Non-abelian Dark Sectors and Their Collider Signatures

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M. Baumgart, C. Cheung, J. Ruderman, I. Yavin and LW, arXiv:0901.0283

Outline

- Basic model ingredients. Neal Weiner's talk.
- Some possible models
  - SUSY with kinetic mixing mediation

    For details: I. Yavin's talk, later in this workshop
- Collider signals with lepton jets:

  Tevatron and LHC.
  - Non-SUSY: production w/ kin mixing.
  - SUSY: modified decay chains.
- Conclusions.

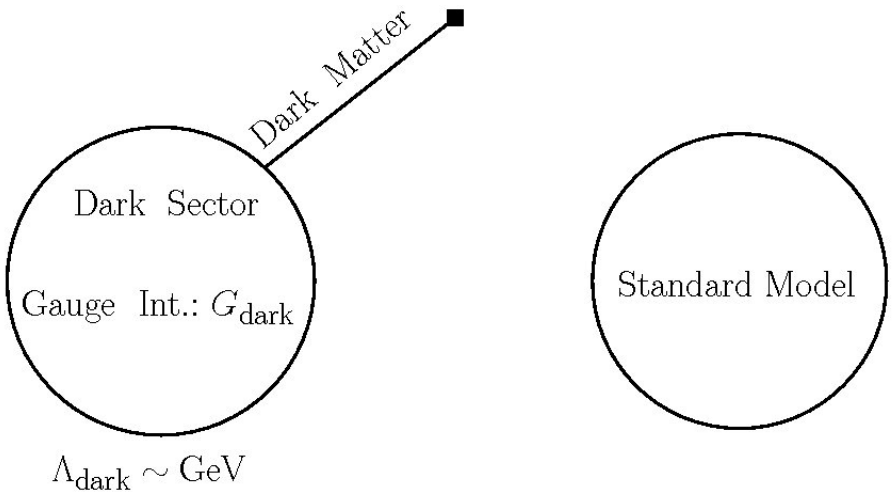
Recent experimental observations

- Evidences for 100s GeV – TeV WIMP
  - HEAT `97 and `04, AMS-01 `07
  - PAMELA `08, ATIC `08
  - WMAP haze, Finkbeiner `99.
  - EGRET `05.
- Possible evidence for a much smaller mass scale(?)
  - INTEGRAL `06, $m \approx 1\,\mathrm{MeV}$
  - DAMA/LIBRA 08, inelastic DM $\delta m \approx 100\,\mathrm{keV}$

Smith and Weiner, 2001 and 2005

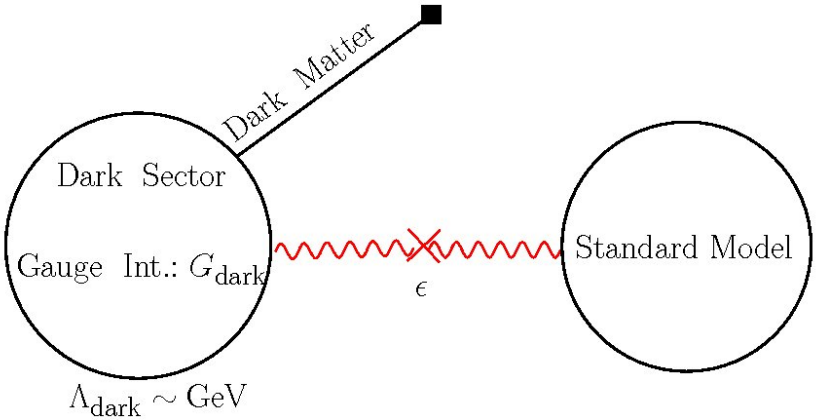
- Many model considerations.
  - See the program of this workshop.
- We will focus a recent proposed scenario with a non-abelien sector at GeV scale.
  - Arkani-Hamed, Finkbeiner, Slatyer, and Weiner, arXiv:0810.
  - Arkani-Hamed, Weiner, arXiv:0810.0714
- We will explore the models and the collider phenomenology of this scenario.
- We will not fit detailed parameters and spectrum to observaions.
  - A non-abelian dark sector is interesting in its own right.
  - General features of phenomenology independent of details of parameter choices.

Basic model ingredient: dark sector



Dark sector: non-abelian gauge symmtry.
Gauge symmetry breaking at 1 GeV.
Dark Matter: non-trivial multiplets under $G_{\rm dark}$.

Basic mode ingredients: kinetic mixing



$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}b_{\mu\nu}b^{\mu\nu} + \frac{\epsilon}{2}B_{\mu\nu}b^{\mu\nu}$$

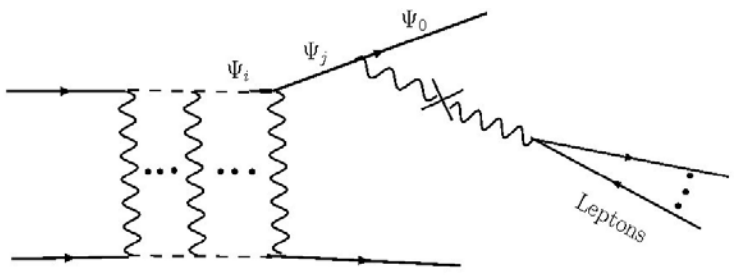
$$\epsilon = -\frac{g_Y g_y}{16\pi^2}\sum_i Q_i q_i \log\left(\frac{M_i^2}{\mu^2}\right) \qquad \epsilon \sim 10^{-4} - 10^{-3}$$

Kinetic mixing: dark U(1) and SM hypercharge.

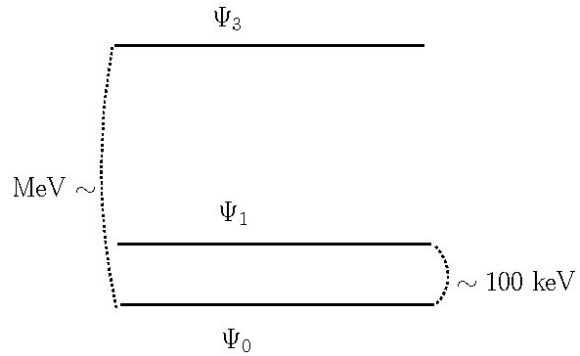
> A ``window" into the dark sector.

Other variations possible. We will focus on this here.

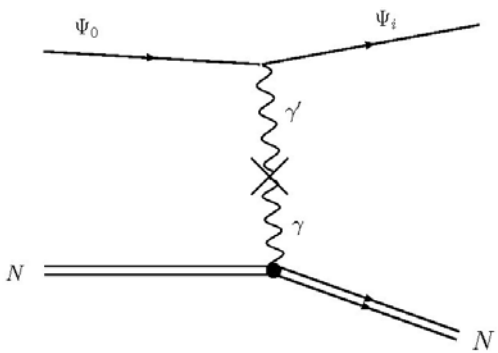
eXciting DM (XDM) and inelastic DM (iDM)



eXciting DM (XDM)



Finkbeiner and Weiner, astro-ph/0702587



inelastic DM (iDM)

Need at least 3 states, and proper mass splittings between them.

