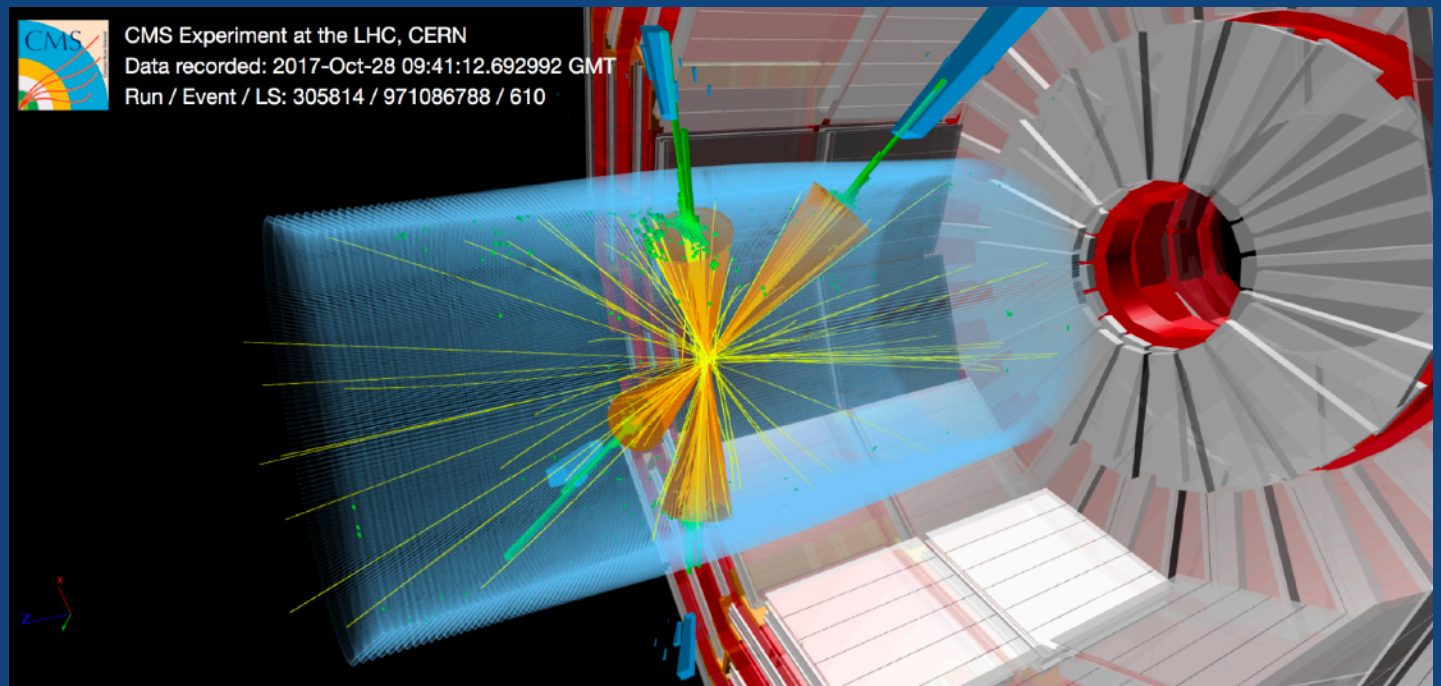
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Phenomenology of Physics Beyond the Standard Model

Exp Lecture 4 : Dark Matter searches

Annapaola de Cosa adecosa@phys.ethz.ch



From last exp.lectures

- SUSY particle searches
  - Invisible vs reconstructable (aka MET-based searches vs bump hunt searches)
- Higgs search and discovery
  - Importance of invariant mass resolution
  - Event categorisation
  - Background types and handles
  - Statistical interpretation: discovery or exclusion
- Hunting MSSM Higgses
  - Diversity of analysis strategies to explore different corners of the model phase space

In this lecture

- Why are we looking for DM? What does DM look like?
- Probing DM from different perspectives:
  - Direct and Indirect DM detection strategies vs particle collider experiments
  - Complementarity of different approaches
- Hunting DM at particle colliders
  - Theoretical approach
  - Experimental approach
  - Interpretation

Not in this lecture

- A review of DM evidence and possible candidates
- A complete introduction to direct and indirect detection experiments and results
- Searches for SUSY particles explaining DM
  - see previous lectures (RPC SUSY)

Not in this lecture

But you can get more information here:

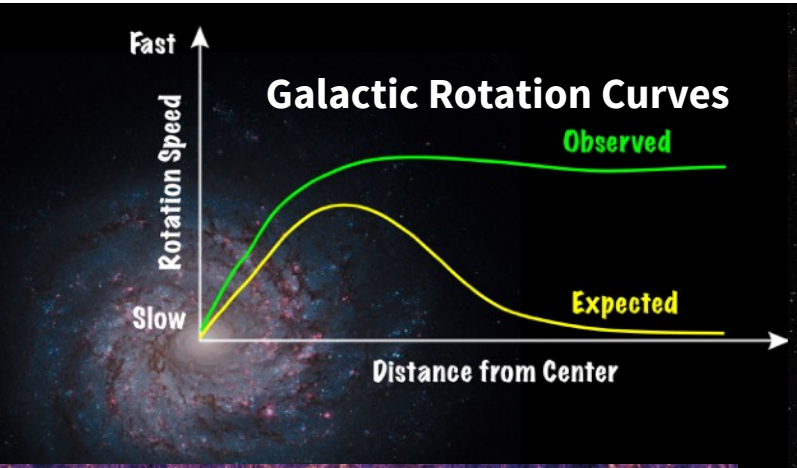
- Particle Dark Matter: Observation, Models and Searches (Bertone et al.) 2013 http://dx.doi.org/10.1017/CBO9780511770739
- Supersymmetric Dark Matter (Jungman et al.) 1996 http://arxiv.org/abs/hep-ph/9506380
- Strategies for Determining the Nature of Dark Matter (Hooper and Baltz), 2008 https://arxiv.org/abs/0802.0702
- Dark matter direct-detection experiments (Marrodan and Rauch), 2015 https://arxiv.org/abs/1509.08767

Or here (video lectures)

- on DM theory by M. Cirelli https://www.youtube.com/playlist?list=PLrLctLPAdPNtEvgK8BG5e5K9HTxO38Qkf
- On direct detection experiments by J.Monroe https://video.ethz.ch/speakers/zurich_physics_colloquium/ff0ccca7-db2b-4699-aeda-61205e1f0e6d.html

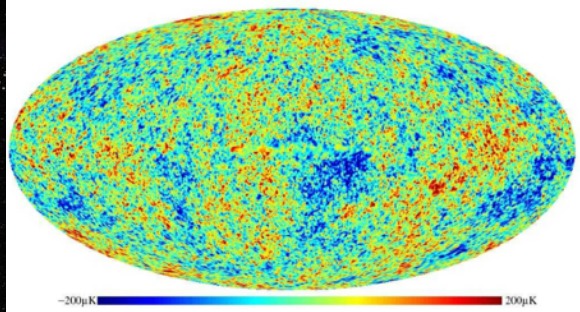
Dark Matter evidence

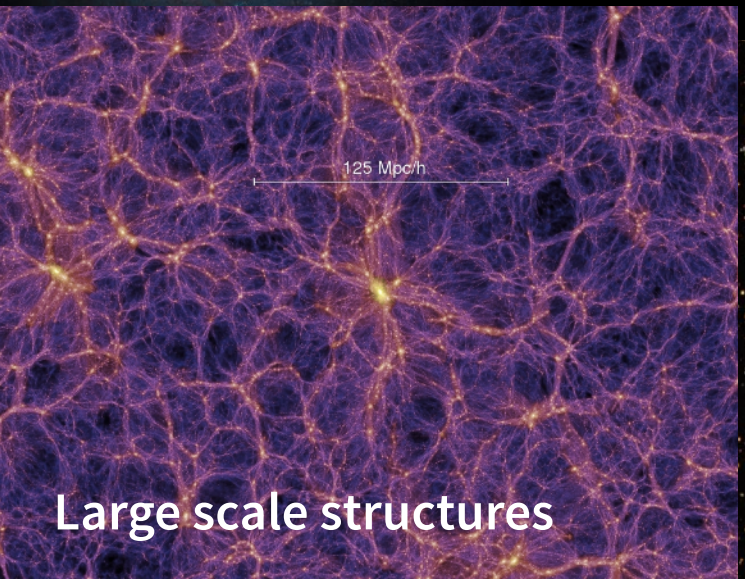
Compelling evidence of Dark Matter existence from astrophysical measurements

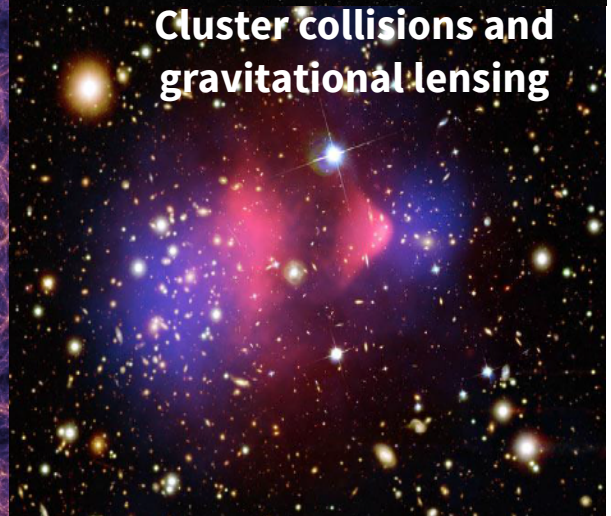




Cosmic Microwave Background radiation







Strong evidence for new physics

First Hints of Dark Matter: 30s

1933: Zwicky measured galaxies velocity in the Coma Cluster

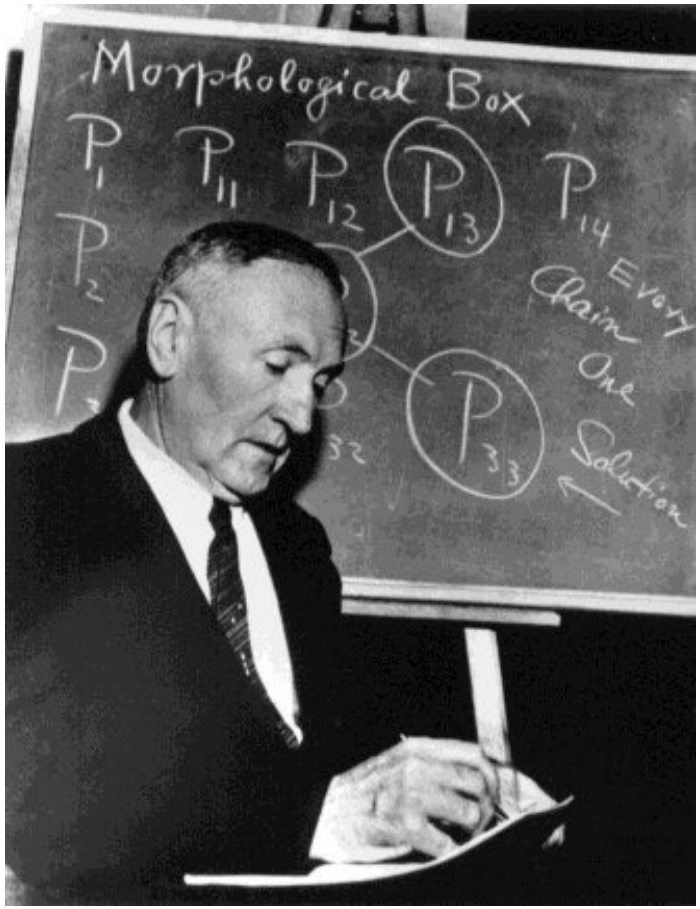
Virial Theorem: $2K = -U$

where:

$$k = \frac{1}{2} M \langle v \rangle^2 \qquad U = \frac{G\ M}{R}$$

Excess in direct mass measurement observed wrt luminosity-based measurements: M~10 M_L

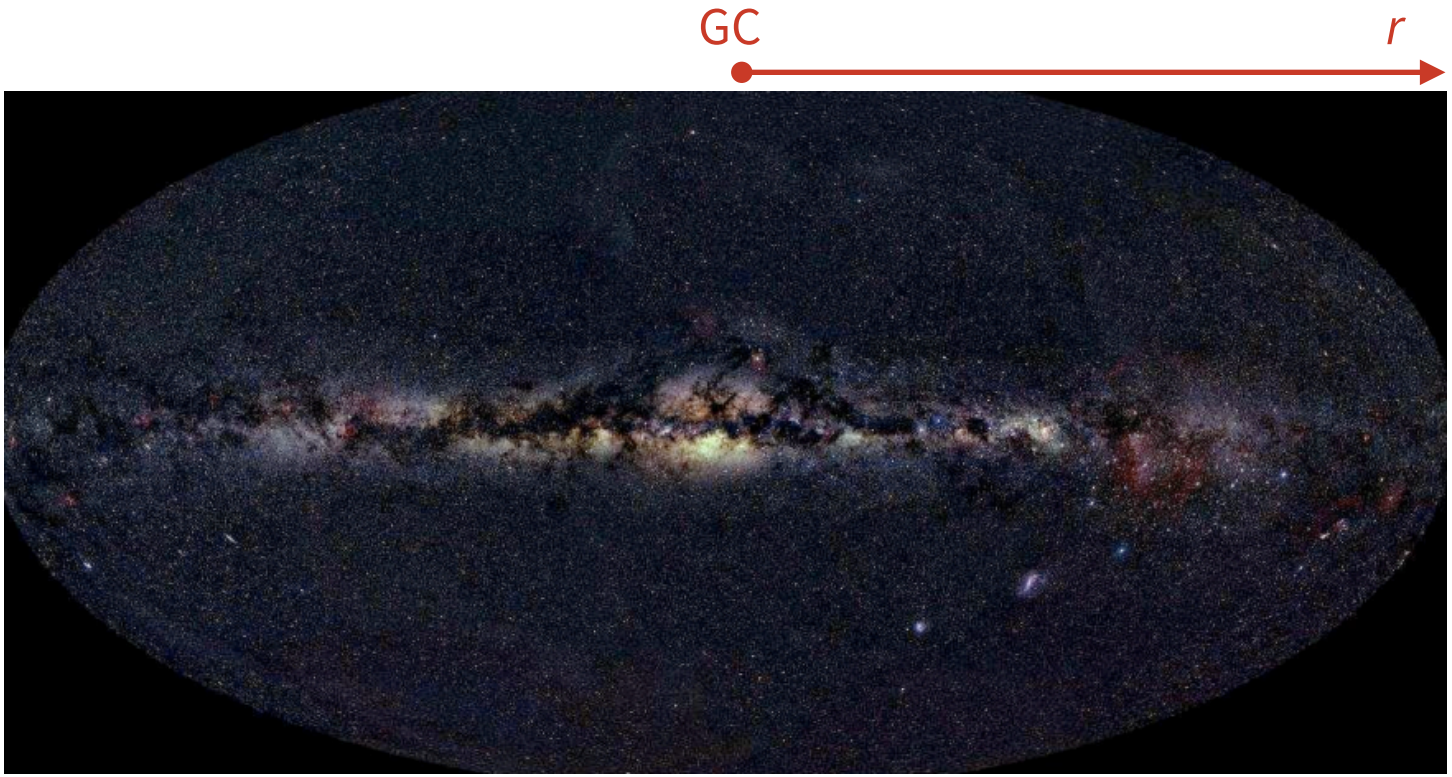
Bulk of matter is DARK



Rotation curves of spiral galaxies

Galactic Rotation Curve: Starts and gas movement within a galaxy depends on the distance r to the Galactic Centre (GC)

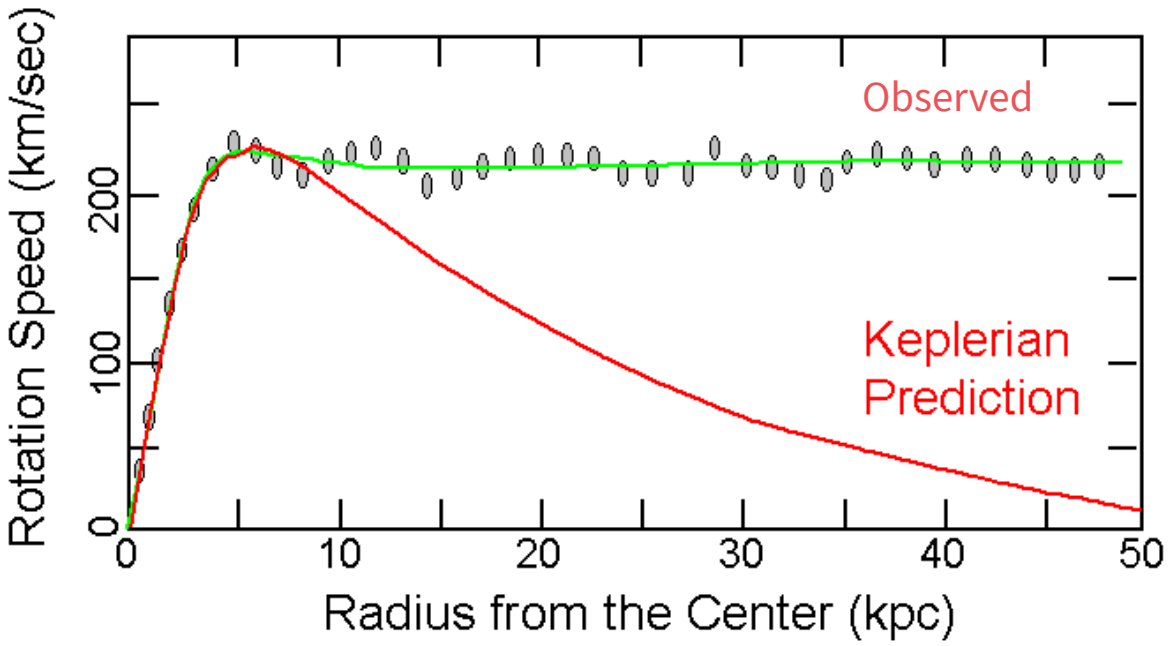
Newtonian expectation at large radii: $v_r(r) \propto 1/\sqrt{(r)}$



Rotation curves of spiral galaxies

Galactic Rotation Curve: Starts and gas movement within a galaxy depends on the distance r to the Galactic Centre (GC)

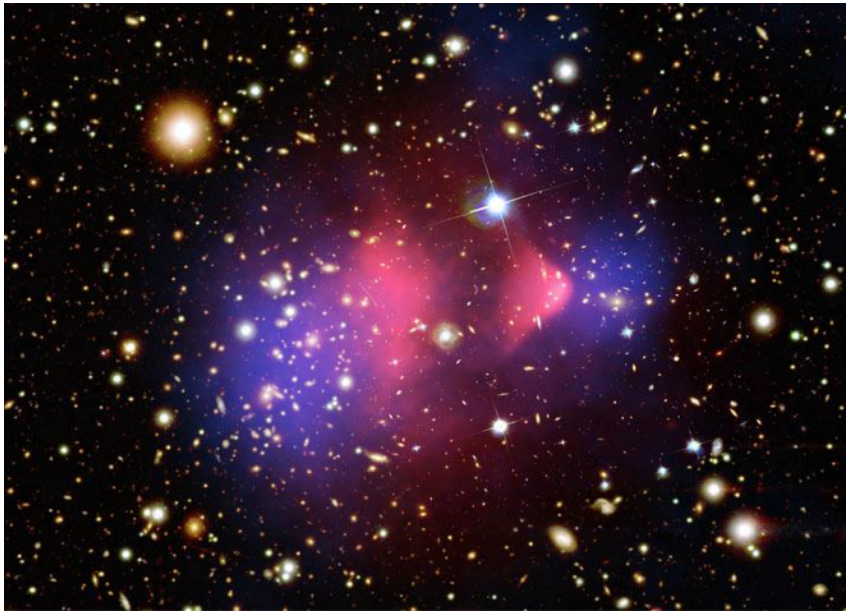
Observed behaviour: $v_r(r \geq R_0) \sim \text{const}$



Non-visible mass component which increases with r must exist

$M(r) \propto R$

What's Dark Matter?



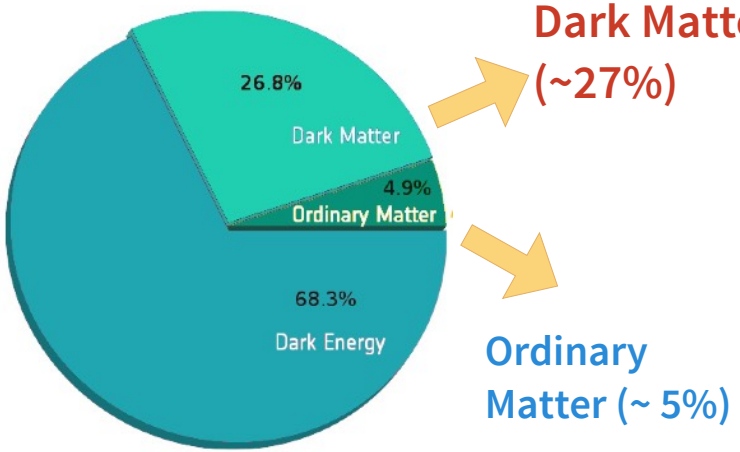
?



