Dark Matter at ~~Colliders~~ Accelerators

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July 28, 2011

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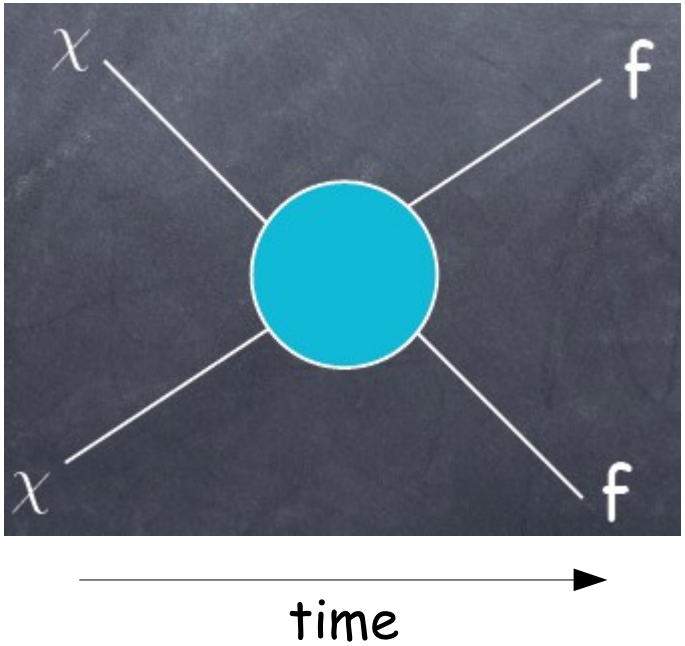
http://www-conf.slac.stanford.edu/ssi/2011/

Introduction

- As long as dark matter has some non-gravitational interactions, we have some chance to "see" it...

- Indirect detection (annihilation)



Introduction

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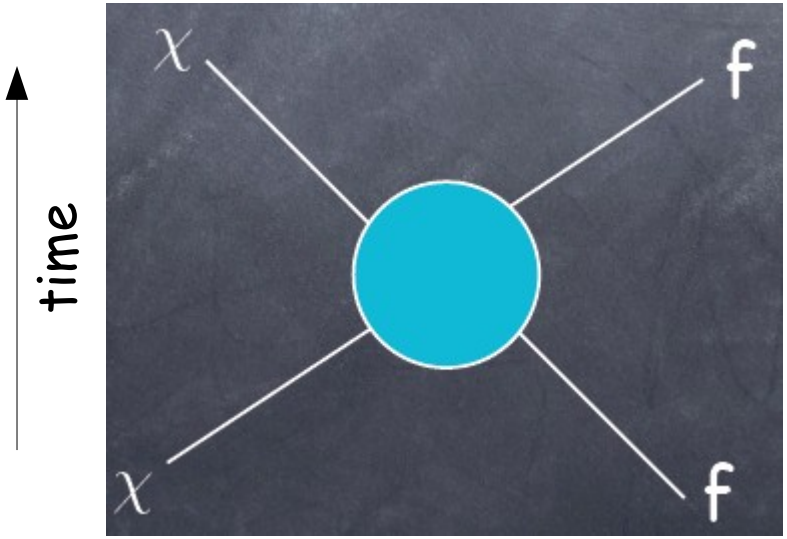
- Indirect detection (annihilation)

- Direct detection (scattering)



Introduction

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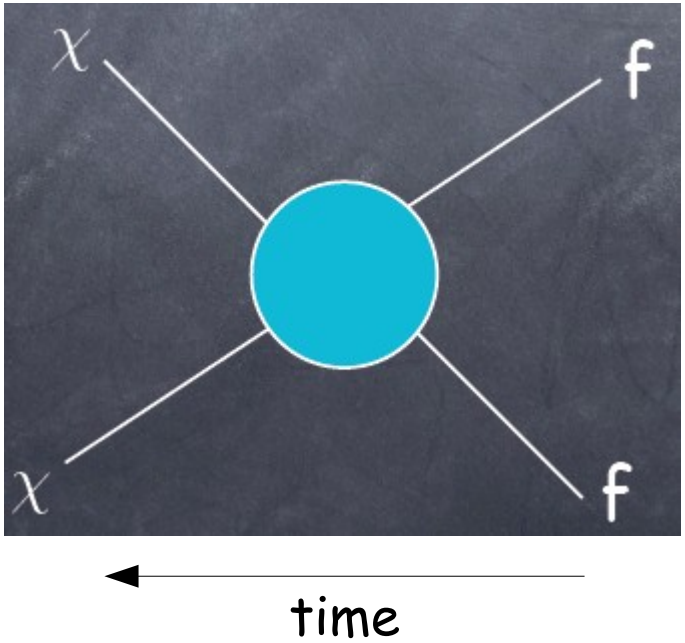
- Indirect detection (annihilation)

- Direct detection (scattering)

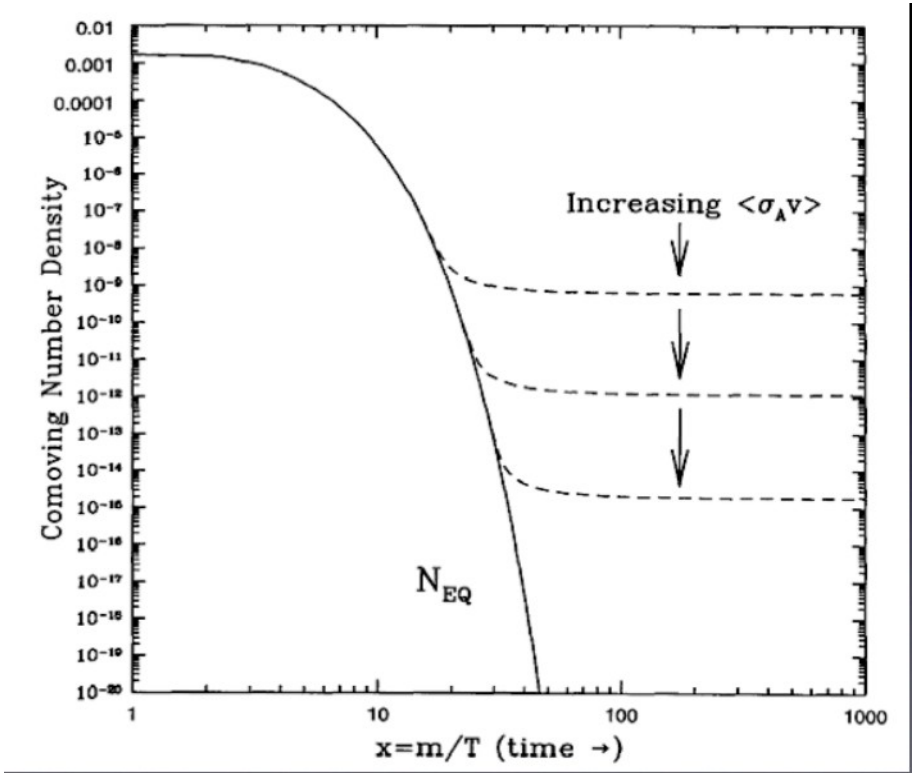
- **Production**



"Make it, break it, or wait for it!" - N. Weiner

WIMP miracle

- Reason to hope DM mass is GeV–TeV and has weak interactions (WIMP)

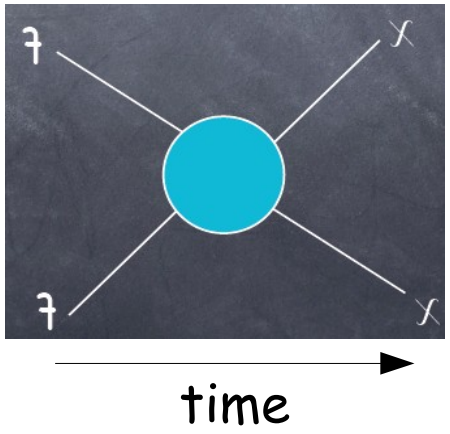


$$\Omega h^2 \approx 0.1 \times \left(\frac{\alpha^2/(100\mathrm{GeV})^2}{\langle \sigma v \rangle} \right)$$

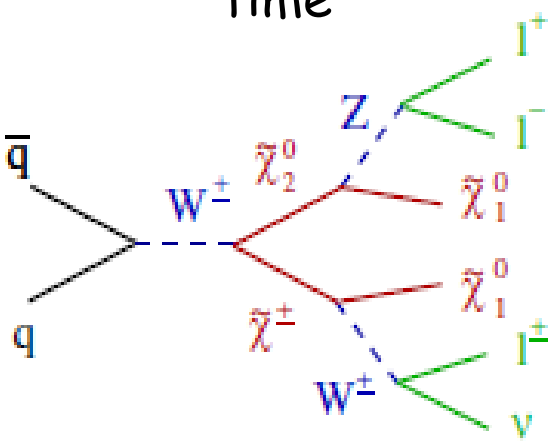
Hopefully Tim already told you about this...

Ways to "make it" ...

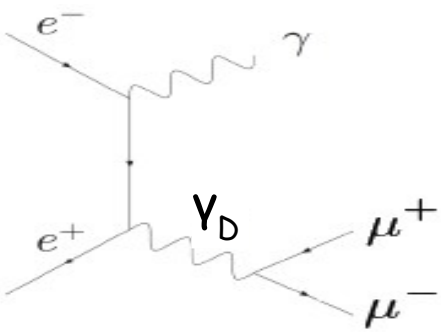
- Directly pair-produce dark matter



- Look for DM in decays of new particle(s) – e.g. SUSY/Higgs
  - Weakly produced (chargino/neutralino)
  - Strongly produced (squarks/gluinos)

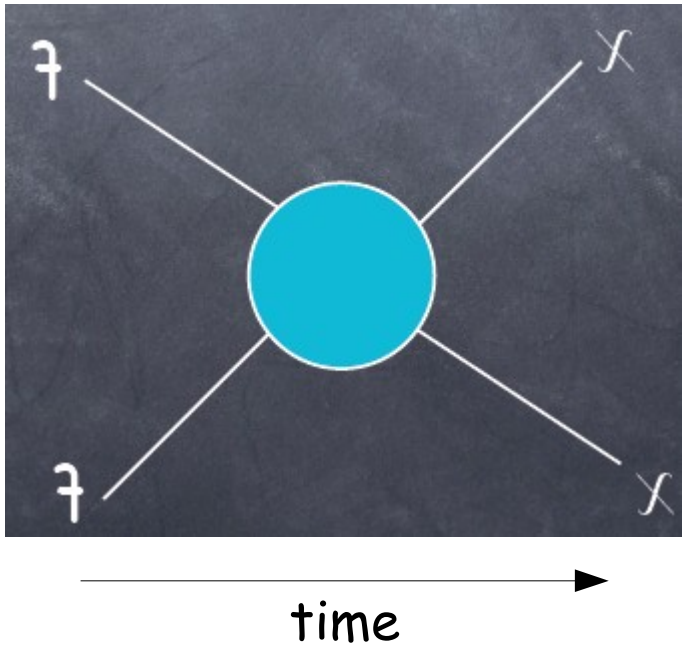


- Hidden sector with a new (weak) force
  - Again look in SUSY/Higgs decays
  - Look for the new particles directly



Directly pair-producing dark matter

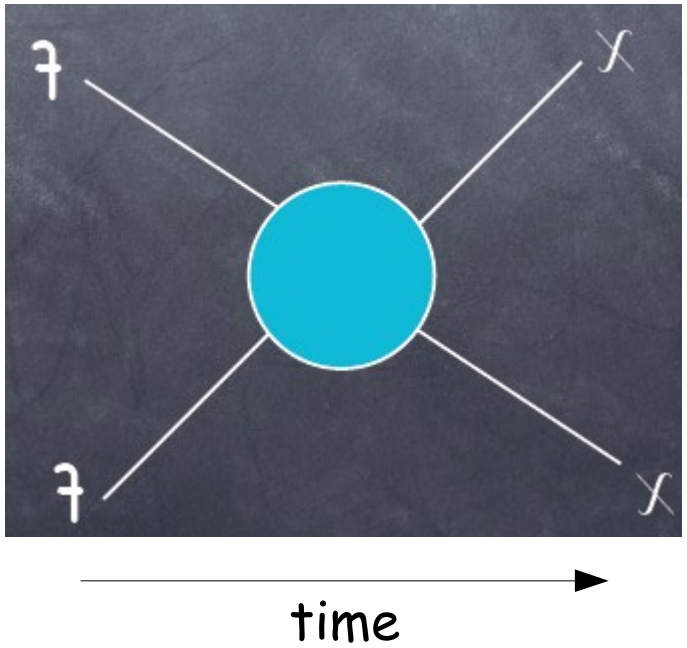
- Should be possible, as long as there's some interaction with our SM that's not horrifically small (like gravity)
- What would this fantastic collision look like in the detector?

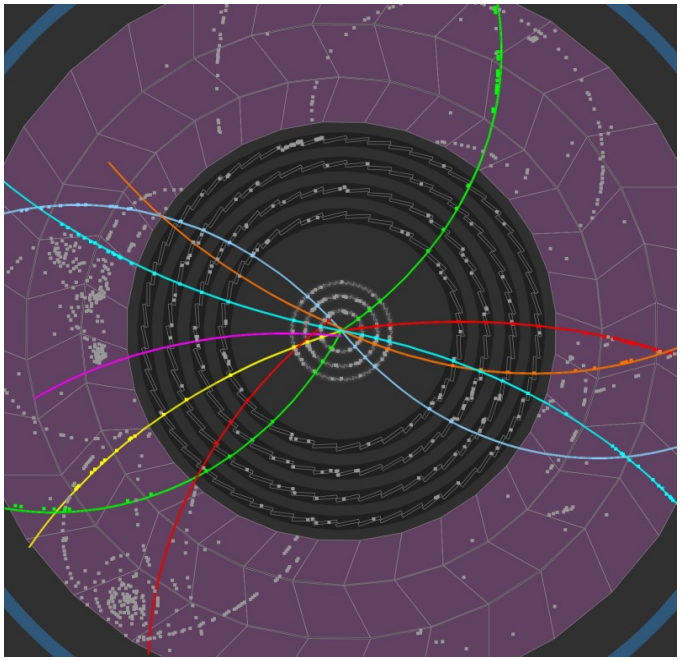


Directly pair-producing dark matter

- Should be possible, as long as there's some interaction with our SM that's not horrifically small (like gravity)

- What would this fantastic collision look like in the detector?
- Just a few tracks! The DM escaped!

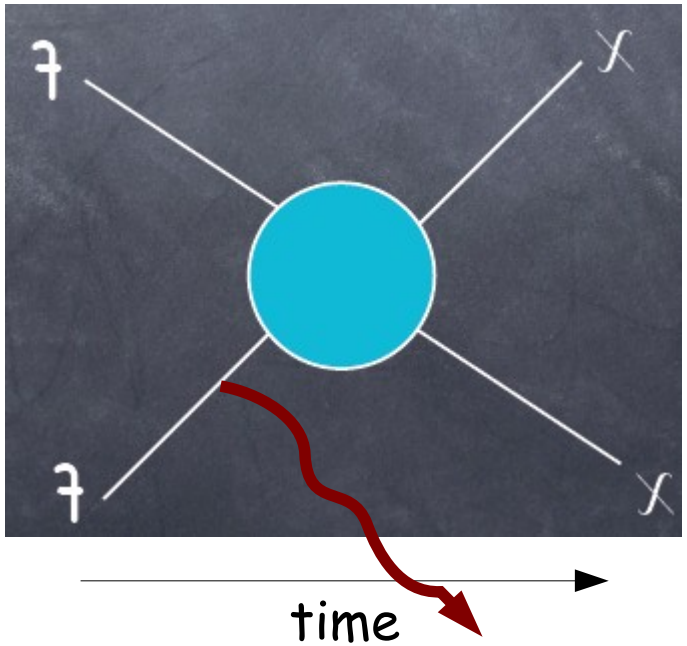


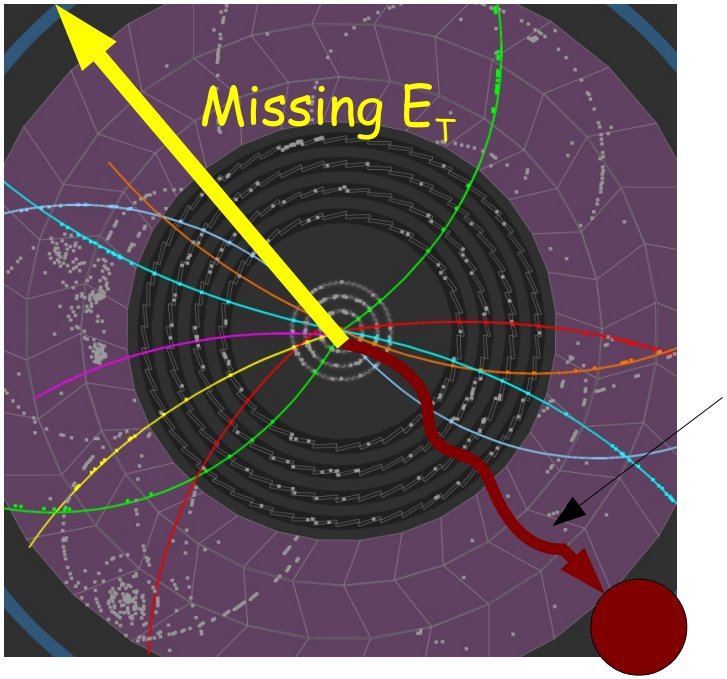


Directly pair-producing dark matter

- Should be possible, as long as there's some interaction with our SM that's not horrifically small (like gravity)

- Fortunately there's a trick... add some "initial-state radiation"
- Now have "missing energy" from DM!



