Physics at Future e^+e^- Colliders Towards Understanding Electroweak Symmetry Breaking

Philip Bechtle

08. March 2013

1. Physics Challenges for Understanding EWSB

2. Machine and Detectors – The ILC Project

3. Physics at the ILC – Here: Full Focus on the Higgs

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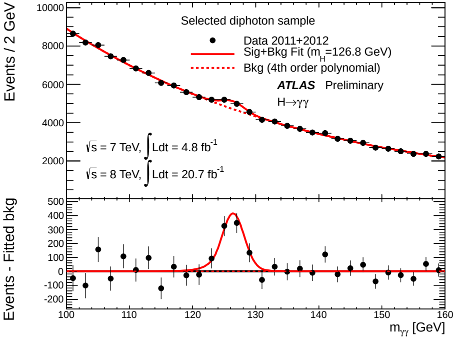
The Puzzle of Electroweak Symmetry Breaking

- Higgs-like particle at $m_h \approx 125$ GeV!
- A whole new window of experimental and theoretical possibilities opens!



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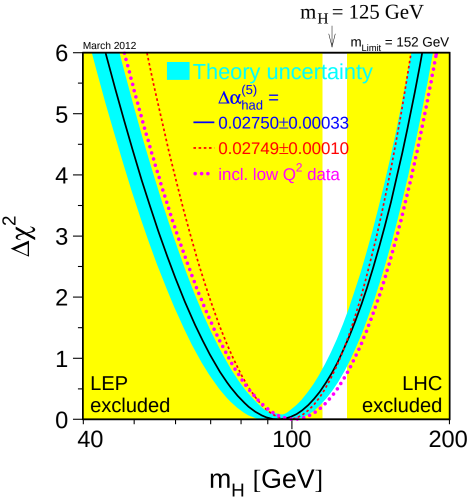

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- Why is that so important?
    - Up to 2011, we directly studied only half of the EW SM Lagrangian!

$$\begin{aligned}\mathcal{L}_{EW}^{SM} &= -\frac{1}{4}W^a_{\mu\nu}W_a^{\mu\nu} - -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\ &+\bar{L}\gamma^\mu\left(i\partial_\mu - \frac{1}{2}g\tau_a W^a_\mu - \frac{1}{2}g'YB_\mu\right)L \\ &+\bar{R}\gamma^\mu\left(i\partial_\mu - -\frac{1}{2}g'YB_\mu\right)R\end{aligned}$$

Studied since 1974 in many great experiments

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& - \left| \left(i\partial_\mu - \frac{1}{2} g \tau_a W^a_\mu - \frac{1}{2} g' Y B_\mu \right) \Phi \right|^2 \\
& + \mu^2 |\Phi|^2 - \lambda |\Phi|^4 \\
& - (\sqrt{2}\lambda_d \bar{L} \Phi R + \sqrt{2}\lambda_u \bar{L} \Phi_c R + h.c.)
\end{aligned}
$$

Only began to explore this part at ATLAS and CMS in 2011

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  - Up to 2011, we directly studied only half of the EW SM Lagrangian!
  - The masses of the particles shape our universe!

e.g. Bohr radius of the Hydrogen:

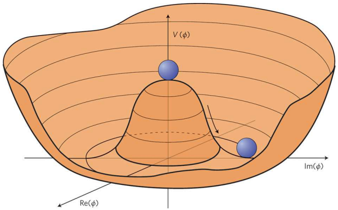
$$a_0 = \frac{\hbar}{m_e c \alpha}$$

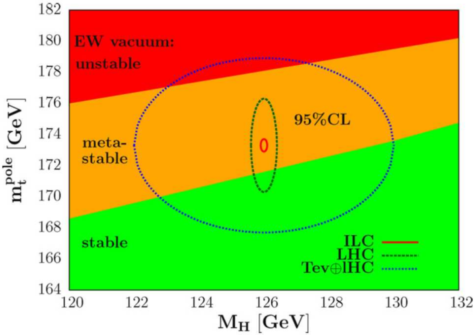
No atoms without fundamental mass!
At least not as we know them . . .

An Important Open Question on EWSB

- Is the SM vacuum stable?

$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$





- Need very precise and systematically clean measurement of m_t
- Need more precise measurement of m_h

Radiative corrections from strong htt couplings $\rightarrow \lambda < 0$ (e.g. Alekhin, Djouadi, Moch arXiv:1207.0980)

- To have New Physics or not to have New Physics might be vital . . .

Fully model independent measurements of

Higgs Physics

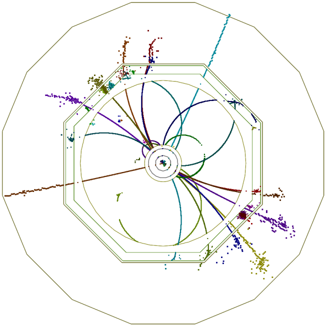
- Most precise mass → LHC
- Spin → LHC
- CP → LHC? Admixtures?
- Total width → e^+e^-
- Absolute couplings → e^+e^-
- Higgs self-coupling → LHC?? e^+e^-!?

Beyond direct Higgs Physics at the future e^+e^- collider:

- Triple gauge Couplings
- Most precise m_t, m_W
- Unitarity of WW scattering at $\sqrt{s}_{e^+e^-} \approx 1$ TeV
- Invisible Higgs decays? Other (invisible?) Higgses?
- Any other sign for new physics . . .
- Much more . . .

What does "Model Independent" Mean?

- There is no "theory free" measurement



What does "Model Independent" Mean?

- There is no "theory free" measurement
- Assumptions:
- Work within a framework of relativistic quantum field theories
- Write down any (effective) Lagrangian of one or more Higgs-like particle(s)
- Can we measure the fundamental couplings independently from any further assumptions on other couplings?

$$-\sqrt{2}\lambda_f(\overline{L}_f \Phi R_f + \overline{R}_f \Phi^+ L_f)$$

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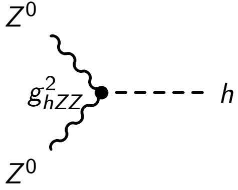
- At a future e^+e^- collider: Yes we can.

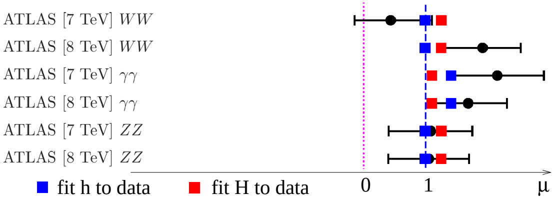


$g^2_{hZZ} = g^2 + g'^2$???

What precision do we need?

New Physics example from PB, Heinemeyer, Stal, Stefaniak, Weiglein, Zeune arXiv:1211.1955 [hep-ph]

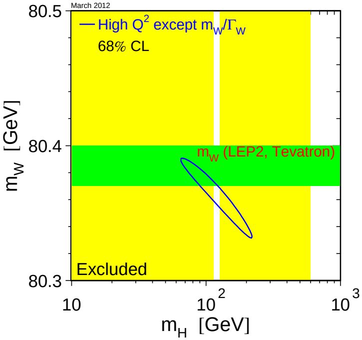
e.g.



- Fit the MSSM to the LHC and Tevatron data with either the h or the H as particle explaining the Higgs observation, taking limits, B-physivs, etc into account
- Partly tiny differences between the fit and the SM (blue line $\mu = 1$)
- Partly small differences between the h and the H interpretation
- In many channels, expect no more than $(\mu_h - 1)/\Delta\mu_{exp} \approx 5 - 20\,\%$
- Given $\Delta\mu_{exp} \approx 50 - 100\,\%$ now, need up to $\Delta\mu_{exp} \approx 2.5\,\%$ in the end!

Beyond the visible Higgs

- m_h is already now "too precise" compared to other observables
- Very precise measurements of m_W (6 MeV), m_t (40 MeV), A_t^{FB} (3 %)
- Want to revisit the Z-peak (GigaZ)
- σ_{WW} at $\sqrt{s} \approx 1$ TeV
- Triple Gauge Couplings
- In addition: Try any way of searching for new physics
    - Invisible Higgs components?
    - New Physics with soft final state and low E_T^{miss} at the LHC?



Make the other measurements as strong as the Higgs!

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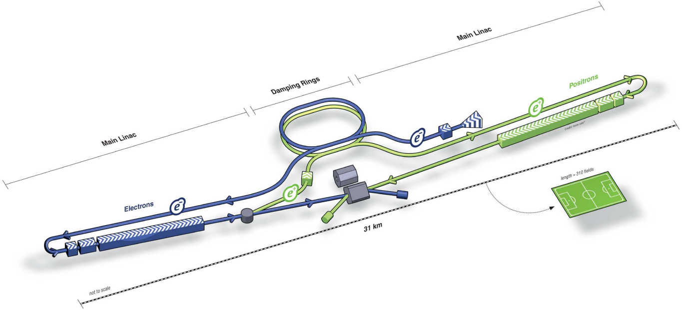
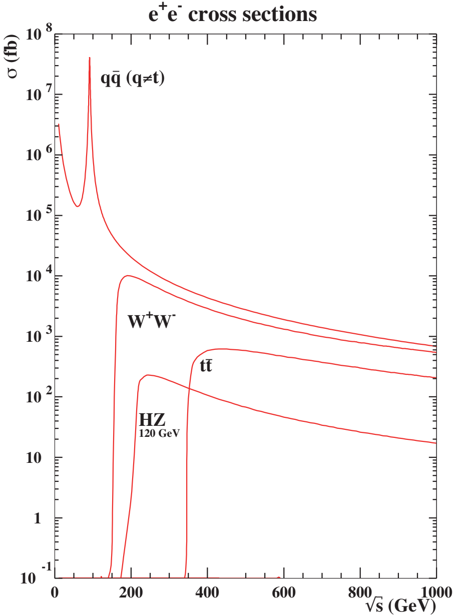
The ILC Machine



The ILC is the most advanced future e^+e^- collider proposal

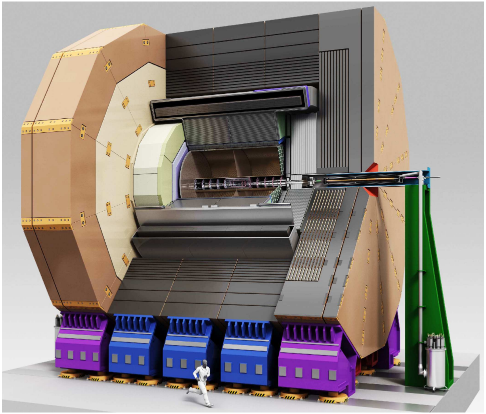
- Polarized $e^+(30\%)e^-(80\%)$
- Superconducting RF technology
- High luminosity from $\sqrt{s} = 250$ GeV to 500 GeV, expandabe to 1 TeV
- About 31 km site length
- Proven technology
- Facilities and tests (final focus, damping rings, positron polarization, RF) exist or under construction (XFEL)
- Industrialization underway

Luminosity Requirements

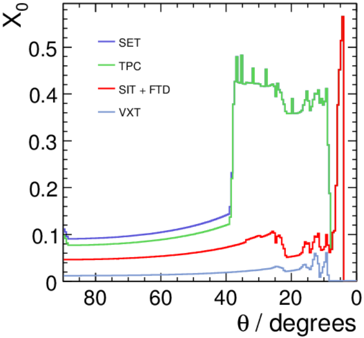


- $1/s$ calls for high luminosity
- 1 % precision: 10000 events
- Need $\int \mathcal{L} = 500\,\mathrm{fb}^{-1}$ for $\sigma = 20\,\mathrm{fb}$
- 250 days at $2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

The Detector Concepts ILD and SiD



ILD

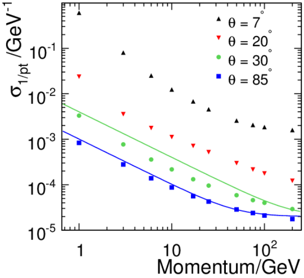


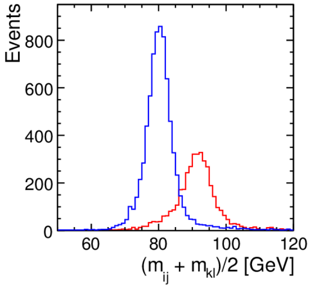
ILD tracking material budget (incl. cabling, cooling, support)

- ILD and SiD concepts optimized for the particle flow concept – imaging calorimetry, coil outside HCAL, large B field (3.5 – 5 T)
- Detailed engineering and R&D going on for every component – lots of test beam activity to test components and verify full sim
- Detector baseline Documents (DBD) going to be public soon

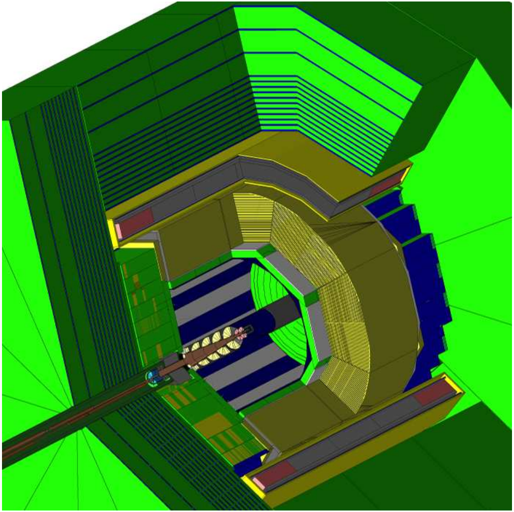
Detector Requirements Derived from known Physics

