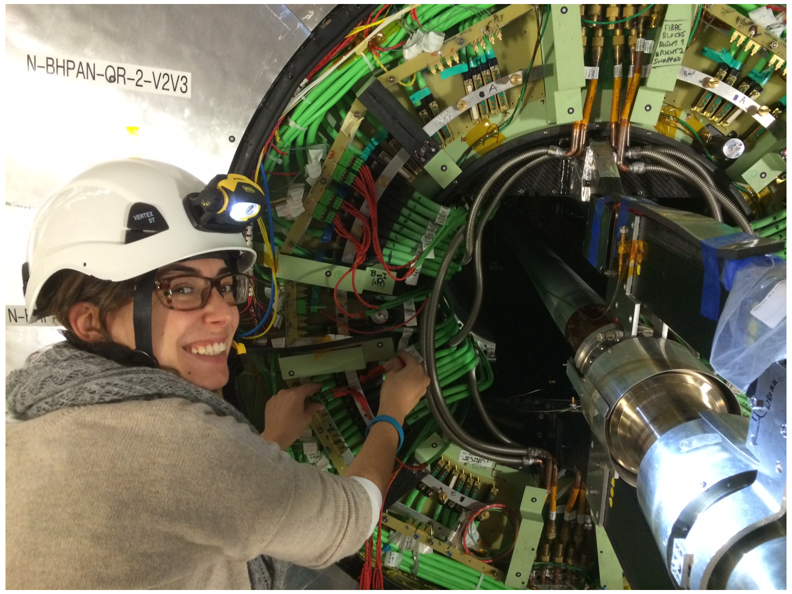
Dark Matter: recipe to search it at colliders

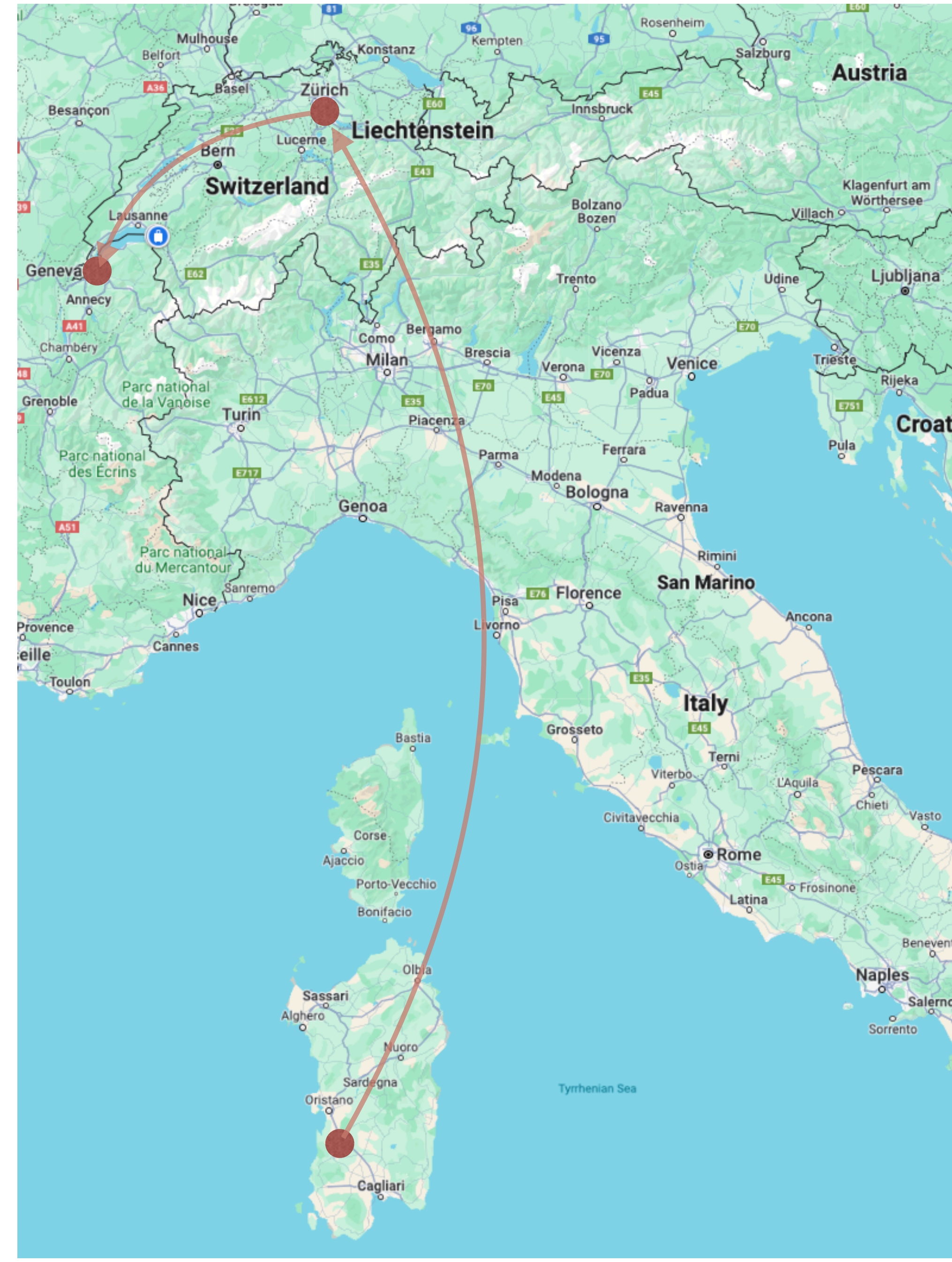
Deborah Pinna
(University of Wisconsin-Madison)

USCMS Undergraduate Summer Internship

10 July 2024

Few words about me …





Deborah Pinna

- Scientist at University of Wisconsin-Madison (based at CERN)
- PhD in Zurich at UZH
- originally from Sardinia (Italy)

Research

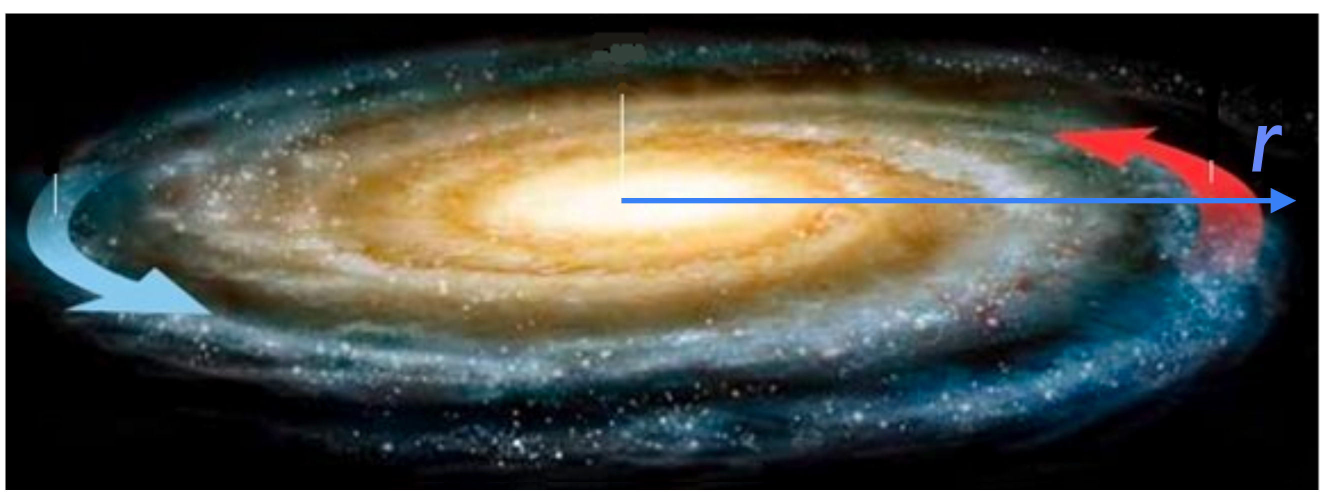
- Searches for Dark Matter, Beyond the Standard Model particles and Standard Model measurements at the CMS Experiment

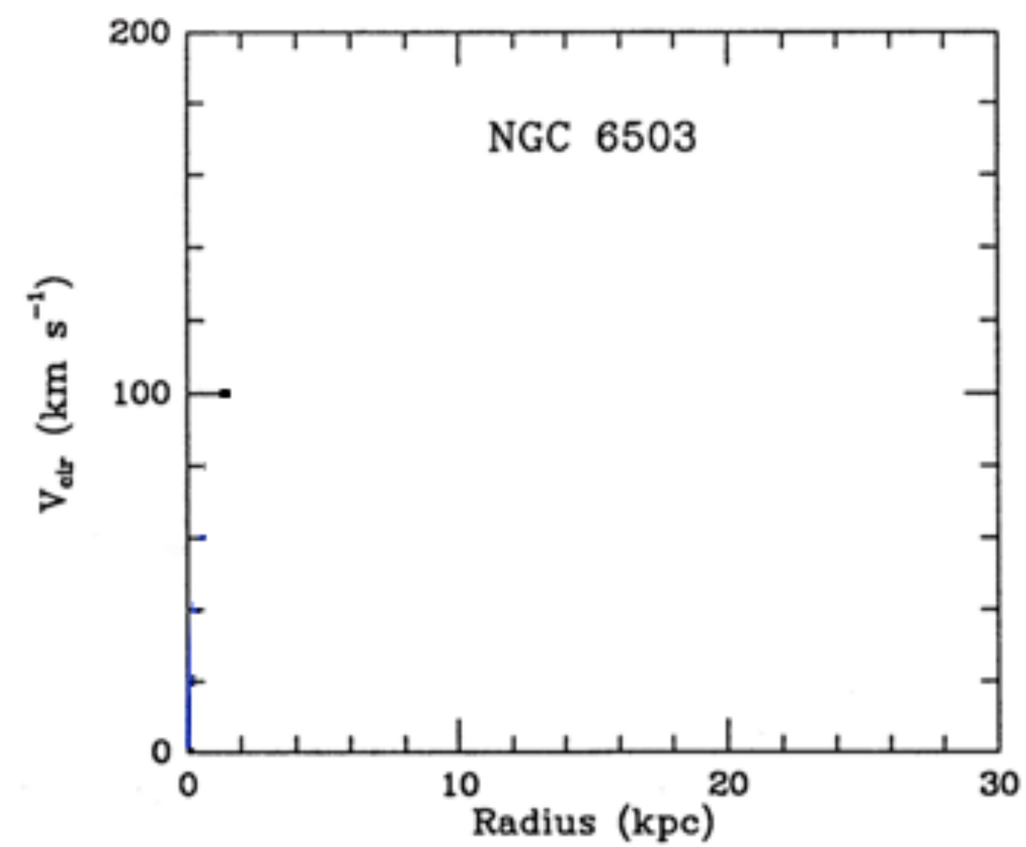
Hobbies

- climbing, painting, traveling

Dark matter, why?

- *Different empirical evidence of DM* from astrophysical observations at different scales
  - first indication from Zwicky's dispersion velocity measurements of galaxies in Coma cluster
  - existence of DM confirmed by measurements of stars and gas circular velocities within a galaxy by Ford and Rubin
    - from Newtonian dynamics expected velocity v(r) of these objects: $v(r) = \sqrt{\frac{GM(r)}{r}}$





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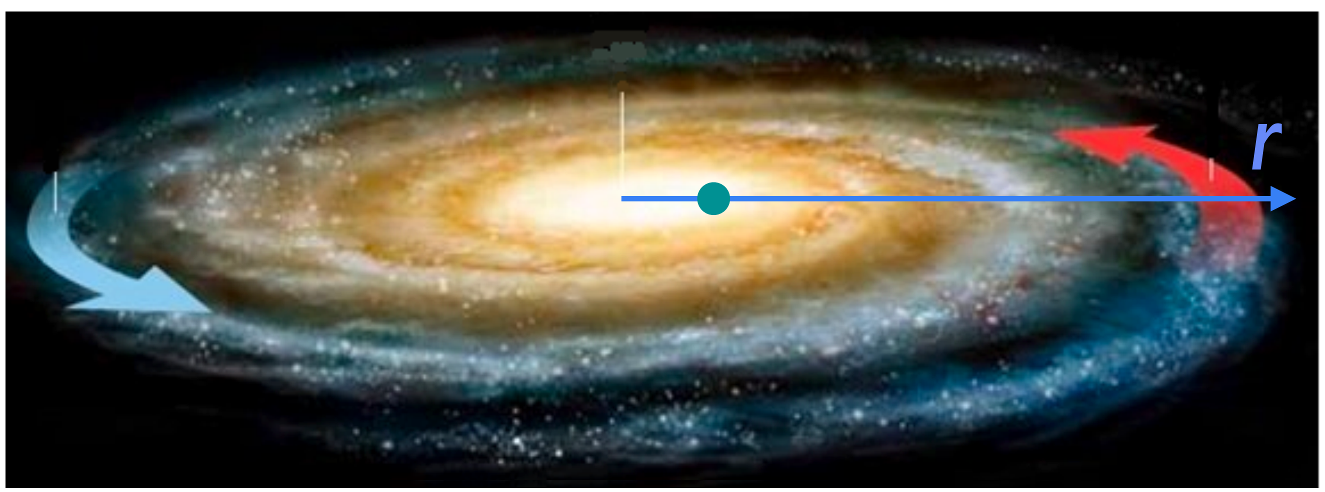

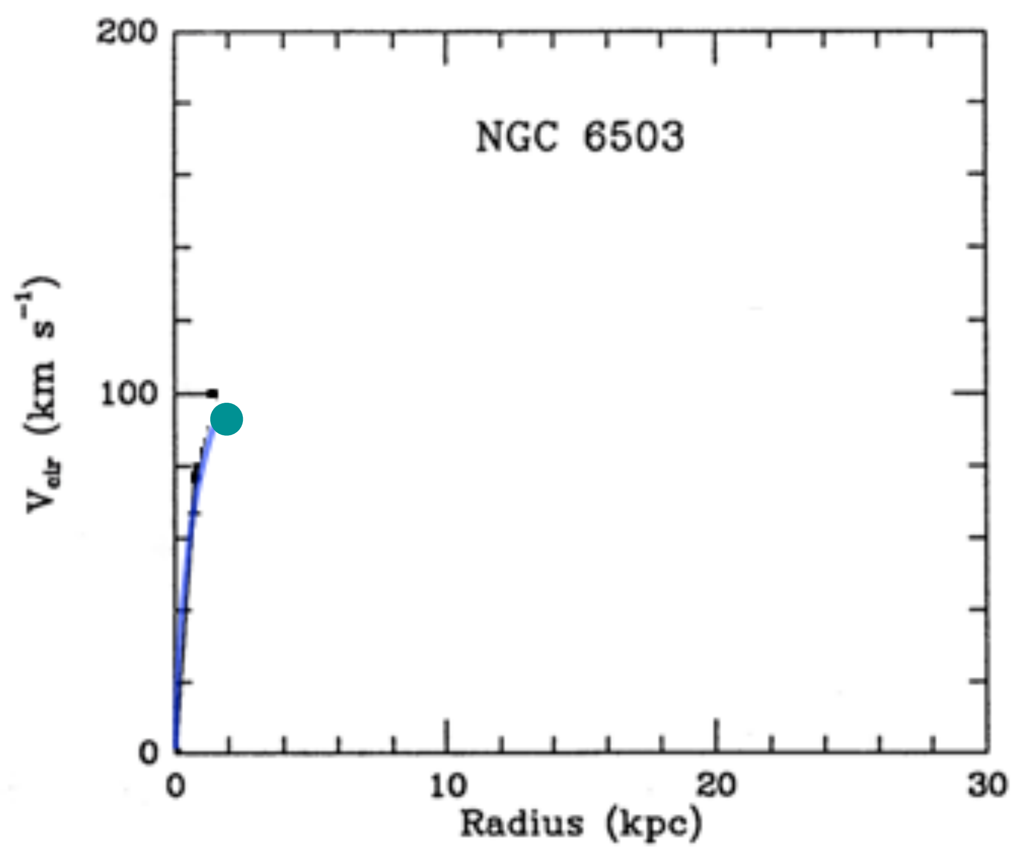

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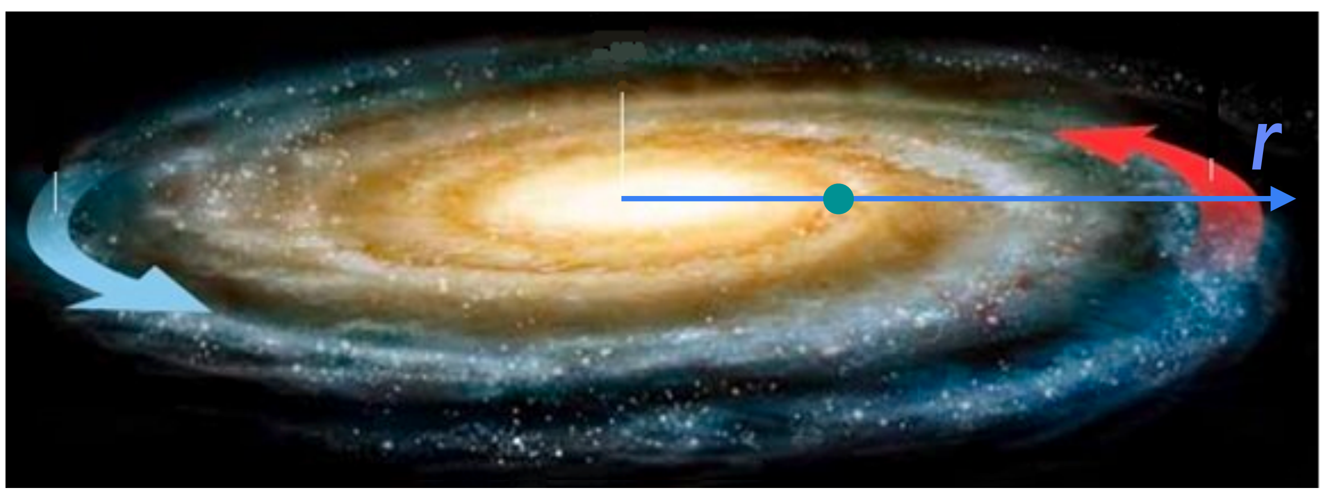

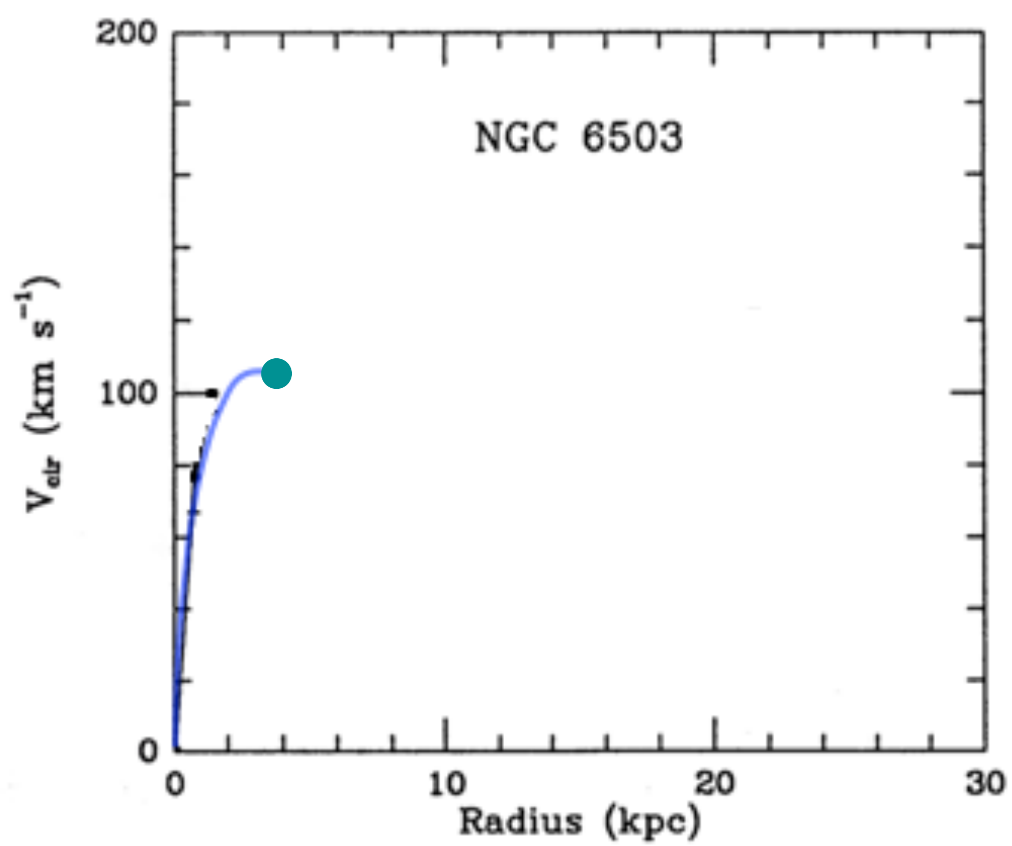

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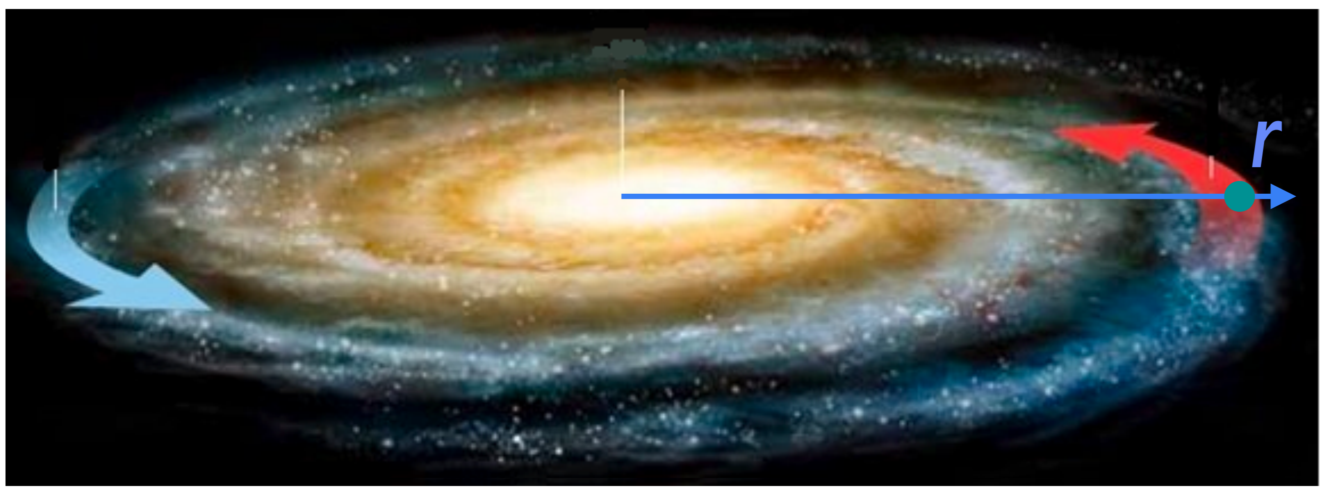

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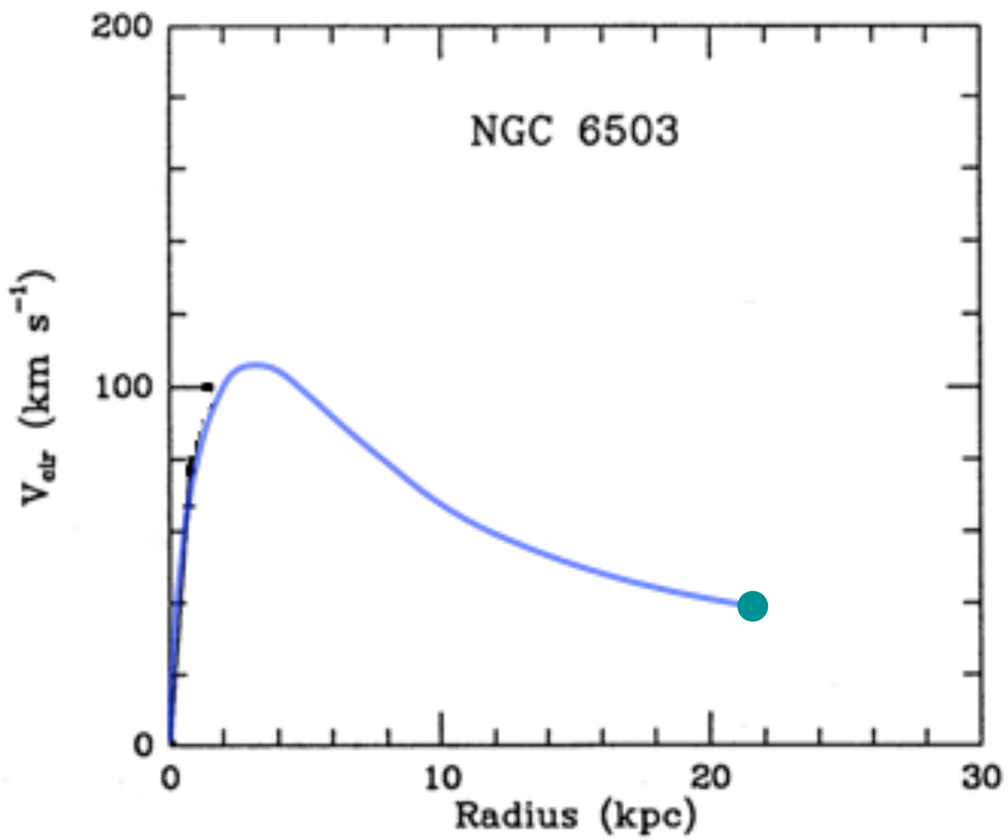

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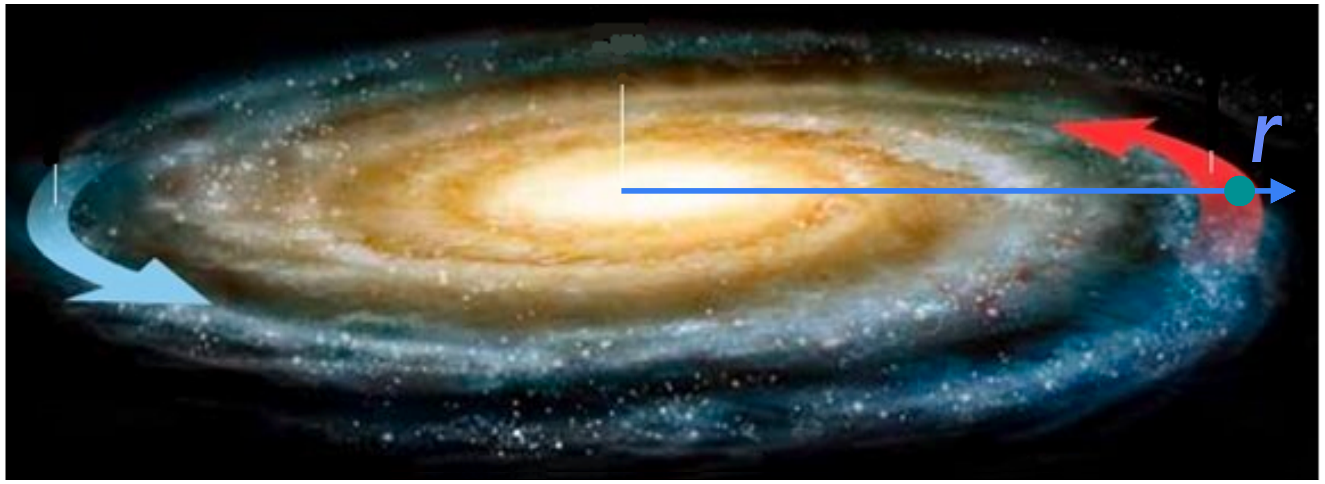

