Beamstrahlung and GUINEA-PIG

Daniel Schulte

Introduction

GUINEA-PIG**:**
Generator of **U**nwanted **I**nteractions for **N**umerical **E**xperiment **A**nalysis
– **P**rogramme **I**nterfaced to **G**EANT

GUINEA-PIG written in C as PhD project at DESY (first version 1994)
Mainly a tool for detector and physics studies for TESLA
⇒ focus on single passage

GUINEA-PIG++:
Translation into C++ at LAL (written in 2007)
some additions like polarisation,
Should now have stabilised
Guy Le Meur, B. Dalena, J. Esberg, C. Rimbault, J. Snuverink

https://gitlab.cern.ch/clic-software/guinea-pig

New fellow starting now to work on the code
Recently modified for muon collider

Physics

GUINEA-PIG simulates the interaction of two colliding ultra-relativistic beams containing electrons, positrons and photons (others can be approximated using tricks)
Made for single collisions, can be used for repeated collisions at some level but with care

Can load electron, positron and gamma beams, typically required because complex energy profile exists, also for gamma-gamma collider

It includes:

- Pinching of the beams
- Emission of beamstrahlung
- Initial state radiation
- Production of incoherent pair background
- Bremsstrahlung
- Beam size effect
- Production of coherent pair background
- Production of hadronic background (also minijets)

GUINEA-PIG++ also includes

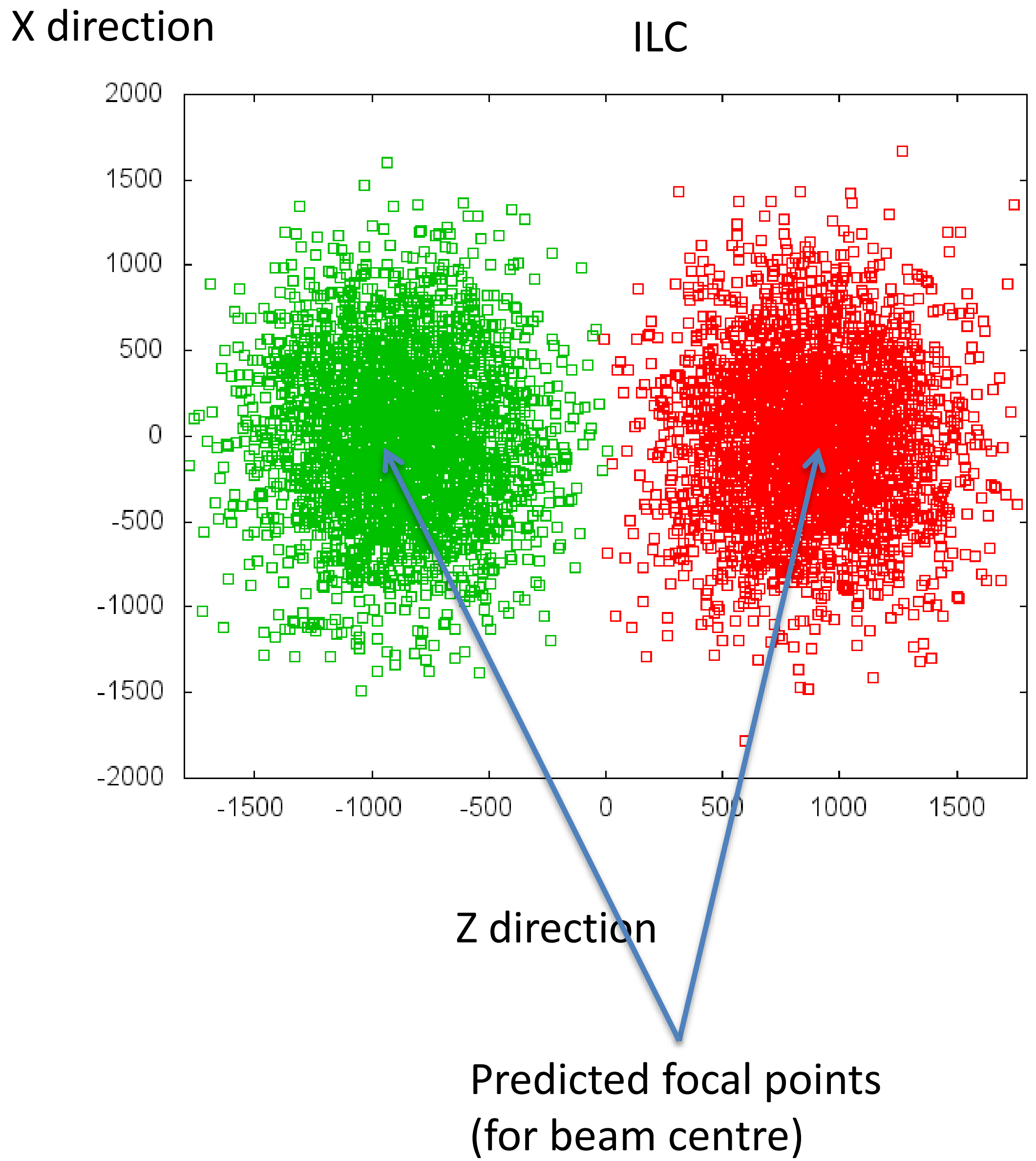
- Beam polarisation
- Trident cascade process
- now also hadrons

Pinch Effect

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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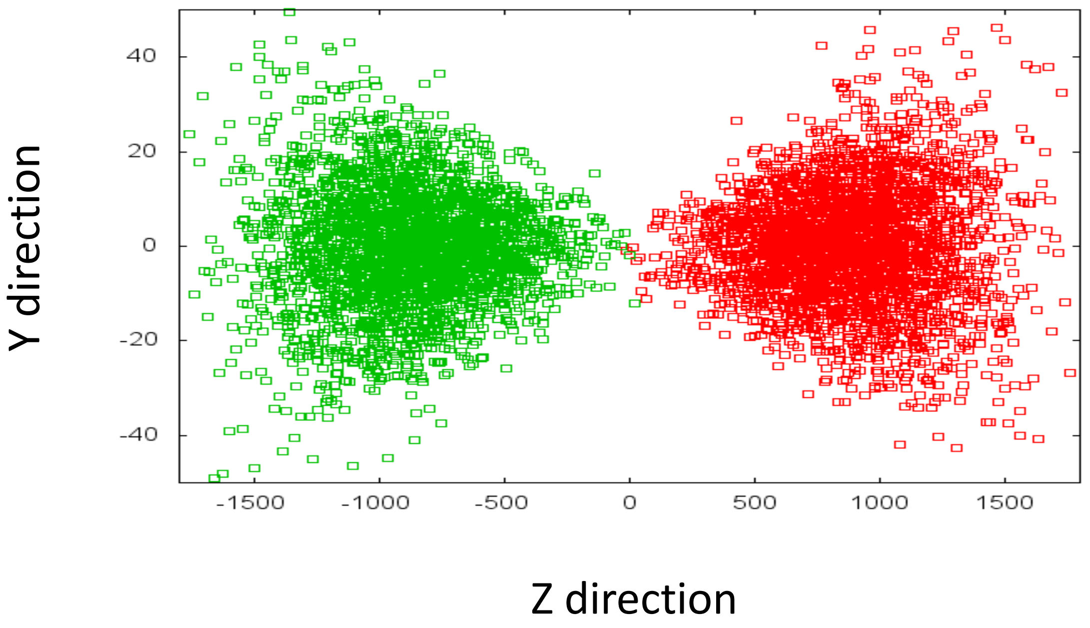
Beam-beam force switched off



Overview

- Modelling of beam-beam interaction
  - based on known physics
  - Total luminosity increase estimate of GUINEA-PIG has been benchmarked at SLC
- Beamstrahlung generator
  - known physics for circular orbit
  - some constraints on beam parameters for validity have to be checked
- Design phase space of colliding beams is complex
  - toss a coin to your local accelerator physicist and get files with input distributions
- Modelling of luminosity spectrum with fits (e.g. CIRCE)
  - seems OK if correlation can be handled
- Phase space of actual beam differs from design and is not fully known
  - static imperfections
  - dynamic imperfections
- Some comment on initial state radiation, bremsstrahlung and incoherent pairs

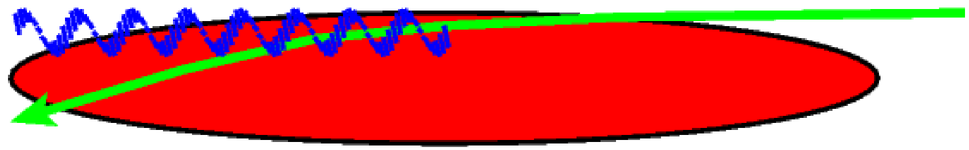
Correct Use

- Fast estimates by defining beam parameters in the acc.dat file
  - allows to define beam size, emittance, beta-function, bunch length, energy spread (Gaussian or rectangular), waist shift, offsets, …

- Better estimates by using input files from tracking codes
  - linear colliders contain correlations in the beam
    - tracking includes these correlations in the input files
  - beam shape in FCC-ee is formed by interaction over many turns
    - special code developed (X. Buffat et al.) to simulate this
  - parameters are an approximation
  - beams vary with time
    - your local accelerator expert can tell about wanted and unwanted changes

- The specific question can require more or less detail

Beamstrahlung Generator



Assume a locally circular orbit

- The radiation forms while particle trajectory is bend by angle of O(1/γ)
- Need to see field of many particles in the opposite beam over this length
  => Is the case in all practical parameter set
- Note: typically one single particle dominates field seen at any given position in beam but averages out over distance of photon emission

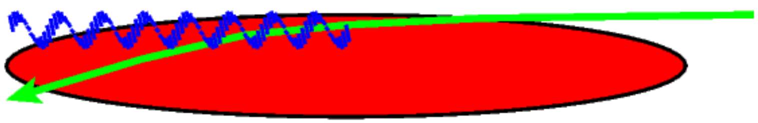
- Need to bend particles by several times 1/γ
  => typically the case, η has to be several, but much smaller than N

$$\eta = \gamma\theta_x = D_x \frac{\sigma_x}{\sigma_z}\gamma = \frac{2Nr_e}{\sigma_x + \sigma_y}$$

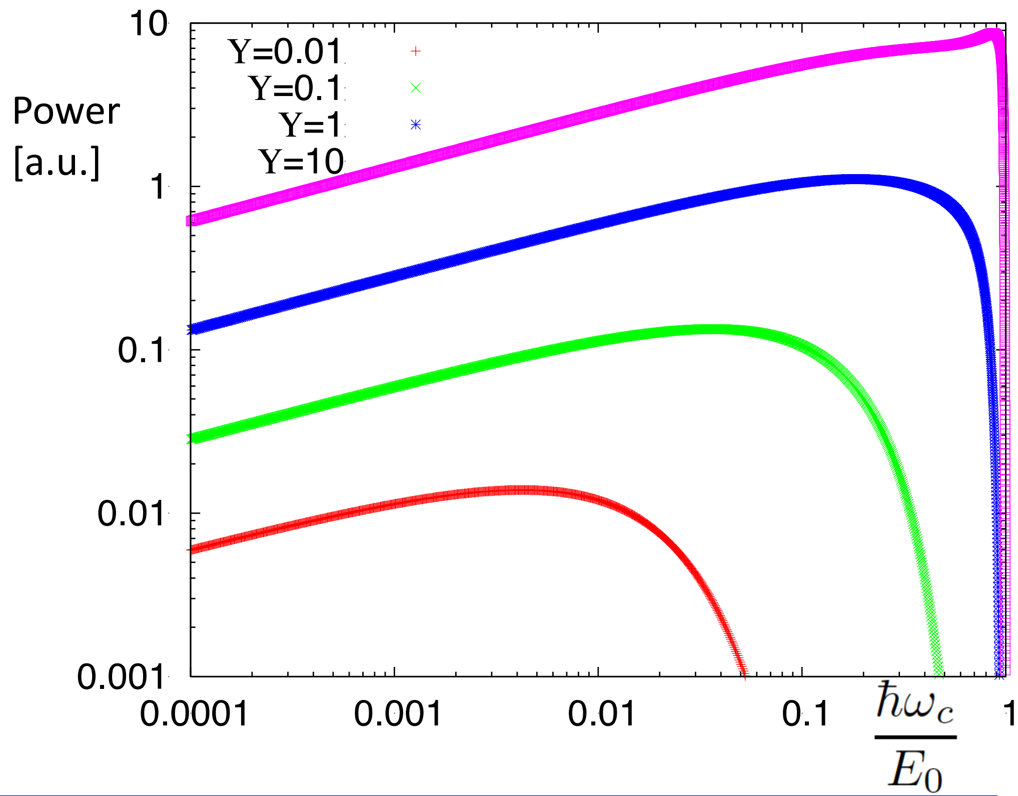
Typically emit O(1) photon per beam particle

⇒ Need a generator to produce individual photons with the correct probability

Beamstrahlung



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



Classical regime $\Upsilon \ll 1$

ILC (0.06), CLIC at 380GeV (0.17)

Quantum regime $\Upsilon \gg 1$

CLIC at 3TeV Y=5

The spectrum is given by Sokolov-Ternov Spectrum

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

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

Nice numerical method by K. Yokoya implemented (KEK-Report 85-9)

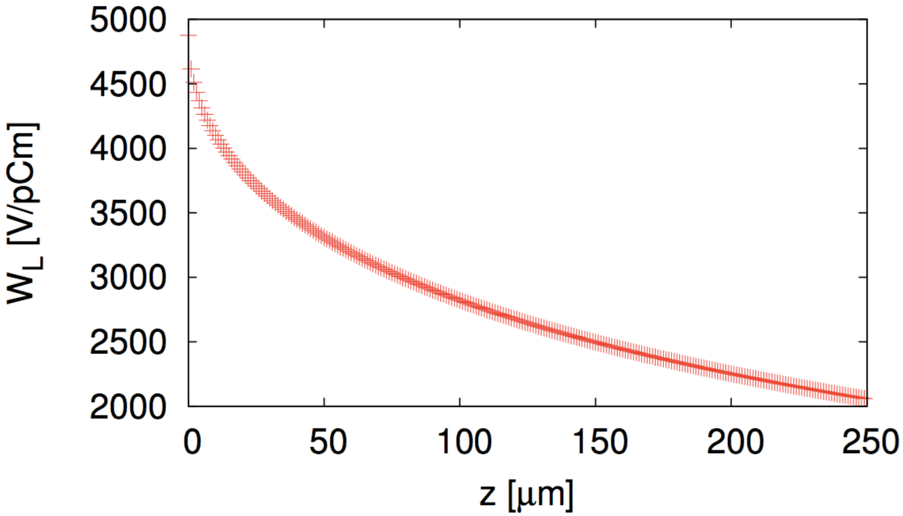
Example: Beam Energy Spread

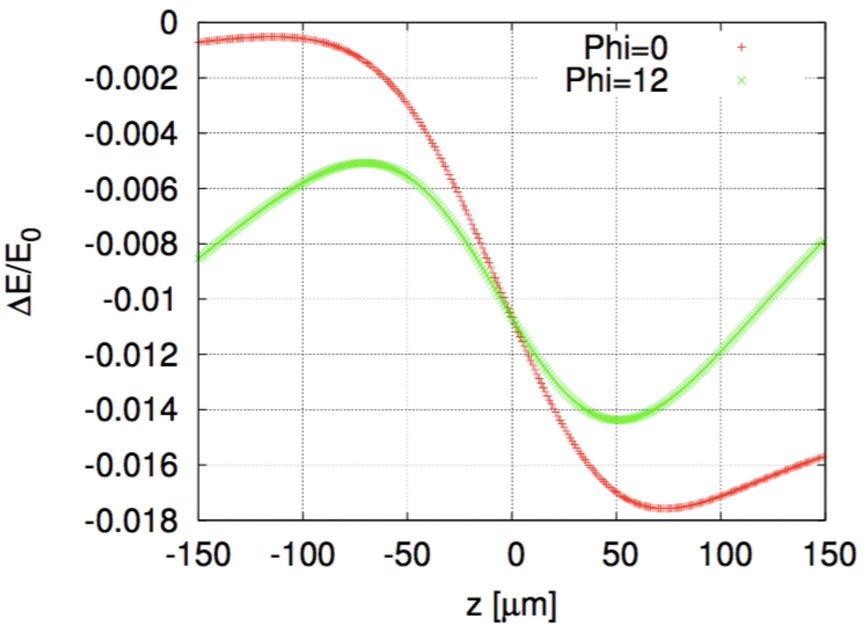
Beam has an uncorrelated energy spread from the damping ring (and the positron production in ILC)

But it also has a correlated energy spread from the acceleration

Cause are wakefields:

- early particles take energy from the cavity so later particles are accelerated less
- Some trick with RF phase reduces the effect but does not fully eliminate it
- More important in CLIC than ILC
- Final energy spread is a key parameter for the beam parameters, efficiency and luminosity
    - more spread is higher efficiency and more luminosity but limited by energy acceptance of BDS

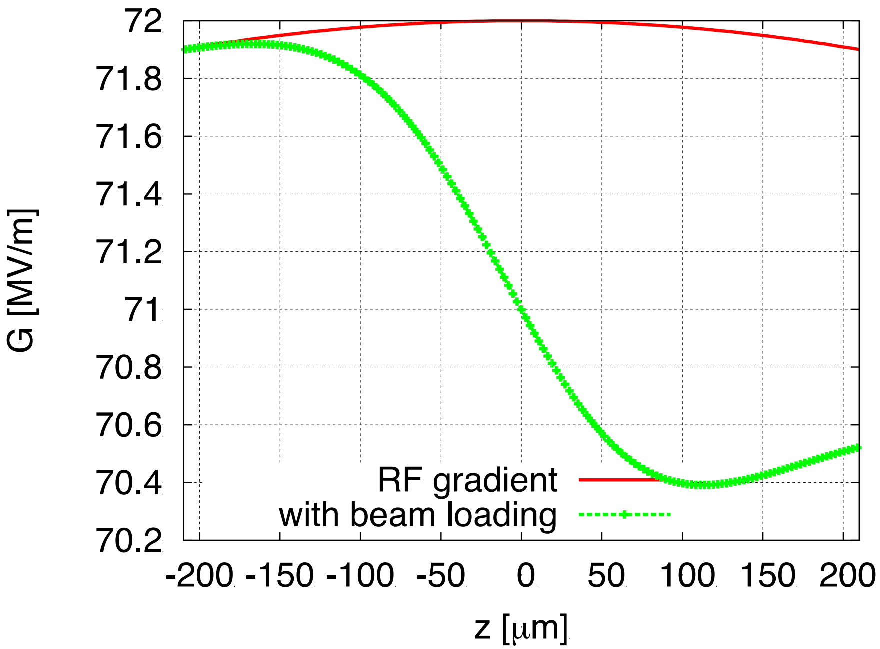


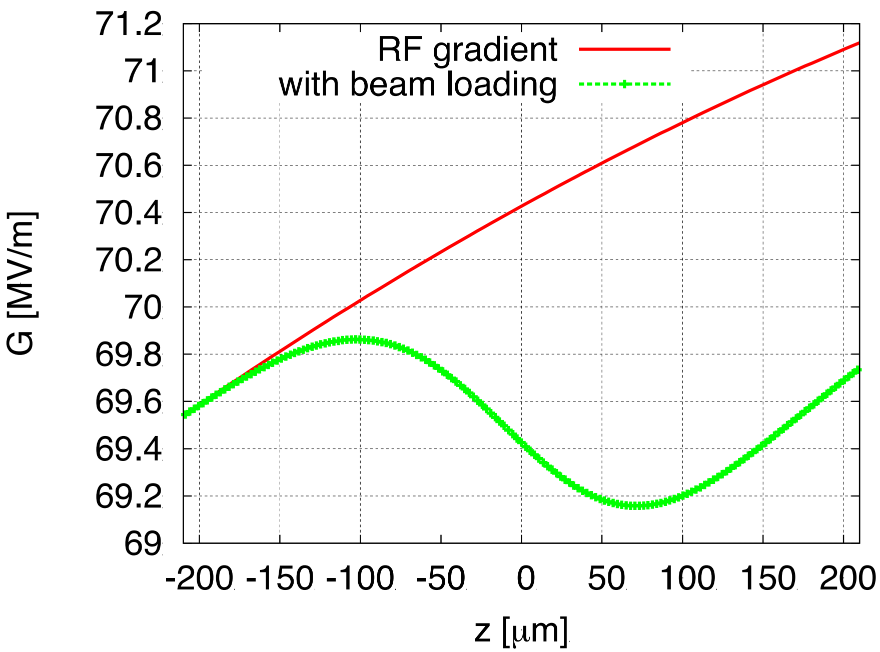


Example: Beam Energy Spread

Loaded gradient seen by a single bunch for on-crest acceleration:

- ➢ 2% full gradient spread
- ➢ 0.7% RMS gradient spread





Loaded gradient seen by a single bunch for off-crest acceleration (12°):

- ➢ 1% full gradient spread
- ➢ 0.35% RMS gradient spread
- ➢Loose about 2% in gradient

Energy Correlation

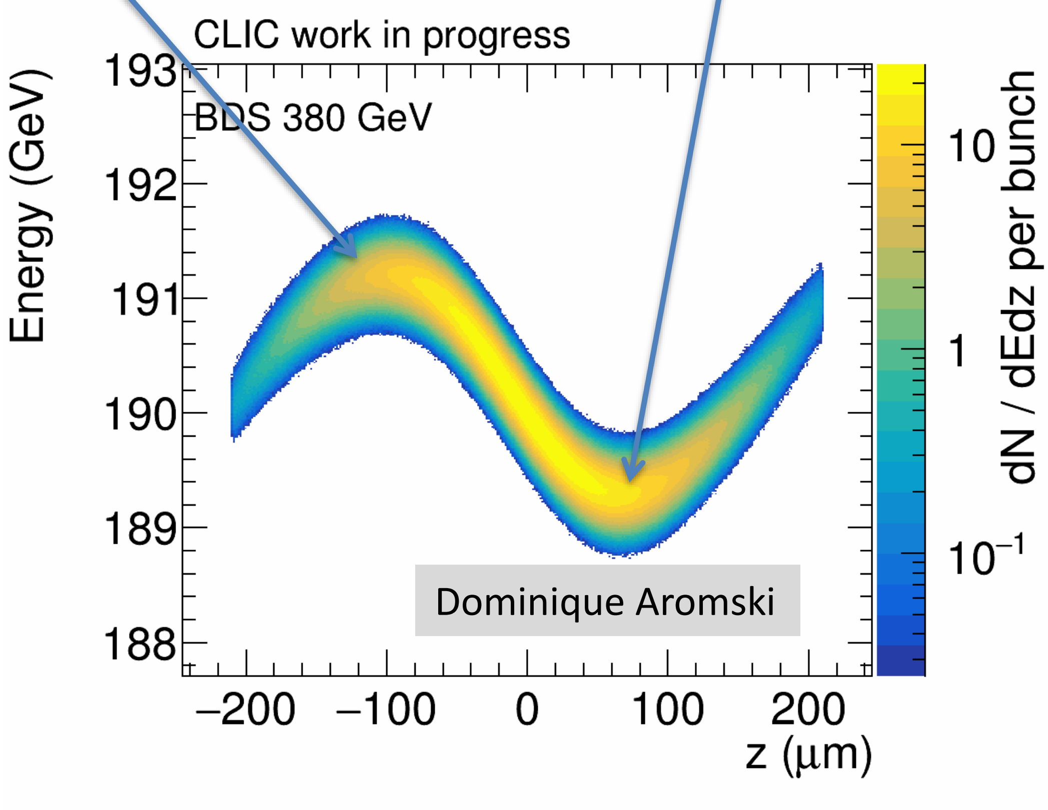
Early particles see full energy in other beam
But other bunch has not yet pinched

Late particles often see particles that lost energy in other beam
But other bunch has pinched

