

# *Summary of SUSY + Cosmology sessions*



**International Workshop on Linear Colliders  
2010 (ECFA-CLIC-ILC Joint Meeting)**

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Many talks on mass/parameter determination  
mostly within standard susy framework:

## SUSY Prediction for the ILC

Determination of Heavy Smuon and  
Selectron Mass at CLIC

### A Study of Light-flavored SQuark Production at CLIC

A Study of Chargino and  
Neutralino Masses using W and h  
Energy Spectra and Threshold  
Scans at CLIC.

Measuring a light neutralino mass at the ILC

### Measuring Unification

## Polarized positrons for Higgs and SUSY

On the possibility of stop mass  
determination in photon-photon and  
 $e^+e^-$  collisions at ILC

Sven Heinemeyer,

J-J.Blaising

Peter Schade  
Frank Simon

N.Alster

John Conley

$M_{\chi_1^0}$  = a few GeV.

Michael Rauch

Gudrid Moortgat-Pick

A.N.Skachkova

and within less common susy

## Dirac gauginos and their scalar partners

Jan Kalinowski

## Bilinear R parity violation at the ILC

[Benedikt Vormwald](#)

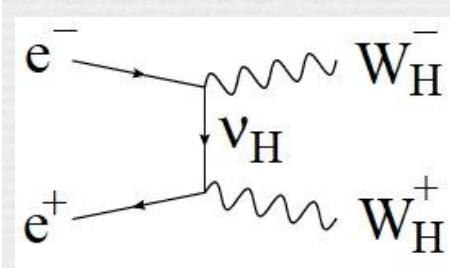
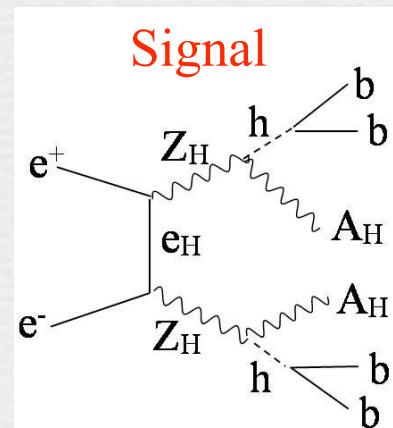
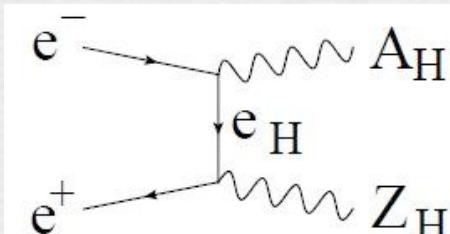
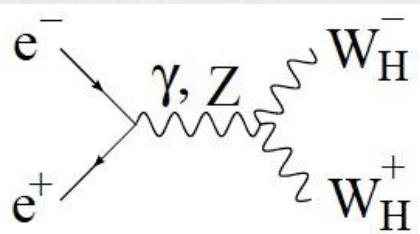
Neutrino physics at colliders?

## Sneutrino dark matter

G. Bélanger

invisible higgs decay (almost 100% BR) into sneutrinos

and beyond susy (heavy gauge bosons in little higgs models)



Y. Takubo

and model-independent approaches

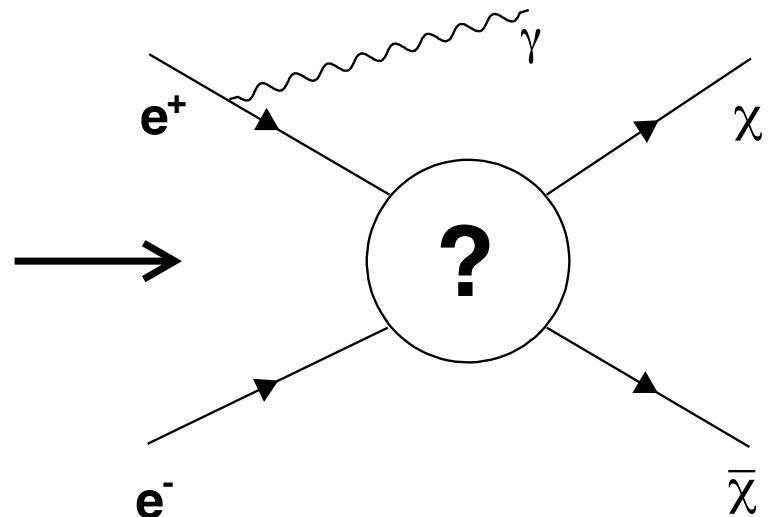
## Model Independent WIMP Searches with Polarized Beams at the ILC

Christoph Bartels

WIMP Detection with ISR

$$e^+ e^- \rightarrow \chi \bar{\chi} \gamma$$

Is it possible to extract  
Masses and  $J_0$  from data?  
Required Luminosity,  
Polarised beams?  
What can we learn about  
the question mark?

