Physics at future Lepton Colliders

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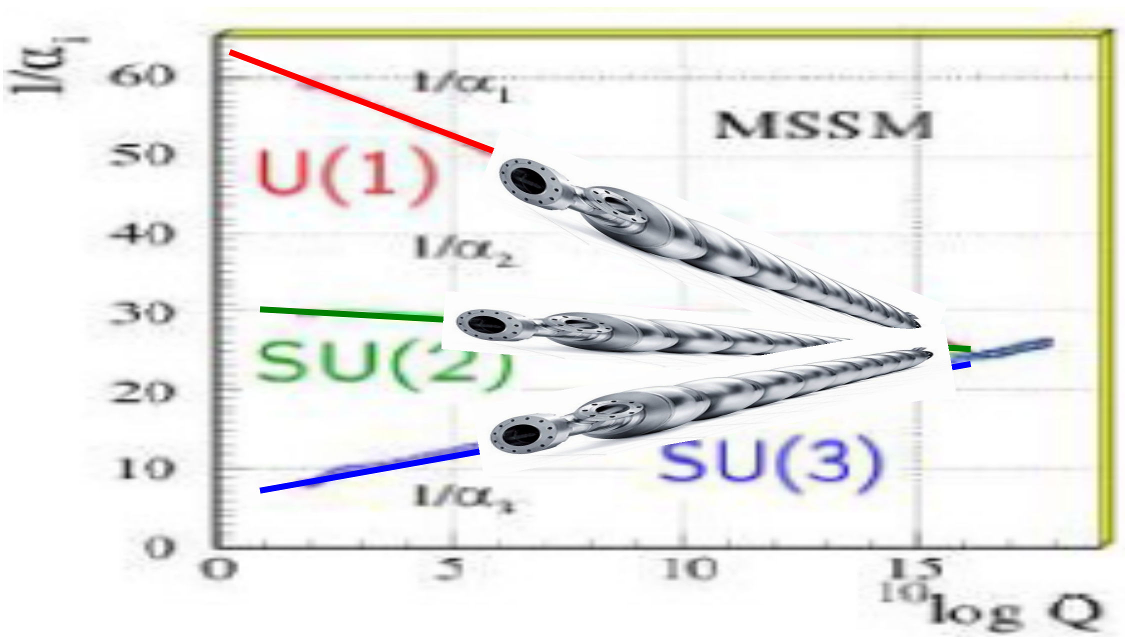


LINEAR COLLIDER COLLABORATION

Physics at future Lepton Colliders

- **Lecture 1**
  - Basics
  - Overview about Higgs,BSM physics at a Lepton Collider
  - Simultaneous polarization of e^- and e^+ beams
- **Lecture 2**
  - Summary of longitudinally and transversely polarized beams
  - Higgs (couplings, wisth, self couplings,CP) at cms=250, 350 and 500 GeV
  - Top quark (mass, Yukawa coupling) at cms=350 and 500 GeV
  - Overview about BSM models, example Supersymmetry
- **Lecture 3**
  - High precision observables
  - GigaZ
  - Overview future Lepton and Hadron Collider Proposals
- **Lecture 4**
  - Technical details (Accelerator, R&D) of a Linear Collider
  - ILC: Status and polarized positron source, prototypes
  - Overview about HALHF concept, adaltion of ILC undulator-based e^+ source

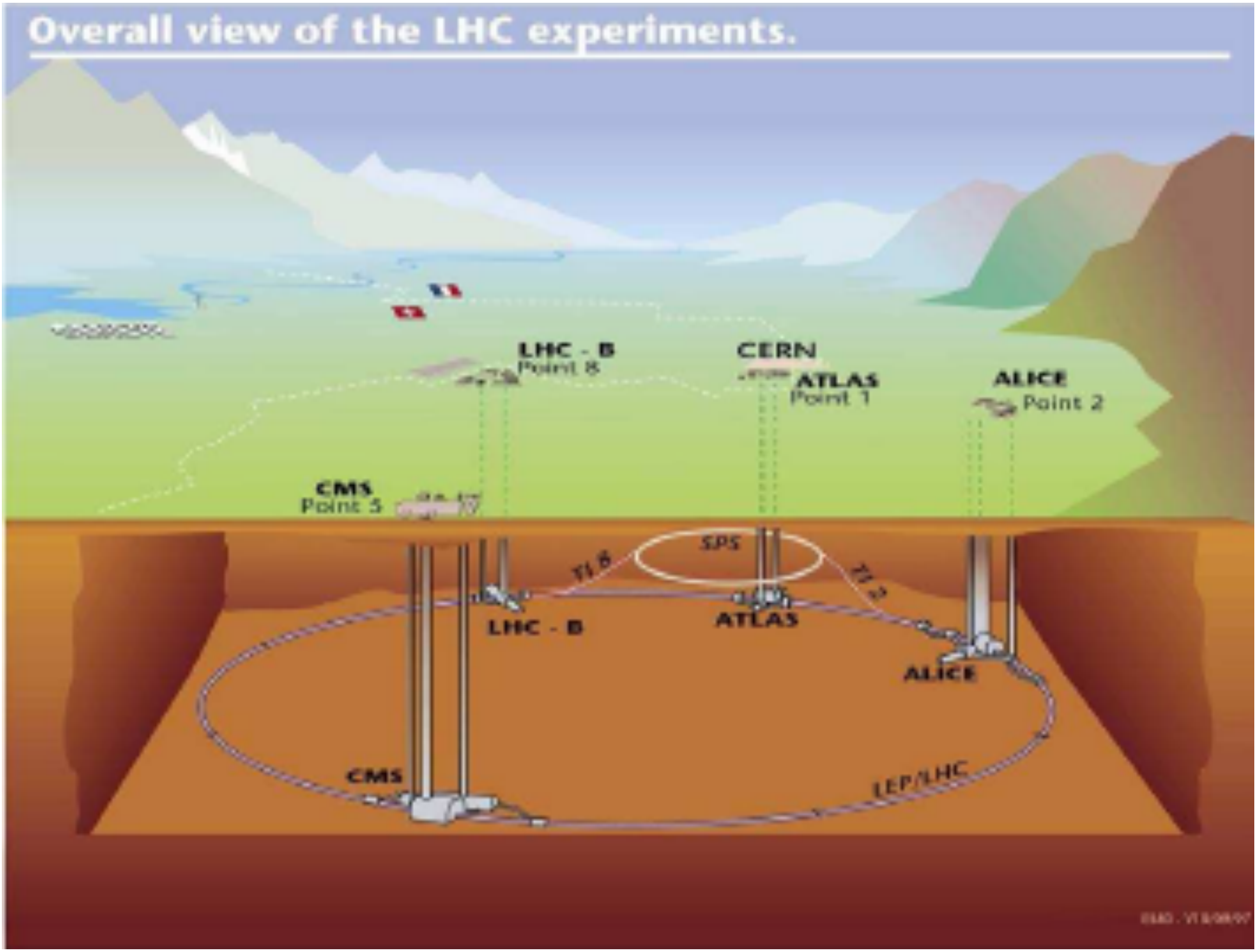
Lecture 1

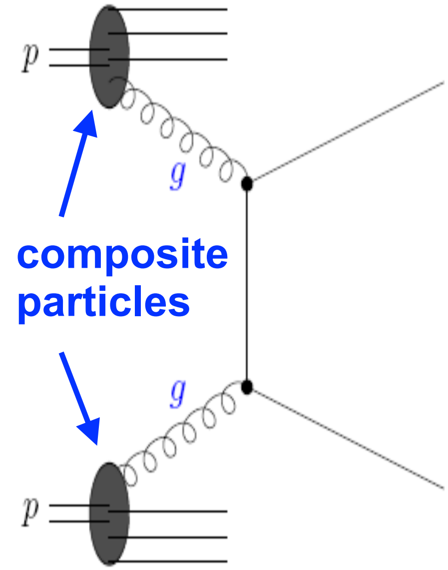
'Big' questions …and possible answers

- **Shortcomings of the Standard Model**
  - •Establish electroweak symmetry breaking — LC
  - •Hierarchy problem? — LHC, LC
  - •Unification of all interactions? — LC
  - •Embedding of gravity in field theory? — cosmo,LHC, LC
  - •Baryon asymmetry in Universe? — ν-, cosmo, LHC, LC
  - •Content of dark matter — ν-, cosmo, LHC, LC
  - •Neutrino mixing and masses — ν-, cosmo-exp.
- **Goal of a Linear Collider?**

  ➢ ***observe, determine and precisely reveal the structure of the underlying physics model !***

Large Hadron Collider: proton-proton

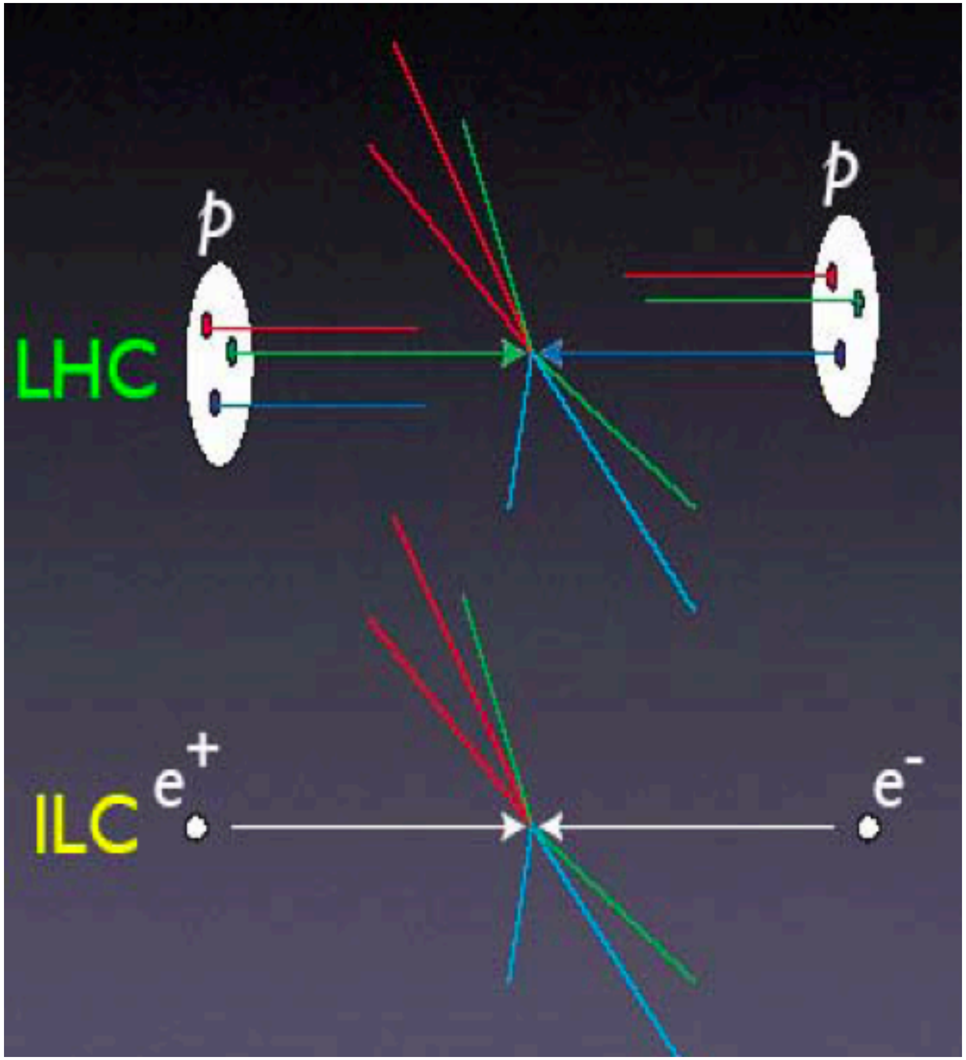


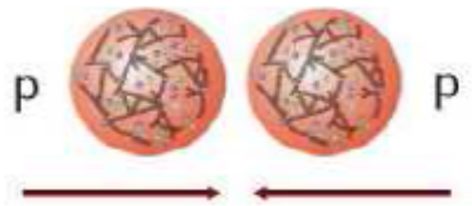


- **LHC: 27 km ring = former LEP, e+e-**

e^+e^- versus pp

- Simple particles
- Well defined:
  energy, angular mom.
- E can be tuned precisely
- Particles produced ~ democratically
- Final states generally fully reconstructable





Characteristics of pp collider

composite particles collide

E(CM) < 2 E(beam)

strong interaction in initial state

superposition with spectator jets

LHC: $\sqrt{s}$ = 14TeV,

used $\hat{s} = x_1 x_2 s$ few TeV

small fraction of events analyzed

multiple triggers

`no' polarization applicable

Large potential for direct discovery

and of the e +e-(γe, γ γ) collider

Pointlike particles collide

E(CM) = 2 E(beam)

well defined initial state

clean final state

ILC: $\sqrt{s}$ = 250 GeV -- 1 TeV, GigaZ

most events in detector analyzed

no triggers required

polarized initial beams possible

Large potential for discovery via high precision

Required features

⇨ In order to reveal the structure of the underlying (new) physics:

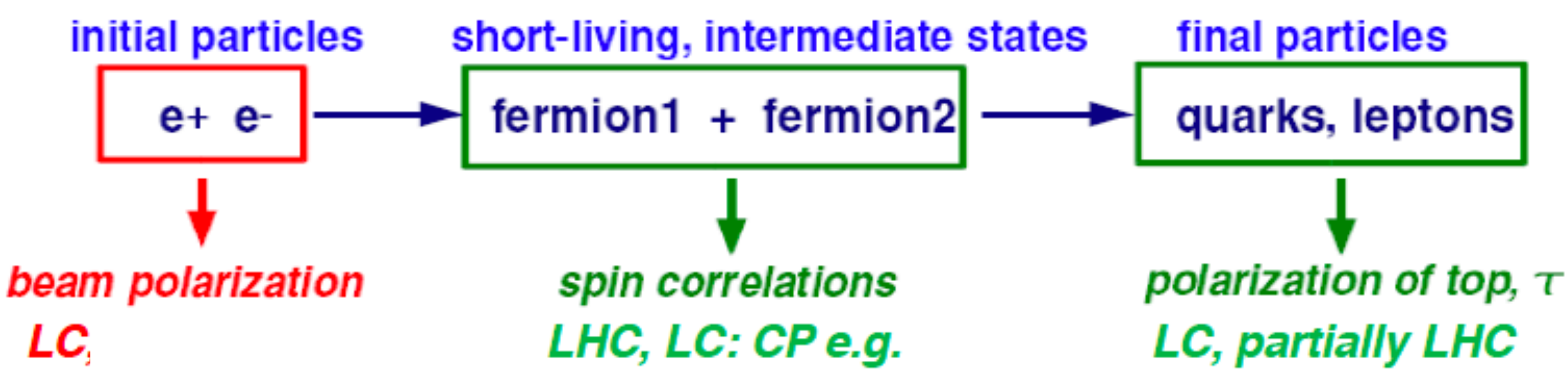
- ⋆ high energy desirable to reach the scale of new physics
- ⋆ high luminosity needed to get sufficient statistics
- ⋆ high level of experimental flexibility needed
- ⋆ high precision measurements needed to get access to the quantum structure

→ *need to be prepared for the unexpected !*

⇨ Spin and polarization physics is important

→ access to quantum properties, structure of couplings, etc.

⇨ How to exploit spin effects in particle reactions?

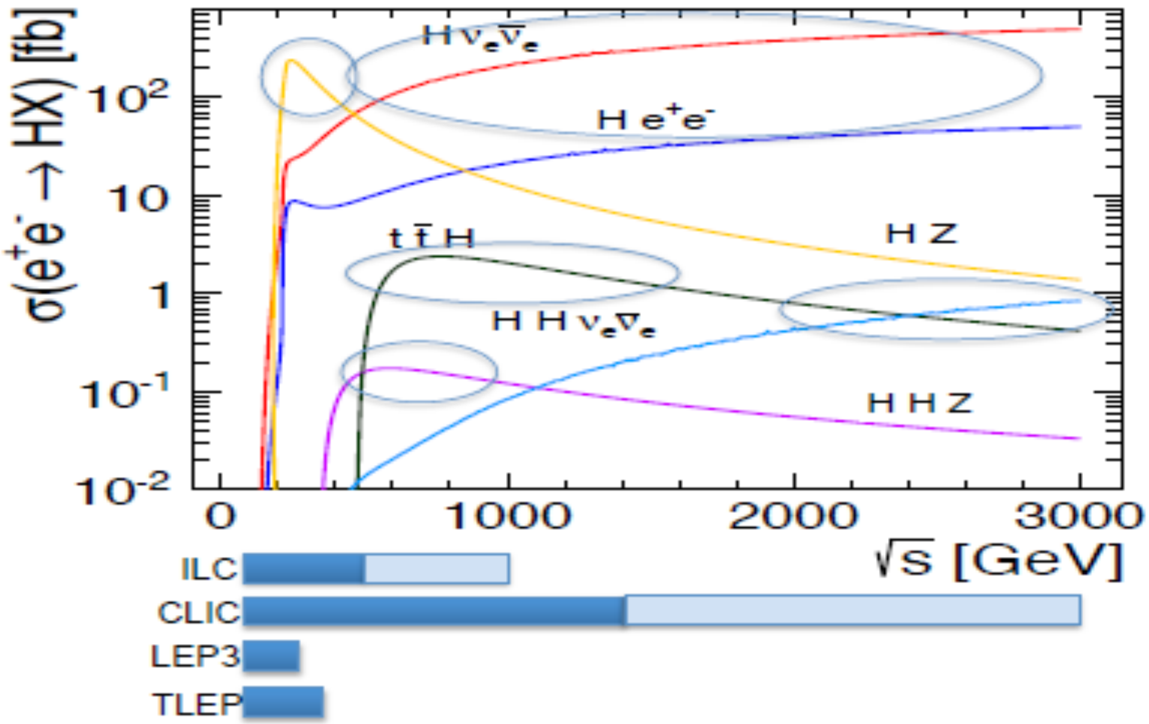


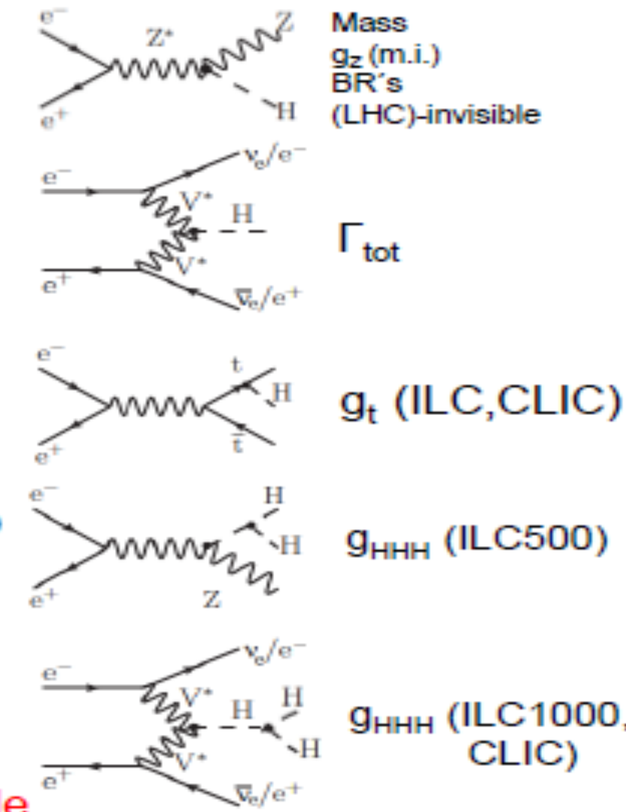
Technical features at a LC

- High luminosity envisaged
- Clean experimental environment
  - low beamstrahlung, stable energy
- Excellent detector resolution
  - Clean b, c tagging (even charge)
  - τ- polarization
  - Large angle covering
- Threshold scans applicable
  - Optimized by precise measurement in continuum
- Polarization of both beams possible
  - Fixing of initial state → revealing of interaction character

Higgs @ LC

Many processes at different √s needed & accessible

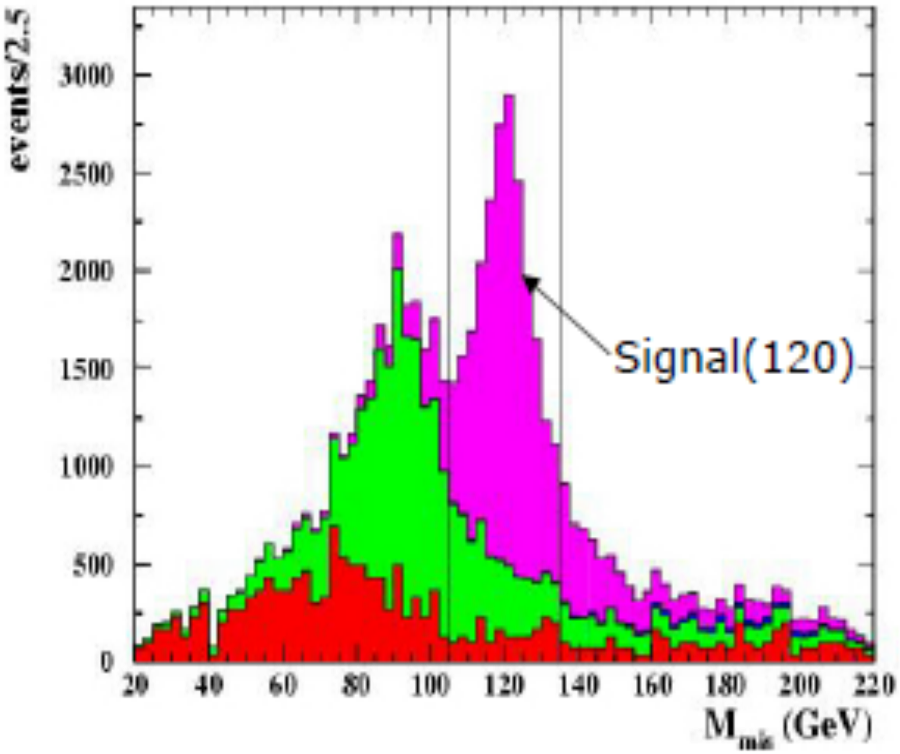


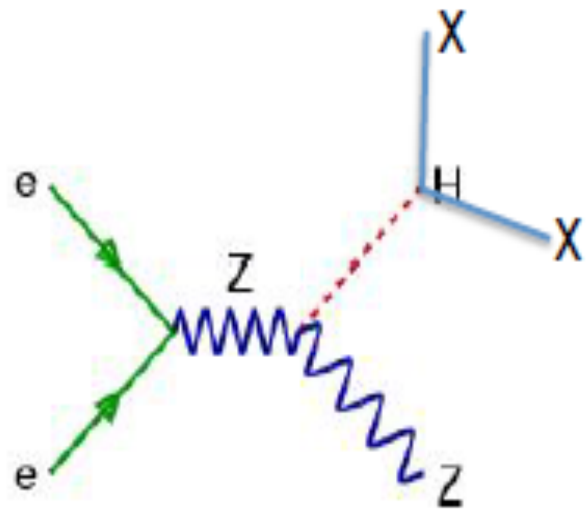


- Many processes at different √s needed & accessible

The Linear Collider is crucial in this regard!

Unique sensitivity at a LC: H⟶ invisible





➢***Recoil method: Unique potential of the LC***

- ***Only measure Z production and decay***
- ***Precise initial state: Higgs reconstruction independ. of decay***

Unique sensitivity at a LC: H$\rightarrow$invisible

- **Dark matter: sizeable deviation to SM predictions possible, even if couplings to gauge bosons and SM fermions are very close to SM**
  - If dark matter consists of one or more particles with a mass below ~63 GeV, then the decay of the state at 125 GeV into a dark matter pair is kinematically open!

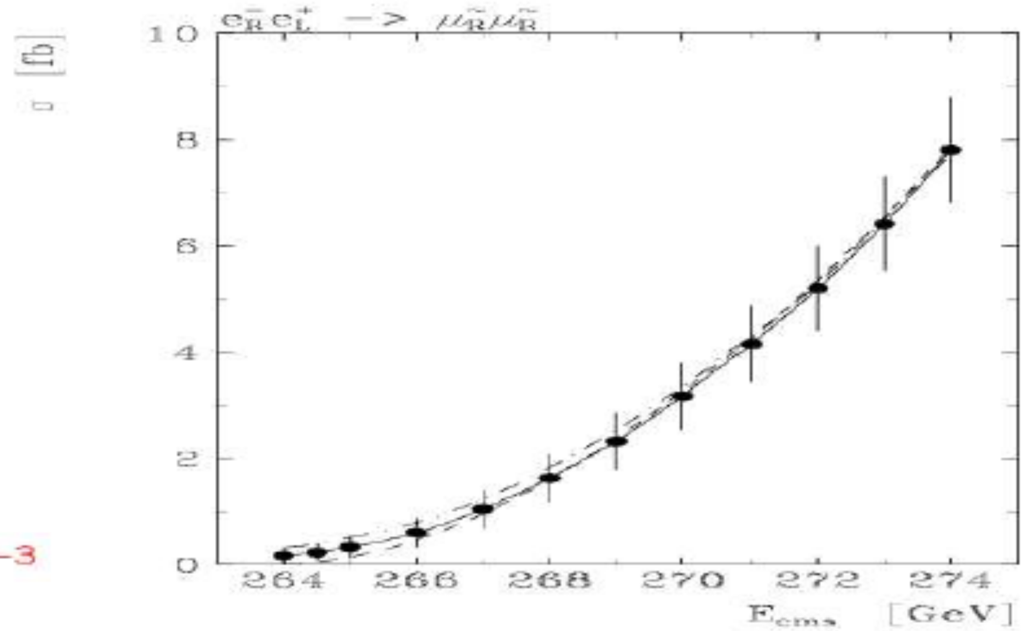
- **Crucial: detection of an invisible decay mode of the 125 GeV-state could be manifestation of BSM physics**
  - Direct search for H$\rightarrow$ invisible
  - Suppression of all other branching ratios

➢ ***Unique potential: high precision recoil method !***

Thresholds: mass measurements at LC

- **Clean signatures, known initial state, tunable energy:**

Determination of mass and spin of $\tilde{\mu}_R$ from production at threshold:
[TESLA TDR '01]



$\Rightarrow \quad \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3}$

$\Rightarrow$ test of $J = 0$ hypothesis

- ***Allows excellent mass measurements !***

The LC offers and challenges

- Staged energy approach:
  - $\sqrt{s}$~240 GeV, `Higgs frontier'
  - $\sqrt{s}$~350 GeV, `Top threshold'
  - $\sqrt{s}$~500 GeV, `Top Yukawa' , 'Higgs potential'
  - ($\sqrt{s}$=91 GeV, `EW Precision frontier')
  - $\sqrt{s}$~1000 GeV, `Higgs potential'
- Polarized beams and threshold scans:
  - impact on 'quality' (and quantity)
  - Something 'new' comp. to LHC analyses
- **Highest precision measurements !**

Why are these features important?

Remember the past: physics gain of polarized beams

- **Past experience:**
  - **excellent e- polarization ~78% at SLC:**
  - **led to best single measurement of $\sin^2\theta = 0.23098 \pm 0.00026$ on basis of $L \sim 10^{30}\ cm^{-2}s^{-1}$ (~600000 Z's)**

- **Compare with results from unpolarized beams at LEP:**
  - **$\sin^2\theta = 0.23221 \pm 0.00029$ but with $L \sim 2x10^{31} cm^{-2}s^{-1}$ (~ 17 million Z's)**

➡ **Polarization essential for suppression of systematics**

➡ **can even compensate order of magnitude in luminosity for specific observables!**

Beam polarization at HEP colliders

- *Polarization* = ensemble of particles with definite helicity λ = -½ left- or +½ right-handed :

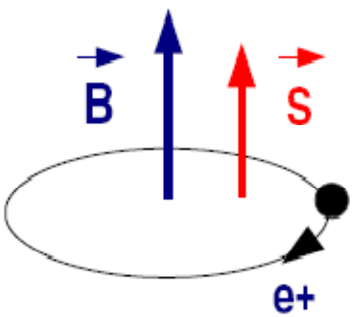
$$\mathcal{P} = \frac{\#N_R - \#N_L}{\#N_R + \#N_L}$$

→ beam polarization gives access to the couplings and unravels the structure of interactions

Polarized beams at circular e^-e^+ colliders:

- Polarization of both beams via Sokolov-Ternov effect

  (= spin-flip effect due to synchrotron radiation)



- At LEP (e+e-): massive depolarization effects; low polarization; not used for physics
- At HERA (ep): excellent e^- / e^+ polarization reached, ~50%-70%; spin rotators used to produce longitudinally polarized beams for physics studies

Polarization basis

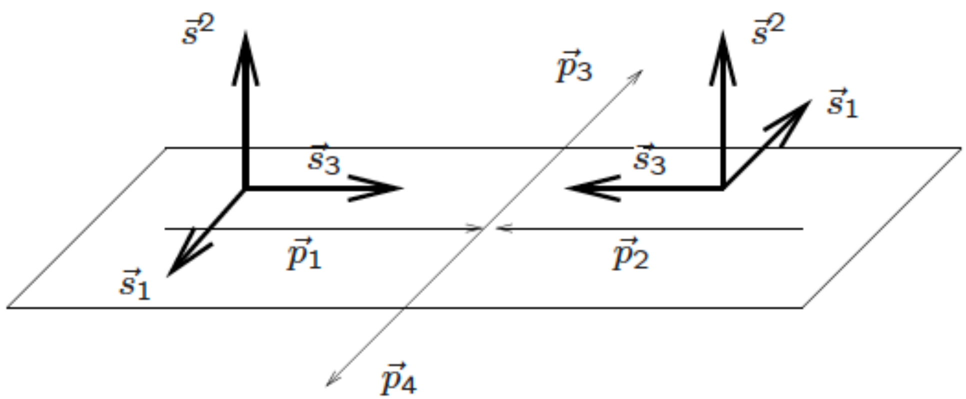
- Formalism: Use e.g. helicity spinors $u(p,\lambda)$, $v(p,\lambda)$ $\rightarrow$ density matrix
- Definition: Basis of Spinvektors s^a, $a = 1,2,3$ with $(s^a p) = 0$:

  build 'right-hand-system' in the CMS of $e^-(p_1)e^+(p_2) \rightarrow X(p_3)Y(p_4)$

  longitudinal Spinvektors: $s^{3\mu}(p_{1,2}) := \frac{1}{m_{1,2}}(|\vec{p_{1,2}}|, E\hat{p}_{1,2})$

  transverse Spinvektors: $s^{2\mu}(p_1) := (0, \vec{p}_1 \times \vec{p}_3)$, $\quad s^{2\mu}(p_2) = s^{2\mu}(p_1)$

  $s^{1\mu}(p_1) := (0, \vec{p}_1 \times \vec{s}^2(p_1))$, $s^{1\mu}(p_2) = -s^{1\mu}(p_1)$



- Definition: 'left-handed' and 'right-handed' $\equiv$ with respect to $\hat{p}$

  If Spinvektor $\vec{s}^3 = \begin{pmatrix} \text{parallel } \vec{p} \\ \text{antiparallel } \vec{p} \end{pmatrix} \equiv \begin{pmatrix} \text{'right-handed': } P>0 \\ \text{'left-handed': } P<0 \end{pmatrix}$

- ***Polarization* = ensemble of particles with definite helicity λ = -½ left- or +½ right-handed :**

$$\mathcal{P} = \frac{\#N_R - \#N_L}{\#N_R + \#N_L}$$

Physics: pol.cross sections in general

Polarized cross sections can be subdivided in:

$$\sigma_{P_{e^-}P_{e^+}} = \frac{1}{4}\{(1+P_{e^-})(1+P_{e^+})\sigma_{\rm RR} + (1-P_{e^-})(1-P_{e^+})\sigma_{\rm LL} + (1+P_{e^-})(1-P_{e^+})\sigma_{\rm RL} + (1-P_{e^-})(1+P_{e^+})\sigma_{\rm LR}\},$$

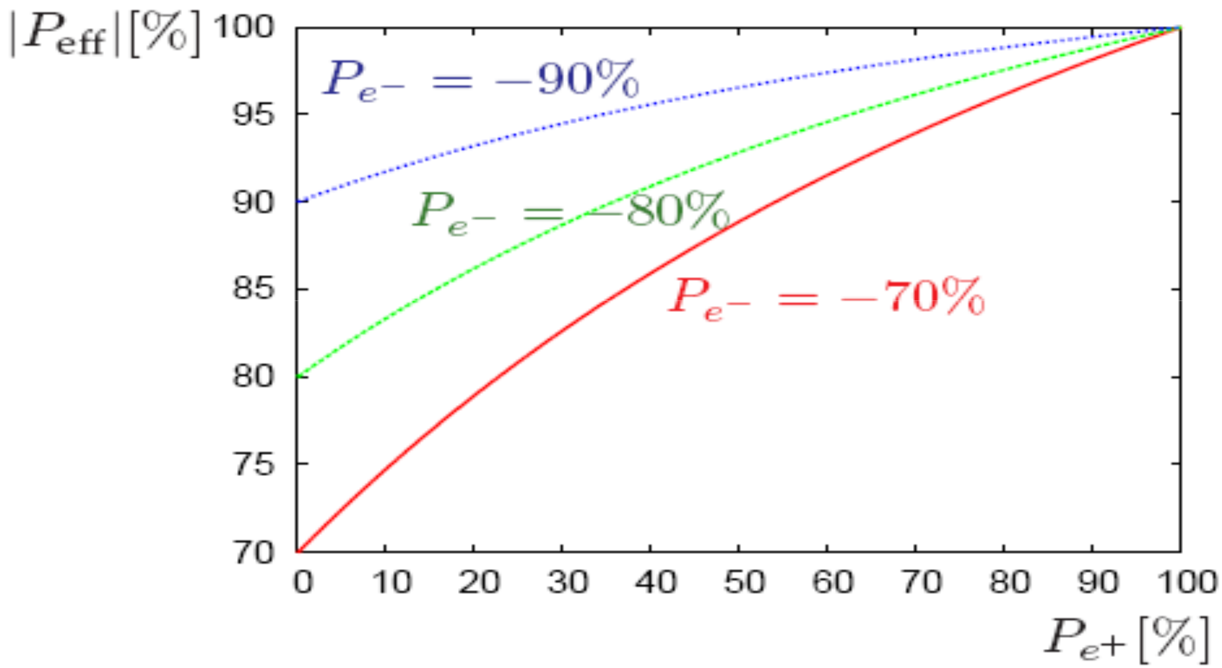
σ_{RR}, σ_{LL}, σ_{RL}, σ_{LR} are contributions with fully polarized L, R beams.

In case of a vector particle only (LR) and (RL) configurations contribute:

$$\begin{aligned}\sigma_{P_{e^-}P_{e^+}} &= \frac{1+P_{e^-}}{2}\frac{1-P_{e^+}}{2}\sigma_{\rm RL} + \frac{1-P_{e^-}}{2}\frac{1+P_{e^+}}{2}\sigma_{\rm LR} \\ &= (1-P_{e^-}P_{e^+})\frac{\sigma_{\rm RL}+\sigma_{\rm LR}}{4}\left[1 - \frac{P_{e^-}-P_{e^+}}{1-P_{e^+}P_{e^-}}\frac{\sigma_{\rm LR}-\sigma_{\rm RL}}{\sigma_{\rm LR}+\sigma_{\rm RL}}\right] \\ &= (1-P_{e^+}P_{e^-})\,\sigma_0\,[1 - P_{\rm eff}A_{\rm LR}],\end{aligned}$$

Effective polarization

Effective polarization: $$P_{\text{eff}} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^+} P_{e^-}}$$



- (80%,60): P_{eff} = 95%   (90%,60%): P_{eff} =97%   (90%, 30%): P_{eff} =94 %

Relation between P_{eff} and A_{LR}

- **How are P_{eff} and A_{LR} related?**

$$A_{\rm LR} = \frac{1}{P_{\rm eff}} A_{LR}^{\rm obs} = \frac{1}{P_{\rm eff}} \frac{\sigma_{-+} - \sigma_{+-}}{\sigma_{-+} + \sigma_{+-}},$$

That means:

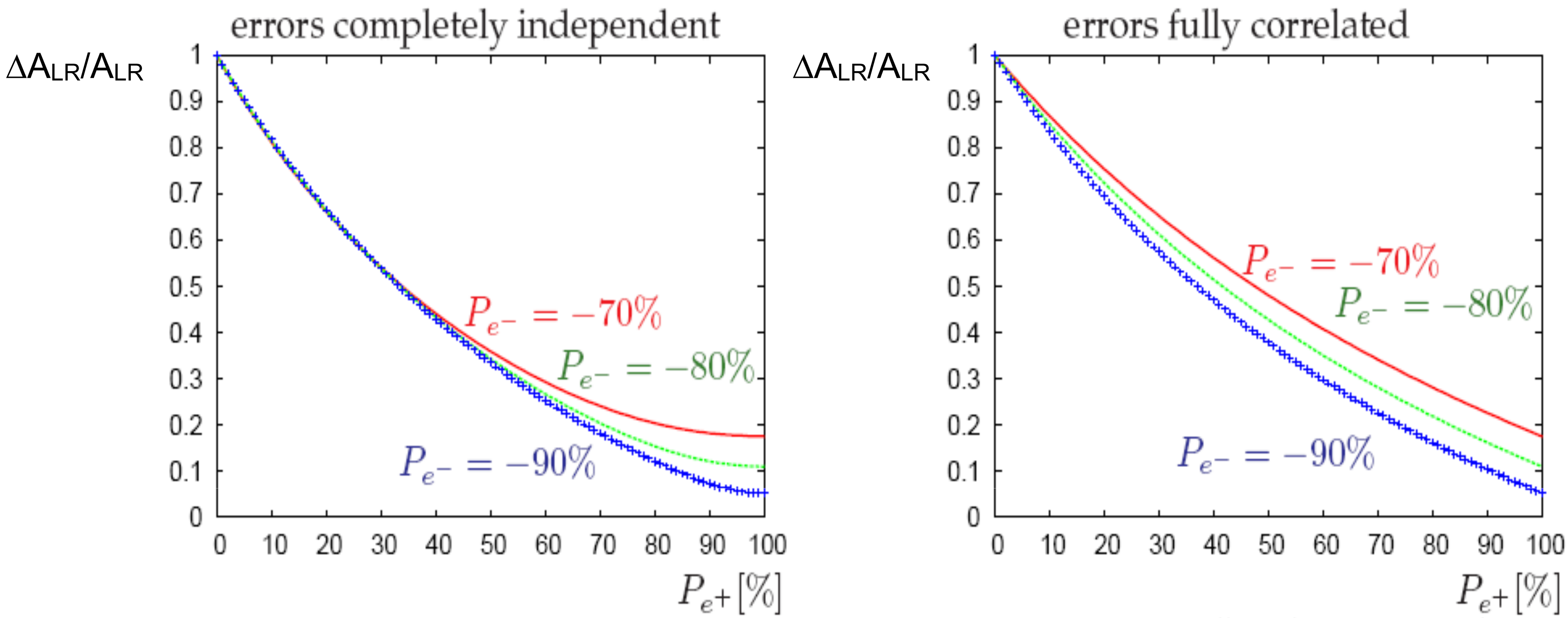
$$\left|\frac{\Delta A_{\rm LR}}{A_{\rm LR}}\right| = \left|\frac{\Delta P_{\rm eff}}{P_{\rm eff}}\right|$$

- **With pure error propagation (and errors uncorrelated), one obtains:**

$$\frac{\Delta P_{\rm eff}}{P_{\rm eff}} = \frac{x}{(|P_{e^+}| + |P_{e^-}|)\,(1 + |P_{e^+}||P_{e^-}|)} \sqrt{(1 - |P_{e^-}|^2)^2 P_{e^+}^2 + (1 - |P_{e^+}|^2)^2 P_{e^-}^2}$$

With $x \equiv \Delta P_{e^-}/P_{e^-} = \Delta P_{e^+}/P_{e^+}$

Gain in accuracy due to P(e+)



- (80%,60): P_{eff} = 95%   (90%,60%): P_{eff} =97%   (90%, 30%): P_{eff} =94 %

  $\Delta A_{LR}/A_{LR}$ = 0.3 $\Delta A_{LR}/A_{LR}$ = 0.27 $\Delta A_{LR}/A_{LR}$ =0.5

gain: factor~3   factor>3   factor~2

→ **NO gain with only polarized e^- !**

Polarization basics

- **Longitudinal polarization:** $\mathcal{P} = \frac{N_R - N_L}{N_R + N_L}$

- **Cross section:**

$$\sigma(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = \frac{1}{4}\{(1+\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+})\sigma_{\rm RR} + (1-\mathcal{P}_{e^-})(1-\mathcal{P}_{e^+})\sigma_{\rm LL} + (1+\mathcal{P}_{e^-})(1-\mathcal{P}_{e^+})\sigma_{\rm RL} + (1-\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+})\sigma_{\rm LR}\}$$

- **Unpolarized cross section:**

$$\sigma_0 = \frac{1}{4}\{\sigma_{\rm RR} + \sigma_{\rm LL} + \sigma_{\rm RL} + \sigma_{\rm LR}\}$$

- **Left-right asymmetry:** $A_{\rm LR} = \frac{(\sigma_{\rm LR} - \sigma_{\rm RL})}{(\sigma_{\rm LR} + \sigma_{\rm RL})}$

- **Effective polarization and luminosity:**

$$\mathcal{P}_{\rm eff} = \frac{\mathcal{P}_{e^-} - \mathcal{P}_{e^+}}{1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+}} \qquad \mathcal{L}_{\rm eff} = \frac{1}{2}(1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+})\mathcal{L}$$

Polarization basics

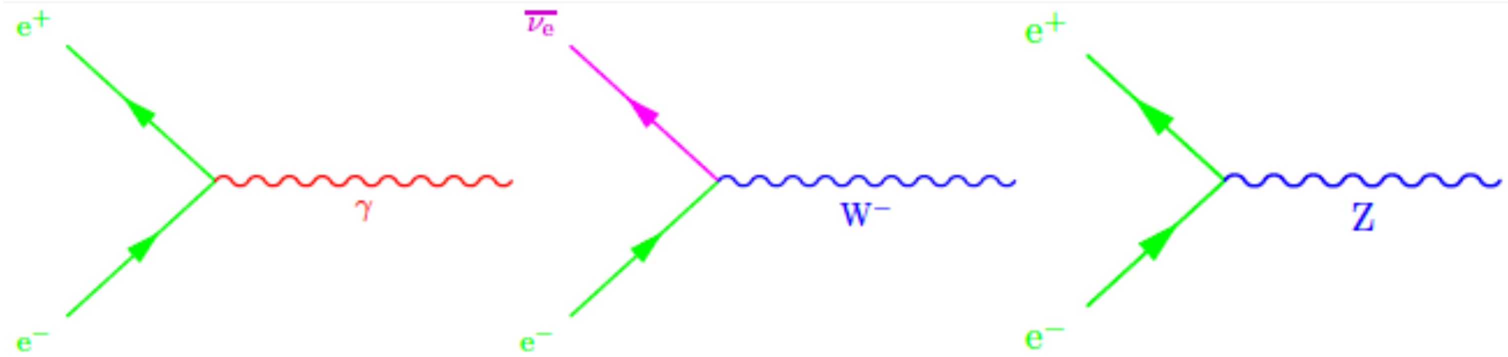
- **Applicable for V,A processes (most SM, some BSM)**

$$\sigma\ (Pe-,Pe+)=(1-Pe-\ Pe+)\ \sigma_{unpol}\ [1-P_{eff}\ A_{LR}]$$

- **With both beams polarized we gain in**
  - **Higher effective polarization (higher effect of polarization)**
  - **Higher effective luminosity (higher fraction of collisions)**

$\sqrt{s}$	$P(e^-)$	$P(e^+)$	P_{eff}	$\mathcal{L}_{eff}/L$	$\frac{1}{x}\Delta P_{eff}/P_{eff}$
total range	$\mp 80\%$	0%	$\mp 80\%$	0.5	1
250 GeV	$\mp 80\%$	$\pm 40\%$	$\mp 91\%$	0.65	0.43
$\geq$350 GeV	$\mp 80\%$	$\pm 55\%$	$\mp 94\%$	0.7	0.30

SM Vertices



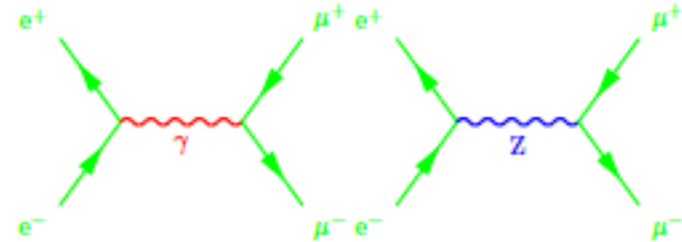
QED: parity conserved, A=0

Charged currents: A=1
Parity violating
only left-handed e^- couple

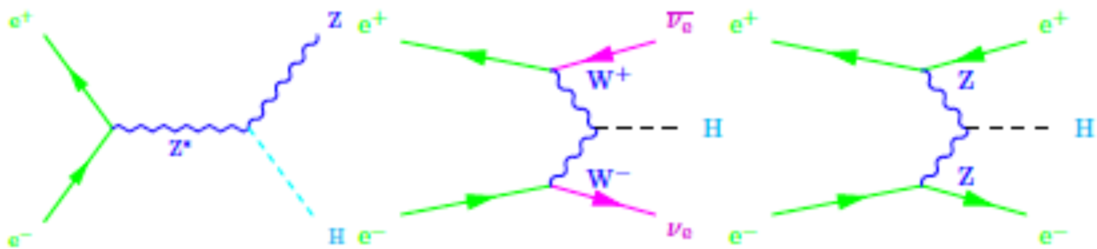
Neutral currents: A=0.15
Parity violating
left-handed e^-, right-handed e^+

SM Processes

2 Fermion: LR, RL

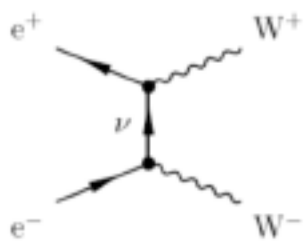


Higgs: LR, RL

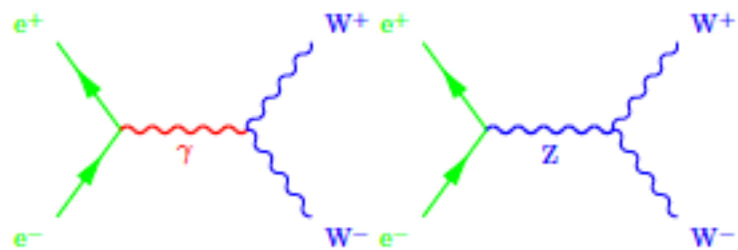


W-production:

only LR:

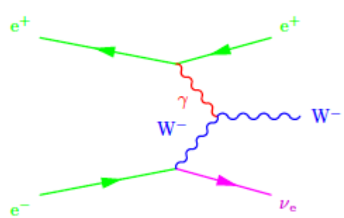


LR, RL:



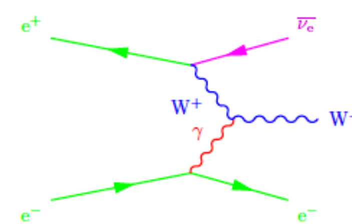
Single W^-:

only LR and LL:



Single W^+:

only LR and RR:



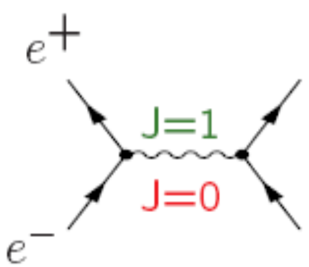
$P(e^{\pm})$ sensitive to interaction structure

Definition: Helicity $\lambda = \vec{s} * \vec{p}/|\vec{p}|$ 'projection of spin'

Chirality = handedness is equal to helicity only of m=0!

Def.: left-handed $\equiv P(e^{\pm}) < 0$ right-handed $\equiv P(e^{\pm}) > 0$

- **Annihilation channel:**



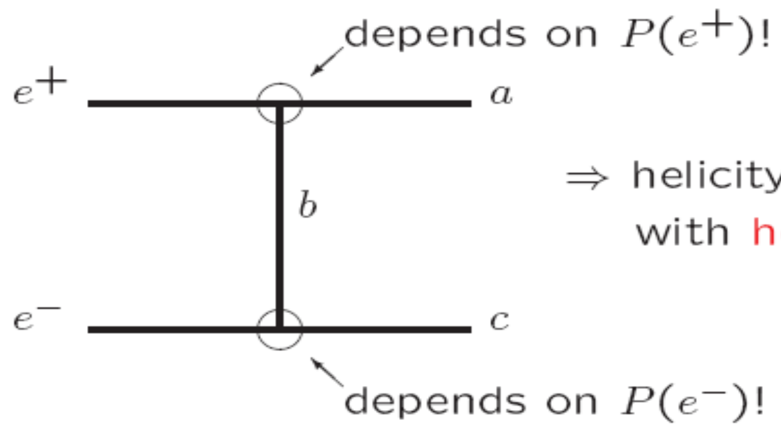
← only from RL,LR: SM (γ, Z)

← only from LL,RR: NP!

⇒ In principle: $P(e^-)$ fixes also helicity of e^+!

Complete fixing of initial state via $P(e^+)$

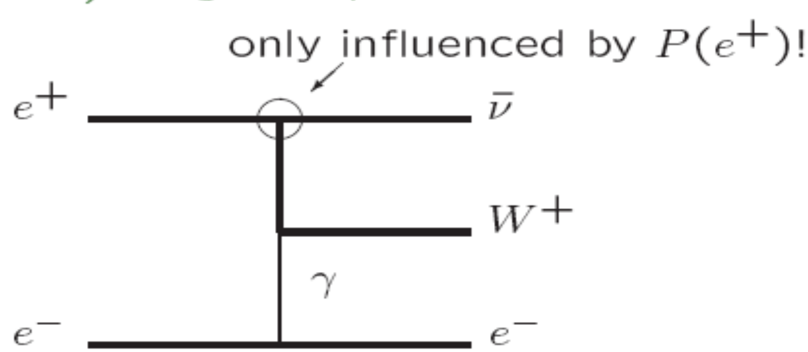
- **Scattering channel: direct access to chirality of final state !**



$\Rightarrow$ helicity of e^- not coupled with helicity of e^+!

Two examples from SM processes

a) Single W production



b) Bhabha scattering

$\Rightarrow$ γ, Z exchange in s–channel: selects LR, RL

$\Rightarrow$ γ, Z exchange in t–channel: LL,RR possible!

unpolarised	4.50 pb
$P_{e^-} = -80\%$	4.63 pb
$P_{e^-} = -80\%$, $P_{e^+} = -60\%$	4.69 pb
$P_{e^-} = -80\%$, $P_{e^+} = +60\%$	4.58 pb

L_{eff} and P_{eff}

- More concrete: If only LR and RL contributions: only 50 % of collisions useful

effective luminosity: $L_{eff}/L = \frac{1}{2}(1 - P_{e-}P_{e+})$

This quantity = the effective number of collisions, can only be changed with P_{e-} and P_{e+}:

here:

With $\mp 80\%$, $\pm 30\%$, the increase is 24% — P_{eff}~89%

With $\mp 80\%$, $\pm 60\%$, the increase is 48%

With $\mp 90\%$, $\pm 60\%$, the increase is 54%

In other words: *no P_{e+} means 24% more running time (!)*

and

10% loss in P_{eff} ≙ 10% loss in analyzing power!

Quite substantial in Higgsstrahlung and electroweak 2f production !

- allows model-independent access!
- Absolute measurement of Higgs cross section σ(HZ) and g_{HZZ}: crucial input for all further Higgs measurement!
- Allows access to H-> invisible/exotic
- Allows with measurement of Γ^h_{tot} absolute measurement of BRs!

L_{eff} and P_{eff}: further example

- Charged currents, i.e. t-channel W- or ν-exchange (A_{LR}=1):

$$\sigma(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = 2\sigma_0(\mathcal{L}_{\rm eff}/\mathcal{L})[1 - \mathcal{P}_{\rm eff}]$$

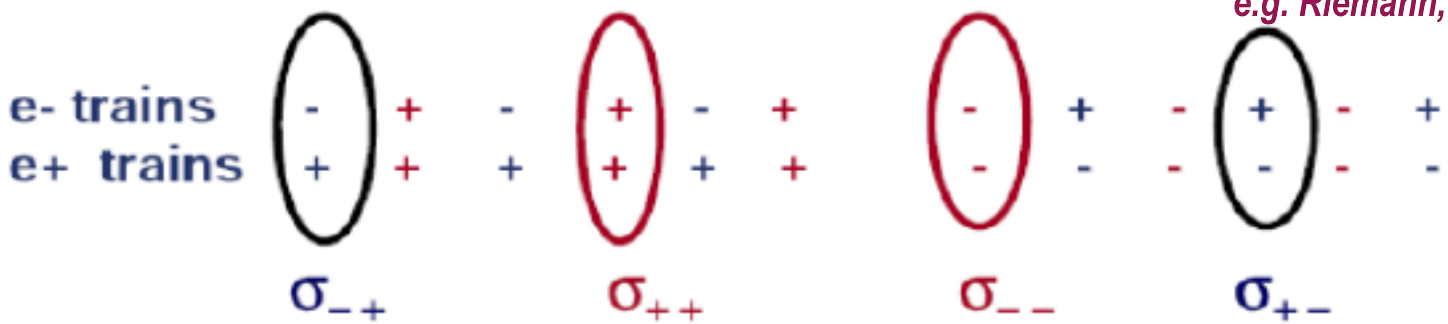
In other words: *no P_{e+} means 30% more running time needed !*

Quite substantial in Higgs production via WW-fusion!

Technical remark: why is helicity flipping required?

- **Gain in effective lumi lost if no flipping available**

e.g. Riemann, S et al.



  - **50% spent to 'inefficient' helicity pairing (most SM, BSM)**
  - **Similar flip frequency for both beams ~ pulse-per-pulse**
- **Gain in ΔP_{eff} remains, but flipping required to understand:**
  - **Systematics and correlations P_{e-} x P_{e+}**

e.g. Malysheva,L et al.

- **Spin rotator before DR and spinflipper has been set-up!**

Statistics Suppression of WW and ZZ production

WW, ZZ production = large background for NP searches!

W^- couples only left–handed:
$\rightarrow$ WW background strongly suppressed with right polarized beams!

Scaling factor= $\sigma^{pol}/\sigma^{unpol}$ for WW and ZZ:

$P_{e^-} = \mp 80\%$, $P_{e^+} = \pm 60\%$	$e^+e^- \rightarrow W^+W^-$	$e^+e^- \rightarrow ZZ$
$(+0)$	0.2	0.76
(-0)	1.8	1.25
$(+-)$	0.1	1.05
$(-+)$	2.85	1.91

'No lose theorem':
scaling factors for
signals&background

	S	B	S/B	$S/\sqrt{B}$
Example 1	$\times 2$	$\times 0.5$	$\times 4$	$\times 2\sqrt{2}$
Example 2	$\times 2$	$\times 2$	Unchanged	$\times\sqrt{2}$

(Some) benefits of simultaneous e^+ polarization

- **Better Statistics: Less running time/operation cost for same physics**
  - higher rates,
  - lower background,
  - higher analyzing power for chosen channels

- **Lower Systematics**
  - key role for reduction of systematics originating from polarization measurement

- **More Observables**
  - Four distinct data-sets: opposite-site polarization collisions plus like-sign configuration

$\longrightarrow$ unique feature of ILC (including transversely but also unpolarized configurations!)

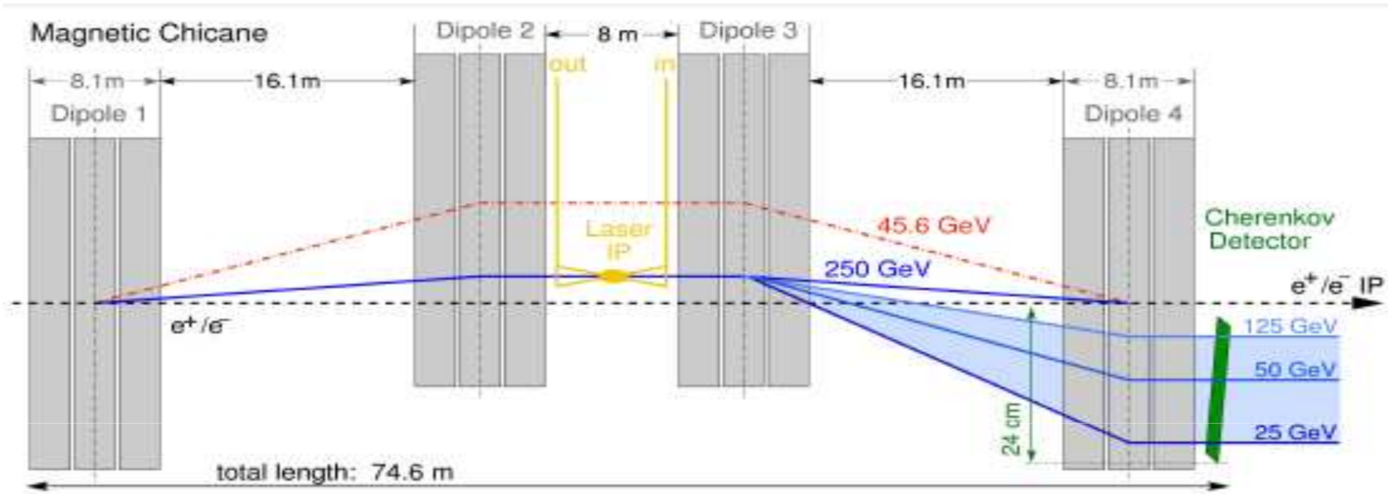
Polarimetry requirements

- **SLC experience: measured ΔP/P=0.5%**
  - **Compton scattered e- measured in magnetic spectrometer**
- **Goal at ILC: measure ΔP/P≤0.25%**
  - **Dedicated Compton polarimeters and Cherenkov detectors**
  - **Use upstream and downstream polarimeters**
    - ➢ **Machine feedback and access to luminosity-weighted polarization**

  - **Use also annihilation data: `average polarization'**
    - ➢ **Longterm absolute calibration scale, up to ΔP/P=0.1%**

Compton polarimetry at ILC

- **Upstream polarimeter: use chicane system**



  - **Can measure individual e± bunches**
  - **Prototype Cherenkov detector tested at ELSA!**
- **Downstream polarimeter: crossing angle required**
  - **Lumi-weighted polarization (via w/o collision)**
  - **Spin-tracking simulations required**

Polarization measurement

- **Compton polarimeters: up- and downstream**
  - envisaged uncertainties of ΔP/P=0.25% (at polarimeters!)
  - But that's is not enough for IP!
- **Use collision data to derive luminosity-weighted polarization**
  - single W, WW, ZZ, Z, etc.: combined fit

$$P^-_{e^\pm} = -|P_{e^\pm}| + \tfrac{1}{2}\delta_{e^\pm} \qquad P^+_{e^\pm} = \ |P_{e^\pm}| + \tfrac{1}{2}\delta_{e^\pm}$$

e.g. Karl, List et al.

  - helicity reversal is important
  - non-perfect helicity-reversal can be compensated
  - 0.1% accuracy in ΔP/P is achievable at IP!
  - *NOT achievable without Pe+!*

Remember: even if no Pe+ (SLC! dedicated experiment at SLACs Endstation A), the P_{e+}~0.0007 had to be derived a posteriori for physics reason!

EW precision measurements@Z-factory

- **GigaZ option at the ILC:**
  - high-lumi running on Z-pole/WW
  - 10^9 Z in 50-100 days of running
  - Needs machine changes (e.g. bypass in the current outline)
- **Dedicated Z-factory:**
  - fraction of GigaZ
  - but strong physics case given already now!
- **Both facilities need polarized e^- and e^+ beams**
  - Use of Blondel scheme required to get $\Delta P/P \leq 0.1\%$
- **Measurement of e.g. $\sin^2\theta_W$ with unprecedented precision achievable!**

Gain in masurement of polarization

- **Important issue: measuring amount of polarization**
  - limiting systematic uncertainty for high statistics measurements
- **Compton polarimeters: up- and downstream**
  - envisaged uncertainties of $\Delta P/P=0.25\%$. Essential for monitoring, but need to correct wrt IP.
- **(Differential) Cross-section based in-situ measurements**
  - need some physics assumptions
  - often under assumption of perfect helicity reversal
- **Adding positron polarization helps in several ways:**
  - Providing additional measurements, improving limiting systematics
  - Enhancing effective polarization
  - ‘Allow’ in-situ measurements: ‘ultimate’ measurements, but require running time in same-sign configurations

Transversely polarized beams

Transversely polarized beams

➡ enables to exploit azimuthal asymmetries in fermion production !

- the process $e^+e^- \to W^+W^-$:
  $\Rightarrow$ azimuthal asymmetry projects out $W_L^+W_L^-$ *e.g. Fleischer et al,*
- the process e+e- ⟶ tt:
  ➡ probe leptoquark models *e.g. Rindani, Poulose, et al.*
- the process e+e- ⟶ ff:
  ➡ probe extra dimensions *e.g. Hewett, Rizzo et al.*

- the construction of CP violating oservables:
  $\Rightarrow$ matrix elements $|M|^2 \sim \mathcal{C} \times \Delta(\alpha)\Delta^*(\beta) \times \mathcal{S}$ ($\mathcal{C}$=coupl., Δ=prop., $\mathcal{S}$=momenta)

  if CP violation: contributions of $Im(\mathcal{C}) \times Im(\mathcal{S})$ (e.g. contributions of ϵ tensors!)

  $\Rightarrow$ azimuthal dependence ('not only in scattering plane')

  $\Rightarrow$ observables are e.g. asymmetries of CP-odd quantities: $\vec{p}_a(\vec{p}_b \times \vec{p}_c)$

  $\vec{s}^{2\mu} := \vec{p}_1 \times \vec{p}_3$ perpendicular scattering plane, CP even

  $\vec{s}^{1\mu} := \vec{p}_1 \times \vec{s}^2(p_1)$ transverse in plane, CP odd

In general: Interactions and Polarization

- **Different Interaction structures:**

S=scalar-, P=pseudoscalar-, V=vector-, A=axial-vector-, T=tensor- like interactions

Interaction structure		Longitudinal		Transverse		Longitudinal/Transverse
Γ_k	$\bar{\Gamma}_\ell$	Bilinear	Linear	Bilinear	Linear	Interference
S	S	$\sim P_{e^-} P_{e^+}$	–	$\sim P^T_{e^-} P^T_{e^+}$	–	–
S	P	–	$\sim P_{e^\pm}$	$\sim P^T_{e^-} P^T_{e^+}$	–	–
S	V,A	–	–	–	$\sim P^T_{e^\pm}$	$\sim P_{e^\pm} P^T_{e^\mp}$
S	T	$\sim P_{e^-} P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-} P^T_{e^+}$		–
P	P	$\sim P_{e^-} P_{e^+}$	–	$\sim P^T_{e^-} P^T_{e^+}$	–	–
P	V,A	$\sim P_{e^-} P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-} P^T_{e^+}$	$\sim P^T_{e^\pm}$	$\sim P_{e^\pm} P^T_{e^\mp}$
P	T	$\sim P_{e^-} P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-} P^T_{e^+}$		–
V,A	V,A	$\sim P_{e^-} P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-} P^T_{e^+}$	–	–
V,A	T	–	–	–	$\sim P^T_{e^\pm}$	$\sim P_{e^\pm} P^T_{e^\mp}$
T	T	$\sim P_{e^-} P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-} P^T_{e^+}$	–	–

‣ **dependence on polarization provides information on kind of interaction**

Be prepared for the 'Unexpected'…

- ➢ the LC +LHC are mandatory………!