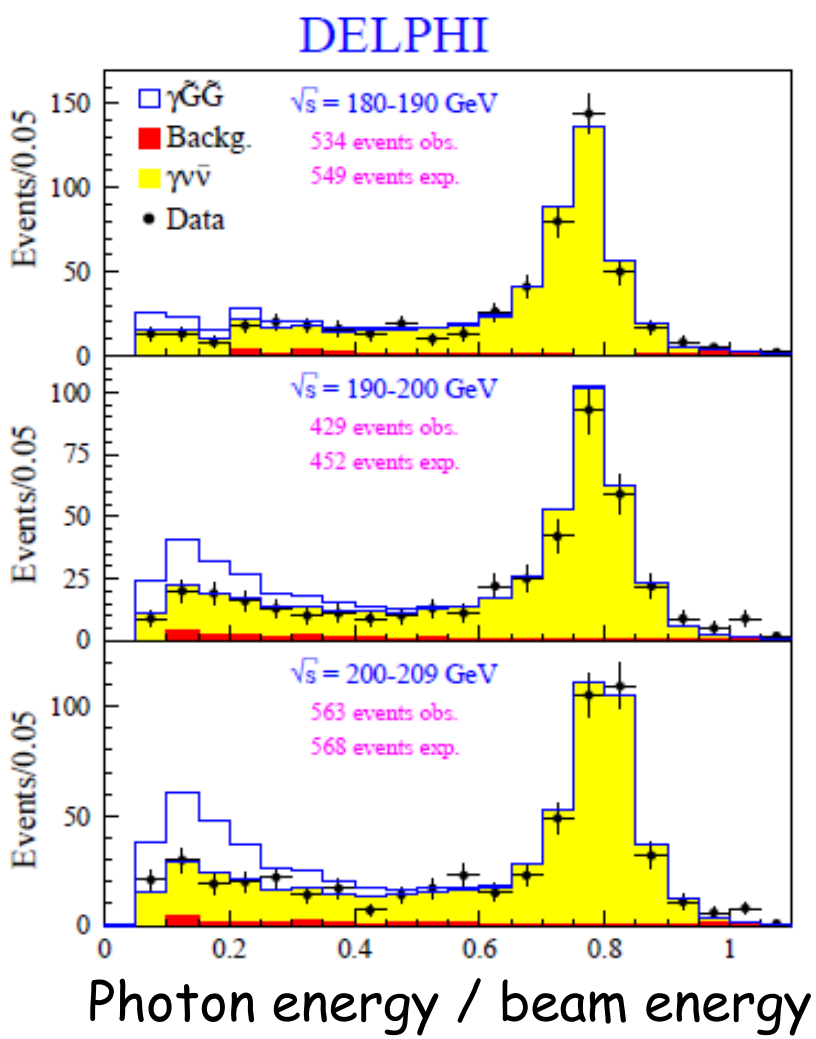


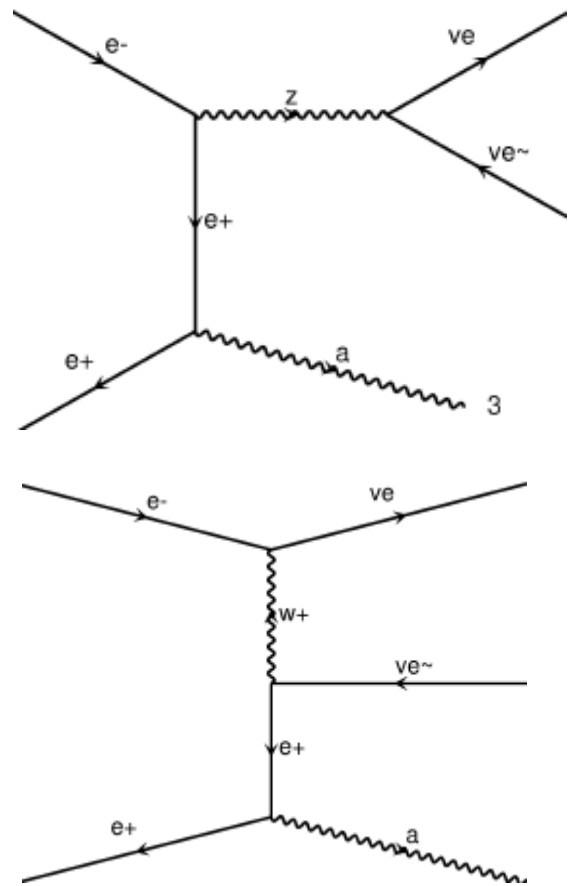
Radiated SM particle(s)

Photon + MET

- LEP: e^+e^- collider, sqrt(s) up to 209 GeV
- Look for a photon + missing energy

arXiv:hep-ex/0406019

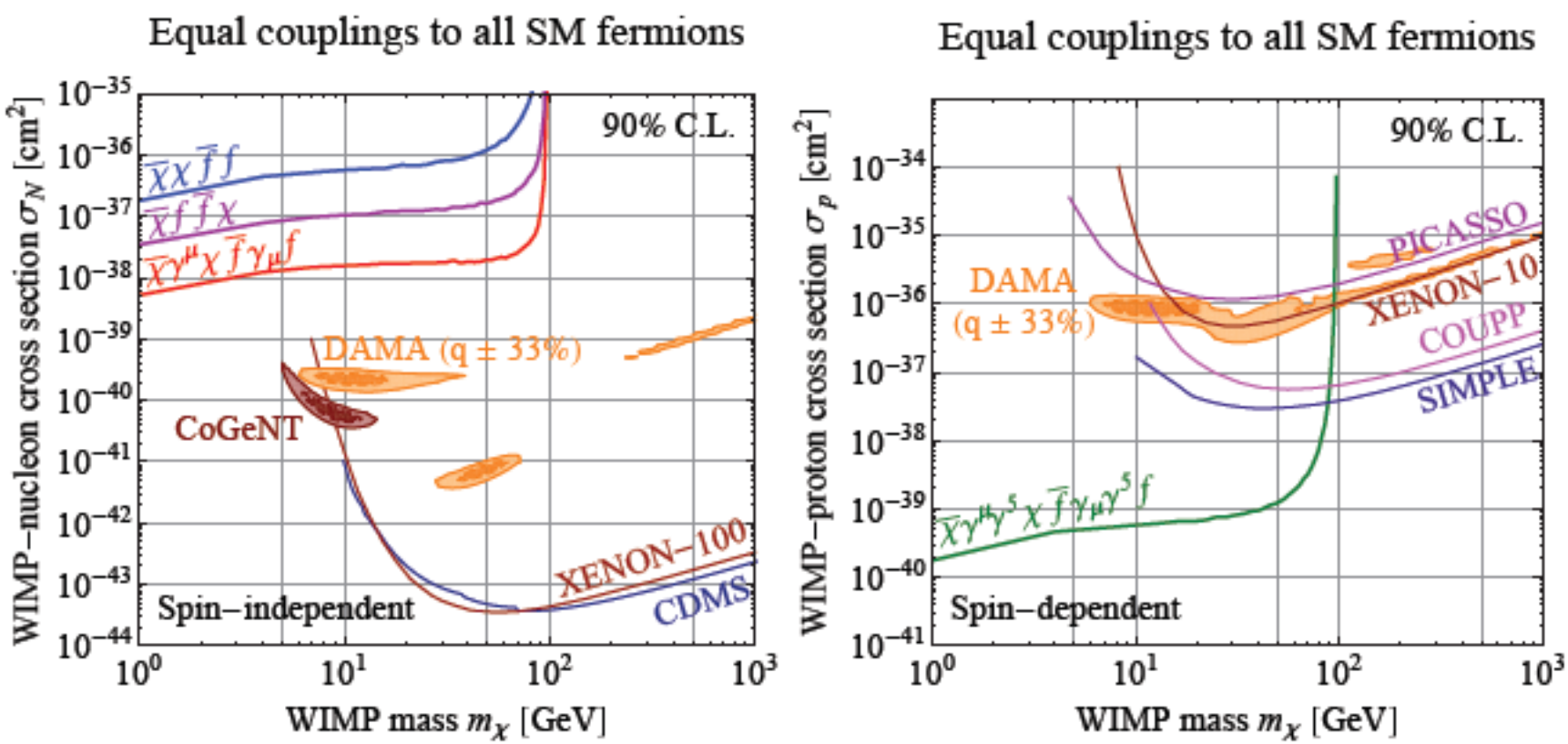




Photon + MET

P. Fox, et al. arXiv:1103.0240

- Convert to limits on nuclear cross-section
  - Assume equal coupling to electrons and quarks
- Sensitive at lower masses than direct-detection
- Strong constraint for spin-dependent case, up to ~100 GeV (no A^2 enhancement for direct-detection)



Photon + MET

P. Fox, et al.
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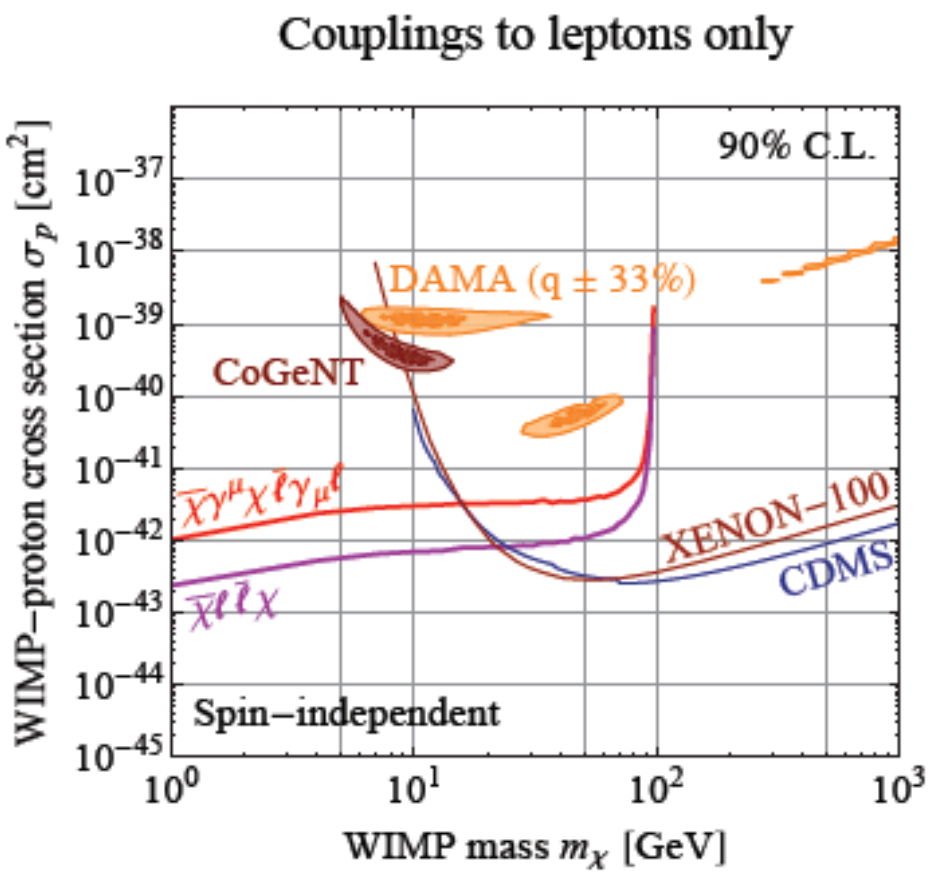
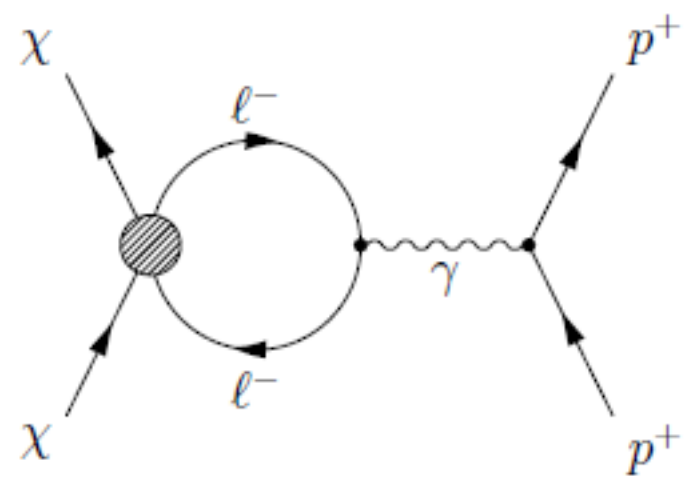
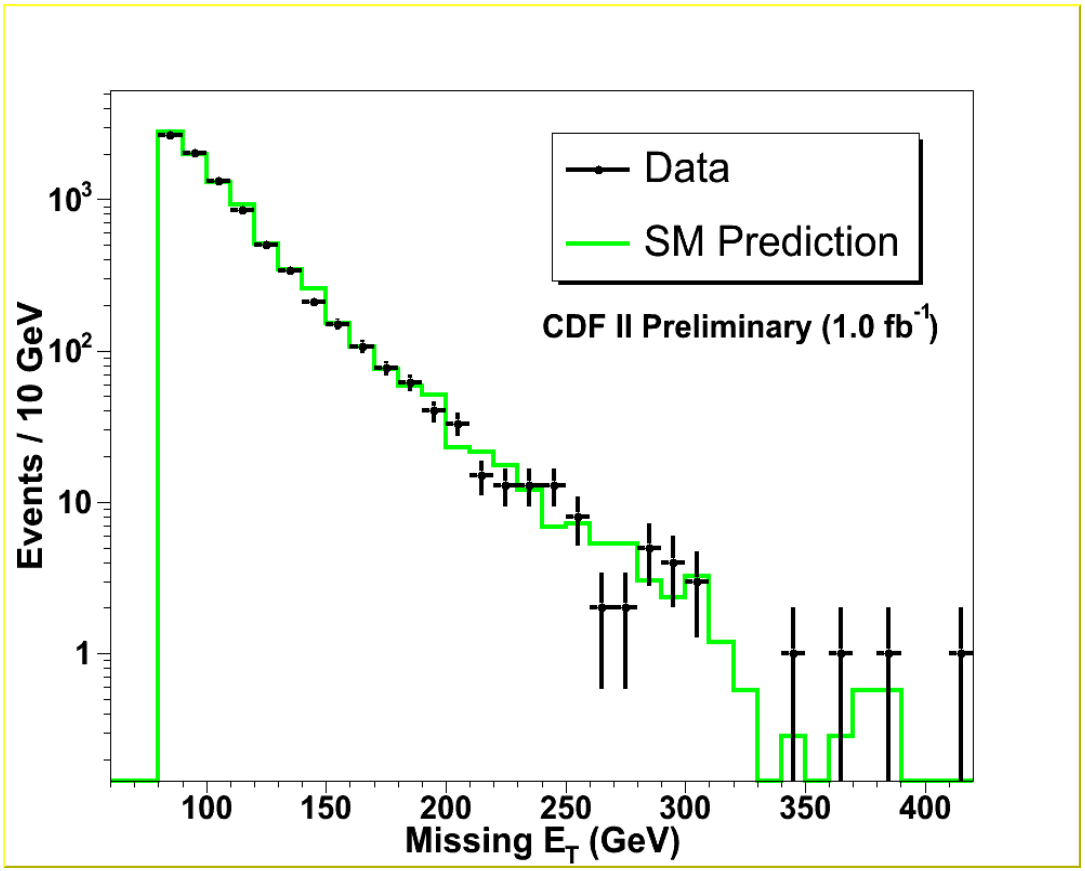
- If dark matter only couples through leptons, the limits from LEP are again strong
  - Nuclear scattering would have to go though a loop

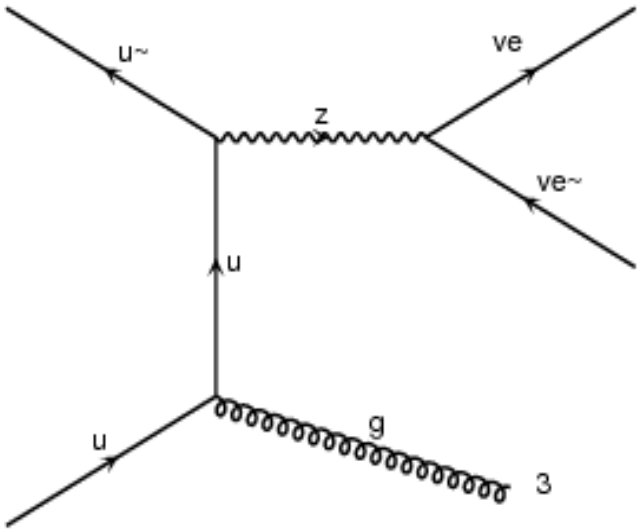




Tevatron mono-jet

- Tevatron: proton-antiproton collider, sqrt(s)=1960 GeV
- Look for a single, high-pT, jet (and thus large MET)
- Backgrounds: Z→νν, W→τν, ...



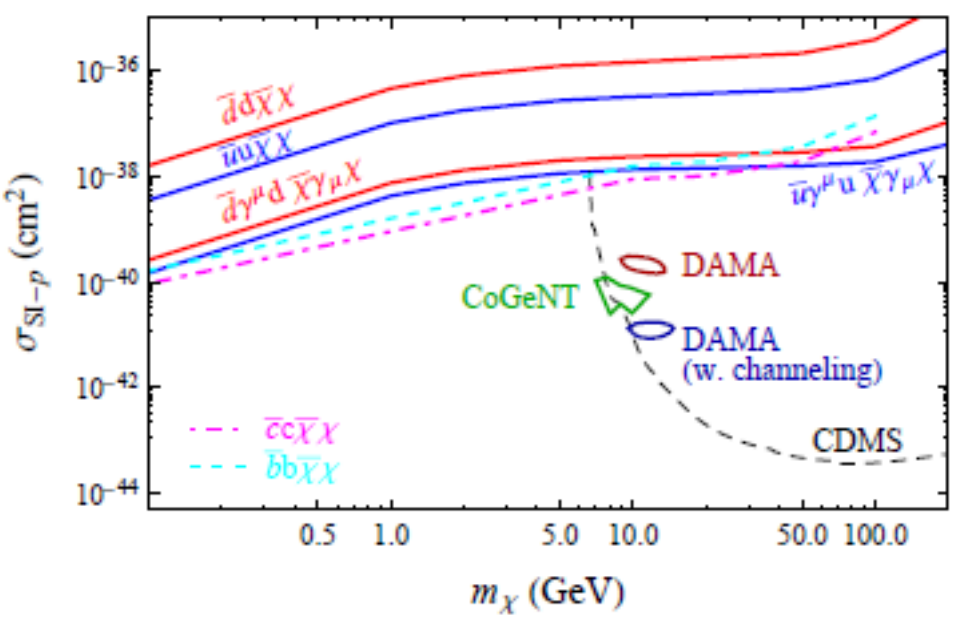


Phys.Rev.Lett.101:181602, 2008

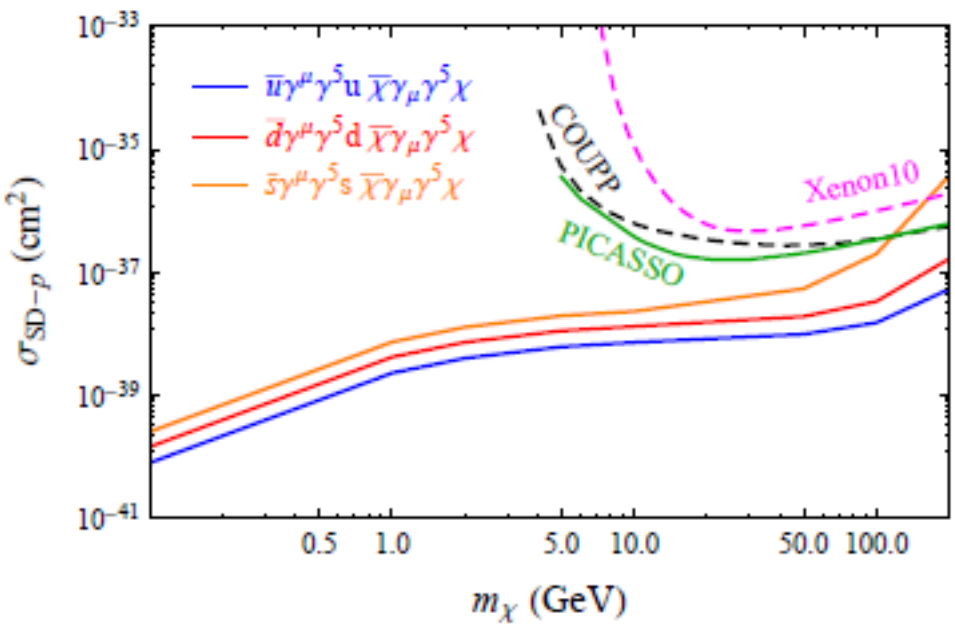
Tevatron mono-jet

P. Fox, et al. arXiv:1005.3797

- Convert to limits on nuclear cross-section
- Similar to LEP mono-photon results
  - Good sensitivity at low masses and for spin-dependent
  - Can reach up to higher masses than LEP, ~few hundred GeV



