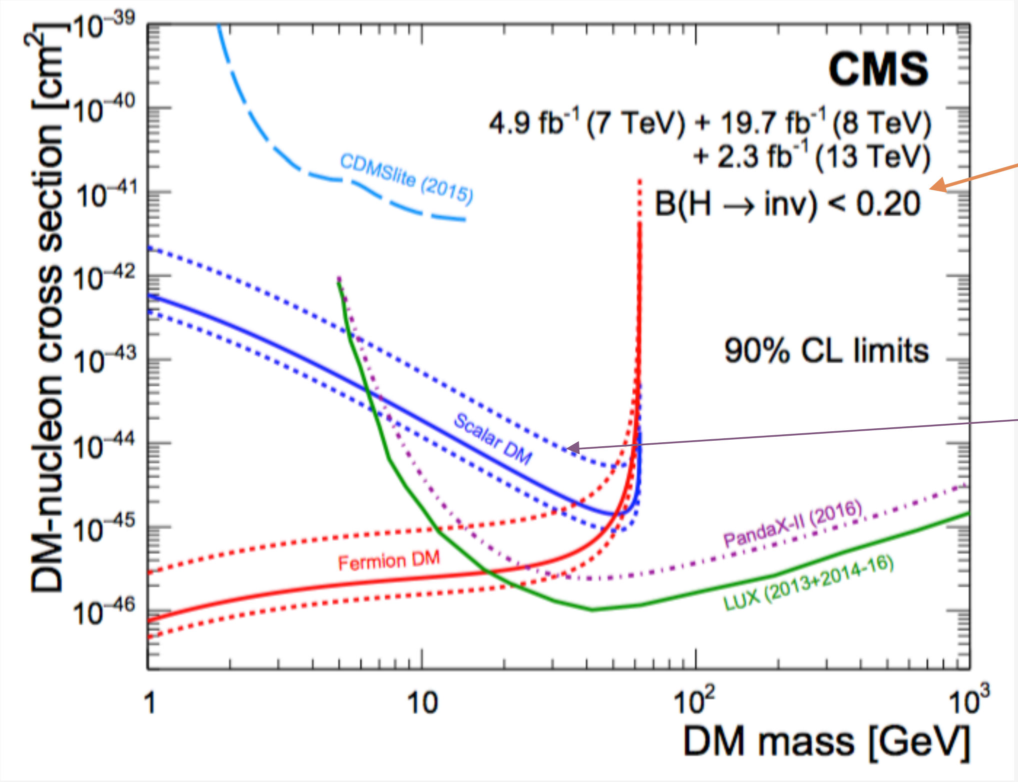


Band: uncertainty on f_N

No limit when $m_h < 2m_{DM}$

Higgs portal: comparison to DD

Considering a higgs mediator model

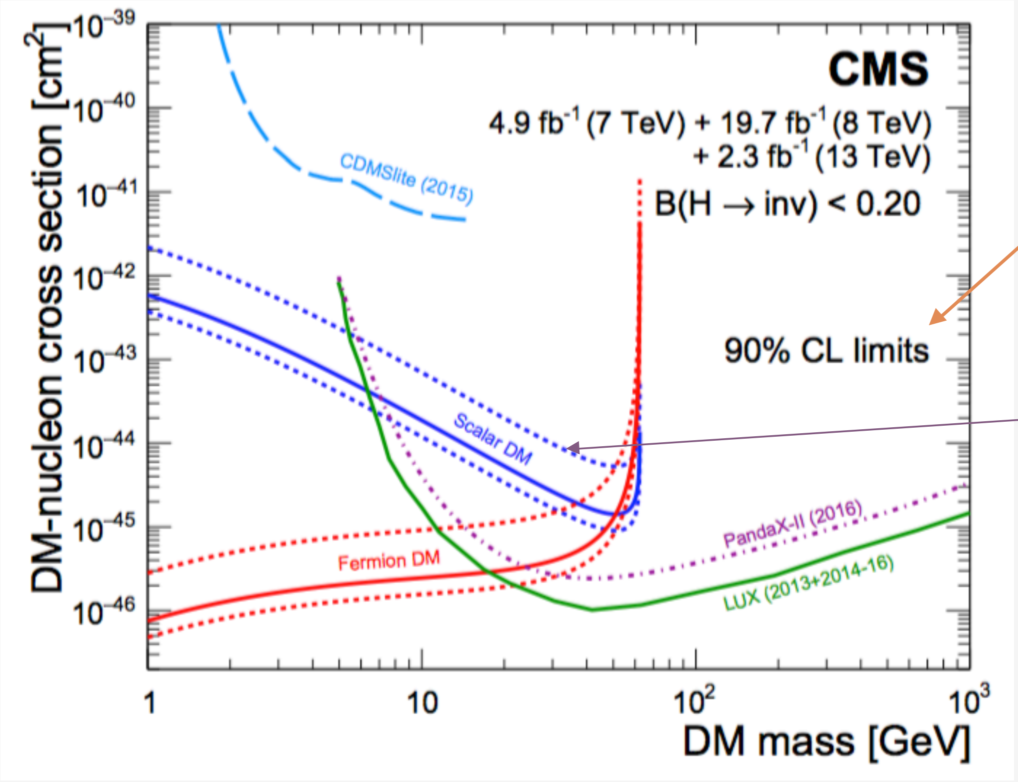


Didn't we just say that the limit was BR<0.24?!

Band: uncertainty on f_N

Higgs portal: comparison to DD

Considering a higgs mediator model

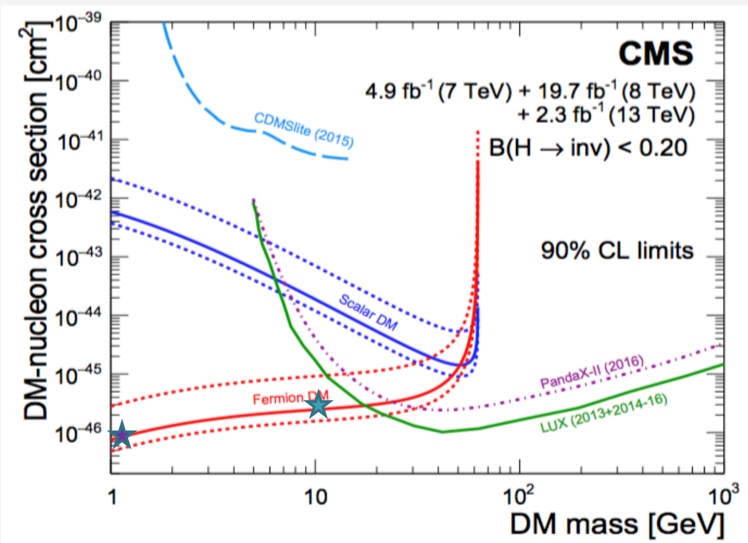


Yes but that was at 95% CL. Here it's the 90% CL limit to compare to direct detection…

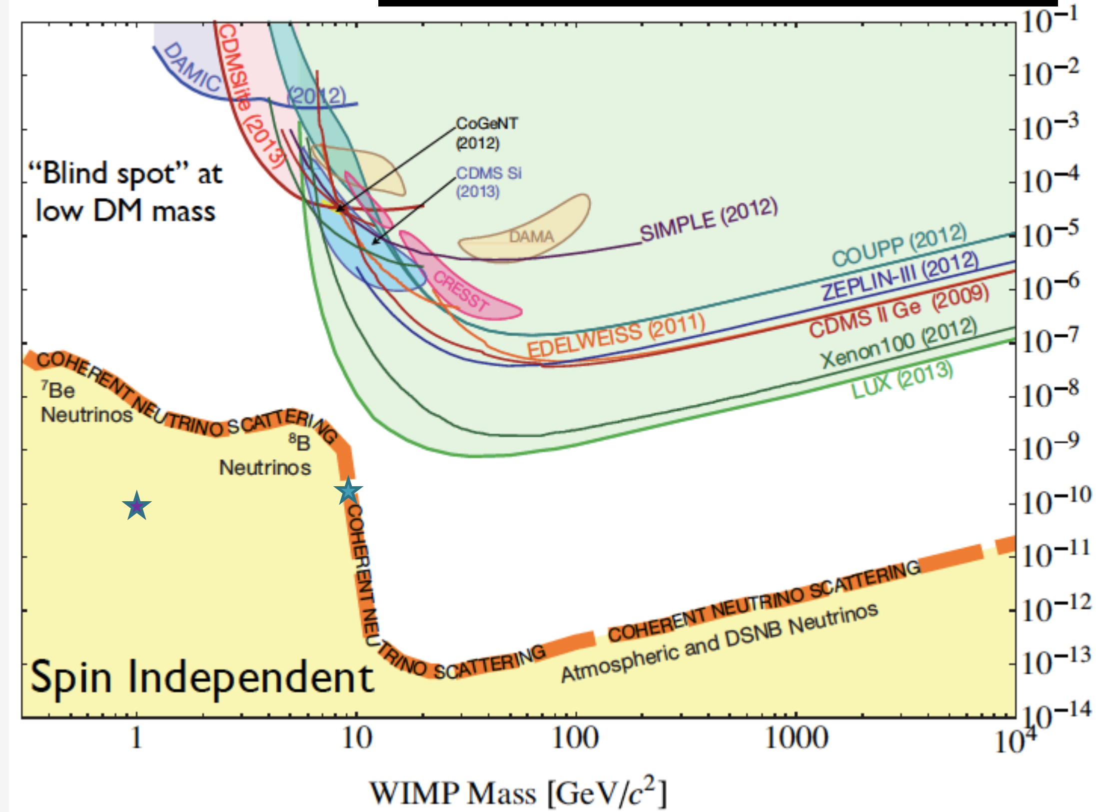
Band: uncertainty on f_N

Higgs portal: comparison to DD

Considering a higgs mediator model



Billard, Figueroa-Feliciano, Strigari 1307.5458

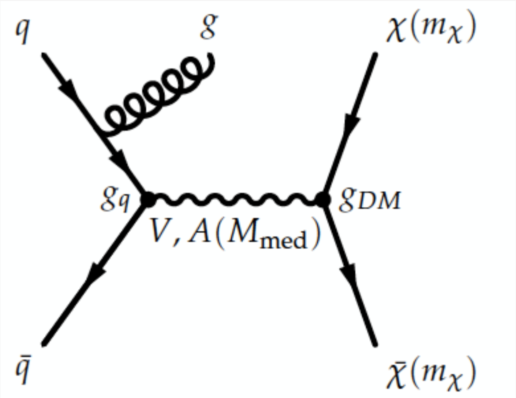


4. The many faces of dark matter at the LHC

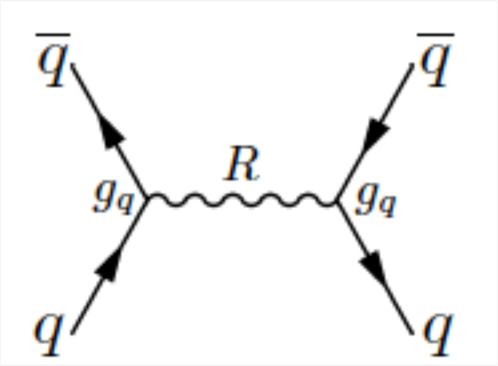
3. What about the mediator?

A light mediator?

- But… if we contemplate simplified models with a mediator mass which is not high enough to be EFT-like… Shouldn't we also be able to produce this mediator otherwise at the LHC?



If this is possible…



Search for a dijet resonance?

Searching for the mediators

- Look for a bump in the dijet mass over a smoothly falling background

- Can probe high masses by requiring two high-p_T jets

- How to go to low masses though?
  - Most of the event production at the LHC is dijet
    → huge rate → trigger wall

- Need some trick:
  - *Use an ISR object on which to trigger (e.g. a photon)*

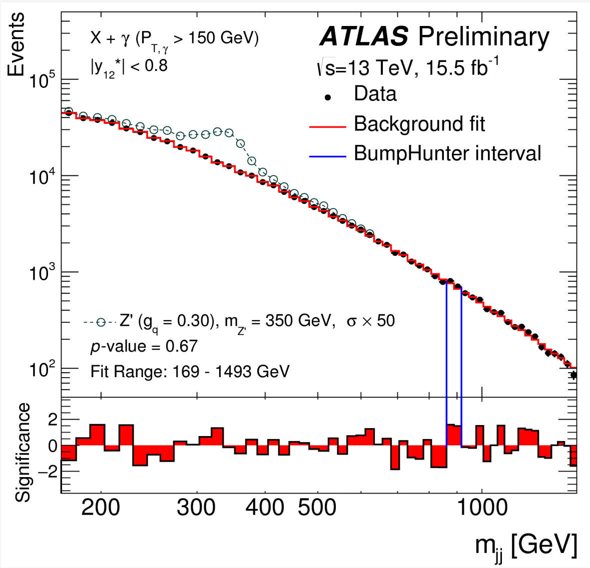
  - *Do the analysis at trigger level (TLA) :*
    - *Bandwith = rate x size*

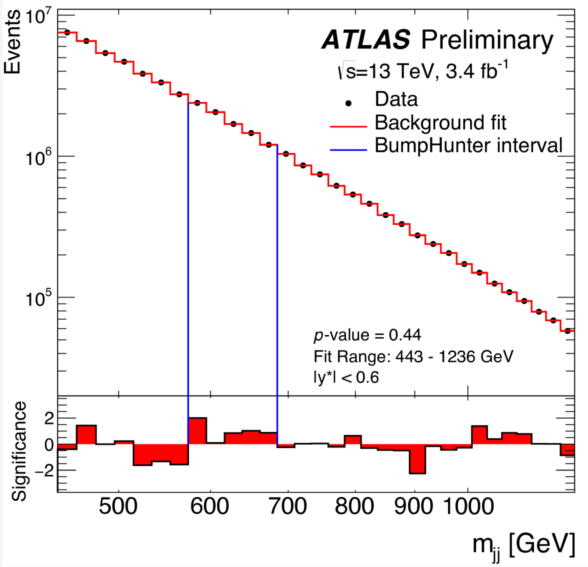
    ➔ *Reduce size by performing 'online' analysis, saving only the information necessary for the search in output*

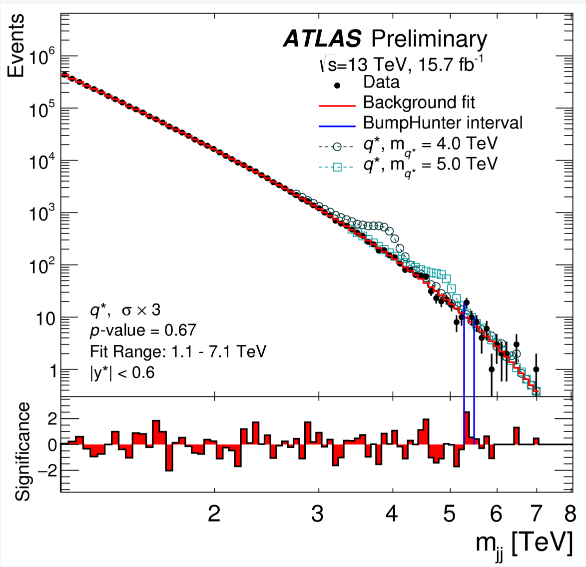
Searching for the mediators

2015 dataset or **ICHEP 2016 dataset**

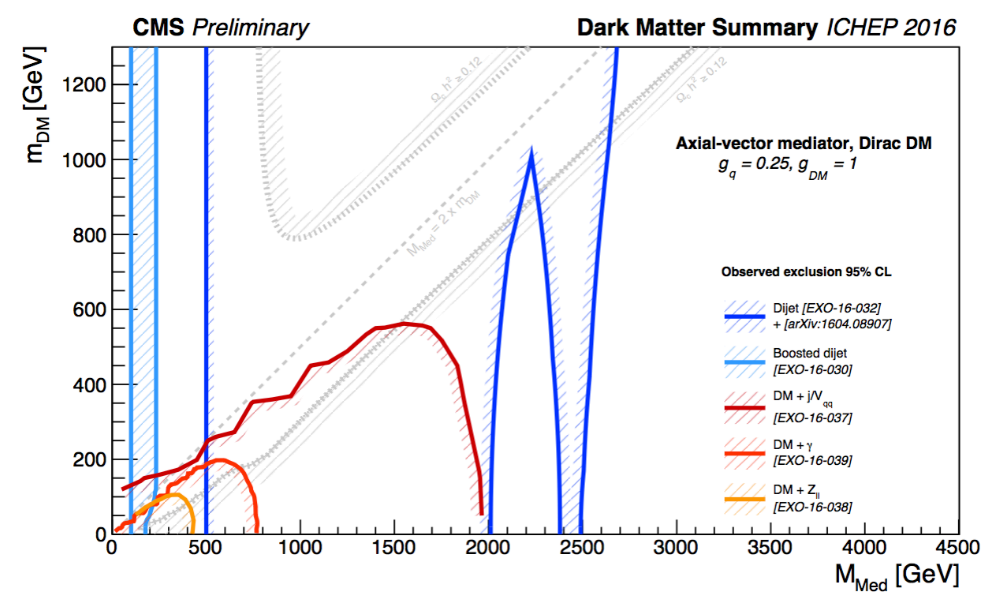
	ATLAS	CMS
Low-mass (ISR)	**ATLAS-CONF 2016-070**	CMS-PAS-EXO-16-030
Low-mass (TLA)	ATLAS-CONF 2016-030	**CMS-PAS-EXO-16-032**
High-mass	**ATLAS-CONF 2016-069**	

