Collider Searches for non-SUSY Dark Matter

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Multi^3 Workshop @ Padova

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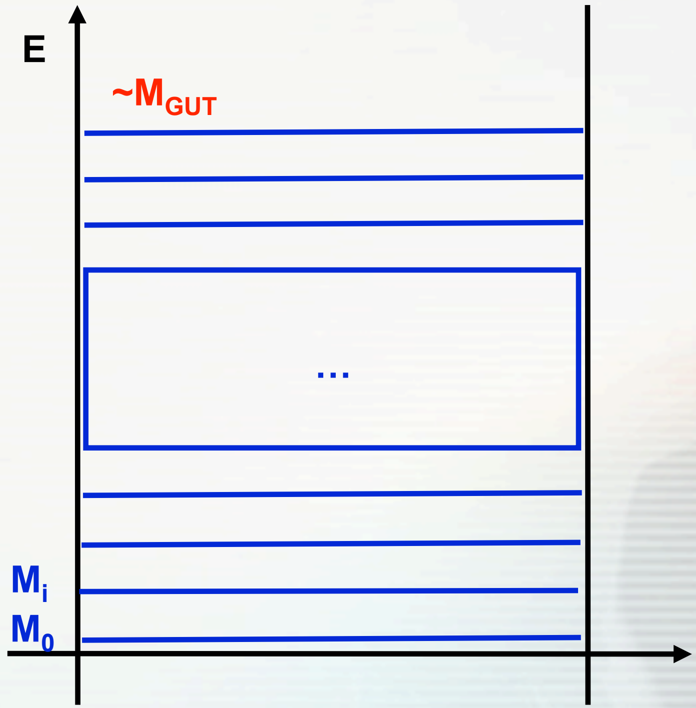
Outline

- Universal Extra Dimensions
- Kaluza-Klein Dark Matter
- Experimental searches for UED
- Dark Matter from Hidden Valleys
- Hidden Valley Signals at Colliders
- Conclusions

Kaluza-Klein Modes

- Imagine adding a compact dimension of a size R to the 3+1 space-time
  - A particle propagating in this extra dimension is a classical problem of a particle in a box
  - Only quantized energy levels are allowed, with the spacing ~1/R
- From the 4-dimensional point of view, these excitations can be considered as a tower of particles with masses $M_i = \sqrt{M_0^2 + i^2/r^2}$, known as Kaluza-Klein modes of the original particle
  - This tower is truncated at a natural ultraviolet scale of the model, often the GUT scale
- Examples: large extra dimensions; Randall-Sundrum model

- Coupling: g_{SM} per KK mode
- Can excite many modes at high energies, thus effectively increasing the coupling



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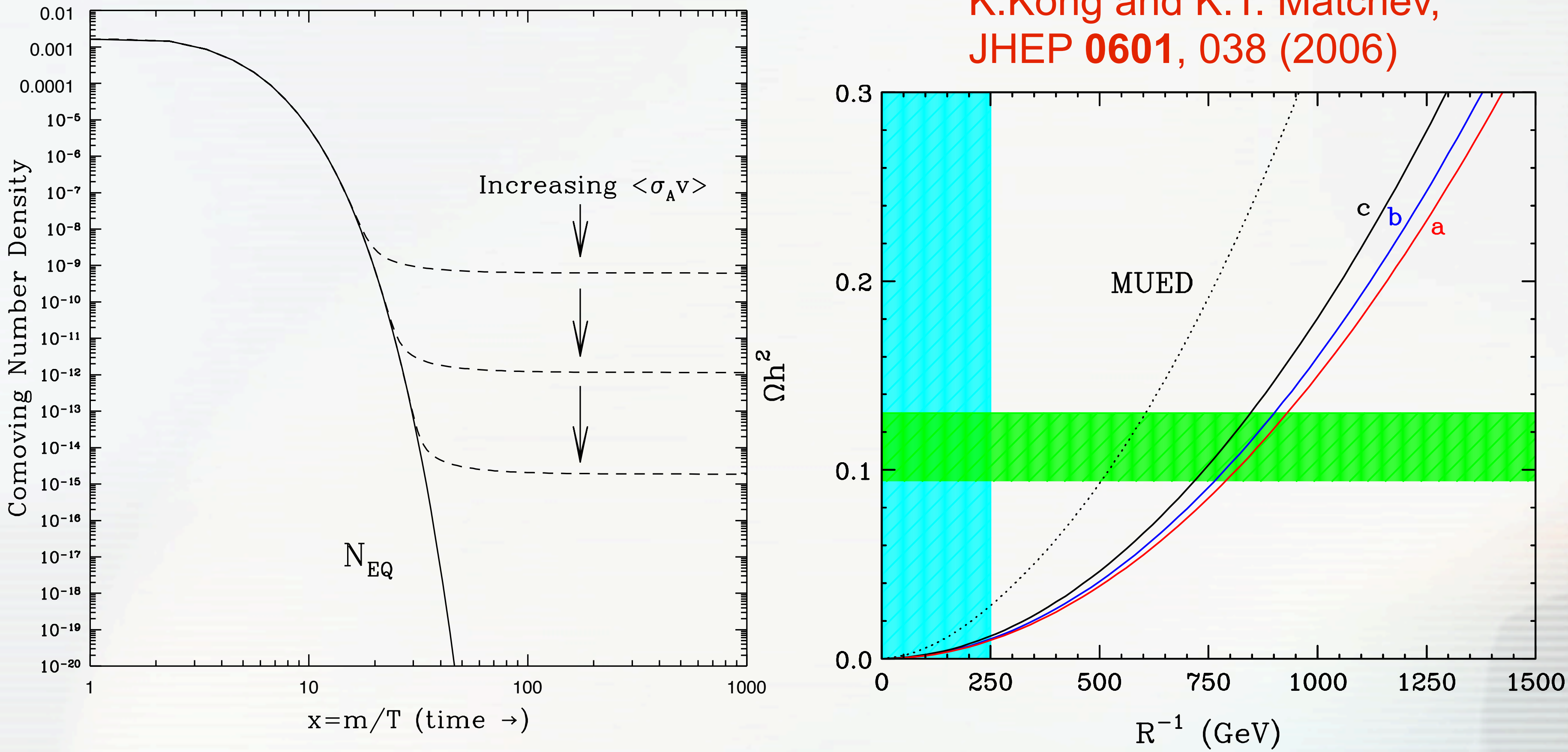
Universal ED - Phenomenology

- The most "democratic" ED model: *all* the SM fields are free to propagate in extra dimension(s) with the size $R = 1/M_c \sim 1\ \text{TeV}^{-1}$ Appelquist, Cheng, Dobrescu [PRD **64**, 035002 (2001)]
  - Instead of chiral doublets and singlets, model contains vector-like quarks and leptons, thus solving the hierarchy problem
  - Gravitational force is not included in this model
- The number of universal extra dimensions is not fixed:
  - it's feasible that there is just one (MUED)
  - the case of two extra dimensions is theoretically attractive, as it breaks down to the chiral Standard Model and has additional nice features, such as guaranteed proton stability, etc.
- Every particle acquires KK modes with the masses $M_n^2 = M_0^2 + M_c^2$, n = 0, 1, 2, …
- Kaluza-Klein number (n) is conserved at tree level, i.e. $n_1 \pm n_2 \pm n_3 \pm \ldots = 0$; consequently, the lightest KK mode (usually γ_1 or Z_1) could be stable (and is an excellent dark matter candidate Cheng, Feng, Matchev [PRL **89**, 211301 (2002)])
- Hence, first level KK-excitations are produced in pairs, similar to SUSY particles
- Consequently, current limits (dominated by precision electroweak measurements, particularly T-parameter) are sufficiently low ($M_c \sim 300$ GeV for MUED and of the same order, albeit more model-dependent for >1 ED)

Right Abundance, Cross Section

- Similar to a neutralino, the lightest KK particle (LKK) with ~1 TeV mass gives right DM abundance

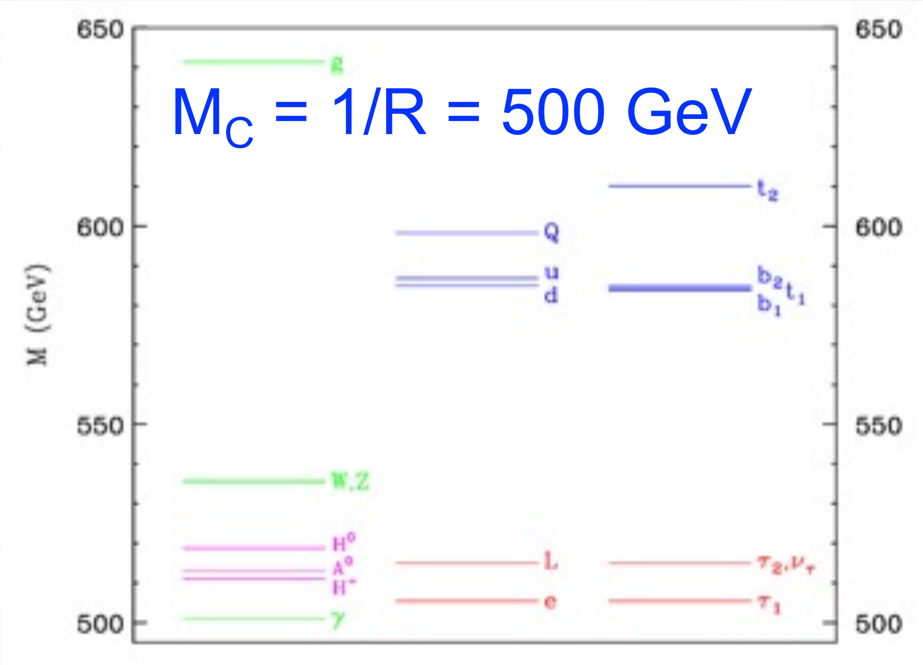
K.Kong and K.T. Matchev, JHEP **0601**, 038 (2006)



UED Phenomenology

- Naively, one would expect large clusters of nearly degenerate states with masses around 1/R, 2/R, …
- Cheng, Feng, Matchev, Schmaltz: not true, as radiative corrections tend to be large (up to 30%); thus the KK excitation mass spectrum resembles that of SUSY!
- Minimal UED model with a single extra dimension, compactified on an S_1/Z_2 orbifold
  - Odd fields do not have 0 modes, so we identify them w/ "wrong" chiralities, so that they vanish in the SM
- Q, L (q, l) are SU(2) doublets (singlets) and contain both chiralities

Cheng, Matchev, Schmaltz [PRD **66**, 056006 (2002)]



