Measuring the Dark Force at the LHC

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Reference: arXiv 0902.0006
(with Yang Bai @ Fermilab)

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Outline

- Motivation
  - Positron/electron excesses in cosmic rays, PAMELA, ATIC, FERMI...
  - A class of dark matter models with a “dark force” mediated by a light (~GeV) particle: a
- Signature and measurements at the LHC
  - Lepton jets
  - Measurements: M_a, M_{DM}, g
  - A simple model as an illustration
- Conclusion

Positron/electron excesses in cosmic rays

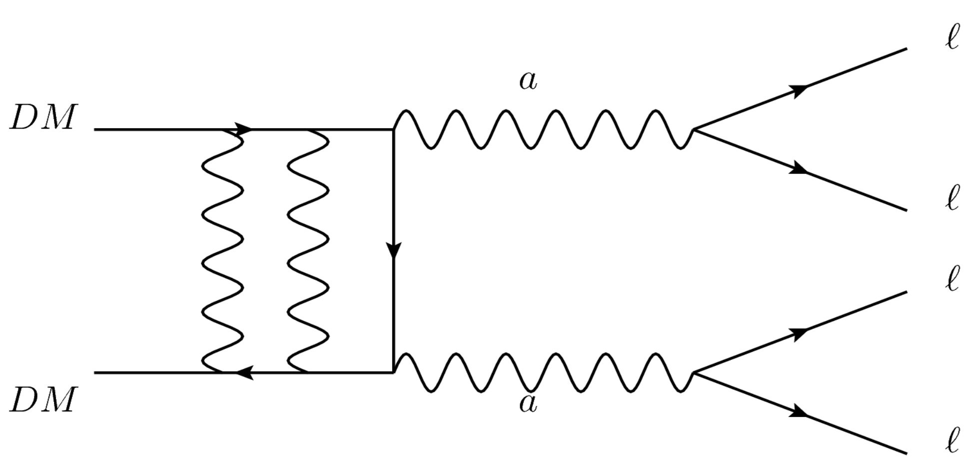
- PAMELA: positron excess 10-100 GeV
- ATIC: positron/electron excess 300-800 GeV
- Fermi LAT: disfavors ATIC, but hint of positron/electron excess (?)

Dark Matter annihilation to positron/electrons?
What is the implication for the LHC?

DM annihilation

(Arkani-Hamed, Finkbeiner, Slatyer and Weiner)

- Dark matter annihilates to a light particle *a*
- The particle *a* dominantly decays to leptons
- Sommerfeld enhancement to give a large cross-section

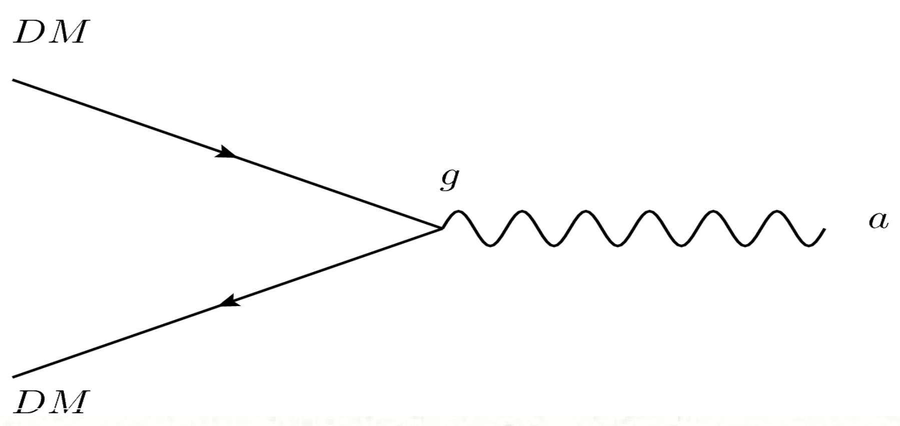


Major ingredients for the LHC

- The relevant ingredients for the LHC:
  - An O(GeV) light particle *a* couples to the DM with order one coupling constant, mediating a "dark force"
  - The light particle *a* dominantly decays to leptons
- Two extra assumptions
  - DM (or other particles charged under the dark force) is produced at the LHC
  - The particle *a* decays within the detector
    - Collinear leptons, "lepton jets" signature