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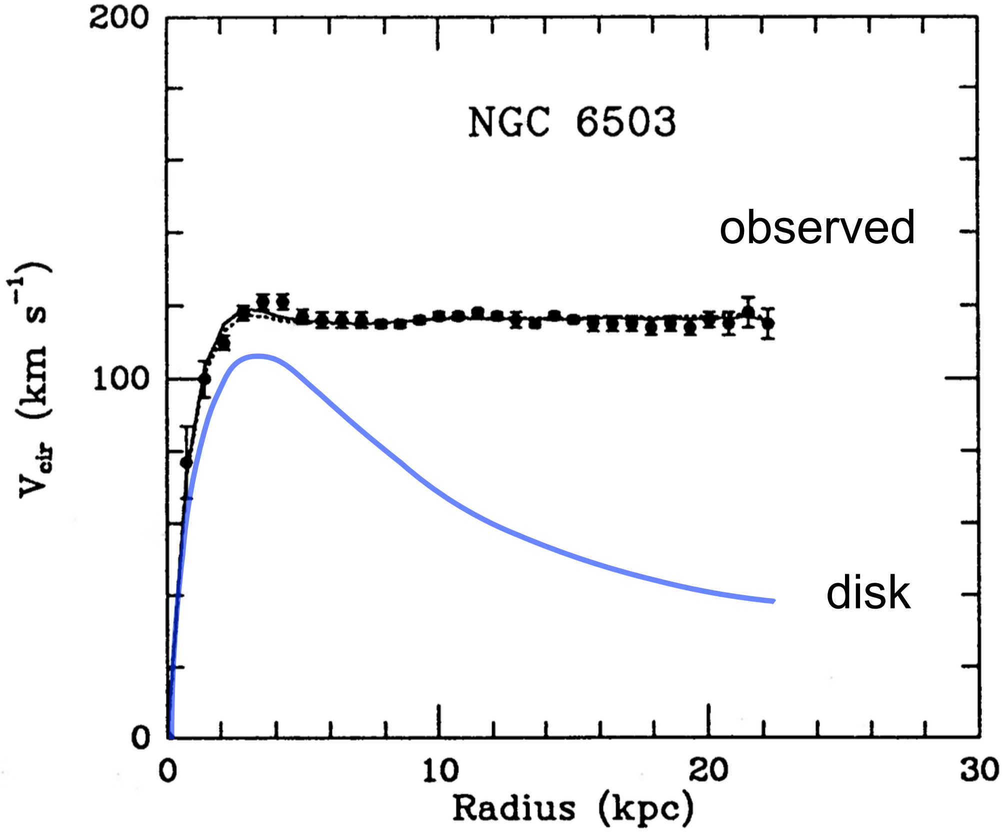

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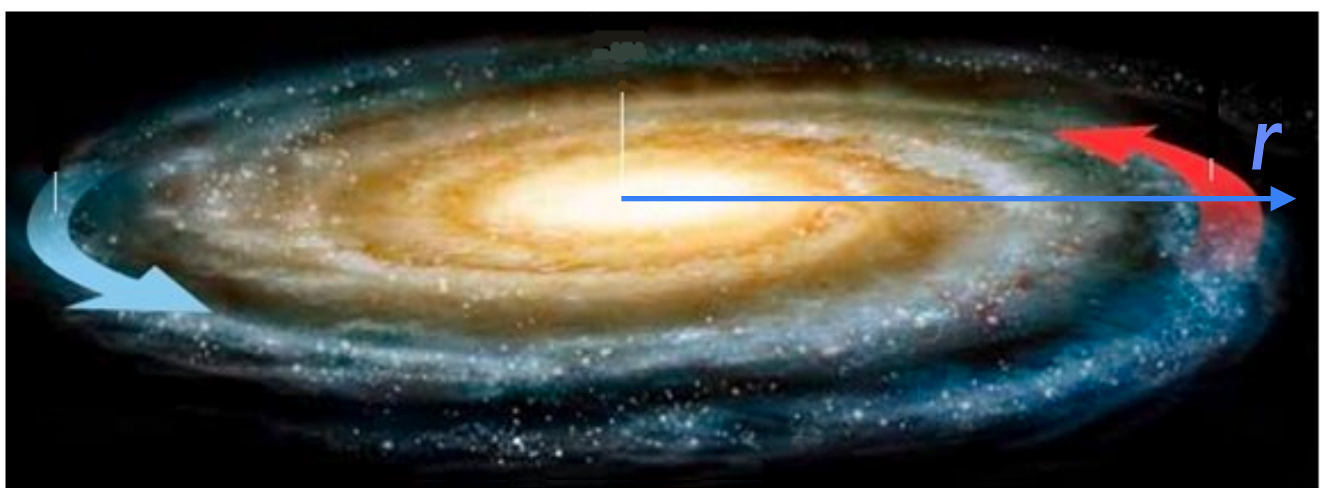

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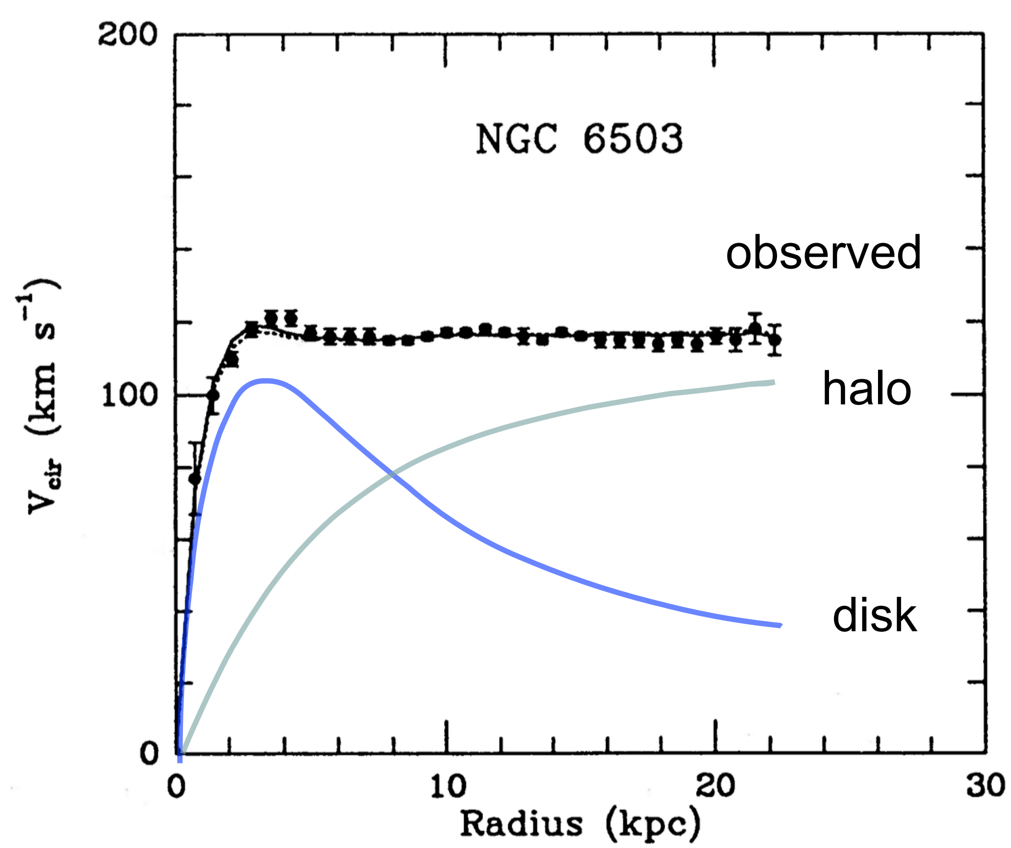
- non-luminous matter halo with spherical distribution in galaxy outer part



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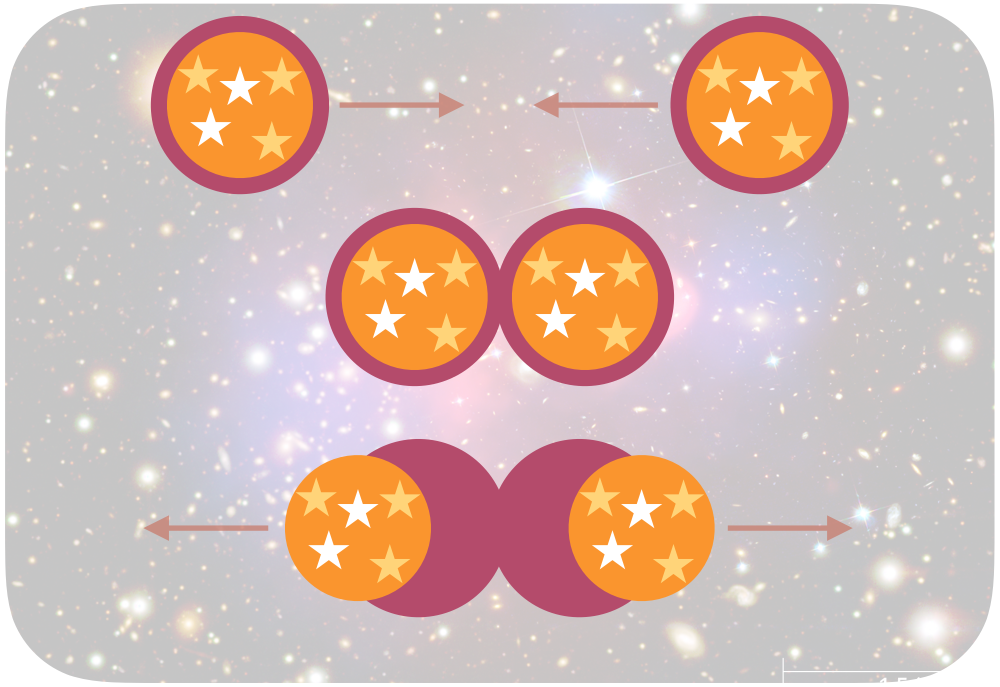
  - stars behave as collisionless particles (orange and white)
  - intracluster hot gas experiences ram pressure, distributed toward the system centre after collision (pink clumps)



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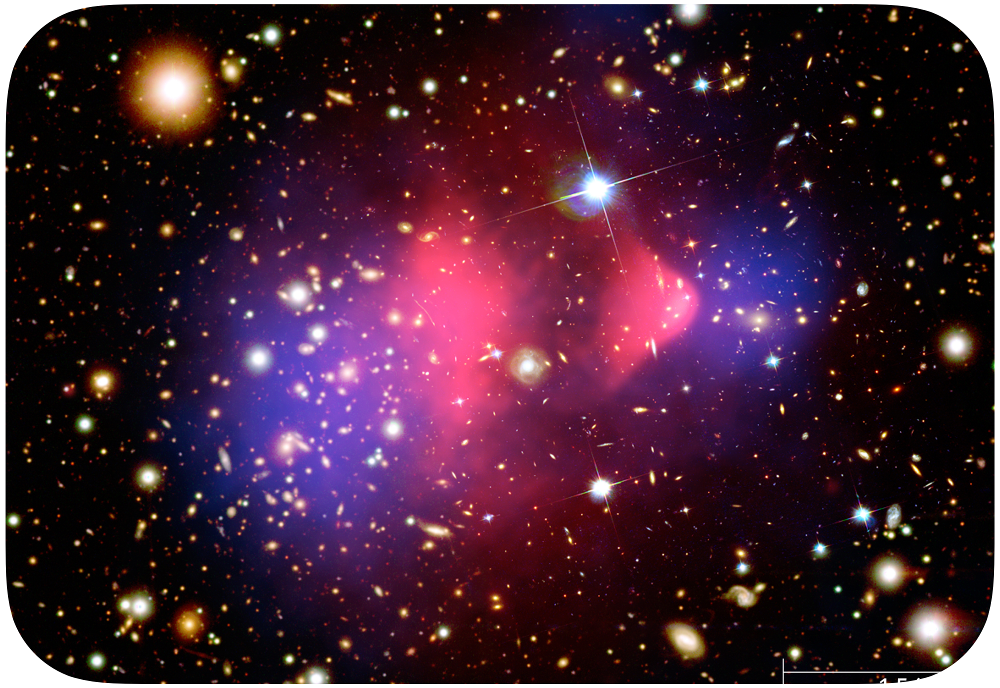

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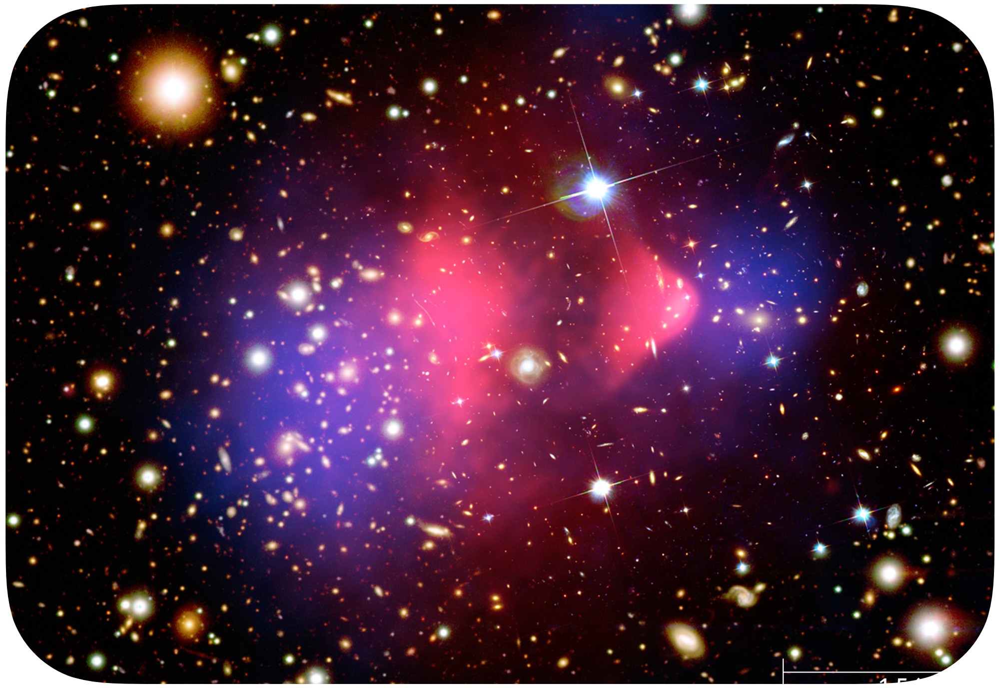
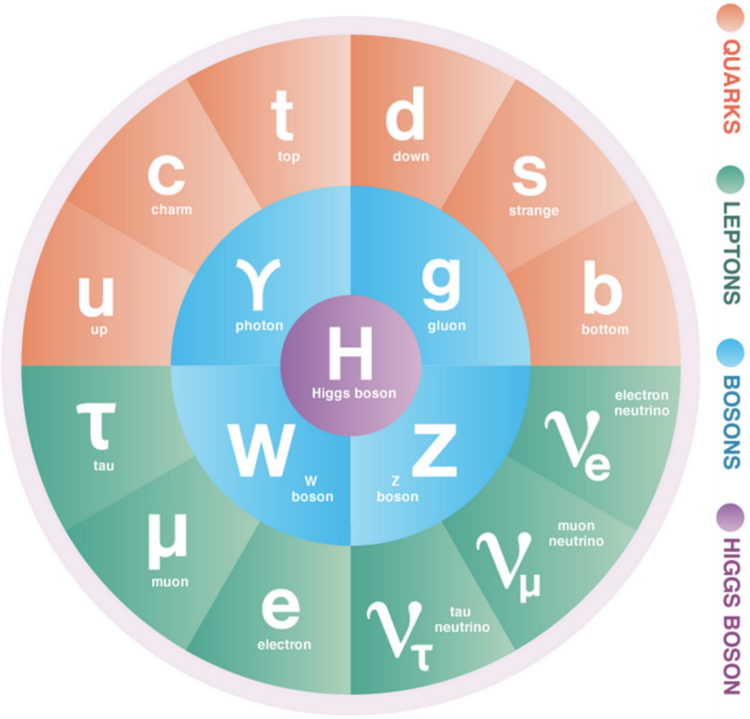


- If only visible matter in galaxies the highest mass concentration would coincide with hot gas distribution
- The observed separation points to presence of collisionless DM. This without assumptions on gravitational force law description

What do we know about DM?

- DM characteristics
  - *stable* - on cosmological scale, relic density
  - *electrically neutral* - does not significantly emit, reflect, or absorb light
  - *massive* - interacts gravitationally
  - *not made of baryons* (protons, neutrons) - 25% of our universe is made of DM from Cosmic Microwave

- A possible DM candidate in the Standard Model?



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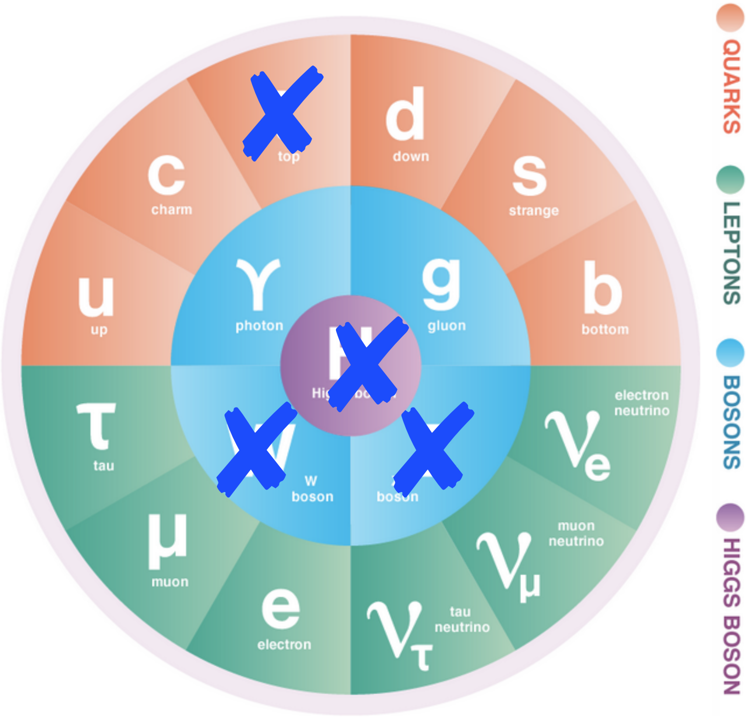

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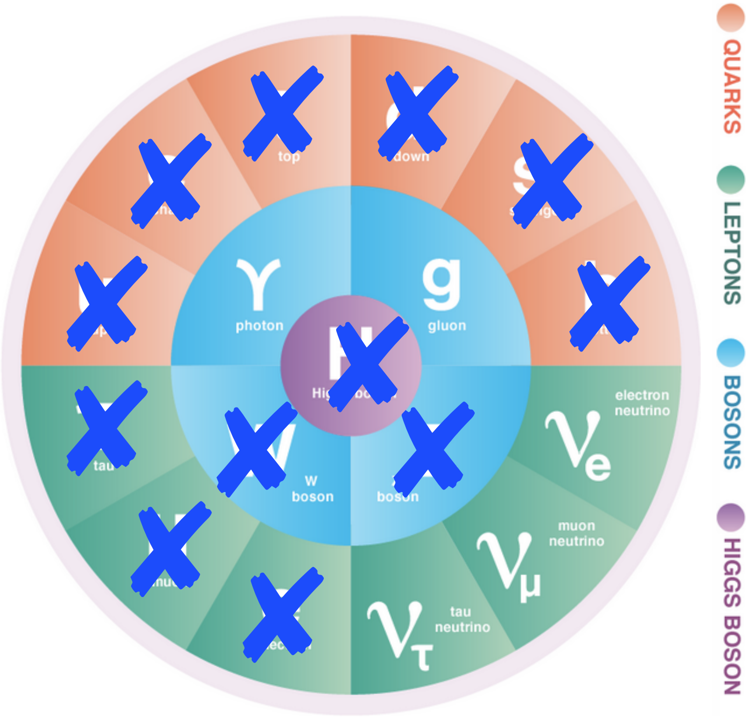

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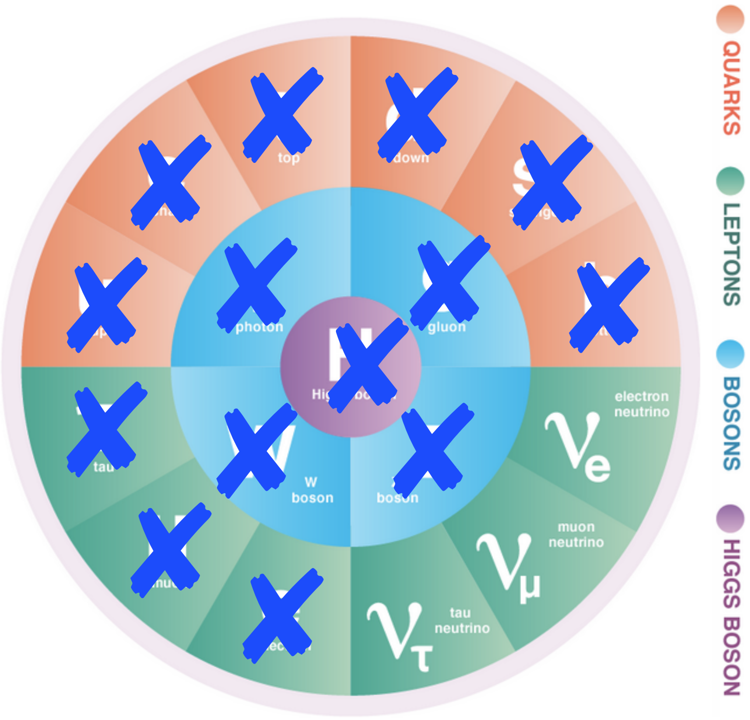
    - if DM relativistic then larger structure would have formed earlier in the evolution of the universe
    - from observations, *dark matter non-relativistic* at the time of galaxies formation



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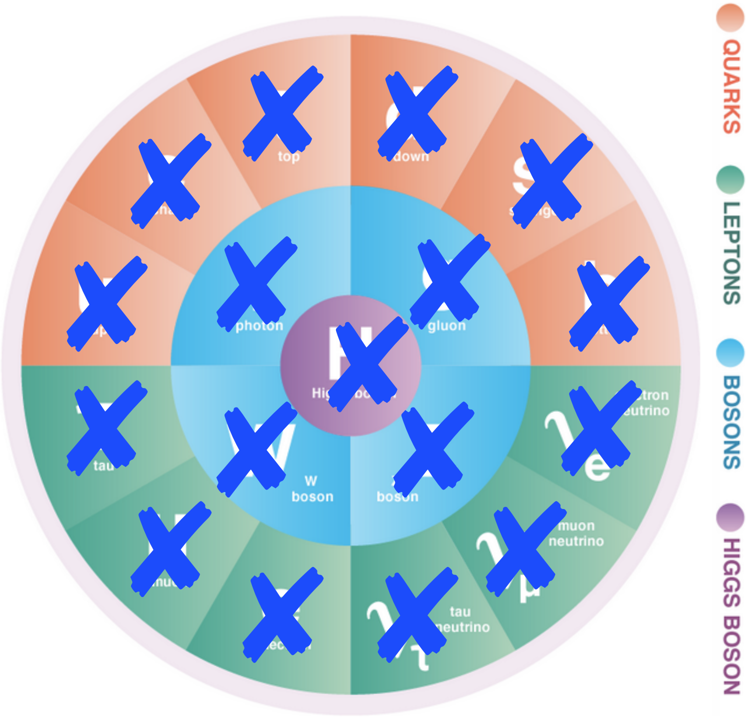
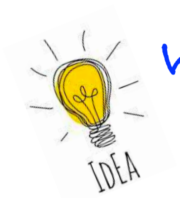


What's beyond the Standard Model for DM?

Recap

- Empirical evidence of DM from astrophysical observations at different scales
  - interacts gravitationally, long lived and neutral
  - no information about its nature



We saw what DM cannot be, but what can be DM?