Smith and Weiner, hep-ph/0101138, Tucker-Smith and Weiner hep-ph/0402065.
Chang, Kribs, Tucker-Smith and Weiner arXiv:0807.2250

Mass splitting, MeV and 100 keV.

- From radiative correction.
  - Members of the dark matter multiplet are split from gauge boson loops after gauge symmetry breaking.

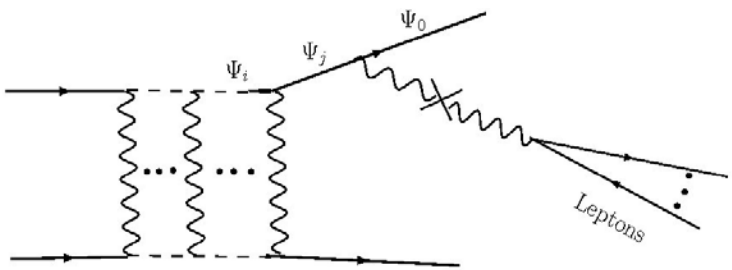
$$\Delta m \approx \alpha \Lambda_{\text{dark}}$$ Thomas and Wells, hep-ph/9804359

  - Right size for $\Lambda_{\text{dark}} \approx \text{GeV}$
  - Detail: choose coupling and charge to get the right splitting.
- From higher dimensional operator involving dark sector and dark matter fields, suppressed by ~TeV.

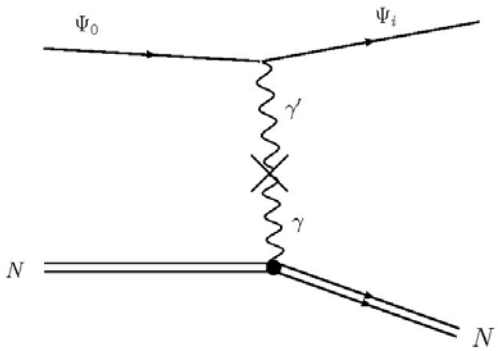
$$\delta m \sim \Lambda_{\text{dark}}^2 / M_X \sim \text{MeV}$$

  - For details: I. Yavin's talk and our paper.

Dark sector symmetry breaking at GeV.



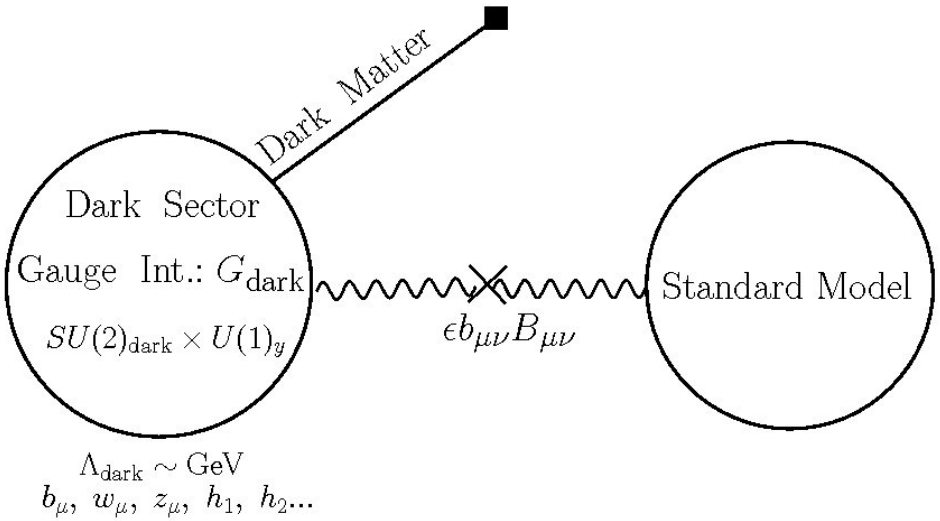
eXciting DM (XDM)



inelastic DM (iDM)

- Break all symmetries. No ``charge" conservation.
- Must have the proper couplings between proper states..

We choose to study the minimal case:

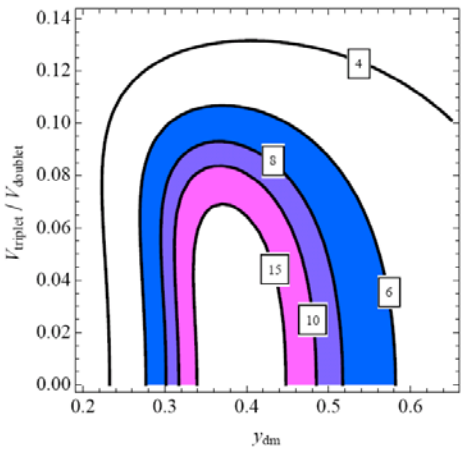


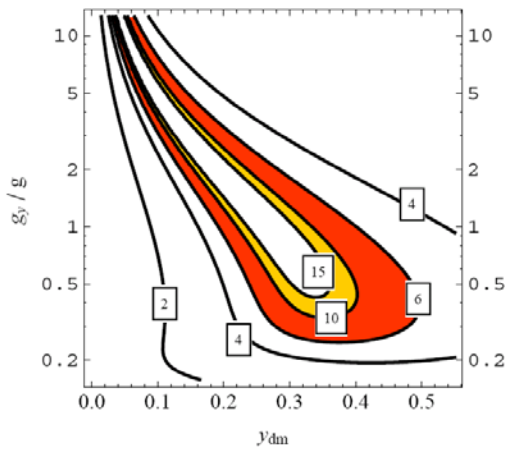
- Dark gauge group: $SU(2)_{dark} \times U(1)_y$
- Dark matter: triplet under $SU(2)_{dark}$
- Additional symmetry:
  - custodial SU(2). Must break to have proper XDM couplings.

We considered several possible Higgs sectors.

- Need extended Higgs sector to break all the symmetries.
- Charge breaking
  - 1 Higgs doublet cannot work. 2HD with misalignment.
- Custodial SU(2) breaking.
  - Radiatively from $U(1)_y$
  - With triplets.
- Extension to SUSY requires more Higgses.
  - Must be complex.
  - Anomaly cancellation.