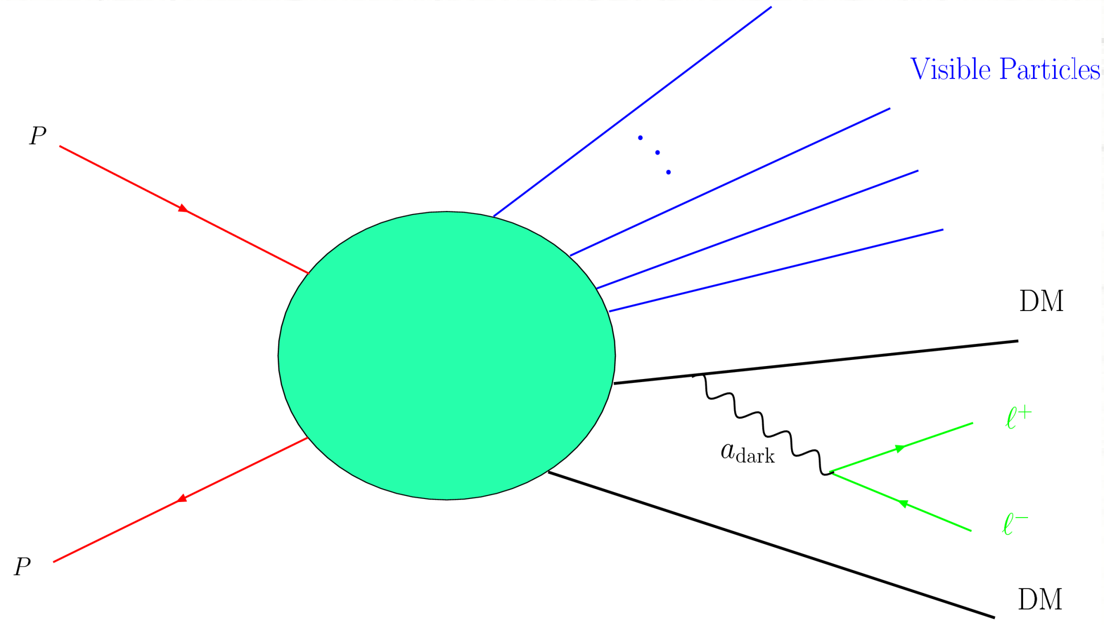
Measuring the Dark Force

- What to measure: M_{DM}, M_a, g
  - Crucial for calculating DM-DM annihilation rate.
  - Consistent with PAMELA, ATIC, Fermi ...?
  - Give the right relic density?



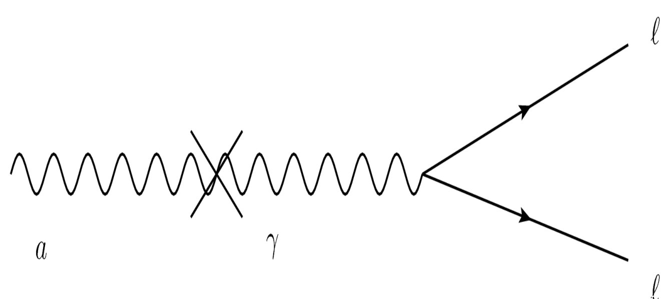
The strategies

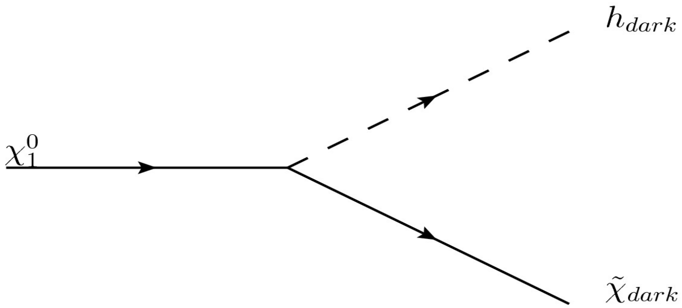
- M_a: measuring the invariant mass of the "lepton jet".
- M_{DM} : model-dependent, edges, m_{T2}, kinematic constraints.....
- The coupling g: dark radiation
  - For any process containing a DM, there is another one with an extra a radiated (extra "lepton jet")
  - Significant rate: $g \sim O(1)$, $Ma \sim$ O(GeV)



