THE HIGH ENERGY FRONTIER I

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Orsay, 01/02/2006

5. Muon Collider: any physics reason to discuss it (already) now?

Muon Collider (energy reach upto several TeV):

Time scale: beyond neutrino factory

Physics justification needs TeV-scale data

No controversial views raised in the discussion

4. What is the physics case for SLHC/DLHC? Which priority?

- LHC luminosity upgrade (SLHC) increases discovery reach by 20-30%, better precision for statistically limited processes.
- Energy upgrade (DLHC) has larger discovery reach.

- SLHC: natural extension of the LHC but physics case (at present) debated
- DLHC: requires physics justification from future data

⇒ SLHC: need to prepare with accelerator and detector R&D

⇒ DLHC: magnet R&D required

3. Is there a clear physics case for a multi-TeV lepton collider now? At which energy?

Our current knowledge does not indicate a clear case for multi-TeV collisions

→ need input from the LHC (and ILC) to set the scale

→ need for continued accelerator R&D (CLIC)

2. Consensus statements in 2001-2004 that a Linear Collider of up to at least 500 GeV, upgradeable to 1 TeV, should be the next major project and requires timely realization. Has the physics case changed since then?

Unanimous view: physics case has not changed since 2001

- Physics case for 400 (500) GeV is solid (see ECFA statement)
- Technology is at hand

→ we are ready to go for it (GDE timescale)

In how far should the decision about ILC construction be connected to LHC results?

The bulk of the discussion was directed to this question with differing opinions

YES: discussion of scenarios with limited ILC sensitivity

NO: Clearly outspoken (not only from the young generation): coupling the ILC to LHC results leads to many drawbacks

- Time line is not well defined (moving target)
- Can lead to discouragement and tensions (what precisely should one demand to see in the LHC data?)

In how far should the decision about ILC construction be connected to LHC results?

⇒

Crucial to push ahead with ILC preparations
for construction (GDE)

Upgrade / options depend on LHC+ILC(phase 1) findings
(need flexibility)

Added value from concurrent running of LHC and ILC

1. What is the physics case for upgrades or new machines if LHC provides a null result?

Null result = no Higgs, no new physics

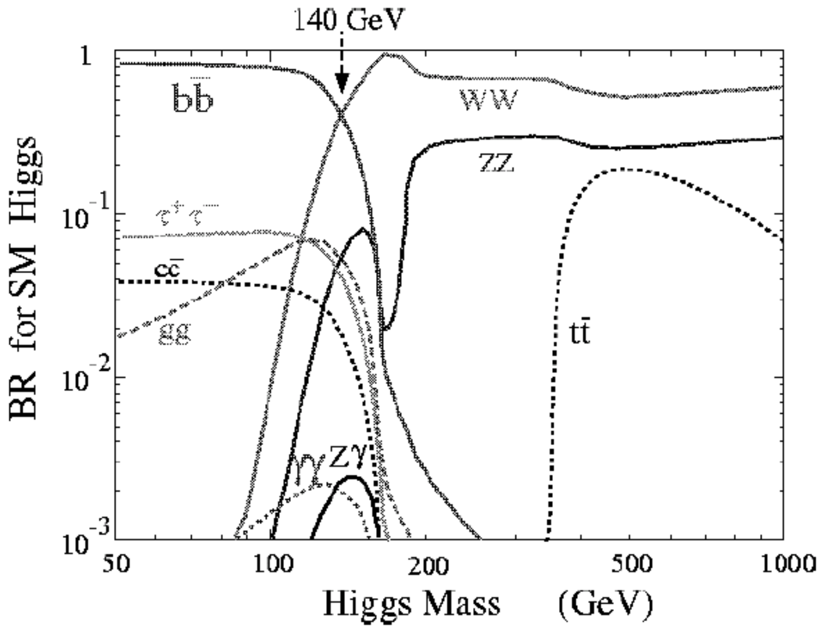
"Catastrophic" scenario (would be very interesting), does not invalidate the physics case for the ILC

Precision measurements at the ILC (and possible discoveries) will be crucial in this case

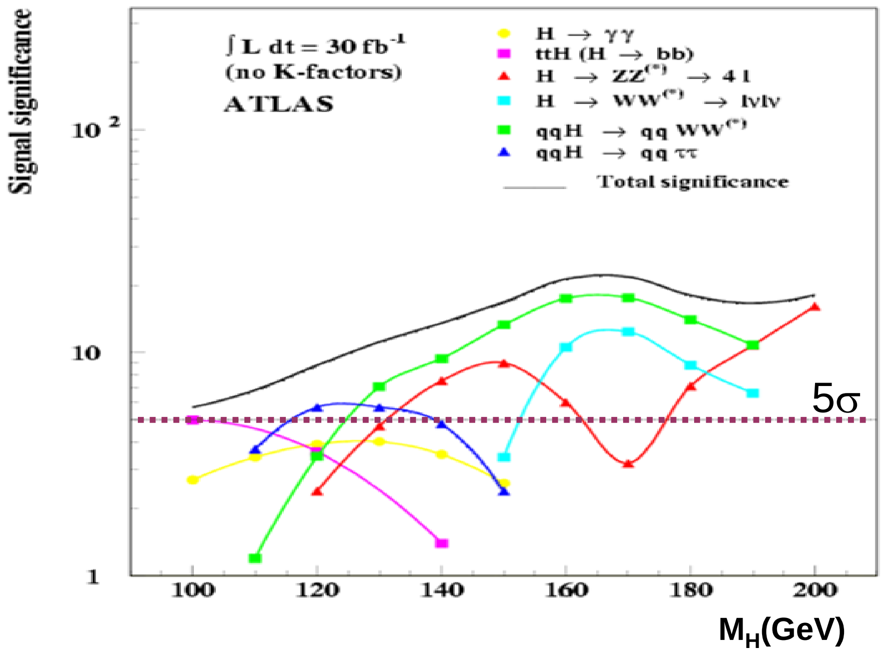
ILC input important for future road map

Higgs boson search at LHC

SM Higgs boson branching ratio



Higgs boson discovery at LHC



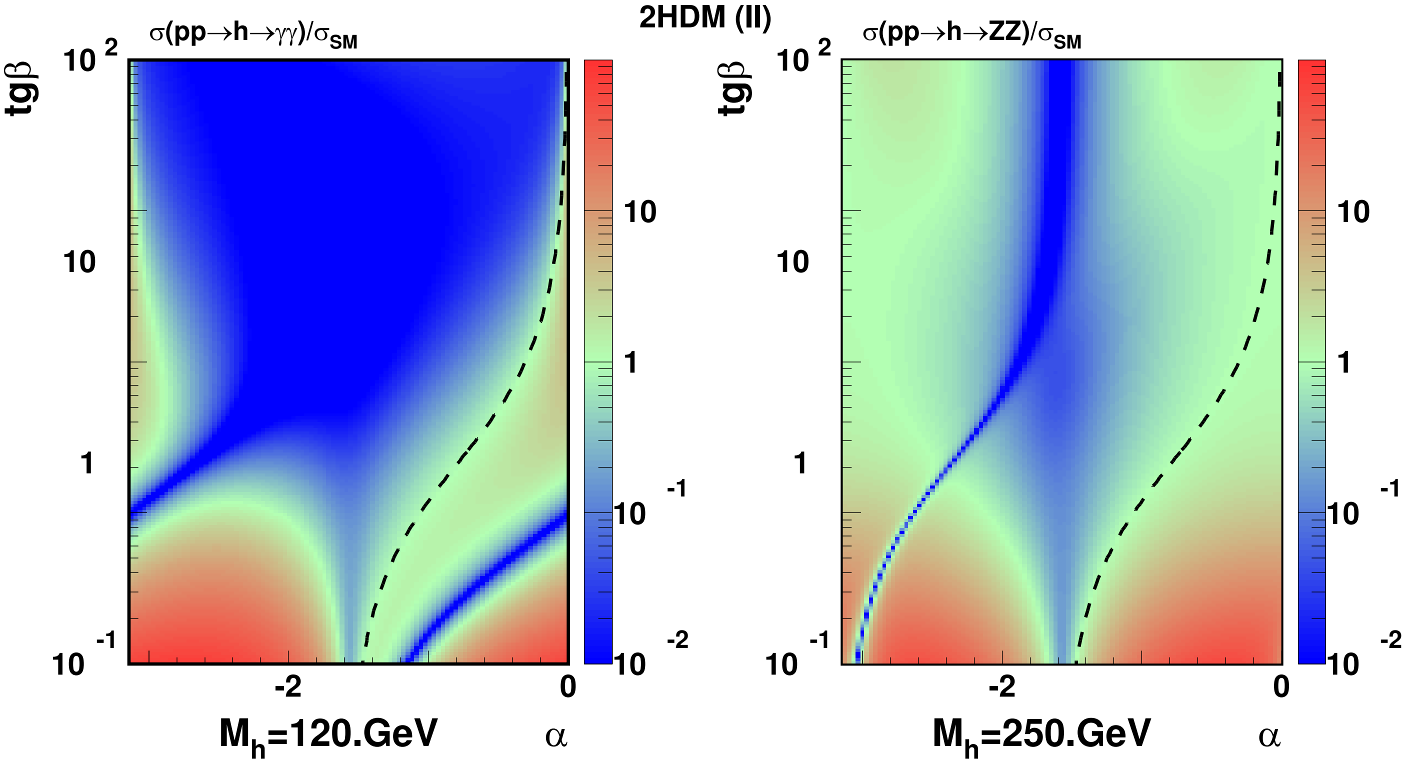
"NO Higgs" scenario

Higgs boson can be missed at LHC if:

* it does not exist ...

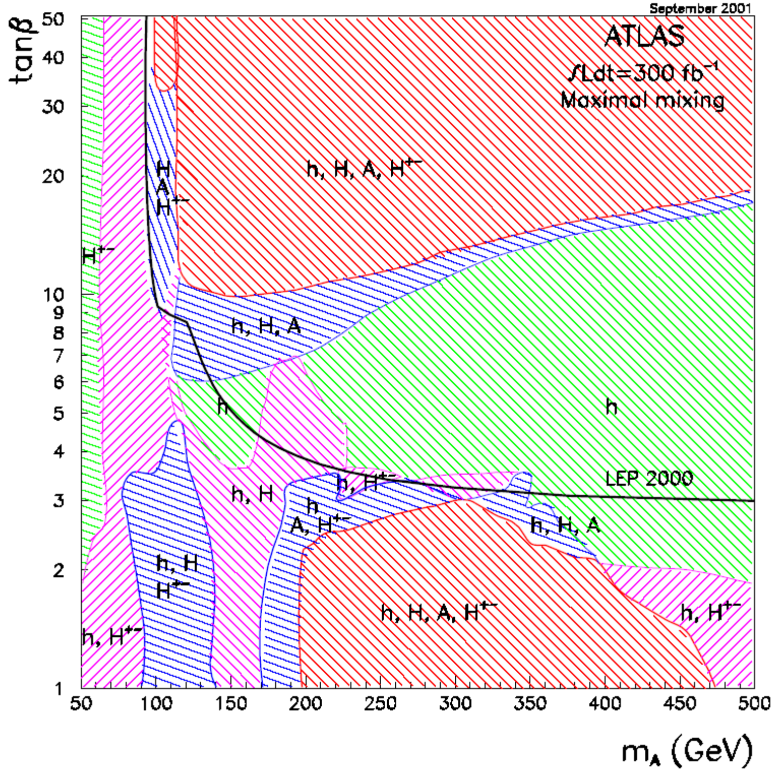
* it has non-standard couplings
  smaller/different from SM
  production cross section smaller

* it has non-standard decay channels (to new particles)
  invisible or
  with high background



