(Electroweak) Precision physics at a future Linear Collider at the TeV Scale

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Outline of Lecture

~Today:

- Brief presentation of ILC and CLIC

- Brief review of development of electroweak theory

- Physics case for e+e- machines at the TeV scale

~Tomorrow

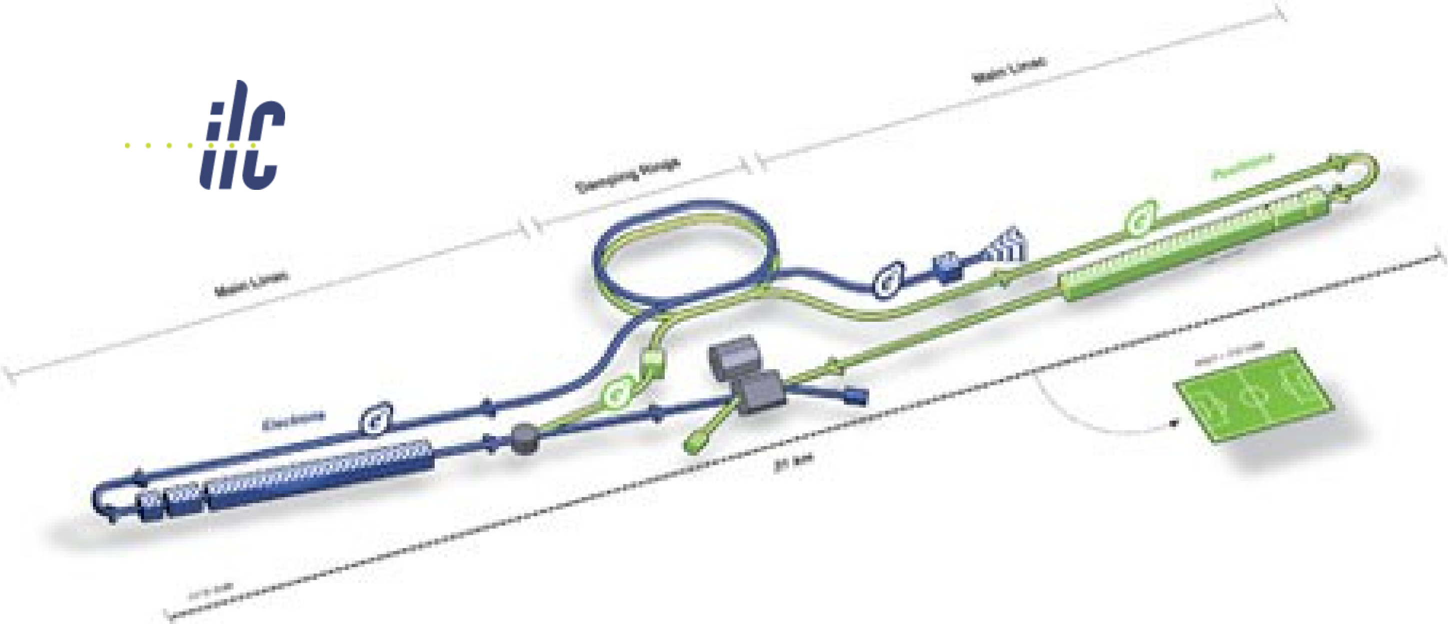
- Linear collider: Machine aspects

- Detectors for Linear Colliders

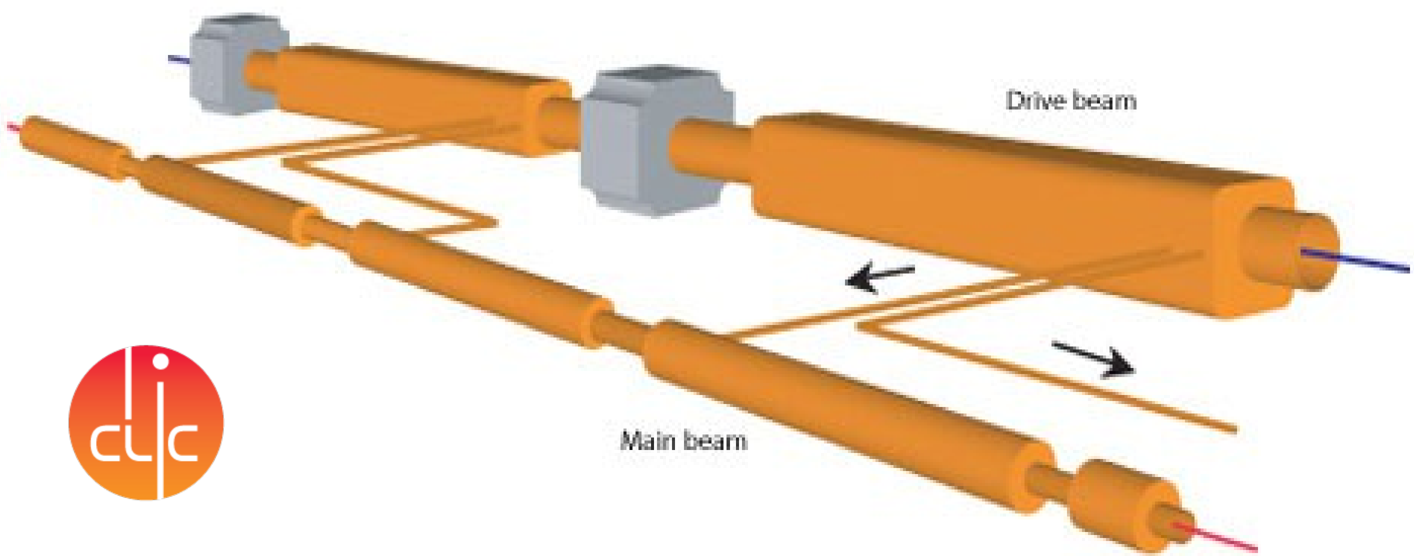
- (if time permits) Political aspects

Chapter I: Brief presentation of ILC and CLIC

(Future) Linear electron-positron colliders



Energy: 0.1 - 1 TeV
lectron (and positron) polarisation
TDR in 2013
+ DBD for detectors
Possible timeline for project see later

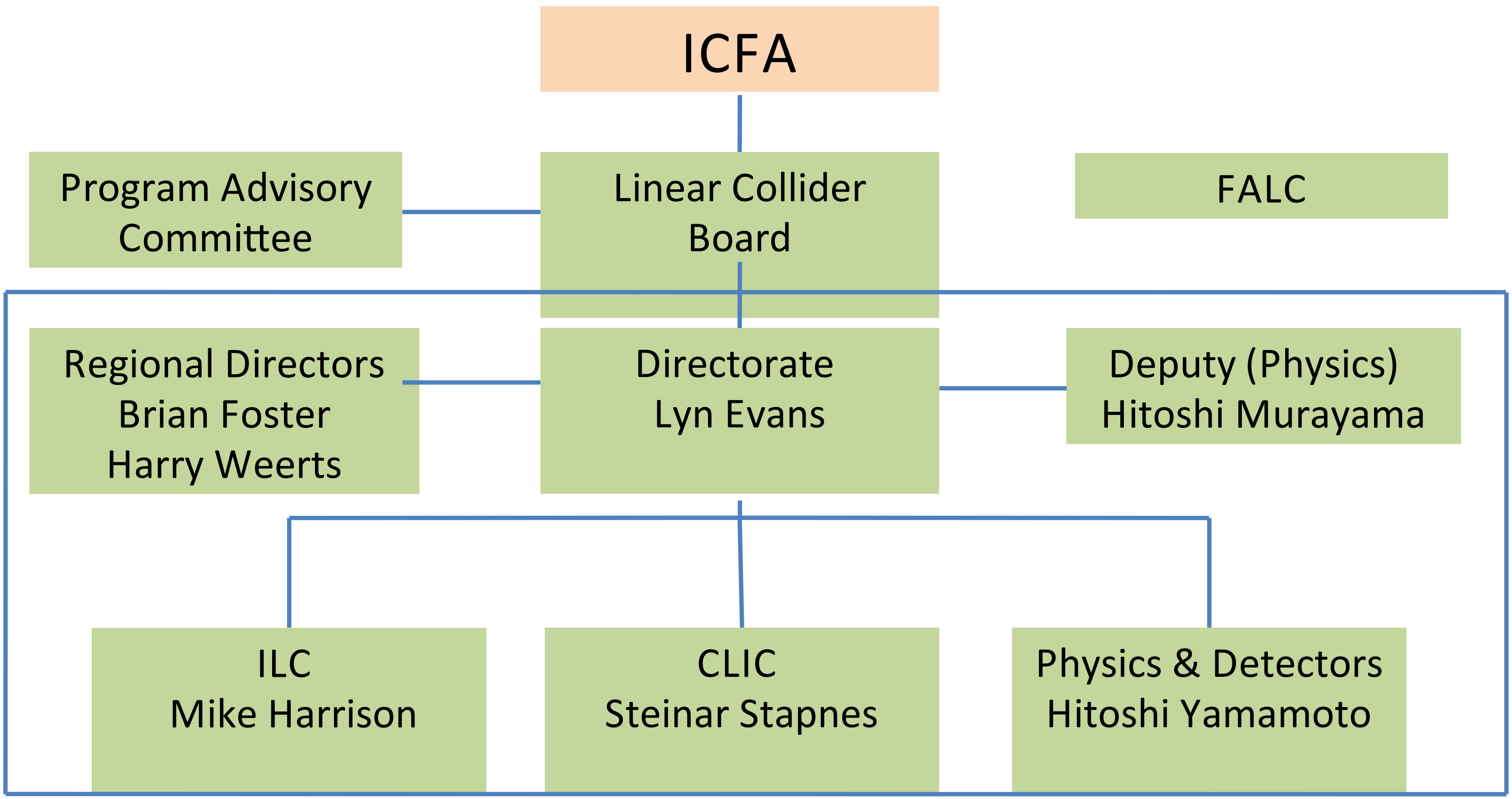


Energy: 0.5 - 3 TeV

CDR in 2012

Linear Collider Collaboration

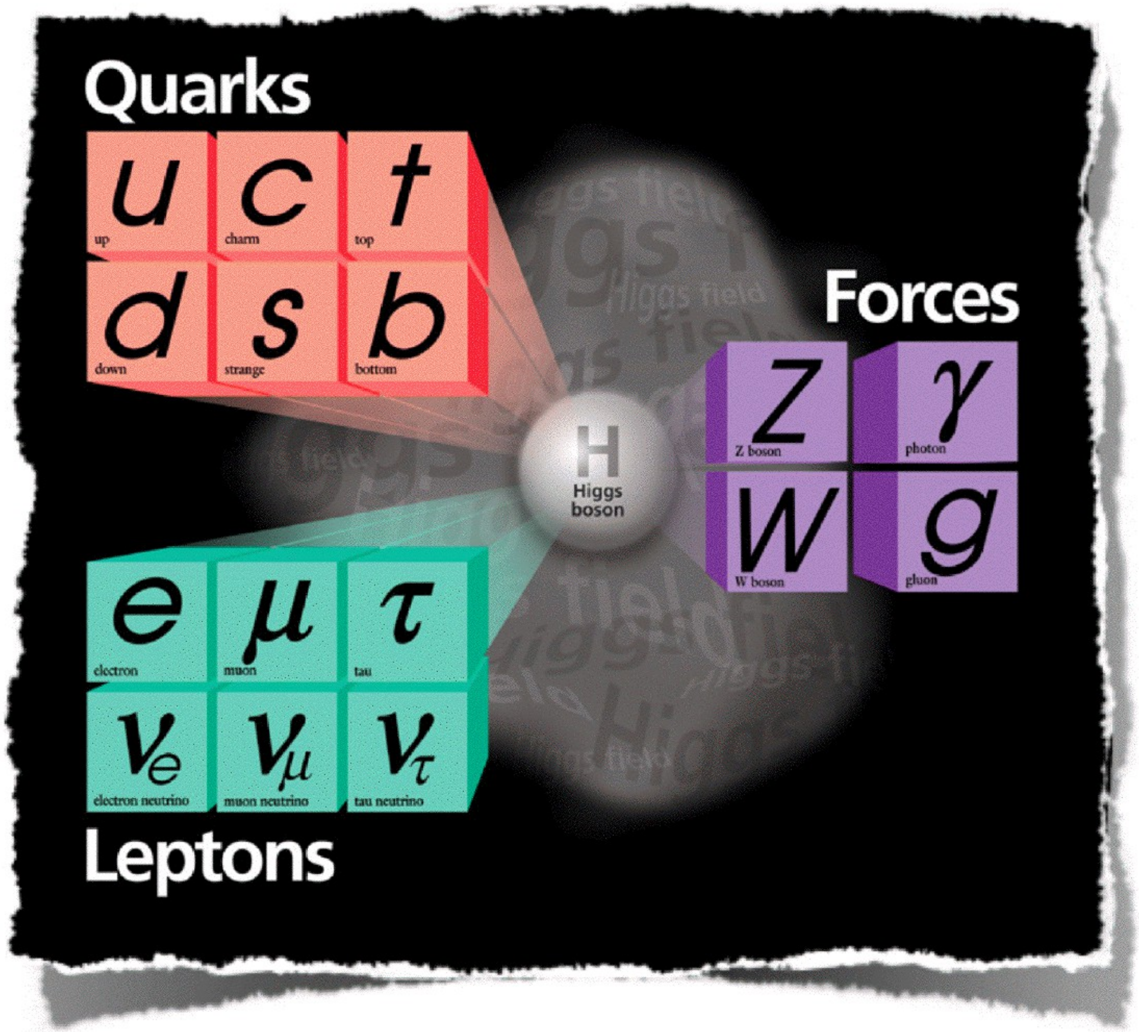
Organization



Worldwide project
Regional balance

Chapter II: Brief history of electroweak theory

The Standard Model of Particle Physics



Matter is composed of 6 Fermions
'Lepton and Quarks'
Interactions through Vector Bosons
'Force Carriers'

SM is relativistic Quantum Field Theory with gauge symmetry

$SU_L(2)$xU(1)x$SU_C(3)$
(main subject of lecture)

Gauge symmetry =>

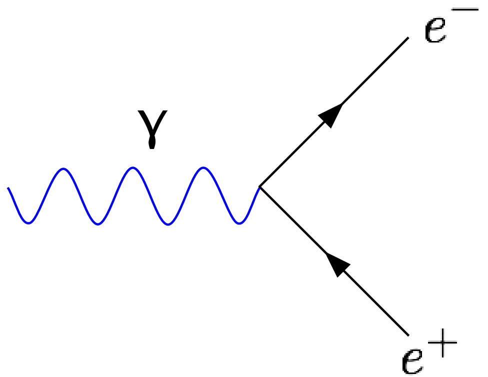
- Conserved quantities
  e.g. Electrical charge in QED
- Vector Bosons
  e.g. Photon

Regard:
$SU_L(2)$x...
=> Standard Model 'prefers'
left handed massless particles

Massive particles through Higgs Mechanism

Electro Weak production – A brief recap

QED: Abelian theory U(1) => 1 gauge boson photon



Interaction term: $e\bar{\psi}\gamma^\mu\psi A_\mu = j^\mu A_\mu$

Some basic features of QED:

- Blue print for all gauge theories, conserved charge => gauge boson

- Photon is massless, massive gauge photon would break gauge invariance

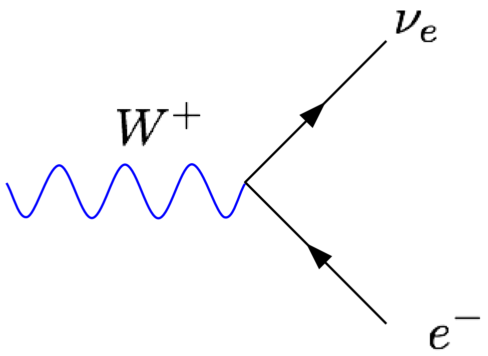
- QED is perfectly left-right symmetric!!!

$j^\mu = e\bar{\psi}\Pi^+\gamma^\mu\Pi^-\psi + e\bar{\psi}\Pi^-\gamma^\mu\Pi^+\psi$ is symmetric under $\vec{p} \to -\vec{p}$

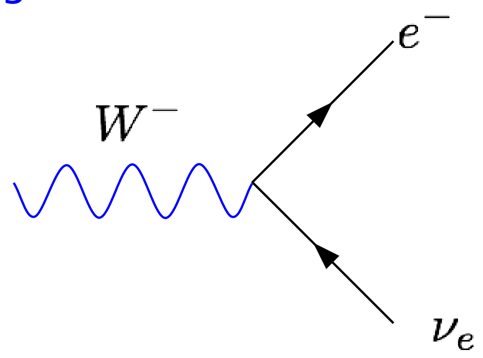
Electro Weak production – A brief recap

Weak interactions: Abelian theory SU(2)=> 3 gauge bosons

Weak Charge currents

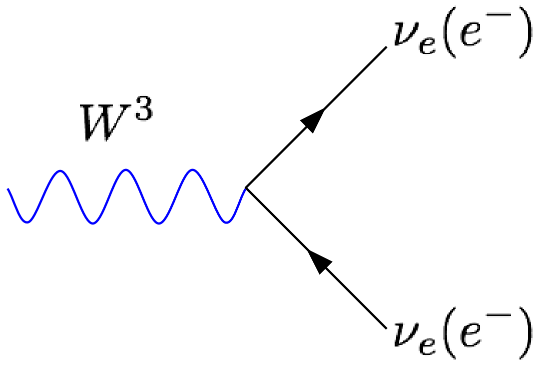


$g[\bar{u}_\nu \gamma^\mu \frac{1}{2}(1-\gamma^5) u_e](W^+)^\mu$



$g[\bar{u}_e \gamma^\mu \frac{1}{2}(1-\gamma^5) u_\nu](W^-)^\mu$

Weak Neutral currents



$g[\bar{u}_e(\bar{u}_\nu)\gamma^\mu \frac{1}{2}(1-\gamma^5)(u_e)u_\nu](W^3)^\mu$

Weak currents mediate transition within doublet $\chi = \begin{pmatrix} \nu \\ e^- \end{pmatrix}_L$

and form Isotriplett $J^i_\mu = \bar{\chi_L}\gamma_\mu \frac{1}{2}\tau_i \chi_L$

with $\tau_i =$ Pauli Matrices and $\tau_\pm = \frac{1}{2}(\tau_1 \pm i\tau_2)$

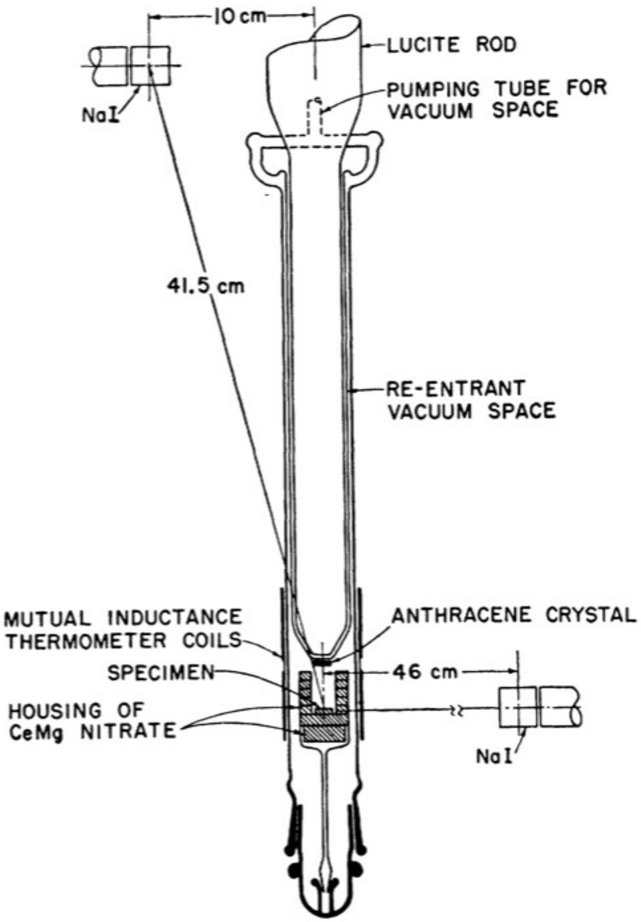
$\gamma^\mu \frac{1}{2}(1-\gamma^5) \Rightarrow$ Coupling to left handed particles only. $(V-A)$ Current

=> Parity violation

Historical Experimental evidences I – Charged currents and Parity violation

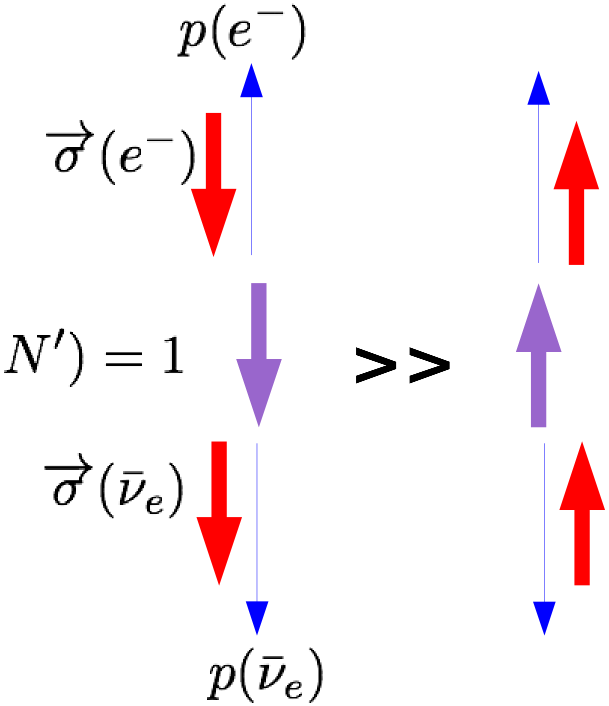
Wu experiment 1957

Polarised 60Co nuclei

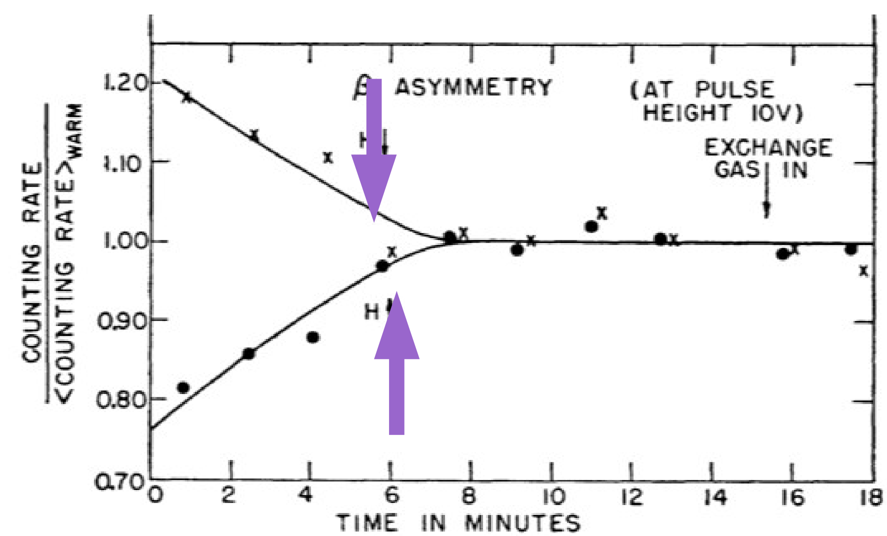


$$^{60}Co \rightarrow ^{60}Ni^{*} + e^{-} + \bar{\nu}_e$$

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$



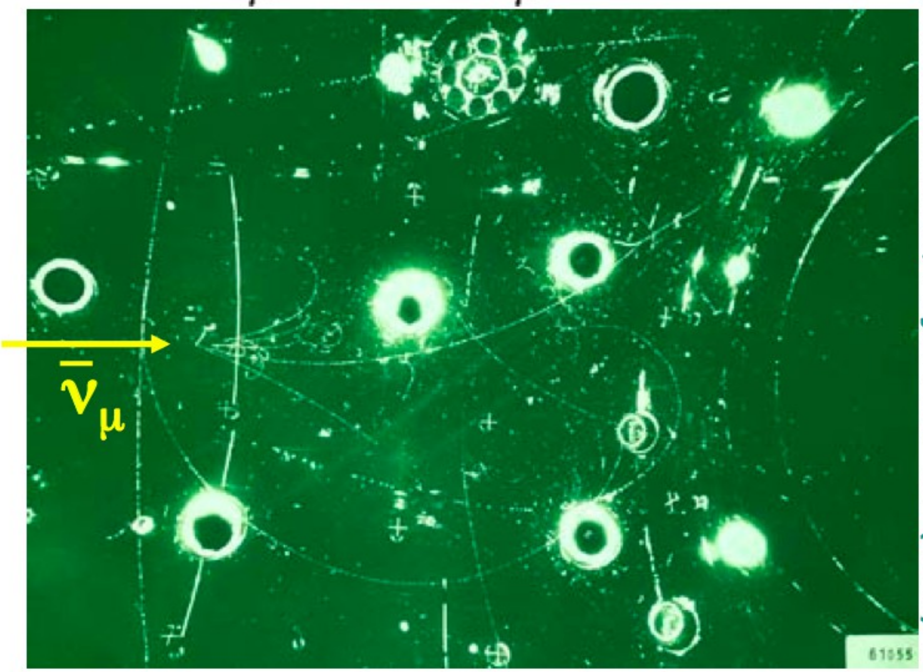
$$\Delta S(N \rightarrow N') = 1$$ >>



Historical Experimental evidences II – Weak Neutral currents I

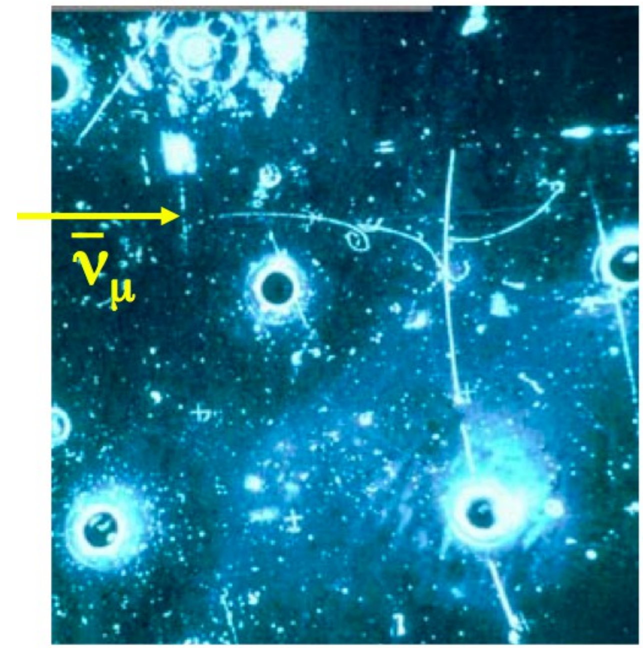
Weak neutral currents – Gargamelle 1973

$$\overline{\nu}_\mu + N \rightarrow \overline{\nu}_\mu + \text{hadrons}$$

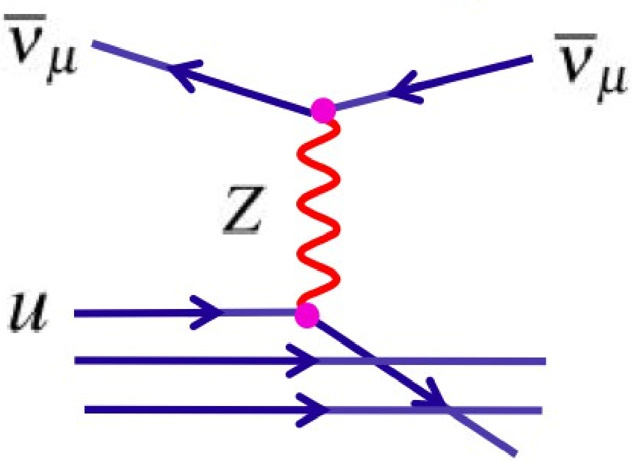


F.J. Hasert et al., Phys. Lett. 46B (1973) 138

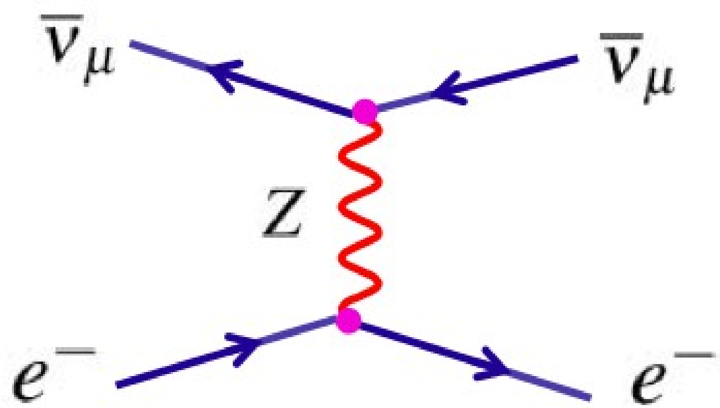
$$\overline{\nu}_\mu + e^- \rightarrow \overline{\nu}_\mu + e^-$$



F.J. Hasert et al., Phys. Lett. 46B (1973) 12



$Z=W^3$?



