Non-SUSY Searches

Yuri Gershtein

Outline

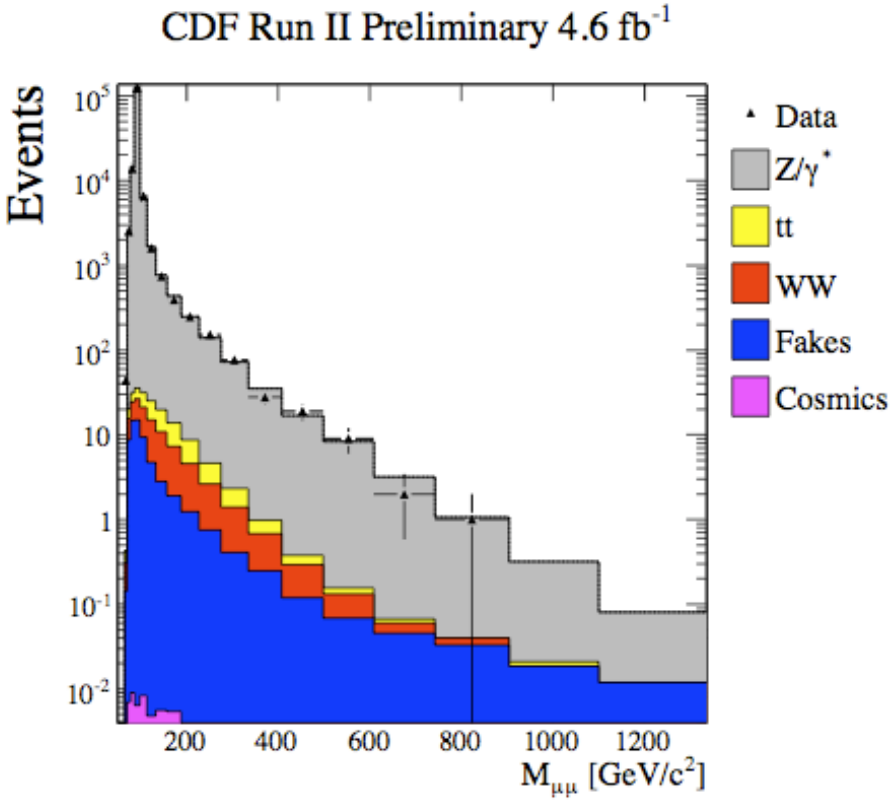
Even if SUSY exist it is unlikely to be the whole story (i.e. flavor)

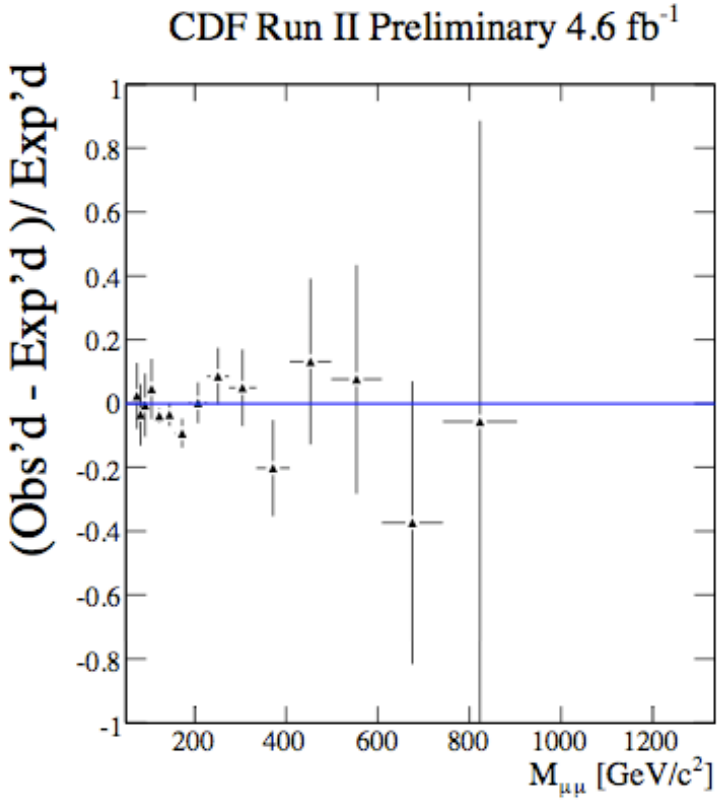
- Extra dimensions
- Extra gauge bosons
- New strong dynamics & leptoquarks
- Extra – and well-hidden! – sectors
- Outlook

A lot of "legacy" Tevatron searches
I will try not to be too Tevatron-centric…
For **more on Tevatron non-SUSY** results please attend parallel presentation by **Eva Halkiadakis** this afternoon
Exciting neutrino results on Monday

Extra Gauge Bosons

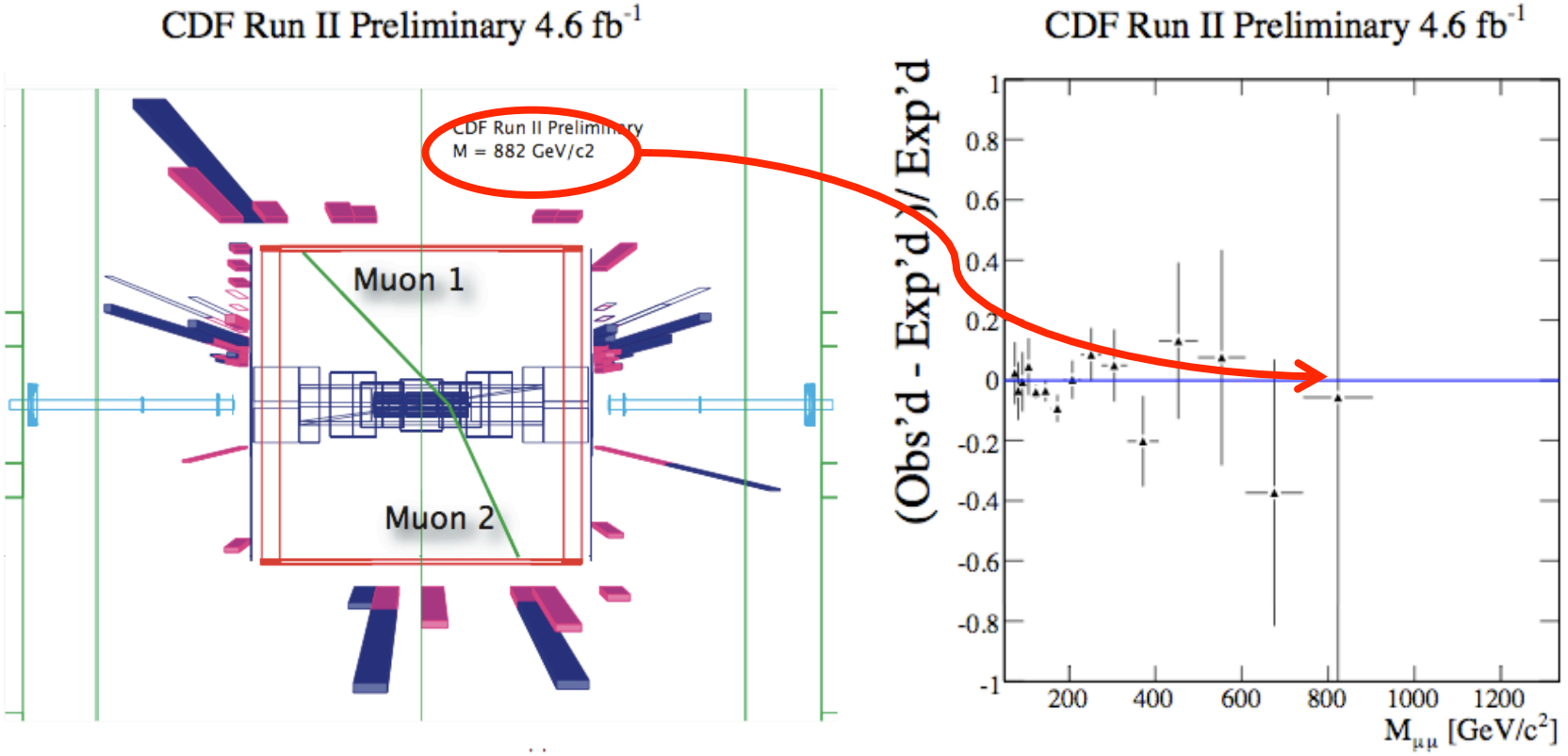
- A staple energy frontier measurement – check if the high energy tails are described





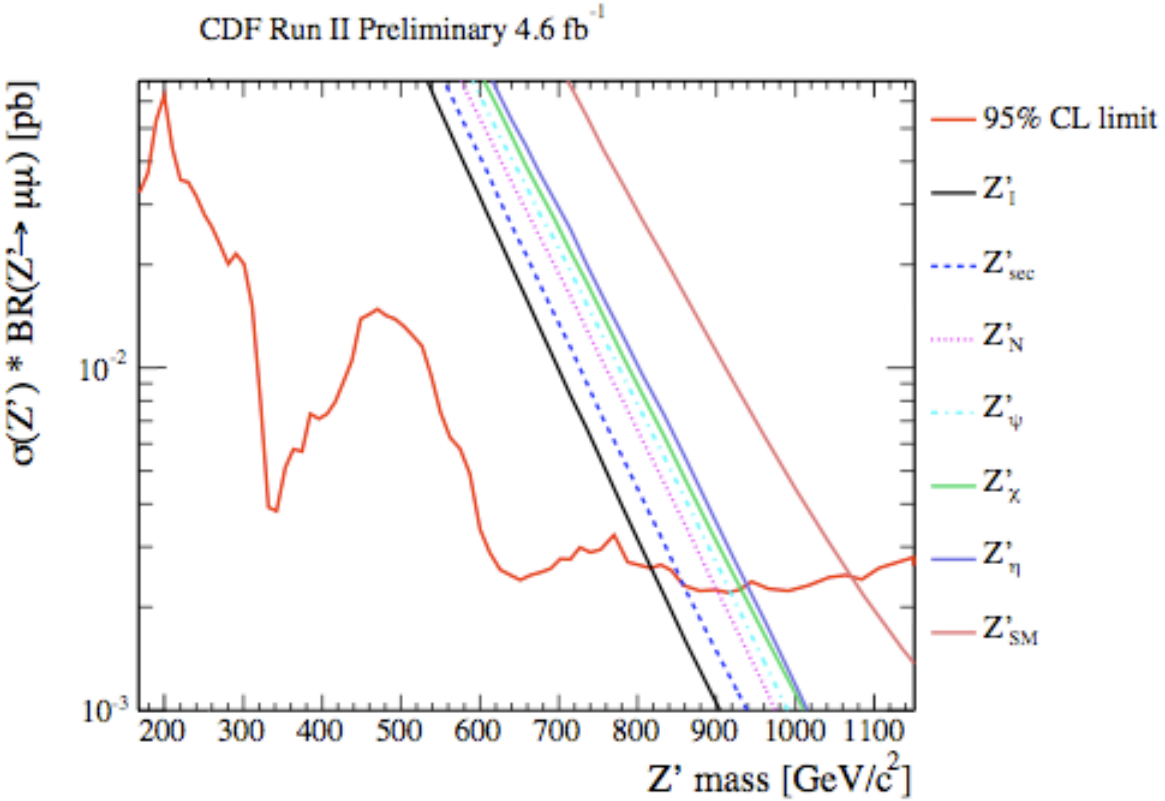
Extra Gauge Bosons

- A staple energy frontier measurement – check if the high energy tails are described



Extra Gauge Bosons

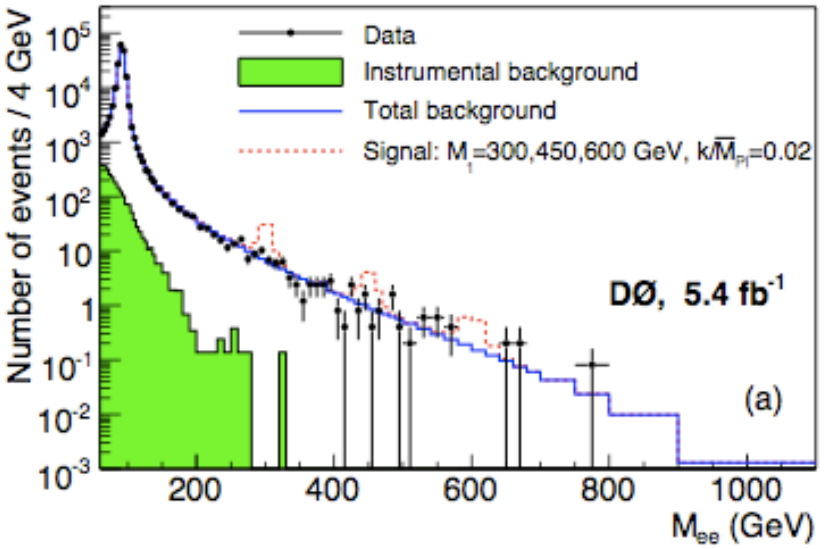
- A staple energy frontier measurement – check if the high energy tails are described



