I always wanted to be a gravitational physicist...
Gravity for Masses

I always wanted to be a gravitational physicist...
I always wanted to be a gravitational physicist...
Gravity for Masses

Masses for Gravity

- Dark Energy: 68.3%
- Ordinary Matter: 4.9%
- Dark Matter: 26.8%
Gravity vs QCD

- It's easy to tell a Moriond Gravity person from a Moriond QCD person on the slopes...
Gravity vs QCD

♦ It's easy to tell a Moriond Gravity person from a Moriond QCD person on the slopes...
Gravity vs QCD

✧ It's easy to tell a Moriond Gravity person from a Moriond QCD person on the slopes...
Gravity vs QCD

- It's easy to tell a Moriond Gravity person from a Moriond QCD person on the slopes...

Gradient decent vs. scattering!
Gravity vs QCD

It's easy to tell a Moriond Gravity person from a Moriond QCD person on the slopes...

Gradient decent vs. scattering!

You mainly care about one force; we mostly care about the other three! I'll try to convince you that they are at least as interesting as the one you study...
Is there place for dark matter in this picture?
Is there place for dark matter in this picture?
Dark Matter from Cosmos
Fritz Zwicky was first to suggest the possibility of DM in the 1930-ies by observing the Coma cluster of galaxies and comparing the velocities to the ones expected from the virial theorem: \( \frac{GM_\odot m}{r} = mv^2 \)

- Found that galaxies move too fast to remain bound unless there is additional invisible mass (DM)
- N.B. Similar technique as used by Le Verrier in 1846 to predict the existence of Neptune from the distortion of the Uranus orbit
Galaxy Rotation Curves

In the 1970-ies, Vera Rubin has measured rotation curves in a number of spiral galaxies, only to find flat distribution, indicative of hidden mass.
One can also infer about the distribution of dark matter mass using weak or strong lensing.
Observation of the Bullet cluster by the Chandra X-ray satellite showed that hot matter is left behind the clouds of dark matter (reconstructed via gravitational lensing).
The leading model of cosmology is $\Lambda_{\text{CDM}}$, favored by cosmic microwave background measurements, baryon acoustic oscillations, gravitational lensing, and other observations.

Latest CMB data dominated by the Planck satellite results, suggest the following components of the energy balance in the universe:

- Dark Matter: 26.8%
- Ordinary Matter: 4.9%
- Dark Energy: 68.3%
With the development of SUSY in the 1970-ies, it was quickly realized that a neutral, weakly interacting particle with the mass of \( \sim 100 \text{ GeV} \) can naturally serve as a DM candidate.

This is known as "WIMP Miracle" and is one of three miracles of SUSY (the other two being a natural solution to the hierarchy problem and the unification of couplings).

As the universe expands and cools down, WIMPs thermally decouple (i.e., can't annihilate any longer), giving fixed DM abundance:

\[
\Omega_{\text{DM}} h^2 = \frac{0.2 \times 10^{-9} \text{GeV}^{-2}}{\langle \sigma v \rangle}
\]

\[
\langle \sigma v \rangle \sim 10^{-9} \text{GeV}^{-2} \quad \text{(weak cross section)}
\]

\[
\Omega_{\text{DM}} \sim 0.2
\]
When DM is in thermal equilibrium with matter, both the formation and annihilation are possible and equal:

\[ \chi \chi \leftrightarrow q \bar{q} \]

As the universe cools down, the formation is not possible, and only annihilation remains:

\[ \chi \chi \rightarrow q \bar{q} \]

As the universe further expands, the annihilation is no longer possible: DM freezes out

This DM is non-relativistic (cold) with typical velocity \( \sim 300 \text{ km/s} \)

\[ \Omega_{\text{DM}} h^2 = 0.12 \]
While WIMPs are the most sought and theoretically preferred DM candidates, they are not the only known possibility:

- Axions (very light pseudoscalar particles proposed to solve the "strong CP" problem) could also serve as a DM candidate
- Dark sector (DM has complicated structure and is found in the dark sector, which only communicates to SM particles weakly)
- Compact astronomical objects and primordial particles, such as super-heavy monopoles, could also be DM candidates

Finally, while a single DM source is economic, the nature may have opted for a more complex solution, and there may be several sources of DM.

In what follows I will nevertheless focus on the WIMP DM, predicted not only by SUSY, but also by other new physics models.

