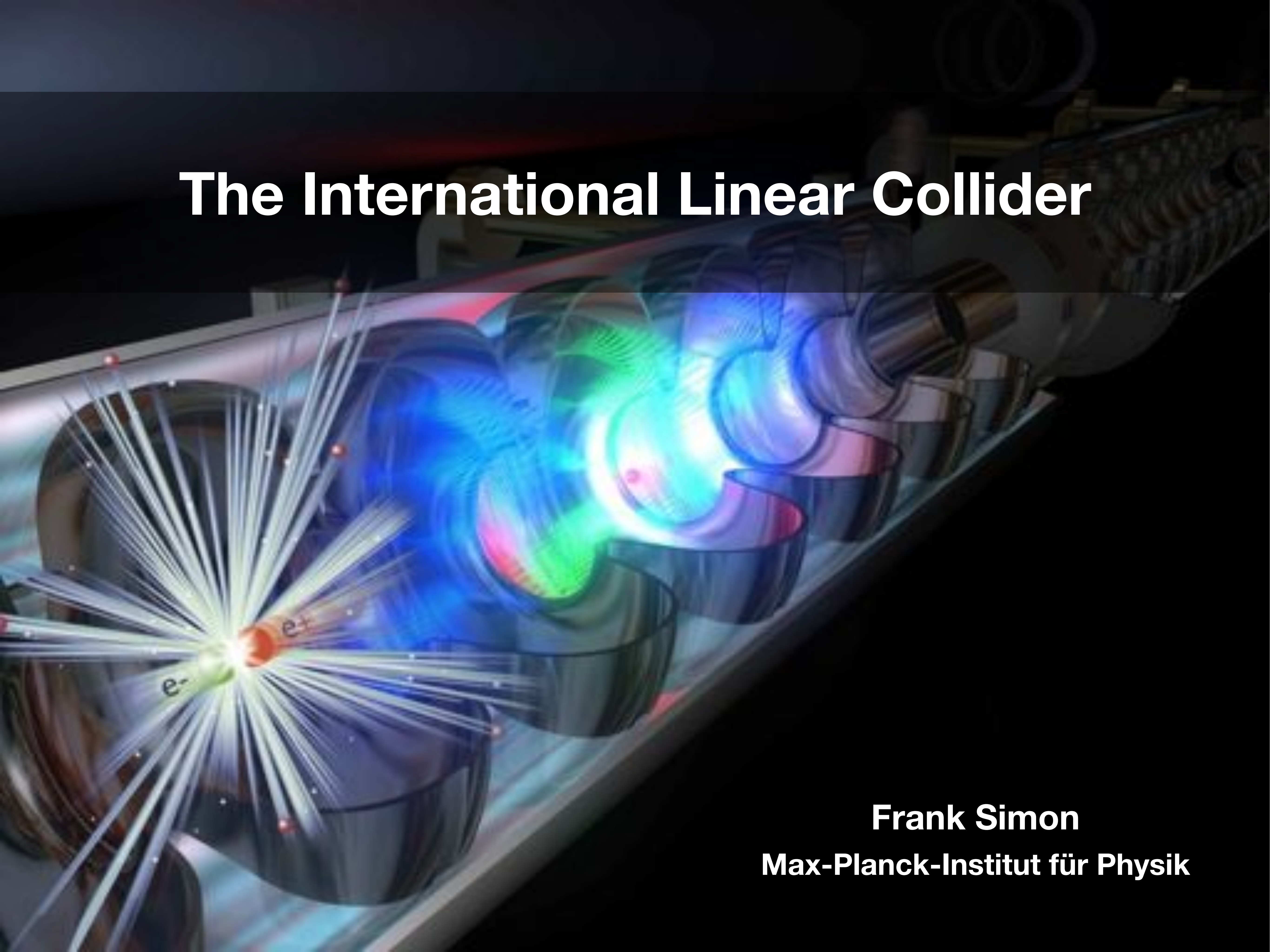
The International Linear Collider



Frank Simon
Max-Planck-Institut für Physik

Outline

- Introduction - Physics at the Energy Frontier
- The International Linear Collider
  - High-energy lepton colliders
  - The ILC design
  - Detectors at ILC
- Physics at the ILC
- Politics, sites & strategies

Physics at the Energy Frontier

BEWARE: Personal bias - use your own judgment!

Current Status of EF Physics - My Perspective

- Research at the energy frontier has brought us the standard model:
  - As higher and higher energies became available discoveries were made, pushing theorists to find explanations with an underlying theory
- A theory allows to make predictions, which can be tested by experiment
  - W, Z bosons: SppS 1983 ✔
  - top quark: Tevatron 1995 ✔
  - Higgs boson: LHC 2012 ✔

With the Higgs, every particle in the SM has been observed - so what is next?

It is obvious that the SM cannot be the final answer, but there is no clear indication where things will break and what should be the next relevant energy scale - unlike the “no-loose” situation for the LHC and the Terascale

Current Status of EF Physics - My Perspective

- What to do without a clear guidance?

Two options in my opinion

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➯ Maximise our knowledge based on things we already know
  - The Higgs: Fully understand electroweak symmetry breaking and the nature of the Higgs potential
  - The Top: Measure its properties as precisely as possible - use it as a potential window for New Physics
  - Other electroweak precision measurements to look for cracks in the SM

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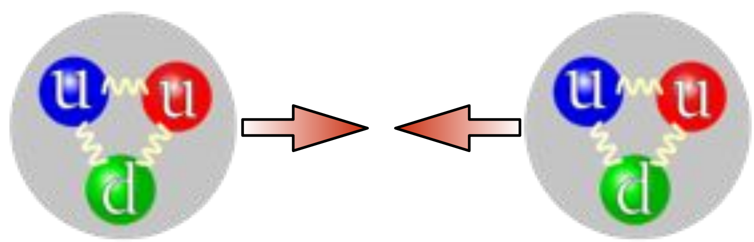
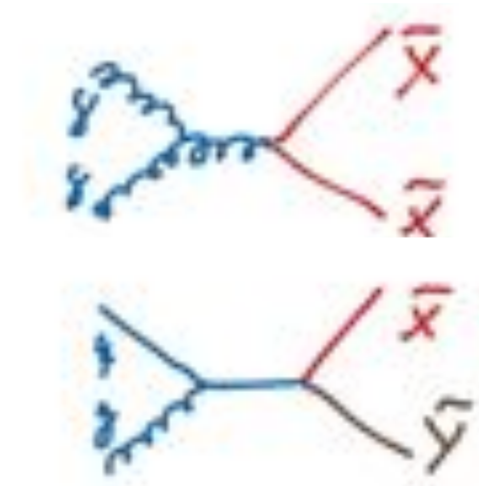
I think we should remember what fundamental research is about:
An open exploration, with uncertain outcome!

Future Facilities at the Energy Frontier - Options

- Two different (complementary) approaches:
  - proton-proton colliders:



composite particles:
initial state unknown,
different processes contribute



technical feature: High mass: (Almost) no radiative losses in synchrotrons
Highest energies - for beyond lepton colliders at present

dominant production via strong interaction (gluons, quarks):
largest cross-sections and highest sensitivity to strongly interacting particles

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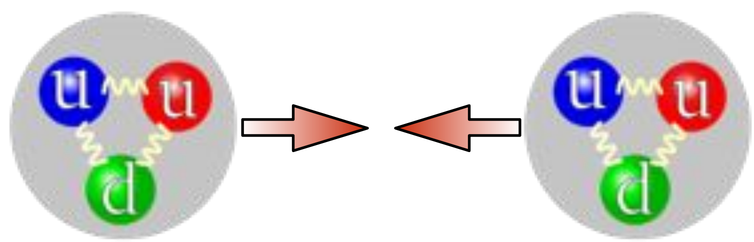

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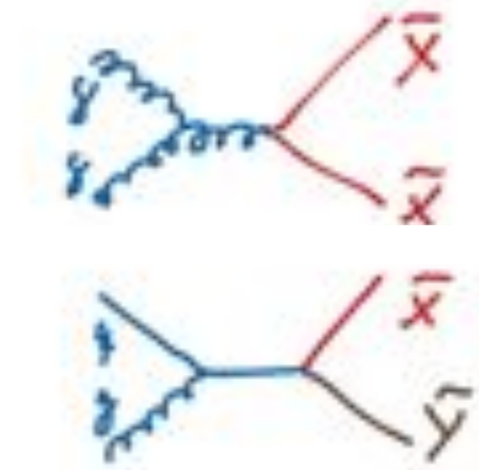

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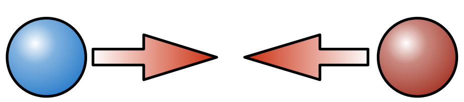
  - electron-positron colliders:

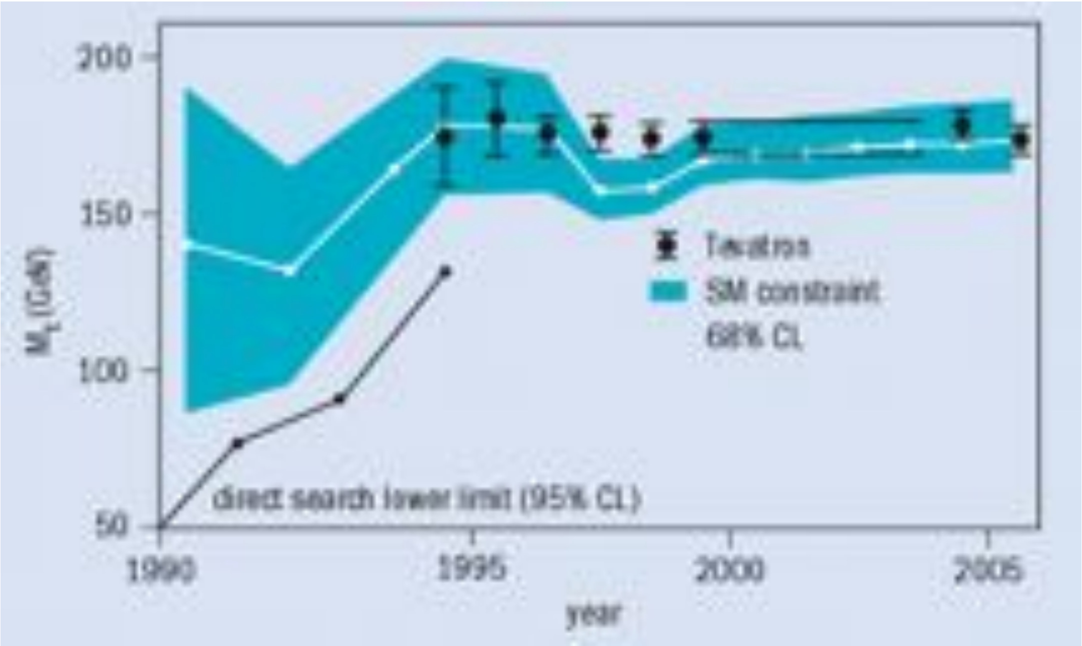


technical feature: low mass: large radiative energy loss in synchrotrons

electroweak production:
all particles produced with ~ equal probability - particularly sensitive to electroweak particles, which are suppressed at hadron colliders

Interplay of Different Facilities - A Success Story

- Pinning down the Top Quark prior to discovery



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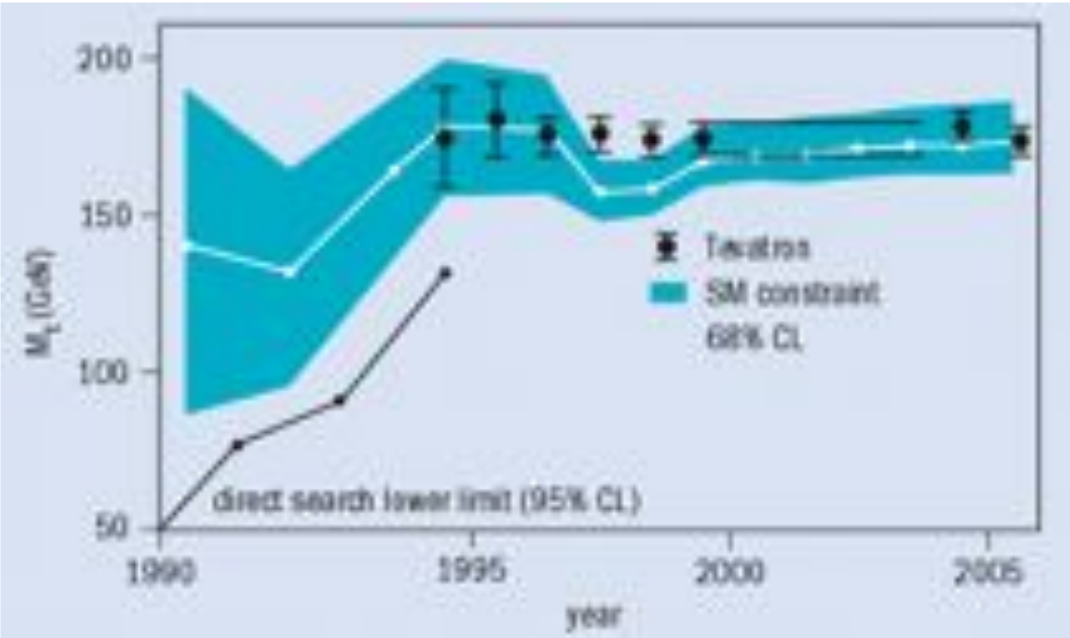
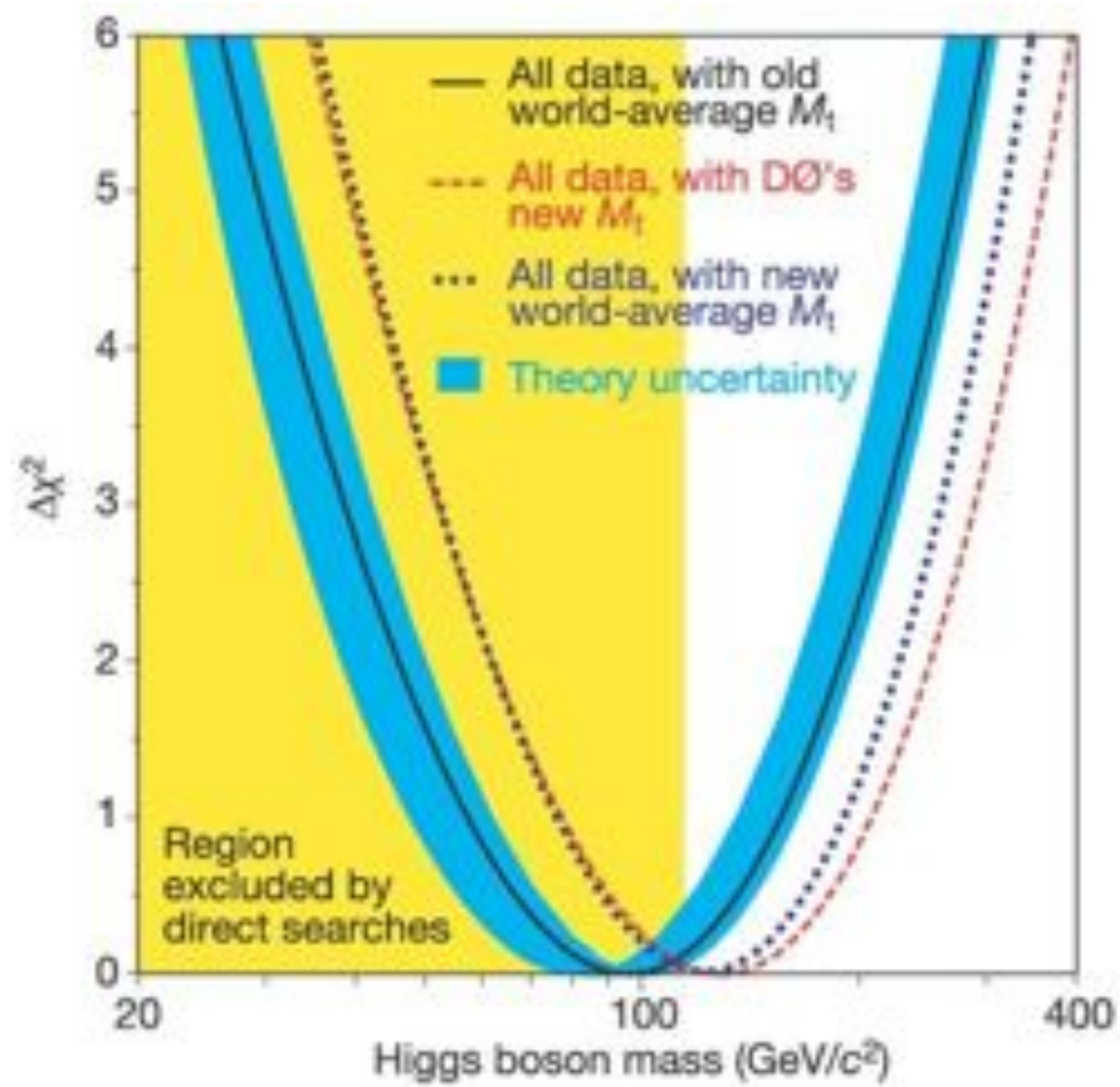


- Indirect constraints of the Higgs mass - highly sensitive to top mass

NB: The world average in this plot is $m_t \sim 180$ GeV - the previous value was substantially closer to the value we have today



Nature 429, 638 (2004)

Interplay of Different Facilities - A Success Story

- Today, often only hadron colliders are associated with discovery
  - Higgs at LHC (2012); Top at Tevatron (1995) ; W, Z at SppS (1983)
- But: also spectacular discoveries with leptons:

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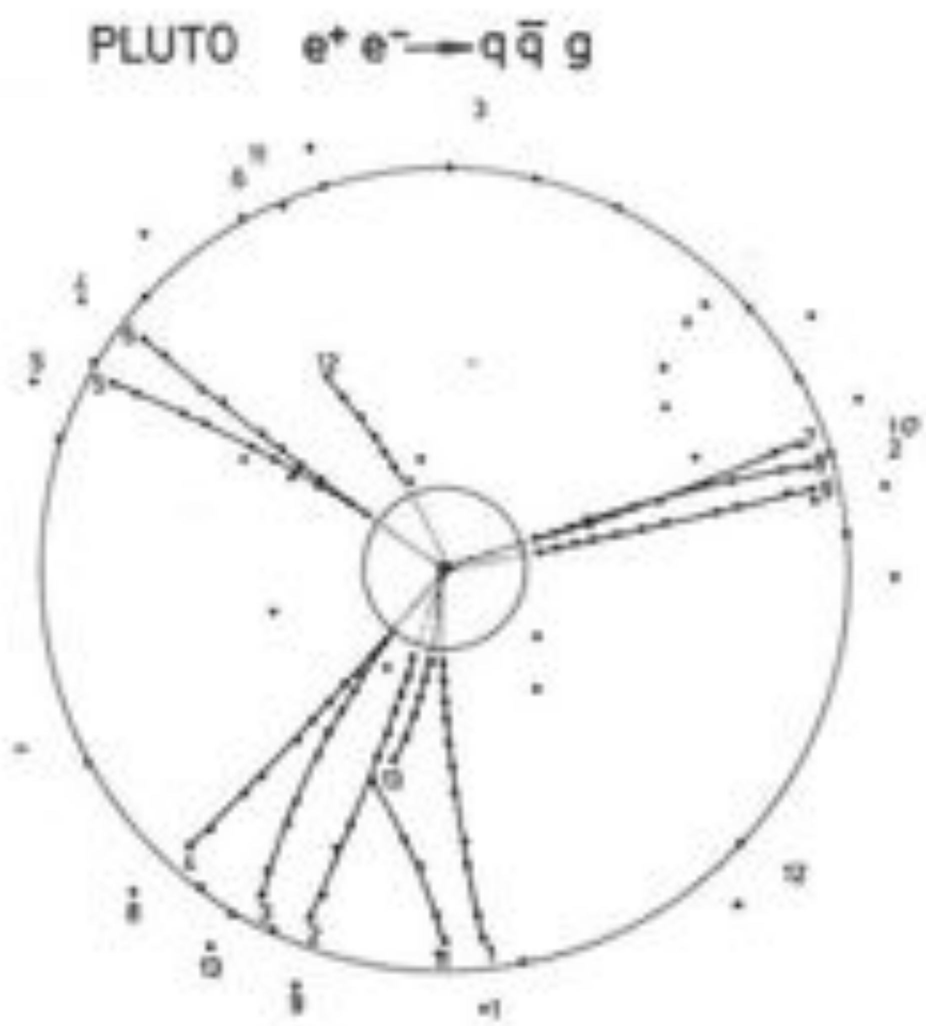
- Proton substructure - quarks at SLAC in DIS experiments (1968)
- J/Ψ at SPEAR (e^+e^- collider at Stanford) (1974) - simultaneously discovered at the AGS (fixed-target hadron beam)
- τ at SPEAR (1975)
- The gluon at DORIS (1978) and PETRA (1979) (e^+e^- colliders at DESY)



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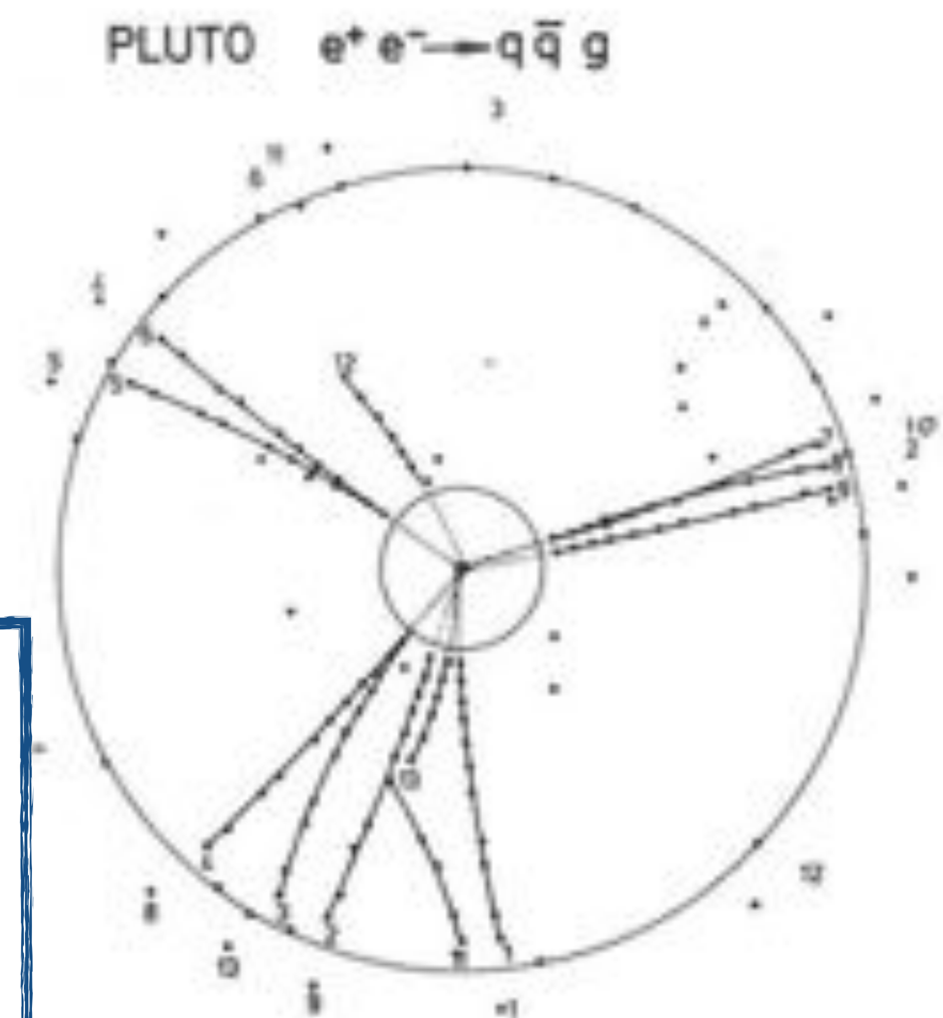
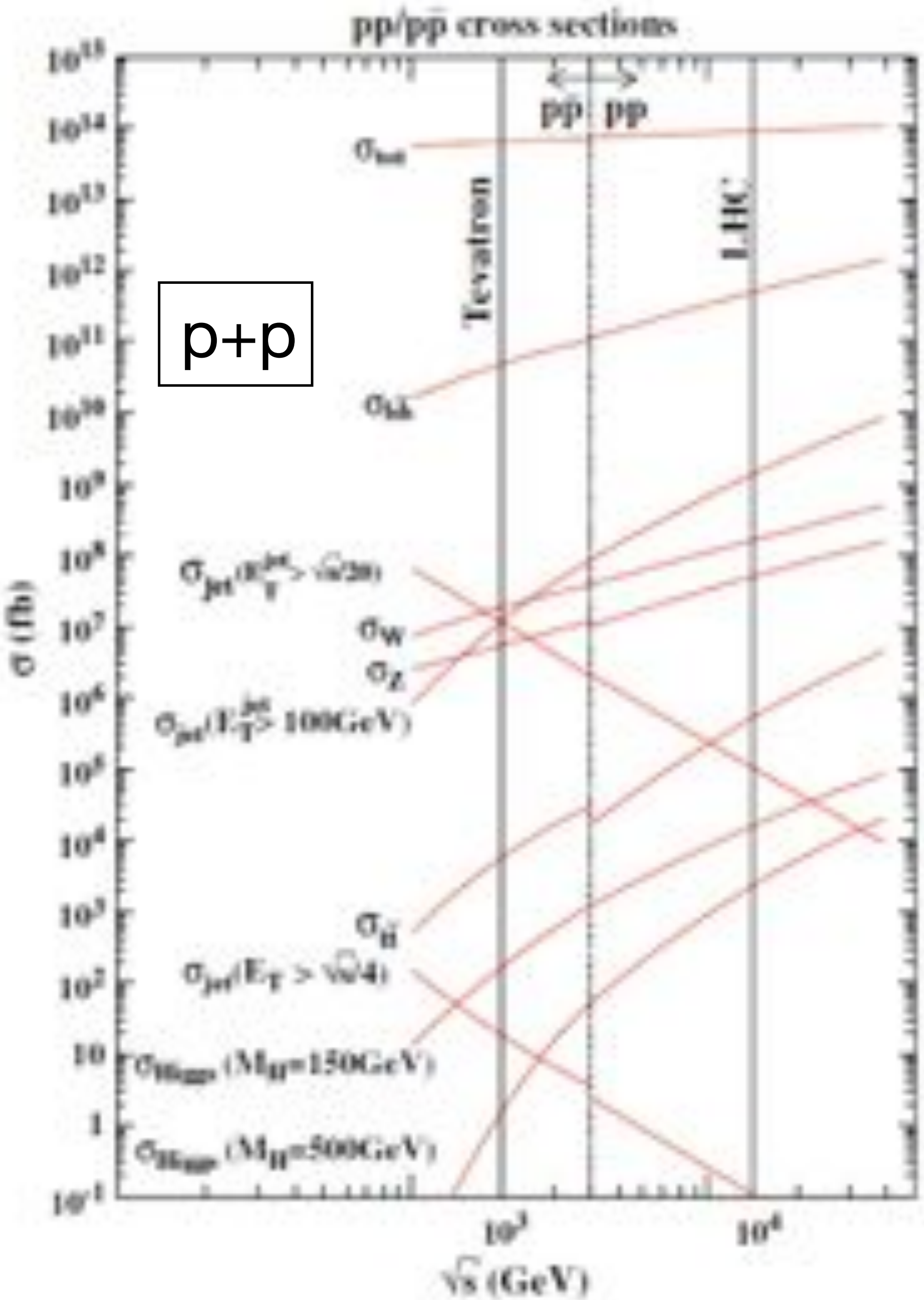
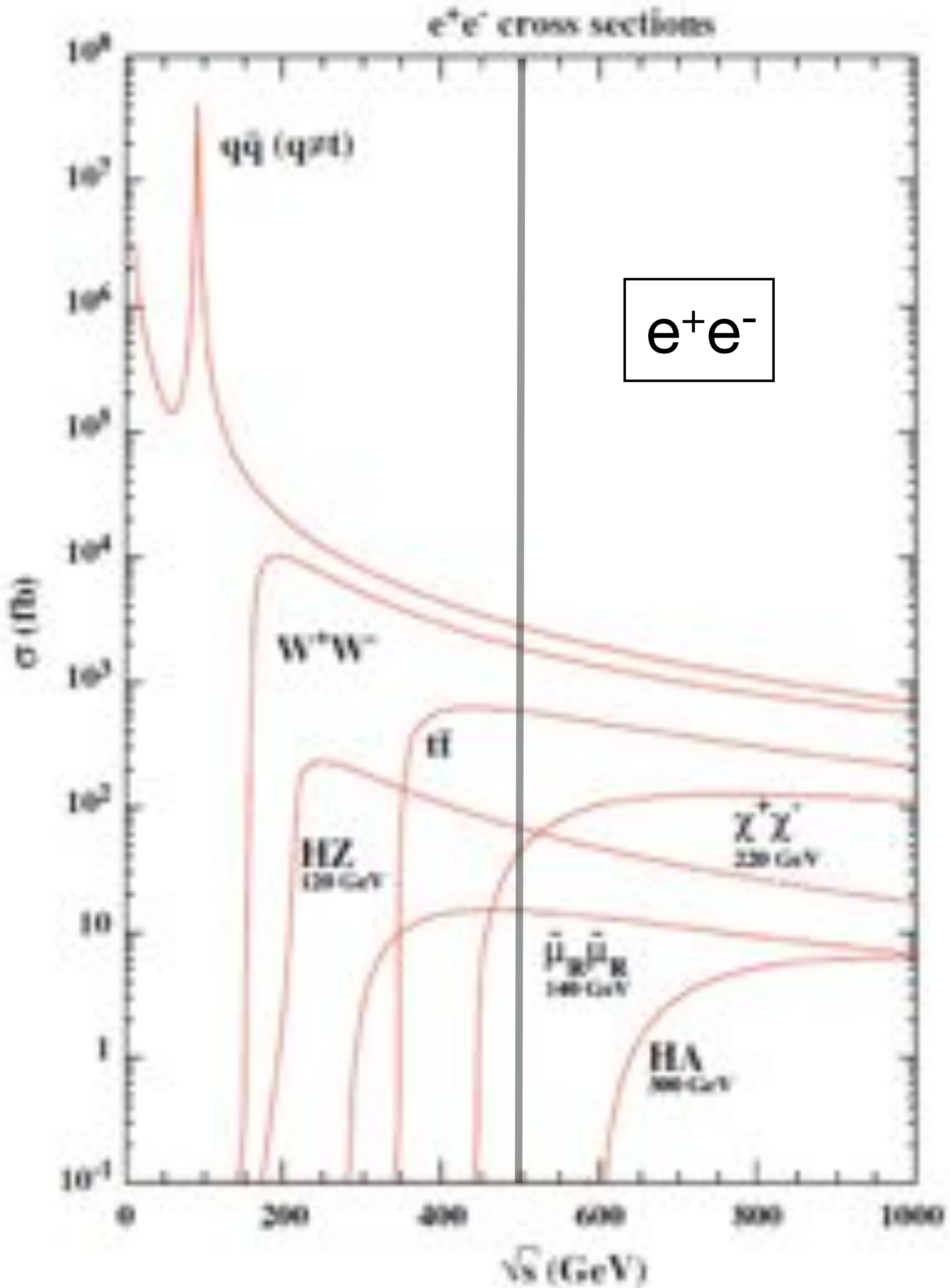


The Standard Model, and with it our understanding of the most fundamental constituents of the universe known to day, was built on discoveries and precision measurements made at a large number of different accelerators using both hadrons and leptons

Hadrons vs Leptons

- Colliding elementary particles, electroweak “universal” production
  - Much more favorable ratio of signal to background





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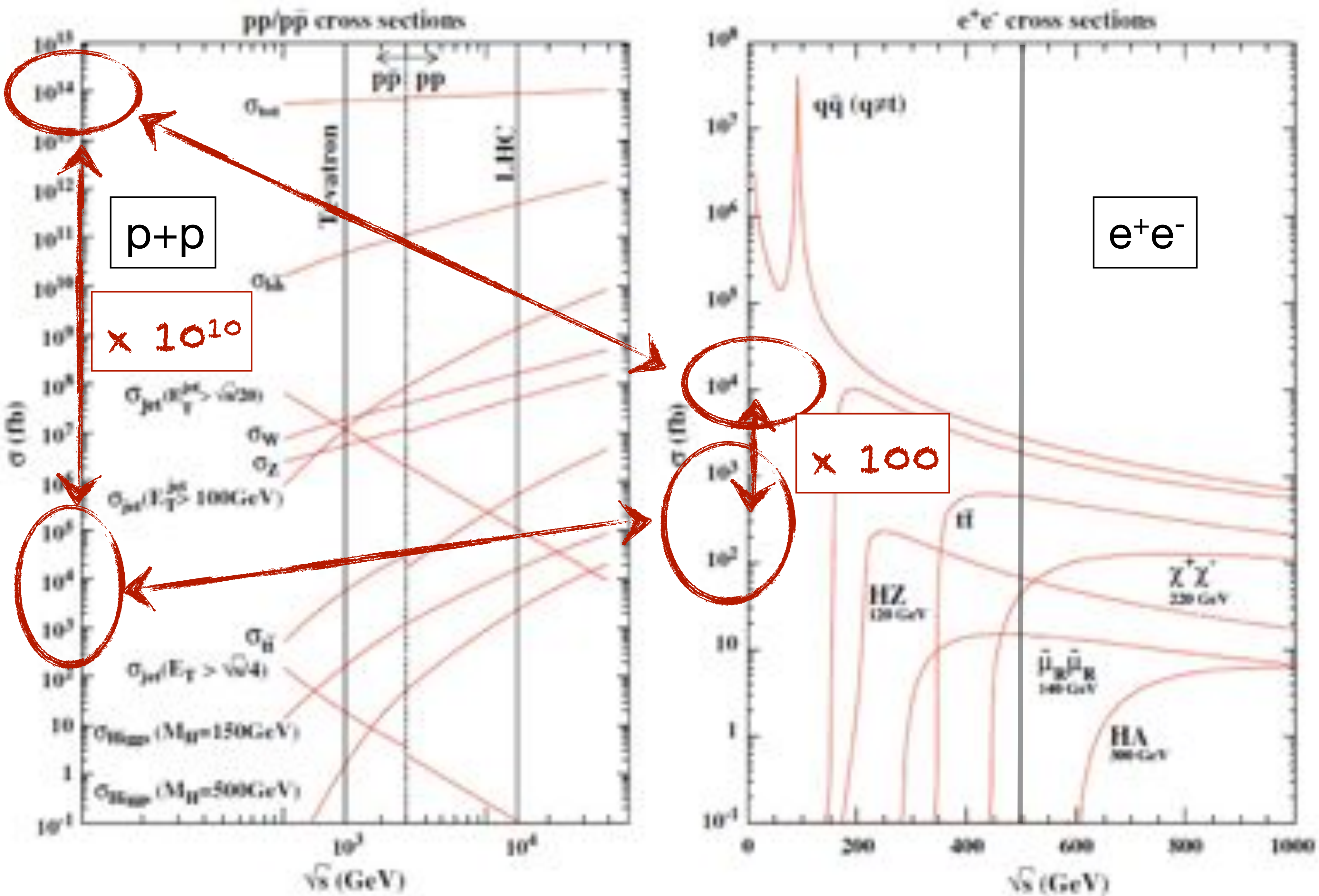

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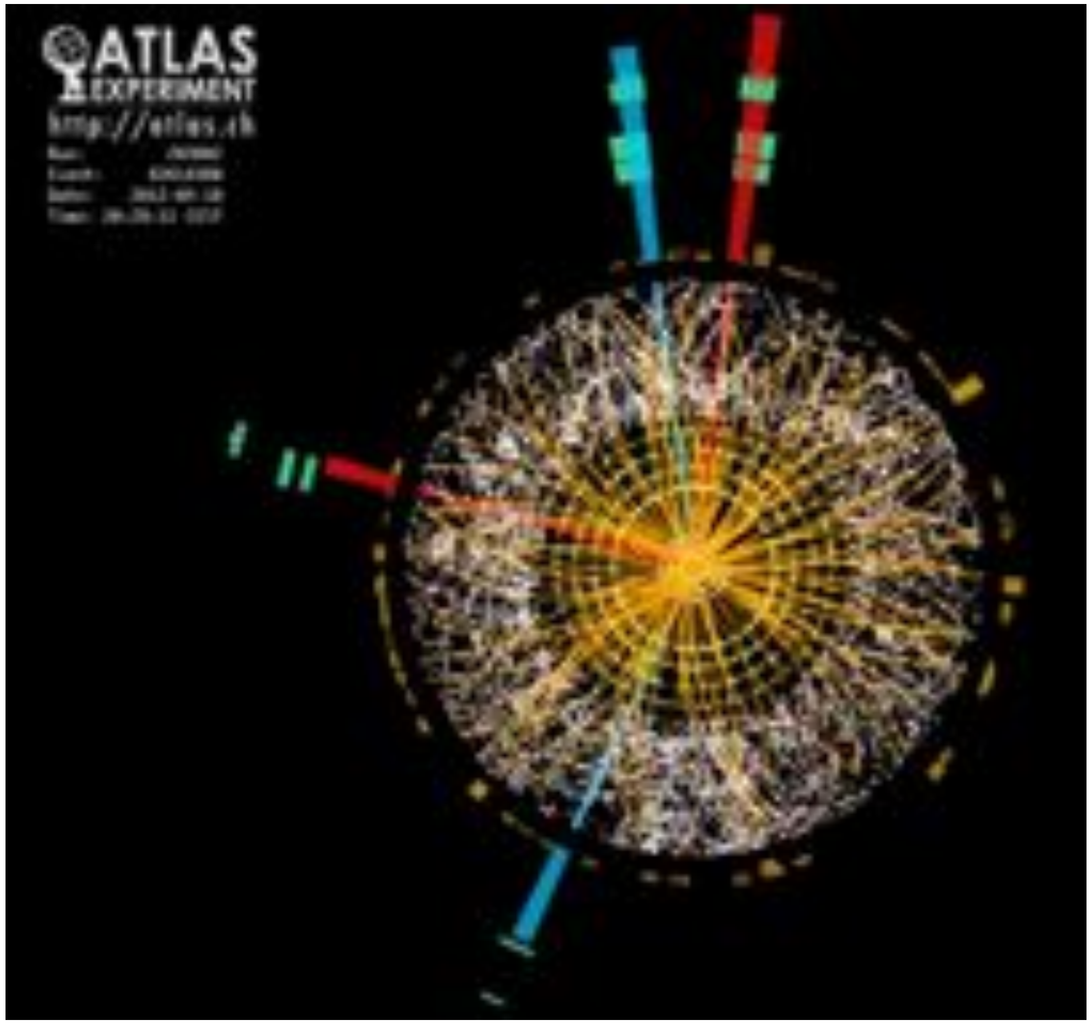
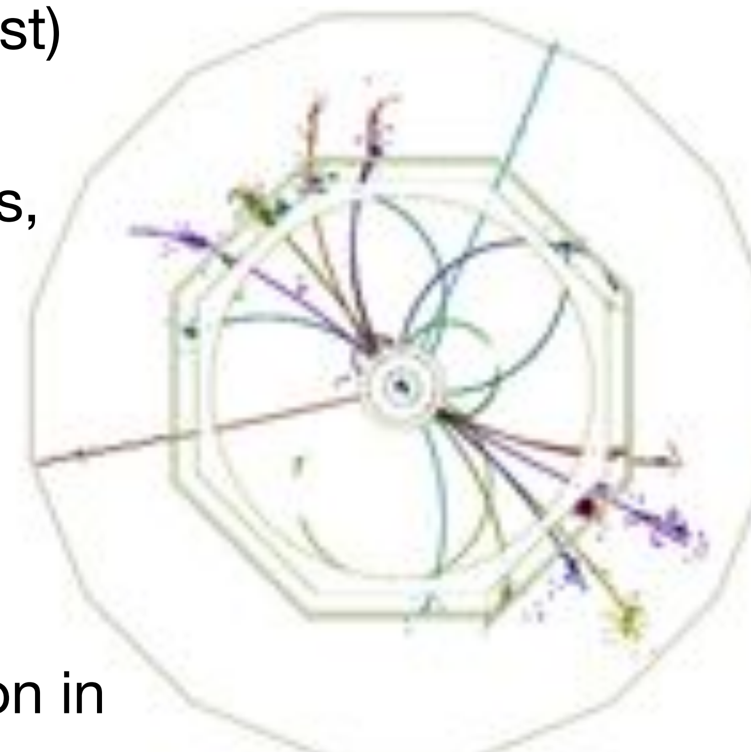


Higgs production in pp: (almost) every particle in the event originates from other reactions, only four leptons are from the Higgs decay



Higgs production in e^+e^-: (almost) every particle in the event originates from the Higgs or the Z produced with it

- At hadron colliders: Triggering is crucial - Need to pick out events based on “interesting” signatures out of 10^9 times higher background
- In e^+e^- collisions: All reactions are equally probable - overall low event rates, but most are interesting - no trigger needed, all collisions are analyzed offline

So - What Next?

- No clear answer - this strongly depends on who you ask…

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My personal conclusion:

➾ We have the LHC - and there is still a lot to come. The energy will almost double next year, and we've seen less than 1% of the total integrated luminosity of the full LHC (including HL-LHC) program - it is far too early to conclude that LHC has found nothing but the Higgs.

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➯ The obvious next step is an e^+e^- collider that can explore all aspects of the Higgs and Top sectors, and complements the LHC for new electroweak particles. This requires energies at least up to 500 GeV, and the possibility to go to 1 TeV or beyond

The International Linear Collider

e^+e^- Colliders at the Energy Frontier

- e^+e^- machines were the first colliders - it started in 1961 with ADA (Frascati)
  - Constructed as storage rings - the synchrotron radiation damping helped with beam capture, leading to small emittance beams
  - Protons more challenging - first collider ISR at CERN (construction start in 1966)
    - A smaller number of machines - most notably ISR, SppS, Tevatron, LHC - but they took the lead in the energy frontier - Why?

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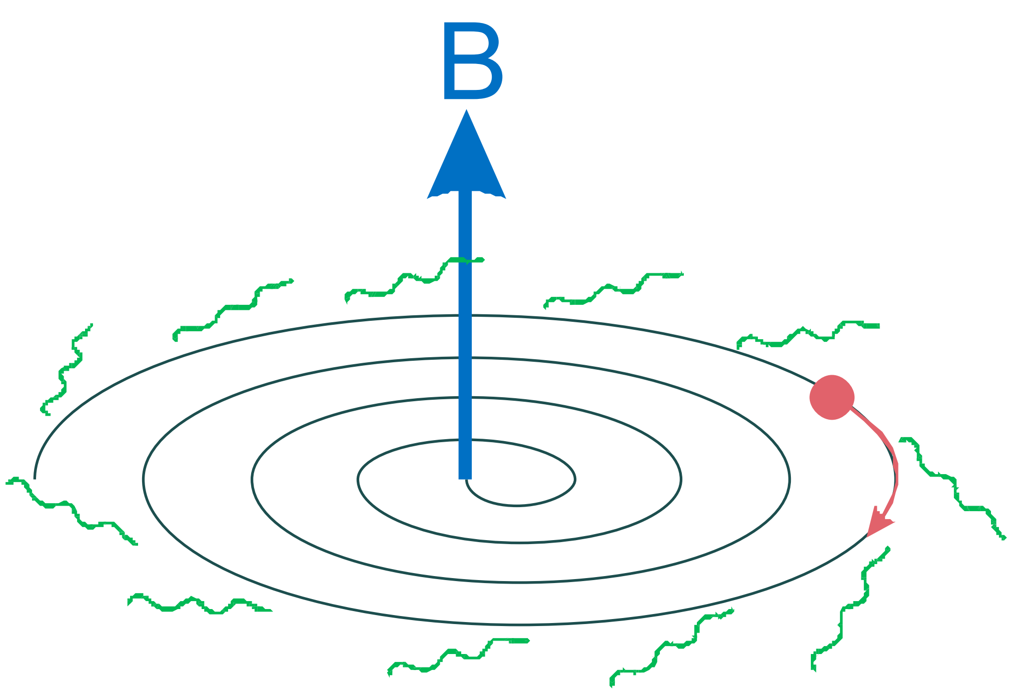
- Charged particles emit electromagnetic radiation when accelerated - for example in a bending magnet of a circular accelerator



Power of radiation proportional to:

γ^4 ➪ **E^4**, or, for constant E: **m^{-4}**

R^2 ➪ energy loss per turn proportional to **R**

➪ Places a hard limit on the energy achievable with electrons in storage rings - at the same energy in the same ring, electrons loose **10^{13} x** more energy than protons

e^+e^- Colliders at the Energy Frontier

- The solution to the synchrotron radiation problem: a linear collider

- So far only done once - SLC - in a somewhat “simplified” form: Only one LINAC for both electrons and positrons
  - SLC was far outperformed by LEP - all big successes in the collider era of HEP come from synchrotrons / storage rings

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One major challenge: Luminosity!

- In a storage ring particles get re-used many times, high bunch-crossing frequency
- At a linear collider each particle gets a single shot - in addition average bunch-crossing frequencies are lower due to the need of constant injection (damping, …)

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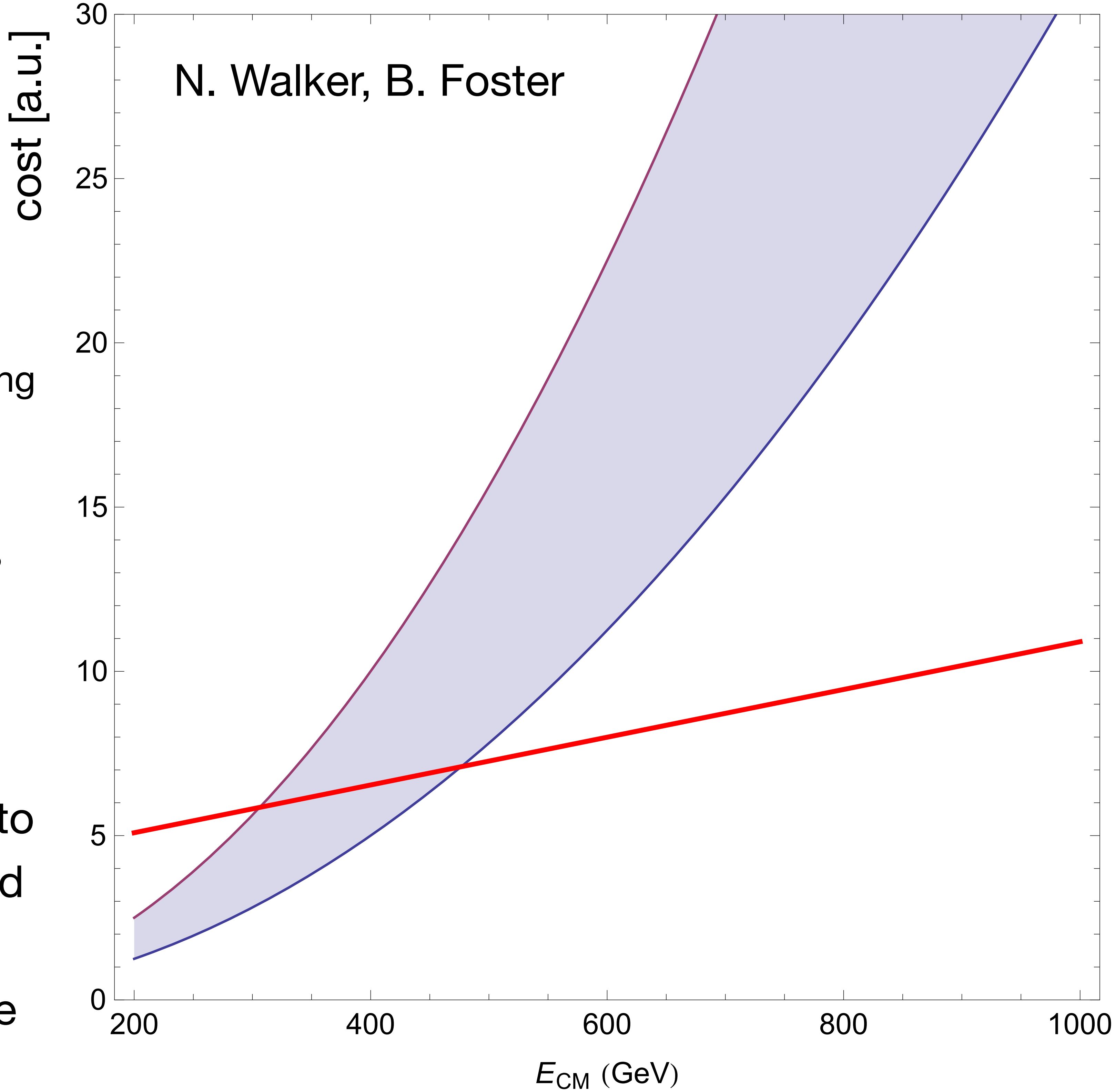
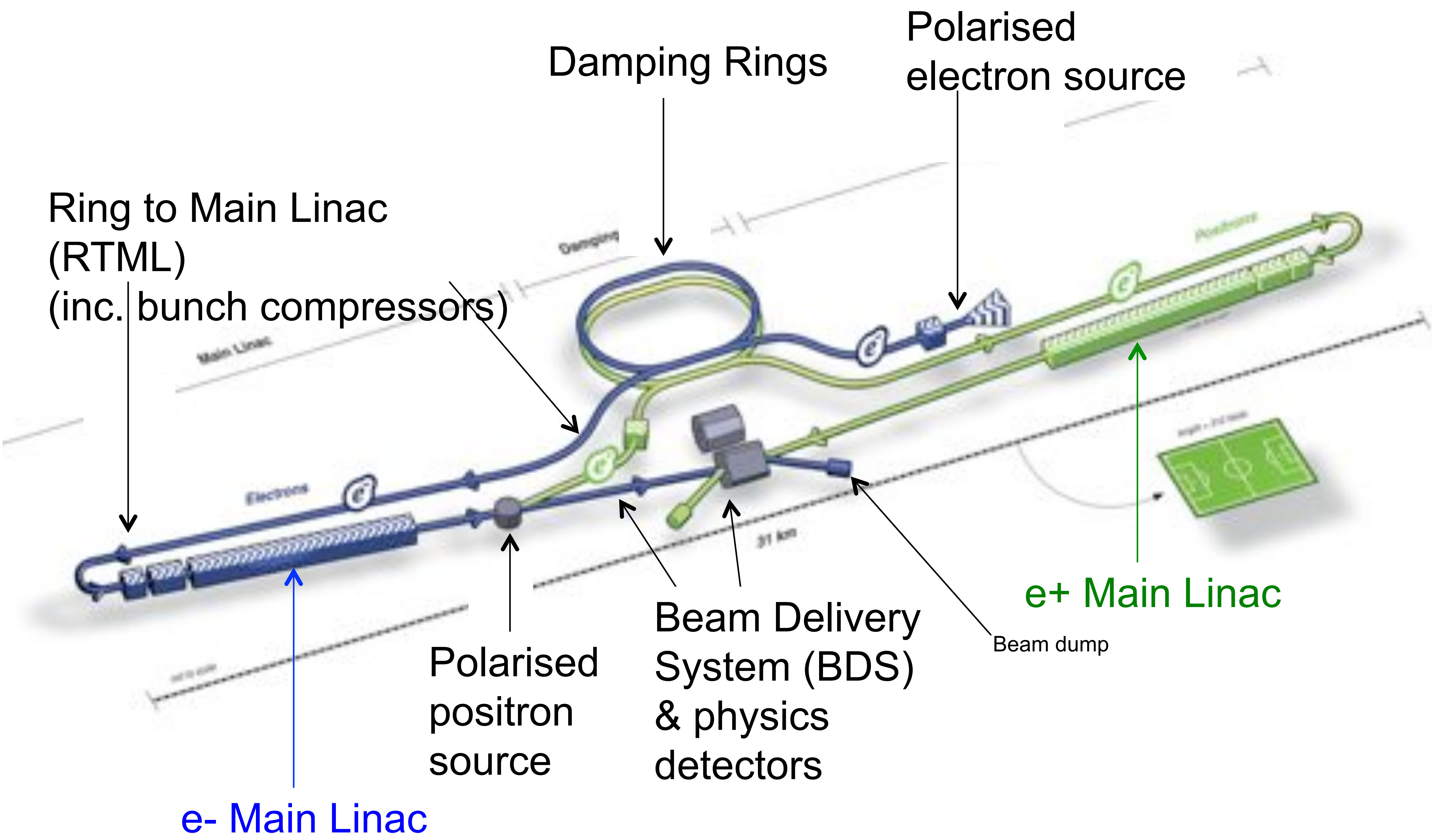
The solution: tiny beams! Cross sections of a few 100 nm x a few nm (compared to a few 100 μm x a few μm at LEP) => a gain of a factor 10^6 - more than compensates for the lower repetition rate

e^+e^- Colliders at the Energy Frontier

- You can't beat the laws of physics:
  - Very simple cost model for storage rings:
    $a\ E^4/R + b\ R$
    (a and b taken from LEP - band using optimistic and pessimistic ways of calculating LEP costs)
    NB: Luminosity steeply drops with E in this scenario!
  - A Linear Collider:
    $c + d\ E$
    NB: Relative large offset due to complex infrastructure needed irrespective of final energy - this makes storage rings more efficient up to ~ 300 GeV

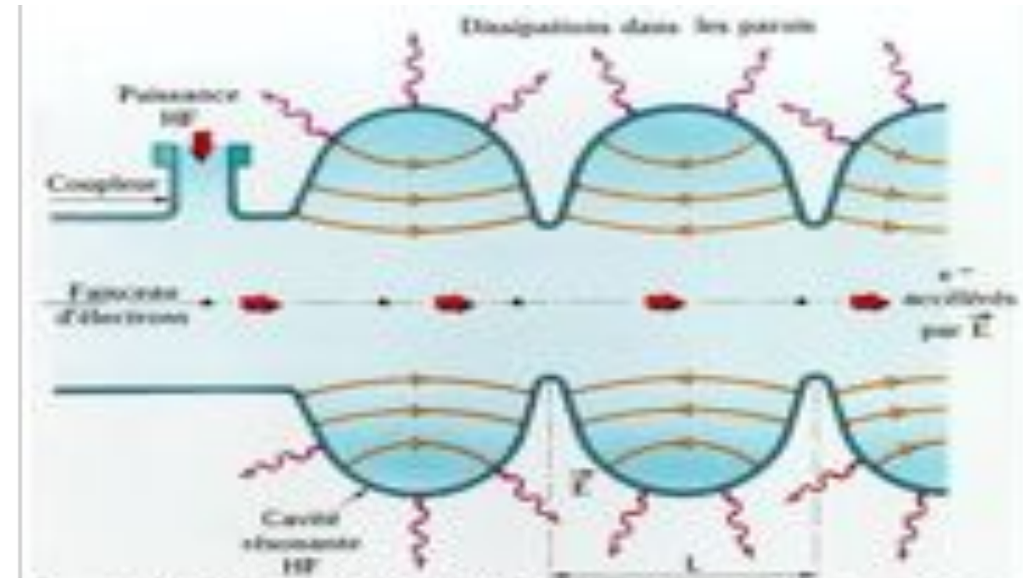


A Linear Collider - The Main Building Blocks



The Heart of ILC: Superconducting RF

- The length of a LC (and with that to some extent the cost) is determined by the acceleration gradient
- For ILC: superconducting RF cavities
  - eliminates ohmic losses on cavity walls - allows long pulses, high efficiency
  - Acceleration gradient 31.5 MV/m
    - For Higgs factory (250 GeV) :
      8 km of pure acceleration structures
    - 500 GeV collider: 16 km



http://www.supraconductivite.fr/media/images/Applications/image037.png

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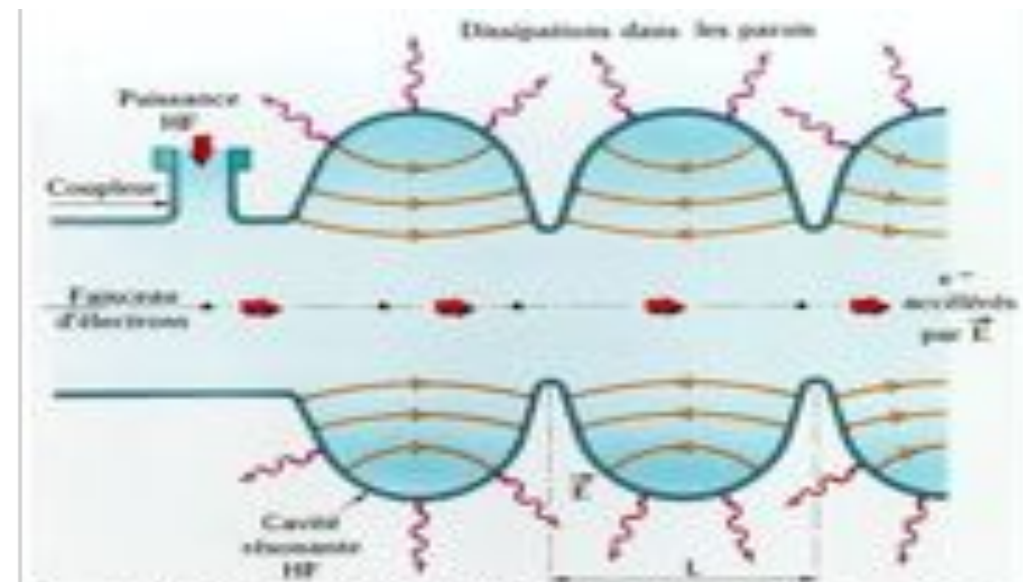

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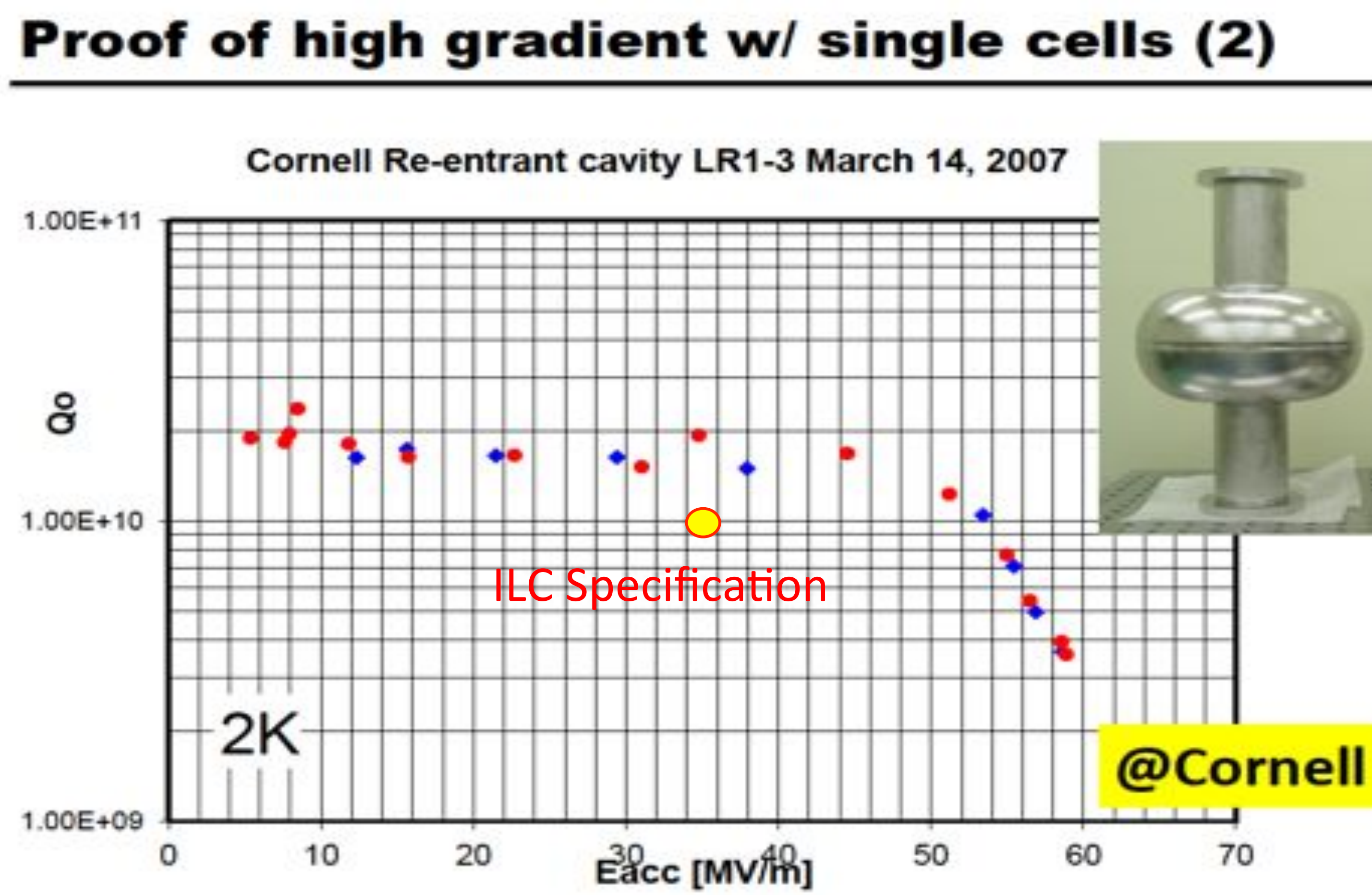
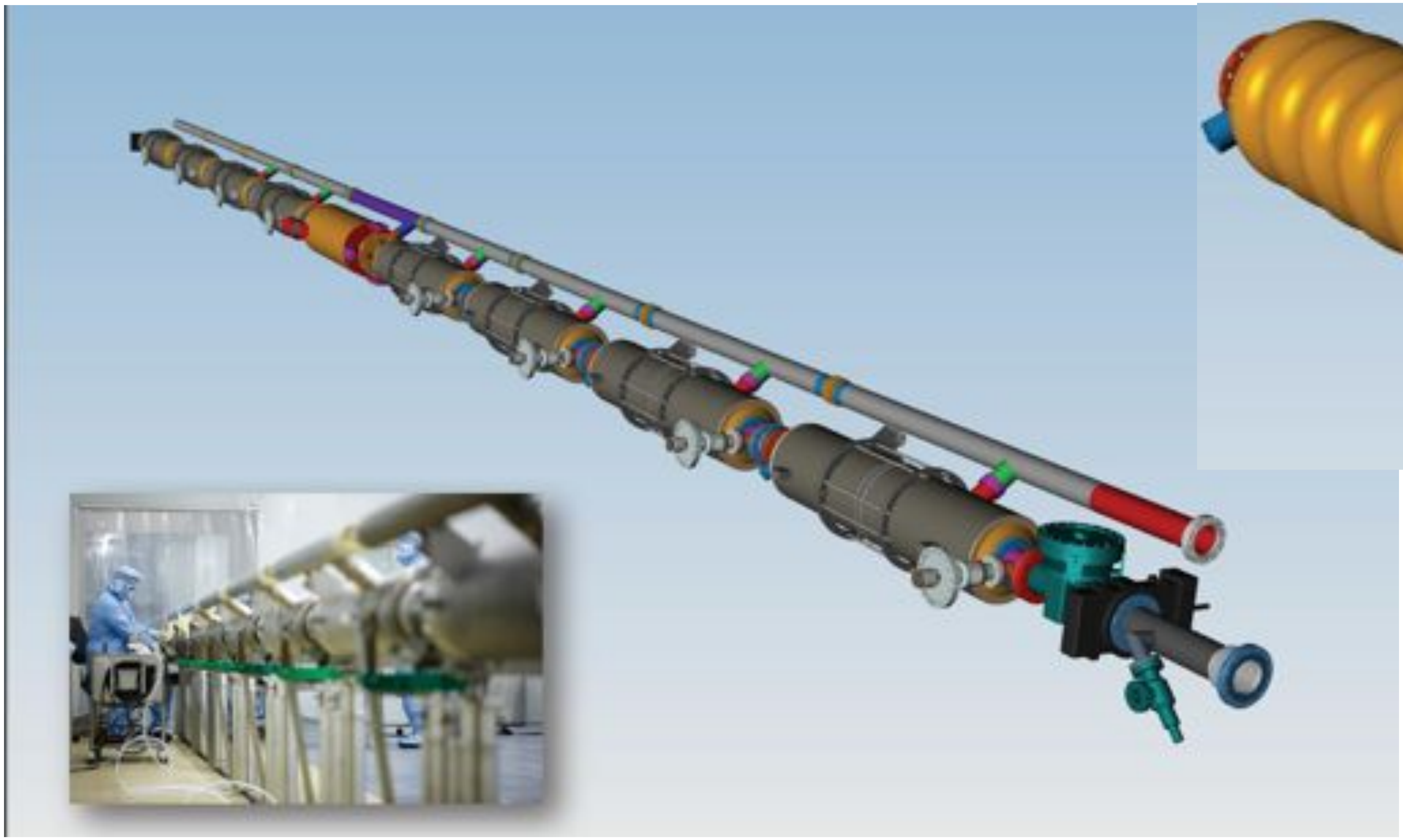
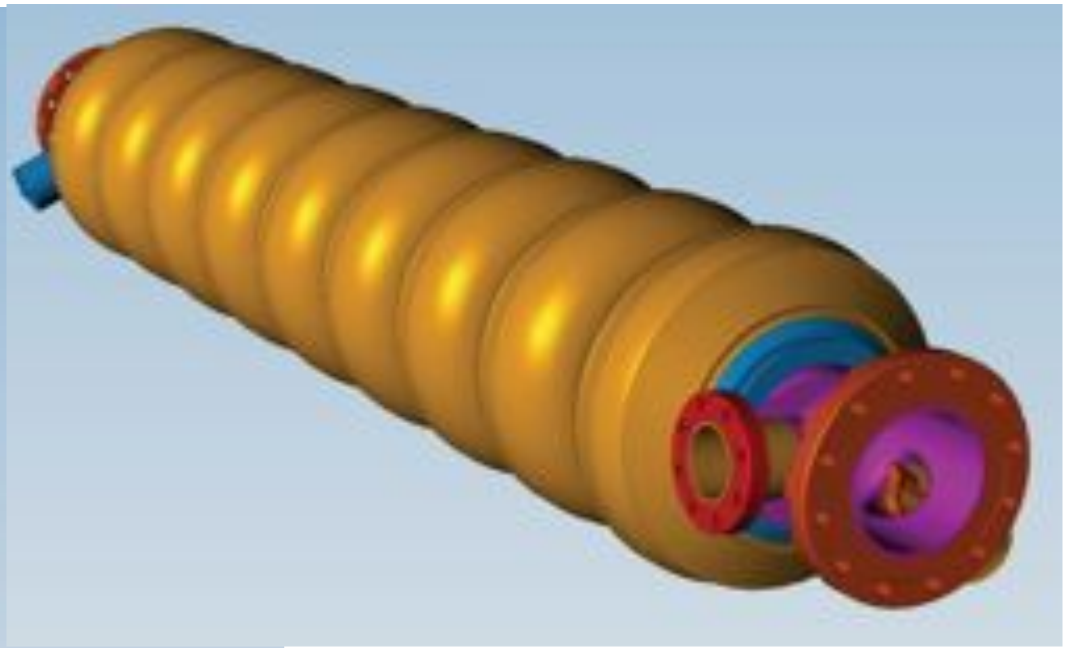
Mature technology - single cells can reach gradients far in excess of requirements: 50+ MV/m



The basic ILC Building Block: A Cryo-Module

- 8 9-cell modules will be combined into a cryo-module





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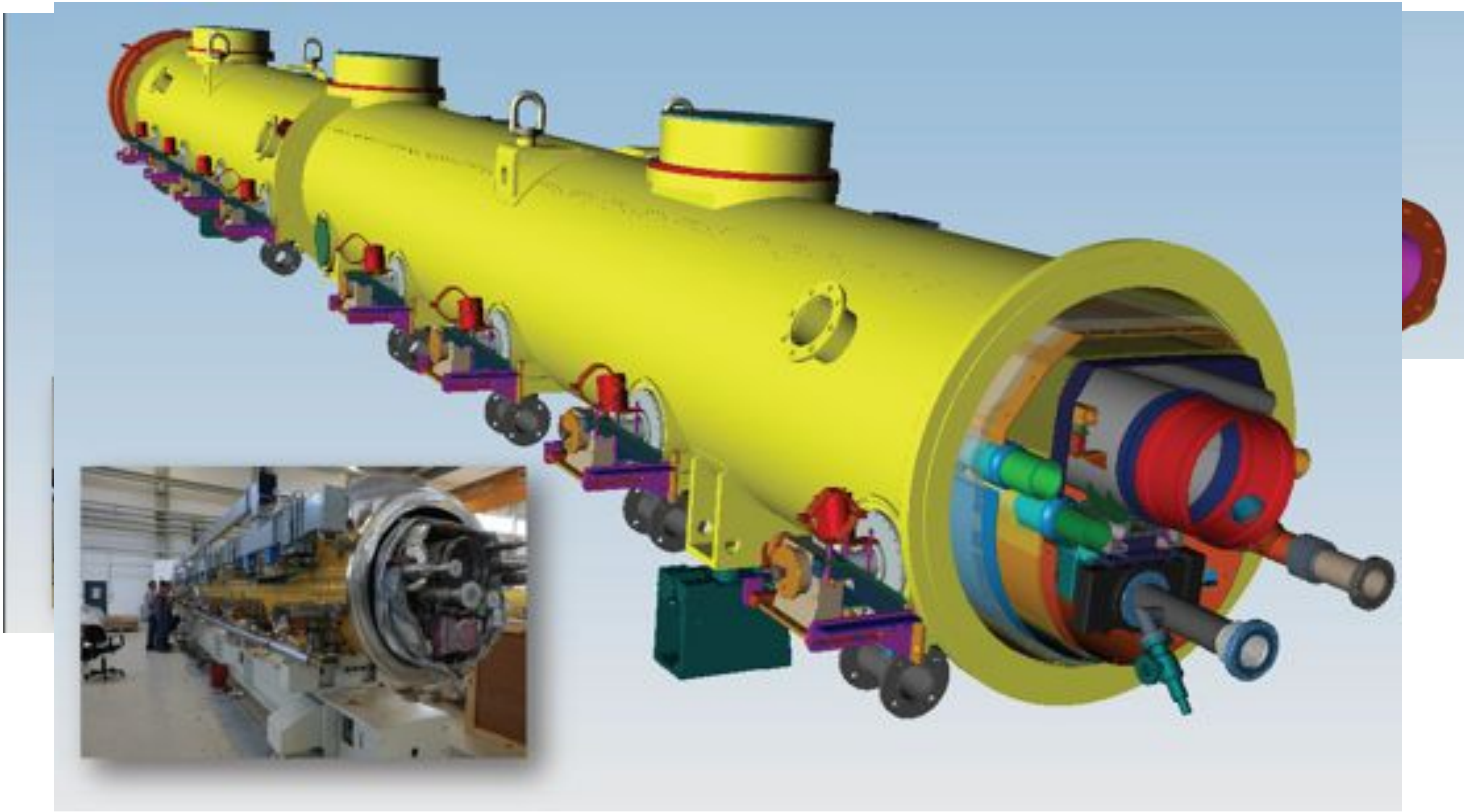
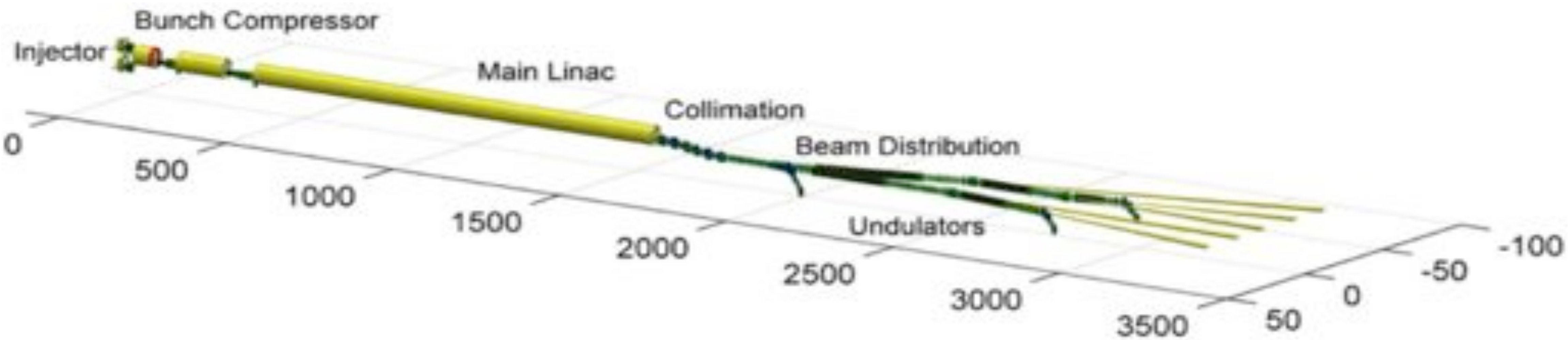


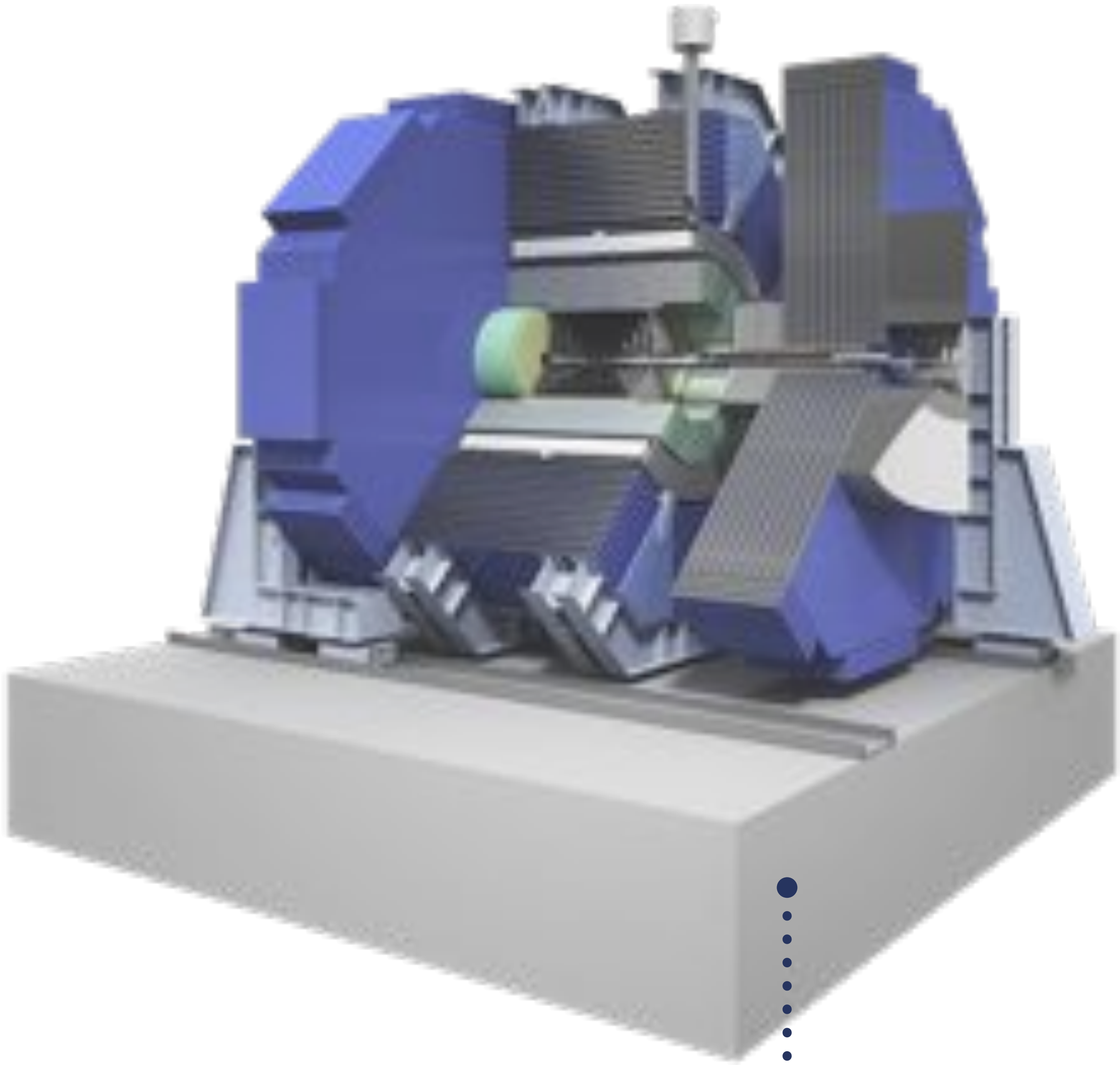
The Technology is real: European XFEL

- 500 GeV ILC: 1855 cryo-modules
  - Currently in construction: XFEL at DESY - 100 cryo-modules based on SCRF a “10% prototype” of the e$^-$ arm of the ILC



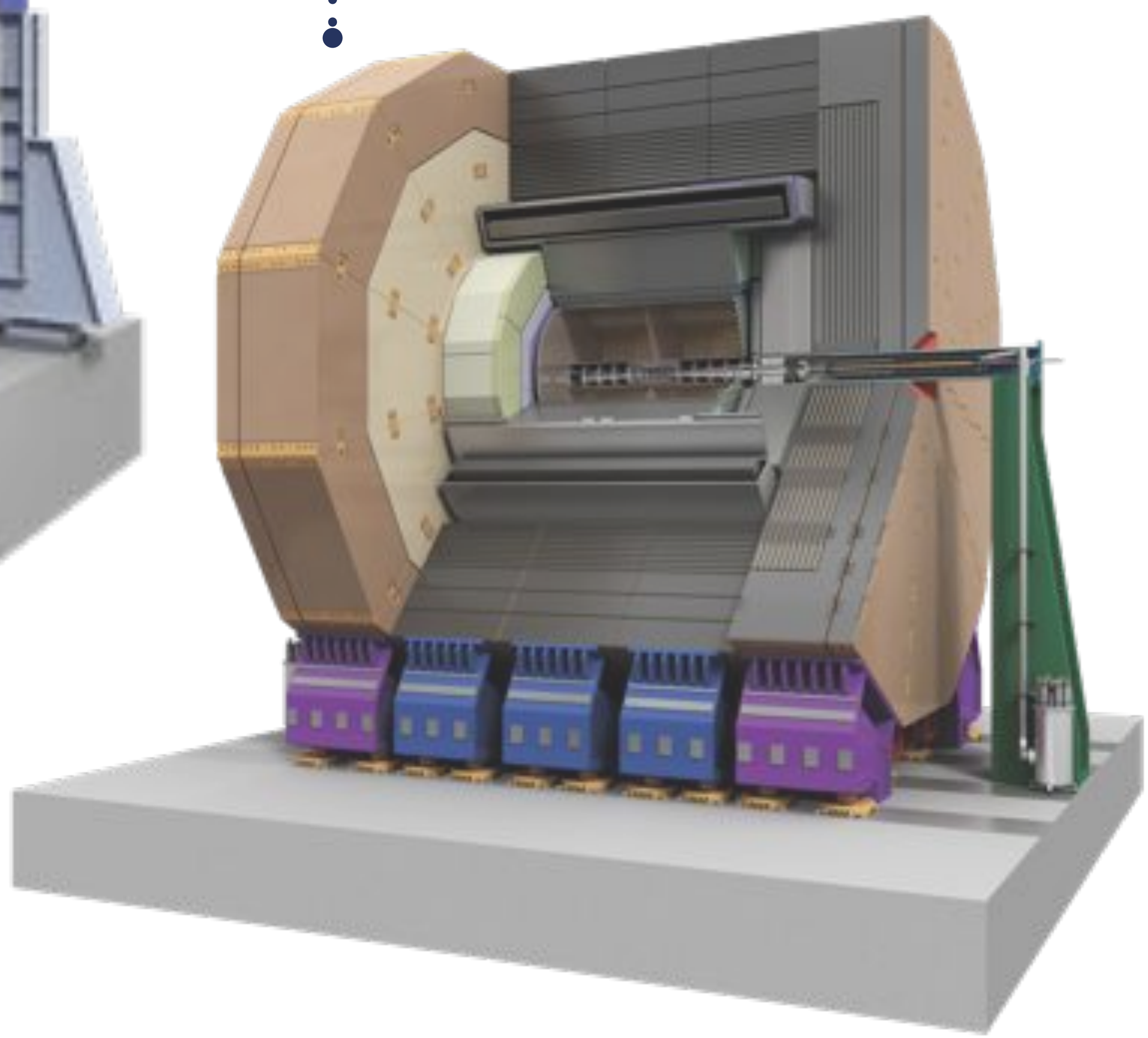
Detectors for the ILC

- Concepts for the Experiments (“Detectors”) at ILC exist, the physics capabilities have been studied in detailed simulations



SiD (Silicon Detector)

ILD (International Large Detector)



Performance Requirements (Physics Driven)

- Precise vertexing - impact parameter resolution for flavor tagging:

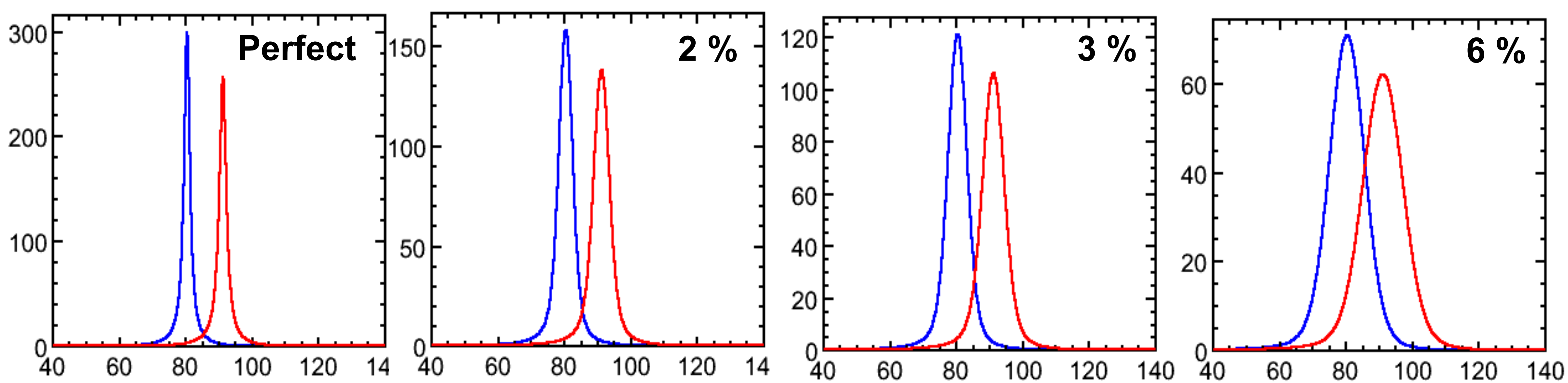
$$\sigma_b < 5 \oplus 10/p\beta \sin^{3/2}\theta \;\mu\text{m}$$

- High resolution tracking - transverse momentum resolution

$$\delta(1/p_T) \simeq 2 \times 10^{-5}/\text{GeV}/c$$

- Jet energy resolution ~ 2.5 σ separation of W, Z (not too far from perfect separation)

$\Delta E_{Jet}/E_{Jet}$ ~ 3.5%



Resulting Main Design Parameters

- A multi-layer pixel detector with small pixels close to the interaction point
- High resolution tracking detectors
- A strong magnetic field
- Low material budget - Eliminate multiple scattering as much as possible
- Imaging calorimeters inside of the magnet & particle flow algorithms

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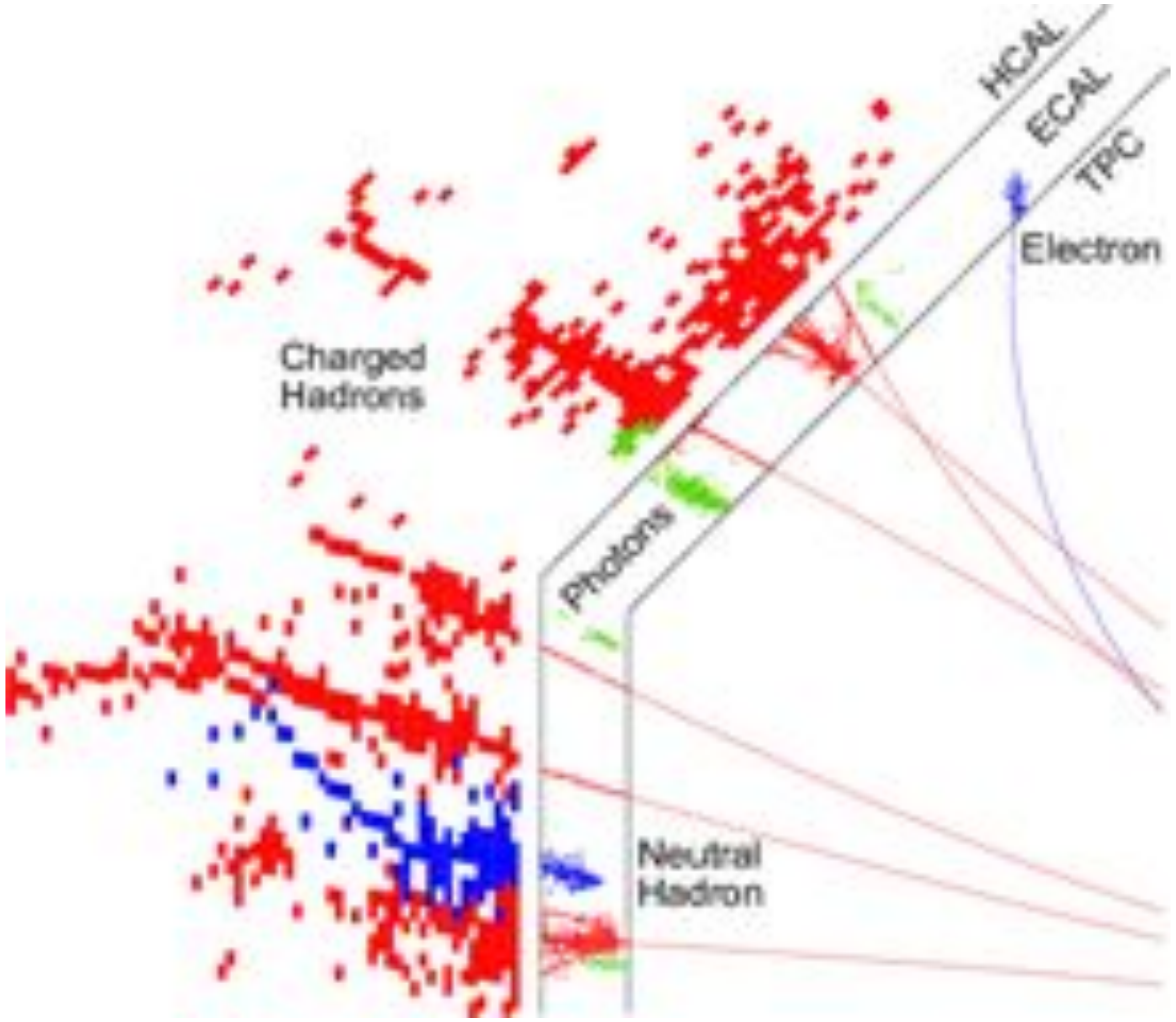
Where this leads you: A detector design a bit like CMS, but

- Shorter detector barrel: Only small boosts of CMS system in ILC collisions
- Very different calorimeters: No emphasis on photon resolution, granularity instead to achieve best jet energy resolution- HCAL plays a central role
- Much more aggressive reduction of material budget
  - Reduced need for cooling: Power-pulsing possible
  - Time for readout between bunch trains
  - Technological advances - Thinner silicon, low-power electronics, light-weight mechanics,...

The Fundamental Design Principle: Particle Flow



- A modern approach to event reconstruction: Reconstruct every single particle in an event, instead of thinking in "towers"
  - Enables excellent jet energy resolution by making use of all available measurements of a particle
    (***p*** in tracker, ***E*** in calorimeters)

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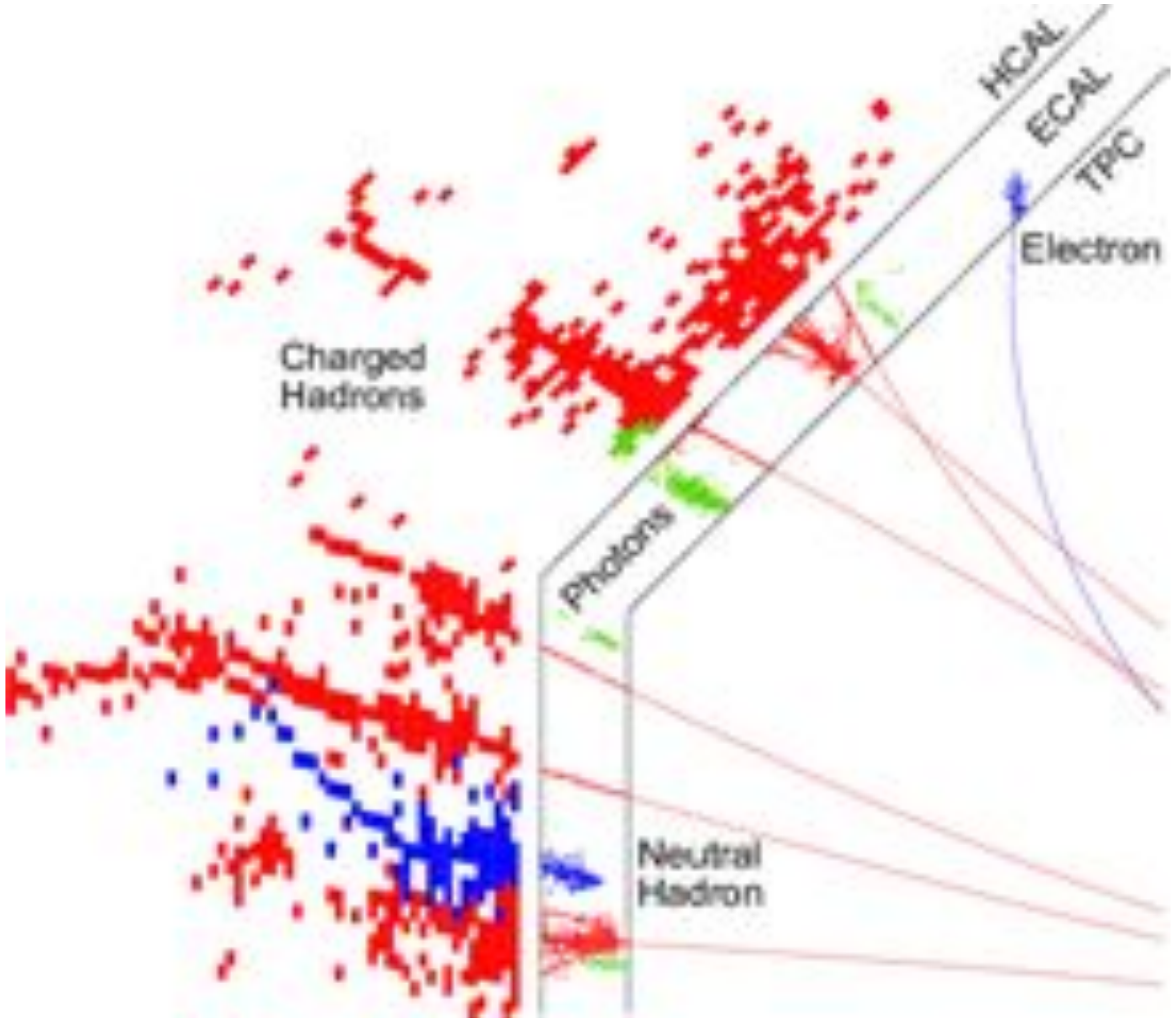
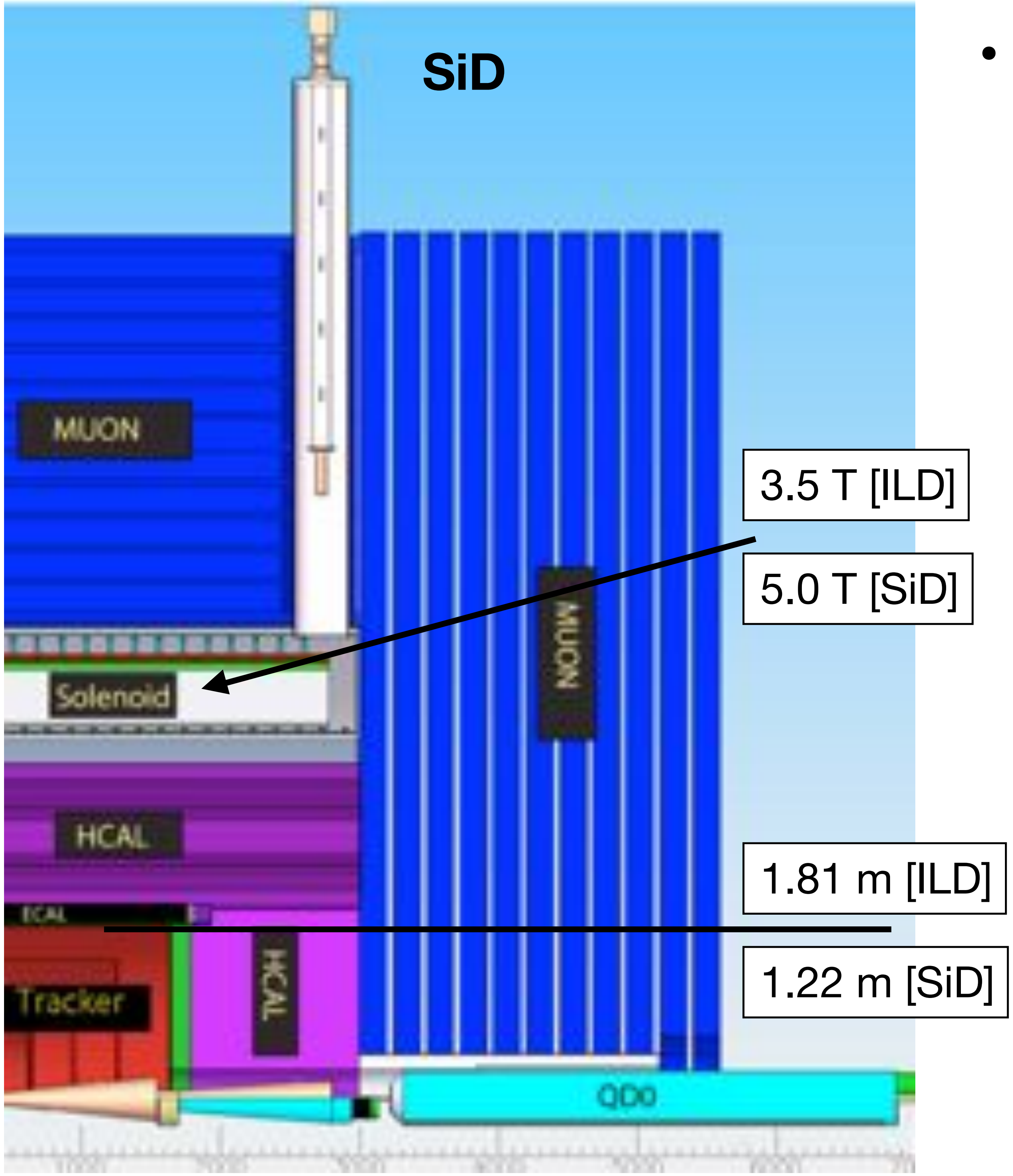


- A modern approach to event reconstruction: Reconstruct every single particle in an event, instead of thinking in “towers”
  - ▸ Enables excellent jet energy resolution by making use of all available measurements of a particle (p in tracker, E in calorimeters)

- Separation of close-by particles often more important than pure energy resolution
  - ▸ Highly granular detector systems, in particular also in the calorimeters!

Two Slightly Different Approaches: ILD & SiD



- The requirements allow some flexibility for design choices - the main parameter is the radius of tracker
  - To reach p_T resolution requirements:
    - smaller tracker requires higher field
    - smaller tracker requires higher spatial resolution for space points
  - To reach required PFA performance:
    - smaller tracker requires higher field to improve particle separation, splitting of charged & neutrals in jets
    - higher field favors higher granularity in calorimeters

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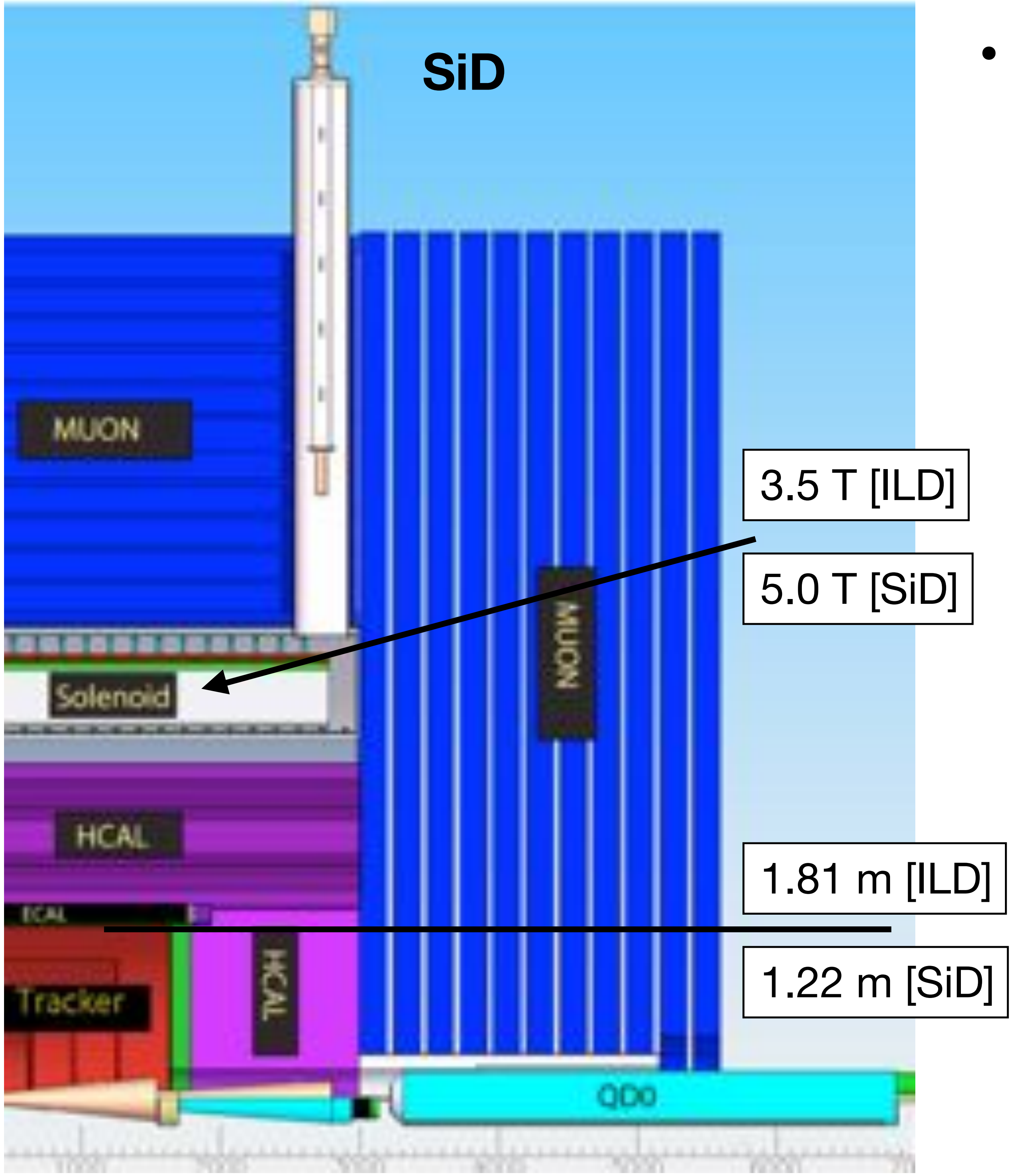

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N.B. : Solenoid cost (and technical feasibility) steeply scales with field and radius => Either large radius or high field!

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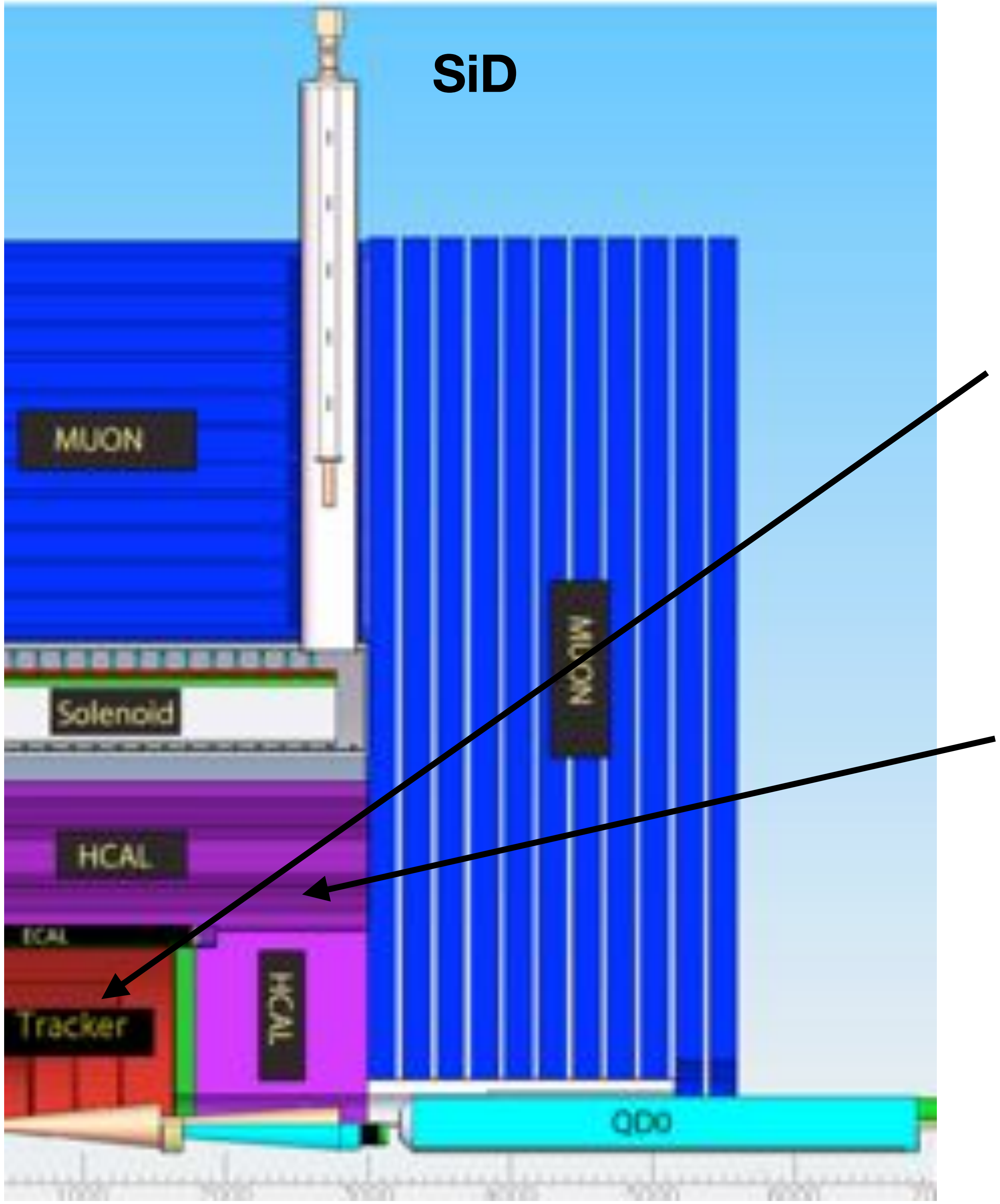

- Different choices in tracker technology: Trade number of measurements and precision of individual measurements
  - Five-layer all-Si tracker in SiD
  - TPC with > 200 space points on a track in ILD (NB: To reach resolution goal, an additional Si layer outside of the TPC is required!)
- Trading cost vs. jet energy resolution at higher energies (1 TeV option): Depth of the calorimeter system
  - SiD HCAL: 4.5 λ_I, ILD HCAL: 6 λ_I

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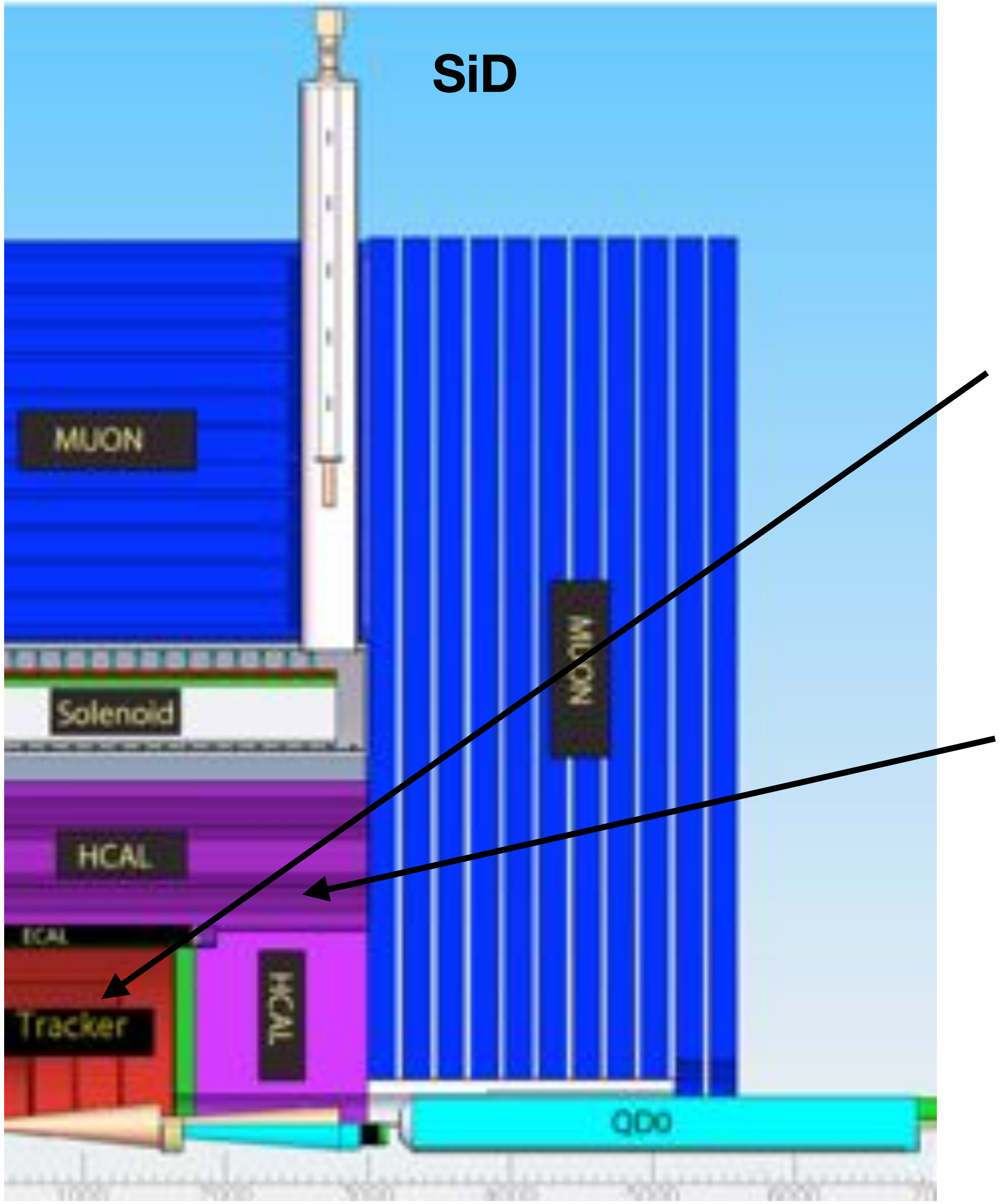

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  - Five-layer all-Si tracker in SiD
  - TPC with > 200 space points on a track in ILD (NB: To reach resolution goal, an additional Si layer outside of the TPC is required!)
- Trading cost vs. jet energy resolution at higher energies (1 TeV option): Depth of the calorimeter system
  - SiD HCAL: 4.5 λ_I, ILD HCAL: 6 λ_I

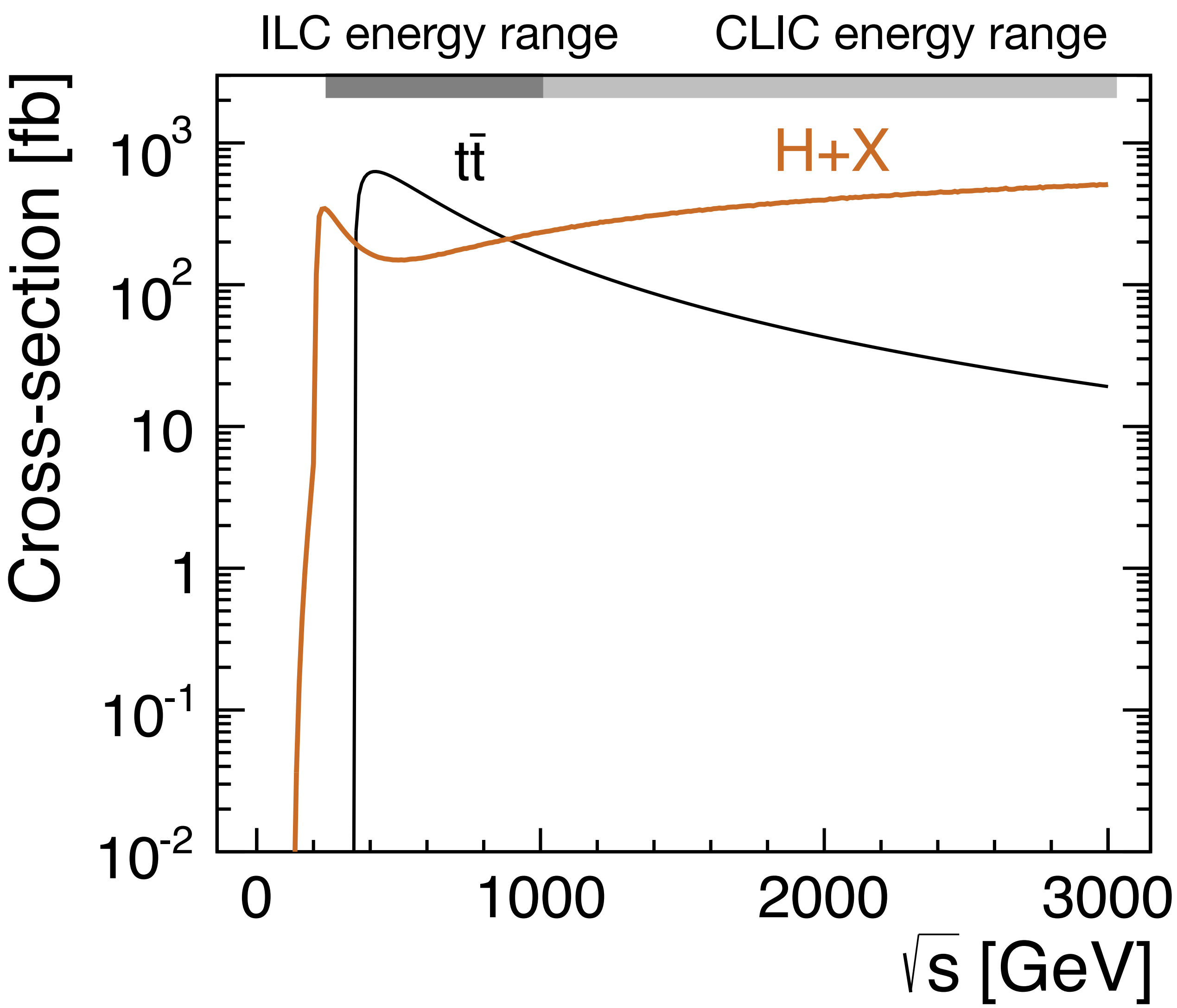
In general: How much cost is emphasized drives the choice between small and large detector: ECAL radius as main cost driver, but larger detector favorable for PFA

Physics at the ILC

The (I)LC Physics Landscape

… a combination of certainty and speculation:

- Excellent physics program guaranteed:
  - Higgs physics - mass, couplings, potential, …
  - Top physics - properties (mass, width,…), top as a probe for New Physics
  - Precision physics - electroweak measurements, QCD, …



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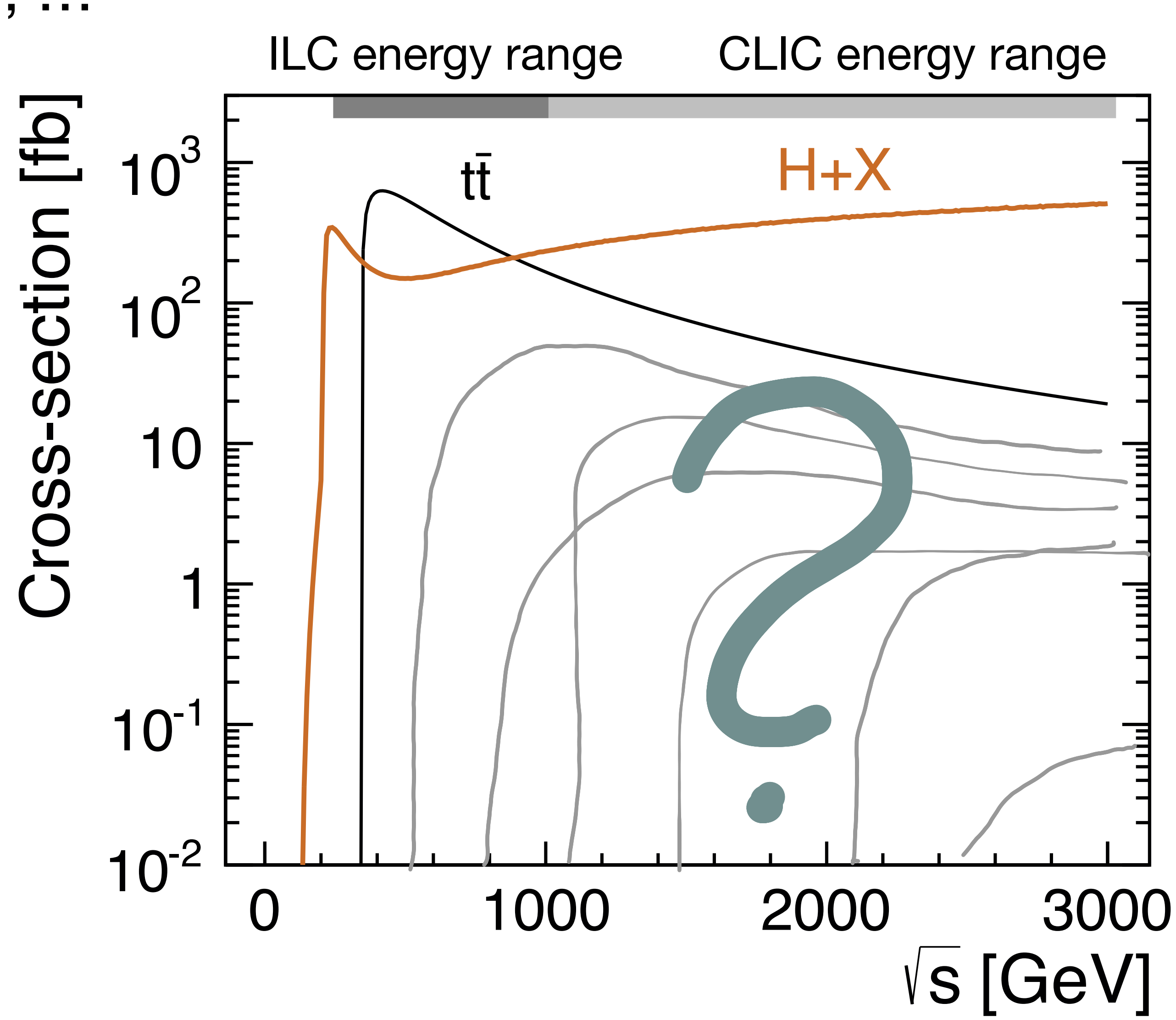
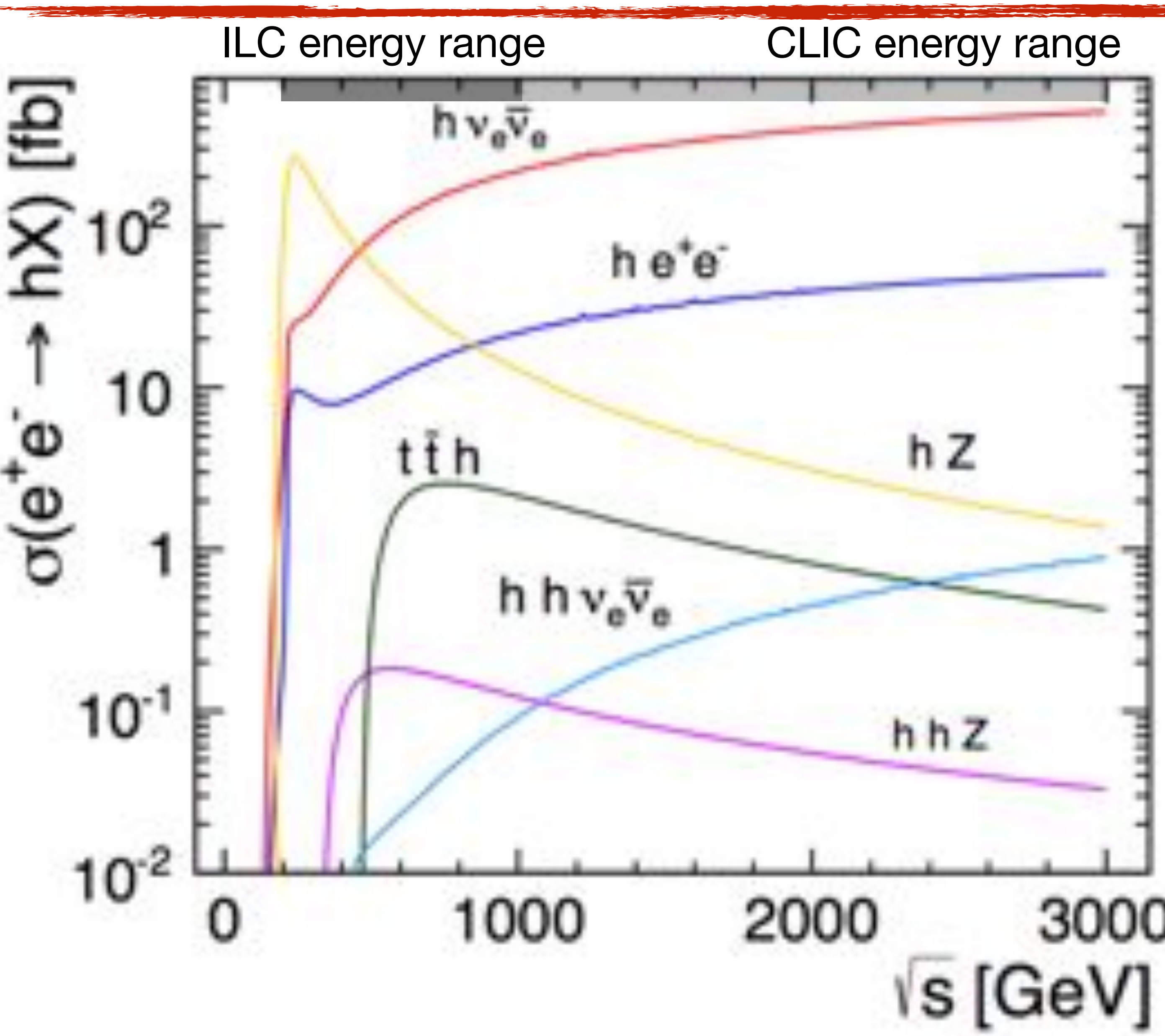
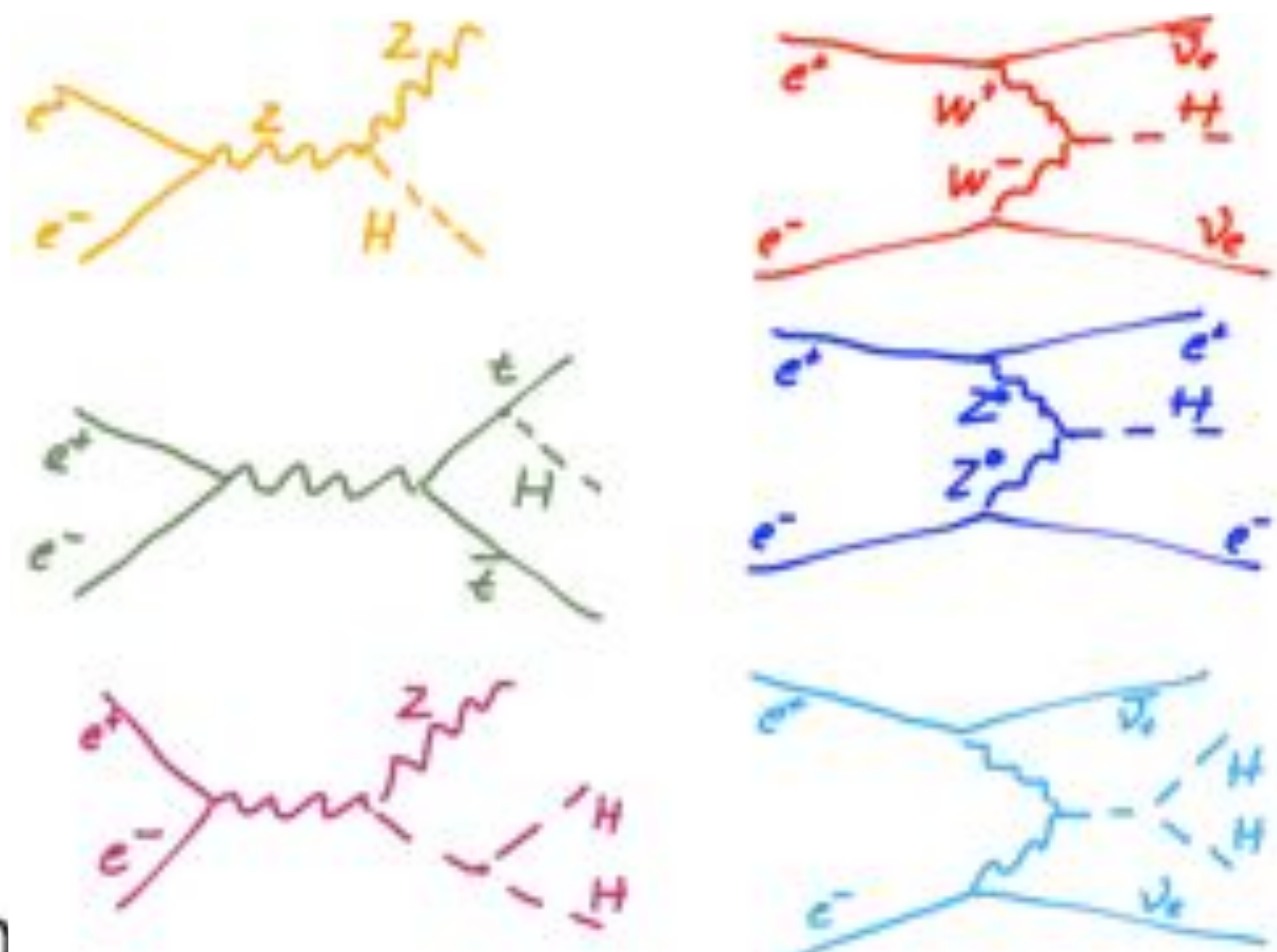


- Discovery potential for New Physics
  - Direct production of new particles - Mass reach up to $\sqrt{s}/2$ for (almost) all particles
    - Spectroscopy of New Physics
  - Indirect (model-dependent) search for New Physics extending far beyond $\sqrt{s}$

A Closer Look at Higgs Production





- Several different Higgs production mechanisms
  - Access to various Higgs properties
  - Different energy to access different processes - from **250 GeV** to **1 TeV** and beyond

Precision Measurements at Linear Colliders

- A flagship measurement: Model-independent Higgs couplings
  What it means: Measure the coupling of the Higgs to bosons and fermions free from model assumptions (e.g. how it decays)
  - Requires: The “tagging” of Higgs production without observing the particle directly
    - Not possible at hadron colliders

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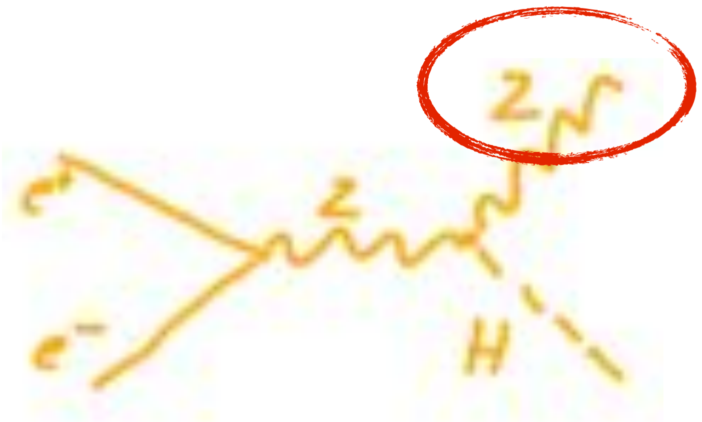
The strategy in e⁺e⁻ collisions:



measure ***only*** the Z boson

from the known e⁺e⁻ center-of-mass energy, calculate the “recoil mass”:

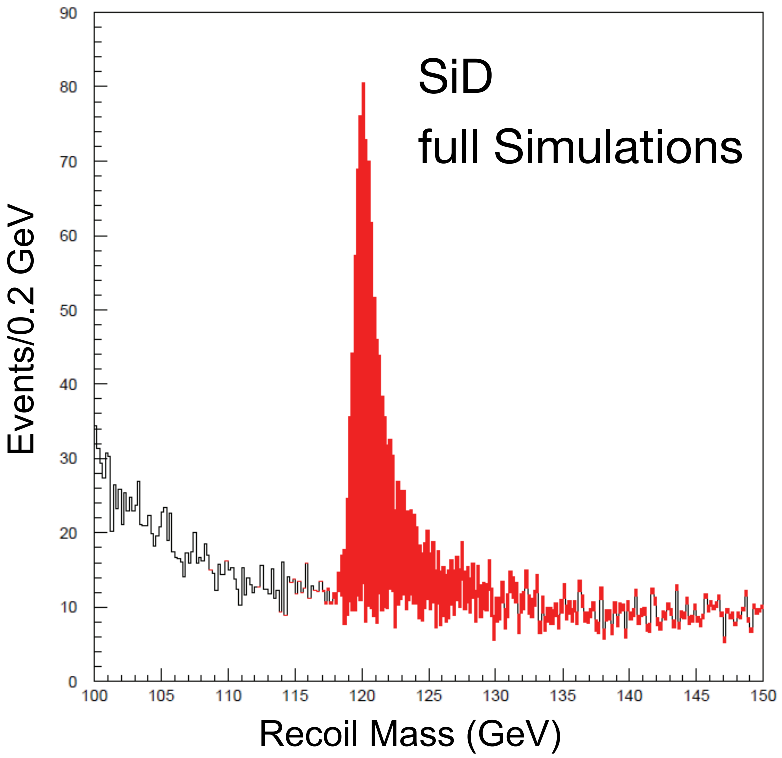
$$\boxed{m_{rec}^2 = s + m_Z^2 - 2E_Z\sqrt{s}}$$

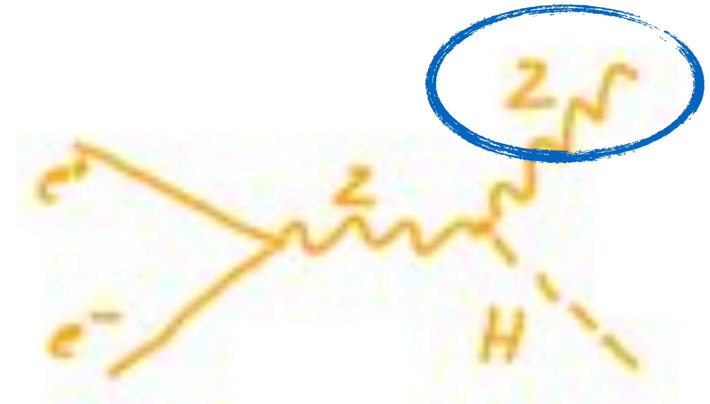
Exploits: known initial state in e⁺e⁻

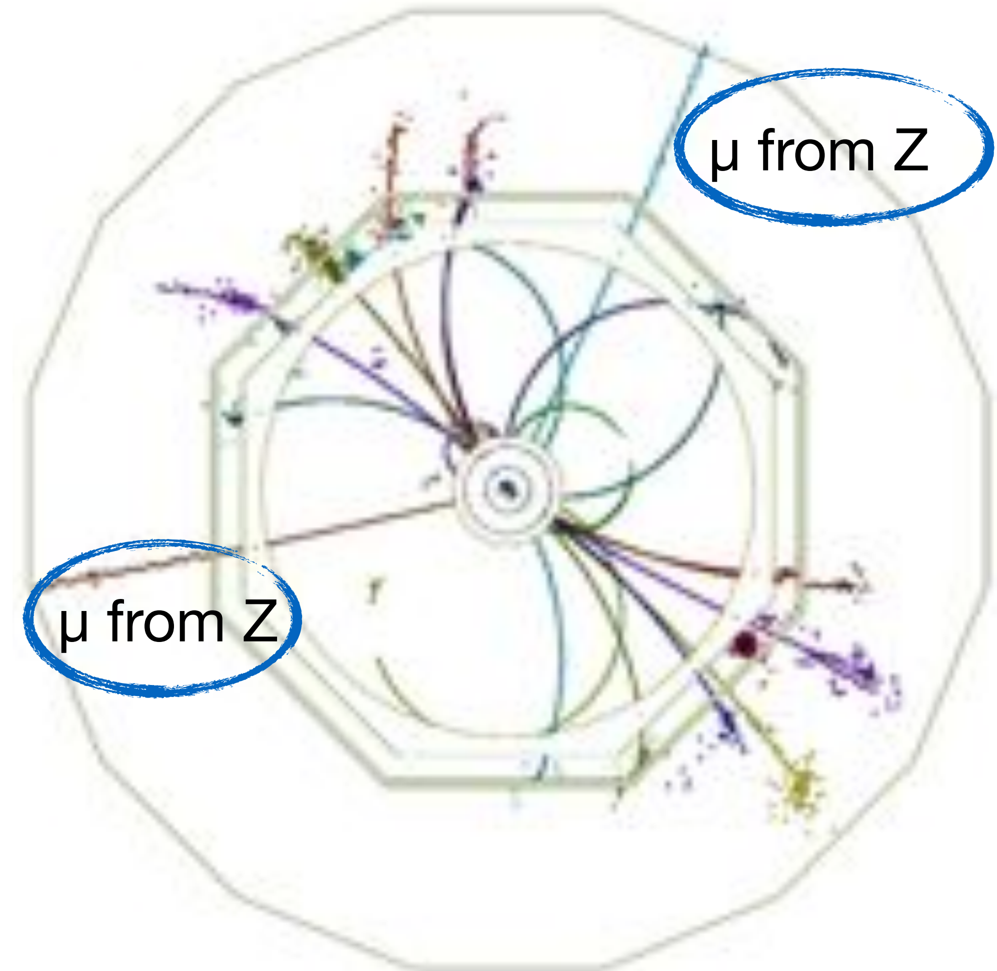
Requires: Identification of Z independent of decay mode of H (or any other particle)

➯ Best results for Z -> μμ, but (almost) model-independent measurements also possible in Z -> qq

Model-Independent Measurement of H Production







$$\boxed{m_{rec}^2 = s + m_Z^2 - 2E_Z\sqrt{s}}$$

$e^+e^- \to ZH \to \mu^+\mu^- b\bar{b}$ ILD, 250 GeV

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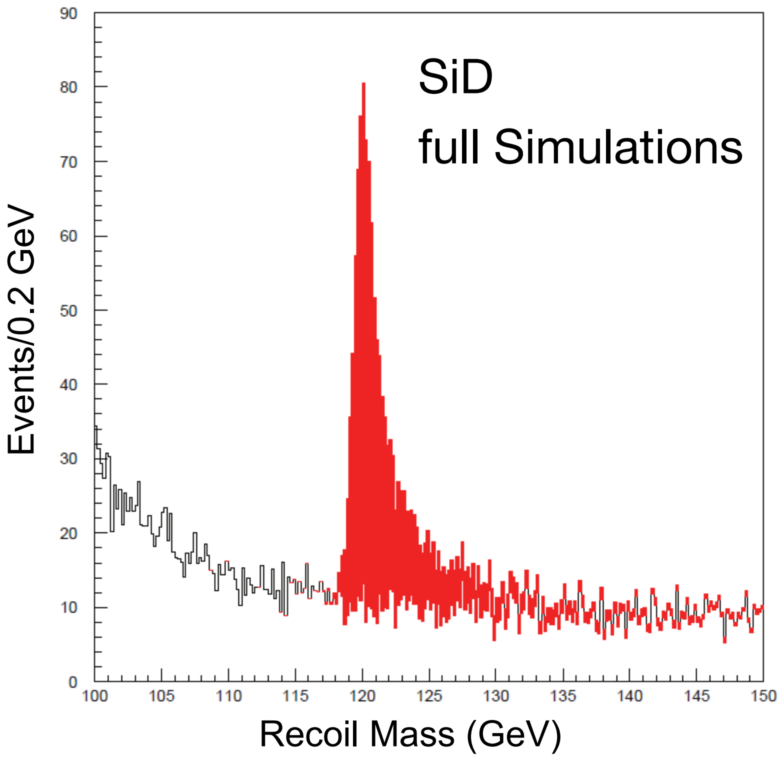

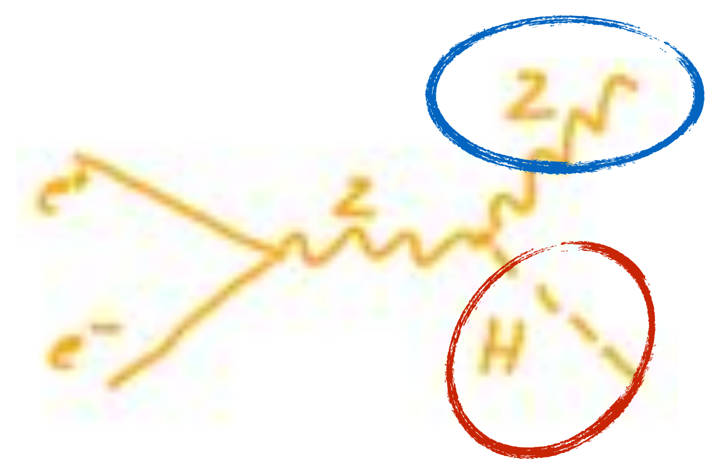

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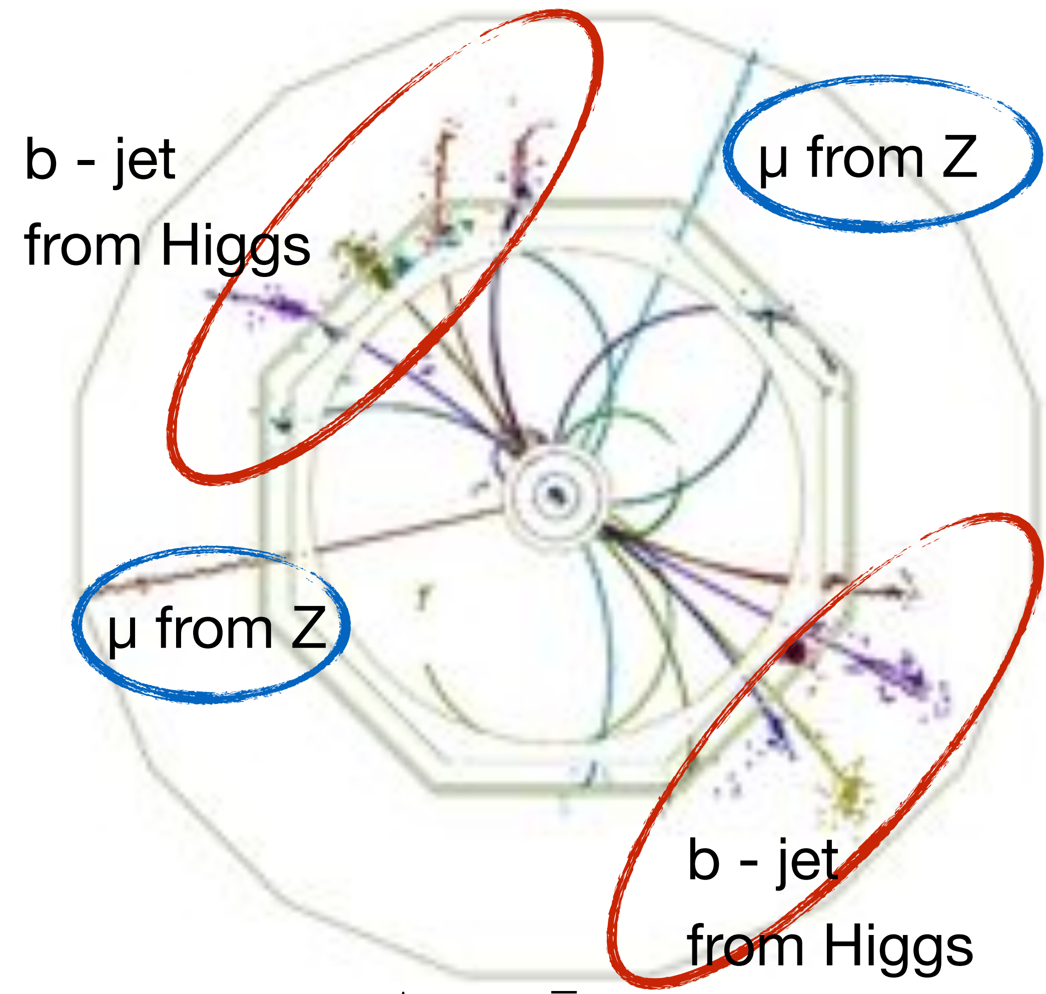


$e^+e^- \to ZH \to \mu^+\mu^- b\bar{b}$ ILD, 250 GeV

What this provides: Total ZH cross section, and with coupling of H to Z

- In addition: Reconstruction of specific final states provides access to couplings to fermions and bosons via Higgs decay
  - Makes use of "clean" e^+e^- environment - also allows the reconstruction of final states which are not accessible at hadron colliders: cc, gg

Getting the Global Picture: All Couplings

- The measurements we are making are:

σ x BR (for specific Higgs decays)
σ (for model-independent recoil mass analysis)

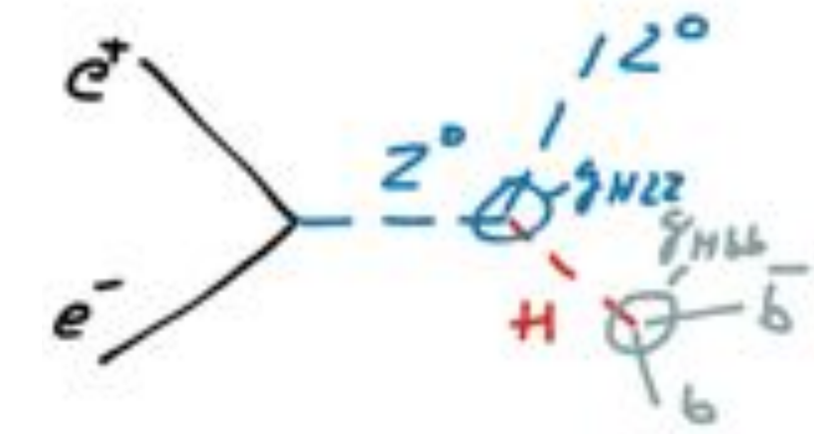
Both are sensitive to the Higgs couplings
to the producing particles and to the final state:

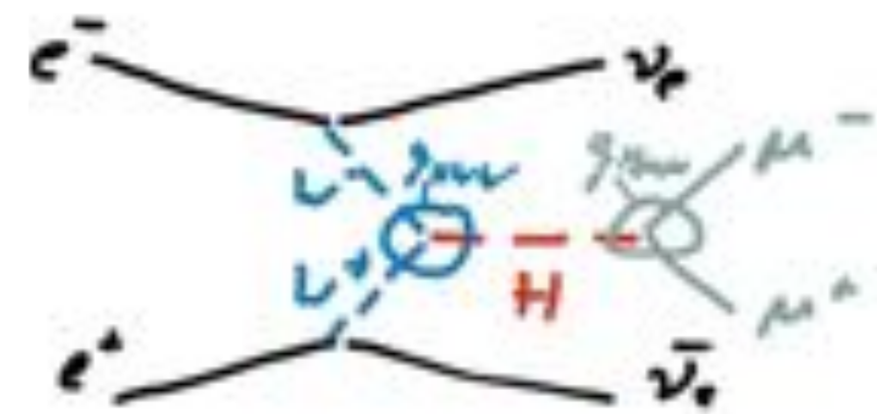
$$\sigma_{\mathrm{recoil}} \propto g^2_{\mathrm{HZZ}}$$ (NB: final state not considered!)

coupling in production coupling in decay

$$\sigma \times \mathrm{BR(H}\rightarrow \mathrm{ff}) \propto \frac{\boxed{g^2_{\mathrm{Hii}}}\boxed{g^2_{\mathrm{Hff}}}}{\Gamma_{\mathrm{tot}}}$$

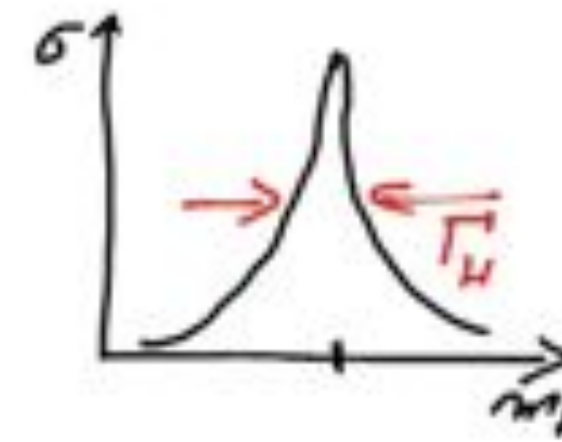
total width





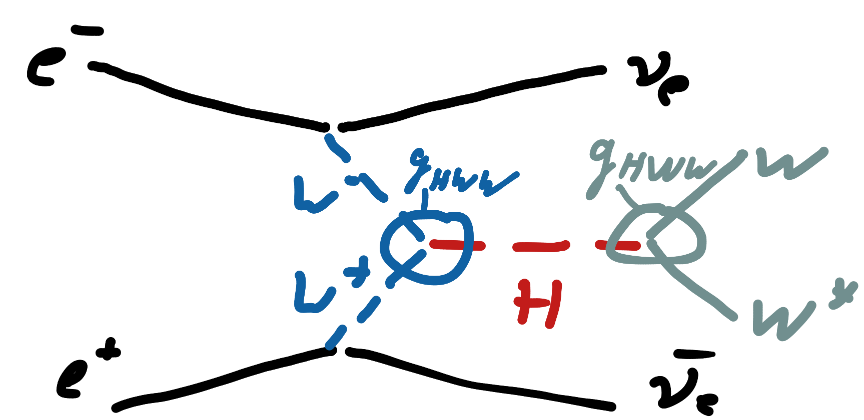
Measuring the Total Width

- The total width of a 125 GeV SM Higgs is ~ 4 MeV - no chance to measure directly (apart maybe from a μ collider) - use other “tricks”
  - e^+e^- offers an (almost) model-independent way (in contrast to techniques at hadron colliders, which always use strong assumptions…):



measure production and decay in the same channel - works for ZZ and WW

but: BR(H->ZZ) ~ 2.8%, BR(H->WW) ~ 22.3% => use:



$$\sigma(\mathrm{H}\nu_e\nu_e) \times \mathrm{BR}(\mathrm{H} \to \mathrm{WW}^*) \propto \frac{g^4_{\mathrm{HWW}}}{\Gamma_{\mathrm{tot}}}$$

in itself not model-independent (requires H reconstruction)

needs 350+ GeV for sizeable WW fusion cross-section

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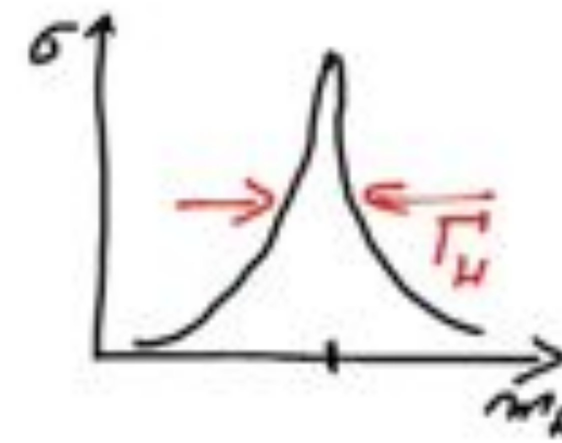

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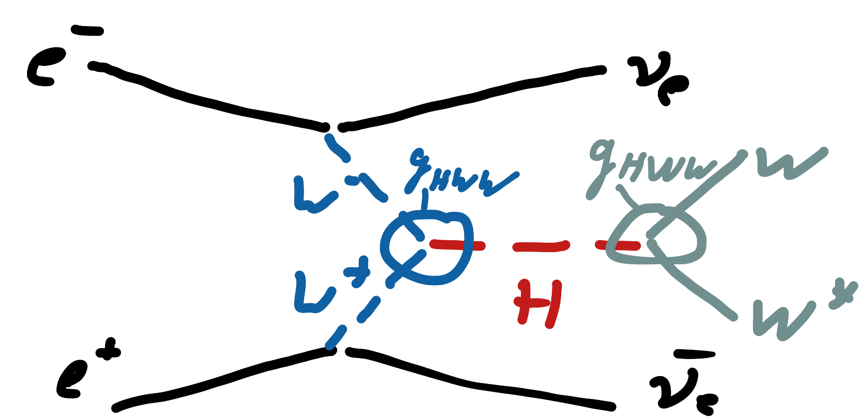

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$$\frac{\sigma(e^+e^- \to \mathrm{ZH}) \times \mathrm{BR}(\mathrm{H} \to b\bar{b})}{\sigma(e^+e^- \to \mathrm{H}\nu_e\nu_e) \times \mathrm{BR}(\mathrm{H} \to b\bar{b})} \propto \frac{g^2_{\mathrm{HZZ}}}{g^2_{\mathrm{HWW}}}$$

g_{HWW} pinned down with model-independent g_{HZZ} and high-BR H->bb decay

Global Fits: Putting it all together

- In the end you don't learn too much from a single measurement - a combination of all results gives a full picture of the couplings of the Higgs, and allows to detect deviations from the SM expectations, potentially pointing at a non-standard Higgs sector

The "simple" approach: Construct a χ^2 with all measurements, perform a global minimization

$$\chi^2 = \sum_i \frac{(\boxed{C_i} - 1)^2}{\boxed{\Delta F_i^2}}$$

ΔF$_i$: uncertainty of measurement (σ or σxBR)

$$C_{\mathrm{ZH}} = g^2_{\mathrm{HZZ}}$$

$$C_{\mathrm{ZH,H}\to b\bar{b}} = \frac{g^2_{\mathrm{HZZ}} g^2_{\mathrm{Hbb}}}{\Gamma_{\mathrm{H}}}$$

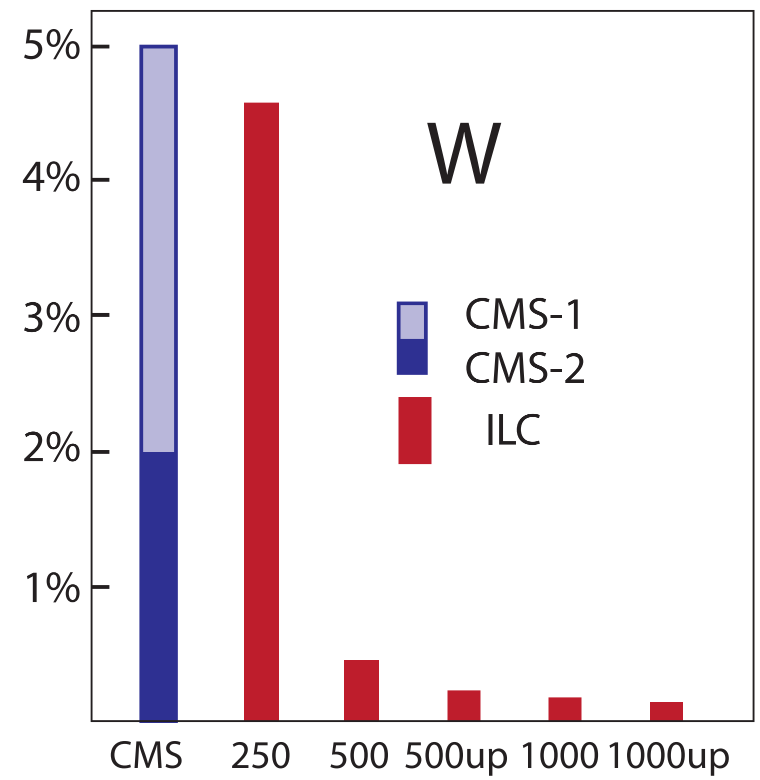
$$C_{\mathrm{H}\nu_e\bar{\nu}_e,\mathrm{H}\to b\bar{b}} = \frac{g^2_{\mathrm{HWW}} g^2_{\mathrm{Hbb}}}{\Gamma_{\mathrm{H}}}$$

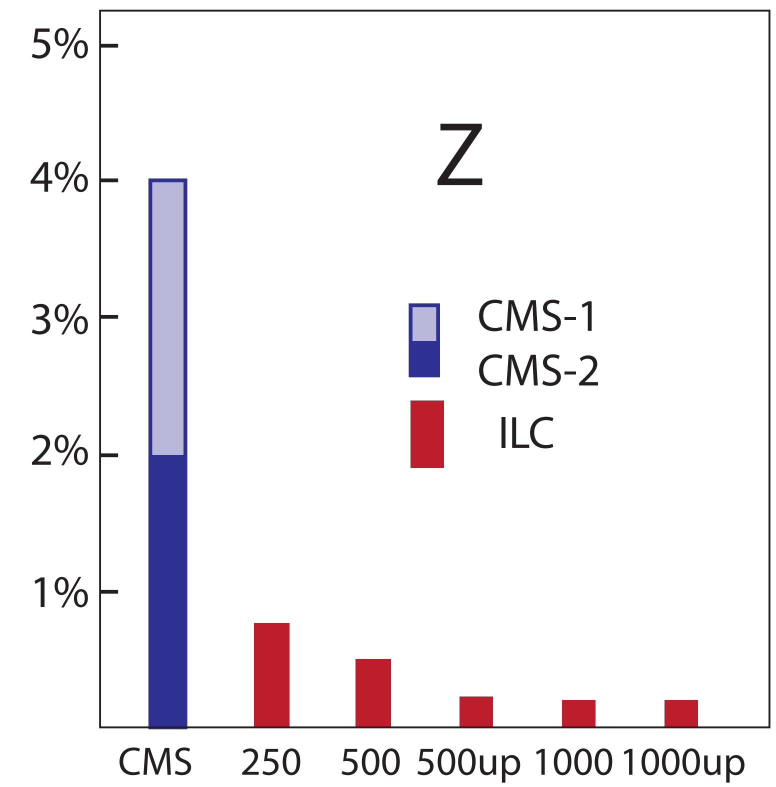
...

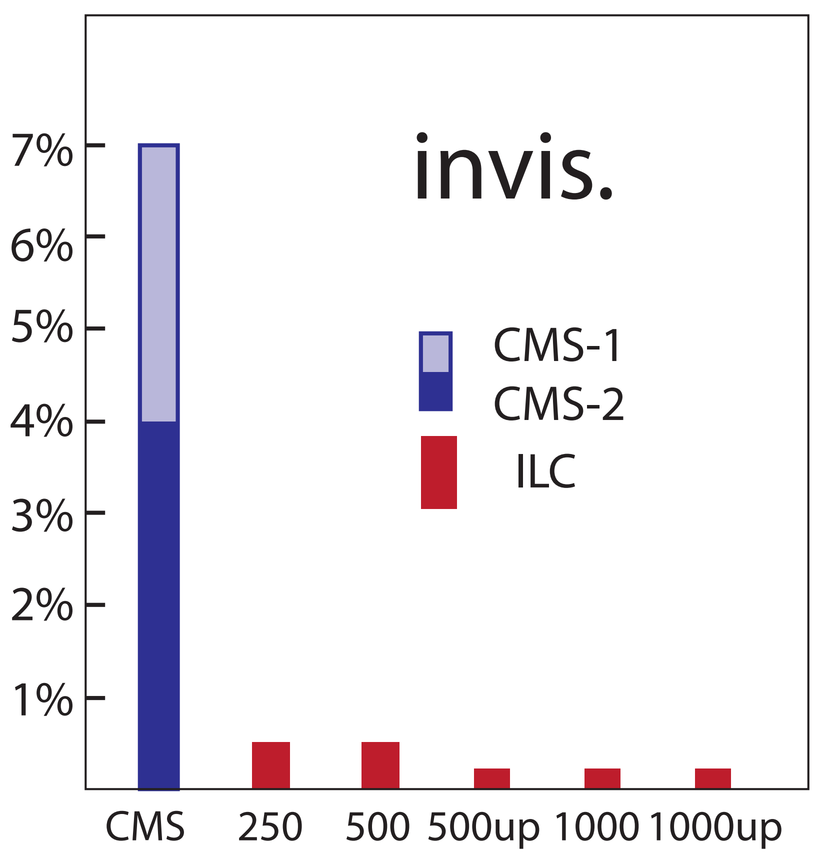
As usual the devil is in the details: need to account for correlations between measurements, find a consistent way of quantifying and treating theoretical uncertainties when comparing to the SM, …

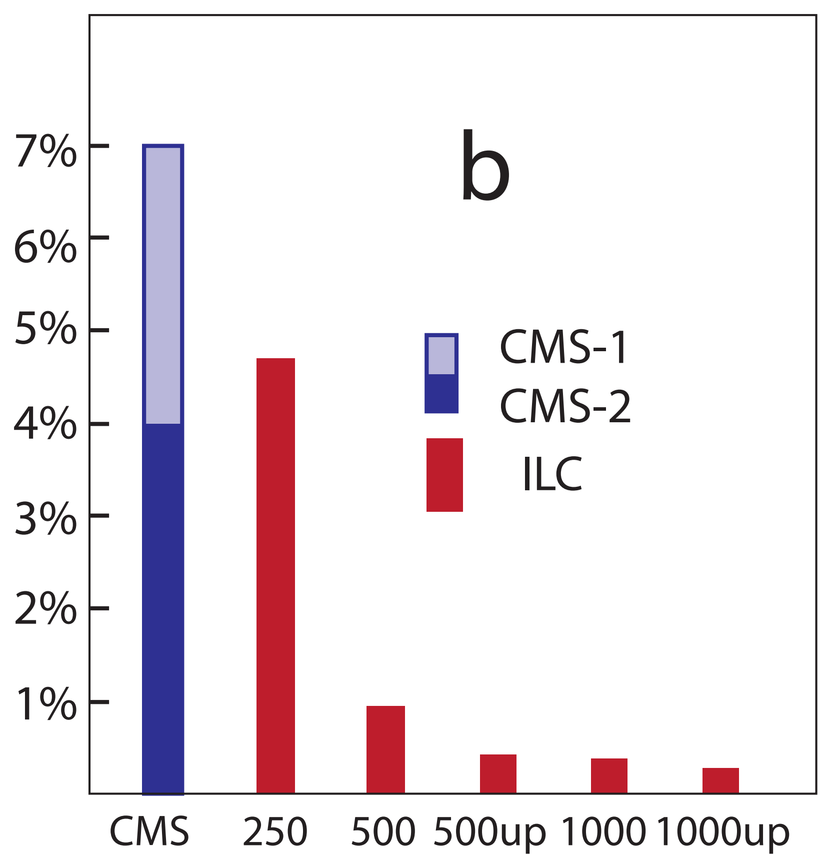
Higgs: The Global Picture

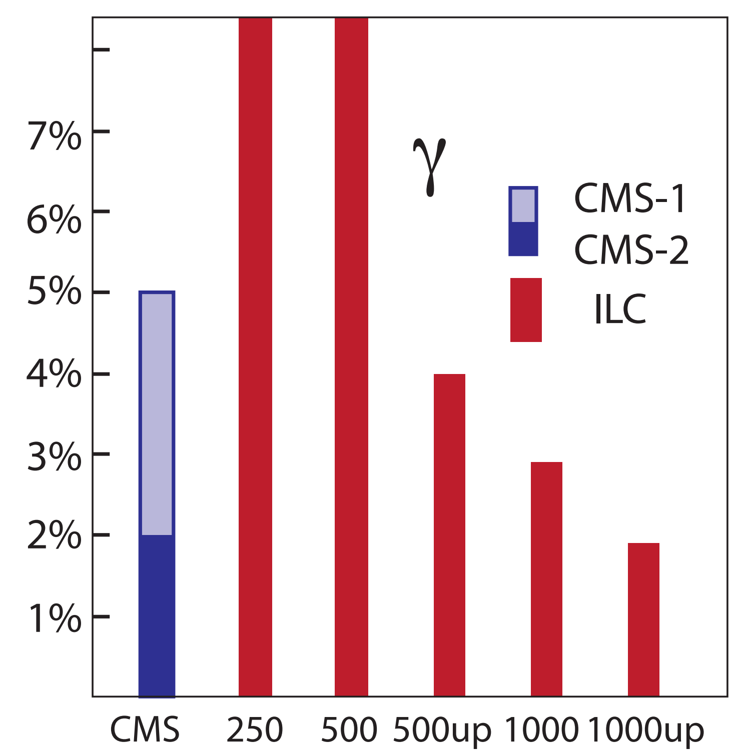
- For fully model-independent measurements ~ 1-2% level precision for most couplings, deviations from the SM can be detected on the per-mille level in some cases (approach comparable to LHC)











analysis by M. Peskin, arXiv:1312.4974

The Ultimate Challenge: Self-coupling

- At present e^+e^- colliders seem to be the only possibility for a significant measurement of the self-coupling of the Higgs
    - Provides a direct probe for the Higgs potential: Highly interesting and important!

σ_{max} at ~ 500 GeV

σ increasing with energy, significant from 1 TeV on

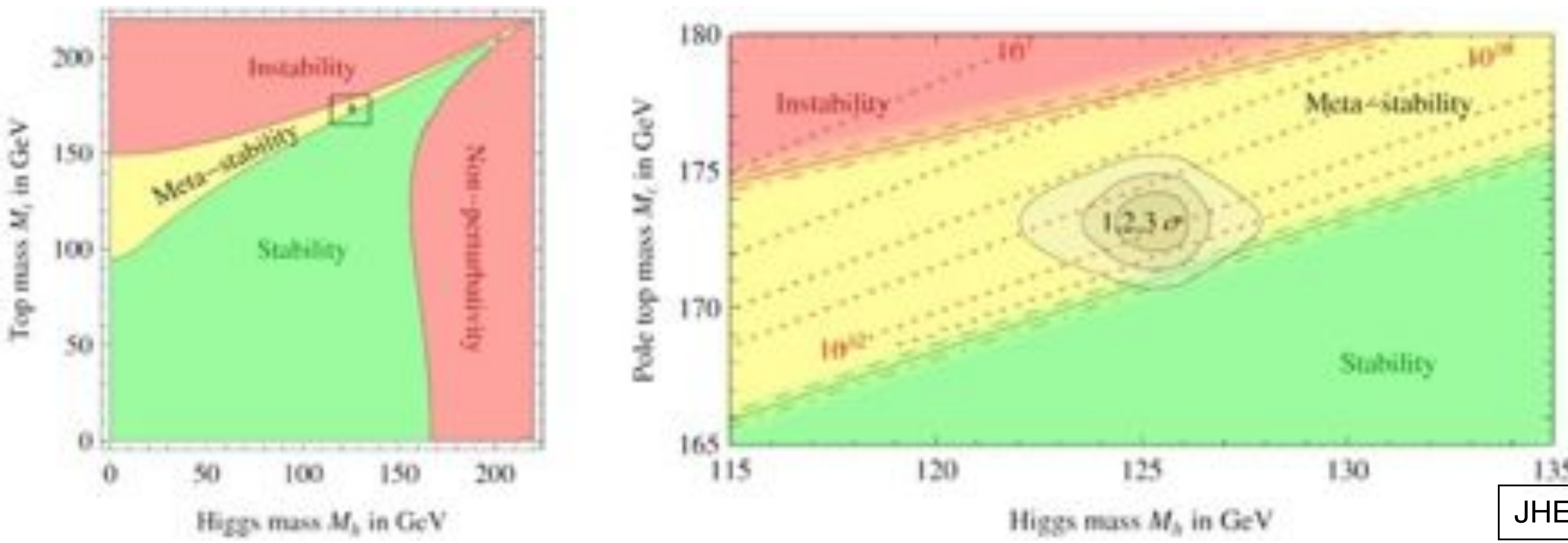
Two processes with two-Higgs final states - low cross-section
➫ separation from background a challenge!

Requires high luminosities in both cases - best prospects at energies of 1(+) TeV

➫ A challenging measurement at any collider - and always requires model assumptions

Pinning Down the Top Quark

- As the heaviest SM particle, the Top plays an important role: Strongest coupling to the Higgs field, potential sensitivity to New Physics
  - One example: “The fate of the Universe”



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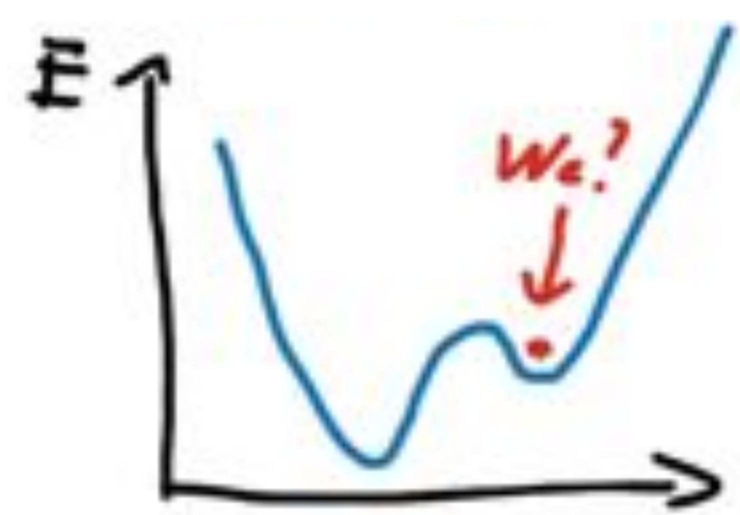
- Top mass, together with Higgs mass, provides information on the stability of the SM vacuum at higher scales
  - Possible validity of the SM up to the Planck scale?
  - Impact on evolution of the early universe



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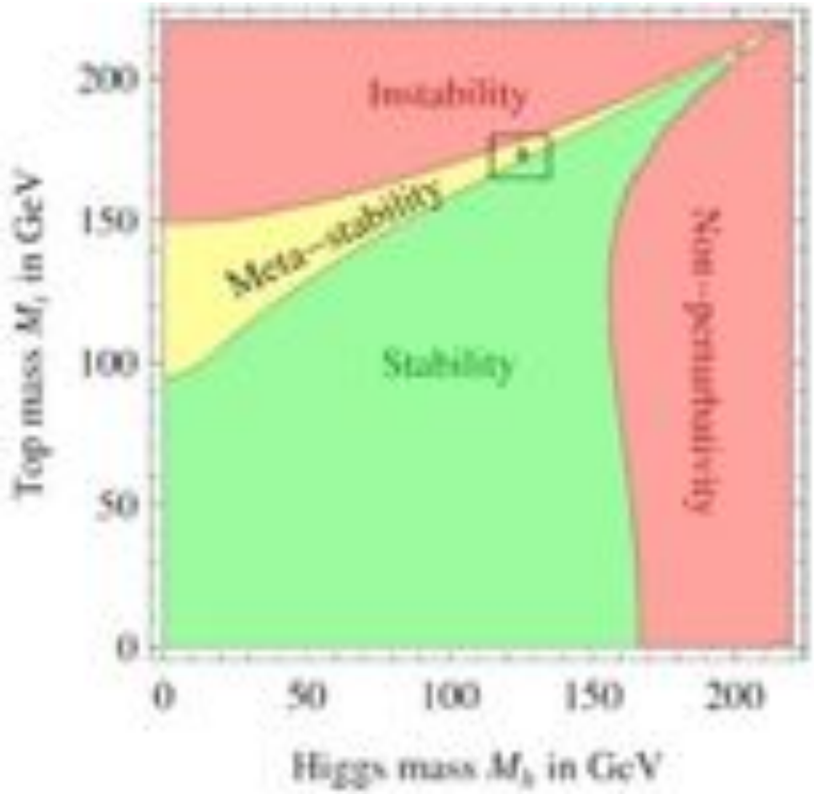

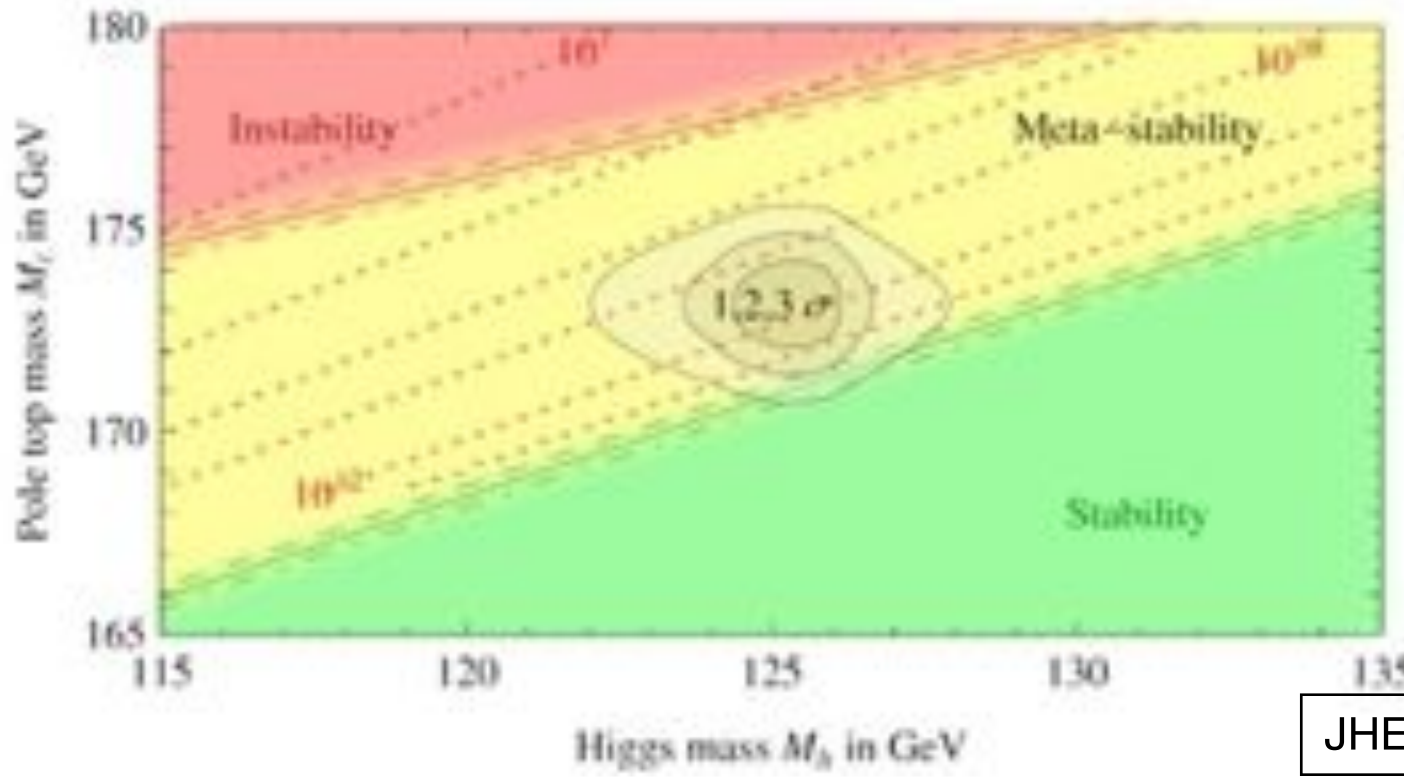

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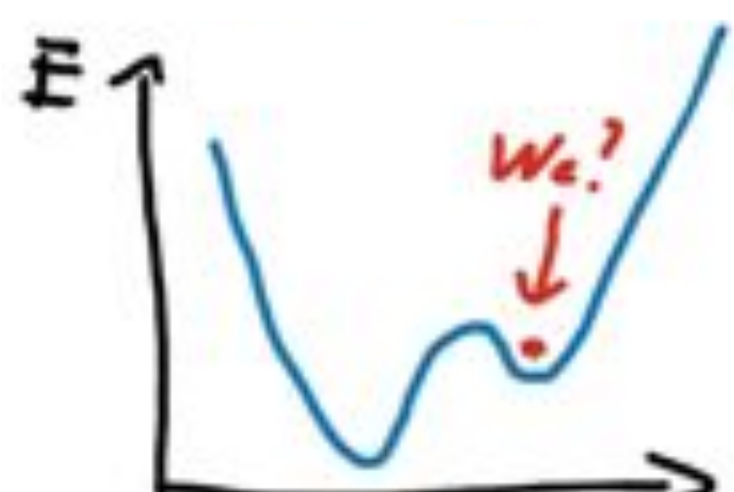
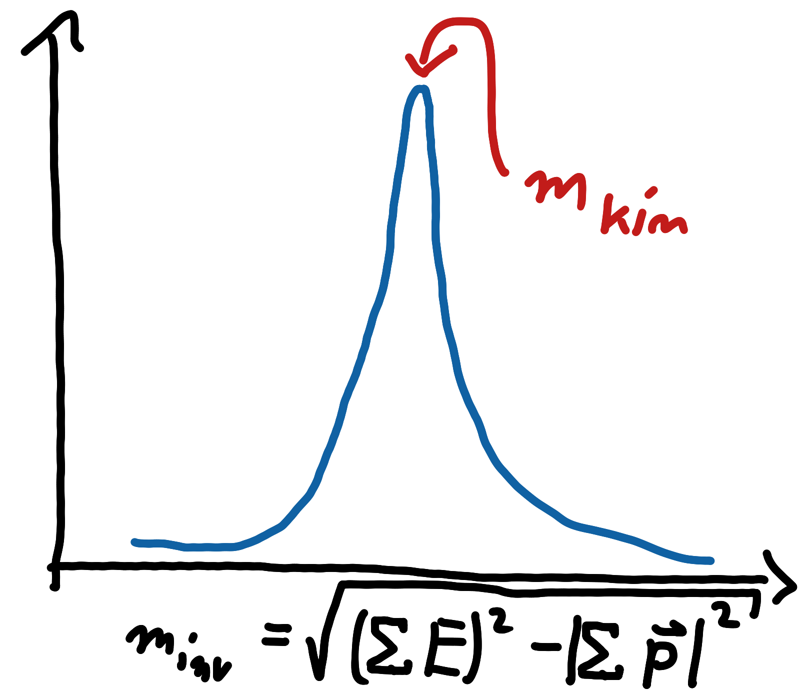
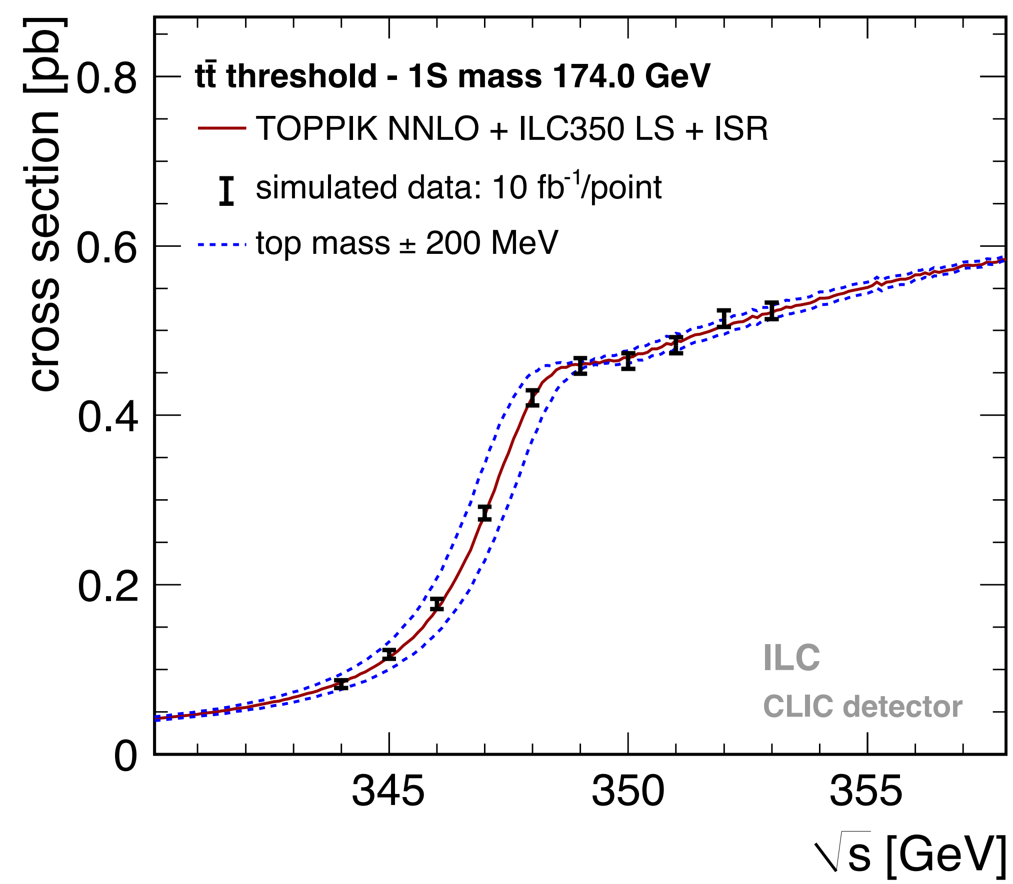


Leading uncertainty: Top Mass!

Measuring the Top Mass

- So far the top quark has only been produced at hadron colliders - Standard mass measurement by kinematic reconstruction
  - suffers from large (*O* GeV) theoretical uncertainties
- e^+e^- collisions allow the measurement of top properties with substantially reduced uncertainties - Smaller QCD effects, precise calculations of cross section in threshold region





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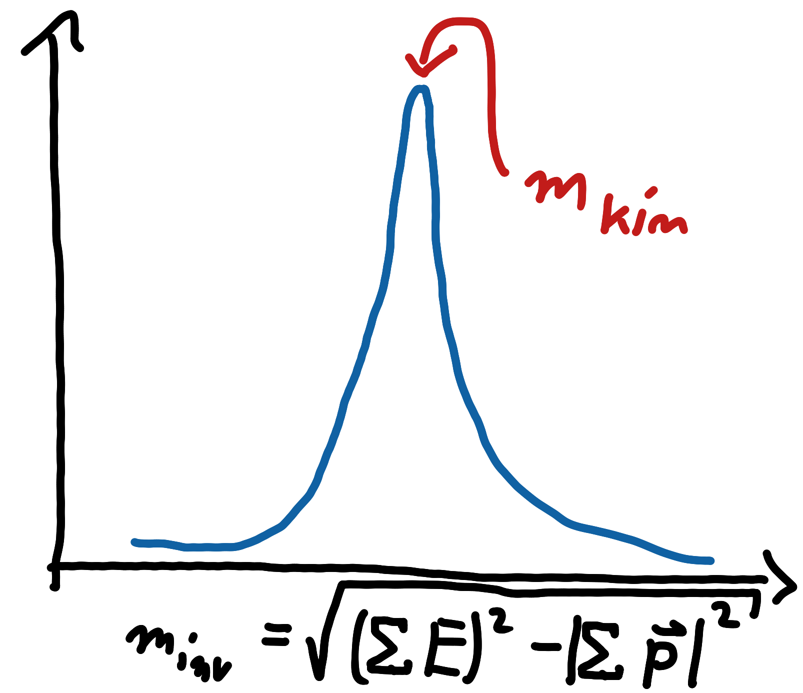
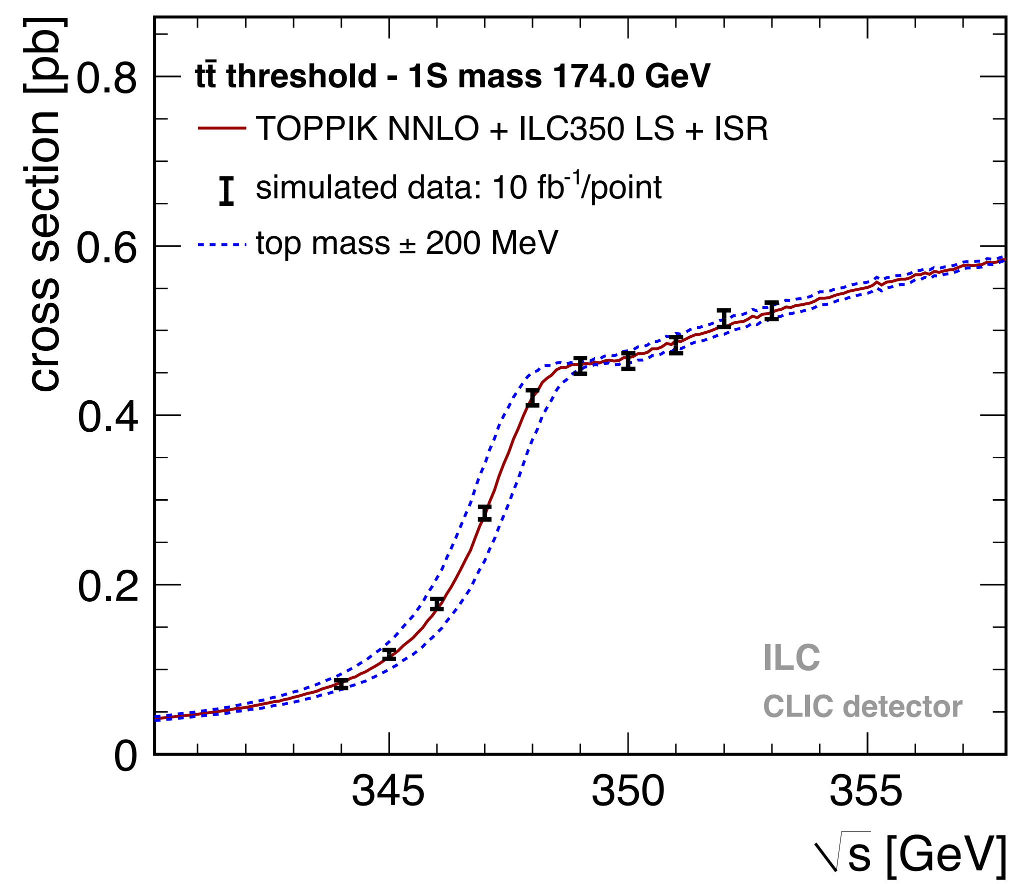


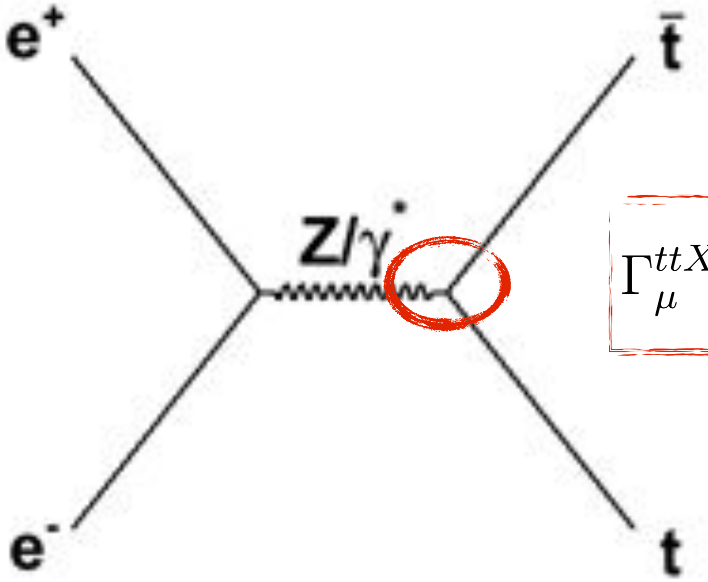
~ 100 MeV (or below) total uncertainty achievable - in a theoretically well-defined mass scheme, including theory systematics

~ 1 order of magnitude better than LHC



Using the Top as a Tool to Explore New Physics

- Probing EW coupling of the top to detect signs of New Physics (ED, …)



The coupling is described several coupling form-factors

$$\Gamma_{\mu}^{ttX}(k^2, q, \overline{q}) = ie \left\{ \gamma_\mu \left(\widetilde{F}_{1V}^X(k^2) + \gamma_5 \widetilde{F}_{1A}^X(k^2) \right) + \frac{(q-\overline{q})_\mu}{2m_t} \left(\widetilde{F}_{2V}^X(k^2) + \gamma_5 \widetilde{F}_{2A}^X(k^2) \right) \right\}$$

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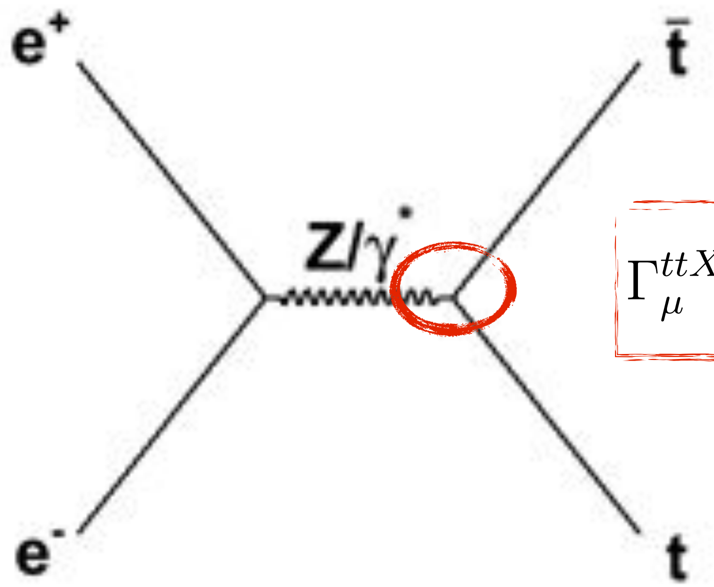

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  - ***Total cross-section***
  - ***Forward-backward Asymmetry A_{FB}***
  - ***Helicity Angle λ*** distribution (related to fraction of left- and right-handed tops)

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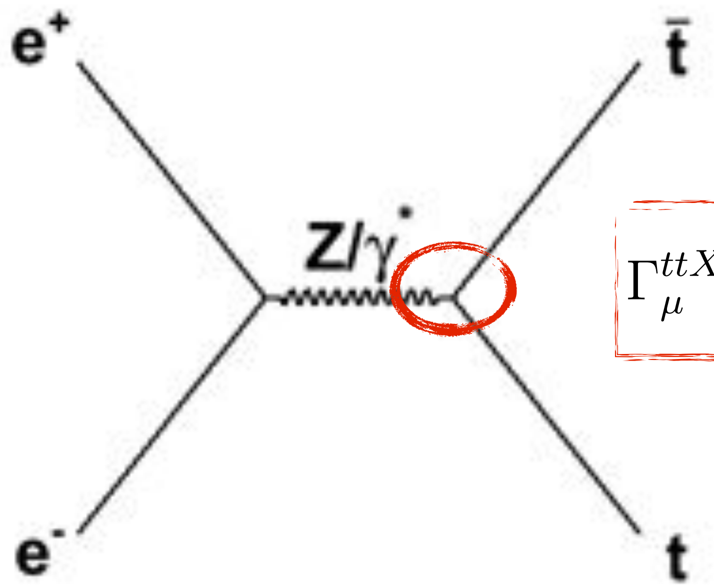

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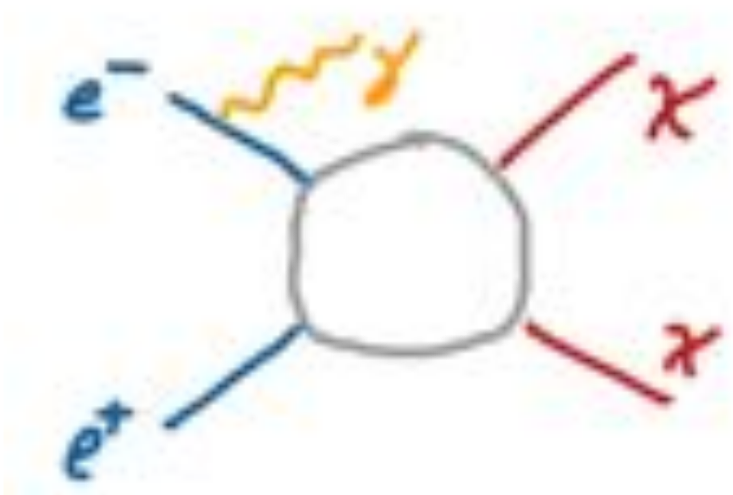
Requires polarized electron and positron beams!

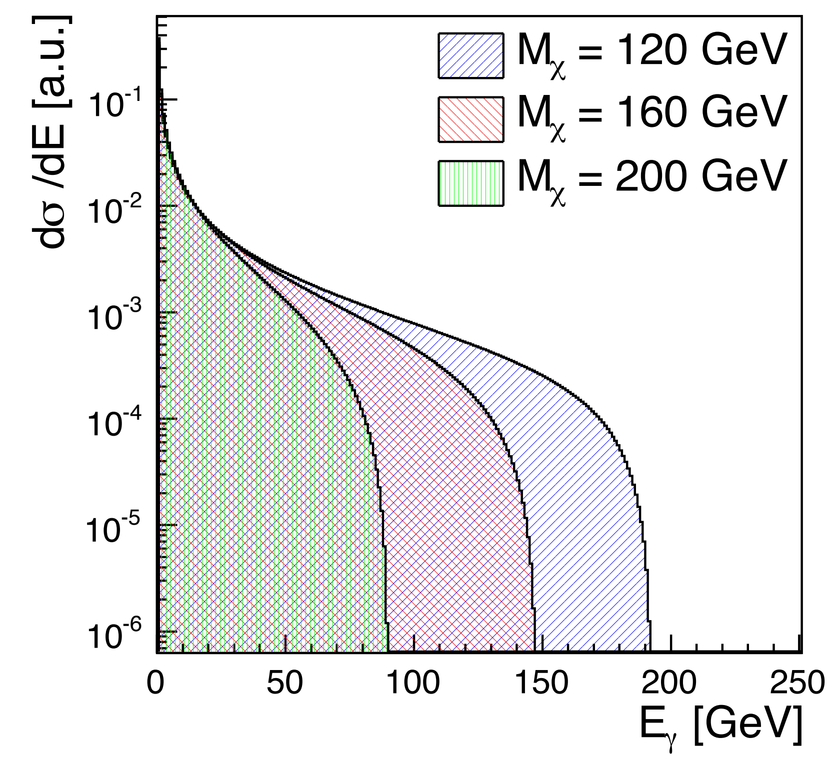
▸ Uniquely available at linear colliders, e^+e^- rings cannot provide high polarisation

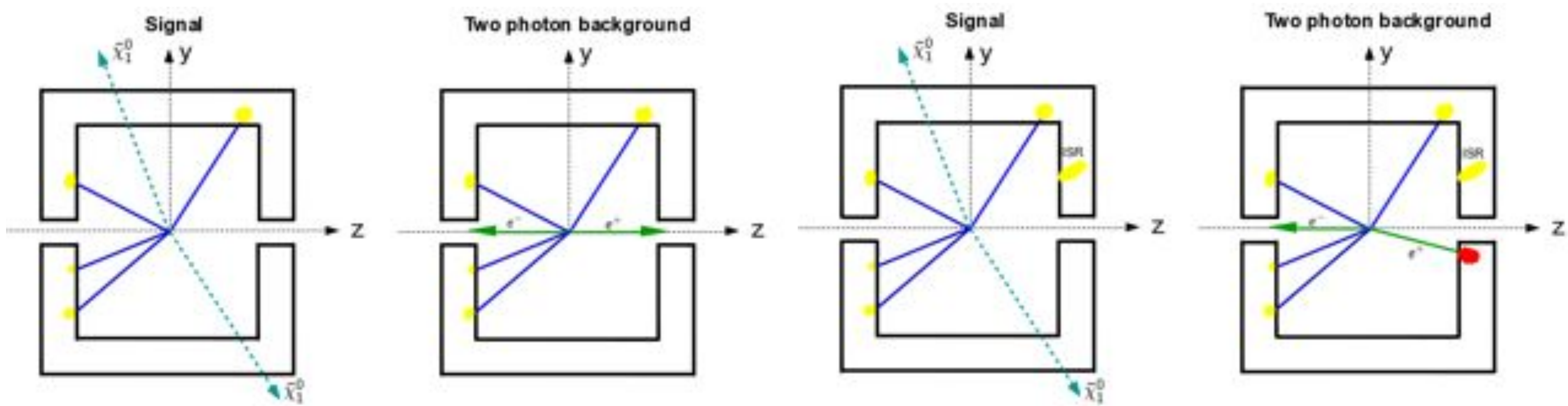
Discovery Potential for New Physics

- The ultimate motivation for a new collider - But entirely based on (more or less well founded) speculations

  A key goal: Studying dark matter at colliders

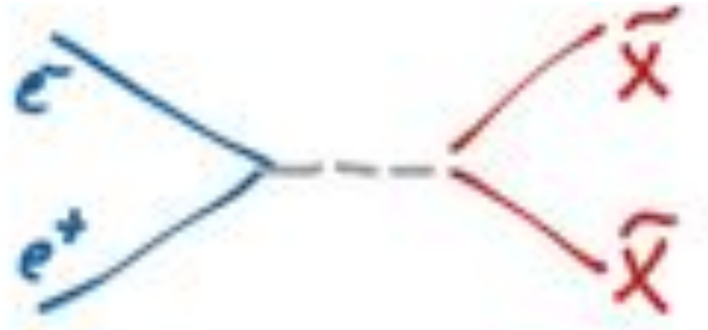






Discovery Potential for New Physics

- In general: Discovery and exploration of BSM physics



Discovery limit ~ $\sqrt{s}$ / 2 for (almost) any type of particle - particular strength (compared to LHC) in electroweak sector - gauginos, sleptons

➯ Can fill in holes LHC cannot cover (due to trigger requirements, high backgrounds, ...)
  - Scenarios with small mass-splittings between particles - soft final states

- Rich possibility for indirect searches:
  - Precision measurements of SM processes, compared with theoretical calculations, can provide indications for New Physics far beyond the energy scale directly accessible at the collider
  - Profits from the possibility for precision calculations of e^+e^- processes

Politics, Sites & Strategies

Getting A New Collider

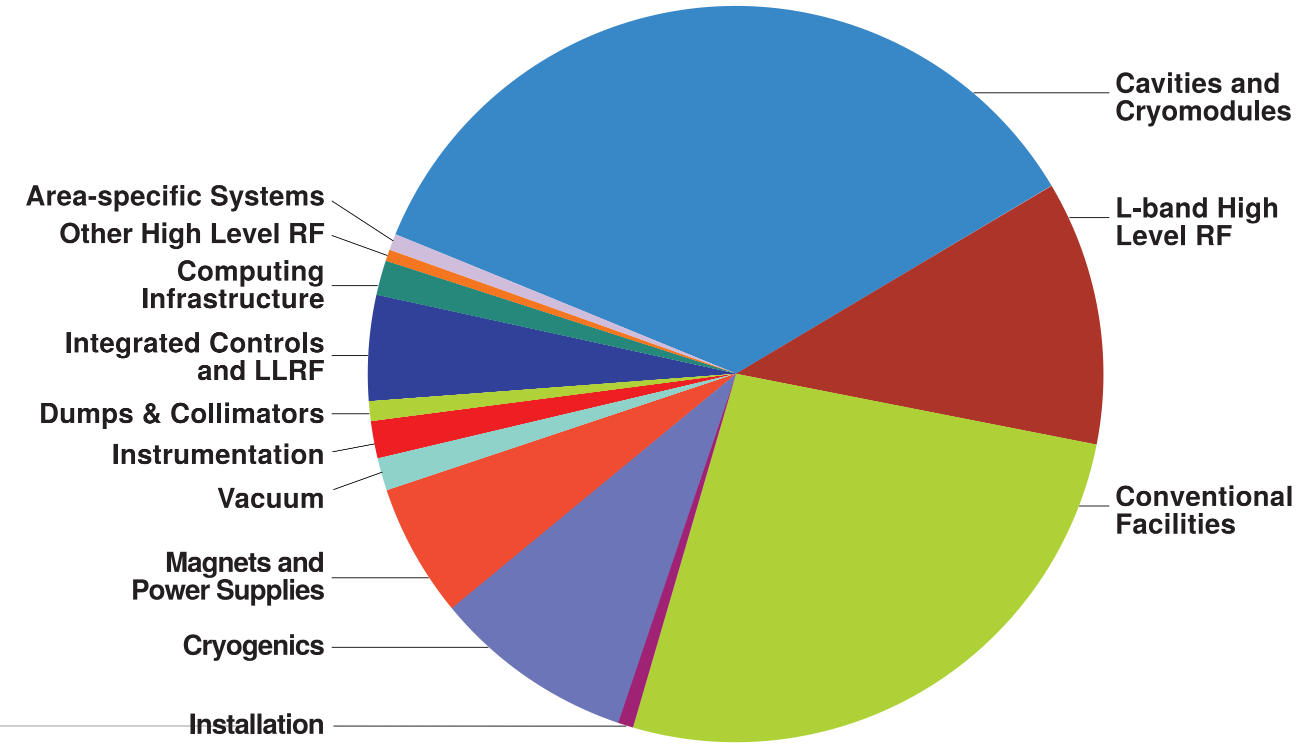
- New energy-frontier collider projects take a very long time - ILC (under various labels) has been developed for over 20 years
  - Technologically challenging
  - Expensive
  - Requires world-wide collaboration, not just for financial reasons, but also manpower: Experimental collaborations with (several) 1000 members, large numbers of accelerator and other specialists
    - Typically means complicated set-up procedures and international negotiations - far beyond the control of scientists

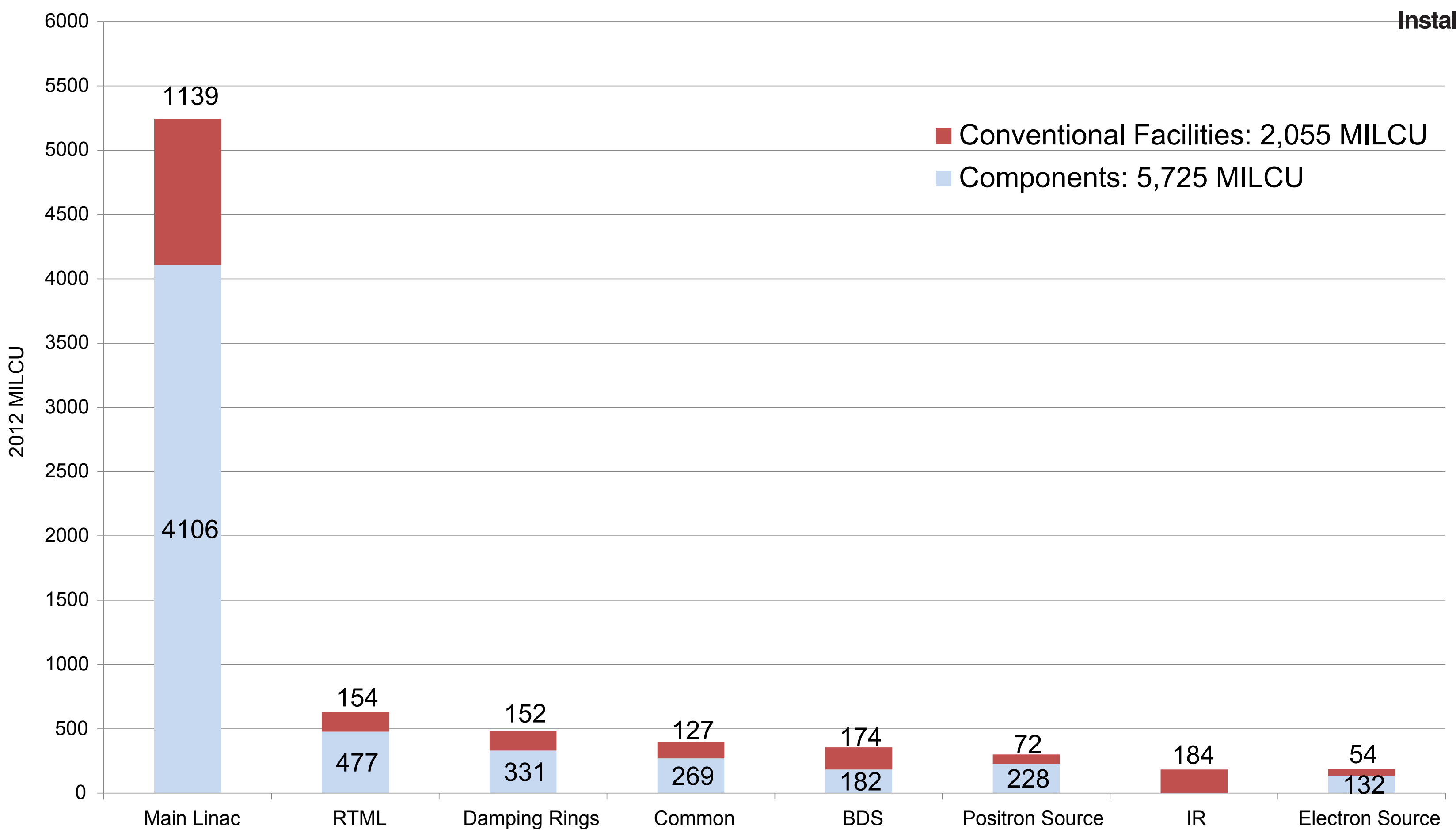
So far: Projects typically have been “local” with international participation

CERN is unique as an international organisation (still Europe-centric) - Similar things do not exist in other regions for particle physics

ILC Cost

- Not surprising: An energy frontier collider is expensive
  - Rather solid cost estimate for the 500 GeV machine: ~ 8 Billion USD
  - Biggest component: Main linac, acceleration structures





- The construction cost will be spread over ~ 10 years, and shared across the globe - details to be worked out!
- Many contributions expected “in kind”: production of components “at home”, installation in ILC

ILC (国際リニアコライダー) in Japan?

- Japan has expressed interest to host ILC - with the goal of a global project with substantial financial contributions from outside, and the establishment of an “international city”
  - A site choice has been made:
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  - A site choice has been made: 北上市 (Kitakami) in Northern Japan
- Strong support by local government and population
- Over the next ~ 1.5 years, a review process with committees by the Japanese science ministry MEXT is taking place - physics case and technical issues
- First contacts on government level about international participation have started

The Kitakami Site - 北上市

Design for conventional facilities well advanced - adaptation to site in progress

Possible Location of the Interaction Point

The Kitakami Site - 北上市

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- Overwhelming local support:

outside Misuzawa train station

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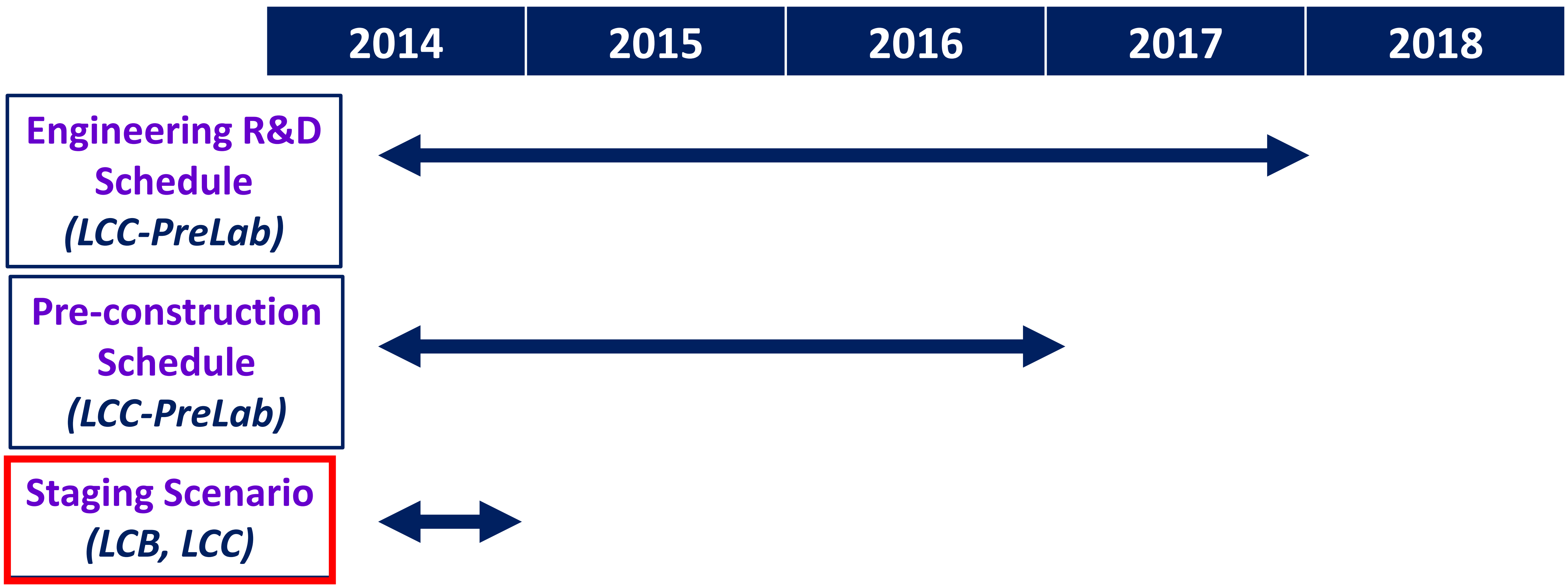
The Time Schedule



International Strategies & Priorities

- Community-driven strategy processes in Europe and the US have been completed recently
    - Update of the European Strategy for Particle Physics 2012/2013
        1. Full exploitation of LHC, including high luminosity upgrade - a program until 2035
        2. Design studies for future CERN projects after LHC, focus on p+p and e^+e^- energy frontier colliders (CLIC, HE-LHC, FCC-hh with FCC-ee as possible precursor) - Prepare for first decision in ~ 2018
        3. Support for ILC in Japan, discuss possible participation
        4. Neutrino programme at CERN to enable strong participation in US projects
    - US Snowmass and P5 (Particle Physics Projects Prioritization Panel) 2013/2014
        1. Continue LHC involvement, including HL-LHC detector upgrades
        2. Support ILC development, increased involvement if ILC proceeds
        3. Develop a coherent short- and long baseline neutrino program hosted at Fermilab
        4. Increase international collaborations for long-baseline neutrino program, highest priority near- and mid-term large project
        5. Long-term R&D on CLIC, Muon Collider and high-field magnets for p+p colliders

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    2. Design studies for future CERN projects after LHC, focus on p+p and e^+e^-, energy

Global consensus:

Fully exploit LHC, including detector and accelerator upgrades

Support ILC as a possible medium-term energy frontier collider

Continue long-term R&D for future projects at (much) higher energy

1. Continue LHC involvement, including HL-LHC detector upgrades
2. Support ILC development, increased involvement if ILC proceeds
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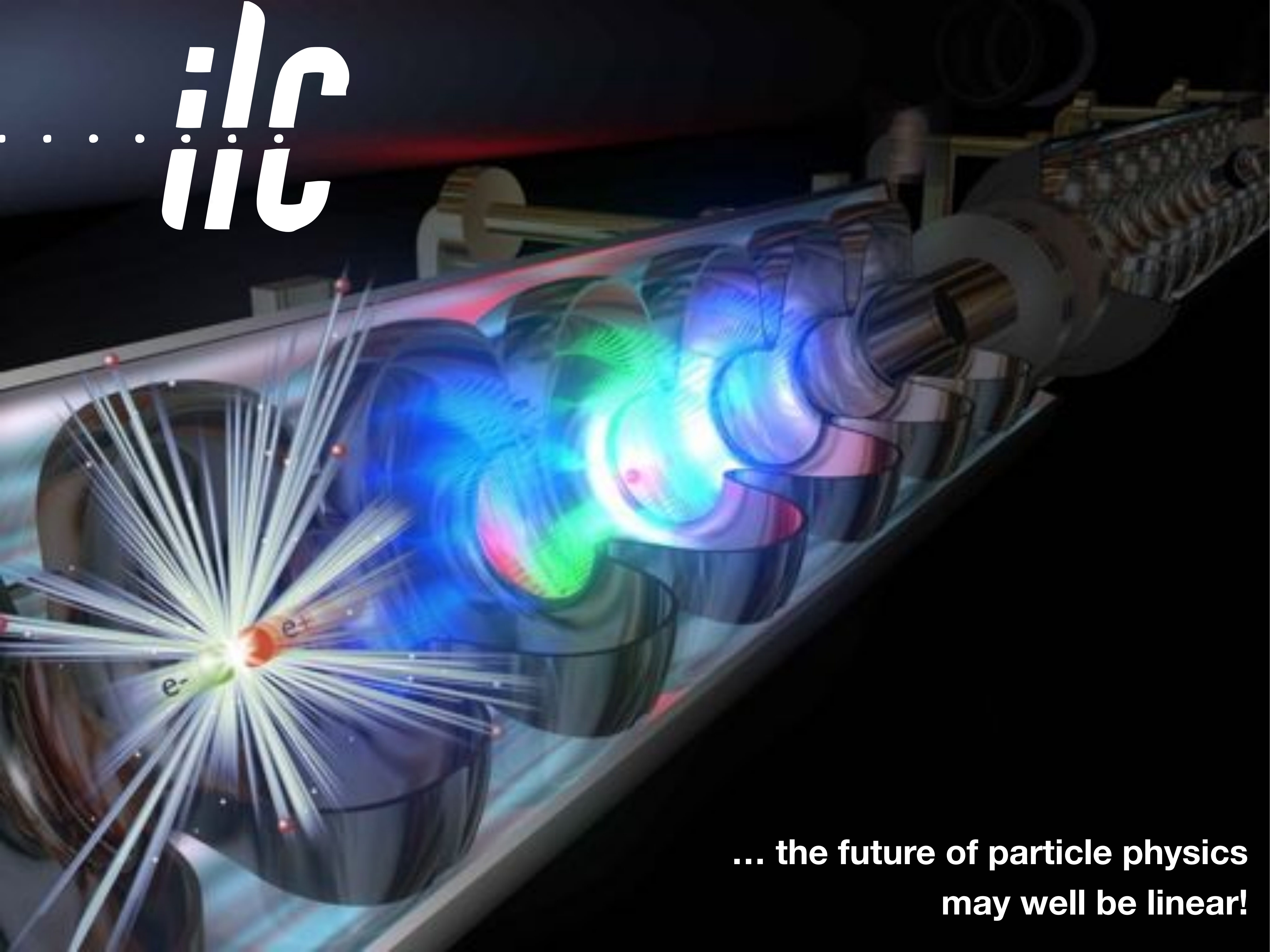
Summary

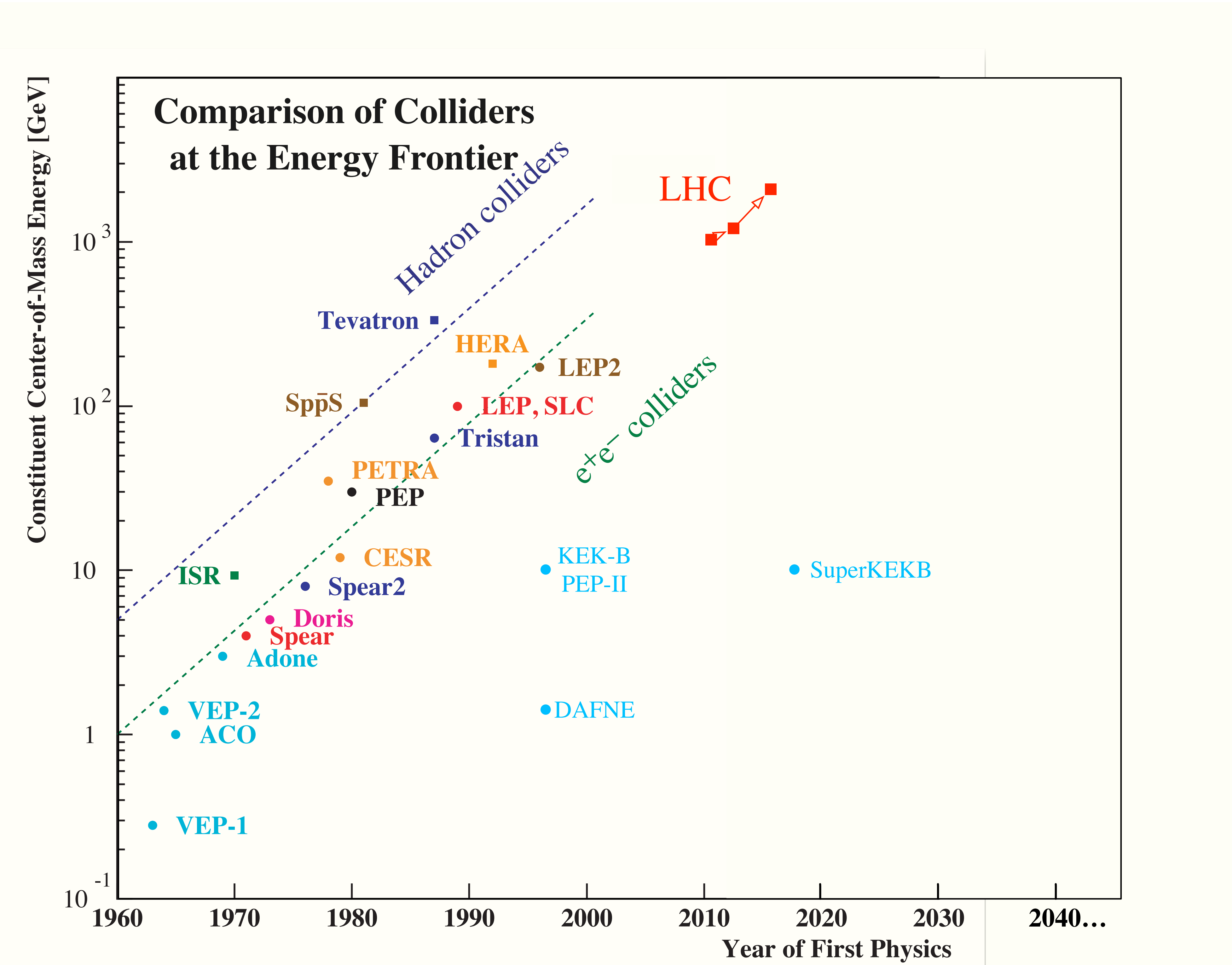
- Accelerator experiments at the energy frontier have always marked the spear-head of our understanding of the most fundamental constituents of the universe
  - fruitful interplay between hadron and lepton colliders
- LHC defines the current “state of the art”, and will continue to do so for the next decade
- The International Linear Collider is the most mature option for the next machine at the energy frontier
  - Technology established - based on superconducting acceleration structures
  - Mature detector concepts based on novel / modern technologies and approaches to event reconstruction
  - Energies up to 500 GeV (1 TeV with upgrade) for a full exploration of the Higgs and Top sector, and a discovery potential for BSM physics complementary to that of the LHC
  - Japan is considering to host the ILC in the Kitakami Mountains - enormous support on the local level, high-level political discussions under way, expect a conclusion by early 2016



… the future of particle physics
may well be linear!

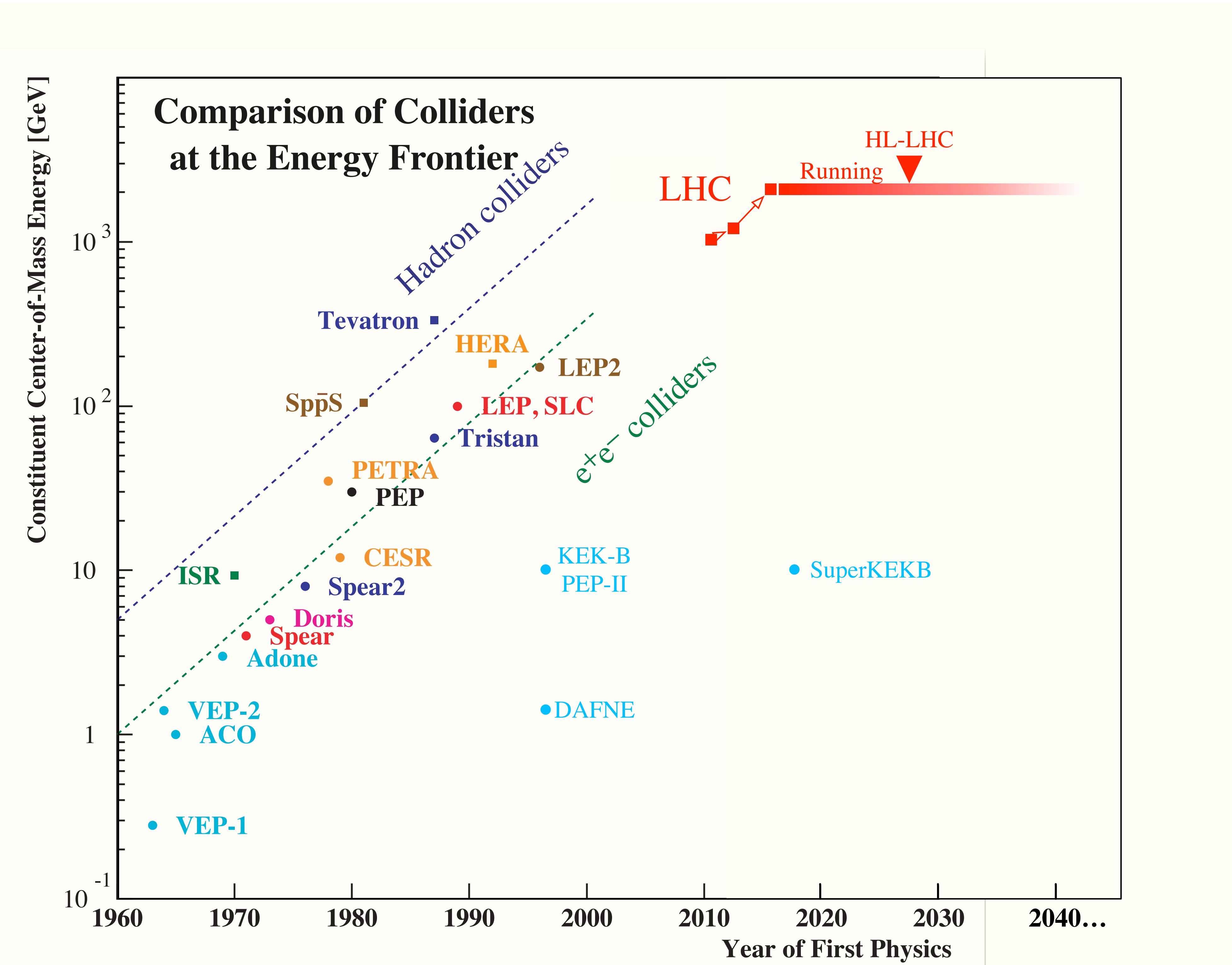
Backup

The Landscape - Past, Present and Future Colliders



taken from Nick Walker

The Landscape - Past, Present and Future Colliders



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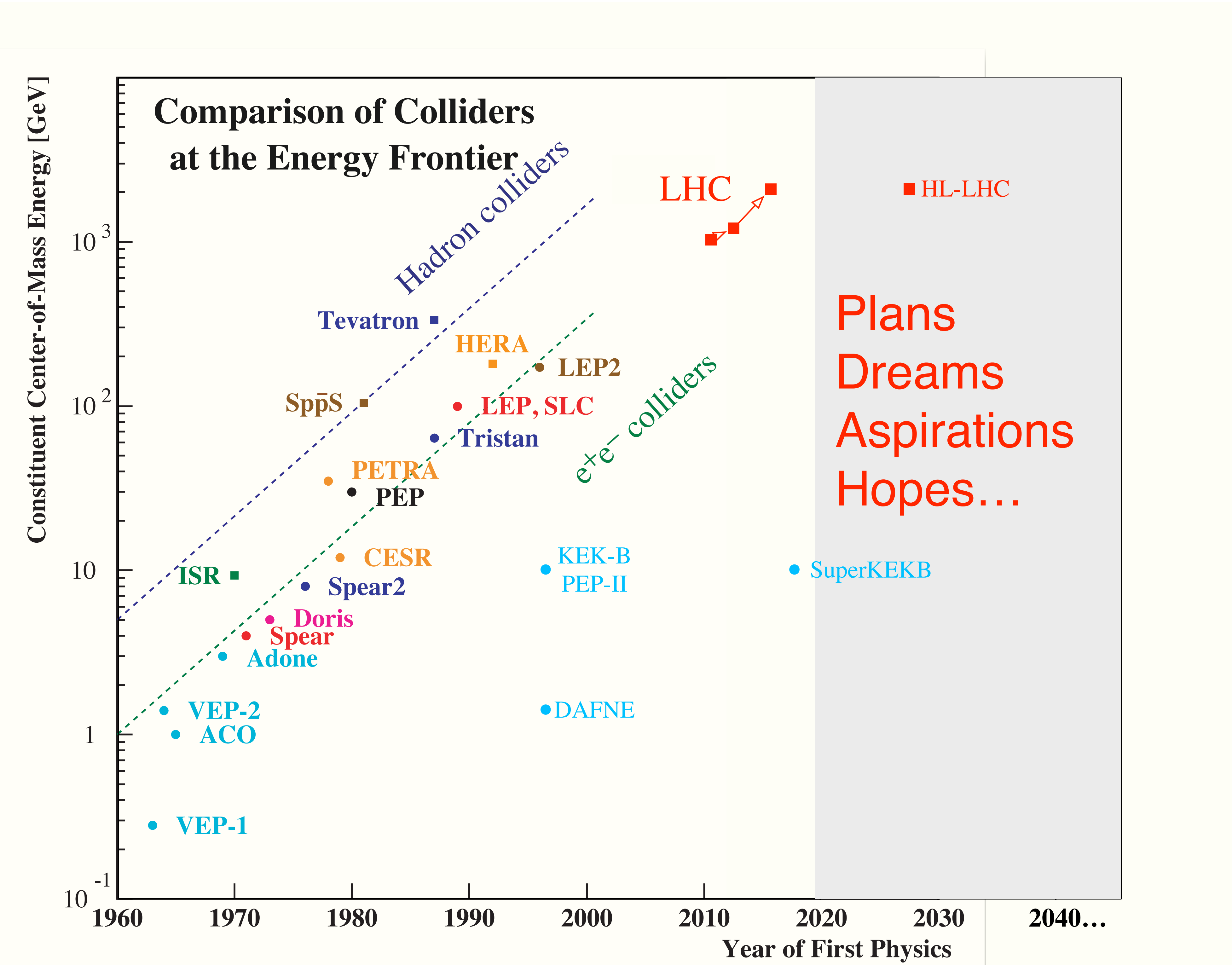

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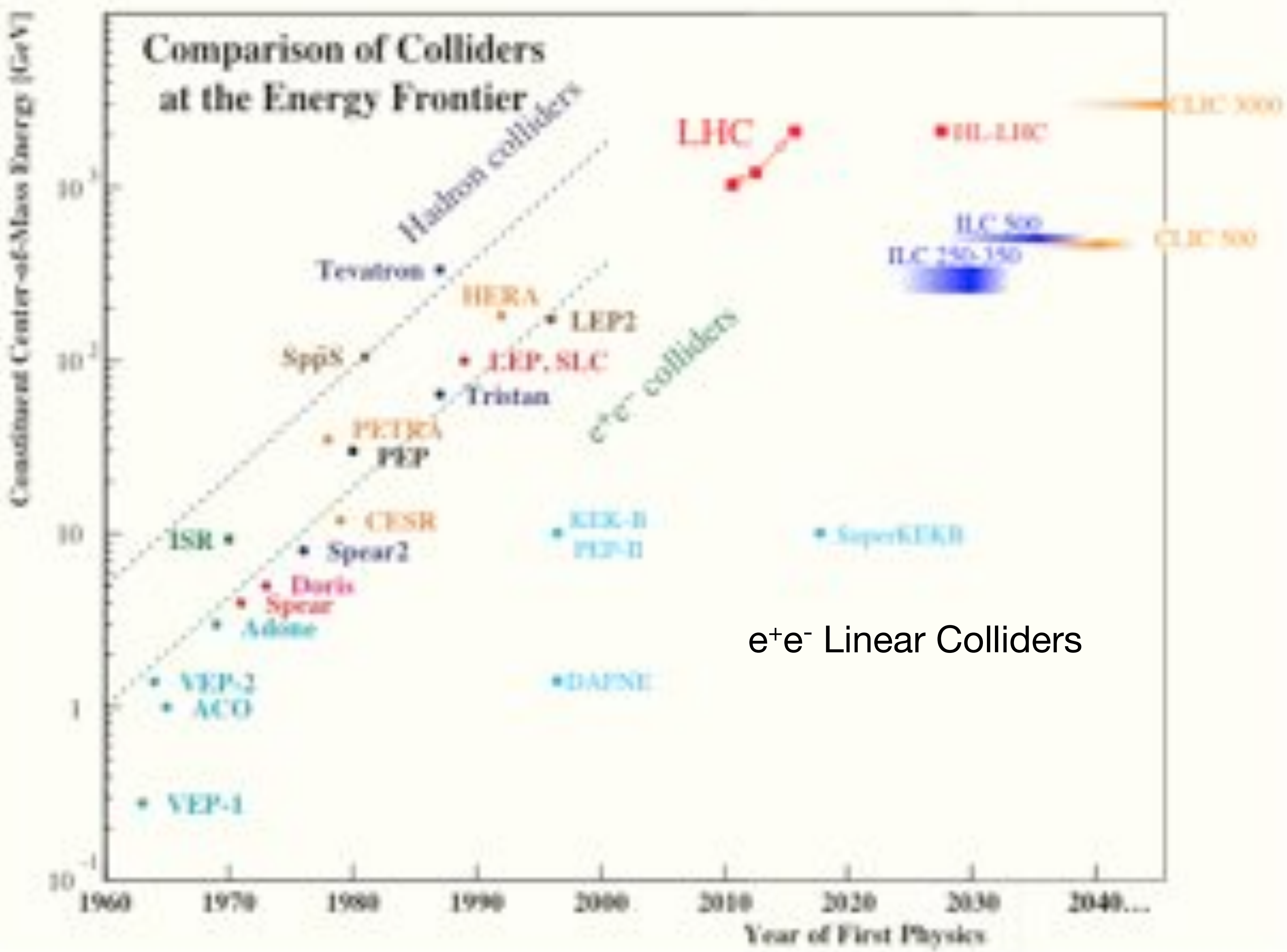
The Landscape - Past, Present and Future Colliders



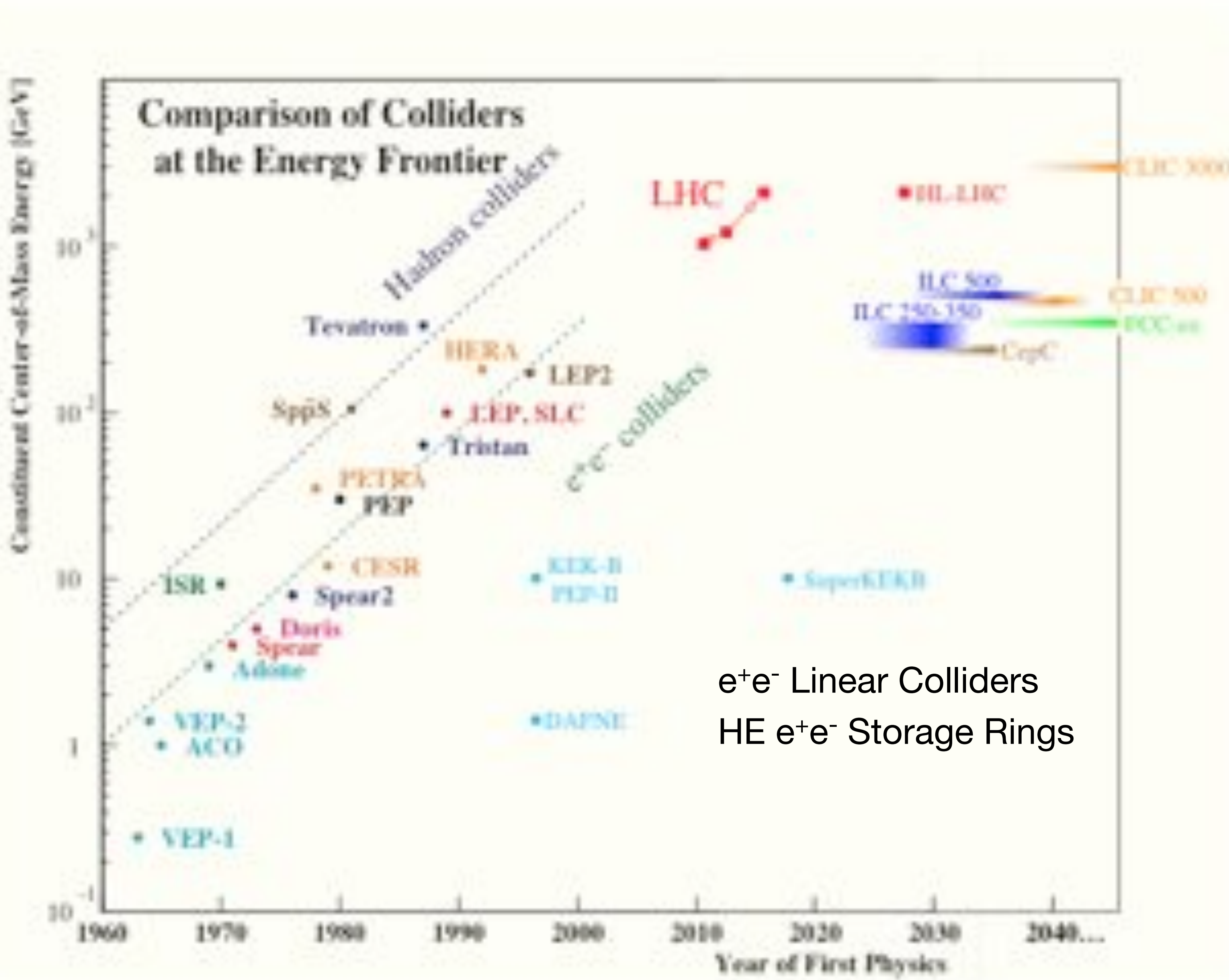
e^+e^- Linear Colliders

Linear Colliders:

30 - 50 km in length

taken from Nick Walker

The Landscape - Past, Present and Future Colliders



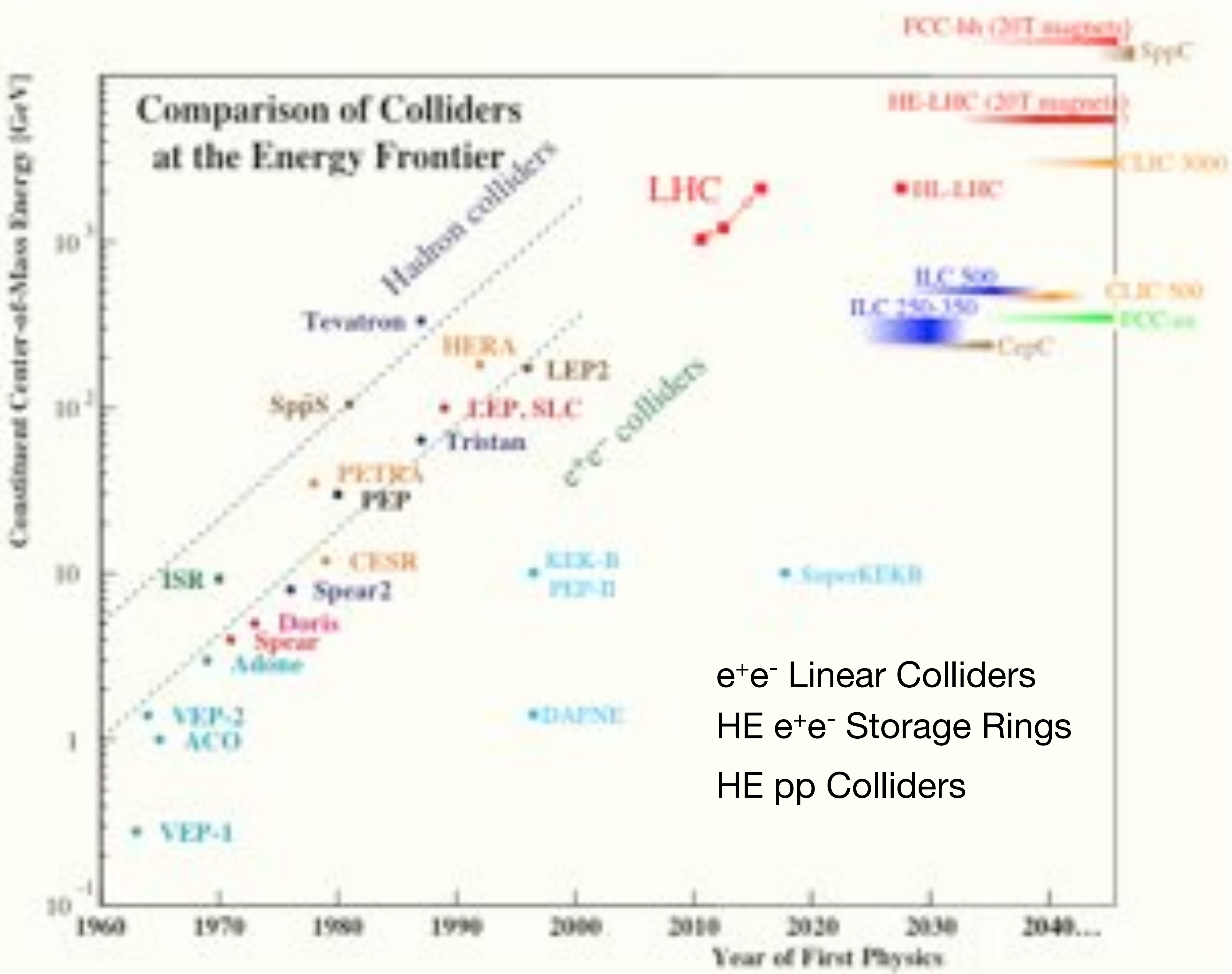
e^+e^- Linear Colliders
HE e^+e^- Storage Rings

Linear Colliders:
30 - 50 km in length

Synchrotrons:
50 km - 100 km tunnels, main drivers typically pp, also come with e^+e^- option

taken from Nick Walker

The Landscape - Past, Present and Future Colliders



Linear Colliders:
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taken from Nick Walker

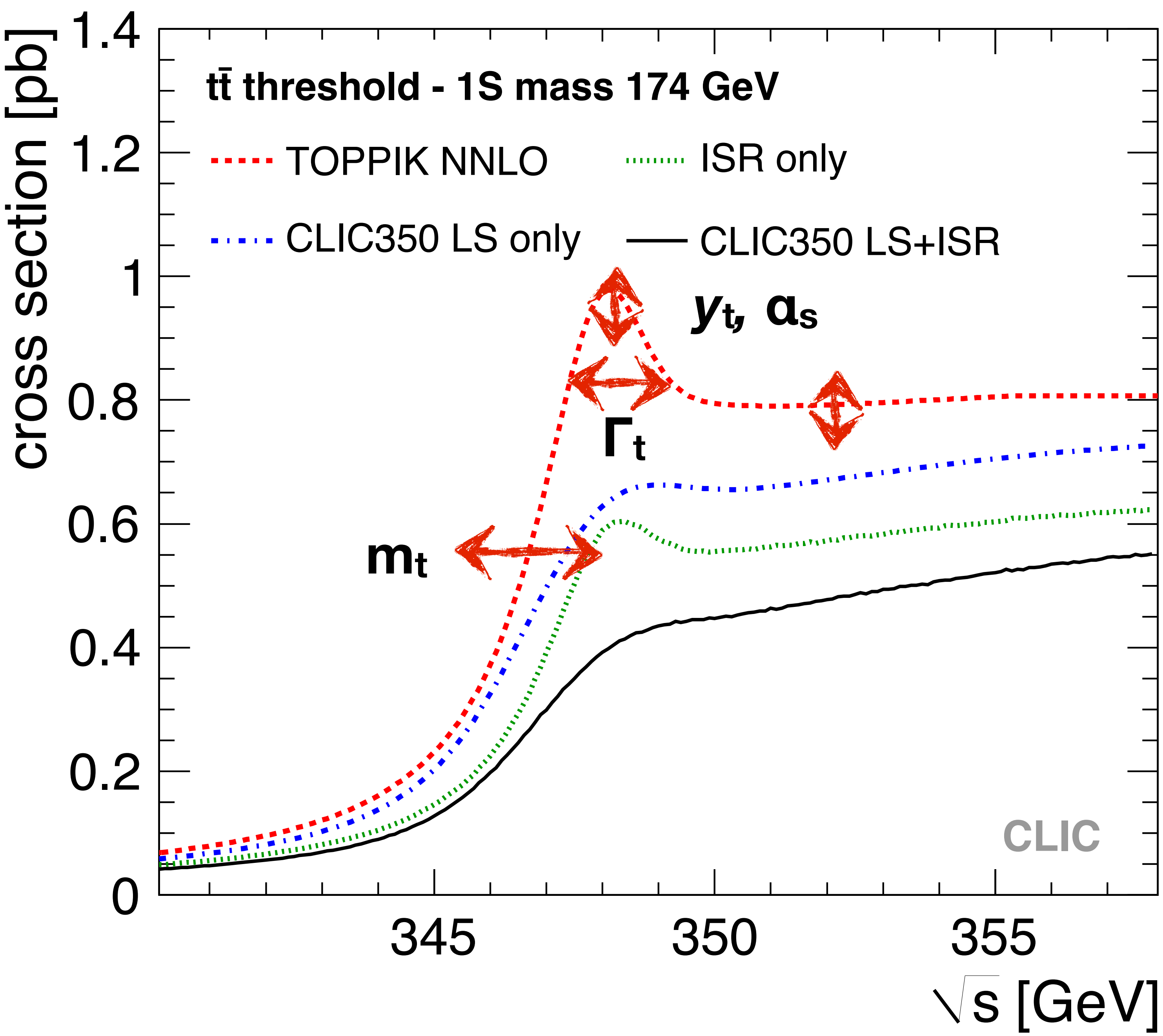
New Colliders - The Line-Up: Linear Colliders

- The **I**nternational **L**inear **C**ollider: a 30 - 50 km long linear tunnel
  - e^+e^- collisions up to 500 GeV / 1 TeV for Higgs, Top, BSM
  - Superconducting acceleration structures, ~ 30 MV/m
  - Technologically far advanced: Technical design report completed in 2012, ILC technology is being used for XFEL construction at DESY
  - Japan as potential host - Site north of Sendai (Kitakami)

Current time line

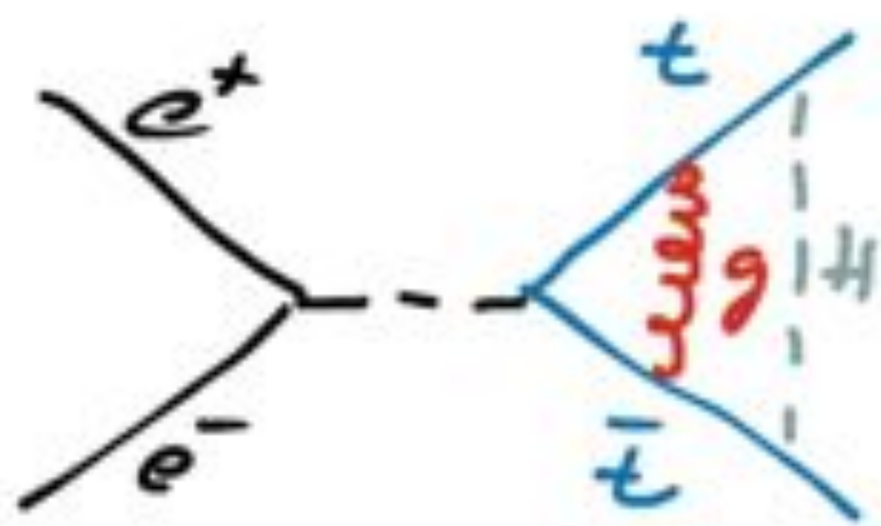
- Construction starting in 2018, physics 2027

Top Threshold Scan - Sensitivities



The cross-section around the threshold is affected by several properties of the top quark and by QCD

- Top mass, width, Yukawa coupling
- Strong coupling constant

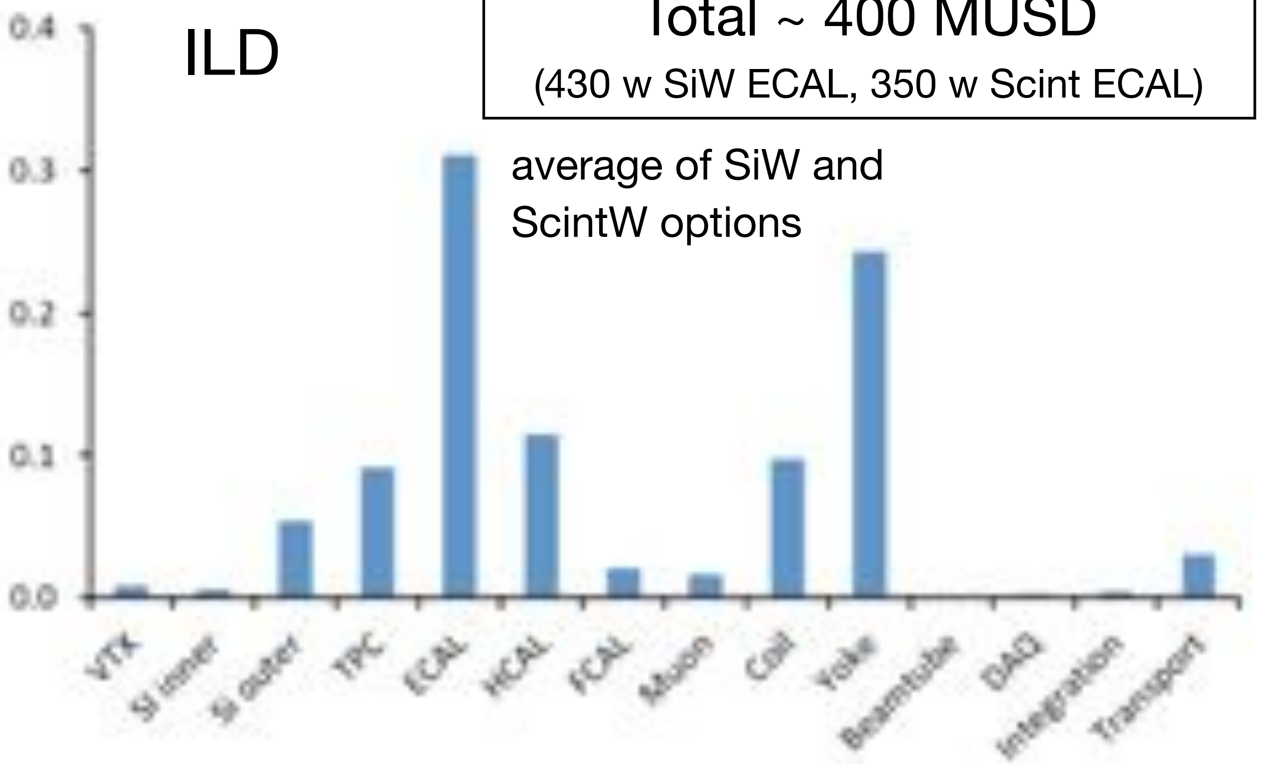


Here: Extract mass and α_s

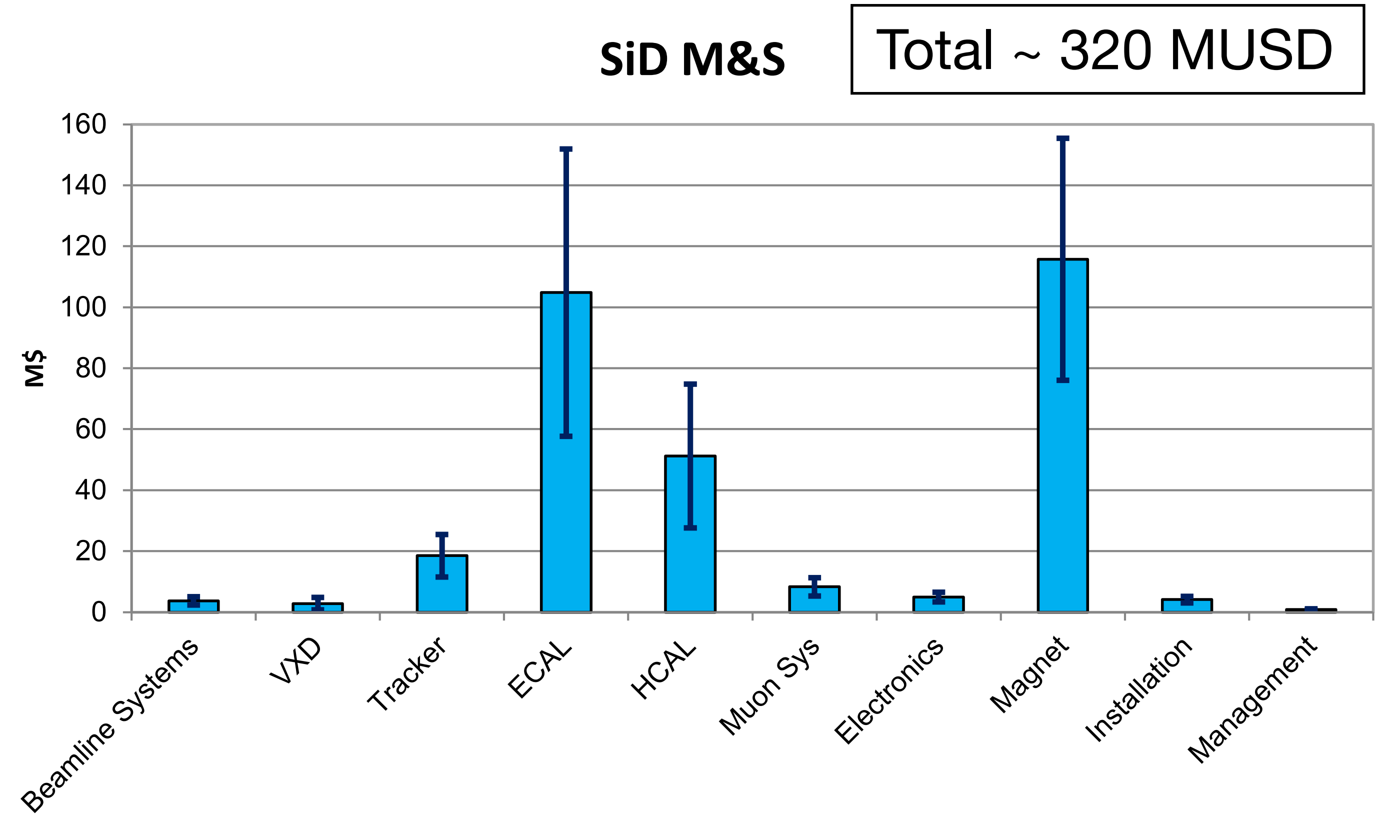
- Effects of some parameters are correlated; dependence on Yukawa coupling rather weak => Needs further study!

ILC Detector Cost

Total ~ 400 MUSD
(430 w SiW ECAL, 350 w Scint ECAL)



Total ~ 320 MUSD



- First estimate of cost (excl. labor) - for the some of the more expensive systems already quite detailed (NB: on some items the cost models of ILD and SiD are different)
  - ▸ Clearly reflects the design for PFA: ~ 50% of the total cost is in the calorimeters
  - ▸ Shows SiD optimization with cost-effectiveness in mind

Studies to evaluate the cost and performance impact of parameter changes are ongoing