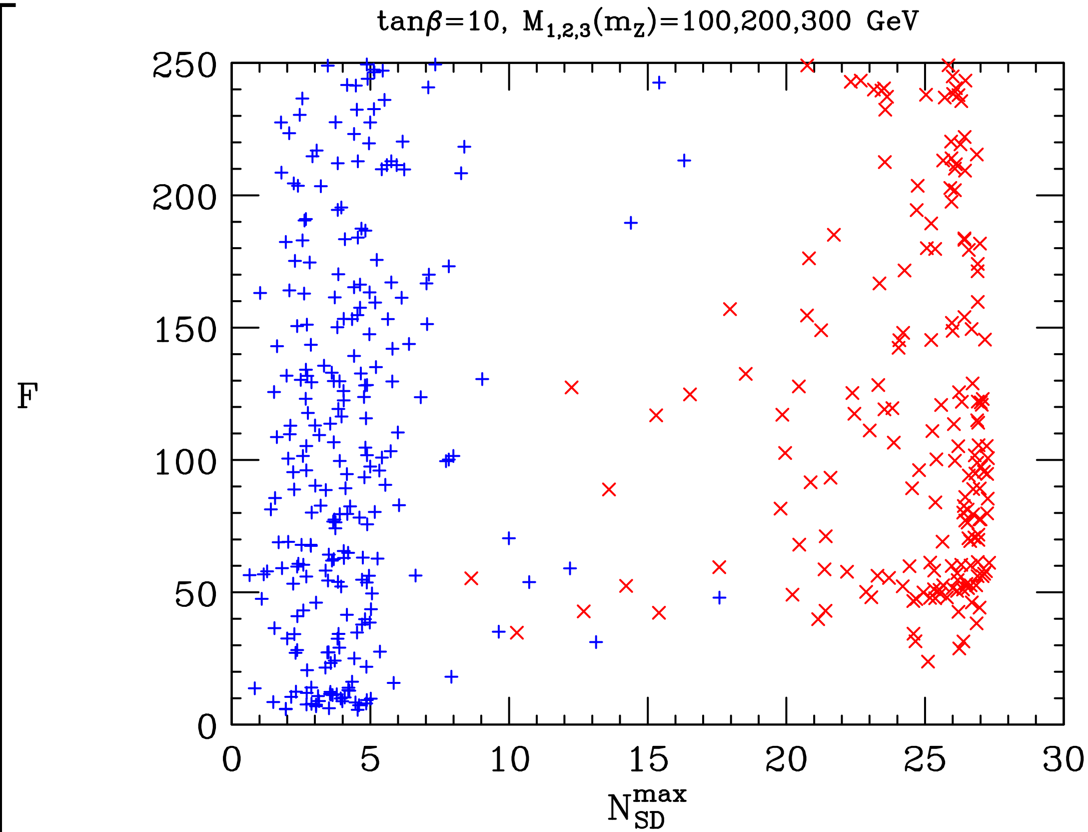
2HDM (II)
σ(pp→h→γγ)/σSM
σ(pp→h→ZZ)/σSM
tgβ
10 2
10
1
10 -1
-2
0
10
1
10 -1
10 -2
Mh=120.GeV
Mh=250.GeV
α

Heavy Higgses at LHC



LHC "wedge" in MSSM

LHC Discovery Potential in NMSSM



Standard decay modes:

$gg \to h/a \to \gamma\gamma$

associated Wh/a or $t\bar{t}h/a$ prod.

with $\gamma\gamma l^{\pm}$ in the final state

$t\bar{t}h/a$ prod. with $h/a \to b\bar{b}$

$b\bar{b}h/a$ prod. with $h/a \to \tau^+\tau^-$

$gg \to h \to ZZ^{(*)} \to$ 4 leptons

$gg \to h \to WW^{(*)} \to l^+l^-\nu\bar{\nu}$

$WW \to h \to \tau^+\tau^-$

$WW \to h \to WW^{(*)}$

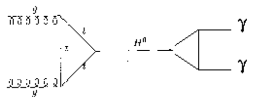
$WW \to h \to invisible$

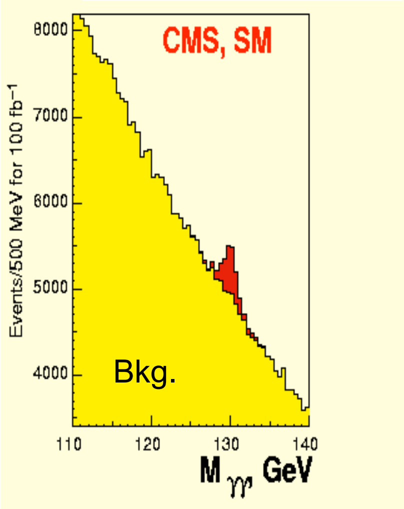
for an integrated luminosity: $L = 300 fb^{-1}$