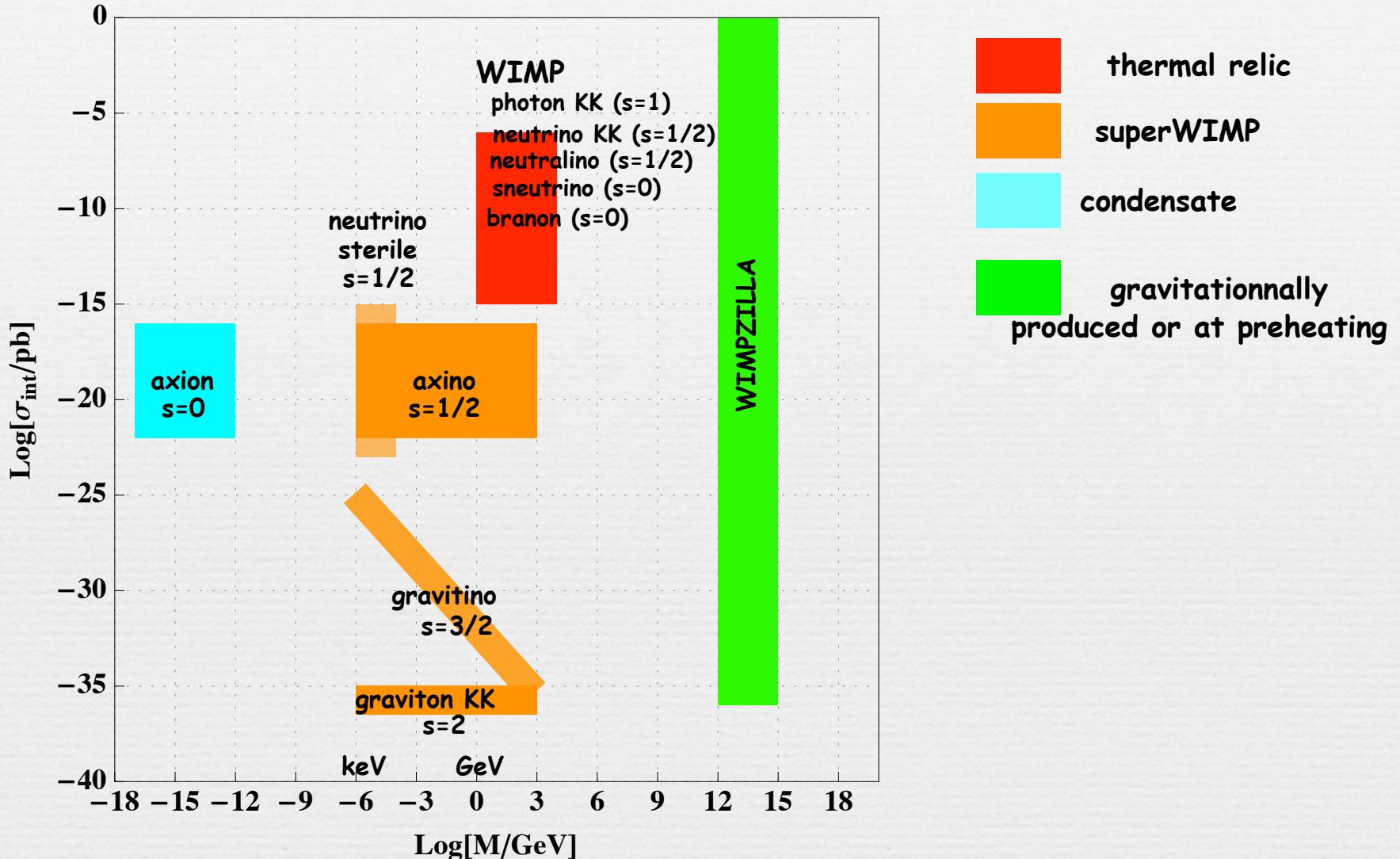


and beyond any expectation

## Dark Energy at Colliders?

Philippe Brax

# Dark Matter Candidates $\Omega \sim 1$



# In Theory Space

Peccei-Quinn

axion

majoron

(almost) Standard Model

sterile neutrino

$SU(2)$ -ntuplet heavy fermion

Technicolor & Composite Higgs

technifermion

GUT

wimpzillas

Supersymmetry

neutralino

axino

gravitino

sneutrino

Extra Dimensions

Kaluza-Klein photon

Kaluza-Klein graviton

Kaluza-Klein neutrino

branon

WIMP thermal relic

superWIMP

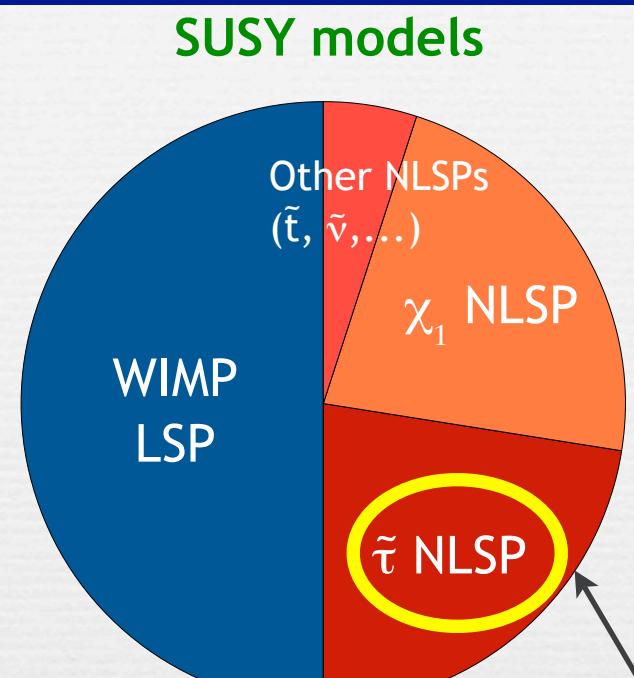
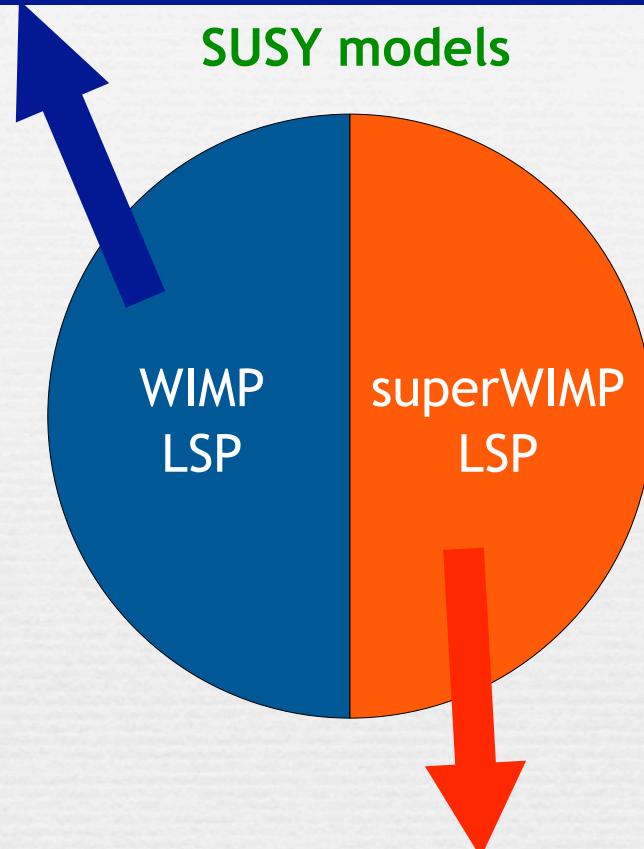
condensate gravitational production or at preheating

On LONG-LIVED STAUS (A. Ibarra)

## Canonical SUSY scenario:

LSP: neutralino

next-to-LSP: lightest stau, chargino (sneutrino, stop)



we should be prepared  
for this possibility

The LSP could also be a **superweakly interacting particle**:

gravitino      axino      Hidden U(1) gaugino

Bolz, Brandenburg, Buchmüller;  
Pradler, Steffen;  
Rychkov, Strumia

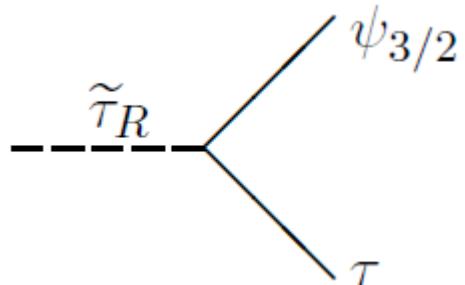
Asaka, Yanagida;  
Covi, Kim, Kim, Roszkowski;  
Brandenburg, Steffen.

Al, Ringwald, Weniger

Interesting and viable scenarios, which could account  
for the dark matter of the Universe

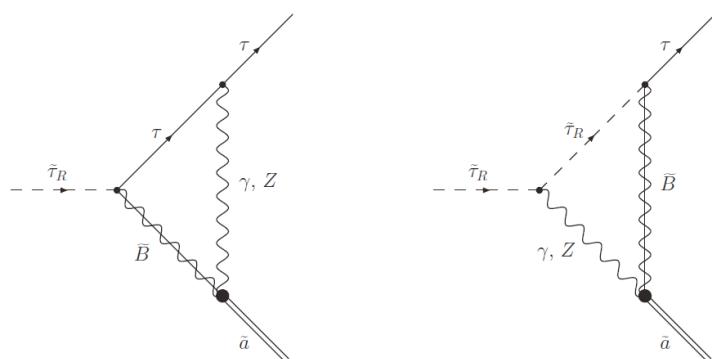
Scenarios with superWIMP LSP share one common feature:  
if R-parity is conserved, **the NLSP is very long lived!**

gravitino



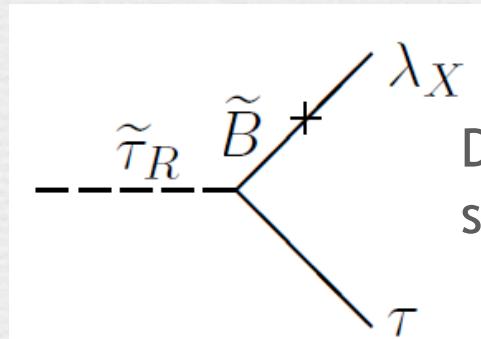
Decay rate suppressed by the Planck mass (or more properly, by the SUSY breaking scale  $F = \sqrt{3} m_{3/2} M_P$ )

axinos



Decay rate suppressed by the Peccei-Quinn scale

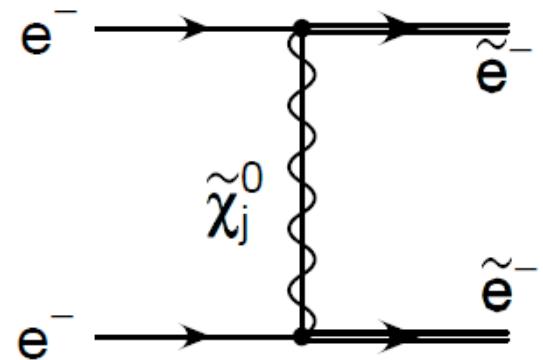
hidden U(1) gauginos



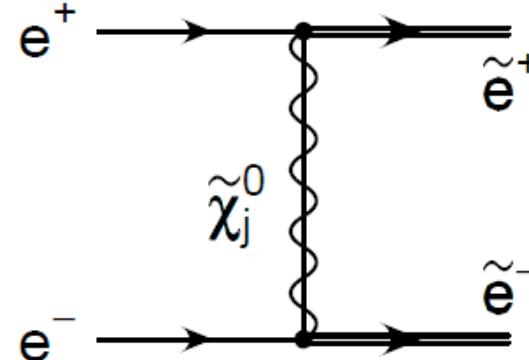
Decay rate suppressed by the small kinetic mixing.