Generally speaking, any model that predicts a weakly interacting massive particle, whose stability must be ensured by a certain symmetry (e.g., R-parity in SUSY), is a good DM candidate.
FIG. 1: Mass ranges for dark matter and mediator particle candidates, experimental anomalies, and search techniques described in this document. All mass ranges are merely representative; for details, see the text. The QCD axion mass upper bound is set by supernova constraints, and may be significantly raised by astrophysical uncertainties. Axion-like dark matter may also have lower masses than depicted. Ultralight Dark Matter and Hidden Sector Dark Matter are broad frameworks. Mass ranges corresponding to various production mechanisms within each framework are shown and are discussed in Sec. II. The Beryllium-8, muon ($g-2$), and small-scale structure anomalies are described in VII. The search techniques of Coherent Field Searches, Direct Detection, and Accelerators are described in Secs. V, IV, and VI, respectively, and Nuclear and Atomic Physics and Microlensing searches are described in Sec. VII.
FIG. 1: Mass ranges for dark matter and mediator particle candidates, experimental anomalies, and search techniques described in this document. All mass ranges are merely representative; for details, see the text. The QCD axion mass upper bound is set by supernova constraints, and may be significantly raised by astrophysical uncertainties. Axion-like dark matter may also have lower masses than depicted. Ultralight Dark Matter and Hidden Sector Dark Matter are broad frameworks. Mass ranges corresponding to various production mechanisms within each framework are shown and are discussed in Sec. II. The Beryllium-8, muon (\( \mu \)), and small-scale structure anomalies are described in VII. The search techniques of Coherent Field Searches, Direct Detection, and Accelerators are described in Secs. V, IV, and VI, respectively, and Nuclear and Atomic Physics and Microlensing searches are described in Sec. VII.

II. SCIENCE CASE FOR A PROGRAM OF SMALL EXPERIMENTS

Given the wide range of possible dark matter candidates, it is useful to focus the search for dark matter by putting it in the context of what is known about our cosmological history and the interactions of the Standard Model, by posing questions like: What is the (particle physics) origin of the dark matter particles' mass? What is the (cosmological) origin of the abundance of dark matter seen today? How do dark matter particles interact, both with one another and with the constituents of familiar matter? And what other observable consequences might we expect from this physics, in addition to the existence of dark matter? Might existing observations or theoretical puzzles be closely tied to the physics of dark matter? These questions have many possible answers — indeed, this is one reason why...
While the true origin of DM is unknown, several things about DM are well understood.

**Assuming that DM has particle origin** we know that:

- It has to be a neutral particle
- It's unlikely that it carries color (strong interactions)
- It must be stable on a cosmological timescale
- It must have the right abundance, which sets constraints on its decay channels, couplings, and mass

For example, ordinary neutrinos can't be a sole source of DM, despite having mass.

In order to get the right abundance, DM must be able to interact with the SM particles, which is achieved via a "mediator" particle coupled to both SM species and DM.
Searching for Dark Matter

- A clever way of searching for DM is to look for a recoil of DM from a heavy nucleus (*scattering again!*)
- These types of experiments use very cold targets and are conducted deep underground to shield cosmic rays
- The sensitivity drops dramatically for a light DM, as there is not much of a recoil!
- Latest generation of experiments uses Xe as the target (LUX, Xenon1T, PandaX, LZ)
  - As the dominant Xe isotope has spin 0, these experiments are sensitive mainly to spin-independent (SI) scattering and benefit from a resonant enhancement $\sim A^2$
  - Other targets are used to probe spin-dependent (SD) scattering ($C_4F_{10}$, CF$_3$Br, etc)
Direct Detection Experiments

- SuperCDMS
- LUX
- CoGeNT
- PICO
- Xe
- PANDAX
Direct Detection Results

- State of the art results dominated by the latest Xenon 1T result, with LUX & PandaX-II being close second/third (SI) and PICO (SD)
- Large neutrino detectors (IceCube, SuperK) are also sensitive to DM via annihilation inside the Sun or (very slow) decay
- N.B.: SD limits are ~6 orders of magnitude weaker than SI ones

**FIG. 8:** Left: Constraints and projections (90% c.l.) for the DM-nucleon scattering cross section. Thick gray lines are current world-leading constraints [108, 116, 129, 130]. Projections are shown with solid/dashed/dotted lines indicating a short/medium/long timescale, respectively, with the same meaning as in Fig. 6. Blue lines denote the DoE G2 experiment projections. Yellow region denotes the WIMP-discovery limit from [131] extended to lower masses for He-based experiments.