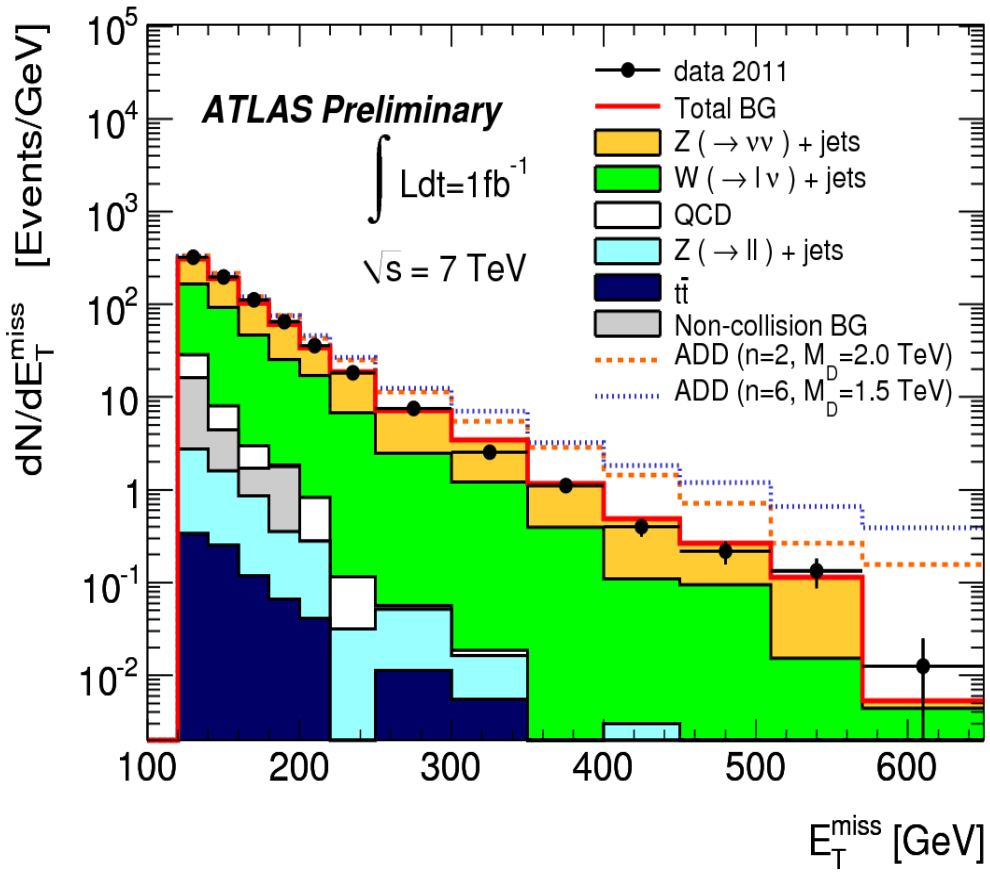
Spin-independent



Spin-dependent

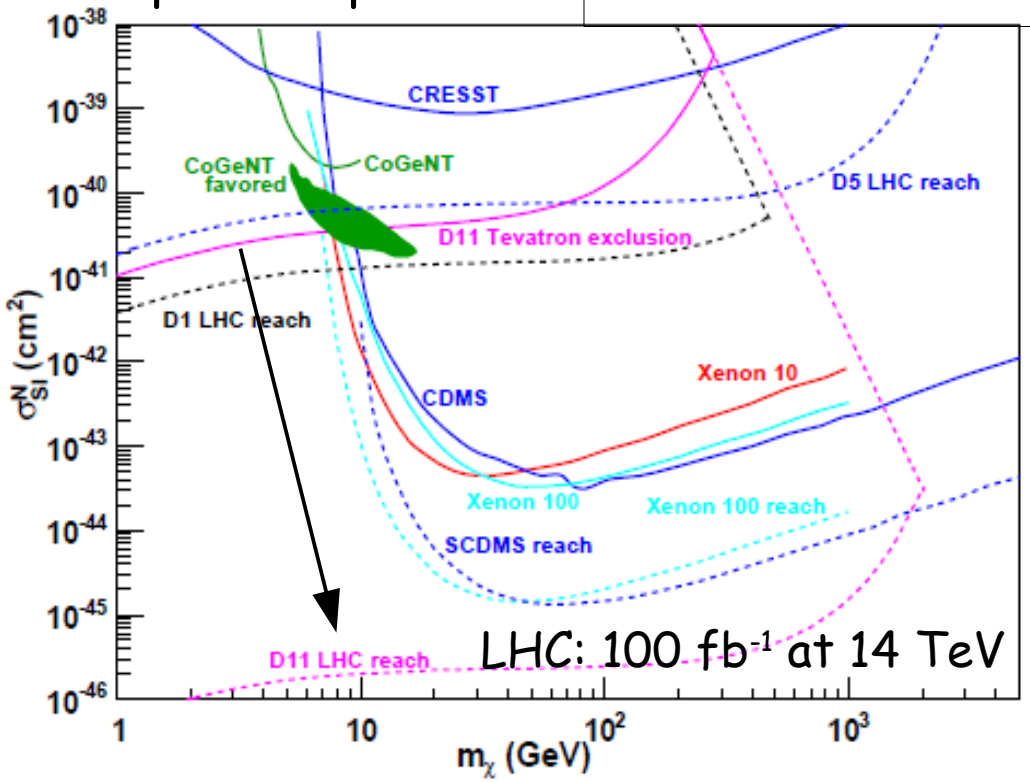
LHC mono-jet

- LHC is higher energy, and will have greater luminosity
- Results from the first 1 fb^{-1} for mono-jet...
- Reach will be large for LHC by ~2016...



T. Tait, et al. arXiv:1008.1783

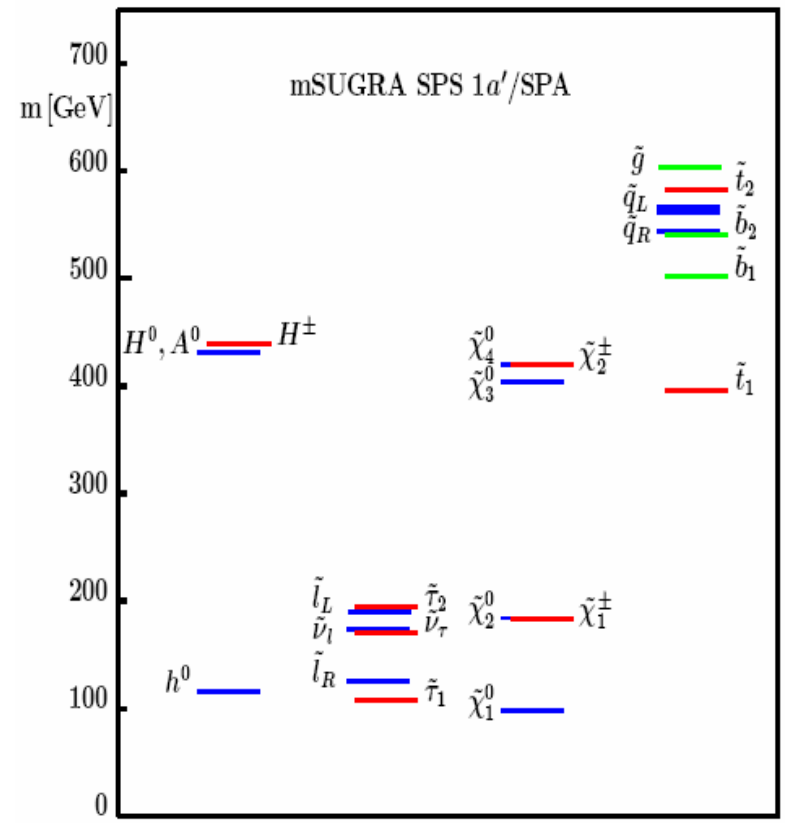
spin-independent



Supersymmetry (SUSY)

- #1 WIMP candidate: lightest supersymmetric particle (LSP)
  - Requires R-parity to be conserved

- We don't know the mass spectrum !



Particles in the Minimal Supersymmetric Model (MSSM)

R–parity = +1 Particle	Symbol	Spin	R–parity = −1 Particle	Symbol	Spin	R–parity = −1 Particle	Symbol	Spin
Lepton	ℓ	$\frac{1}{2}$	Slepton	$\tilde{\ell}_L, \tilde{\ell}_R$	0			
Neutrino	ν	$\frac{1}{2}$	Sneutrino	$\tilde{\nu}$	0			
Quark	q	$\frac{1}{2}$	Squark	$\tilde{q}_L, \tilde{q}_R$	0			
Gluon	g	1	Gluino	$\tilde{g}$	$\frac{1}{2}$			
Photon	γ	1	Photino	$\tilde{\gamma}$	$\frac{1}{2}$			
Z Boson	Z	1	Zino	$\tilde{Z}$	$\frac{1}{2}$	4 Neutralinos	$\tilde{\chi}_i^0$	$\frac{1}{2}$
W Boson	$W^\pm$	1	Wino	$\tilde{W}^\pm$	$\frac{1}{2}$	2 Charginos	$\tilde{\chi}_i^\pm$	$\frac{1}{2}$
Higgs	$H^0, H^\pm$	0	Higgsino	$\tilde{H}_1^0, \tilde{H}_2^+$	$\frac{1}{2}$			
	h^0, A^0	0		$\tilde{H}_1^-, \tilde{H}_2^0$	$\frac{1}{2}$			

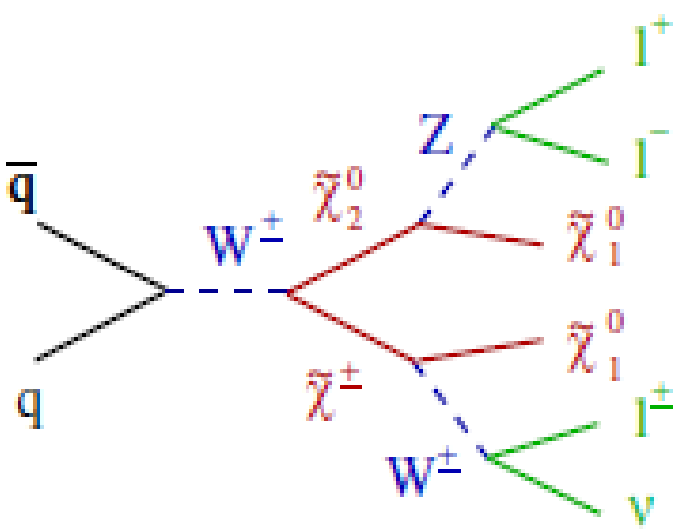
+ gravitino?

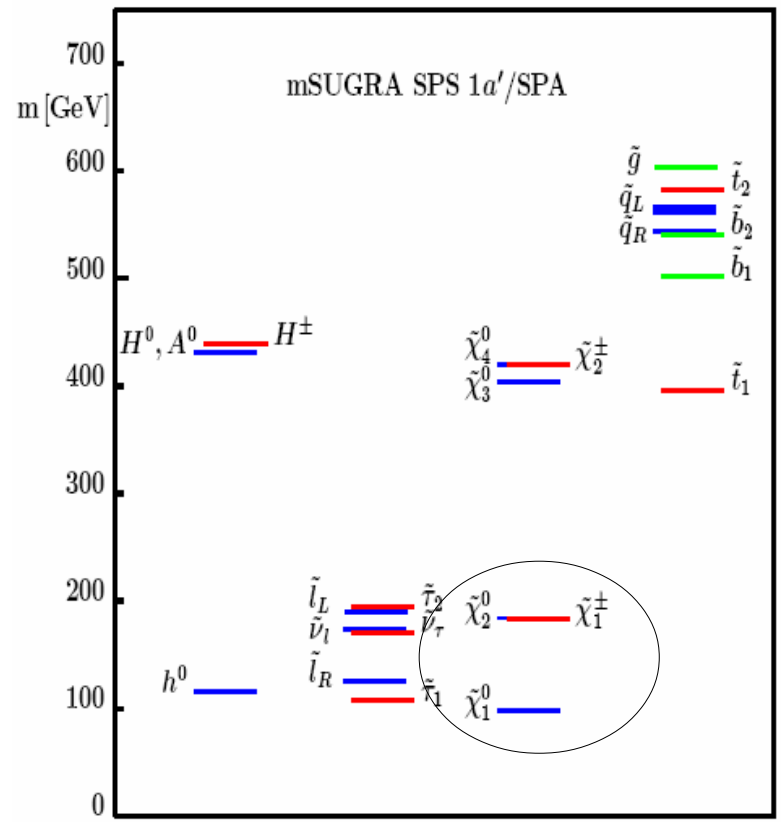
Weak SUSY production

- Let's be somewhat pessimistic first:
  1 light chargino and 2 light neutralinos, everything else heavy

- Dark matter (MET) + 3 leptons

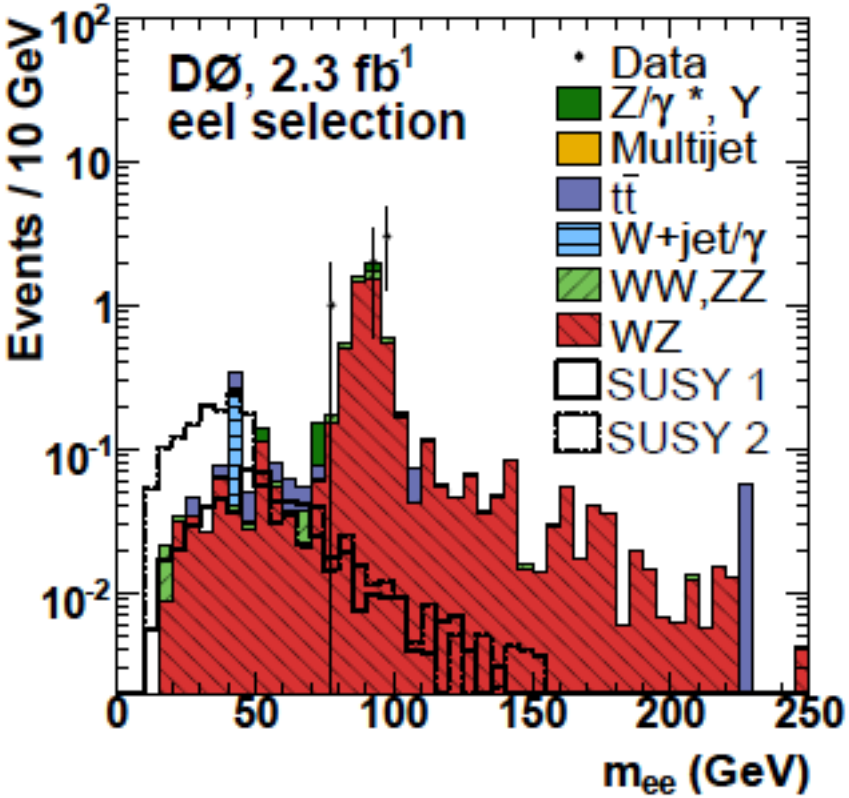
- Small mX_2-mX_1 gives *soft leptons*





Weak SUSY production

- Tevatron still has the best limits...
  - Low mass, need high luminosity
- D0 analysis:
  - 2 isolated leptons, pT> 12, 8 GeV
  - *Isolated track*, pT>4 GeV
    - Good efficiency at low pT
    - Picks up tau decays too
  - Large MET and MET significance*
  - 4 events observed, 3.3 expected
  - Dominated by 3 real leptons from WZ

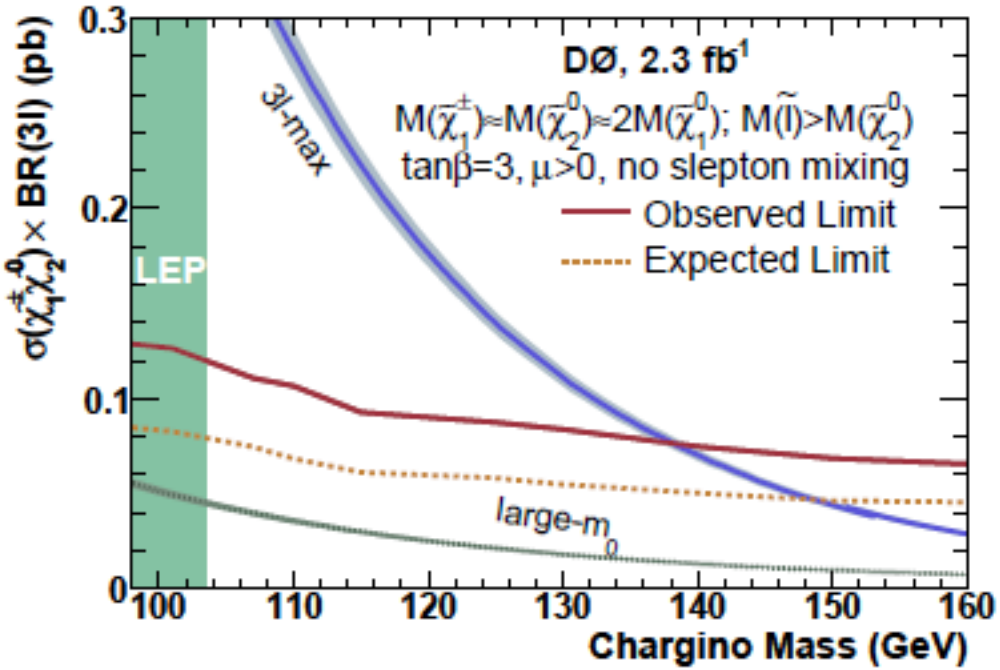


*MET not pointing along a mis-measured jet or lepton/track

Weak SUSY production

- Tevatron still has the best limits...
  - Low mass, need high luminosity

- D0 analysis:
  - Not quite sensitive yet if sleptons are heavy (large-m_0)
  - Chargino < 138 GeV excluded for light sleptons (3l-max)
  - Need to update with more luminosity (~10 fb^{-1} recorded) and combine with CDF

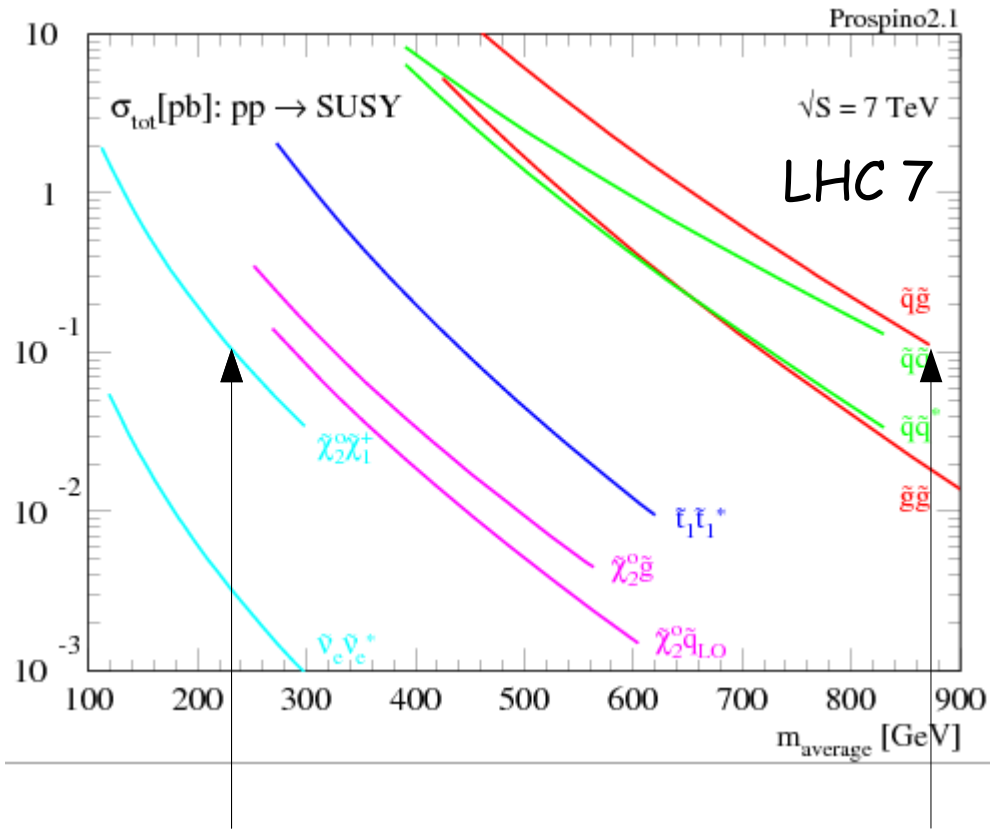


- We'll soon have results from the LHC ...