# Production of long lived staus

$e^-e^-$  collider



$e^+e^-$  collider

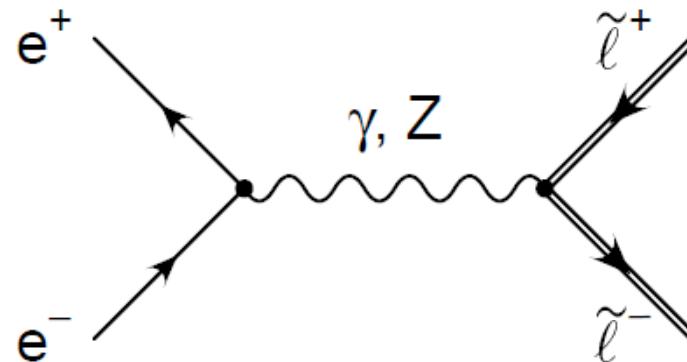


The selectron decays producing staus:

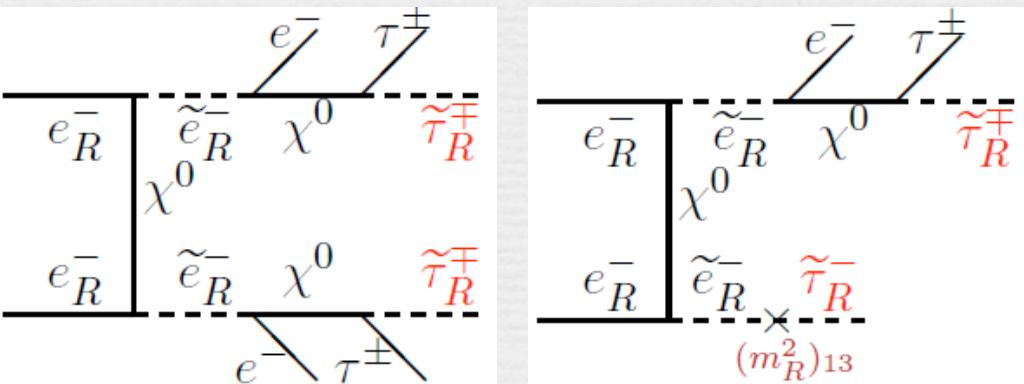
$$\tilde{e}_R^- \rightarrow e^- \tau^\pm \tilde{\tau}_1^\mp$$

$$\tilde{e}_L^- \rightarrow e^- \tau^\pm \tilde{\tau}_1^\mp$$

$$\tilde{e}_L^- \rightarrow \nu_e \bar{\nu}_\tau \tilde{\tau}_1^-$$



Direct production of staus



■ Four/Two charged fermions and two heavily ionizing tracks

# Detection of long lived staus

Charged track in the detector. **Very similar to a muon**, but with some differences:

- Large mass. Use kinematical cuts.
- Slow. Use a good Time of Flight (ToF) device.

In a large detector ( $r=2\text{m}$ ), the mean time of flight of a muon ( $\beta=1$ ) is 6.7 ns. A heavy particle ( $\beta<1$ ) will reach the detector later.

Assuming a time of flight measurement with an error of 50ps, the cut  $\Delta t > 0.13$  ns removes 99% of the muon background.

⇒ Efficiency in the identification 60-80% for stau masses 140-250 GeV

- Ionizing particle. Use a good Time Projection Chamber (TPC)

In contrast to muons (which lose energy mostly by radiation), heavy charged particles lose energy by ionization. Assuming a 5% resolution in the measurement of  $dE/dx$ , the cut  $\frac{dE/dx - dE/dx(\text{muon})}{\sigma(dE/dx)} > 3$  provides an efficiency in the identification >90% for stau masses larger than 180 GeV.

# Physics opportunities with long lived staus

1- Mass measurements

2- Searches for lepton flavour violation

AI, Roy

Hamaguchi, AI

If the LSP is the gravitino, measure the Planck mass

$$M_P = \sqrt{\frac{t_\tau m_\tau}{48\pi}} \frac{m_\tau^2}{m_{3/2}} \left[ 1 - \frac{m_{3/2}^2}{m_\tau^2} \right]^2$$

Buchmüller, Hamaguchi, Ratz, Yanagida

If the LSP is the axino, estimate the Peccei-Quinn scale

Brandenburg et al

If the LSP is the hidden gaugino, measure the kinetic mixing

AI, Ringwald, Weniger

Determine the spin of the invisible particle

Buchmuller et al.  
Brandenburg et al

# Hidden sectors and Dark forces (B. Batell)

## Secluded Dark Matter

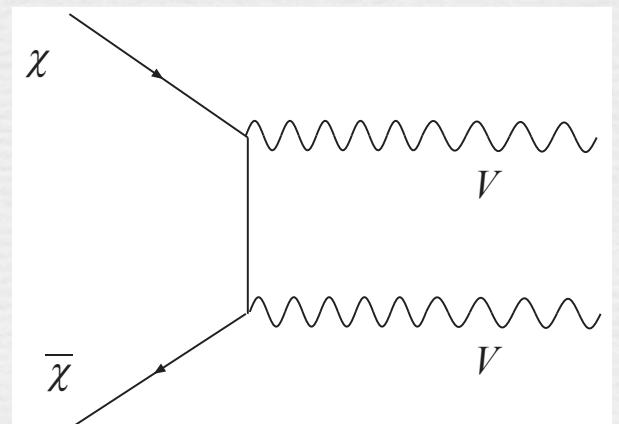
Pospelov, Ritz, Voloshin '07

- Dark Matter is a SM gauge singlet
- Talks to SM through mediator



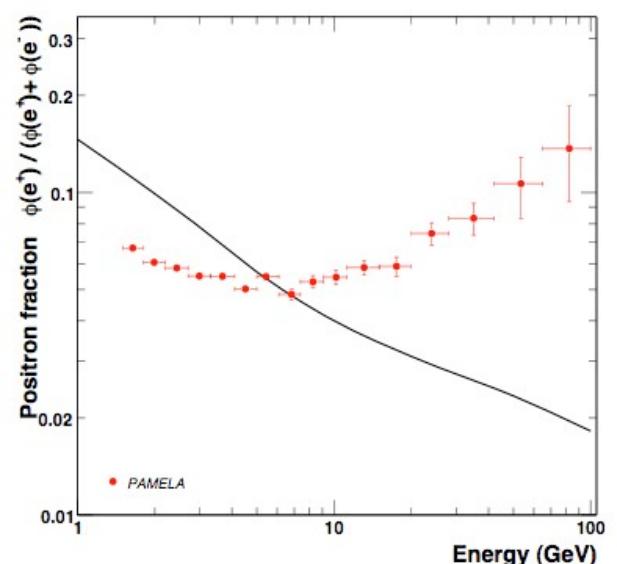
Example: dark matter via kinetic mixing

$$\mathcal{L} = i\bar{\chi}\gamma^\mu(\partial_\mu - ig_D V_\mu)\chi - \frac{\kappa}{2}V_{\mu\nu}B^{\mu\nu} + \dots$$