Right: As in left plot, but focused on the 100 MeV to 10 GeV DM mass range.

**FIG. 9:** Constraints from direct-detection experiments (solid lines), colliders and indirect detection (labelled, dashed), and projections for new experiments (labelled, dashed/dotted lines) for the spin-dependent scattering cross section for protons or neutrons on nuclei. Constraints are shown from PICO-60 [116], LUX [132], PICO-2L [133], PICO-60 CF3I [134], and IceCube [135]. Projections from PICO (proton) and LZ (neutron) are also shown [115]. The expected background from atmospheric, supernova and solar neutrinos in both xenon and CF3I is shown by the shaded regions [131].

Direct Detection Results

✦ State of the art results dominated by the latest Xenon 1T result, with LUX & PandaX-II being close second/third (SI) and PICO (SD)
✦ Large neutrino detectors (IceCube, SuperK) are also sensitive to DM via annihilation inside the Sun or (very slow) decay
✦ N.B.: SD limits are ~6 orders of magnitude weaker than SI ones
Future of Direct Detection

Next generation of DD experiments will reach the "ν floor"
Next generation of DD experiments will reach the "ν floor"
Indirect Detection

- Look for DM annihilation into SM particles, further decaying to lighter species (bb, ττ, ...)
  - Every time a π⁰ is created, it decays into two photons - look for an excess of γ rays in the sky
- Number of ground-based (HESS, Magic, Veritas) and space-based (Fermi-LAT) instruments
  - Look for γ ray emission from the center of galaxy, cluster of galaxies, dwarf galaxies, etc.
  - Certain hints (galactic center, dwarf galaxies) have been reported, but no definitive observation (yet)
  - Could also look for positron emission (AMS, Pamela)
  - Results are reported in terms of velocity-averaged annihilation cross section
Mono-mania, or LHC as a Dark Matter Factory
There are three main approaches to detect DM:

- DM-nucleon scattering (direct detection)
- Annihilation (Indirect detection)
- Pair production at colliders

All three processes are nothing but topological permutations of one and the same Feynman diagram:

- But: how to trigger on a pair of DM particles at colliders?
- Initial-state radiation (ISR: $g$, $\gamma$, $W/Z$, $H$, ...) to rescue!

Original idea - to use the ISR - appeared nine years ago:

More phenomenological follow-ups sparked interest from the collider community:

- Bai, Fox, Harnik, arXiv:1005.3797, 371 citations
- Goodman et al, arXiv:1008.1783, 595 citations
- Fox, Harnik, Kopp, Tsai, arXiv:1103.0240, 245 citations - LEP reinterpretation
- Fox, Harnik, Kopp, Tsai, arXiv:1109.4398, 435 citations - LHC case

The first experimental search came from the CDF collaboration:

- Mono-top, arXiv:1202.5653, 31 citations
- Monojets, arXiv:1203.0742, 87 citations

Was quickly followed and superseded by ATLAS and CMS:

- CMS, Monophotons, arXiv:1204.0821, 192 citations
- CMS, Monojets, arXiv:1206.5663, 276 citations
- ATLAS, Monophotons, arXiv:1209.4625, 172 citations
- ATLAS, Monojets, arXiv:1210.4491, 253 citations

...and then the hell broke loose with dozens of other mono-X searches
Effective Field Theory

- Effective Field Theory (EFT) is a convenient simplified description of a complicated process via effective operator (and effective coupling)
- Most well-known example: Fermi theory of muon decay

\[ \Gamma_{\mu} = \frac{g_w^4}{M_W^4} \frac{m_\mu^2 E_2(m_\mu - 2E_2)}{2(4\pi)^3} \int_0^{m_\mu/2} E^2 \left(1 - \frac{4E}{3m_\mu}\right) dE \]

\[ \tau_\mu = \frac{192\pi^3}{G_F^2 m_\mu^5} \]

\[ G_F = \frac{\sqrt{2}g_w^2}{8M_W^2} \]

- But, just like applying Fermi theory to describe $W$ production at the LHC would fail completely, one has to be very careful about applicability of the effective theory for DM searches
Dark Matter Interactions

✦ Early DM searches: EFT based
  ◦ Since then understood the fundamental limitations of EFT and largely moved to simplified models of DM

