Hunting for SUSY in Run II at DØ

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(on behalf of the DØ Collaboration)

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Outline

- What is in and What is not in this Talk
- Run II Data Sheet
- Key Features of the DØ Detector in Run II
- Desperately Sought SUSY...
- Run II Hunt Strategy
- GMSB Models
- Beyond the MSSM and Exotics
- Large Extra Dimensions
- Conclusions

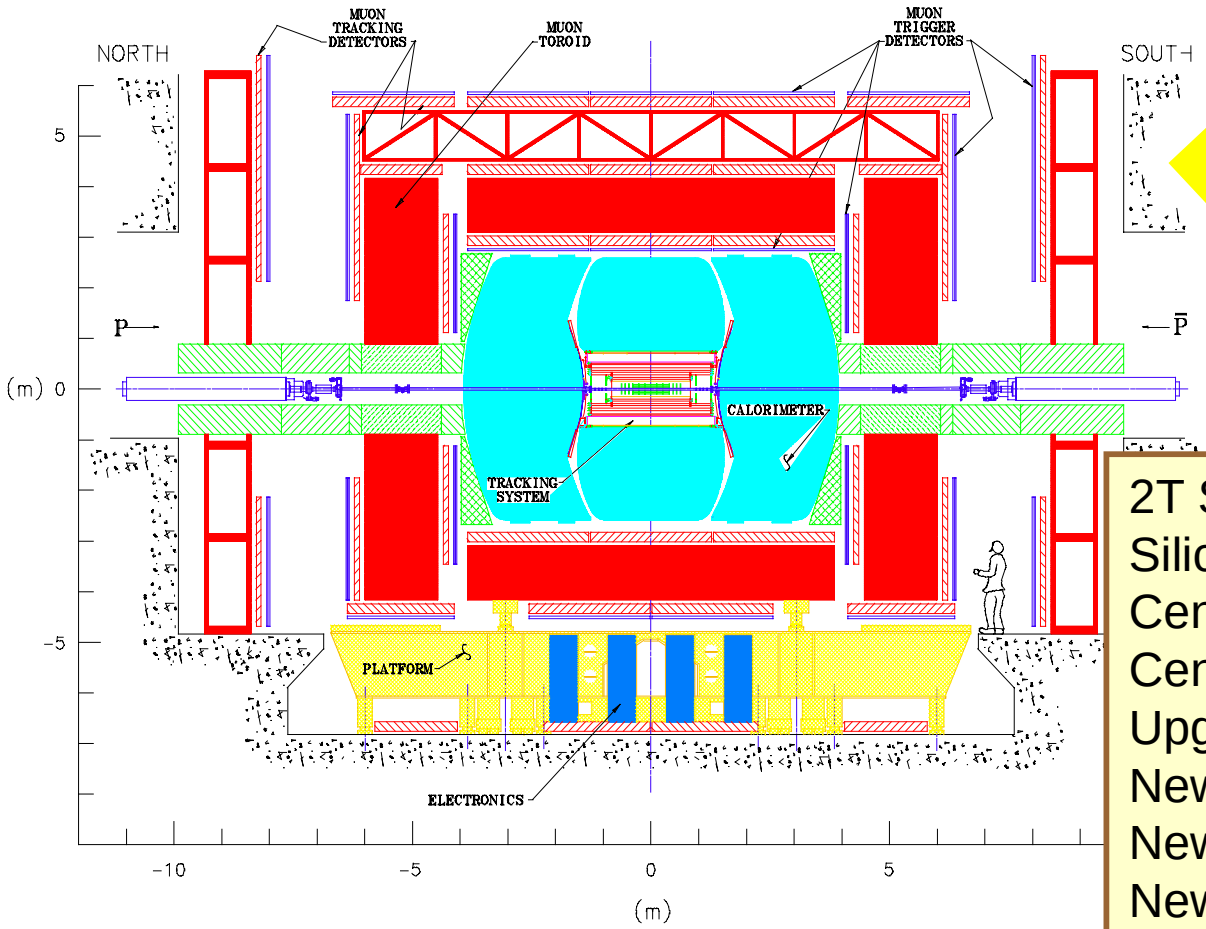
What's in and what isn't in this talk

- Both CDF and DØ will be quite competitive in new physics search in Run II, so given a similar talk by Regina Demina (CDF), I'd like concentrate on features that make DØ unique
- E.g., SUGRA signatures will be covered in detail in Regina's talk; I just want to add that DØ will do just as good!
- Many results shown in this talk were obtained as a part of the Run II SUSY/Higgs workshop at Fermilab that really brought theorists and experimentalists closer together (you taught us words "messenger" and "infrared fixed point solution", and we taught you the words "trigger" and "particle ID") - many thanks to Marcela Carena & Joe Lykken!
- I tried to avoid showing pages and pages of limit plots, and will attempt to show you our search philosophy and our capabilities instead
- Some topics I am going to discuss are subject of questions from my theoretical colleagues, so I tried to include the answers to these "DØ in Run II FAQ" in this talk

Run II Data Sheet

Stats: Start at $\sqrt{s}$ = 2 TeV, L ≈ 10^{32} $cm^{-2}s^{-1}$, 396 ns crossing time
L = 10^8 $b^{-1}Hz$ = 10^{-4} $pb^{-1}Hz$
Run II (operational definition): I = $\int Ldt$ = 2 fb^{-1} (about 1.5 years)
Sometimes during the run switch to 132 ns bunch crossing
Average no. of interactions/crossing: 3-6 (396 ns) or 1-2 (132 ns)
Trigger rates: 10 KHz, 1 KHz, 20 Hz or 100 μb, 10 μb, 200 nb
Total $p\bar{p}$ interaction cross section: ~100 mb
Accept rate: ~10^{-6}
Total number of events to tape: 400 million (official: 6×10^8)
Cost: 10¢/event, but with the cost of MI, etc. more like $1/event
Four events per every US taxpayer (eight together with CDF!)
Discovery accept rate: ~10^{-8}
It's like winning a lottery, except it is not gambling!

Top Investment Pick for the New Millennium



BEST BUY
$45,000,000

- 2T Superconducting Solenoid
- Silicon Microstrip Tracker
- Central Fiber Tracker
- Central & Forward Preshowers
- Upgraded Central Muon System
- New Forward Muon System
- New Pipelined Readout Electronics
- New Three-Level Trigger System
- Windows NT based Level 3/DAQ

DØ in the Next Millennium

Key Features of the DØ Detector in Run II

- Nearly hermetic U/LAr Calorimeter with preshower detectors: $\sigma_E/E = 15\%/\sqrt{E}$ [GeV] (e/γ) or $80\%/\sqrt{E}$ [GeV] (jets); $\sigma_{XY} \sim 1$ mm (e/γ) and $\sigma_{XY} \sim 1$ cm (jets)
- Eight-layer Central Fiber Tracker (CFT) with 77K channels and $\sigma_{XY} \sim 80\ \mu$m, $\sigma_z \sim 1.5$ mm (via 3° stereo-layers)
- Four-layer (two double-sided) Silicon Microstrip Tracker (SMT) with 800K channels; $\sigma_{XY} \sim 10\ \mu$m, $\sigma_Z \sim 100\ \mu$m; $\delta p_T/p_T = 0.002p_T$ [GeV/c] $\oplus$ 0.02; $\sigma_{ip} = (12.6 \oplus 50/p_T$ [GeV/c]) μm
- Muon Spectrometer with fast scintillator tiles and drift tubes; momentum resolution is determined by tracking
- Rapidity coverage: $|\eta|<1.1$ or $1.5<|\eta|<2.5$ (e/γ); $|\eta|<4$ (jets); $|\eta|<1.7$ (μ); $|\eta|<2$ (CFT tracks); $|\eta|<3$ (SMT tracks)

Run I Searches for SUSY

- We desperately sought Susy...
- But we really were looking under the lamp post!
- Our detectors were not versatile enough to study many interesting channels
- Our data sets were not large enough to probe the most interesting regions of the SUSY parameter space
- And thus far we found none...

Hunting Ground

l+jets+$\not{E}_T$

ll+jets+$\not{E}_T$

taus+$\not{E}_T$

jets+$\not{E}_T$

HIT

bb+$\not{E}_T$

lll+jets+$\not{E}_T$

ll+bb+$\not{E}_T$

ll+jets

γ+jets+$\not{E}_T$

undetectable

Kinks

$llll$+$\not{E}_T$

monojets

γ+ll+$\not{E}_T$

non-pointing Z

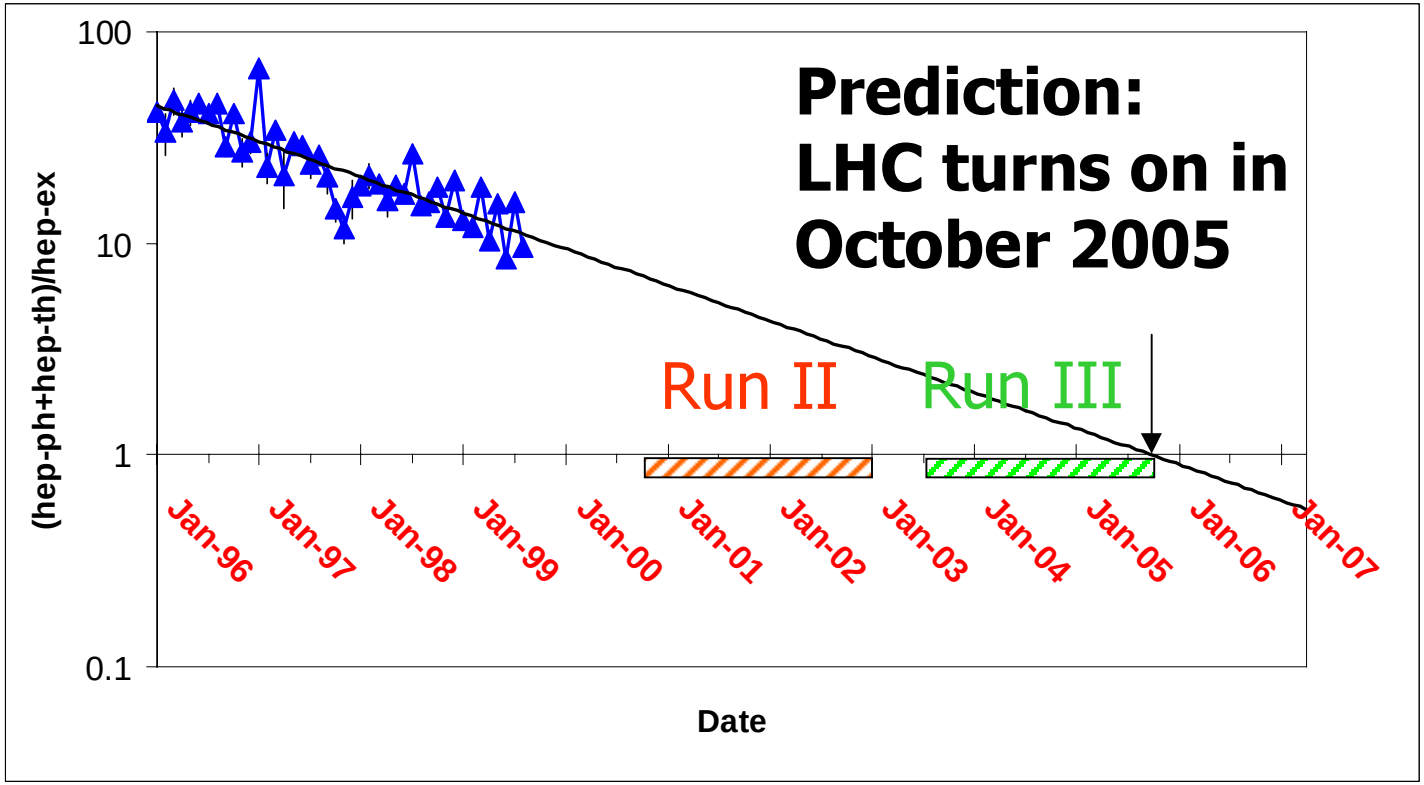
delayed photons

$\gamma\gamma$+E_T

It's a MESS!