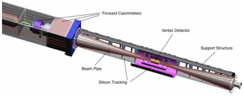
- Tracking: Higgs recoil mass spectrum: $\delta(1/p) = 7 \times 10^{-5}/\mathrm{GeV}$ (1/10 LEP, LHC)
  2-lepton mass resolution $< \mathrm{Z}$ width
- Vertexing: b - c quark separation: $\delta d_0 = 5 \times \frac{10}{p\,(\mathrm{GeV})}\,\mu\mathrm{m}$ (1/3 A/C)
  for the mesurement of $\mathrm{h} \to \mathrm{c}\bar{\mathrm{c}}$
- Calorimetry: $\delta E_{\mathrm{jet}} < 0.3\sqrt{E_{\mathrm{jet}}\,(\mathrm{GeV})}$ (<1/2 LEP)
  $h \to hh$, separate $W \to qq'$ from $Z \to q\bar{q}$
- Hermeticity: missing energy signals, tagging of forward objects (ISR) for kinematic fits, down to $\theta = 5\,$mrad
- Consequence: Very low material budget

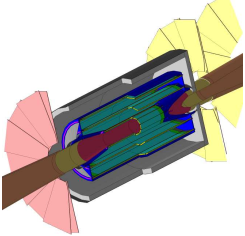


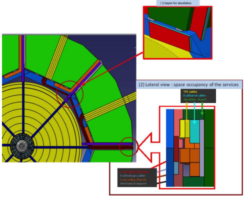


The Depth of Detail of the Simulation



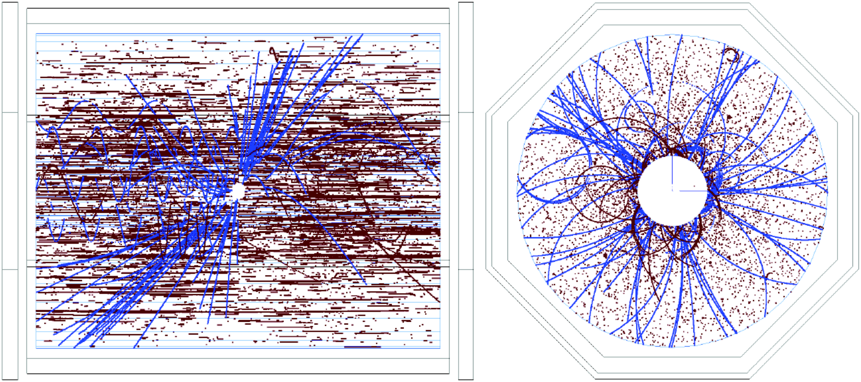






Very detailed implementation of the detector in the full GEANT4 simulation

Taking Backgrounds fully into account



$t\bar{t}$ event with 150 BX background overlayed

- Never had such advanced and controlled full simulation for a new project at such an early state!
- Need high $B > 3.5$ T to control beam backgrounds

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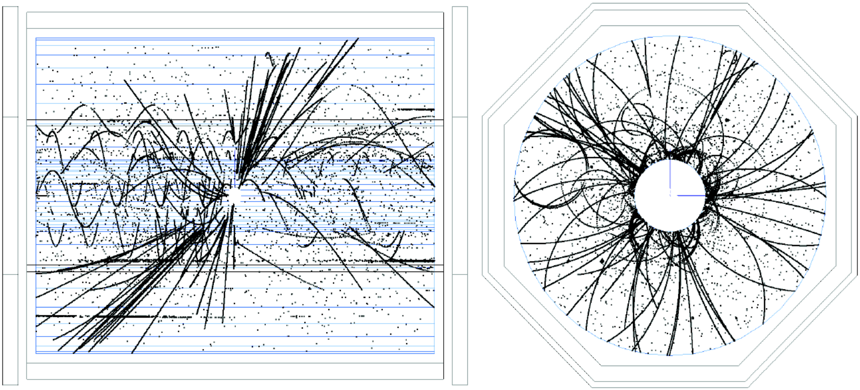

same event after microcurler removal algorithm

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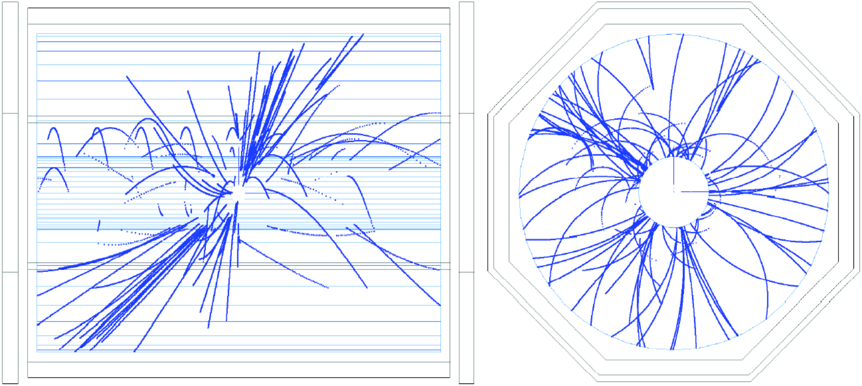

result from track finding (hits attached to tracks) clean event

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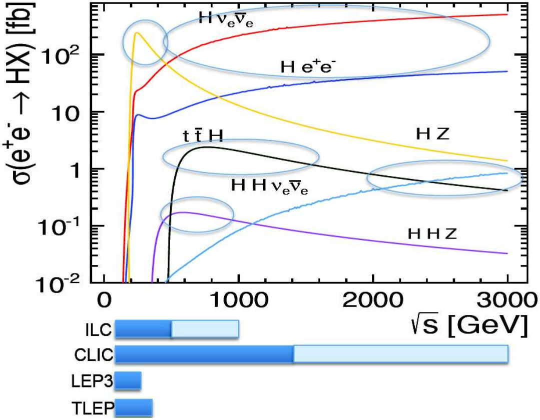
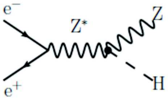
Necessary Processes

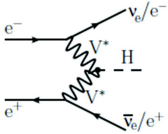
Use the power of experimental precision to exploit each process selectively



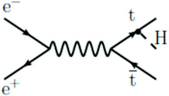
Many interesting processes at a wide range of $\sqrt{s}$



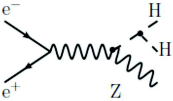
m_h, absolute BR, g_Z, inv.



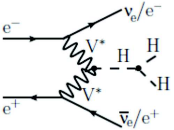
Γ_{tot}



g_t (at least $\sqrt{s}$ = 500 GeV)

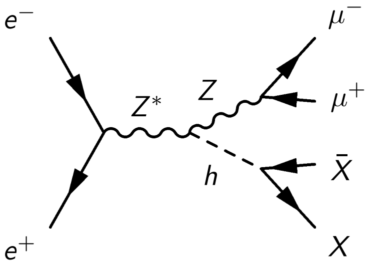


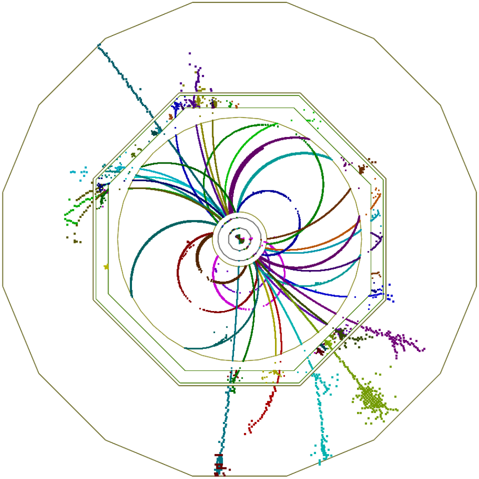
g_{HHH} ($\sqrt{s}$ = 500 – 1000 GeV)



g_{HHH} ($\sqrt{s} \geq 1000$ GeV)

Observe the Higgs without looking at it





- Reconstruct the Higgs mass from the recoiling Z:

$$s = m_h^2 + m_Z^2 + 2((\sqrt{s}, \vec{0}) - p_Z)p_Z \quad \rightarrow \quad m_h = \sqrt{s + m_Z^2 - 2E_Z\sqrt{s}}$$

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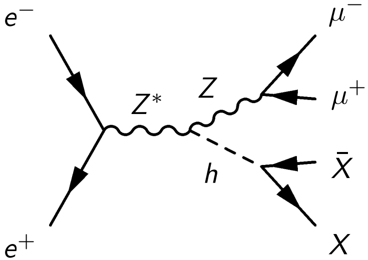

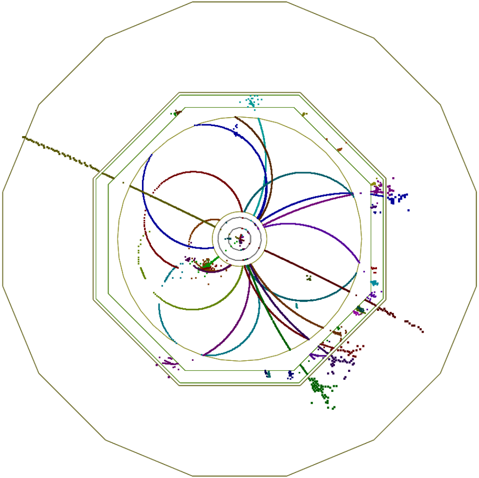

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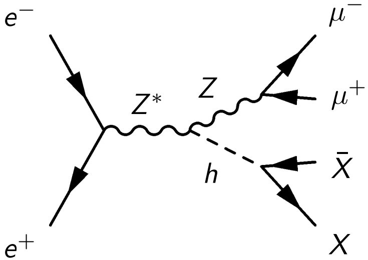

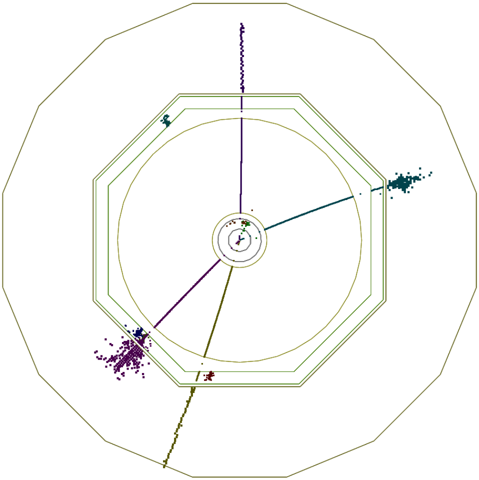

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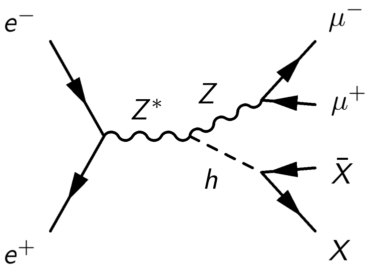

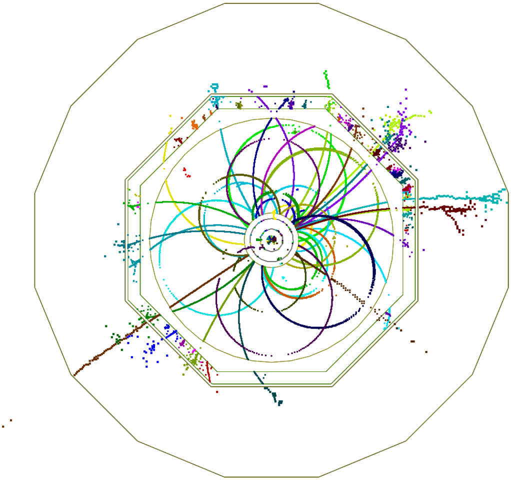

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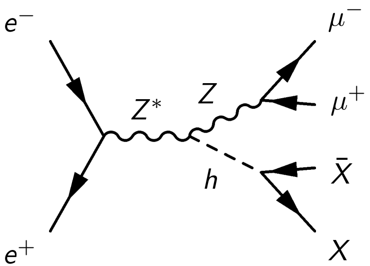

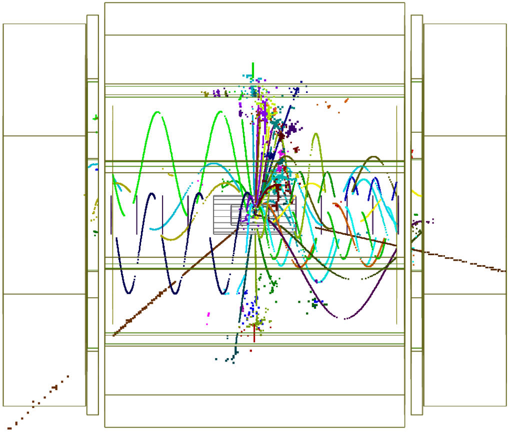

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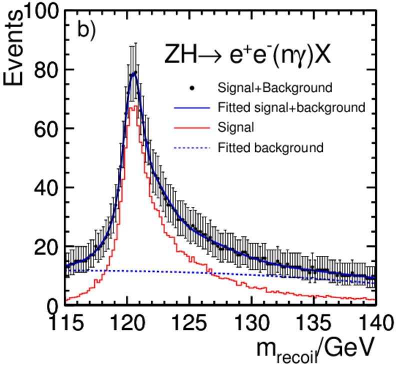
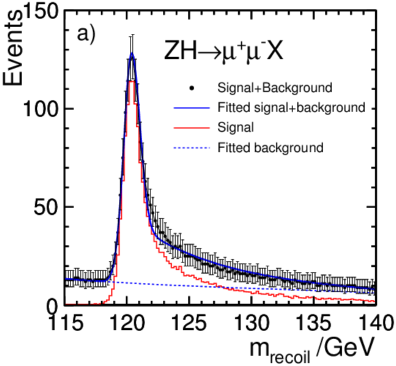
Fully Model Independent Absolute Higgs BR

- Step 1: Measure total σ_{hZ} model-independently from recoil mass
- Only g^2_{hZZ}, but no absolute Yukawa couplings yet!
- $\Delta\sigma_{hZ} \approx 2\,\%$ drives precision for the couplings!
- "Side product": $\Delta m_h \approx 30\,\text{MeV}$



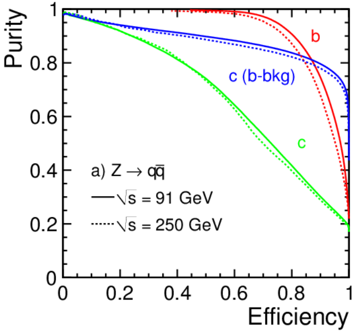


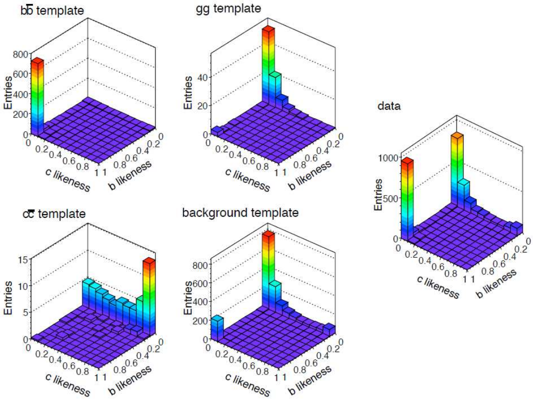
H. Li, R. Poeschl

Fully Model Independent Absolute Higgs BR

- Step 2: Measure $\sigma_{hZ} \times BR_X$ model-independently, then calculate

$$BR_X = (\sigma_{hZ} \times BR_X)/\sigma_{hZ}$$





R. Walsh et al.

Total Higgs Width and Absolute Couplings

- $\sigma_f = \sigma_{prod} \times BR(f) \propto g^2_{prod} \frac{\Gamma_f}{\Gamma_{tot}} \propto \frac{g^2_{prod} g^2_f}{\Gamma_{tot}}$
- At LHC: No way to know Γ_{tot}, there measurements of Γ_i / Γ_j
- In e^+e^-: Measure Γ_{tot} and g^2_{prod} model-independently and extract g^2_f!

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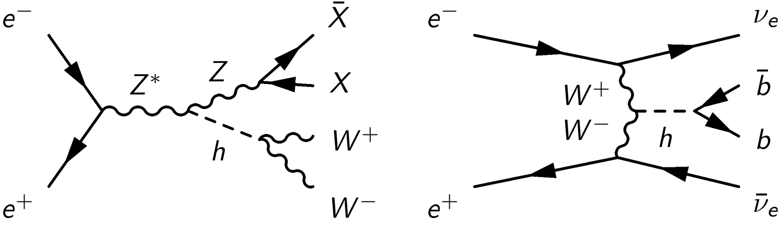
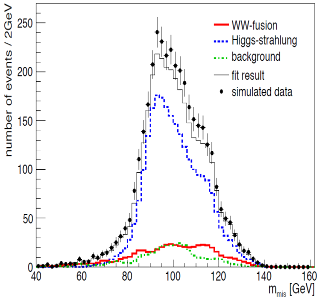
- $\Gamma^{SM}_{tot} \approx$ few MeV, can't measure lineshape!

Total Higgs Width and Absolute Couplings

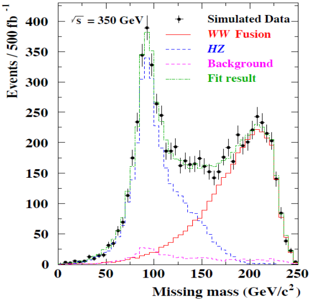
- $\sigma_f = \sigma_{prod} \times BR(f) \propto g^2_{prod} \frac{\Gamma_f}{\Gamma_{tot}} \propto \frac{g^2_{prod} g^2_f}{\Gamma_{tot}}$
- At LHC: No way to know Γ_{tot}, there measurements of Γ_i/Γ_j
- In e^+e^-: Measure Γ_{tot} and g^2_{prod} model-independently and extract g^2_f!
- $\Gamma^{SM}_{tot} \approx$ few MeV, can't measure lineshape!
- $\Gamma_{tot} \propto \frac{g^2_{hXX}}{BR(h \to XX)}$
- Use either
  - $BR(h \to ZZ)$ and g^2_{hZZ} from recoil mass measurement
  - $BR(h \to WW)$ and g^2_{hWW} from WW fusion



Total Higgs Width and Absolute Couplings



$\sqrt{s} = 250\,\mathrm{GeV}$
$\mathcal{P}_- = -80\,\%,$
$\mathcal{P}_+ = +30\,\%$



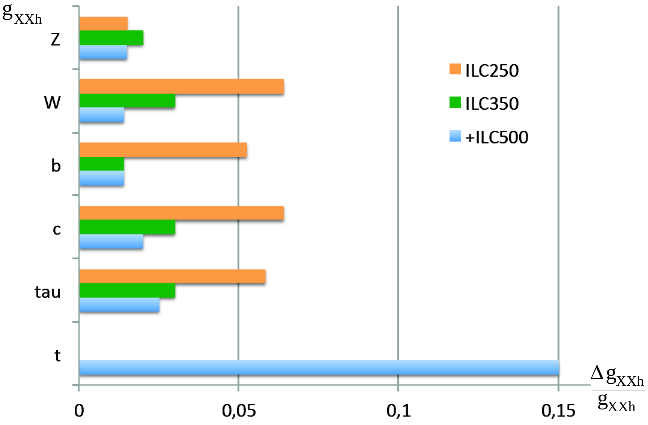
$\sqrt{s} = 350\,\mathrm{GeV}$

E_{cm}	$\Delta\sigma_{WW\to h} / \sigma_{WW\to h}$
$\sqrt{s} = 250$ GeV:	11 %
$\sqrt{s} = 350$ GeV:	3.6 %
$\sqrt{s} = 500$ GeV:	3.2 %

- Need polarization to enhance $e^+e^- \to \nu_e\bar{\nu}_e WW$, especially at 250 GeV!
- Want at least 350 GeV to 500 GeV for full potential!

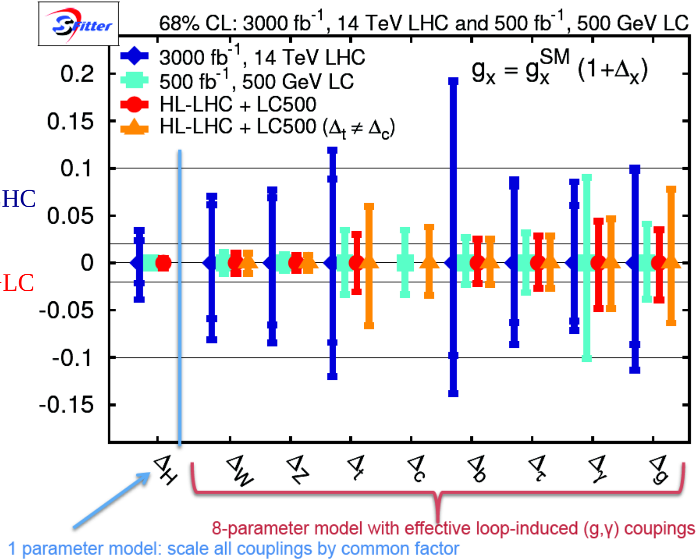
C. Dürig T 47.11, N. Meyer, PB, K. Desch

Absolute Higgs Couplings



- Based on European Strategy Group compilation
- No comparable model independent numbers from LHC
- Mostly reach required (from arbitrary model fit) precision of $\Delta_g \approx 2.5\,\%$, and even better: on absolute couplings!
- Need 500 GeV for g^2_{ttH}, want 1 TeV for $\sigma_{WW\to WW}$ and g^2_{HHH}

The Improvement Expressed in Terms of Global Fits



Δ_H HLLHC = 4.0%

Δ_H HL+LC = 0.6%

Klute, Lafaye, Plehn, Rauch, Zerwas, arxiv:1301.1322

Summary

- ILC: A rich physics case studied in very detailed full simulation
- The Higgs seems to be there, and the ILC is ready, just in time
- The LHC and its High-Lumi upgrade can already study the Higgs sector thoroughly
- ILC250 – ILC1000: The most advanced e^+e^- proposal, covering the full energy range motivated by known physics
- Fully exploit the physics of EWSB in a model-independent way with unprecedented precision
- In addition to the Higgs: extreme precision measurements of the SM!
- And maybe discoveries that evade the LHC?
- If lucky, a bid to host the ILC could be coming from Japan soon

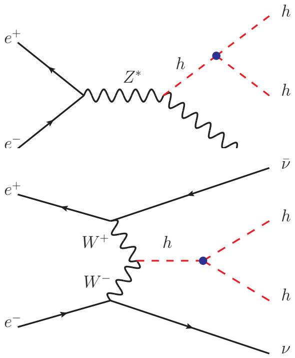
Backup Slides

Check List

- Established over and over again:
  - m_h
  - Abolute σ
  - Absolute BR
  - Total width Γ_h – also for very small width
  - Absolute couplings to gauge bosons (establish EWSB) and fermions (establish Yukawa couplings)
  - Spin
  - CP (admixture?)
- Ongoing studies focus on:
  - Higgs self coupling – overdetermine the shape of the Higgs potential
  - Direct measurment of the top Yukawa coupling
- Other interesting ongoing ideas:
  - $h \to WW*$ anomalies
  - Making use of beam polarization: Anomalos Higgs couplings

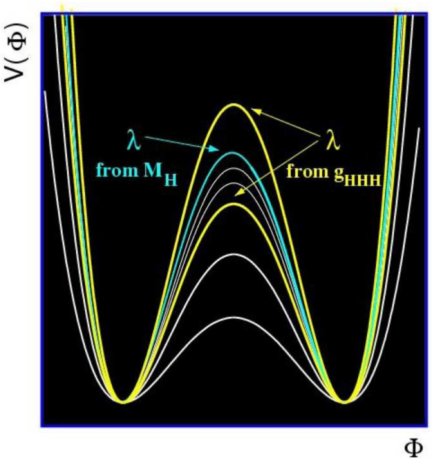
Ultimate Challenge: Higgs Self-Coupling

- Again: Measure precisely whether the observed particle is the SM Higgs
- Check $\lambda = m_h^2/(2v^2)$



- We need highest luminosities ($\geq 1\,\mathrm{ab}^{-1}$) and best detectors for that!

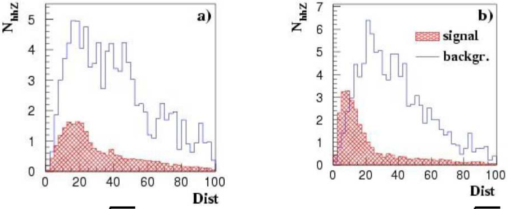
Overconstrain this!

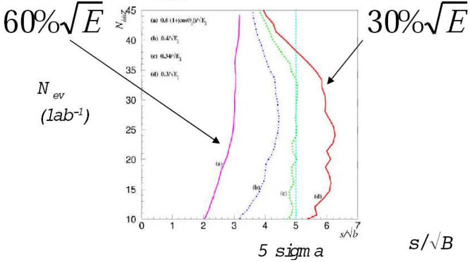


$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

Old Fast Simulation Studies: Higgs Self Coupling

- At ILC use $e^+e^- \to hhZ \to 6j$ at 500 GeV
- Calculate $Dist = \sqrt{\sum_{i=1}^{3}(m_{jj}^{i,rec} - m^{i,target})^2}$
- Only a few tens of events for $\int \mathcal{L} = 1\,\mathrm{ab}^{-1}$
- Here: Fast simlation

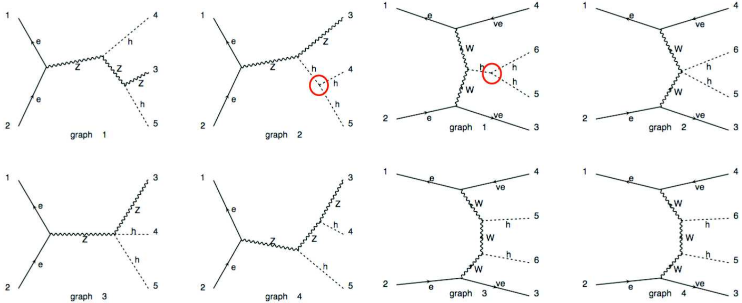




- $\sigma_{jet} = 30\,\%/\sqrt{E}$ established for $Z \to uds$ in full simulation
- At high jet multiplicities, the calorimeter is not getting worse . . .
- But the confusion between jets rises even in an imaging calorimeter, thus increasing $\langle E_{parton} - E_{jet} \rangle$

Current Results: Higgs Self Coupling

- Zhh and $\nu\bar{\nu}hh$ not a pure Higgs final state
- Need both channels to cancel dilution from non-Higgs channels



- Updated Studies including $e^+e^- \to \nu\bar{\nu}hh \to \nu\bar{\nu}(b\bar{b})(b\bar{b})$
- At ILC with $\sqrt{s} = 1$ TeV, $\mathcal{L}^{int} = 2\,\mathrm{ab}^{-1}$
- Traditionally: Jet finding → Vertex Fitting → b-tag
- Now: Vertex Fitting → Jet finding → b-tag
- Helps strongly to clean up combinatorics

Current Results: Higgs Self Coupling

- In $\mathcal{L}^{int} = 2\,\mathrm{ab}^{-1}$ at $\sqrt{s} = 1$ TeV: Produce only 350 signal events!
- Use optimized b-tagging, 2 NNs against $t\bar{t}$ and $\nu\bar{\nu}ZZ$ events
- Current result:

ILC500/500fb^{-1}

$\frac{\Delta\sigma}{\sigma} \approx 27\,\%$ $\quad$ $\frac{\Delta\lambda}{\lambda} \approx 44\,\%$

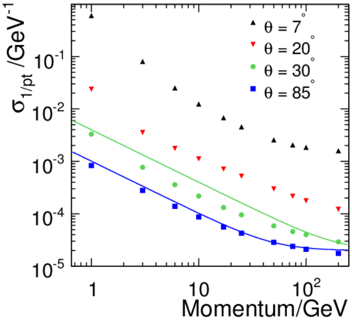
ILC1000/2ab^{-1}

$\frac{\Delta\sigma}{\sigma} \approx 22\,\%$ $\quad$ $\frac{\Delta\lambda}{\lambda} \approx 19\,\%$

- Still use Durham jet clusterig, probably by far not optimal, updates with other LHC-inspired jet finding algorithms ongoing
- At ILC only: Straightforward to convert σ_{Xhh} into λ_{Xhh}
- To be compared with $\approx 3\sigma$ sensitivity from LHC3000 in $hh \to b\bar{b}\gamma\gamma$

Detector Requirements Derived from known Physics

- Tracking: Higgs recoil mass spectrum:
  $\delta(1/p) = 7 \times 10^{-5}/\mathrm{GeV}$ (1/10 LEP, LHC)
  2-lepton mass resolution $< \mathrm{Z}$ width
- Vertexing: b - c quark separation:
  $\delta d_0 = 5 \times \frac{10}{p\,(\mathrm{GeV})}\,\mu\mathrm{m}$ (1/3 SLD)
  for the mesurement of $\mathrm{h} \rightarrow \mathrm{c}\bar{\mathrm{c}}$
- Calorimetry:
  $\delta E_{\mathrm{jet}} < 0.3\sqrt{E_{\mathrm{jet}}\,(\mathrm{GeV})}$ (<1/2 LEP)
  driven by $h \rightarrow hh$, $\mathrm{h} \rightarrow \mathrm{WW}$, $\mathrm{h} \rightarrow \mathrm{ZZ}$, WW scattering
- Hermeticity: missing energy signals, tagging of forward objects (ISR) for kinematic fits
- Very low material budget



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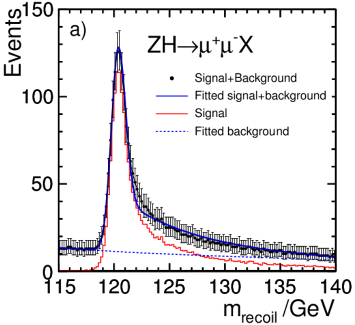

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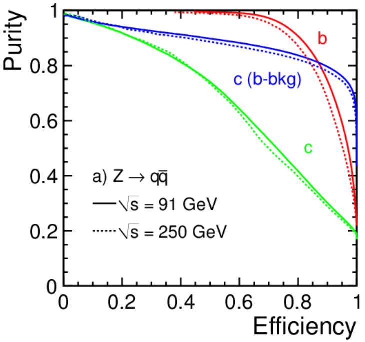

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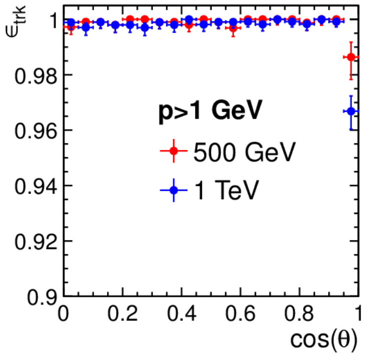

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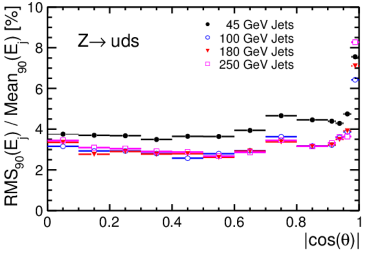

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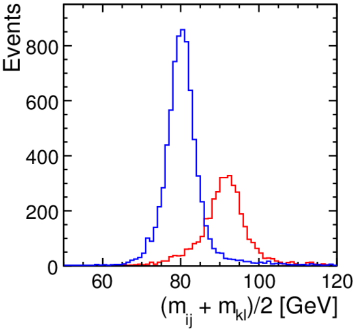

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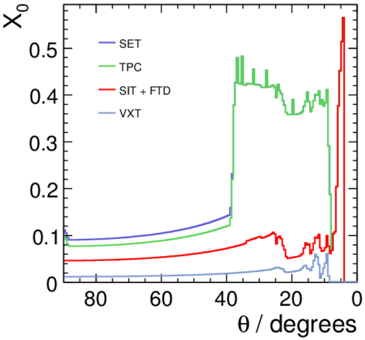
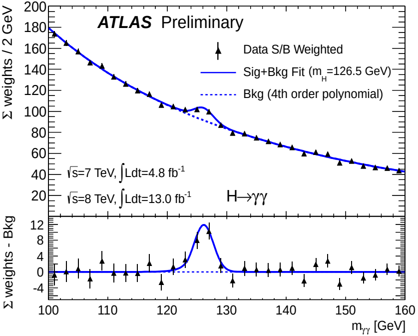
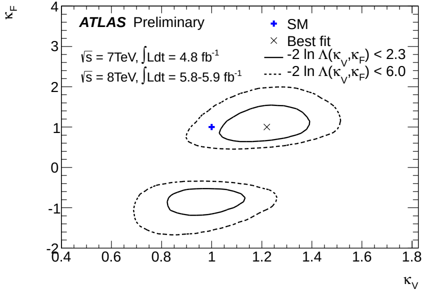


The Success of the LHC

- The LHC has found a new particle which looks like the SM Higgs
- And started to measured its properties





- What could be added to the LHC in a non-destructive and complementary way?

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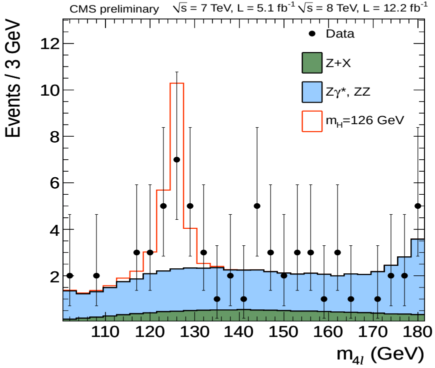
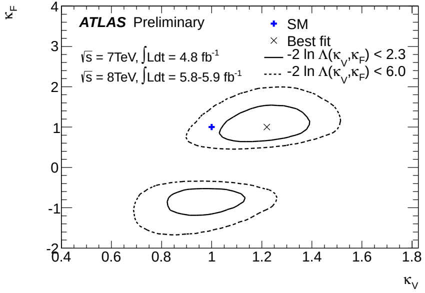




- What could be added to the LHC in a non-destructive and complementary way?

The Strategy towards the ILC

From the Proposed Update of the European Strategy for Particle Physics 2013:

> *"There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. Europe looks forward to a proposal from Japan to discuss a possible participation."*

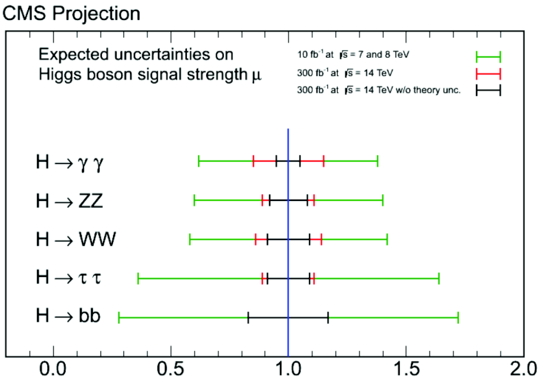
The time to move forward has come!

The ILC in Japan

What we can expect to extract from the LHC?

from the European Strategy Group Briefing Book

- Only observable is signal strength μ_i
- Can convert that into Γ_i/Γ_j
- To extract couplings, need many assumtions:
  - No hidden Higgs
  - Upper limit on Γ_{tot}
  - Fixed set of couplings



$\sigma_\mu \approx 15 - 20\,\%$

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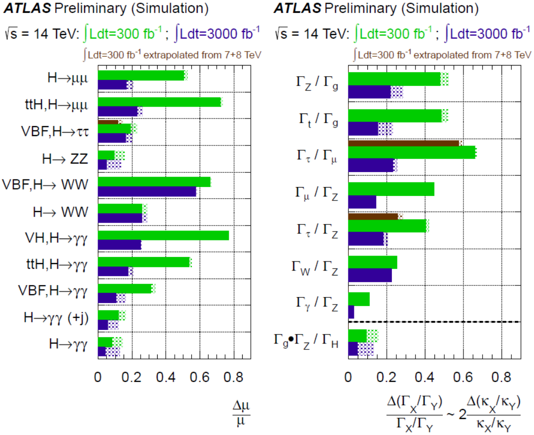
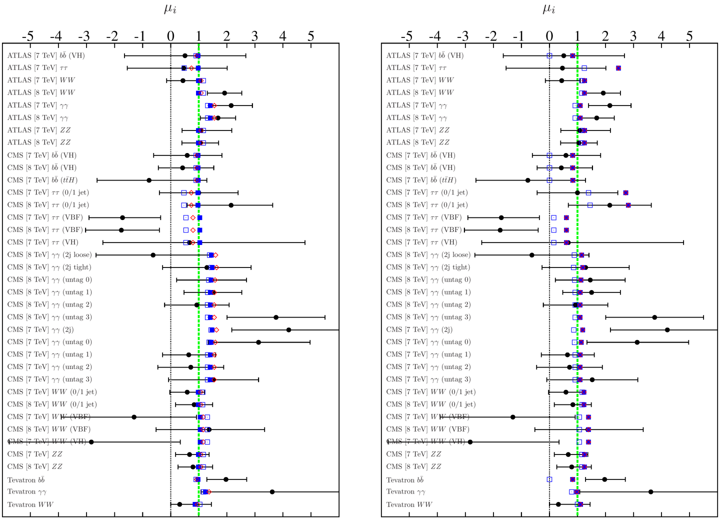


$$\mathcal{L}^{int}_{LHC} = 300\,\mathrm{fb}^{-1}:\ \Delta(\Gamma_i/\Gamma_j) \approx 10 - 60\,\%$$
$$\mathcal{L}^{int}_{LHC} = 3000\,\mathrm{fb}^{-1}:\ \Delta(\Gamma_i/\Gamma_j) \approx 5 - 30\,\%$$

Just some arbitrary example: What we might need

Take an actual New Physics example from PB,Heinemeyer, Stal, Stefaniak, Weiglein, Zeune arXiv:1211.1955 [hep-ph]

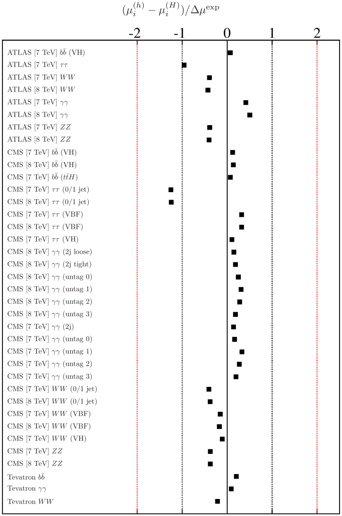


Just some arbitrary example: What we might need

Take an actual New Physics example from PB,Heinemeyer, Stal, Stefaniak, Weiglein, Zeune arXiv:1211.1955 [hep-ph]

What you can't see here:

- Fit the MSSM to the data with either the h or the H as particle explaining the Higgs observation, taking limits, B-physivs, etc into account
- Partly tiny differences between the h and the H interpeetation
- In many channels, expect no more than $\Delta\mu_{h-H}/\Delta\mu_{exp} \approx 5-10\,\%$
- This is at or below the expected improvements from now to $\mathcal{L}^{int}_{LHC} \approx 300\,\mathrm{fb}^{-1}$ (factor 3 to 5)
- Given $\sigma_\mu \approx 50-100\,\%$ now, need up to $\sigma_\mu \approx 2.5\,\%$ in the end!



Open Questions on EWSB

- Does the same particle give mass to fermions and bosons, and if yes, why?

Gauge Bosons: Gauge coupling, no free parameter

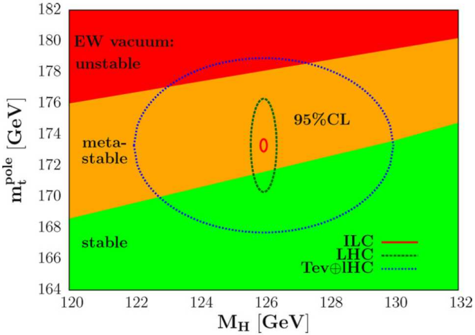
$$\mathcal{L} \propto \frac{1}{4} g^2 v^2 W_\mu^+ W_\mu^-$$

Fermions: Yukawa coupling, free parameter λ_f for every fermion

$$\mathcal{L} \propto -\sqrt{2}\lambda_f (\overline{L}_f \Phi R_f + \overline{R}_f \Phi^+ L_f)$$

Open Questions on EWSB

- Does the same particle give mass to fermions and bosons, and if yes, why?
- Is the SM vacuum stable?



In the SM, $\lambda = m_h^2/2\nu^2$ needs to be positive

Radiative corrections from strong *htt* couplings break that at high energies for light m_h (e.g. Alekhin, Djouadi, Moch arXiv:1207.0980)

Open Questions on EWSB

- Does the same particle give mass to fermions and bosons, and if yes, why?
- Is the SM vacuum stable?
- Why is $m_h \ll M_{Planck}$?
- Is WW scattering unitary?
- Does the Higgs potential look like in the SM?
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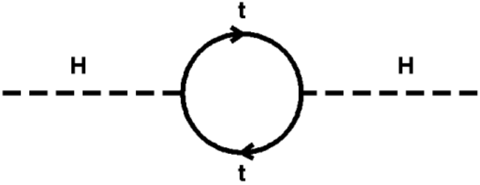

$$m_h^2 \sim \Lambda^2$$

in the presence of gravity:

natural $m_h = \Lambda = M_{Planck} \approx 10^{19}\,\mathrm{GeV}$

Finetuning at M_{Planck}:

$$m_{h,obs}^2 = m_{h,bare}^2 +$$

$$(\mathrm{fine-tuned\,difference\,of\,couplings}$$

$$\approx M_{Planck}^{-2}) \times M_{Planck}^2$$

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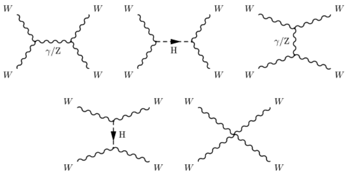

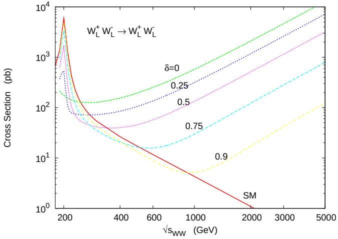

example from
arxiv:0803.2661 [hep-ph]

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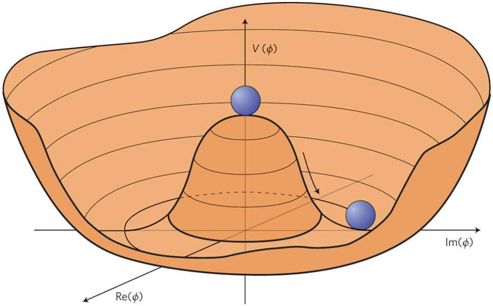

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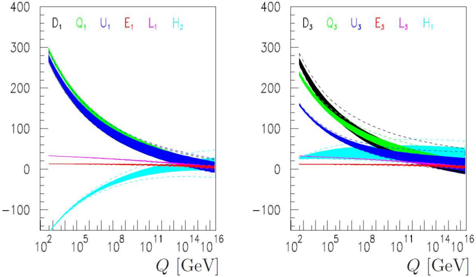
naturally explain signs in

$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

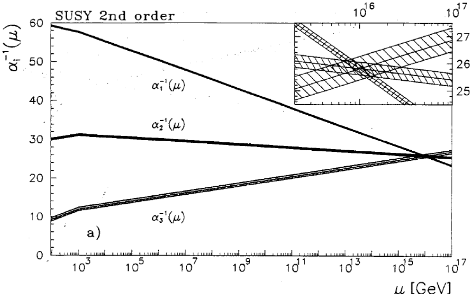
with some mechanism?



example from hep-ph/0511006

Open Questions on EWSB

- Does the same particle give mass to fermions and bosons, and if yes, why?
- Is the SM vacuum stable?
- Why is $m_h \ll M_{Planck}$?
- Is WW scattering unitary?
- Does the Higgs potential look like in the SM?
- If yes, why the heck does it look so?
- Is the SM vacuum stable?



„Prediction" of $\sin^2\theta_W$ in SUSY:

$$\sin^2\theta_W^{SUSY} = 0.2335(17)$$

$$\sin^2\theta_W^{exp} = 0.2315(02)$$

Wim de Boer *et al.* (1991)

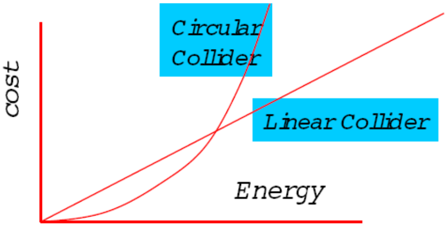
Open Questions on EWSB

- Does the same particle give mass to fermions and bosons, and if yes, why?
- Is the SM vacuum stable?
- Why is $m_h \ll M_{Planck}$?
- Is WW scattering unitary?
- Does the Higgs potential look like in the SM?
- If yes, why the heck does it look so?
- Is the SM vacuum stable?

Fully model independent measurements of

- Most precise mass (not critical)
- Absolute width
- Spin (not critical, since straight forward at LHC)
- CP
- Absolute couplings
- Including self-coupling
- WW scattering at $\sqrt{s}_{e^+e^-} \approx 1$ TeV
- m_t, m_W
- Any other sign for new physics . . .

Linear vs. Circular



- Synchrotron Radiation:
  - $\Delta E \sim E^4/(m^4 R)$: At LEP2: $4\,\mathrm{GeV}$ per turn per particle
- Cost:
  - Circular: $C_C = aR + b\Delta E = aR + bE^4/(m^4 R)$ Optimize for cost: $R \sim E^2 \rightarrow C_C \sim dE^2$
  - Linear: $C_L = eL$, $L \sim E$

Difficult to say what d currently is – very advanced costing on e (ILC) vs. back-of-the-envelope for d (LEP3, TLEP)

ILC Costing

From B. Foster:

- TDR: 7 780 MILCU & 22.6 M person-hours
- RDR: 7 266 MILCU, corrected for inflation, & 24.4 M person-hours
- Comparison: Materials up by 7 %, hours down by 7 %

1 ILCU $\approx$ 1 US $ (2012)
Manpower $\approx$ 25 $ of the total cost

ILD Costing

System	Option	Cost [MILCU]	Mean Cost [MILCU]
Vertex			3.4
	CMOS	3.2	
	FPCCD	4.0	
	DEPFET	3.0	
Silicon tracking	inner	2.3	2.3
Silicon tracking	outer	21.0	21.0
TPC		35.9	35.9
ECAL			116.9
	SiECAL	157.7	
	ScECAL	74.0	
HCAL			44.9
	AHCAL	44.9	
	SDHCAL	44.8	
FCAL		8.1	8.1
Muon		6.5	6.5
Coil, incl anciliaries		38.0	38.0
Yoke		95.0	95.0
Beamtube		0.5	0.5
Global DAQ		1.1	1.1
Integration		1.5	1.5
Global Transportation		12.0	12.0
Sum ILD			391.8

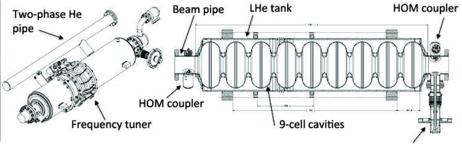
All theoretical e^+e^- Machine Options

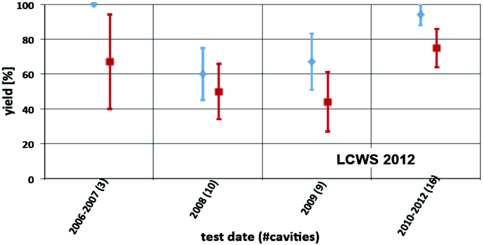
Facility	Year	E_{cm} [GeV]	Luminosity [$10^{34}\,cm^{-2}s^{-1}$]	Tunnel length [km]
ILC 250	<2030	250	0.75	
ILC 500		500	1.8	~ 30
ILC 1000		1000		~ 50
CLIC 500	>2030	500	2.3 (1.3)*	~ 13
CLIC 1400		1400 (1500)*	3.2 (3.7)*	~ 27
CLIC 3000		3000	5.9	~ 48
LEP3	>2024	240	1	LEP/LHC
TLEP	>2030	240	5	80 (ring)
TLEP		350	0.65	80 (ring)

Main ILC Parameters

Centre-of-mass energy	E_{CM}	GeV	200	230	250	350	500
Luminosity pulse repetition rate		Hz	5	5	5	5	5
Positron production mode			10 Hz	10 Hz	10 Hz	nom.	nom.
Bunch population	N	$\times 10^{10}$	2	2	2	2	2
Number of bunches	n_b		1312	1312	1312	1312	1312
Linac bunch interval	Δt_b	ns	554	554	554	554	554
RMS bunch length	σ_z	µm	300	300	300	300	300
Normalized horizontal emittance at IP	$\gamma\epsilon_x$	µm	10	10	10	10	10
Normalized vertical emittance at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
Horizontal beta function at IP	β_x^*	mm	16	14	13	16	11
Vertical beta function at IP	β_y^*	mm	0.34	0.38	0.41	0.34	0.48
RMS horizontal beam size at IP	σ_x^*	nm	904	789	729	684	474
RMS vertical beam size at IP	σ_y^*	nm	7.8	7.7	7.7	5.9	5.9
Vertical disruption parameter	D_y		24.3	24.5	24.5	24.3	24.6
Fractional RMS energy loss to beamstrahlung	δ_{BS}	%	0.65	0.83	0.97	1.9	4.5
Luminosity	L	$\times 10^{34}$ cm^{-2}s^{-1}	0.56	0.67	0.75	1.0	1.8
Fraction of L in top 1% E_{CM}	$L_{0.01}$	%	91	89	87	77	58
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30
Electron relative energy spread at IP	$\Delta p/p$	%	0.20	0.19	0.19	0.16	0.13
Positron relative energy spread at IP	$\Delta p/p$	%	0.19	0.17	0.15	0.10	0.07

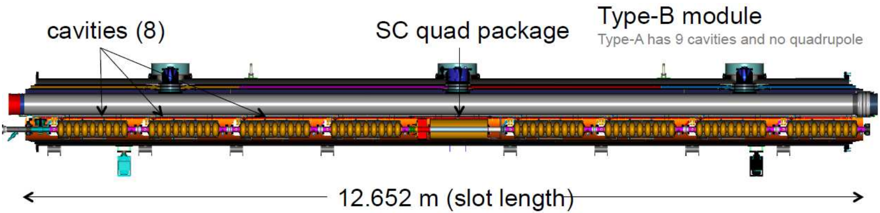
ILC Cavity Development

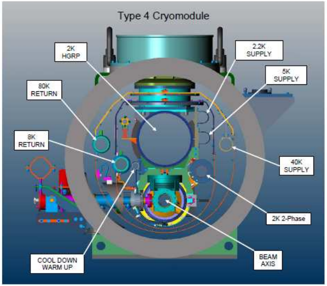




1.3 GHz Nb 9-cellCavities	16,024
Cryomodules	1,855
SC quadrupole pkg	673
10 MW MB Klystrons & modulators	436 / 471 *

ILC Cryomodule Setup





Achievements from RF and FF Test Facilities

Achievements
Understanding and mitigation of field emission at low gradient.
Establishment of a baseline sequence of cavity fabrication and surface preparation for ILC.
Achievement of a production yield of 94 % at 28 MV/m and of 75 % at 35 MV/m ± 20 %.
Achievement of an average gradient of 37.1 MV/m in the ensemble.
Achievement of an average field gradient of 32 MV/m in a prototype cryomodule for the European XFEL program.
Demonstration of the technical feasibility of assembling ILC cryomodules with global in-kind contributions.

+ 70 nm vertical beam size at ATF2 – expected performance scaled for Energy!

Statement from the Japanese Community

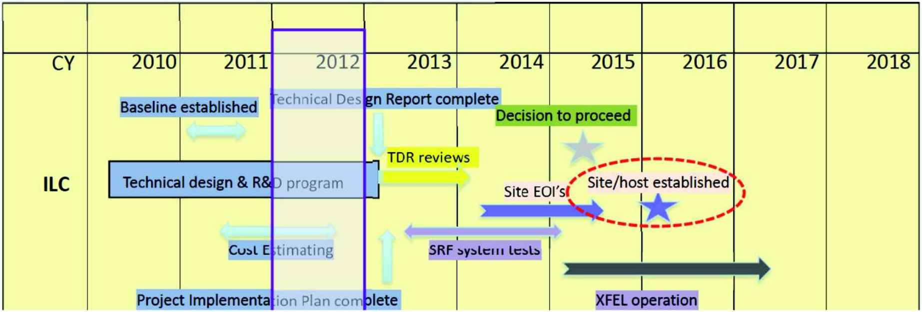
ILC Plan in Japan

(After the discovery of a Higgs-like particle)

- Japanese HEP community proposes to host ILC based on the "staging scenario" to the Japanese Government.
  - ILC starts as a 250GeV Higgs factory, and will evolve to a 500GeV machine.
  - Technical extendability to 1TeV is to be preserved.
- It is assumed that one half of the cost of the 500GeV machine is to be covered by Japanese Government. However, the share has to be referred to inter-governmental negotiation.

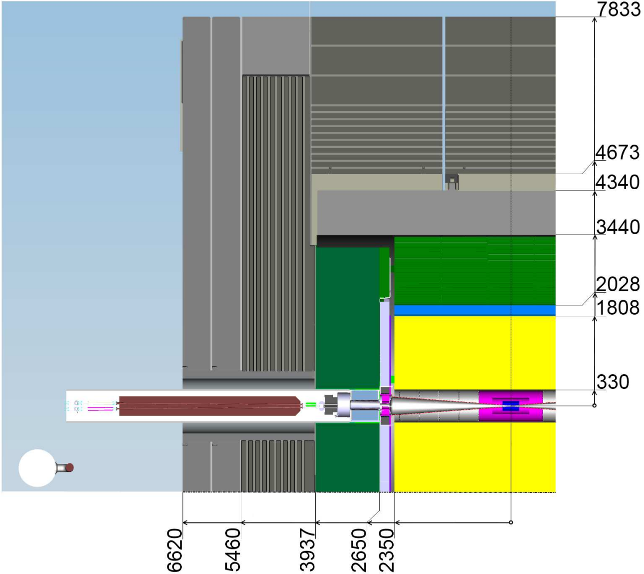
Statement from Y. Okada @ CPM12, Fermilab

Timeline from the japanese Community



from A. Suzuki

ILD Quadrant View



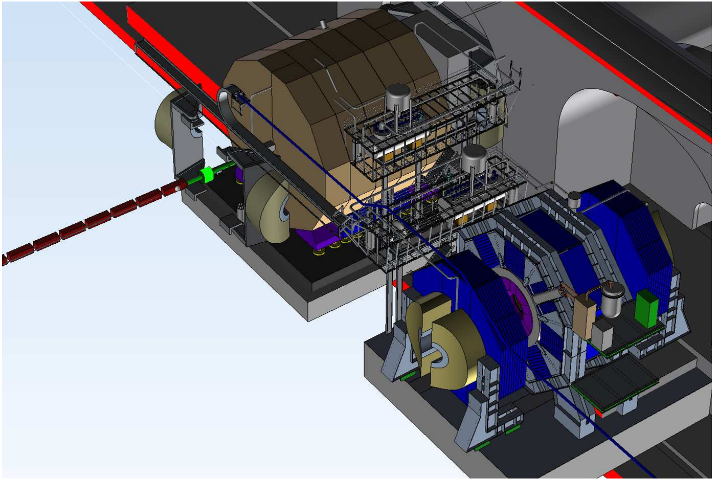
ILD Parameters Barrel

Barrel system						
System	R(in)	R(out) [mm]	z	comments		
VTX	16	60	125	3 double layers	Silicon pixel sensors,	
				layer 1:	layer 2:	layer 3-6
				$\sigma < 3\mu m$	$\sigma < 6\mu m$	$\sigma < 4\mu m$
Silicon						
- SIT	153	300	644	2 silicon strip layers	$\sigma = 7\mu m$	
- SET	1811		2300	2 silicon strip layers	$\sigma = 7\mu m$	
- TPC	330	1808	2350	MPGD readout	$1 \times 6 mm^2$ pads	$\sigma = 60\mu m$ at zero drift
ECAL	1843	2028	2350	W absorber	SiECAL	30 Silicon sensor layers, 5×5 mm^2 cells
					ScECAL	30 Scintillator layers, 5×45 mm^2 strips
HCAL	2058	3410	2350	Fe absorber	AHCAL	48 Scintillator layers, $3 \times 3 cm^2$ cells, analogue
					SDHCAL	48 Gas RPC layers, 1×1 cm^2 cells, semi-digital
Coil	3440	4400	3950	3.5 T field	2λ	
Muon	4450	7755	2800	14 scintillator layers		

ILD Parameters End Cap

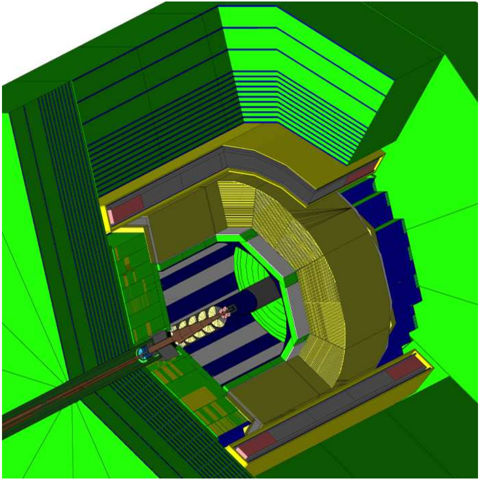
End cap system						
System	z(min)	z(max) [mm]	r(min), r(max)	comments		
FTD	220	371		2 pixel disks 5 strip disks	$\sigma = 2 - 6\mu m$ $\sigma = 7\mu m$	
ETD	2420	2445	419-1822	2 silicon strip layers	$\sigma = 7\mu m$	
ECAL	2450	2635		W-absorber	SiECAL ScECAL	Si readout layers Scintillator layers
HCAL	2650	3937	335-3190	Fe absorber	AHCAL	48 Scintillator layers $3 \times 3\text{cm}^2$ cells, analogue
					SDHCAL	48 gas RPC layers $1 \times 1\text{cm}^2$ cells, semi-digital
BeamCal	3595	3715	20-150	W absorber	30 GaAs readout layers	
Lumical	2500	2634	76-280	W absorber	30 Silicon layers	
LHCAL	2680	3205	93-331	W absorber		
Muon	2560		300-7755	12 scintillator layers		

The Depth of Detail of the Simulation



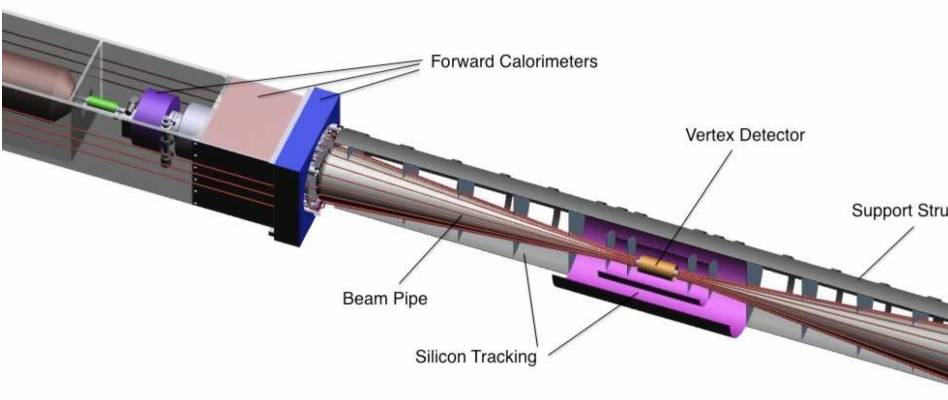
Full simulation and engineering of the final focus, the hall, push-pull

The Depth of Detail of the Simulation



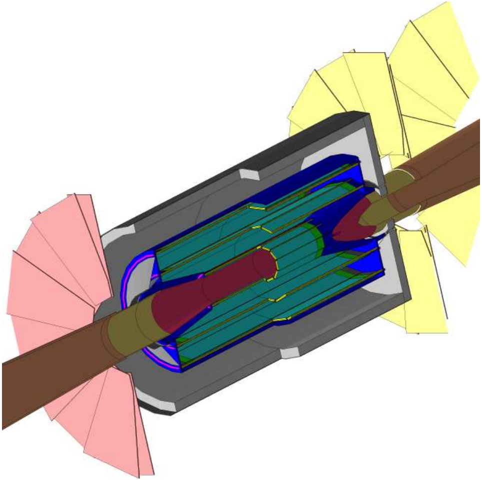
Very detailed implementation of the detector in the full GEANT4 simulation

The Depth of Detail of the Simulation



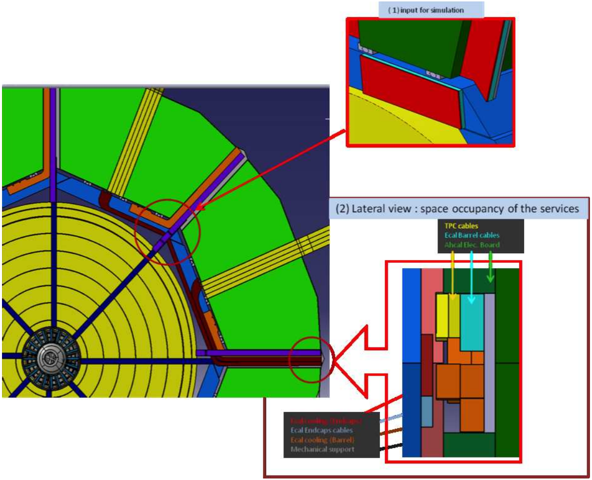
Detailed engineering of the machine/detector interface – backgrounds!

The Depth of Detail of the Simulation



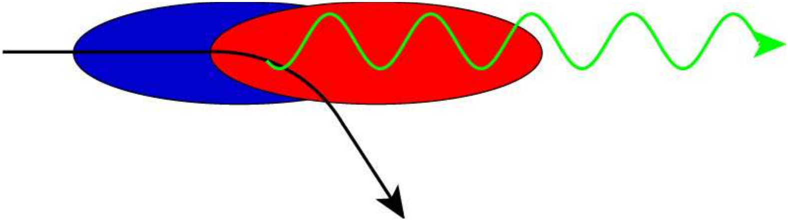
Full account of engineering model material for cables, cooling in the full simulation

The Depth of Detail of the Simulation



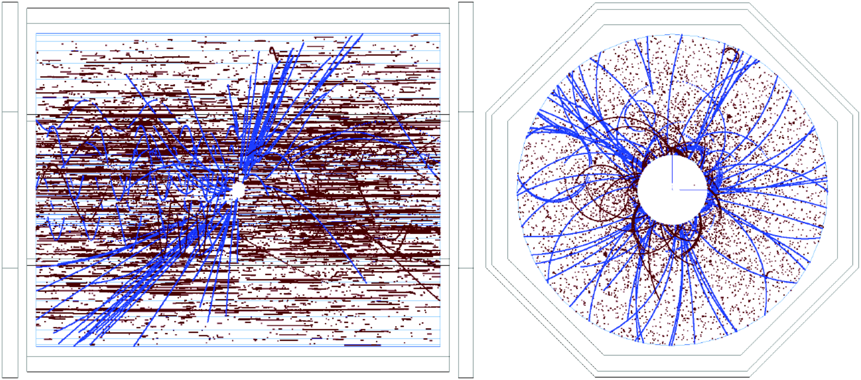
also for the calorimeters

Taking Backgrounds fully into account



The bunches feel the effective B-fields of the opposite bunch, creating deflected e, photons and $\gamma\gamma \to e^+e^-$

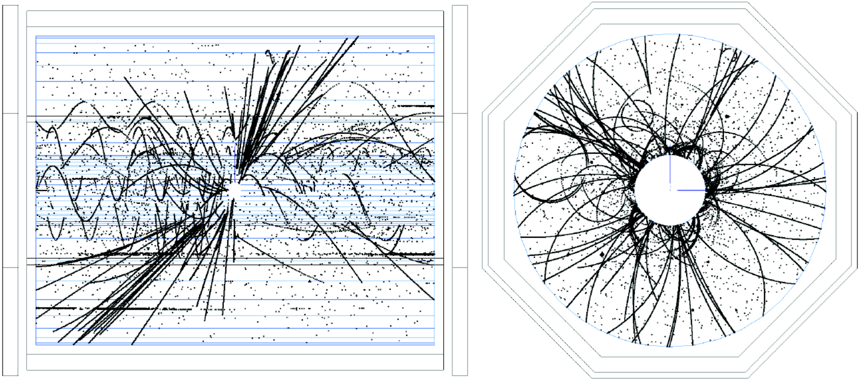
Taking Backgrounds fully into account



$t\bar{t}$ event with 150 BX background overlayed

- Never had such advanced and controlled full simulation for a new project at such an early state!
- Need high $B > 3.5$ T to control beam backgrounds

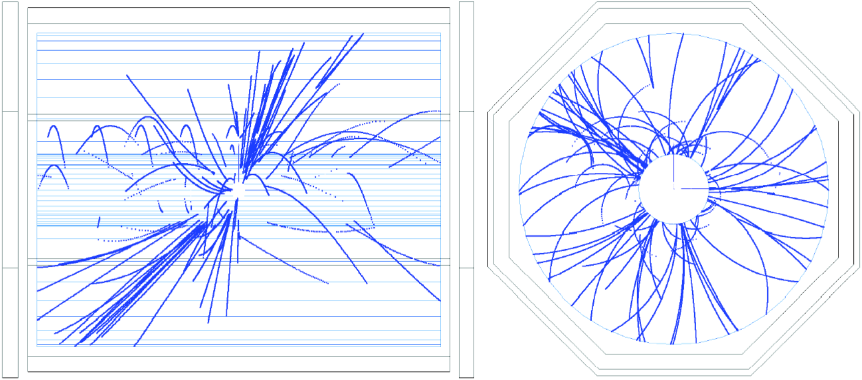
Taking Backgrounds fully into account



same event after microcurler removal algorithm

- Never had such advanced and controlled full simulation for a new project at such an early state!
- Need high $B > 3.5$ T to control beam backgrounds

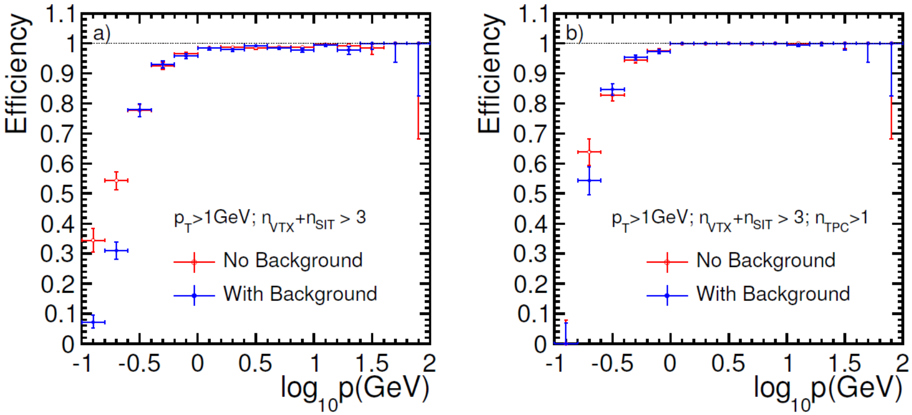
Taking Backgrounds fully into account



result from track finding (hits attached to tracks) clean event

- Never had such advanced and controlled full simulation for a new project at such an early state!
- Need high $B > 3.5$ T to control beam backgrounds

Taking Backgrounds fully into account

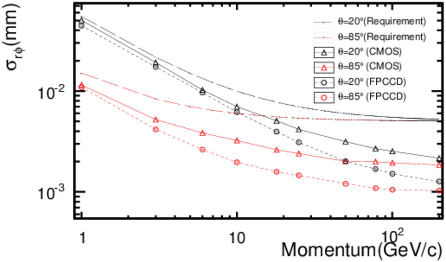


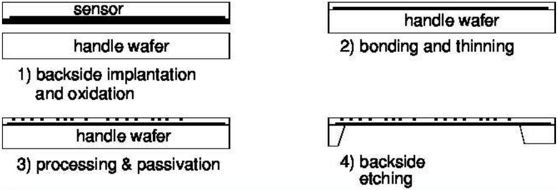
Virtually no effect on tracking perfrmance for $p > 0.5$ GeV

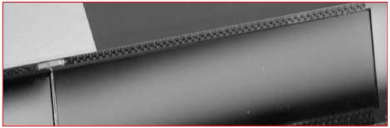
- Never had such advanced and controlled full simulation for a new project at such an early state!
- Need high $B > 3.5$ T to control beam backgrounds

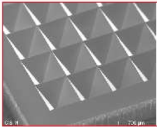
Vertex Detector Setup and Performance

	R (mm)	$\lvert z\rvert$ (mm)	$\lvert\cos\theta\rvert$	σ (μm)
Layer 1	16	62.5	0.97	2.8
Layer 2	18	62.5	0.96	6
Layer 3	37	125	0.96	4
Layer 4	39	125	0.95	4
Layer 5	58	125	0.91	4
Layer 6	60	125	0.9	4

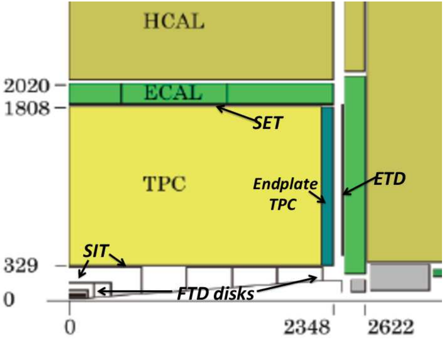


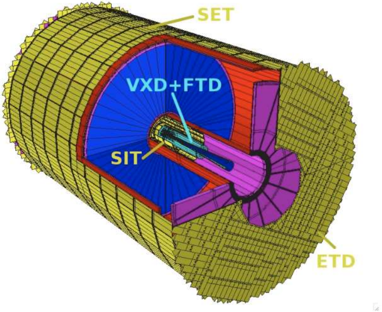


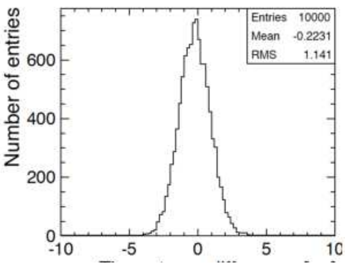


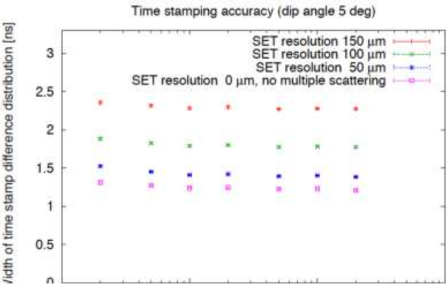


Silicon External Tracker





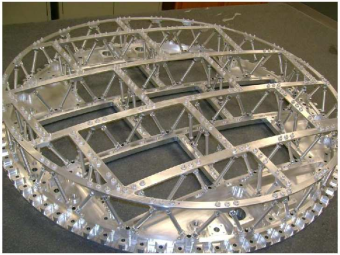


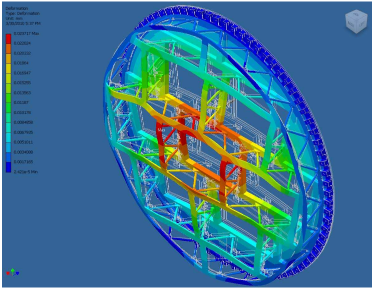


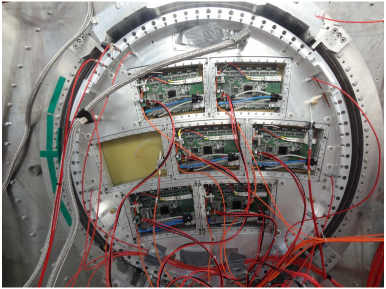
Time Projection Chamber

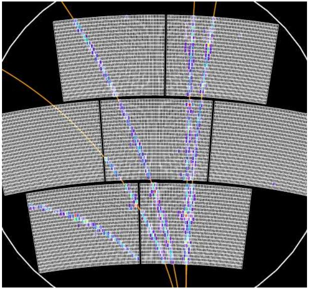
Parameter			
Geometrical parameters	r_{in} 329 mm	r_{out} 1808 mm	z $\pm$ 2350 mm
Solid angle coverage	Up to $\cos\theta \simeq 0.98$ (10 pad rows)		
TPC material budget	$\simeq$ 0.05 X_0 including outer fieldcage in r		
	$<$ 0.25 X_0 for readout endcaps in z		
Number of pads/timebuckets	$\simeq$ 1-2 $\times 10^6$/1000 per endcap		
Pad pitch/ no.padrows	$\simeq 1\times 6$ mm^2 for 220 padrows		
σ_{point} in $r\phi$	$\simeq$ 60 μm for zero drift, $<$ 100 μm overall		
σ_{point} in rz	$\simeq 0.4 - 1.4$ mm (for zero – full drift)		
2-hit resolution in $r\phi$	$\simeq$ 2 mm		
2-hit resolution in rz	$\simeq$ 6 mm		
dE/dx resolution	$\simeq$ 5 %		
Momentum resolution at B=3.5 T	$\delta(1/p_t) \simeq 10^{-4}$/GeV/c (TPC only)		

Time Projection Chamber

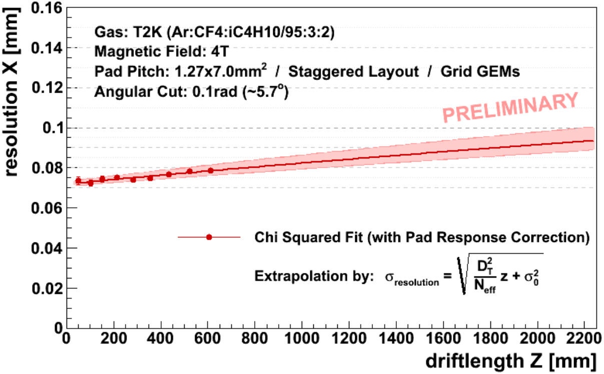




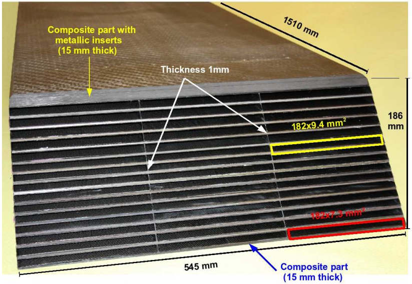


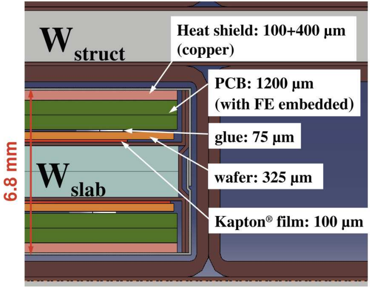


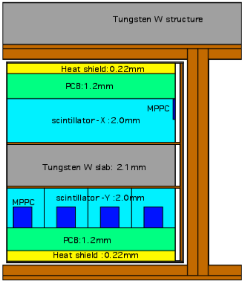
Time Projection Chamber Performance



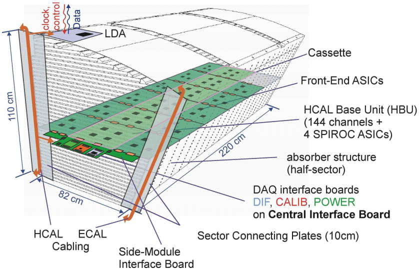
ECAL

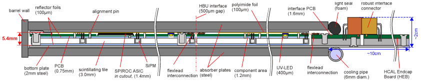

Composite part with
metallic inserts
(15 mm thick)
Thickness 1mm
1510 mm
186
mm
182x9.4 mm²
182x7.3 mm²
545 mm
Composite part
(15 mm thick)

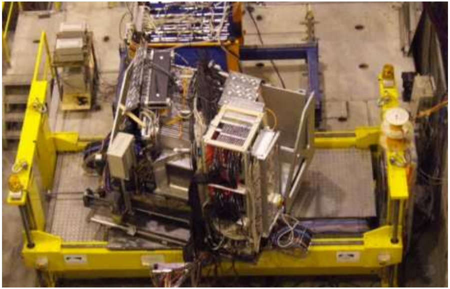

W struct
Heat shield: 100+400 µm
(copper)
PCB: 1200 µm
(with FE embedded)
glue: 75 µm
wafer: 325 µm
Kapton® film: 100 µm
W slab
6.8 mm

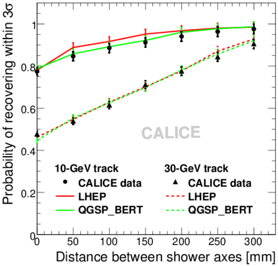

Tungsten W structure
Heat shield:0.22mm
PCB:1.2mm
MPPC
scintillator-X:2.0mm
Tungsten W slab: 2.1mm
MPPC
scintillator-Y:2.0mm
PCB:1.2mm
Heat shield :0.22mm

HCAL & CALICE

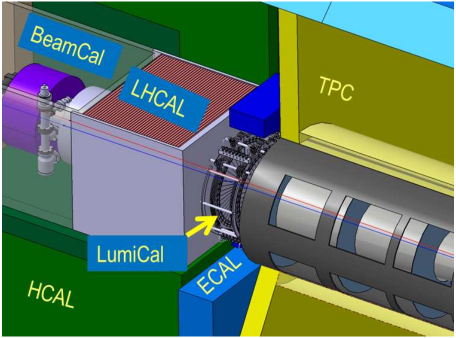

clock, control
Data
LDA
Cassette
Front-End ASICs
HCAL Base Unit (HBU)
(144 channels +
4 SPIROC ASICs)
absorber structure
(half-sector)
DAQ interface boards
DIF, CALIB, POWER
on Central Interface Board
Sector Connecting Plates (10cm)
110 cm
220 cm
82 cm
HCAL
ECAL
Cabling
Side-Module
Interface Board

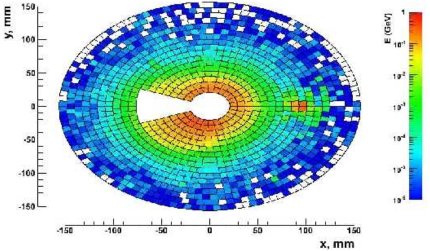

barrel wall
reflector foils (100μm)
alignment pin
HBU interface (500μm gap)
polyimide foil (100μm)
interface PCB (1.6mm)
light seal (foam)
robust interface connector
5.4mm
~2cm
~10cm
bottom plate (2mm steel)
PCB (0.75mm)
scintillating tile (3.0mm)
SPIROC ASIC in cutout, (1.4mm)
SiPM
flexlead interconnection
absorber plates (steel)
component area (1.2mm)
UV-LED (400μm)
flexlead interconnection
cooling pipe (6mm diam.)
HCAL Endcap Board (HEB)



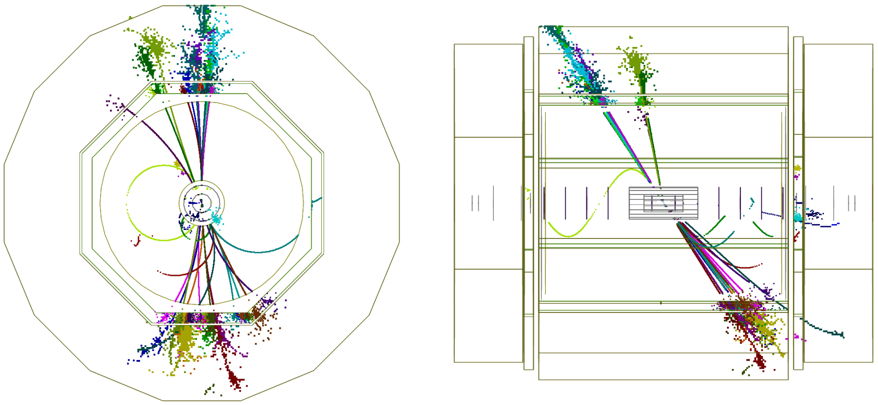

Probability of recovering within 3σ
Distance between shower axes [mm]
CALICE
10-GeV track
CALICE data
LHEP
QGSP_BERT
30-GeV track
CALICE data
LHEP
QGSP_BERT
0
0.2
0.4
0.6
0.8
1
50
100
150
200
250
300

Forward Detectors



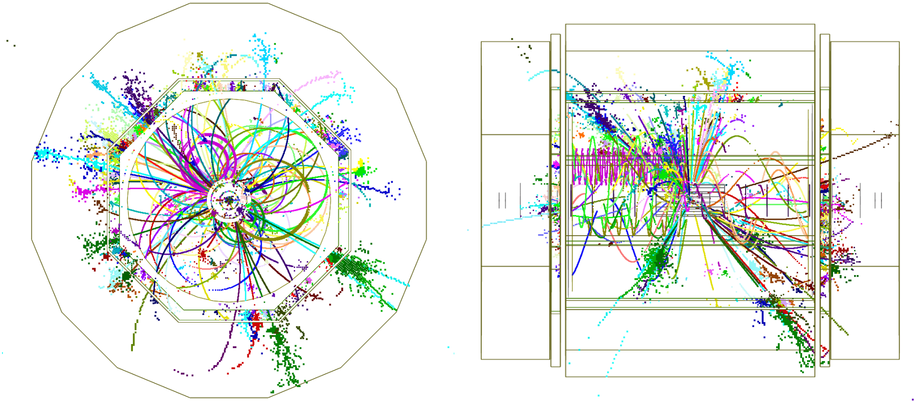


Sources of Uncertainty from Confusion



Confusion between charged and neutral components within the same jet
e.g. $e^+e^- \to WW \to 4q$

Sources of Uncertainty from Confusion

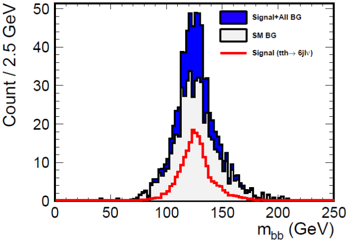


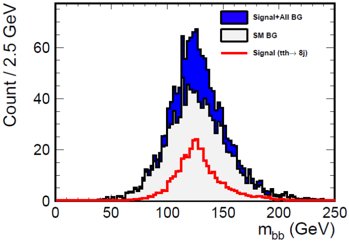
Confusion of assignement of PFlow objects to jets

e.g. $e^+e^- \rightarrow t\bar{t}h \rightarrow 8q$

Top Yukawa coulings

- Use $tth \to 6j + b\bar{b}$ and $tth \to 4j\ell\nu + b\bar{b}$ final states @ $\sqrt{s} = 500\,\text{GeV}$ and $\mathcal{L}^{int} = 500\,\text{fb}^{-1}$

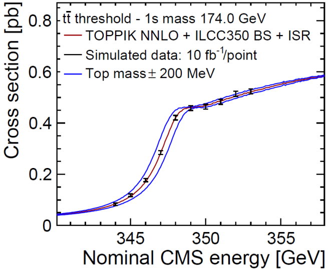


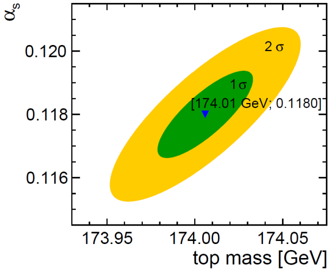


- Need sophisicated event shape analysis
- Still based on Durham jet finding. Will maybe improve with jet finding more suited for dense environments?
- m_{bb} distributions after cuts look not so helpful, but background can be completely determined from data (e.g. $t\bar{t}Z \to 6j + \ell^+\ell^-$ to determine $t\bar{t}Z \to 6j + b\bar{b}$, etc.)
- Statistical precision $\Delta g_{t\bar{t}h}/g_{t\bar{t}h} = 4.3\,\%$

Top Mass Threshold Scan

- Quite sensitive to beam energy spread
- Use 10 fb^{-1} each at 10 different points in $\sqrt{s}$ around the threshold



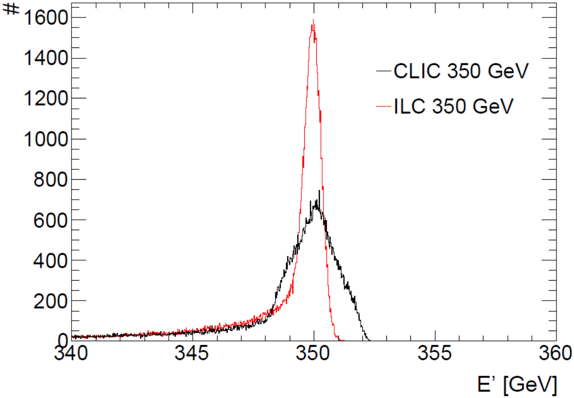


- α_s influences shape of the turn-on through radiative corrections and gluon radiation

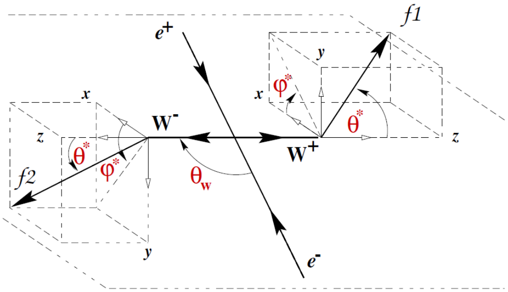
measurement	m_t stat. error	α_s stat. error
ten point scan 1D fit	18 MeV	-
ten point scan 2D fit	27 MeV	0.0008

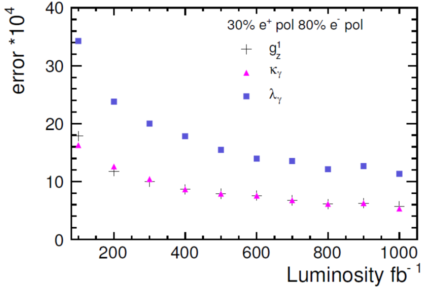
LC-REP-2012-069

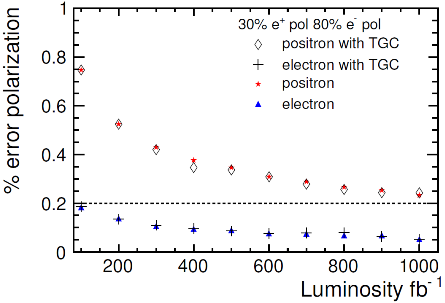
ILC and CLIC beam energy spreads



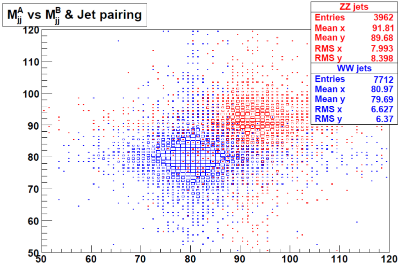
TGCs and Beam Polarization

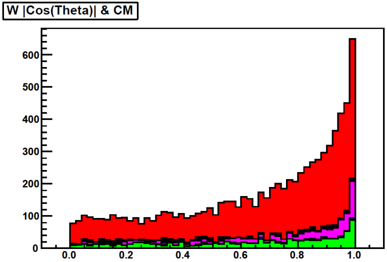




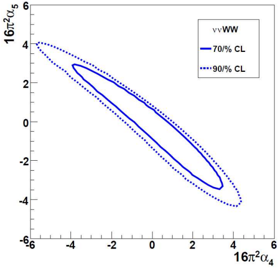


WW scattering @ 1 TeV



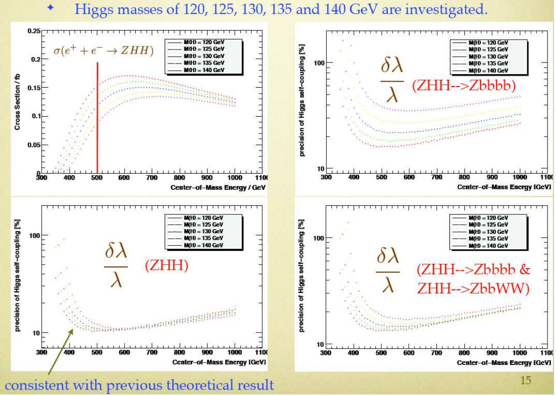


Channel	$\nu_e\bar{\nu}_e WW$	$\nu_e\bar{\nu}_e ZZ$
$\nu_e\bar{\nu}_e WW \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	6308	
$\nu_e\bar{\nu}_e ZZ \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$		2073
$\nu_e\bar{\nu}_e q\bar{q}q\bar{q}$ (background)	968	311
$e\nu_e WZ \to e\nu_e q\bar{q}q\bar{q}$	40	38
$eeWW/ZZ \to eeq\bar{q}q\bar{q}$	1	0
$\nu_\mu\bar{\nu}_\mu WW/ZZ \to \nu_\mu\bar{\nu}_\mu q\bar{q}q\bar{q}$	378	17
$\nu_\tau\bar{\nu}_\tau WW/ZZ \to \nu_\tau\bar{\nu}_\tau q\bar{q}q\bar{q}$	360	22
$e\nu_e W \to e\nu_e q\bar{q}$	90	0
$t\bar{t} \to X$	284	84



Present developments: Higgs Self Coupling

- At first glance, 500 GeV looks most promising:

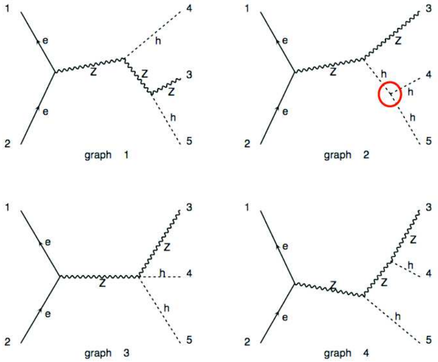


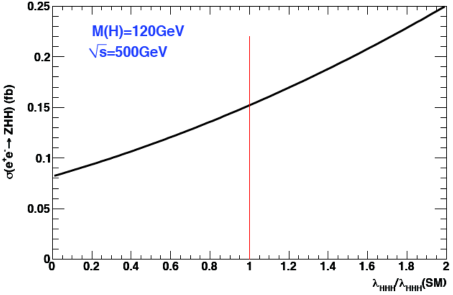
- This doesn't need to be the full story – $t\bar{t}$ combinatorics might decrease strongly at larger boost

Thanks to Junping Tian at al.

Higgs Self Coupling Maesurement

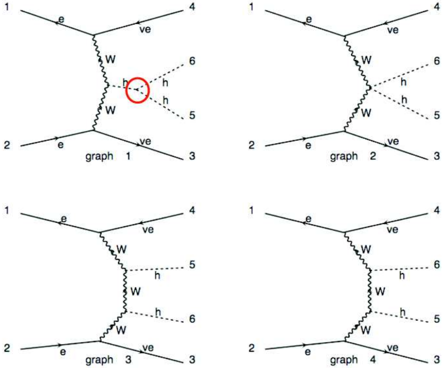
- Need to combine several channels, because the Higgs self coupling graph is only one of several graphs
- $\Delta\lambda/\lambda = 1.8\Delta\sigma/\sigma$

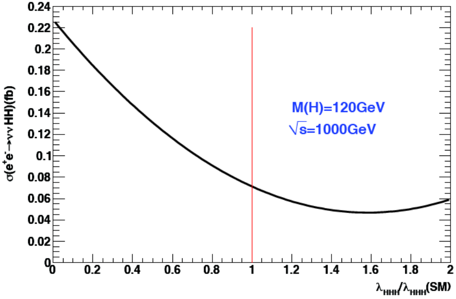




Higgs Self Coupling Maesurement

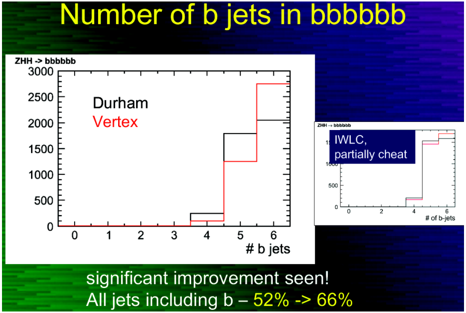
- The very challenging $\bar{\nu}\nu$ channel helps strongly in transferring σ to λ
- $\Delta\lambda/\lambda = 0.85\Delta\sigma/\sigma$

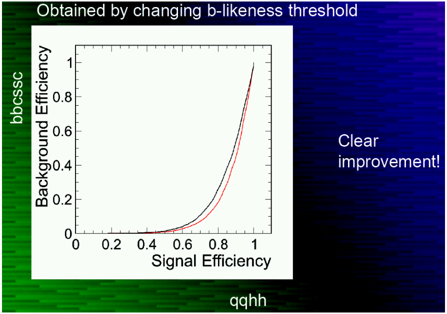




Higgs Self Coupling Maesurement: Important Improvements

- Traditionally: Jet finding → Vertex Fitting → b-tag
- Now: Vertex Fitting → Jet finding → b-tag
- Helps strongly to clean up combinatorics

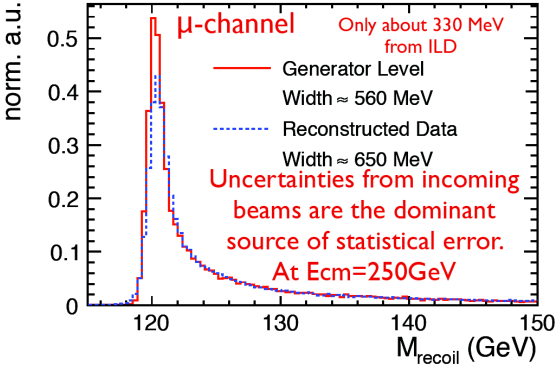




Thanks to Taikan Suehara et al.

Higgs Recoil Analysis: Very sensitive to the machine

- Many different machine designs have been studied to optimize perf/cost
- Typically: Lower cost = lower power, lower beamcurrent, higher beam BG, bigger beam energy spread



- Physics studies needed to control machine design!

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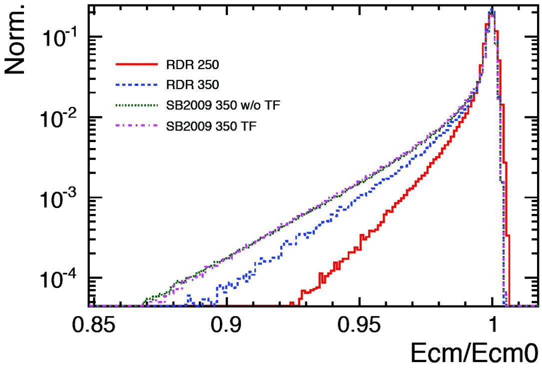

- Physics studies needed to control machine design!