✦ Moving away from EFT allows for a more fair LHC vs. DD/ID experiments comparison and emphasizes the complementarity of these three approaches

Fundamentally 4D problem!
Monojets: the Classics
Monojet Searches

- Monojet analysis is a classical search for a number of new physics phenomena
  - Smoking gun signature for supersymmetry, large extra dimensions, dark matter production, ...
  - Was pursued since early 1980s

- The signature is deceptively simple, yet it's not
  - Backgrounds from instrumental effects
  - Irreducible $Z(\nu\nu)+$jet background
  - Reducible backgrounds from jet mismeasurements and $W+$jets with a lost lepton

- Number of techniques have been developed since the first search by UA1; will show the state-of-the-art results from CMS
We've come a long way since Carlo Rubbia's first attempt!

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY
ACCOMPANIED BY A JET OR A PHOTON(S) IN $p\bar{p}$ COLLISIONS
AT $\sqrt{s} = 540$ GeV

[PL, 139B, 115 (1984)]

UA1 Collaboration, CERN, Geneva, Switzerland
We've come a long way since Carlo Rubbia's first attempt!

**Experimental Observation of Events with Large Missing Transverse Energy Accompanied by a Jet or a Photon(s) in pp Collisions**

AT \( \sqrt{s} = 540 \text{ GeV} \)

[PL, **139B**, 115 (1984)]

UA1 Collaboration, CERN, Geneva, Switzerland

**Abstract**

We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet and of two similar events with a neutral electromagnetic cluster (either one or more closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.
We've come a long way since Carlo Rubbia's first attempt!

We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet and of two similar events with a neutral electromagnetic cluster (either one or more closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.

\[ W \rightarrow \tau\nu \rightarrow \text{hadrons} + \text{neutrinos} \]

\[ Z(\nu\bar{\nu})+\text{jet} \]
Results and interpretation

Table 5: Expected event yields in each \( p_T^{\text{miss}} \) bin for various background processes in the mono-\( V \) signal region. The background yields and the corresponding uncertainties are obtained after performing a combined fit to data in all the control samples, but excluding data in the signal region. The other backgrounds include QCD multijet and \( g+\)jets processes. The expected signal contribution for a 2 TeV axial-vector mediator decaying to 1 GeV DM particles and the observed event yields in the mono-\( V \) signal region are also reported.

<table>
<thead>
<tr>
<th>( p_T^{\text{miss}} ) Bin</th>
<th>Signal ( Z(vv)+)jets</th>
<th>W((v)+jets)</th>
<th>Top quark</th>
<th>Diboson</th>
<th>Other</th>
<th>Total bkg.</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>250-300 GeV</td>
<td>11.7 ± 0.6</td>
<td>5300 ± 170</td>
<td>3390 ± 120</td>
<td>553 ± 54</td>
<td>396 ± 69</td>
<td>128 ± 25</td>
<td>9770 ± 290</td>
</tr>
<tr>
<td>300-350 GeV</td>
<td>15.7 ± 0.7</td>
<td>3720 ± 98</td>
<td>1823 ± 53</td>
<td>257 ± 27</td>
<td>261 ± 46</td>
<td>79.8 ± 13</td>
<td>6140 ± 140</td>
</tr>
<tr>
<td>350-400 GeV</td>
<td>11.8 ± 0.6</td>
<td>1911 ± 59</td>
<td>808 ± 28</td>
<td>101 ± 12</td>
<td>134 ± 25</td>
<td>25.0 ± 4.8</td>
<td>2982 ± 79</td>
</tr>
<tr>
<td>400-500 GeV</td>
<td>15.8 ± 0.7</td>
<td>1468 ± 45</td>
<td>521 ± 15</td>
<td>48.8 ± 5.7</td>
<td>101 ± 20</td>
<td>20.0 ± 3.6</td>
<td>2165 ± 55</td>
</tr>
<tr>
<td>500-600 GeV</td>
<td>8.59 ± 0.56</td>
<td>388 ± 18</td>
<td>103.0 ± 5.1</td>
<td>10.7 ± 1.9</td>
<td>10.7 ± 3.6</td>
<td>33.8 ± 7.0</td>
<td>1.76 ± 0.53</td>
</tr>
<tr>
<td>600-750 GeV</td>
<td>7.04 ± 0.47</td>
<td>151.0 ± 9.9</td>
<td>33.4 ± 2.3</td>
<td>1.9 ± 1.1</td>
<td>20.2 ± 4.5</td>
<td>1.05 ± 0.25</td>
<td>208 ± 11</td>
</tr>
<tr>
<td>&gt;750 GeV</td>
<td>4.48 ± 0.40</td>
<td>37.7 ± 3.7</td>
<td>7.09 ± 0.69</td>
<td>0.28 ± 0.25</td>
<td>10.2 ± 2.3</td>
<td>0.06 ± 0.03</td>
<td>55.3 ± 4.6</td>
</tr>
</tbody>
</table>