Fermion mass splitting



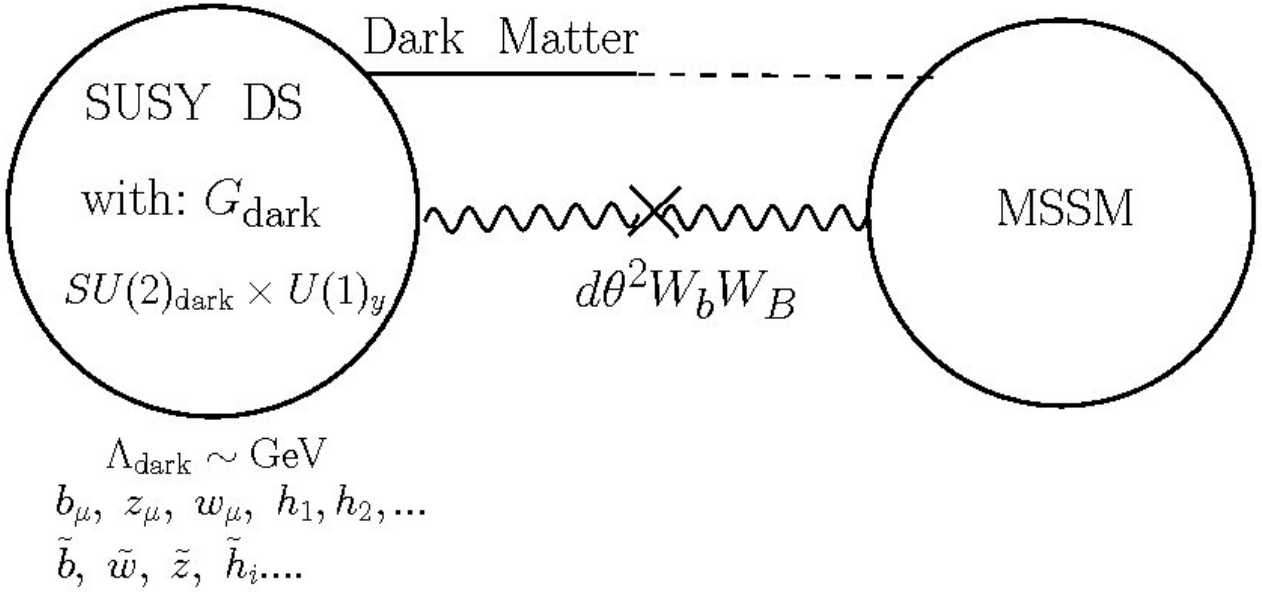


Ratio of XDM and iDM mass splittings,
in a 2 doublet 1 triplet model.

We show proper couplings can also be obtained.
Several examples are given in our paper.

Dark sector GeV scale generation

- Supersymmetry is probably most elegant way of GeV scale generation.



Supersymmetric dark sector models.

- ``Plank slop".
  - High scale GMSB and gravity mediation for DS.
- GMSB, dark matter as messenger.
  - Could be consistent with unification if dark matter is $\mathbf{5} + \bar{\mathbf{5}}$

    These two options are in the original proposal.
- Kinetic mixing mediation. Our new proposal.
  - A little more detail here. (I. Yavin's talk.)

We presented examples of both non-SUSY and SUSY models.

Kinetic mixing mediation.

$$\mathcal{L}_{\text{gauge}} = \frac{1}{4}\int d^2\theta \left(W_Y W_Y + W_y W_y - 2\epsilon W_Y W_y + \text{h.c.}\right)$$

$$V_{\text{gauge}} = \frac{1}{2}D_Y^2 + \frac{1}{2}D_y^2 - \epsilon D_Y D_y + g_Y D_Y \sum_i Q_i \left|H_i\right|^2 + g_y D_y \sum_i q_i \left|h_i\right|^2$$

After integrating out the MSSM Higgs:

$$V_{\text{gauge}} \supset \epsilon D_y \langle D_Y \rangle = \xi D_y$$

$$\xi = \epsilon \langle D_Y \rangle = \epsilon \frac{g_Y}{2} \cos 2\beta \, v^2$$

Effrctive FI term.

Kinetic mixing mediation

- Effective FI term, ``mass" term for dark Higgses.

$$\xi = \epsilon \langle D_Y \rangle = \epsilon \frac{g_Y}{2} \cos 2\beta \, v^2$$

- The natural size of kinetic mixing.
  - If theory embedding in GUT, O(1) mixing forbidden.
  - Only induced after GUT breaking by loops.

$$\epsilon \sim -\frac{g_Y g_y}{16\pi^2} \log\left(\frac{M^2}{M'^2}\right) \qquad \epsilon \sim 10^{-3} - 10^{-4}$$

  - Therefore, FI term $\approx \sqrt{\in g_y} v_{\mathrm{EW}} \approx$ GeV
    - generate the scale of the order of GeV.
    - This is the *leading* $\propto \sqrt{\in}$ contribution to DS from kin. Mixing.

Two directions in kinetic mixing mediation.

- Vanishing superpotential. SUSY preserving.
  - Light goldstones, higgsinos
- Superpotential determines the dynamics
  - SUSY breaking by D-term
  - Light gauginos
- Best model probably somewhere in between.

Colliders will play a crucial role in identifying the dark matter.

- ``conventional'' WIMP signal.
  - Couples to MSSM directly, no other interactions.
  - Missing energy.
- Signal of new dark interactions (dark sector).
  - Suppressed interaction with SM.
  - Rich pheno, ``window" to the dark sector

Collider pheno of GeV non-abelian dark sector

- Crucial gateway: kinetic mixing
  - Lepton jets
- Non-abelian:
  - More interesting lepton jets
- Supersymmetry:
  - Change the end of decay chain.

Kinetic mixing: couplings. B. Holdom, 1986

$$\mathcal{L}_{\text{gauge mix}} = -\frac{1}{4}W_{3\mu\nu}W_3^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}b_{\mu\nu}b^{\mu\nu} + \frac{\epsilon}{2}B_{\mu\nu}b^{\mu\nu}$$
$$= -\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}b_{\mu\nu}b^{\mu\nu} + \frac{\epsilon}{2}(\cos\theta_W F_{\mu\nu} - \sin\theta_W Z_{\mu\nu})b^{\mu\nu}$$