Pics and Drawings From M. Thomson

Historical Experimental Evidences III – Weak Neutral currents II

Regard electron current

Pure $(V-A)$ current

$$\bar{e}\gamma_\mu(1-\gamma_5)e \rightarrow \bar{e}\gamma_\mu(c_V - c_A\gamma_5)e$$

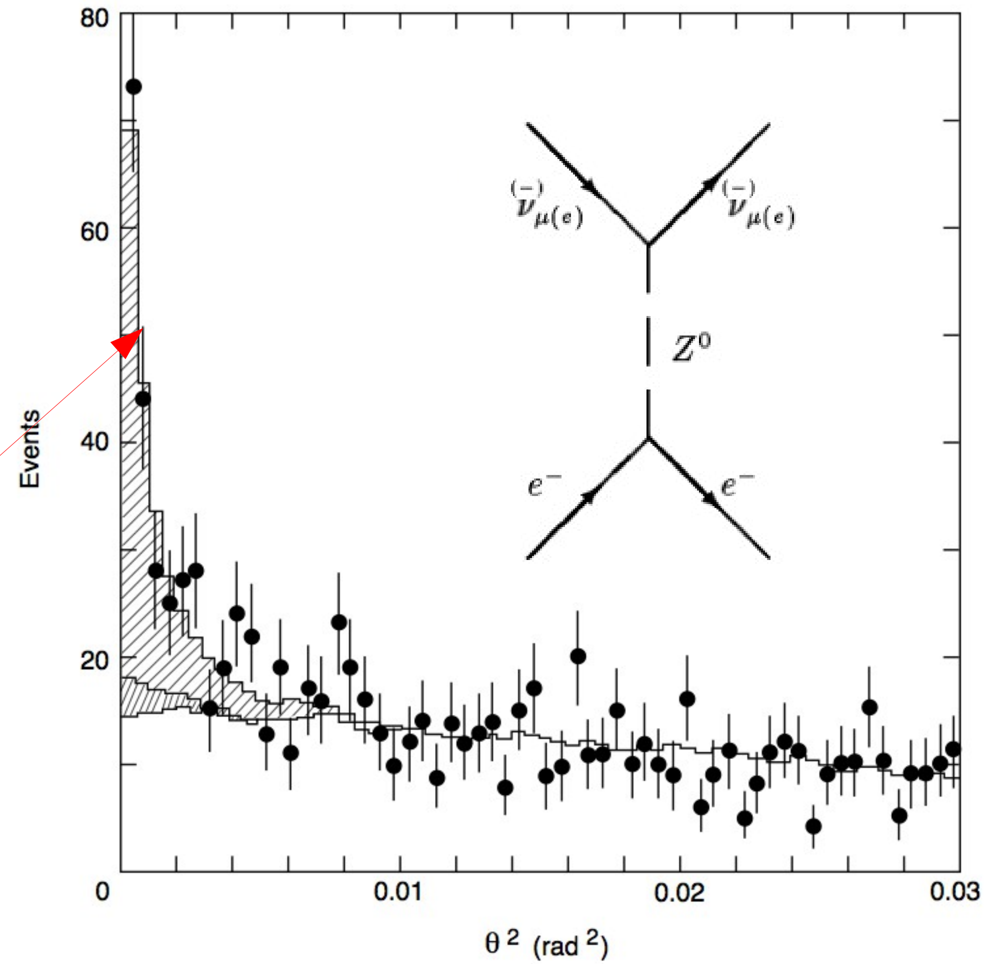
Define:

$$g_L = \frac{1}{2}(c_V + c_A) \quad g_R = \frac{1}{2}(c_V - c_A)$$

Differential cross section:

$$\frac{d\sigma^{\nu_\mu}}{dy} \sim \left[g_L^2 + g_R^2(1-y)^2\right]$$

Fermilab Experiment E734



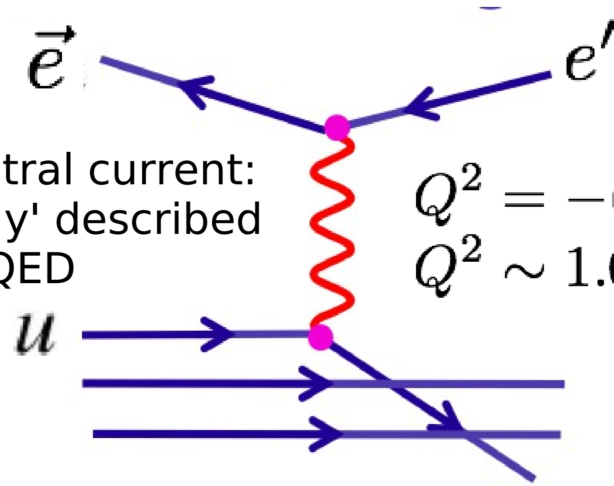
Need right handed component of neutral weak to explain differential cross section

Neutrino (massless fermion): $c_V = c_A = \frac{1}{2}$

Electron (massive fermion): $c_V \neq c_A$

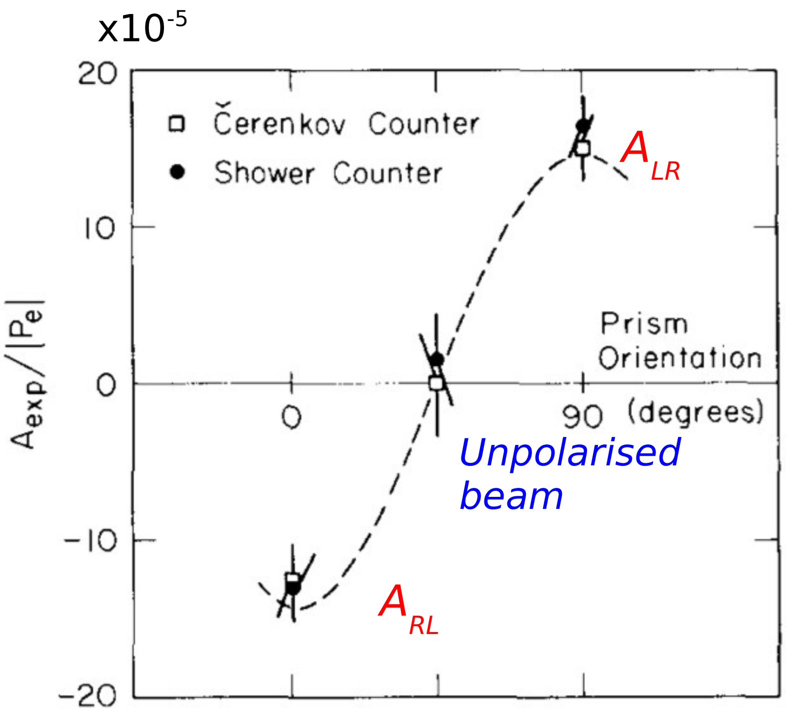
Historical Experimental Evidences IV - Neutral currents w/o neutrinos

E122@SLAC 1978: Inelastic_scattering of polarised electrons on deuterium:



Neutral current:
'Fully' described
by QED

$$Q^2 = -(k(\vec{e}) - k(e'))$$
$$Q^2 \sim 1.6\,\mathrm{GeV}^2$$



Define Asymmetries:

$$A_{RL} \sim \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$A_{LR} \sim L \leftrightarrow R$$

R,L: Polarisation of
Incoming electron beam

Expectation:

$\sigma_R = \sigma_L$ for pure QED

=> Any deviation from 0 is
sign of parity violation

Result: $A_{RL}/Q^2 = (-9.5 \pm 1.6) \times 10^{-5}$

The press echo ...

IL PICCOLO

GIORNALE DI TRIESTE

LO HA AFFERMATO L'AMBASCIATORE AMERICANO GARDNER

PARLANO GLI ESPONENTI

Rinaldi: la Dc è

DECADIMENTO RADIOATTIVO E FORZE ELETTROMAGNETICHE

La teoria Salam-Weinberg confermata dagli americani

L'importanza della scoperta viene paragonata a quella di Newton

Nell'ambito della sesta conferenza sulla fisica delle particelle al Centro internazionale di fisica teorica di Miramare, il risultato in assoluto di maggior interesse, non solo per gli ambienti scientifici mondiali ma anche per la cronaca cittadina, è emerso da una comunicazione fatta dal prof. Charles Prescott del laboratorio Slac (cioè dell'acceleratore lineare) di Stanford (California). Lo studioso americano ha annunciato il pieno successo di un esperimento (per il quale sono occorsi cinque anni di preparativi minuziosi e sei mesi per la realizzazione) che confermerebbe quella che il consulente scientifico del «Times» di Londra ha definito «una delle più importanti teorie della fisica dopo quella di Newton sulla forza di gravità».

La notizia riveste importanza particolare anche per Trieste in quanto la teoria è frutto degli studi del prof. Agdus Salam, direttore del Centro di fisica teorica di Miramare, e del prof. Steven Weinberg della Harvard University. L'esperimento («estremamente complicato e laborioso», ha ammesso il prof. Prescott) dandone la conferma in maniera ufficiale, apre nuove prospettive per la comprensione delle proprietà e dell'interazione proprie delle particelle elementari del nucleo atomico.

«E' stato uno degli esperimenti più importanti degli ultimi anni — ha dichiarato il prof. Salam — dopo questo esperimento posso veramente dire di credere alla mia teoria».

Prof. Abdus Salam

Prof. Prescott (Italfoto)

Il cinquantaduenne direttore del Centro di Miramare si è complimentato con il prof. Prescott, che, a 39 anni, è uno dei più prestigiosi componenti dell'équipe del laboratorio californiano. Alle varie fasi dell'esperimento hanno preso parte 20 fisici e 40 tecnici di diversi laboratori, dalla Yale University al Cern di Ginevra, dalla Scuola superiore di Aquisgrana all'Istituto di fisica sperimentale di Amburgo. In sei anni di lavoro, le prove hanno impegnato numerosi esperti delle diverse branche della fisica, da quella dei laser alla fisica allo stato solido.

La teoria Weinberg - Salam (così, infatti, è conosciuta negli ambienti scientifici internazionali) afferma che le forze che presiedono al cosiddetto «radioactive decay» (letteralmente, «decadimento radioattivo») e quelle che tengono insieme gli atomi sono due aspetti di una medesima forza. Se questa teoria «unificante» («unifying theory») è corretta — questo è ciò che ha dimostrato, fino a prova contraria, l'esperimento di Stanford — l'importanza della scoperta è equiparabile a quella che fece Isaac Newton quando, grazie alla famosa mela, scoprì la legge di gravità, e successivamente dimostrò che la forza responsabile della caduta degli oggetti era la medesima che tiene la Terra in orbita attorno al Sole.

La verifica della teoria di [...]

portato a termine non adoperando gli atomi bensì particelle ancora più piccole, cioè gli elettroni e i neutroni, per «sondare» il nucleo dell'atomo di idrogeno, per accertare la consistenza della teoria Weinberg - Salam sull'unificazione delle interazioni deboli ed elettromagnetiche. Il successo che ha coronato l'esperimento sembra che abbia convinto anche i fisici più dubbiosi. Noi lo riferiamo in termini di cronaca (al di là della spiegazione «tecnica» della scoperta) per l'importanza della notizia in sé, augurandoci di poter annunciare presto un riconoscimento internazionale per il prof. Abdus Salam e il suo collega statunitense.

Messa di suffragio per mons. Fogar

Domani, sabato, alle ore 19.30, nella chiesa parrocchiale di San Giacomo, il vescovo mons. Bellomi celebrerà una messa di suffragio per mons. Luigi Fogar, già vescovo di Trieste.

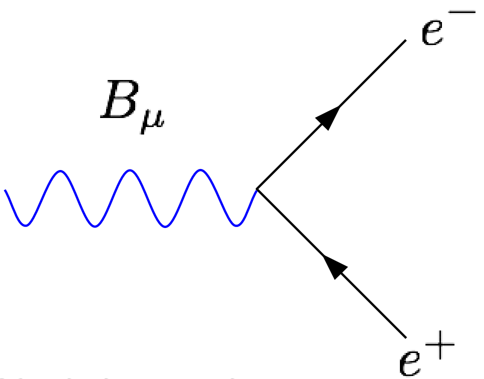
Il comitato per le onoranze a mons. Luigi Fogar, nell'intendimento di tenere sempre vivo il ricordo e l'insegnamento dell'indimenticabile presule, invita tutti i soci della Gioventù italiana di azione cattolica, i sacerdoti della diocesi, soci e simpatizzanti dell'Azione cattolica e quanti intendano onorare la memoria di mons. Luigi Fogar ad intervenire al rito.

Dopo la messa, mons. Bellomi si incontrerà con tutti gli ex soci della Giac, promotori dell'iniziativa, nella sala parrocchiale di campo San Giacomo 10.

FINANZA STA RICERCANDO TRE TRIESTINI

RECRUDESCENZA DEGLI ATTI

Unification of Weak and Electromagnetic Currents – Glashow, Salam, Weinberg



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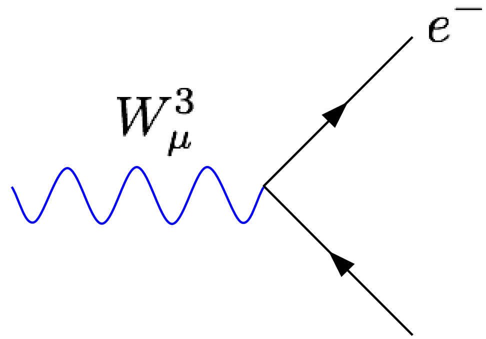

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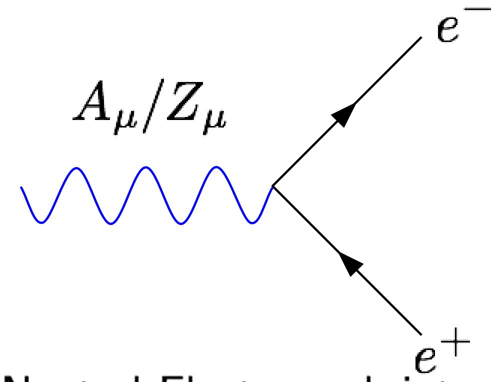


Weak hypercharge interaction
$\bar{\psi}\gamma^\mu Y \psi B_\mu$
U(1) symmetry as QED

Weak interaction
$[\bar{\psi}\gamma^\mu \frac{1}{2}(1-\gamma^5)\psi](W^3)_\mu$
as part of SU(2) triplet with $W^\pm$

Neutral Electroweak interaction
$\bar{\psi}\gamma^\mu \psi B_\mu + [\bar{\psi}\gamma^\mu \frac{1}{2}(1-\gamma^5)\psi](W^3)_\mu$
as part of SU(2)xU(1) symmetry

Combination of weak and electromagnetic currents yields:

Basic electroweak interaction

$$-i\frac{g'}{2}\bar{\psi}\gamma^\mu\psi B_\mu - ig[\bar{\chi}\gamma^\mu \frac{1}{2}(1-\gamma^5)\chi]^i (W^i)_\mu$$

Mixing of B_μ and W^3_μ to physical fields A_μ and Z_μ

$$A_\mu = B_\mu \cos\theta_W + W^3_\mu \sin\theta_W$$

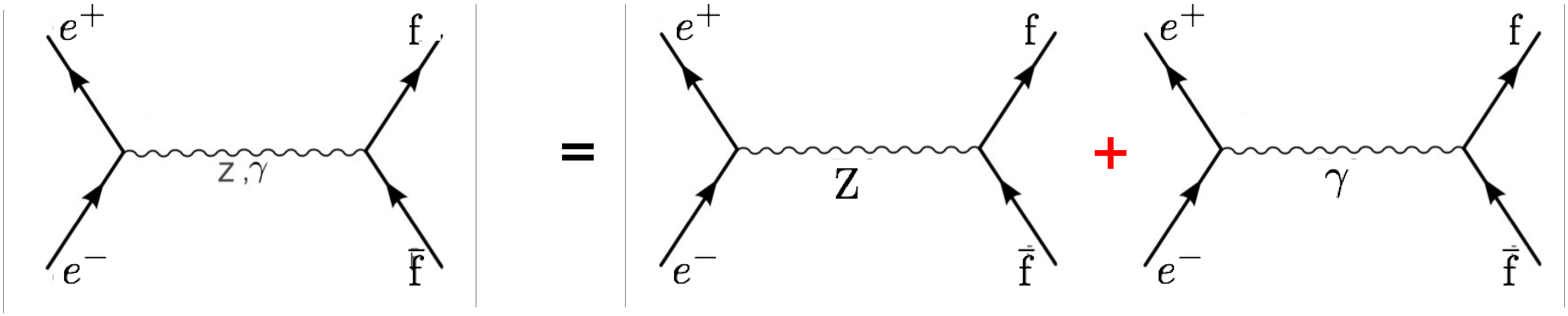
$$Z_\mu = -B_\mu \sin\theta_W + W^3_\mu \cos\theta_W$$

Neutral current in terms of elm. current

$$J^{NC}_\mu = J^3_\mu - \sin^2\theta_W j^{elm.}_\mu$$

θ_W = weak mixing angle (Weinberg angle)
Parameterises parity violation in neutral current sector
$\sin\theta_W \sim 0.23$

Cross section $e^+e^- \to f\bar{f}$



Interference between individual amplitudes of γ and Z exchange

$$\mathcal{M}_Z = -\frac{\sqrt{2}G_F M_Z^2}{s - M_Z^2}\left[\bar{\mathrm{f}}\gamma^\rho\left(c_V^f - c_A^F\gamma^5\right)\mathrm{f}\right] g_{\rho\sigma}\left[\bar{e}\gamma^\sigma\left(c_V^f - c_A^F\gamma^5\right)e\right]$$

$$\mathcal{M}_\gamma = -\frac{e^2}{s}(\bar{\mathrm{f}}\gamma^\nu \mathrm{f})\mathrm{g}_{\mu\nu}(\bar{\mathrm{e}}\gamma^\nu \mathrm{e})$$

Differential cross section:

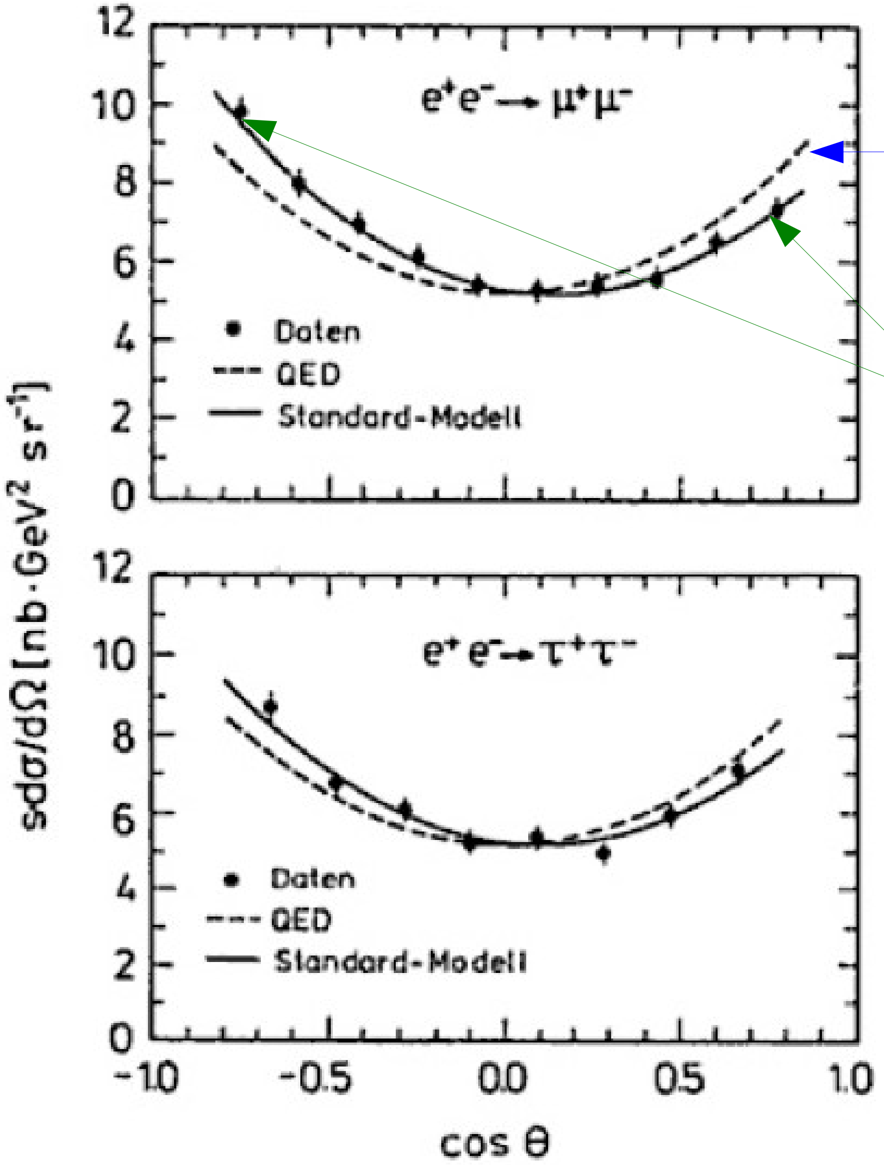
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\left[A_0(1+\cos^2\theta) + A_1\cos\theta\right]\begin{cases} \sim (1+\cos^2\theta) & \text{'Usual' Vector current, symmetric in } \cos\theta \\ \backsim \cos\theta & \text{Axial Vector current, asymmetric in } \cos\theta \end{cases}$$

Weak interaction introduces forward backward asymmetry

=> Asymmetry is intrinsic to electroweak processes!!!

Experimental observation of Forward Backward Asymmetry

e^+e^- collisions at $\sqrt{s} = 35\,\mathrm{GeV}$ at PETRA storage ring at DESY



Data do not follow $1+\cos^2\theta$ as expected from QED (Vector Current)

Clear production asymmetry between small and large values of polar angle

Data well fitted by model based on **γ/Z interference**

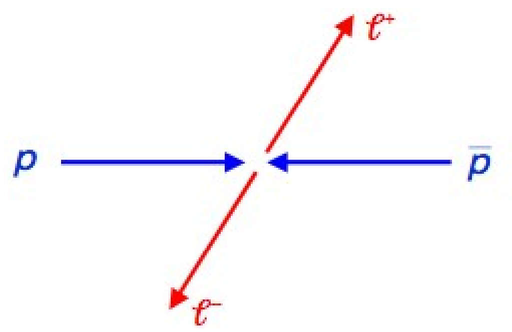
Size of deviation from QED allow for estimation of Z Mass

Massive vector bosons I

Short distance nature of e.g. Beta decay and onset of parity violating effects in ee collisions are compatible with massive vector Bosons W,Z

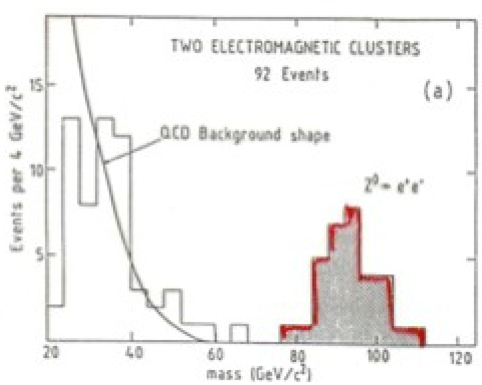
Z discovery: Event signature: $p\bar{p} \to Z \to f\bar{f} + X$

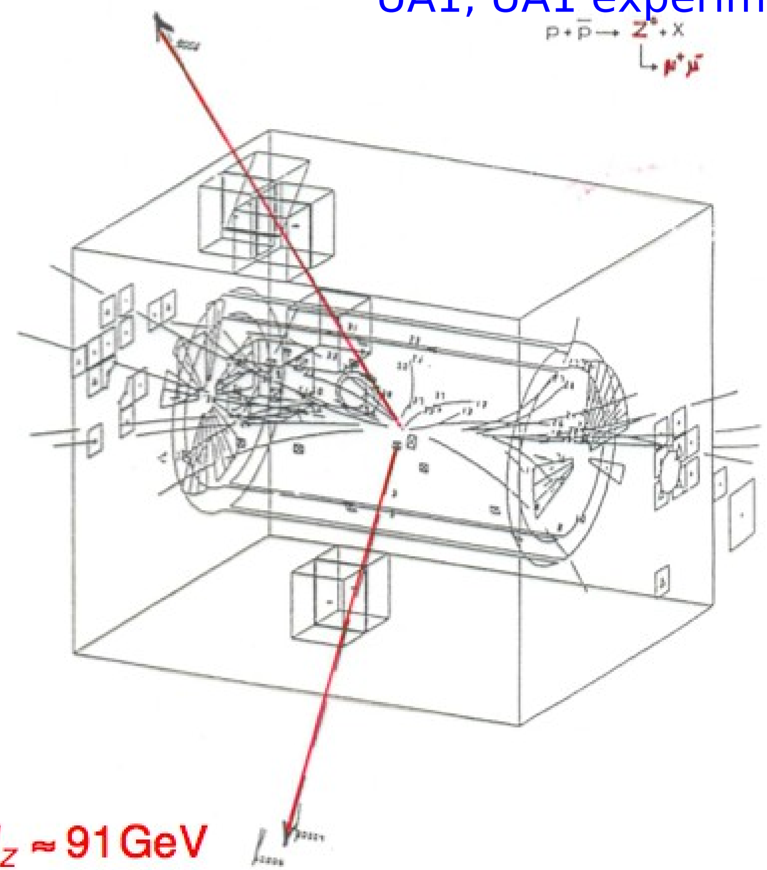
SPPS CERN $\sqrt{s}$ = 450 GeV:
UA1, UA1 experiments