Figure 9: Observed \( p_T^{\text{miss}} \) distribution in the monojet (left) and mono-\( V \) (right) signal regions compared with the post-fit background expectations for various SM processes. The last bin includes all events with \( p_T^{\text{miss}} > 1250 \) (750) GeV for the monojet (mono-\( V \)) category. The expected background distributions are evaluated after performing a combined fit to the data in all the control samples, as well as in the signal region. The fit is performed assuming the absence of any signal. Expected signal distributions for the 125 GeV Higgs boson decaying exclusively to invisible particles, and a 2 TeV axial-vector mediator decaying to 1 GeV DM particles, are overlaid. The description of the lower panels is the same as in Fig. 5.

The results for vector, axial-vector, and pseudoscalar mediators are compared to constraints from the observed cosmological relic density of DM as determined from measurements of the cosmic microwave background by the Planck satellite experiment [97].

State-of-the-art analysis, which employs multiple control regions and the latest theory calculations of NLO EW and QCD corrections.
A Monojet Event
Present the limits in terms of constraints on the mediator vs. DM particle masses for fixed value of couplings

Convention: $g_q = 0.25; g_{DM} = 1$

**Vector mediators**

**Axial-vector mediators**

---

Figure 10: Exclusion limits at 95% CL on $\mu_s/s_{th}$ in the $m_{med}$–$m_{DM}$ plane assuming vector (left) and axial-vector (right) mediators. The solid (dotted) red (black) line shows the contour for the observed (expected) exclusion. The solid contours around the observed limit and the dashed contours around the expected limit represent one standard deviation due to theoretical uncertainties in the signal cross section and the combination of the statistical and experimental systematic uncertainties, respectively. Constraints from the Planck satellite experiment [97] are shown as dark blue contours; in the shaded area DM is overabundant.

Figure 11: Expected (dotted black line) and observed (solid black line) 95% CL upper limits on the signal strength $\mu_s/s_{th}$ as a function of the mediator mass for the scalar mediators (left) for $m_{DM} = 1$ GeV. The horizontal red line denotes $\mu_s = 1$. Exclusion limits at 95% CL on $\mu_s/s_{th}$ in the $m_{med}$–$m_{DM}$ plane assuming pseudoscalar mediators (right). The solid (dashed) red (back) line shows the contours for the observed (expected) exclusion. Constraints from the Planck satellite experiment [97] are shown with the dark blue contours; in the shaded area DM is overabundant.

Abundance is estimated, separately for each model, using the thermal freeze-out mechanism implemented in the MADDM [98] framework and compared to the observed cold DM density $\Omega_c h^2 = 0.12$ [99], where $\Omega_c$ is the DM relic abundance and $h$ is the Hubble constant.

---

**CMS arXiv:1712.02345**
(Pseudo)Scalar mediators are harder, because of the assumed Yukawa couplings (don't couple to light quarks; need top quark loop in production)

**Scalar mediators**

**Pseudoscalar mediators**
**Complementarity w/ DD**

Collider experiments win over direct detection in SD case (axial-vector mediator) up to $m_{DM} \sim 500$ GeV and in the SI case (vector mediator) for very light DM ($m_{DM} < 5$ GeV)

<table>
<thead>
<tr>
<th>$m_{DM}$ [GeV]</th>
<th>$\sigma^{SD}_{DM-nucleon}$ [$\text{cm}^2$]</th>
<th>$\sigma^{SI}_{DM-nucleon}$ [$\text{cm}^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$10^{-27}$</td>
<td>$10^{-27}$</td>
</tr>
<tr>
<td>10</td>
<td>$10^{-29}$</td>
<td>$10^{-29}$</td>
</tr>
<tr>
<td>100</td>
<td>$10^{-31}$</td>
<td>$10^{-31}$</td>
</tr>
<tr>
<td>1000</td>
<td>$10^{-33}$</td>
<td>$10^{-33}$</td>
</tr>
</tbody>
</table>

**Figure 13:** Exclusion limits at 90%CL in the $m_{DM}$ vs. $\sigma^{SI/SD}$ plane for vector (left) and axial-vector (right) mediator models. The solid red (dotted black) line shows the contour for the observed (expected) exclusion in this search. Limits from CDMSLite [102], LUX [103], XENON-1T [104], PANDAX-II [105], and CRESST-II [106] are shown for the vector mediator. Limits from Picasso [107], PICO-60 [108], IceCube [109], and Super-Kamiokande [110] are shown for the axial-vector mediator.