Only ~5% of the Universe is known

The rest is unknown

No experimental evidence of DM nature yet



Non-BSM candidates

Possible non-BSM solutions to DM puzzle:

1. Modified Newtonian dynamics (MOND)

   → Difficulty in reproducing all features of CMB anisotropy spectrum and explanation of the bullet cluster dynamics

Non-BSM candidates

Possible non-BSM solutions to DM puzzle:

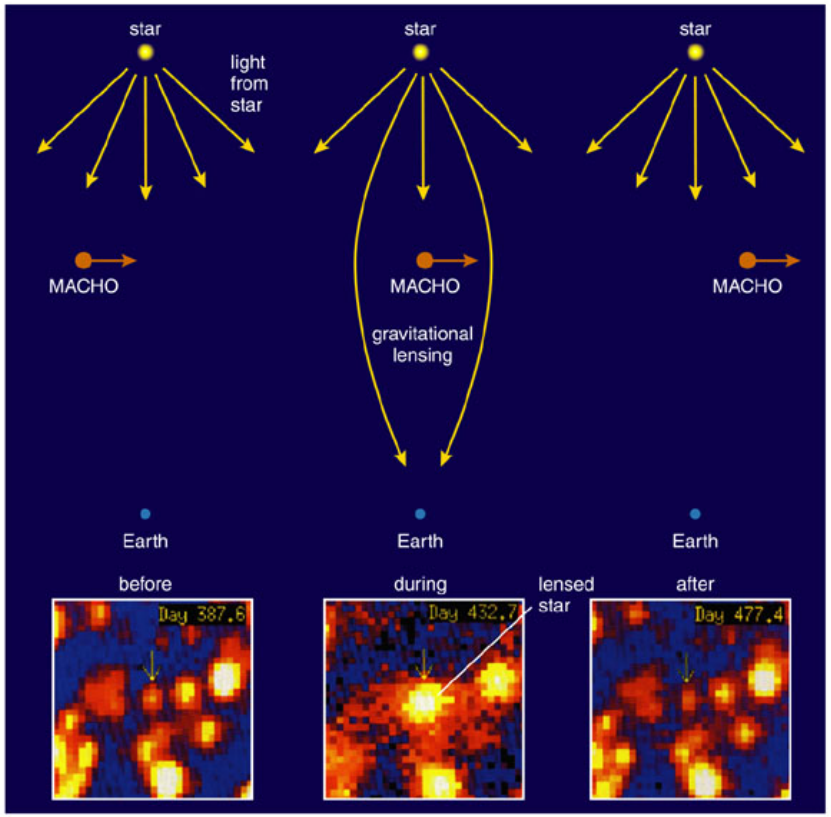
1. Modified Newtonian dynamics (MOND)

   → Difficulty in reproducing all features of CMB anisotropy spectrum and explanation of the bullet cluster dynamics

2. Massive astrophysical compact halo objects (MACHOs): neutron stars, brown dwarfs or unassociated planets that would emit little to no radiation, detected via micro-lensing effects.

   → Could explain only up to 20% of DM in our galaxy
   → Baryonic nature of DM also ruled out by Big-Bang nucleosynthesis model

gravitational micro-lensing for MACHOs detection



Non-BSM candidates

Possible non-BSM solutions to DM puzzle:

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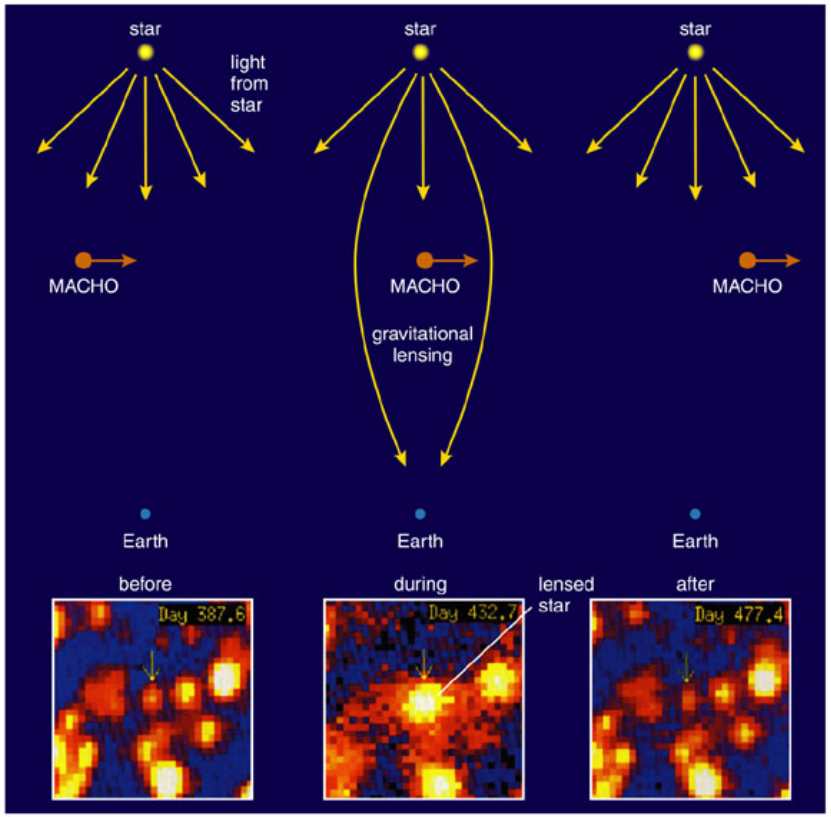
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3. SM Neutrinos ?

gravitational micro-lensing for MACHOs detection



Non-BSM candidates: neutrinos ?

Standard Model neutrinos were considered in the past possible DM candidates, for their “undisputed virtue of been known to exist”

Non-BSM candidates: neutrinos ?

Standard Model neutrinos were considered in the past possible DM candidates, for their "undisputed virtue of been known to exist"

Neutrinos make a contribution to the energy density of the Universe given by

$$\Omega_\nu h^2 = \frac{m_{tot}}{94\,\mathrm{eV}}$$

m_{tot} the sum of the individual masses of all neutrino species

To fulfill direct limit on the DM abundance ($\Omega_{DM}\, h^2 \sim 0.12$) $\Rightarrow$ $m_{tot} \sim 11$ eV

Current direct measurement of electron neutrino: $m_{\nu e} < 2.05$ eV

This must hold true also for the other neutrino families, because from neutrino oscillations experiments:

- $\Delta m_{sol}^2 \sim 7 \times 10^{-5}$ eV^2
- $\Delta m_{atm}^2 \sim 3 \times 10^{-3}$ eV^2

$\Rightarrow$ SM neutrinos not massive enough to make up DM

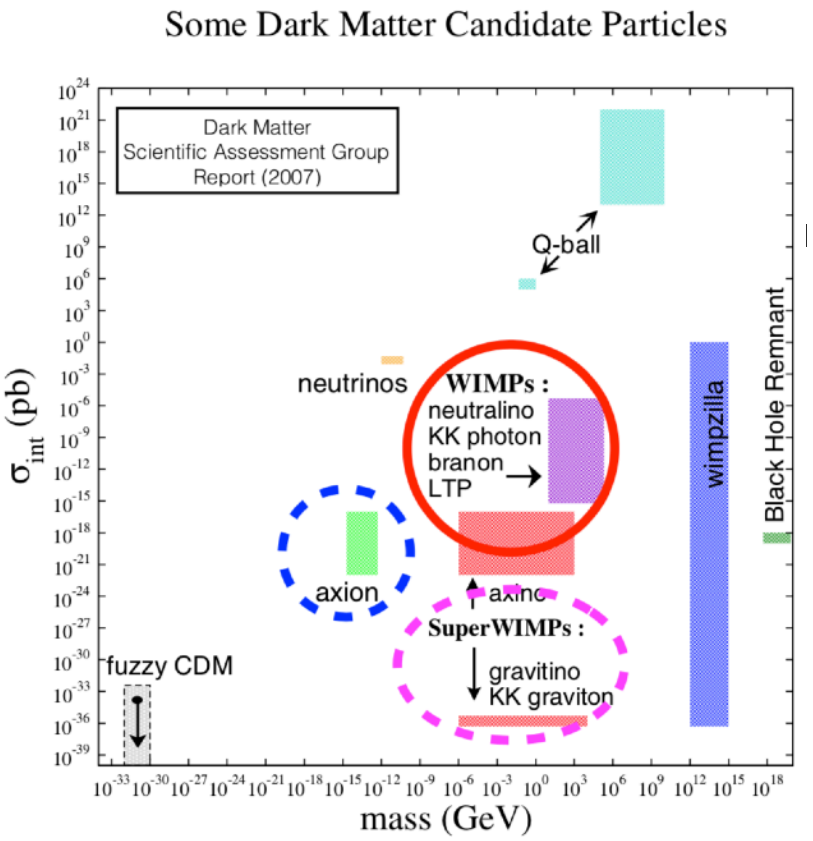
Moreover, if DM was relativistic, it would tend to spread out large scale structure in the Universe

- from galaxy surveys it is excluded that all DM is relativistic

BSM candidates

DM candidate must be massive, optically dark, neutral, interact very weakly with other SM particles, stable over the age of the Universe and its predicted abundance must match observed Ω_{DM}

- A wealth of candidates have been proposed with these characteristics !



WIMPs (weakly interacting massive particles) are one of the many possibilities:

- thermally produced in the early Universe
- mass in the GeV-TeV regime
- coupling "weakly" with the particles of the SM

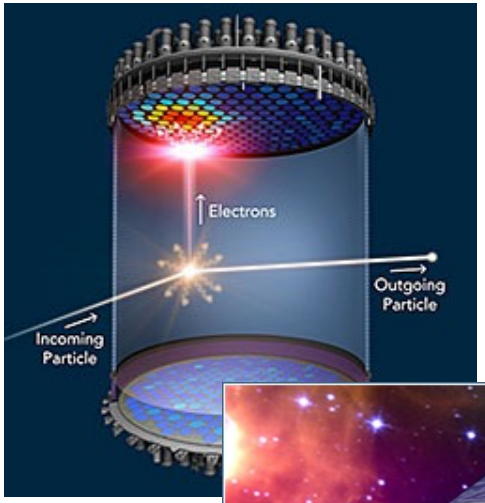
=> naturally have the correct Ω_{DM}

WIMPs are accessible to colliders, direct and indirect detection experiments

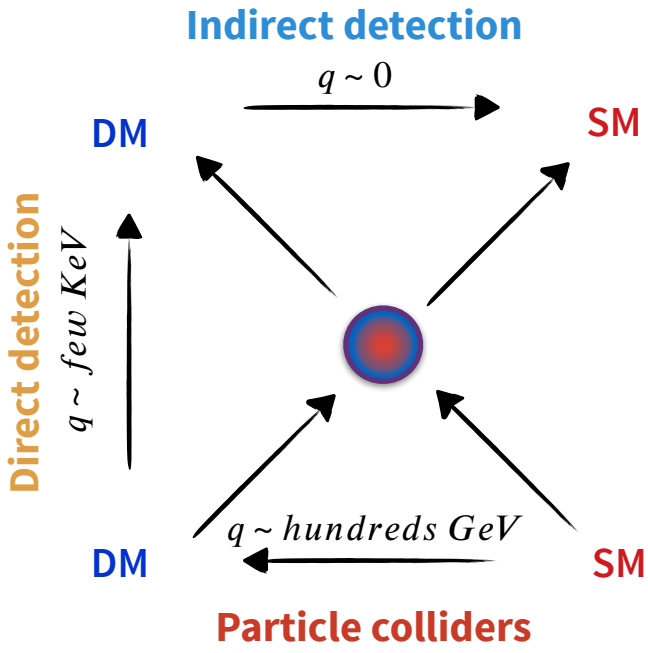
Supersymmetric LSP is a WIMP, but other BSM models predict WIMPs!

Probing Dark Matter

- Three main strategies to search for weakly interacting DM
  - Direct detection
  - Indirect detection
  - Production at particle colliders

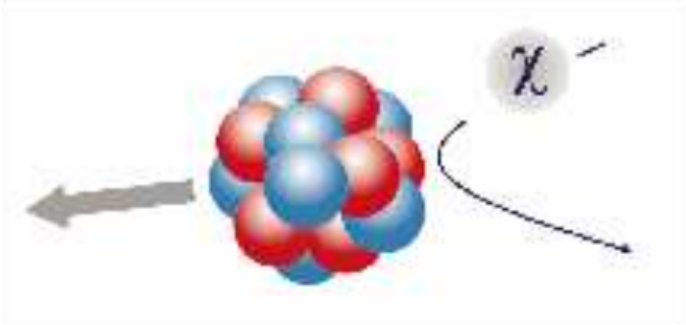








Direct detection experiments



DD experiments measure the nuclear recoil after WIMP-nucleus elastic scattering in a large detector volume

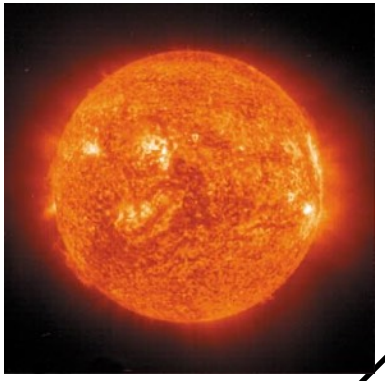
Direct detection experiments

DD experiments aim to observe dark matter scattering off nuclei in underground detectors

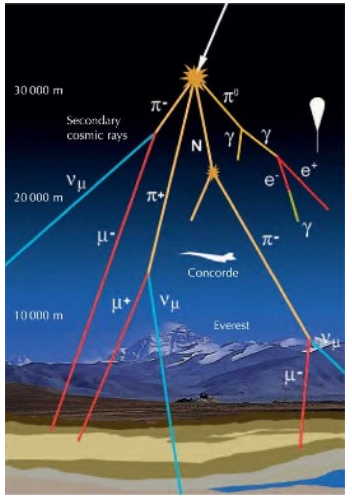
Space

Cosmic rays plus solar neutrinos





cosmic rays

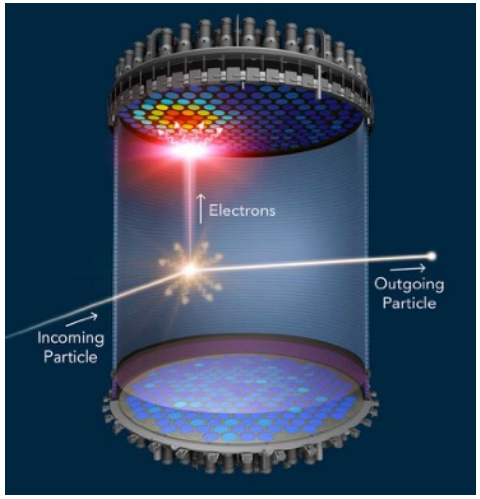


WIMPs

ν

Undeground

Shielding cosmic rays leaving only WIMPs and neutrinos traversing



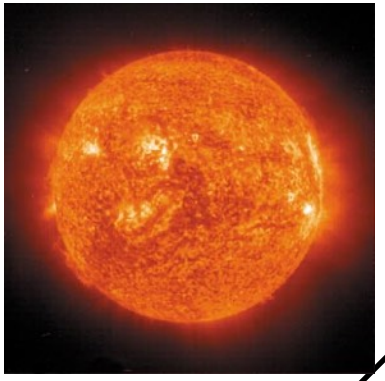
WIMPs

Direct detection experiments

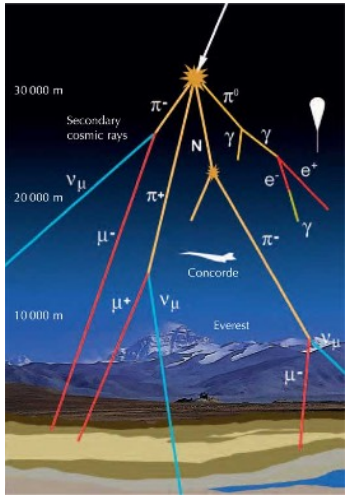
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Space





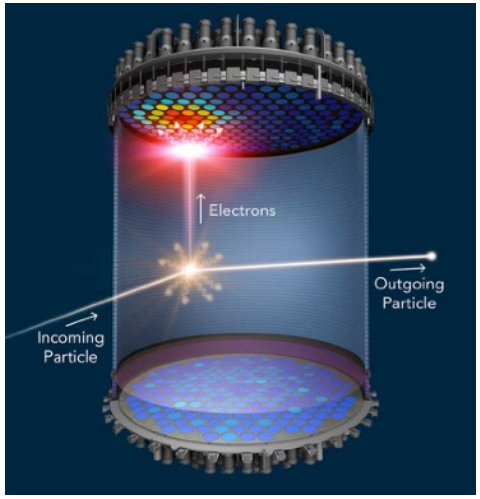
cosmic rays



WIMPs

ν

Undeground



WIMPs

< 50 KeV recoil for WIMPs with mass in the GeV-TeV range

<1 evt per kg per year

Measure the **nuclei recoil energy** distribution transformed into ionisation, scintillation light or phonons

Major sources of background

Signal: few KeV nuclear recoil

Signal: $\chi\, N \rightarrow \chi\, N$

ɣ, β radiation from natural radioactivity
⇒ Electrons from β decay or from compton/photo-electric (ɣ)
⇒ **"electronic"** recoil in the detector

Neutron scattering from cosmic muon spallation or neutrons from natural radioactivity
⇒ **"nuclear"** recoil

Backgrounds:
$\gamma\, e^- \rightarrow \gamma\, e^-$
$n\, N \rightarrow n\, N$
$N \rightarrow N' + \alpha, e^-$
$\nu\, N \rightarrow \nu\, N$

Solar and atmospheric neutrinos
⇒ **"nuclear"** recoil from elastic neutrino scattering

General design principles

- Shielding from cosmic and natural background
- Ultra-high radio-purity of all involved passive and active detector materials
- Extra coincidence detectors
- Reduce thermal noise

Reduce background rate

General design principles

- Shielding from cosmic and natural background
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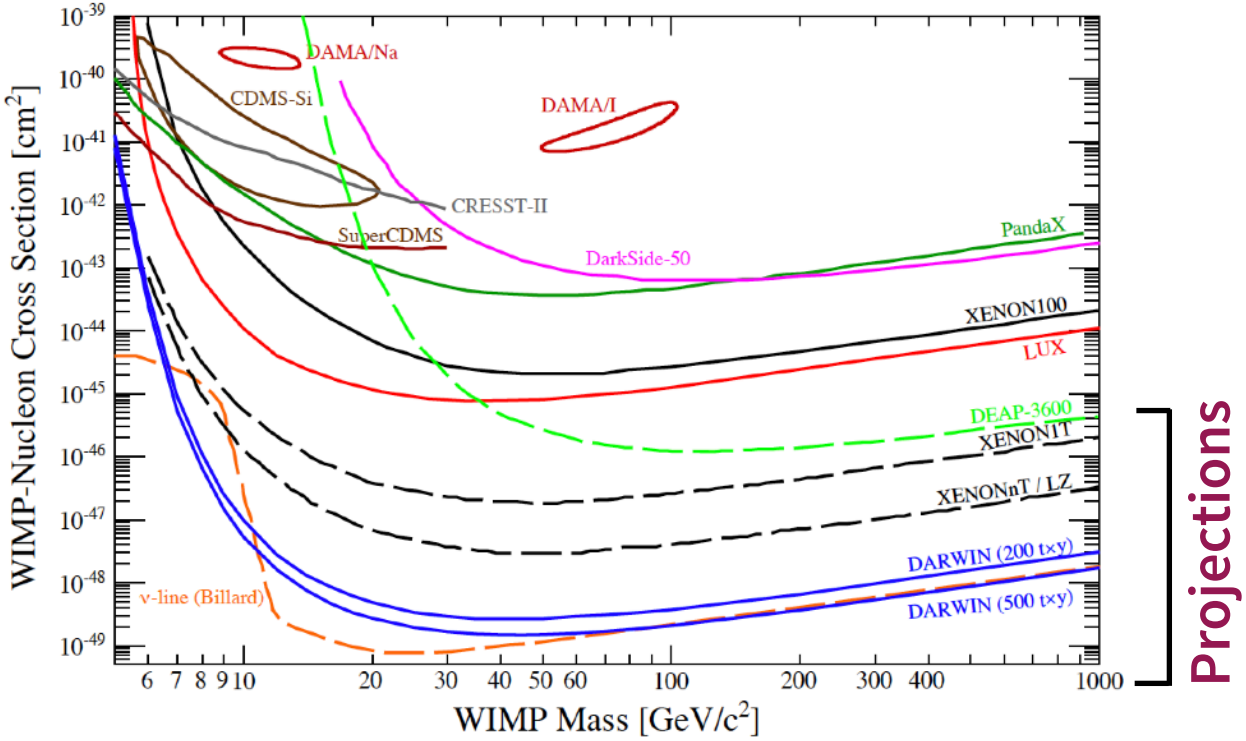
Reduce background rate

- Massive detector and very long data-taking periods
- As sensitive detector as possible

Increase signal rate

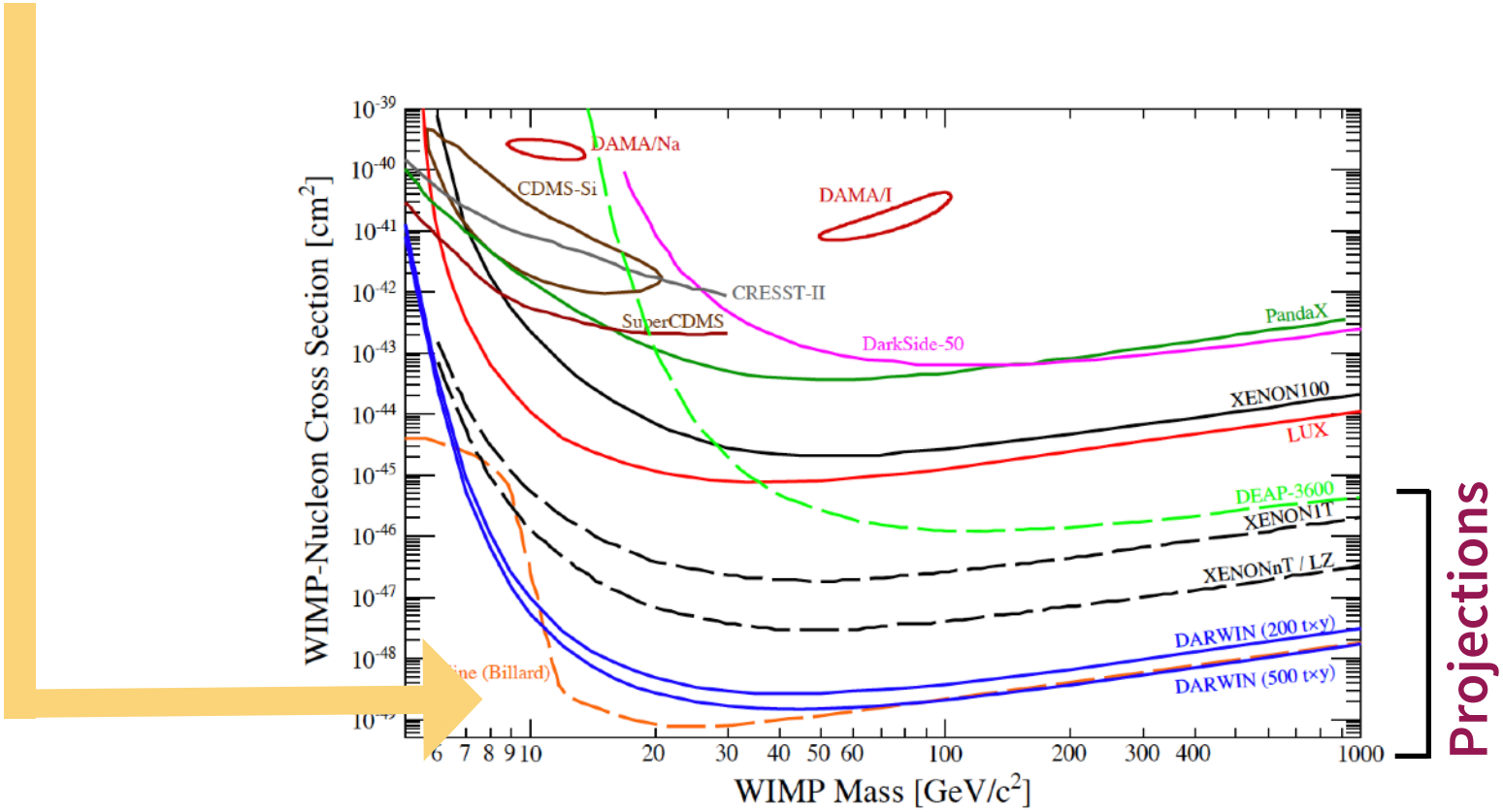
Direct detection experiments

- DD experiments characterised by:
  - Ultra-low background noise
  - Low energy thresholds
  - Large targets