CLIC at 380 GeV is shown

Full energy difference is 1%

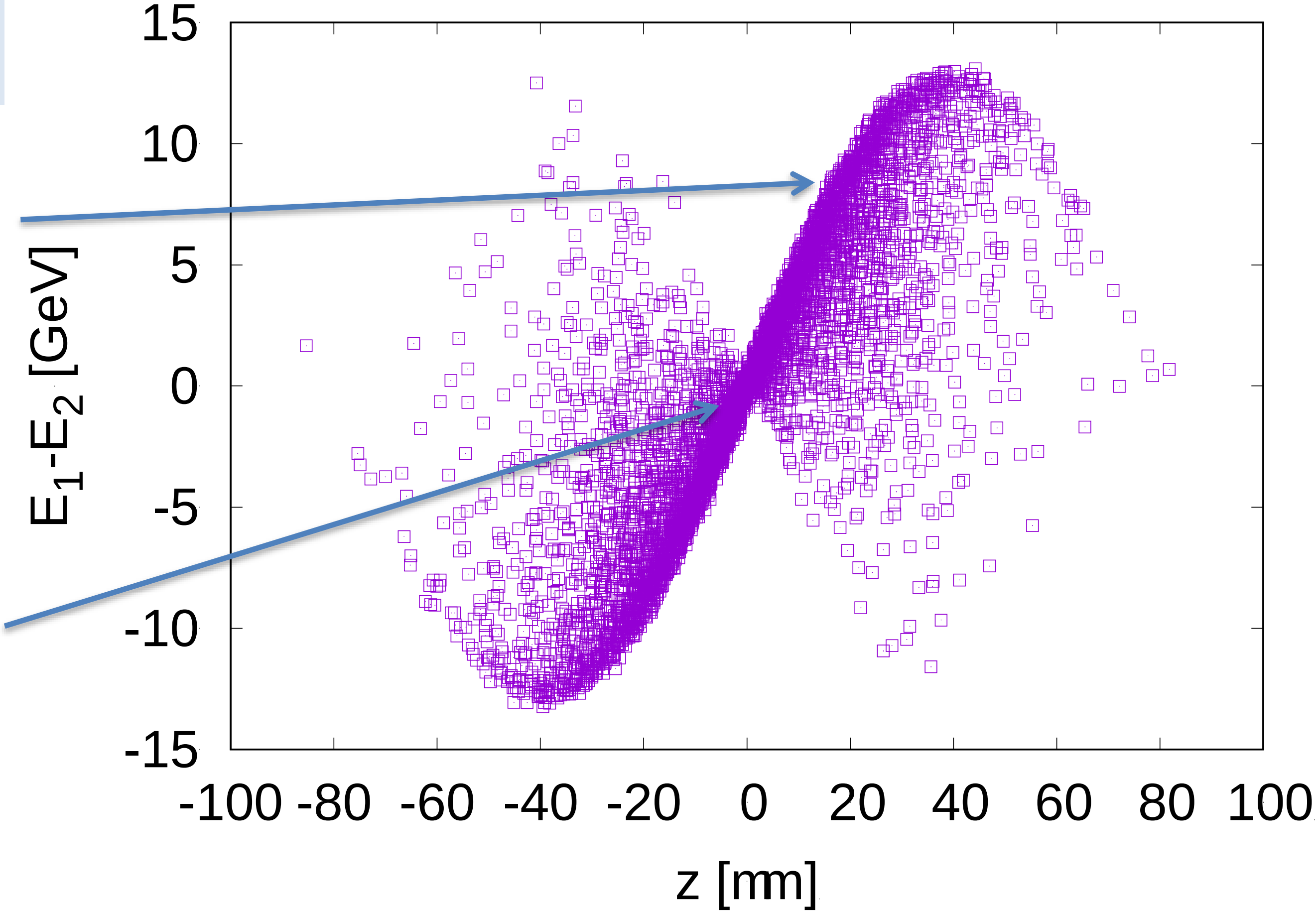
Note: CLIC studies take these correlations fully into account



Example Correlation

CLIC 3 TeV
no beamstrahlung

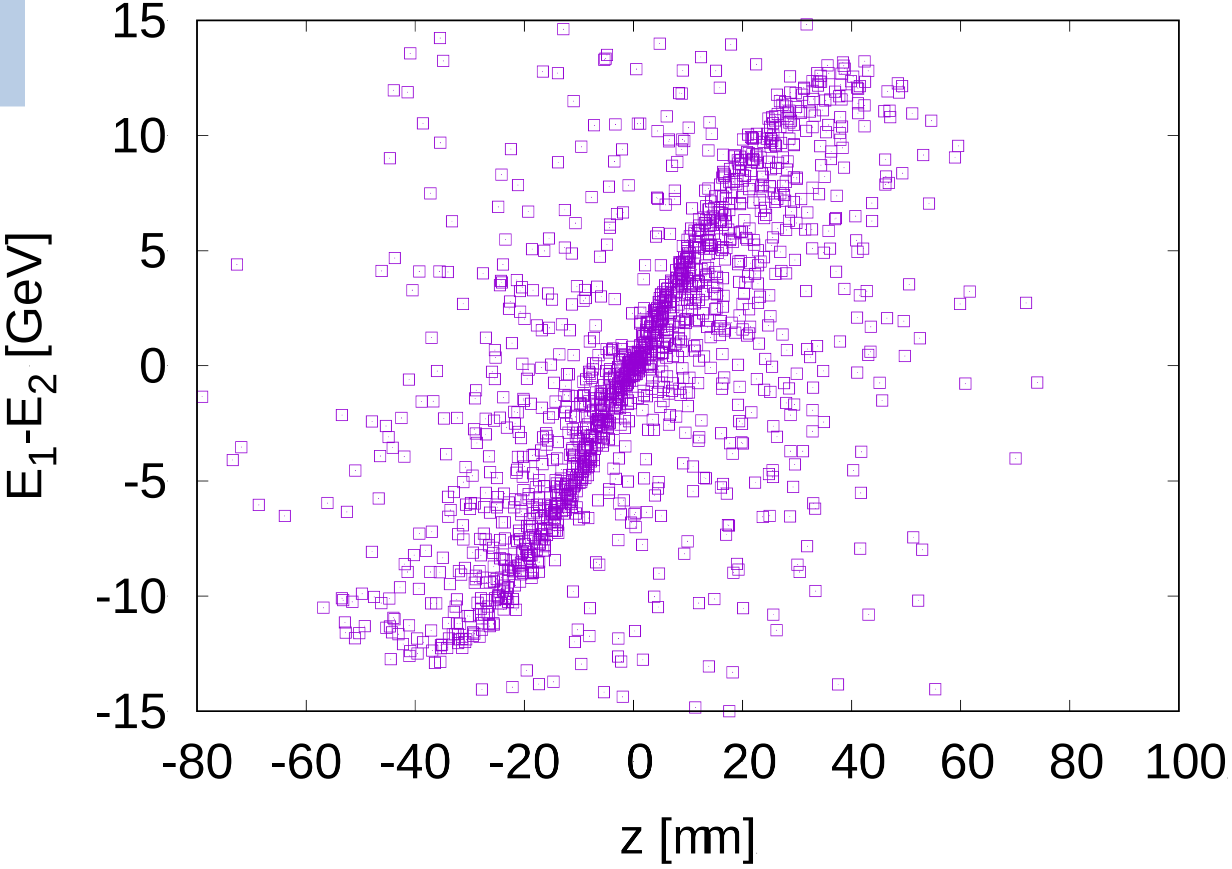
Particles in head (higher energy) collide more on far side



In centre both beams always have the same energy (but collision energy changes)

Example Correlation

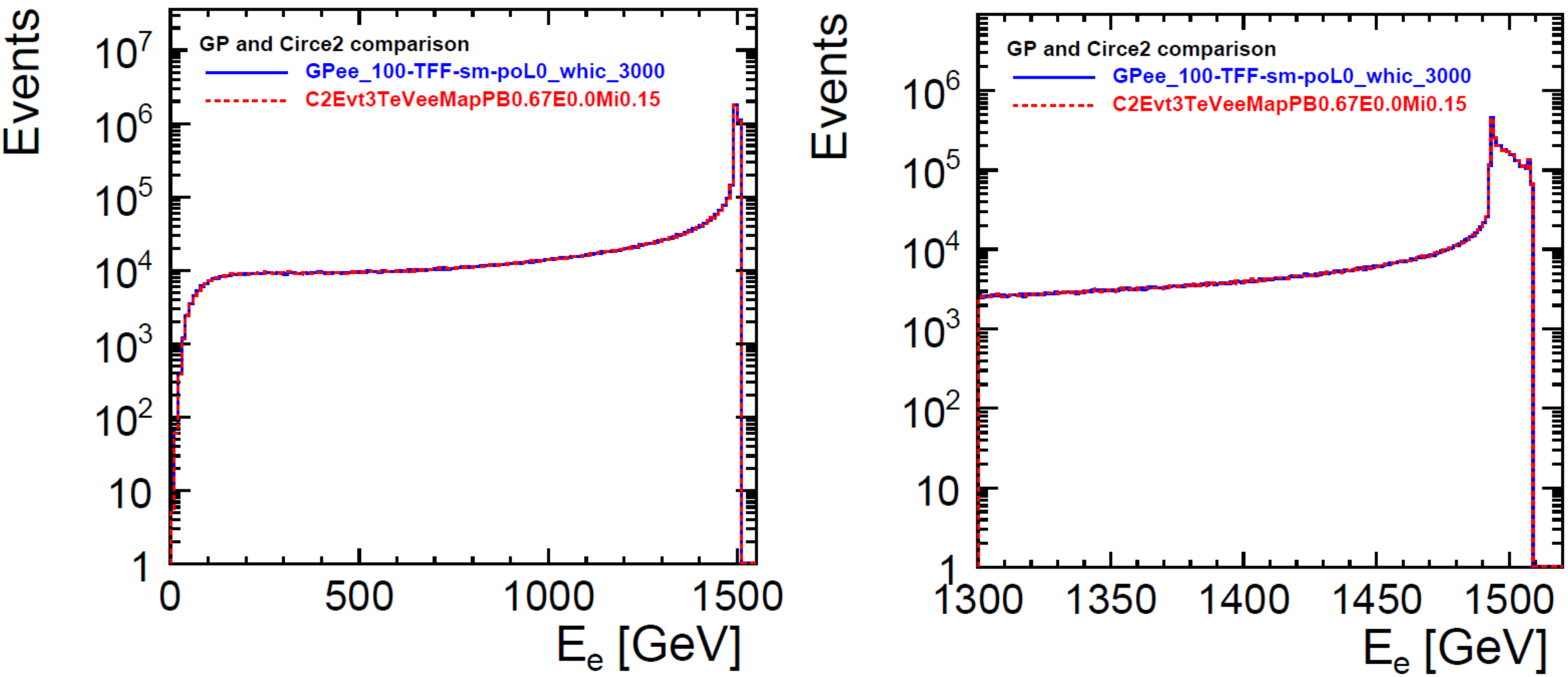
CLIC 3 TeV with beamstrahlung



Still a correlation of energy difference and longitudinal position close to nominal centre-of-mass energy

Modelling Beam Spectrum 3TeV

J-J. Blaising, LAPP/IN2P3



Left: dN/dEe distribution Guineapig events (blue) and Circe2 generated events using a Power function mapping (red); 20 GeV bins.
Right: zoom in the high energy region; 1 GeV bins/
Good agreement with Guineapig events in the whole E range.

Modelling Beam Spectrum 3TeV

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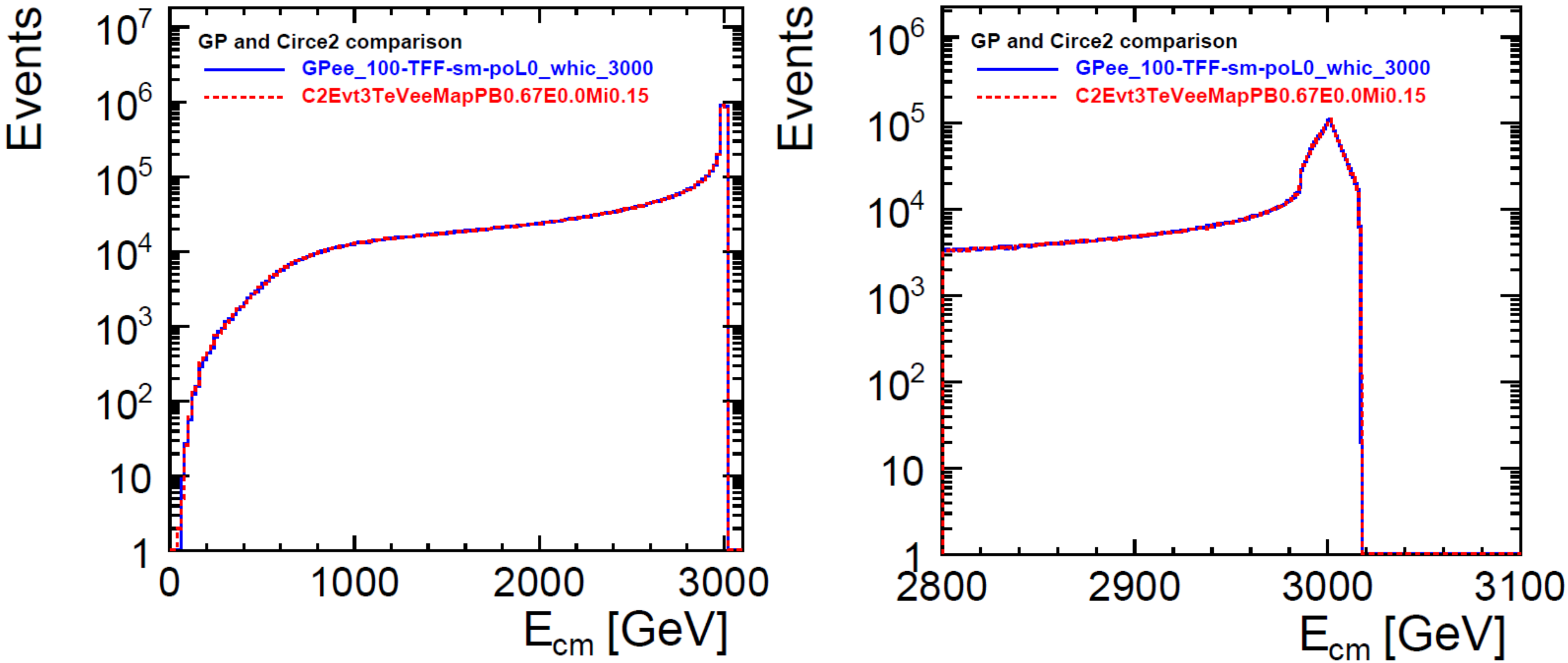


Left: dN/d√s distribution Guineapig events (blue) and Circe2 generated events using a power function mapping (red); 20 GeV bins.
Right: zoom into the high √s region; 1 GeV bins; looks good.
Check the distribution ratios.

Beam Emittance

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

$$\sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

Damping ring main source of horizontal emittance
But value is OK, as we will see

Imperfections are main source of final vertical emittance

Require 90% likelihood to meet static emittance growth target

	$\Delta\epsilon_x$ [nm]	$\Delta\epsilon_y$ [nm]		
	Total contribution	Design limits	Static imperf.	Dynamic imperf.
Damping ring exit	700	5	0	0
End of RTML	150	1	2	2
End of main linac	50	0	5	5
Interaction point	50	0	5	5
sum	950	6	12	12

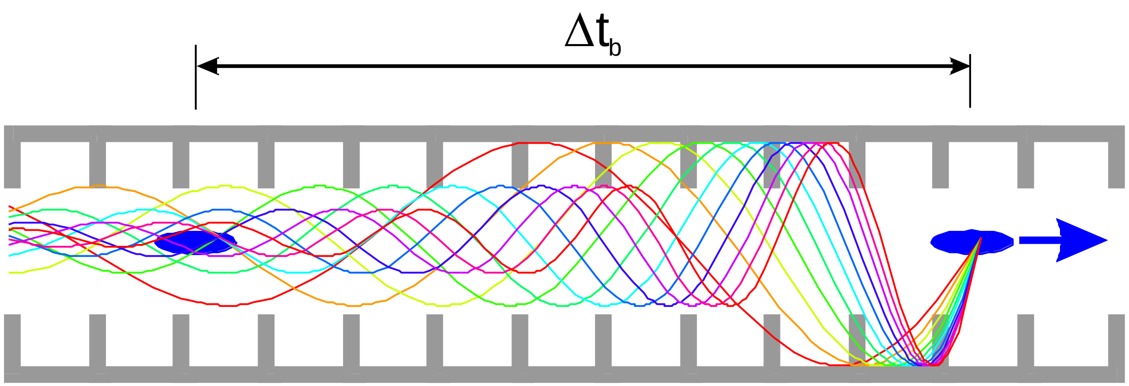
Total emittance: 30 nm

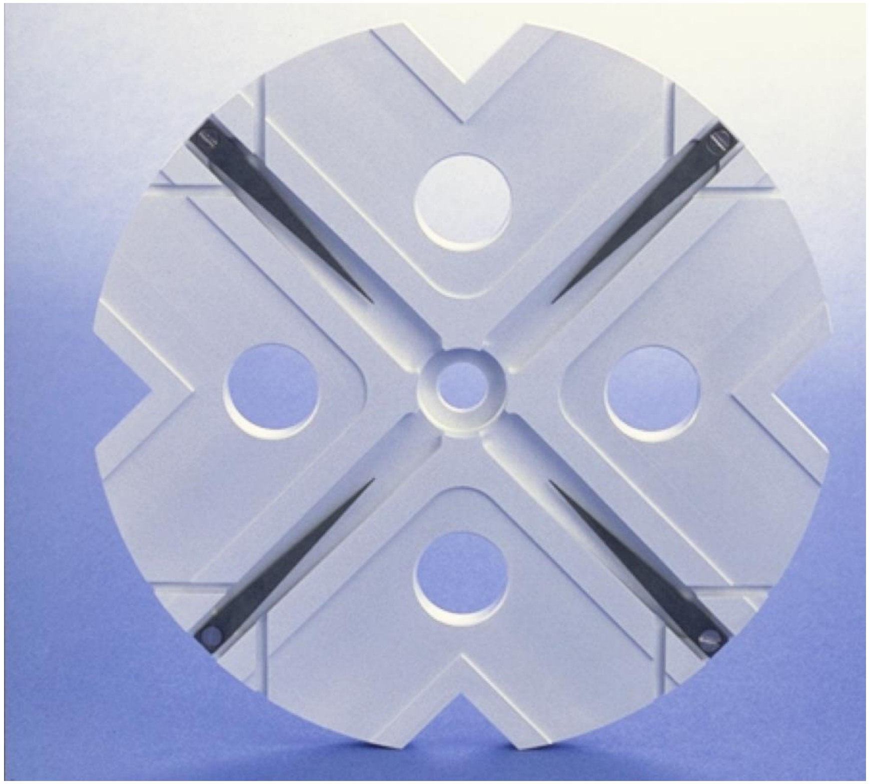
Not very Gaussian
Can be smaller

Example Imperfection: Wakefields

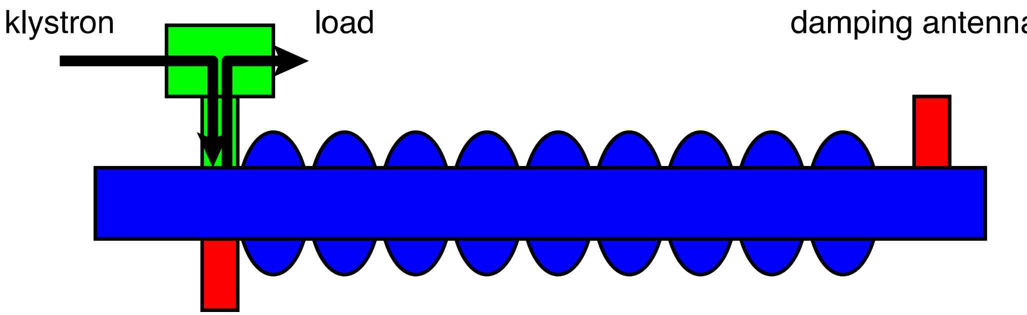
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

Wakefields can lead to instability/emittance growth

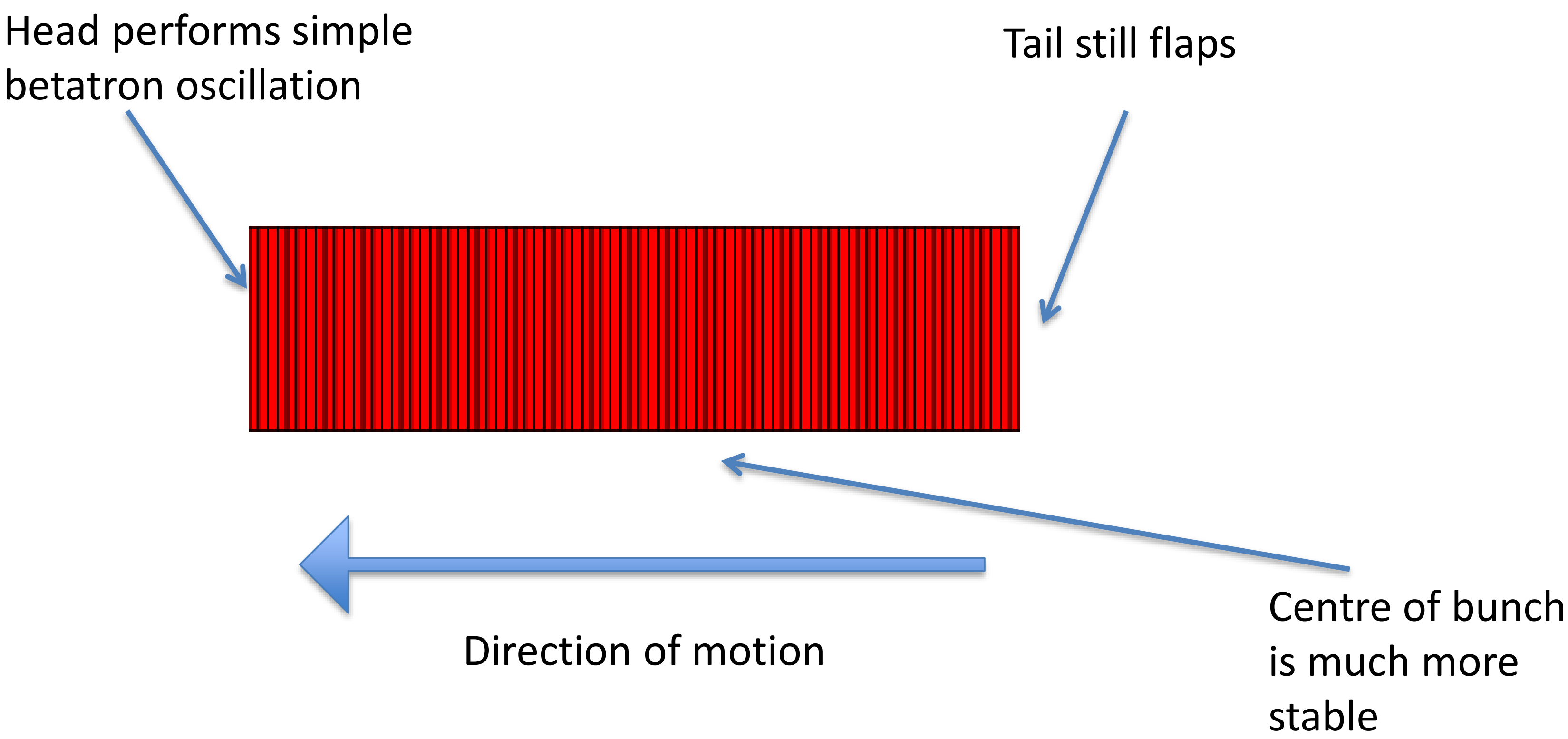




This effect is larger in higher frequency structures, hence $N=2\times10^{10}$ vs. $N=4\times10^{9}$



