The International Linear Collider

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„I hear the roar of a big machine....“
The Sisters of Mercy

Programme

- Introduction
- ILC Accelerator Design
- ILC Detectors
- Global Context
- Outlook

Introduction

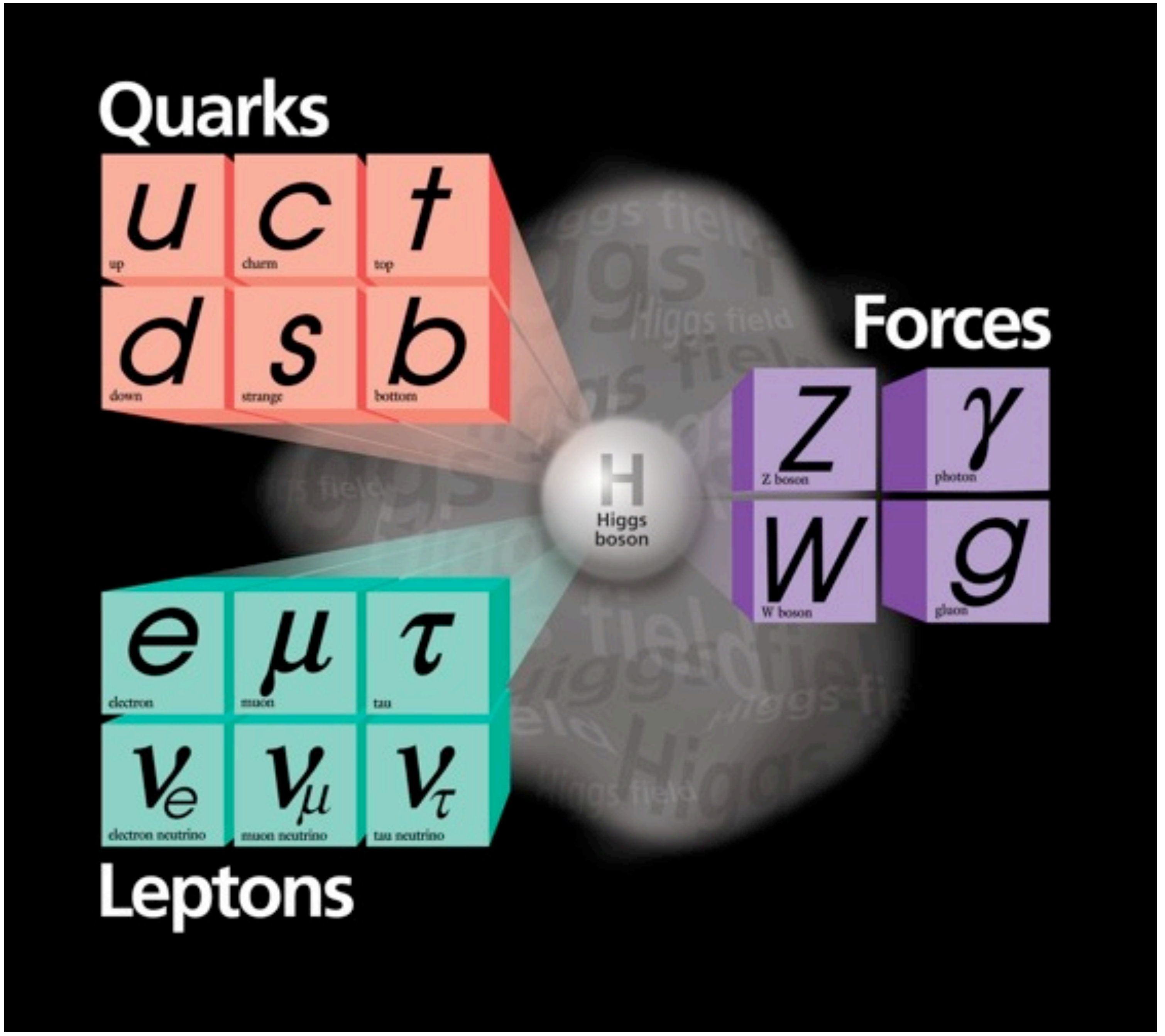
Standard Model of Particle Physics

- Extremely succesful description of the microcosm
- 12 matter particles
- 4 force mediators

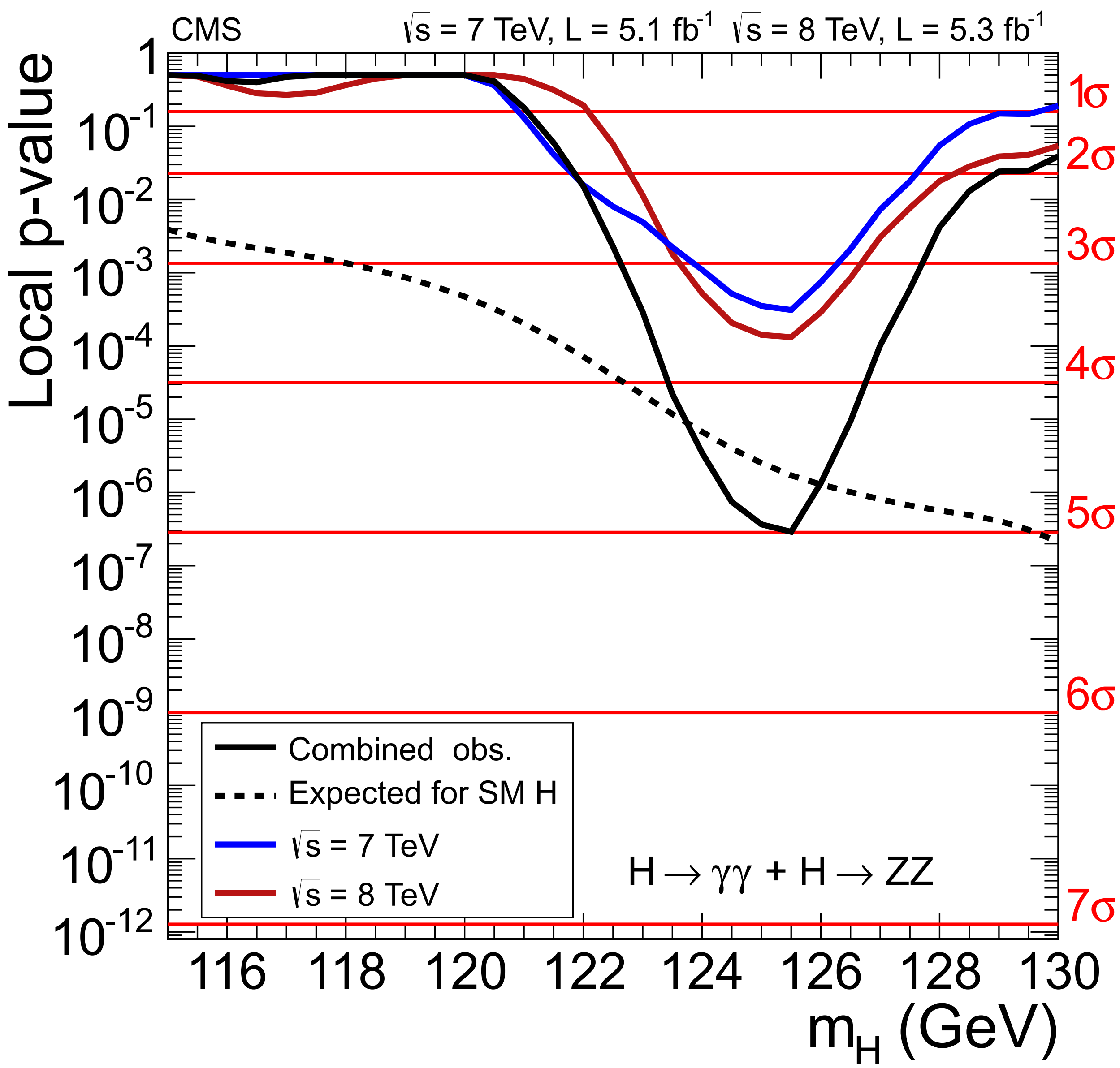
- and the one no longer missing piece:

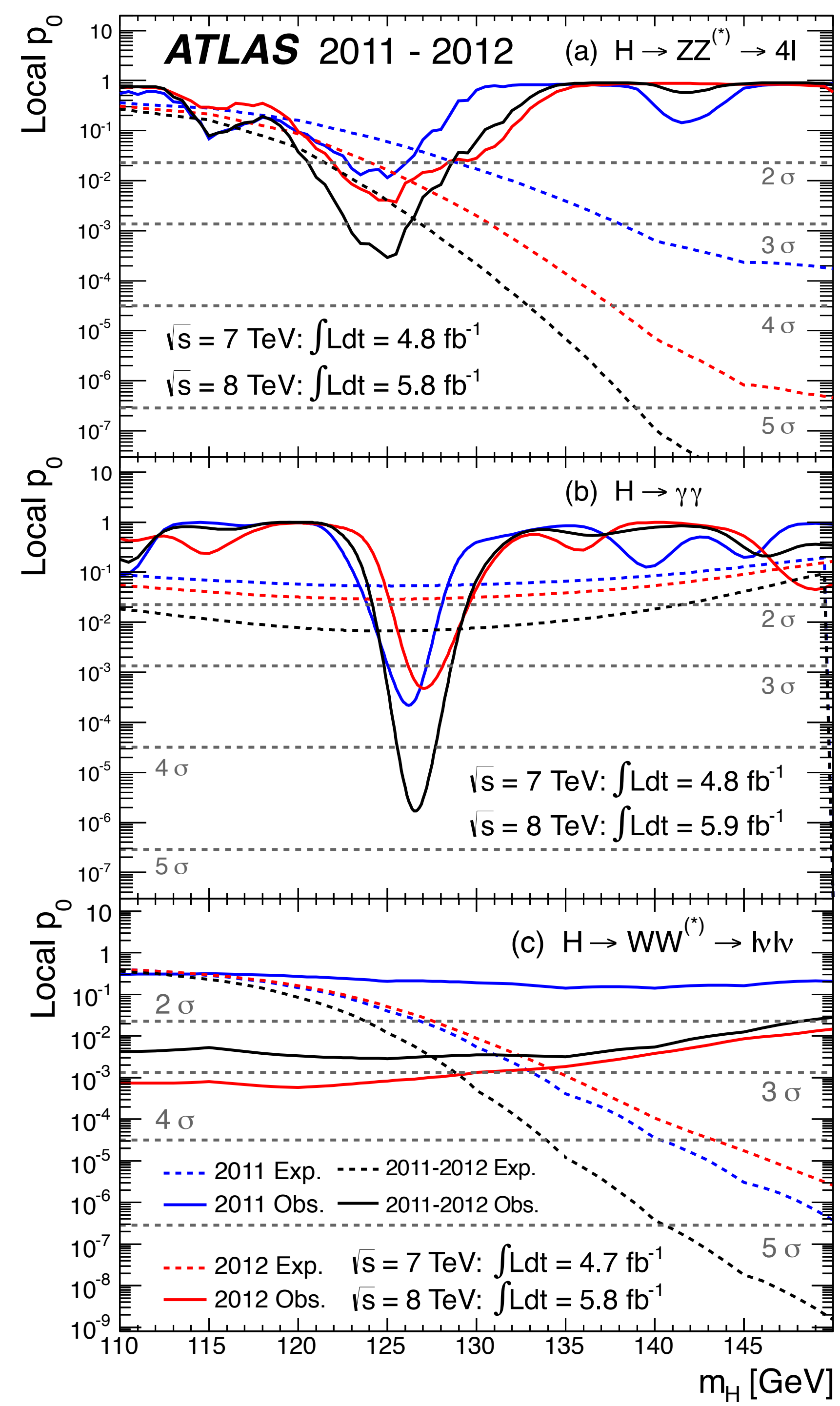
  Higgs Boson

  or whatever has been discovered at 125 GeV!



Discovery of a New Boson at 125 GeV



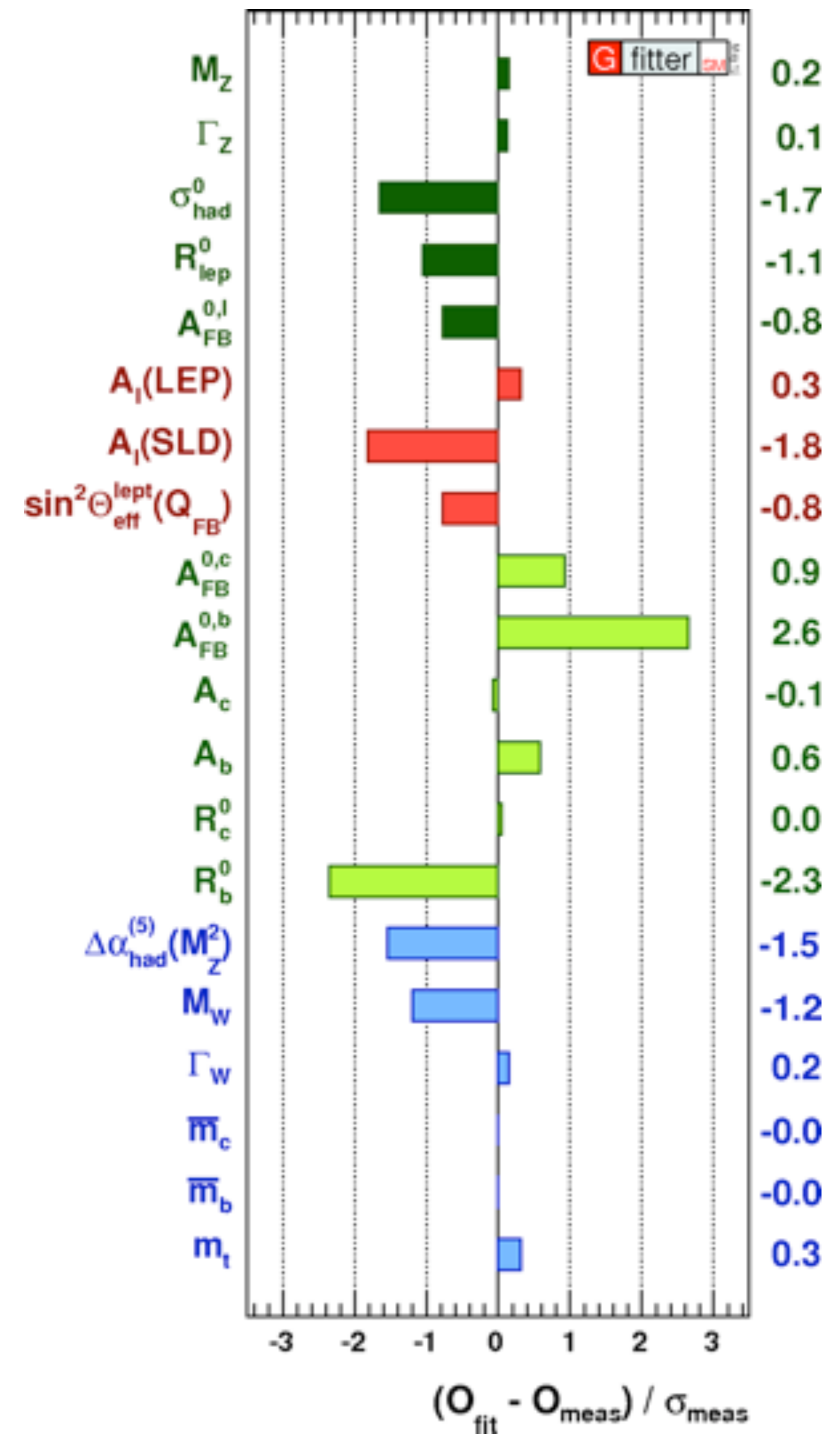


- Now have to establish the nature of the observed boson!

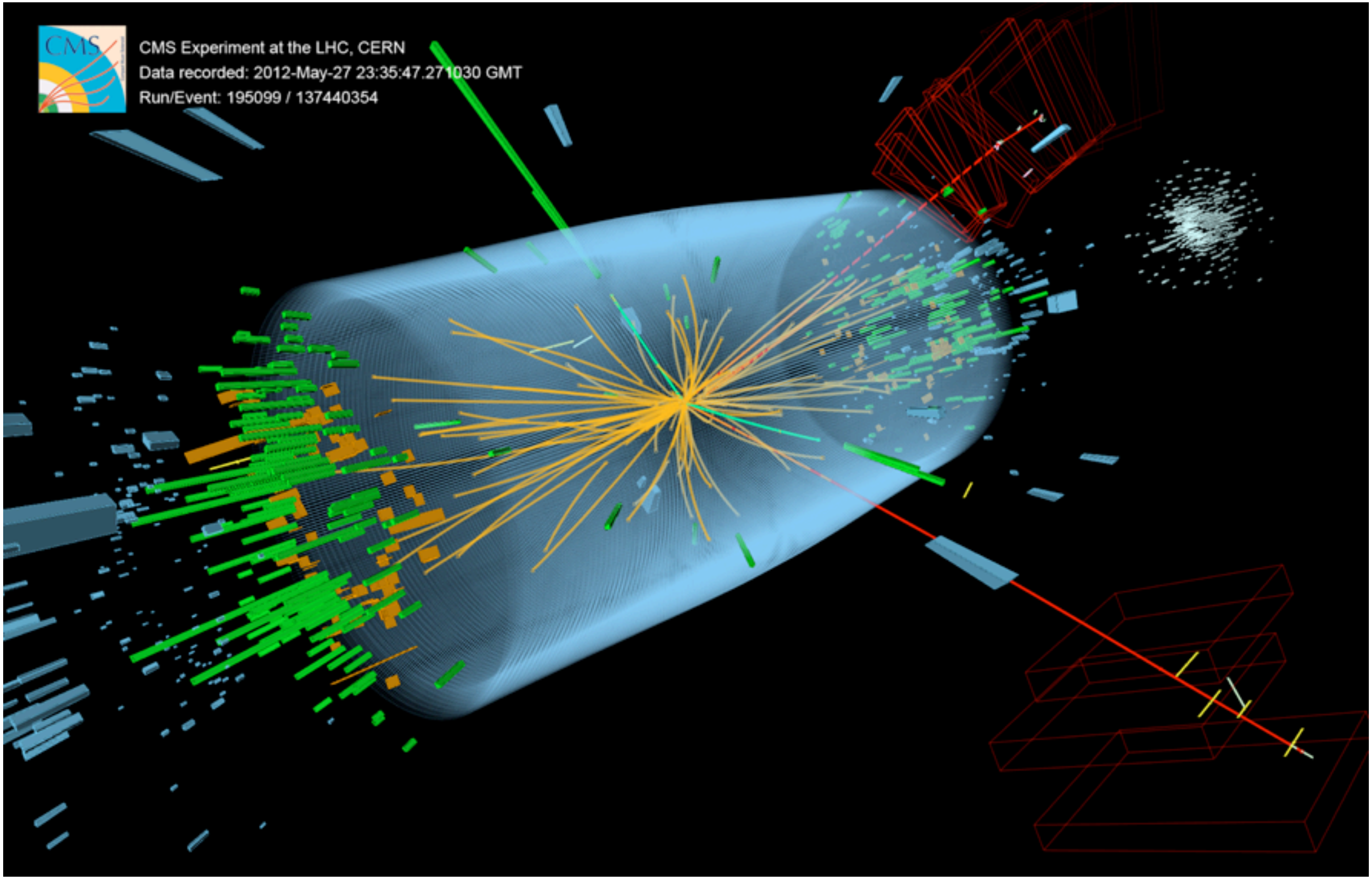
Standard Model Tests

- The Standard Model has been tested by many precision experiments at LEP, Tevatron, LHC, HERA, B factories, etc.
- No significant deviation found
- Perfect theory?

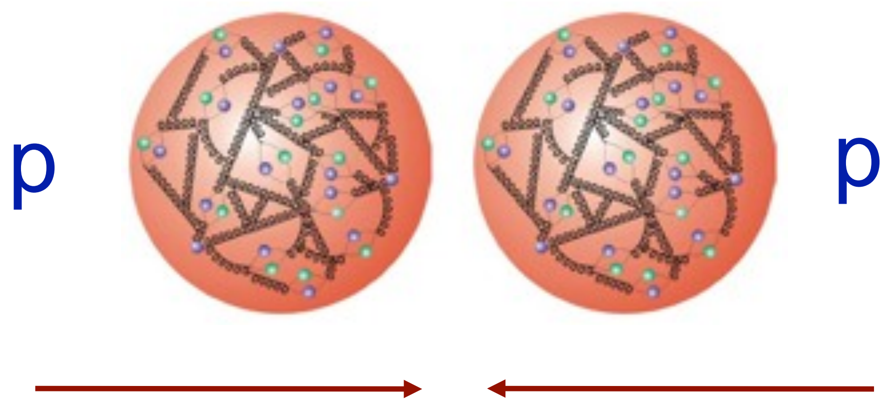
- Good reasons to assume SM is only a low-energy approximation of a grand unifying theory

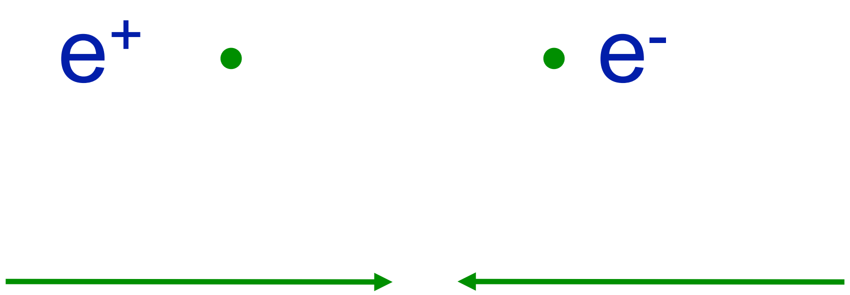


The Large Hadron Collider



Hadron and Lepton Colliders

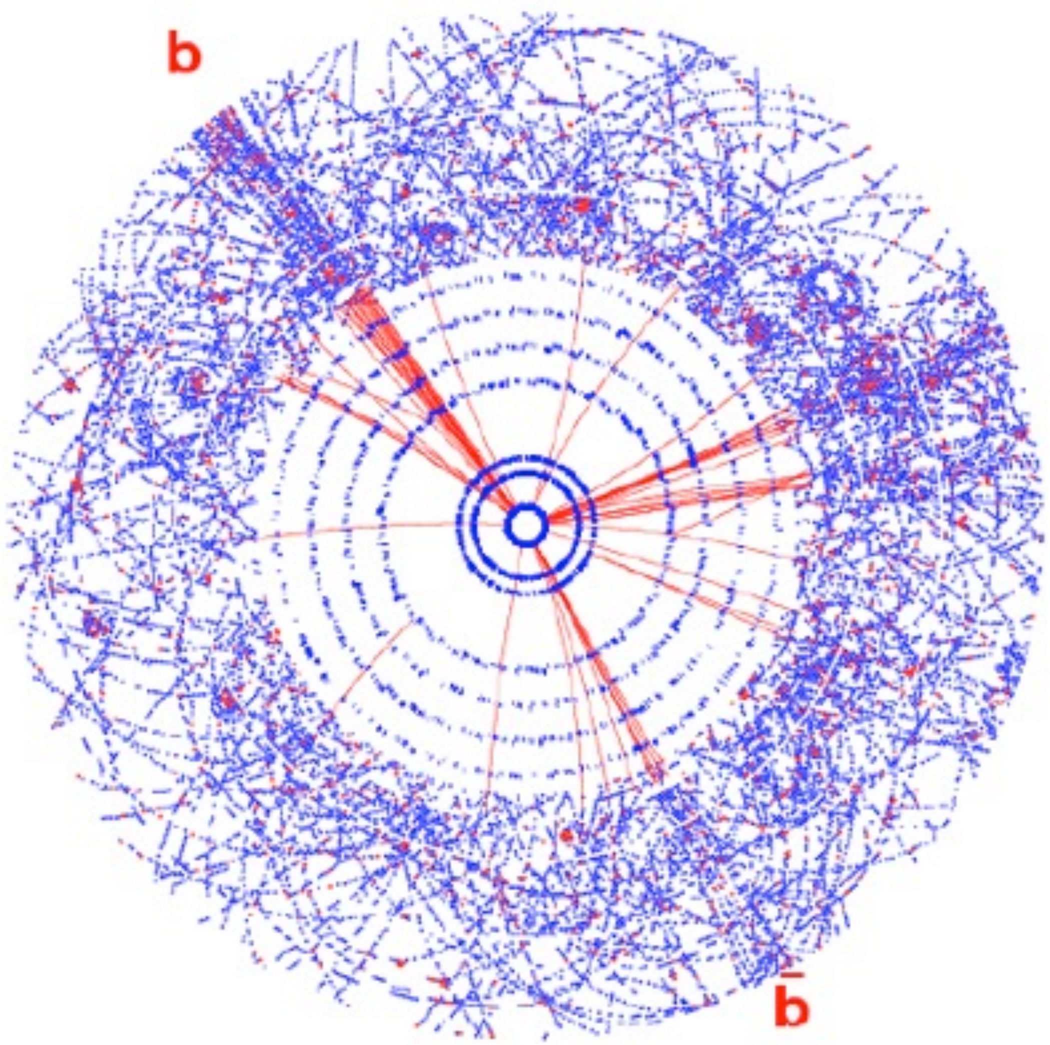


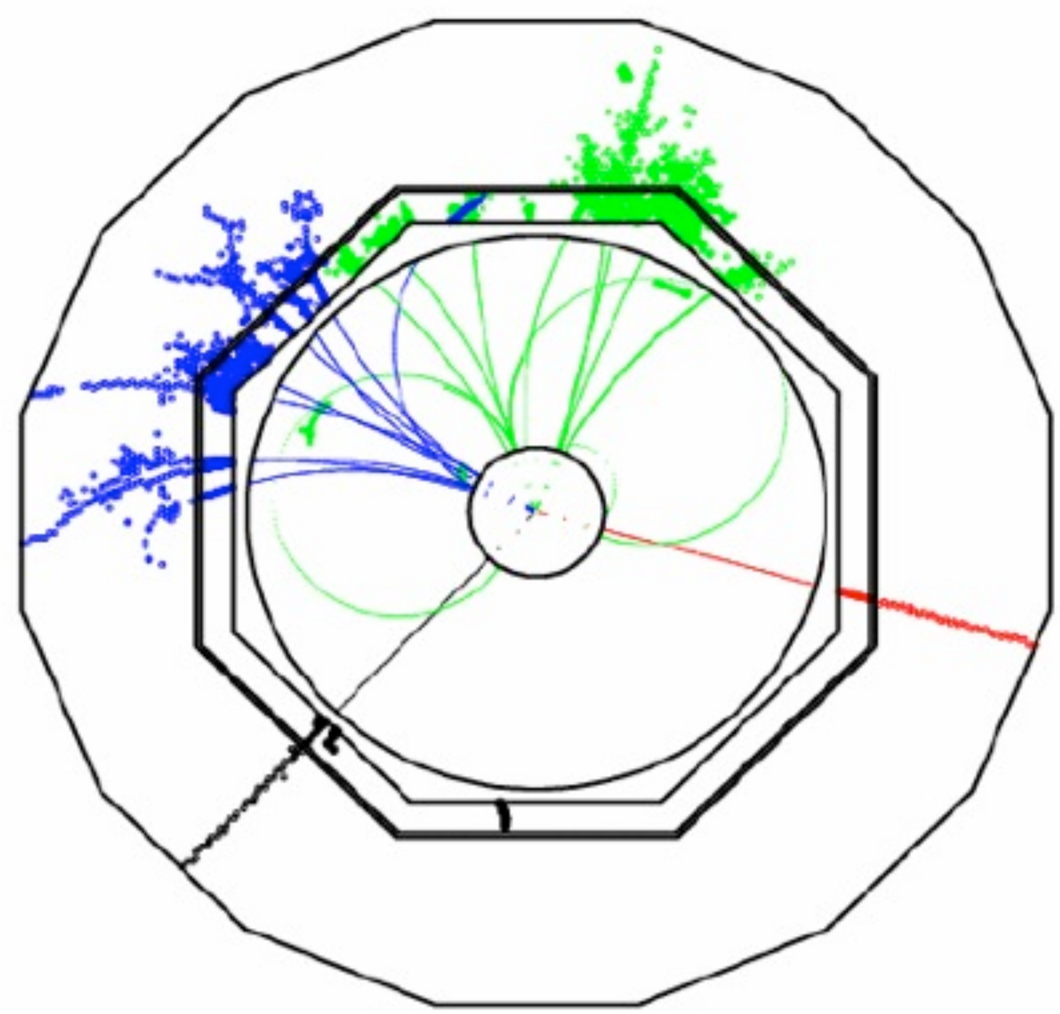


- Proton (anti-) proton colliders:
  - Energy range high (limited by bending magnets power)
  - Composite particles, different initial state constituents and energies in each collision
  - Difficult hadronic final states
- Discovery machines
- Precision measurement potential

- Electron positron colliders:
  - Energy range limited (by RF power)
  - Pointlike particles, well defined initial state quantum numbers and eneries
  - Easier final states
- Precision machines
- Discovery potential

Hadron or Lepton Colliders

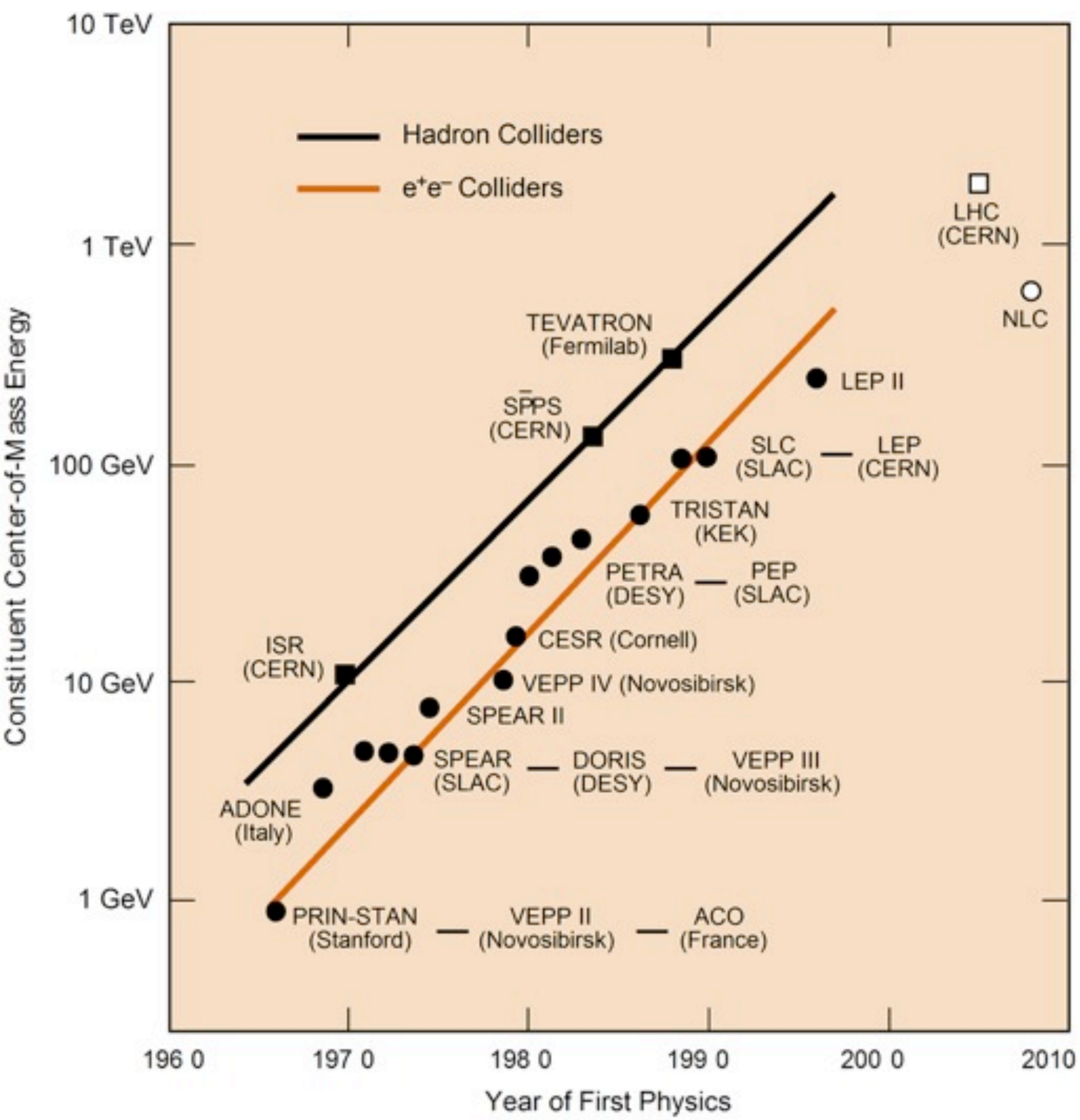


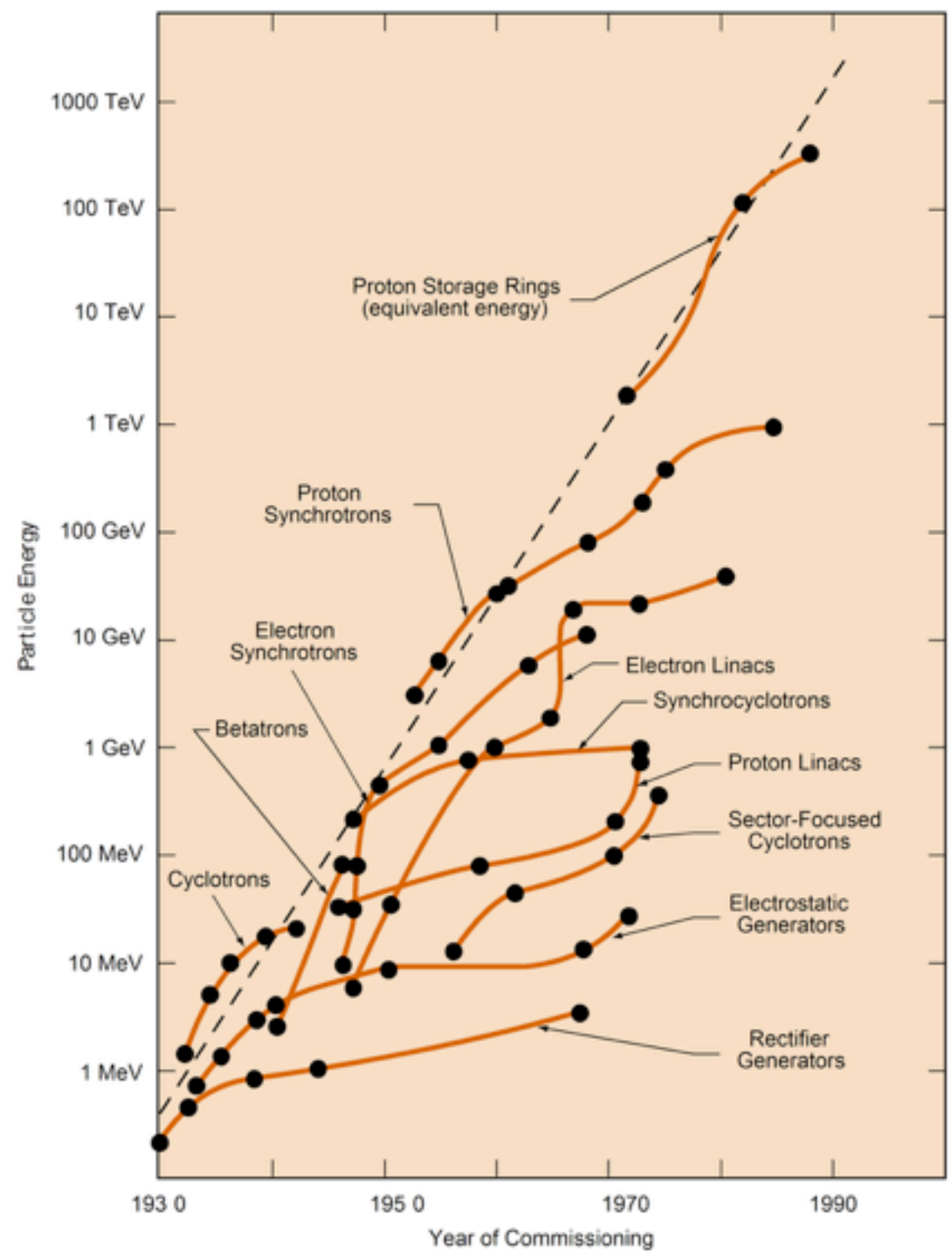


pp ➔ H + X

e^+e^- ➔ HZ

Collider History

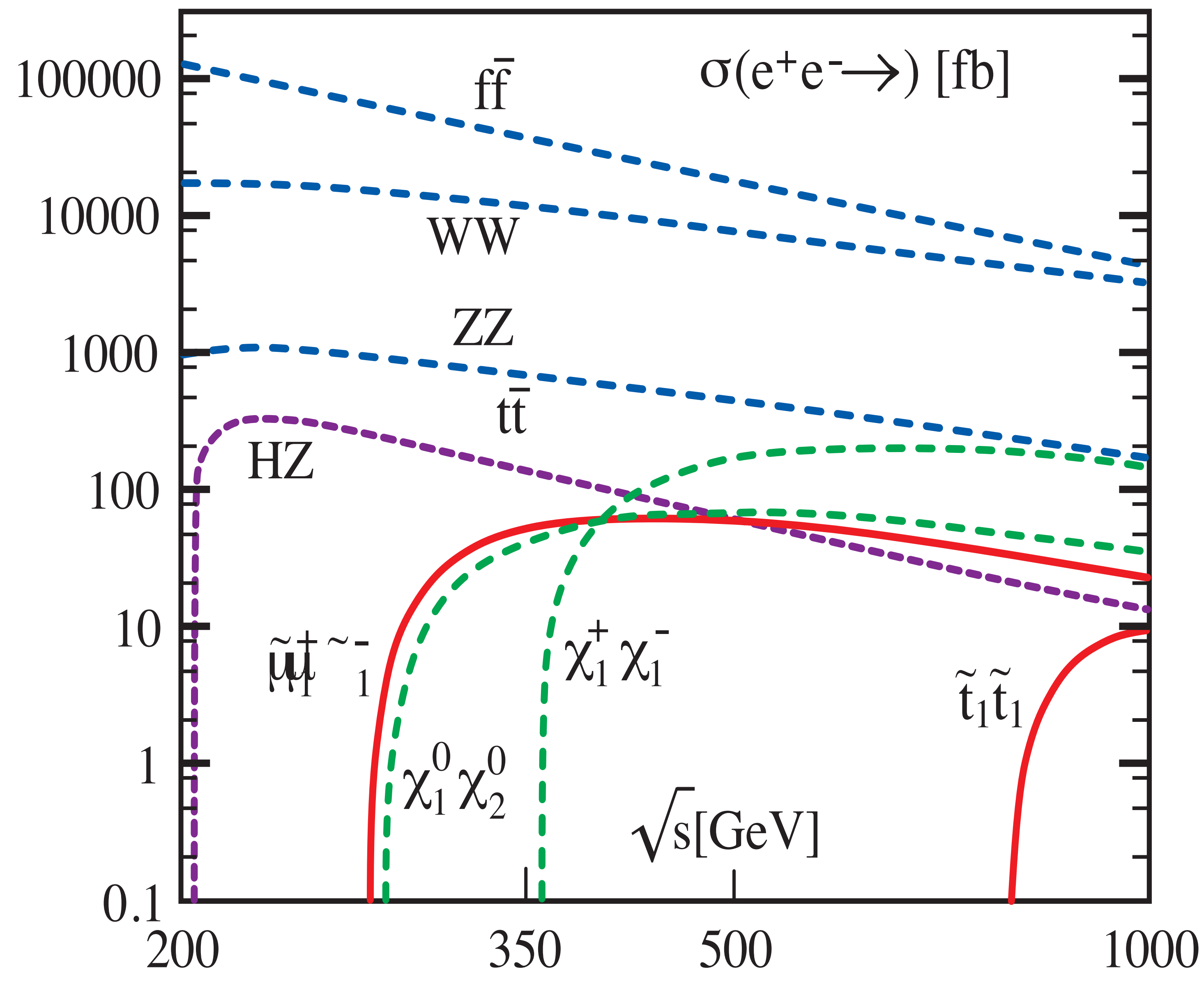




Future Lepton Collider Requirements

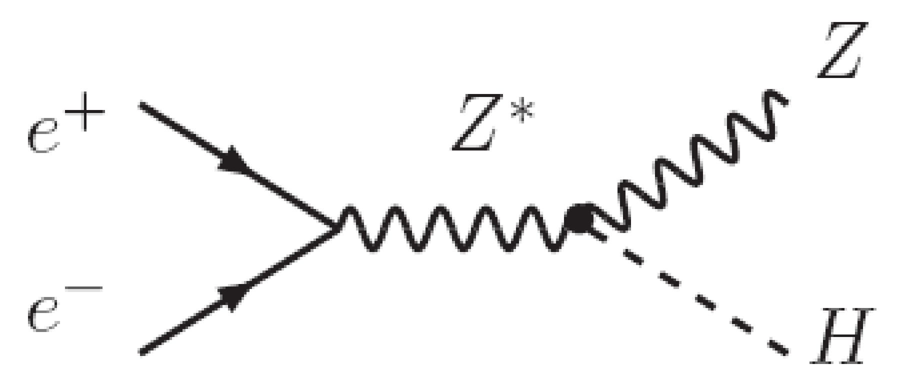
- The e+e- cross section drops ~1/s; some t-channel processes rise logarithmically

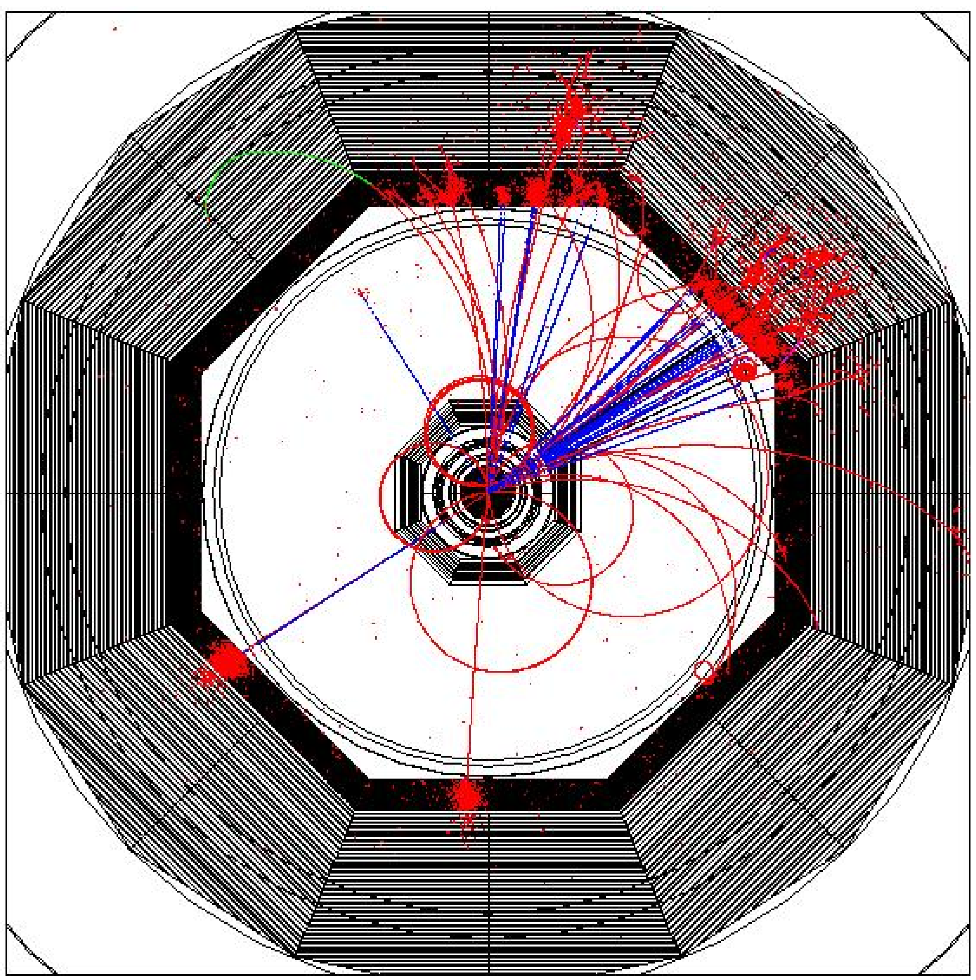
- The key parameters for a competitive e+e- machine are
  - the right energy window
  - luminosity

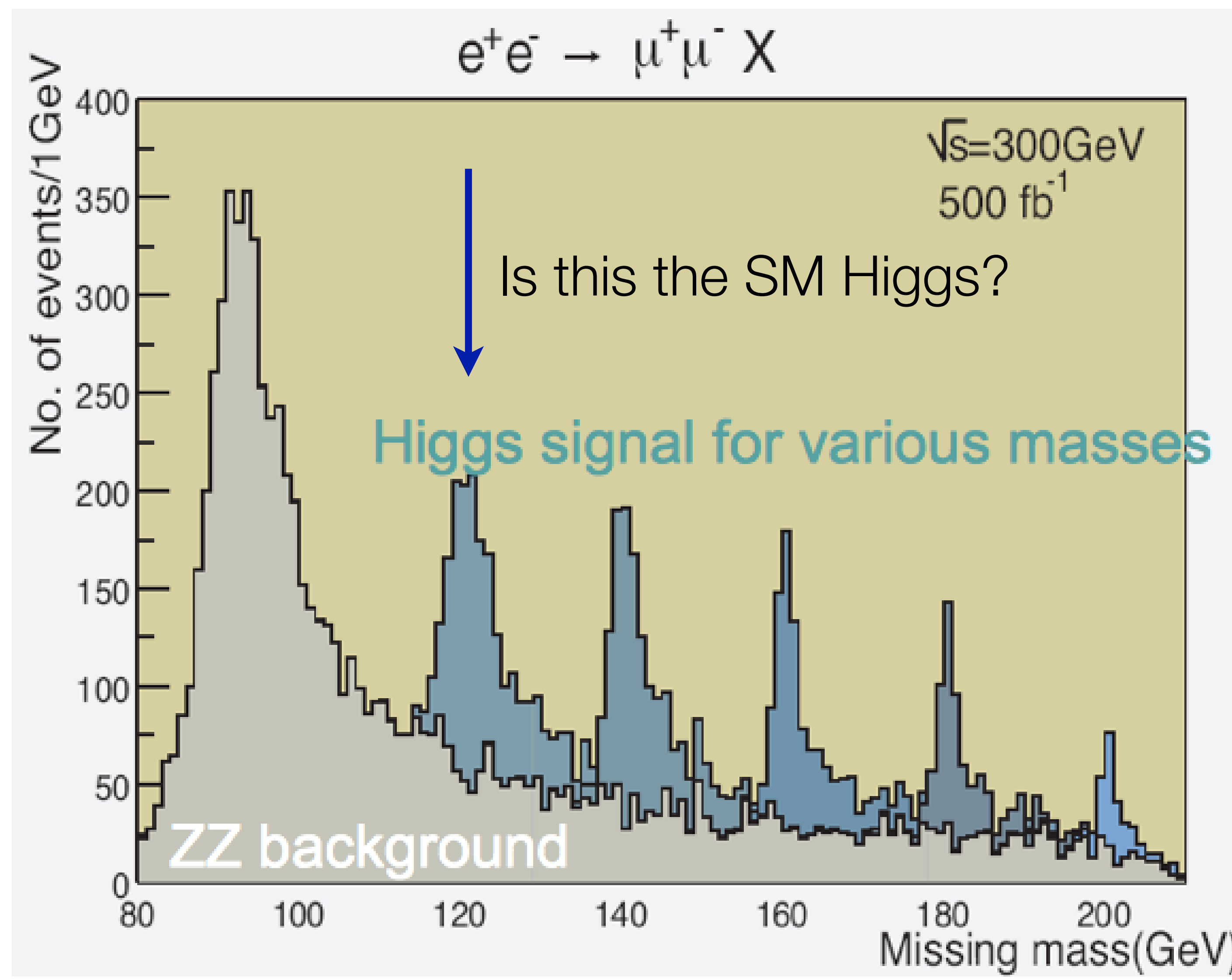


Higgs Physics

- Model independent Higgs measurement
  - recoil independent of branching ratios of Higgs particle

