Searching for Dark Matter at the LHC

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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?
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3. Interpreting the results:
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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) \(\rightarrow\) Booster (1.4 GeV) \(\rightarrow\) PS (25 GeV) \(\rightarrow\) 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

\[ \mathcal{L} = \frac{f_{\text{revolution}} N_{\text{bunches}} N_{\text{protons/bunch}}^2}{A} \]

*Design: \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\) (max in 2016: \(1.37 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\))

• The integrated luminosity : \[ L = \int \mathcal{L} dt \]
Orders of magnitude

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

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

For 40 fb$^{-1}$ of data:

- $\sigma_{\text{inelastic}} \sim 80 \text{ mb} \rightarrow N_{\text{in}} \sim O(3 \times 10^{15})$ : huge!
- Impossible to save everything to disk
- trigger system : save only ‘interesting events’ 40 MHz $\rightarrow$ 1 kHz!
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- *Multiple interactions per bunch crossing (« pile-up »)*

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![Image of particle collisions and distributions](image.png)
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  - Multiple interactions per bunch crossing (« pile-up »)

- $\sigma_{\text{tt}} \sim 1 \text{ nb} \rightarrow N \sim O(4 \times 10^{7})$
  - Top « factory »!

- $\sigma_{\text{higgs}} \sim 40 \text{ pb} \rightarrow N \sim O(2 \times 10^{6})$
  - but most in $h \rightarrow bb$… $BR(h \rightarrow \gamma\gamma) \sim 2 \times 10^{-3}$ : $N_{h \rightarrow \gamma\gamma} \sim O(4k)$
**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
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 $\phi$
• Pseudorapidity $\eta$:

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

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**Neutrinos (or dark matter!):**

- 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)

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*Finally, we get to it 😊*
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 $X+E_{T\text{miss}}$ 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+$E_T^{\text{miss}}$ analysis
Well-known standard model processes can also give the same final states:

The signal

Irreducible BG

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

DM signal
Background
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 + \( E_{T}^{\text{miss}} \) 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...)

  - "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 $Z(\nu\nu)+\text{jet}$, select events in data which have $Z(\mu\mu)+\text{jet}$ instead (control region).

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

\[
N_{data}^{Z \rightarrow \nu\nu, SR} = N_{data}^{W \rightarrow \mu\nu, CR} \times \frac{N_{Z \rightarrow \nu\nu, CR}^{Monte\ Carlo}}{N_{W \rightarrow \mu\nu, CR}^{Monte\ Carlo}}
\]
$E_T^{miss} + jet$ in ATLAS: backgrounds

- The second largest background is $W(l\nu)+jet$, where the charged lepton is missed in the reconstruction
  - **Idea:** Again, use a CR enriched in $W(\mu\nu)+jet$

- 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.
$E_T^{\text{miss}} + \text{jet in ATLAS}$

Data vs expectation

Examples of BSM signals

Uncertainty

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?
Theories of Dark Matter?
Let’s start simple…  
What about an effective field theory?

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

<table>
<thead>
<tr>
<th>Name</th>
<th>Initial state</th>
<th>Type</th>
<th>Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>$qq$</td>
<td>scalar</td>
<td>$\frac{m}{M^2} \bar{\chi} \gamma^\mu \bar{q} q q$</td>
</tr>
<tr>
<td>D5</td>
<td>$qq$</td>
<td>vector</td>
<td>$\frac{1}{M^2} \bar{\chi} \gamma^\mu \bar{q} \gamma^\nu q q$</td>
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<tr>
<td>D8</td>
<td>$qq$</td>
<td>axial-vector</td>
<td>$\frac{1}{M^2} \bar{\chi} \gamma^\mu \gamma^\nu \bar{q} \gamma^\rho q q$</td>
</tr>
<tr>
<td>D9</td>
<td>$qq$</td>
<td>tensor</td>
<td>$\frac{1}{M^2} \bar{\chi} \sigma^{\mu\nu} \bar{q} \sigma_{\mu\nu} q q$</td>
</tr>
<tr>
<td>D11</td>
<td>$gg$</td>
<td>scalar</td>
<td>$\frac{1}{M^2} \bar{\chi} \chi g_s (G^a_{\mu\nu})^2$</td>
</tr>
</tbody>
</table>
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:
But are EFTs a valid approach?

