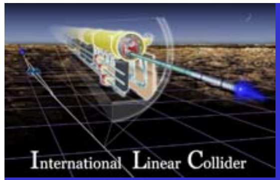
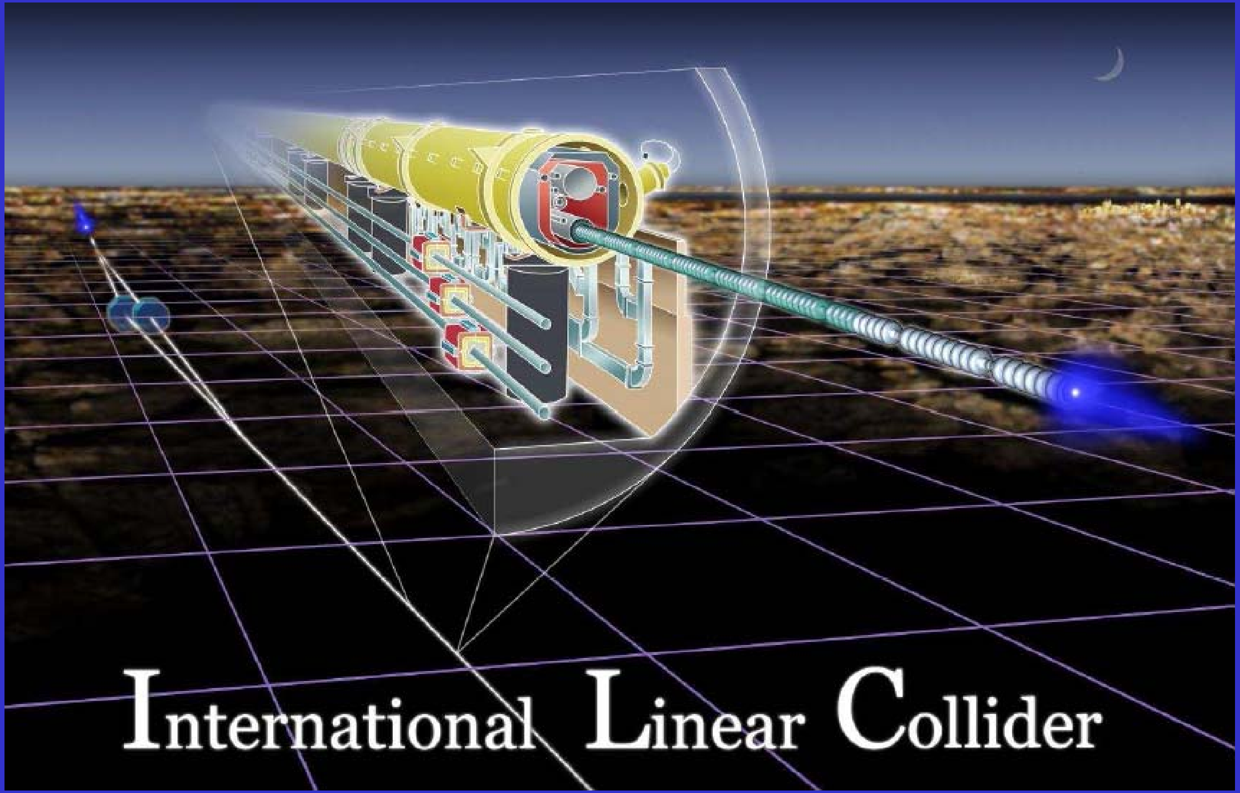


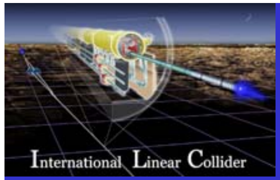
Experimental Aspects of Investigating Missing Energy Signatures at the ILC



Graham W. Wilson University of Kansas

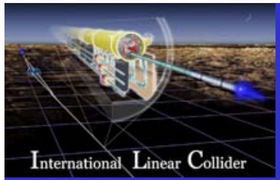
Outline

- Opening Remarks
- Kinematic Considerations for Missing Energy detection
- Smuons as a case study with some real data
- Some detector details
- Contrasting e^+e^- / LHC
- Some supersymmetry remarks
- Some questions for LHC



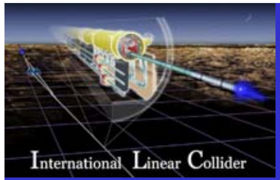
Opening Remarks

- Will try to convey the simplicity, elegance and power of e^+e^- collisions for investigating physics with missing energy.
- I am very concerned that this workshop will lend scientific credence to the fallacy that LHC results are essential to an ILC green-light.
  - This may be the political reality, but as an experimentalist with experience of e^+e^- and pp, I can not fathom this logic.
  - A properly designed **linear** ILC with scope to extend $\sqrt{s}$, is a unique machine in its own right, and from the scientific perspective could have been started more than 10 years ago.



Doing Experiments

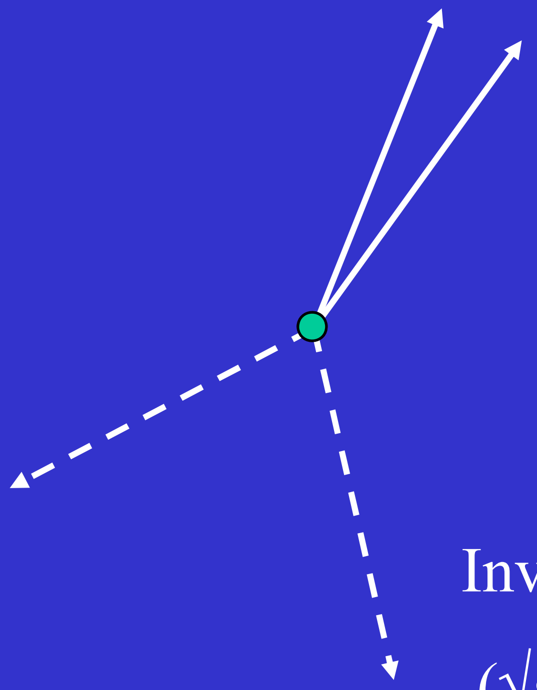
- We **do** experiments because we do not understand our world that well.
  - We will learn by **doing** experiments and probably find many surprises.
  - Ask many questions we never thought of.
  - Historically, progress has been made with a broad range of instruments – but in particular hadron **and** e^+e^- colliders



The Nature of e^+e^- Physics with ILC

- Flexible (can really experiment)
  - √s adjustable
  - Beams are highly polarizable
    - e^- for sure (80-90%). e^+ very likely (40-60%)
  - e^-e^- option. Perhaps γγ, eγ.
- Clean
  - Signals can be extracted from background with relative ease and high efficiency
- Kinematic Constraints
  - Beamstrahlung degradation comparable to initial-state radiation. Beam energy known.
- Complete
  - Detection of individual particles over close to 4π
- Calculable with High Precision
  - Excellent and valued work by a few theorists. Leads to good understanding of S and B.
- Triggerable
  - Actually, no trigger required at all ! (=> all visible decay modes are feasible)
- Precisely Normalizable
  - Precision of few ‰ achievable → absolute cross-section measurements

Kinematics 101



Initial State

$(\sqrt{s}, 0)$

Visible Final State

$(E_{vis}, \mathbf{p}_{vis})$

Invisible Final State

$(\sqrt{s} - E_{vis}, -\mathbf{p}_{vis})$

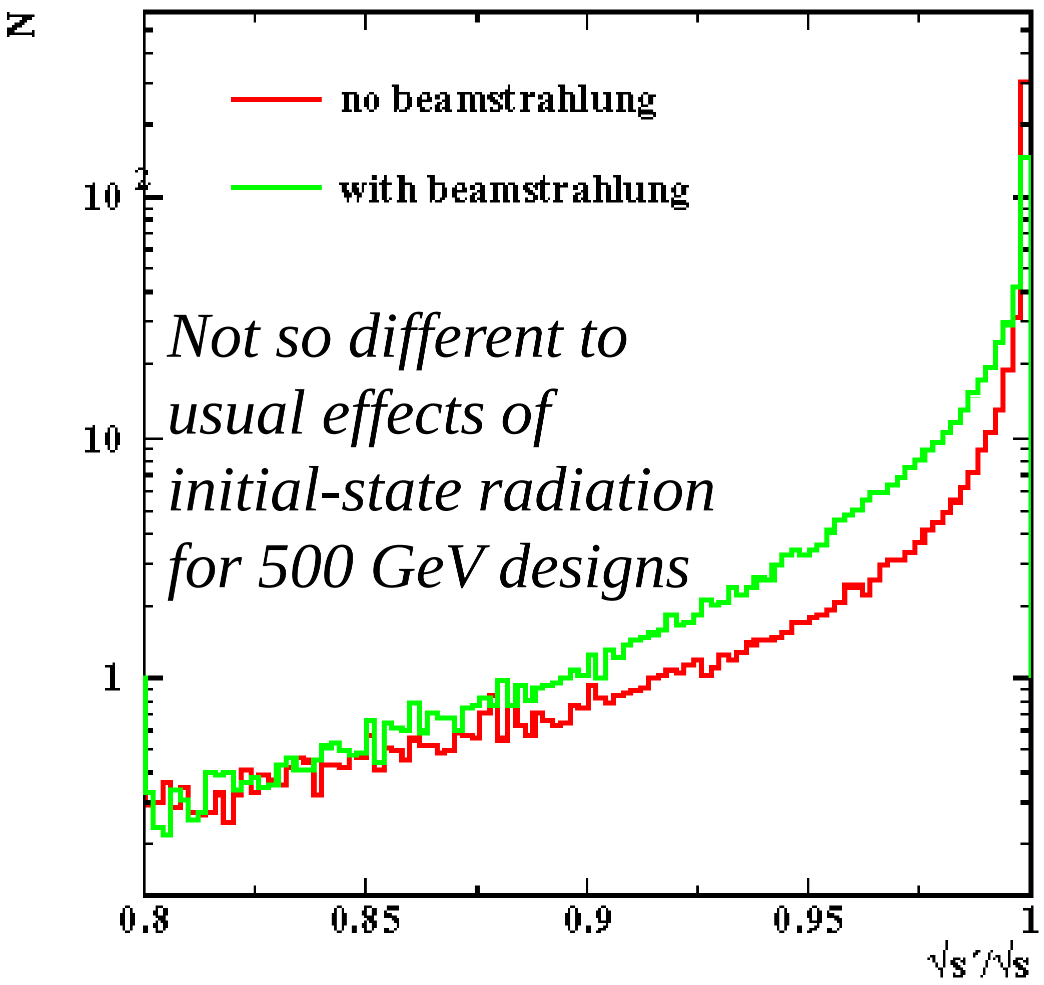
So, assuming (E, **p**) conservation can measure the 4-vector of the missing system, and thus the missing mass.

Is an E_{beam} constraint reasonable ?

Yes.

There is still a very strong peak at the nominal energy.

But, ISR and beamstrahlung do happen, so the measured quantity also includes the mass from those possible additional photons, and any particles undetected at low angle.

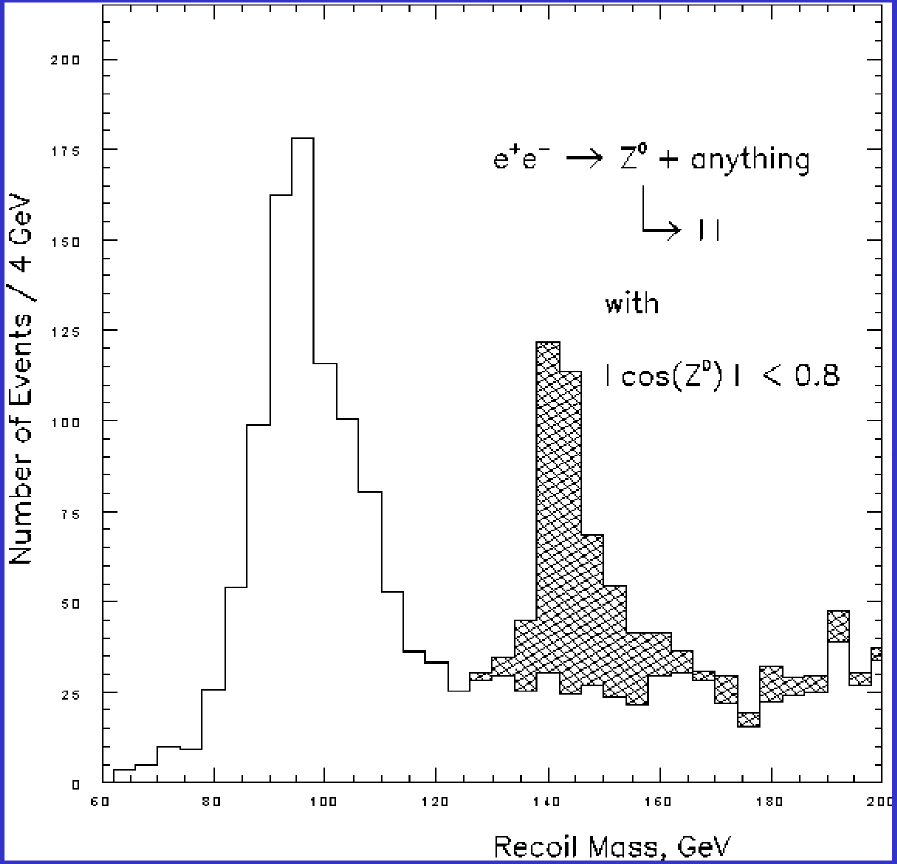


Not so different to usual effects of initial-state radiation for 500 GeV designs

Example

Schreiber et al.