Strong SUSY production

- Gluinos / squarks are light (<~TeV) → big production rate
- LHC is the place to be !
- Look for jets + MET

$$\tilde{g} \rightarrow qq\tilde{\chi}_1^0 \qquad \tilde{q} \rightarrow q\tilde{\chi}_1^0$$



~1 event after BR → leptons in 1 fb^{-1}

~100 events in 1 fb^{-1} !

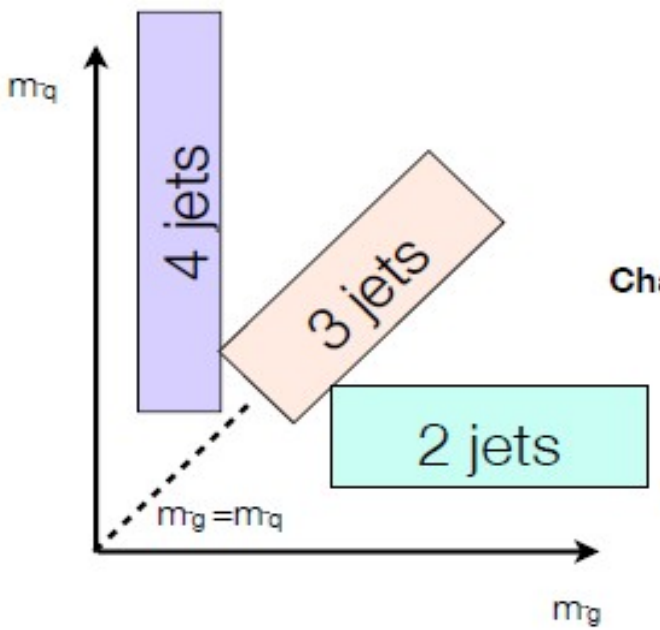
Strong SUSY production

- Look for jets + MET

$$\tilde{g} \rightarrow qq\tilde{\chi}_1^0 \qquad \tilde{q} \rightarrow q\tilde{\chi}_1^0$$

Veto leptons to reduce SM backgrounds (like W->lν + jets)

- Either 2, 3, or 4 jets + MET
  - depends on whether squark or gluino is lighter



	Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets	High mass
Trigger requirements	E_T^{miss}	> 130	> 130	> 130	> 130
	Leading jet p_T	> 130	> 130	> 130	> 130
Channel definition	Second jet p_T	> 40	> 40	> 40	> 80
	Third jet p_T	–	> 40	> 40	> 80
	Fourth jet p_T	–	–	> 40	> 80
Reduce QCD	$\Delta\phi(\text{jet}, E_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
	E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
Enhance signal	m_{eff} [GeV]	> 1000	> 1000	> 500/1000	> 1100

$$m_{eff} = \sum_{i=1}^{n} |\vec{p}_T^{\,jet\ i}| + E_T^{miss}$$

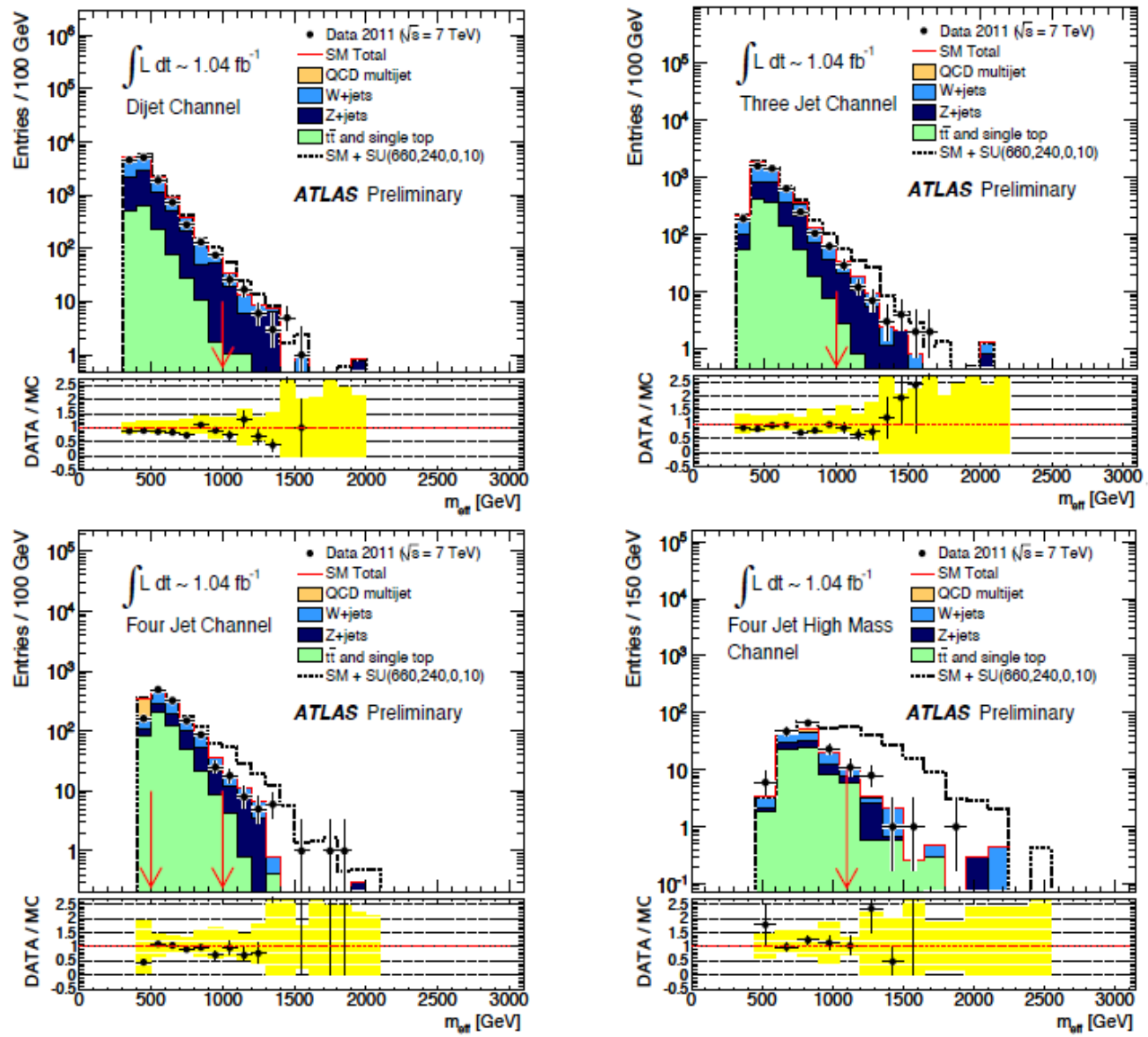
Strong SUSY production

- Background from SM with neutrinos:
  Z(->νν)+jets
  W(->lν)+jets
  tt->WW(->lν)+jets
  (missing the lepton)

- Control samples:
  Z(->ll)+jets
  W(->lν)+(0b) jets
  tt->WW(->lν)+(>0b) jets
  (seeing the lepton)

- *No excess above backgrounds at large MET…*

Reference point: mSUGRA/CMSSM with m_0 = 660 GeV, $m_{1/2}$ = 240 GeV, A_0 = 0, tanβ = 10, μ > 0

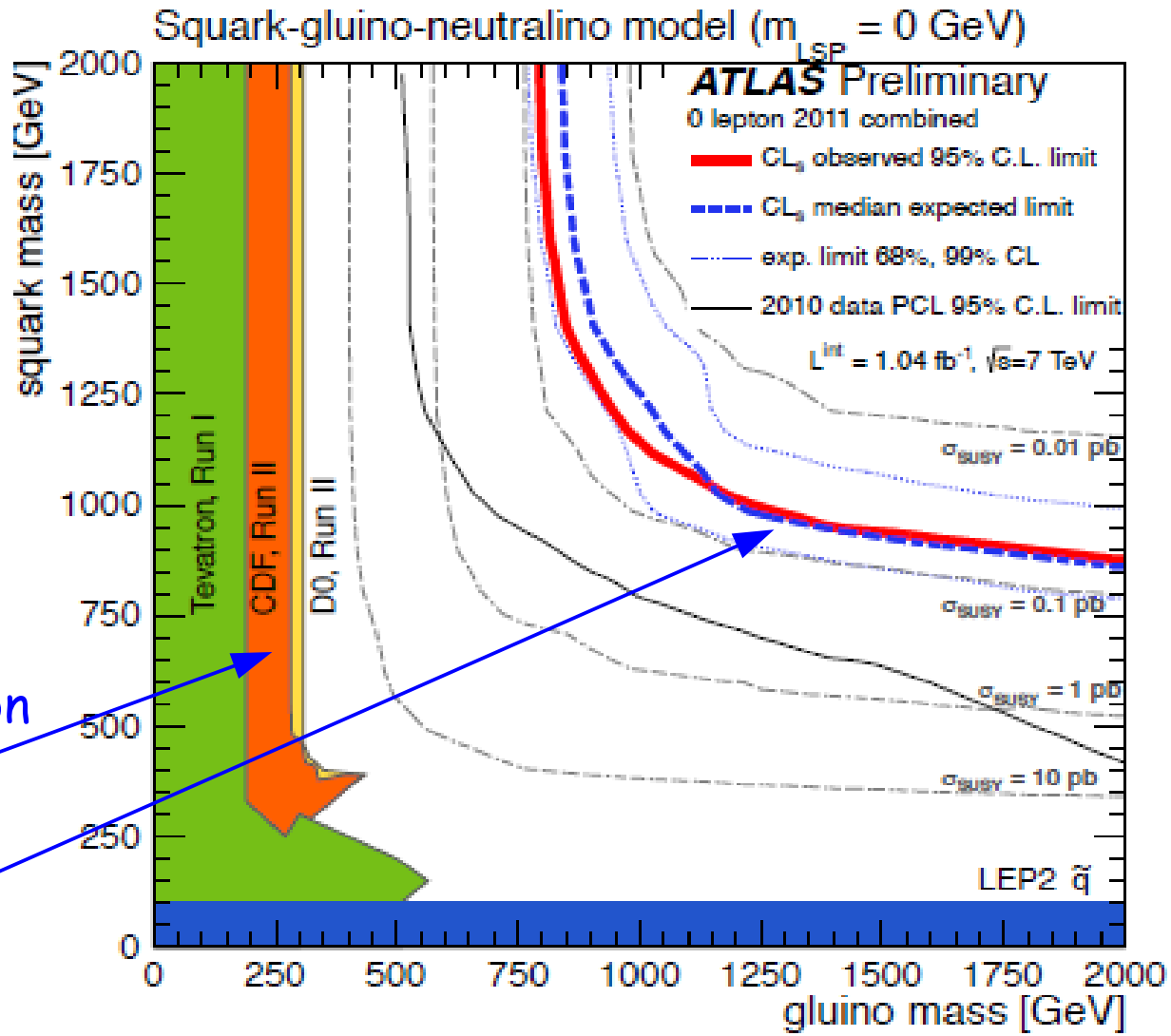


Strong SUSY production

- Squark / gluino mass > ~1 TeV !

  (for small LSP mass)

- CMS excludes a similar region



Tevatron limits

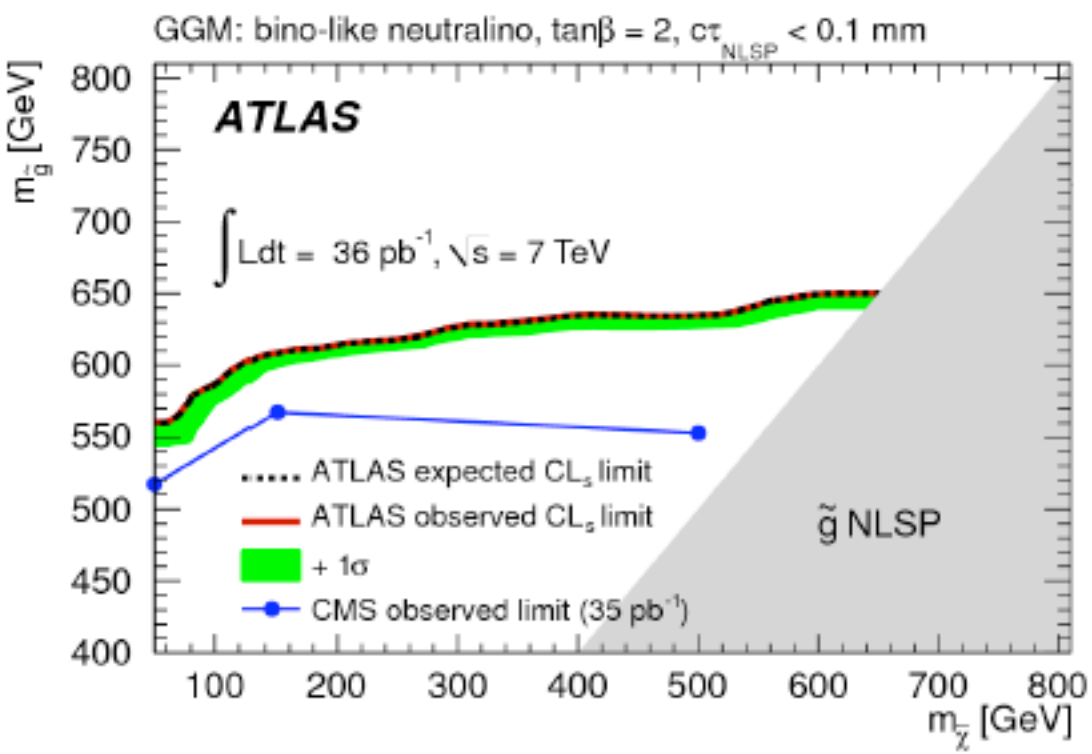
LHC limits

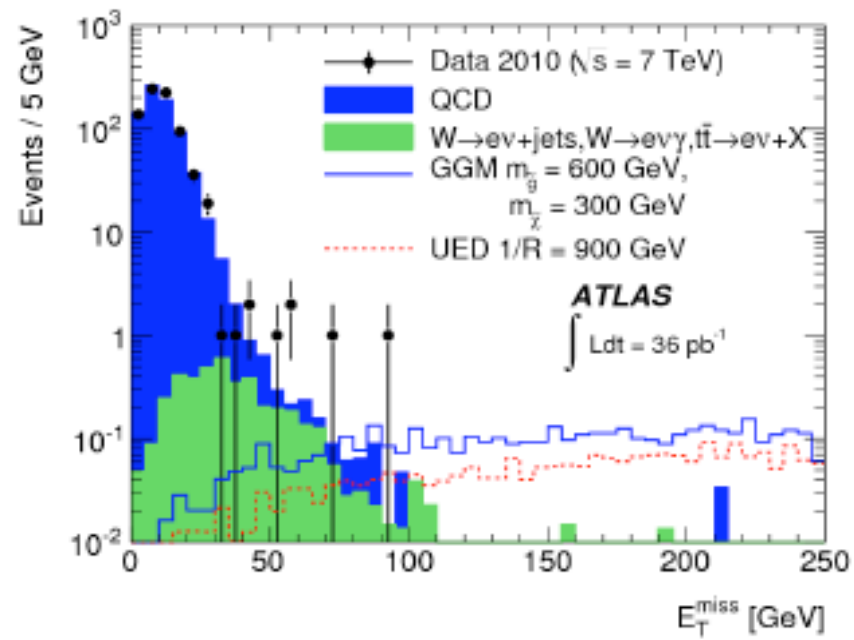
Gravitino dark matter

- Gauge-mediated supersymmetry breaking → light gravitino

$$\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$$

- 2 photons (pT>25 GeV) + MET





Gluino mass > 560-640 GeV
(just 0.036 fb^{-1} analyzed)

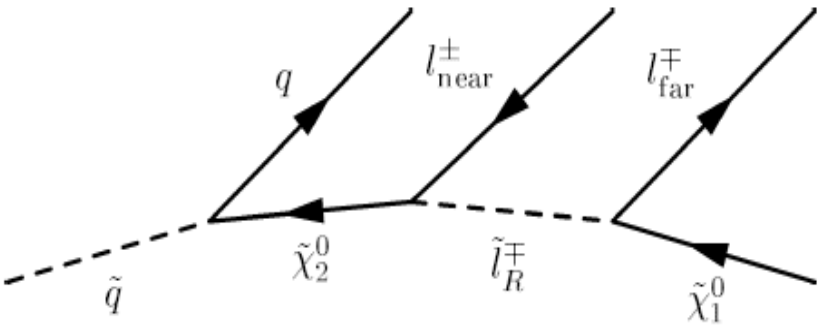
Measuring dark matter

- Let's say we discovered supersymmetry in events with MET at the LHC ...

- What could we really learn about the dark matter?
  - Mass of LSP? Spin?
  - Scattering cross-section on nuclei?
  - Annihilation rate at threshold? (galaxy center)
  - What about it's production (and annihilation) in the Big Bang?
    - How much should be in the Universe today?
    - Does it explain *all* the observed dark matter?