- most studied class of theories: let's assume DM is a weakly interacting massive particle

- Assuming DM-SM interactions enables different searches:
  - indirect detection,
    search for stable final SM products (neutrinos, gamma rays, positrons, antiprotons and their antiparticles) from annihilation of DM particles
  - direct detection,
    search for nuclear recoils produced in the elastic scattering of DM particles on nuclei
  - colliders,
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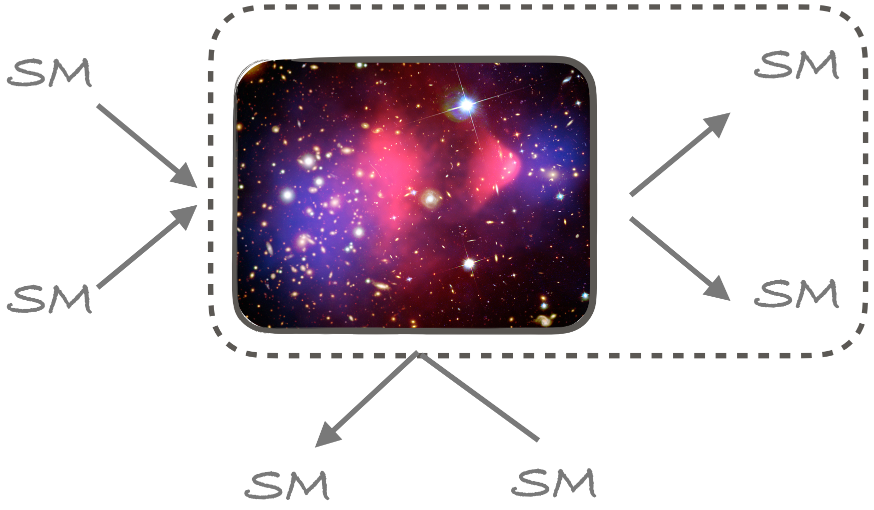

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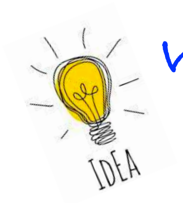

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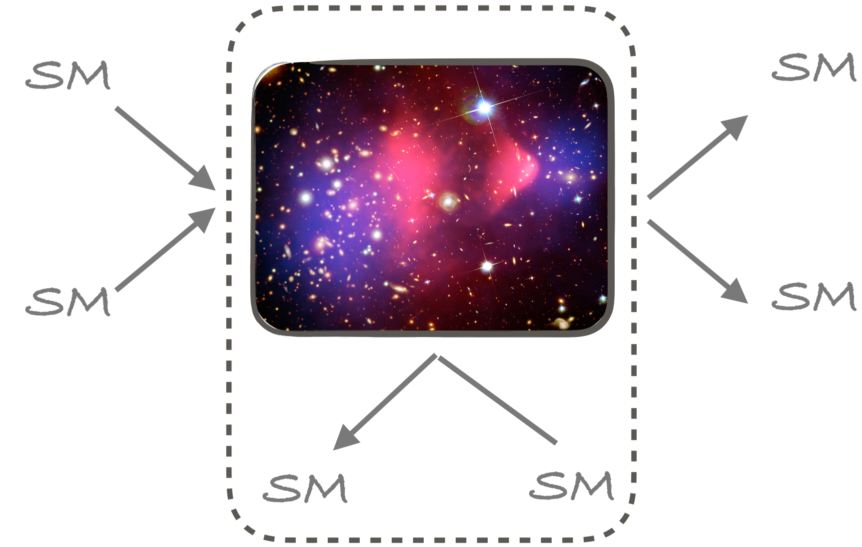

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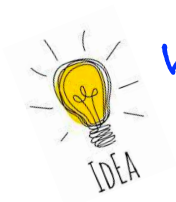

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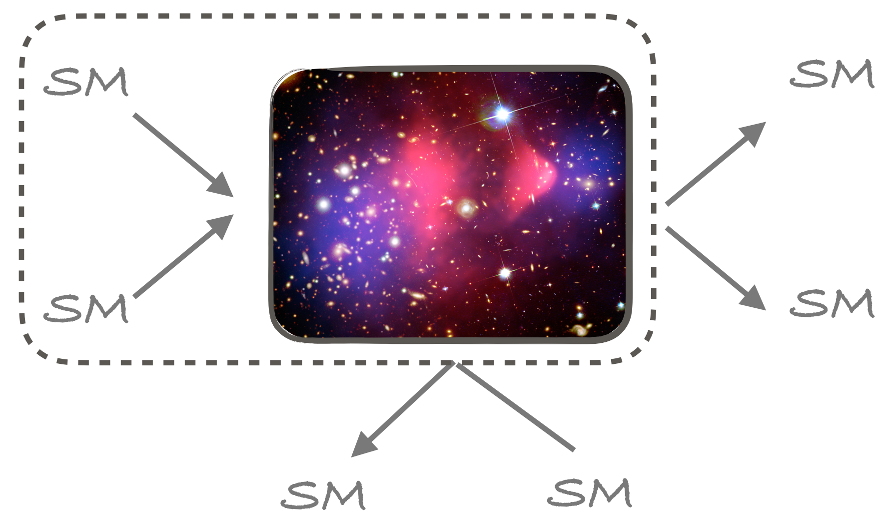

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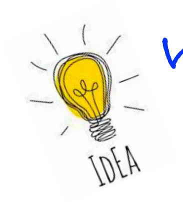

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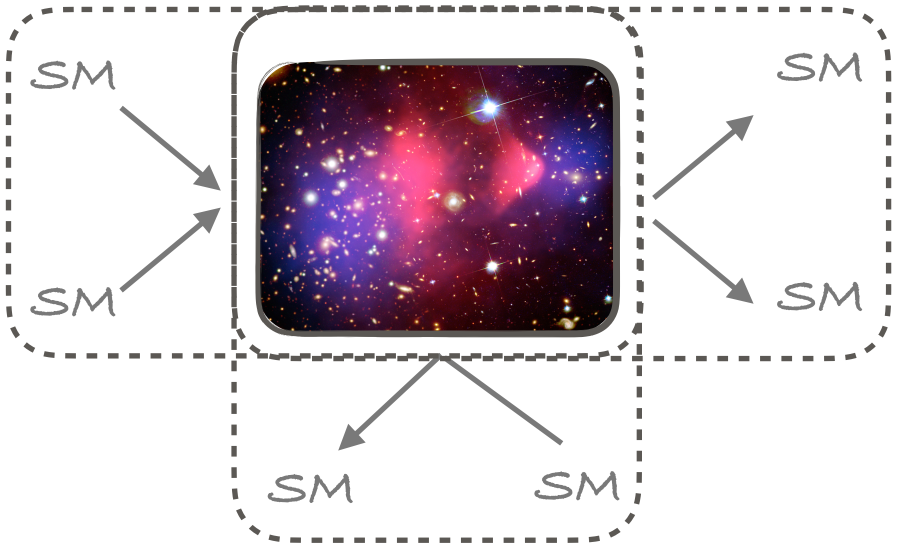
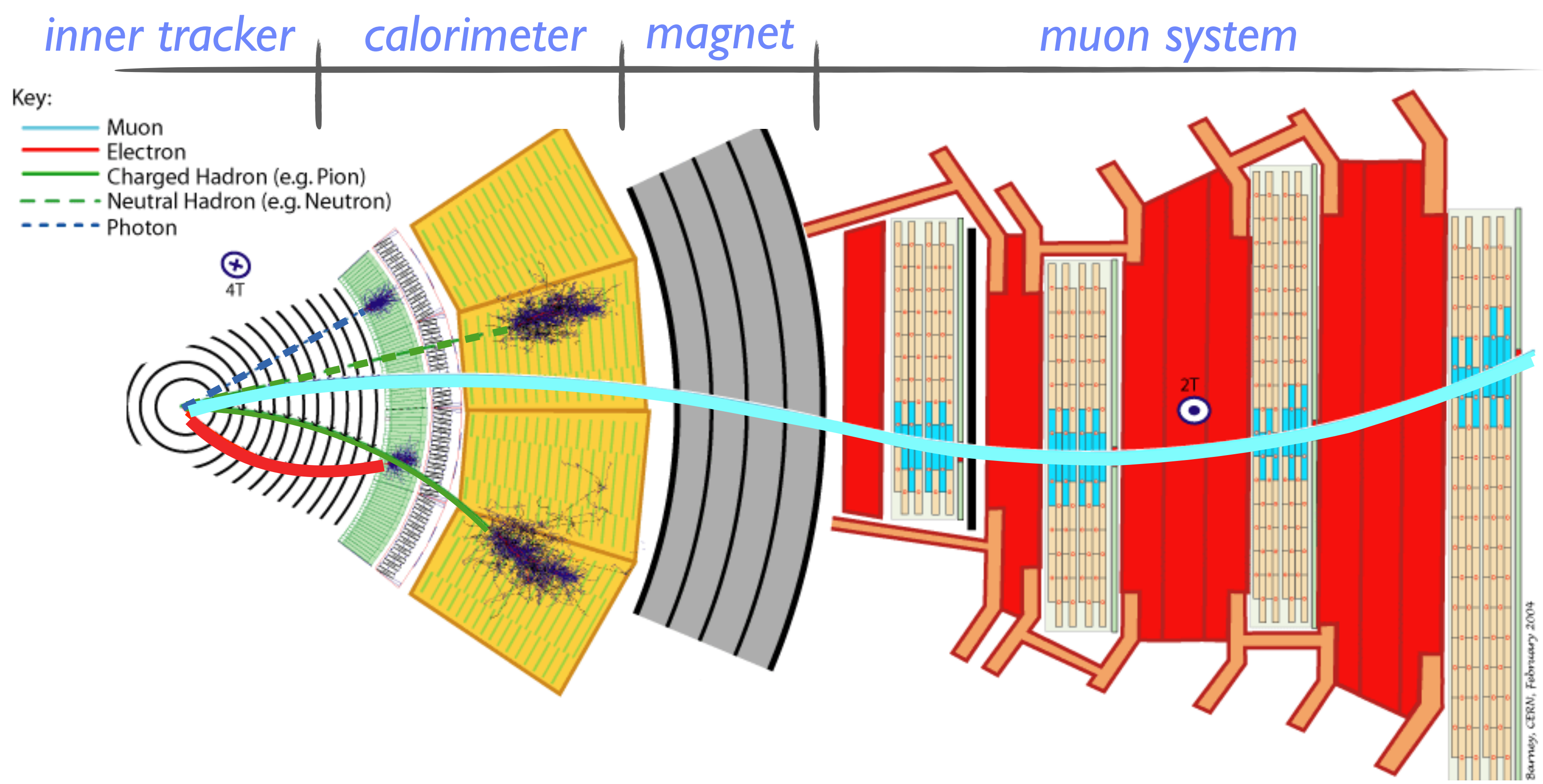


* Complementarity essential: eg. info about lifetime in case of DM discovery at colliders (~10^{-7}s), particle properties compared with cosmological constraints

How can we detect particles at colliders?



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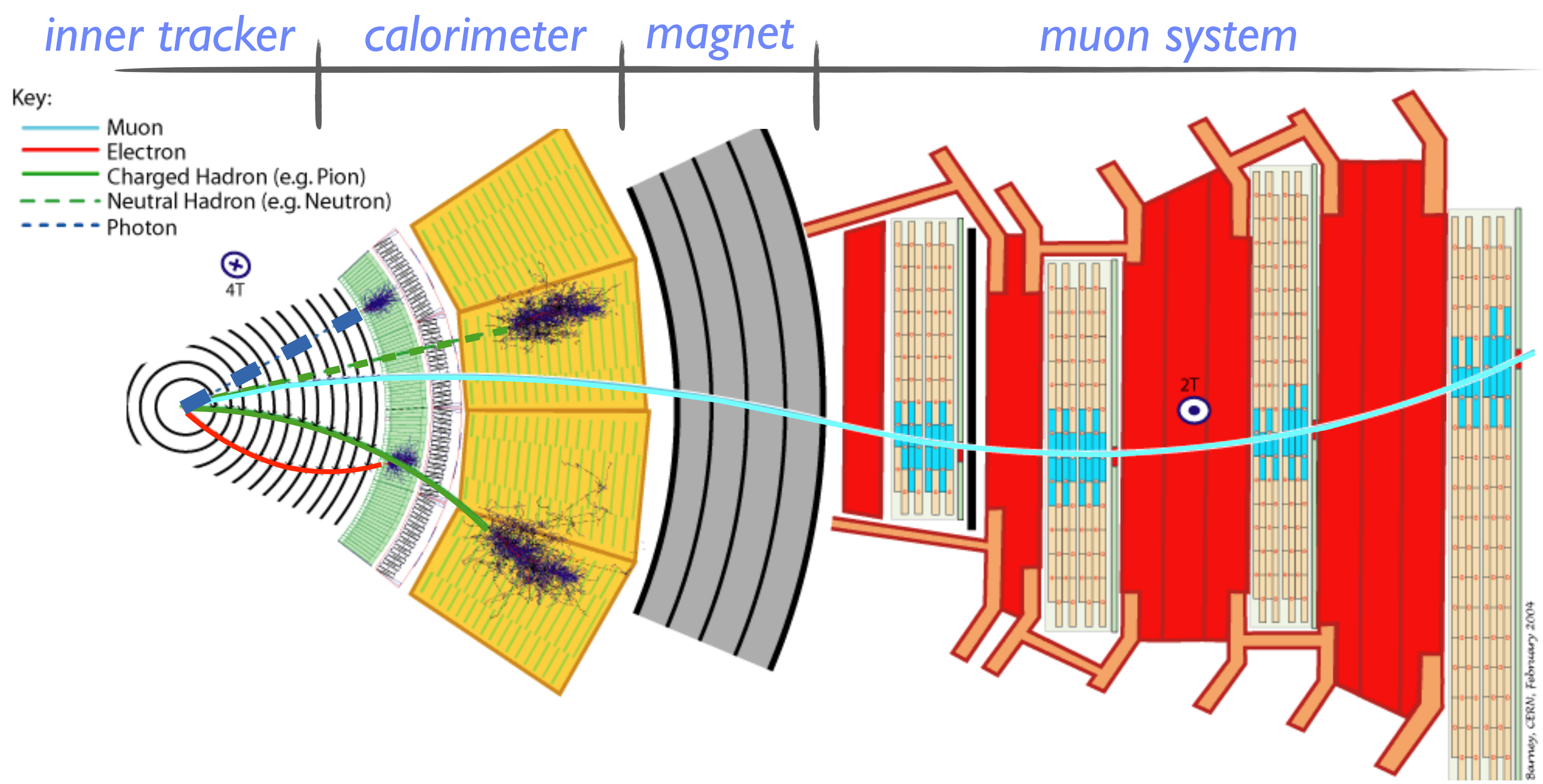

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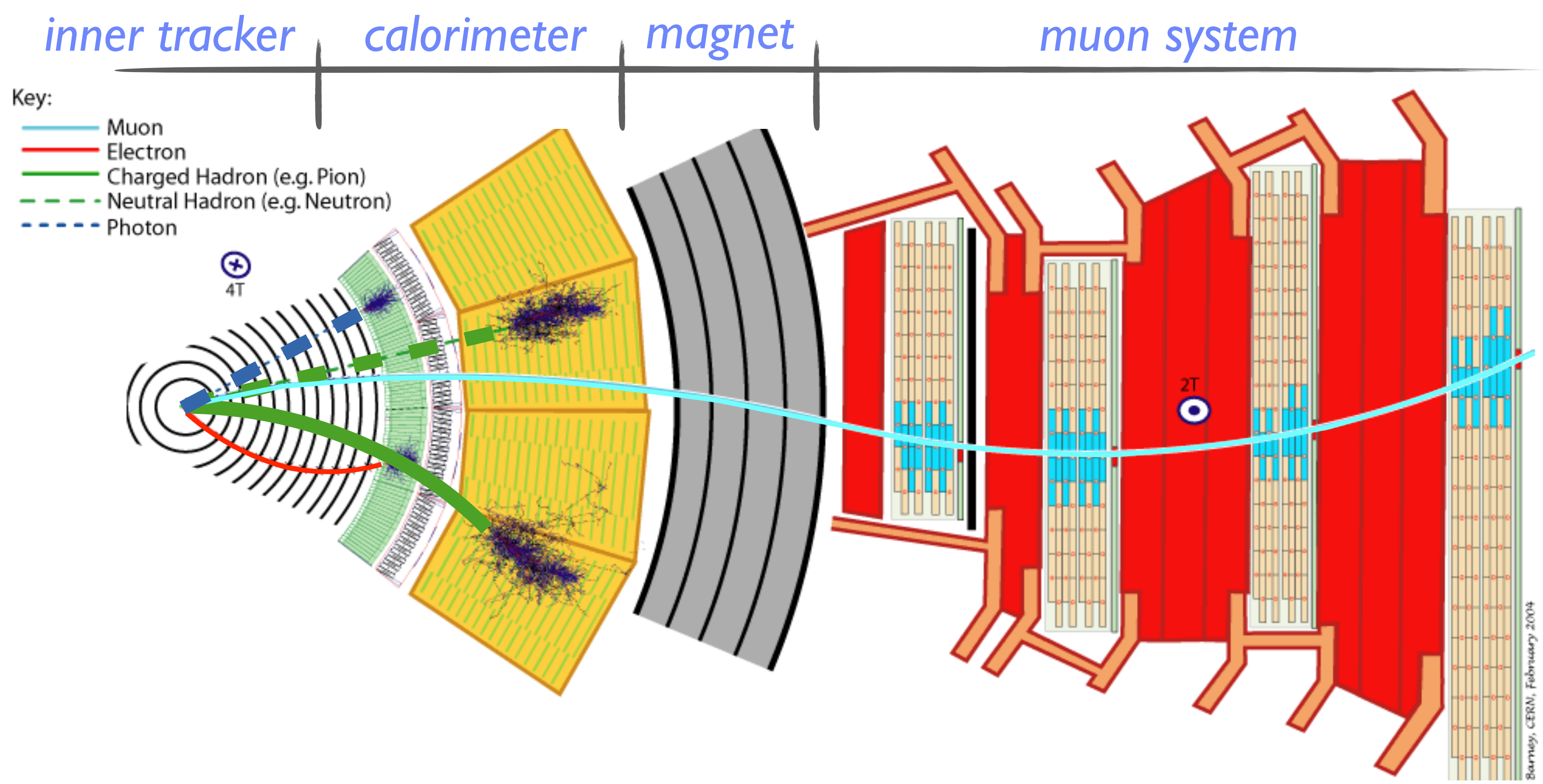

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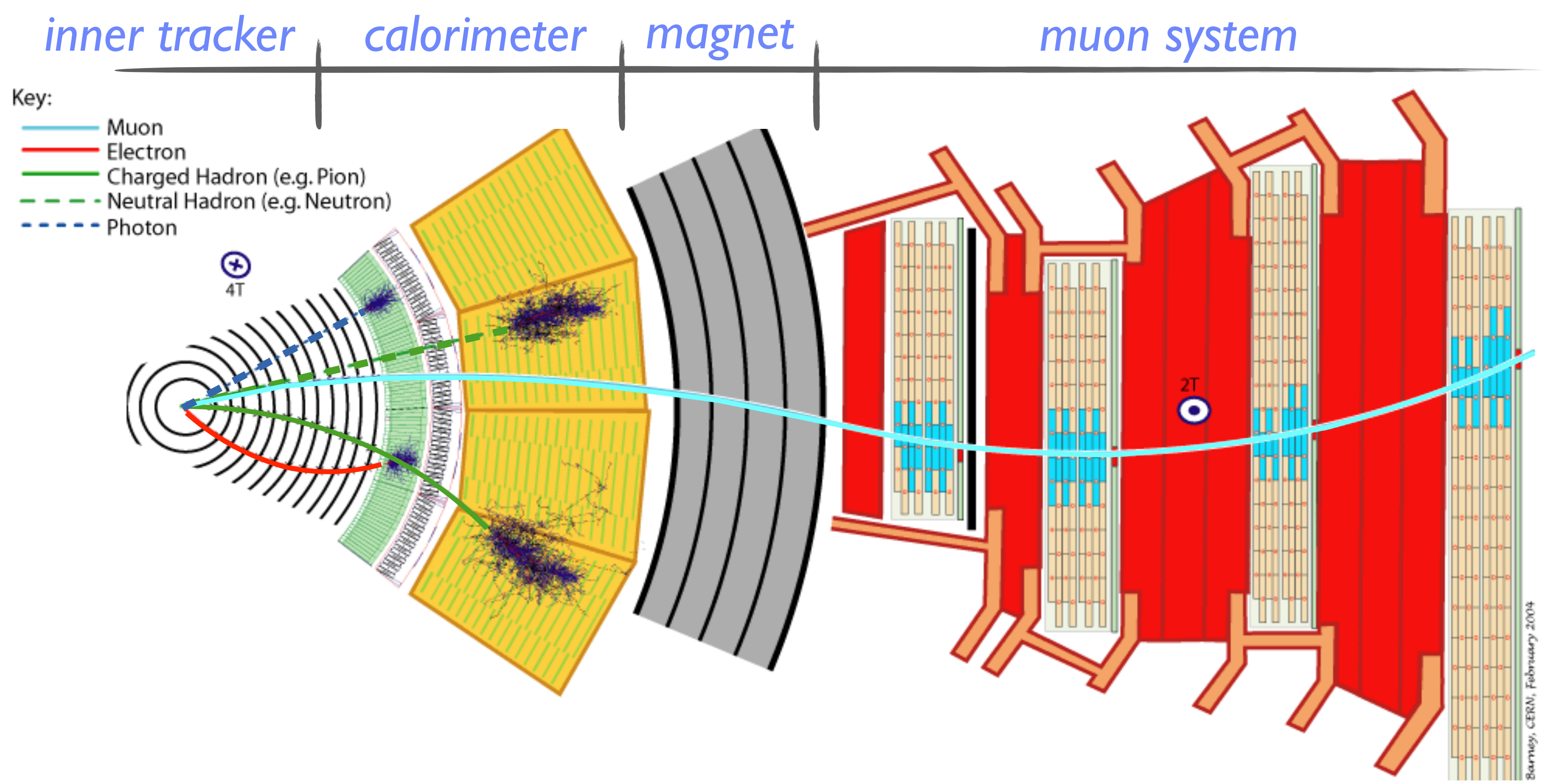

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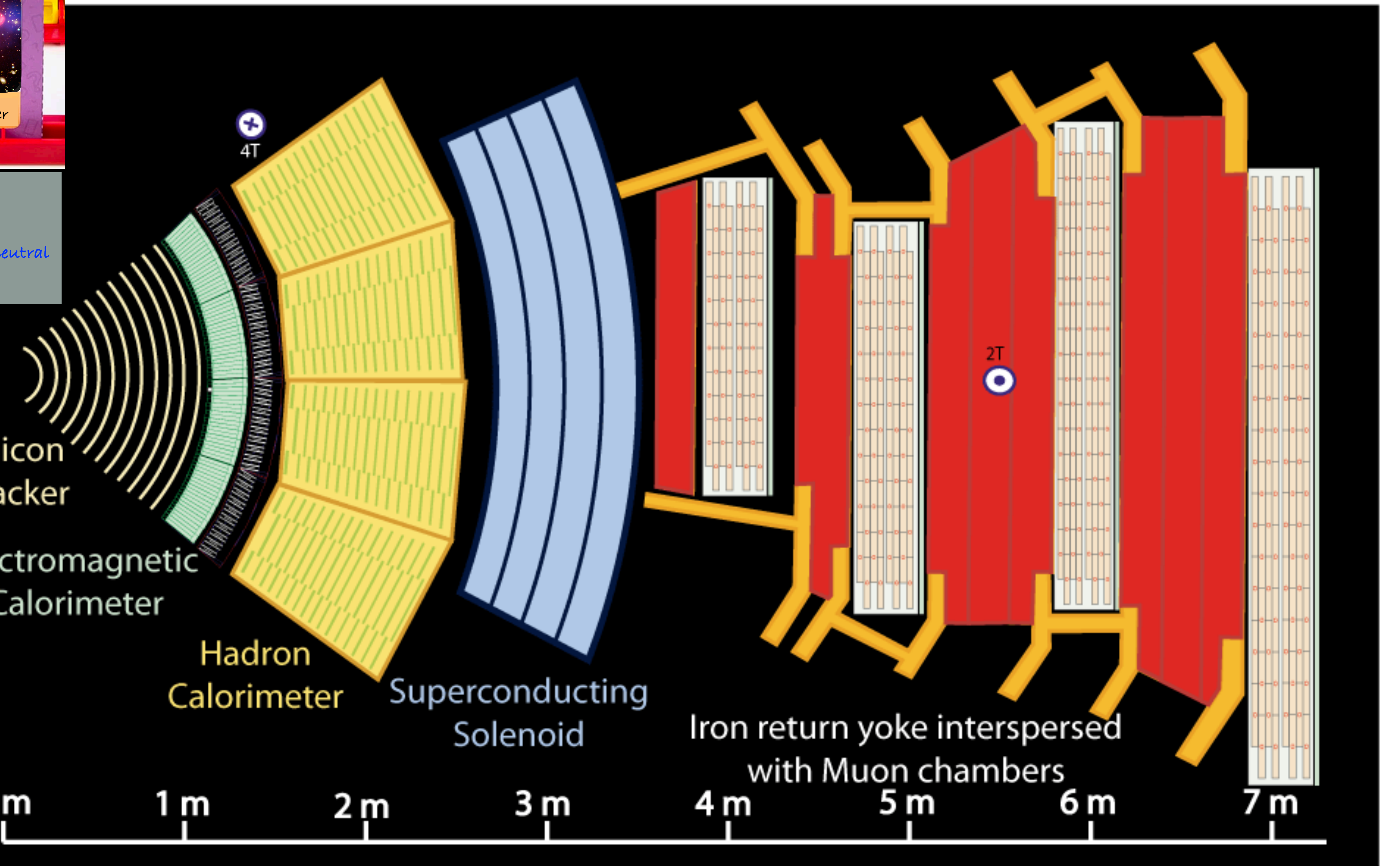
Properties
- stable
- electrically neutral
- massive



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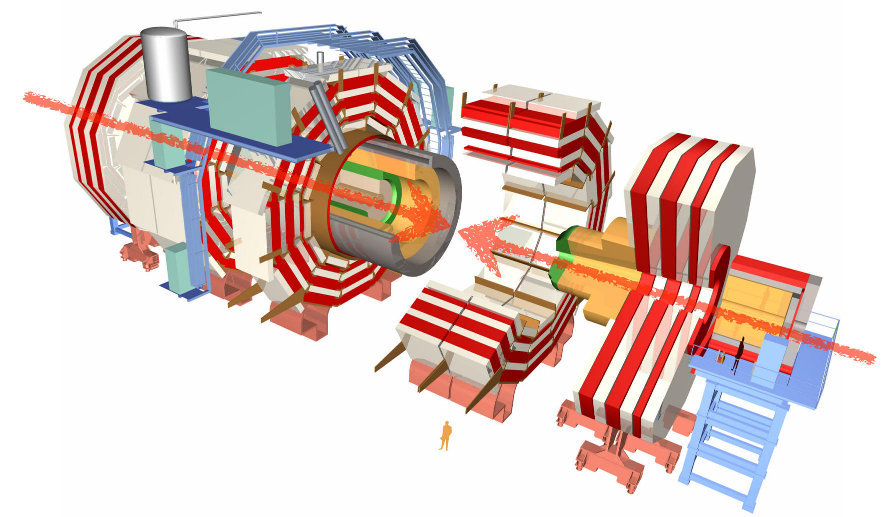
- DM could be produced at colliders (rare process)
  - no direct trace in the detector, but could create a p_T imbalance (***MET***)



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    - no information about longitudinal momentum of colliding partons
    - but total initial parton $p_T=0$
      - need to be conserved after the collision $\sum \vec{p}_T = 0$
      - if $\sum \vec{p}_T != 0$ some particles escaped the detector carrying $\vec{E}_T^{miss} = -\sum \vec{p}_T$
      - $|\vec{E}_T^{miss}|$ = missing transverse energy (MET)

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  - need visible particle to which DM particle recoils against
  - "mono-X searches": X includes jets, vector bosons, top, …

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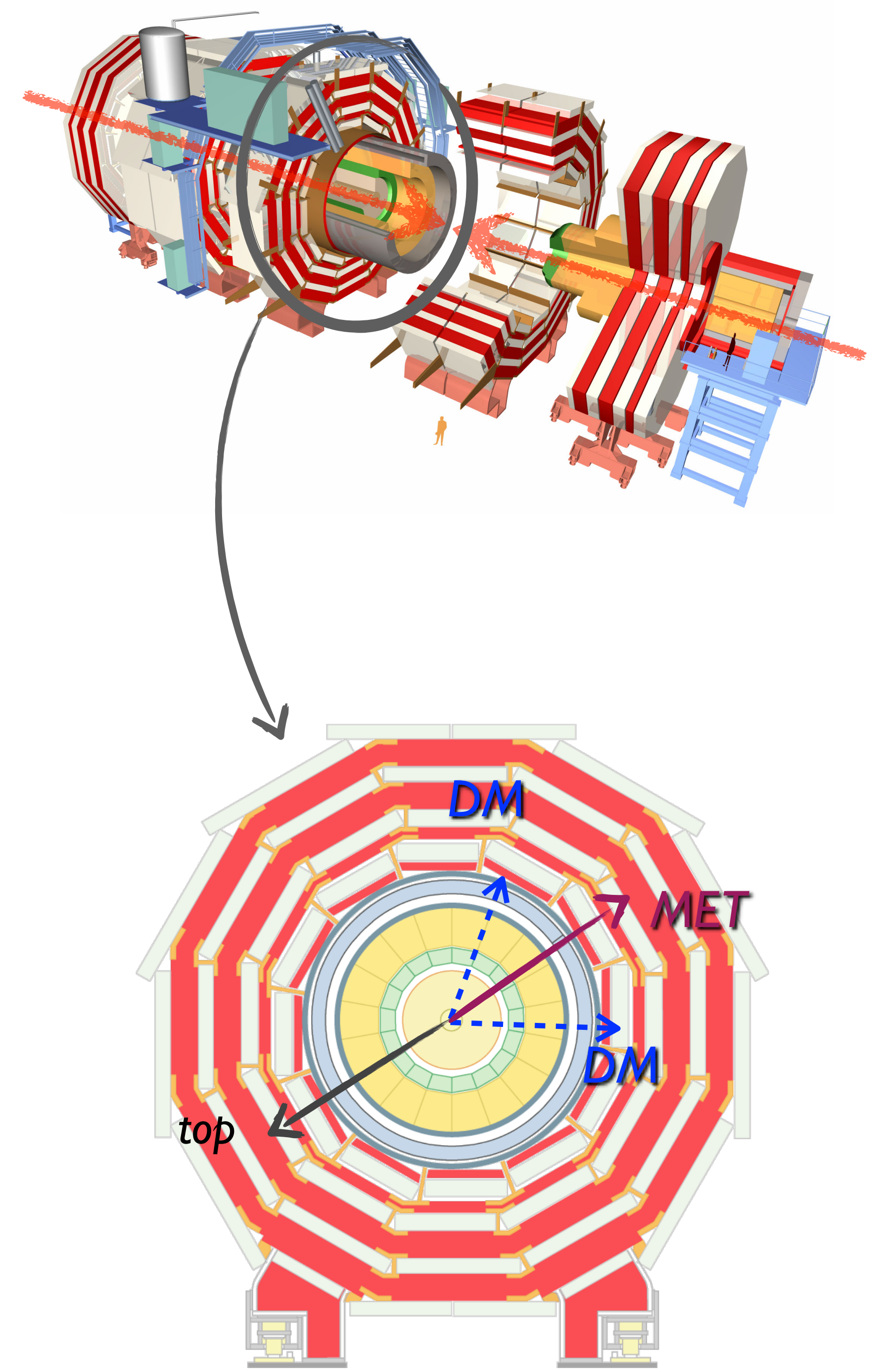