see the talk of J. Gunion, at LHC-ILC on Wednesday

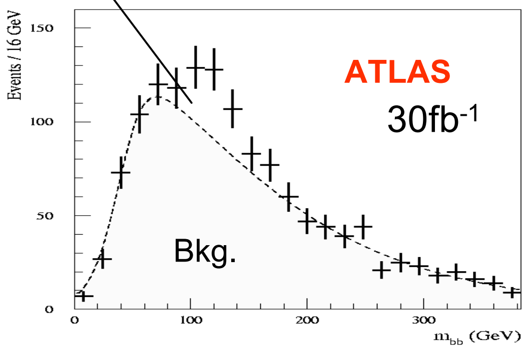
LHC Higgs signal

H→γγ



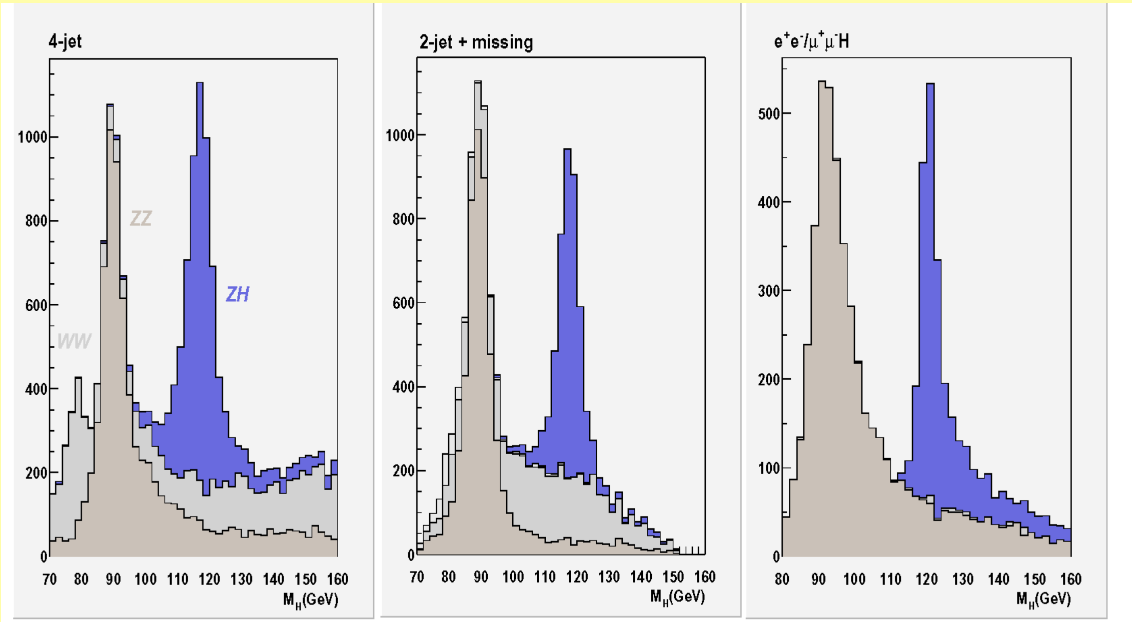


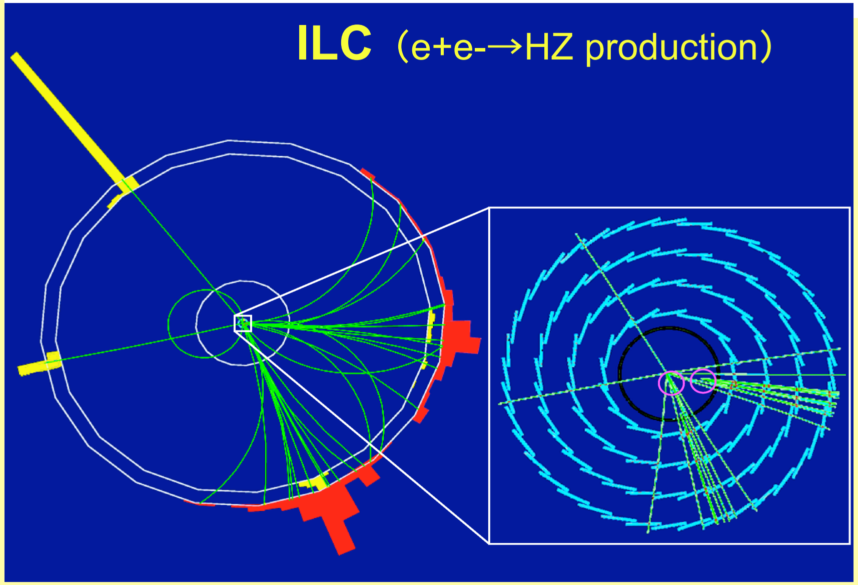
ttH→WbWbbb→lνjjbbbb



Satoru Yamashita, ACFA LCWS 7
Nov.9 2004

ILC Higgs signal





Typical numbers

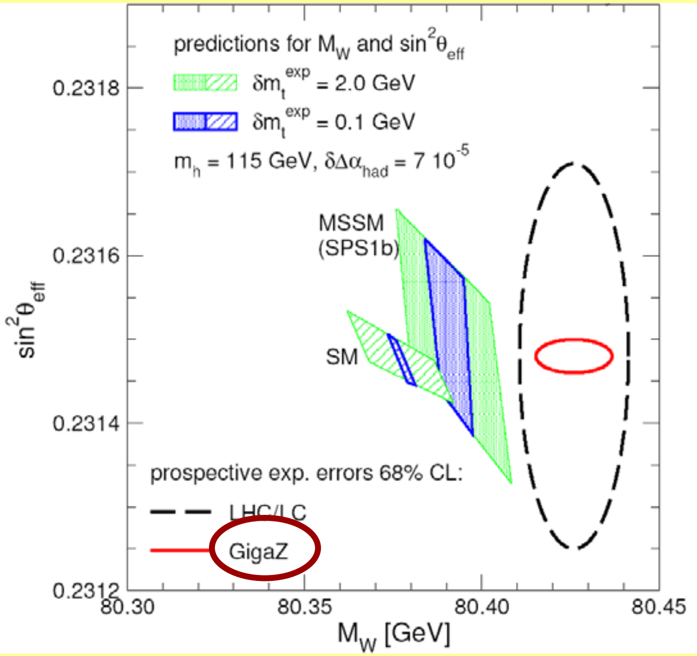
Tagging efficiency ~ 30-50 %

S/N > 1

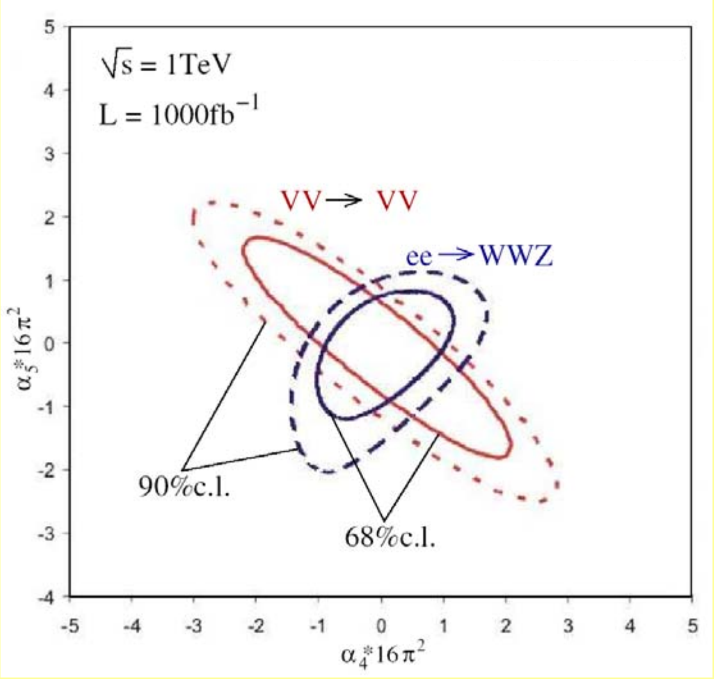
No Higgs seen at LHC: tasks for ILC

1. Make sure LHC hasn't missed it e.g. invisible or purely hadronic

2. Find out why rad. corrections are inconsistent



3. Look for effects of strong EWSB: deviations in $V_LV_L \rightarrow V_LV_L$, WWZ, and Triple Gauge Couplings



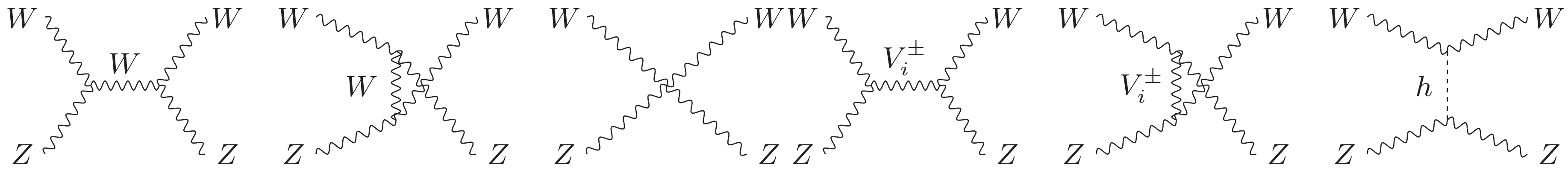
Sensitivity up to Λ ~ 3 TeV similar but complementary to LHC

Collider Phenomenology

(Birkedal, Matchev, Perelstein)

Common feature of the Higgless models: the scale of perturbative unitarity violation is raised by new massive vector bosons whose masses and couplings are constrained by *unitarity sum rules*.

Example: $W_L Z_L$ elastic scattering



A good test → analysis of the vector boson fusion at future colliders

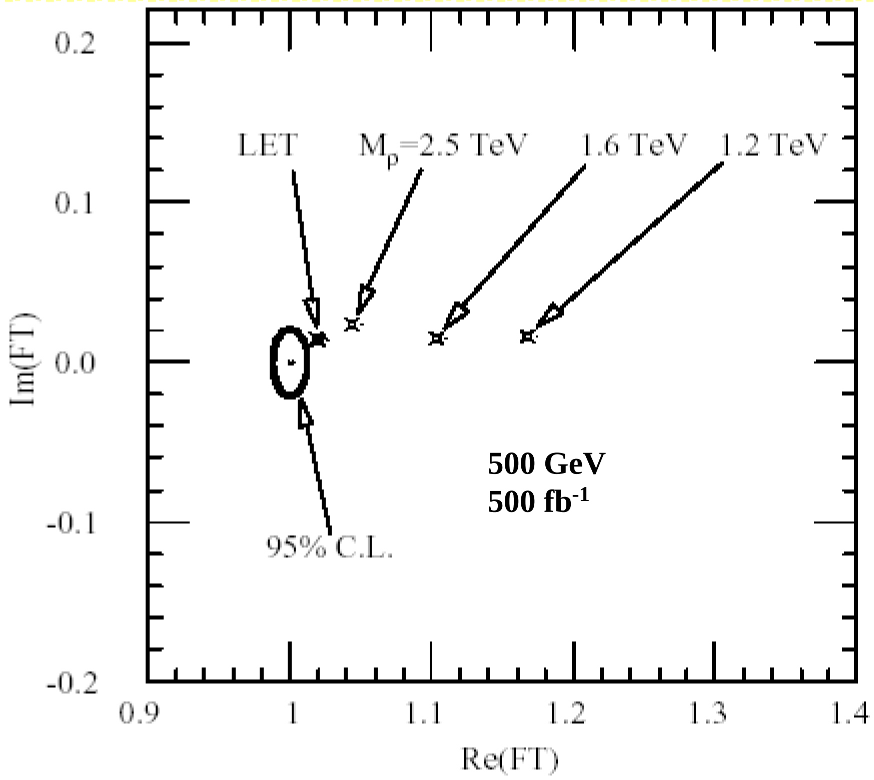
(the most promising channel for Higgsless models with fermion delocalization since the KK resonances are fermiophobic)

Birkedal, Matchev, Perelstein: simplifying assumption that the sum rules are saturated by the first KK resonance V^1

$$g_{WV^1Z} < \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_V^1 M_W}, \qquad \Gamma(V^1) = \frac{\alpha (M_V^1)^3}{144 s_W^2 M_W^2}$$

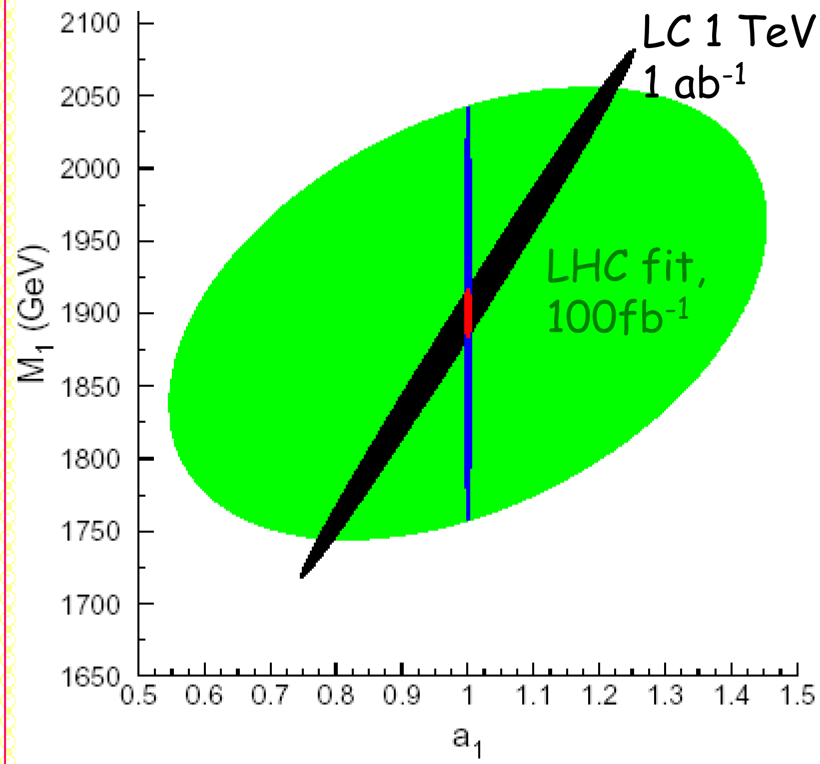
a very narrow and light resonance in WZ scattering

Or $W_L W_L$ Resonances; LHC sees direct up to ~1.5 TeV



$e^+e^- \rightarrow WW$ scattering amplitudes sensitive even to Low Energy Theorem effects. 15 s.d. for 1.9 TeV resonance. (Barklow, Snowmass)

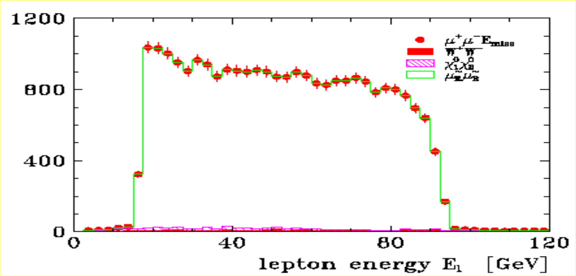
1.9 TeV resonance parameters; above direct threshold for both colliders.



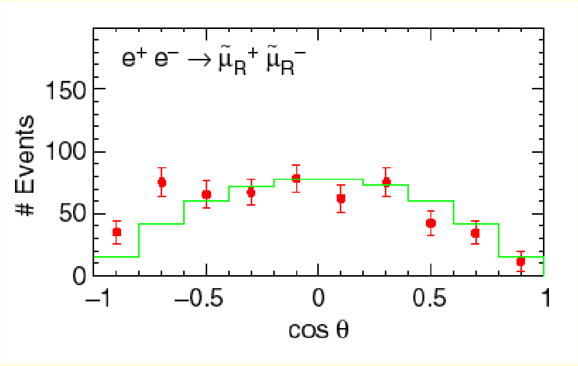
Imposing $a_1=1$ (S.M. coupling) get blue bar from LHC, red from ILC.

ILC resolves single resonance from LET point up to 2.5 TeV ($\sqrt{s}$ = 500), 4.1 TeV ($\sqrt{s}$ = 1000 GeV).

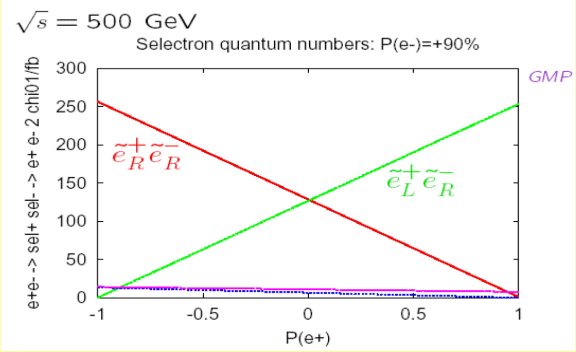
SUSY at ILC



precise masses of color-neutral states
(50 MeV to 1 GeV)