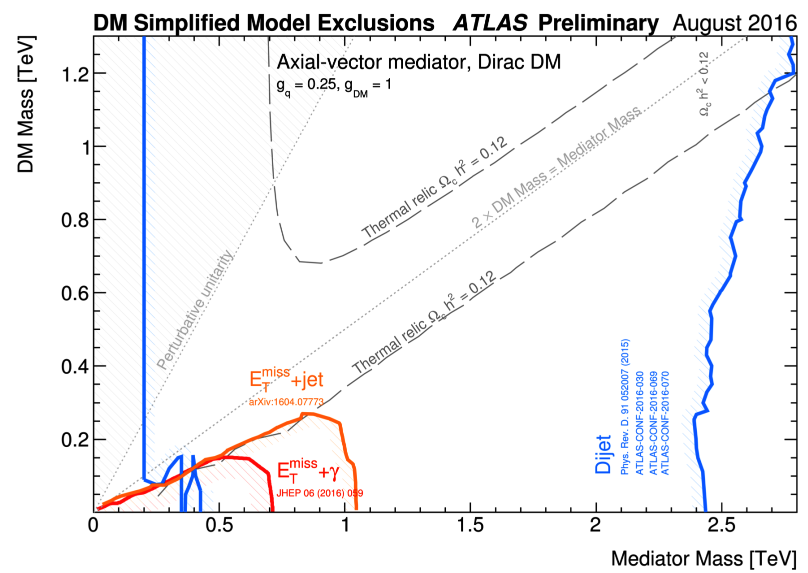






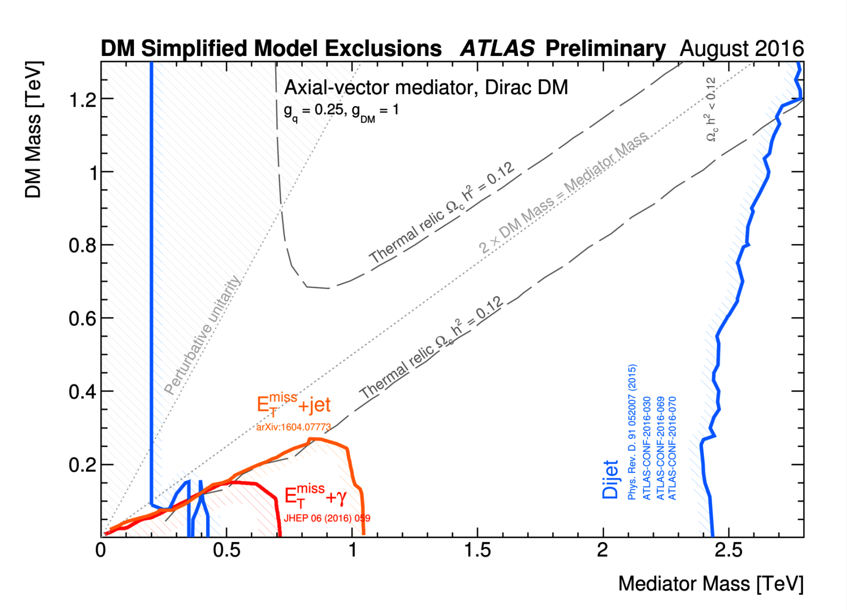
Summary: axial-vector mediator



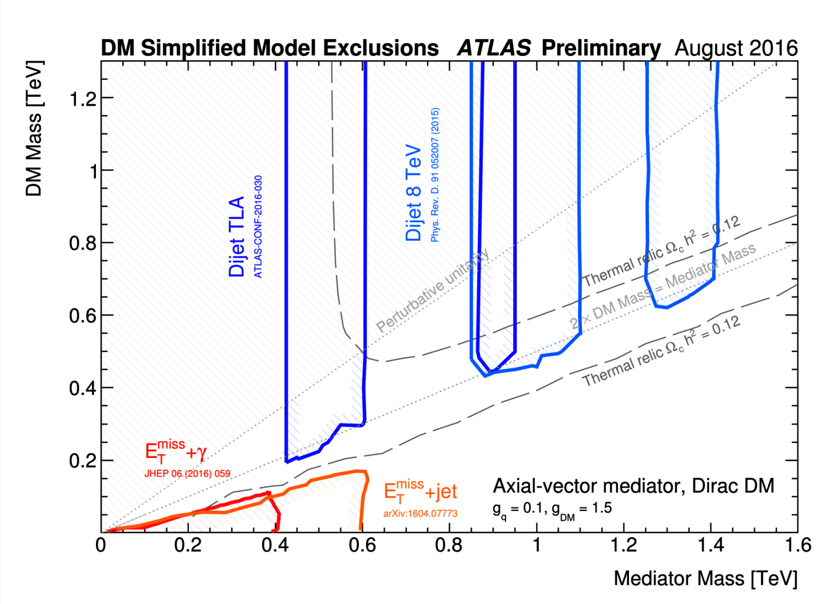


Mono-jet / dijet interplay

g_q=0.25, g_{DM}=1



g_q=0.1, g_{DM}=1.5



The interplay depends on the couplings…
Complementary approaches to probe the DM parameter space thoroughly

4. The many faces of dark matter at the LHC

4. What about more complete models?

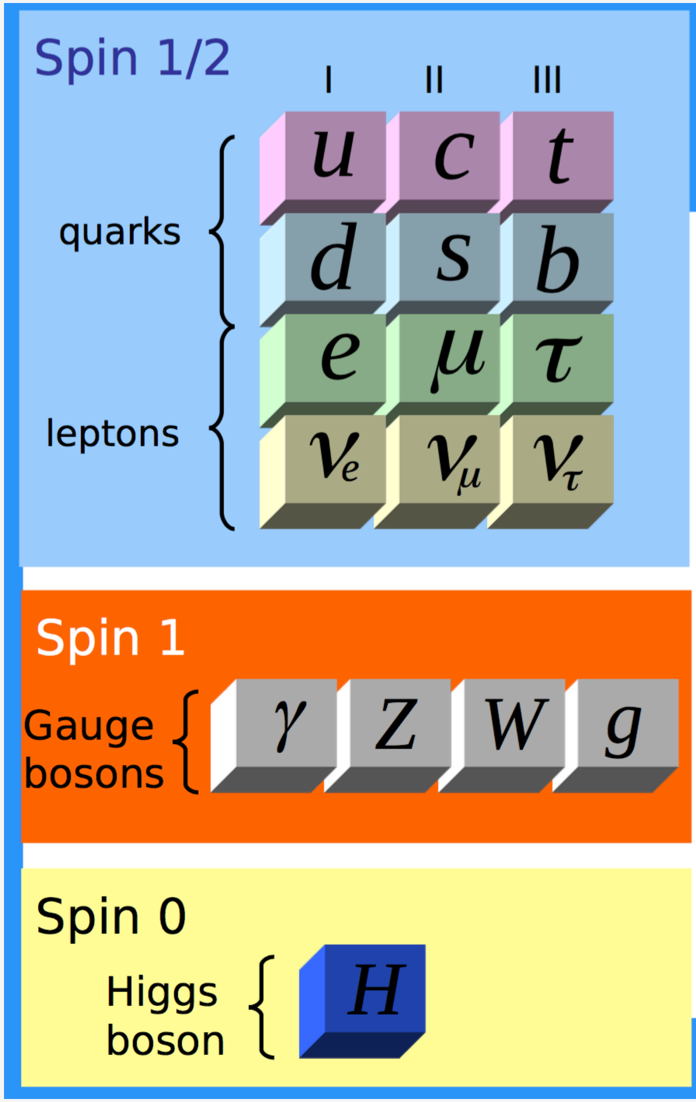
Simplified models

A more complete model…

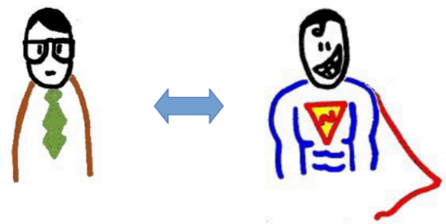
Why constrain ourselves to simplified models?

- We don't! For example, we have plenty of supersymmetry (SUSY) or large extra dimension searches – more « complete » models which can include DM candidates…

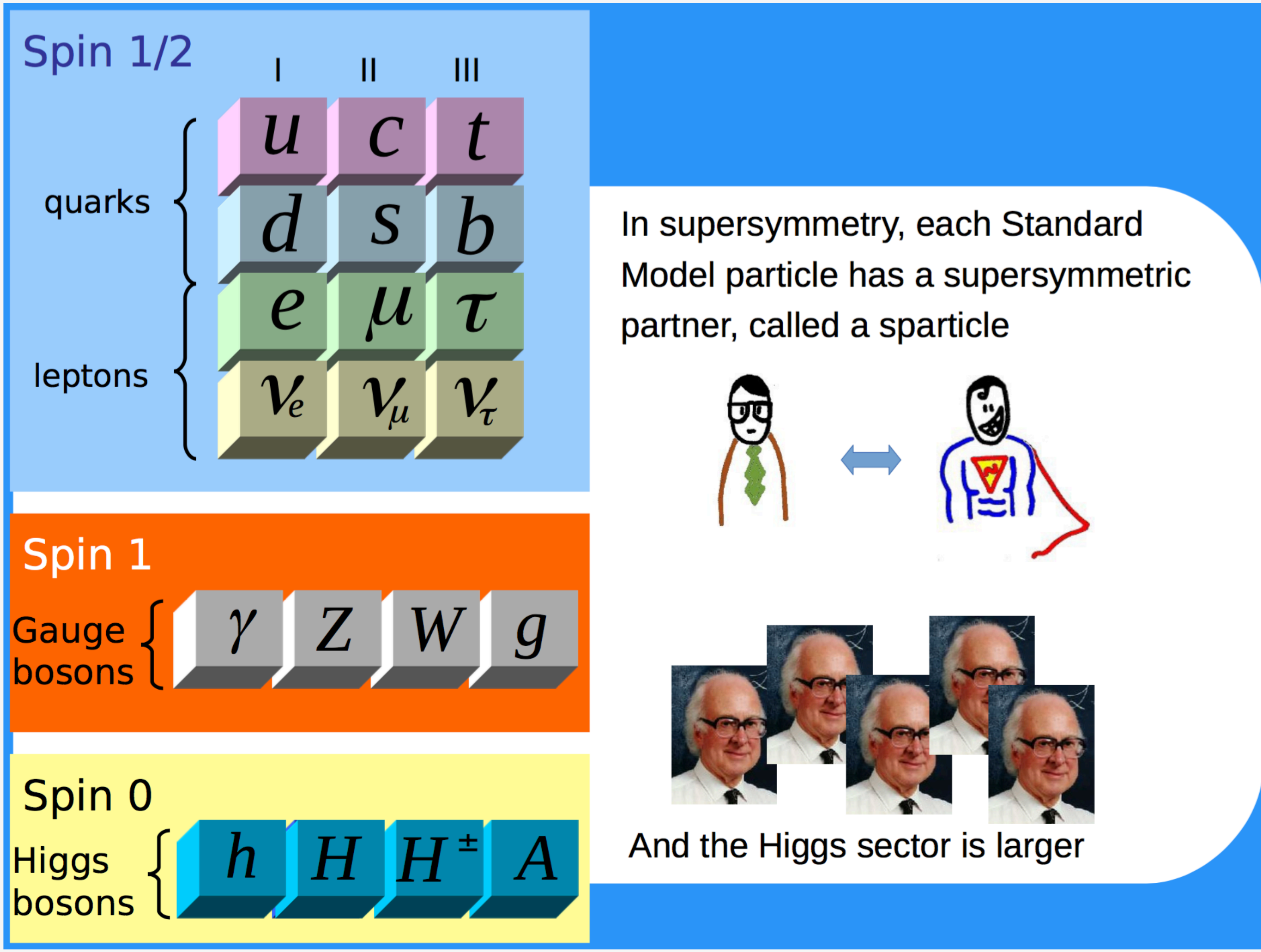
A brief reminder of SUSY



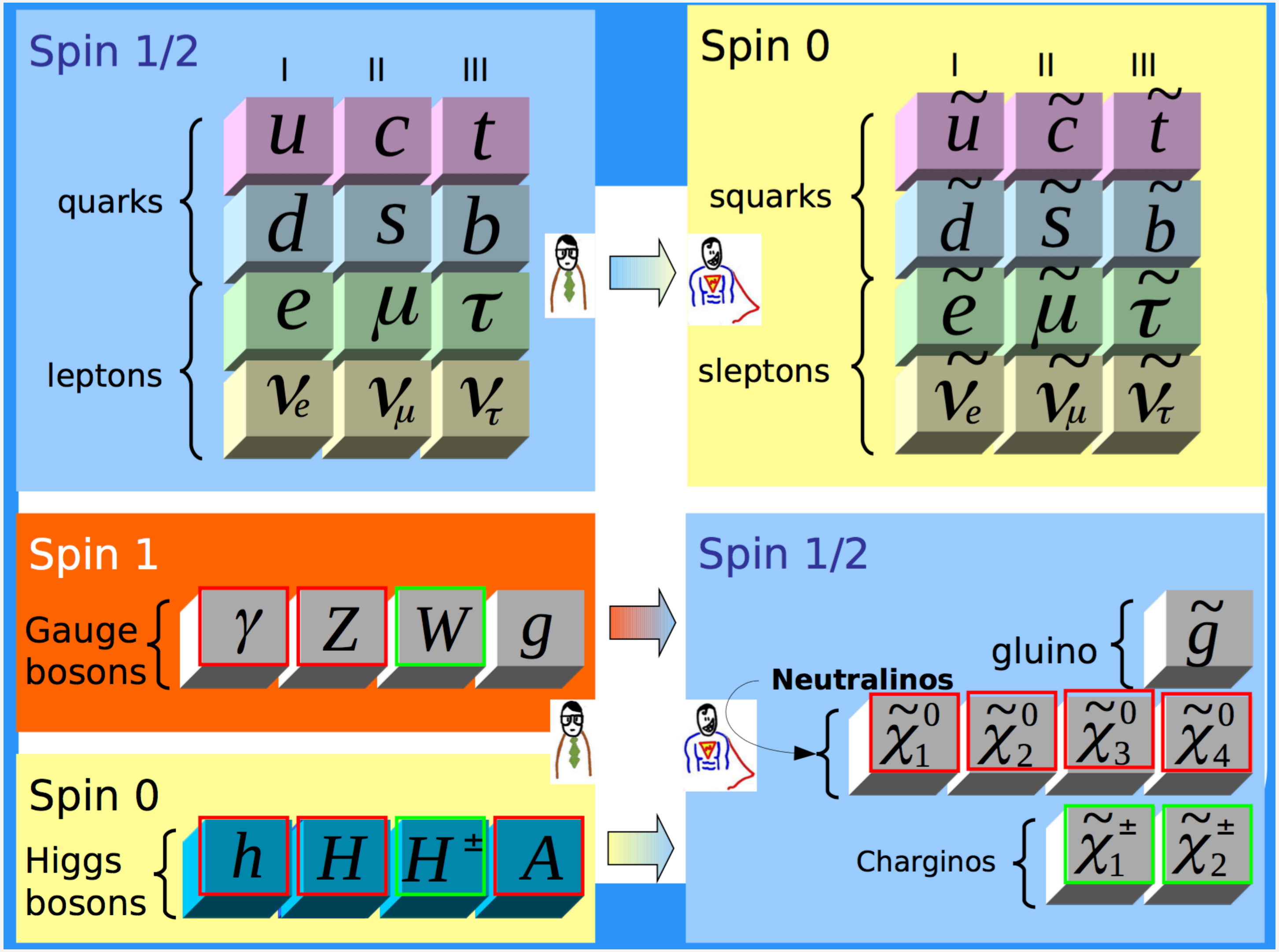
In supersymmetry, each Standard Model particle has a supersymmetric partner, called a sparticle