Direct detection experiments

Irreducible background from solar neutrino-induced nuclear recoils limits the cross section sensitivity to low WIMP mass



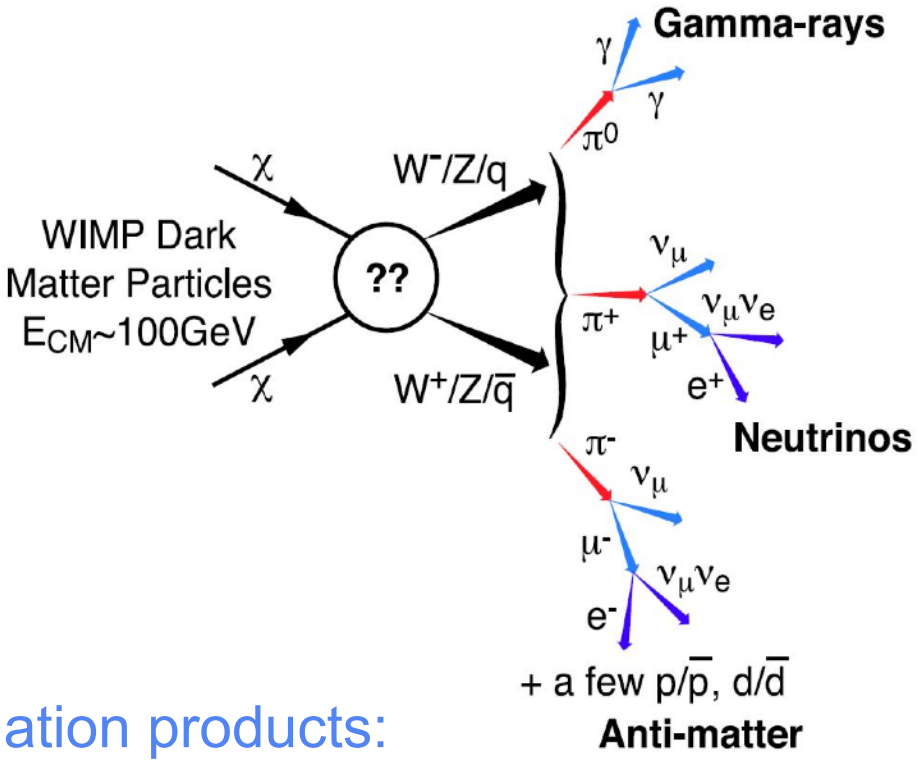
Indirect detection experiments

Relic χ's are gravitationally captured by massive astrophysical bodies, or dense regions of the galactic halo

Indirect detection experiments

Relic χ's are gravitationally captured by massive astrophysical bodies, or dense regions of the galactic halo

χ's can annihilate and be observed via their annihilation products

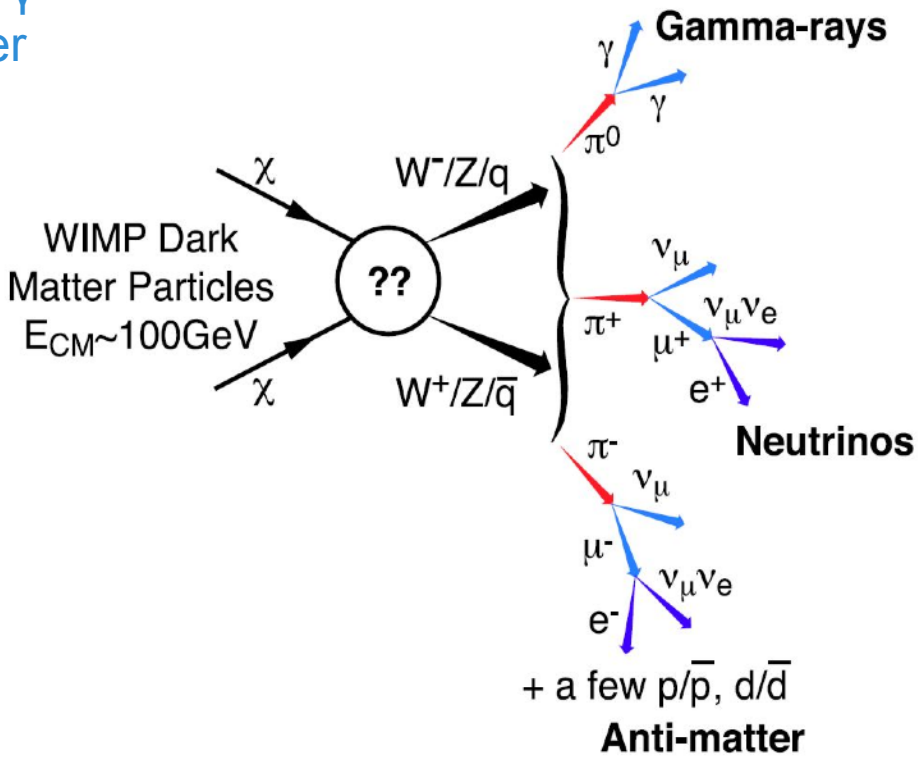


Indirect detection - via $\chi\chi$ annihilation products:

$\chi\chi \rightarrow$ ν's, γ's, positrons, …

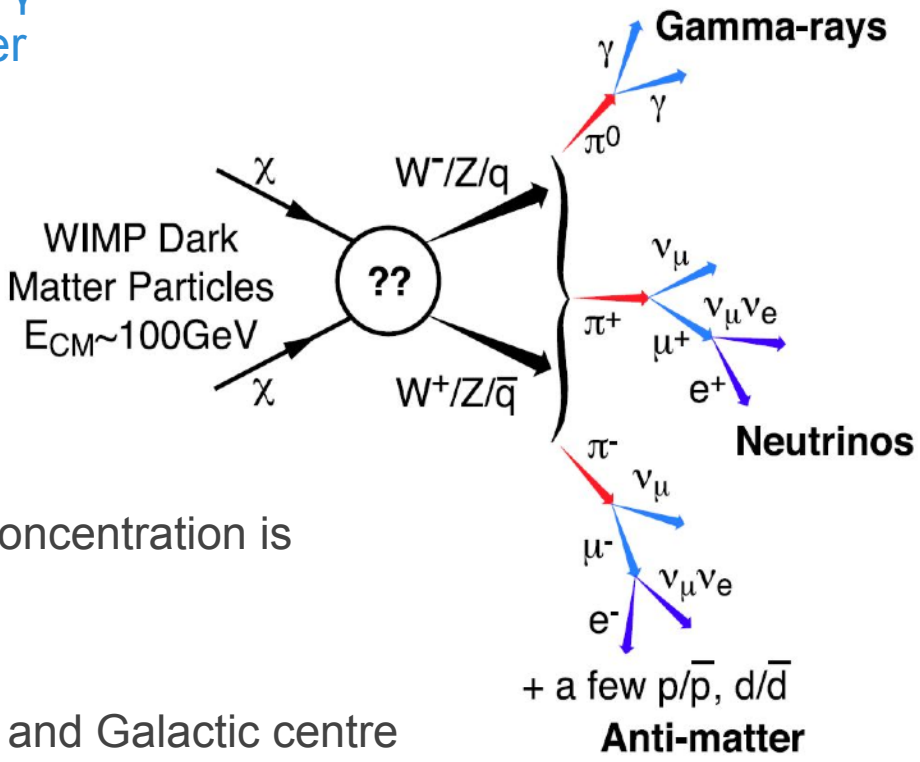
Indirect detection experiments

ID experiments aim to identify DM annihilation products looking for excess of γ-rays/cosmic-rays/neutrinos/anti-matter over astrophysical background



Indirect detection experiments

ID experiments aim to identify DM annihilation products looking for excess of γ-rays/cosmic-rays/neutrinos/anti-matter over astrophysical background



Annihilation flux proportional to $(\rho_W/m_W)2$

- favourite regions are those where WIMP concentration is expected to be higher

Potential signatures

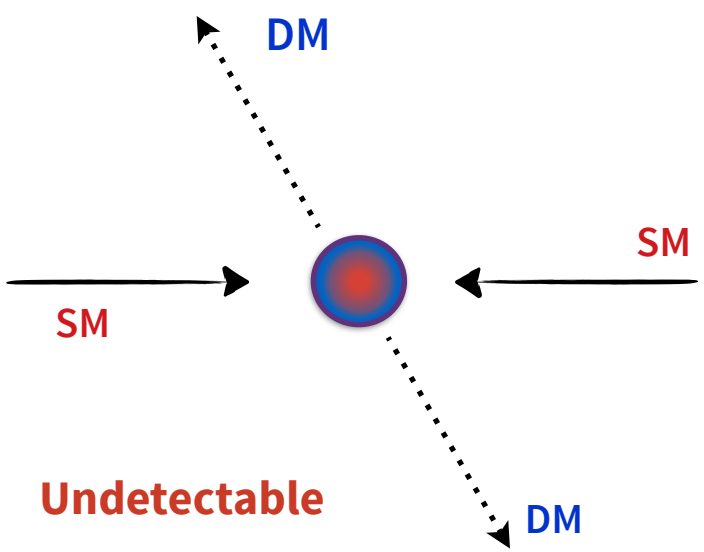
- high energy neutrinos from the Sun's core and Galactic centre
- gamma-rays from Galactic centre and dwarf spheroidal galaxies
- positrons, antiprotons and antideuterons from galactic halo

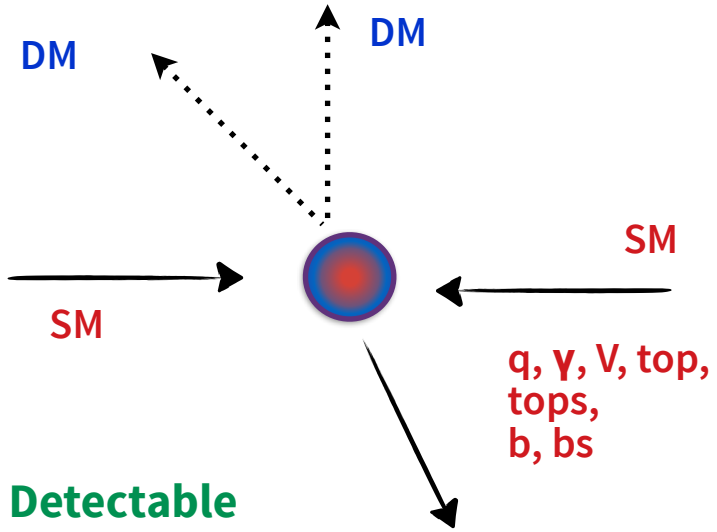
Producing DM at particle colliders

In particle collisions DM would be produced directly and in pairs

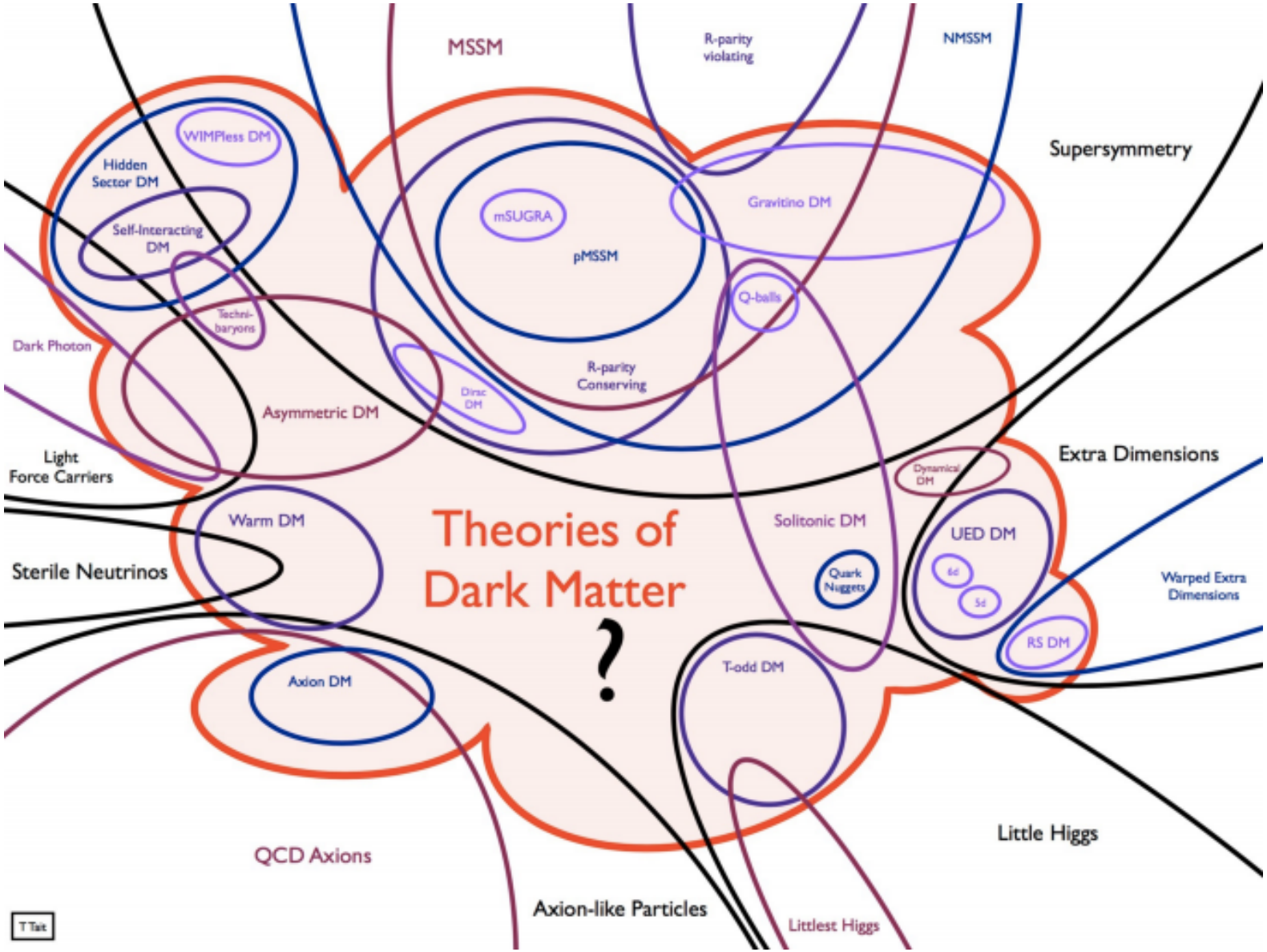
- **Dark Matter particles invisible to the detector**
- Infer its production by measuring energy imbalance in the detectors
  - Missing transverse energy, $E_T^{miss} = \sqrt{\left(\sum_n E_x\right)^2 + \left(\sum_n E_y\right)^2}$
- Visible objects used to flag DM production

Search for DM in the tails of MET spectrum





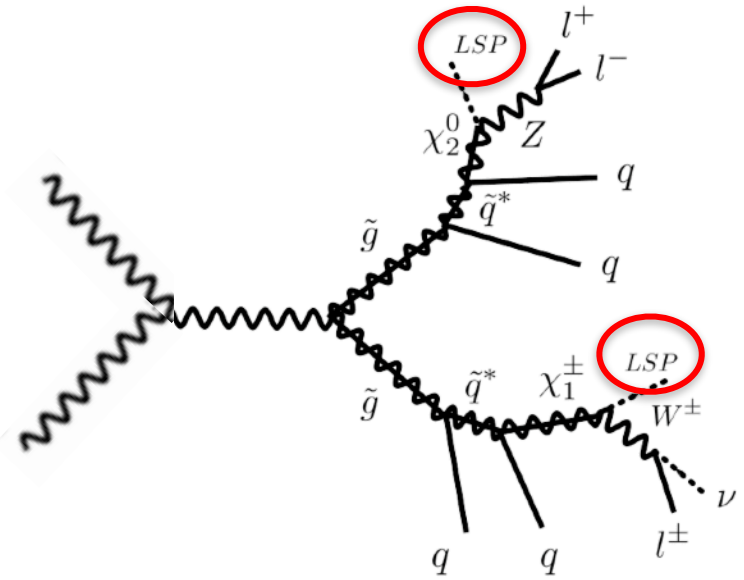
A theory of Dark Matter?



Tim Tait

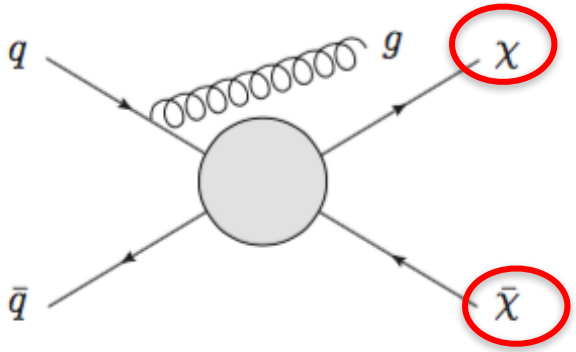
A theory of Dark Matter?

DM-candidates produced in the decay cascades of particles (e.g. RPC SUSY)



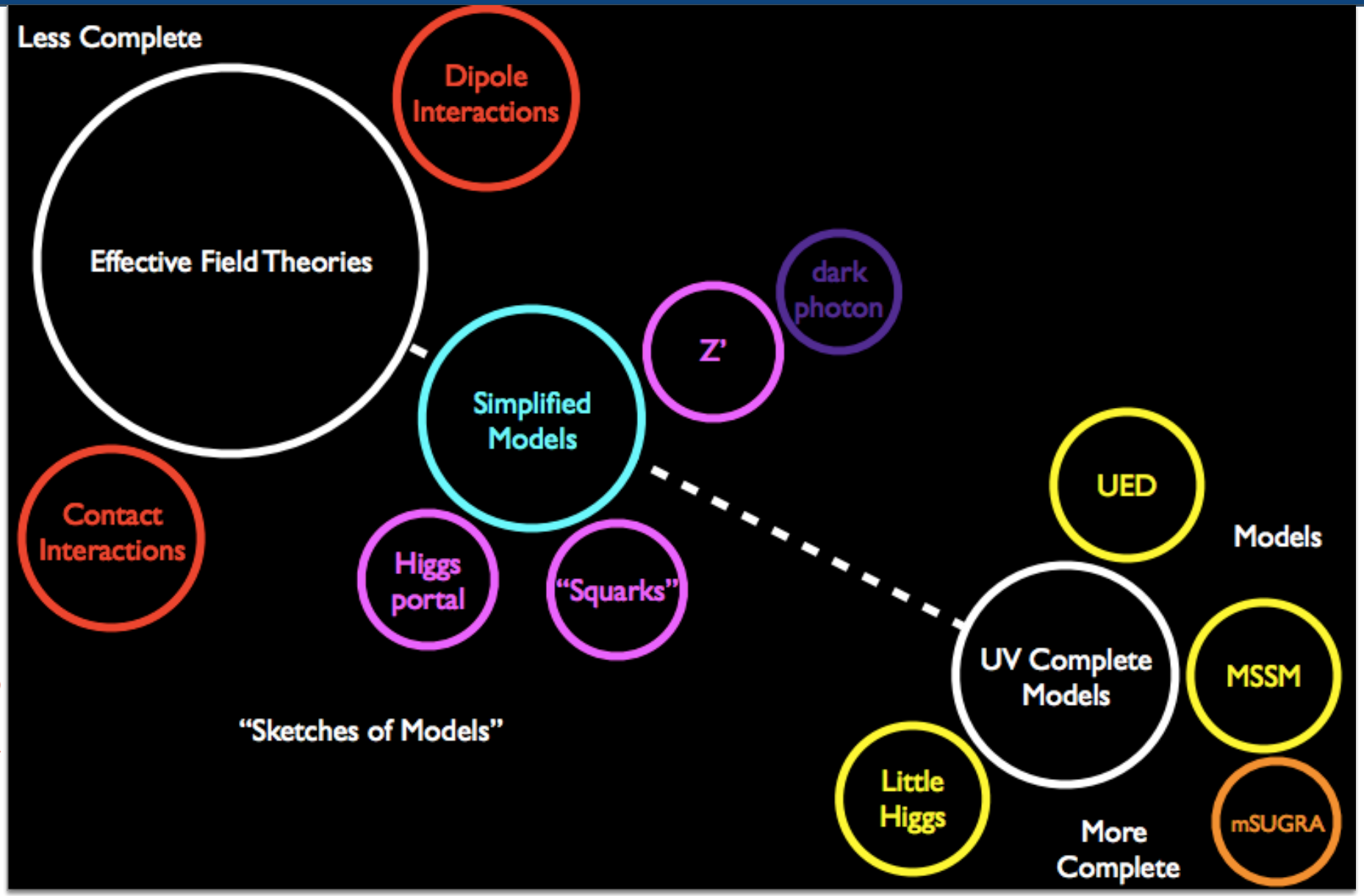
Exp signature:
large MET + hard jets + hard leptons

DM-candidate pairs produced directly



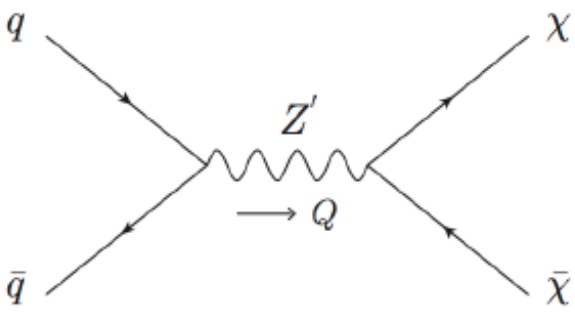
Exp signature:
MET+X (jet, V, H, tt, etc..)