**Figure 14:** For the pseudoscalar mediator, limits are compared to the the velocity averaged DM annihilation cross section upper limits from Fermi-LAT [101]. There are no comparable limits from direct detection experiments, as the scattering cross section between DM particles and SM quarks is suppressed at nonrelativistic velocities for a pseudoscalar mediator [111, 112].

Complementarity w/ DD
- Collider experiments win over direct detection in SD case (axial-vector mediator) up to $m_{DM} \sim 500$ GeV and in the SI case (vector mediator) for very light DM ($m_{DM} < 5$ GeV)

**References:**
- CMS arXiv:1712.02345
Complementarity w/ ID

- For a pseudoscalar mediator, the nucleon scattering cross section is velocity suppressed due to the following factor in the matrix element: \( M \sim (\vec{v}_f - \vec{v}_i) \cdot \vec{\sigma}_n \)
- Given \( v \sim 10^{-3} \), the sensitivity of DD experiments vanishes
- The collider results can be compared w/ ID experiments and are more stringent for DM masses below ~150 GeV

![Graph showing complementarity with ID experiments](attachment:image.png)
Beyond Monojets
Higgs boson could couple to DM and decay invisibly if its mass $m_{DM} < m_H/2 = 62.5$ GeV

- **ATLAS**: $\text{B}(H \rightarrow \text{inv.}) < 0.26$ (0.17) @ 95% CL
- **CMS**: $\text{B}(H \rightarrow \text{inv.}) < 0.19$ (0.15) @ 95% CL

Can use dedicated searches for H(inv.) or reinterpret monojet results
Best sensitivity is achieved in combination
Results are competitive with DD experiments for $m_{DM} < 10$ GeV
Since SUSY gives a perfect WIMP candidate, direct searches for neutralino production set limit on DM.

Depending on the nature of the neutralino (wino, bino, Higgsino), limits are still not very strong, particularly if superpartners of leptons are heavy.

---

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/
At first glance, the TeV scale SUSY is simply not there...
But: Read the Fine Print!

Keep in mind that:

- Searches typically assume 100% branching fraction in a particular channel
- Many searches assume mass degeneracy between various SUSY particles, e.g., squarks of different generation
- Interpretation is usually done via simplified model framework, not in the full model
But: Read the Fine Print!

Keep in mind that:

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- Many searches assume mass degeneracy between various SUSY particles, e.g., squarks of different generation
- Interpretation is usually done via simplified model framework, not in the full model
Mono-Higgs Production

MONO-Higgs searches in the latest addition in the context of certain vector mediator ($Z'$) models

$g_{Z'} = 0.8$, $\tan \beta = 1$

$g_q = 0.25$, $g_\chi = 1$
Searches for the Mediator
Search for the Mediator

- One doesn’t need to produce DM at the LHC to look for a mediator
- Even if it's too heavy to be produced or too light to be observed, one can focus on the mediator particle, which very well could be within the reach of the LHC!
- Since the mediator is coupled to the initial state, one could look for dijet decays of the mediator by "recycling" dijet resonance searches
  - Also possible to reinterpret dilepton searches if the mediator couples to leptons in addition to quarks
Dijet Resonance Searches

- Standard search to do at any new energy
- Recent addition to the dijet search portfolio:
  - Scouting (trigger-level) analysis based on low-threshold triggers writing only very limited information about the event
Dijet Resonance Searches

- Standard search to do at any new energy
- Recent addition to the dijet search portfolio:
  - Scouting (trigger-level) analysis based on low-threshold triggers writing only very limited information about the event

![Graph showing dijet mass distribution](image)

**Figure 4:** The reconstructed dijet mass distribution (filled points) for events in the data and the background estimate, considering only statistical uncertainties. The solid lines depict the background estimate obtained by a sliding-window fit. Overall agreement between the background estimate and the data is quantified by the p-value. The most discrepant interval identified by the BumpHunter algorithm is indicated by the vertical lines. The open points only on the coupling of the candidate. No interference with the SM is simulated. Signal samples were generated so that the decay rate of the resonance with mass equal to 750 GeV for the simplified model is negligible and the dijet production rate and resonance width depend only on the coupling of the resonance to quarks, including parton shower and detector resolution effects, is approximately 7%.