A simple model with hidden U(1)

- A usual MSSM sector + hidden sector
- MSSM has a bino-like (N)LSP
- The dark sector: a supersymmetric (broken) U(1) gauge theory with Higgsino-like LSP, lighter than bino.
- DM: dark Higgsino, mediator: dark photon $a_{dark=}a$
- Gauge mixing: a decays to leptons, MSSM bino decays to dark Higgsino + h_{dark}





Benchmark numbers

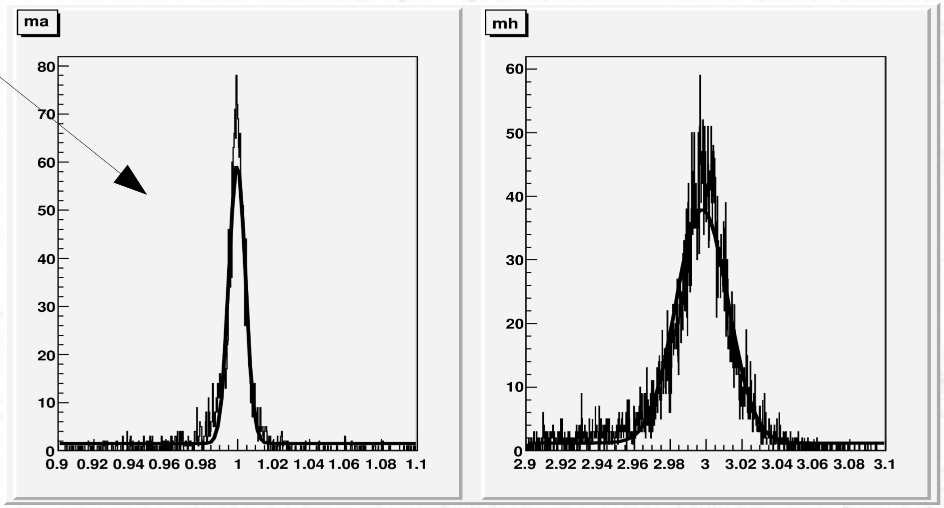
- MSSM
  - MSSM LSP: 700 GeV
  - Squark 1000 GeV, gluino 1200 GeV, 0.84 pb for squark/gluino production. 8400 events for 10 inverse fb
  - All squarks decays directly to bino + quark
- Dark sector
  - $M_{DM} = 600\ GeV$
  - $M_a = 1\ GeV$, $M_h = 3$ GeV (fine tuned), *h->aa->4l ("h-jet")*
  - Coupling $g = 0.41$ (to give the correct relic density)
- Generated events with Madgraph/BRIDGE/Calchep/PYTHIA/PGS

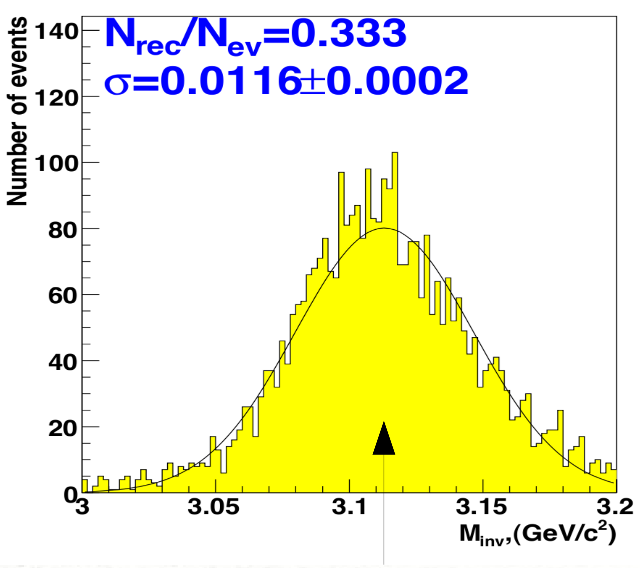
Identify the lepton jets

- Group muons in small cones
    - All muons are sorted by p_T
    - Take the highest p_T muon as the seed of a lepton jet.
    - Add muons within 0.2 *rad* of the seed muon to the jet. Remove used muons from the list.
    - Repeat until all muons used
- Tag the jets
    - 4 or 3 muons: *h-jet*
    - 2 muons: *a-jet*
    - 5 or 6 muons? *a* and *h* tends to be colinear: "*h&a-jet*"

M_h , M_a Measurements

PGS





2-muon jets and 4-muon jets

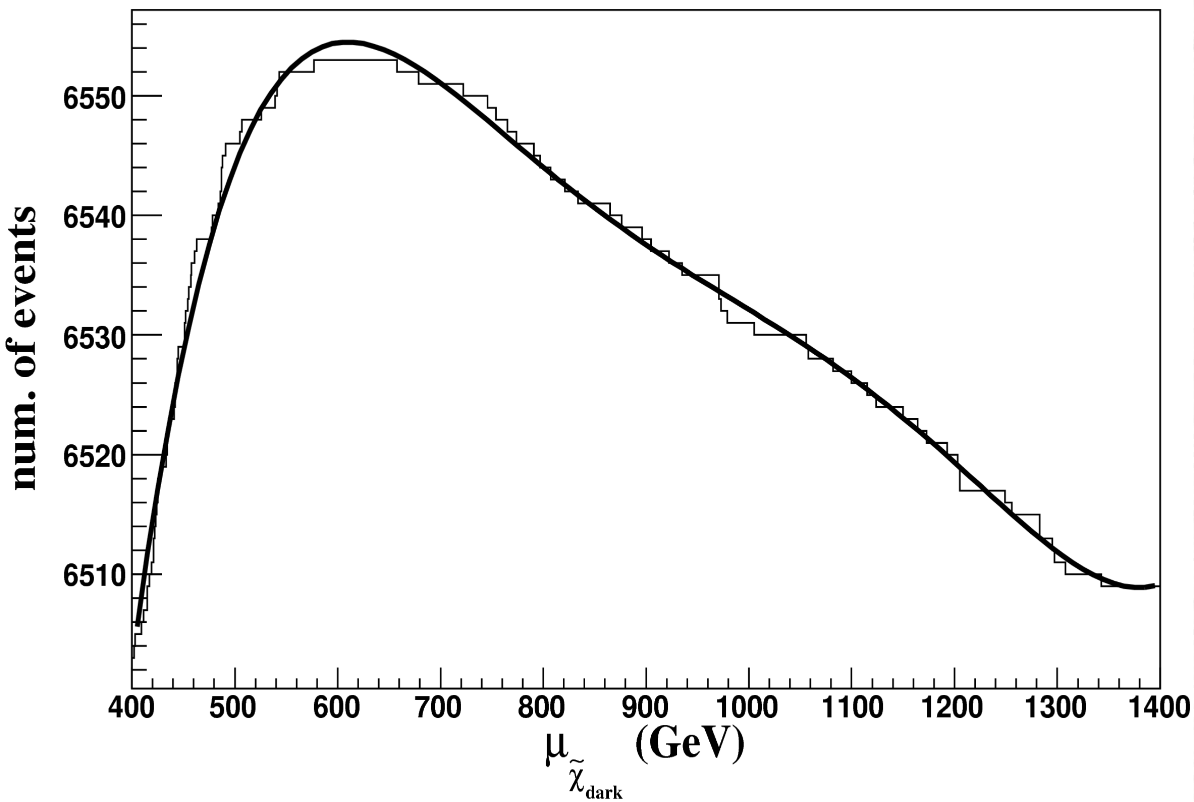
J/psi, dimuon, CMS Technical Design Report

Resolution ~ m/100

Resolution ~ m/30

More precise than the other measurements

Determining m_{DM} using kinematic constraints

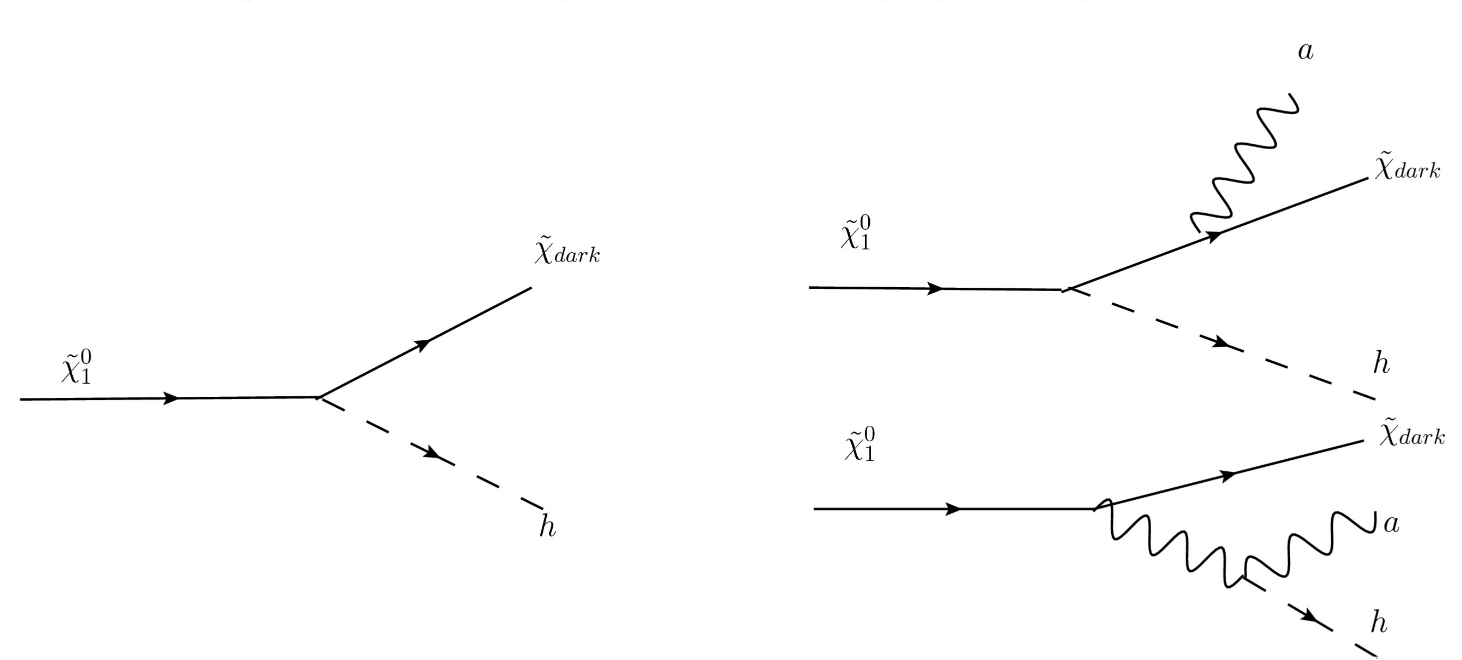


Count the number of events consistent with assumed masses.

$$m_{\tilde{\chi}_{\rm dark}} = 616 \pm 12 {\rm GeV}, \quad m_{\tilde{\chi}_1^0} - m_{\tilde{\chi}_{\rm dark}} = 101.6 \pm 0.6 {\rm GeV}$$

Measuring the coupling g

Dark radiation: 2-body decay vs 3 body-decay



$$R = \mathrm{BR}(\tilde{\chi}_1^0 \to \tilde{\chi}_{dark}\, h\, a)/\mathrm{BR}(\tilde{\chi}_1^0 \to \tilde{\chi}_{\mathrm{dark}}\, h).$$

Count the number of *2h* events and *2h+1a* events, take the ratio = 2*R*

Determining g

- For *g*=0.41, 10 inverse fb, expect 230 *2h1a* (three-body decay) events, 4k *2h* events. *2h1a* dominates the error.
- Count the number of events with 2*h*-jets + 1 *a*-jet or 1*h*-jet + 1 *h*&*a*-jet (5 or 6 muons): 70 events identified
- R = R(*g*, m) =>

$$g = 0.40 \pm 0.03$$

Relic density

- Calculate the DM relic density (10 inverse fb)

$$\Omega_{DM}h^2 = 0.119 \pm 0.033$$

- Compare with WMAP error:

$$\Omega_{DM}h^2 = 0.113 \pm 0.0034$$

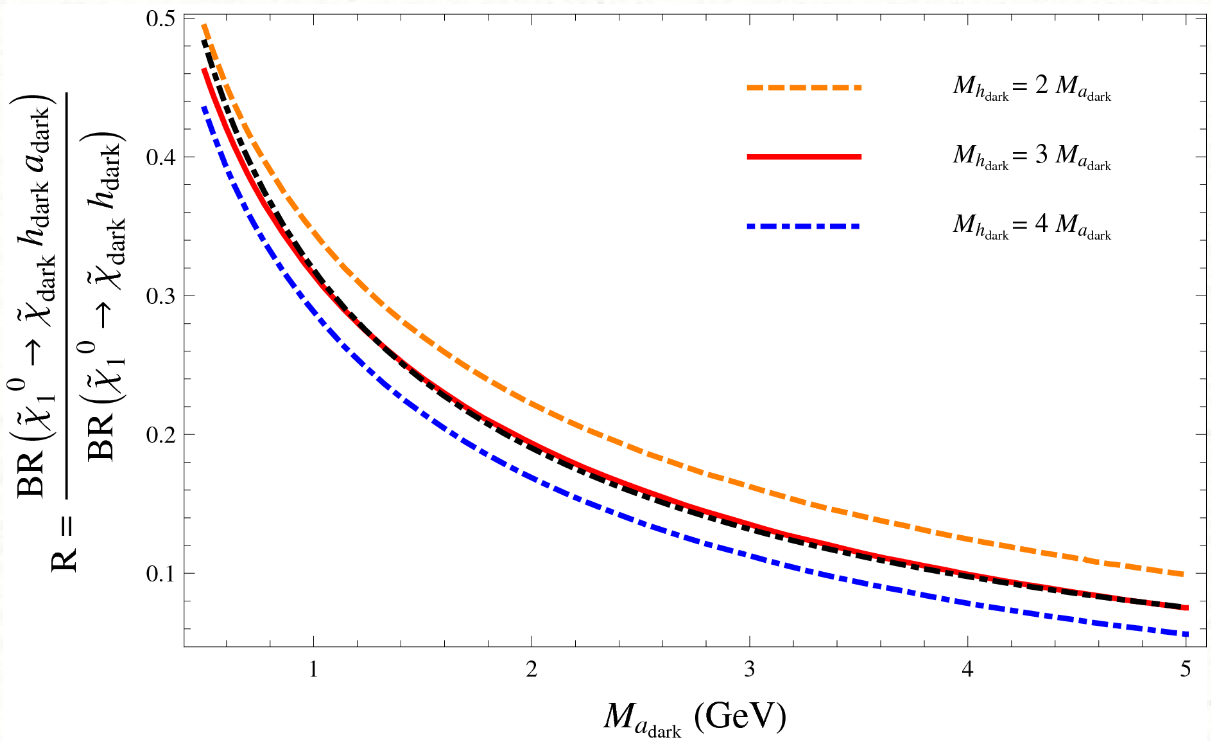
- Not as precise, but encouraging if consistent

Conclusion and outlook

- It is possible to measure the dark force at the LHC
  - Important for calculating DM annihilation rate
  - Illustrated with a simple model
- Many theoretical possibilities unexplored
- Electrons experimentally more challenging

Backup Slides

The ratio R



g = 1

Approximate formula for $M_h = 3M_a$:

$$\begin{aligned} R \;\approx\; & \frac{11\, g^2}{120\, \pi^2}\, \left[4((\log(1 - r_{DM}) - 4\log 2 - 2)\log(1 - r_{DM})\right. \\ + \;& \log^2 r_a - (4\log(1 - r_{DM}) - 8\log 2 - 4)\log r_a \\ + \;& \left. 3\log^2 2 + 4\log 2 + 2)\right]\;, \end{aligned} \qquad (2)$$

The electrons

- “Electron jets” characterized by ECAL energy deposit, no/small HCAL energy deposit and multiple tracks from the interacting vertex.
  - Contamination from converted photons?
  - What's the efficiency for identifying electron jets? electon+muon jets?
- To measure the invariant mass, have to measure individual electrons' momentum in a jet. Prefer relatively soft electrons:
  - Can be separated by the magnetic field before they hit the ECAL (~10GeV)
  - Better measured by the tracker.