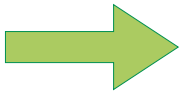
Theoretical approach

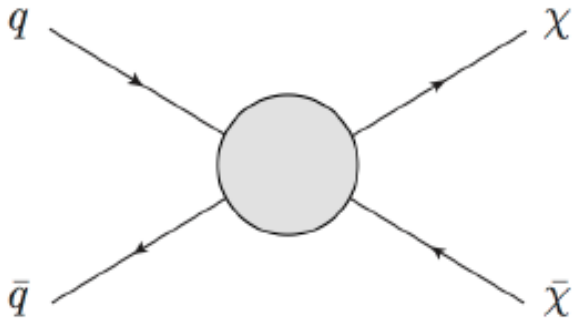


Theoretical approach: Effective Field Theory

Interpret the search in terms of Effective Field Theory (EFT)







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

2 theory parameters

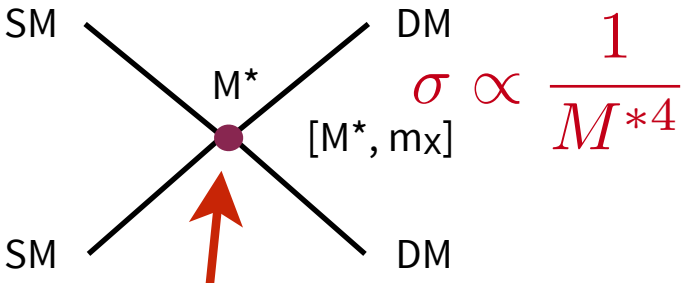
- Dark Matter particle mass m_χ
- Interaction scale $M^* = M_{med}/\sqrt{(g_\chi g_q)}$

Plus interaction nature

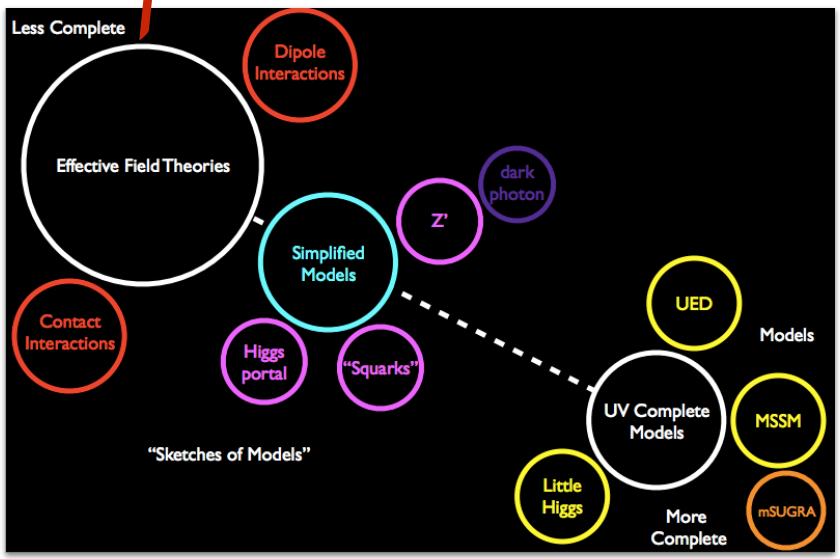
Beyond EFT: Simplified models

EFT approach adopted for first DM interpretations at LHC

Limited validity at high energies, when transferred momentum > M_{med}



$$\sigma \propto \frac{1}{M^{*4}}$$

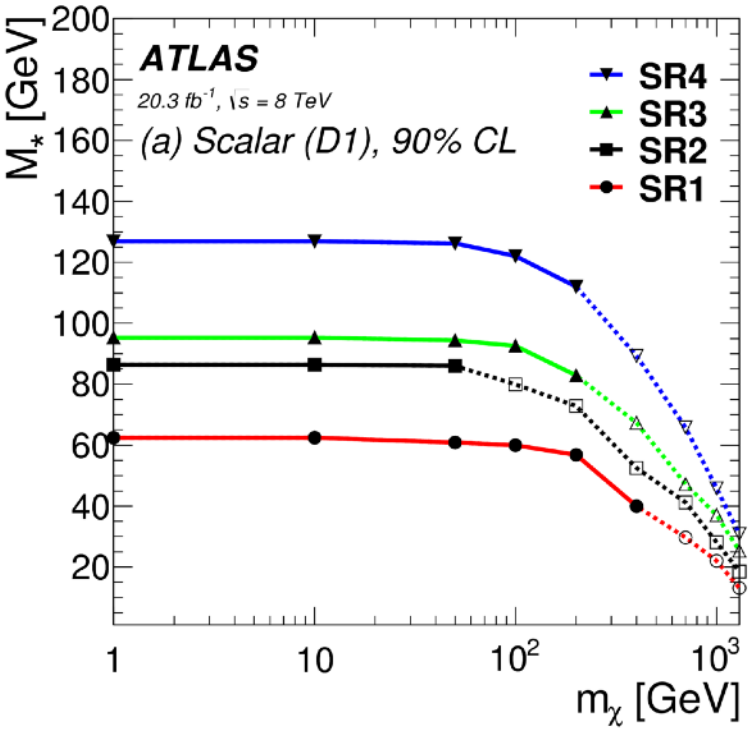


Tim Tait, DM@LHC 2013

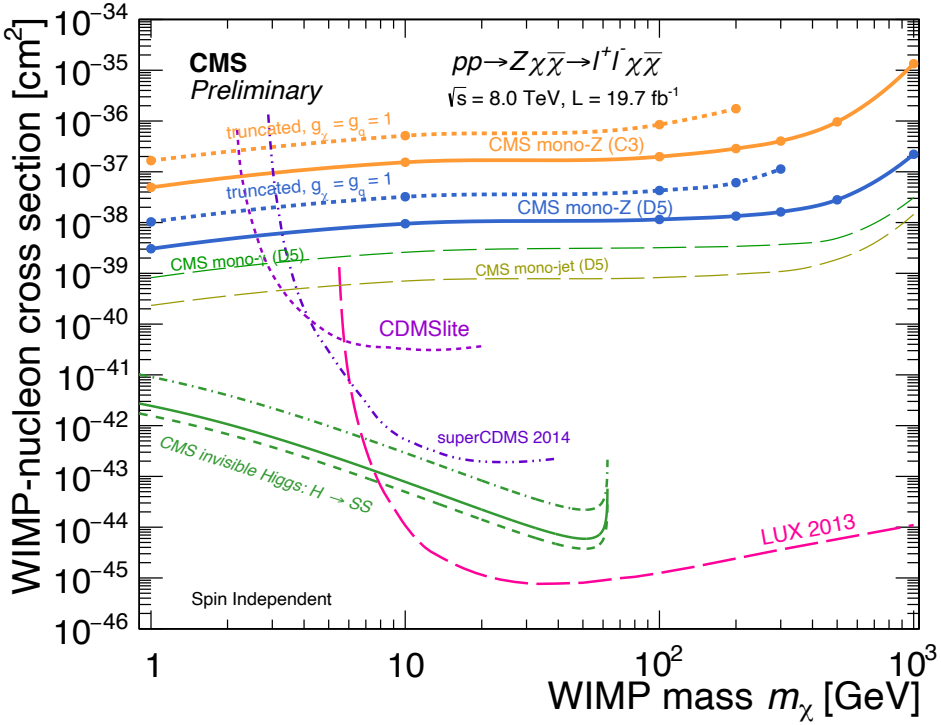
Comparison to DD experiments

EFT allow a comparison to direct detection searches

Constraint on M*



Constraint on σ_{DM-n}



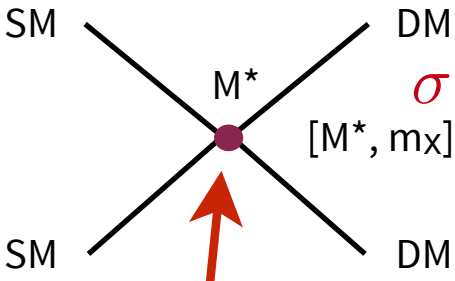
Collider searches sensitive to low DM mass region

Complementarity to DD experiments

Beyond EFT: Simplified models

EFT approach adopted for first DM interpretations at LHC

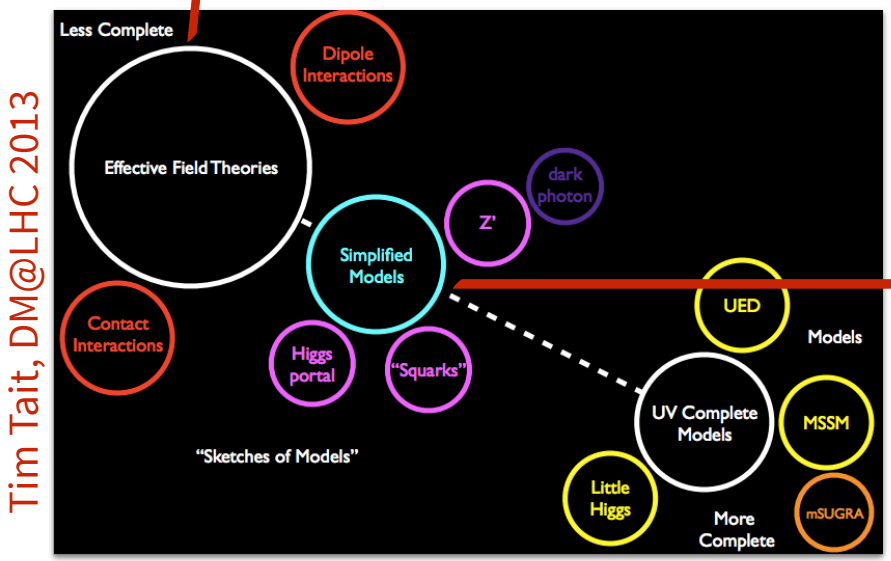
Limited validity at high energies, when transferred momentum > M_{med}



$$\sigma \propto \frac{1}{M^{*4}}$$

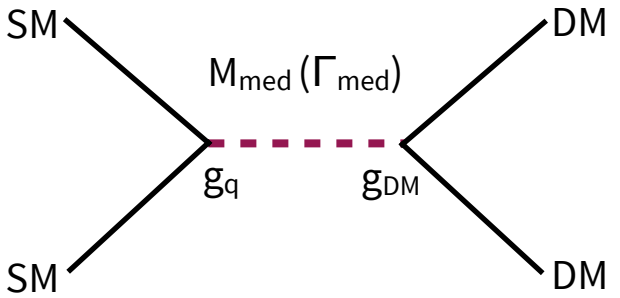
Moved to simplified models to overcome validity issues

Including mediating particles

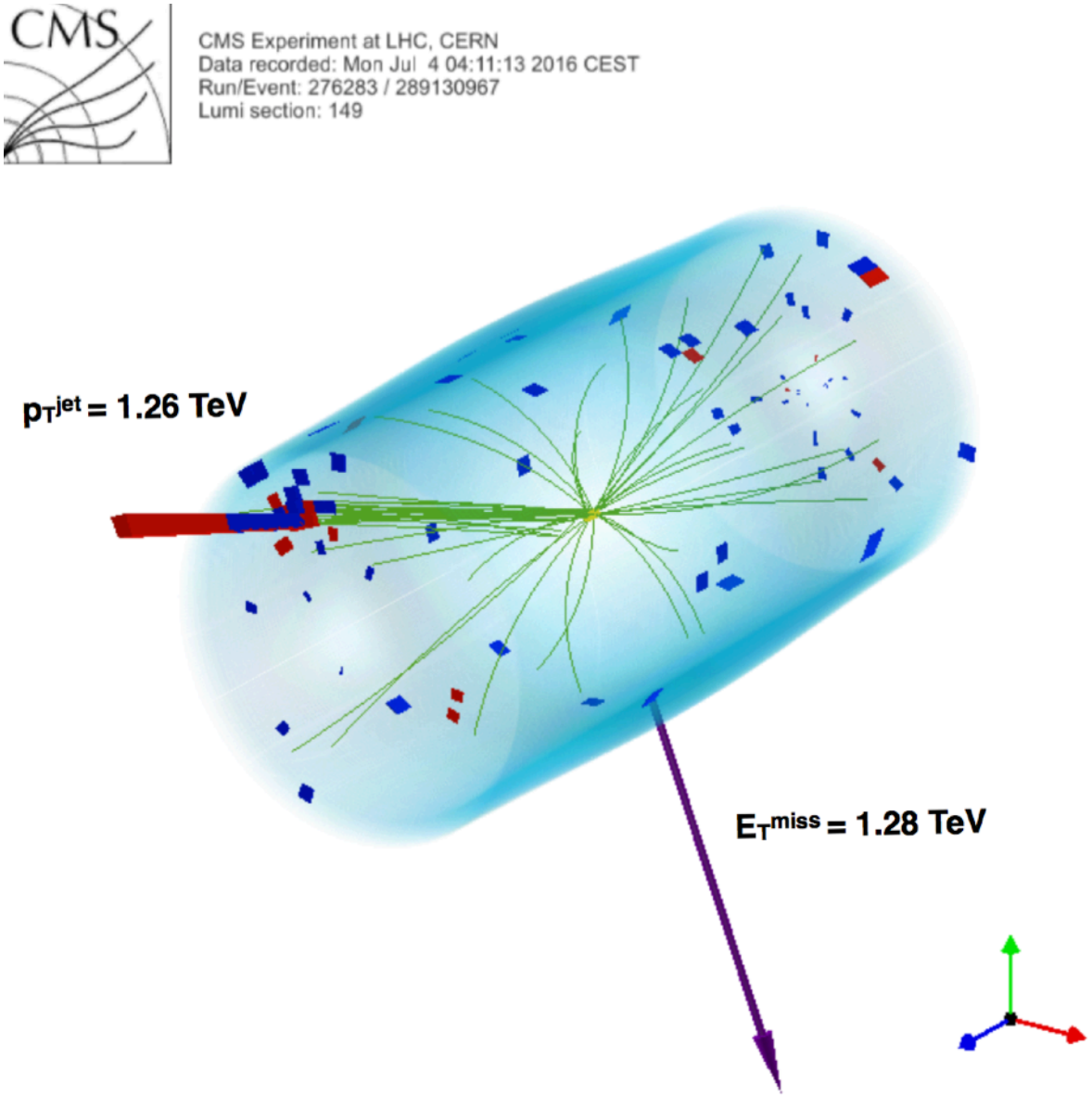


$$\sigma \propto \frac{g_{SM}^2 g_{DM}^2}{M_{med}^4}$$

$[M_{med}, \Gamma_{min}, m_X, g_{SM}, g_{DM}]$



Experimental approach



Experimental Approach to DM searches

Select events with large amount of missing momentum

Indicates production of DM particles



Use reconstructed visible objects to flag DM production

Jet/s from ISR, Vector bosons (W, Z), Higgs boson, other visible particles



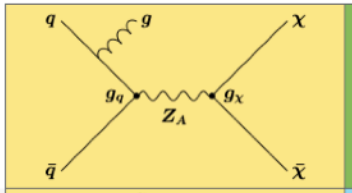
Estimate backgrounds from data

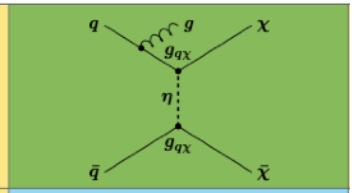


Interpret search results

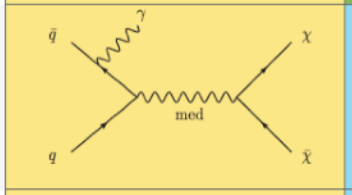
Production at particle colliders

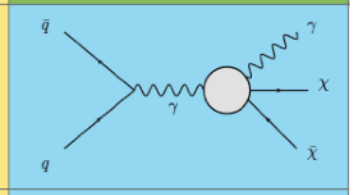
Mono-Jet



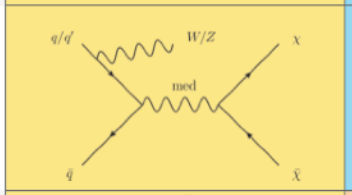


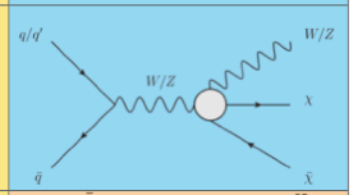
Mono-Photon



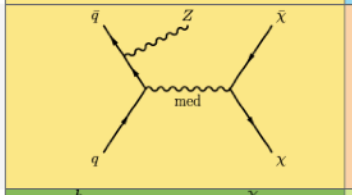


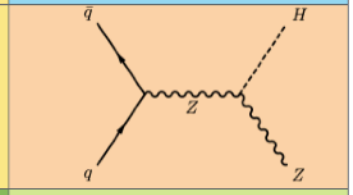
Mono-W/Z hadronic



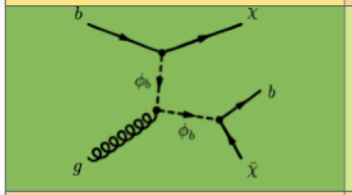


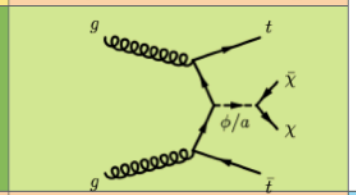
Mono-Z(ll)



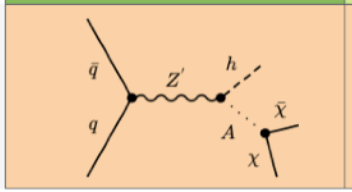


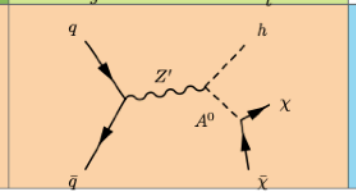
Mono-HF

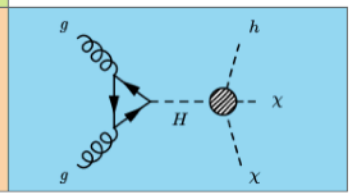




Mono-H





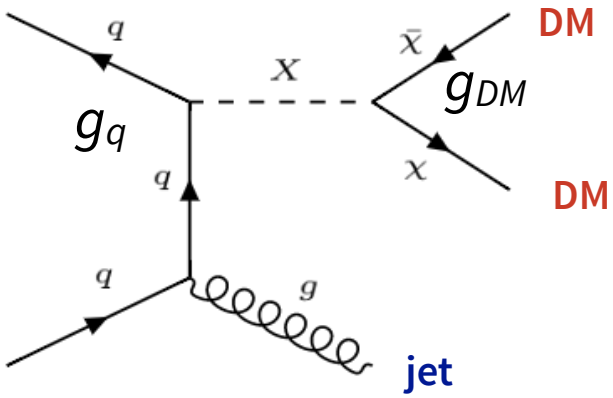


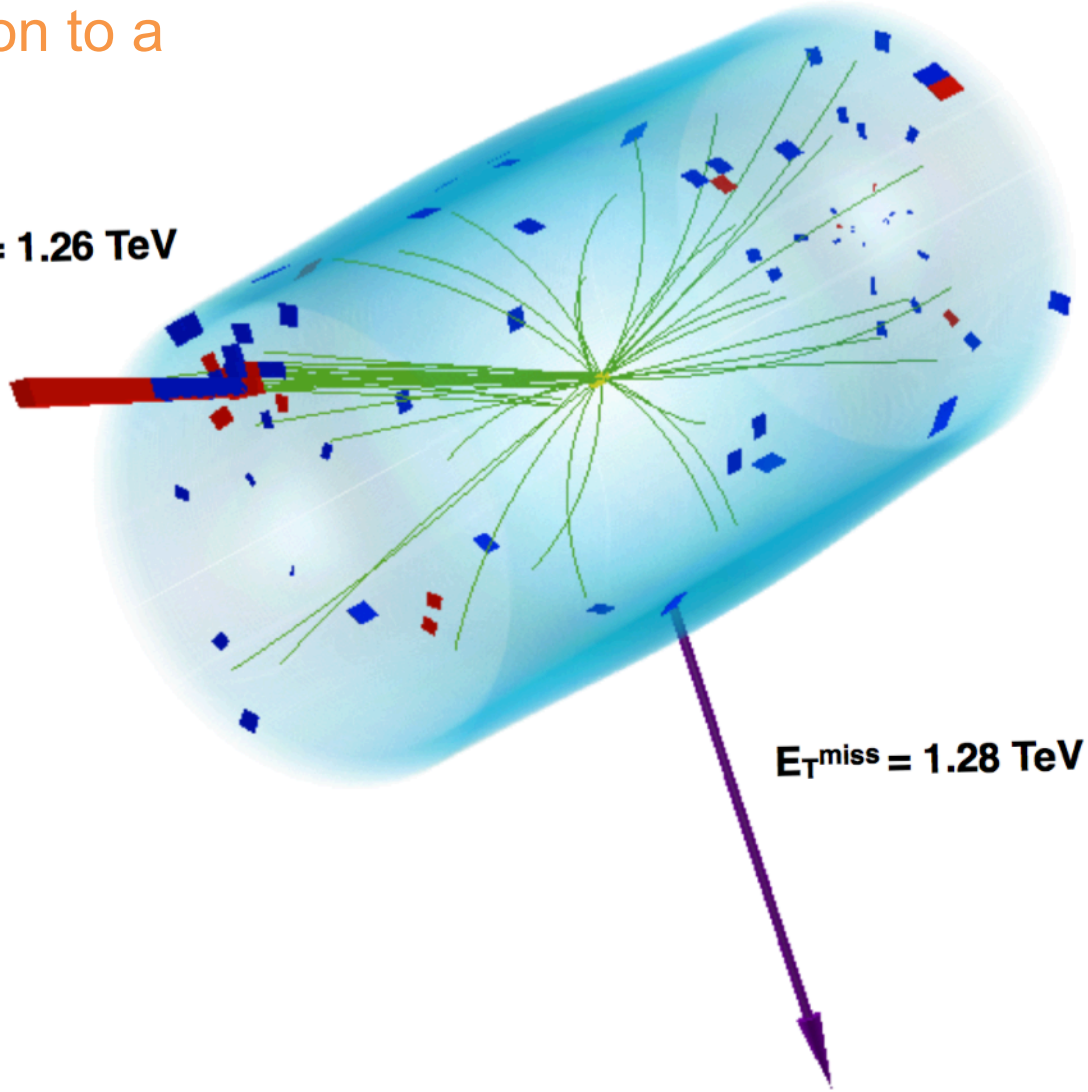
Examples of simplified/EFT models for Mono-X searches