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

\[ M^* = \frac{M_{\text{med}}}{\Gamma_{\text{mediator}}} \]

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?

![Graph](image)

\[ M_{\text{med}} = M^* \times \sqrt{g_q g_{\text{DM}}} \]

The \( \sim 1 \) TeV EFT limit on \( M^* \) is only always valid in the case of very large couplings:

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

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

**Free parameters:**
- $m_{DM}$, $M_{med}$, $g_{DM}$, $g_{q}$
- $\Gamma_{med}$ 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

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

Excluded region

Much smaller production rate for $M_{med} < 2 m_{DM}$: difficult to set limits there
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:
    \[ \sigma_{SI} = \frac{f^2(g_q)g_{DM}^2 \mu_{nX}^2}{\pi M_{med}^4} \]
  • Pseudo-scalar and axial-vector mediators would lead to spin-dependent interactions:
    \[ \sigma_{SD} = \frac{3f_s^2(g_q)g_{DM}^2 \mu_{nX}^2}{\pi M_{med}^4} \]

* \(f\) and \(f_s\): factors to translate quark interaction into nucleon interaction

\[ \mu_{nX} = m_n m_{DM}/(m_n + m_{DM}) \]
Comparison to direct detection

“LHC style”
Comparison to direct detection

“LHC style”
Comparison to direct detection

“LHC style”
Comparison to direct detection

“LHC style”
Comparison to direct detection

"LHC style"

"Direct detection style"
Comparison to direct detection

The LHC is able to probe the low masses

But one must remember the **assumption of the model** considered. It’s not a competition with direct detection: we are complementary!
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4. The many faces of dark matter at the LHC
   1. Overview of the ‘mono-X’ analyses
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   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 $E_{\text{miss}}+X$ 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 $E_T^{\text{miss}} + X$ searches in Run-2

<table>
<thead>
<tr>
<th>$X$</th>
<th>ATLAS</th>
<th>CMS</th>
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<tr>
<td>W or Z (qq)</td>
<td>arXiv:1608.02372 (subm. to PLB)</td>
<td>CMS-PAS-EXO-16-037</td>
</tr>
<tr>
<td>Z(ll)</td>
<td>ATLAS-CONF-2016-056</td>
<td>CMS-PAS-EXO-16-038</td>
</tr>
<tr>
<td>Photon</td>
<td>JHEP 1606 (2016) 059</td>
<td>CMS-PAS-EXO-16-039</td>
</tr>
<tr>
<td>b quark(s)</td>
<td>ATLAS-CONF-2016-086</td>
<td>CMS-PAS-B2G-15-007</td>
</tr>
<tr>
<td>Top quark(s)</td>
<td>ATLAS-CONF-2016-050 (1-lepton)</td>
<td>CMS-PAS-EXO-16-005</td>
</tr>
<tr>
<td></td>
<td>ATLAS-CONF-2016-076 (2-lepton)</td>
<td>CMS-PAS-EXO-16-028</td>
</tr>
<tr>
<td></td>
<td>ATLAS-CONF-2016-077 (0-lepton)</td>
<td>CMP PAS EXO-16-040</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1 boosted top)</td>
</tr>
<tr>
<td>H($\gamma\gamma$)</td>
<td>ATLAS-CONF-2016-087</td>
<td>CMS-PAS-EXO-16-011</td>
</tr>
<tr>
<td>H(bb)</td>
<td>arXiv:1609.04572 (subm. to PLB)</td>
<td>CMS-PAS-EXO-16-012</td>
</tr>
<tr>
<td>H(4l)</td>
<td>ATLAS-CONF-2015-059</td>
<td></td>
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2015 dataset or ICHEP 2016 dataset

Probably more results to come out for the Moriond conference next week!
The $E_T^{\text{miss}}+X$ searches in Run-2

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We will now go through the $E_T^{\text{miss}}+X$ 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 $E_T^{\text{miss}}$
  - Veto extra objects (e.g.: no $e$ or $\mu$ in mono-$\gamma$)
  - Avoid mismeasured objects which could lead to fake $E_T^{\text{miss}}$ (e.g.: no jet pointing in the $E_T^{\text{miss}}$ 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 $m_{\text{DM}}/m_{\text{Med}}$ plane
$E_T^{\text{miss}} + W/Z(\text{hadronic})$