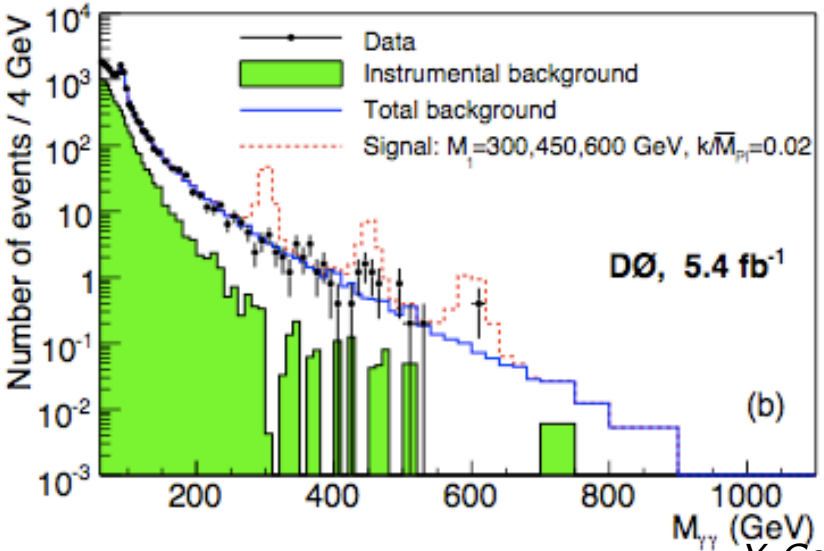
Sequential Z' limit at 1.1 TeV

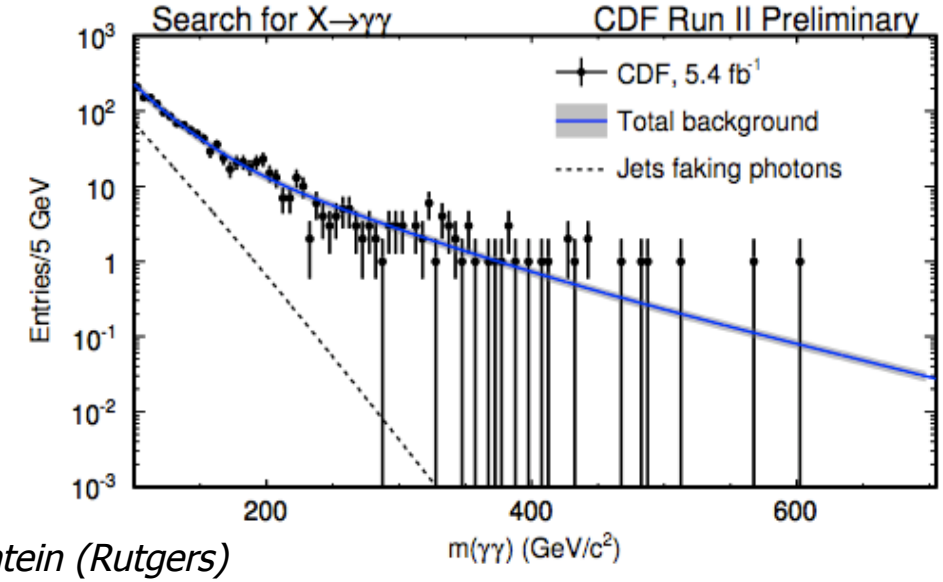
legacy Tevatron measurements

RS Gravitons

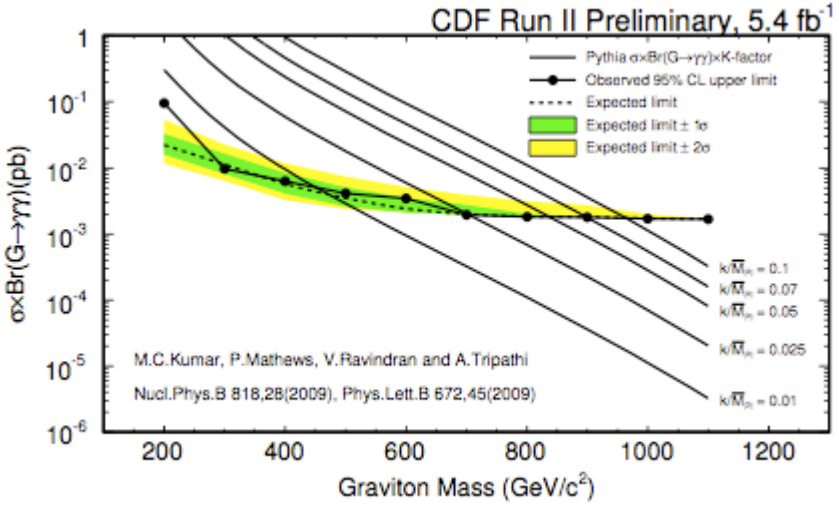


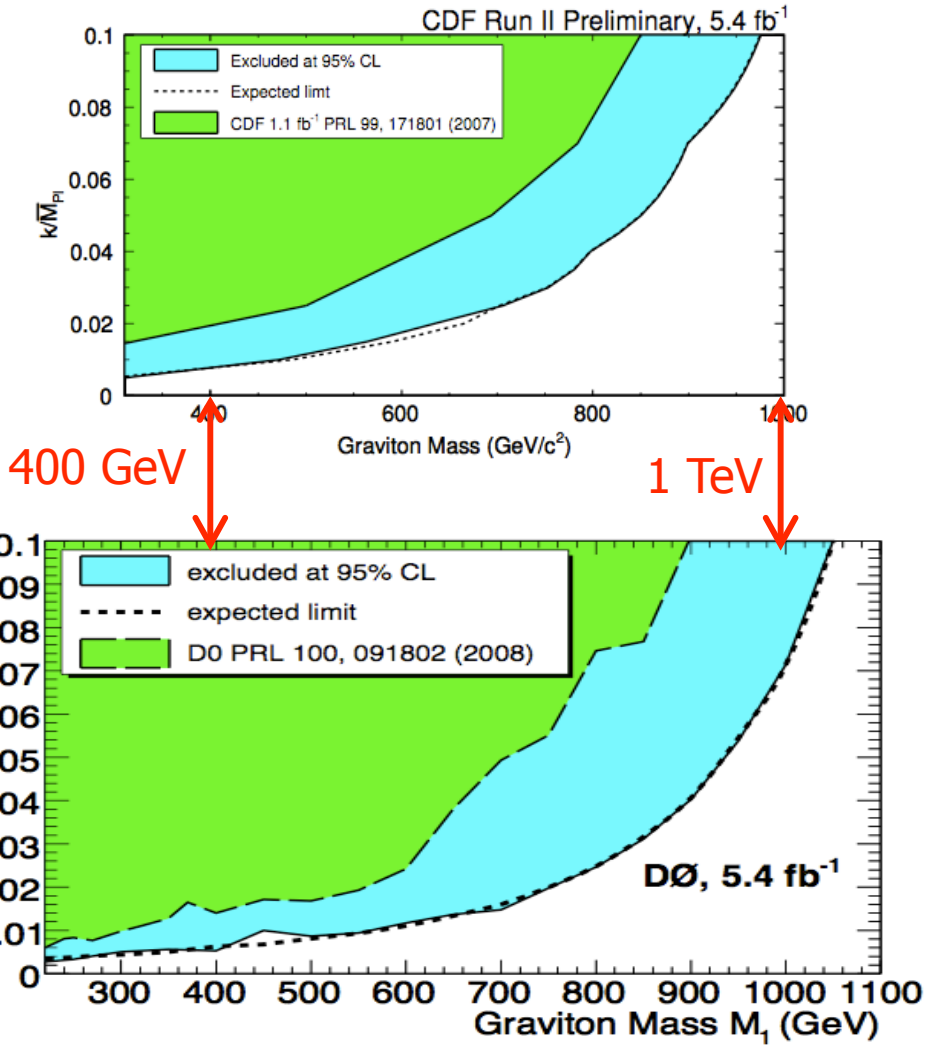
- single warped extra dimension – only graviton propagates in it
  - tower of KK excitations with a ~TeV separation
- Decays to SM particles: i.e. di-leptons, but branching into photons larger
- highest di-electron mass ~800, di-photon ~600 GeV





RS Gravitons





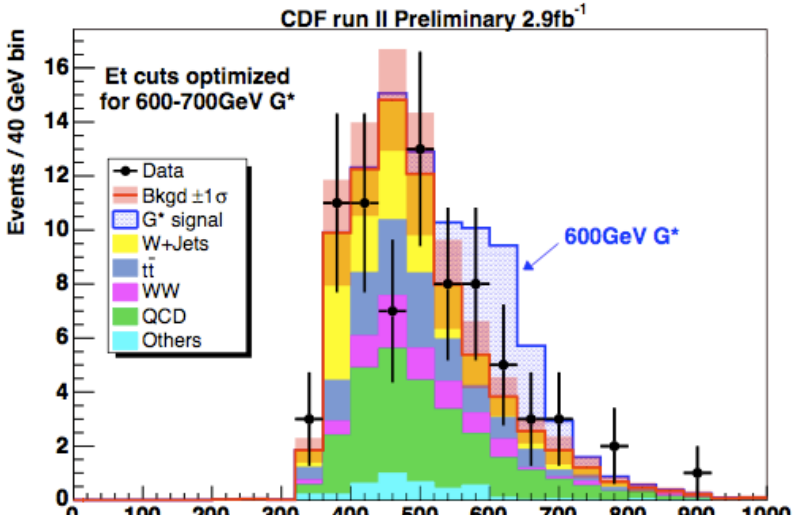
- k is the curvature of the warped dimension
- k/M_{Pl} is dimensionless coupling to particles on SM brane

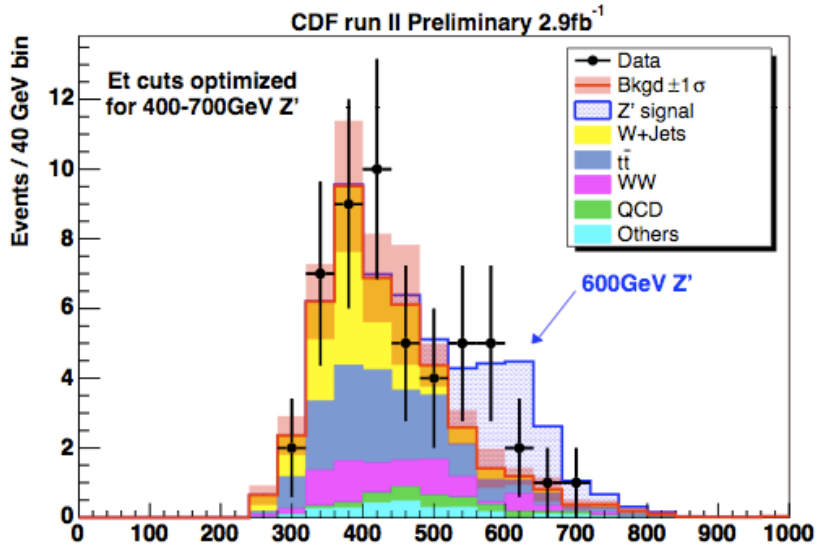
High mass resonances in WW/WZ

Both W'/Z' and RS gravitons could also decay into gauge bosons

$$W' \rightarrow WZ \rightarrow e\nu jj \qquad G^*, Z' \rightarrow WW \rightarrow e\nu jj$$

One neutrino per event: two solutions for neutrino p_z. Keep both



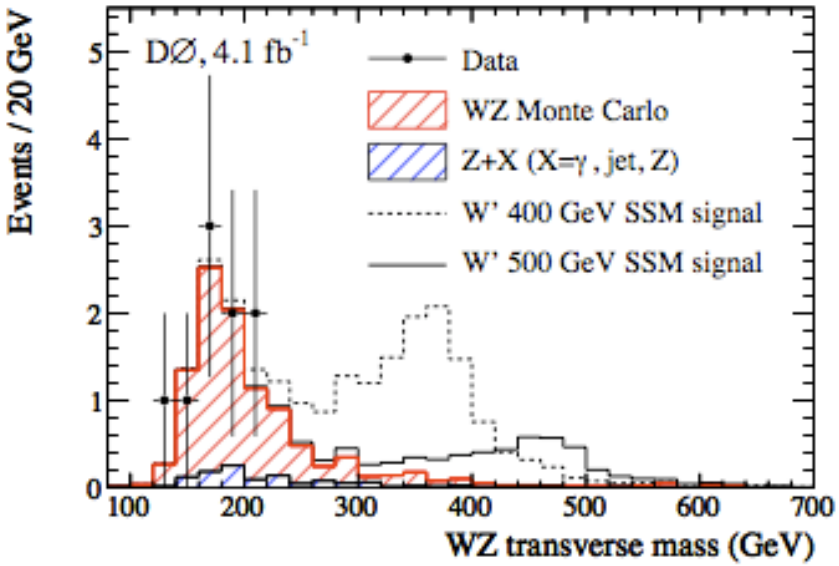


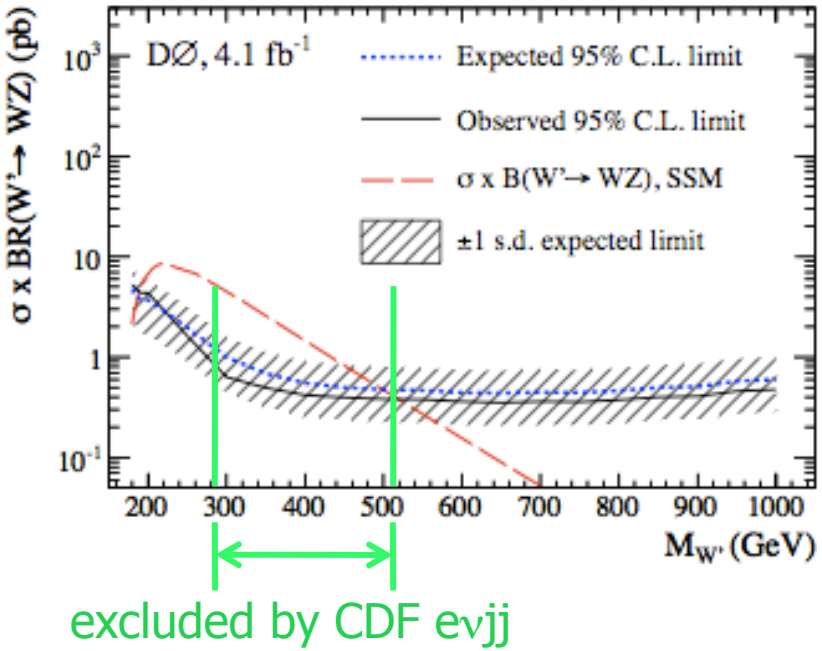
	G*	Z'	W'
Expected Exclusion	< 632 GeV	257 - 630 GeV	381-420 GeV
Data Exclusion	< 606 GeV	247 - 545 GeV	284-515 GeV