How to Hunt for New Physics?

"Running theory-experiment coupling"



- Do not expect us to test EVERY model - we will test CHANNELS, not MODELS!

Detached Vertices and τ-ID

- Even though we do not know exactly what new physics will turn out to be, we have all reasons to believe that it will be strongly coupled to the third generation of matter
- SMT will allow for b- (and c-) tagging both offline and (we hope) as early as the second trigger level
- τ-ID will be essential for searches for new physics; it will be done in the SMT and based on the low track multiplicity jets and will allow to go as low as p_T^τ = 10 GeV/c
- Despite the fact that the CDF silicon vertex detector is larger and faster than that for DØ, both experiments are expected to have similar capabilities in high-p_T τ/b identification both at the trigger level and offline

"It's all About Triggers, Stupid!"

- If we can trigger on it, we will find it offline no matter how complicated it looks (e.g., kinks in tracker, non-pointing tracks or photons)
- Level 1 (available budget 10 KHz)
  - Single isolated CFT track: 20/50/150/2500 KHz (10/5/3/1.5 GeV/c)
  - Two isolated CFT tracks: 0.7/3/10/1000 KHz (10/5/3/1.5 GeV/c)
  - Two jets: 1.7/0.9 KHz (7/20 GeV)
  - Central ($|\eta| < 1.5$) muon: 0.03/0.05/0.1/22 KHz (11/7/4/2 GeV/c)
  - Central dimuons: 1/1900 Hz (11/2 GeV/c)
  - Central photons 400/1000 Hz (10/8 GeV)
- Level 2 (Available budget 1 KHz)
  - CFT tracks - no additional rejection
  - SVX tracks - increased momentum range for track candidates
  - detached vertices: b-jets, τ's (?)
  - Extensive use of the preshower detectors
- Level 3 (Available budget 20 Hz, expandable to 50 Hz)
  - High level software algorithms, preliminary event reconstruction

Long Lived Particles: Subject De Jour

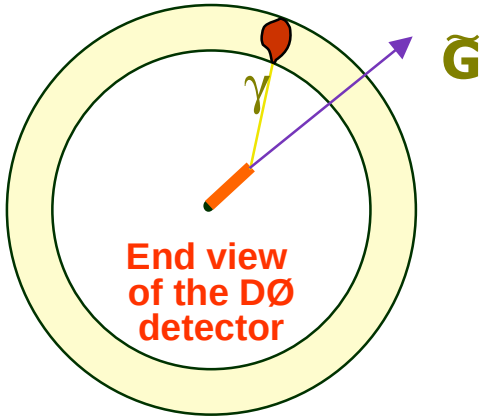
Long lived neutralino NLSP:
Chen, Gunion, PRD **58** (1998) 075005
...
Nearly degenerate Wino/Zino:
Randall, Sundrum, hep-th/9810155
Feng, Moroi, Randall, Strassler, Su, hep-ph/9904250
Gherghetta, Giudice, Wells, hep/ph/9904378
Gunion, Mrenna, hep-ph/9906270
...
Long-lived sleptons:
Feng, Moroi, PRD **58** (1998) 035001
Martin, Wells, PRD **59** (1999) 035008
...
Heavy Gluino LSP/NLSP:
Baer, Cheung, Gunion, PRD **59** (1999) 075002
Raby, Toby, NP **B539** (1999) 3
...

Second most popular subject after large extra dimensions!

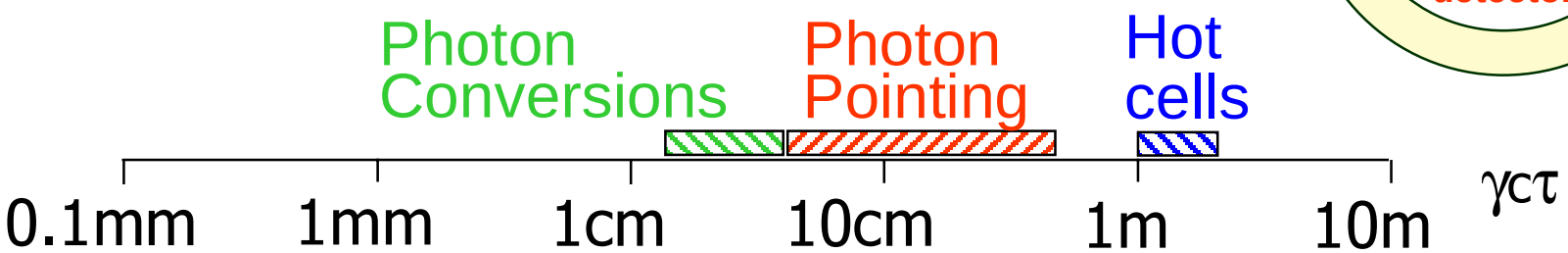
Long lived particles appear in many theories with suppressed NLSP decay or high mass degeneracy; they result in very characteristic signatures, such as highly-ionizing tracks (HIT), kinks, displaced vertices, etc.

Search for Long-Lived Particles at DØ

- The key question is the lifetime, or $\gamma c\tau$
- The key issue is the triggering

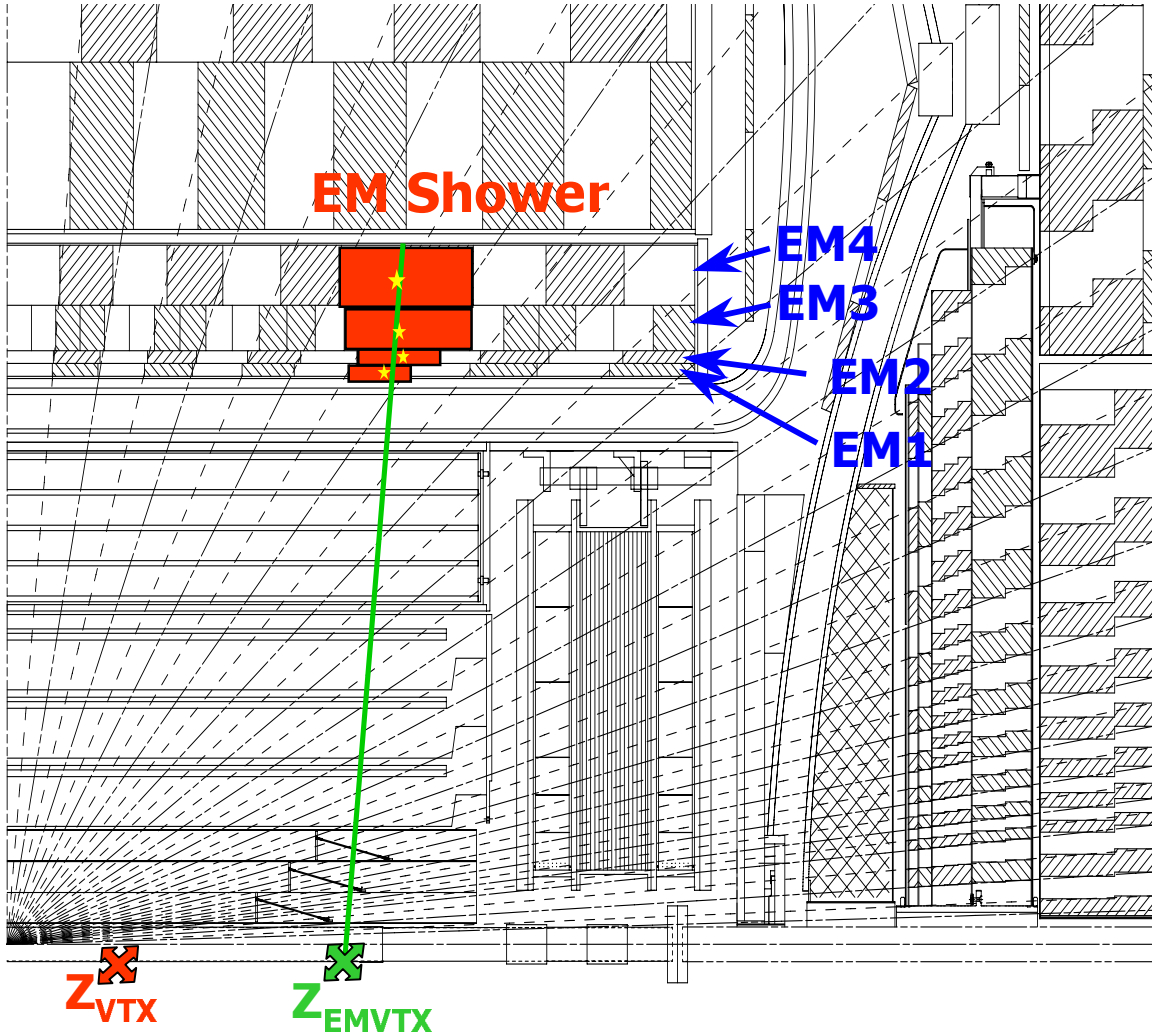


Neutral Long-Lived Particles:



Charged Long-Lived Particles:

Photon Pointing in the Last Millennium



4-point fit (EM1-EM4):