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$\rightarrow$qq
      - 3 ‘lumps’: looks like a t$\rightarrow$Wb$\rightarrow$qqb
$E_T^{miss} + W/Z$(hadronic) in ATLAS

Selection:
- $E_T^{miss} > 250$ GeV, $p_T^{miss} > 30$ GeV and $\Delta\phi(p_T^{miss}, E_T^{miss}) < \pi/2$, $\Delta\phi$(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
(2$\mu$ for Z, 1$\mu$ + b-jet/no b-jet for top/W)

Bear in mind the EFT validity issues...
$E_T^{miss} + \text{jet/Z/W(hadronic)}$ 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
$E_T^{\text{miss}} + Z(ll)$

**Selection:**
- ee or $\mu\mu$ pairs compatible with the $Z$ mass, away from $E_T^{\text{miss}}$ and whose $p_T$ is well balanced with the large $E_T^{\text{miss}}$
- jet/$E_T^{\text{miss}}$ 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

![Image of graph showing distributions and limits](image-url)

Sometimes limits can look ‘funky’ due e.g. to a limit grid of simulated signal points.
$E_T^{\text{miss}} + \text{photon}$

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

BG estimation:
- $Z/W^+\gamma$ 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 $e\gamma$ to $ee$ events compatible with the $Z$ mass

2. Apply this rate to a sample of $e+E_T^{\text{miss}}$ events to know how many events are expected in the SR
$E_T^{\text{miss}} + \text{photon}$
$E_T^{\text{miss}} + b \text{ quark(s)}$

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

Selection:
Large $E_T^{\text{miss}}$ 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
\( E_T^{\text{miss}} + \text{top quarks in ATLAS} \)

- 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: \( \text{MET} + W(qq')b + W(qq')b \)
    - Semi-leptonic: \( \text{MET} + W(l\nu)b + W(qq')b \)
    - Di-leptonic: \( \text{MET} + W(l\nu)b + W(l\nu)b \)

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

Example: dileptonic $tt$ BG in the semi-leptonic channel

1. Identify the objects: 2 b-jets, 1 lepton, $E_T^{\text{miss}}$

2. Assume that it’s a dileptonic $tt$ BG in which one lepton is not identified – this lepton will thus be part of the $E_T^{\text{miss}}$

3. Reconstruct the mass of the ”top” with all object permutations compatible with the assumption – take the permutation giving the minimal mass

$$M_{T_2}^{W} = \min \left\{ m_y \text{ consistent with: } \left[ p_1^T + p_2^T = \vec{E}_T^{\text{miss}}, \ p_1^2 = 0, \ (p_1 + p_\ell)^2 = p_2^2 = M_W^2, \ (p_1 + p_\ell + p_{b_1})^2 = (p_2 + p_{b_2})^2 = m_y^2 \right] \right\}$$

Requiring $m_{T_2} > m_{\text{top}}$ 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
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**

\[ E_T^{\text{miss}} + \text{top quark searches competitive with mono-jet/V at low } M_{\text{Med}} \]

*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. $\tau$)

**BG estimation** from leptonic CRs
$E_T^{\text{miss}} + \text{Higgs}$

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

Selection:

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

$$E_{T\text{miss}} + \text{jet}$$

*Wait a minute… haven’t we done that search before?*
Higgs portal?

• Let’s check for an invisible Higgs!
• Multiple topologies can be used:

\[ E_{T\text{miss}} + Z \]

Huh, and this one too?
**Higgs portal?**

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

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

Finally, something new!
$E_T^{\text{miss}} + \text{VBF in CMS}$

CMS-PAS-HIG-16-016

Selection:

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

BG estimation through $W/Z$ CRs
Higgs portal: $BR(H \rightarrow \text{invisible})$

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

$$\Gamma_H \rightarrow \Gamma_H + \Gamma_H^{inv} \quad \Gamma_H : \text{SM Higgs decay width: 4 MeV}$$

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

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

$$\Gamma_H^{inv} = \frac{BF(H \rightarrow \text{invisible})}{1 - BF(H \rightarrow \text{invisible})} \times \Gamma_H$$
Combining the results

CMS Run-1 + 2015 data (arXiv:1610.09218)
If SM production is assumed:
  • $\text{BF}(h \rightarrow \text{inv}) < 0.24$