$$A_\mu J^\mu_{\text{em}} + Z_\mu J^\mu_Z + b_\mu J^\mu_b + w_\mu J^\mu_w$$

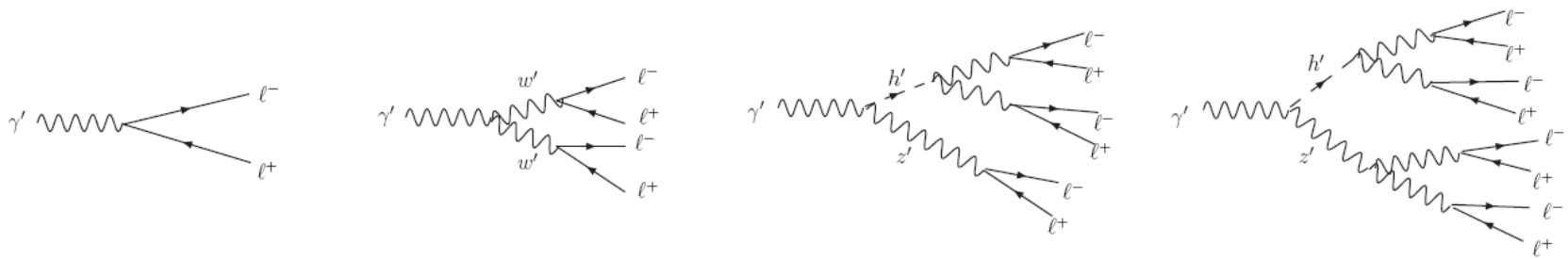
Eliminating kin. Mixing by $A_\mu \to A_\mu + \epsilon\cos\theta_W b_\mu$

$$\boxed{\epsilon b_\mu \left(\cos\theta_W J^\mu_{\text{em}}\right.} + \mathcal{O}(m_b^2/m_Z^2)J^\mu_Z\Big)$$

SM charged particle charged under dark $U(1)_y$.
Dark sector neutral under SM $U(1)_{EM}$.

Dark sector decay cascades

- Lightest dark sector states eventually decay into SM charged particles, leptons.
- Non-abelian: more leptons
  - 2, 4, 6, 8 leptons



- With typical dark states $p_T \sim \mathcal{O}(10s)\ \mathrm{GeV}$, lepton collimated $\delta\theta \sim m_{\gamma'}/p_T < 0.1$. Lepton jets!

Arkani-Hamed, Weiner, arXiv:0810.0714

Deccay life time

- 2-body cascade

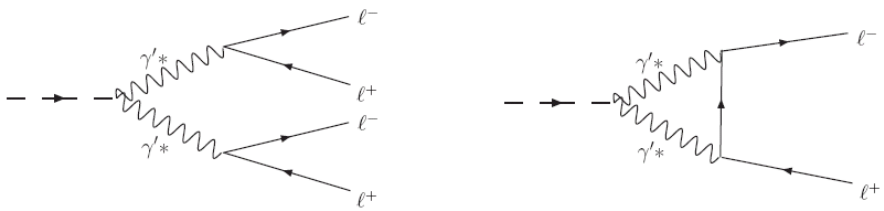
$$c\tau_{2-\mathrm{body}}^{\gamma' \to \mathrm{n}\ell} \sim \frac{1}{\alpha\epsilon^2 m_{\gamma'}} = 2.7 \times 10^{-6}\ \mathrm{cm}\ \left(\frac{\mathrm{GeV}}{m_{\gamma'}}\right)\left(\frac{10^{-3}}{\epsilon}\right)^2$$

  - Prompt in general.
  - Decay could produce displaced vertex with smaller coupling and somewhat large boost.
- 3 body decay if 2 body is kinematically forbidden.
  - Displaced vertices from different resonances in the cascade.

Missing energy

- 3-body with more phase space suppression.

- If lightest particle is scalar.



$$c\tau \sim \mathcal{O}(\mathrm{km}) \text{ for } m_{h'_0} \lesssim \text{ GeV}.$$

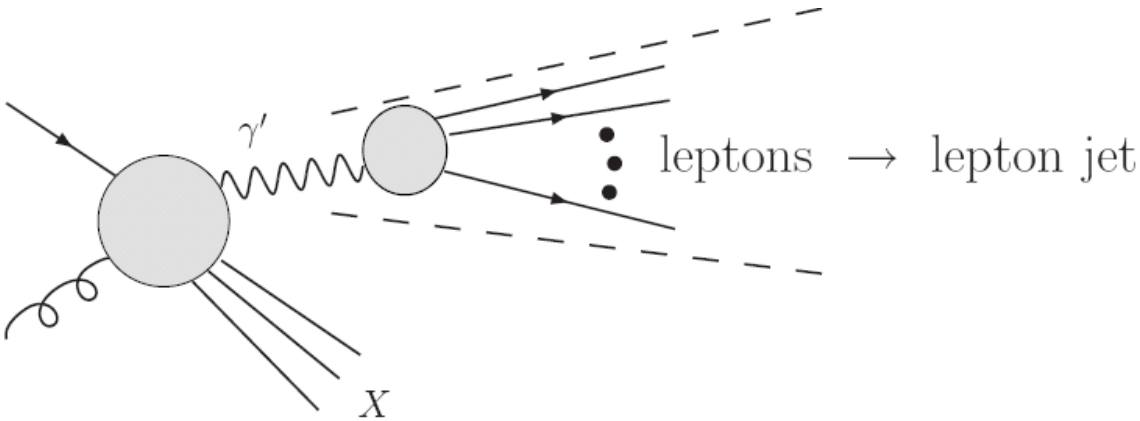
- Important feature: missing energy is often collimated with the lepton jets.