	Properties of the new Mediator		
Model Type	**spin**	**parity**	**color**
Simpli	1	+1, -1	neutral
Simpli	0	+1, -1	neutral
Simpli	0	+1	charged
Simpli	Models involving Higgs boson and/ or additional Higgs bosons		
EFT	effective field theory operators		

Mono Jet: MET + Jet

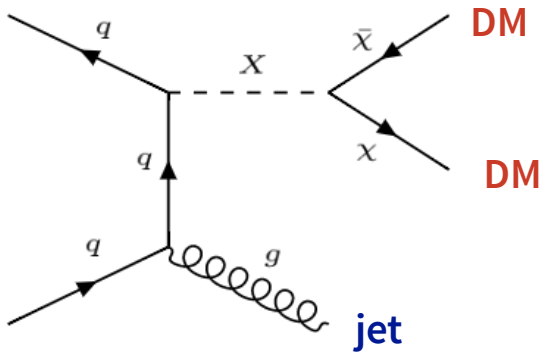
Hard jet/s from initial state radiation (ISR) produced in association to a pair of DM particles





Mono Jet search

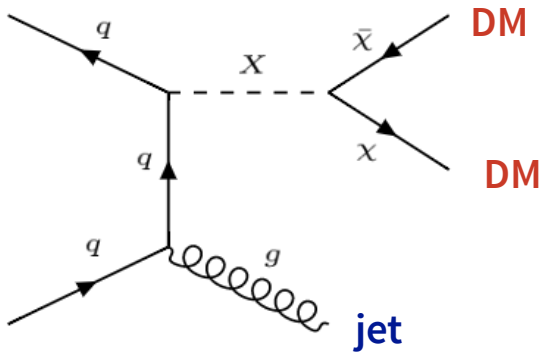
- WIMP particles recoiling against jet from ISR
- Channel highly sensitive to WIMP production
    - High gluon production cross-section



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Mono Jet search

- WIMP particles recoiling against jet from ISR
- Channel highly sensitive to WIMP production
  - High gluon production cross-section

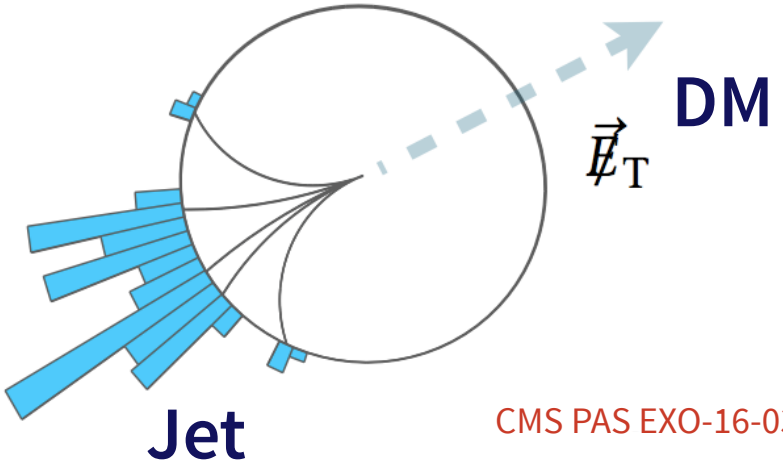


Signature: MET + JET

- At least 1 high p_T jet
- Large energy imbalance
- Large azimuthal opening angle between jet and MET
- No leptons or photons

Backgrounds: Z(vv)/W(lv)+jets

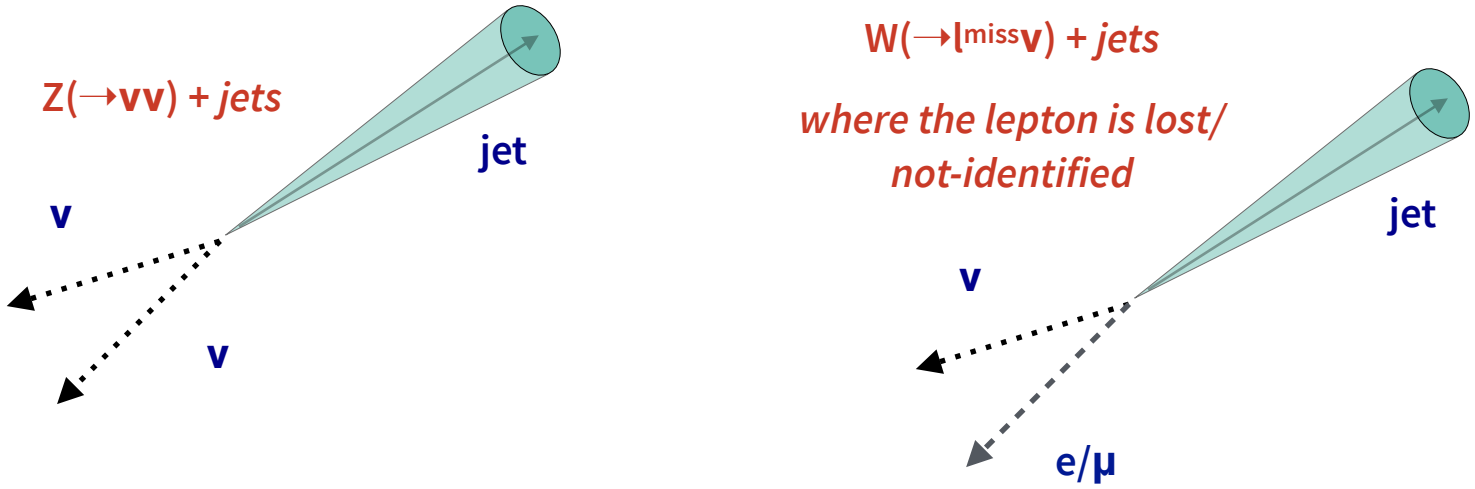
Key variable: E_T^{miss}



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EWK backgrounds

Z(→νν) + jets and W($l^{miss}\nu$) + jets ~90% of background events

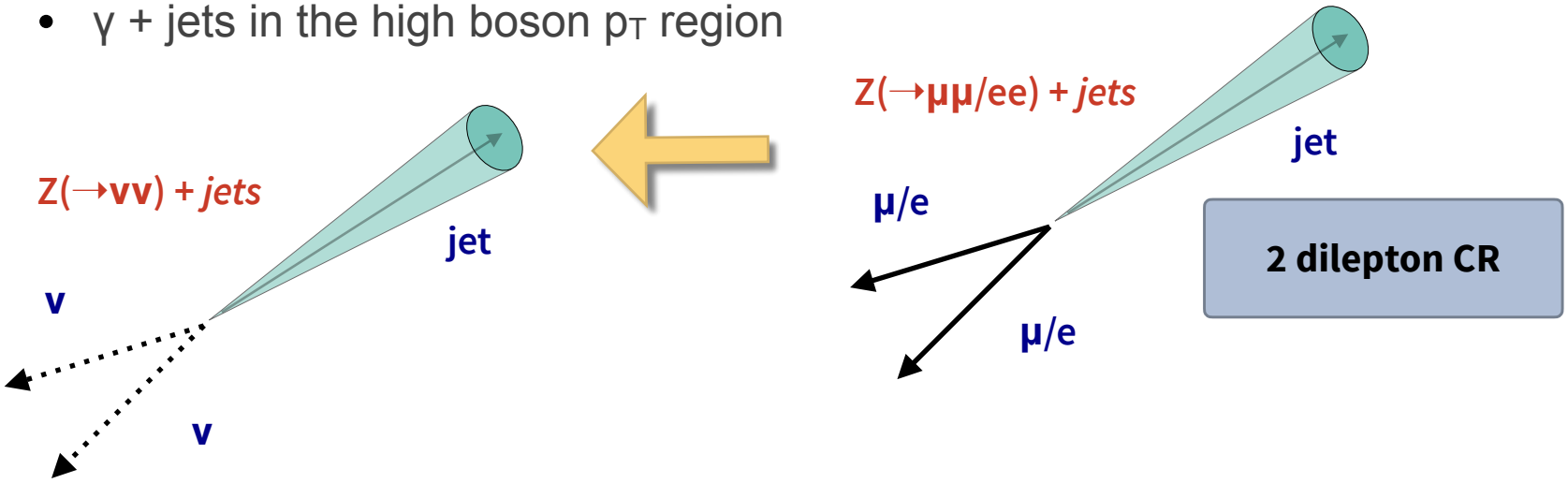


Multi-jet background suppressed by requirement on azimuthal opening angle between E_T^{miss} and jet p_T

Z(νν)+Jets background

Background estimation: Data-driven methods based on control regions

- Z(→νν) + jets inferred from :
  - analogous events in which Z decays leptonically
  - γ + jets in the high boson p_T region



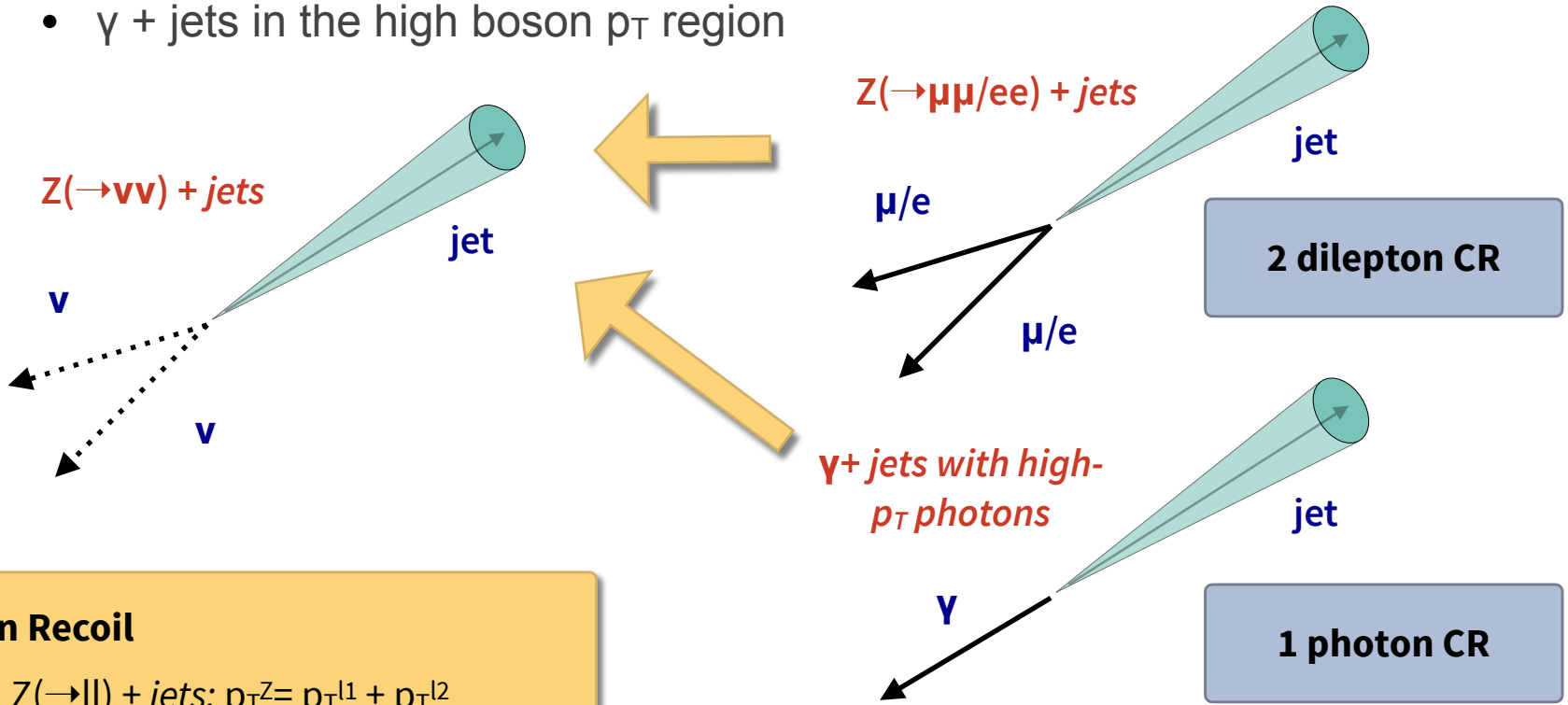
Boson Recoil

- Z(→ll) + *jets:* $p_T^Z = p_T^{l1} + p_T^{l2}$

Z(νν)+Jets background

Background estimation: Data-driven methods based on control regions

- Z(→νν) + jets inferred from :
  - analogous events in which Z decays leptonically
  - γ + jets in the high boson p_T region



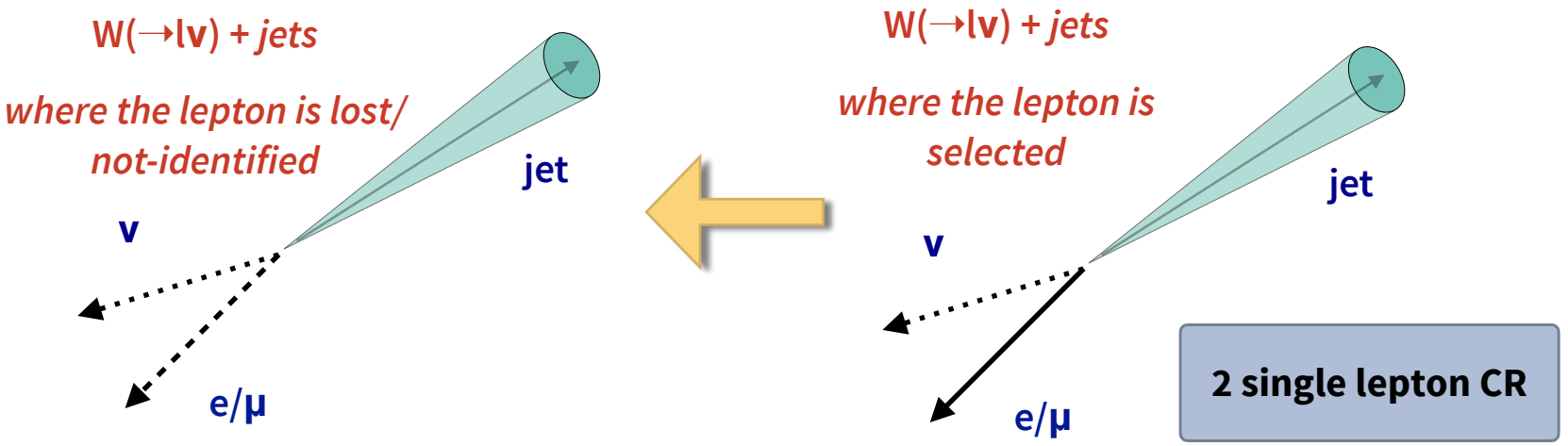
Boson Recoil

- Z(→ll) + *jets:* $p_T^Z = p_T^{l1} + p_T^{l2}$
- γ+*jets:* p_T^γ

W(l^{miss}ν)+ Jets background

Background estimation: Data-driven methods based on control regions

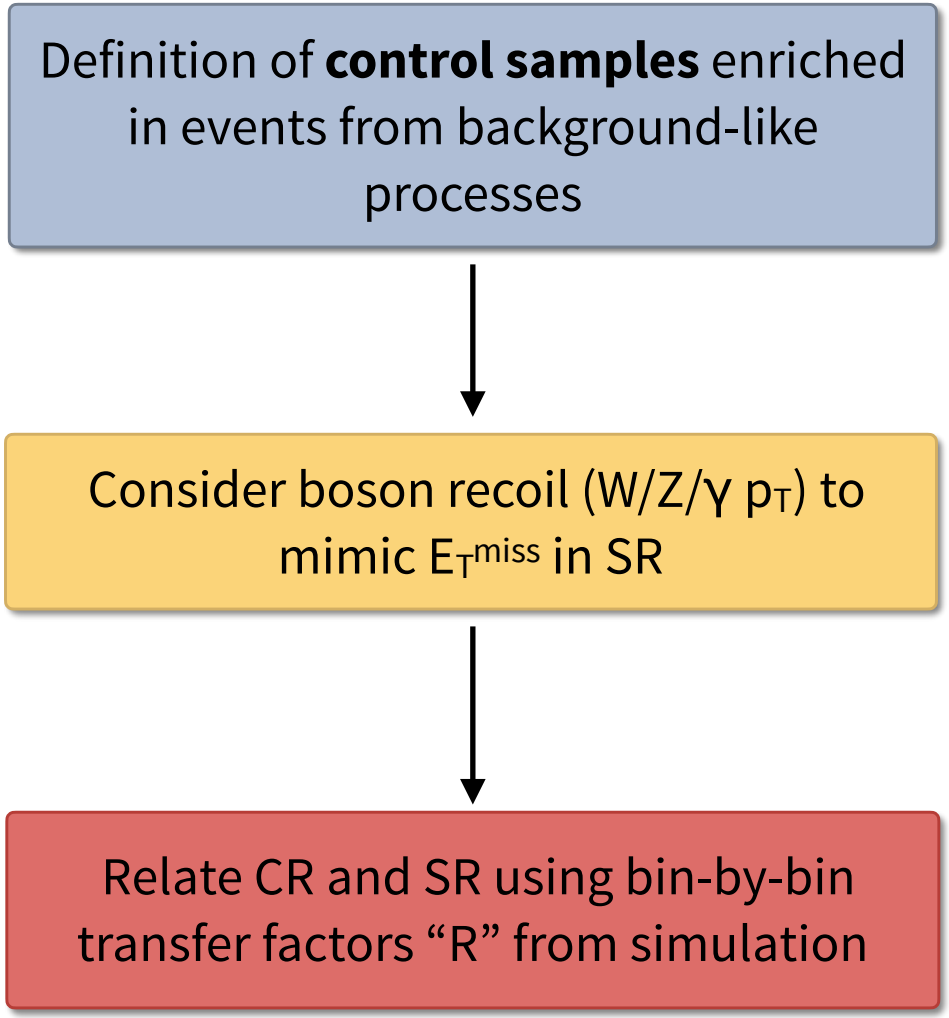
- W(→l^{miss}ν) + jets inferred from W(→lν) + jets events in which the lepton is not correctly identified



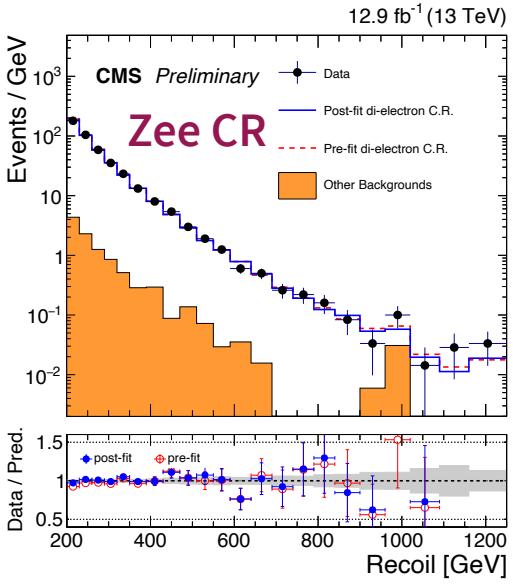
Boson Recoil

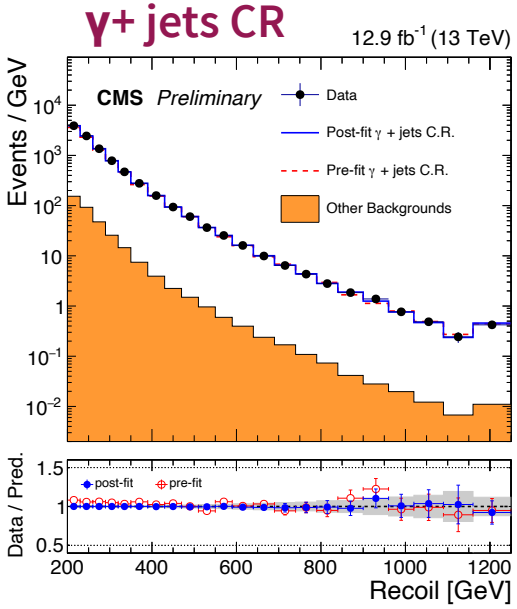
- W(→lν) + *jets:* $p_T^W = p_T^l + p_T^\nu$