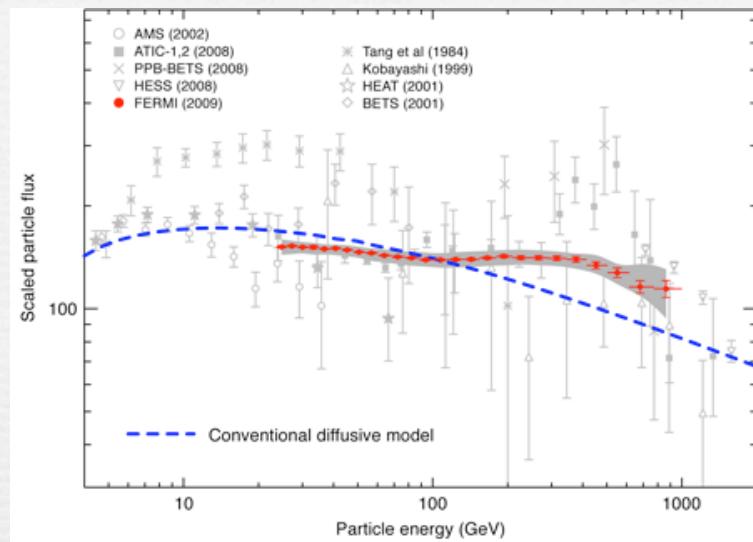


# Motivation

## PAMELA



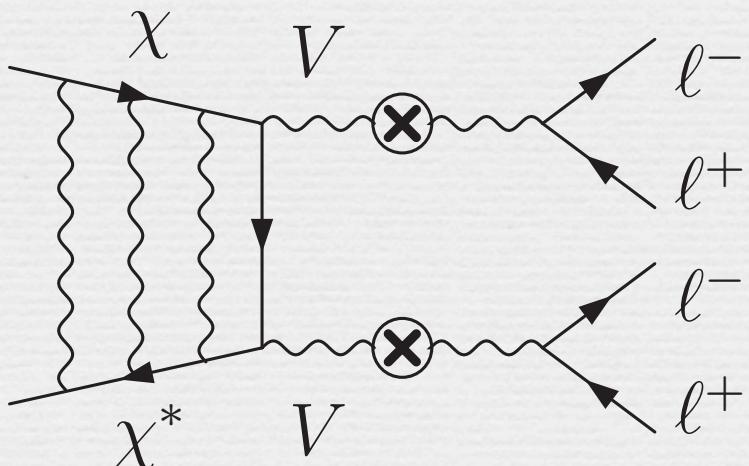
## FERMI



## GeV-scale ‘Dark’ force

Arkani-Hamed, Finkbeiner, Slatyer, Weiner '08  
Pospelov, Ritz '08

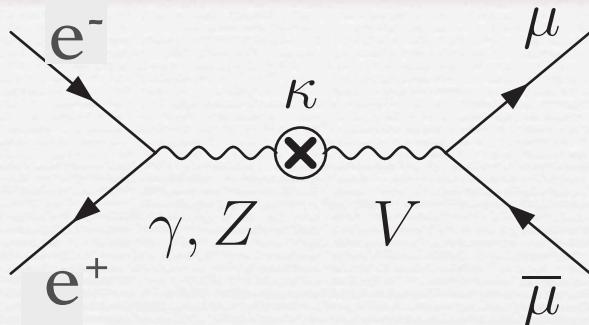
- Long range attractive force enhances  $\langle \sigma v \rangle_{\text{halo}}$
- Annihilation products cannot decay to anti-protons by kinematics



# Hidden sector at ILC

Kumar, Wells '06

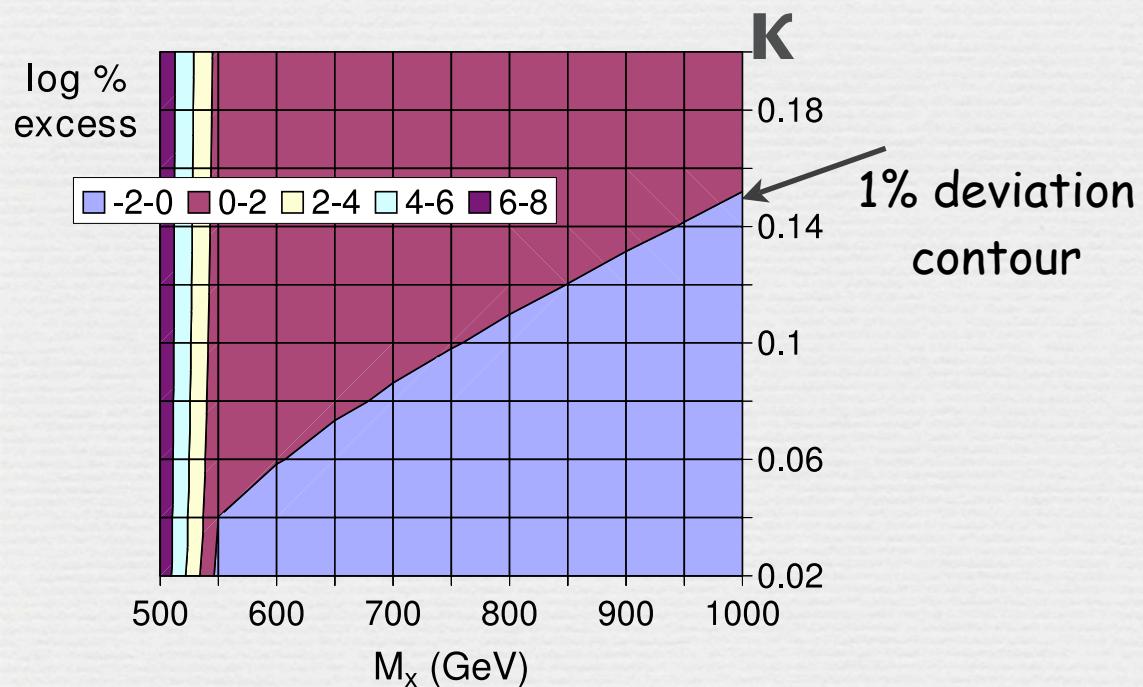
$$\mathcal{L} \supset -\frac{\kappa}{2} B_{\mu\nu} V^{\mu\nu}$$



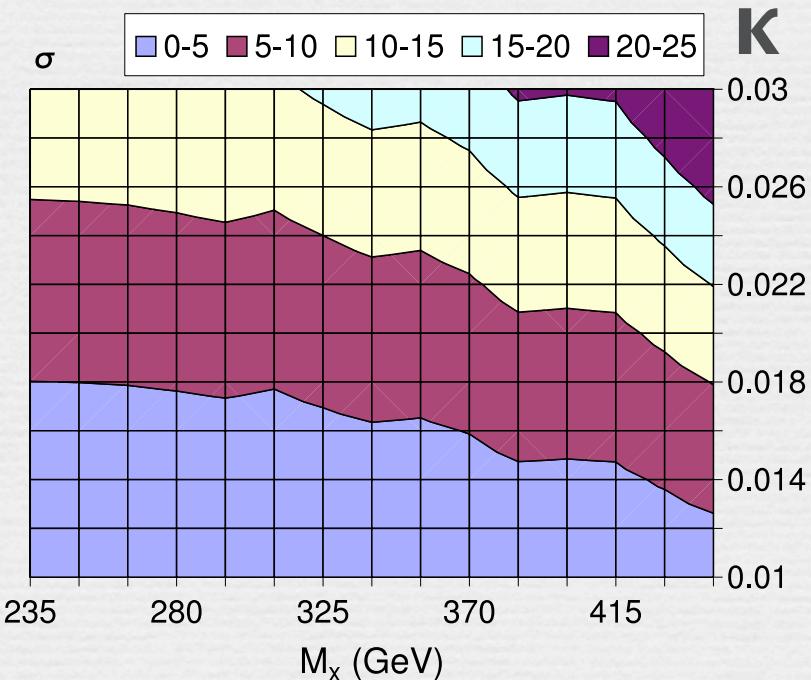
- Direct production  $\implies$  pay  $\kappa^2$