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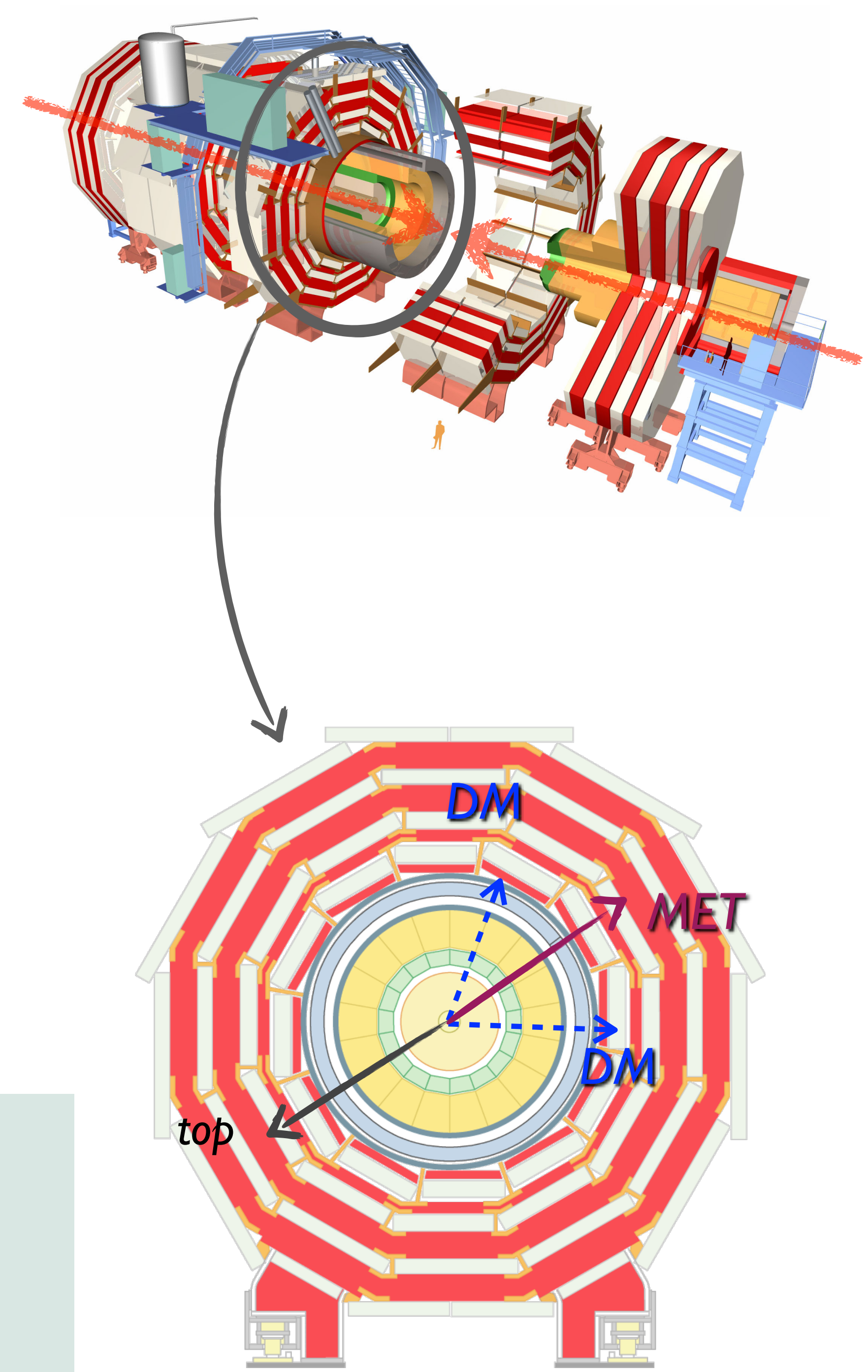

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Dark matter phenomenology: guess "who"

- *We do not have information about the DM nature, how to discover DM?*
  - we can remain very general and make very *little assumptions*
    - eg. for this board: "is it a 2D shape?"
  - we can make be make more assumptions and tests *more specific models*
    - eg. for this board: "is it a 2D shape, yellow color and with only 90° angles?"

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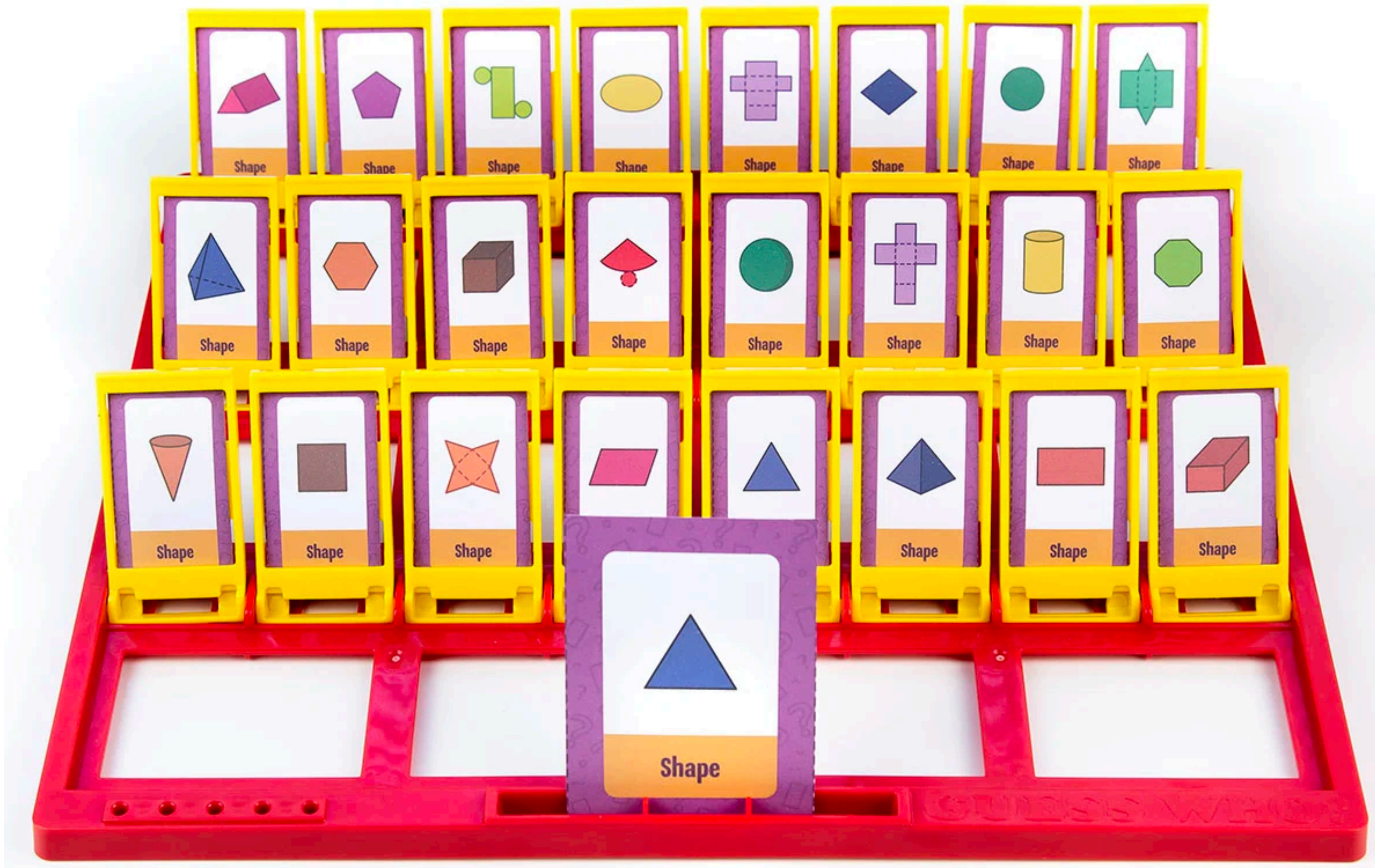

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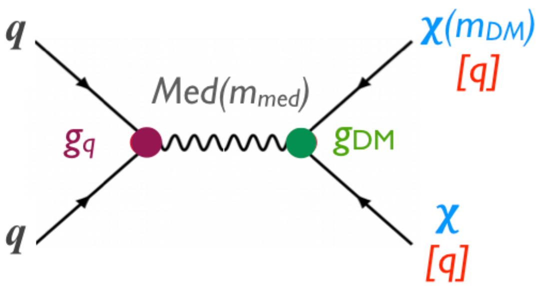
  - we can remain very general and make very *little assumptions*
    - eg. for this board: "is it a 2D shape?"
  - we can make be make more assumptions and tests *more specific models*
    - eg. for this board: "is it a 2D shape, yellow color and with only 90° angles?"

Dark matter? *phenomenology at colliders*

simpler
(less parameters)

Simplified models: SM/BSM mediator



Beyond SM mediator

- one new mediator (spin-1 or spin-0), one DM particle
- set of parameters (m_{DM}, m_{med}, g_q, g_{DM})

spin-1	*vector* $g_q \sum_q V_\mu \bar{q}\gamma^\mu q$	*axial-vector* $g_q \sum_q A_\mu \bar{q}\gamma^\mu\gamma^5 q$
spin-0	*scalar* $g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$	*pseudoscalar* $g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f}\gamma^5 f$

choose X to increase xsec or bkg rejection

choose X to exploit coupling ∝ to quark mass (or increase xsec)

Higgs portal DM

- the SM-DM mediator could be the Higgs boson (spin-0)
- Higgs decay branching fractions not yet sufficiently constrained

SUSY models

- see more on N. Strobbe's talk

more complex
(more parameters)

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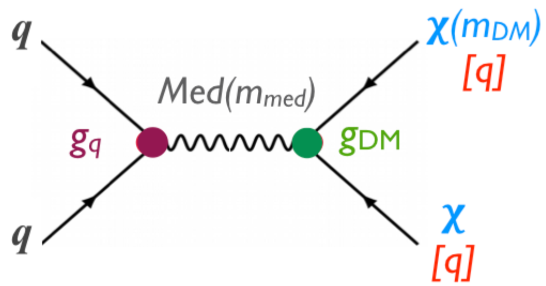

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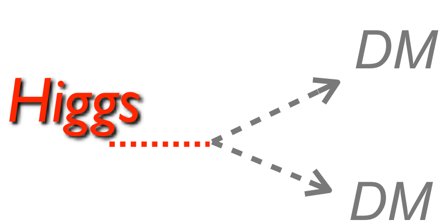

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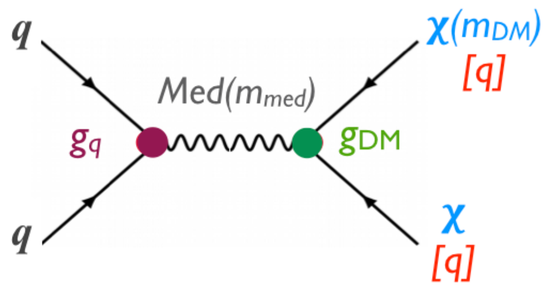

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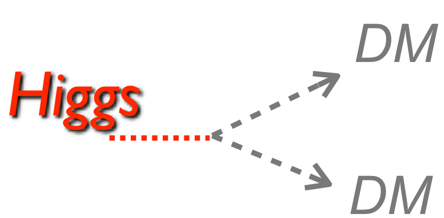
choose X to increase xsec or bkg rejection (spin-1)

choose X to exploit coupling ∝ to quark mass (or increase xsec) (spin-0)



Higgs portal DM

- the SM-DM mediator could be the Higgs boson (spin-0)
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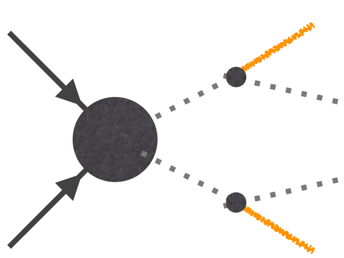
Complete models: eg. MSSM



SUSY models

more complex
(more parameters)

How do we search for DM at colliders?

Recap

- DM could be produced at colliders, rare process
- long lived and neutral, will appear as MET

Signature: which DM process we want to study?

- phenomenology, eg. simplified model
- X visible particles, which decays?
- allow to identify main characteristics of process of interest (signal)

Reminder:

vector: $g_q \sum_q V_\mu \bar{q}\gamma^\mu q$ | axial-vector: $g_q \sum_q A_\mu \bar{q}\gamma^\mu \gamma^5 q$

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* choose X to exploit coupling ∝ to quark mass (or increase xsec)

Pre-selection

- in this case, large values of MET (from DM), 1 jet with high p_T (for energy conservation), no jets from b-quarks

How do we search for DM at colliders?

Recap

- DM could be produced at colliders, *rare process*
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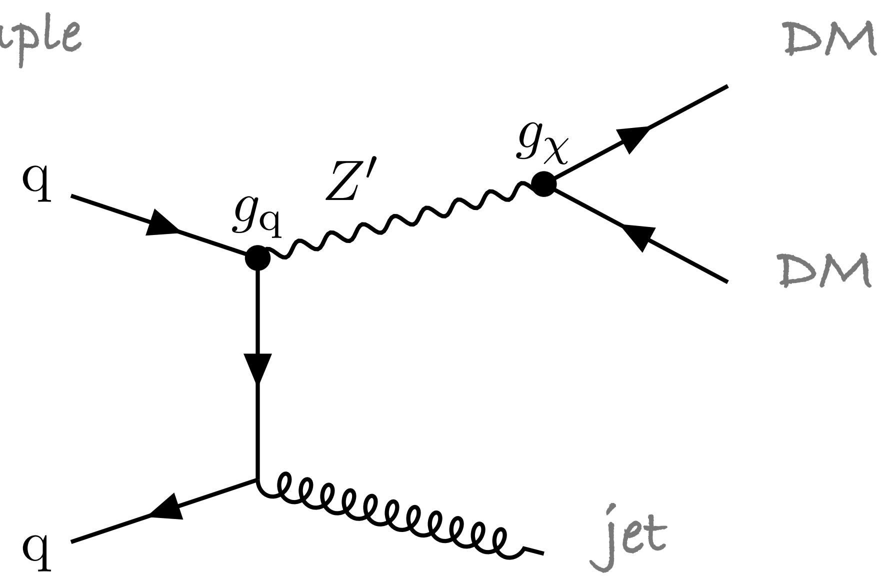
example



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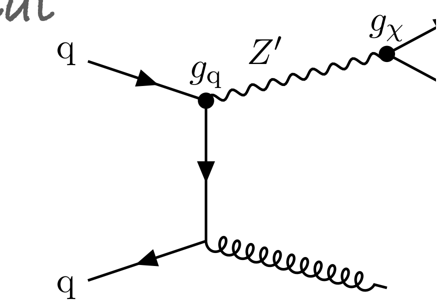
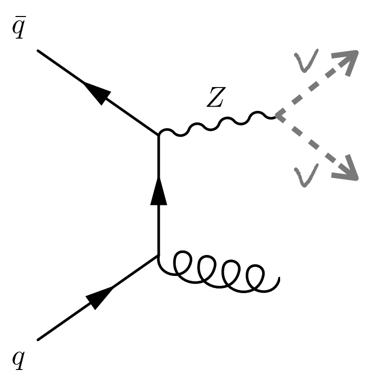


bkg



1- Selection

- many SM processes can have similar characteristics (or fake them) as the signal - SM background
- these SM processes are much more probable than signal
- require additional criteria to enhance the signal vs background - signal region (SR)

How do we search for DM at colliders?

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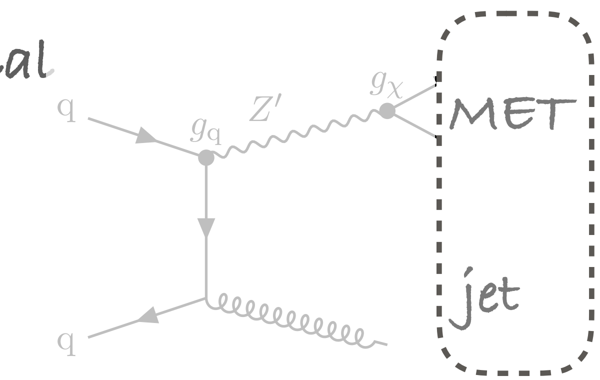
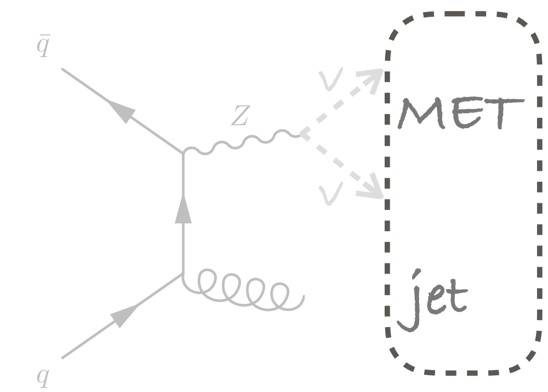
signal



bkg



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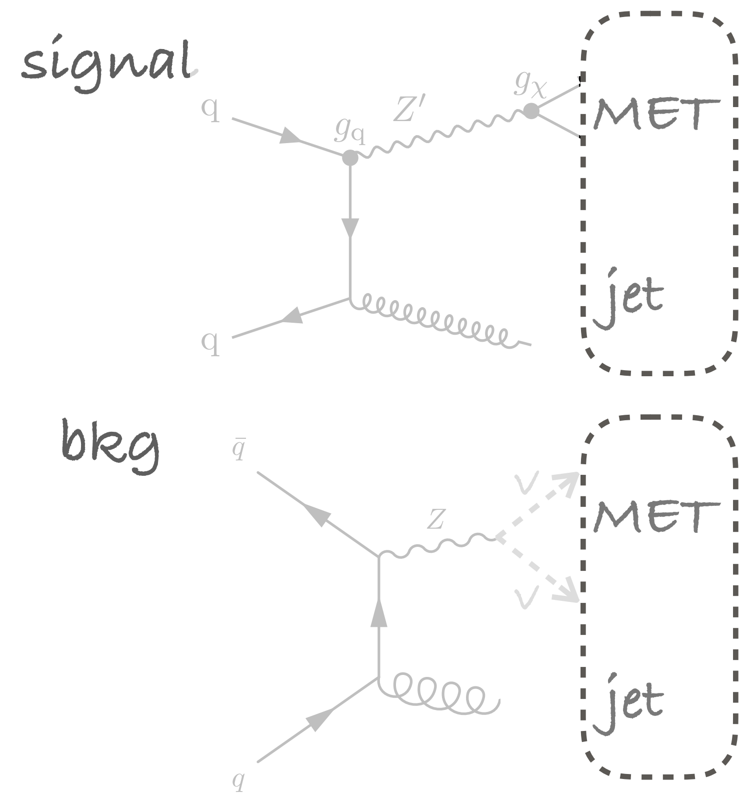

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SR →

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signal

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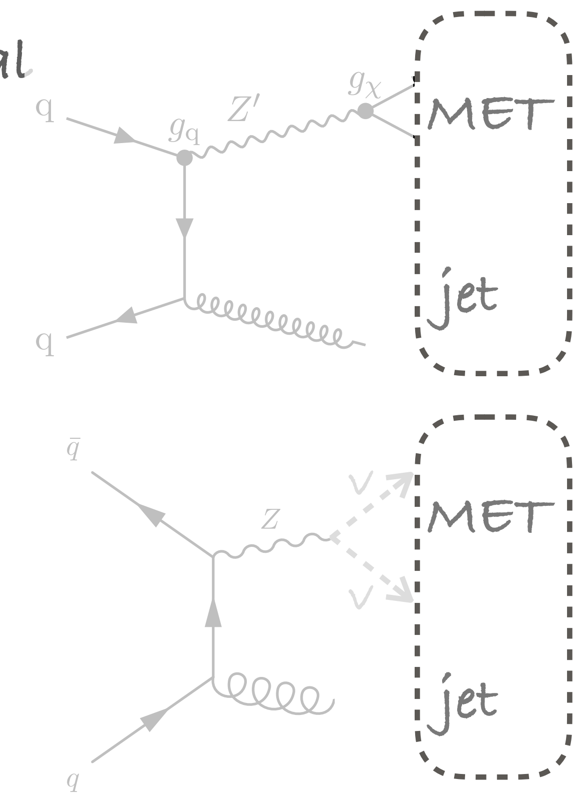

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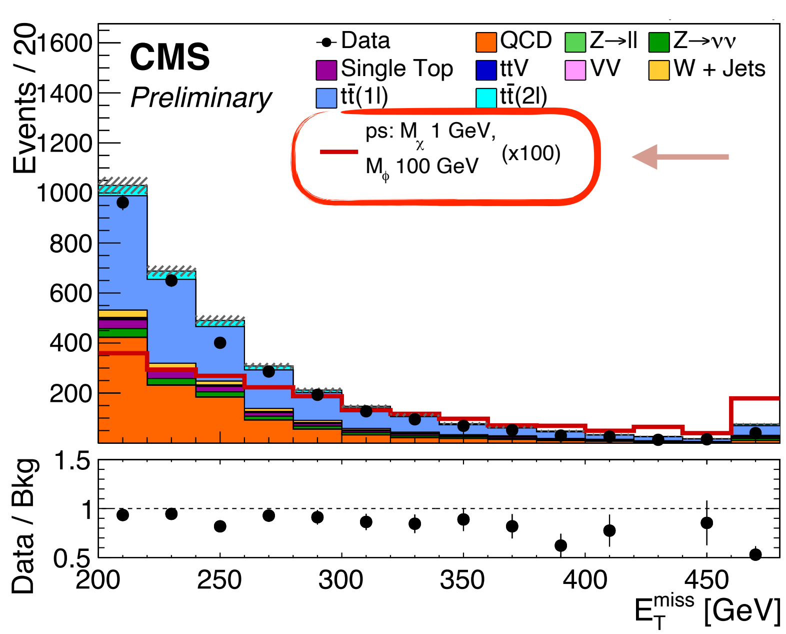
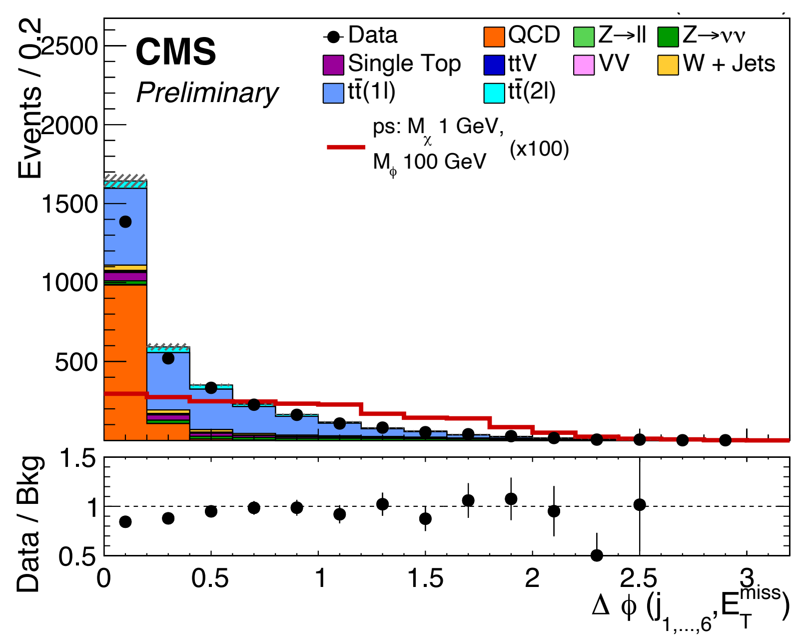
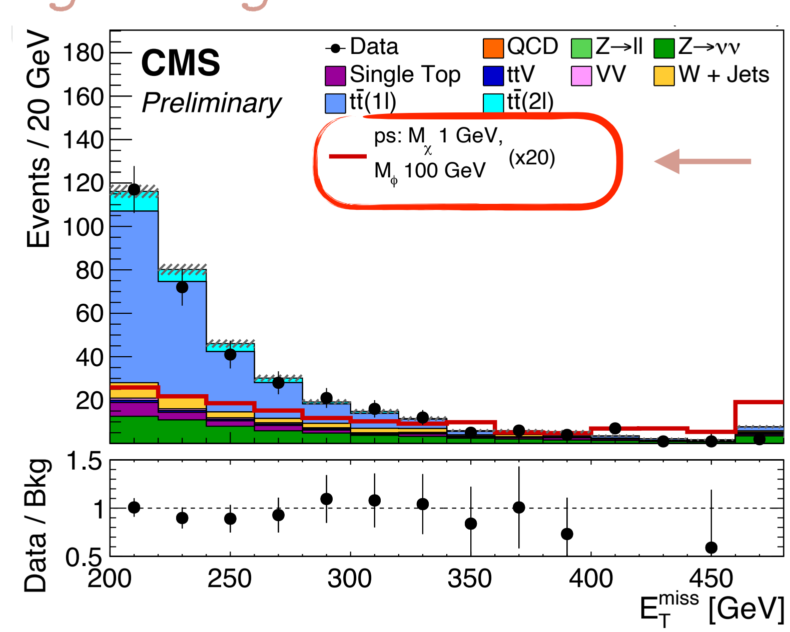
pre-selection



additional criteria



signal region



How do we search for DM at colliders?

Recap

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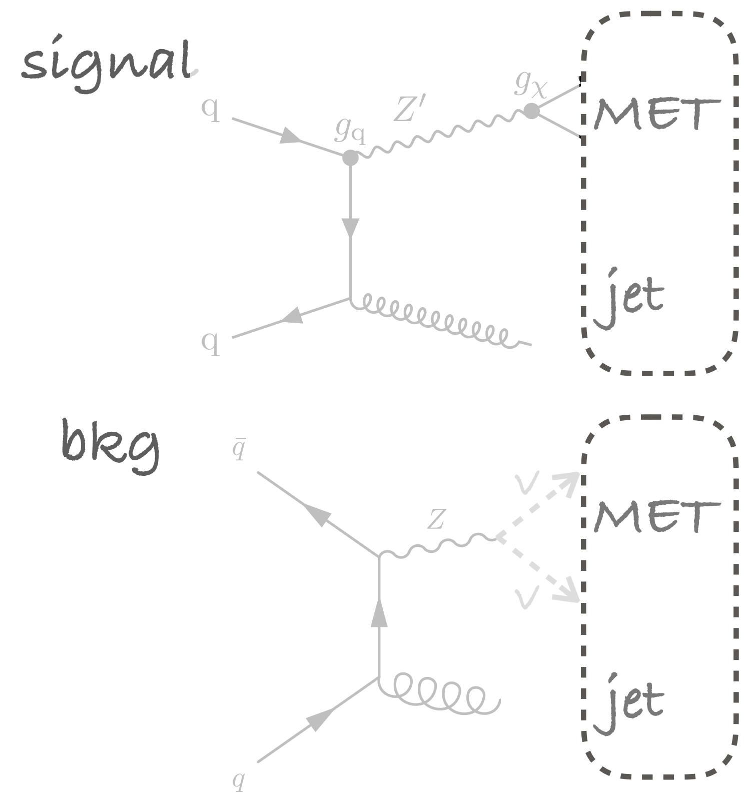

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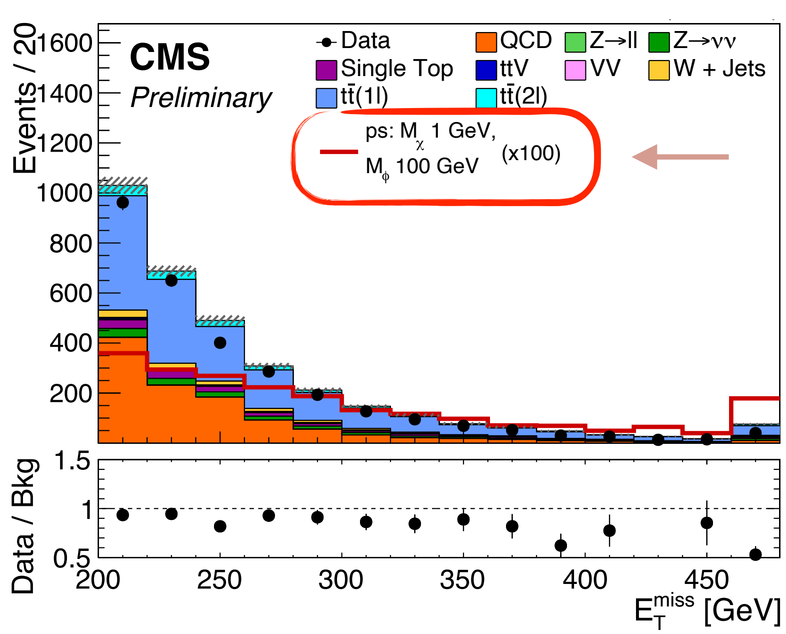
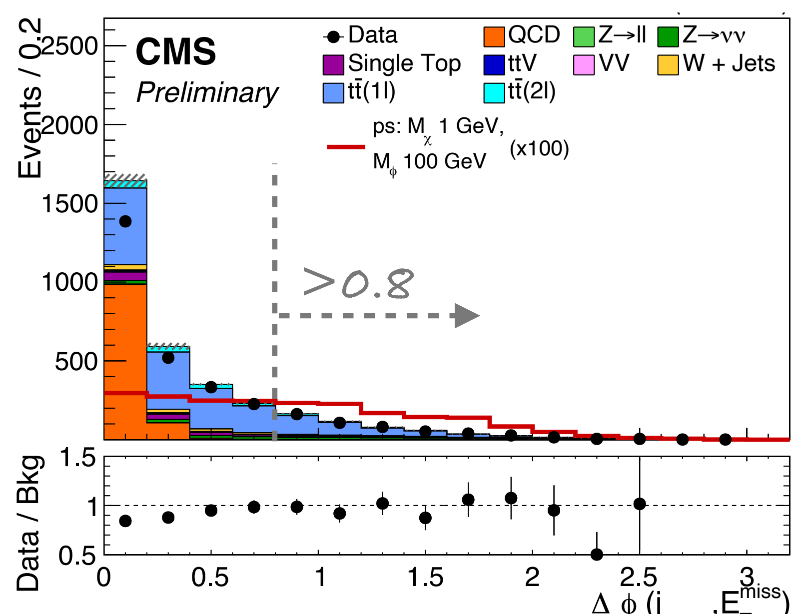


additional criteria



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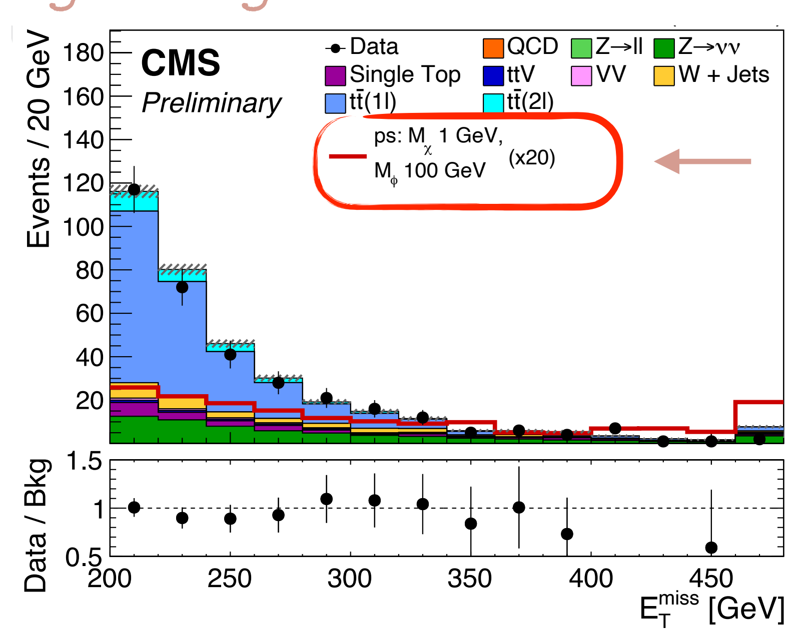


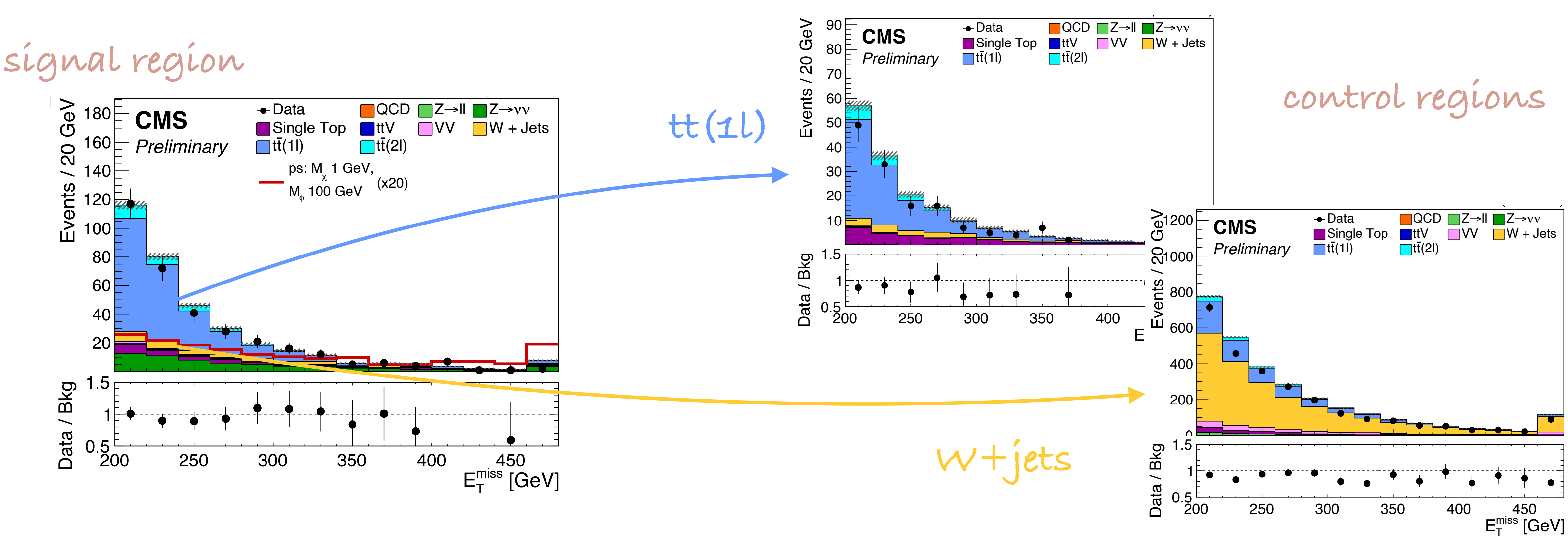
How do we search for DM at colliders?

Recap

- DM could be produced at colliders, *rare process*
- long lived and neutral, *will appear as MET*

2- Background

- DM production is a *rare process*. We need a *precise modeling and evaluation of SM bkg* in SR essential to “see” the signal
- Achieved through use of multiple *control regions* (CRs)
- *CR definition*: similar to the SR, good purity in bkg we want to check, no signal



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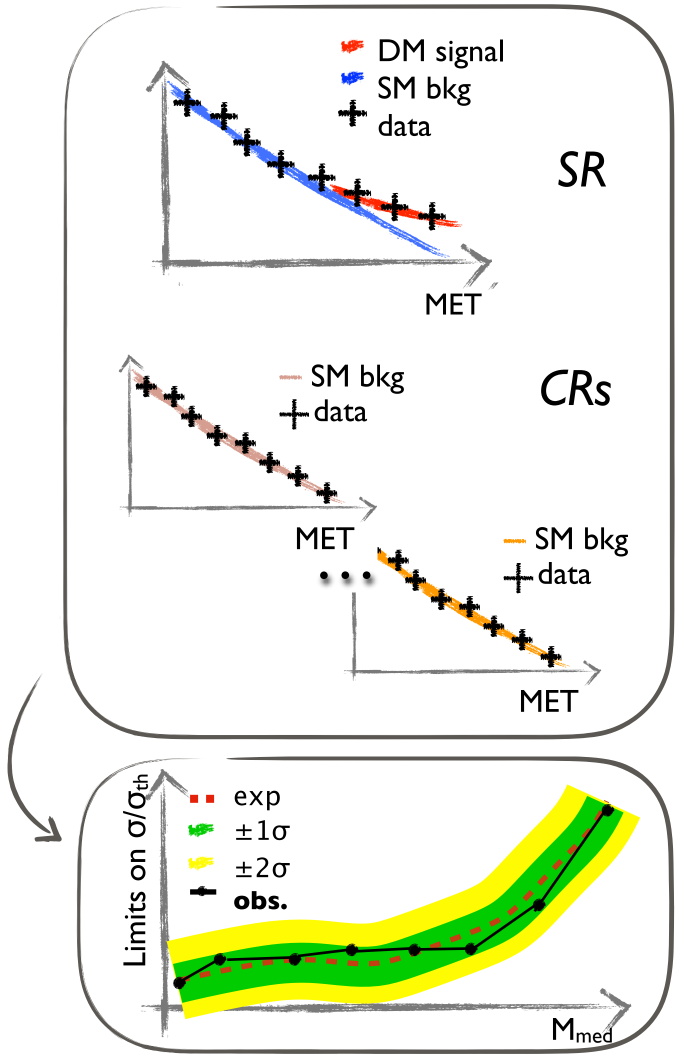


▶ **3- Results**

- DM appears as excess of events in MET tail in SR wrt SM background
  - no very striking signature, eg. mass peak, m_T kinematic endpoint
- excess of events in data. Did we find DM?
- no excess, interpret result in terms of model parameters

Experimental challenges

- accurate *E* calibration/resolution of visible objects *("fake" MET from mis-measured jets)*
- precise particle reconstruction and identification
- mitigate effects from additional *pp* collisions (pile-up)
- MET thresholds affected by trigger (very high collision rates)

Simplified models

Reminder:

vector	axial-vector
$g_q \sum_q V_\mu \bar{q}\gamma^\mu q$	$g_q \sum_q A_\mu \bar{q}\gamma^\mu \gamma^5 q$

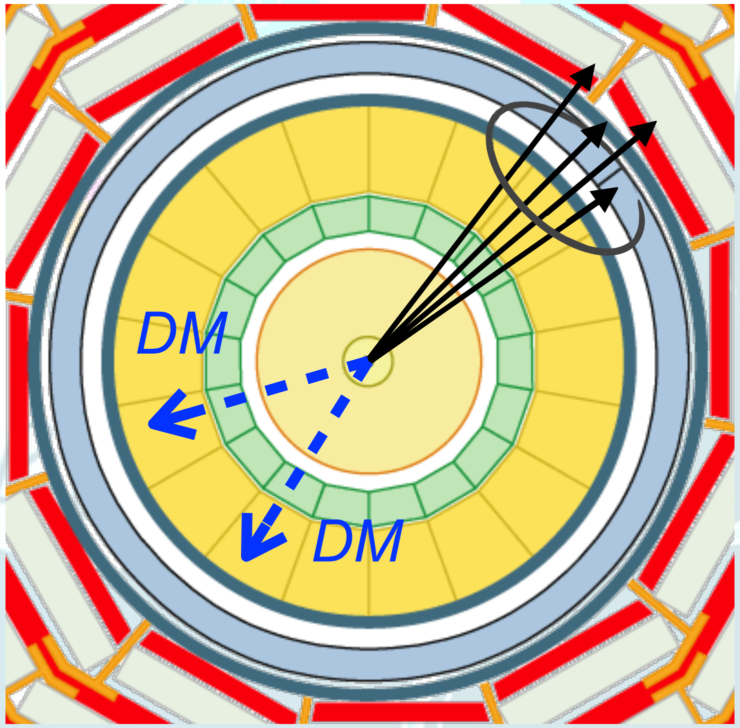
* choose X to increase xsec or bkg rejection

scalar	pseudoscalar
$g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$	$g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f}\gamma^5 f$

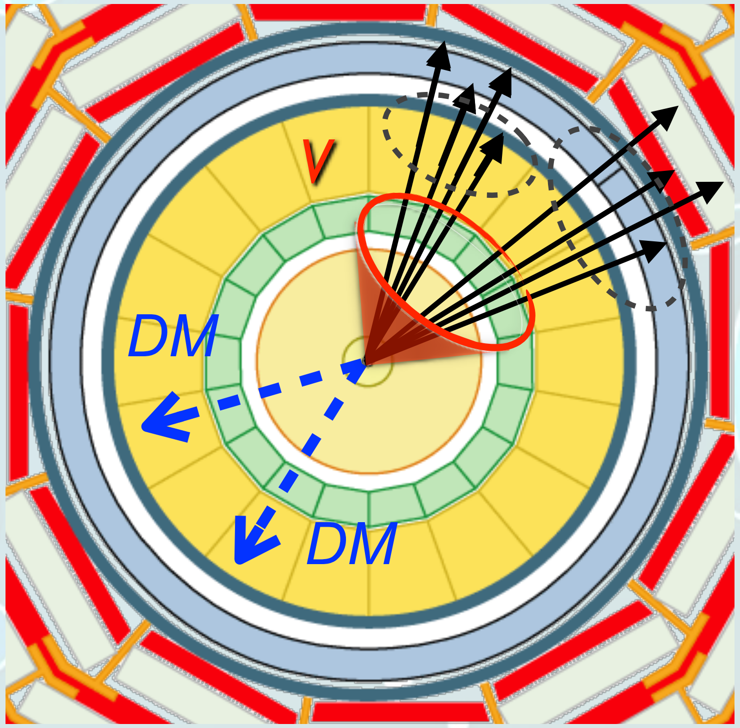
* choose X to exploit coupling ∝ to quark mass (or increase xsec)

Signature: large MET and ≥1 high-p_T jet/vector boson

mono-jet



mono-V(=W,Z)



* CMS: EXO-20-004 (2016-2018)

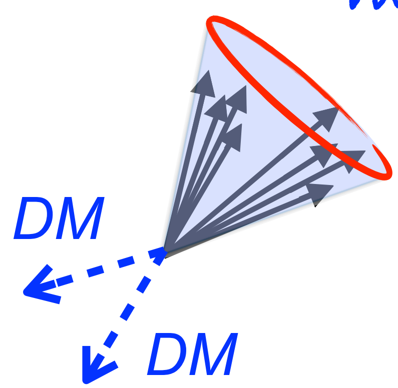
selected results

DM+jet/V search

CMS: EXO-20-004

- **1 - Selection:** events categorized based on jet nature

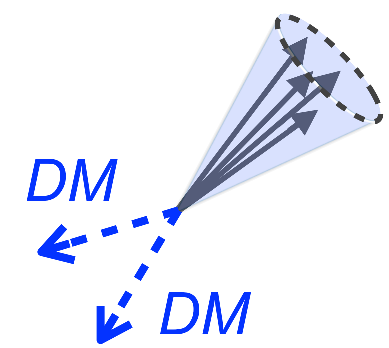
mono-V



J [large-cone jet, eg. R=0.8]

- MET > 250 GeV
- ≥ 1 jets, $p_T(j_1)$ > 250 GeV
- *machine learning technique* to identify V hadronic decays
  - categories based on MVA score
- *jet mass* consistent with V

mono-jet



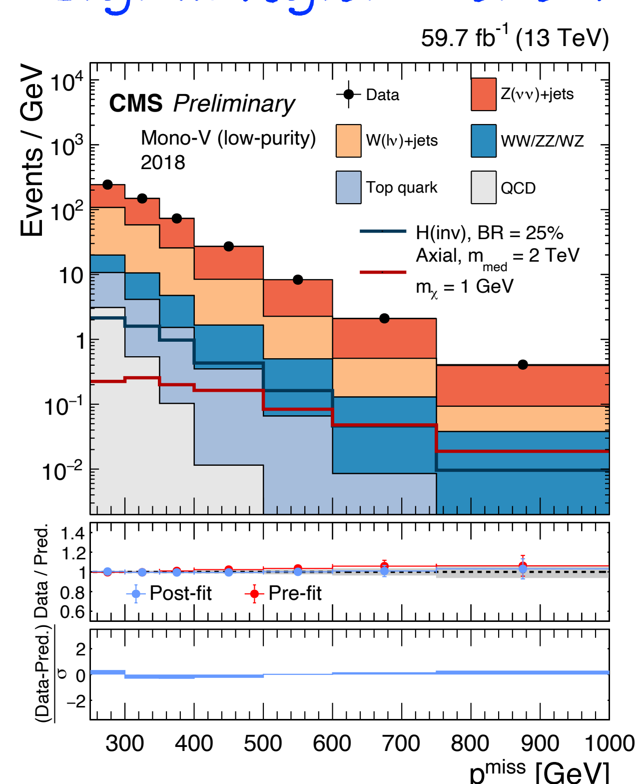
j [small-cone jet, eg. R=0.4]

- not selected as mono-V
- ≥ 1 jets, $p_T(j)$ > 100 GeV
- b-tagged jets veto

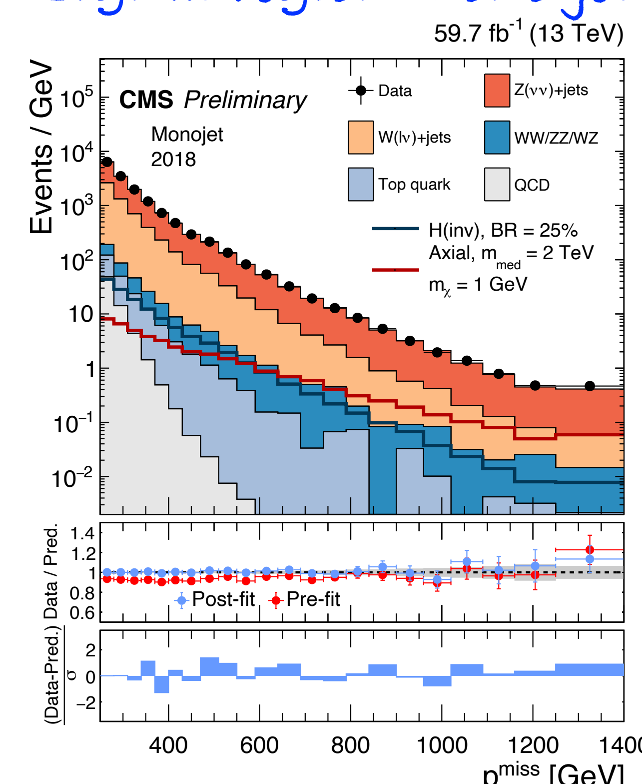
- **2- Bkg:**
  - **Z(vv)+jets and W(lv)+jets** from CRs
- **3- Results:** *combined fit of SRs, CRs*
  - systematic unc. included as nuisance parameters

- prefit: as from simulation
- post-fit: after allowing simulation to vary within unc and the scaling factors from CRs

signal region mono-V



signal region mono-jet

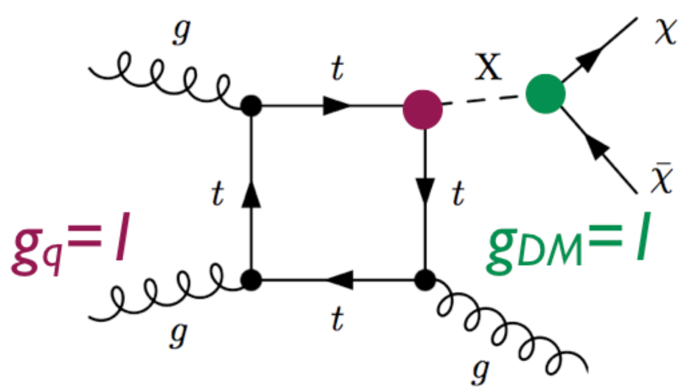


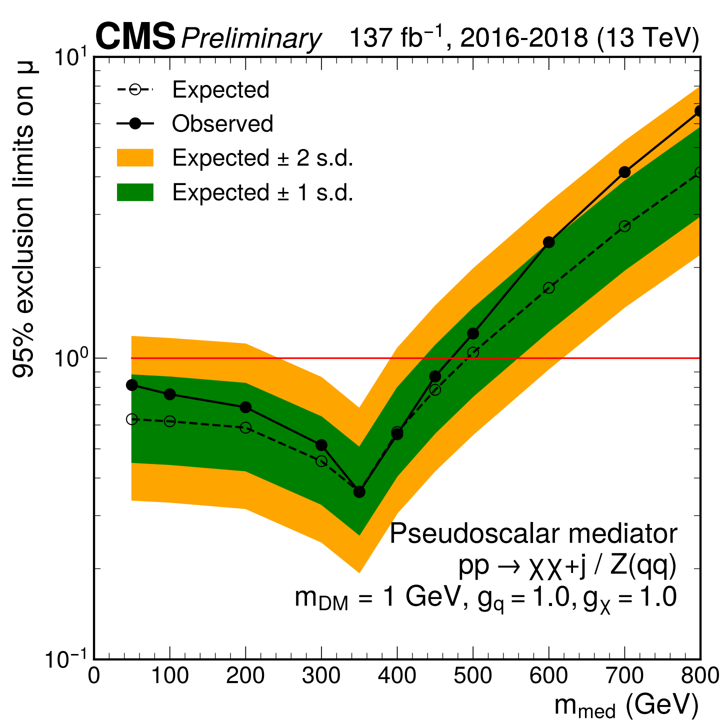
DM+jet/V search

CMS: EXO-20-004

- 3- Results: interpretation in terms of DM model, upper limits at 95% CL on cross section

Simplified pseudo model





Simplified axial-vector model

- $\mu = \sigma/\sigma_{th}$, $\mu=1$ exclude the theory value, $\mu<1$ exclude below theory value, $\mu>1$ does not exclude theory value
- parameter: cannot scan all parameters at once. Fixed ones only affect xsec but not kinematic (selection)

- here $\mu = \sigma/\sigma_{th}$ in on z axis (notice here $\log_{10}(\mu)$)
- parameter: here we scan 2 parameters at the time

see also N. Strobbe's talk

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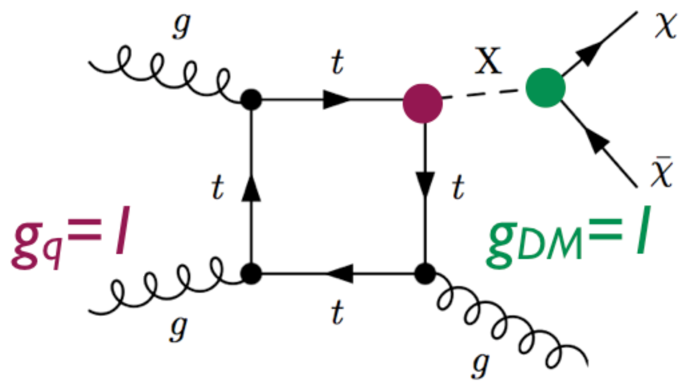

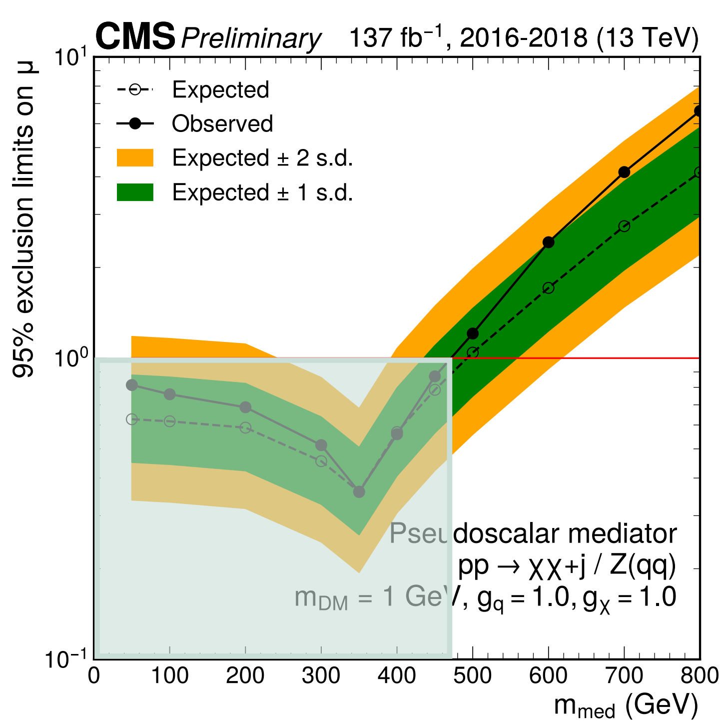

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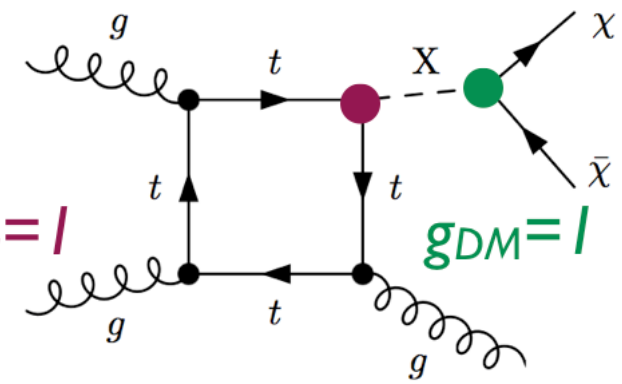
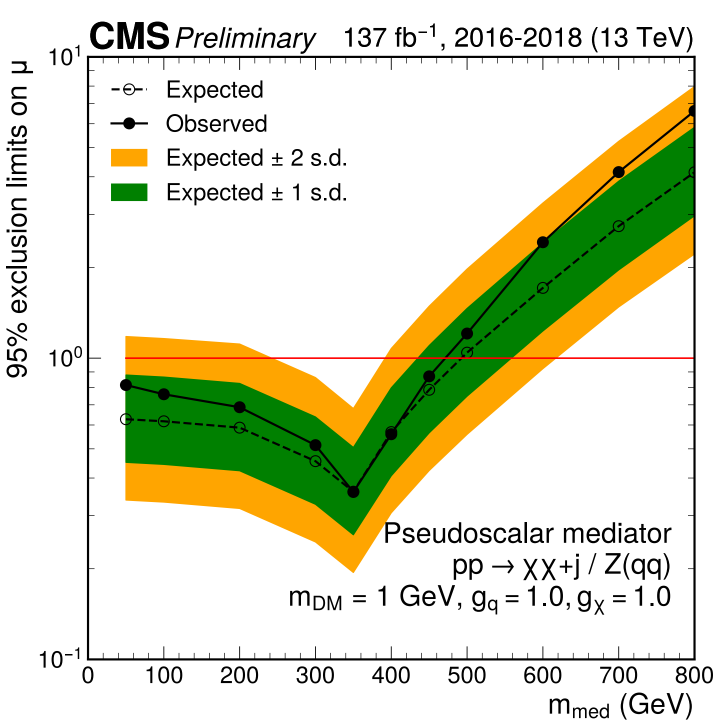