High mass resonances in WW/WZ

Both W'/Z' and RS gravitons could also decay into gauge bosons

$$W' \rightarrow WZ \rightarrow \ell\ell\ell\nu$$ low branching, but very clean





Results are also interpreted as measurements of tri-linear gauge couplings, …

Technicolor

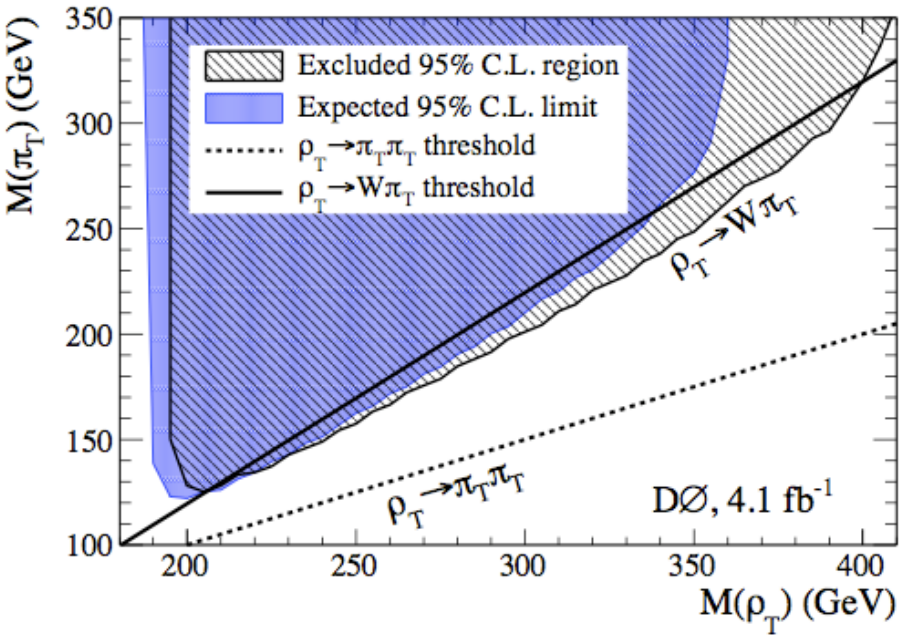
- Beautiful idea, but it seems that every time a calculable model is made, experiment instantly rules it out…
- look for resonant production of techni-rho:

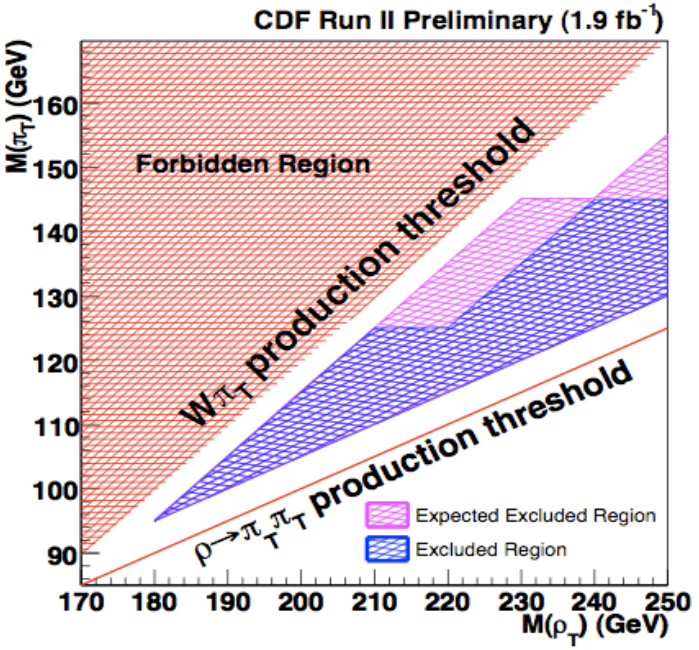
$$\rho_T^{\pm} \to W^{\pm} Z \to \ell\ell\ell\nu$$

re-interpretation of DØ W′ result

$$\rho_T^{\pm,0} \to W^{\pm} \pi_T^{0,\mp} \to \ell\nu QQ$$

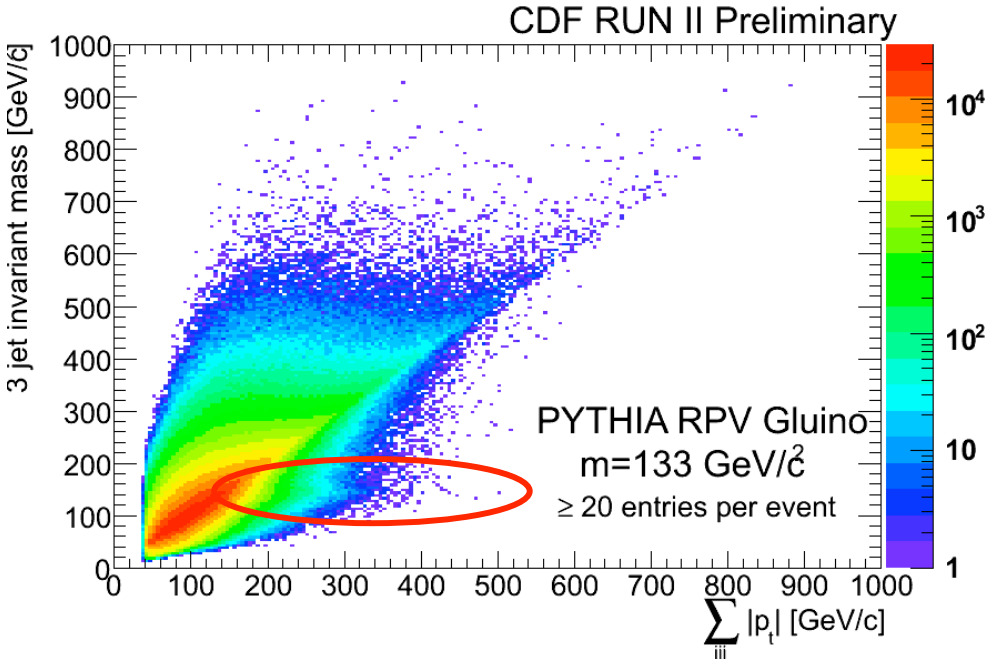
re-interpretation of CDF Higgs search

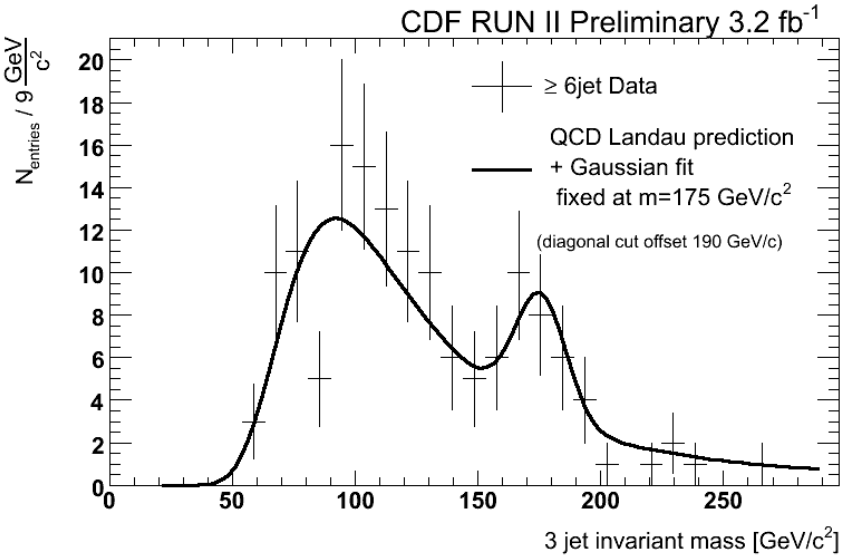




Multi-jets

- processes like $p\bar{p} \rightarrow \rho_T^+ \rightarrow \pi_T^+ \pi_T^0 \rightarrow b\bar{c}b\bar{b}$ are extremely hard to extract out of QCD background, despite multiple mass constraints in the system – jet fluctuate a lot and once ISR and FSR is taken into account it is very hard to make correct jet→parent assignments.
- A huge cross-section signals, up to few pb, can remain unobserved
- Recently, CDF has introduced a new method for investigating such final states and applied it to six jet events
  - a way to find a corner of the phase space which has kinematics that gives correct assignments and high S/B (see Eva Halkiadakis' talk this afternoon)
  - background shape is extracted from data

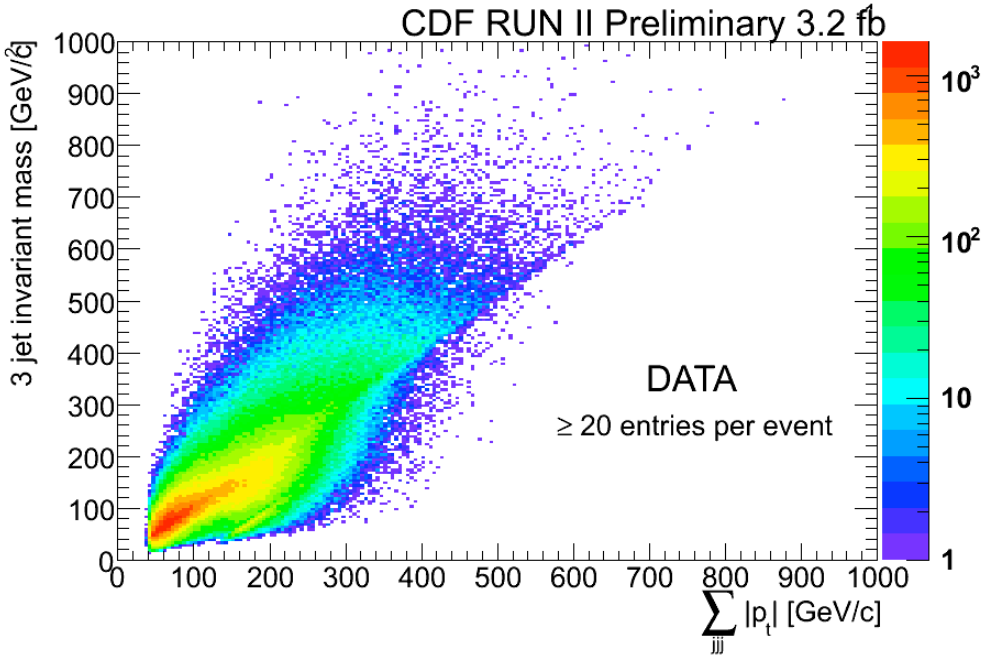


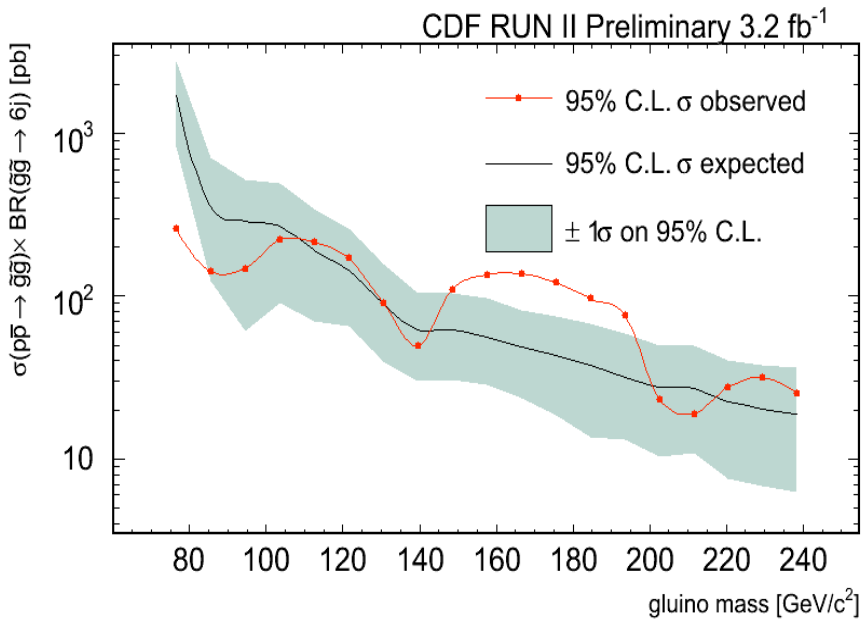


http://www-cdf.fnal.gov/physics/exotic/r2a/20100715.multijetsensembles/

Multi-jets

- processes like $p\bar{p} \rightarrow \rho_T^+ \rightarrow \pi_T^+ \pi_T^0 \rightarrow b\bar{c}b\bar{b}$ are extremely hard to extract out of QCD background, despite multiple mass constraints in the system – jet fluctuate a lot and once ISR and FSR is taken into account it is very hard to make correct jet→parent assignments.
- A huge cross-section signals, up to few pb, can remain unobserved
- Recently, CDF has introduced a new method for investigating such final states and applied it to six jet events
  - a way to find a corner of the phase space which has kinematics that gives correct assignments and high S/B (see Eva Halkiadakis' talk this afternoon)
  - background shape is extracted from data





http://www-cdf.fnal.gov/physics/exotic/r2a/20100715.multijetsensembles/

4th generation: t′

- If there is fourth generation, there is theoretical preference to have almost degenerate t′ and b′, i.e. $M_{b'}+M_W > M_{t'}$
  - t′ then decays into Wq, where q is a down-type quark

$$p\bar{p} \rightarrow t'\bar{t}' \rightarrow WWq\bar{q} \rightarrow \ell + 4j + \not{E}_T$$

- perform a kinematic fit to the t′t′ hypothesis, minimizing

$$\chi^2 = \sum_{i=\ell,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_j^2}$$

