ILC Physics that Challenges SiD

- An *Incomplete* list of challenging processes
- LHC will be 1st: can guide what will be needed
  but may have missed something!
- Don't forget the Tevatron – New Physics hints

Long List of Benchmark Processes

TABLE II: Benchmark reactions for the evaluation of ILC detectors

	Process and Final states	Energy (TeV)	Observables	Target Accuracy	Detector Challenge	Notes
Higgs	$ee \to Z^0h^0 \to \ell^+\ell^- X$	0.35	M_{recoil}, σ_{Zh}, BR_{bb}	$\delta\sigma_{Zh} = 2.5\%$, $\delta BR_{bb} = 1\%$	T	{1}
	$ee \to Z^0h^0,\ h^0 \to b\bar{b}/c\bar{c}/\tau\tau$	0.35	Jet flavour , jet $(E,\vec{p})$	δM_h=40 MeV, $\delta(\sigma_{Zh} \times BR)$=1%/7%/5%	V	{2}
	$ee \to Z^0h^0, h^0 \to WW^*$	0.35	M_Z, M_W, σ_{qqWW^*}	$\delta(\sigma_{Zh} \times BR_{WW^*})$=5%	C	{3}
	$ee \to Z^0h^0/h^0\nu\bar{\nu},\ h^0 \to \gamma\gamma$	1.0	$M_{\gamma\gamma}$	$\delta(\sigma_{Zh} \times BR_{\gamma\gamma})$=5%	C	{4}
	$ee \to Z^0h^0/h^0\nu\bar{\nu},\ h^0 \to \mu^+\mu^-$	1.0	$M_{\mu\mu}$	5σ Evidence for $M_h = 120$ GeV	T	{5}
	$ee \to Z^0h^0, h^0 \to invisible$	0.35	σ_{qqE}	5σ Evidence for $BR_{invisible}$=2.5%	C	{6}
	$ee \to h^0\nu\bar{\nu}$	0.5	$\sigma_{bb\nu\nu}$, M_{bb}	$\delta(\sigma_{\nu\nu h} \times BR_{bb}) = 1\%$	C	{7}
	$ee \to t\bar{t}h^0$	1.0	σ_{tth}	δg_{tth}=5%	C	{8}
	$ee \to Z^0h^0h^0,\ h^0h^0\nu\bar{\nu}$	0.5/1.0	σ_{Zhh}, $\sigma_{\nu\nu hh}$, M_{hh}	δg_{hhh}=20/10%	C	{9}
SSB	$ee \to W^+W^-$	0.5		$\Delta\kappa_\gamma, \lambda_\gamma = 2 \cdot 10^{-4}$	V	{10}
	$ee \to W^+W^-\nu\bar{\nu}/Z^0Z^0\nu\bar{\nu}$	1.0	σ	$\Lambda_{*4}, \Lambda_{*5} = 3$ TeV	C	{11}
SUSY	$ee \to \tilde{e}^+_R\tilde{e}^-_R$ (Point 1)	0.5	E_e	$\delta M_{\tilde{\chi}^0_1}$=50 MeV	T	{12}
	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1,\ \tilde{\chi}^+_1\tilde{\chi}^-_1$ (Point 1)	0.5	E_π, $E_{2\pi}$, $E_{3\pi}$	$\delta(M_{\tilde{\tau}_1} - M_{\tilde{\chi}^0_1})$=200 MeV	T	{13}
	$ee \to \tilde{t}_1\tilde{t}_1$ (Point 1)	1.0		$\delta M_{\tilde{t}_1}$=2 GeV		{14}
-CDM	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1,\ \tilde{\chi}^+_1\tilde{\chi}^-_1$ (Point 3)	0.5		$\delta M_{\tilde{\tau}_1}$=1 GeV, $\delta M_{\tilde{\chi}^0_1}$=500 MeV,	F	{15}
	$ee \to \tilde{\chi}^0_2\tilde{\chi}^0_3,\ \tilde{\chi}^+_1\tilde{\chi}^-_1$ (Point 2)	0.5	M_{jj} in $jj\not{E}$, $M_{\ell\ell}$ in $jj\ell\ell\not{E}$	$\delta\sigma_{\tilde{\chi}_2\tilde{\chi}_3} = 4\%$, $\delta(M_{\tilde{\chi}^0_2} - M_{\tilde{\chi}^0_1})$= 500 MeV	C	{16}
	$ee \to \tilde{\chi}^+_1\tilde{\chi}^-_1/\tilde{\chi}^0_i\tilde{\chi}^0_j$ (Point 5)	0.5/1.0	$ZZ\not{E}$, $WW\not{E}$	$\delta\sigma_{\tilde{\chi}\tilde{\chi}}$=10%, $\delta(M_{\tilde{\chi}^0_3} - M_{\tilde{\chi}^0_1})$ =2 GeV	C	{17}
	$ee \to H^0A^0 \to b\bar{b}b\bar{b}$ (Point 4)	1.0	Mass constrained M_{bb}	δM_A=1 GeV	C	{18}
-alternative	$ee \to \tilde{\tau}^+_1\tilde{\tau}^-_1$ (Point 6)	0.5	Heavy stable particle	$\delta M_{\tilde{\tau}_1}$	T	{19}
SUSY	$\tilde{\chi}^0_1 \to \gamma + \not{E}$ (Point 7)	0.5	Non-pointing γ	$\delta c\tau$=10%	C	{20}
breaking	$\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 + \pi^\pm_{soft}$ (Point 8)	0.5	Soft $\pi^\pm$ above $\gamma\gamma$ bkgd	5σ Evidence for $\Delta\tilde{m}$=0.2-2 GeV	F	{21}
Precision SM	$ee \to t\bar{t} \to 6\ jets$	1.0		5σ Sensitivity for $(g-2)_t/2 \leq 10^{-3}$	V	{22}
	$ee \to f\bar{f}$ $(f = e, \mu, \tau; b, c)$	1.0	$\sigma_{f\bar{f}}$, A_{FB}, A_{LR}	5σ Sensitivity to $M_{Z_{LR}} = 7$ TeV	V	{23}
New Physics	$ee \to \gamma G$ (ADD)	1.0	$\sigma(\gamma + \not{E})$	5σ Sensitivity	C	{24}
	$ee \to KK \to f\bar{f}$ (RS)	1.0			T	{25}
Energy/Lumi	$ee \to ee_{fwd}$	0.3/1.0		δM_{top}=50 MeV	T	{26}
Meas.	$ee \to Z^0\gamma$	0.5/1.0			T	{27}

Battaglia etal

This is a good list!

Reduced List of Benchmarks

0. Single $e^\pm$, $\mu^\pm$, $\pi^\pm$, π^0, $K^\pm$, K^0_S, γ, $0 < |\cos\theta| < 1$, $0 < p < 500$ GeV

1. $e^+e^- \to f\bar{f}$, $f = e$, τ, u, s, c, b at $\sqrt{s}$=0.091, 0.35, 0.5 and 1.0 TeV;

2. $e^+e^- \to Z^0h^0 \to \ell^+\ell^- X$, $M_h = 120$ GeV at $\sqrt{s}$=0.35 TeV;

3. $e^+e^- \to Z^0h^0$, $h^0 \to c\bar{c}$, $\tau^+\tau^-$, WW^*, $M_h = 120$ GeV at $\sqrt{s}$=0.35 TeV;

4. $e^+e^- \to Z^0h^0h^0$, $M_h = 120$ GeV at $\sqrt{s}$=0.5 TeV;

5. $e^+e^- \to \tilde{e}^+_R\tilde{e}^-_R$ at Point 1 at $\sqrt{s}$=0.5 TeV;

6. $e^+e^- \to \tilde{\tau}^+_1\tilde{\tau}^-_1$, at Point 3 at $\sqrt{s}$=0.5 TeV;

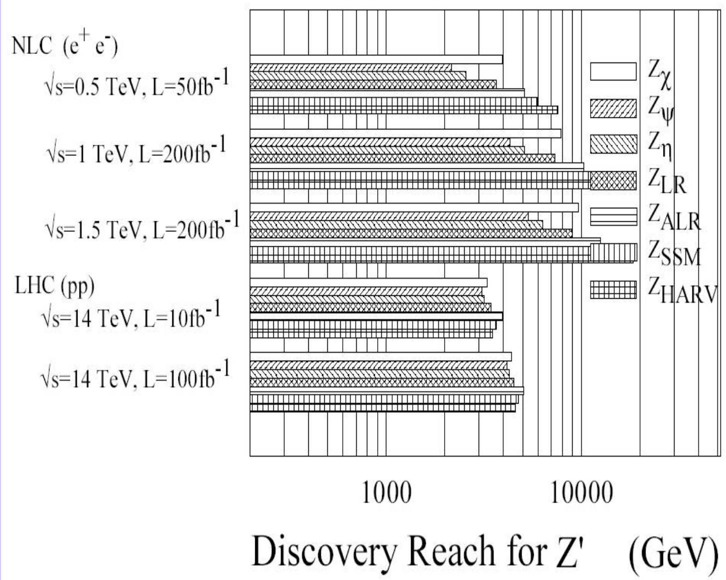
7. $e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1/\tilde{\chi}^0_2\tilde{\chi}^0_2$ at Point 5 at $\sqrt{s}$=0.5 TeV;

I have some questions about this:
Where is MET + γ, or MET + h, or top? Why $e^+e^- \to u\bar{u}$?