$g_q = 1$ $g_{DM} = 1$



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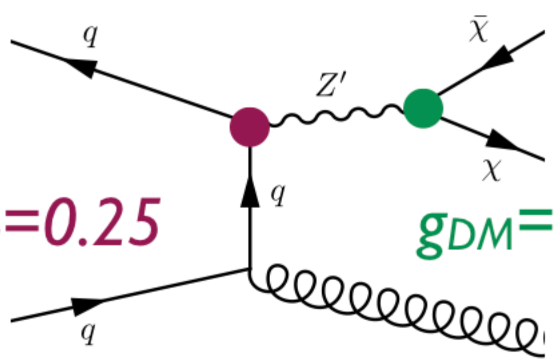
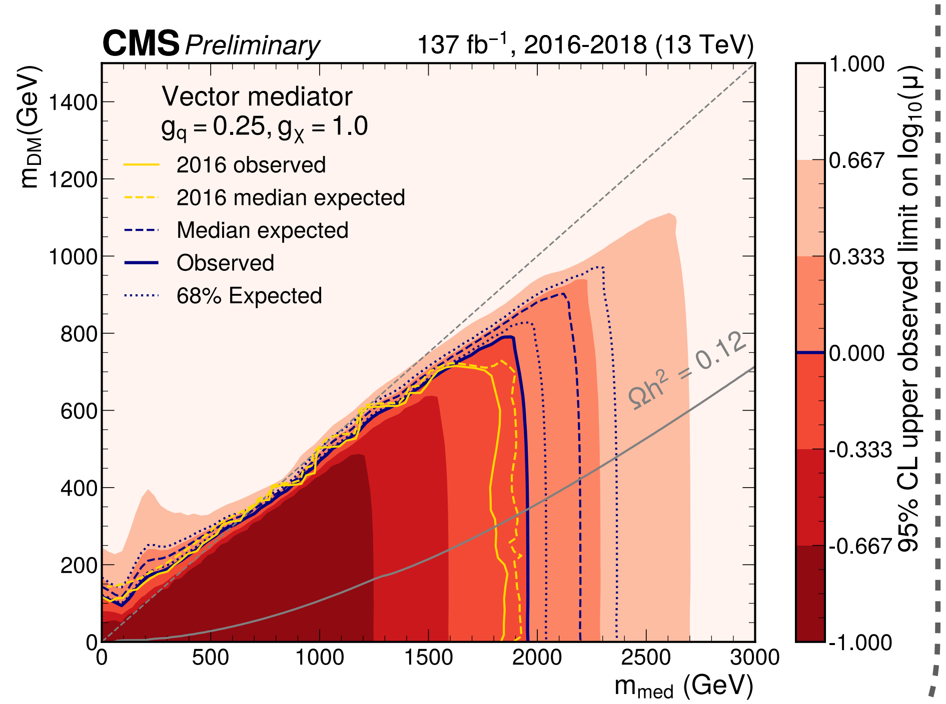


$g_q = 0.25$ $g_{DM} = 1$



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DM+jet/V search

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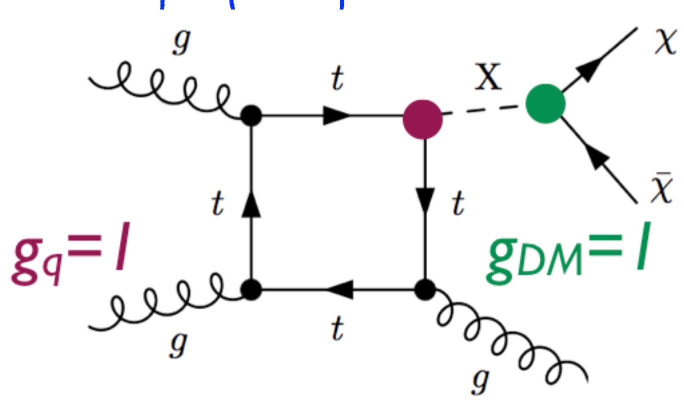

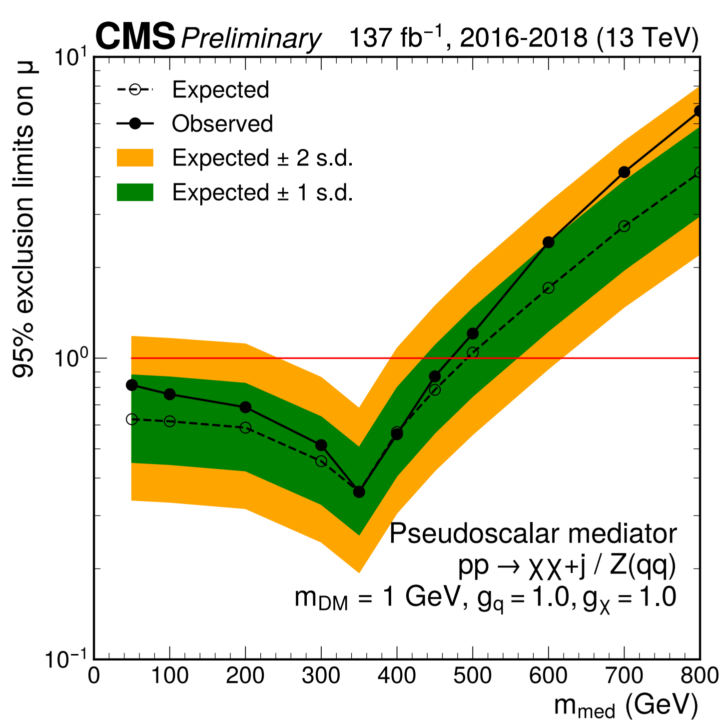

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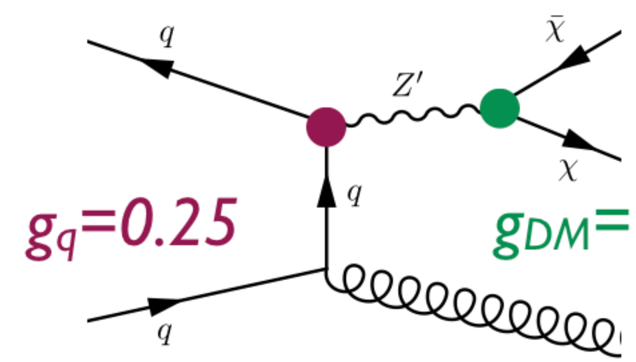

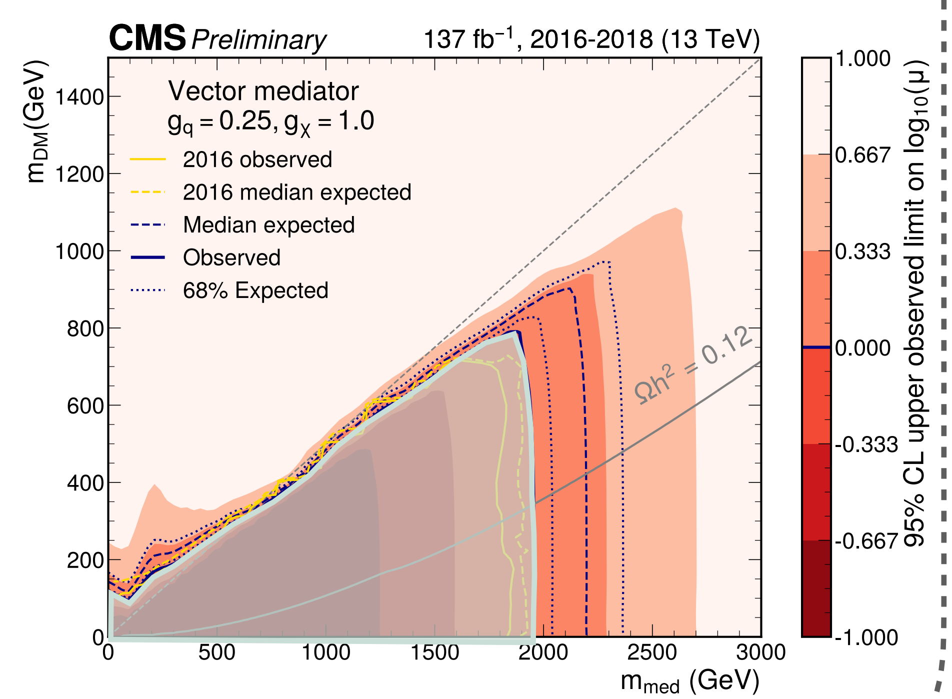

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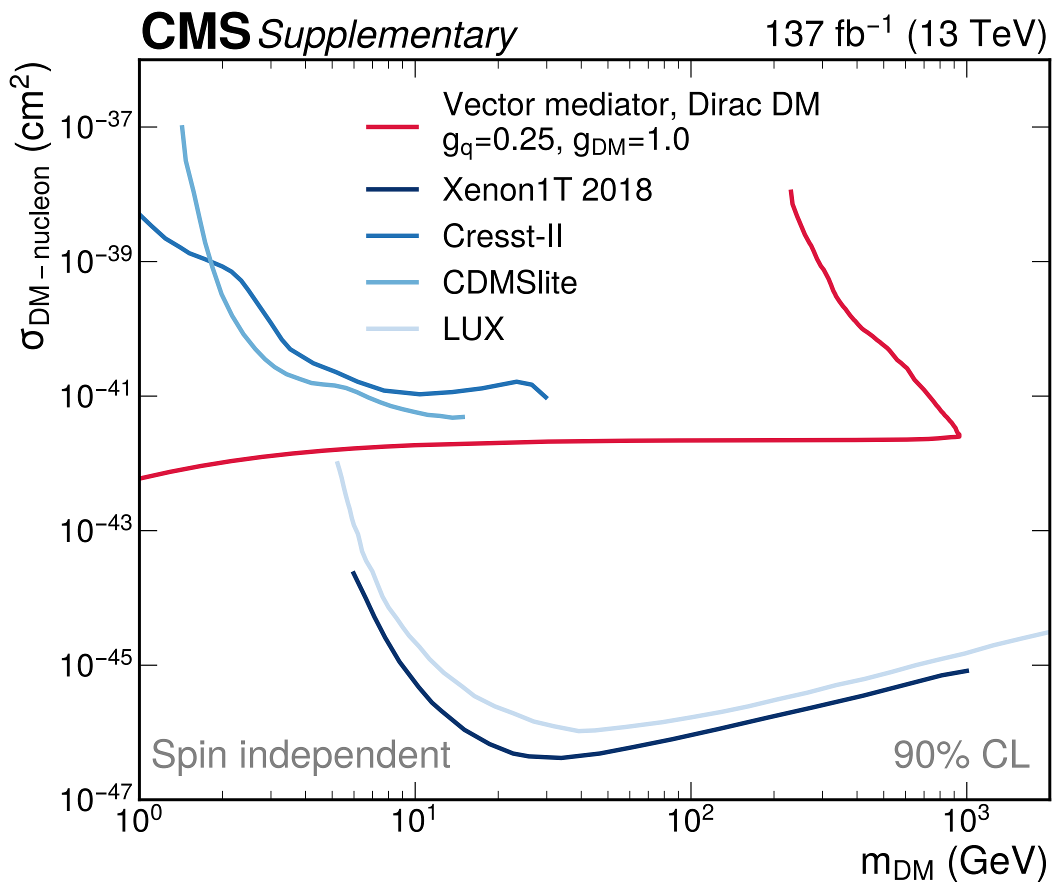
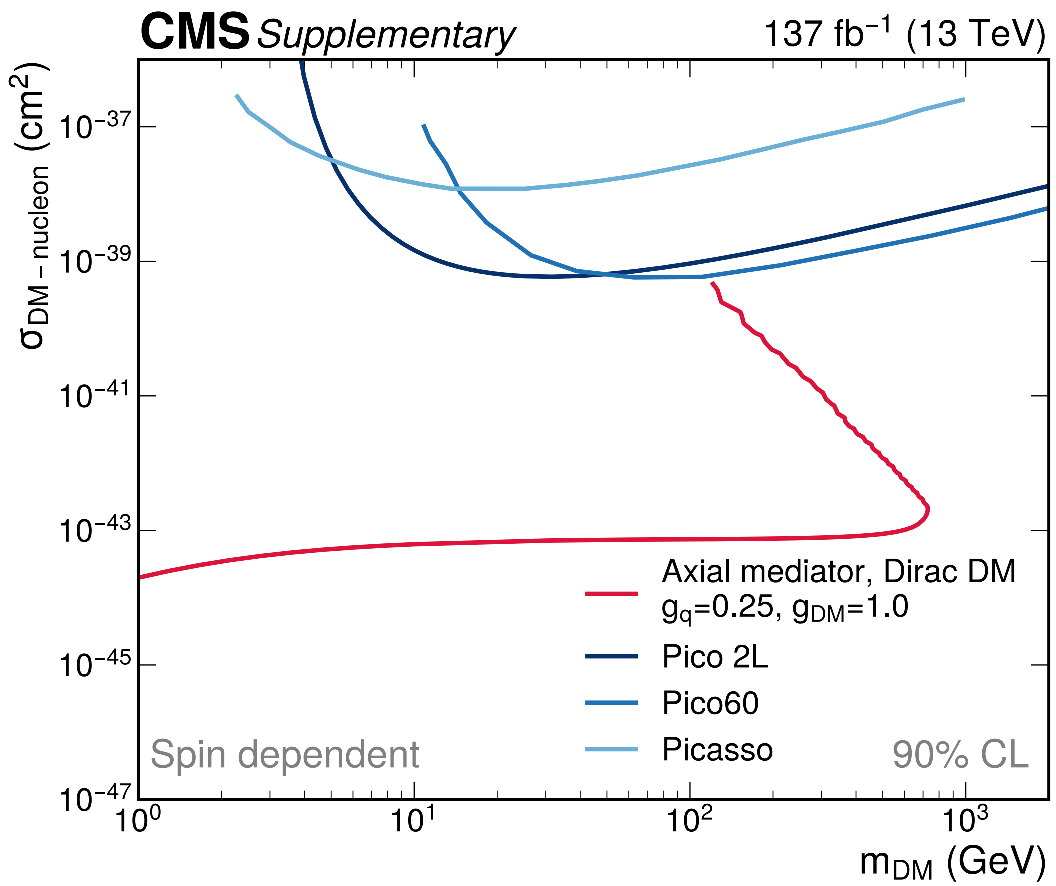
DM+jet/V: interplay with direct detection

CMS: [EXO-20-004]

▶ **3- Results:** lower limits at 90% CL on interaction cross section between DM candidates and the nuclei





Comparison

- DM particle non-relativistic: dominant DM-nuclei interactions described by spin-independent and spin-dependent scattering cross section
  - *vector/scalar* mediator lead to a *SI* interaction
  - *axial-vector/pseudo-scalar* lead to *SD* interaction
- comparison is very model dependent
  - DD bounds may be valid for multiple models, LHC limits hold exclusively for considered simpl. model

comparisons recommendations [arXiv:1603.04156]

DM+jet/V: interplay with direct detection

CMS: EXO-20-004

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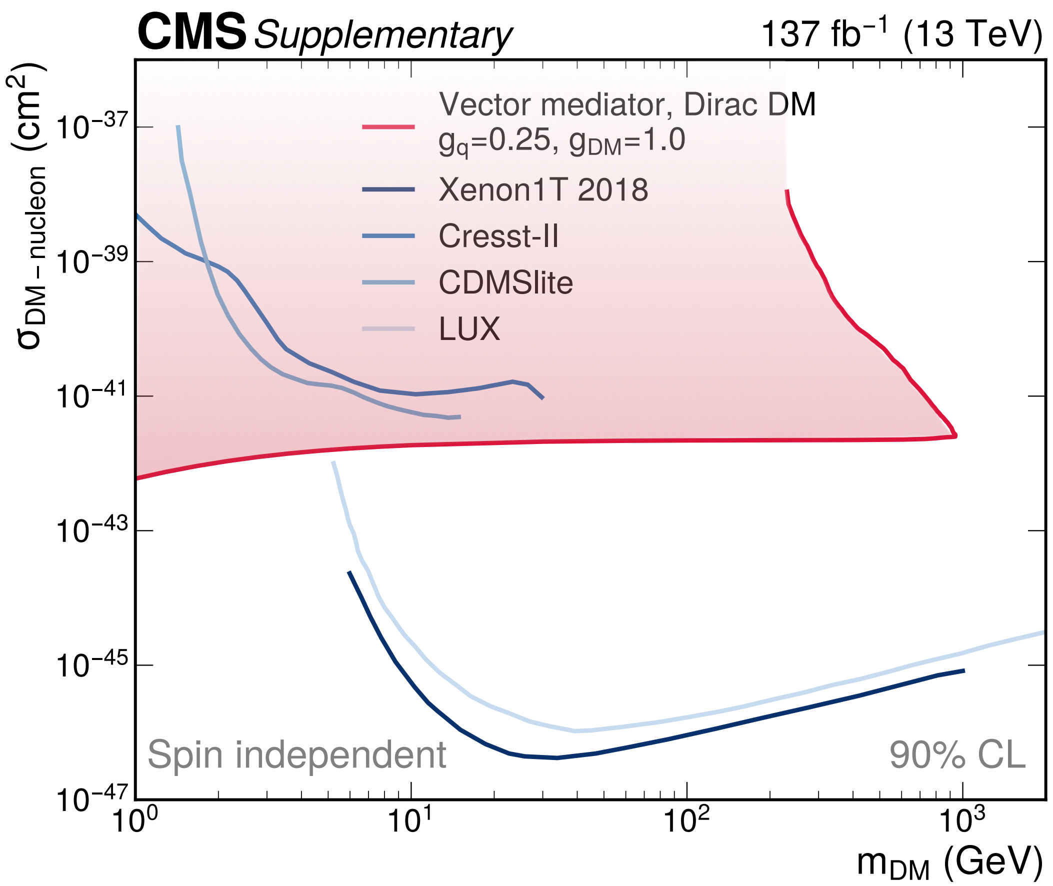

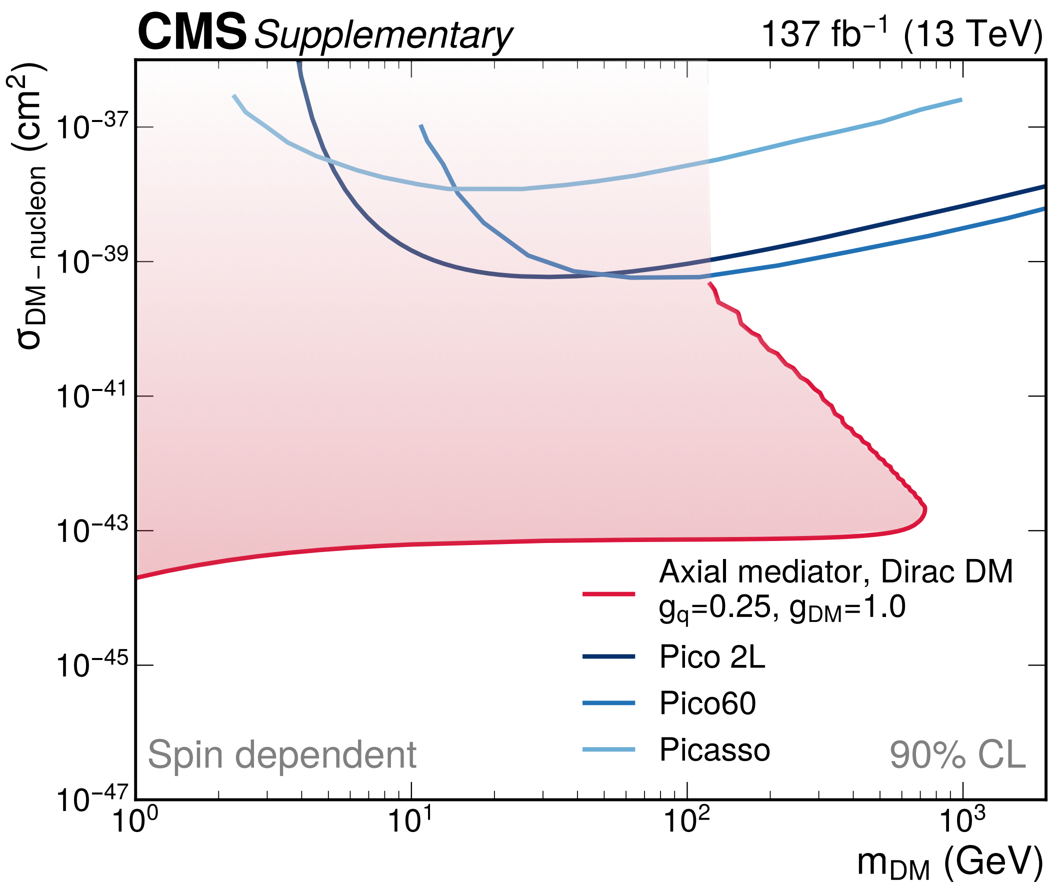

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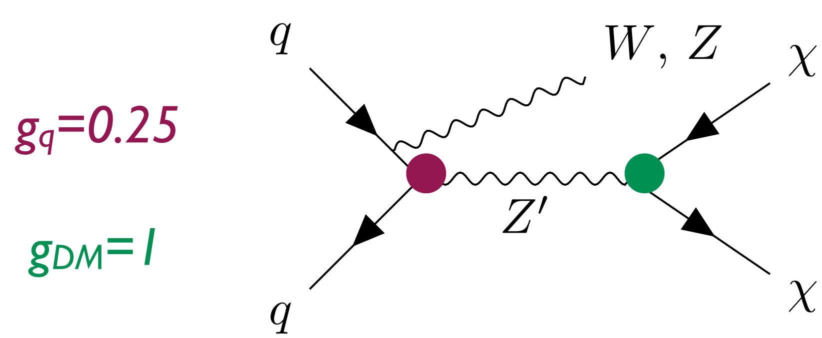
Simplified models

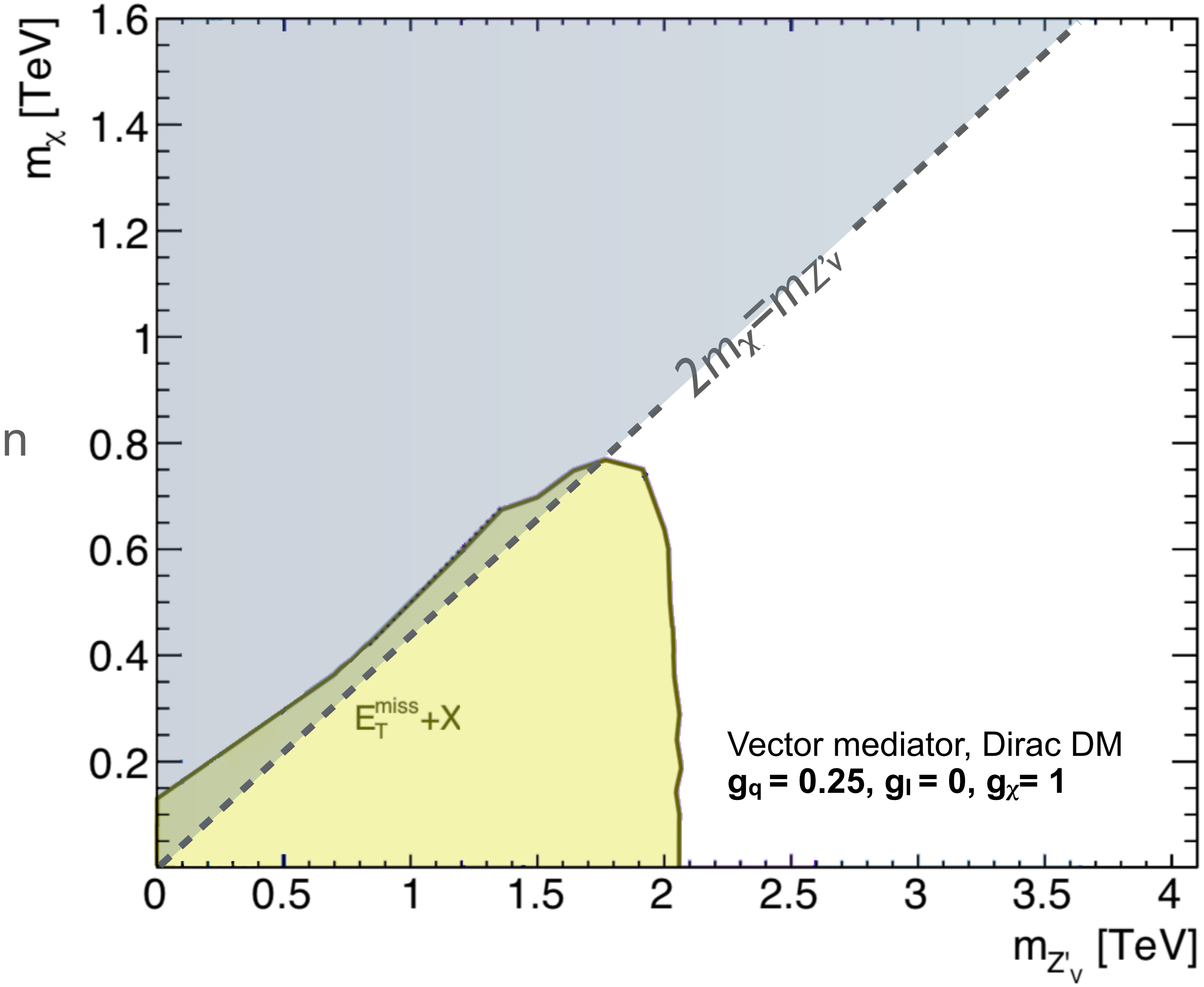
Simplified vector model



- low sensitivity to off-shell region due to strong reduction of production cross-section

- *Can we recover the sensitivity?*

✱ ATLAS: ATL-PHYS-PUB-2021-006



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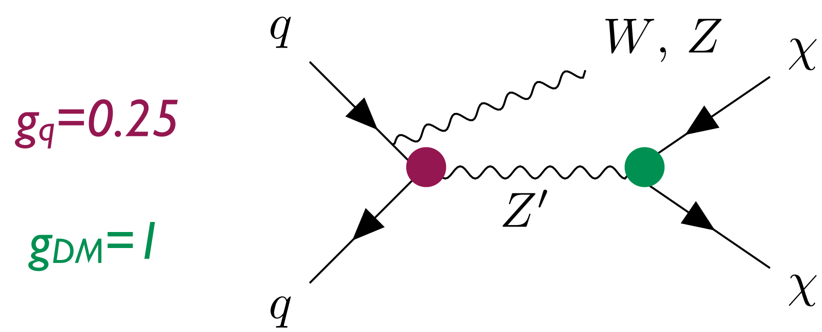