A brief reminder of SUSY



A brief reminder of SUSY



DM in SUSY

Possibility of a dark matter candidate

$$R=(-1)^{(L+3B+2J)} \quad \text{where} \quad \begin{cases} L = \text{leptonic number} \\ B = \text{baryonic number} \\ J = \text{spin} \end{cases}$$

R = -1 for sparticles

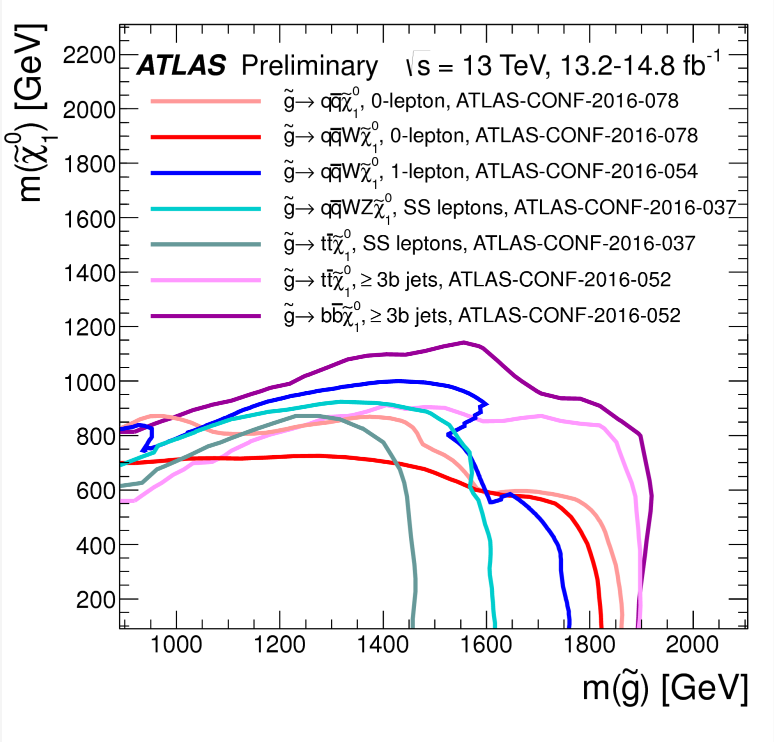
R = +1 for SM particles

R-parity conservation :

- Lightest sparticle (LSP) stable (**WIMP candidate**)
- Pair produced sparticles
- Cascade decay down to the LSP

Looking for SUSY

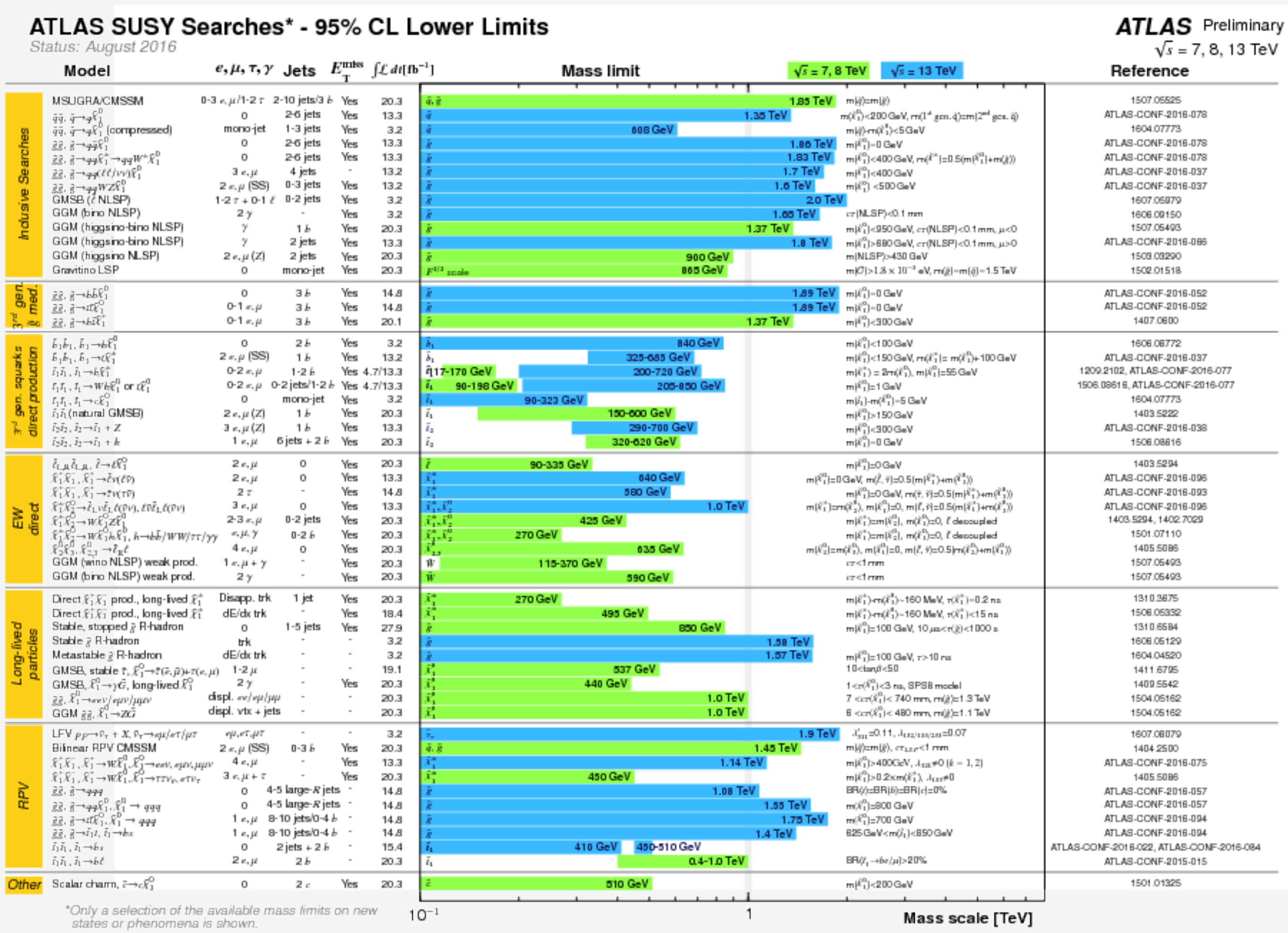
- Looking for the production of these new particles at the LHC, decaying to the DM candidate (leptons, jets, photons,… + E_T^{miss})



Example:
Search for the production of a gluino pair (supersymmetric gluon partner), each decaying into SM particles and the lightest neutralino (DM candidate)

Note though: *even SUSY searches are usually presented in terms of simplified SUSY models as there are very many free parameters (SUSY is broken by an unknown mechanism)*

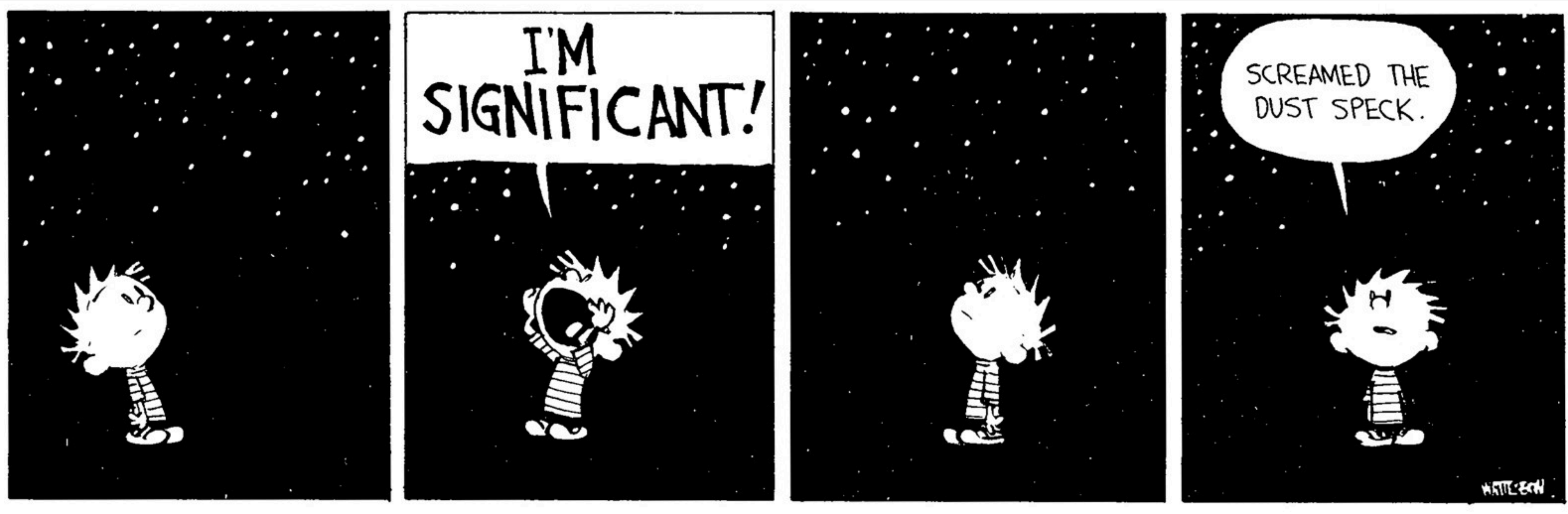
Looking for SUSY…



The subject for a few more hours, certainly!

Limits, limits, limits

As much as we would have liked to see something new in our searches for DM, we must admit we haven't so far…



Limits, limits, limits

One thing is for sure…

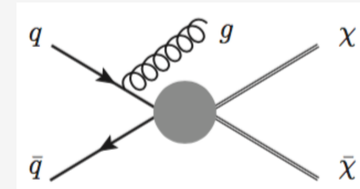
…and there is more data to come!

- The 13 TeV dataset should increase by a factor ~3 by the end of Run-2 in 2018 – 45 fb^{-1} more awaited in 2017 alone!

- After the long shutdown 2, data taking should resume in 2021 with Run-3 lasting until the end of 2023, possibly at 14 TeV
    - By then, expect ~300 fb^{-1} of data to analyse

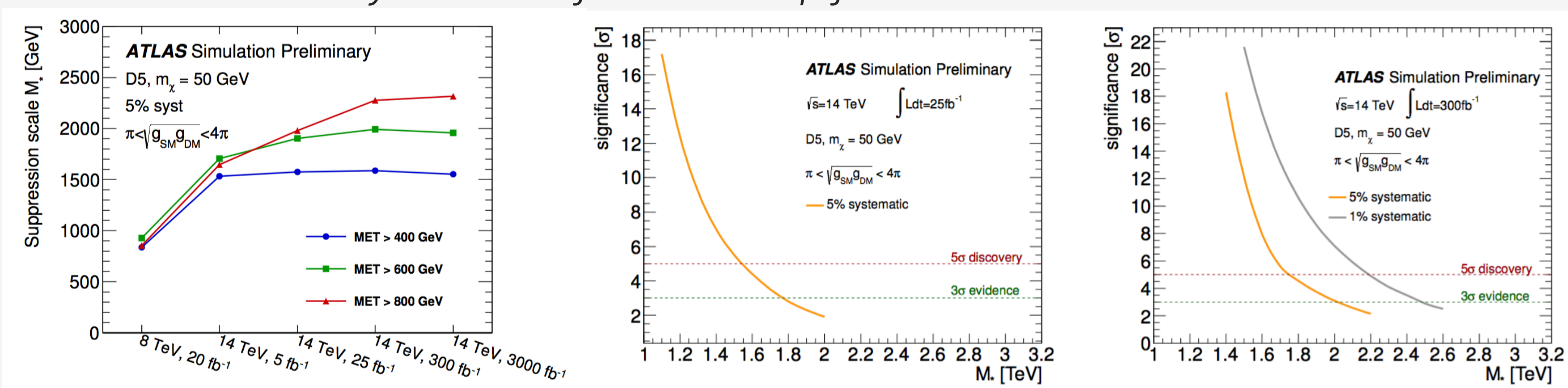
- And that's not even talking about the High-Lumi(HL)-LHC which could bring us to 3 ab^{-1} by ~2037…

The future of jet+E_T^{miss}



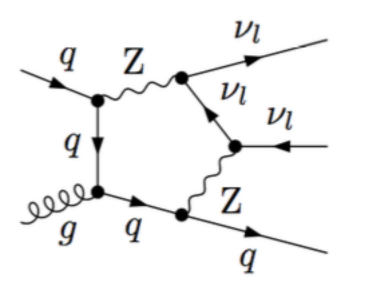
- Projection studies done before the start on Run-2, based on the model used at that time: EFT (vector type) with suppression scale M_*
  - *Increase in sensitivity was also confirmed with simplified models.*

ATL-PHYS-PUB-2014-007

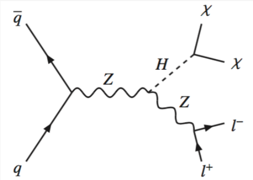


- Important to have tighter signal regions in E_T^{miss} to keep improving with data
  - Up to >800 GeV in the study, but could possibly gain further with larger dataset
- Optimistic scenario: if one could reduce the systematic uncertainty to 1% at the end of Run-3, could gain 0.5 TeV more

The future of jet+E_T^{miss}



- At the moment, the largest uncertainty in the highest E_T^{miss} bin:
  - Statistical (data in CR): 10%
  - Total: 12.0%
- Important systematic from Z+jet/W+jet ratio :
  - EW NLO correction differences in W+jets and Z+jets increase with the boson p_T
    - Up to 4% in the highest E_T^{miss} SR
  - Could become a limiting factor… especially as it increases with tighter cuts
  - Discussions / work in progress in the LHC DM WG



The future of H→ invisible

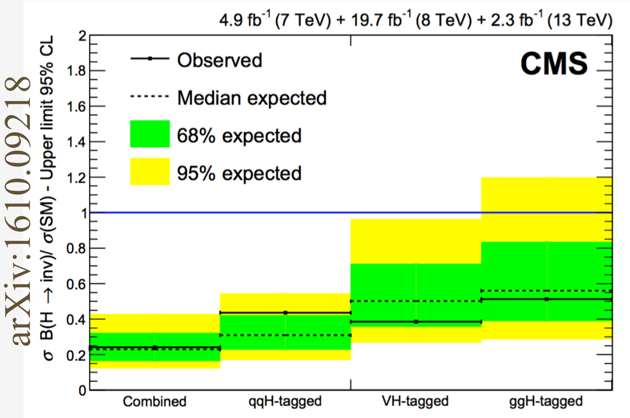
- Predictions done before Run-2 for 300 fb^{-1} in the Z(ll)H(inv) channel :

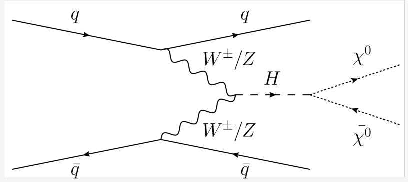
BR(H→inv.) limits at 95%CL	CMS	ATLAS
Best scenario *Assumptions*	17% *Theo. uncert. halved, others scaling as 1/sqrt(L)*	23% *Uncert. on the main BG scales as 1/sqrt(L)*
Conservative scenario *Systematics as before*	28%	32%
Run-1 limit observed/expected in this channel	81% / 83% *Eur. Phys. J. C* **74** (2014) 2980	75% / 62% *Phys. Rev. Lett.* **112** (2014) 201802

ATL-PHYS-PUB-2013-014
CMS NOTE-13-002

- Nice improvement foreseen, but VBF is the most sensitive channel:

arXiv:1610.09218





As for the jet+MET analysis, the Z(νν)+jets main BG is constrained using W(μν) control regions

- *Important to reduce the Z / W ratio uncertainty*

The future of dijet resonances

- Predicted limit evolution with data (14 TeV) for two benchmarks (excited quarks and ADD quantum black hole with n_D=6):

integrated luminosity [fb^{-1}]	m_{q^*} [TeV]	m_{QBH} [TeV]
0.1	4.0	8.2
1	5.0	8.9
5	5.9	9.2
25	6.6	9.7
300	7.4	10.0
3000	8.0	10.1

ATL-PHYS-PUB-2015-004

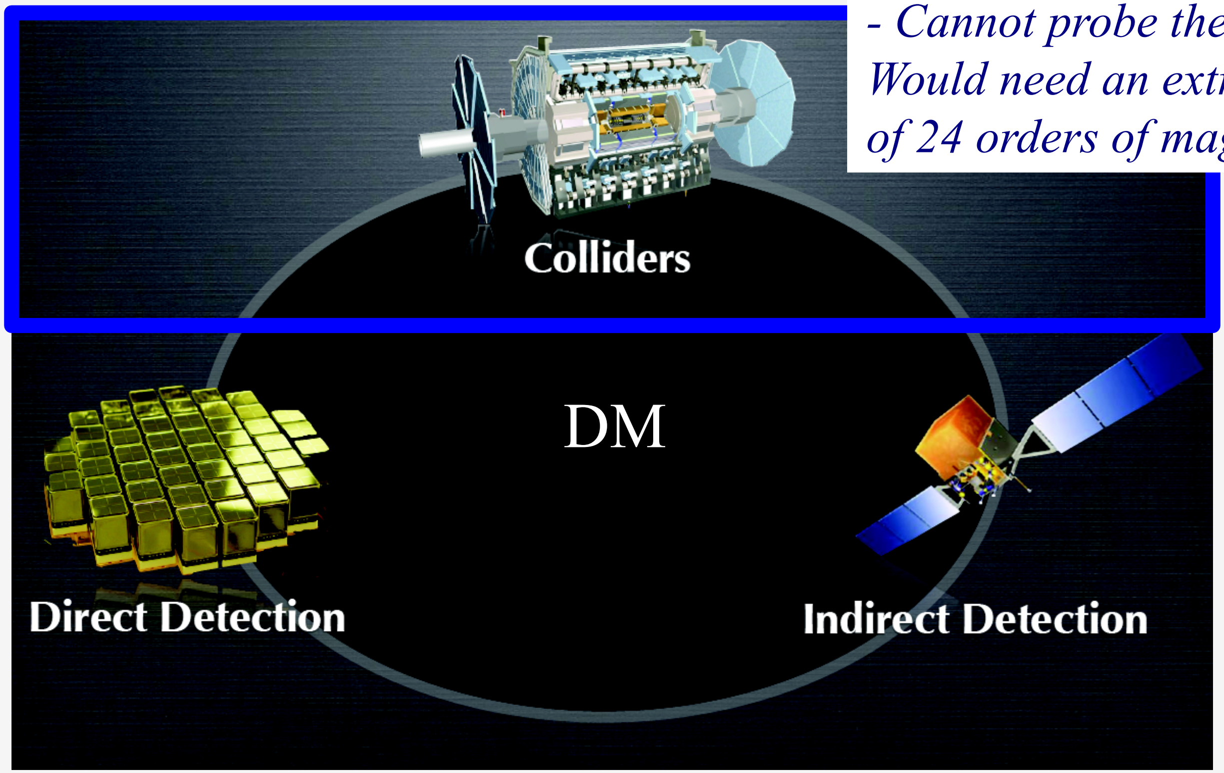
- Current limit with 15.7 fb^{-1} of **13 TeV data**:
  - q*> 5.6 TeV (5.5 TeV) observed (expected)
  - m_{QBH}> 8.7 TeV (obs & exp)]

The last few words

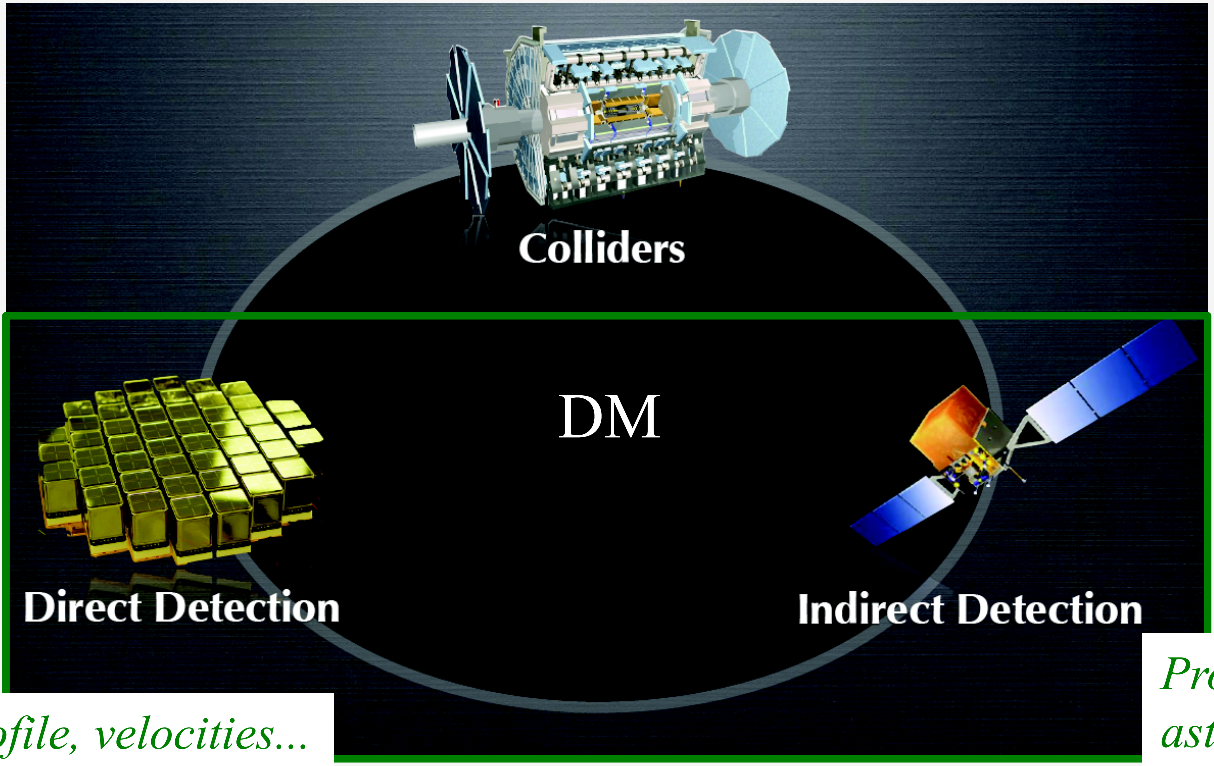
Complementarity is the key

Collider experiments cannot discover dark matter.

- Cannot probe the stability :
Would need an extrapolation
of 24 orders of magnitude in lifetime



Complementarity is the key

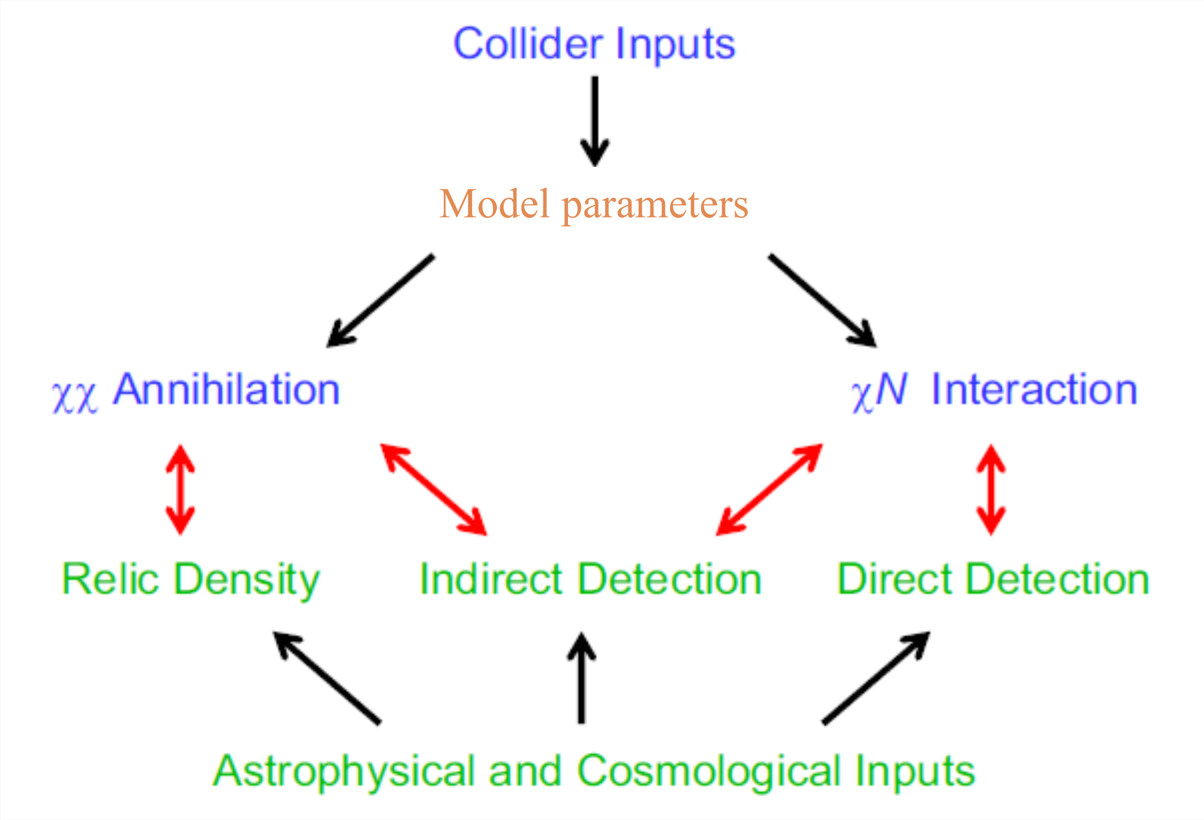


Halo profile, velocities...

Propagation models, astrophysical sources...

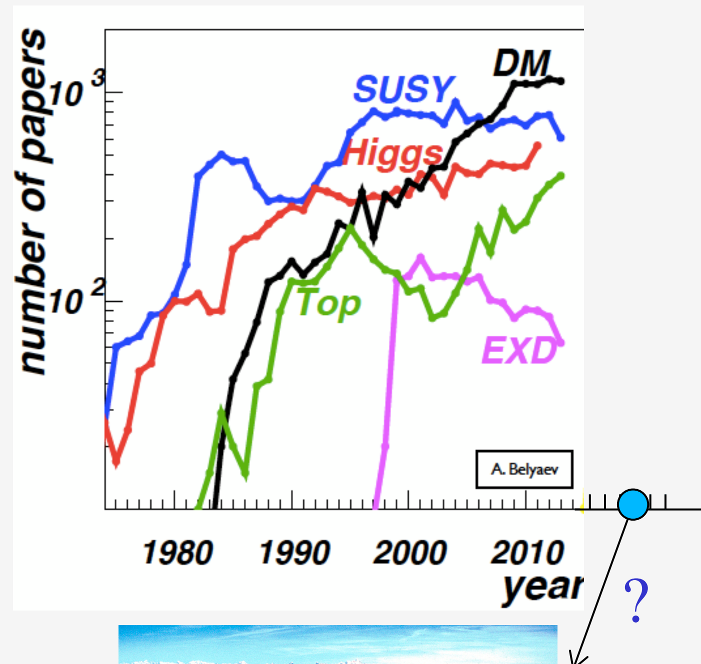
Implications of such experiments for particle physics are clouded by significant astrophysical ambiguities

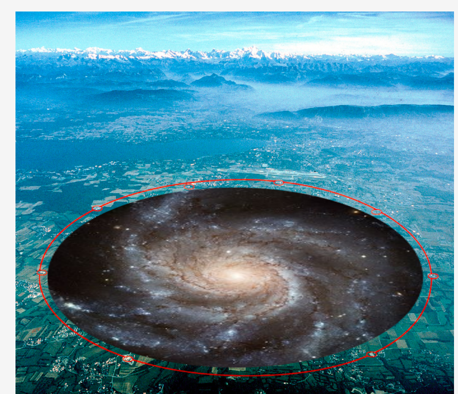
The dream picture…



Conclusions

- Dark Matter is still a puzzle today… 83 years after being evinced for the first time
- The LHC is now probing models which could explain the dark matter puzzle, looking for DM which could be produced in the pp collisions
- The field is evolving fast… so stay tuned!
- Will physics beyond the standard model finally be found ?
- Will a coherent picture emerge ?

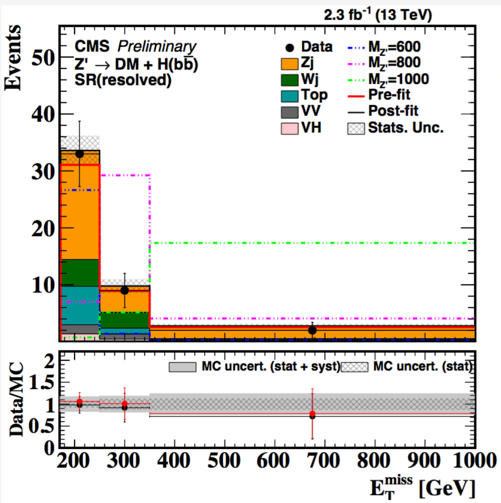


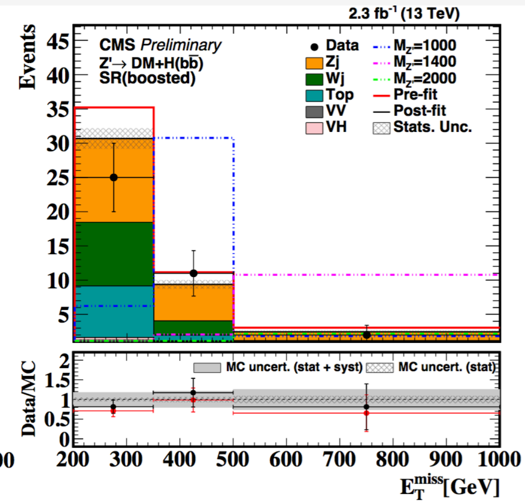


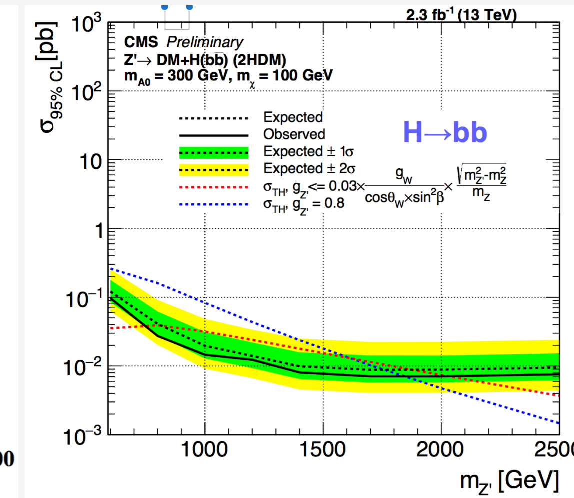
E_T^{miss} + $h(bb)$ in CMS

CMS:

- Resolved: 2 AK4 b-tagged jets, $p_T(bb)$ / E_T^{miss} > 150 / 170 GeV
- Boosted: 1 AK8 jet with subjets b-tagged, p_{Tj} / E_T^{miss} > 200 GeV







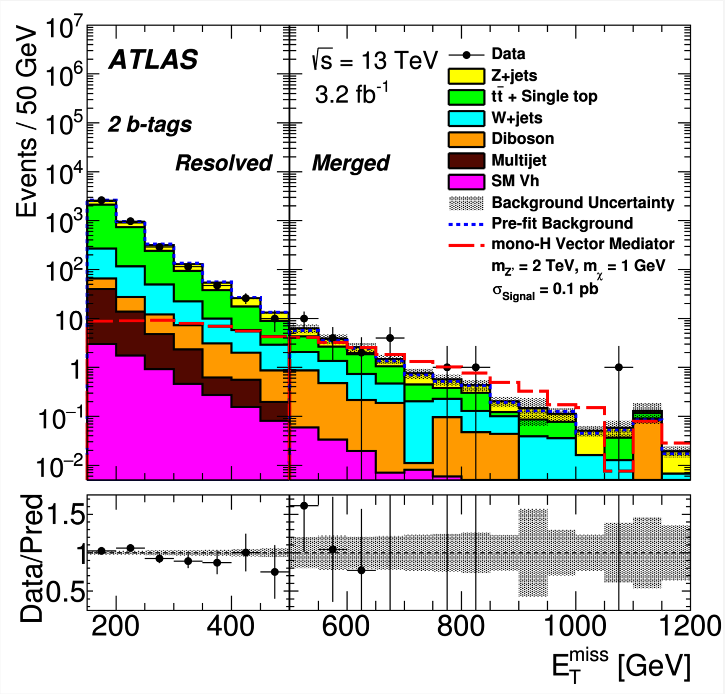
$E_T^{miss} + h(bb)$ in ATLAS

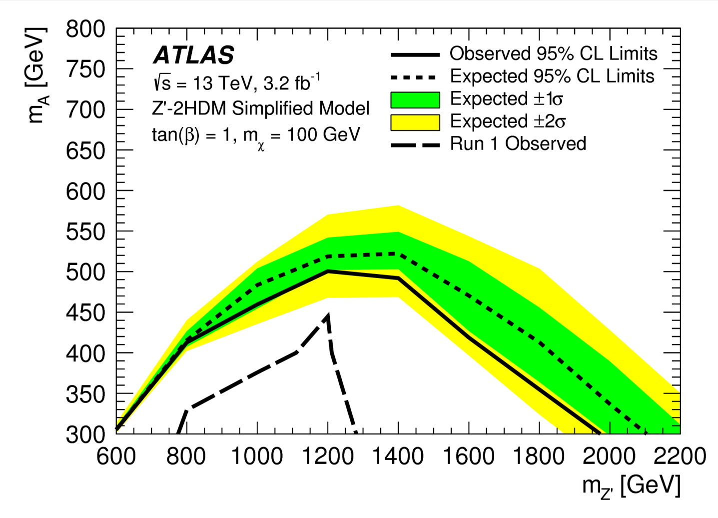
- The two b-jets from Higgs decay can be resolved or merged into a fat jet, depending on the boost : cover both possibilities