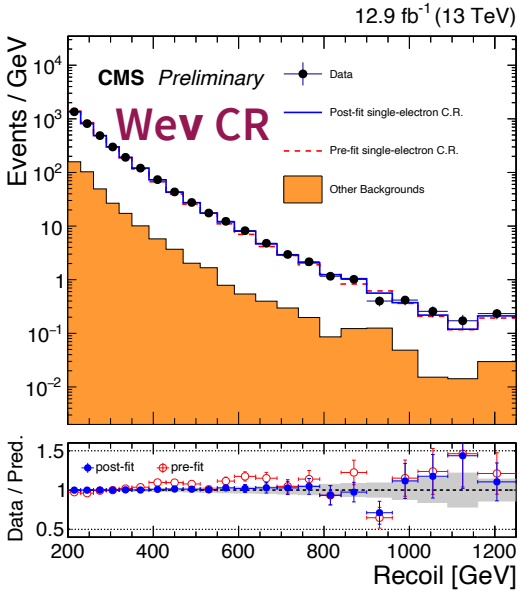
Background Estimation Procedure

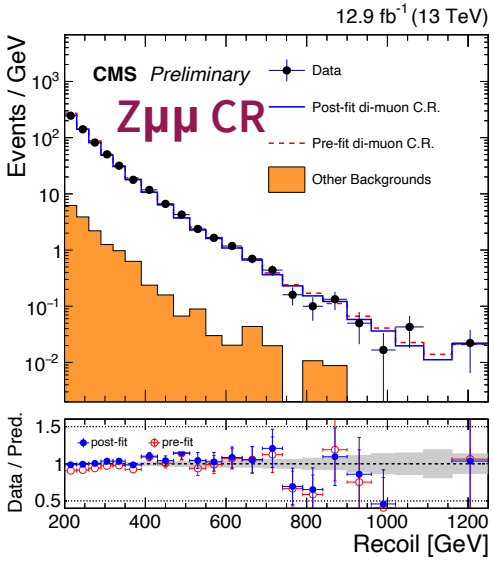


Constraining backgrounds in SR

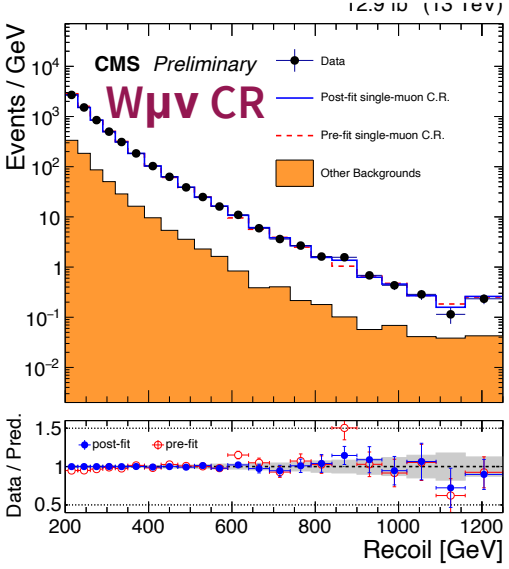




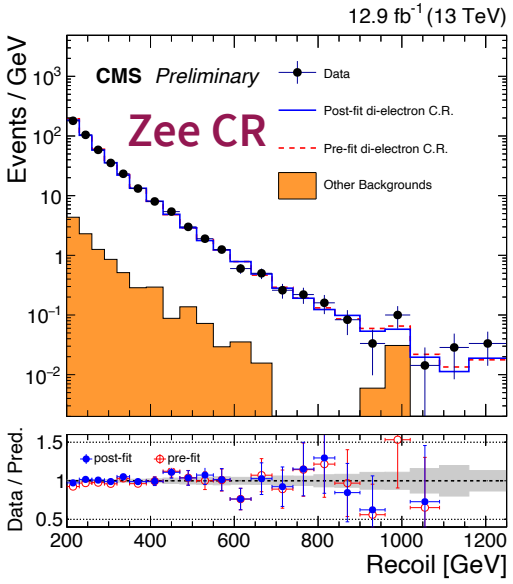




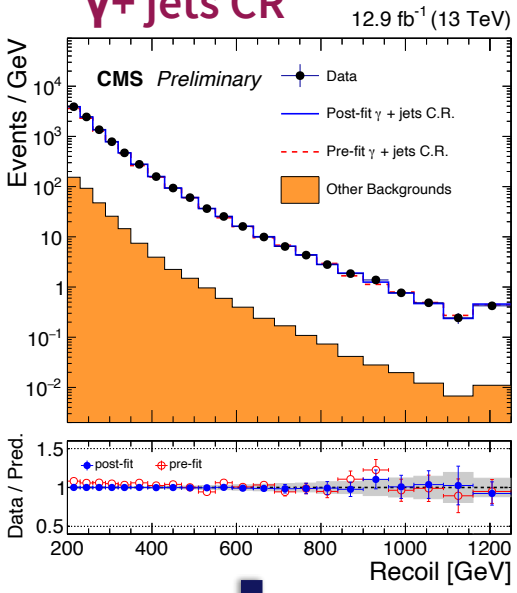
Signal region

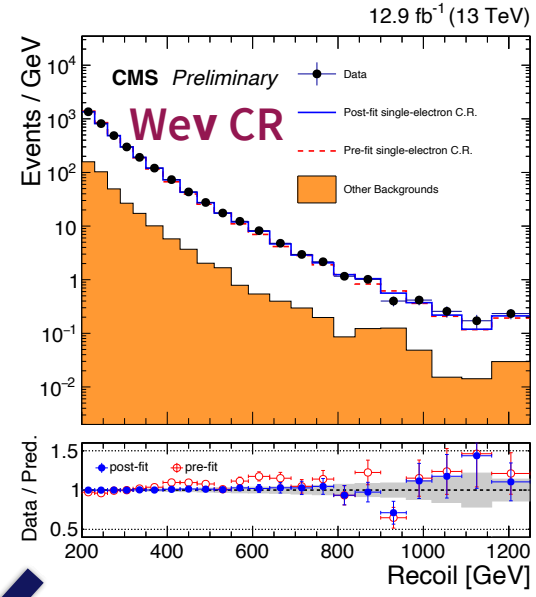


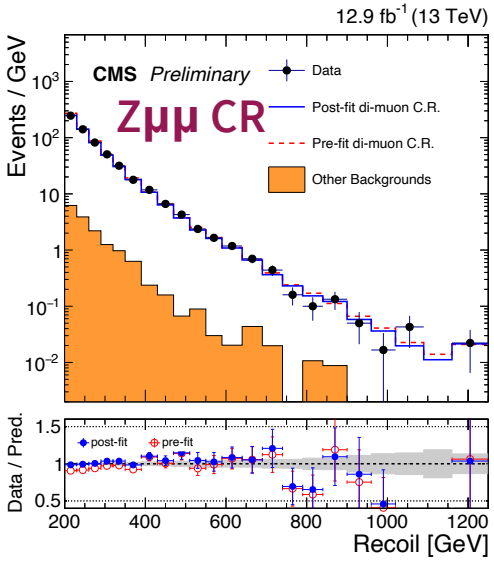
Constraining backgrounds in SR



γ+ jets CR

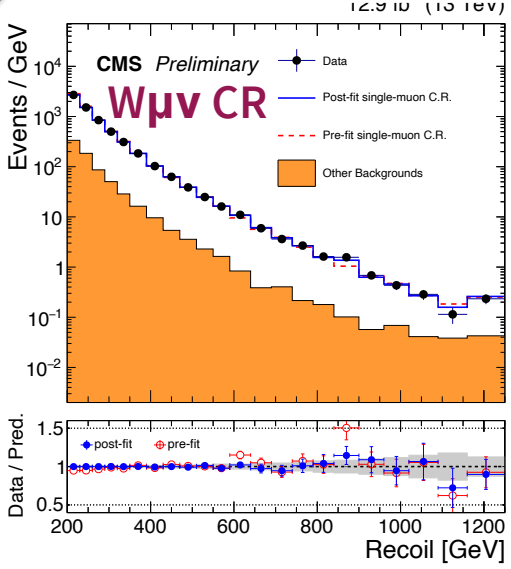






$R^{Z(ee)}$ R^{γ} $R^{W(ev)}$

$R^{Z(\mu\mu)}$ **Signal region** $R^{W(\mu\nu)}$



- $N_i^{Z(SR)} = N_i^{Z(ll)} \times R^{Z(ll)}$
- $N_i^{Z(SR)} = N_i^{\gamma} \times R^{\gamma}$
- $N_i^{W(SR)} = N_i^{W(l\nu)} \times R^{W(l\nu)}$

Fit to signal and control regions

Combined maximum likelihood fit to CRs and SR to estimate E_T^{miss} shape and normalisation of EWK backgrounds

Fit to signal and control regions

Combined maximum likelihood fit to CRs and SR to estimate E_T^{miss} shape and normalisation of EWK backgrounds

signal region

$$\mathcal{L}(\mu, \mu^{Z\to\nu\nu}, \mu^{W\to l\nu}, \theta) = \prod_i \text{Poisson}\left(d_i | B_i(\theta) + \mu_i^{W\to l\nu} + \mu_i^{Z\to\nu\nu} + \mu S_i(\theta)\right)$$

$$\times \prod_i \text{Poisson}\left(d_i^Z | B_i^Z(\theta) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^Z(\theta)}\right) \quad \textbf{dilepton CR}$$

$$\times \prod_i \text{Poisson}\left(d_i^\gamma | B_i^\gamma(\theta) + \frac{\mu_i^{Z\to\nu\nu}}{R_i^\gamma(\theta)}\right) \quad \textbf{photon CR}$$

$$\times \prod_i \text{Poisson}\left(d_i^W | B_i^W(\theta) + \frac{\mu_i^{W\to l\nu}}{R_i^W(\theta)}\right) \quad \textbf{single lepton CR}$$

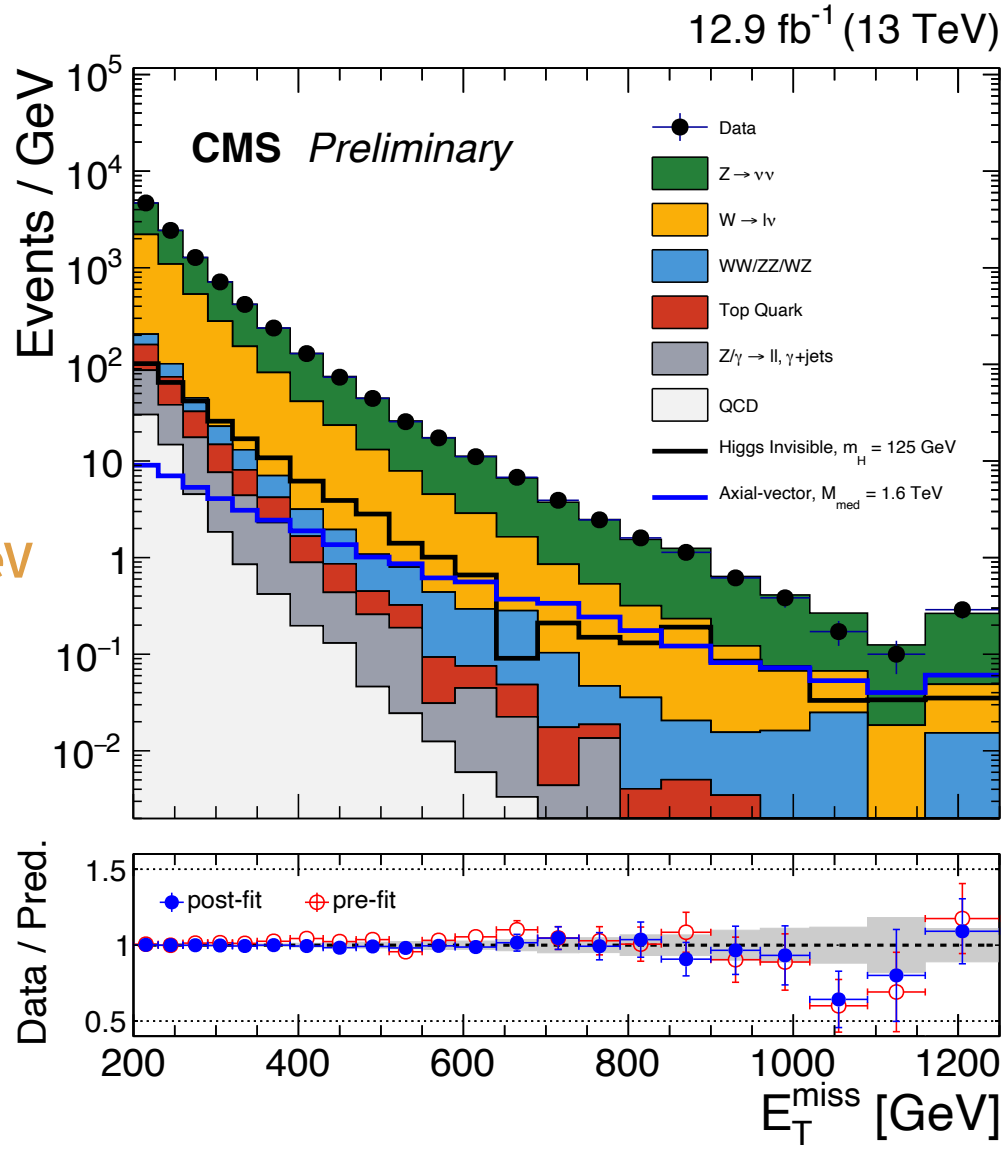
Z(→νν) + jets and W(→μ/e ν) + jets estimates further constrained by Z/W cross-section ratio

$$\mu^{W\to l\nu} \to f_i(\theta) \cdot \mu^{Z\to\nu\nu}$$

Mono-Jet Results

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12.9 fb-1 @ 13 TeV



Constraints on DM Simplified Models

For fixed couplings, the mono-jet sensitivity to this simplified model depends on:

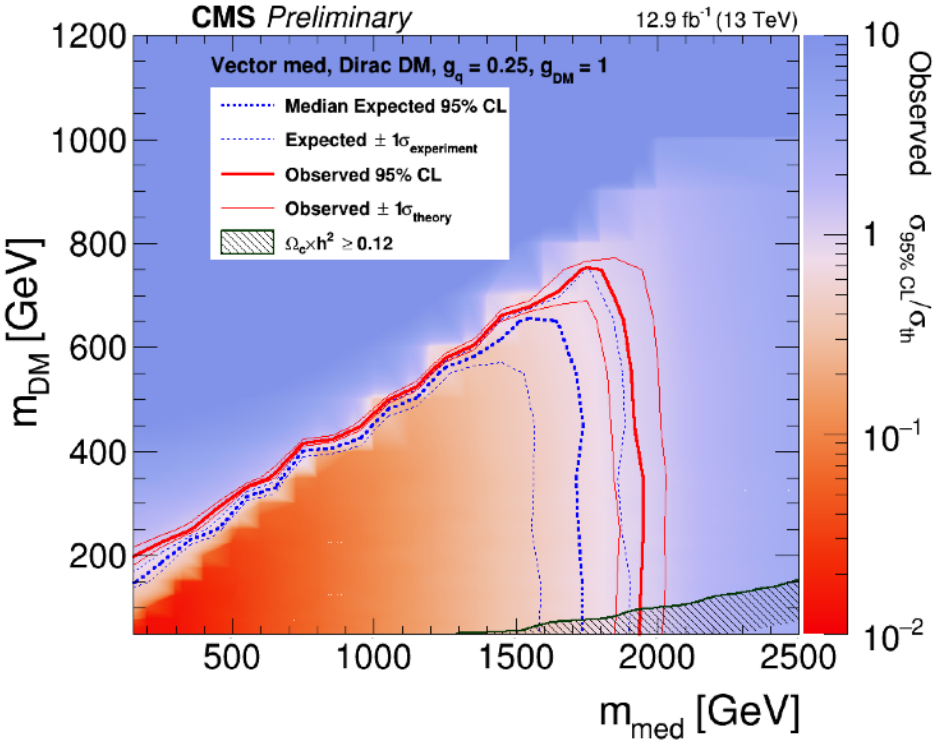
- **higher mediator mass** ⇒ harder p_T of DM

  but lower production cross-section
- **higher DM mass** ⇒ softer p_T of DM

  ⇒ lower analysis acceptance
- **for $m_Z < 2m_\chi$** (off-shell) ⇒

  cross-section too low (no sensitivity)

Vector mediator

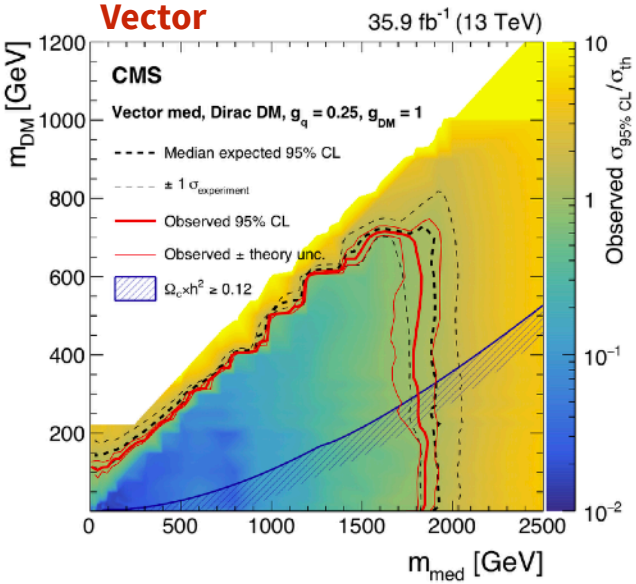


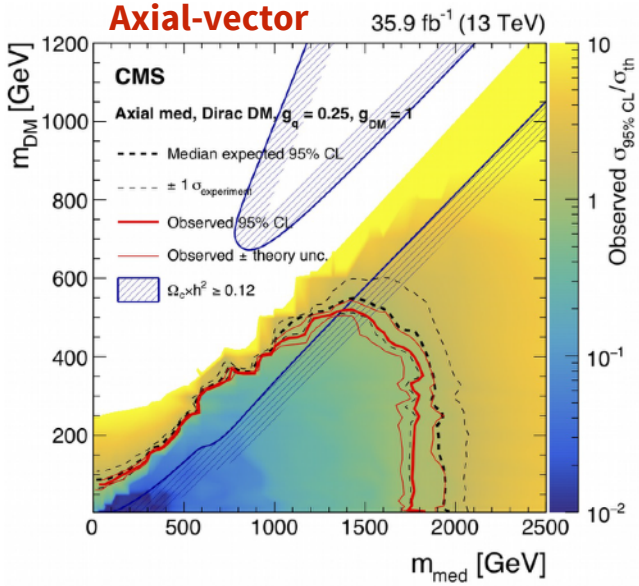
CMS PAS EXO-16-037

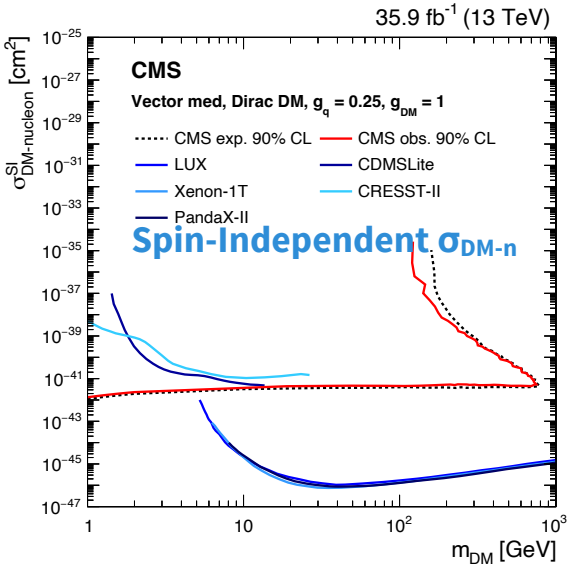
Interpretation

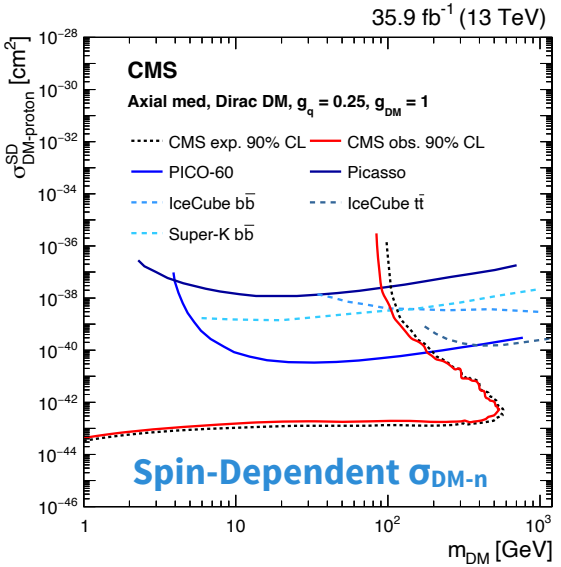
Interpretation in terms of simplified models

Limits recast in terms of DM-nucleon cross section





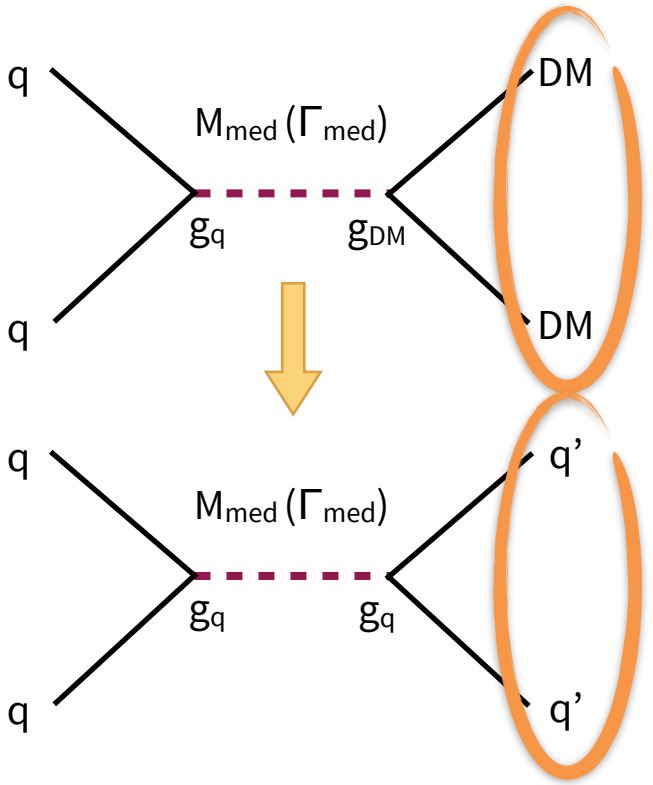




Direct search for SM-DM mediators

Look for visible decays of DM mediator

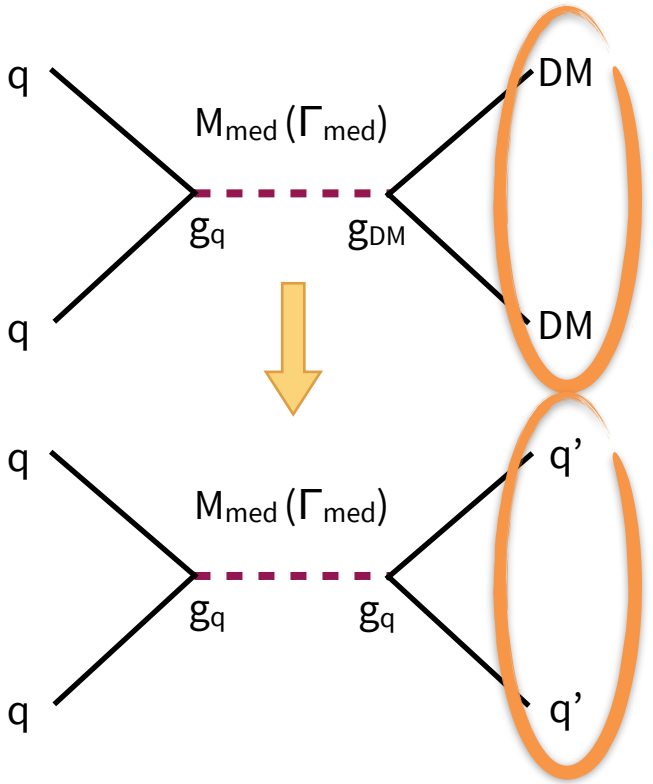
- Bump-Hunt search in di-jet (and di-lepton) spectrum
- Visible search complementary to invisible one