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

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
<td>0.31</td>
<td>0.28</td>
</tr>
<tr>
<td>V(jj)H</td>
<td>0.86</td>
<td>0.78</td>
</tr>
<tr>
<td>Z(\ell\ell)H</td>
<td>0.62</td>
<td>0.75</td>
</tr>
<tr>
<td>Combine</td>
<td>0.27</td>
<td>0.25</td>
</tr>
</tbody>
</table>

• incl. visible decay rate measurements:
  • $\text{BF}(h \rightarrow \text{inv}) < 0.23$
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:

\[
\Gamma_{H \rightarrow S S}^{\text{inv}} = \frac{\lambda_{H S S}^2 v^2 \beta_S}{64\pi m_H}
\]

\[
\Gamma_{H \rightarrow f f}^{\text{inv}} = \frac{\lambda_{H f f}^2 v^2 m_H \beta_f^3}{32\pi \Lambda^2}
\]

where:

- \( v \) is the vacuum expectation value (246 GeV)
- \( \beta_\chi = \sqrt{1 - 4m_\chi^2/m_H^2} \)
- the \( \lambda \)'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:

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

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

where:

- \( m_N \sim 0.94 \text{ GeV} \) 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 \( \lambda \)'s are still the coupling constants on which we set limits at the LHC.
Higgs portal: comparison to DD

Considering a higgs mediator model

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

Band: uncertainty on $f_N$
Higgs portal: comparison to DD

Considering a higgs mediator model

Didn’t we just say that the limit was $BR<0.24$?!
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
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
    $\rightarrow$ huge rate $\rightarrow$ 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 $\times$ size
    $\rightarrow$ *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**

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-mass (ISR)</td>
<td><strong>ATLAS-CONF 2016-070</strong></td>
<td><strong>CMS-PAS-EXO-16-030</strong></td>
</tr>
<tr>
<td>Low-mass (TLA)</td>
<td><strong>ATLAS-CONF 2016-030</strong></td>
<td></td>
</tr>
<tr>
<td>High-mass</td>
<td><strong>ATLAS-CONF 2016-069</strong></td>
<td><strong>CMS-PAS-EXO-16-032</strong></td>
</tr>
</tbody>
</table>

ATLAS Preliminary

**$X + \gamma \ (P_{T,\gamma} > 150 \text{ GeV})$**

- Data
- Background fit
- BumpHunter interval

**$\sqrt{s} = 13 \text{ TeV}, 15.5 \text{ fb}^{-1}$**

$|y| < 0.8$

**Events**

- $Z' (g_{\gamma} = 0.30), m_{Z'} = 350 \text{ GeV}, \sigma \times 50$
- $p$-value = 0.67

**Fit Range:** 169 - 1493 GeV

---

CMS Preliminary

**$\sqrt{s} = 13 \text{ TeV}, 3.4 \text{ fb}^{-1}$**

- Data
- Background fit
- BumpHunter interval

$|y| < 0.8$

- $p$-value = 0.44
- Fit Range: 443 - 1236 GeV

---

ATLAS Preliminary

**$\sqrt{s} = 13 \text{ TeV}, 15.7 \text{ fb}^{-1}$**

- Data
- Background fit
- BumpHunter interval

- $q'^{\pm}, m_{\gamma} = 4.0 \text{ TeV}$
- $q'^{\pm}, m_{\gamma} = 5.0 \text{ TeV}$

**$q'^{\pm}, \sigma \times 3$

- $p$-value = 0.67
- Fit Range: 1.1 - 7.1 TeV

$|y| < 0.6$
Summary: axial-vector mediator
Mono-jet / dijet interplay

\[ g_q = 0.25, \quad g_{DM} = 1 \]

\[ g_q = 0.1, \quad g_{DM} = 1.5 \]

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

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

And the Higgs sector is larger.
A brief reminder of SUSY
DM in SUSY

Possibility of a dark matter candidate

\[ R = (-1)^{L+3B+2J} \]

where

- \( L \) = lepton number
- \( B \) = baryon number
- \( J \) = spin

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,… + $E_T^{\text{miss}}$)