Resolved	Boosted
150 < E_T^{miss} < 500 GeV (split in 3 regions)	E_T^{miss} > 500 GeV
≥ 2 jets, ranked by b-tagging, centrality and p_T	≥ 1 large-R jet associated with ≥ 2 track jets
The 2 highest ranked reconstruct the Higgs mass	Split in different b-tagging categories
Large p_T sum of the jets, $j_{h,1}$ or $j_{h,2}$ has p_T>45 GeV	Shape fit of the large-R mass distribution
Df(jets, E_T^{miss})>20°	p_T^{miss} > 30 GeV
p_T^{miss} > 30 GeV and Df(p_T^{miss}, E_T^{miss})<p/2	
Df(E_T^{miss},h_{bb})>120°	
Df($j_{h,1}$, $j_{h,2}$)<140°	
Veto on leptons	

- The main BG is top pairs, Z(νν)+jets, W+jets
  - Use mass sidebands + leptonic CRs

$E_T^{miss} + h(bb)$ in ATLAS





E_T^{miss} + top quarks in CMS

Hadronic:

E_T^{miss} , ≥ 1 or 2 b-jet, Multivariate analysis resolved-hadronic-top tagger based on multiple kinematic variables: categorize by number of top tags

Semi-leptonic (e or μ):

E_T^{miss} , ≥ 1 b-jet, m_T, m_{T2}^W

Di-leptonic (e or μ):

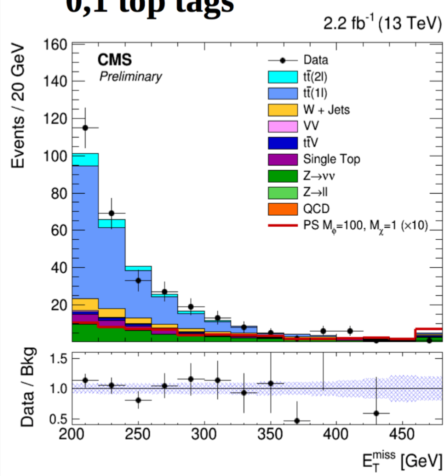
E_T^{miss}, Z(ll) veto, ≥ 1 b-jet, $\Delta\phi(E_T^{miss}, ll)$

Combination of the three channels

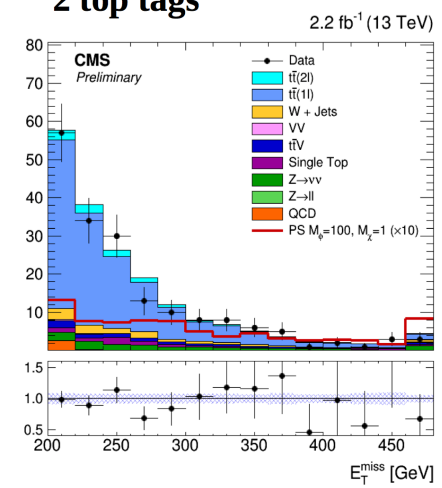
Fit to the E_T^{miss} distributions to extract the signal

Hadronic

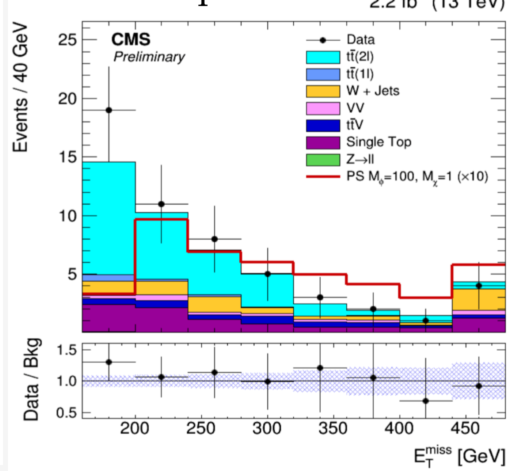
0,1 top tags



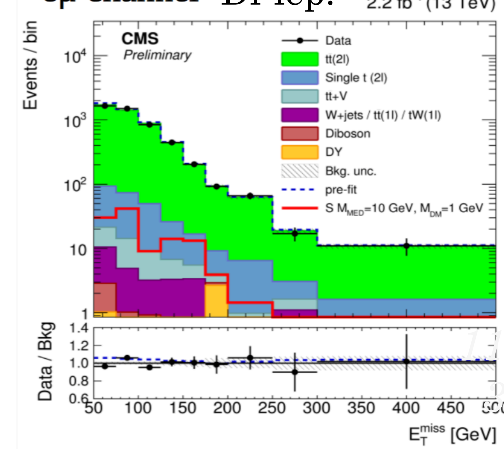
2 top tags



Semi-lep.

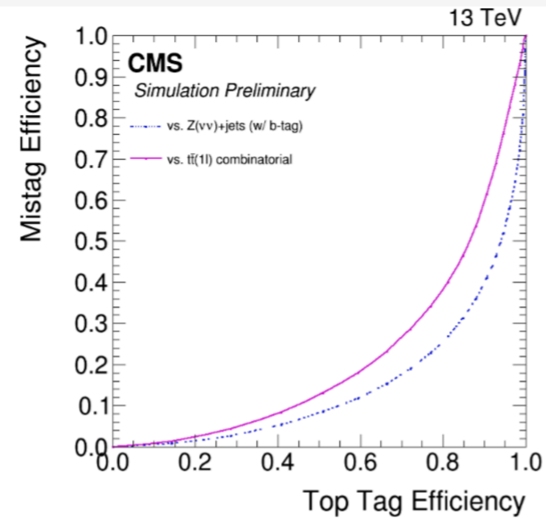


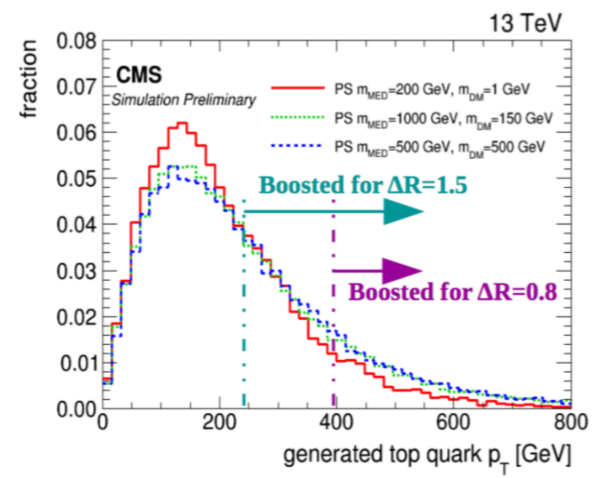
eμ channel Di-lep.



Resolved top tagger in CMS

- MVA discriminant to identify tri-jet combinations from top quark decays
- Training a BDT with simulated $t\bar{t}$ events
- Input variables:
  - Kinematic fit probability
  - b-tag discriminant
  - Quark/gluon likelihood
  - $\Delta R(j_1,b)$, $\Delta R(j_2,b)$
  - $\Delta\varphi(j_1,b)$, $\Delta\varphi(j_2,b)$
- Efficiencies in MC calibrated with $t\bar{t}$ events in data
- Tops in $t\bar{t}$+DM production generally have moderate p_T

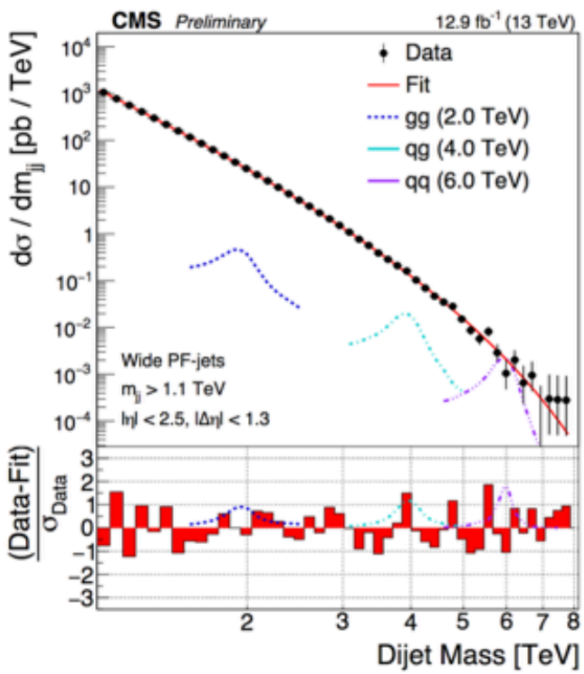




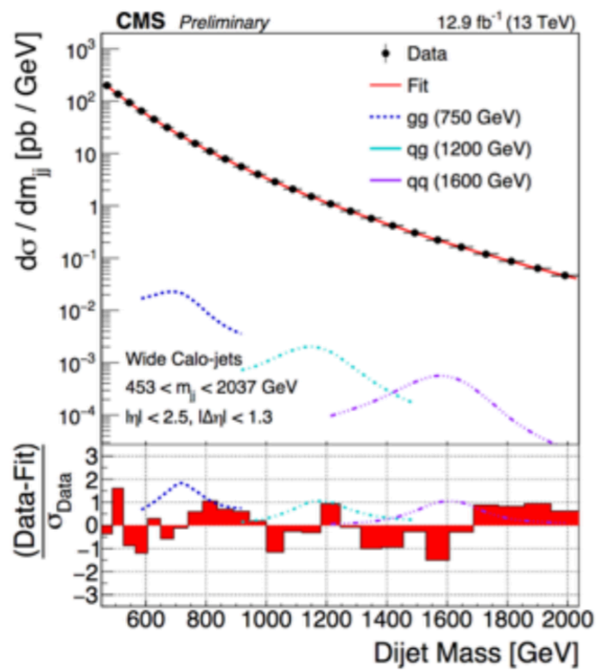
CMS-PAS-EXO-16-005

CMS dijet searches

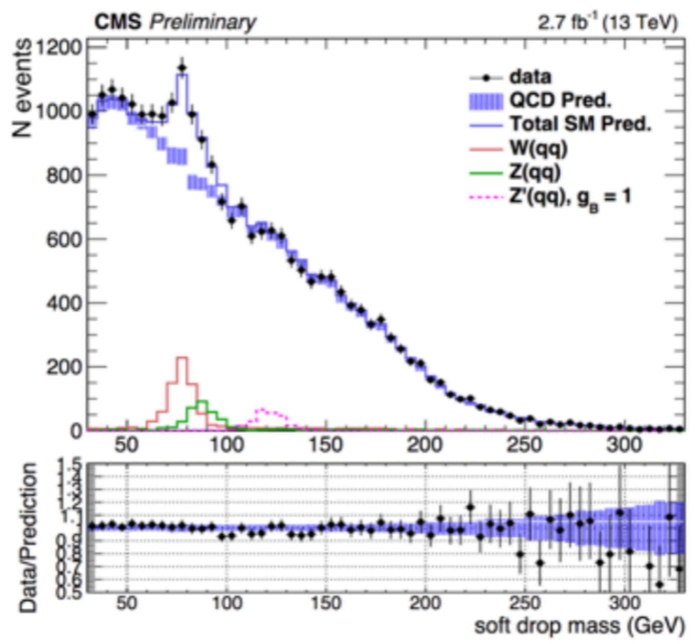
High mass



With trigger



With ISR



Evidence for Dark Matter

2006:

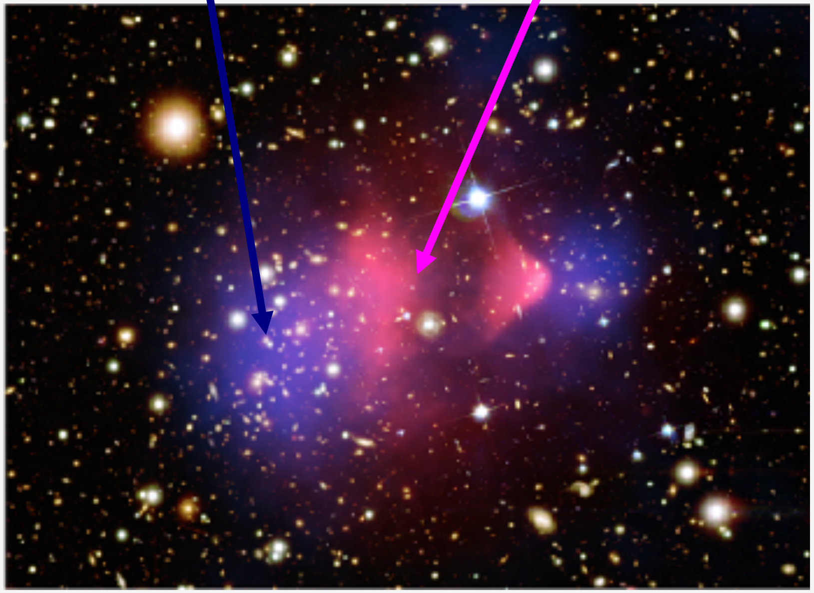
The bullet cluster, formed by the collision of two galactic clusters

Evidence for Dark Matter

2006:

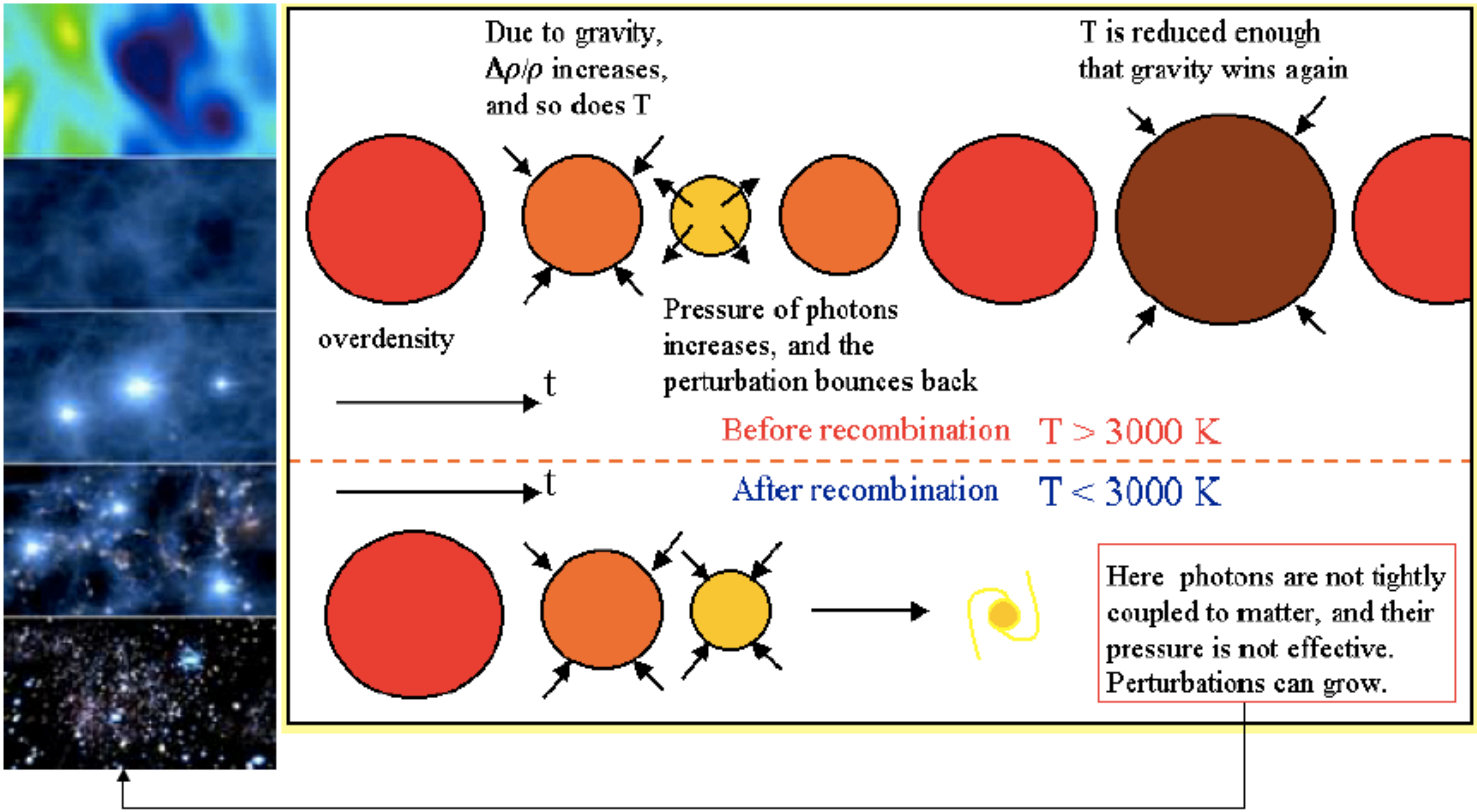
The bullet cluster, formed by the collision of two galactic clusters