Example: Bunch in Main Linac



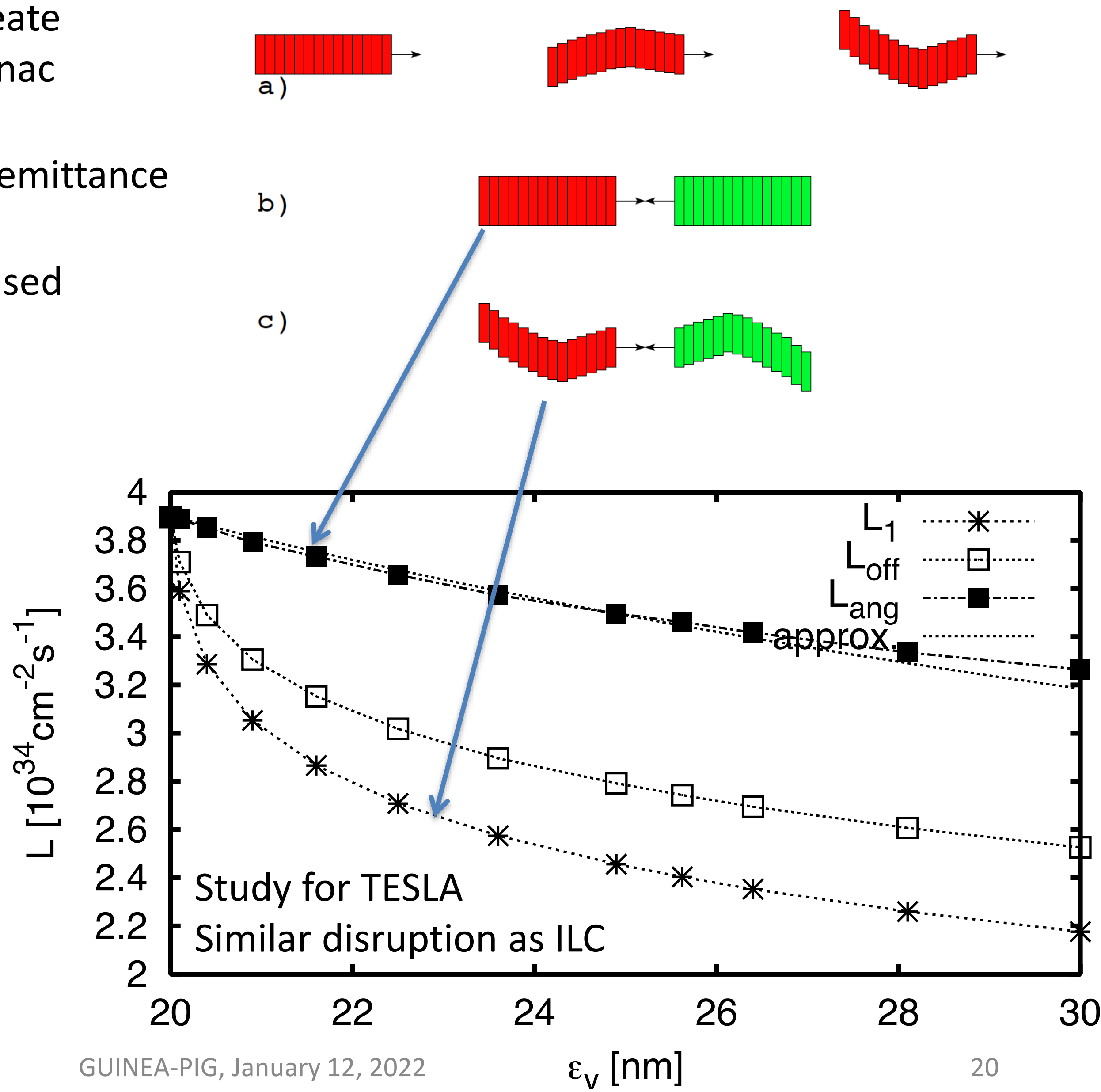
The Banana Effect

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



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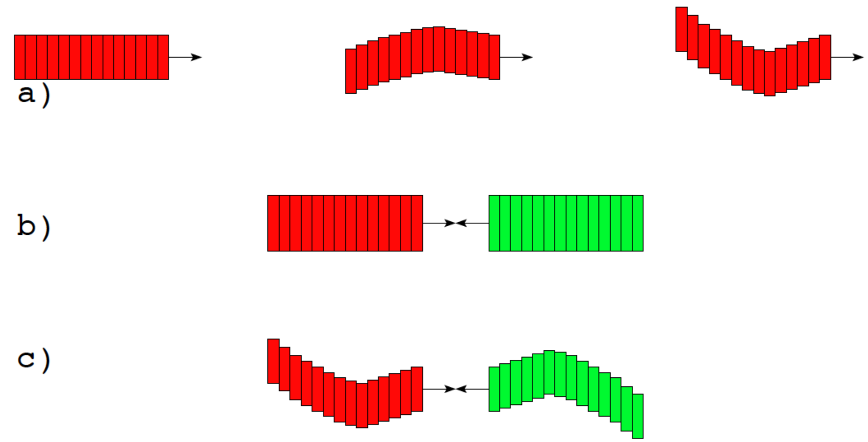
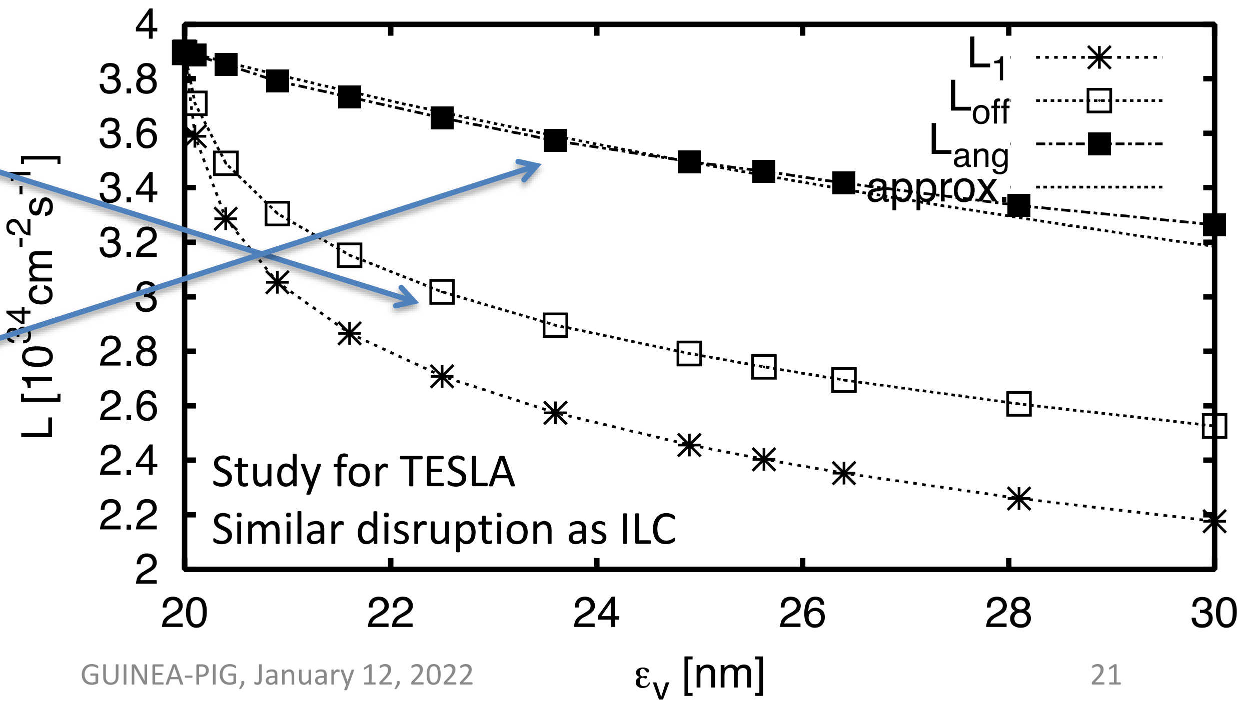


For large disruption (ILC) banana can reduce luminosity

Introduce offset to maximise luminosity

Introduce angle to maximise luminosity

But still some change in luminosity spectrum



Luminosity and Offset

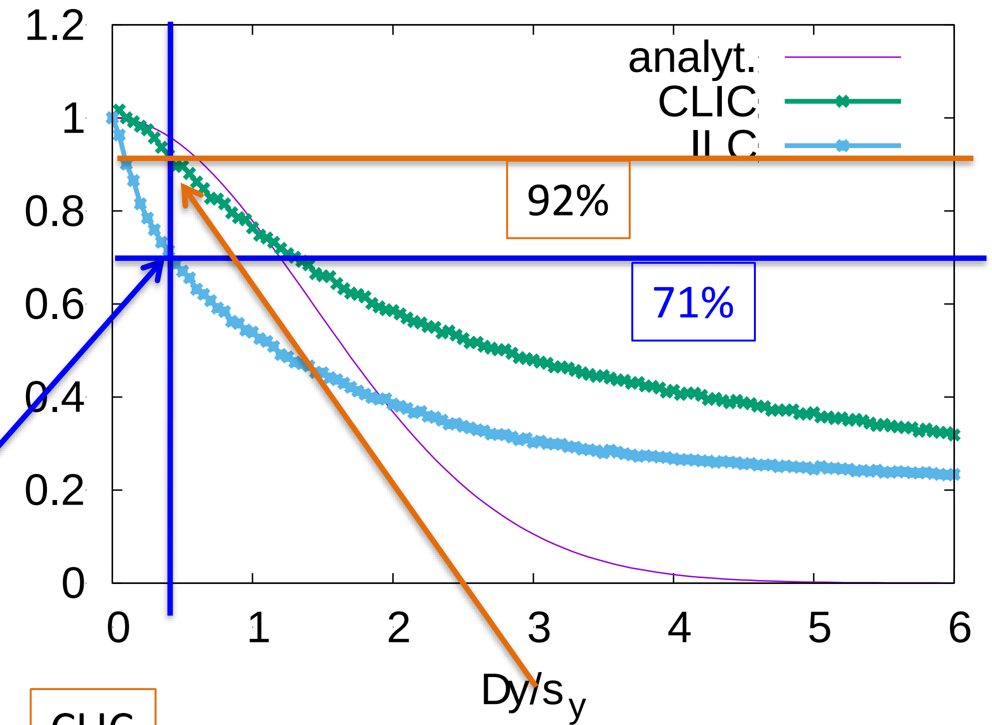
Luminosity loss for beam offsets depends strongly on disruption parameter

$\Delta y = 0.4\ \sigma_y$

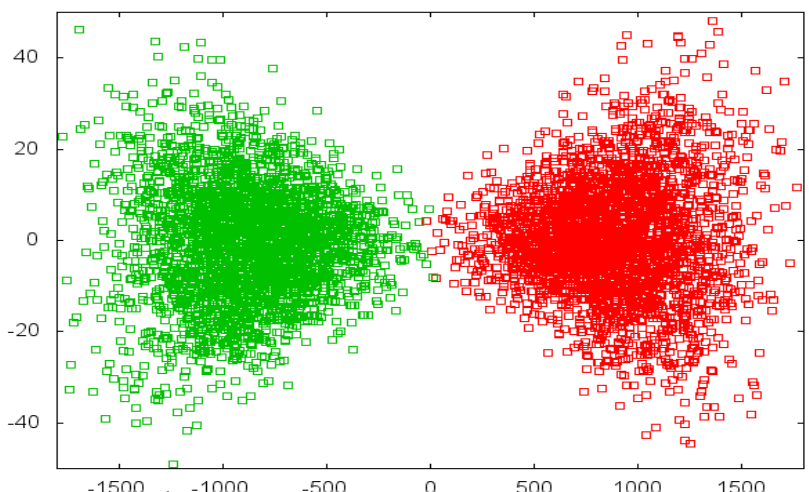
$L = 0.71\ L_0$ D_y~24

$L = 0.92\ L_0$ D_y~12

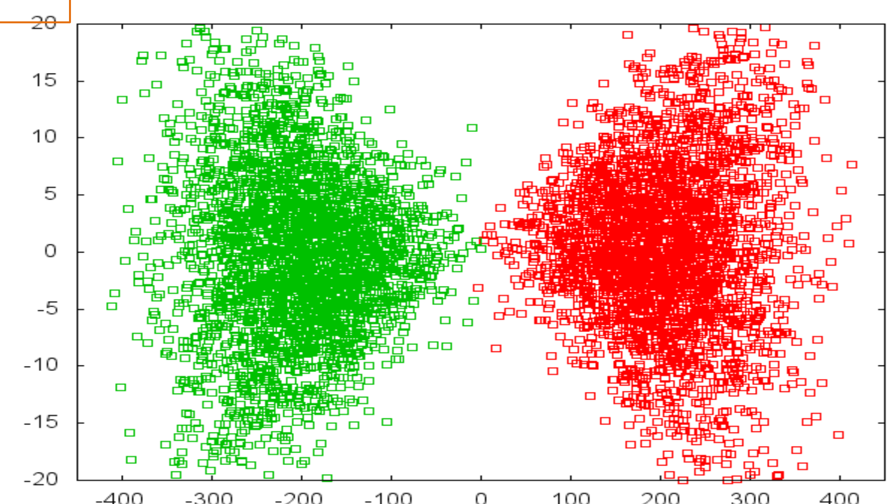
Will potentially impact spectrum



ILC

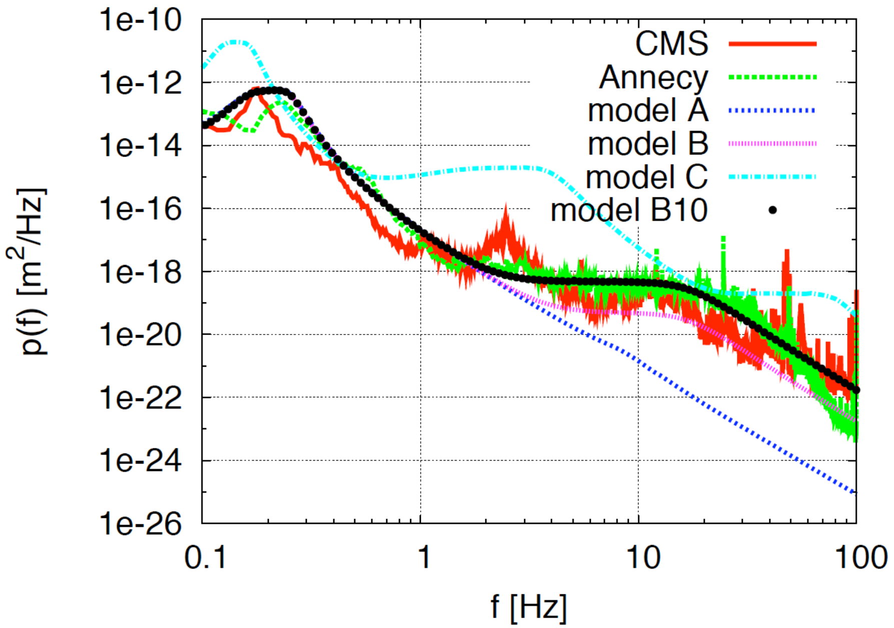


CLIC



Dynamic Variations

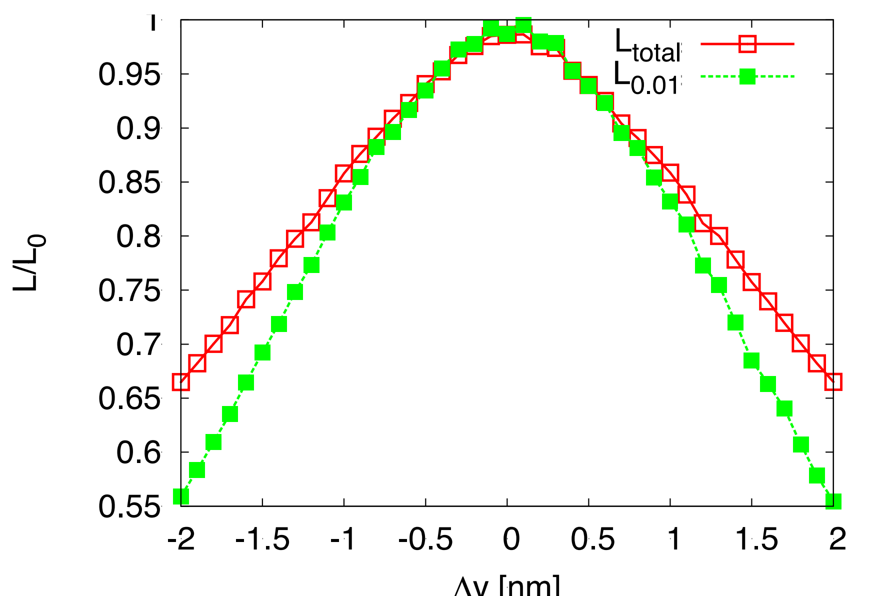
Many sources of variations
- ground motion
- vibration of components
- damping ring extraction kickers
- RF phase and amplitude jitters
- timing system jitters
- …



Leads to some modification of the spectrum (CLIC 3 TeV example)

Typically try to keep these effects small
but some variation with time will be present

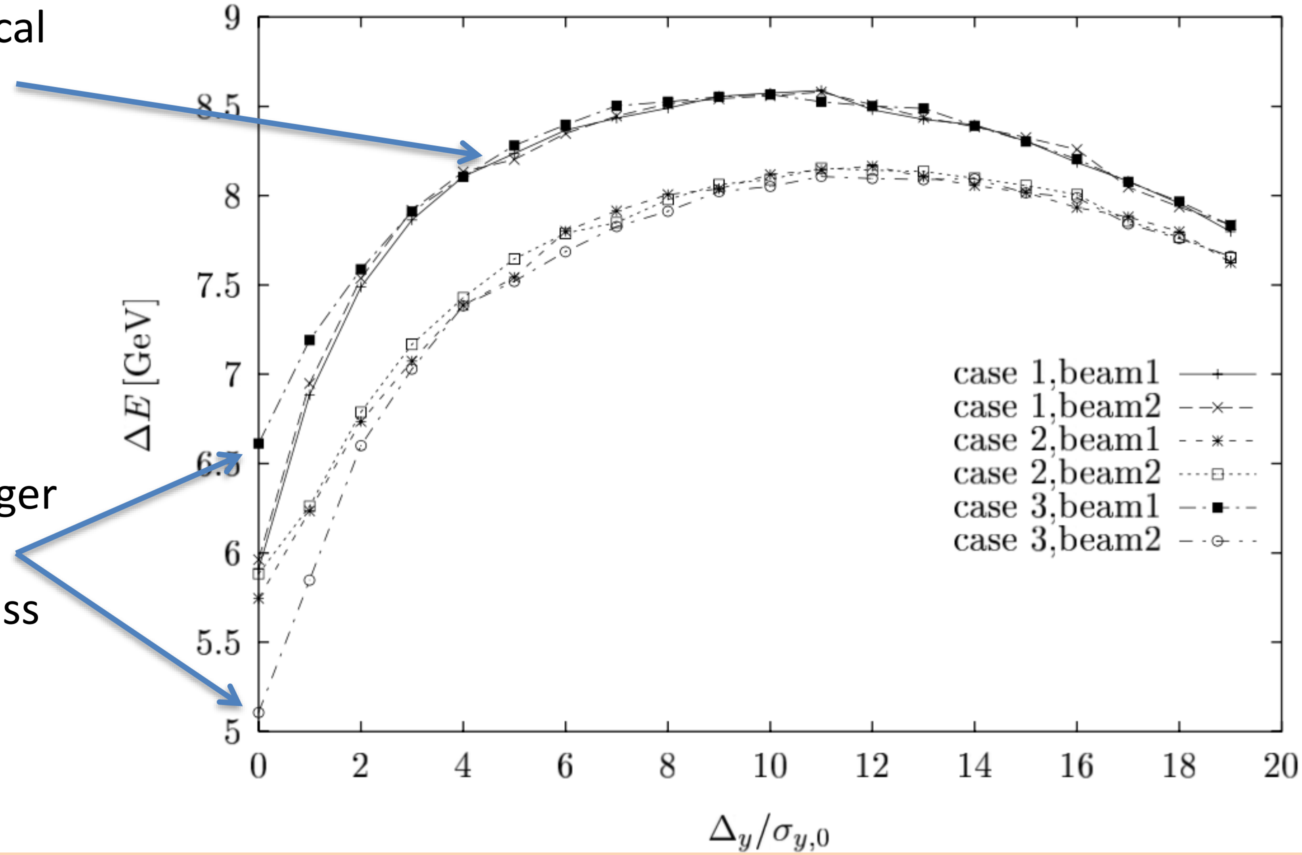
For FCC-ee one needs to consider injection of fresh beam in top-up
- will affect circulating beam to some extend



Note: Benefit of Beamstrahlung

If beams collider with vertical offset, beamstrahlung is increased

If one beam is vertically larger it emits more radiation the other beam will emit less



Can use beamstrahlung to tune the beams

- e.g. tune vertical knobs on the beam that emits more to reduce its beamstrahlung and increase the one of the other beam
- We found this allows to effectively tune luminosity

Luminosity Spectrum Uncertainty

Main uncertainties arise from limited knowledge of colliding beams

- You will typically receive a relevant example of beams
- But actual beams in the collider can differ

Main implications

- Need to measure luminosity spectrum
  - Challenge is that Bhabha events allow to measure E1 / E2 but not directly E1 x E2
  - Bhabha particles are deflected by beam so total of transverse momentum of final pair is not not zero
  - Can be simulated with GUINEA-PIG++
- In FCC-ee calibration of energy at Z-pole could be performed using non-colliding circulating beams, but need to understand error of estimate for colliding beams

Use for Luminosity Files

Have to use some switches in master input file acc.dat

do_lumi=7; Switches all luminosity calculations on
num_lumi=1000000; Will store up to 1000,000 samples
electron_ratio=1.0; Default is 0.0, which leads to no files, probability to use each beam particle for luminosity calculation per step
photon_ratio=1.0;
lumi_p=1e-20; Or some other value that is large enough, collisions are stored with probability lumi_p x “single collision luminosity”

Load beams if you received the associated files

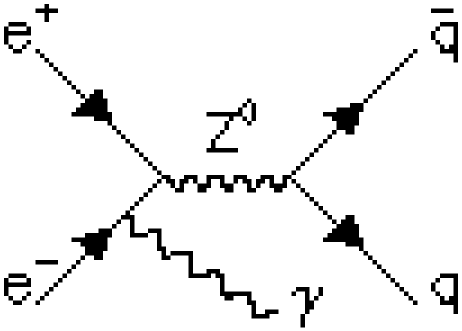
load_beam=3; For historical reasons, the best solution is option 3

This will load electron.ini and positron.ini, with each line containing
Energy [GeV], x, y, z [in µm at s=0], vx, vy [in µradian]

Make sure that n_macro is set to the number of particles in each file

https://gitlab.cern.ch/clic-software/guinea-pig and TESLA-97-08

Note: Initial State Radiation



Can be switched on, if required

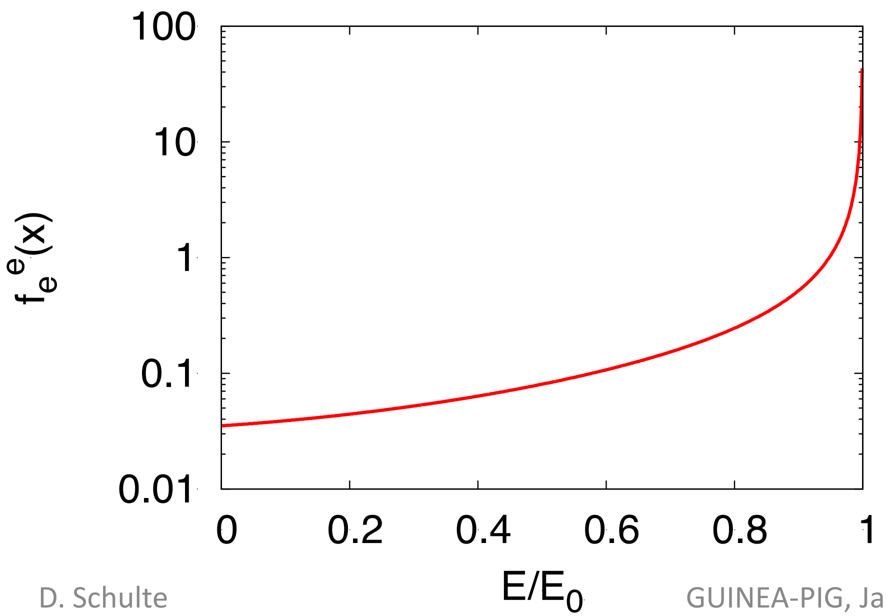
- default is **off**
- i.e. do_isr=0;

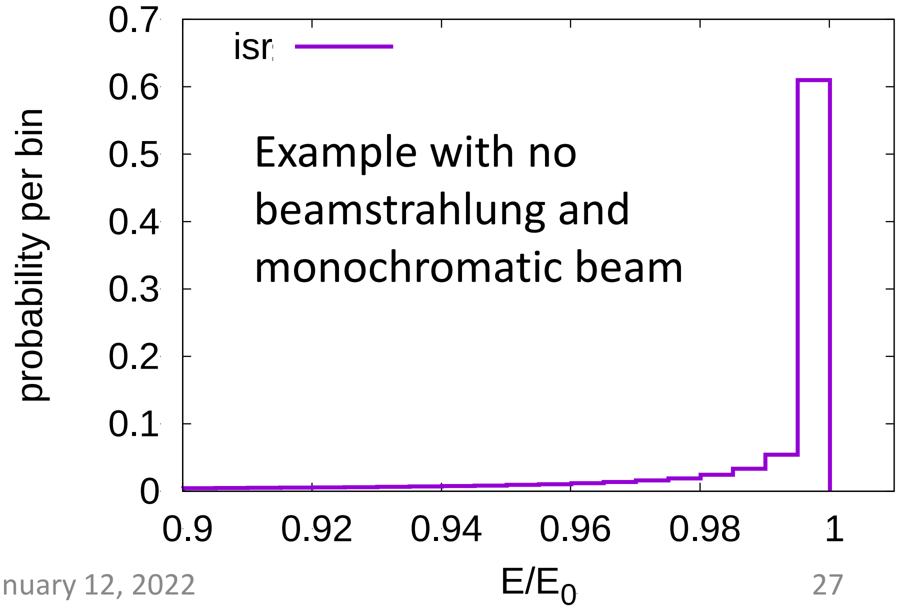
Uses simple model

It probably is best to do it separately in the physics generator

$$f_e^e(x,Q^2) = \frac{\beta}{2}(1-x)^{\frac{\beta}{2}-1}\left(1+\frac{3}{8}\beta\right) - \frac{\beta}{4}(1+x)$$

$$\beta = \frac{2\alpha}{\pi}\left(\ln\frac{Q^2}{m^2}-1\right)$$

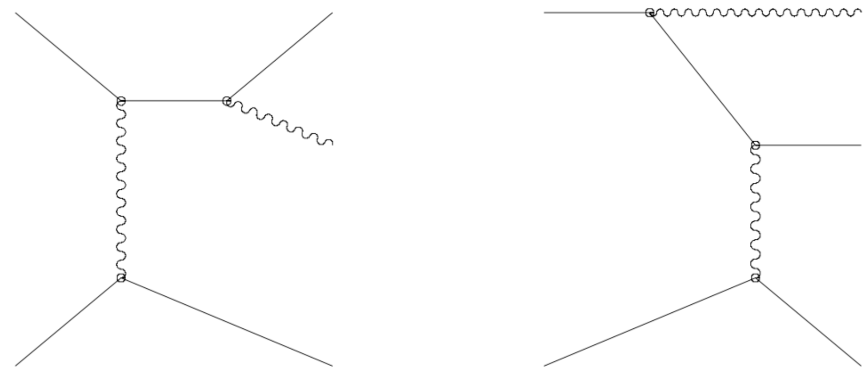


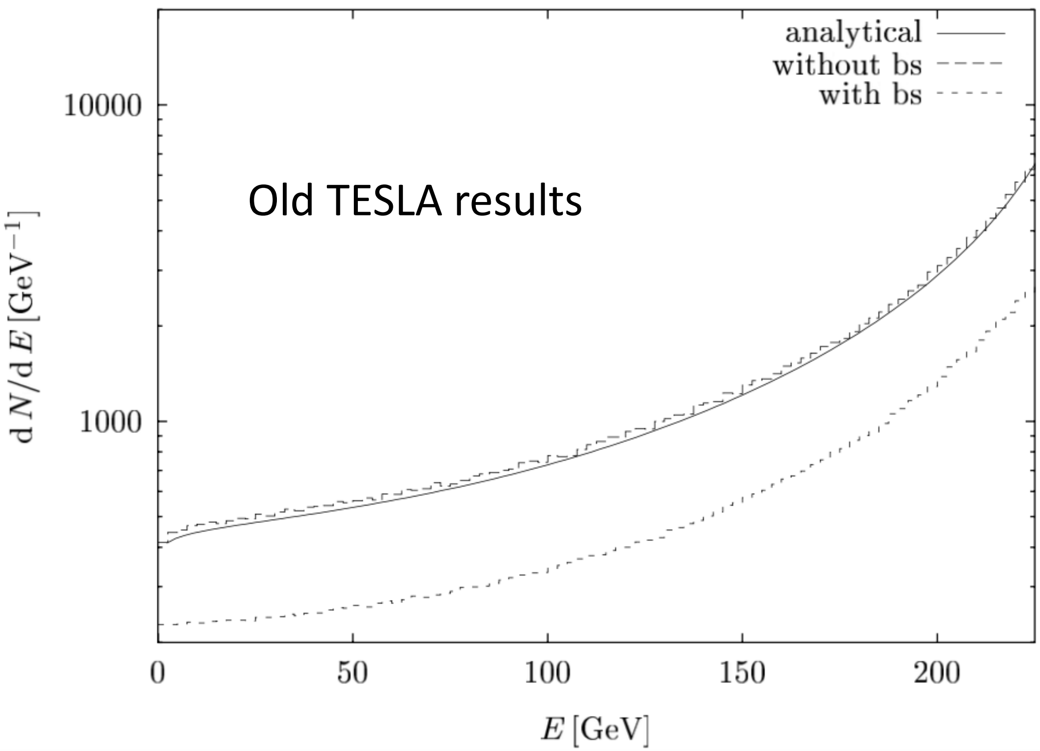


Note: Bremsstrahlung

Modeled as Compton scattering on virtual photons

Beam size effect is taken into account as displacement of virtual photon from original particle