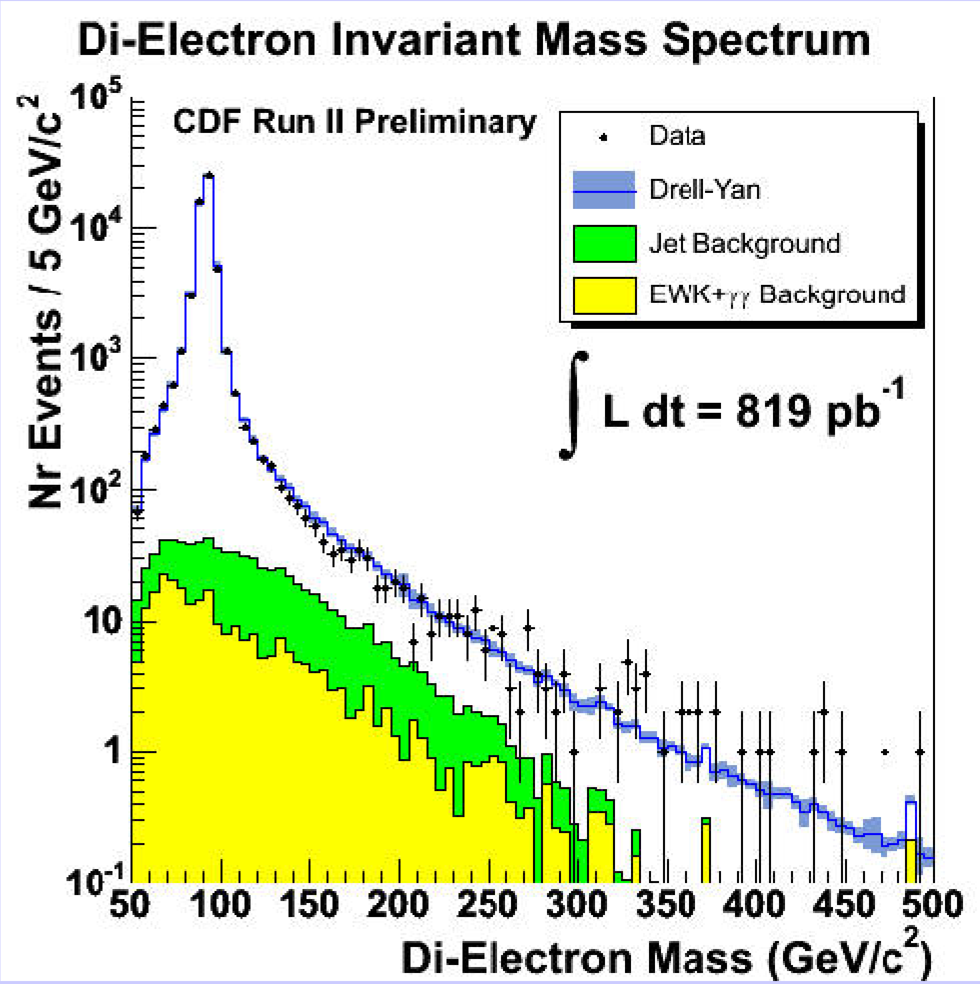
Precision Tests of the SM: Indirect Signals of New Physics

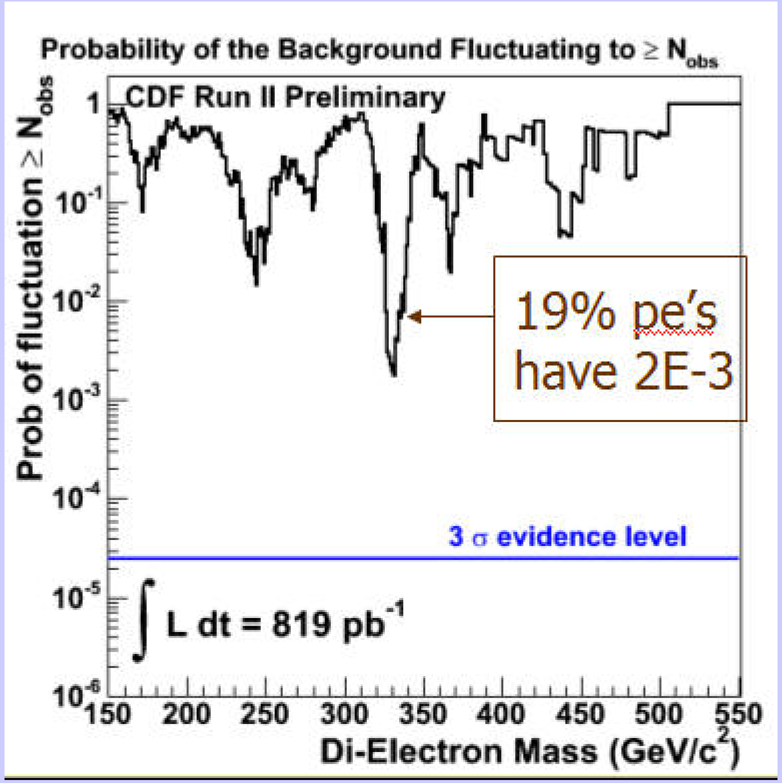
- Common feature of many models is a contact interaction type signature
  - New gauge bosons, Large extra dimensions, SUSY with R-parity violation, Compositness, Leptoquarks, String excitations….
- Usually arises from exchange of $M_X \gg \sqrt{s}$ in $e^+e^- \to f\bar{f}$, results in deviations of SM predictions

- ILC has large sensitivity to M_X, covers most of/more than LHC reach
- Determining origin of such deviations is a forte of the ILC!
- Determine spin & couplings of M_X
  - Single most important ingredient is angular dependence of final state



Tevatron Check: Dilepton Mass Spectrum

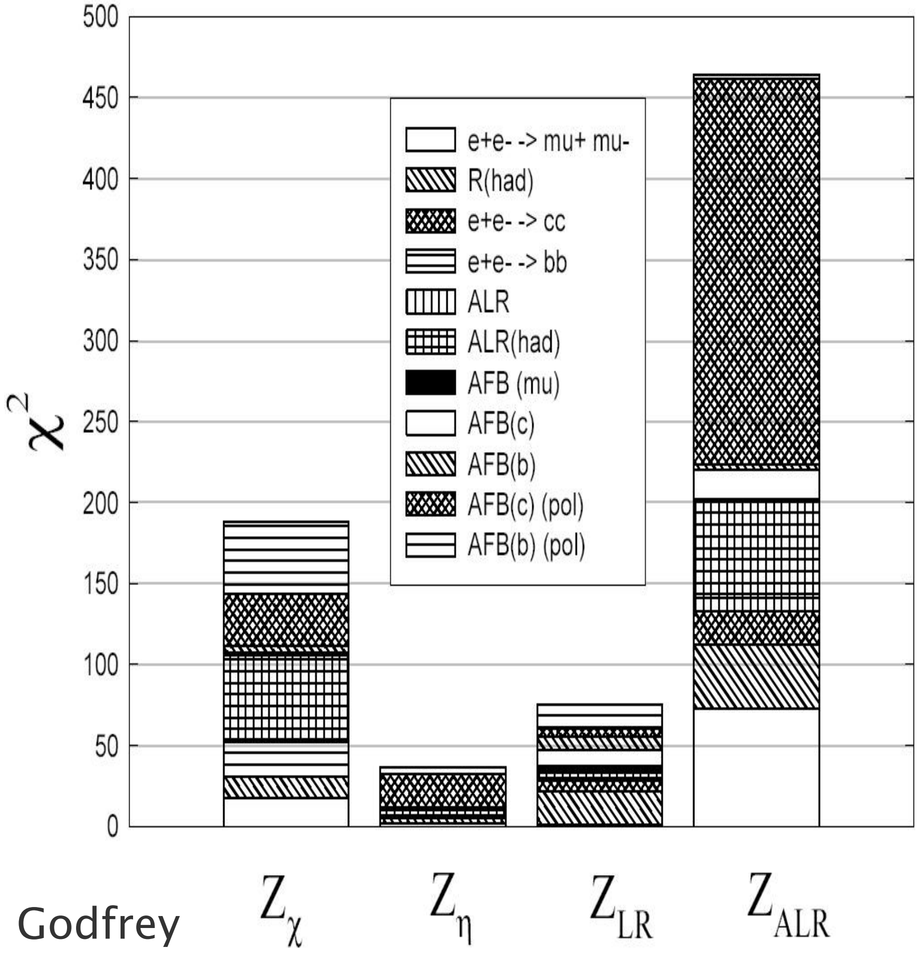




Contributions to Search Reach

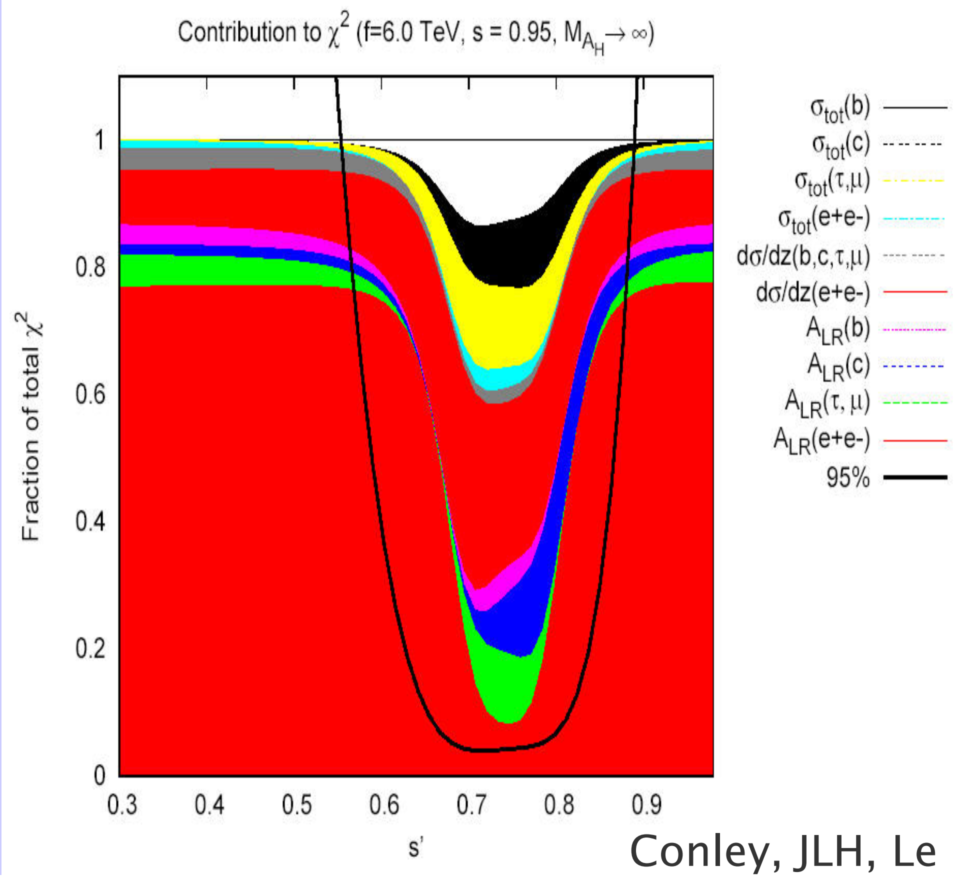
There is no single model independent dominant observable!
All contributions are potentially important

E_6 Z' Models



Godfrey

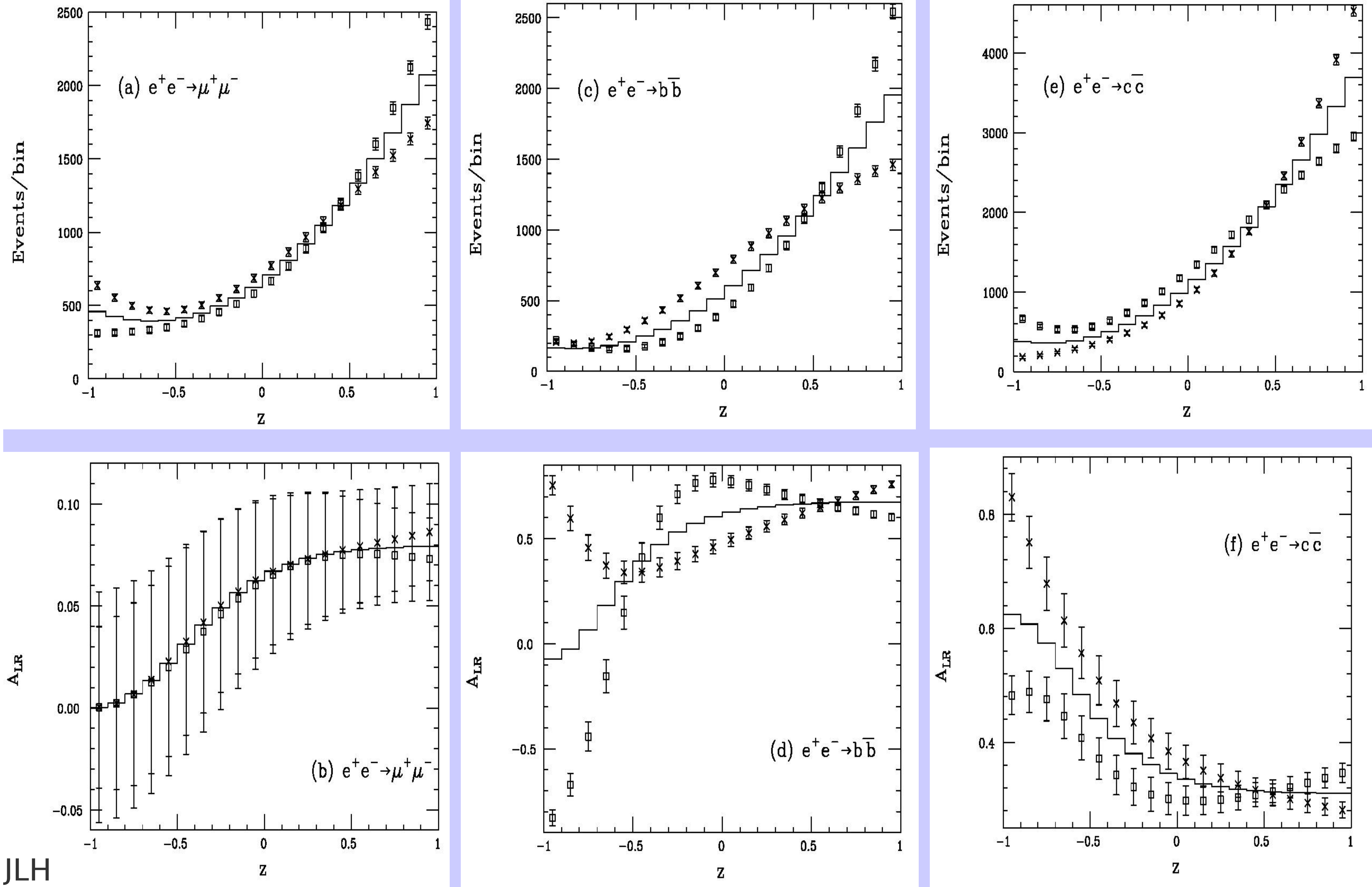
Little Higgs Z'



Conley, JLH, Le

Indirect Exchange of KK Gravitons

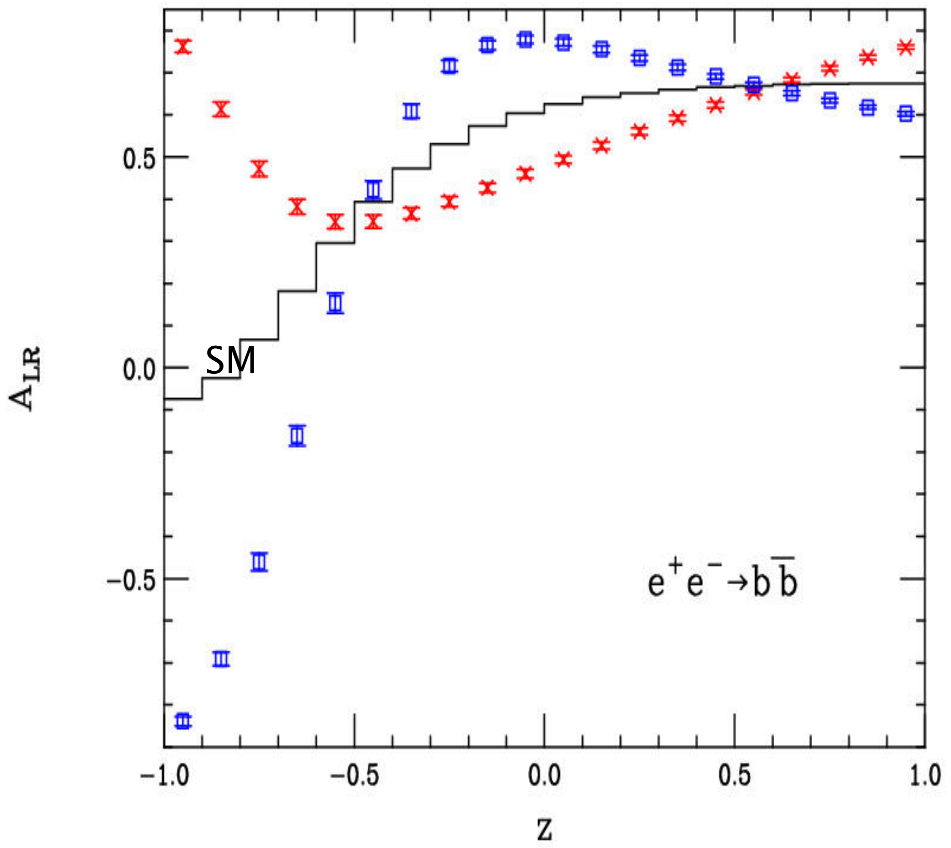
$\sqrt{s}$ = 500 GeV, Λ = 1.5 TeV, 75 fb^{-1}