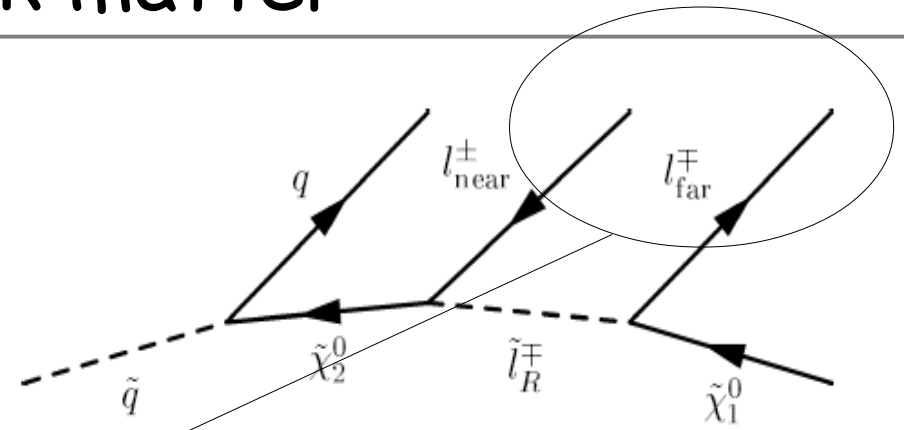
Measuring dark matter

- Depends on the SUSY model...

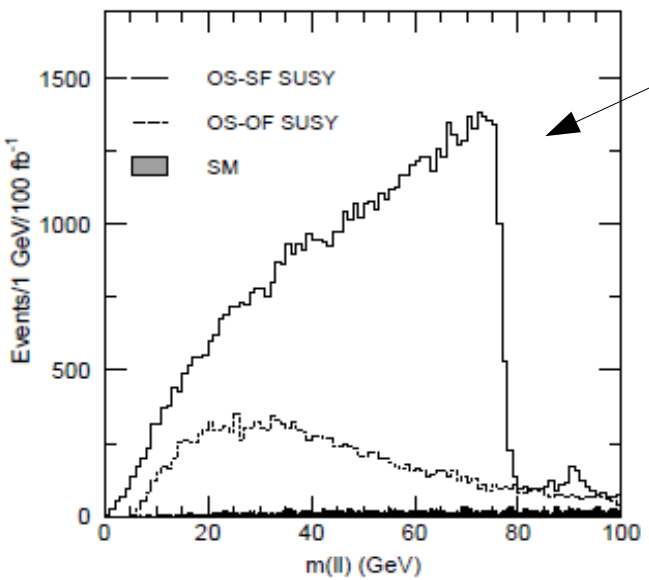


Measuring dark matter

- Depends on the SUSY model…

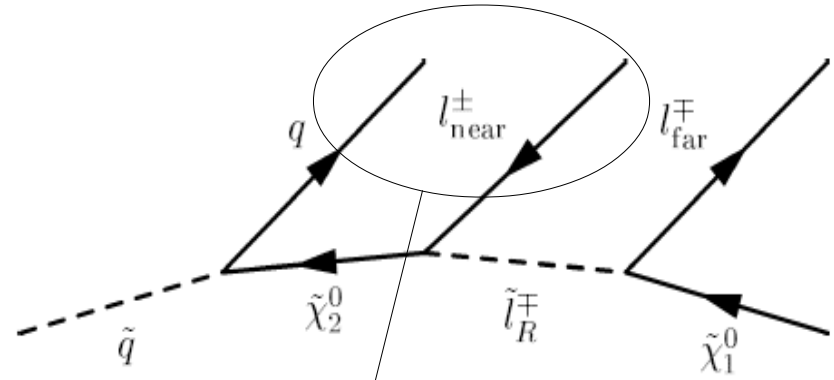


- Lots of leptons → sharp kinematic edges

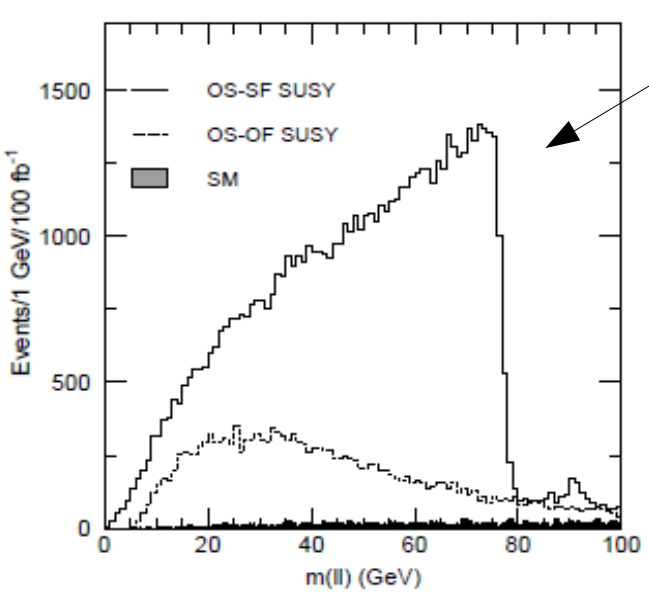


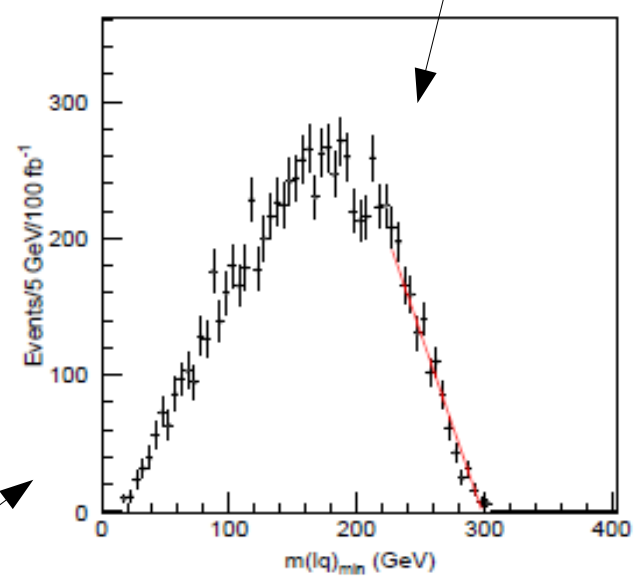
Measuring dark matter

- Depends on the SUSY model...



- Lots of leptons → sharp kinematic edges

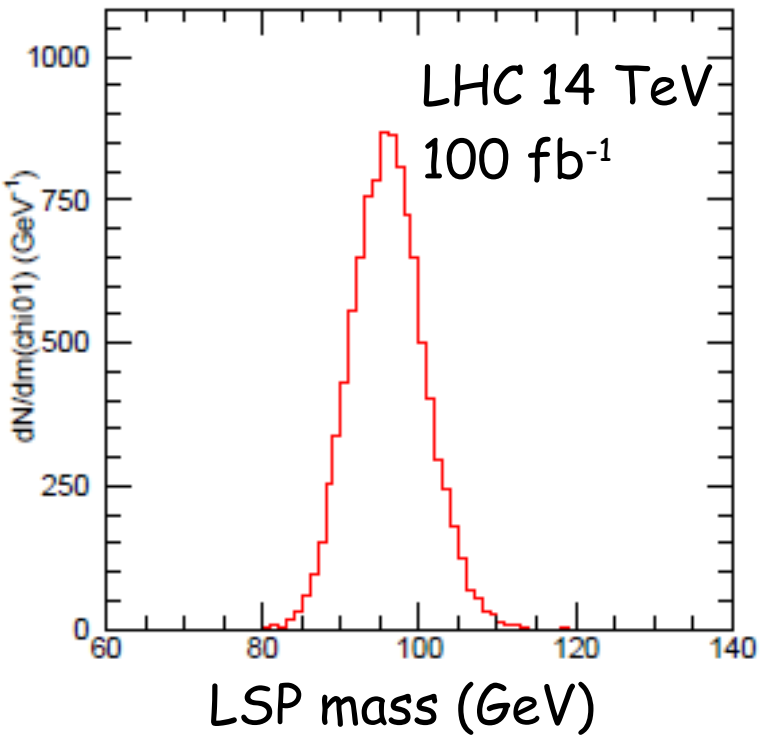


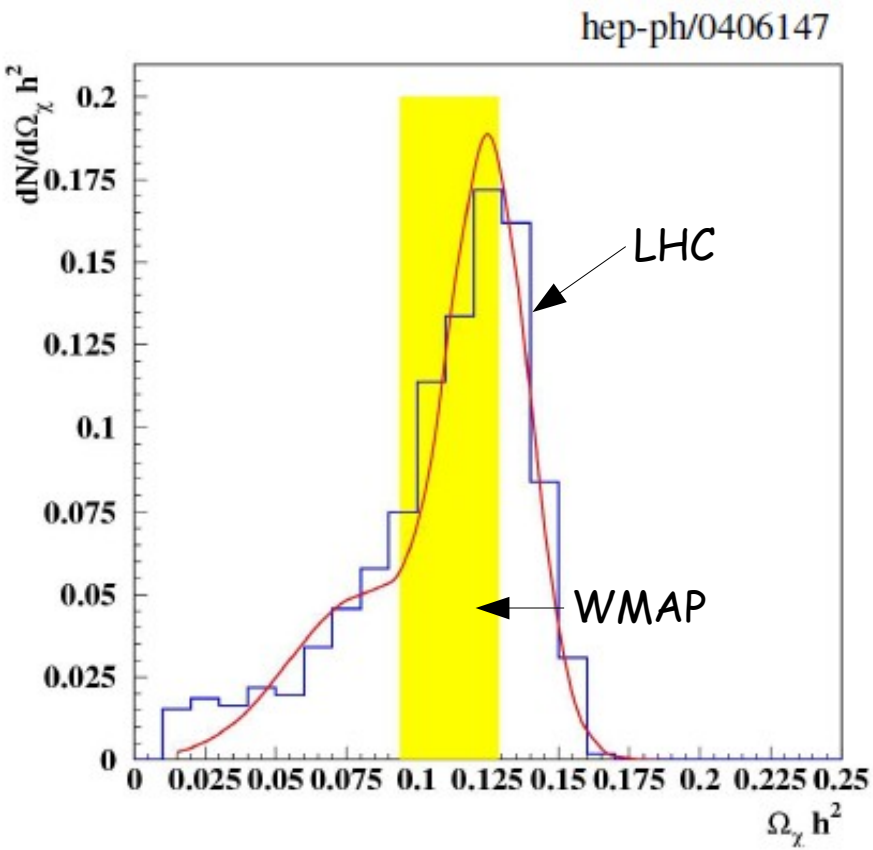


- When you have to use jets, they're fuzzier

Measuring dark matter

- For an optimistic scenario (SPS1a), could measure LSP mass to ~±5% at the LHC (after ~100 fb^{-1})...

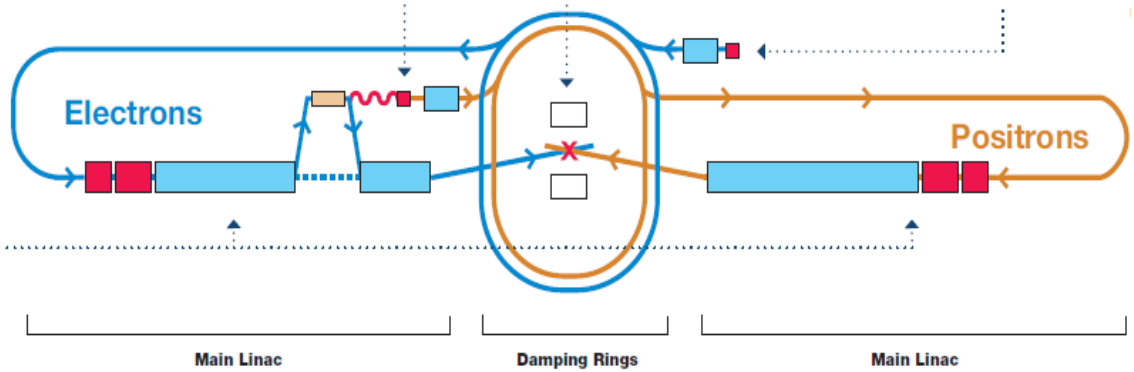




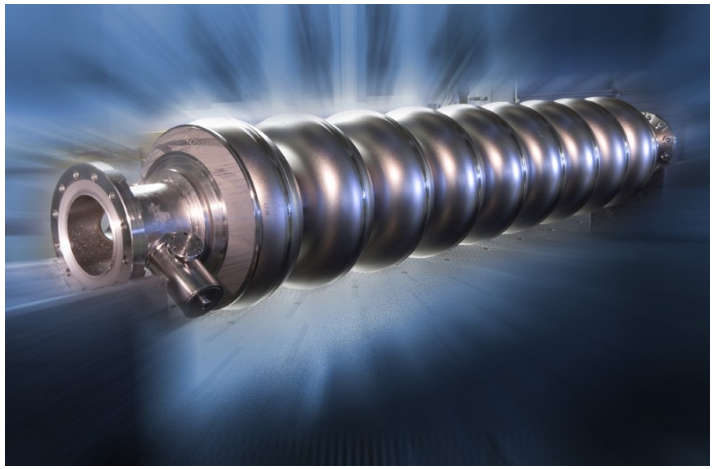
- After measuring the whole SUSY model, could estimate the dark matter density left over from the Big Bang

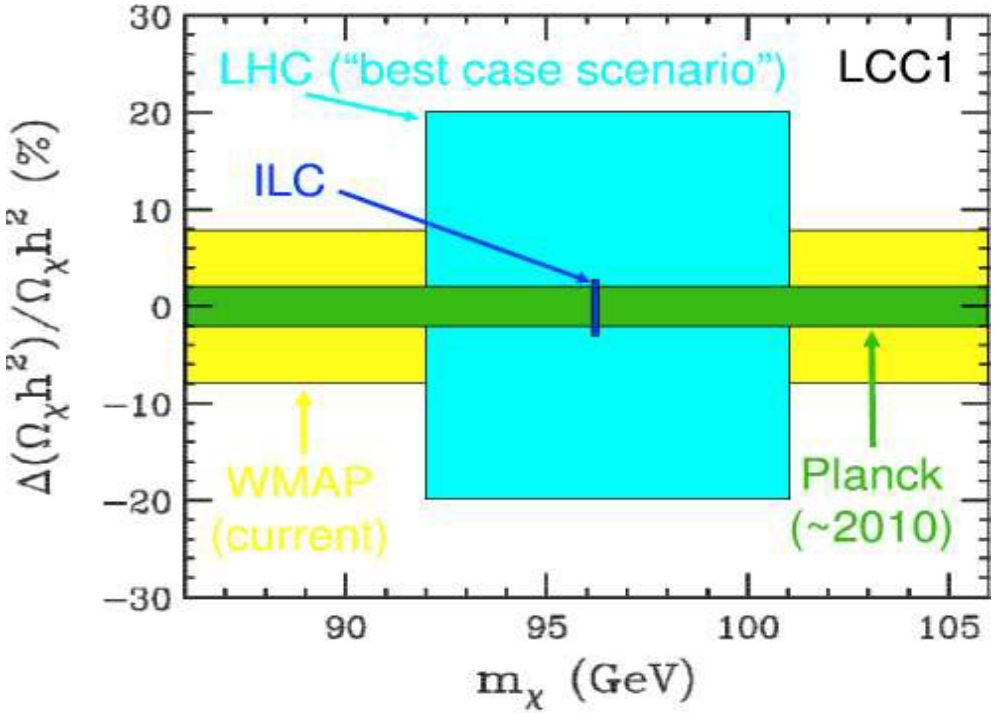
Precision dark matter

- Lepton collider
  e^+e^- at 0.5-1, or 3 TeV
  (or $\mu^+\mu^-$ at 4 TeV?)



- Low backgrounds
- Clean initial (and final) state
- Can tune beam energy

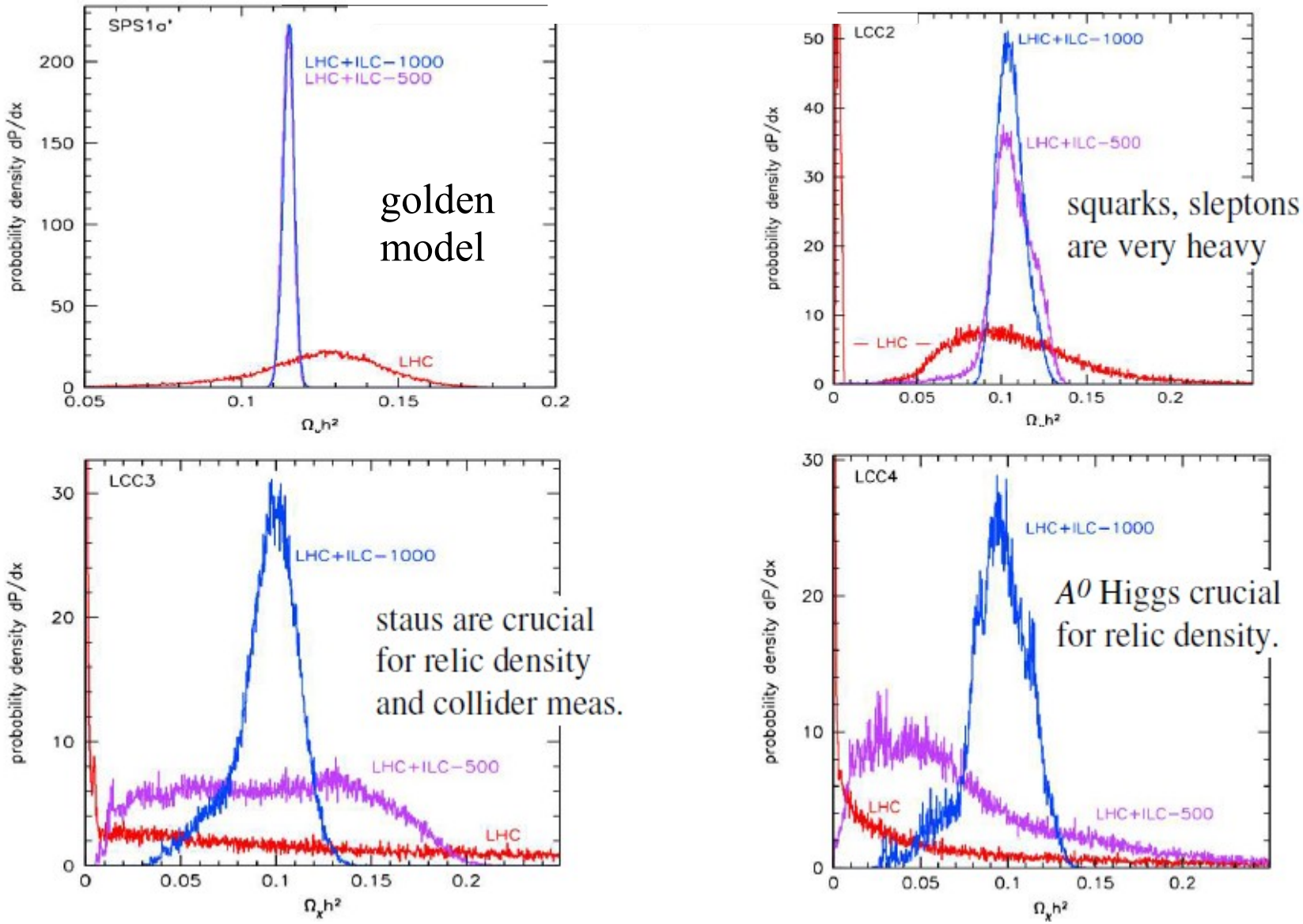




Assuming you can produce and measure all SUSY particle states...