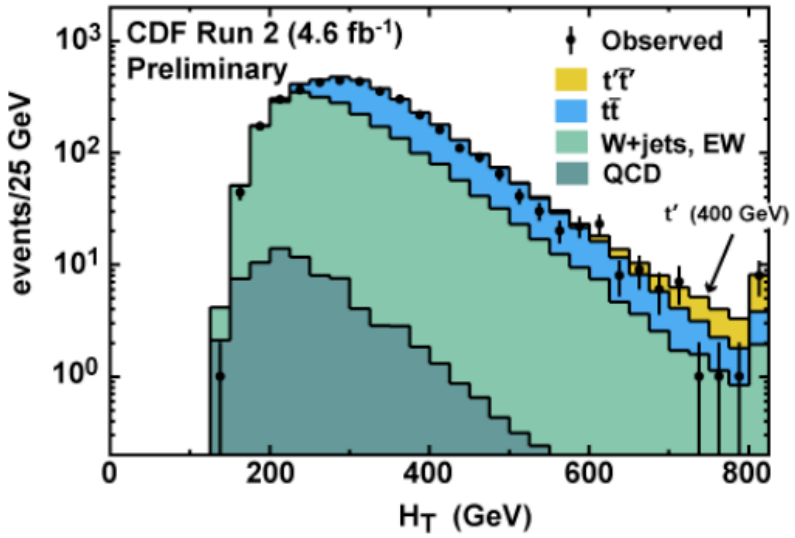
$$+ \frac{(m_{jj} - m_W)^2}{\Gamma_W^2} + \frac{(m_{\ell\nu} - m_W)^2}{\Gamma_W^2} + \frac{(m_{bjj} - m_t)^2}{\Gamma_t^2} + \frac{(m_{b\ell\nu} - m_t)^2}{\Gamma_t^2}$$

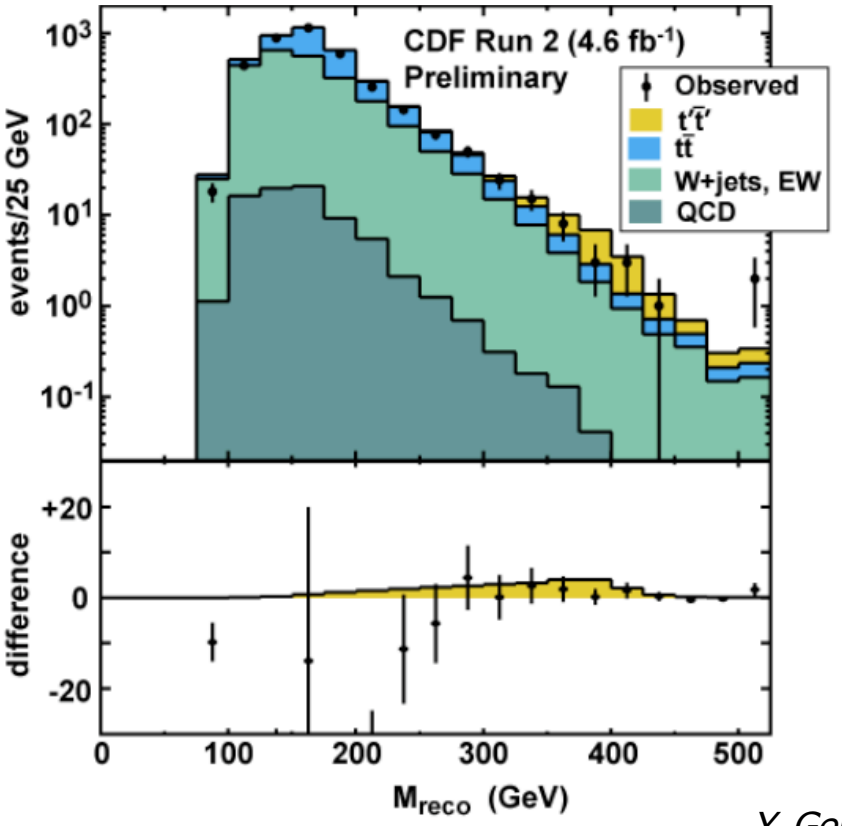
- correct matching is achieved for 24% tt and 36% t′t′
- establish four event categories with different S/B:

  a) $\chi^2<8$, $N_{jet}=4$; b) $\chi^2<8$, $N_{jet}\geq 5$

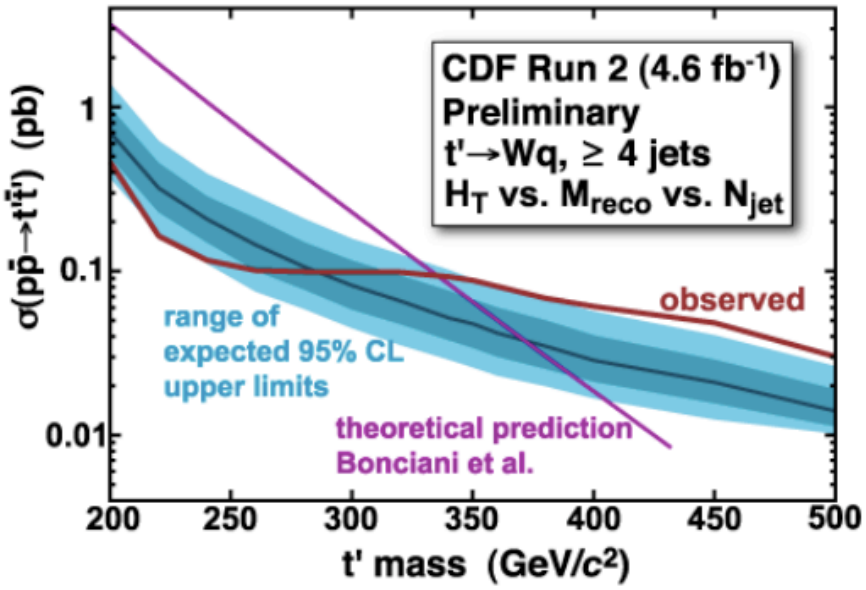
  c) $\chi^2>8$, $N_{jet}=4$; d) $\chi^2>8$, $N_{jet}\geq 5$

4th generation: t′





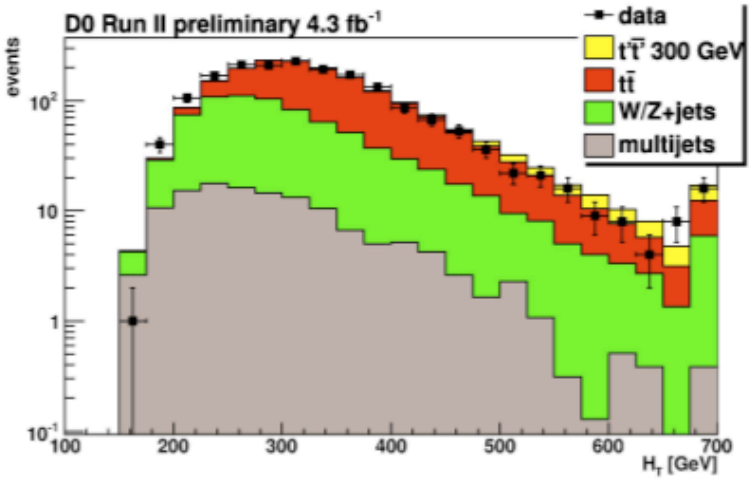
- observe ~2σ excess, but not enough to claim evidence

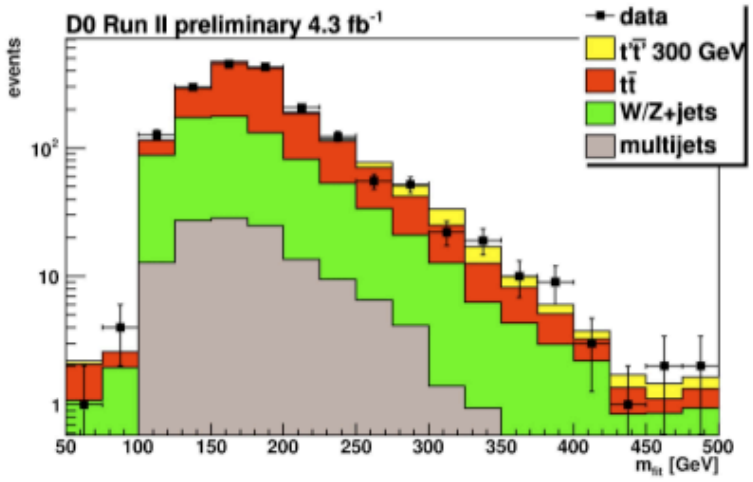


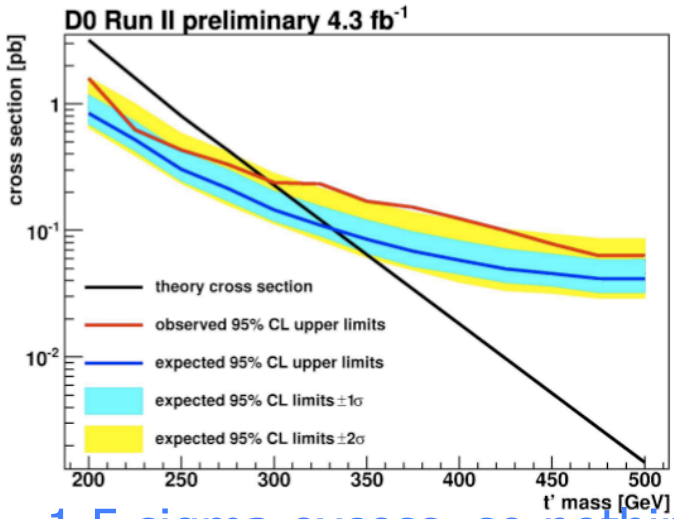
t′ search

- similar to CDF χ^2 selection of correct jet assignments
- use 2D cut in H_T and m(t′) plane

Expected limit $m_{t'} > 330$ GeV
Observerd limit $m_{t'} > 296$ GeV @ 95% C.L.





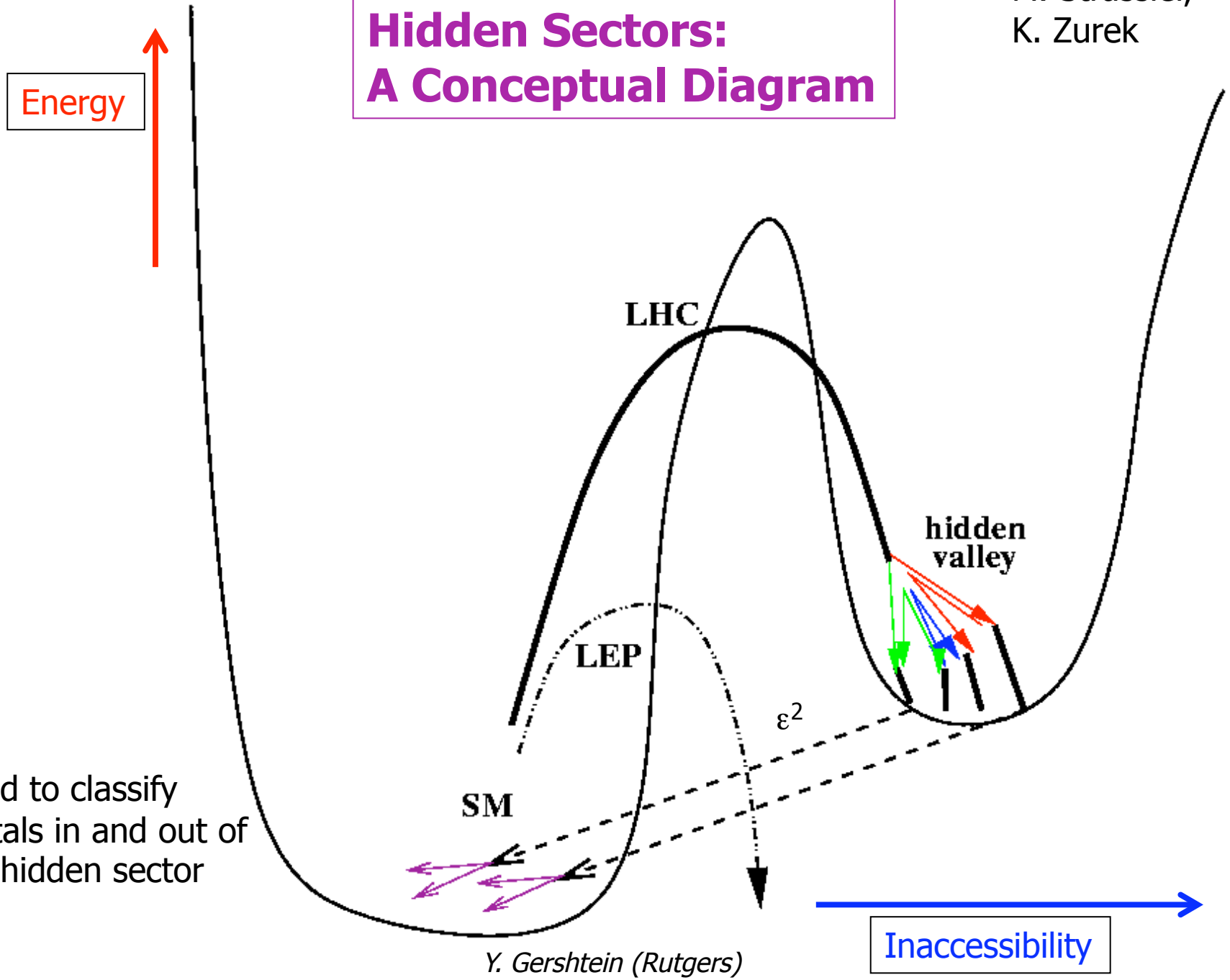


~1.5 sigma excess, so nothing to get too excited about…
The excess in not exactly at the same place as in CDF

but remember 3.2σ discrepancy in inclusive di-muon charge asymmetry from B decays observed by DØ!!