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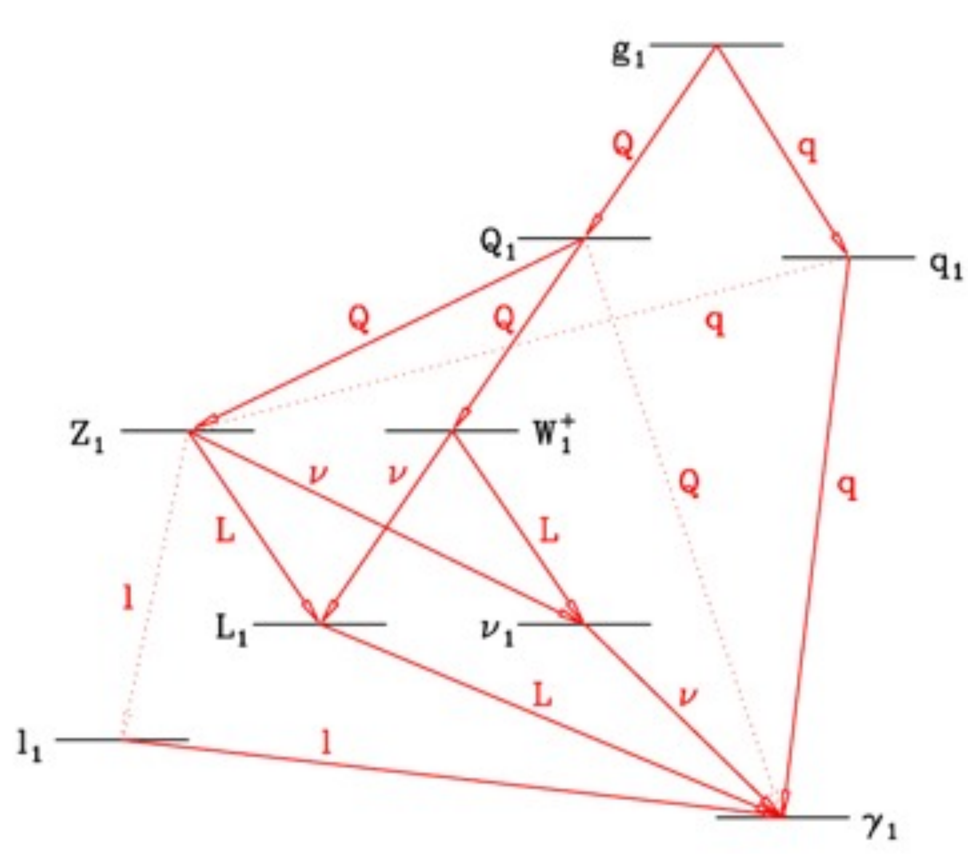
Mass Spectrum and Decays

- First level KK-states spectroscopy

Cheng, Matchev, Schmaltz
[PRD **66**, 056006 (2002)]



Decay:

$B(g_1 \to Q_1 Q) \sim 50\%$

$B(g_1 \to q_1 q) \sim 50\%$

$B(q_1 \to q\gamma_1) \sim 100\%$

$B(t_1 \to W_1 b, H_1^{+} b) \sim 100\%$

$B(Q_1 \to QZ_1 : W_1 : \gamma_1) \sim 33\%:65\%:2\%$

$B(W_1 \to \nu L_1 : \nu_1 L) = 1/6:1/6$ (per flavor)

$B(Z_1 \to \nu\nu_1 : LL_1) \sim 1/6:1/6$ (per flavor)

$B(L_1 \to \gamma_1 L) \sim 100\%$

$B(\nu_1 \to \gamma_1 \nu) \sim 100\%$

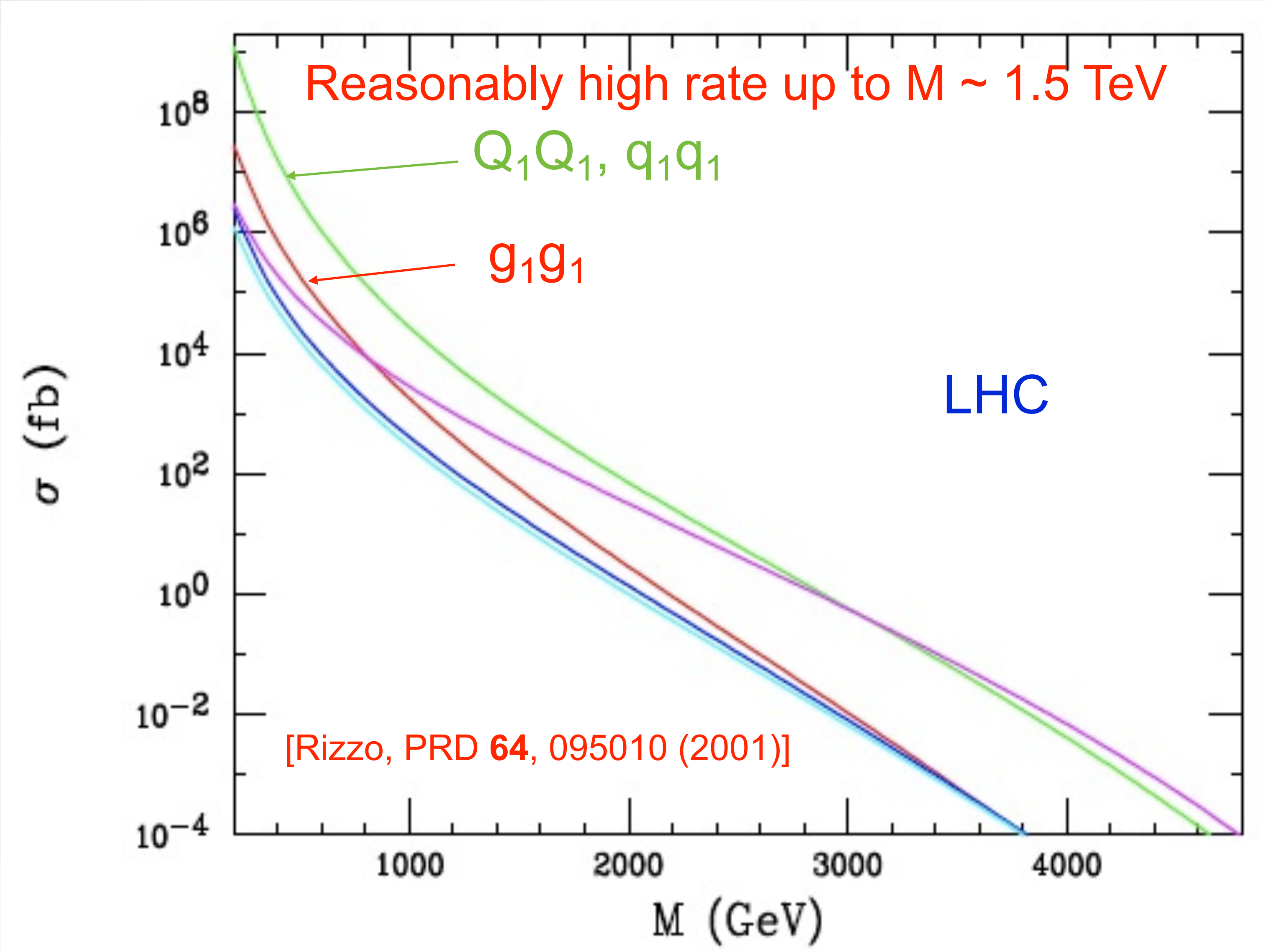
$B(H_1^{\pm} \to \gamma\gamma_1, H^{\pm}\gamma_1) \sim 100\%$

Production:

$q_1 q_1 + X \to ME_T$ + jets ($\sim\sigma_{had}/4$); but: low ME_T

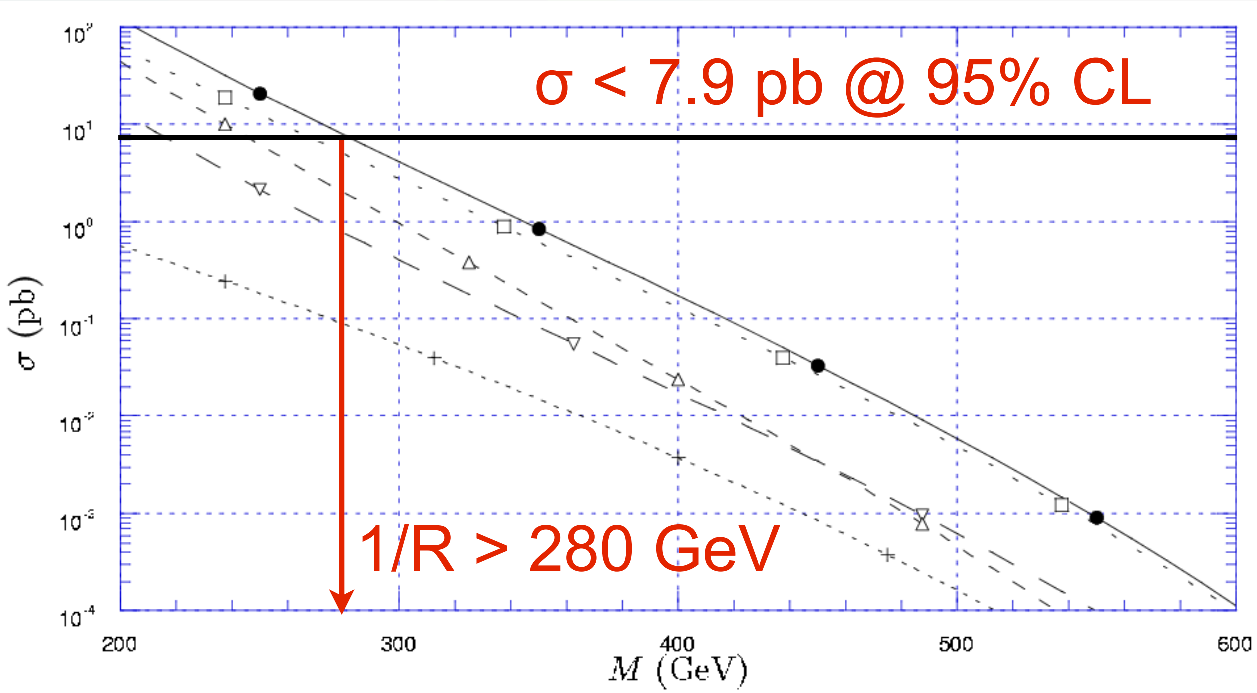
$Q_1 Q_1 + X \to V_1 V'_1$ + jets $\to$ 2-4 ℓ + ME_T ($\sim\sigma_{had}/4$)

Production Cross Section



Current Collider Limits

[Chun Lin, Ph.D. Thesis, Yale University, 2005]

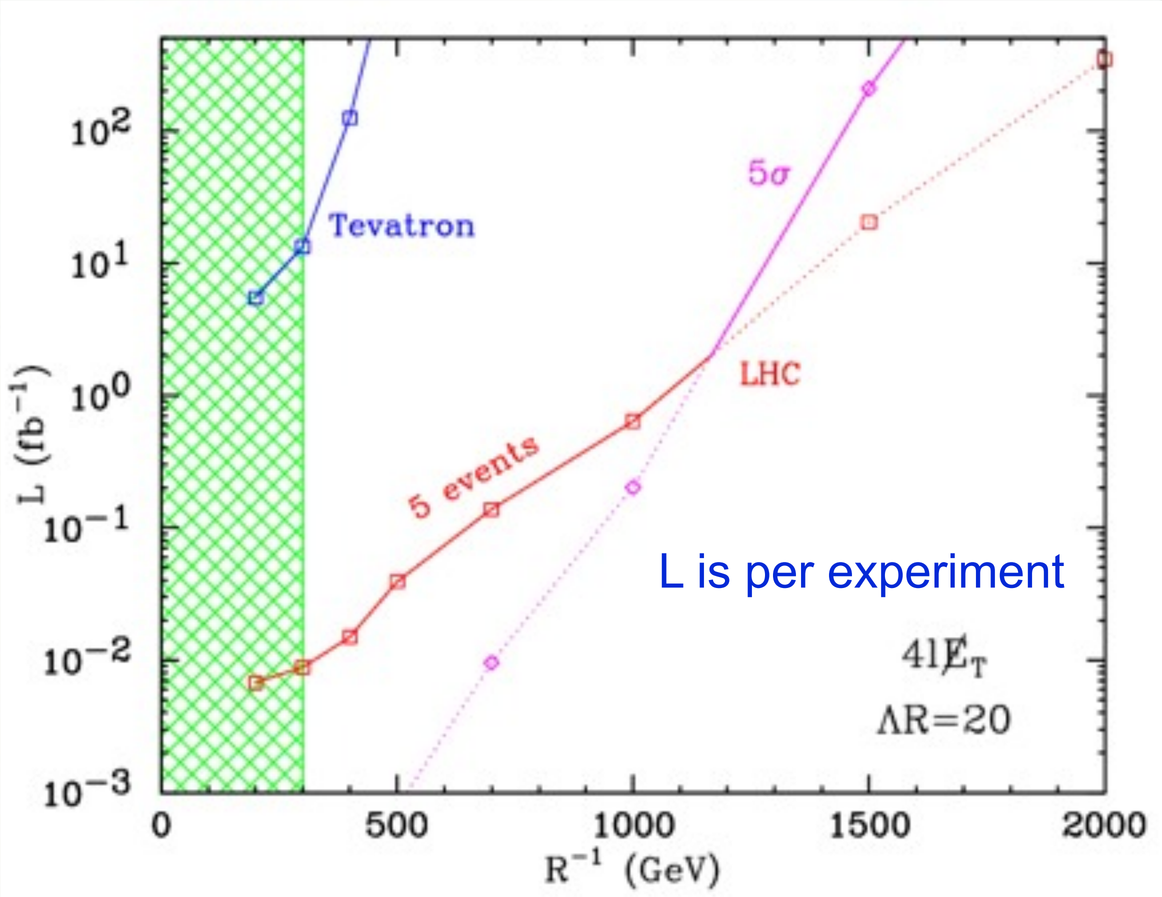


- 88 pb^{-1} of CDF Run I data in the trilepton(e/μ) + ME_T channel ("recycling" of a SUSY search)
- N.B. This is NOT an official CDF result, but it represents the only direct limits from collider searches so far