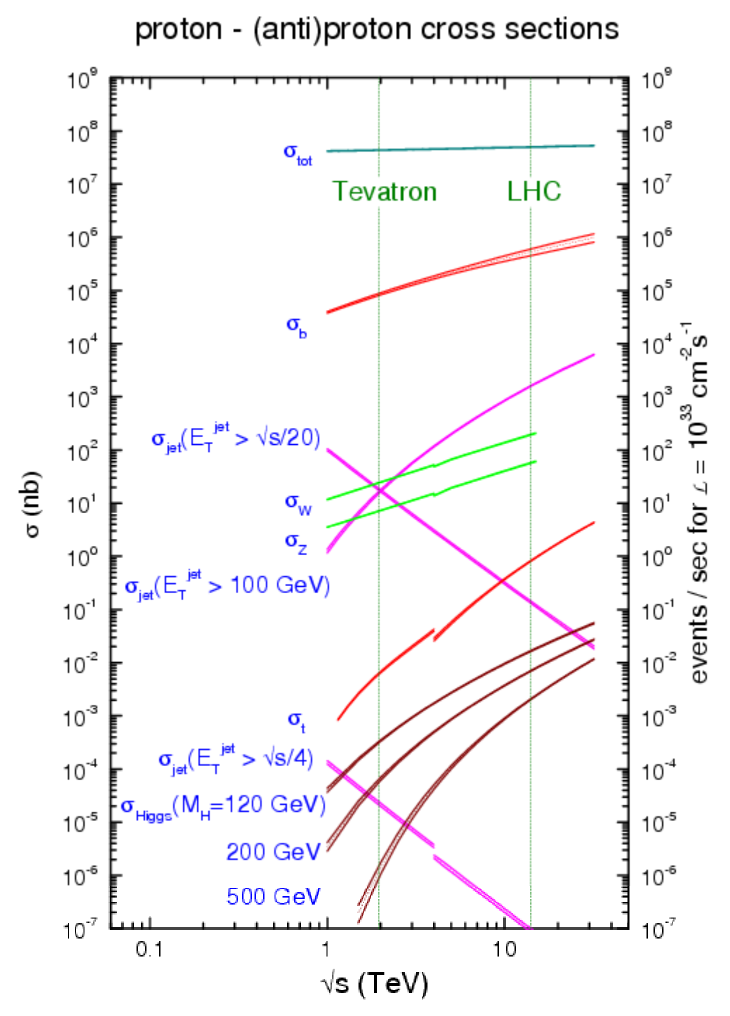
$\sqrt{s}$=360 GeV, 50 fb^{-1}



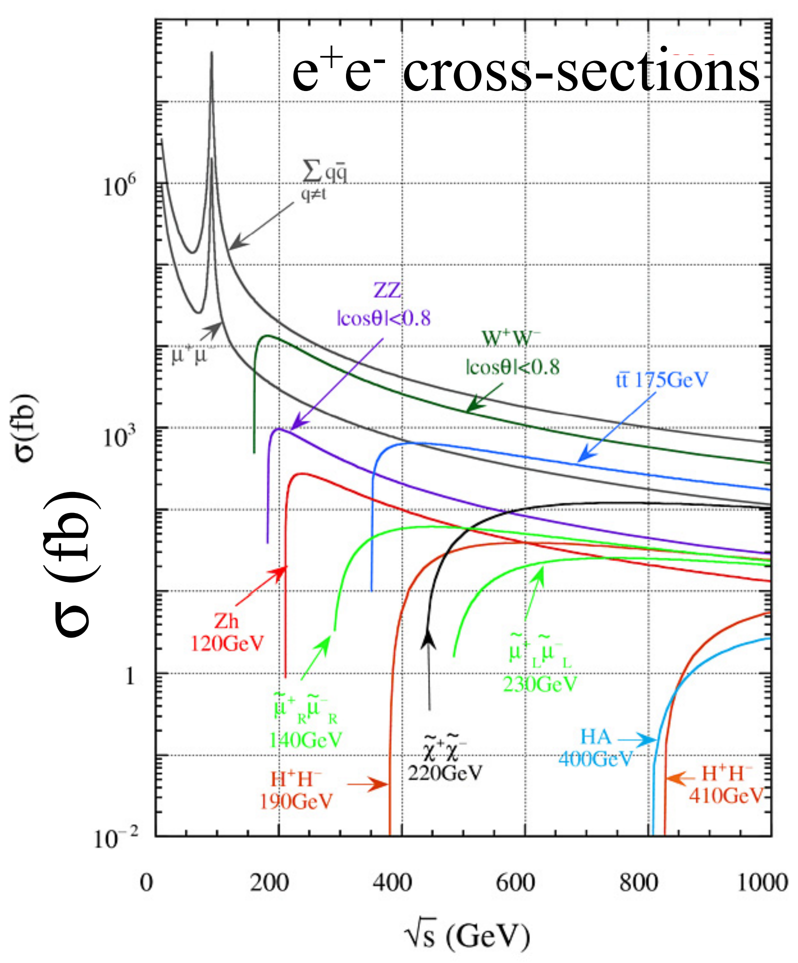
New particles decaying invisibly can be reconstructed from the missing mass (aka recoil mass).

Example here shows that the Higgs mass can be reconstructed without knowing the decay modes. In particular the Higgs could decay invisibly.

Sources of fake missing E_T



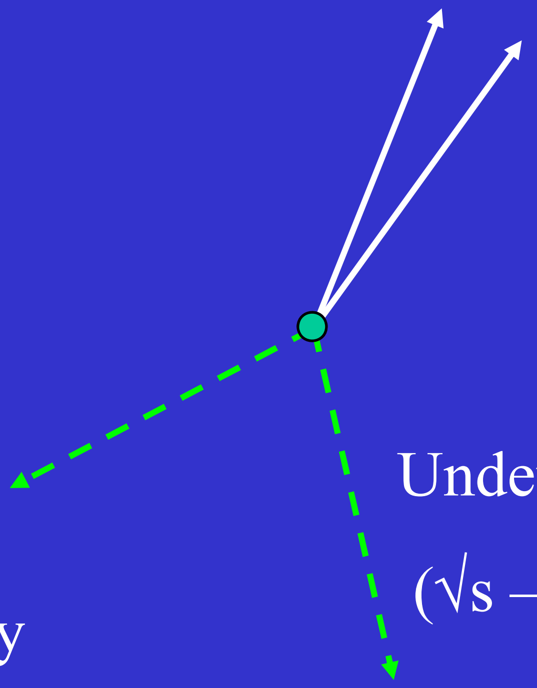
LHC: jets



ILC: Large cross-sections for Bhabha and two-photon processes. Use characteristic electron signatures to reject.

Genuine missing E_T predominates above WW threshold.

Kinematics 101



Initial State

($\sqrt{s}$, 0)

Visible Final State

(E_{vis}, $\mathbf{p}_{vis}$)

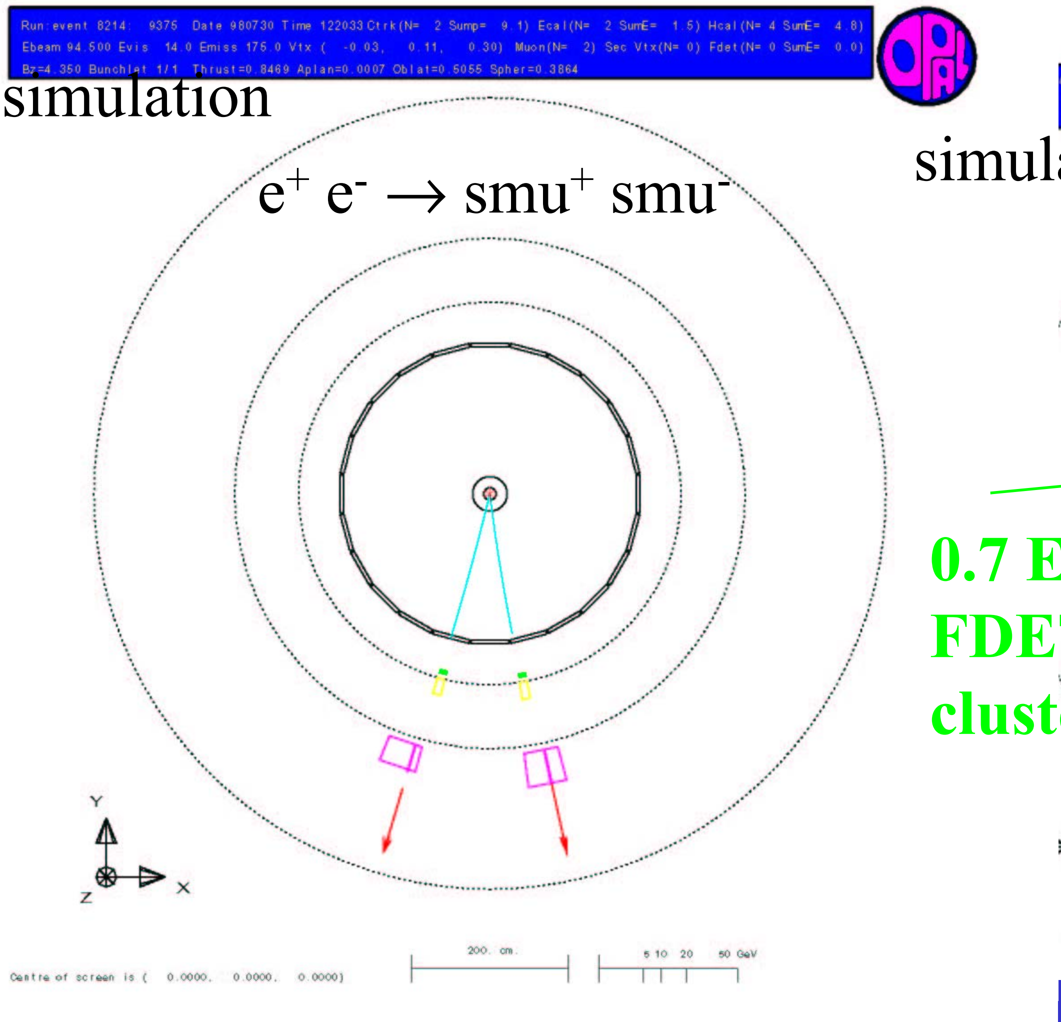
Undetected Final State

($\sqrt{s} - E_{vis}$, - $\mathbf{p}_{vis}$)

Major issue is when close to beam energy electrons escape below the detector acceptance with $\theta < \theta_{min.}$

Kinematic rejection of fake missing E_T by requiring: $p_{T\ vis} > (2E_{beam} - E_{vis}) \sin \theta_{min}$

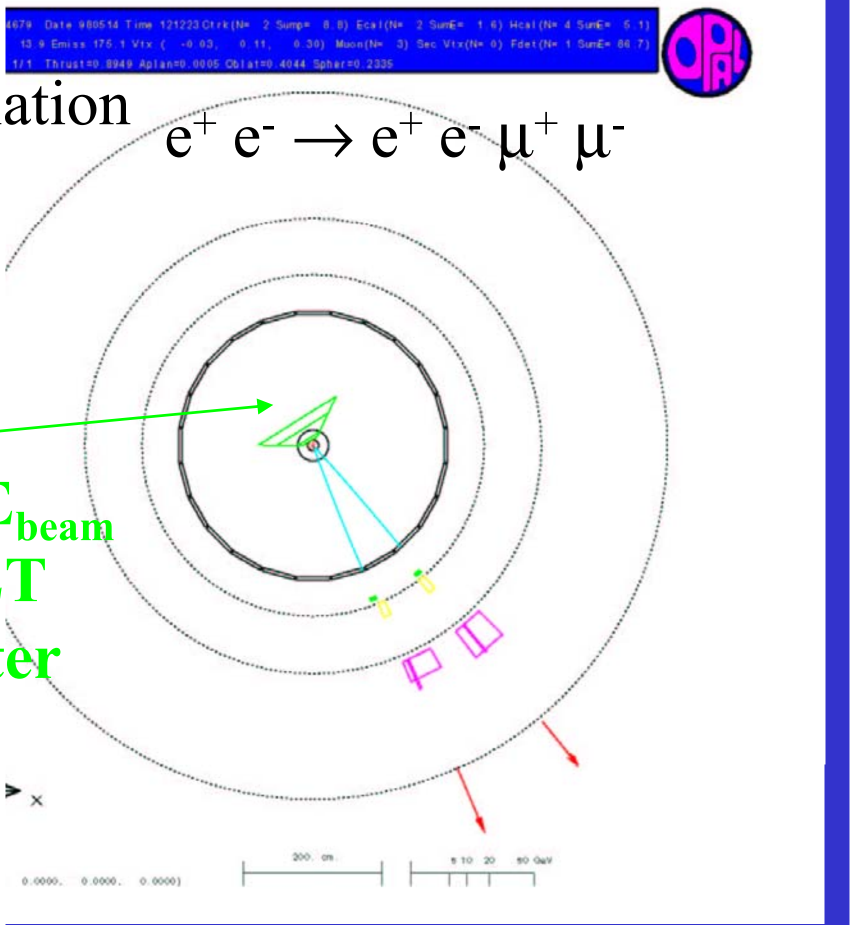
Why is hermeticity important ?



```
Run:event 8214:  9375  Date 980730 Time 122033 Ctrk(N=  2 Sump=  9.1) Ecal(N=  2 SumE=  1.5) Hcal(N= 4 SumE=  4.8)
Ebeam 94.500 Evis  14.0 Emiss 175.0 Vtx (  -0.03,   0.11,   0.30) Muon(N=  2) Sec Vtx(N= 0) Fdet(N= 0 SumE=  0.0)
Bz=4.350 Bunchlet 1/1  Thrust=0.8469 Aplan=0.0007 Oblat=0.5055 Spher=0.3864
```

simulation

$e^+ e^- \rightarrow smu^+ smu^-$



```
4679  Date 980514 Time 121223 Ctrk(N=  2 Sump=  8.8) Ecal(N=  2 SumE=  1.6) Hcal(N= 4 SumE=  5.1)
 13.9 Emiss 175.1 Vtx (  -0.03,   0.11,   0.30) Muon(N=  3) Sec Vtx(N= 0) Fdet(N= 1 SumE= 86.7)
1/1  Thrust=0.8949 Aplan=0.0005 Oblat=0.4044 Spher=0.2335
```

simulation

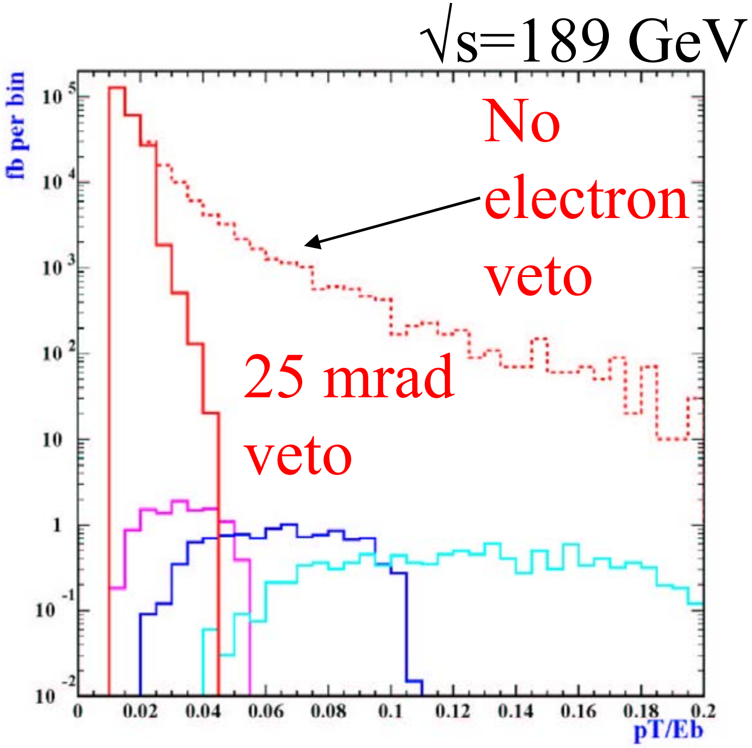
$e^+ e^- \rightarrow e^+ e^- \mu^+ \mu^-$

0.7 E_{beam}
FDET
cluster

Only difference between supersymmetry and 2-photon event is the observation of an electron in the FDET balancing the di-muon p_T

Hermeticity in action

$(M_{smu}-M_{LSP})/M_{smu}$ = 2.8%, 5.6%, 11%



Red: eeμμ background

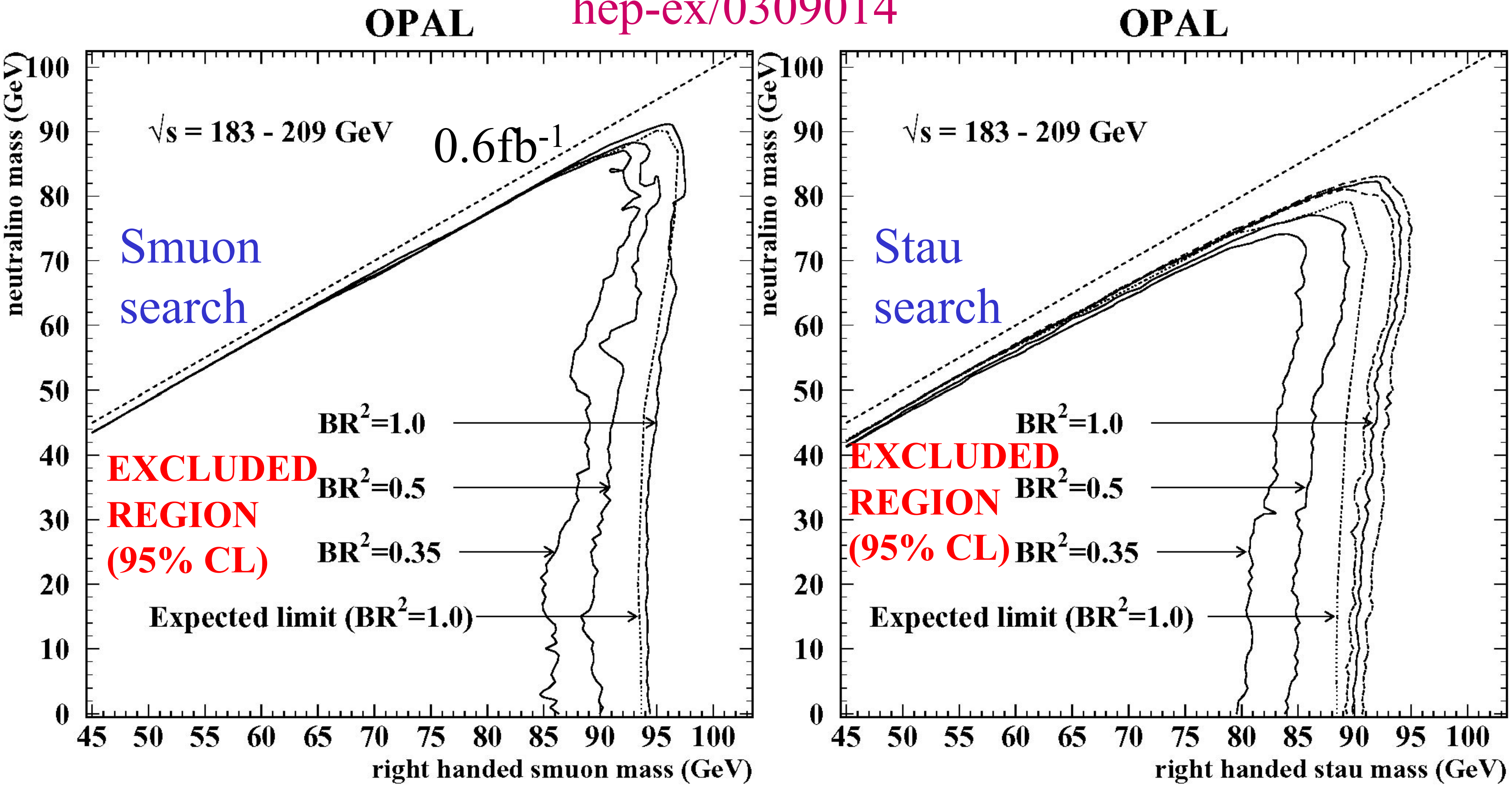
1fb/bin signal : smuons (M=90 GeV)

Generically, ANY missing energy signal will have this kind of background from “single nearly tagged” and “double nearly tagged” eeX events.