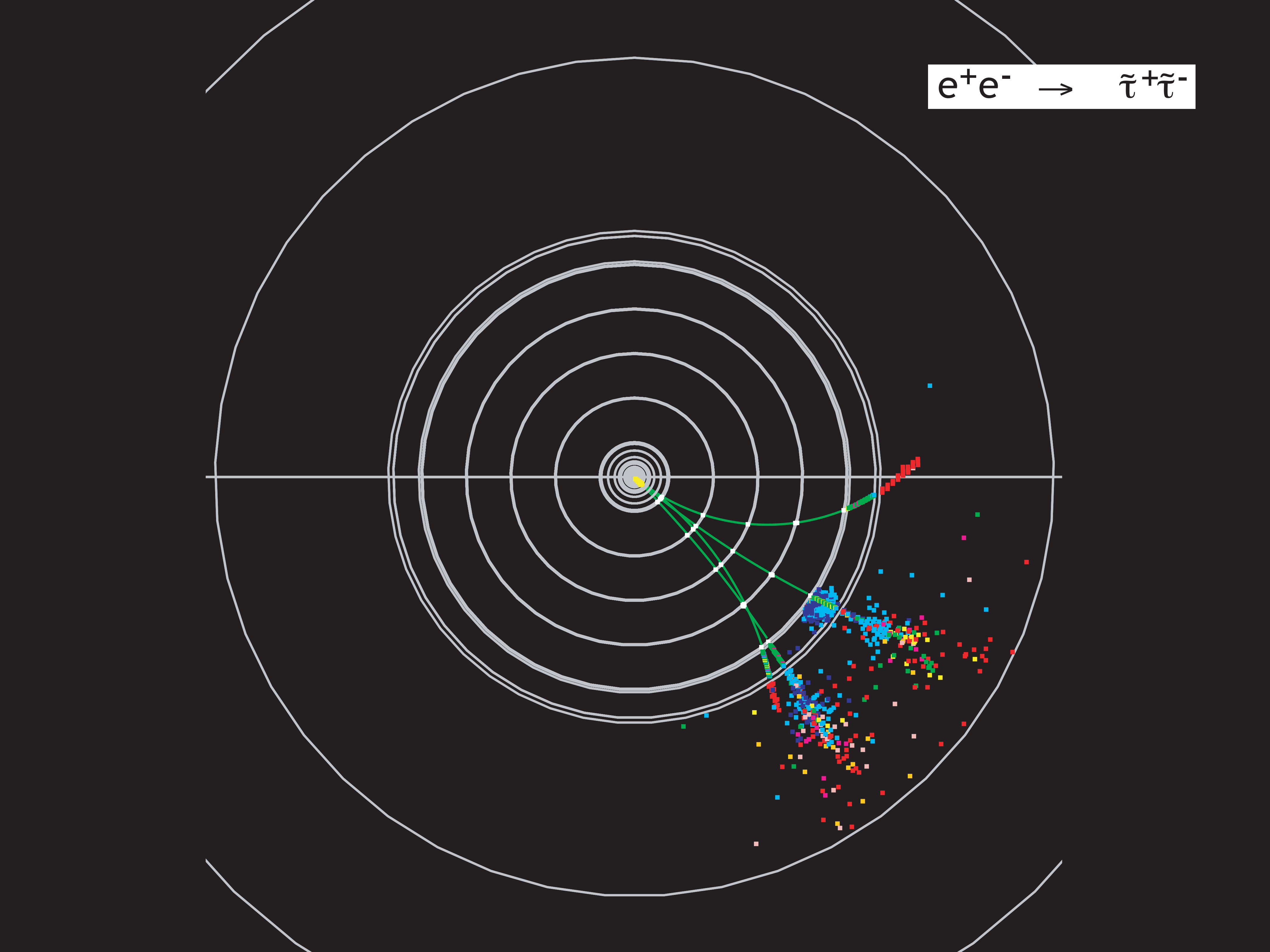


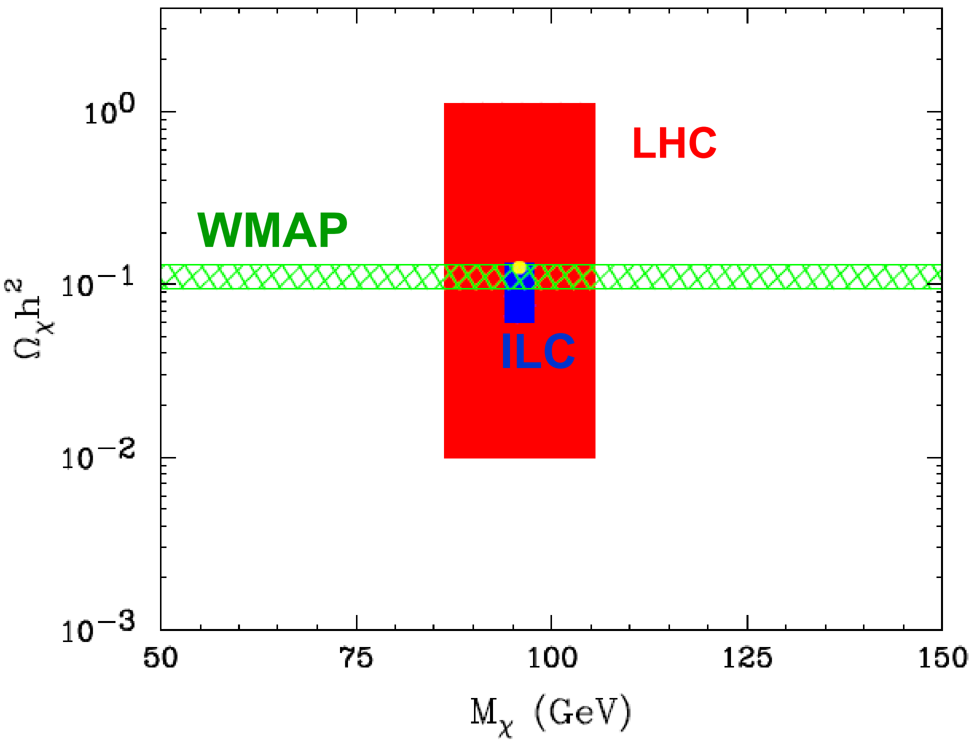
spin (angular distributions)



chiral quantum numbers (polarisation!)

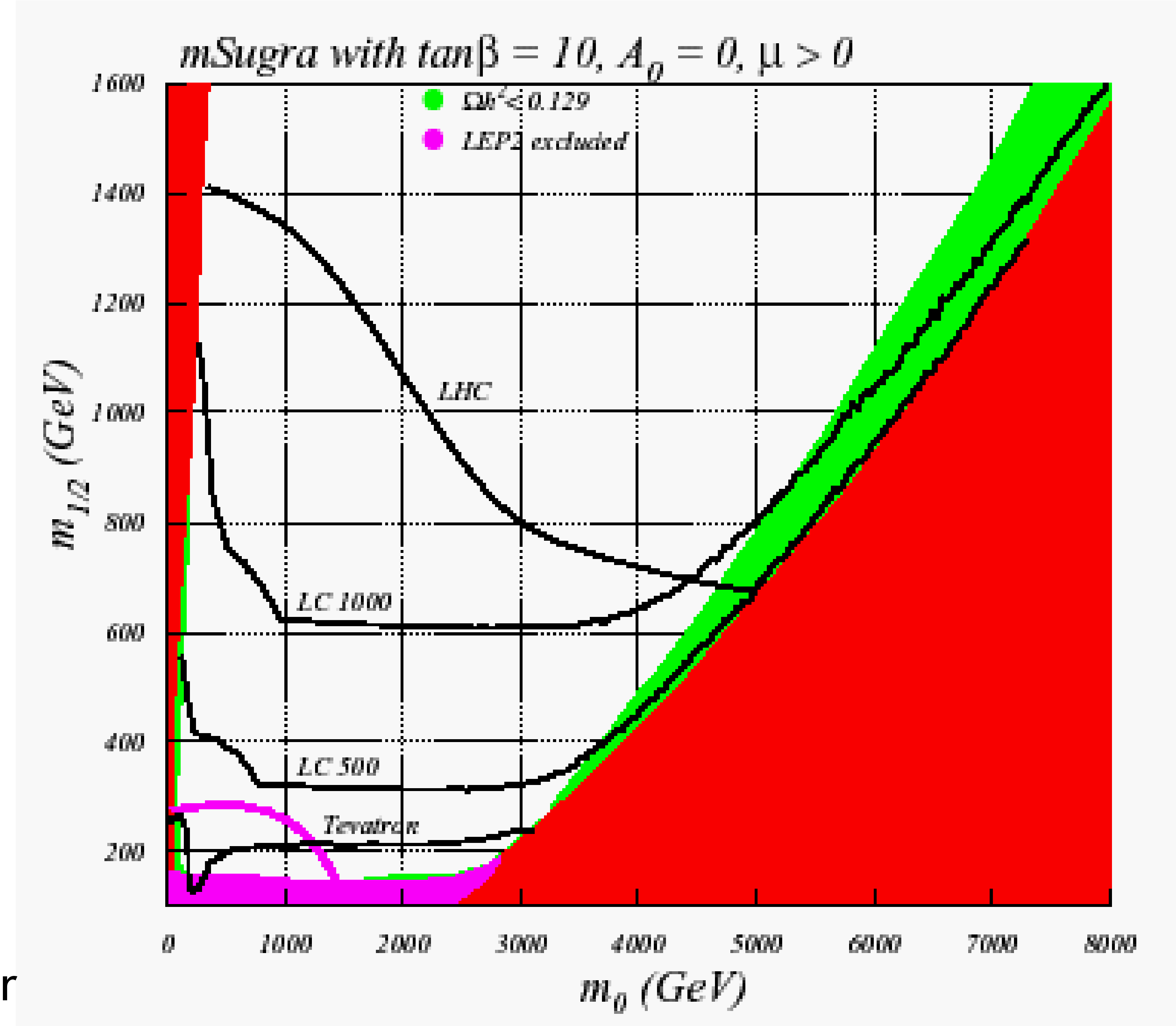
→ prove that it is SUSY
→ no model assumptions
→ learn about SUSY breaking


$e^+e^- \rightarrow \tilde{\tau}^+\tilde{\tau}^-$



Accuracies of determining the LSP mass and its relic density

[Alexander et al., hep-ph/0507214]

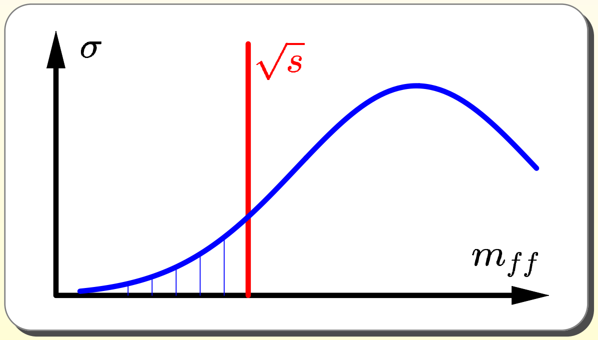

mSugra with tanβ = 10, A0 = 0, μ > 0
Ωh² < 0.129
LEP2 excluded
LHC
LC 1000
LC 500
Tevatron
m1/2 (GeV)
m0 (GeV)
1600
1400
1200
1000
800
600
400
200
0
1000
2000
3000
4000
5000
6000
7000
8000

Baer

Z' bosons at a future linear collider

Heavy Z' bosons $M_{Z'} > 1$ TeV:

- Small Z–Z' mixing
  $\rightarrow$ negligible effect on Z-pole data



- Propagator effects of Z' modify

$$e^+e^- \xrightarrow{\gamma, Z, Z'} f\bar{f}$$

$\rightarrow$ High luminosity 500–1000 fb^{-1} allows sensitivity for $M_{Z'} \gg \sqrt{s}$

- Sensitive observables:
  - total cross-section σ_{tot}
  - forward-backward asymmetry A_{FB}
- With e^- beam polarization
  - left-right asymmetry A_{LR}
  - polarization asymmetry A_{pol}

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{tot}}}$$

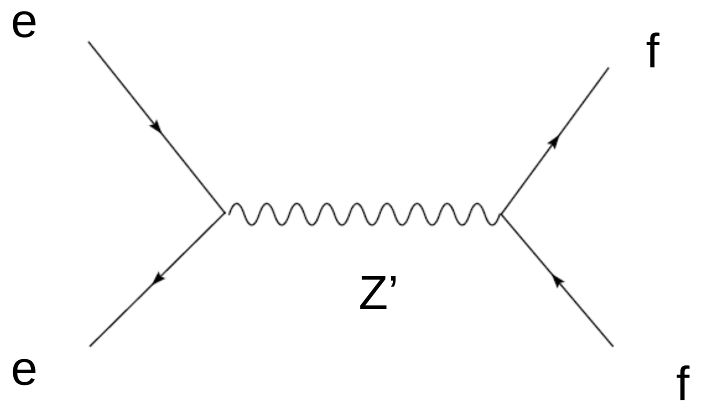
$$A_{\mathrm{LR}} = \frac{\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}}}{\sigma_{\mathrm{tot}}}$$

$$A_{\mathrm{pol}} = \frac{(\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}})_{\mathrm{F}} - (\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}})_{\mathrm{B}}}{\sigma_{\mathrm{tot}}}$$

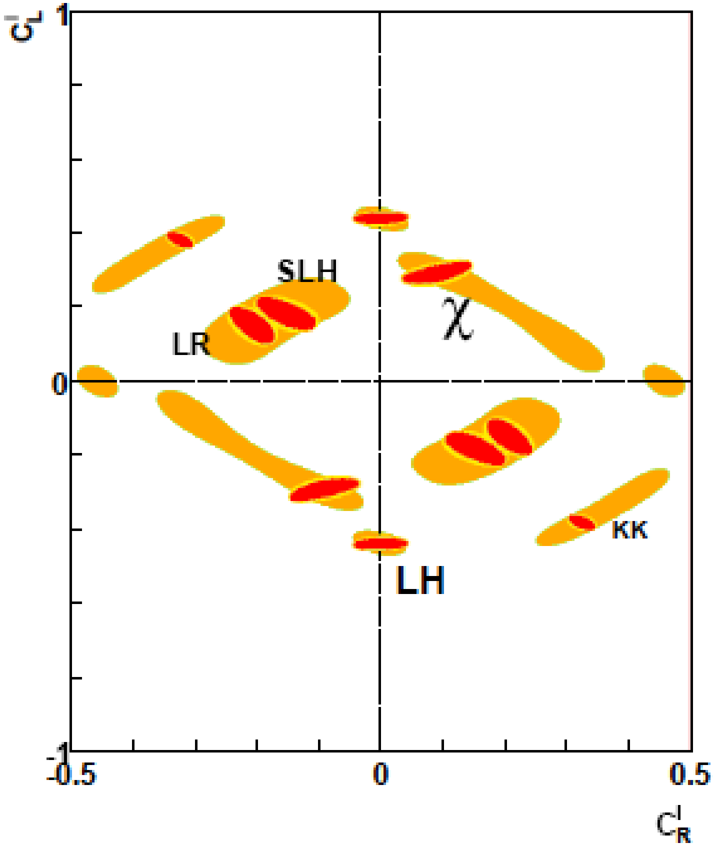
Z' and e^+e^-->ff processes

Even if ILC at 500 GeV cannot produce a new Z' particle kinematically,we can determine left-handed and right-handed couplings from ee-> ff processes.
This will give important information to identify the correct theory.