Sensitivity in the Four-Lepton Mode

- Only the gold-plated 4-leptons + ME_T mode has been considered in the original paper and the subsequent studies
- Other promising channels:
  - dileptons + jets + ME_T + X (x9 cross section)
  - trileptons + jets + ME_T + X (x5 cross section)
  - Single production of the second KK excitation (via one loop)
- Detailed simulations are required: CompHEP and PYTHIA implementations now exist

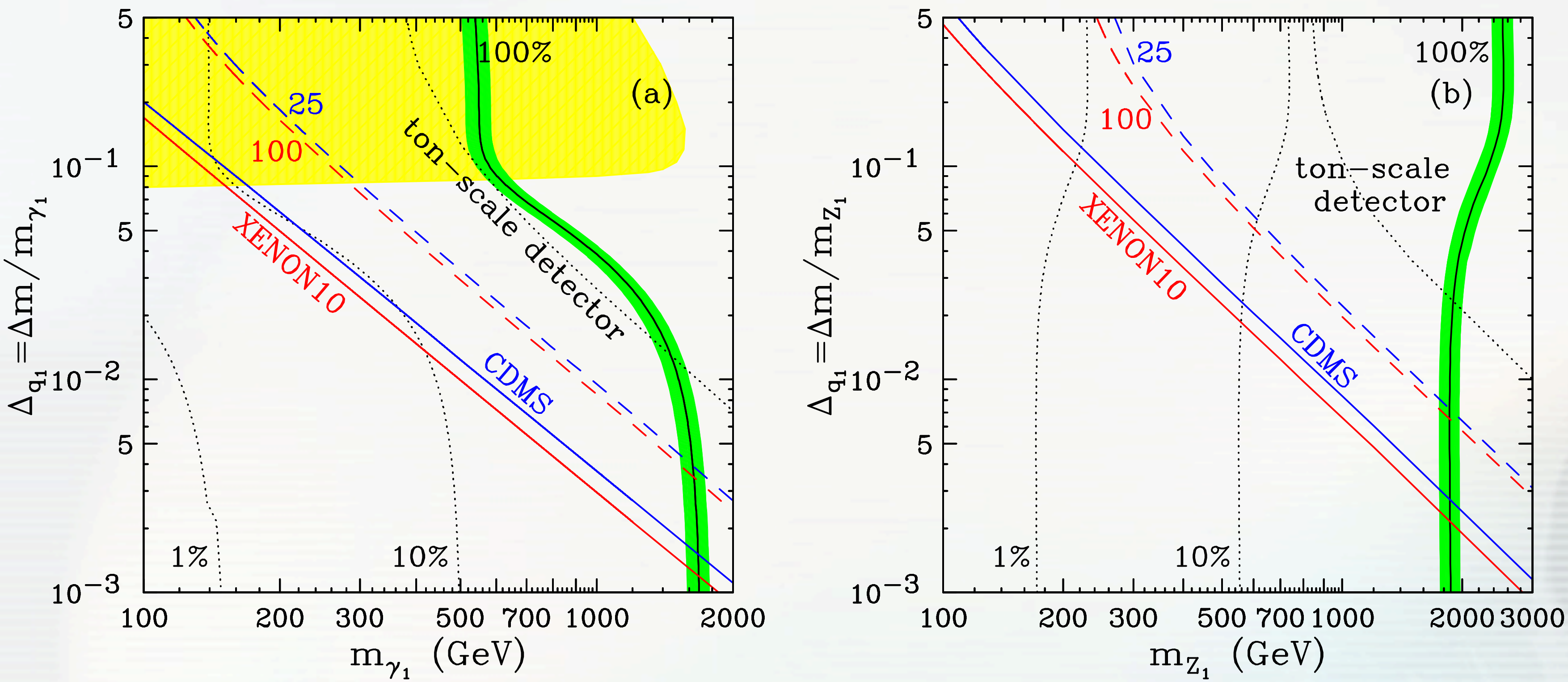
Cheng, Matchev, Schmaltz [PRD **66**, 056006 (2002)]



Complementarity

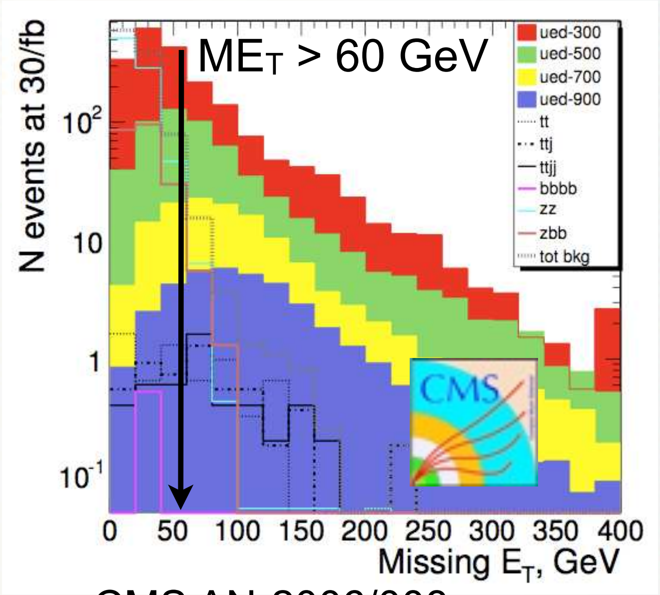
- LHC generally gives stronger mass bounds on the LKP, but the sensitivity stops at low values of q_1/γ_1 splitting
- No dedicated studies on Z_1 LKP at colliders exist as of yet

S. Arrenberg, L. Baudis, K. Kong, K.T. Matchev, and J. Yoo
[Phys. Rev. D **78**, 056002 (2008)]

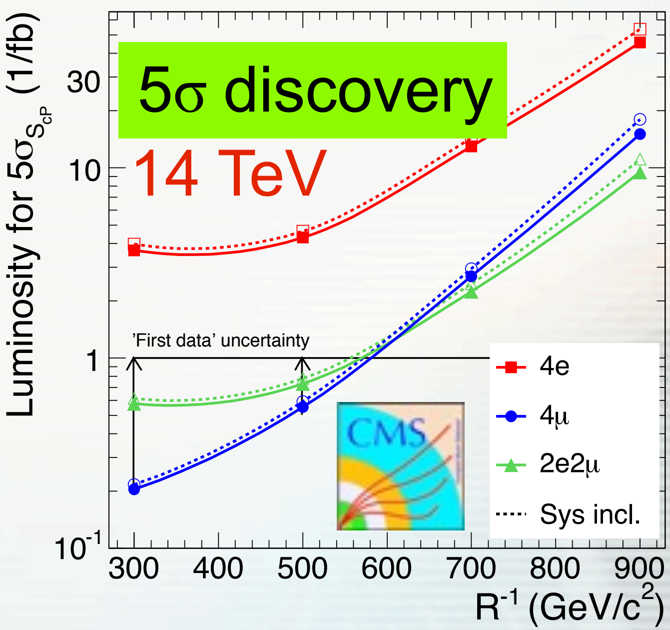


Early UED Searches in CMS

- Consider 4e, 4μ, 2e2μ channels
- Tight selection for low 1/R and looser selection for high 1/R
- Signal is found at low dilepton invariant mass and moderately high missing E_T
- Background is dominated by the physics tt background with extra lepton coming from the b decays
- Start getting into interesting region with a fraction of fb^{-1}
- The reach is being reevaluated for the 7 TeV machine energy
- Also, combination of all three channels is being pursued

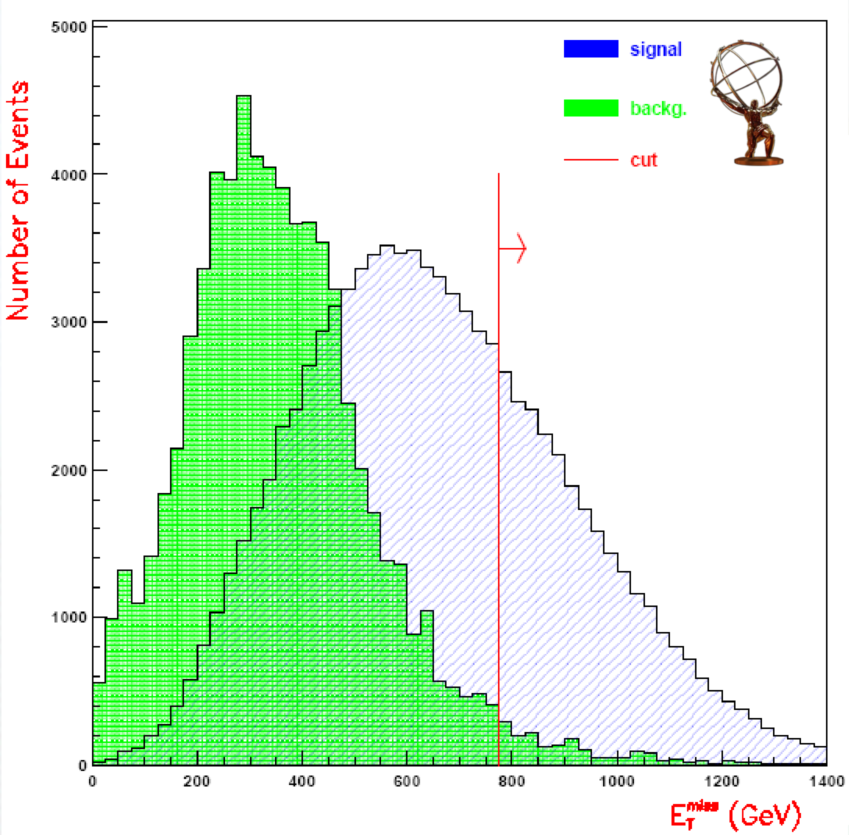


CMS AN-2006/008

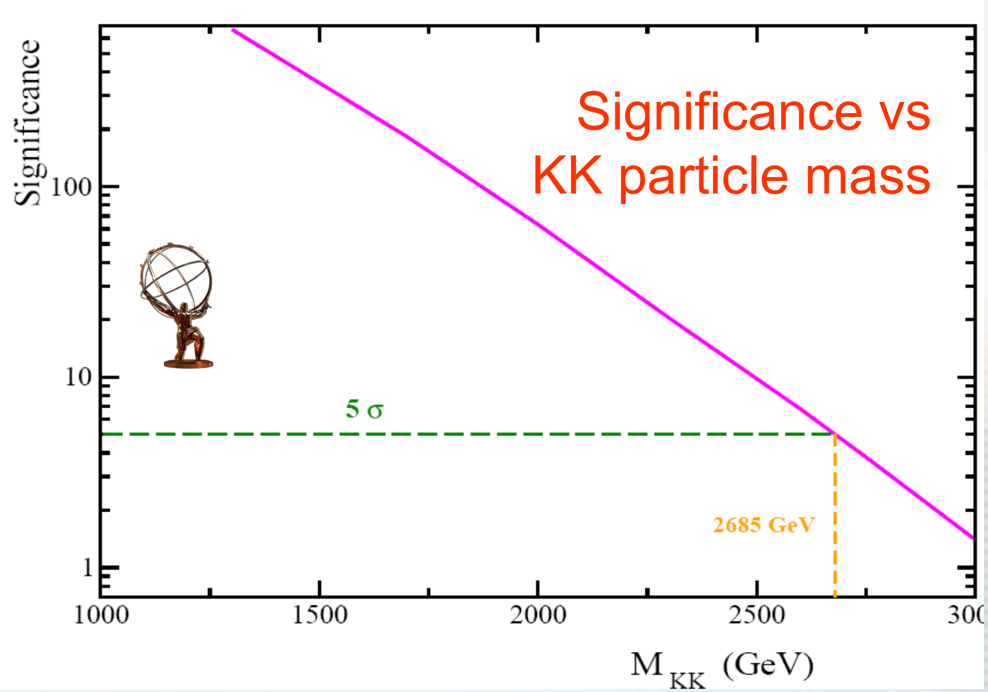


Other Ways of Looking for UED

- KK quarks can decay into a jet and an LKK, resulting in the dijet $+ME_T$ topology
- Look for signal at large ME_T
- For the compactification scale as low as 1.3 TeV, only 6 pb^{-1} is needed; with 100 fb^{-1} the reach up to 2.7 TeV can be achieved