- Mass distribution mapped by gravitational lensing of background galaxies
- The visible mass is dominated by the X-ray emitting gas
- DM did not interacted with the gas: clear separation of DM and gas clouds



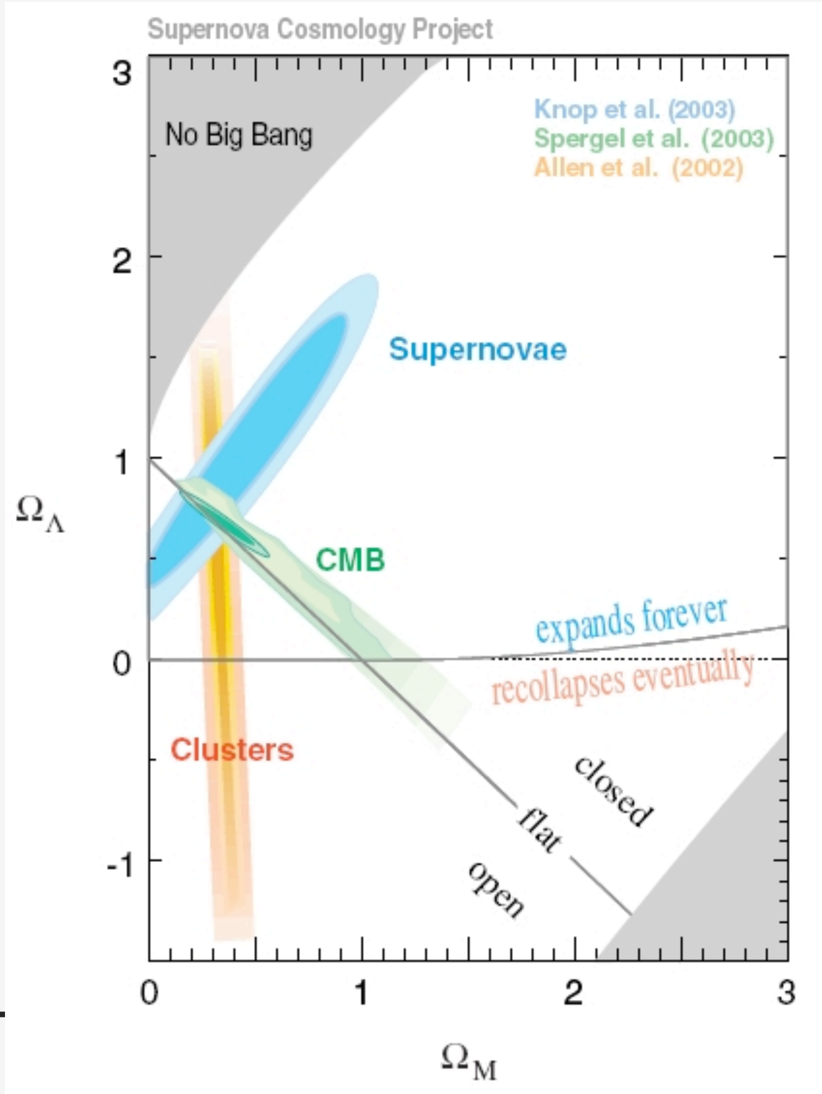
Also observed in other mergers:
~~Baby bullet, Musket ball, El Gordo~~…

CMB

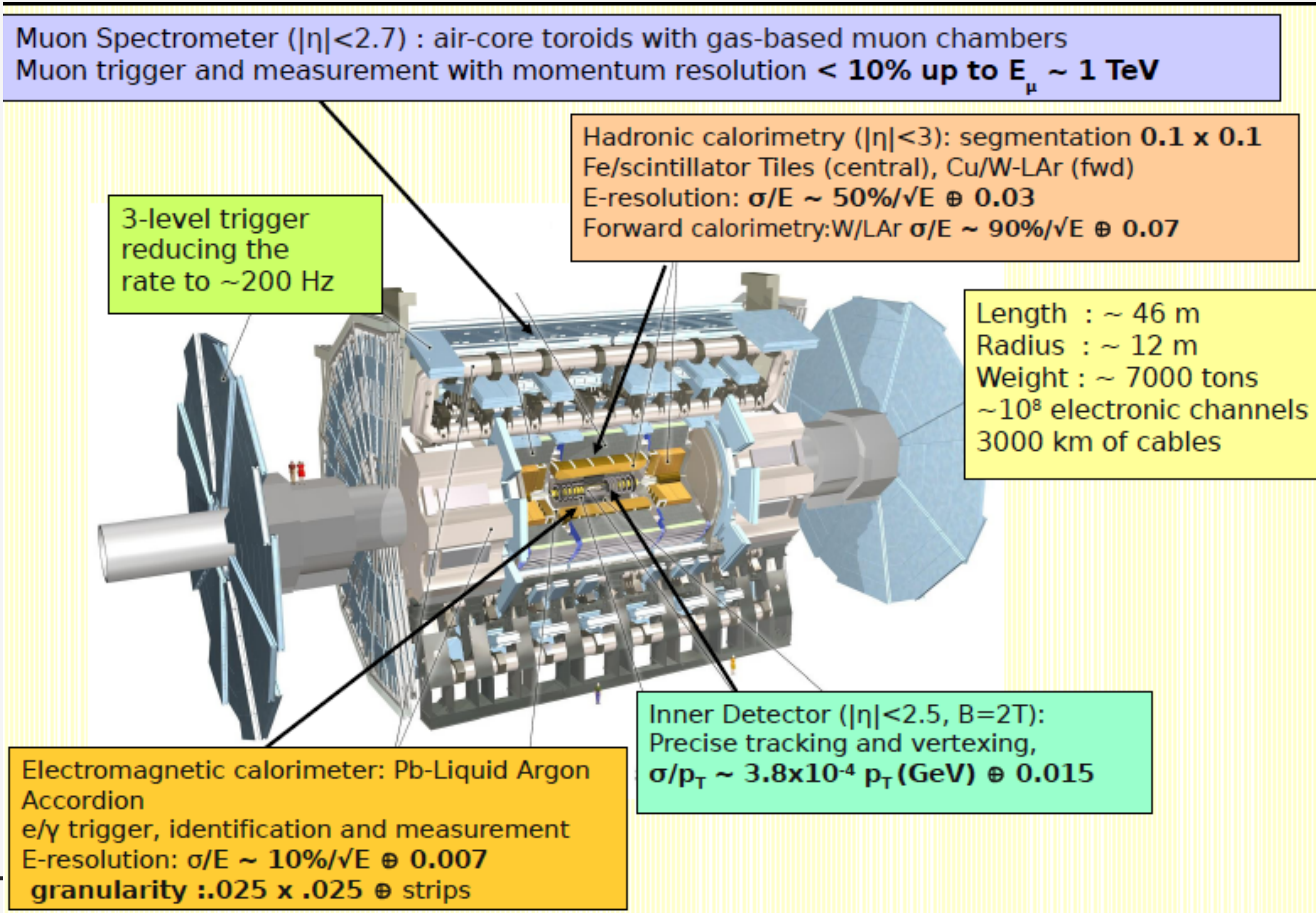


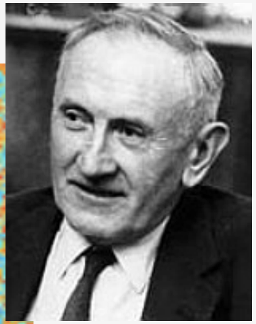
Due to gravity,
$\Delta\rho/\rho$ increases,
and so does T
T is reduced enough
that gravity wins again
overdensity
Pressure of photons
increases, and the
perturbation bounces back
t
Before recombination T > 3000 K
After recombination T < 3000 K
t
Here photons are not tightly
coupled to matter, and their
pressure is not effective.
Perturbations can grow.

Evidence for Dark Matter: The CMB

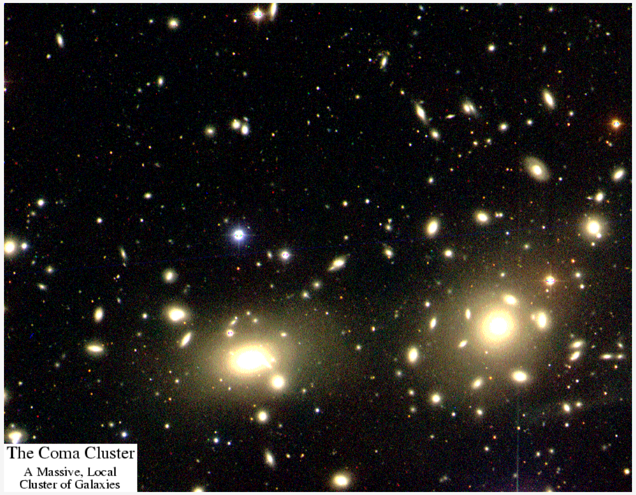


The composition of the universe obtained from CMB measurements agree with other independent measurements like supernovae redshifts and cluster measurements.


Muon Spectrometer (|η|<2.7) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV
Hadronic calorimetry (|η|<3): segmentation 0.1 x 0.1
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$
Forward calorimetry:W/LAr $\sigma/E \sim 90\%/\sqrt{E} \oplus 0.07$
3-level trigger reducing the rate to ~200 Hz
Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables
Inner Detector (|η|<2.5, B=2T):
Precise tracking and vertexing,
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$
Electromagnetic calorimeter: Pb-Liquid Argon Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.007$
granularity :.025 x .025 ⊕ strips



Evidence for Dark Matter: galaxy clusters



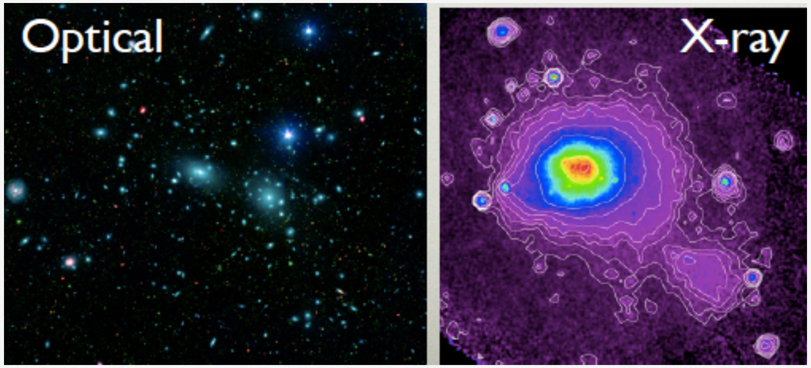
Clusters of galaxies are the largest gravitationally bound systems known in the Universe, containing ~10s to 1000s of galaxies

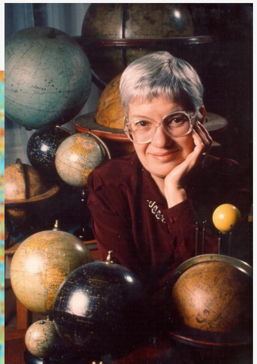
- 1933:

  Fritz Zwicky studies galaxies of the Coma Cluster. He finds that their velocities are much larger than expected from gravitational calculations.

His conclusions: the Coma cluster contains hundreds of times more mass than is visible …

Modern measurements for a typical cluster:
~1-2% stars, ~5-15% gas
The rest is dark matter





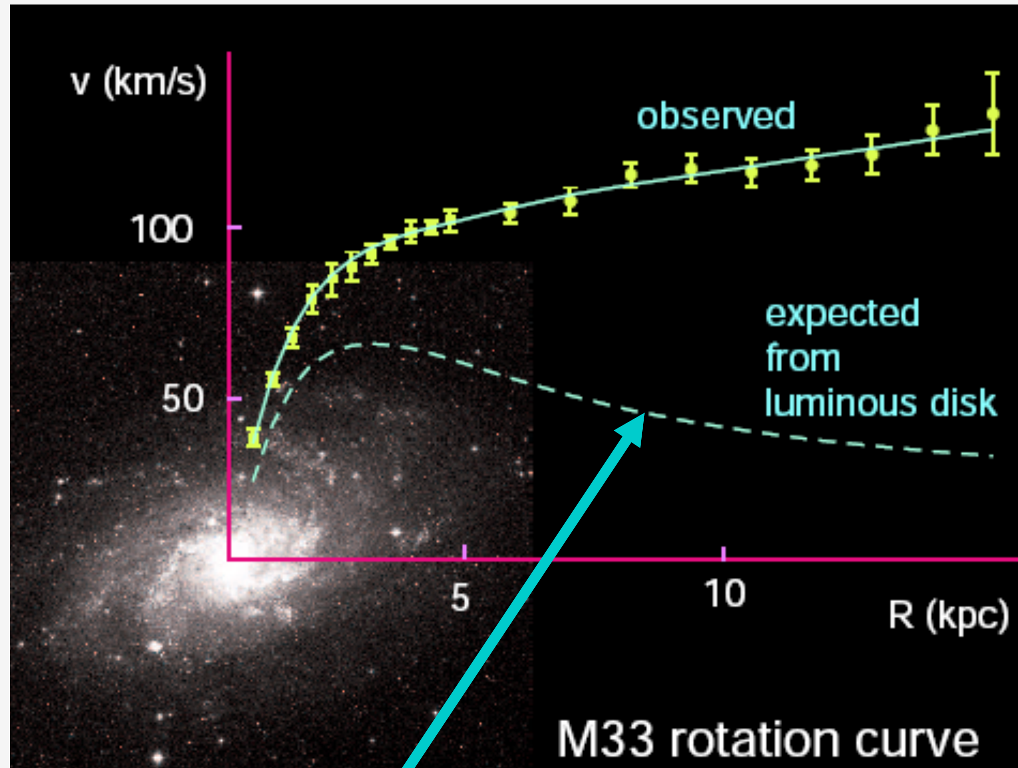
Evidence for Dark Matter: galactic rotation curves

- 1974:

  Vera Rubin measures the speed at which the stars rotate around the center of galaxies. It does not match the expectations...