Precision dark matter

- Can't always do quite so well...



Hidden dark matter

- Nature doesn't have to be just SU(3)xSU(2)xU(1)

- String theory naturally has additional gauge groups, weakly-coupled to the SM

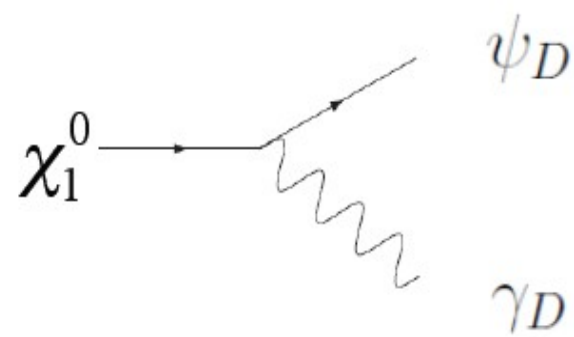
New, kinetically coupled U(1)

$$\mathcal{L}_{\text{gauge mix}} = -\frac{1}{2}\epsilon_1 b_{\mu\nu} A^{\mu\nu} - \frac{1}{2}\epsilon_2 b_{\mu\nu} Z^{\mu\nu}$$

- Old dark matter WIMP now decays into hidden sector !
  (and creates a dark photon)

Lightest SUSY particle in hidden sector

"darkino" = MET



"dark photon"

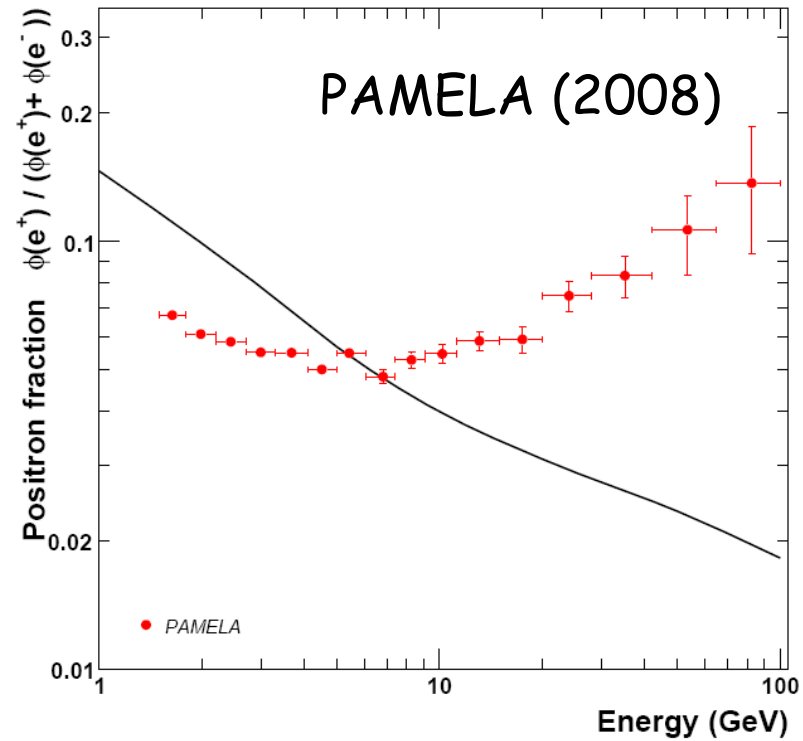
Force carrier in hidden sector

Arkani-Hamed, Finkbeiner, Slatyer, Weiner Phys.Rev.D79:015014,2009.

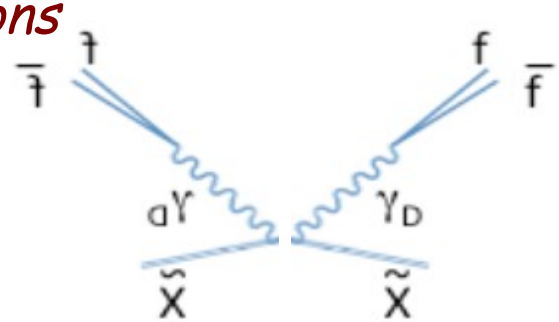
Hidden dark matter - motivation

- Excess of positrons in space
- No excess of anti-protons

- Hidden sector gives
  DM+DM → e^+e^- only
  for dark photon mass <~$2m_{proton}$

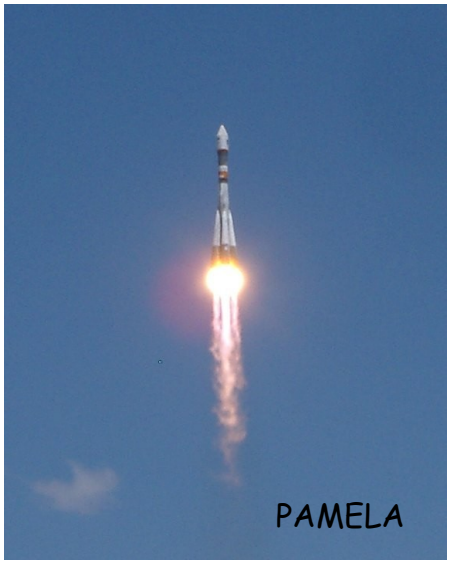


electrons or muons



electrons or muons

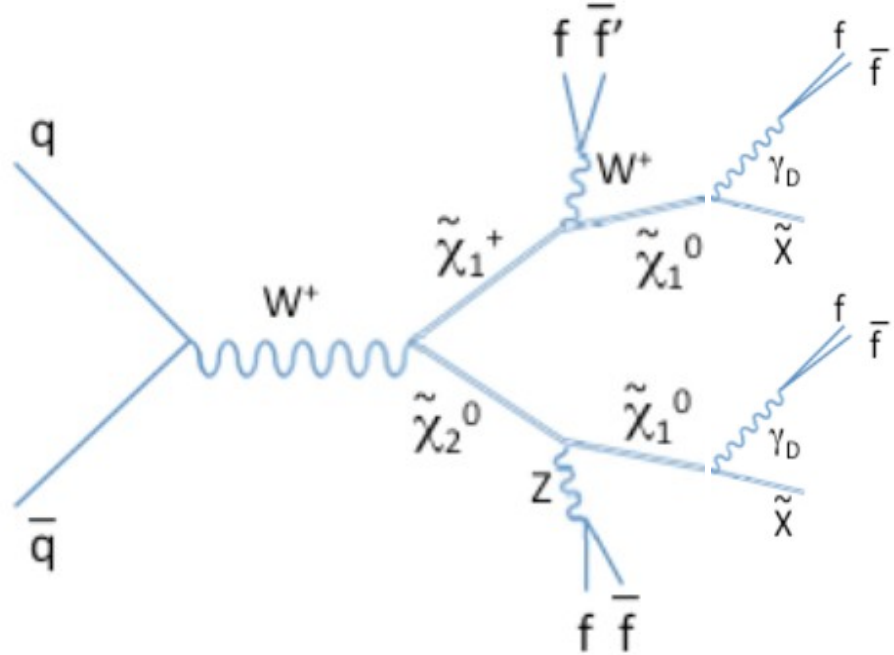
Also may be able to explain DAMA results...



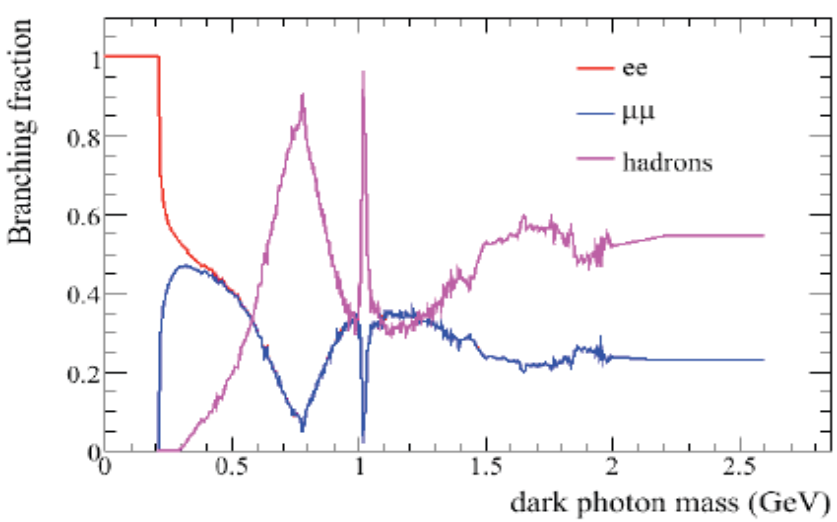
D.P. Finkbeiner and N. Weiner
*Phys.Rev.D **76** 083519 (2007).*

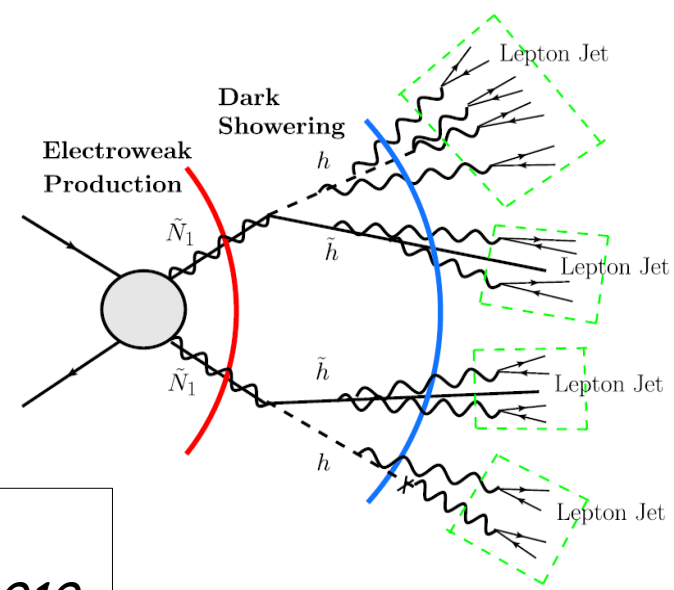
Hidden dark matter at colliders

- Changes the signature of SUSY dark matter
  - Less MET
  - Two dark photons



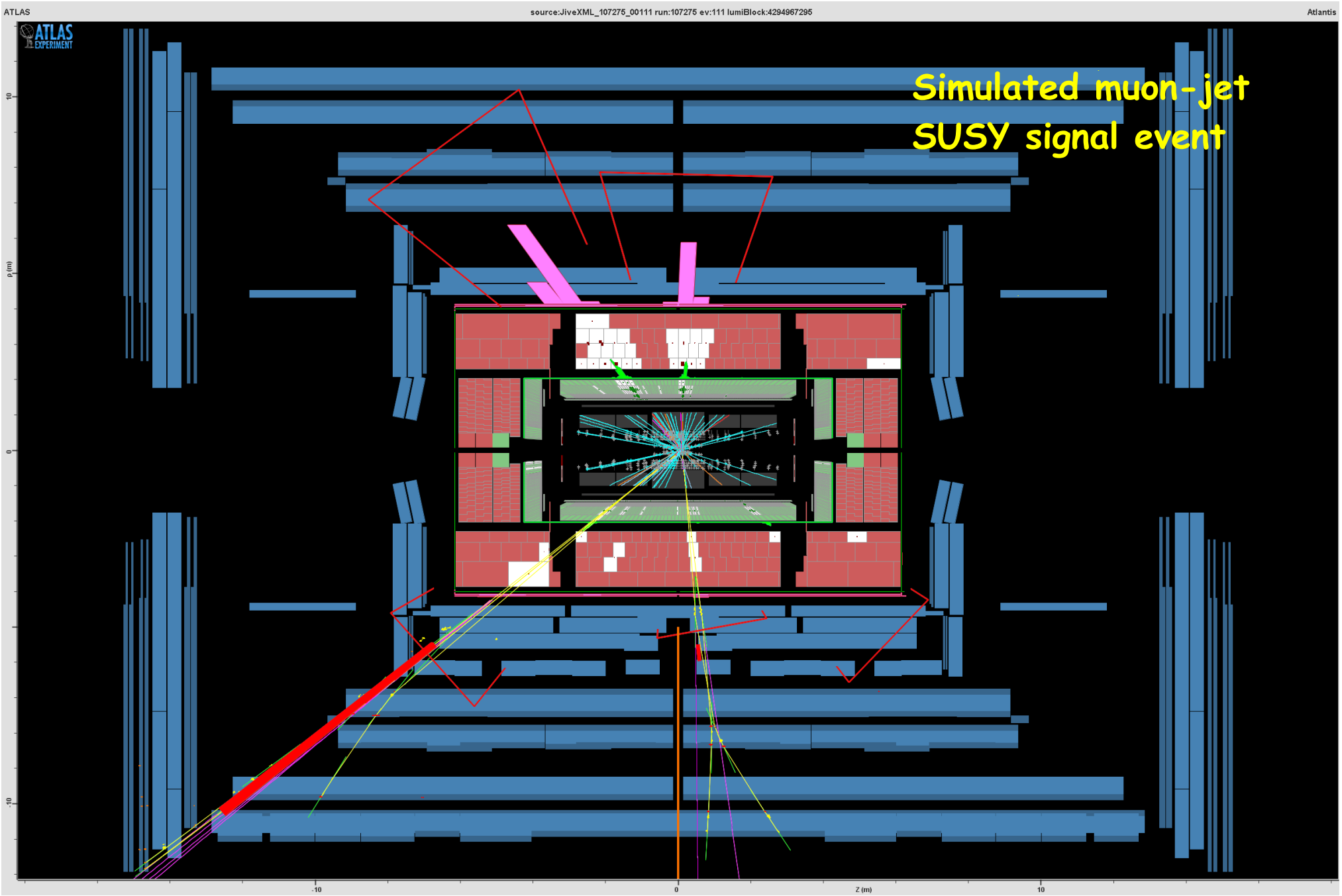
- Dark photons are boosted
  - Create "lepton jets": pair of collinear electrons or muons





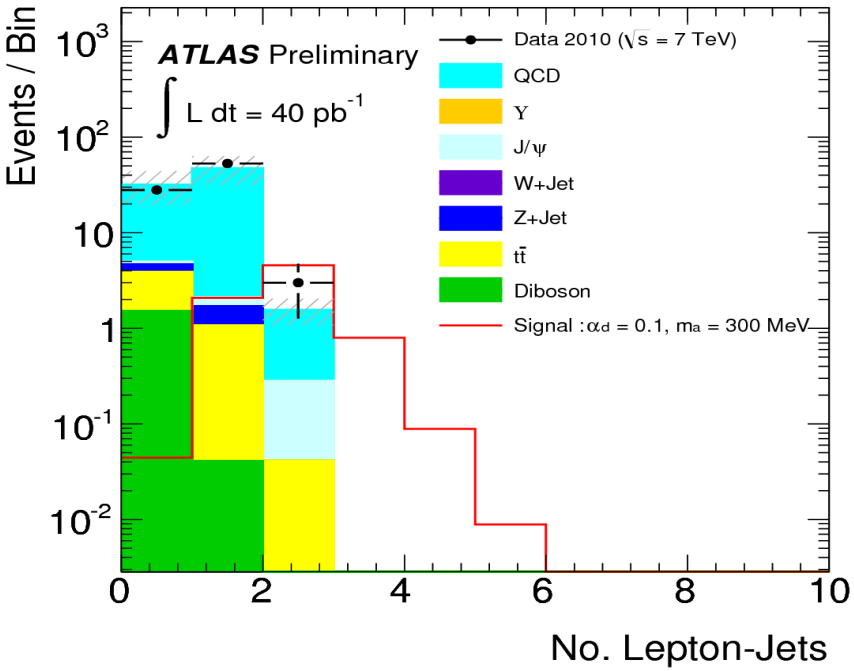
Cheung et al. JHEP 1004:116,2010.

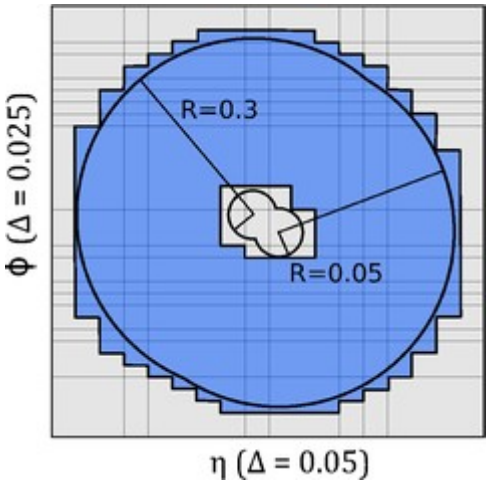
Hidden dark matter at colliders

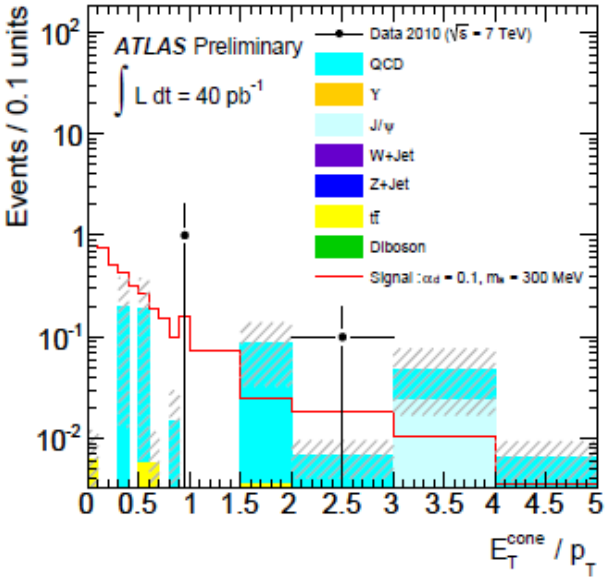


Hidden dark matter at colliders

- ATLAS search for 2 muon-jets with 2010 data
- Custom multi-muon calorimeter isolation calculated, to reject QCD jets
- No events seen with 2 *isolated* muon-jets