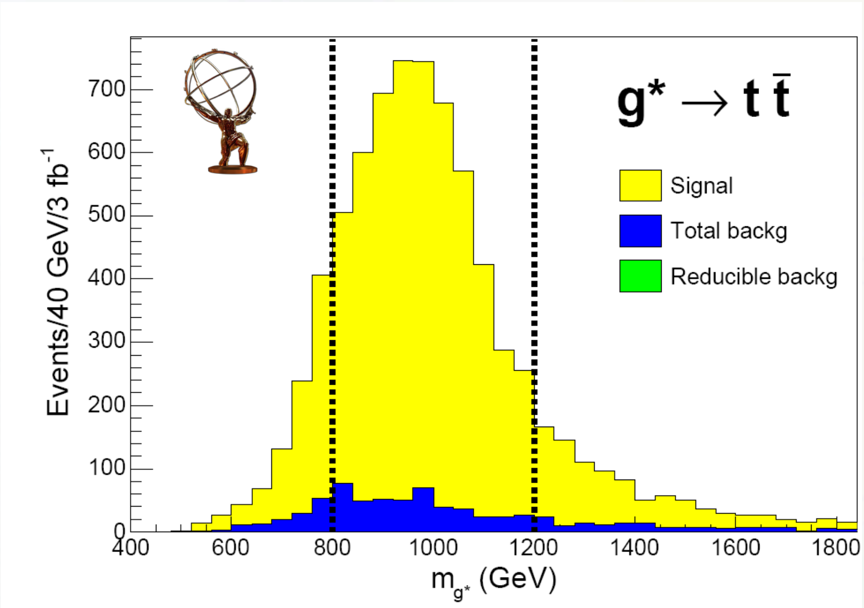
ATL-PHYS-PUB-2005-03

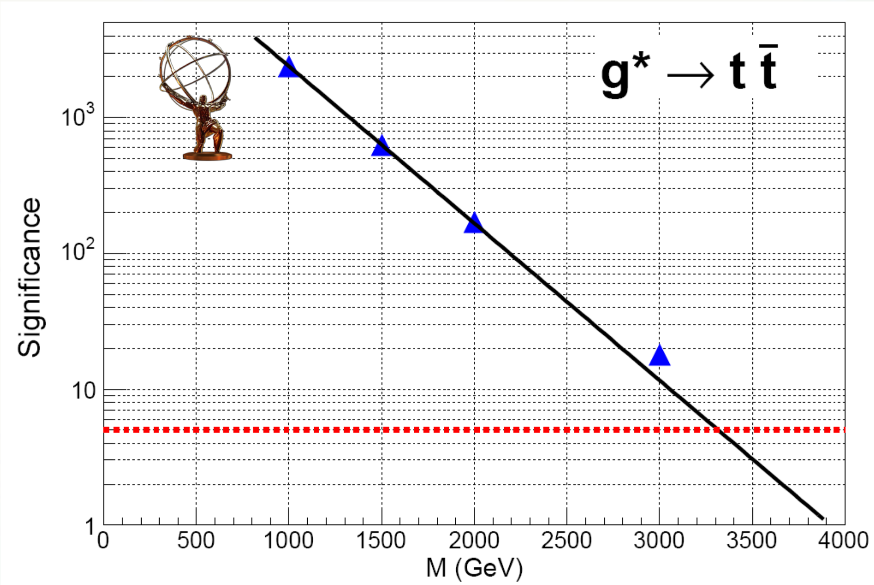


Yet More Ways to find UED

- For certain cases, Kaluza-Klein gluons can decay with KK-parity violation into two heavy quarks (bb or tt)
- Reach up to the g_{KK} mass of 3.5 TeV at 100 fb^{-1}
- Challenge: at high masses, decay products of the top quark are strongly boosted; thus making it non-trivial to reconstruct the final state correctly

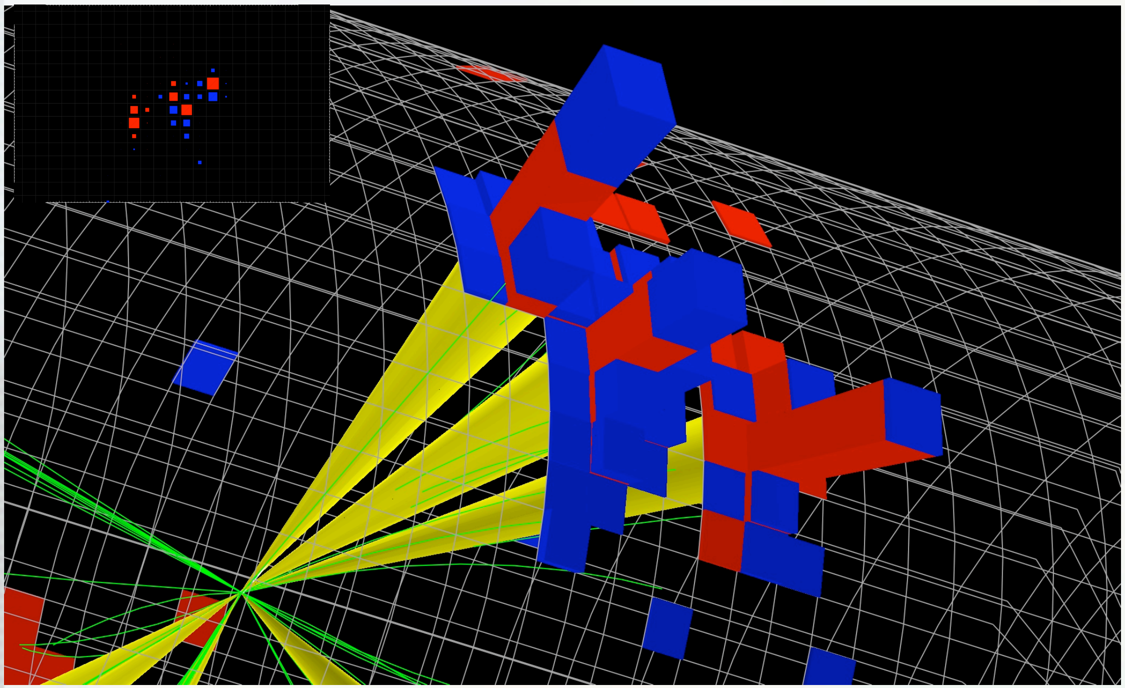
ATL-PHYS-PUB-2006-002

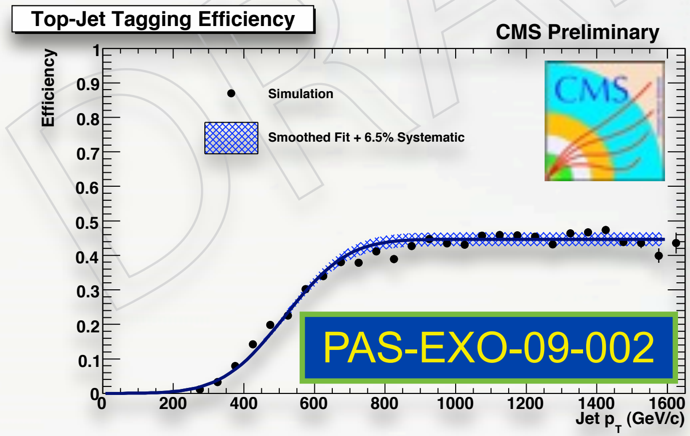


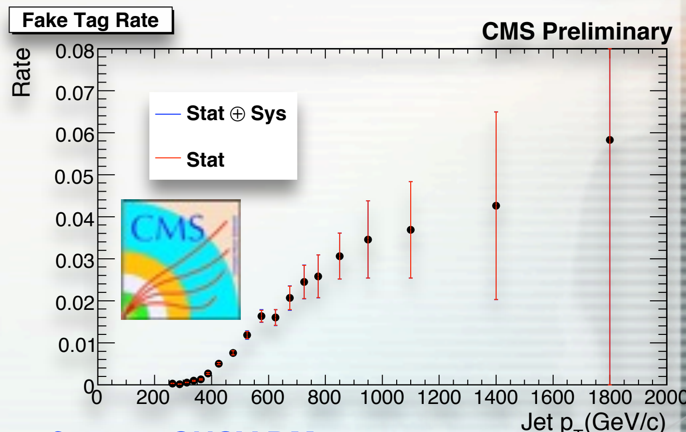


Remedies

- New techniques in jet reconstruction and b-tagging
- Work in progress at both ATLAS and CMS
- Preliminary CMS studies show that boosted top tagging efficiency can reach ~40% with a few per cent mistag rate - similar to b-tagging performance!