Prompt-photon-like production

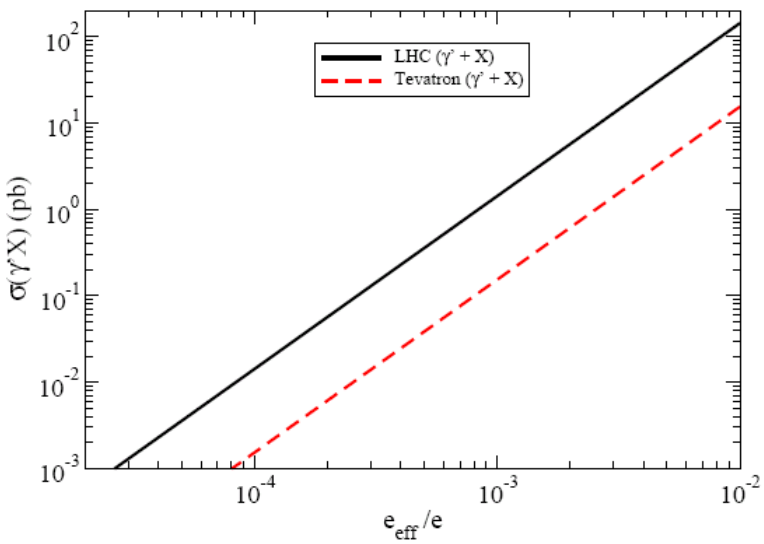
- Effective coupling

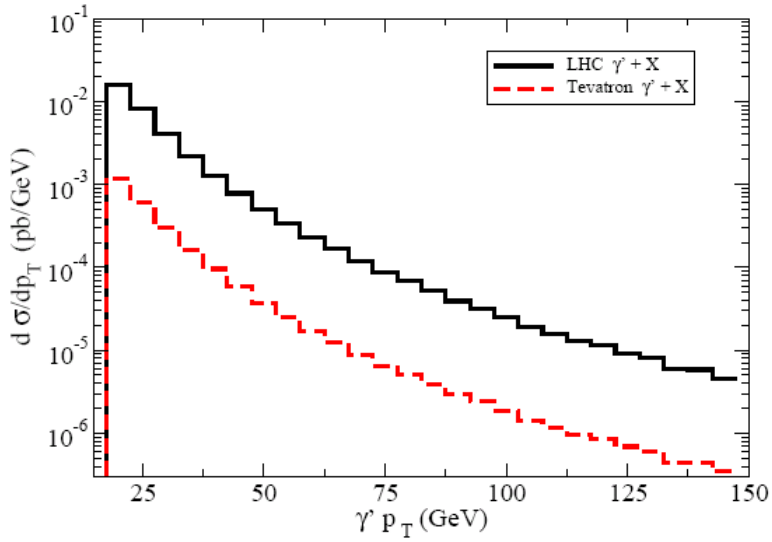
$$\epsilon b_\mu \left(\cos\theta_W J^\mu_{\rm em} + \mathcal{O}(m_b^2/m_Z^2) J^\mu_Z\right)$$

$$e_{\rm eff} = \epsilon e \cos\theta_W f_b$$



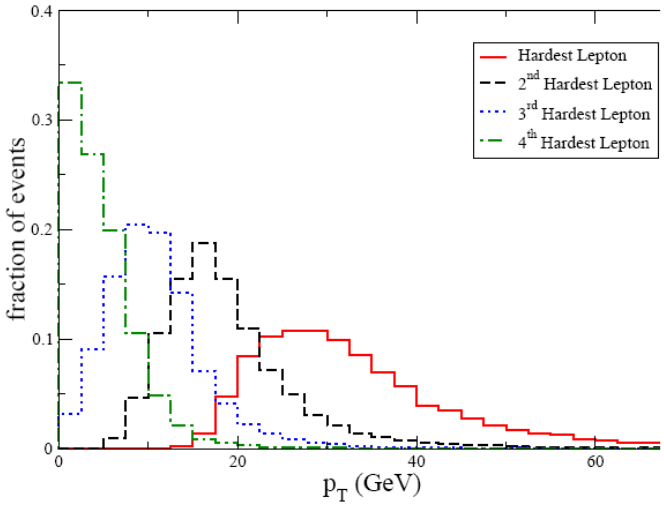
Rates



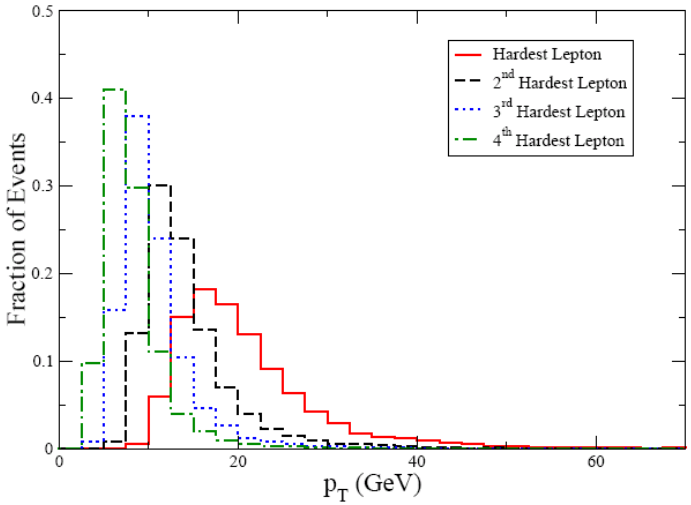


Cuts: $p_{\mathrm{T}} > 10\,\mathrm{GeV}, |\eta|_{\text{lepton jet}} < 2.4$

Triggering



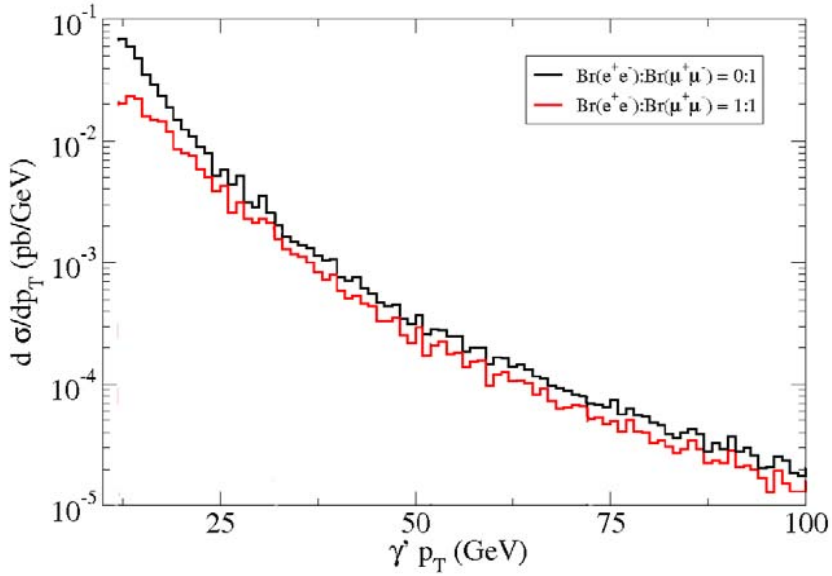
4-lepton LJ



8-lepton LJ

- Consider muon only, no isolation on trigger.
- At least a couple of them have hard p_T.

Rates with triggering on muon



For example, estimating using CMS numbers.

2 muons with $p_T > 3$ GeV in $|\eta| < 2.4$

1 muon with $p_T > 7$ GeV and $|\eta| < 2.4$

CMS technical design report.

Identifying leptons within lepton jets

- Small opening angle

$$\Delta\theta \approx \frac{\text{GeV}}{P_{\text{T}}} < 10^{-1} \Rightarrow 10^{-2}$$

- Should fly apart when reaching muon system.
  - For example: 20 GeV muons with 5 GeV difference. About 10 cm apart when reaching muon system at CMS.
  - Opposite sign muons even further away. 40 GeV tracks 0.5m apart.
- More detailed simulation certainly necessary, isolation(?).
- Identifying multiple muons (>2) suppresses most physics backgrounds, heavy flavor, J/ψ , etc.