**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!

---

**ATLAS SUSY Searches** - 95% CL Lower Limits

_Share August 2016_

<table>
<thead>
<tr>
<th>Model</th>
<th>(k, m, r, y, \text{Jets} )</th>
<th>( F_{\text{inv}}^{\text{inv}} )</th>
<th>( F_{\text{inv}}^{\text{inv}} )</th>
<th>( m_{\chi_{1}} \text{[GeV]} )</th>
<th>( \gamma \rightarrow \chi_{1} + \text{Jets} )</th>
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</thead>
<tbody>
<tr>
<td>Higgsinos</td>
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<td>( \tilde{g} \rightarrow \chi_{1} + \text{Jets} )</td>
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<tr>
<td>( \tilde{t} \rightarrow \chi_{1} + \text{Jets} )</td>
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</tbody>
</table>

**ATLAS Preliminary**

\( \gamma = 7, 8, 13 \text{ TeV} \)

<table>
<thead>
<tr>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS⁺002</td>
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<tr>
<td>ATLAS⁺003</td>
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<tr>
<td>ATLAS⁺004</td>
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<tr>
<td>ATLAS⁺005</td>
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<tr>
<td>ATLAS⁺006</td>
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<td>ATLAS⁺007</td>
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<td>ATLAS⁺008</td>
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<td>ATLAS⁺013</td>
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<tr>
<td>ATLAS⁺014</td>
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<tr>
<td>ATLAS⁺015</td>
</tr>
</tbody>
</table>

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\*Only a selection of the available cases limits on new states or resonances is shown.
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...

THERE’S SOMETHING OUT THERE
...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+$E_T^{\text{miss}}$

- 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.

- Important to have tighter signal regions in $E_T^{\text{miss}}$ 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 $H \rightarrow \text{invisible}$

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

<table>
<thead>
<tr>
<th>BR($H \rightarrow \text{inv.}$) limits at 95%CL</th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best scenario</td>
<td>17%</td>
<td></td>
</tr>
<tr>
<td><em>Assumptions</em></td>
<td></td>
<td>23%</td>
</tr>
<tr>
<td>Theo. uncert. halved, others scaling as $1/\sqrt{L}$</td>
<td></td>
<td>Uncert. on the main BG scales as $1/\sqrt{L}$</td>
</tr>
<tr>
<td>Conservative scenario</td>
<td>28%</td>
<td>32%</td>
</tr>
<tr>
<td><em>Systematics as before</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run-1 limit observed/expected</td>
<td>81% / 83%</td>
<td>75% / 62%</td>
</tr>
</tbody>
</table>

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

As for the jet+MET analysis, the $Z(\nu\nu)+\text{jets}$ main BG is constrained using $W(\mu\nu)$ 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 $n_D=6$):

<table>
<thead>
<tr>
<th>integrated luminosity [fb$^{-1}$]</th>
<th>$m_{q^*}$ [TeV]</th>
<th>$m_{QBH}$ [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>4.0</td>
<td>8.2</td>
</tr>
<tr>
<td>1</td>
<td>5.0</td>
<td>8.9</td>
</tr>
<tr>
<td>5</td>
<td>5.9</td>
<td>9.2</td>
</tr>
<tr>
<td>25</td>
<td>6.6</td>
<td>9.7</td>
</tr>
<tr>
<td>300</td>
<td>7.4</td>
<td>10.0</td>
</tr>
<tr>
<td>3000</td>
<td>8.0</td>
<td>10.1</td>
</tr>
</tbody>
</table>

• 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.
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, $p_T(j) / E_T^{miss} > 200$ GeV
$E_T^{\text{miss}} + h(\text{bb})$ 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

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

- The main BG is top pairs, $Z(vv)+$jets, $W+$jets
  - Use mass sidebands + leptonic CRs
$E_T^{\text{miss}} + h(bb)$ in ATLAS
$E_T^{\text{miss}} + \text{top quarks in CMS}$

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

Semi-leptonic (e or $\mu$):
$E_T^{\text{miss}}, \geq 1 \text{ b-jet}, m_T, m_{T^W}$

Di-leptonic (e or $\mu$):
$E_T^{\text{miss}}, Z(\ell\ell) \text{ veto, } \geq 1 \text{ b-jet, } \Delta\phi(E_T^{\text{miss}}, \ell\ell)$

Combination of the three channels

Fit to the $E_T^{\text{miss}}$ distributions to extract the signal
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
  - $\Delta R(j_1,b)$, $\Delta R(j_2,b)$
  - $\Delta \phi(j_1,b)$, $\Delta \phi(j_2,b)$
- Efficiencies in MC calibrated with $t\bar{t}$ events in data
- Tops in $t\bar{t}$+DM production generally have moderate $p_T$
CMS 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…
Due to gravity, $\Delta \rho / \rho$ increases, and so does $T$.