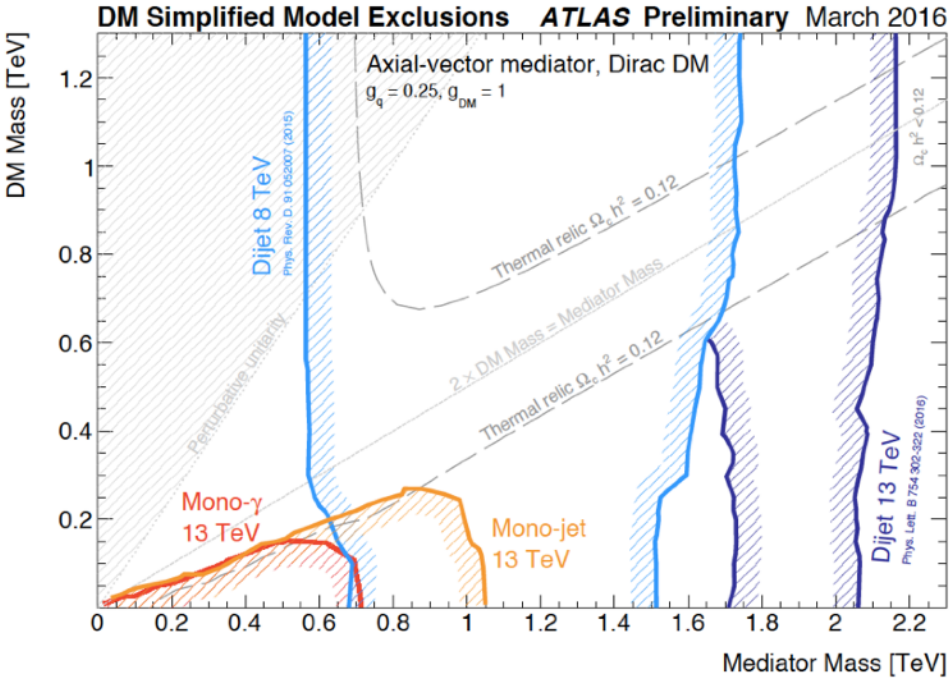


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- Bump-Hunt search in di-jet (and di-lepton) spectrum
- Visible search complementary to invisible one

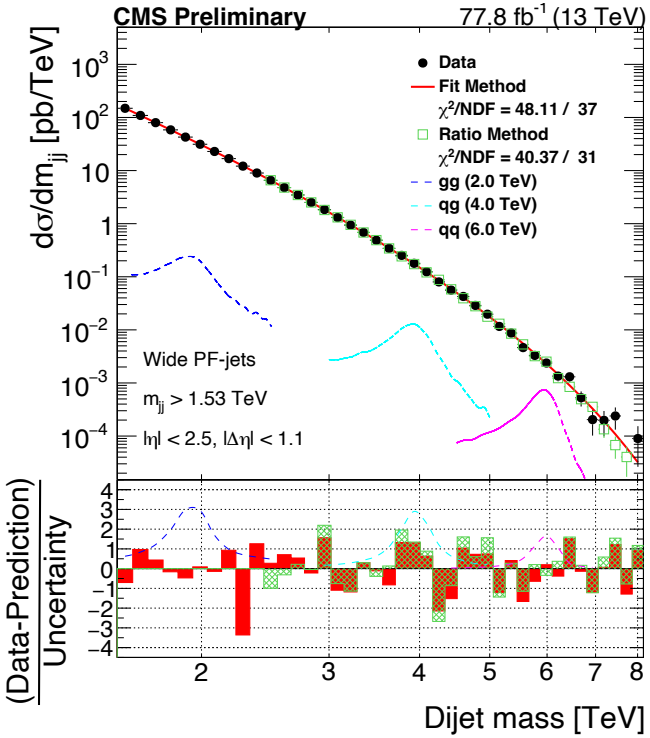


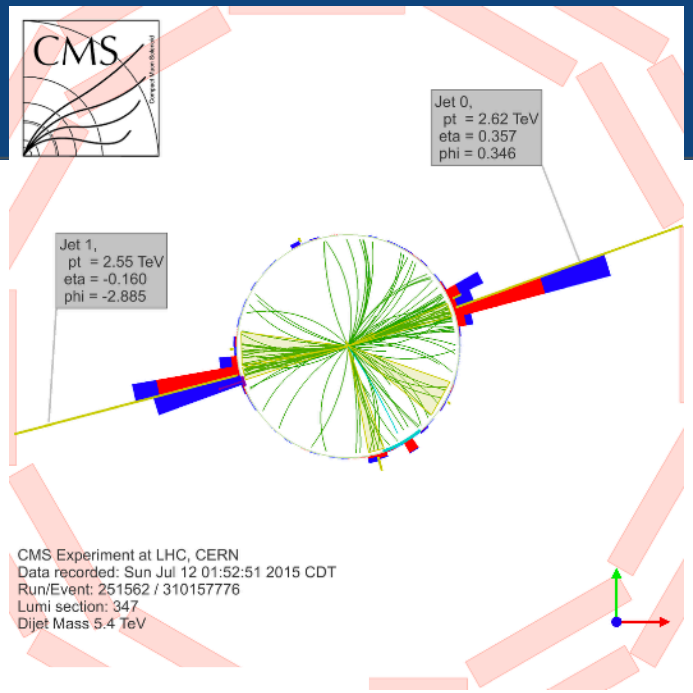


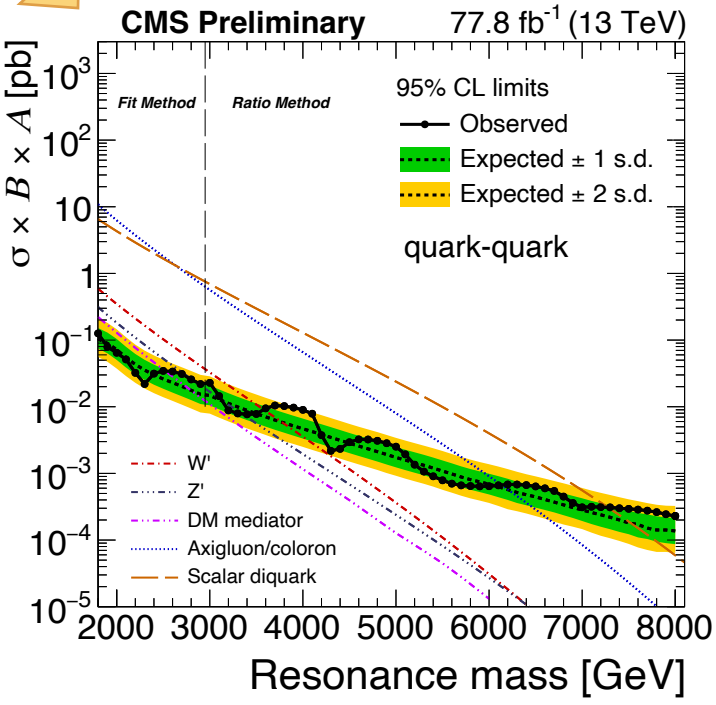
Sensitivity limited at low masses by thresholds at trigger level

- Need to adopt different strategies for different mass ranges

Dijet search





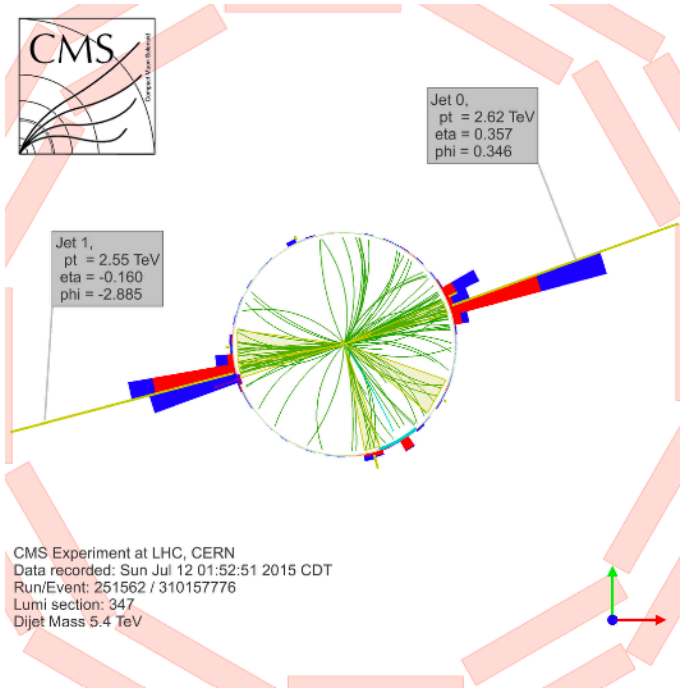


CMS-PAS-EXO-17-026

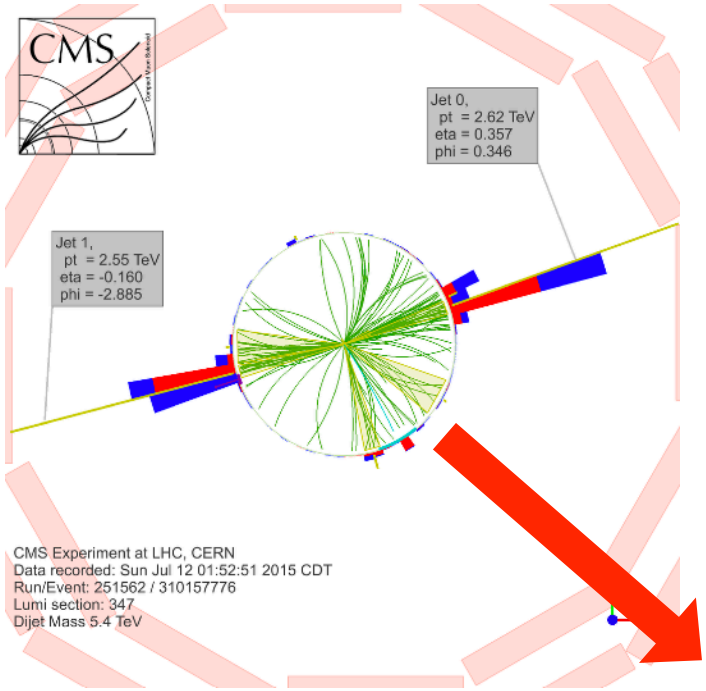
Probing low mass with ISR photons

Sensitivity at low mass limited by tight cuts on jet pT

Extend reach to lower pT thresholds (and hence masses) by triggering on associated photon



Dijet



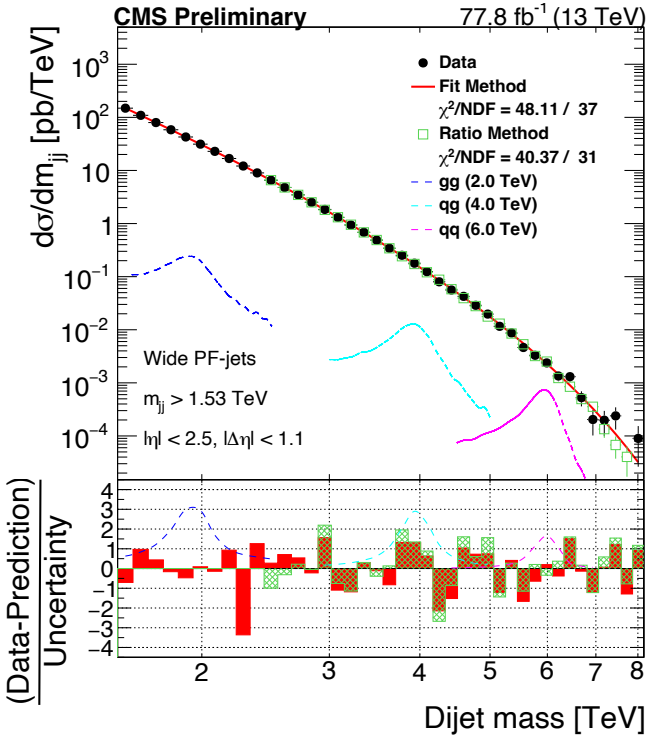
Dijet + Photon

JHEP08(2018)130

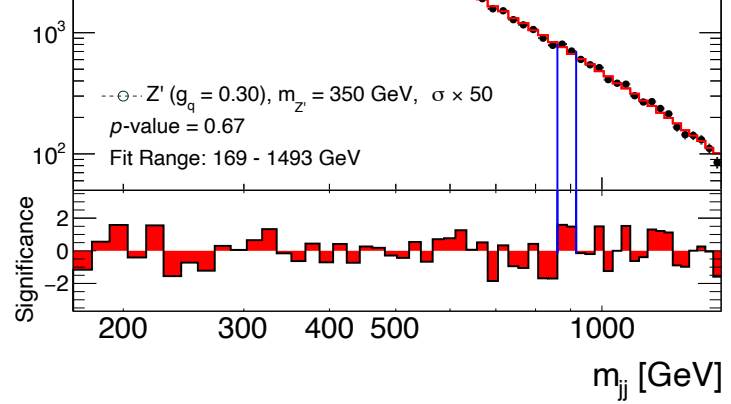
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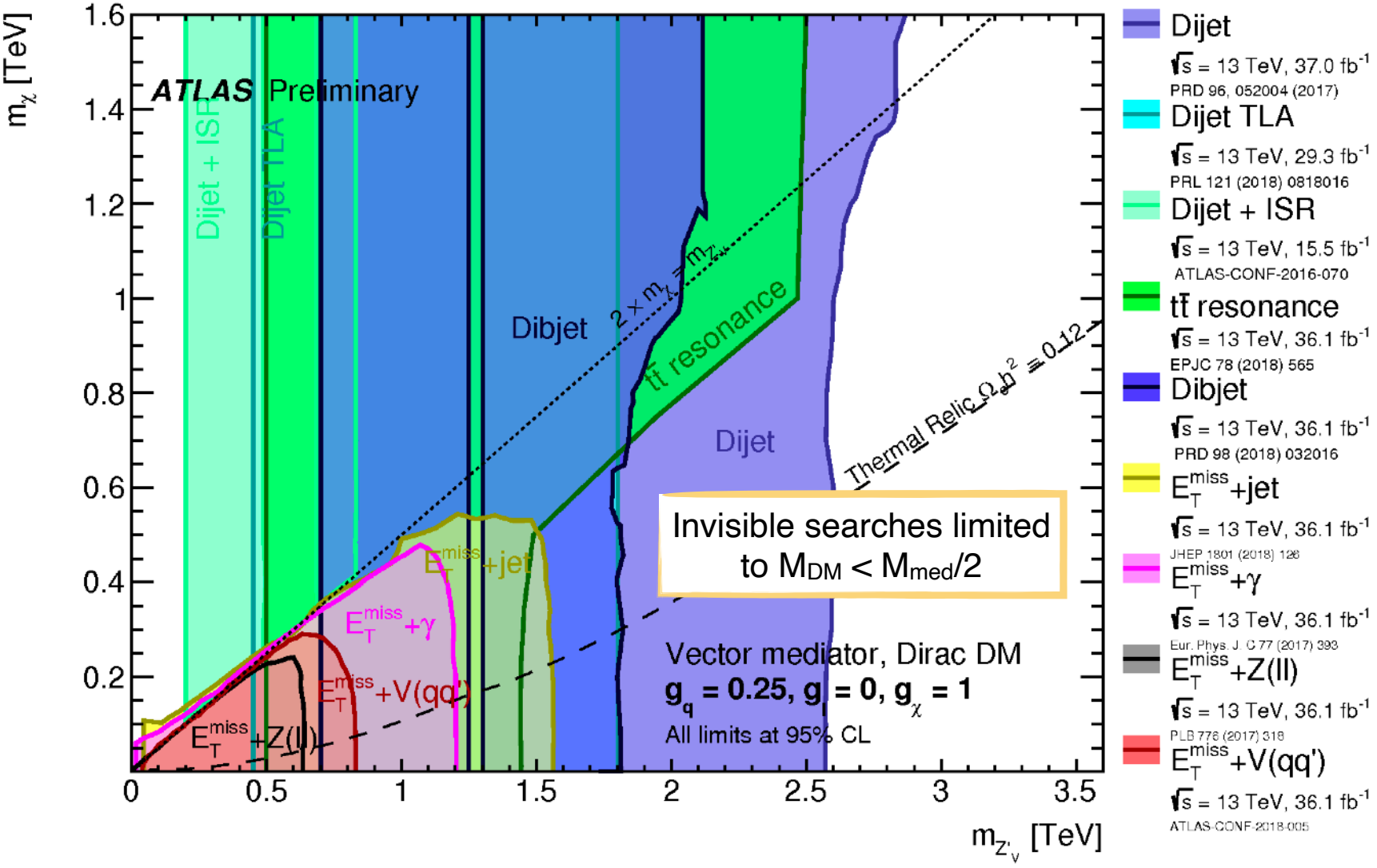
Dijet



Dijet + Photon

The big picture in the M_{DM}-M_{med} plane

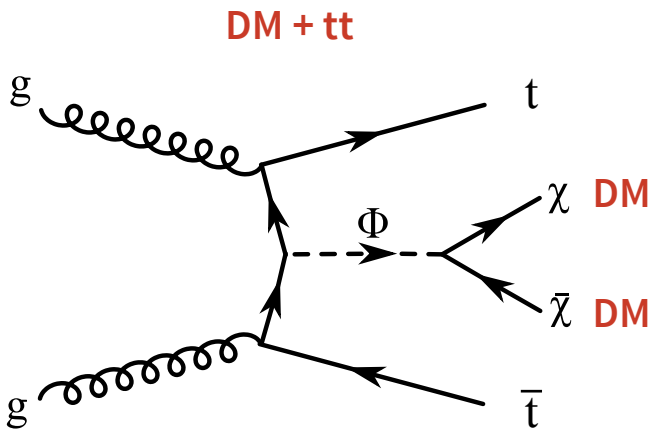
ATLAS-CONF-2018-051



DM + 3rd generation

DM production in association to heavy flavour quarks favoured in case of *spin 0* (scalar/pseudoscalar) mediator models

- Under the assumption of Yukawa-like coupling ($\propto m_q$), strongest DM mediator coupling to heavy fermions (top quark)



DM + 3rd generartion

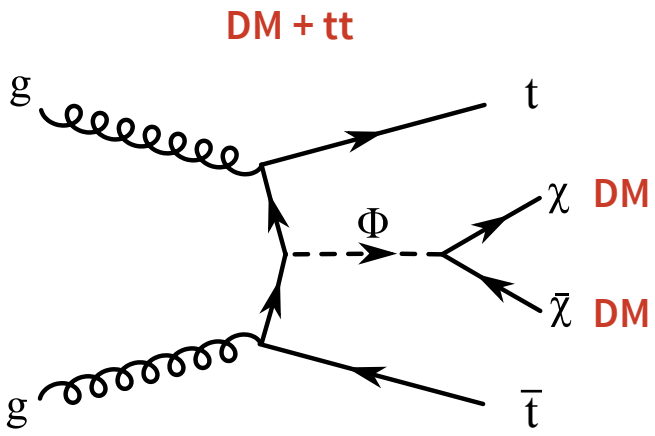
DM production in association to heavy flavour quarks favoured in case of *spin 0* (scalar/pseudoscalar) mediator models

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MET + tops

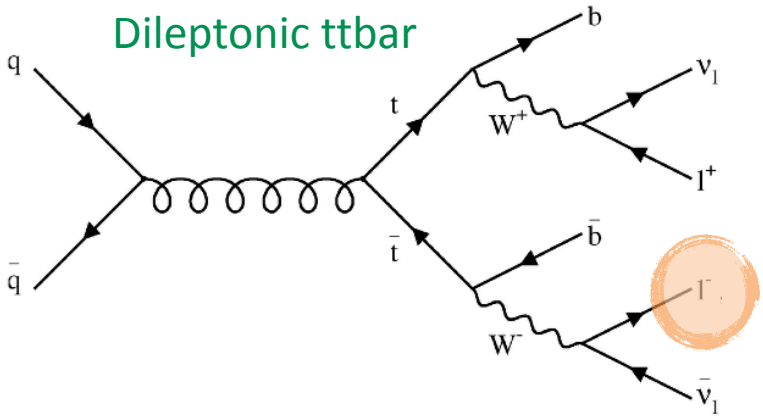
Signal characterisation

- Large imbalance in energy
- Presence of heavy flavour jets
- 0/1/2 leptons in the final states depending on the decay channel

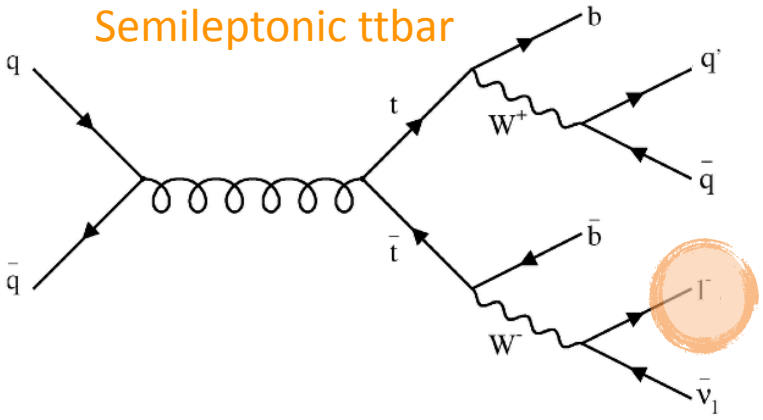


tt background

Dileptonic ttbar



Semileptonic ttbar



Not detected lepton → additional source of E_T^{miss}

tt+DM: Single-lepton channel

Signal selection

- 1 lepton and at least 3 jets
    - out of which 1 b-jet
- Large E_T^{miss}

tt+DM: Single-lepton channel

Signal selection

- 1 lepton and at least 3 jets
  - out of which 1 b-jet
- Large E_T^{miss}

Background contamination

- Dominant backgrounds from
  - **tt+jets (2l)**, **W(→lν) + jets**
- Minor contributions from
  - Z(→ll)+jets, SingleTop, Dibosons

tt+DM: Single-lepton channel

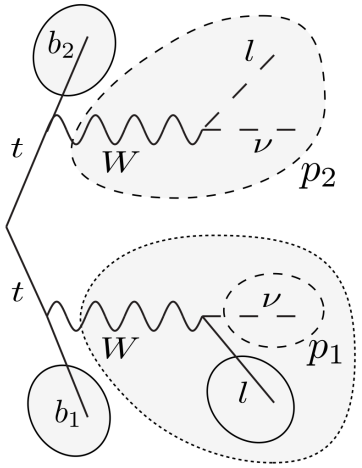
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  - Z(→ll)+jets, SingleTop, Dibosons

tt + Jets suppression through selection on m_{T2}^W



Dileptonic tt+jets with 1 lepton lost

m_{T2}^W: minimal mother particle mass compatible with t t → lνb lνb event topology and daughter particle mass