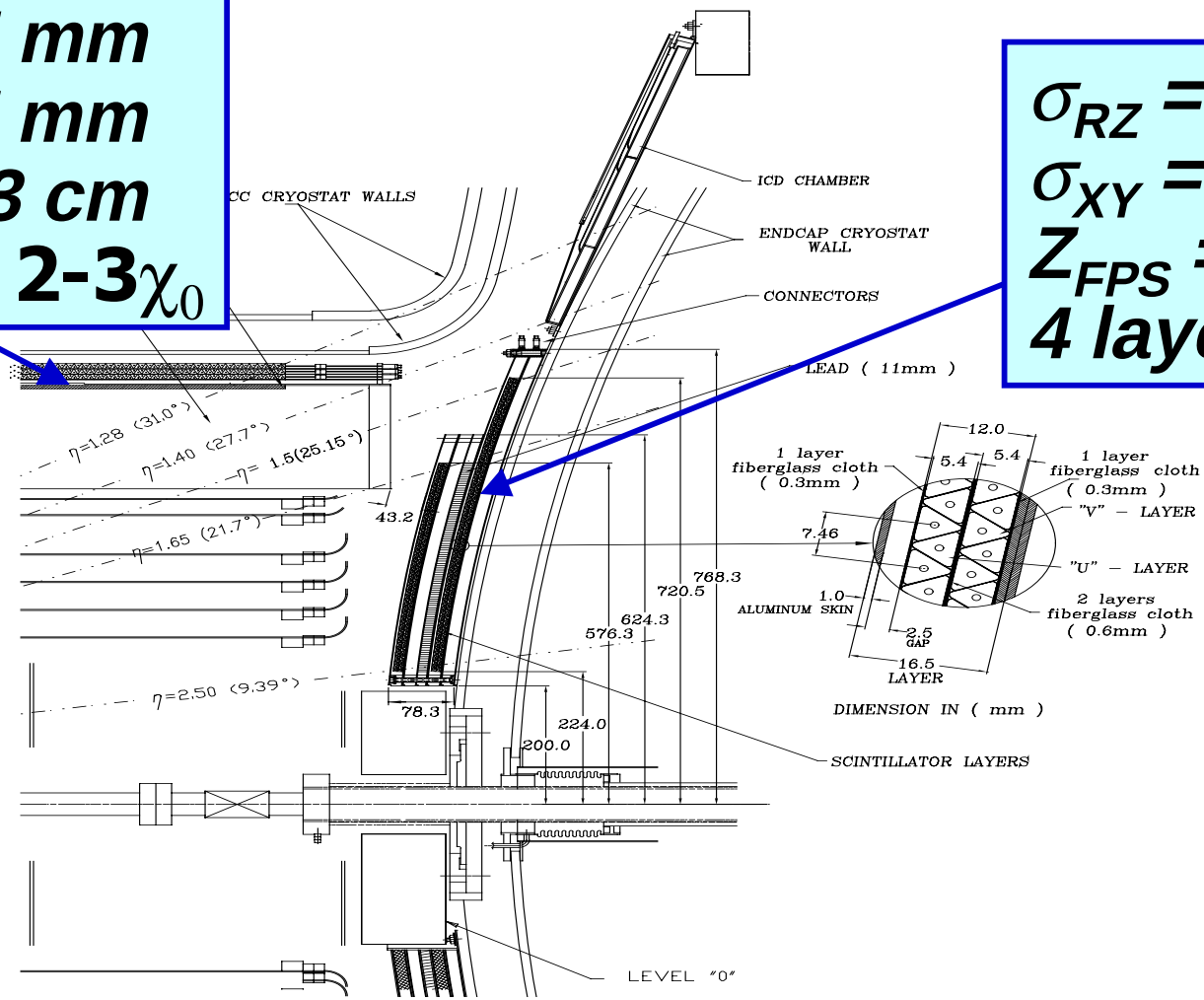
$\sigma_{XY} \sim$ **10 cm**
$\sigma_{RZ} \sim$ **15 cm**

Even though the resolutions are not very high, this tool was used in several analyses to confirm the primary vertex and suppress various backgrounds

Central and Forward Preshowers

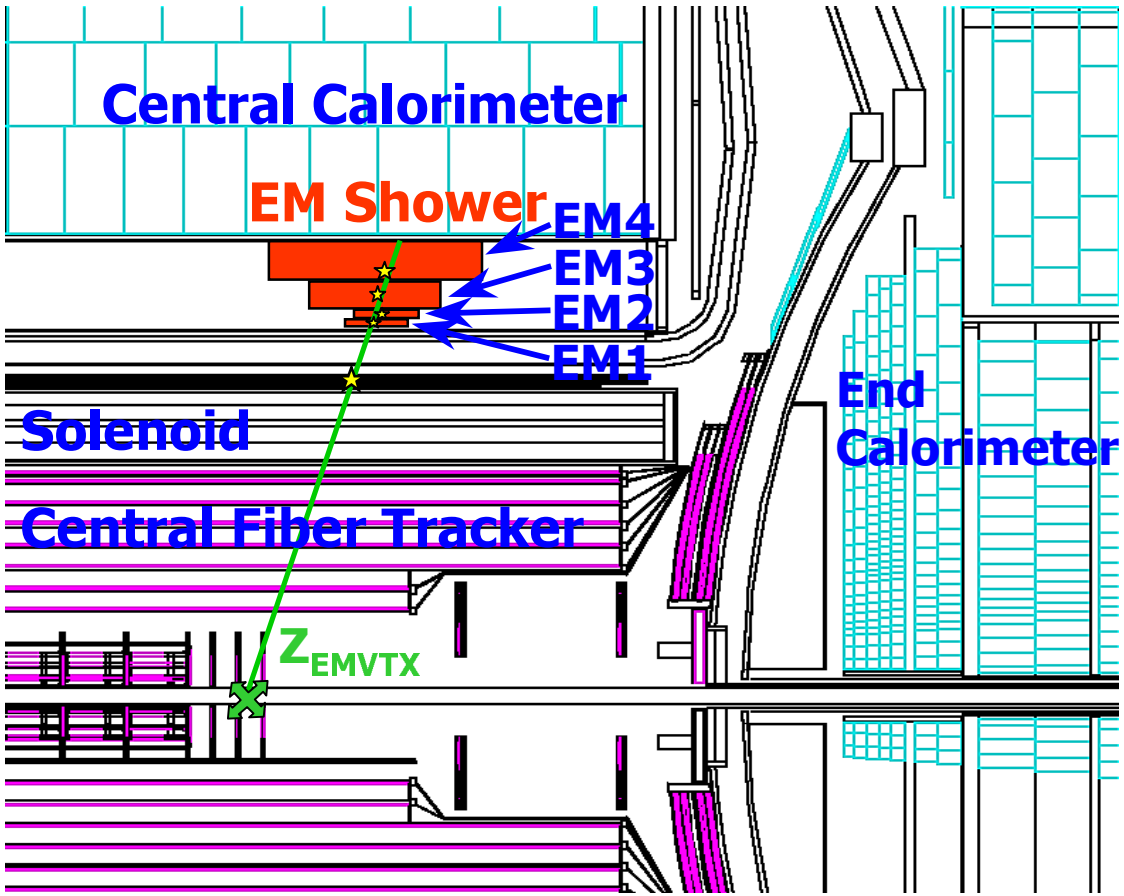
σ_{RZ} = 2.5 mm
σ_{XY} = 1.5 mm
R_{CPS} = 73 cm
3 layers, 2-3χ_0

σ_{RZ} = 1.5 mm
σ_{XY} = 2.5 mm
Z_{FPS} = 142 cm
4 layers, 2χ_0



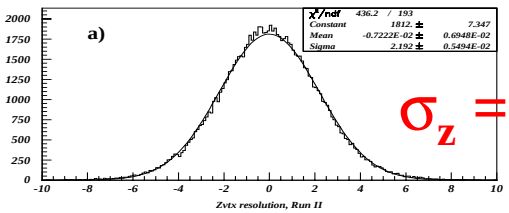
Photon Pointing in the Next Millennium

Side view of DØ in Run II

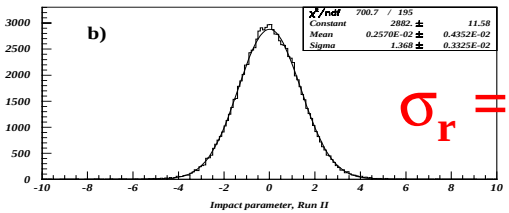


[D.Cutts, GL, hep-ph/9904396]

