Measuring Dark Force at the LHC

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Outline

Motivations

- High Energy Positron Excesses from PAMELA and ATIC
- Dark Matter Explanations [Neal Weiner's talk]

How to test this class of models at the LHC?

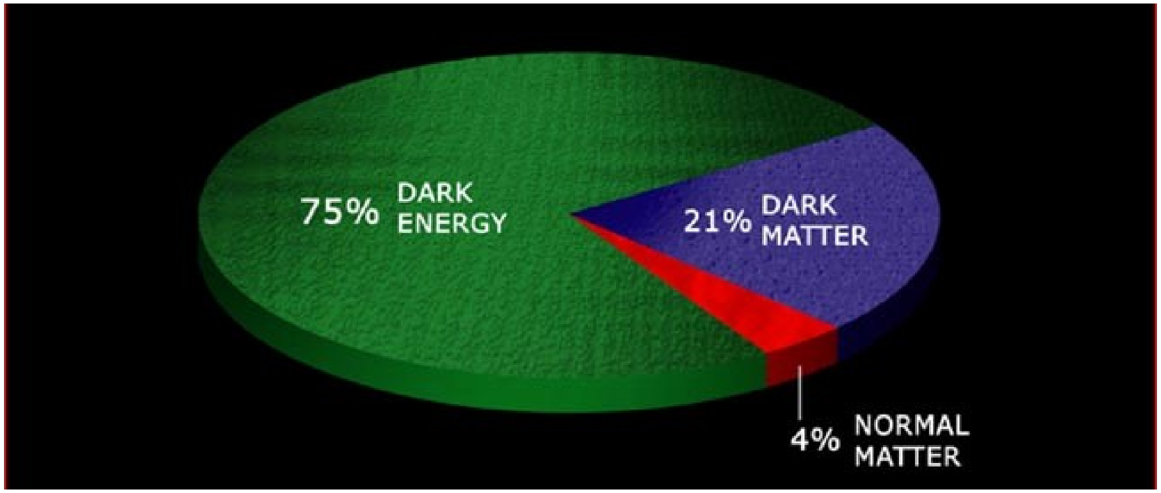
- Observations and strategy
- A few but crucial assumptions

One simple model as an example

- Coupling measurement
- Mass measurement
- The dark matter relic abundance

Conclusions

Motivations



Dark matter has no explanation in the standard model.

Once beyond the standard model:

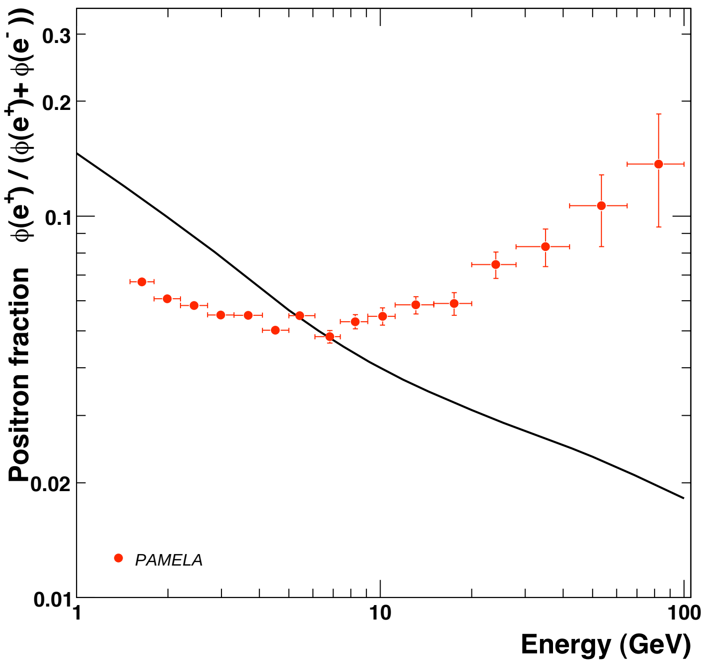
- Hot dark matter: axions, $\cdots$
- Cold dark matter: WIMPs, Q-balls, $\cdots$

  TeV scale, stable due to discrete symmetries: LSP (SUSY), LKP (UED), LTP (LHT)

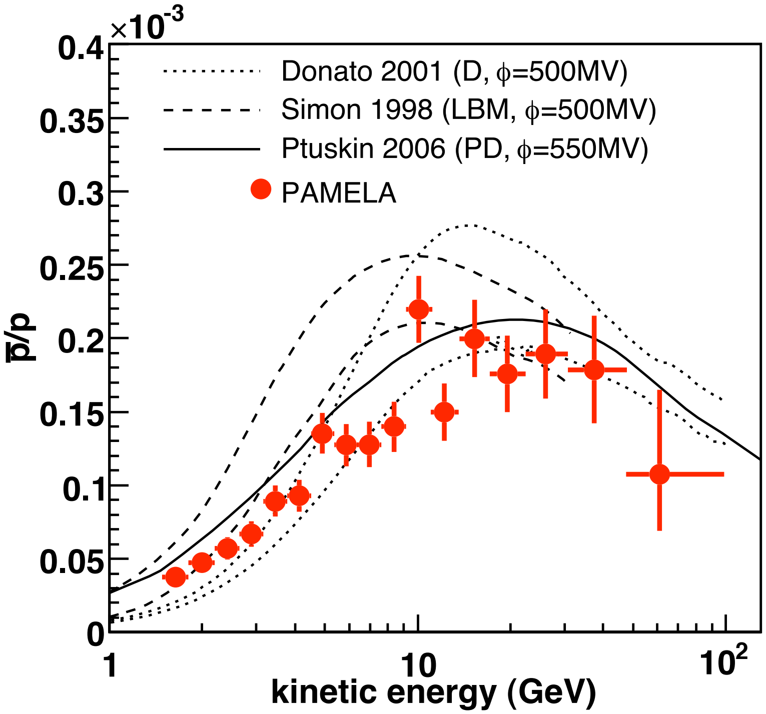
Direct detection of dark matter: CDMS, XENON, DAMA, $\cdots$

Indirect detection also sheds light on the dark matter particle.

Cosmic Ray Positron Excesses



from arXiv: 0810.4995 (PAMELA)

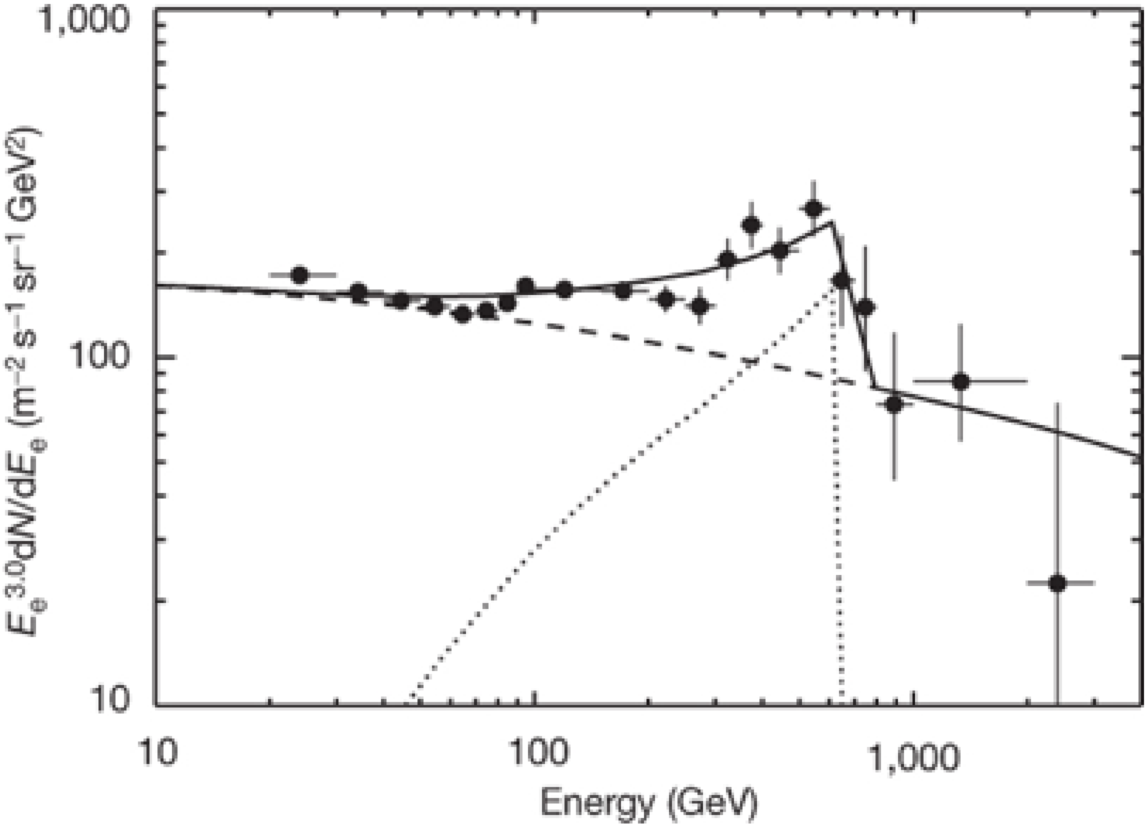


from arXiv: 0810.4994 (PAMELA)

- The secondary positrons in the background mainly come from primary cosmic protons colliding with interstellar matter in the galaxy.

- We anticipate that the positron spectrum decreases as energy increases, because primary proton flux $\propto E^{-2.7}$.

Cosmic Ray Positron Excesses



from Natural, vol 456, 07477 (ATIC)

- If it is due to dark matter annihilation, the cross section rate should be $\sim 1 \times 10^{-23}\mathrm{cm}^3\mathrm{s}^{-1}$. This cross section is larger than the typical annihilation cross section $\sim 3 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ to satisfy the dark matter relic abundance by $O(100)$.

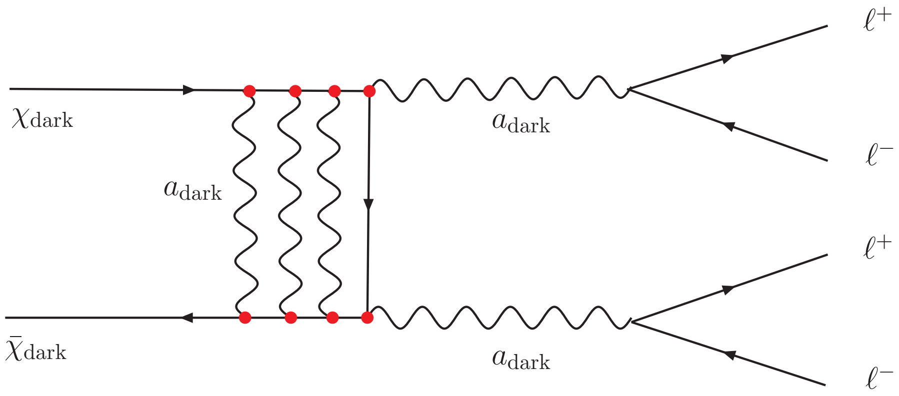
Possible Explanations

Not dark matter

- Nearby pulsars: Hooper, Blasi and Serpico; Profumo

Still due to dark matter, but not a simple dark sector

- Decaying dark matter: Chen, Takahashi and Yanagida
- Nonthermal dark matter: Grajek, Kane, Phalen, Pierce, Watson
- "Sommerfeld enhancement": Arkani-hamed, Finkbeiner, Slatyer and Weiner



- ▷ An attractive long-range force ($M_{a_{dark}} \ll \alpha M_\chi$) between dark matter particles can enhance their annihilation cross section at low velocity. $\sigma v \sim 1/v$ for a small v.
- ▷ At the freeze-out temperature: $v \approx 0.3c$.
- ▷ In the galactic halo: $v \approx 0.001c$.

An Abelian hidden gauge symmetry in SUSY[Arkani-hamed etc.]

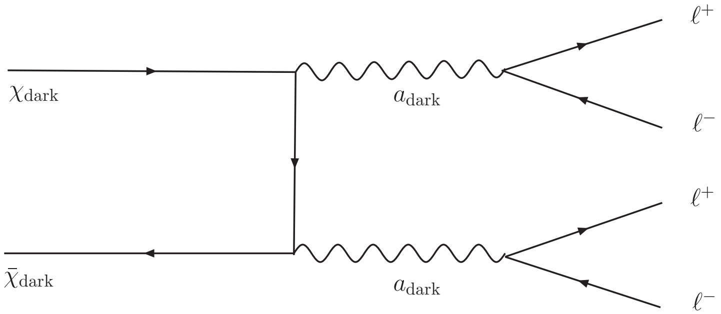
- Introduce a dark sector: $U(1)_{dark}$ gauge symmetry; dark Higgs fields develop VEV's to break the gauge symmetry. The dark gauge boson has a mass $M_{a_{dark}} \sim 1$ GeV.

- The dark sector talks to the SM sector via gauge boson and gaugino kinetic mixings. $\epsilon\, f_{\mu\nu} F^{\mu\nu}$

- After diagonalization, the dark gauge boson couples to SM partcles proportional to their electric charge.

$$\epsilon\, a^{\mu}_{dark}\, J^{EM}_{\mu}$$

- If the LSP in the dark sector is made of Higgsino and lighter than the LSP in the SM, the dark LSP χ_{dark} is the dark matter candidate in the whole model.



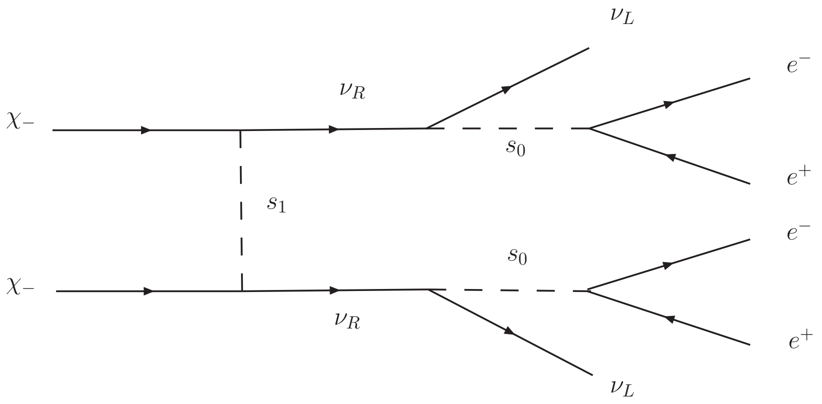
- The LSP in the MSSM $\tilde{\chi}^0_1$ will decay into χ_{dark} plus a_{dark} or h_{dark}, which decay to leptons.

Singlets extension of the UED model

[Bai and Han, arXiv: 0811.0387]

$$
\begin{aligned}
S_{5D} \quad = \quad & \int d^4 x \int_0^{\pi R} d\, y \Big[\mathcal{L}_{SM} - \sqrt{\pi R}\, y_\nu\, \bar{L}\, \tilde{H}\, N - \frac{1}{2}\, m\, N^T\, \mathcal{C}_5\, N - \frac{1}{2}\, \mu^2\, S^2 \\
& - (\pi R)^2\, y'_e\, S\, \bar{L}\, H\, E - (\pi R)^2\, y'_D\, S\, \bar{L}\, \tilde{H}\, N - \frac{1}{2}\sqrt{\pi R}\, y_M\, S\, N^T\, \mathcal{C}_5\, N + h.c. \Big] \,.
\end{aligned}
$$

- KK-even light particles: s^0 and ν_R
- KK-odd particles (mass scale $\sim 1/R$): χ^-, χ^+ and s^1



- The usual LKP in minimal UED, KK-photon B^1, will decay into χ^- via

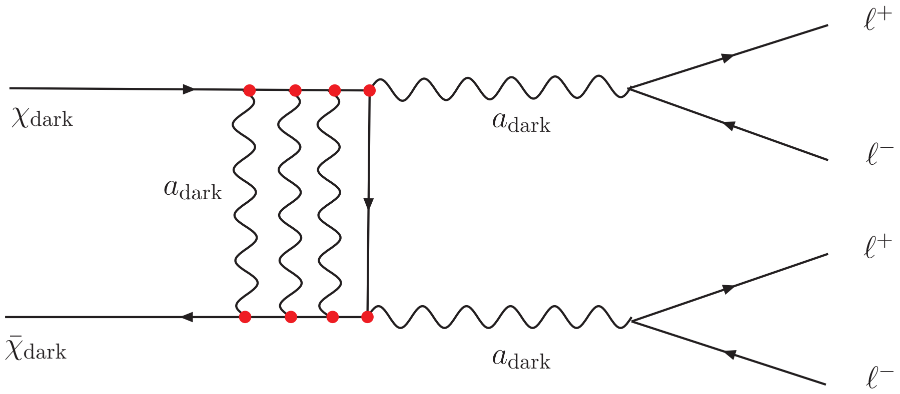
$$
B^1 \longrightarrow s_1\, e^+\, e^- \longrightarrow \chi^-\, \nu_L^*\, e^+\, e^-
$$

Observations

- The mass of dark matter particle is moderate heavy: O(500 GeV), for ATIC.
- The dark matter particle couples to the light mediator with a fairly large coupling: O(1).
- The light mediator (1 GeV) is really light compared to the dark matter mass with the mass ratio as: O(1/100).
- Lots of leptons can be produced at the LHC, if heavier Z_2-odd particles are generated and directly or cascade decay to the dark matter particles.
- If mass differences are O(100) GeV, the associate decaying product, the light mediator, is highly boosted and generate collimated leptons, “lepton jets” [Arkani-hamed and Weiner].

Test this new class of dark matter models at the LHC?

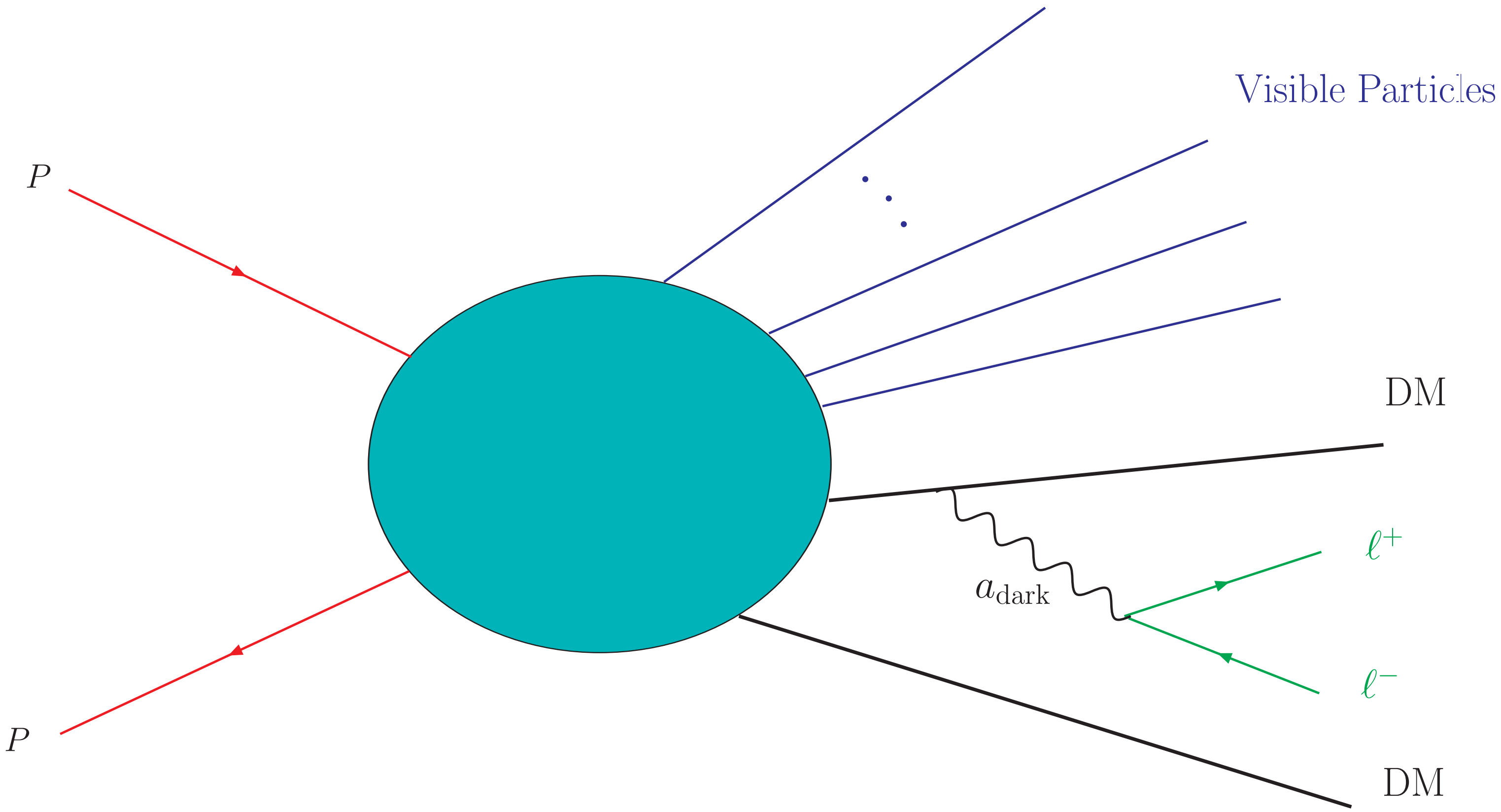
A long range force, “Dark Force”, between the dark matter particles



It is critical to discover the light mediator and measure its coupling to the dark matter particle

- Dark matter annihilation cross section $\Rightarrow$ dark matter relic abundance
- The Sommerfeld enhancement factor $\Rightarrow B \propto g^2$

Our strategy



$$\frac{\sigma(p\,p\;\to\;X\;DM\;DM\;a_{dark})}{\sigma(p\,p\;\to\;X\;DM\;DM)}\approx C\,\frac{g^2}{4\,\pi^2}\,\log\left(\frac{q^2}{M^2_{a_{dark}}}\right)\,\log\left(\frac{q^2}{m^2_{DM}}\right)\;\sim\;0.1$$

Our assumptions

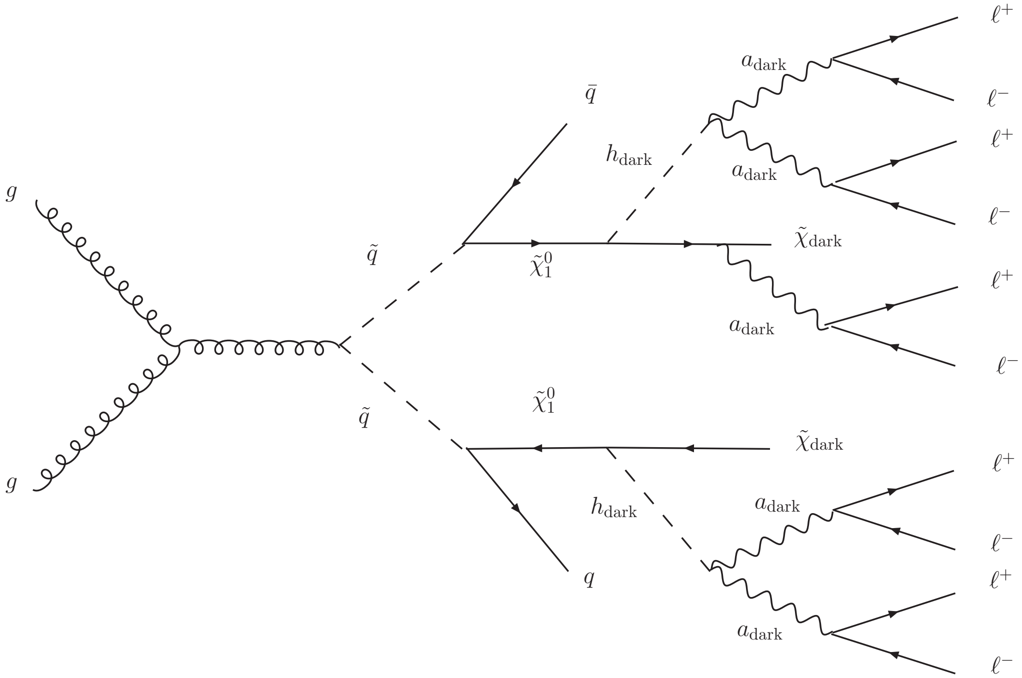
- Dark matter can be copiously produced at the LHC. For example, colored parity-odd particles cascade decay to the dark matter particle.
- a_{dark} mainly decays into leptons. In our analysis, only muons are included.
- The life-time of a_{dark} is short and can promptly decay into leptons inside the detector,

$$\tau\, c \;\sim\; 3 \times 10^{-6}\, cm\; \left(\frac{M a_{dark}}{1\; GeV}\right) \left(\frac{g_\ell}{10^{-3}}\right)^{-2}$$

  so we can easily discover a_{dark} and reconstruct its mass.

- The usual LSP (neutralino) or LKP (KK-photon) directly decay into the dark matter particle plus "lepton jets".

One example as a case study



- The h_{dark} mass is larger than twice of the a_{dark} mass
- The ratio R of dark matter production cross sections with and without radiating an a_{dark} field can be simply measured by counting the number of leptons in the final state. For the case at hand, 10 leptons .vs. 8 leptons.
- Since leptons are collinear, we should observe "h-jet" and "a-jet". This becomes a question to count events with two h-jets and events with two h-jets plus one a-jet.

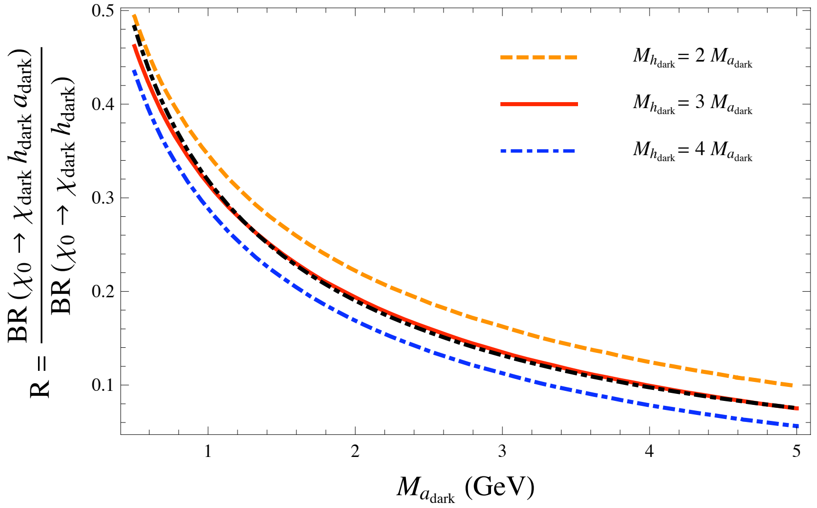
The ratio R

- The ratio R can be further simplified as the ratio of neutralino three-body decay over two-body decay.

$$R = \frac{\chi_0 \to \chi_{dark}\, h_{dark}\, a_{dark}}{\chi_0 \to \chi_{dark}\, h_{dark}}$$

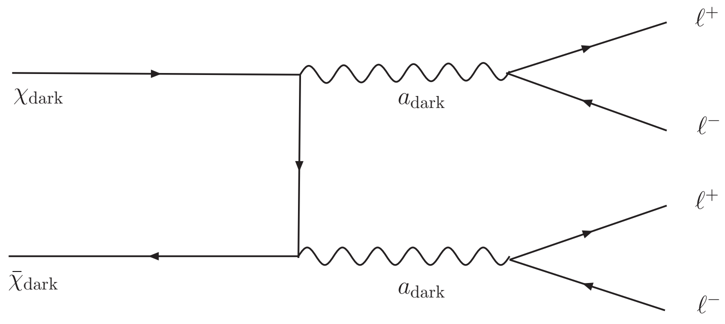
- Approximate formula (for $M_{h_{dark}} = 3\, M_{a_{dark}}$, $r_a \equiv M^2_{a_{dark}}/m^2_{\chi_0}$ and $r_{dm} \equiv m^2_{\chi_{dark}}/m^2_{\chi_0}$)

$$\begin{aligned} R \quad &\approx \quad \frac{11\, g^2}{120\, \pi^2} \Big[\log^2 r_a - (4 \log(1 - r_{dm}) - 8 \log 2 - 4) \log r_a \\ &+ \quad 4((\log(1 - r_{dm}) - 4 \log 2 - 2) \log(1 - r_{dm}) + 3 \log^2 2 + 4 \log 2 + 2) \Big] \end{aligned}$$



$m_{\chi_0} = 700$ GeV, $m_{\chi_{dark}} = 600$ GeV and $g = 1$

The coupling g



- The annihilation cross section is controlled by the gauge coupling and the dark matter particle mass and given as

$$\sigma v = \left(\frac{g}{0.41}\right)^4 \left(\frac{600\,GeV}{m_{\chi_{dark}}}\right)^2 \times 2.3 \times 10^{-26} cm^3/s$$

- For $g = 0.41$ and $m_{\chi_{dark}} = 600$ GeV. Hence, the ratio $R \approx 0.054$ for $M_{a_{dark}} = 1$ GeV.
- We anticipate $2R \approx 11\%$ of total events with three-body decay, or with 2 $\boldsymbol{h}$-jets plus 1 $\boldsymbol{a}$-jet.
- At the LHC (14 TeV) and with the masses of the gluino, squarks and the lightest neutralino as 1200 GeV, 1000 GeV and 700 GeV, the inclusive production cross section of $\tilde{\chi}_1^0$ is 0.84 pb.
- At 10 fb^{-1}, there are roughly 8400/4=2100 two-body decay events and $2100 \times 11\% \approx 230$ three-body decay events.

Events simulation

- We choose the dark matter ($\tilde{\chi}_{dark}$) mass to be 600 GeV. For the MSSM, we choose the masses of the gluino, squarks and neutralino to be 1200 GeV, 1000 GeV and 700 GeV. The gluino directly decays to quarks and squarks. The squarks decay directly to quarks and $\tilde{\chi}_1^0$.
- We generate parton level events in the squark/gluino pair production channels with Madgraph/Madevents.
- We perform the 2-body and 3-body decays of $\tilde{\chi}_1^0$ to $\tilde{\chi}_{dark}$ with Calchep.
- All other particles, including the super particles, a_{dark} and h_{dark}, are decayed with BRIDGE.
- The parton level events are further processed with PYTHIA for showering and hadronization, and PGS for detector simulation.
- An $H_T > 500$ GeV cut is imposed to reduce the SM background, where H_T is defined as the scalar sum of all objects' p_T (including $\not{p}_T$) in the events.
- The SM background mainly comes from b-hadron decays, which is below 1% of the signal events after the above cuts and neglected in the following analysis.

Reconstruction

- The crucial point is to identify the “lepton jet”: $\boldsymbol{h}$-jet and $\boldsymbol{a}$-jet.
- Only muons are included in the current analysis.
- All muons are first sorted according to their p_T.
- We choose the highest p_T muon in the list as a “seed” of the lepton jet.
- All muons within 0.2 rad of the seed muon direction are included as a part of the lepton jet.
- Lepton jets with 2 muons are tagged as $\boldsymbol{a}$-jets and lepton jets with 3 or 4 muons are tagged as $\boldsymbol{h}$-jets.
- Used muons are removed from the list. We repeat the procedure until all muons are used.
- Events containing untagged muons are discarded.

Measurement of R

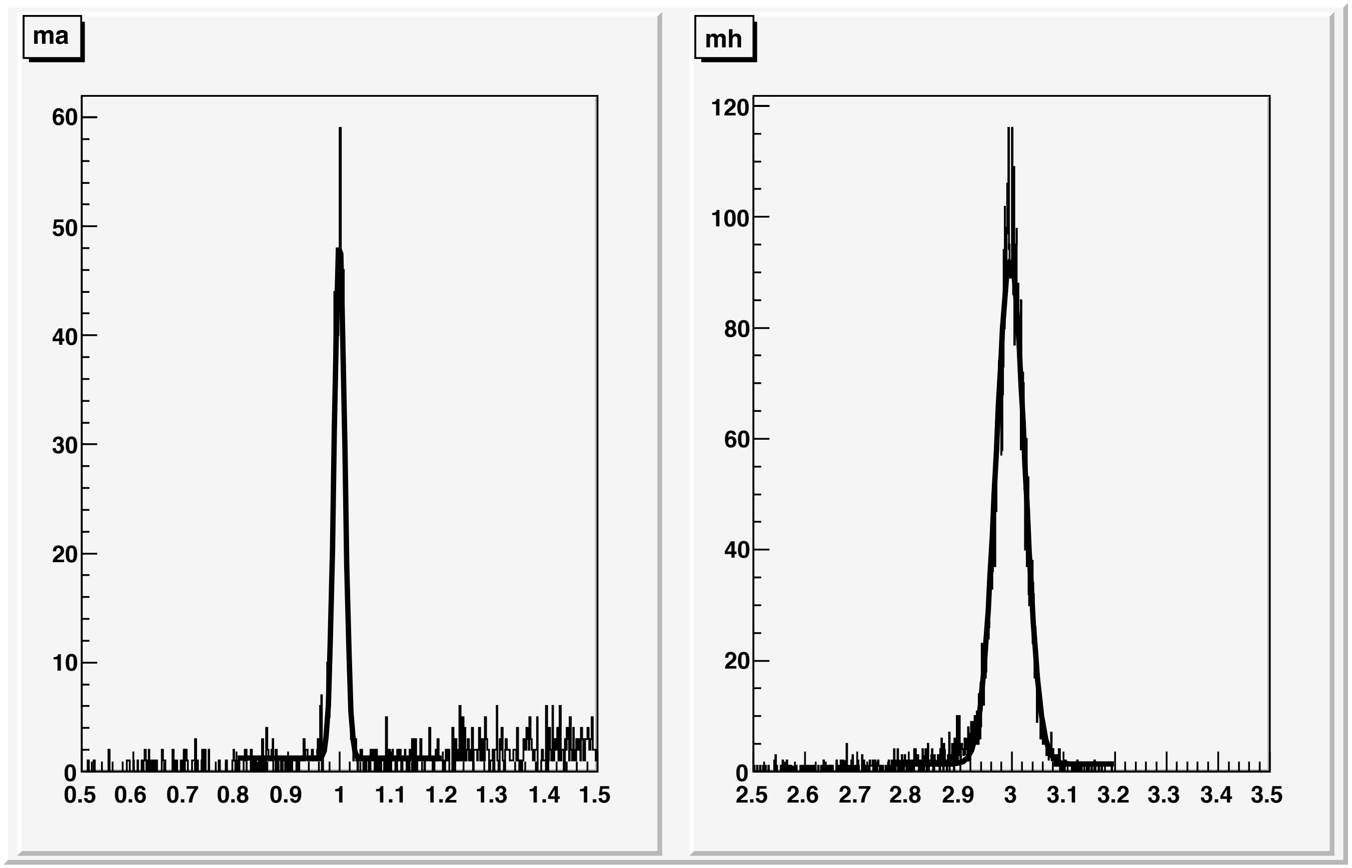
- At 10 fb^{-1}, we anticipate 230 $\boldsymbol{2h1a}$ type three-body decay events.
- However, the $\boldsymbol{a}$-jets tend to be collinear with the $\boldsymbol{h}$-jets and/or contain soft muons that are not registered by the detector.
- This drastically reduces the efficiency for identifying $\boldsymbol{2h1a}$ events. Therefore, we also include events with one $\boldsymbol{h}$-jet and one lepton jet with 5 or more muons in a cone as three-body decay events.
- Thus, we obtain the efficiency of identifying three-body events to be about 30% (to be improved), which have to be taken into consideration when calculating the ratio $\boldsymbol{R}$.
- The number of three-body decay events is reduced to be 70, which results in an error about 12% for the measurement of the ratio $\boldsymbol{R}$.