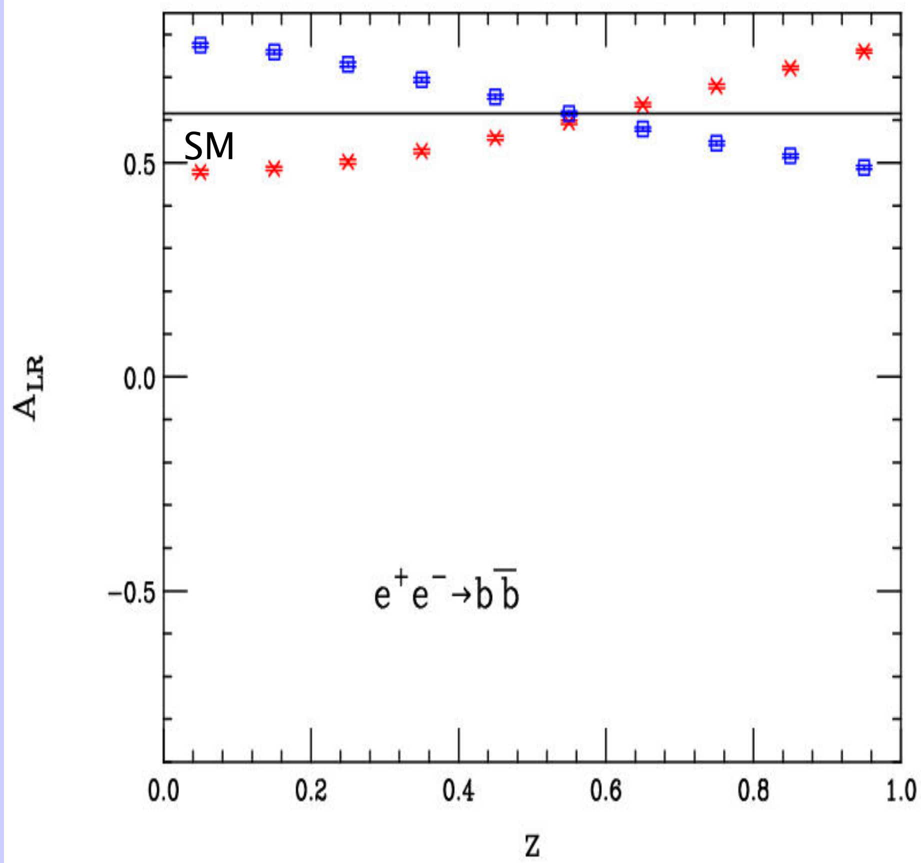
JLH

Full angular dependence in b pairs is important: requires jet-charge measurement

with jet-charge info



without jet-charge info



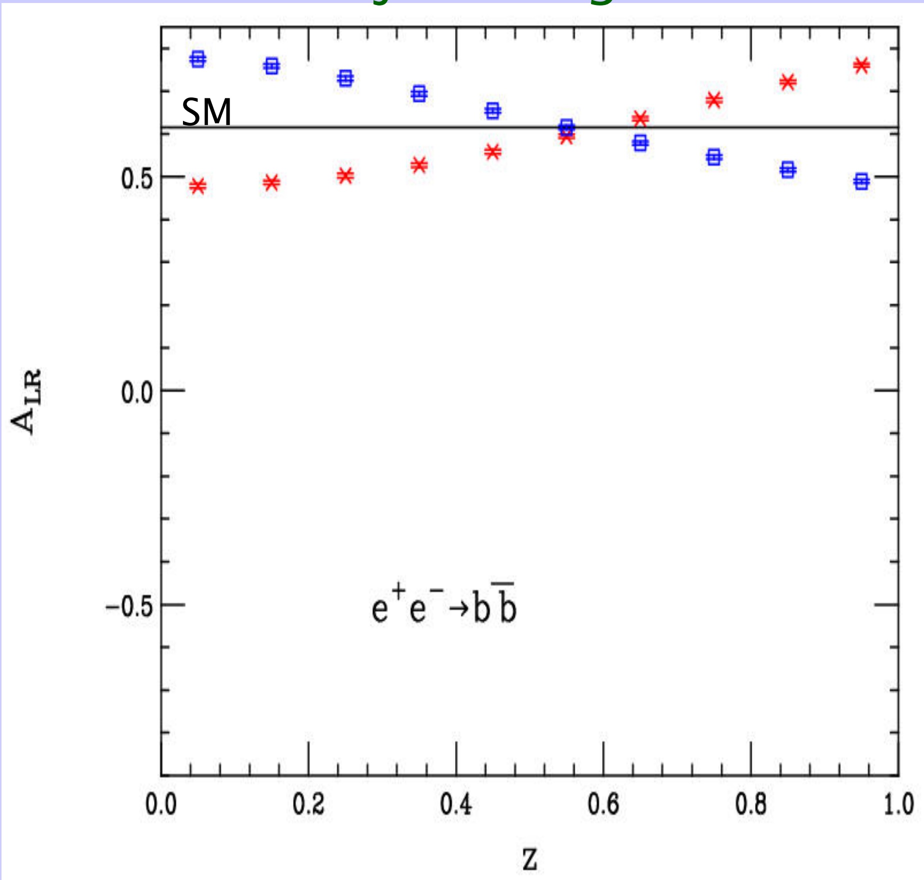
KK graviton exchange

$\sqrt{s}$ = 500 GeV, Λ = 1.5 TeV, 500 fb^{-1}

Clearly a loss of sensitivity when cannot distinguish b from $\bar{b}$

Full angular dependence in b pairs is important: requires jet-charge measurement

without jet-charge info



KK graviton exchange

However, this is interesting!

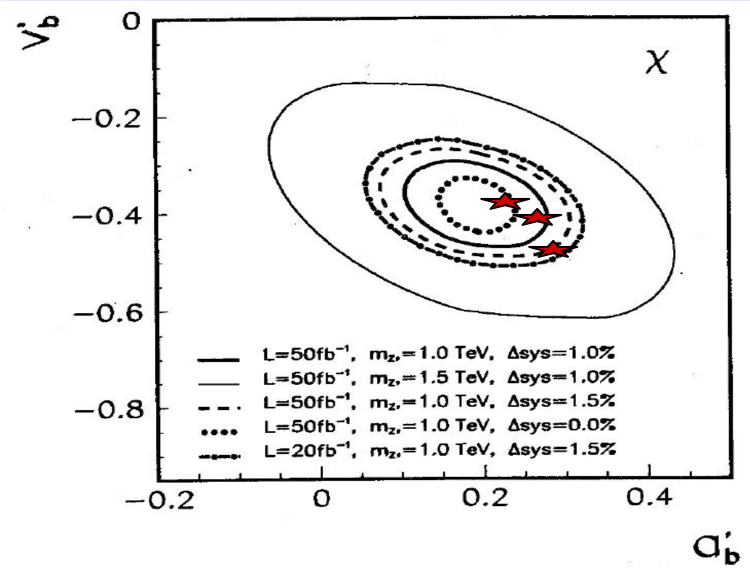
SM and all spin-1 exchange has a constant distribution.

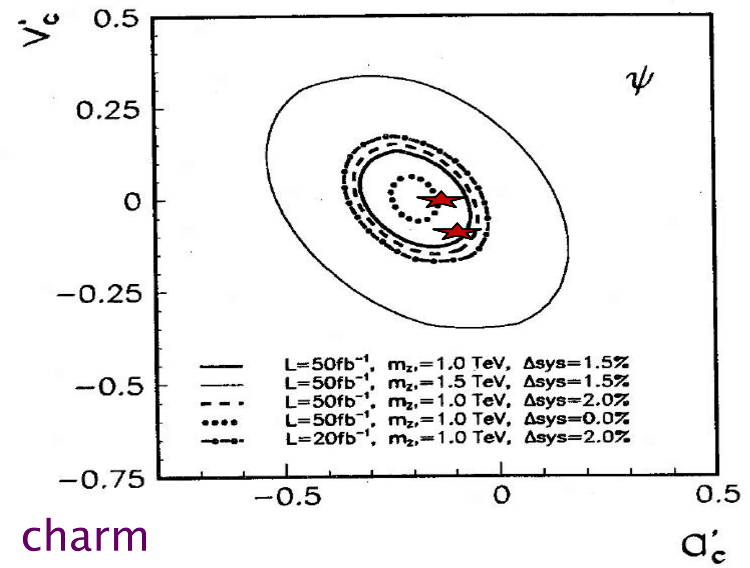
Works for any fermion final state

$\Rightarrow$ Any deviation from a constant value is a measurement of spin $\neq$ 1 (such as sneutrino or graviton)!!