**Limits:**
- Limits are set on the cross-section,
- Limits also set on a generic model where the signal is modeled as a Gaussian contribution to the background.

**Results and limits:**
- Recent addition to the dijet search portfolio:
  - Standard search to do at any new energy
  - Scouting (trigger-level) analysis based on low-threshold triggers writing only very limited information about the event

---

**3 Limits on the coupling**
- Limits are obtained accounting for the scaling of the signal cross-section with resonance mass, 
- The acceptance for a mass of 550 GeV is 20%.
- The acceptance for a mass of 550 GeV is 20%.
- The acceptance for a mass of 550 GeV is 20%.
Dijet Event Display

M = 8 TeV

ATLAS EXPERIMENT

Run: 305777
Event: 4144227629
2016-08-08 08:51:15 CEST
At first, we were looking at the highest masses, which opened up due to the record-high machine energy.

These are low-background searches, but only sensitive to large couplings.

Last few years marked a shift in paradigm: we are going for high-background, experimentally challenging searches for low couplings and low masses - something that earlier machines may have missed!
Trijets as Dijet Proxies

✦ Usually, initial-state radiation (ISR) creates difficulties at the LHC, as it pollutes final states we are interested in with extra jets

![Diagram of jet production](image)

✦ However, it could also be our best friend:
  - It gives the possibility to trigger on an event when everything else fails - perfect for low-mass final states (or DM!)
  - While one has to pay a price for an energetic ISR jet (or a photon), it's a great (only?) way to trigger...
Typical trigger threshold on an ISR jet is \(~500\) GeV.

If we want to extend the dijet search to even lower masses than the scouting technique allows, we typically have a boosted topology.

\[ \gamma \approx \frac{p_T^{ISR}}{m(Z')} ; \text{ for } m(Z') \sim 100 \text{ GeV, } \gamma \sim 5, \text{ and } \alpha \sim 0.5: \text{ reconstructed as a single jet} \]
In the past 10 years, we saw significant theoretical and experimental developments in identifying jet with substructure.

These involve several steps:

- **Jet grooming** - removing soft, wide-angle radiation that artificially increases the jet invariant mass.
- **Jet substructure**: how likely is that a large-radius jet consists of N subjets.
- **Jet mass measurement** - after grooming and determining that the jet has a substructure, jet invariant mass becomes a powerful discriminant to look for resonances decaying into two jets.
To illustrate the complementarity of the searches \cite{60,62}, three dijet angular analyses are presented for these models. The dibjet 

\begin{align*}
\Gamma/m_Z &= 0.15 \\
\Gamma/m_Z &= 0.1 \\
\Gamma/m_Z &= 0.07 \\
\end{align*}

for the leptophobic axial-vector mediator. Benchmark width lines are indicated in the canvas. The TLA dijet analysis has two parts, employing different datasets with different selections in the rapidity difference.

The exclusions from the resonance searches (dijet, dibjet, dilepton) in the same region of sensitivity of the dijet, TLA dijet, and boosted dijet + ISR analyses.

The TLA dijet search with different coupling scenarios are also considered in the interpretation of the results: the lower lepton coupling value is set to highlight the dilepton search sensitivity even for very small values of this parameter.

The ATLAS dijet search with the limits placed on resonances reconstructed with a Gaussian shape, while the limits from the dibjet angular analysis is sensitive up to $|y^*_{12}| < 0.6$. The yellow contour shows the results of the dijet search using Dirac DM $m_\chi = 10$ TeV, $g_\chi = 1.0$.
Low-Mass Dijets

ATLAS arXiv:1804.03496

\( \sqrt{s} = 13 \text{ TeV}, 3.6-37.0 \text{ fb}^{-1} \)

95% CL upper limits

- - - Expected

- Observed

Dijet 8 TeV
20.3 fb\(^{-1}\)