Kinetic mixing: Z decay

$$\mathcal{L}_{\text{gauge mix}} = -\frac{1}{4}W_{3\mu\nu}W_3^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}b_{\mu\nu}b^{\mu\nu} + \frac{\epsilon}{2}B_{\mu\nu}b^{\mu\nu}$$
$$= -\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}b_{\mu\nu}b^{\mu\nu} + \frac{\epsilon}{2}(\cos\theta_W F_{\mu\nu} - \sin\theta_W Z_{\mu\nu})b^{\mu\nu}$$

$$b_\mu \to b_\mu - \epsilon \sin\theta_W Z_\mu$$

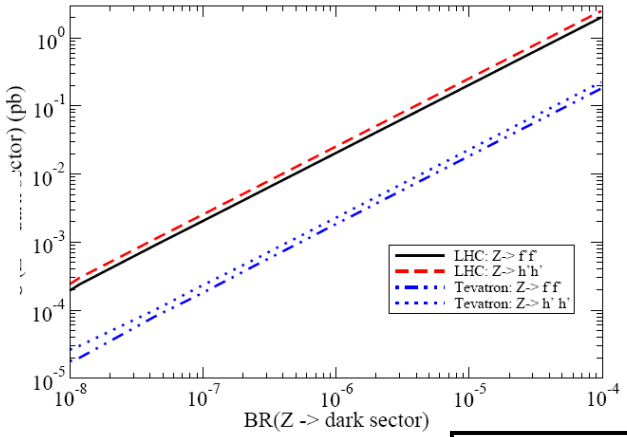
$$\epsilon Z_\mu \left(-\sin\theta_W J_b^\mu + \mathcal{O}(m_b^2/m_Z^2) J_w^\mu\right)$$

$b_\mu \to \bar{\nu}\nu$ Suppressed by $\left(\frac{m_b}{M_Z}\right)^2$

Production.

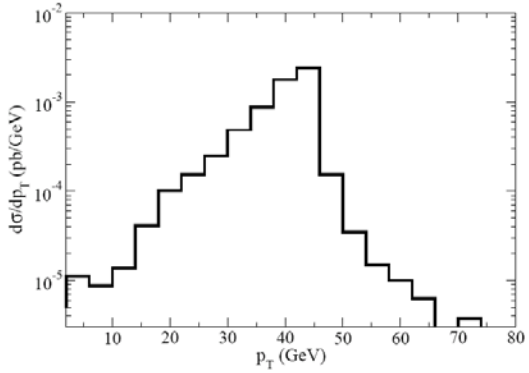
- Useful rate

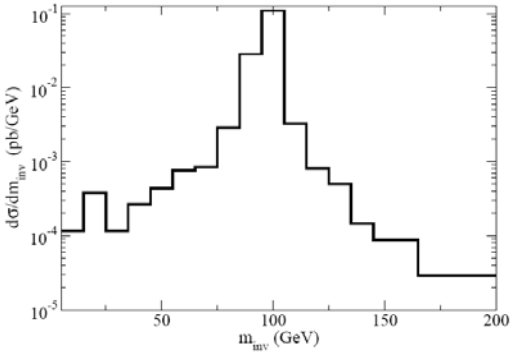
$$\mathrm{BR}(Z^0 \to d_i d_i) = \frac{c_{d_i}}{\Gamma_Z^0} \frac{\epsilon^2 g_y^2 y_{d_i}^2 \sin^2\theta_W}{48\pi} M_{Z^0},$$



- Hard lepton jets. Reconstruct Z.

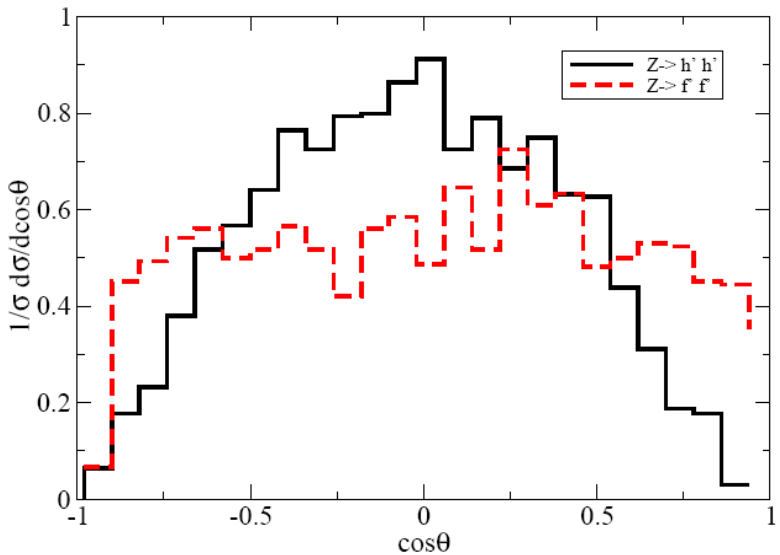
Cut imposed
$|\eta|_{\text{lepton jet}} < 2.4$





Dark sector spin measurement.

- Decaying into dark fermion or dark boson



- Need high statistics.

SUSY cascades: couplings

- Gaugino kinetic mixing

$$\mathcal{L}_{\text{gaugino mix}} = -2i\epsilon\lambda_{\tilde{b}}^{\dagger}\bar{\sigma}^{\mu}\partial_{\mu}\lambda_{\tilde{B}} + \text{h.c.}$$

$$\text{shift it by } \lambda_{\tilde{b}} \to \lambda_{\tilde{b}} + \epsilon\lambda_{\tilde{B}}$$

$$\mathcal{L}_{\text{coupling}} = \epsilon\left(\lambda_{\tilde{B}}\tilde{J}_b + \mathcal{O}(M_{\tilde{b}}/M_{\tilde{B}})\lambda_{\tilde{b}}\tilde{J}_B\right)$$

$$\tilde{J}_b = g_y \sum_i q_i \tilde{h}_i^{\dagger} h_i$$

$$\tilde{J}_B = g_Y \sum_i Q_i \tilde{H}_i^{\dagger} H_i$$

- MSSM Bino to dark sector, coupling order $\in$.
- MSSM sfermion to dark gaugino couplings are suppressed by an additional factor of $\mathcal{O}(M_{\tilde{b}}/M_{\tilde{B}})$

Supersymmetric cascades: MSSM to DS

- Decay cascades. MSSM $\rightarrow$ Dark Sector
  - Neutralino LSP, prompt.

$$\tau_{\mathrm{LSP}\to h+\tilde{h}} \sim \left(\alpha_y^{\mathrm{dark}} f_{\tilde{B}}^2 \epsilon^2 M_{\mathrm{LSP}}\right)^{-1}$$
$$= 7\times 10^{-19}\ \mathrm{s}\ \left(\frac{100\ \mathrm{GeV}}{M_{\mathrm{LSP}}}\right)^2 \left(\frac{0.01}{\alpha_y^{\mathrm{dark}}}\right) \left(\frac{1.0}{f_{\tilde{B}}}\right)^2 \left(\frac{10^{-3}}{\epsilon}\right)^2$$