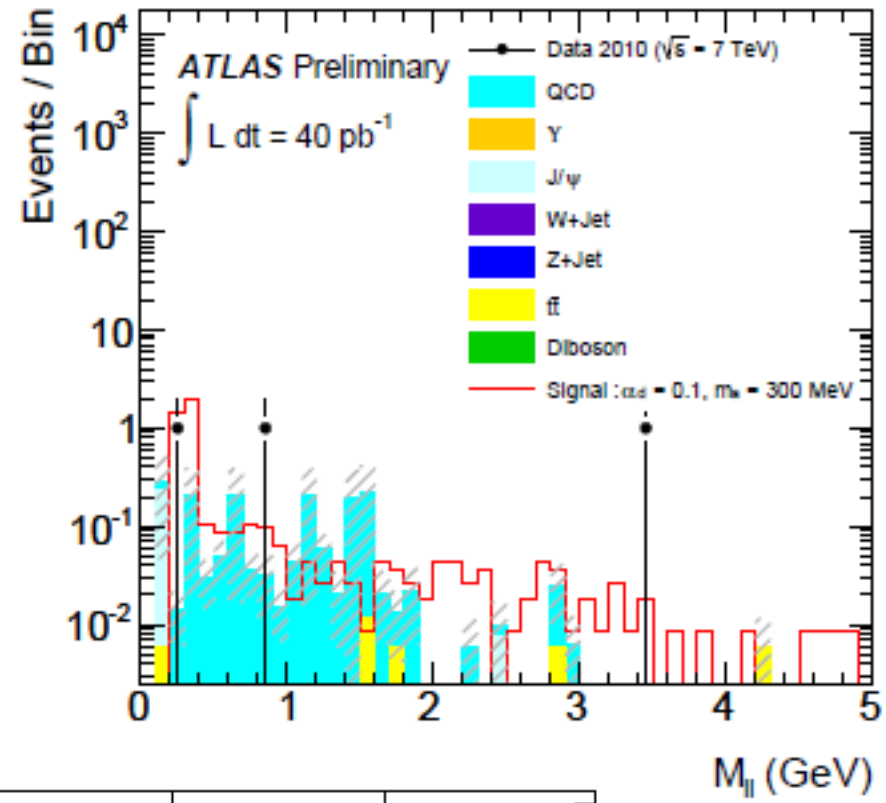


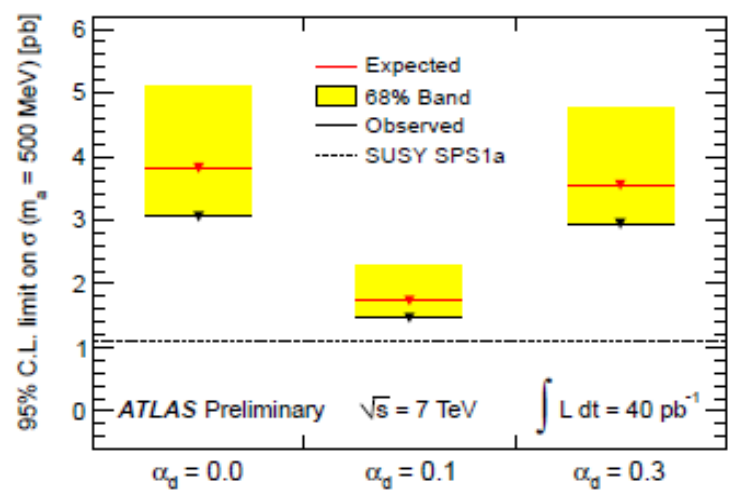


Hidden dark matter at colliders

- Dark photon → $\mu^+\mu^-$ would give peak at dark photon mass
  - None observed

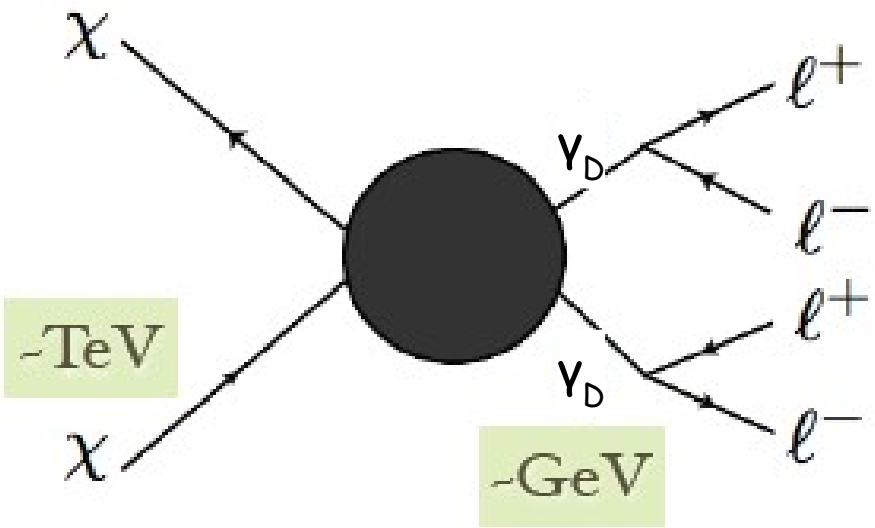
- Limits set on SUSY production with hidden dark matter up to m(gluino) ~500 GeV, depending on details of hidden sector model



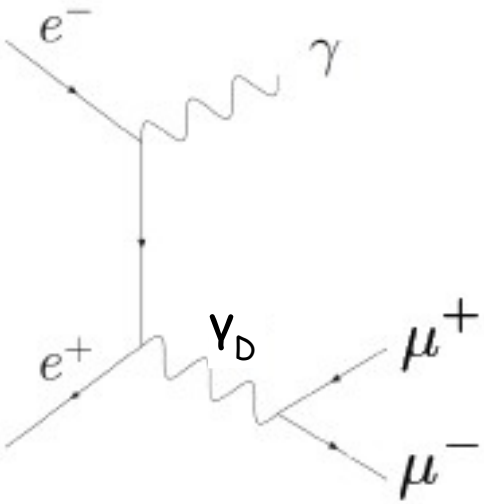


Directly seeing the hidden sector

- Maybe SUSY doesn't exist, or is too heavy to see at LHC
- Maybe (hidden) dark matter is also very heavy, >~TeV

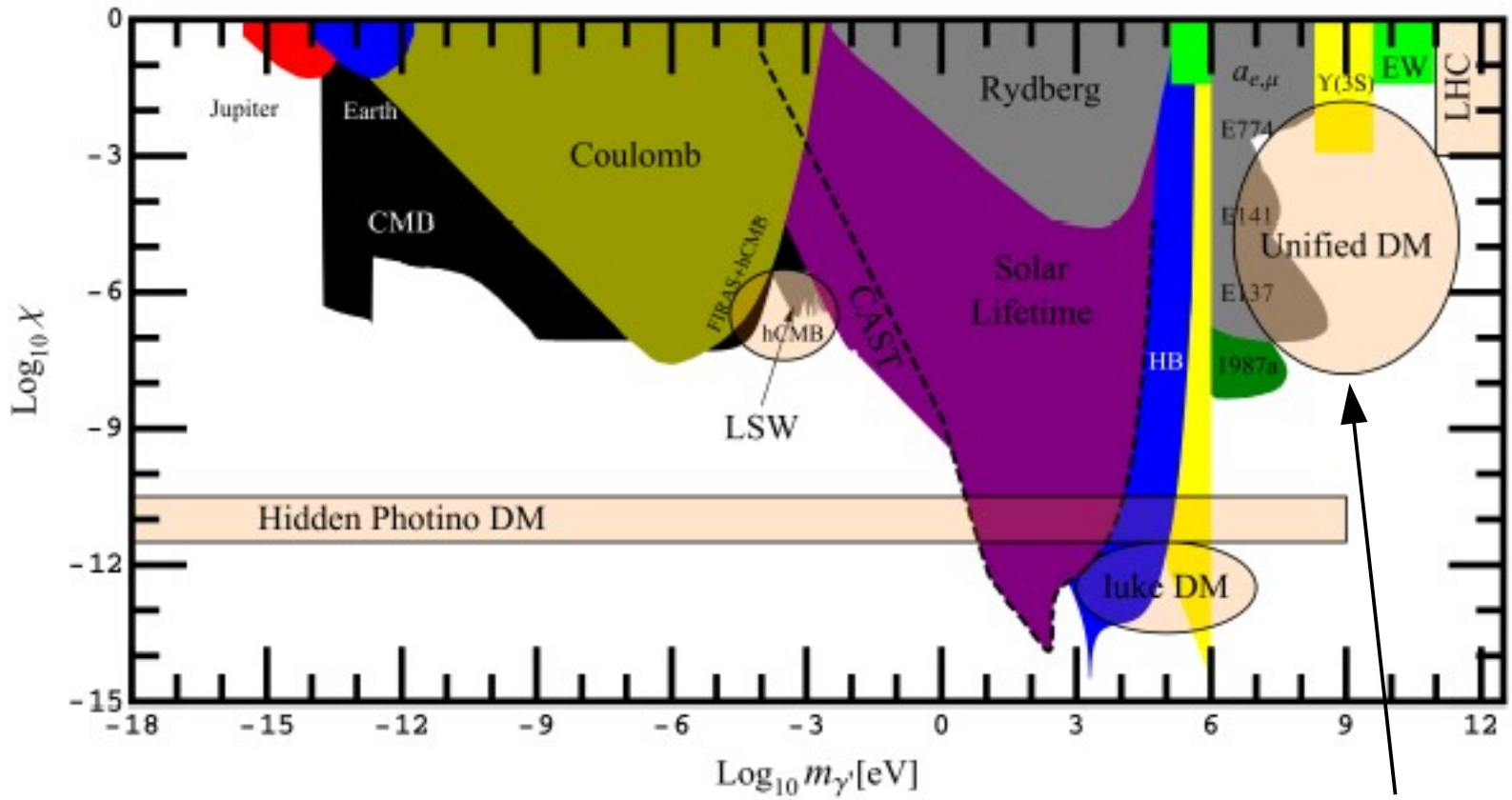


- Dark matter may be hard to see!
- But we can directly make dark photons...



Directly seeing the hidden sector

- Long and fascinating history of "heavy photon" experiments



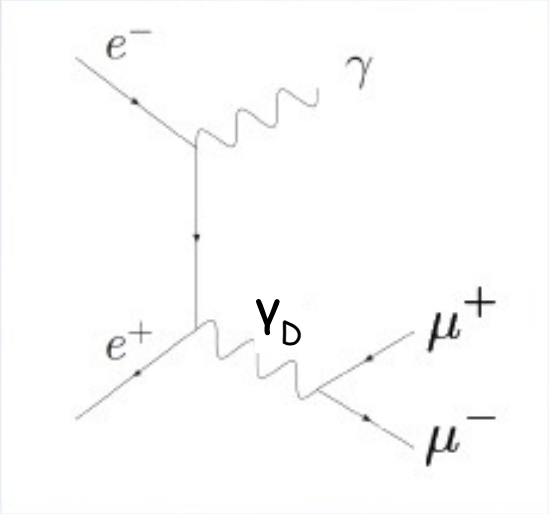
We would like to look here !

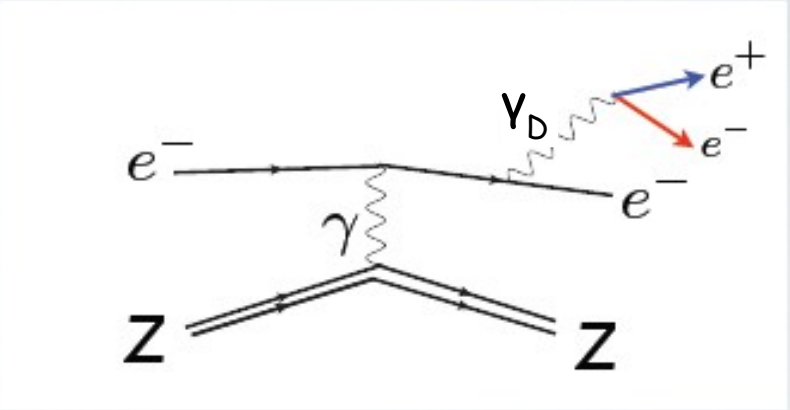
Joerg Jaeckel, Andreas Ringwald arXiv:1002.0329

Directly seeing the hidden sector

- Since the dark photon mass is small, you don't need a collider!

Collider vs. Fixed Target





$$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$$

$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$

$O\ ab^{-1}$ per decade

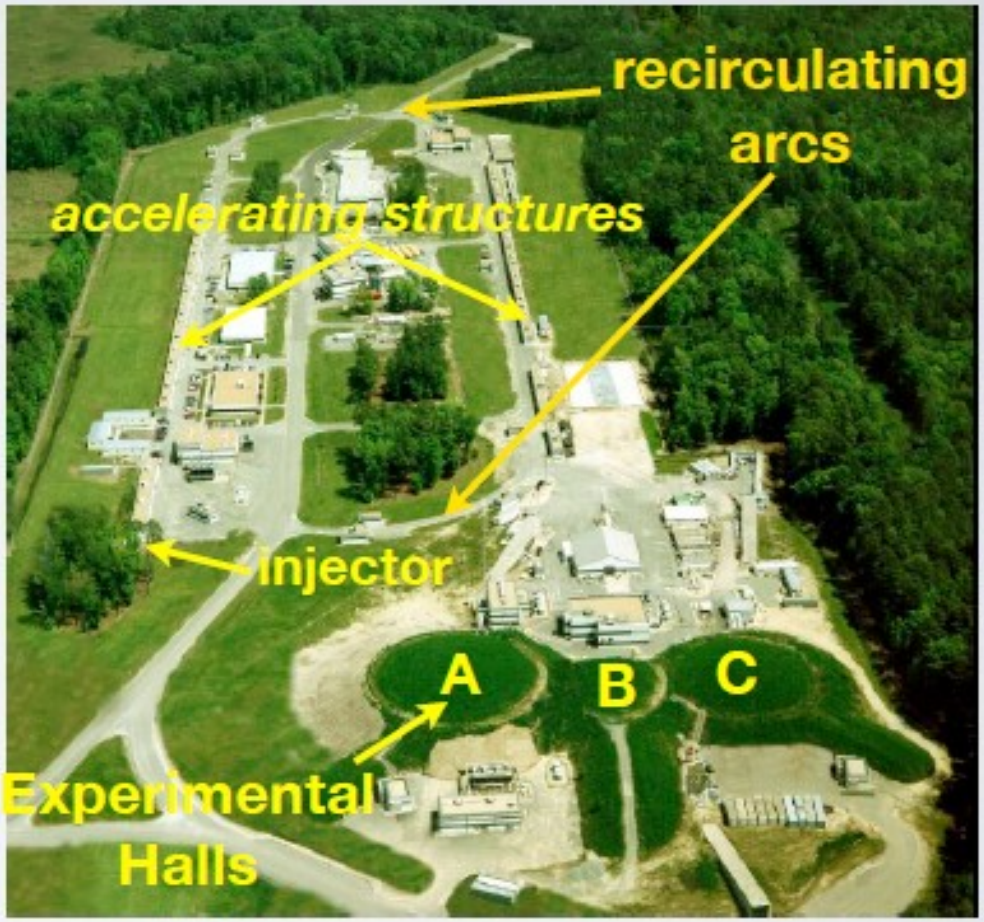
$O\ ab^{-1}$ per day

Directly seeing the hidden sector

- CEBAF accelerator at Jefferson Lab – Virginia, US
- Very intense, moderate energy, electron beam

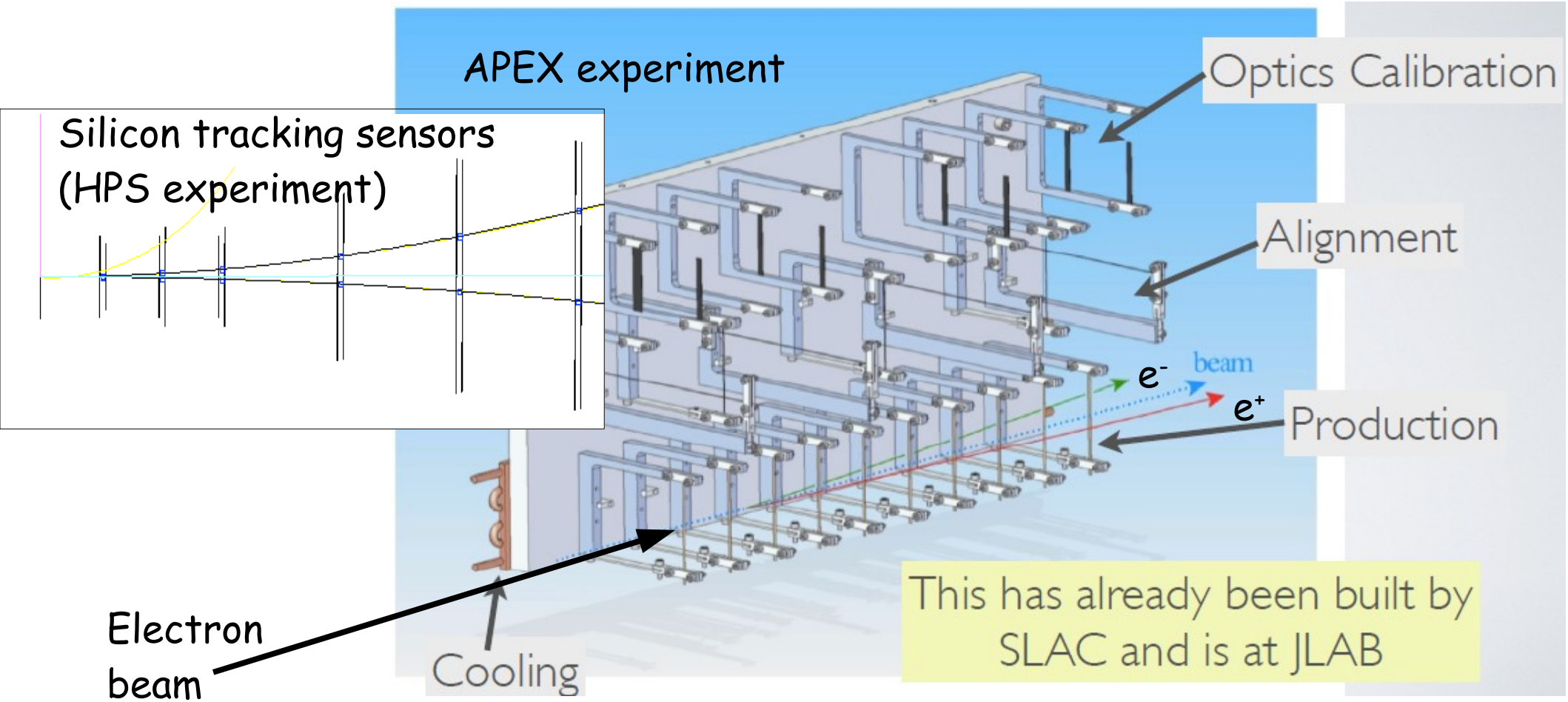
Simultaneous delivery of electron beams at different energies and intensities in three experimental halls.