LHC=> mass
ILC => coupling



Z' coupling determination at ILC



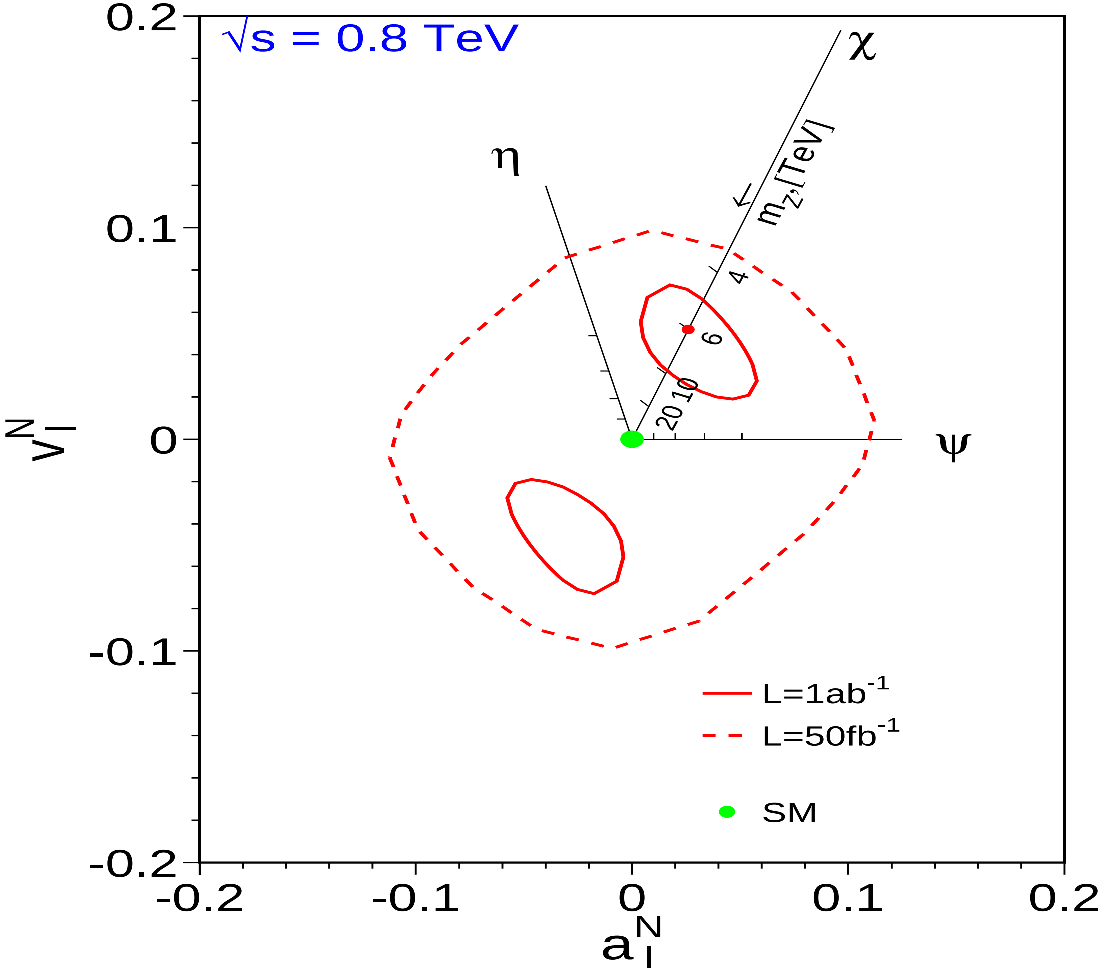
$m_{Z'}$ =2TeV,Ecm=500 GeV, L=1ab^{-1}
with and w/o beam polarization

S.Godfrey, P.Kalyniak, A.Tomkins

No Z′ at LHC ⇒ situation is NOT hopeless!

$m_{Z'} > 5$ TeV

$$a_f^N = a'_f \sqrt{\frac{s}{m_{Z'}^2 - s}}; \qquad v_f^N = v'_f \sqrt{\frac{s}{m_{Z'}^2 - s}}.$$



Reconstruction of a 6 TeV Z′(χ model) (95% C.L.):

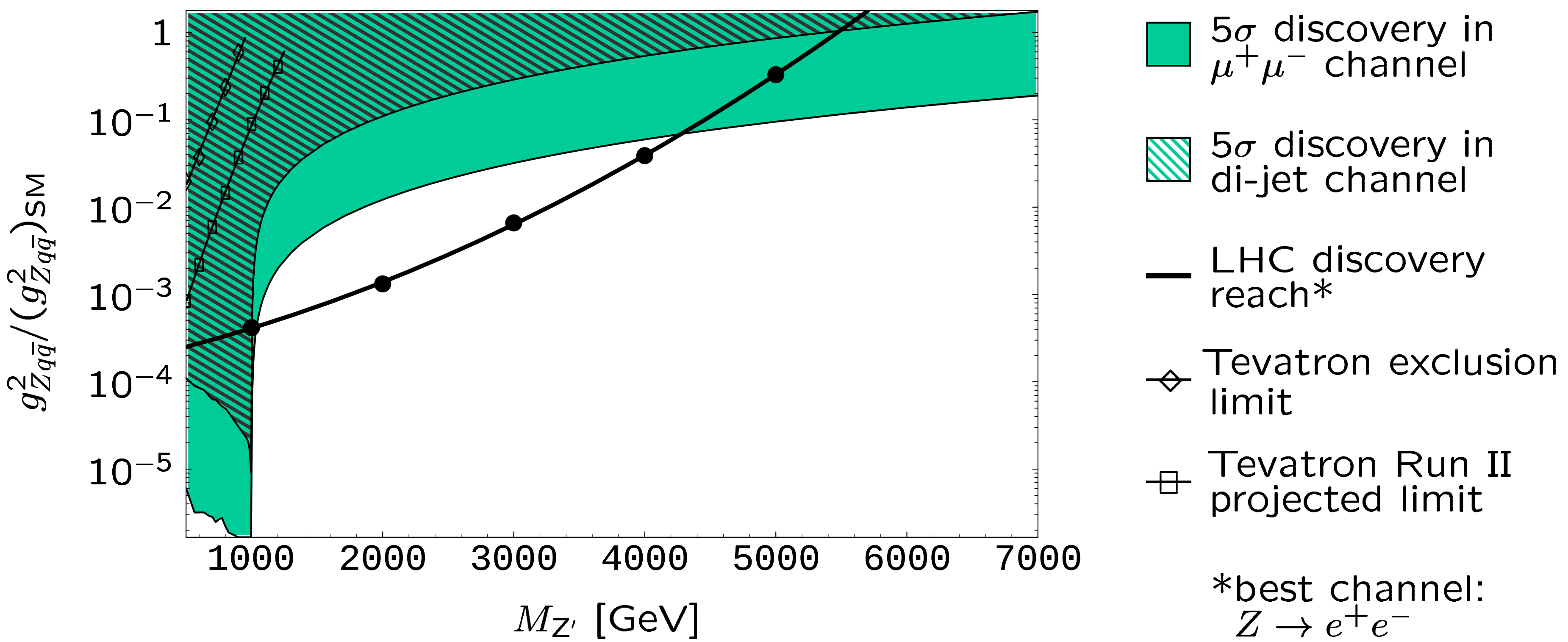
- $\mathcal{L}_{int} = 1ab^{-1}, \quad \Delta\mathcal{L}_{int} = 0.2\%$
- $P_- = 0.8, \quad P_+ = 0.6, \quad \Delta P_- = \Delta P_+ = 0.5\%$
- Δ sys(lept)=0.2%

Special case: $Z_{\mathrm{B-L}}$

Z' has pure $B - L$ couplings $\rightarrow$ corresponding to $z_u = z_q$

$\Rightarrow$ No mixing between Z and Z' (i.e. no constraints from Z-pole)

$\sqrt{s} = 1000$ GeV, $\int \mathcal{L} = 1000$ fb^{-1}



Projected sensitivity

- Look for deviations from SM background

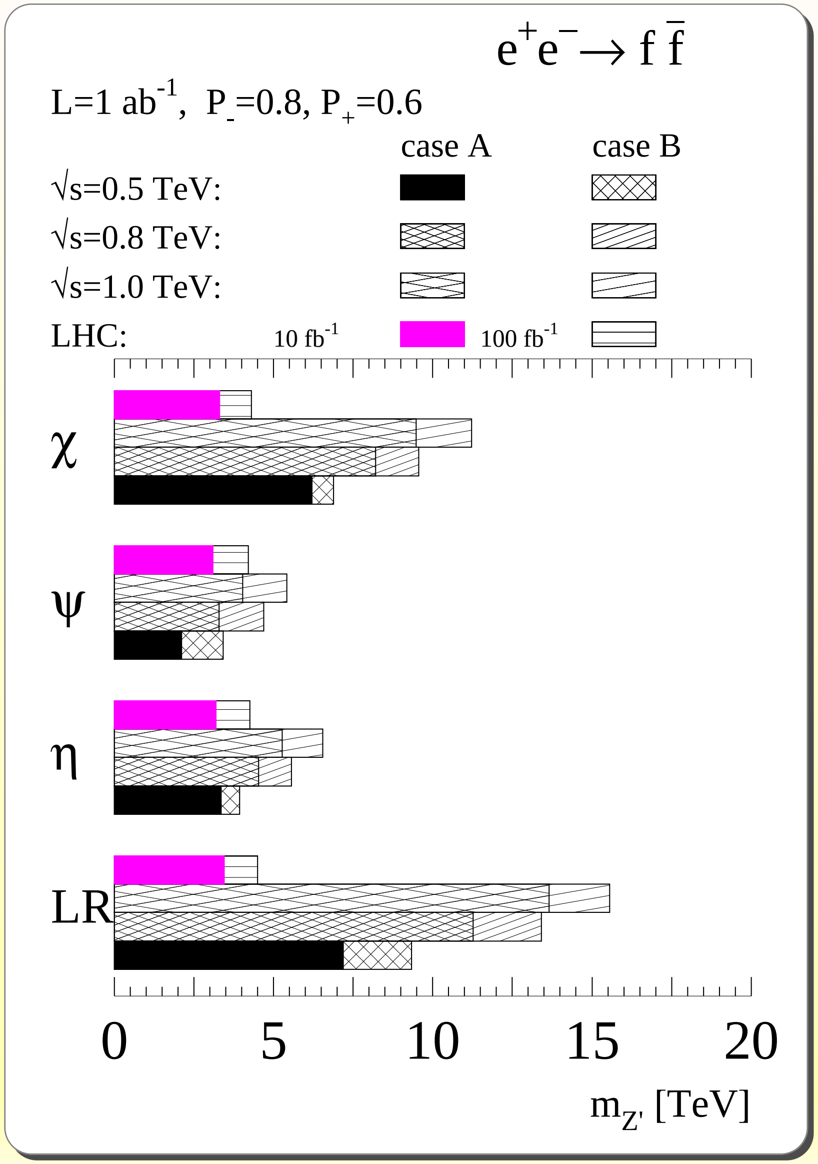
$$e^+e^- \xrightarrow{\gamma^*,Z^*} f\bar{f}$$

- Assume $P(e^-) = 80\%$
  $P(e^+) = 60\%$
  (slight improvement from e^+ pol.)