  - Sfermion LSP.
    - 3 body off-shell MSSM gaugino.

$$\tau_{\tilde{f}\to 3-\mathrm{body}} \sim \left[\alpha_y^{\mathrm{dark}} g_Y^2 c_{f\chi}^2 f_{\tilde{B}}^2 \epsilon^2 \frac{m_{\tilde{f}}}{16\pi^2} P(m_{\tilde{f}}/M_\chi)\right]^{-1}$$
$$= 8.3\times 10^{-16}\ \mathrm{s}\ \left(\frac{100\ \mathrm{GeV}}{m_{\tilde{f}}}\right) \left(\frac{0.01}{\alpha_y^{\mathrm{dark}}}\right) \left(\frac{1.0}{c_{f\chi} f_{\tilde{B}}}\right)^2 \left(\frac{10^{-3}}{\epsilon}\right)^2 \frac{1}{P(m_{\tilde{f}}/M_\chi)}$$

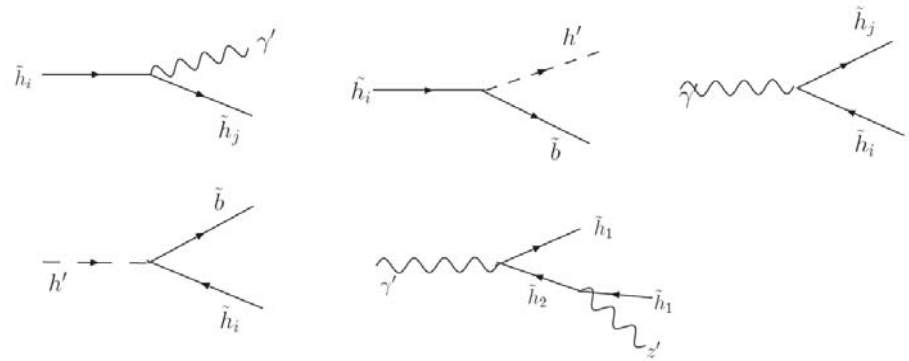
    - 2 body.

$$\tau_{\tilde{f}\to f+\tilde{b}} \sim \left[\alpha_Y \epsilon^2 m_{\tilde{f}} \left(\frac{M_{\tilde{b}}}{M_{\tilde{B}}}\right)^2\right]^{-1}$$
$$= 6.6\times 10^{-15}\ \mathrm{s}\ \left(\frac{100\ \mathrm{GeV}}{m_{\tilde{f}}}\right) \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{1\ \mathrm{GeV}}{M_{\tilde{b}}}\right)^2 \left(\frac{M_{\tilde{B}}}{100\ \mathrm{GeV}}\right)^2$$

3 body and 2-body channels can be comparable

Decay cascades in the dark sector

- Typically
  - Lepton jets



- Dark LSP (LDSP) decays to gravitino

$$\tau_{\tilde{b}\to\gamma\tilde{G}} \sim \left[\frac{\epsilon^2}{16\pi}\frac{M_{\tilde{b}}^5}{F^2}\right]^{-1} = 3.3\times 10^3\ \mathrm{s}\ \left(\frac{10^{-3}}{\epsilon}\right)^2\left(\frac{1\ \mathrm{GeV}}{M_{\tilde{b}}}\right)^5\left(\frac{\sqrt{F}}{100\ \mathrm{TeV}}\right)^4$$

- Outside detector. No photon like normal GMSB.

SUSY MSSM + dark sector decays

- Lepton jets at the end of the MSSM SUSY decay chain.
  - (much) More observable.
- Missing energy.
  - Massless and collimated with the lepton jets.

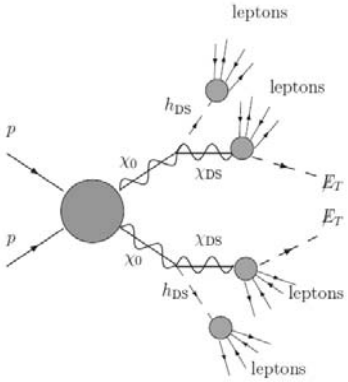
Greatly enhanced observablity of EW-ino production

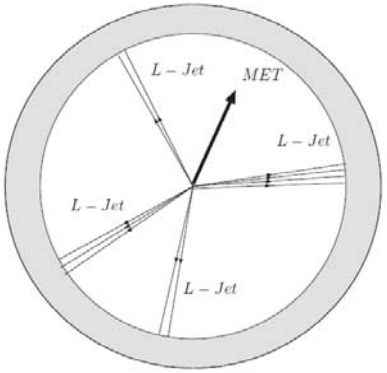
- Electroweak-ino production in MSSM
  - Crucial for discovery and measurement
  - However, hard to observe
    - LSP production, trigger on additional radiation?
    - Large SM backrgound with similar final states: WW, WZ, …
- MSSM + dark sector

Additional lepton jets

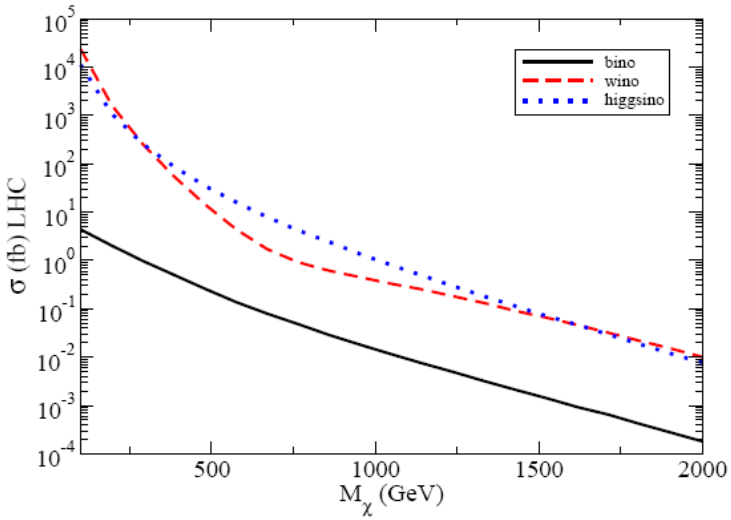
Easier to trigger on.

