Report on the Workshop: "From the LHC To Future Colliders"

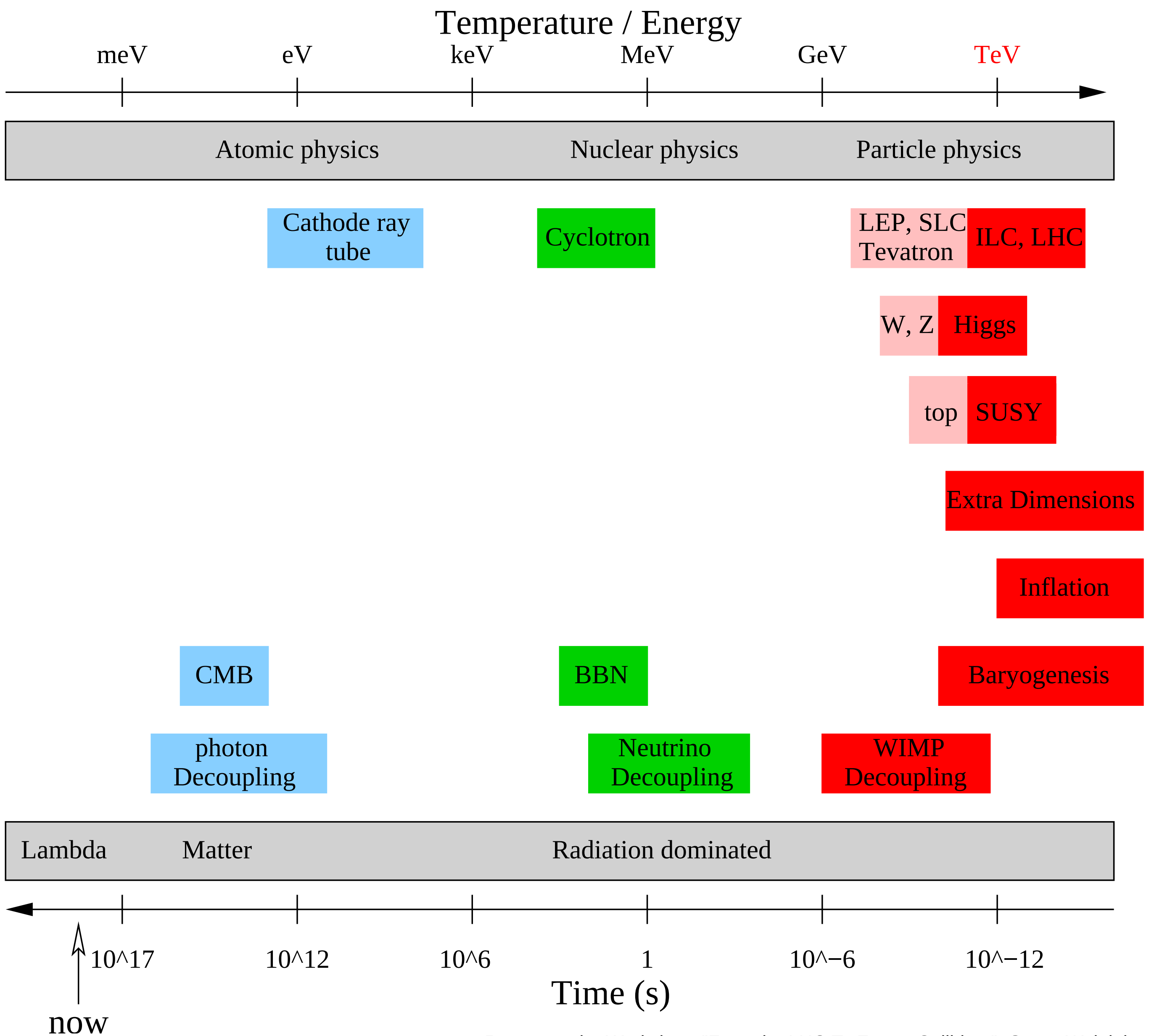
Georg Weiglein

IPPP Durham

Tsukuba, 04/2009

Introduction: on the way to the TeV scale

$$1\ \text{TeV} \approx 1000 \times m_{\text{proton}} \Leftrightarrow 2 \times 10^{-19}\ \text{m}$$



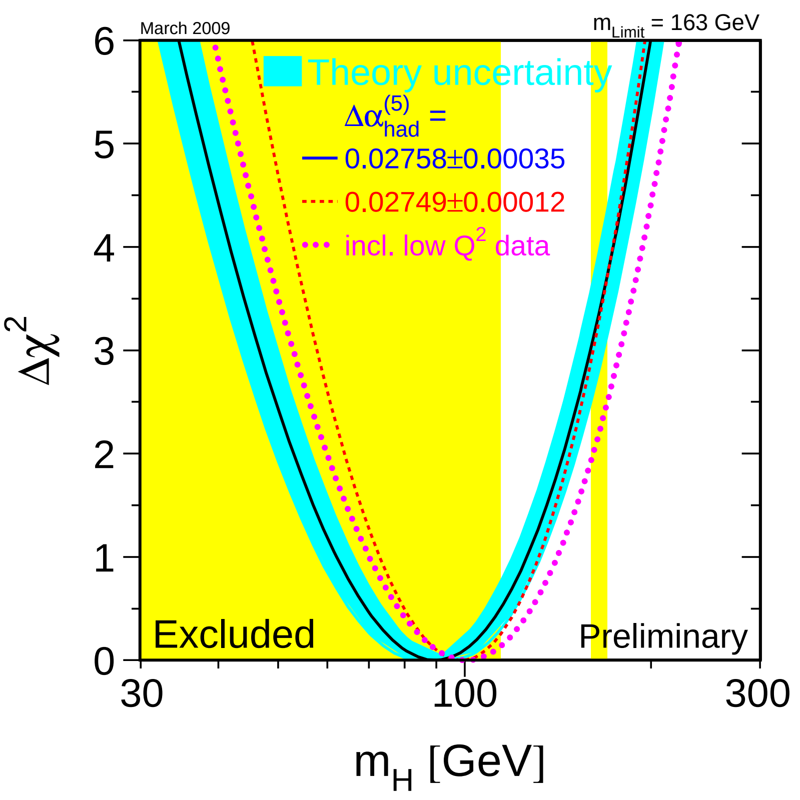
What can we learn from exploring the new territory of TeV-scale physics?

- How do elementary particles obtain the property of mass: what is the mechanism of electroweak symmetry breaking?
- Do all the forces of nature arise from a single fundamental interaction?
- Are there more than three dimensions of space?
- Are space and time embedded into a “superspace”?
- Can dark matter be produced in the laboratory?
- . . .

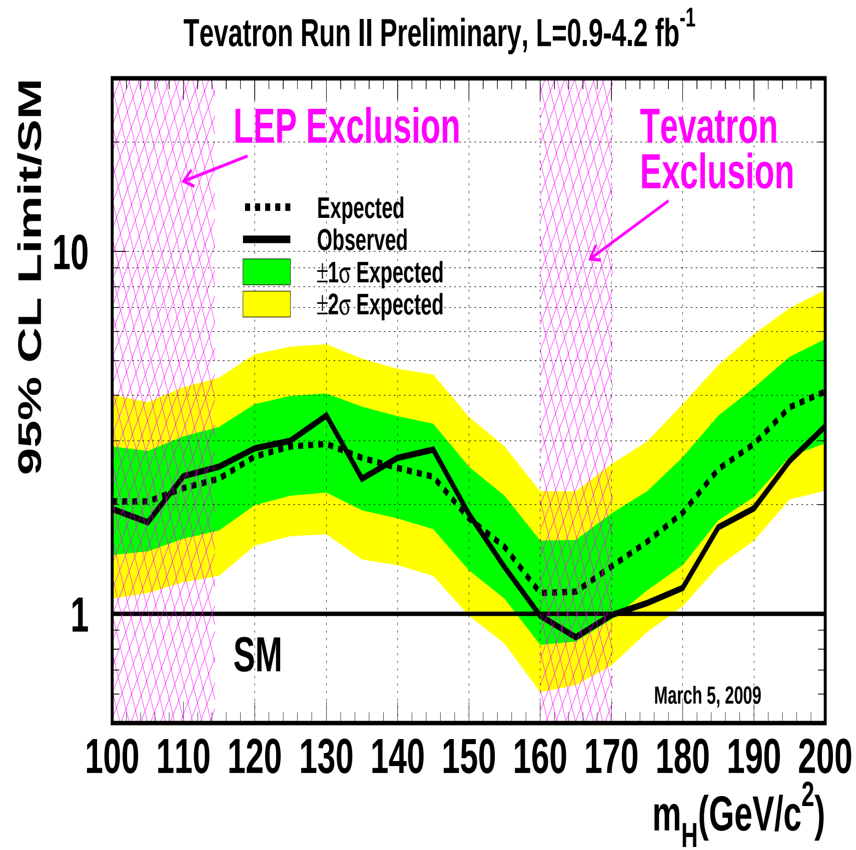
Hints from electroweak precision data?

SM Higgs: ew. prec. data + direct search at LEP & Tevatron

[*LEPEWWG '09*]



[*TEVNPH Working Group '09*]



⇒ Preference for a light Higgs

Global CMSSM fit using indirect experimental and cosmological constraints

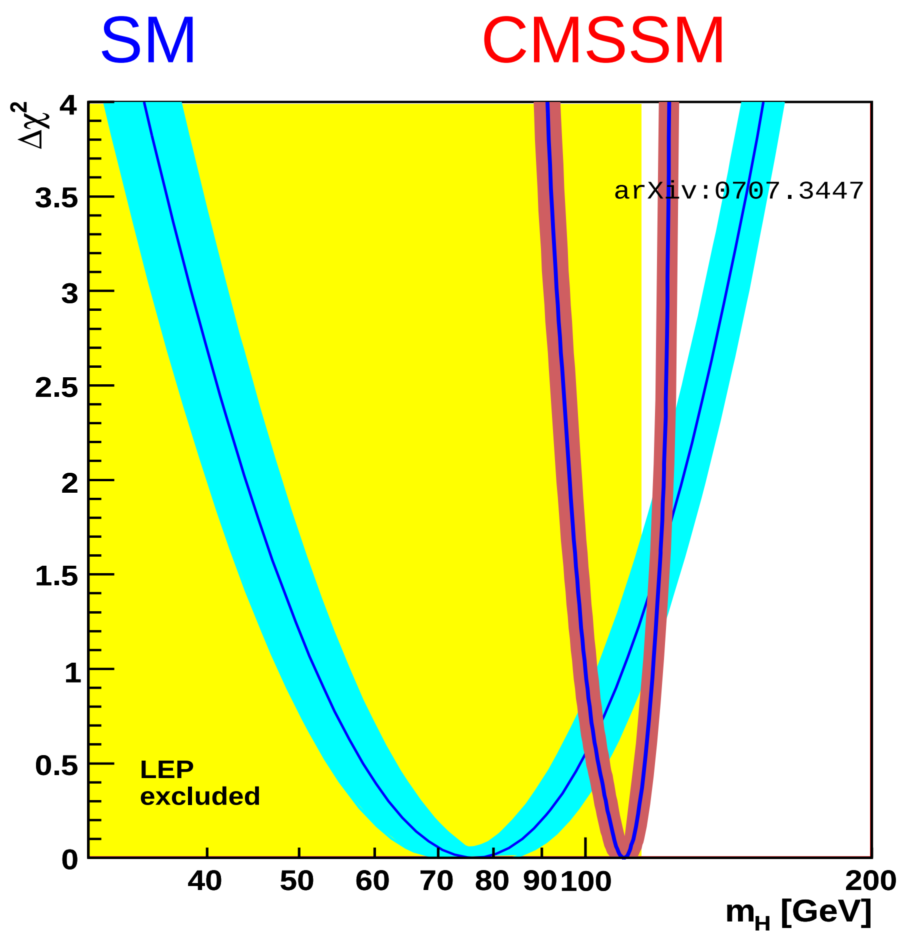
Global χ^2 fit in the Constrained MSSM (CMSSM):
$m_{1/2}$, m_0, A_0 (GUT scale), $\tan\beta$, $\mathrm{sign}(\mu)$ (weak scale)

Fit includes (*MasterCode*, Markov-chain Monte Carlo sampling):
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '08*]

- All observables used in the SM fit of the LEPEWWG
- $+$ Cold dark matter (CDM) density (WMAP, . . .),
  $\Omega_{\mathrm{CDM}}\, h^2 = 0.1099 \pm 0.0062$
- $+ \; (g-2)_\mu$
- $+$ BPO: $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$, $\mathrm{BR}(B \to \tau\nu)$, . . .
- $+$ Kaon decay data: $\mathrm{BR}(K \to \mu\nu)$, . . .

Indirect limits on the light Higgs mass in the CMSSM EWPO + BPO + dark matter constraints

χ^2 fit for M_h, without imposing direct search limit [*O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07*]

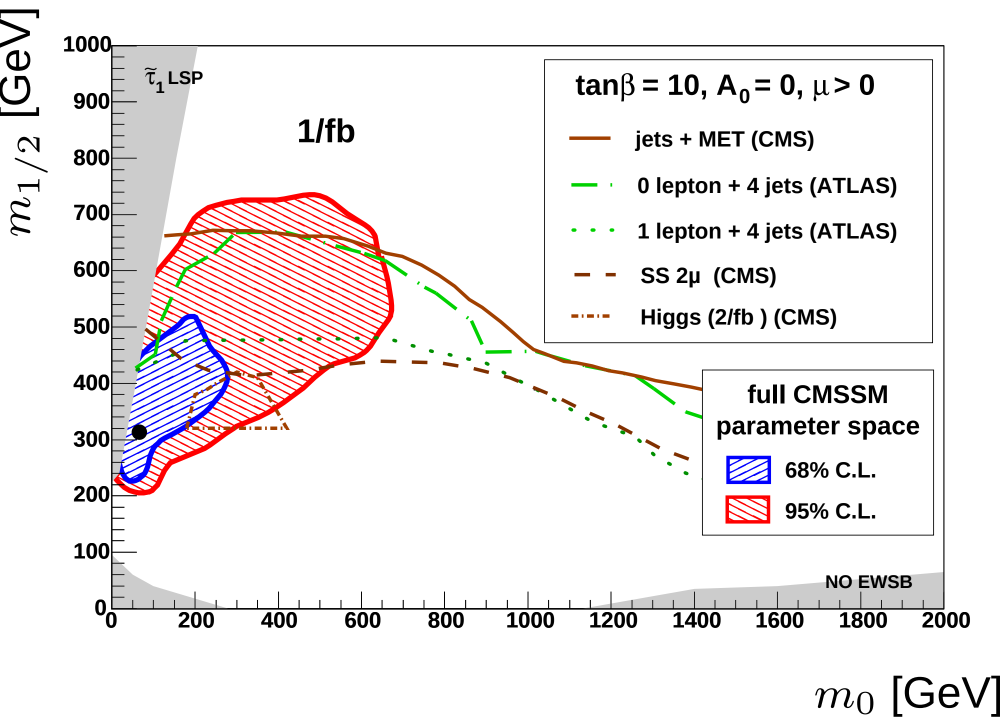


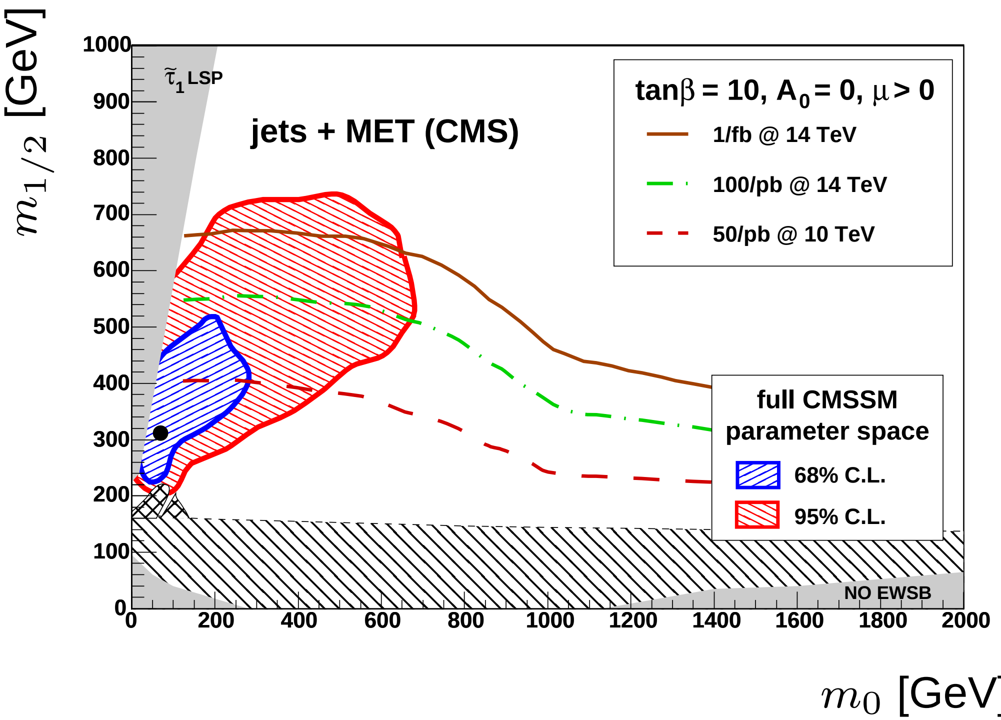
⇒ Accurate indirect prediction; Higgs "just around the corner"?

Comparison: preferred region in m_0–$m_{1/2}$ plane vs. LHC discovery reach

68% and 95% C.L. contours from the fit vs. LHC discovery reach for $1, 0.1, 0.05\ \mathrm{fb}^{-1}$ of understood data

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. ’08*]





$\Rightarrow$ Preferred region would lead to early discovery

Early LHC data: shaping the future of particle physics

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LC status so far: there is a strong physics case for a 500 GeV LC as the next step beyond the LHC, even before we know what the LHC will tell us (consensus documents, . . .)

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Early LHC data $\Rightarrow$ shape the future of particle physics

$\Rightarrow$ We will need to reassess our future options in the light of results of the LHC

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Early LHC data ⇒ shape the future of particle physics

⇒ We will need to reassess our future options in the light of results of the LHC and the Tevatron

Early LHC results: a possible window of opportunity

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$\Rightarrow$ It is useful to discuss possible ways ahead already before the first LHC data become available

What will we know after the first $\approx$10 fb^{-1} of data at the LHC?

"Early LHC data:" $\approx 10\,\mathrm{fb}^{-1}$

What will we know after the first ≈10 fb^{-1} of data at the LHC?

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But it is expected that there will still be significant room for interpretation concerning the nature of new physics

Possible scenarios of early LHC results

- Detection of a state in the first 10 fb^{-1} of LHC data with properties that are compatible with those of a Higgs boson (either SM-type or non SM-type) $+$ anything else

- No observation in the first 10 fb^{-1} of LHC data of a state with properties compatible with a Higgs boson ($+$ anything else)

- Detection of new states of physics beyond the Standard Model:
  - leptonic resonances
  - multi-gauge-boson signals
  - missing energy ($+$nothing, leptons, jets)
  - all other signatures of new states of BSM physics

First Workshop: 'The LHC early phase for the ILC', April 12–14, 2007, Fermilab

Focus was on implications for the ILC; workshop charge:

- What could be the impact of early LHC results on the choice of the ultimate ILC energy range and the ILC upgrade path?

  Could there be issues that would need to be implemented into the ILC machine and detectors design from the start?

- Could there be cases that would change the consensus about the physics case for an ILC with an energy of about 500 GeV?

- What are the prospects for LHC / ILC interplay based on early LHC data?

CERN Theory Institute: "From the LHC to Future Colliders", February 9–27, 2009, at CERN

Organisers: *Albert De Roeck, John Ellis, Christophe Grojean, Sven Heinemeyer, Karl Jakobs, G. W., James Wells*

Goals:

- Past: Discuss recent physics developments
- Present: Anticipate near-term capabilities of Tevatron, LHC and other experiments
- Future: Have discussions on the most effective ways to be prepared for giving science input to plans of the post-LHC era

Considered future options for accelerator-based facilities at the TeV scale beyond the first phase of the LHC:
SLHC, ILC, CLIC, LHeC, Muon Collider, . . .

LHC luminosity upgrade: the SLHC

SuperLHC (SLHC): upgrade of LHC design luminosity by a factor of 10 to about $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

- Moderate extension of LHC mass reach
- More precise measurements of processes that are statistically limited
- Extended reach for rare processes

Difficult experimental environment: higher radiation levels in the detectors, increased pile-up background

Upgrades of ATLAS and CMS required

DLHC: *energy doubling of the LHC*

Double beam energy to 14 TeV?

DLHC needs new magnets $\Rightarrow$ new machine

Significant increase of LHC search reach, but very good physics justification from future data needed

LHeC: electron–proton collisions in the LHC tunnel

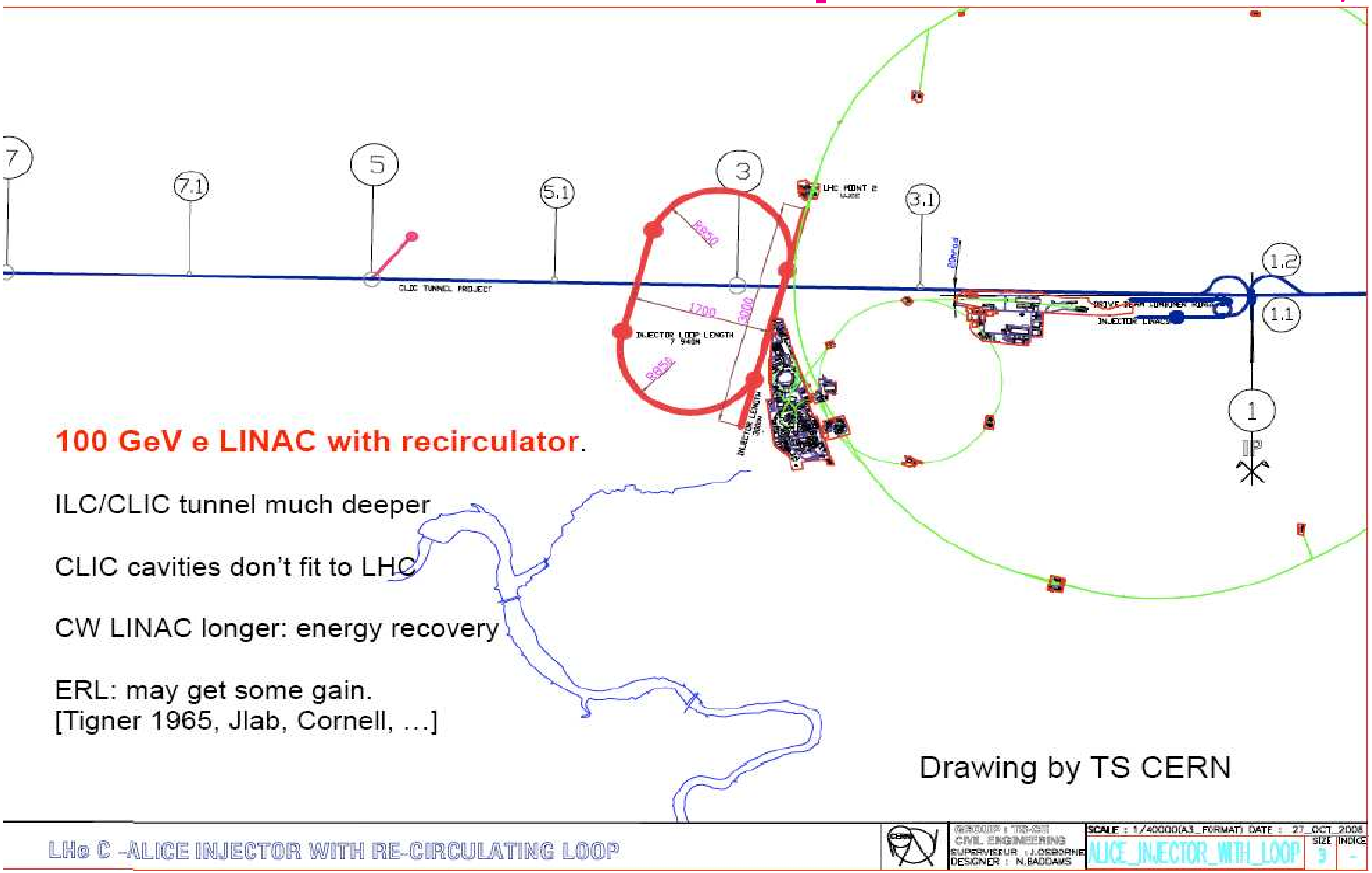
Ring-Ring (RR) vs. Linac-Ring (LR) option

RR: energy limited (70 GeV), better prospects for higher luminosity

LR: energy not physics limited, 140 GeV; which luminosity can be reached with how much electrical power?

LHeC: Linac-Ring option

[*M. Klein, LHC2FC Workshop '09*]



100 GeV e LINAC with recirculator.

ILC/CLIC tunnel much deeper

CLIC cavities don't fit to LHC

CW LINAC longer: energy recovery

ERL: may get some gain.
[Tigner 1965, Jlab, Cornell, ...]

LC: ILC and CLIC

[*K. Desch, LHC2FC Workshop ’09*]

LC specs – what any LC needs to fulfil (at least)

[http://www.fnal.gov/directorate/icfa/para-Nov20-final.pdf, Heuer et al]

<u>The baseline:</u>

e^+e^- LC operating from M_Z to 500 GeV, tunable energy

beam energy stability and precision: 10^{-3} or better

e^- polarization 80%

at least 500 fb^{-1} in the first 4 years ($L \sim 2 \times 10^{34} cm^{-2} s^{-1}$)

<u>Upgrade:</u> to ~ 1 TeV 1 ab^{-1} / 3-4 years

<u>Options :</u>

- e^+ polarization >50%
- GigaZ (high luminosity running at M_Z and $2M_W$)
- $\gamma\gamma$, $e\gamma$, e^-e^- collisions

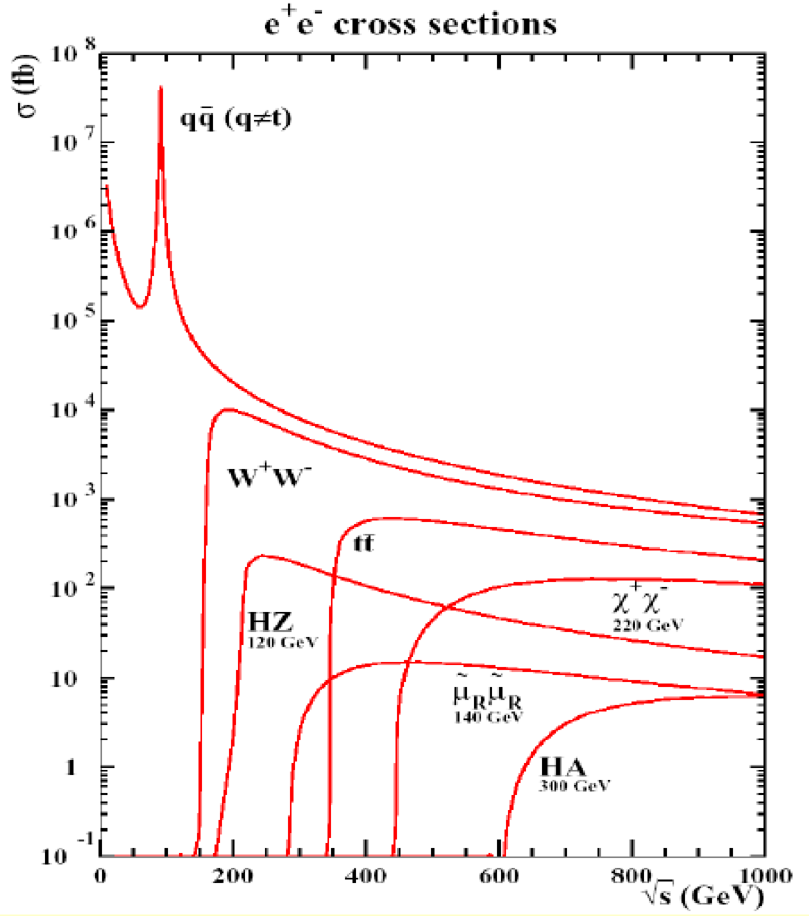
Choice of options depends on LHC+ILC results (but they are needed!)

LC: ILC and CLIC

[K. Desch, LHC2FC Workshop '09]

LC specs – What any LC needs to fulfil

$$\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-) = (\hbar c)^2 \frac{4\pi\alpha^2}{3s} = \frac{87 \text{ nb}}{s\,(\text{GeV}^2)} = 87 \text{ fb at 1 TeV}$$



Remark:

e^+e^- cross section at $\sqrt{s}$ > 500 GeV are small o (10-100 fb), multi-fermion processes smaller

500 fb^{-1} at 500 GeV are „only"

- 40000 HZ events
- 2500 HZ, Z→ll events
- 5000 smoun (m=140) pairs
- 200 HHZ events

By far most measurements at LC will be statistics-limited

Possibly have many thresholds to scan

→ Luminosity requirement of 2×10^{34} is a lower limit!

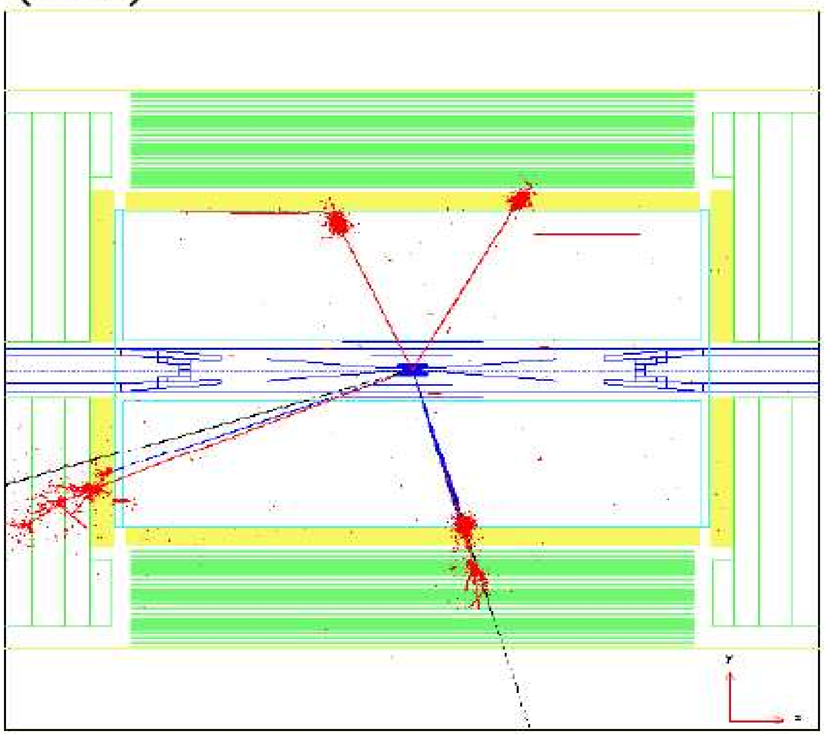
LC: ILC and CLIC

[*K. Desch, LHC2FC Workshop ’09*]

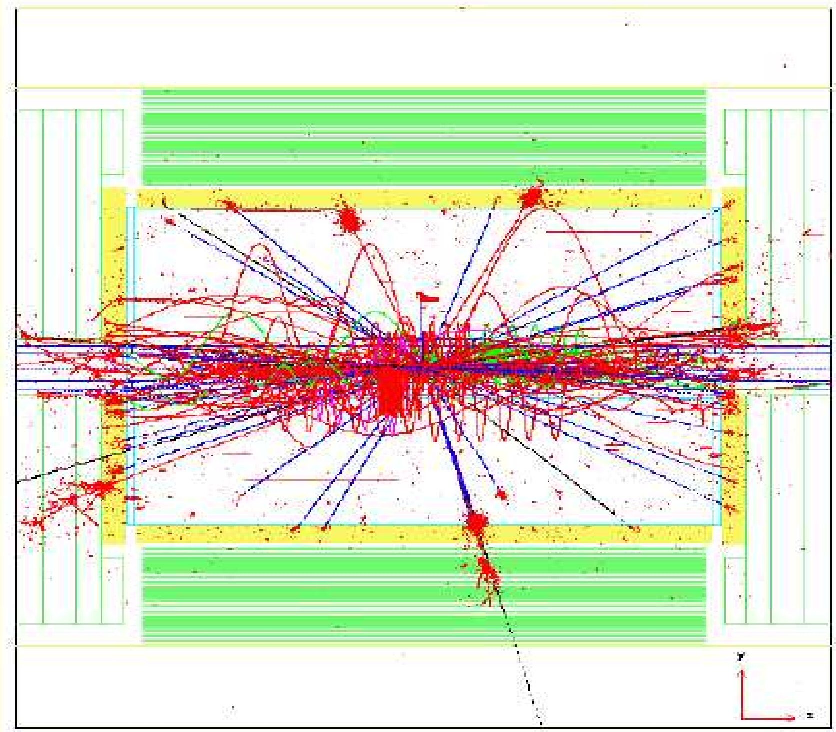
Does LC Technology matter?

$HZ \rightarrow \tau\tau ee$ event

Without soft hadronic events overlaid (=ILC)



With 32 BX (=16 ns) „CLIC nominal 500" overlaid



note: CLIC 3000 nominal has 14 times CLIC500 overlaid

LHC2FC Workshop Programme

Future Colliders Series: technology status and physics case

4 Working Groups, investigate for different signatures:

- How well do the observed signatures in the early LHC data constrain the possible physics scenario?
- What could be the impact of early LHC results on the choice of the next facility and its (ultimate) energy reach and luminosity?
- What would be the possible implications for the machine and the detector design?
- How would additional LHC luminosity further constrain / support the scenario and the choice of the future facility?
- What are the prospects for an interplay with results from the LHC, low-energy experiments and cosmological data?

WG 1: Detection of a state with properties that are compatible with a Higgs (SM-like or non-SM-like)

Convenors:

[*Sally Dawson, Sven Heinemeyer, Chiara Mariotti, Markus Schumacher*]

- measurement of mass and spin, quantum numbers
- self-couplings
- precision top studies and electroweak precision physics
- . . .

WG2: No Higgs signal

$\Rightarrow$ No Higgs candidate in the first $\approx 10\ \mathrm{fb}^{-1}$ at the LHC
($+$ anything else)

Convenors: [*Georges Azuelos, Christophe Grojean, Mark Lancaster, G. W.*]

- gauge boson self-couplings
- longitudinal vector boson scattering
- exotic Higgs scenarios
- invisibly decaying Higgs scenarios
- ...

WG 3: Missing energy (+ nothing, leptons, jets)

Convenors:

[*Ben Gripaios, Filip Moortgat, Gudrid Moortgat-Pick, Giacomo Polesello*]

- measurement of mass and spin, quantum numbers
- dark matter / connection with cosmology
- . . .

WG 4: Other new signatures

Convenors: [*Tao Han, JoAnne Hewett, Albert De Roeck, Sabine Riemann*]

- Leptonic resonances
- multi-gauge-boson signals
- measurement of mass and spin, quantum numbers
- leptoquark-type signatures
- flavour physics
- fourth generation-type signatures, exotic quarks
- TeV scale gravity-type signatures
- other possible signatures of new physics

LHC2FC Workshop

More than 100 participants, very lively meeting

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The workshop is not over yet

Reports of the four working groups are currently being prepared (10–20 pages each)

The aim is to have a document containing the four working group reports and overall introduction / conclusions sections by middle of June; will be submitted to the arXiv and possibly appear as a CERN Yellow Report

In the following: some examples of issues discussed at the CERN meeting; far from a comprehensive coverage

A light Higgs candidate at the LHC

[C. Mariotti, LHC2FC Workshop '09]

Low mass: 114<M_H<130 GeV

- **$H \to \gamma\gamma$**

  is maybe the only channel where we can discover it (differences between Atlas and CMS - are the methods used or are the intrinsic different detectors?)
- **VBF $H \to \tau\tau$** (currently at 2-3 sigma level per exp -> room for improvements)
- **ttH, $H \to bb$:**

  Feasible only later, when it will be discovered.

  New ideas: Boosted H in association with W/Z (under study now) Butterworth et al

  Or with very high lumi: VBF H + hard γ or W Gabrielli et al, Ballestrero et al,

The future colliders will do better:

plus they can see $H \to \mu\mu$, $H \to \gamma Z$.

Coupling, SelfCouplings, [mass], width, and spin will be best measured at LeptonColliders.

A light Higgs candidate at the LHC

Initial information from the LHC:

From decay to $\gamma\gamma$ or $ZZ^{(*)}$ $\Rightarrow$ mass

From production in WBF or decay to $WW^{(*)}$, $ZZ^{(*)}$ $\Rightarrow$ gauge coupling is present

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$\Rightarrow$ new state will be produced at the LC in the HZ mode

$\Rightarrow$ Bonanza for a $\lesssim 350\,\mathrm{GeV}$ LC ("HTLC"):

comprehensive info on the properties of the new state

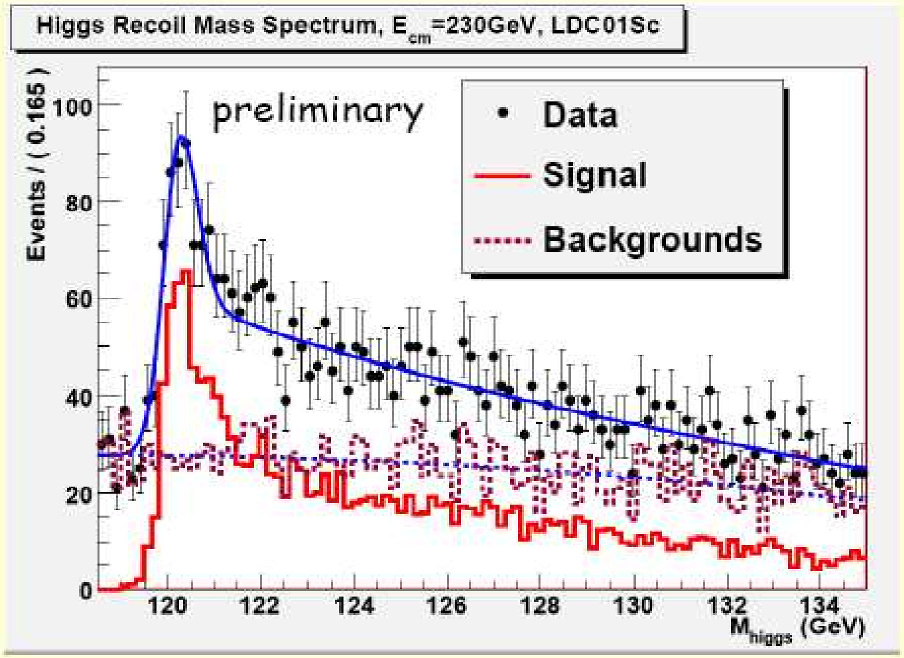
$+$ top physics $+$ GigaZ $+$ ...

HZ **production at the ILC**

[K. Desch, LHC2FC Workshop '09]

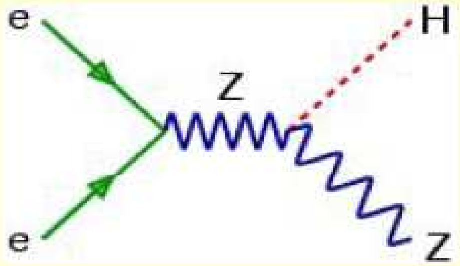
Higgs physics – model independent

Anchor of LC Higgs physics
(why LC Higgs physics is qualitatively different from LHC)



Full detector simulation & Analysis

[Li,Richard,Poeschl,Zhang 09]



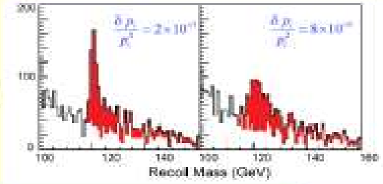
- select di-lepton events consistent with Z→ee/μμ
- calculate recoil mass:

$$m_H^2 = (p_{\ell\ell} - p_{\mathrm{initial}})^2$$

model independent,

decay-mode independent

small note:
tracking resolution counts!



If a Higgs candidate has been detected: experimental questions

- Is it a Higgs boson?
- What are its mass, spin and $\mathcal{CP}$ properties?
- What are its couplings to fermions and gauge bosons? Are they really proportional to the masses of the particles?
- What are its self-couplings?
- Are its properties compatible with the SM, the MSSM, the NMSSM, . . . ?
- Are there indications that there are more than one Higgs bosons?
- Are there indications for other new states that influence Higgs physics?

Example: Higgs coupling determination

LHC: no absolute measurement of total production cross section (no recoil method like LEP, ILC: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$)

Production $\times$ decay at the LHC yields combinations of Higgs couplings ($\Gamma_{\rm prod,\,decay} \sim g^2_{\rm prod,\,decay}$):

$$\sigma(H) \times {\rm BR}(H \to a + b) \sim \frac{\Gamma_{\rm prod}\Gamma_{\rm decay}}{\Gamma_{\rm tot}},$$

Large uncertainty on dominant decay for light Higgs: $H \to b\bar{b}$

$\Rightarrow$ LHC can directly determine only ratios of couplings, e.g. $g^2_{H\tau\tau}/g^2_{HWW}$

Higgs coupling determination at the LHC

Absolute values of the couplings at the LHC can be obtained with an additional (mild) theory assumption:
[*M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld '04*]

$$g^2_{HVV} \leq (g^2_{HVV})^{\mathrm{SM}}, \quad V = W, Z$$

$\Rightarrow$ Upper bound on Γ_V

Observation of Higgs production
$\Rightarrow$ Lower bound on production couplings and Γ_{tot}

Observation of $H \to VV$ in WBF
$\Rightarrow$ Determines $\Gamma^2_V/\Gamma_{\mathrm{tot}}$ $\Rightarrow$ Upper bound on Γ_{tot}

$\Rightarrow$ Absolute determination of Γ_{tot} and Higgs couplings

Intermediate mass Higgs, $M_{\mathrm{H}} \lesssim 180$ GeV*, at the LHC*

[*C. Mariotti, LHC2FC Workshop '09*]

- Higgs can be studied when produced via gg fusion and via WBF
- In the region 150–180 GeV, LHC can measure very well the couplings to ZZ, WW

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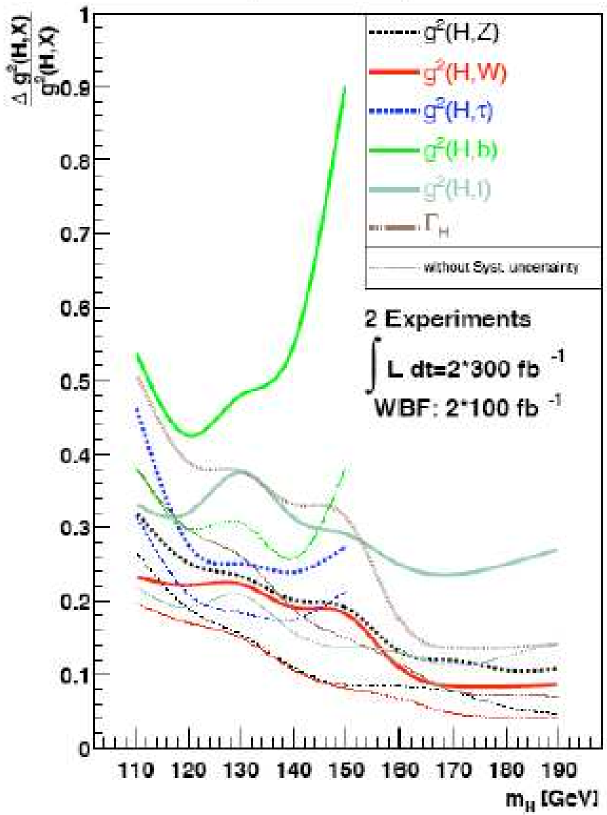
  But: For a Higgs decaying into $WW^{(*)}, ZZ^{(*)}$, this region may soon be excluded by the Tevatron

- In the lower mass range (130–150 GeV) also $\gamma\gamma$ and $\tau^+\tau^-$ couplings can be explored
- The couplings below 150 GeV crucially depend on the possibility to measure $H \to b\bar{b}$

Measurement of the couplings

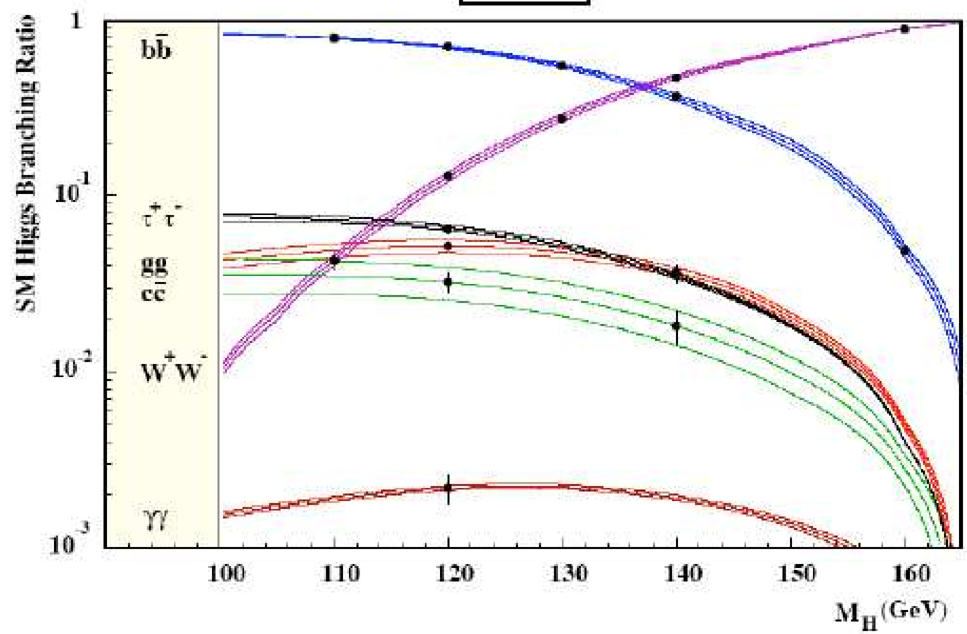
[C. Mariotti, LHC2FC Workshop ’09]

LHC



We need H->bb otherwise measurements only for >150 GeV

ILC



Decay mode	Rel. prec. (%) $m_{\mathrm{H}} = 120$ GeV
$b\bar{b}$	1.0–2.4
$c\bar{c}$	8.1–12.3
$\tau^+\tau^-$	4.6–7.1
gg	4.8–10
WW	3.6–5.3

ILC can also measure the total width

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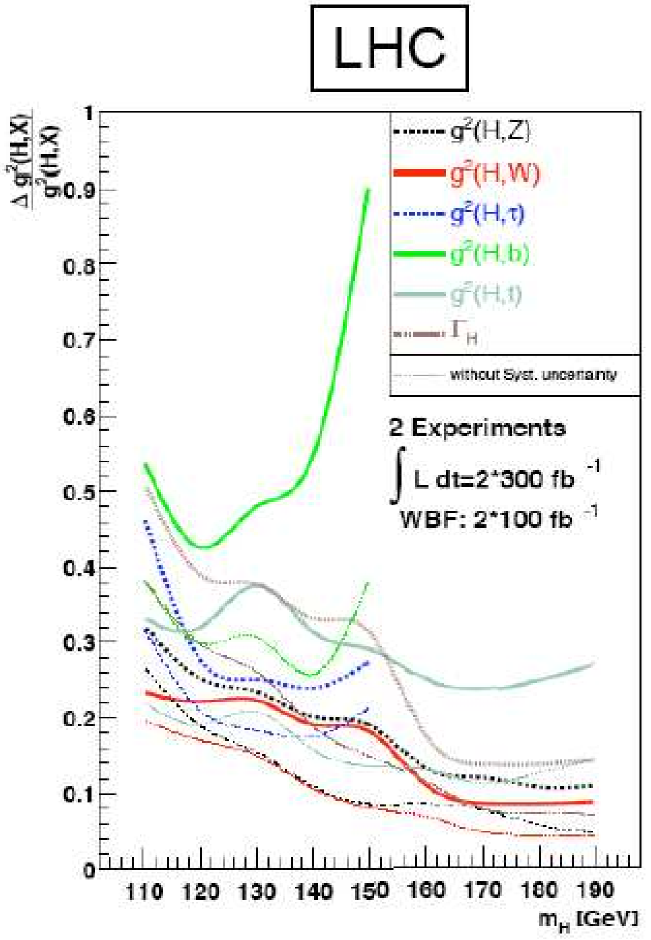
Measurement of the couplings

[C. Mariotti, LHC2FC Workshop '09]



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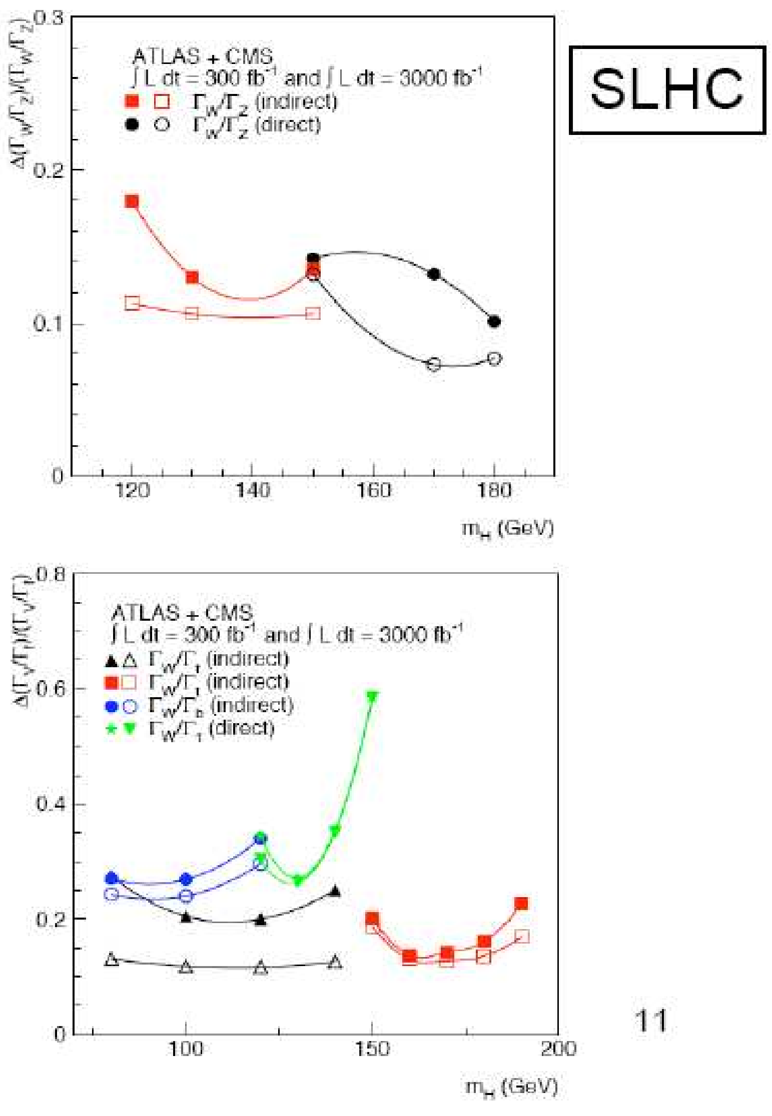

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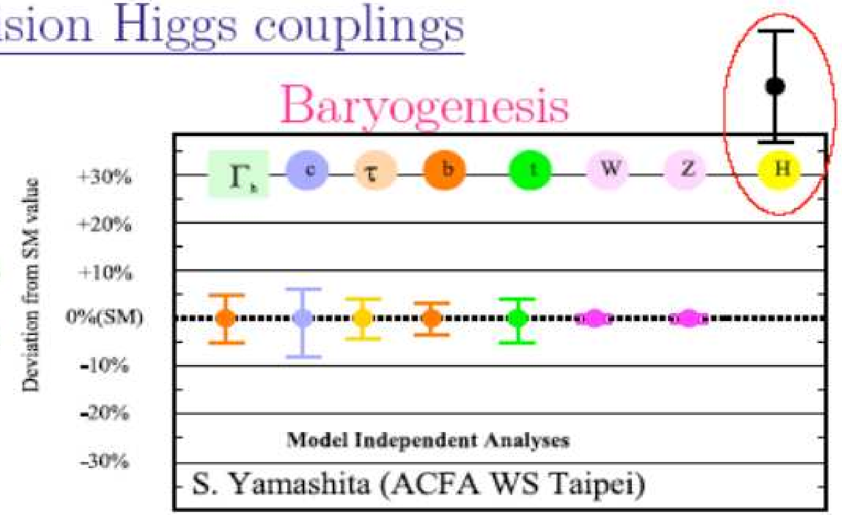
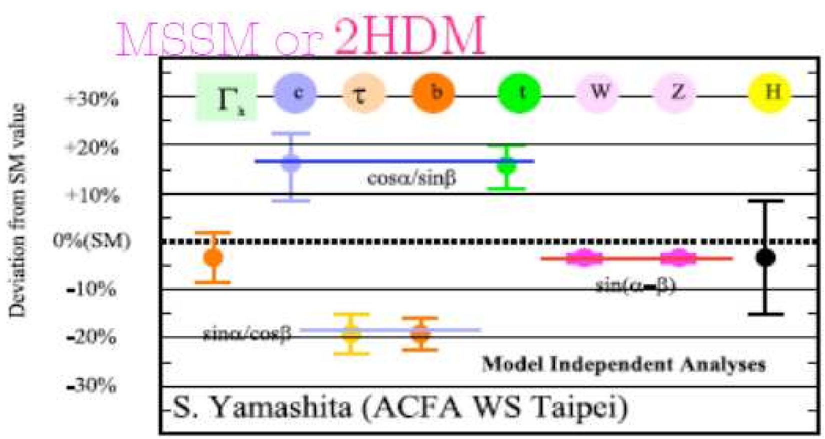
Higgs couplings: what precision do we need?

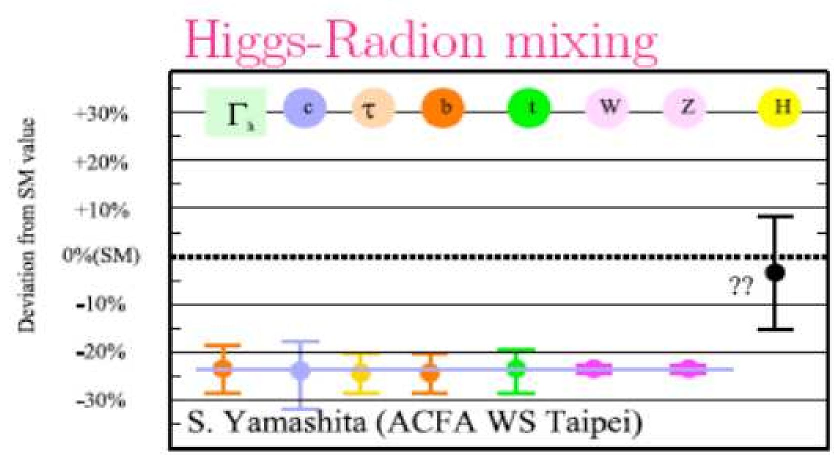
[C. Mariotti, LHC2FC Workshop '09]

Applications of precision Higgs couplings

Patterns of deviations can give ideas which type of model can course them







Lepton colliders are better suited for tests on Couplings

The Higgs as a composite object

Renewed interest in composite Higgs models, mostly from extra dimensions

[*N. Arkani-Hamed, A. Cohen, H. Georgi '01*]

[*K. Agashe, R. Contino, A. Pomarol '05*], . . .

Composite Higgs: light remnant of a strong force

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Relation extra dimensions $\Leftrightarrow$ new strong forces?

Correspondence (AdS/CFT):

Warped gravity model $\Leftrightarrow$ Technicolour-like theory in 4D

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Signatures at LHC: new resonances, W', Z', t', KK excitations

Under pressure from electroweak precision tests

Effective field-theory description of a composite Higgs

Agreement with electroweak precision data can be improved if there is a strongly interacting light Higgs, e.g.

Little Higgs [*N. Arkani-Hamed, A. Cohen, E. Katz, A. Nelson '02*]

Holographic Higgs [*R. Contino, Y. Nomura, A. Pomarol '03*], [*K. Agashe, R. Contino, A. Pomarol '05*], . . .

Effective Lagrangian formalism for model-independent analysis of effects of a Strongly-Interacting Light Higgs (SILH) [*G. Giudice, C. Grojean, A. Pomarol, R. Ratazzi '07*]

$\Rightarrow$ Specific pattern of modified Higgs couplings

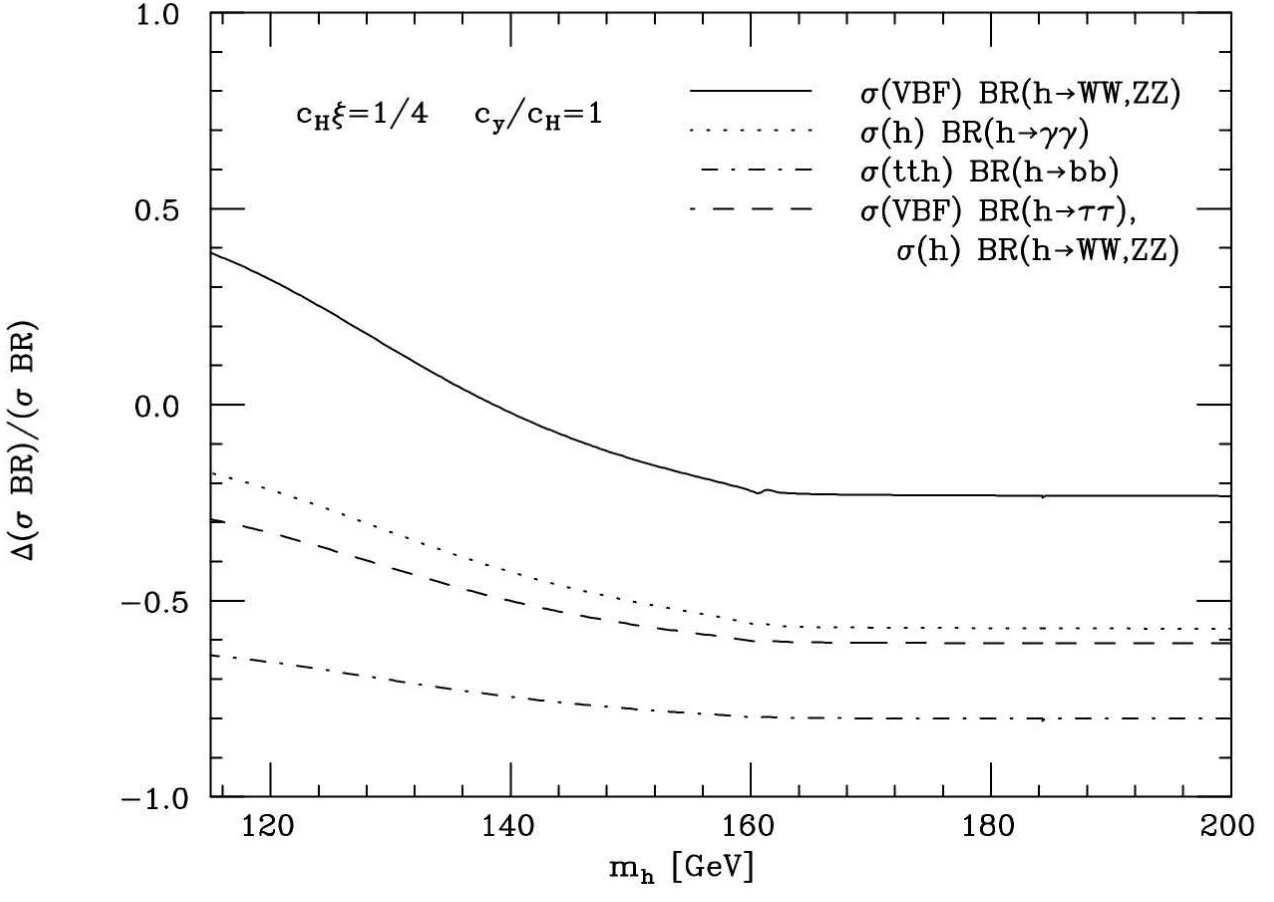
Strong WW scattering at high energies despite light Higgs

$\Rightarrow$ Need precision measurement of Higgs couplings

$+$ test of longitudinal gauge-boson scattering

Strongly-Interacting Light Higgs: deviation of $\sigma \times \mathrm{BR}$ from the case of a SM Higgs

[*G. Giudice, C. Grojean, A. Pomarol, R. Ratazzi '07*]



Sensitivity at LHC: 20–40%, ILC: 1%

$\Rightarrow$ ILC can test scales up to ~ 30 TeV

High-mass Higgs, $M_{\mathrm{H}} \gtrsim 180~\mathrm{GeV}$

[*C. Mariotti, LHC2FC Workshop '09*]

If there is a disagreement between the Mass of the observed Higgs and the Precision Data or some of the sigma x BR are strongly enhanced then:

– Look for other particles

Tecnicolors, ED… : LHC can do very well up to 2-3 TeV. After then one would want or more Lumi with SLHC or CLIC.

– WW scattering at E>1TeV - Will be the key to Symmetry Breaking:

LHC with High Lumi or CLIC can explore this region

(It is only the higgs who breaks it or we need also contribution from Strong Interaction?)

No Higgs candidate in the first $\approx 10 \text{ fb}^{-1}$ *at the LHC*

Possible options:

No Higgs candidate in the first $\approx 10\ \mathrm{fb}^{-1}$ *at the LHC*

Possible options:

- There is a Higgs boson (or more than one), but it has non-standard properties that make it difficult to detect:
  - Suppressed couplings to gauge bosons and / or fermions
  - Higgs decays into jets, invisible Higgs decays, . . .

  Examples: MSSM with complex parameters, NMSSM, Higgs–radion mixing, . . .

No Higgs candidate in the first $\approx 10\ \mathrm{fb}^{-1}$ at the LHC

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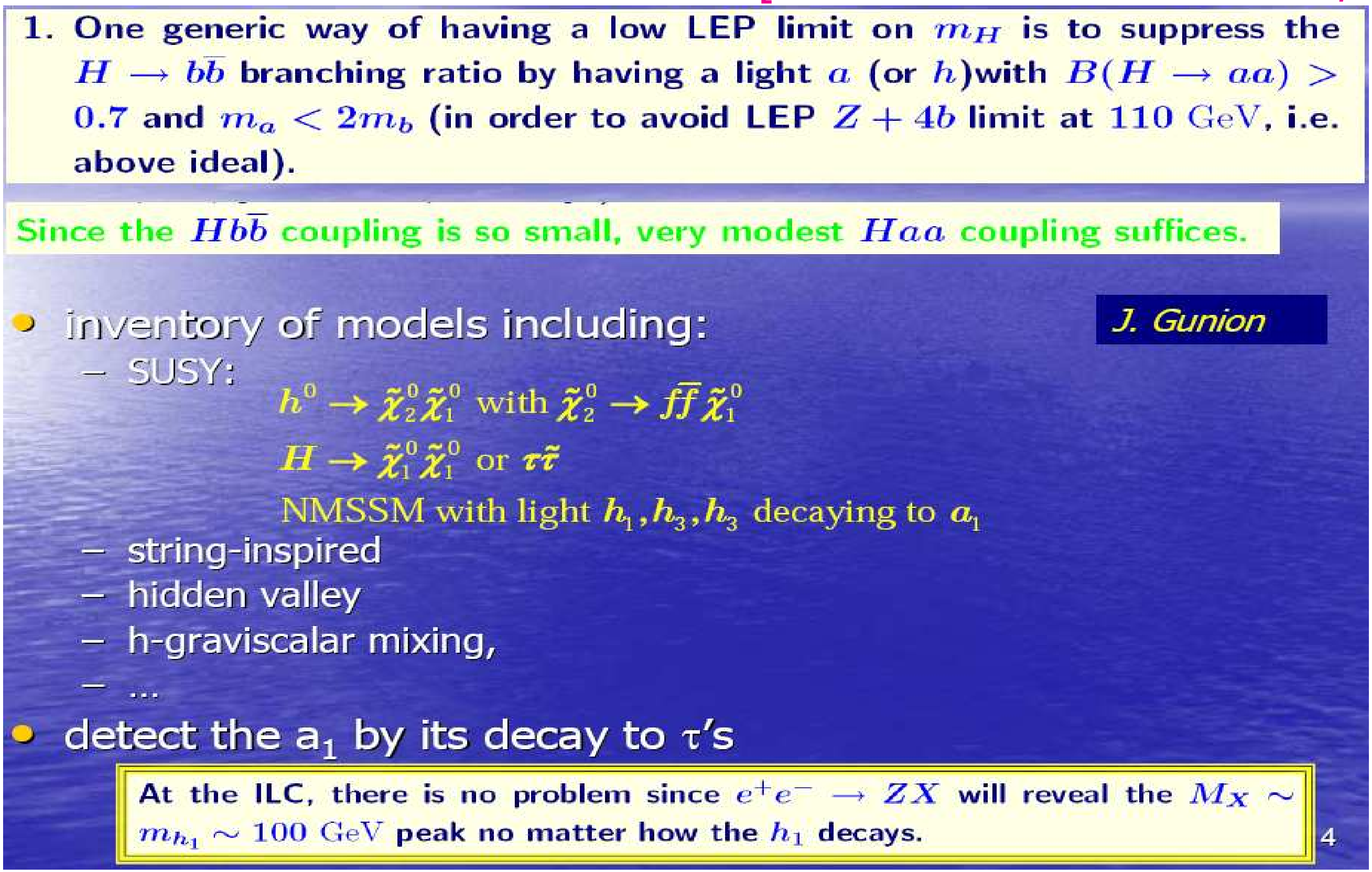
  Examples: MSSM with complex parameters, NMSSM, Higgs–radion mixing, . . .

- There is really no Higgs boson:
  - Technicolour-like models, BESS models, . . .
  - Higgsless models in extra dimensions

  Impact on longitudinal vector boson scattering, gauge boson self-couplings: anom. couplings, resonances, . . .

Scenarios with a light Higgs that is unexcluded by LEP searches

[G. Azuelos, LHC2FC Workshop '09]

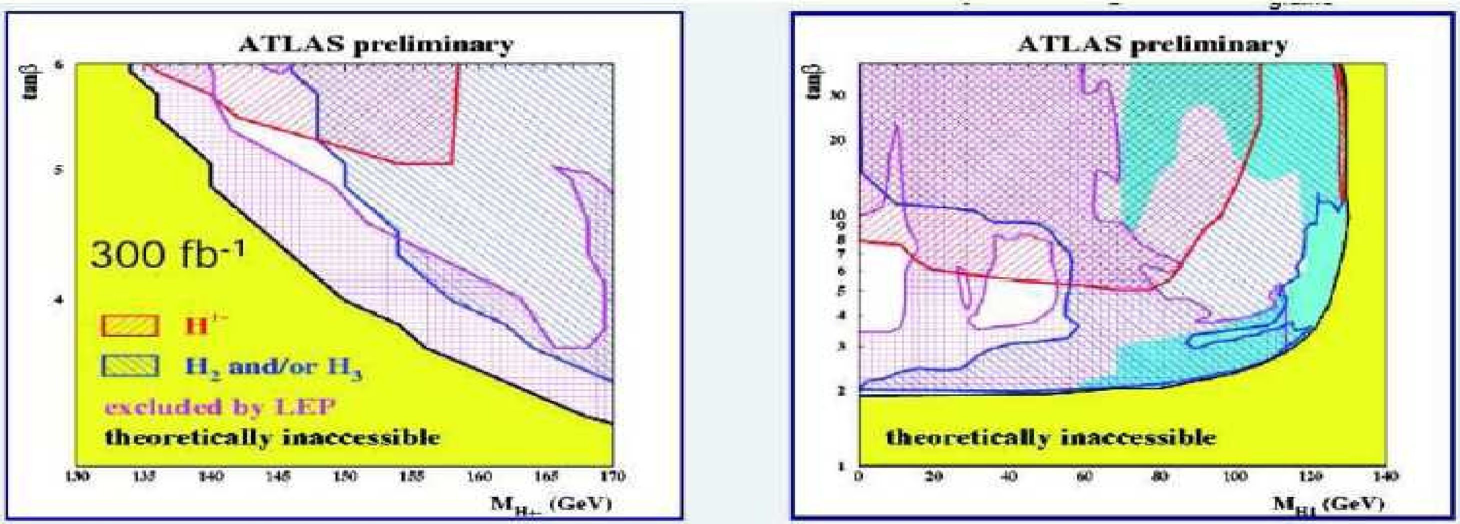


Example: MSSM with CP-violating phases

[*G. Azuelos, LHC2FC Workshop '09*]

CPX holes are difficult to cover at the LHC

[*M. Schumacher, ATLAS '07*]



M_{H1}: < 50 GeV, M_{H2}: 105 to 115 GeV , M_{H3}: 140 to 180 GeV, M $_{H+-}$:130 to 170 GeV

Markus Schumacher Prospect for Higgs Boson Physics at LHC Euro-GDR SUSY07, Brussels

⇒ "CPX holes" cannot be covered in conventional channels

WG2: Plans for the Remainder of the Workshop, Georg Weiglein, CERN, 02/2009 – p.14

- SUSY particles should be accessible in this scenario, cascade decays

⇒ Strong motivation for a 500 GeV e^+e^- Linear Collider?

G. Weiglein

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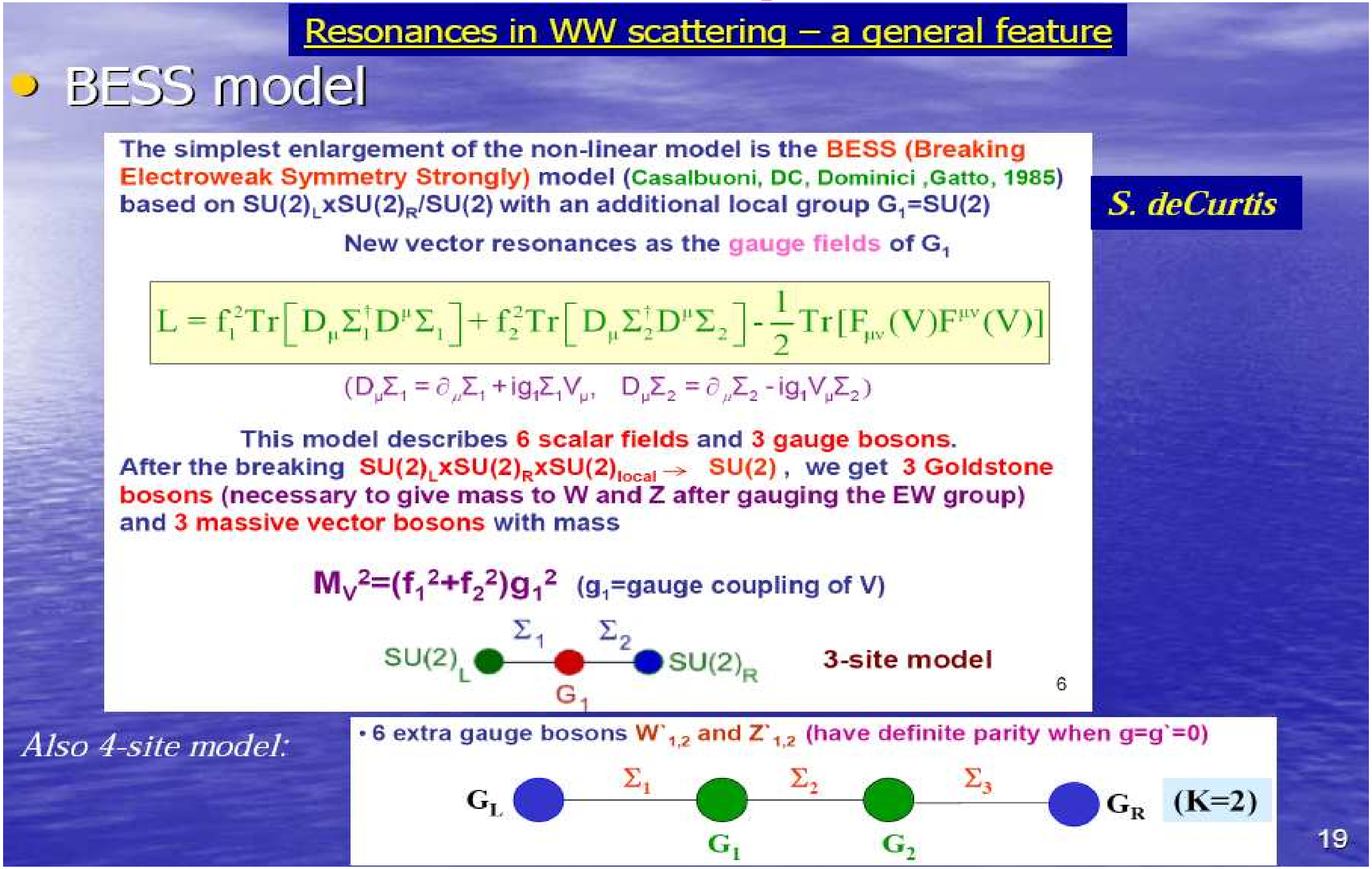
Scenarios without a fundamental Higgs

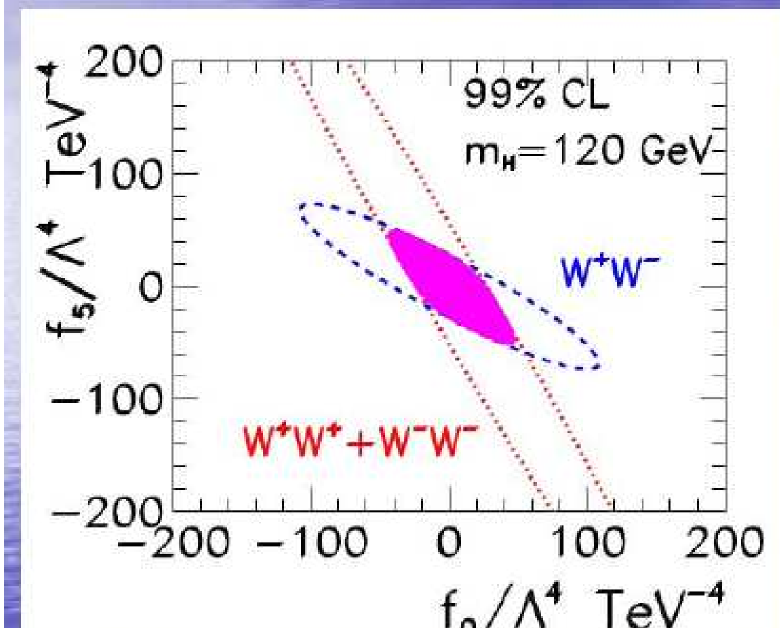
[*G. Azuelos, LHC2FC Workshop '09*]

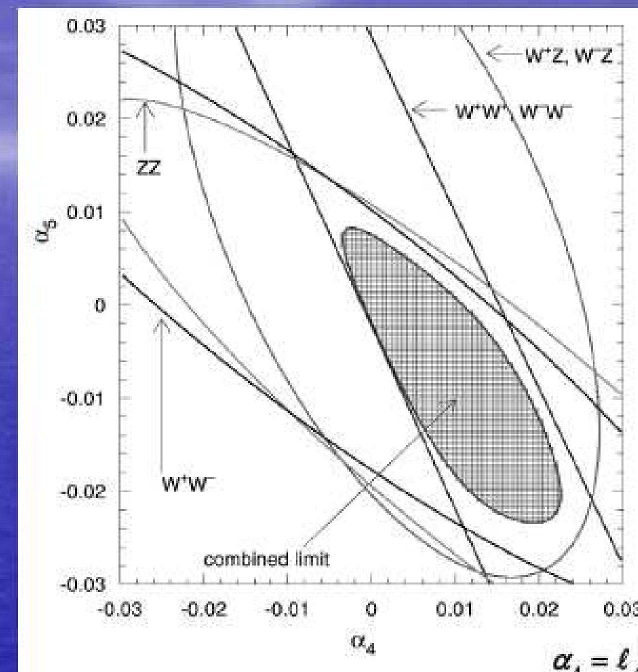


Non-standard couplings at the LHC

[*G. Azuelos, LHC2FC Workshop '09*]

- quadrilinear couplings





$\alpha_4 = \ell_4\left(\frac{v^2}{\Lambda^2}\right)$

$\mathcal{L}^{VVV'V'} = c_0^{VV'} C_0^{VV'} + c_1^{VV'} C_1^{VV'}$, 0,1

for different couplings ($W^+W^-W^+W^-, W^+W^+W^-W^-$)

$\Delta c_i^{VV'} \sim \frac{f_i}{\Lambda^4}$

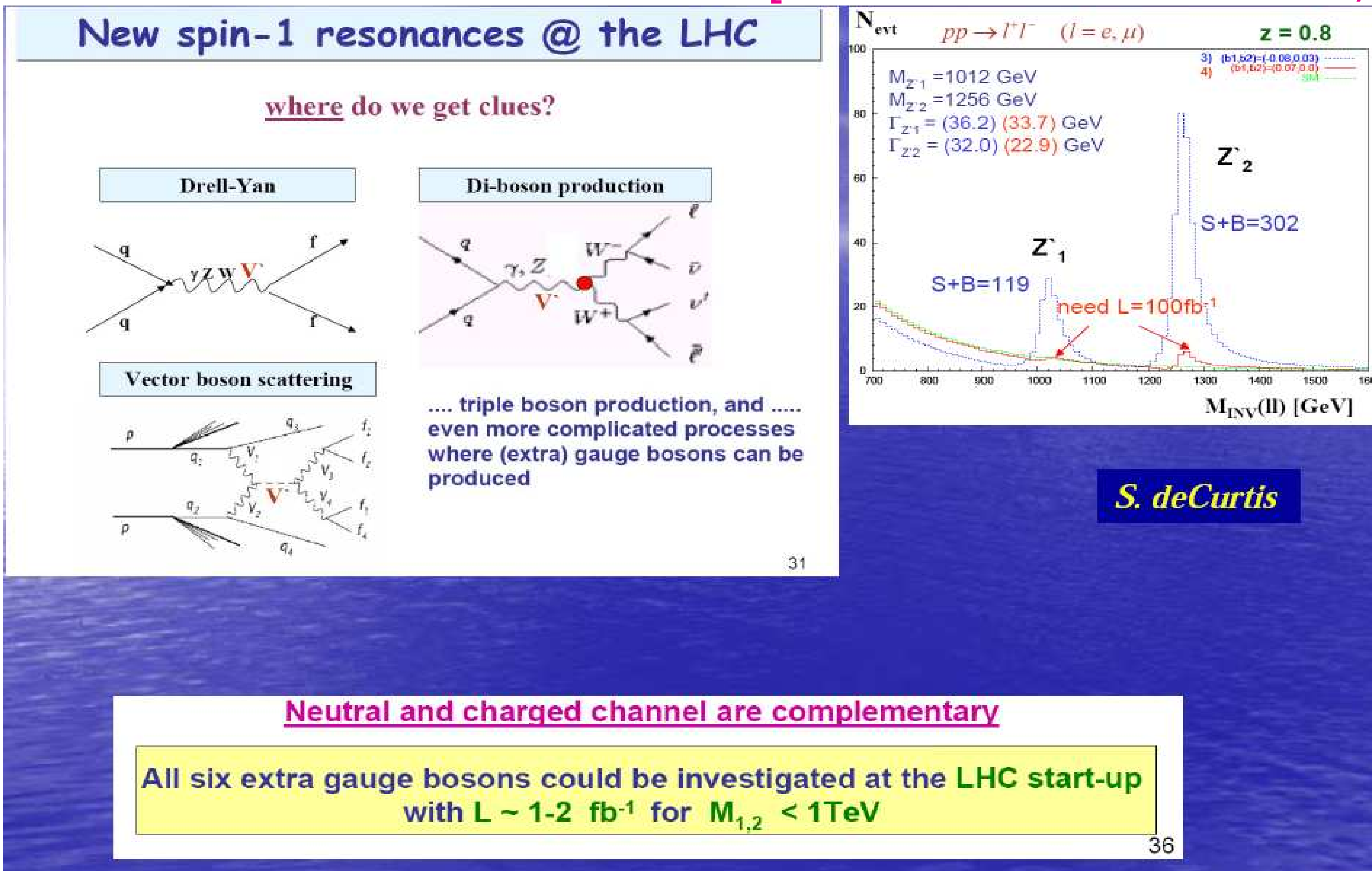
Order of magnitude improvement over LEP, but still too large in case of light Higgs

LHC sensitivity to α_4, α_5 too poor → vector and scalar resonance will be the only characteristic signatures

A. Belyaev et al., Phys Rev D59 015022 (1998)
O J P Éboli et al., hep-ph/0606118

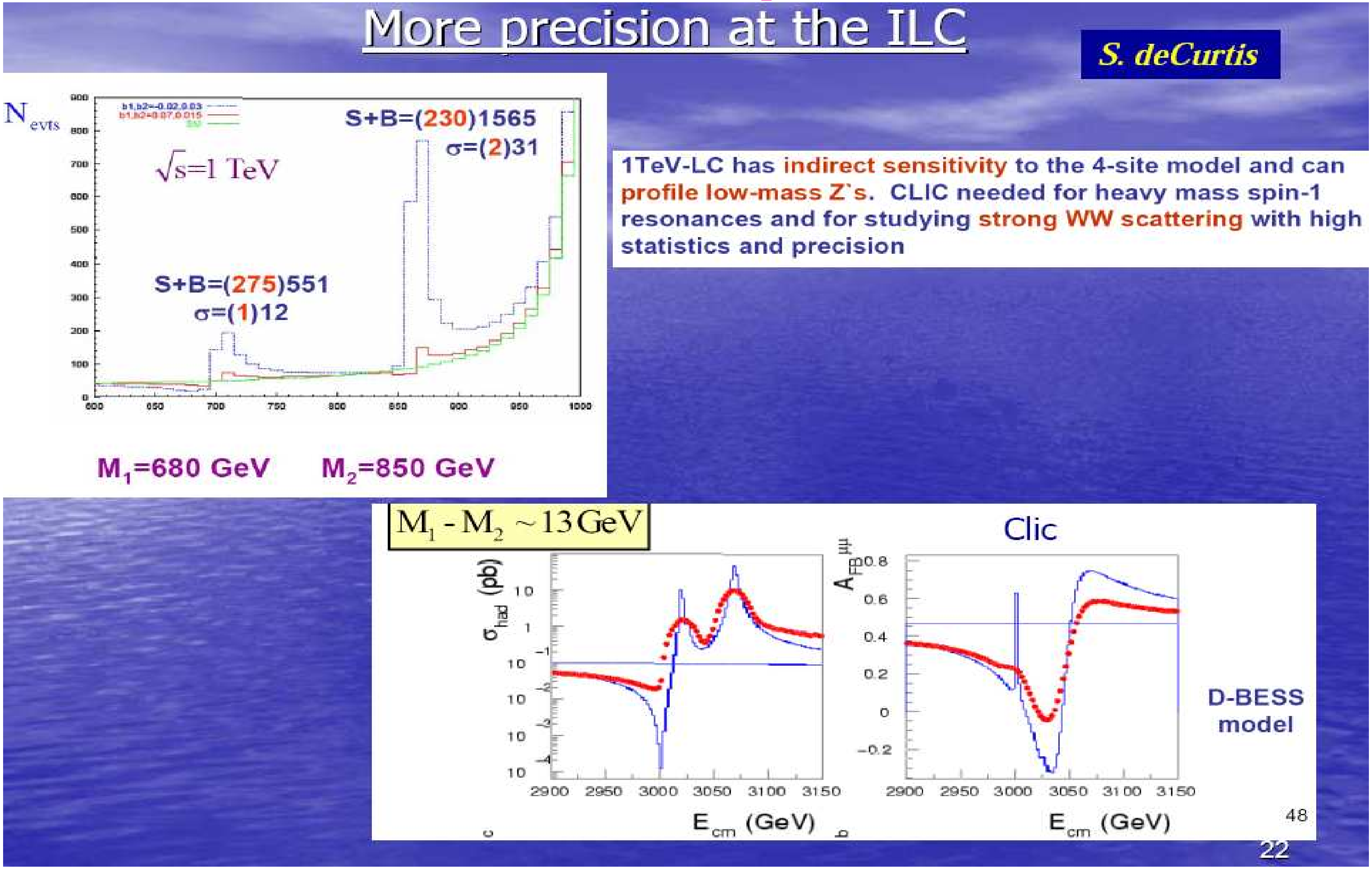
Resonances at the LHC

[G. Azuelos, LHC2FC Workshop '09]



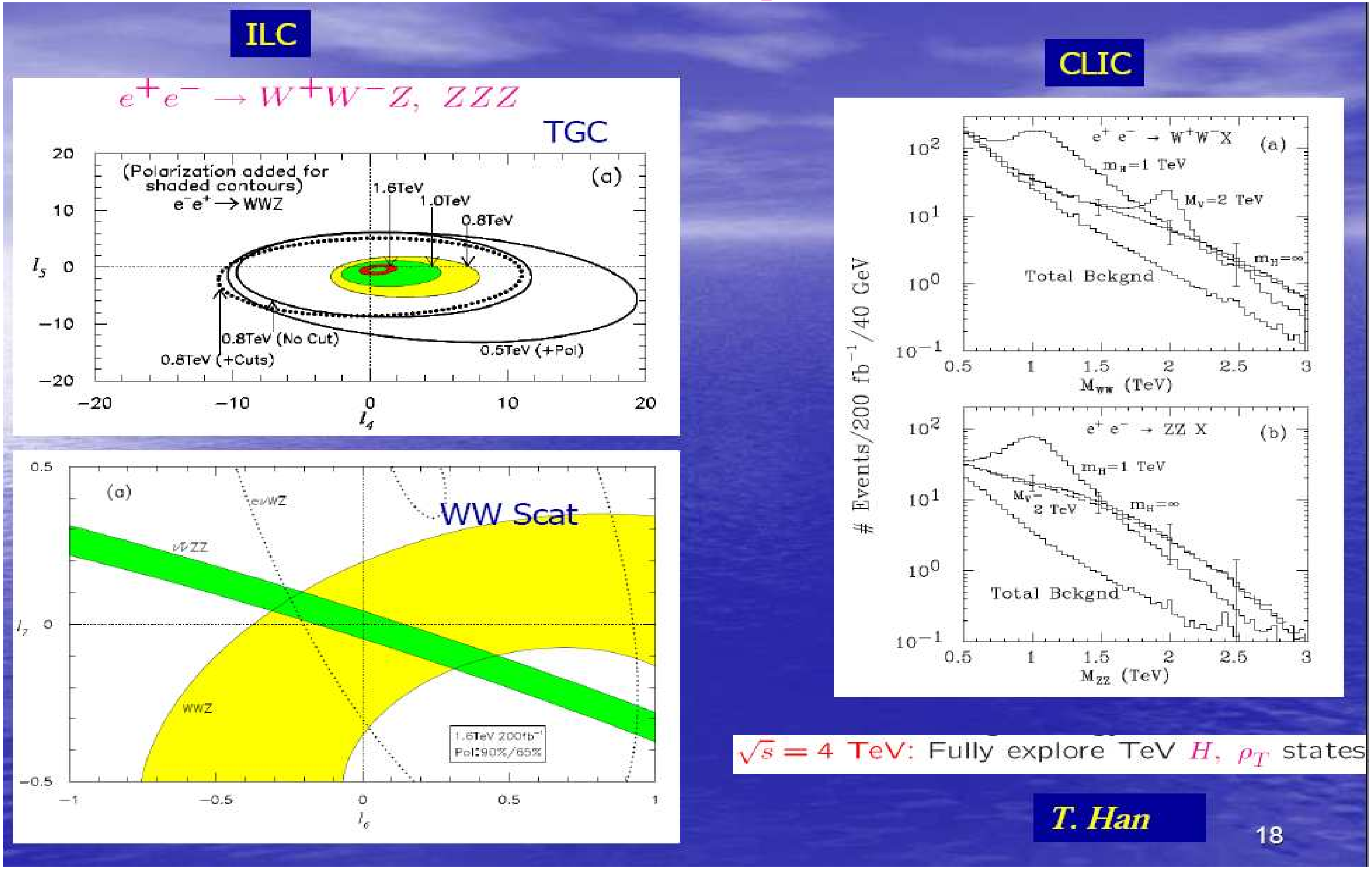
Sensitivity at ILC and CLIC

[*G. Azuelos, LHC2FC Workshop '09*]



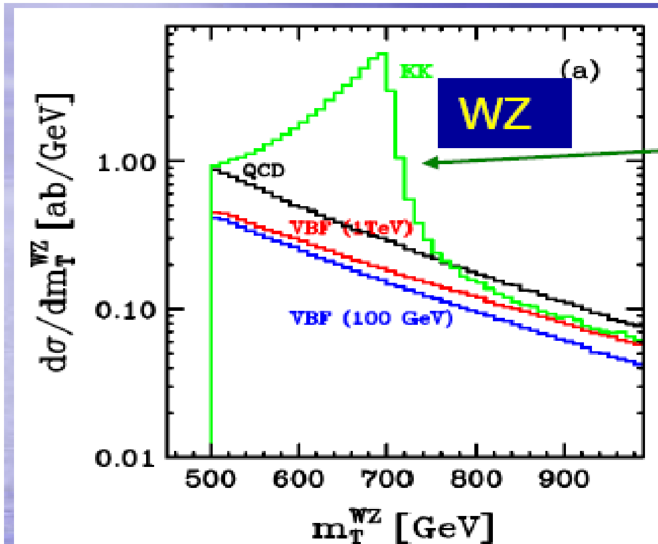
Non-standard couplings: ILC and CLIC

[G. Azuelos, LHC2FC Workshop '09]

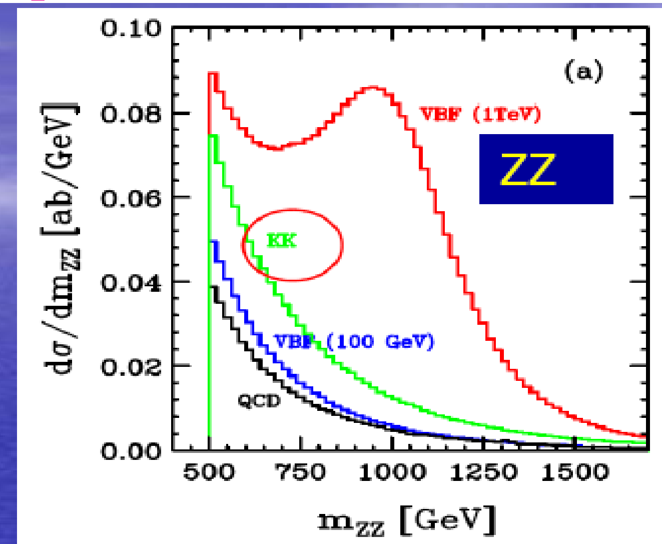


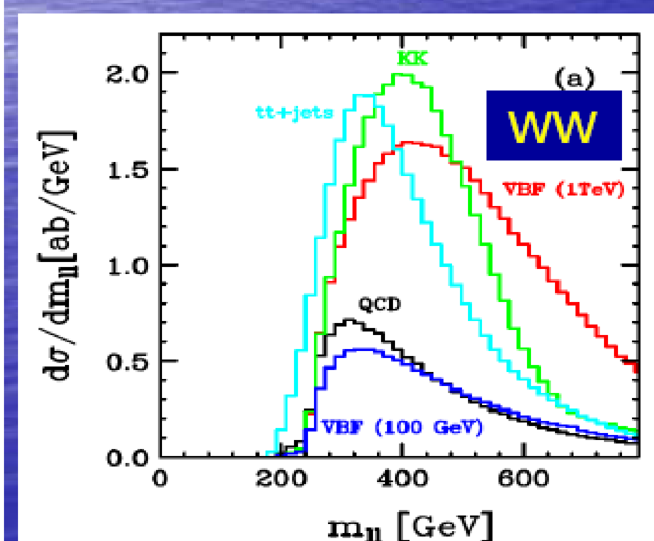
Strong scattering at the LHC: purely leptonic

[G. Azuelos, LHC2FC Workshop '09]



Higgsless model





C. Englert[1], B. Jäger[2,3], M. Worek[1,4], D. Zeppenfeld[1]

arXiv:0810.4861

Clearly, need for v. high luminosity !

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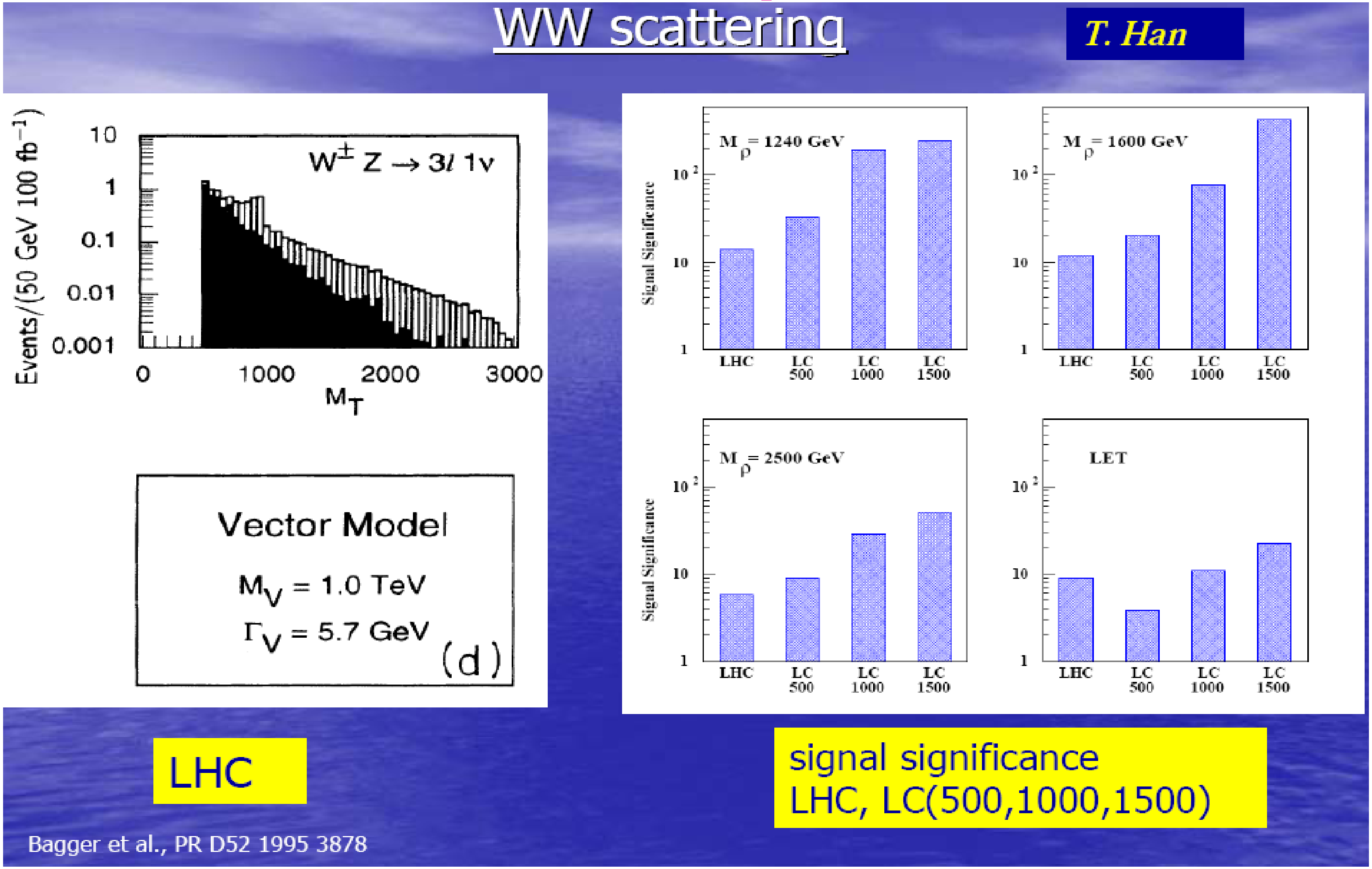
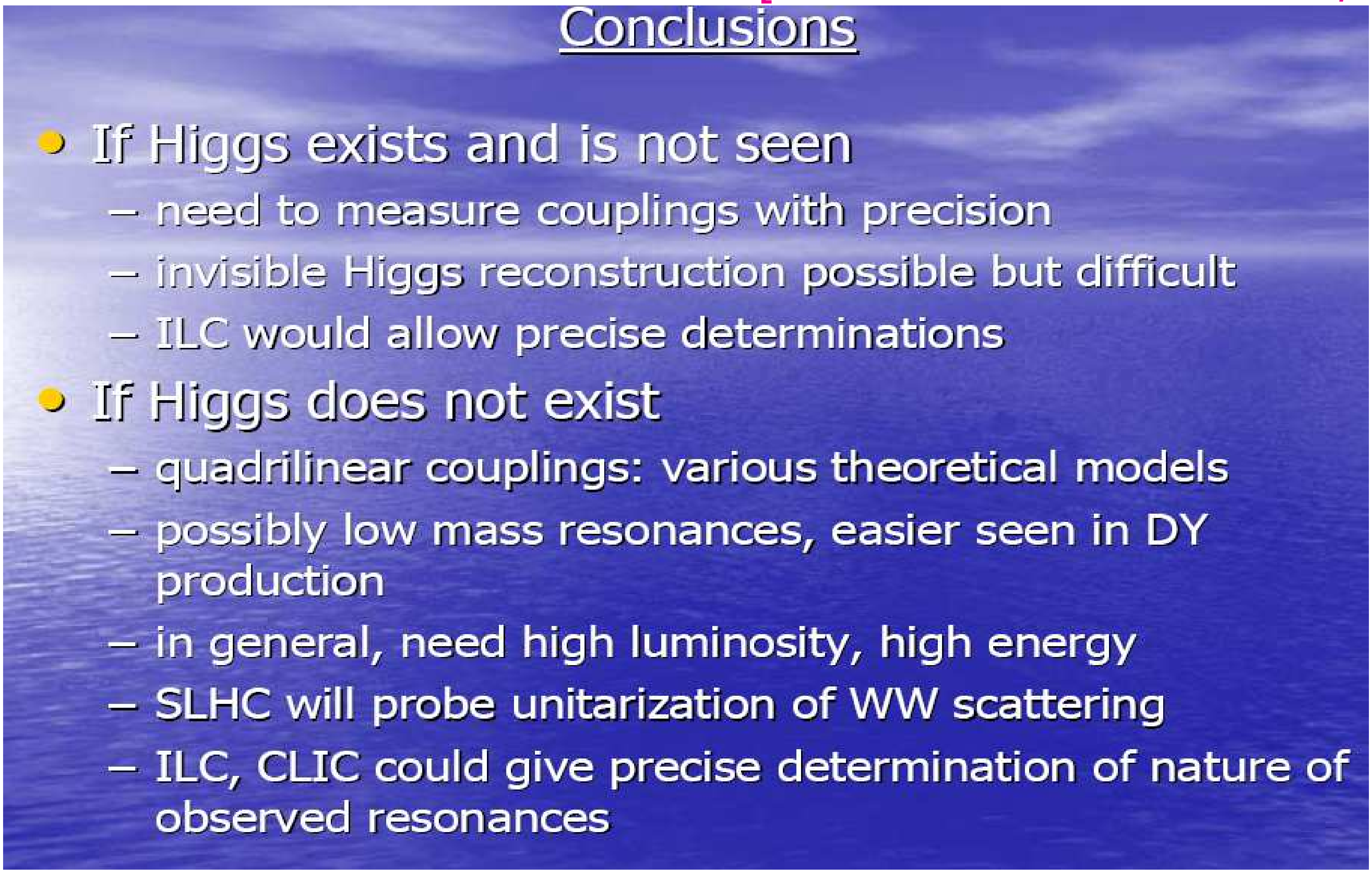
Sensitivity to signals od strong EWSB

[*G. Azuelos, LHC2FC Workshop '09*]



Summary on scenarios without a Higgs candidate in the early LHC data

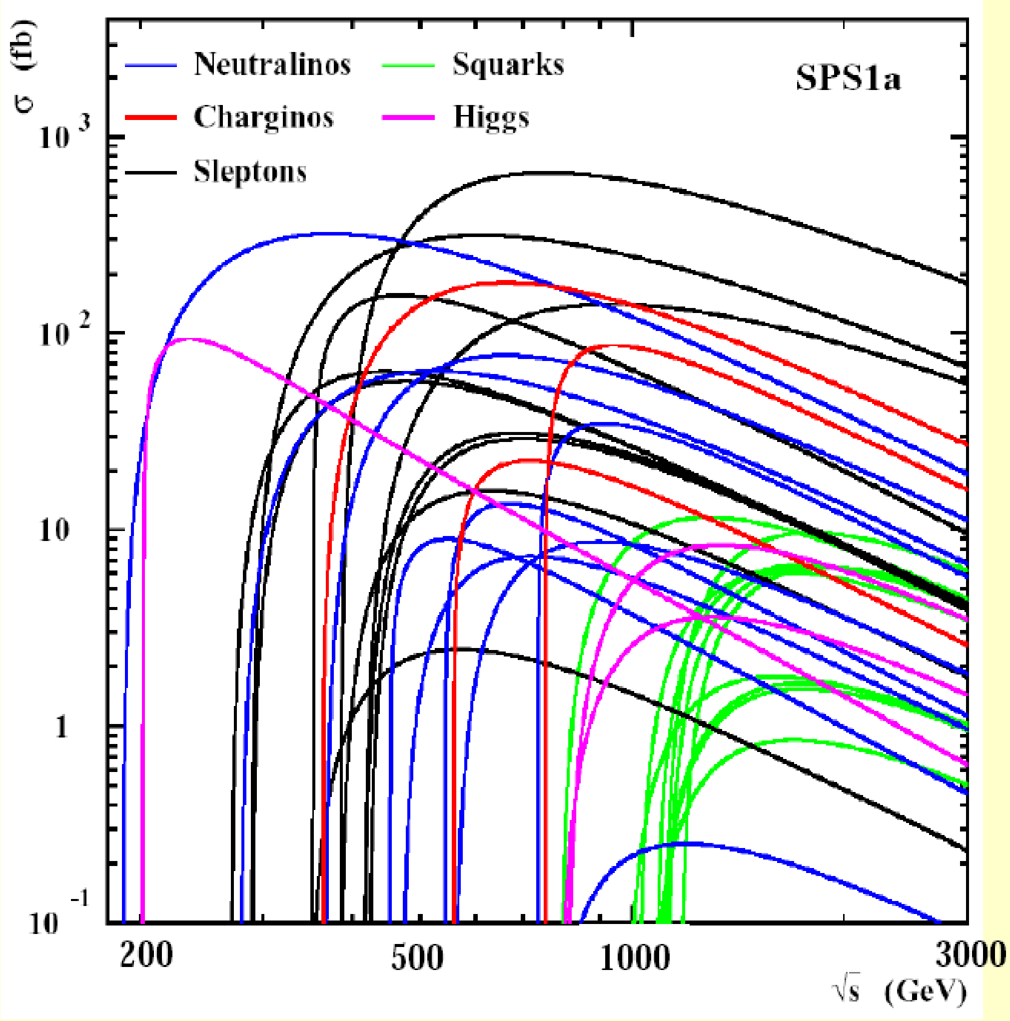
[*G. Azuelos, LHC2FC Workshop '09*]



Missing energy signatures

SUSY thresholds at the LC: SPS1a scenario

[*K. Desch, LHC2FC Workshop '09*]



cross sections in the

10 - 1000 fb range

$o(10^3 - 10^5)$ events

to disentangle this 'chaos'

the various LC options,

in particular are vital!

- tunable $\sqrt{s}$
- tunable beam polarisation
- high luminostiy!

Spin measurements at the LHC

[*F. Moortgat, LHC2FC Workshop '09*]

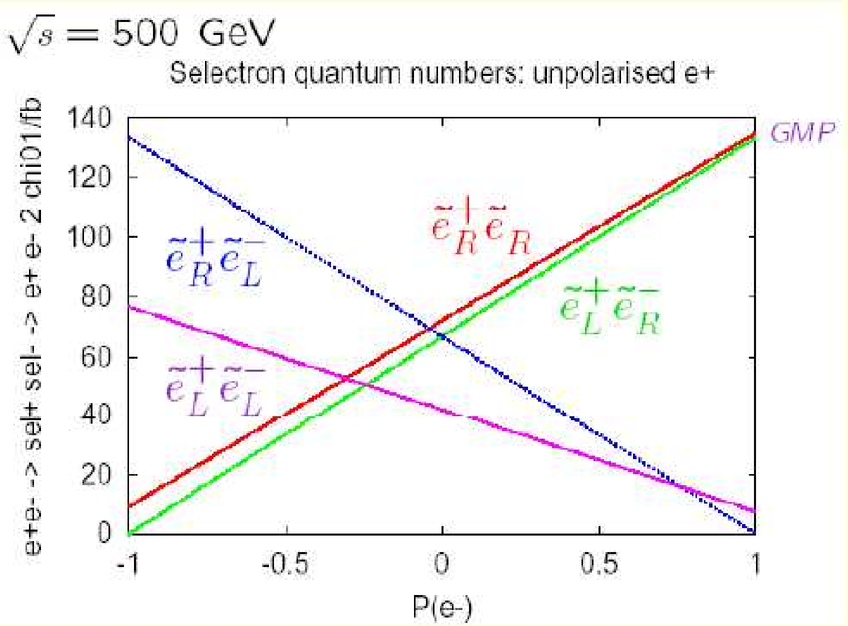
- ultimate proof for SUSY is spin measurement

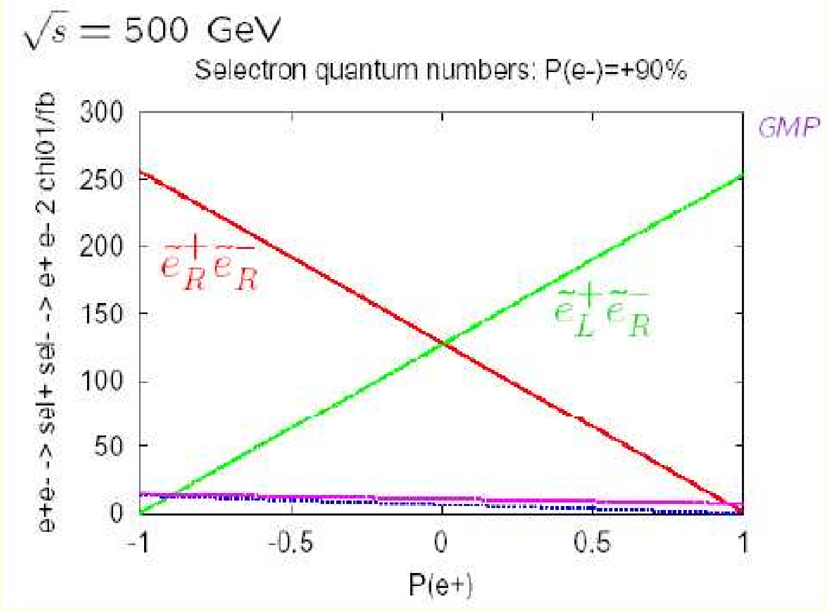
- methods for measuring the spins:

  - asymmetry method : very difficult
  - cross sections are very sensitive
  - new: MT2-assisted on-shell reconstruction of WIMP momentum allows gluino reconstruction -- then use s-distribution to distinguish UED from SUSY
  - new: include freedom in couplings, mixing angles, p/anti-p fraction and recombine into 3 free parameters

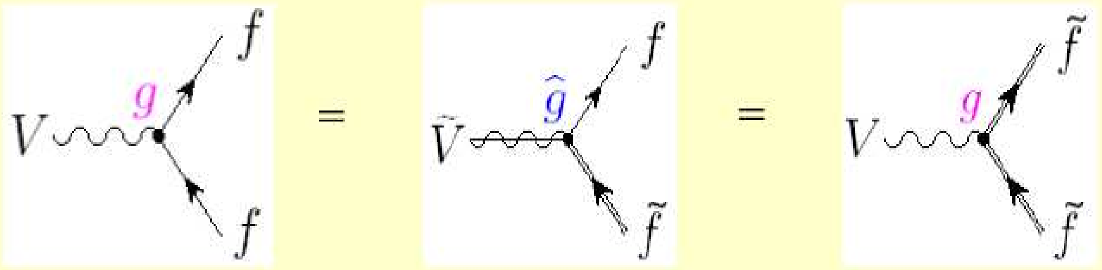
LC: Determination of chiral quantum numbers

[*K. Desch, LHC2FC Workshop '09*]





Test fundamental SUSY relations



[Moortgat-Pick]

CP-violating effects at LHC and LC

[G. Moortgat-Pick, LHC2FC Workshop '09]

- SUSY provides many new sources for CP-violation
  - constraints on parameters from e, n, Hg dipole moments, LEP, Tevatron, b -> sγ, g_μ-2, dark matter searches, etc....
- Determination of phases in two steps
  - observation of unique effects of CP-violation at LHC
  - disentangling and determination of corresponding phase parameter at ILC

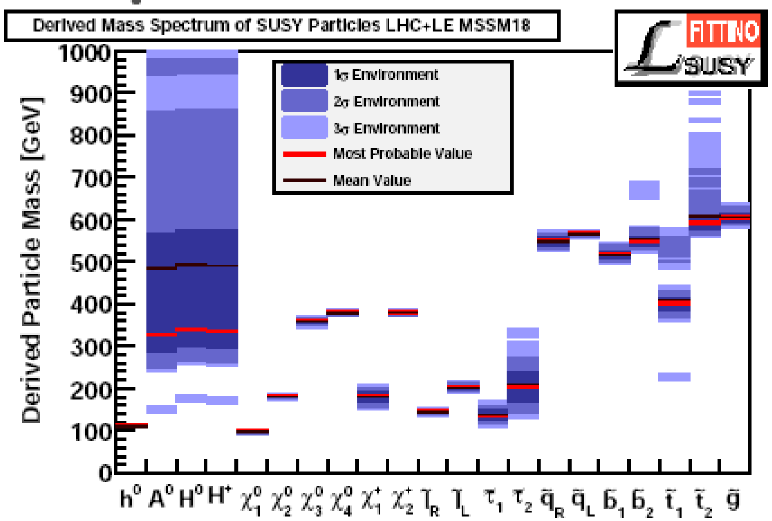
Use CP-odd observable:

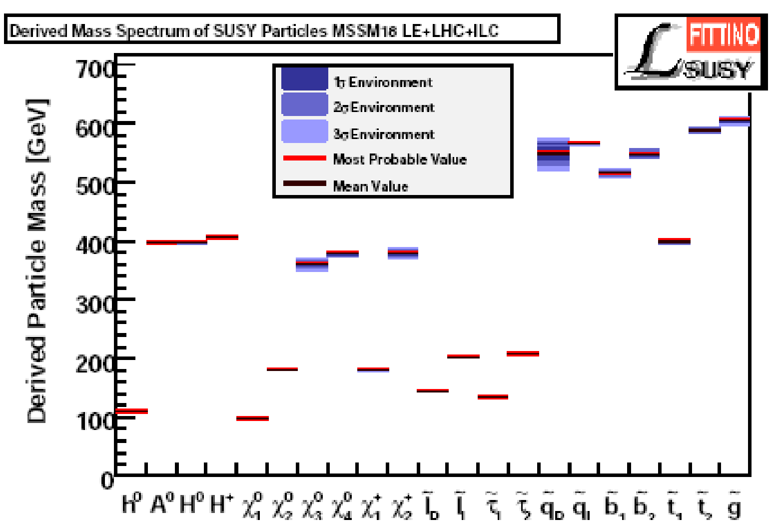
- Triple product correlations show different dependence on phases
- At LHC: qq,gg -> squarks -> gauginos -> leptons

Global fit for MSSM low-energy parameters: precision observables + LHC + ILC

[P. Bechtle, LHC2FC Workshop '09]

Comparison of the Collider Measurements of Masses





- Tremendous improvement of the Higgs sector
- Strong improvement of the slepton and gaugino sector
- Some improvement in the squark sector
- No bias any more
- Gaussian distributions

Summary on missing energy signatures

[*F. Moortgat, LHC2FC Workshop '09*]

From the LHC towards a Future Collider ...

- Getting ready for early LHC running:
  - ATLAS and CMS working on data-driven MET control methods
  - simplified approach to (early) new physics: OSET's

- Progress on methods for SUSY mass/parameter determination:
  - a lot of progress on MT2 and on mass relation method
  - also new techniques for spin measurements
  - feasibility to observe CP phases at the LHC

- Predicting the SUSY mass scales
  - from all existing data to LHC, and from the LHC to FC
  - baysian and frequentist approaches
  - not only constrained models, also full pMSSM

General observations on the talks:
- FC is still assumed to be a LC ... what about the other options?

Other new signatures

[*A. De Roeck, LHC2FC Workshop '09*]

- New "classical" signatures
  - Extend discovery reach @ LHC
  - Measuring properties of the new particles/interactions
- New unusual "exotic" signatures
  - Impact on present and future detectors (eg at LC)
- Connection with flavor physics
- Discussion on data presentation and archiving
- Discussion of "What if" scenarios: which machines are optimal/useful for the next steps
  - Plenary discussions and discussion sessions on specific topics
  - General context: the charge of our WG for the physics classes allocated to us

Z' studies

[A. De Roeck, LHC2FC Workshop '09]

T. Rizzo

A Z'-like state at the TeV scale in the Drell-Yan channel is a very common prediction in *many* BSM scenarios:

- Extended SUSY-GUT groups
- Sneutrinos in R-Parity violating SUSY
- String constructions/intersecting branes
- Little Higgs models
- Hidden Valley/Sector models
- Extra dimensions: gauge & graviton KK's
- String excitations
- Twin Higgs models
- Unparticles
- Wimponia
- ?????? = all the stuff we haven't though of yet

c/o Kevin Black

The LHC will open up a window to look for such states very soon… *but* how do we know what we've found???

2

Summary on Z'-like objects

[*A. De Roeck, LHC2FC Workshop '09*]

- If coupling not small and Z' not too heavy: discoveries with 10 fb^{-1} (200 pb^{-1}/10 TeV) possible!
- Detailed information on Z' needs more data: full LHC or even SLHC
- Weakly coupled Z' need full LHC luminosity to be detected and/or SLHC or can be missed all together...
- Full map of the couplings needs lots of luminosity or most likely another collider
  - E.g the LHeC (or a linear collider) can add/resolve the couplings
  - If few TeV Z' like object is found, then CLIC would be the most ideal machine (or muon collider, if feasible)
- Indirect Z' searches at LHC not likely to be useful

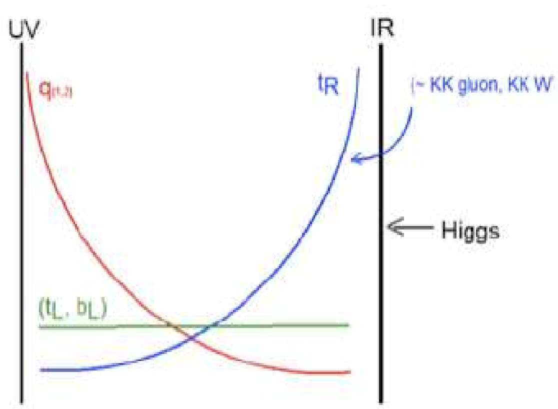
The top quark as a tool for new physics searches

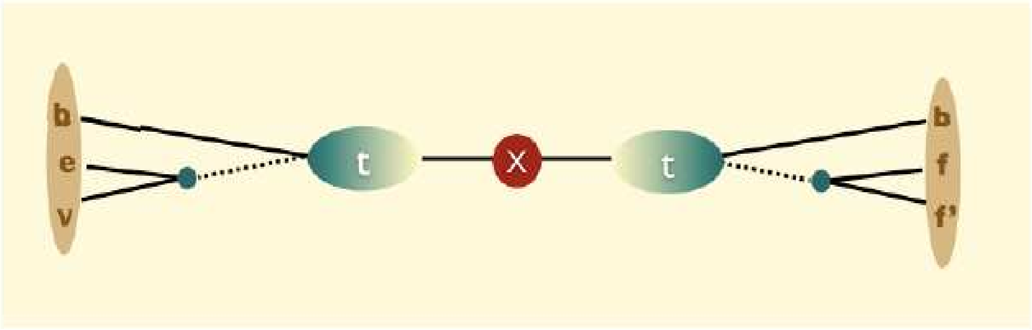
[A. De Roeck, LHC2FC Workshop '09]

Recent developments in models: the prominent role of top production
Top co-anihilation SUSY, top resonances, RS→top top etc.
Often this leads to 'boosted top' ie the hadronic decay jets merge

T. Han et al.

- Eg RS → t tbar





The jets typically appear as 'fat' jets
with internal structure

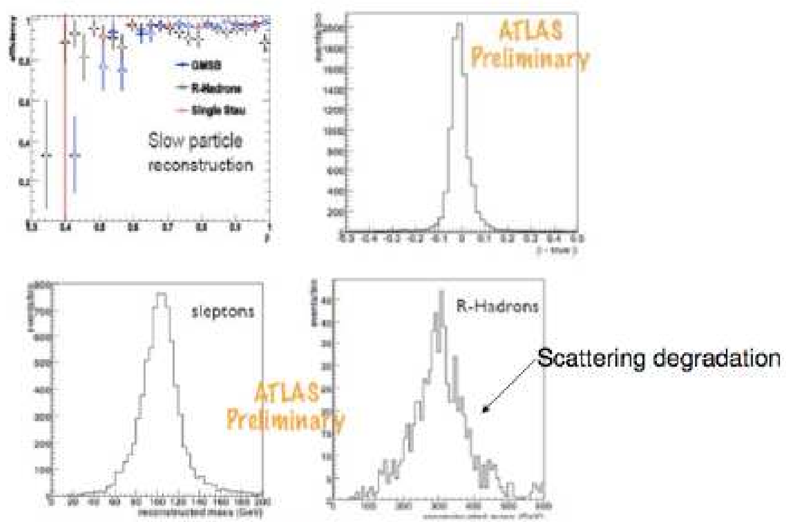
⇒High P_T tops

Re-emphasized as being a major tool for NP searches

Heavy charged stable particles

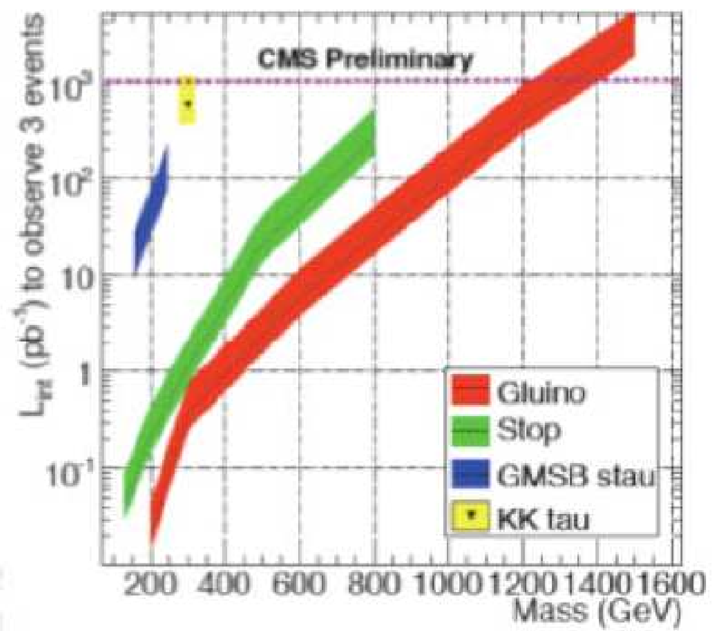
[*A. De Roeck, LHC2FC Workshop '09*]

Reconstructing slow particles



arXiv:0901.0512

Stable Exotic particles



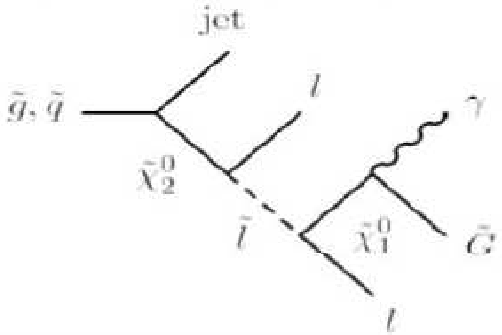
Impact on future detectors: TOF or multi-bunch information will become more important (SLHC?)
Mass scale determines the energy of the next machine

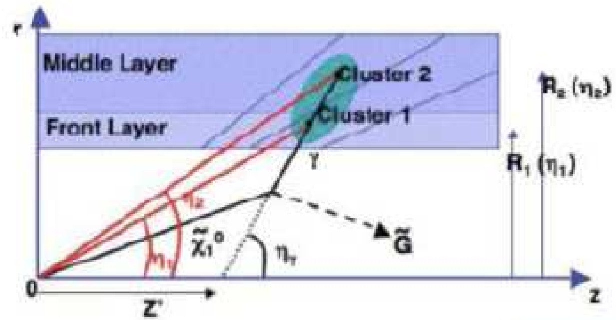
Non-pointing photons

[*A. De Roeck, LHC2FC Workshop ’09*]

GMSB scenarios - neutralino NLSP.

name	NLO (LO) σ [pb]	Λ [TeV]	M_m [TeV]	$C_{\tilde{G}}$	$c\tau$ [mm]	$M_{\tilde{\chi}_1^0}$ [GeV]
GMSB1	7.8 (5.1)	90	500	1.0	1.1	118.8
GMSB2	7.8 (5.1)	90	500	30.0	$9.5 \cdot 10^2$	118.8
GMSB3	7.8 (5.1)	90	500	55.0	$3.2 \cdot 10^3$	118.8



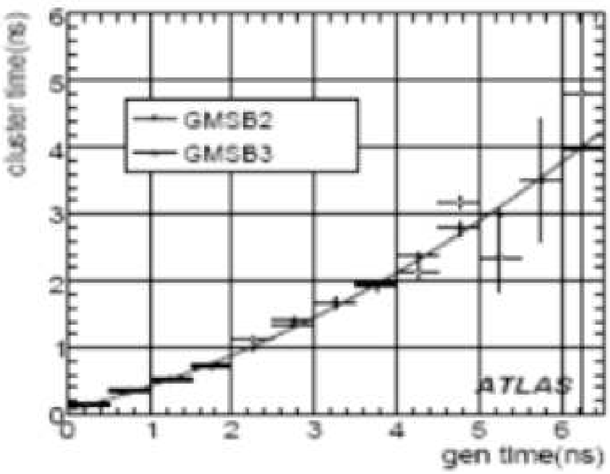


$C_{grav} > 1$

$\Rightarrow$ neutralino decays away from IP.

$\Rightarrow$ non-pointing high p_T photon.

Δt reconstruction

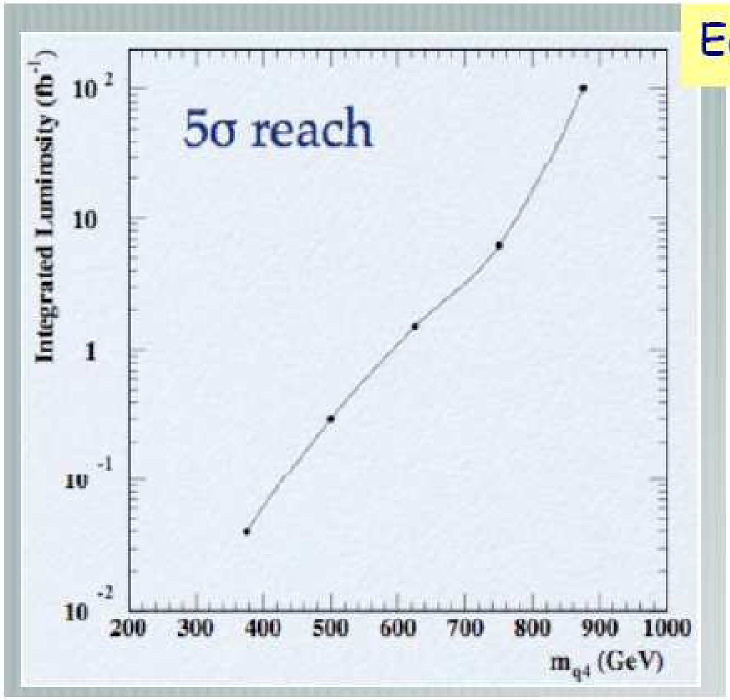


Impact on future detector

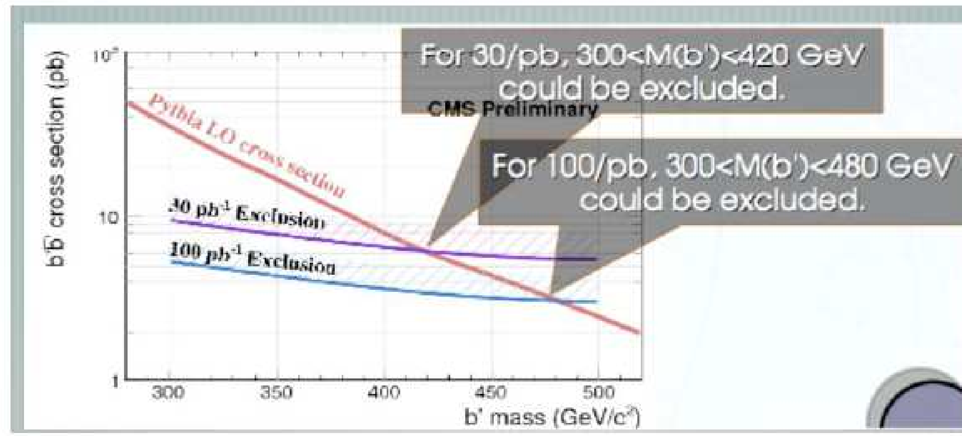
4th-generation quarks at the LHC

A hint from the Tevatron?

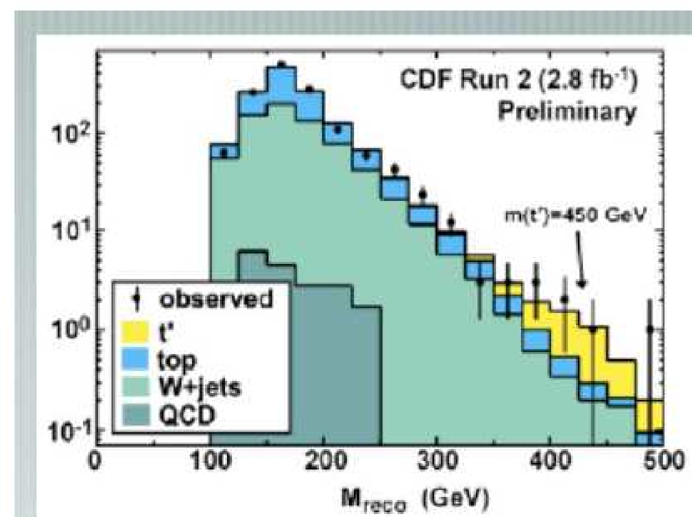
[A. De Roeck, LHC2FC Workshop '09]



Early data will cover the region up to 500 GeV



Tantalizing 'hint' from CDF on t'
What does D0 say?
What is the MC 'tail' uncertainty?

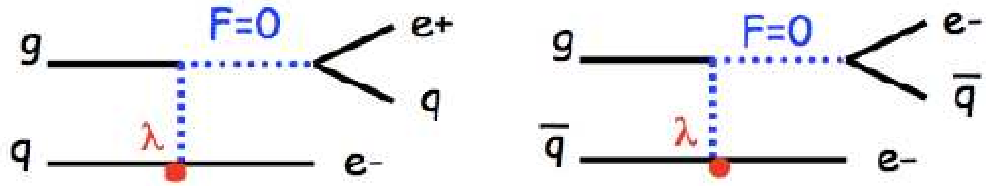


Leptoquarks at LHeC

[E. Perez, LHC2FC Workshop '09]

Determination of LQ properties in single production: e.g. Fermion Number

In pp: look at signal separately when resonance is formed by (e^+ + jet) and (e^- + jet) :



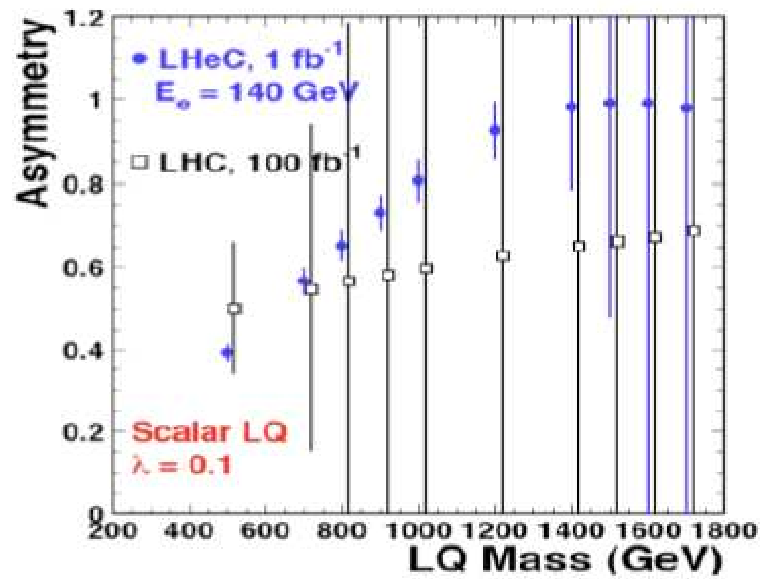
$\sigma(e^+_{out}) > \sigma(e^-_{out})$
for F=0

Sign of the asymmetry gives F, but could be statistically limited at LHC. (*)

Easier in ep ! Just look at the signal with incident e+ and incident e–, build the asymmetry between $\sigma(e^+_{in})$ and $\sigma(e^-_{in})$.

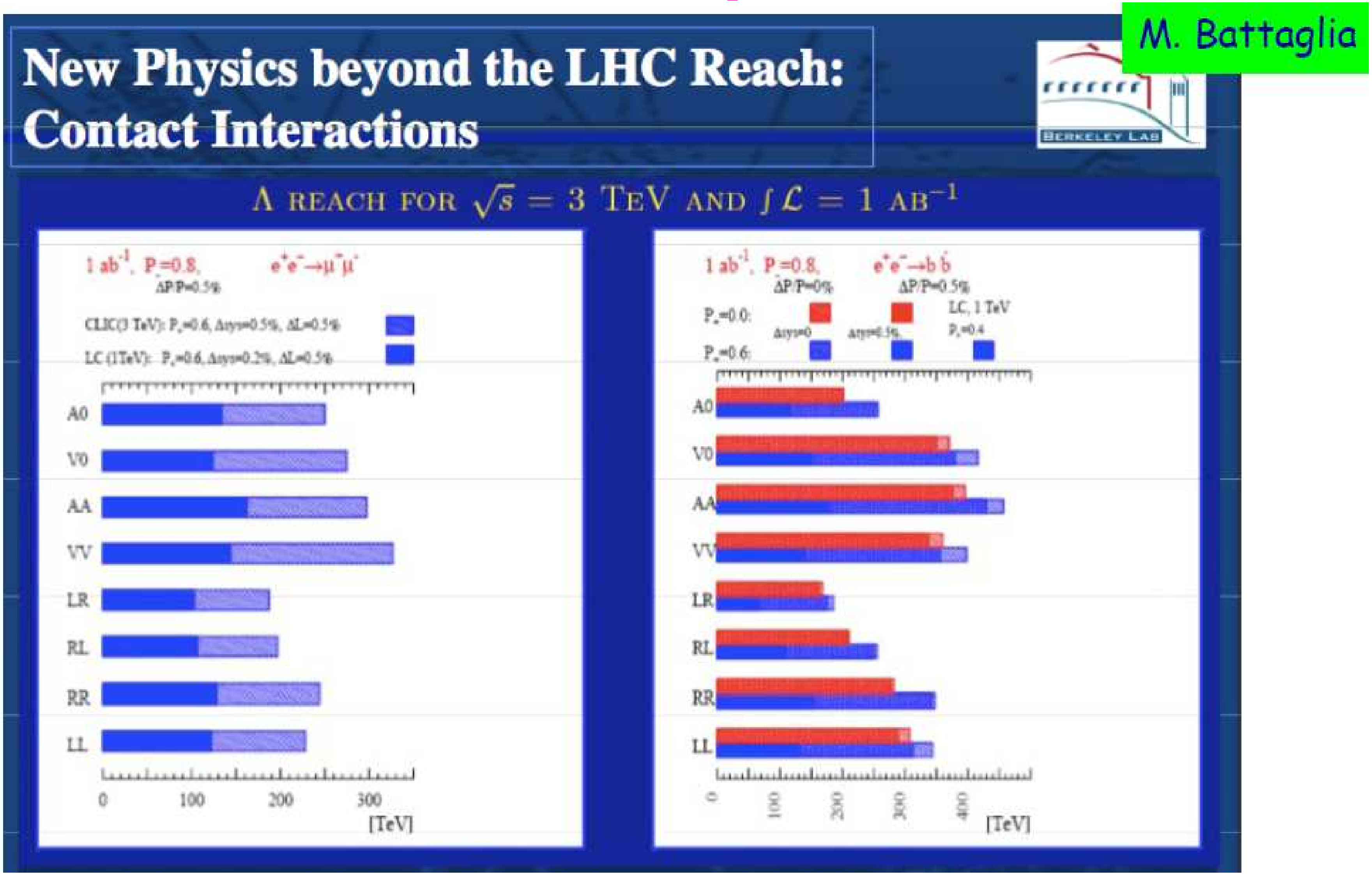
If LHC observes a LQ-like resonance, M < 1 - 1.5 TeV, with indications (single prod) that λ not too small, LHeC would solve the possibly remaining ambiguities.

(*) First rough study done for the 2006 paper. Need to check / refine with a full analysis of signal and backgrounds.



Contact interactions at CLIC

[*A. De Roeck, LHC2FC Workshop '09*]



Indicative physics reach of future colliders

[A. De Roeck, LHC2FC Workshop ’09]

Ellis, Gianotti, ADR
hep-ex/0112004+ few updates

Units are TeV (except $W_L W_L$ reach)
∫Ldt correspond to 1 year of running at nominal luminosity for 1 experiment

PROCESS	LHC 14 TeV 100 fb^{-1}	SLHC 14 TeV 1000 fb^{-1}	DLHC 28 TeV 100 fb^{-1}	VLHC 40 TeV 100 fb^{-1}	VLHC 200 TeV 100 fb^{-1}	ILC 0.8 TeV 500 fb^{-1}	CLIC 5 TeV 1000 fb^{-1}
Squarks	2.5	3	4	5	20	0.4	2.5
$W_L W_L$	2σ	4σ	4.5σ	7σ	18σ	6σ	90σ
Z'	5	6	8	11	35	8†	30†
Extra-dim (δ=2)	9	12	15	25	65	5-8.5†	30-55†
q*	6.5	7.5	9.5	13	75	0.8	5
Λcompositeness	30	40	40	50	100	100	400
TGC (λ_γ)	0.0014	0.0006	0.0008		0.0003	0.0004	0.00008

† indirect reach
(from precision measurements)

Approximate mass reach machines:
$\sqrt{s}$ = 14 TeV, L=10^{34} (LHC) : up to ≈ 6.5 TeV
$\sqrt{s}$ = 14 TeV, L=10^{35} (SLHC) : up to ≈ 8 TeV
$\sqrt{s}$ = 28 TeV, L=10^{34} : up to ≈ 10 TeV

To-do list for WG4 write-up

[*A. De Roeck, LHC2FC Workshop '09*]

- Many of the exotica signals are accessible already with low luminosity. More lumi will extend the reach and allows to measure for characteristics. Some model tests will take more time (Eg. little Higgs)
  - Road-map of present knowledge on when we are sensitive to what mass 200 pb^{-1} (10 TeV) - 10 fb^{-1} (14 TeV) but also higher, up to SLHC (see example). What if NO signal? Interpretation of Signal
  - What characteristics can we determine with LHC alone and what would be needed as next machine... Energy/luminosity?
  - Detector design: unusual signatures. When can we get exp. feedback on stopped gluinos, Hidden Valley, Heavy stable charged particles?
- For our study: select a few benchmark processes like Z', leptoquarks? Contact interactions? Fourth generation...
- Some scenarios identified where good next options would be SLHC, LHeC, ILC or CLIC. No specific scenario for a muon collider, but should be similar to CLIC. DLHC/VLHC extend discovery reach, as shown

Conclusions

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- The main future option beyond LHC / SLHC remains a Linear Collider (ILC / CLIC), with a likely first phase at 500 GeV or below; intense discussions at the workshop

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Conclusions

- The main future option beyond LHC / SLHC remains a Linear Collider (ILC / CLIC), with a likely first phase at 500 GeV or below; intense discussions at the workshop
- Much less activity on the other options
- LC performance (machine and detector(s)) & cost will be crucial factors
- A Workshop Report is in preparation
- Looking forward to exciting results from the LHC!