Boosted dijet + ISR
36.1 fb\(^{-1}\)
arXiv: 1801.08769

Resolved dijet + ISR (\( \gamma \))
Preliminary, 15.5 fb\(^{-1}\)
ATLAS-CONF-2016-070

Resolved dijet + ISR (j)
Preliminary, 15.5 fb\(^{-1}\)
ATLAS-CONF-2016-070

Dijet
24.3 & 36.1 fb\(^{-1}\)

Dijet TLA
3.6 & 29.7 fb\(^{-1}\)

\( t\bar{t} \) resonances
36.1 fb\(^{-1}\)

Dijet
37.0 fb\(^{-1}\)

Dijet angular
37.0 fb\(^{-1}\)

Axial vector mediator
Dirac DM
\( m_\chi = 10 \text{ TeV}, g_\chi = 1.0 \)

100 200 1000 2000

\( m_{Z_A} \) [GeV]

\(|y_{12}| < 0.3\)
\(|y_{12}| < 0.6\)
Low-Mass Dijets

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#Dijet_summary_plots
Analogous limits for axial vector mediators

The complementarity depends significantly on the coupling values!
Analogous limits for axial vector mediators

The complementarity depends significantly on the coupling values!
Comparison w/ DD

✦ Nice complementarity with DD experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Energy</th>
<th>Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>$13$ TeV</td>
<td>$37.0$ fb$^{-1}$</td>
</tr>
<tr>
<td>Dijet</td>
<td>$13$ TeV</td>
<td>$37.0$ fb$^{-1}$</td>
</tr>
<tr>
<td>Dijet TLA</td>
<td>$13$ TeV</td>
<td>$29.3$ fb$^{-1}$</td>
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<tr>
<td>ATLAS</td>
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<td>CRESST III</td>
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<td>DarkSide-50</td>
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</tr>
<tr>
<td>LUX</td>
<td>$13$ TeV</td>
<td>$36.1$ fb$^{-1}$</td>
</tr>
</tbody>
</table>

ATLAS limits at 95% CL, direct detection limits at 90% CL.
Comparison w/ DD

Nice complementarity with DD experiments

ATLAS

PICO-60 C₃F₈

Dilepton

ATLAS limits at 95% CL, direct detection limits at 90% CL

Axial-vector mediator, Dirac DM

$g_q = 0.1, g_l = 0.1, g_\chi = 1$

$\sigma_{SD} (\chi$-proton) [cm²]

$m_\chi [GeV]$
For the first time started probing spin-0 mediators

- CMS Preliminary
- ICHEP 2018

Pseudoscalar Mediator
- Dirac DM
  - $g_q = 1.0$
  - $g_{DM} = 1.0$
  - $m_{DM} = 1$ GeV

Graph showing the ratio of signal to background for different mediator mass values.

- $\sigma_{an}$ (LHC DM WG)
- Observed exclusion 95% CL
- Expected exclusion 95% CL
- DM + j/V(qq) (35.9 fb$^{-1}$) [arXiv:1712.02345]
- DM + Z(II) (35.9 fb$^{-1}$) [arXiv:1711.00431]
- DM + tt comb. (35.9 fb$^{-1}$) [EXO-16-049]
For the first time started probing spin-0 mediators.
We hope that the multi-prong attack on the DM will bear fruit

- DD experiments are moving to a multi-ton mass range and will soon reach the neutrino floor
- Many new ideas of non-WIMP and light DM searches (electron recoil, CCD detectors, etc.)
- New generation of axion searches curbing the available parameter space
- New indirect detection experiments coming online, and exciting hints from the present ones are being followed up
- Collider experiments are processing large amount of Run 2 data and are moving toward more sophisticated models of dark matter, including hidden-sector searches
Conclusions

✦ There is an overwhelming evidence that dark matter exists and outweighs ordinary matter by a factor of five
  ◦ While there is no guarantee that dark matter has particle physics origin, this is certainly a compelling possibility
  ◦ If exist, dark matter particles could be produced at the LHC, leading to exciting mono-X signatures
  ◦ In addition, LHC can look directly for the dark matter mediators

✦ A lot of theoretical and experimental progress in the past few years - an exciting and rapidly developing subject

✦ LHC searches are complementary to both direct and indirect detection and offer unique sensitivity for pseudoscalar mediator and/or very light dark matter particles

✦ Many searches ongoing with the large data sets accumulated in the last few years - please stay tuned!

✦ Gravity may be not the only force the dark matter feels!
Thank You!