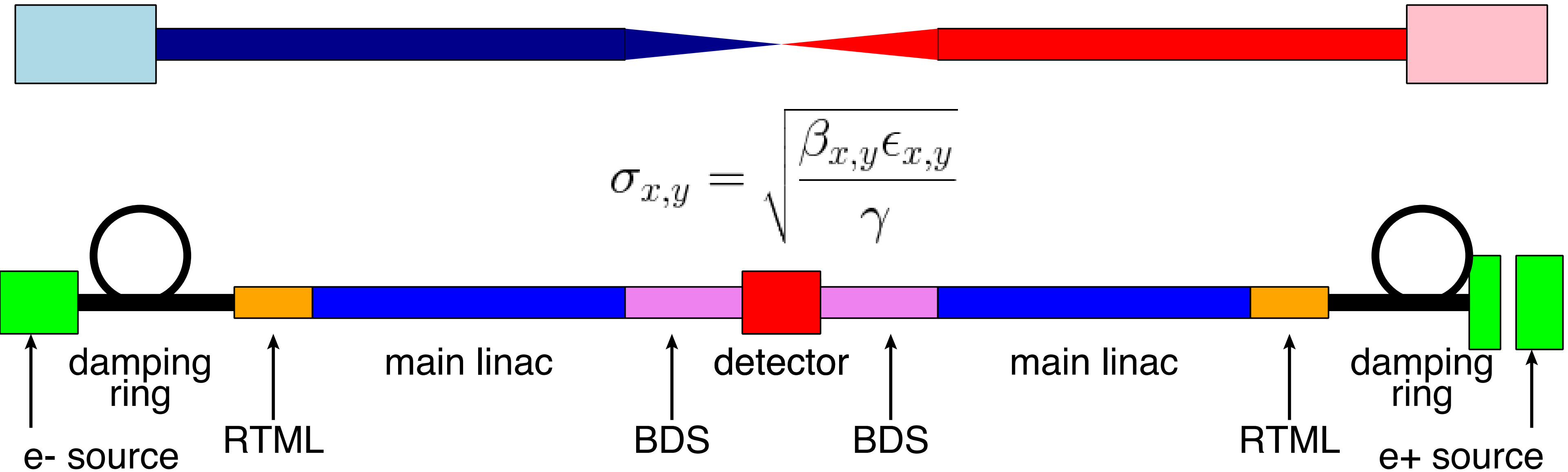
Beam-beam Effects in Linear Colliders

Daniel Schulte

Generic Linear Collider



$$\sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\epsilon_{x,y}}{\gamma}}$$

Single pass poses luminosity challenge

Low emittances are produced in the damping rings

They must be maintained with limited degradation

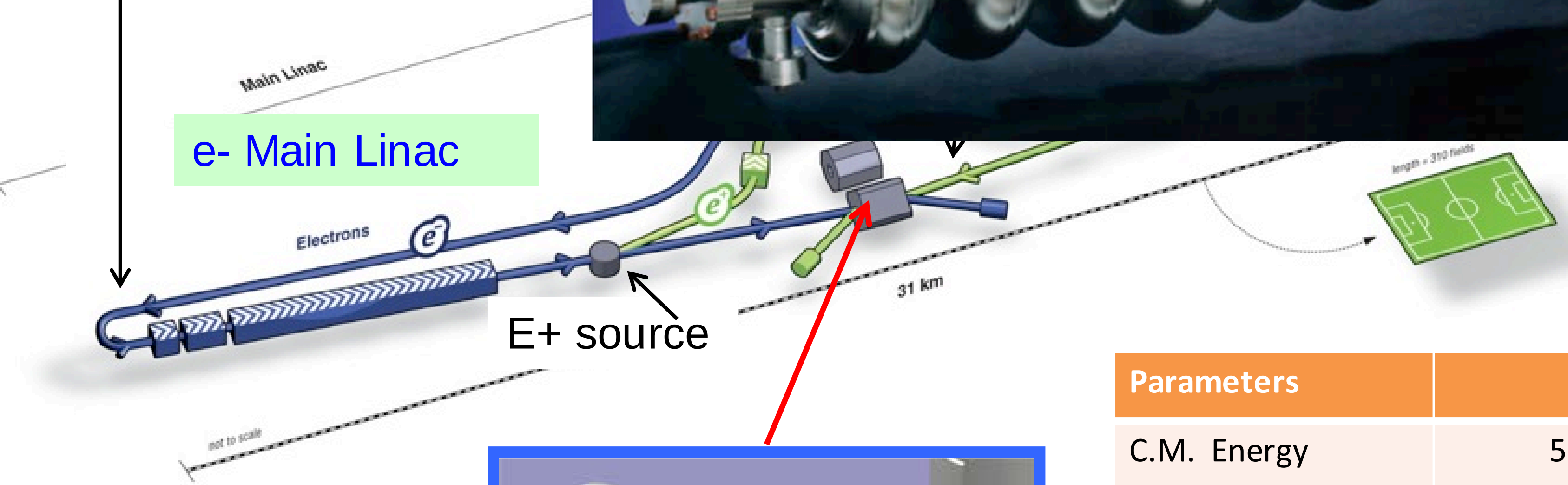
The beam delivery system (BDS) squeezes the beam as much as possible

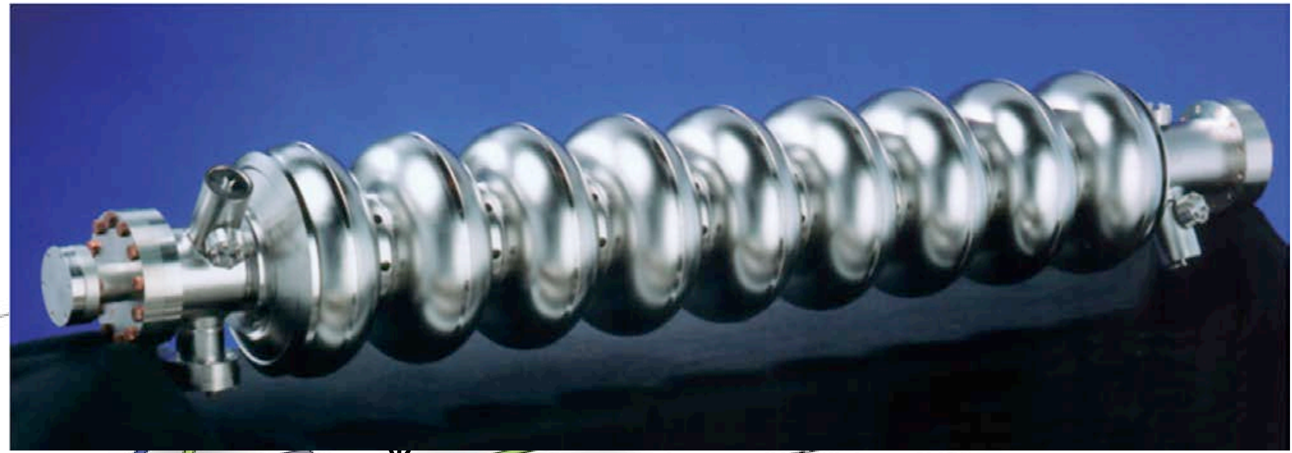
ILC

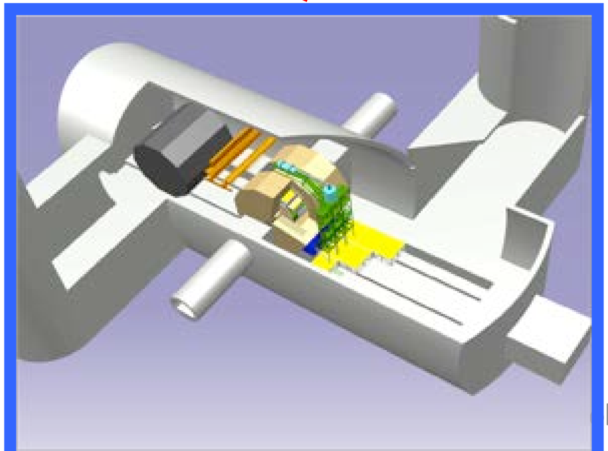
Ring to Main Linac (RTML)
(w. bunch compressors)

e- Main Linac

E+ source

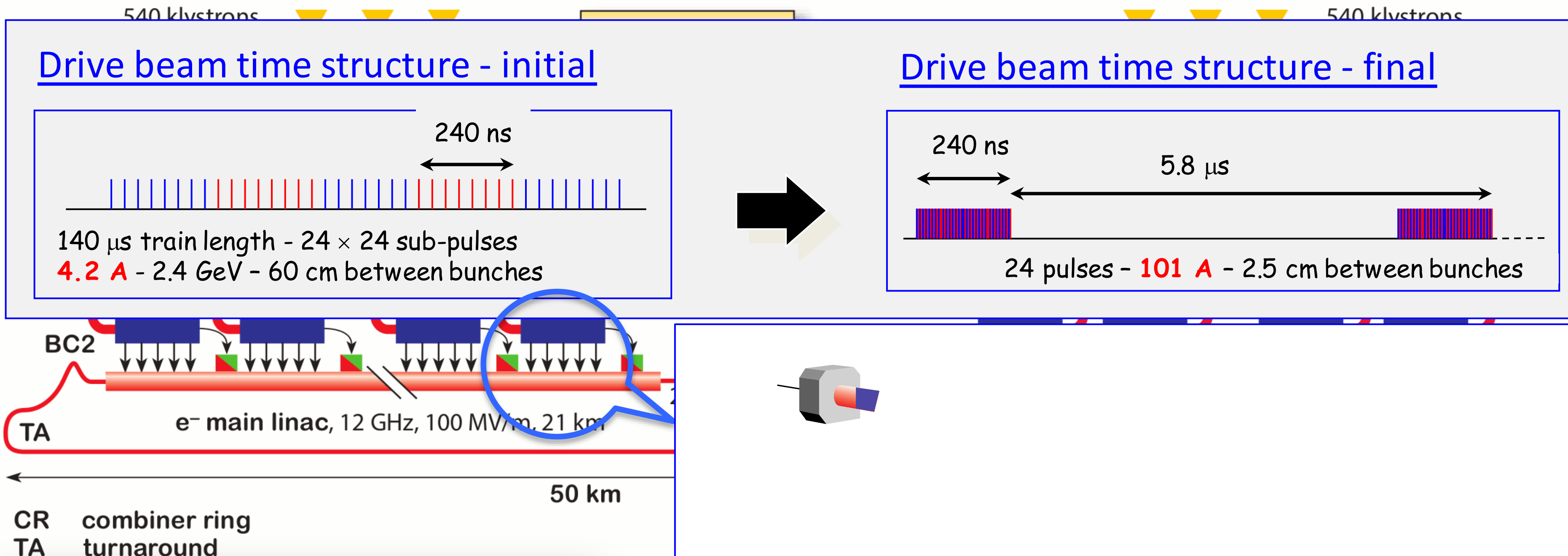


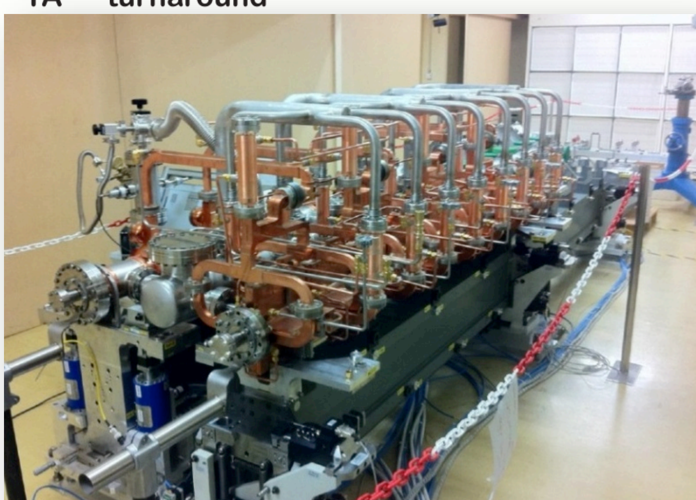


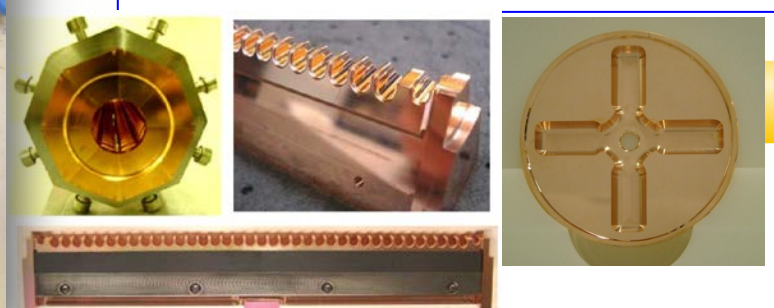


Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

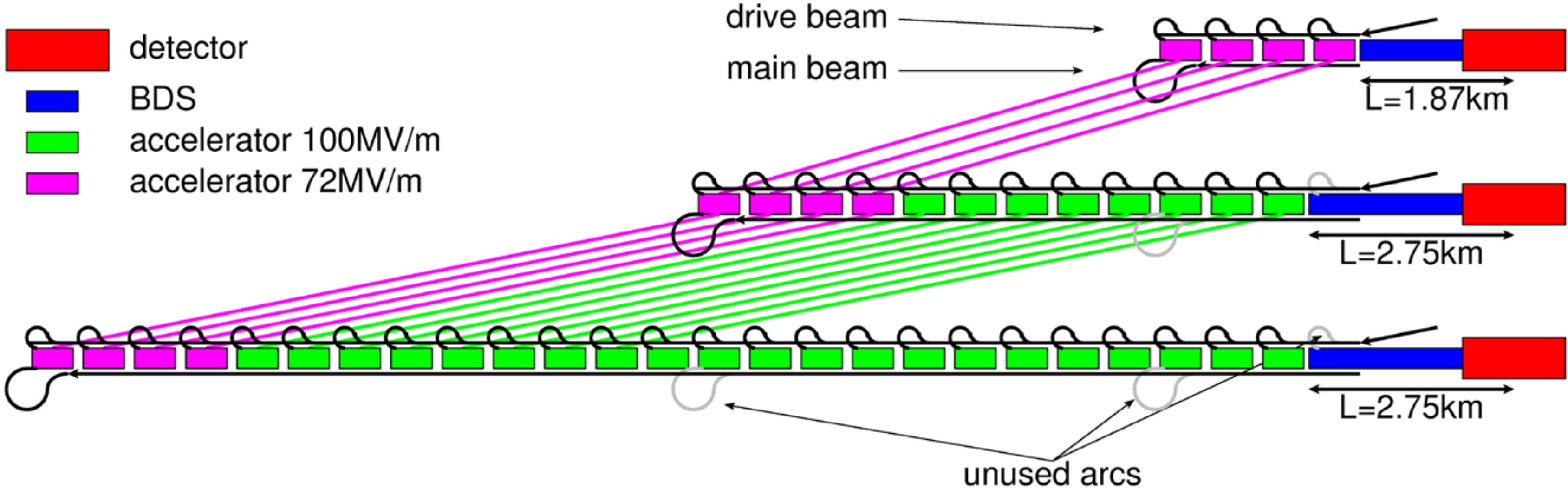
CLIC (at 3TeV)


540 klystrons
540 klystrons
Drive beam time structure - initial
240 ns
140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches
Drive beam time structure - final
240 ns
5.8 μs
24 pulses – 101 A – 2.5 cm between bunches
BC2
TA
e⁻ main linac, 12 GHz, 100 MV/m, 21 km
50 km
CR combiner ring
TA turnaround



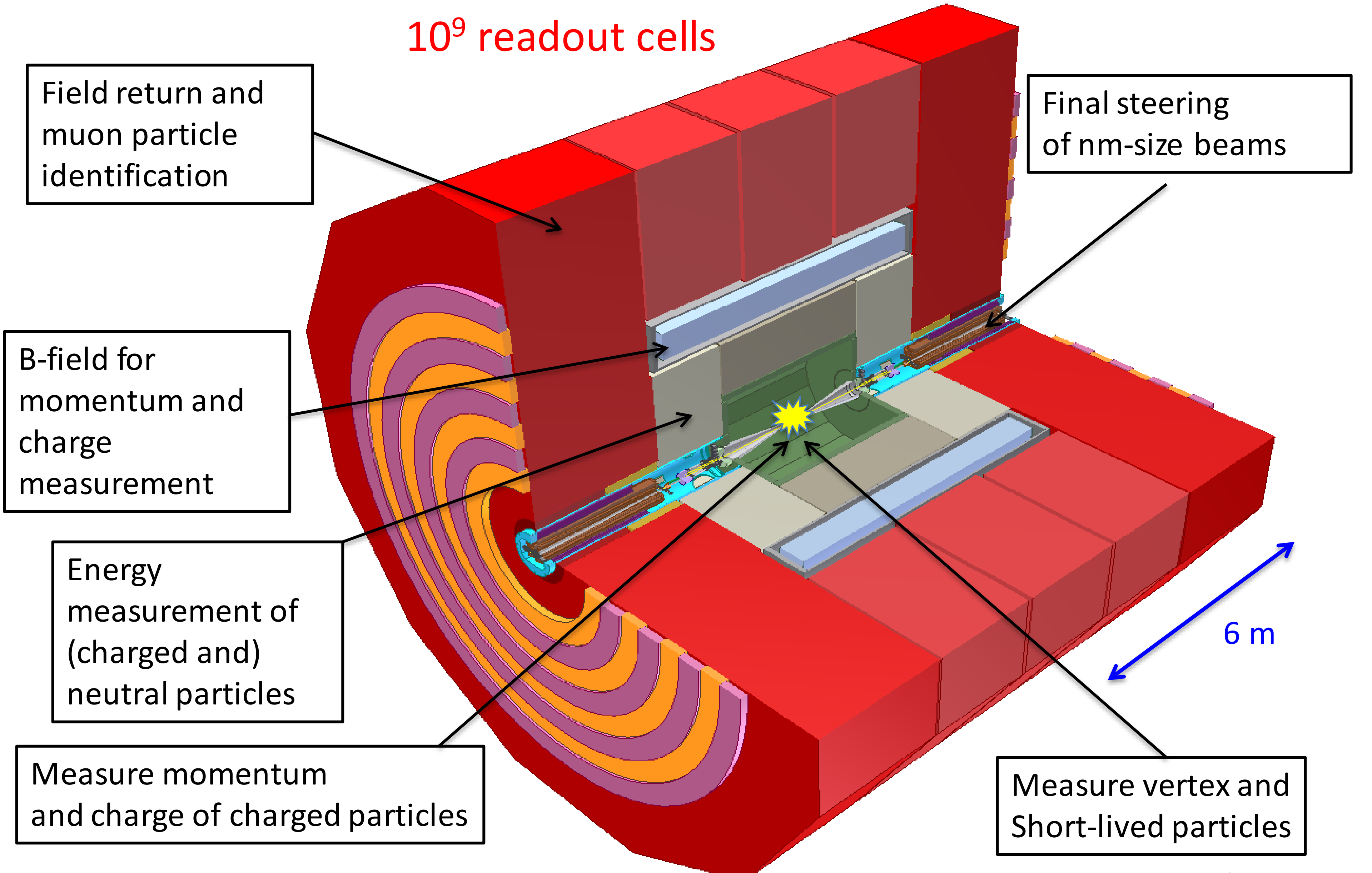


CLIC Staged Approach



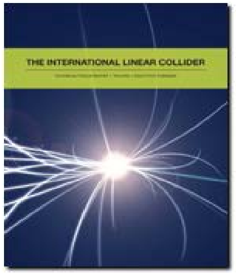
- First stage: E_{cms}=380Gev, L=1.5x10^{34}cm^{-2}s^{-1}, $L_{0.01}$/L>0.6
- Second stage: E_{cms}=O(1.5TeV)
- Final stage: E_{cms}=3TeV, $L_{0.01}$=2x10^{34}cm^{-2}s^{-1}, $L_{0.01}$/L>0.3

Linear Collider Experiment



Note: ILC TDR

Volume 1 - Executive Summary



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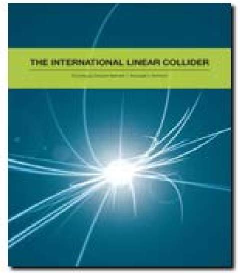
Volume 2 - Physics



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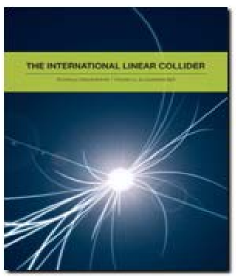
Volume 3 - Accelerator



Part I:
R&D in the Technical Design Phase

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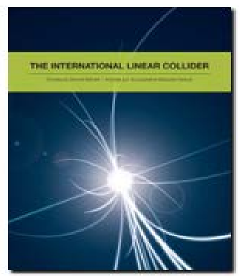
Volume 3 - Accelerator



Part II:
Baseline Design

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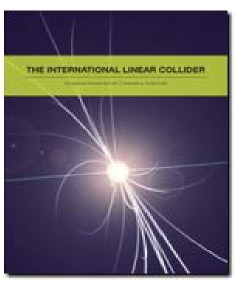
Volume 4 - Detectors



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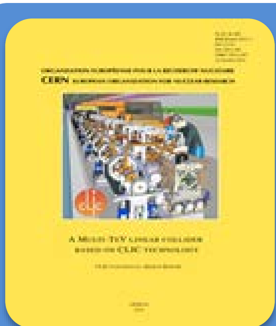
From Design to Reality

Download the pdf (5.5 MB)
Visit the web site

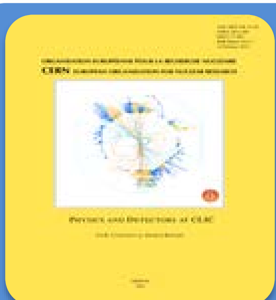
http://www.linearcollider.org/ILC/Publications/Technical-Design-Report

Note: CLIC CDR



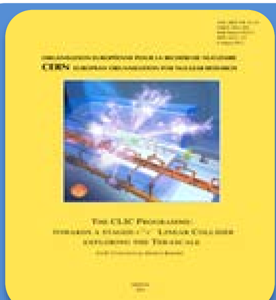
Vol 1: The CLIC accelerator and site facilities

- CLIC concept with exploration over multi-TeV energy range up to 3 TeV
- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)
- Consider also 500 GeV, and intermediate energy range
- https://edms.cern.ch/document/1234244/



Vol 2: Physics and detectors at CLIC

- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions
- External review procedure in October 2011
- http://arxiv.org/pdf/1202.5940v1



Vol 3: "CLIC study summary"

- Summary and available for the European Strategy process, including possible implementation stages for a CLIC machine as well as costing and cost-drives
- Proposing objectives and work plan of post CDR phase (2012-16)
- http://arxiv.org/pdf/1209.2543v1

In addition a shorter overview document was submitted as input to the European Strategy update, available at: http://arxiv.org/pdf/1208.1402v1

Input documents to Snowmass 2013 has also been submitted: http://arxiv.org/abs/1305.5766 and http://arxiv.org/abs/1307.5288

ILC and CLIC Main Parameters

Parameter	Symbol [unit]	SLC	ILC	CLIC	CLIC
Centre of mass energy	E_{cm} [GeV]	92	500	380	3000
Geometric luminosity	L_{geom} [$10^{34}cm^{-2}s^{-1}$]	0.00015	0.75	0.8	4.3
Total luminosity	L [$10^{34}cm^{-2}s^{-1}$]	0.0003	1.8	1.5	6
Luminosity in peak	$L_{0.01}$ [$10^{34}cm^{-2}s^{-1}$]	0.0003	1	0.9	2
Gradient	G [MV/m]	20	31.5	72	100
Particles per bunch	N [10^9]	37	20	5.2	3.72
Bunch length	σ_z [μm]	1000	300	70	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	1700/600	474/5.9	149/2.9	40/1
Emittance	$\varepsilon_{x,y}$ [μm/nm]	~3/3000	10/35	0.95/30	0.66/20
Betafunction	$\beta_{x,y}$ [mm/mm]	~100/10	11/0.48	8.2/0.1	6/0.07
Bunches per pulse	n_b	1	1312	352	312
Distance between bunches	Δz [ns]	-	554	0.5	0.5
Repetition rate	f_r [Hz]	120	5	50	50

There are more parameter sets for ILC and CLIC at different energies
CLIC at 3TeV has higher order optics and radiation effects

Luminosity and Parameter Drivers

Can re-write normal luminosity formula (note: no crossing angle assumed)

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

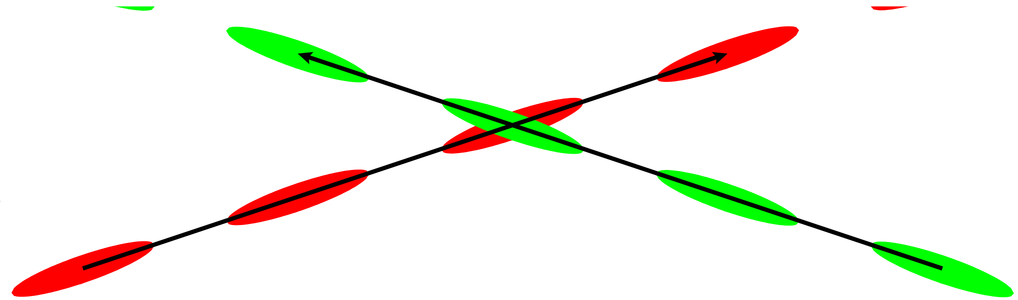
$$\mathcal{L} \propto H_D \ \frac{N}{\sigma_x} \ N n_b f_r \ \frac{1}{\sigma_y}$$

- $\frac{N}{\sigma_x}$: Luminosity spectrum
- $N n_b f_r$: Beam power
- $\frac{1}{\sigma_y}$: Beam Quality (+bunch length)

Somewhat simplified view

Note: Crossing Angle

Have crossing angles
- ILC: 14mradian
- CLIC: 20mradian
- to reduce effects of parasitic crossings
- to extract the spent beam cleanly

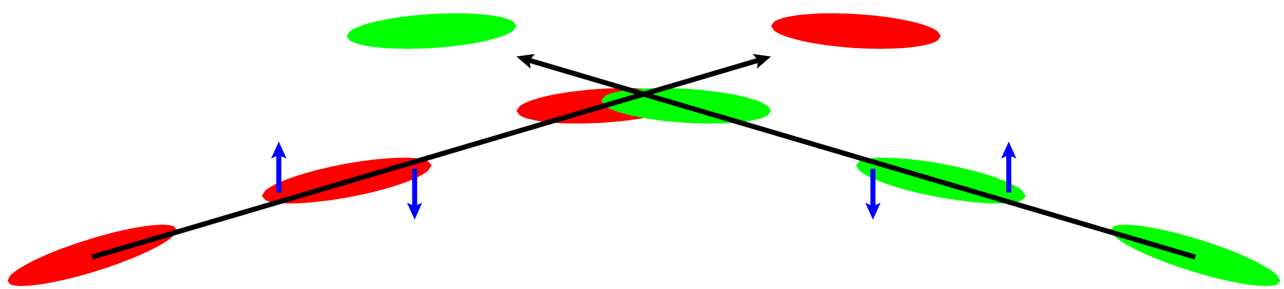


Luminosity with crossing angle

$$\mathcal{L} = H_D \frac{N^2 f_r n_b}{4\pi\sigma_x\sigma_y} \frac{1}{\sqrt{1+\left(\frac{\sigma_z}{\sigma_x}\tan\frac{\theta_c}{2}\right)^2}}$$

0.1-0.2

Use crab cavities:



Can ignore crossing angle for beam-beam calculation
But not in detector design

Beam-beam Effect

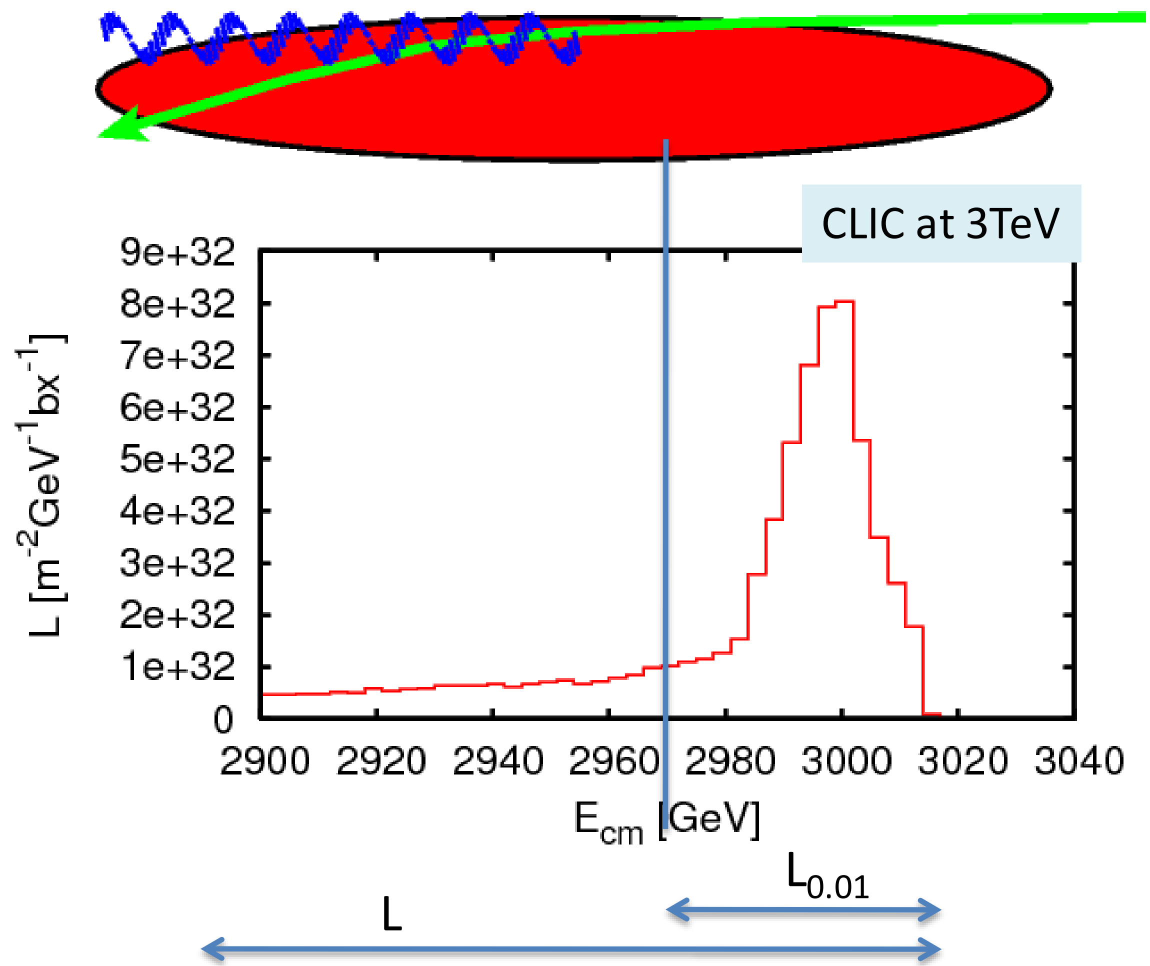
Bunches are squeezed strongly to maximise luminosity

Electron magnetic fields are very strong

Beam particles travel on curved trajectories

They emit photons (O(1)) (beamstrahlung)

They collide with less than nominal energy

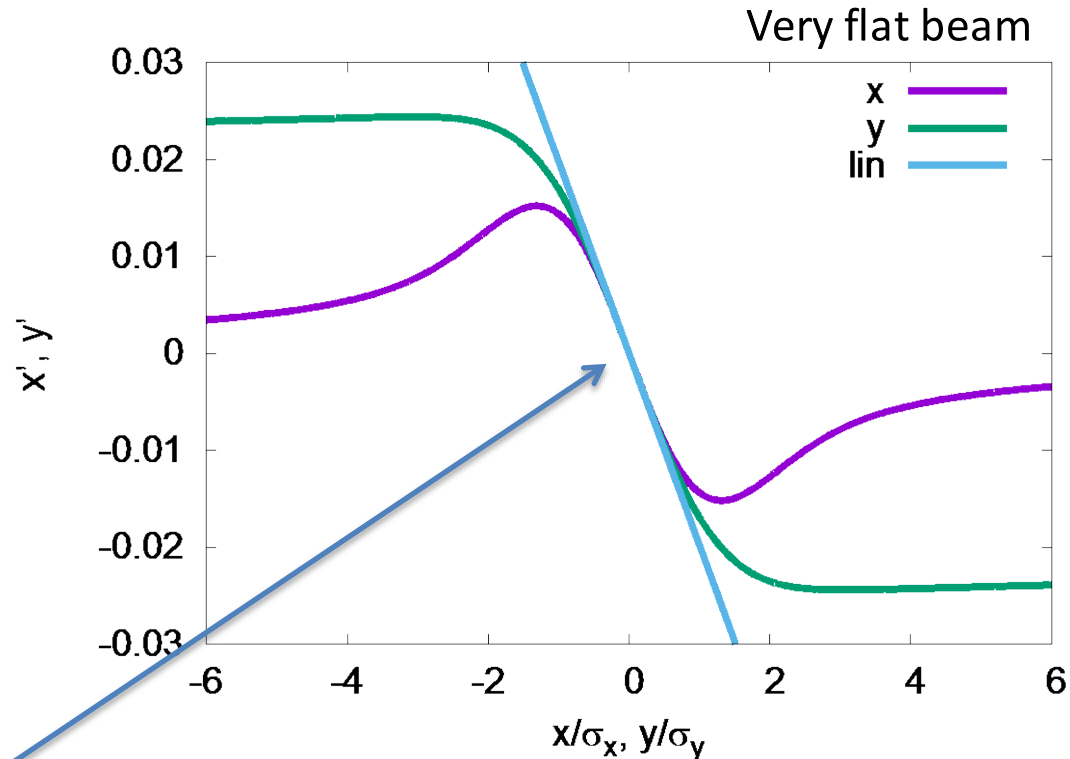


Request from physics
$L_{0.01}/L>0.6$ below 500GeV
$L_{0.01}/L>0.3$ at 3TeV

Beam Focusing

Note: The colliding beams are flat to reduce beamstrahlung, we will see later why

Deflection easy to calculate for
- small offset to the axis
- no initial angle
- negligible change of trajectory



In each plane core of beam is focused to one point

$$s = f_x \qquad s = f_y$$

Previous lecture showed

$$\left.\frac{dx}{dz}\right|_{final} = -\frac{2Nr_e x}{\gamma\sigma_x(\sigma_x+\sigma_y)}$$

$$\left.\frac{dy}{dz}\right|_{final} = -\frac{2Nr_e y}{\gamma\sigma_y(\sigma_x+\sigma_y)}$$

$$r_e \approx 2.8 \times 10^{-15}\ \mathrm{m}$$

Disruption Parameter

We define the disruption parameters to compare the focal length of the bunch to its length

$$D_x = \frac{\sigma_z}{f_x} = \frac{2Nr_e\sigma_z}{\gamma(\sigma_x+\sigma_y)\sigma_x} \qquad D_y = \frac{\sigma_z}{f_y} = \frac{2Nr_e\sigma_z}{\gamma(\sigma_x+\sigma_y)\sigma_y}$$

$$D \ll 1$$

Particles do not move much in beam
$\Rightarrow$ Thin lens approximation is OK
$\Rightarrow$ Analytic calculation possible
$\Rightarrow$ Weak-strong simulation sufficient

$\Rightarrow$ Typical for x-plane

$$D \gg 1$$

Particles do move in beam
$\Rightarrow$ thin lens assumption has been wrong
$\Rightarrow$ Analytic calculation tough
$\Rightarrow$ Strong-strong simulation required

$\Rightarrow$ Typical for y-plane

Typical Disruption

Parameter	Symbol [unit]	SLC	ILC	CLIC	CLIC
Centre of mass energy	E_{cm} [GeV]	92	500	380	3000
Particles per bunch	N [10^9]	37	20	5.2	3.72
Bunch length	σ_z [μm]	1000	300	70	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	1700/600	474/5.9	149/2.9	40/1
Vertical emittance	$\varepsilon_{x,y}$ [nm]	3000	35	40	20
Horizontal disruption	D_x	0.6	0.3	0.24	0.2
Vertical disruption	D_y	1.7	24.3	12.5	7.6

$D_x \ll 1$ and $D_y \gg 1$ → Need to resort to strong-strong simulation

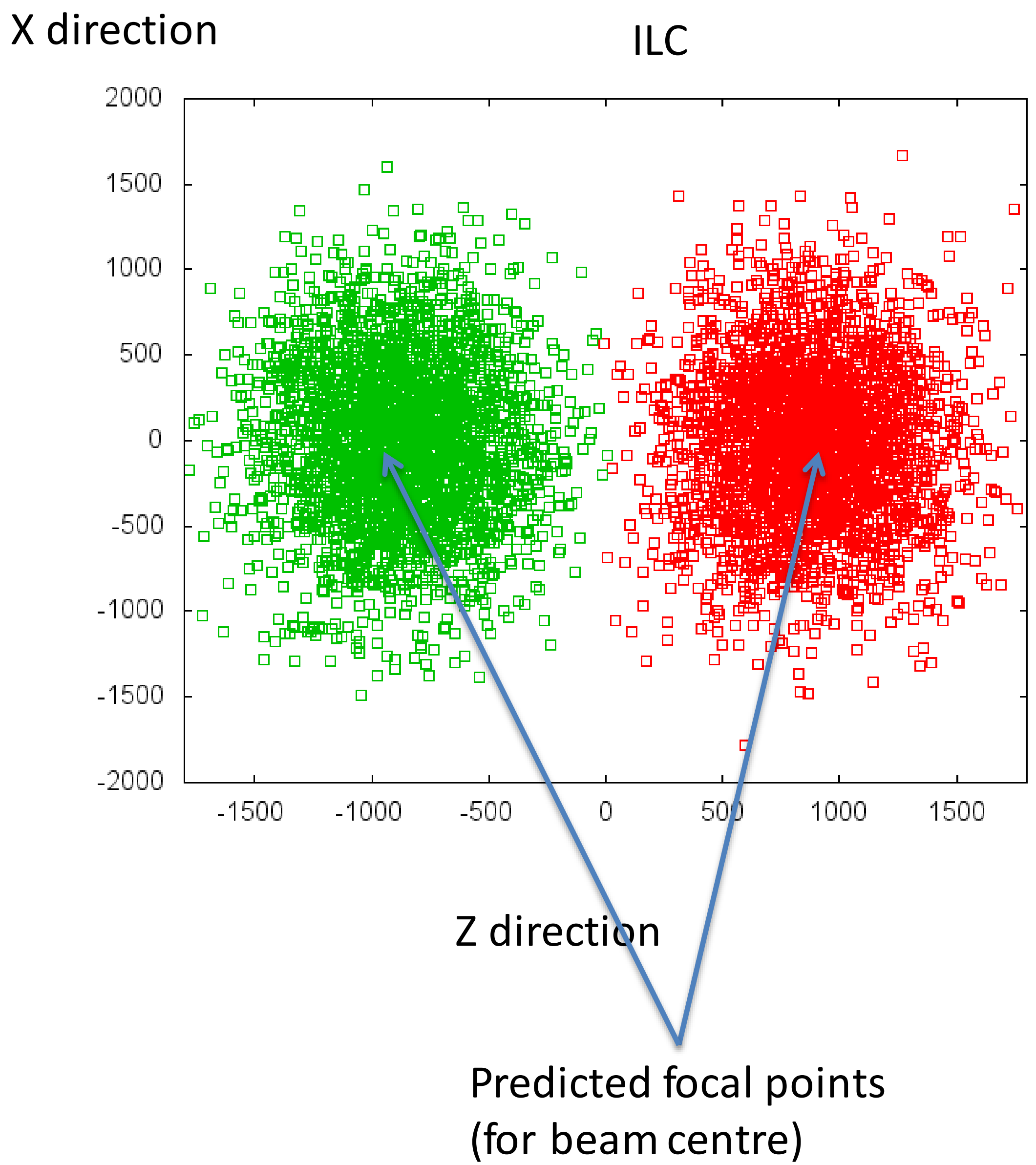
Simulation Codes

Need strong-strong code

- CAIN (K. Yokoya et al.)
- GUINEA-PIG (D. Schulte et al.)

- Beams => macro particles
- Beams => slices
- Slices => cells
- The simulation is performed in a number of time steps in each of them
- The macro-particle charges are distributed over the cells
    - The forces at the cell locations are calculated
    - The forces are applied to the macro particles
    - The particles are advanced

All simulation performed with GUINEA-PIG



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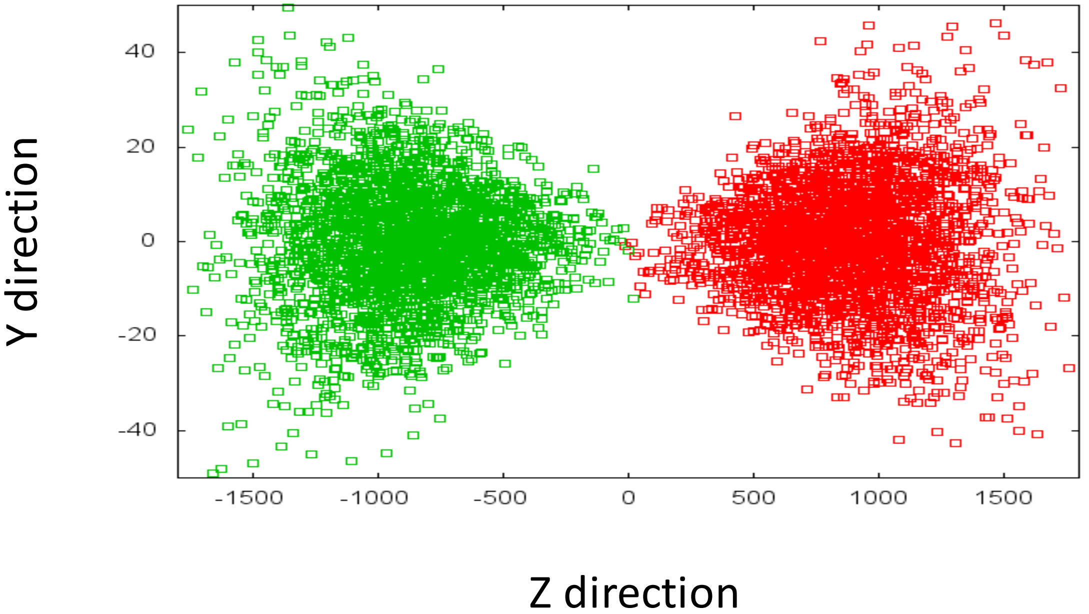
Beam-beam force switched off



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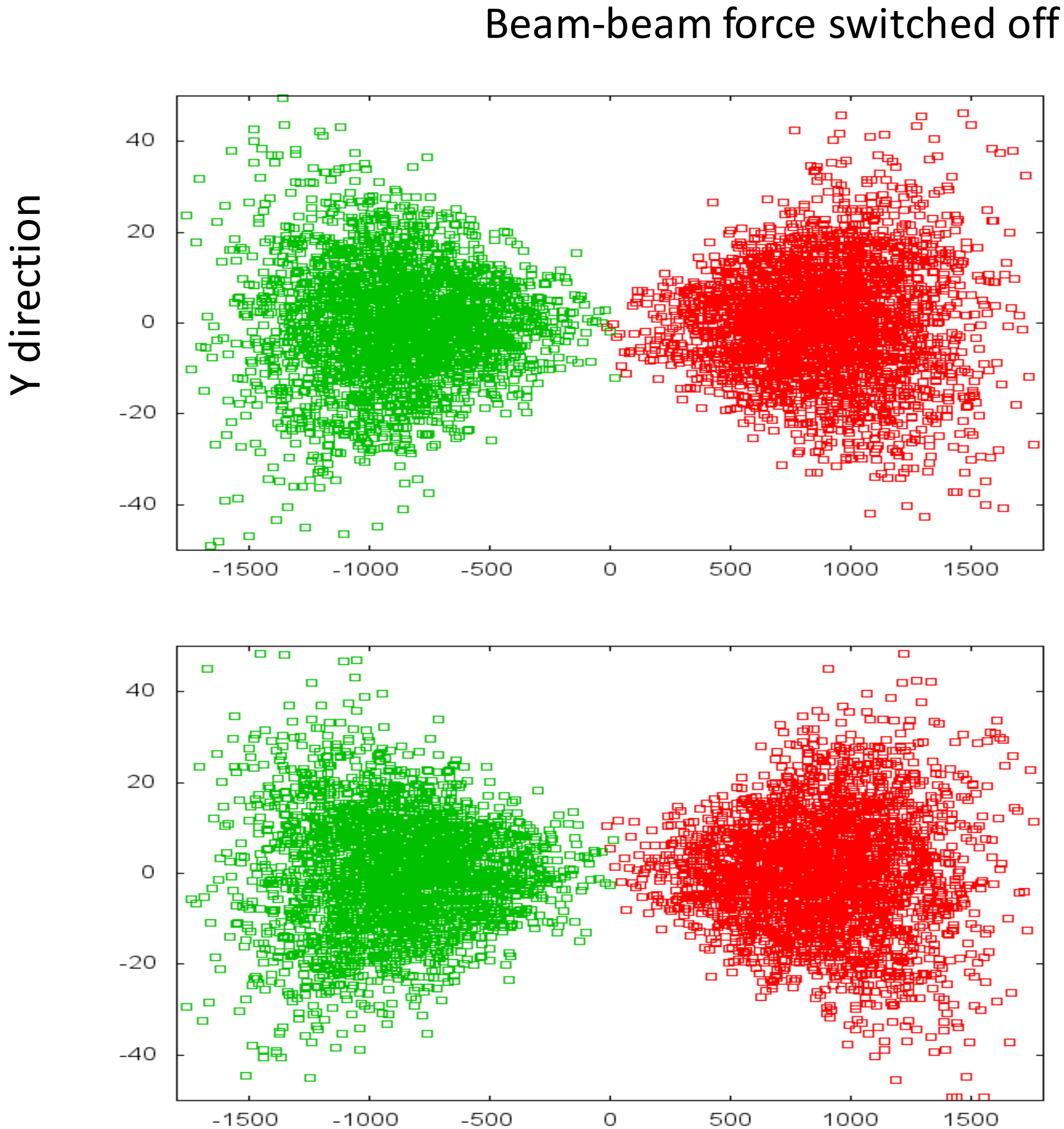
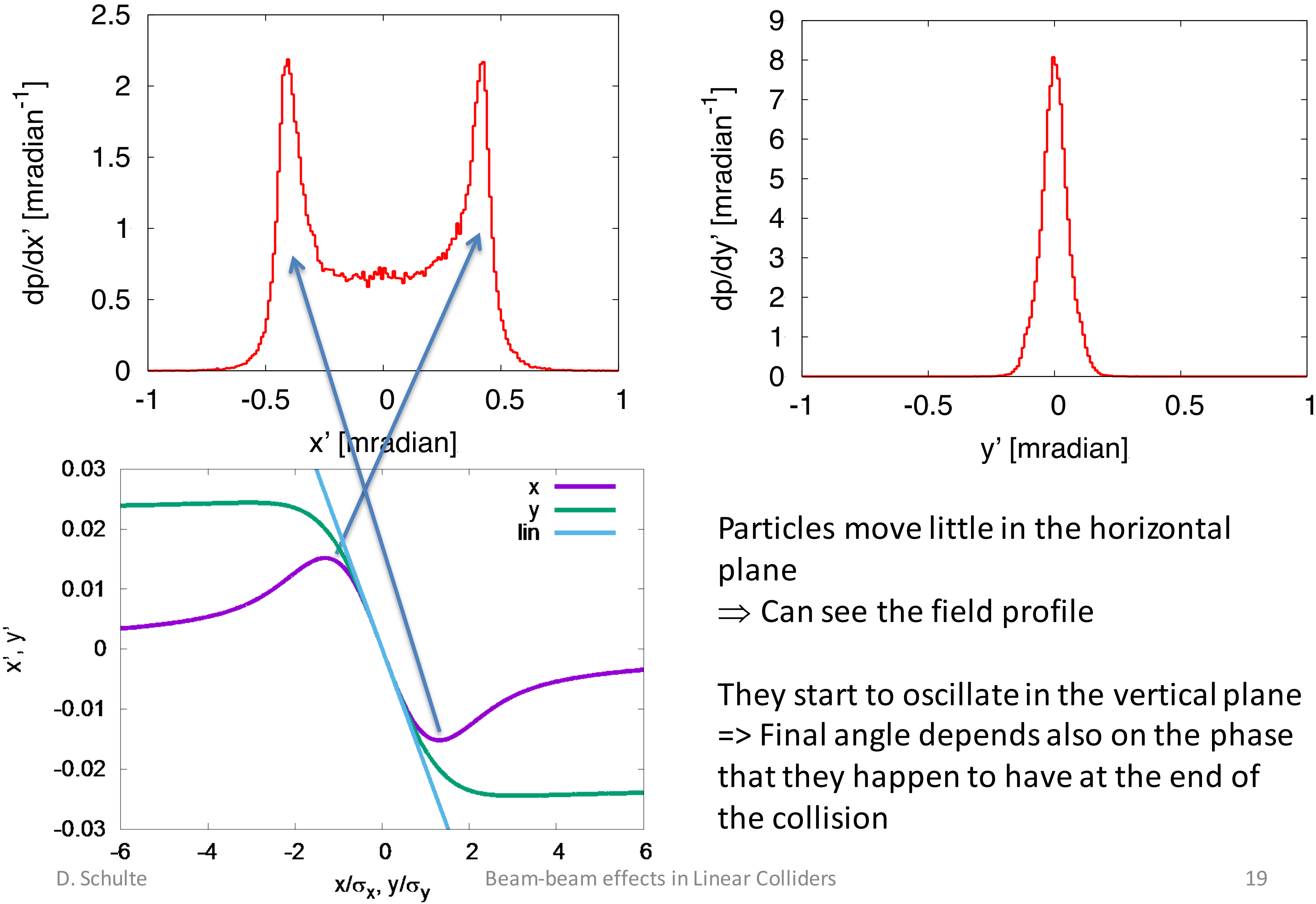


The Spent Beam



Particles move little in the horizontal plane

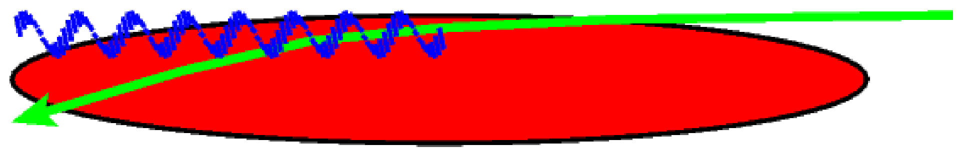
⇒ Can see the field profile

They start to oscillate in the vertical plane

=> Final angle depends also on the phase that they happen to have at the end of the collision

Beamstrahlung

Similar to synchrotron radiation



From local trajectory curvature calculate critical

$$\hbar\omega_c = \frac{3}{2}\frac{\gamma^3\hbar c}{\rho}$$

Define beamstrahlung parameter Upsilon

$$\Upsilon = \frac{2}{3}\frac{\hbar\omega_c}{E_0}$$

Average Upsilon is approximately given by

$$\langle\Upsilon\rangle = \frac{5}{6}\frac{N r_e^2 \gamma}{\alpha(\sigma_x + \sigma_y)\sigma_z}$$

Beamstrahlung Power Spectrum

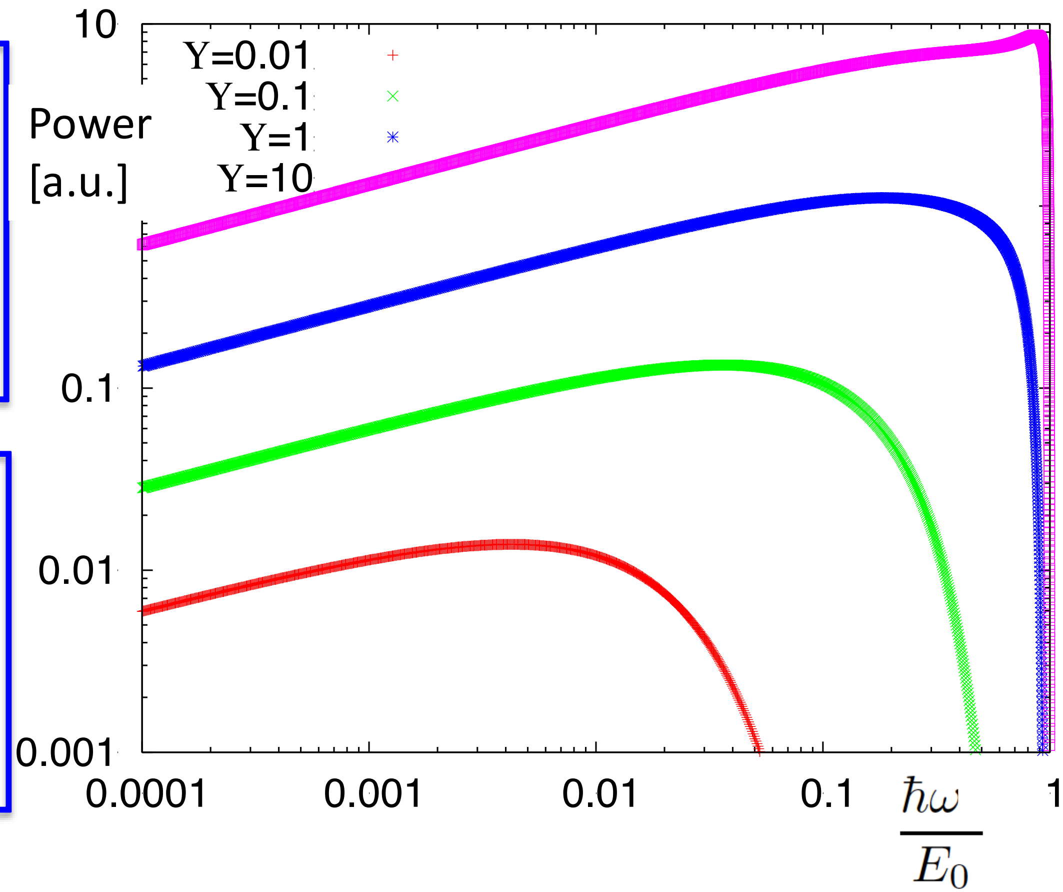
Classical regime $\Upsilon \ll 1$

ILC Υ=0.06

CLIC at 380GeV Υ=0.17

Quantum regime $\Upsilon \gg 1$

CLIC at 3TeV Υ=5



The spectrum is given by
$$\frac{d\dot{w}}{d\omega} = \frac{\alpha}{\sqrt{3}\pi\gamma^2}\left[\int_x^\infty K_{\frac{5}{3}}(x')dx' + \frac{\hbar\omega}{E}\frac{\hbar\omega}{E-\hbar\omega}K_{\frac{2}{3}}(x)\right]$$

With modified Bessel functions $K_{\frac{5}{3}}$ and $K_{\frac{2}{3}}$ $\quad x = \frac{\omega}{\omega_c}\frac{E}{E-\hbar\omega}$

Photons in the Classical Regime $\Upsilon \ll 1$

Number of photons
Dominates $L/L_{0.01}$

Energy of photons
Defines shape of tail

$$n_\gamma \propto \frac{N}{\sigma_x + \sigma_y}$$

$$\frac{E_\gamma}{E_0} \propto \frac{N}{\sigma_x + \sigma_y} \frac{\gamma}{\sigma_z}$$

+

$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

$$\propto n_\gamma$$

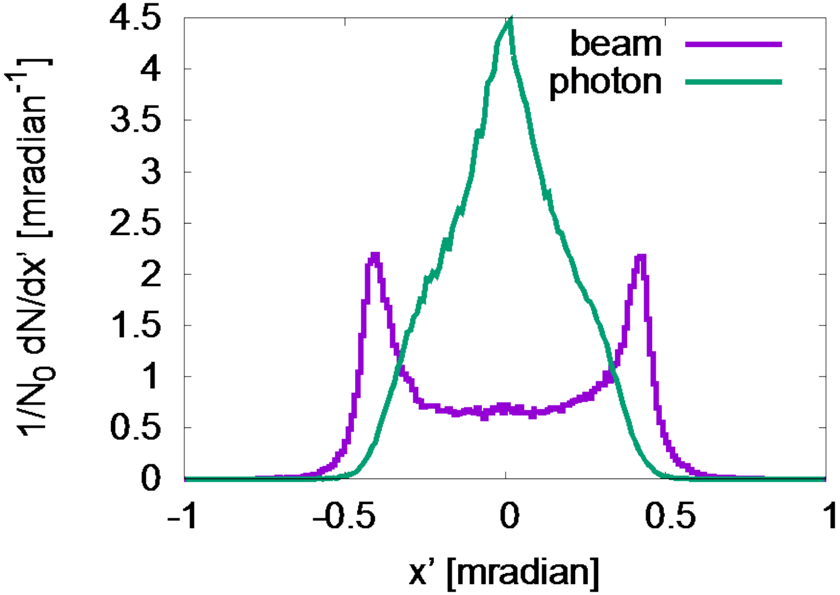
$$\sigma_x \gg \sigma_y$$

$$\sigma_x + \sigma_y \approx \sigma_x$$

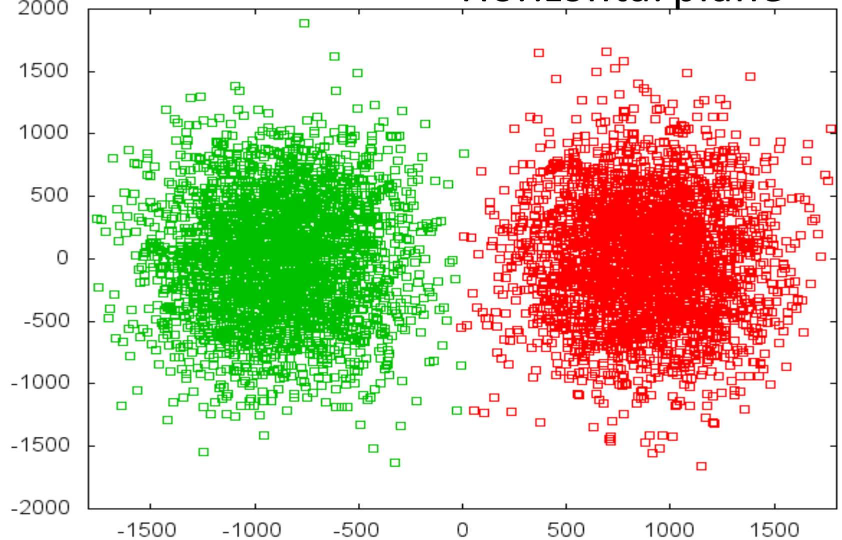
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

Determined by beamstrahlung

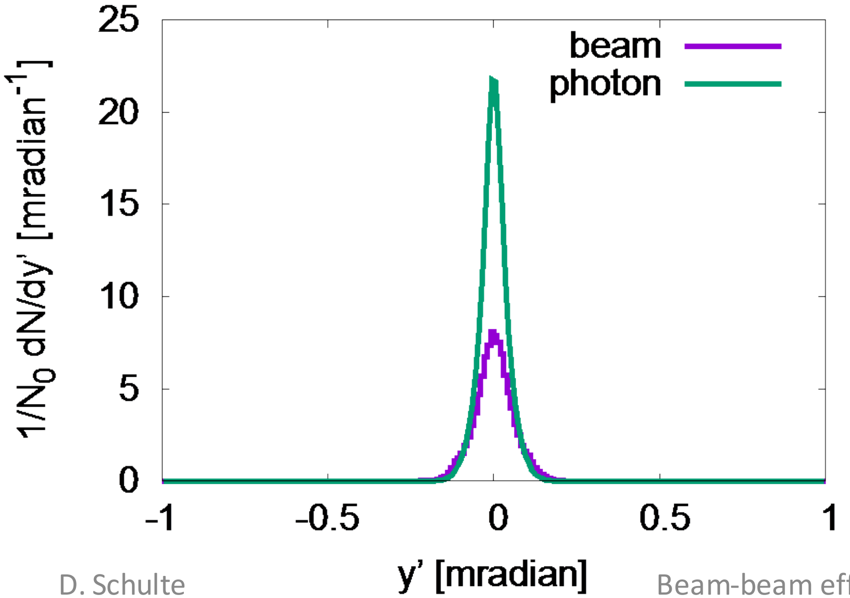
Photon Production

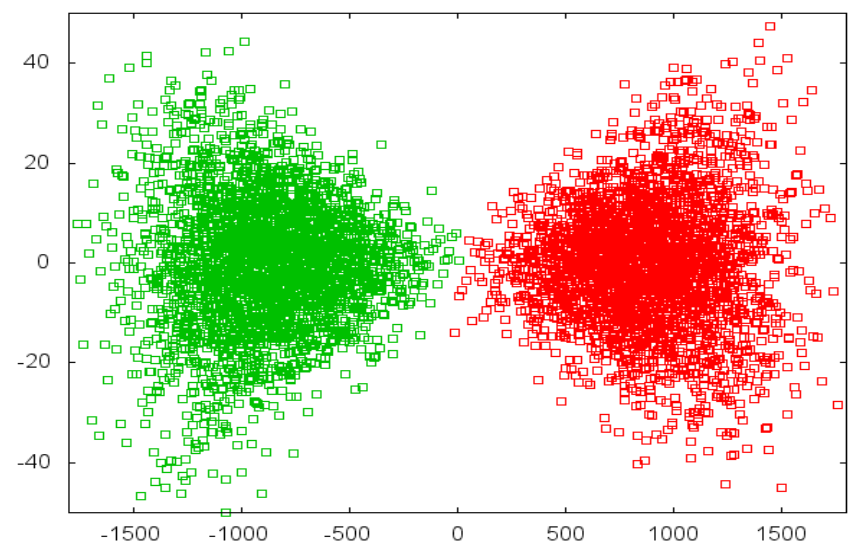


Horizontal plane



Vertical plane





ILC and CLIC Main Parameters

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Particles per bunch	N [10^{9}]	20	5.2	3.72
Bunch length	σ_z [μm]	300	70	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	474/5.9	149/2.9	40/1
Vertical emittance	$\varepsilon_{x,y}$ [nm]	35	40	20
Photons per beam particle	n_γ	1.9	1.5	2.1
Average photon energy	$\langle E_\gamma/E_0 \rangle$ [%]	2.4	4.5	13

Photon numbers and $L_{0.01}/L$ are similar for ILC and CLIC at low energies

Average photon energy does not seem to matter too much for $L_{0.01}$

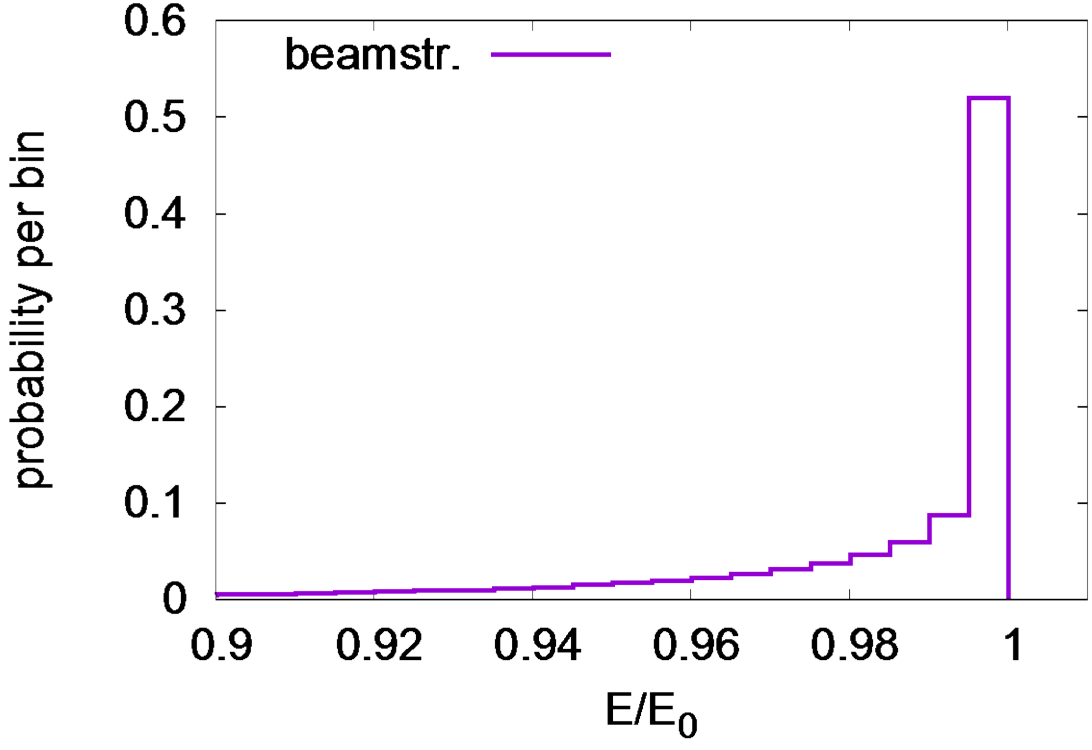
Luminosity Spectrum

Luminosity spectrum for ILC, CLIC at 380GeV looks similar

(beam energy spread is ignored)

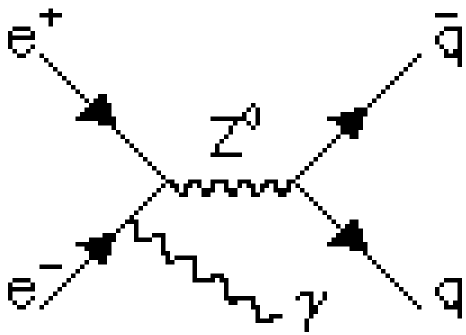
Luminosity $L_{0.01}$ above 99% of nominal CMS energy is $L_{0.01}/L = 60\%$

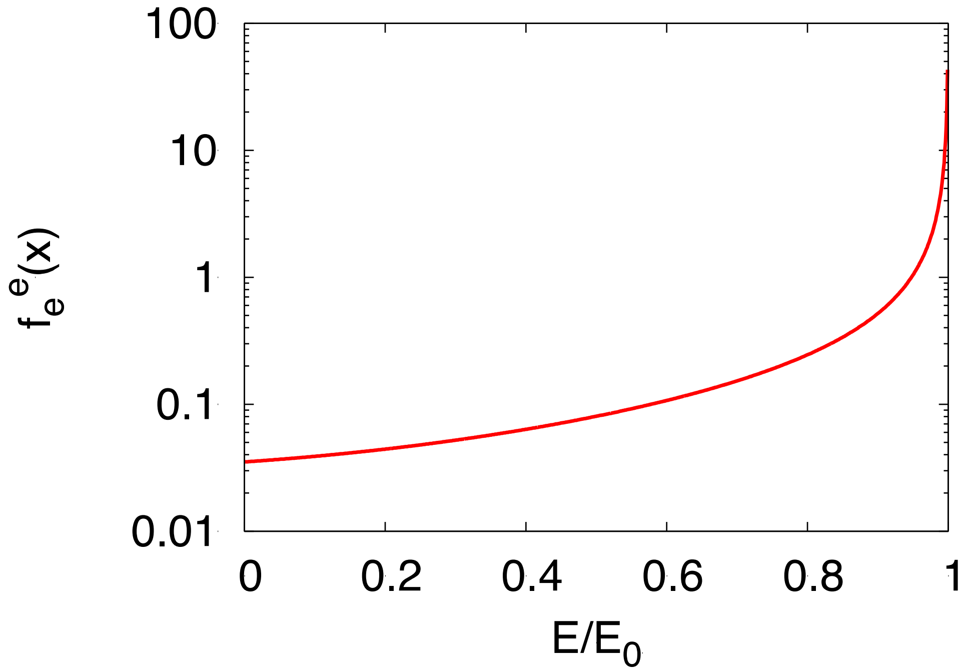
For CLIC380, this has been the design criterion



But why did the experiments chose $L_{0.01}/L > 60\%$?

Note: Initial State Radiation

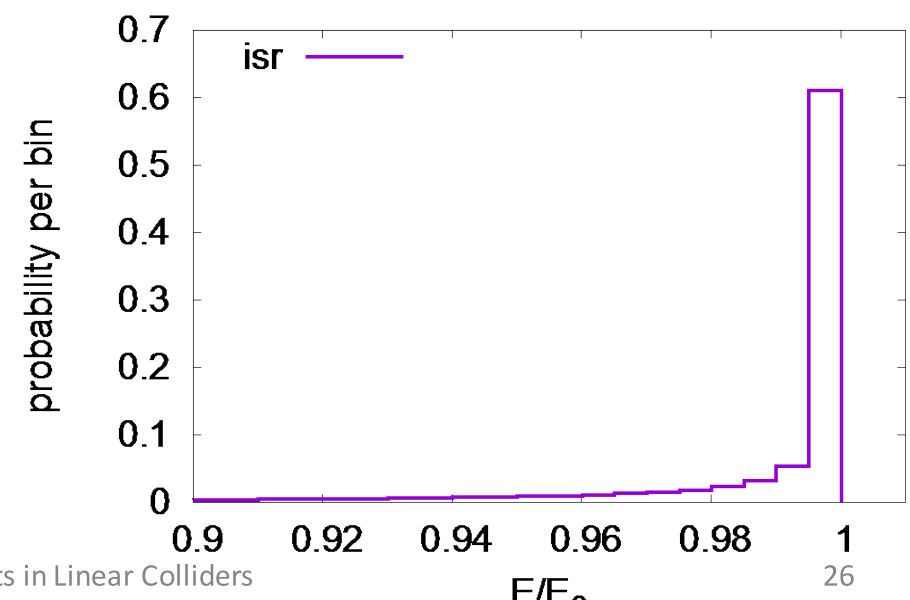




Electrons often emit a photon before the collision

$\Rightarrow$ Initial State Radiation

The electron can be replaced by a spectrum of electrons

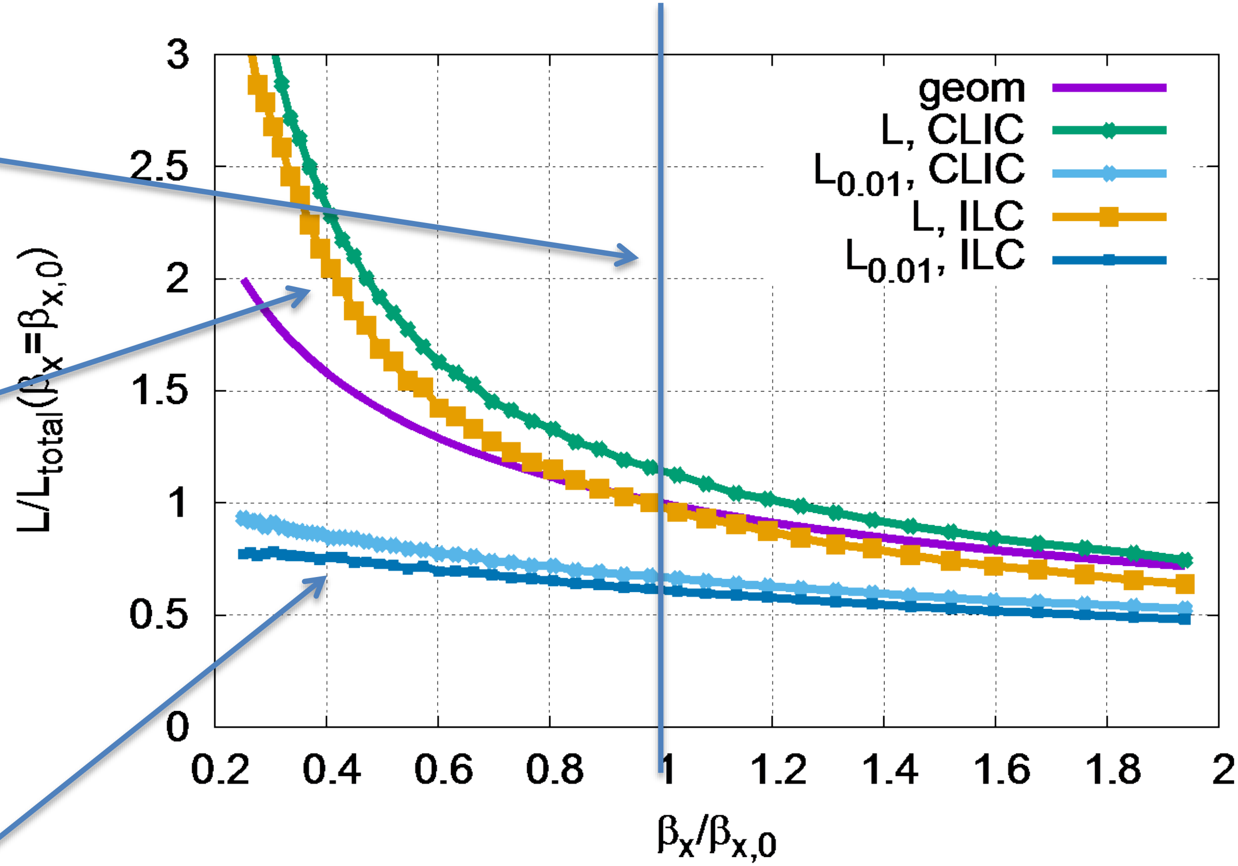


This yields a luminosity spectrum

About 65% probability of collision with more than 99% of nominal energy

Luminosity Spectrum

Design value
$L_{0.01}/L=60\%$



The total luminosity L varies strongly with beta-function

But $L_{0.01}$ does not change so much

Hard to push beta-functions
That low

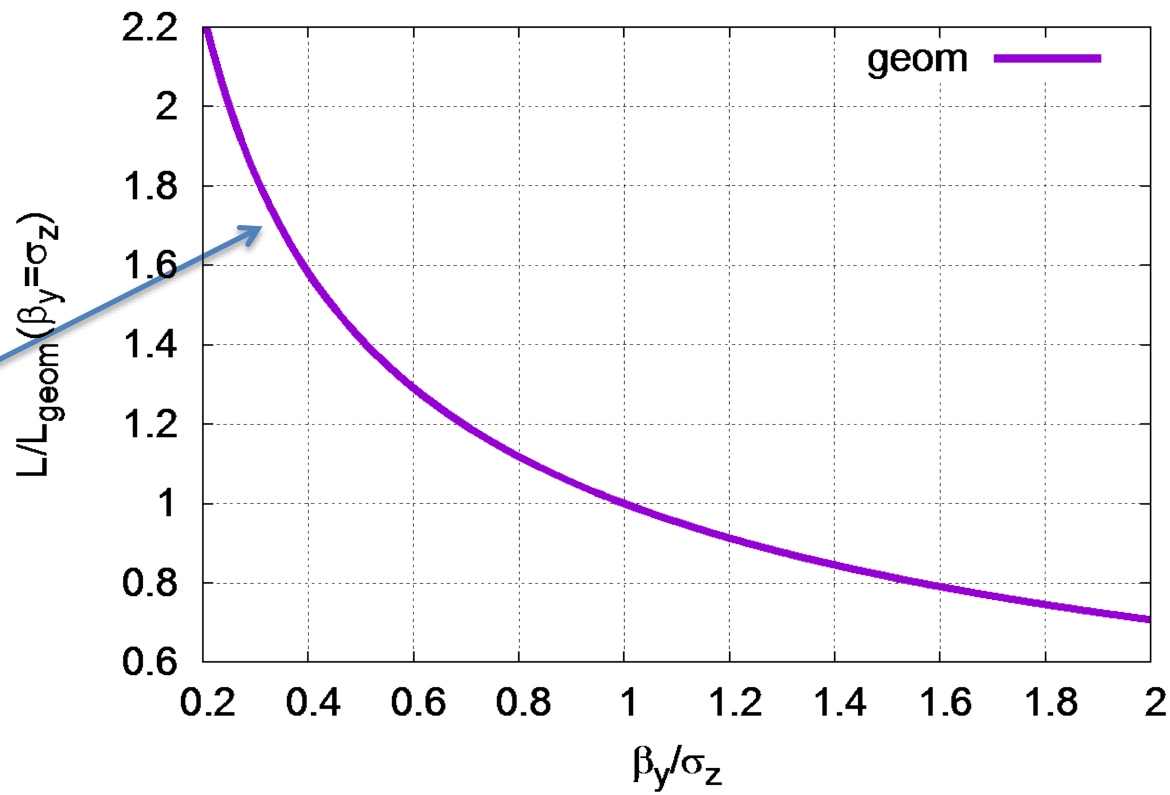
So tend to use $L_{0.01}/L=60\%$ as criterion

Reasonable compromise for most physics studies

Vertical Beamsize

Using the naïve luminosity calculation with beta-function at the IP we find that the luminosity can be increased by reducing β_y

$$\mathcal{L} = \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$



There are two limits:

The lattice design tends to find a practical lower limit a bit below β_y=100 μm
CLIC at 3TeV has β_y=70 μm but strong geometric aberrations

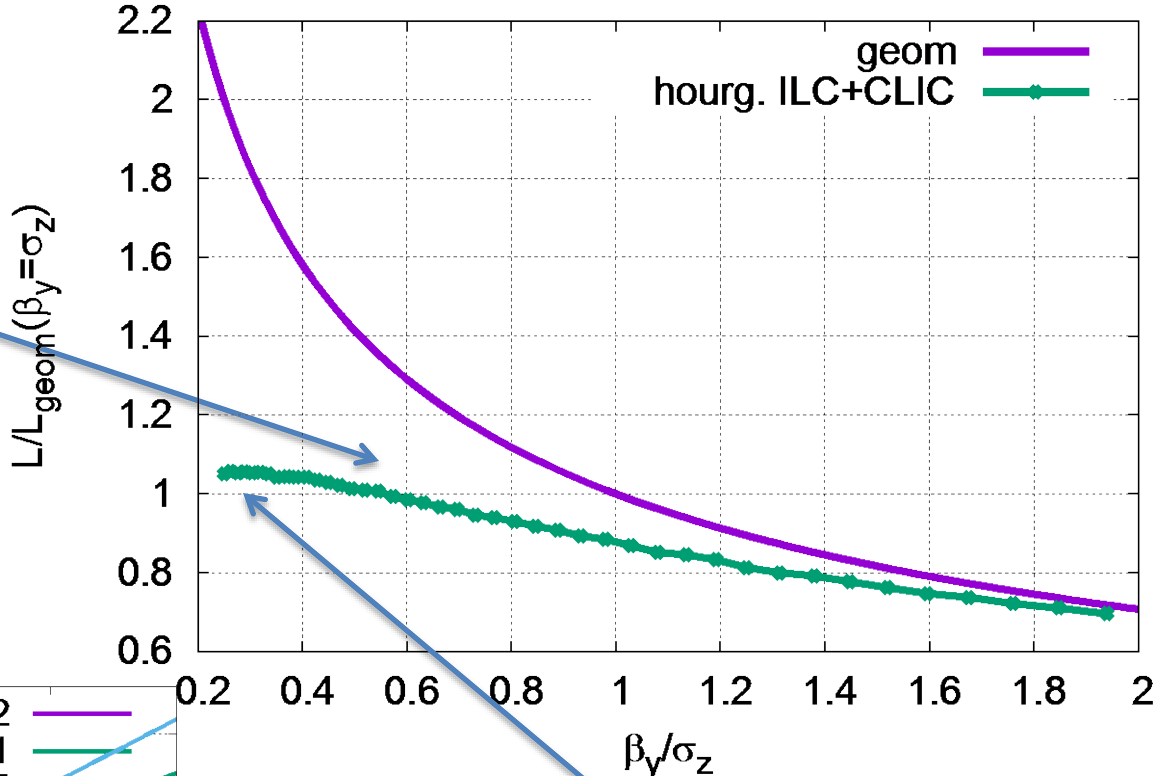
Luminosity actually increases not as predicted

Not excluded that this can be improved but people worked on it for years

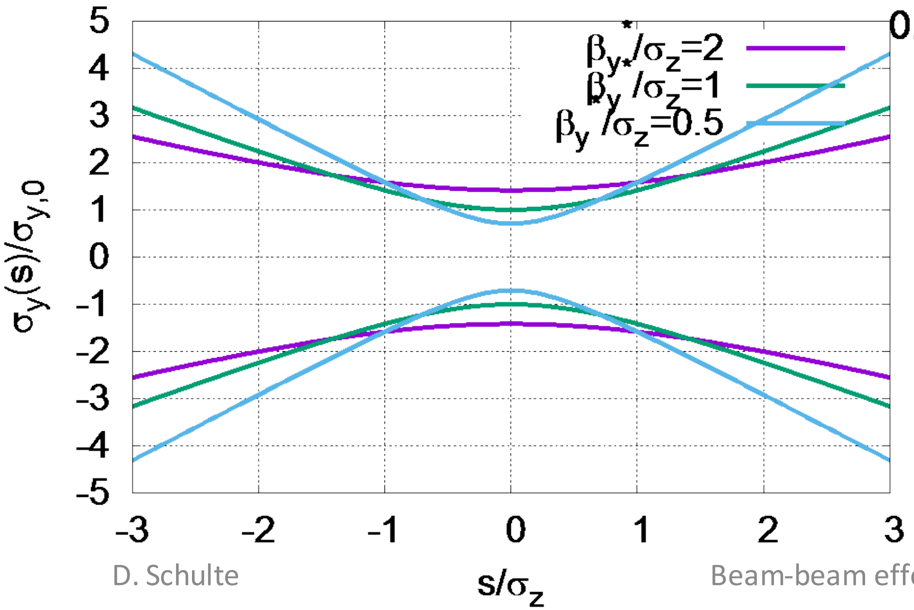
Hourglass Effect

Taking into account hourglass effect

$$\beta(s) = \sqrt{\beta(0) + \frac{s^2}{\beta(0)}}$$



Luminosity does not improve much below $\beta_y < \sigma_z$



For flat beams, the optimum is around $\beta_y = 0.25 \times \sigma_z$

Note: This is different for round beams

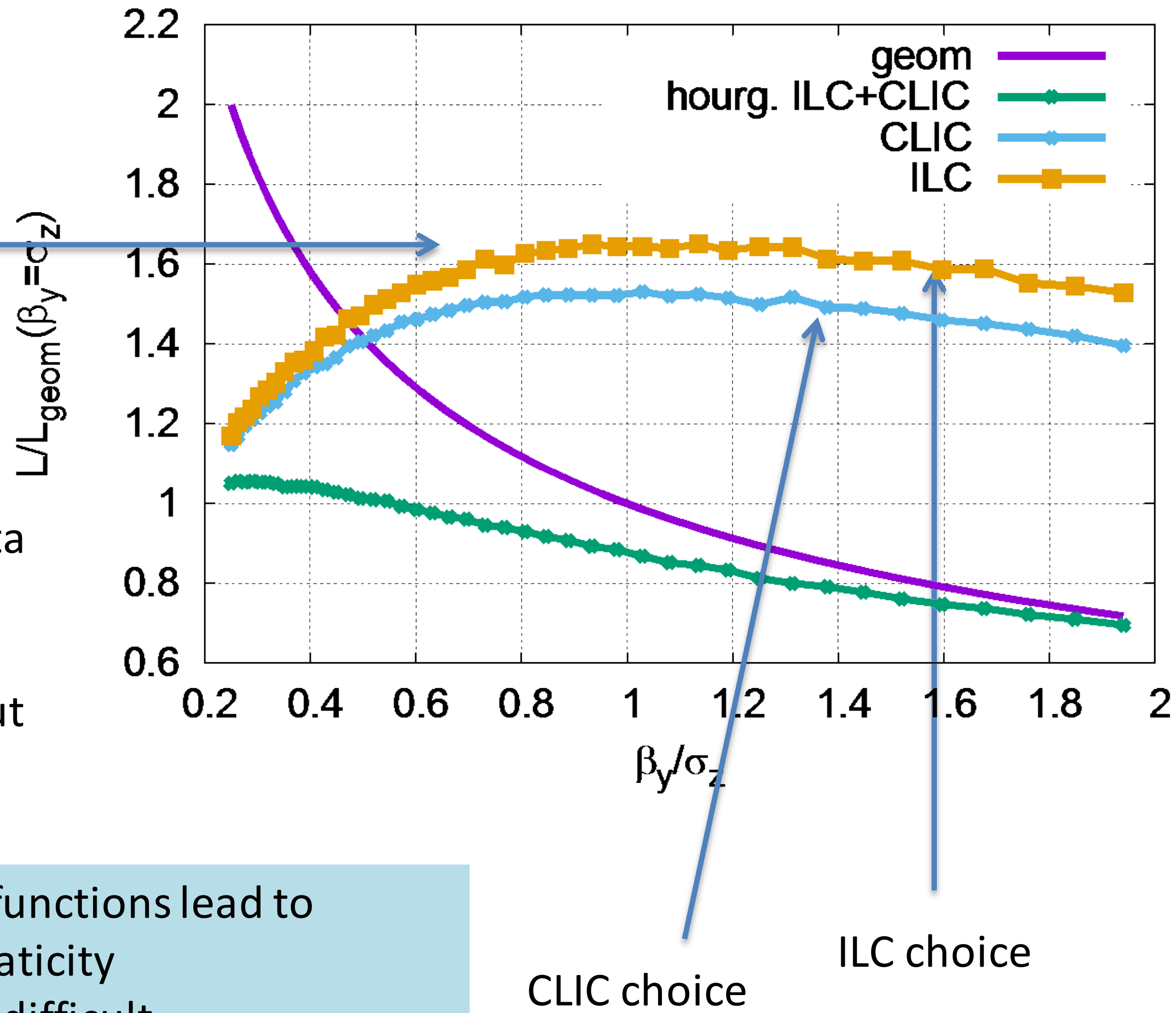
Beam-beam Effects

Including pinch effect

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

There is an optimum value for beta

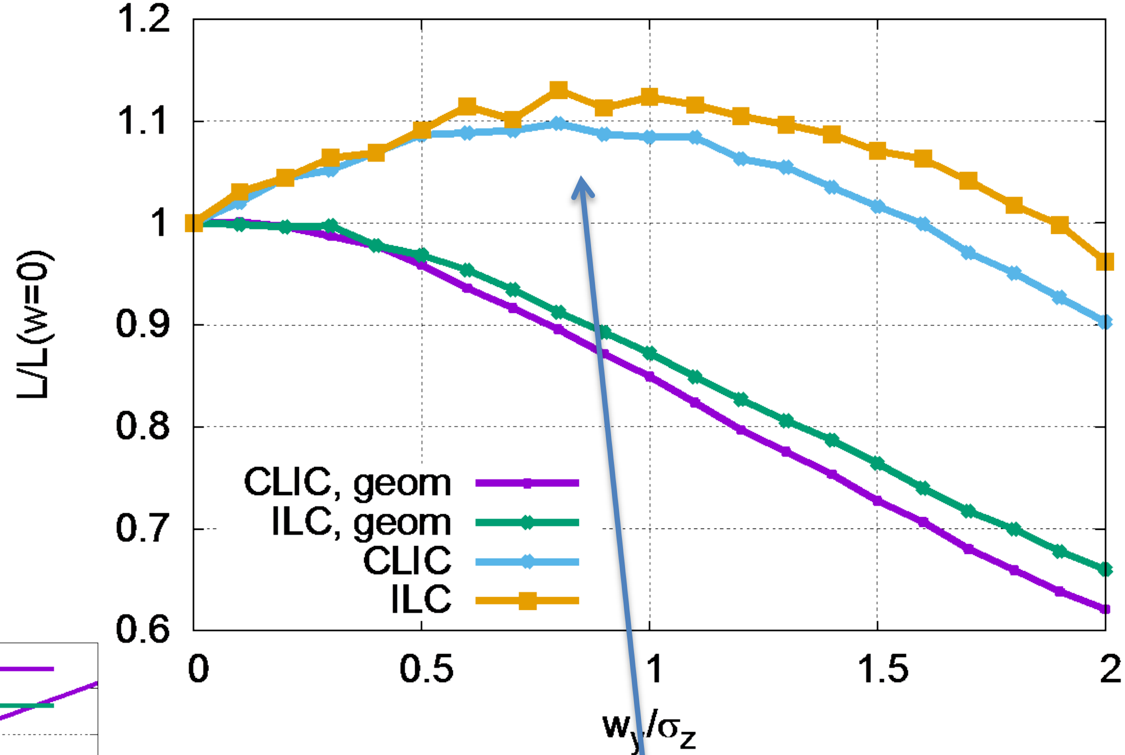
For smaller beta-function the geometric luminosity increases but the enhancement is reduced



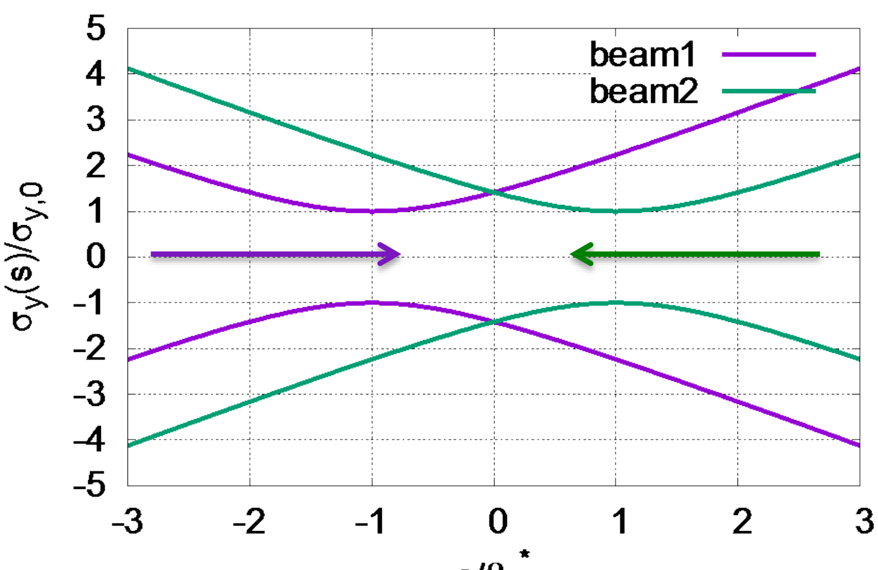
Small beta-functions lead to
High chromaticity
$\Rightarrow$ Optics is difficult
Large divergence
$\Rightarrow$ Quadrupole aperture is limited

Waist Shift

Focusing before IP leads to more luminosity (D.S.)



For CLIC and ILC ~10% luminosity gain

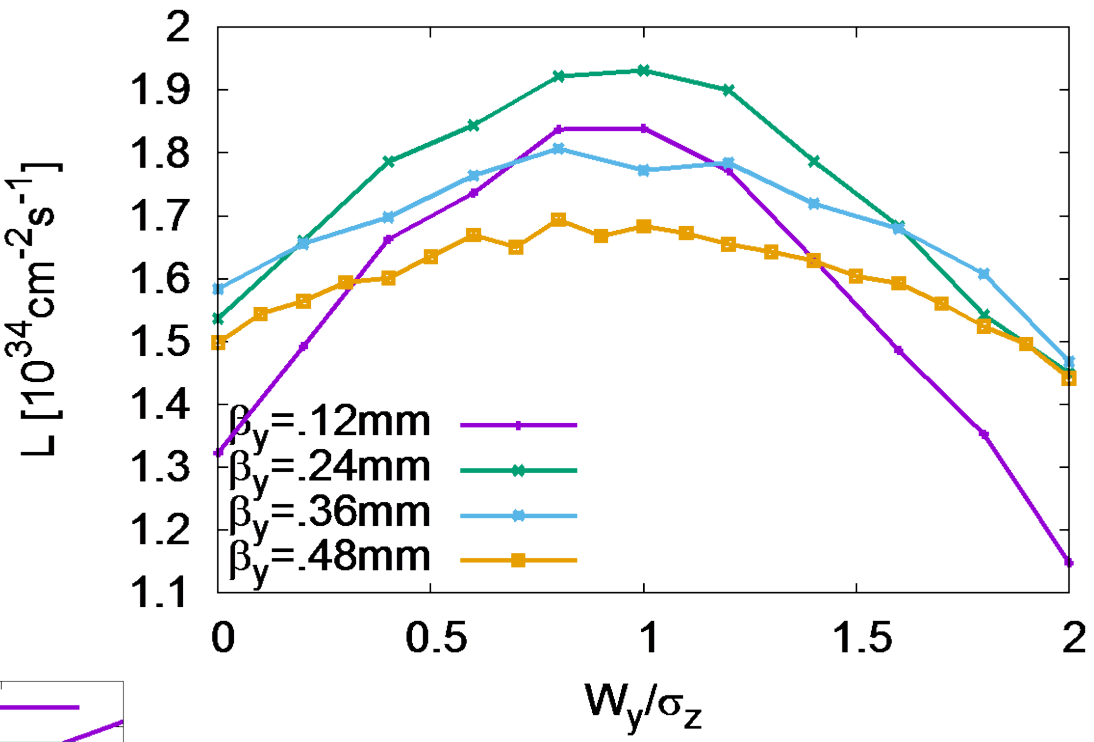


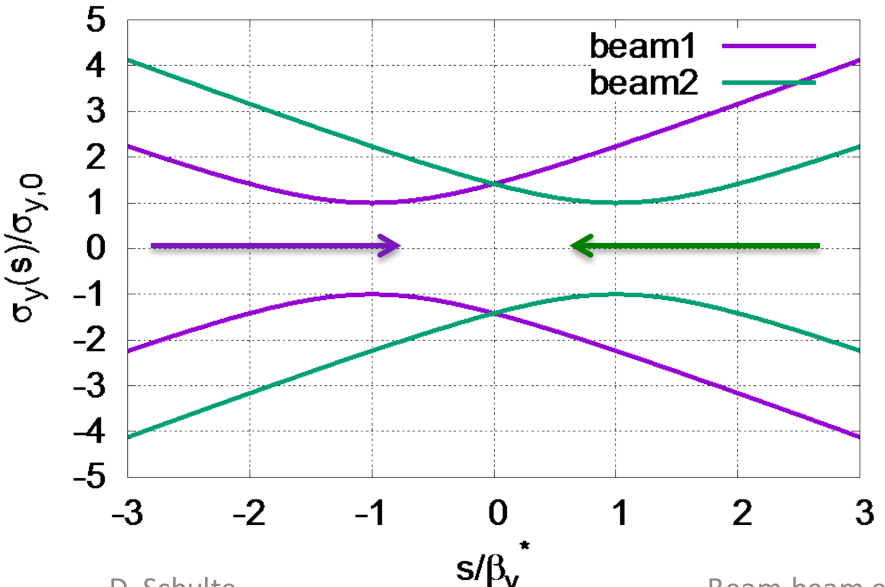
Note: ILC Full Optimisation

For ILC could consider smaller vertical beta-functions

Smaller beta-functions profit more from waist shift
⇒ 0.24mm seems best

Would gain 15% luminosity



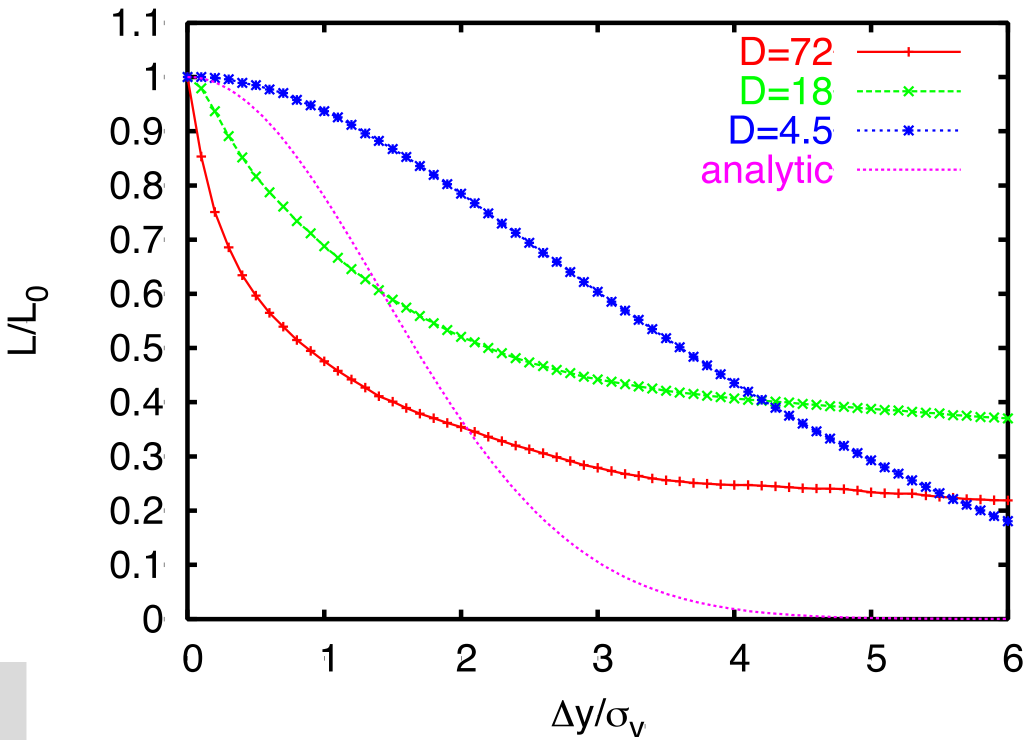


But still more difficult to produce (larger divergence)
And tolerances become tighter

Luminosity and Offset

Luminosity loss for rigid bunches with offset

$$\frac{\mathcal{L}}{\mathcal{L}_0} = \exp\left(-\frac{\Delta y^2}{4\sigma_y^2}\right)$$



Actual loss depends strongly on disruption

Note: the simulations suffer from noise (use of macroparticles)

Need to enforce symmetric charge distribution to simulate high disruption

Can you trust the results in real life?

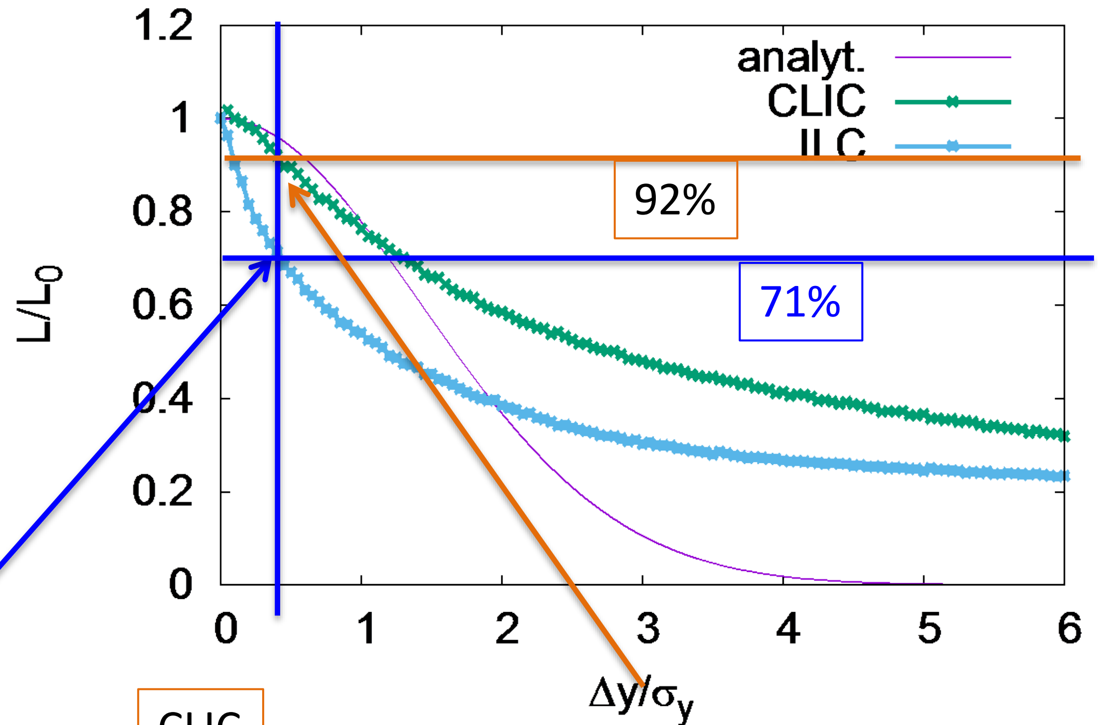
Luminosity and Offset

Luminosity loss for beam offsets depends strongly on disruption parameter

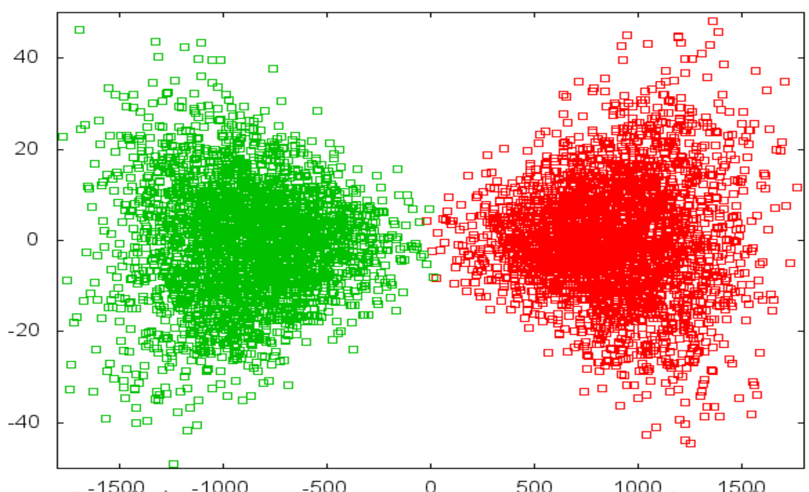
$\Delta y = 0.4\ \sigma_y$

$L = 0.71\ L_0$ D_y~24

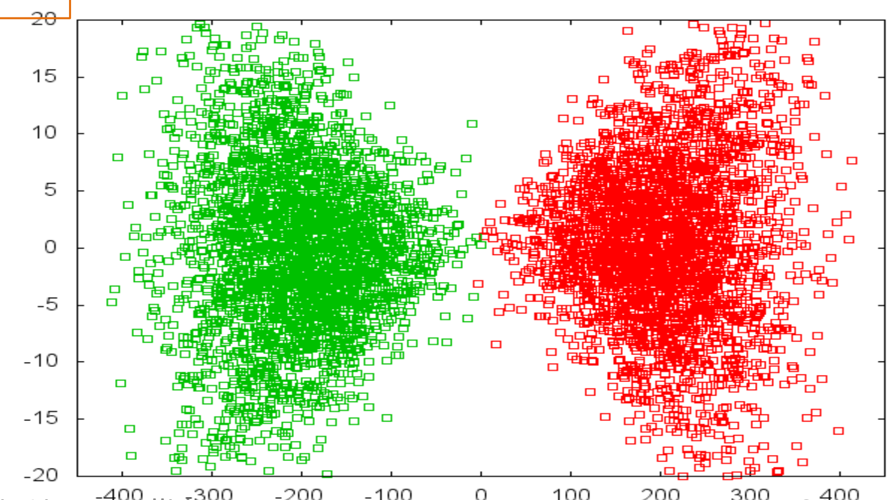
$L = 0.92\ L_0$ D_y~12



ILC



CLIC



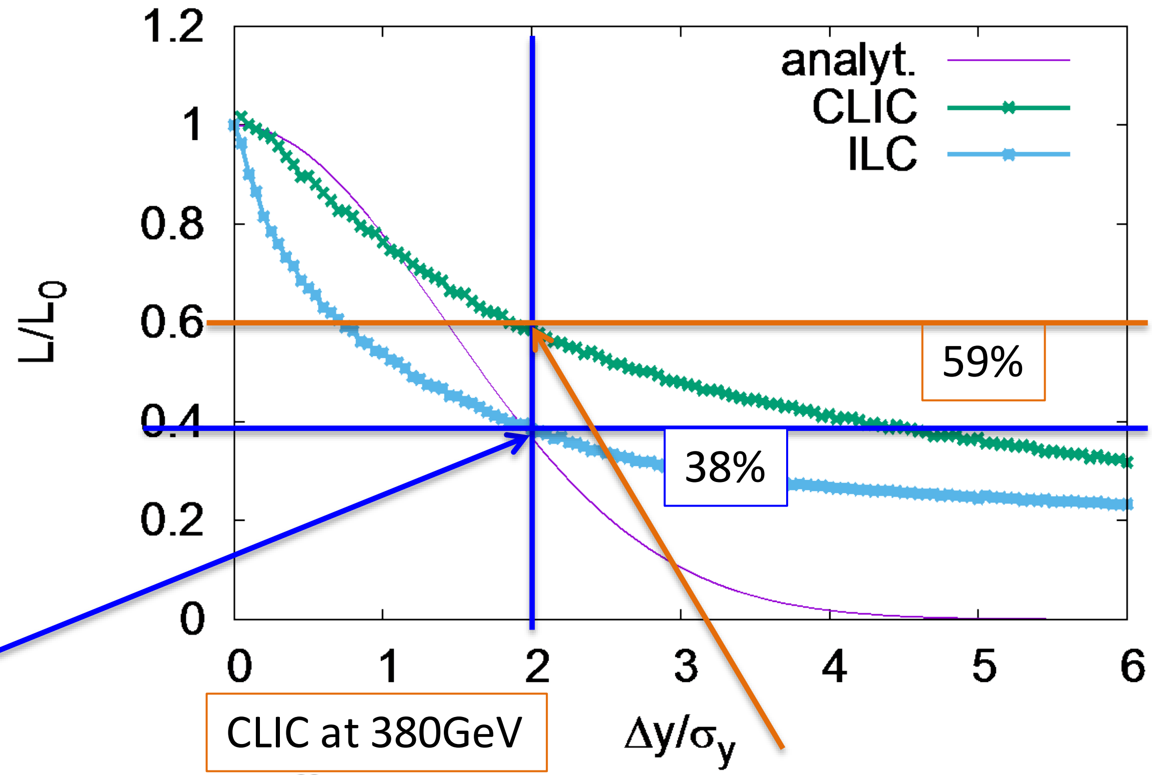
Luminosity and Offset

Luminosity loss for beam offsets depends strongly on disruption parameter

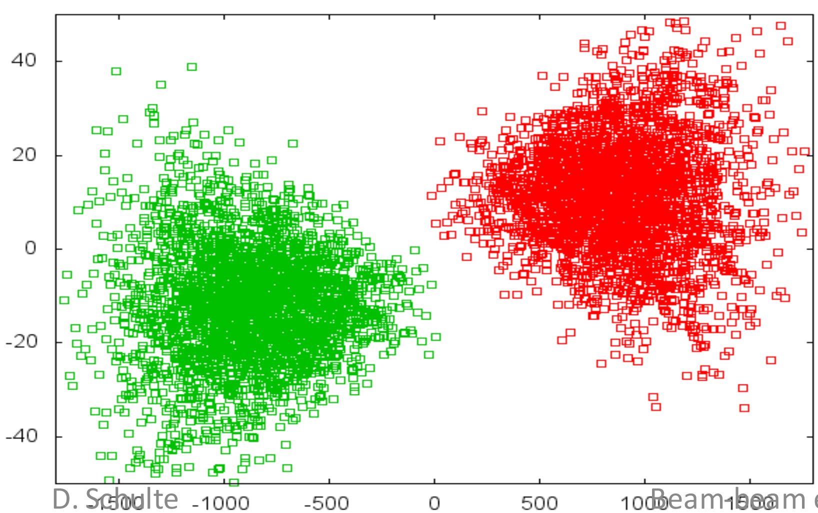
$\Delta y = 2\,\sigma_y$

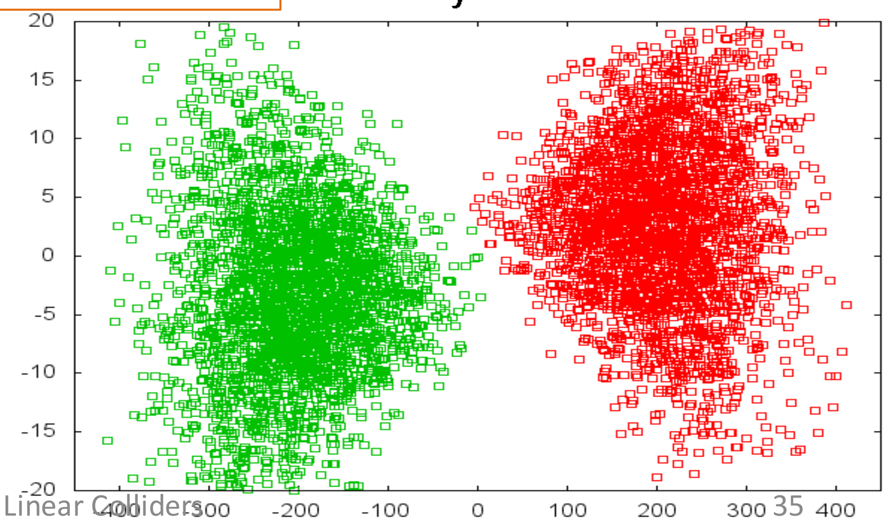
$L = 0.38\,L_0$

$L = 0.59\,L_0$



ILC



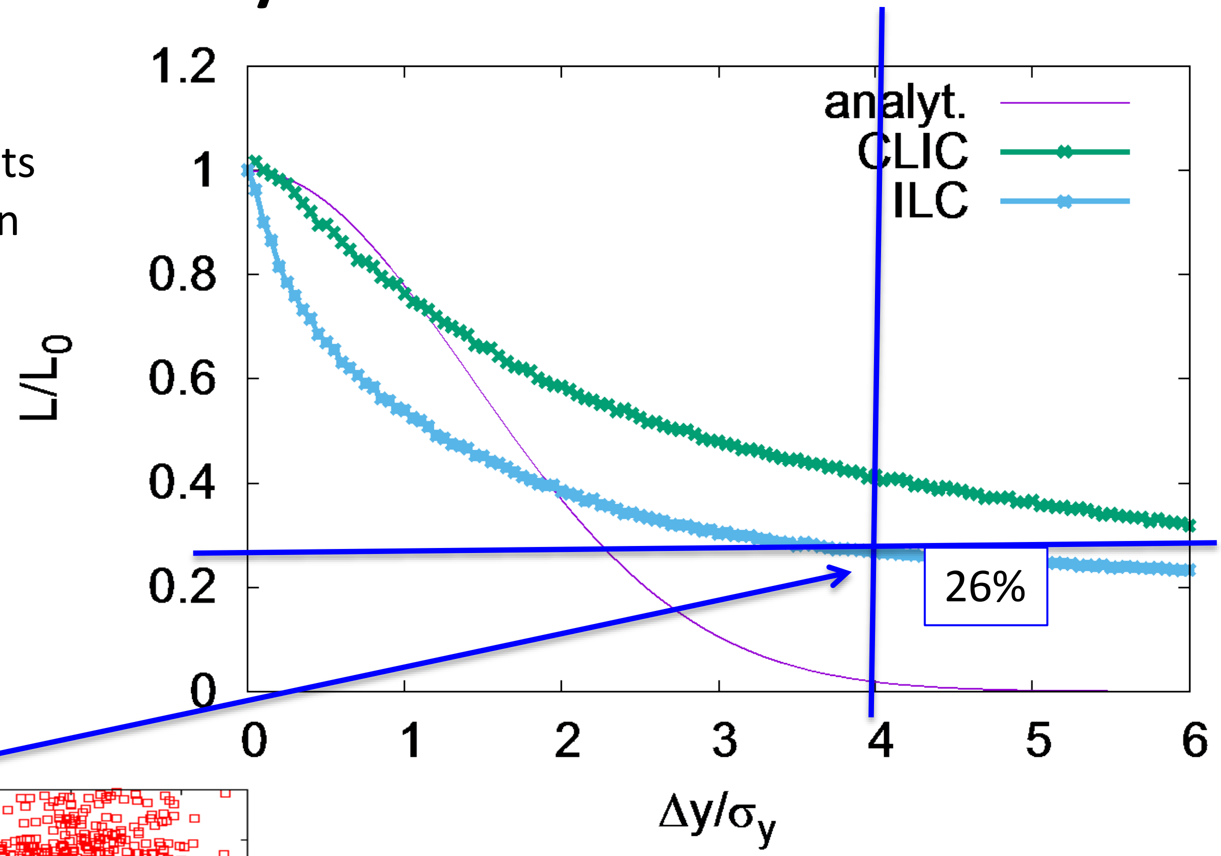


Luminosity and Offset

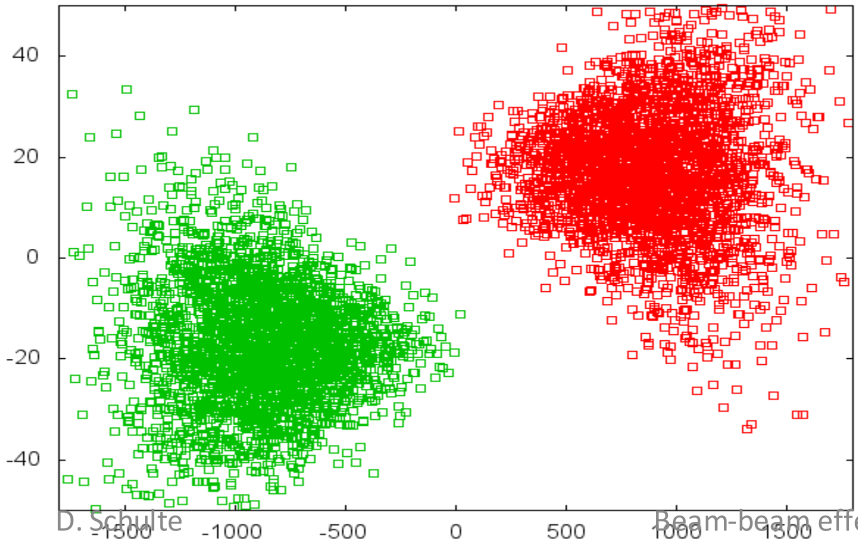
Luminosity loss for beam offsets depends strongly on disruption parameter

$\Delta y = 4\ \sigma_y$

$L = 0.26\ L_0$



ILC

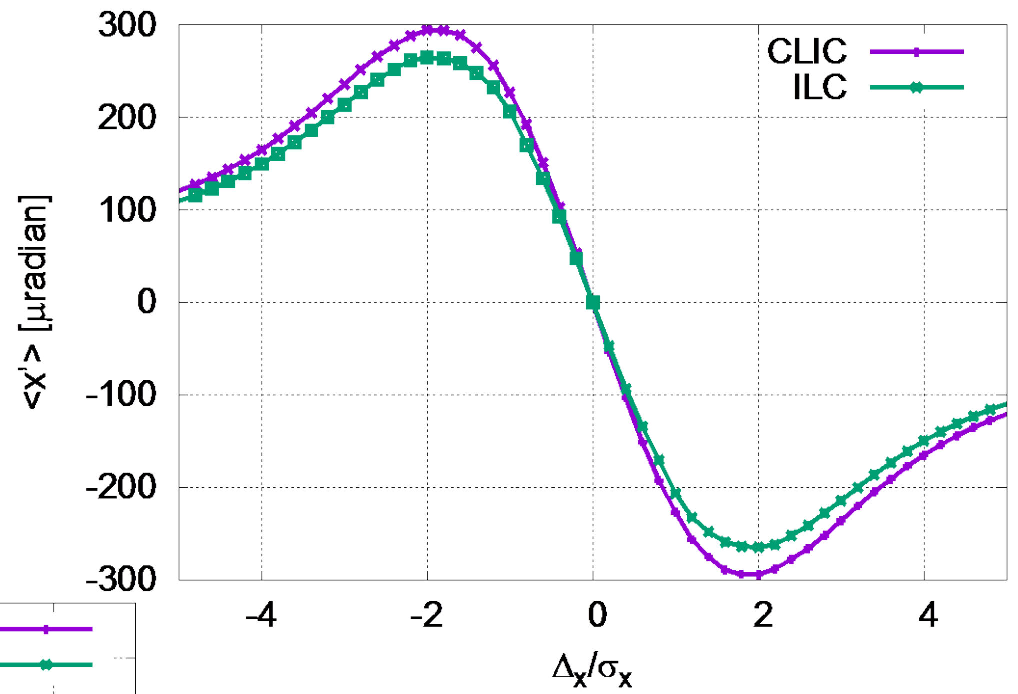


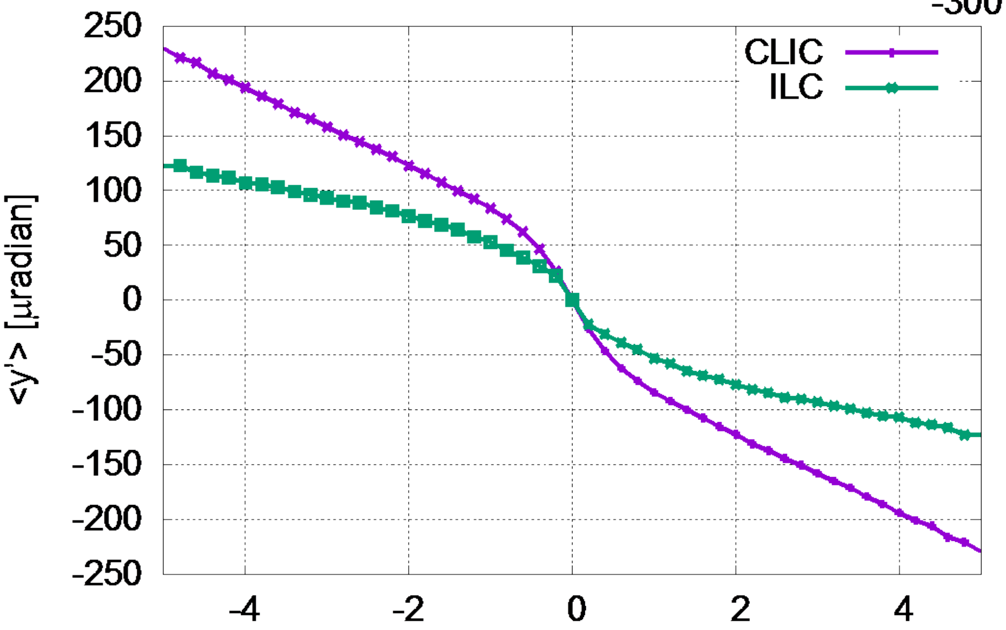
Beam-beam Deflection

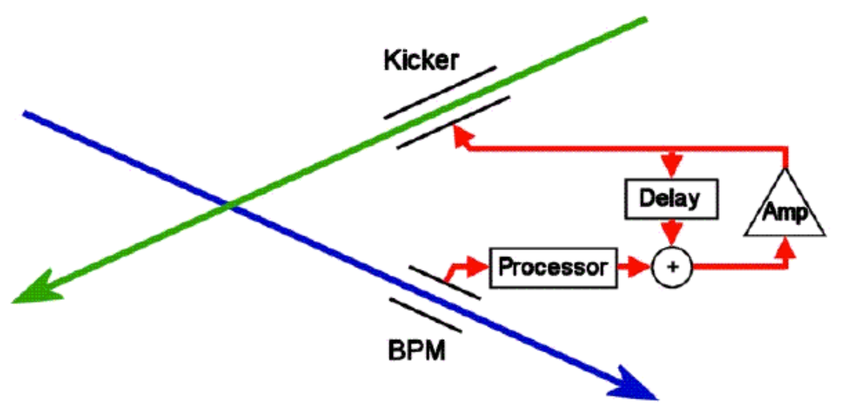
Strong deflection allows to easily measure and correct offset

In CLIC an offset $\Delta_y = 0.1\sigma_y = 0.1$nm
$\Rightarrow$ 3m downstream of IP 40μm beam offset

Get great signals for the BPMs





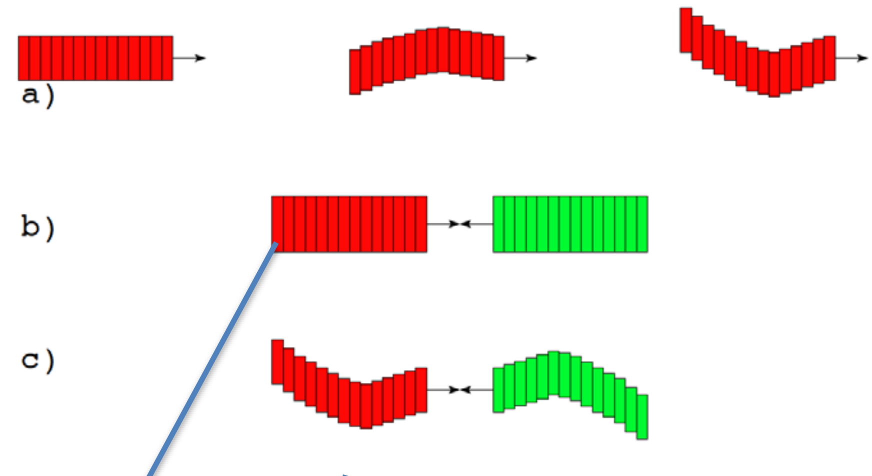


Note: The Banana Effect

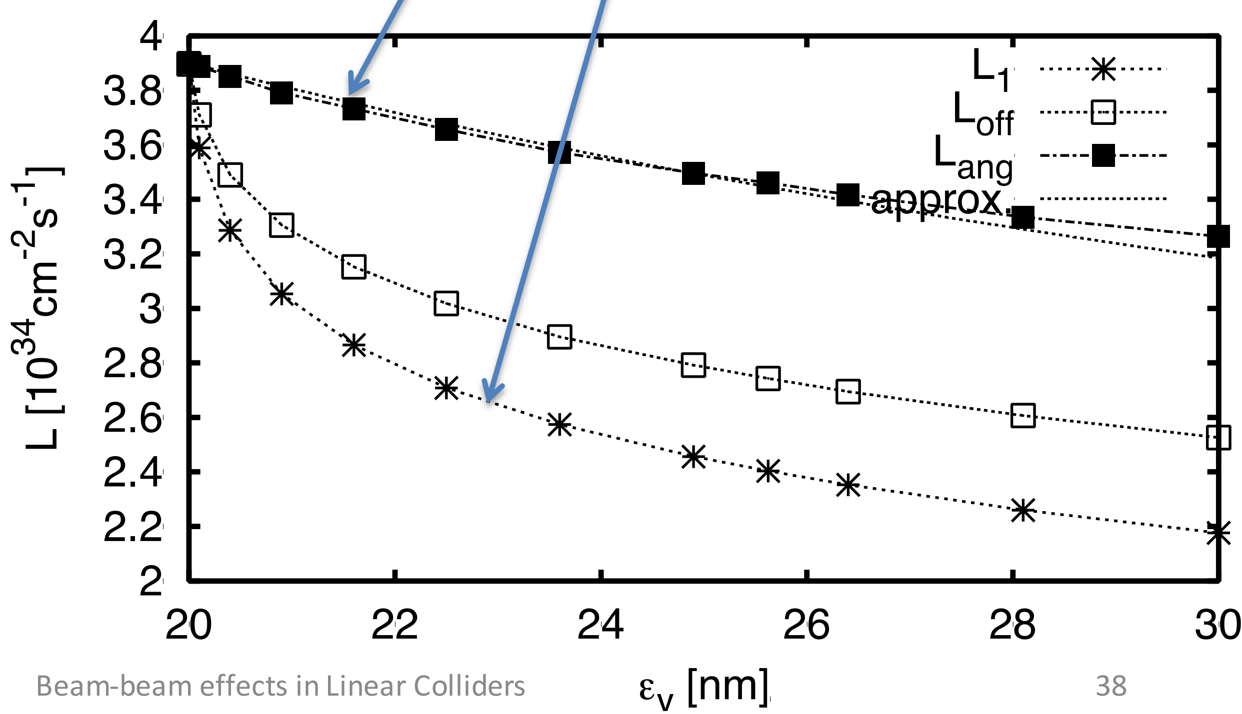
a) Wakefields+dispersion can create banana-shaped bunch in main linac

b) Do not model with projected emittance

c) The correct shape should be used



For large disruption (ILC) banana can reduce luminosity



Study done for TESLA
Similar disruption as ILC

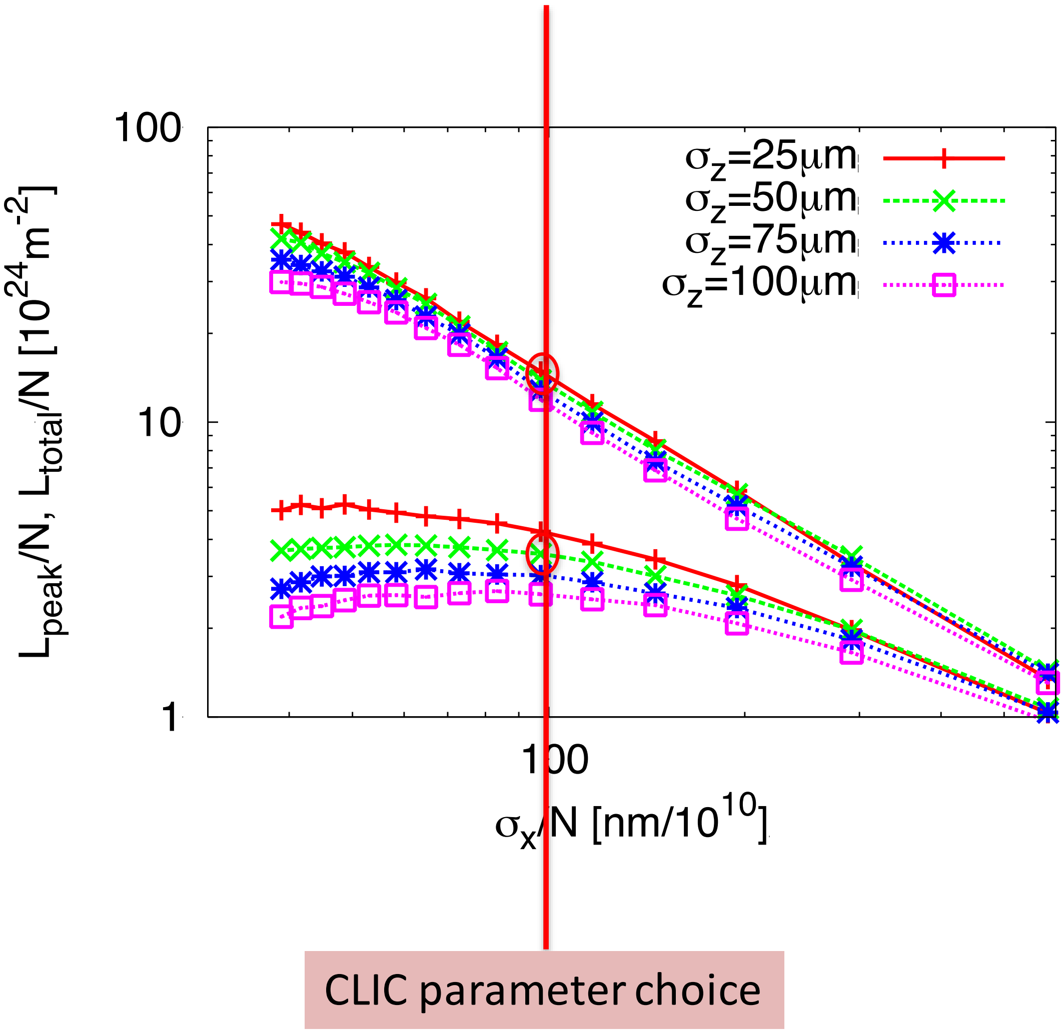
CLIC 3TeV Beamstrahlung

Goal is to maximise $L_{0.01}$
And $L_{0.01}/L > 0.3$

$$\Upsilon \gg 1$$

$$n_\gamma \propto \left(\frac{\sigma_z}{\gamma}\right)^{\frac{1}{3}} \left(\frac{N}{\sigma_x + \sigma_y}\right)^{\frac{2}{3}}$$

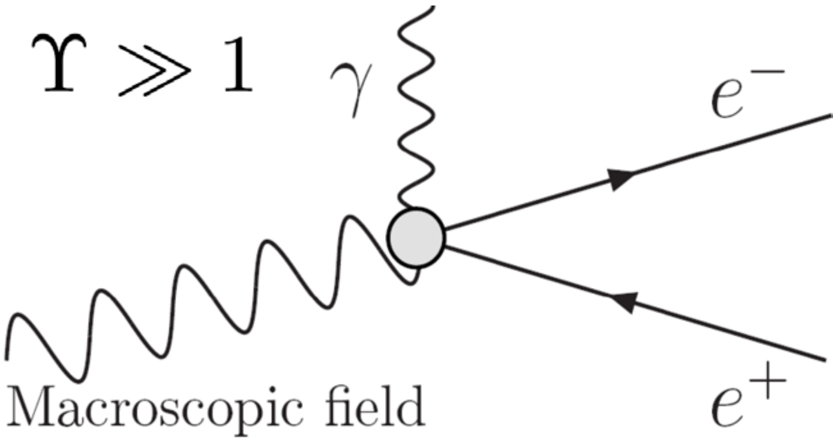
$$\mathcal{L} \propto \frac{n_\gamma^{3/2}}{\sqrt{\sigma_z}} \eta P_{wall} \frac{1}{\sigma_y} \cdot H_D$$



Coherent Pair Creation

Beam fields in the rest system of a photon can reach the **Schwinger Critical Field**
⇒ The quantum electrodynamics becomes non-linear

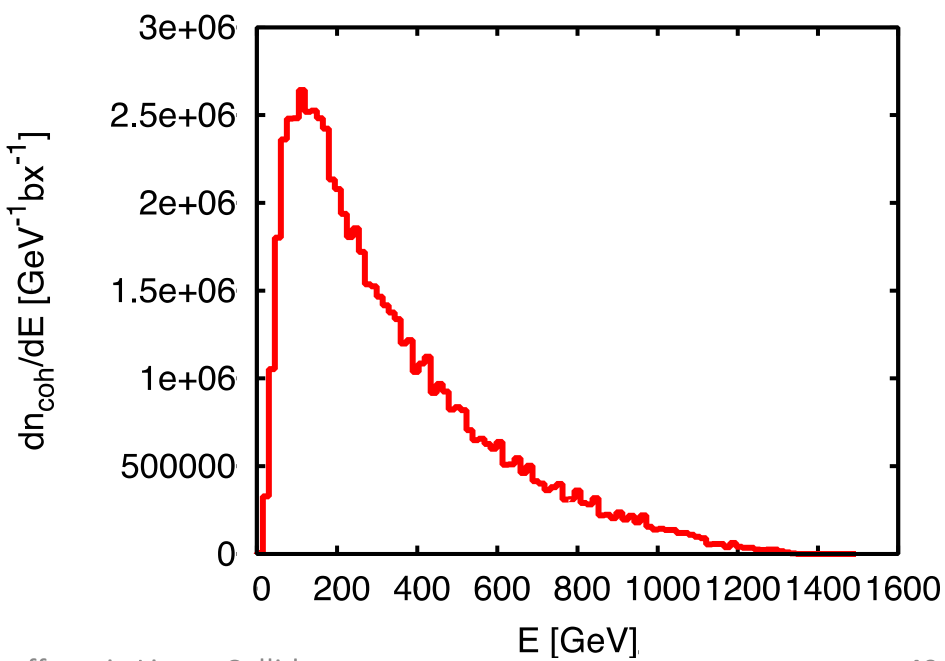
A photon in a very strong field can form an electron-positron pair
⇒ Coherent pair creation



$$\frac{\gamma B}{B_c} = \Upsilon$$

$$B_c \approx 4.4 \times 10^9 \mathrm{T}$$

Produce 6.8×10^8 pairs
Average particle energy 0.3TeV



Spent Beam Divergence

Beam particles are focused by oncoming beam

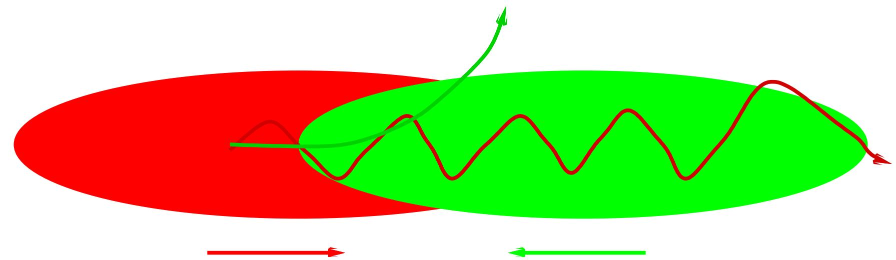
Photons are radiated into direction of beam particles

Coherent pair particles can be focused or defocused by the beams but deflection limited due to their high energy

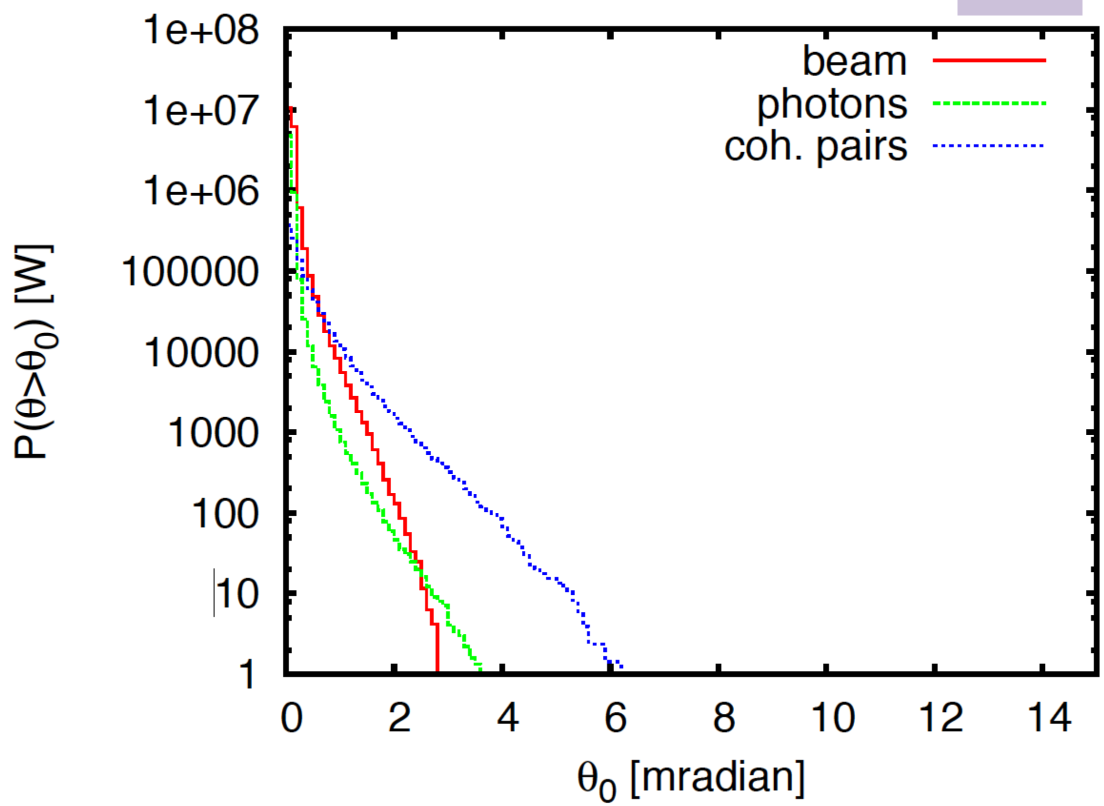
-> Extraction hole angle should be significantly larger than 6mradian

We chose 10mradian for CLIC
-> 20mradian crossing angle

ILC requires 14mradian crossing angle

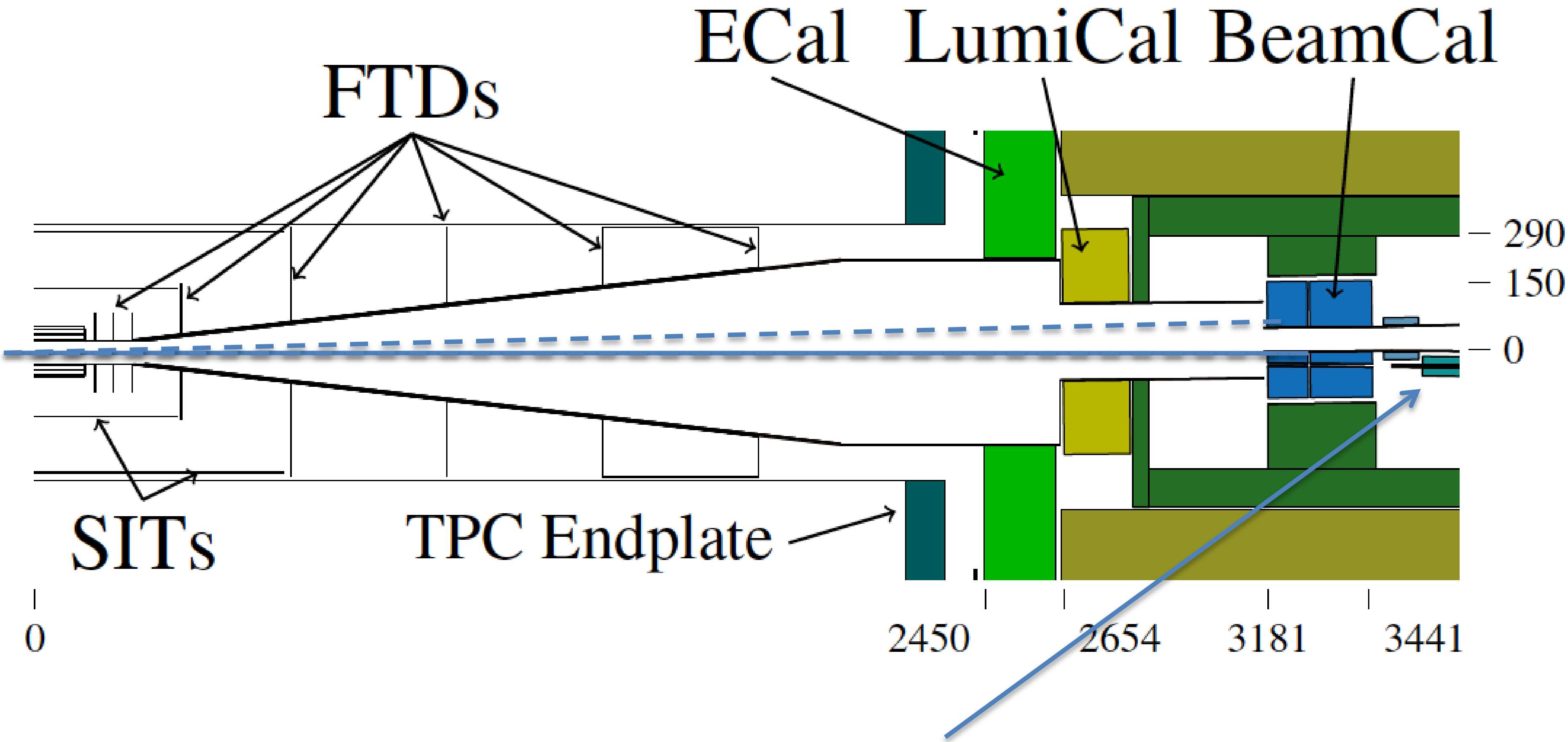


CLIC



$1\,\mathrm{W} \approx 400\,\mathrm{TeV/bx} \approx 300\,\mathrm{beamparticles/bx}$

CLIC Inner Detector Layout

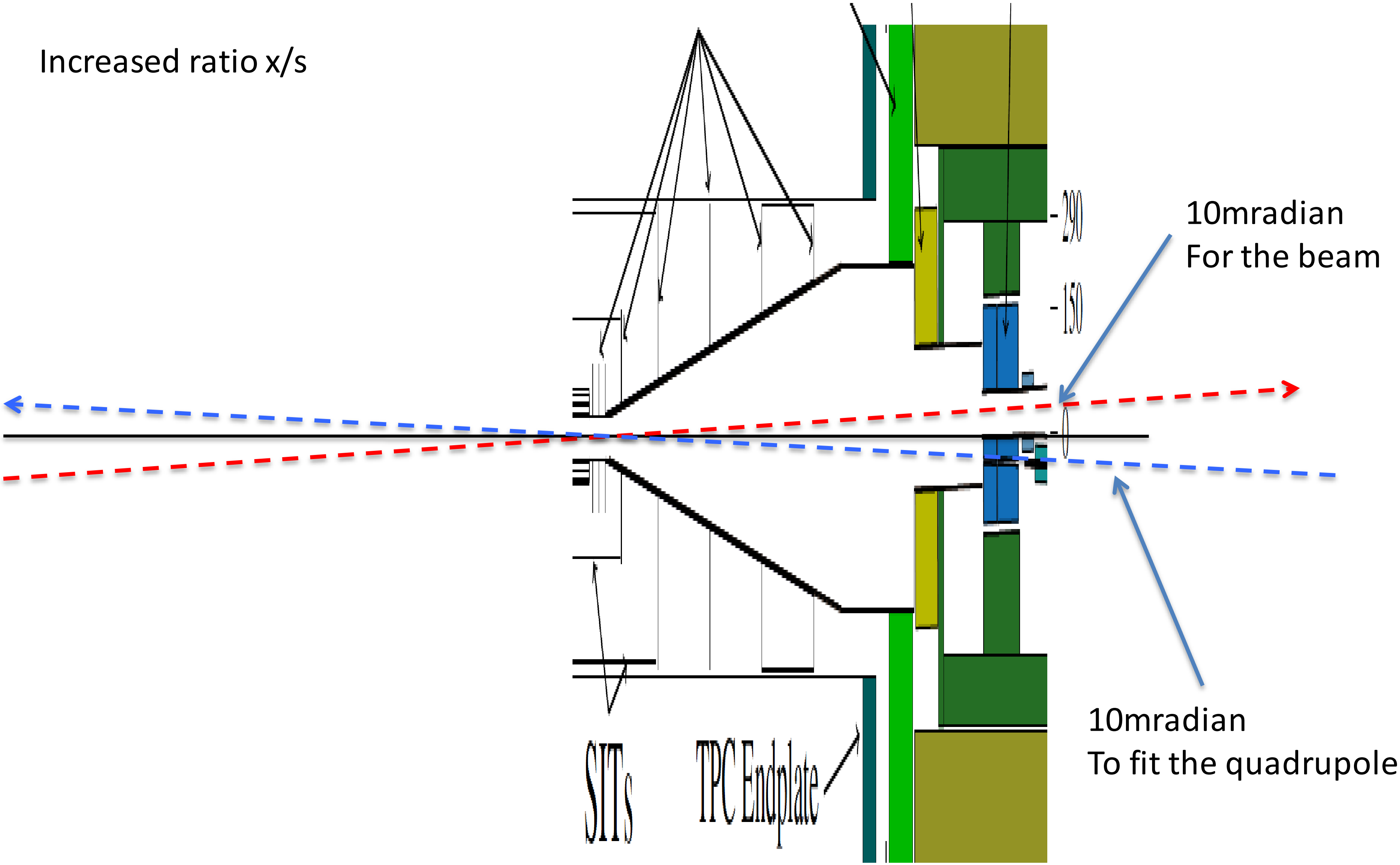


The last focusing magnet of the machine is inside of the detector

A. Seiler

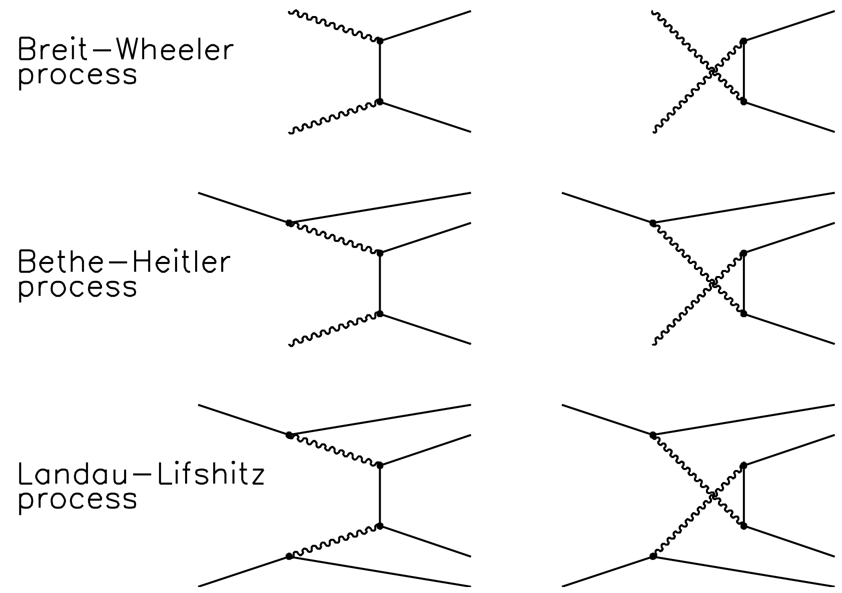
CLIC Inner Detector Layout

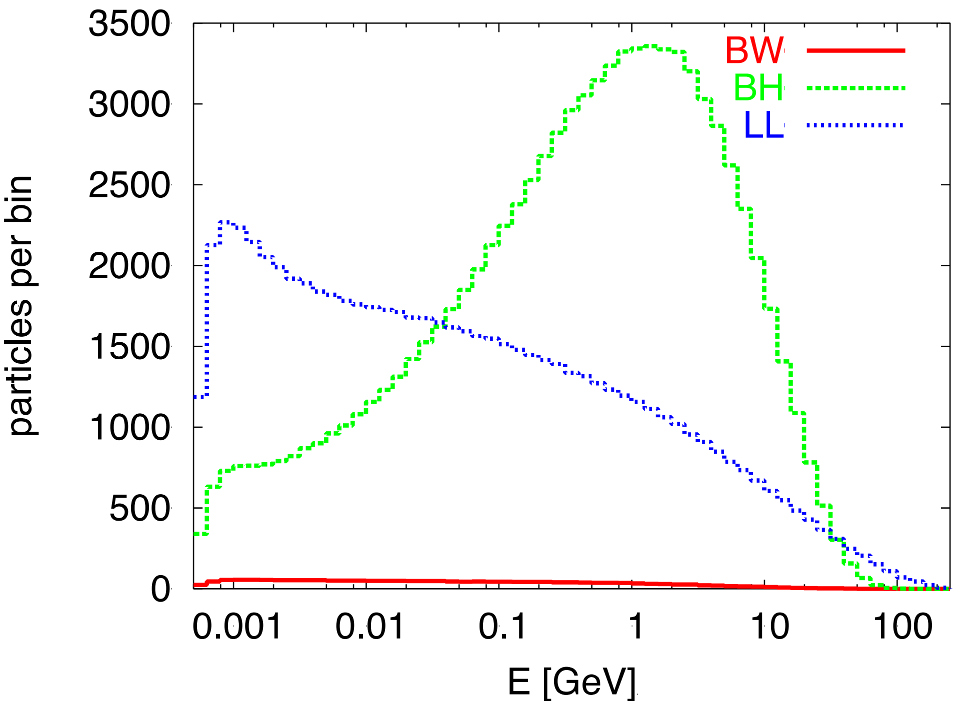
Increased ratio x/s



Electron-Positron Pair Production

Colliding photons can produce electron-positron pairs (incoherent pair production)
O(10^5) per bunch crossing





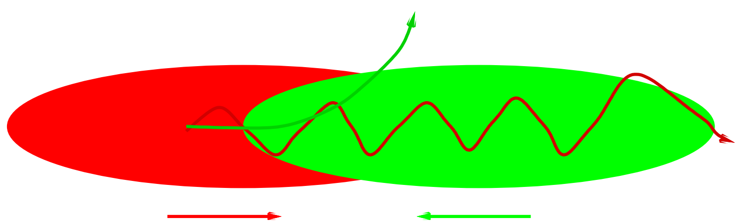
Note: beamsize effect gives some reduction, ignored here

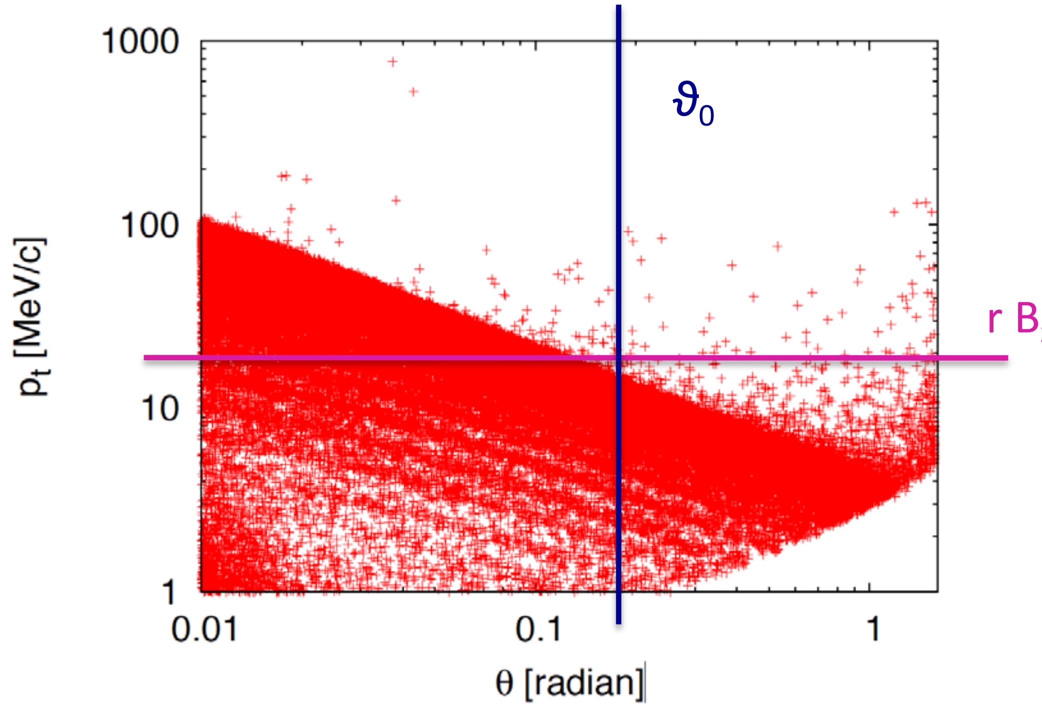
Also muons can be produced, but small rate

ILC and CLIC Main Parameters

Parameter	Symbol [unit]	ILC	CLIC	CLIC
Centre of mass energy	E_{cm} [GeV]	500	380	3000
Total luminosity	L [$10^{34}cm^{-2}s^{-1}$]	1.8	1.5	6
Luminosity in peak	$L_{0.01}$ [$10^{34}cm^{-2}s^{-1}$]	1	0.9	2
Particles per bunch	N [10^9]	20	5.2	3.72
Bunch length	σ_z [μm]	300	70	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	474/5.9	149/2.9	40/1
Vertical emittance	$\varepsilon_{x,y}$ [nm]	35	40	20
Photons per beam particle	n_γ	1.9	1.5	2.1
Average photon energy	$\langle E_\gamma/E_0 \rangle$ [%]	2.4	4.5	13
Coherent pairs	N_{coh}	-	-	6.8×10^8
Their energy	E_{coh} [TeV]	-	-	2.1×10^8
Incoherent pairs	N_{incoh}	196×10^3	58×10^3	300×10^3
Their energy	E_{incoh} [TeV]	484	187	2.3×10^4

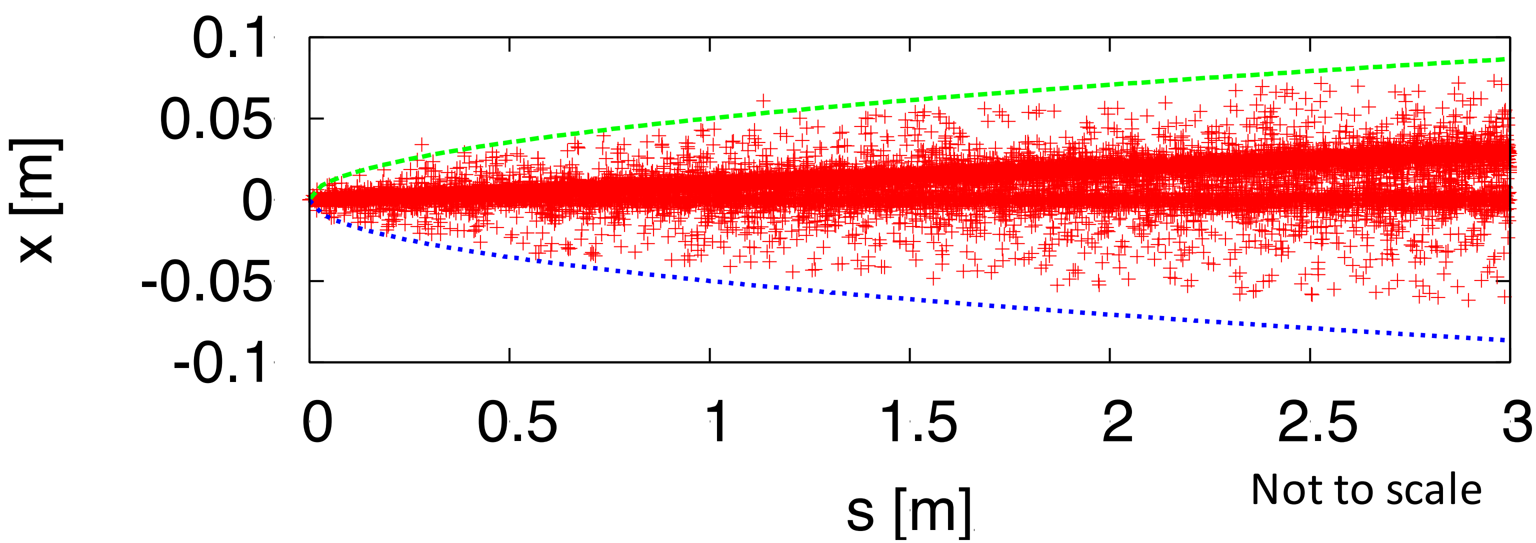
Incoherent Pairs





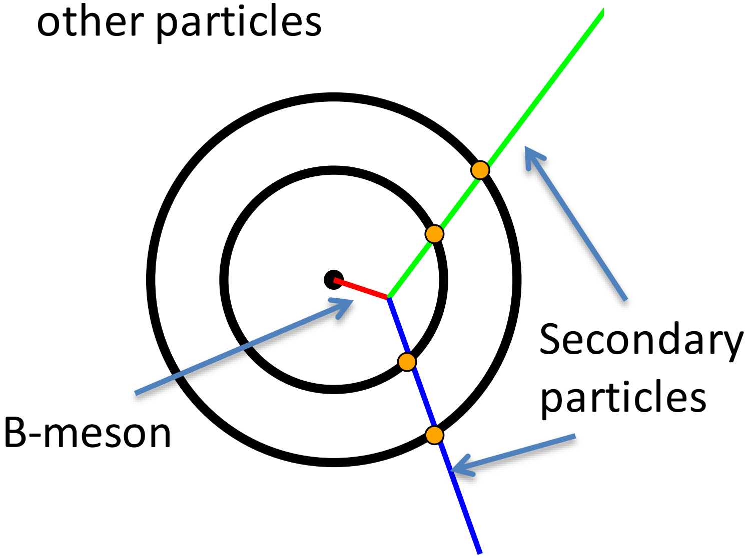
Incoherent pairs can be strongly deflected by the

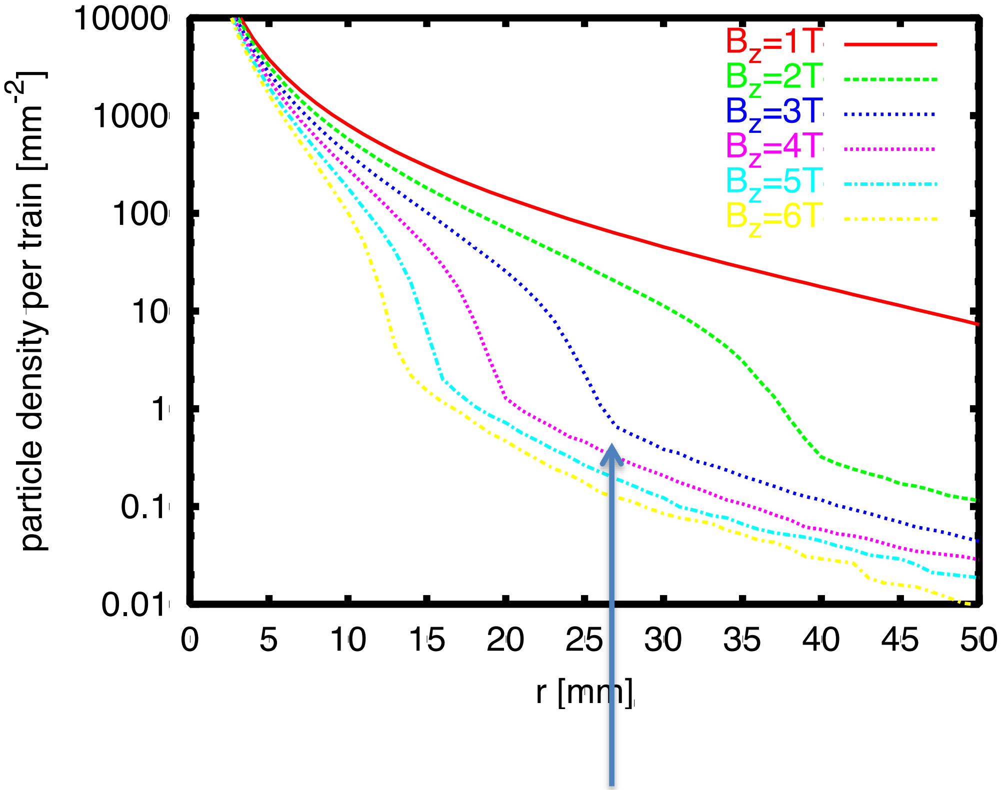
Maximum deflection angle depends on their energy



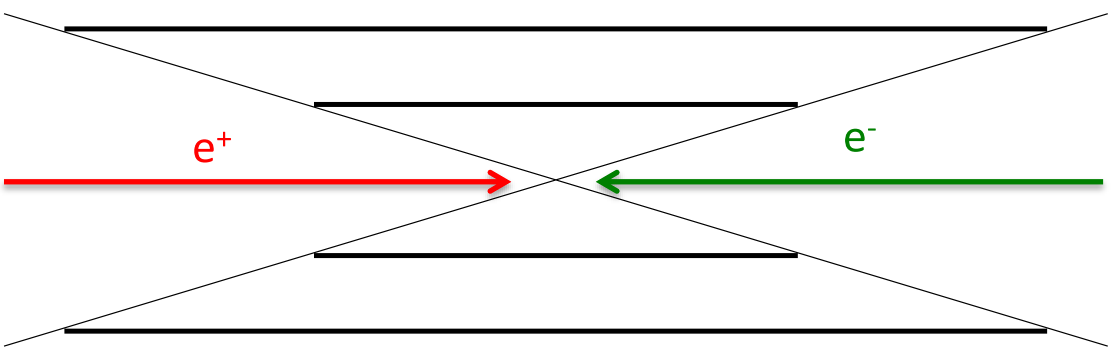
Impact on Vertex Detector

To vertex detector can identify particles originating from decays of other particles





Need a certain angular coverage



Hit density from pairs depends on radius and field

Edge is due to beam-beam deflection

Limit O(1mm^{-2})

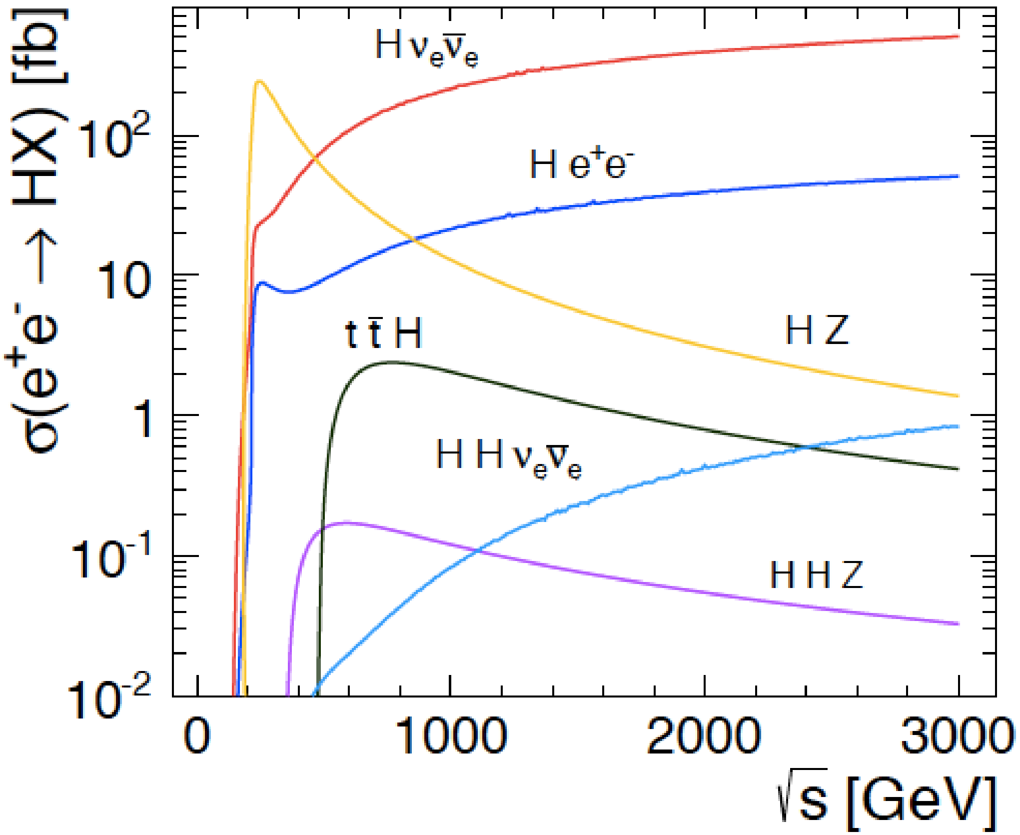
Conclusion

- Beam-beam effects have critical impact on luminosity in linear colliders
  - Strong pinching enhances luminosity
  - Simulations tool are important
  - Beamstrahlung requires flat beams and gives lower limit on horizontal size
    - Has impact on experiment performance
  - For high disruption collisions can be unstable
    - Very good beam-beam stability is required
  - Non-linear QED can appear at high energies
    - Beam charge can increase by O(10%)

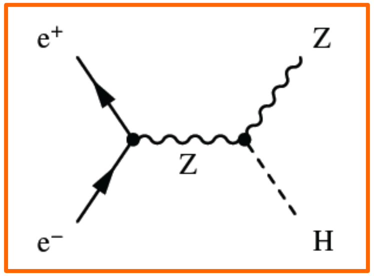
- Machine background poses important constraints on the experiment
  - Minimum vertex detector radius is given by beam parameters

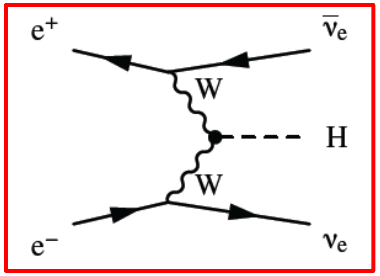
Reserve

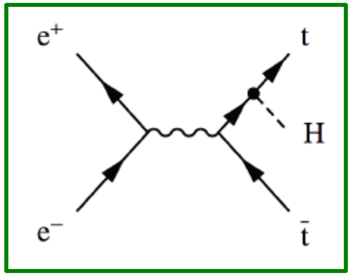
Higgs Physics in e+e- Collisions

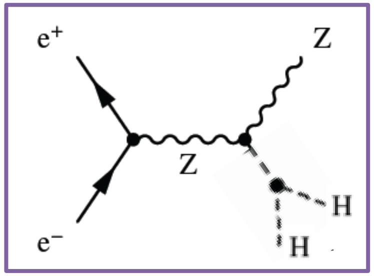


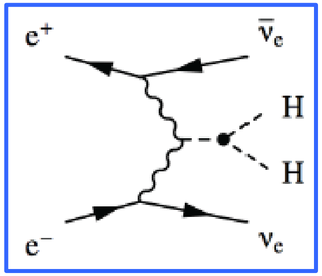
- **Precision Higgs measurements**
- Model-independent
  - Higgs couplings
  - Higgs mass
- Large energy span of linear colliders allows to collect a maximum of information:
  - ILC: 500 GeV (1 TeV)
  - CLIC: ~350 GeV – 3 TeV









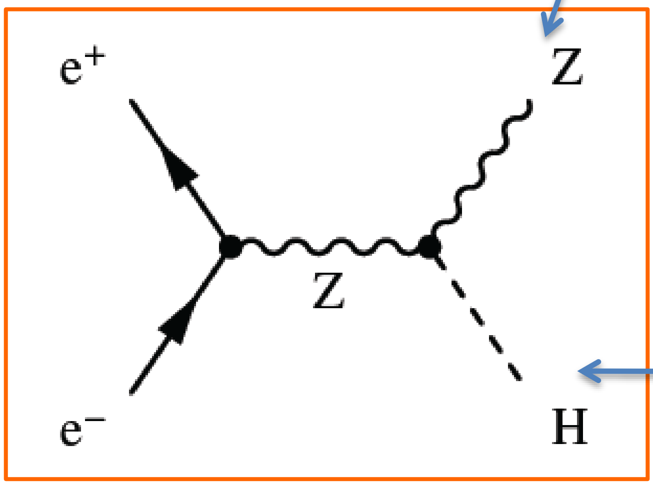


Invisible Higgs Decays

Can we check that the Higgs does not decay into something invisible, e.g. neutrinos?

Yes, missing mass (or recoil mass) analysis:

1) Measure the Z, e.g. from produced jets



2) Subtract Z momentum from initial state
$(E_{cm},0,0,0)-(E_Z, P_{Z,x}, P_{Z,y}, P_{Z,z})=(E_H, P_{H,x}, P_{H,y}, P_{H,z})$

3) Result is mass and momentum of other particle
Even if we do not see it

So we know the missing particle

Automatic Parameter Determination

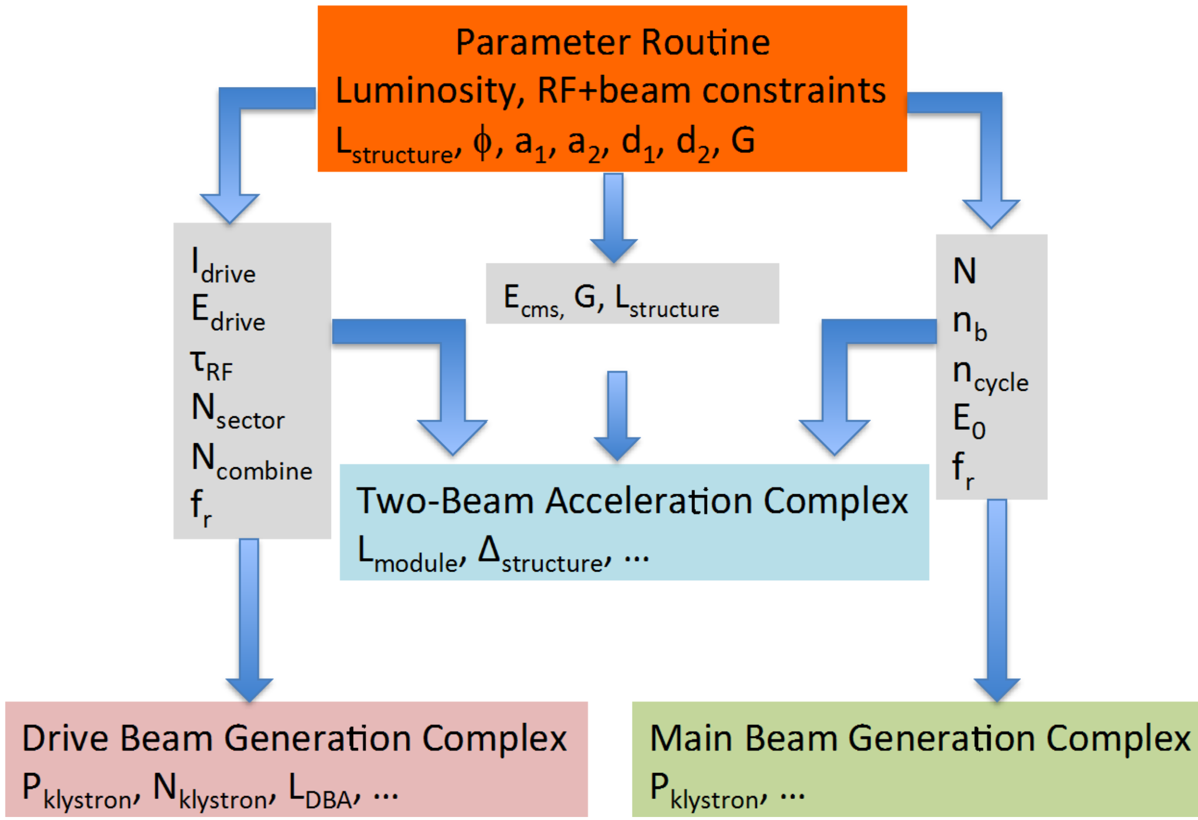
Structure design fixed by few parameters

$a_1, a_2, d_1, d_2, N_c, \phi, G$

Beam parameters derived automatically to reach specific energy and luminosity

Consistency of structure with RF constraints is checked

Repeat for 1.7 billion cases



Design choices and specific studies

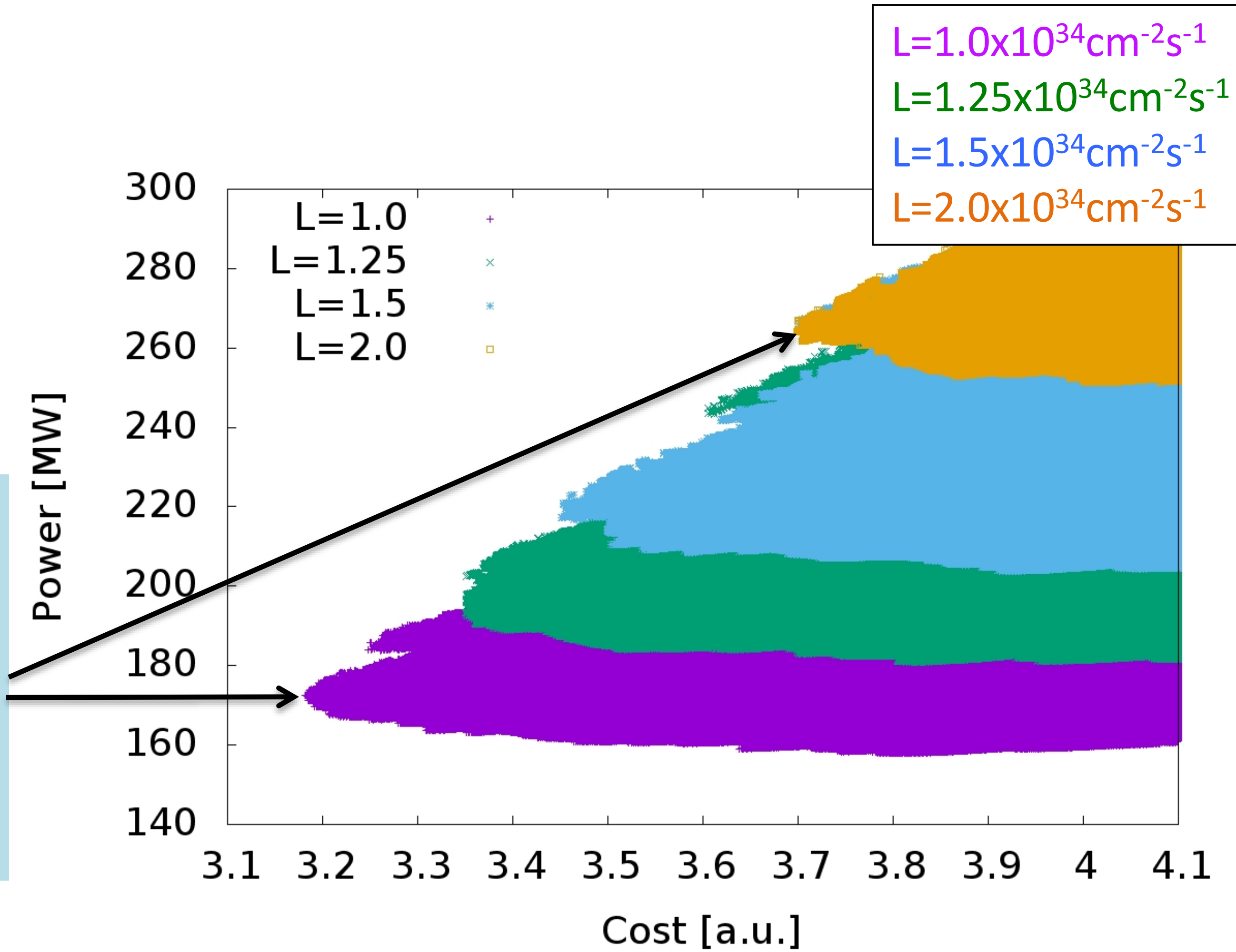
- Use 50Hz operation for beam stability
- Scale horizontal emittance with charge to keep the same risk in damping ring
- Scale for constant local stability in main linac, i.e. tolerances vary but stay above CDR values
- BDS design similar to CDR, use improved β_x-reach as reserve
-

Optimisation at 380GeV

Many thanks to the rebaselining team that provided the models that are integrated in the code

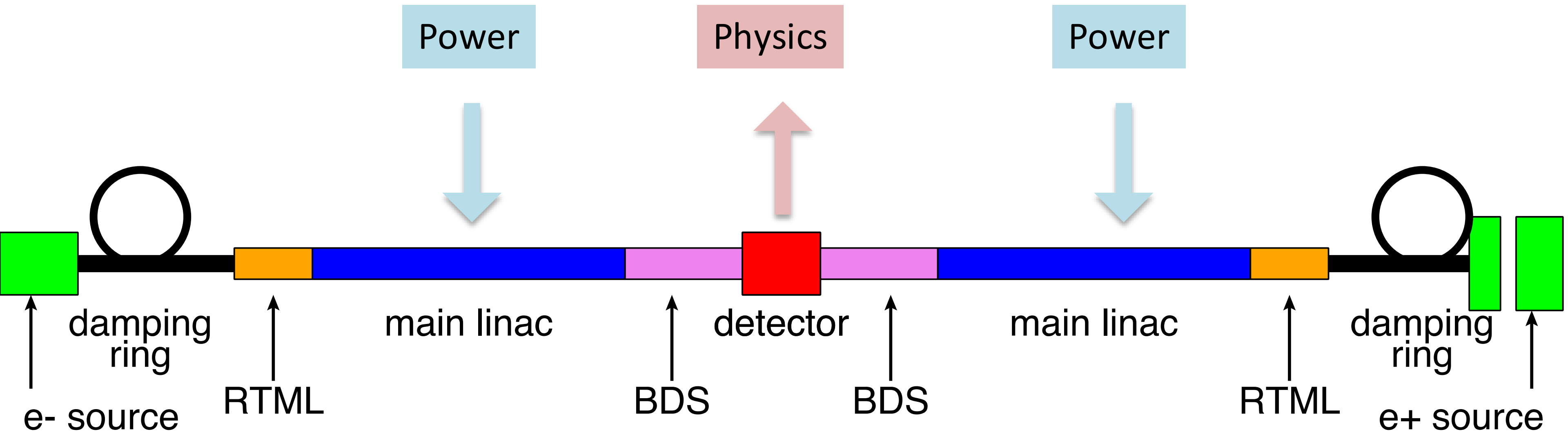
Luminosity goal significantly impact minimum cost
For $L=1\times10^{34}cm^{-2}s^{-1}$ to $L=2\times10^{34}cm^{-2}s^{-1}$:

Costs 0.5 a.u.
And O(100MW)



Cheapest machine is close to lowest power consumption => small potential for trade-off

Generic Linear Collider



Can reach high electron-positron centre-of-mass energies

- almost no synchrotron radiation

Single pass, hence two main challenges

- gradient
- luminosity

Note: Luminosity Enhancement

Parameter	Symbol [unit]	ILC	CLIC	CLIC
Centre of mass energy	E_{cm} [GeV]	500	380	3000
Total luminosity	L [$10^{34}cm^{-2}s^{-1}$]	1.8	1.5	6
Luminosity in peak	$L_{0.01}$ [$10^{34}cm^{-2}s^{-1}$]	1	0.9	2
Particles per bunch	N [10^9]	20	5.2	3.72
Bunch length	σ_z [μm]	300	70	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	474/5.9	149/2.9	40/1
Vertical emittance	$\varepsilon_{x,y}$ [nm]	35	40	20
Geometric luminosity	L_{geom} [$10^{34}cm^{-2}s^{-1}$]	0.75	0.8	4.3
Enhancement factor	H_D	2.4	1.9	1.5

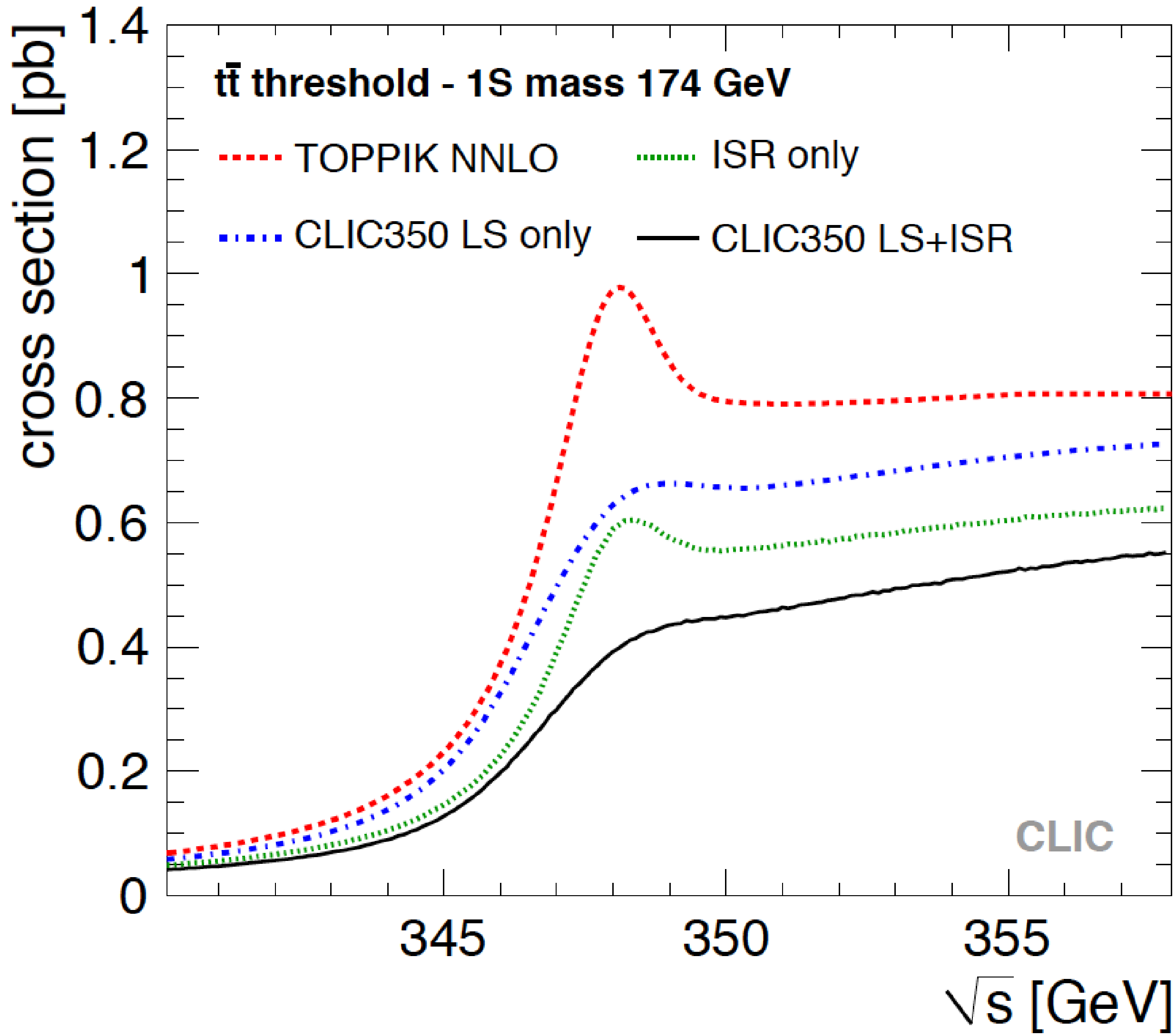
Top Production at Threshold

K. Seidel et al. **arXiv:1303.3758**

Top production at threshold is strongly affected by beam energy spread and beamstrahlung

For $L_{0.01} > 0.6$ L impact of beamstrahlung is comparable to ISR

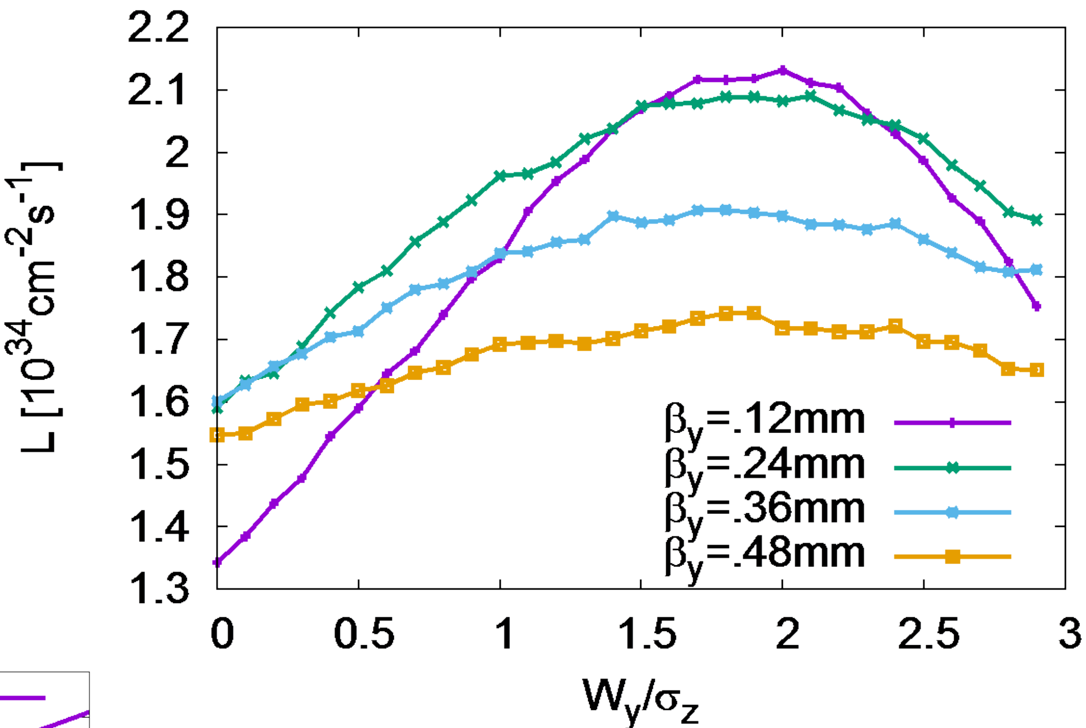
But depends on physics

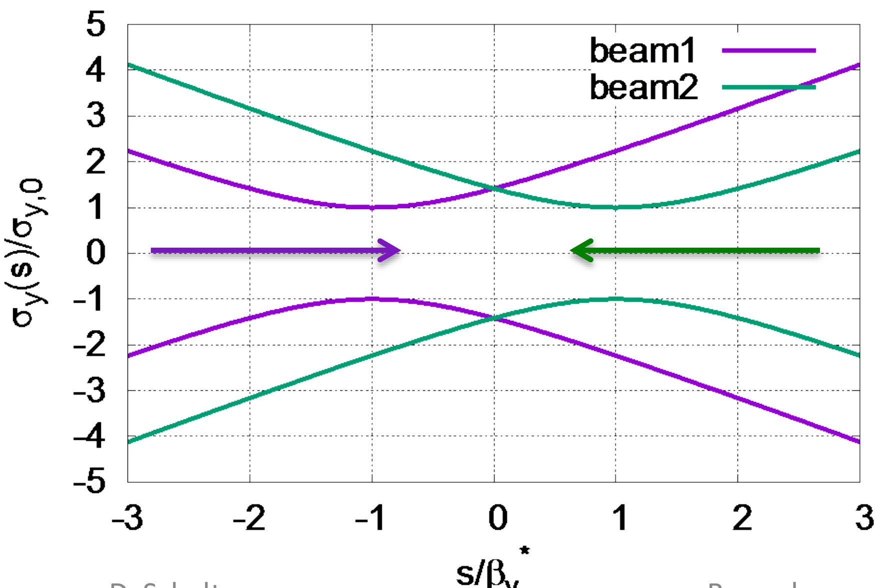


Note: Travelling Focus

Travelling focus (Balakin):
We focus each slice of the beam on one point of the oncoming beam, e.g. $2\sigma_z$ before the centre

The beam-beam forces keep the beam small

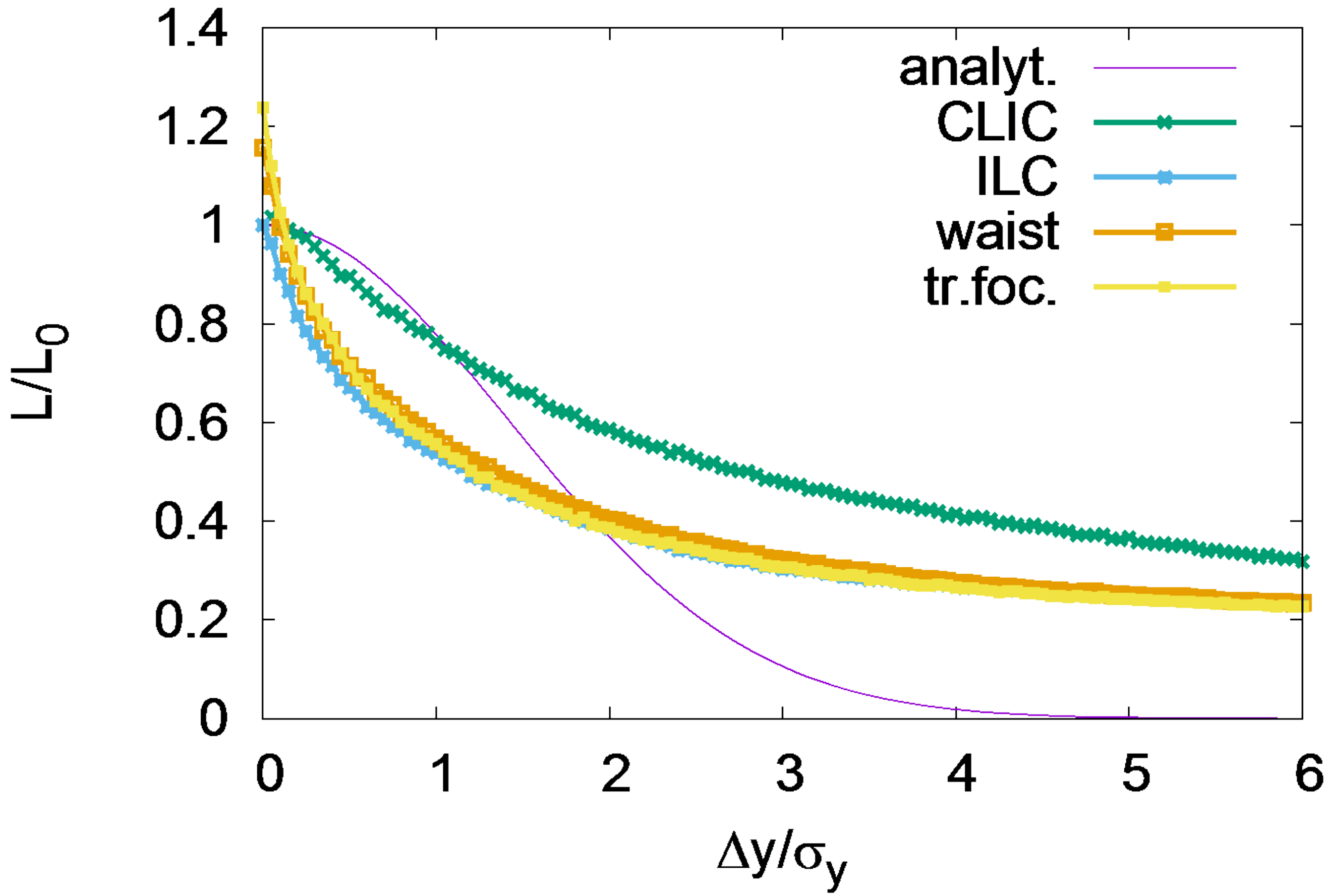




Additional gain of 10% in luminosity

Note: ILC with β_y=0.24mm

Even stronger offset dependence for smaller beta-function



So in practice less gain than expected