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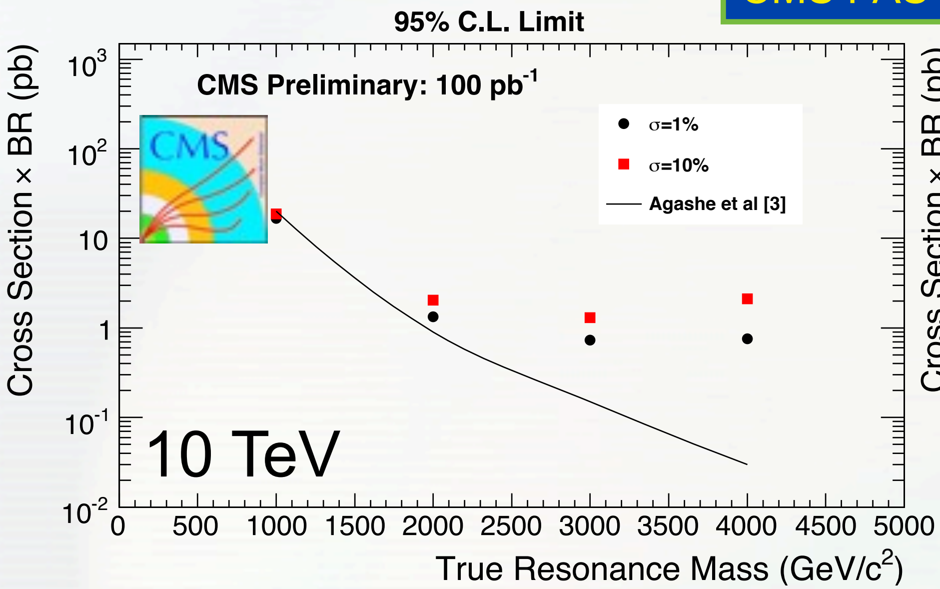
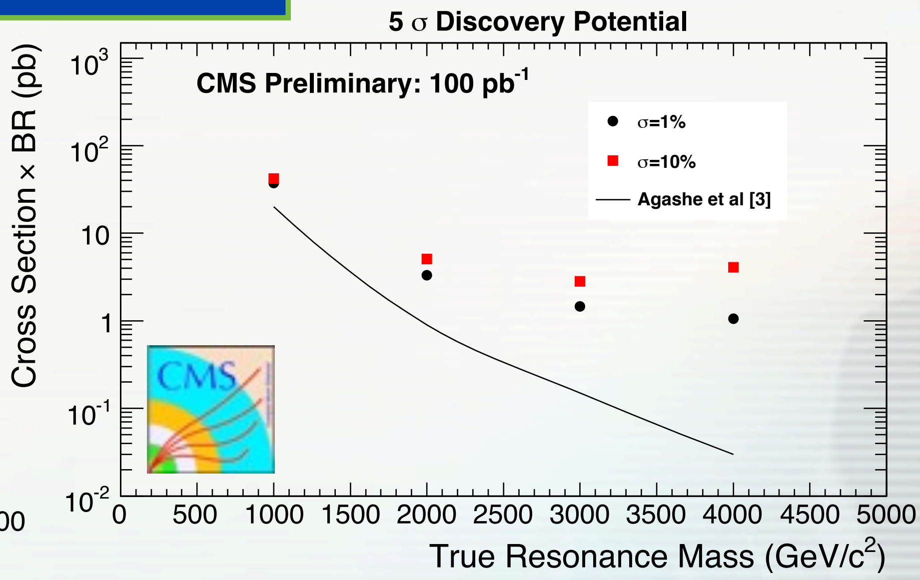
CMS Sensitivity in Boosted Top

- Top-tagging techniques allow to extend the reach to KK gluons in all-hadronic decay mode of the top quarks (two "fat jets")
- A different model was used as a benchmark (RS1), but the production cross section is similar
- Branching fraction into tt in this model is close to 1

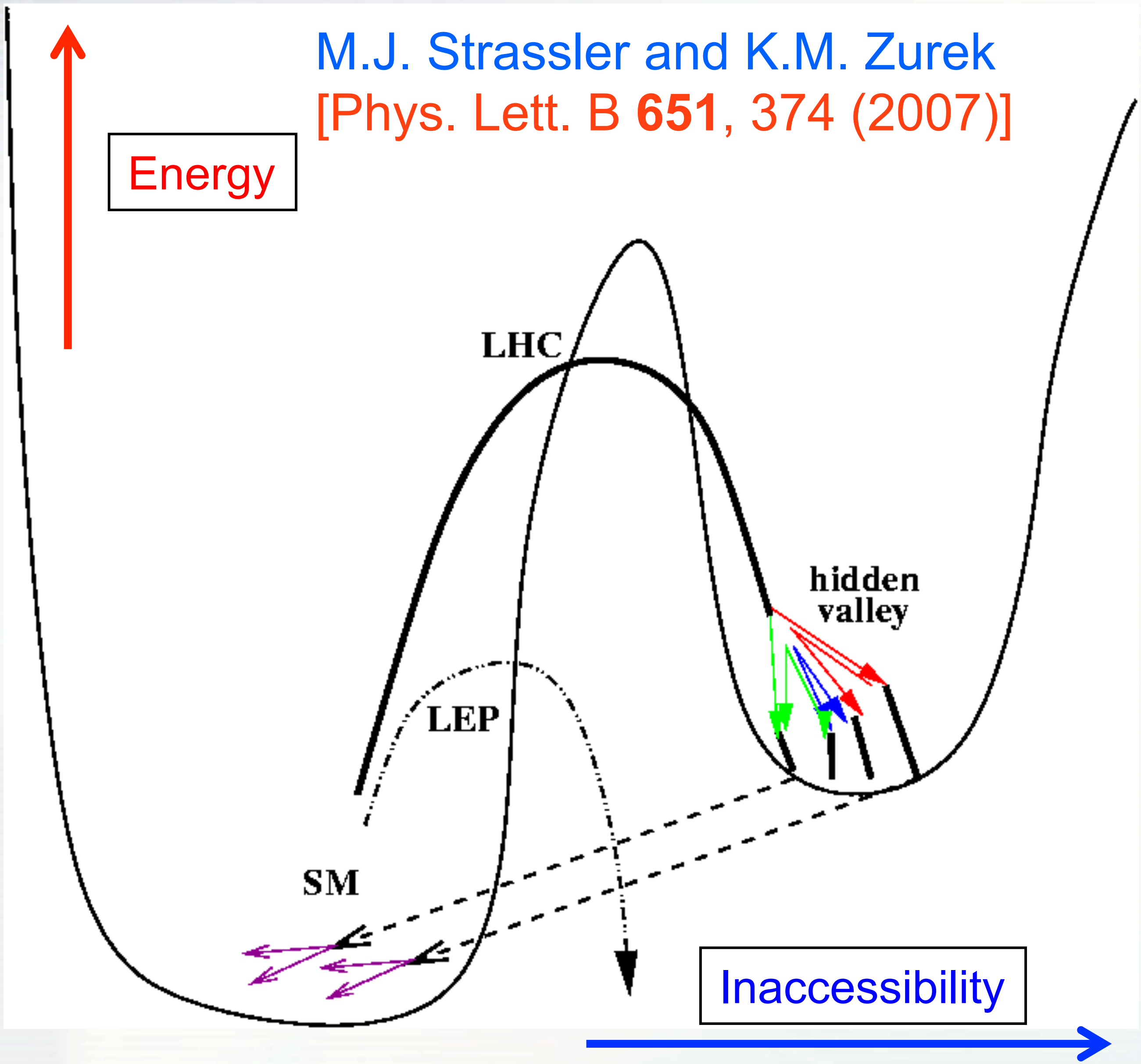
CMS PAS-EXO-09-002





Generic Hidden Valley Models

M.J. Strassler and K.M. Zurek
[Phys. Lett. B **651**, 374 (2007)]



Various communicators are allowed: Z', LSP, Higgses, sterile neutrinos, loops, ...

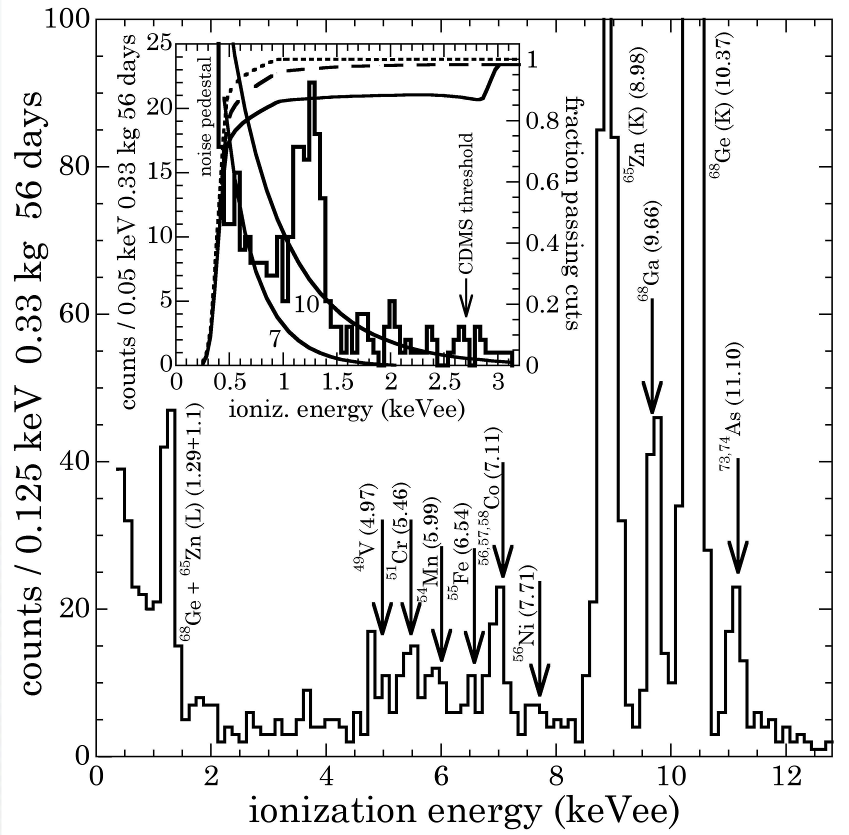
Dark Photons

- New recent class of models inspired by PAMELA and ATIC excess, along with DAMA annual variation, INTEGRAL excess, WMAP haze, and EGRET excess
- Propose a light (~1 GeV) U(1) boson in the "dark sector"
  - N. Arkani-Hamed and N. Weiner [JHEP **0812**, 104 (2008)]
  - N. Arkani-Hamed, D.P. Finkbeiner, T.R. Slatyer, and N. Weiner [Phys. Rev. D **79**, 015014 (2009)]
  - M. Pospelov, A. Ritz [Phys. Lett. B 671, 391, (2009)]
- Large co-annihilation cross section due to Sommerfeld enhancement
  - Needed to explain the rates in ATIC/PAMELA
- Large leptonic branching fraction due to direct decays into pair of leptons
  - Needed to explain the positron excess

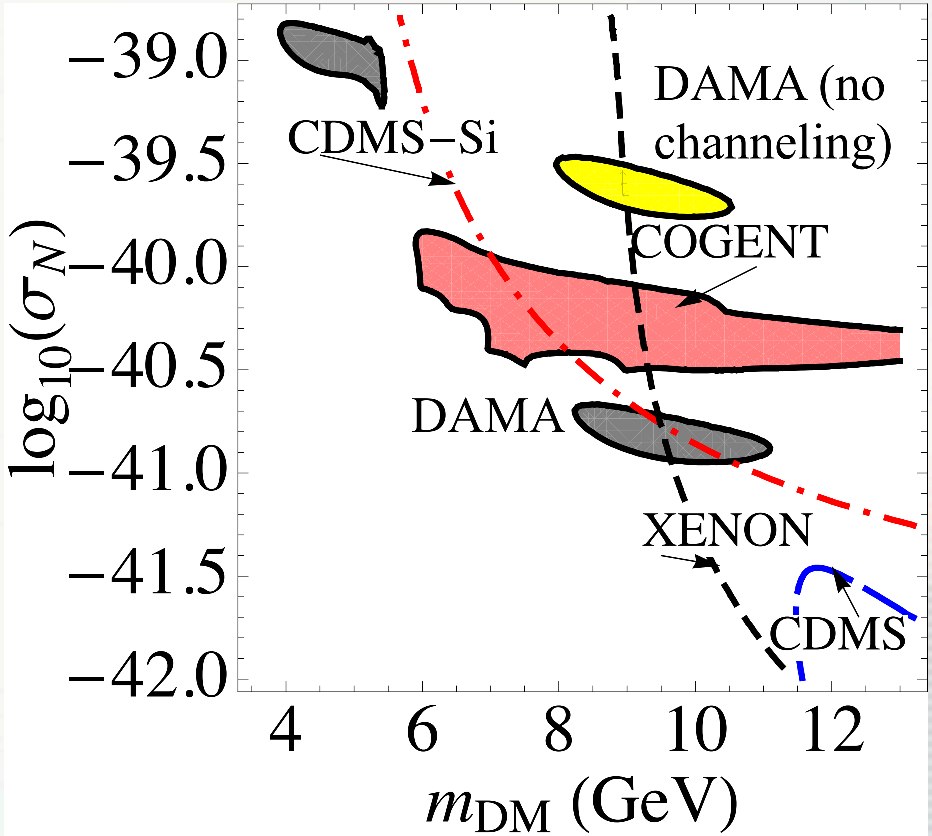
CoGeNT and Light DM

- Very recent CoGeNT results can be interpreted as a signal of a ~10 GeV scalar DM particle, together with DAMA data with small fraction of "channeled" events

CoGeNT [arXiv:1002.4703]

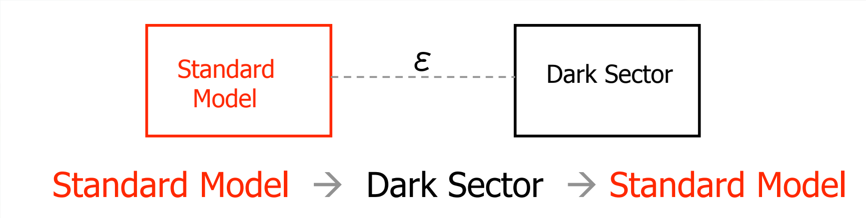


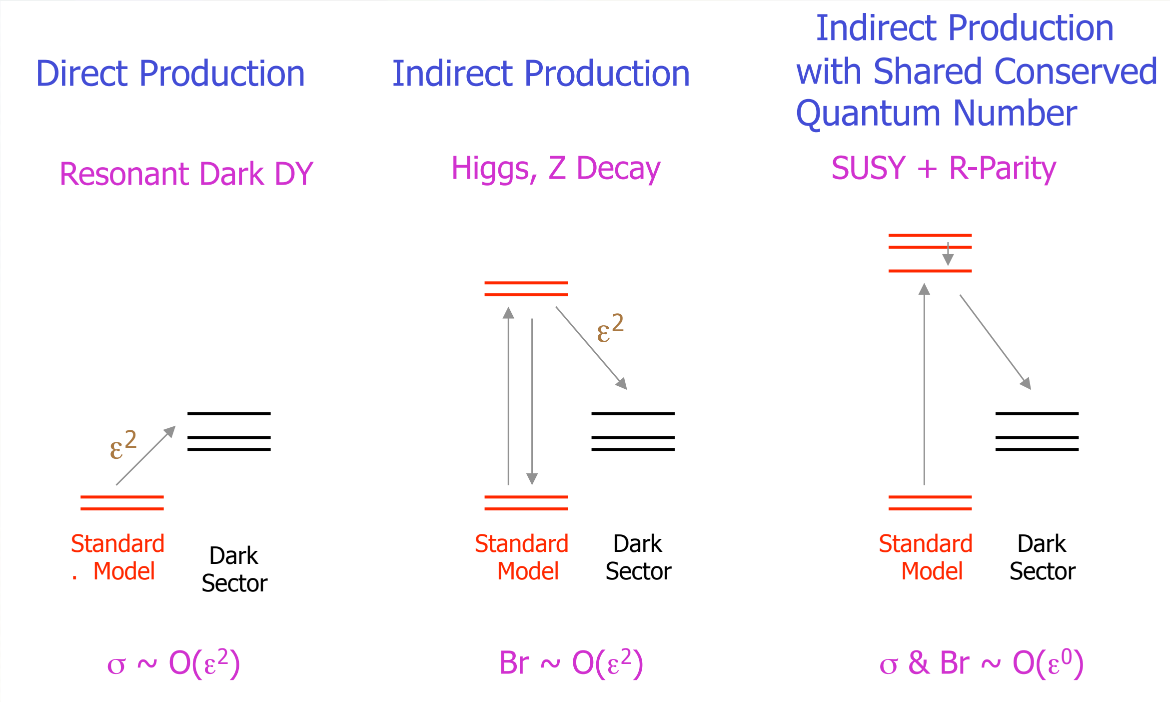
A. Liam Fitzpatrick, D. Hooper, and K.M. Zurek [arXiv:1003.0014]



Collider Phenomenology - I

- Dark sector is weakly (ε) coupled to the Standard Model
- To study dark sector with colliders, one needs mechanisms to produce dark sector particles

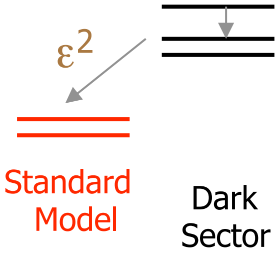




For more details, see Y. Gershtein, Dark Forces Workshop http://www-conf.slac.stanford.edu/darkforces2009/

Collider Phenomenology - II

- One further needs them to decay into SM particles



If No Dark Decay Mode Open – Dark Sector State Can Decay Back to Standard Model Through Portals

Guaranteed for LDSP if no Conserved Quantum #

All, Some, or None of the Dark Sector States May Have Prompt Decays Back to the Standard Model

Very Wide Range of Possibilities Depending On:

Production Portal

Dark Spectrum

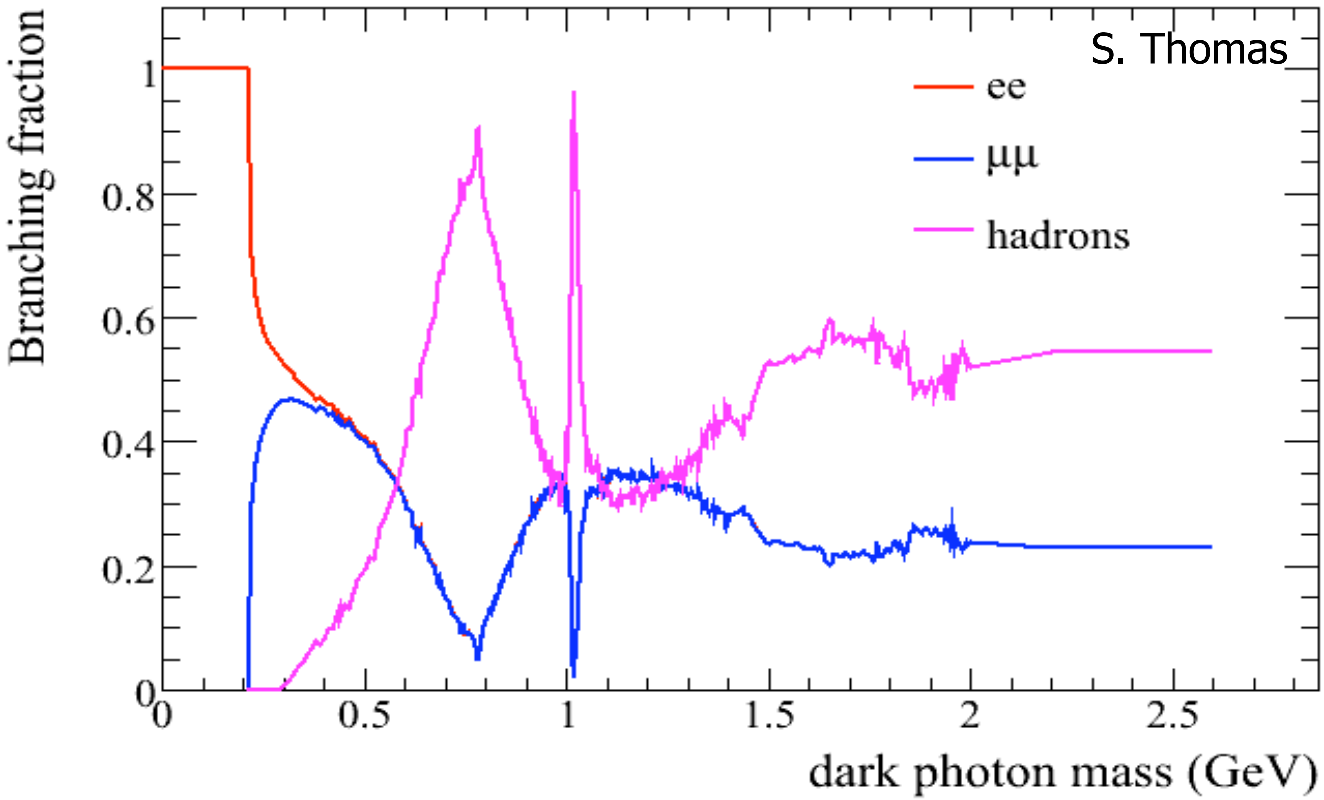
Dark Cascade Decays

Dark Showering

Decay Portal

Dark Photon Decays

- Dark photon decays through its mixing with light photon, so its branchings can be calculated from measurement of R
- for $\varepsilon > 10^{-4}$ decays are prompt

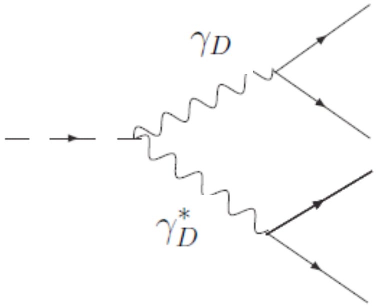


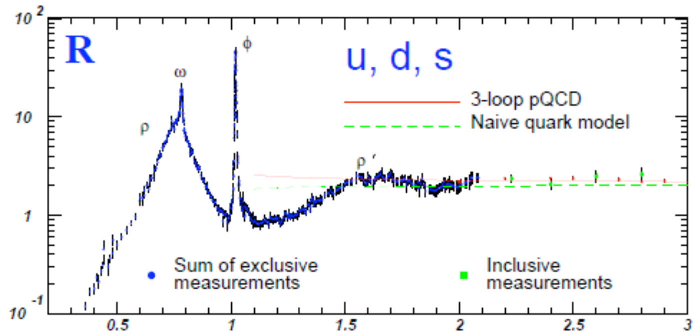
- Experimental signature: two very close leptons or hadrons

There Could be Dark Higgs...

Dark Higgs Decays

- Dark Higgs should be at same scale O(GeV)
- can decay in the dark sector similarly to ours Higgs
  - if $m_h > 2m_{\gamma d}$ decay into two dark photons open
  - if $m_{\gamma d} < m_h < 2m_{\gamma d}$ decays through $\gamma_D{}^*$ - mostly through hadronic resonances
  - if $m_h < m_{\gamma d}$ then can decay into SM fermion pairs (possibly with very long lifetime) or stays in the dark sector

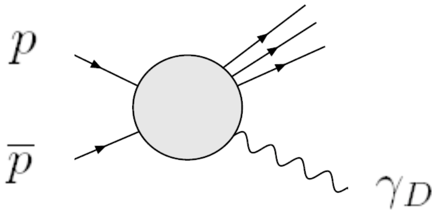


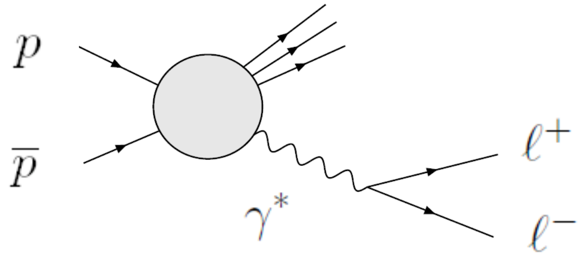


- experimental issues with non-isolated spatially close lepton pairs, especially with hadronic dark photon decays

Possible Final States

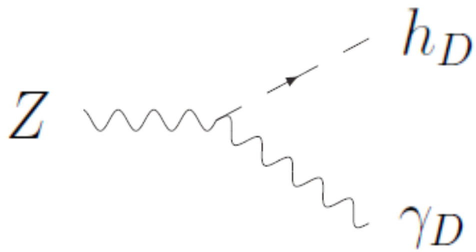
- Direct dark photon Drell-Yan production





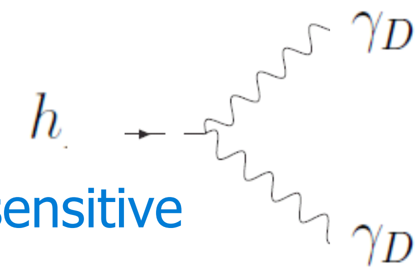
  - swamped by background?