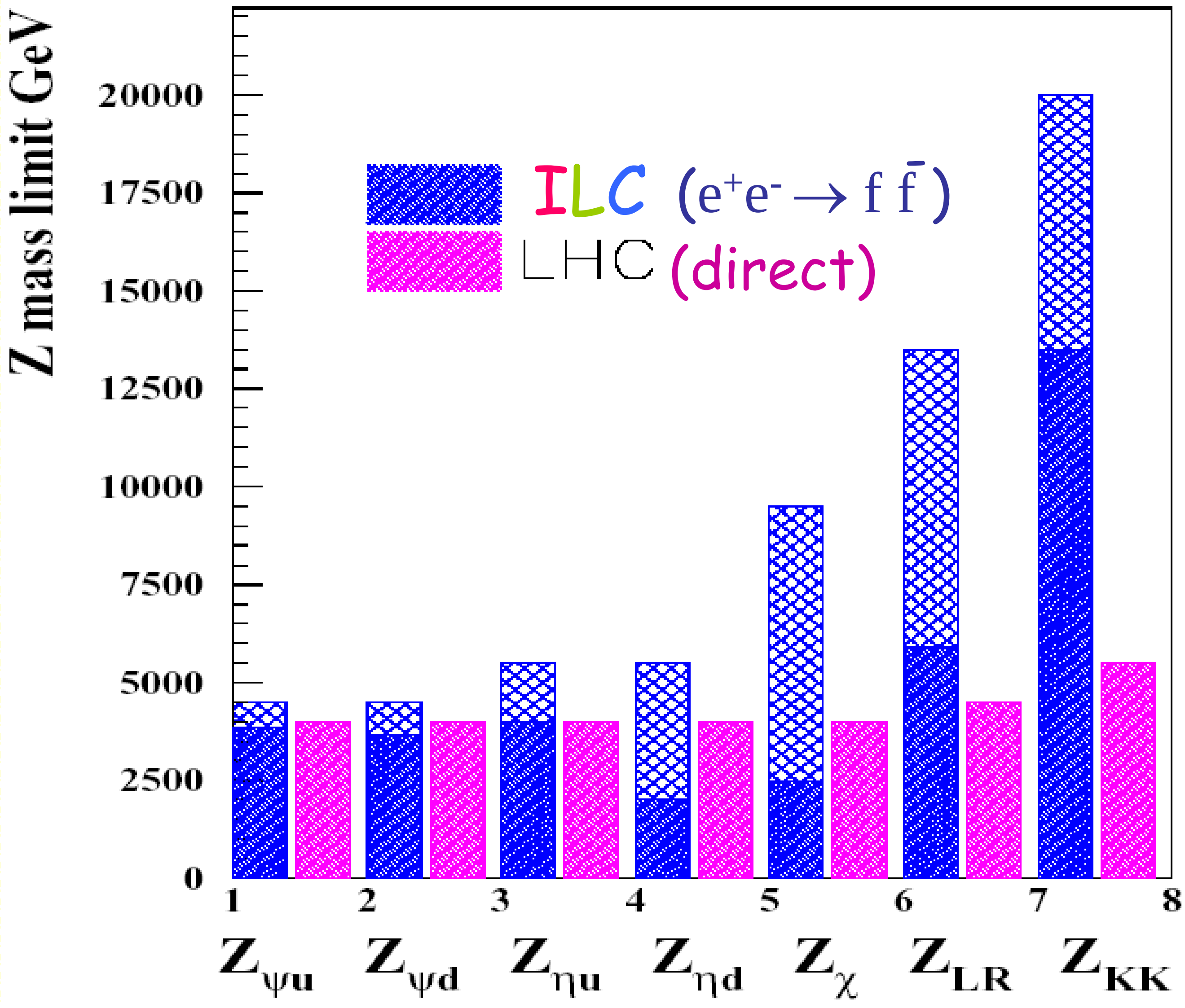
- Combine all observables
  σ_{tot}, A_{FB}, A_{LR}, A_{pol}

case A,B : different assumptions about sys. errors

S. Riemann '00



Sensitivity to heavy Z' in different models



ILC includes GigaZ (Z-Z' mixing) and 1 TeV LC (interference) [Richard, hep-ph/0303107]

Contact Interactions

- New interactions can be parametrized in terms of 4-fermion interactions if √s << Λ

$$L = \sum_{i,j=L,R} \eta_{ij} \frac{g^2}{\Lambda_{ij}^2} \left(\bar{f}_i \gamma^\mu f_i\right)\left(\bar{F}_i \gamma^\mu F_i\right) \qquad \Lambda \sim M_{Z'}$$

Reach in Tev: LHC LC

Model		LL	RR	LR	RL	LL	RR	LR	RL
eeqq	Λ_+	20.1	20.2	22.1	21.8	64	24	92	22
	Λ_-	33.8	33.7	29.2	29.7	63	35	92	24
eeμμ	Λ_+					90	88	72	72
	Λ_-					90	88	72	72
eeee	Λ_+					45	43	52	52
	Λ_-					44	42	51	51

If contact interaction is exchange of spin-1 Z', then angular distribution $(1 \pm \cos\theta)^2$

95% cl limits.

LHC: 100 fb^{-1}

LC: L=1 ab^{-1}, √s=500 GeV, P_-=.8, P_+=.6

Riemann, LHC/LC Study

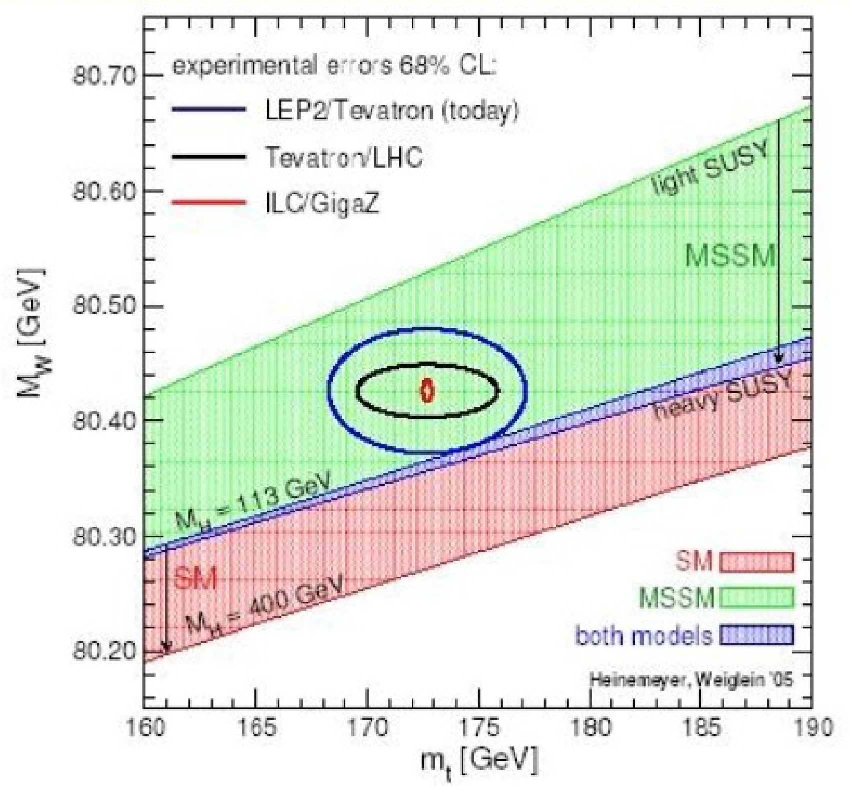
Motivation: Why is the top quark so interesting?

- Top quark sector of the SM is NOT established yet!
  - Possible anomalous couplings in $tbW, t\bar{t}Z/\gamma$
  - Does the top mass come from a single Higgs? $(y_t \Leftrightarrow m_t)$
- Top quark plays a key role in EWSB
  - Many models distinguish top from light quarks
  - Precise top mass determination is clue to New Physics

MSSM parameters varied

SM Higgs varied

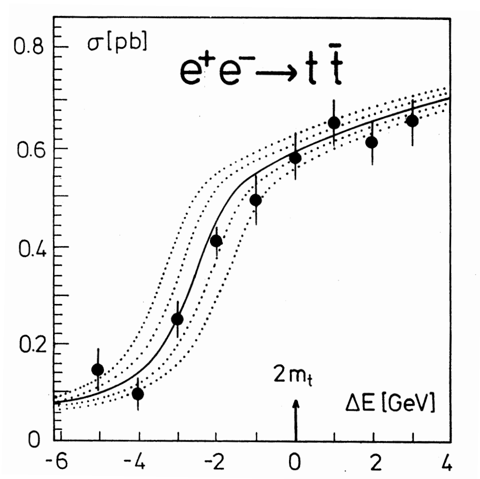
(Heinemeyer+Weiglein Snowmass)



High Precision Top Mass

Threshold Scan: $\sqrt{s} \simeq 350$ GeV (Phase I)

- ▷ count number of $t\bar{t}$ events
- ▷ color singlet state
- ▷ background is non-resonant
- ▷ physics quite well understood (renormalons, summations)



+ top momentum distribution

+ asymmetries

$\rightarrow \delta m_t^{\rm exp} \simeq 50$ MeV

$\rightarrow \delta m_t^{\rm th} \simeq 100$ MeV

(param. est. $\rightarrow$ many authors)

What mass?

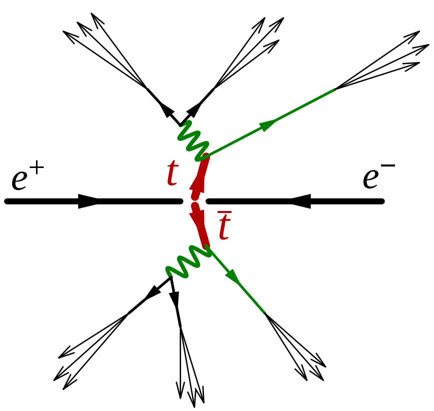
$\sqrt{s}_{\rm rise} \sim 2m_t^{\rm thr} +$ pert.series

(short distance mass: 1S $\leftrightarrow$ $\overline{\rm MS}$)

Reconstruction: any $\sqrt{s}$ (Phase I + II)

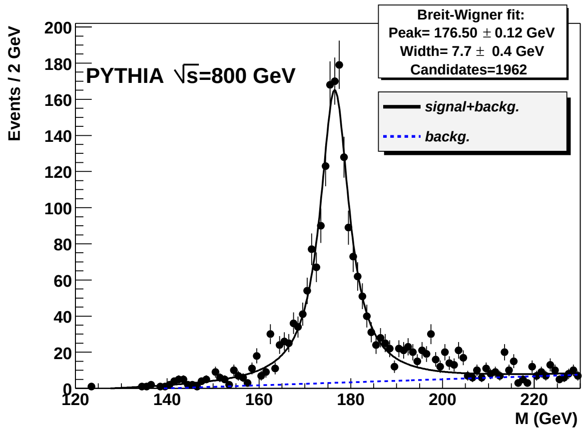
Chekanov,Morgunov:

- ▷ $e^+e^- \rightarrow 6$ jets ($y^6_{\rm cut}$)
- ▷ b-tagging
- ▷ $\vec{P}_1 + \vec{P}_2 < \Delta_p$
- ▷ $M_1 + M_2 < \Delta_M$



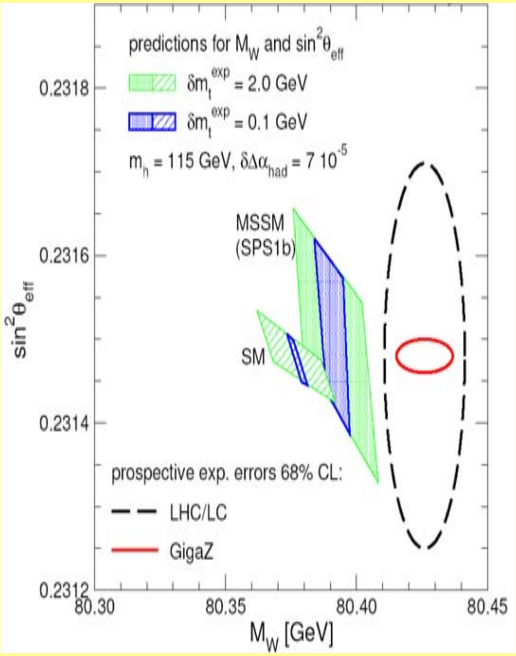
$\rightarrow \delta m_t^{\rm ex,stat} \simeq 100$ MeV

$(\mathcal{L} = 300\,{\rm fb}^{-1})$

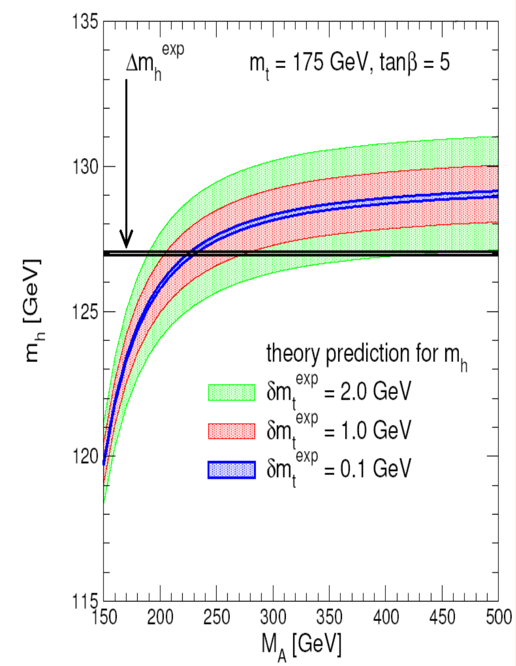


Where the top mass comes into play

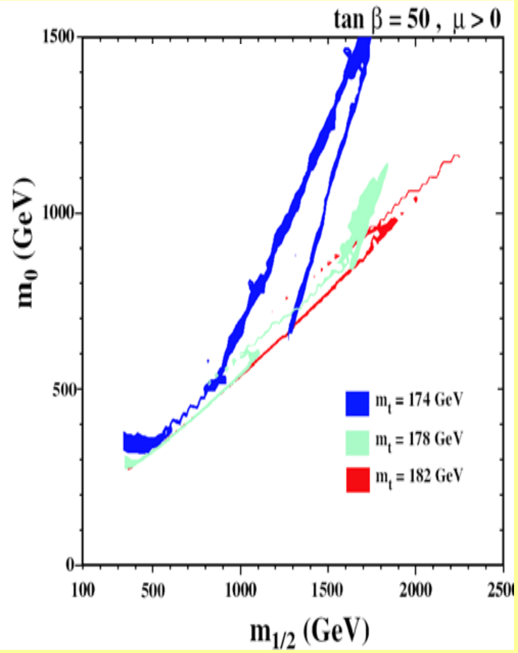
predictions of EW parameters:



Light Higgs mass prediction in SUSY:



Prediction of DM density

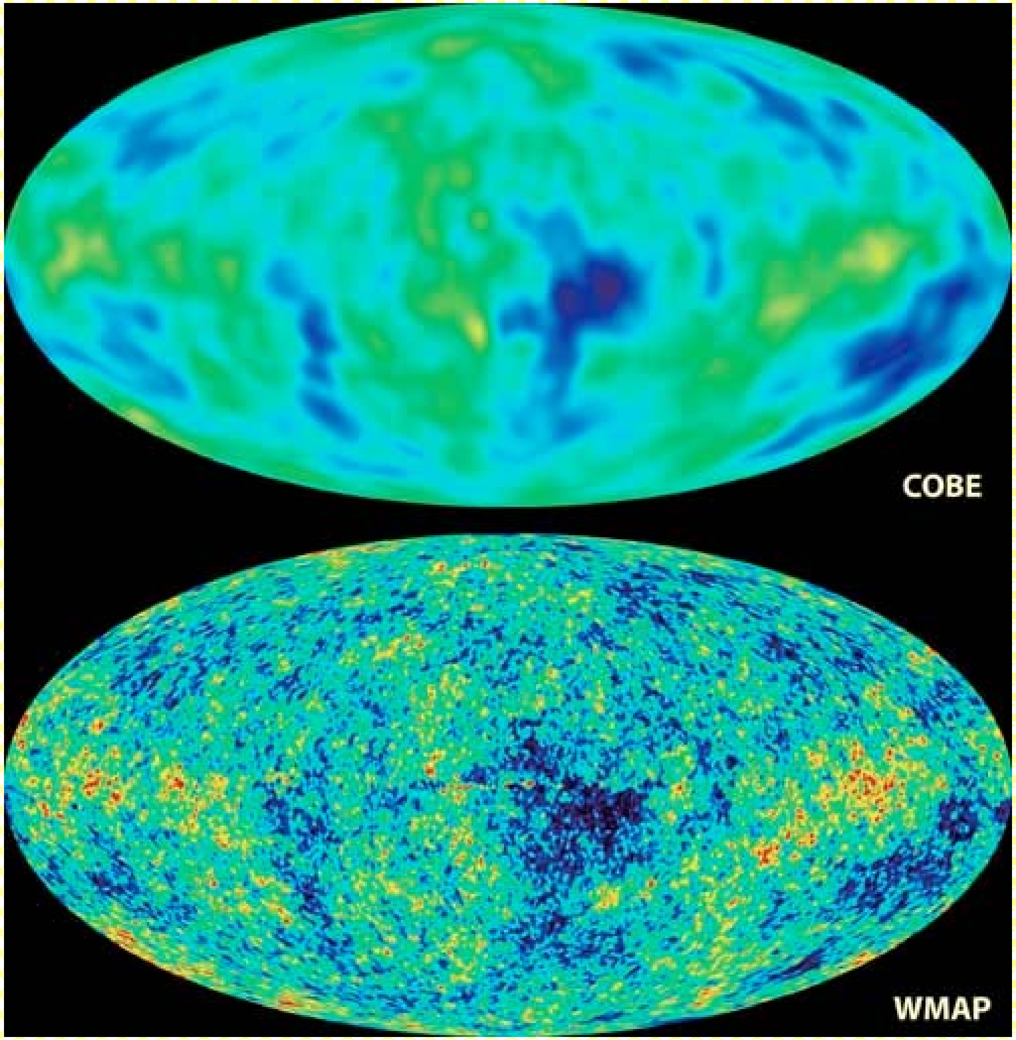


$\Delta m_H/\Delta m_t \sim 1!$

Higher precision *can give discoveries.*

Then

Now



Cosmic Microwave Background

WMAP constrains $\Omega_\Lambda + \Omega_M$

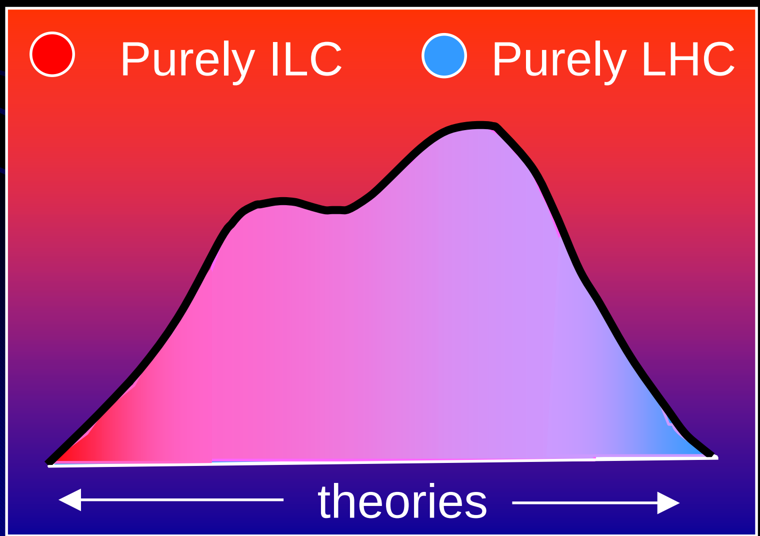
Wouldn't know it's there from COBE

AND Planck is coming; more precise still

WITH Polarisation

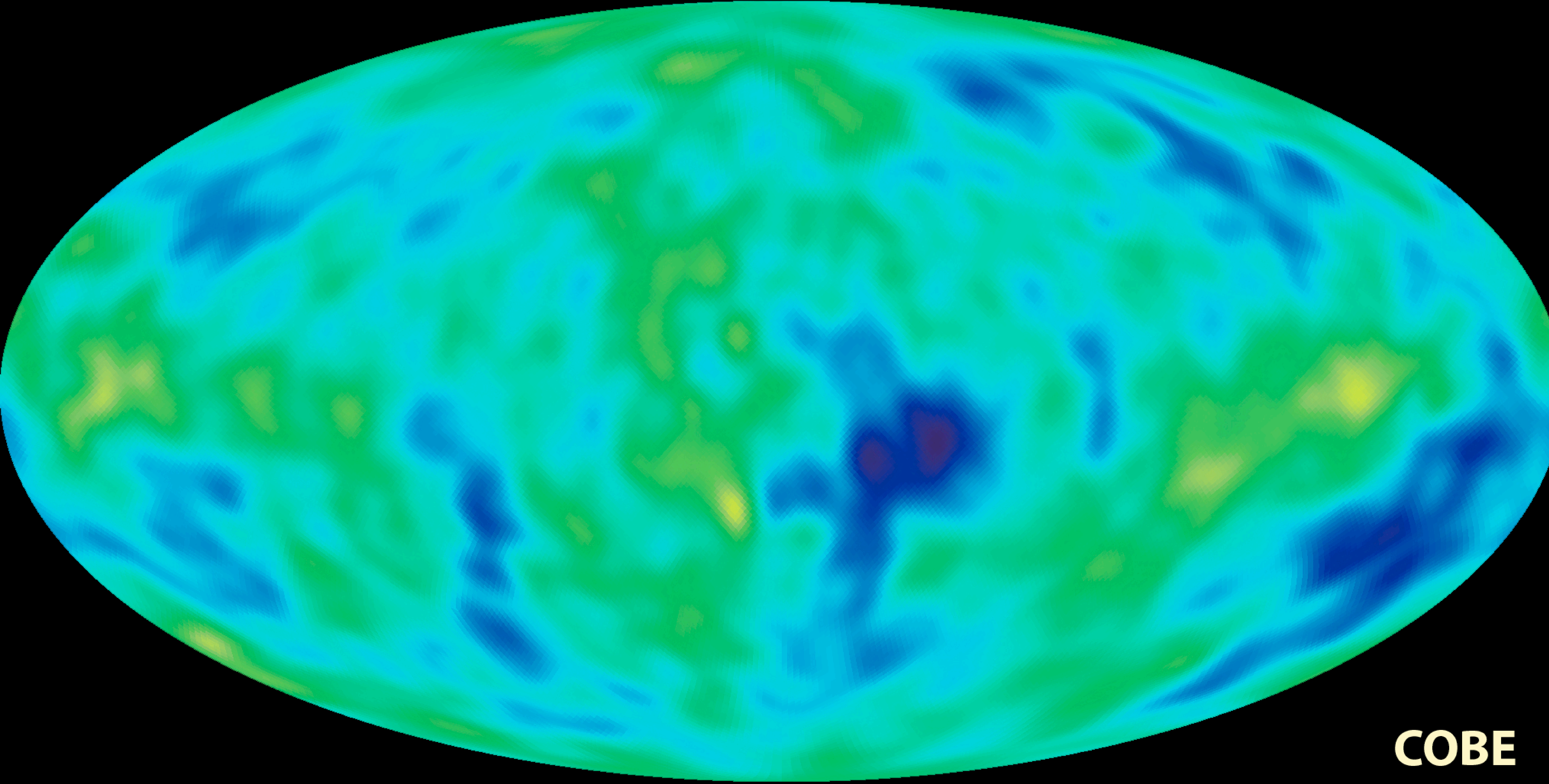
The Energy Frontier: why ILC?

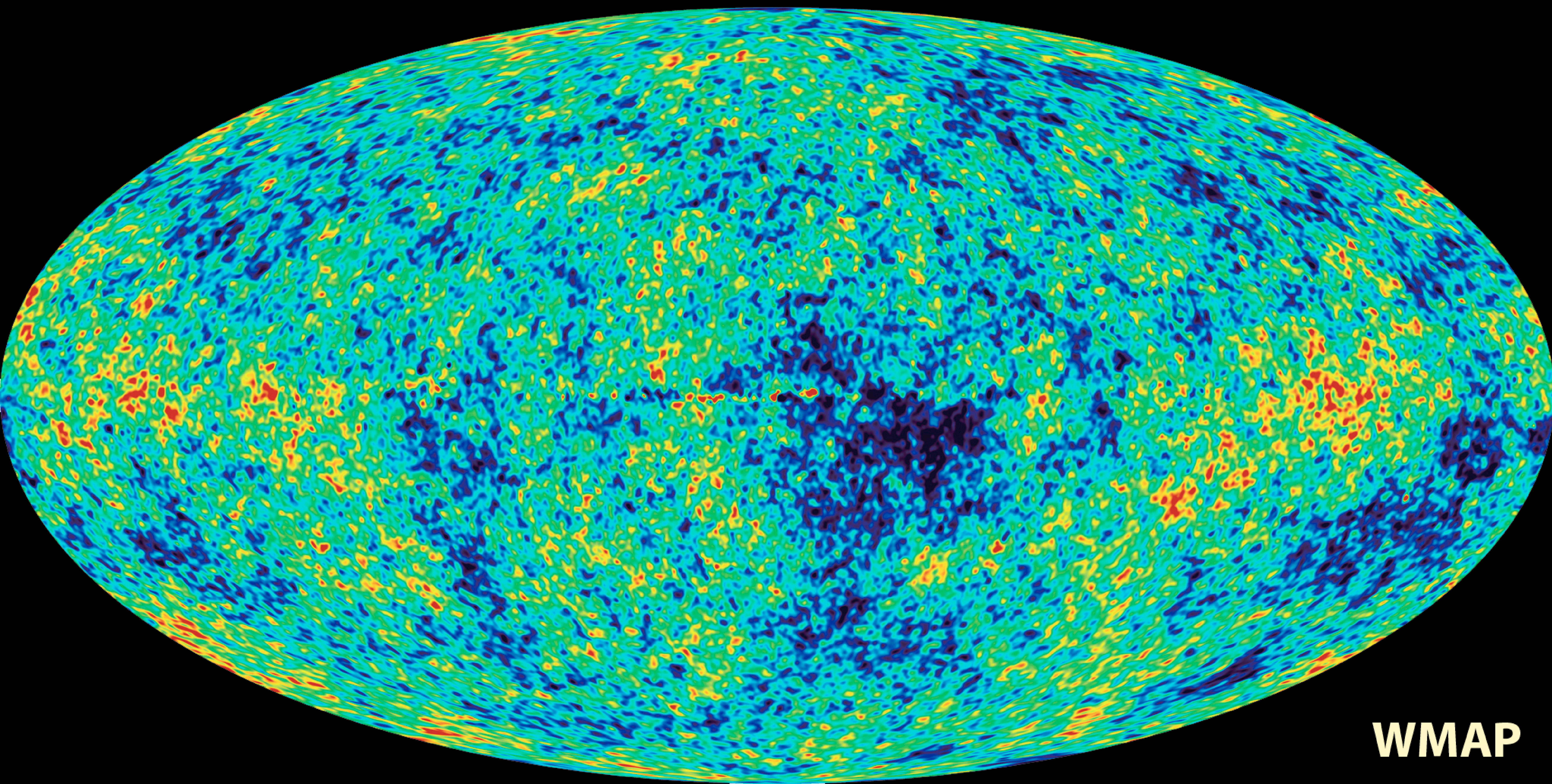
- We expect the greatest richness at the energy frontier
- Few phenomena will manifest themselves in only one machine



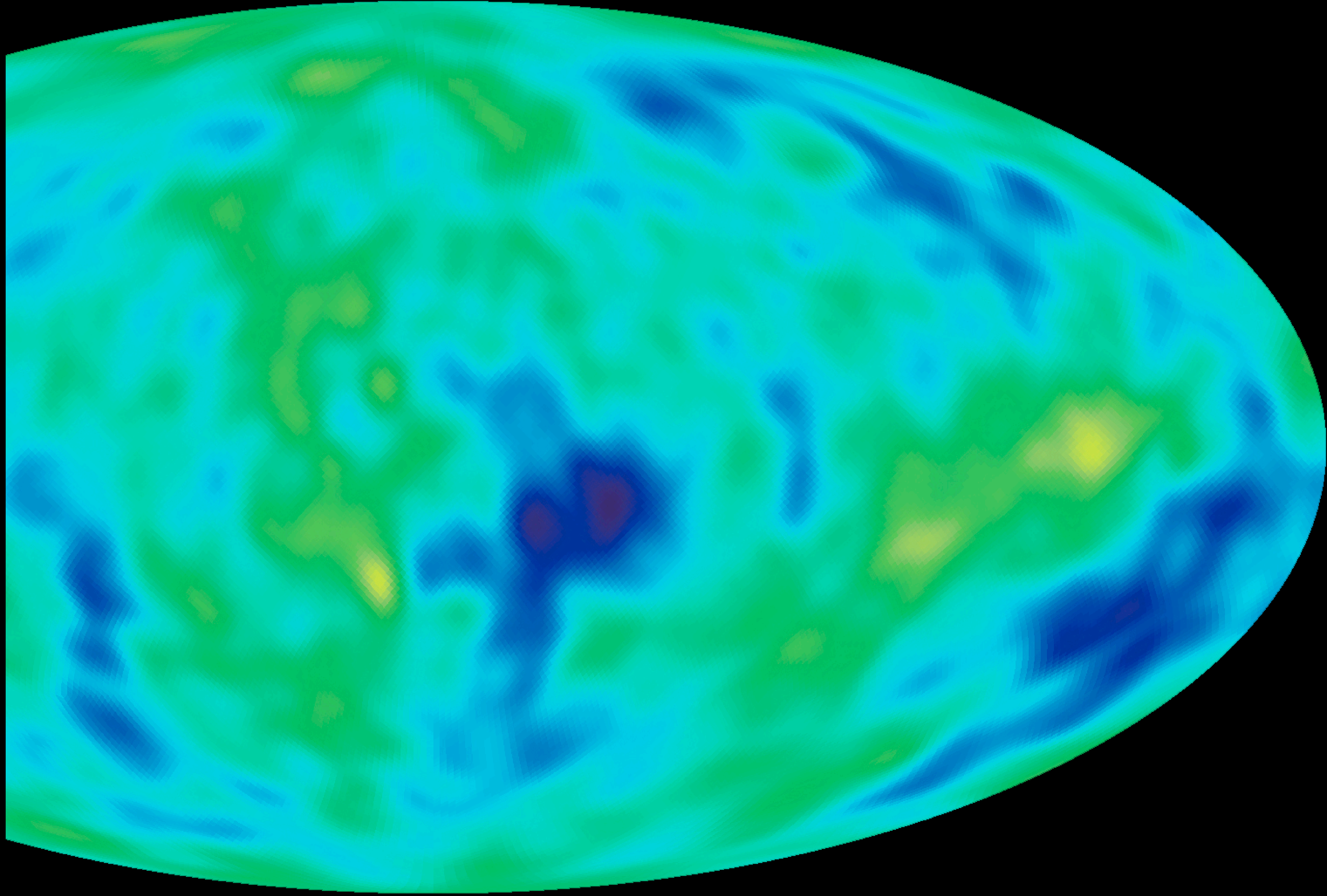
- We will build on the foundation of LHC to make major discoveries at ILC

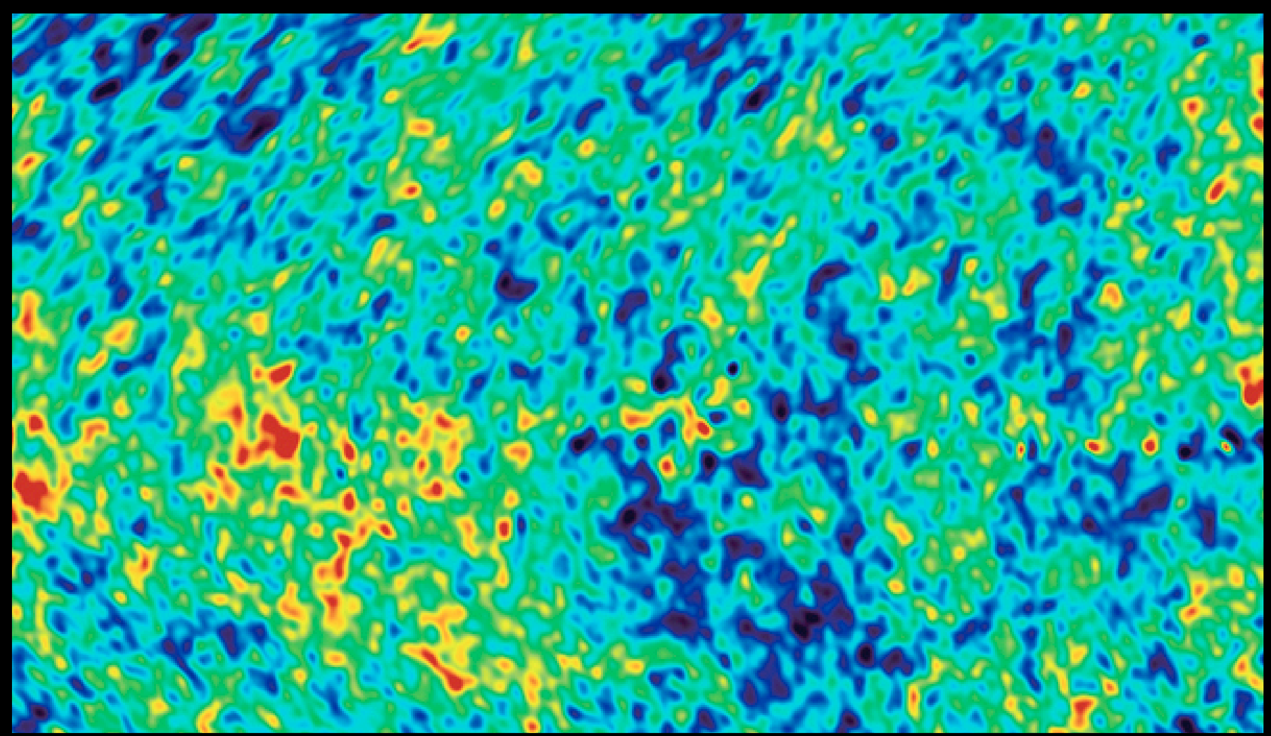
2020. Both pillars needed to see to the Temple of Unification


COBE


WMAP

LHC





ILC