Pressure of photons increases, and the perturbation bounces back.

Before recombination $T > 3000$ K

After recombination $T < 3000$ K

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 ($|\eta|<2.7$): air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution $<10\%$ up to $E_\mu \sim 1$ TeV

Hadronic calorimetry ($|\eta|<3$): segmentation $0.1 \times 0.1$
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 $\sim 200$ Hz

Electromagnetic calorimeter: Pb-Liquid Argon
Accordion
e/$\gamma$ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.007$
granularity $0.025 \times 0.025 \oplus$ strips

Length: $\sim 46$ m
Radius: $\sim 12$ m
Weight: $\sim 7000$ tons
$\sim 10^8$ electronic channels
3000 km of cables

Inner Detector ($|\eta|<2.5$, $B=2T$):
Precise tracking and vertexing,
$\sigma/p_T \sim 3.8 \times 10^{-4} p_T (GeV) \oplus 0.015$
Evidence for Dark Matter: galaxy clusters

• 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

Clusters of galaxies are the largest gravitationally bound systems known in the Universe, containing ~10s to 1000s of galaxies
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: \( \rho(8.5 \text{ kpc}) \sim 0.2-0.5 \text{ GeV/cm}^3 \)

The expected curve is calculated using the luminous mass:

\[
v_{\text{rot}} = \sqrt{\frac{GM_r}{r}}
\]
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.
~400k years after the Big Bang, the electrons and protons combined and the universe became transparent to radiation, leading to the cosmic microwave background $T=2.725\text{K}$, $\Delta T\sim 200\mu\text{K}$

Planck has measured 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, ...

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

\( \Omega_{b} \quad \Omega_{m} \quad \Omega_{\text{tot}} \)

\(~85\%\) 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** from galactic halo  
\(v \sim 220 \text{ km/s}\)

**Target Nucleus** in laboratory  
\(v \sim 0 \text{ km/s}\)

**Elastic collision**

**WIMP**

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

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

\[
\sigma_{SD} = \frac{32\mu^2}{\pi} G_F^2 \frac{J + 1}{J} \left[ a_p \langle S_p \rangle + a_n \langle S_n \rangle \right]^2 \quad \text{Nucleus with spin } 19_F, 23_{\text{Na}}, 73_{\text{Ge}}, 127_{\text{I}}, 131_{\text{Xe}}, 133_{\text{Cs}}
\]

**WIMP Scatt. Rates per 100kg per day for different targets (Xe, Ge, Ar)**

- 18 events/100-kg/year (Xe, \(E_R=5 \text{ keVr}\))
- 8 events/100-kg/year (Xe, \(E_R=15 \text{ keVr}\))
- \(M_{WIMP}=100 \text{ GeV}\)
- \(\sigma_{SI}=10^{-44} \text{ cm}^2\)

**Small and uncertain rates**

**Rare event search:** minimize BG!

**Tiny** \(E_{\text{recoil}}\)

**Featureless spectrum**
Direct search

WIMP from galactic halo

\[ v \sim 220 \text{ km/s} \]

Target Nucleus in laboratory

\[ v \sim 0 \text{ km/s} \]

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\]

\[^{19}\text{F, }^{23}\text{Na, }^{72}\text{Ge, }^{127}\text{I, }^{129}\text{Xe, }^{131}\text{Xe, }^{133}\text{Cs}\]

DAMA:

0.8 ton-years, 8.2\sigma significance (modulation)

*Annual modulation of the rate
Direct search

Shielding is paramount

Combining different detection techniques helps isolating the signal
Direct search: future complications…

“Blind spot” at low DM mass

Spin Independent

WIMP Mass [GeV/c^2]

Billard, Figueroa-Feliciano, Strigari 1307.5458

Direct search: WIMP-nucleon scattering

Indirect search: WIMP-annihilation

Hadron collider search
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

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: