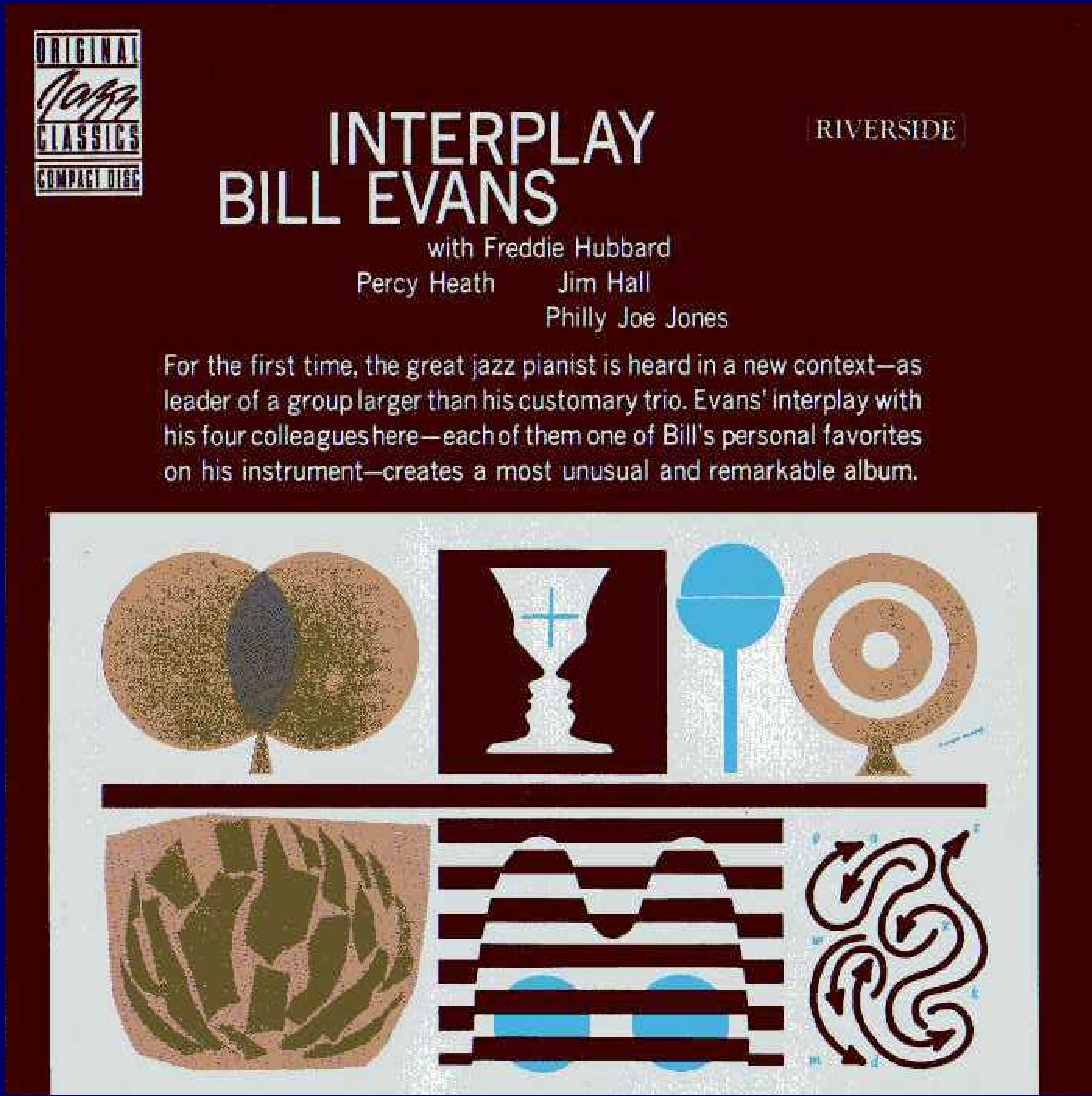
# LHC ILC Interplay



**Klaus Desch**
**University of Bonn**

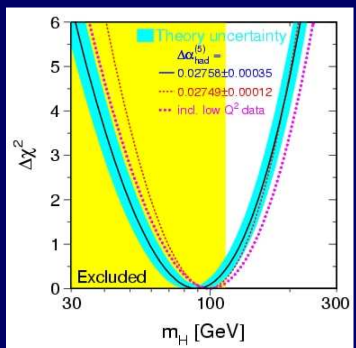

**Fermilab, April 13, 2007**

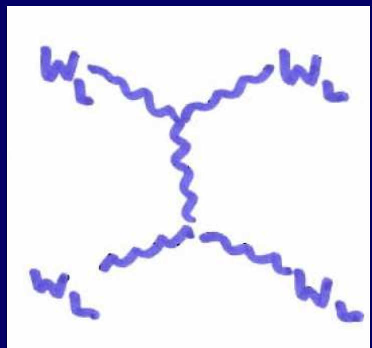

ORIGINAL Jazz CLASSICS COMPACT DISC
INTERPLAY
BILL EVANS
RIVERSIDE
with Freddie Hubbard
Percy Heath
Jim Hall
Philly Joe Jones
For the first time, the great jazz pianist is heard in a new context—as leader of a group larger than his customary trio. Evans' interplay with his four colleagues here—each of them one of Bill's personal favorites on his instrument—creates a most unusual and remarkable album.

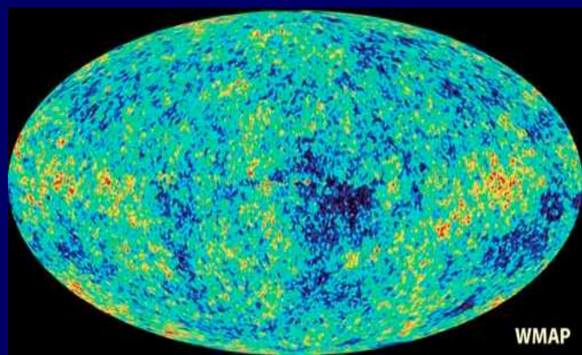
# The Terascale

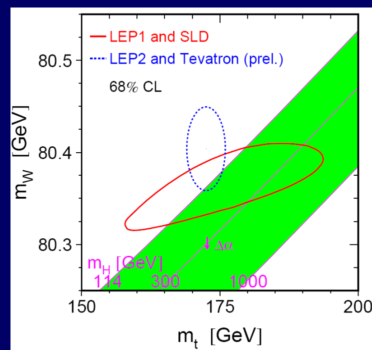
**Very good reasons to explore the TeV-scale:**

- **Evidence for light Higgs**
- **SM without Higgs violates unitarity at ~1.3 TeV**
- **Hierarchy between $m_{weak}$ and $m_{Planck}$ to be protected at TeV scale**
- **Dark matter consistent with sub-TeV-scale WIMP (e.g. SUSY-LSP)**
- **$2m_{top}$ = 350 GeV**









# Driving Physics Questions

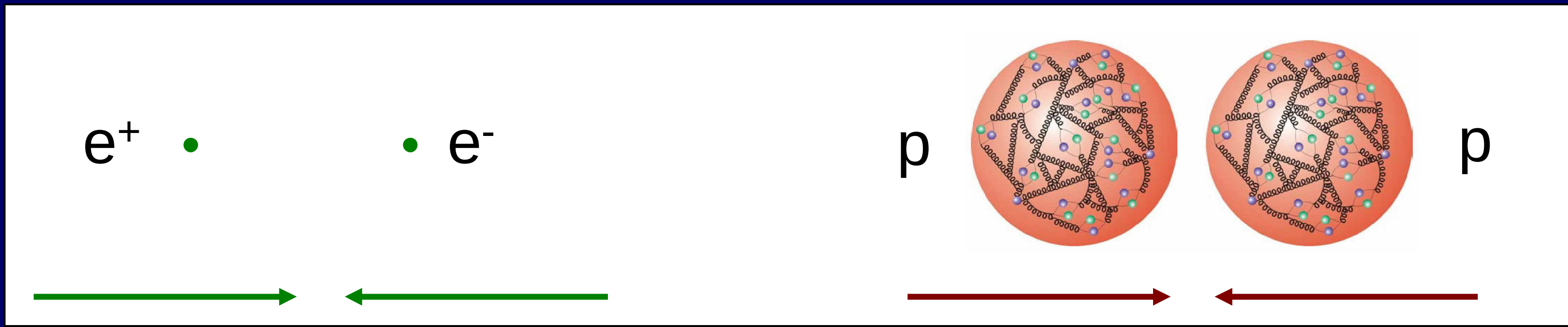
**Broad and rich spectrum of fundamental questions are awaiting answers at the Terascale:**

- **Electroweak Symmetry Breaking**
- **New Symmetries and Unification of Forces**
- **Space-Time Structure**

\+ **Connecting Cosmology and Particle Physics**

**and surprises…**

# Complementarity of tools




**Electron positron collisions at high energy provide a powerful tool to explore TeV-scale physics complementary to the LHC**

**Due to their point-like structure and absence of strong interactions there are clear advantages of $e^+e^-$ collisions:**

- **known and tunable centre-of-mass energy**
- **clean, fully reconstructable events**
- **polarized beams**
- **moderate backgrounds**
  **→ no trigger**

**→broad consensus for a Linear Collider with up to at least ~500 GeV**

# Complementarity of tools

**EPP2010 report**

TABLE 3-1 Potential Synergies Between the ILC and LHC in Explorations of the Terascale

| If LHC Discovers: | What ILC Could Do: |
|---|---|
| A Higgs particle | Discover why the Higgs exists and who its cousins are. Discover effects of extra dimensions or a new source of matter-antimatter asymmetry. |
| Superpartner particles | Detect the symmetry or supersymmetry. Reveal the supersymmetric nature of dark matter. Discover force unification and matter unification at ultra-high energies. |
| Evidence for extra dimensions | Discover the number and shape of the extra dimensions. Discover which particles are travelers in extra dimensions and determine their locations within them. |
| Missing energy from a weakly interacting heavy particle | Discover its identity as dark matter. Determine what fraction of the total dark matter it accounts for. |
| Heavy charged particles that appear to be stable | Discover that these eventually decay into very weakly interacting massive particles; identify these "super WIMPS" as dark matter. |
| A Z-prime particle, representing a previously unknown force of nature | Discover the origin of the Z-prime. Connect this new force to the unification of quarks with neutrinos, or quarks with the Higgs, or with extra dimensions. |
| Superpartner particles matching the predictions of supergravity | Discover telltale effects from the vibrations of superstrings. |

# Interplay and Synergy

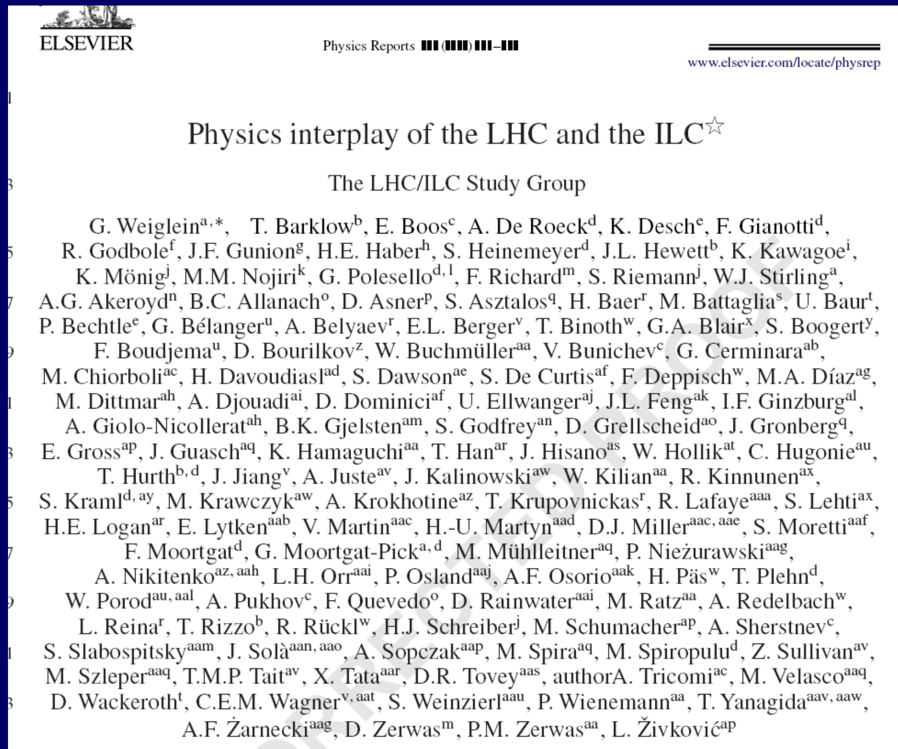
$$HC + LC > HC$$

$$HC \oplus LC > HC + LC$$

$$HC \otimes LC > HC \oplus LC$$

LCWS Korea 2002

→ **LHC/ILC Study group**
**Phys. Rept. 426 (2006) 47**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Physics interplay of the LHC and the ILC☆

The LHC/ILC Study Group

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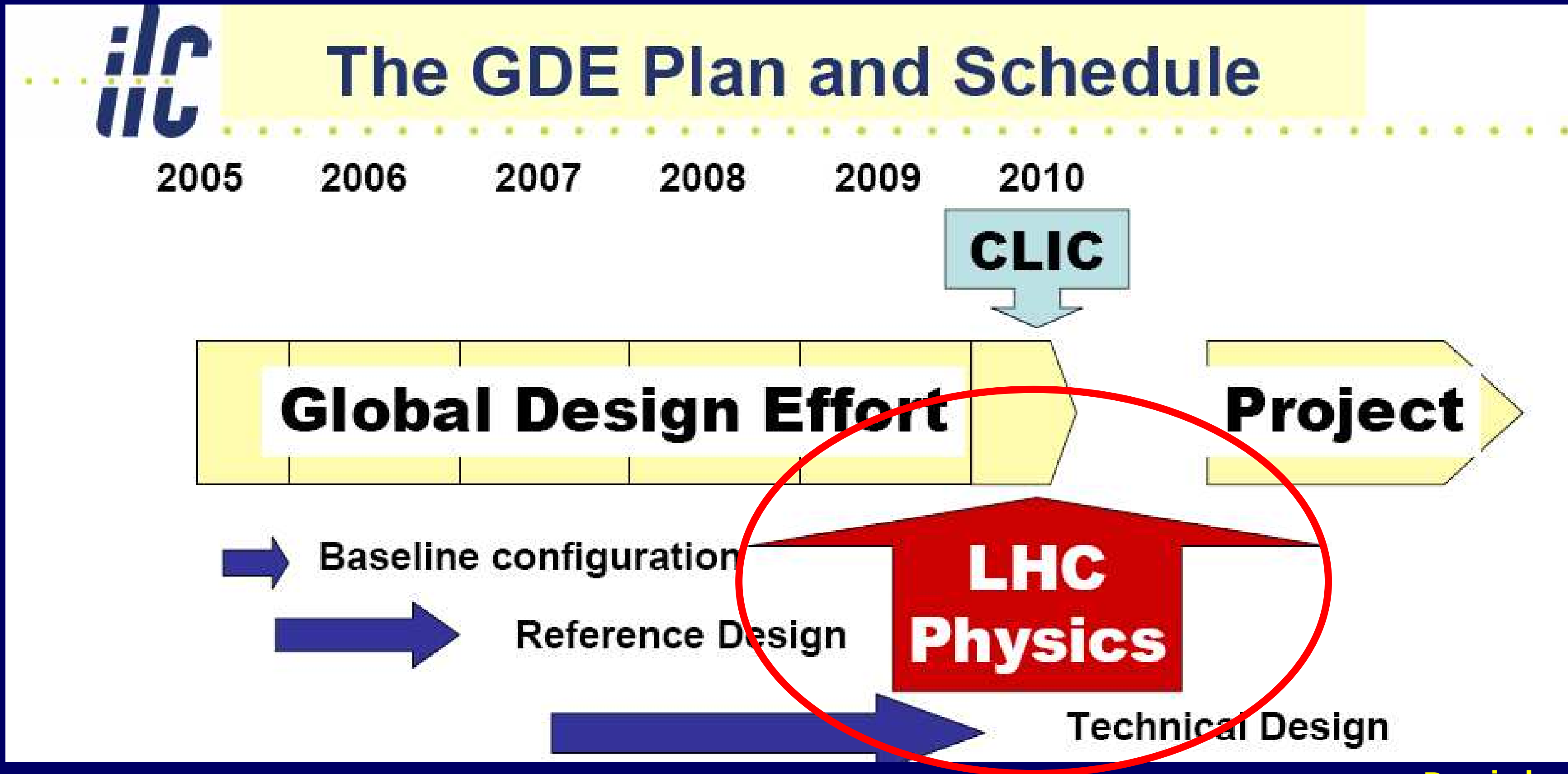
# Getting excited




Barish

**With first collisions at 14 TeV next year, it is obvious that we have to start understanding implications of LHC discoveries for the ILC in much more detail**

# Getting excited

Basic (since 2001): Case for a 500 GeV Linear Collider upgradable to 1 TeV
$\rightarrow$ general physics case of the ILC does not depend on the LHC
(no matter what LHC will see, ILC has an important additional value)

Advanced (2002-2006): Explore the synergies if LHC and ILC
$\rightarrow$ both machines, if analyzed (and ideally running) simultaneously,
will provide added value

Facing the real thing (2007-): Optimizing the ILC choices in the light of LHC discoveries

$\rightarrow$ no reason to get nervous but a reason to get excited

Abe Seiden @ SLAC : “It could be that the physics is not in the ILC reach”
could that really be the case? under which circumstances?
Burt Richter @ SLAC: “How interesting will 500 GeV be in 2020?”
are there scenarios where the initial ILC parameters (energy,luminosity) need revisiting?
Need good answers to this scepticism a.s.a.p.!

## The LHC Early Phase 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?

## Strategy

Largely signal-driven (not so much model driven)

1. The detection of only one state with properties that are compatible with those of a Higgs boson

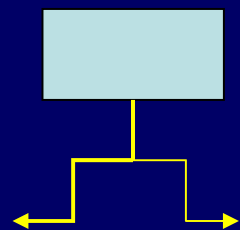
2. No experimental evidence for a Higgs boson at the early stage of LHC

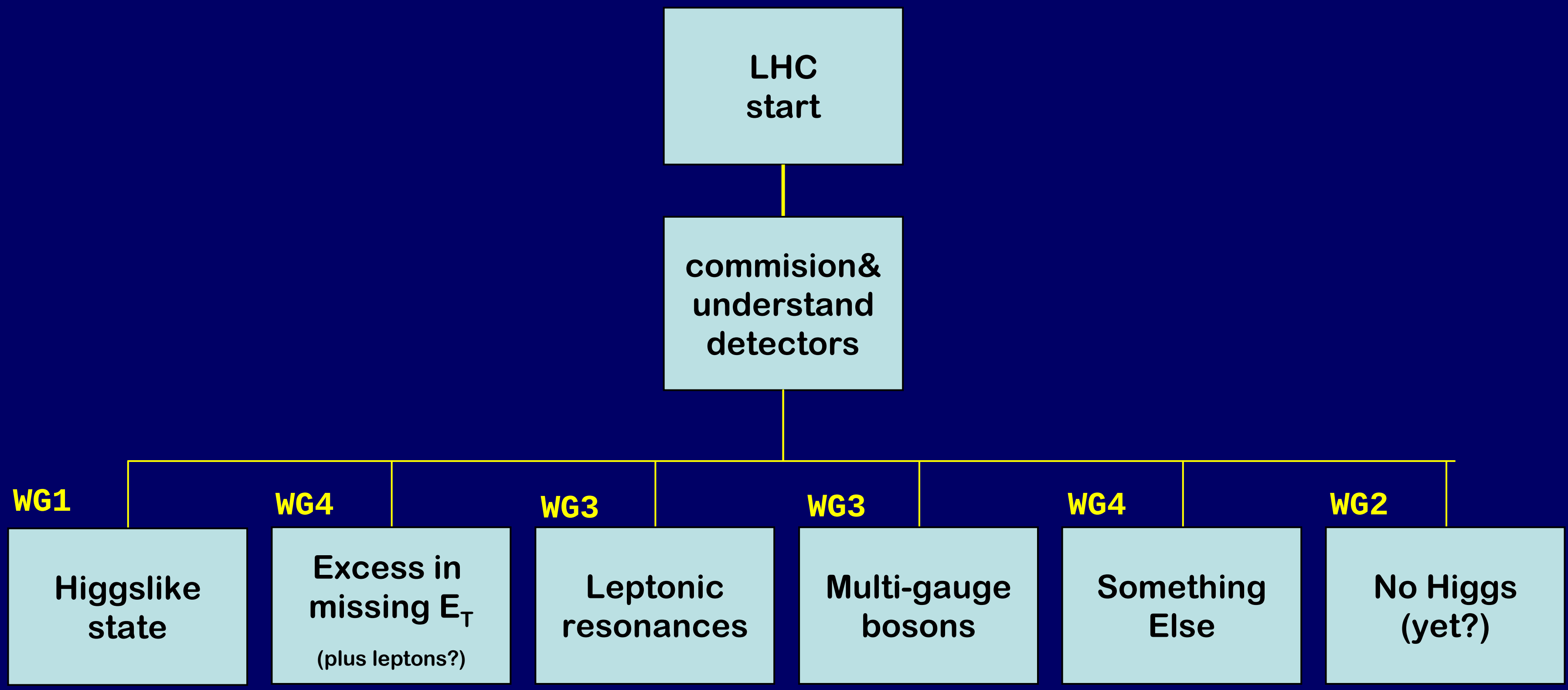
3. The detection of new states of physics beyond the Standard Model.

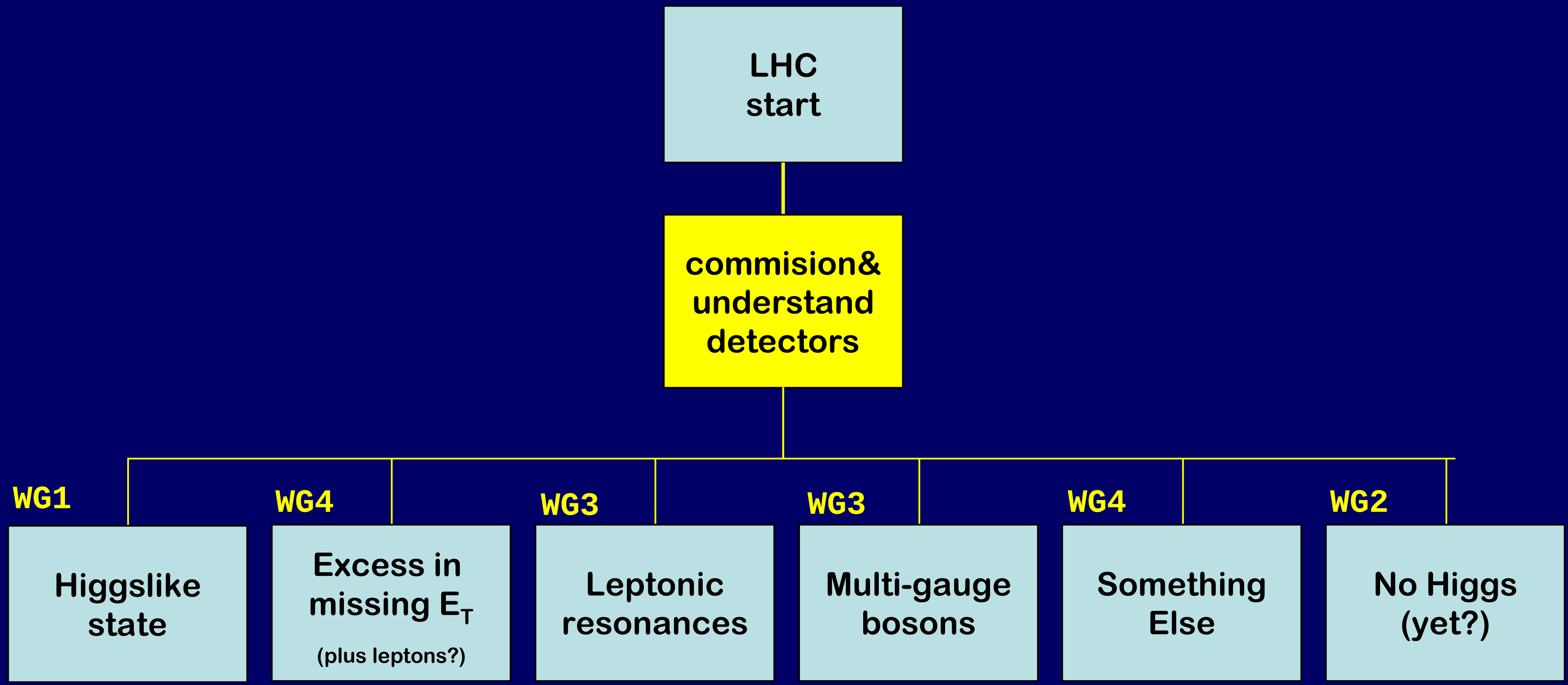
   a. Missing Energy (+nothing, leptons, jets) signals
   b. Leptonic resonances
   c. Multi-Gauge-Boson signals
   d. Everything else.

# From a maze to a decision tree


**Here, the artist might have failed:**
**There is more than one path from the LHC to the ILC!**




LHC start
commision& understand detectors
WG1
Higgslike state
WG4
Excess in missing $E_T$
(plus leptons?)
WG3
Leptonic resonances
WG3
Multi-gauge bosons
WG4
Something Else
WG2
No Higgs (yet?)

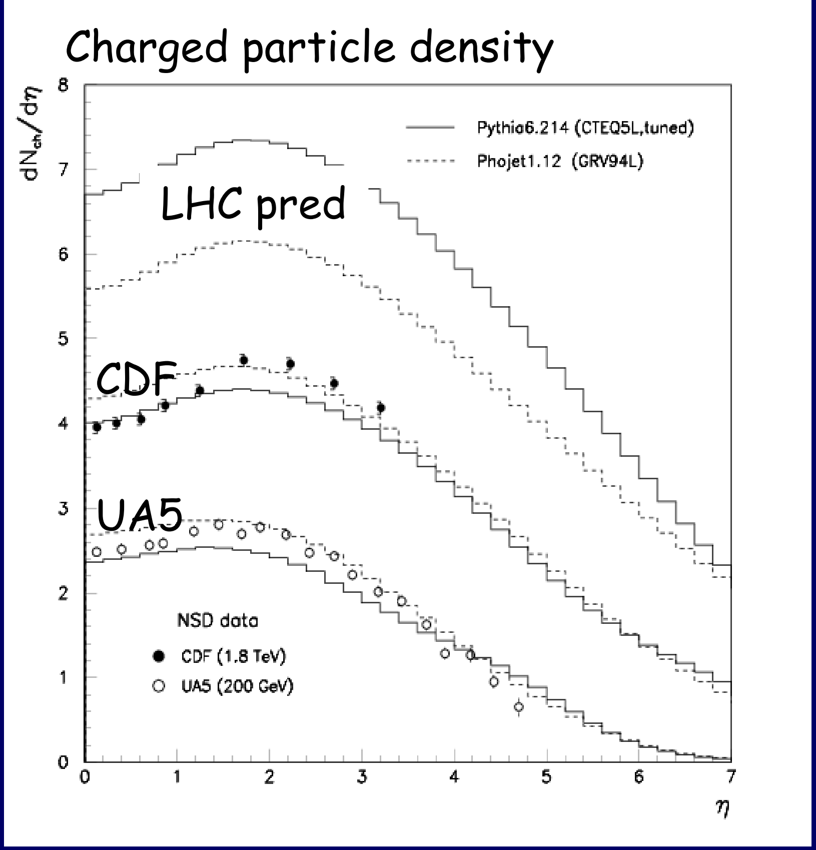


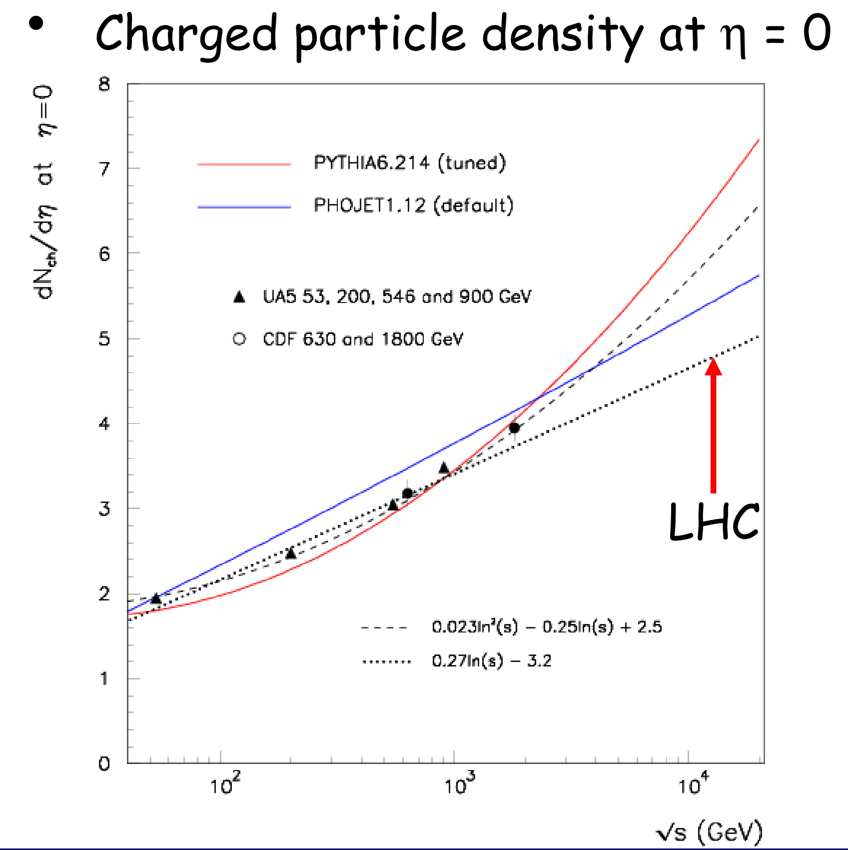

When we talk about the first 10 $fb^{-1}$ we have to account for additional time to get the detectors into a state where they are ready for discoveries.

This time certainly depends on the complexity of the signal but ATLAS + CMS deserve some patience from the community
Solid results are better than fast results

# Before discovery: work hard

## The first three minutes of data taking…




Energy dependence of dN/dη ?

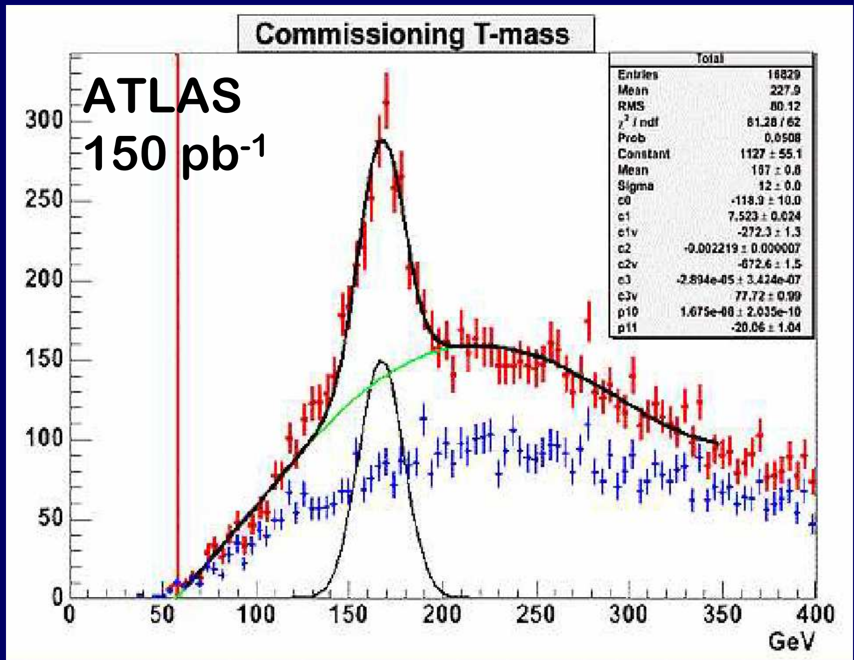
Vital for tuning Underlying Event model, Important of Jet-Energy, Etmiss

Only requires a few thousand events but needs to be accounted for in subsequent searches

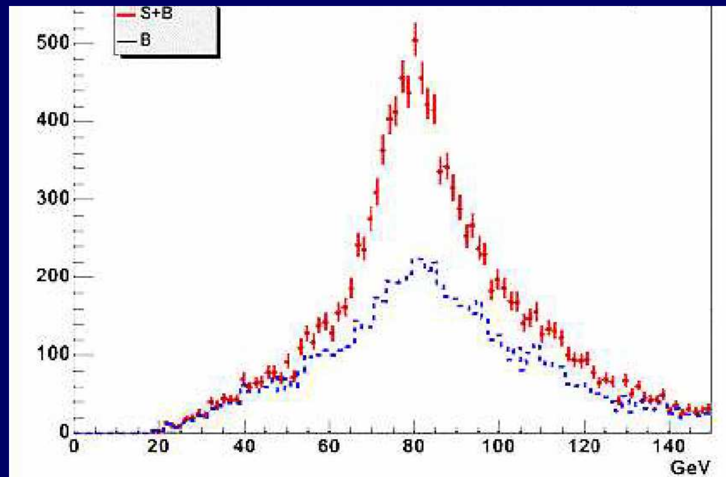
# Before discovery: work hard

## Establish the major SM signals: Z, W, top

example top:




| Channel | events/100 pb$^{-1}$ |
|---|---|
| $W \to \mu\nu$ | ~$10^6$ |
| $Z \to \mu\mu$ | ~$10^5$ |
| $tt \to \mu\nu bjjb$ | ~$10^4$ |
| jets w $p_T$>1TeV | ~$10^3$ |




also: hadronic W-mass peak
(→jet E-scale)

**No one will believe in a discovery if Z+jets, W+jets, tt+jets are not observed in agreement with SM predictions and well modelled**

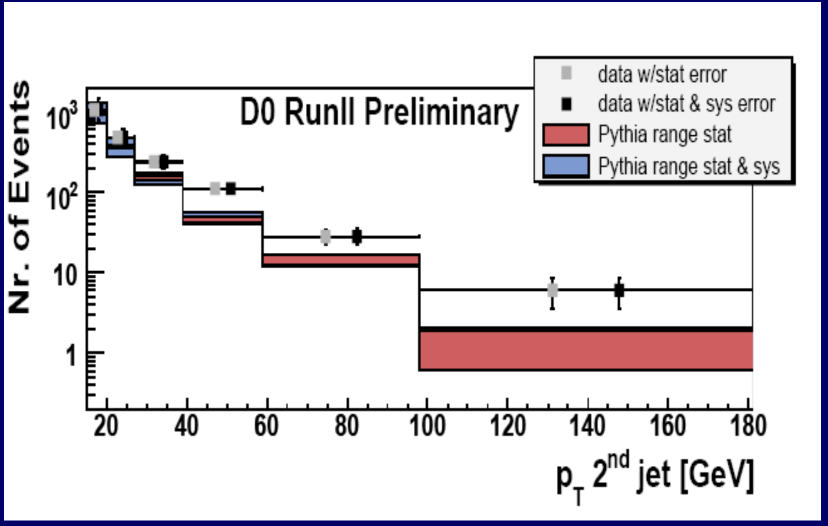
## Before discovery: work hard

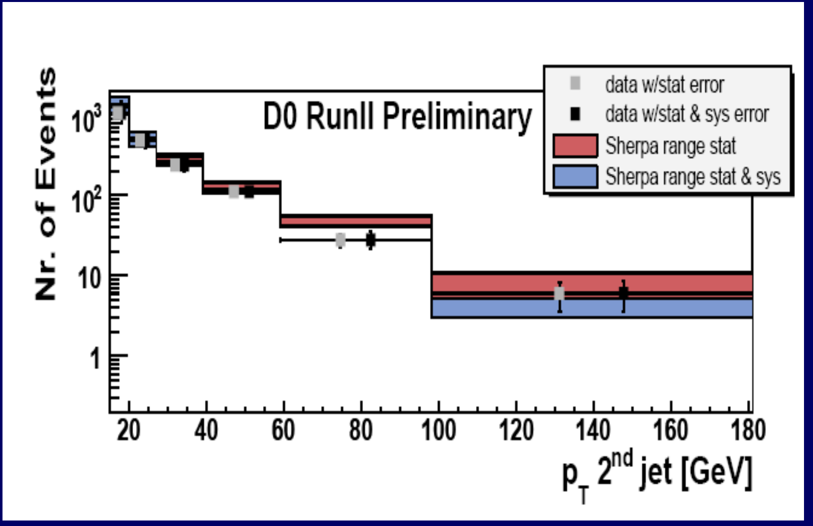
**Understand and calibrate Jets & Etmiss**

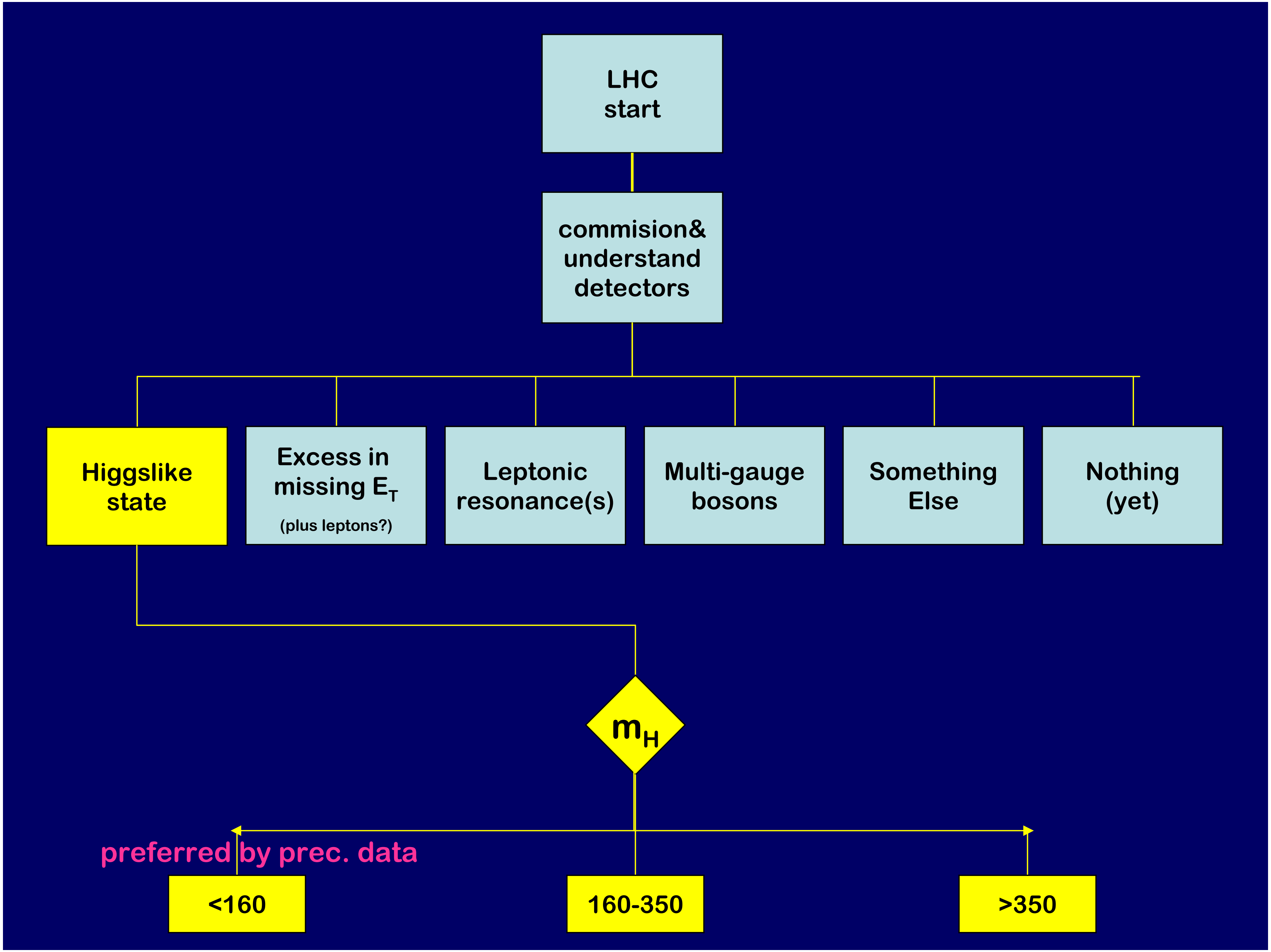
To understand the major backgrounds at the LHC (Z+jets, W+jets, tt+jets,…) we need Monte Carlo simulations beyond the classical LO+ parton shower approach.

Recent developments
MC@NLO (1 additional jet at full NLO)
ALPGEN, SHERPA, … (n additional jets as LO matrix element +
„matching“ of ME and PS

Here, the Tevatron is an important training camp…

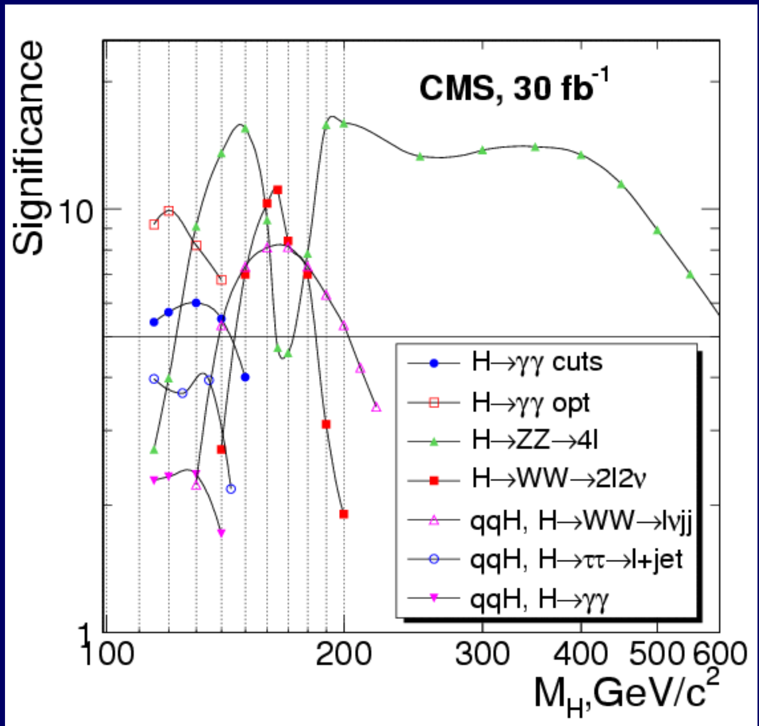


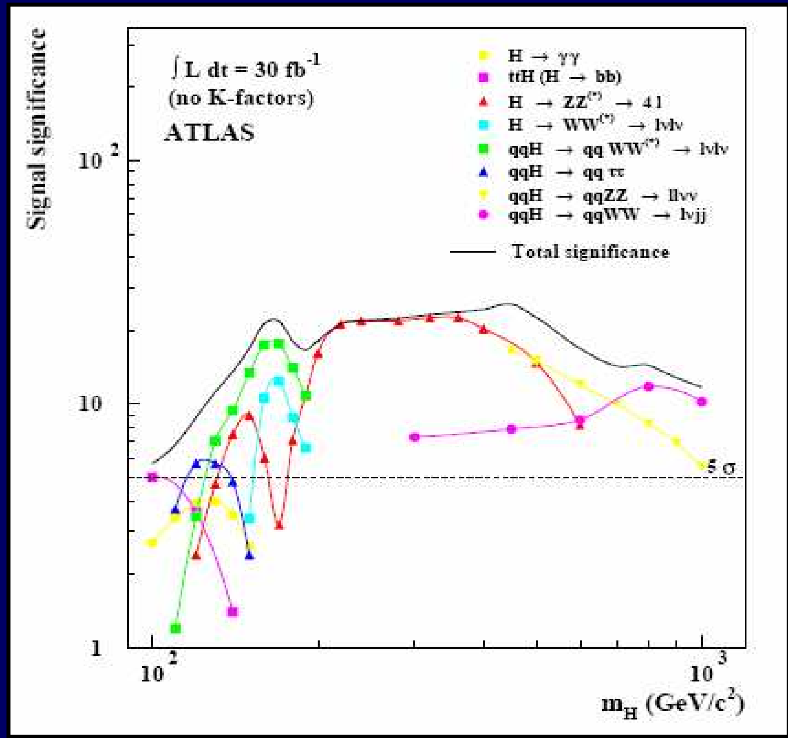





LHC start
commision& understand detectors
Higgslike state
Excess in missing $E_T$
(plus leptons?)
Leptonic resonance(s)
Multi-gauge bosons
Something Else
Nothing (yet)
$m_H$
preferred by prec. data
<160
160-350
>350

# Higgs at LHC

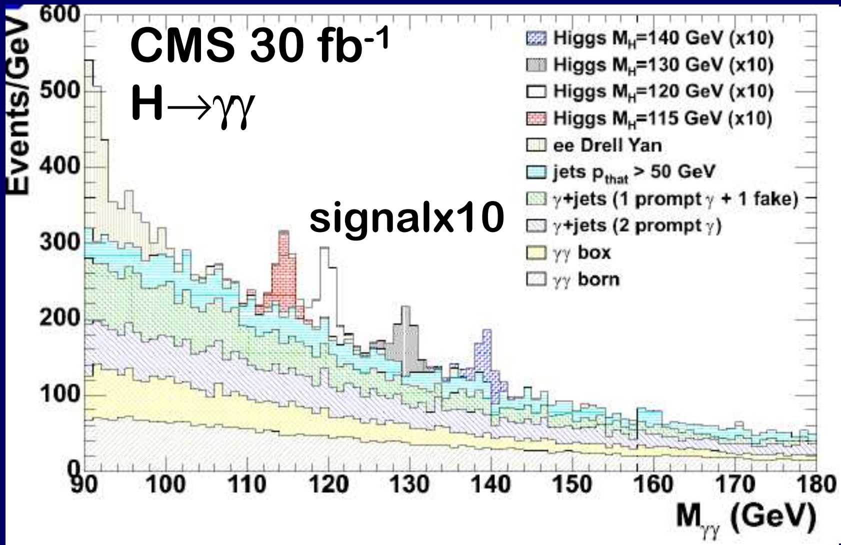


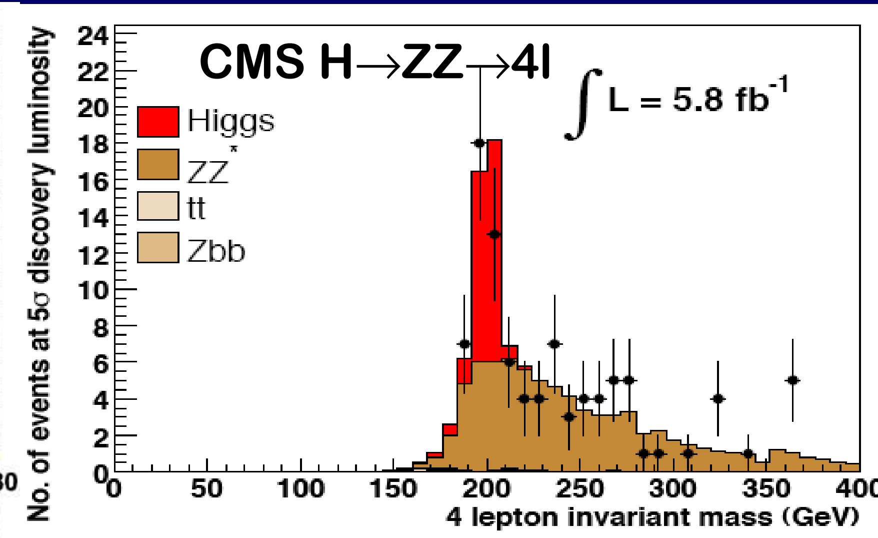



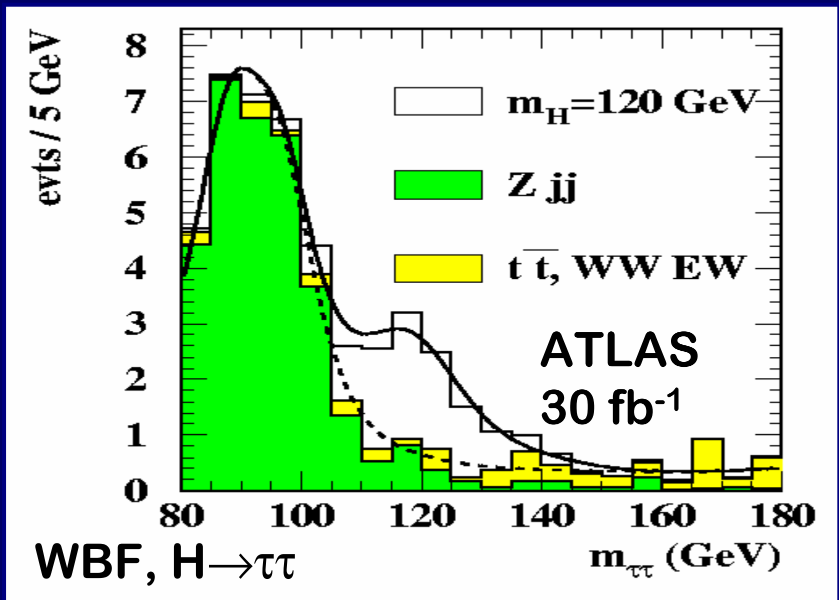

**SM Higgs discovery assured for ~10 fb$^{-1}$ over full mass range if nothing goes wrong**

**- rather easy (and fast) for $m_H$ > 140 GeV**
**- more involved for light Higgs $m_H$ < 140 GeV**

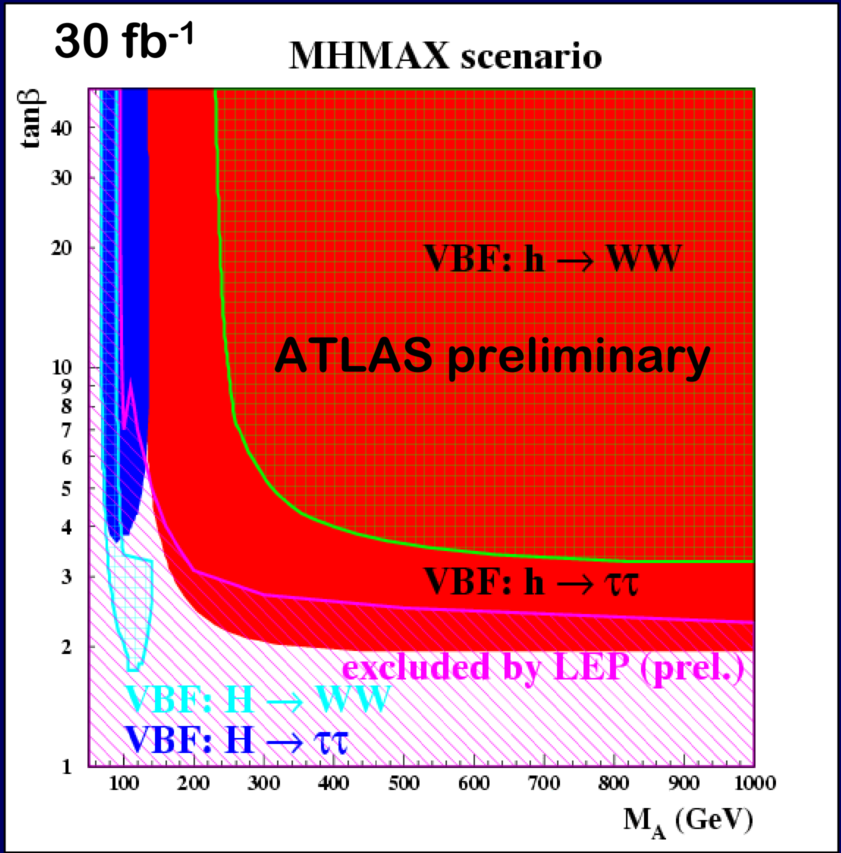
# Higgs signals at the LHC

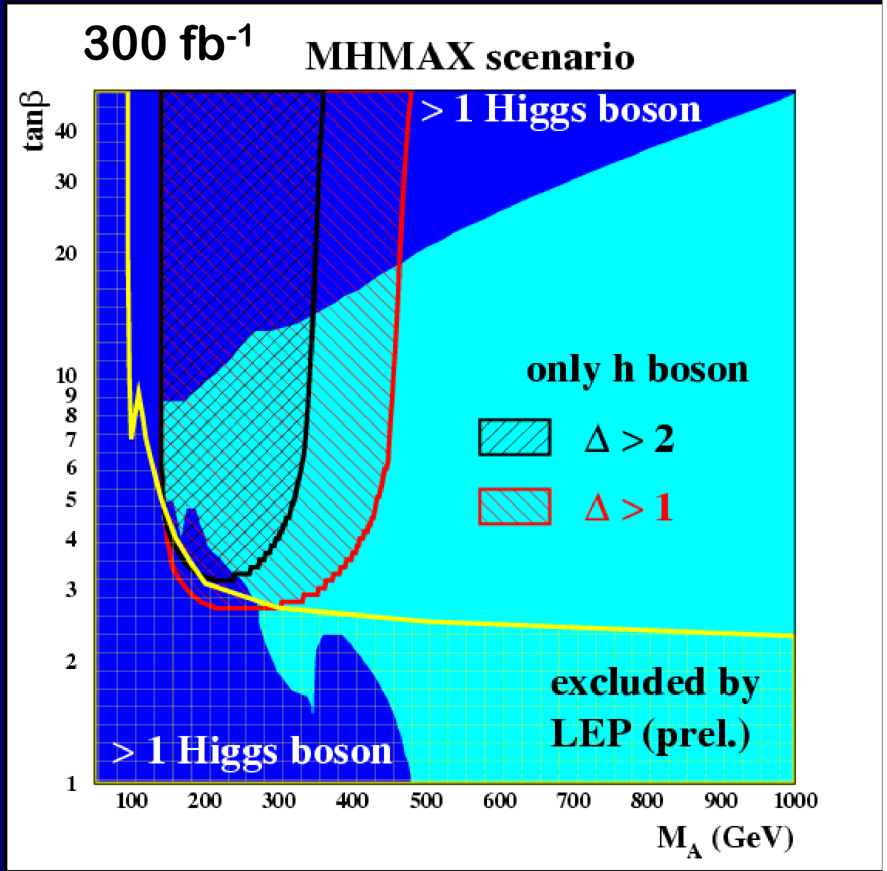


# MSSM Higgs at LHC



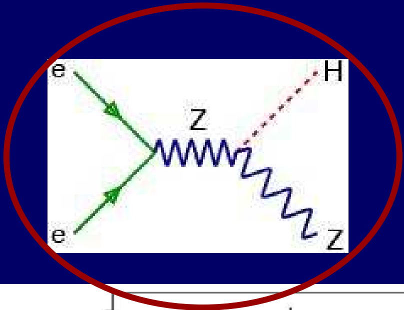

Weak Boson Fusion can cover whole parameter space for lightest MSSM Higgs boson with 30 $fb^{-1}$

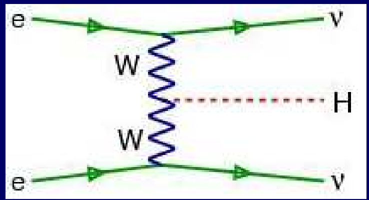
With more luminosity heavier MSSM Higgses are accessible only for large tanβ, some indirect sensitivity from light h:

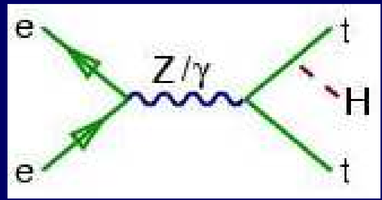
$$R = \frac{BR(H \to WW)}{BR(H \to \tau\tau)} \qquad \Delta = R / R_{SM}$$

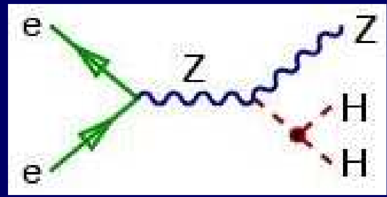
# ILC: if $m_H$ < 160 GeV

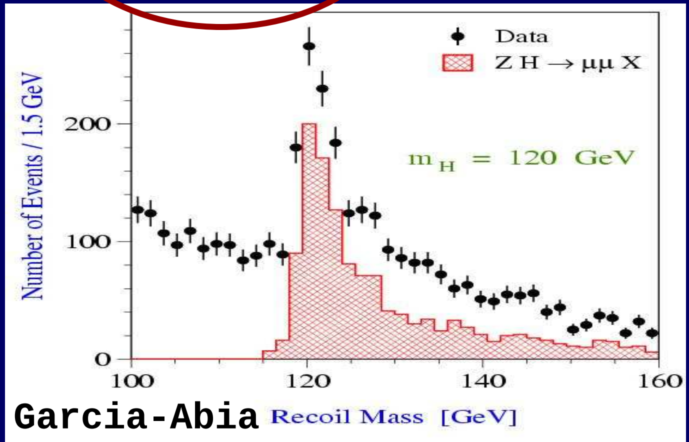
**Full program of Higgs precision measurements can (and must) be done**

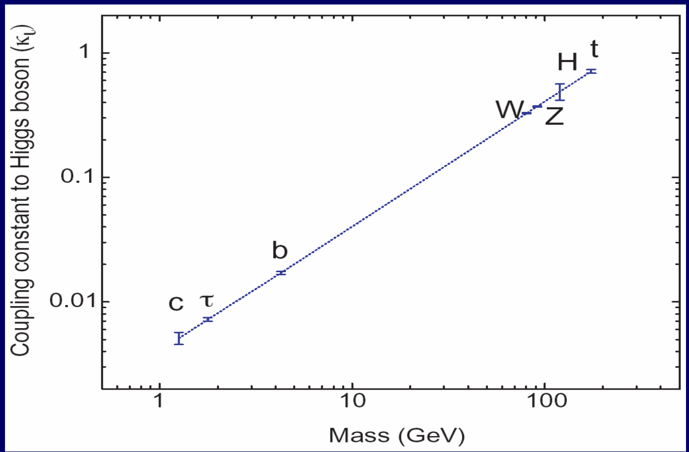


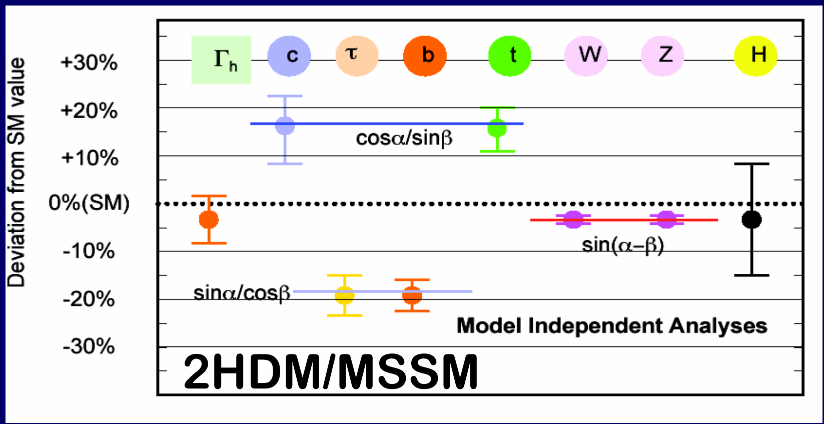



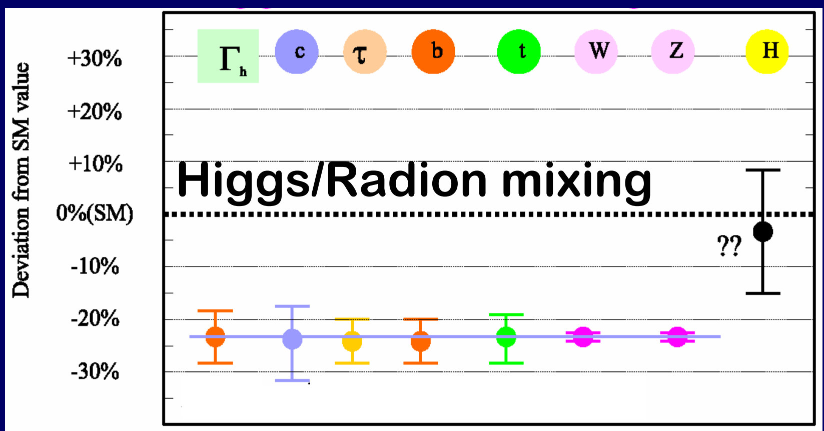

- decay-mode-independent observation
- mass (50 MeV)
- absolute couplings (Z,W,t,b,c,$\tau$) (1-5%)
- total width (model-independent)
- spin, CP
- top Yukawa coupling (~5%)
- self coupling (~20%, 120-140 GeV)
- $\Gamma_{\gamma\gamma}$ at photon collider (2%)

**fully establish Higgs mechanism!**

# Many motivations for precise measurements…

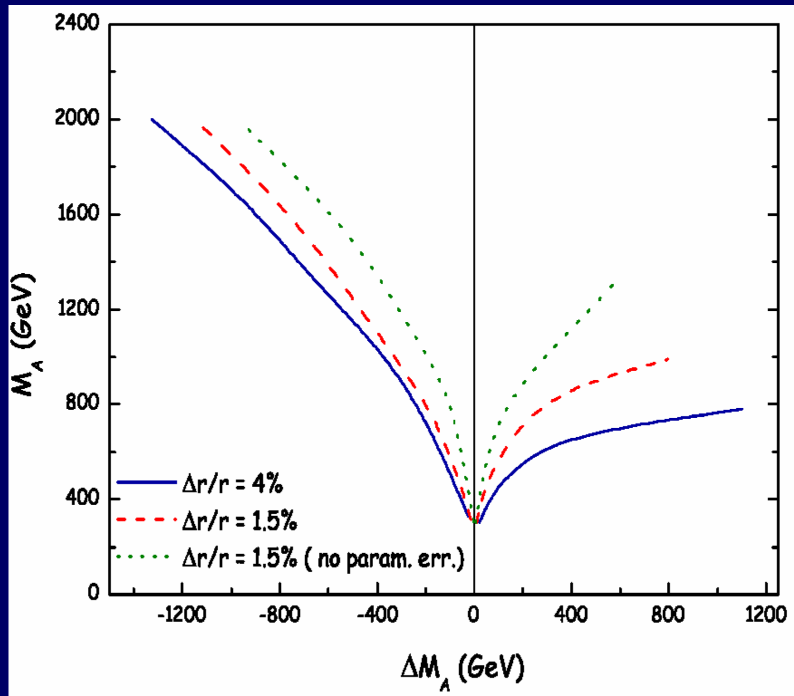
## distinguish models




Yamashita

## indirect mass determination of heavy Higgses, if there (MSSM):

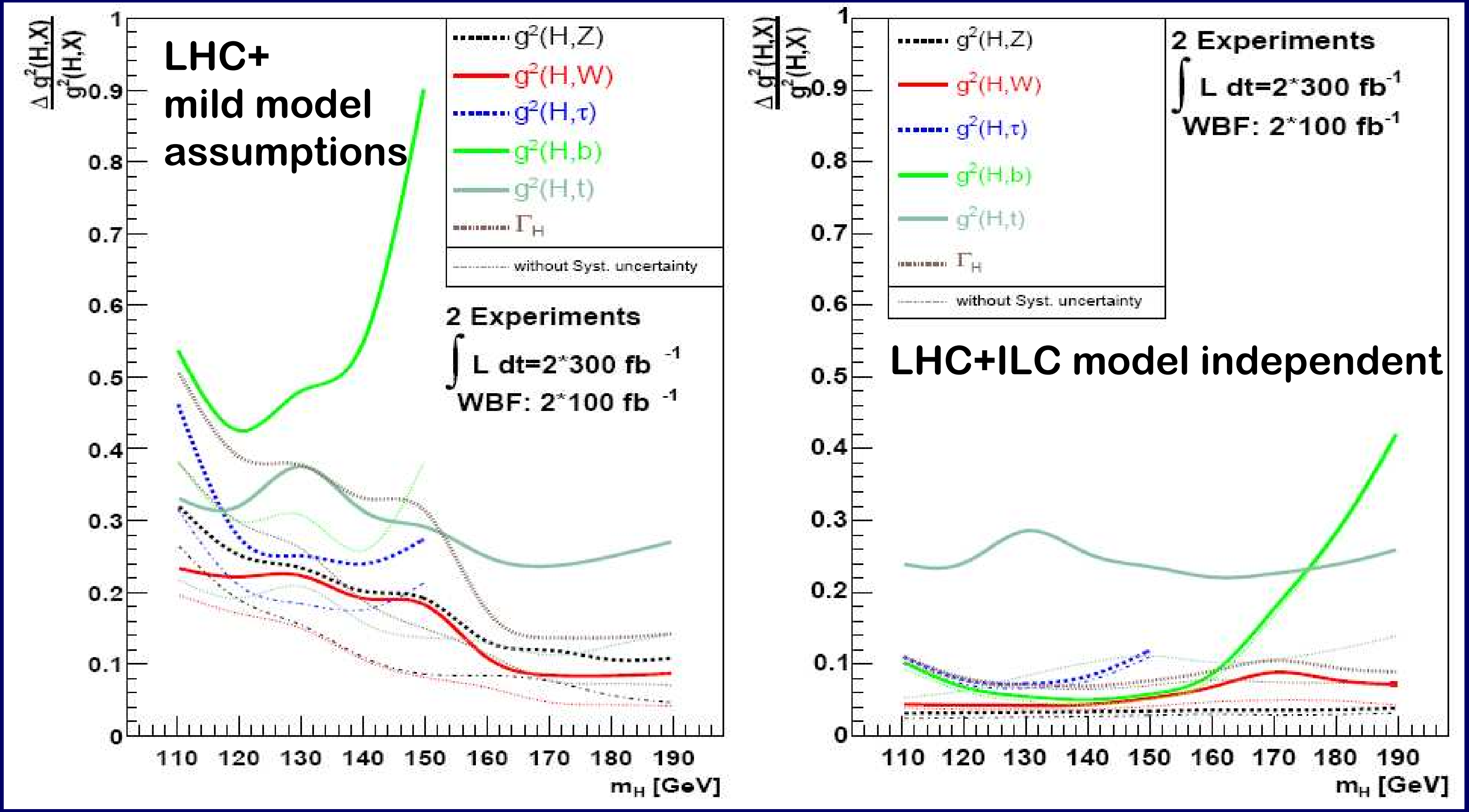



Zivkovic et al

$\Delta m_A$ = 30% for $m_A$ = 800 GeV

also in parameter regions where LHC is blind

# LHC-ILC interplay on Higgs couplings




KD, Dührssen, Heinemyer, Logan, Rainwater, Weiglein, Zeppenfeld - preliminary

## $m_H$>~160 GeV

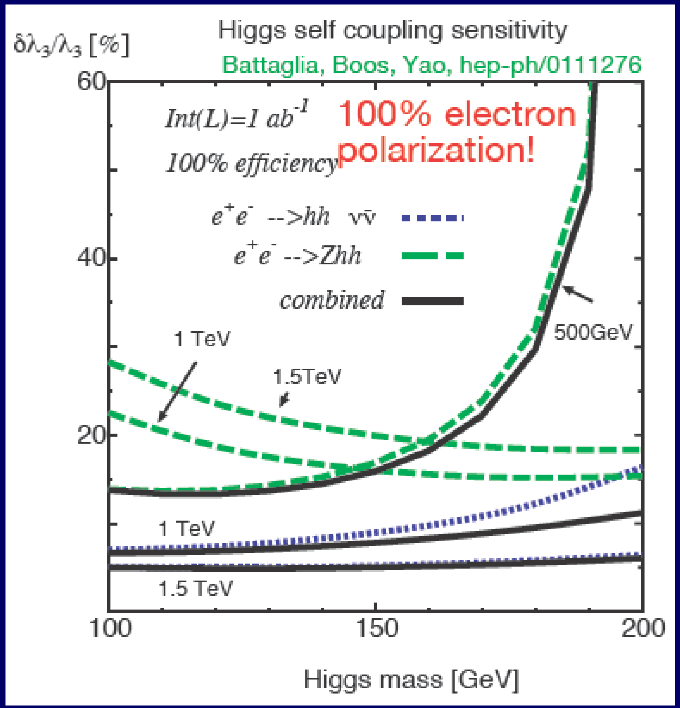
Here we need more work for the ILC

Shopping list:

- couplings to WW, ZZ still measurable (but how much better than LHC?)
  $\rightarrow$ improve precision (include hadronic Z?, more luminosity?)
- fully explore WW-Fusion
- Yukawa couplings hard to access
  $\rightarrow$ BR($H \rightarrow bb$) measurable up to ~ 220 GeV
  $\rightarrow$ $H \rightarrow tt^*$ below threshold ?
  $\rightarrow$ ttH needs high energy (studied up to $m_H$= 200 GeV so far…)

- explore total width measurement from $WW \rightarrow H \rightarrow WW$!
- total width from threshold scan?

- selfcoupling from $\nu\nu HH \rightarrow \nu\nu WWWW$ (energy, luminosity)?



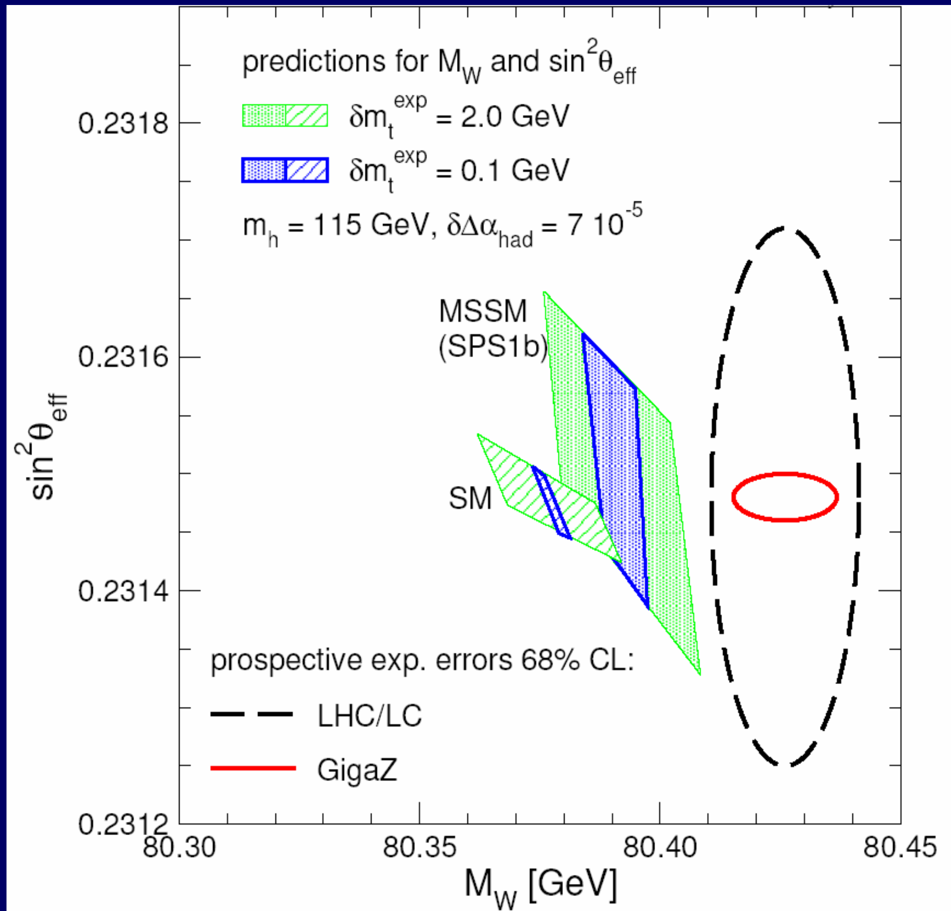

upper limit on sensitivity…

# $m_H$>~160 GeV: SM precision measurements

If there is a heavy SM-like Higgs we need precision measurements to test quantum structure → indication for new physics close by.

We will need:

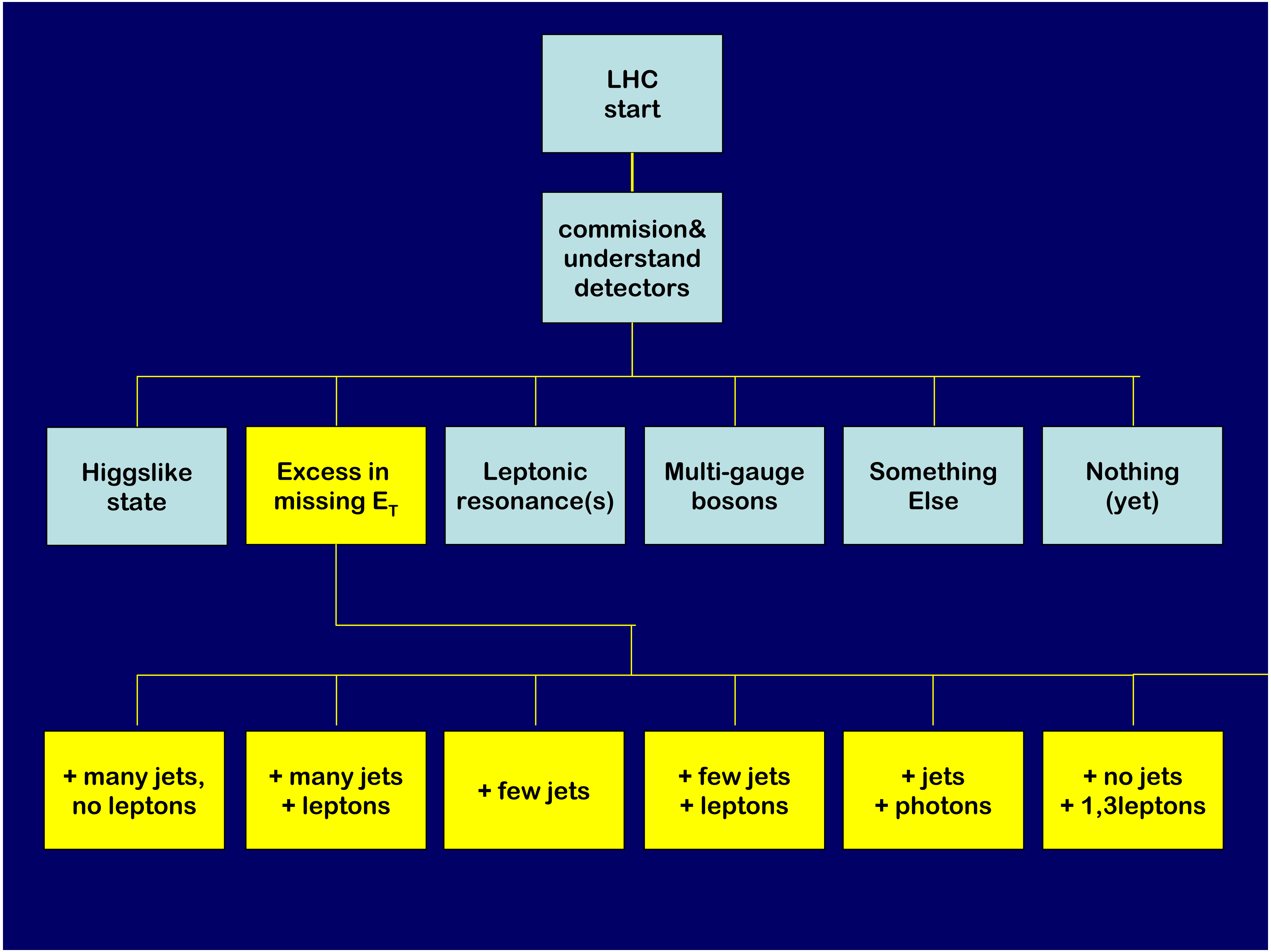
- precise $m_{top}$ (100 MeV) from tt-threshold
- precise $m_W$ (6 MeV) from WW threshold
- precise $\sin^2\Theta_w$ from Giga-Z
- $e^+e^- \to$ff, WW, …




Heinemeyer,Kraml,Porod,Weiglein

## Summary on Higgs-like state

- excellent discovery prospects at the LHC
- discovery of heavier SM-like Higgs (140, >160) may be very fast
- light Higgs (<160) discovery calls for ILC precision Higgs program immediately (even w/o further new physics observed yet)
- heavier Higgs (>160) likely also calls for ILC precision Higgs program + SM precision program (needs more activity)!


LHC start
commision& understand detectors
Higgslike state
Excess in missing $E_T$
Leptonic resonance(s)
Multi-gauge bosons
Something Else
Nothing (yet)
+ many jets, no leptons
+ many jets + leptons
+ few jets
+ few jets + leptons
+ jets + photons
+ no jets + 1,3leptons

# Huge variety of possible models with large MET

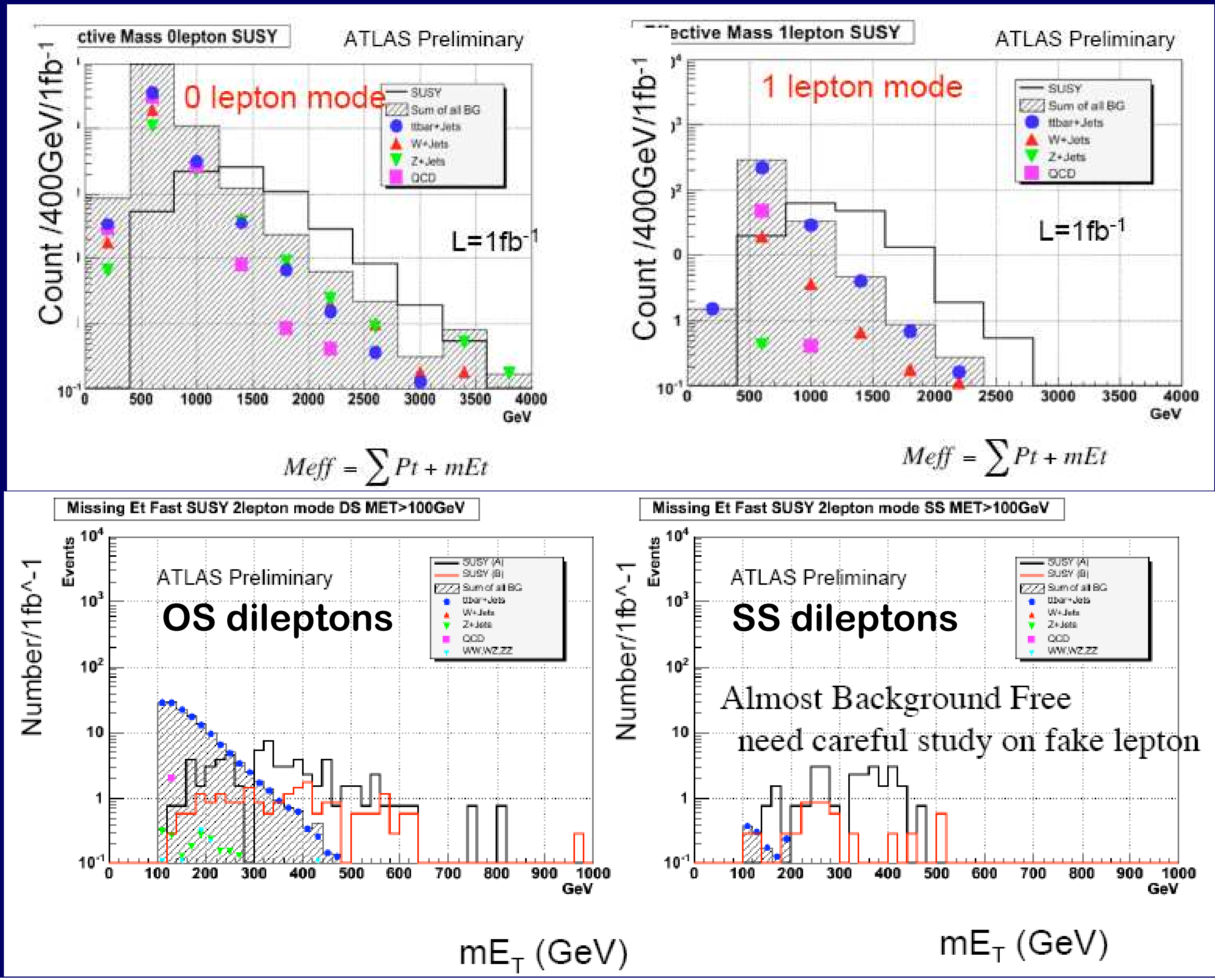
| Jet multi (high Pt) | Additional | Favored scenario | Dominant background processes |
|---|---|---|---|
| High Multiplicity Nj>=3,4 | No lepton | SUGRA,AMSB, Heavy $\tilde{q}$ | QCD(light & bb/cc)<br>$t\bar{t}(\to bb\,q\bar{q}\,\tau\nu)$<br>Z(->nunu) and W(->taunu) |
| | One lepton | SUGRA,AMSB, Heavy $\tilde{q}$ | $t\bar{t}(\to b\bar{b}\,q\bar{q}\,\ell\nu)$<br>W(->taunu) |
| | Dilepton,3L | SUGRA,AMSB, GMSB (Nm>1) | OS: $t\bar{t}(\to b\bar{b}\,\ell\nu\ell\nu)$<br>SS,3L ZW,ZZ $t\bar{t}(\to b\bar{b}\,\ell\nu\ell\nu)$ |
| | Tau (ditau) | Large tanβ, GMSB (Nm>1) | W (->taunu)<br>$t\bar{t}(\to b\bar{b}\,q\bar{q}\,\tau\nu)$ |
| | γγ | GMSB (Nm∽1)<br>$\tilde{\chi}_1^0 \to \gamma\tilde{G}$ | Almost BG Free<br>$t\bar{t}(\to b\bar{b}\,e\nu e\nu)$ FSR |
| Low Multiplicity Nj∽1,2 | No lepton | Heavy $\tilde{g}$<br>KK Graviton | Z(->nunu)<br>W(->taunu) |
| | One lepton | Heavy $\tilde{g}$<br>Top like particle<br>LH(W'Z') | $W,Z$ $t\bar{t}(\to b\bar{b}\,\ell\nu\ell\nu)$ |
| No jet Nj = 0 | One Lepton | W' | W |
| | Dilepton,3L | Direct $\tilde{\chi}$ | WW,WZ,ZZ<br>WZ main for 3L |

S.Asai

in addition to model-driven searches, topology-driven searches required

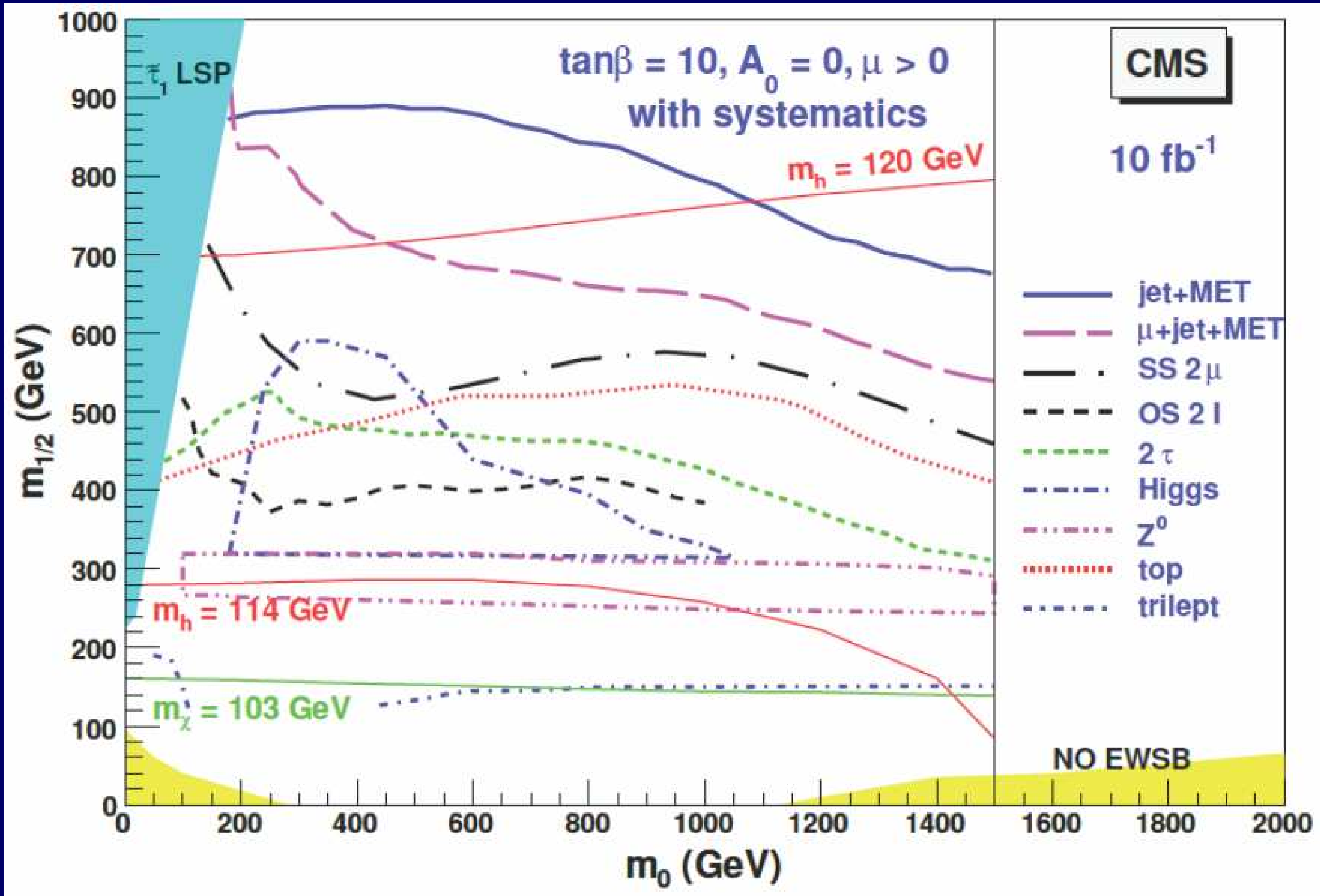
# SUSY at LHC

**1 $fb^{-1}$, m(squark,gluino) ~ 1 TeV**



# SUSY at LHC

mSugra discovery reach with 10 fb$^{-1}$



# MET signal at LHC

**after observation of an excess:**
**need estimate of thresholds at ILC**

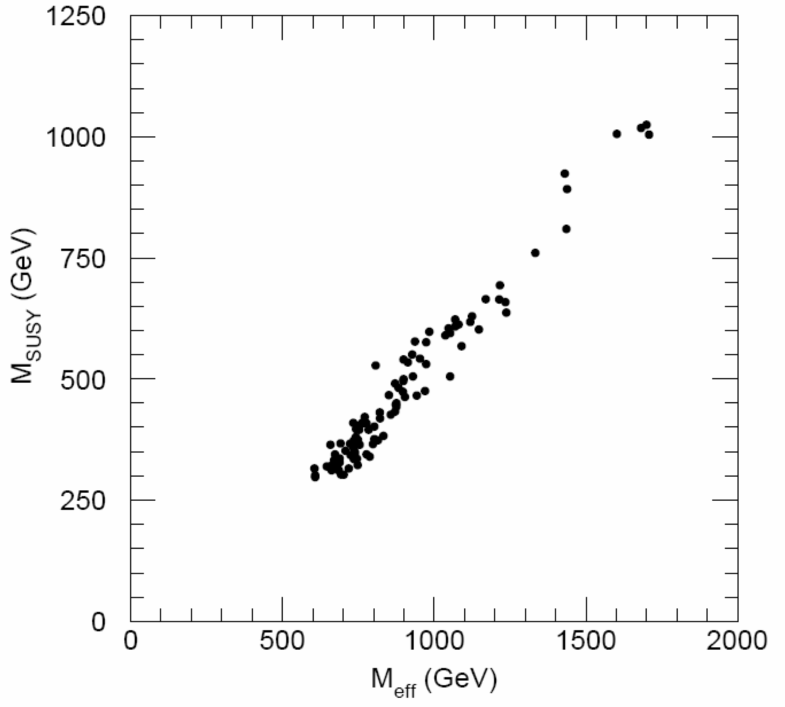
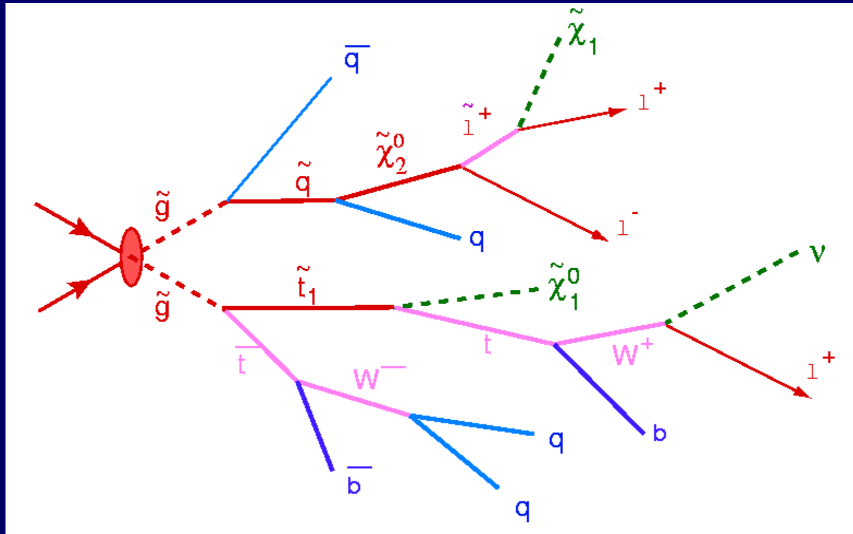



**Figure 20-5** Peak of $M_{\rm eff}$ distribution as a function of. $M_{\rm SUSY} = \min(M_{\tilde{g}}, M_{\tilde{u}_R})$ for various models.

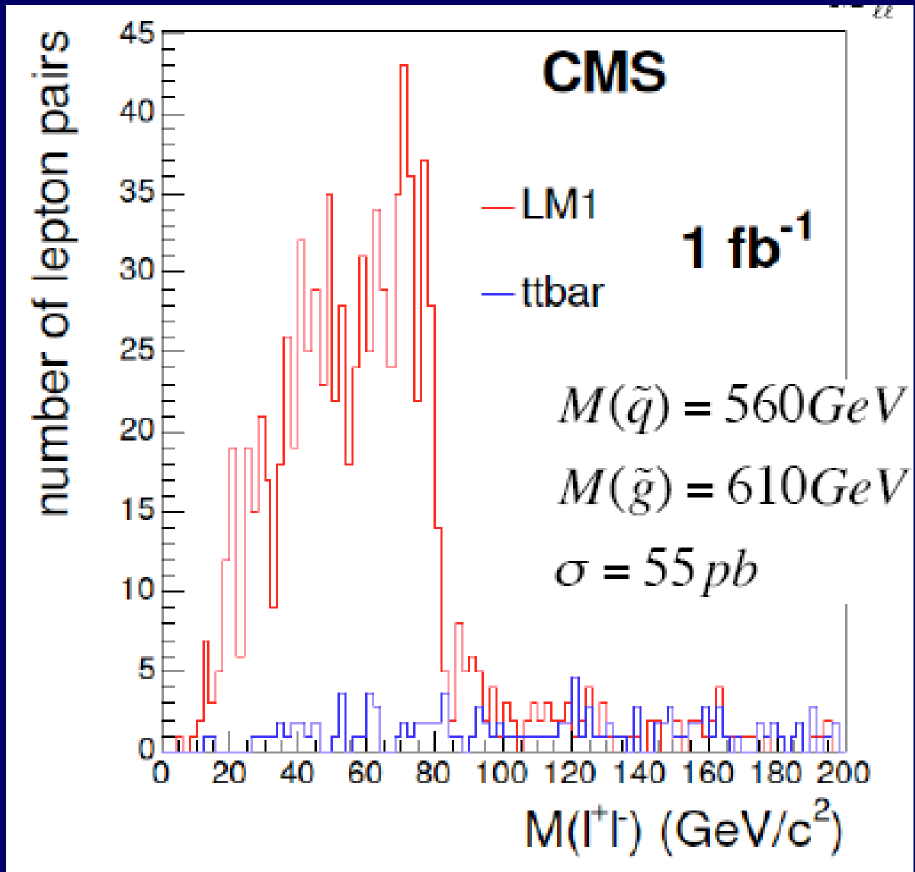
**Fast estimate of m(gluino), m(squark) is not enough!**

**need to get estimates of masses of the cascading particles!**



# SUSY at LHC

## Dileptons:




**A sharp edge in the dilepton mass spectrum is a "go" for the ILC**

$$M_{\ell\ell}^{max} = m(\tilde{\chi}_2^0)\sqrt{1-\left(\frac{m(\tilde{\ell}_R^{\pm})}{m(\tilde{\chi}_2^0)}\right)^2}\sqrt{1-\left(\frac{m(\tilde{\chi}_1^0)}{m(\tilde{\ell}_R^{\pm})}\right)^2}$$

## `MET signal at LHC

what we need is a model-independent estimate
of the particle masses in cascade decays, which end in an
invisible massive particle (DM candidate)

Full kinematic reconstruction is tough
see e.g. Kawagoe,Nojiri,Polesello hep-ph/0410160

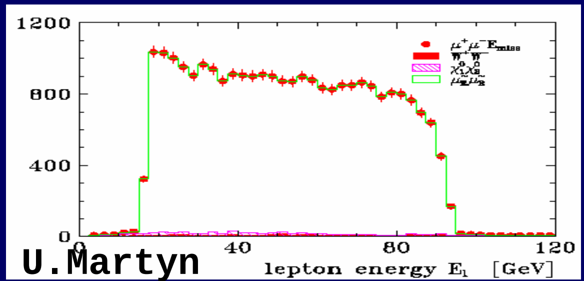
Need more effort here…

Fully exploit

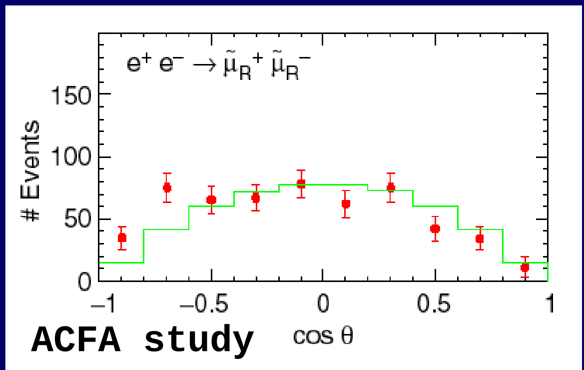
- $p_T$ spectra of visible objects and MET
- invariant masses
- rates!

# SUSY at ILC

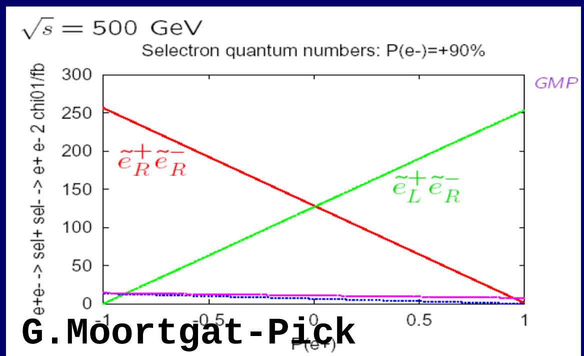
once a few thresholds are in reach, the ILC is the place to reveal SUSY




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




spin (angular distributions)

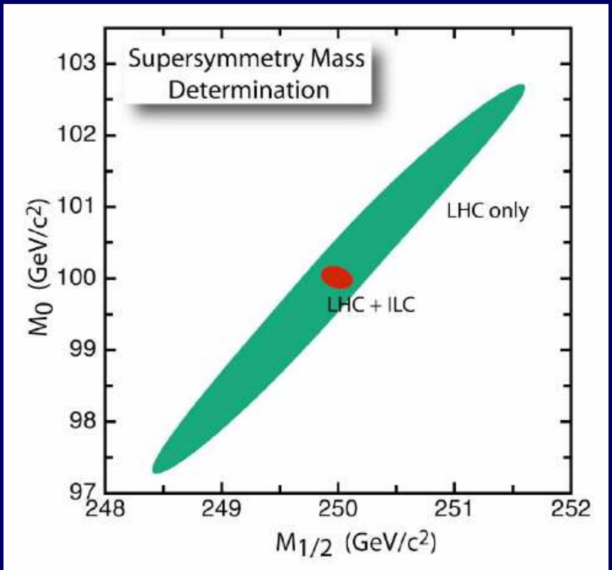



chiral quantum numbers (polarisation!)

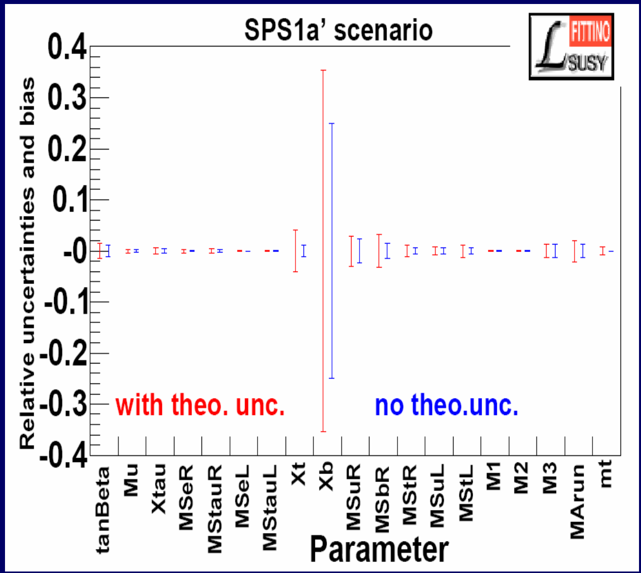
→ prove that it is SUSY
→ no model assumptions
→ learn about SUSY breaking

# SUSY at ILC + LHC

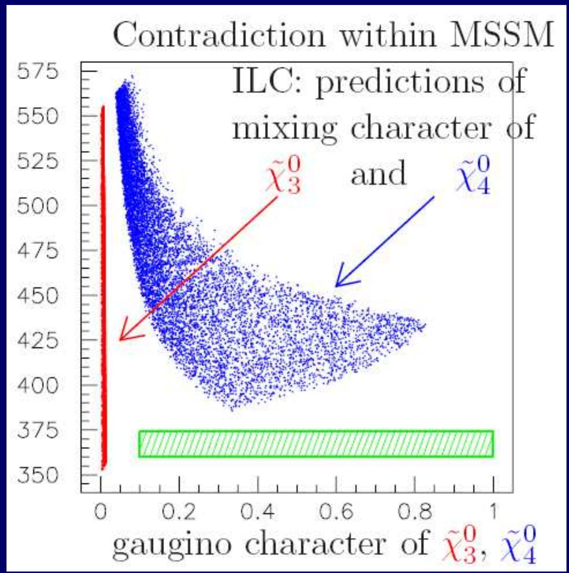
**ILC and LHC together can likely measure precisely**
- **the parameters of constrained models (mSugra…)**
- **determine the underlying SUSY parameters w/o model assumptions**
- **determine the properties of the LSP $\rightarrow$ dark matter density**
- **test more complex realisations (e.g. NMSSM)**



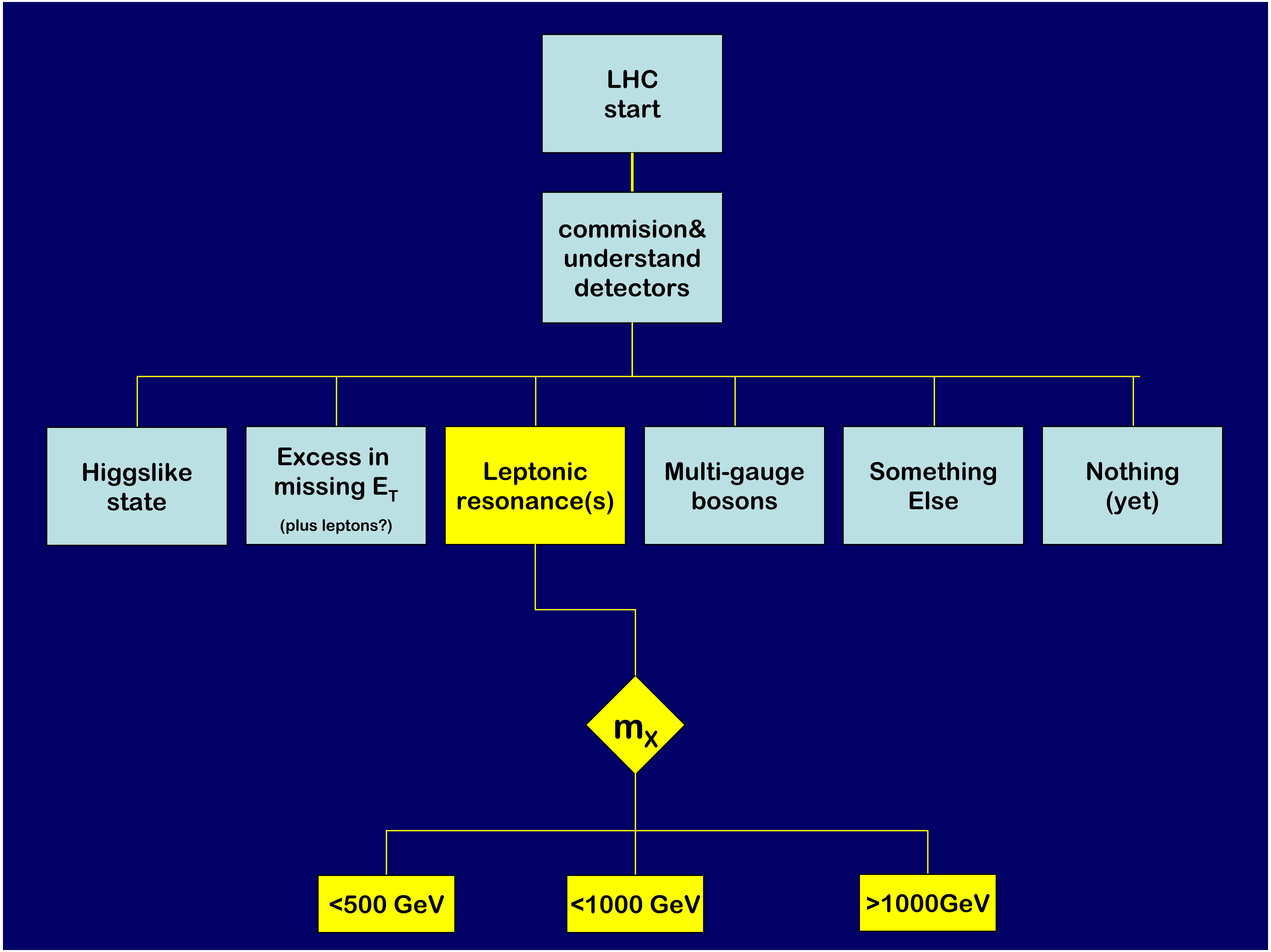

LHC-ILC report




Bechtle, KD, Wienemann
also SFITTER: Plehn ea



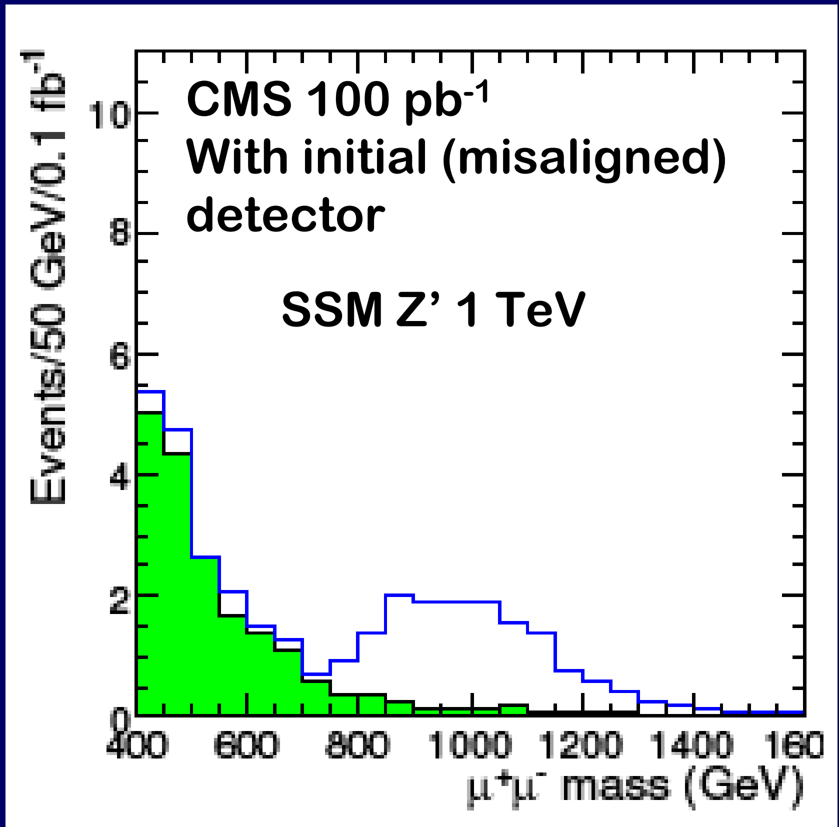

Hesselbach, Moortgat-Pick

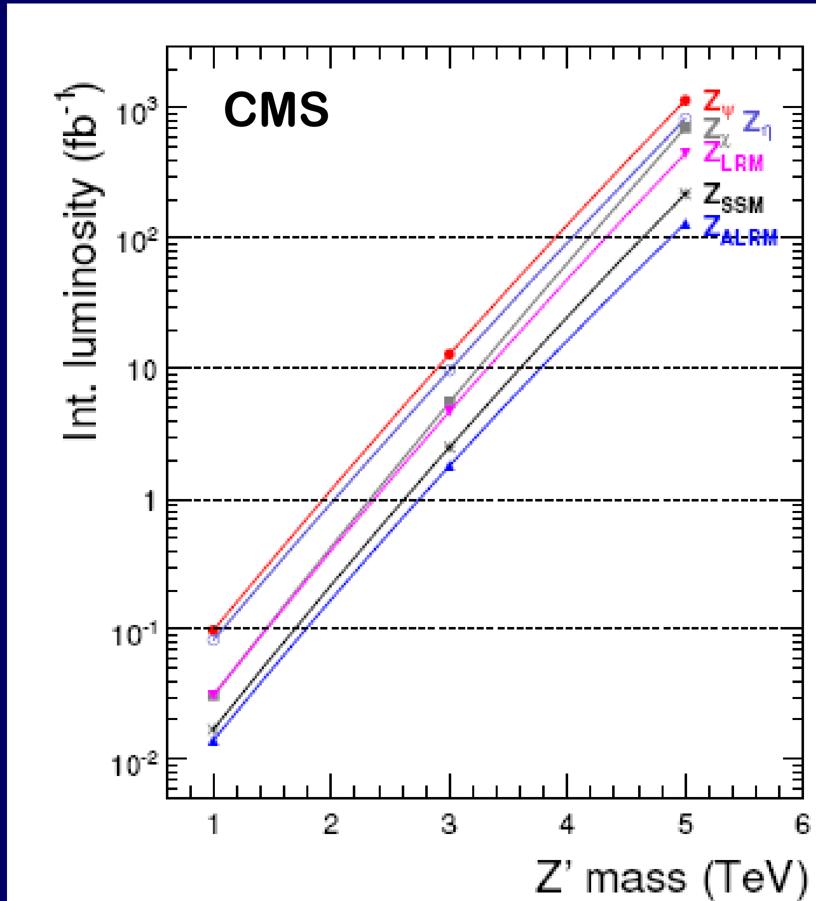


LHC start
commision& understand detectors
Higgslike state
Excess in missing $E_T$
(plus leptons?)
Leptonic resonance(s)
Multi-gauge bosons
Something Else
Nothing (yet)
$m_X$
<500 GeV
<1000 GeV
>1000GeV

# Leptonic Resonances at LHC

**can possibly be seen very early…**

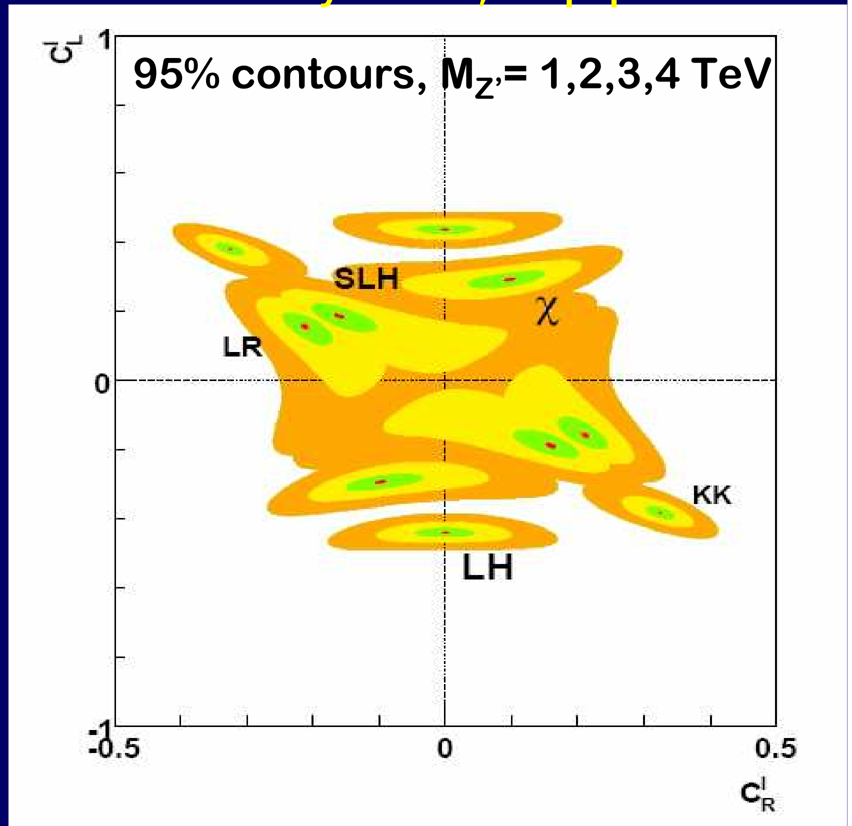



**Discovery reach 3-4 TeV with 10 $fb^{-1}$**

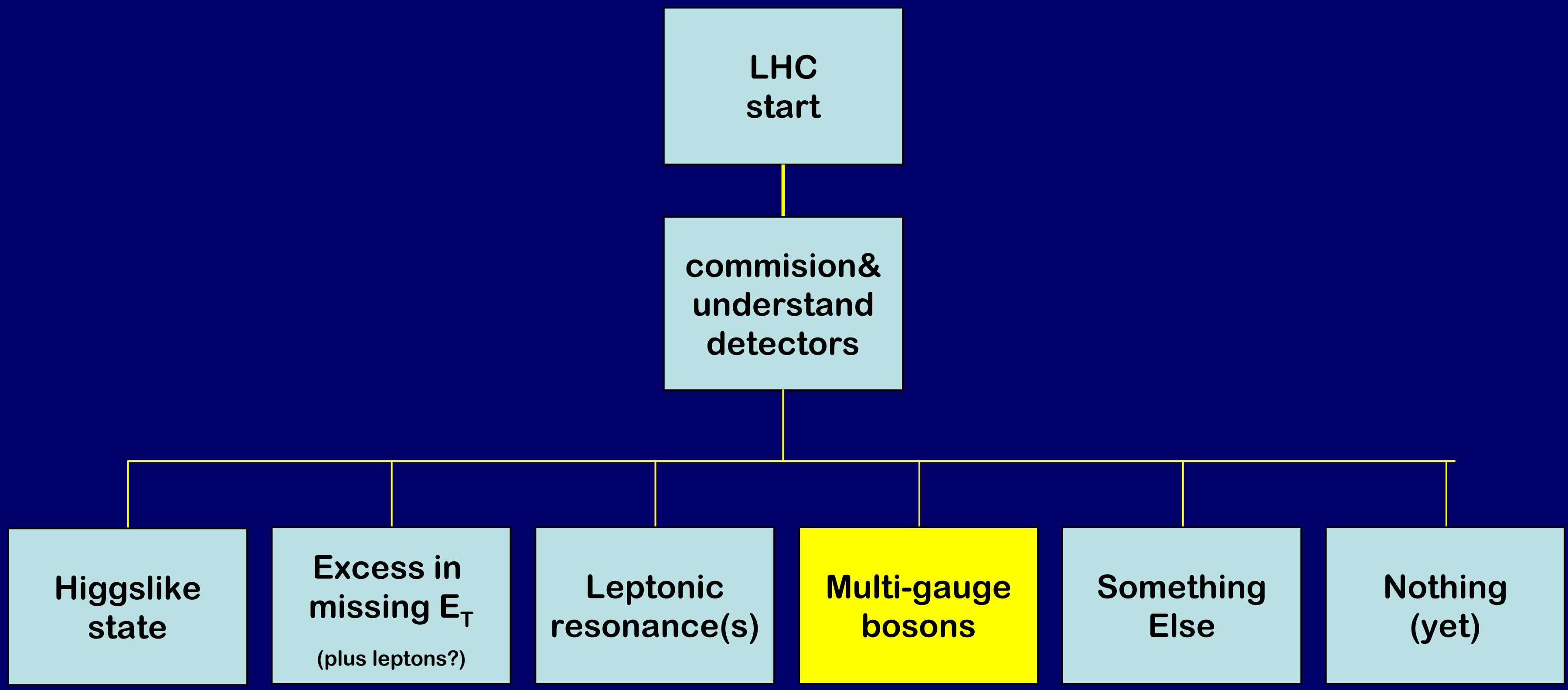
# Resonances: ILC consequences

Godfrey et al, hep-ph/0511335




- Not very likely, that a <500 GeV ll-Resonance appears (but ILC would of course study it in s-channel ☺☺)
- A resonance within the direct reach of an upgraded ILC would probably call for a fast upgrade path (still would like to do the precision Higgs (if there) and SM program)
- A resonance beyond the direct ILC reach: ILC+LHC can determine coupling structure from interference with γ/Z exchange to determine its nature

E6 χ model
LR symmetric
Littelest Higgs (LH)
Simplest Little Higgs (SLH)
KK excitations in ED



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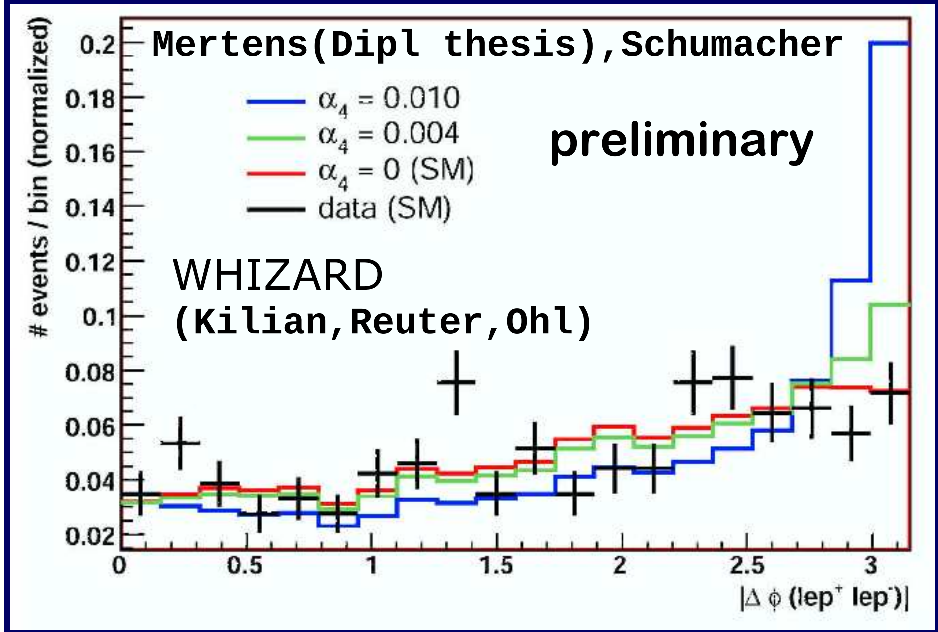
Something Else
Nothing (yet)

# Multigauge bosons at LHC

**Rich field**
- **Measure TGCs in WW,WZ,ZZ**
- **Measure QGCs in WWZ, WW$\gamma$**

**Crucial test of EWSB: Weak boson fusion at high mass:**
**e.g. qq $\rightarrow$jjWW$\rightarrow$jjl$\nu$l$\nu$**

**Needs more attention at LHC (did I miss something?)**
**Important for ILC planning!**



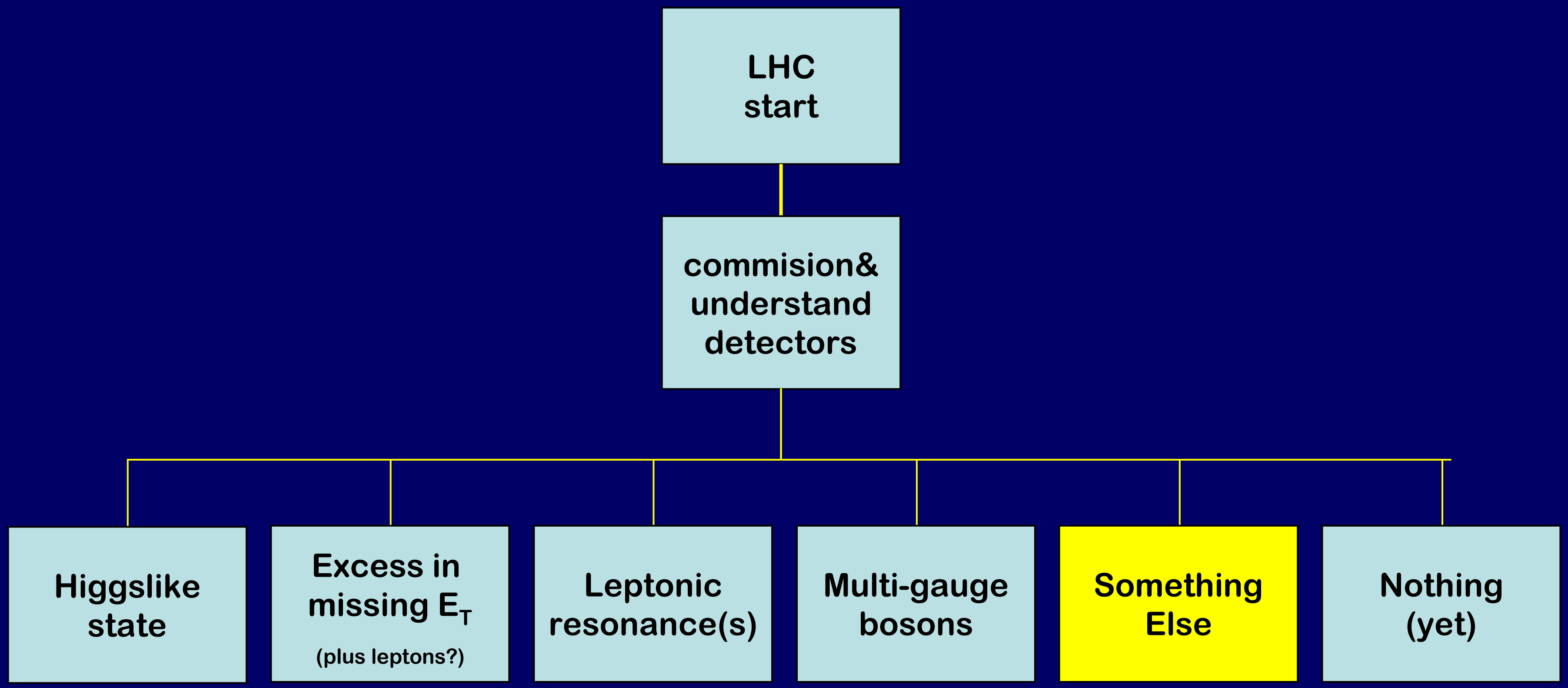

$$L_4 = \frac{\alpha_4}{16\pi^2} tr(V_\mu V_\nu) tr(V^\mu V^\nu)$$

$$L_5 = \frac{\alpha_5}{16\pi^2} tr(V_\mu V^\mu) tr(V_\nu V^\nu)$$

**effective Lagrangian approach valid at m(WW)>1.2 TeV??**

**exclusion potential?**

**see also Kilian,Reuter hep-ph/0507099**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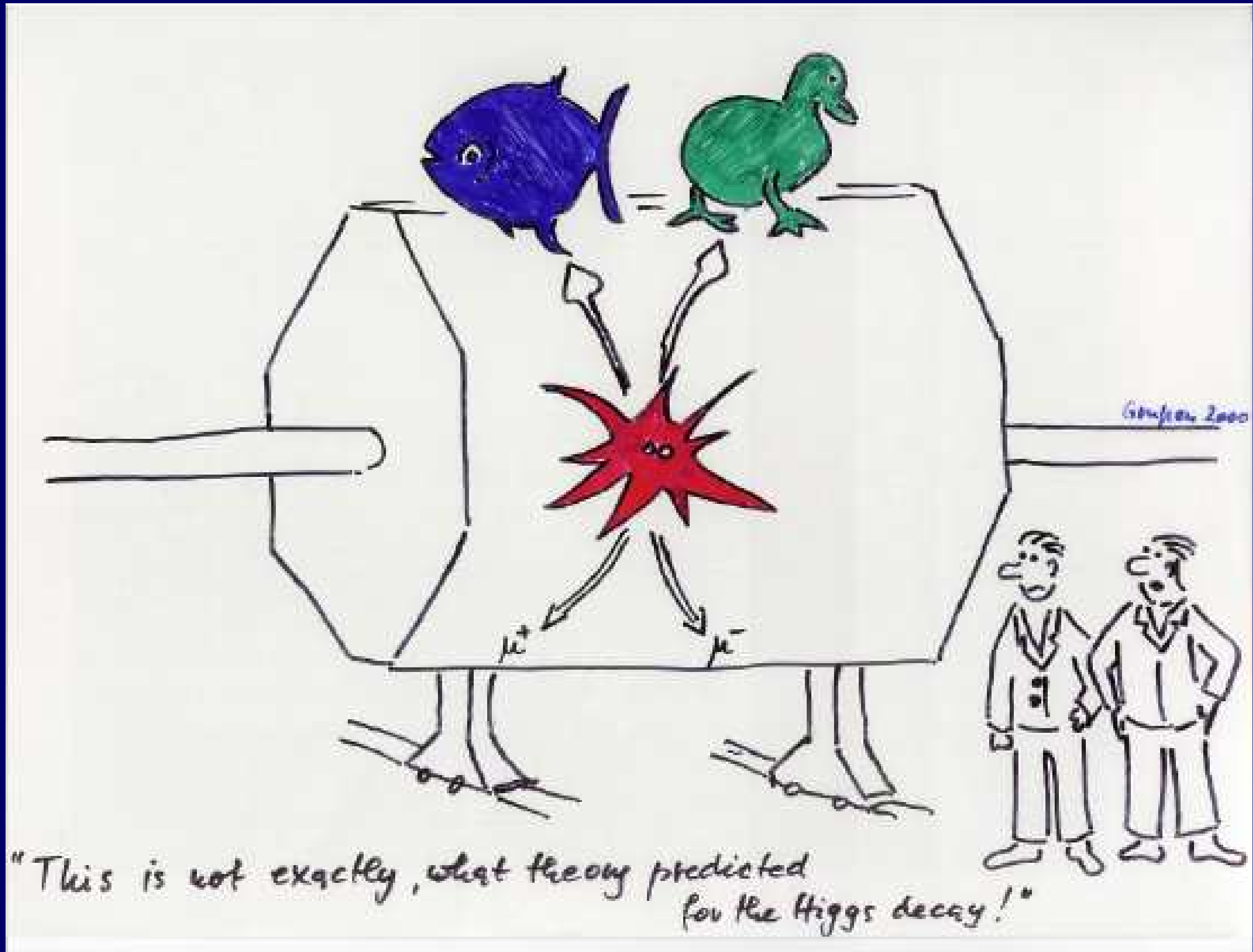
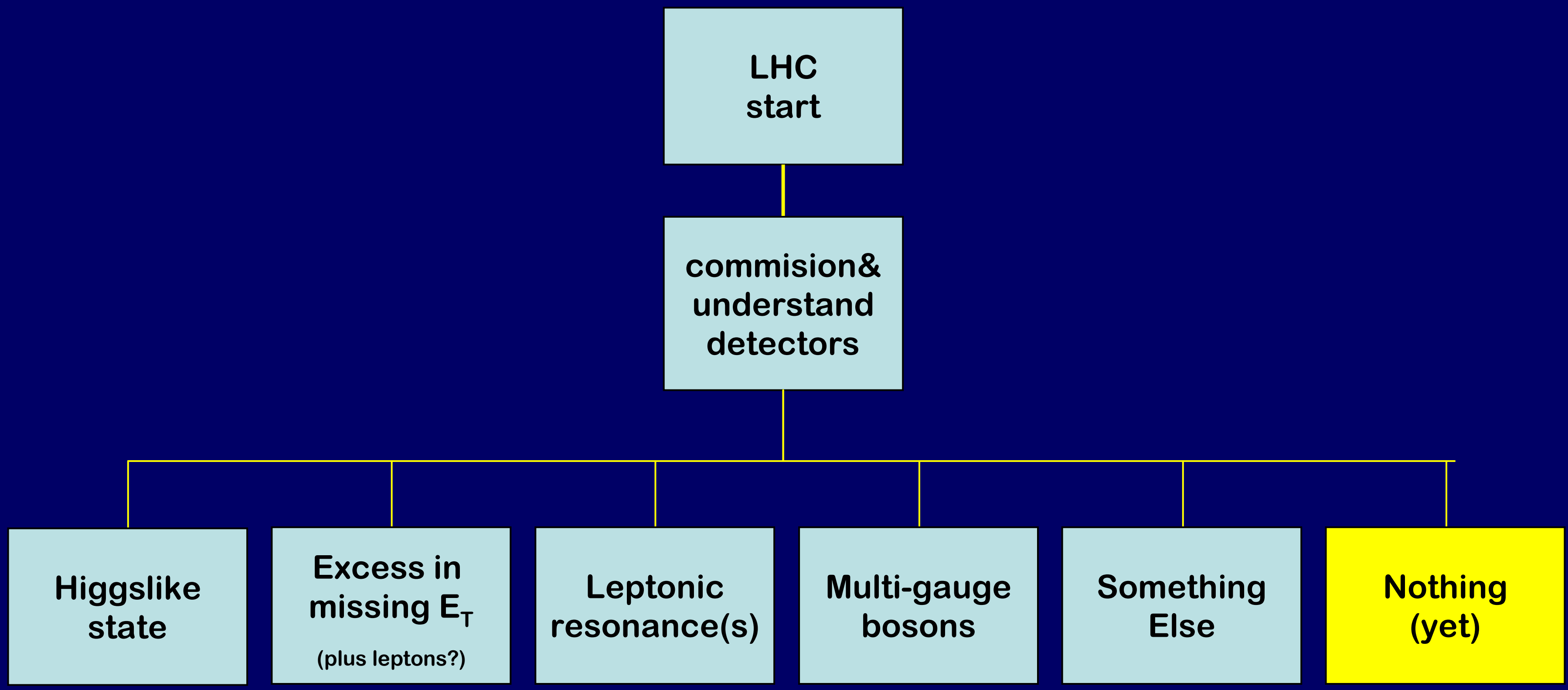
Nothing (yet)

# Something else




Grupen

**Not unlikely, but hard to prepare for**
**Important that ATLAS+CMS are open-minded enough and perform broadband searches…**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resonance(s)
Multi-gauge
bosons
Something
Else
Nothing
(yet)

## Nothing yet…

With 10-30 $fb^{-1}$ analysed at the LHC, many of our favourite scenarios can be excluded:

- SM Higgs
- MSSM Higgs
- MSSM indirect: absence of light Higgs, direct: up to ~1.5 TeV
- …

Major focus then: EWSB

1. has the LHC missed the Higgs(es)?
 (e.g. invisible, Higgs continuum, $H \rightarrow$jets, …)
 ILC can discover the Higgs in these scenarios.

2. there is really no Higgs
 Technicolor/Higgsless models
 Signals might show up with higher luminosity
 (WW scattering at high masses crucial)
 if this scenario can be excluded at LHC, revisit option 1.

# Conclusions

The LHC Early Phase will be exciting!

The LHC Early Phase will confront our ideas about Terascale physics with real data

We will have to demonstrate that there is indeed a strong case for the ILC in the light of these data: that's no free lunch!
(but I'm not nervous…)

Some possible signals at LHC (light Higgs, SUSY-like signals, leptonic resonances,…) are clear "go ahead" signs for ILC

Others (e.g. heavier Higgs) need more studies to assess the ILC physics potential within the various physics scenarios

Optimal ILC run plan and upgrade path have to be inferred from LHC data