Central region

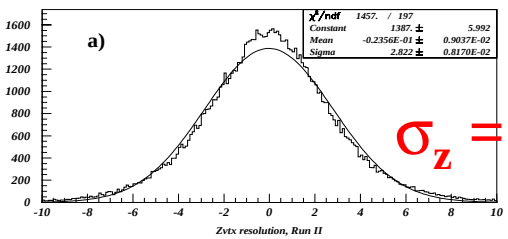


σ_z = 2.2 cm

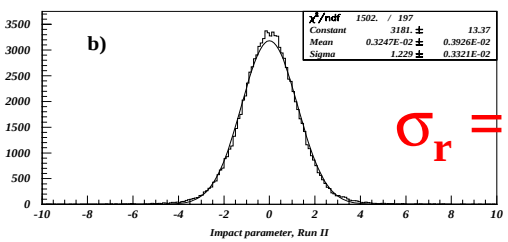


σ_r = 1.4 cm

Forward region



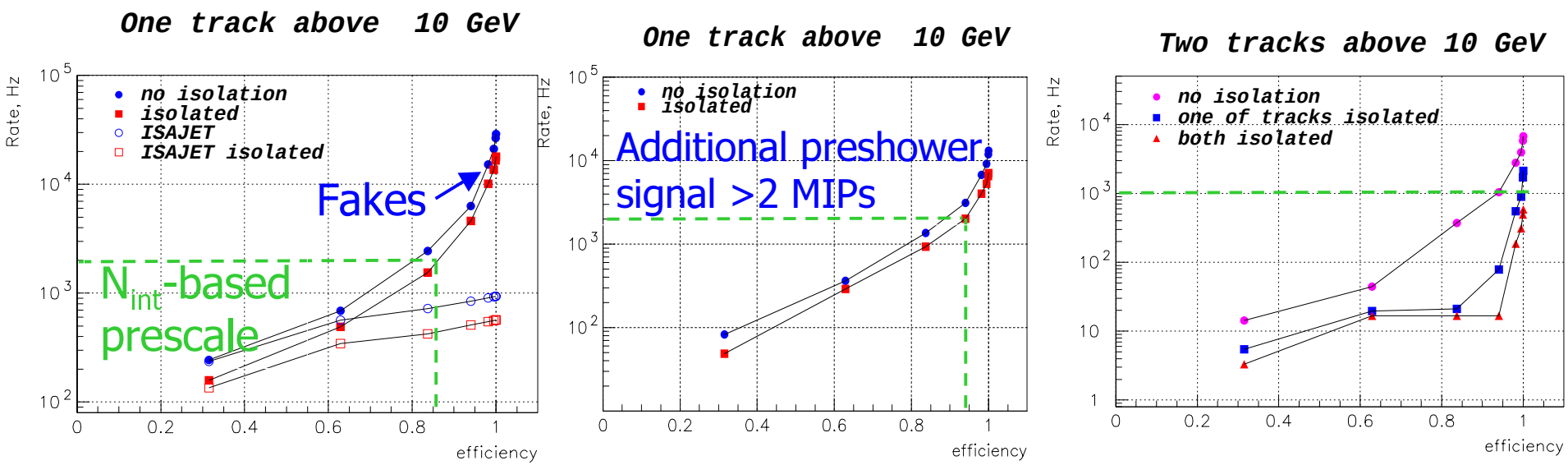
σ_z = 2.8 cm



σ_r = 1.2 cm

HIT: Level 1 Triggering

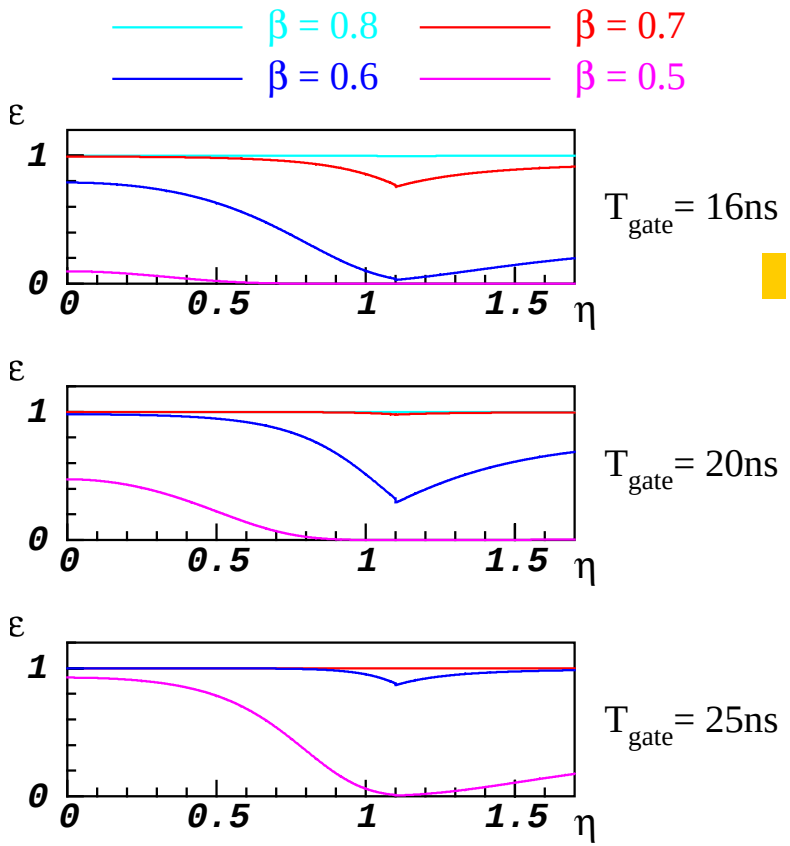
- If the long-lived particles are pair-produced, and if the decay chain does not contain any high-p_T detectable particles (e.g., $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^{0} + \pi^{\pm}$), there are just two ways to trigger:
  - Require an associated jet, and trigger on jet + $\not{E}_T$ ($\varepsilon \sim 10\%$)
  - Trigger on a single isolated track or a pair of tracks (high rates)



[Y.Gershtein, DØ trigger studies]

Additional Handles

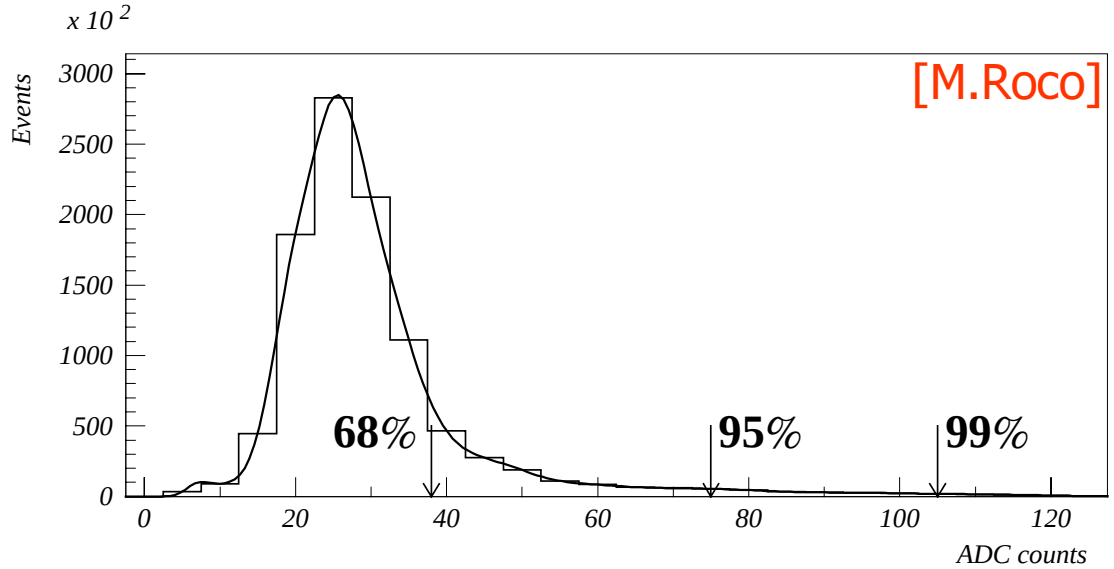
- For a really long-lived particle, additional rejection from muon chambers: both from confirmation and, possibly, from timing



- Caveat: it is not clear that we can keep the timing gate long due to random coincidence background that would otherwise blow up our standard muon trigger rate

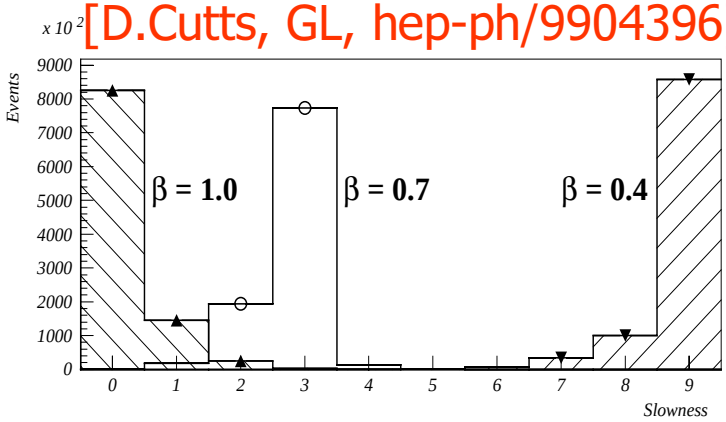
HIT: dE/dx in SMT

- dE/dx in SMT



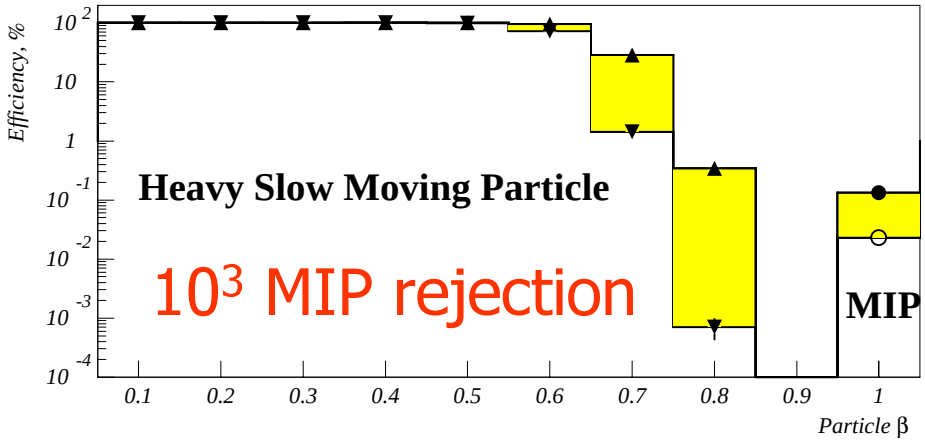
- dE/dx in CFT: 0.1 MIP/layer
- dE/dx in preshower detectors
- dE/dx in the calorimeter

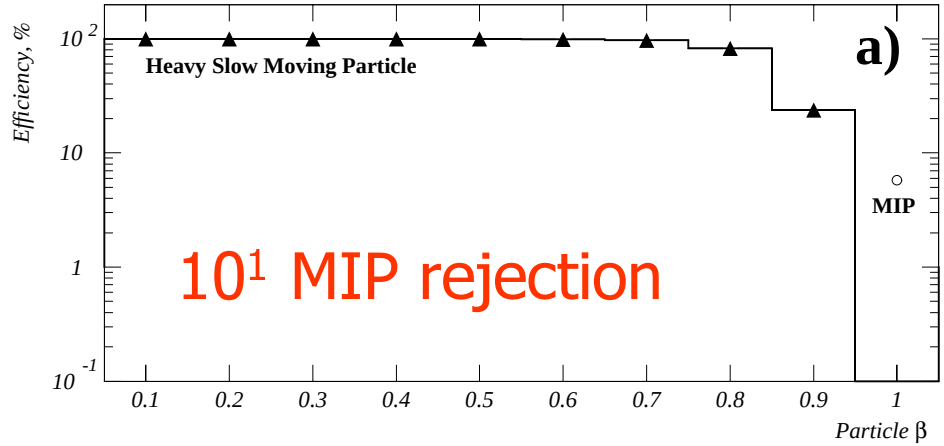
Slowness per layer:
S = 0: <68%
S = 1: >68% (1σ)
S = 2: >95% (2σ)
S = 3: >99% (3σ)
4 layers, remove one with the highest dE/dx
Slowness: sum of S_i over three remaining layers
$S \in \{0..9\}$
[D.Cutts, GL, hep-ph/9904396]



