e^+e^- Linear Collider

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DESY Summer Student Programme, 2007

Plan of Lecture

- Today
  - Introduction to Physics at the Terascale
  - Accelerators requirements at the highest energy
  - Linear Collider – general concepts
  - Luminosity
- Tomorrow
  - ILC – piece by piece

Physics Need for Terascale

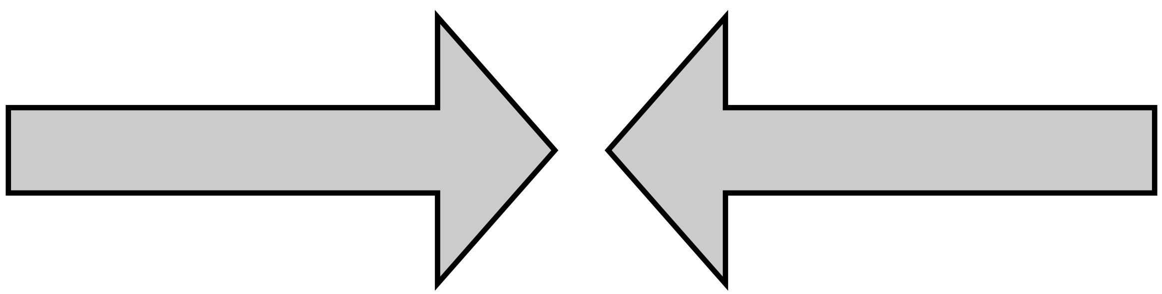
- Standard Model is successfully describing essentially all observed features of particle physics
- Yet, it is known to be incomplete
  - Electroweak symmetry breaking
  - Origin of mass
  - Larger symmetries
  - …

High Energy Colliders

- Heisenberg
  - the highest momenta are required to unravel the smallest features of nature

$$\Delta x \Delta p \approx \hbar$$

- best achieved with head-on collision of particles



Choice of Force

Force	rel. strength	reach [m]	Particle
Gravitation	6×10^{-39}	∞	all
electrom.	1/137	∞	charged
strong	~1	10^{-15}–10^{-16}	hadrons
weak	10^{-5}	$\ll10^{-16}$	hadrons & leptons

Large Hadron Collider (LHC)

- Large Hadron Collider
  - pp-collider,
    (intersecting synchrotrons)
  - strong force
    - Large production cross section
  - Centre-of-mass energy 14 TeV
    - but - protons consists of constituents, quarks and gluons carrying typically ~1/6 of the total momentum

LHC Tunnel

$$\sqrt{s_{\mathrm{eff}}} \approx 1 - 2\,\mathrm{TeV}$$

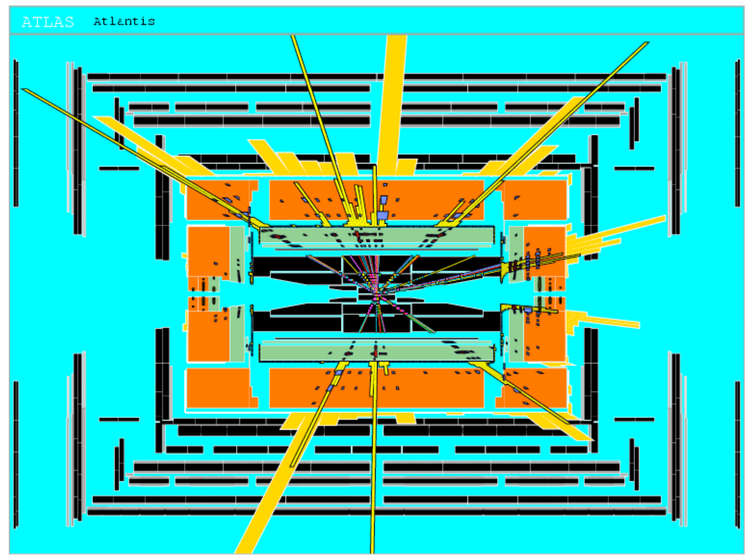
LHC

- Fast path to highest energies
- economic since protons are heavy and loose little energy due to synchrotron radiation on their circular path
    - LHC reuses the tunnel originally built for LEP @ CERN
    - will turn on in mid 2008
    - first "sighting" of the Terascale

Physics Menu of the LHC

much more to come in subsequent lectures

- LHC is likely to be a discovery tool for
  - Higgs
  - Supersymmetric particles or whatever nature chooses to have in store
  - extra dimensions
  - black holes
  - ...

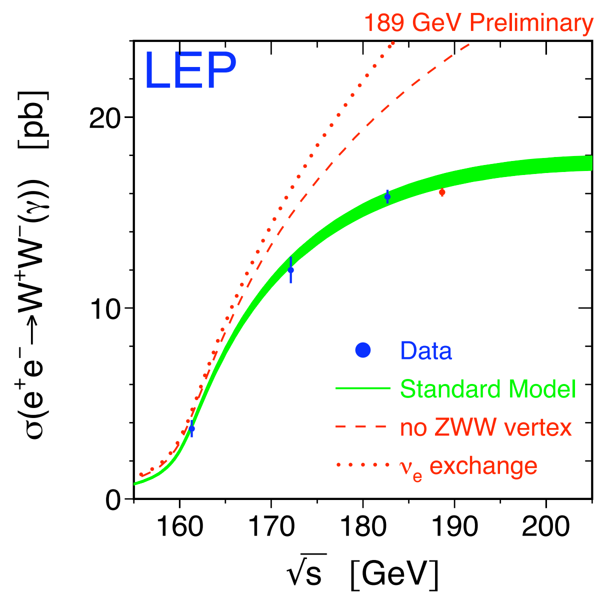


Will the LHC be able to discern the options?

e^+e^- Linear Collider

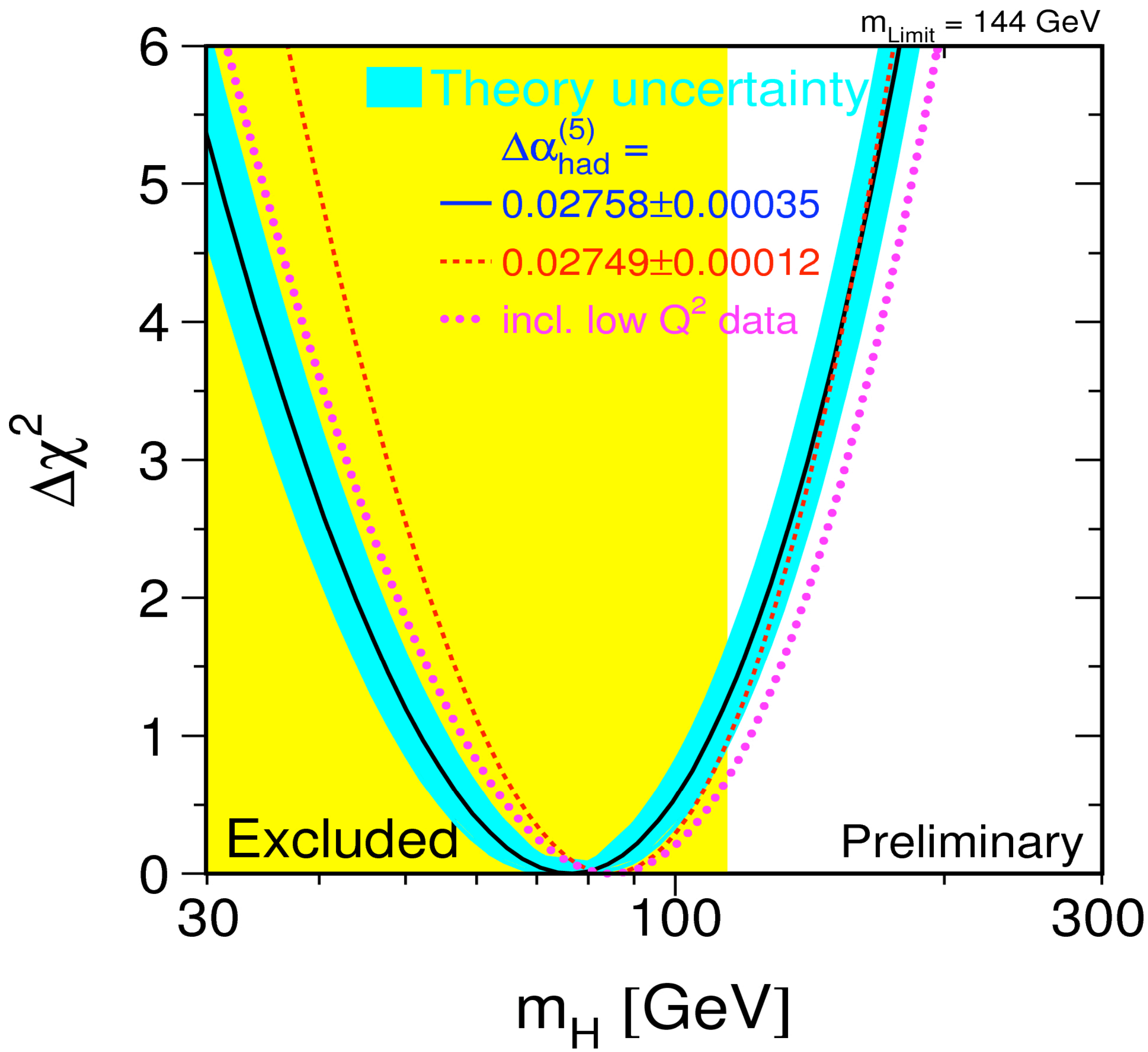
- Particle physics has a long history of complementary exploration with hadron and lepton machines, i.e. pp- or ee-colliders
- Features of e^+e^- colliders:
  - point-like particles
    - well defined cms energy
    - full energy available in cms
    - well defined quantum state
  - electroweak interaction of beam particles
    - requires tremendous luminosity
    - many "background processes" vanish as 1/s.