Add on to this resolution (red peak broadens a little).

Example: slepton pair search at LEP

hep-ex/0309014



Comprehensive search: efficiencies as high as 90% ! Definitive exclusion over all kinematic parameter space, apart from in small mass difference corridor (driven by θ_{min} of ≈ 25 mrad).

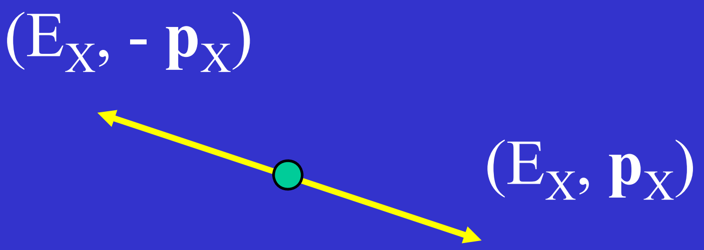
Kinematics 201: Pair production

$e^+ e^- \rightarrow X^+ X^-$

Initial State

Final Intermediate State

$(\sqrt{s}, \mathbf{0})$

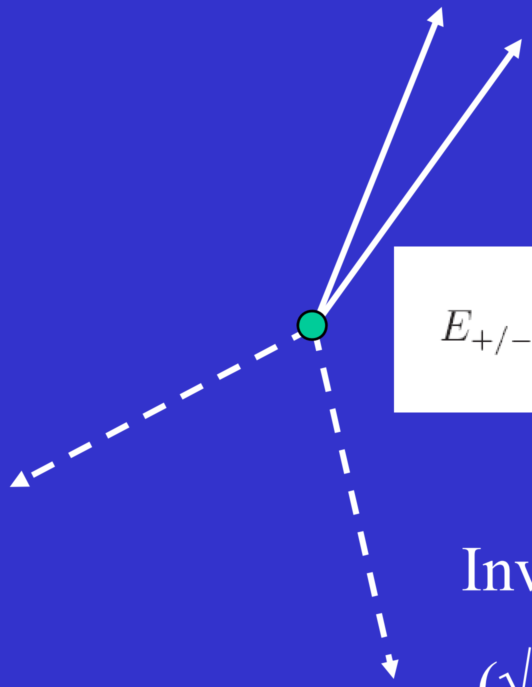


$(E_X, -\mathbf{p}_X)$

$(E_X, \mathbf{p}_X)$

Kinematics 201: Pair production

$$e^+ e^- \rightarrow X^+ X^- \rightarrow f\,\bar{f}\,X^0\,X^0$$



Initial State

Visible Final State

$(\sqrt{s}, \mathbf{0})$

$(E_{vis}, \mathbf{p}_{vis})$

$$E_{+/-} = \frac{\sqrt{s}}{4}\left(\frac{m_{\tilde{\ell}}^2 - m_{\tilde{\chi}}^2}{m_{\tilde{\ell}}^2}\right)\left(1 \pm \sqrt{1 - 4\,m_{\tilde{\ell}}^2/s}\right)$$

Invisible Final State

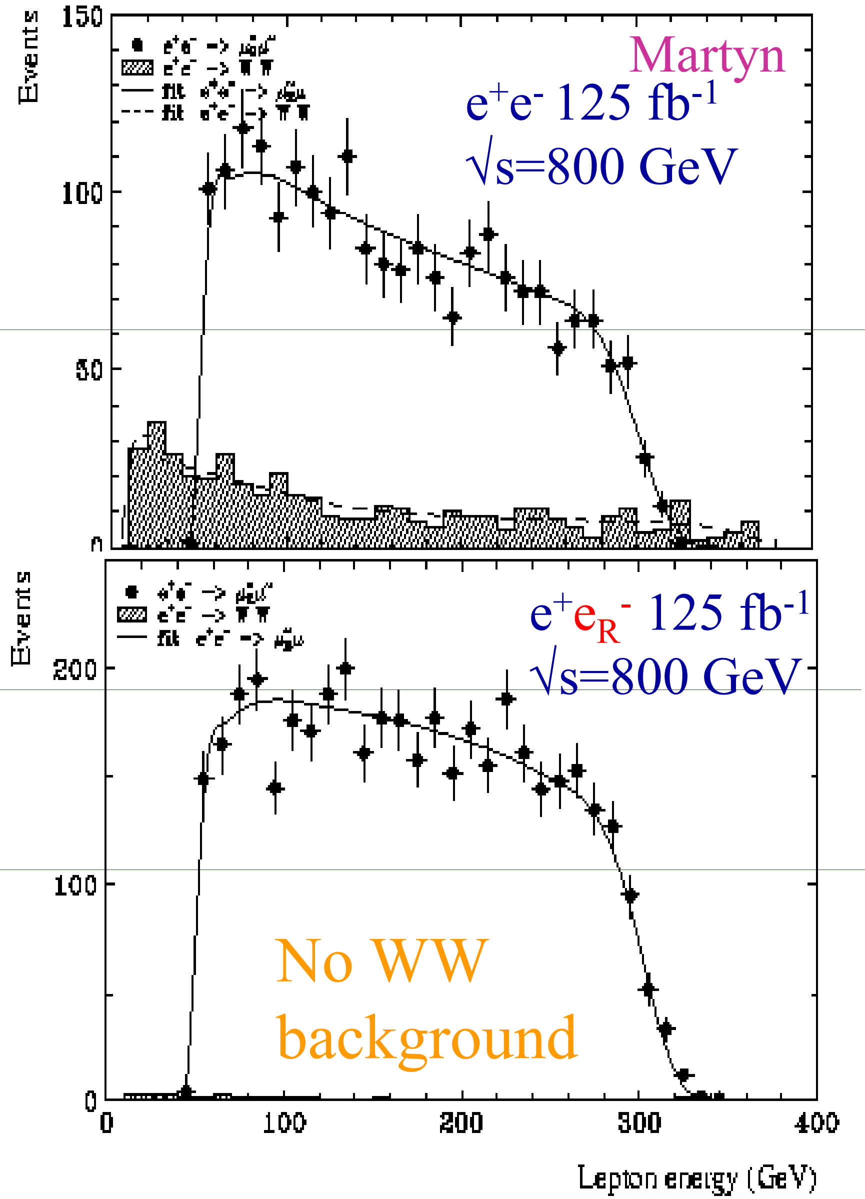
$(\sqrt{s} - E_{vis}, -\,\mathbf{p}_{vis})$

Use energy end-points to measure m_X and m_{X^0}.

Missing mass will exceed 2 m_{X^0}

SuSy Measurements

Example : Smuon Pair Production



Martyn

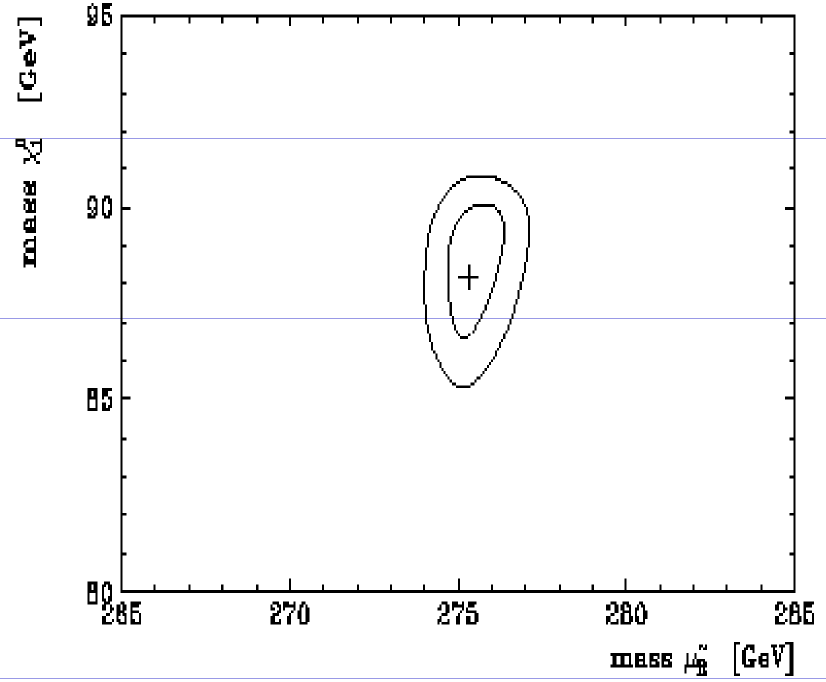
e^+e^- 125 fb^{-1}

$\sqrt{s}$=800 GeV

$e^+e_R^-$ 125 fb^{-1}

$\sqrt{s}$=800 GeV

No WW background



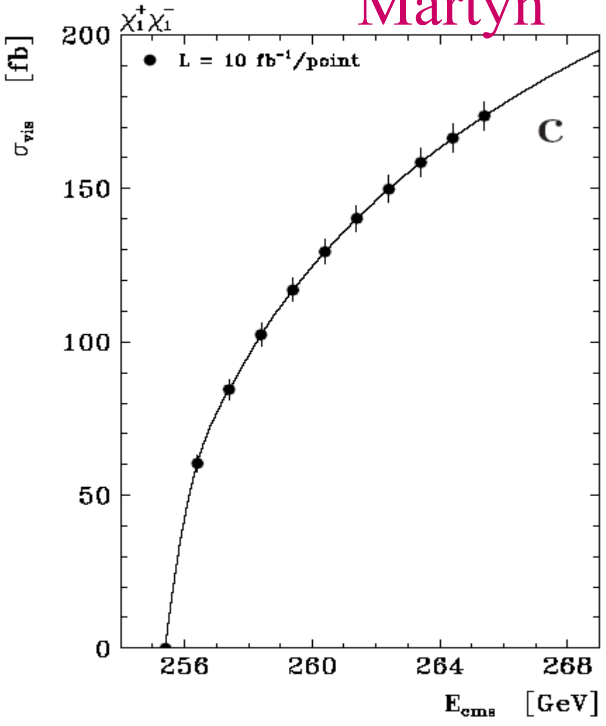
With polarised e^- can measure

smuon mass to 0.8 GeV

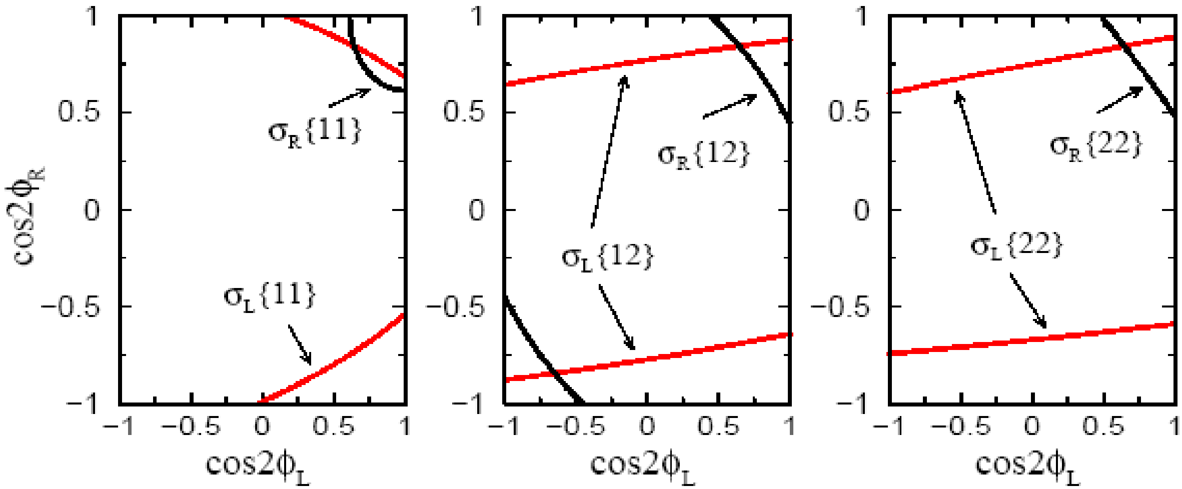
neutralino mass to 1.7 GeV

Charginos

Martyn



Choi et al.



Using polarization, can reconstruct chargino mixing matrix unambiguously (independently of neutralino sector)

Mass from β rise at threshold

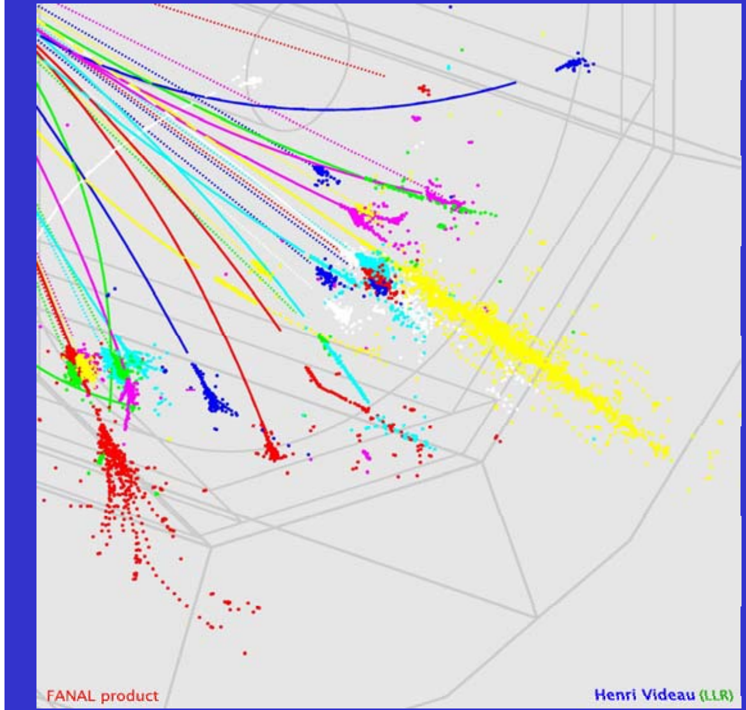
Use threshold scan and polarization to explore the physics