Hidden Sectors: A Conceptual Diagram

M. Strassler, K. Zurek



Need to classify portals in and out of the hidden sector

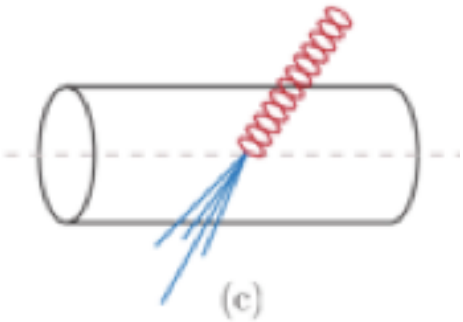
Motivation for Hidden Sectors

- From the point of view of superstrings & GUT theories, extra sectors are quite natural
  - usually model builders have to work hard to eliminate them
- It is possible to hide these sectors without violating any precision EWK data
  - phenomenology can be very different from the "usual" new phenomena
  - some natural scenarios give signatures that are very hard to detect with current experiment hardware, trigger, and software design

Like looking for non-magnetic needle in a haystack!

Quirks

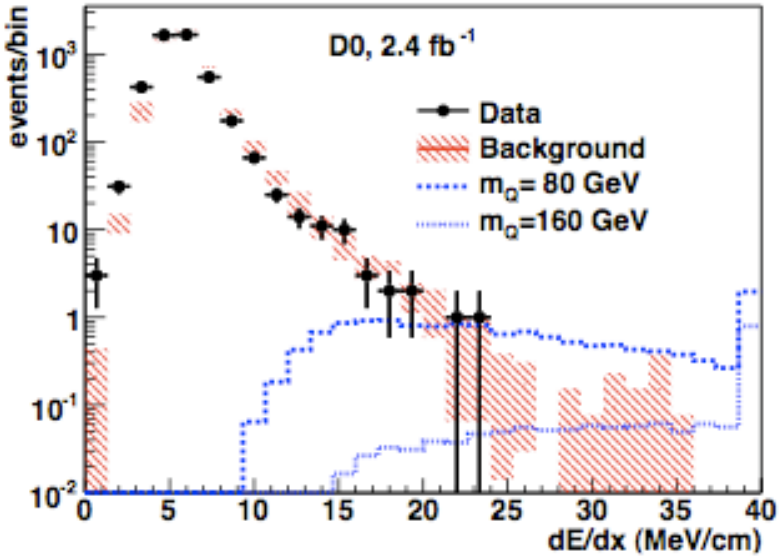
- Extra SU(3): new fermions ("quirks") and new "QCD" with some scale Λ. Phenomenology depends on Λ/m_Q J. Kang, M. Luty, JHEP 0911:065 (2009)
- If Quirks have SM charges – can be produced at colliders
- If $\Lambda << M_Q$ the string can become macroscopic
- This search considers string sizes of up to ~50 microns
- Quirk pairs like this most times do not even enter the tracker – they fly slowly along the beam pipe and annihilate some time later
- Way to find them is to trigger on ISR jet
- The two quirks then would appear as a single straight highly ionizing track

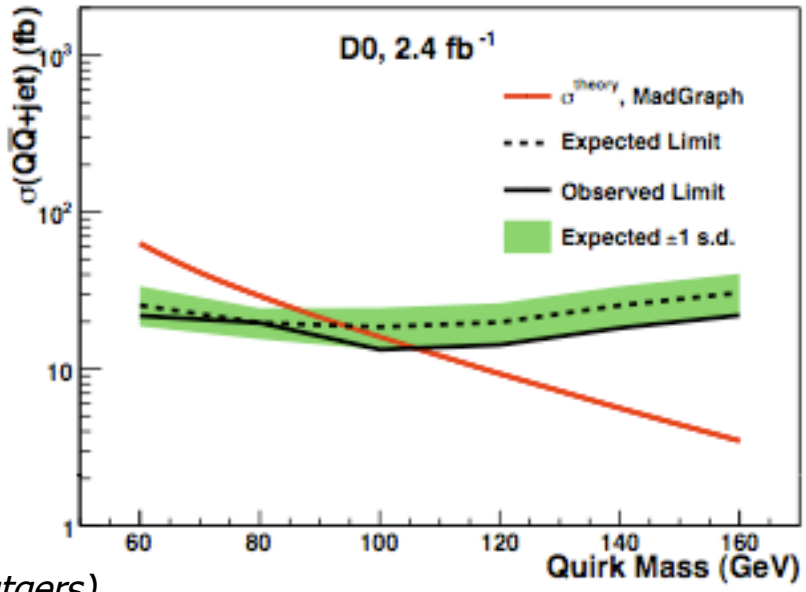


- Requiring ISR jet cuts down the statistics, but this is often the only way to find particles that are register mostly as strange-looking tracks

Quirks

- Select events with high E_T jet, high E_T isolated high quality track back-to-back with it and significant MET
  - SM background: W(→μν)+jet and QCD
- Quirk pair ionization is larger because of double charge and slowness
  - somewhat reduced due to relative movement of the quirks
- Use non-isolated tracks and high E_T leptons from W/Z to extract dE/dx for particles with v≈c
- Scale the measured dE/dx by theoretical boost distribution and make a cut on dE/dx optimized for each Quirk mass



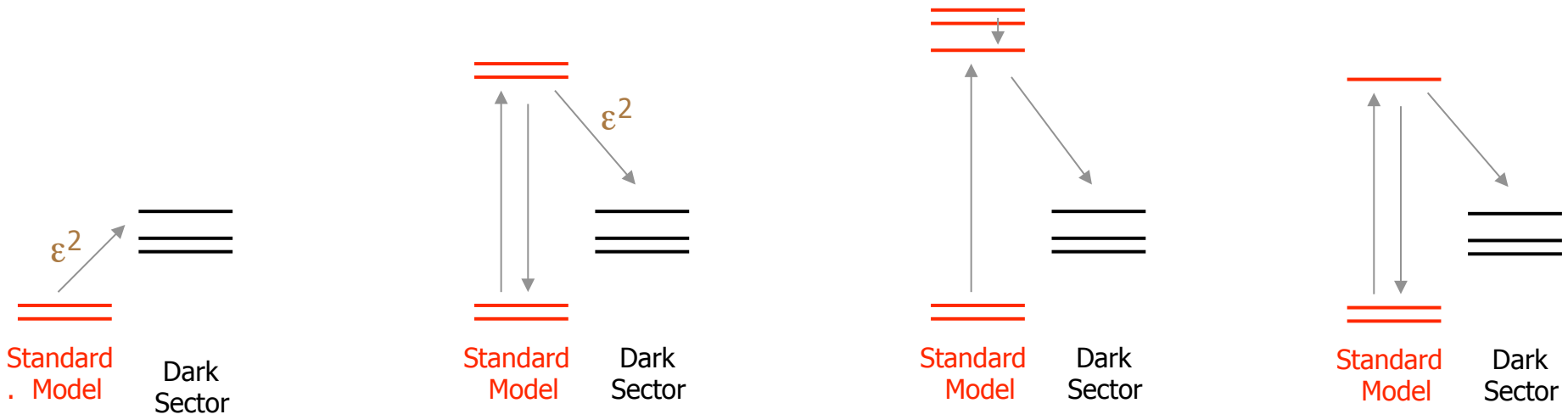


Extra U(1) sector with force carrier ~O(GeV) and weak coupling to SM ($\varepsilon^2 < 10^{-5}$)

- Motivated by non-collider observations
- Direct Dark Matter detection
  - DAMA/LIBRA – anomaly?
- Cosmological anomalies
  - low energy positrons from galactic center: INTEGRAL and 511 keV line
  - new sources of high energy electrons/positrons in cosmic rays: PAMELA, FERMI/LAT, ATIC, WMAP

Weakly coupled Hidden Sector Production at Colliders

Direct Production	Indirect Production	Indirect Production with Shared Conserved Quantum Number	Direct communicator production
Resonant Dark DY	Higgs, Z Decay	SUSY + R-Parity	Z' Decay

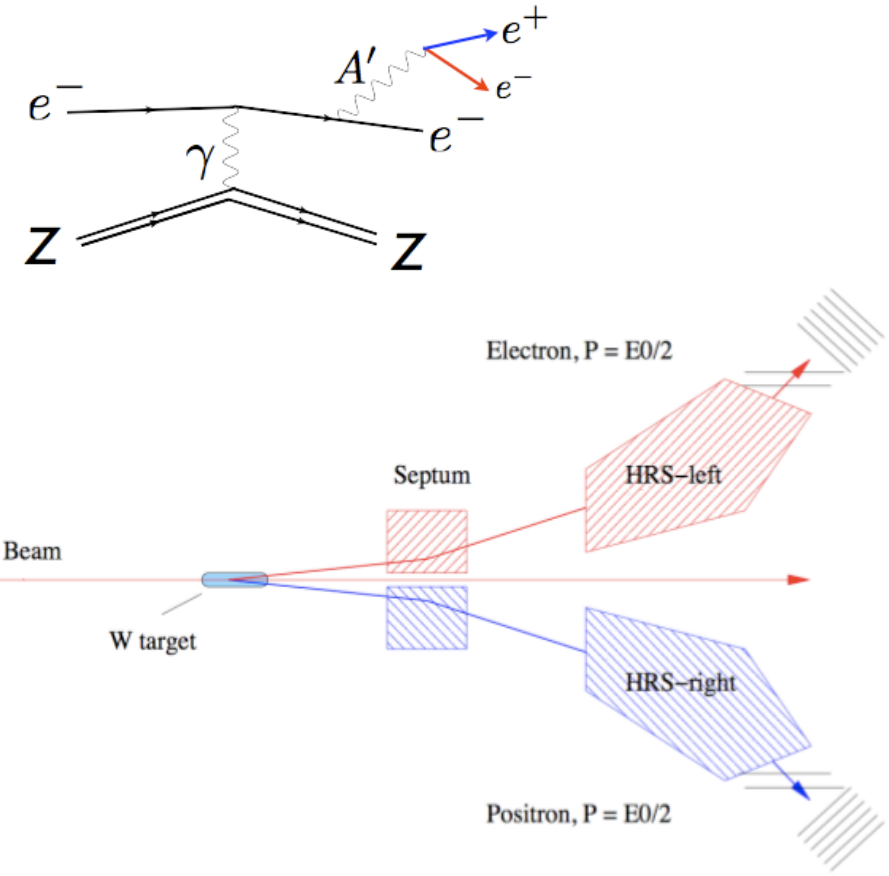


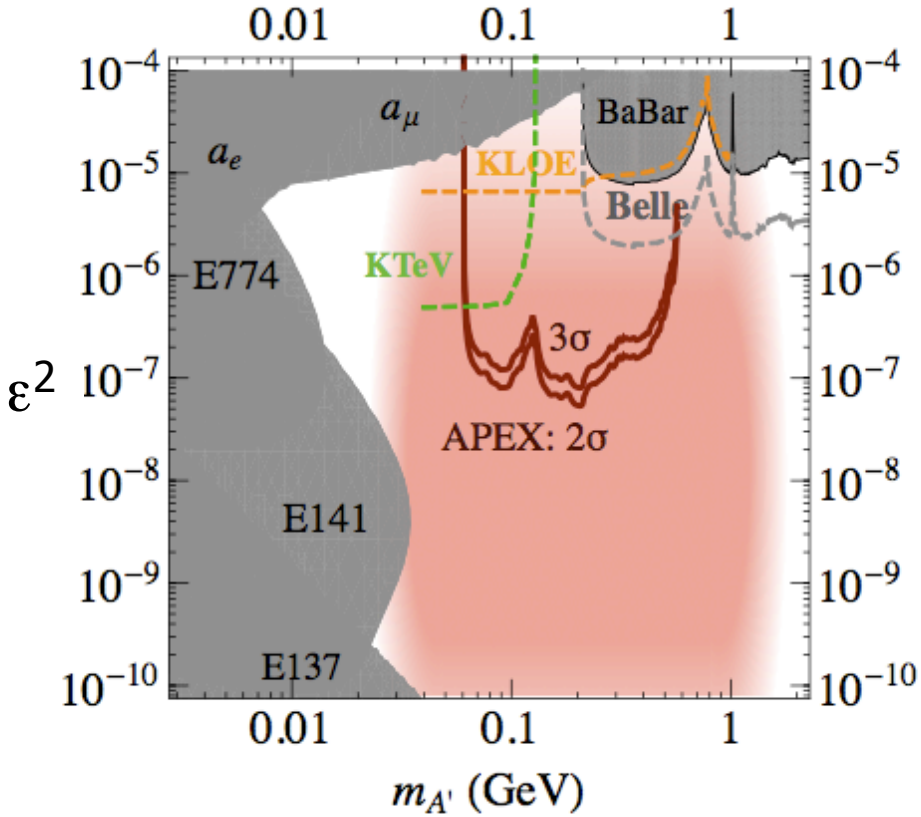
$\sigma \sim O(\varepsilon^2)$	$Br \sim O(\varepsilon^2)$	σ & $Br \sim O(\varepsilon^0)$	σ & $Br \sim O(\varepsilon^0)$

