Physics at the LHC
Lecture 15: LHC Upgrade and Future Accelerators

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Schedule of the LHC

A (very rough) schedule of the LHC could be

- 2010: Run at $\sqrt{s} = 7 - 10\,\text{TeV}$ with $\mathcal{L} = 0.2 - 1\ \text{fb}^{-1}/a$
- 2011–2014: Run at $\sqrt{s} = 14\,\text{TeV}$ with $\mathcal{L} \sim 10^{33}\text{cm}^{-2}\text{s}^{-1}$ corresponding to $\mathcal{L} \sim 10\ \text{fb}^{-1}/a$
- 2015–2017: Run at $\sqrt{s} = 14\,\text{TeV}$ with $\mathcal{L} \sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$ corresponding to $\mathcal{L} \sim 100\ \text{fb}^{-1}/a$

After that progress in statistical errors will be slow ($\Delta X \propto \sqrt{\mathcal{L}}$)

Possible upgrades:

- SLHC: increase luminosity
- DLHC: increase energy

SLHC

Peak luminosity of a collider:

$$\mathcal{L} = \frac{N_b^2 n_b f_r \gamma}{4\pi\sigma_x\sigma_y} F = \frac{N_b^2 n_b f_r \gamma}{4\pi\varepsilon_n\beta^*} F$$

N_b**:** number of particles per bunch

n_b**:** number of bunches in the machine

f_r**:** revolution frequency

ε_n**:** normalised emmitance

β^***:** beta value at the IP (focusing strength)

F**:** reduction factor due to crossing angle

Determined by:

N_b, ε_n**:** injection chain

β^***:** focusing magnets around experiment

F**:** beam separation scheme

n_b**:** electron cloud effect

First stage:

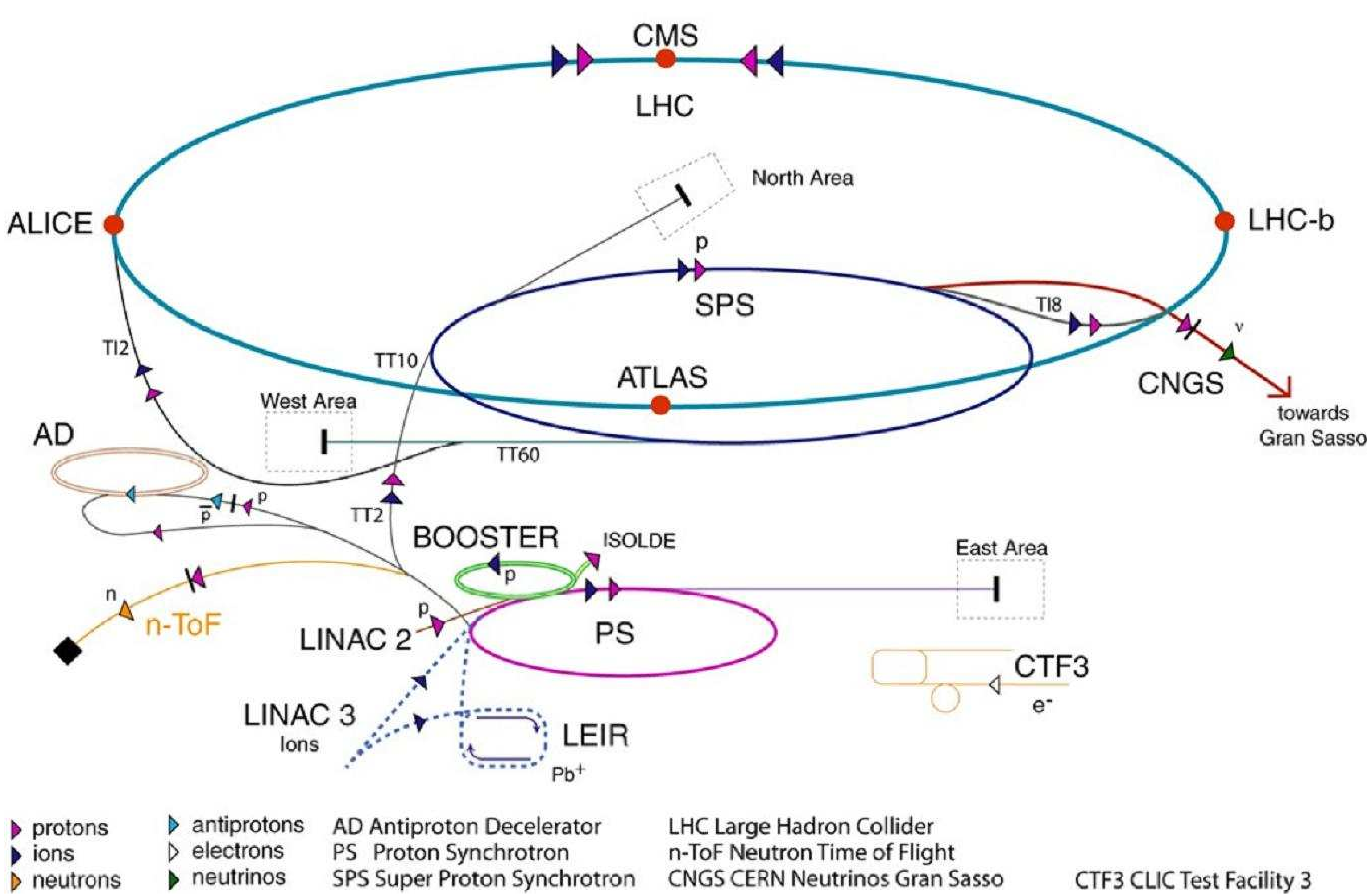
Replace final focusing magnets by stronger ones: $\Rightarrow \beta^* = 25\text{cm} \;\; \Rightarrow \mathcal{L} = 2 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$ factor 2

Second stage:

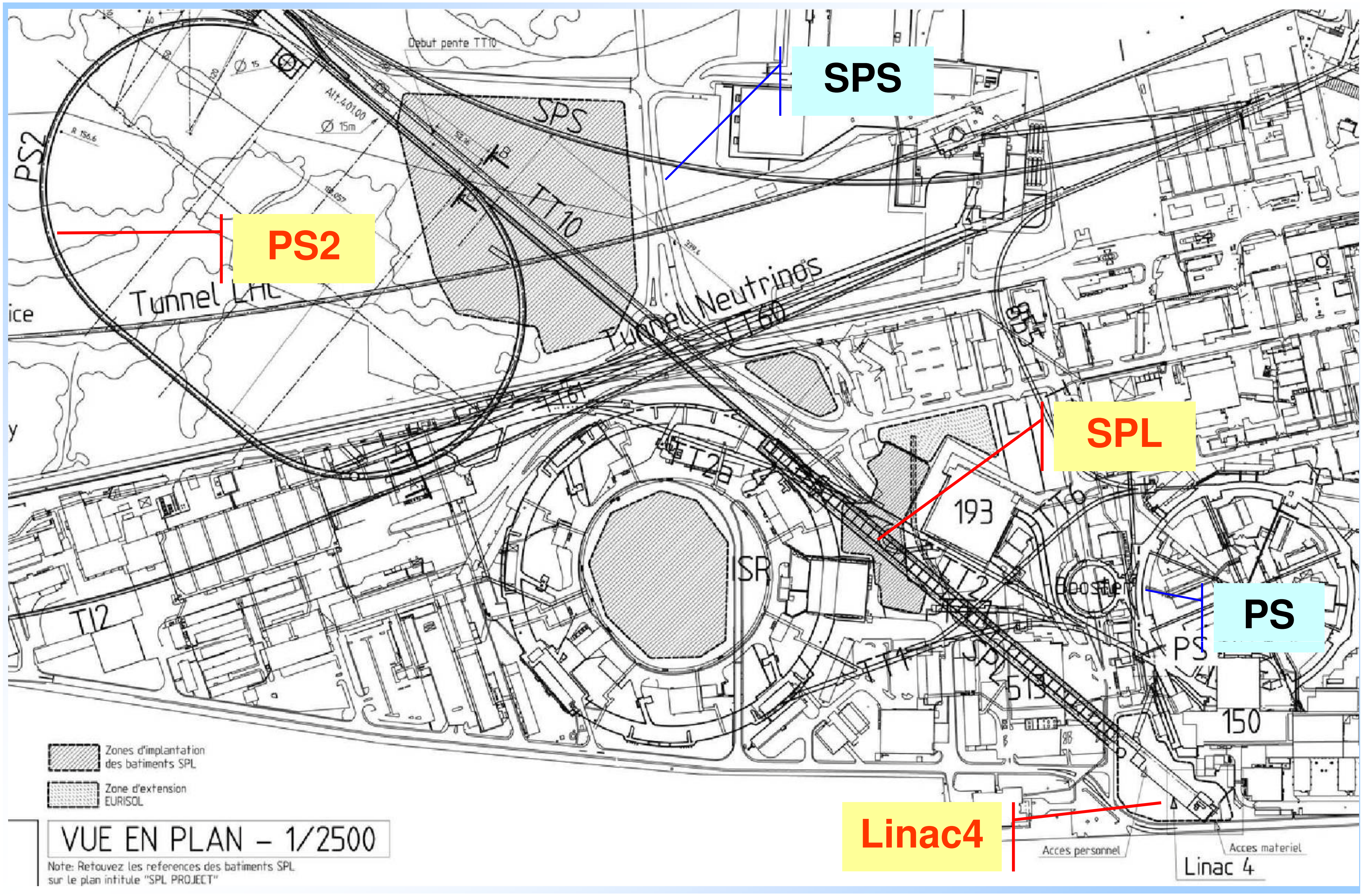
Improve N_b, ε_n by rebuilding part of the injection system:

- injection system is anyway old and partly unreliable (PS is 50 years)
- limit is space charge effects in booster and PS
- build new linacs to enter in PS with higher energy
- rebuild PS
- goal $\mathcal{L} = 10^{35}\text{cm}^{-2}\text{s}^{-1}$ by 2019

The CERN accelerator complex



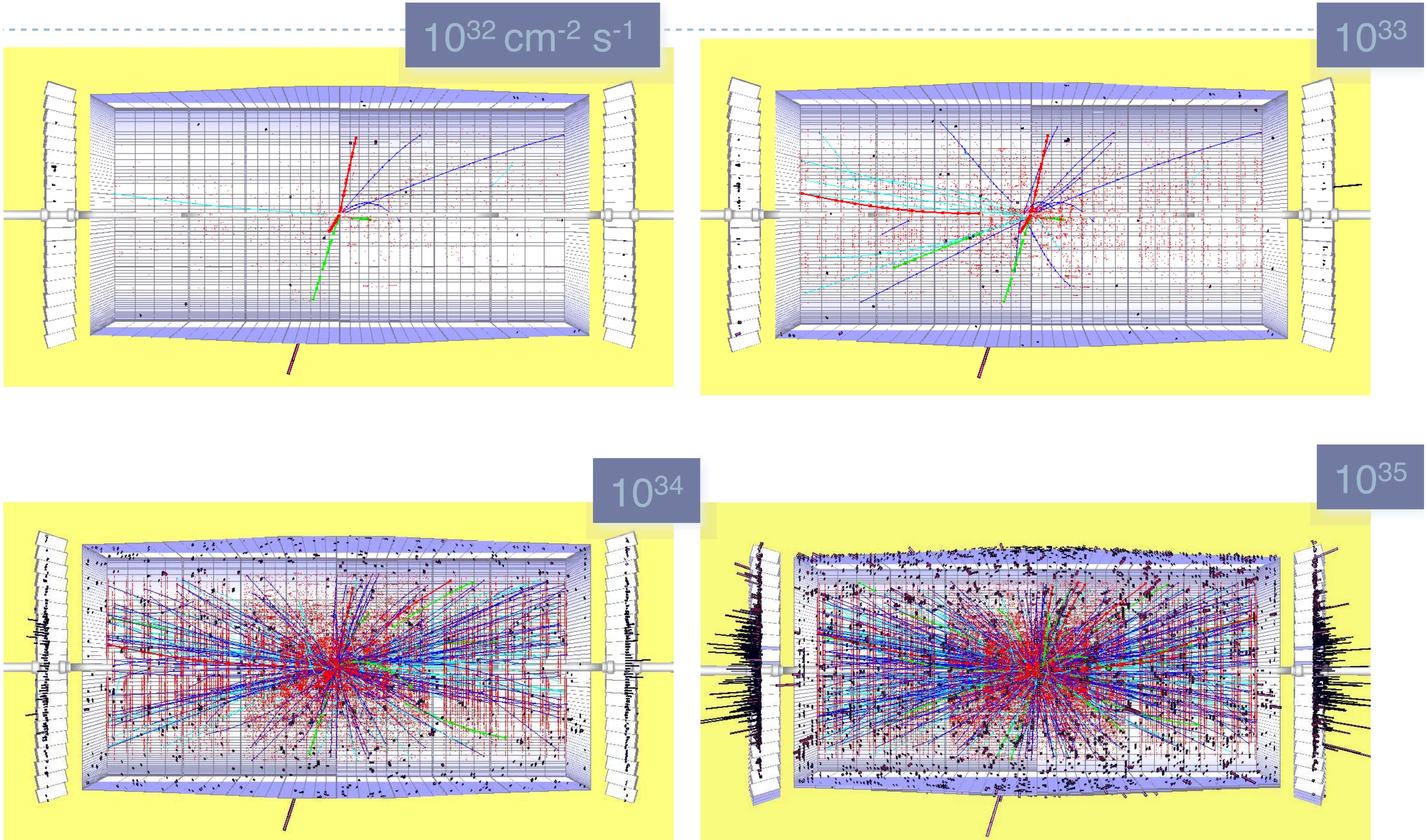
The upgraded a injector chain



Detectors for the SLHC

- The inner detectors will die from radiation
- The granularity needs to be increased to cope with 300 minimum bias events per bunch crossing
- This means finer pixels, more pixel layers, shorter strips, all silicon tracking
- Some trigger upgrades may be needed to cope with the higher rates
- The other detectors should be ok

Detector occupancy for different luminosities



DLHC

- Need to replace all magnets to increase the energy significantly
- Doubling the field or even more is only possible with new materials
- Magnet R&D has started
- In any case this will be very expensive

The physics case for SLHC and DLHC

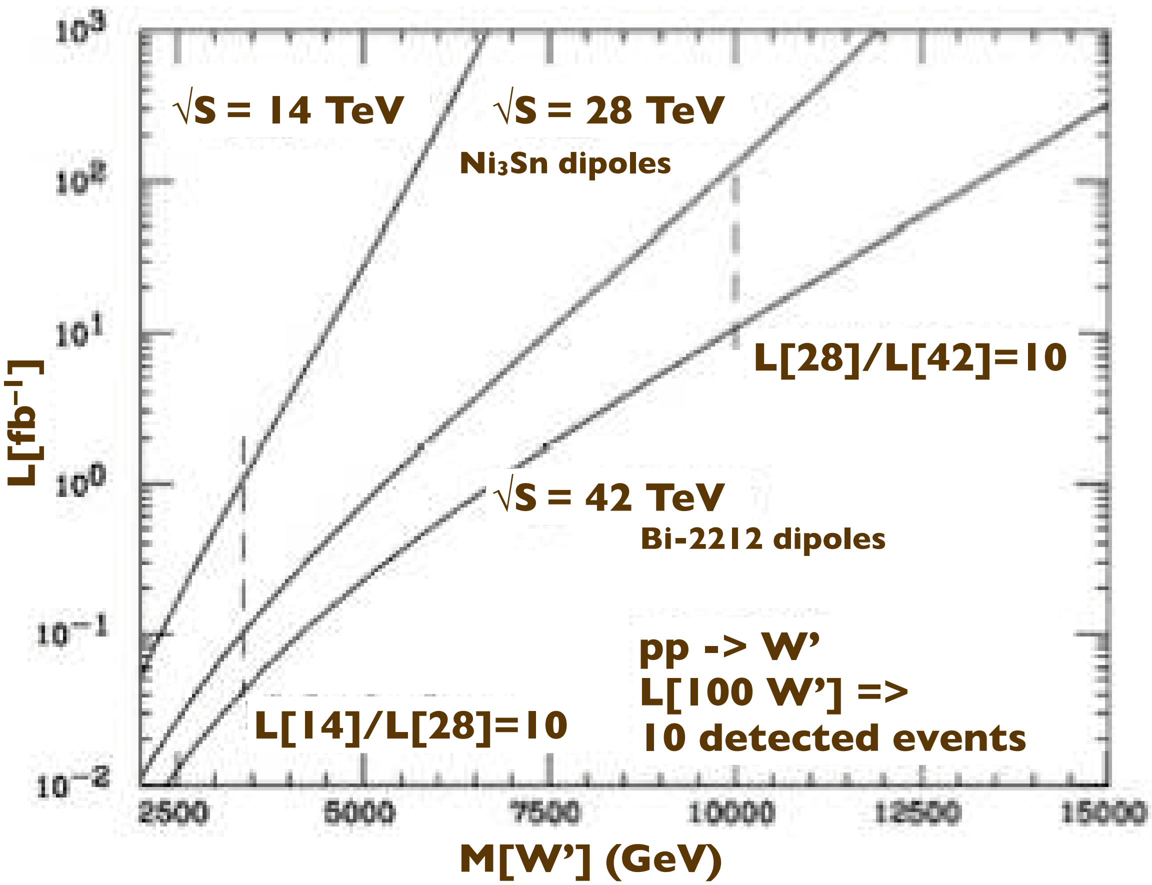
Reach for new discoveries:

- The PDFs are steeply falling at high x

➠ The energy reach increases by typically 20% for a 10 fold luminosity increase

- The PDFs stay almost constant for a two-fold energy increase
- The cross section typically falls with $1/s$ however the luminosity should grow $\propto s$

➠ The reach about doubles for doubling the energy



Measurements and rare processes:

- The statistical error goes with $\sqrt{n}$ or $S/\sqrt{B}$

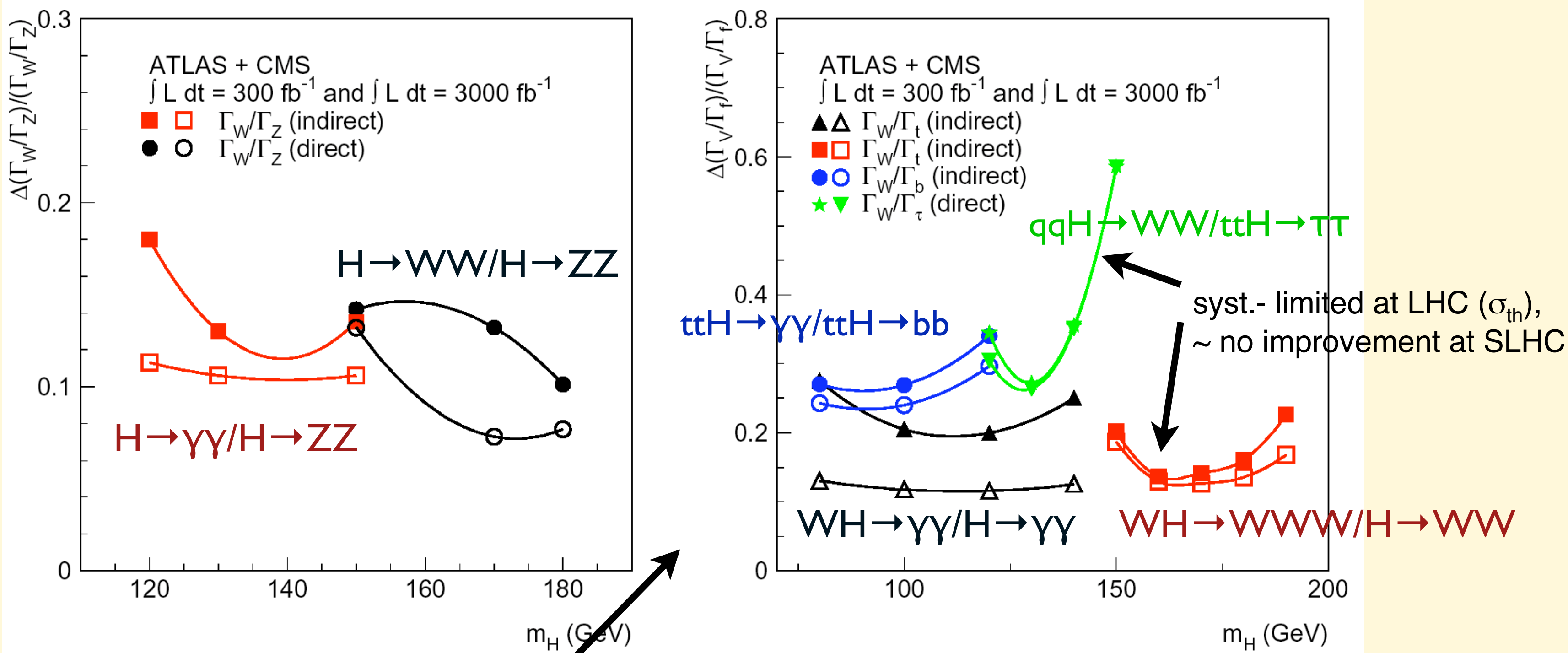
➠ The statistical power increases by a factor 3 for 10-fold luminosity

- In case of no background the sensitivity can even scale with $1/\mathcal{L}$
- However many measurements are systematics limited ➠ no or only little improvement

Example Higgs

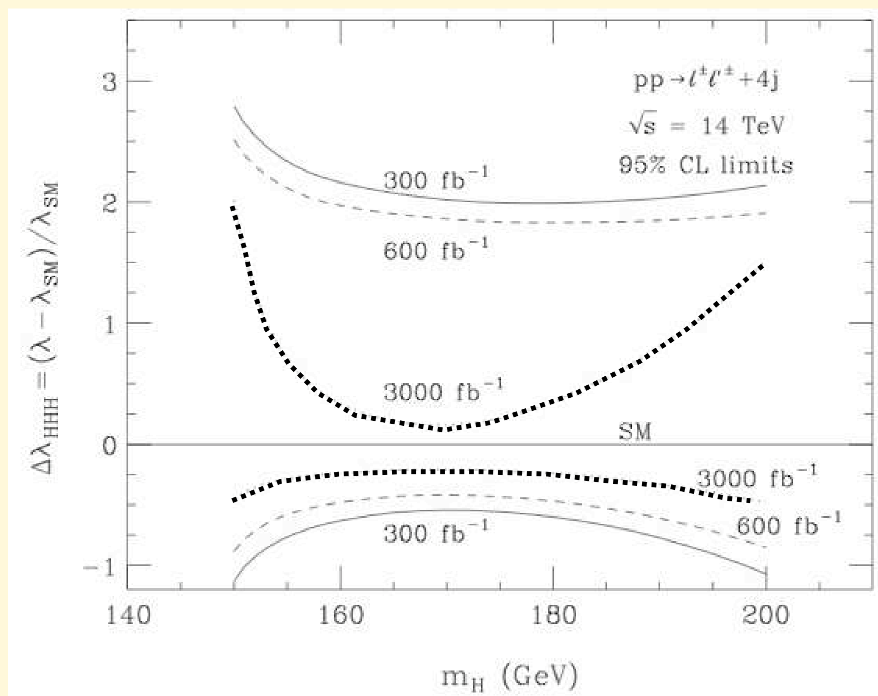
Rare decays:

	$600\ \mathrm{fb}^{-1}$	$6000\ \mathrm{fb}^{-1}$
$H \to Z\gamma$	3.5σ	11σ
$H \to \mu\mu$	$< 3.5\sigma$	$\sim 7\sigma$



Higgs boson couplings to fermions and gauge bosons

Higgs boson selfcouplings



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Next generation lepton colliders

Disadvantages of hadron colliders:

- Parton energies are much lower than proton energy
- Interaction on the parton level is unknown
- Proton remnant disappears in beam-pipe
  $\Rightarrow$ kinematics must be reconstructed from the decay products
- Protons have strong interactions
  - High background
  - Not all processes can be reconstructed

In principle all problems can be solved with lepton colliders

- Leptons are point like
  - Interaction energy = e^+e^--energy
  - Energy-momentum conservation can be used to reconstruct the event kinematics
- Leptons have no strong interactions
  - Low backgrounds
  - All events can be reconstructed
- Leptons can be polarised
  - Helicity structure of couplings can be measured

Problem: Synchrotron radiation

- Synchrotron radiation in circular machines: $\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{r}$
- LEP: $\sqrt{s} = 200\,\mathrm{GeV}$, circumference=27 km ➠ $\Delta E = 2.5\,\mathrm{GeV}$ per turn
- Circular machines no longer possible
  (A 500 GeV in the LEP/LHC tunnel would have 100 GeV loss/turn)
- Way out: Linear Collider
  - can use each bunch only once $\Rightarrow$ luminosity loss
  - compensate by extreme focusing (bunch size around $\mathcal{O}(5 \times 100\mathrm{nm})$)
  - main challenges: high accelerating gradients to keep machine reasonably short and beam steering to achieve small beam size

The ILC project

- The ILC is a linear collider based on superconducting technology
- The ILC is an international project supported by all regions
- A reference design report has been written
- A detailed technical design is currently under way

Gross parameters:

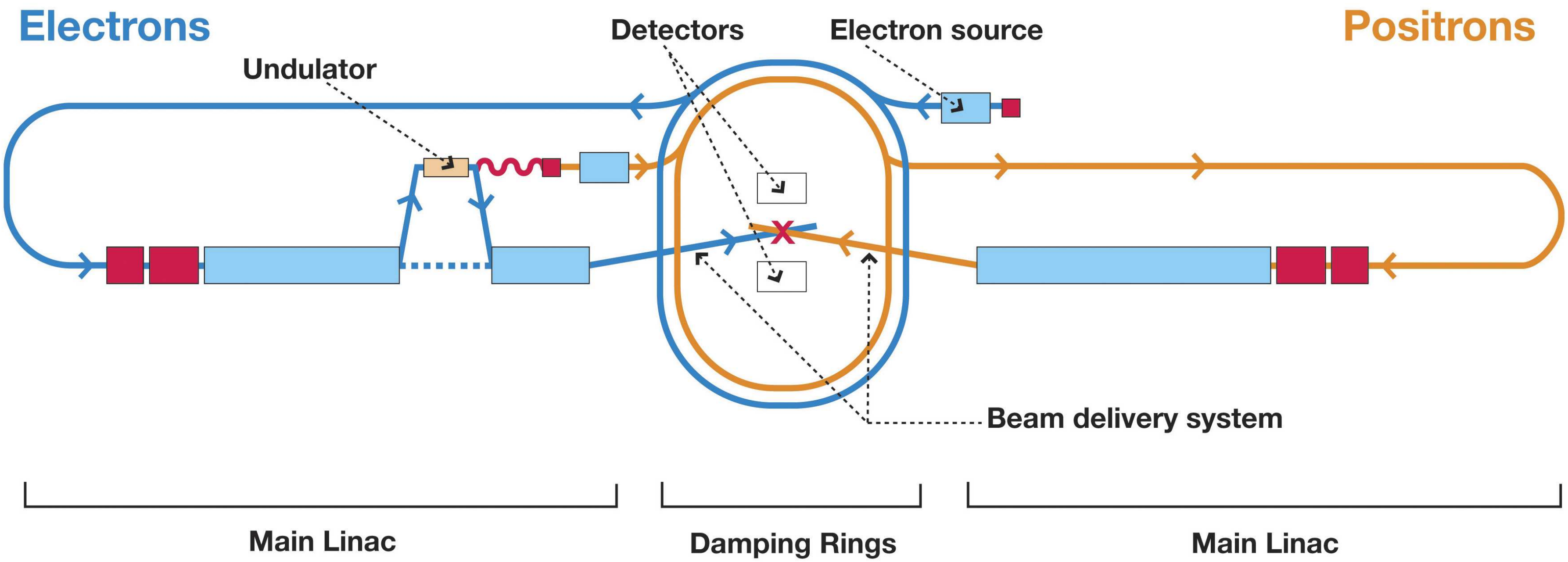
- First phase: $\sqrt{s} \leq 500\,\mathrm{GeV}$
- Upgrade: $\sqrt{s} \approx 1\,\mathrm{TeV}$
- Tunnel length $\sim$ 30km
- Acceleration gradient $\sim 35\,\mathrm{MeV/m}$
- Luminosity $\mathcal{L} \approx 2 - 5 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1} \Rightarrow \sim 200 - 500\ \mathrm{fb}^{-1}/\mathrm{year}$
- Polarised electron beams (P = 80-90%)

Program options

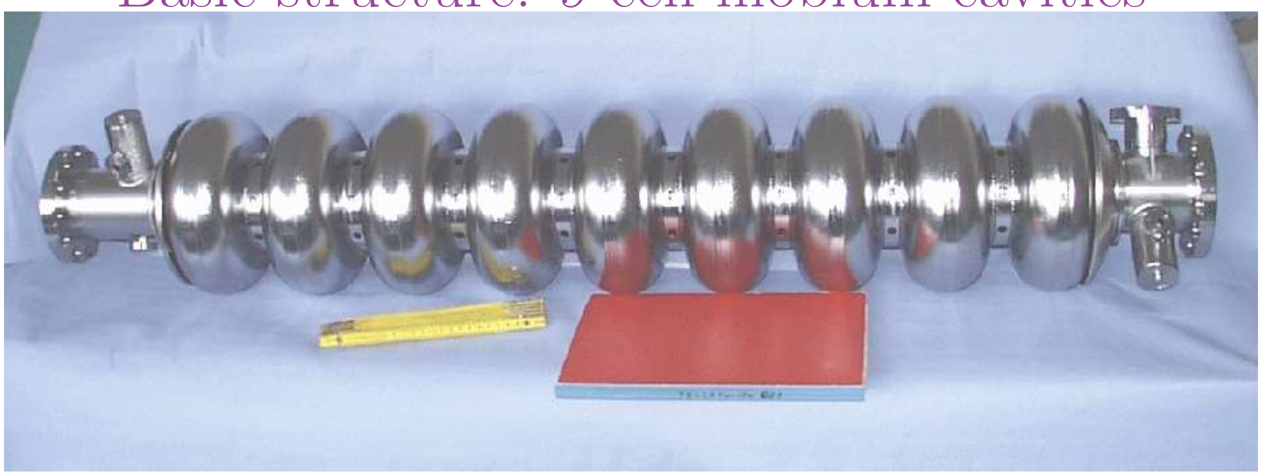
Depending on the physics several options can be realised at the ILC

- Polarised Positrons
  - Positron source (helical undulator) produces polarised positrons at the high energy end
  - With a small upgrade P = 40-60% at the IP is possible
- GigaZ
  - ILC can be run at the Z pole with small modifications
  - 10^9 events at the Z pole with polarised beams and W mass from threshold scan to $\sim 6\,\mathrm{MeV}$
- $\mathrm{e^-e^-}$ running ($\mathcal{L}(\mathrm{e^-e^-}) \sim 1/3\mathcal{L}(\mathrm{e^+e^-})$)
- $\gamma\gamma$, $\mathrm{e}\gamma$ collider
  - The electron bunches can be collided with a high power laser a few mm in front of the IP
  - This "converts" the electron beam into a photon beam ($E_\gamma \leq 0.8 E_e$)
  - $\mathcal{L}(\sqrt{s}(\gamma\gamma) > 0.8\sqrt{s}) \sim 0.1\mathcal{L}(\mathrm{e^-e^-})$)

Basic layout of a Linear Collider



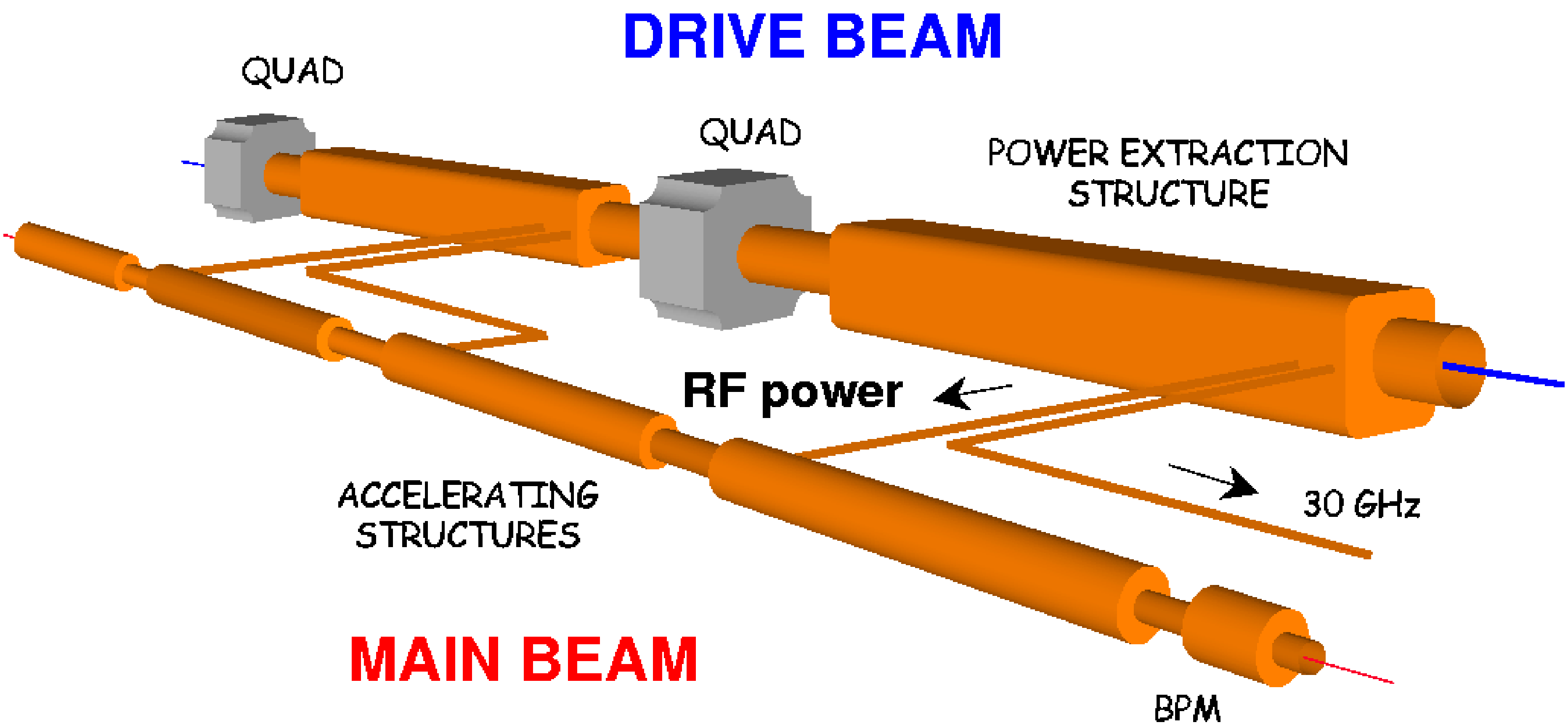
Basic structure: 9-cell niobium cavities



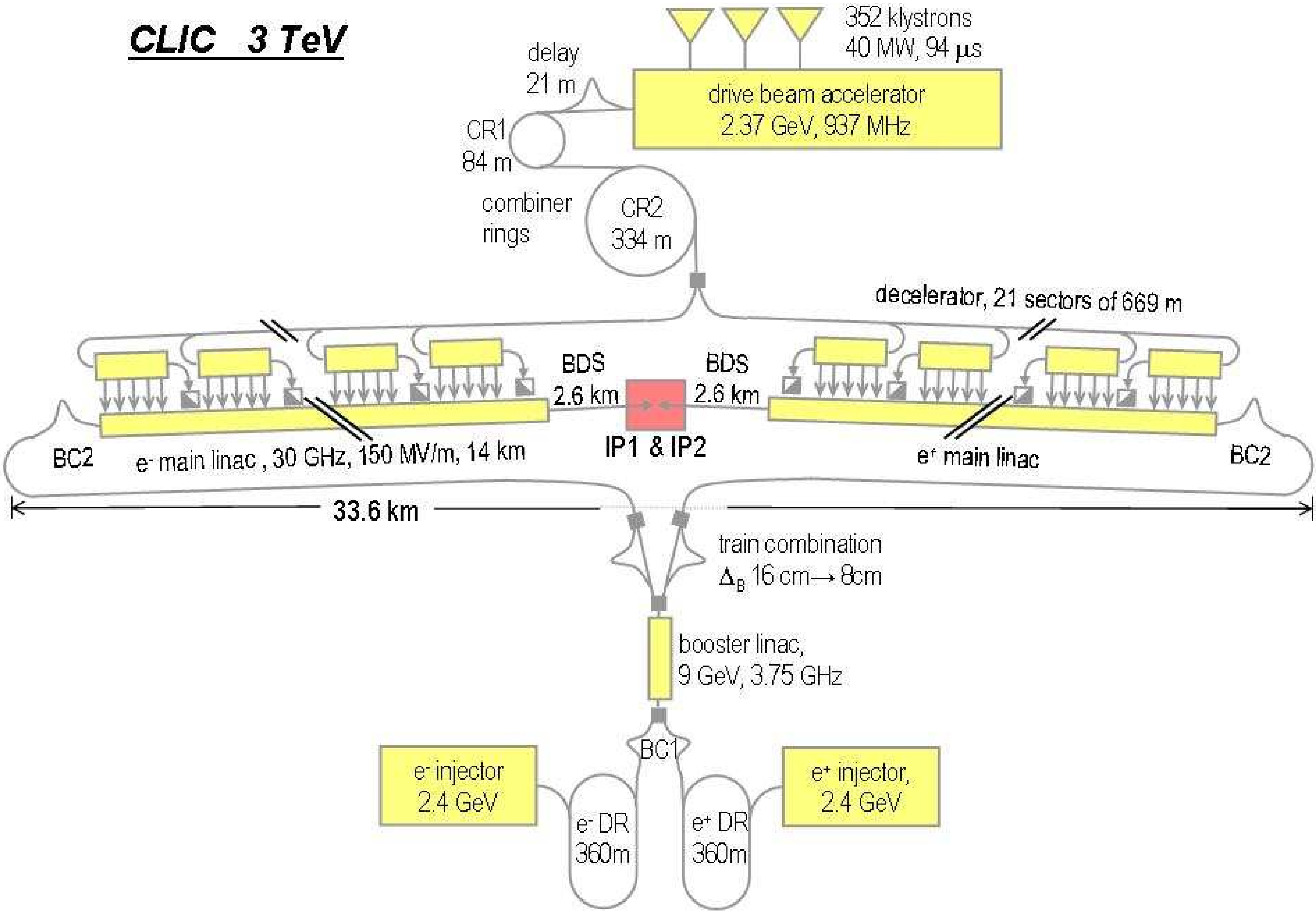
The CLIC project

- From the physics case it would be nice to have a several TeV e^+e^- collider
- The ILC technology gets too expensive going significantly above 1 TeV
- Possible alternative: two beam scheme:
  - generate a high current low energy drive beam
  - guide this beam through unpowered cavities where it excites oscillations
  - transfer the energy into a parallel structure
  - use this structure to accelerate a high energy beam
- Hope to reach a gradient of $\sim 150\,\mathrm{MeV/m}$ ($4\times$ ILC)

The CLIC principle



Possible layout of CLIC



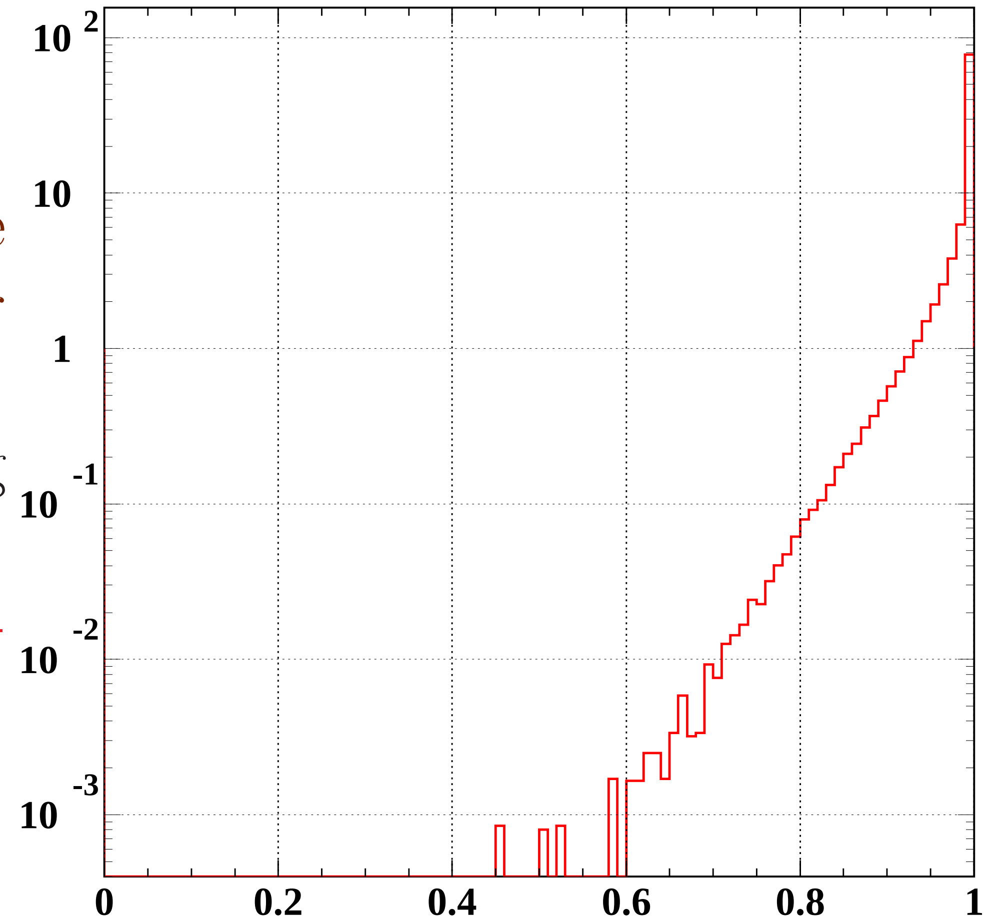
CLIC status

- The two-beam scheme itself is verified
- A full technology demonstration is planned around 2010
- After first LHC results around 2012 a decision for one of the e^+e^- linear collider projects can be taken
- Construction time for both projects is around 8 years (+political delays)

New problem at linear colliders: beamstrahlung

Beams at IP are extremely collimated with many electrons/bunch

Energy of colliding electrons



→ very high charge density

⇒ Electrons of one bunch radiate against the coherent field of the other bunch (Beamstrahlung)

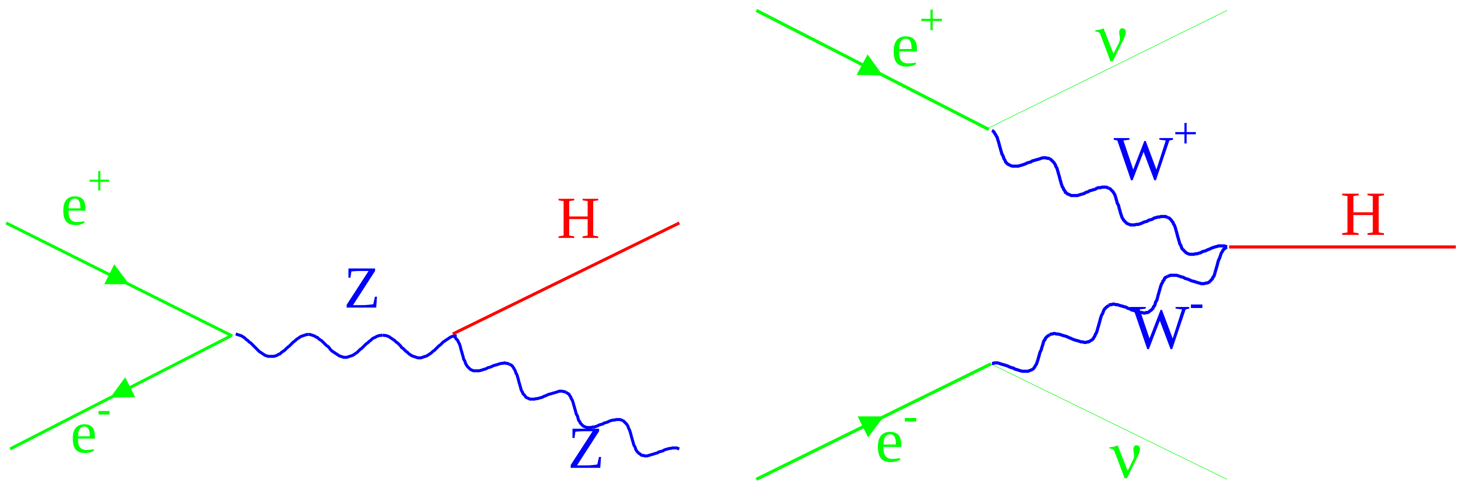
Average energy loss for colliding e^+e^--pairs at 500 GeV: $\sim 1.5\%$

Beam energy constraint gets weakened (like for ISR)

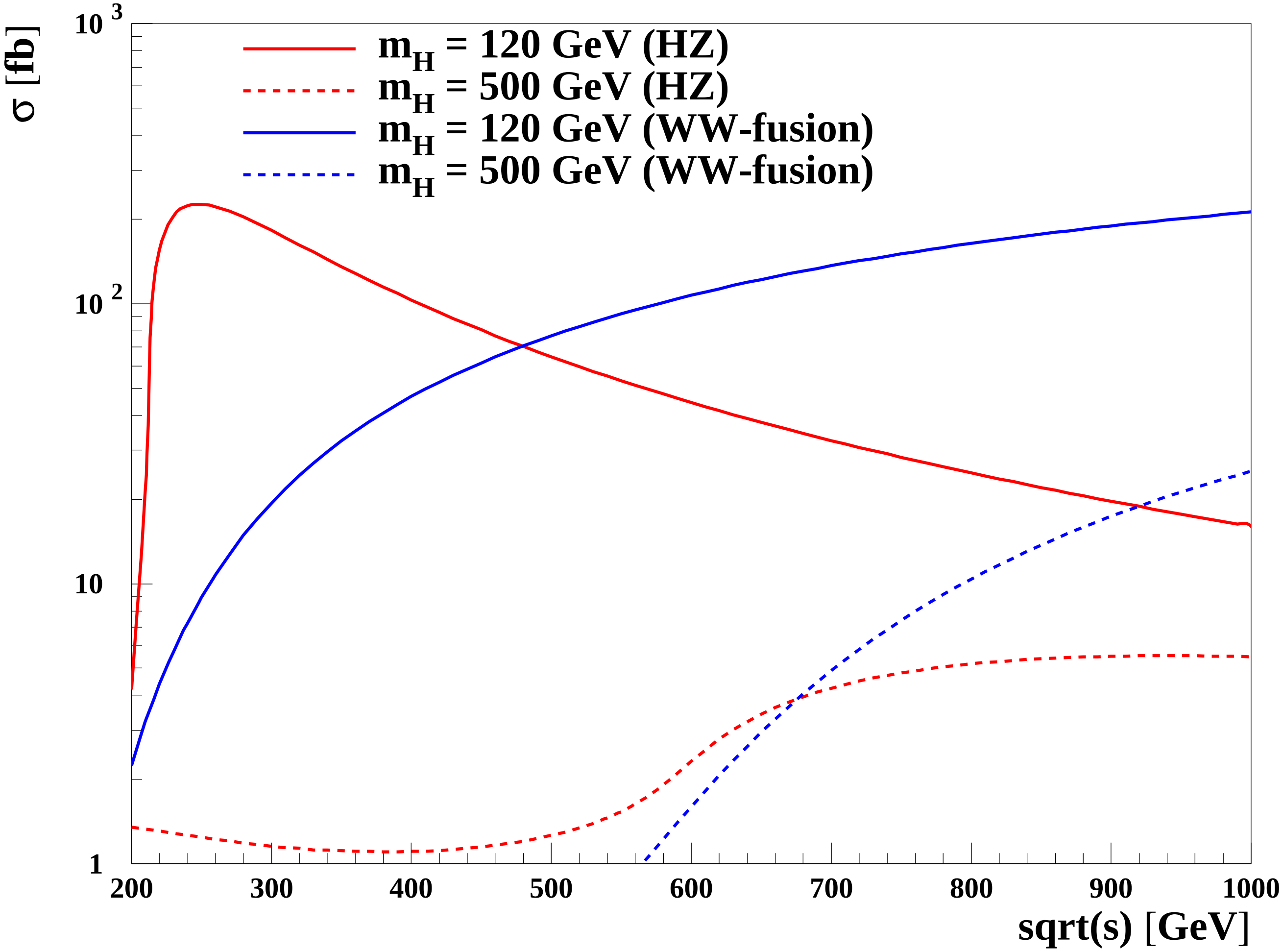
The Physics case for e^+e^- linear colliders

Example I: Higgs

- If a Higgs exists, the LHC will find it
- However the LHC can measure its properties only with a limited accuracy
- In e^+e^- the Higgs is visible in in Higgsstrahlung and WW-fusion

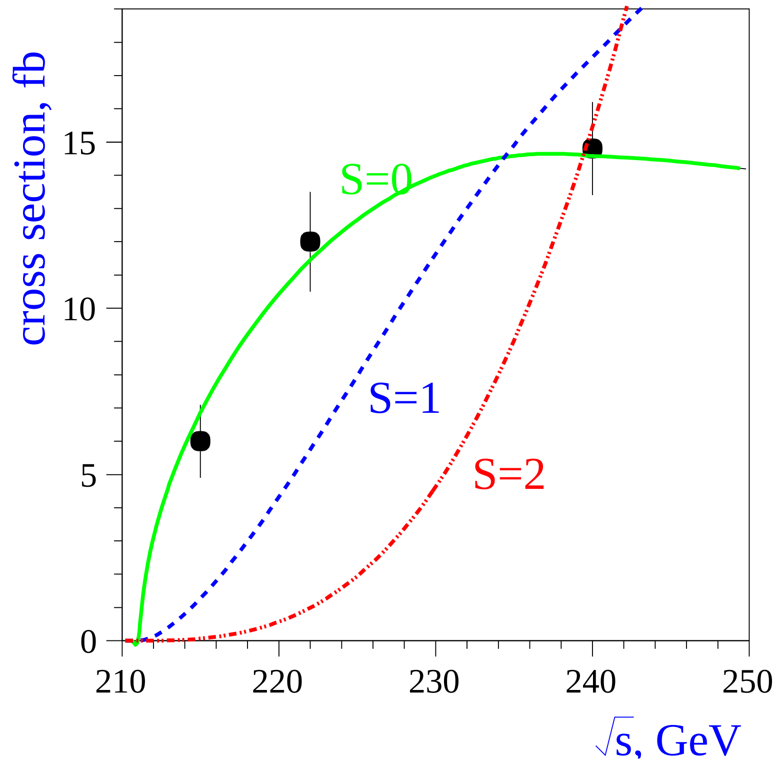


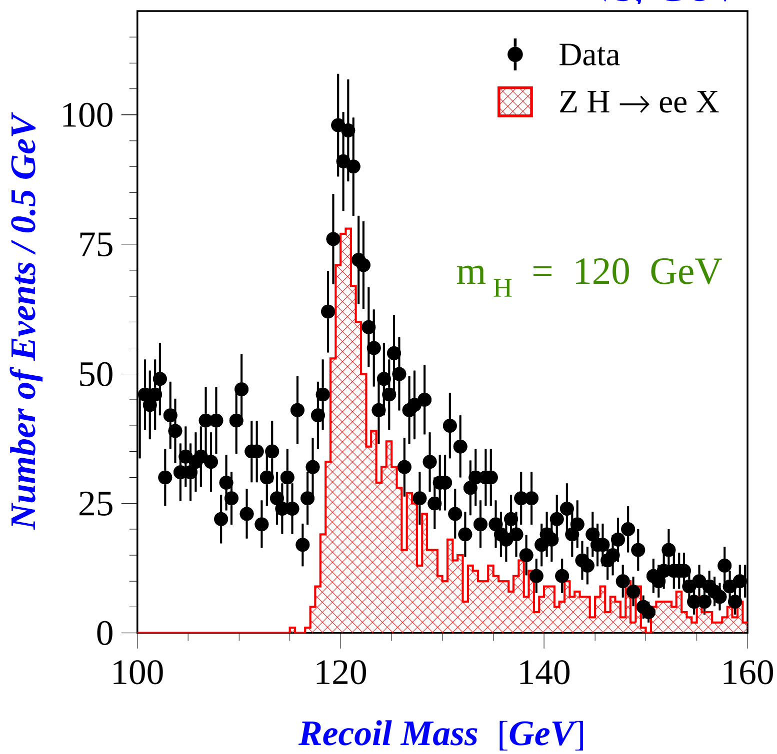
Higgs production cross section:



- At low energy Higgstrahlung dominates
- At high energy the fusion cross section still grows

- A scan of the HZ threshold can determine the quantum numbers (spin, parity)
- For $Z \to e^+e^-, \mu^+\mu^-$ the Higgs can be seen from the recoil-mass independent of its decays
- This allows a model independent measurement of the HZZ coupling and the Higgs branching ratios
- The $t\bar{t}H$ couplings can be measured from $e^+e^- \to t\bar{t}H$
- Higgs selfcouplings can be obtained from double Higgs production



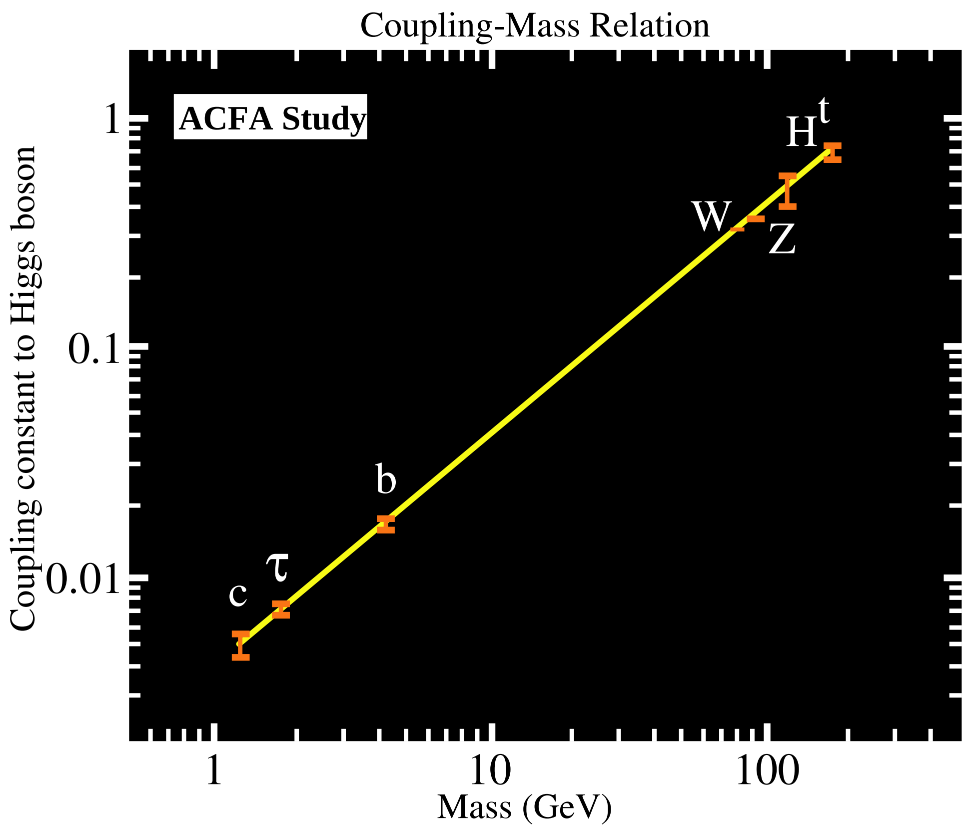


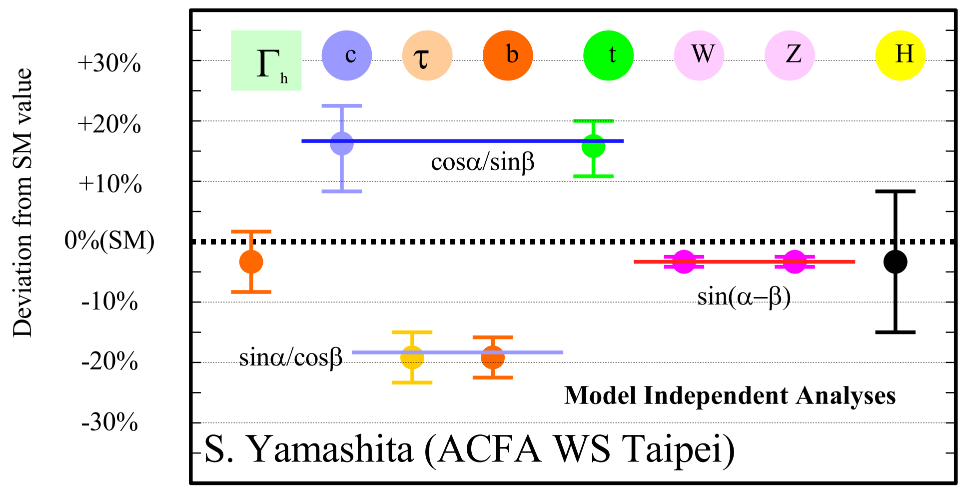
This can show that the Higgs really couples to mass

The branching ratios are also a sensitive indicator for models beyond th SM

e.g. a model with two Higgs-doublets (SUSY):

- The two original Higgs particles (H_1, H_2) are responsible for the masses of the up- and down-type fermions
- The h is a mixture of H_1 and H_2
- Its couplings can be shifted w.r.t. the SM prediction



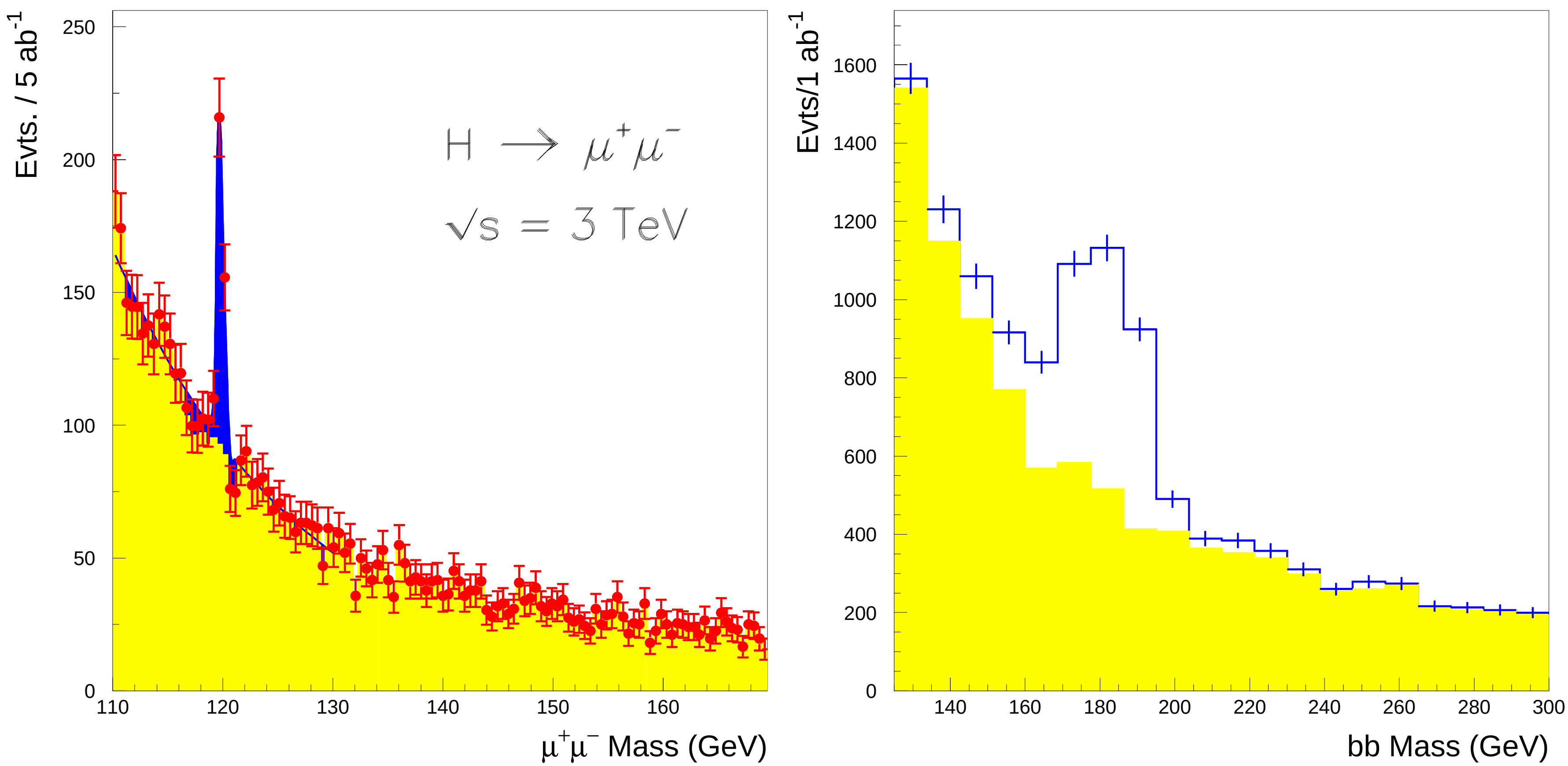


What can CLIC contribute to the Higgs?

- The fusion cross section and the luminosity rise with energy

➠ very large Higgs statistics

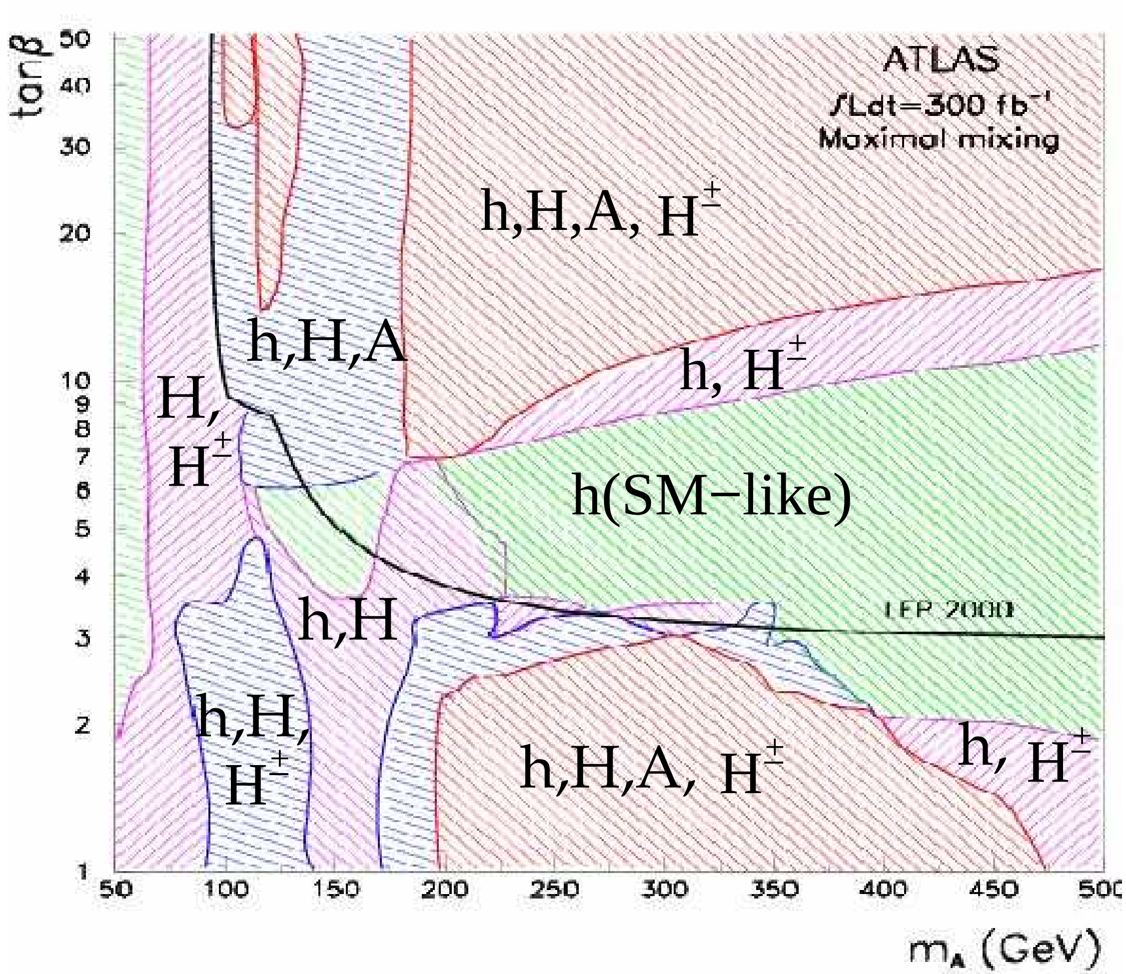
➠ can measure rare decays like $H \to \mu^+\mu^-$ for small $m_{\rm H}$ or $H \to {\rm b\bar{b}}$ for large $m_{\rm H}$ with few % precision



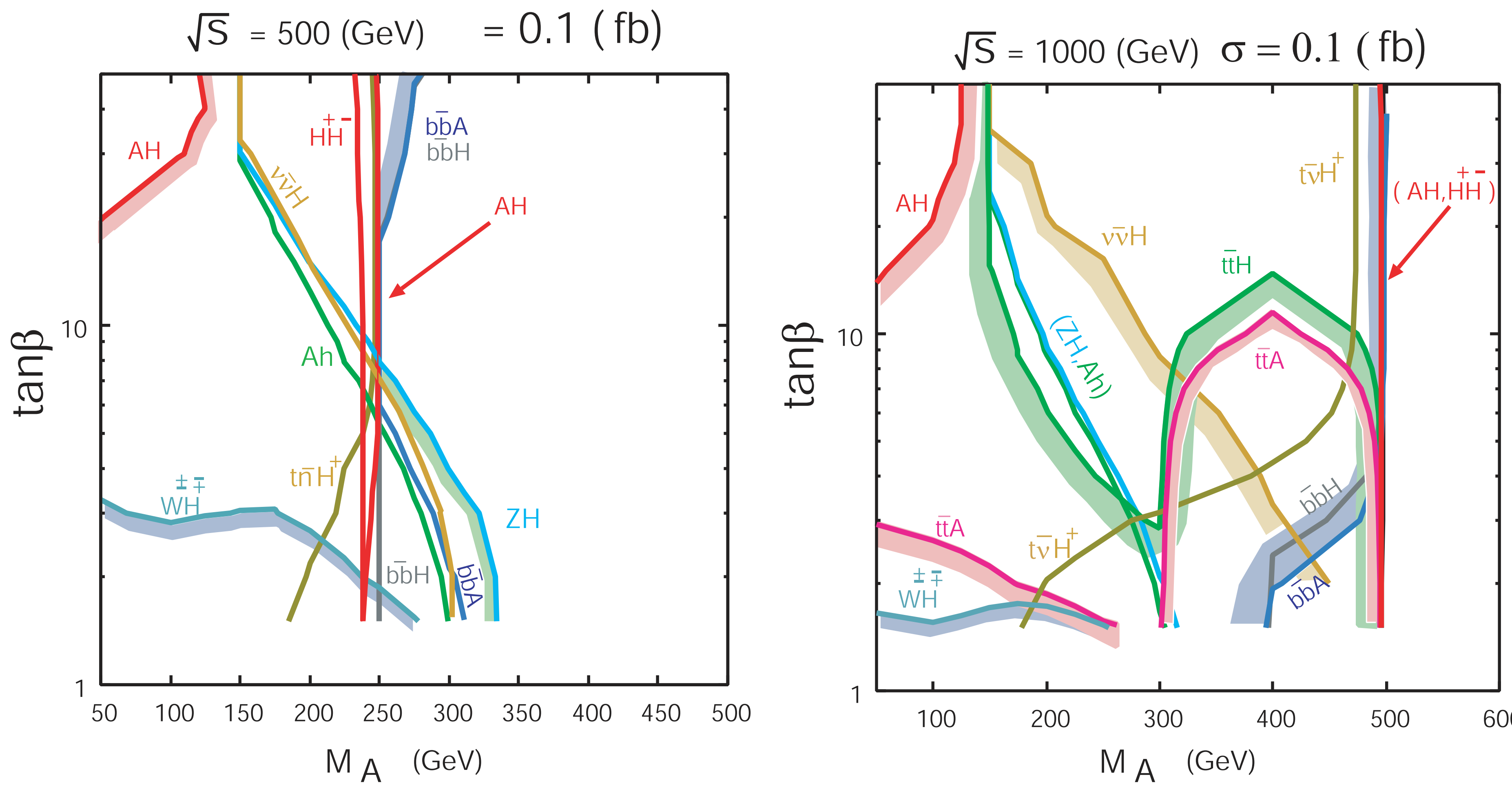
MSSM Higgses

- At the LHC the heavy MSSM Higgses are only visible at low and high $\tan\beta$

Visible SUSY-Higgses at the LHC

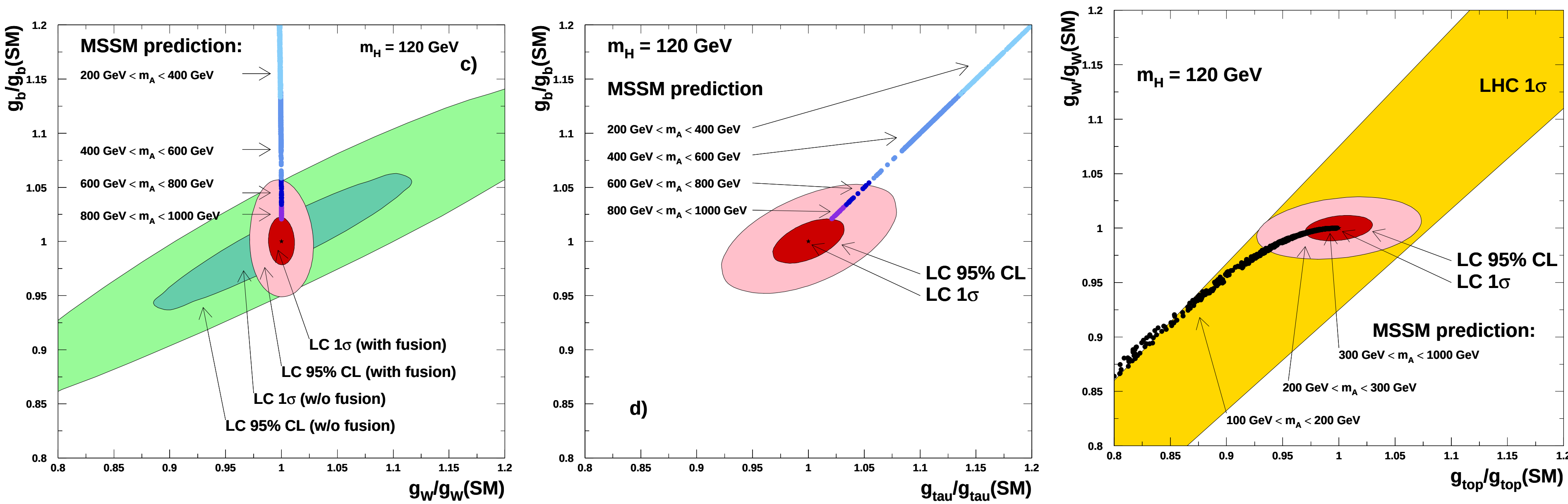


- At e^+e^- colliders the heavy Higgses are visible up to (at least) $\sqrt{s}/2$



However also the precision measurements at 500 GeV are sensitive to the heavier Higgses:

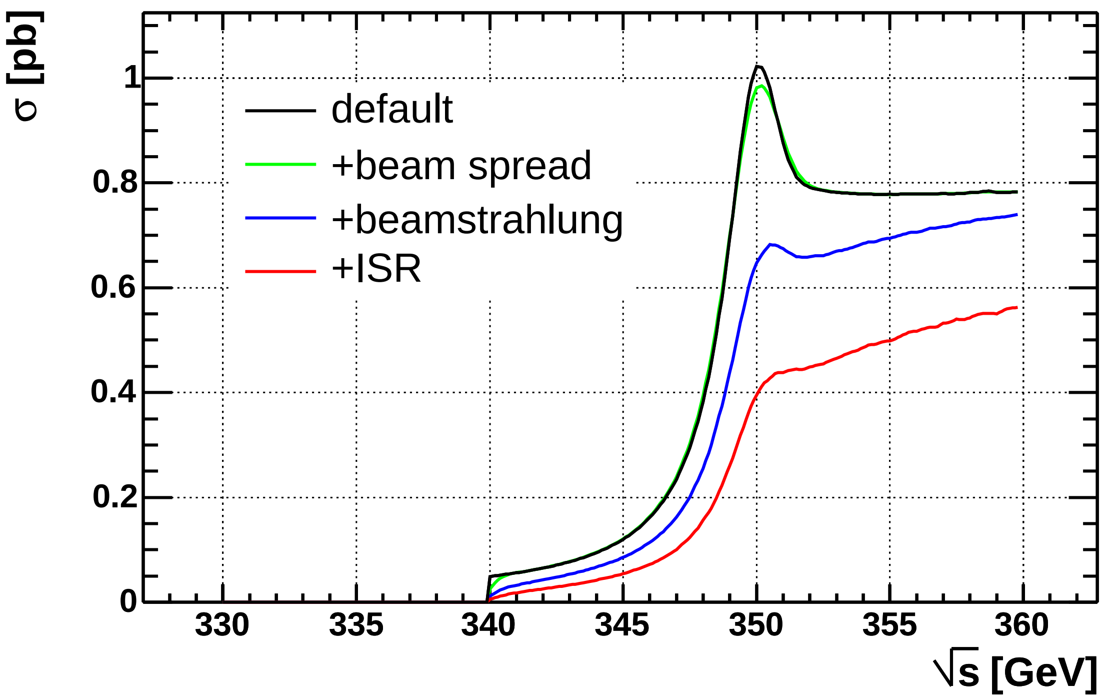
- The $H_1 - H_2$ mixing angle depends on m_A and $\tan\beta$
- In the calculation of the h-fermion couplings $\tan\beta$ almost drops out
- Especially the down-type fermions are sensitive to m_A
- There is sensitivity up to $m_A = 600\,\mathrm{GeV}$



Example II: Top

- At lepton colliders top quarks are produced by γ or Z s-channel exchange
- Because of the large top width there are no toponium resonances at threshold
- The top mass can be measured to a precision of $50-100\,\text{MeV}$ with a threshold scan

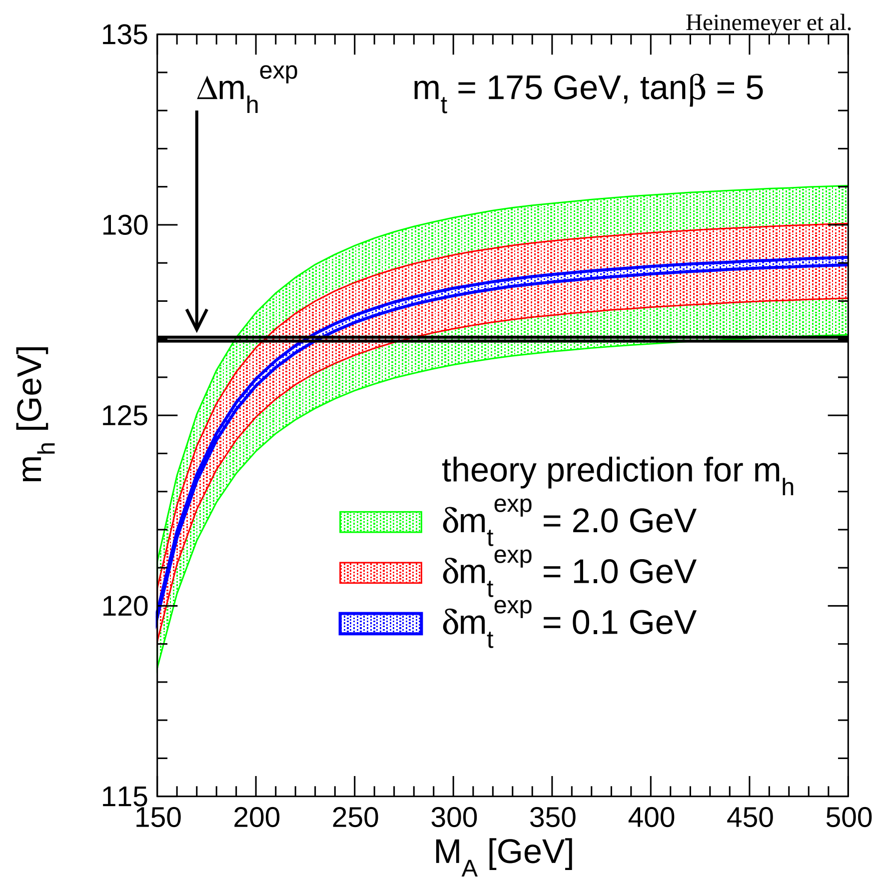
- At LHC there are always theoretical uncertainties in the top mass definition of $\sim 1\,\text{GeV}$
- For a threshold scan also the theoretical uncertainties are in the $50-100\,\text{MeV}$ range



Why is the top mass so important?

- In models beyond the SM the Higgs mass(es) should be given by the model
- However there are radiative corrections from the particles coupling to the Higgs
- Because of the large Yukawa coupling the top corrections are of the order $\Delta m_{\rm H}/\Delta m_{\rm t} \sim 1$

➠ a Higgs mass precision (much) better than the top mass precision is almost useless



Example: SUSY

- $m_{\rm A}$ can be calculated when $m_{\rm h}$ and $\tan\beta$ are known
- This may only be possible with an accurate $m_{\rm t}$

Example III: SUSY

- The ILC tests smaller masses in SUSY ($\sqrt{s}/2$)
- However it has many advantages
  - All particles, especially the weakly interacting ones, are visible
  - The known kinematics allows the reconstruction of the LSP
  - The known initial state allows precise coupling measurements
- These precise measurements are needed to prove thar the new particles are really superpartners of the SM ones
- The combination of ILC and LHC is necessary to measure most of the $\mathcal{O}(100)$ free parameters and to understand the mechanism of SUSY breaking

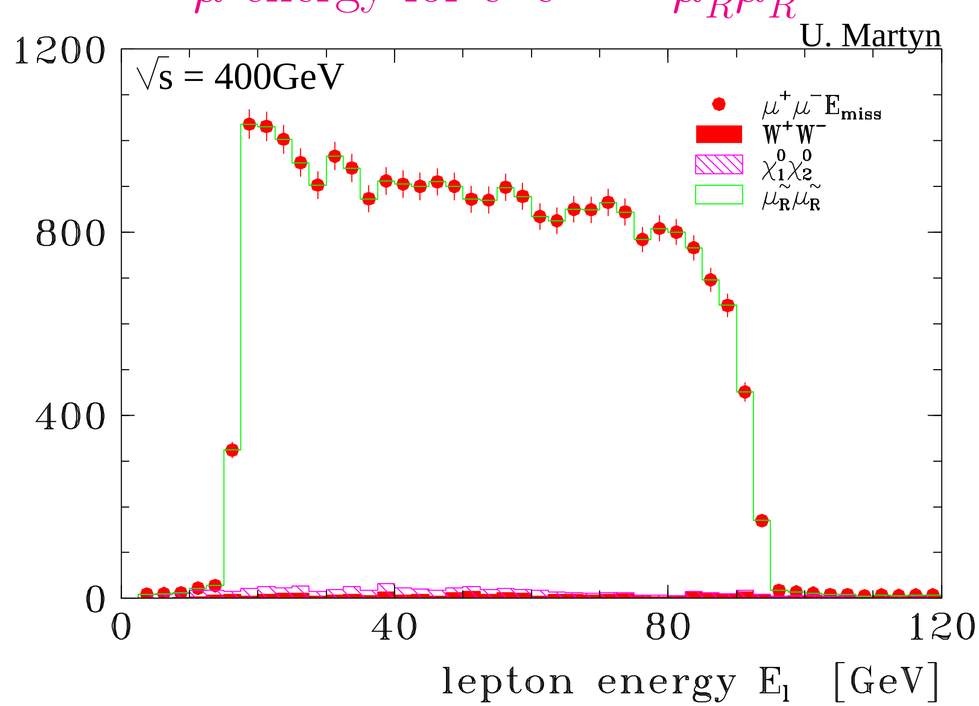
Mass measurements

- With direct reconstruction or threshold scans the masses of all accessible particles can be measured
- This is also true for the LSP which is difficult to measure at the LHC
- Reconstruction of sfermion decay $\tilde{f} \rightarrow f\chi^0$:
  - Decay is isotropic in rest frame
  - ➡ Fermion energy in lab frame flat with endpoints

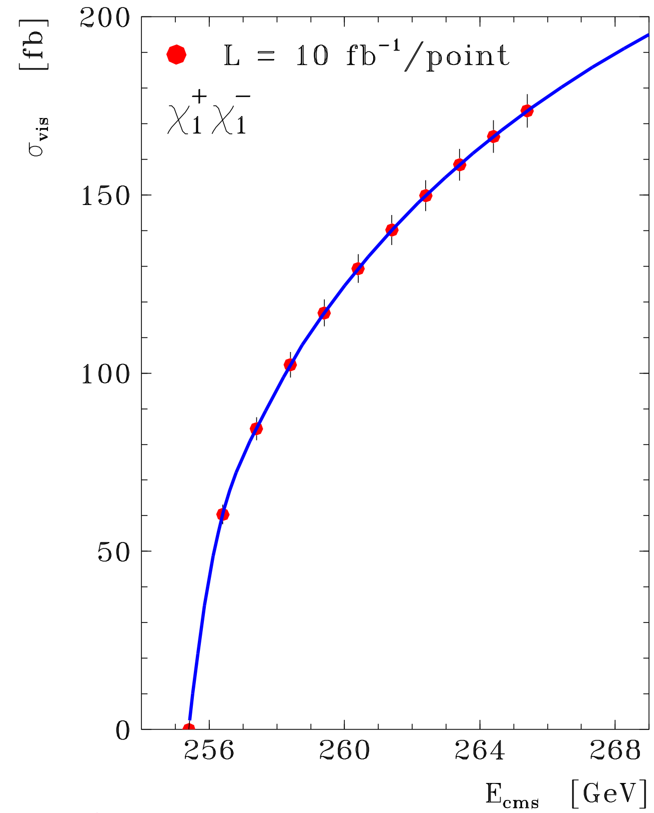
$$\frac{E_f}{E_{\mathrm{beam}}} = \frac{1}{2}(1 \pm \beta)\left(1 - \frac{m_\chi^2}{m_{\tilde{f}}^2}\right)$$

➡ $\tilde{f}$- and χ^0-mass can be measured

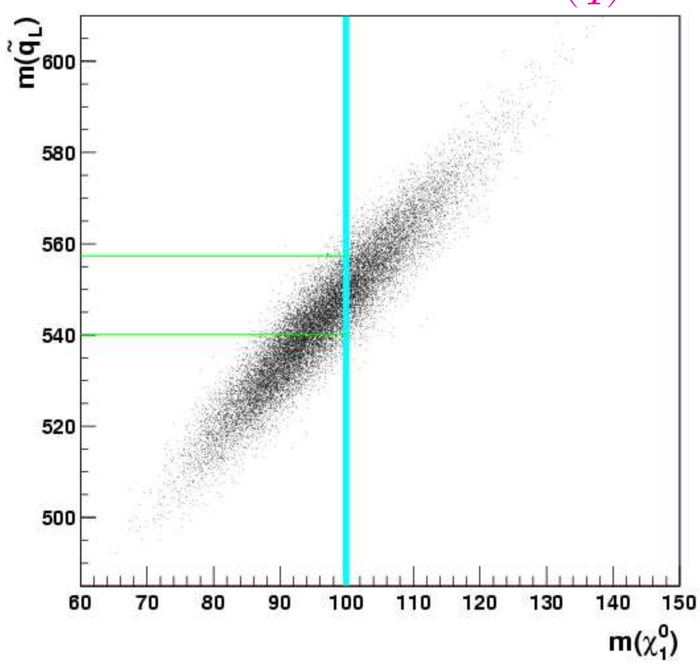
μ energy for $e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^-$



- 2nd method: threshold scans
- Gauginos: threshold suppression $\propto \beta$
  $\Rightarrow$ good precision for mass measurement
- Using both methods all accessible particle can be measured with typically $< 0.1\%$ precision
- By combination with the LHC also the precision of non-accessible particles can be improved

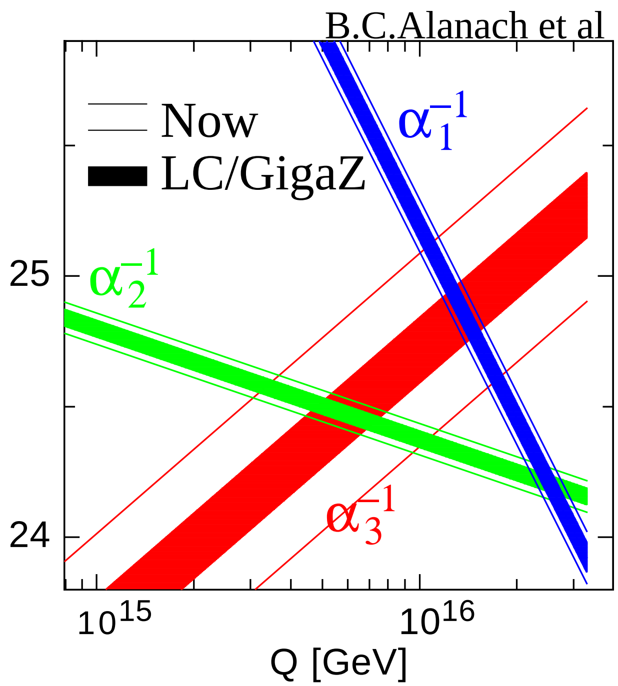


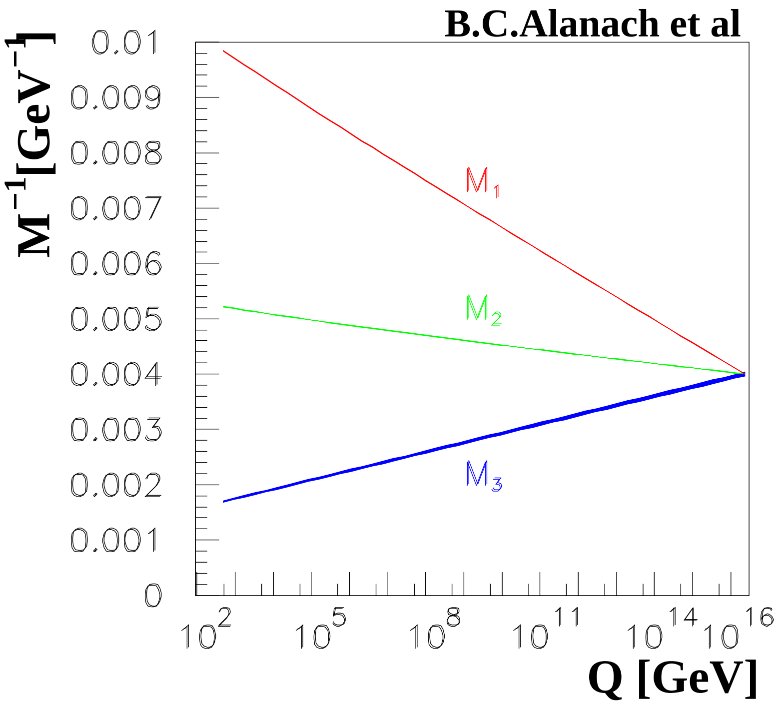
LHC-ILC combination for $m(\tilde{q})$- $m(\tilde{\chi}_1^0)$



SUSY and the unification of forces

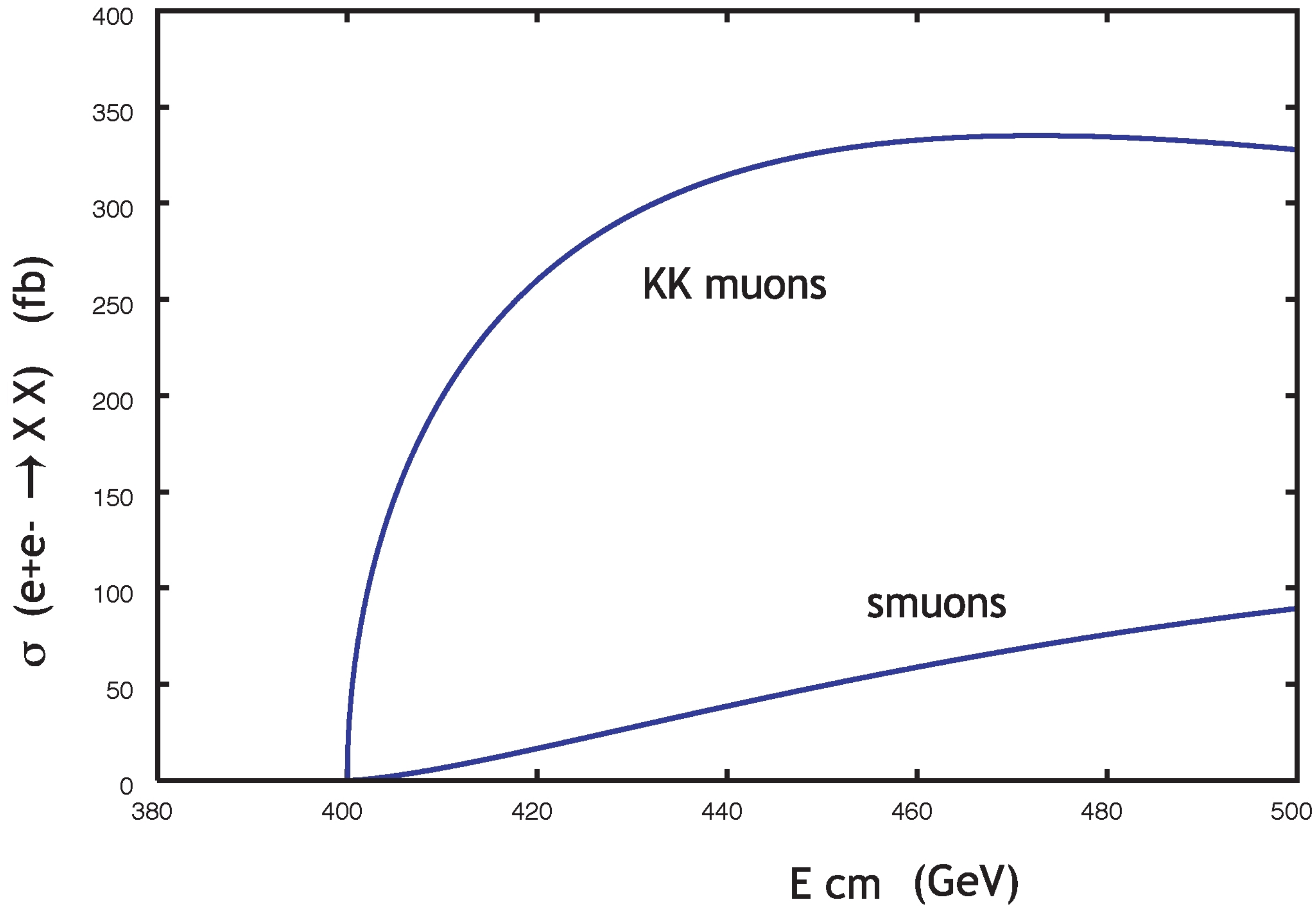
- Masses and coupling constants can be extrapolated to high energies
- Their behaviour gives information about the unification of forces
- Small deviations are a hint for small corrections from string theory





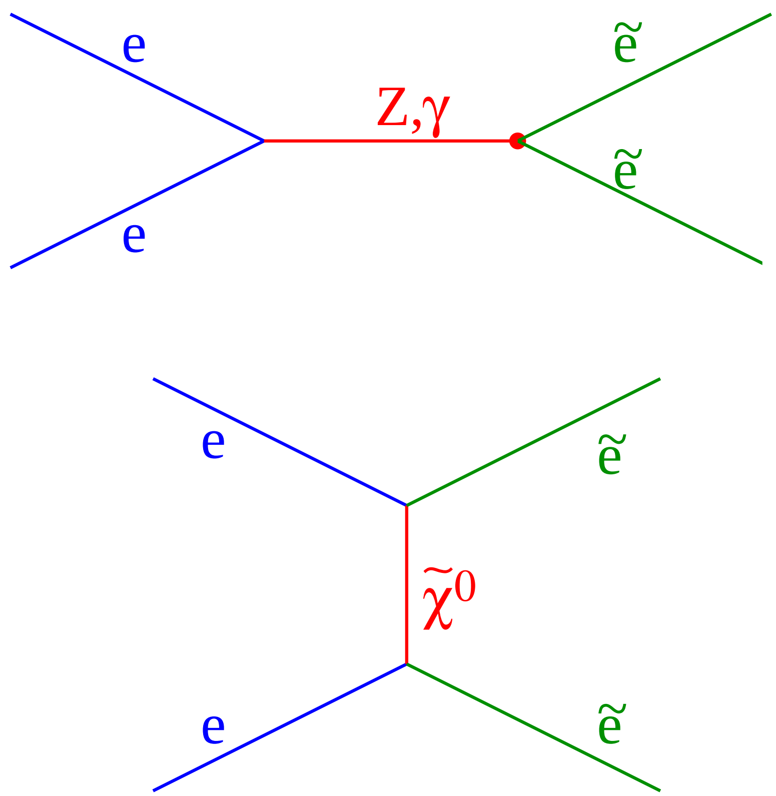
Spin measurements

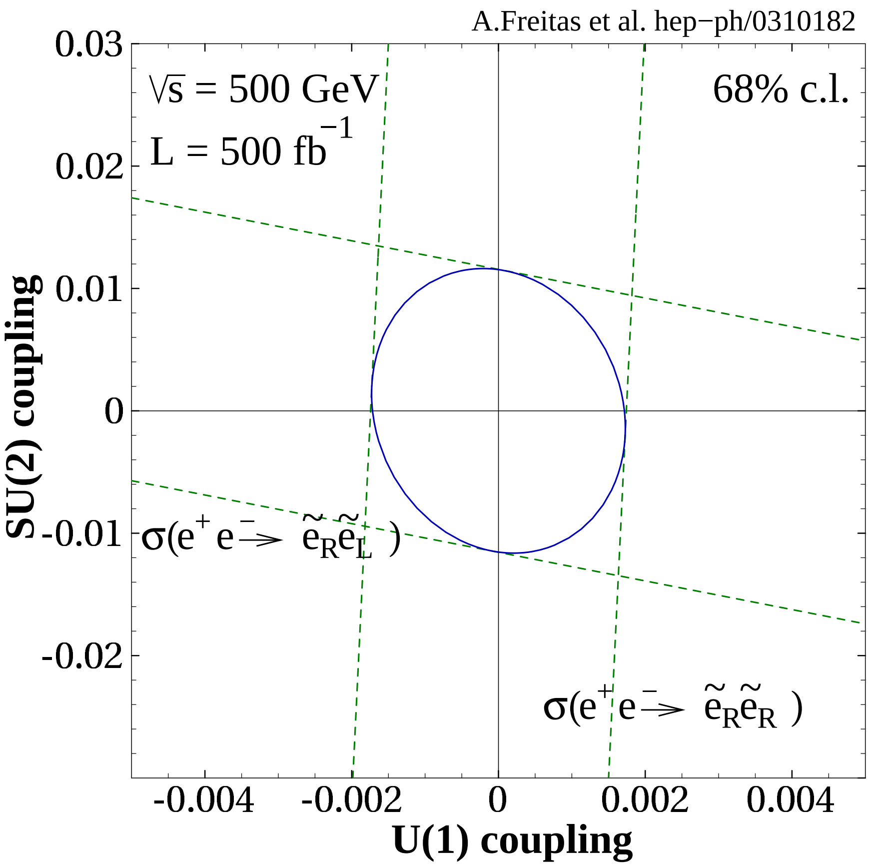
- To prove that it is SUSY it must be shown that the spin of the new particles differs by 1/2
- This can be done e.g. with threshold scans



Coupling measurements

- An e^+e^- collider can measure cross sections and asymmetries
- Measurements can be done for different beam polarisations
- With the different observables all involved couplings can be disentangled
- Example: $e^+e^- \to \tilde{e}^+\tilde{e}^-$

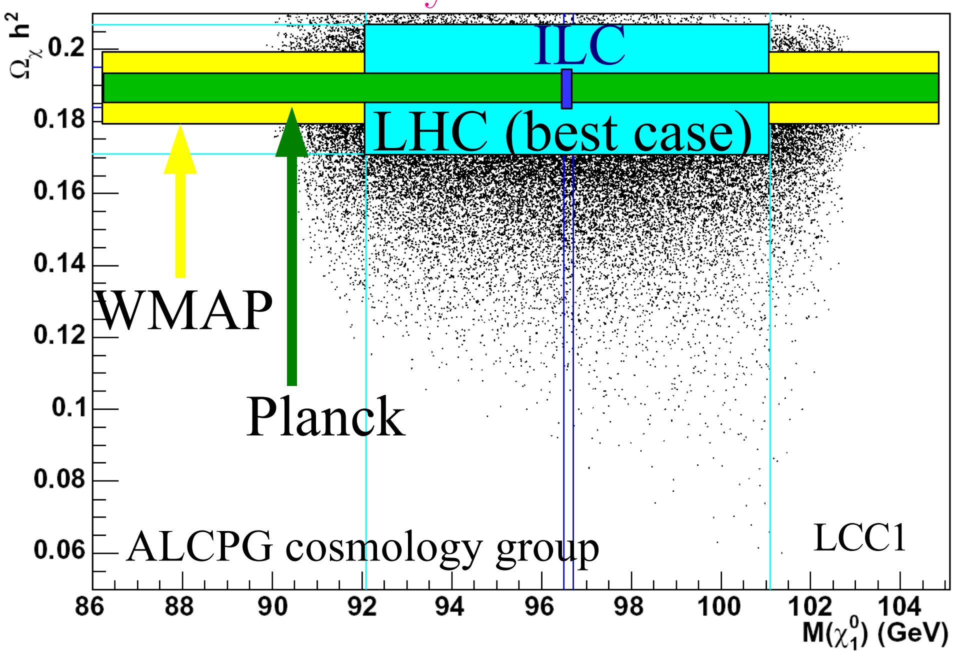




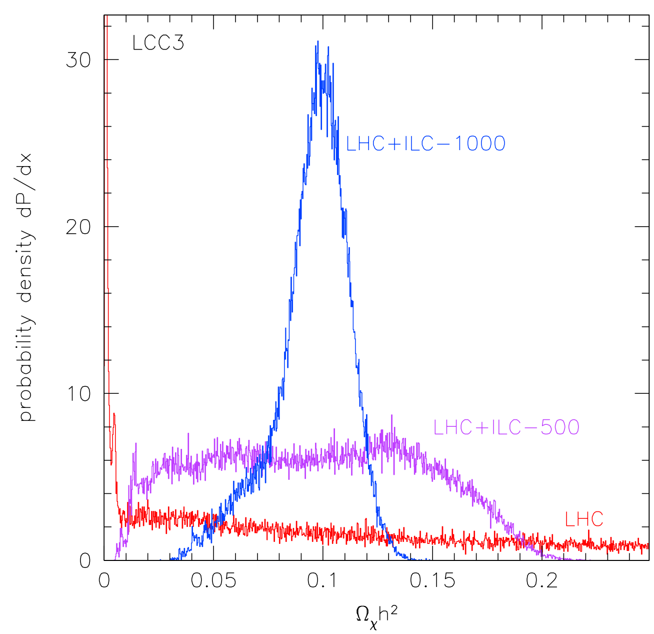
Dark matter

- Depending on the scenario properties of different particles must be measured
- Only a lepton collider has the possibility to do this
- It is very probable that such a machine is needed to understand if the new particles found at the LHC account for the dark matter in the universe

Dark matter density in the easiest scenario

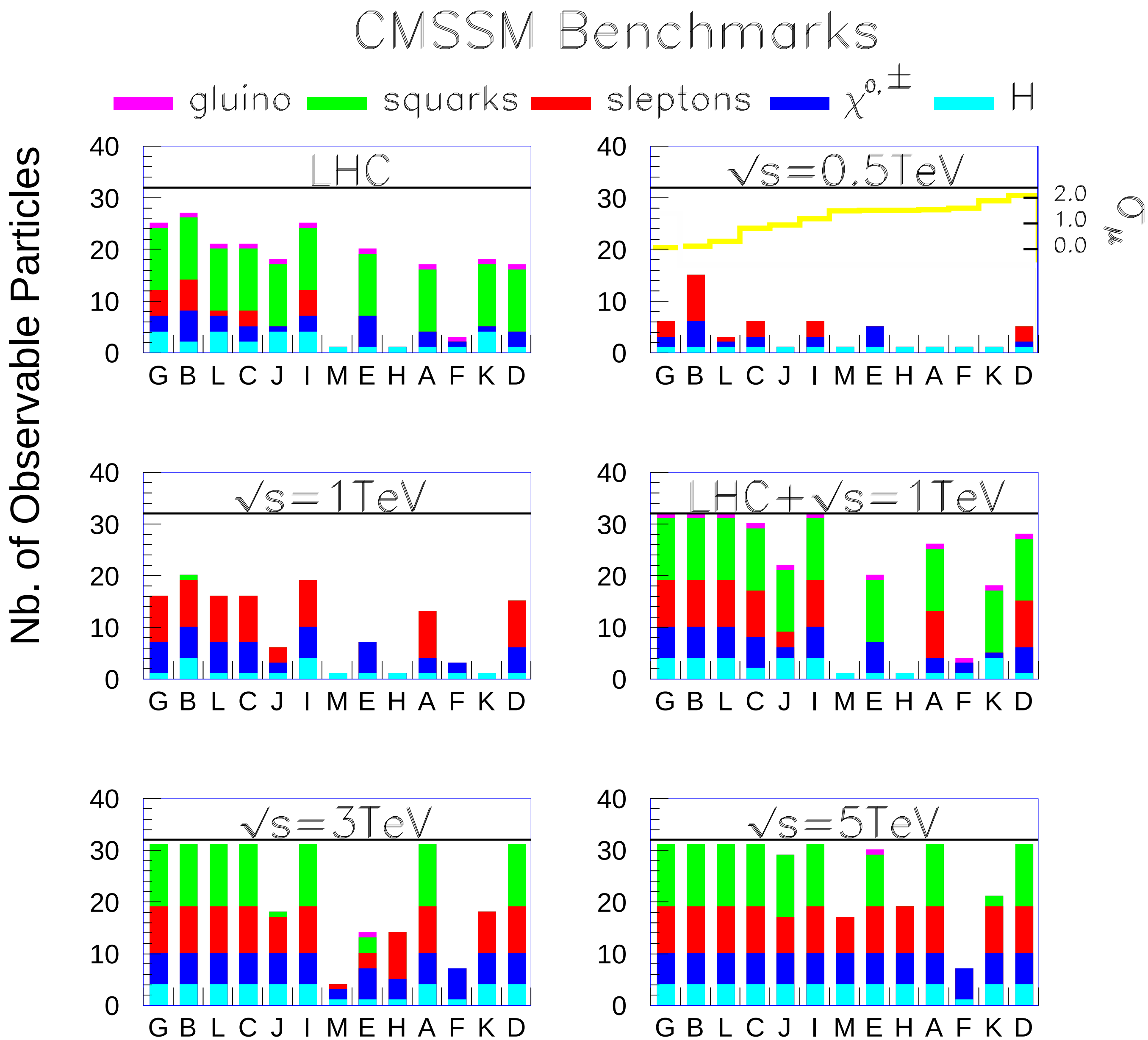


Ωh^2 in coannihilation region



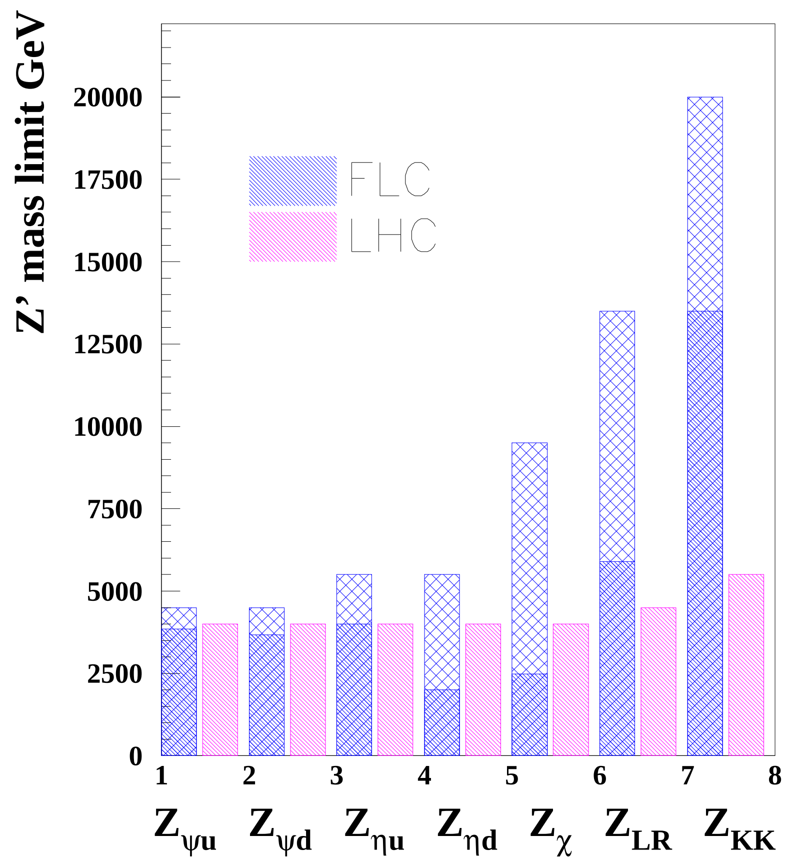
What e^+e^- energy is needed?

- Many scenarios (e.g. focus point) allow pretty high masses
- A 1 TeV collider often only gets the sleptons and the (lighter) neutralinos and charginos
- Only a 3 – 5 TeV collider has a reasonable coverage using present day knowledge



Example IV: Z'

- Z' effects are visible much below the Z' mass:
  - propagator $p \propto \frac{1}{s-m^2_{Z'}+im_{Z'}\Gamma_{Z'}}$
  - Z' exchange: $\propto 1/p^2$
  - interference with SM amplitude: $\propto 1/p$
  - ➡ mainly interference visible
  - ➡ large sensitivity to helicity structure
- PEP and PETRA could already measure Z properties that way
- Measurement of cross sections and asymmetries gives access to vector- and axial-vector-couplings separately
- Model dependent analyses:
  - assume a given model ➡ all couplings are defined
  - can use leptonic and hadronic events
  - deviations from SM prediction translate directly into Z'-mass



- In general sensitivity is similar to LHC
- However much larger difference between models, since sensitivity is in interference term
- On the contrary LC is not sensitive to the total width of the Z'
- One should remember that no resonance is seen, so interpretation may not be unique

Model independent analyses:

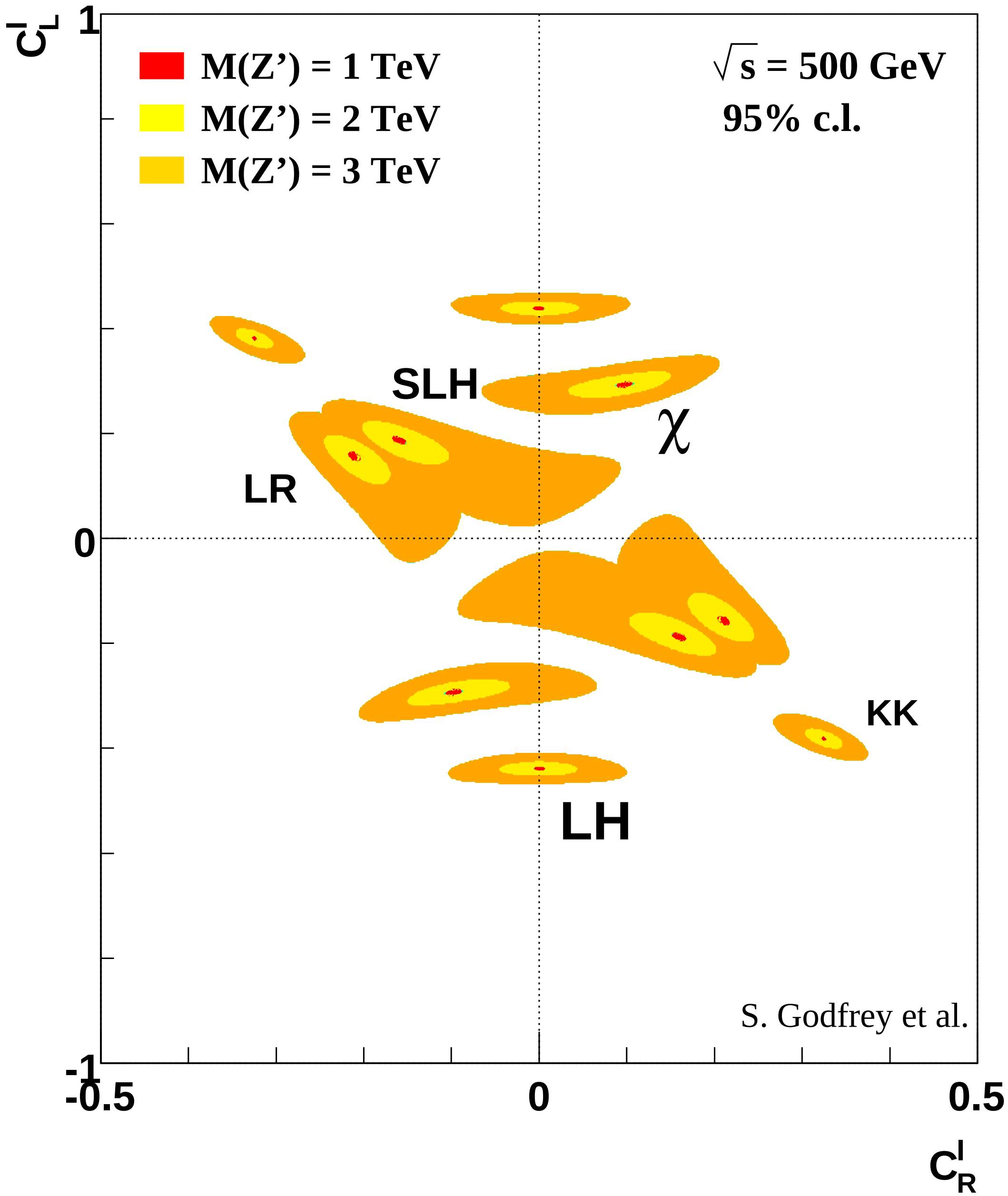
- ILC sensitive to normalised couplings

$$a_f^N = a'_f \sqrt{\frac{s}{m_{Z'}^2 - s}}$$
$$v_f^N = v'_f \sqrt{\frac{s}{m_{Z'}^2 - s}}$$

- For leptons can obtain model independent limits/measurements on normalised couplings
- All hadronic observables depend on product of leptonic couplings (Z'-production) and hadronic couplings (Z'-decay)

➡ Can measure hadronic couplings only if leptonic couplings deviate significantly from zero

Ideal case: LHC discovers a Z', so mass is known and ILC can measure the couplings



- Measure leptonic couplings to few % $m_{Z'} < 2\,\mathrm{TeV}$
- Limits roughly stay constant for $m_{Z'}/\sqrt{s} = \mathrm{const}$
- The ILC can distinguish the models over basically the full LHC discovery range

Conclusions

- There will be a need for new experiments after the end of LHC
- LHC upgrades can solve some of the open problems
- However almost certainly an e^+e^- linear collider will be needed
- The technology for a collider up to 1 TeV exists, the technology for 3 TeV is being developed
- The energy can only be decided once LHC results are there