Systematics Dependence of Z' Heavy Quark Coupling Determinations

bottom



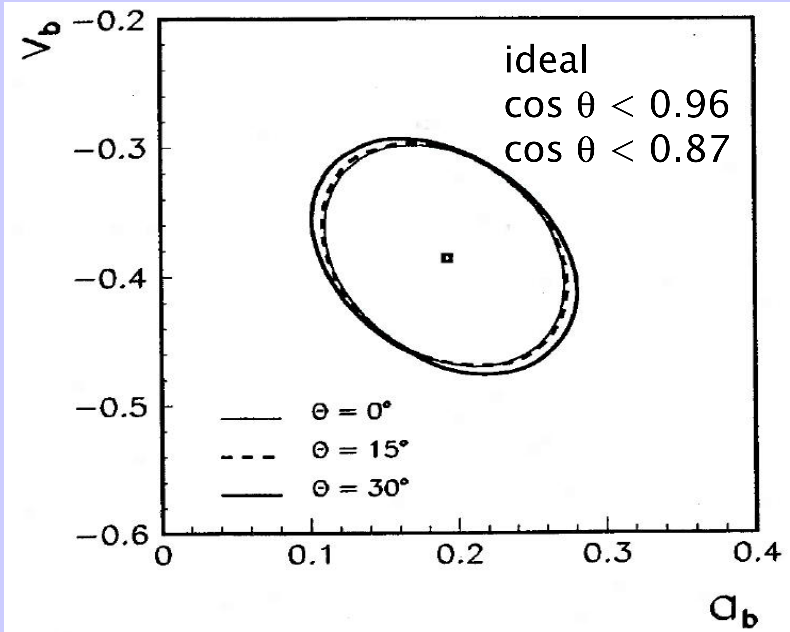


charm

Analysis uses event rate + full (un+)polarized angular info on heavy quark jets

S. Riemann
50 fb^{-1}

Dependence on fiducial volume of vertex detector



Does the New Physics have Generational Dependent Couplings?

When something is discovered, it's a question we will ask

- Will measure generational dependence in leptonic sector, will also want to study quark sector
- We will want to compare top & charm event rates and (un +)polarized angular distributions.
- It would be awfully, awfully nice to compare bottom and strange event rates and (un +)polarized angular distributions as well (e.g., SLD measurement of A_s)

This would give a full check on the theory

Supersymmetry: Some Superdifficult Processes

Some very likely, yet difficult signatures:

- Charm tagging in stop decays (soft charm)
- Small mass splitting between sparticle & LSP
  - Chargino decay
- LSP is only kinematically accessible sparticle

$$e^+e^- \rightarrow \tilde{t}_1\overline{\tilde{t}}_1 \rightarrow c\tilde{\chi}_0^1\bar{c}\tilde{\chi}_0^1$$

- Stops can be "light" in various SUSY models
  - Off-diagonal matrix element proportional to m_t
- Main decay mode can be through a Flavor Changing Neutral Current – loop decay!

stop $\rightarrow$ charm + LSP

- Challenges
  - Vertex detector to tag charm (could be soft)
  - Hermiticity (MET)

C. Milstene

$$e^+e^- \rightarrow \tilde{t}_1\overline{\tilde{t}_1} \rightarrow c\tilde{\chi}_0^1\overline{c}\tilde{\chi}_0^1$$

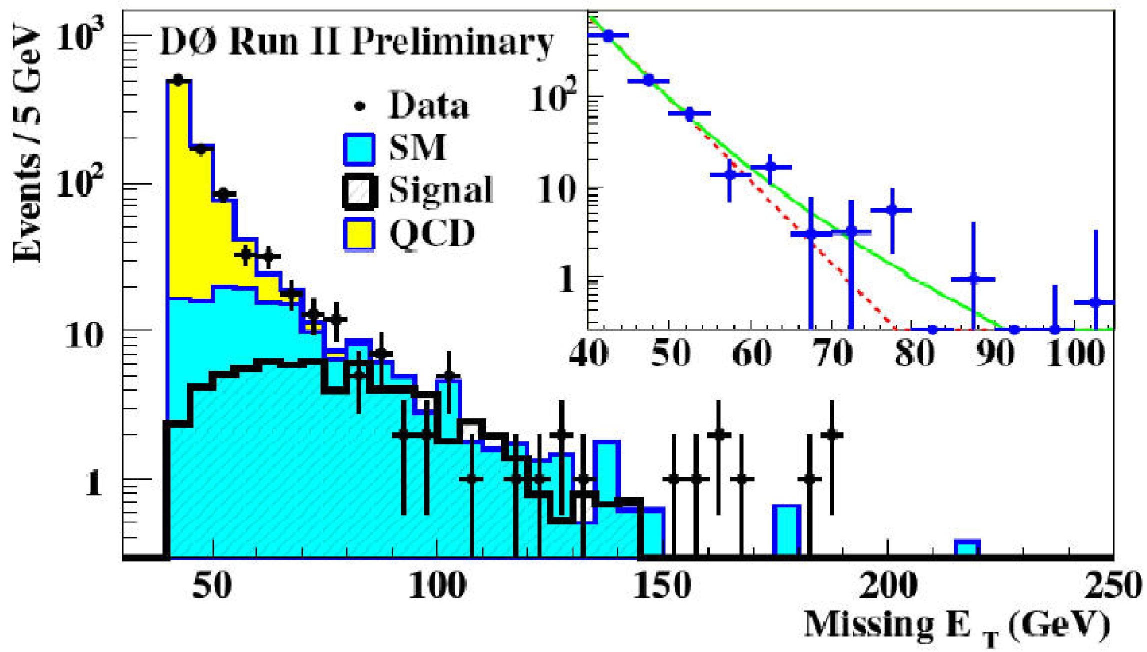
Do we need to pay attention?: Theoretically, this is a *very real* possibility

$$e^+e^- \rightarrow \tilde{t}_1\overline{\tilde{t}_1} \rightarrow c\tilde{\chi}_0^1\overline{c}\tilde{\chi}_0^1$$

Do we need to pay attention?: Tevatron check!

D0 analysis:

- Signature is two acoplanar c-jets
- Cuts:
  - Exactly two jets, pT > 40, 20 GeV, dphi<165
  - Quality cuts on mET vs. jet directions
  - At least one jet lifetime tag (c-tag)
  - mET>70 GeV (optimized for each stop mass)
- Slight excess in data at high mET



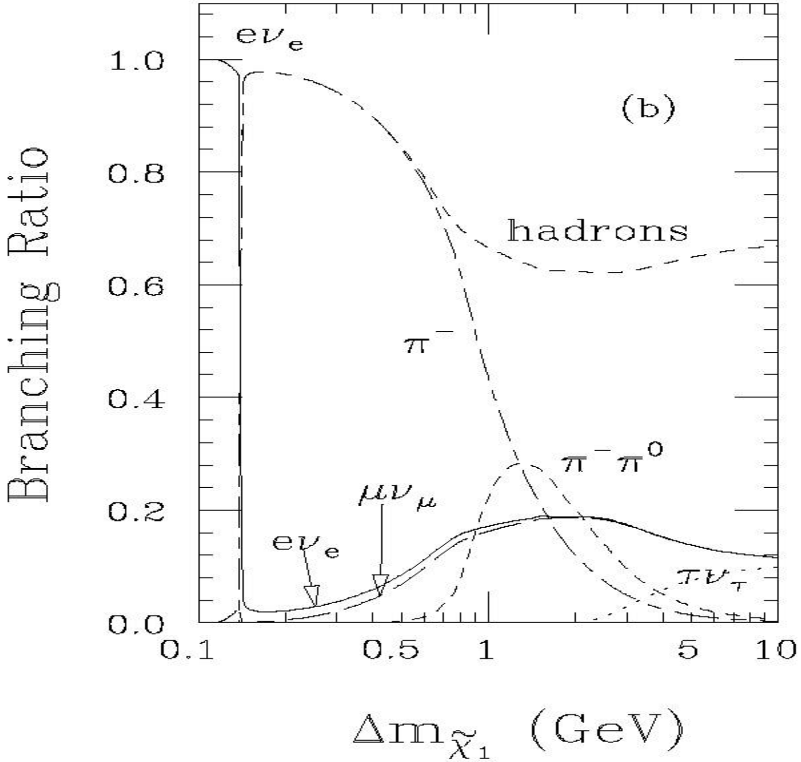
Small Mass Splittings: Degenerate $\chi_1^\pm, \chi_1^0$

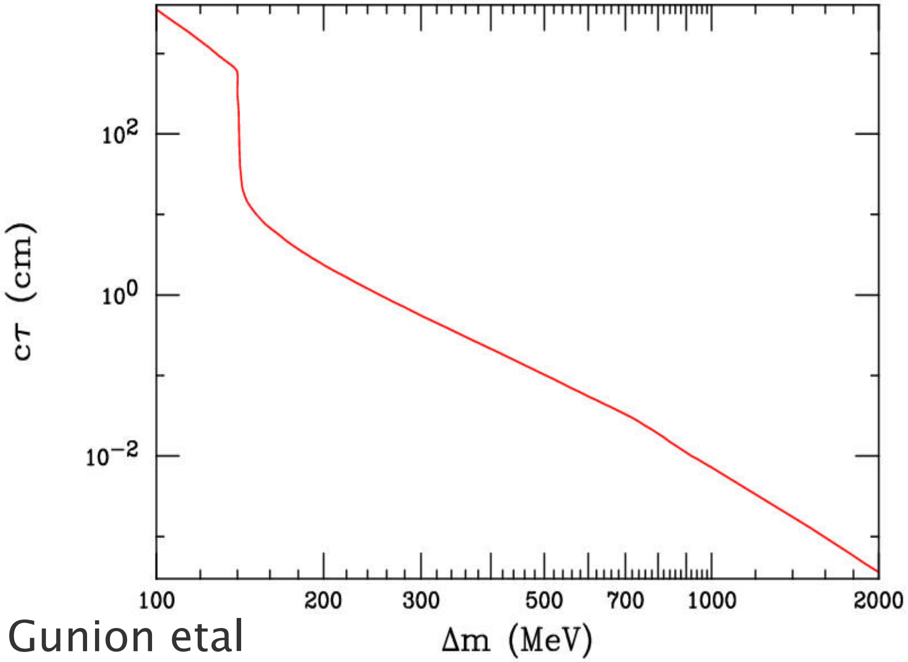
- As lightest chargino and LSP become degenerate, chargino decay channels change
- Chargino main decay channel can be