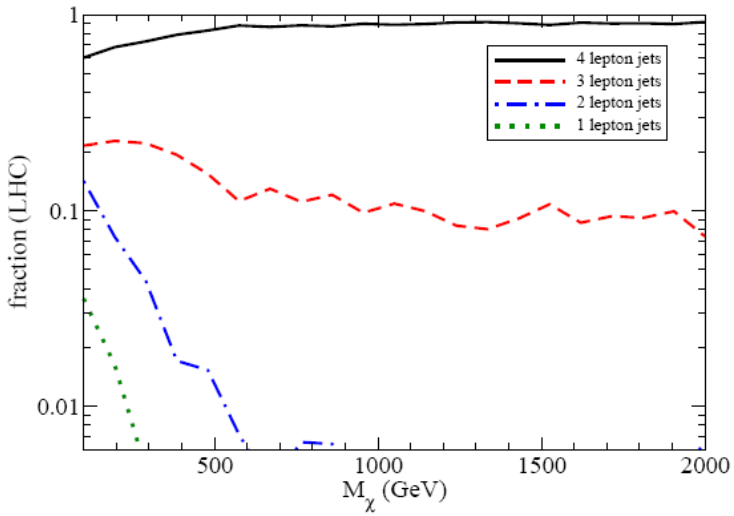
Good for background suppression





Electroweak-ino production at the LHC





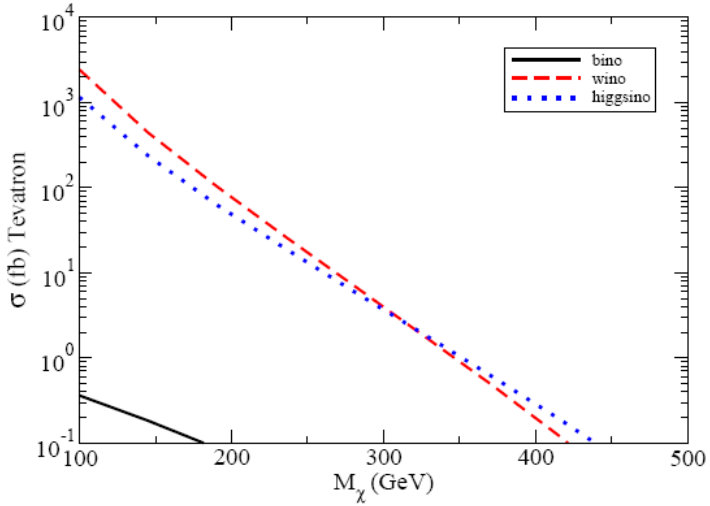
$$m_{\text{squark}} = 750\ \text{GeV}$$
$$|\eta|_{\text{Lepton jet}} < 2.4$$

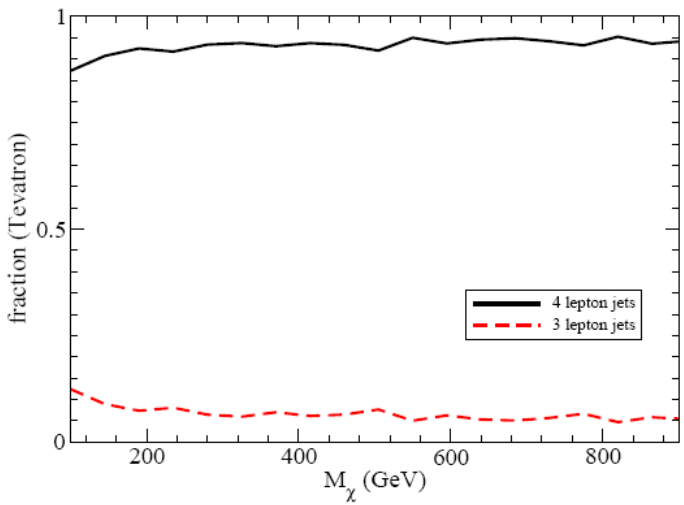
- Bino. LSP pair production. Up to 1 TeV.
- Wino/higgsino.

  LSP + degenerate chargino/neutralino

  Up to 2 TeV

Electroweak-ino production at the Tevatron





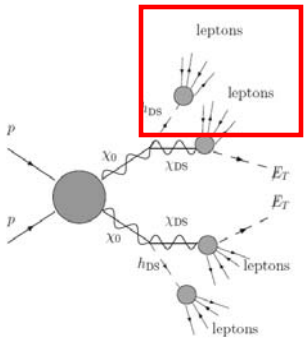
- Bino. LSP pair production. Hard. Small rate.
- Wino/higgsino.

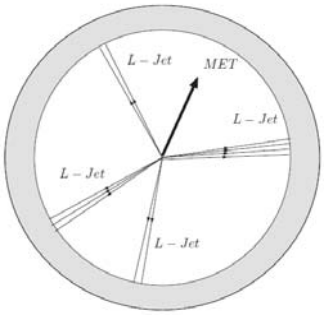
  LSP + degenerate chargino/neutralino

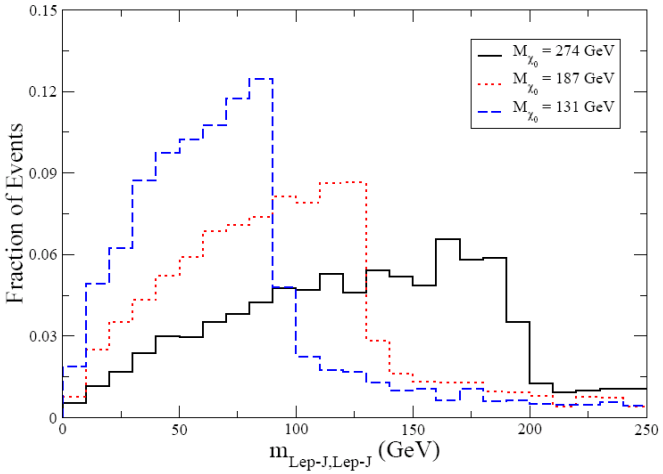
  Up to 300 GeV

Mass measurements and event reconstruction.

- Measuring the MSSM LSP mass.







- Edge: $M_{\chi_0}/\sqrt{2}$
  - Inv. Mass of lepton jets in the same decay chain.
- Can even fully reconstruct the dynamics.
- More measurements: spin….

Conclusions

- A GeV non-abelian dark sector typically have an extended dark Higgs sector as well.
  - We have given a set of examples.
- Supersymmetric implementations can generate the GeV scale natural, GMSB, ``Planck slop".
  - We propose a new mechanism, D-term kinetic mixing.
- Non-abelian DS with kin. Mixing with SM gives rich phenomenology.
  - Lepton jets have more than 2 leptons in it.
  - Produce through prompt photon-like process and Z-rare decay.
  - Promising at the LHC, could be possible at Tevatron.

Conclusions

- Lepton jets significantly alters conventional SUSY collider siganl.
  - Extended reach for electroweak-ino direct production.
  - Much better even reconstruction.
- Much more model building and phenomenology study have to be carried out to fully explore the possibilities.

Production of dark matter multiplet.

- Impossible to see if the full dark matter multiplet is color neutral.

- Possible in the some extensions
  - Example:

Vector quark.

Long-lived colored particle.