M_{T2}^W has a kinematic endpoint at top-quark mass in ttbar background events

Dileptonic tt+jets event have lower values of m_{T2}^W with respect to signal

tt+DM: Single-lepton channel

Signal selection

- 1 lepton and at least 3 jets
  - out of which 1 b-jet
- Large E_T^{miss}

Background contamination

- Dominant backgrounds from
  - **tt+jets (2l)**, **W(→lν) + jets**
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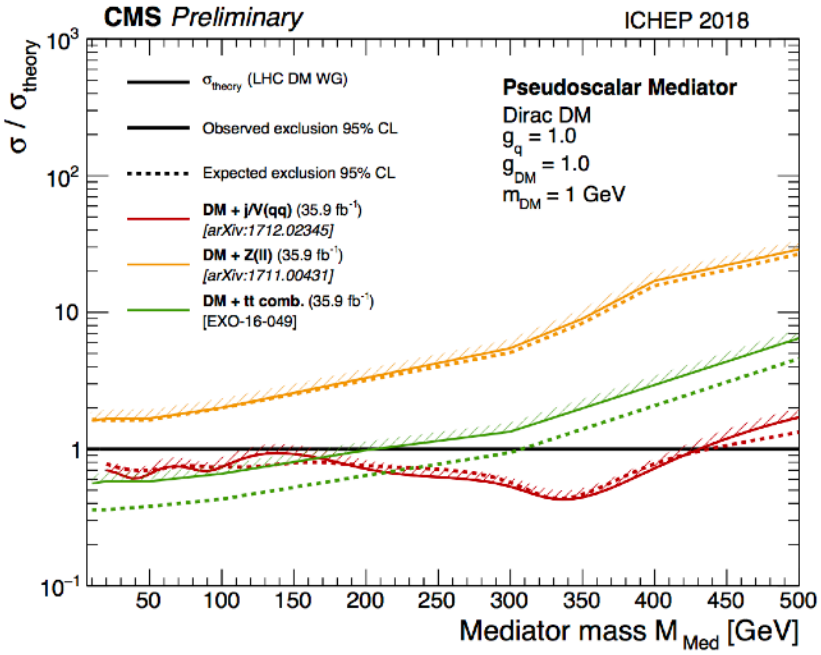
W(→lν) + Jets suppression through selection on m_T^W

$$m_T^W = \sqrt{2 p_T^{lep} E_T^{miss} (1 - \cos(\Delta\phi(lep, E_T^{miss})))}$$

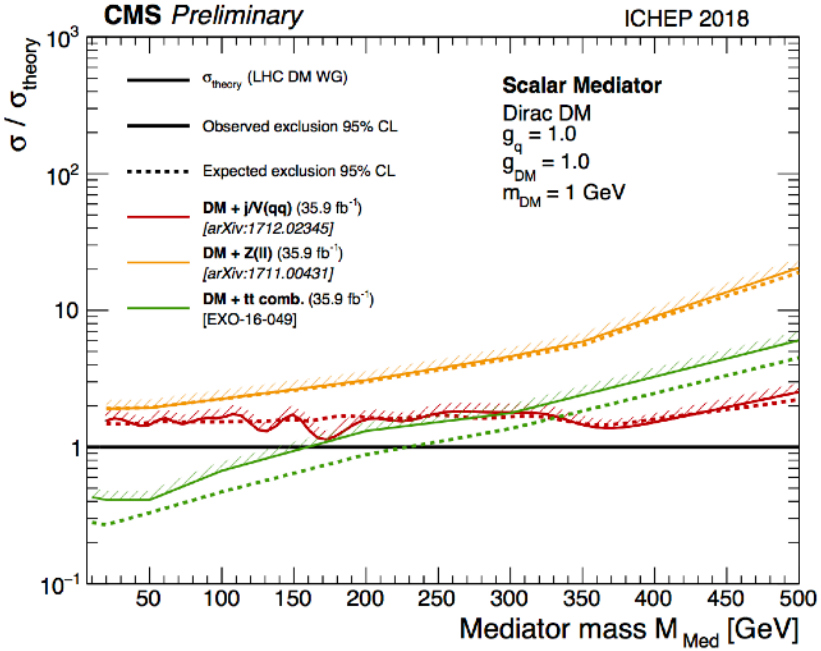
Constraints on scalar/Pseudoscalar

DM with Heavy flavour can strongly constrain scalar/pseudoscalar DM mediators

Scalar



Pseudoscalar



tt +DM more sensitive to scalar interaction than Monojet despite lower statistics

Summary

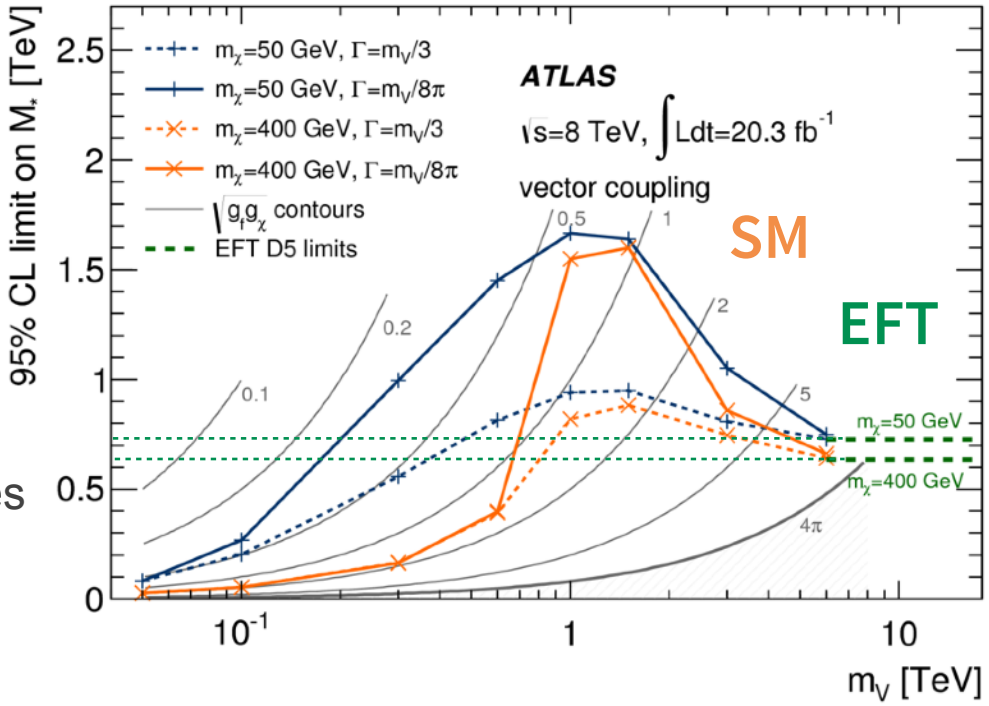
- Wide programme of WIMP searches at the LHC
  - Mainly MET-driven searches complemented by direct searches for DM mediator
  - Use of additional visible objects to flag the (otherwise undetectable) production of DM particles
- Complementarity of DM searches at colliders to direct and indirect detection ones
  - Different sensitivity to phase space regions, different detection techniques and systematic uncertainties
- What if DM particles are not WIMPS?
  - We'll see more next time!

Additional material

EFT limitations

EFT doesn't correctly account for kinematics and is not valid for transferred momenta Q > m_{MED}

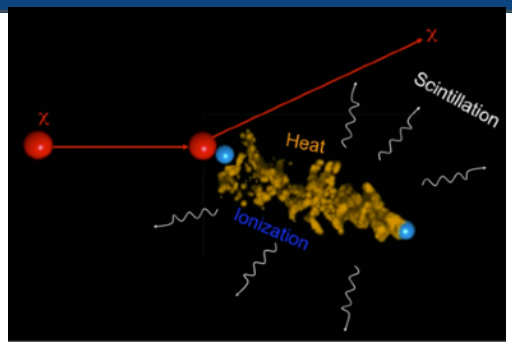
- High m_{Med}:
  - EFT consistent with SM
- Intermediate m_{Med}:
  - On-shell production increases σ
  - EFT limits too weak
- Low m_{Med}:
  - Off-shell production → σ decreases
  - Events are softer
  - EFT limits too strong



EFT not an appropriate approach to reach a comprehensive interpretation of DM searches

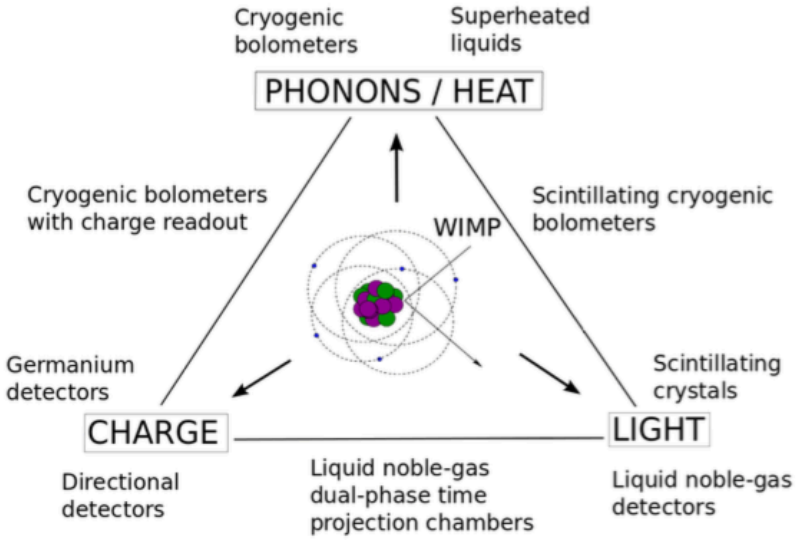
Direct detection "signals"

Nuclear recoil from WIMP scattering can produce **Heat**/ phonons, **ionization**, and **scintillation light**, or combinations of the three depending on the material/technology employed



J.Monroe, Zurich Colloquium, 2019

CDMS II



DAMA

Xenon/LUX

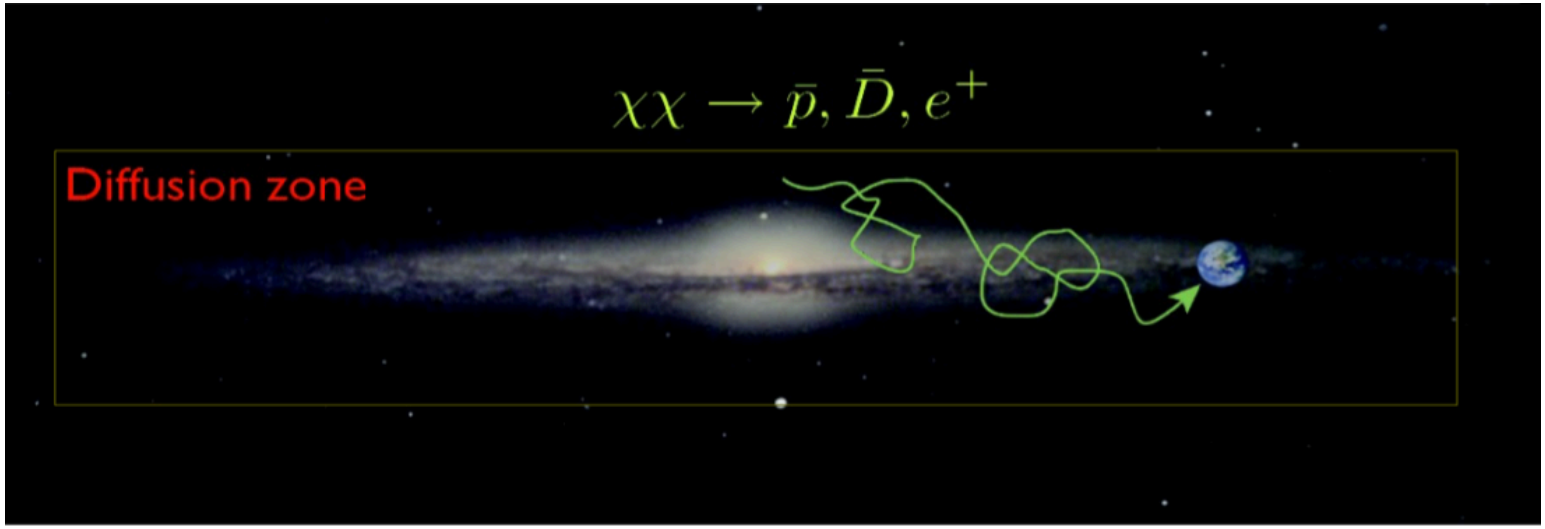
Detectors that detect the recoil energy through two types of processes (hybrid detectors) can better discriminate nuclear recoil from electronic recoil

Indirect detection through e+,anti-p, etc..

- Unlike gammas, charged particles are affected by magnetic fields: they don't point directly to the source
- Unlike gammas, charged particle spectrum is modified by interaction with interstellar medium

large uncertainty on propagation → on fluxes of cosmic rays of non-DM origin

ratios of particle/antiparticle fluxes usually more sensitive to potential excesses of DM origin



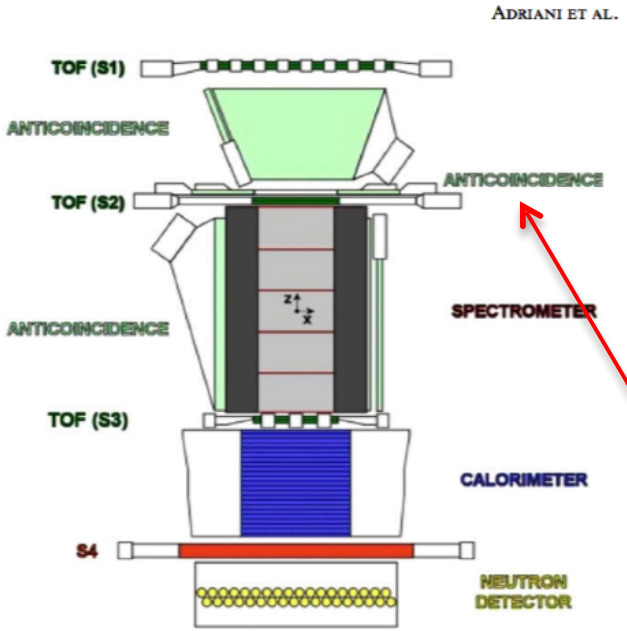
PAMELA and AMS

PAMELA (2006)

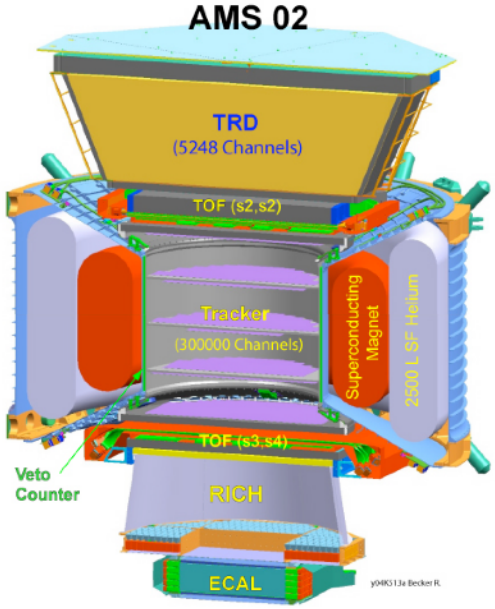


AMS-02 (2011--)

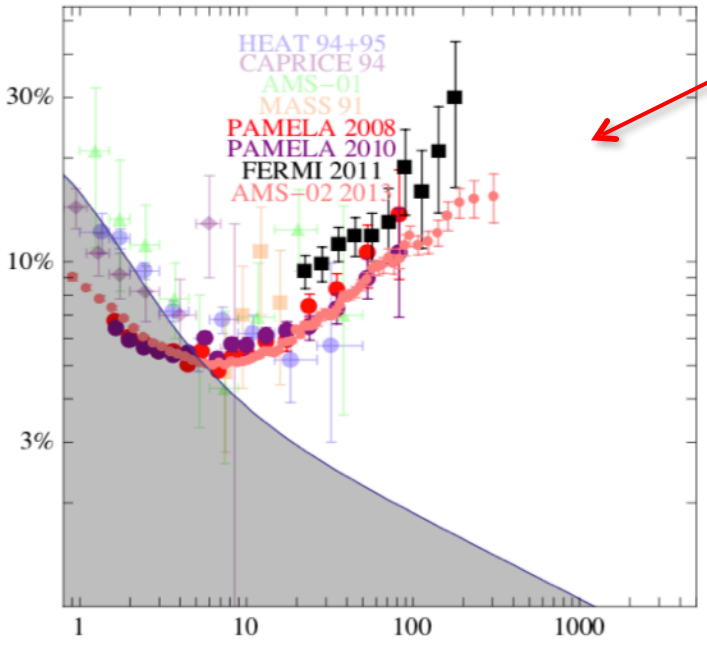




accelerator-like detectors in space



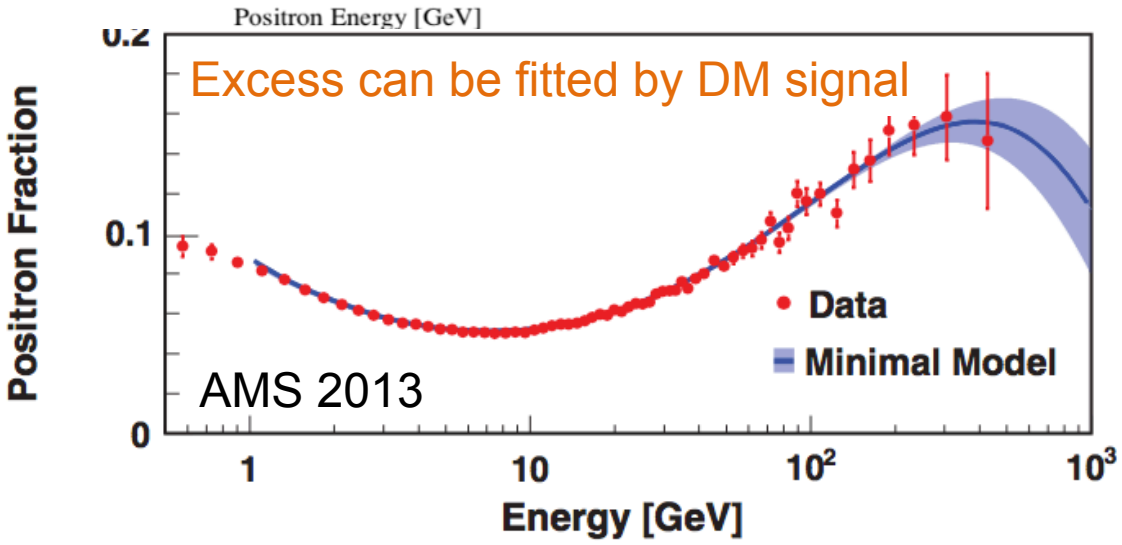
PAMELA and AMS



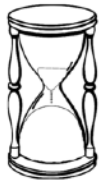
Steep excess in $e^+/(e^+ + e^-)$ above 10 GeV first measured by PAMELA in 2008
→ later confirmed by AMS

Two main hypothesis:

- Pulsar: slow decrease of the ratio after flattening-out
- WIMP: sharp decrease of the ratio at the value of the WIMP mass



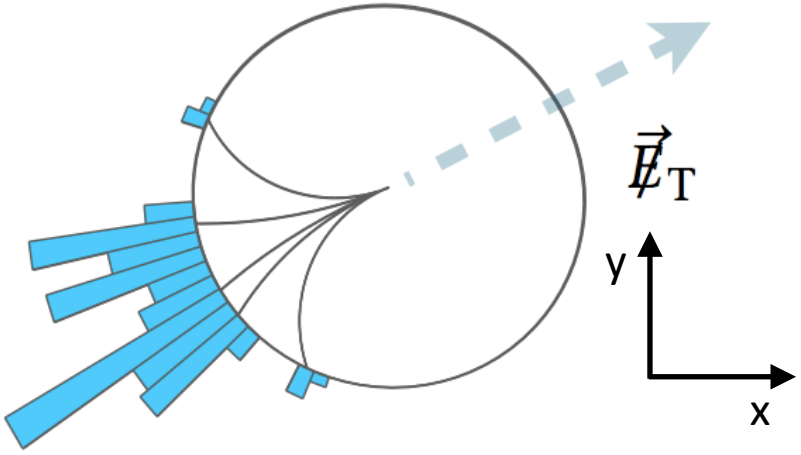
Need to wait for larger data set to be recorded

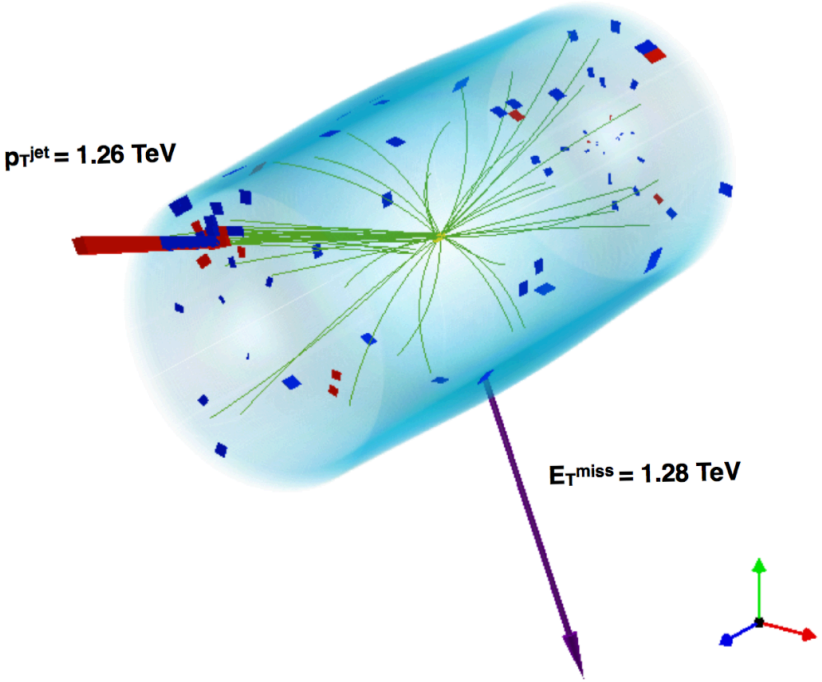


Reminder: Missing momentum

Particles such as neutrinos are invisible to detectors

- Their signature is actually a ***missing signature***, identified by an energy imbalance in the plane transverse to the beams





- **Missing transverse momentum, MET,** (E_T^{miss}) is defined as ***the negative sum of the transverse momenta of all reconstructed particles***

$$\mathrm{E_T^{miss}} = -\sum_i \mathrm{p_T}^i$$