Detector Requirements for Missing Energy Signatures

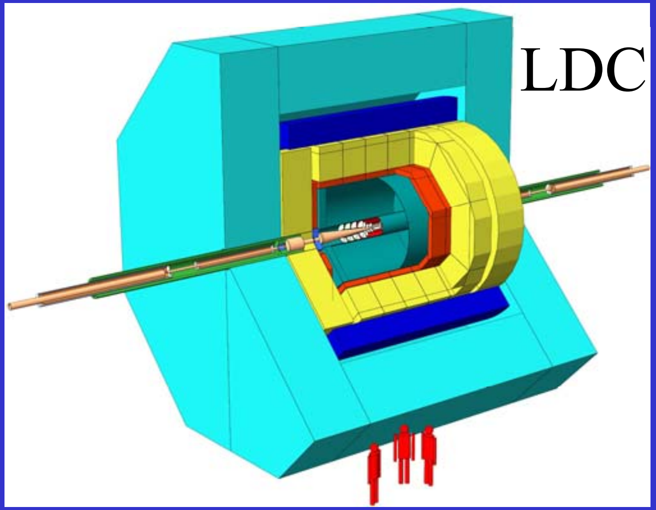
- Hermetic coverage to low angle especially for electrons and photons.
- Robust and accurate measurement of the visible particles.
- Missing E_T resolution in the hadron collider sense is close to irrelevant.
  - the major backgrounds are sources with genuine missing $E_{T.}$ (ZZ, WW, Zh, tt)
  - the exclusive nature of event selections often render many of these backgrounds moot.
  - Can use $\sqrt{s}$ and beam polarization to control

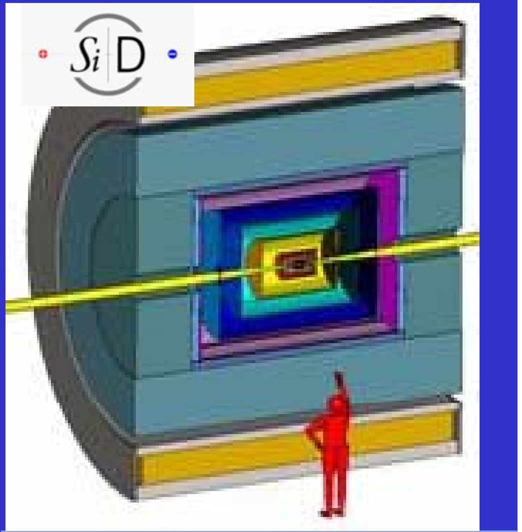
International Linear Collider

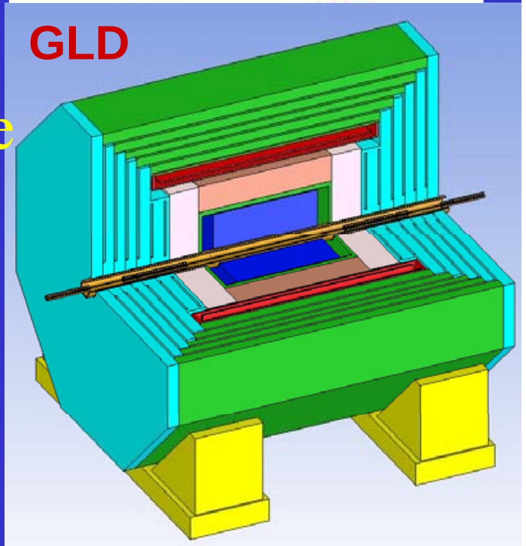
ILC Detector Concepts



also 4th

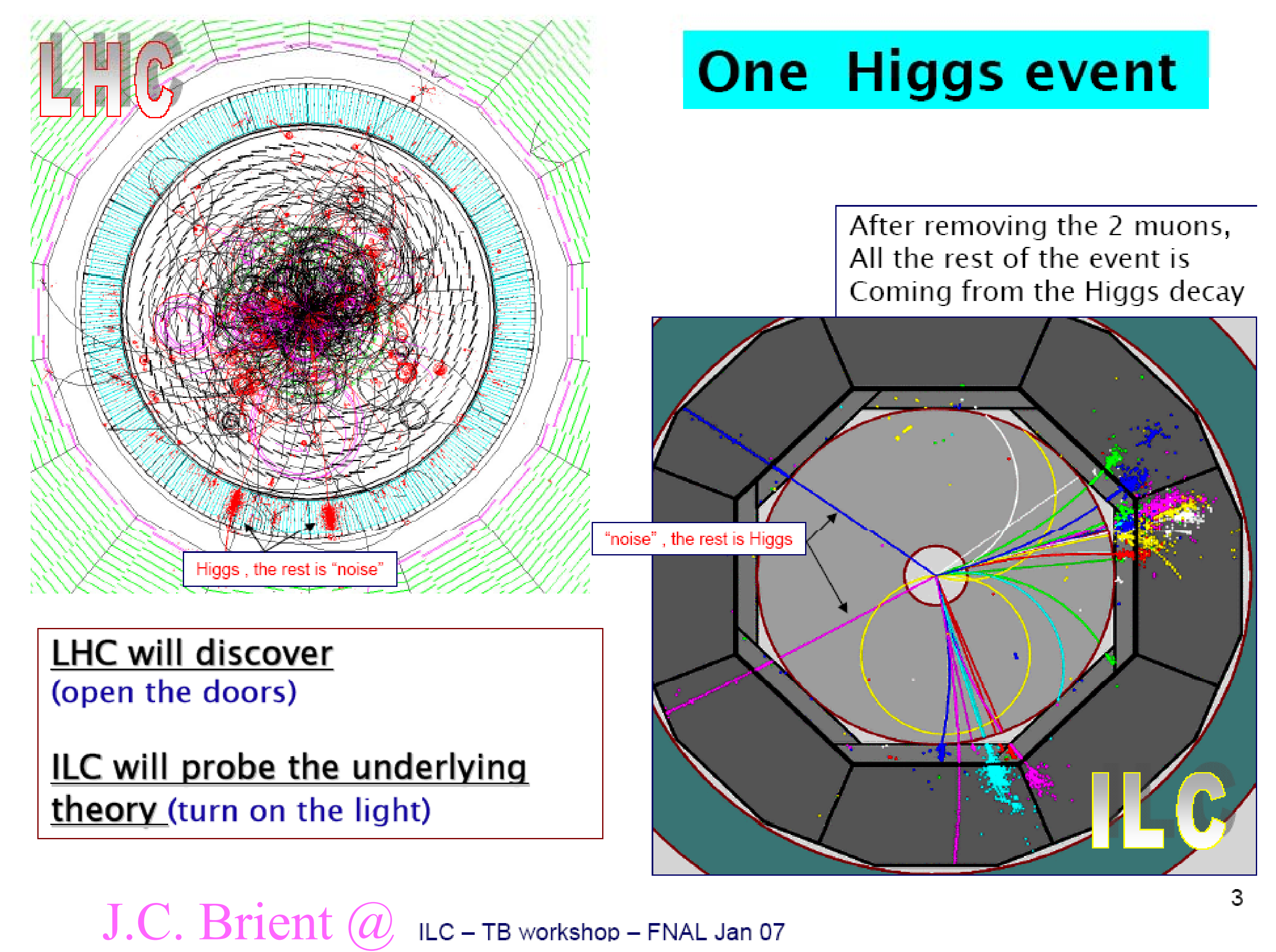






Investigating *highly granular* detectors which promise particle-by-particle reconstruction of hadronic jets with unprecedented jet energy resolution.

Detector R&D is focussed on approaches which emphasize precision vertexing, precision tracking and particle-flow calorimetry. Very different from LHC.



One Higgs event

After removing the 2 muons,
All the rest of the event is
Coming from the Higgs decay

Higgs , the rest is “noise”

“noise” , the rest is Higgs

LHC will discover
(open the doors)

ILC will probe the underlying theory (turn on the light)

J.C. Brient @ ILC – TB workshop – FNAL Jan 07

3

Detectors are necessarily radically different and challenging in their own right. Radiation damage and speed (ΔT_{BX}) NOT major issues for ILC.

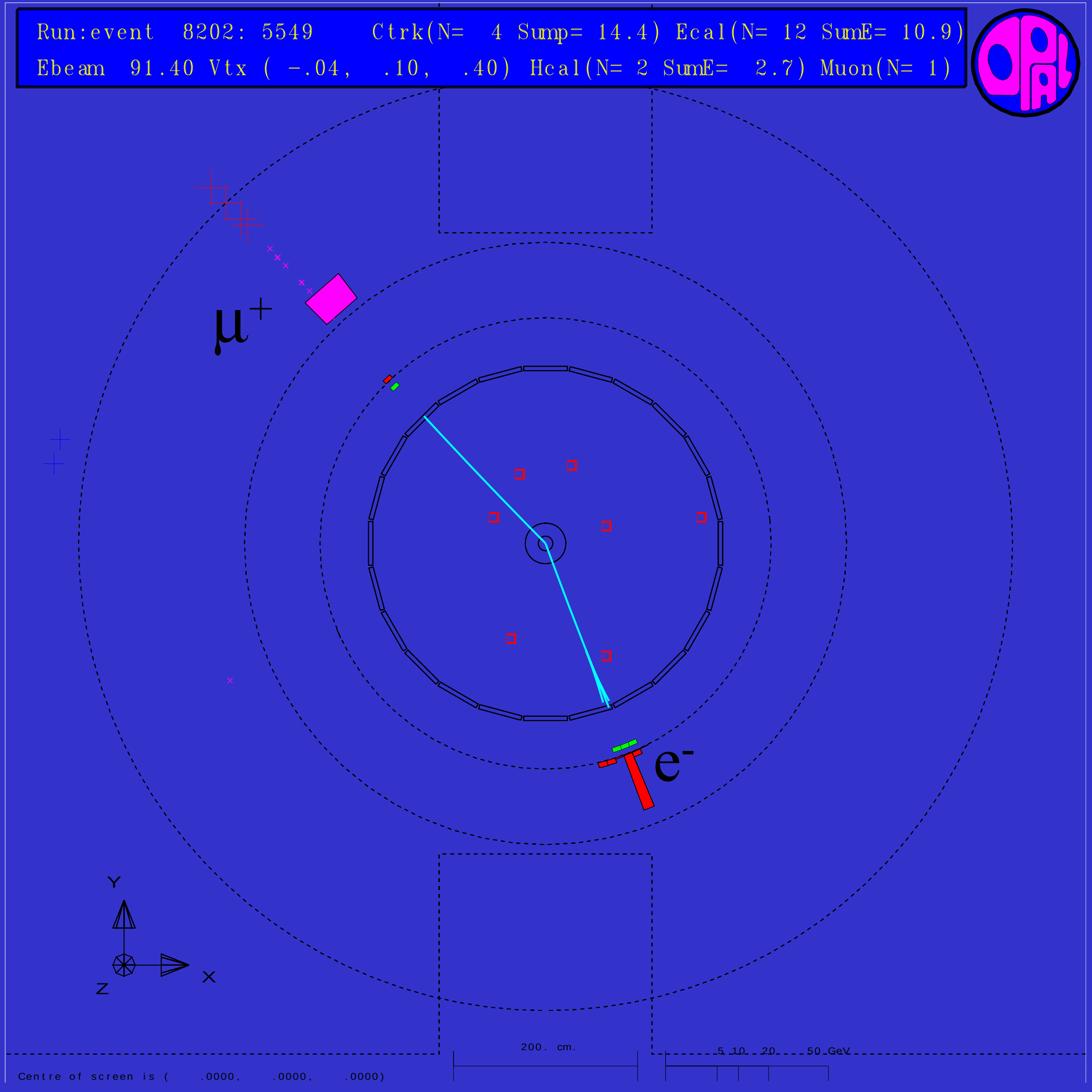
Is detecting electrons and photons all I need care about ?

To first order yes (it is an electron collider – and the electron and photon populations are large)

- To be really sure you have genuine missing energy you also need to care about
  - Missing muons. (the FDET region needs to aim for MIP detection)
  - Missing taus
  - Missing jets
  - Missing neutral jets
  - Missing softer wider angle electrons and photons
  - Extraneous muons (cosmics, halo …)
  - Etc, etc.

Muon hermeticity

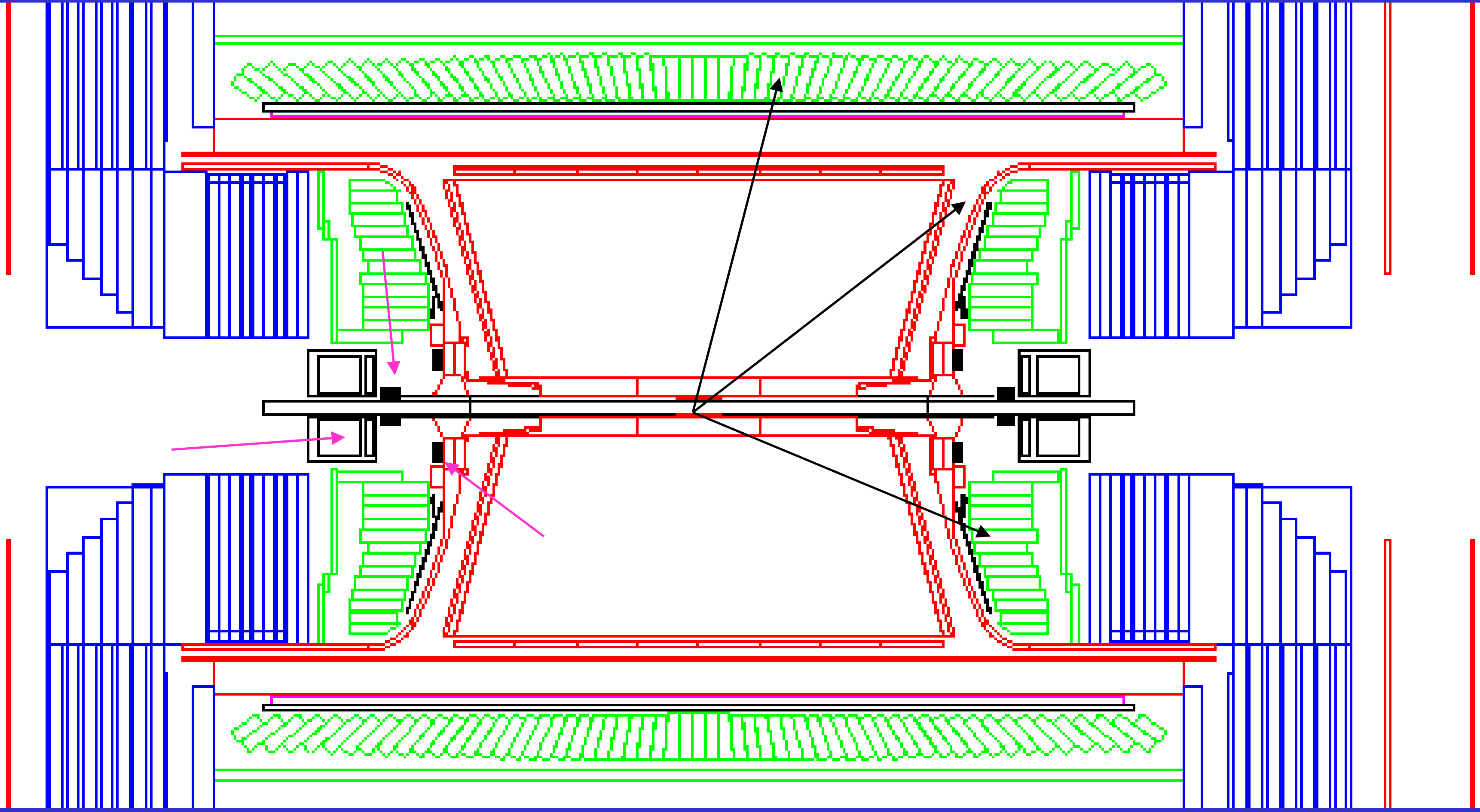
An $e^+e^- \rightarrow e^+e^- \mu^+\mu^-$ **data** event with a forward muon escaping the tracking acceptance.



Missing muon is detected in forward MIP-PLUG scintillator (not shown) and such events are vetoed

Electro-magnetic Hermeticity

OPAL detector was designed so that large missing E_T cannot be faked by undetected electrons or photons

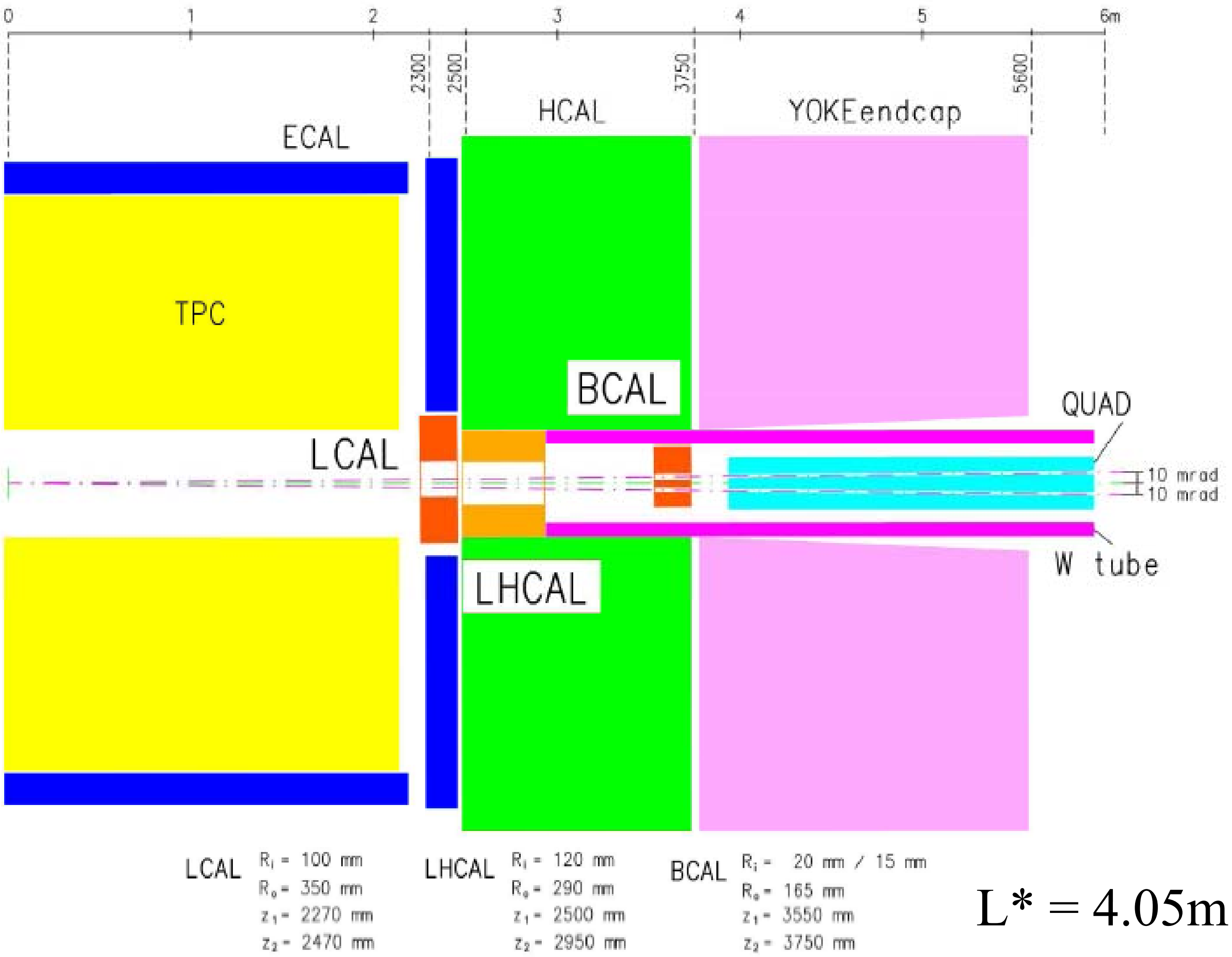


Continuous EM calorimetry to 24 mrad (99.97% of 4π)

A 100 GeV electron in the beam-pipe carries at most 2.4 GeV of p_T

ILC Forward region design

LDC



L* = 4.05m

Figure 66: New design of the forward region for the 20 mrad crossing angle geometries.

Big-picture

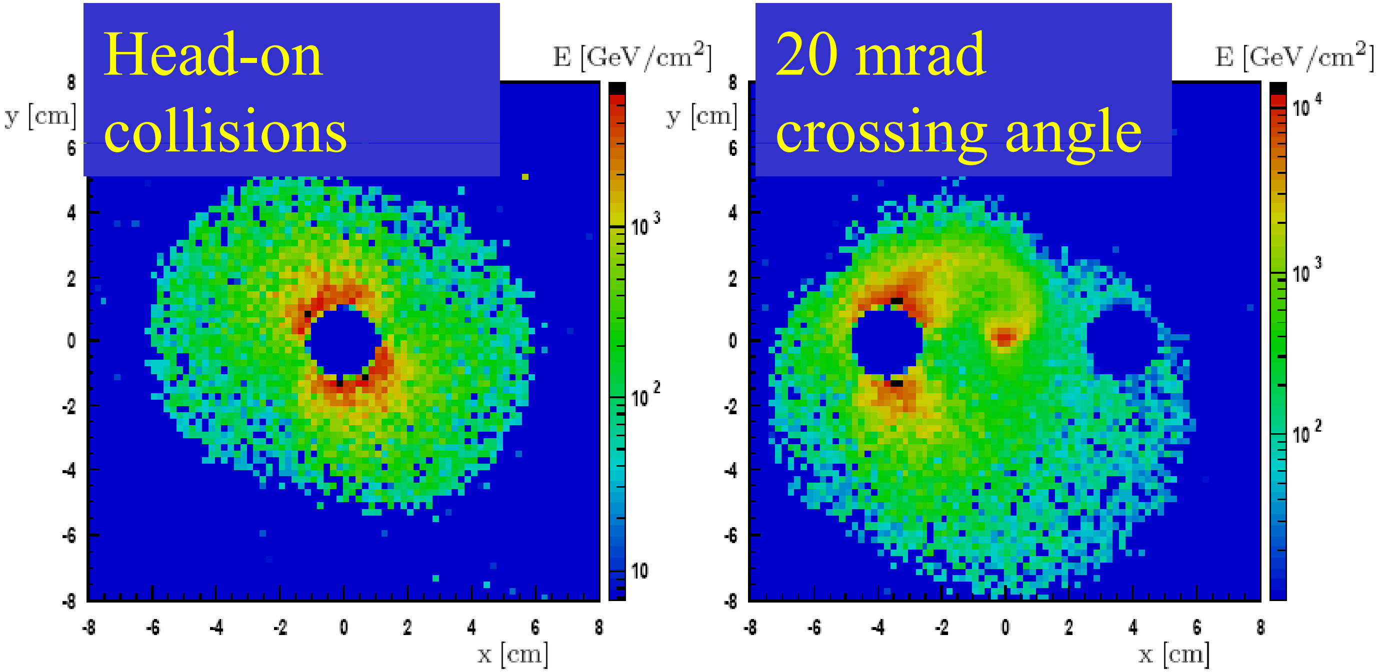
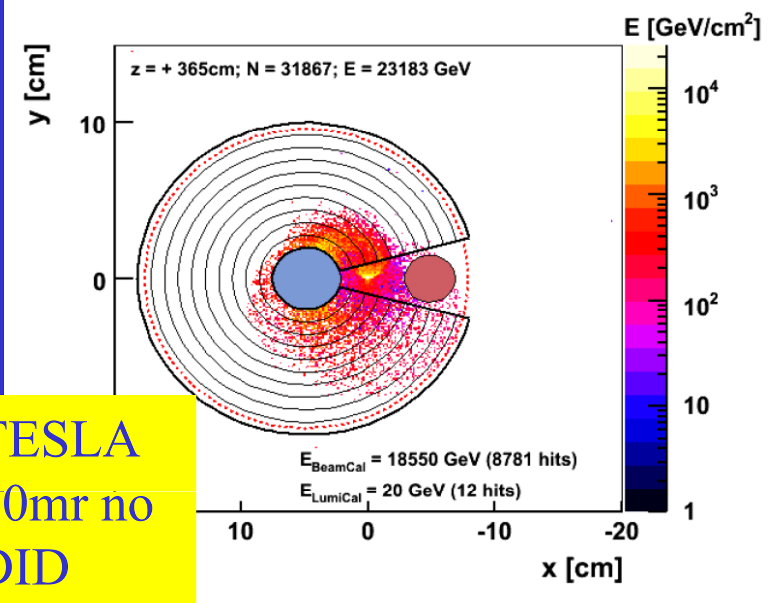


Figure 1: Energy deposits [GeV/cm^2] from beamstrahlung at $\sqrt{s}$ = 500 GeV for head-on collisions (left) and crossed beams (right) in a plane perpendicular to the beams at 3.7 m from the interaction point [10]

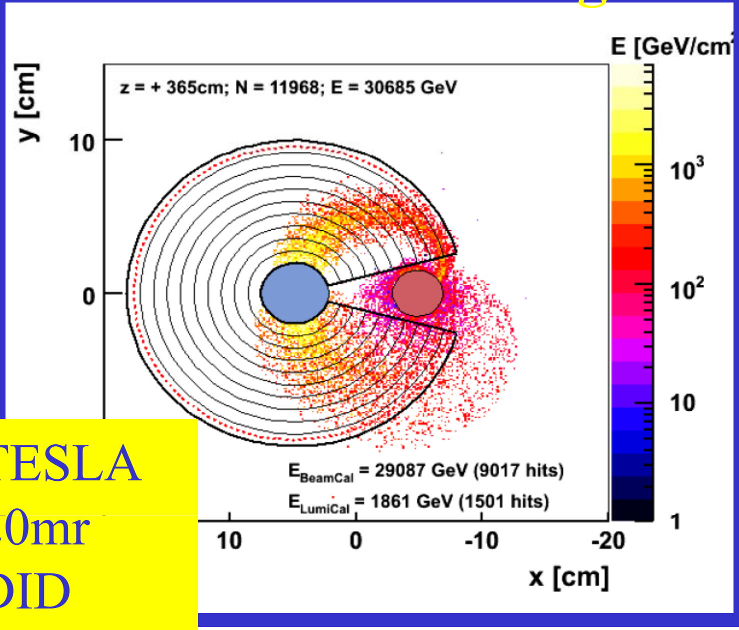
Old plot from 2004 …. now more realistic

Forward electron detectability vs (θ,φ)

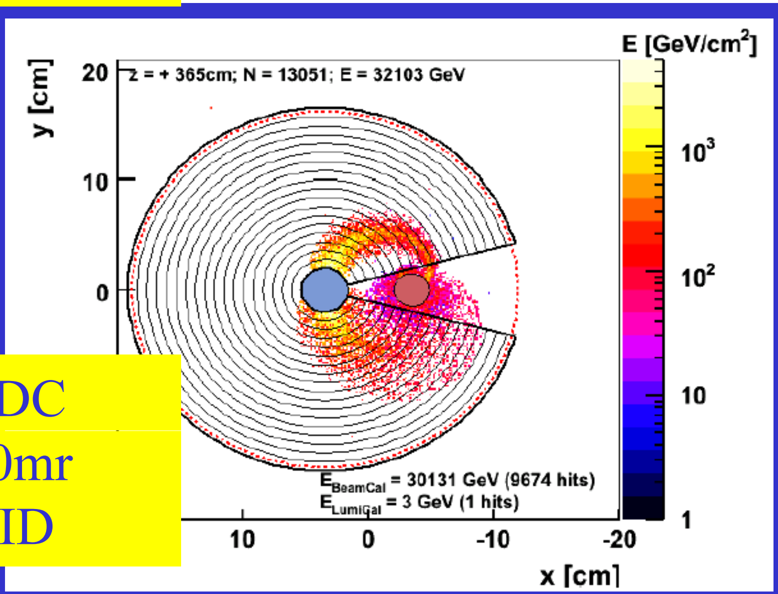
√s=500 GeV depends on machine/detector interface design



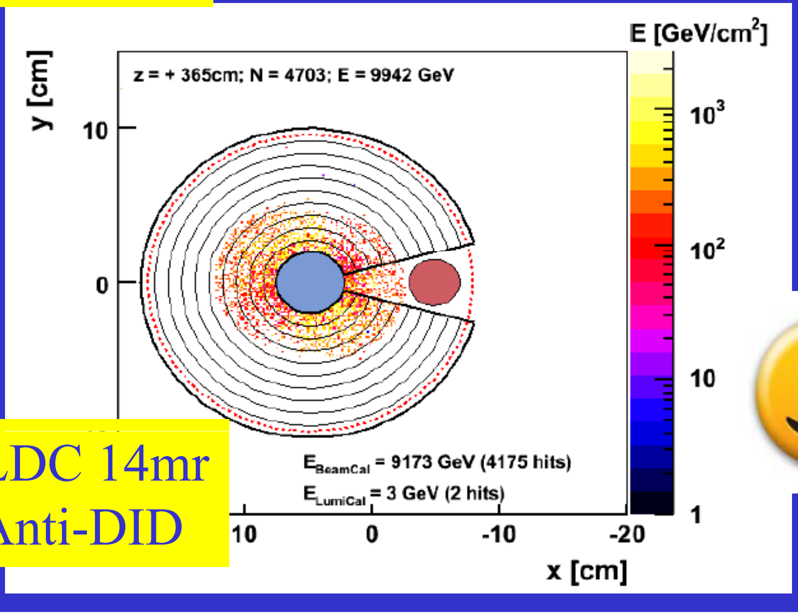
TESLA
20mr no
DID



TESLA
20mr
DID

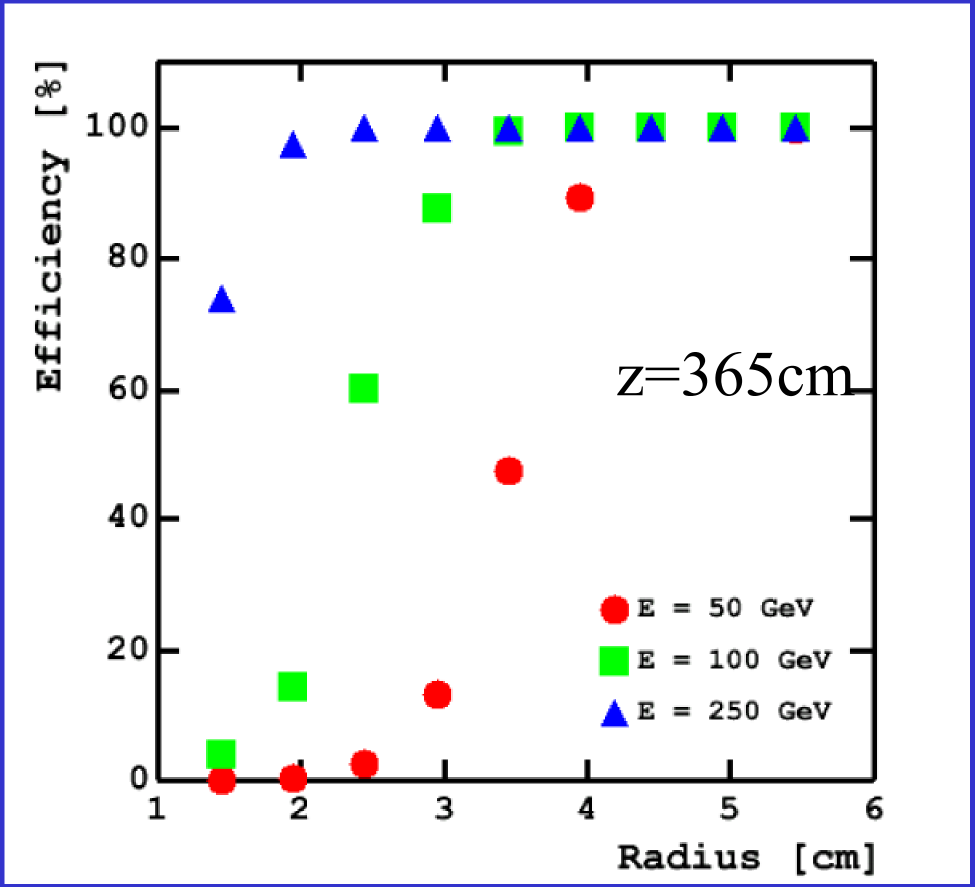


LDC
20mr
DID



LDC 14mr
Anti-DID

What is θ_{min} ?



Electron veto efficiency

Detailed predictions depend on machine design, eg. crossing angle, detector designs and machine background modelling.