Assuming there is a lot of mass in the galaxy that is not visible (dark matter), one can fit the observed curve

Similar exercise for the Milky Way yields the local DM density: ρ(8.5 kpc)~0.2-0.5 GeV/cm^3

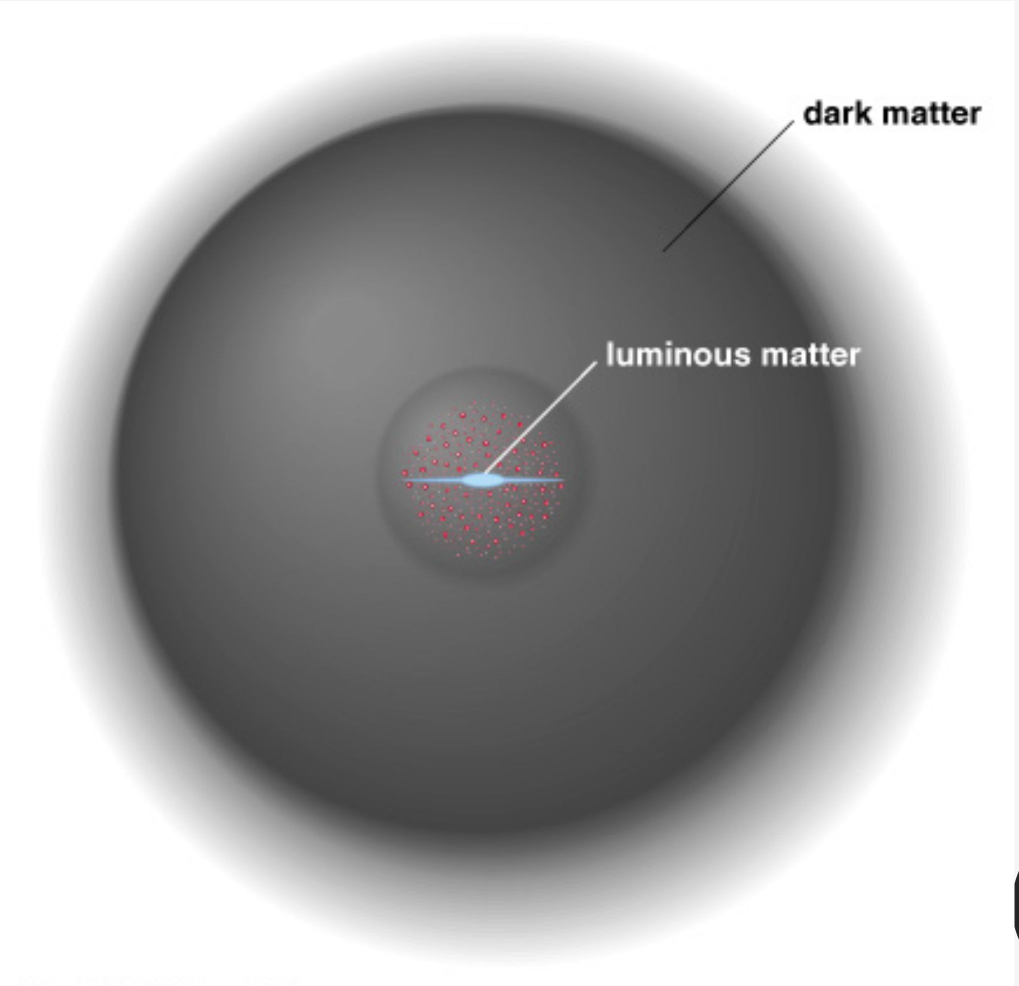


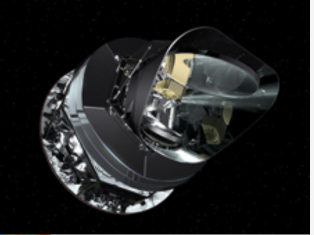
The expected curve is calculated using the luminous mass...

$$v_{rot} = \sqrt{\frac{GM_r}{r}}$$

The Dark Matter halo

In order to match the observations, we have to think that the galaxies are embedded in a halo of dark matter which extends far beyond the visible galaxy.



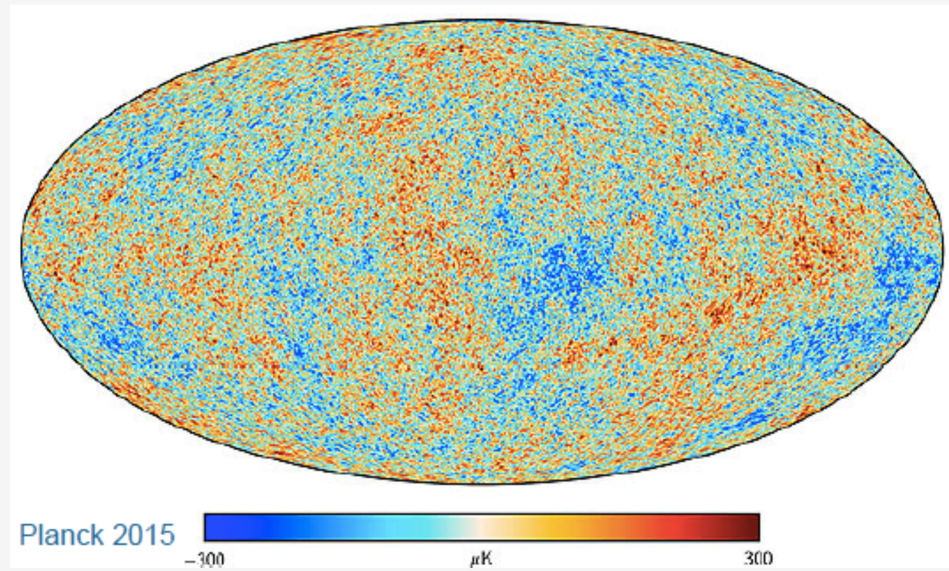


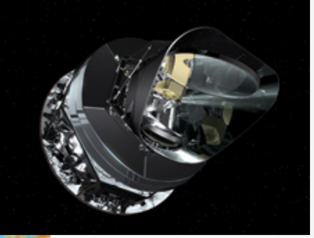
Evidence for Dark Matter: The CMB

~400k years after the Big Bang, the electrons and protons combined and the universe became transparent to radiation, leading to the cosmic microwave background

T=2.725K, ΔT~200μK

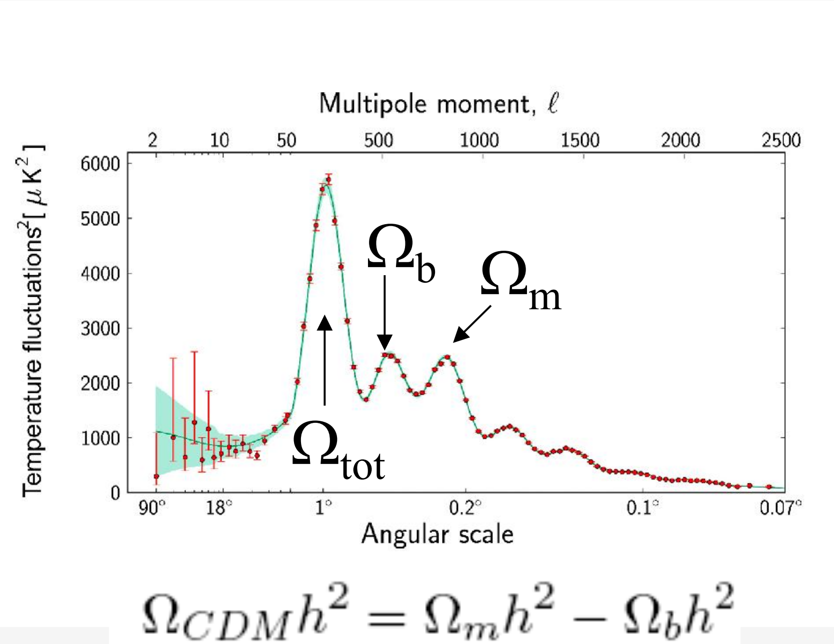
Planck has mesured the cosmic microwave background anisotropies, which came from regions of over/underdensity at the moment of recombination.



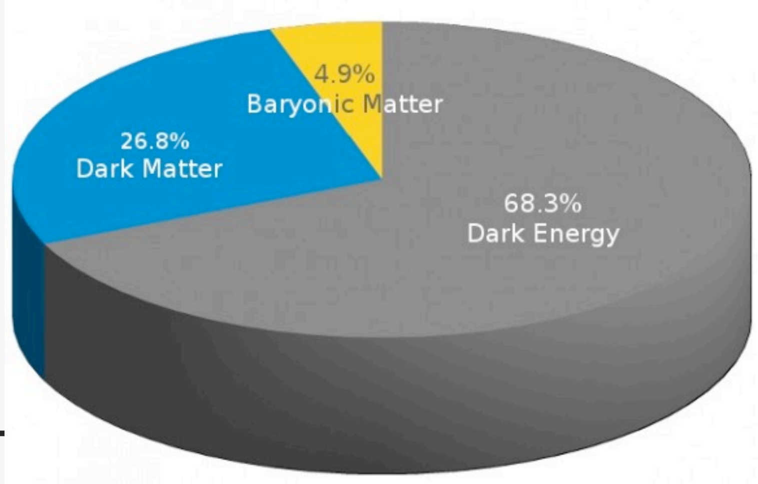


Evidence for Dark Matter: The CMB

The position and relative heights of the anisotropy peaks in the multipole moment representation gives information about the geometry of the universe, on its composition, ...



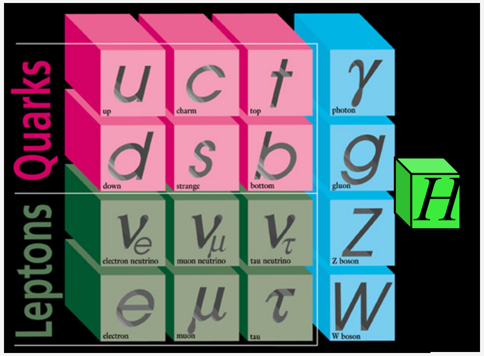
$$\Omega_{CDM}h^2 = \Omega_m h^2 - \Omega_b h^2$$



~85 % of the matter in the universe is Cold Dark Matter

What we know
and what we know we don't know

It's out there! But what is it?



- We know it is:
    - not baryonic matter
    - stable or veeery long-lived
    - neutral
    - cold (i.e non-relativistic at the beginning of the universe to allow for structure formation early enough and with the proper 'clumpiness')
- The SM doesn't not give us such a candidate (neutrinos would be hot DM)
    - we do not know what it is; we need to go beyond the SM
- But we also know its relic density – i.e. the amount of DM there is now in the universe

The WIMP miracle

If the produced DM is in equilibrium with the SM particles in the early universe

As the universe expands and cools down, the equilibrium breaks

The SM particles do not have enough energy to produce DM

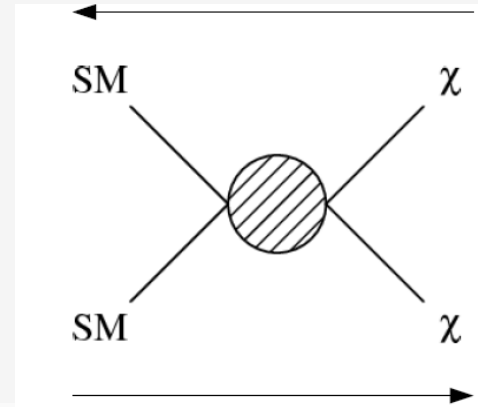
The DM particles get too diluted to annihilate

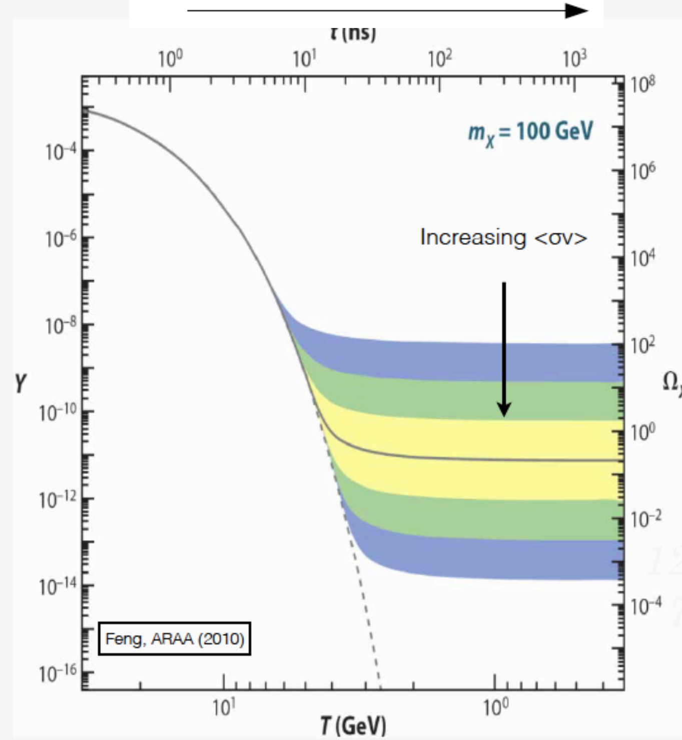
The density of DM particles freezes out to give the relic density

When this happens depend on the cross section and the mass

Weak scale interactions give the correct relic density ! This is the WIMP miracle!

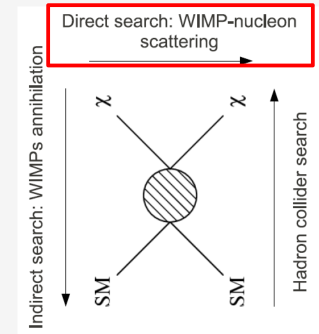
A **stable Massive Weakly Interacting Particle** is a good DM candidate*

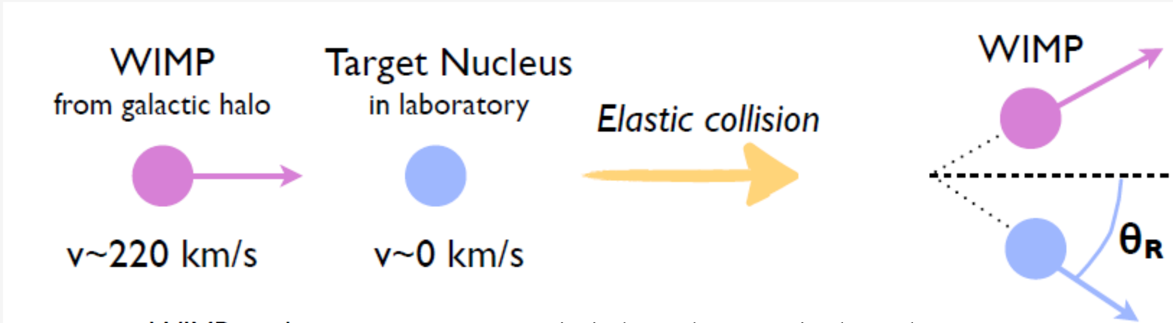




* but there are other candidates too…

Direct search



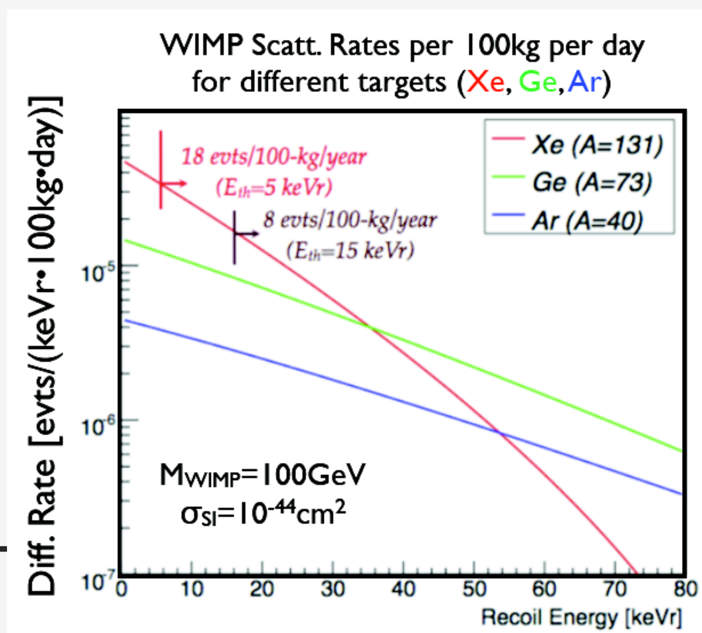


WIMP-nucleus cross sections: spin-independent or spin-dependent

$$\sigma_{SI} = \frac{4\mu^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2 \propto A^2$$ *Better with higher A*

$$\sigma_{SD} = \frac{32\mu^2}{\pi} G_F^2 \frac{J+1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$ *Nucleus with spin*

^{19}F, ^{23}Na, ^{73}Ge, ^{127}I, ^{129}Xe, ^{131}Xe, ^{133}Cs



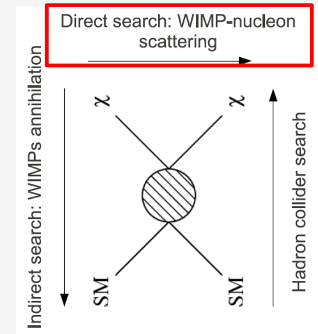
Small and uncertain rates

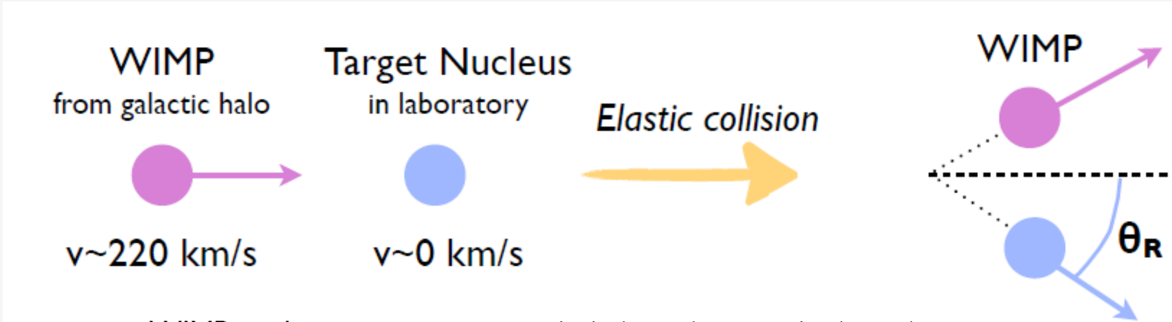
Rare event search: minimize BG!