  $\chi_1^\pm \to \pi + \chi_1^0,\ \pi\pi + \chi_1^0$, with soft pions
- This is main region of parameter space where model identification is impossible @ LHC   C. Berger etal

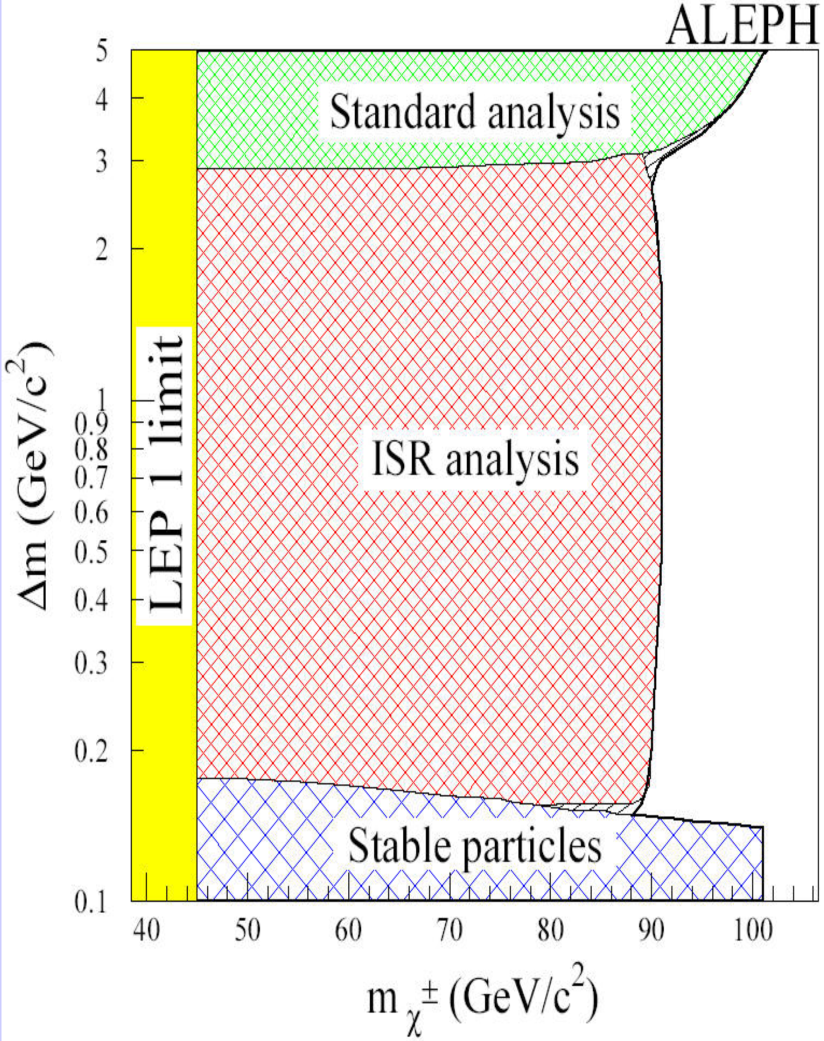
- Trigger on γ in $e^+e^- \to \chi_1^\pm \chi_1^\pm + \gamma$ radiative production

Results: Degenerate Chargino/LSP $\Rightarrow$ need to detect soft π's!





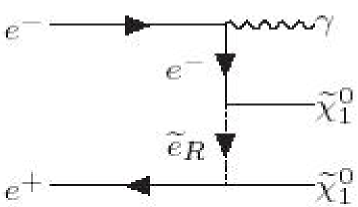
Gunion etal



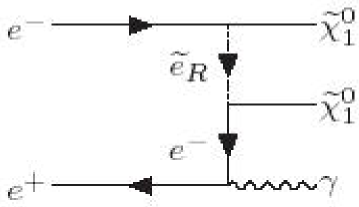
SUSY is Heavy: Radiative Neutralino Production

- If LSP is only kinematically accessible sparticle
  - $e^+e^- \to \chi_1{}^0\,\chi_1{}^0 + \gamma$ becomes important
- Backgounds:

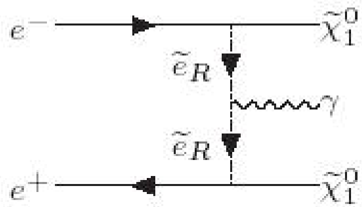
$$e^+ + e^- \to \nu_\ell + \bar{\nu}_\ell + \gamma\,, \qquad \ell = e, \mu, \tau$$
$$e^+ + e^- \to \tilde{\nu}_\ell + \tilde{\nu}_\ell^* + \gamma\,, \qquad \ell = e, \mu, \tau$$



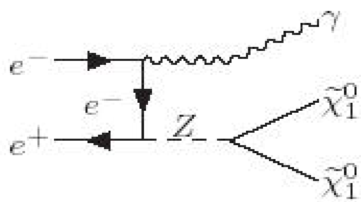
diagr. 1/4



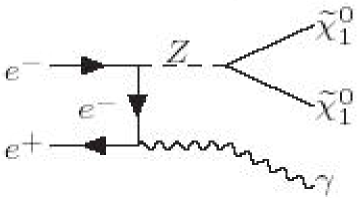
diagr. 2/5



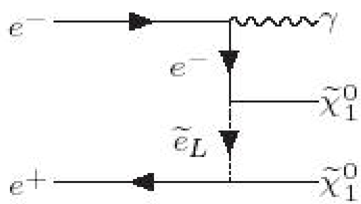
diagr. 3/6



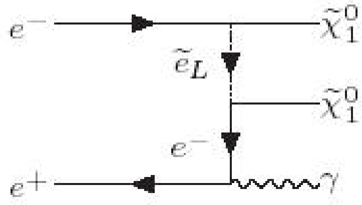
diagr. 7



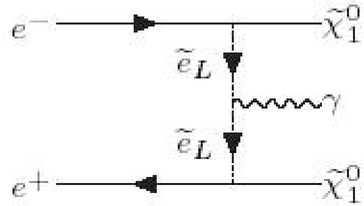
diagr. 8



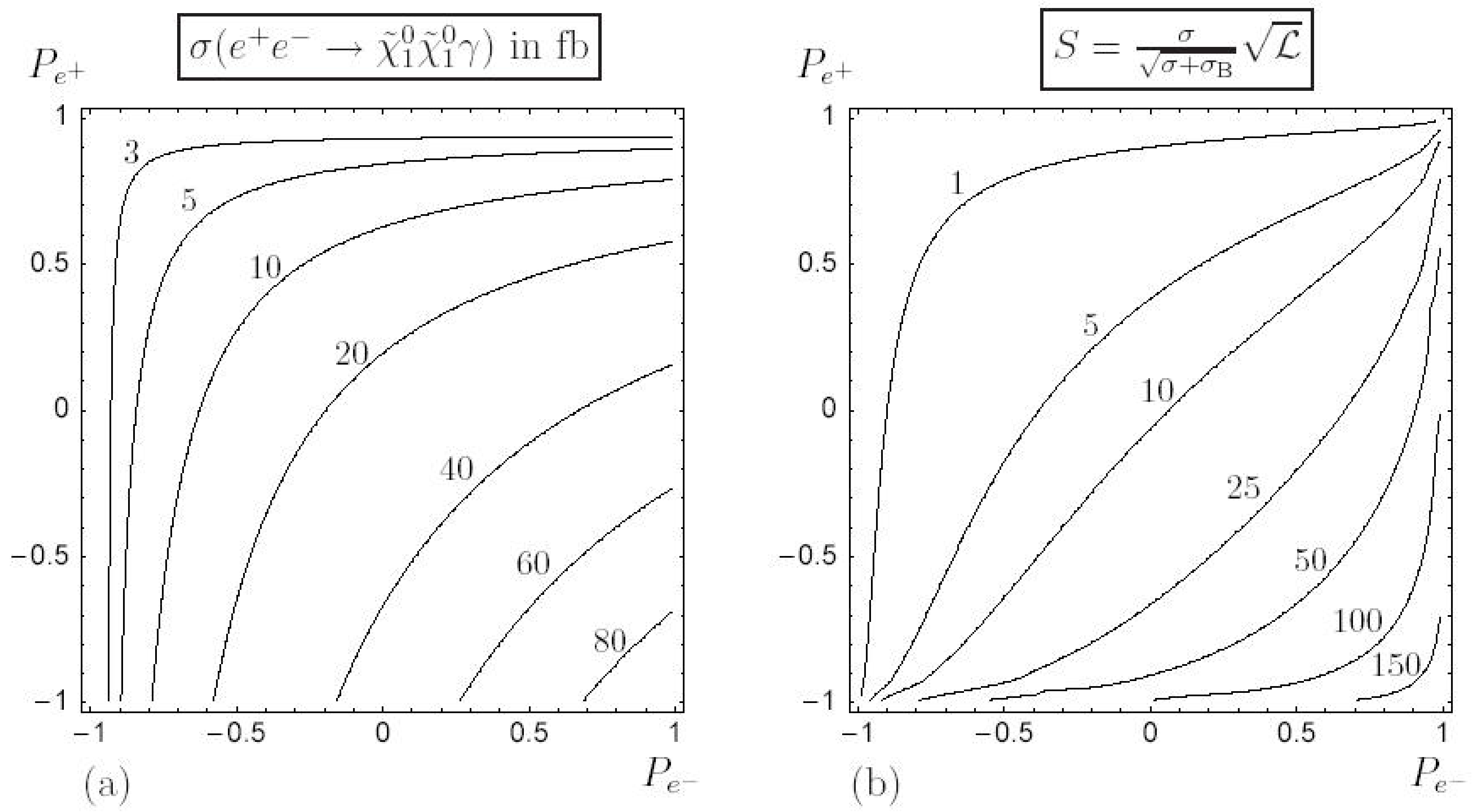
diagr. 9/12



diagr. 10/13



diagr. 11/14



$$-0.99 \leq \cos\theta_\gamma \leq 0.99, \qquad 0.02 \leq x \leq 1 - \frac{m^2_{\chi^0_1}}{E^2_{\rm beam}}, \qquad x = \frac{E_\gamma}{E_{\rm beam}}$$