Which Hidden Sector States Populated – Depends on Production Portals

Direct Production

- Do not need high energy – but need very high intensity

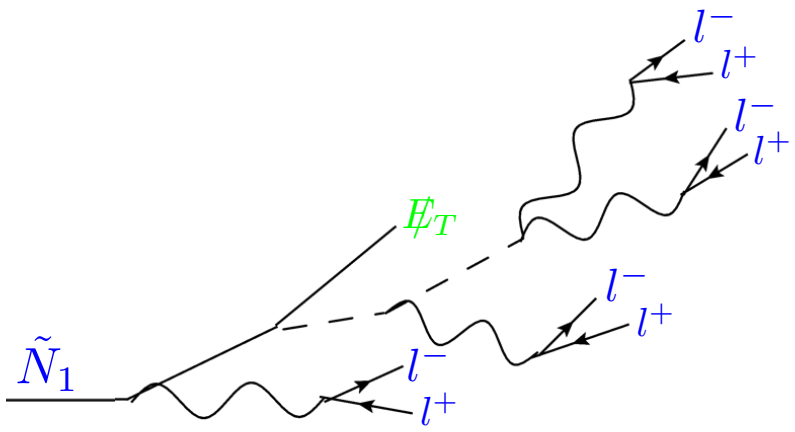


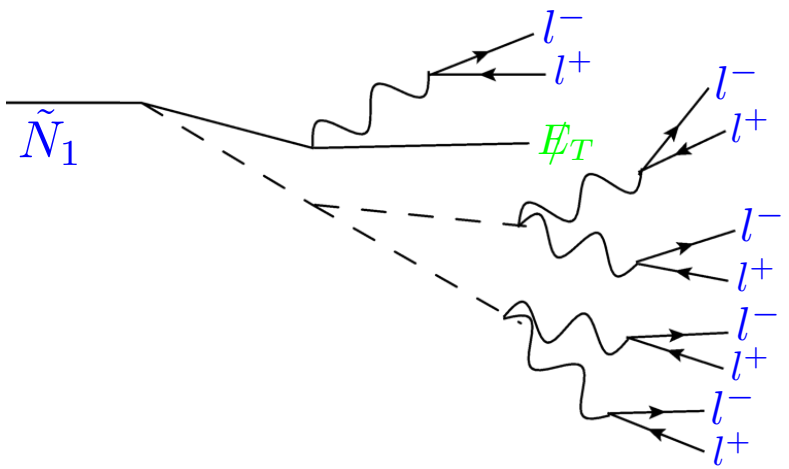


- APEX (JLAB) and MAMI (Maintz) had successful test runs and seem to be on the way to make the measurements
- Another approach – try to detect light shining through a wall

Hidden U(1) in "SM" LSP Decays

- Decays and their rates are really model-dependent
- However, there are features common to all models
  - bino → dark photon + darkino (i.e. true LSP in the hidden sector)
  - higgsino → dark higgs + darkino
  - nMSSM scalar → dark photon + darkino or SM photon + darkino
- Should not forget the FSR!
  - α is small in our U(1), but this may not be true for hidden U(1)

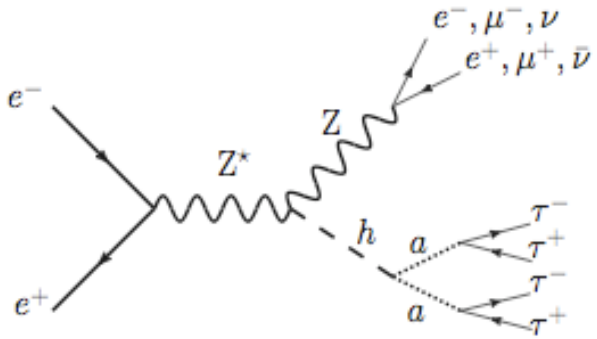




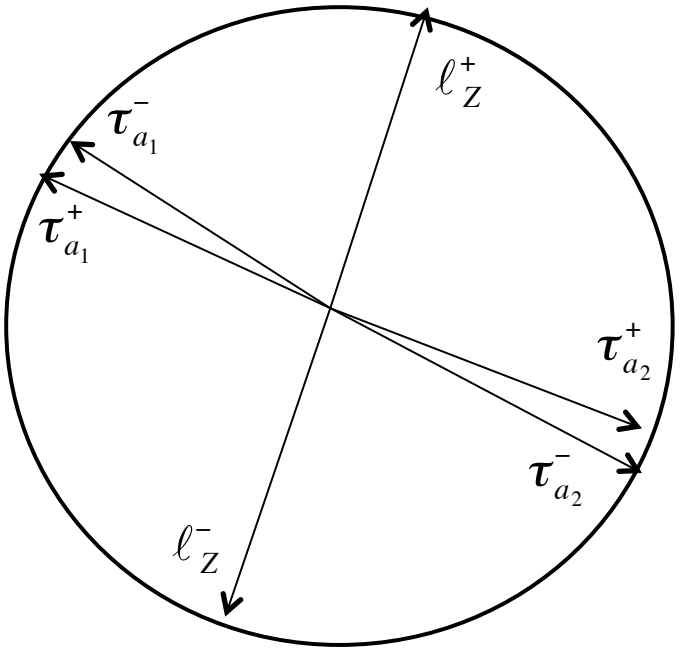
- 2, 4, 6, … visible tracks per neutralino decay
- some but not all of them are leptons – "leptonic jets", l-jets

LEP is still publishing!

- Recent ALEPH paper on non-standard Higgs searches are very sensitive to dark sectors

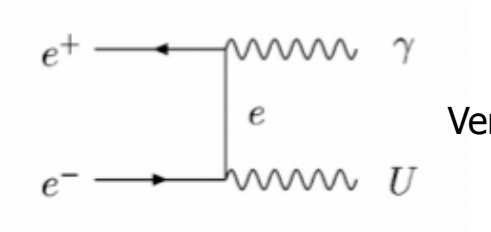


arXiv:1003.0705



- ALEPH requires 2, 4, or 6 tracks per di-tau
- perfect for nMSSM scenarios with light neutralino:
  - higgs decays into two neutralinos, i.e. two l-jets plus MET

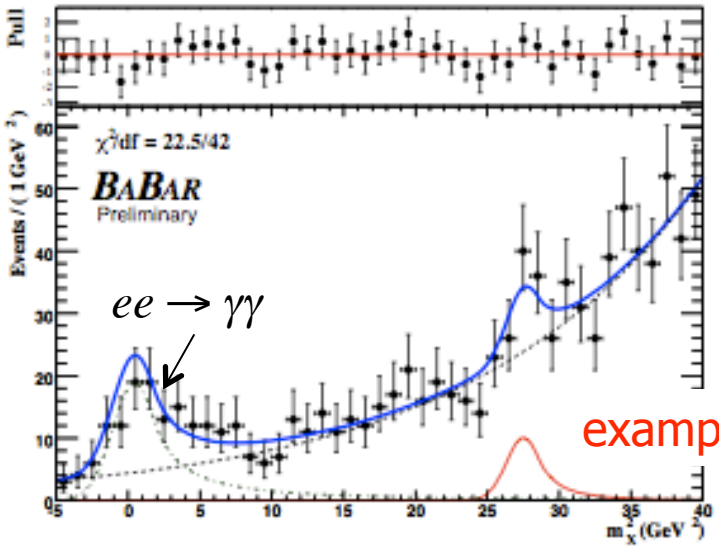
Exotic bosons at e^+e^- colliders



Very challenging…

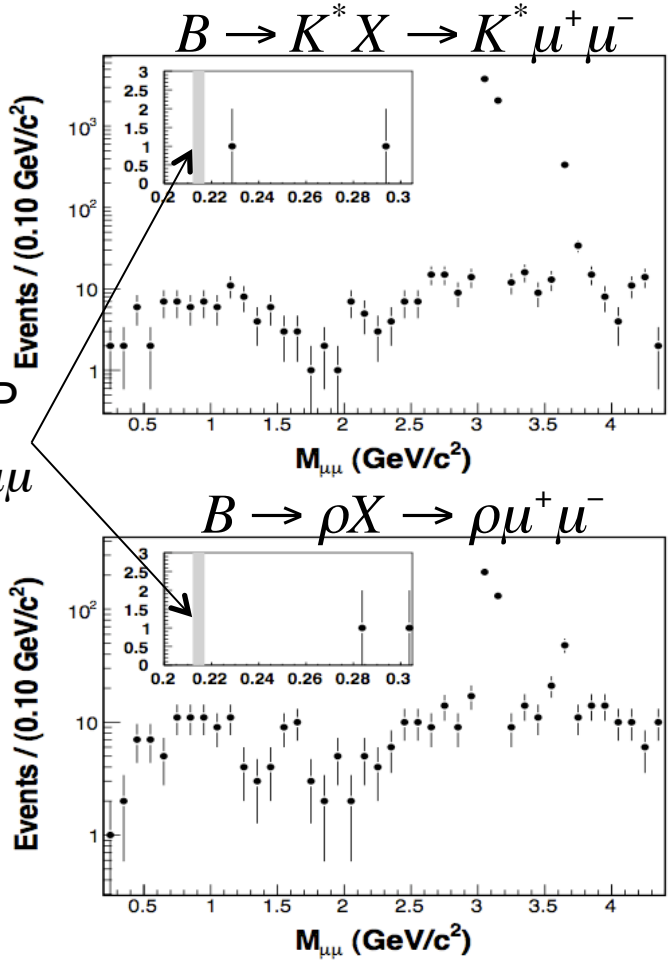
If the dark boson is a scalar, Y should be able to radiatively decay into it.

BaBar searches for invisible *a* and for $a \to \mu\mu, \tau\tau$
Phys.Rev.Lett.103:081803,2009,
Phys.Rev.Lett.103:181801,2009



example signal

Belle, arXiv:1005.1450

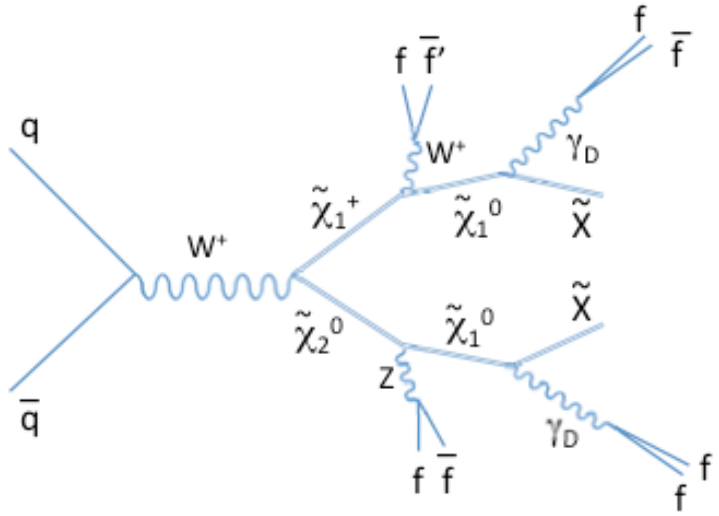


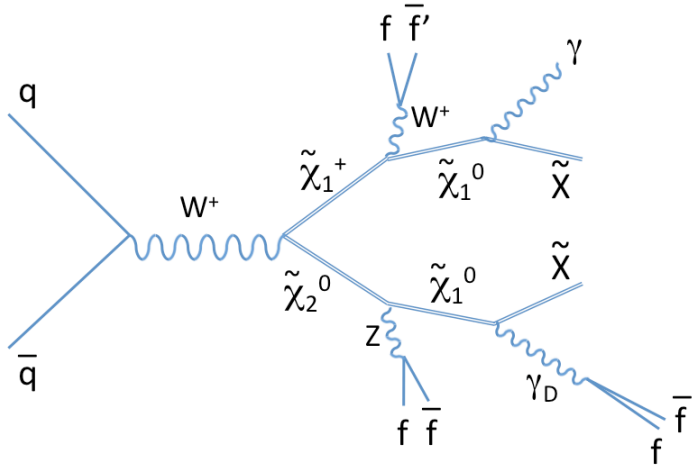
HyperCP
$\Sigma^+ \to p\mu\mu$
region

Dark Photons at Tevatron

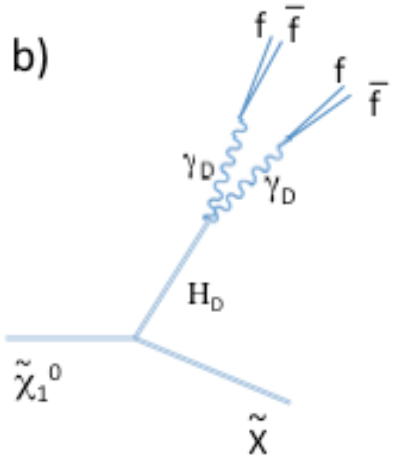
- Leads to final states that could have been missed – non-isolated leptons!

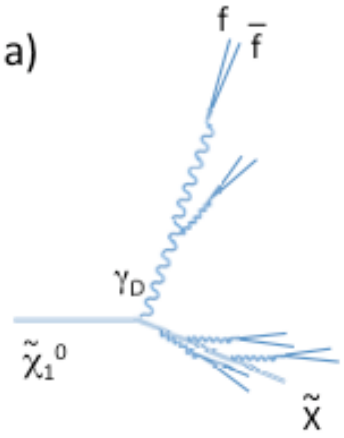
DØ, PRL 103, 081802 (2009)





- could also lead to "jets" of dark photons, either through cascades or showering



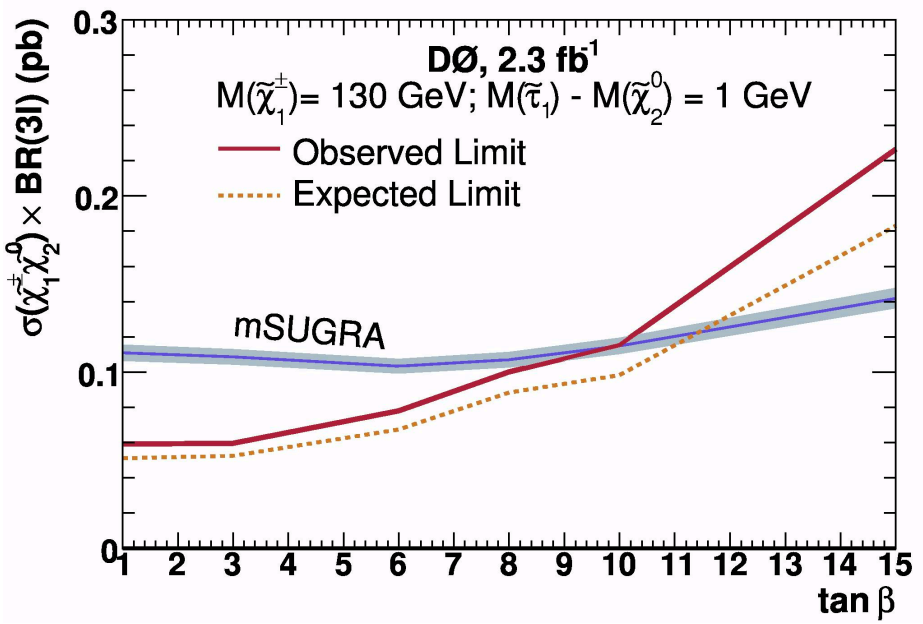


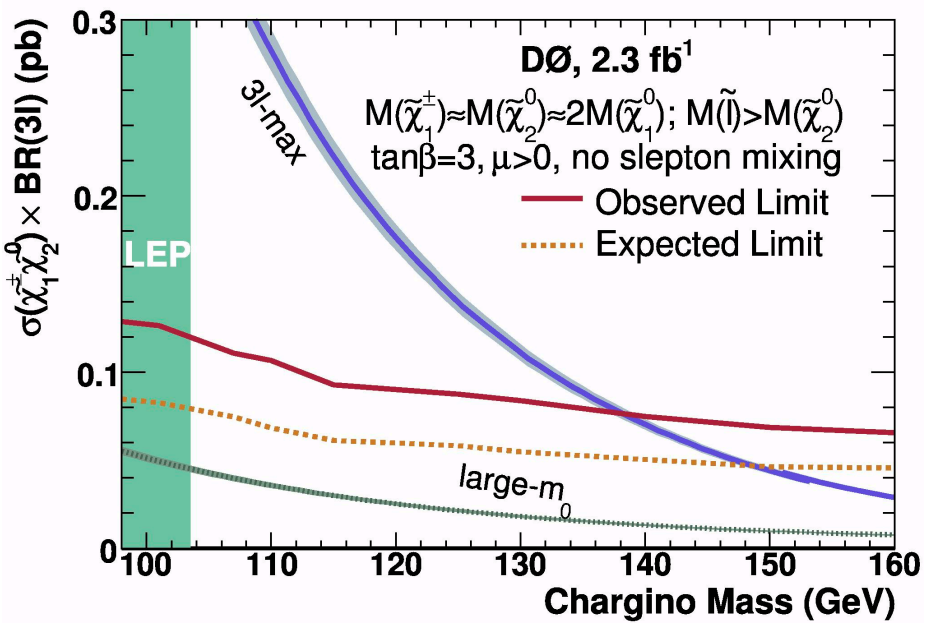
Dark radiation is modeled following M. Baumgart, C. Cheung, J. T. Ruderman, L. T. Wang and I. Yavin

0901.0283 [hep-ph]
0909.0290[hep-ph]

Limits from trilepton searches

cross-section for SUSY signals with dark photons can be as high as **200 fb** even for chargino mass as high as 130 GeV…

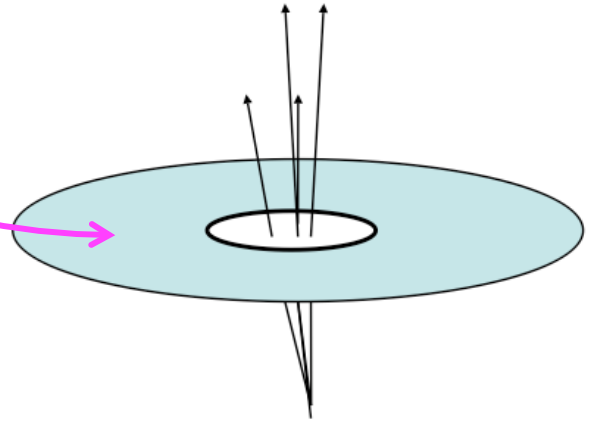




… and can be even higher for lower chargino masses (model independent limit is 105 GeV) or if sleptons are only slightly lighter then charginos

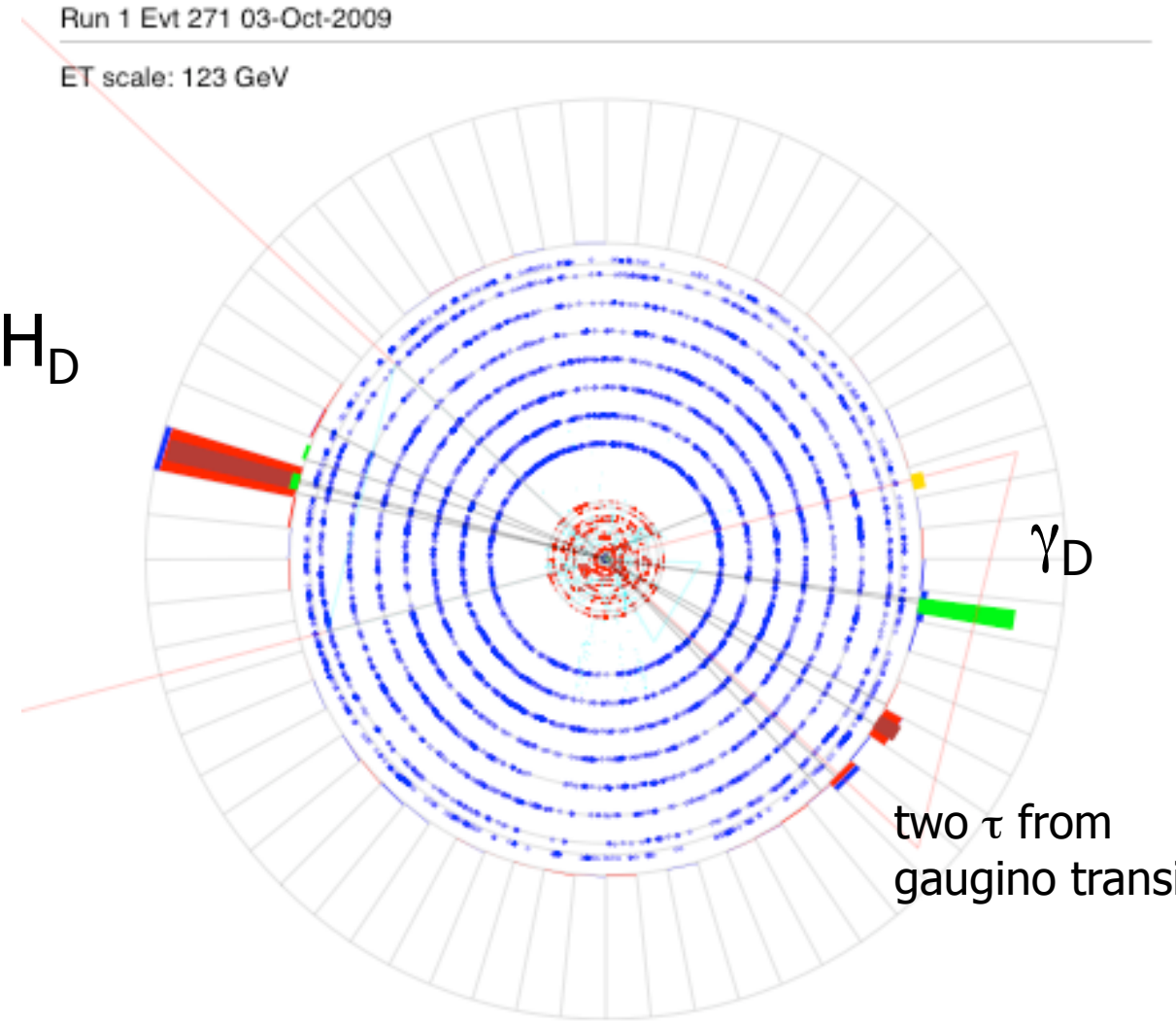
Leptonic Jet Definition

- Pair of oppositely charged tracks with $\Delta R<0.2$
  - $p_T>10$, 4 GeV
  - match to muon or cluster of EM energy
- main handle for identification: isolation
  - do not restrict activity in the core
  - require track and calorimeter isolation in the annulus



- Efficiency to reconstruct spatially close tracks is the main source of systematic uncertainty

Letponic Jet Definition

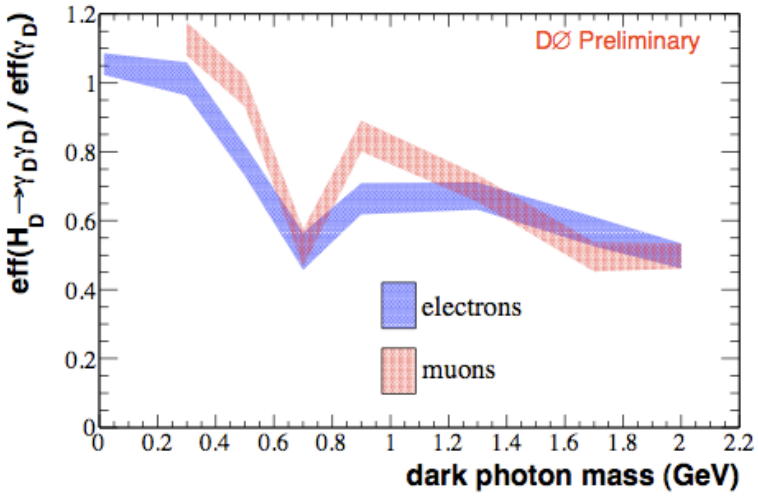


Two leptonic jets + MET

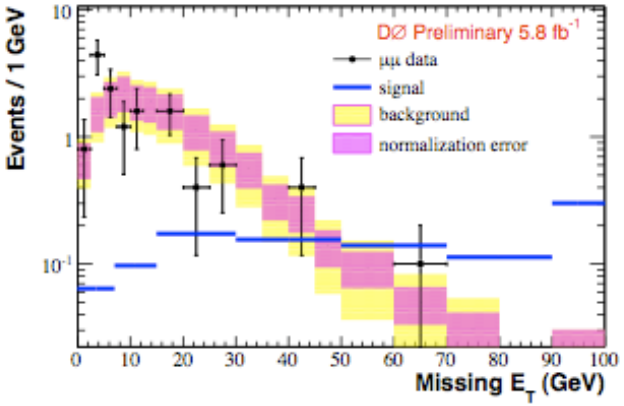
- Background is dominated by heavy flavor and direct photon production (for electron l-jets)
- Background shape is extracted from data

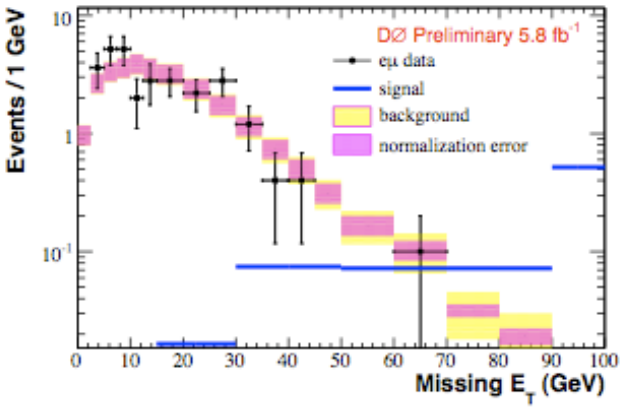
Channel	Data	Background	SPS8 Acc.	Reco. eff.	Total eff.
ee	7	10.2 ± 1.7	0.45	0.20	8.9 %
$e\mu$	11	17.5 ± 4.2	0.53	0.15	7.8 %
$\mu\mu$	3	8.6 ± 4.5	0.50	0.12	5.8 %

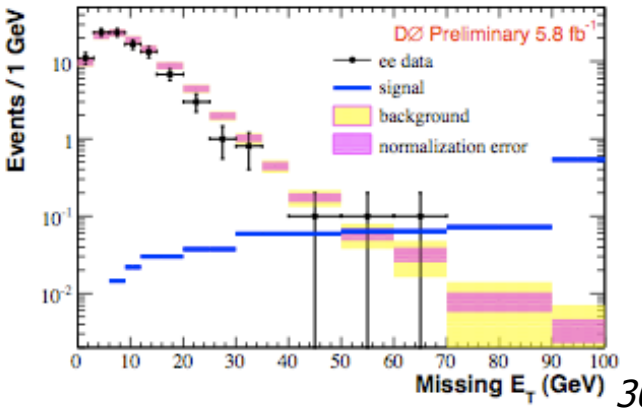
- Efficiency depends on the l-jet composition



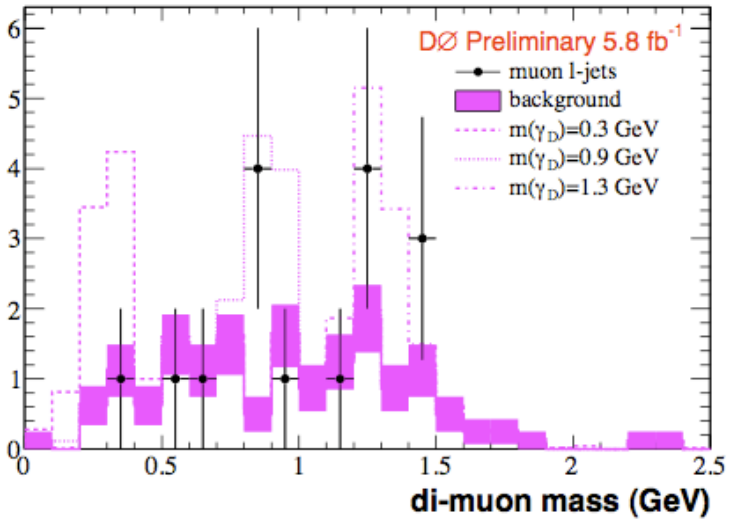
efficiency decreases by ~20% for α_D=0.3 compared to no dark radiation