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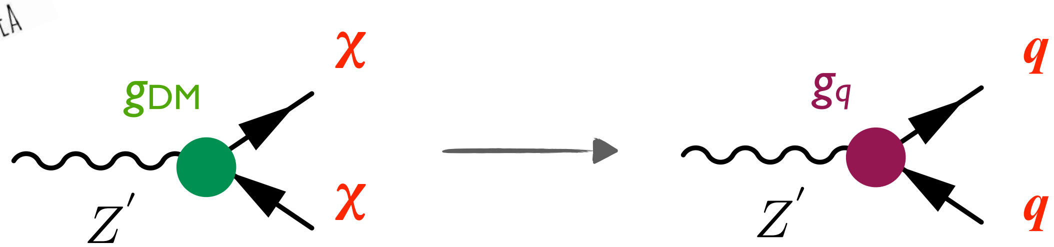
- **Can we recover the sensitivity?**

visible decays



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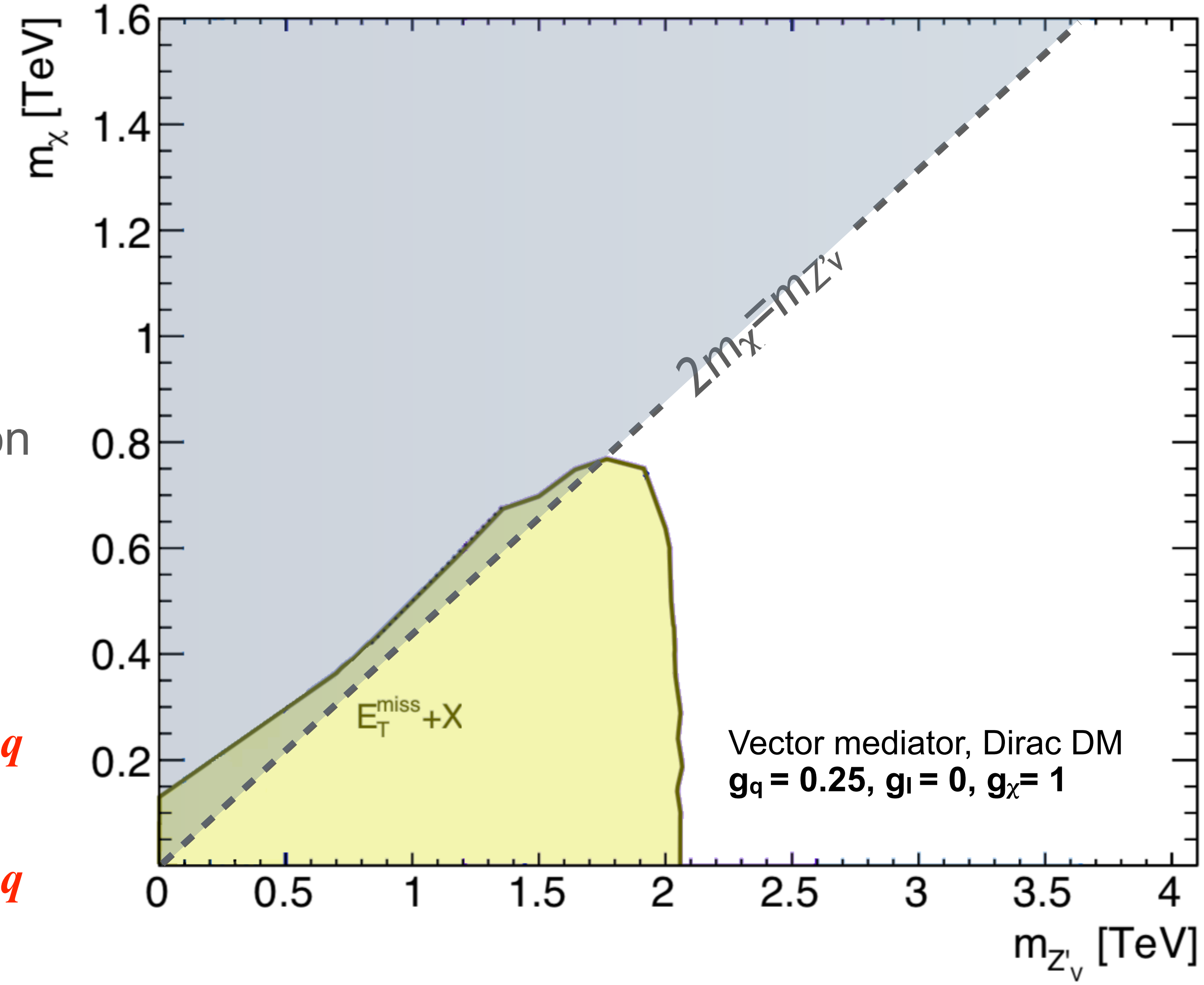

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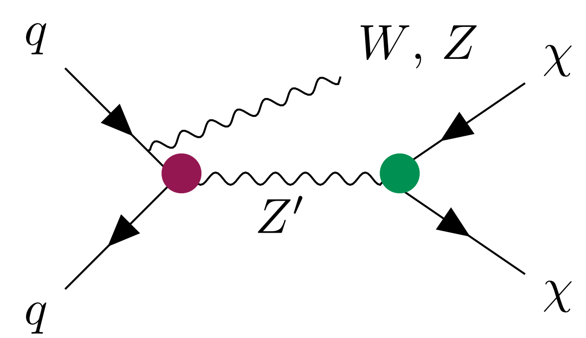
g_q=0.25

g_{DM}=1



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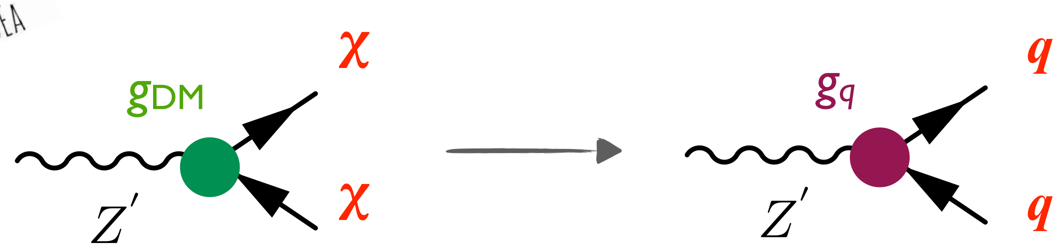

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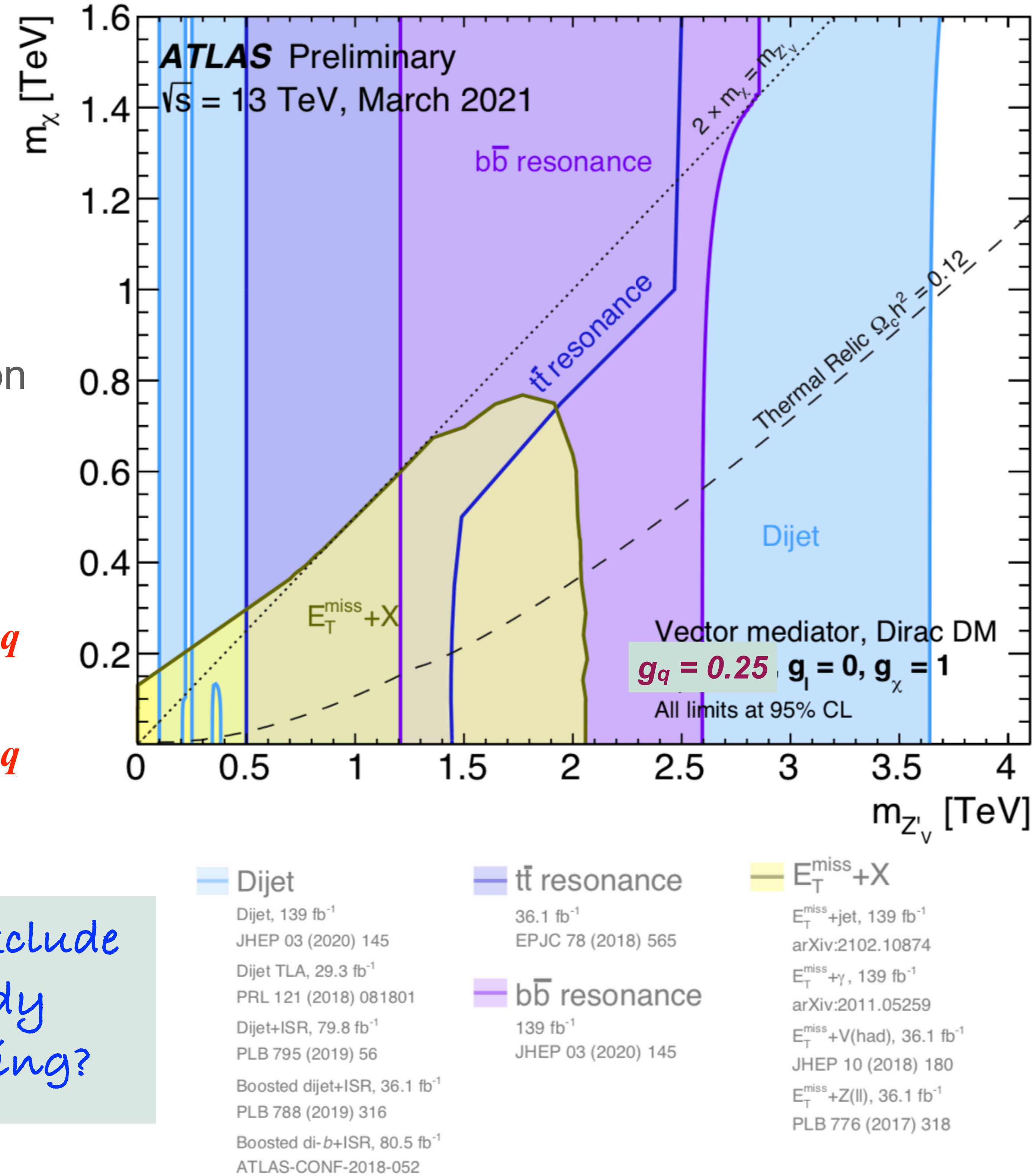

✱ mediator

g_q=
- narrow resonance
- wide resonance

Did we exclude already everything?

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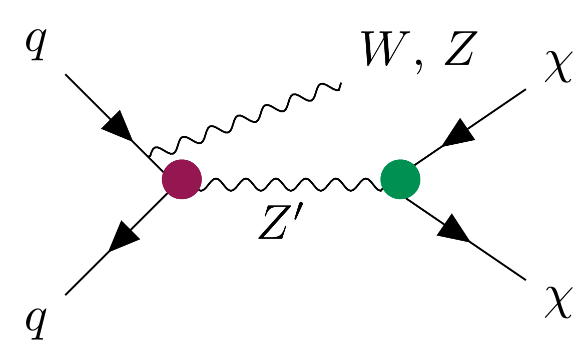

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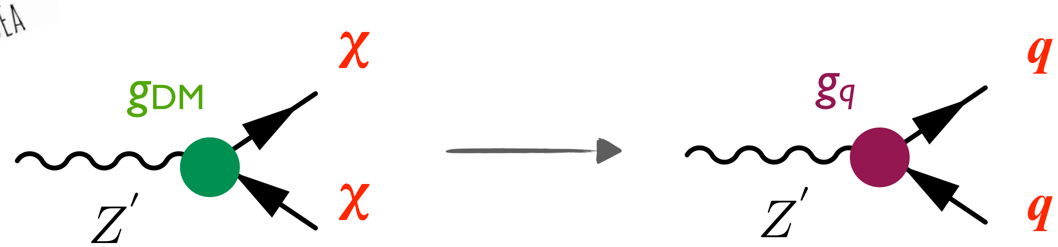
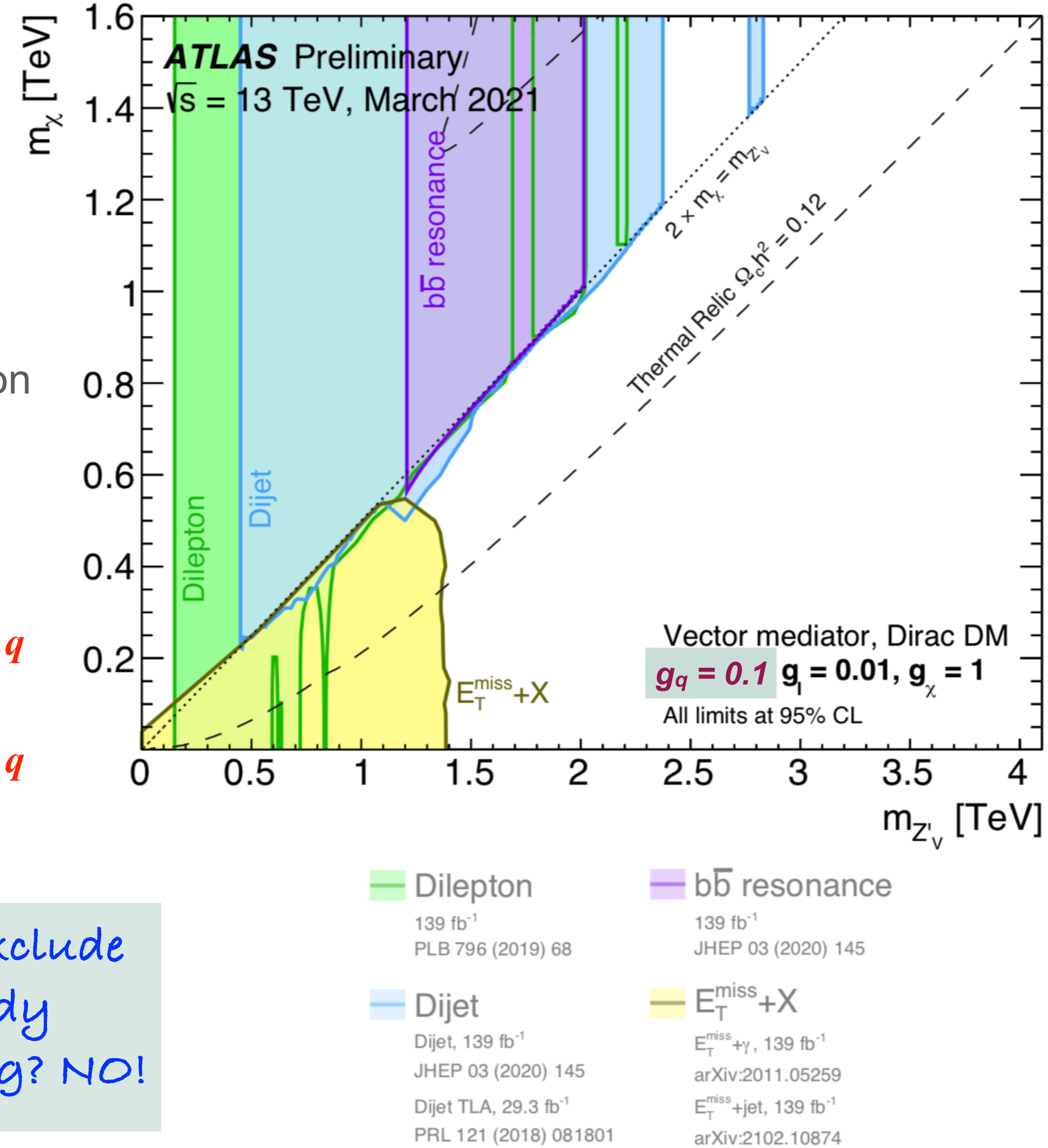


g_q=
- mediator
  - narrow resonance
  - wide resonance
- interplay changes

Did we exclude already everything? NO!

ATLAS:ATL-PHYS-PUB-2021-006



Simplified models …

… many more mono-X

Reminder:

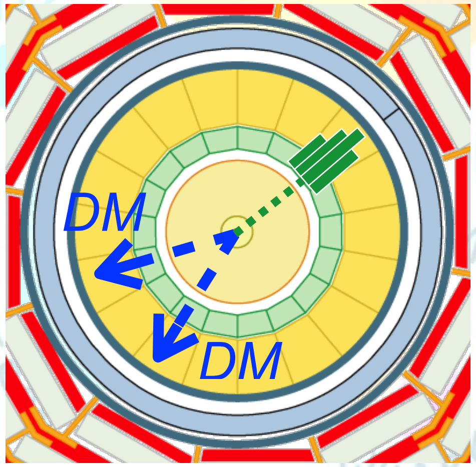
vector	axial-vector
$g_q \sum_q V_\mu \bar{q}\gamma^\mu q$	$g_q \sum_q A_\mu \bar{q}\gamma^\mu \gamma^5 q$

⁎ choose X to increase xsec or bkg rejection

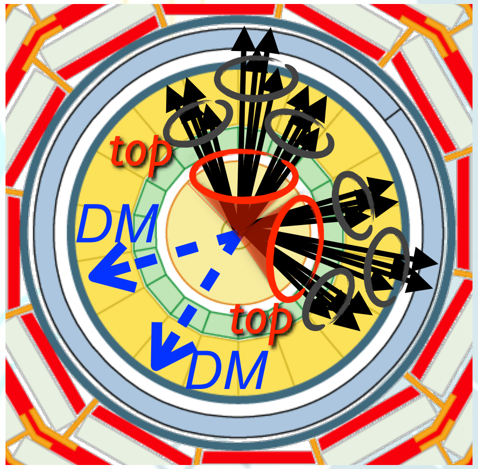
scalar	pseudoscalar
$g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$	$g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f}\gamma^5 f$

⁎ choose X to exploit coupling ∝ to quark mass (or increase xsec)

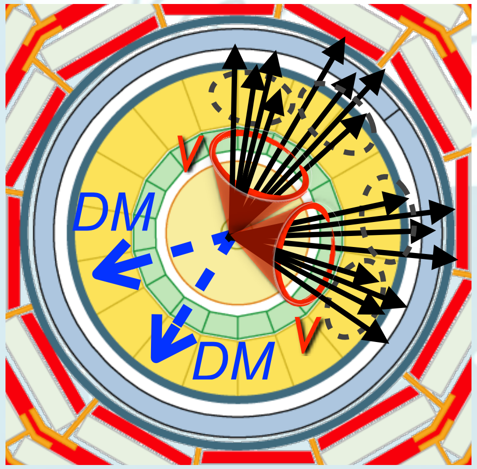
mono-γ



DM+tt

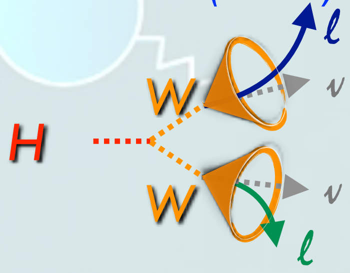


mono-VV(=WW,ZZ)



DM+top: t/tW-channel

mono-H(WW)



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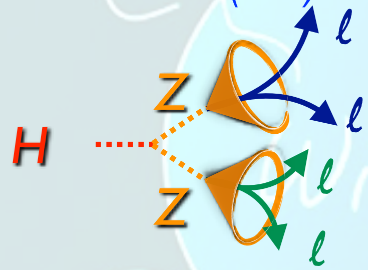
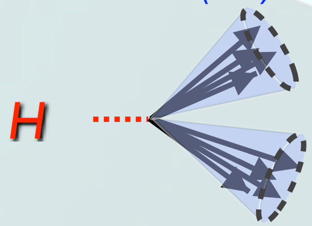


mono-H(bb)

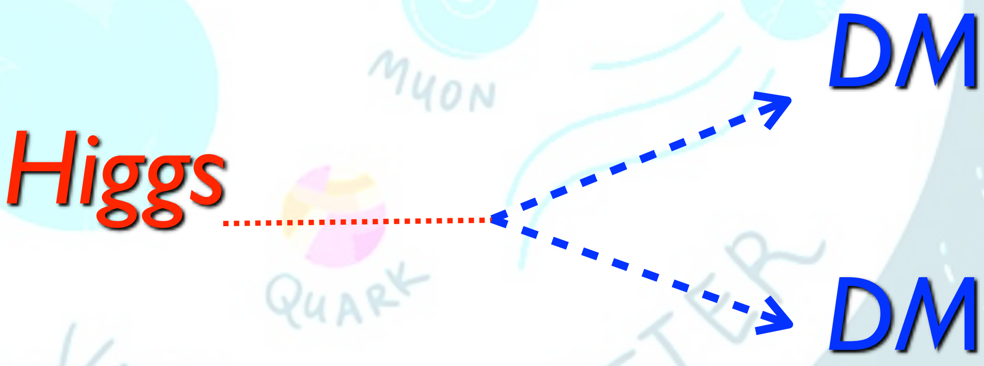


⁎ selected results

Simplified models: Higgs boson portal DM

Reminder:

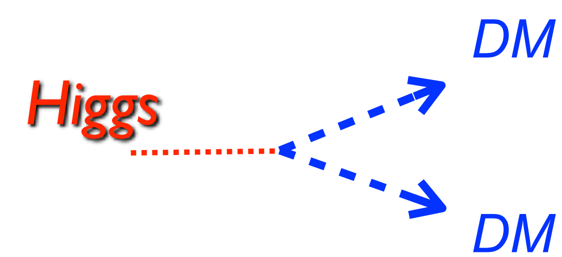
- Higgs decay branching fractions not yet sufficiently constrained
  - in SM, H→inv ~0.1%
  - direct coupling H-DM will enhance H invisible decays



Higgs: a portal to the invisible?

CMS: arXiv1809.05937

- **DM-SM interactions mediated by Higgs boson**
  - direct coupling to DM enhance H invisible decays (SM ~0.1%)



- **Higgs production as in SM**
  - gluon fusion (MET+j)
  - associated VH (MET+V)
  - ✱ vector-boson fusion (MET+2jets)

- 1 - Selection:
  - 2 jets (large $|\Delta\eta_{jj}|$, small $|\Delta\Phi_{jj}|$), MET > 180-250 GeV

- 2- Bkg:
  - **V+jets** main bkg from CRs

Experimental challenges

✱ precise estimation of bkg m_{jj} shape distribution, signal as excess of events at large m_{jj}

✱ excellent calorimetry in forward region to measure jets

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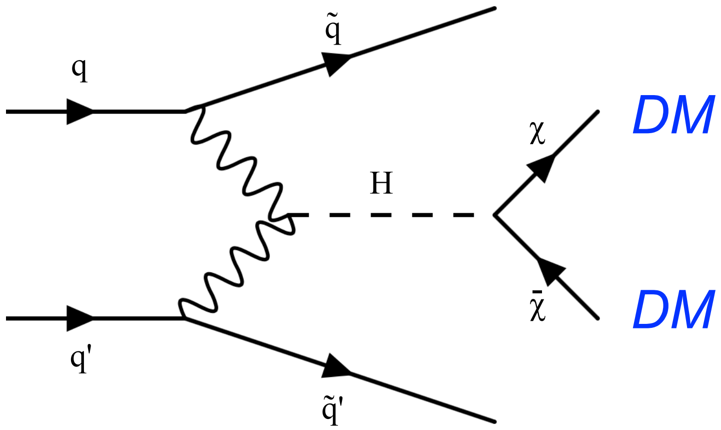

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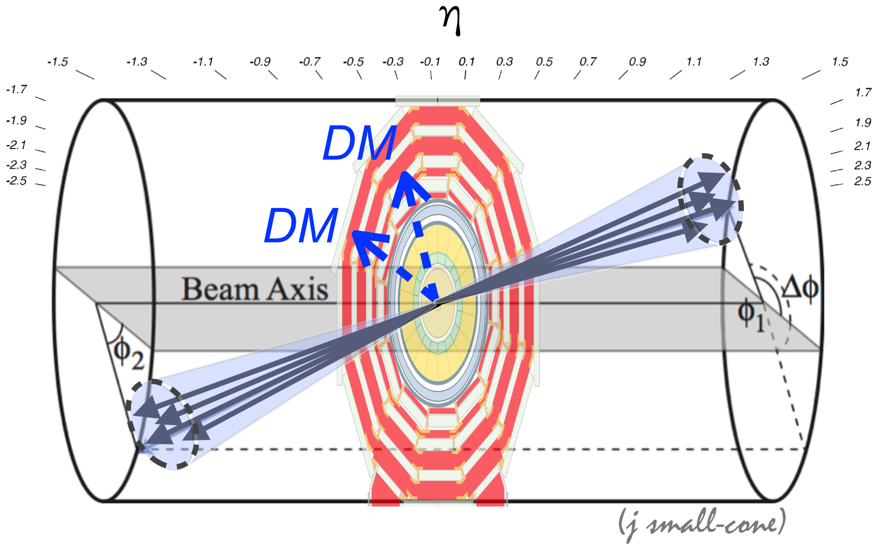

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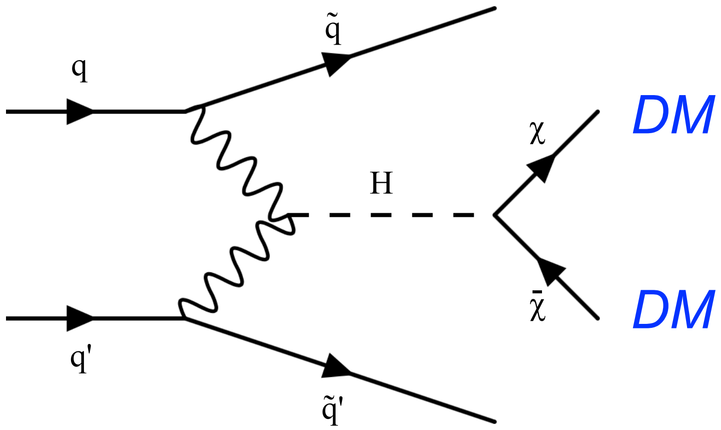

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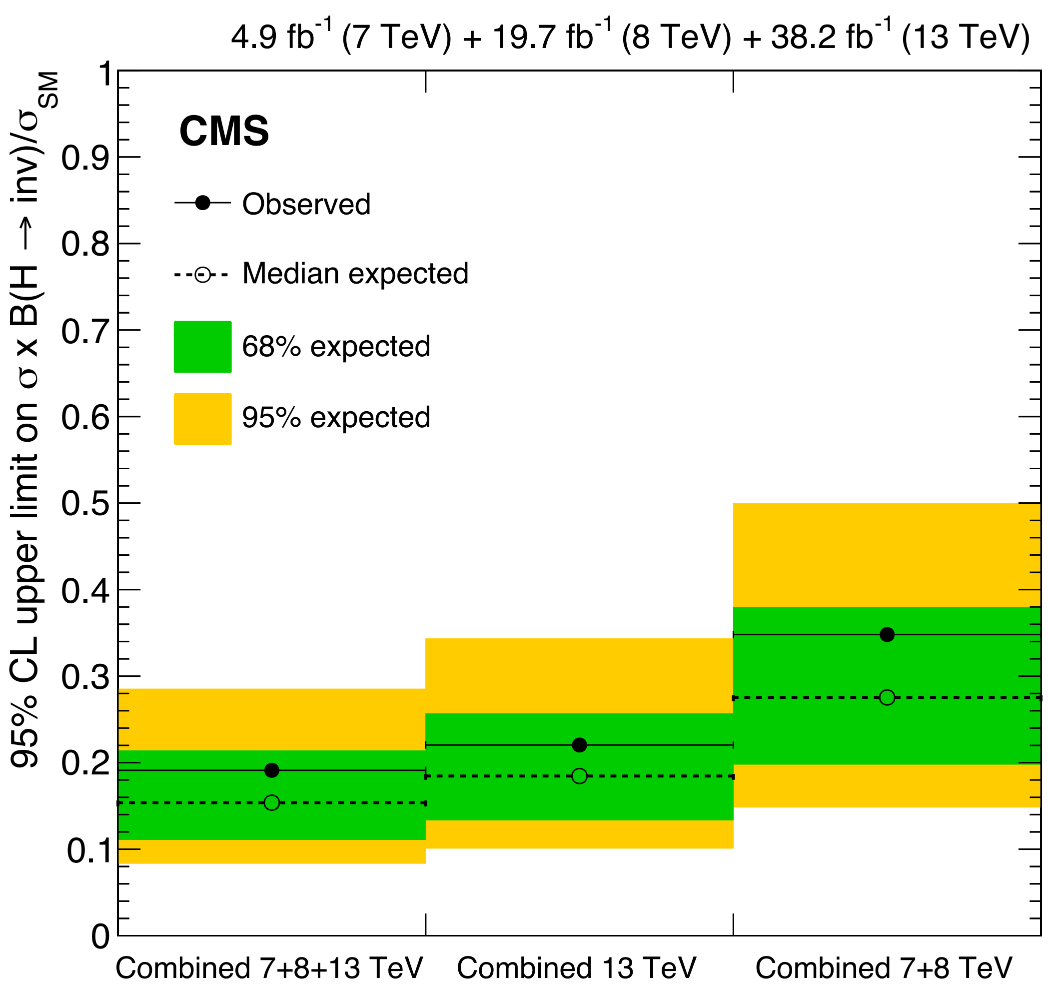
- 3- Results:
  - combined fit of SRs and CRs to m_{jj}
  - upper limits on on cross section x probability to decay to invisible particles (branching ratio - BR)

BR(H→inv) <0.19 (0.15) obs (exp.)