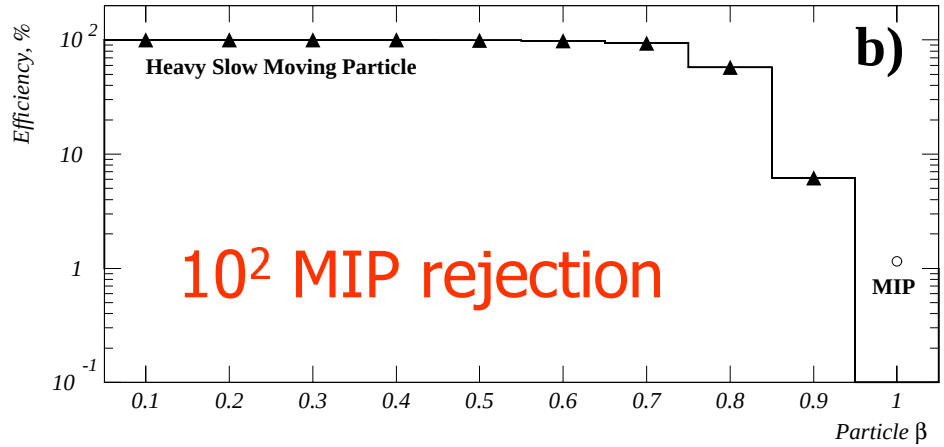
HIT: Level 2 Triggering

[D.Cutts, GL, hep-ph/9904396]





By adjusting the definition of slowness and the value of the cut one could be efficient up to β=0.9 with 10-1000 MIP rejection factor at the trigger level 2



Probing GMSB Models

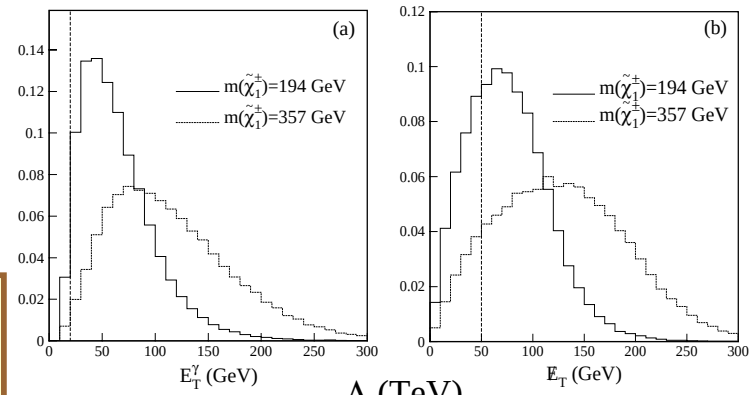
- GMSB model mass spectrum depends on the following parameters:
  - $\Lambda = F/S$: ratio of SUSY DSB scale and the scalar field vev
  - M,N: Messenger scale, number of messengers
  - $\tan\beta$ and sign(μ) (ratio of vev's of the two Higgs doublets and sign of the Higgs mass parameter)
- Low energy phenomenology mainly depends on Λ and on the nature of the NLSP (Goldstino is the LSP)
- For neutral NLSP phenomenology is given by the radiative decay: NLSP $\rightarrow \gamma + \tilde{G}$ (photons + $\not{E}_T$ final state)
- For charged NLSP phenomenology is given by NLSP $\rightarrow \boldsymbol{l} + \tilde{G}$ (leptons + $\not{E}_T$ final state)
- The lifetime of the NLSP is the key issue

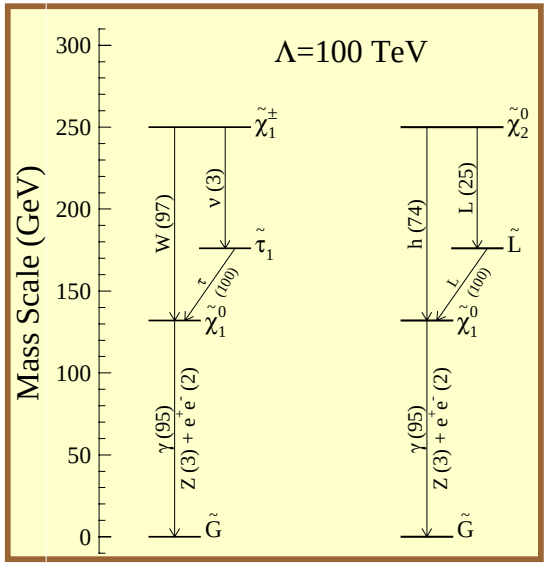
NLSP and its lifetime

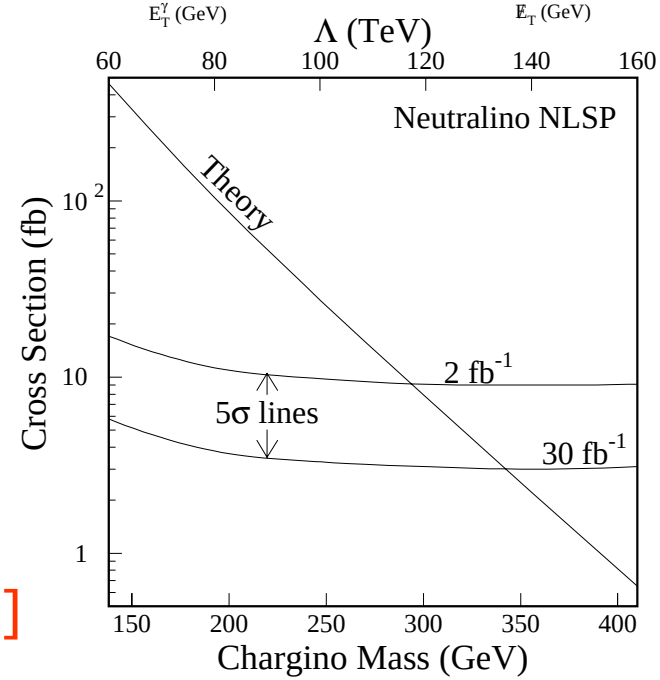
- Neutralino NLSP:
  - $\tilde{\chi}_1^0 \to \gamma + \tilde{G}$ decay, $\gamma\gamma + \not{E}_T$ +X final state
  - $\gamma c\tau \sim 100\,(\sqrt{F}/100\text{ TeV})^4\,(100\text{ GeV}/M(\tilde{\chi}_1^0))^5\ \mu\text{m}$
  - For $\gamma c\tau \gtrsim$ 1m - undetectable
- Stau NLSP:
  - $\tilde{\tau}_1 \to \tau + \tilde{G}$ ($\tilde{\tau}_1$ is the lighter of the two mixed states of $\tilde{\tau}_R$ and $\tilde{\tau}_L$)
  - $\gamma c\tau \sim (\sqrt{F}/100\text{ TeV})^4 \times (100\text{ GeV}/M(\tilde{\tau}_1))^5$ cm
- Stau/Slepton as Co-NLSP's:
  - $\gamma c\tau$ is the same as for the stau NLSP case
- Higgsino NLSP:
  - $\gamma c\tau$ very much depends on the mass relative to that of Z, h

Search for Prompt Neutralino NLSP Decays

- Production: $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$
- Final state: $\gamma\gamma + \not{E}_T$ + jets
- Cuts: $\geq 2\gamma$, $E_T > 20$ GeV; $\not{E}_T > 50$ GeV
- Backgrounds: 0.4 fb (QCD) + 0.2 fb (fakes) → 1.2 events
- Acceptance: 15-30%
- Sensitivity: $M(\tilde{\chi}_1^{\pm}) \gtrsim 300$ GeV at 5σ



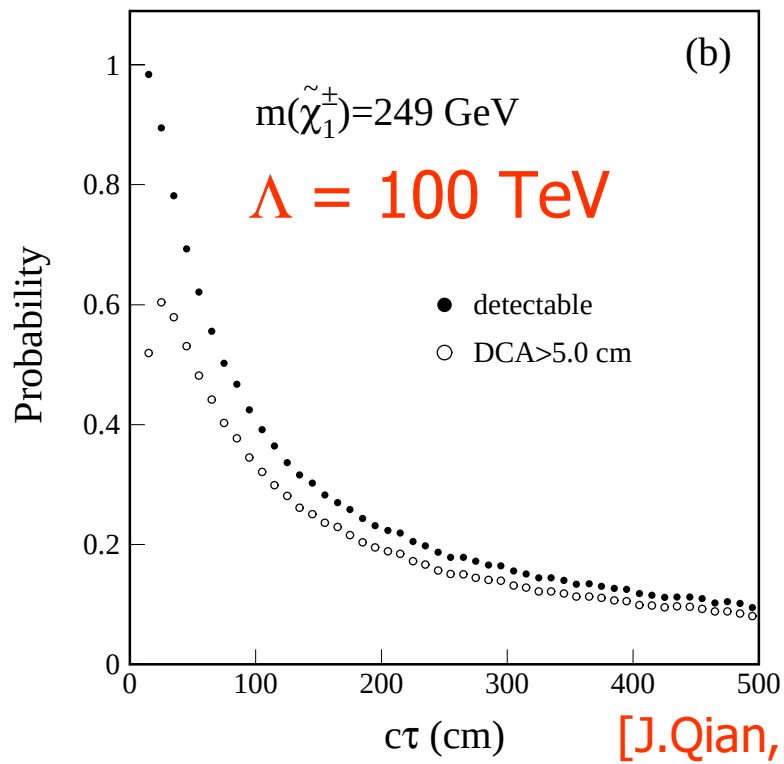


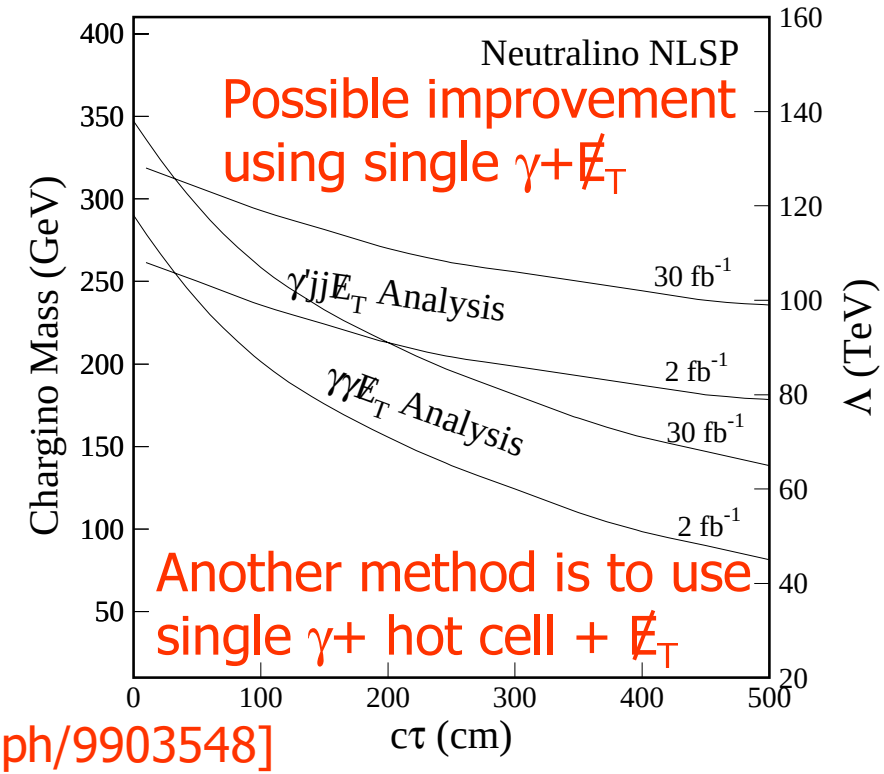


[J.Qian, hep-ph/9903548]

Search for Long-Lived Neutralino Decays

- Use single photons to increase acceptance
- Additional jets might be necessary to require to reduce backgrounds
- Use photon pointing: impact parameter > 5 cm

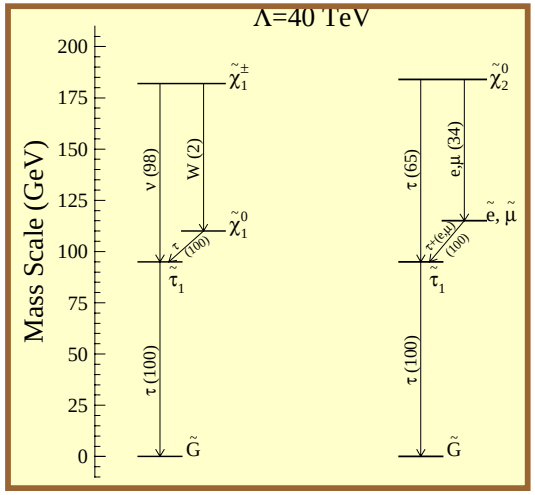


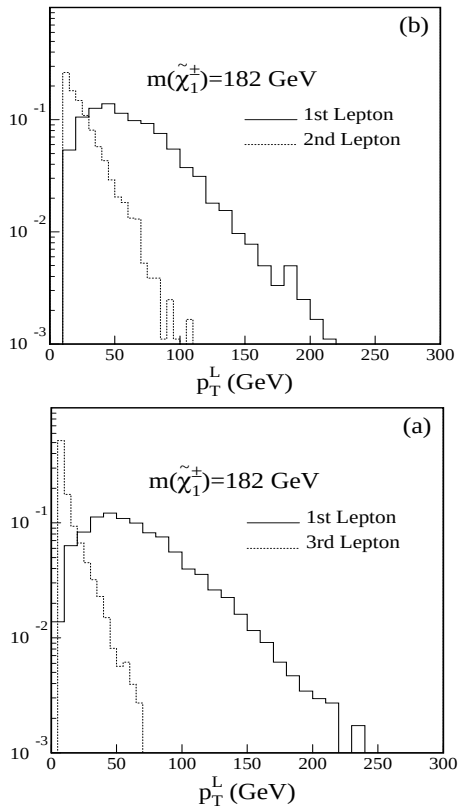


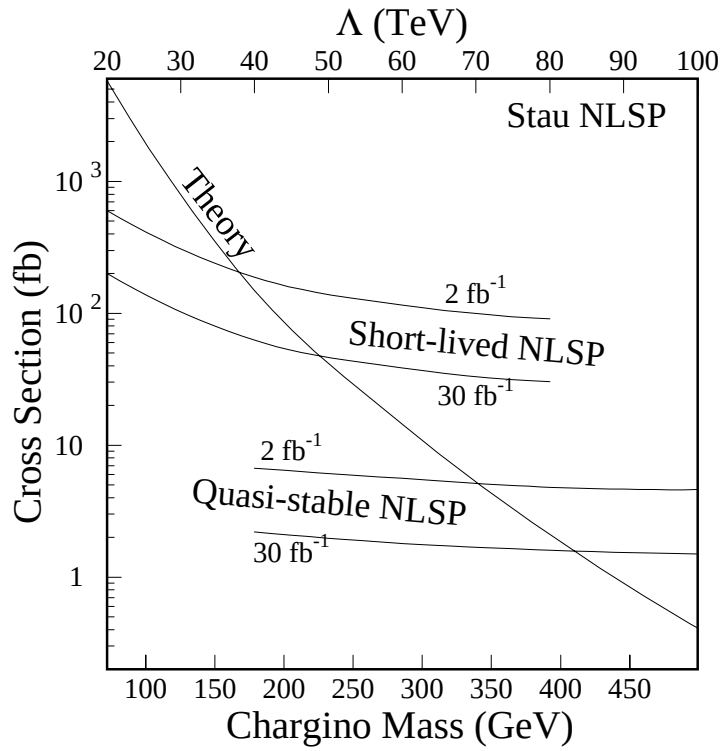
[J.Qian, hep-ph/9903548]

Stau NLSP

- SUGRA-like l+jets+$\not\!\!E_T$, ll+jets+$\not\!\!E_T$ and lll+jet(s)+$\not\!\!E_T$ channels
- Leptons from cascade decays, so one needs low p_T^l threshold
- Dominant backgrounds: W/Z + jets; trilepton channel is clean



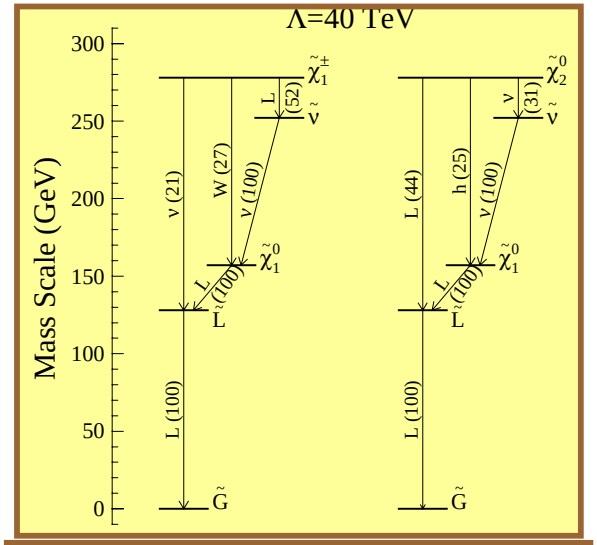


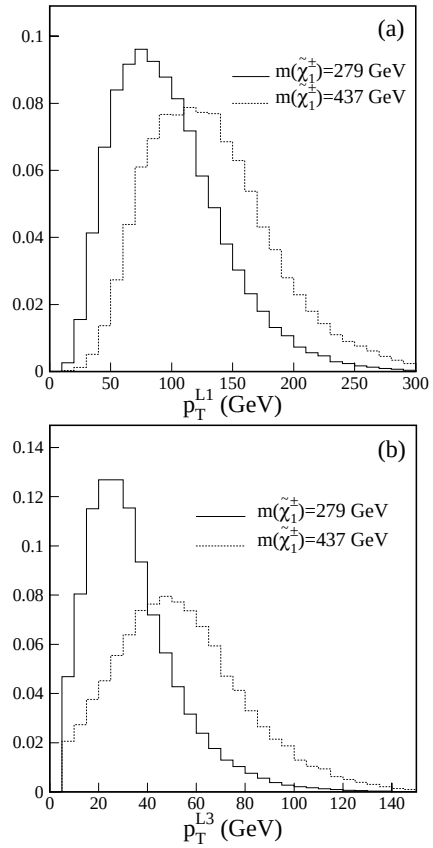


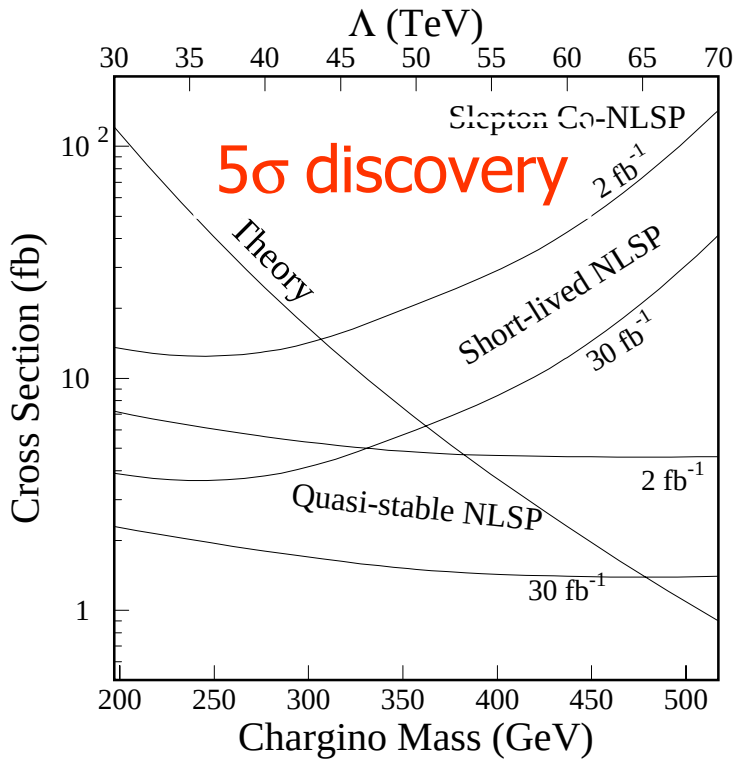
- Long lived $\tilde{\tau}$ are detected via HIT
- $c\tau \sim 30$ cm is tough for triggering

Stau/Slepton Co-NLSP's

- $ll+\not{E}_T$ - swamped by copious WW/WZ/$t\bar{t}$
- lll+jet+$\not{E}_T$ channel due to cascade decays of $\tilde{\chi}_1^{\pm,0}$ is, however, possible
- This trilepton channel is clean



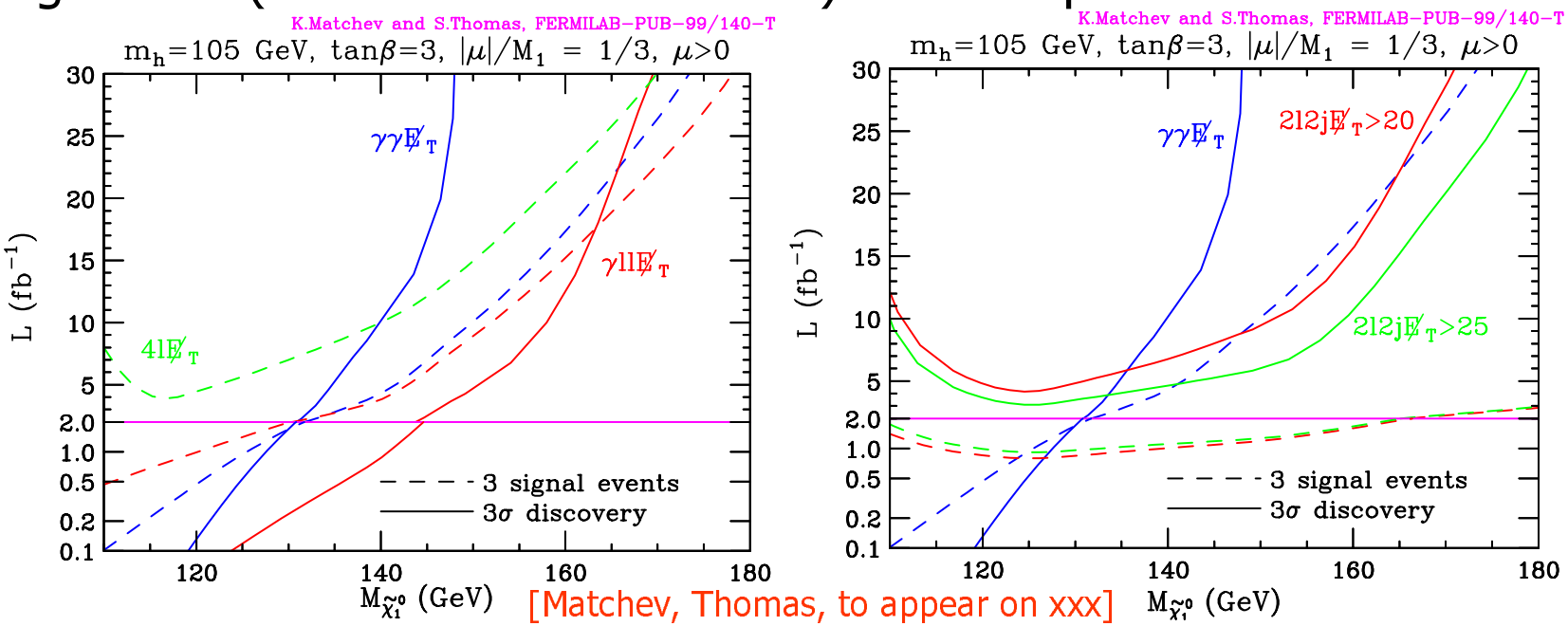




- Long lived $\tilde{\tau}$ are detected via HIT
- $c\tau \sim 30$ cm is tough for triggering

Higgsino NLSP

- Novel phenomenology that has not been studied in detail before
- Depending on the gaugino/higgsino components of the $\tilde{\chi}_1^0$, decay modes are $\gamma\tilde{G}$, $Z\tilde{G}$, $h\tilde{G}$, that correspond to $\gamma\gamma+\not{E}_T$, $\gamma+\not{E}_T$(+jets), jets+$\not{E}_T$, $\gamma l^+l^-+\not{E}_T$, $l^+l^-+\not{E}_T$(+jets), $4l+\not{E}_T$, where some jets are from b-quarks
- Non-prompt decays were not studied yet, but they should give striking signatures (like a detached Z vertex!) that are quite detectable



[Matchev, Thomas, to appear on xxx]

Phenomenology of the RPV SUSY

SUSY introduces an extra discrete symmetry: R-parity, R_p:

$$R_p = (-1)^{3B+L+2S}$$

B - baryon number
L - lepton number
S - particle spin

Originated in a footnote[±7] *of classical Farrar-Fayet paper [PL **76B** (1978) 575]*

R_p

"Ordinary" particles **+1** ↔ **-1** **SUSY particles**

P-parity? - Was taken!; Q-parity? - Excuse my French!; hence - R-parity

RPV couplings describe lepton or baryon number non-conservation (assuming that angular momentum is still conserved!)

Experimental Bounds on the RPV Couplings

9 + 27 + 9 = 45

$$W_{R_p} = \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k$$

Lepton number violation

Baryon number violation

Why bother? We have enough free parameters already! - Experimental limits are very weak...

Current RPV coupling bounds:

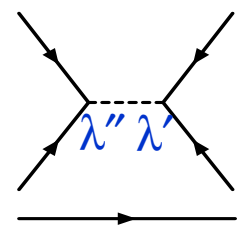
ijk	λ_{ijk}	ijk	λ'_{ijk}	ijk	λ'_{ijk}	ijk	λ'_{ijk}	ijk	λ''_{ijk}
121	0.05	111	0.001	211	0.09	311	0.16	112	10^{-6}
122		112	0.02	212		312		113	10^{-5}
123		113		213		313		123	1.25
131	0.06	121	0.035	221	0.18	321	0.20	212	
132		122	0.06	222		322		213	
133	0.004	123	0.20	223		323		223	
231	0.06	131	0.035	231	0.22	331	0.26	312	0.43
232		132	0.33	232	0.39	332		313	
233		133	0.002	233		333		323	

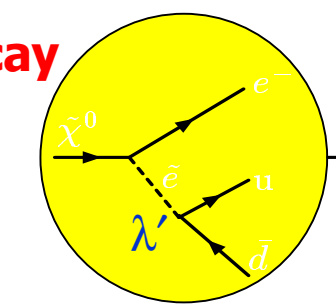
CC universality	double β	$R_l(Z)$	ν_μ DIS	$n \leftrightarrow$ n-bar
$\tau \to e\nu\nu/\mu\nu\nu$	Atomic Parity V.	$\pi \to e\nu/\mu\nu$	$\tau \to \pi\nu$	Indirect
ν_e mass	D^0-D^0-bar mixing	$D^+ \to K^*\mu\nu/K^*e\nu$	Heavy nucleon decay	2σ bounds

[H.Dreiner, hep-ph/9707435]

(mostly 1σ, $\tilde{m} = 100$ GeV)

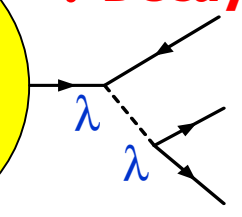
Proton Decay





Neutralino Decay

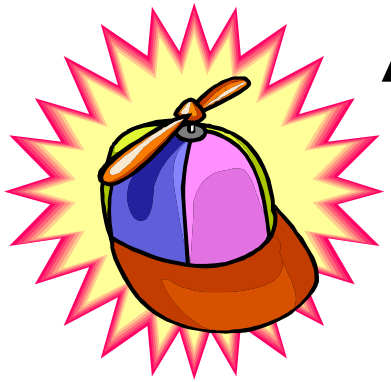
τ-Decay



What Skeptics Say…

Pierre Ramond: "I'll eat my hat if the RPV is found"

It's not the first time physicists promised to eat their hat if something is discovered. Some actually did (cf. J/Ψ)



λ

λ'

λ''

Might make quite a demonstration at the SUSY`02 Conference!

Search for R-Parity Violation in Run II with DØ

$$p\bar{p} \to \cdots \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X \to (l\tilde{l})(l\tilde{l}) + X \xrightarrow{\not{R}_p} l\,(q\bar{q}')\; l\,(q\bar{q}') + X$$

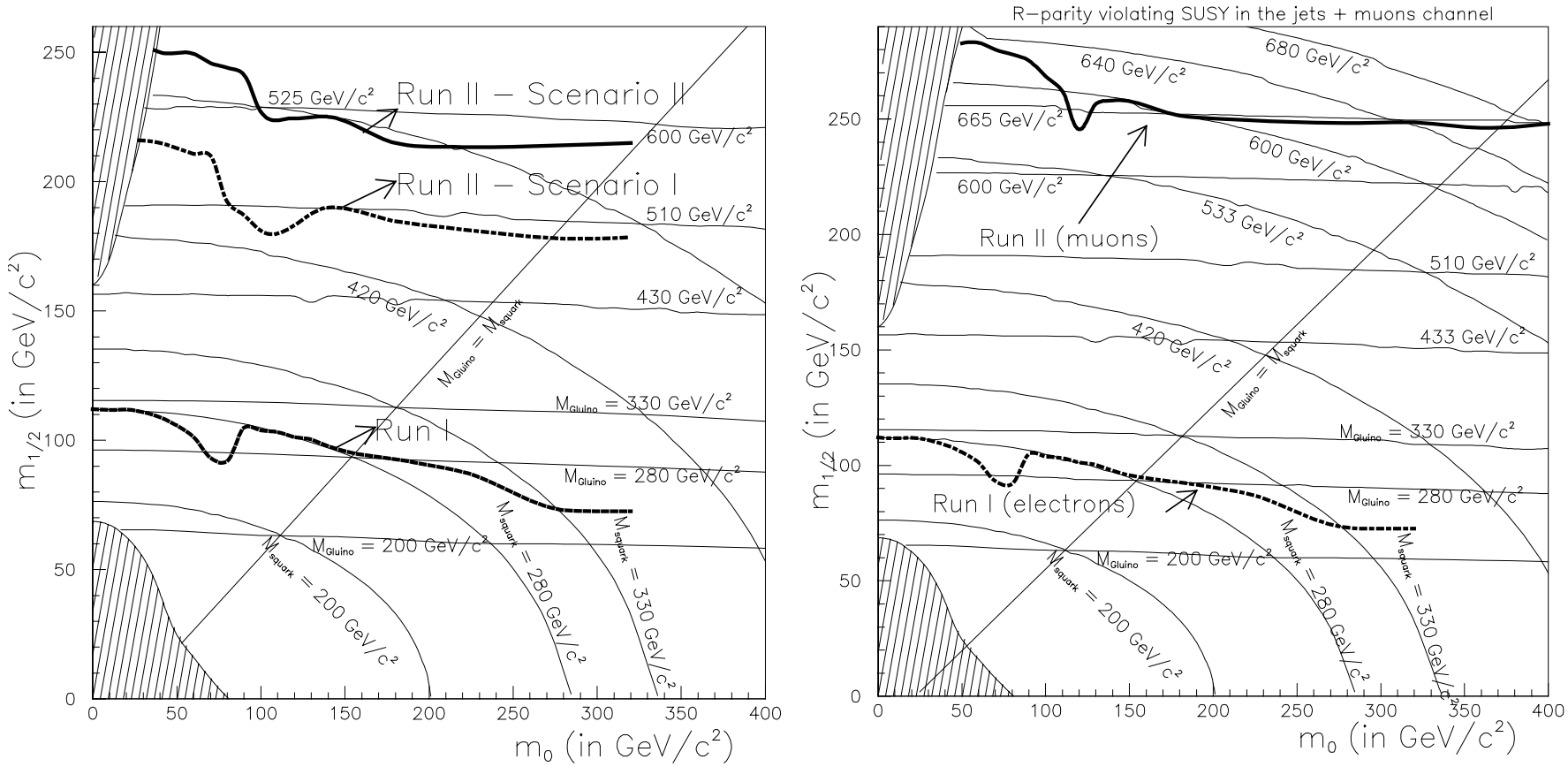
$$p\bar{p} \to ll + \geq 4\,jets, \quad l = e, \mu \qquad \lambda'_{1ij}, \lambda'_{2ij}$$

- Model:
  - Neutralino is the LSP and decays inside the fiducial volume, i.e. $\lambda' > 10^{-3}$
  - SUGRA framework: m_0, $m_{1/2}$, $\tan\beta = 2$, A_0, sign(μ)<0
  - Studies done on the basis of the Run I analyses
- Cuts:
  - $\geq 2l$ with E_T > 15,10 GeV, $|\eta_l|$ < 2.3-2.5
  - $\geq$4 jets with E_T > 15 GeV, $|\eta_j|$ < 2.5
  - Z(ll)-veto
- Backgrounds:
  - DY + 4 jets
  - $t\bar{t} \to l$ + jets
  - Fakes (e channel)

Total background from Run I scaling:
36 (15) events for e+4jets, scenario I (II)
10 events for μ+4jets

RPV SUSY reach in Run II

$\tan\beta = 2$; retain sensitivity for $\tan\beta \lesssim 10$



[S.Banerjee, N.Mondal, V.Narasimham, and N.Parua, hep-ph/9904397]

Other RPV Searches

- Also plan to explore like-sign lepton channels accessible via squark decays (including stop!):

$$p\bar{p} \to \tilde{q}\bar{\tilde{q}} \to \left(q\tilde{\chi}_1^0\right)\left(\bar{q}\tilde{\chi}_1^0\right) \xrightarrow{\not{R}_p} q\left(q\bar{q}'l^{\pm}\right)\bar{q}\left(q\bar{q}'l^{\pm}\right)$$

$$p\bar{p} \to \left(l^+l^+ \text{ or } l^-l^-\right) + \geq 2\,jets,\ l = e,\mu \qquad \lambda'_{1ij}, \lambda'_{2ij}$$

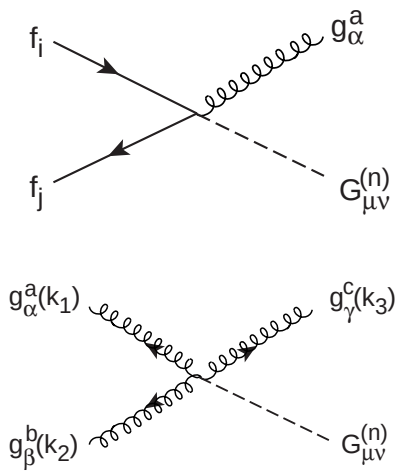
- Like-sign leptons can appear since neutralino is a Majorana particle
- Significant advantage: very low backgrounds
- Studies done by CDF based on their Run I analysis show expected sensitivity to the squark masses ~400 GeV [M.Chertok, in hep-ph/9906224]
- Also plan to search for λ couplings via multilepton final states

The Importance of Being Earnest

- Even though SUSY is a very interesting possibility, one should always keep in mind that it is STILL just a model, and therefore could be wrong!
- Fortunately, the signature-based approach is much less model-dependent than the model-based one
- SUSY hunting ground is also that for non-SUSY models: technicolor, extra dimensions, as well as beyond the MSSM extensions that contain leptoquarks, excited quarks and fermions, extra gauge bosons, fourth generation of matter, stable heavy quarks, etc.
- DØ is VERY OPEN-MINDED to these possibilities (earnest, too!) and we will try to probe all these models simultaneously in Run II

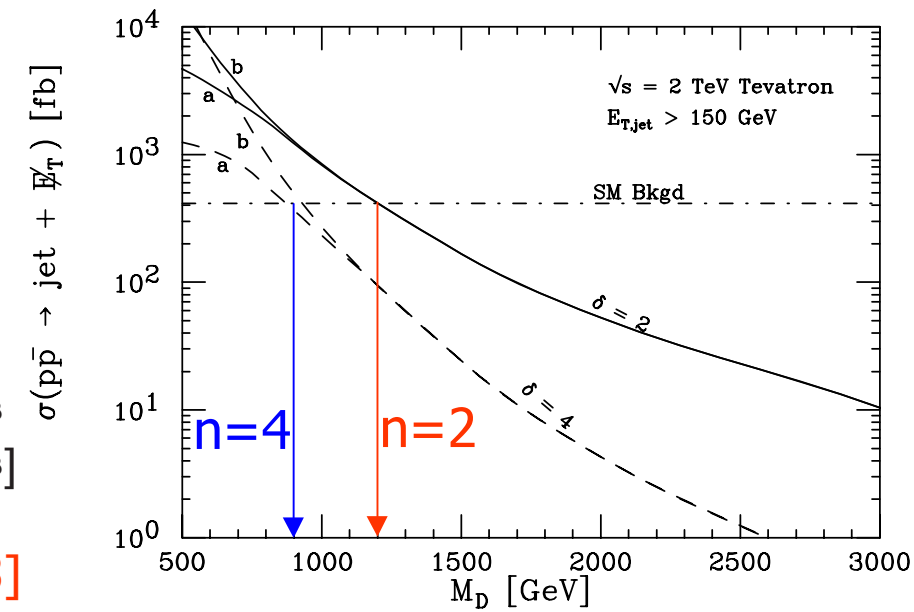
Search for Large Extra Dimensions - Direct g_{KK}

- Direct Kaluza-Klein graviton emission:
  - Monojet analysis, trying to understand the ET tails using Run I data with direct implication for Run II
  - Monophoton analysis has similar sensitivity



$$-\frac{i}{2\overline{M}_P} g_s t^a_{ji} \left(X_{\mu\nu\alpha} + X_{\nu\mu\alpha}\right)$$

$$\frac{g_s}{\overline{M}_P} f^{abc} \left[Y(k_1)_{\mu\nu\alpha\beta\gamma} + Y(k_2)_{\mu\nu\beta\gamma\alpha} + Y(k_3)_{\mu\nu\gamma\alpha\beta} + Y(k_1)_{\nu\mu\alpha\beta\gamma} + Y(k_2)_{\nu\mu\beta\gamma\alpha} + Y(k_3)_{\nu\mu\gamma\alpha\beta} \right]$$



[Giudice, Rattazzi, Wells, NP **B544** (1999) 3]

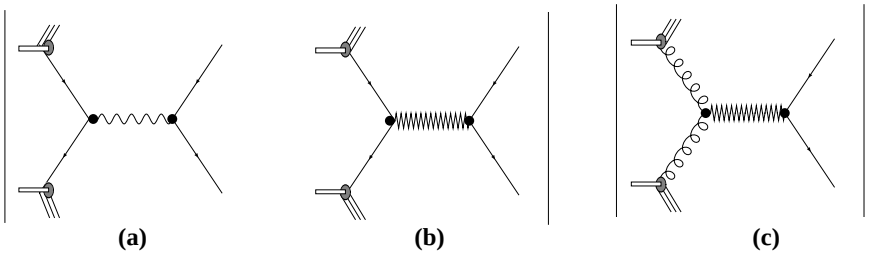
[Mirabelli, Perelstein, Peskin, PRL **82** (1999) 2236]

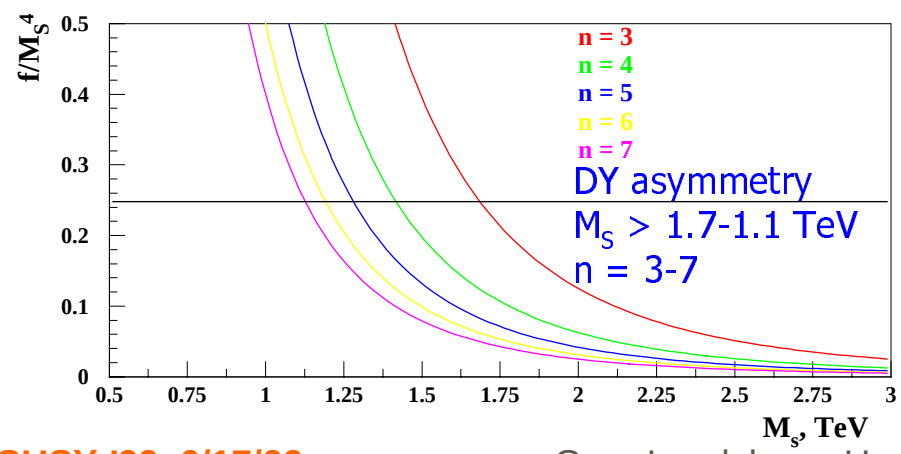
...

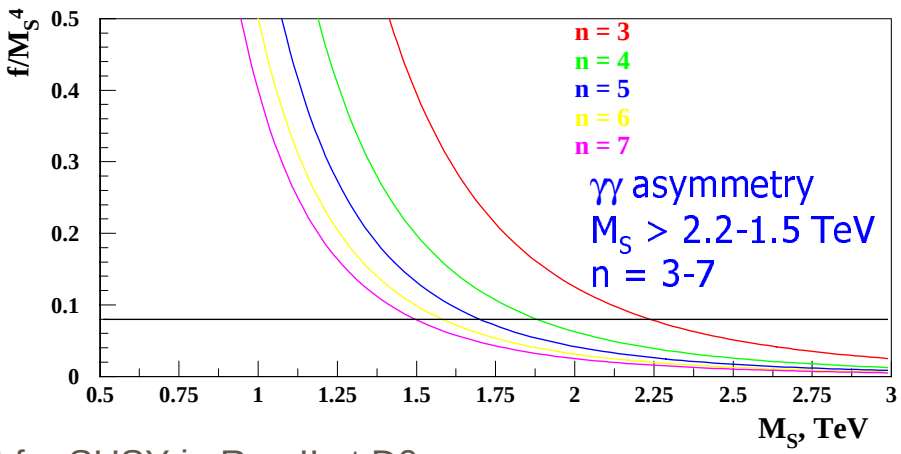
M_S > 900-1200 GeV, n=4-2

Search for Large Extra Dimensions - Virtual g_{KK}

- Virtual graviton Drell-Yan and diphoton production
  - Mass spectrum has been looked at [Gupta, Mondal, Raychaudhuri, hep-ph/9904234, Cheung, hep-ph/9904266, hep-ph/9904510]
  - Key improvement: analyzing angular distributions [Cheung, GL - to appear on xxx] (see Kingman Cheung's talk this afternoon)







Conclusions

- Run II offers so many exciting discovery possibilities that we can not wait to start it (in just a year!)
- So, let's

just

DØ

it!

- First recorded events by SUSY'00