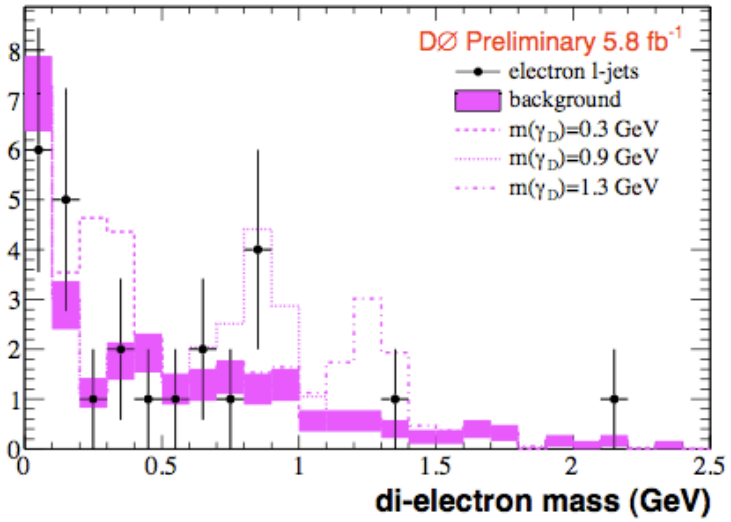




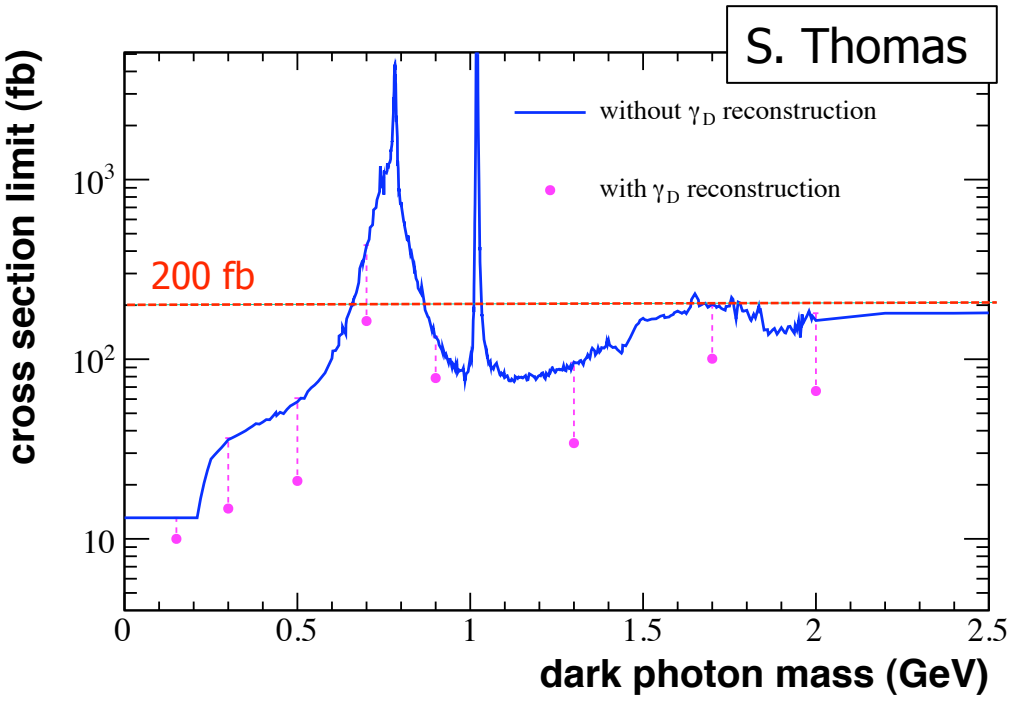


Dark photon mass in high MET Events

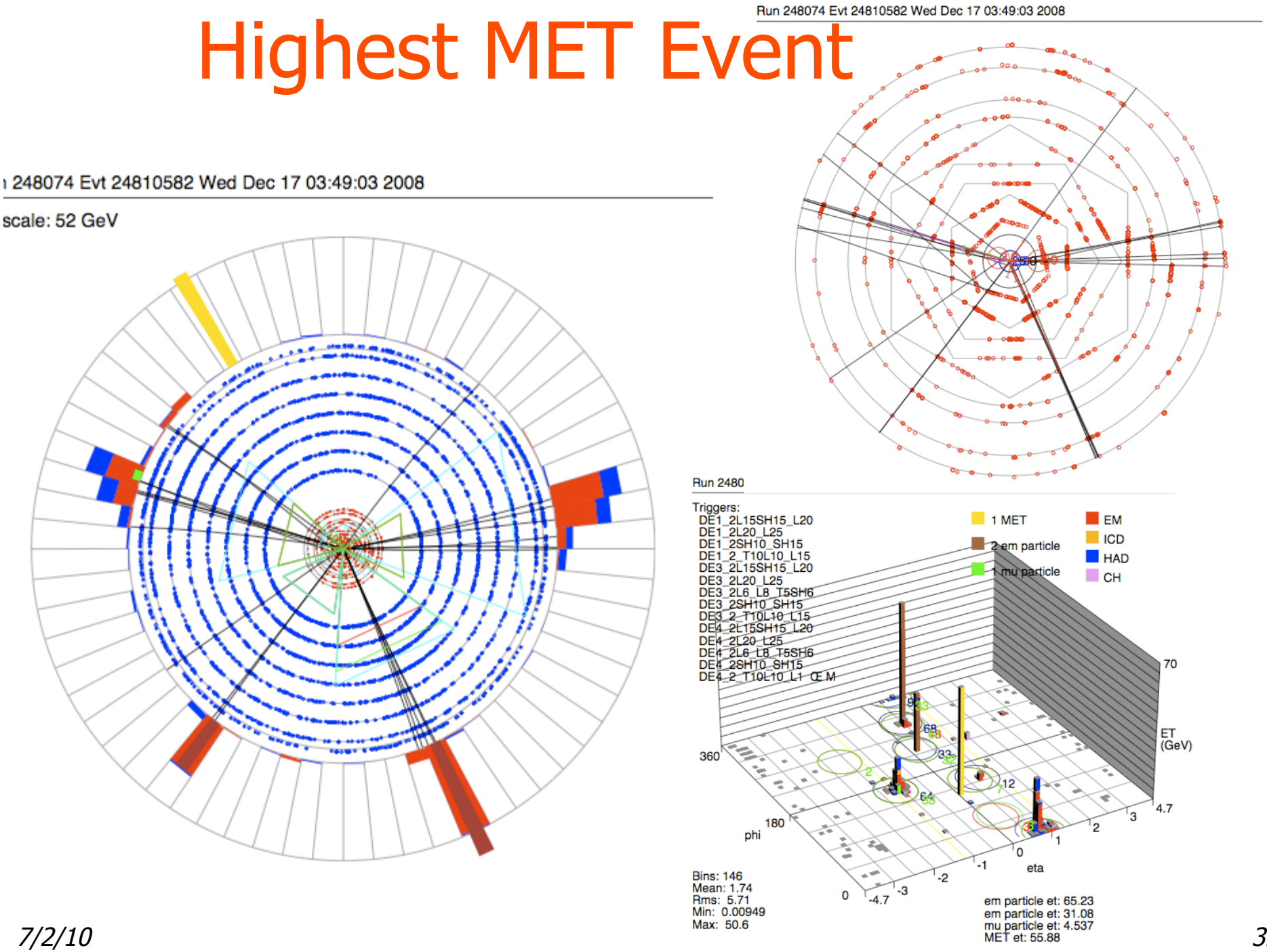




- Extra information: invariant mass of the track pair in l-jet
- allows to improve limits by a factor of ~4



Highest MET Event



Summary

- Unambiguous discovery of new physics still eludes us…
- Tevatron searches approach their ultimate sensitivity
  - if 4fb^{-1} search does not show deviation, 10fb^{-1} can not yield discovery
  - There are a lot of searches that are not updated from 1-2 fb^{-1}: still some room for surprizes!
- Astrophysical motivation for light hidden sector is still holding – but even if it does not, the theoretical advantages of these types of scenarios are being explored
  - A new direction in new physics searches is forming – intensity frontier as opposed to energy frontier

Outlook

- For the next year or so Tevatron and LHC will compete for different kinds of new physics
  - **LHC wins if new physics has color**
  - Tevatron wins if new physics is produced weakly

- Both can be scooped by low-energy experiments – or even non-accelerator experiments!

THE TRUTH IS OUT THERE

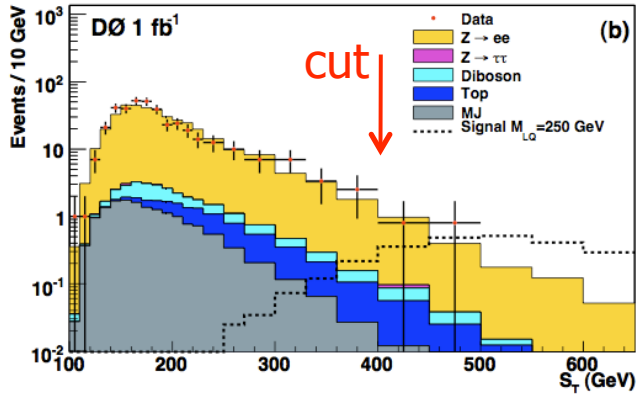
Leptoquarks

- carry both lepton number and color
- come in three generations
- decay into lepton+quark
- at hadron collider: non-resonant strong pair-production
  - final states: $\ell^+\ell^- jj, \quad \ell^\pm jj + \not\!\!E_T, \quad jj + \not\!\!E_T$

$$\beta = \frac{Br(LQ_f \to \ell^\pm_f q_f)}{Br(LQ_f \to \ell^\pm_f q_f) + Br(LQ_f \to \nu_f q_f)}$$

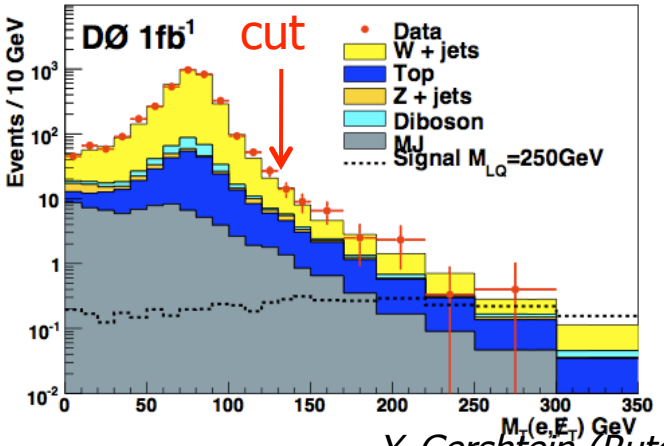
eejj: cut on M(ee) and

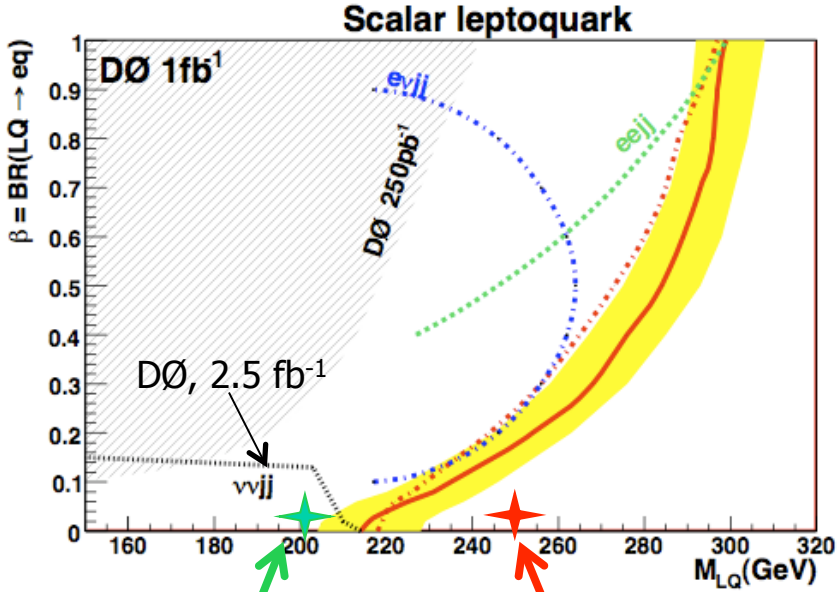
$$S_T = \sum_{e,j} E_T$$



eνjj: cut on M_T(e,MET) and

$$S_T = \sum_{e,j,\not\!\!E_T} E_T$$





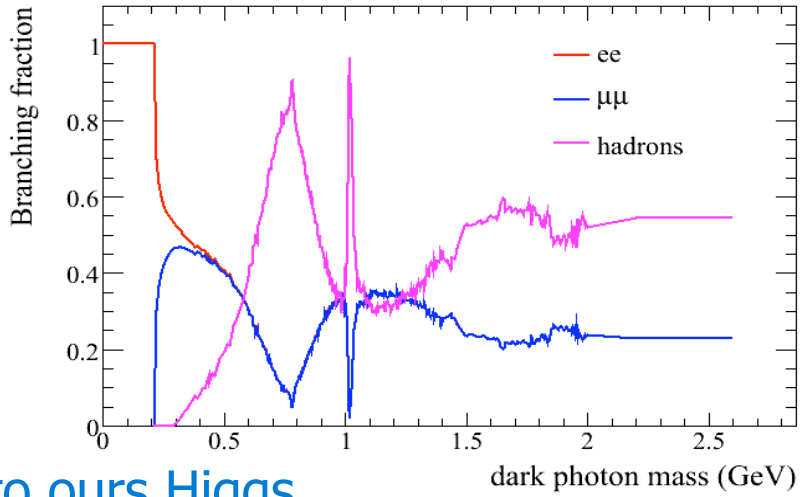
CDF prelim. 2fb^{-1}

DØ, bb+MET 4 fb^{-1}

Dark Photon/Higgs Decays

- Dark photon decays through its mixing with light photon, so its branchings can be calculated from measurement of R
  - for $\varepsilon^2 > 10^{-8}$ decays are prompt
  - if mass of dark photon is 1.02 GeV it mostly decays into kaons – not-quite-lepton jet…
  - some upgrades detecting hadrons and/or muons to APEX-like experiments would be very useful

S. Thomas



- Dark Higgs has mass O(GeV)
- can decay in the dark sector similarly to ours Higgs
  - if $m_h > 2m_{\gamma d}$ decays into two dark photons open
  - if $m_{\gamma d} < m_h < 2m_{\gamma d}$ decays through γ_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
- If there's also SUSY – more higgses in the hidden sector, more cascades