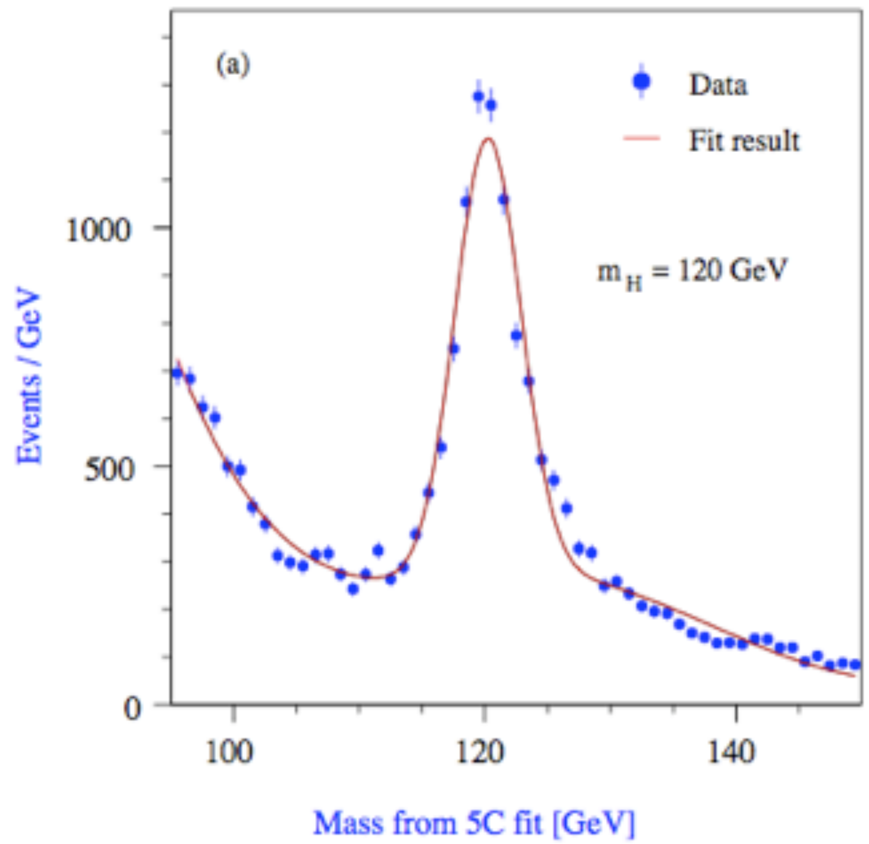




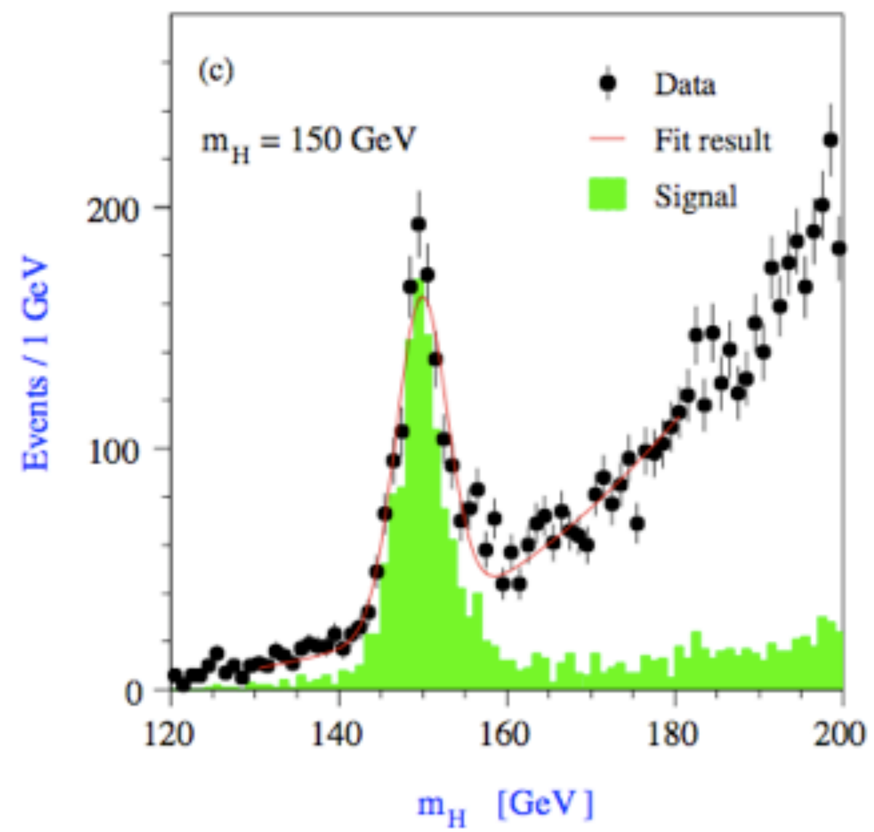


Higgs Mass Measurement

HZ→ bbqq



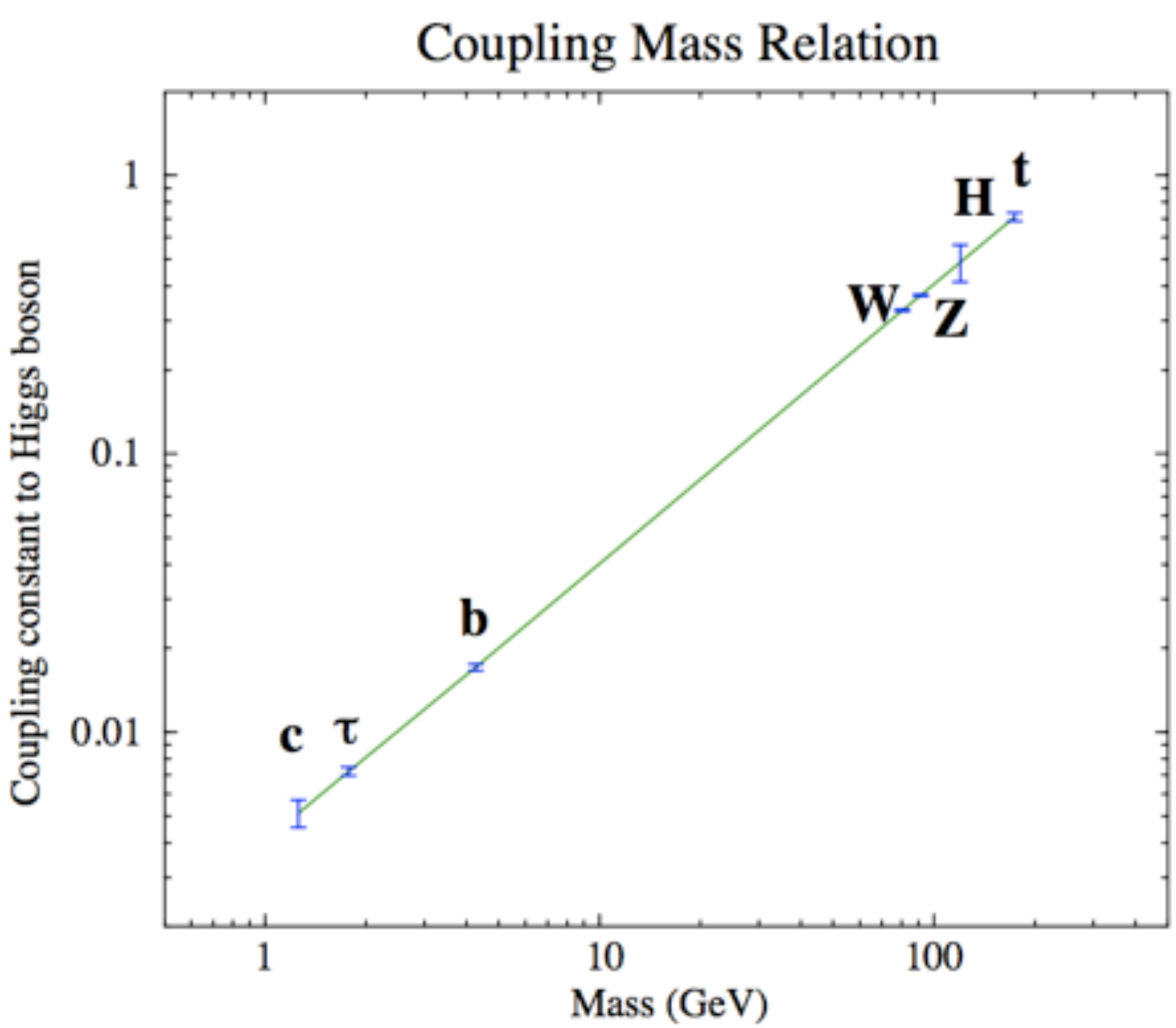
HZ→ W^+W^-qq



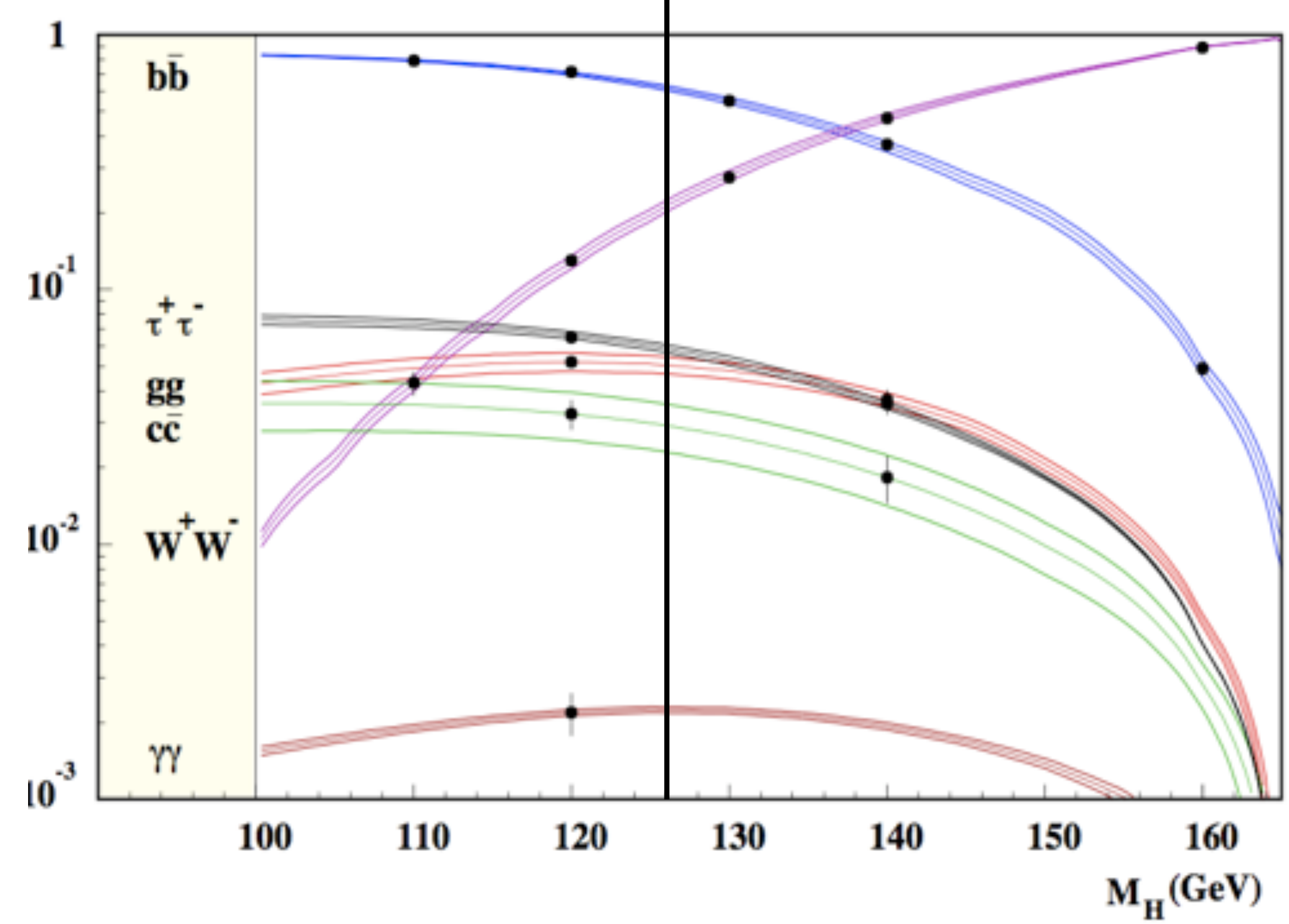
- Combined mass resolutions:
  - m_H=120 GeV: 40 MeV

Establishing the Higgs-Mechanism

- Measuring the couplings of the Higgs to massive particles
- Check coupling-mass relation
  - The key feature of the Higgs particle



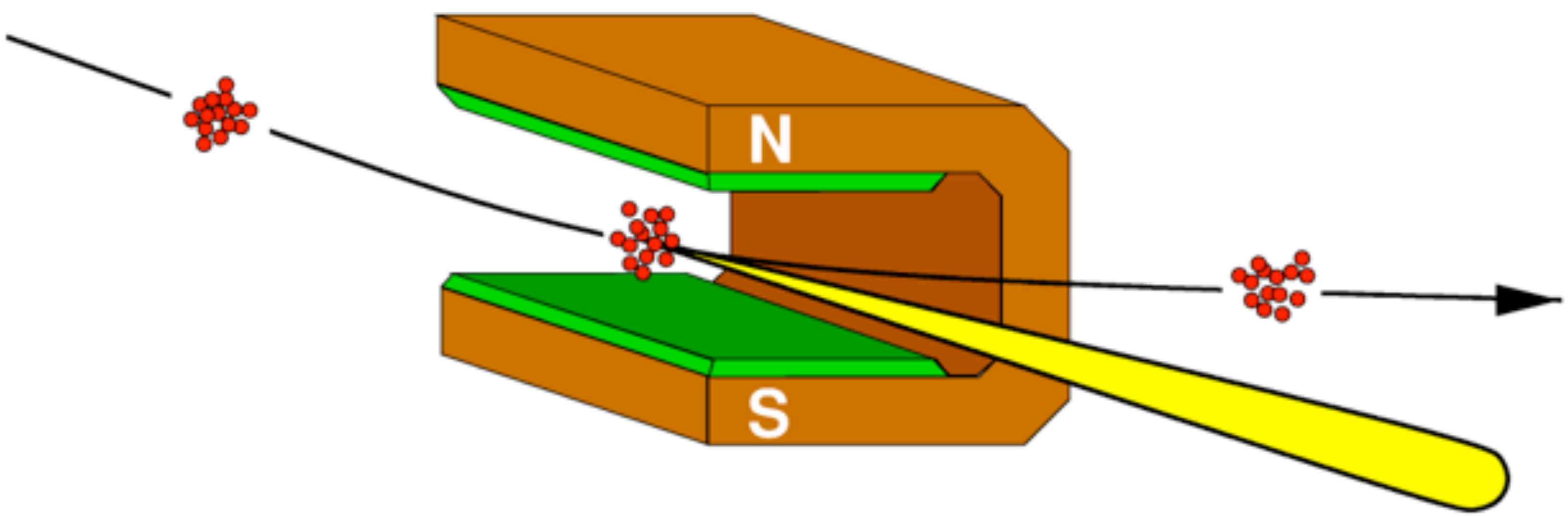
A Higgs at 125 GeV has favourable BR to several particles

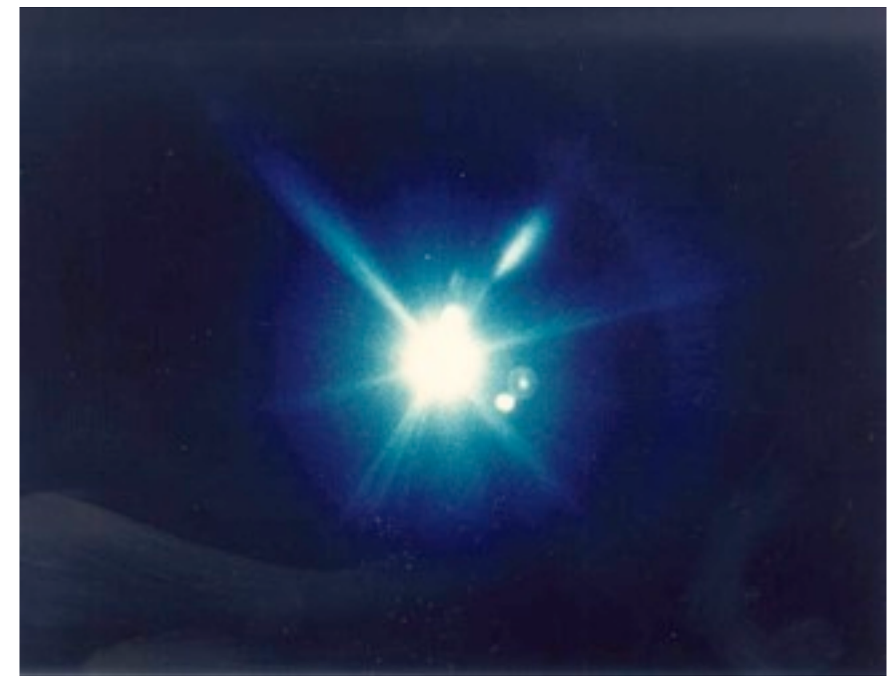


Accelerator Issues

The Limits of Storage Rings

- Charged particles radiate on curved trajectories





- Energy loss per revolution ~$1/m^4$
- RF power for acceleration: P_{RF} ~E^4/r

Cost Scaling for Storage Rings

- Cost for RF:
  - $€_{RF} \sim E^4/r$
- Linear cost (tunneling, beam lines, etc.):
  - $€_{lin} \sim r$
- Total cost optimum:
  - $€_{tot} = €_{RF}+€_{lin} \sim E^2$
  - $r_{opt} \sim E^2$
- For details: B. Richter, NIM 136 (1976) oo. 47-60

Scaling LEP

	LEP-II	Super-LEP	HYPER-LEP
E_{cm}	180 GeV	500 GeV	2 TeV
L	27 km	200 km	3200 km
ΔE	1.5 GeV	12 GeV	240 GeV
€$_{tot}$	2 billion	15 billion	240 billion!

Table by James Jones

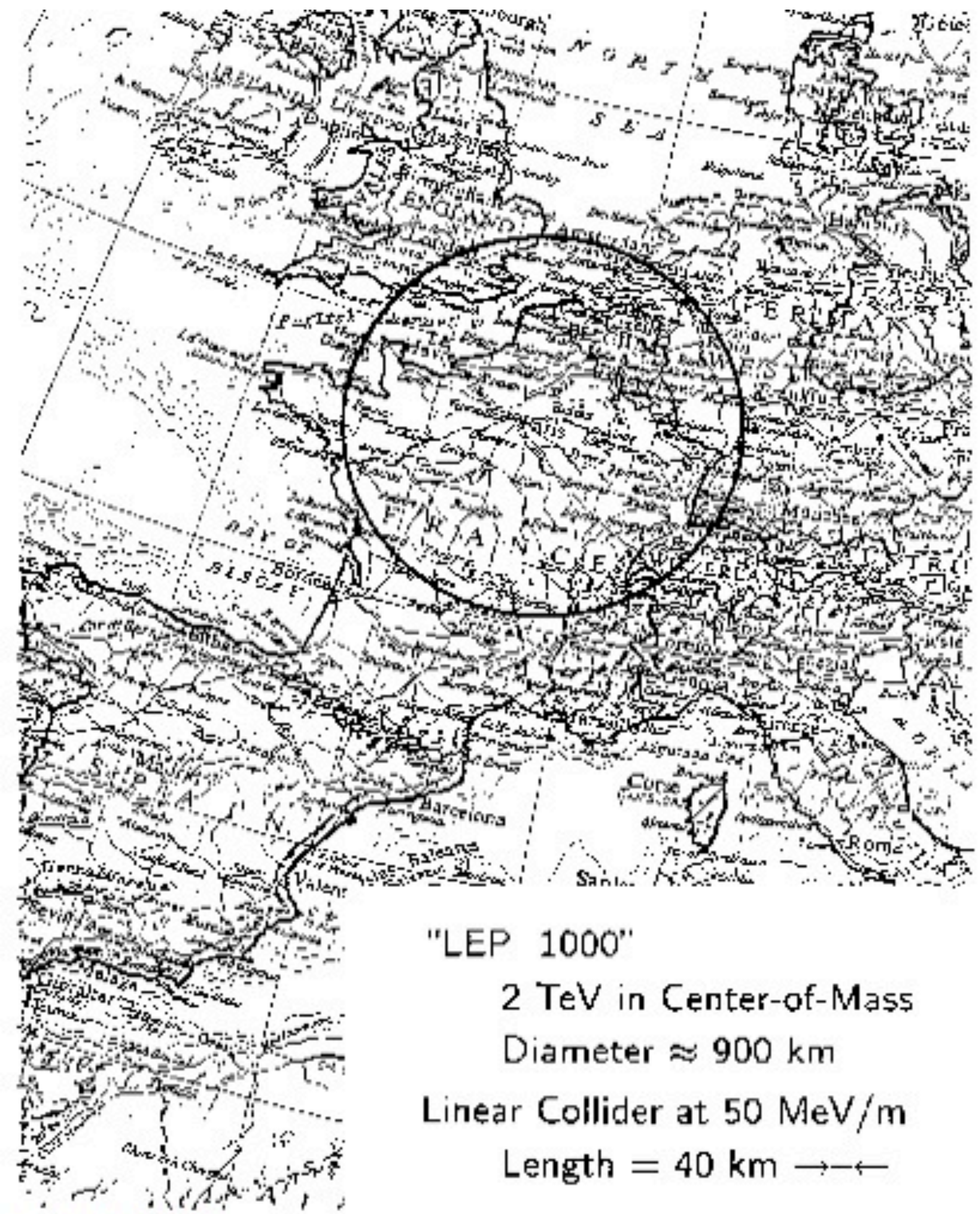
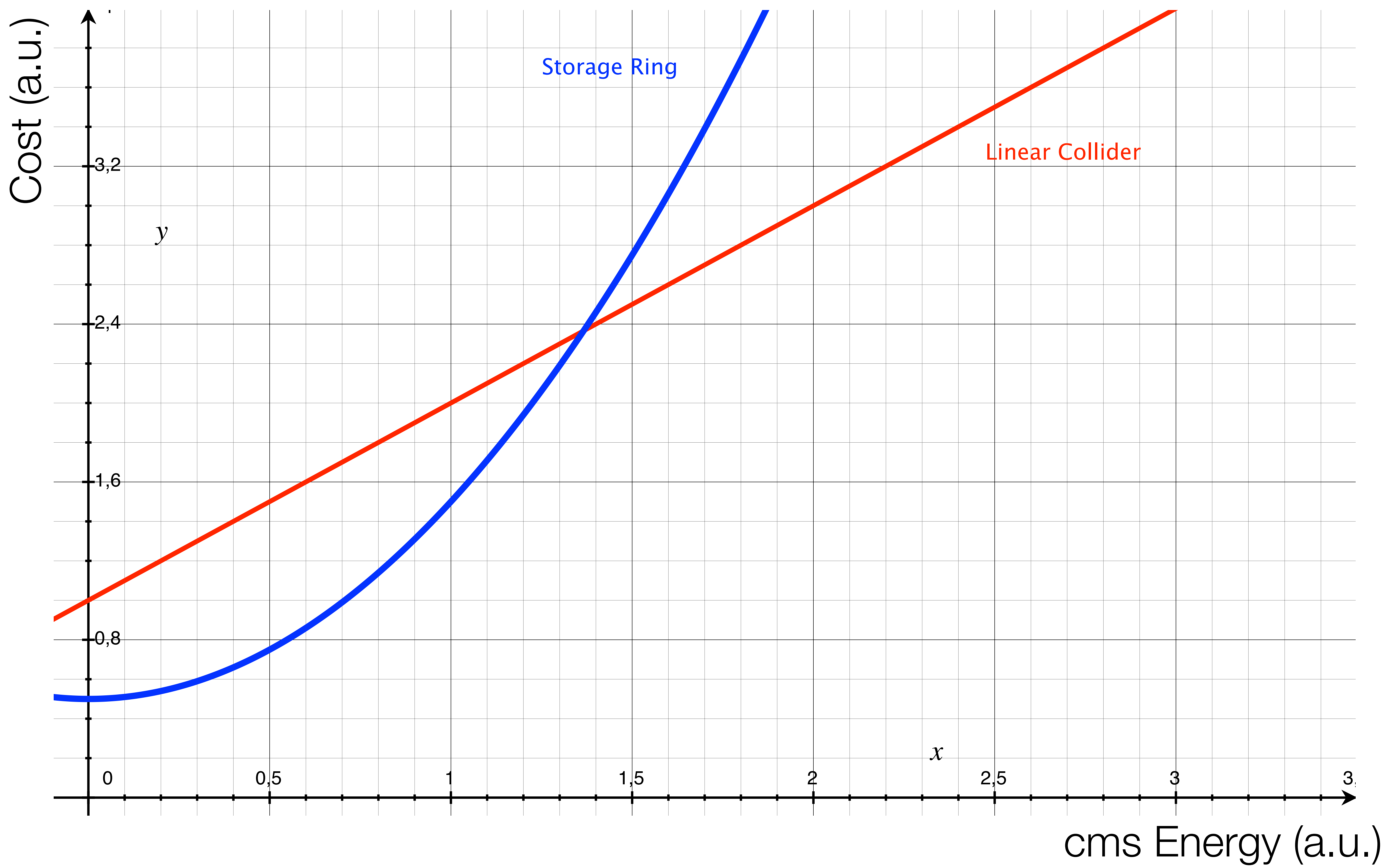


Figure by Gregory Loew

- The next high energy e^+e^- collider will be linear:
- €$_{LC}$ ~ E + const.

Cost Scaling



- Linear colliders are the economical choice above ~200 GeV cms energy

The Efficiency of Circular Accelerators

The Thrill of Linear Acceleration

The Luminosity Problem

- The luminosity ($cm^{-2}s^{-1}$) for a collider with Gaussian beams is given by:

$$L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y} H_D$$

- n_b = bunches per train
- N = particles per bunch
- f_{rep} = repetition frequency
- $4\pi\sigma_x\sigma_y$ = beam cross section at the interaction point
- H_D = beam-beam enhancement factor

The Luminosity Problem

- Introducing the beam power:

$$n_b N f_{rep} E_{cm} = P_{beams}$$
$$= \eta_{RF \rightarrow beam} P_{RF}$$

- yields

$$L = \frac{\left(E_{cm} n_b N f_{rep}\right) N}{4\pi \sigma_x \sigma_y E_{cm}} H_D \longrightarrow L = \frac{\eta_{RF} P_{RF} N}{4\pi \sigma_x \sigma_y E_{cm}} H_D$$

- $\eta_{RF \rightarrow beam}$: conversion efficiency RF to beam

RF Power

- Some numbers:
  - E_{cm} = 500 GeV
  - N = 10^{10}
  - n_b = 100
  - f_{rep} = 100 Hz
  - ⇒ P_{beams} = 8 MW
- adding efficiencies
  - Wall plug ⟶ RF ⟶ beam

$$L = \frac{\eta_{RF} P_{RF} N}{4\pi \sigma_x \sigma_y E_{cm}} H_D$$

$$L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y} H_D$$

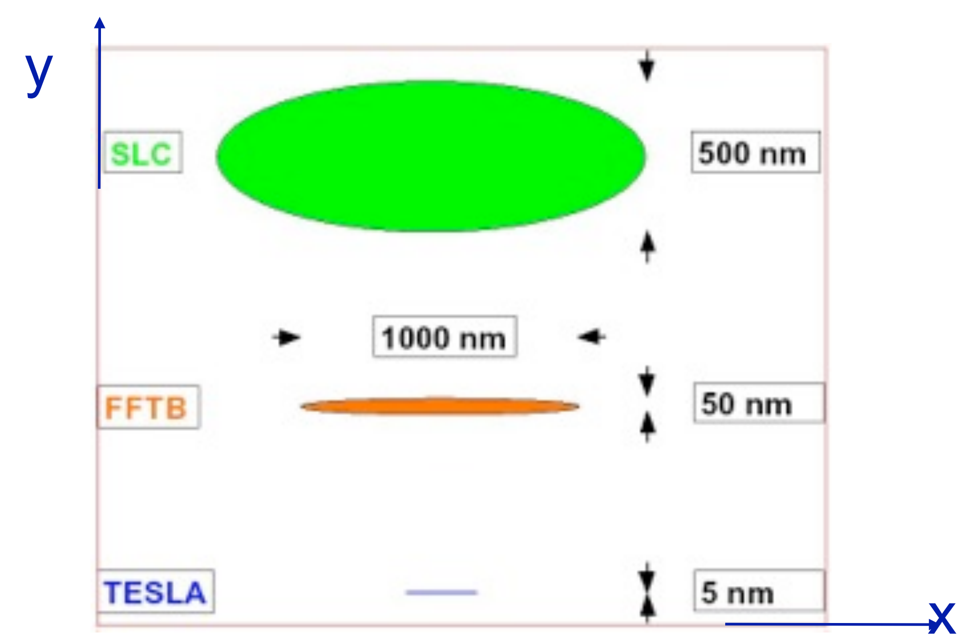
- yields AC power needs >100 MW just to accelerate beams and maintain luminosity!!!

Storage Ring vs Linear Collider

- LEP f_{rep}: 44 kHz
- ILC f_{rep}: few to 100 Hz (power limited)

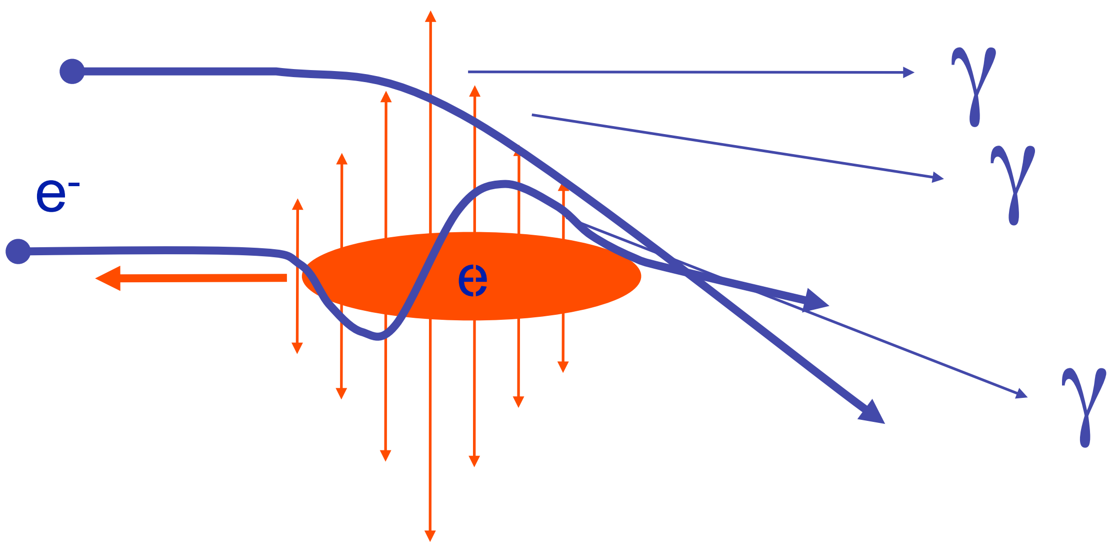
$$L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y} H_D$$

- Factor ~1000 in Luminosity already lost!
- Recover by pushing hard on the beam spot sizes at collision:
  - LEP: 130 x 6 μm^2
  - ILC: 500 x 5 nm^2
- Needed to achieve $L=O(10^{34}\ cm^{-2}\ s^{-1})$



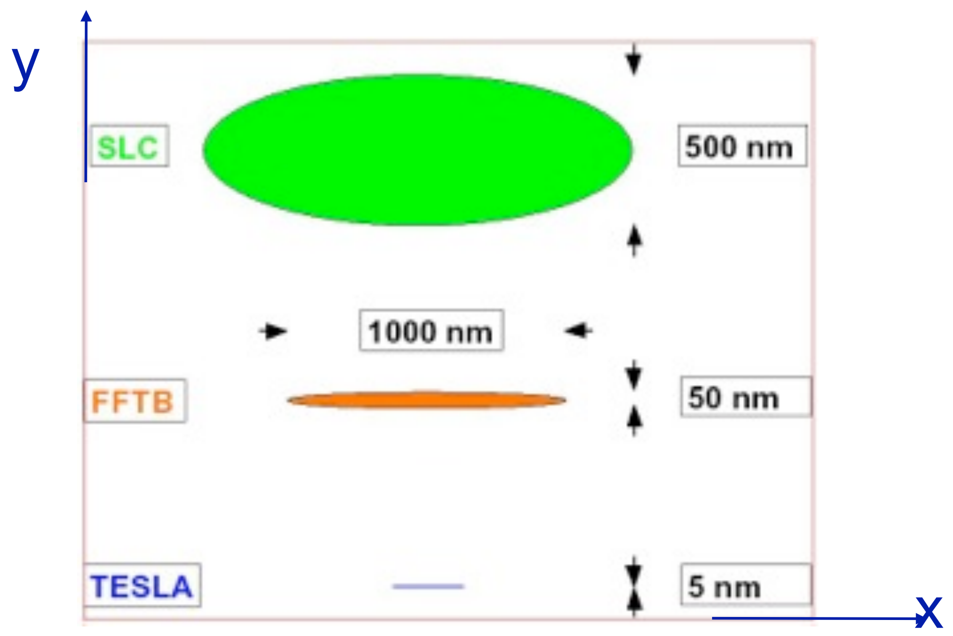
Beamstrahlung

- Strong mutual focusing of beam gives rise to significant luminosity enhancement ($H_d \approx 2$): pinch effect
- electrons/positrons pass through intense field of opposite beam, radiate hard photons: Beamstrahlung



$$\delta_{BS} \approx 0.86 \frac{e r_e^3}{2 m_0 c^2} \left(\frac{E_{cm}}{\sigma_z} \right) \frac{N^2}{(\sigma_x + \sigma_y)^2}$$

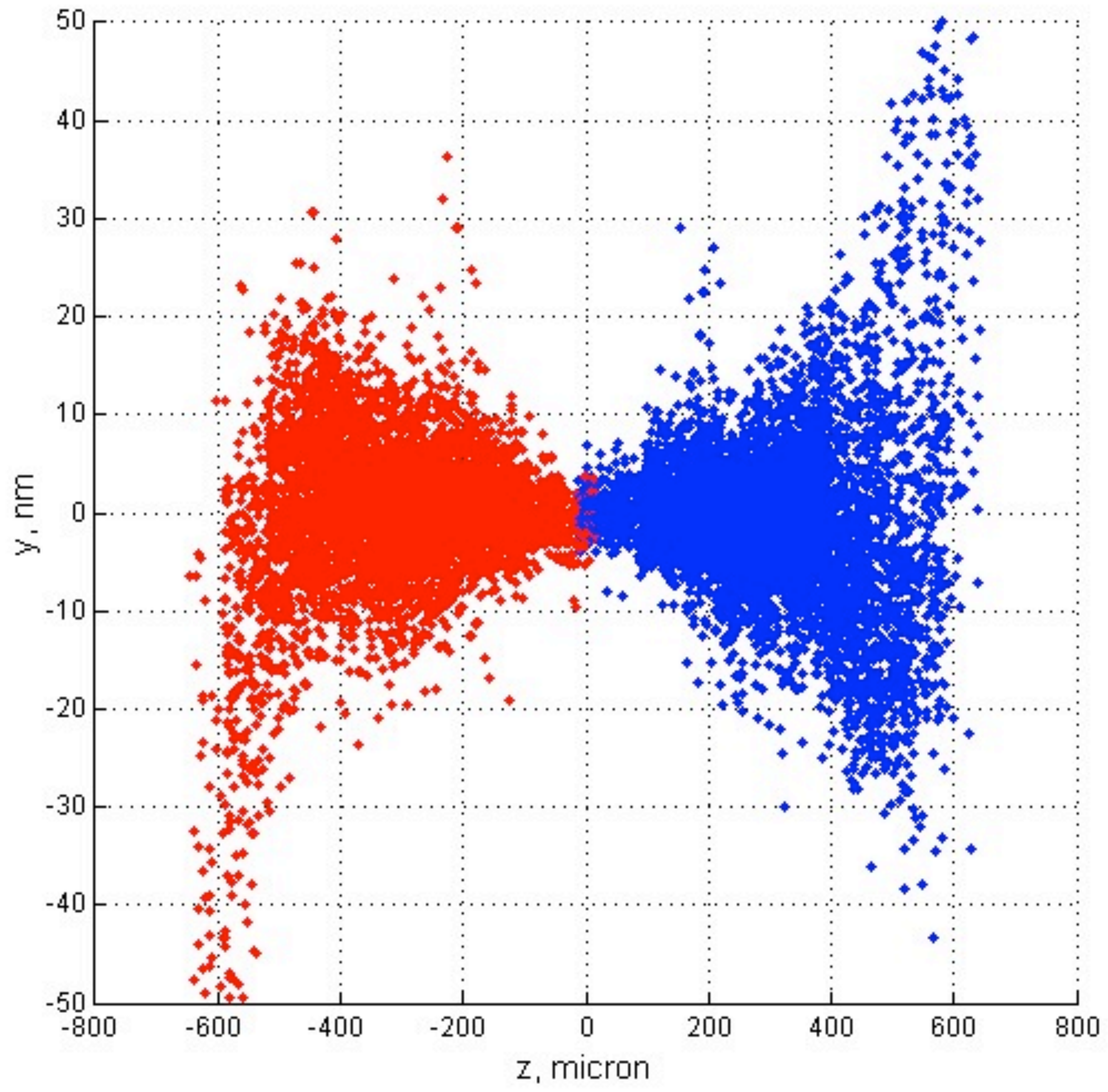
$$L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y} H_D$$



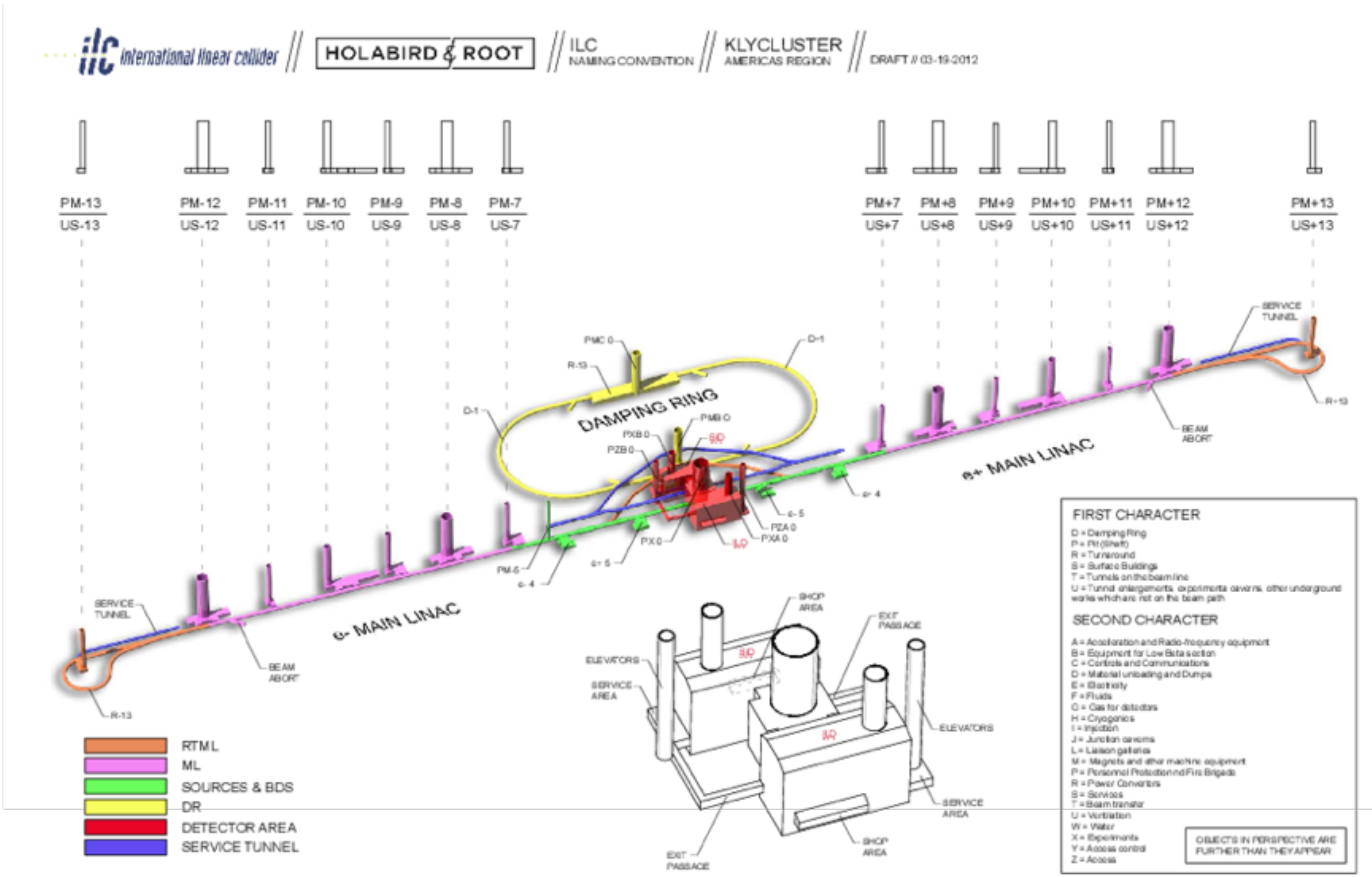
Chose flat beams!

Beam-Beam Interaction

Beam-Beam Interaction



ILC Baseline Design



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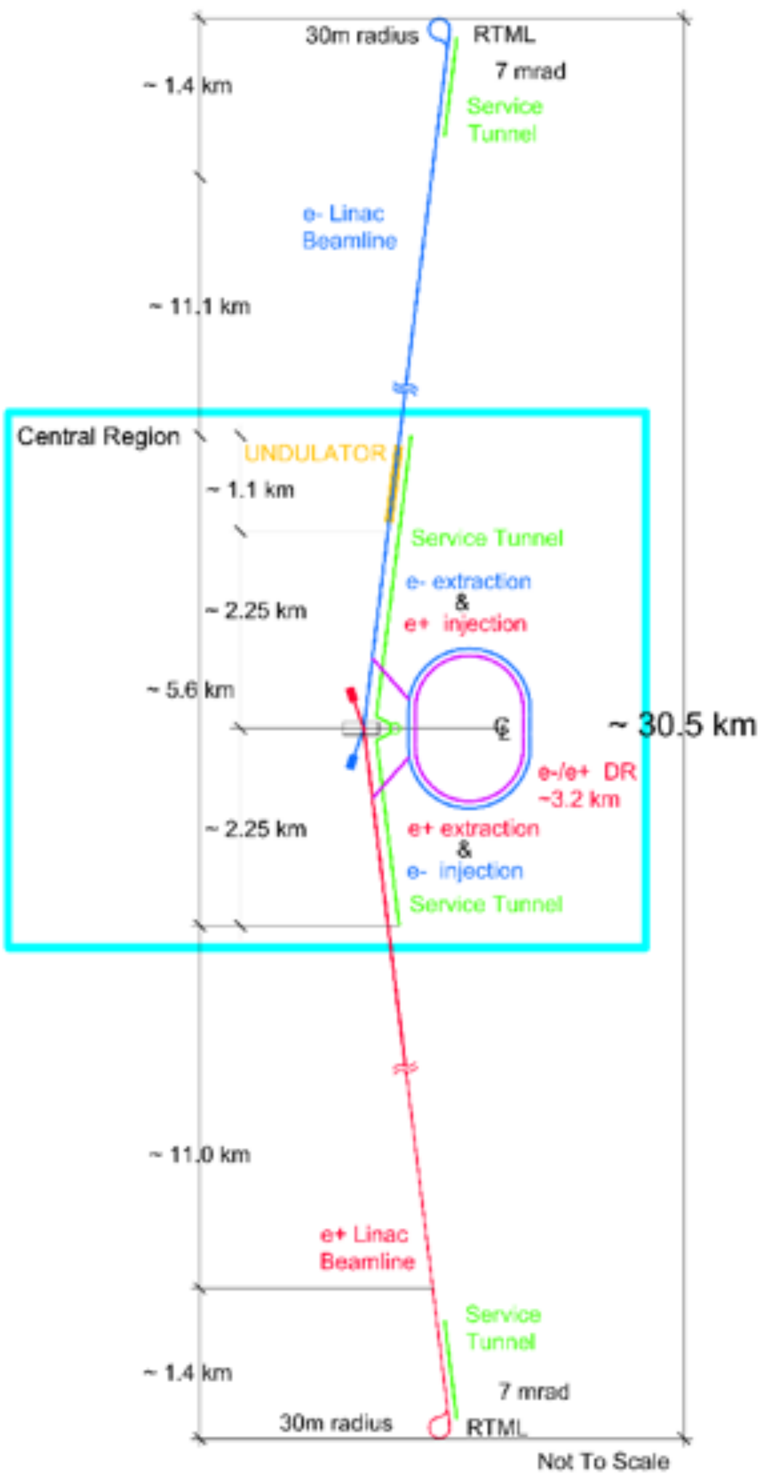
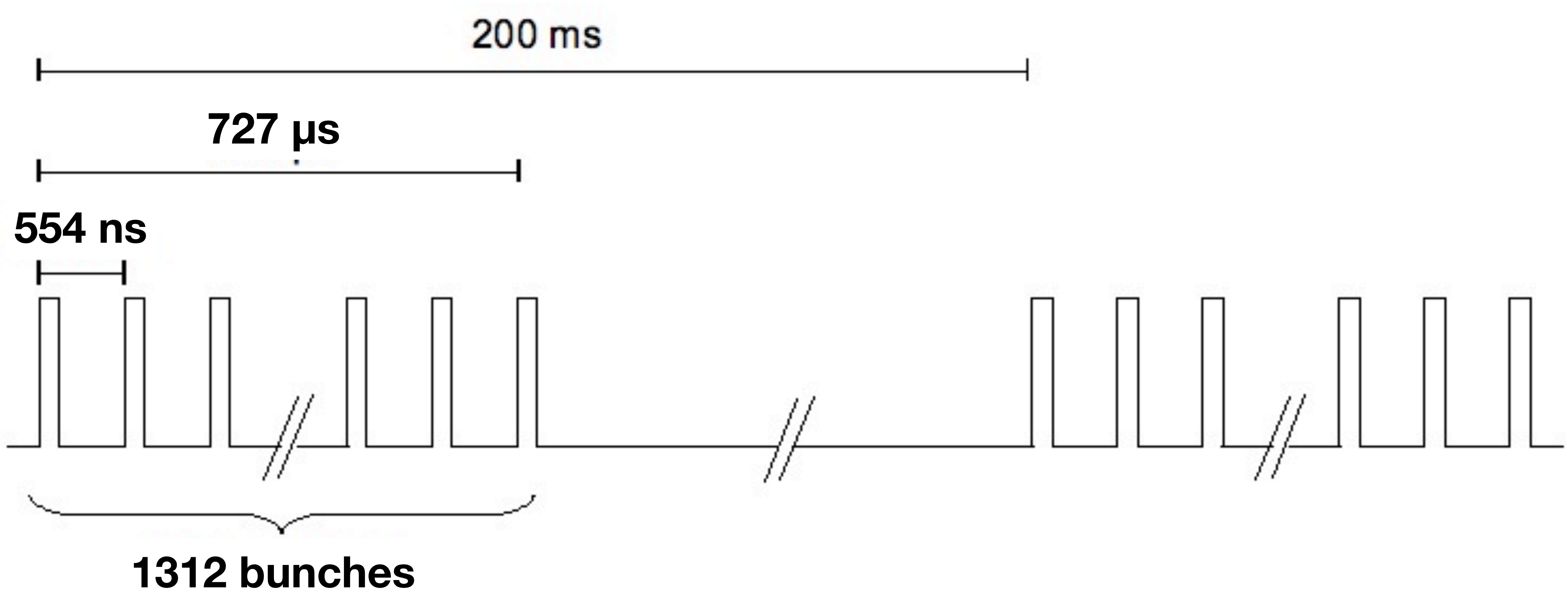


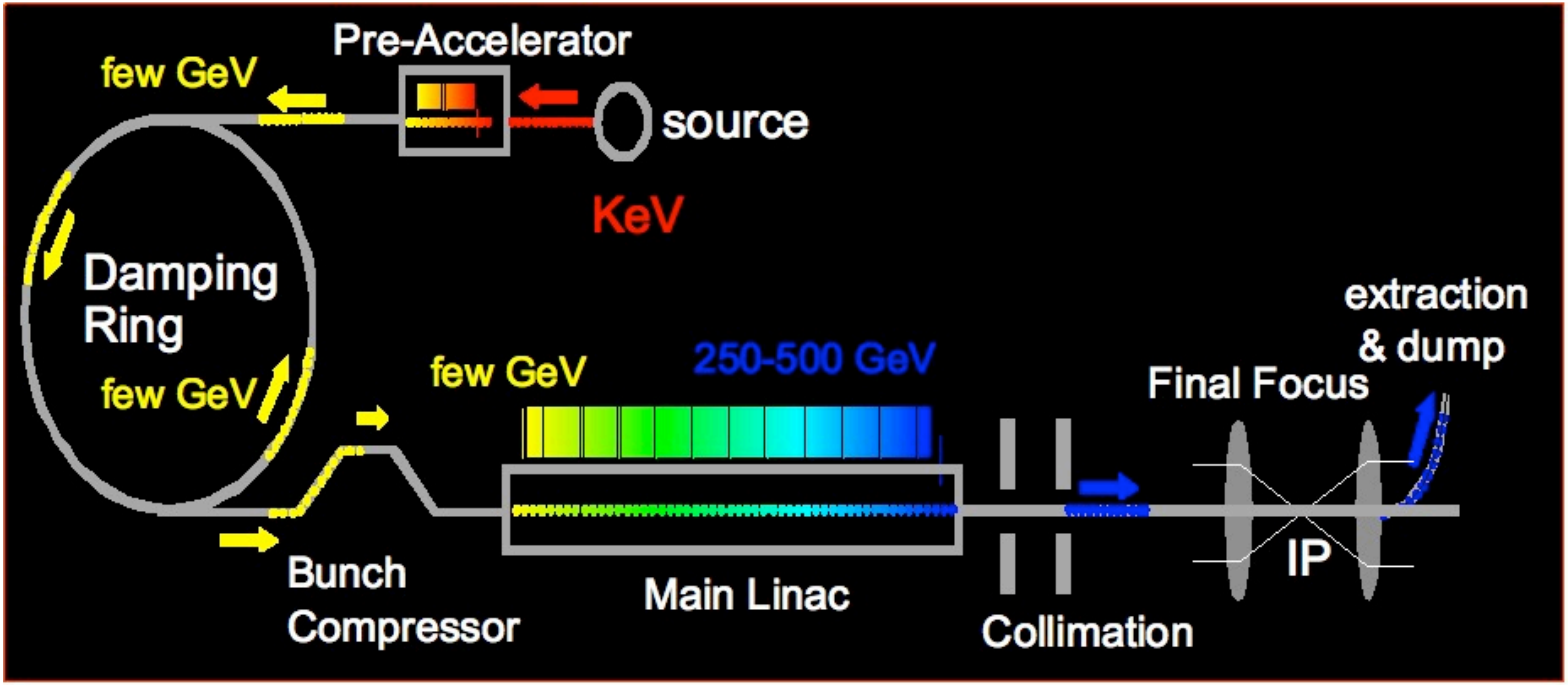
cms energy range	GeV	200-500
peak luminosity (at 500 GeV)	$cm^{-2}s^{-1}$	1.8×10^{34}
fraction of L in top 1% E_{cm}	%	60-90
avg. beam current in pulse	mA	6-9
pulse rate	Hz	5 (10)
bunch distance	ns	554
number of bunches	#	1312
charge per bunch	$\#(e^{\pm})$	2×10^{10}
accelerating gradient	MV/m	31.5
RF pulse length	ms	1.65
beam power per beam (at 500 GeV)	MW	5.3
beam size at IP (at 500 GeV)	nm x nm	474 x 5.9
total power consumption	MW	163
polaristation	$\%(e^+,e^-)$	30,80

ILC Bunch Structure

- Superconducting RF has small dissipation losses in cavity walls
- ⇒ long pulses (~1ms) with large bunch spacing

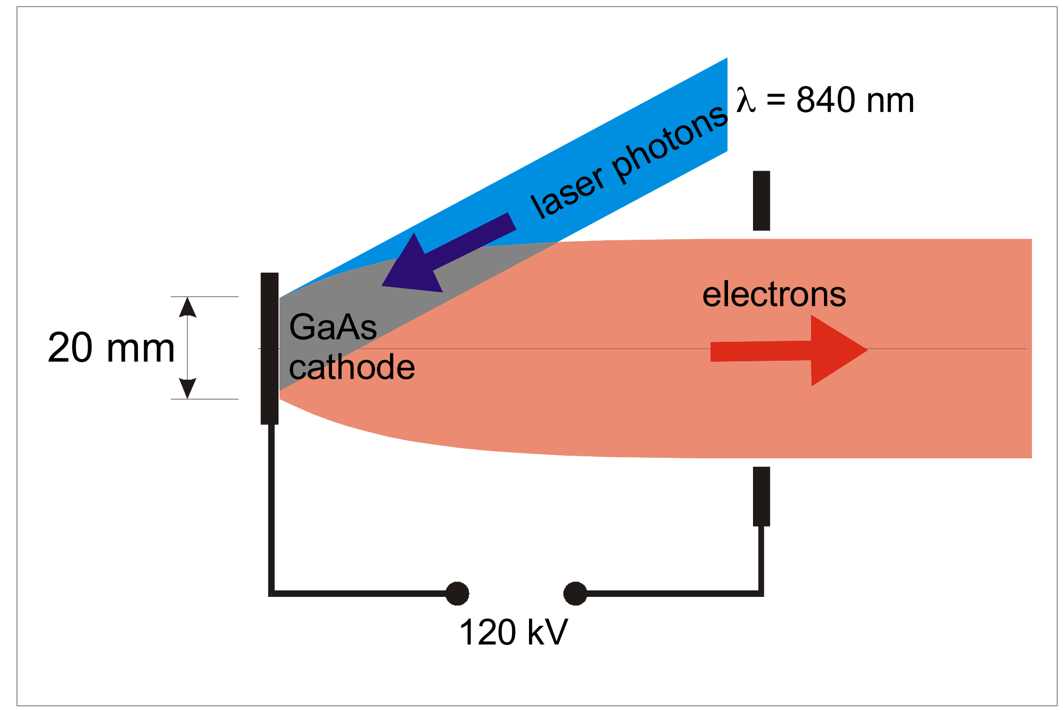


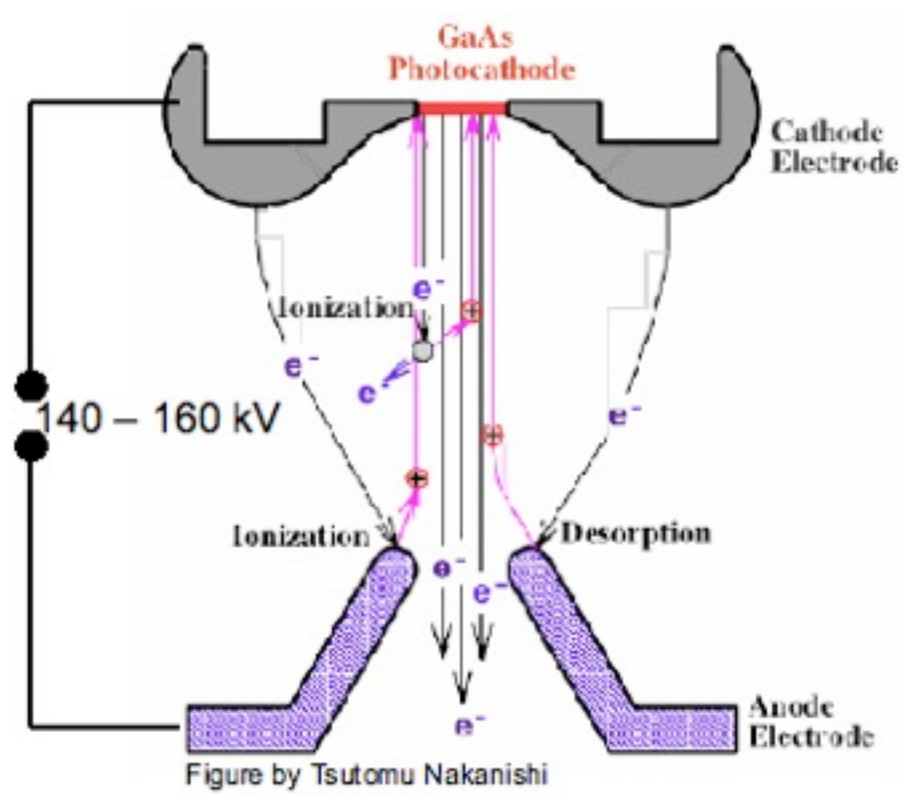
Sources


Pre-Accelerator
few GeV
source
KeV
Damping Ring
few GeV
few GeV
250-500 GeV
extraction & dump
Final Focus
IP
Bunch Compressor
Main Linac
Collimation