Deviations of  $e^+ e^- \rightarrow \mu \bar{\mu}$

at ILC at  $\sqrt{s} = 500$  GeV  
for  $500 \text{ fb}^{-1}$



Signal significance plot of  
 $e^+ e^- \rightarrow \gamma X \rightarrow \gamma \mu \bar{\mu}$



# Possible bridges to the hidden sector

- $W, Z$
- Higgs
- LSP, LKP, LTP, ...
- $Z'$
- Techni- $\rho$
- RS Gravitons

Higgs portal       $\mathcal{L} \supset \lambda H^\dagger H S^2$

## Exotic Higgs Decays:

- $h \rightarrow SS \rightarrow \text{missing energy}$

Silveira, Zee '85

- $h \rightarrow aa \rightarrow 4b, 4c, 4\tau \dots 4\gamma$

Dobrescu, Landsberg, Matchev '01

Dermisek, Gunion '04

Chang, Fox, Weiner '05

- $h \rightarrow VV \rightarrow 4l$

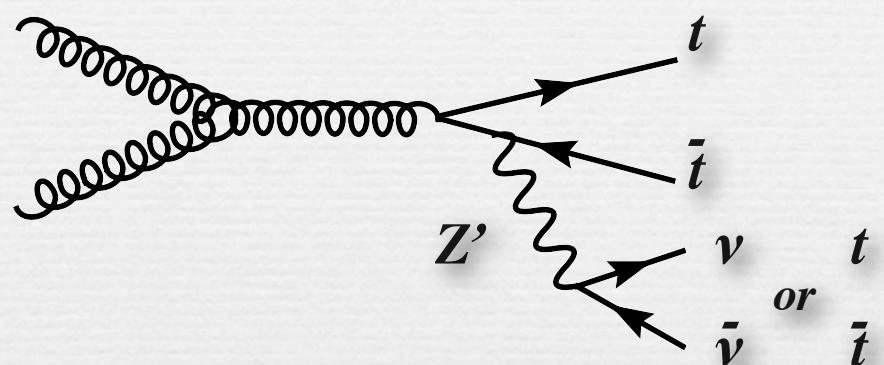
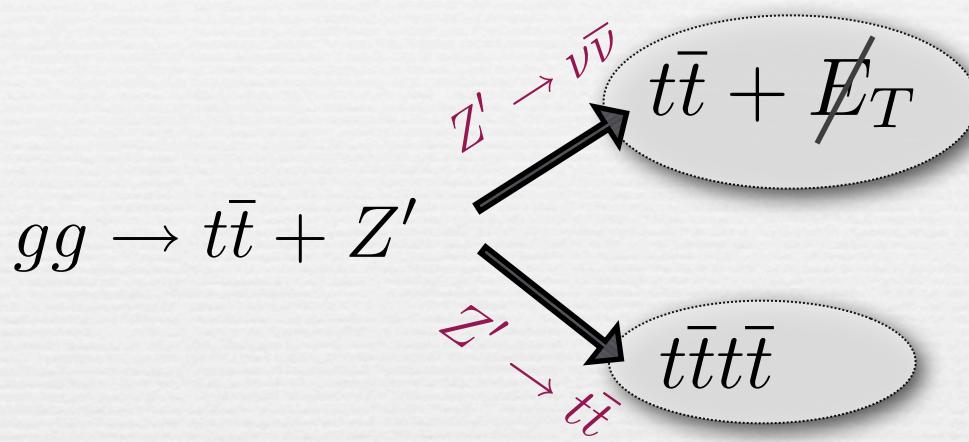
Gopalakrishna, Jung, Wells '08

- $h \rightarrow \eta\eta \rightarrow 4g, 4c$

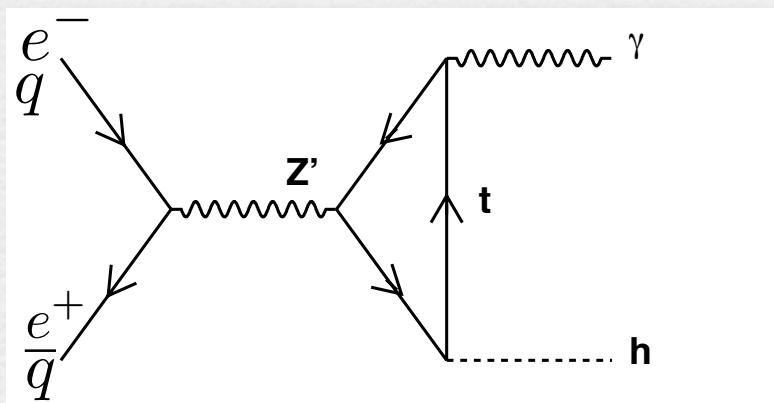
Bellazzini, Csaki, Falkowski, Weiler '01

# Collider signatures of a top (and DM)-philic $Z'$

- $f\bar{f} \rightarrow Z' \rightarrow t\bar{t}$   $Z'$  has suppressed couplings to light quarks  
→ no observable  $t\bar{t}$  resonances



- $f\bar{f} \rightarrow Z' \rightarrow \gamma H$

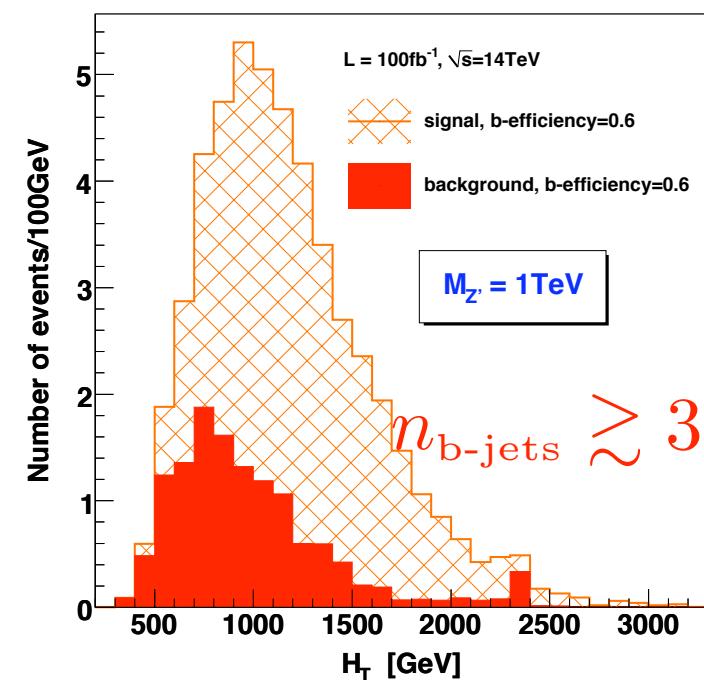
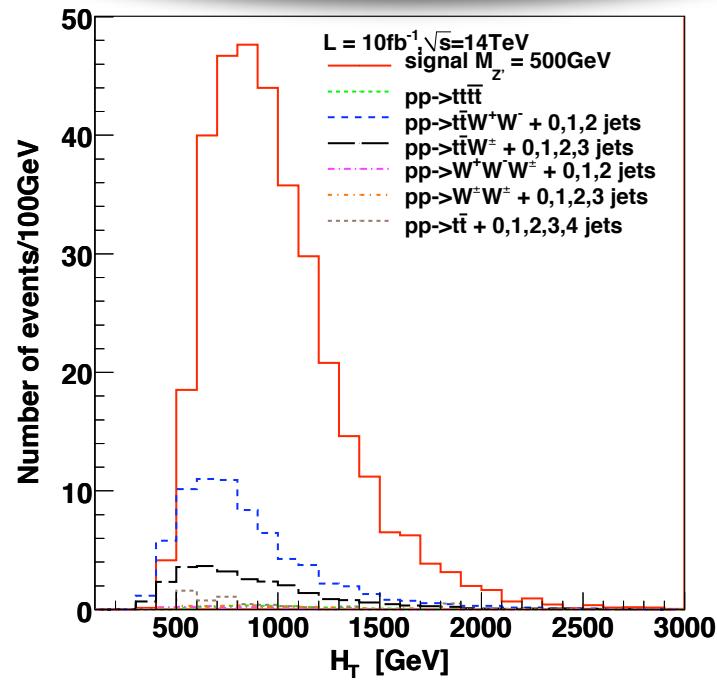
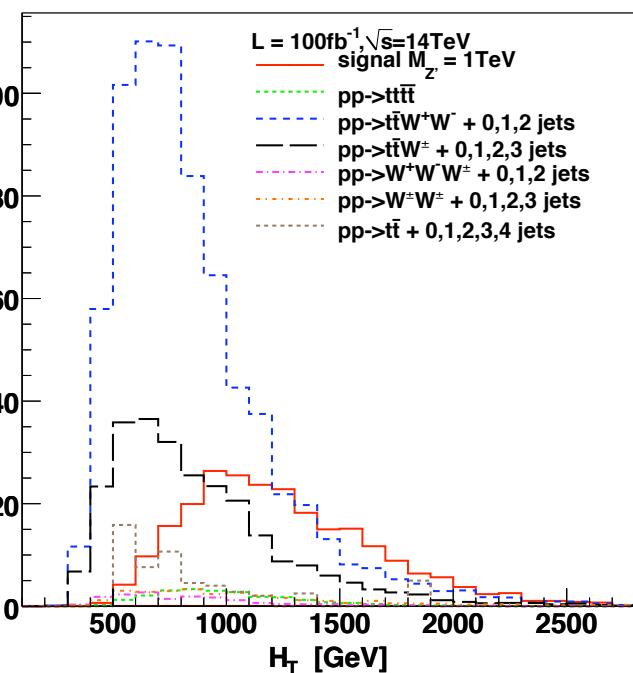