Dreiner etal

Yet another important source of γ + MET with non-pointing γ

Challenges Calorimeter for $\delta\theta$, $\delta\phi$

Long-lived/Stable Particles

Many models predict them

- Supersymmetry: Gauge Mediated SUSY Breaking
  Split Supersymmetry
  R-Parity Violation
- Heavy fermions with nearly degenerate masses
- ….

Signatures in the Detector

- particle decay inside detector, timing not coordinated with collision
- jets, leptons, π's, γ's appearing from nowhere
- kinks in tracks

Gauge Mediated SUSY Breaking

- High scale hidden (messenger) sector breaks SUSY
- Sparticle masses proportional to gauge couplings
- Gravitino is the LSP with mass ~ few eV
- NLSP typically neutralino or stau and is long-lived

$\chi_1^0 \rightarrow \tilde{G} + \gamma/Z$

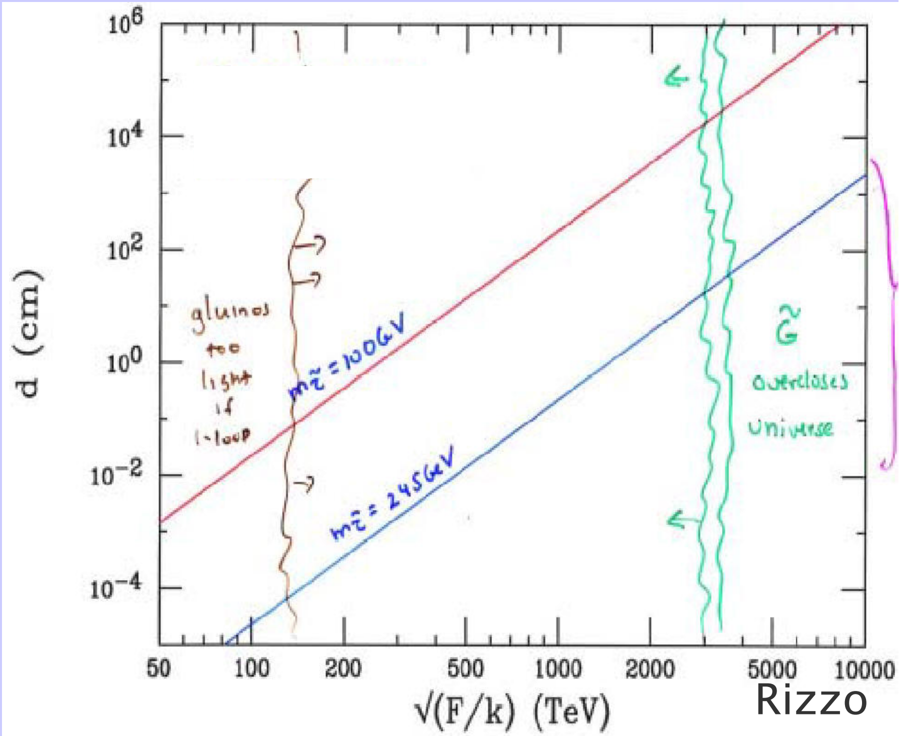
$\tilde{\tau} \rightarrow \tilde{G} + \tau$

$\Gamma(\chi_1^0/\tilde{\tau}) = (k/F)^2\,(m_{\chi,\tau}^5/16\pi)\,\kappa_{\gamma,Z}$

k ~ messenger coupling

F ~ fundamental scale

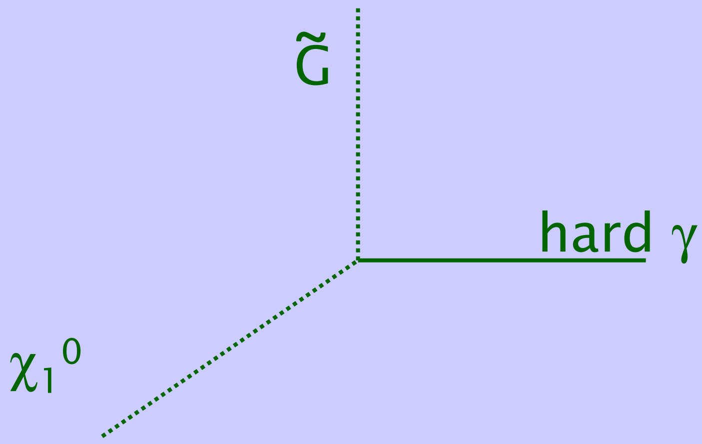
$\kappa_{\gamma,Z}$ ~ Clebsch, O(1)

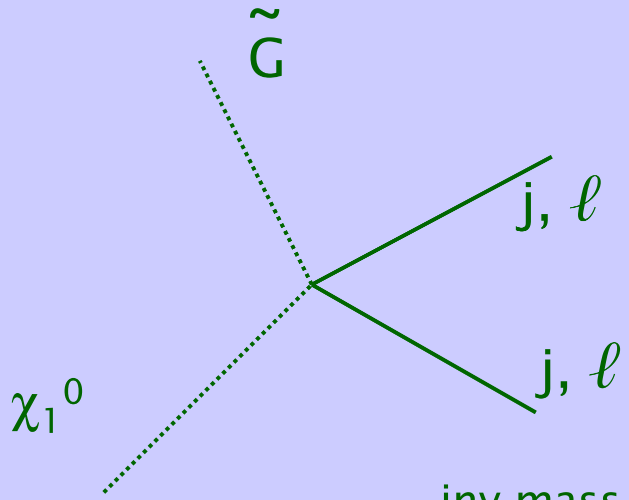


Rizzo

Signatures: χ_1^0, $\tilde{\tau}$ decays inside the detector

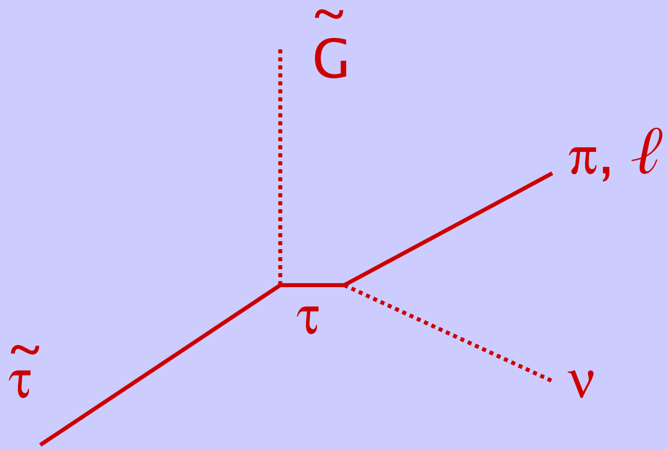
χ_1^0 :





inv mass is M_Z

$\tilde{\tau}$:



tracks not pointing
to vertex!
decay not timed
with collision!