Tiny E_{recoil}

Featureless spectrum*

Direct search





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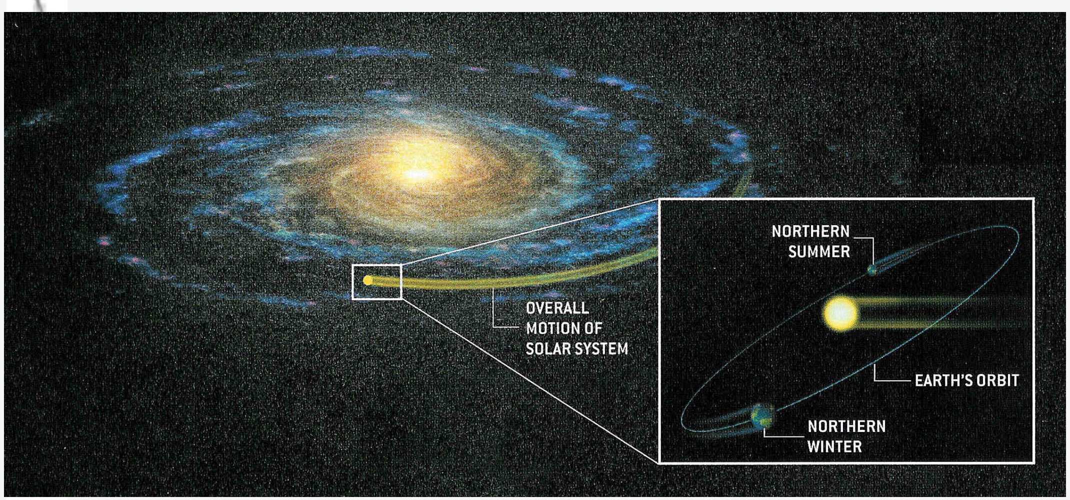
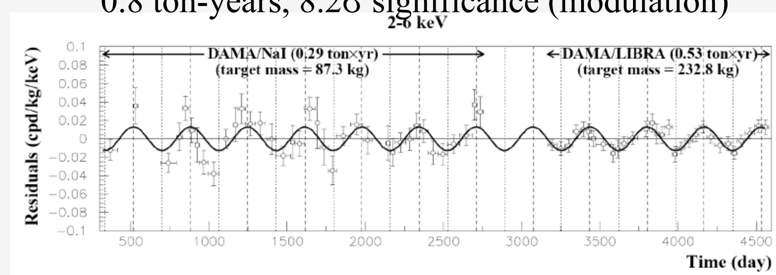
^{19}F, ^{23}Na, ^{73}Ge, ^{127}I, ^{129}Xe, ^{131}Xe, ^{133}Cs



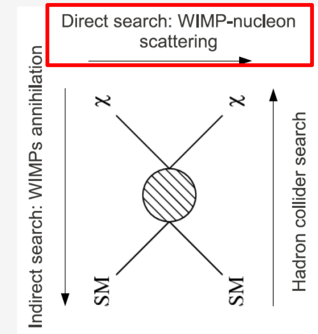
*Annual modulation of the rate

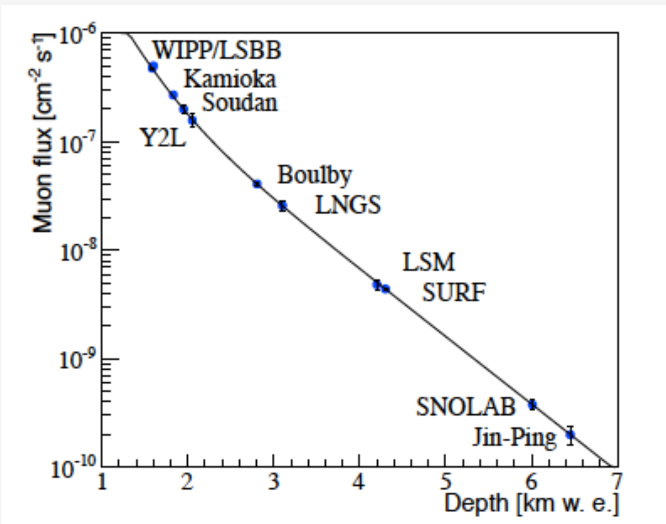
DAMA :

0.8 ton-years, 8.2σ significance (modulation)

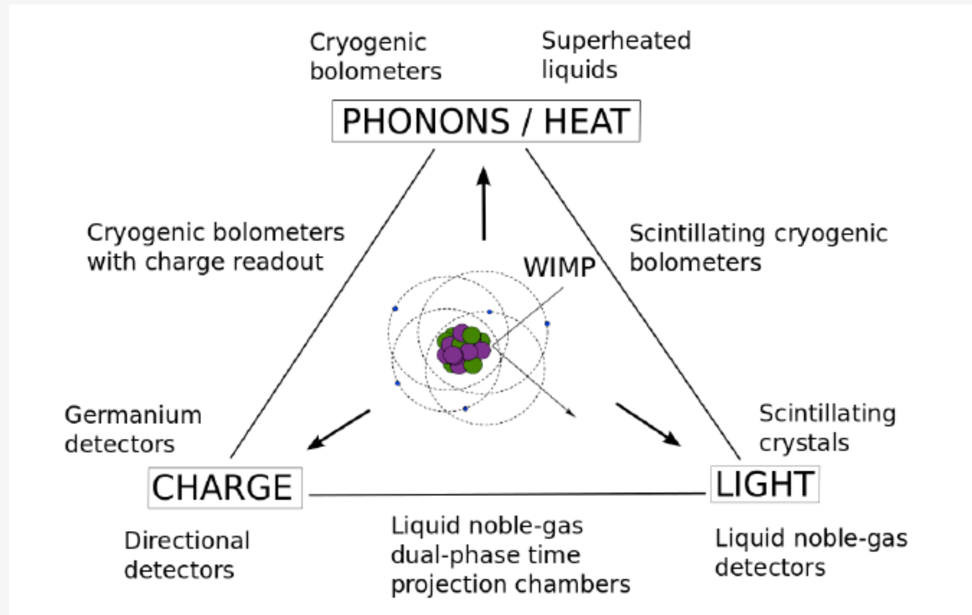


Direct search



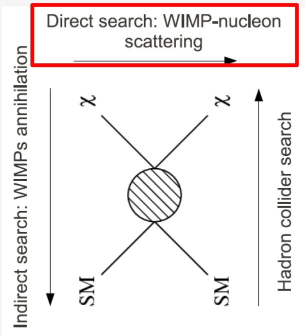


Shielding is paramount

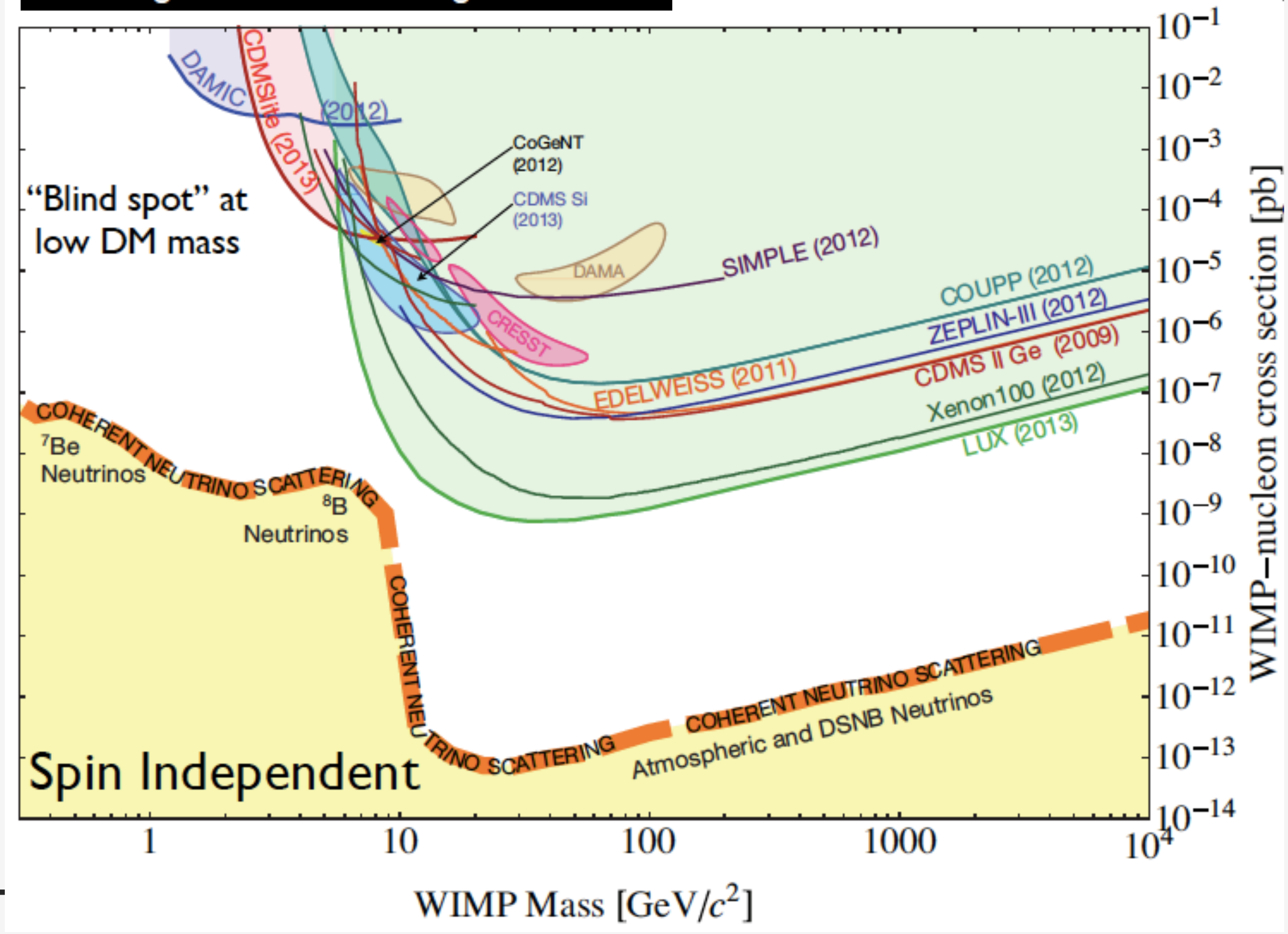


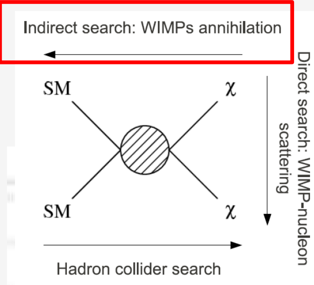
Combining different detection techniques helps isolating the signal

Direct search: future complications...

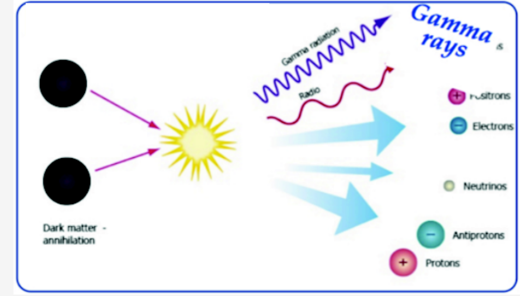


Billard, Figueroa-Feliciano, Strigari 1307.5458





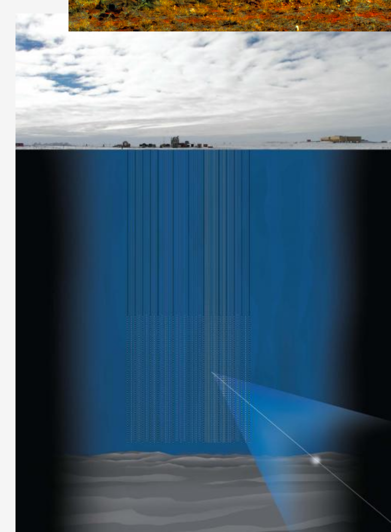
Indirect search



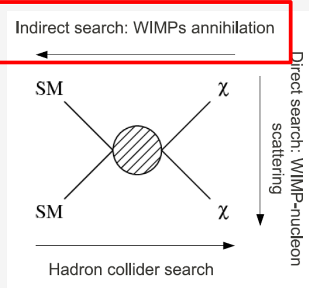
- Annihilation of Dark Matter particles in the galactic halo (the Sun, the Earth) could produce gamma rays, antimatter, neutrinos…

  - Can be measured in space–based detectors:
  - Fermi (gamma), PAMELA, AMS (antimatter)

  - Can be measured in telescopes (gamma):
  - MAGIC, HESS, VERITAS, CANGAROO

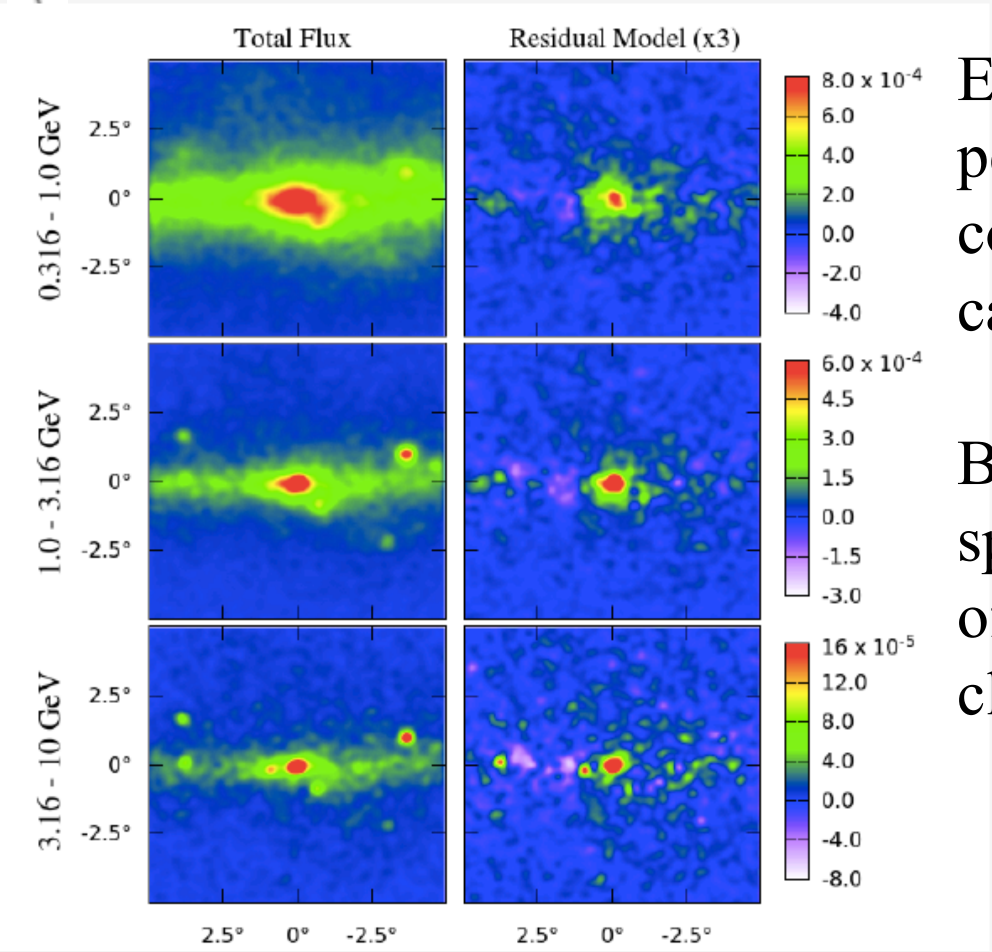


  - Can be measured in neutrino telescopes :
  - ANTARES, ICECUBE



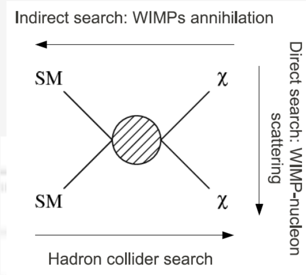
Indirect search: the Fermi galactic center excess

Phys.Lett.B697:412-428,2011
arXiv:1402.6703



Excess from the galactic center peaking at a few GeV, which can be compatible with a ~40 GeV DM candidate annihilating into b's

But no evidence from dwarf spheroidal satellite galaxies (dSphs) of the Milky Way (which should be cleaner)



Indirect searches: interesting but difficult

- Understanding the gamma-ray sky: