MC4BSM: from a user's view

Measuring dark force at the LHC

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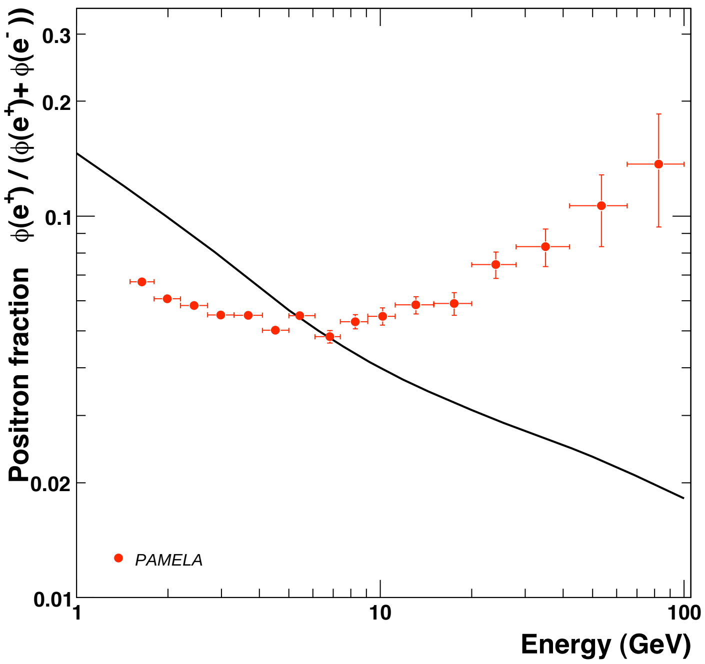
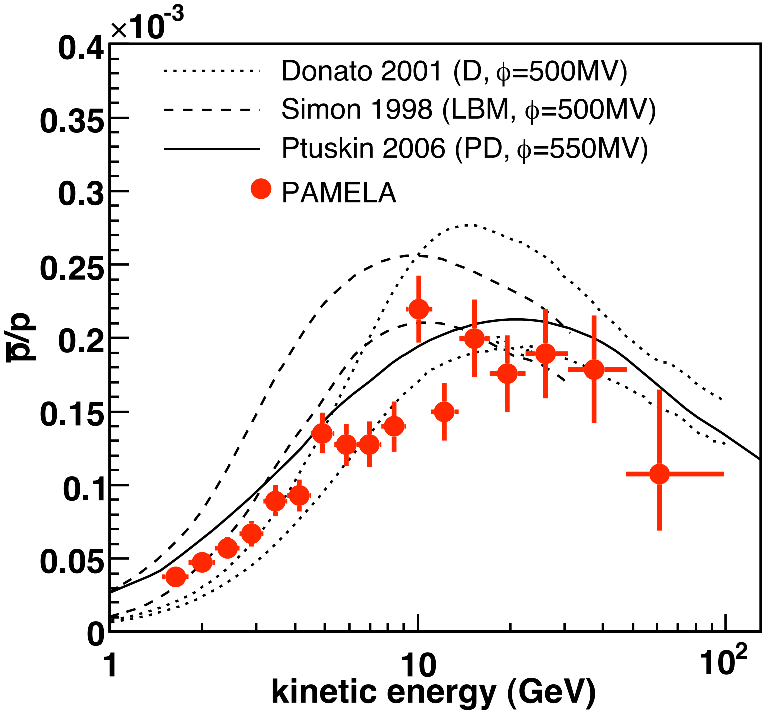
Cosmic Ray Positron Excesses



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 $\propto E^{-2.7}$.

Possible Explanations

Not dark matter

- Standard scenario: [Blasi, 0903.2794]
- Nearby pulsars: [Hooper, Blasi and Serpico; Profumo]

Due to dark matter

- Decaying dark matter
- Dark matter annihilation

Is there any existing well motivated BSM to explain PAMELA?

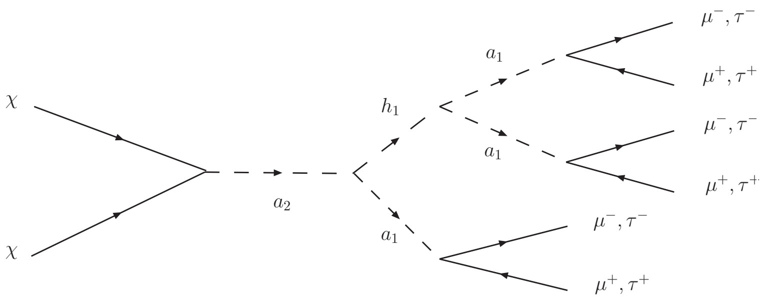
- Dark matter particles mainly annihilate into leptons
- A large dark matter annihilation cross section

How about NMSSM?

- Introducing a singlet $\hat{S}$ to solve the "μ-problem" in the MSSM

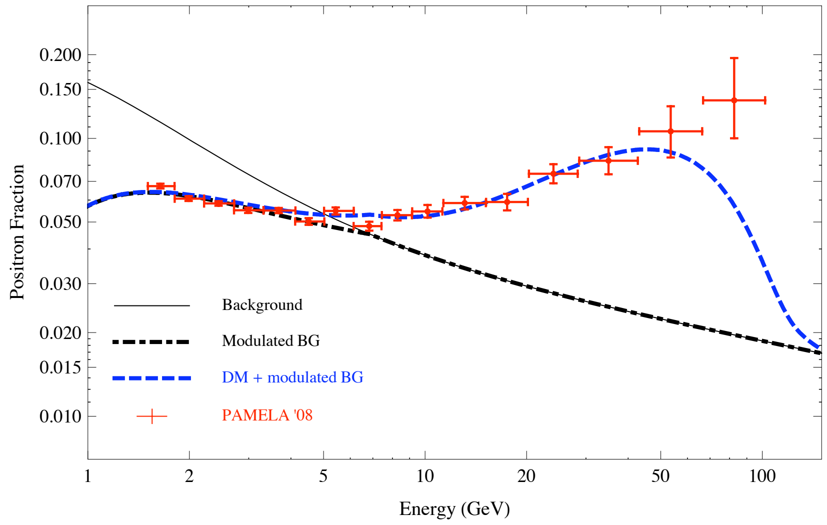
$$W = \lambda \, \hat{S} \, \hat{H}_u \, \hat{H}_d + \frac{\kappa}{3} \, \hat{S}^3 \qquad\qquad V = \lambda \, A_\lambda \, S \, H_u \, H_d + \frac{\kappa}{3} \, A_\kappa \, S^3 + h.c.$$

- Three new particles beyond MSSM: one CP-odd scalar, one CP-even scalar and one neutralino
- The lightest CP-odd scalar a_1 can be extremely light   Dermisek, Gunion, 0811.3537
- From kinematic reasons, a_1 can mainly decay into 2 τ's if $2\, m_\tau < m_{a_1} < 2\, m_b$, or even decay into 2 μ's if $m_{a_1} < 1$ GeV

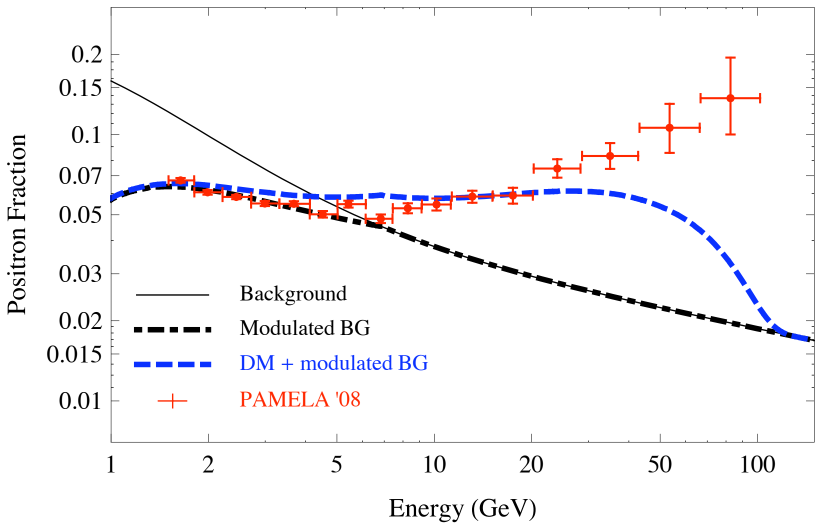


- The LSP is mainly Bino with a small fraction of Higgsino. Needs M_{a_2} close to twice of m_χ to have a large annihilation cross section
- The LSP should have a mass below the top quark mass. $m_\chi < m_t$ prediction

Fit to PAMELA [YB, M. Carena and J. Lykken, in preparation]



μ case



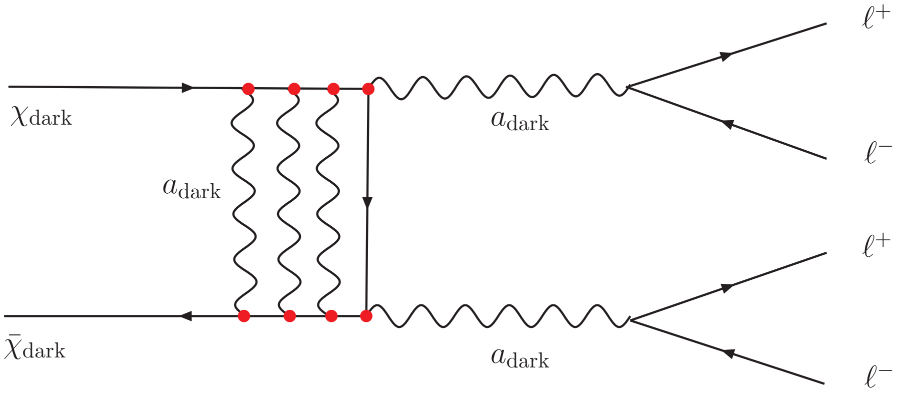
τ case

The inclusive positron spectrum out of tau decay is calculated through Pythia by calling TAUOLA

- The 6 μ's final state is preferred by the PAMELA positron data.
- However, the $h \to aa \to \mu^+\mu^-\mu^+\mu^-$ is highly constrained at D0 [Conference Note 5891-CONF], $\sigma(p\bar{p} \to h + X) \times BR(h \to aa) \times BR(a \to \mu^+\mu^-)^2 < 10\ fb$
- Needs h mainly to decay into $b\bar{b}$ to suppress $BR(h \to aa)$. The final state of dark matter annihilation contains hadrons. NMSSM is not a very compelling model for explanation of PAMELA, although a narrow model parameter space can be found.

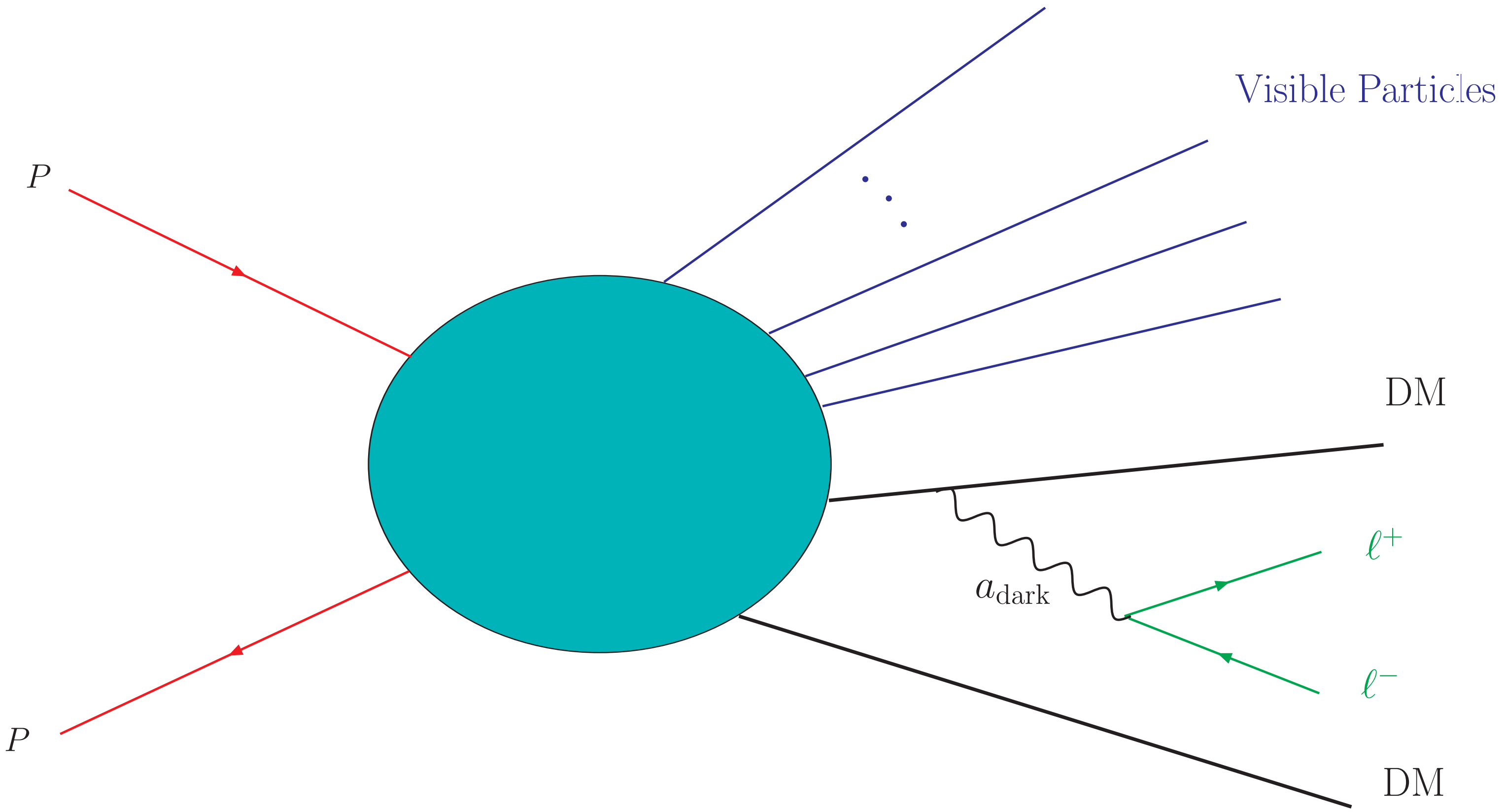
An Abelian hidden gauge symmetry in SUSY [Arkani-hamed et.cl., 0810.0713]

- 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.



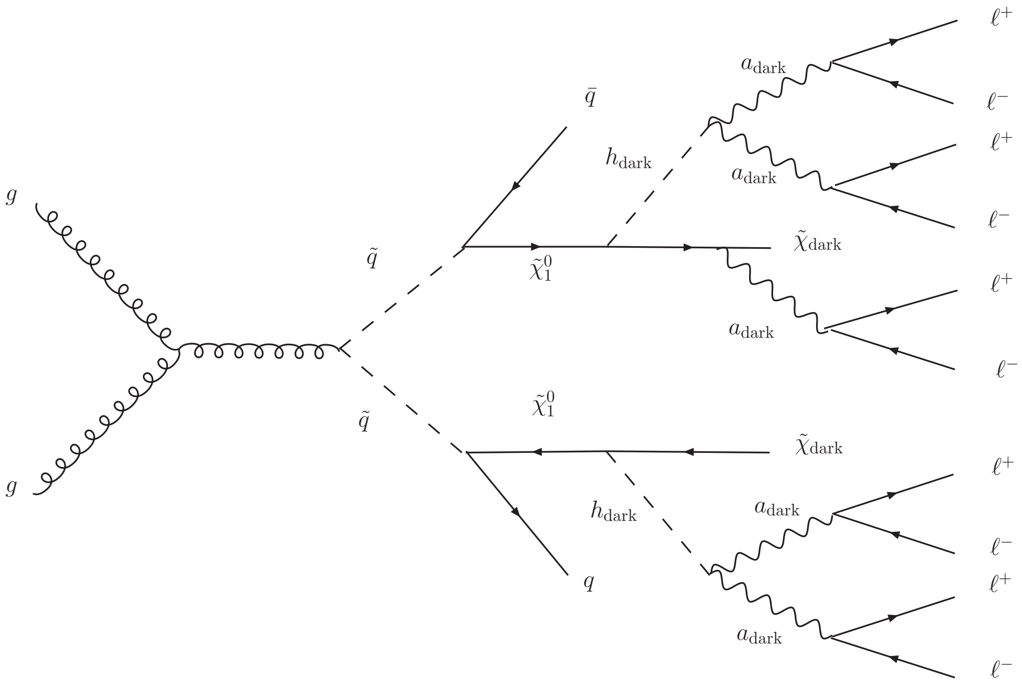
- The LSP in the MSSM $\tilde{\chi}^0_1$ will decay into χ_{dark} plus a_{dark} or h_{dark}, which decay to leptons.

Our strategy [YB and Z. Han, 0902.0006]



$$\frac{\sigma(p\,p\ \rightarrow\ X\ DM\ DM\ a_{dark})}{\sigma(p\,p\ \rightarrow\ X\ DM\ DM)} \approx C\,\frac{g^2}{4\,\pi^2}\,\log\left(\frac{q^2}{M_{a_{dark}}^2}\right)\,\log\left(\frac{q^2}{m_{DM}^2}\right)\sim 0.1$$

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.

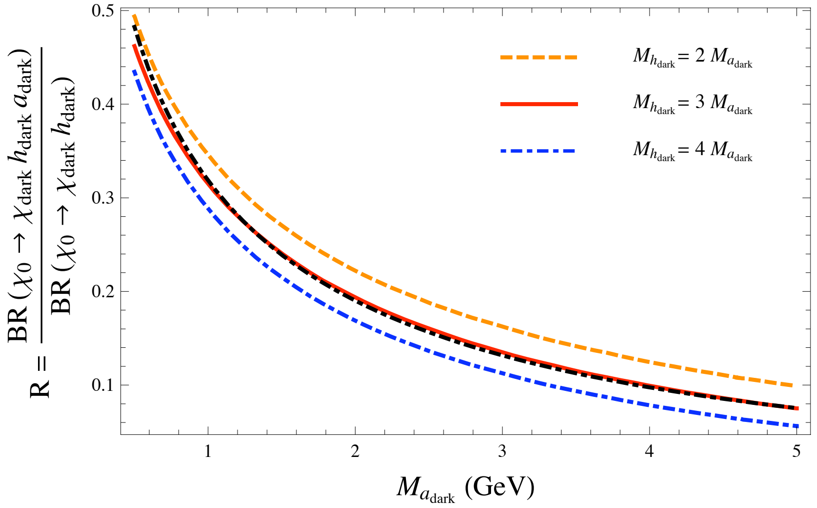
The ratio R

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

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

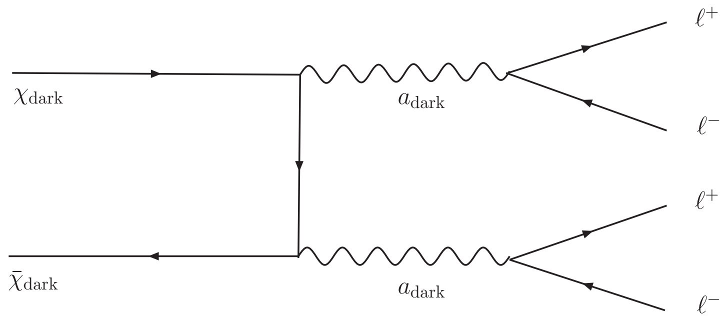
- Approximate formula (for $M_{h_{dark}} = 3\, M_{a_{dark}}$, $r_a \equiv M^2_{a_{dark}}/m^2_{\chi_0}$ and $r_{dm} \equiv m^2_{\chi_{dark}}/m^2_{\chi_0}$)

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



$m_{\chi_0} = 700$ 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 generate the model files for Calchep using Lanhep.
- We perform the 2-body and 3-body decays of $\tilde{\chi}_1^0$ to $\tilde{\chi}_{dark}$, h_{dark} and a_{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.

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

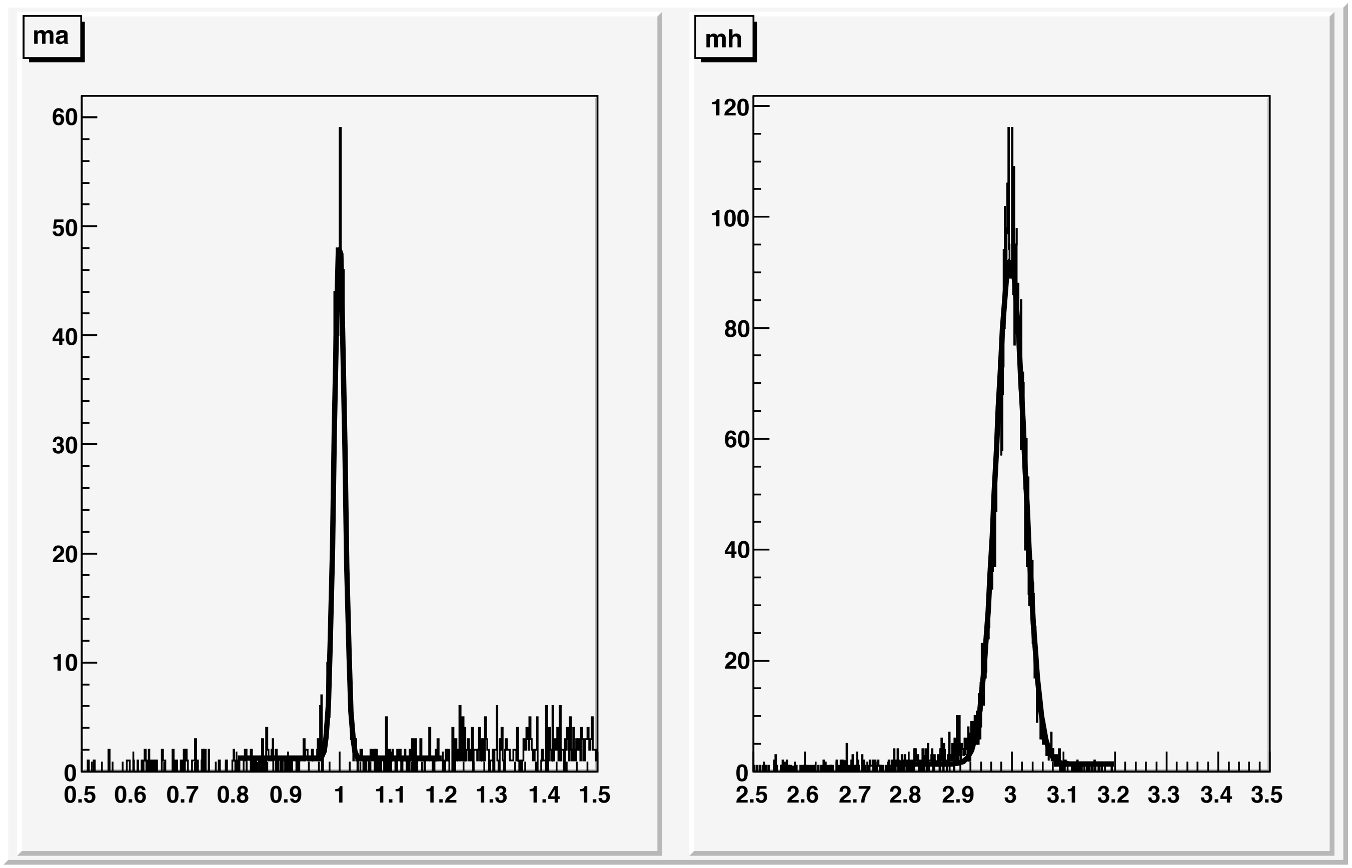
- At 10 fb^{-1}, we anticipate 230 $2h1a$ type three-body decay events.
- However, the a-jets tend to be collinear with the h-jets and/or contain soft muons that are not registered by the detector.
- This drastically reduces the efficiency for identifying $2h1a$ events. Therefore, we also include events with one 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 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 R.

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

To measure the dark force or the hidden gauge coupling g

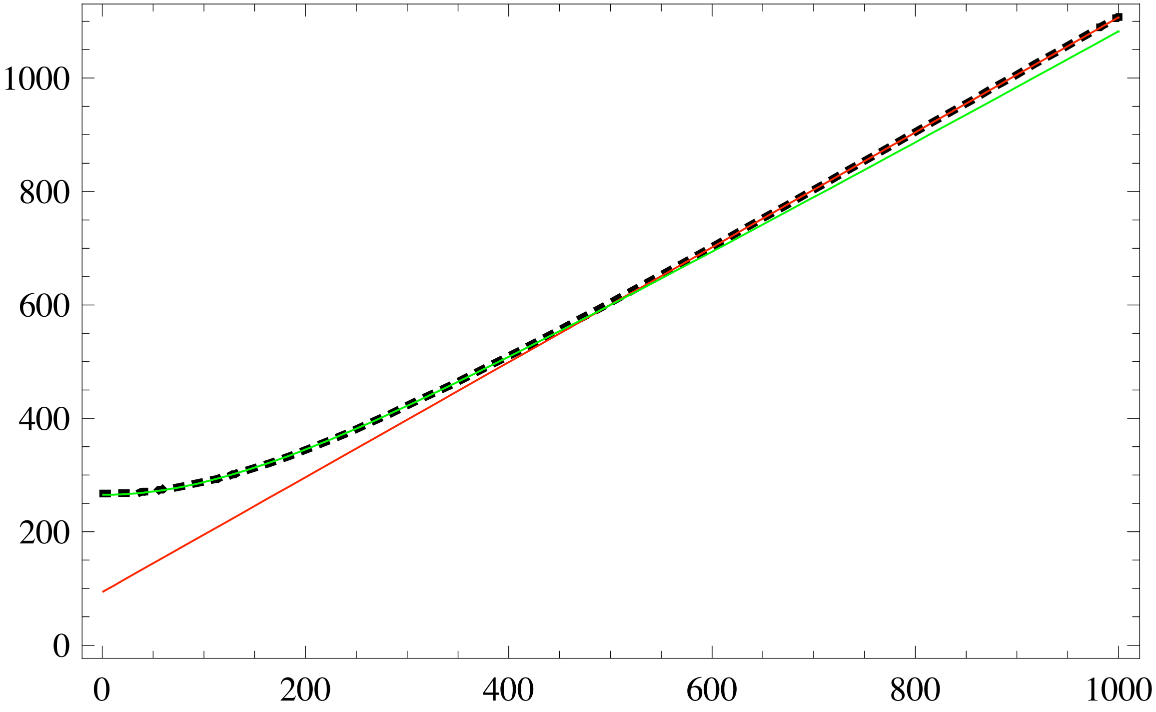
$$g(R, m_{\chi_0}, m_{\chi_{dark}}, M_{a_{dark}}, M_{h_{dark}})$$

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.

Find Kink [Cho, Choi, Kim and Park]



x: trial dark matter mass y: 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.

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

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

Relic Abundance

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

$$g = 0.40 \pm 0.03$$

- 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, $\boldsymbol{\Omega_{dm}\, h^2 = 0.113 \pm 0.0034}$ at 68% CL.
- From LHC and at 10 fb^{-1}, we will have

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

Conclusions

Beyond the standard model:

- NMSSM may have a good chance to explain the PAMELA positron excess, although only in a fine-tuned parameter space.
- 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.

Monto Carlo tools:

- The following tools have been used:

  Lanhep, Madgraph/Madevent, Calchep, Bridge, Pythia and PGS

- The tools are powerful enough for me to explore "traditional" BSM.