Split Supersymmetry:

Arkani-Hamed, Dimopoulos
Giudice, Romanino

Energy (GeV)

M_{GUT} ~ 10^{16} GeV

M_S : SUSY broken at high scale ~ 10^{9-13} GeV

Scalars receive mass @ high scale

Squarks, Sleptons

M_{weak}

1 light Higgs + Fermions

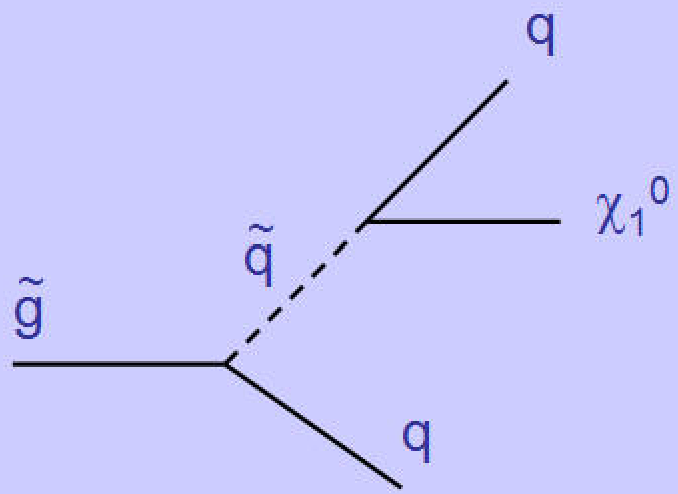
Standard Model +
Gauginos/Higgsinos

protected by chiral symmetry

Gluinos are long-lived

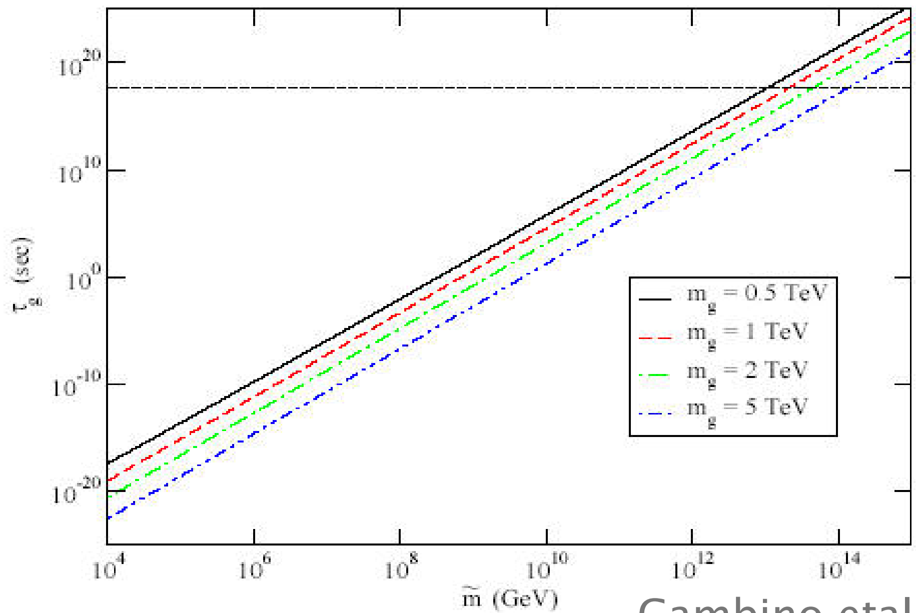
Gluino lifetime:

$$\tau \simeq 8 \left(\frac{m_S}{10^9 \text{ GeV}} \right)^4 \left(\frac{1 \text{ TeV}}{m_{\tilde{g}}} \right)^5 \text{s}$$



ranges from ps to age of the universe
for TeV-scale gluinos (Cosmological constraints)

- $\tau \sim$ ps, decays in vertex detector
- ps $< \tau <$ 100 ns, decays in detector
- $\tau > 10^{-7}$ s, decays outside detector $\Rightarrow$ bulk of parameter space!



Gambino etal

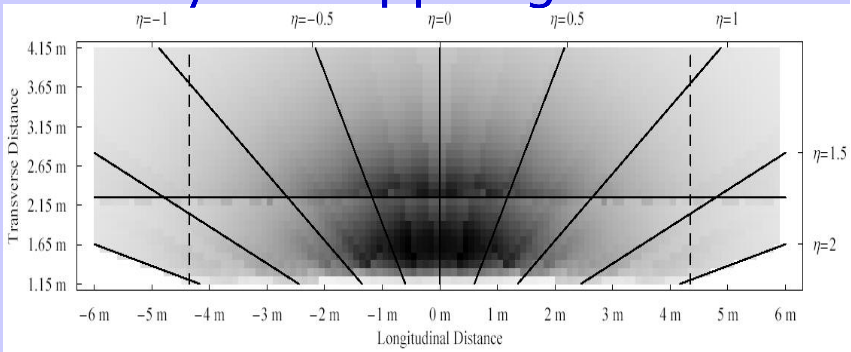
Gluino Phenomenology

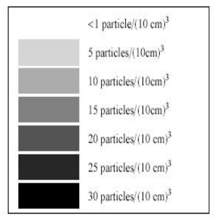
Gluino hadronizes into color singlet R-hadron

$\tilde{g}q\bar{q}$ $\tilde{g}qqq$ $\tilde{g}g$

- R is neutral: energy loss via hadronic collisions as it propagates through detector (Had Cal)
- R is charged: energy loss via hadronic interactions and ionization (Had & EM CAL)
- R flips sign: hadronic interactions can change charge of R, can be alternately charged and neutral! ⇒ ionization tracks may stop & start!
  - Heavy, charged, slow gluinos can stop in the detector due to ionization energy loss
  - Exact calculation of rate highly model dependent!!!
  - Signature: off-line analysis of calorimetric energy deposition, no tracks and not timed to collision

Density of stopped $\tilde{g}$ in ATLAS



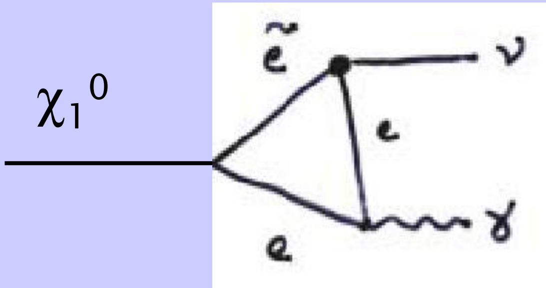


Arvanitaki etal

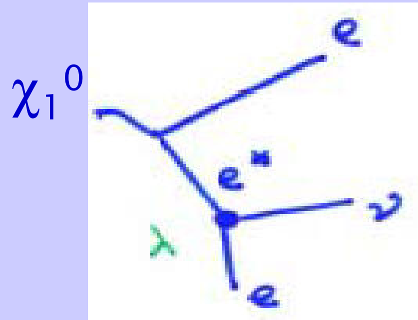
SUSY with R-Parity Violation

- LSP decays
- Superpotential: $W = \lambda LLE^c + \lambda' LQD^c + \lambda'' UD^cD^c$

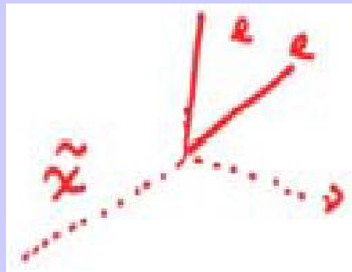
Loop decay:



tree-level decay:



Signatures:



$\Gamma_\chi/\Gamma_\mu = 10^{20} (\lambda/g)^2 (m_\chi /100 \text{ GeV})^5$

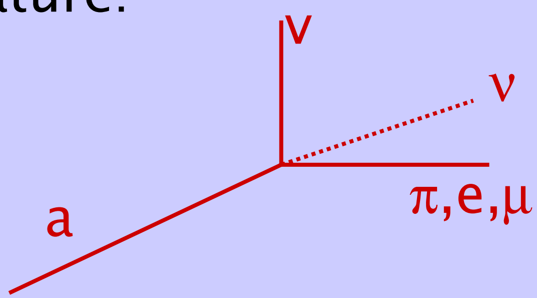
Degenerate Heavy Fermions

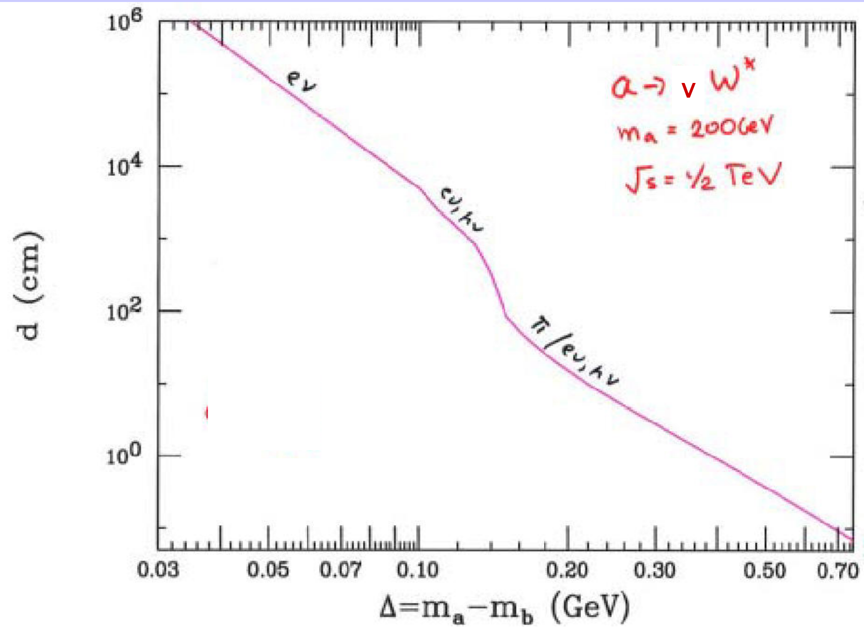
- Vector-like fermions naturally degenerate to avoid bounds on STU oblique parameters
- Vector-like fermions contained in many models, e.g., Little Higgs, E_6

$\begin{bmatrix} a \\ v \end{bmatrix}_{L,R}$ $a \to vW^*,\ W^* \to \{\pi\text{'s},\ e\nu,\ \mu\nu\}$

Large PS suppression leads to long lifetime

Signature:





Summary: A Theorist's Perspective

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- Nature most likely will have even more surprises in store

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A Theorist's Plea: please ensure the GDE doesn't descope the machine. We need to keep the machine in line with the parameters in the consensus document!!!