Electron Source

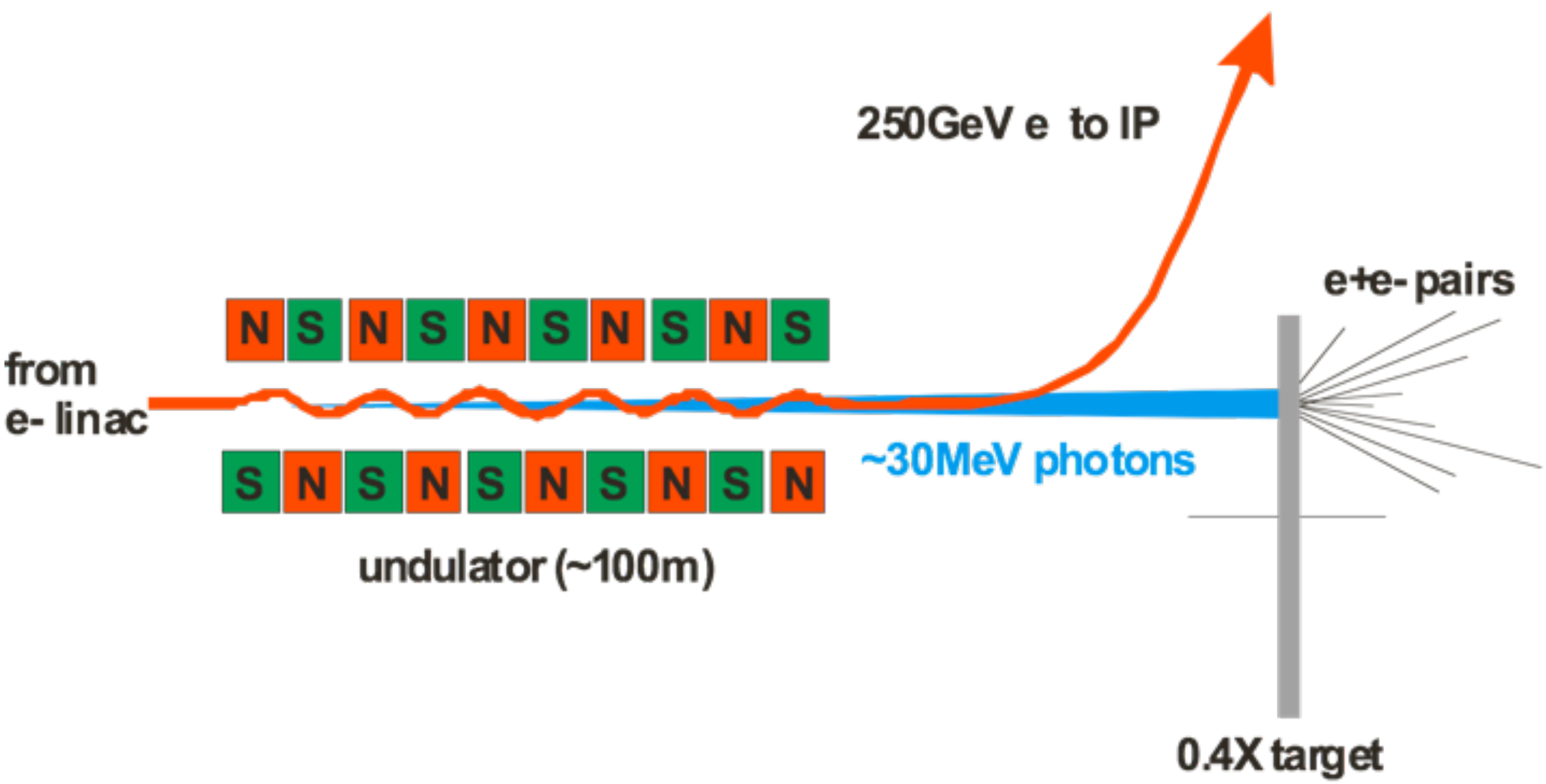
- Laser driven photo injector based on SLC design
- Circular polarised photons on GaAs cathode produce longitudinal polarised electrons
- very high vacuum requirements to protect cathode from impurities and ion backdrift
- 140-160 keV electron energy at exit
- 1ns bunch length at 3 MHz
- ~5 nC/ns peak current



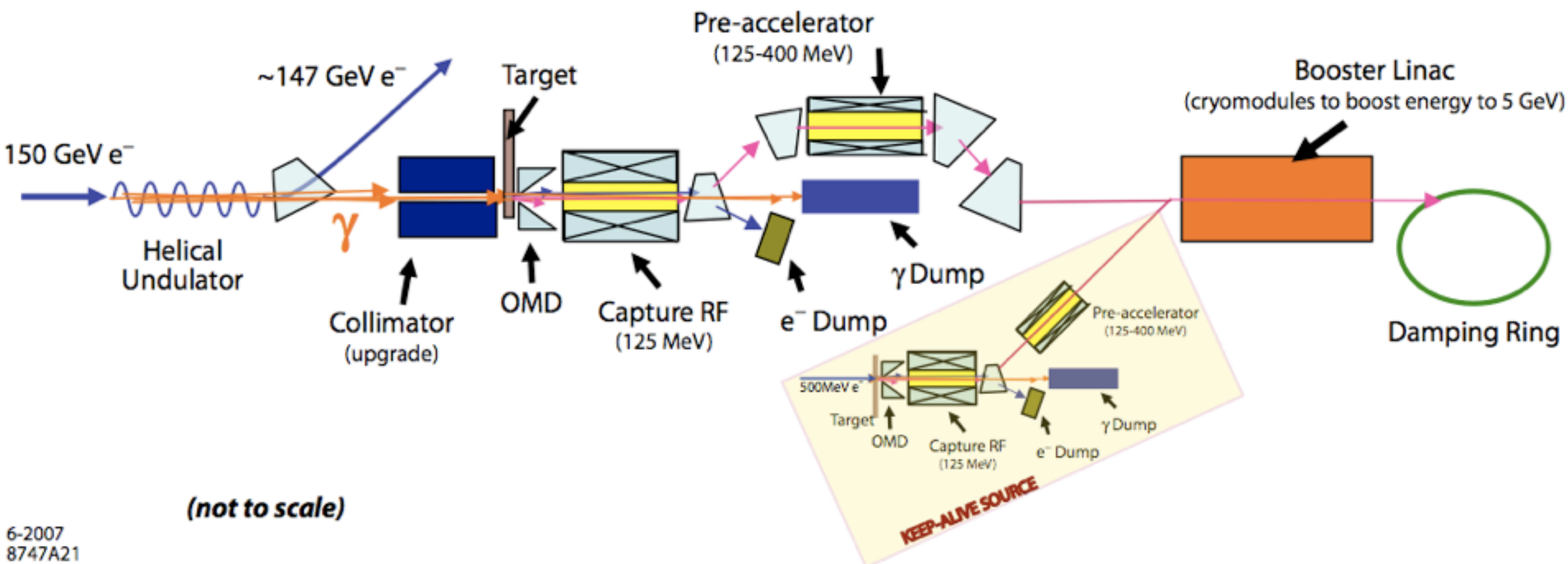


Positron Source

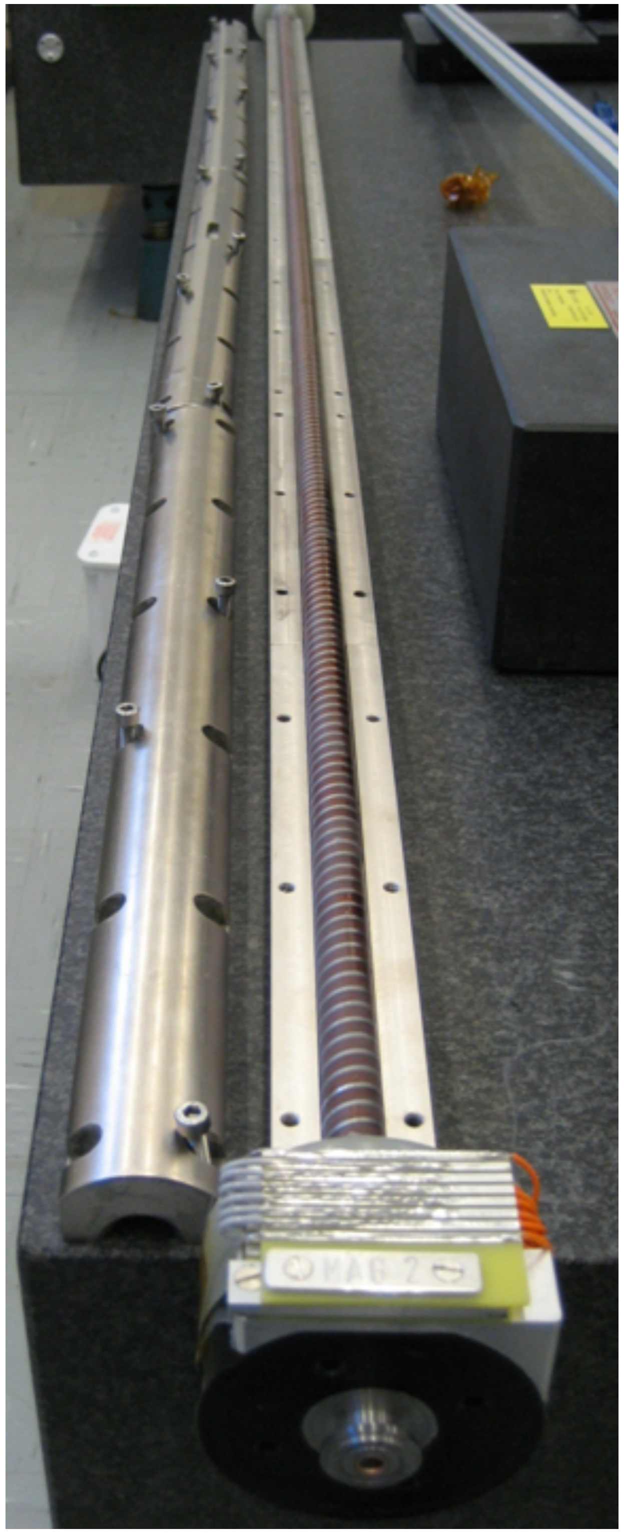
- Production of $e^{\pm}$ pairs from 30 MeV undulator photons hitting a thin (0.4 X_0) target
- Thin target reduces multiple scattering, hence better emittance
- Needs >150 GeV electrons in undulator

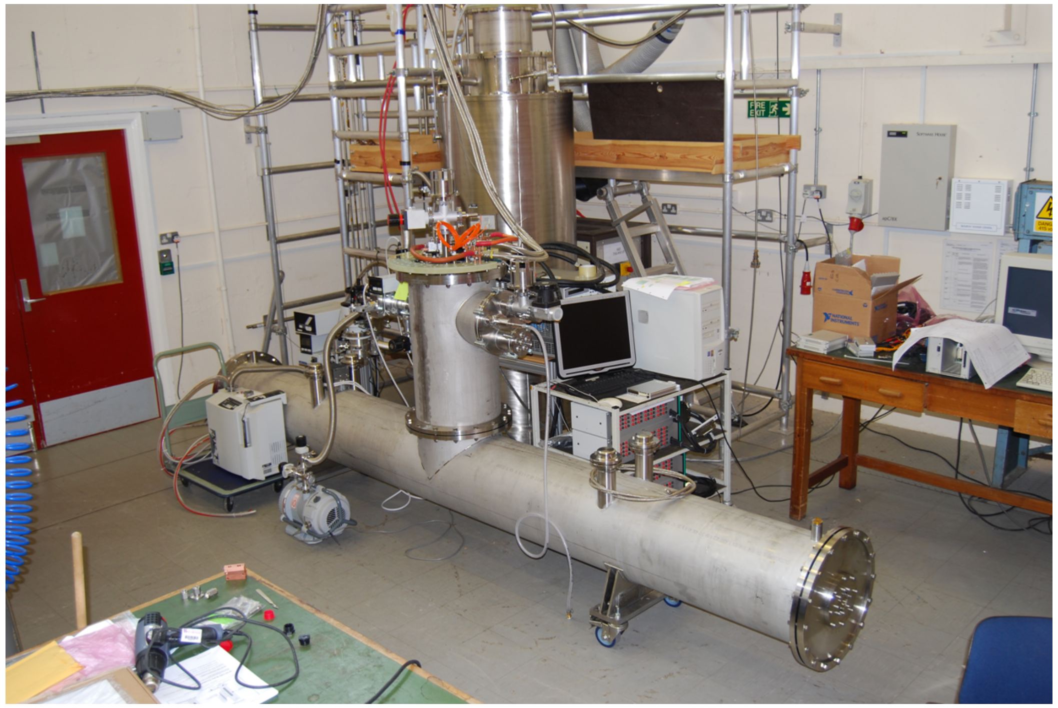


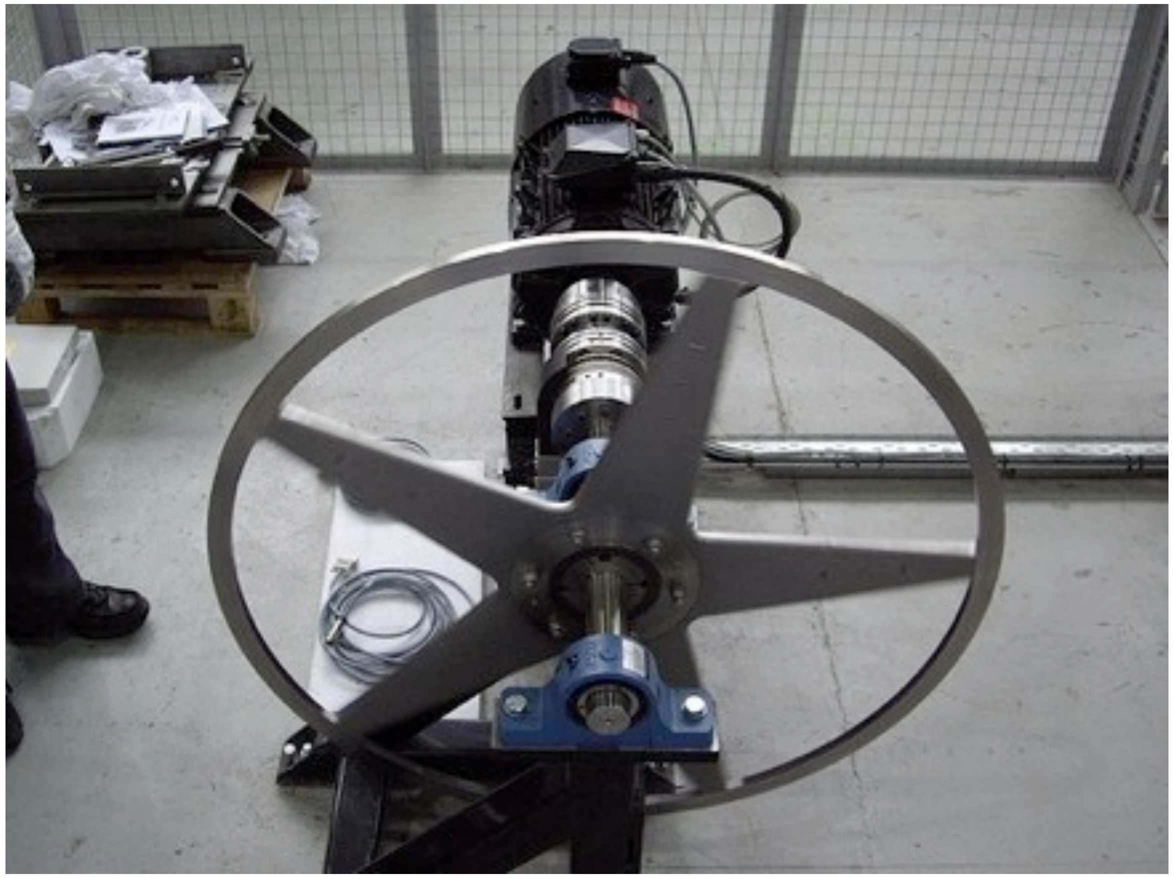
Positron Source Design



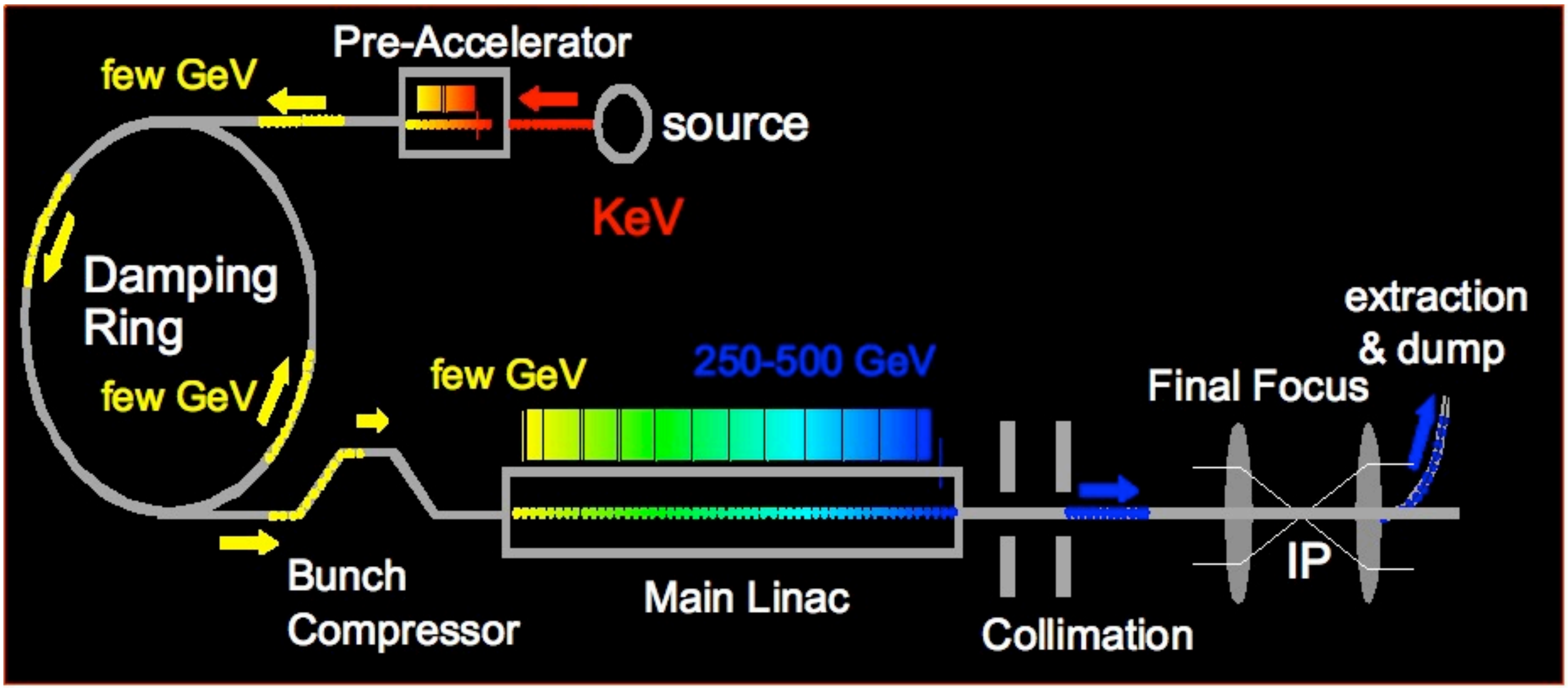
Positron Source Prototyping





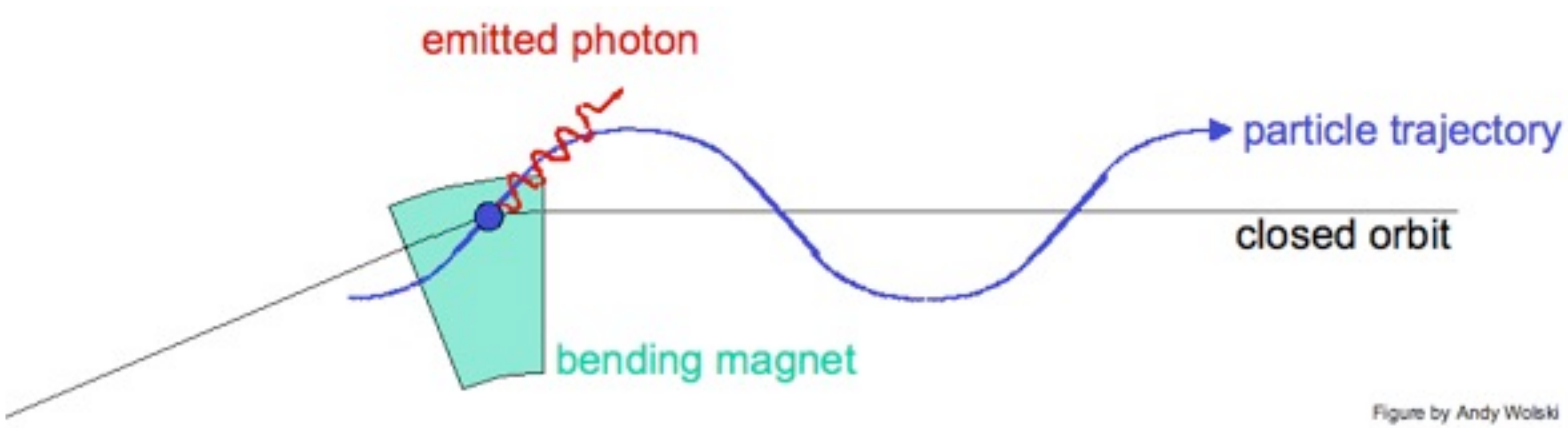


Damping Rings

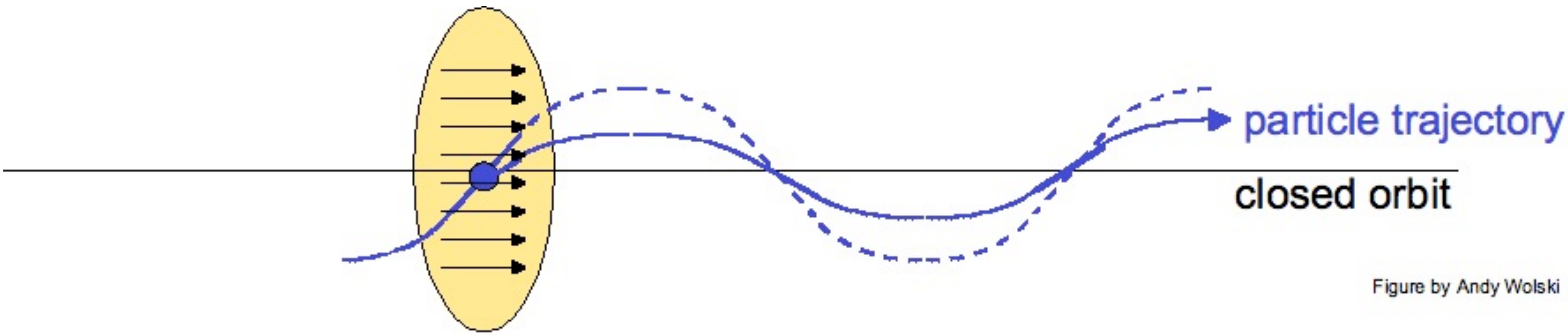


Damping Rings Purpose

- Emittance of beams from the sources are orders of magnitudes too big
- Beams need to be cooled
- Use synchrotron radiation in damping rings to cool beams
  - Particles lose longitudinal and transverse momentum
  - replenish only longitudinal momentum

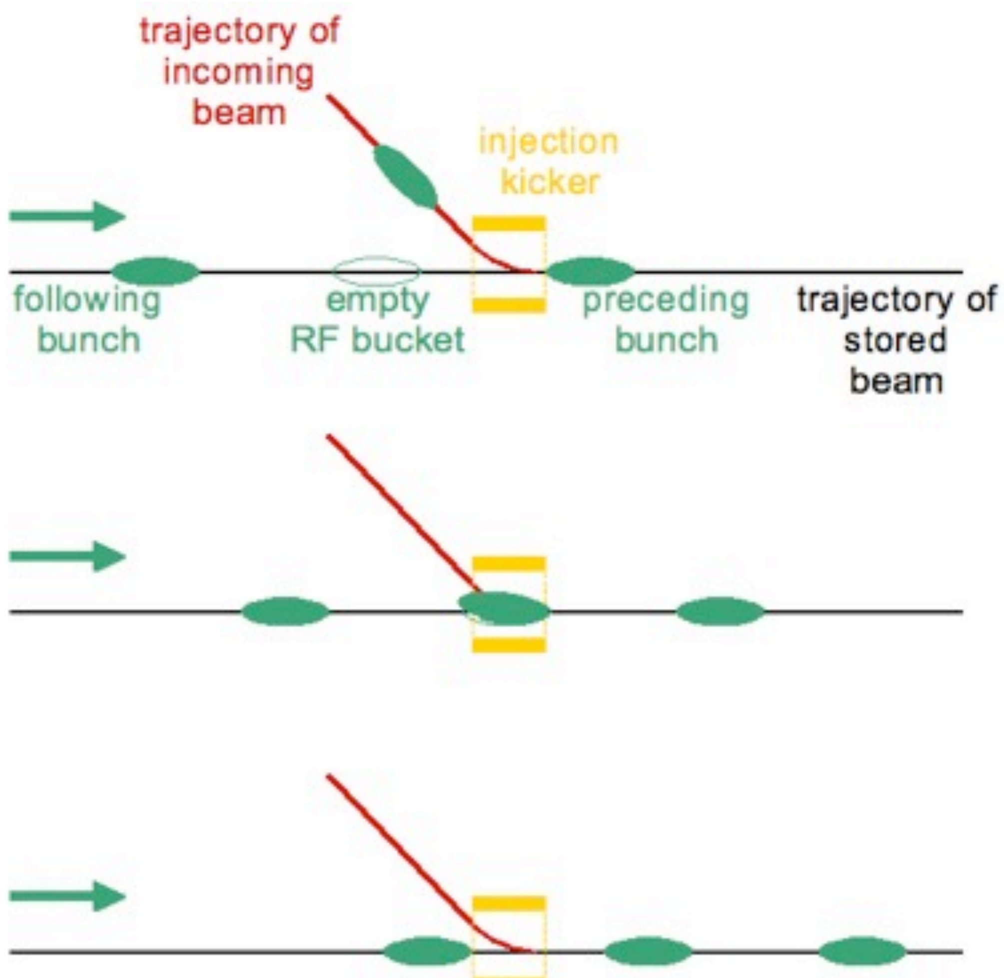


Damping Rings

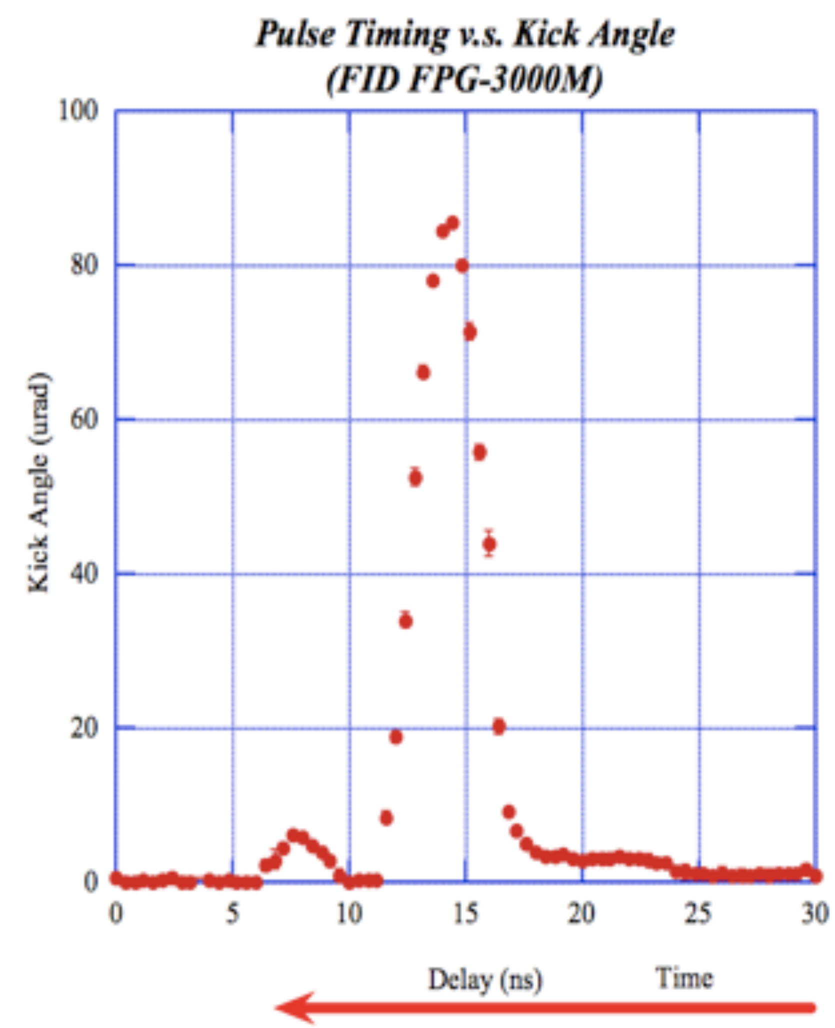


- RF system in damping rings accelerates beam particles in longitudinal direction
- Interplay between radiation and RF reduces transverse emittance!
- Typical damping times are of order 100 ms
  - Linac RD pulse length is 1ms!
  - Whole bunch train (200 km @ 560 ns) needs to be stored in a damping ring O(3 km)!
  - Bunch train, i.e. bunch-bunch spacing, needs to be compressed in damping ring

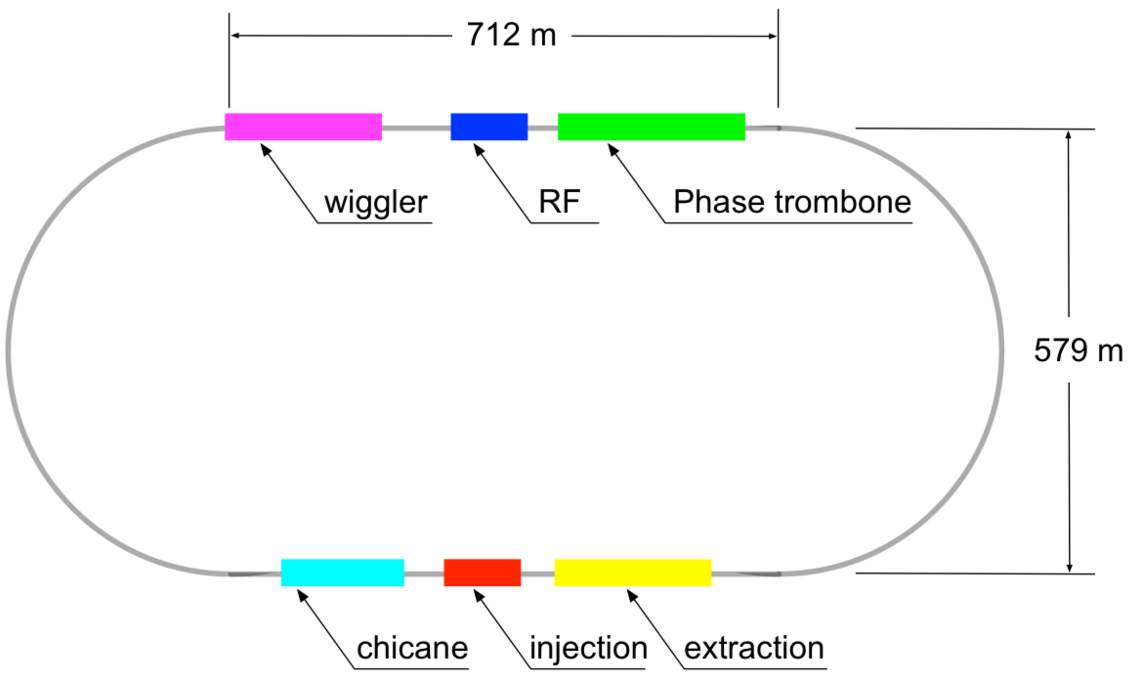
DR Injection/Extraction

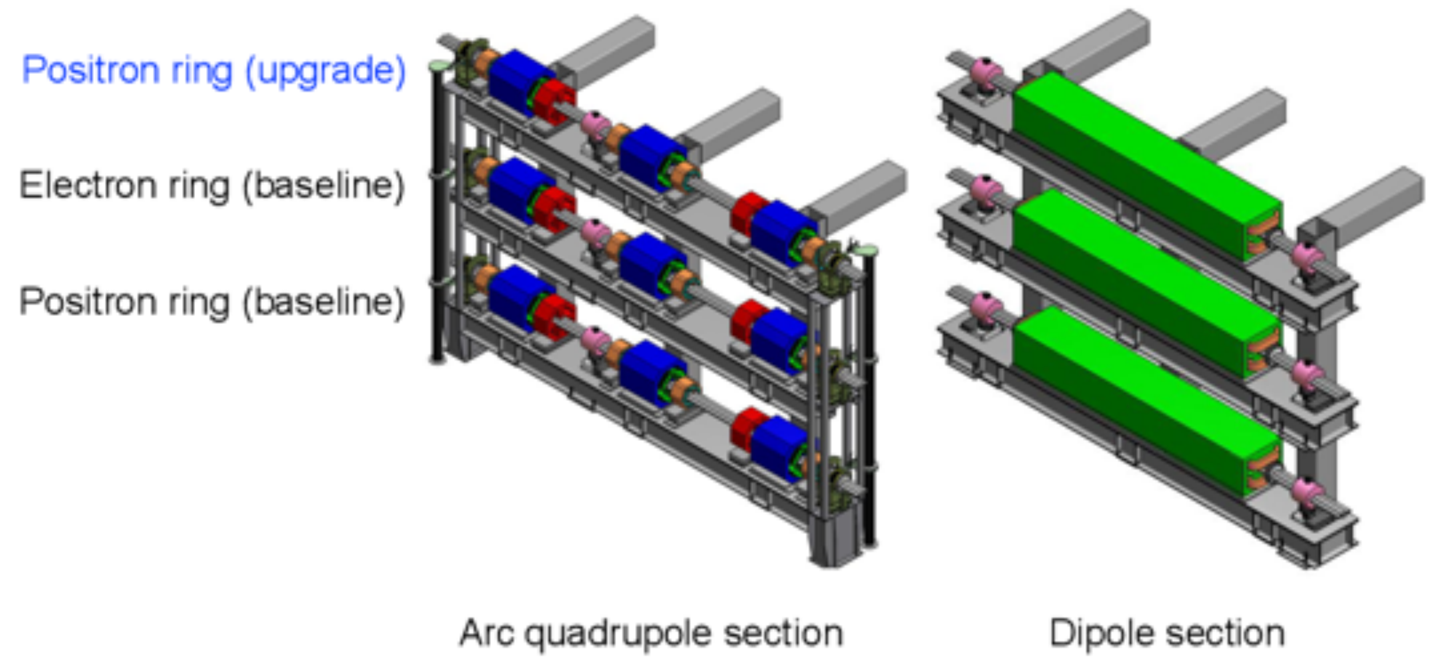


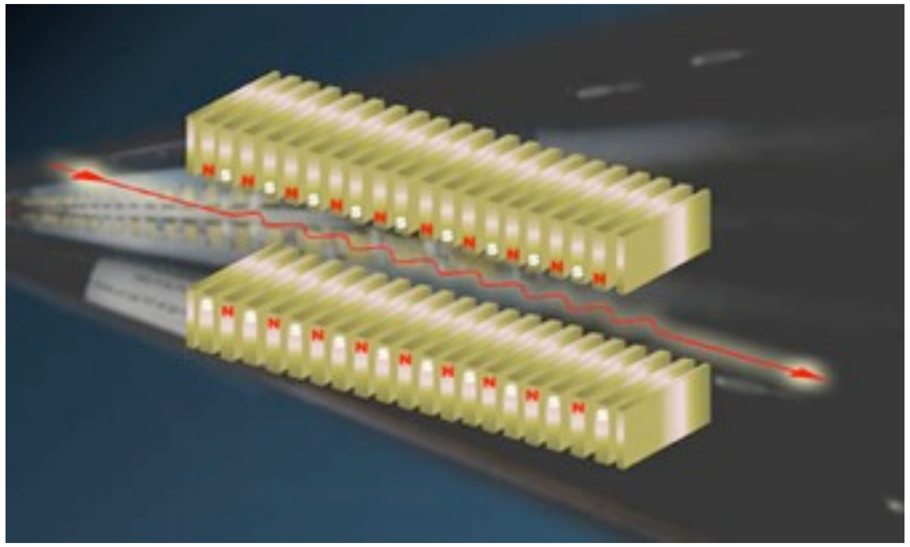
1. Kicker is off. "Preceding" bunch exits kicker electrodes.
   Kicker starts to turn on.
2. Kicker is on.
   "Incoming" bunch is deflected by kicker.
   Kicker starts to turn off.
3. Kicker is off by the time the following bunch reaches the kicker.



ILC Damping Ring Design

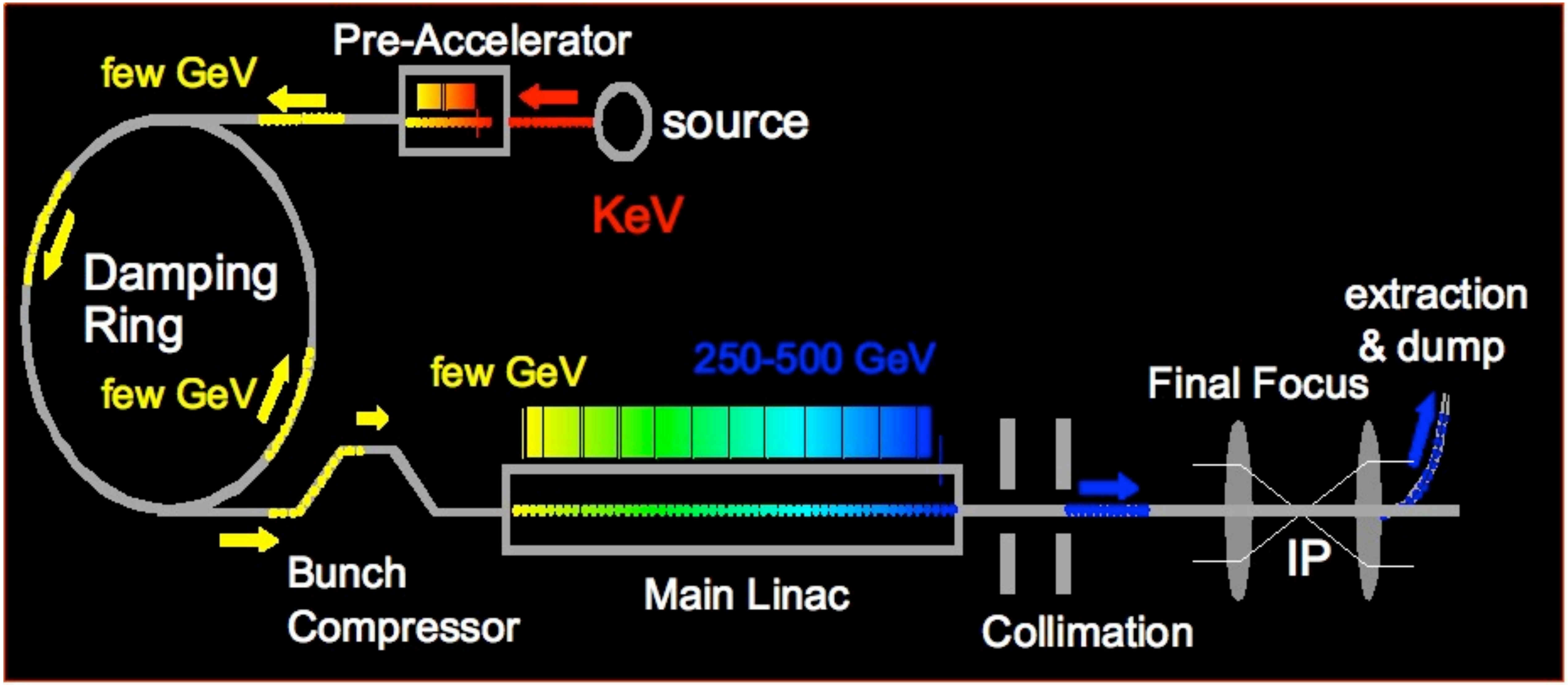






- Damping time by SR from bending magnets too large O(400ms)
- Include damping wigglers in the beam to reduce damping time to ~25ms

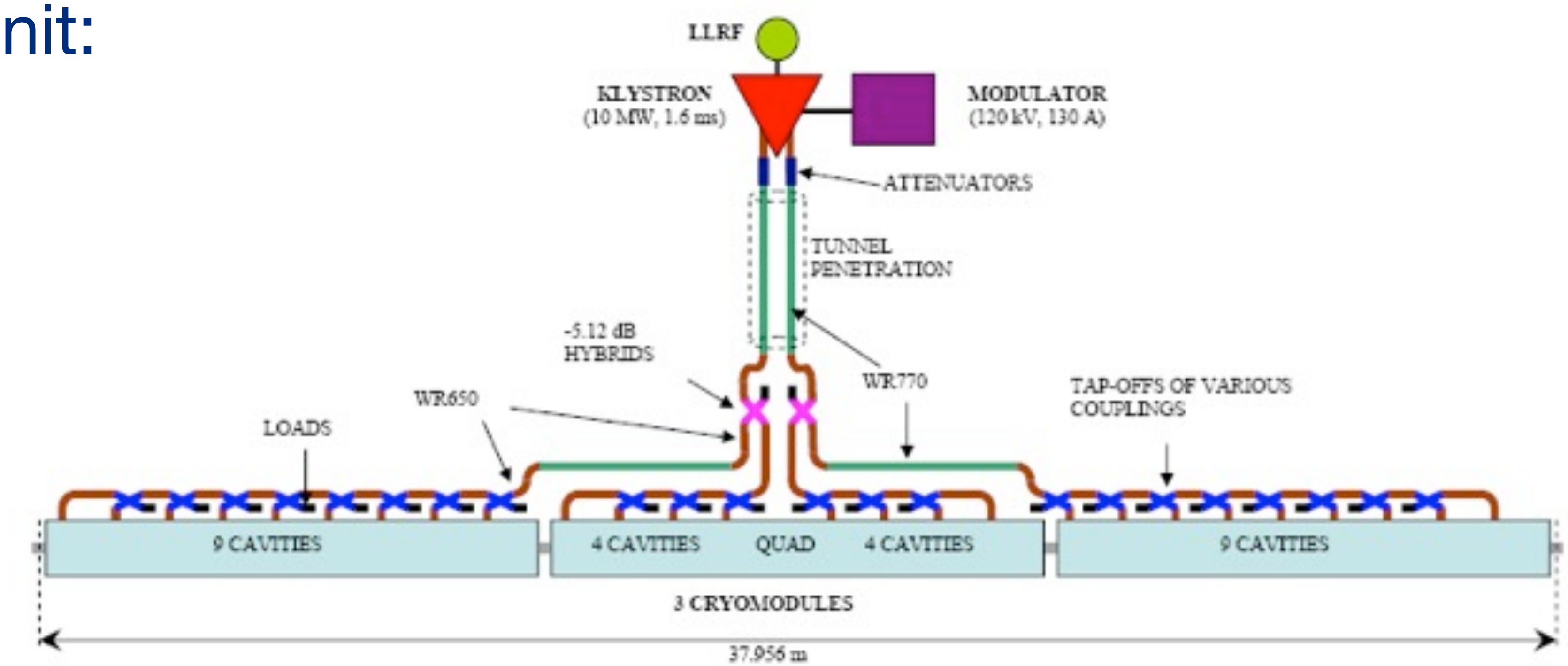
Main Linacs

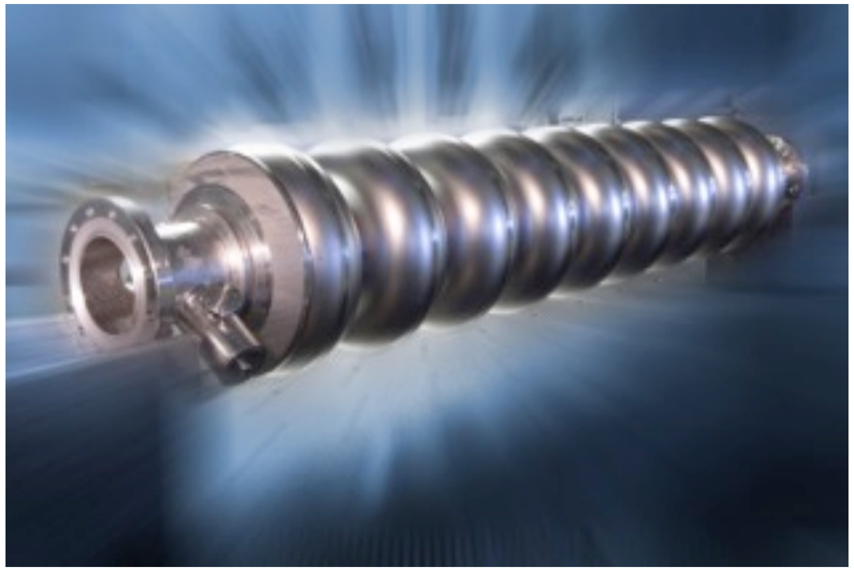


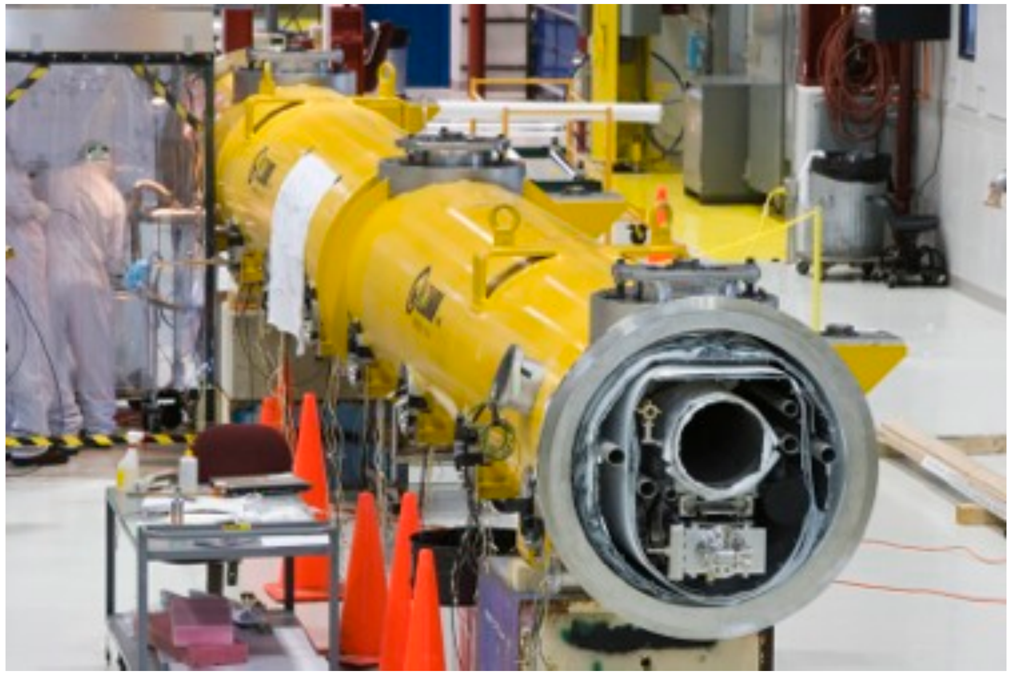
Pre-Accelerator
few GeV
source
KeV
Damping Ring
few GeV
few GeV
250-500 GeV
extraction & dump
Final Focus
IP
Bunch Compressor
Main Linac
Collimation

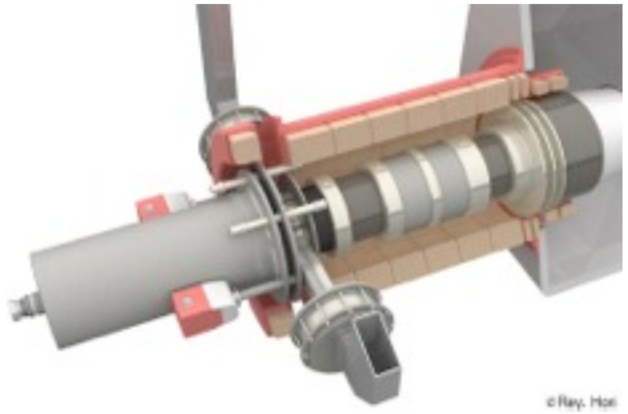
Main Linac Components

- One RF Unit:





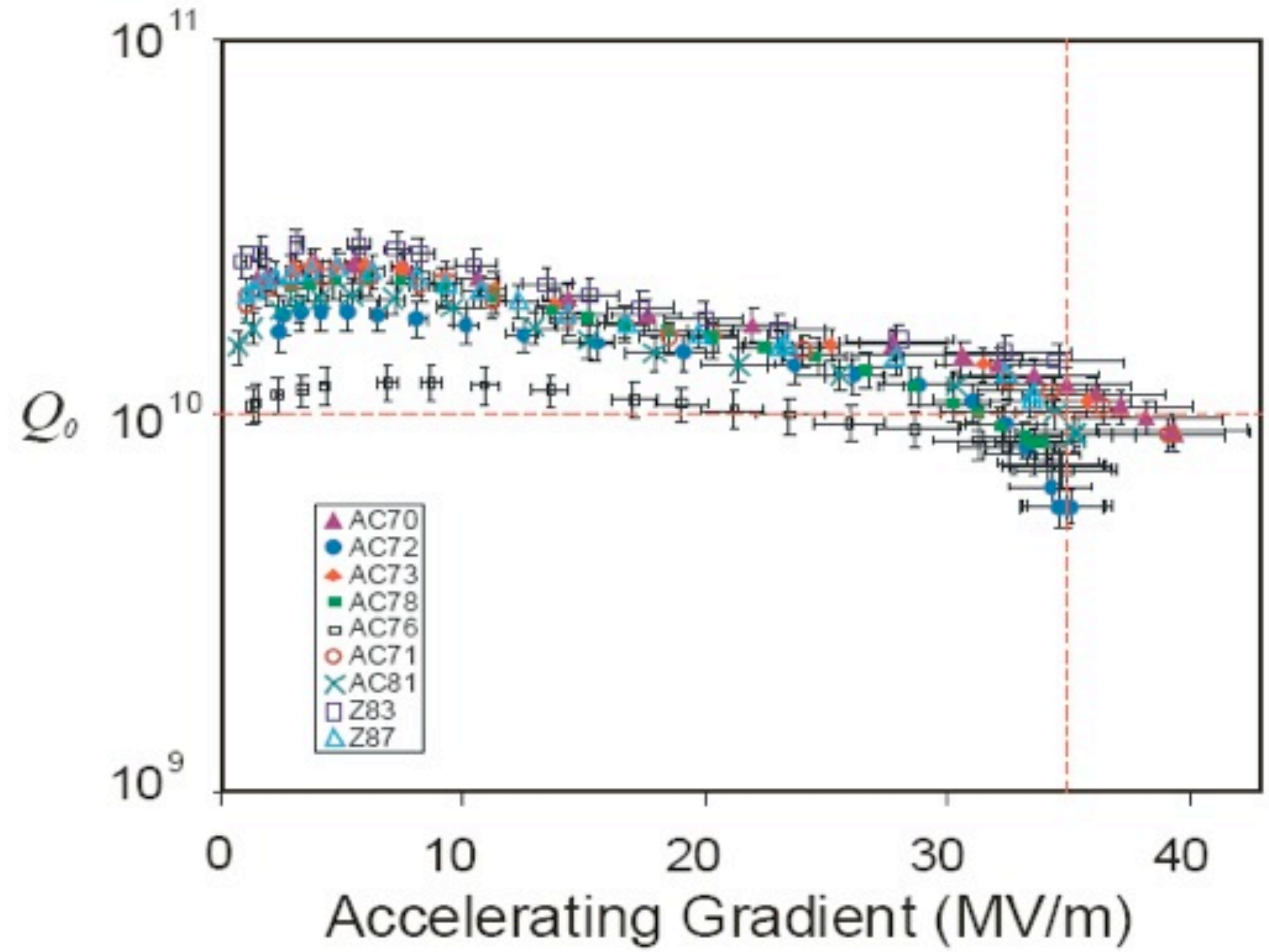


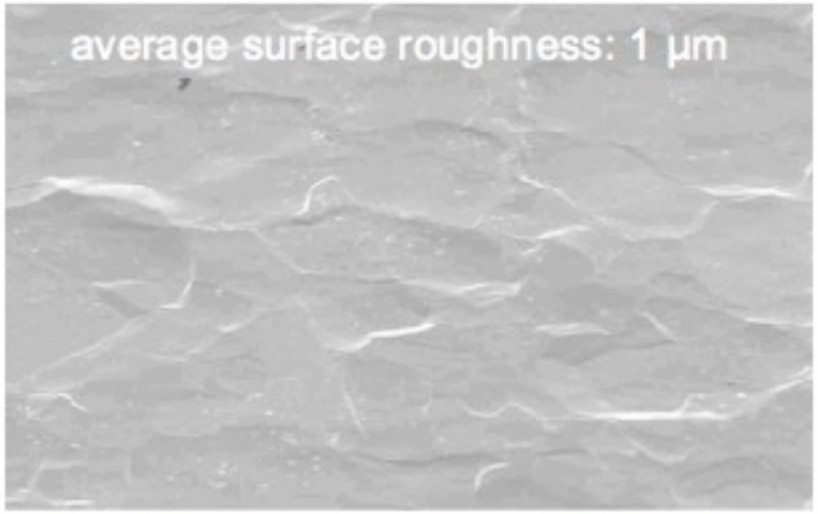


SCRF Cavities

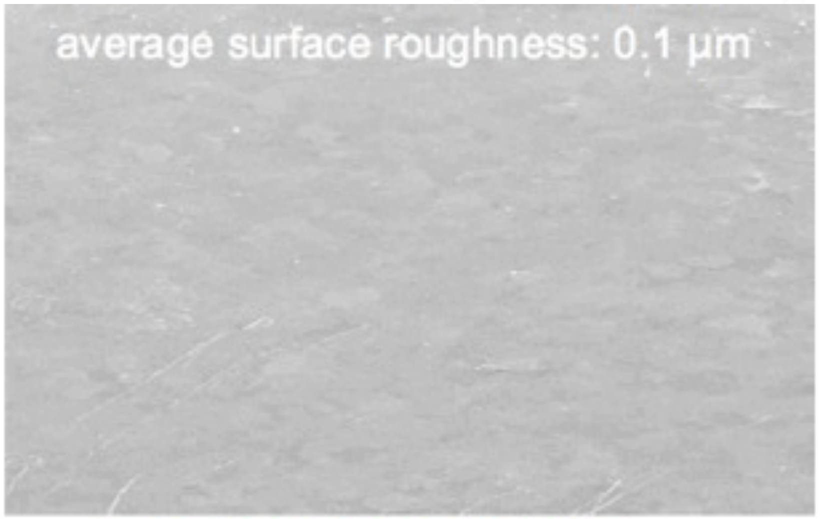
ILC Cavities

- Acceleration gradient goal:
  - 35 MV/m in 9-cell cavities with production yield >80%
  - 50 MV/m have been reached with single cavities
  - Mass production reliability is the key problem





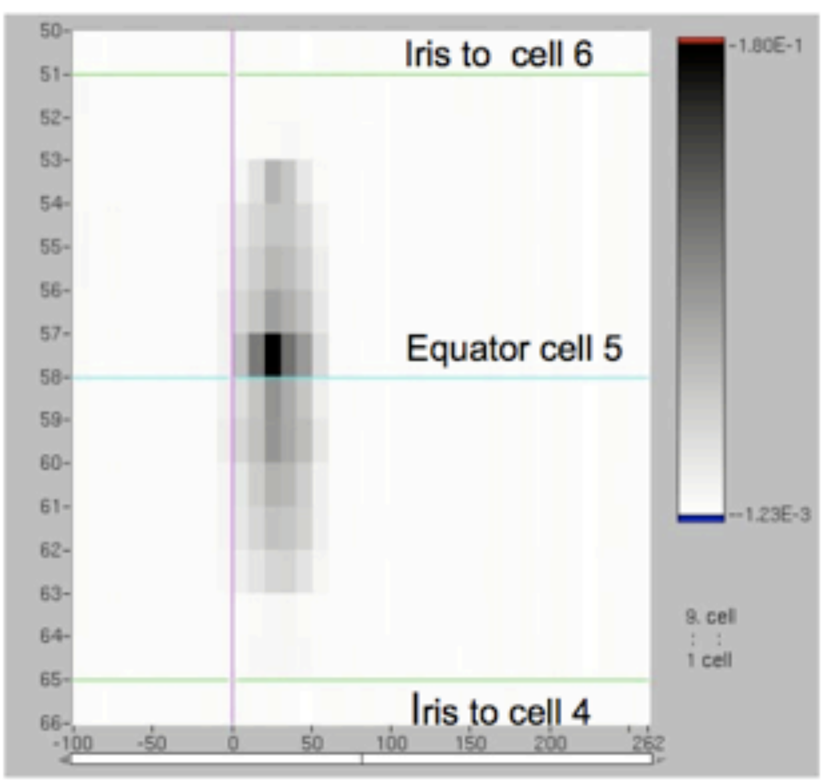
buffered chemical polishing



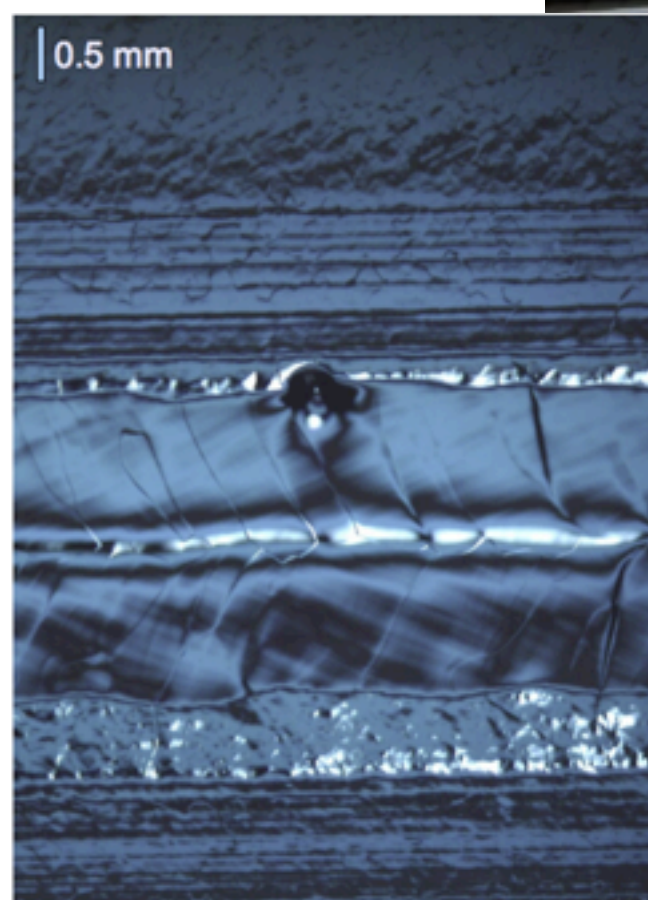
electrolytic polishing

Cavity Diagnostics

- Quality control and assurance
- Need 18.000 9 cell cavities for ILC
- Yield of 80% means to throw away 3600....
- Identifiying and reprocessing defunct cavities might help

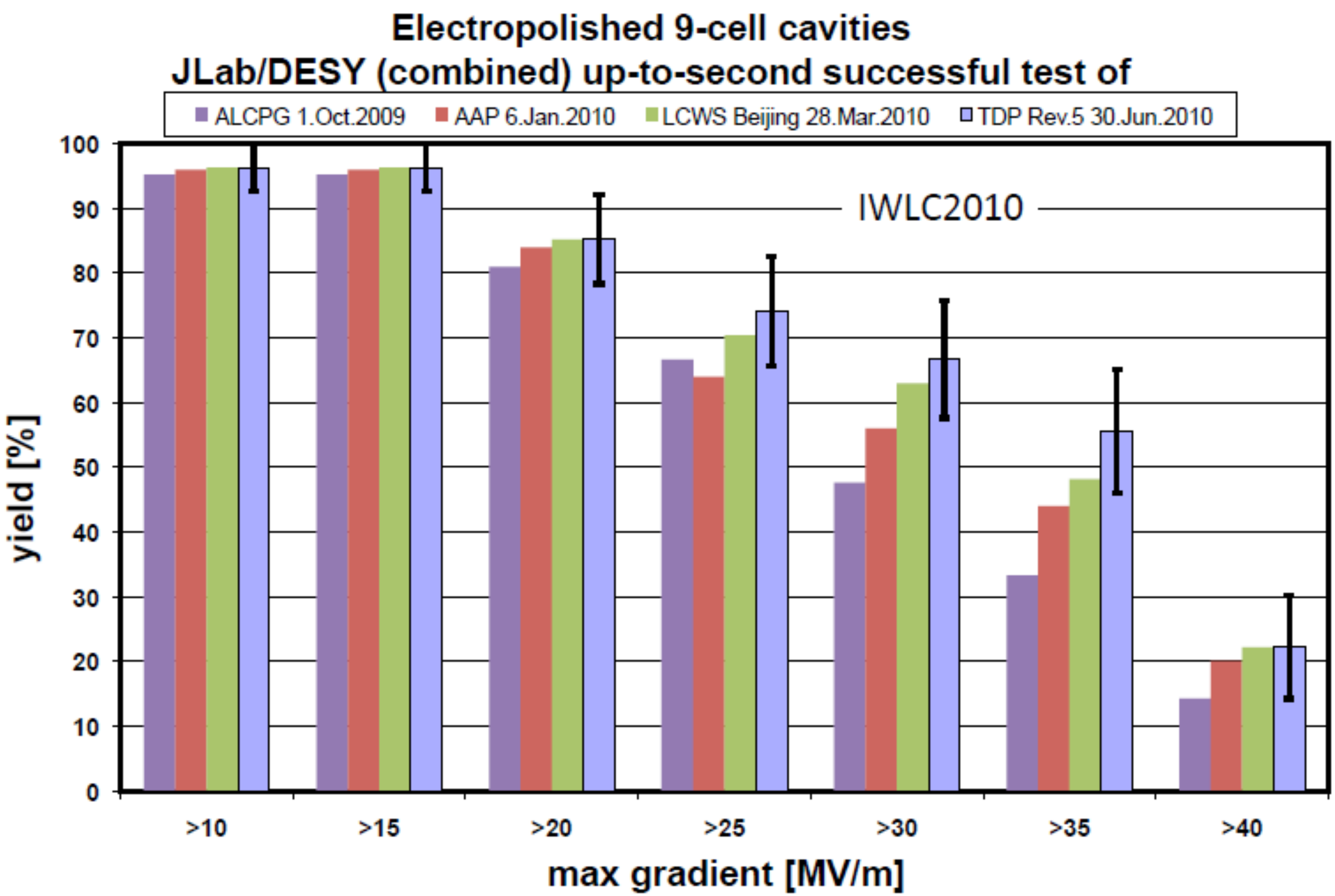


Z130: Quench in 3π/9-mode at 22 MV/m

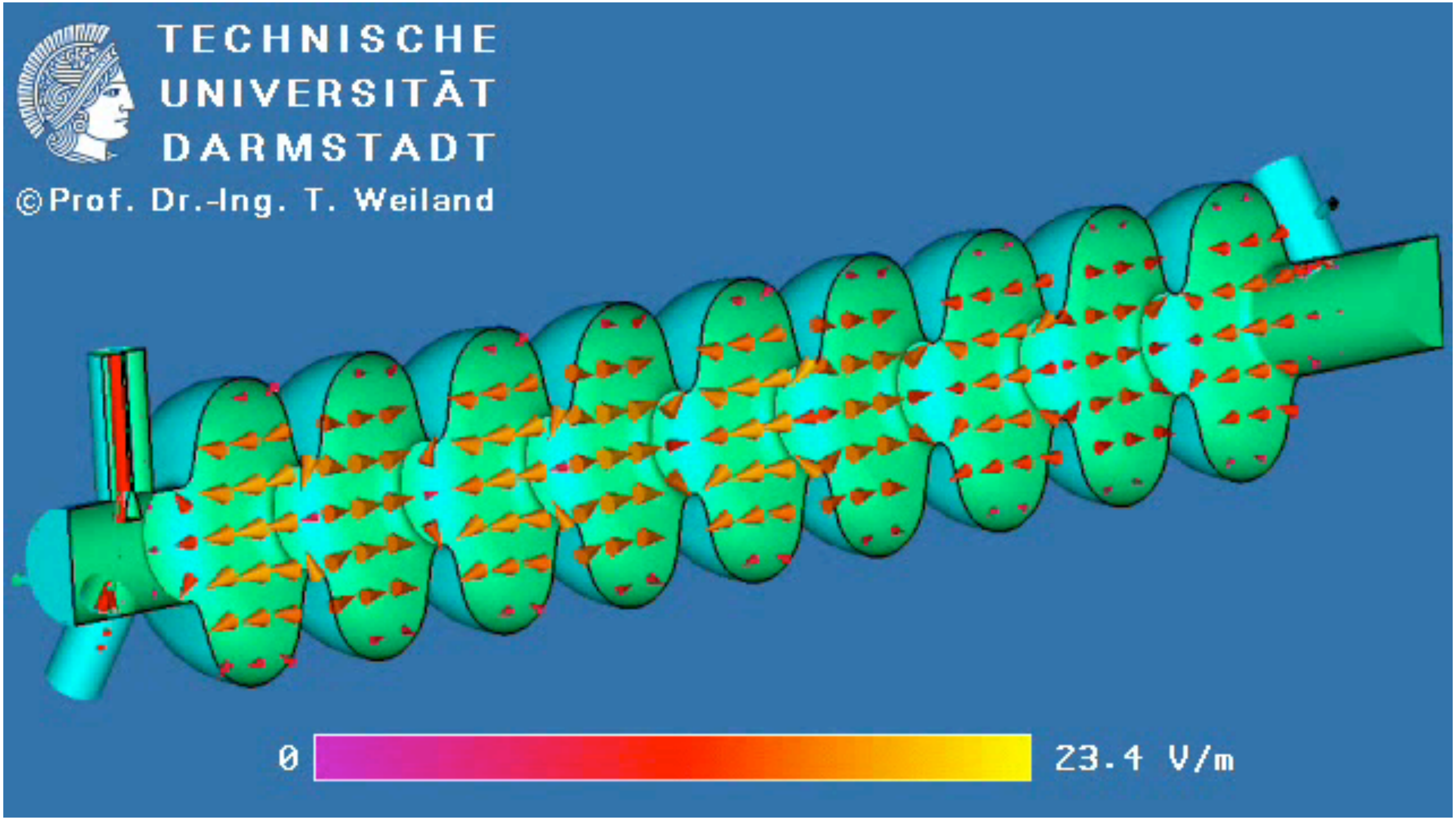


Picture at same location

Cavity Production Yield



RF Field Simulation

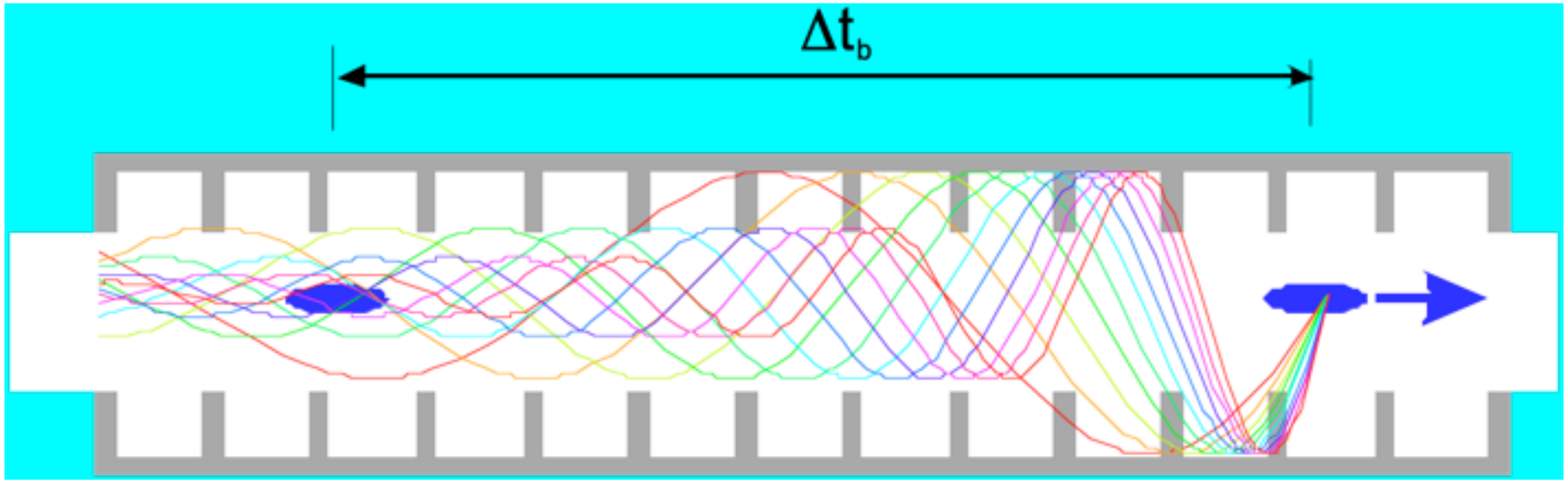


Q Factor

- Superconducting cavity:
  - surface resistance ~0
  - $Q_0 \sim 1/\delta$
  - $Q_0 > 10^{10}$
  - decay times of seconds even at 1.3 GHz
- A church bell (300 Hz) with $Q_0 = 5 \times 10^{10}$ would ring – once excited – longer than one year!

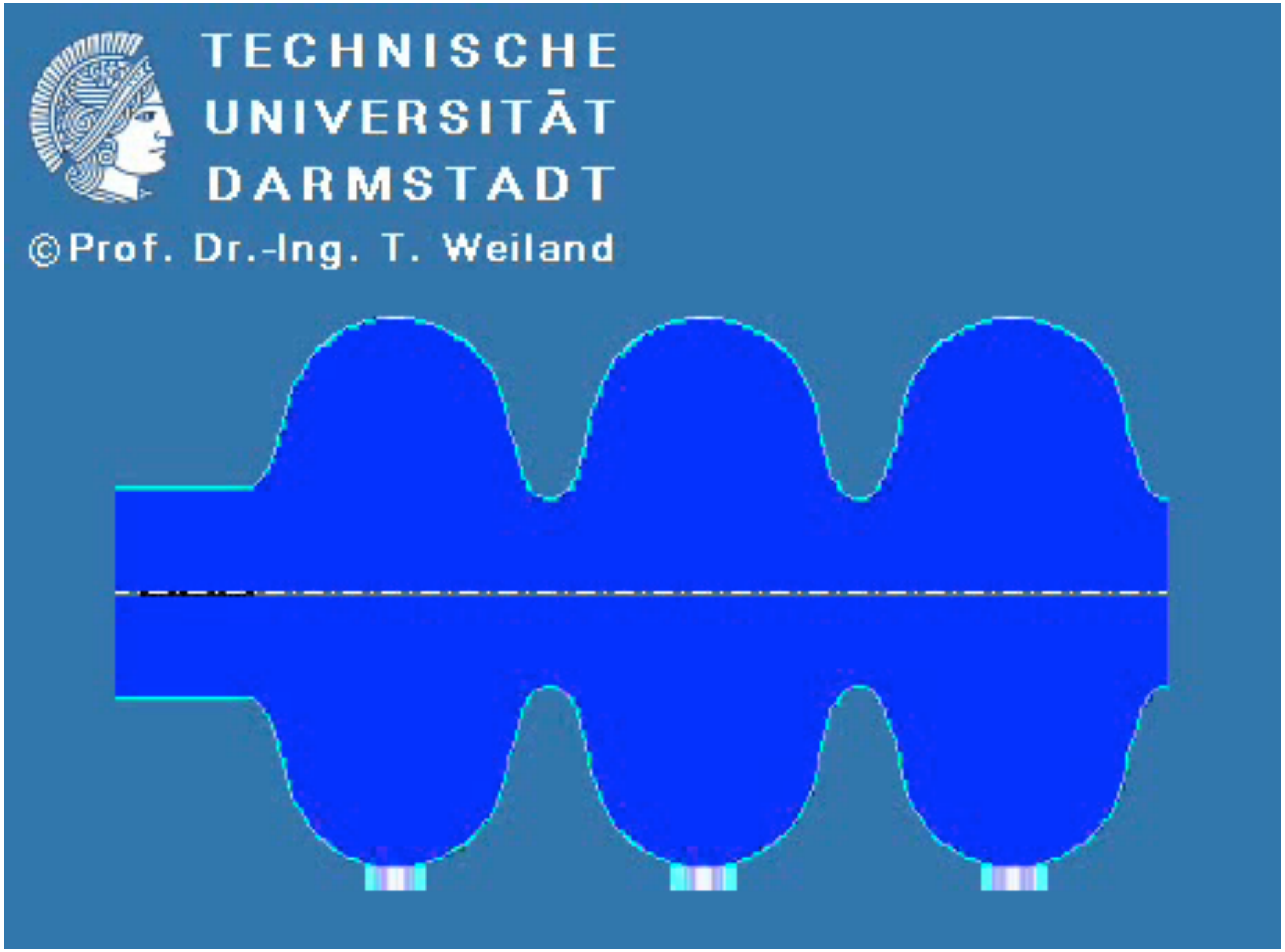
Transverse Wakefields

- Bunch currents generate transverse deflecting modes when bunches are not on cavity axis:

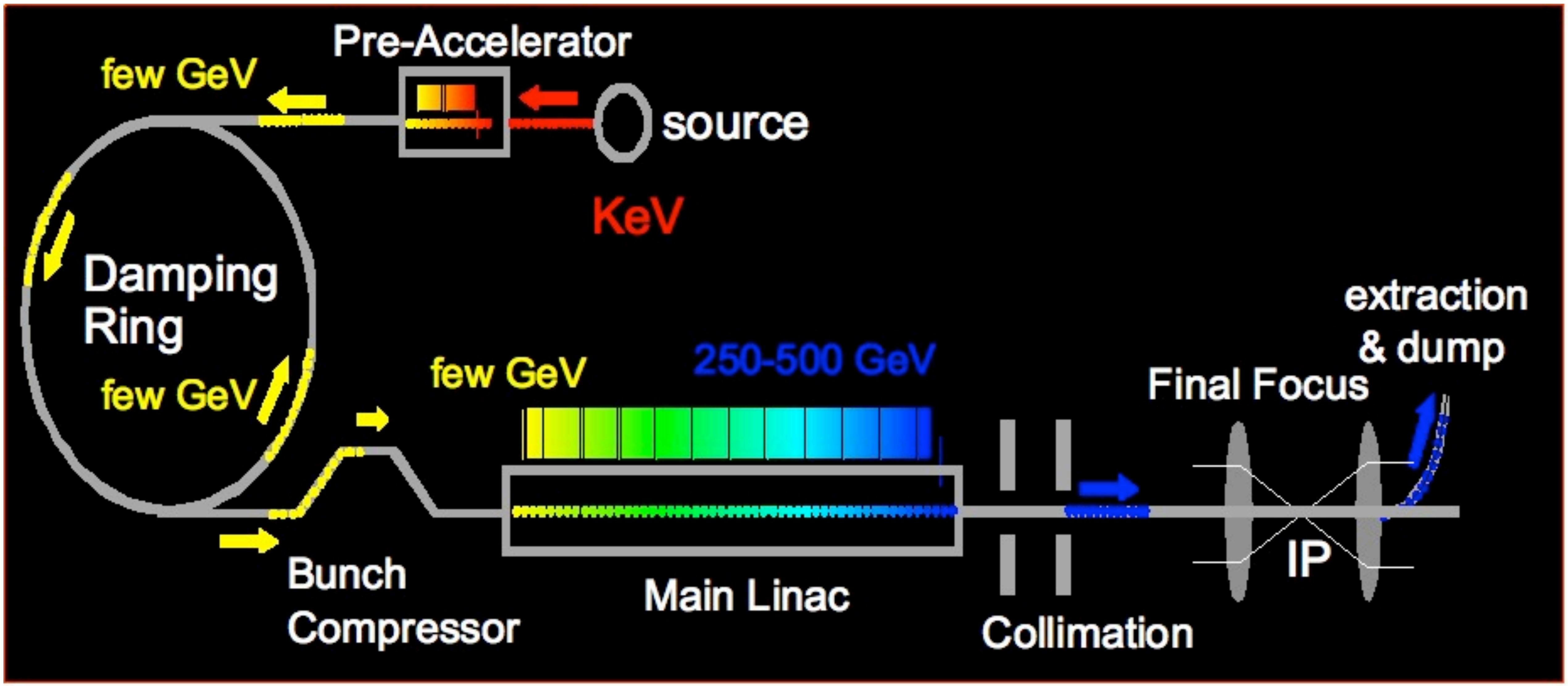


- Fields build up resonantly and kick later bunches transversely
- Dilutes Emittance!

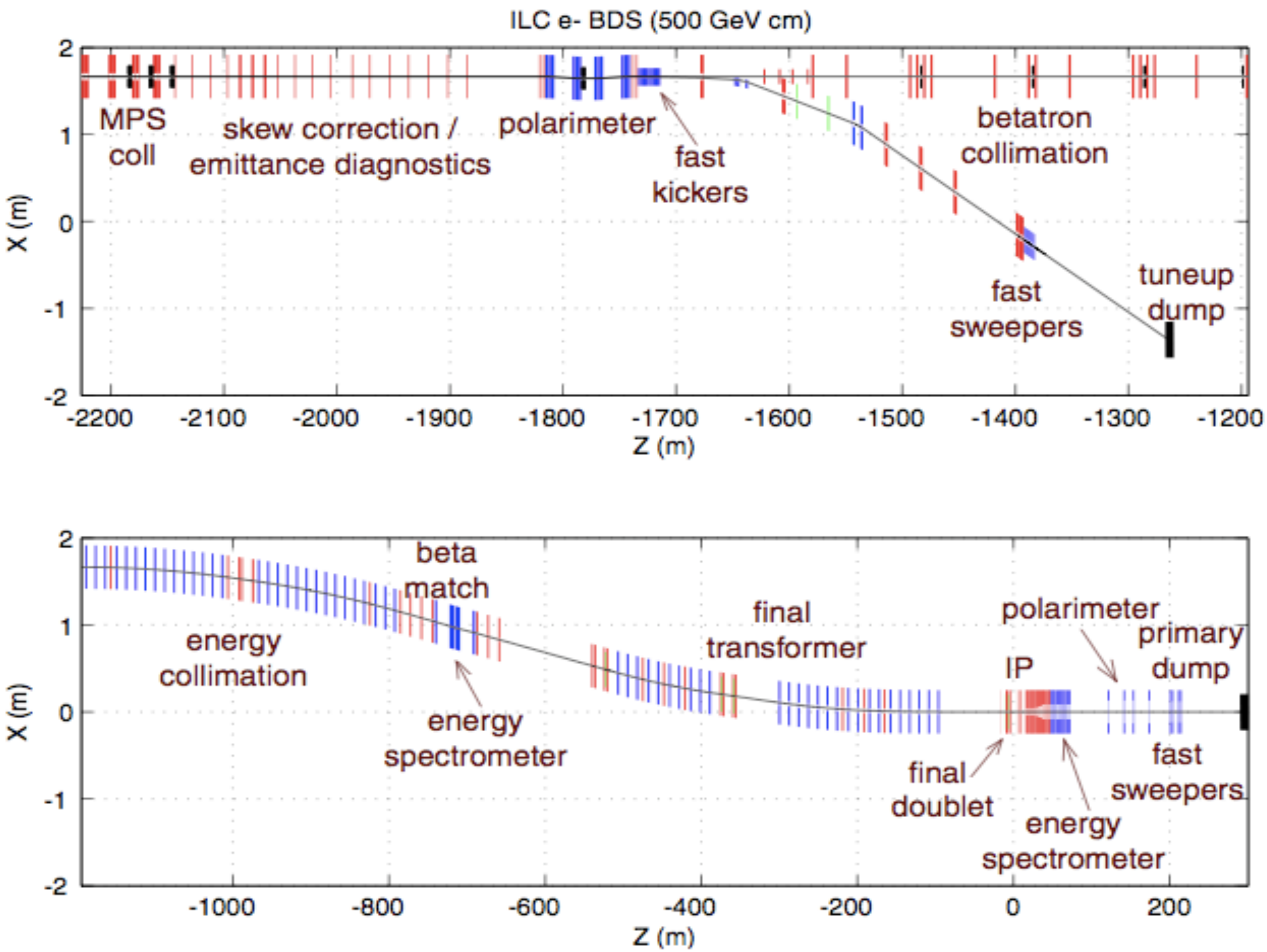
Wakefield Simulation



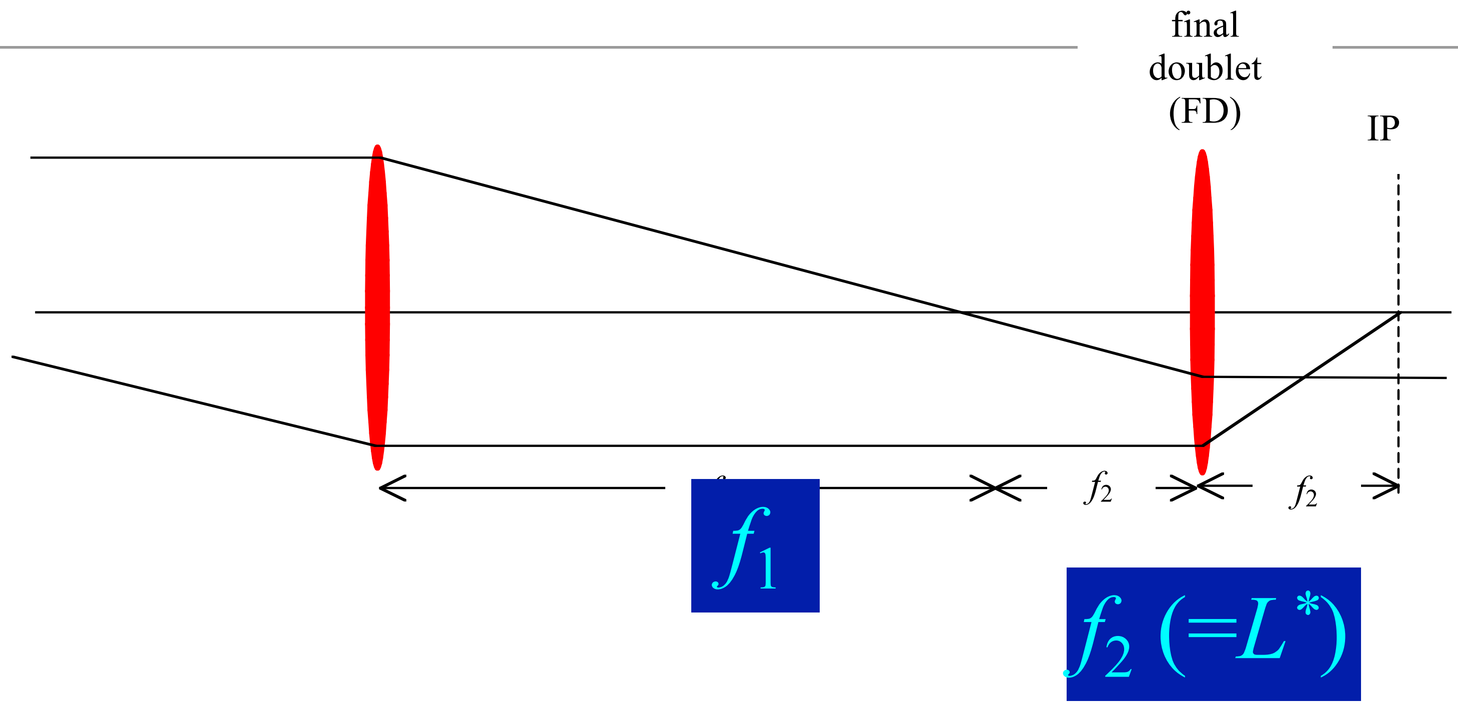
Beam Delivery System



BDS Optics


ILC e- BDS (500 GeV cm)
MPS coll
skew correction / emittance diagnostics
polarimeter
fast kickers
betatron collimation
fast sweepers
tuneup dump
X (m)
Z (m)
2
1
0
-1
-2
-2200
-2100
-2000
-1900
-1800
-1700
-1600
-1500
-1400
-1300
-1200
beta match
energy collimation
energy spectrometer
final transformer
polarimeter
primary dump
IP
fast sweepers
final doublet
energy spectrometer
-1000
-800
-600
-400
-200
0
200

Final Focus



Use telescope optics to de-magnify beam by factor $m = f_1/f_2 = f_1/L^*$

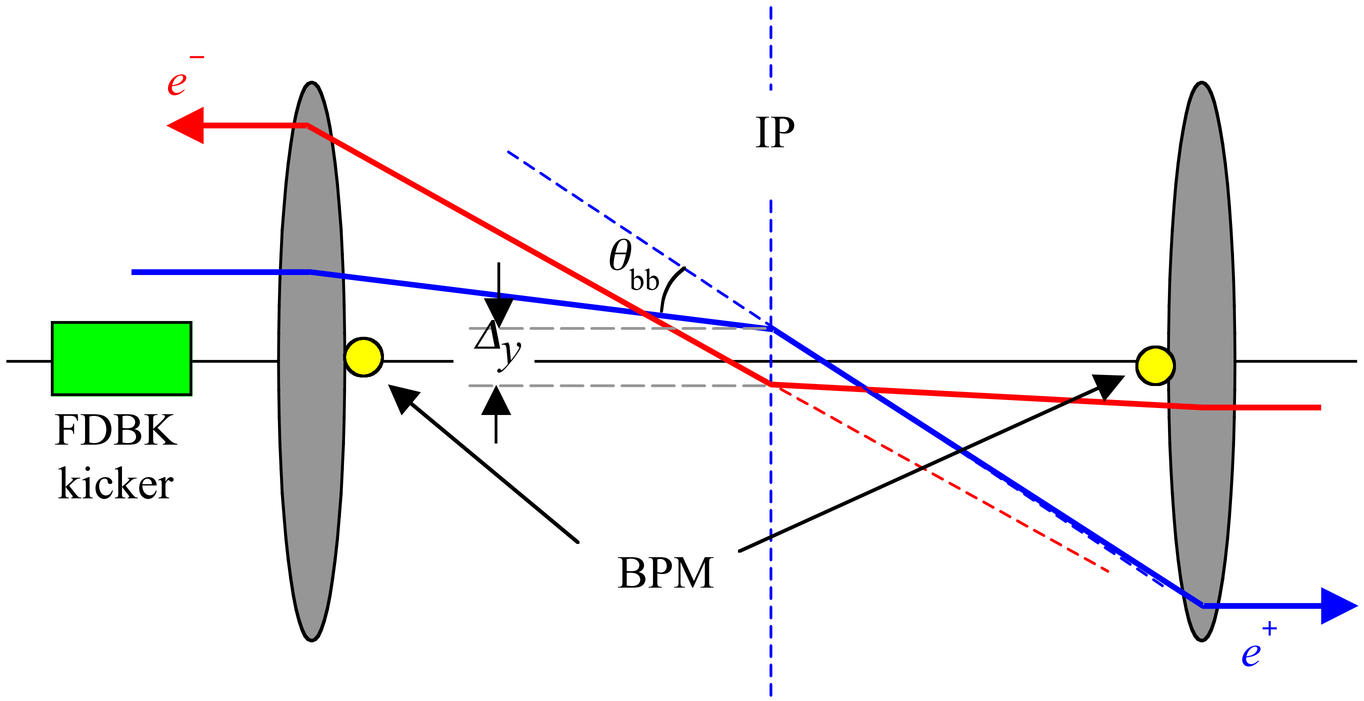
Need typically $m = 300$

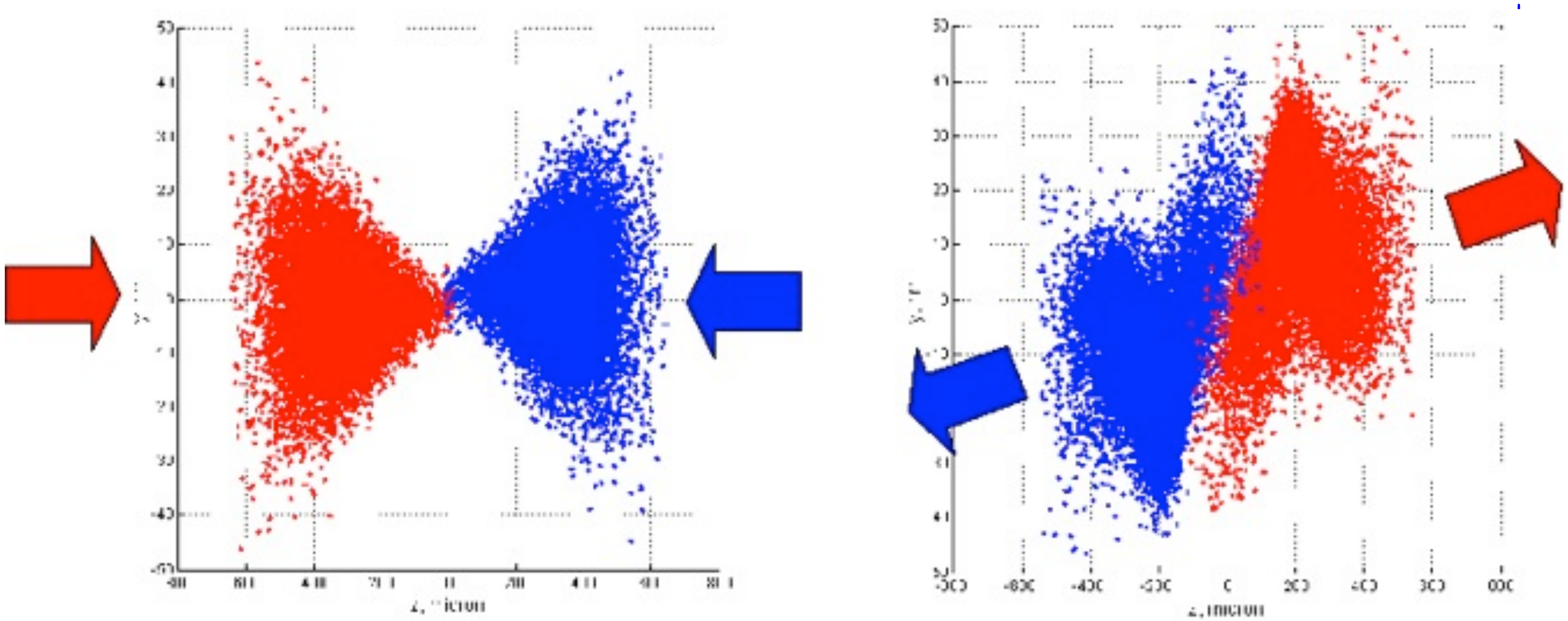
putting $L^* = 2\text{m} \Rightarrow f_1 = 600\text{m}$

In real life more complicated: correction for large chromatic and geometric aberrations needed → principle design challenge

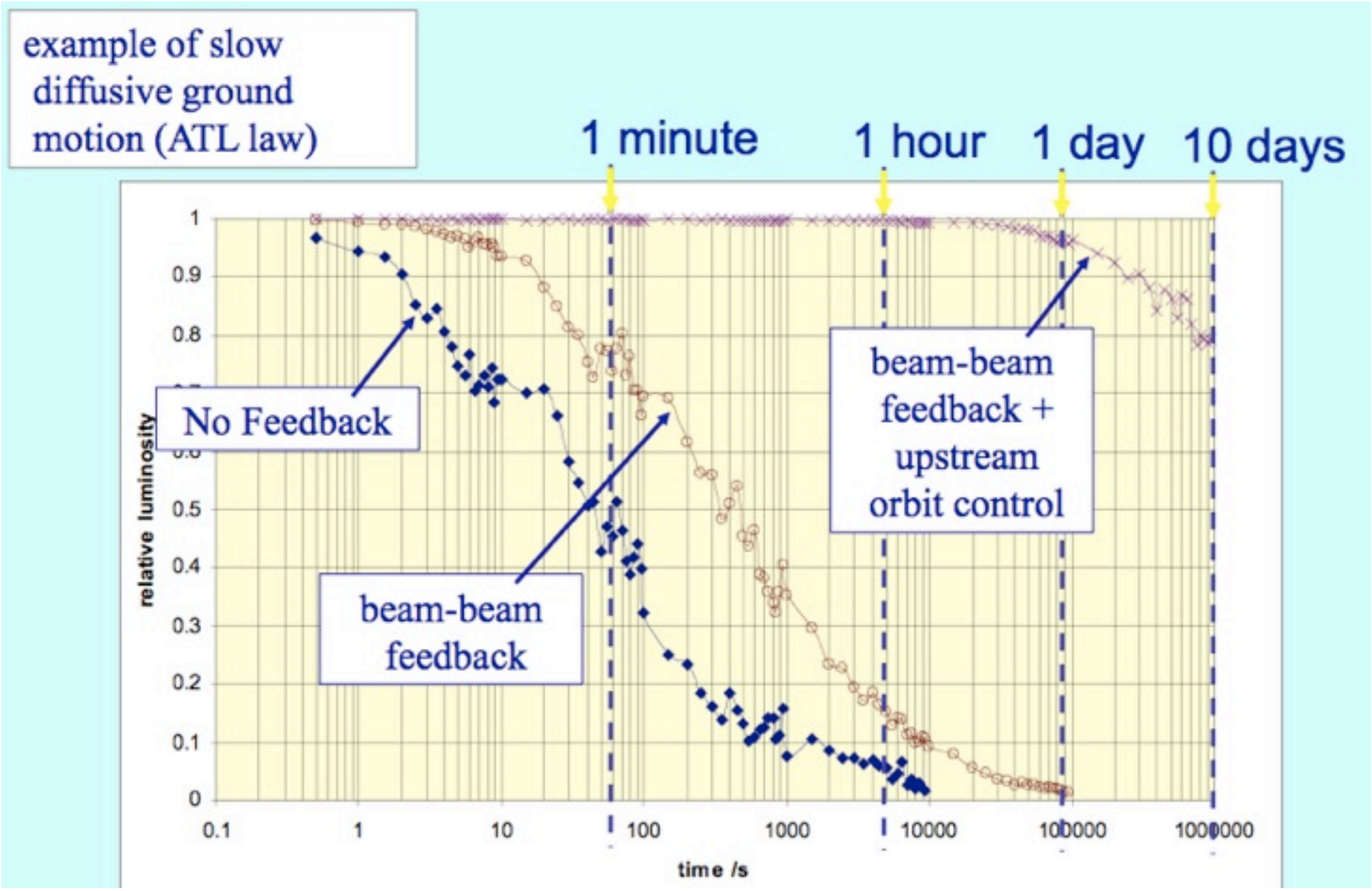
Beam-Beam Orbit Feedback

- Beam-beam kick transforms nanometre offsets at the IP to large measurable effects downstream
- Used in feedback system to optimise luminosity

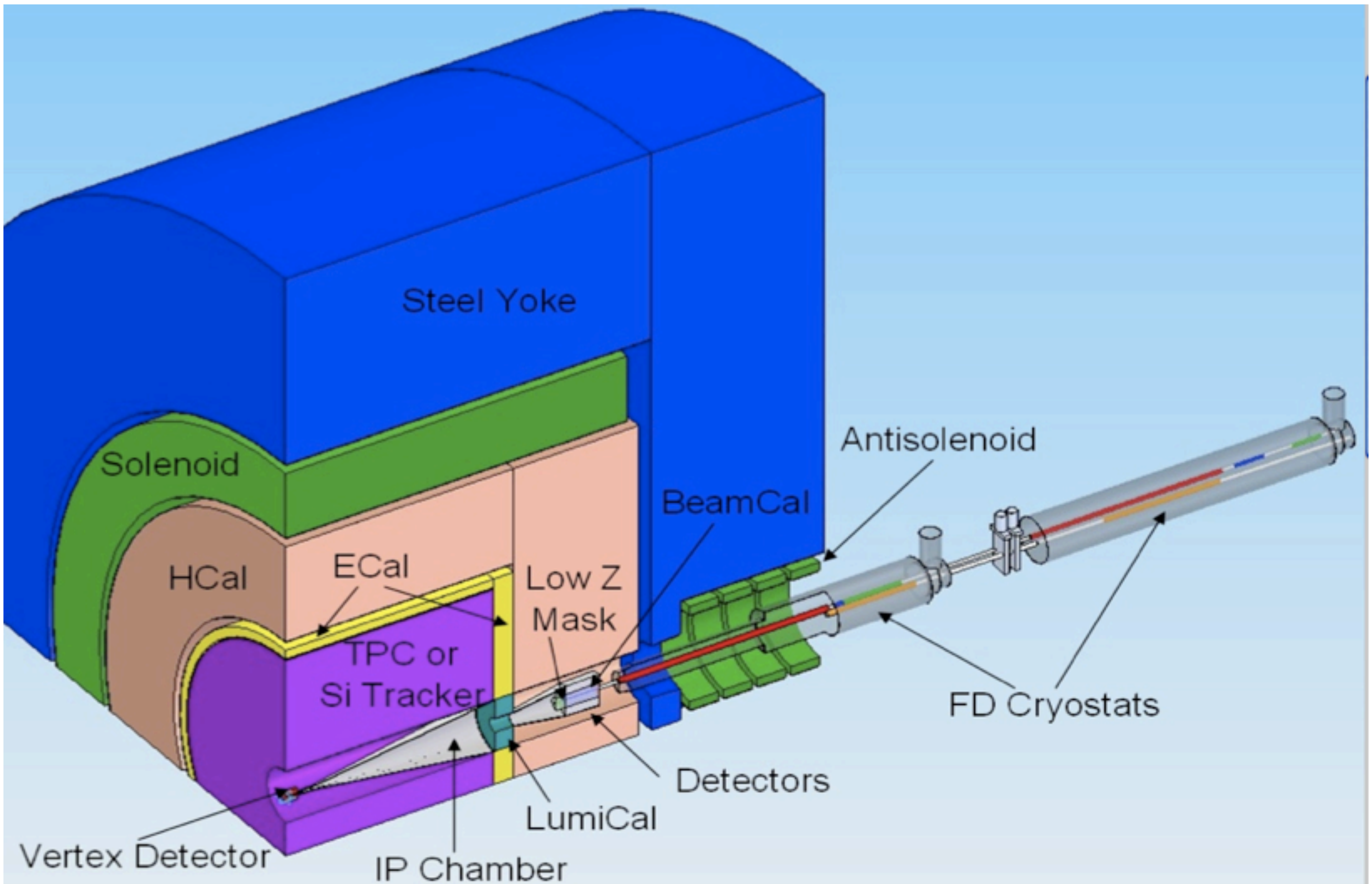




Long Term Stability

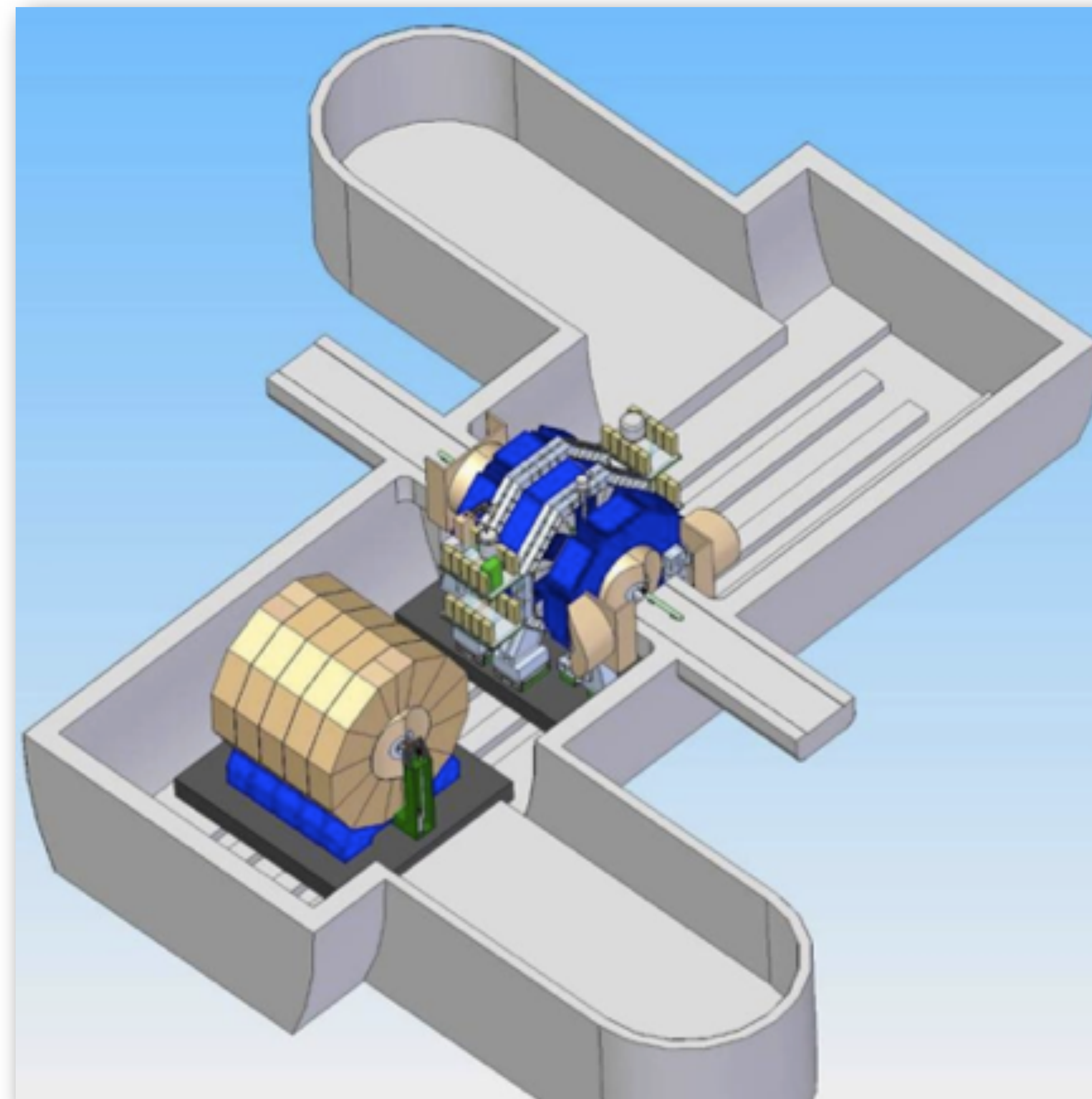


IP Region


Steel Yoke
Solenoid
Antisolenoid
BeamCal
HCal
ECal
Low Z
Mask
TPC or
Si Tracker
FD Cryostats
Detectors
LumiCal
Vertex Detector
IP Chamber

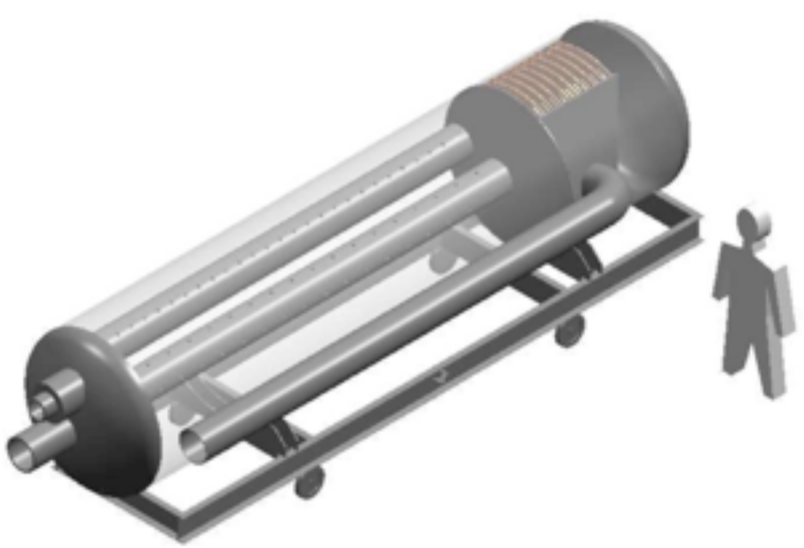
Detectors and Push/Pull

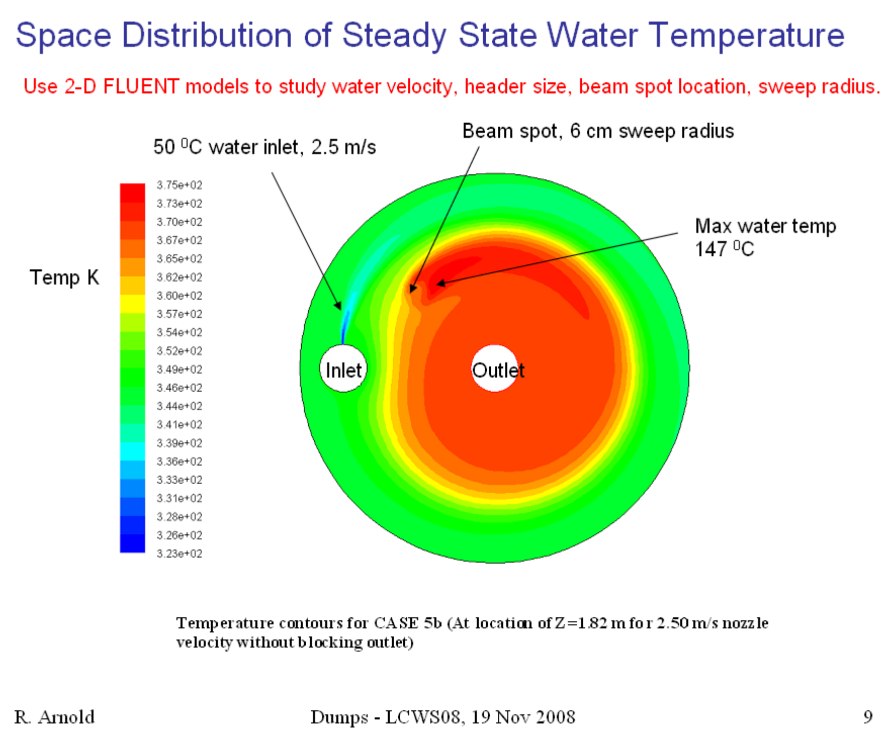
- Integrated luminosity at linear colliders does not scale with the number of interaction regions
- ILC has just one interaction beam line (cost issue) but should have two detectors
- Two detectors share one interaction region
  - → Push/Pull System

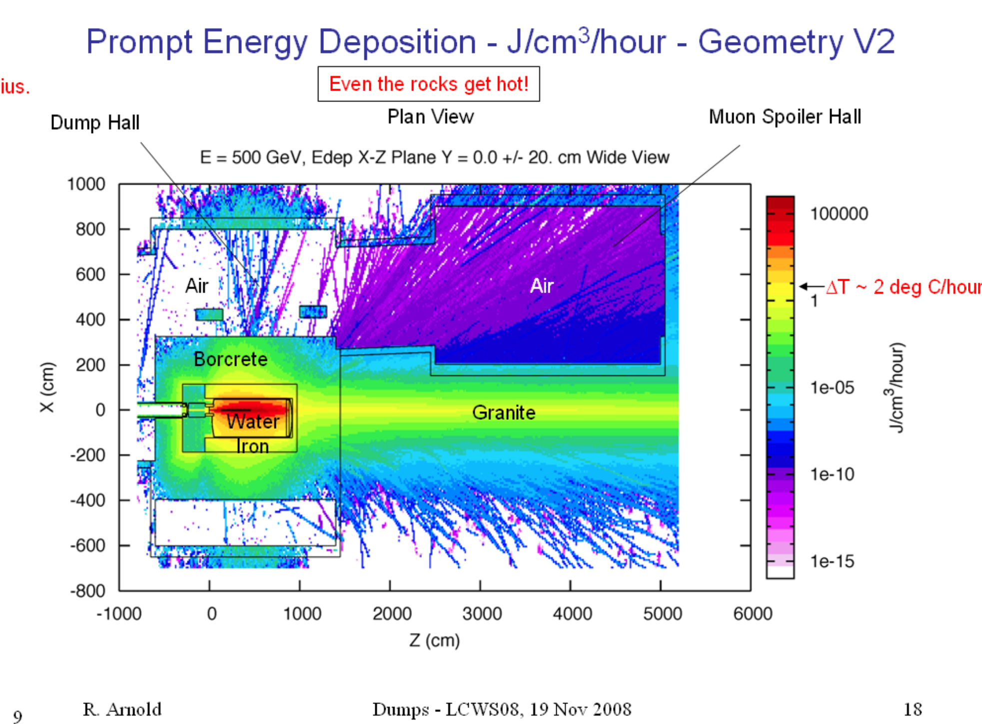


Beam Dumps

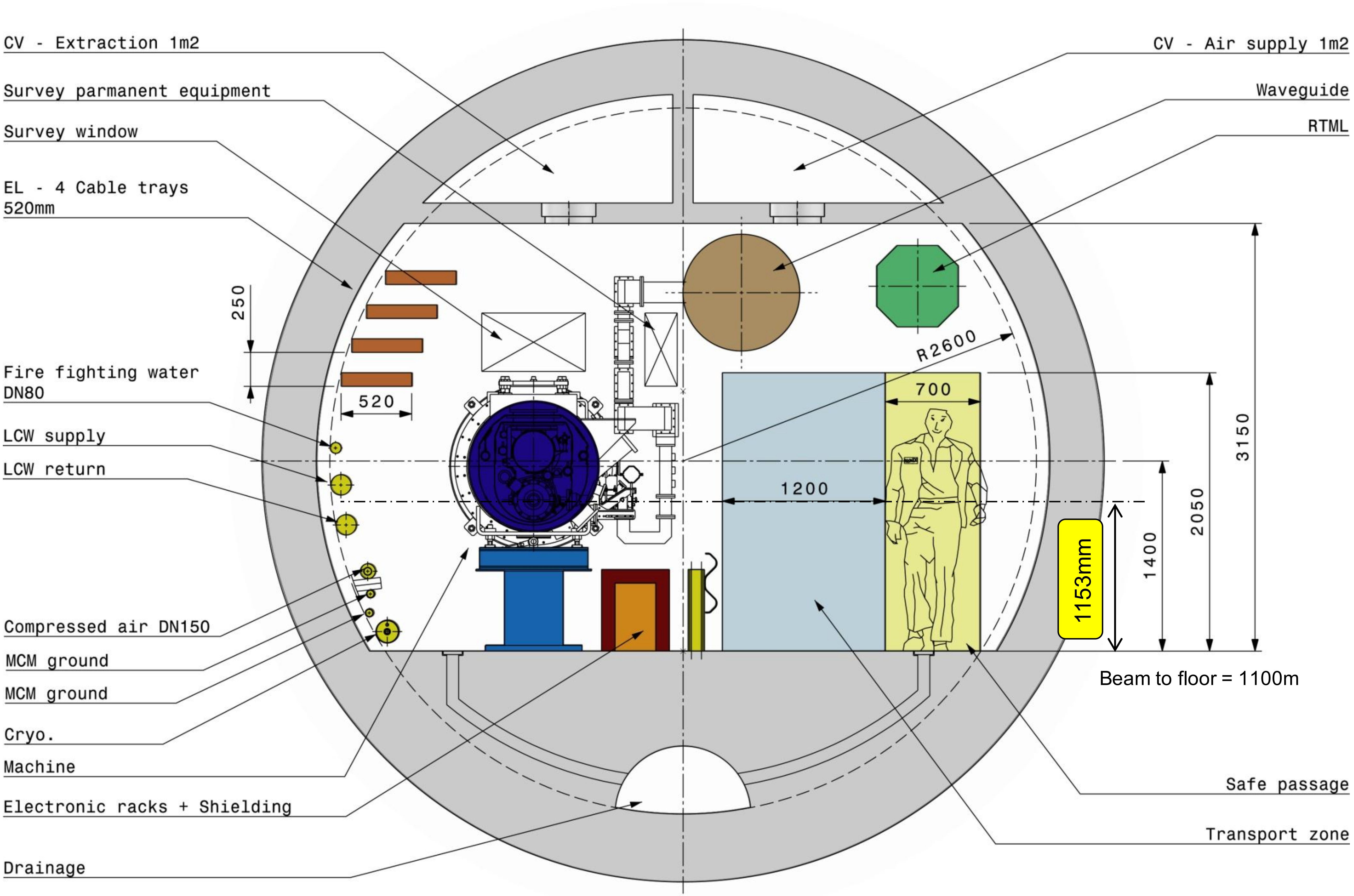
- Beam dumps designed for 1 TeV machine: 18 MW (!)
- 10 bar pressurised water (avoid boiling) plus copper sandwich
- Beam sweeped over entry window
- Heat exchange system (8500 l/min) removes power
- Significant challenges:
  - Tritium production
  - H_2O radiolysis



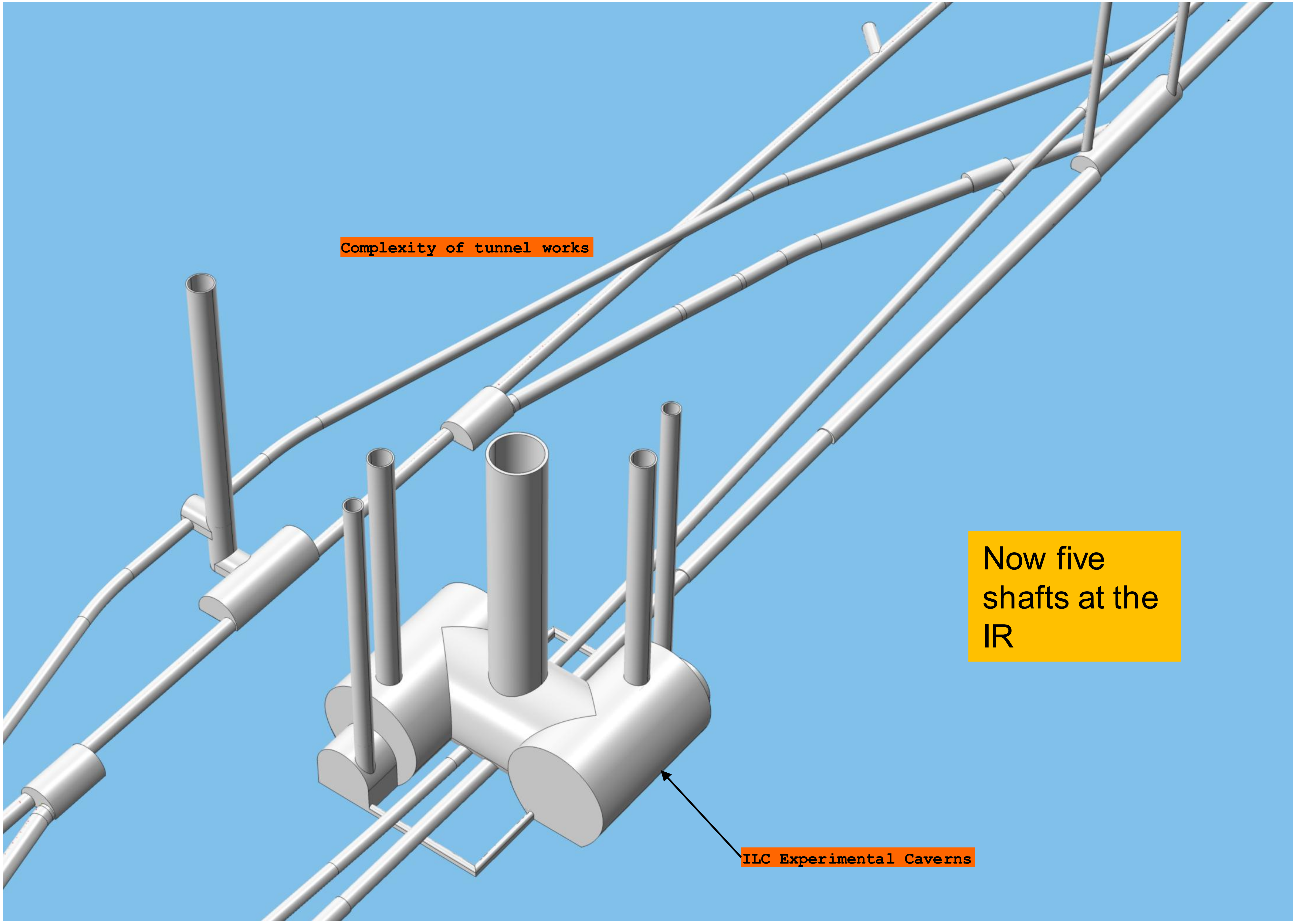




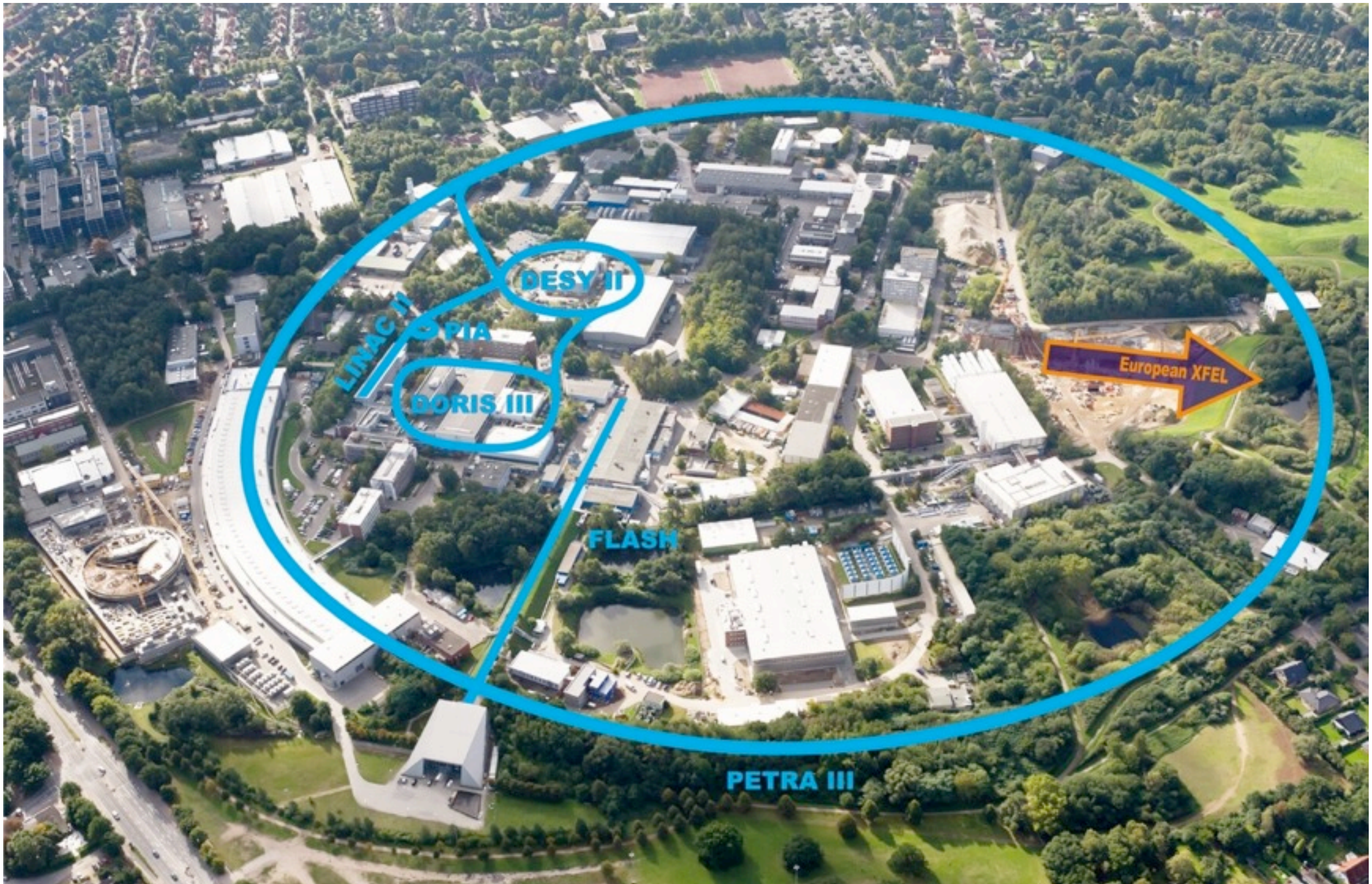
Typical Main Linac Cross Section for Klycluster Scheme on the CERN Site



ILC - Typical Cross Section - Diameter 5200mm - Scale 1:25 (A3)


Complexity of tunnel works
Now five shafts at the IR
ILC Experimental Caverns

FLASH@DESY



FLASH/TTF

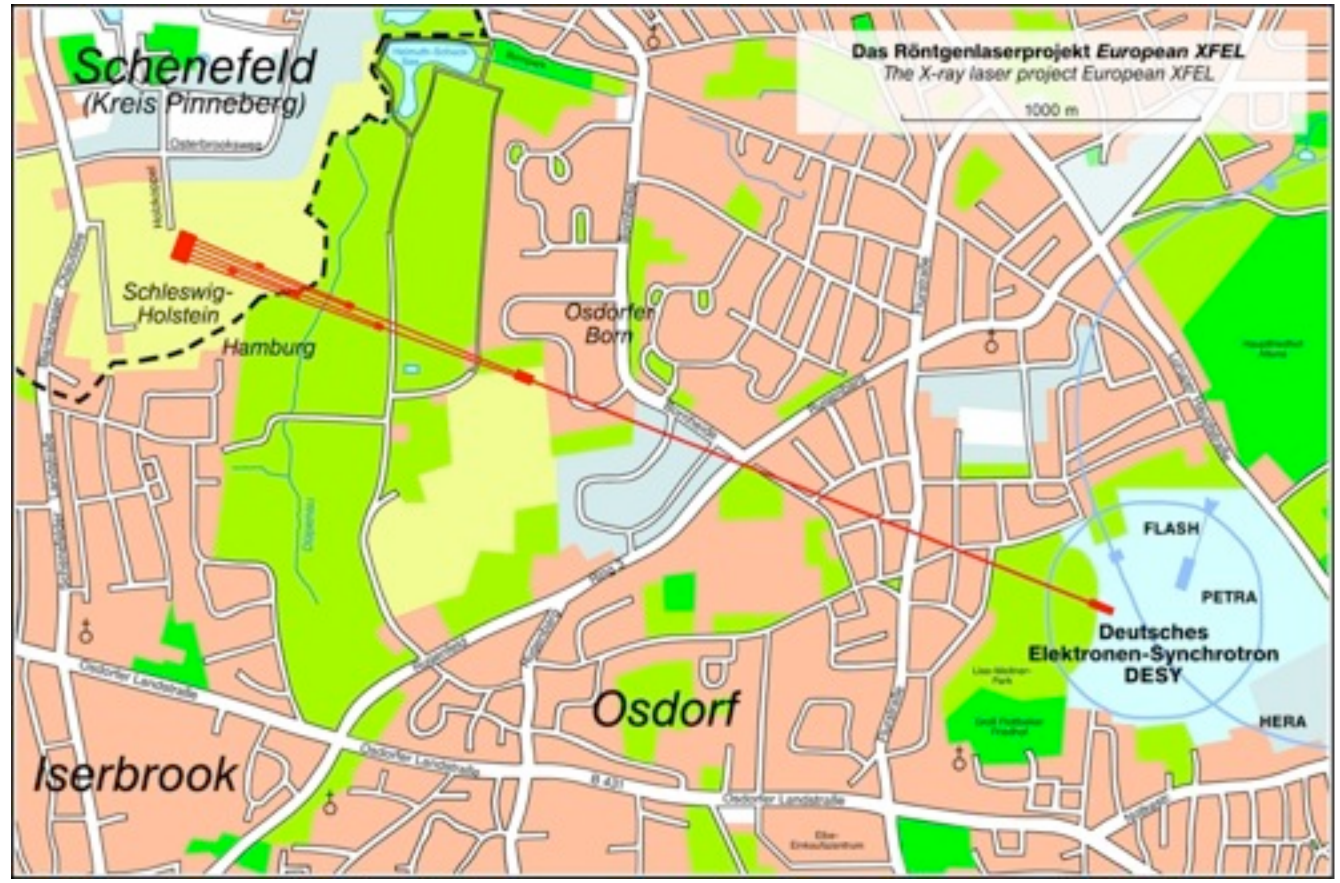
- Complete System Test
- 1 GeV e^- Linac
- 9 mA beams have been accelerated
- ILC-like pulse structure
- 0.5% prototype for the ILC....

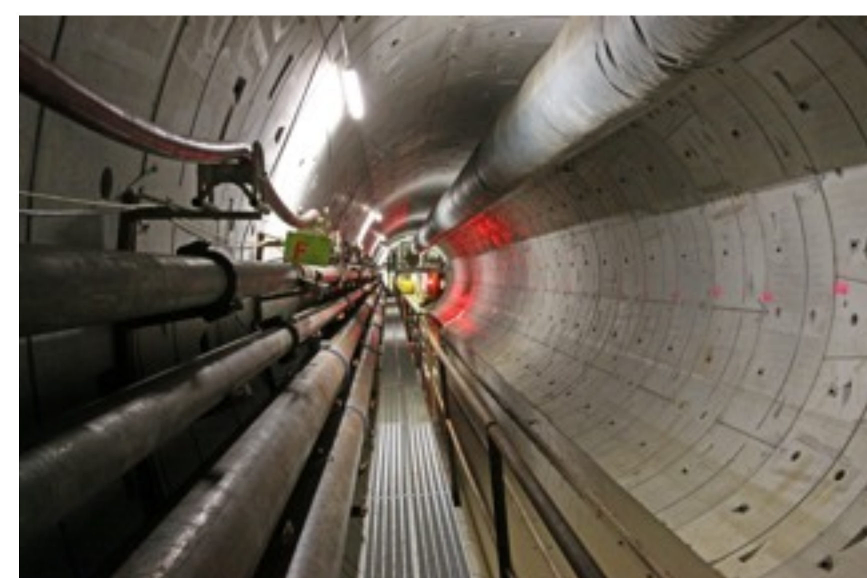
- User facility:
  - UV Free Electron Laser

The European XFEL

X-Ray Free Electron Laser

- ILC technology
- Length: 3,4 km
- Beam energy: 17,5 GeV
- Laser wavelength: 0,085 - 6 nm
- Laser pulse length: < 100 fs
- Construction start: 2009
- First beam: 2014
- Applied material research
- Linac: 10% prototype for ILC.....





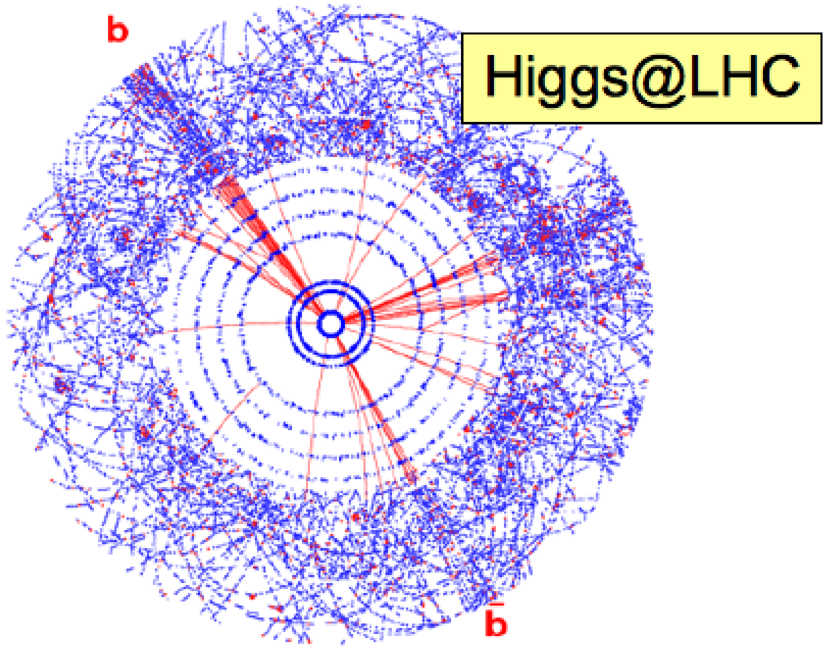
Detector Issues

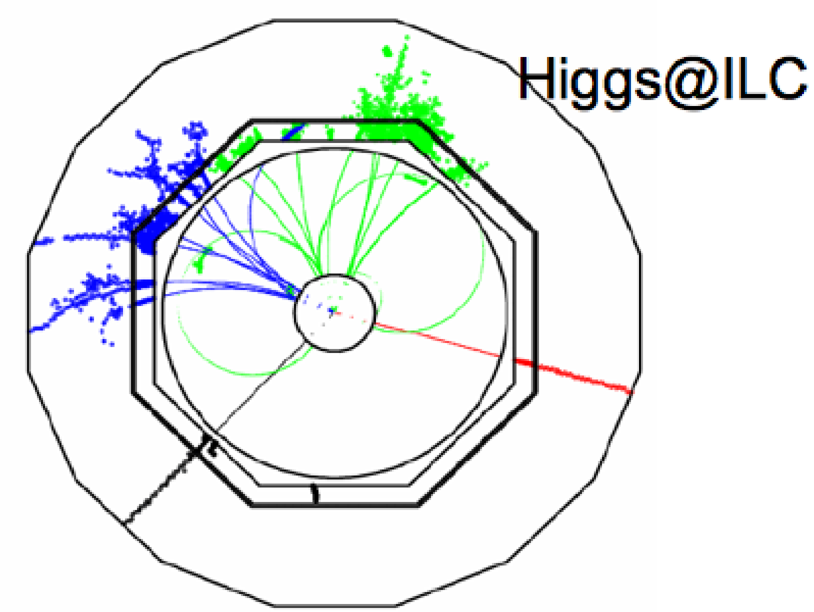
Why not copy LHC detectors?

LHC detectors were primarily designed to survive the harsh LHC environment (radiation hardness) and to cope with the short bunch spacing (25 ns).

ILC detector design is driven by precision:

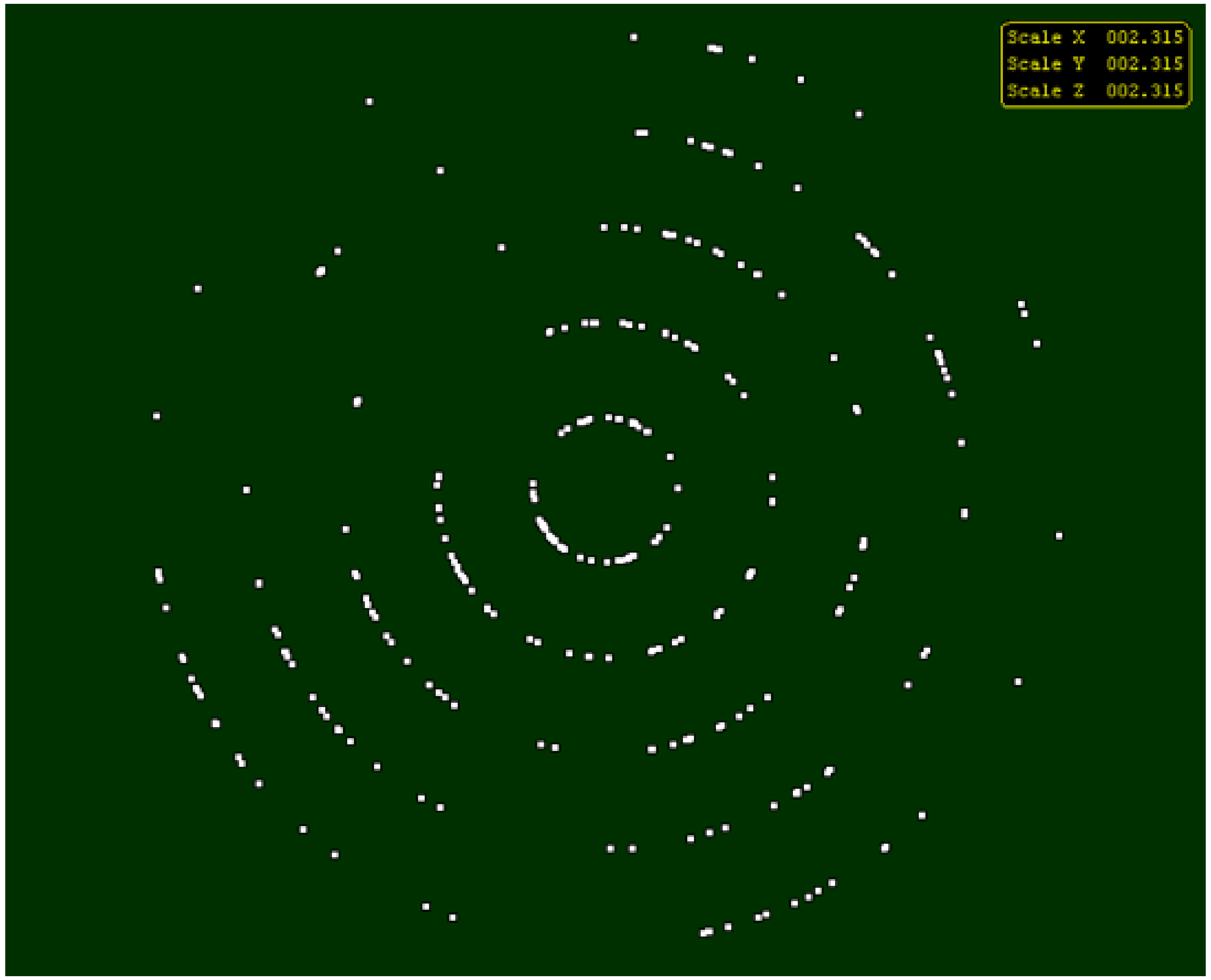
- Inner vertex layer ~3-6 times closer to IP
- Vertex pixel size ~30 times smaller
- Vertex detector layer ~30 times thinner
- Material in tracker ~30 times less
- Track momentum resolution ~10 better
- Granularity in electromagnetic calorimeter ~200 times better





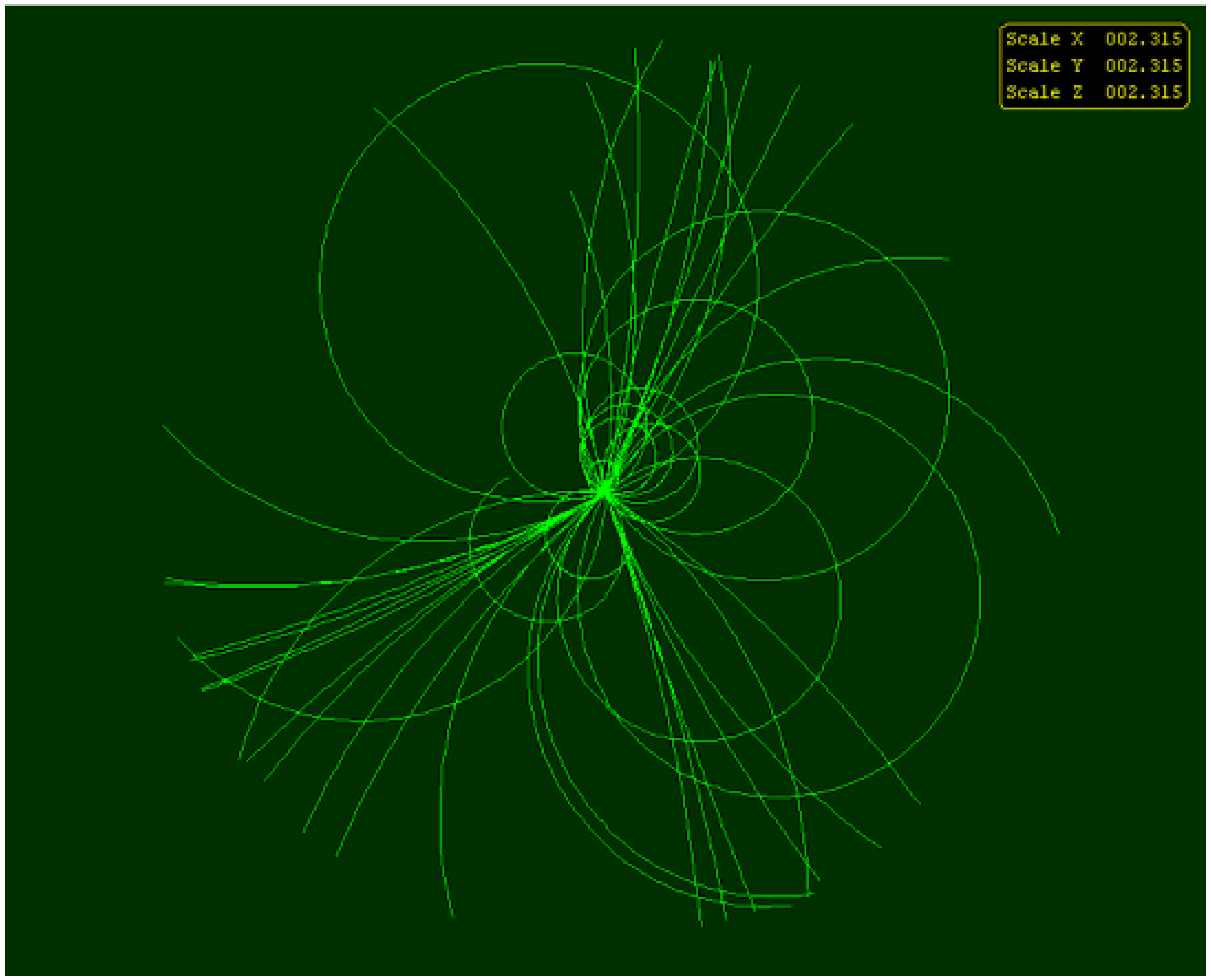
Tracking Options: Pixelated or Gaseous?

Silicon tracker



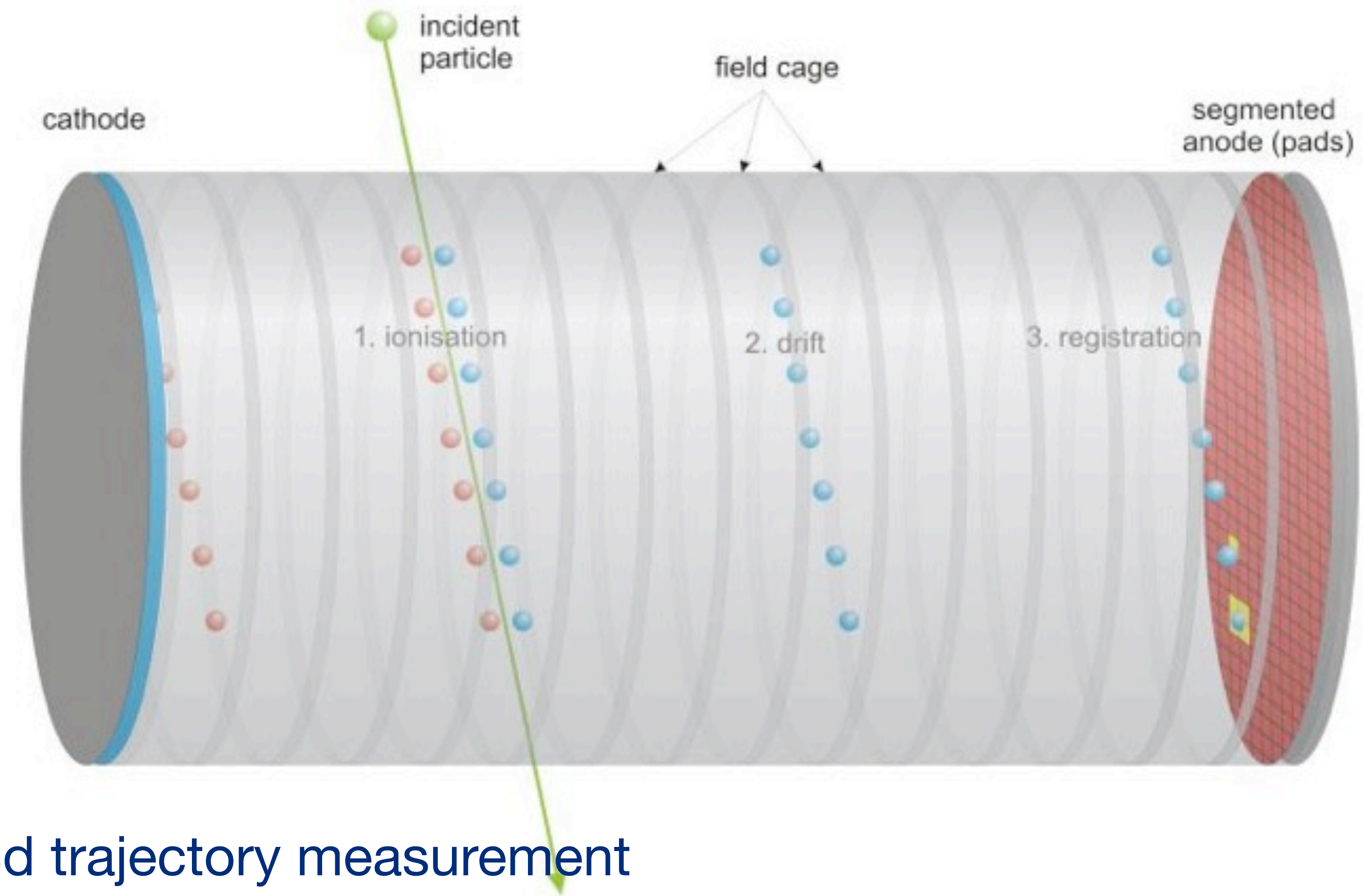
a few space points with extreme precision

Gaseous tracker



many space points with moderate precision

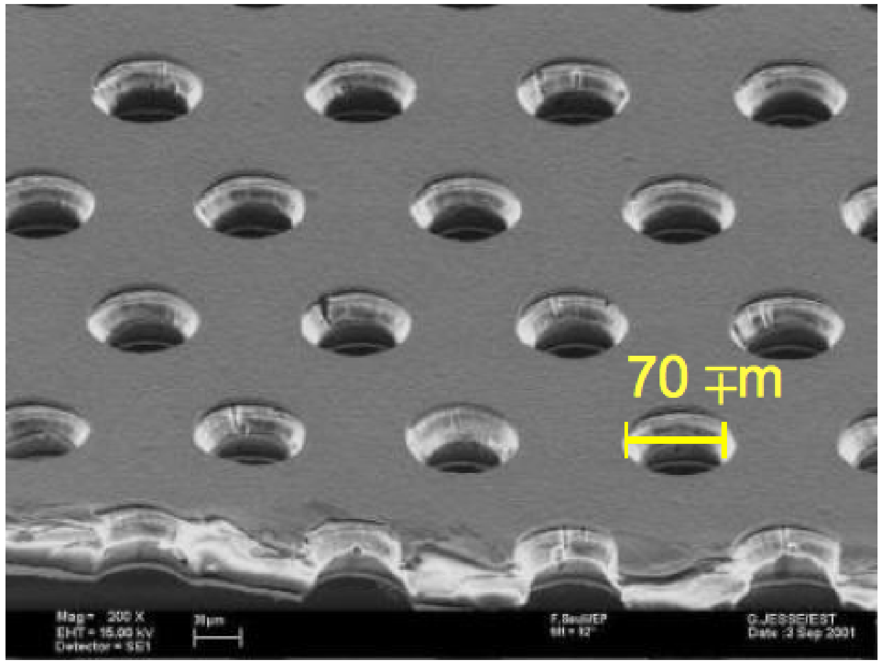
Tracking System Option: Time Projection Chamber

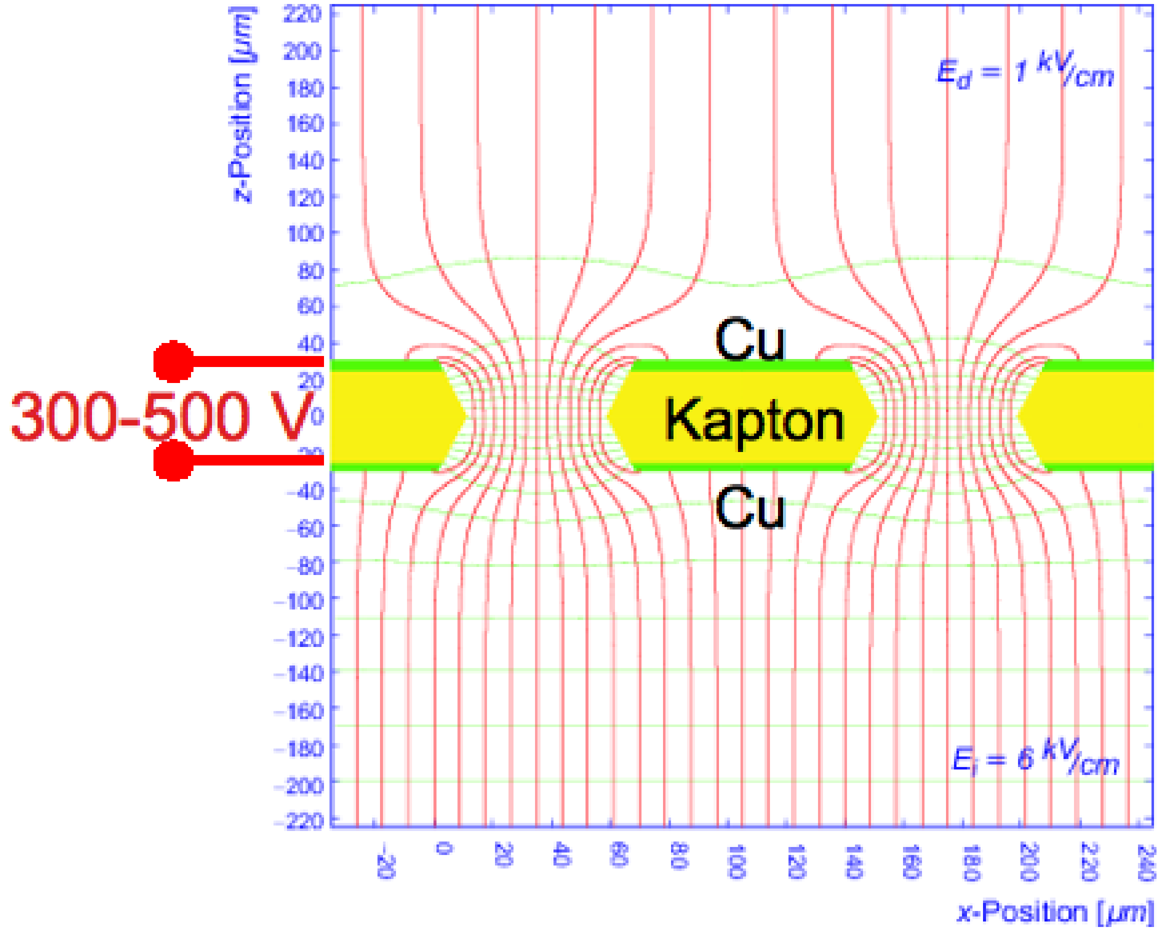


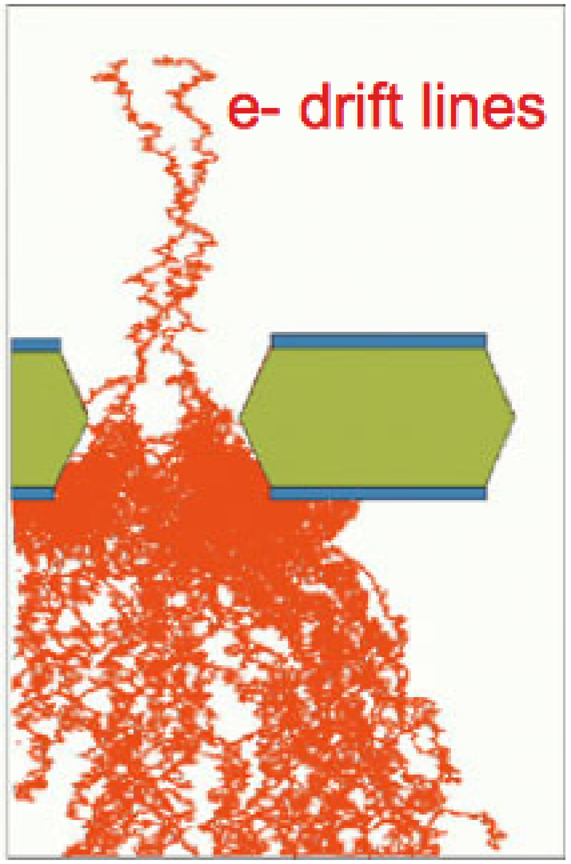
- Genuine 3d trajectory measurement
- Spacepoint resolution ~100μm
- Minimal amount of material in front of calorimeters
- Rather slow: 150 bunch crossings per picture

TPC Readout

- Electron signal amplification
- example:
  GEM - gas electron multiplier

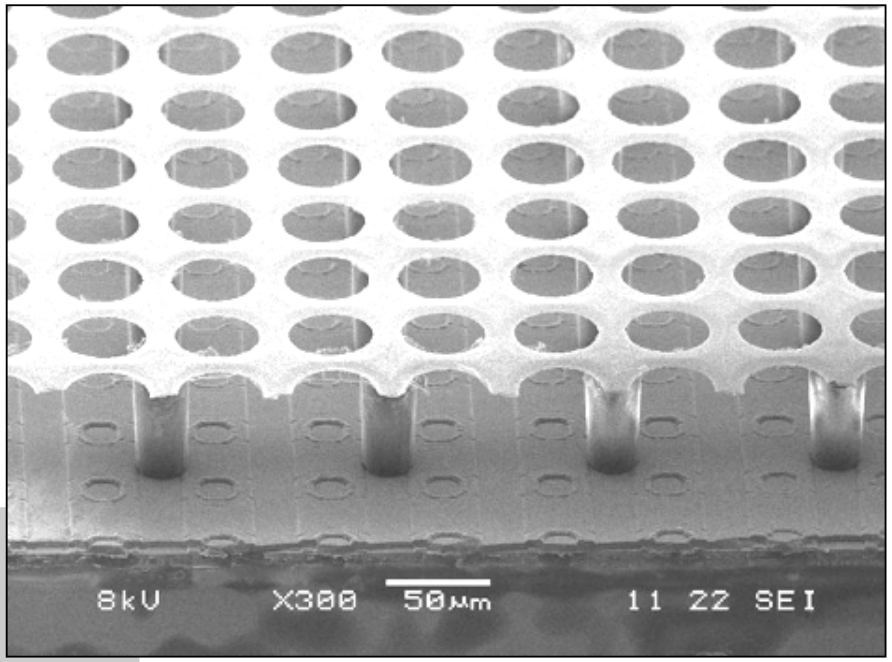


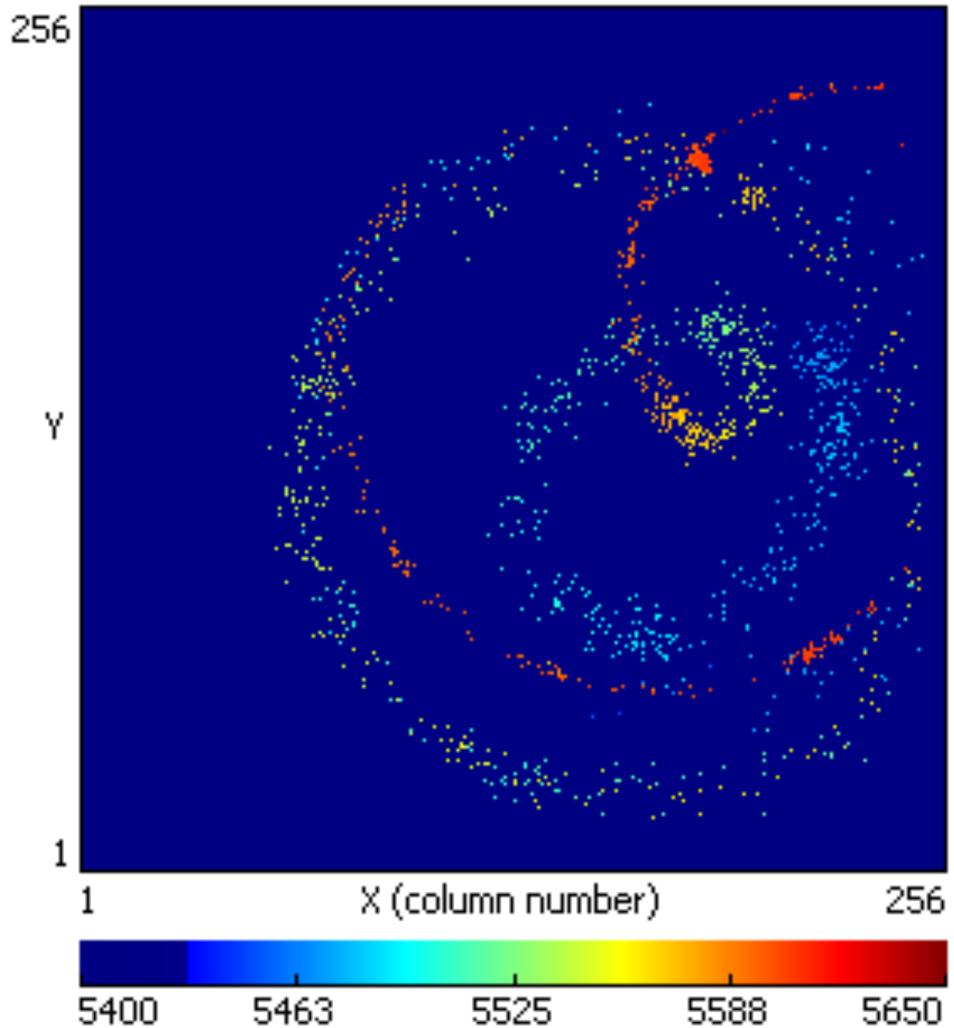


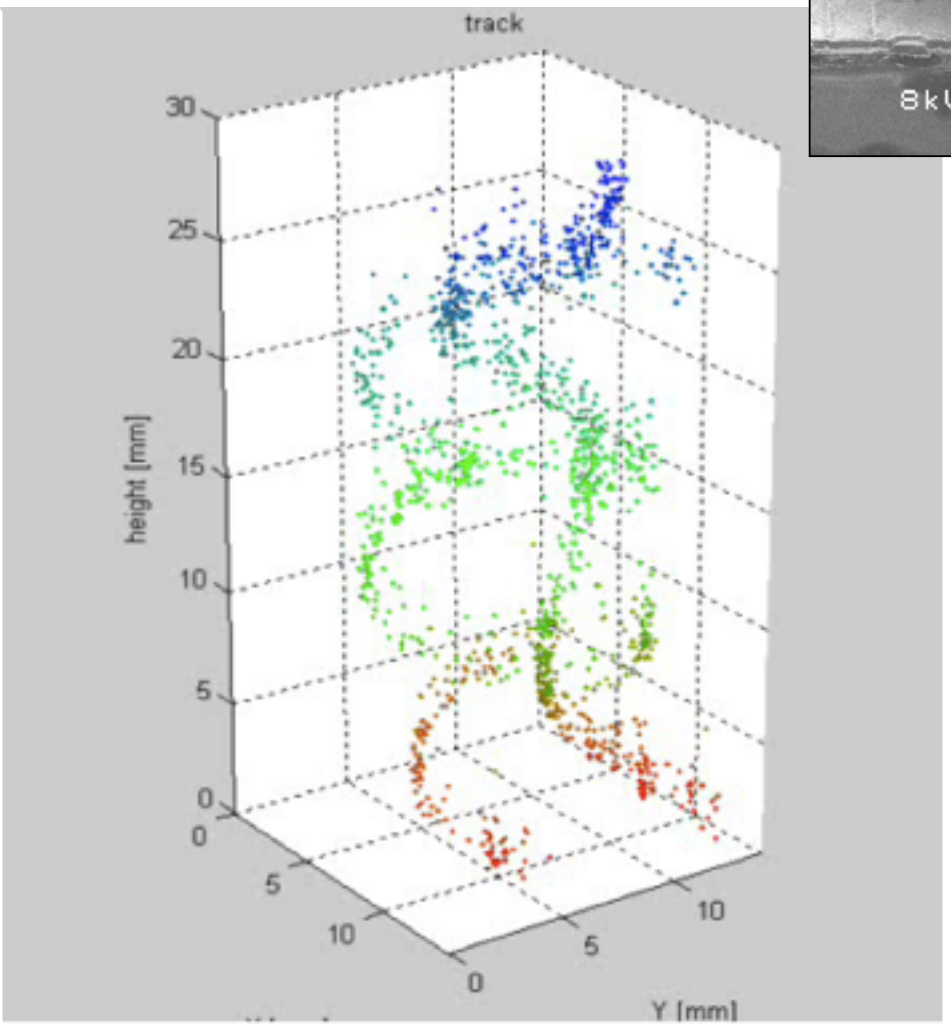


Combine Silicon and TPC Tracking?

- Readout TPC with pixel chip with integrated amplification structure
  - Example: electrons from ^{90}Sr in small (5 cm^3) test setup (B=0.2T)

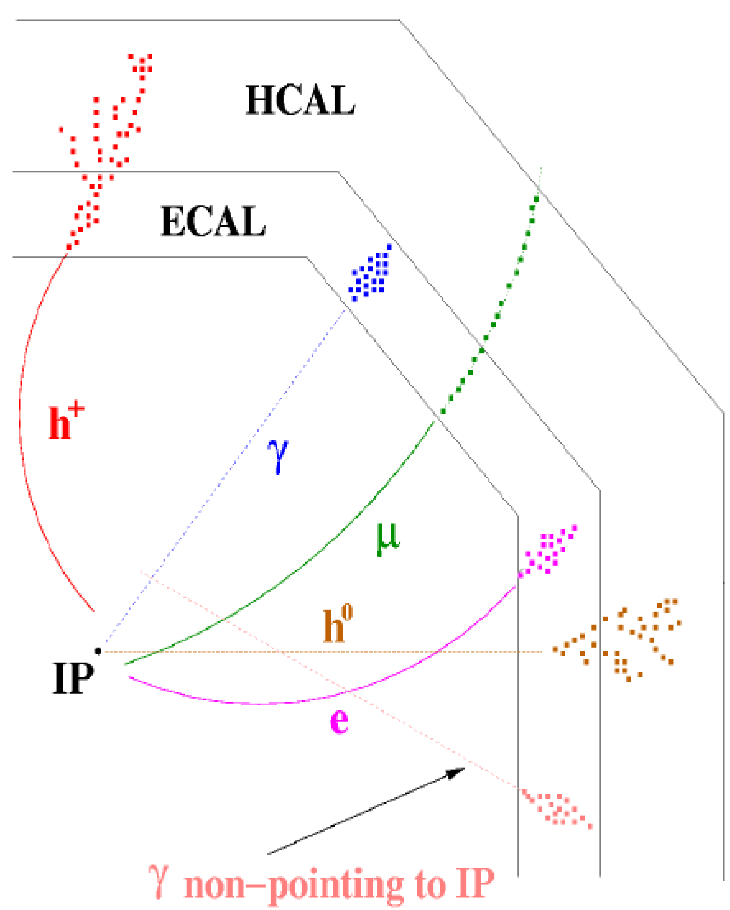


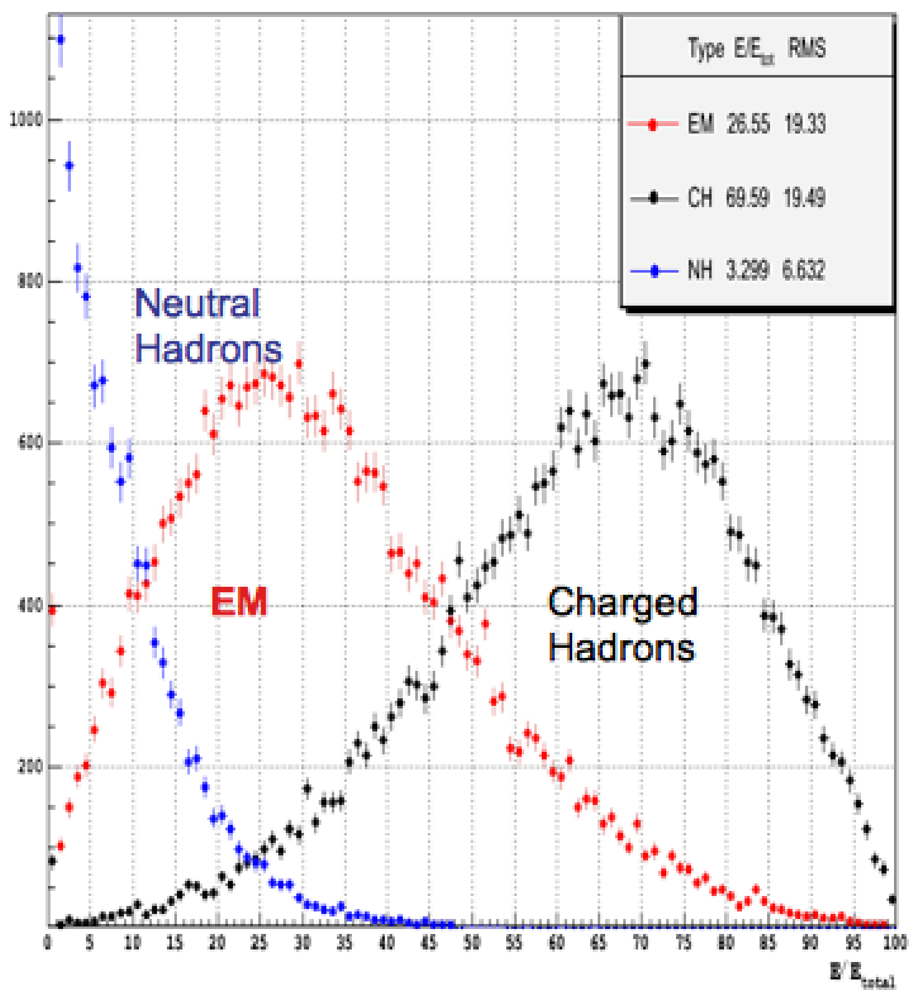




Calorimetry

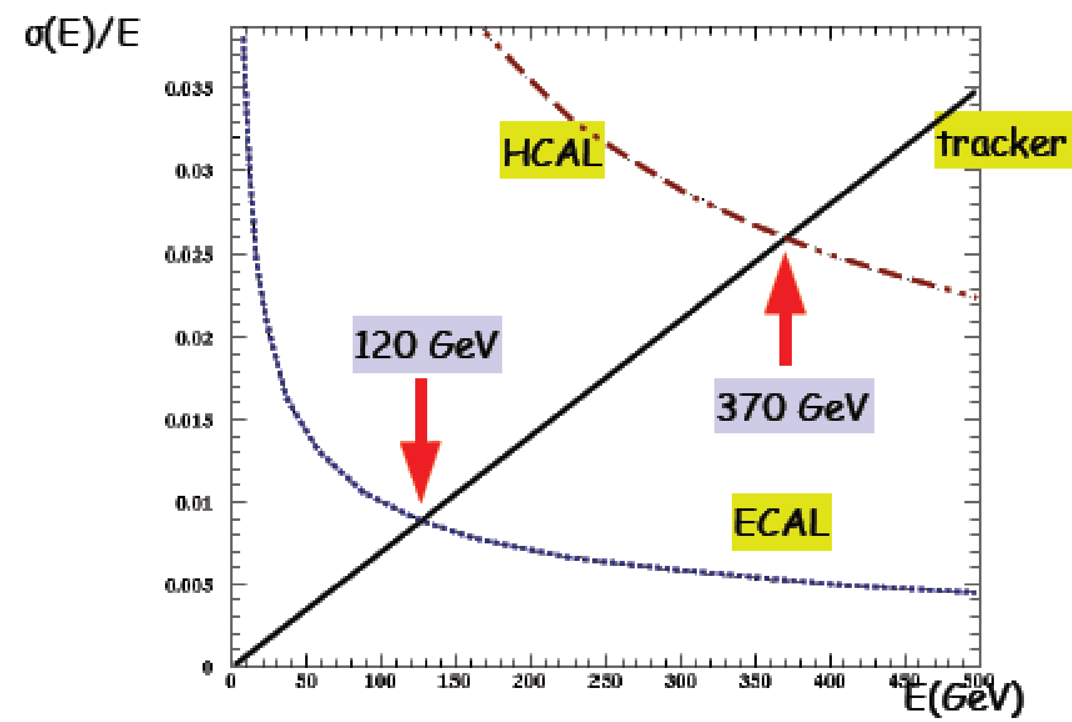
- Typical jet:
  - 65% visible jet energy from charged hadrons
  - 25% photons (from $\pi^0 \rightarrow \gamma\gamma$)
  - 10% neutral hadrons
- Traditional approach:
  - measure total visible jet energy in ECAL and HCAL
  - Problem: large fluctuations



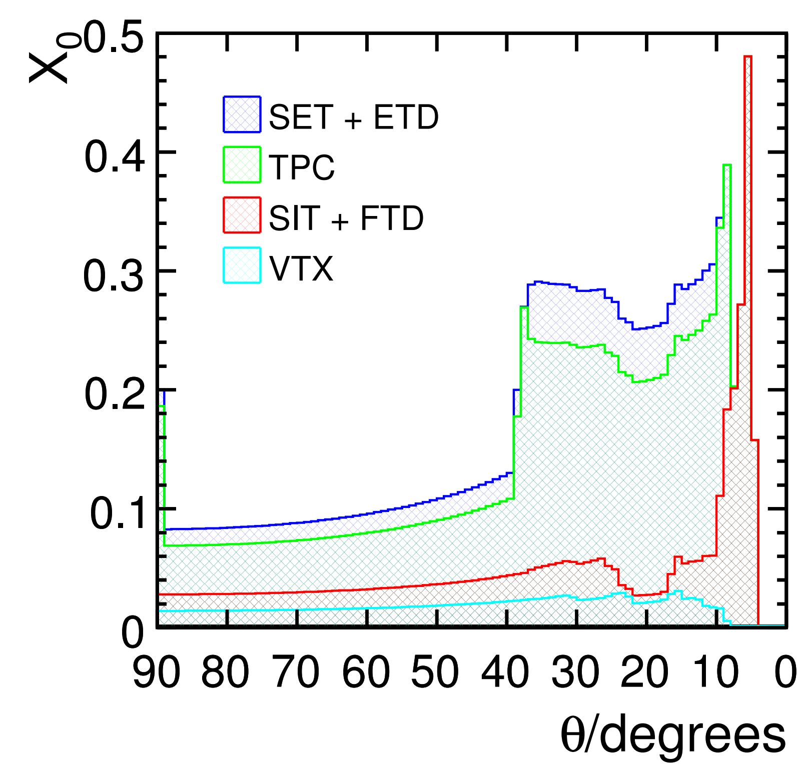


The Particle Flow Concept

- Idea: use the sub-detector with the best resolution for the energy measurement!
- Charged particles: tracking system
- Photons: ECAL
- Neutral Hadrons: HCAL



- Avoid double counting!
  - Trace every single particle through the detector

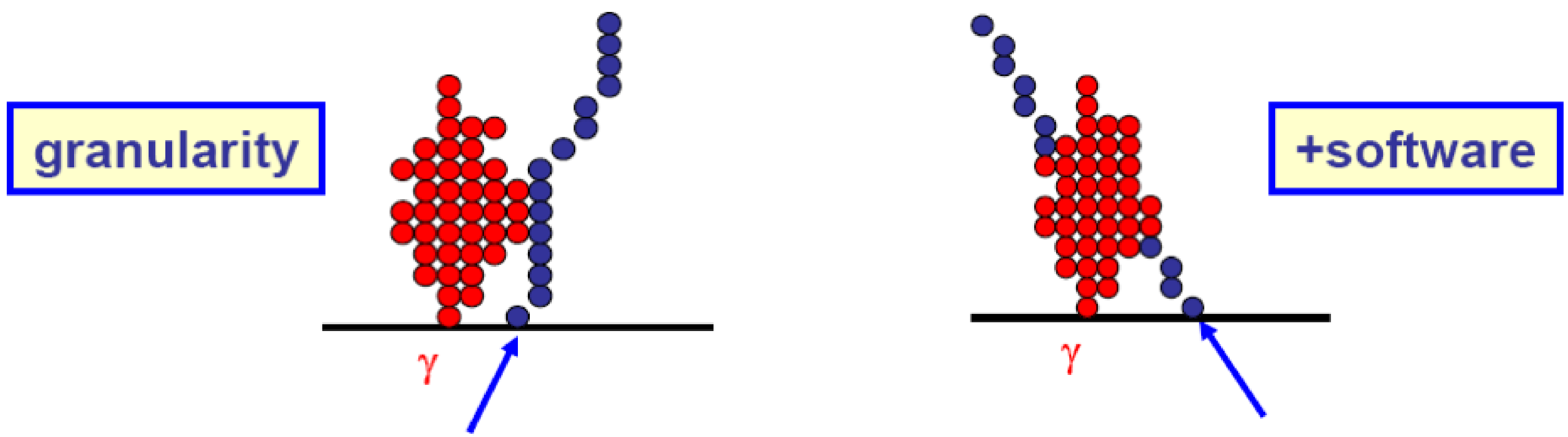


- $E_{jet} = E_{charged} + E_{photons} + E_{neutral\ hadr.}$
- $\sigma^2(E_{jet}) = \sigma^2(E_{charged}) + \sigma^2(E_{photons}) + \sigma^2(E_{neutral\ hadr.}) + \sigma^2_{confusion}$

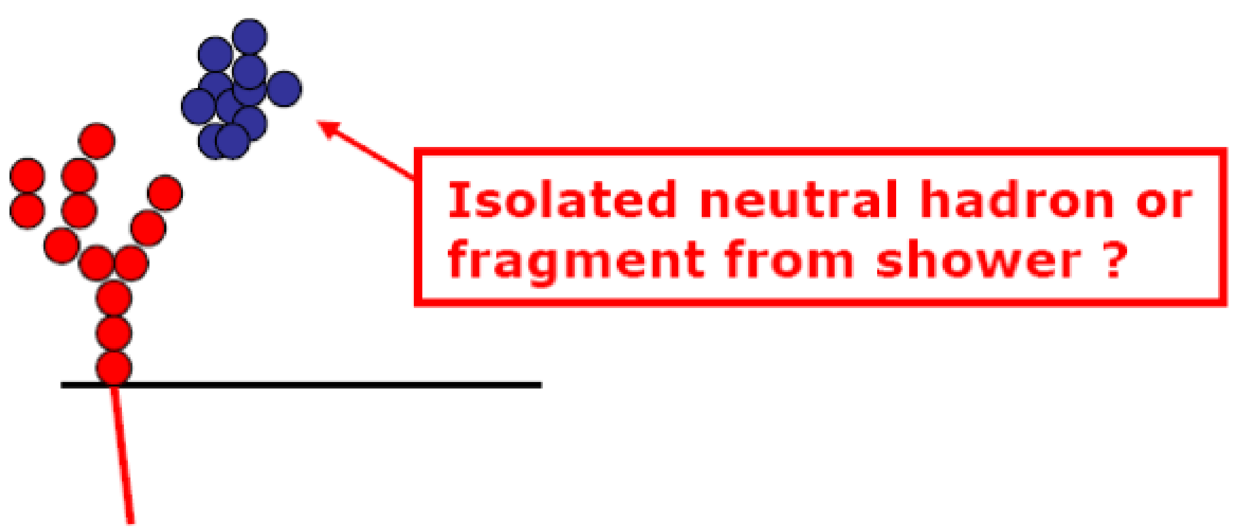
Particle Flow Challenge

Separate energy deposits and avoid double counting

Example: need to separate “tracks” (charged hadrons) from photons

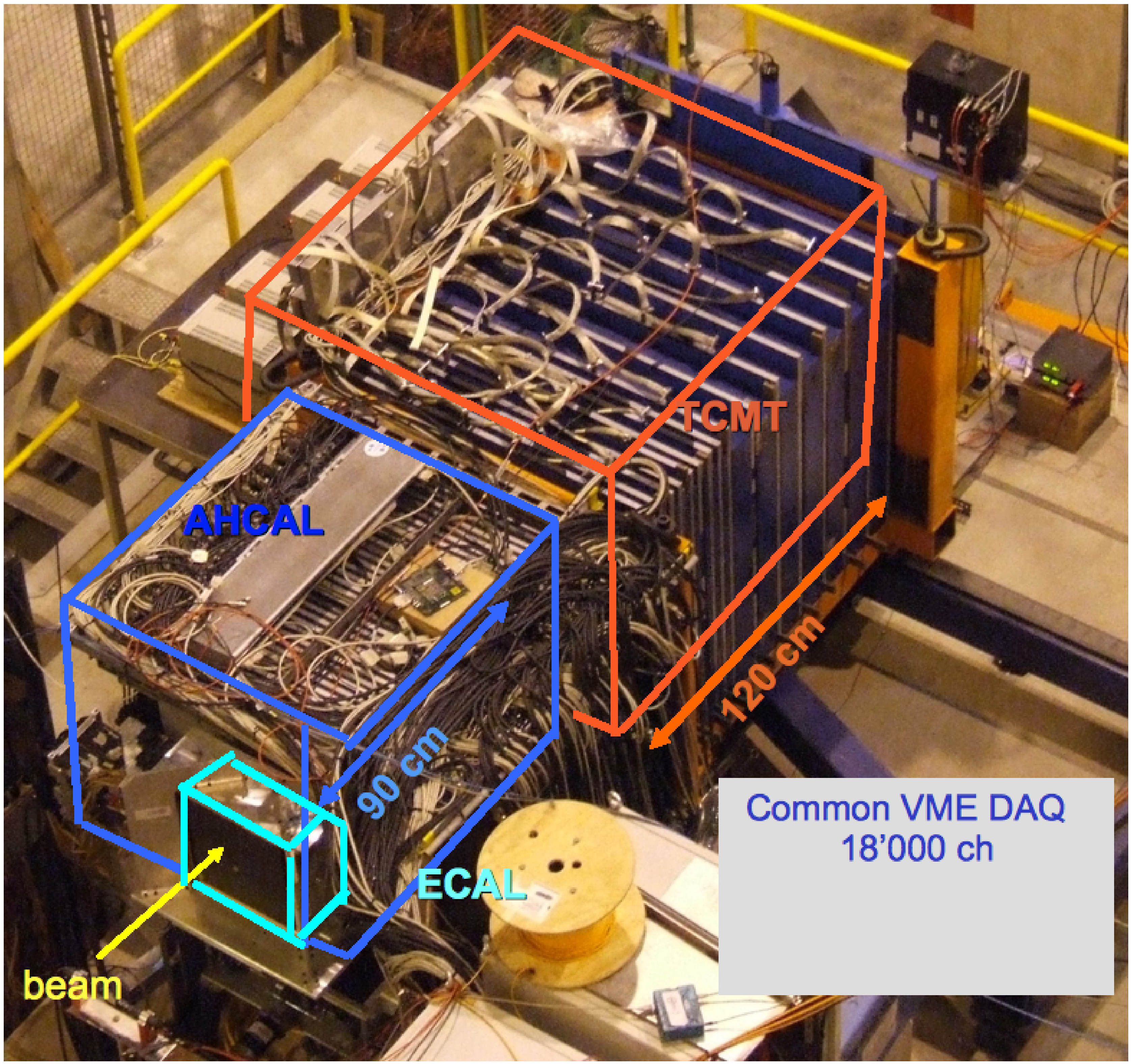


Need to separate neutral hadrons from charged hadrons

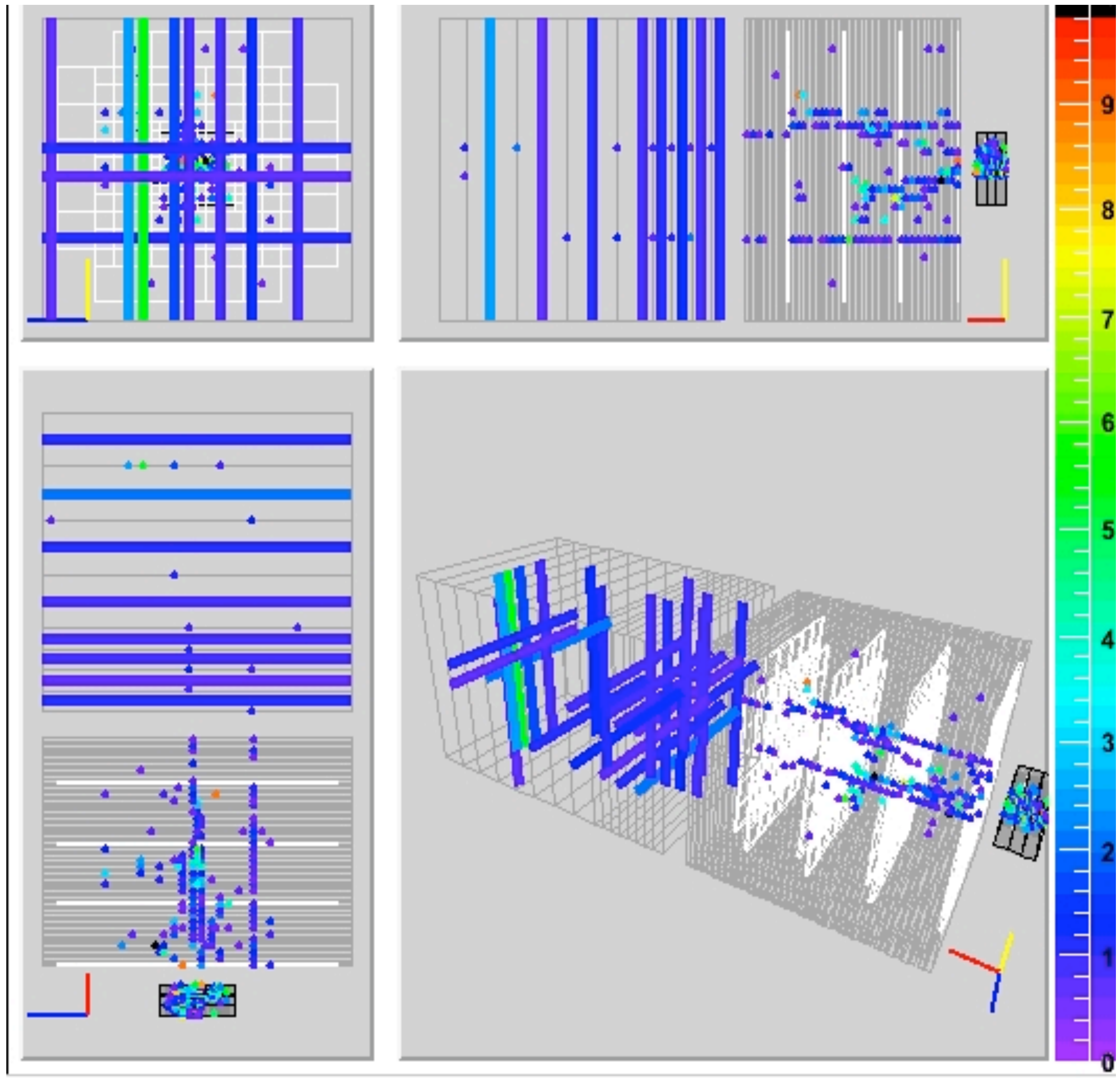


Granularity helps
But less clear…

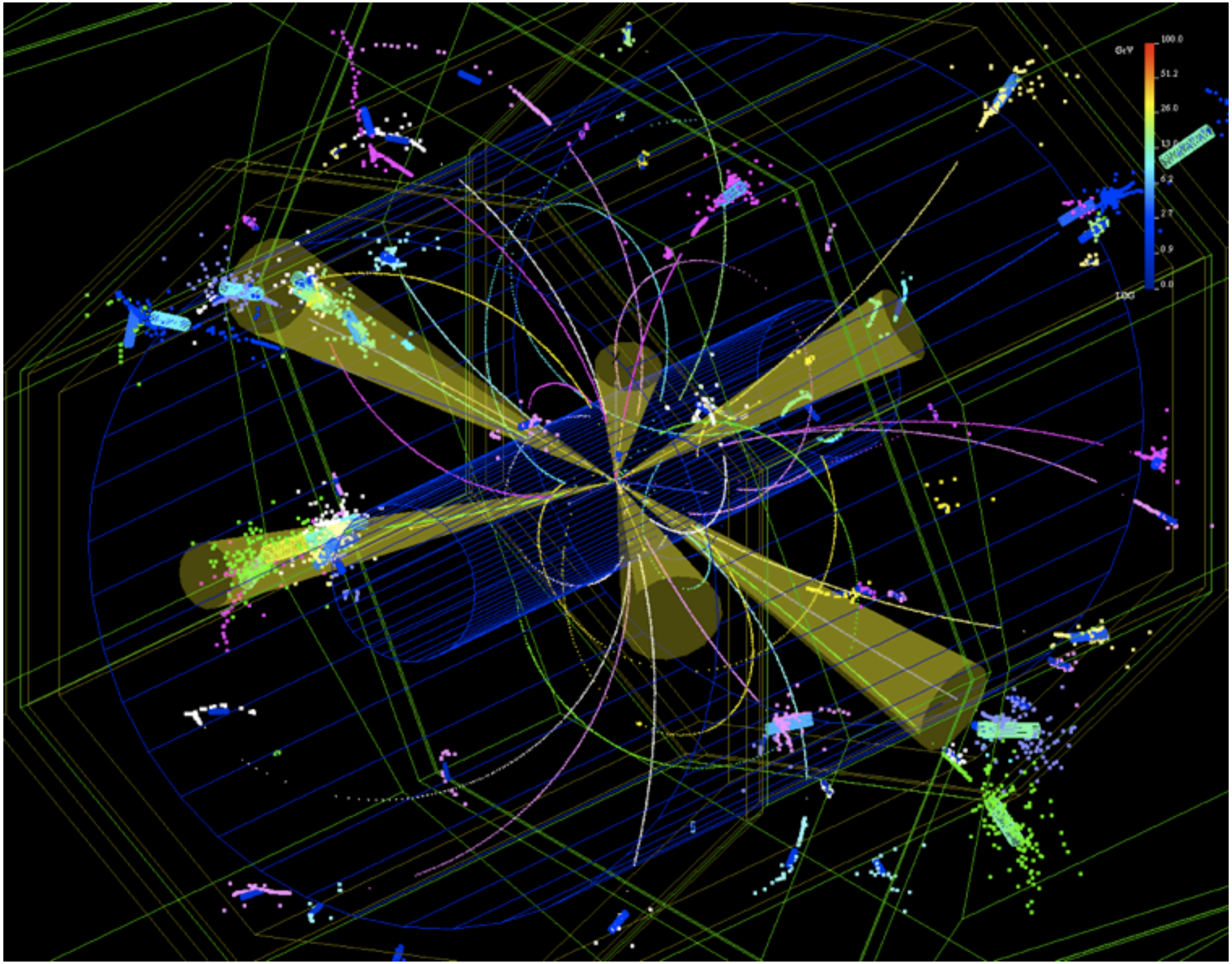
Calorimetry: Integrated Testbeam Experiments



Testbeam Experiments: Imaging Calorimetry

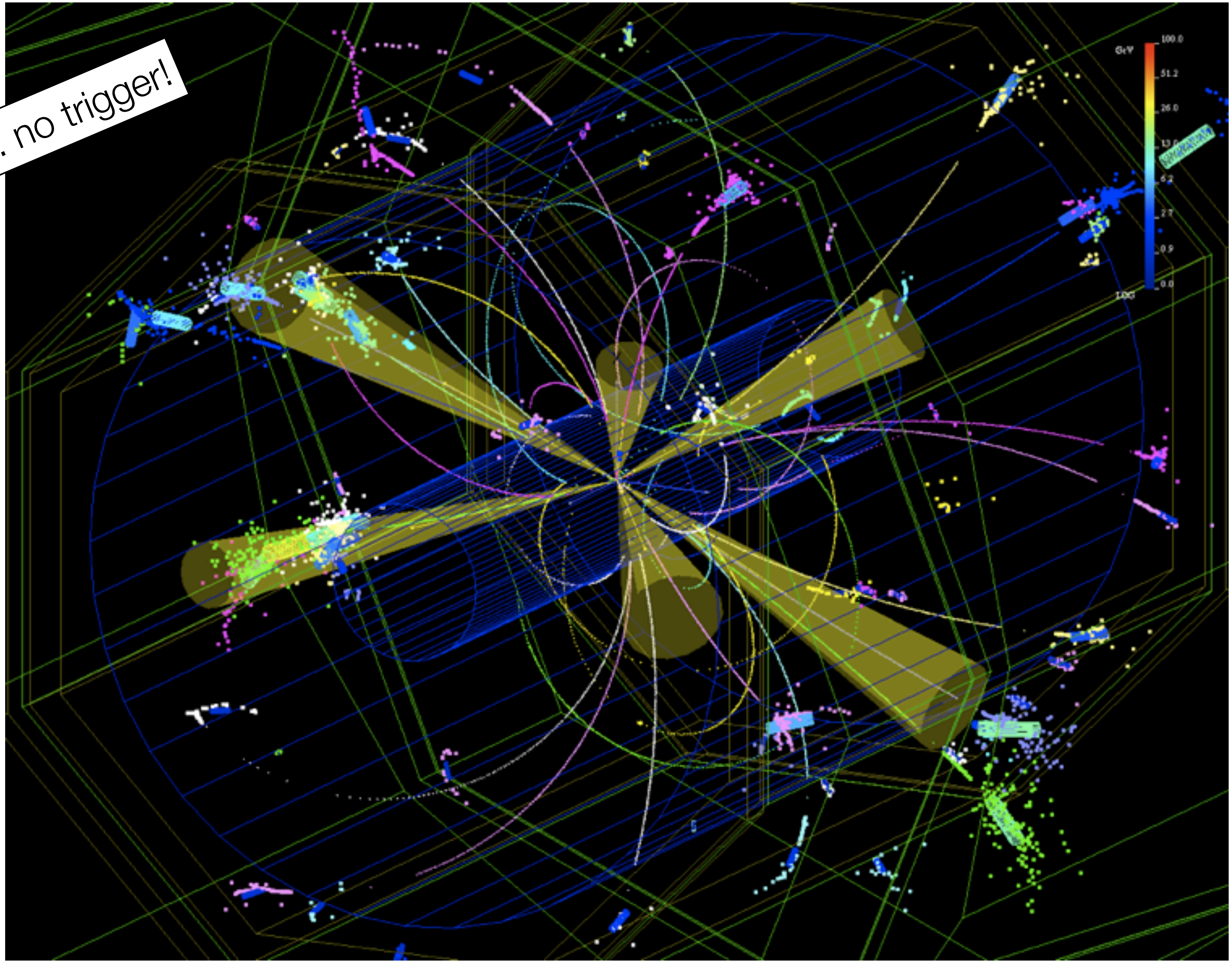


Imaging Detector

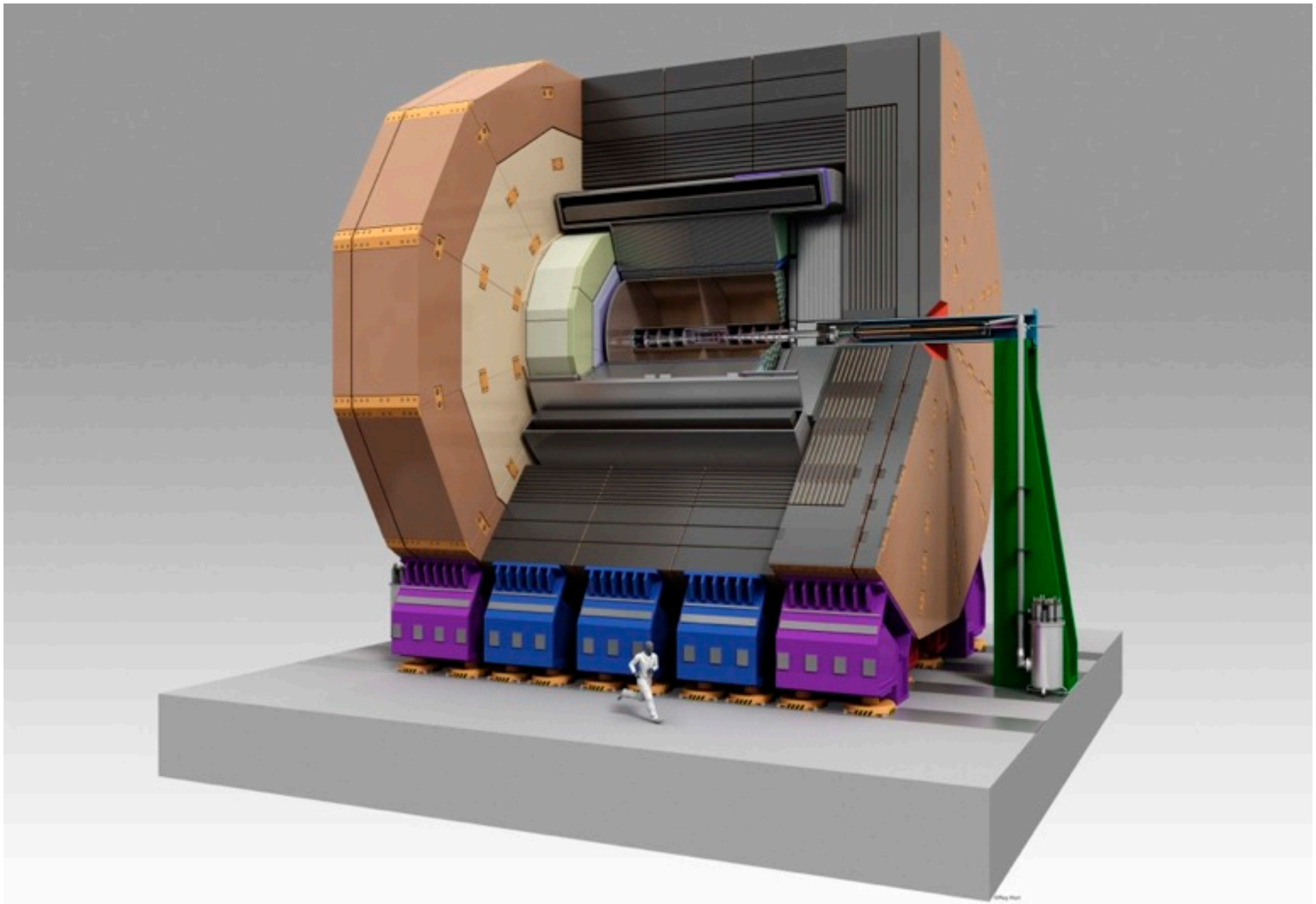


Imaging Detector

btw: no trigger!



ILD Detector



The Global Context

Timeline

- Physics will decide the way forward!
  - LHC will tell us which energy reach will be needed

- Years 2012+ provide the basis for decision:
  - ILC, CLIC, LHC-Upgrades, something completely different?
  - European Strategy Process 2012 (and similar in Asia and Americas)

The Staged Linear Collider

- In principle, the ILC can run on any energy between ~90 GeV and several TeV
  - linear colliders are scalable, it is only a question of cost....
- Why not develop a staged approach
  - start where interesting physics is guaranteed, extend to higher energies later

- ILC$_{250}$: Higgs measurements (mass, spin, couplings), EW physics, (...)
- ILC$_{350}$: Top physics, (...)
- ILC$_{500}$: Higgs self coupling, Top-Higgs Yukawa coupling, (...)
- ILC$_{1000+}$: SUSY, whatever comes, (...)

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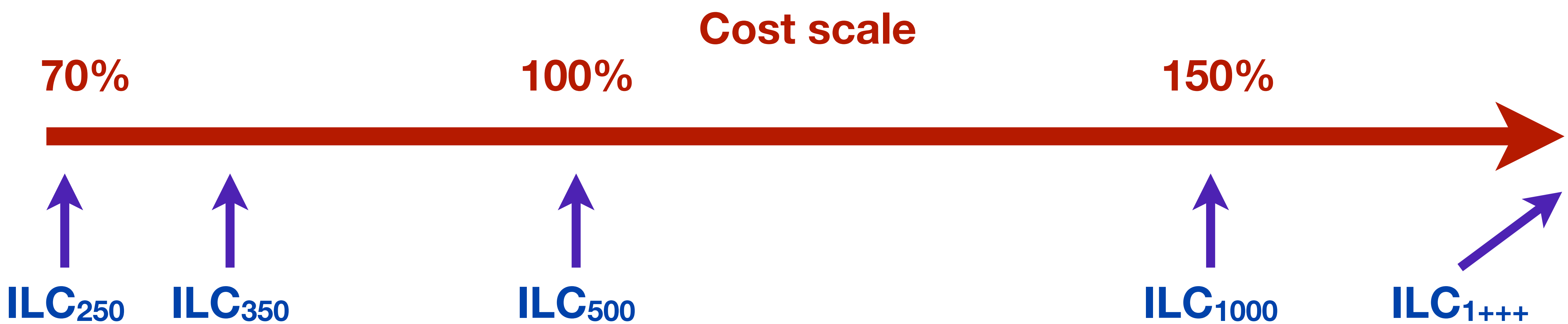


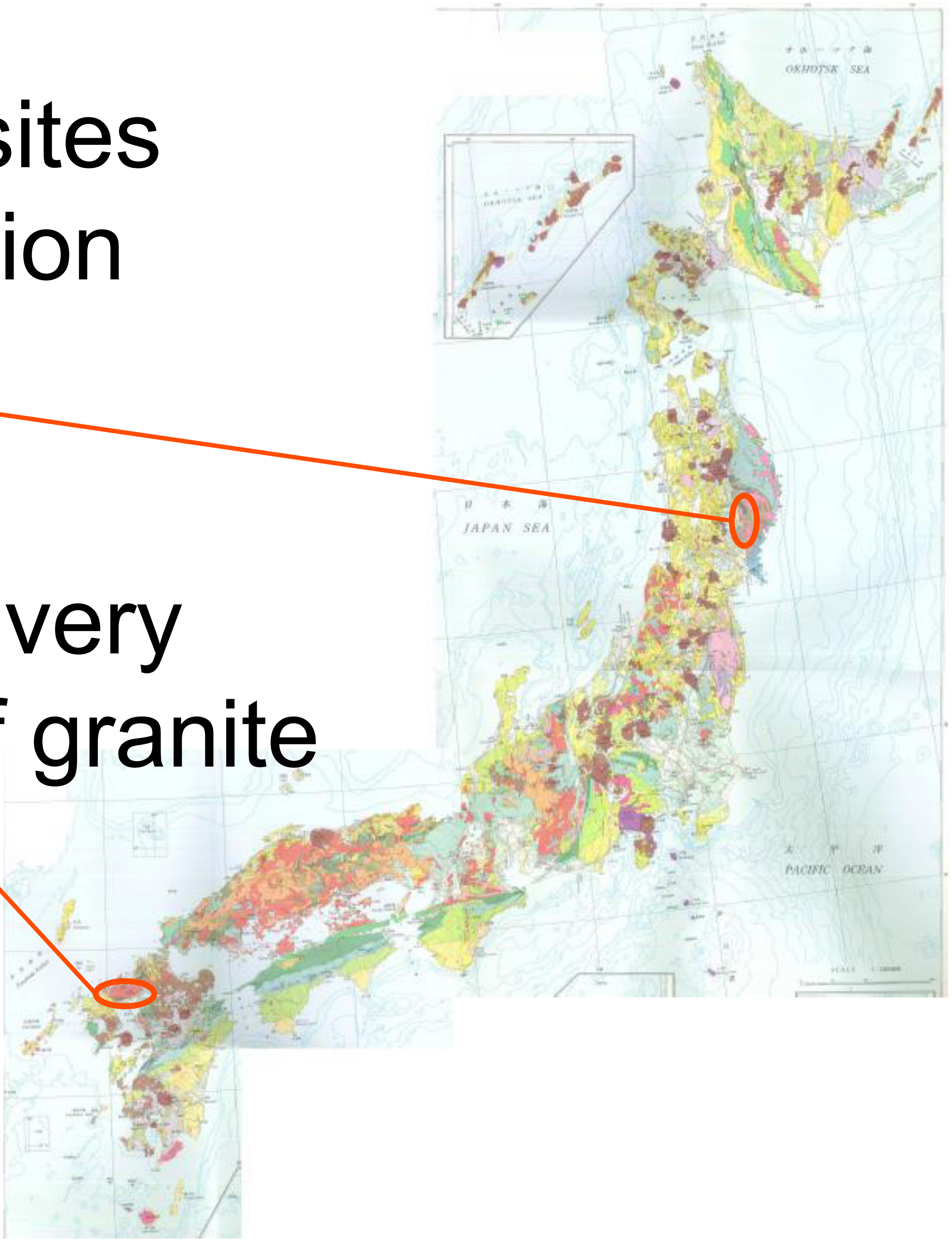
- ILC$_{250}$: Higgs measurements (mass, spin, couplings), EW physics, (...)
- ILC$_{350}$: Top physics, (...)
- ILC$_{500}$: Higgs self coupling, Top-Higgs Yukawa coupling, (...)
- ILC$_{1000+}$: SUSY, whatever comes, (...)

Where will it be built?

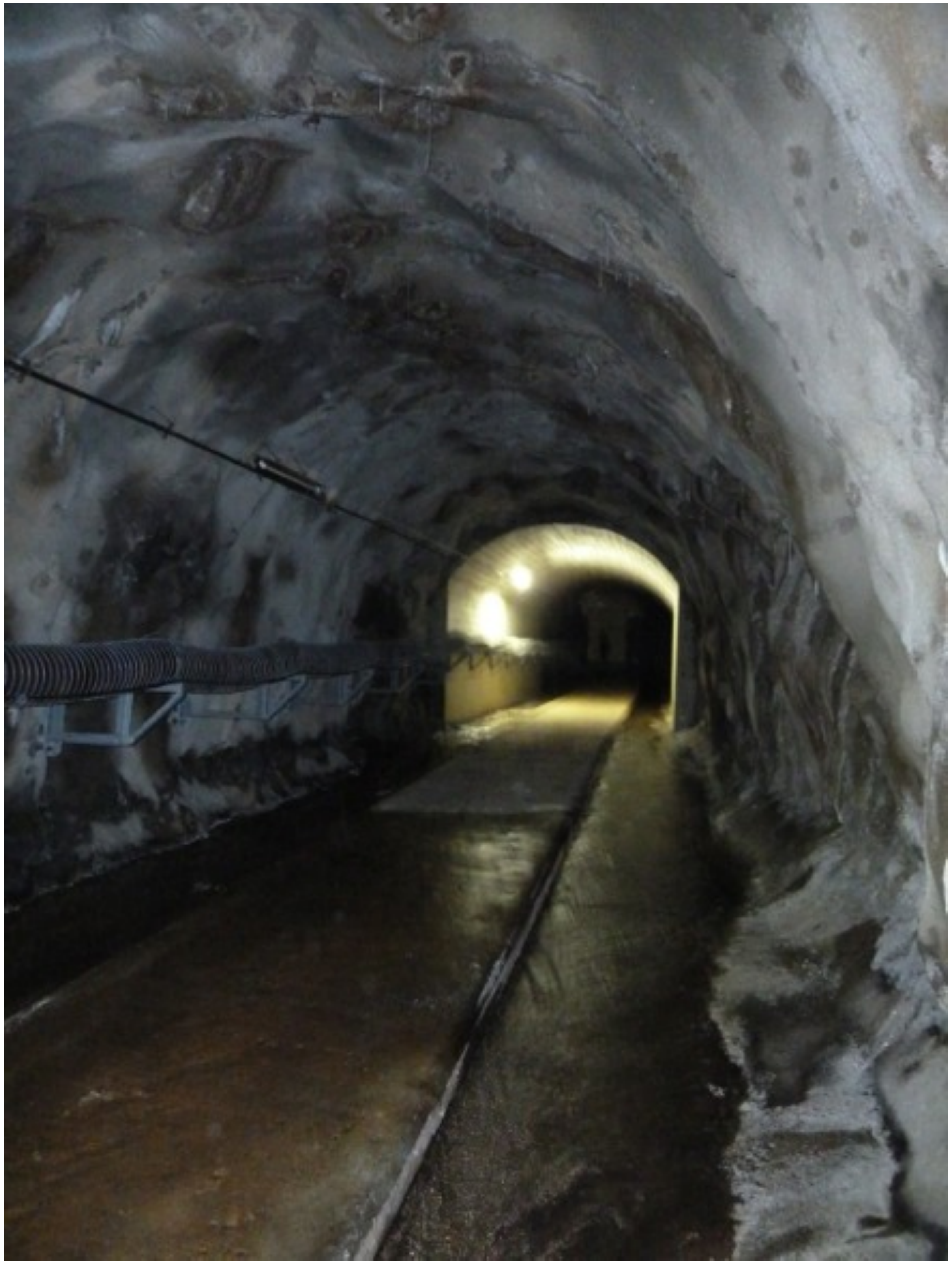
- Site decision will be a political decision...
- Different sample sites under study
  - Americas (Fermilab)
  - Europe (CERN)
  - Asia (Japan, 2 sites)
- All very different in topology, geology, culture

Japanese candidate sites

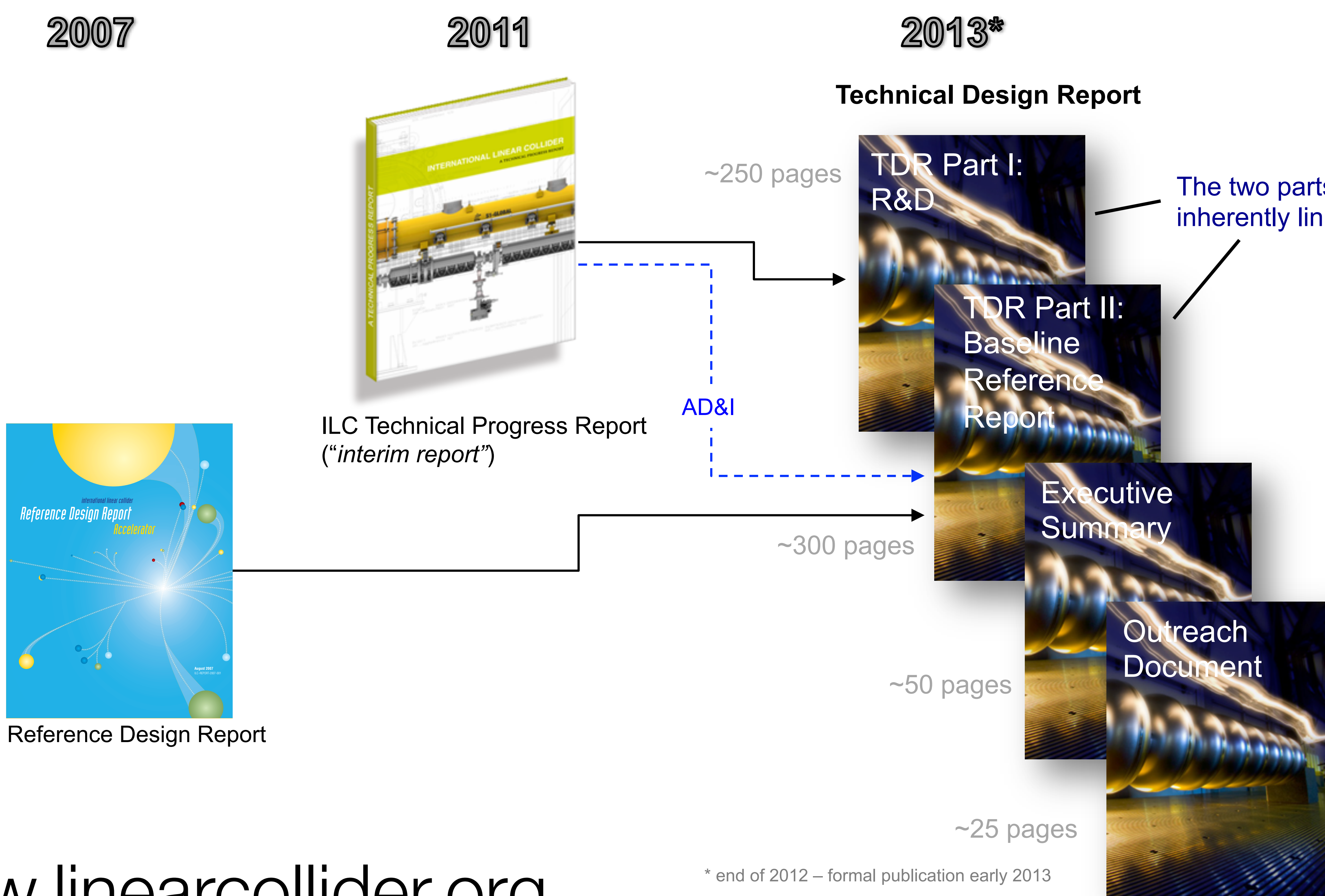
- Two candidate sites under investigation
  - Kitakami
  - Sefuri
- Both sites have very good geology of granite



Sefuri Mountain



ILC Technical Design Report (in preparation)



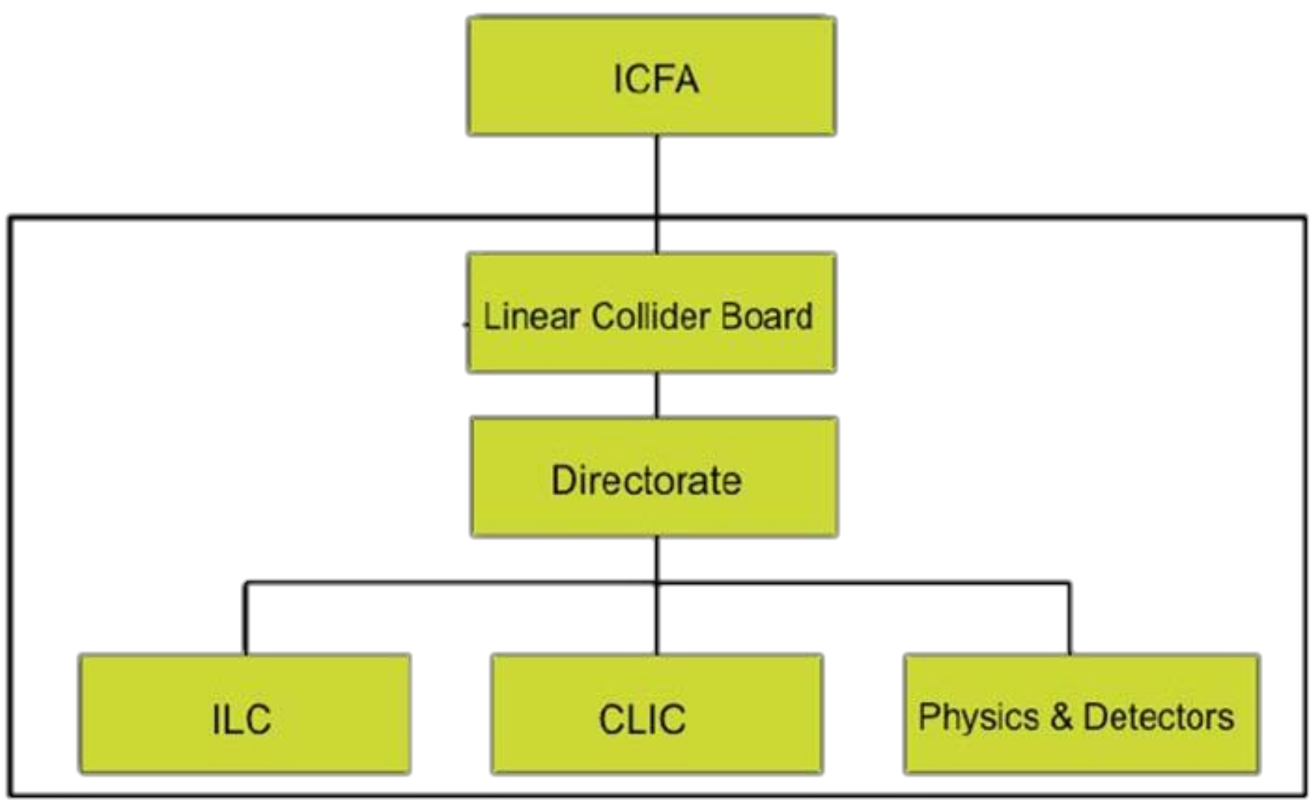
www.linearcollider.org

The Cost

- Costing is a very complicated exercise in a global project....
- Reference Design Report (2007) cost estimate:
  - 6.62 BILCUs (1 ILCU = 1 US$ in 2007)
  - 24 Mh person labour
- Cost will be updated for Technical Design Report (2013):
  - much better knowledge about industrialisation issues
  - lessons from XFEL realisation
  - better understanding of site dependent cost
  - use of purchase power parity approaches
  - will not be higher than the RDR cost....

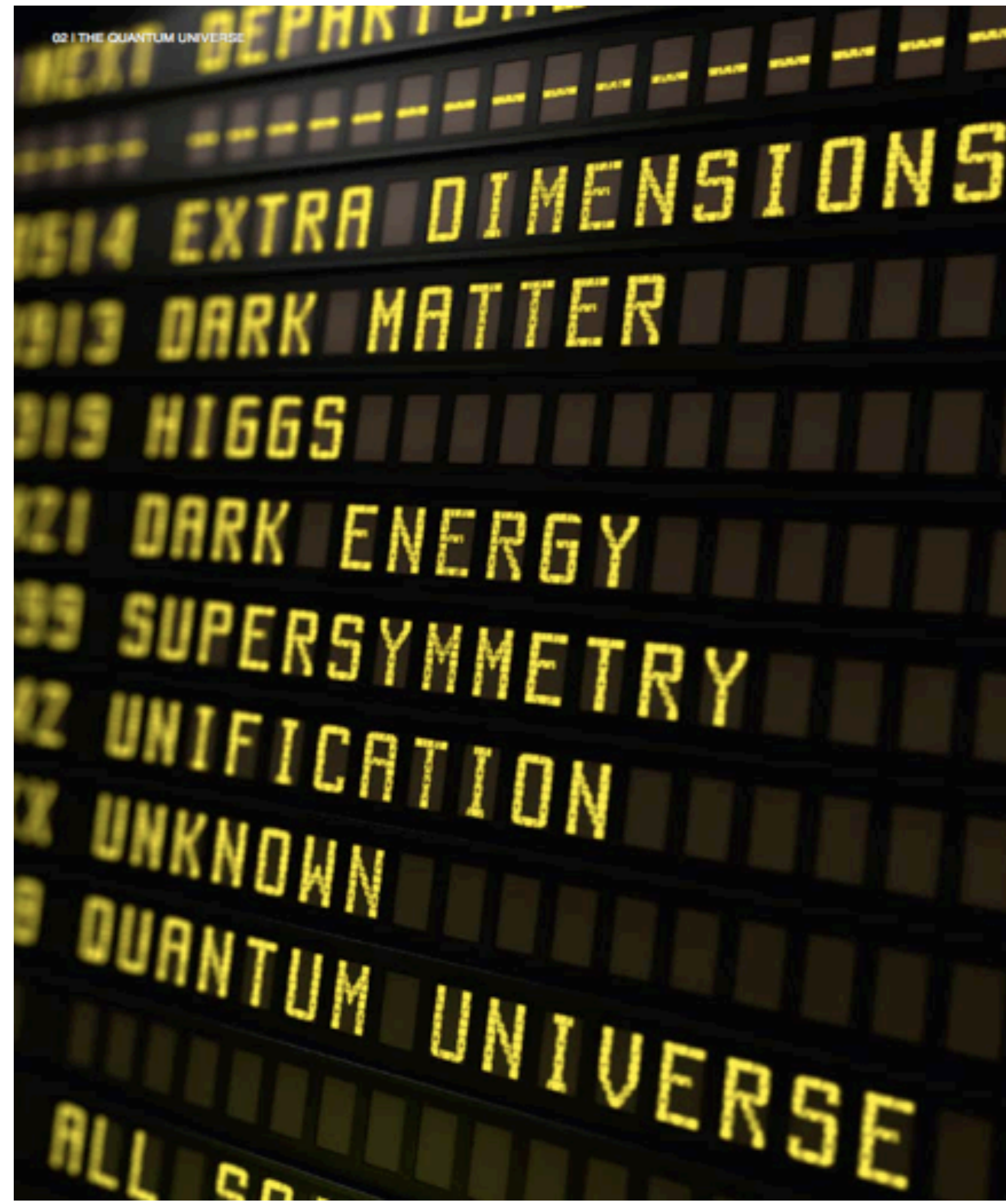
The Linear Collider Project

- The ILC is the most advanced future project for research at the energy frontier
- CLIC is a possible high-energy option
  - International project teams: ILC Global Design Effort and CLIC collaboration
  - Joint effort of all leading accelerator labs
- New organisation under the supervision of ICFA: the Linear Collider
  - director: Lyn Evans



Conclusion

- LHC will need to be complemented by an e^+e^-- collider for precision measurements
- LHC has established the energy scale of the Higgs; this requires a $\sqrt{s}$~240 GeV e^+e^--collider, minimum
- ILC is the most advanced collider design and ready for construction
  - 20 year history of system R&D
- CLIC could be a high-energy option
  - on a longer timescale though...
- Machine and experiments demand high-tech solutions on yet untested scales



International Linear Collider - Artist‘s View

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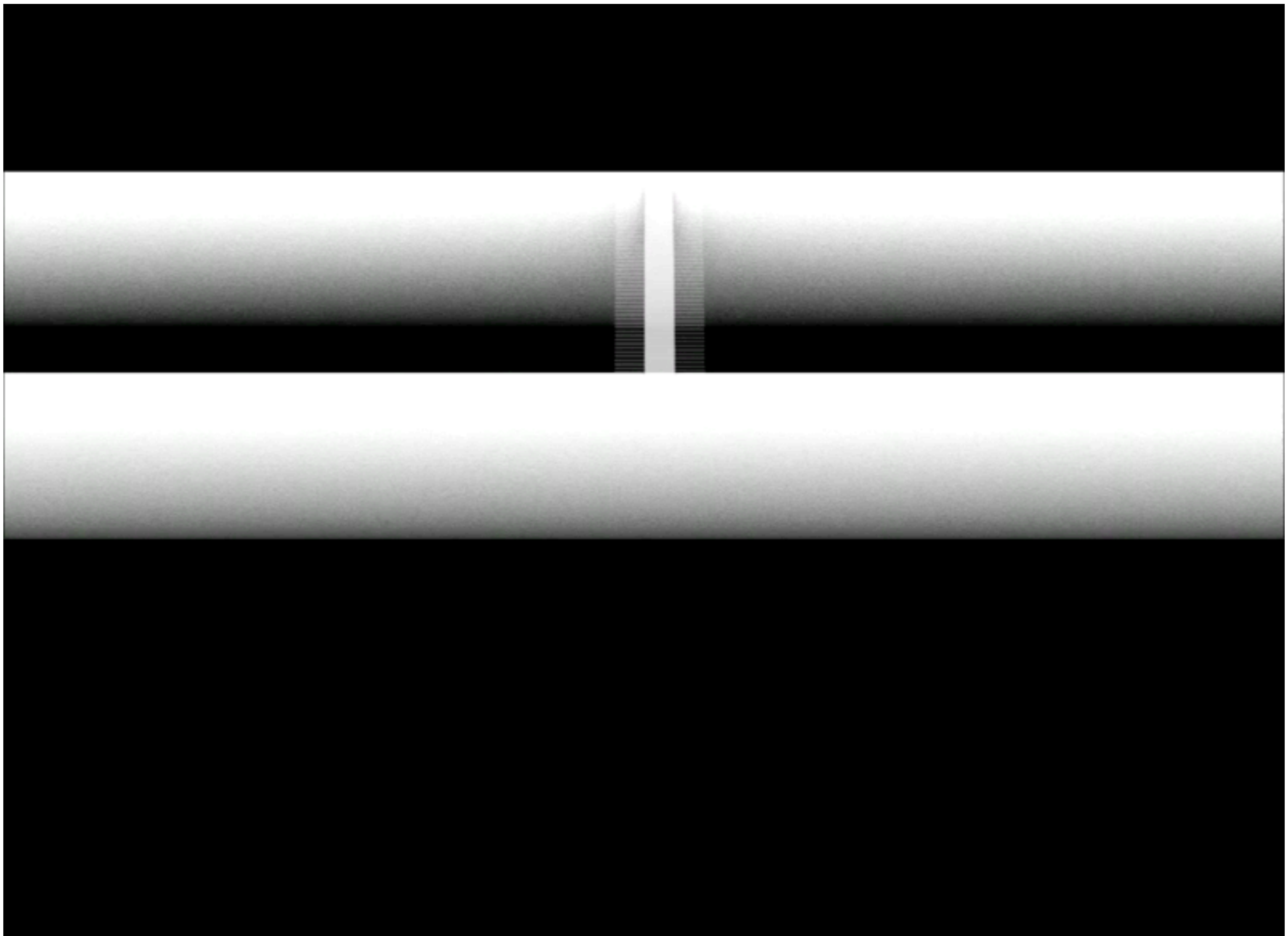
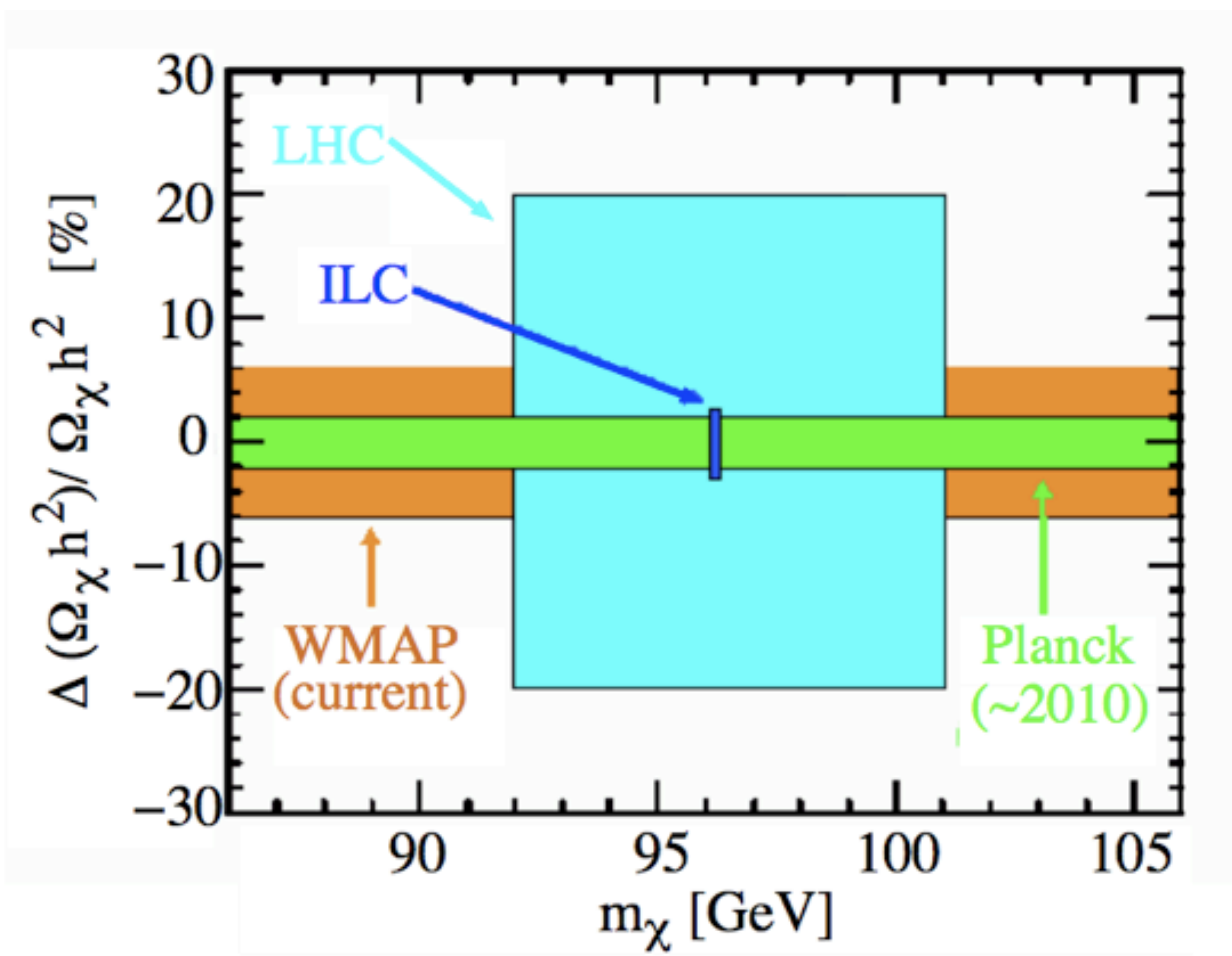


Backup Slides

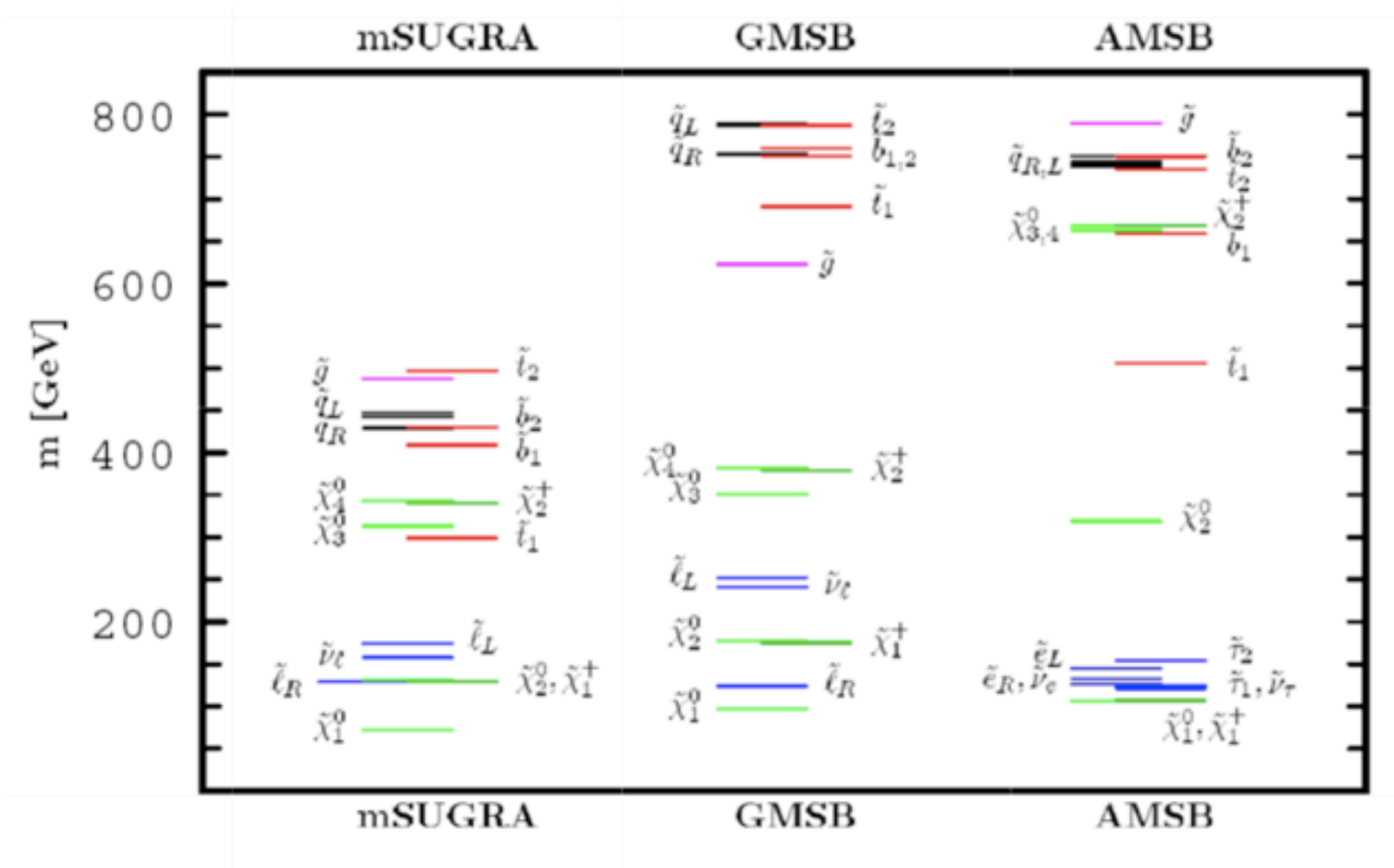
The Cosmological Connection

- Could SUSY particles be the Cold Dark Matter?
- Astrophysics experiments measure just densities
- ILC could close the loop



SUSY Spectrometry

- If SUSY exists, it has to be a broken symmetry
- Symmetry breaking mechanisms predict different SUSY particle spectra

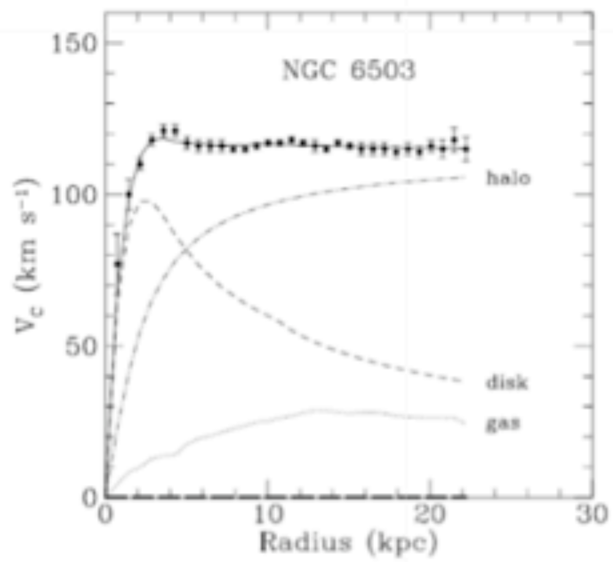


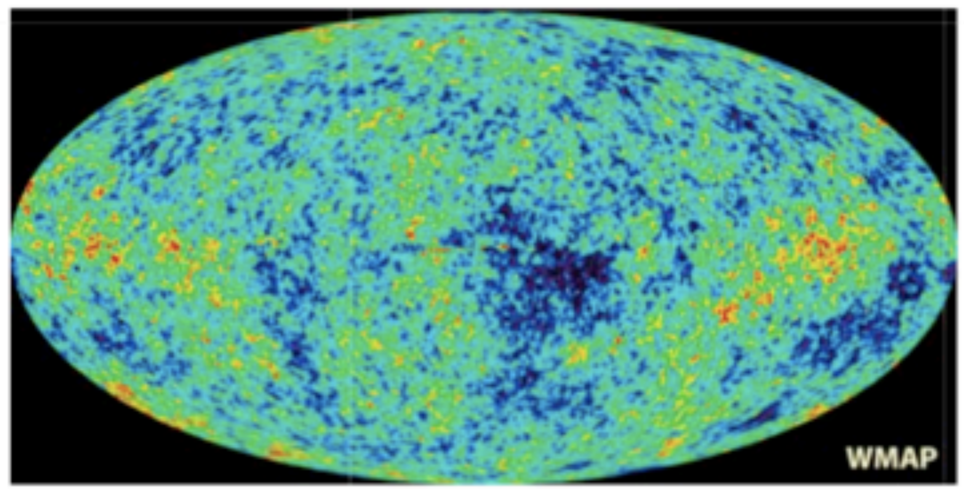
Shortcomings of the Standard Model

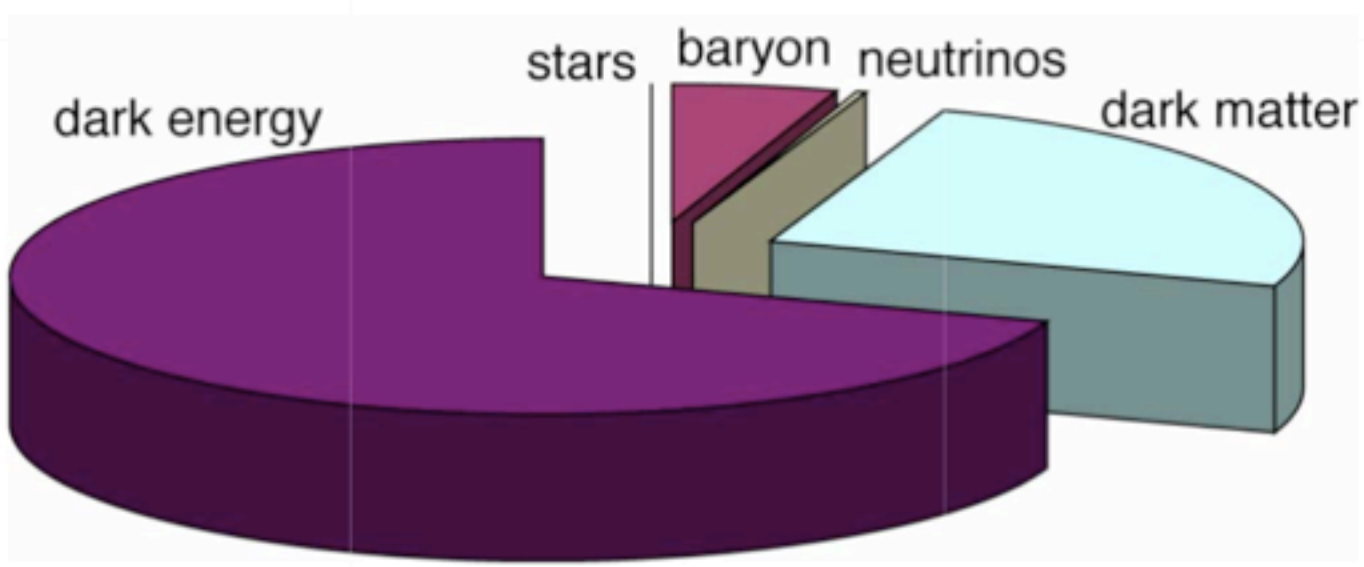
- The Standard Model leaves open questions:
  - Do the forces unite?
  - Why are there three generation of particles?
  - Why are there 19 free parameters?
  - Why do the electric charges of electrons and protons cancel exactly?
  - What is the origin of Dark Matter and Dark Energy?
  - (...)

- We are looking for an underlying unifying theory of everything!

Dark Matter and Dark Energy







composition of universe
from WMAP measurement:

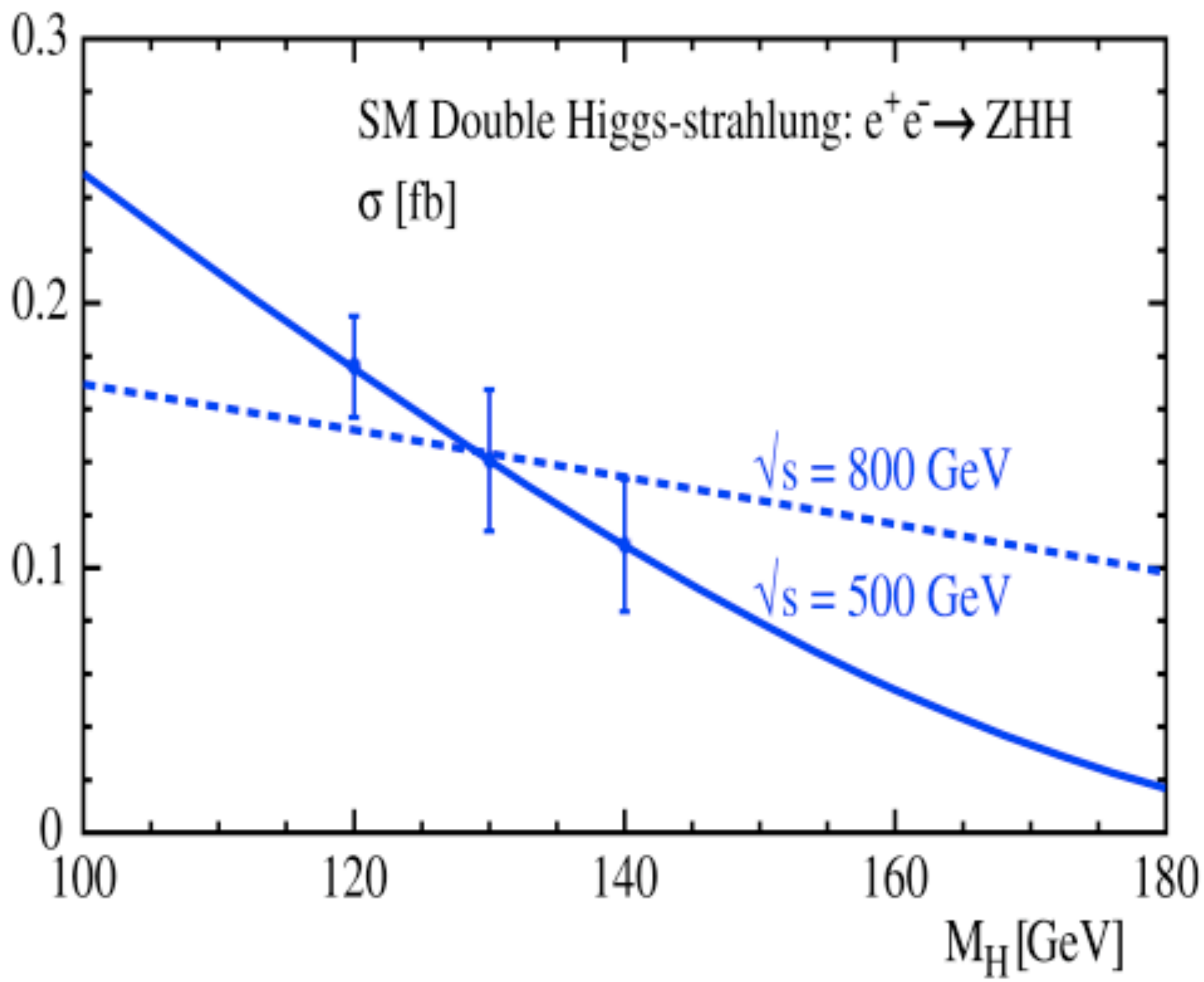
4 %   SM matter

23 % dark matter

73 % dark energy

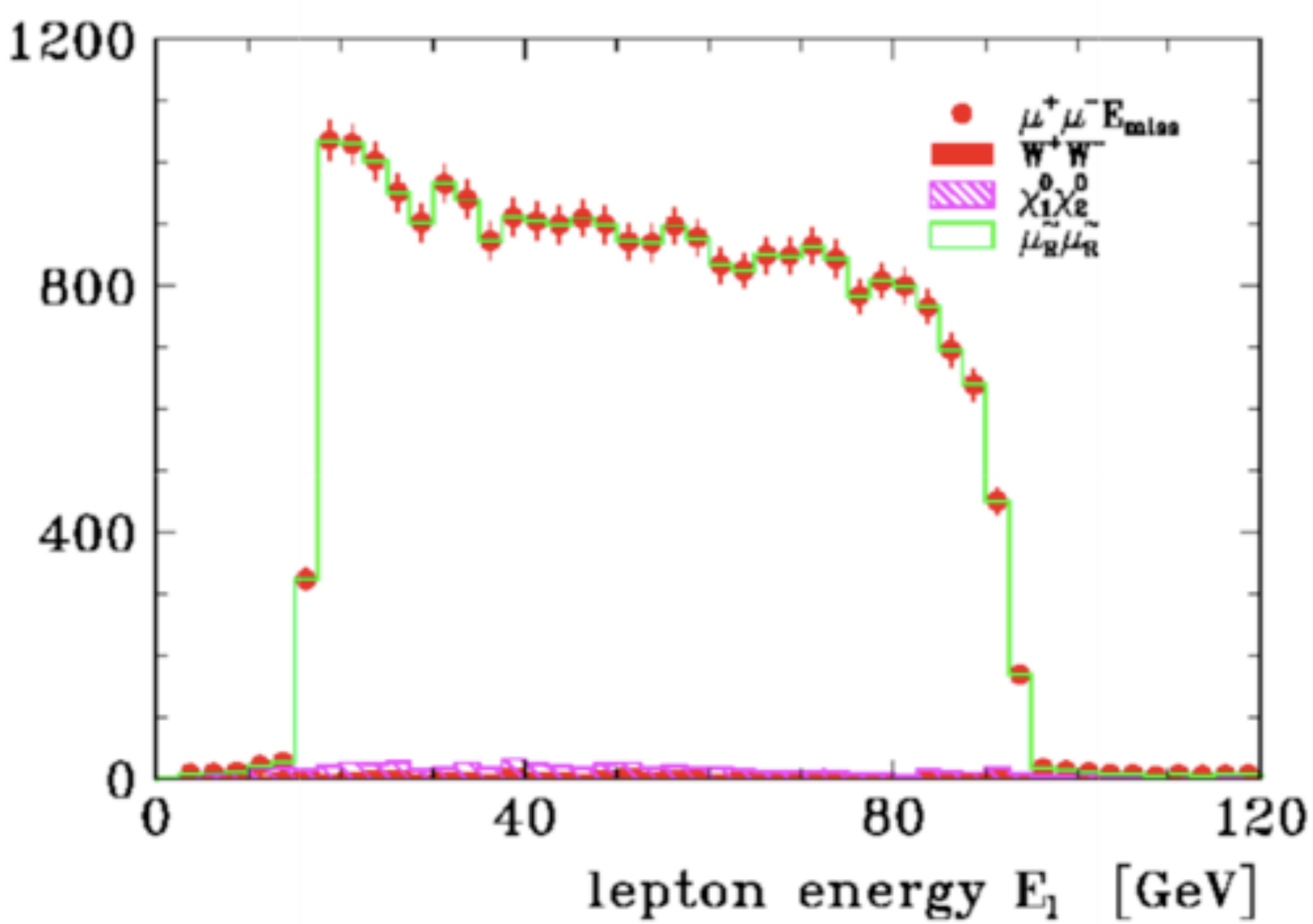
Higgs Self-Coupling

- Measure $e^+e^- \rightarrow ZHH$



SUSY Mass Measurements

- SUSY particles would be produced in pairs at the ILC, e.g. $e^+e^- \rightarrow \tilde{\mu}^+\tilde{\mu}^- \rightarrow \mu^+X_1^0\, \mu^-X_1^0$
- Detector Signature: two muons, lots of missing energy
- Masses of the smuons and neutralinos can be accessed by using kinematics

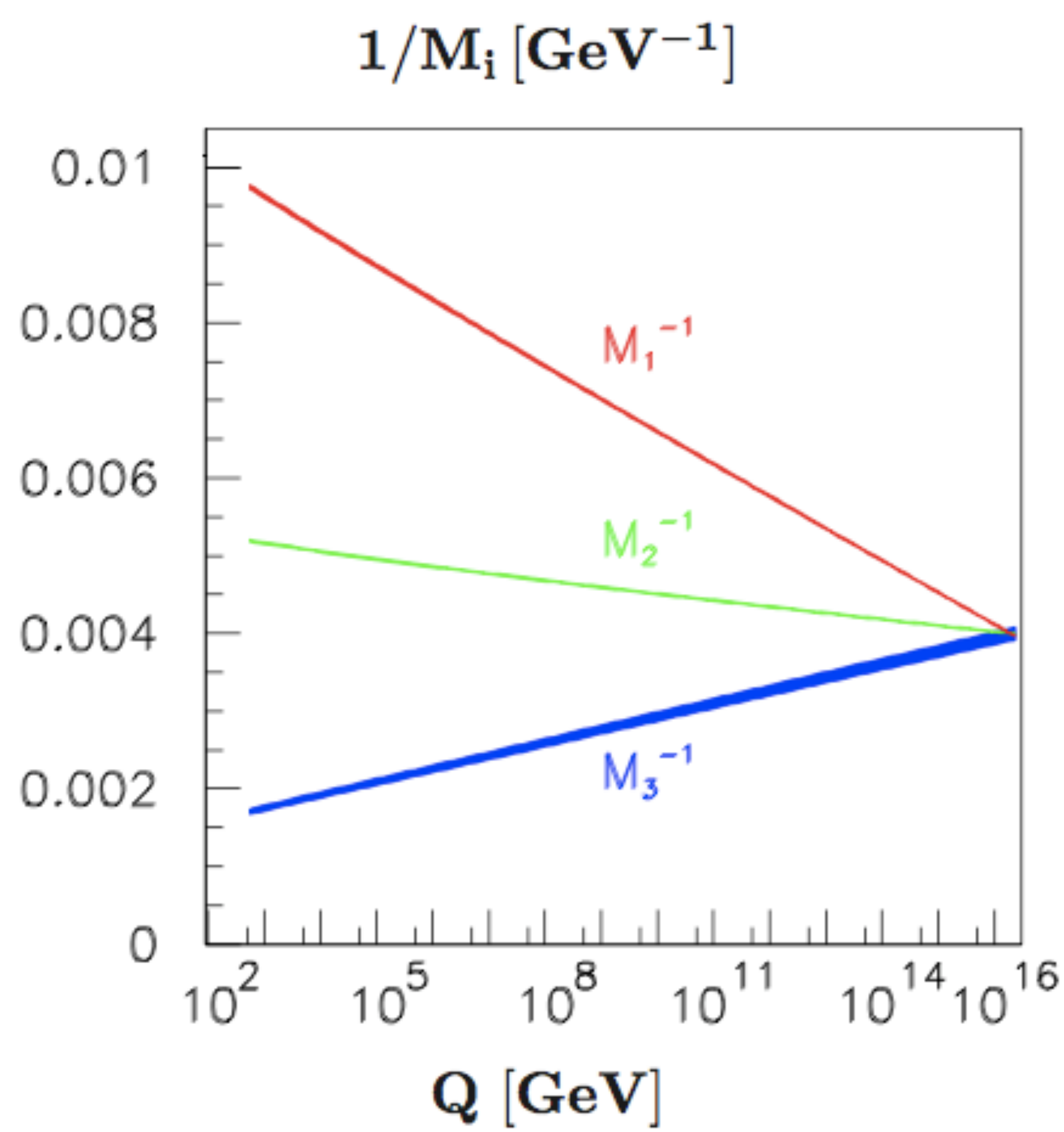


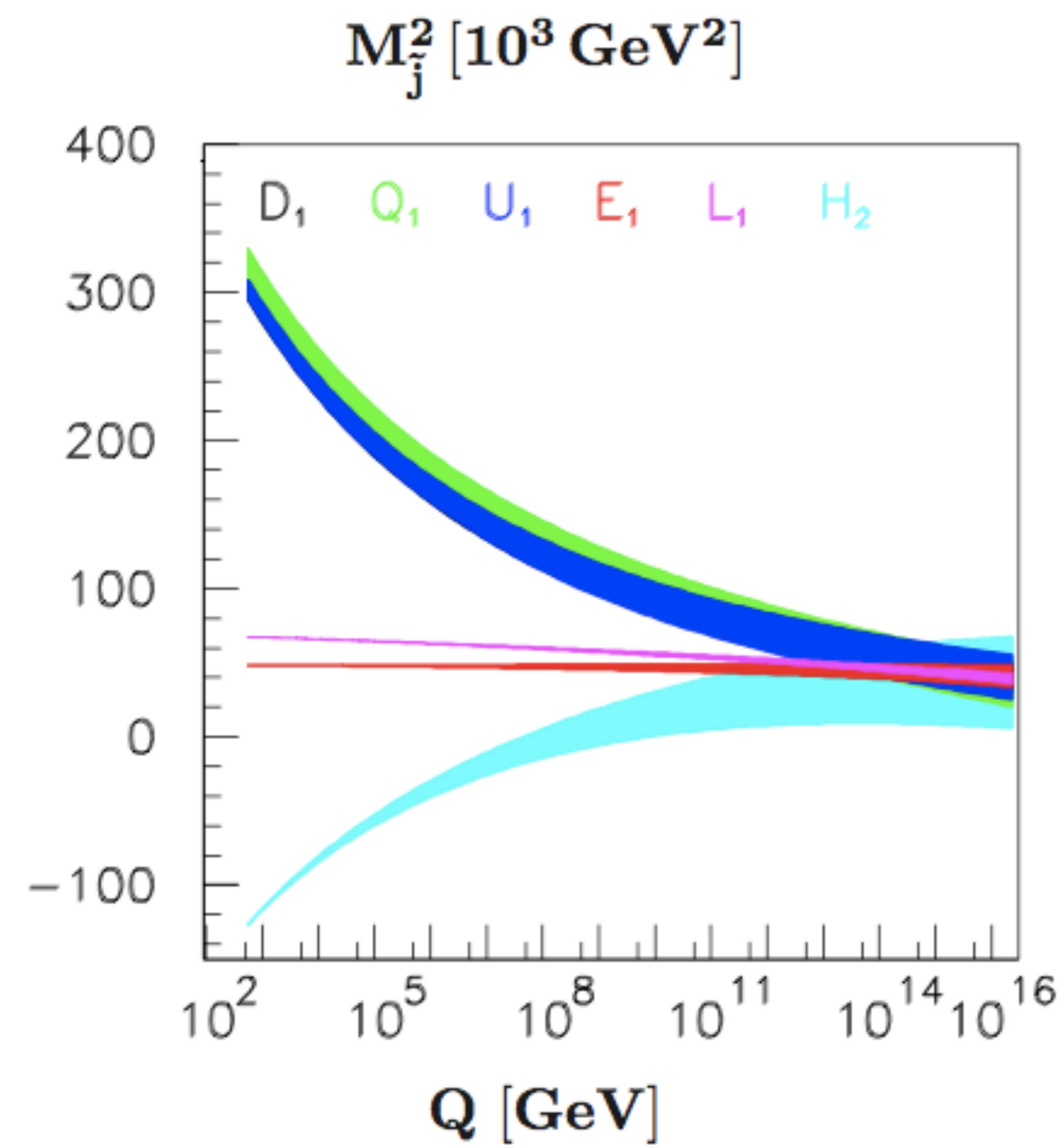
$$m_{\tilde{l}} = \frac{\sqrt{s}}{E_- + E_+}\sqrt{E_- E_+}$$

$$m_{\tilde{\chi}} = m_{\tilde{l}}\sqrt{1 - \frac{E_- + E_+}{\sqrt{s}/2}}$$

SUSY Mass Parameters

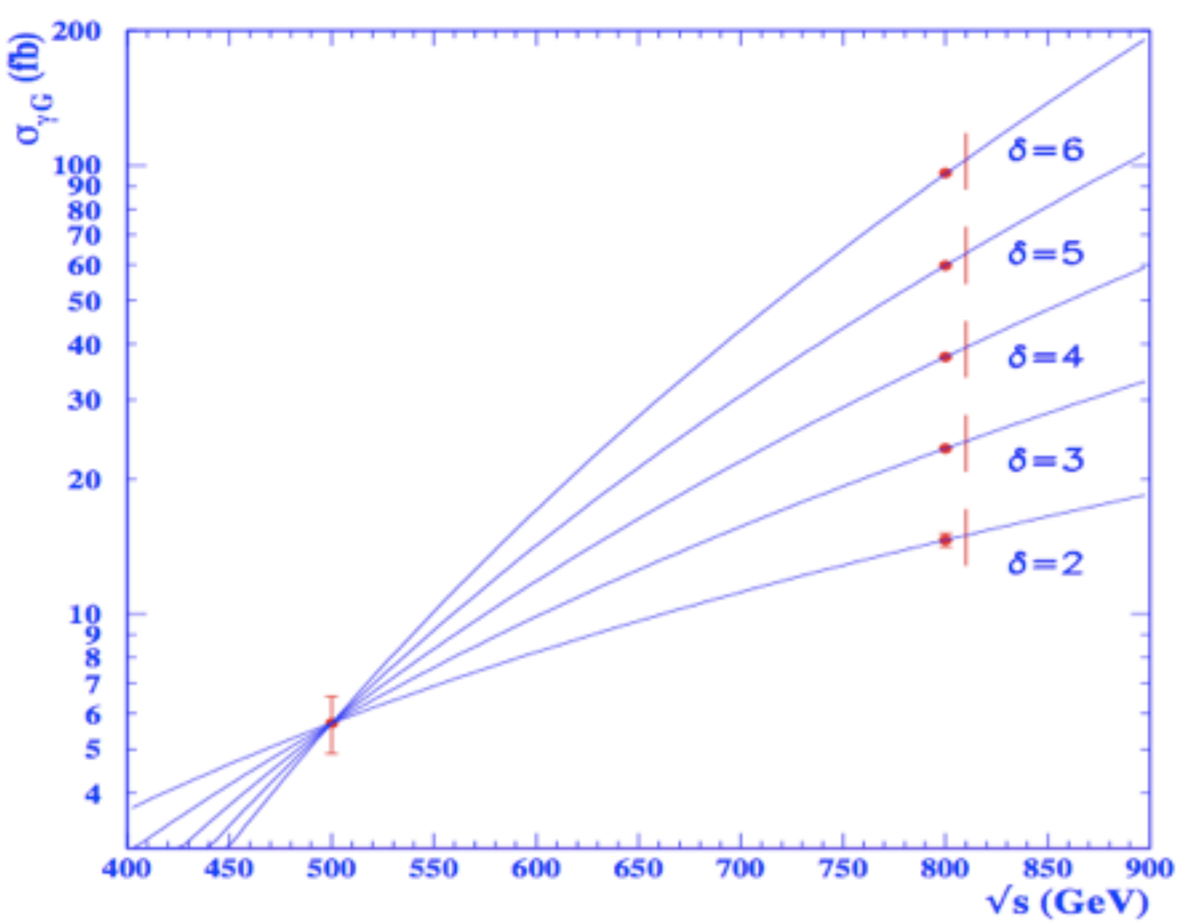
- Precision measurements at LHC and ILC make predictions up to GUT scale:

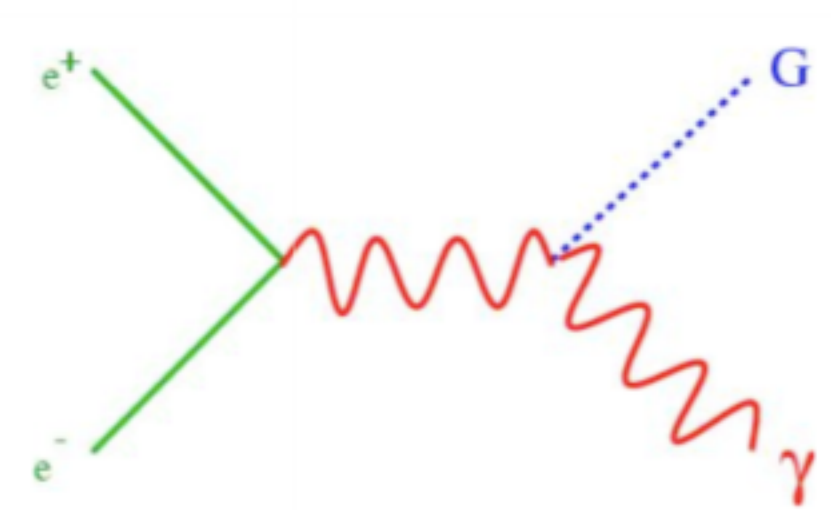




Large Extra Dimensions

- Why is gravity so weak?
- If extra-dimensions would exist, gravitons could escape into other dimensions
- Real graviton emission should be measurable
  - single photon plus missing energy in the detector





Luminosity Scaling Law

- Chose flat beam ($\sigma_y << \sigma_x$):

$$\frac{N}{\sigma_x} \propto \sqrt{\frac{\sigma_z \delta_{BS}}{E_{cm}}}$$

- Luminosity law:

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \left(\frac{N}{\sigma_x} \right) \frac{1}{\sigma_y}$$

- yields:

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \frac{\sqrt{\delta_{BS} \sigma_z}}{\sigma_y}$$

Maximising Luminosity

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \frac{\sqrt{\delta_{BS} \sigma_z}}{\sigma_y}$$

- high RF beam-power conversion efficiency η_{RF}
- high RF power P_{RF}
- small vertical beam size σ_y
- large bunch length σ_z
- high beamstrahlung δ_{BS}, if compatible with physics goals

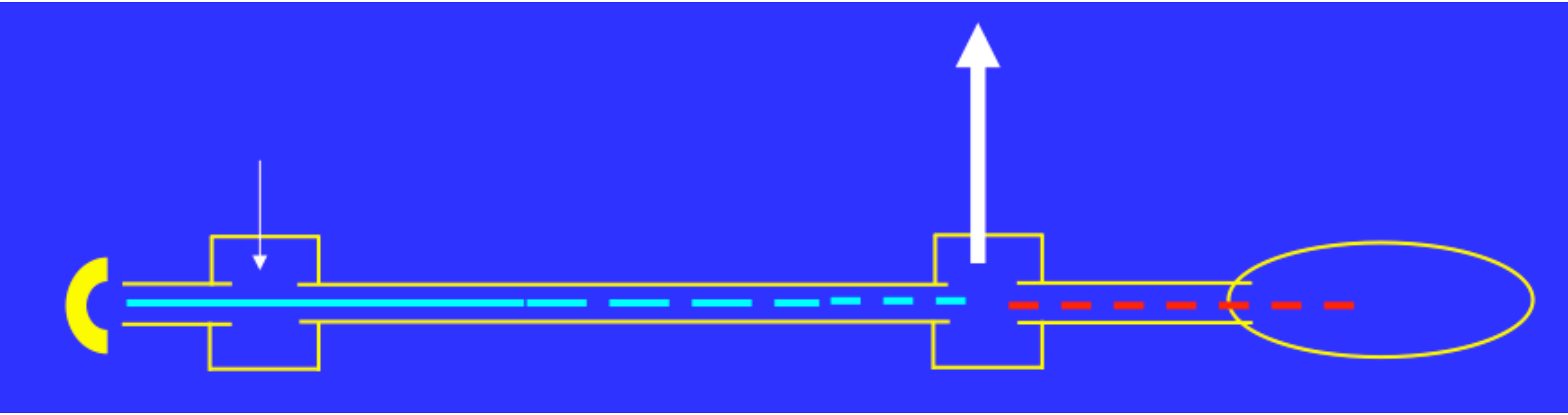
ILC Klystrons

- 10 MW multibeam klystron

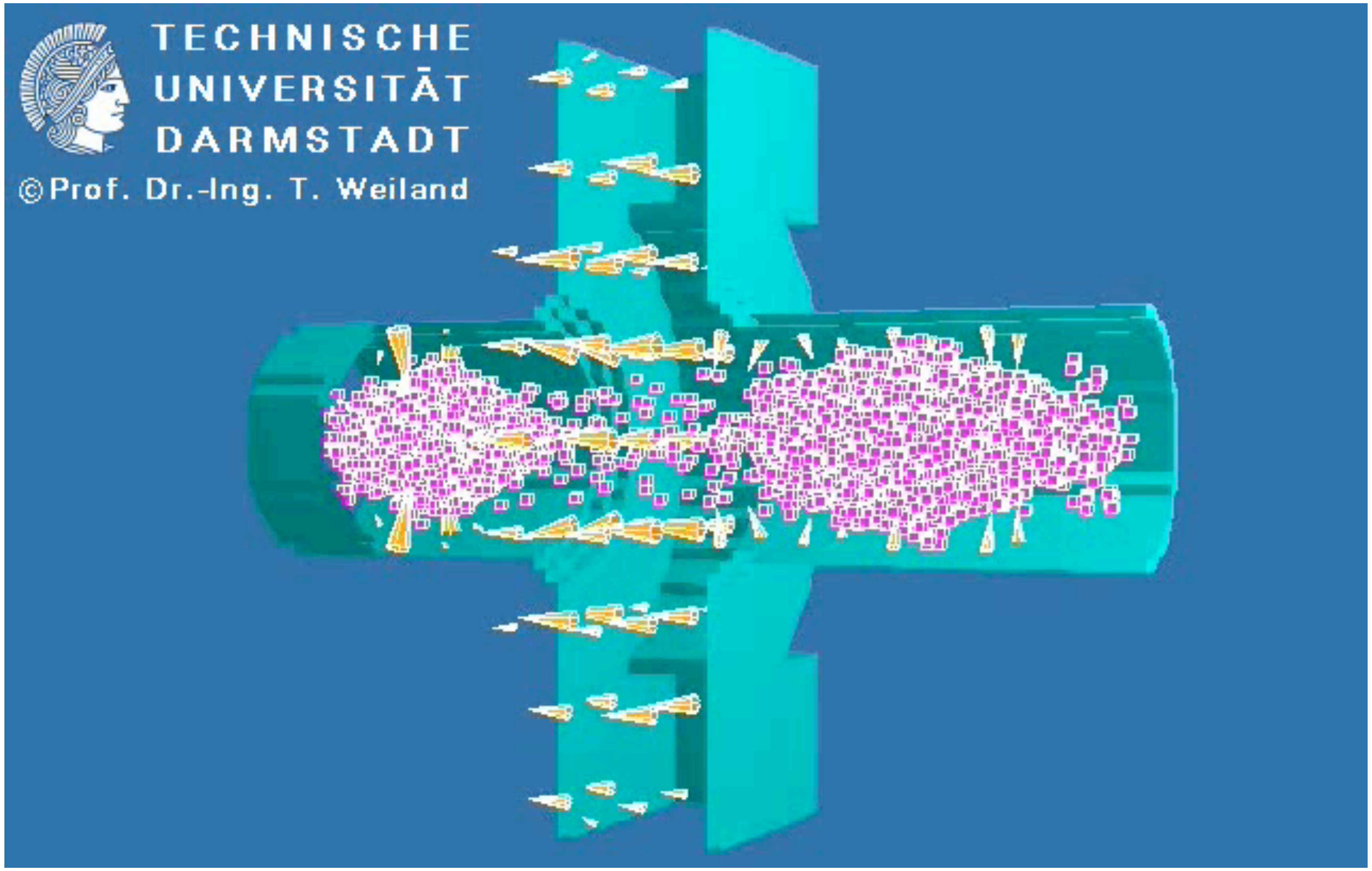
Parameter	Specification
Frequency	1.3 GHz
Peak Power Output	10 MW
RF Pulse Width	1.565 ms
Repetition Rate	5 Hz
Average Power Output	78 kW
Efficiency	65%
Saturated Gain	≥47 db
Instantaneous 1 db BW	>3 MHz
Cathode Voltage	≤120 kV
Cathode Current	≤140 A
Power Asymmetry	≤1%
Lifetime	>40,000 hours

How does a Klystron work?

- DC beam at high voltage (<500 kV, < 500 A) is emitted from the gun
- A low-power signal at the design frequency excites the input cavity
- Particles are accelerated or decelerated in the input cavity, depending on phase/arrival time
- Velocity modulation turned into density modulation in the long drift tube (beam is bunched at drive frequency)
- Bunched beam excites output cavity at design frequency (beam loading)
- Spent beam is stopped in the collector.

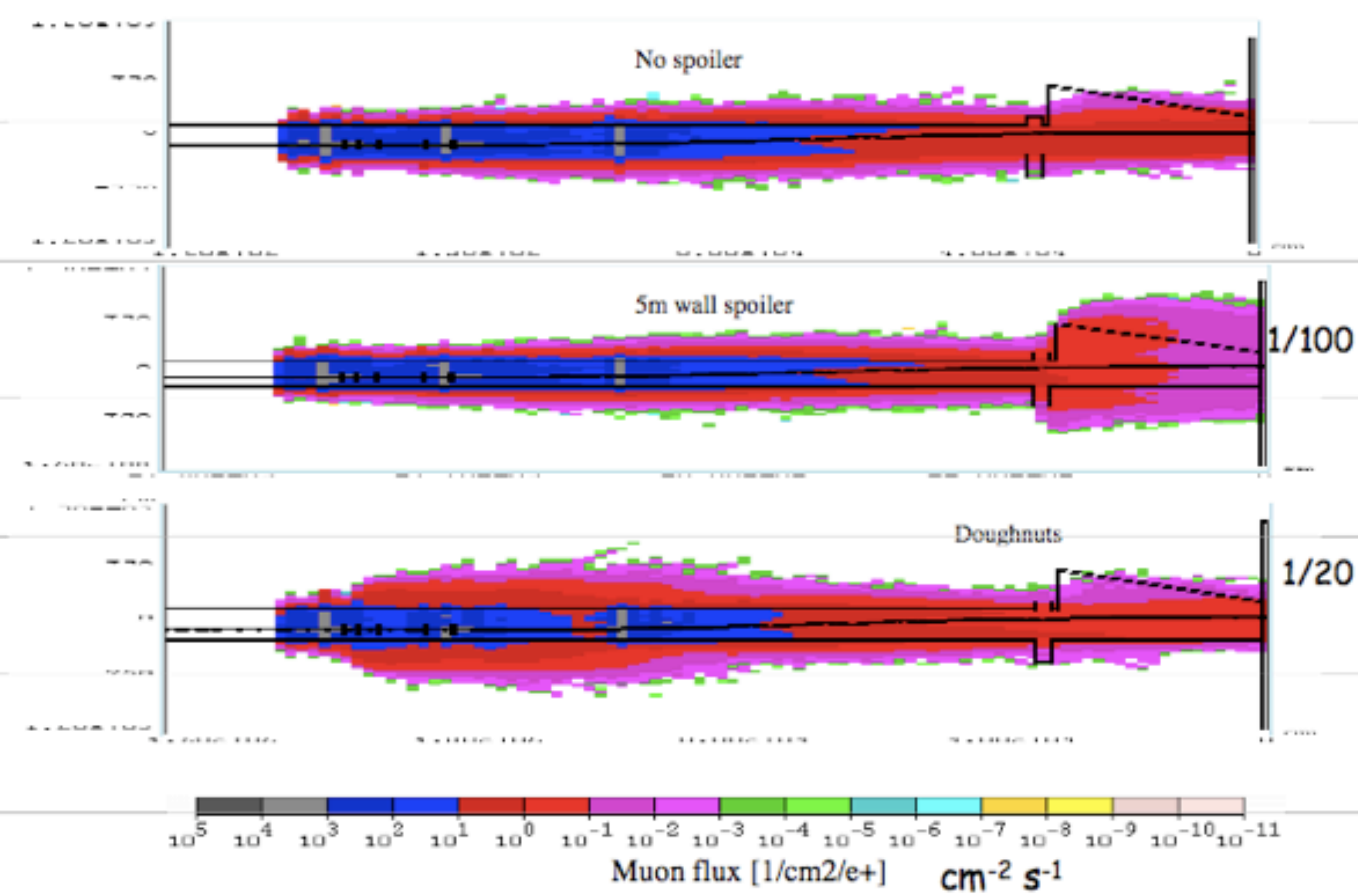


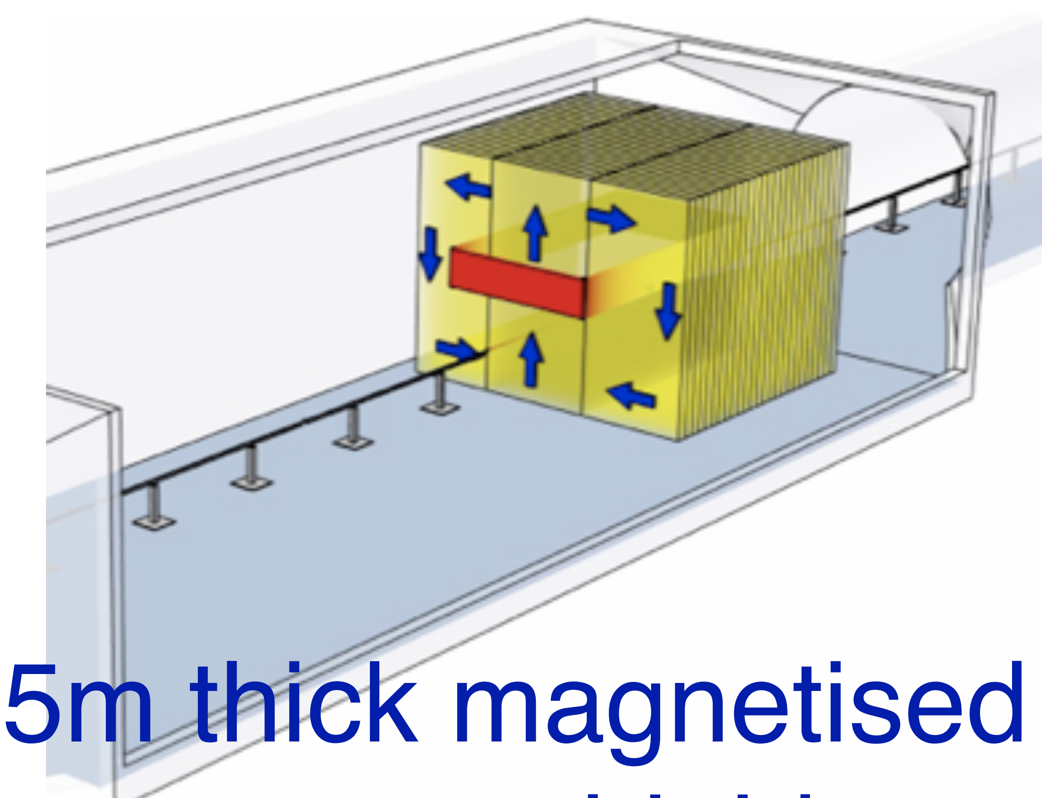
Klystron Animation



Collimation System

- Collimators scrape away halo outside
  ~8-10 σ_x and ~60-80 σ_y
- Removes potential background at the IP but is a source of muon background itself

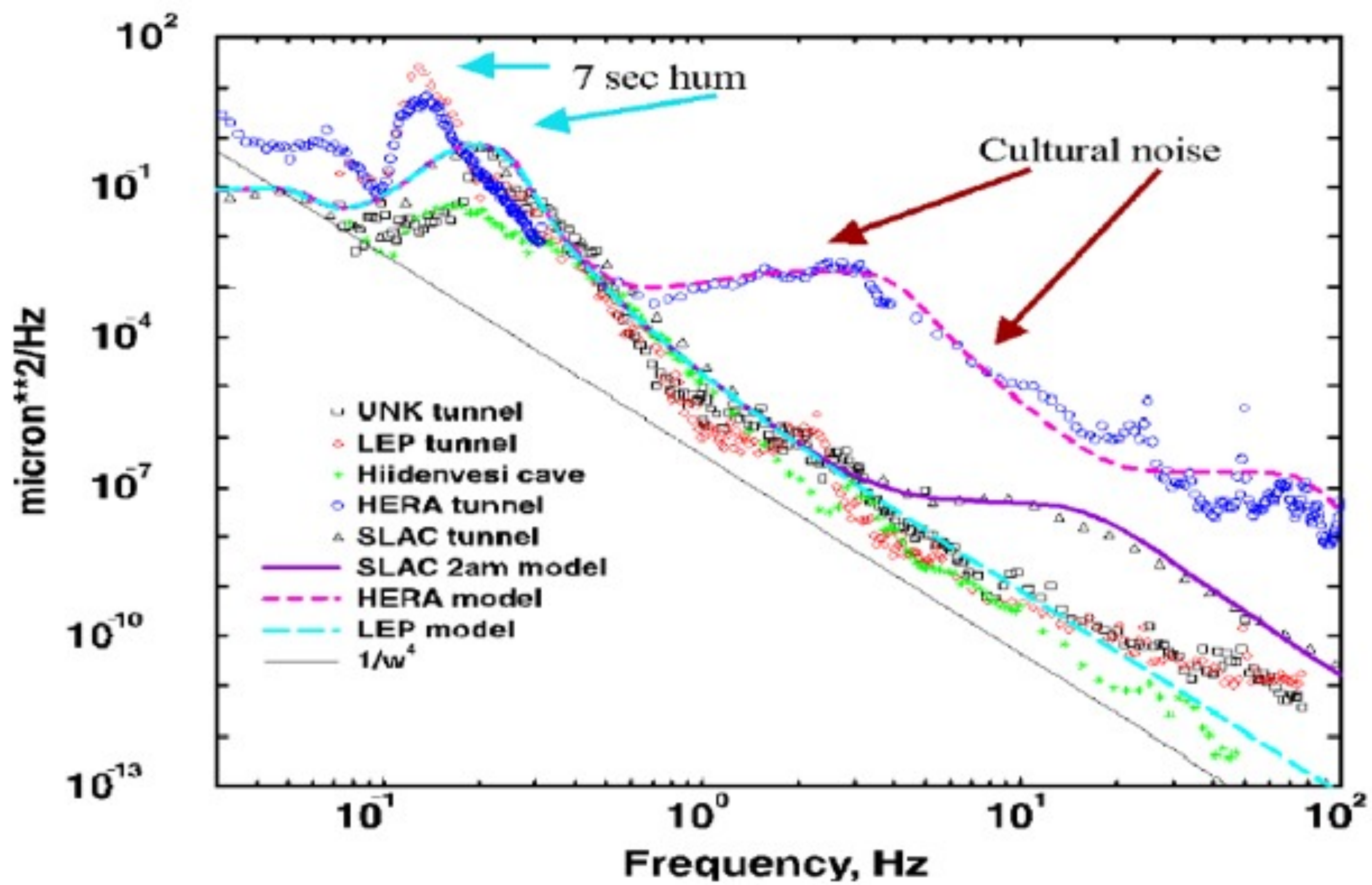




5m thick magnetised muon shield

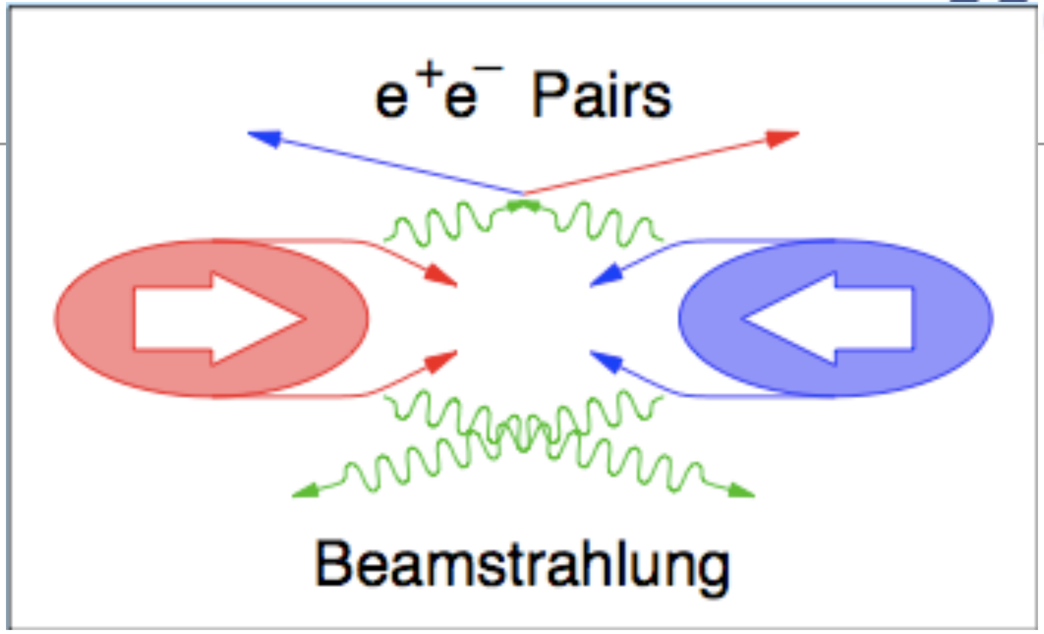
Stability

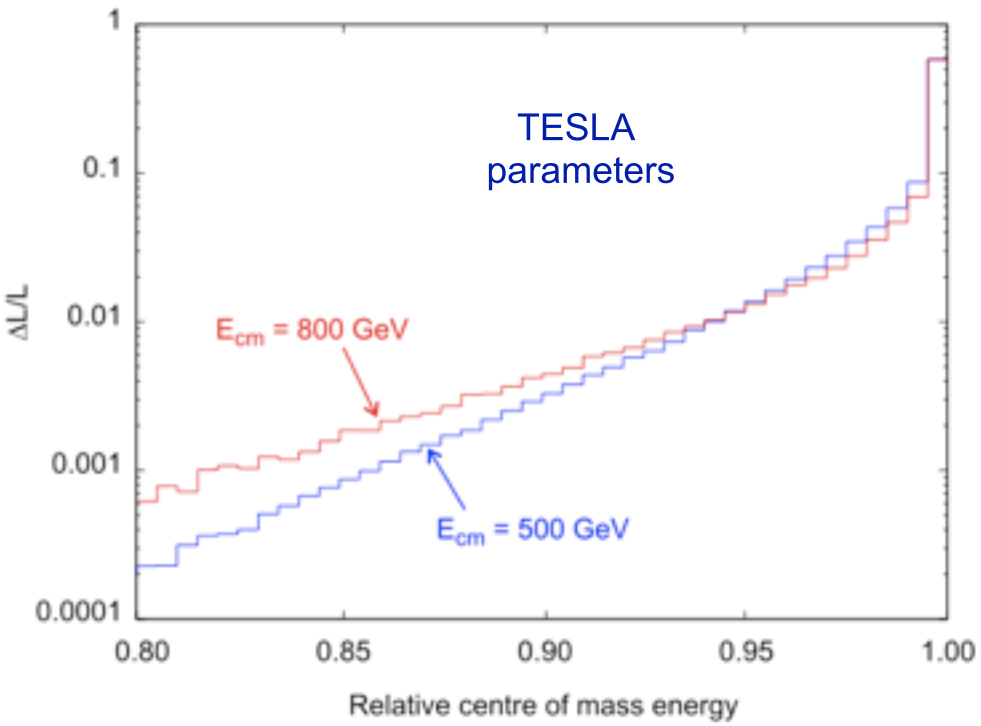
- Requirements:
  - Cavity alignment (RMS): ~µm
  - Linac magnets: 100 nm
  - FF magnets: 10-100 nm
  - Final lens: ~nm (!)

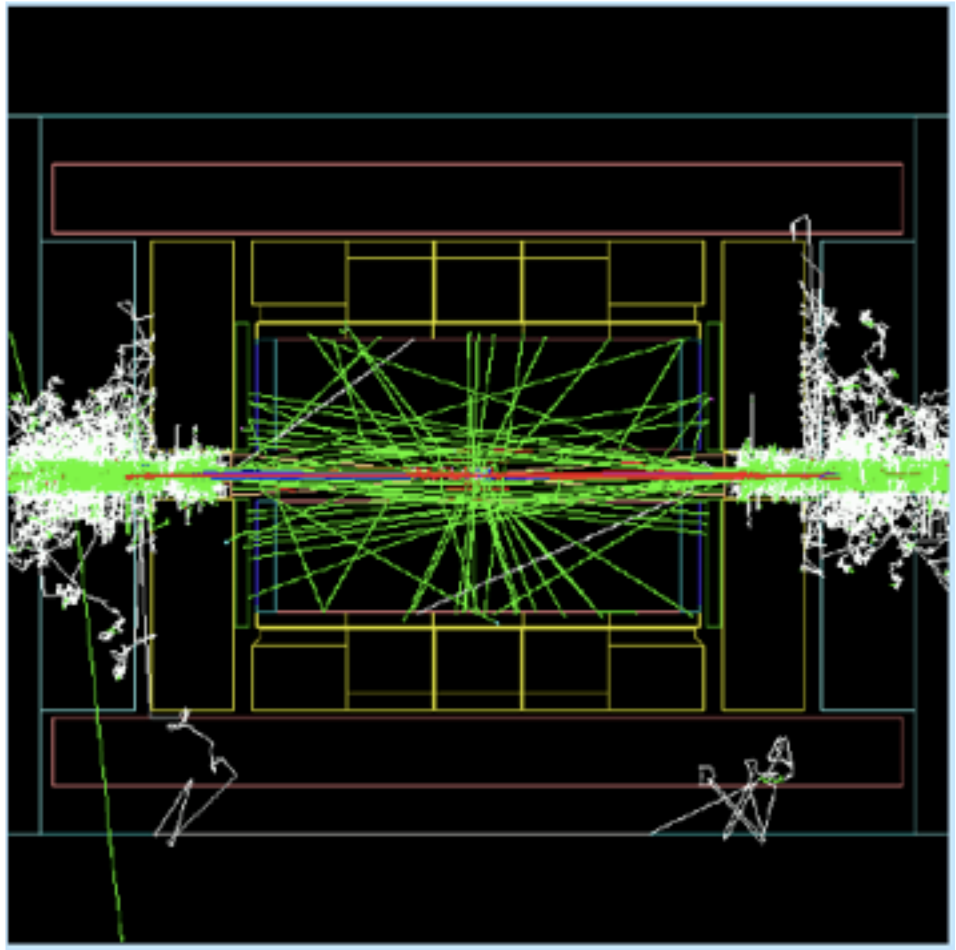


Beamstrahlung Revisited

- Beam-beam effect leads to the production of beamstrahlung
- Beamstrahlung dilutes luminosity spectrum of the collider
- Beamstrahlung photons can produce e± pairs which generate detector background





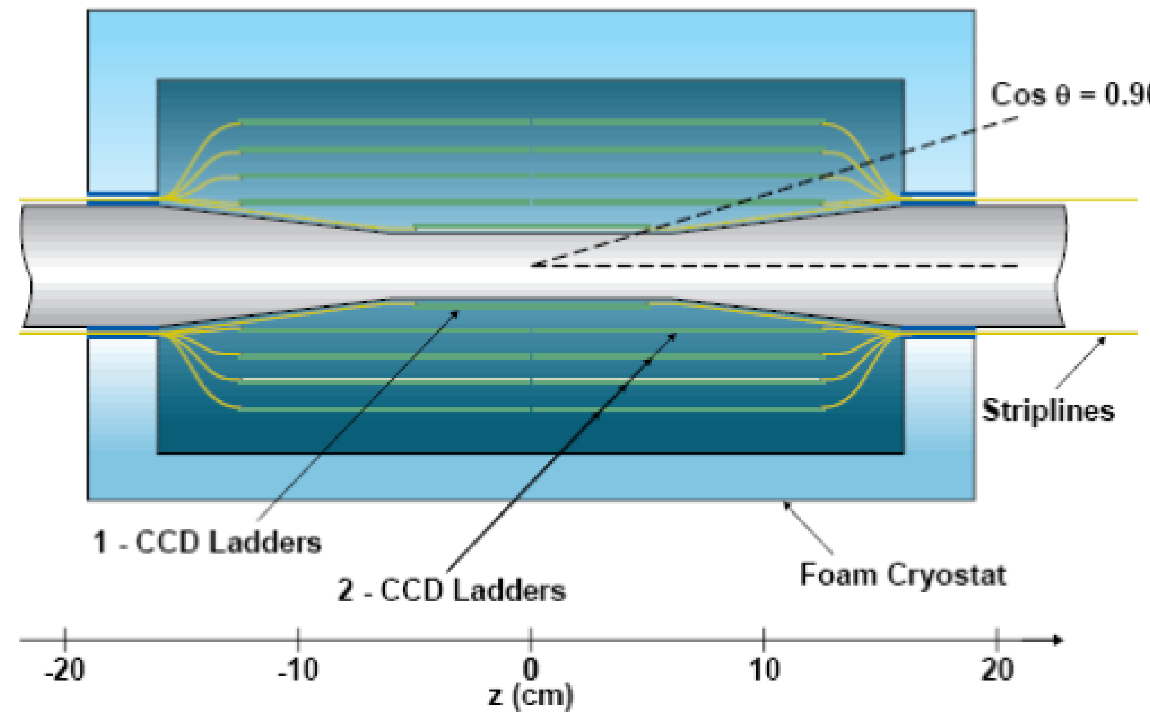


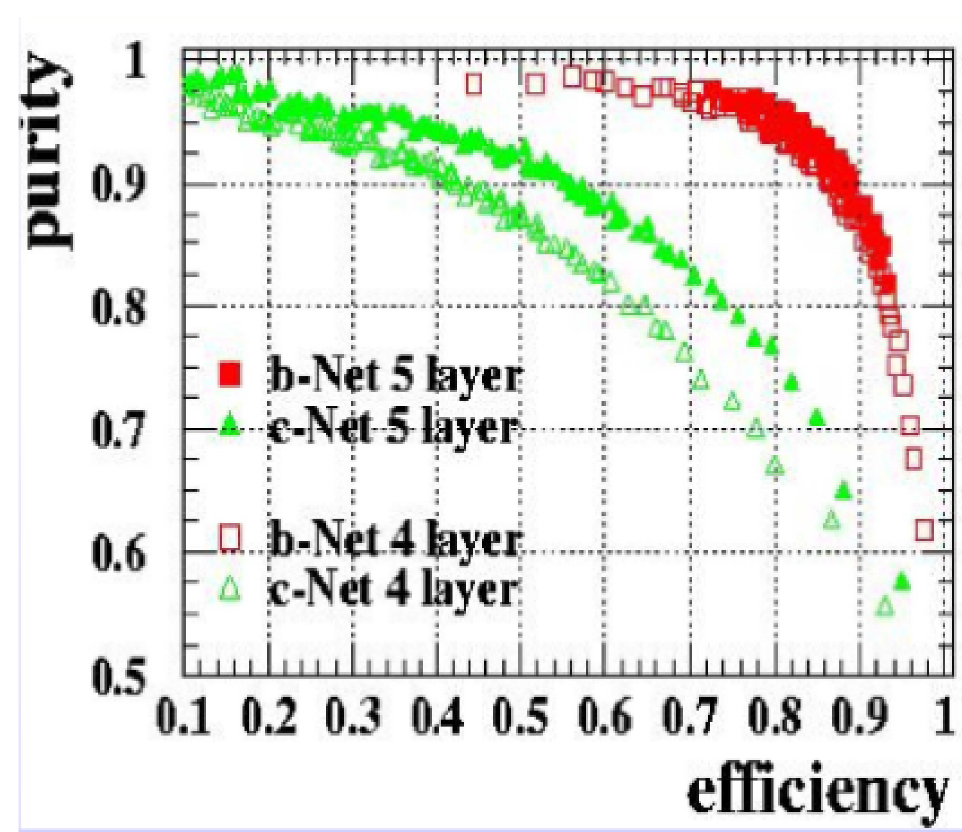
Vertex Detector

- Requirements:
  - excellent point resolution <4μm
  - small pixel sizes: 20 x 20 μm^2
  - ~10^9 channels
  - low material budget: ~0.1% X_0
  - fast read-out to minimise pile-up
  - immune against EMI effects

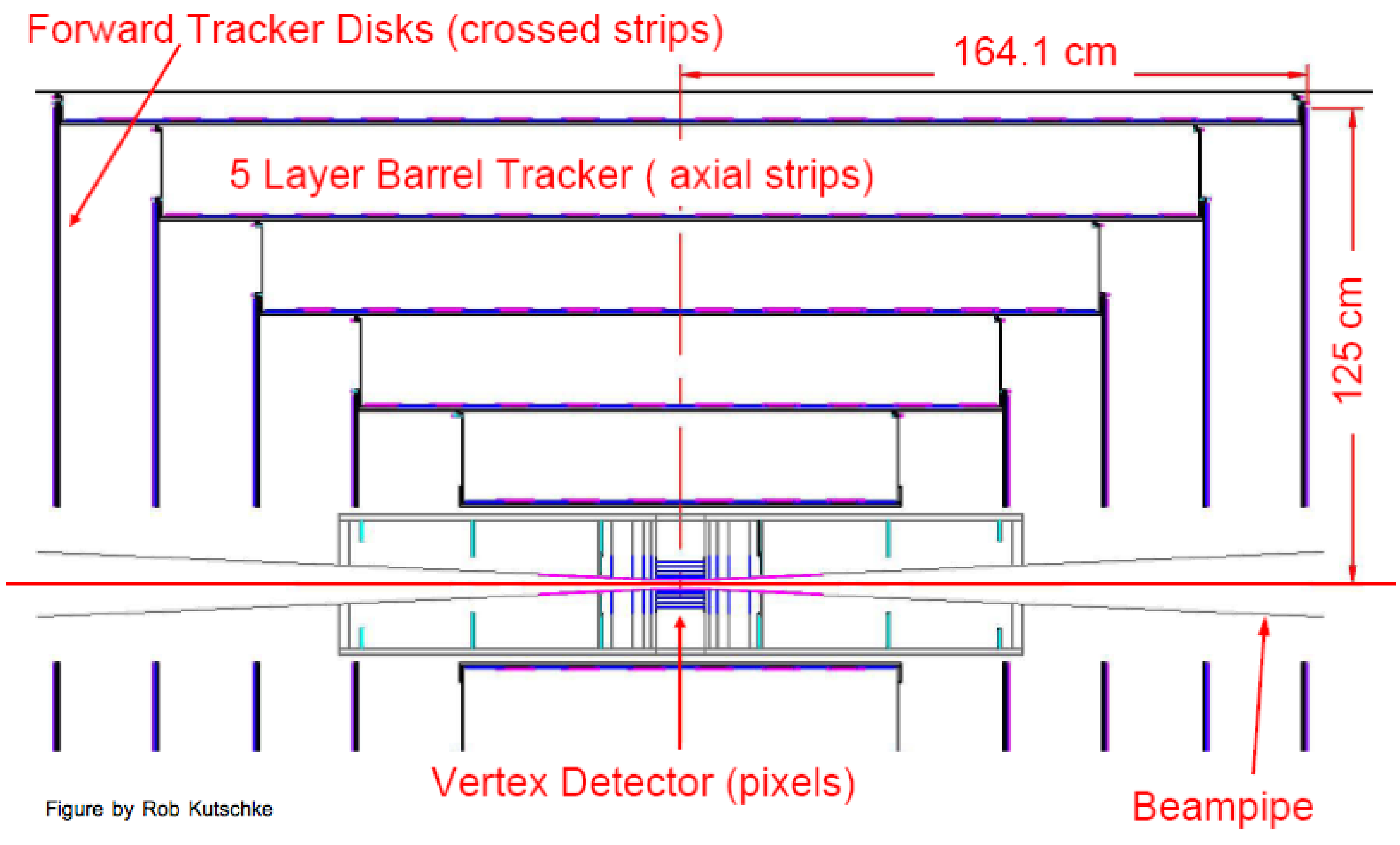
- Flavour tagging is crucial
  - b-tagging easier than c-tagging

- Many technologies under study





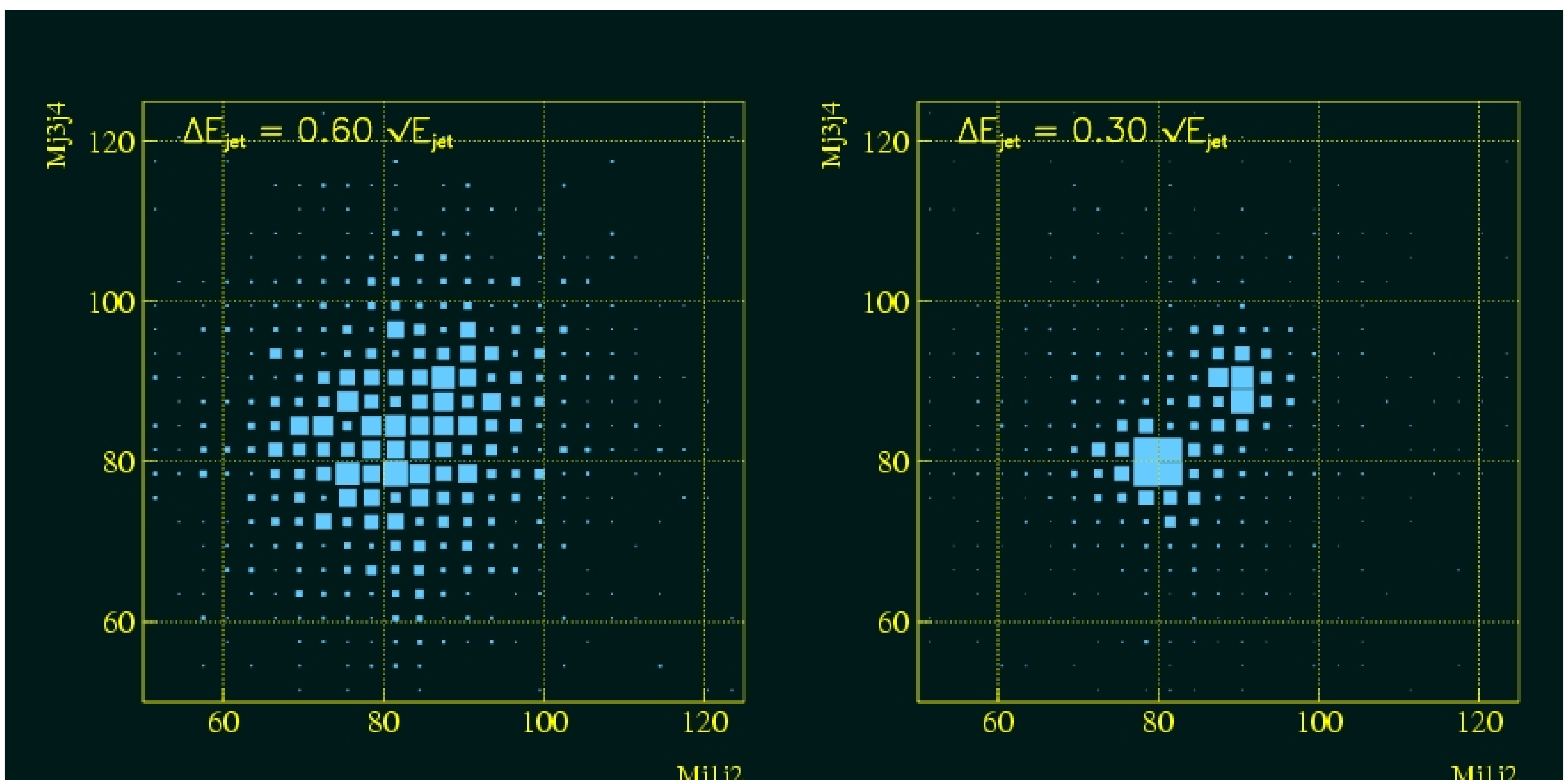
Tracking System Option: Silicon Tracker

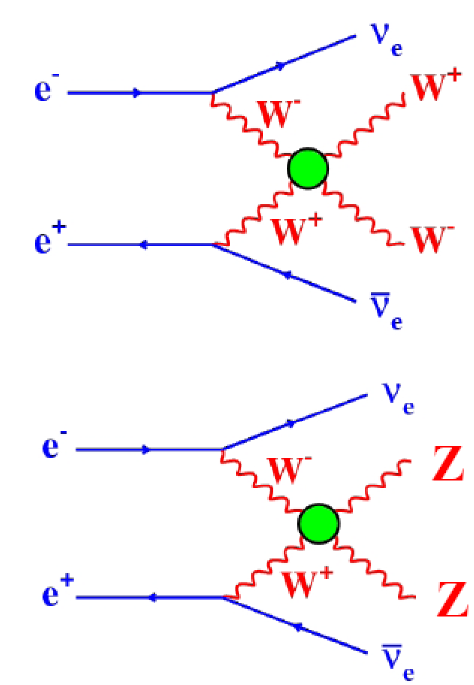


- Axial strips, no z information

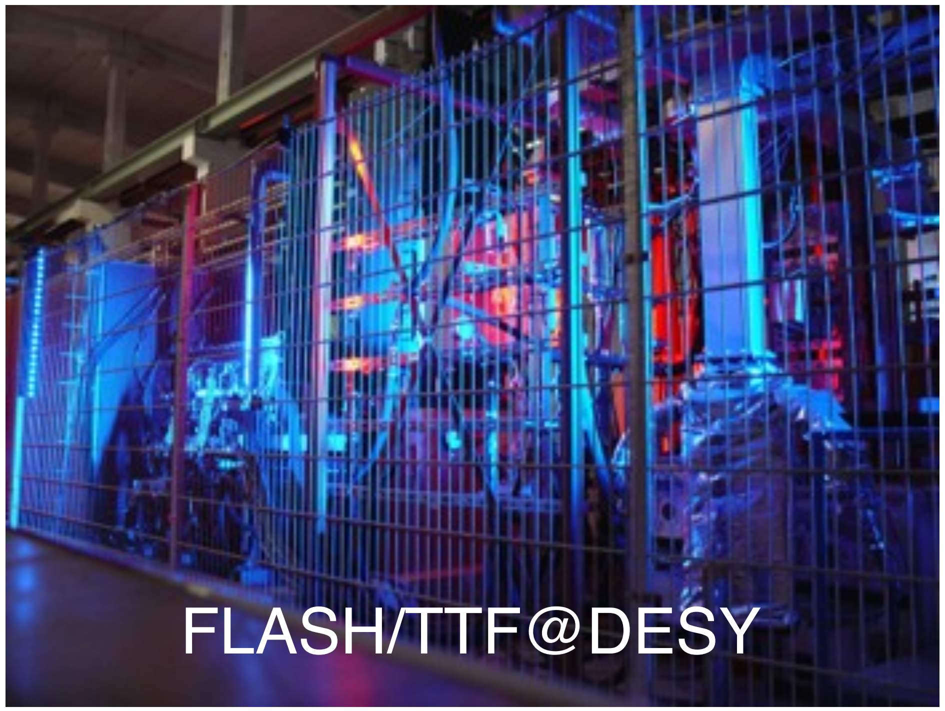
The Calorimetry Challenge

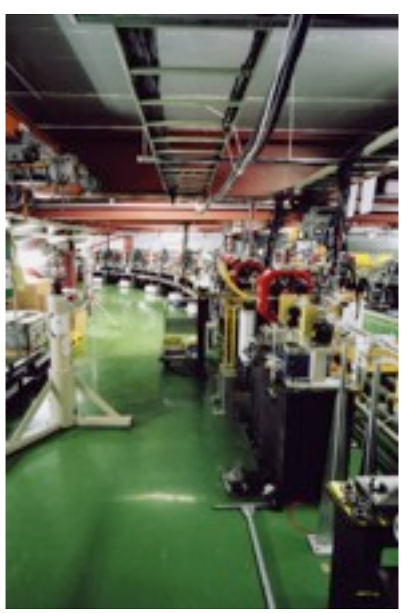
- WW and ZZ di-jet mass separation
- Jet energy resolution of 30%/√E (GeV) needed!
- Very challenging with traditional calorimetry
- Particle flow concept is promising



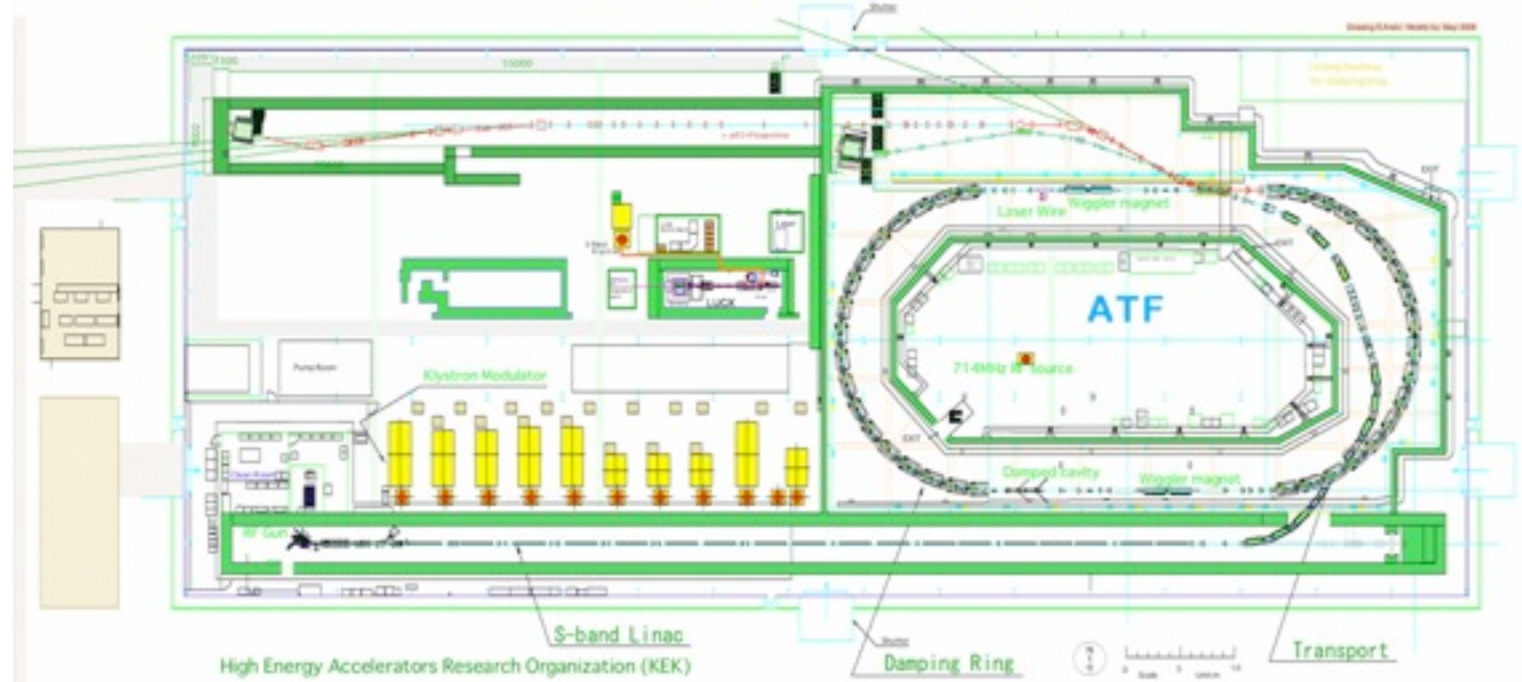


ILC Test Facilities (Examples)



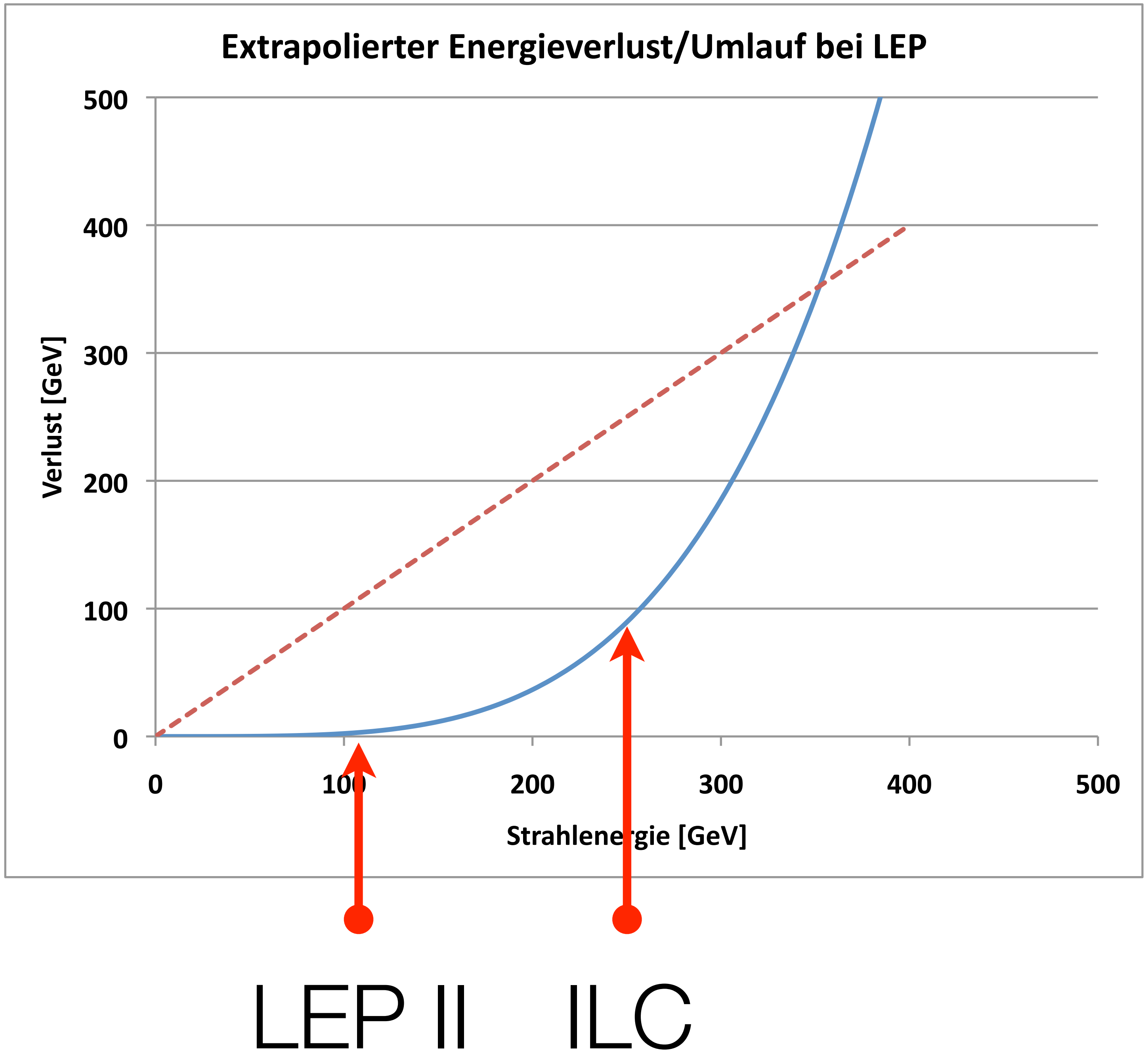


ATF/ATF2@KEK ATF2 LAYOUT



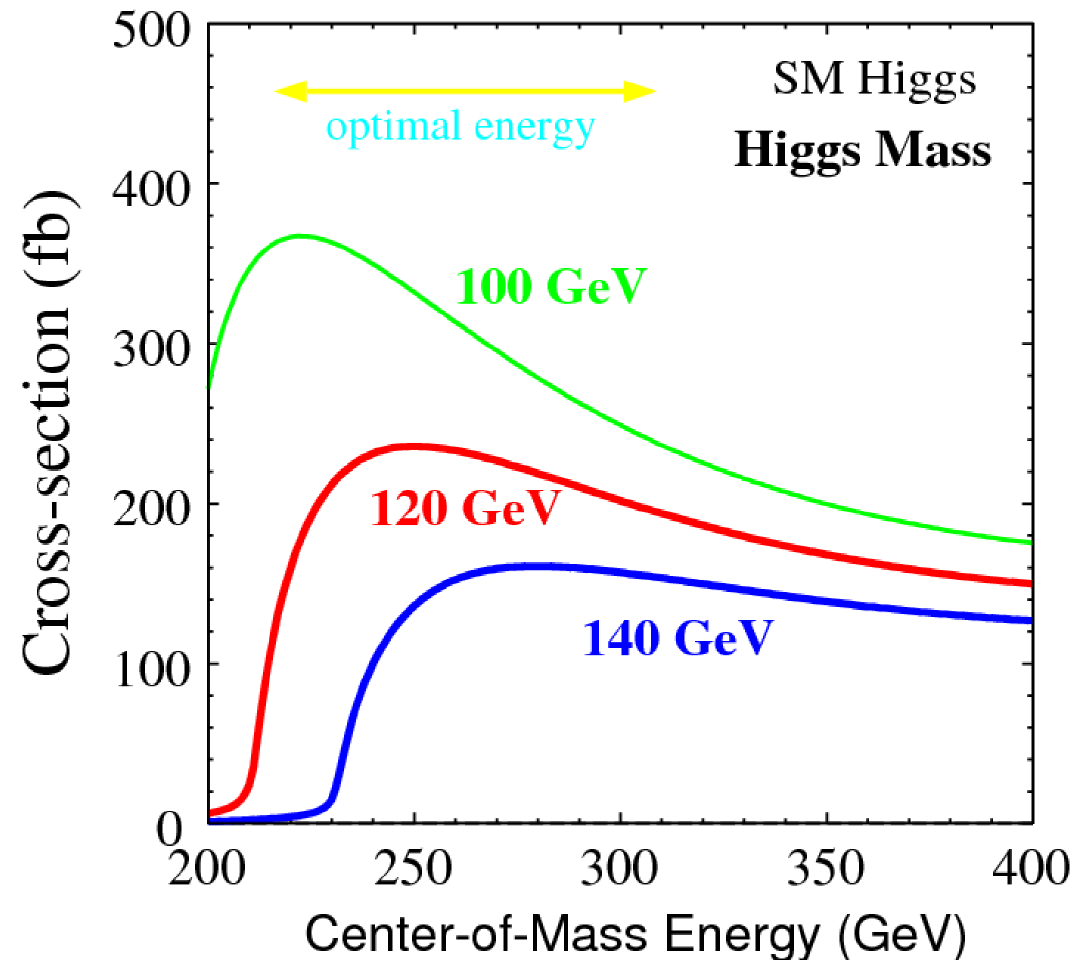
Circular e^+e^- collider for Higgs study?

- Synchrotron radiation
  - Energy loss for E>100 GeV is a considerable fraction of the beam energy
  - Momentum acceptance of the rings!
  - for E>350 GeV the entire energy is radiated in one turn
- At 240 GeV cms it may still be possible…
  - Luminosity?



LEP3 to study a light Higgs?

- If a light Higgs were established at LHC could it be produced in the LEP/LHC tunnel?
- Higgs of 125 GeV requires an e^+e^--collision energy of 240-250 GeV (peak of cross section in Higgsstrahlung process: $e^+e^- \rightarrow ZH$)
- for heavy quarks an additional boost in helpful, i.e. $\sqrt{s}$>250 GeV
- σ_{Higgs} ~200 fb
- 10-100 fb^{-1}/a required (10^{33} - 10^{34} $cm^{-2}s^{-1}$)



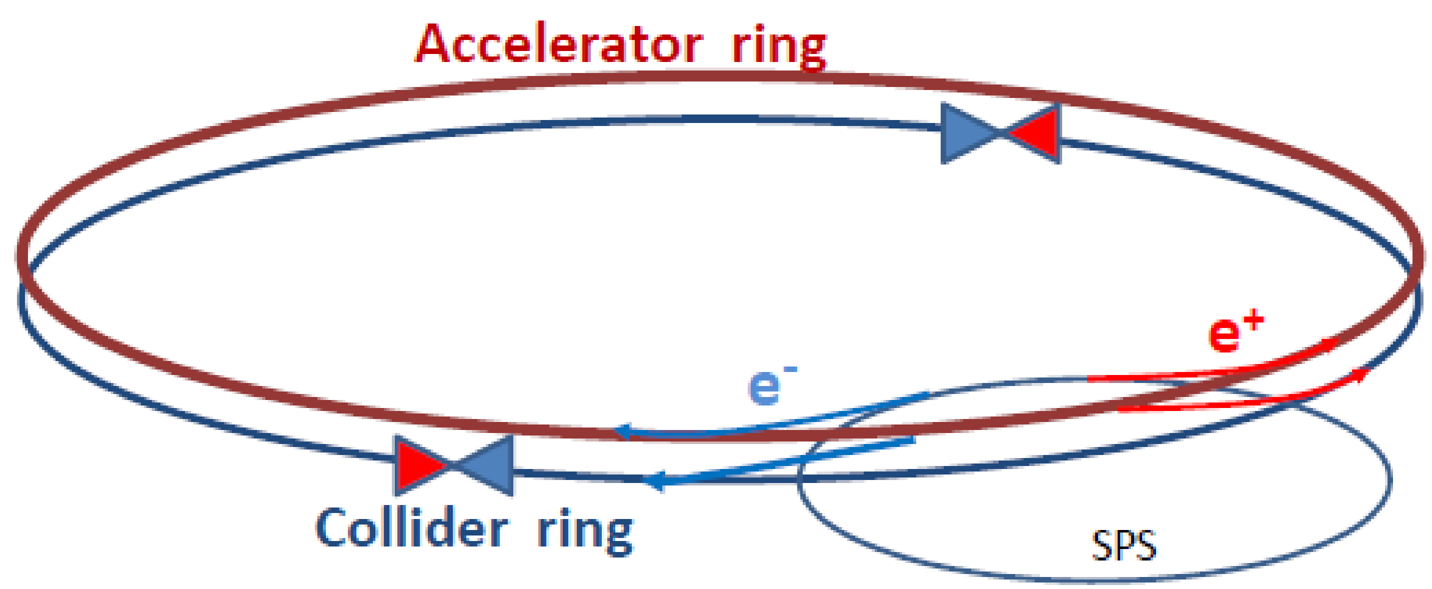
from A.Blondel et al., arXiv:1112.2518

Luminosity is the challenge

LEP3 Study Proposal

- Collider ring
- 2 x 120 GeV
- 7 GeV SR-loss per turn
- 4 bunches of $4{\times}10^{12}$ e^-
  50 MW loss per beam
- τ_{beam} = 16 min
  determined by Bhabha scattering
- Top-up ring
- fast ramping synchrotron chain;
  SPS and accelerator ring
  44-120 GeV

A.Blondel et al., arXiv:1112.2518 and
IPAC12, TUPPR078 and references therein



Parameters at the limit
– no energy margin
– concept of storage doubtful

- beam dynamics studies and optics; HOM heating with large bunch currents and very small bunch lengths (<0.3cm), vertical emittance tuning, single-bunch charge limits, longitudinal effects associated with a Q_s of 0.35, low beta insertion with large momentum acceptance, parameter optimization, beam-beam effects, including beamstrahlung, and the top-up scheme;
- optics design and beam dynamics for the accelerator ring, and its ramping speed;
- the design and prototyping of a collider-ring dipole magnet, an accelerator-ring dipole magnet, and a low-beta quadrupole;
- 100 MW synchrotron radiation effects: damage considerations, energy consumption, irradiation effects on LHC and LEP3 equipment, associated shielding and cooling;
- SRF and cryogenics design and prototyping
- determining the optimum RF gradient as a compromise between cryo power and space, and the optimum RF frequency with regard to impedance, RF efficiency and bunch length;
- machine-detector interface, e.g. the integration of warm low-beta quadrupoles inside the ATLAS and CMS detectors

	LEP2	LHeC	LEP3
b. energy E_b [GeV]	104.5	60	120
circumf. [km]	26.7	26.7	26.7
beam current [mA]	4	100	7.2
#bunches/beam	4	2808	4
$\#e-$/beam [10^{12}]	2.3	56	4.0
horiz. emit. [nm]	48	5	25
vert. emit. [nm]	0.25	2.5	0.10
bending rad. [km]	3.1	2.6	2.6
part. number J_ε	1.1	1.5	1.5
mom. c. α_c [10^{-5}]	18.5	8.1	8.1
SR p./beam [MW]	11	44	50
β^*_x [m]	1.5	0.18	0.2
β^*_y [cm]	5	10	0.1
σ^*_x [μm]	270	30	71
σ^*_y [μm]	3.5	16	0.32
hourglass F_{hg}	0.98	0.99	0.67
E^{SR}_{loss}/turn [GeV]	3.41	0.44	6.99
$V_{RF,tot}$ [GV]	3.64	0.5	12.0
$\delta_{max,RF}$ [%]	0.77	0.66	4.2
ξ_x/IP	0.025	N/A	0.09
ξ_y/IP	0.065	N/A	0.08
f_s [kHz]	1.6	0.65	3.91
E_{acc} [MV/m]	7.5	11.9	20
eff. RF length [m]	485	42	606
f_{RF} [MHz]	352	721	1300
δ^{SR}_{rms} [%]	0.22	0.12	0.23
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.69	0.23
L/IP[10^{32}cm^{-2}s^{-1}]	1.25	N/A	107
number of IPs	4	1	2
beam lifetime [min]	360	N/A	16
Υ_{BS} [10^{-4}]	0.2	0.05	10
n_γ/collision	0.08	0.16	0.60
ΔE^{BS}/col. [MeV]	0.1	0.02	33
ΔE^{BS}_{rms}/col. [MeV]	0.3	0.07	48

But most importantly

- It will require dismantling major parts of LHC
- dead-end from the point of view of energy reach
    - which spurs proponents to propose an 80 km ring…