energetic monochromatic  $\gamma$

$n_j \geq 6, p_T > 30 \text{ GeV}$

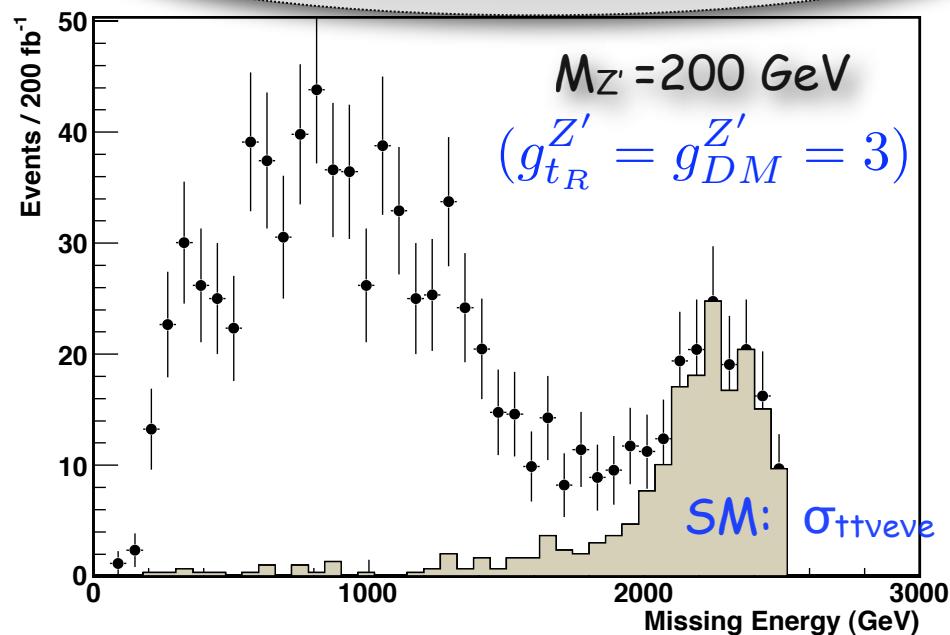
$\text{pp} \rightarrow t\bar{t}tt\bar{t}$  @ 14 TeV LHC

in same-sign dilepton  
channel



$e^+ e^- \rightarrow t\bar{t} + E_T$  @ 3 TeV CLIC

Gauthier-Servant



Battaglia-Servant 1005.4632

A common signature:

$t \bar{t} + \text{large } E_T$

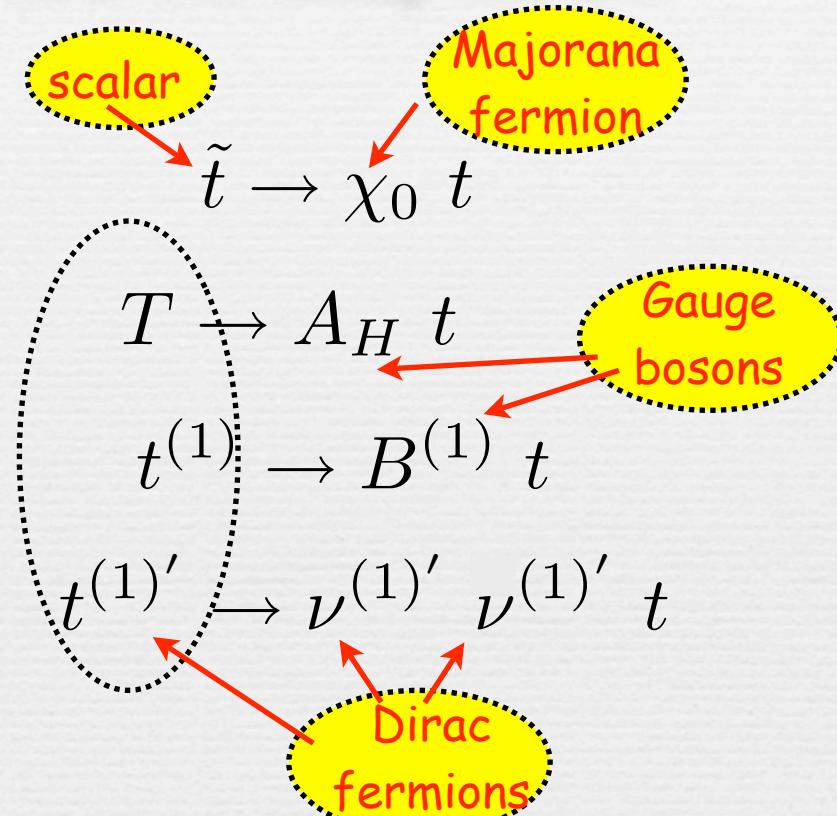
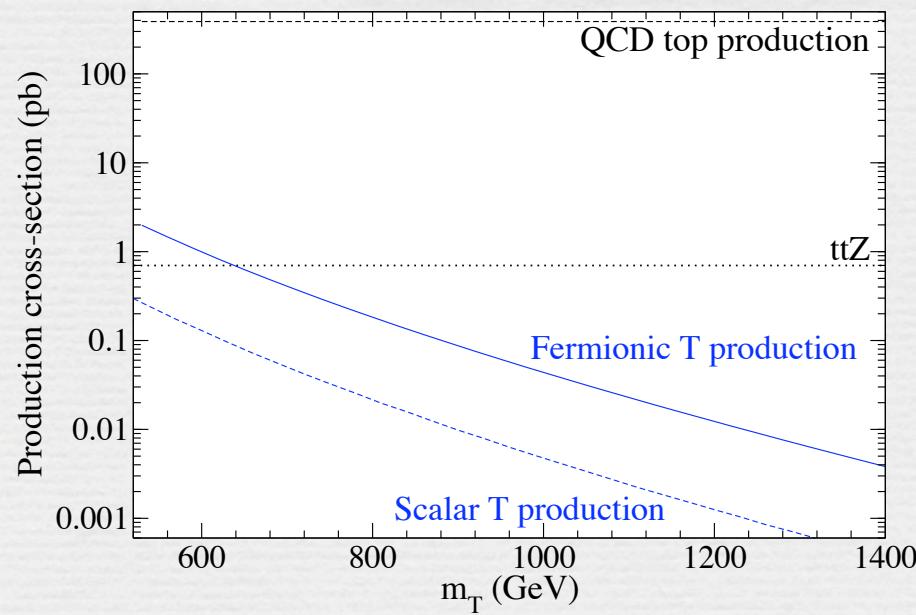
from pair-production of top partners that decay into DM