- Rare Z decays



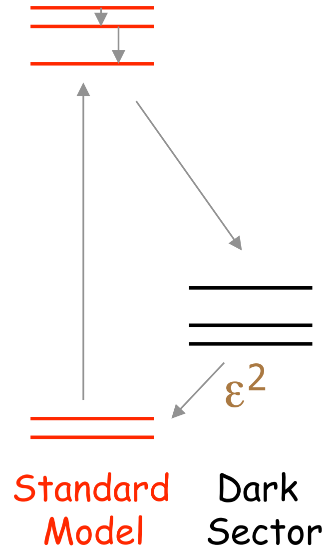
  - very low event yield, but several mass peaks – dark photon, dark higgs, and, finally, Z itself (doable?)

- Higgs decays
  - h→4 leptons
  - DZero h→4μ search is ~sensitive



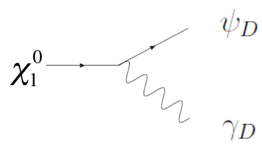
Benchmark Model

- Supersymmetry with conserved R-parity
  - lightest neutralino in our sector is no longer LSP
  - will decay into the dark sector
  - some of the dark states may decay back into SM

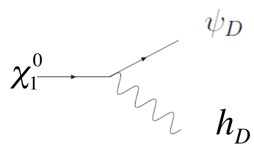


- Assuming that some dark states decay back, all SUSY signals at colliders (no matter what is SUSY phenomenology) will have those
  - phenomenology may be quite striking

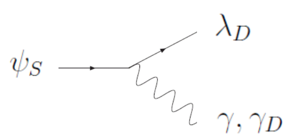
- Bino → Darkino plus Dark Photon
  - every event has
    two isolated dark photons plus MET



- Higgsino → Darkino plus Dark Higgs
  - every event has
    two isolated "lepton jets" plus MET



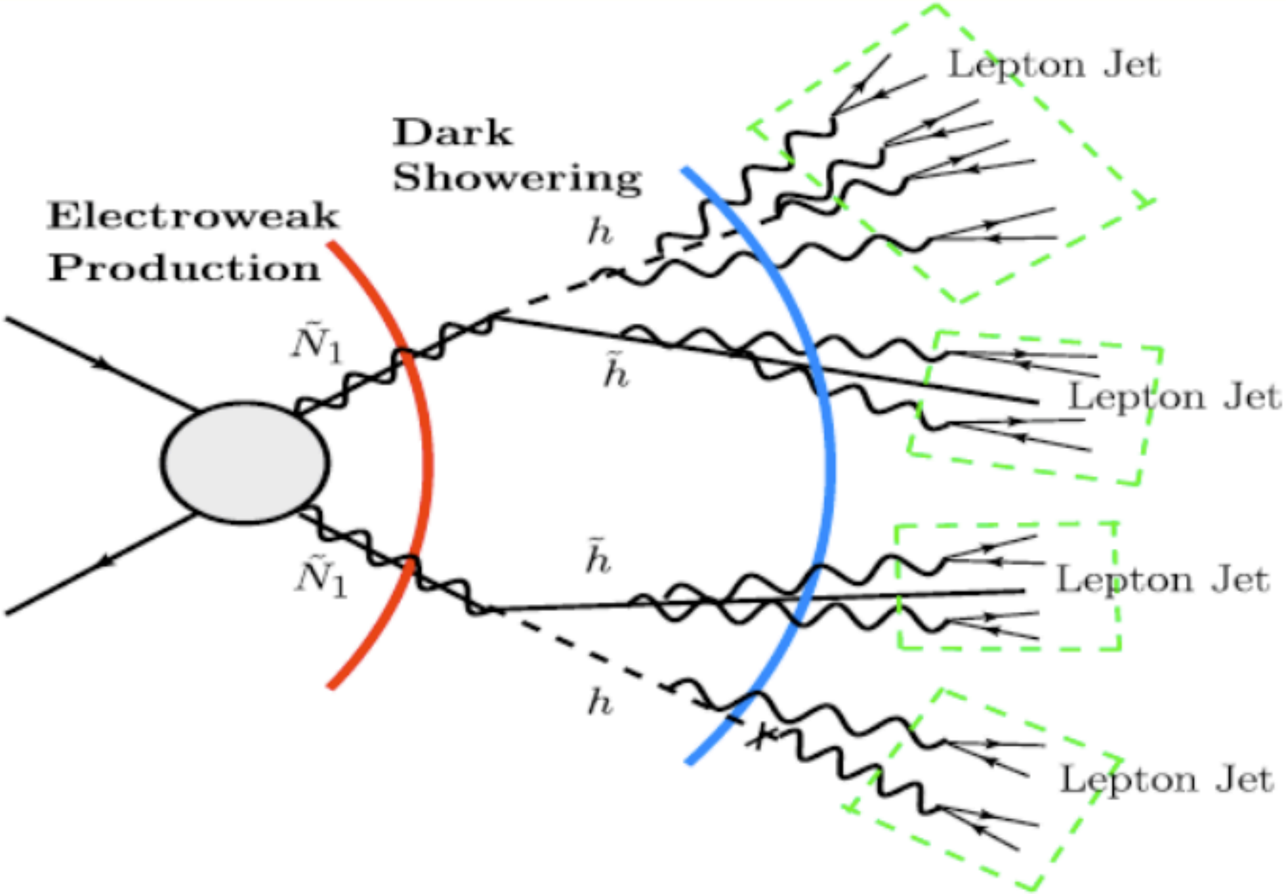
- SM Singlet → Darkino plus Photon or Dark Photon
  - every event has
    two isolated dark or light photons plus MET



$$\mathrm{Br}(\psi_S \to \lambda_D \gamma) + \mathrm{Br}(\psi_S \to \lambda_D \gamma_D) \simeq 1$$

Dark Showering

- Showering in the hidden sector may create even more complex signatures ("lepton jets")

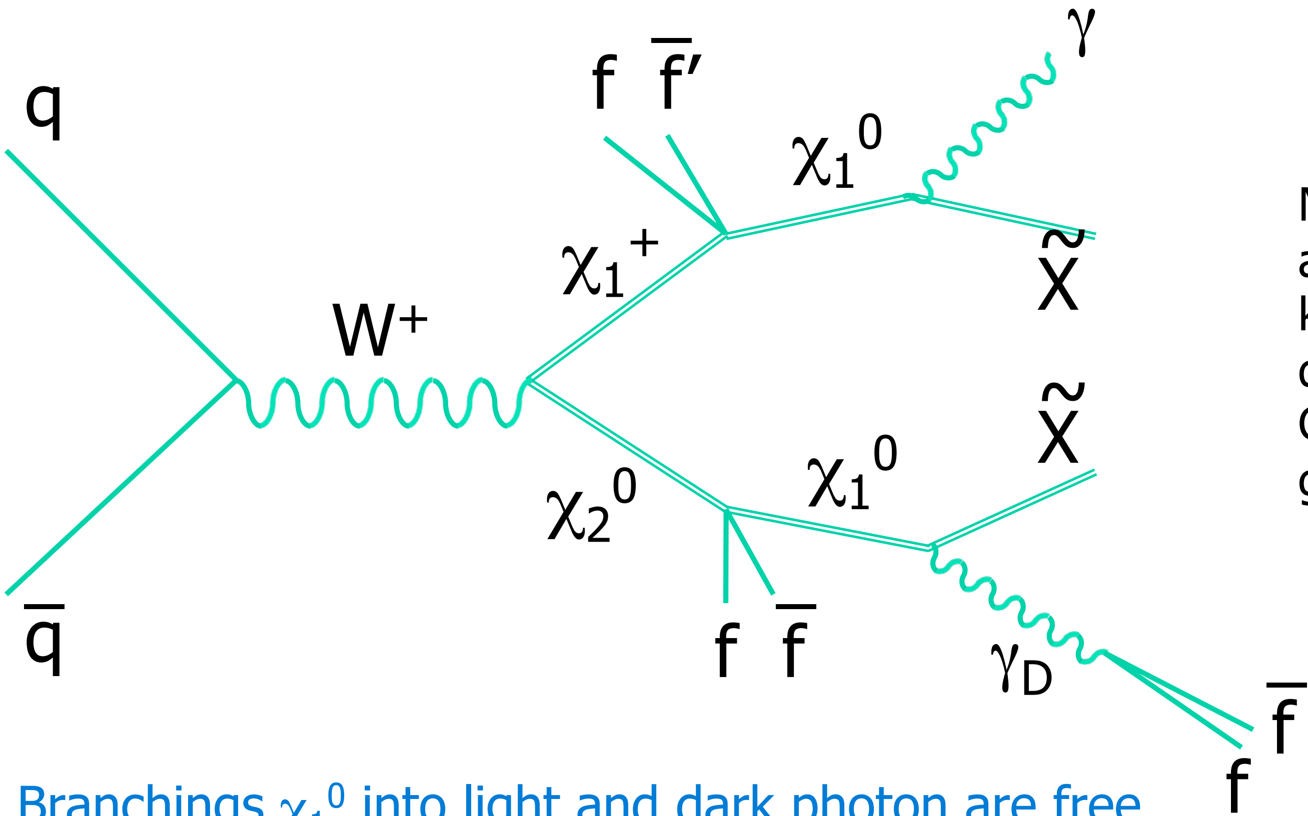


M. Baumgart, C. Cheung, J. T. Ruderman, L. T. Wang and I. Yavin 0901.0283 [hep-ph]

C. Cheung, J. T. Ruderman, L. T. Wang and I. Yavin 0909.0290[hep-ph]

Tevatron Search

- DZero analysis, assumes SUSY and Hidden Sector

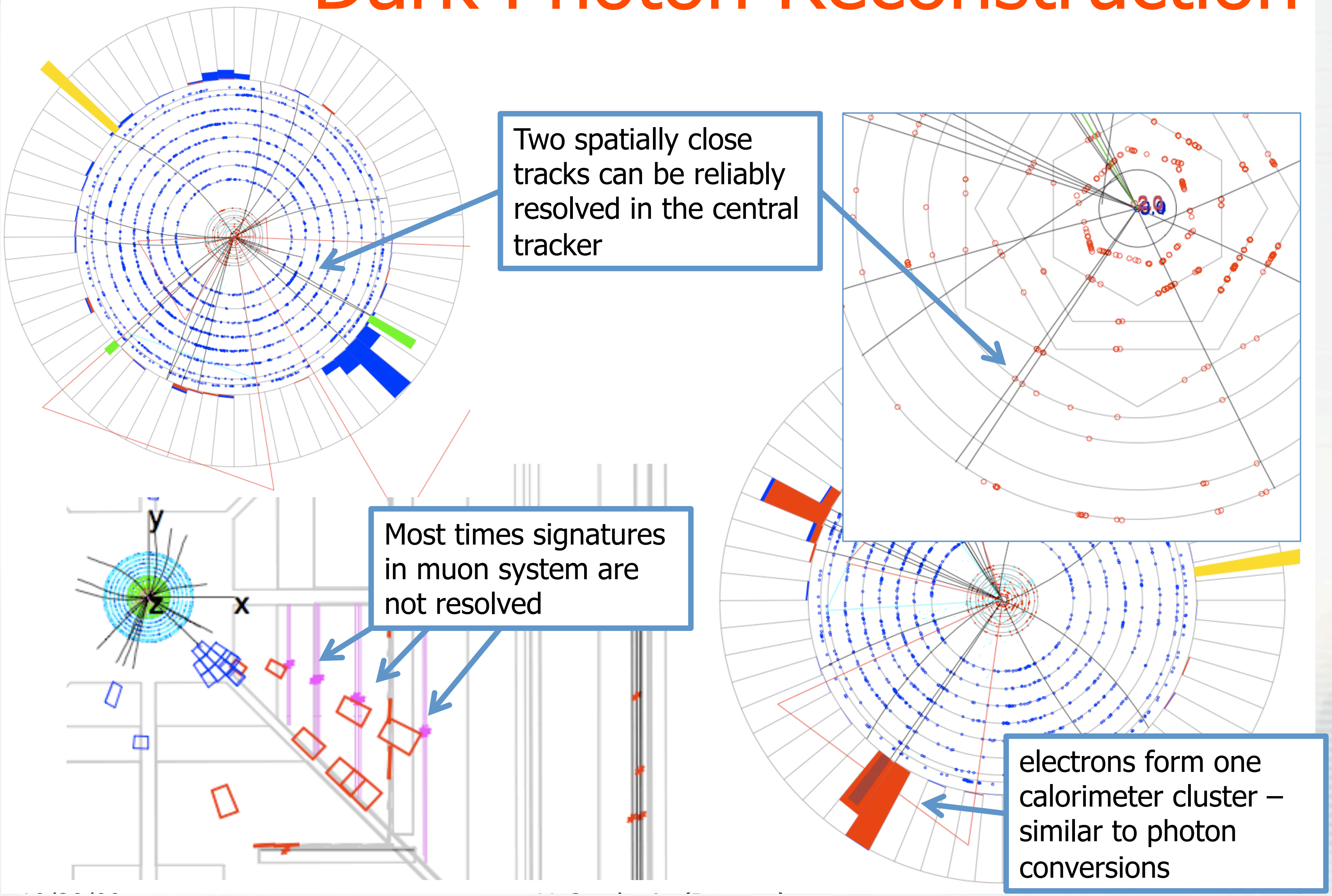


M(X) = O(GeV)
assume kinematics of the decay identical to GMSB decays into gravitino