$$\Delta R/R \approx 12\%$$

To measure the dark force or the hidden gauge coupling g

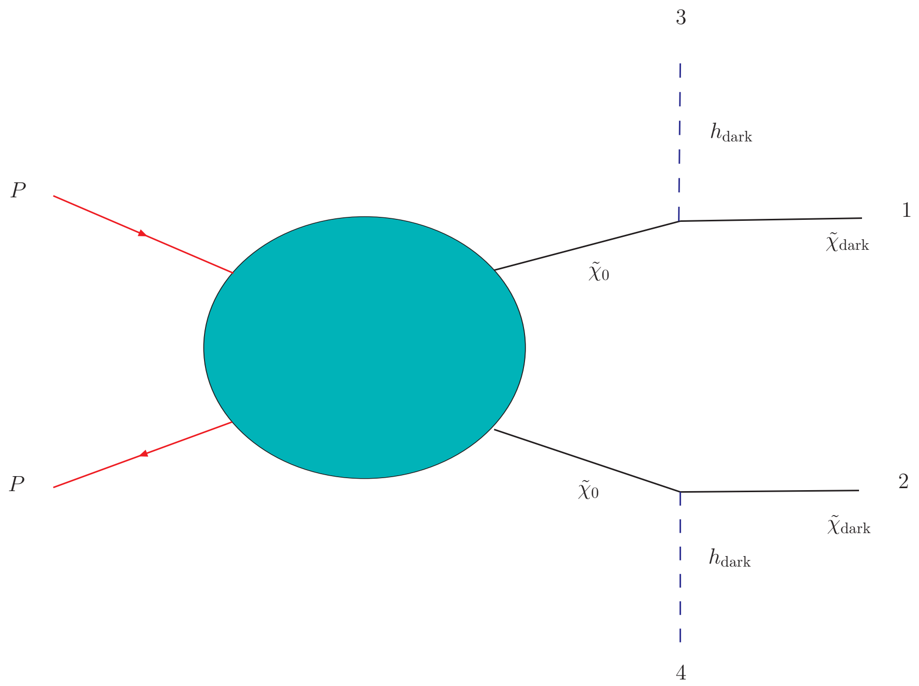
$$g(R, m_{\chi_0}, m_{\chi_{dark}}, M_{a_{dark}}, M_{h_{dark}})$$

Measurements of $M_{a_{dark}}$ and $M_{h_{dark}}$



- Errors come from the resolution of muon energy measurement. For example, CMS can achieve $\Delta P_T/P_T \sim 1\%$.
- The precision of $M_{a_{dark}}$ and $M_{h_{dark}}$ is $\sim M/(100\sqrt{N})$. Therefore, they can be measured very precise.

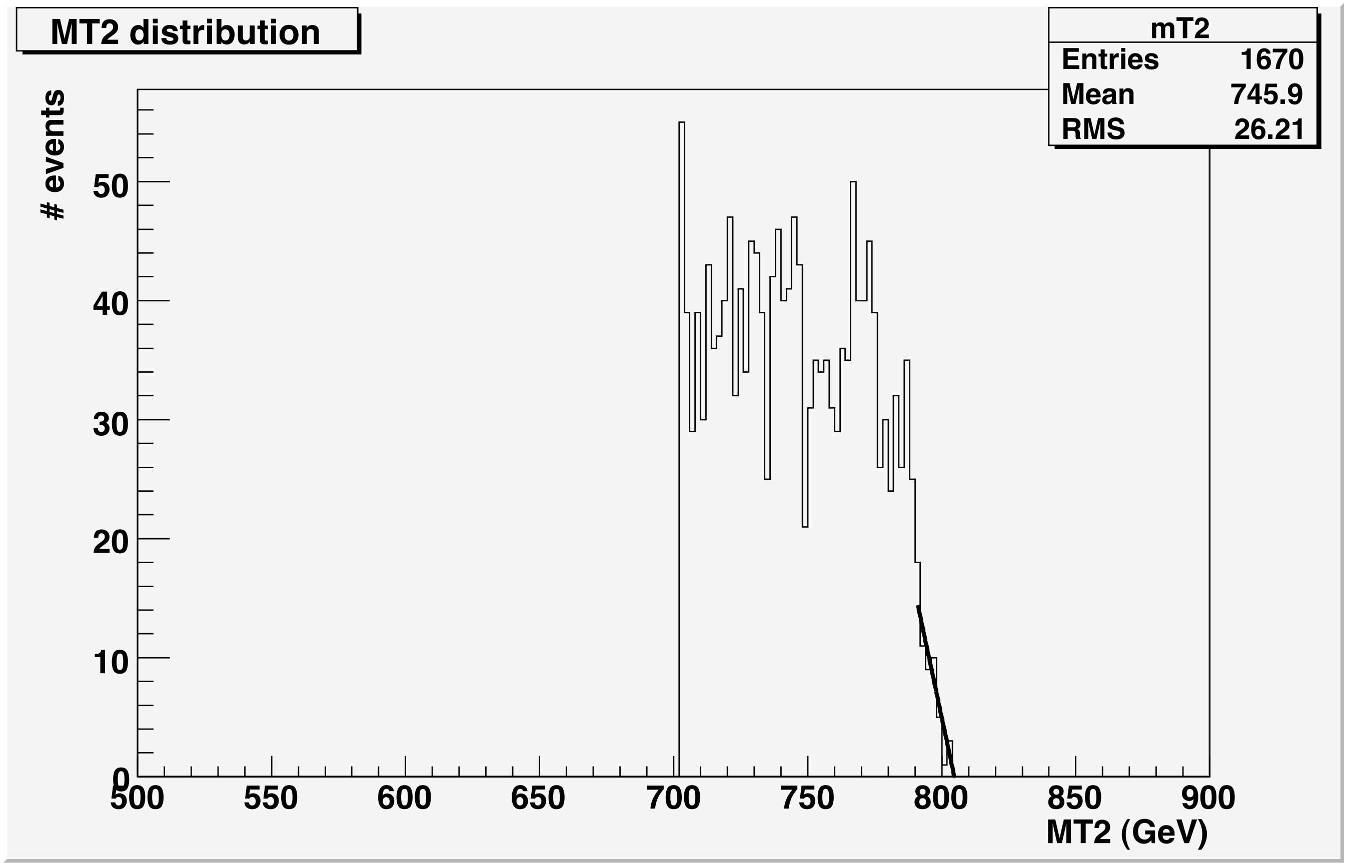
Measurement of $m_{\chi_{dark}}$ and m_{χ_0}



- Since we can only measure total missing transverse momentums $\not{p}_T$ at the LHC, we need to use special methods to measure the dark matter mass. M_{T2} [Lester and Summers; Barr, Lester, Stephens].
- Define $2+1$ dimensional momentum: $\alpha^i \equiv (E^i, p_x^i, p_y^i)$, with $E^i \equiv \sqrt{(p_x^i)^2 + (p_y^i)^2 + m_i^2}$.
- Define transverse mass or $2+1$ dimensional invariant mass: $M_T^2(i,j) \equiv (\alpha^i + \alpha^j)^2$.

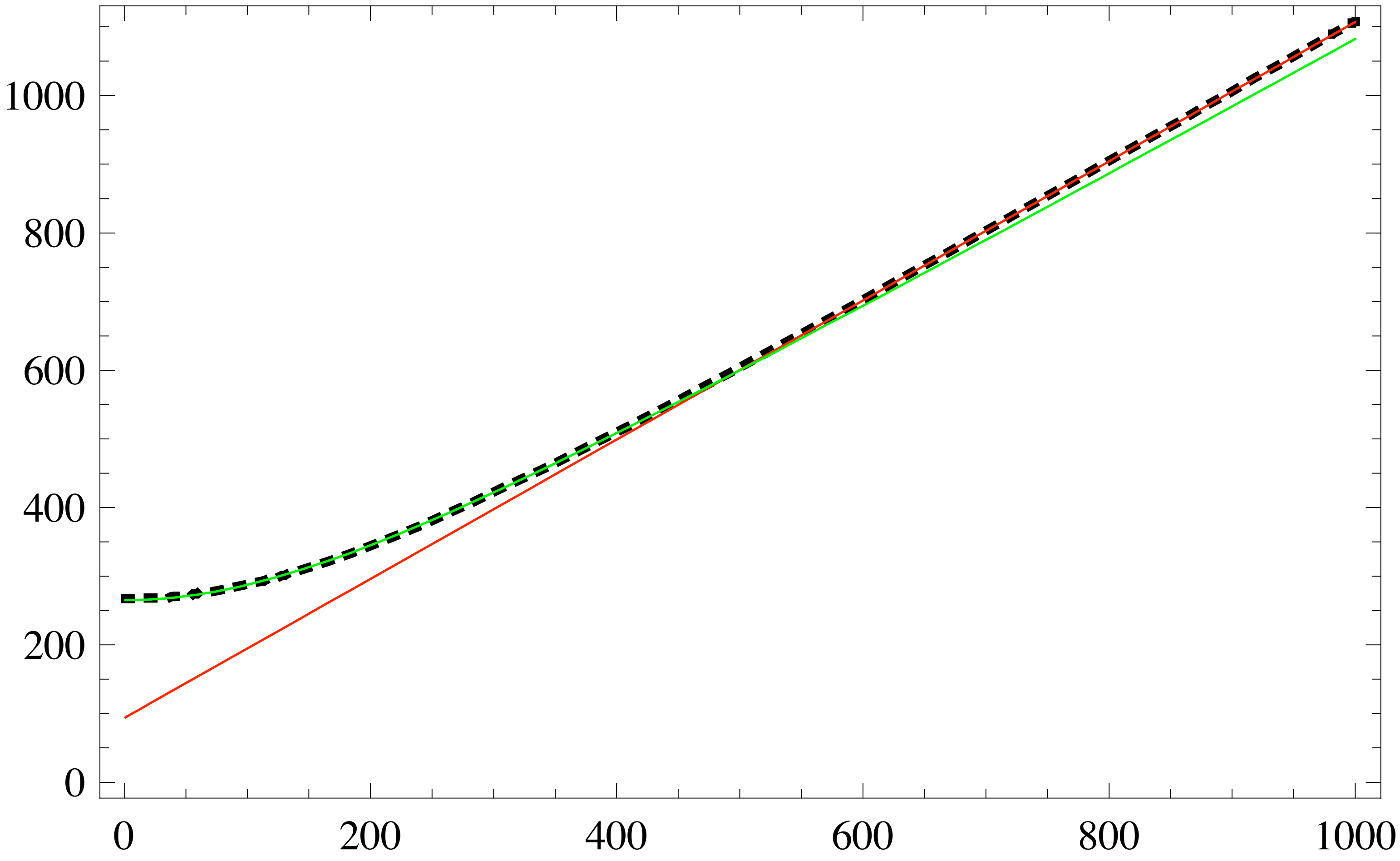
$$M_{T2}(\mu_N) \equiv \min_{p_T^1 + p_T^2 = \not{p}_T} \left[\max\{M_T(1,3;\mu_N), M_T(2,4;\mu_N\}\right]$$

M_{T2} end point



for a 700 GeV trial dark matter mass

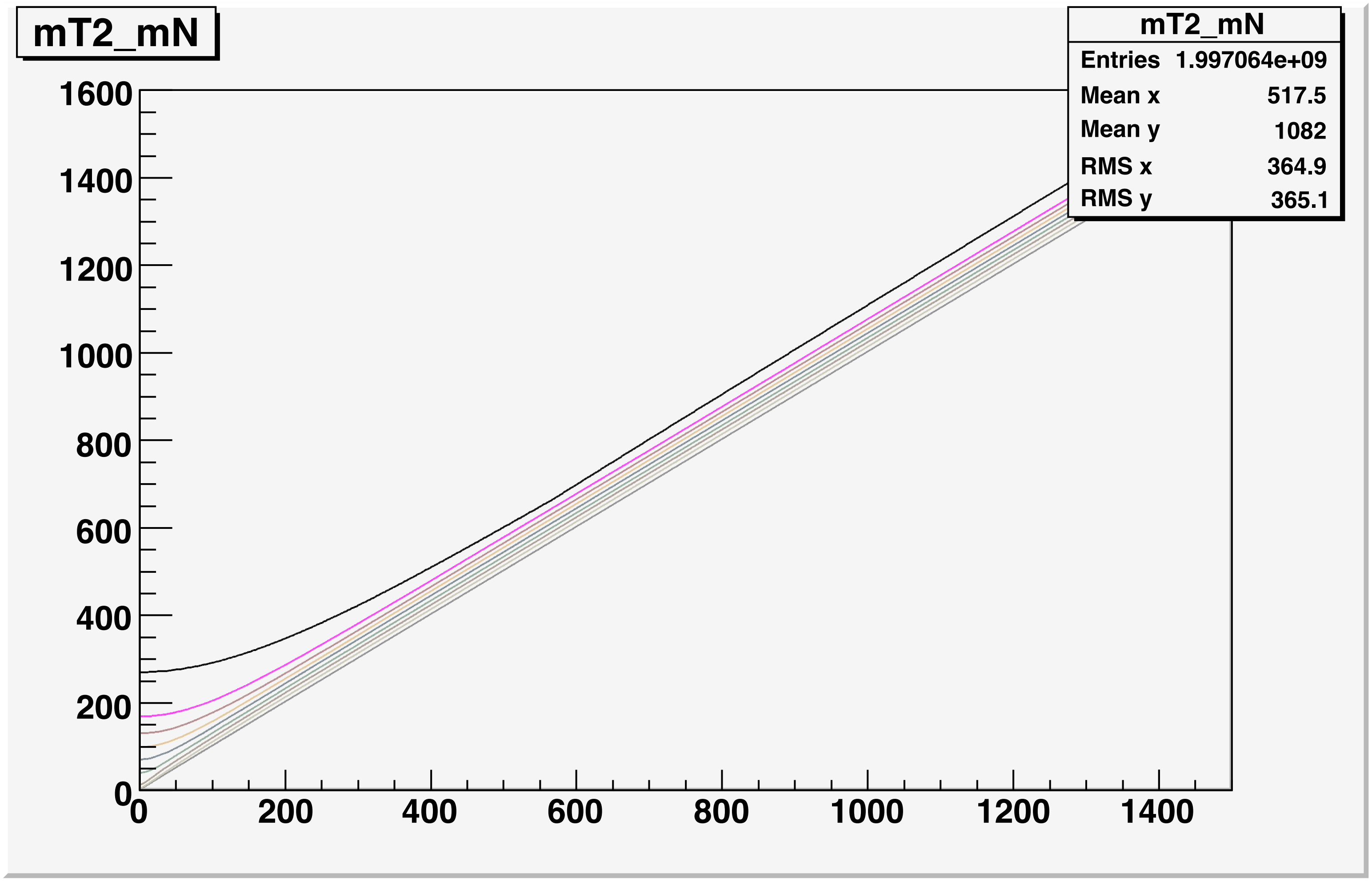
Find Kink [Cho, Choi, Kim and Park]



x-axes: trial dark matter mass y-axes: M_{T2} end point

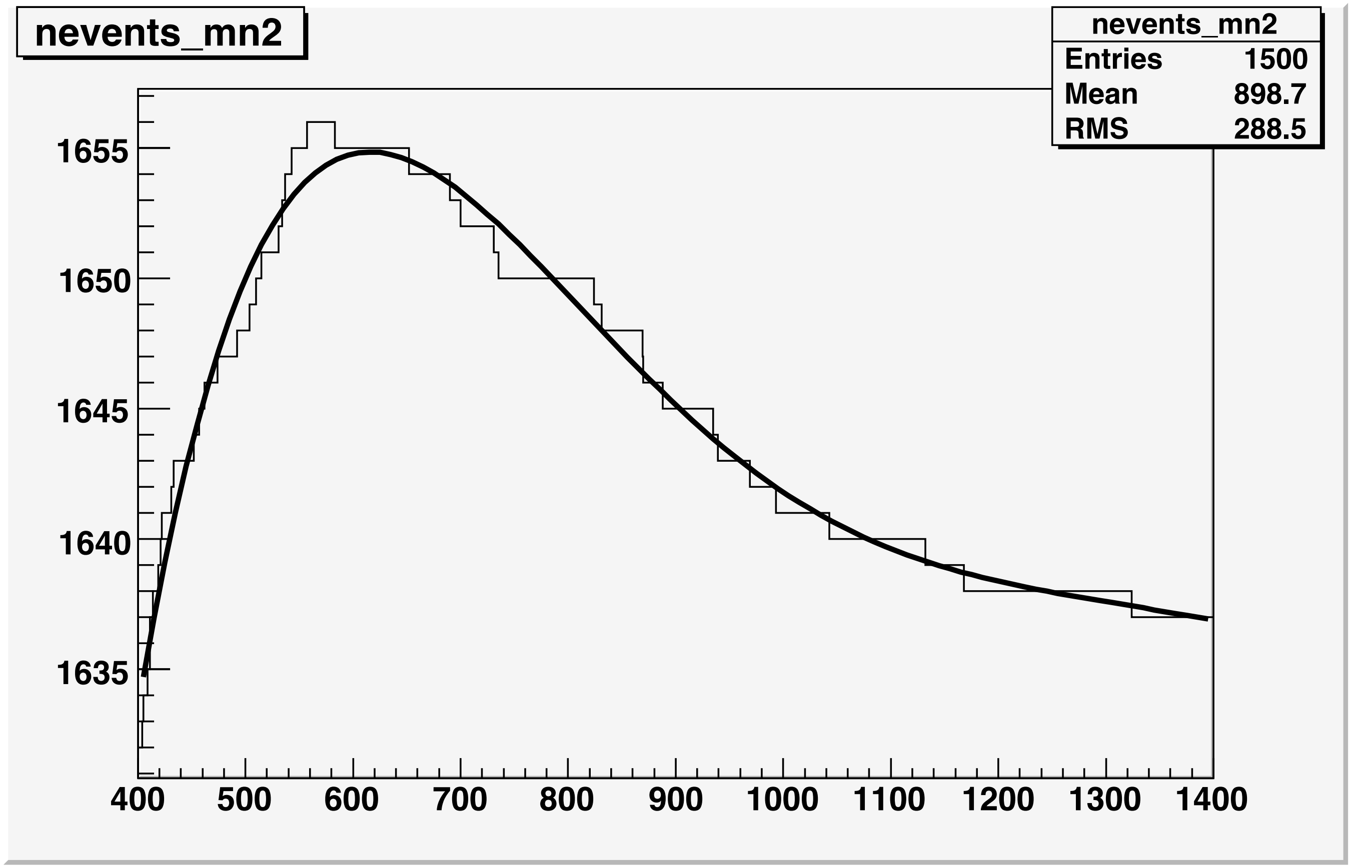
- The M_{T2} end point as a function of dark matter trial mass has a first-derivative discontinuity at the true dark matter mass.

M_{T2} contour plot [Han and Cheng]



consistent events contour plot

Mass determination



- The error of this measurements is estimated by repeating the procedure for 10 different datasets.

$m_{\chi_{dark}} = 616 \pm 12$ GeV $\quad m_{\chi_0} - m_{\chi_{dark}} = 101.6 \pm 0.6$ GeV $\quad$ input : $(600, 700)$ GeV

Coupling Measurement

$$g(R, m_{\chi_0}, m_{\chi_{dark}}, M_{a_{dark}}, M_{h_{dark}})$$

- To estimate the error on the gauge coupling measurement, we can neglect errors coming from precisely measured quantities and rewrite the parameter dependence of g as:

$$g(R, m_{\chi_{dark}}) \qquad \text{with} \;\; m_{\chi_0} = m_{\chi_{dark}} + 100$$

- The error of g is given by

$$\Delta g \;=\; \sqrt{(\frac{\partial g}{\partial R})^2(\Delta R)^2 + (\frac{\partial g}{\partial m_{\chi_{dark}}})^2(\Delta m_{\chi_{dark}})^2}$$

- Using the results $\Delta R/R = 12\%$ and $m_{\chi_{dark}} = 616 \pm 12$ GeV:

$$g = 0.40 \pm 0.03$$

- The input value is 0.41. The gauge coupling is mildly dependent on the overall scale of the dark matter mass.

Relic Abundance

- The dark matter relic abundance for a cold dark matter candidate

$$\Omega_{dm}\, h^2 \approx \frac{1 \times 10^9}{M_{pl}} \frac{x_F}{\sqrt{g_*}} \frac{1}{\langle \sigma v \rangle} \sim \frac{m^2_{\chi_{dark}}}{g^4}$$

- From WMAP, $\Omega_{dm}\, h^2 = 0.113 \pm 0.0034$ at 68% CL. [Ben Gold's talk]
- From LHC and at 10 fb^{-1}, we will have

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

Conclusions

- Dark matter may be more complicated than what we thought.
- One compelling dark matter annihilation explanation of the ATIC and PAMELA cosmic ray excesses can have interesting collider signatures.
- A class of models with a long range force (dark force) between dark matter particles can be tested at the LHC by looking at the channel with dark matter radiating a light mediator, which subsequently decays to leptons.
- The measurements of the dark force and the dark matter mass can then be used to determine the dark matter annihilation cross section, hence the dark matter relic abundance.

Backup (electrons)

- Requiring all electrons to be isolated from hadronic jets by $\Delta R > 0.4$ and considering the electron acceptance efficiency to be 85% reduce the efficiency for identifying the signal events to be approximately 35%.
- The error for the coupling measurement is then increased by a factor of 3.
- If the light mediator only decays to electrons, we will have to determine the mediator's mass from individual electrons' momenta in an "electron-jet".
- Relatively soft electrons are favored because they can be sufficiently separated by the magnetic field before they hit the electromagnetic calorimeter (ECAL).
- A rough estimation for the CMS detector shows that if the electron energy is ≤ 10 GeV, two collinear electrons are well separated to be measured in the ECAL.
- Moreover, low momentum electrons are also well measured with the tracker.
- We believe a full detector simulation is needed to estimate the efficiency for identifying lepton jets containing electrons and how well we can measure their masses and momenta.