SUSY:

Little Higgs

Universal extra dimensions

Randall-Sundrum GUTs



# $Z_3$ symmetry in the SM:

Agashe-Servant'04

number of color indices

$$\Phi \rightarrow \Phi e^{2\pi i \left[ B - \frac{(\alpha - \bar{\alpha})}{3} \right]}$$

conserved in any theory where baryon number is a good symmetry

any non-colored particle that carries  
baryon number will be charged under  $Z_3$

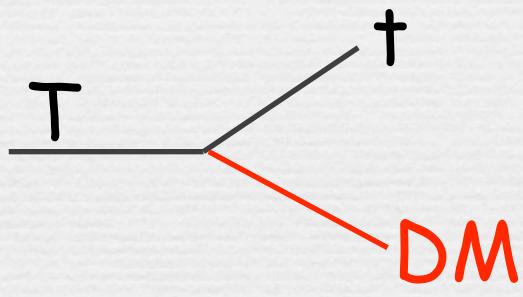
e.g warped GUTs

# $Z_2$ versus $Z_3$ Dark Matter

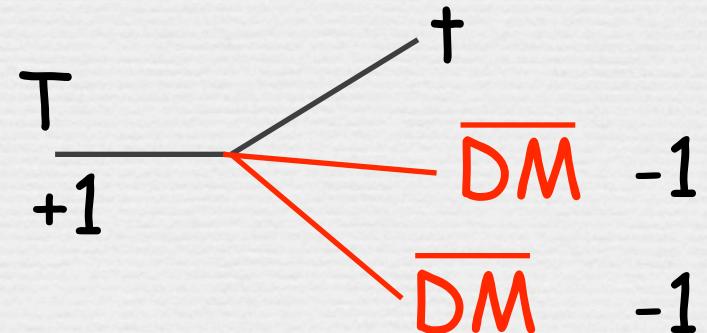
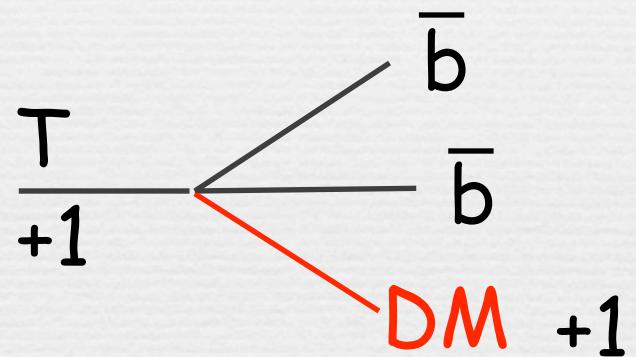
Agashe et al, 1003.0899  
Mahbubani-Servant, in prep.

Most Dark Matter models rely on a  $Z_2$  symmetry. However, other symmetries can stabilize dark matter. Can the nature of the underlying symmetry be tested?

$Z_2$

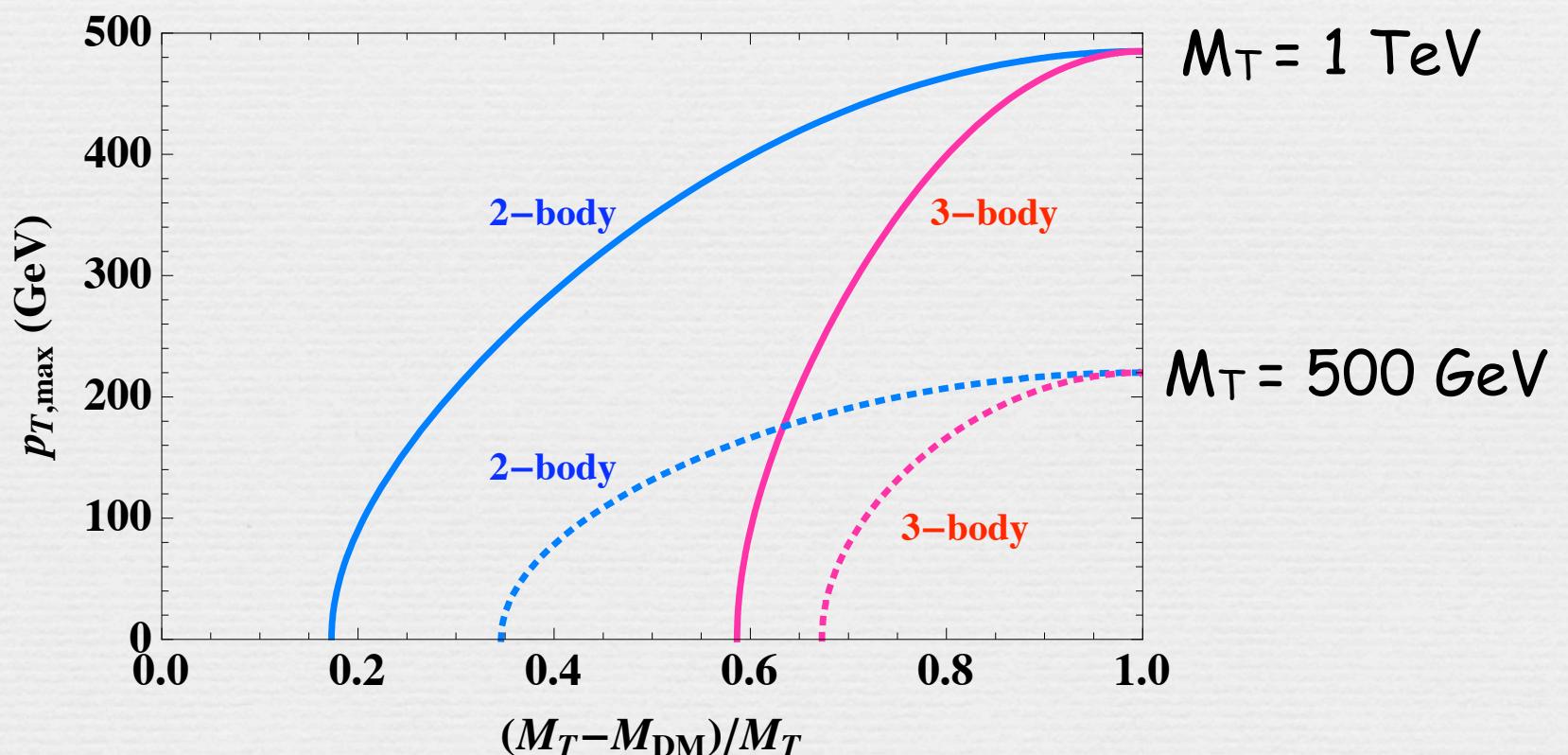


$Z_3$  (+1=-2)



# $Z_2$ versus $Z_3$ Dark Matter

In rest frame of the mother particle, the maximum of the  $p_T$  distributions is different in these 2 cases:

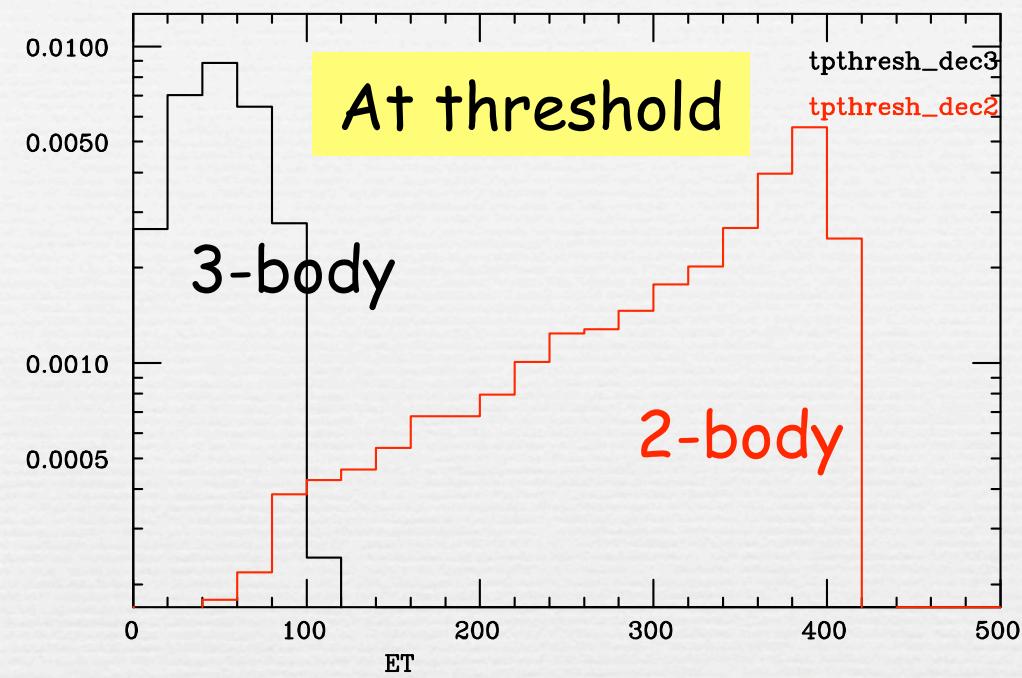


Example:

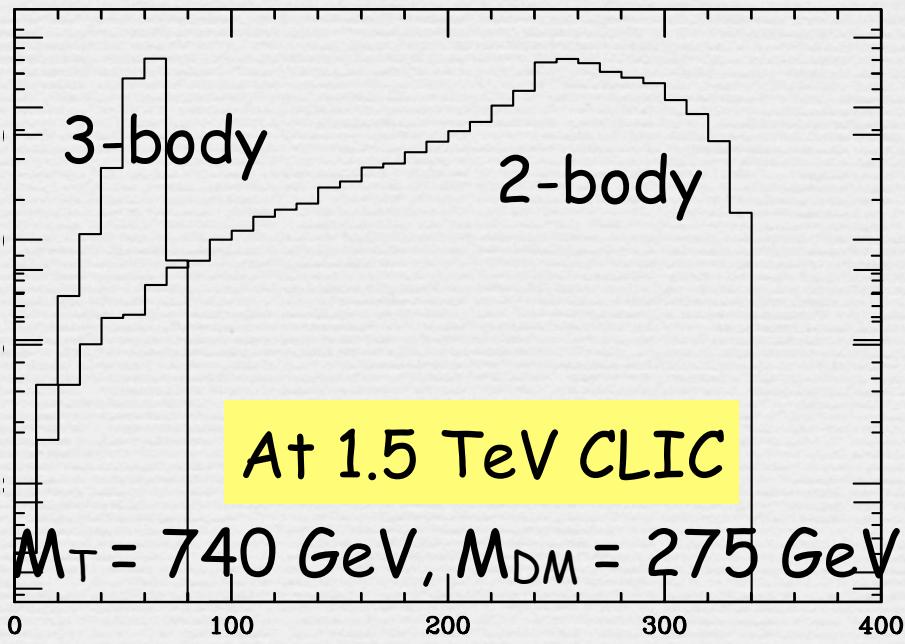
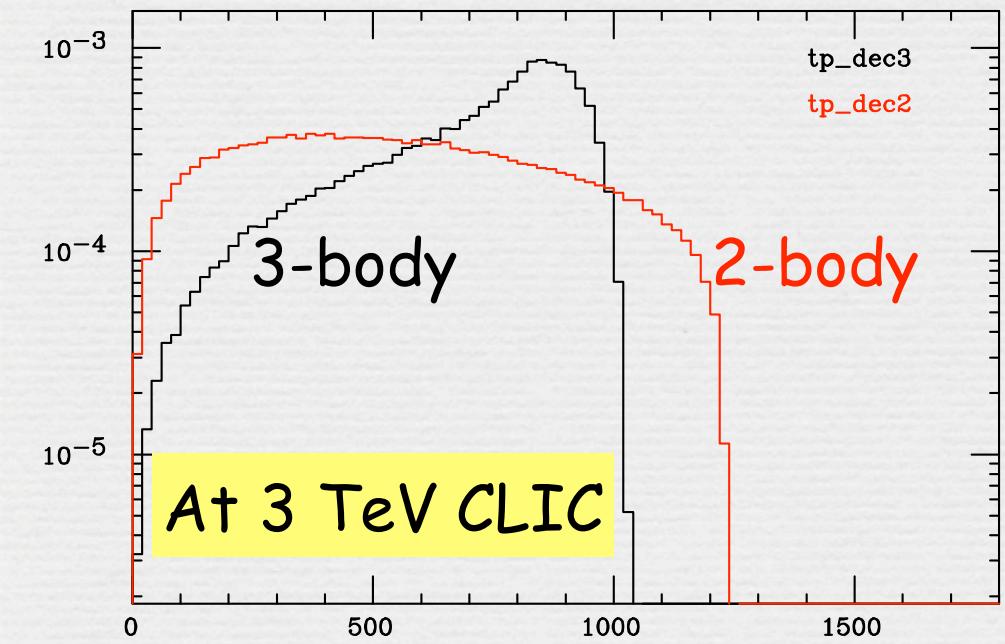
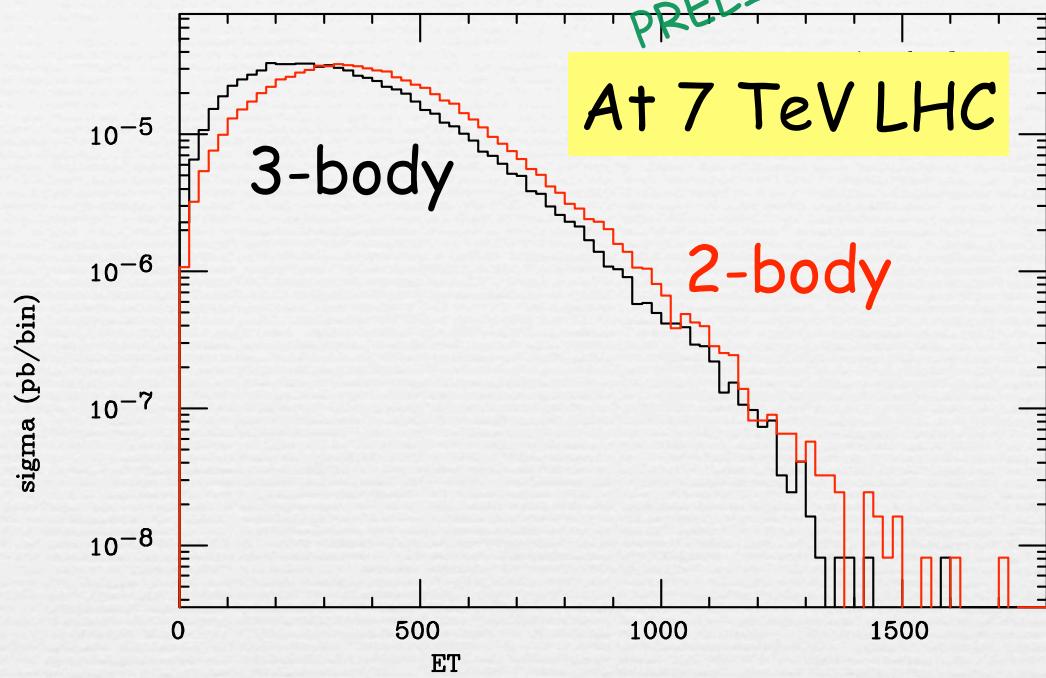
$M_T = 1 \text{ TeV}$ ,  $M_{\text{DM}} = 400 \text{ GeV}$

Mahbubani-Servant

Missing ET



Missing ET



# Conclusion

Large effort in susy studies

Little outside of the standard  
susy scenario.

Very little beyond susy  
(as far as DM is concerned)