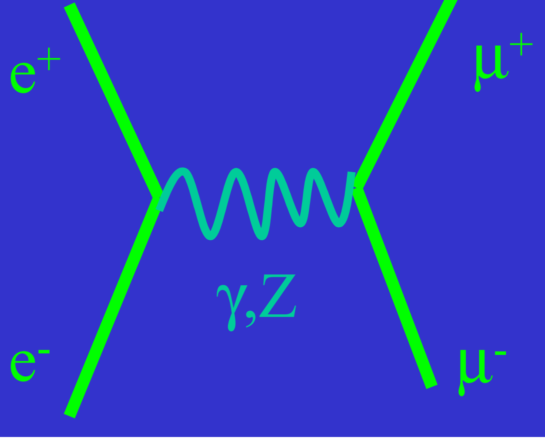
Also some effects from incoming beam-hole.

Efficiency turns on in the 5-10 mrad range.

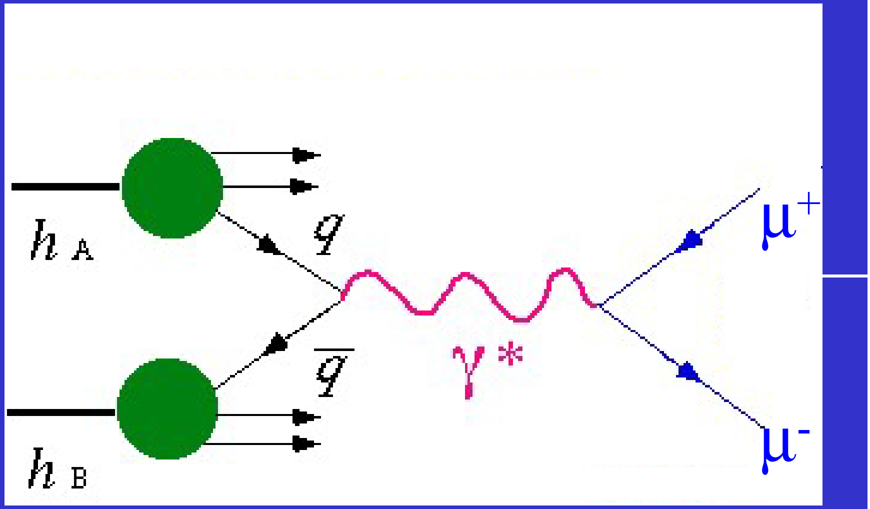
This is a factor of about 5 better than a typical LEP2 detector.

Comparing e^+e^- and hadron colliders

TRIGGER STRAIGHTFORWARD



Initial beam particles are fundamental fermions. Energy can be adjusted, and beams can be polarized.



Collide hadrons.

Quark and gluon constituents of the hadrons participate in the interesting interactions. (accompanied by the remnants of the initial hadrons)

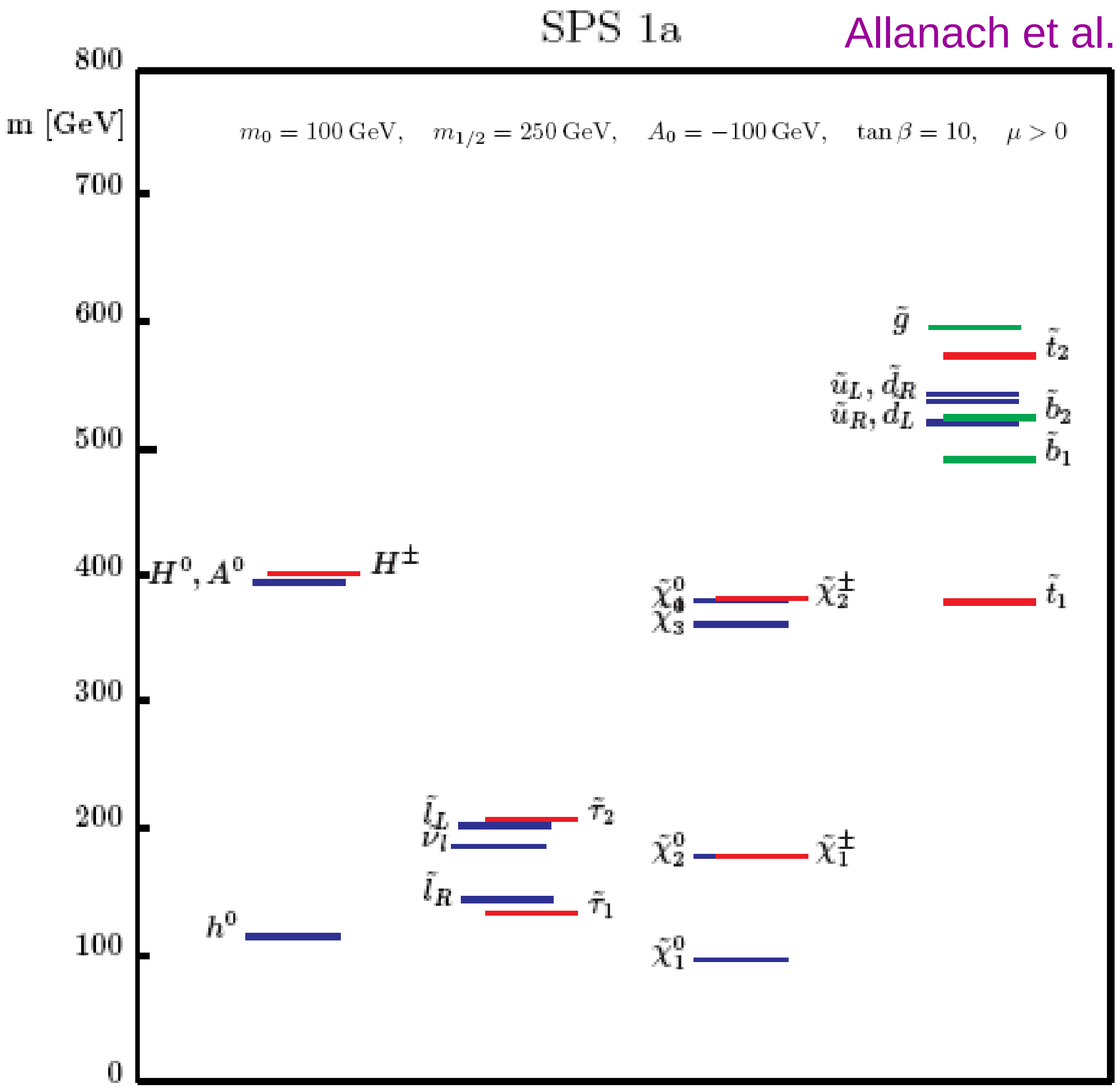
No control over which partons actually collide, and at what energy, $\sqrt{s}$ ⑥ $\sqrt{\hat{s}_{hh}}$ and collisions are boosted

TRIGGER = THE CHALLENGE

Comparing e^+e^- and hadron colliders

- A prevalent opinion is :
  - LHC is a “discovery machine”
  - ILC is a “precision machine”
    - “will happen if/when discoveries are made at LHC”
- I often compare :
  - ISR (63 GeV) / SPEAR (3 GeV) (J/ψ, τ)
  - Tevatron (2 TeV) / LEP (0.2 TeV) (top)
    - And assess whether it makes much sense scientifically to couple the ILC decision to LHC
  - LHC (14 TeV) / ILC (0.1 → > 1 TeV)
- Bottom-line. Just plain different. ILC is complementary both in a quantitative and especially *qualitative* manner.
  - Results from LHC may help refine and prioritize the physics program, but fundamentally the $\sqrt{s}$ ⊙ 500 GeV physics program has been sensible since the top discovery

Example post-LEP SUSY spectrum



Allanach et al.

Particular models have well defined relationships between sparticles.

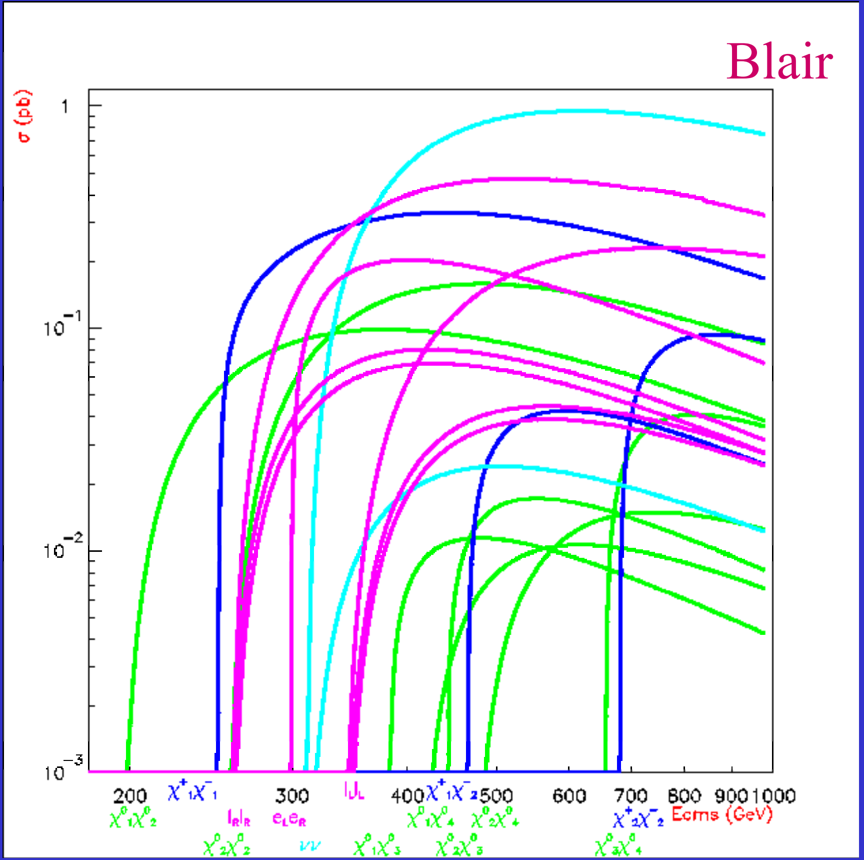
Squarks, gluino expected to be most massive (easiest to produce at a hadron collider)

Sparticles with only EW interactions are expected to be much lighter (difficult to produce at hadron colliders, but easy at lepton colliders)

Note: mSUGRA mass splittings are large

Supersymmetry Exploration

- LHC is well suited to production of squarks, gluinos.
  - Perhaps even with a MET signal, there will not be any additional channels observed (besides a light Higgs)
  - Deciphering cascade decays could be challenging.
- ILC ideal for systematic approach to charginos, neutralinos, sleptons.


Blair

Is LHC really going to reliably tell us that the above is excluded ?

In the last 7 years, the Tevatron has not advanced our knowledge of these sectors beyond that of LEP2.

Perhaps the question to LHC …

Is there significant model-independent sensitivity beyond that of LEP2 for directly produced weakly interacting sparticles ?

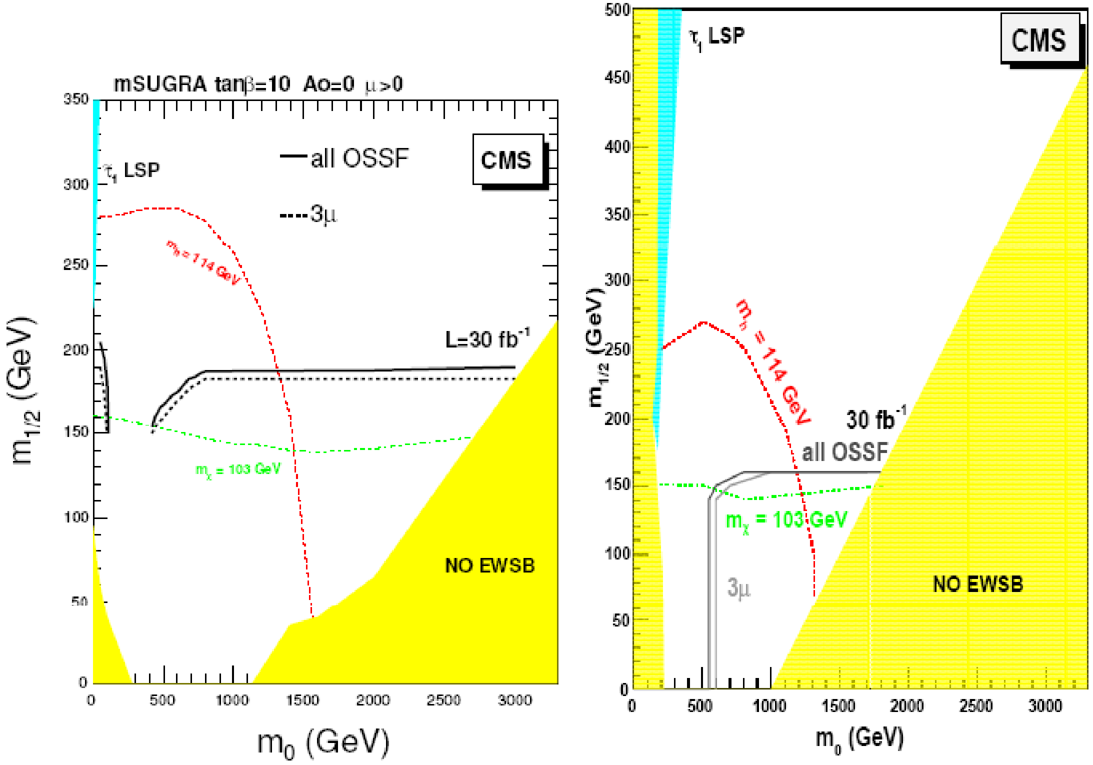
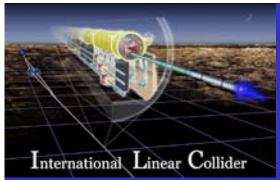


Figure 13.28: Discovery reach of tri-lepton from the $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ production at $\mathcal{L}_{int}$=30 fb^{-1} for all SFOS lepton combinations (dashed) and for the tri-muon final state (solid) including systematic uncertainties from reconstruction. (left) for $\tan\beta = 10$ and (right) for $\tan\beta = 50$.

These plots barely go beyond LEP2, and still make the usual favorable assumption that $\Delta M = M_{LSP}$ leading to high MET



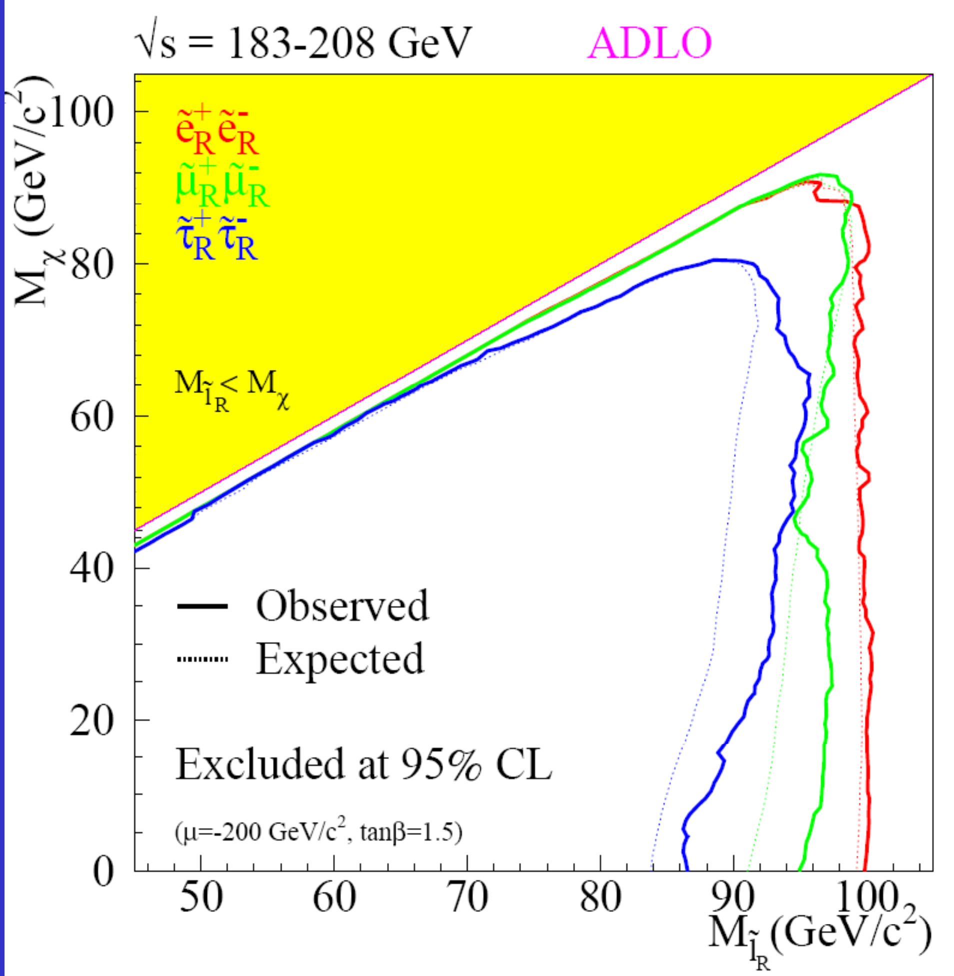
Another question to LHC

- Suppose:
  - A light Higgs is found. Consistent with SM, SUSY.
  - Only a jets+MET signal is found at LHC.
- What is the minimum √shat involved in the signal ?
  - Can we estimate the e^+e^- production threshold reliably ? (not clear).
- Can the signal be produced in e^+e^-. (does it couple to the γ, W, Z, h) ?
  - Presumably no info will be available.
  - Maybe it's a gluino. Seems to me e^+e^- is probably irrelevant for direct tests of such hypotheses.
- Is there ANY robust logical inference on the masses of lighter particles that can be made, eg. M_{LSP} ???
- Be careful what you wish for !
  - You may find that LHC can't tell you very much of value in diagnosing this new physics.
  - And that ILC at any energy may not be a useful diagnostic tool for your **particular** hadron collider signature.

Another question to LHC

If and when we give up on mSUGRA assumptions, what fraction of the (msquark, m_{LSP}) plane will actually be experimentally accessible ?

Can we have model independent limits for the squarks and gluinos ???, analagous to the slepton searches at LEP2 with coverage to low MET ??

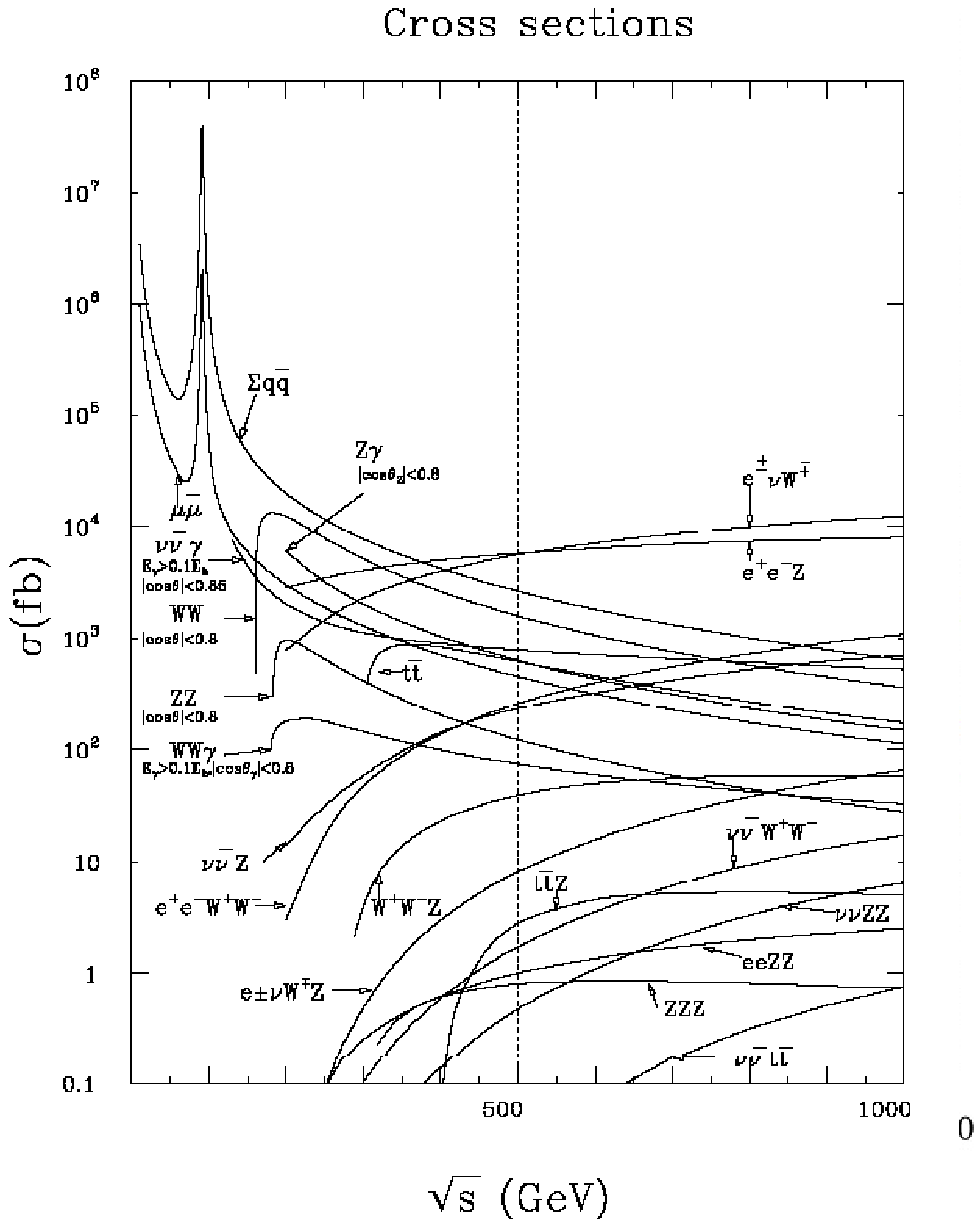


Conclusion

- Given the opportunity, the ILC will excel at investigating kinematically accessible missing energy signals.
- Energy extensibility is the key to a successful long-term physics program.
- LHC data will be interesting
  - Maybe there is a very rich SUSY-like structure.
    - And it will be obvious that the ILC has a primary role to play in probing more directly aspects of an initial LHC observation.
    - The “Higgs profile” would then take a back seat.
  - But given the nature of SUSY production and decay, it may be very challenging to convert a robust experimental discovery at LHC (inconsistency with SM) into sharp hypotheses which merit immediate alteration of the ILC run plan.
  - Can low mass colored sparticles hide from LHC ?

Backup Slides

The e^+e^- Landscape

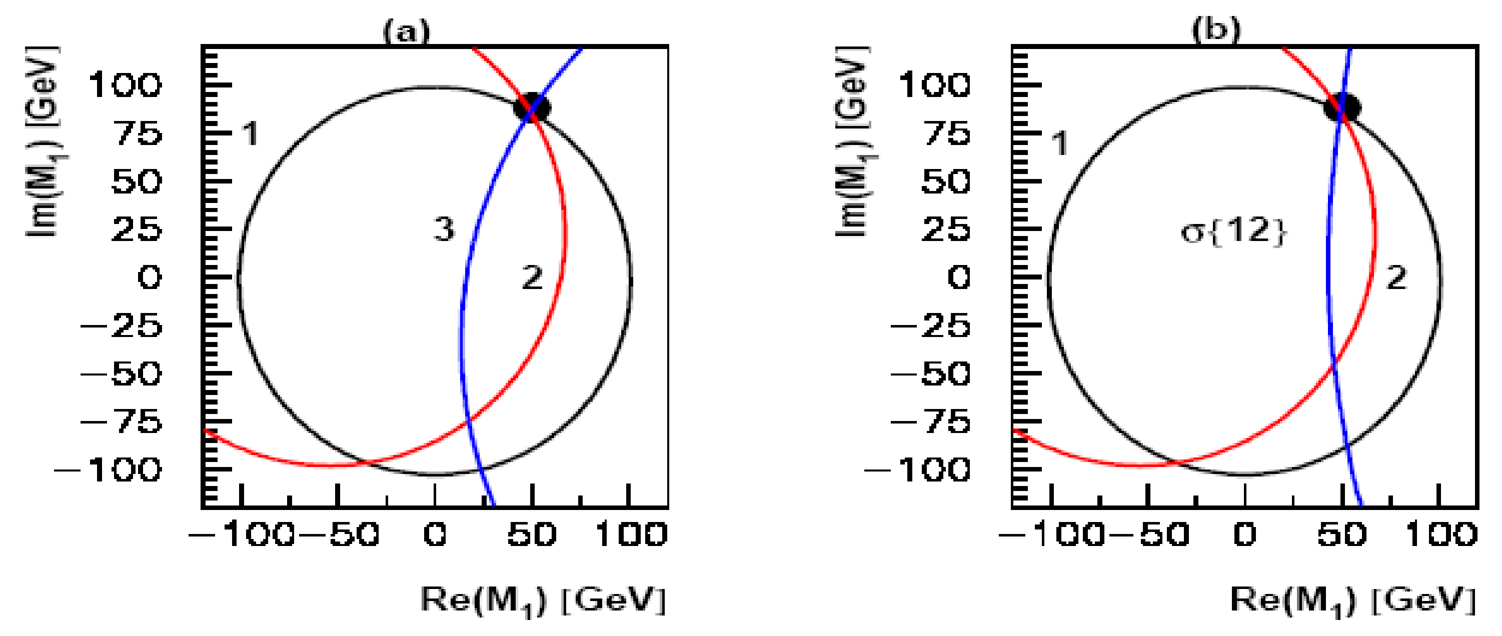


Standard Model processes in e^+e^-
(this first plot has more of the 4f, 6f processes)

New physics processes tend to have cross-sections comparable to standard processes

Neutralinos

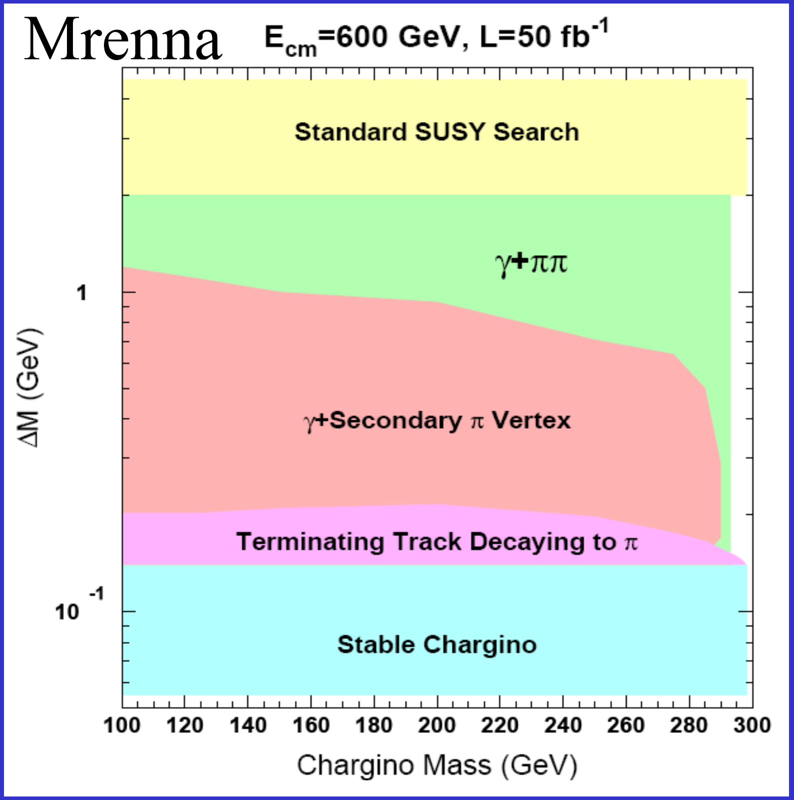
Choi et al.



Similarly in the neutralino sector, measurements of masses and cross-sections yield unambiguous determination of the U(1) mass parameter (M_1) and reconstruction of the neutralino mixing matrix.

=> Quantitative understanding of the dark matter candidate couplings

Low Visible Energy



Experimental methods exist for exploring chargino-pair production in the complete (mC, mLSP) plane even at low ΔM

Many of the solutions adopted to get acceptable relic densities in SUSY, have nearly mass degenerate sparticles. Eg. stau co-annihilation.

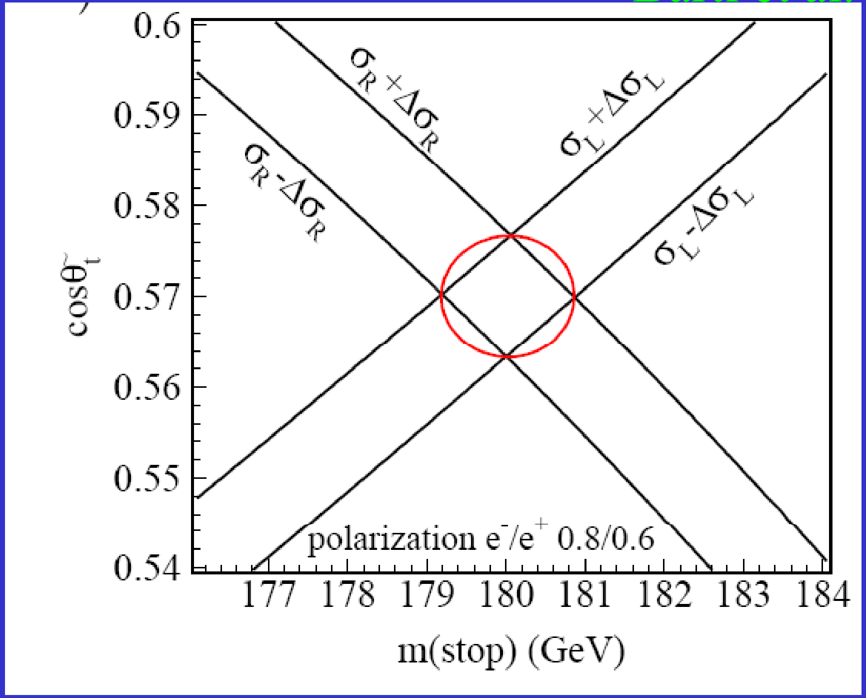
In such cases, SUSY detection at LHC will be harder.

ILC, with its ability to detect low missing E_T topologies, would have unique capabilities

Sfermion Mixing

Example for stop (stau, sbottom similar)

Bartl et al.

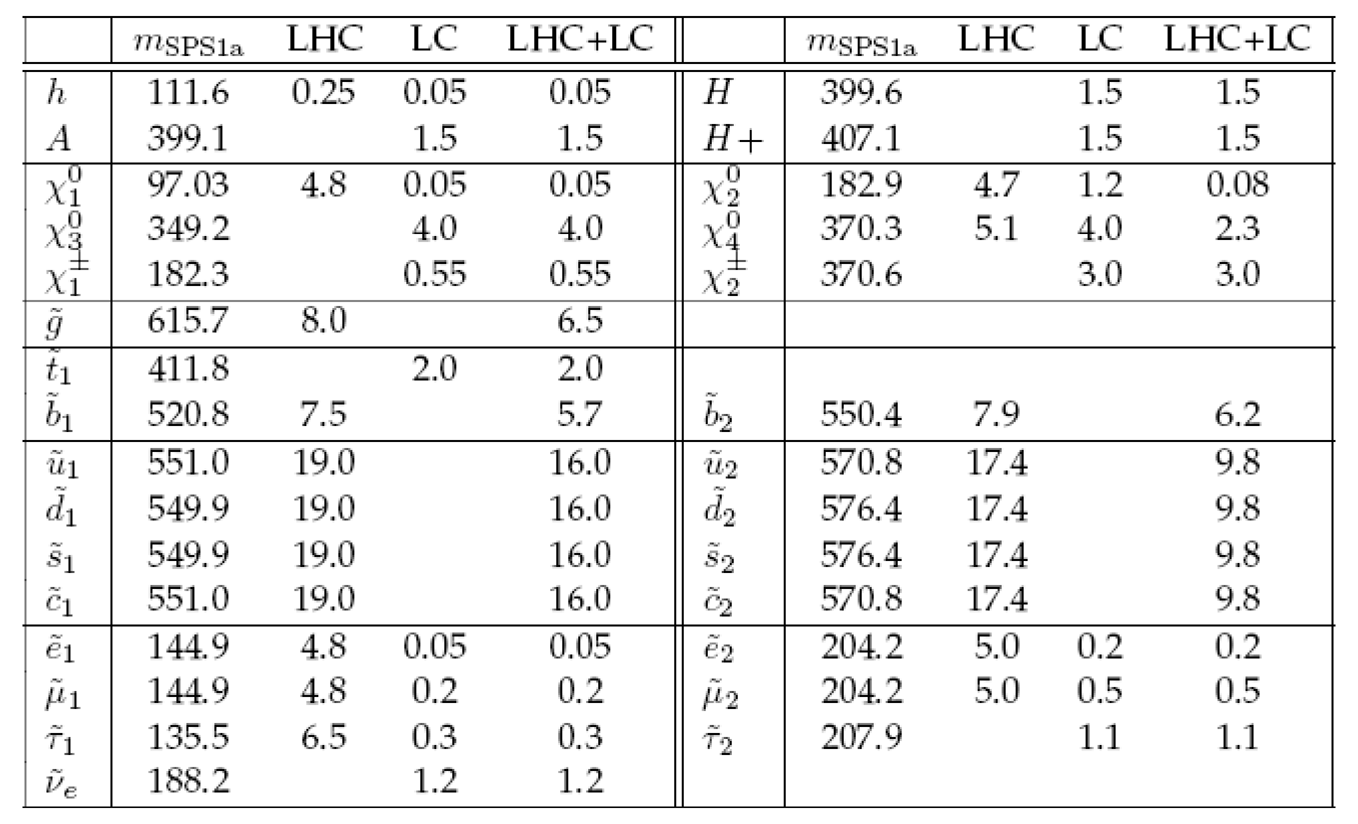


- The chiral nature of the SM and theories like supersymmetry, makes polarization an invaluable tool for doing this physics.