- Branchings χ_1^0 into light and dark photon are free (depend on how large is α_{dark} compared to our α.
- These two decays dominate in large fraction of parameter space
- For large Br into light photon -> identical to GMSB

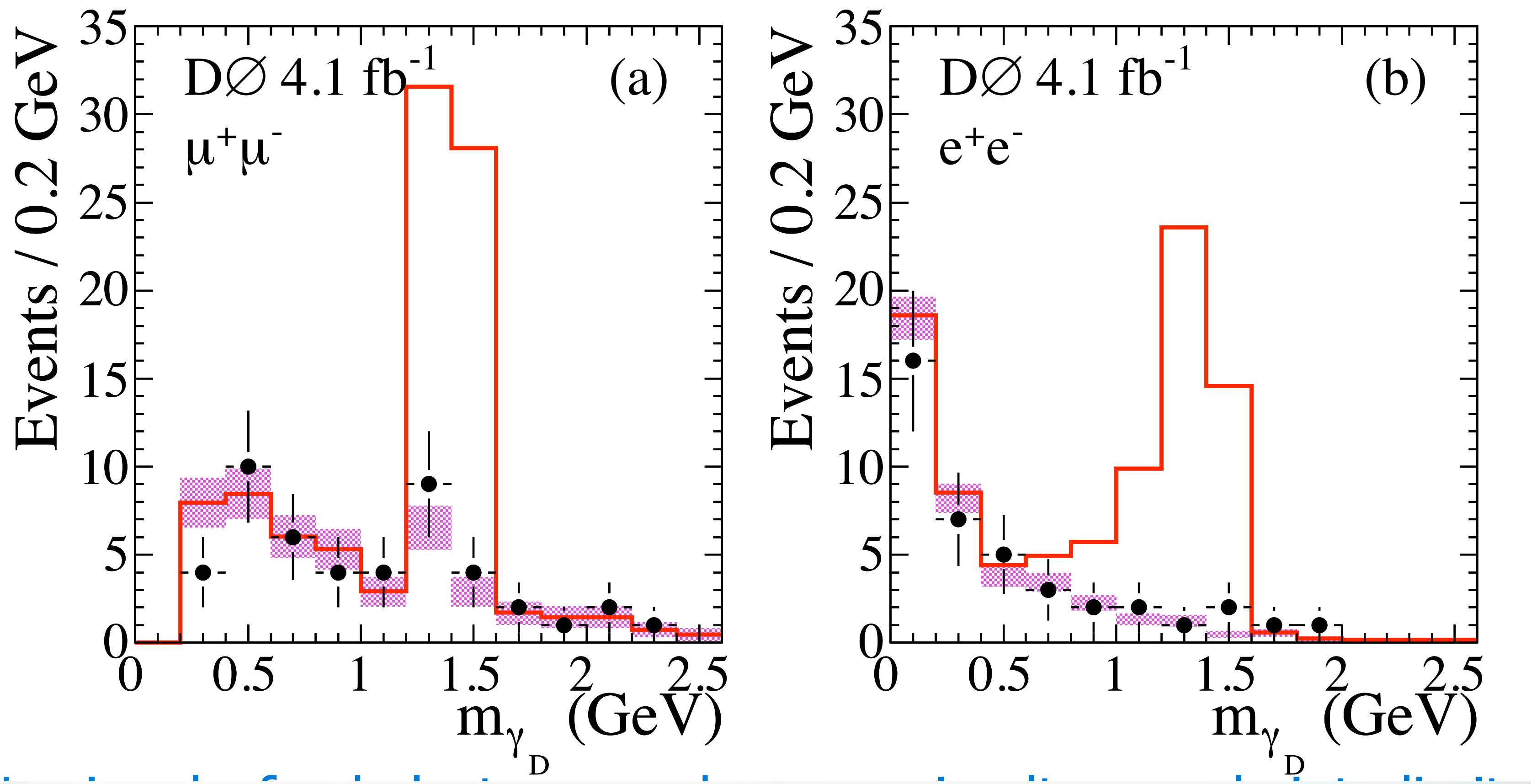
Experimental Signature

Dark Photon Reconstruction

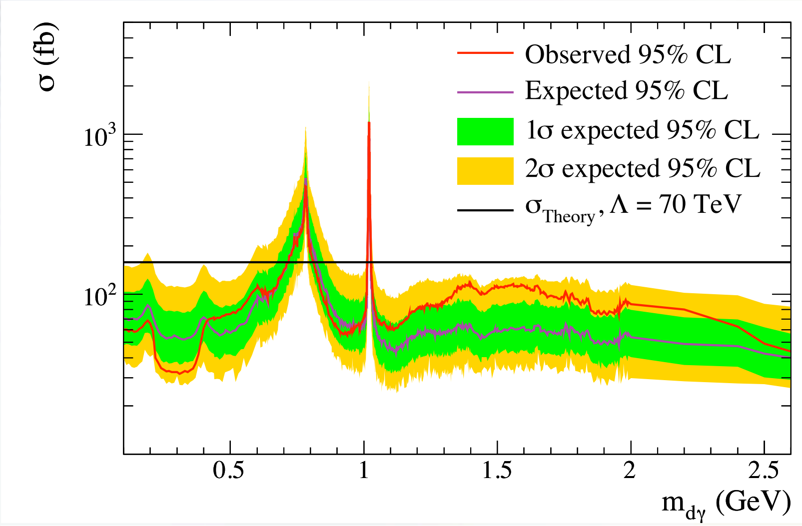


Search Results

- Look for close-by pair of muons and electrons
- Data agree with the SM predictions

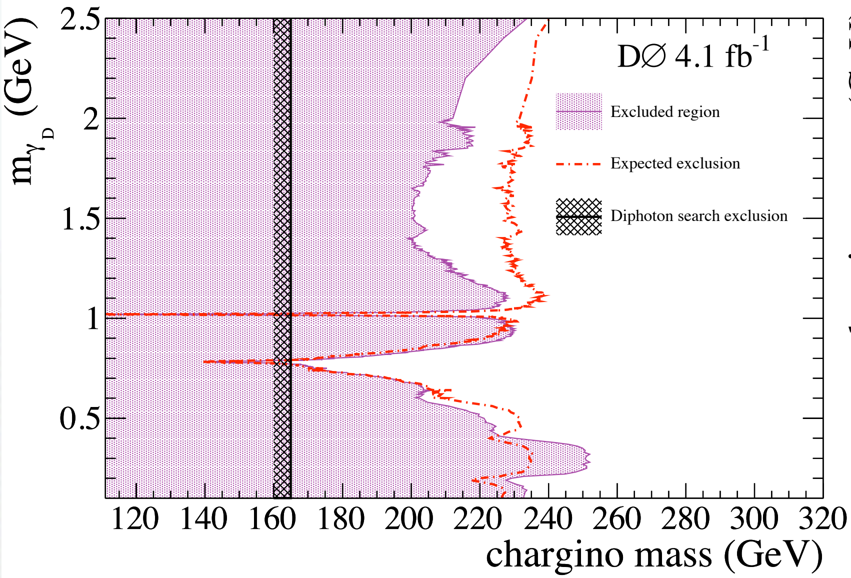


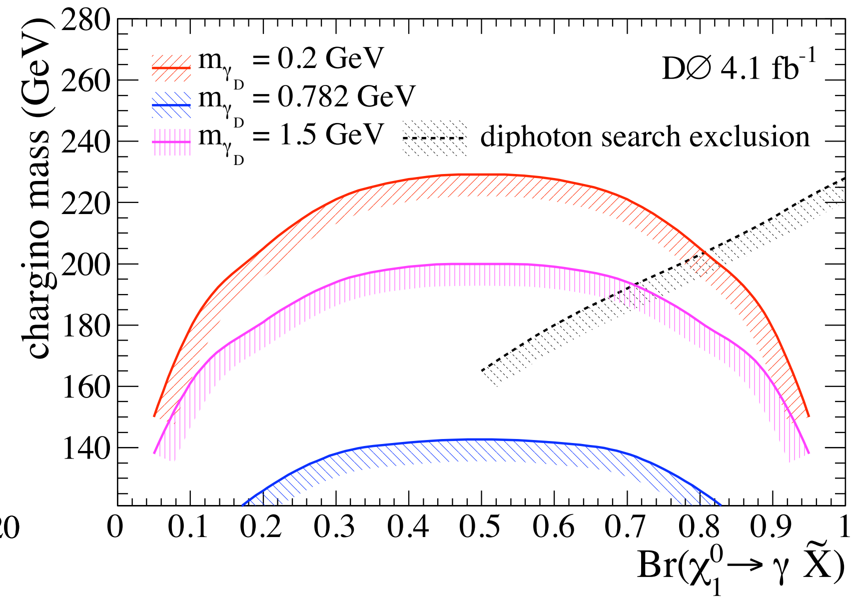
Setting Limits



- Limits depend on dark photon mass strongly due to meson resonances decaying leptonically (ρ, ω, φ, ...)

Br(χ_1^0 → dark photon) = 0.5





Phys. Rev. Lett. 103, 081802 (2009)

Outlook

- LHC successfully started operations last year
- The machine is being commissioned for 1.5-year long 7 TeV run with ~1 fb^{-1} of data expected by the end of 2011
  - Watch for big media event at the end of this month!
- Both ATLAS and CMS pursue searches in models with hidden valleys, including the above benchmark example
  - Some signatures of hidden valleys can be pretty challenging and require special triggers, now implemented in both experiments
- Yet, there will be a long way from a discovery of an excess to DM interpretation and DM parameter determination
  - May require combination with astrophysical results and/or a dedicated machine, such as linear collider

Conclusions

- While SUSY remains an attractive theoretical possibility and provides an excellent DM candidate, modern model-building offers viable alternatives to SUSY
- Particularly, KK DM and light Hidden Valley DM offer more flexibility in explaining recent excesses observed in several experiments
- Both these classes of models have rich phenomenology at colliders, particularly at the LHC and are being vigorously sought experimentally
- Collider searches are largely complementary to direct and indirect DM detection
- It's likely that all three approaches will need to come together to determine the true nature of DM