Example: WW Threshold



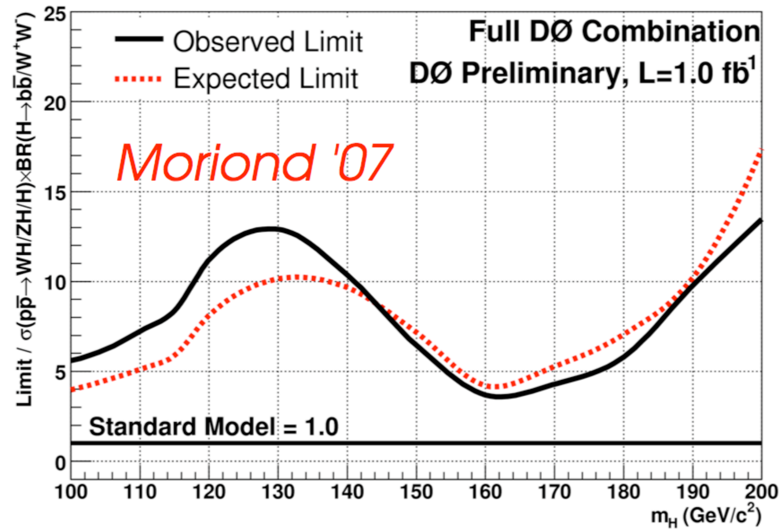
Higgs Particle Search (Status EPS07)

- $m_H = 76^{+33}_{-24}$ GeV
  $m_H < 144$ GeV @ 95% CL
- Direct search @ LEP
  $m_H > 114$ GeV (95% CL)
- Probability M_H>114 GeV
  15%
- so if the Higgs is there and heavier than 114 GeV
  $m_H < 182$ GeV @ 95% CL

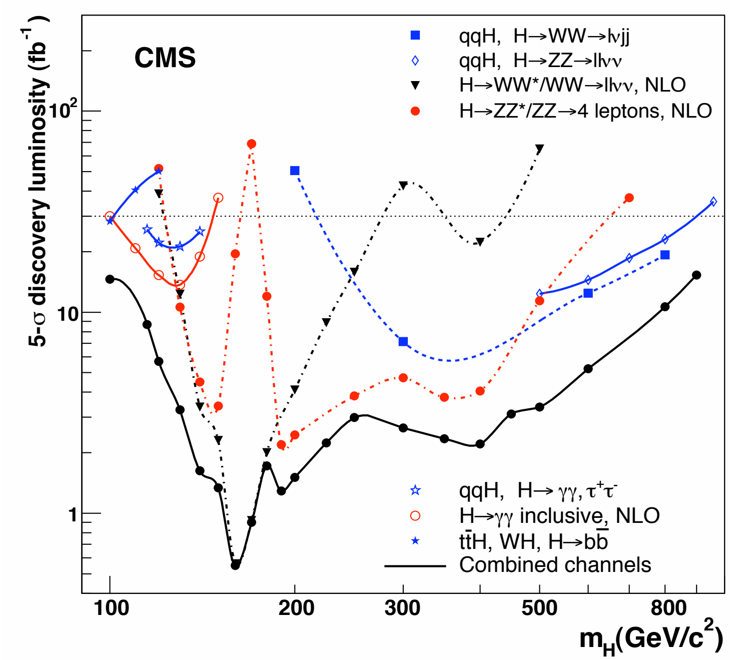


Higgs Search @ Hadron Colliders

- a light Higgs particle is difficult to detect at hadron colliders
- several decay modes have to be combined
- sophisticated analyses are required
    - Tevatron
    - LHC



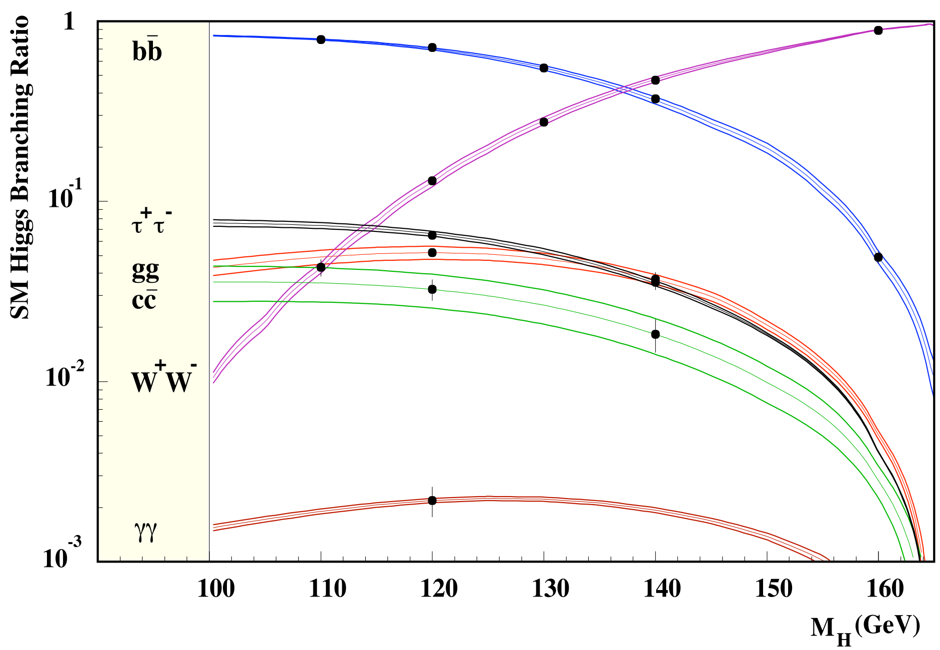
LHC prospects

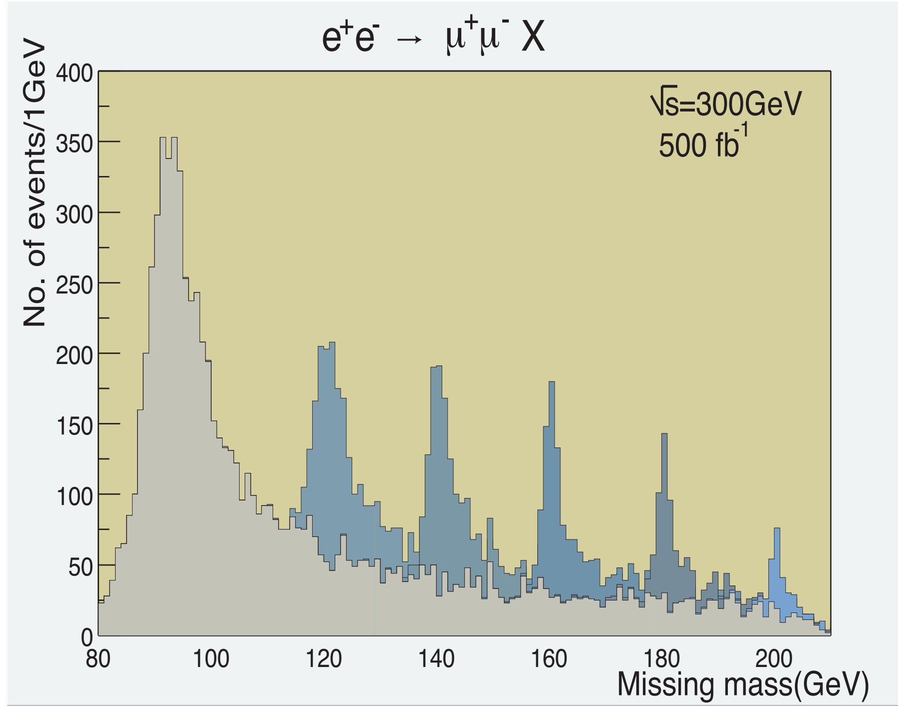


Higgs Detection Prospects at the ILC

- a light Higgs is easily detected at the ILC

- its properties can be measured



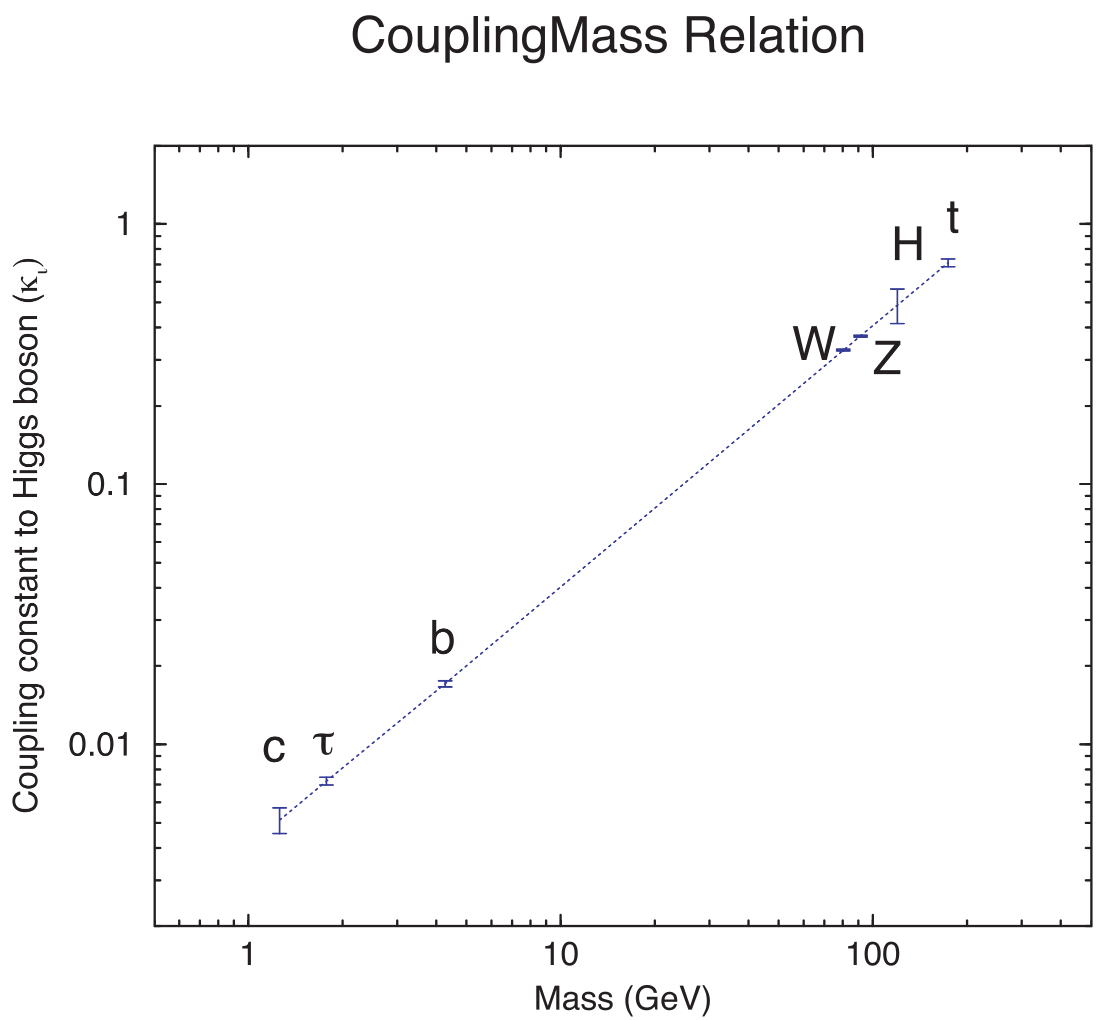


$$e^+e^- \to ZH \to \underbrace{H}\mu^+\mu^-$$

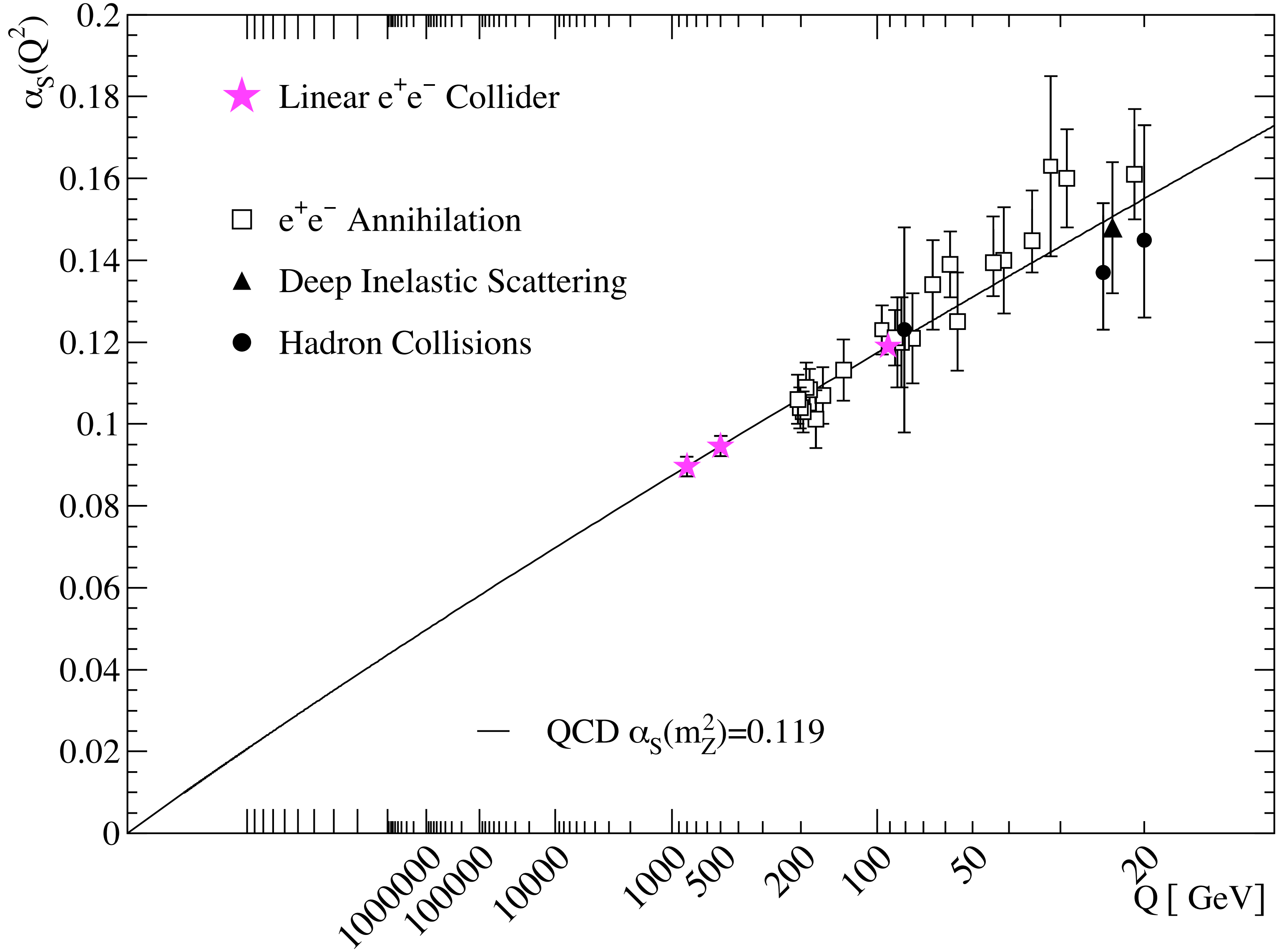
possibly invisible

Higgs Couplings

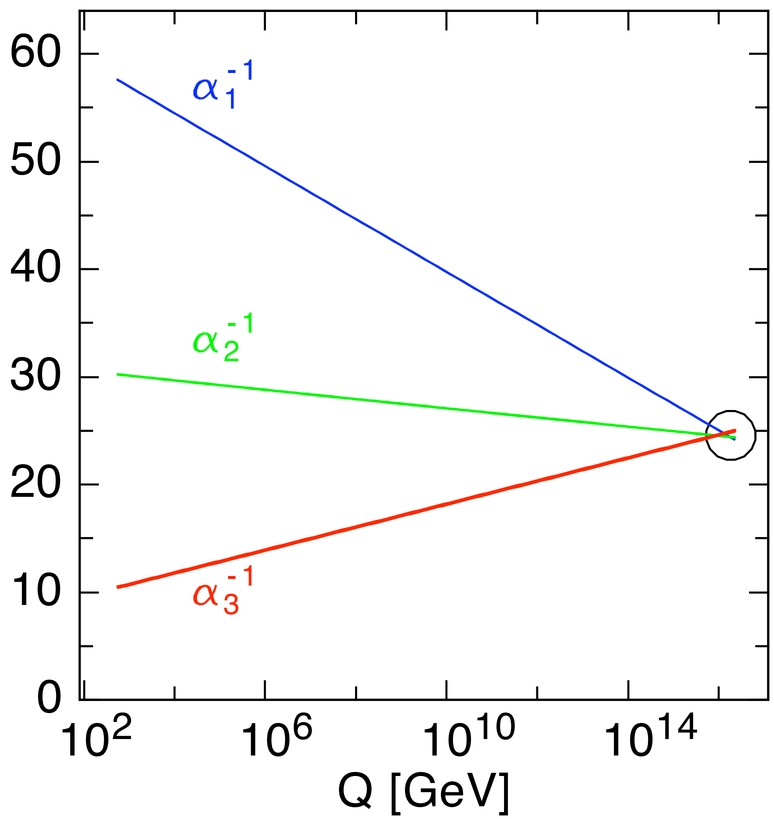
- Higgs couples proportional to mass
    - determine couplings precisely at ILC
        - 500 fb^{-1}
        - more for trilinear coupling and higher cms energy

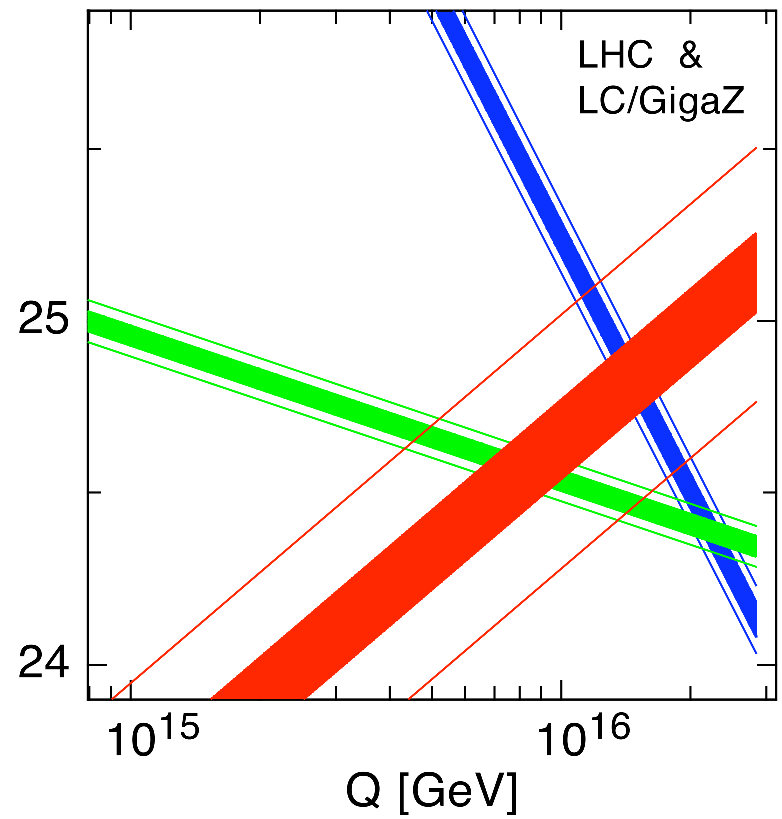


Example: Measurement of Strong Couplings



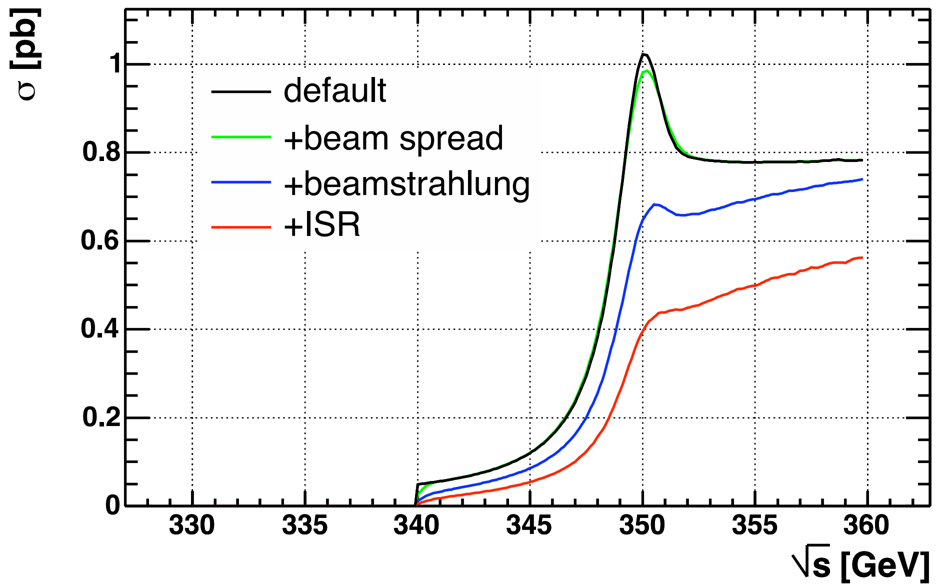
Measurement of Gauge Couplings

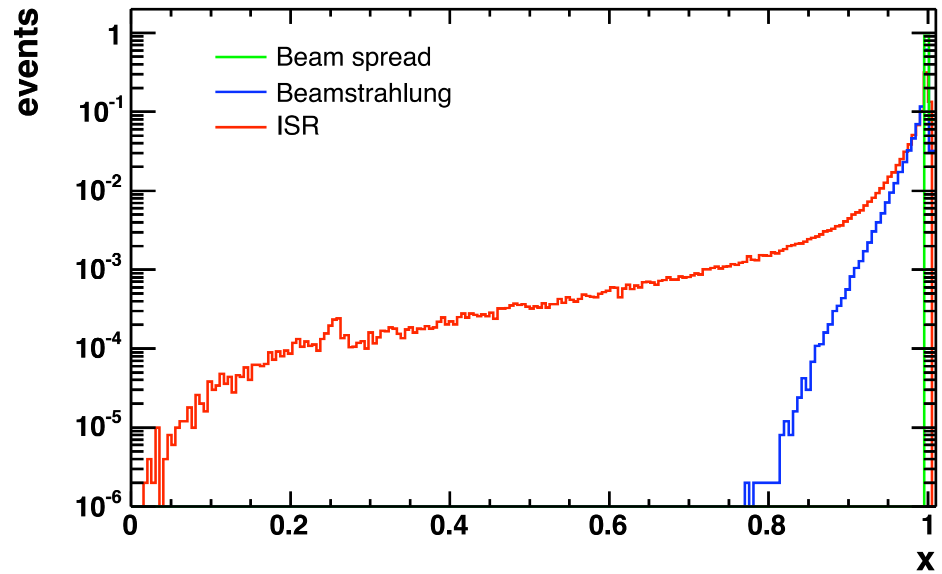




Combination of LHC and LC results will constrain coupling extrapolation to high energies

Top Mass Measurement



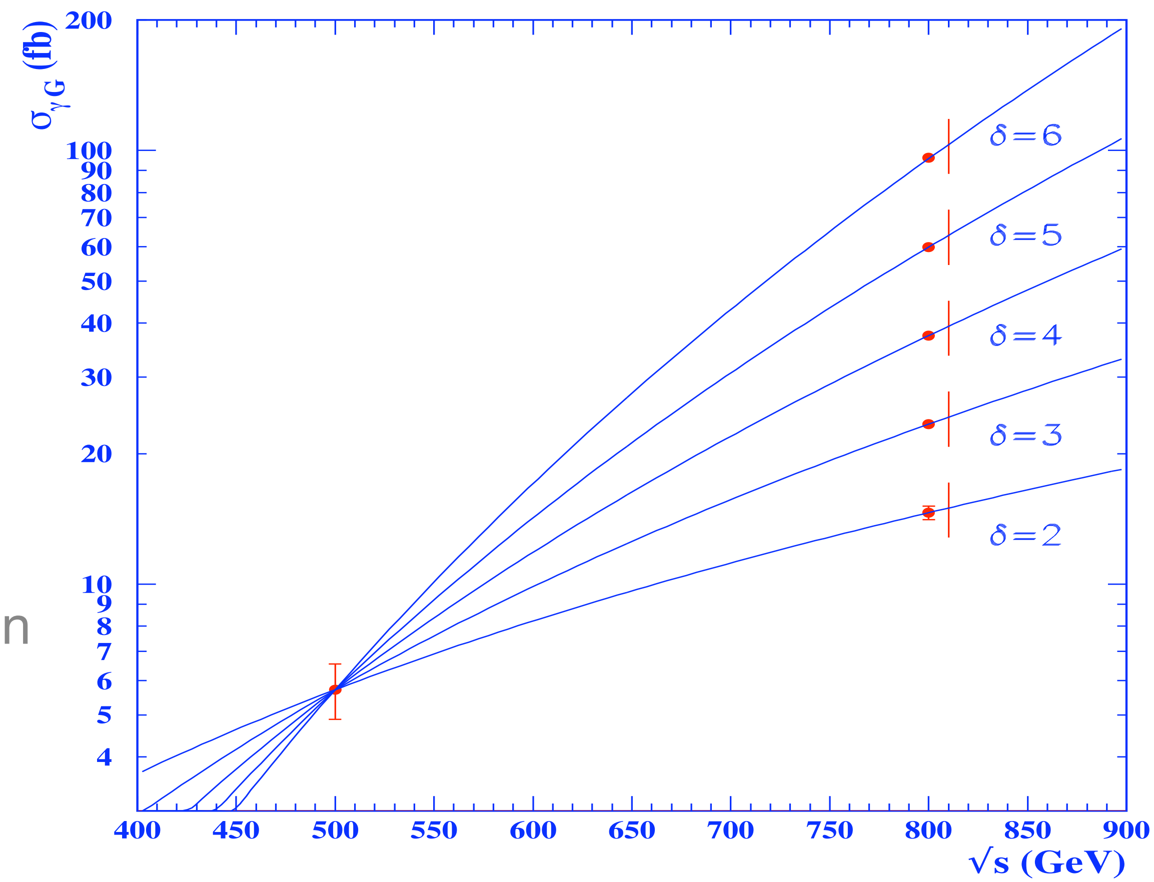


- Expected accuracy of top mass
  - ILC: 100 - 200 MeV
  - LHC: 1 - 2 GeV

Important ingredient in electroweak theory

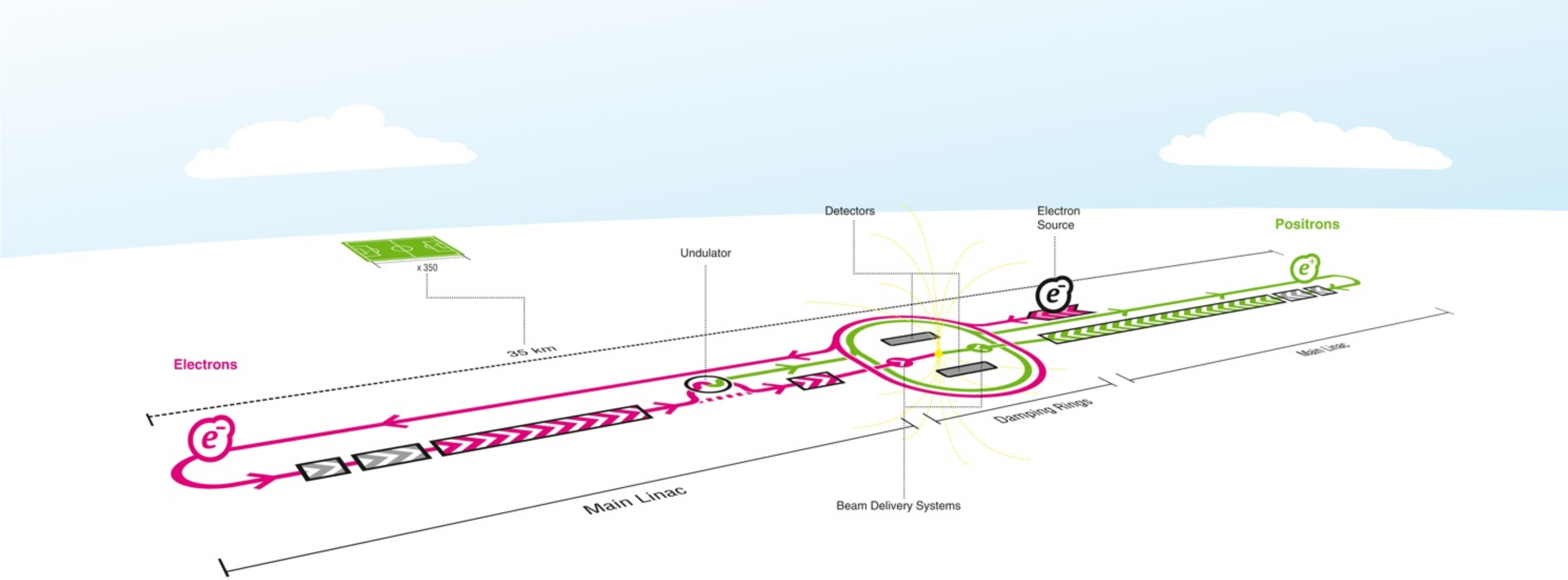
Large Extra Dimensions

- Assume δ extra dimensions where only the graviton propagates
- Kaluza-Klein modes of the graviton reduce the effective scale
- detected using the polarisation of the e-beam to reduce backgrounds
- a measurement at two cms energies will determine the number of extra dimensions



$$e^+e^- \rightarrow G_{KK}\gamma$$

International Linear Collider



- No longer circular
  where energy could repeatedly be transferred in the same structure
- Why still a ring?
  Damping rings are required to produce the low emittance beams
- complicated sources
  intensity issue

Radiation of a non-relativistic moving Charge

Power:

$$P_s = \frac{e^2}{6\pi\epsilon_0 m_0^2 c^3} \left(\frac{\mathrm{d}\vec{p}}{\mathrm{d}t}\right)^2$$

Lamor

Hertz' Dipole:

$$\frac{\mathrm{d}P_s}{\mathrm{d}\Omega} = \frac{e^2}{16\pi^2\epsilon_0 m_0^2 c^3} \left(\frac{\mathrm{d}\vec{p}}{\mathrm{d}t}\right)^2 \sin^2\Psi$$

Radiation of a relativistic Charge

$$\mathrm{d}t \longrightarrow \mathrm{d}\tau = \frac{1}{\gamma}\mathrm{d}t \quad \text{where} \quad \gamma = \frac{E}{m_0 c^2} = \frac{1}{\sqrt{1-\beta^2}}$$

Replace: $$\left(\frac{\mathrm{d}P_\mu}{\mathrm{d}\tau}\right)^2 \longrightarrow \left(\frac{\mathrm{d}\vec{p}}{\mathrm{d}\tau}\right)^2 - \frac{1}{c^2}\left(\frac{\mathrm{d}E}{\mathrm{d}\tau}\right)^2$$

Details J.D.Jackson

$$P_s = \frac{e^2 c}{6\pi\epsilon_0}\frac{1}{(m_0 c^2)^2}\left[\left(\frac{\mathrm{d}\vec{p}}{\mathrm{d}\tau}\right)^2 - \frac{1}{c^2}\left(\frac{\mathrm{d}E}{\mathrm{d}\tau}\right)^2\right]$$

Radiation in Direction of Particle Motion

$$E\frac{\mathrm{d}E}{\mathrm{d}\tau} = c^2 p \frac{\mathrm{d}p}{\mathrm{d}\tau}$$

$$P_s = \frac{e^2 c}{6\pi\epsilon_0 (m_0 c^2)^2} \left(\frac{\mathrm{d}p}{\gamma \mathrm{d}\tau}\right)^2$$

With $\frac{\mathrm{d}p}{\mathrm{d}t} = \frac{\mathrm{d}E}{\mathrm{d}x}$

$$P_s = \frac{e^2 c}{6\pi\epsilon_0 (m_0 c^2)^2} \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)^2$$

Can be neglected w.r.t. accelerating gradient, only 10^{-13} of typical gradients.

Transverse Acceleration

$$E\frac{\mathrm{d}E}{\mathrm{d}t} = 0$$

$$P_s = \frac{e^2 c}{6\pi\epsilon_0}\frac{1}{(m_0 c^2)^2}\left(\frac{\mathrm{d}p}{\mathrm{d}\tau}\right)^2$$

$$P_s = \frac{e^2 c\gamma^2}{6\pi\epsilon_0}\frac{1}{(m_0 c^2)^2}\left(\frac{\mathrm{d}p}{\mathrm{d}t}\right)^2$$

with

$$\frac{\mathrm{d}p}{\mathrm{d}t} = p\omega = p\frac{v}{R}$$

$$P_s = \frac{e^2 c}{6\pi\epsilon_0}\frac{1}{(m_0 c^2)^2}\frac{E^4}{R^2}$$

relativistic

Energy loss per turn

$$\Delta E = \oint P_s \mathrm{d}t = P_s t_b = P_s \frac{2\pi R}{c}$$

$$\Delta E = \frac{e^2}{3\epsilon_0 (m_0 c^2)^4} \frac{E^4}{R}$$

$$\Delta E\,[\mathrm{keV}] = 88.5 \frac{E^4\,\left[\mathrm{GeV}^4\right]}{R\,[\mathrm{m}]}$$

Synchrotron Radiation – Angular dependence

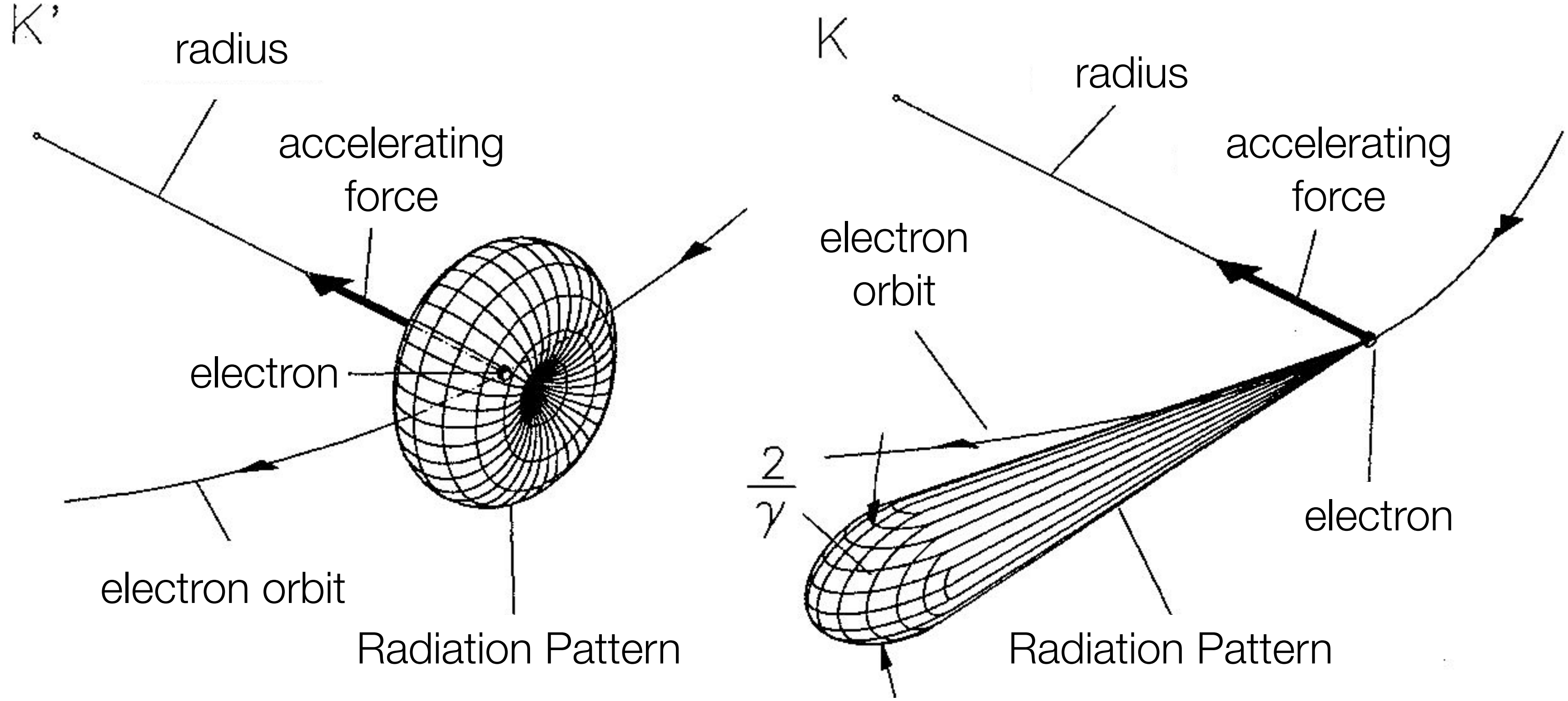
$$P'_\mu = \begin{pmatrix} p_t \\ p_x \\ p_y \\ p_z \end{pmatrix} = \begin{pmatrix} E'_s/c \\ 0 \\ p'_0 \\ 0 \end{pmatrix}$$

Single photon in y-direction

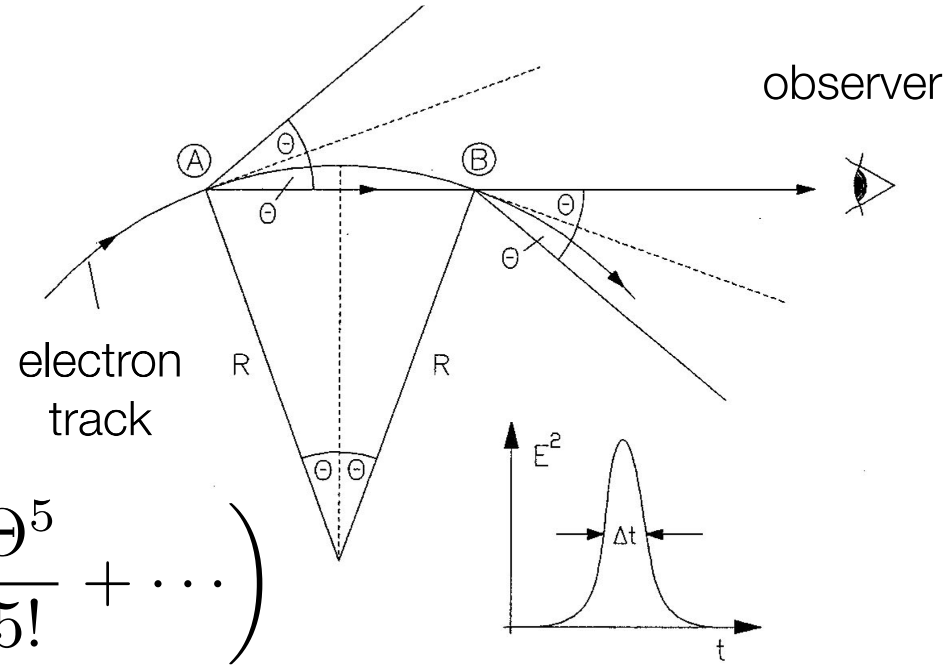
$$P_\mu = \begin{pmatrix} \gamma & 0 & 0 & \beta\gamma \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \beta\gamma & 0 & 0 & \gamma \end{pmatrix} \begin{pmatrix} E'_s/c \\ 0 \\ p'_0 \\ 0 \end{pmatrix} = \begin{pmatrix} \gamma E'_s/c \\ 0 \\ p'_0 \\ \gamma\beta E'_s/c \end{pmatrix}$$

$$\tan\Theta = \frac{p_y}{p_z} = \frac{p'_0}{\beta\gamma p'_0} \approx \frac{1}{\gamma}$$

Radiation Pattern



Time Structure



$$\begin{aligned}\Delta t &= \frac{2R\Theta}{c\beta} - \frac{2R\sin\Theta}{c} \\ &= \frac{2R}{c}\left(\frac{\Theta}{\beta} - \Theta + \frac{\Theta^3}{3!} - \frac{\Theta^5}{5!} + \cdots\right) \\ &\approx \frac{2R}{c}\left(\frac{1}{\beta\gamma} - \frac{1}{\gamma} + \frac{1}{6\gamma^3}\right) \approx \frac{4R}{3c\gamma^3}\end{aligned}$$

Broad Frequency spectrum

$$\omega_{\mathrm{typ}} = \frac{2\pi}{\Delta t} = \frac{3\pi c\gamma^3}{2R}$$

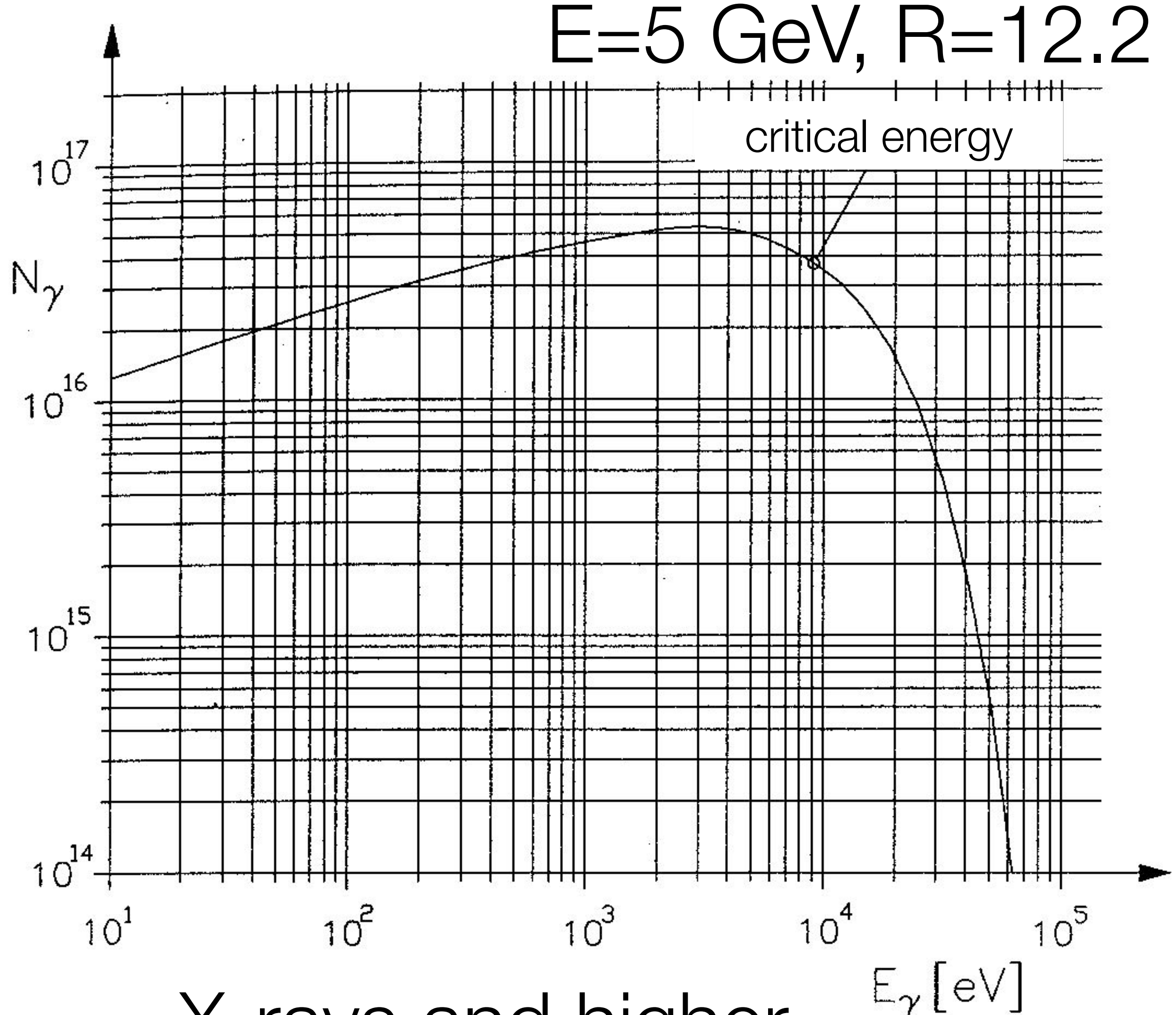
Spectral Density

$$\xi = \frac{\omega}{\omega_c}$$

$$\int_0^1 S_s(\xi)\mathrm{d}\xi = \frac{1}{2}$$

Definition of critical energy

E=5 GeV, R=12.2 m

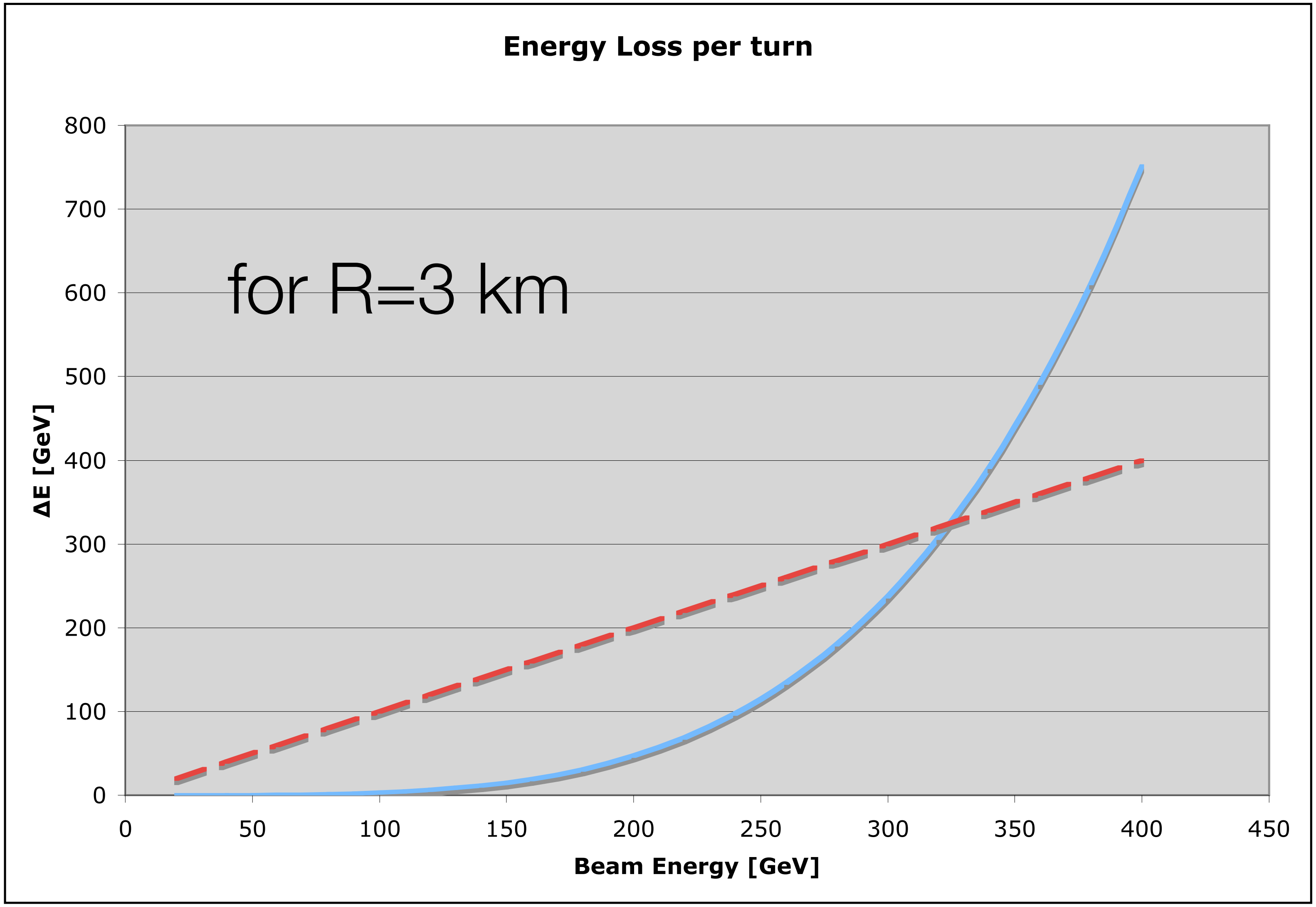


X-rays and higher

Examples of Energy Loss for Accelerators

Accelerator	L [m]	E [GeV]	R [m]	ΔE[MeV]
Doris	288	5.0	12.2	4.5
PETRA	2304	23.5	195	138
LEP I	27000	70	3000	708
LEP II		100		3000

Extending LEP?



Cost Scaling

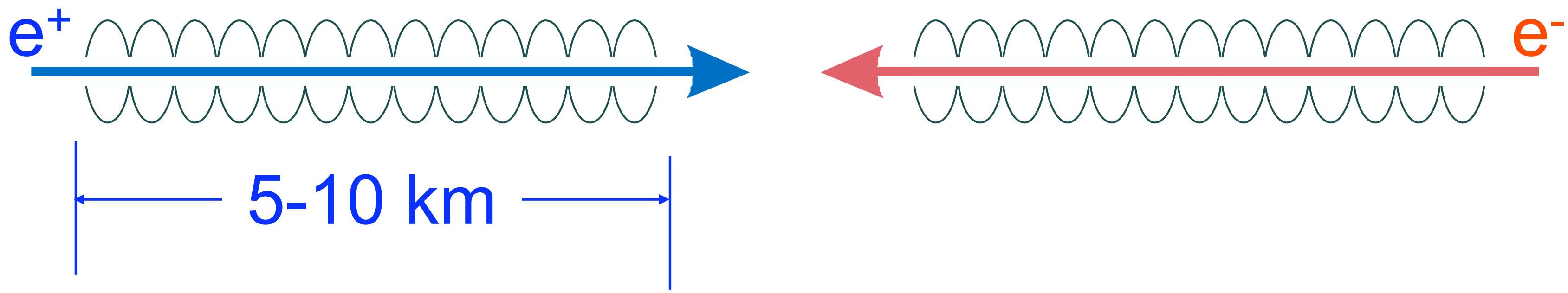
- Linear cost: tunnel, magnets, infrastructure
  $€_{lin} \sim \rho$

- RF cost
  $€_{RF} \sim E^4 / \rho$

- Optimum at
  $€_{lin} = €_{RF}$

Thus optimised cost ($€_{lin} + €_{RF}$) scales as E^2.

Solution: Linear Collider

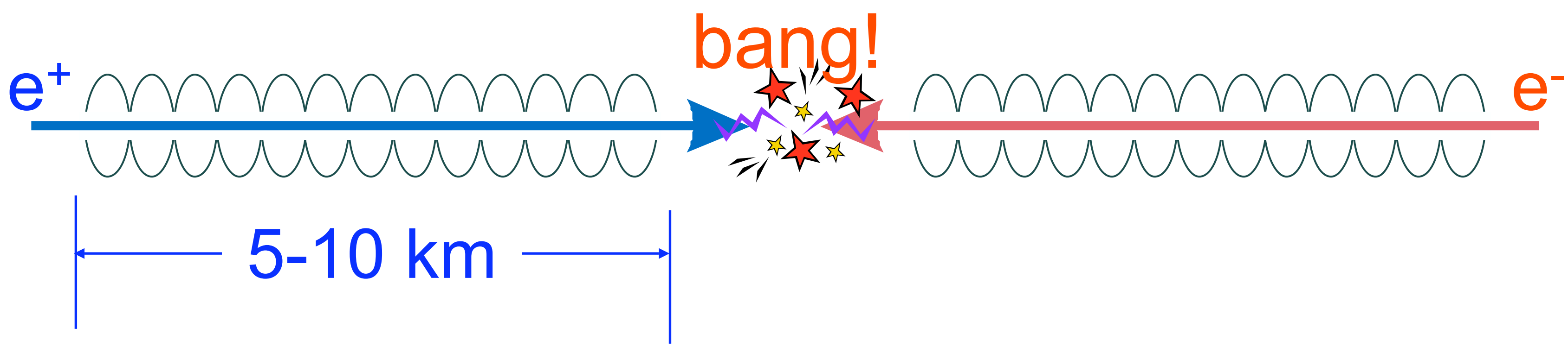


- long linac constructed of many RF accelerating structures

- typical gradients 25 – 100 MV/m; ILC nominal gradient 31.5 MV/m

- cost scales as E

Solution: Linear Collider



- long linac constructed of many RF accelerating structures
- typical gradients 25 – 100 MV/m; ILC nominal gradient 31.5 MV/m
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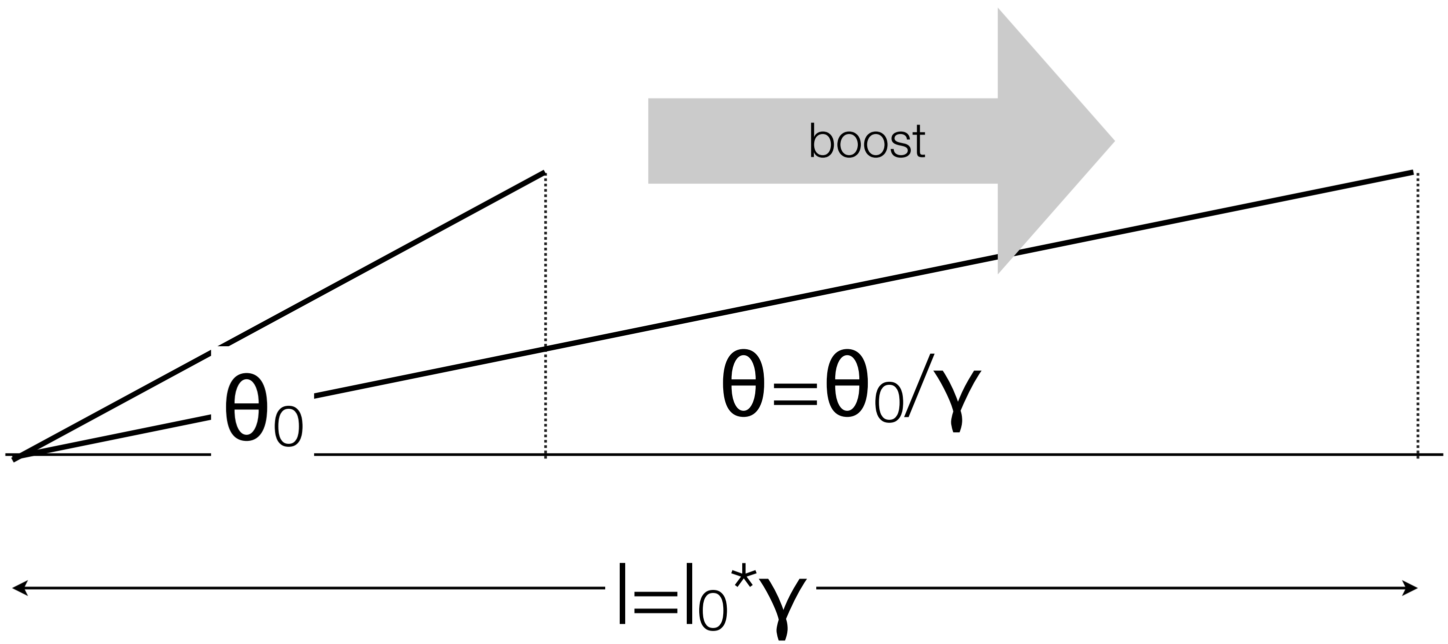
Emittance in Linear Collider



- similarly
  $\epsilon = \epsilon / \gamma$

- angular divergence is reduced relativistically

Luminosity

Collider luminosity is approximately given by

$$\mathcal{L} = \frac{n_b N^2 f_{\text{rep}}}{A} H_D$$

where:

$$\begin{aligned} n_b &= \text{bunches/train} \\ N &= \text{particles per bunch} \\ f_{\text{rep}} &= \text{repetition frequency} \\ A &= \text{beam cross section at IP} \\ H_D &= \text{beam} - \text{beam enhancement factor} \end{aligned}$$

for Gaussian beams

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

Luminosity: RF Power

With centre of mass energy

$$\mathcal{L} = \frac{(E_{\mathrm{cm}} n_b N f_{\mathrm{rep}})N}{4\pi\sigma_x\sigma_y E_{\mathrm{cm}}} H_D$$

$$\begin{aligned} n_b N f_{\mathrm{rep}} E_{\mathrm{cm}} &= P_{\mathrm{beams}} \\ &= \eta_{\mathrm{RF}} P_{\mathrm{RF}} \end{aligned}$$

for Gaussian beam

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

Luminosity: RF Power

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

Power Estimate

$$\left.\begin{array}{rcl} E_{\mathrm{cm}} & = & 500\,\mathrm{GeV} \\ N & = & 10^{10} \\ n_b & = & 100 \\ f_{\mathrm{rep}} & = & 100\ (5)\,\mathrm{Hz} \end{array}\right\} P_{\mathrm{beams}} = 8\mathrm{MW}$$

Need to include efficiencies

RF⇒beam: range 20-60%

Wall plug ⇒ RF: range 28-40% Linac Technology!

AC power >100 MW just to accelerate beams and achieve luminosity.

Storage Ring vs LC

Repetition rate

LEP: 44 kHz

LC: few to 100 Hz

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

Factor 400 lost!

Compensate by beam cross section at IP

$$\begin{array}{llll} \mathrm{LEP}: & \sigma_x \sigma_y & \approx & 130 \times 6 \mu\mathrm{m}^2 \\ \mathrm{LC}: & \sigma_x \sigma_y & \approx & (200 - 500) \times (3 - 5)\mathrm{nm}^2 \end{array}$$

Factor 10^6 gained!

Needed to obtain $\mathcal{L} = \mathrm{a\ few\ } 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

Intense Beams at IP

$$\mathcal{L} = \frac{1}{4\pi}(\eta_{\mathrm{RF}} P_{\mathrm{RF}}) \left(\frac{N}{\sigma_x \sigma_y} H_D \right)$$

<u>Choice of linac technology</u>

- efficiency
- available power

<u>Beam-Beam effects</u>

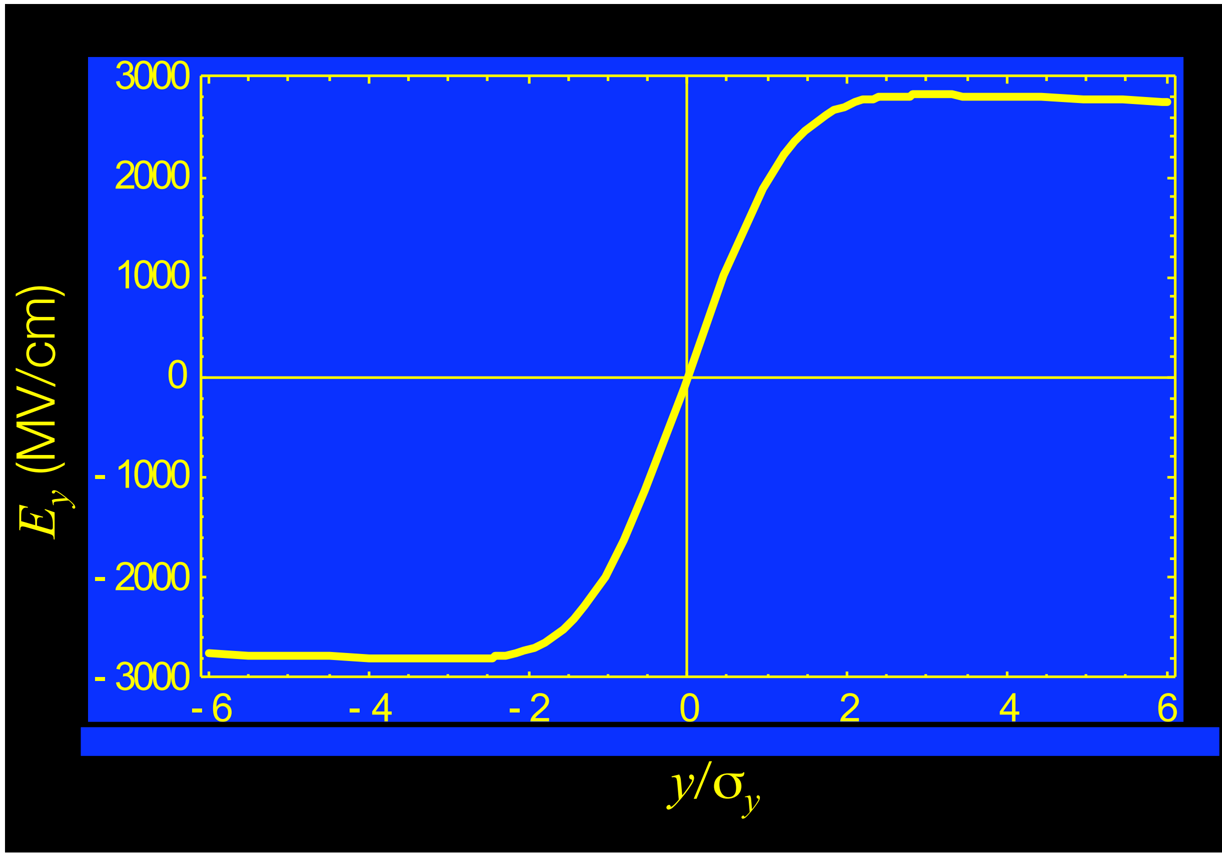
- beamstrahlung
- disruption

<u>Strong focusing</u>

- optical aberrations
- stability issues and tolerances

Luminosity Issue. Beam-beam Interaction

- strong mutual focusing of beams (pinch) gives rise to luminosity enhancement HD
- As $e^{\pm}$ pass through intense field of opposing beam, they radiate hard photons [beamstrahlung] and loose energy
- Interaction of beamstrahlung photons with intense field causes copious e^+e^- pair production [background]



Beam Beam Interaction at IP

Beam beam characterized by *Disruption* parameter:

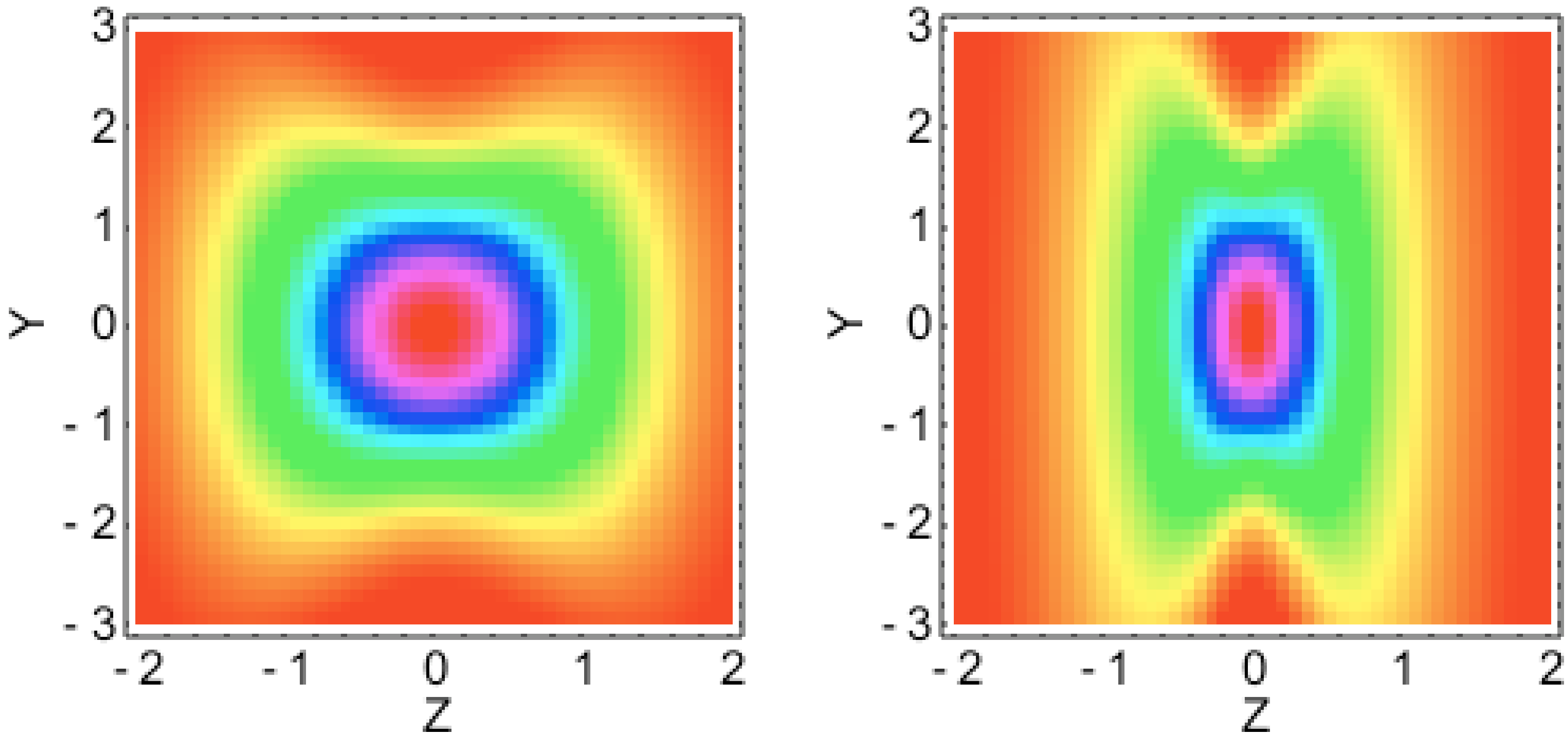
$$D_{x,y} = \frac{2 r_e N \sigma_z}{\gamma \sigma_{x,y}(\sigma_x + \sigma_y)} \approx \frac{\sigma_z}{f_{\mathrm{beam}}}$$

For storage rings $f_{beam} \sim \sigma_z$ and $D_{x,y} \sim 1$.
In a LC, $D_y \sim 10\text{-}20$ and hence $f_{beam} < \sigma_z$

Enhancement factor (typically $H_D \sim 2$)

$$H_{D_{x,y}} = 1 + D_{x,y}^{1/4} \left(\frac{D_{x,y}^3}{1 + D_{x,y}^3} \right) \left[\ln(\sqrt{D_{x,y}} + 1) + 2 \underbrace{\ln \left(\frac{0.8 \beta_{x,y}}{\sigma_z} \right)}_{\text{Hour glass effect}} \right]$$

Hour Glass Effect



β = "depth of focus"
reasonable lower limit for
β is bunch length σ_z

Beamstrahlung

RMS relative energy loss

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

Would like to make **σ**$_x$ **σ**$_y$ small to maximise luminosity.

BUT keep (**σ**$_x$ + **σ**$_y$) large to reduce δ_{SB}.

Trick: use "flat beams" with $\sigma_x \gg \sigma_y$

$$\delta_{BS} \propto \left(\frac{E_{cm}}{\sigma_z} \right) \frac{N^2}{\sigma_x^2}$$

Now we set **σ**$_x$ to fix δ_{SB}, and make **σ**$_y$ as small as possible to achieve high luminosity.

For most LC designs, δ_{SB} ~ 3-10%

Beamstrahlung

Returning to our L scaling law, and ignoring H_D

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

From flat-beam beamstrahlung

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

hence

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

So far:

For high luminosity we need:

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

- high RF-beam conversion efficiency
- high RF power
- small vertical beam size
- large bunch length (to be reconsidered)
- and could allow for larger beamstrahlung if willing to live with consequences

Small vertical beam size

$$\mathcal{L} \propto \frac{\eta_{\rm RF} P_{\rm RF}}{E_{\rm cm}^{3/2}} \frac{\sqrt{\delta_{\rm BS}\sigma_z}}{\sigma_y} \qquad \sigma_y = \sqrt{\frac{\beta_y \epsilon_{n,y}}{\gamma}}$$

with $\epsilon_{n,y}$ normalised vertical emittance and β_y the vertical β-function at the IP.

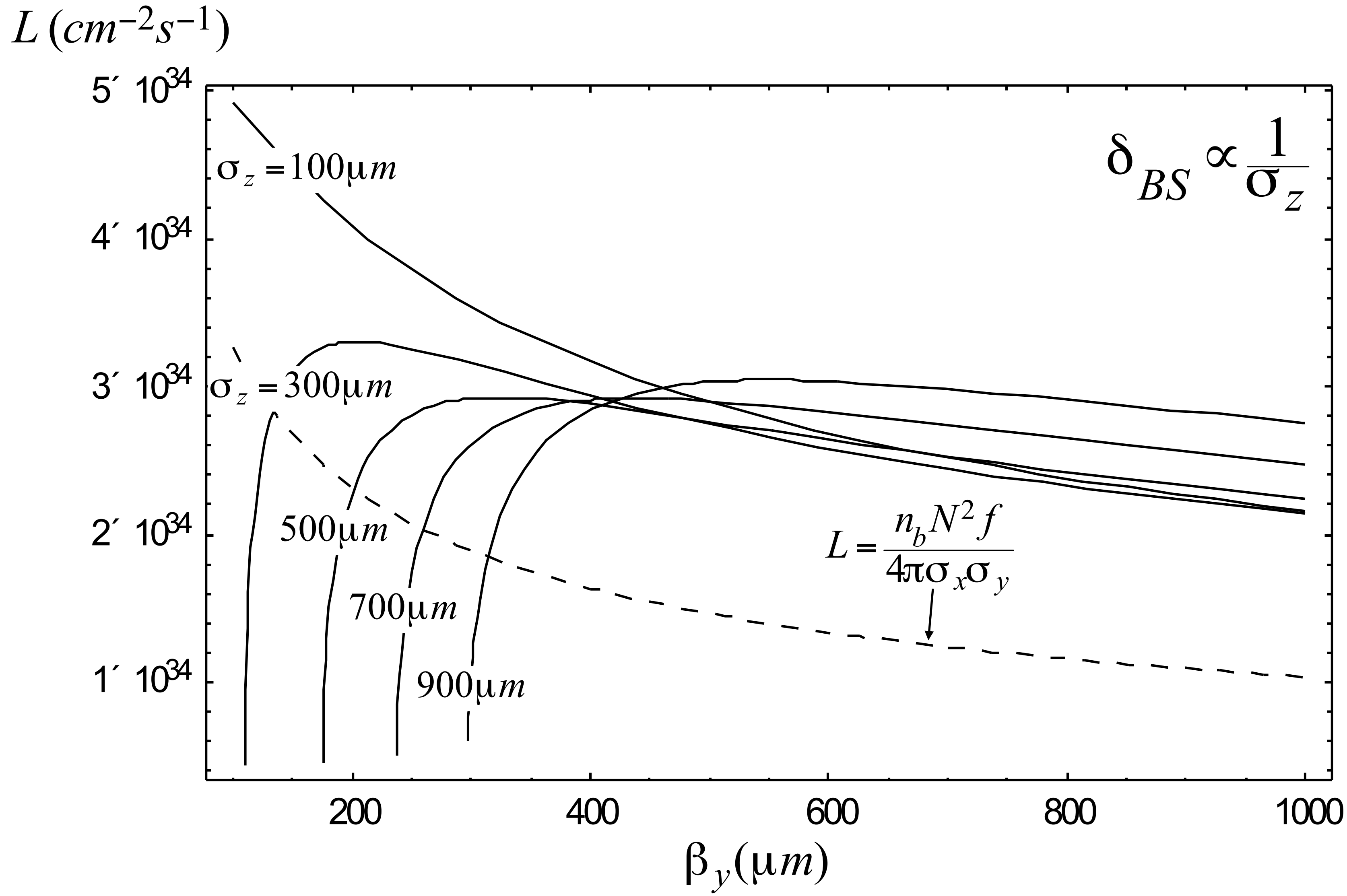
$$\mathcal{L} \propto \frac{\eta_{\rm RF} P_{\rm RF}}{E_{\rm cm}^{3/2}} \sqrt{\frac{\delta_{\rm BS}\gamma}{\epsilon_{n,y}}} \sqrt{\frac{\sigma_z}{\beta_y}} \propto \frac{\eta_{\rm RF} P_{\rm RF}}{E_{\rm cm}} \sqrt{\frac{\delta_{\rm BS}}{\epsilon_{n,y}}} \sqrt{\frac{\sigma_z}{\beta_y}}$$

Optimised Scaling Law

$$\mathcal{L} \propto \frac{\eta_{\mathrm{RF}} P_{\mathrm{RF}}}{E_{\mathrm{cm}}} \sqrt{\frac{\delta_{\mathrm{BS}}}{\epsilon_{n,y}}} H_D \quad \text{for } \sigma_z \approx \beta_y$$

- high RF-beam conversion efficiency
- high RF power
- small normalised vertical emittance
- strong focussing at IP (small β_y and hence small σ_z!)
- and could allow for larger beamstrahlung if willing to live with consequences

Luminosity as a function of β_y



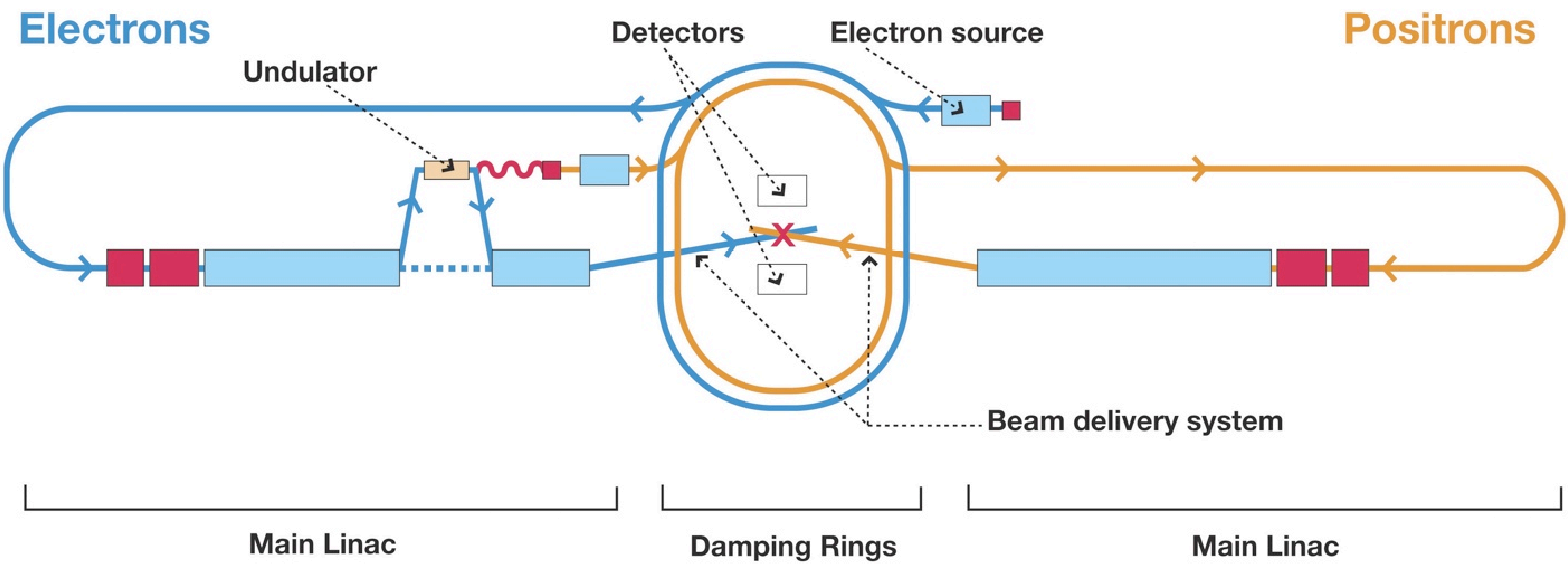
Past and Future

	SLC	ILC	
E_{CM}	100	500-1000	GeV
P_{Beam}	0.04	5-20	MW
σ^*_y	500	1-5	nm
δ_E/E_{bs}	0.03	3-10	%
L	0.0003	~3	10^{34} $cm^{-2}s^{-1}$

generally quoted as ‘proof of principle’

but a long way to go!

Components of the ILC



www.linearcollider.org

HOW DOES THE ILC WORK?

Supersymmetry. Dark matter. Extra dimensions. Scientists have proposed the International Linear Collider (ILC), a next-generation project designed to smash together electrons and their antiparticles at a higher-than-ever energy, to learn more about these and other mysteries of the universe. The ILC Global Design Effort team, which includes more than 60 scientists and engineers from around the world, has agreed on the baseline configuration for the roughly 31-kilometer long, 500 billion-electronvolt (GeV) particle collider.

The Linacs
Scientists will use two main linear accelerators ("linacs"), one for electrons and one for positrons, each 12 kilometers long, to accelerate the bunches of particles toward the collision point. Each linac consists of 8,000 superconducting cavities nestled within a series of cooled vessels to form cryomodules. The modules use liquid helium to cool the cavities to -271°C, only slightly above absolute zero. Scientists will launch traveling electromagnetic waves into the cavities to "push" the particles through, and accelerate them to energies that will total 500 GeV.

Positrons
Positrons, the antimatter partners of electrons, do not exist naturally on earth. To produce them scientists will send the high-energy electron beam through an undulator, a special arrangement of magnets in which electrons are sent on a "roller-coaster" course. This turbulent motion will cause the electrons to emit a stream of photons. Just beyond the undulator the electrons will return to the main accelerator, while the photons will hit a titanium-alloy target and produce pairs of electrons and positrons. The positrons will be collected and launched into their own 250-meter 5-GeV accelerator.

The Detectors
Traveling towards each other at nearly the speed of light, the electron and positron bunches will collide with a total energy of 500 GeV. Scientists will record the spectacular collisions in two giant particle detectors. These work like gigantic cameras, taking snapshots of the particles produced by the electron-positron annihilations. The two detectors will incorporate different but complementary state-of-the-art technologies to capture information about every particle produced in each collision. Having these two detectors will allow vital cross-checking of the potentially-subtle physics discovery signatures.

The Damping Rings
When created, neither the electron nor the positron bunches are compact enough to yield the high density needed to produce collisions inside the detectors. Scientists will solve this problem by using seven-kilometer-circumference damping rings, one for electrons and one for positrons. In each ring, the bunches will travel through a series of wigglers that literally "wiggle" the beam to emit photons. This process makes the bunches more compact. Each bunch will circle the damping ring roughly 10,000 times in only two tenths of a second. Upon exiting the damping rings, the bunches will be a few millimeters long and thinner than a human hair.

Electrons
To produce electrons scientists will fire high-intensity, two-nanosecond light pulses from a laser at a target and knock out billions of electrons per pulse. They will gather the electrons using electric and magnetic fields to create bunches of particles and launch them into a 250-meter linear accelerator that boosts their energy to 5 GeV.

Drawing not to scale
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