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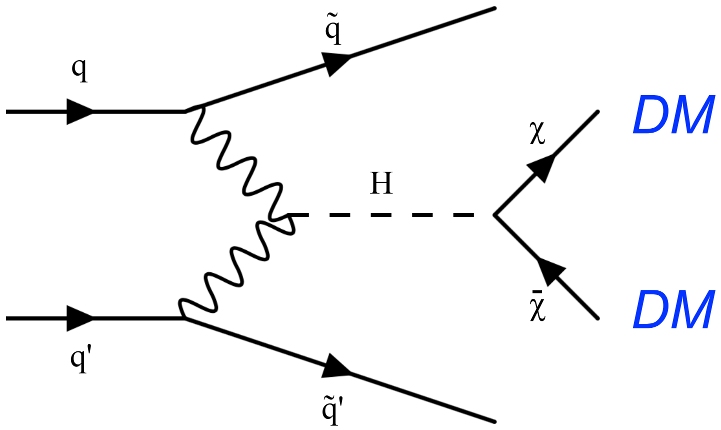
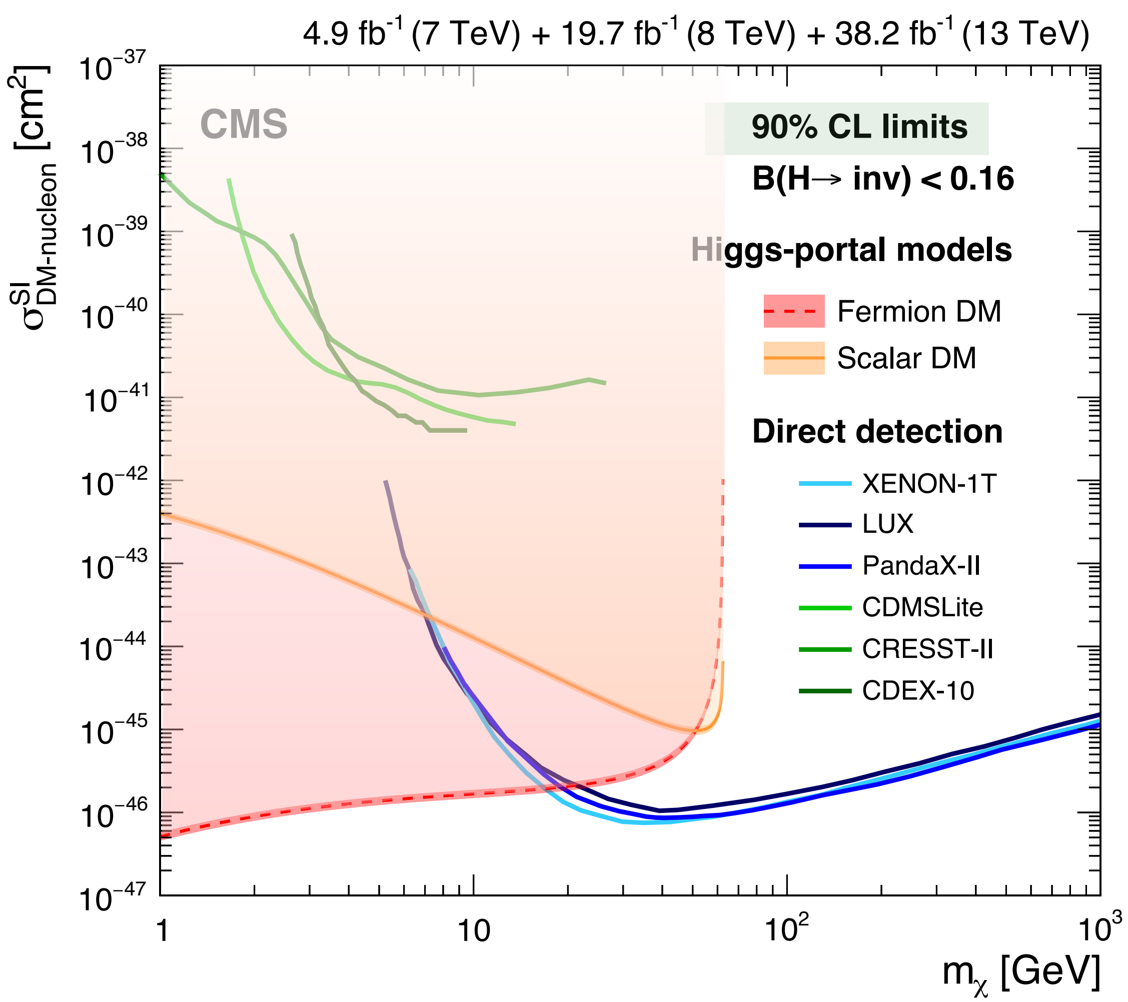


- 3- Results:
  - upper limits on on cross section x probability to decay to invisible particles (branching ratio - BR)
  - translated into a spin-independent DM-nucleon elastic scattering xsec limit
    - m_{DM} smaller than half of m_H
    - interaction between DM and nucleus mediated by H exchange



Summary

DM nature
(large region of parameter
space of DM models

assume weak
interaction
with SM

DM production

different interactions/signature
investigated

benchmark models to
interpret the results

* Rich DM physics program at colliders
  - essential complementarity with non-collider searches
  - inputs from various signatures (mono-X, resonances, H→inv, …)
  - supersymmetry can be a dark matter model too see more in N. Strobbe's talk
* Many new results with Run-3 data are expected!

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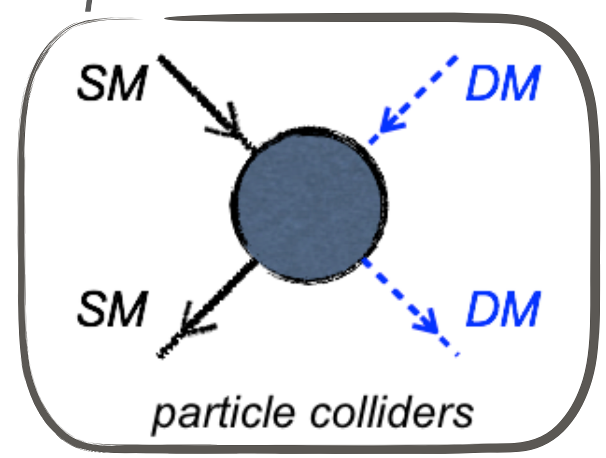

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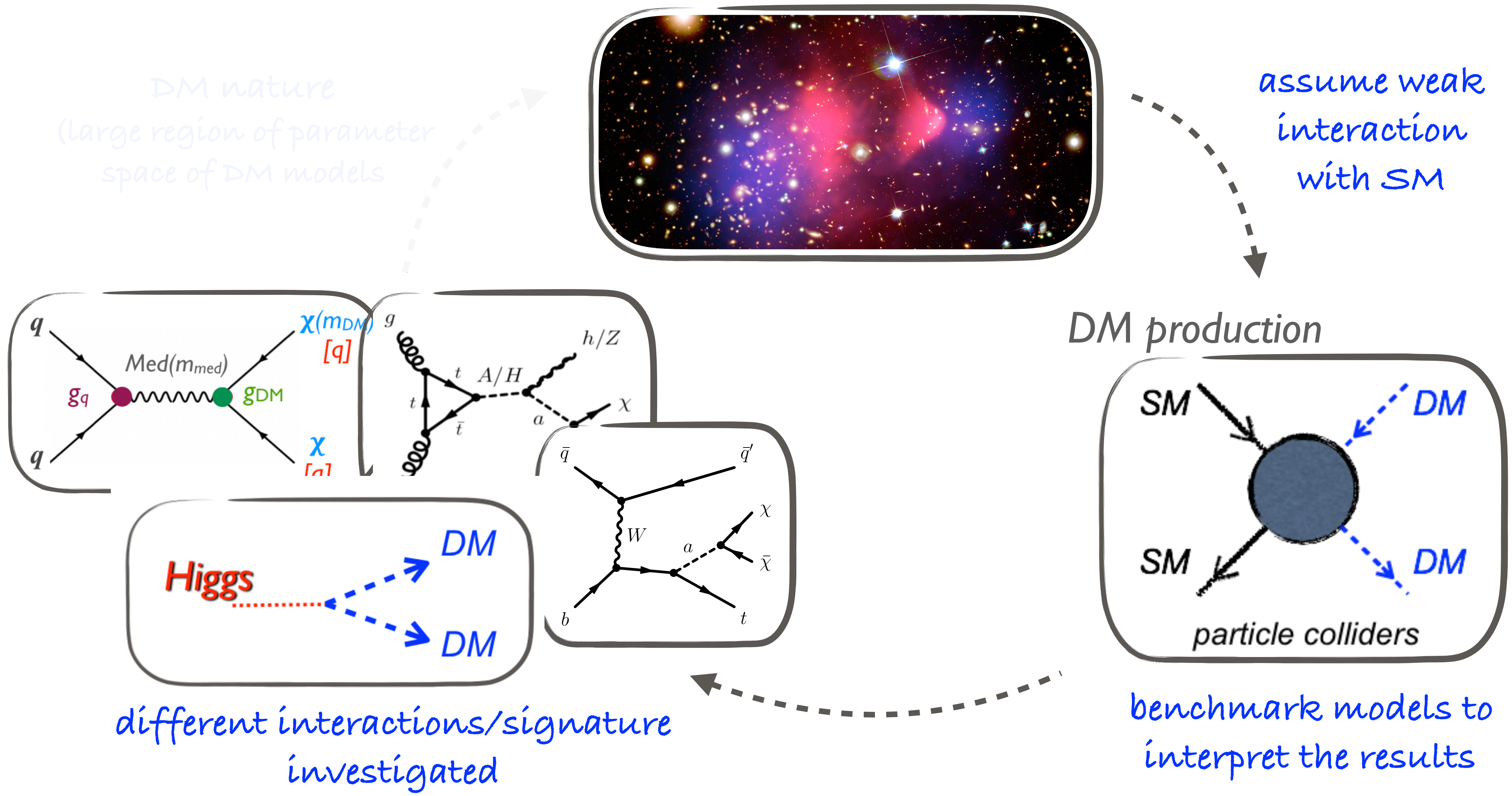

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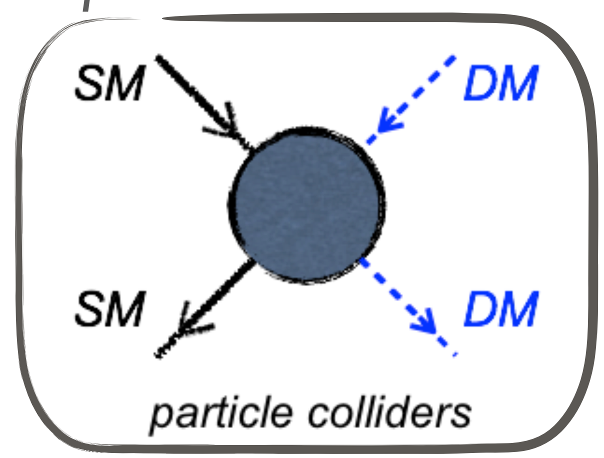

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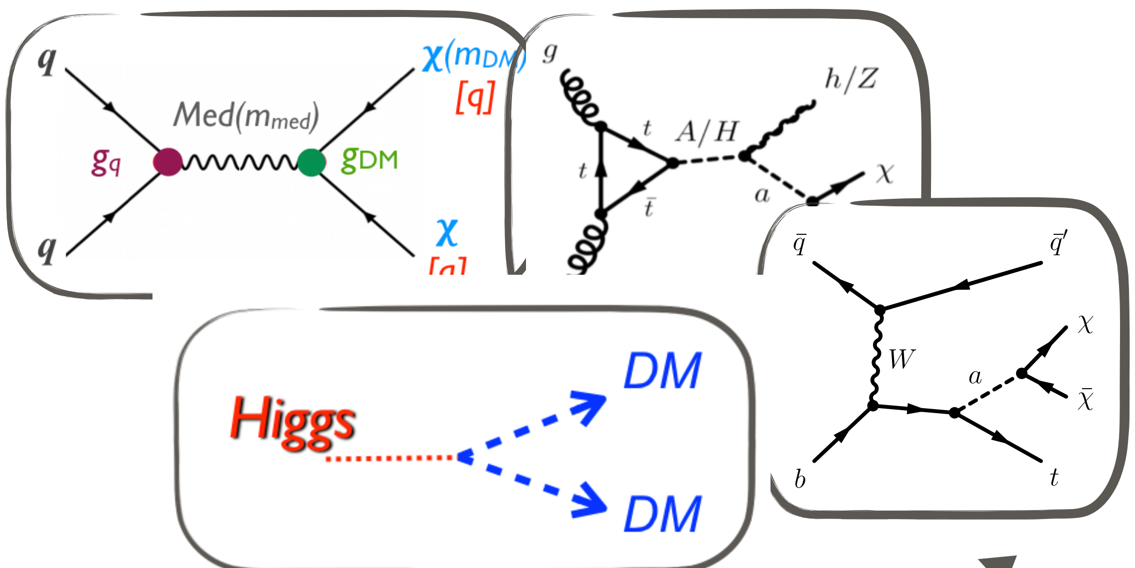

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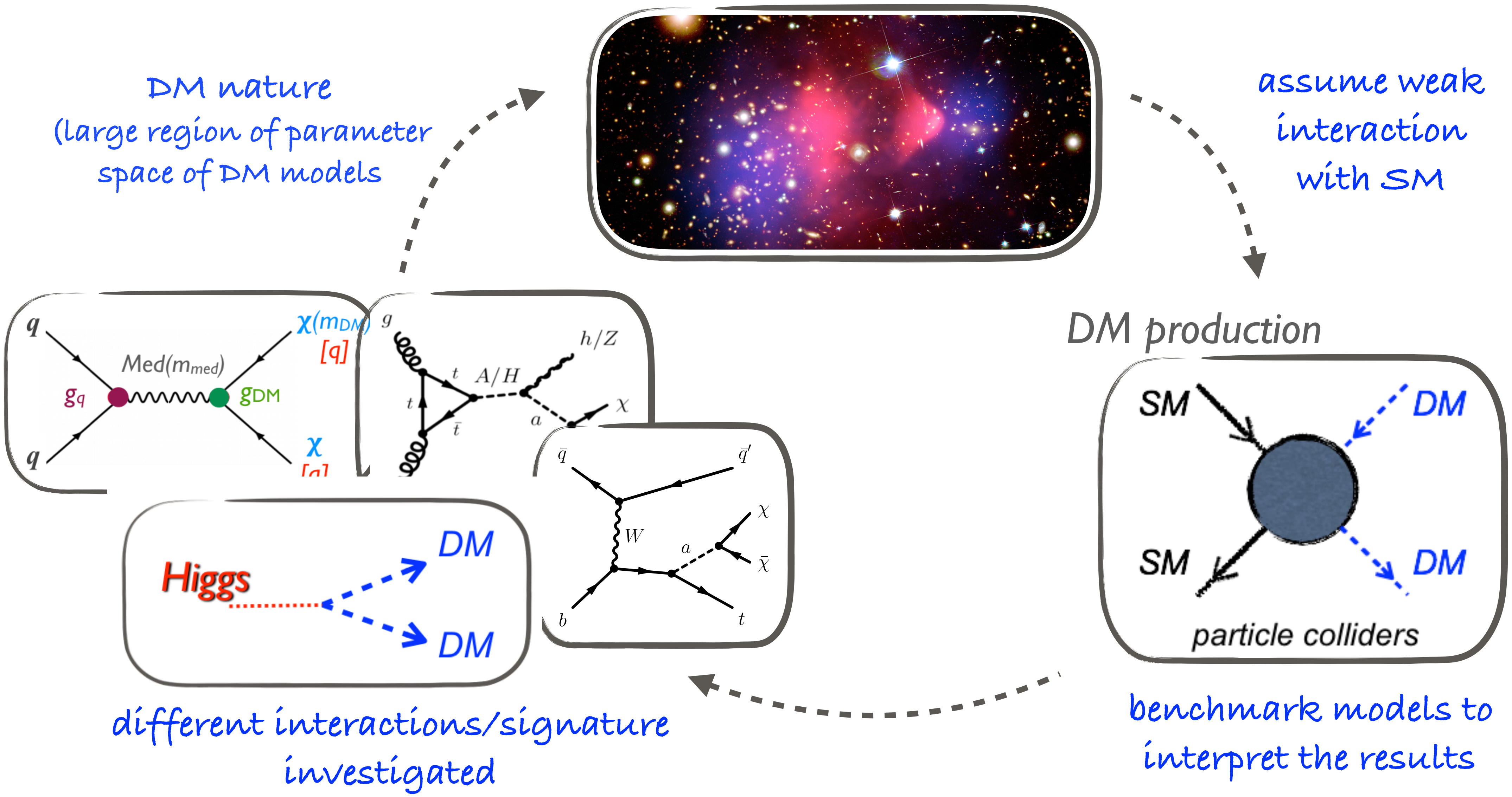

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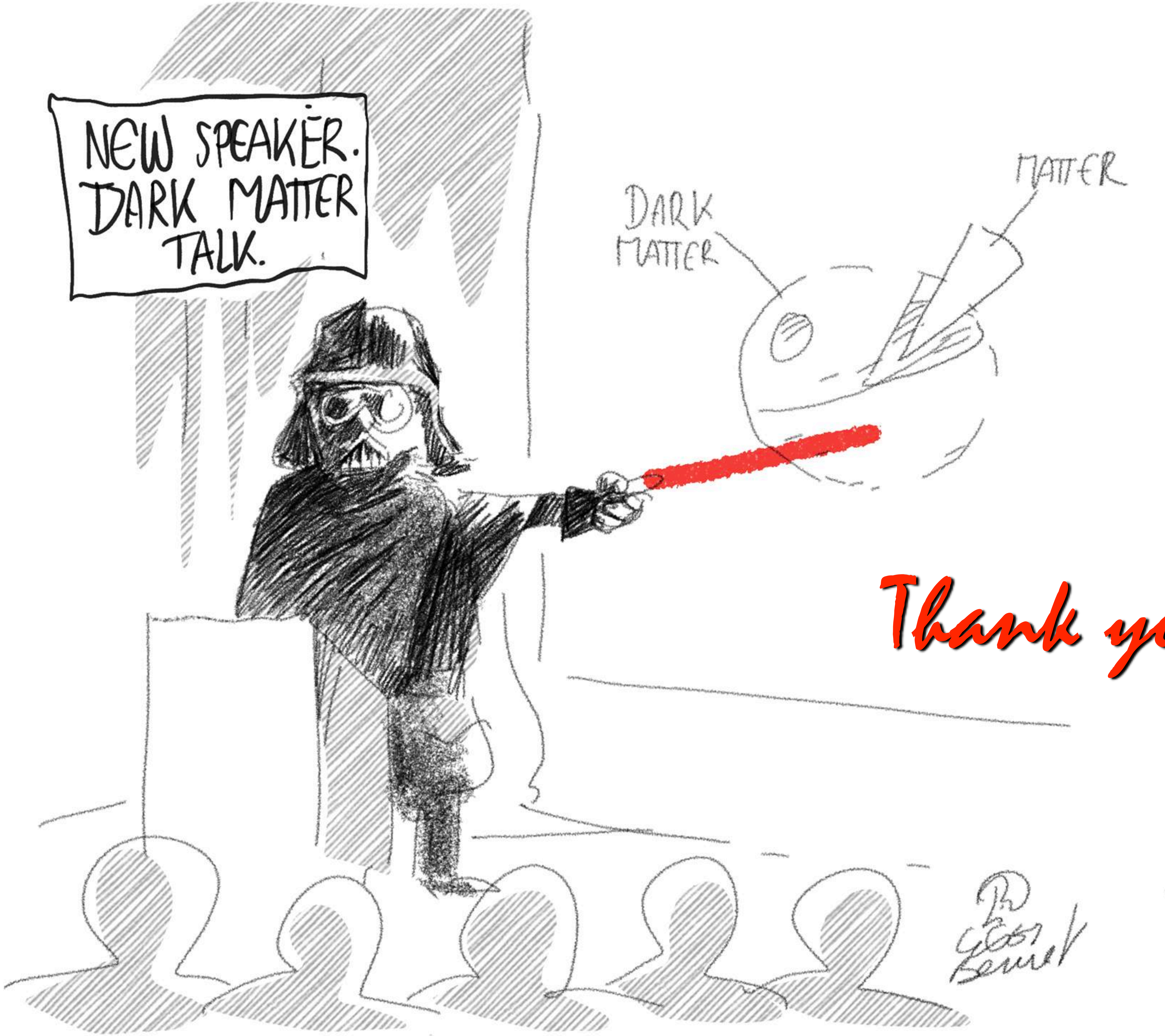
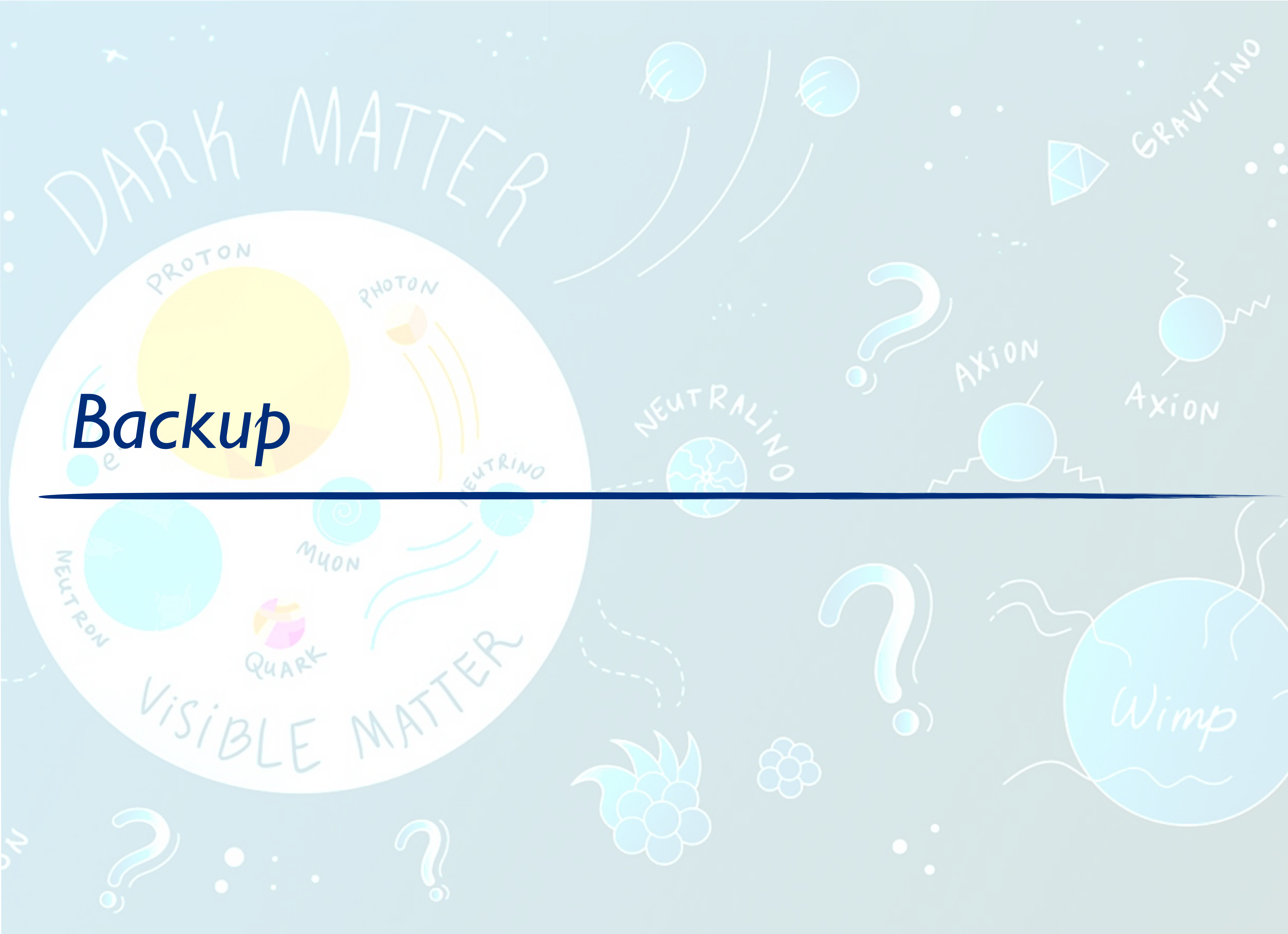


Thank you!

Backup


DARK MATTER
PROTON
PHOTON
NEUTRINO
MUON
NEUTRON
QUARK
VISIBLE MATTER
NEUTRALINO
AXION
AXION
GRAVITINO
Wimp

Di-lepton high-mass resonances

CMS: arXiv:2103.02708

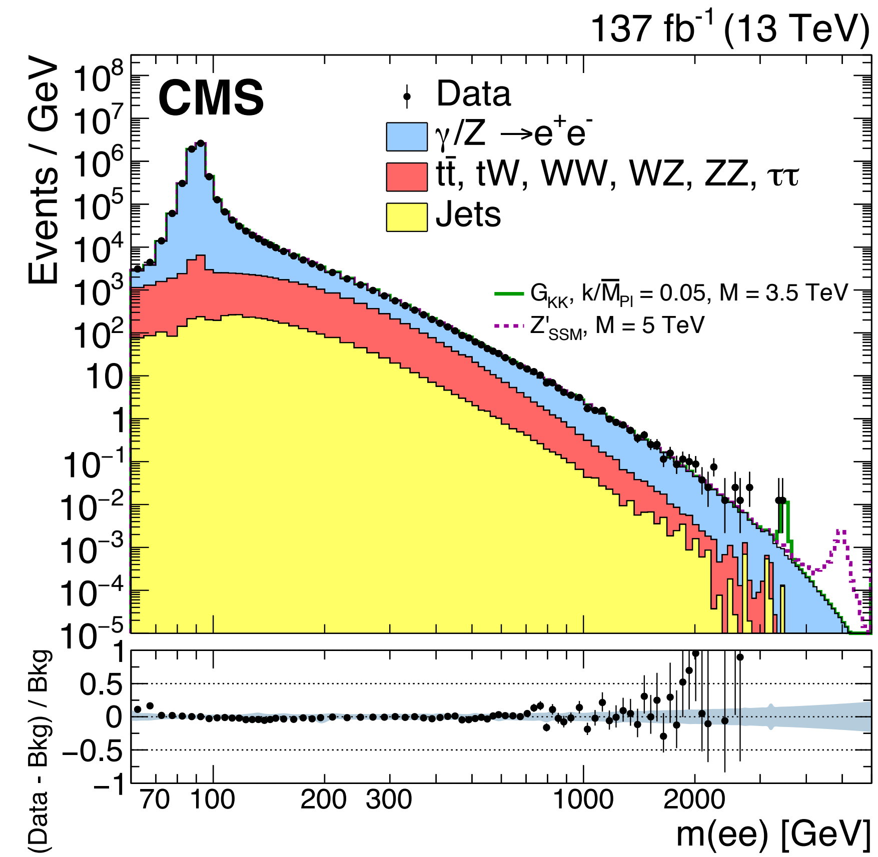
1 - Selection: resonance appears as peak wrt SM invariant mass spectrum

- 2 electrons *or* 2 opp-sign muons

2 - Bkg:

- **Z(ll)** main bkg, normalized from CR
- **QCD multi-jet, W+jets** with mis-identified leptons from CR

3 - Results: compare SM predictions with data, fit to dilepton invariant mass (systematic unc. included as nuisance parameters)



Di-lepton high-mass resonances

- lower masses wrt searches for di-jet resonances (lower thresholds for lepton triggers)
- can investigate very low mass mediators