- $E_{\text{beam}} = n \times 1.1$ GeV, n≤5 (5.5 GeV Max)
- $I_{\text{beam}} < 200\ \mu$A (A&C), <700 nA (B)
- bunch separation: 2.004 ns
- energy upgrade complete 2014:
  $E_{\text{beam}} = n \times 2.2$ GeV, n≤5 (11 GeV max)



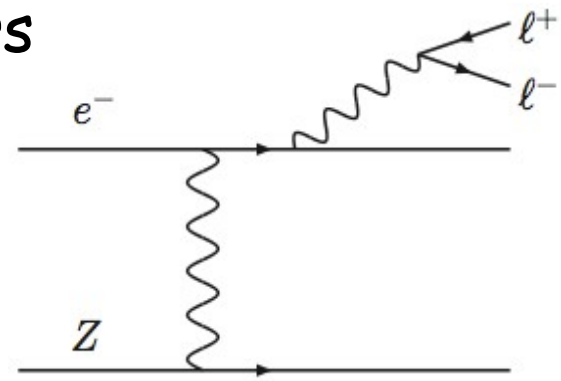
Directly seeing the hidden sector

- Beam goes through 10 Tungsten "targets", each 15μm thick
- Look for e^+e^- from decays of the dark photons

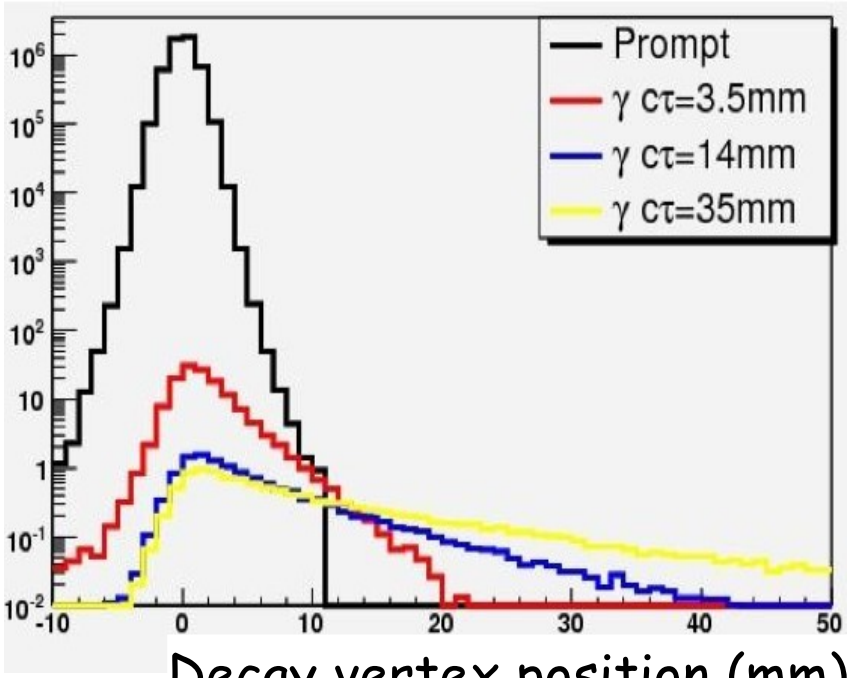


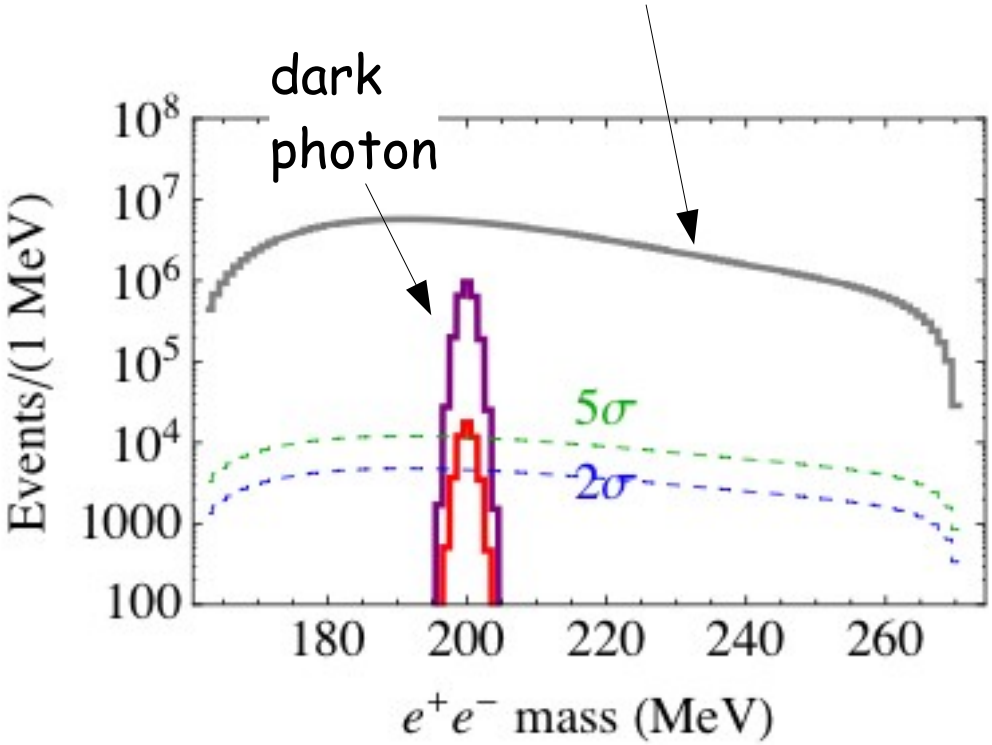
Directly seeing the hidden sector

- Background from "radiative" electron pairs
- Dark photon would make mass peak



- Vertex would also be displaced if dark photon is long lived

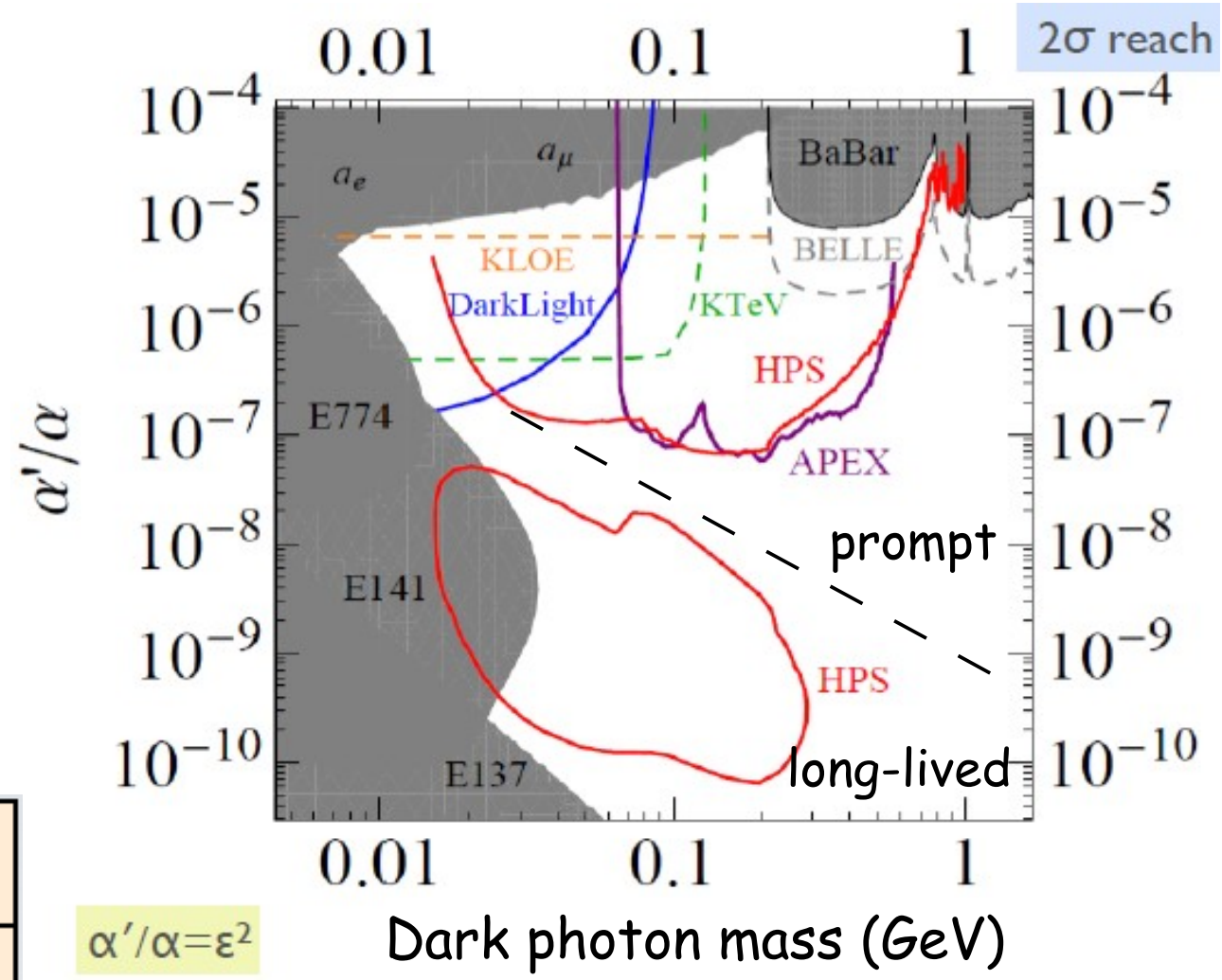




Directly seeing the hidden sector

- Results coming soon!

- APEX: 2012?
- DarkLight: 2013?
- HPS: test in 2012? Sensitive at long lifetime...



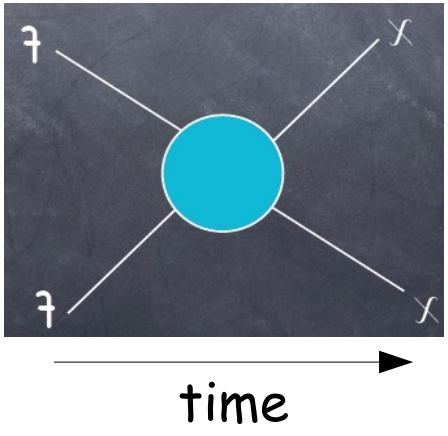
	Shield (m)	E_{beam} (GeV)	Lumi (e^-)
E137	200	20	10^{20}
E141	0.12	9	2×10^{15}
E774	0.3	275	5×10^{9}

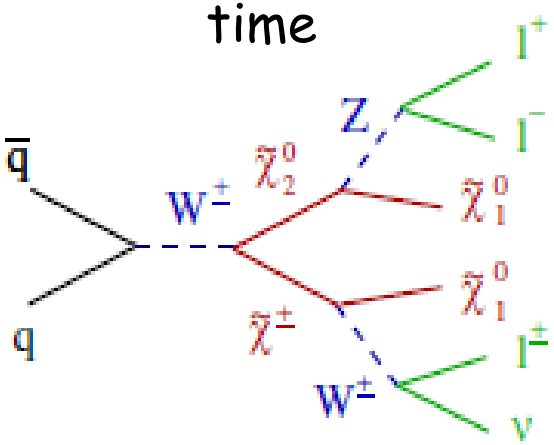
Conclusions

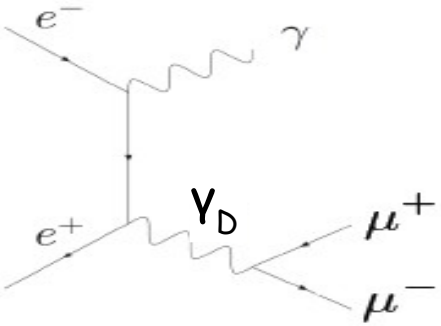
- How much can we learn about DM with colliders/accelerators ?

- It depends ...
  - what dark matter is made of
  - what else (like SUSY) comes along with dark matter

- Direct production "MET searches"
- DM searches in SUSY (or other) decays
- Colliders or fixed-target accelerator searches for a new dark sector
- Other new ideas, or surprises !







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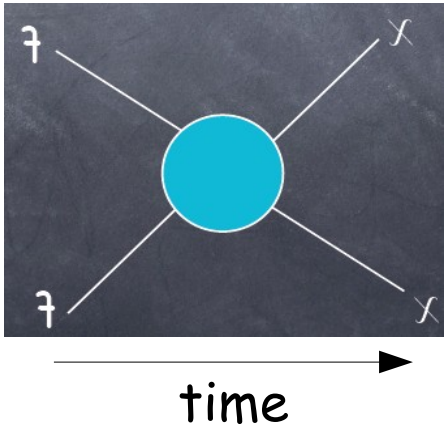

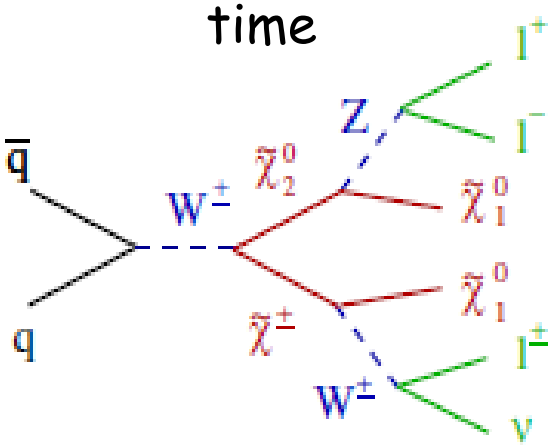

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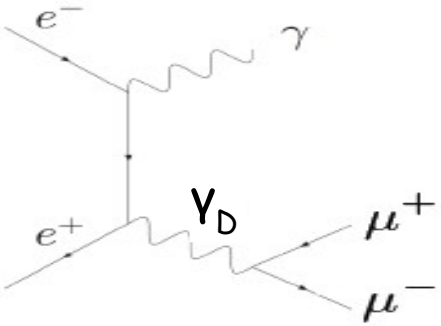
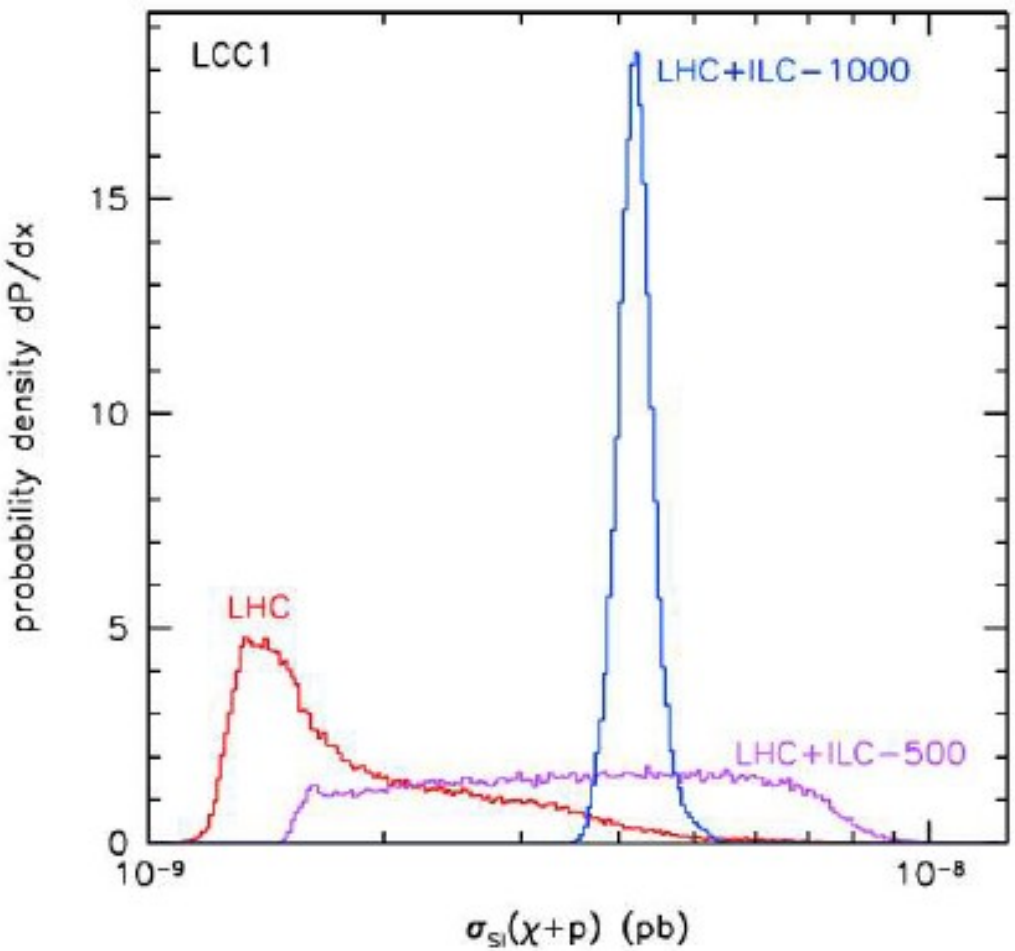
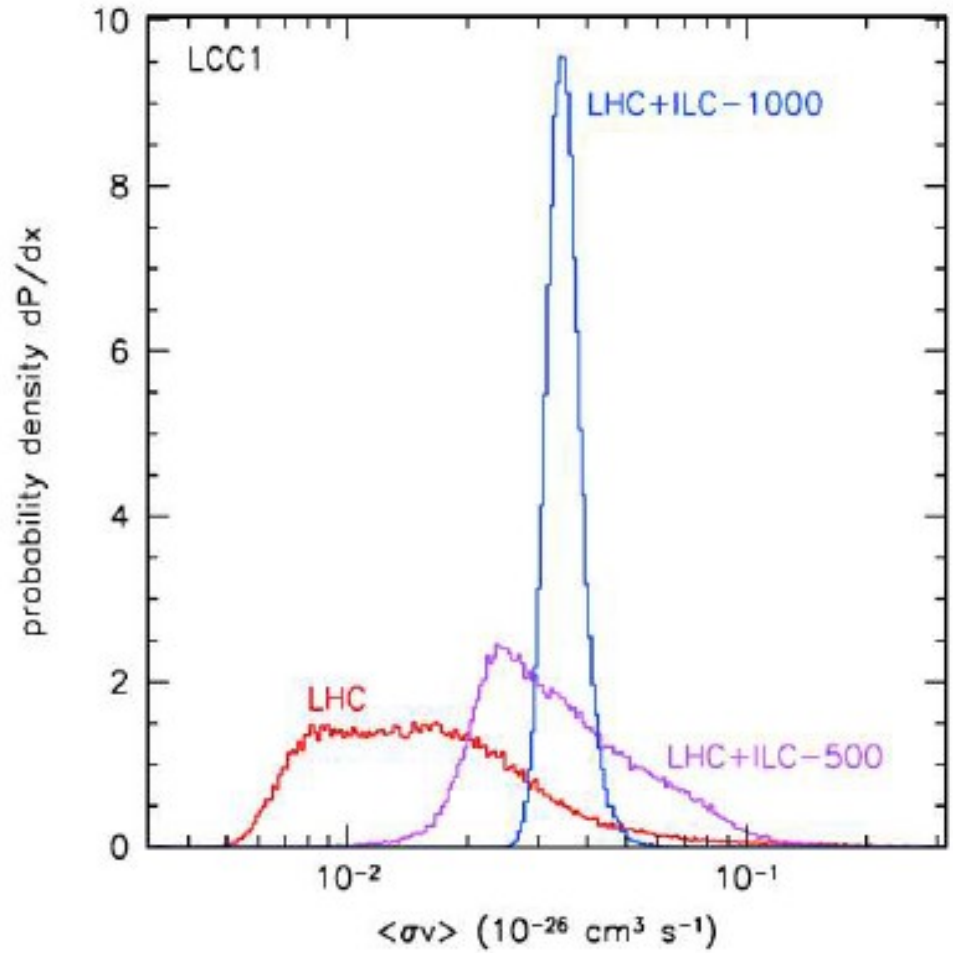


Let's hope this universe has dark matter we can make !

Backup

Precision dark matter





scattering cross-section for direct-detection experiments

WIMP annihilation cross-section at threshold