High-energy lepton pair:

$$m_{\ell\ell}^2 = (p_{\ell^+} + p_{\ell^-})^2 = M_Z^2$$



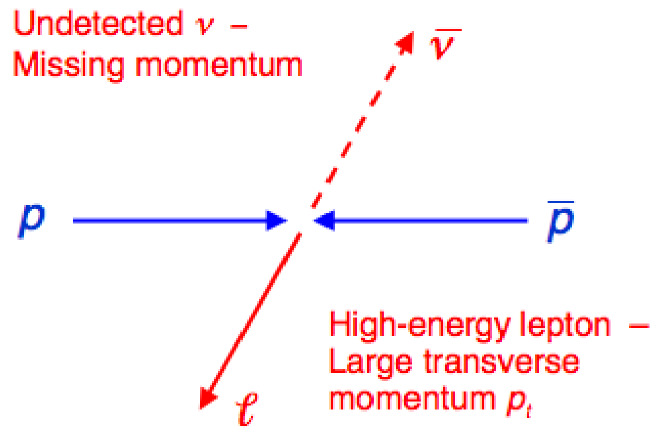


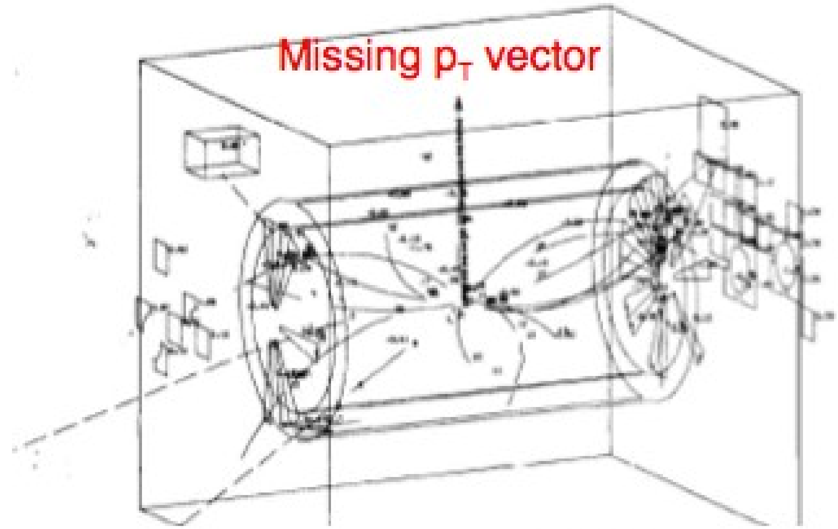
$M_Z \approx 91\,\mathrm{GeV}$

Slide from P. Uwer
Lecture Uni Heidelberg

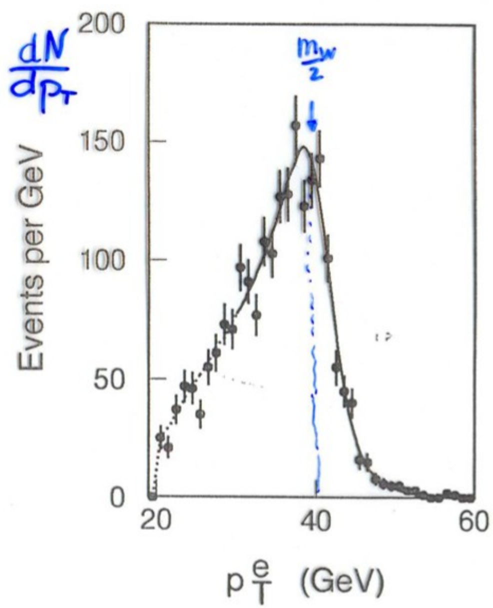
Massive vector bosons II – W Discovery

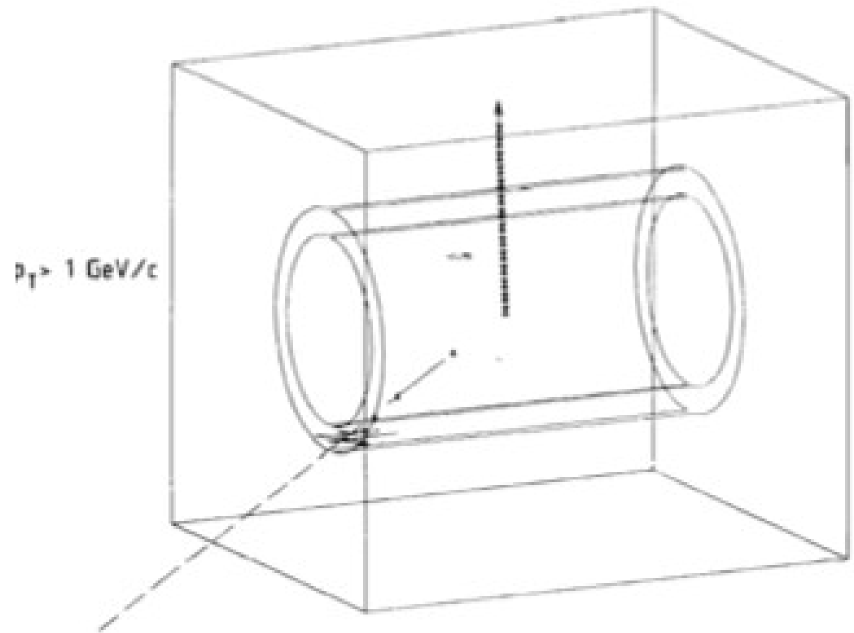
Event signature: $p\bar{p} \to W \to \ell\bar{\nu}_\ell + X$





Discovery through transverse mass





$M_W \approx 80$ GeV

How do the Particles get their Masses?

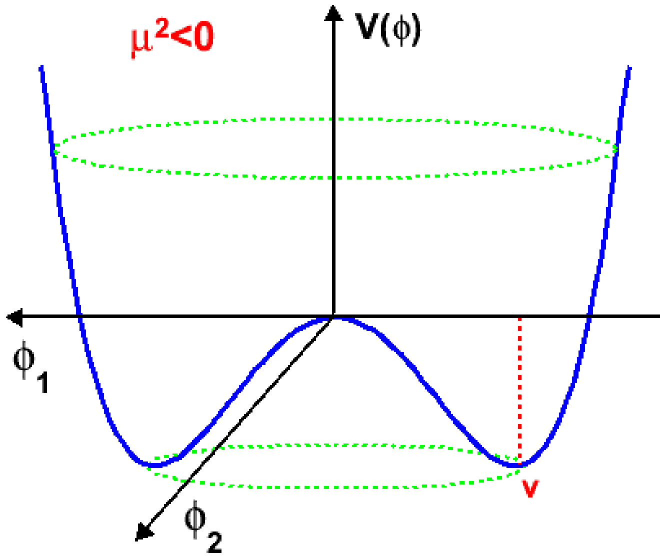
Higgs Mechanism

Scalar field which doesn't vanish in the vacuum

Choice in SM: Doublet Field $\Phi = \begin{pmatrix} \phi^{+} \\ \phi^{0} \end{pmatrix}$ 4 degrees of freedom

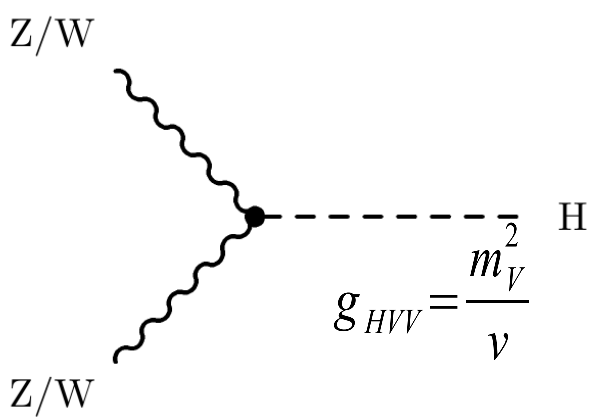
→ Higgs Boson

→ Longitudinally degrees of W,Z Bosons

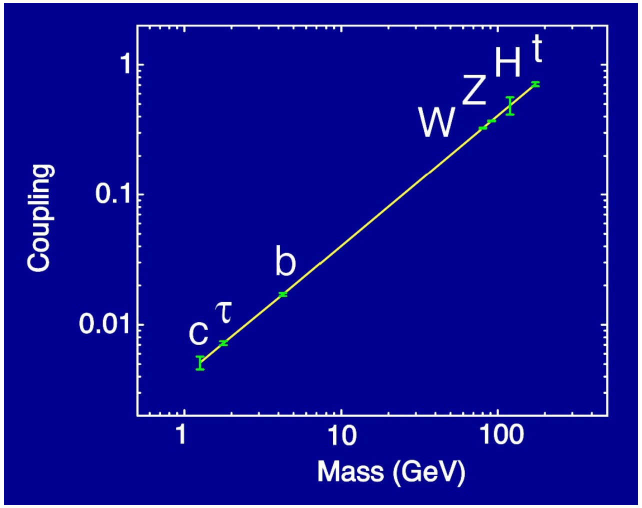


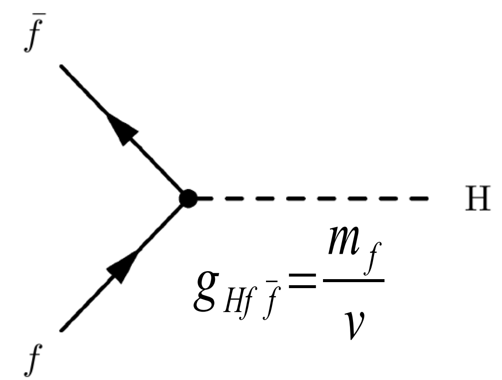
Couplings to Higgs Boson in Standard Model

Increase with particle mass



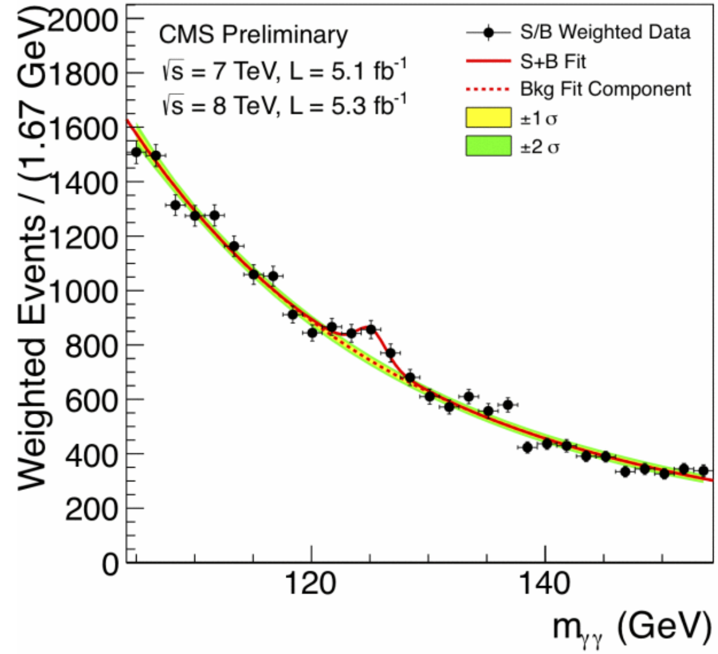
$$g_{HVV} = \frac{m_V^2}{v}$$

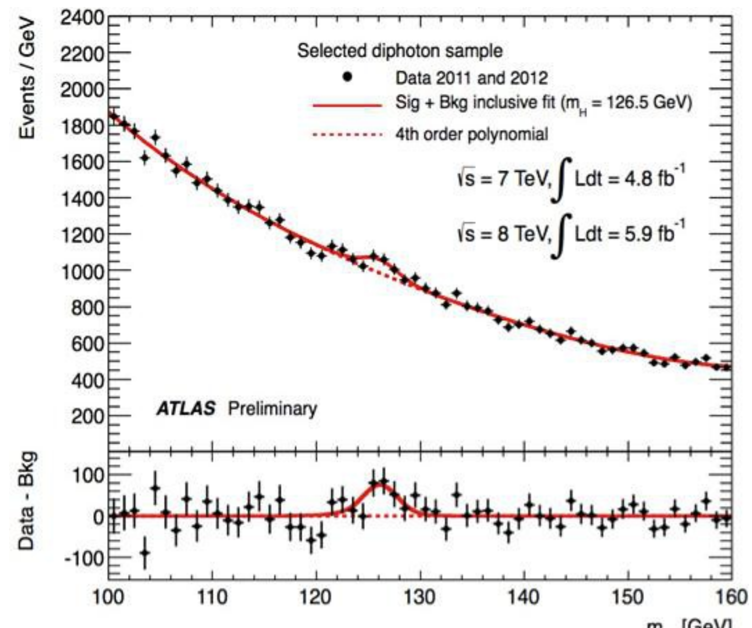




$$g_{Hf\bar{f}} = \frac{m_f}{v}$$

4^{th} of July 2012





Chapter III: Physics case for e+e- machines at the TeV scale

We see particle physics through new glasses ...

Coronation of the Standard Model

and

First step on a road yet largely unexplored

Slightly modified citation of Barbieri arXiv:1309.3447

Chip Brook, Snowmass Summary Talk

Where do we go from here?

Open questions

How to make progress?

1) Collisions at energies well above the electroweak scale

- Requires now and in the foreseeable future Hadron colliders
- Direct production of new particles
- Produce large number of rare particles and study rare decays
- First precision measurements of key particles of electroweak theory

-> High energy, High luminosity LHC

2) e+e-Collisions at energies at the electroweak scale

- Probe the electroweak scale with high precision
- ... in particular particles that carry the “imprint of the Higgs Field such as W, Z and top”

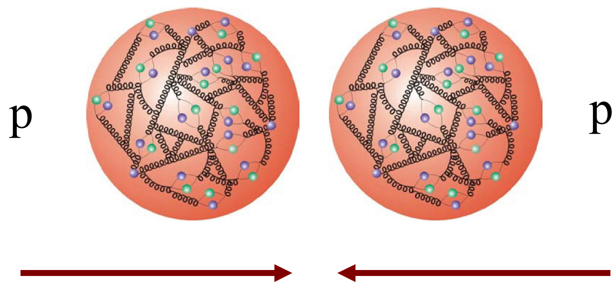
-> ILC

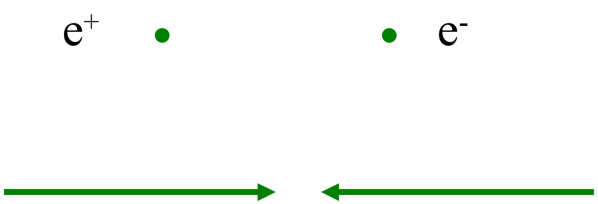
3) e+e- collisions at 'smaller' energies

- Requires high luminosity to get sensitive to tiny quantum effects

-> SuperKEKB

Why electron positron collisions ?





Proton:

Composed particle (hadron)
Unknown energy of collision partners
Parasitic reactions
Strong interaction
=> Considerable physics background
Advantage: Scan of energy
Range within one experiment

Electron:

Elementary particle
Well known and adjustable energy of collision partners

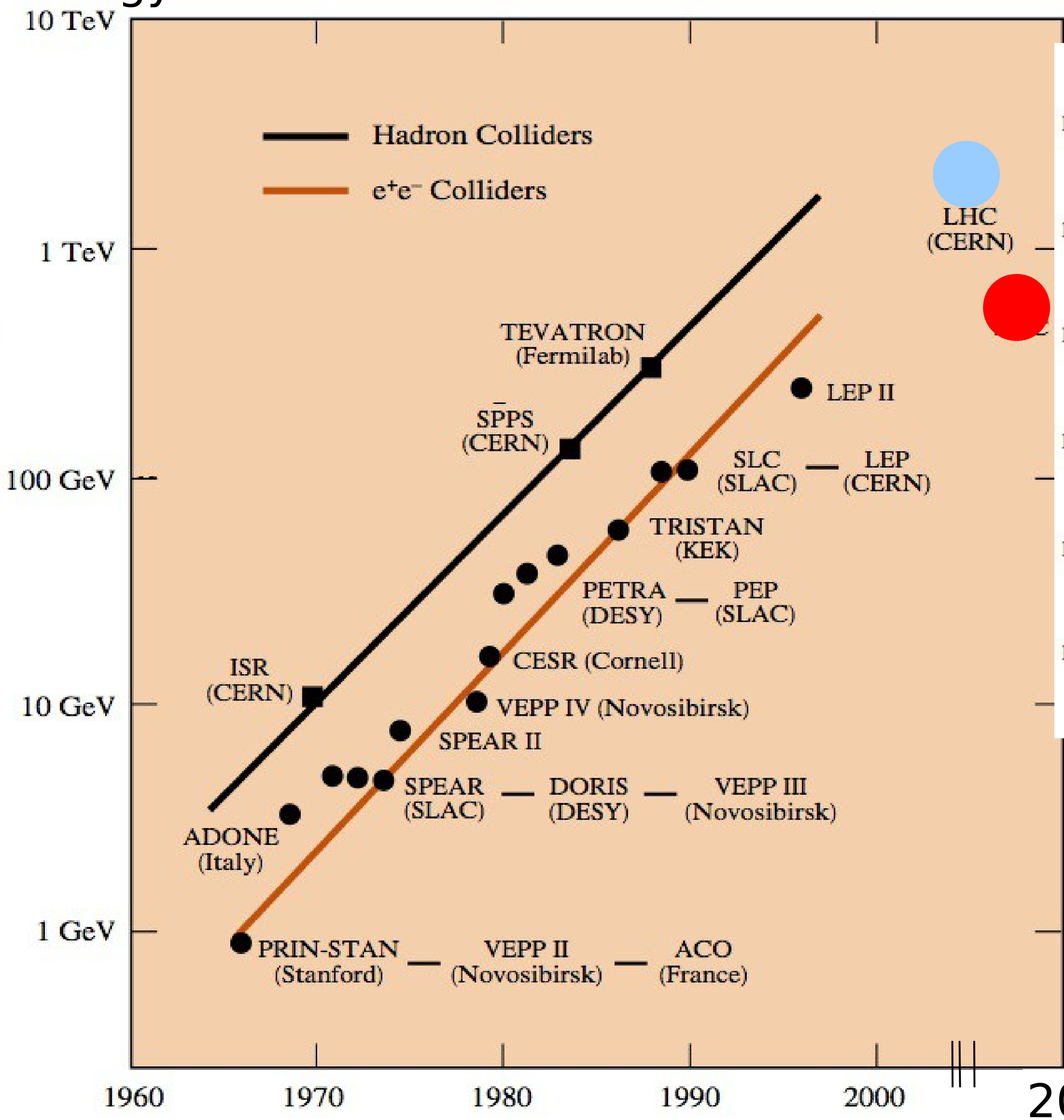
Each energy point needs a
New set of machine parameters

High precision measurements

In this lecture I will speak very general about e+e- collisions but I will always assume to have a machine “at hand” capable to reach at least $\sqrt{s}$ 500 GeV

Brief history of particle accelerators

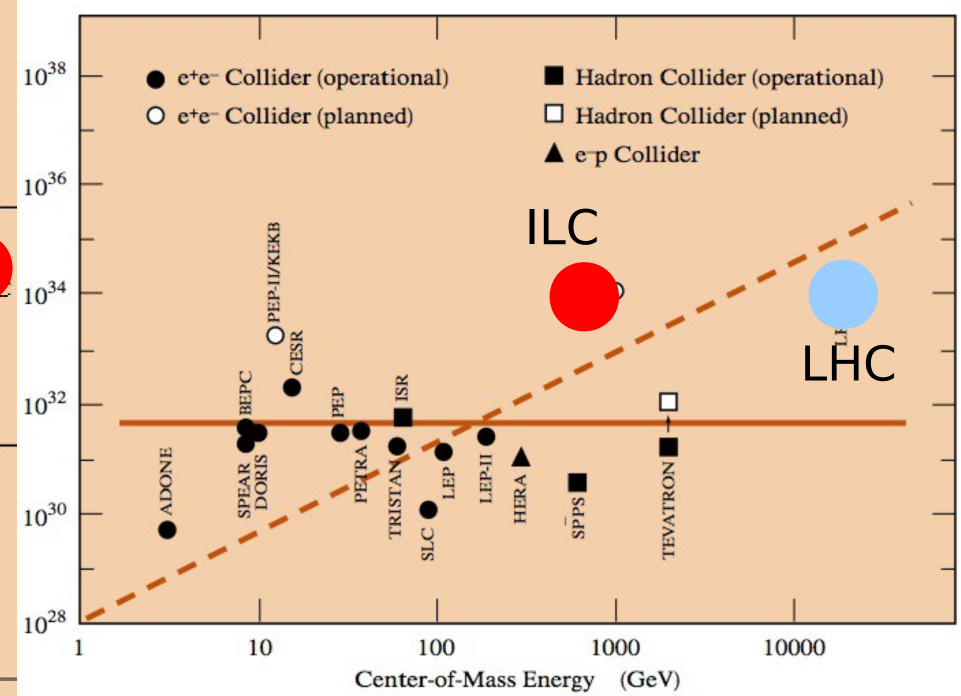
Energy



2020

Start of running

Luminosity

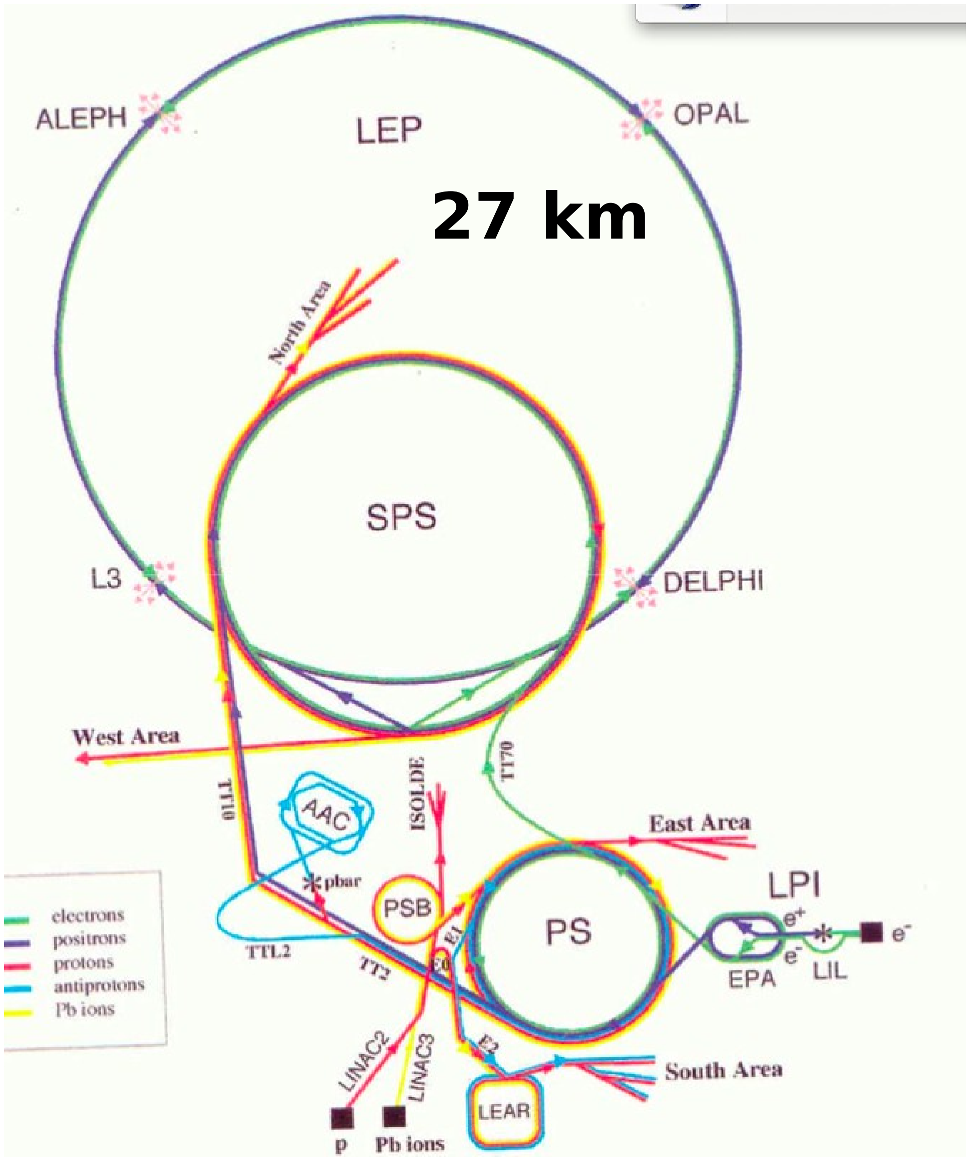


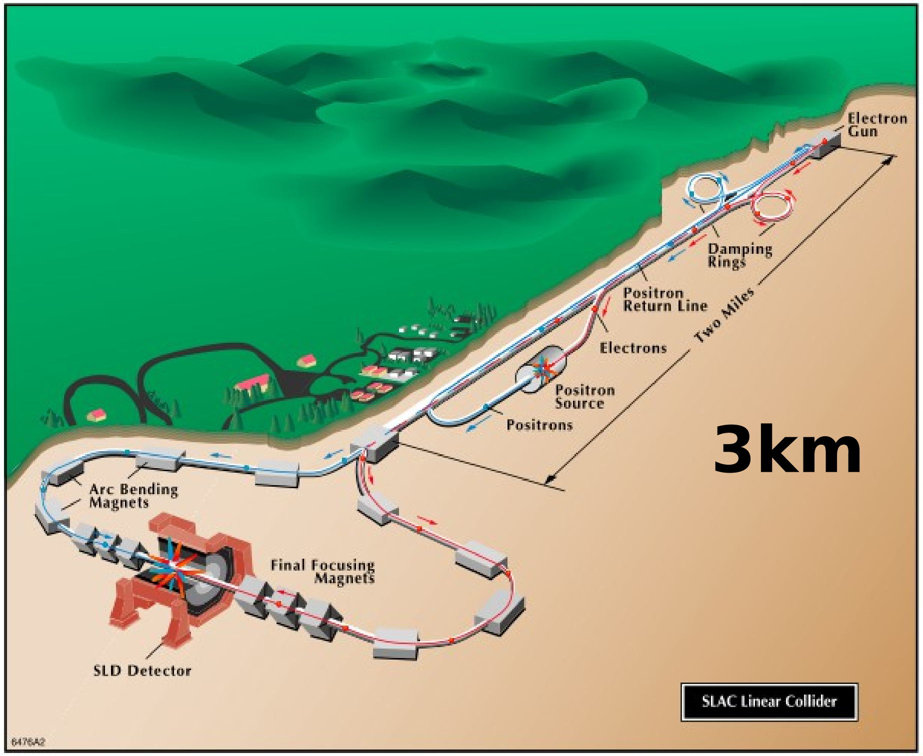
Energy

- Traditionally parallel operation of Hadron and lepton machines

- Note : Lepton colliders have typically smaller centre of mass energies Than their contemporary partners

Powerful electron positron colliders – The last generation



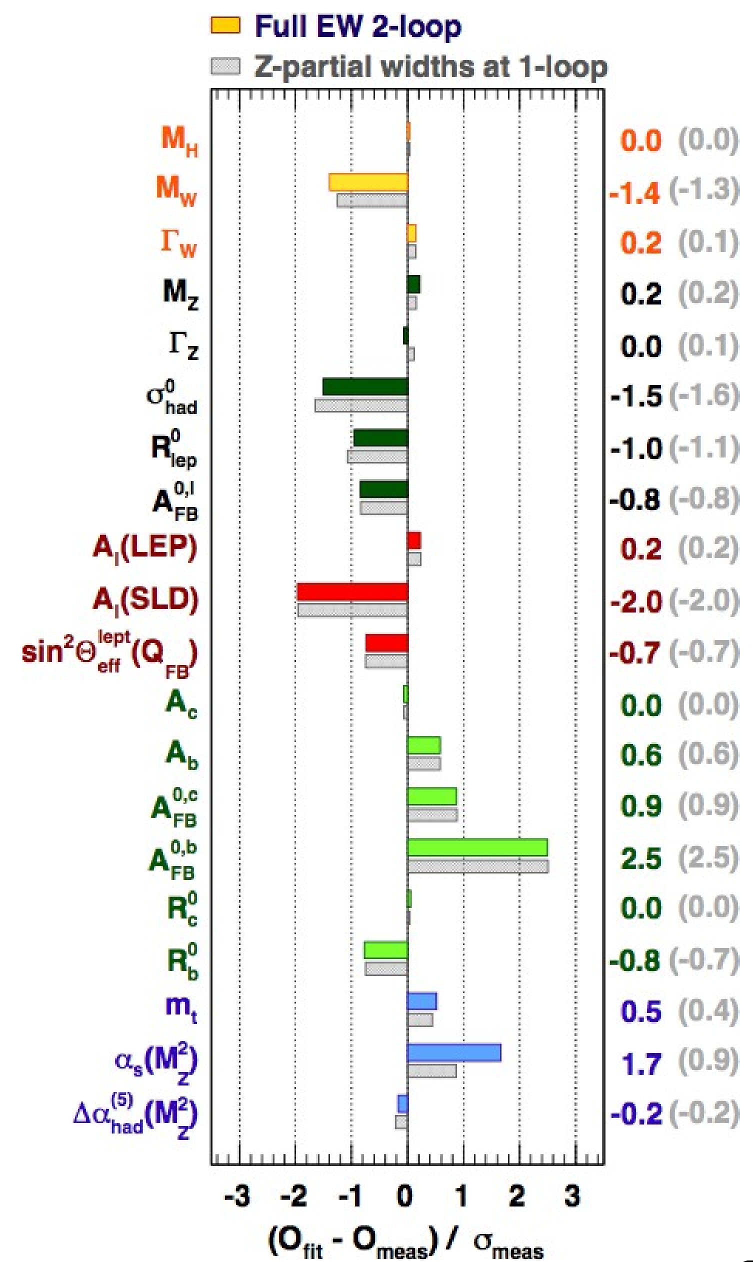


	SLC	LEP (Z^0)
"Circumference"	3 km	27 km
Beam Size IP	3x1 μm	400x16 μm
e^-/bunch	4×10^{10}	30×10^{10}
Crossing Rate	120 Hz	45 kHz
Z/day/experiment	3,000	30,000
e^- polarization	75 %	0

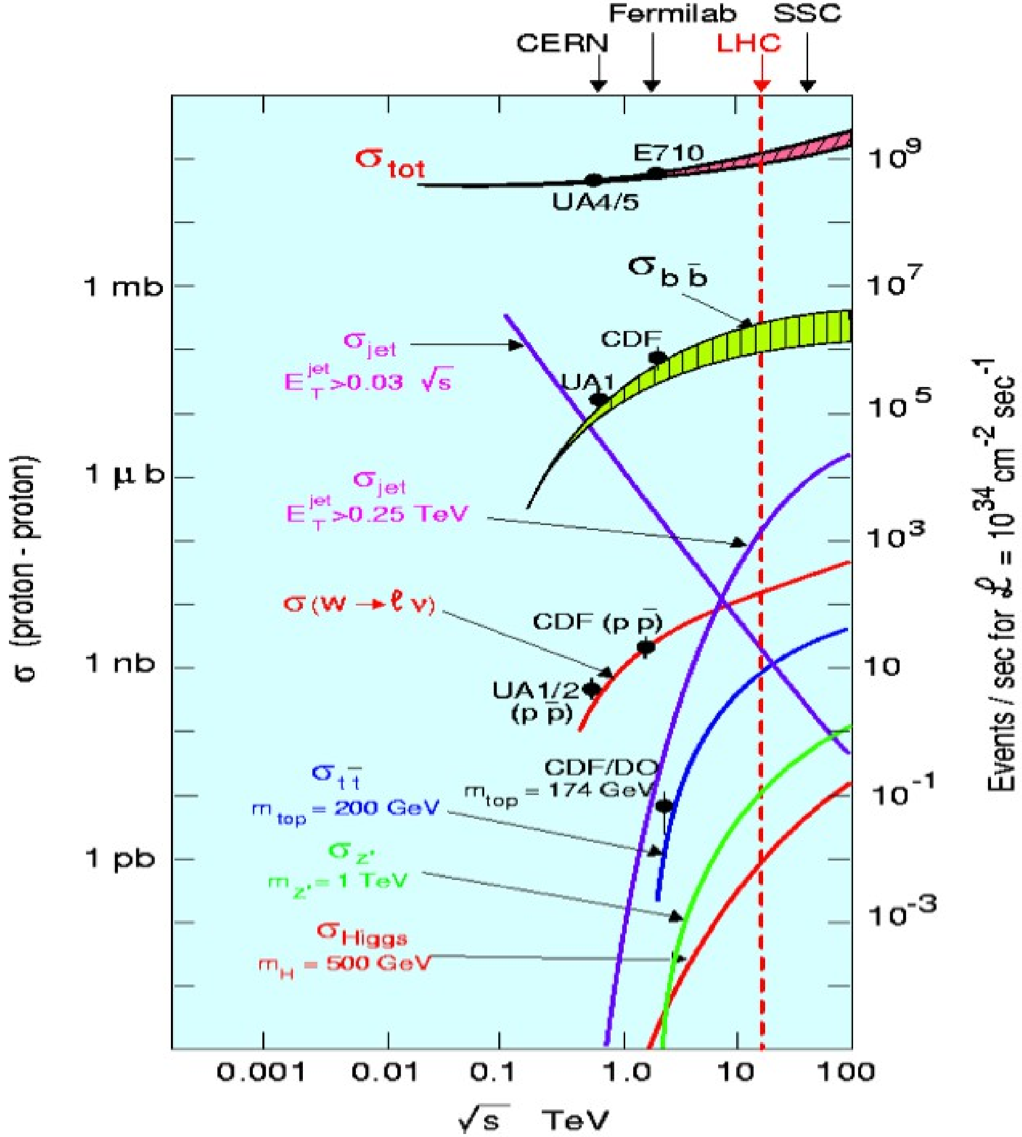
Lepton and hadron colliders – Interplay of results

The electroweak fit – Testing compatibility of measurements with Standard Model

M_H [GeV]$^{(\circ)}$	125.14 ± 0.24	LHC
M_W [GeV]	80.385 ± 0.015	Tev.
Γ_W [GeV]	2.085 ± 0.042	Tev.
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	LEP
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	LEP
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	LEP
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	LEP, SLD
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	LEP
A_c	0.670 ± 0.027	SLD
A_b	0.923 ± 0.020	SLD
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	LEP
R^0_c	0.1721 ± 0.0030	LEP, SLD
R^0_b	0.21629 ± 0.00066	LEP, SLD
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.34 ± 0.76	Tev.+LHC
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)$	2757 ± 10	

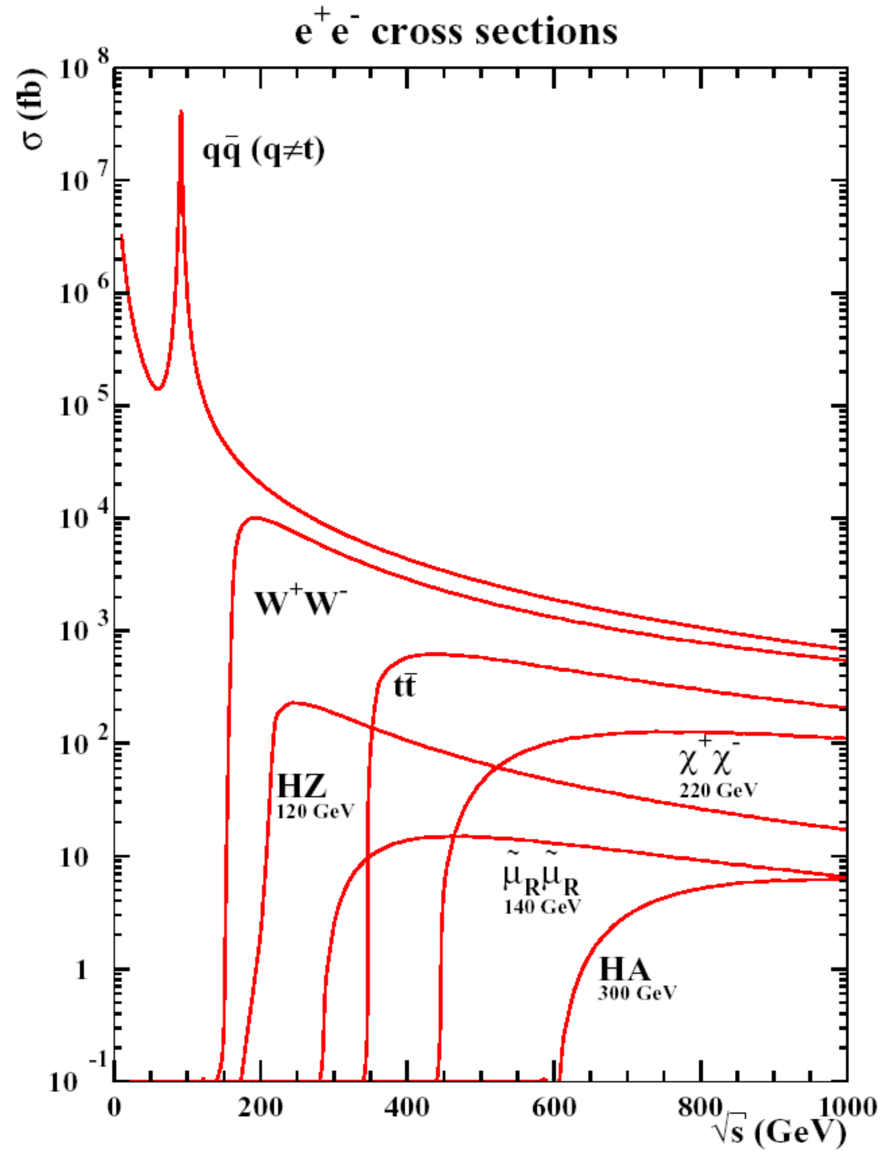


Cross sections



Strong hierarchy

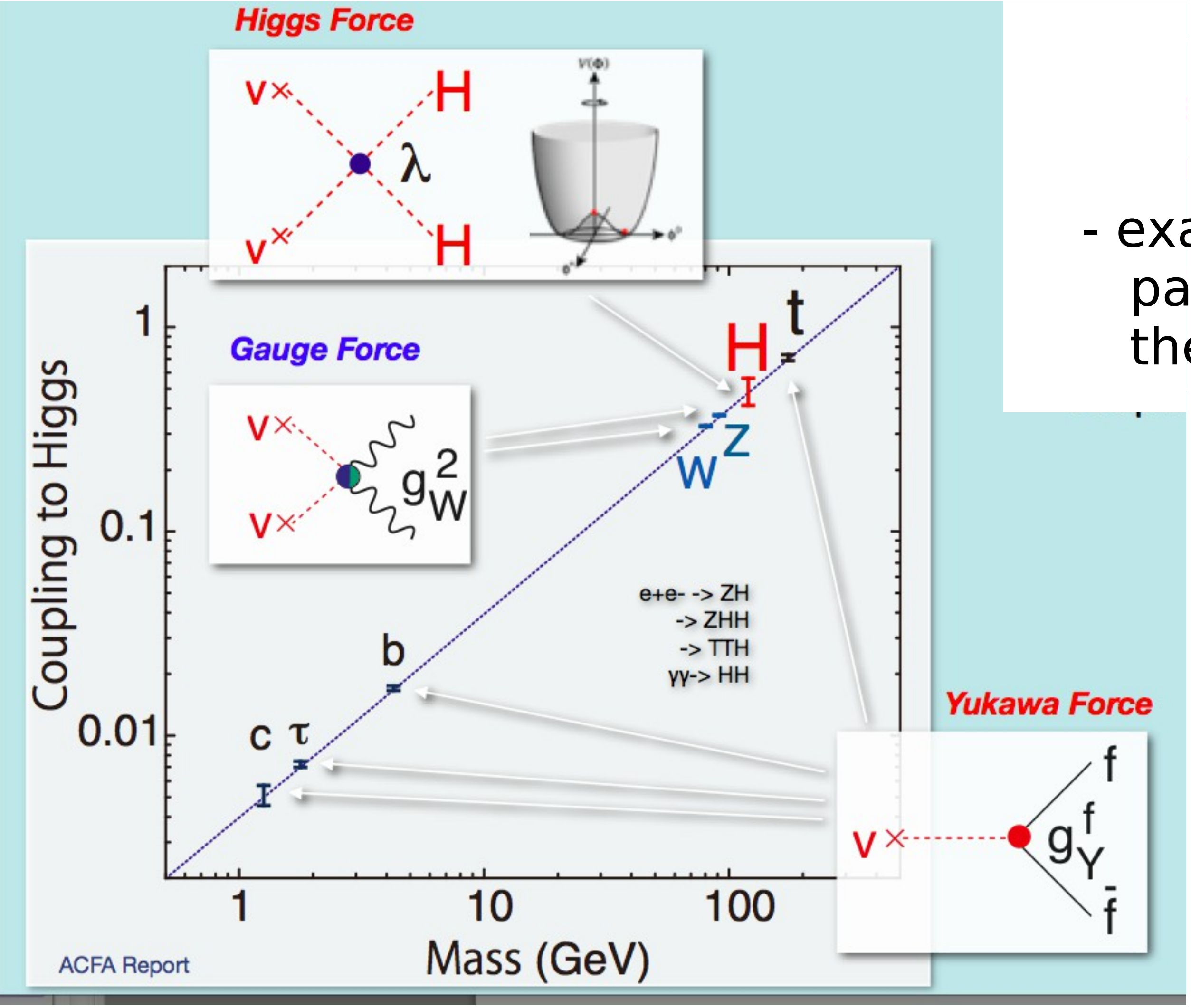
Requires complicated trigger system



Democratic production

Permits trigger less detection system

Precision Higgs Physics



- exact correlation between particle masses couplings to the Higgs in Standard Model

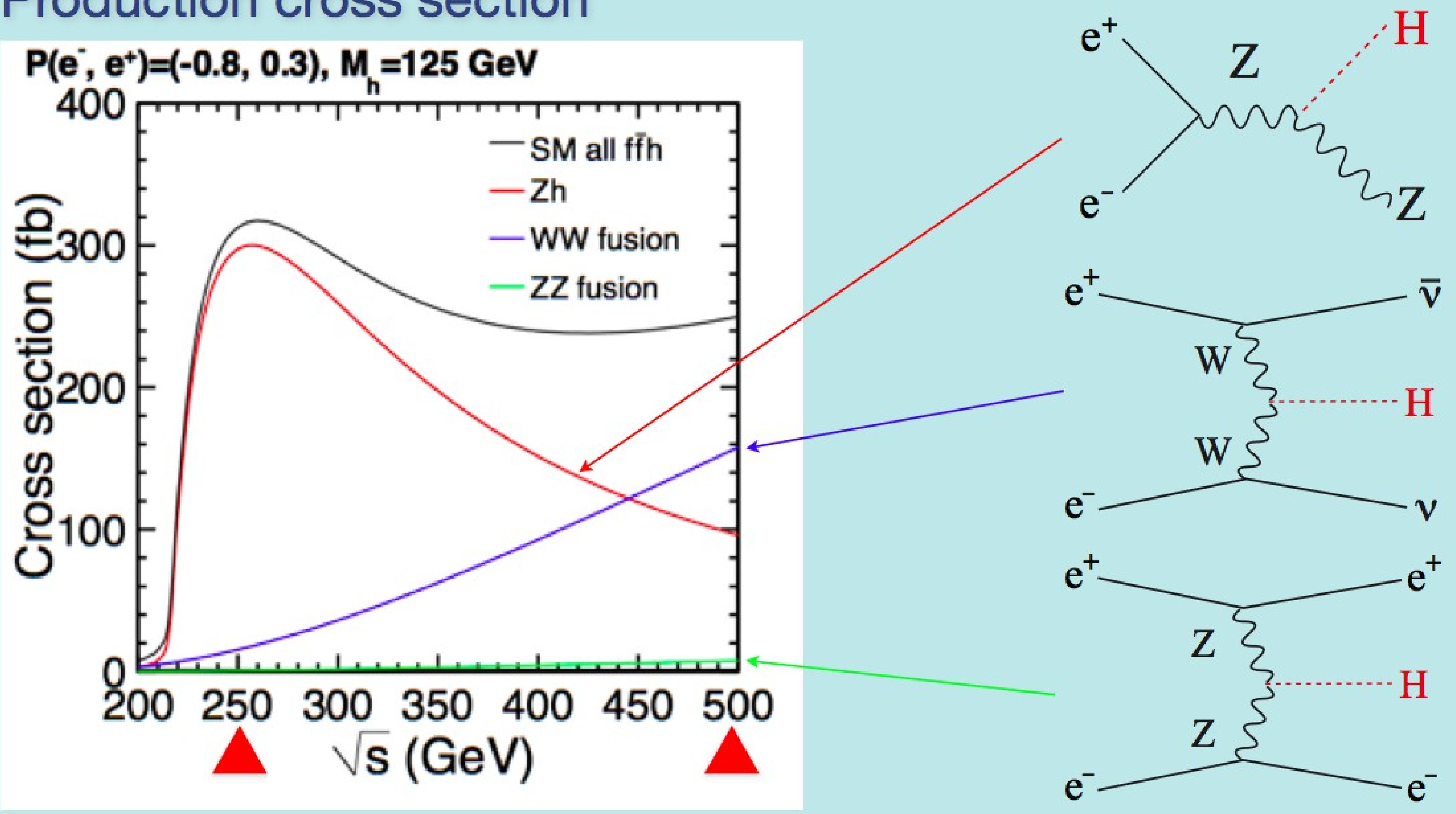
- Any tiny deviation is New Physics

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	$10\%^a$, $100\%^b$
LHC 14 TeV, 3 ab^{-1}	8%	10%	15%

- Need precision on Higgs couplings at least 5%

Single Higgs Production at Lepton Colliders

Production cross section



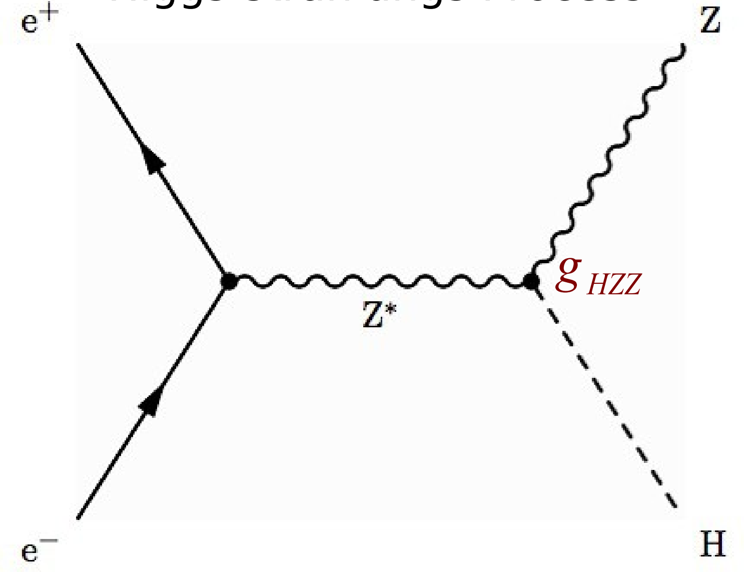
ZH dominates at 250 GeV
(~80k ev: 250 fb^{-1})

vvH takes over at 500 GeV
(~125k ev: 500 fb^{-1})

K. Fujii
LC School 2014

Higgs-strahlung at lepton colldiers

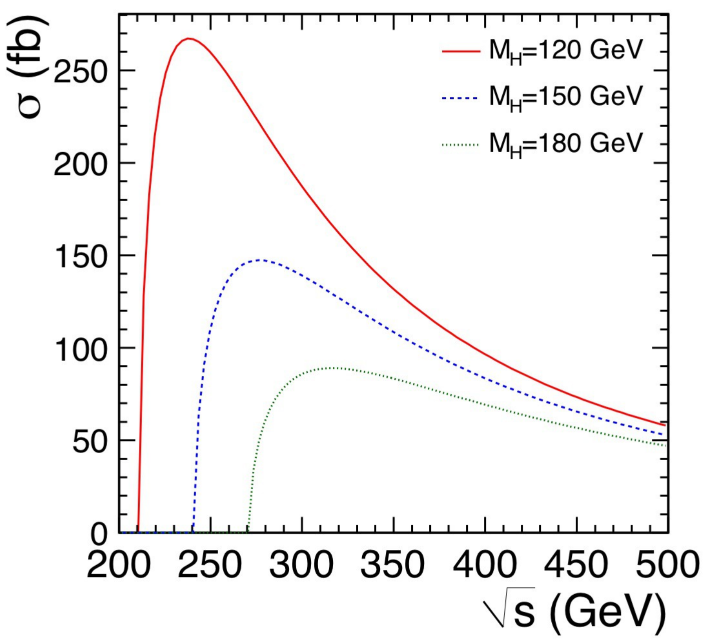
Higgs-strahlungs Process



Golden Plated Channel at e^+e^- Colliders

Sensitive to coupling at HZZ Vertex

Model independent due to clean Reconstruction of Z boson



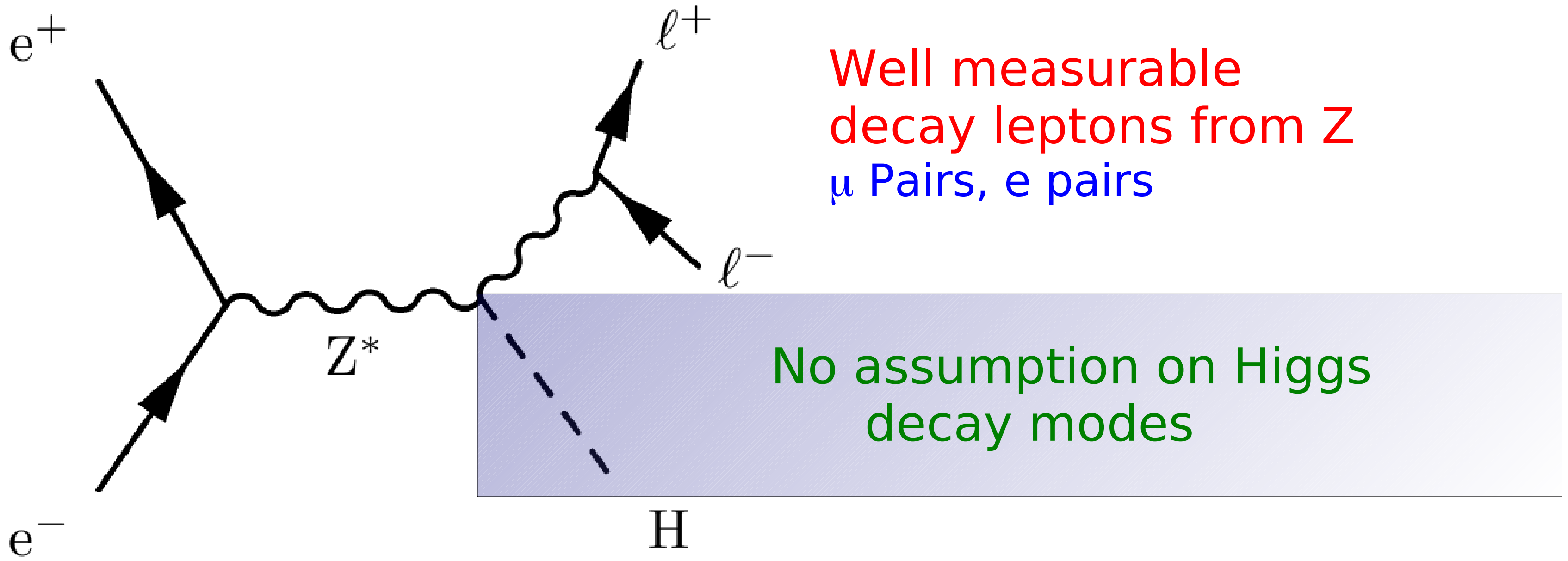
Production Cross Section of SM Higgs Boson

Maximal at HZ production threshold

Higgs Strahlung at $\sqrt{s}$ = 250 GeV for m_H = 120 GeV

Why golden plated Channel?

Higgs Mass and ZZH coupling by
Model Independent
measurement



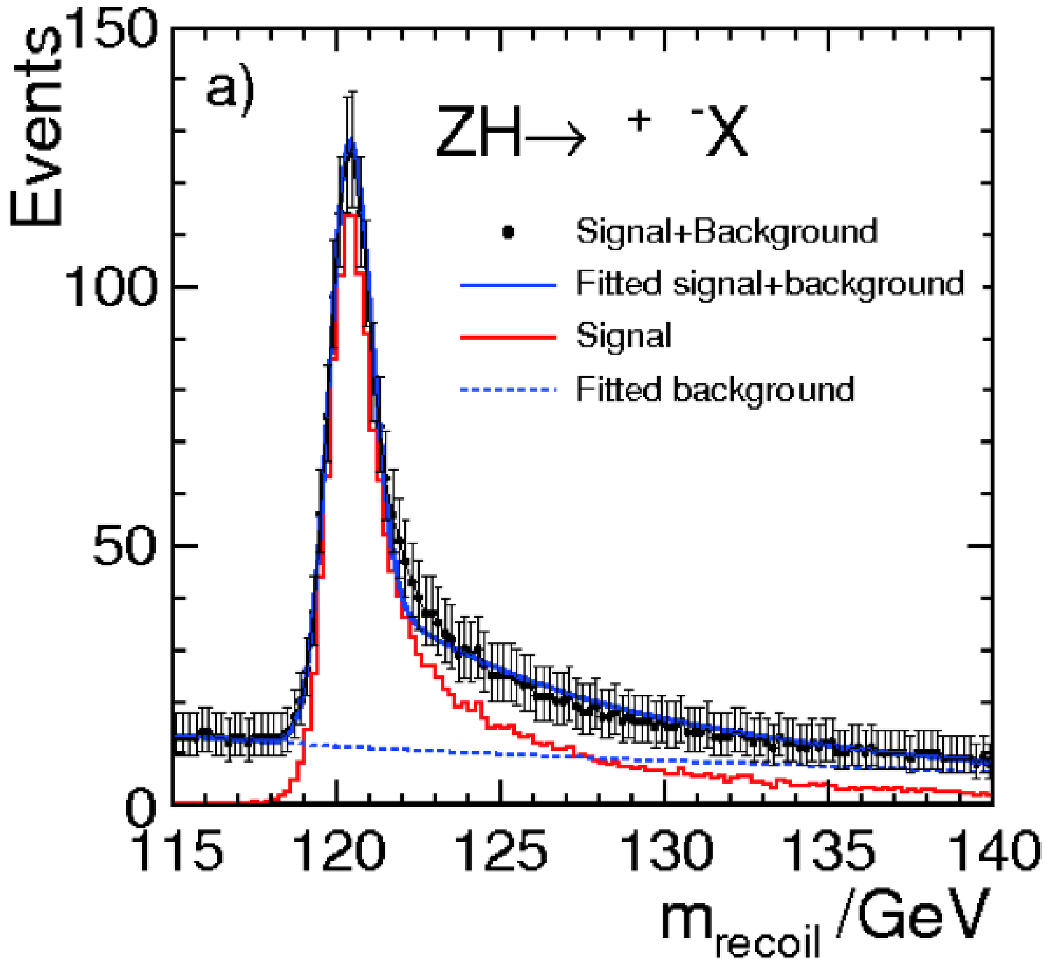
Well measurable decay leptons from Z
μ Pairs, e pairs

Higgs Recoil Mass: $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2 E_Z \sqrt{s}$

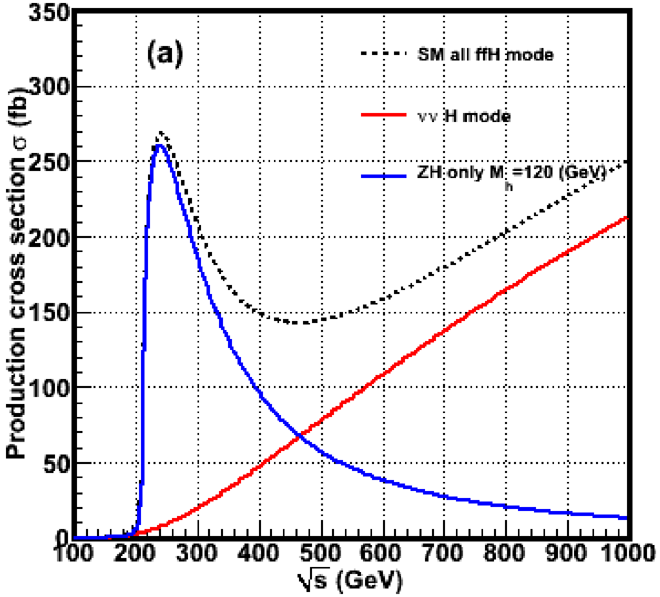
Homework: Derive recoil mass

Result of full simulation study at 250 GeV – arXiv 1202.1439

Z-recoil method: $e^+e^- \to ZH \to \mu^+\mu^- X$



The Higgs total width

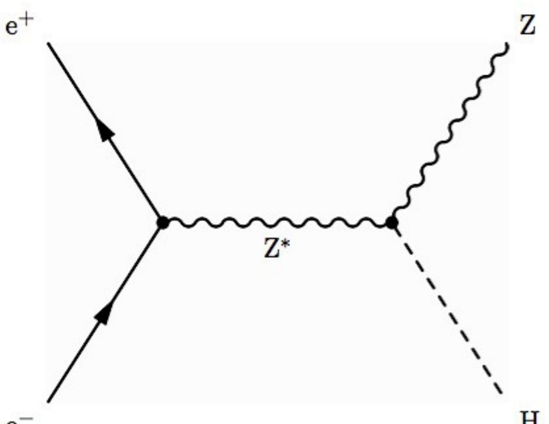


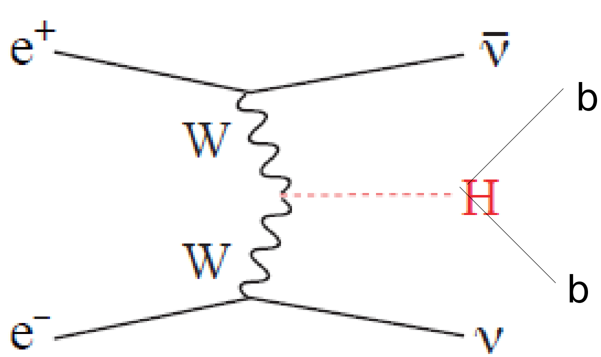
Preferred method:

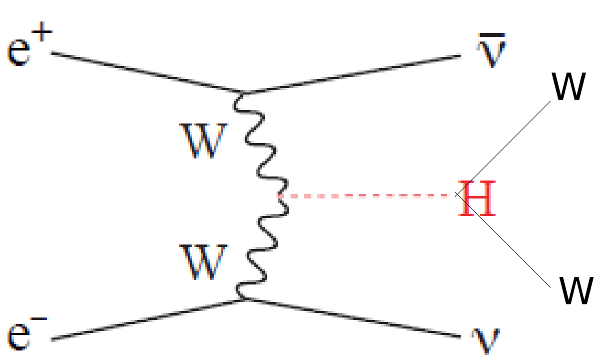
$$\Gamma_{tot} \sim \frac{BR(H \to W)}{g^2_{HW}}$$

For this crucial observable running at 500 GeV or higher is mandatory

Can be derived from model independant measurements







Current prospects - $\delta\Gamma_{tot}$ ~ 5% @ 500 GeV

~ 4% @ 1 TeV (2% technically possible)

Homework: derive Γ_{tot} from processes, Additional information: Use H->bb in ee-> ZH

Literature: arXiv:1310.0763

Individual couplings to the Higgs

$$\sigma_{YH} \times BR(H \to xx) \propto \frac{g^2_{HYY} g^2_{Hxx}}{\Gamma_T}$$

Y=W,Z xx=Decay Product of Higgs

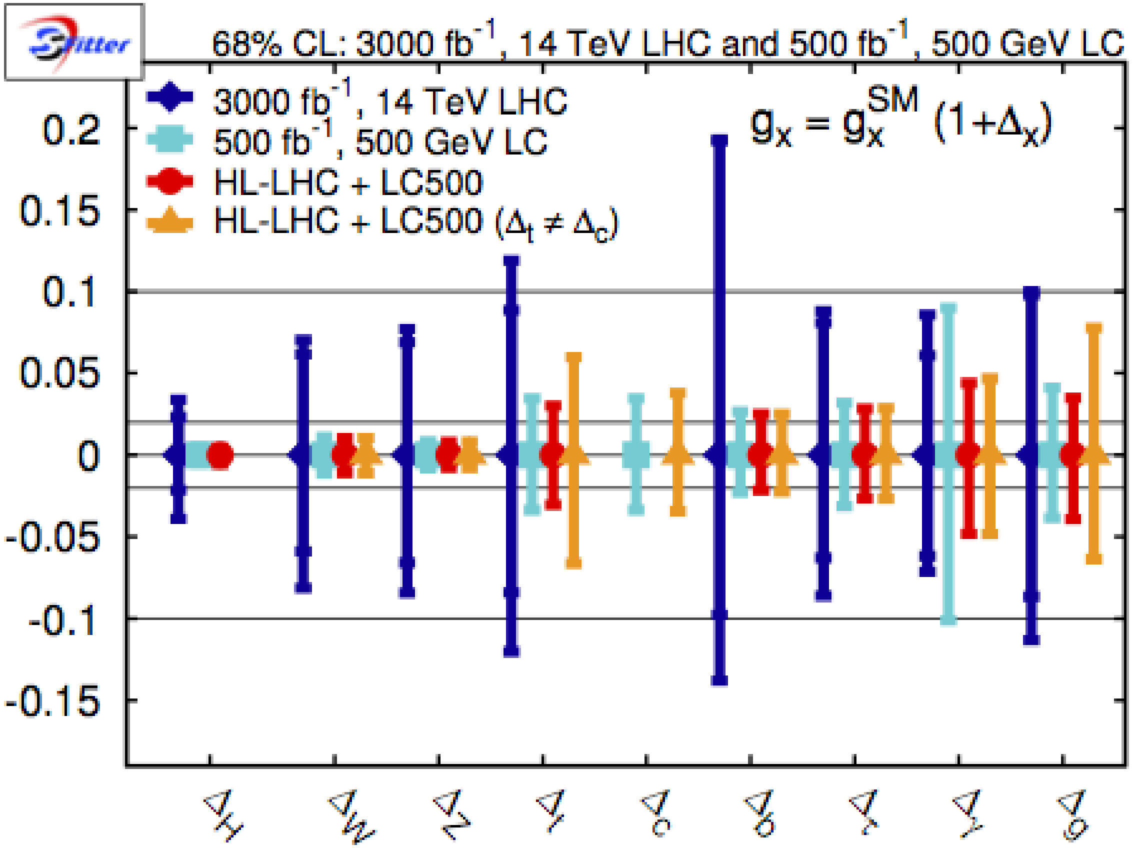
Get g^2_{HYY} and Γ_T from model independent measurements, see above

=> Can measure individual couplings to the Higgs in a model independent way

This is another immediate consequence of the precise knowledge of the initial state
... and a striking difference (advantage) to the situation at hadron colliders

Typical LHC analyses need conventions on how to parameterise the dependence on the absolute values of the couplings
=> “Famous” parameter κ and μ (see other lectures at this school)

Individual couplings to the Higgs

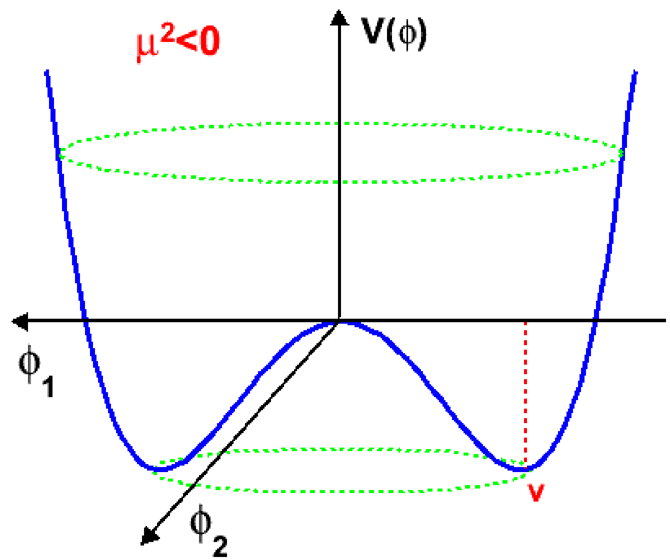


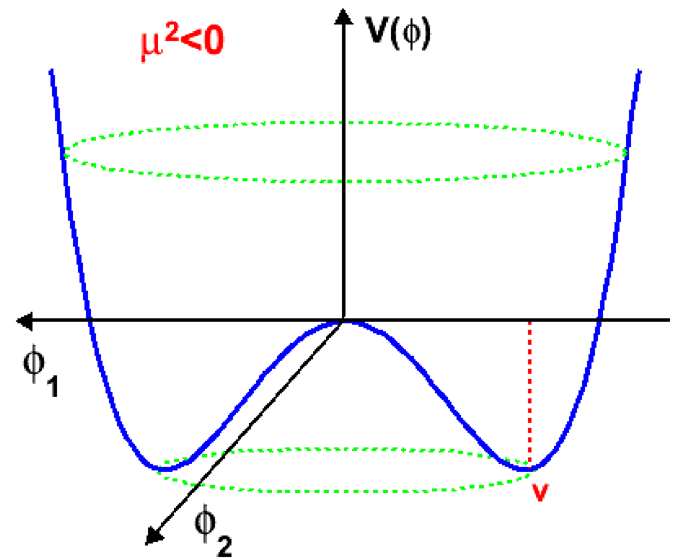
- A e+e- machine (Linear Collider) running at several energies will provide precise measurements of relevant Higgs couplings: Possibility to confirm the Higgs mechanism of the SM
- Precision matters: Detect deviations, for example due to extended Higgs sectors (SUSY,composite, ...):Expected on the 10% - 15% level in fermions,on the few % level in gauge bosons in typical Two-Higgs-Doublet models

Going beyond the Standard Model

No reason that there exists only one Higgs Doublet

=> Minimal extension: Introduction of a second doublet





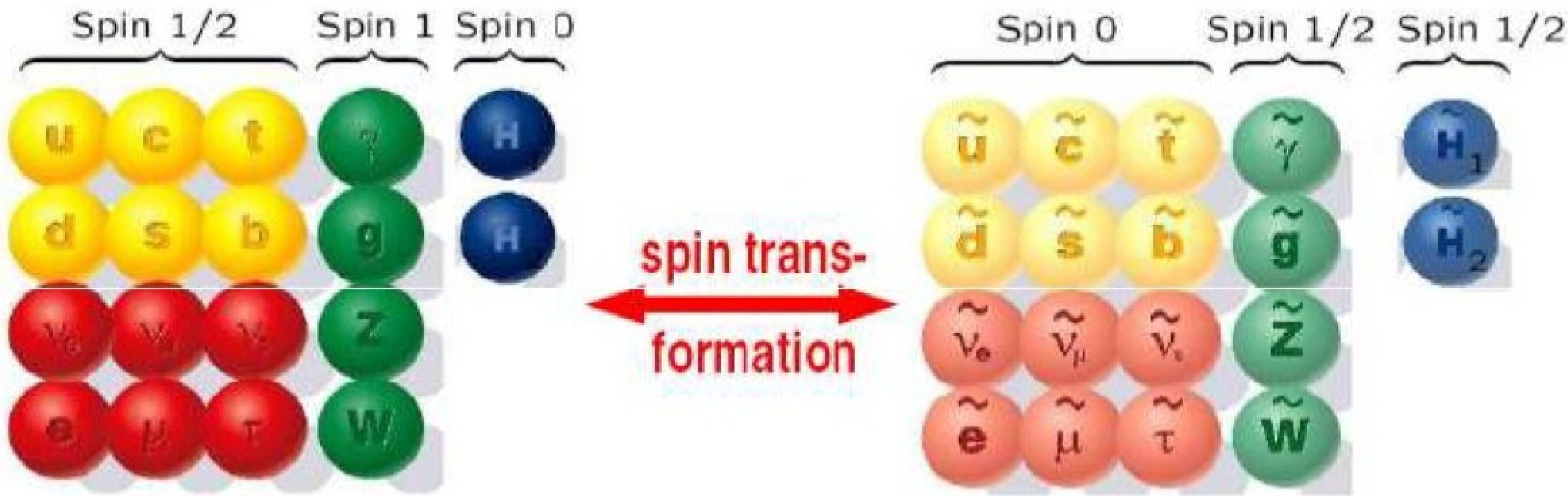
$$\langle\Phi_1\rangle_0 = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix} \qquad \tan\beta = \frac{v_1}{v_2} \qquad \langle\Phi_2\rangle_0 = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

=> Five Higgs bosons: One CP odd scalar A
A pair of charged Higgs Bosons $H^{\pm}$
Two CP even scalars h, H

Observation of a second Higgs Boson is New Physics
Many (Most) New Physics Models contain Higgs Doublet, e.g. Supersymmetry

Going beyond the Standard Model

- **Symmetry between fermions and bosons**



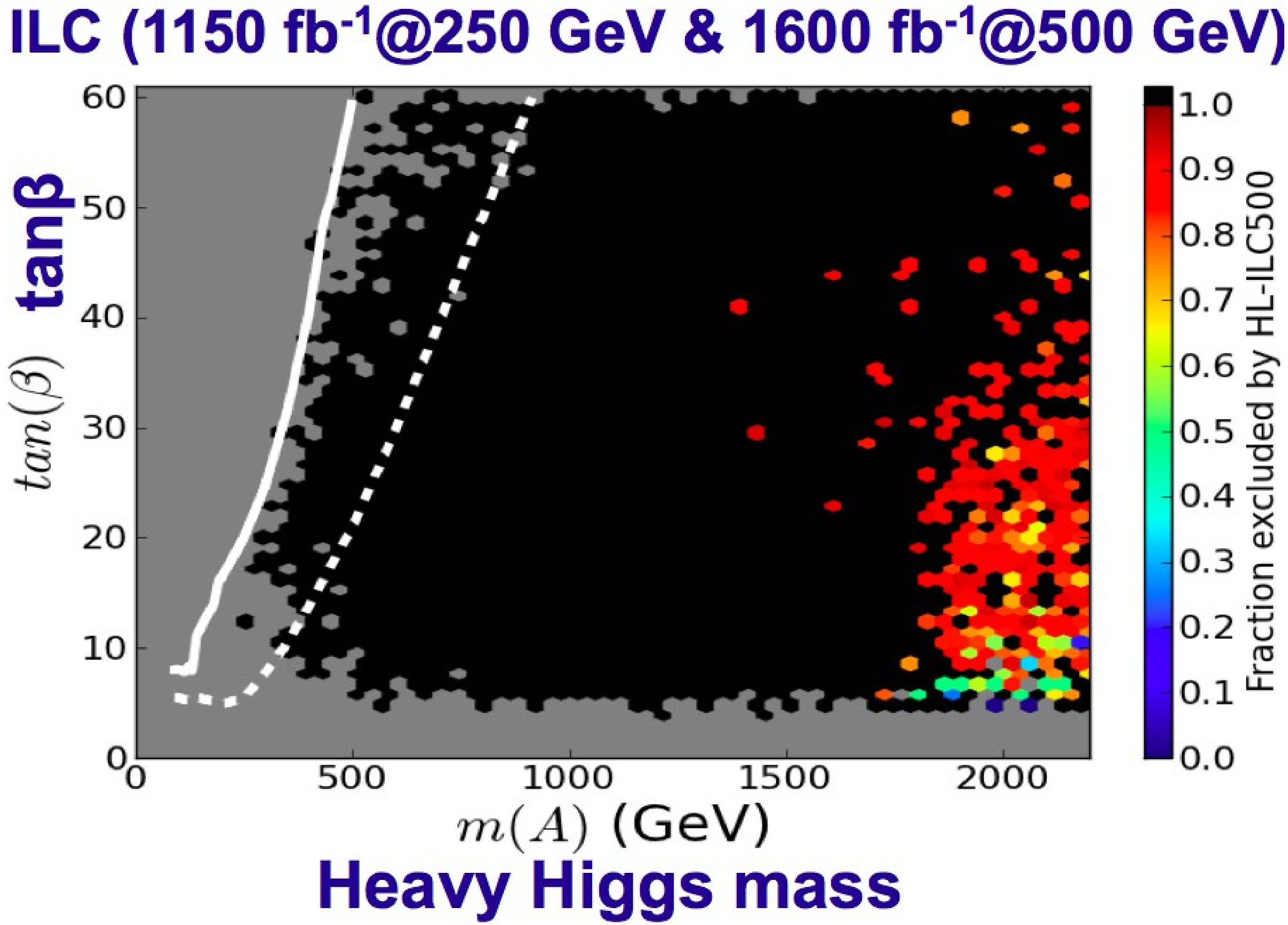
'The search for SUSY is one of the biggest adventures in present-day physics.' Ed Witten (1999)

- **Idea:** ***New symmetry relating internal symmetries (gauge invariance) to space-time symmetries (general relativity)?***

See Lecture by ...

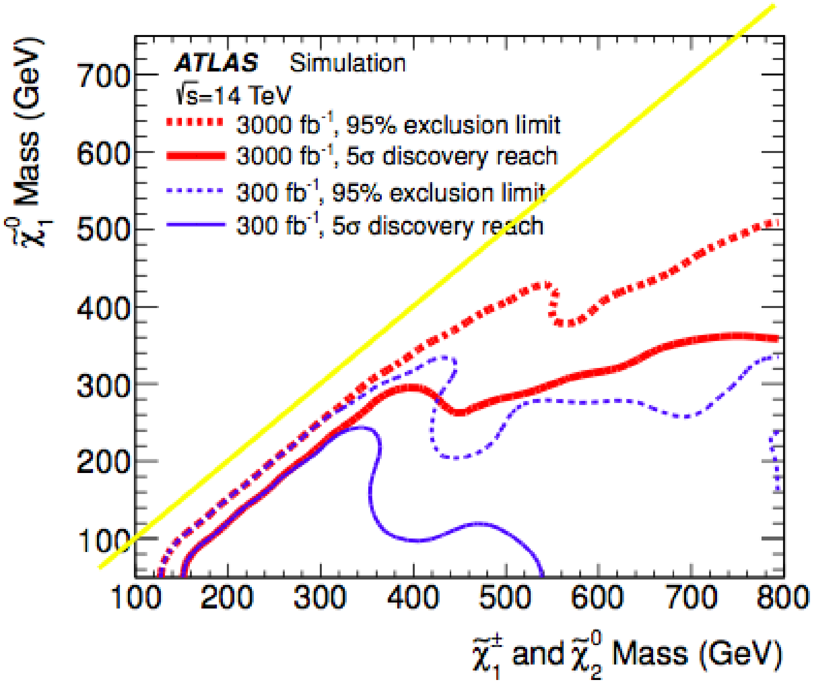
Supersymmetric Higgs Boson (MSSM case)

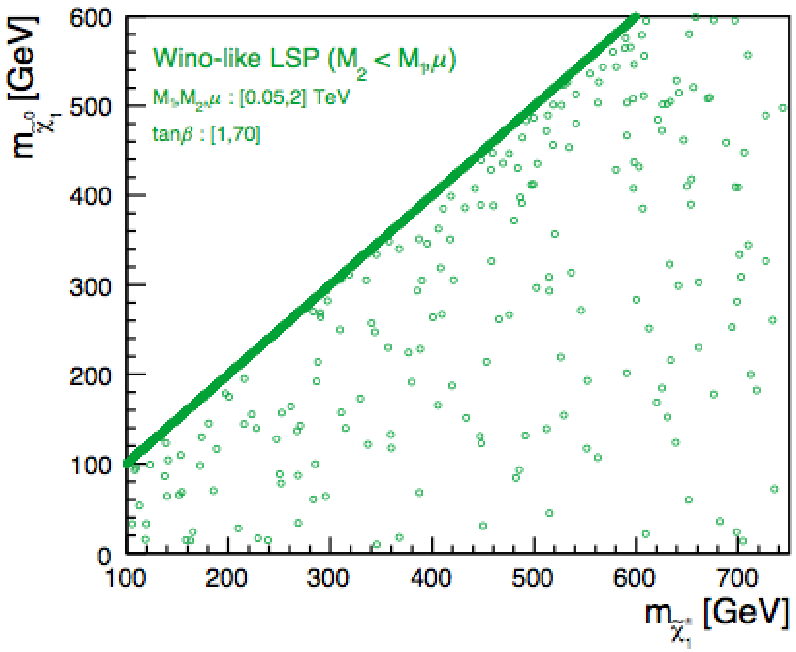
Exlusion of pMSSM points via Higgs Couplings – arXiv 1407.7021



Precision Higgs coupling measurements are sensitive probe for heavy Higgs Bosons m_A ~ 2 TeV reach for any tanβ in high energy e+e- collisions

What about direct searches ?





- Hadron colliders strong In detecting coloured Supersymmetric particles (if any)

- Hadron colliders have also a potential to discover electrically charged or Neutrally charged supersymmetric particles

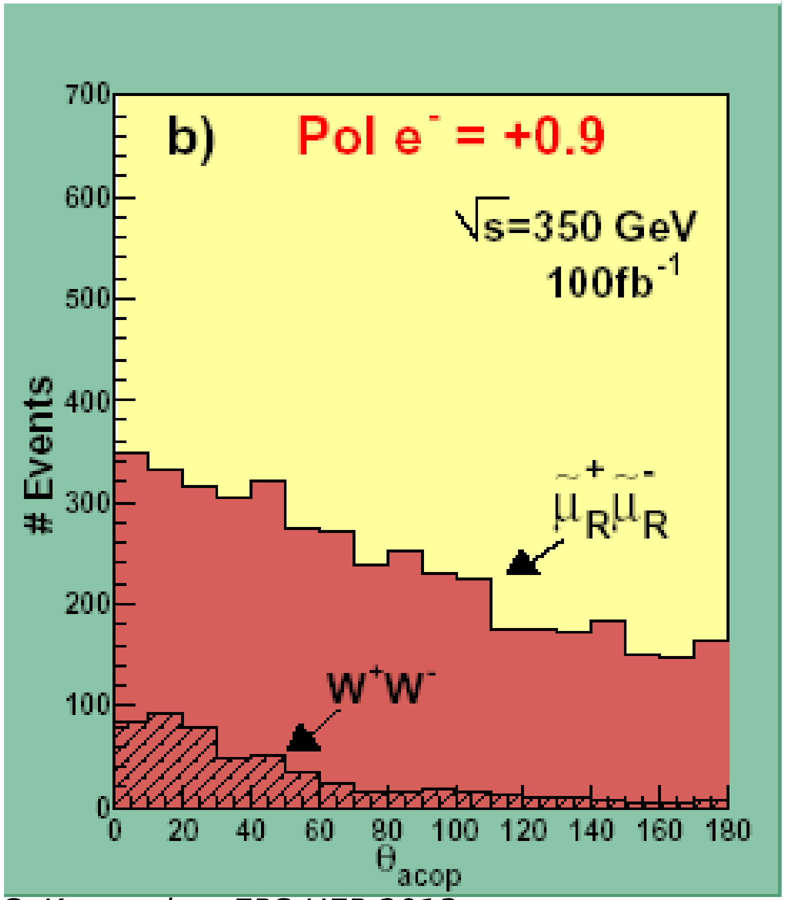
- However, lightest neutralino and chargino Masses tend to degenerate

=> There exists a region in parameter space down to very small masses That cannot be excluded by e.g. LHC

Mass differences < 1 GeV can be measured at e.g. a machine with 500 GeV centre-of-mass energy

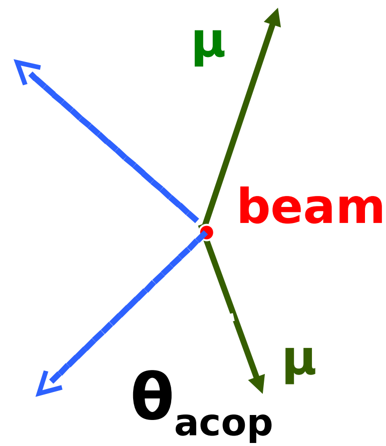
Power of (electron) polarisation

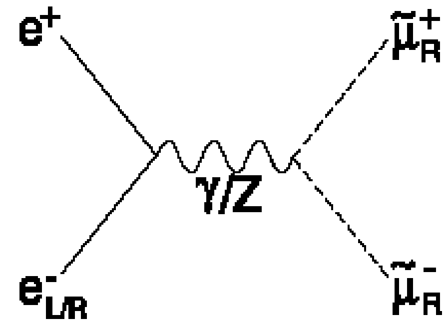
Scalar muon production

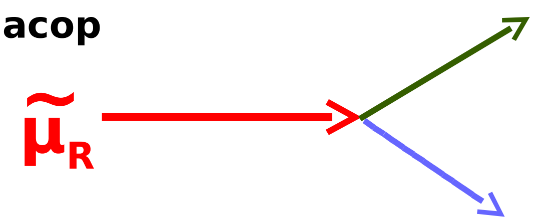


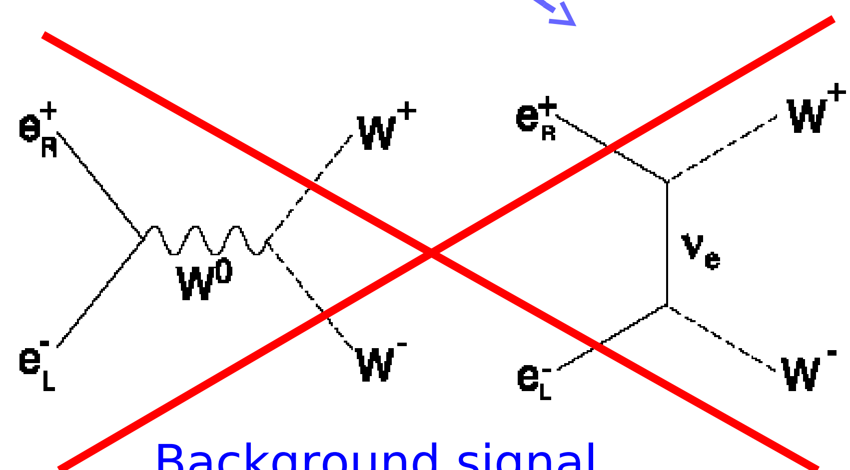
S. Komamiya, EPS-HEP 2013

Polarized (90% e^-_R)









Background signal

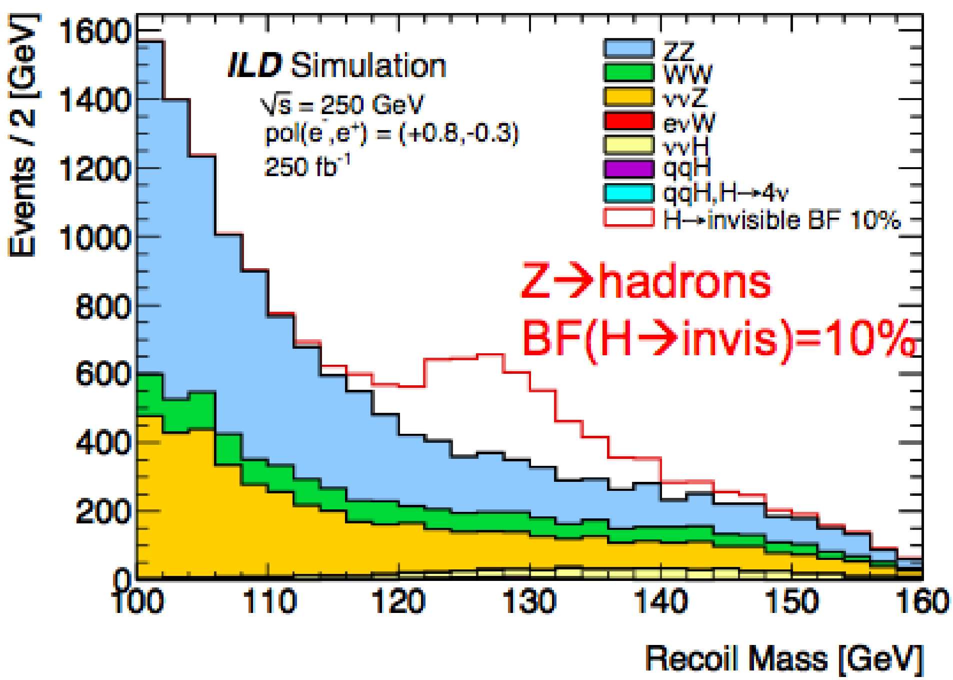
Beam polarisation is efficient tool to suppress (Standard Model) background

WIMP and Dark Matter Searches

WIMP searches at colliders are complementary to direct/indirect searches.

Examples at the ILC:

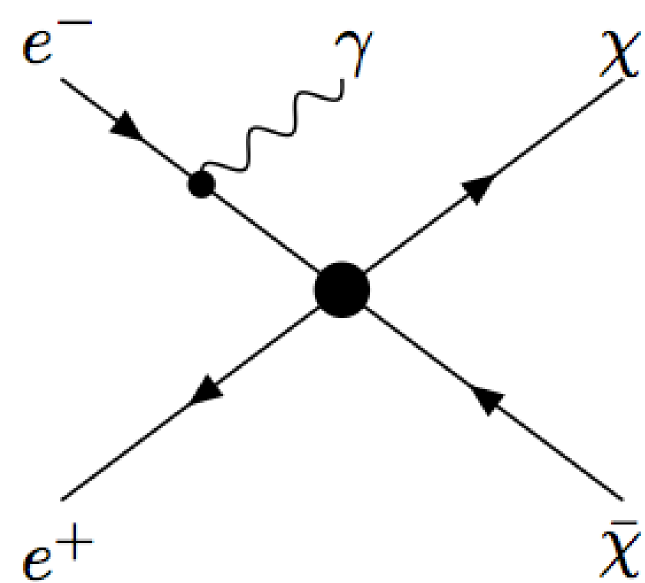
Higgs Invisible Decays



BR(H→invis.) < 0.4% at 250 GeV, 1150 fb^{-1}

Impact of jet energy resolution

Monophoton Searches



→ DM mass sensitivity nearly half √s

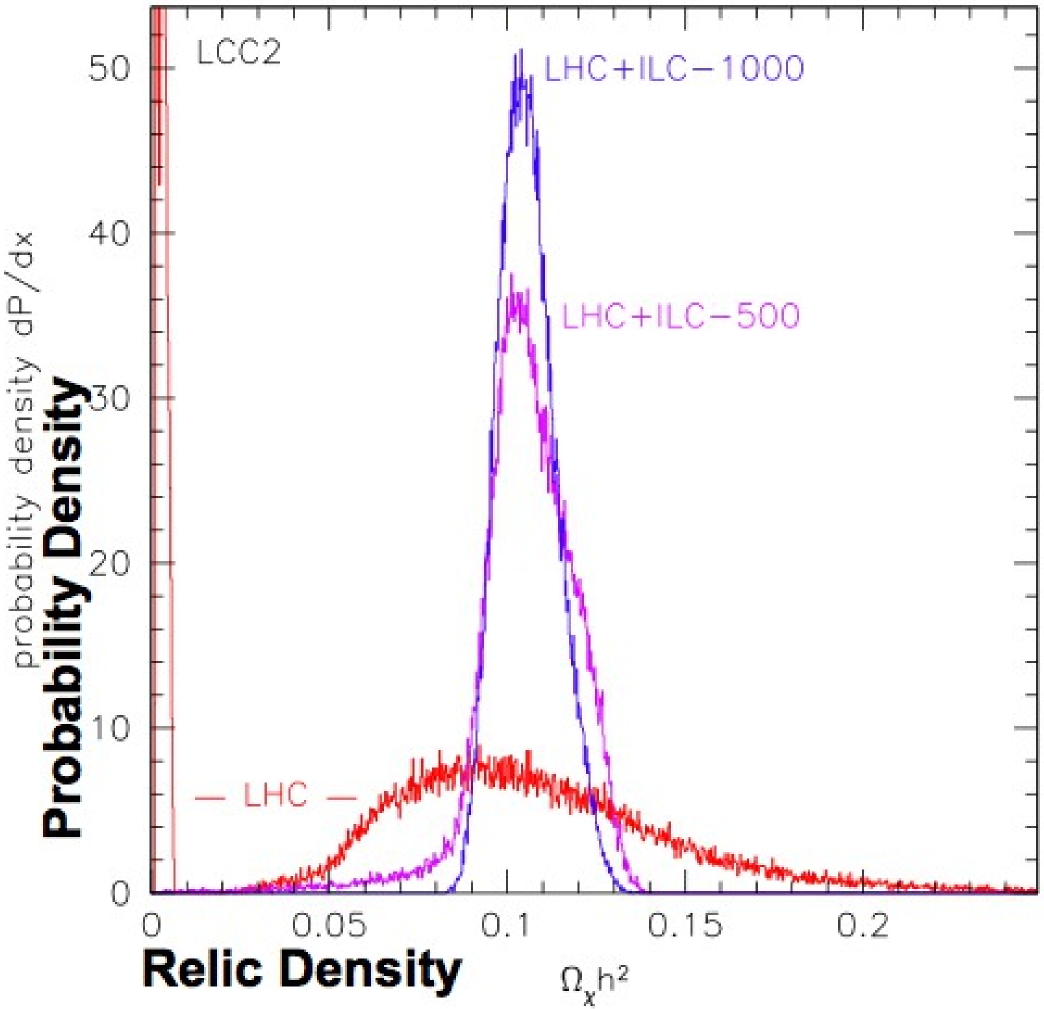
Soft photons, forward detectors

Tomohiko Tanabe
ILD Meeting 2014

Connection to relic matter density

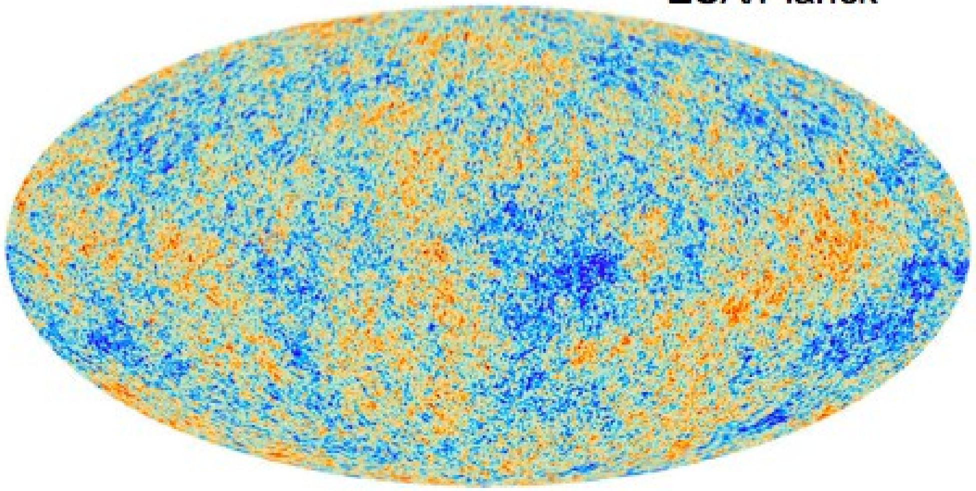
WMAP/Planck (68% CL)

$$\Omega_c h^2 = 0.1196 \pm 0.0027$$



Baltz, Battaglia, Peskin, Wizansky
PRD74 (2006) 103521, arXiv:hep-ph/0602187

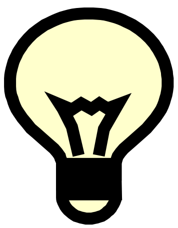
ESA/Planck



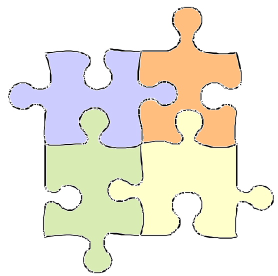
Once a DM candidate is discovered, need to check the consistency with the measured DM relic abundance.

→ ILC's precise measurements of the mass and cross sections provide crucial input.

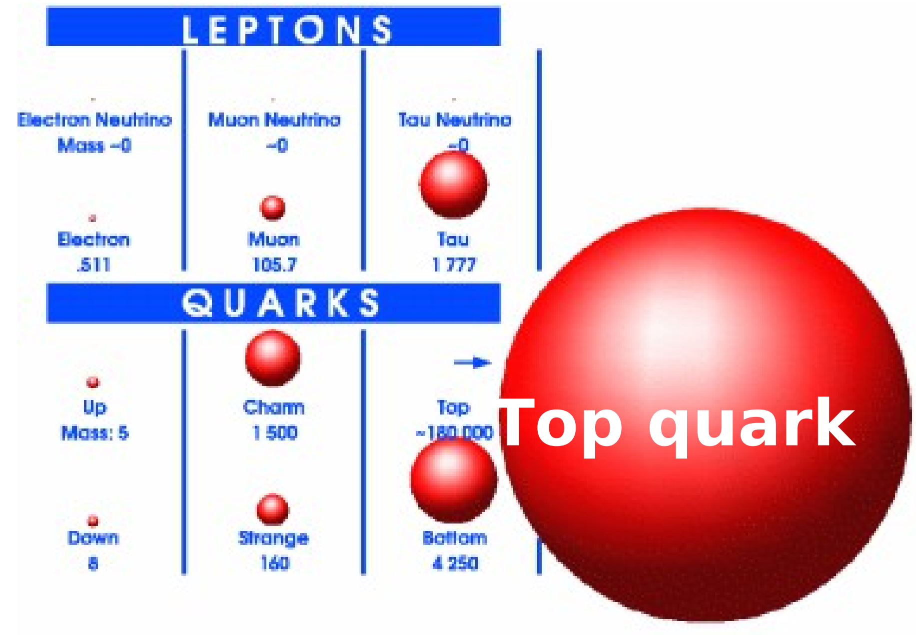
An enigmatic couple ...



Elementary Scalar?

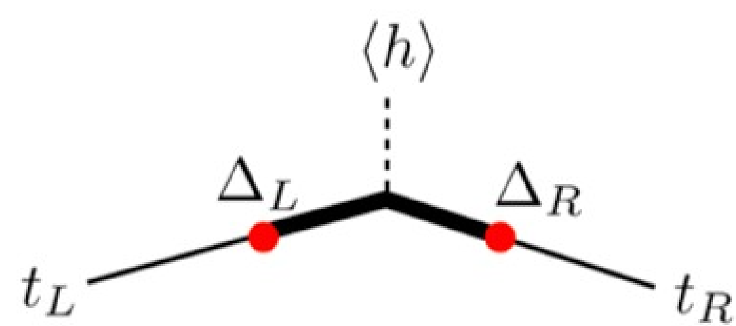


Composite object?



More on top quark
Lecture by Thomas Müller

- Higgs and top quark are intimately coupled!
  Top Yukawa coupling O(1) !
  => Top mass important SM Parameter



Courtesy of S. Rychkov

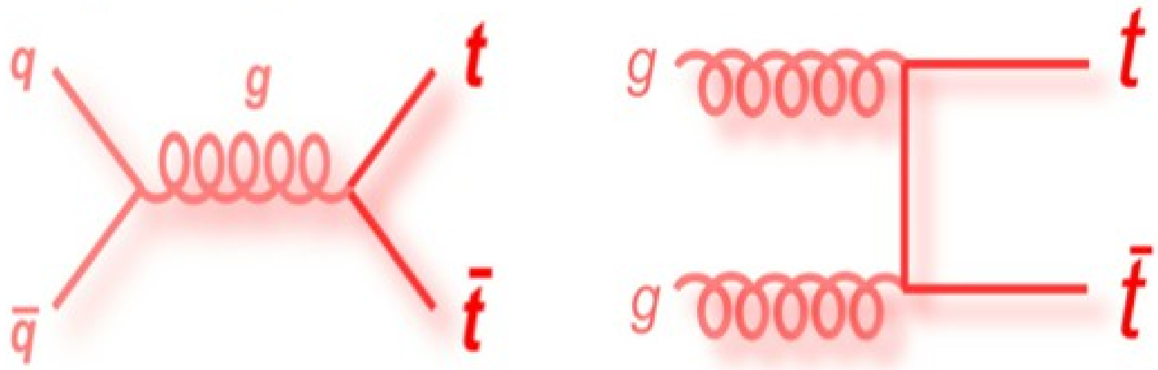
- New physics by compositeness?
  Higgs <u>and</u> top composite objects?

- **LC perfectly suited to decipher both particles**

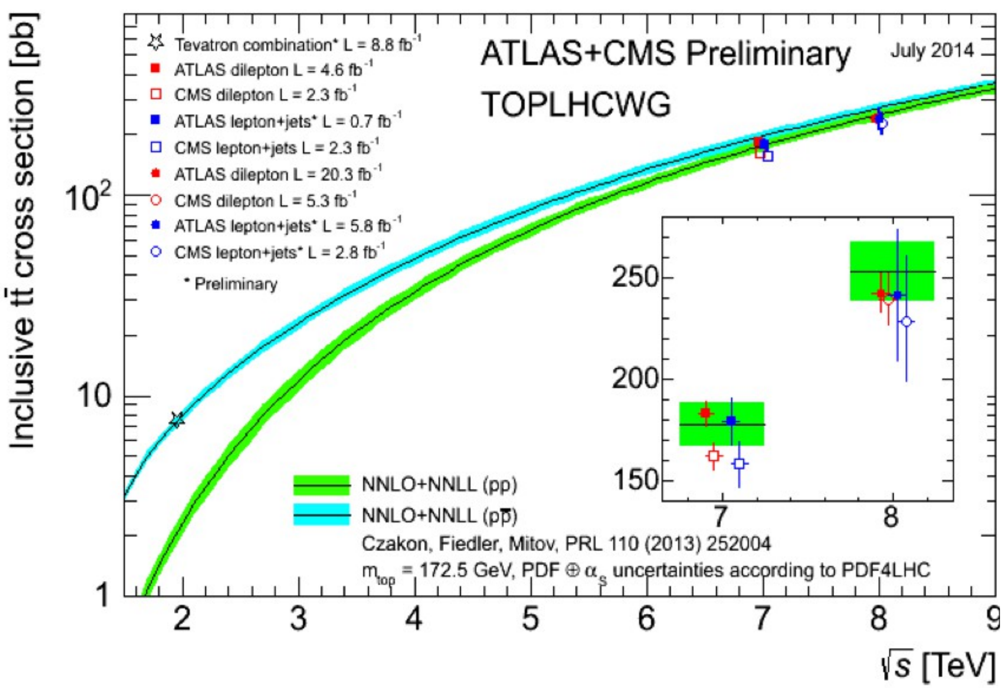
Top quark pair production at hadron colliders

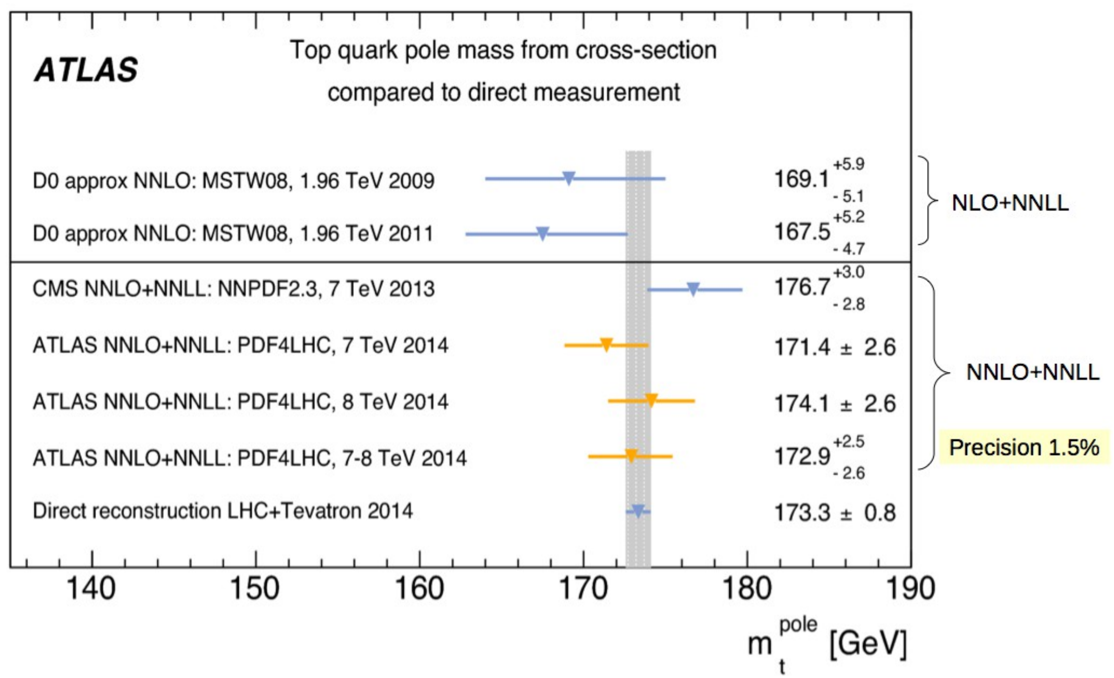
So, far top quarks have only been observed at hadron colliders ...

Example diagrams:



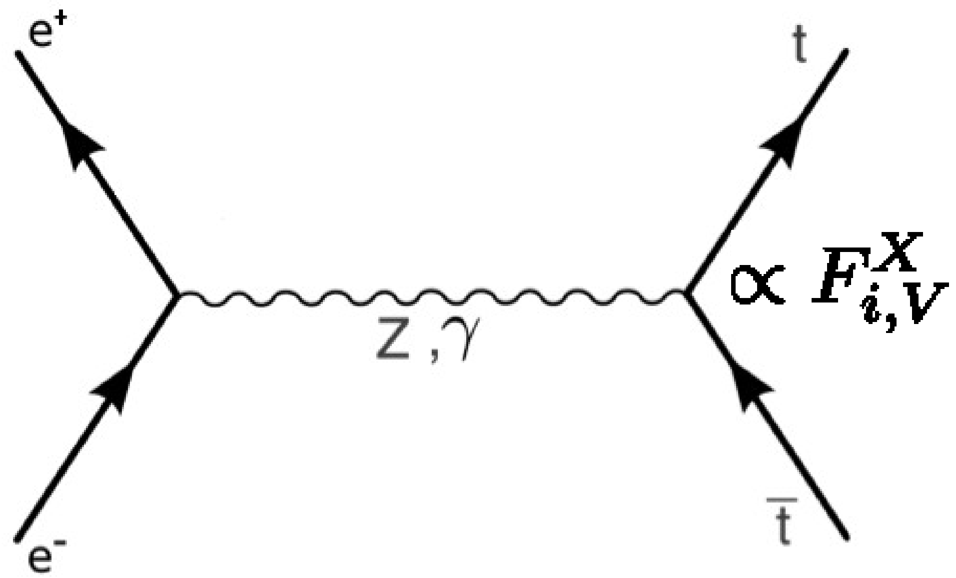
	σ_{gg}/σ_{tot}
Tevatron	$\approx 15\%$
LHC 7 TeV	$\approx 85\%$
LHC 14 TeV	$\approx 90\%$

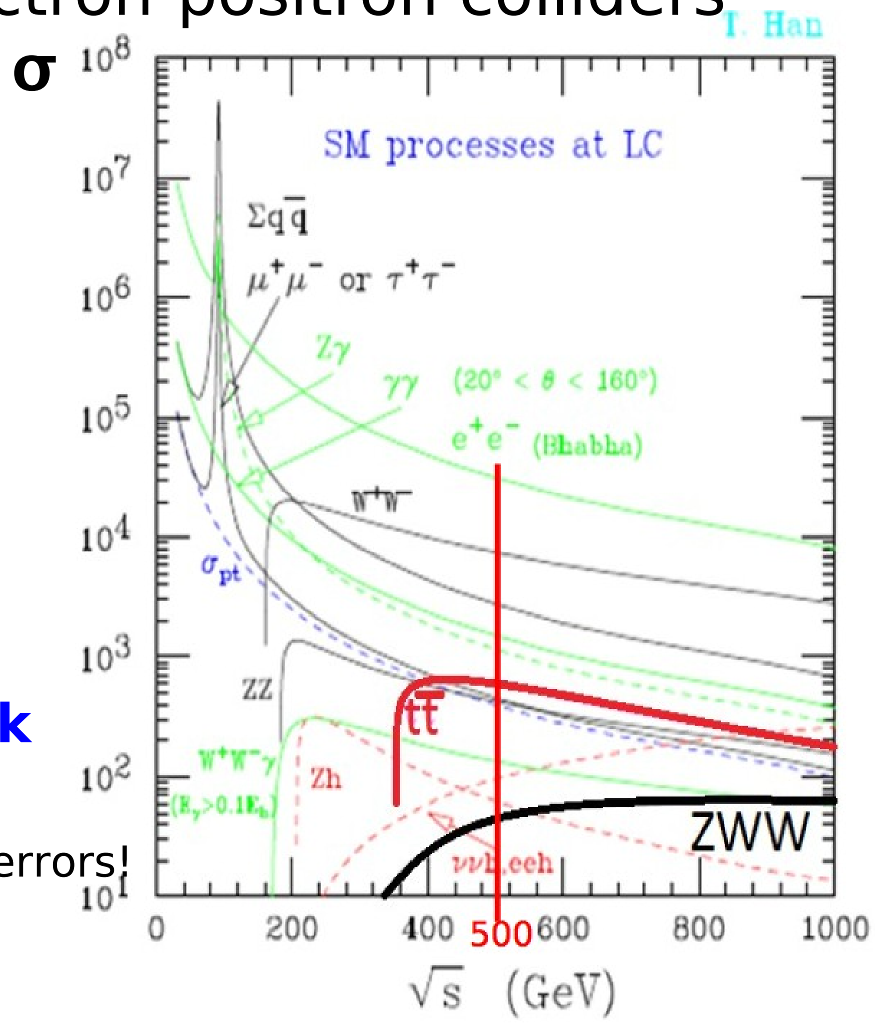




=> High time to see them at lepton colliders!

Top quark physics at electron-positron colliders





- Top quark production through **electroweak** processes,

no competing QCD production => Small theoretical errors!

- High precision measurements

Top quark mass at ~ 350 GeV through threshold scan

Polarised beams allow testing chiral structure at ttX vertex

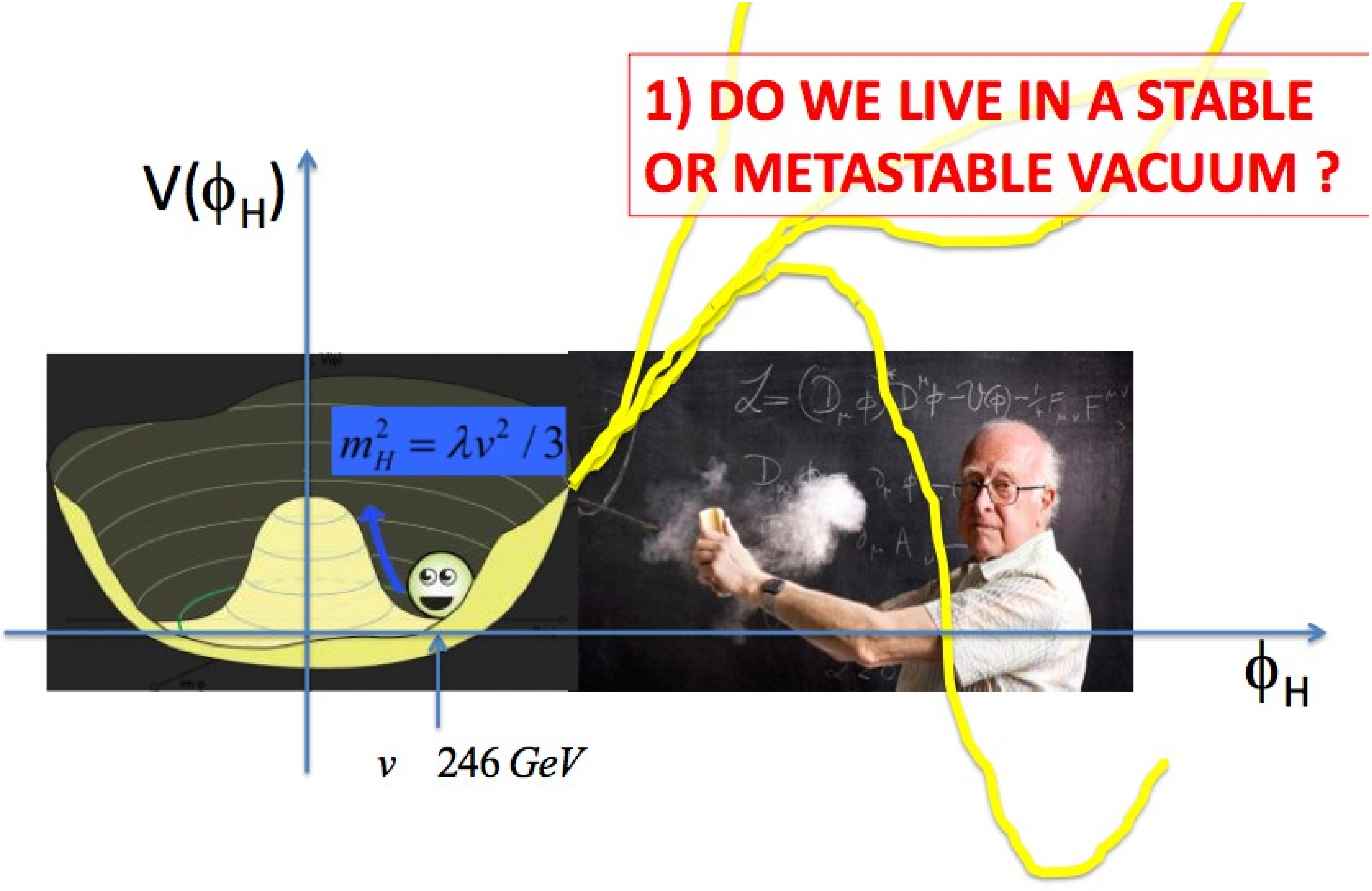
=> Precision on form factors F

- Studies presented here deal with no or only mildly boosted tops, beta~0.7

- A major difference between LC and LHC is that an LC will run triggerless

-> Unbiased event samples, all event selection happens off-line!

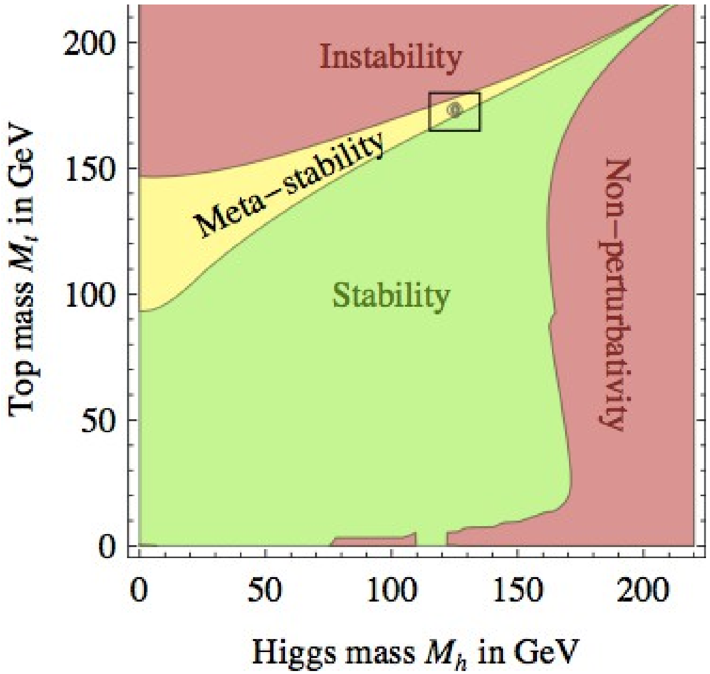
The fate of the universe

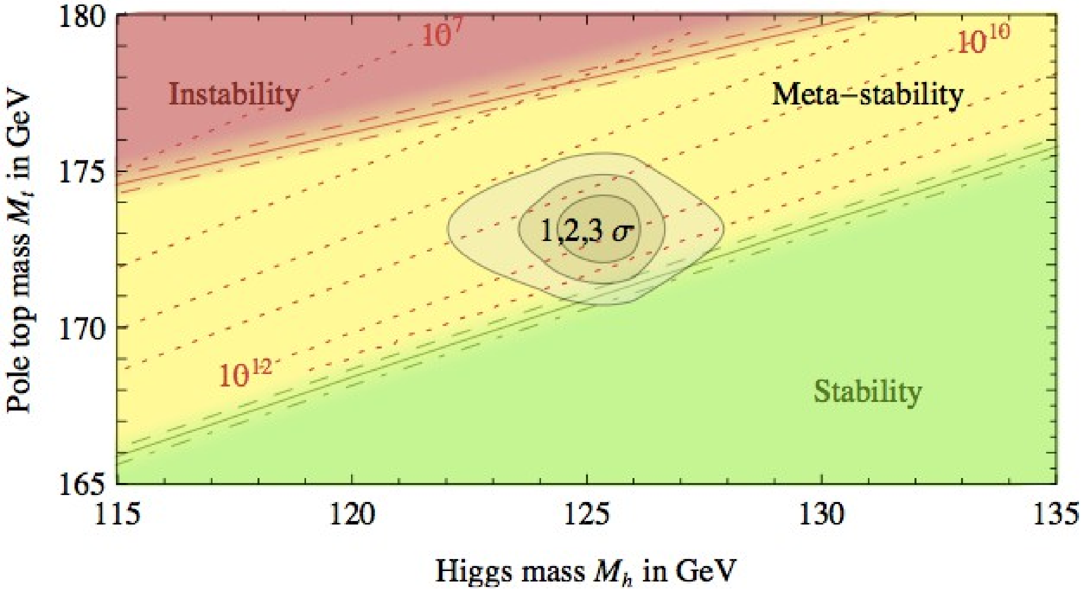


Vacuum stability and top quark mass

Degrassi et al.
arXiv:1205.6497

$$M_h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}\ .$$



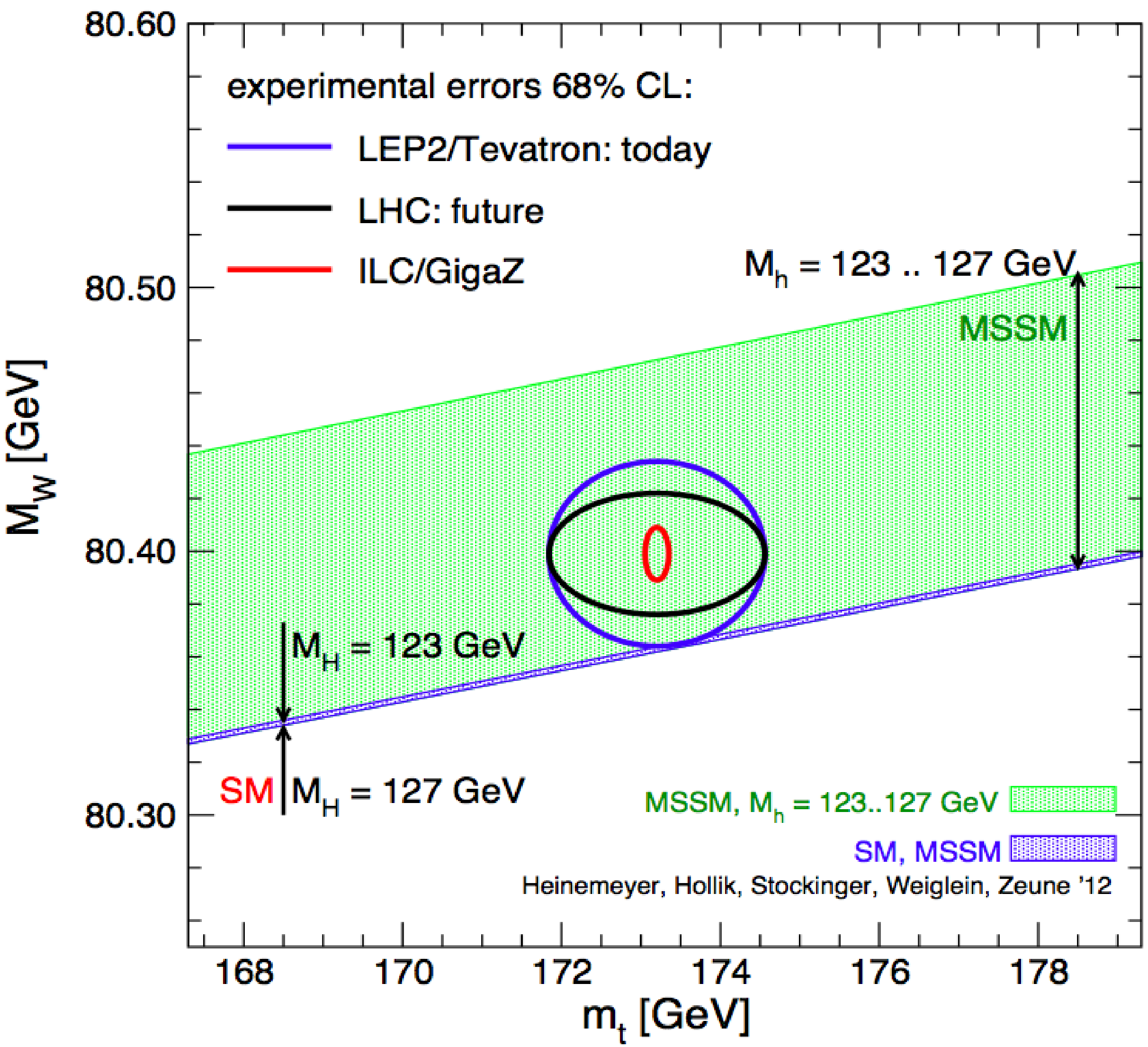


Type of error	Estimate of the error	Impact on M_h
M_t	experimental uncertainty in M_t	$\pm$1.4 GeV
α_s	experimental uncertainty in α_s	$\pm$0.5 GeV
Experiment	**Total combined in quadrature**	**$\pm$1.5 GeV**
λ	scale variation in λ	$\pm$0.7 GeV
y_t	$\mathcal{O}(\Lambda_{\mathrm{QCD}})$ correction to M_t	$\pm$0.6 GeV
y_t	QCD threshold at 4 loops	$\pm$0.3 GeV
RGE	EW at 3 loops + QCD at 4 loops	$\pm$0.2 GeV
Theory	**Total combined in quadrature**	**$\pm$1.0 GeV**

Uncertainty on **(pole)** top quark mass dominates uncertainty on stability conditions

(argument is repeated In literature!)

Top mass Higgs Mass and BSM – SM vs. MSSM



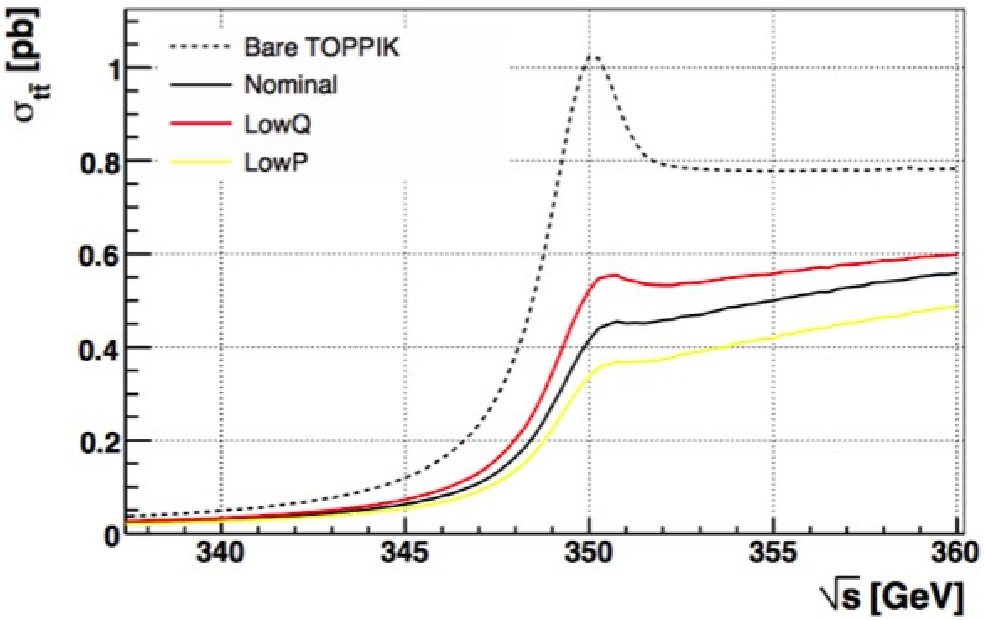
Precise Top (and W) mass crucial to test compatibility of measured Higgs mass

MS might not be sufficient to explain Higgs mass

LHC may not reach sufficient discriminative power

A lepton collider will

Total tt cross section in e+e- collisions



Principle: $\mathbf{m_t}$ **from** $\sigma_{tt}(\mathbf{m_t})$

Advantages:

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

➢ Top decay protects from non-pert effects

Much of the discriminating power of the approach related to the strong mass-dependence (ttbar resonance).

Peak position very stable in theory predictions (threshold mass scheme).

Typical results:

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

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

What mass?

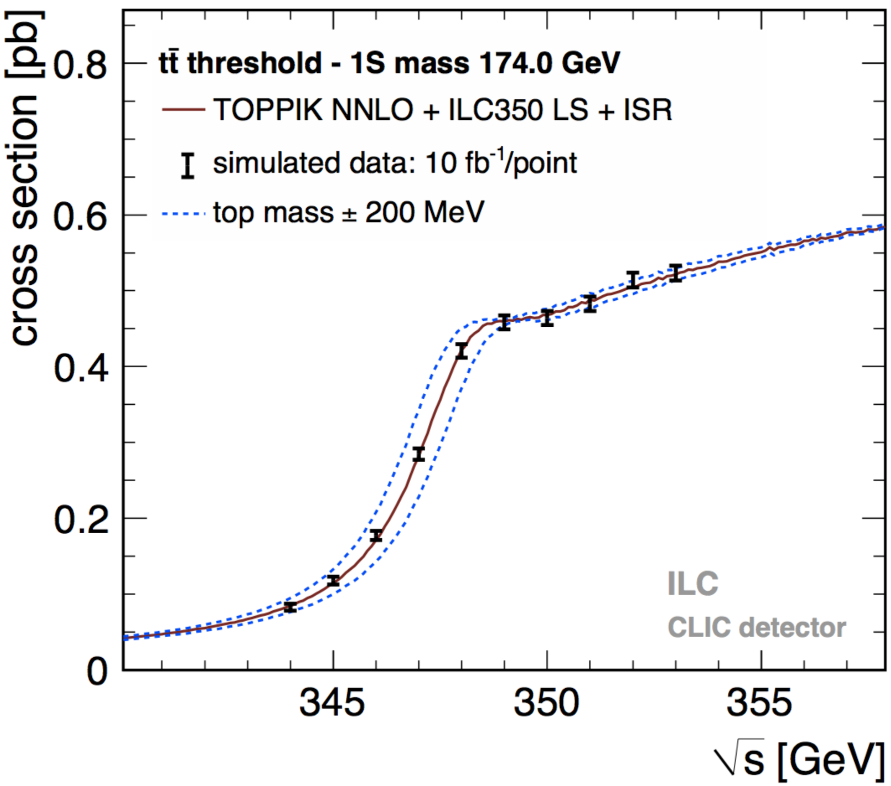
$\sqrt{s}_{\mathrm{rise}} \sim 2m_t^{\mathrm{thr}} +$ pert.series

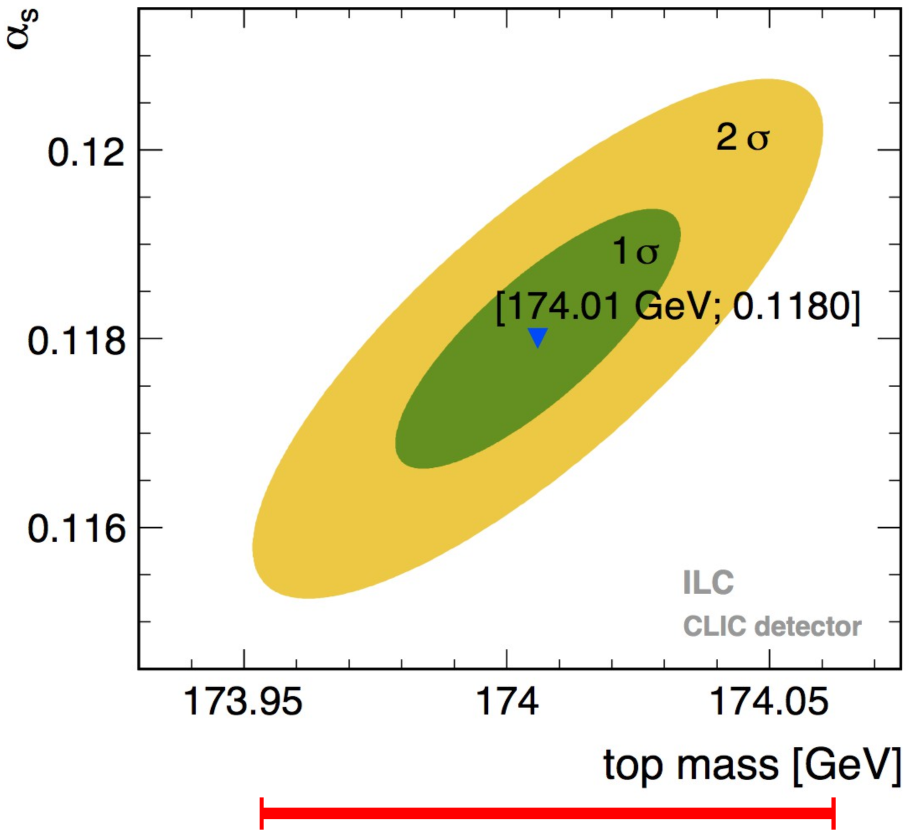
(short distance mass: 1S $\leftrightarrow \overline{\mathrm{MS}}$)

A. Hoang

Top quark mass – Results of full simulation studies

Mass and α_s

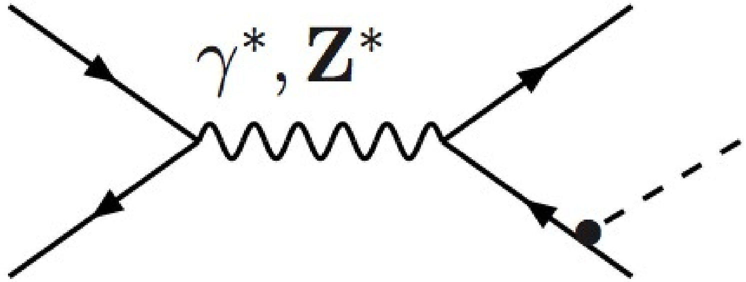


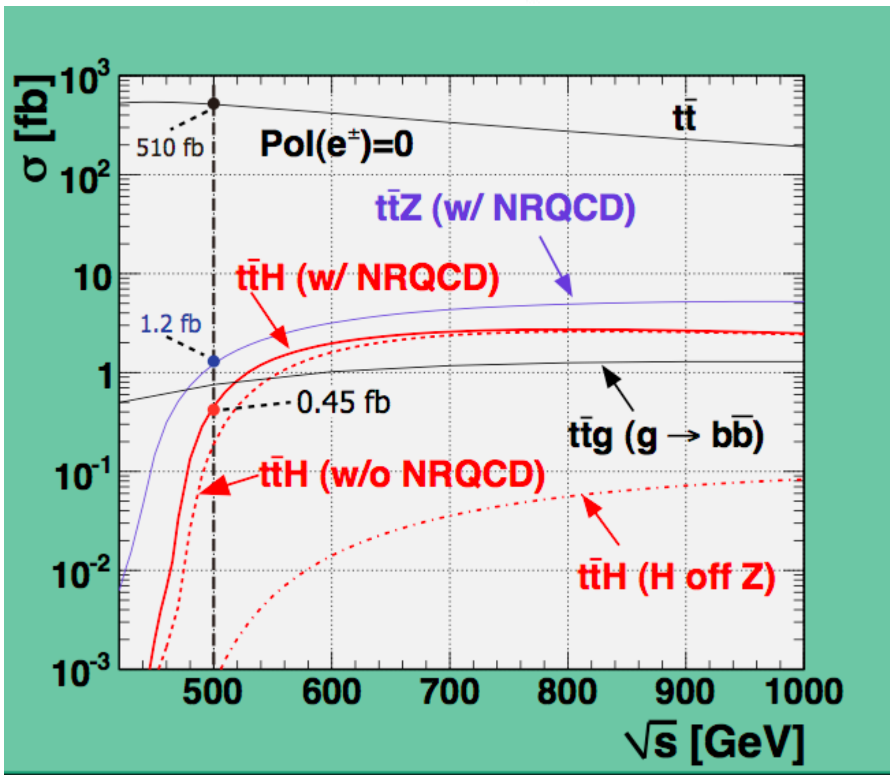


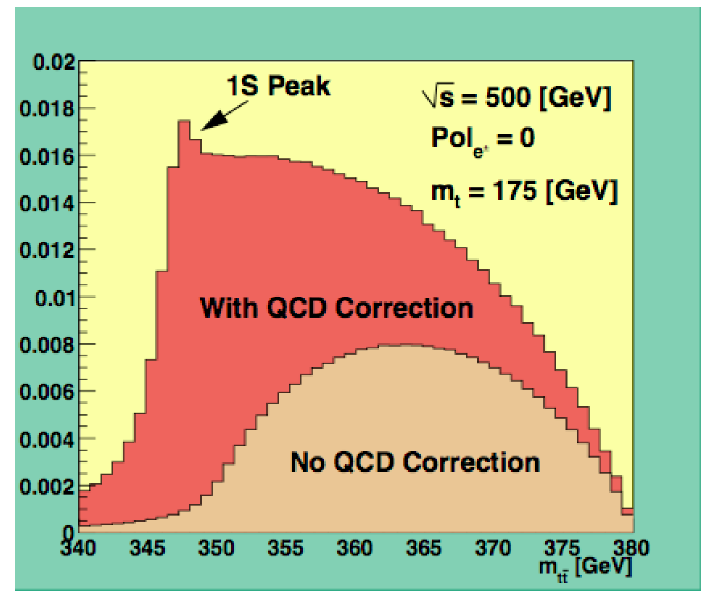
1S top mass and α_s combined 2D fit	
m_t stat. error	27 MeV
m_t theory syst. (1%/3%)	5 MeV / 9 MeV
α_s stat. error	0.0008
α_s theory syst. (1%/3%)	0.0007 / 0.0022

~100 MeV

Top Yukawa coupling above threshold







~ Factor 2 enhancement
From QCD bound states

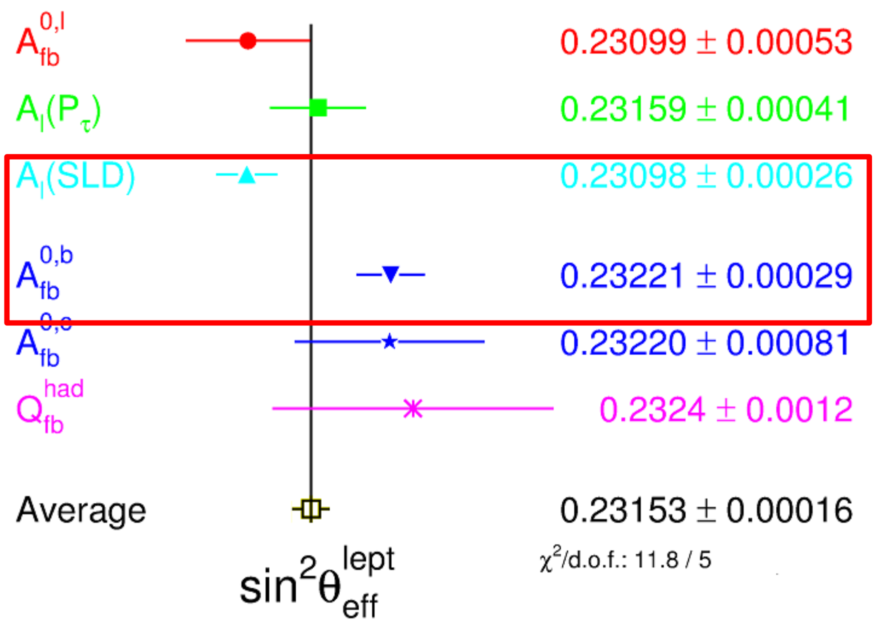
$\Delta g_{ttH} / g_{ttH}$	500 GeV	500 GeV + 1 TeV
Canonical	14%	3.2%
LumiUP	7.8%	2.0%

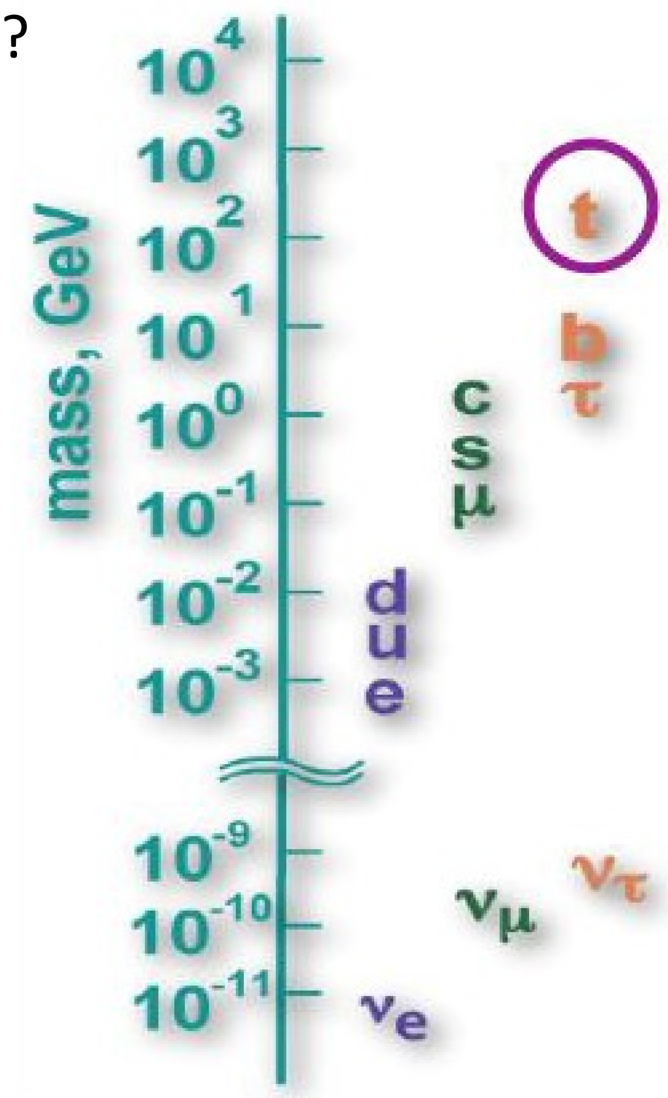
← ILC TDR

← Technically possible

R. Horiguchi et al.
T. Tanabe, T. Price

- Flavor hierarchy ? Role of 3rd generation ?





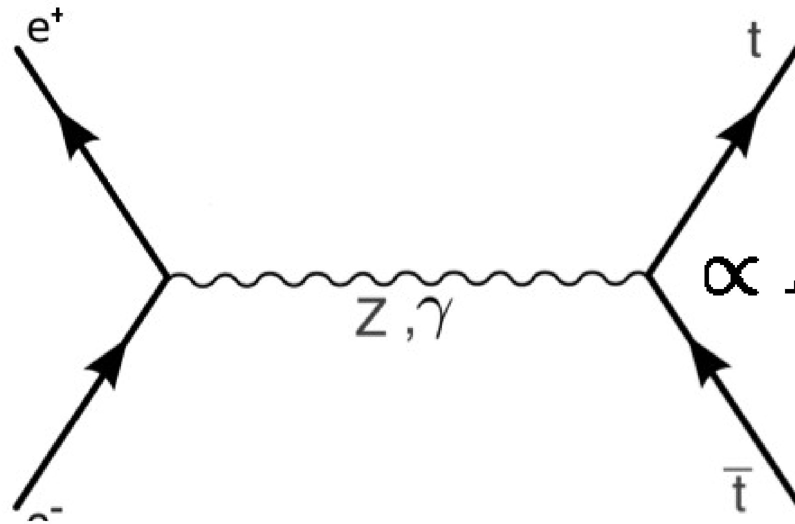
- A_{FB} anomaly at LEP for b quark
  Tensions at Tevatron?

- Heavy fermion effect

Strong motivation to study chiral structure of top vertex in high energy e+e- collisions

Why is it sooo heavy?

Testing the chiral structure of the Standard Model



$\propto F^{X}_{i,V}$

$$\Gamma^{ttX}_{\mu}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu \left(F^X_{1V}(k^2) + \gamma_5 F^X_{1A}(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\mu \left(iF^X_{2V}(k^2) + \gamma_5 F^X_{2A}(k^2)\right)\right\}, \tag{2}$$

$$\mathcal{F}^L_{ij} = -F^\gamma_{ij} + \left(\frac{-\frac{1}{2} + s_w^2}{s_w c_w}\right)\left(\frac{s}{s - m_Z^2}\right) F^Z_{ij}$$

$$\mathcal{F}^R_{ij} = -F^\gamma_{ij} + \left(\frac{s_w^2}{s_w c_w}\right)\left(\frac{s}{s - m_Z^2}\right) F^Z_{ij} \ ,$$

Pure γ or pure Z^0 : $\sigma \backsim (F_i)^2 \Rightarrow$ No sensitivity to sign of Form Factors

Z^0/γ interference : $\sigma \backsim (F_i) \Rightarrow$ Sensitivity to sign of Form Factors

Disentangling

At ILC **no** separate access to ttZ or ttγ vertex, but ...

ILC 'provides' two beam polarisations

$P(e^-) = \pm 80\%$ $\qquad$ $P(e^+) = \mp 30\%$

There exist a number of observables sensitive to chiral structure, e.g.

$$\sigma_I \qquad A^t_{FB,I} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)} \qquad (F_R)_I = \frac{(\sigma_{t_R})_I}{\sigma_I}$$

x-section $\qquad$ Forward backward asymmetry $\qquad$ Fraction of right handed top quarks

⇩

Extraction of six (five) unknowns

$$F^{\gamma}_{1V},\ F^{Z}_{1V},\ F^{\gamma}_{1A} = 0,\ F^{Z}_{1A}$$

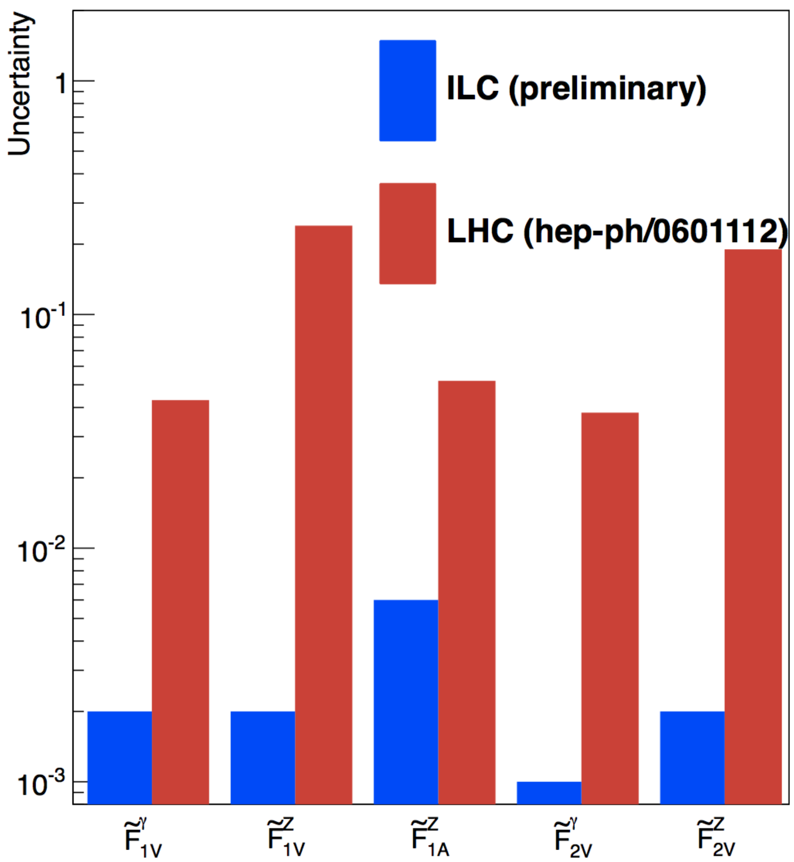
$$F^{\gamma}_{2V},\ F^{Z}_{2V}$$

Results of full simulation study for DBD at $\sqrt{s}$ = 500 GeV

ArXiv: 1307.8102

Precision: cross section ~ 0.5%, Precision A_{FB} ~ 2%, Precision λ_t ~ 3-4%

Accuracy on CP conserving couplings



- ILC might be up to two orders of magnitude more precise than LHC ($\sqrt{s}$ = 14 TeV, 300 fb^{-1})
  Disentangling of couplings for ILC
  One variable at a time For LHC
  However LHC projections from 8 years old study

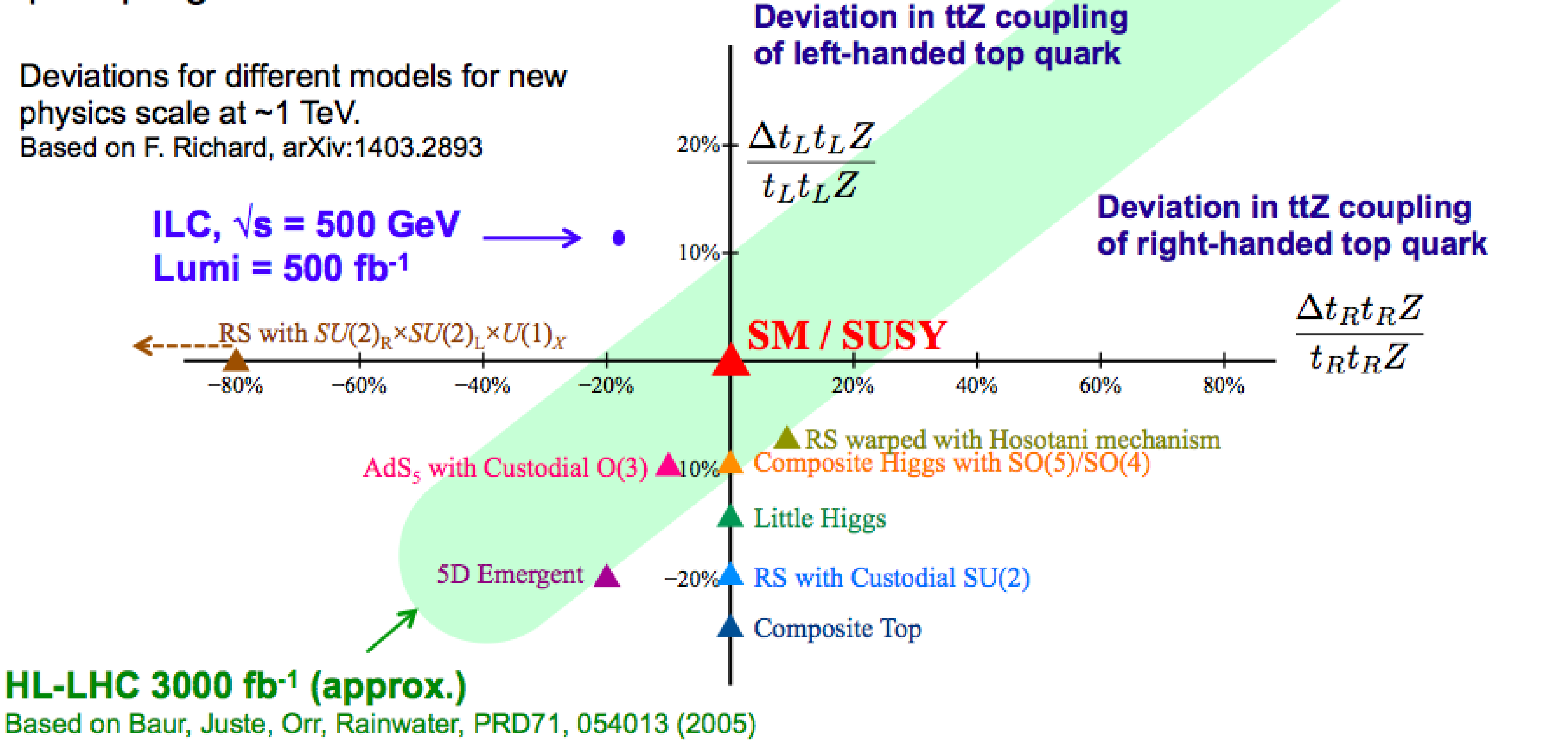
- Need to control experimental (e.g. Top angle) and theoretical uncertainties (e.g. Electroweak corrections)
  -> Dedicated work has started

- Potential for CP violating couplings at ILC under study

ILC promises to be high precision machine for electroweak top couplings

Sensitivity to New Physics

Composite Higgs theories have an impact on the top sector. Composite Higgs models can be tested at the ILC through precise measurements of the top couplings. Beam polarization (both e- and e+) is essential to distinguish the ttZ and ttγ couplings.

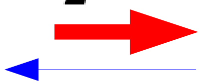


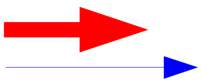
Backup

Helicity and Chirality of Fermions

Helicity is projection of Spin $\vec{\sigma}$ onto direction $\hat{\mathbf{p}}$ of motion of massive particle

Eigenvalues of $\frac{1}{2}\vec{\sigma}\hat{\mathbf{p}}$:

-1/2  Left handed helicity

1/2  Right handed helicity

Caveat:
Helicity is frame dependent!
(why?)
=> Not Lorentz invariant

Helicity projection operator

$$\Pi^{\pm}(\mathbf{p}) = \frac{1}{2}(1 \pm \vec{\sigma}\hat{\mathbf{p}})$$

m=0 →

Chirality projection operator

$$\Pi^{\pm}(\mathbf{p}) = \frac{1}{2}(1 \pm \gamma^5)$$

Chirality is projection of Spin $\vec{\sigma}$ onto direction $\hat{\mathbf{p}}$ of motion of massless particle

Chirality is frame independent! => Basis to define helicity states

$$u_L = \left(1 + \frac{|\vec{p}|}{E+m}\right) u_{LC} + \left(1 - \frac{|\vec{p}|}{E+m}\right) u_{RC}$$

$$u_R = \left(1 - \frac{|\vec{p}|}{E+m}\right) u_{LC} + \left(1 + \frac{|\vec{p}|}{E+m}\right) u_{RC}$$

E >> m

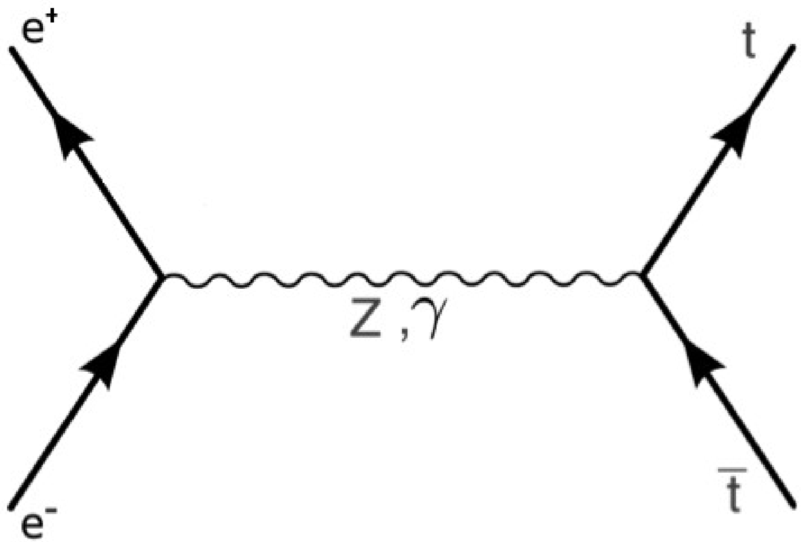
$u_L = u_{LC}$

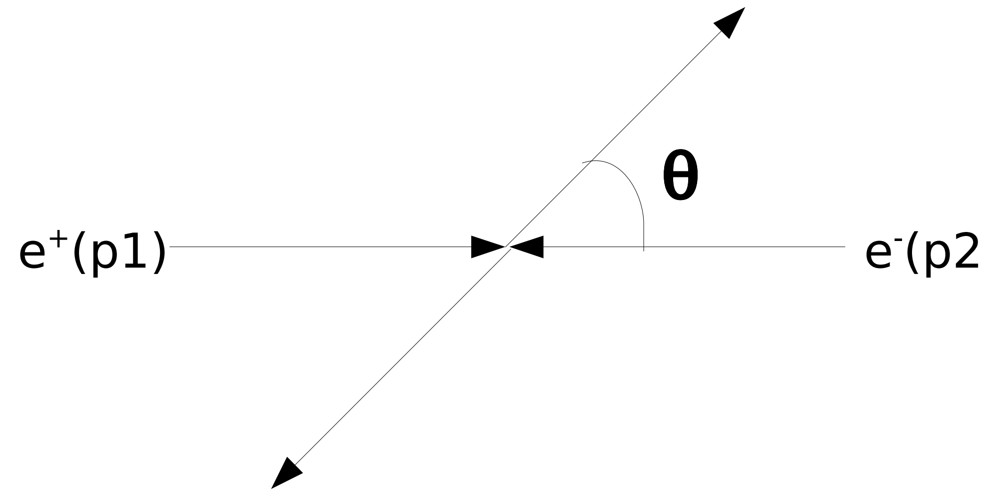
$u_R = u_{RC}$

Remark: Literature and physicists are often sloppy
Always check whether people speak about helicity or chirality

Collisions between leptons

Basic s-channel process





Reaction characterised by

- Well know four vectors of initial state particles

$$p^{\mu}(e^{+}) = (\sqrt{m_e + p_z^2}, 0, 0, p_z)$$
$$p^{\mu}(e^{-}) = (\sqrt{m_e + p_z^2}, 0, 0, -p_z)$$

- Four momentum of initial and Final state are fully constrained

- Polar angle of scattering θ

Compare with (at hadron colliders)

– Unknown/partially known four Vectors of initial state particles

$$p^{\mu}(q/g) = (\xi|p_z|, 0, 0, \xi p_z)$$
$$p^{\mu}(\bar{q}/g) = (\xi'|p_z|, 0, 0, -\xi' p_z)$$

– Only transverse momentum is constrained

– Rapidity y replaces polar angle Δy is boost invariant -> Show!!!

Take home messages so far

- A lepton collider is the ideal machine to study the Nature of the discovered scalar particle in full depth

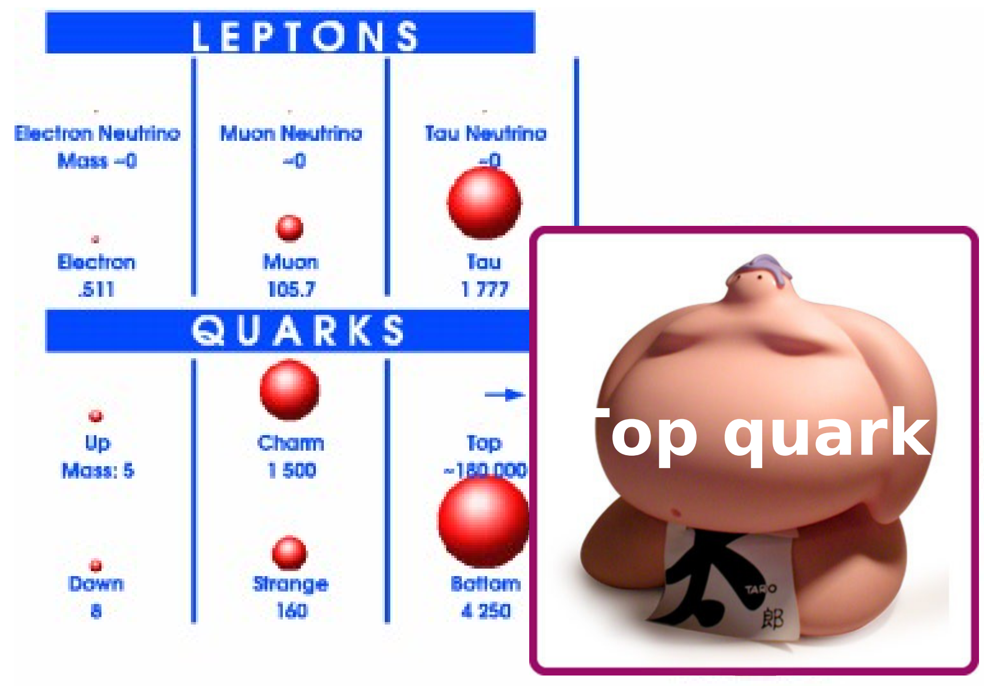
- Strong and narrow Higgs Signal

- Model independent measurements of couplings to all (known) particles

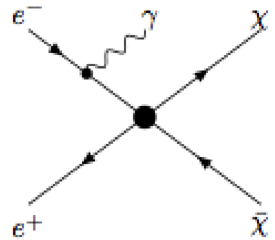
- These measurements require a series of individual measurements at different centre-of-mass energies
  - gHZZ at ~250 GeV
  - Fermion couplings at 350 GeV (or higher)
  - WW fusion at 500 GeV (or higher)
  - Higgs self coupling at > 500 GeV

What do we know about the top quark?

- The top quark is the heaviest known elementary particle
- mt ~ 173 GeV (~m of Gold atom)
- Electrical charge $Q_t = 2/3$
- Spin ½ => fermion
- Lifetime $\tau \sim 5 \times 10^{-25}$ s (SM decays)
- Total width $\Gamma_t \sim 1.5$ GeV
- No hadronisation, behaves like a free quark
  'However ...' see later
- Predominant decays
  $t \rightarrow Wb$ (BR~100%)

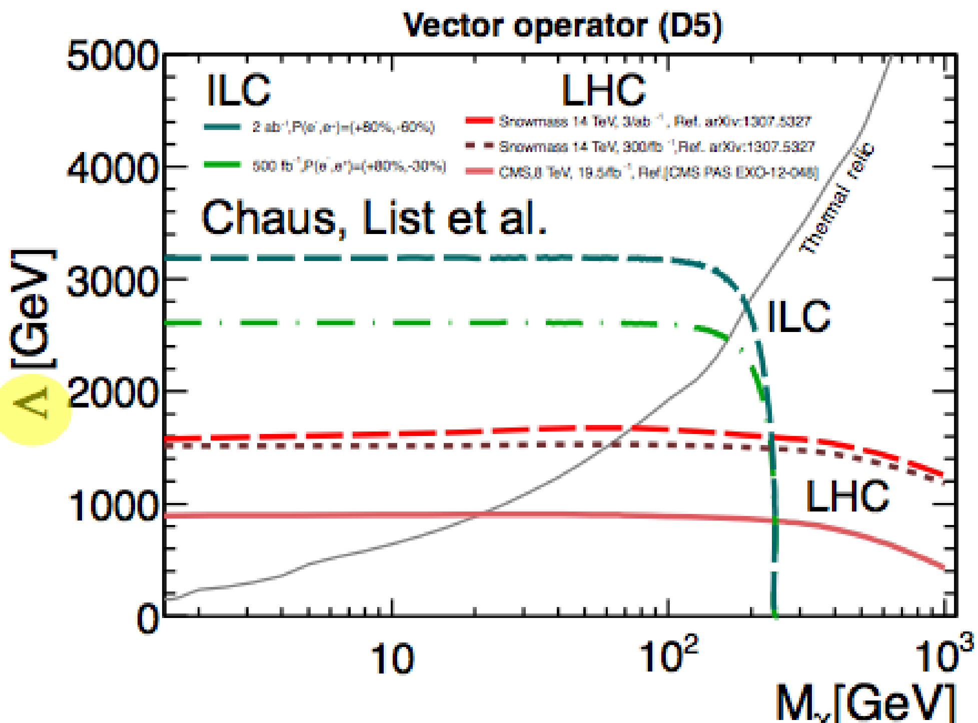


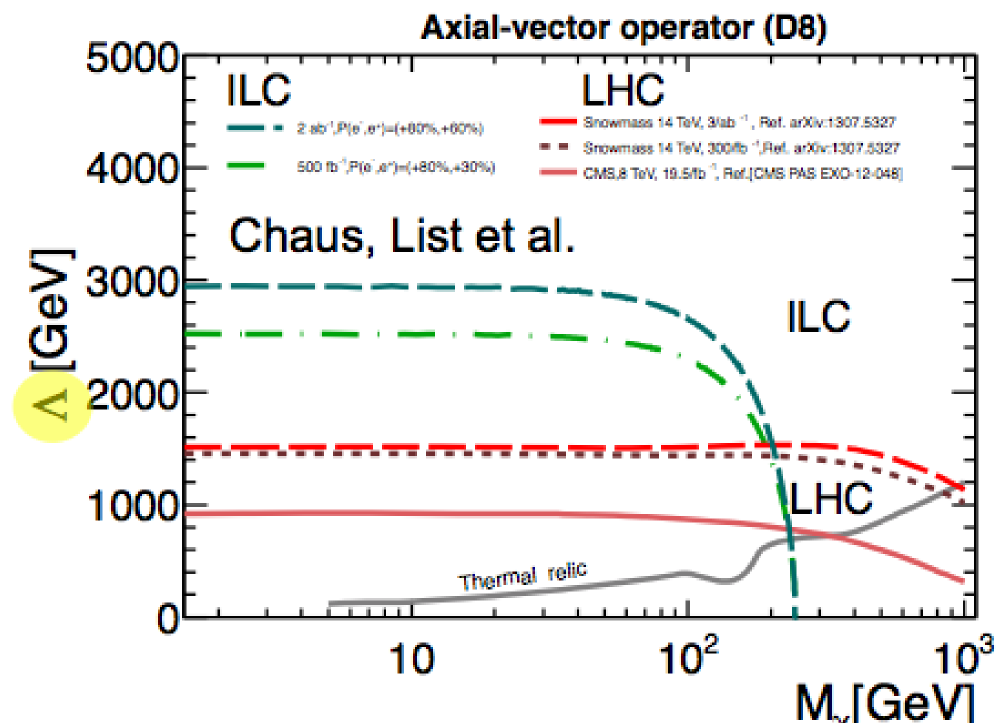
WIMP and Dark Matter Searches



$$\mathcal{L}_{\rm int} = \frac{1}{\Lambda^2}\mathcal{O}_i$$

$$\mathcal{O}_V = (\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell) \qquad \mathcal{O}_A = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma^5\ell)$$





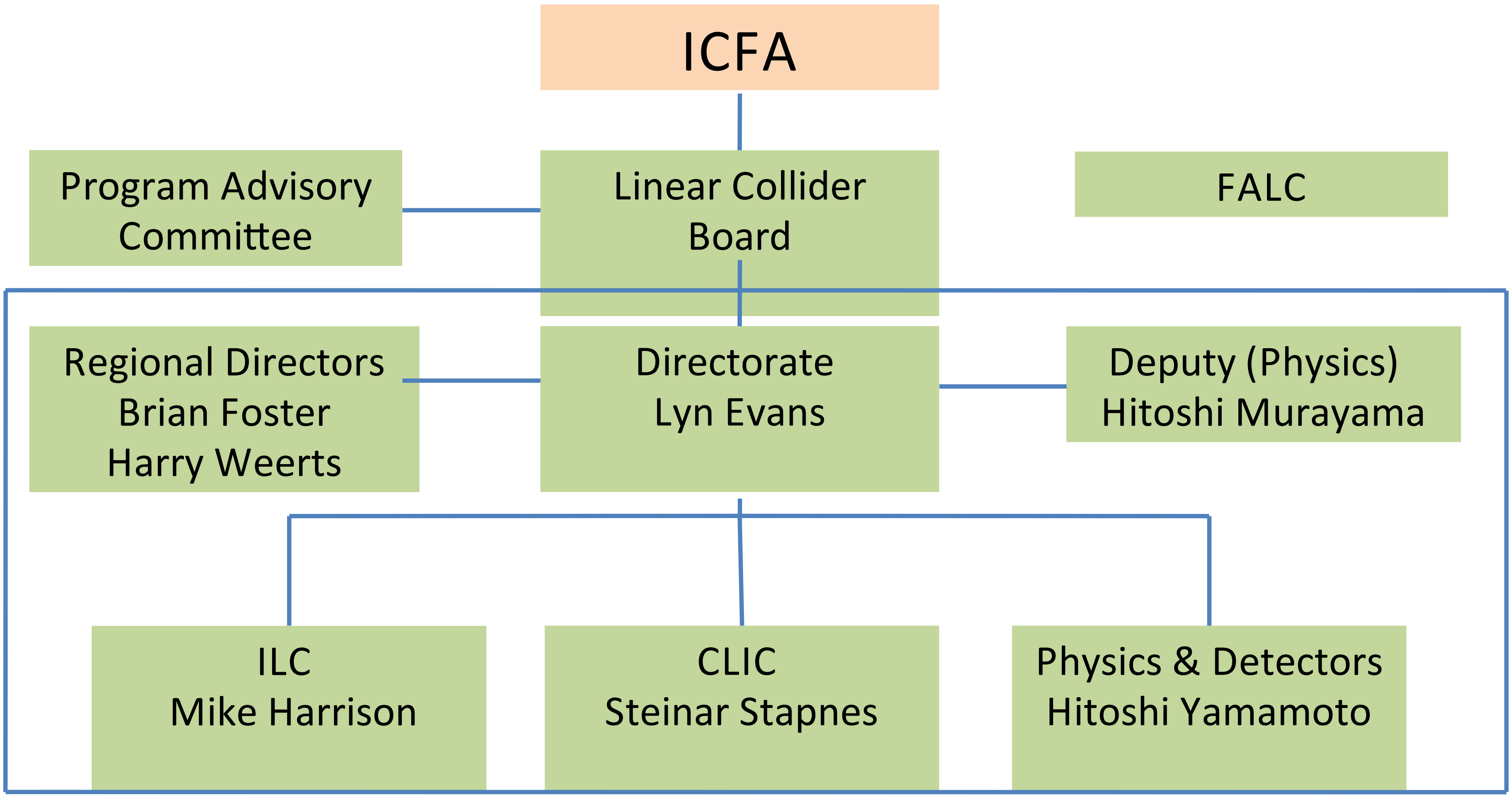
LHC sensitivity: Mediator mass up to Λ~1.5 TeV for large DM mass

ILC sensitivity: Mediator mass up to Λ~3 TeV for DM mass up to ~√s/2

Tomohiko Tanabe
ILD Meeting 2014

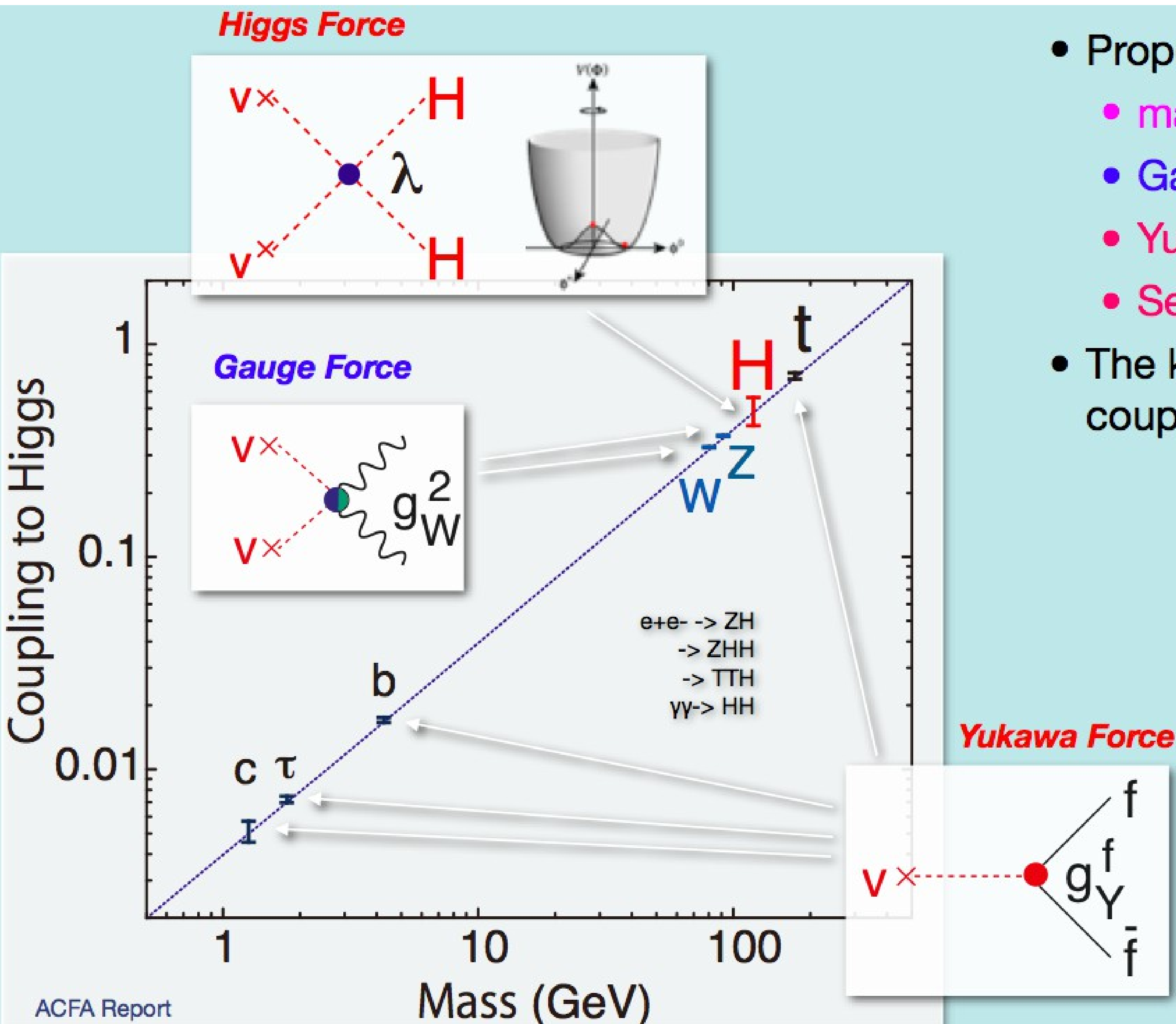
Linear Collider Collaboration

Organization



Worldwide project
Regional balance

Single Higgs Production at Lepton Colliders



- Properties to measure are
  - mass, width, J^{PC}
  - Gauge couplings
  - Yukawa couplings
  - Self-coupling
- The key is to measure the mass-coupling relation

If the 125GeV boson is the one to give masses to all the SM particles, coupling should be proportional to mass.

Any deviation from the straight line signals BSM!