Mass Determination

Much studied, optimistic scenario

LHC observability is highly scenario dependent.



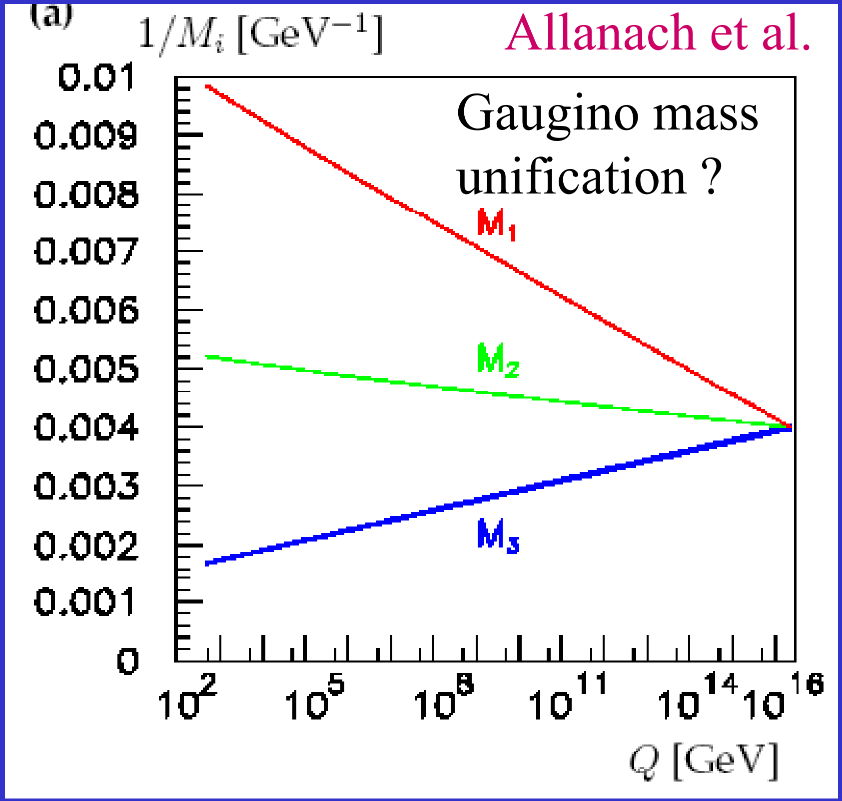
	m_{SPS1a}	LHC	LC	LHC+LC		m_{SPS1a}	LHC	LC	LHC+LC
h	111.6	0.25	0.05	0.05	H	399.6		1.5	1.5
A	399.1		1.5	1.5	$H+$	407.1		1.5	1.5
χ_1^0	97.03	4.8	0.05	0.05	χ_2^0	182.9	4.7	1.2	0.08
χ_3^0	349.2		4.0	4.0	χ_4^0	370.3	5.1	4.0	2.3
$\chi_1^\pm$	182.3		0.55	0.55	$\chi_2^\pm$	370.6		3.0	3.0
$\tilde{g}$	615.7	8.0		6.5					
$\tilde{t}_1$	411.8		2.0	2.0					
$\tilde{b}_1$	520.8	7.5		5.7	$\tilde{b}_2$	550.4	7.9		6.2
$\tilde{u}_1$	551.0	19.0		16.0	$\tilde{u}_2$	570.8	17.4		9.8
$\tilde{d}_1$	549.9	19.0		16.0	$\tilde{d}_2$	576.4	17.4		9.8
$\tilde{s}_1$	549.9	19.0		16.0	$\tilde{s}_2$	576.4	17.4		9.8
$\tilde{c}_1$	551.0	19.0		16.0	$\tilde{c}_2$	570.8	17.4		9.8
$\tilde{e}_1$	144.9	4.8	0.05	0.05	$\tilde{e}_2$	204.2	5.0	0.2	0.2
$\tilde{\mu}_1$	144.9	4.8	0.2	0.2	$\tilde{\mu}_2$	204.2	5.0	0.5	0.5
$\tilde{\tau}_1$	135.5	6.5	0.3	0.3	$\tilde{\tau}_2$	207.9		1.1	1.1
$\tilde{\nu}_e$	188.2		1.2	1.2					

ILC brings precision and thoroughness to measurement of masses of kinematically accessible sparticles

Can imagine testing the dark matter relic abundance calculations

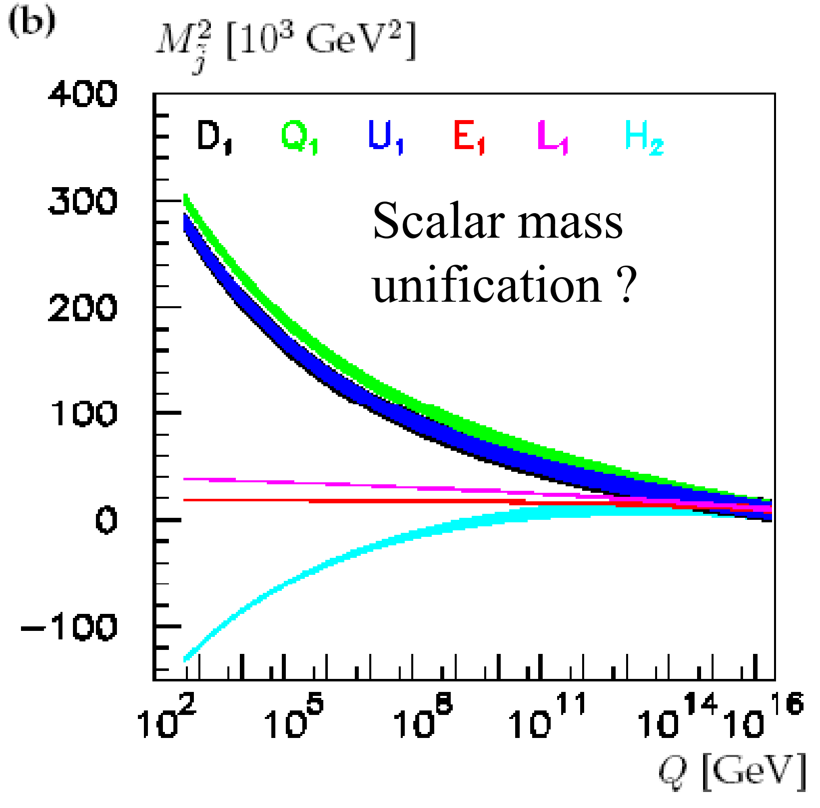
Extrapolating to ≈ the Planck scale

Bottom-up approach : from **precisely** measured sparticle spectrum at low energy – evolve measured masses to high scales



Allanach et al.

Gaugino mass unification ?



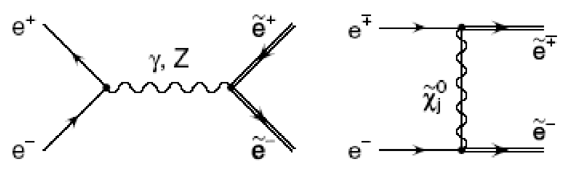
Scalar mass unification ?

(mSUGRA models)

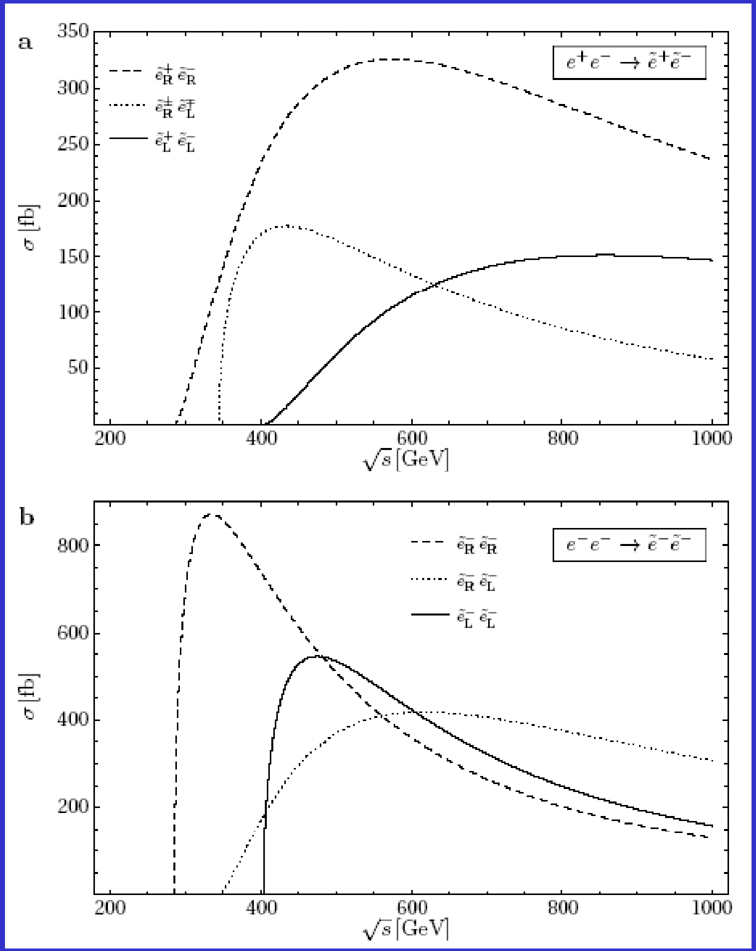
Precision Tests of Supersymmetry

Test the identity of the Yukawa couplings $\hat{g}(f\ \tilde{f}\ \tilde{V})$

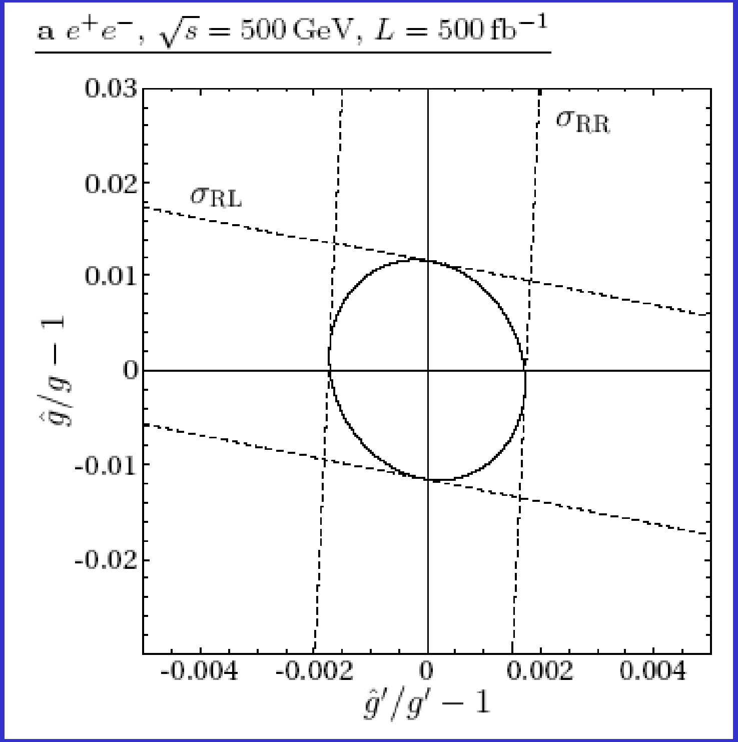
and the gauge couplings g(f f V), and g($\tilde{f}\ \tilde{f}$ V)



Freitas et al.



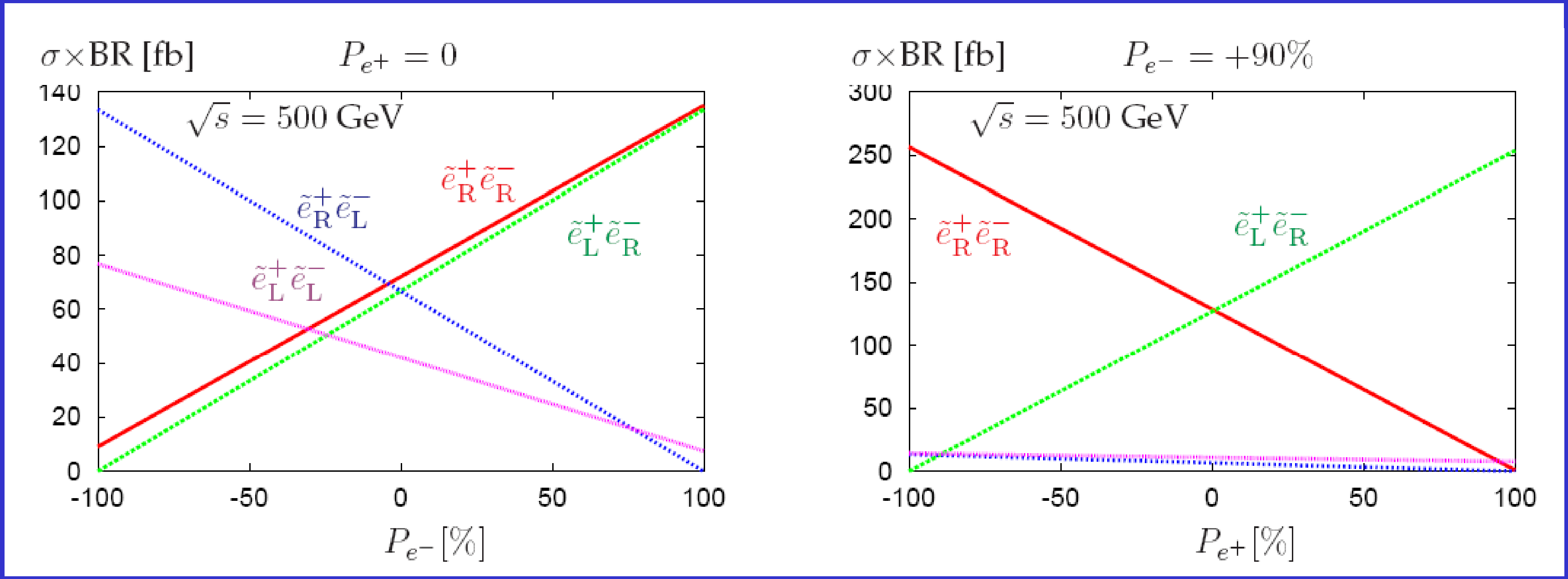
SU(2) coupling



U(1) coupling

Why e^+ Polarization ?

A) It’s like a luminosity upgrade



B) For some channels, eg. selectrons it really helps (distinguish the red and green processes)

Many more details see hep-ph/0507011

References

- TESLA TDR
- Snowmass 2001
- ACFA report
- Consensus Document
- ZDR
- POWER
- CDR (Accomando et al.)
- LCWS proceedings
- GDE
- LHC/ILC report
- ALCPG web-page