The beam size can have a significant impact on the bremsstrahlung cross section

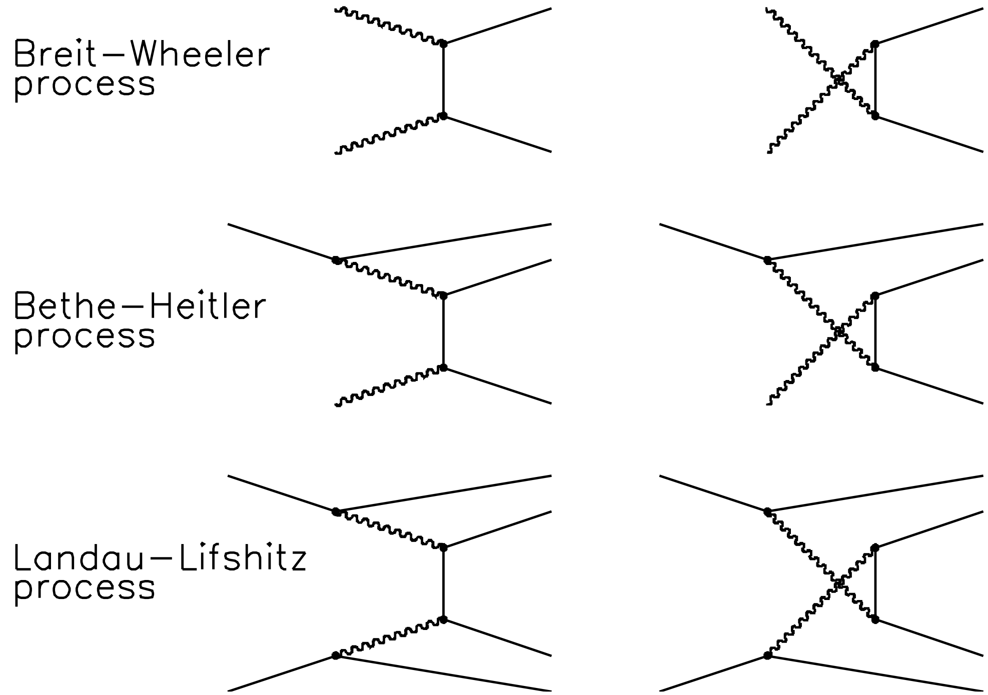
For actual luminosity measurements careful benchmarking will be required

In principle beam size effect should impact all processes

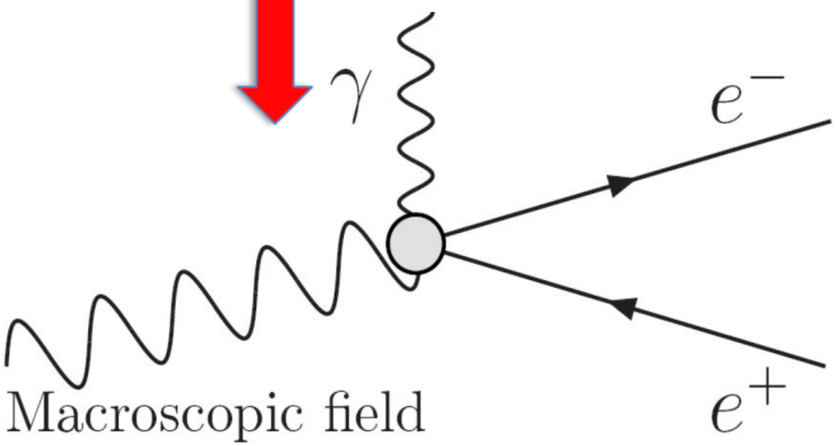
- but should play a small role for reasonably hard processes

Lepton Pair Production

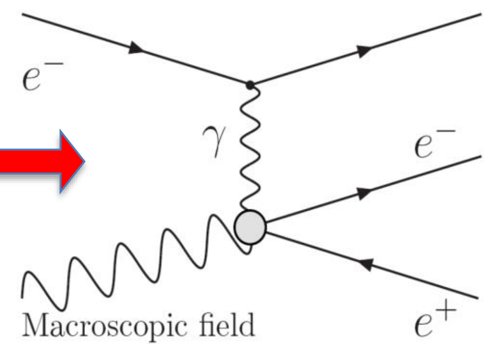
Colliding Photons can produce electron-positron pairs (incoherent pair production)
O(10^5) per bunch crossing



Beamstrahlung photons can turn into pair in strong field (coherent pair production)
O(1-10^8) per bunch crossing



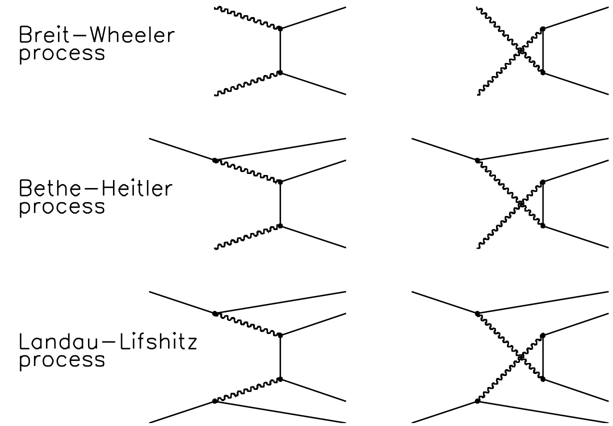
Trident cascade

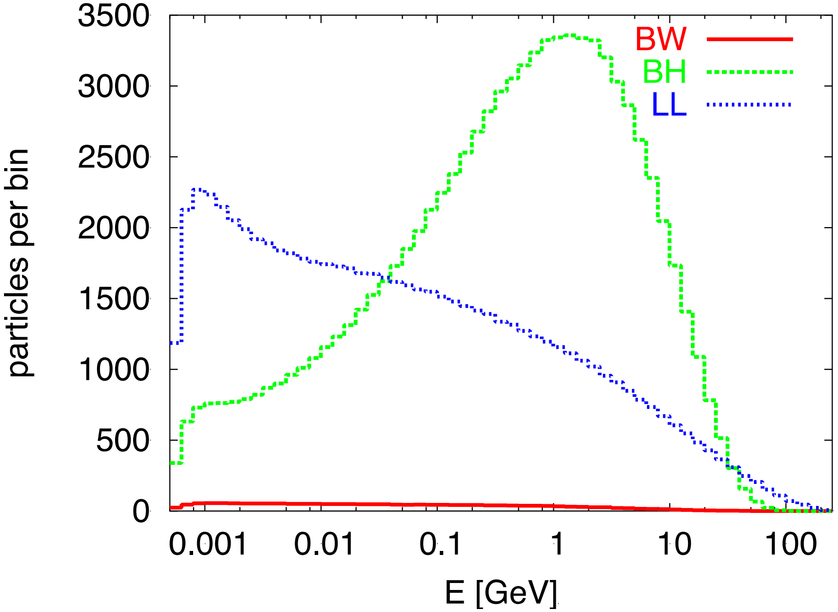


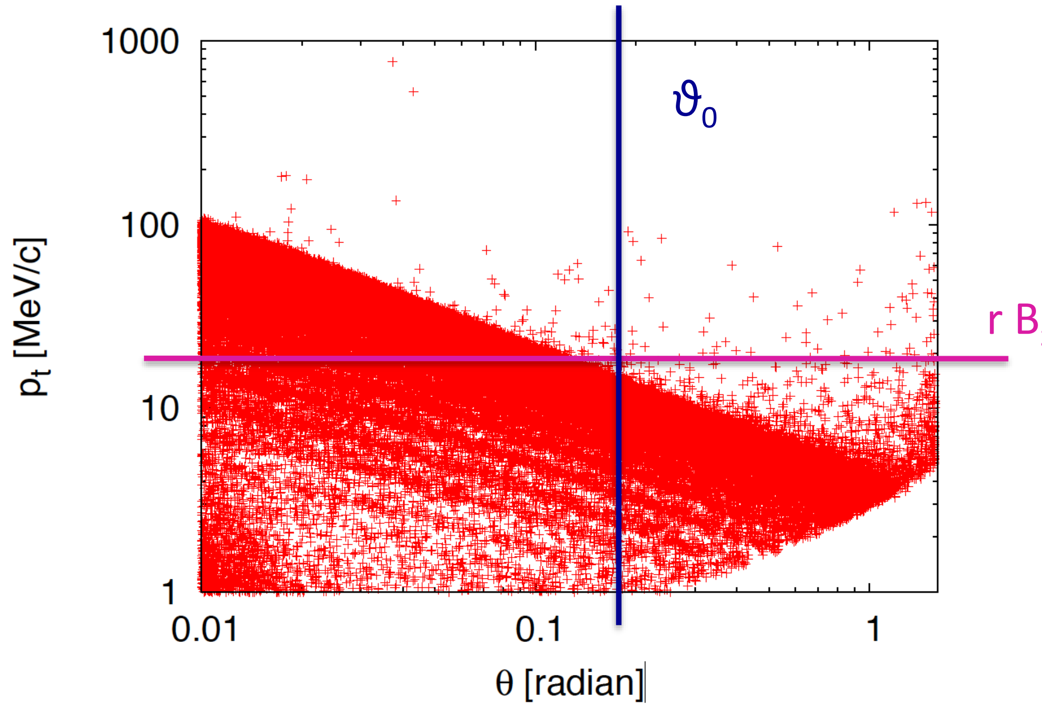
Electron-Positron Pair Production

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

Virtual photon approximation used (beam size and external field effect can be included)
GUINEA-PIG benchmarked to Vermaseren Monte Carlo (for Landau-Lifshitz process)







Virtual Photon Approximation

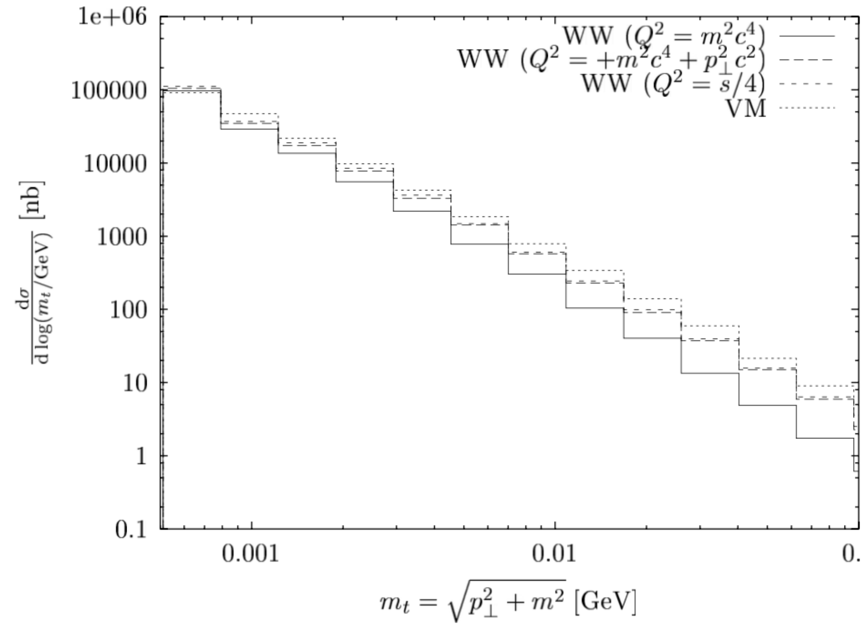
Choice of maximum virtuality Q is somewhat uncertain
Model: full cross section below cut, zero above

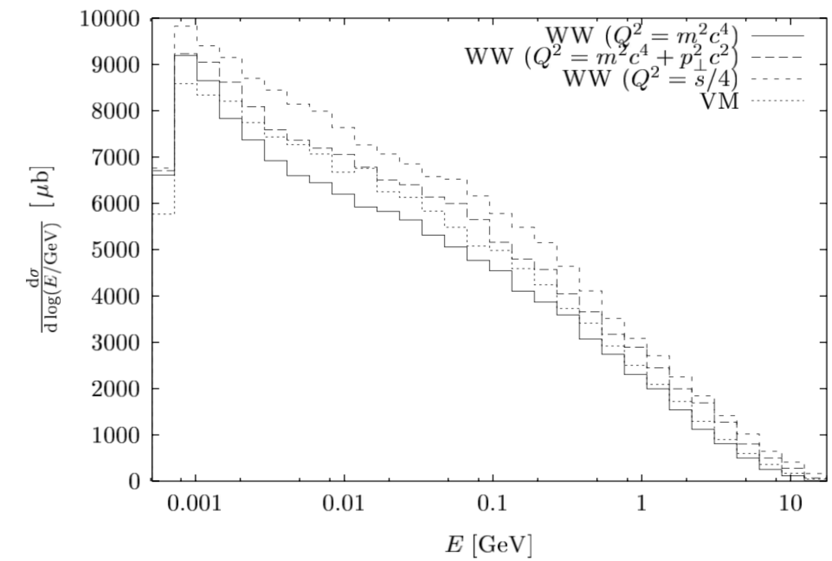
Impact on spectrum of pairs is limited
But impact on transverse distribution can matter

$$\frac{d^2 n_v(x)}{d\,x\,d\,Q^2} = \frac{\alpha}{2\pi}\frac{1+(1-x)^2}{x}\frac{1}{Q^2}$$

$$\frac{d\,n_v(x)}{d\,x} = \frac{\alpha}{2\pi}\frac{1+(1-x)^2}{x}\ln\frac{\hat{Q}^2}{\check{Q}^2}$$

At the time important difference with respect to ABEL



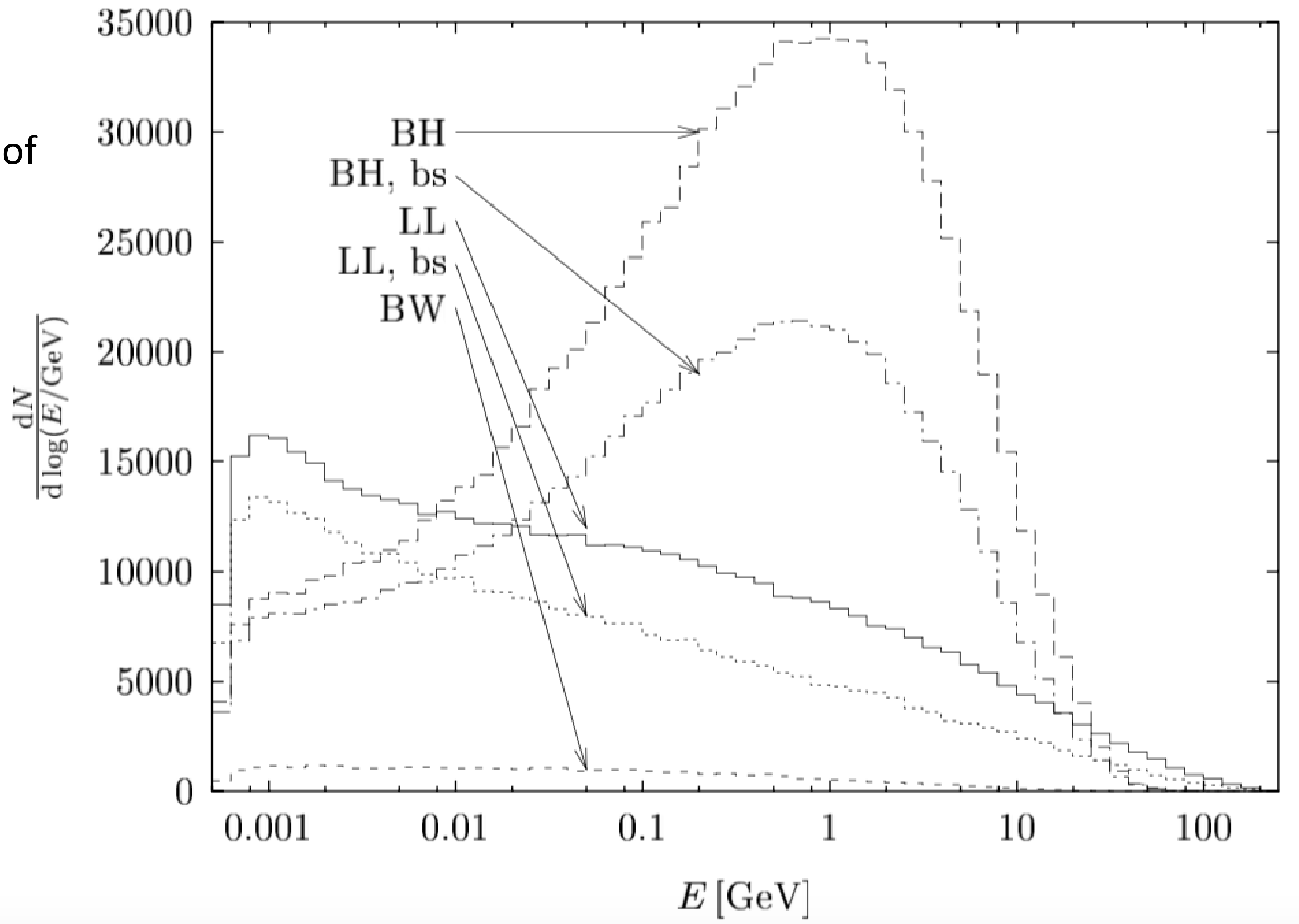


Beamsize and Pairs

Old TESLA results

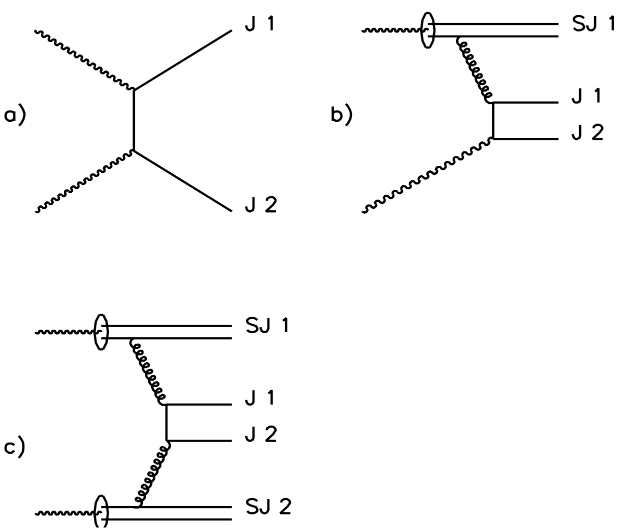
Significant change of cross section

Typically try to be conservative and ignore effect



Hadronic Background

Two colliding photons can also produce hadrons
(photons look like part-time like a hadron)



Two implementations in GUINEA-PIG:

Total cross section parametrisation
- In particular PYTHIA cross section
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- Easily modified to include any other cross section
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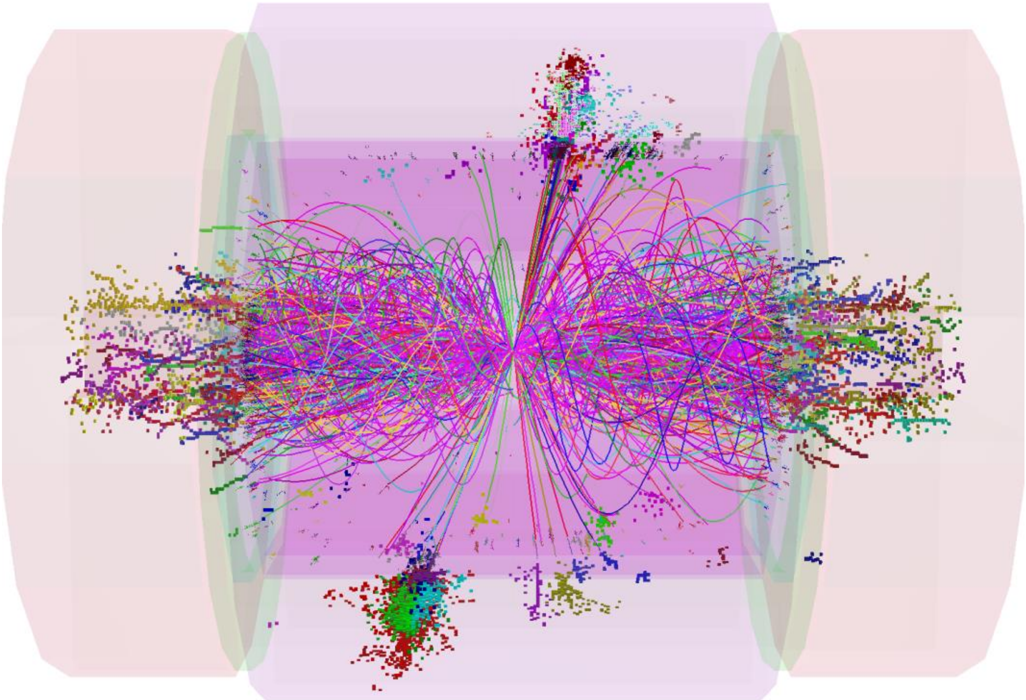


Conclusion

- Main uncertainties arise from missing knowledge of actual input distribution
- Can provide representative examples for physics studies
- But they are not the ones in the actual machine
- Need reconstruction of spectrum with measurement
- Should be able to improve this by using information from the simulation
  - but check for robustness with varying initial beams

Reserve

Physics

GUINEA-PIG simulates the interaction of two colliding ultra-relativistic beams containing electrons, positrons and photons (others can be approximated using tricks)
Made for single collisions, can be used for repeated collisions at some level but with care

Can load electron, positron and gamma beams, typically required because complex energy profile exists, also for gamma-gamma collider

It includes:

- Pinching of the beams
- Emission of beamstrahlung
- Initial state radiation
- Production of incoherent pair background
- Bremsstrahlung
- Beam size effect
- Production of coherent pair background
- Production of hadronic background (also minijets)

GUINEA-PIG++ also includes

- Beam polarisation
- Trident cascade process
- but no hadrons

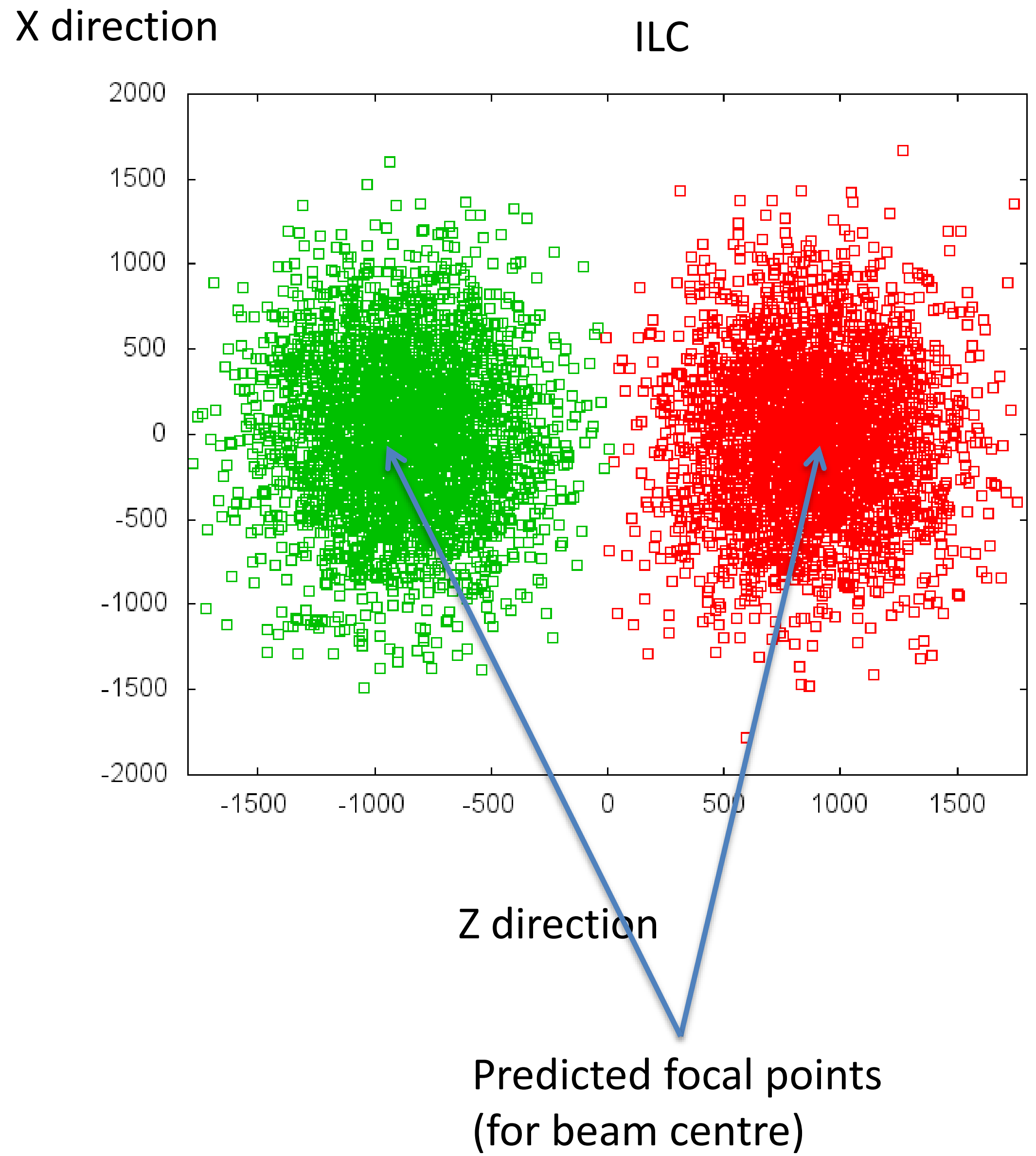
Pinch Effect

Need strong-strong code

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

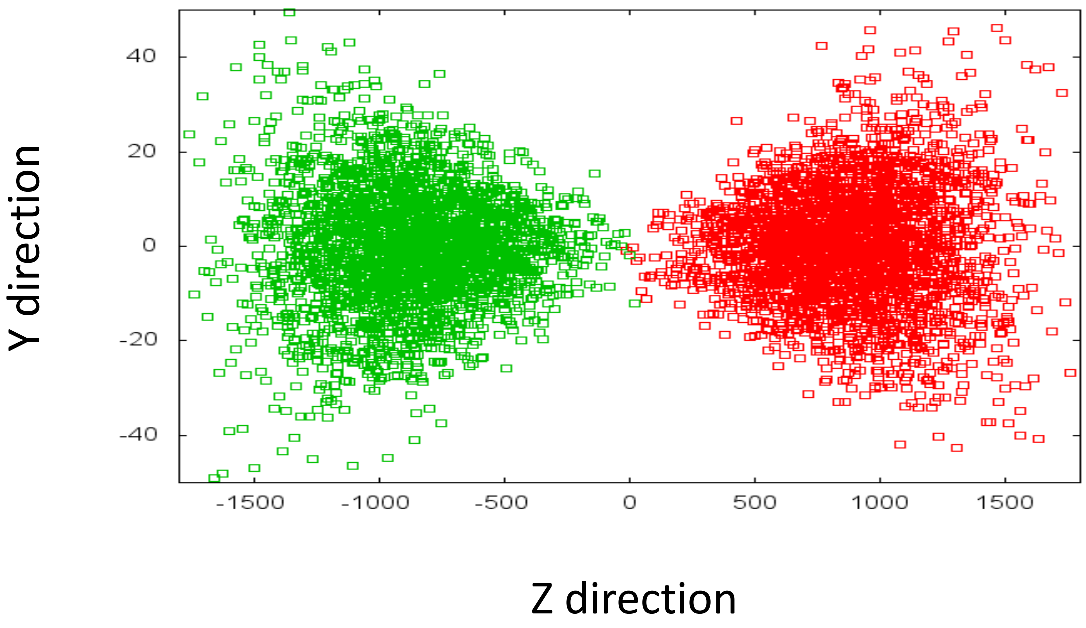
- Beams => macro particles
- Beams => slices
- Slices => cells
- The simulation is performed in a number of time steps in each of them
- The macro-particle charges are distributed over the cells
    - ○ The forces at the cell locations are calculated
    - ○ The forces are applied to the macro particles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

All simulation performed with GUINEA-PIG



Pinch Effect

Beam-beam force switched off



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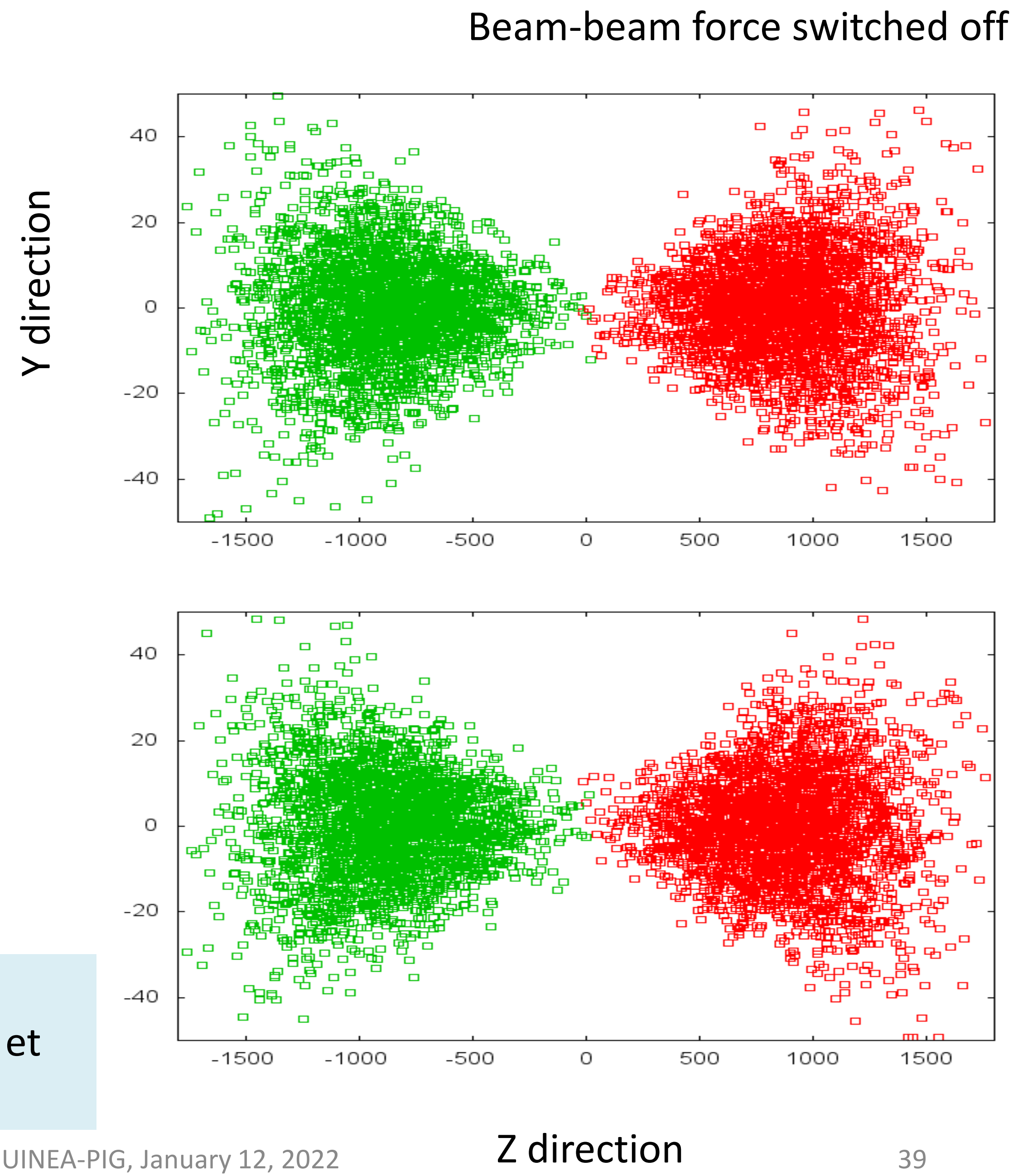
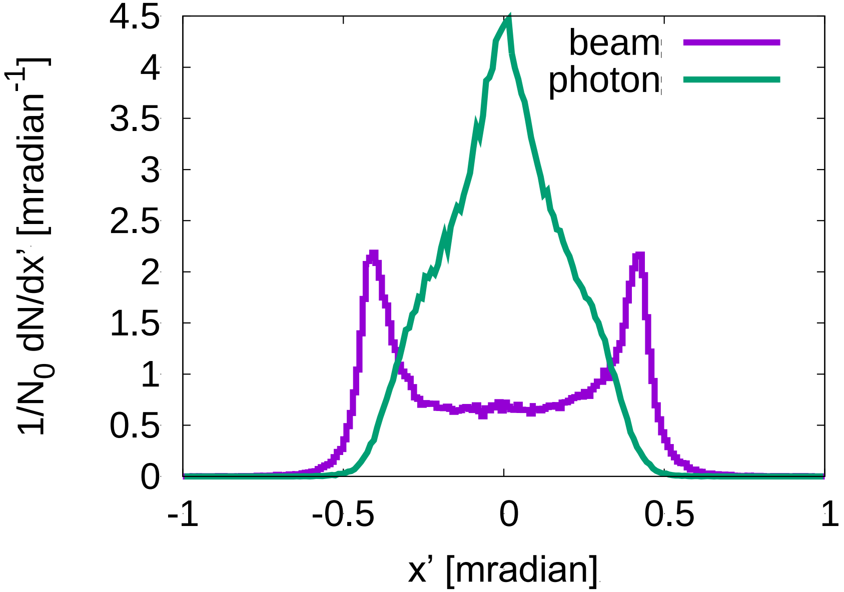
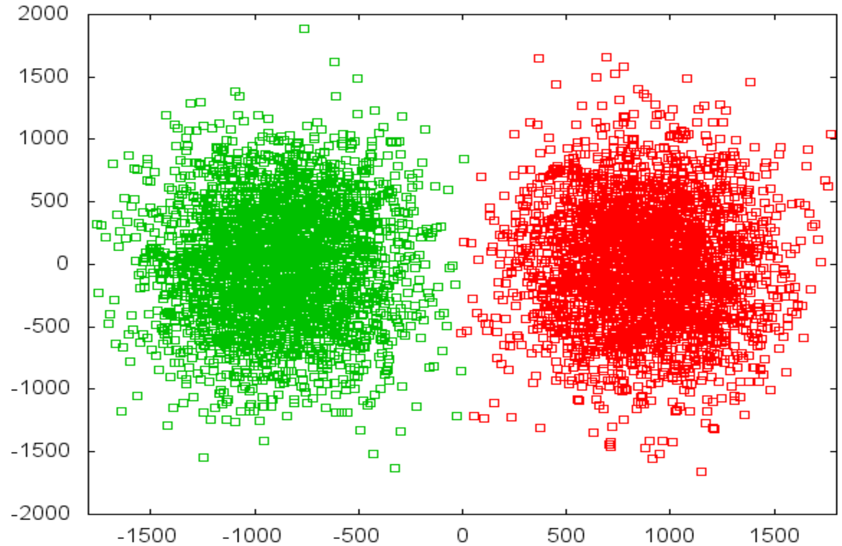
Note: Luminosity increase has been benchmarked to SLC (F. Zimmermann et al.)

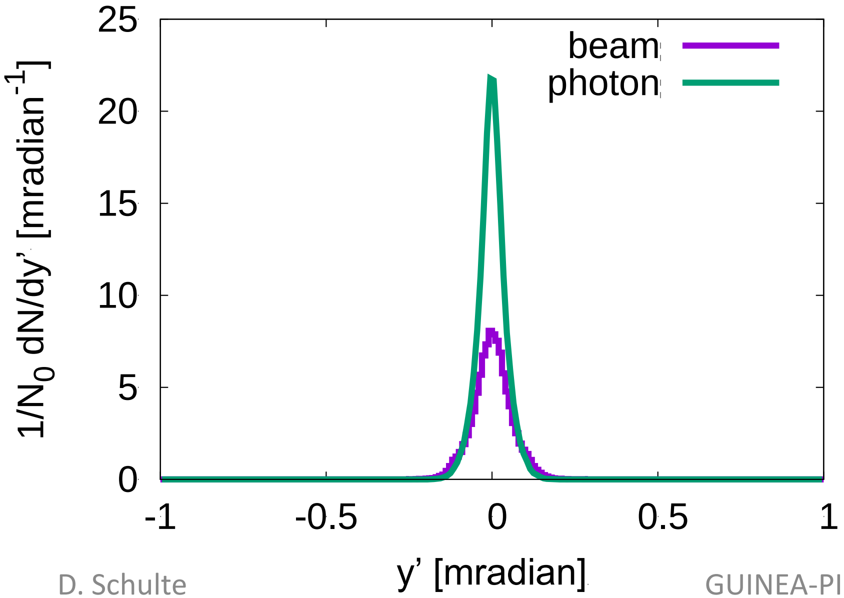


Photon Production

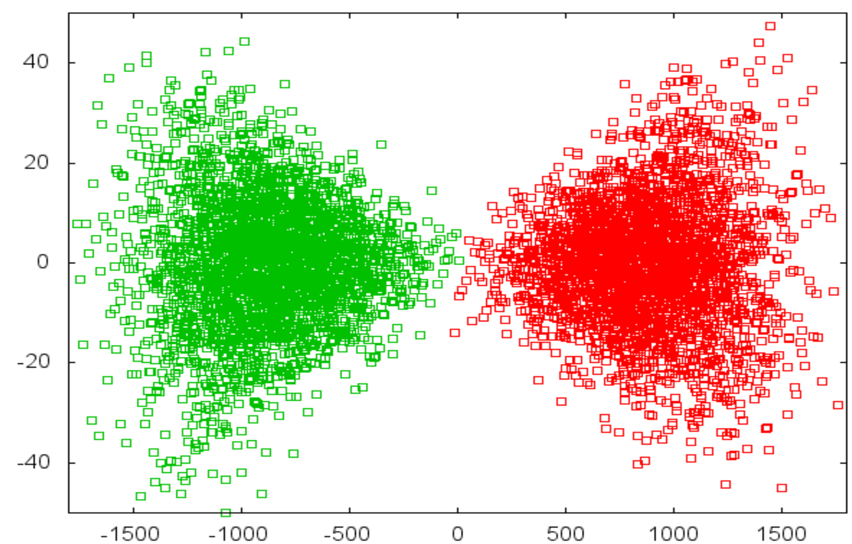


Horizontal plane





Vertical plane



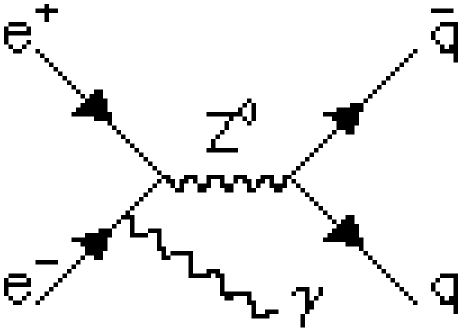
Note: Initial State Radiation

Can be switched on, if required

- default is **off**

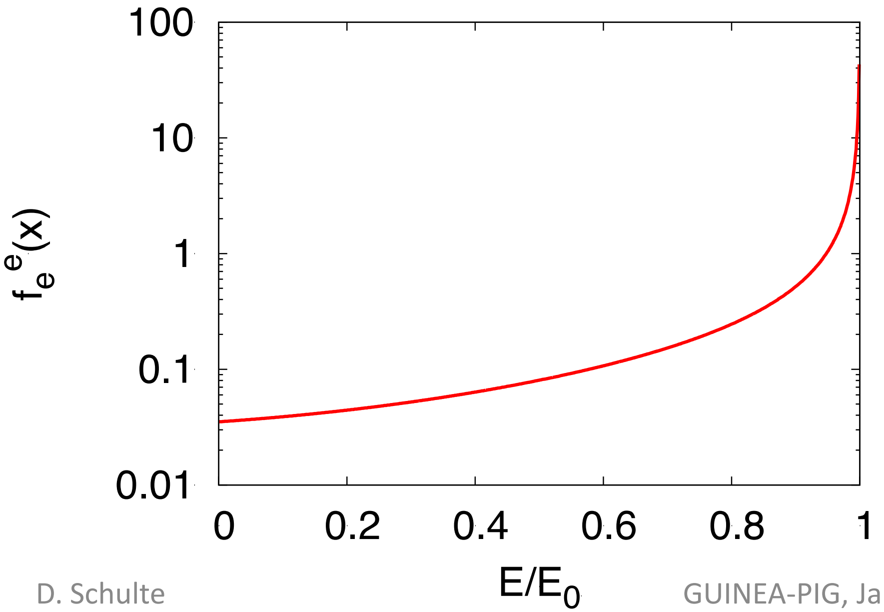
Uses simple model

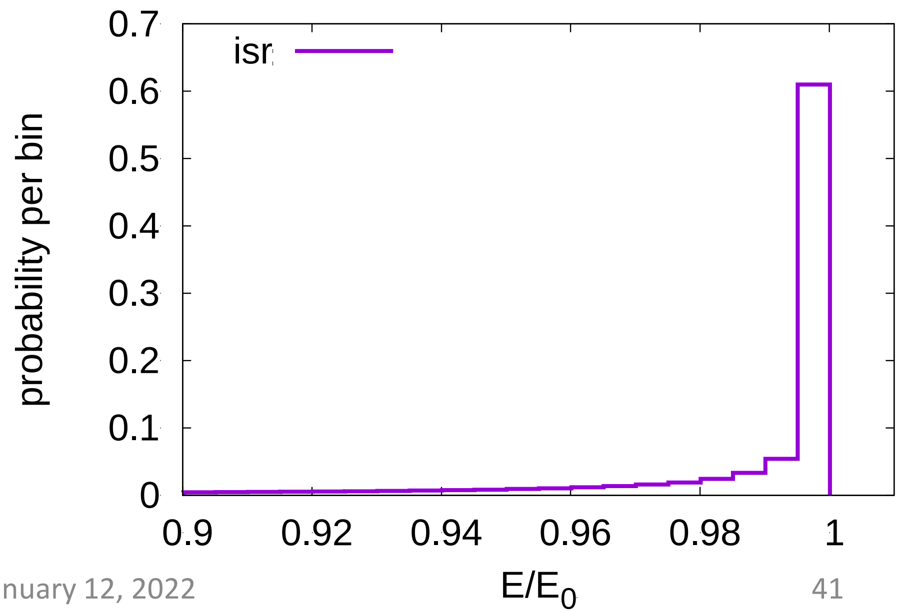
It probably is best to do it separately in the physics generator



$$f_e^e(x,Q^2) = \frac{\beta}{2}(1-x)^{\frac{\beta}{2}-1}\left(1+\frac{3}{8}\beta\right) - \frac{\beta}{4}(1+x)$$

$$\beta = \frac{2\alpha}{\pi}\left(\ln\frac{Q^2}{m^2}-1\right)$$





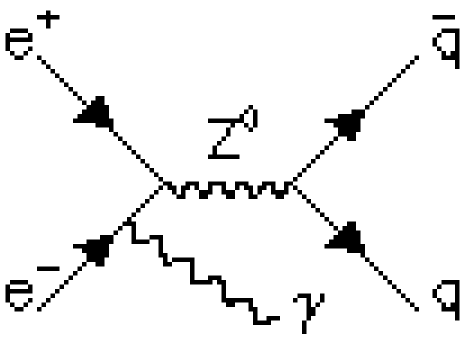
Example: Top Production at Threshold

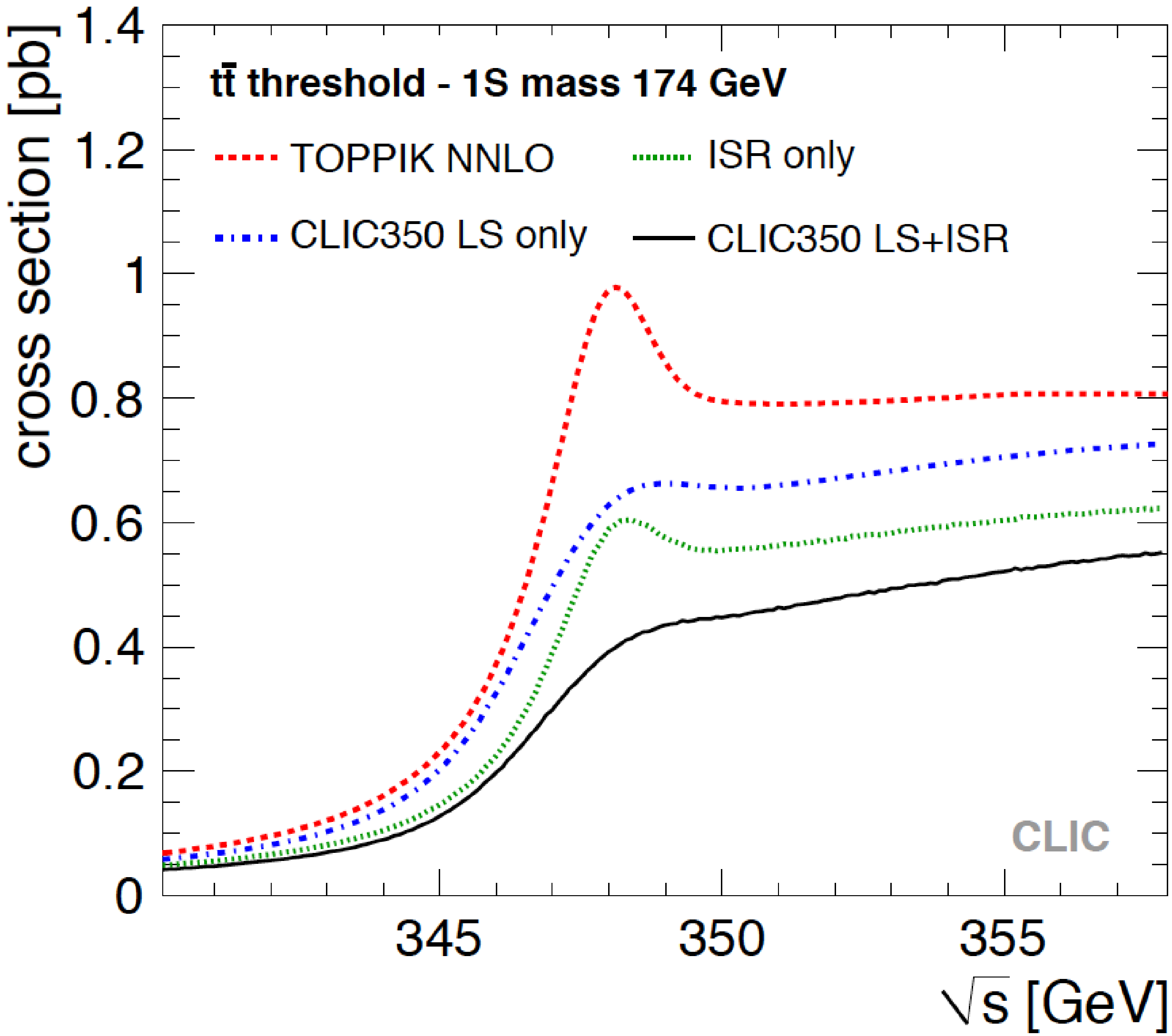
K. Seidel et al. **arXiv:1303.3758**

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

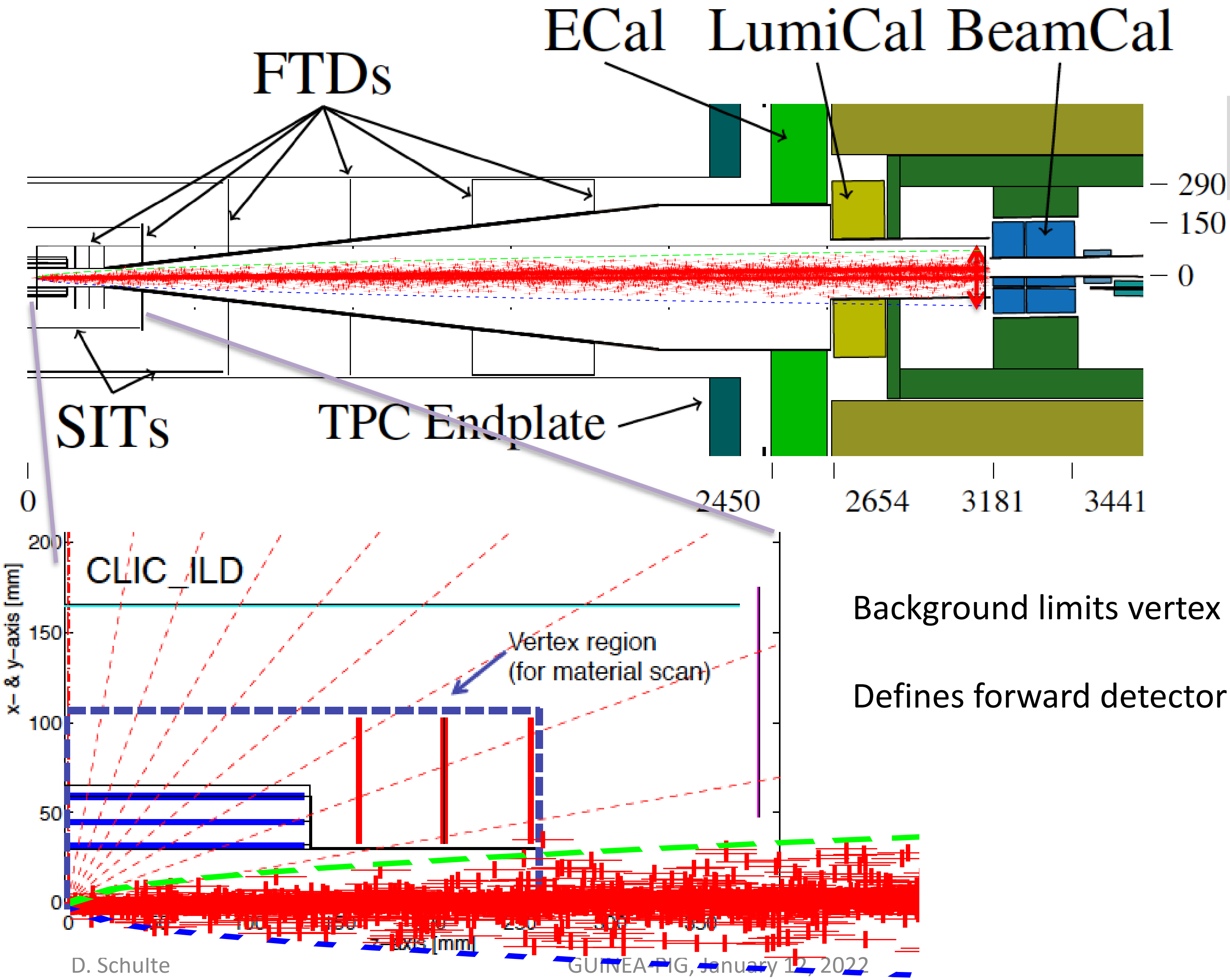
For $L_{0.01} > 0.6$ L impact of beamstrahlung is comparable to ISR

But depends on physics





Impact on Detector Design



CLICdp
A. Sailer

Background limits vertex detector

Defines forward detector design

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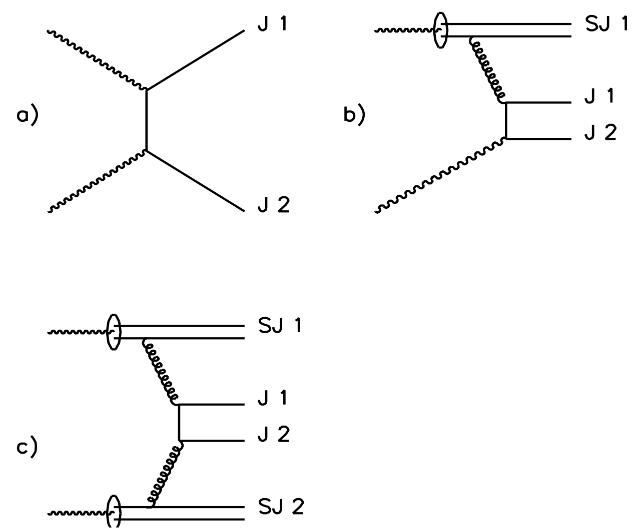
Two colliding photons can also produce hadrons
(photons look like part-time like a hadron)

Two implementations in GUINEA-PIG:



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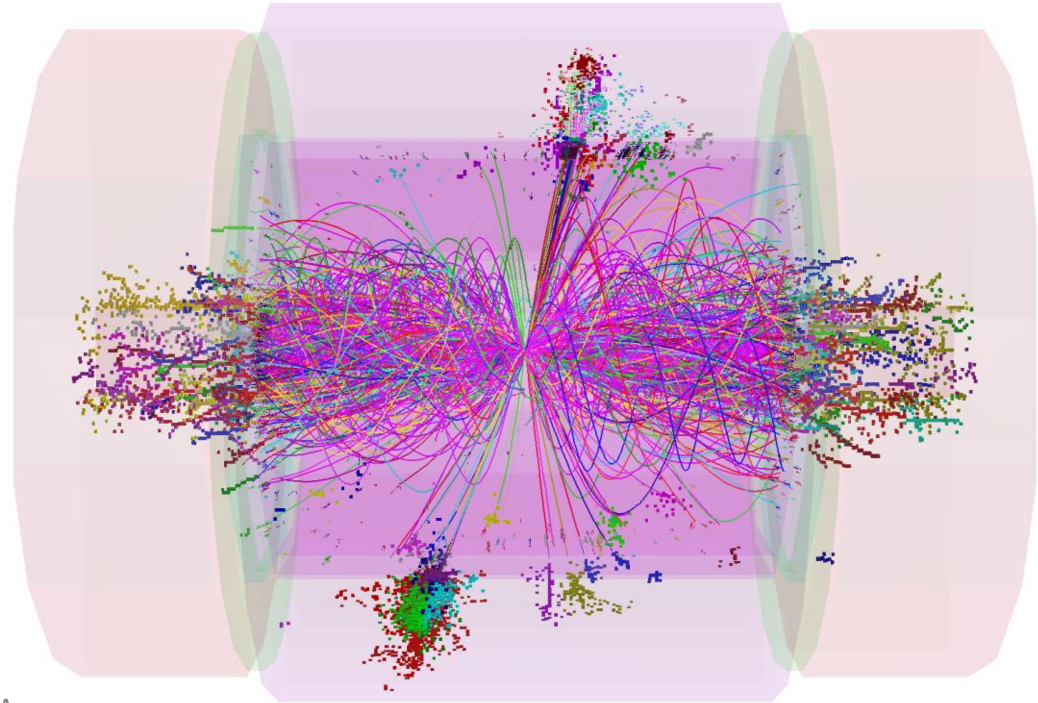


How to Run

GUINEA-PIG is steered using a database and potentially some input files

Beam (electrons, positrons, photons) is described by charge, emittance, beta-function, bunch length, energy and energy spread
Or can be loaded from a file (format corresponds to our main tracking code PLACET)

Processes can be switched on or off setting variable in database

Computational parameters can be chosen

- number of macro-particles ($O(10^5)$ or more)
- number of slices (O(30))
- grid size and number of cells (64x64 or more)
- Cut-off for Weizäcker-Williams method (electron mass, photon collision energy, transverse momentum of final state)
- beam size effect (incoherent pairs, hadrons, bremsstrahlung)
- hadronic cross section/parton model
- …

Be careful when choosing and confirm convergence and stability of results

Output

Different results and spectra in main output file, e.g.

- luminosity
- luminosity spectrum for all particle combinations
- number and energy of beamstrahlung photons produced
- …

Specialised files

- Luminosity weighted collisions (electron-positron, electron-photon, photon-photon, …)
    - 3x3 matrix of options
- Cross section weighed collisions producing hadronic events (with real and virtual photons)
- Spent beam (in tracking format for PLACET), photons, coherent/trident pairs
- Incoherent pairs before/after tracking though beam fields
- All files have trivial format: e.g. one line, one particle or one collision

- Note: Cross section for collision files is adjusted on the fly to avoid overflow if initial cross section is too large

Code Implementation

GUINEA-PIG

- Written in C (my C++ compiler was broken)
- Mainly functional, some object oriented methods
- Requires C compiler, GCC is a great choice
- Advisable (but not required) to use FFTW2 or FFTW3
- Can use input from beam tracking (e.g. PLACET)
- Some output can be used in physics tools (e.g. PYTHIA, CIRCE, CALYPSO)
- No parallelisation in public version
    - as always not simple to switch between grid and tracking

GUINEA-PIG++

- Translation of GUINEA-PIG to C++
- Was originally meant to be parallel

Can be found on the web, e.g. https://gitlab.cern.ch/clic-software/guinea-pig
Some documentation is available
Normally, I manage to answer questions, Barbara Dalena (CEA FR) can also help

Performance

The performance is adequate for many applications

- Has been the basis for a large set of linear collider studies for the machine and for the detector
- Ran originally on i486

Can run many cases in parallel

- Sequential runs in same directory can hand over random number generator status to have different sequence each time
- In different directories need to use the proper random number generator (sorry, in the code, could be made public if demand exists)
- Could imagine to use more advanced generator

For some applications a speed-up of single run would be useful

- Simulation of dynamic effects in linear colliders (many subsequent collisions)
- Circular colliders (many turns)

Best to fill results into reference data base

- More convenient to use
- Can be used to verify results
- It is not fully straightforward to correctly model the machine

Conclusion

GUINEA-PIG simulates beam-beam interaction in lepton colliders

- Strong-strong beam dynamics
- Production of secondaries

Core tool for linear colliders

- Machine studies
- Detector design
- Physics performance prediction

Code(s) are publicly available

- Limited maintenance
- But at the same level as the past 20+ years
- Will have a new fellow in January

- Will consider to upgrade to muons
  - some first results are based on

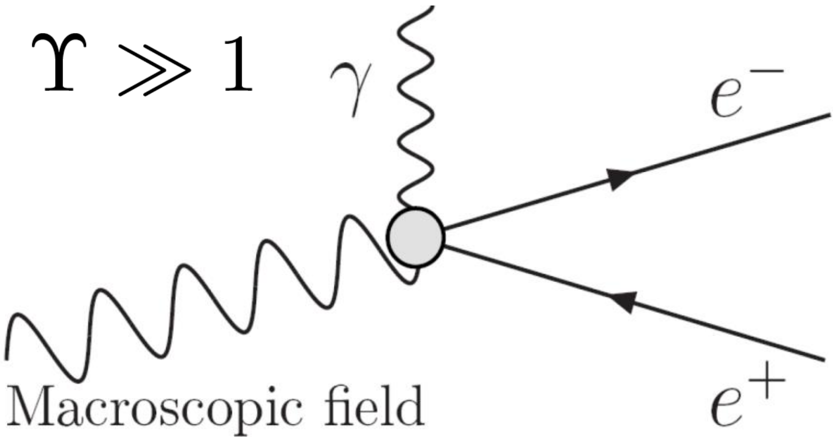
- An effort to develop general purpose code for all types of particles and multiple turns is ongoing

Reserve

Coherent Pair Creation

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

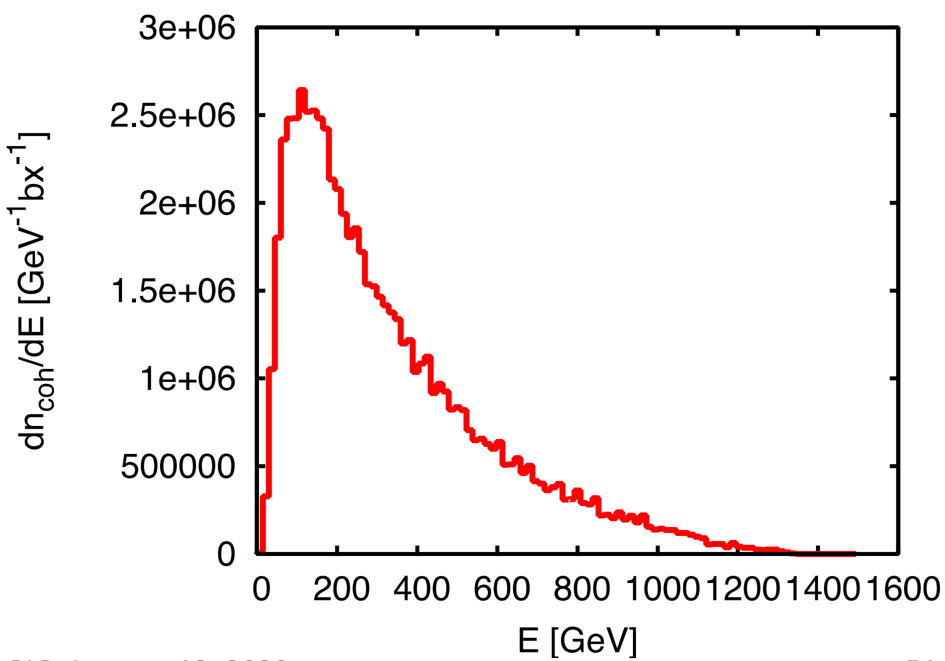
A photon in a very strong field can form an electron-positron pair
⇒ Coherent pair creation



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

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

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



Computational Model

The beam is represented by macro-particles (typically O(>10^5))

- Can be generated on the fly or loaded from files

The beams are sliced, slices interact pairwise (typically O(30))

Slice interactions are using grids (typically O(64x64) cells)

- Beam particles are distributed
- Transverse fields use clouds-in-cell model and FFT for the convolution
- Generation of
  - Beamstrahlung photons
  - Coherent pairs
  - (Trident cascade)
- Virtual photons are created at each step and also distributed on the grid
- Particles in the same cell can collide and produce secondaries
  - Hadrons are stored
  - Pairs are tracked further
- Stepping of particles
- Note: Larger grids are used for low energy background

Spent Beam Content

Spent beam particles

Beamstrahlung

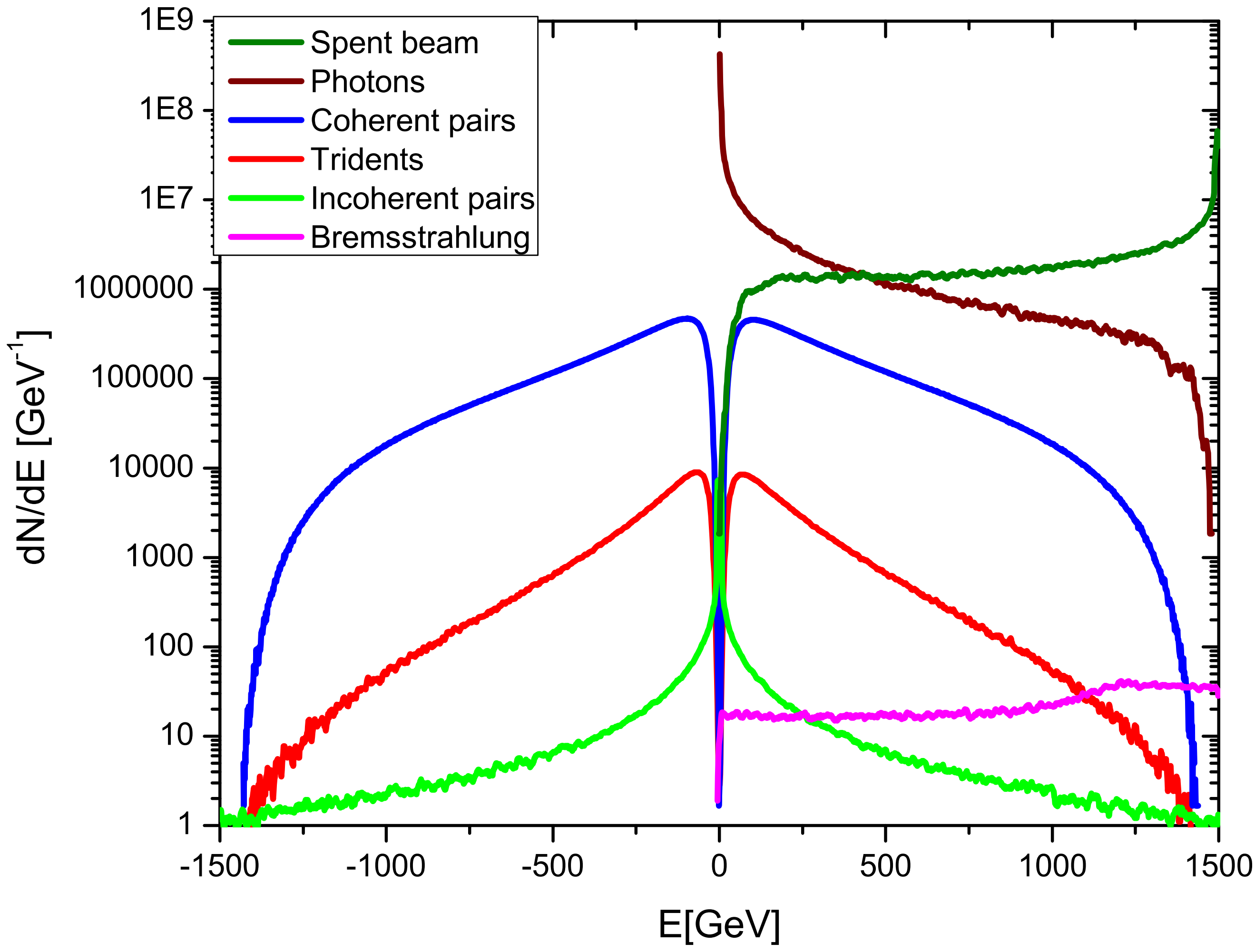
Coherent pairs

Trident cascade pairs

Incoherent pairs

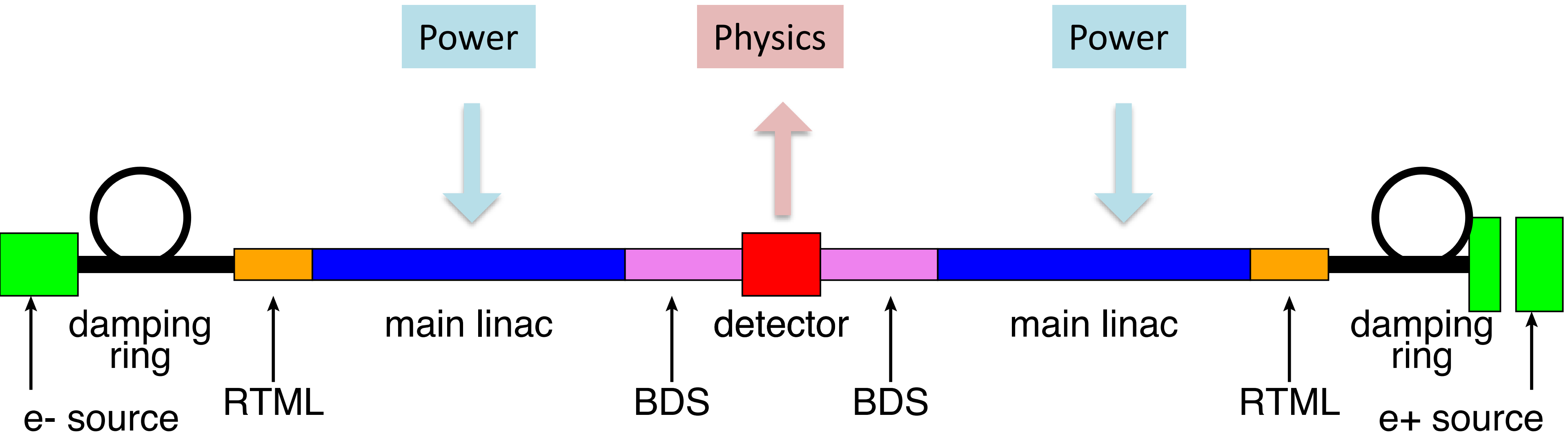
Hadrons

...



J. Esberg

Generic Linear Collider



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

- almost no synchrotron radiation

Single pass, hence two main challenges

- gradient
- luminosity

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

Beam-beam Effect

Bunches are squeezed strongly to maximise luminosity

↓

Electron magnetic fields are very strong

↓

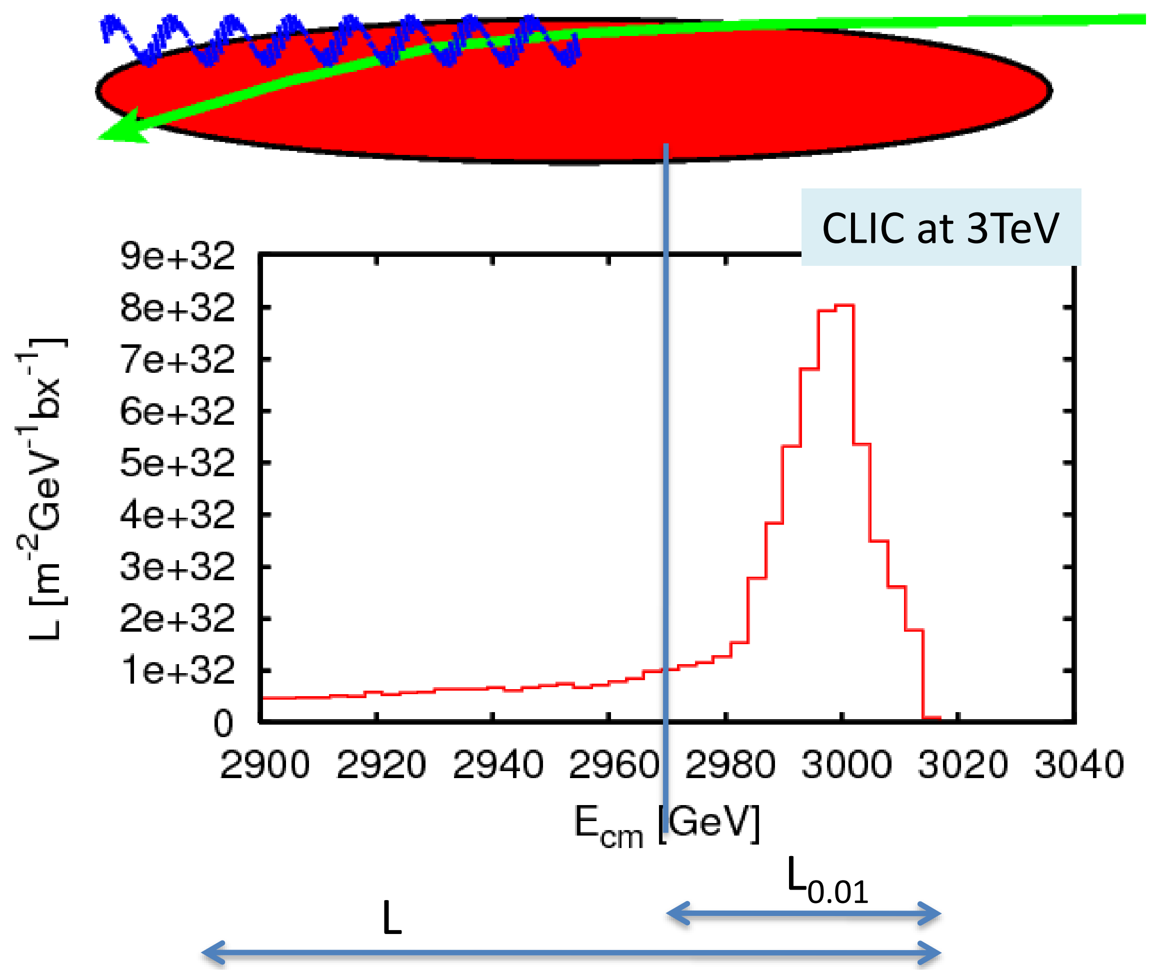
Beam particles travel on curved trajectories

↓

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

Beam have linear focusing force

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

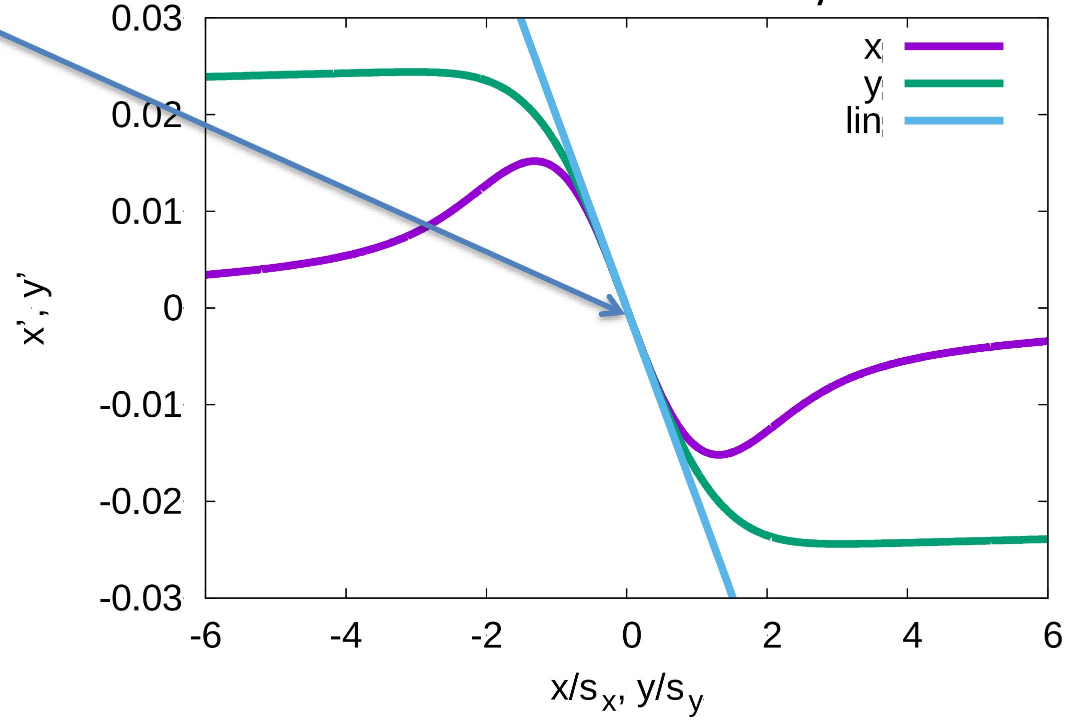
$$D_x = \frac{\sigma_z}{f_x} = \frac{2Nr_e\sigma_z}{\gamma(\sigma_x+\sigma_y)\sigma_x}$$

Typically smaller than 1

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

Typically much larger than 1

Very flat beam



Parameter	Symbol [unit]	SLC	ILC	CLIC	CLIC
Horizontal disruption	D_x	0.6	0.3	0.24	0.2
Vertical disruption	D_y	1.7	24.3	12.5	7.6

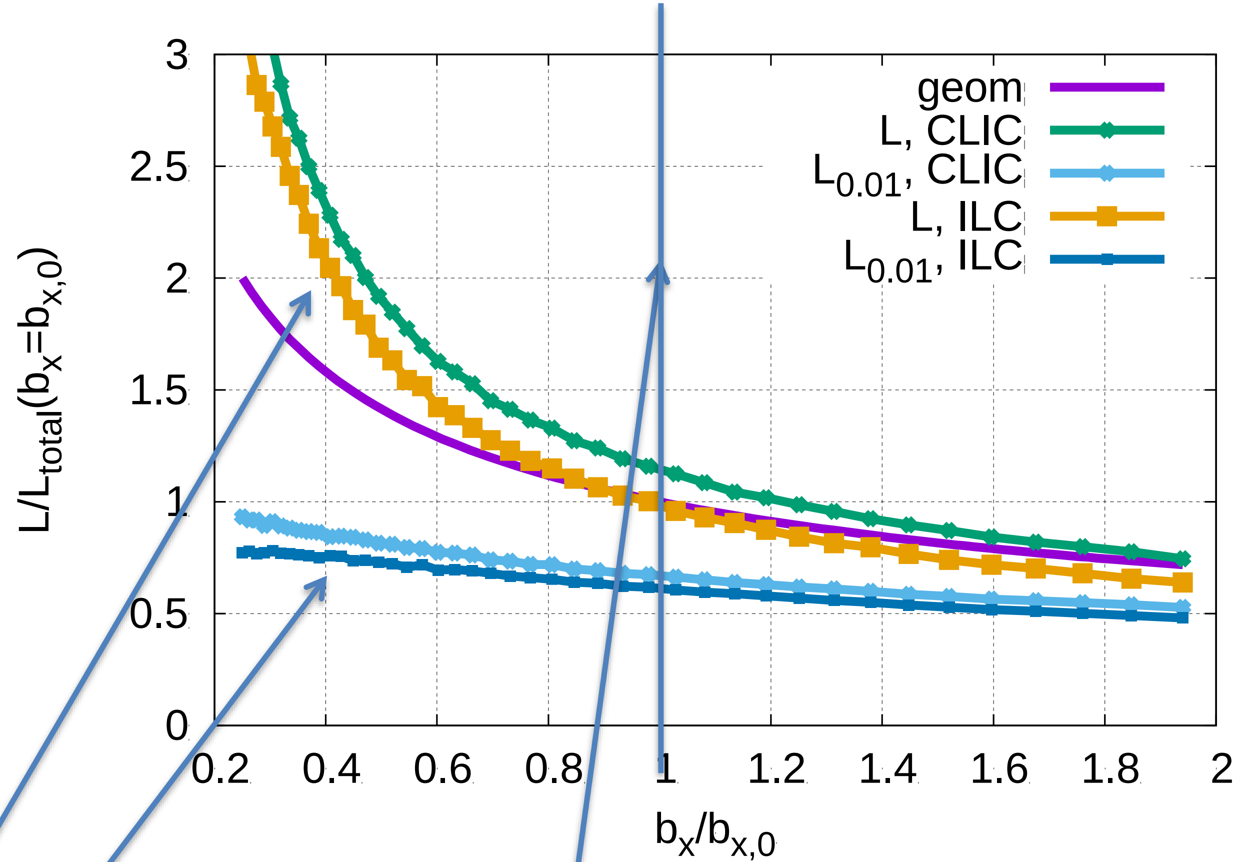
Luminosity Spectrum

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

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

$$\sigma_x \gg \sigma_y$$

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



The total luminosity L varies strongly with beta-function

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

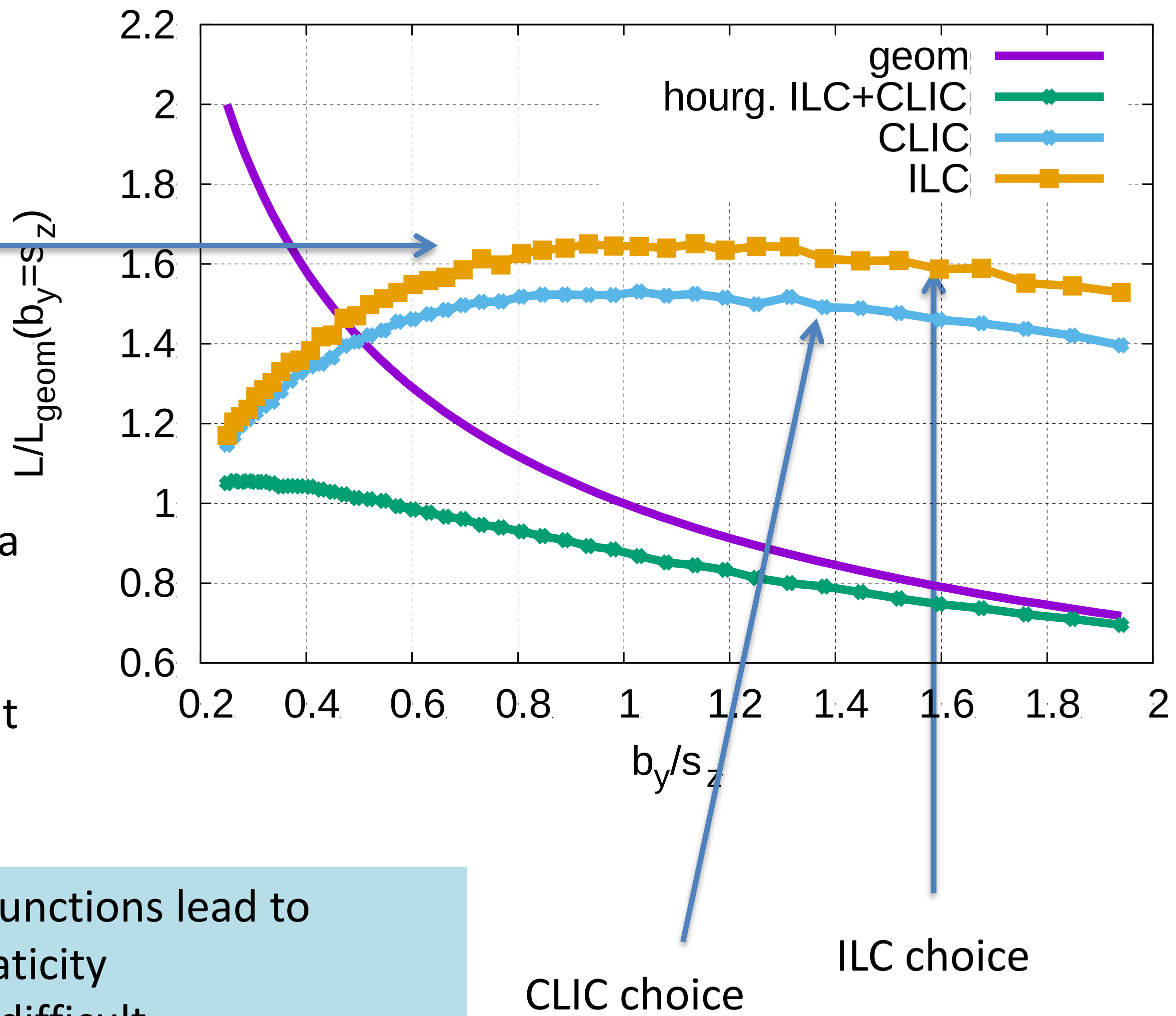
So tend to use $L_{0.01}/L$=60% as criterion
i.e. typically n_γ=1.5-2

Reasonable compromise for most physics studies

Hourglass and 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

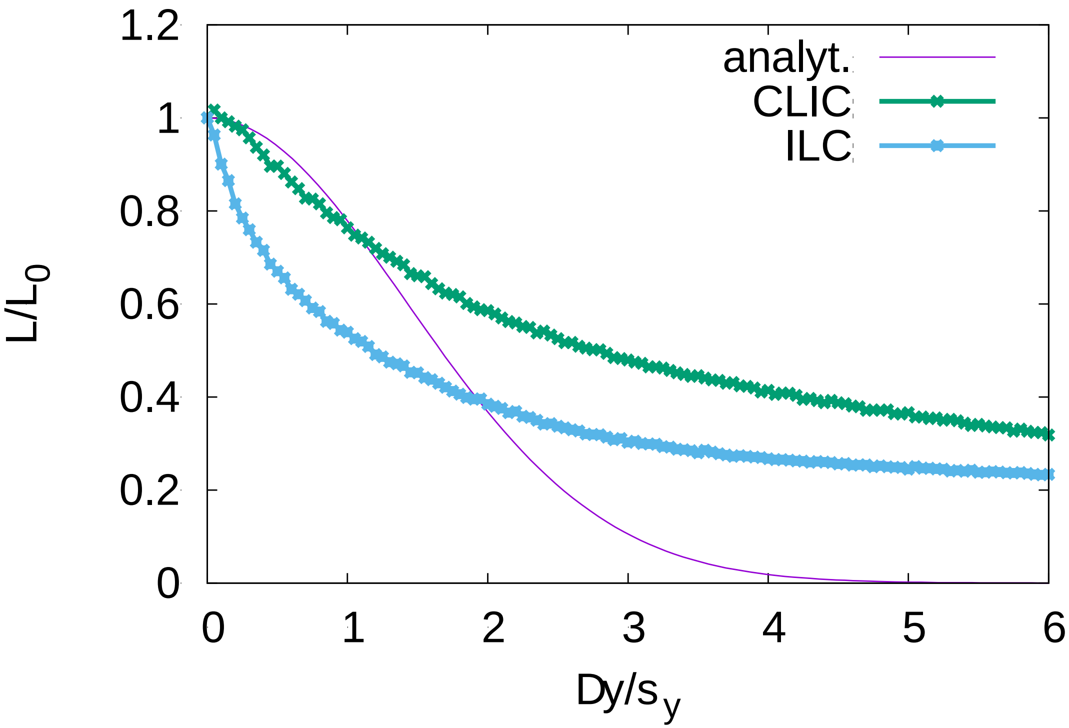
Luminosity and Offset

Luminosity loss for beam offsets depends strongly on disruption parameter

$\Delta y = 0.4\ \sigma_y$

$L = 0.71\ L_0$ $D_y \sim 24$

$L = 0.92\ L_0$ $D_y \sim 12$



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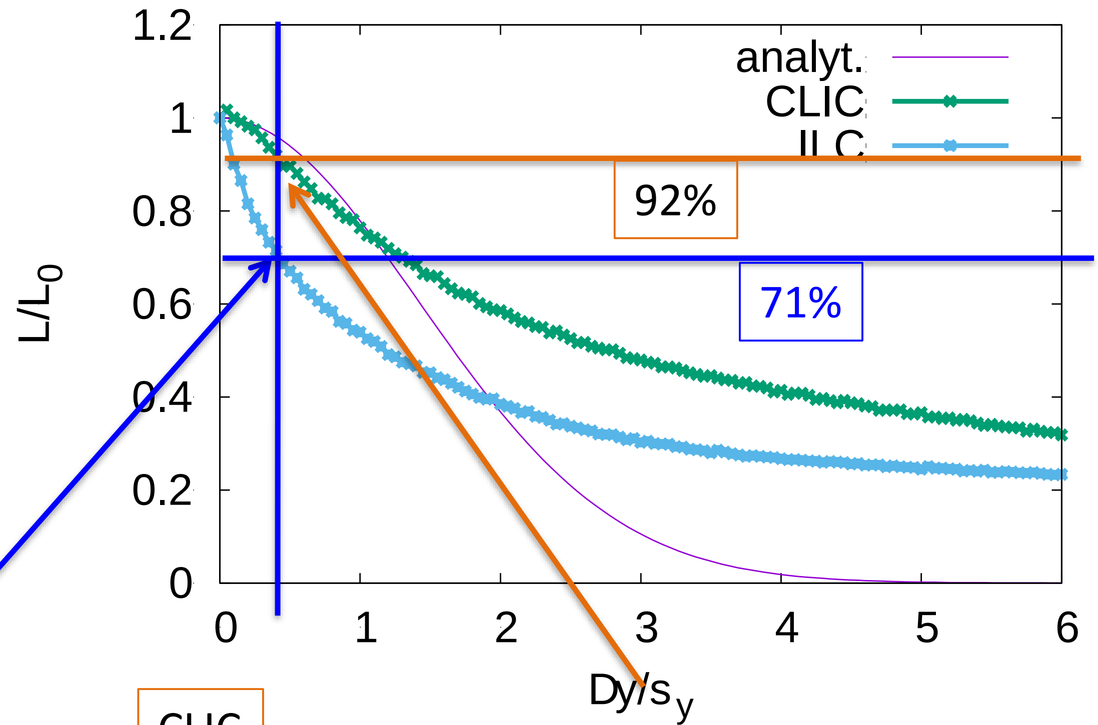
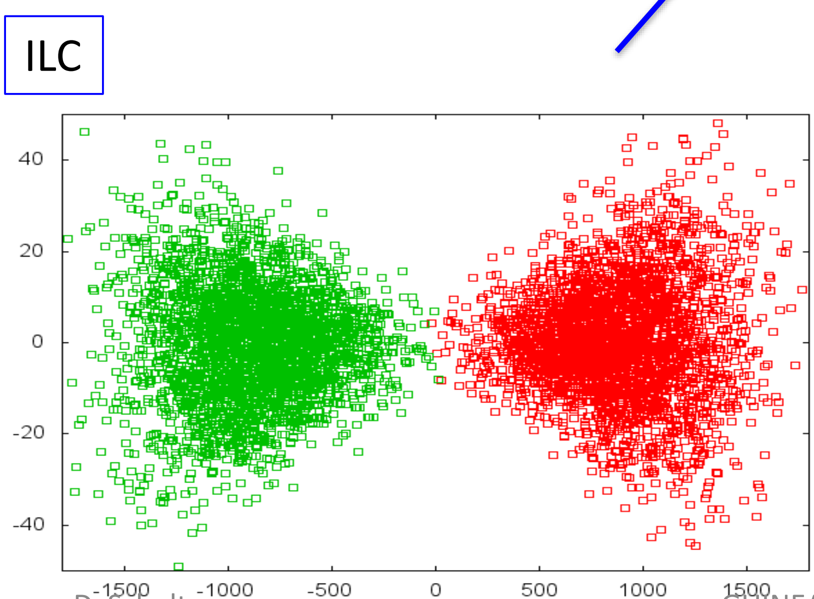
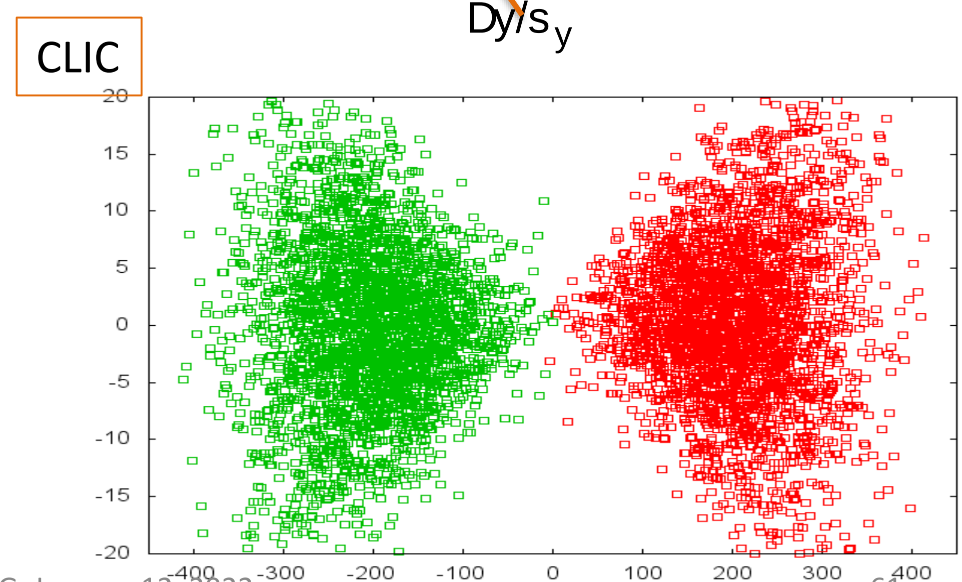




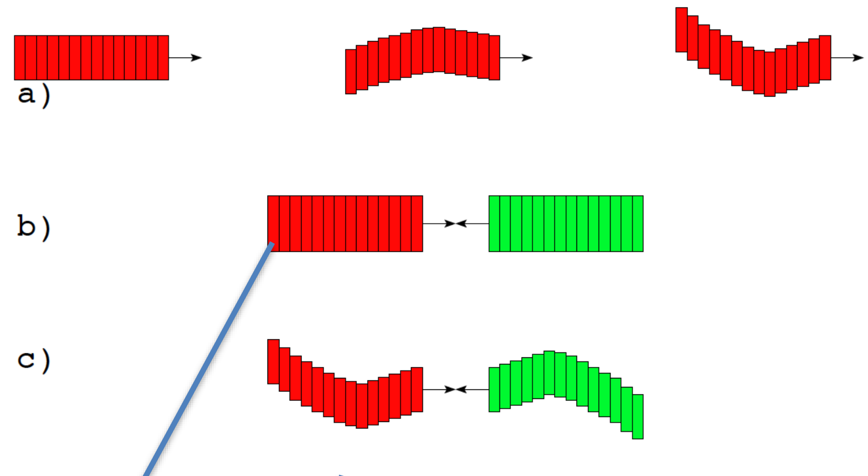


Note: The Banana Effect

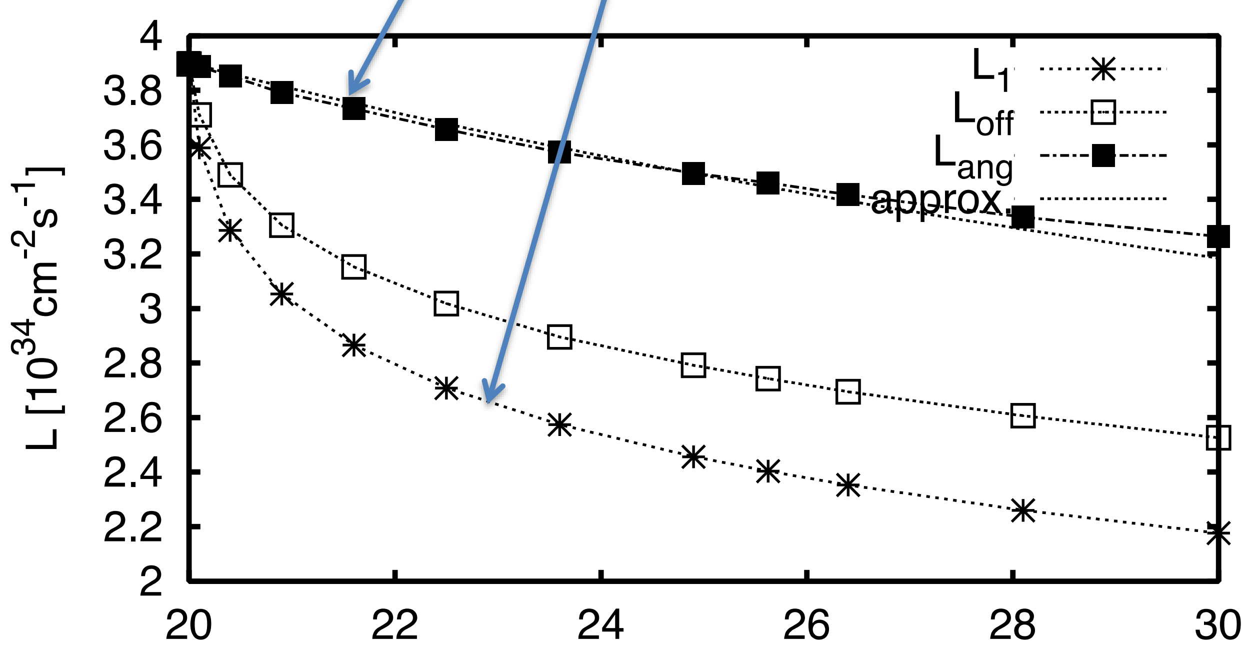
a) Wakefields+dispersion can create banana-shaped bunch in main linac

b) Do not model with projected emittance

c) The correct shape should be used

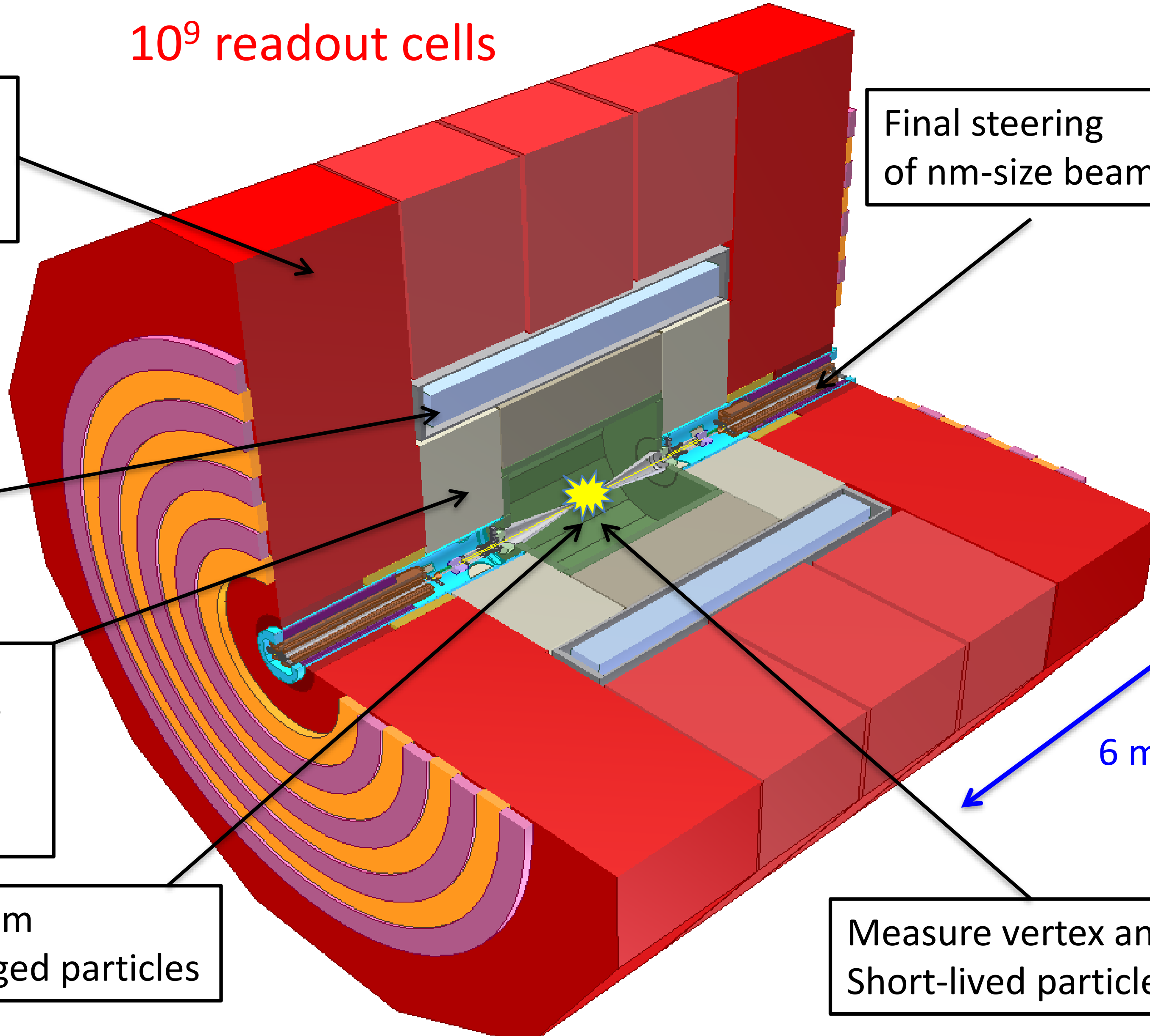


For large disruption (ILC) banana can reduce luminosity



Study done for TESLA
Similar disruption as ILC

Linear Collider Experiment



L. Linssen

Spent Beam Divergence

Beam particles are focused by oncoming beam

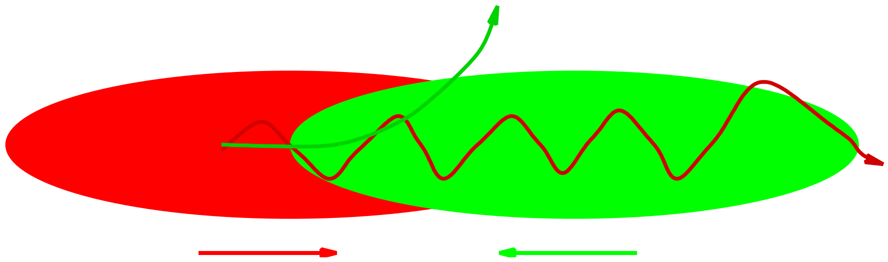
Photons are radiated into direction of beam particles

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

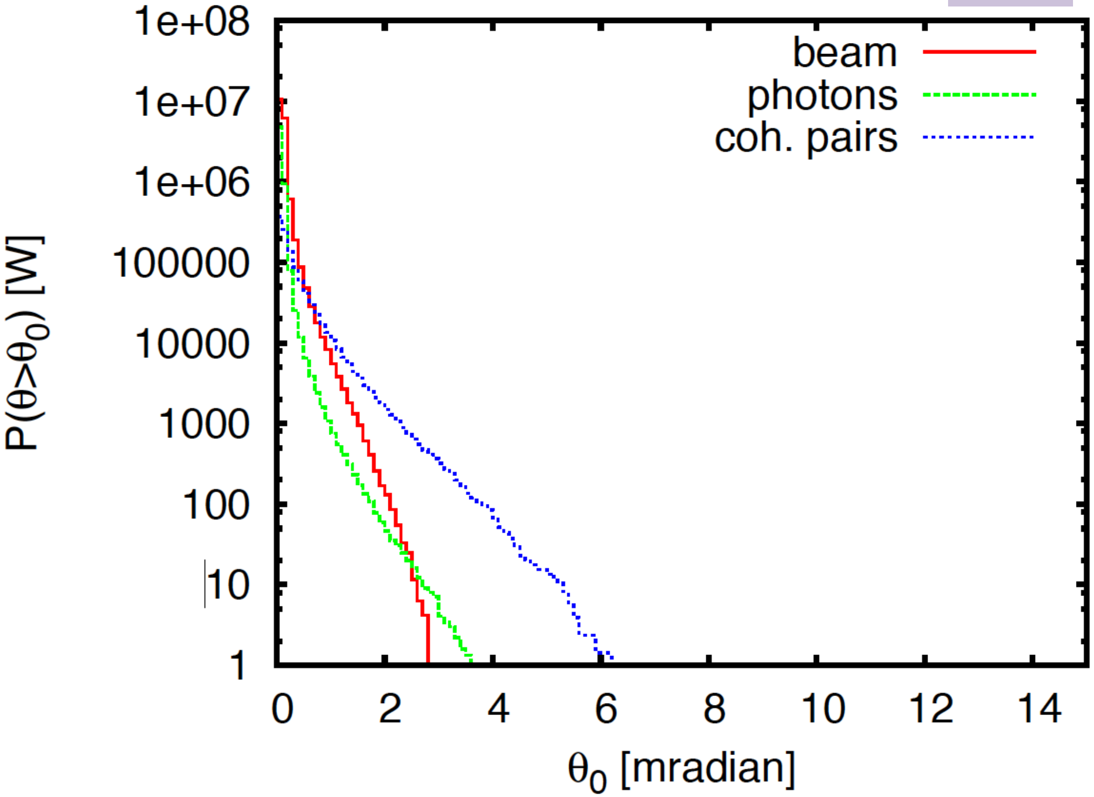
-> Extraction hole angle should be significantly larger than 6mradian

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

ILC requires 14mradian crossing angle



CLIC



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

GUINEA-PIG Impact on CERN Studies

GUINEA-PIG is central for linear collider machine, detector and physics studies

- Used on TESLA, SLC, SBLC, JLC, VLEPP, CLIC, ILC, plasma-based collider, …
- Luminosity estimates
  - Including imperfections
- Produces luminosity spectrum for physics analysis
  - Actually used in optimisation of machine for physics
  - Used for estimation of physics performance
- Produces background data for detector design
  - E.g. pair background defines vertex detector
  - Used for estimation of physics performance

LHeC and FCC-he

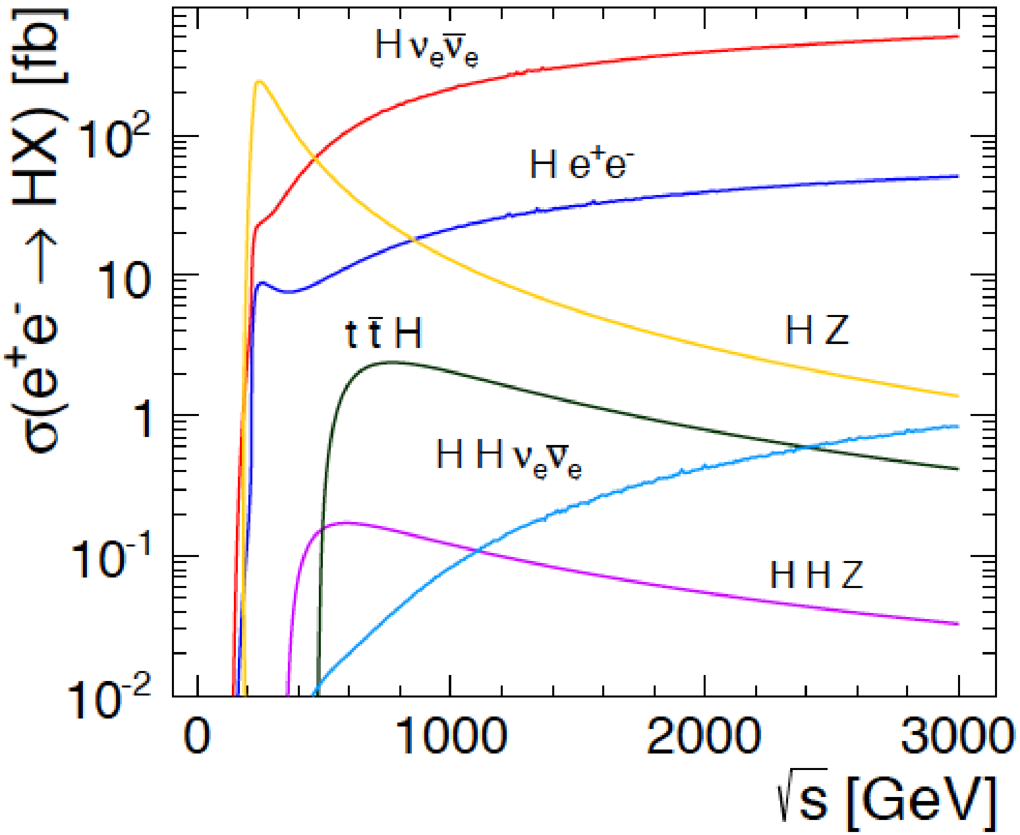
- Prediction of luminosity
- Impact of electron beam on proton beam emittance

FCC-ee, LEP3

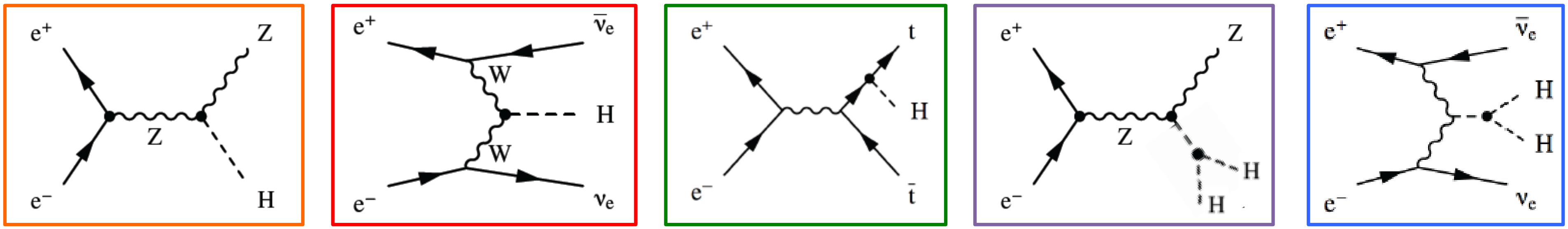
- Some simulations of beam-beam and particle energy loss

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

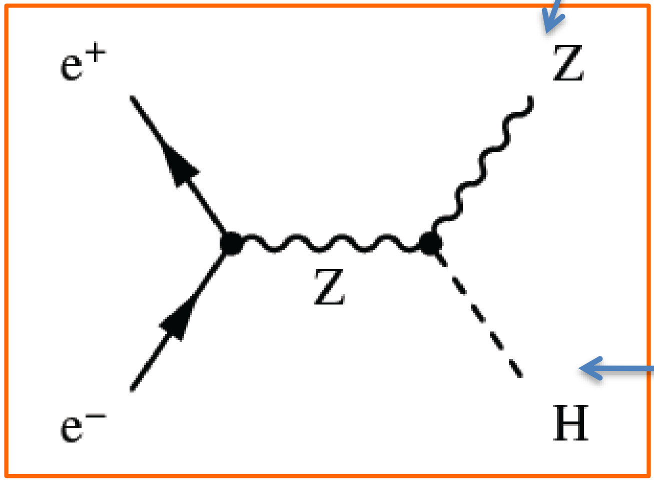


Invisible Higgs Decays

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

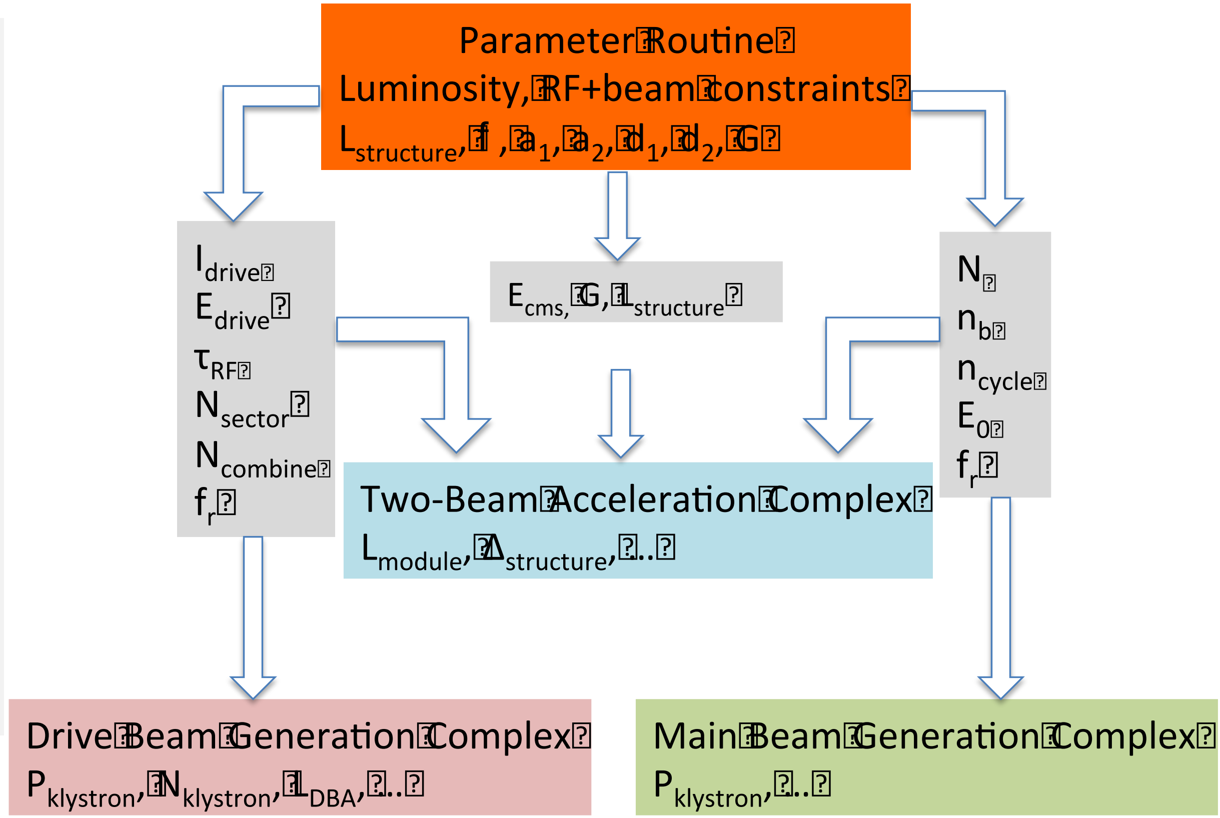
Structure design fixed by few parameters

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

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

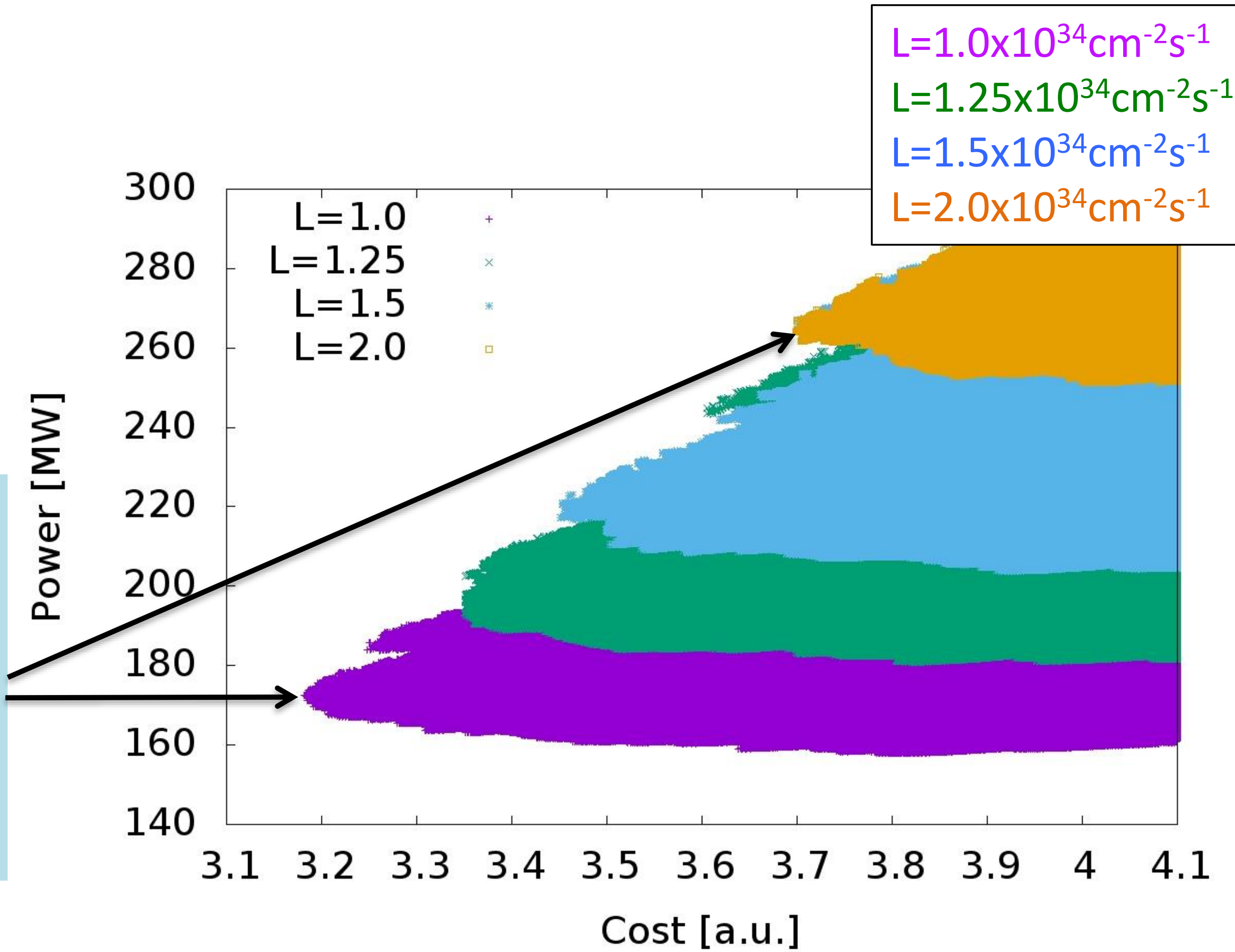
- Use 50Hz operation for beam stability
- Scale horizontal emittance with charge to keep the same risk in damping ring
- Scale for constant local stability in main linac, i.e. tolerances vary but stay above CDR values
- BDS design similar to CDR, use improved β_x-reach as reserve
-

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 $L=1x10^{34}cm^{-2}s^{-1}$ to $L=2x10^{34}cm^{-2}s^{-1}$:

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



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

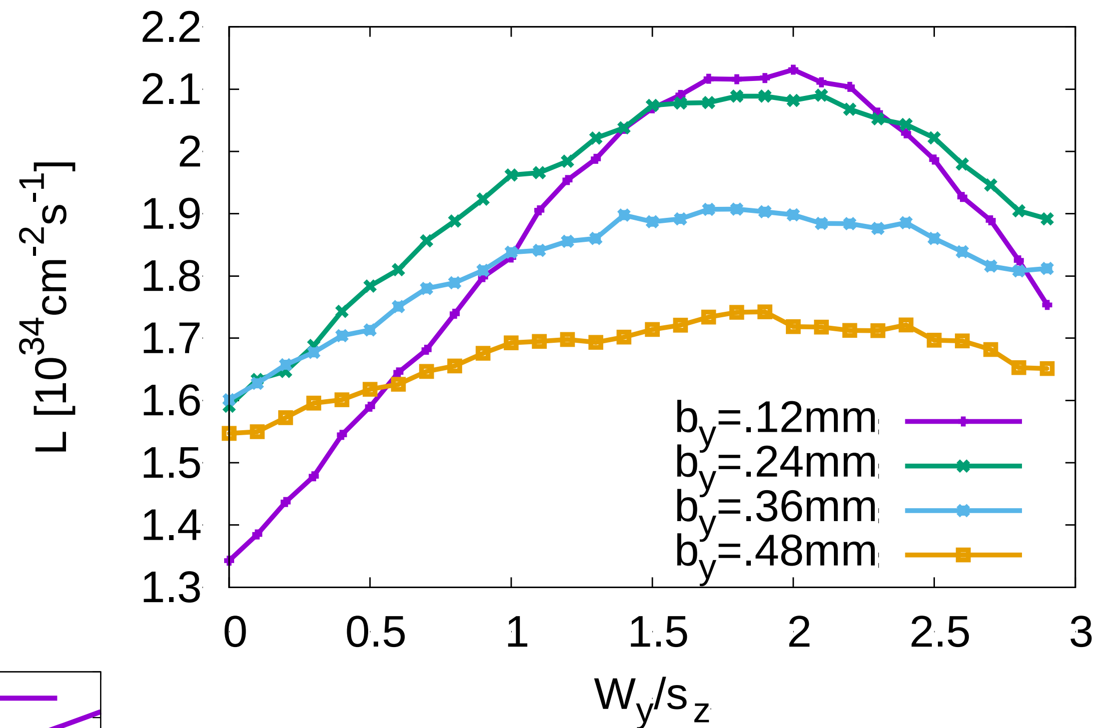
Note: Luminosity Enhancement

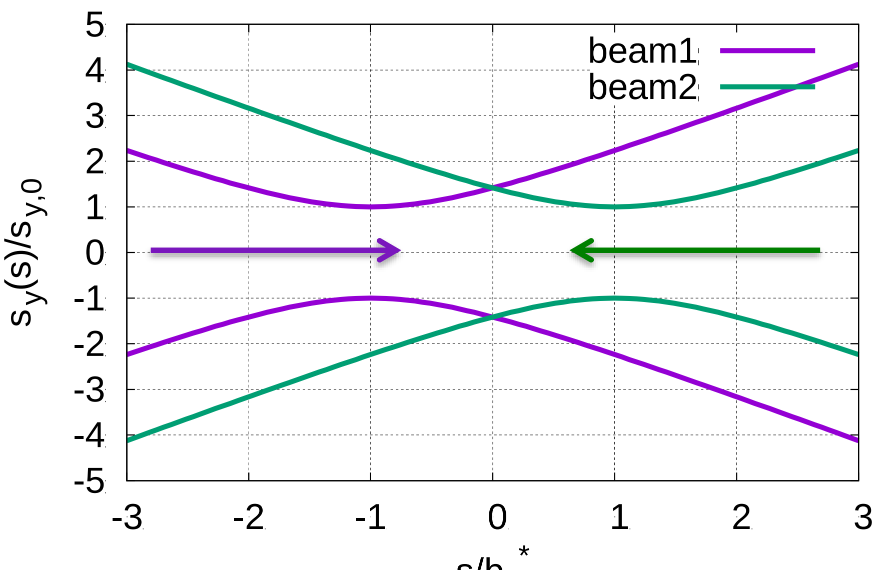
Parameter	Symbol [unit]	ILC	CLIC	CLIC
Centre of mass energy	E_{cm} [GeV]	500	380	3000
Total luminosity	L [$10^{34}cm^{-2}s^{-1}$]	1.8	1.5	6
Luminosity in peak	$L_{0.01}$ [$10^{34}cm^{-2}s^{-1}$]	1	0.9	2
Particles per bunch	N [10^9]	20	5.2	3.72
Bunch length	σ_z [μm]	300	70	44
Collision beam size	$\sigma_{x,y}$ [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

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

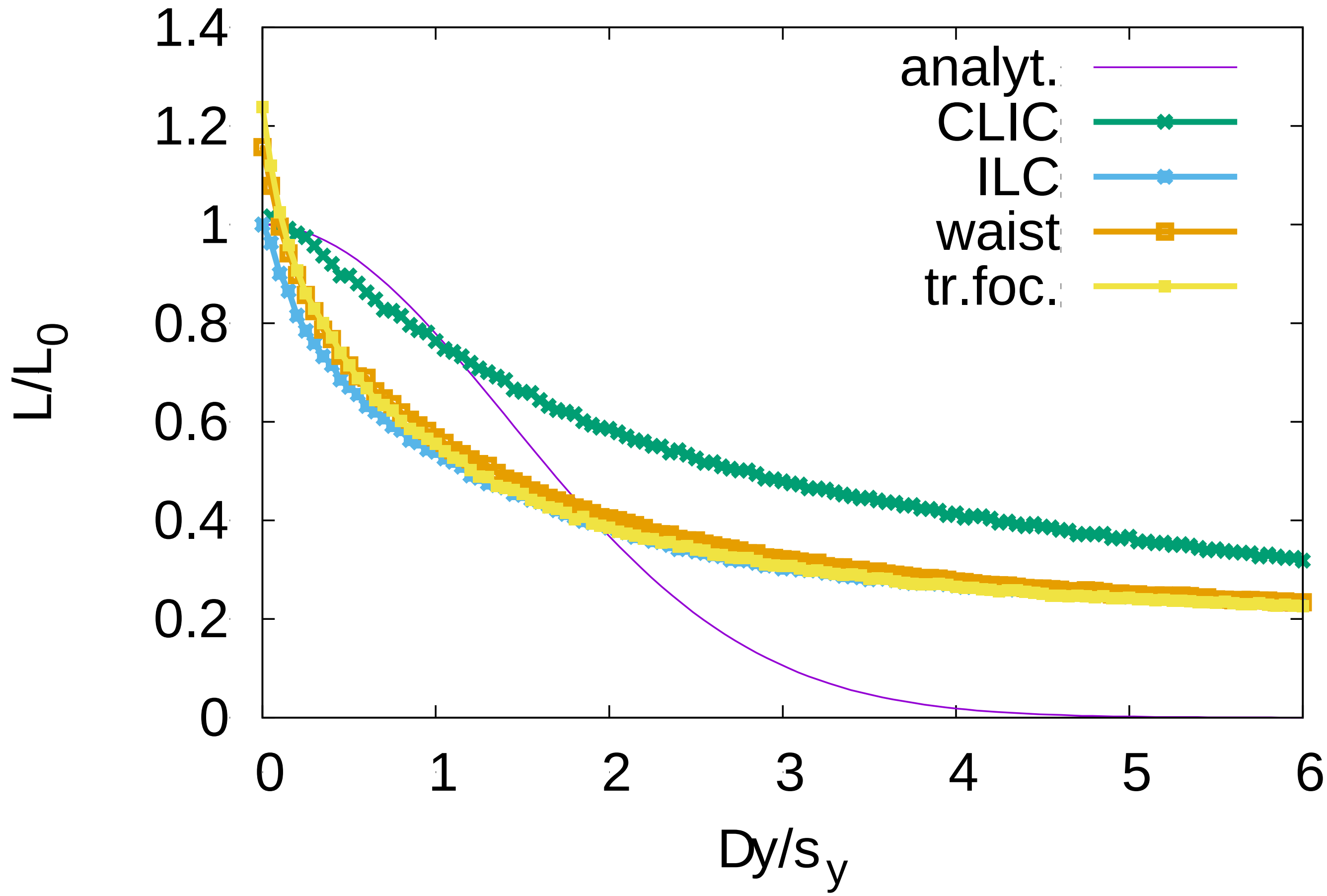




Additional gain of 10% in luminosity

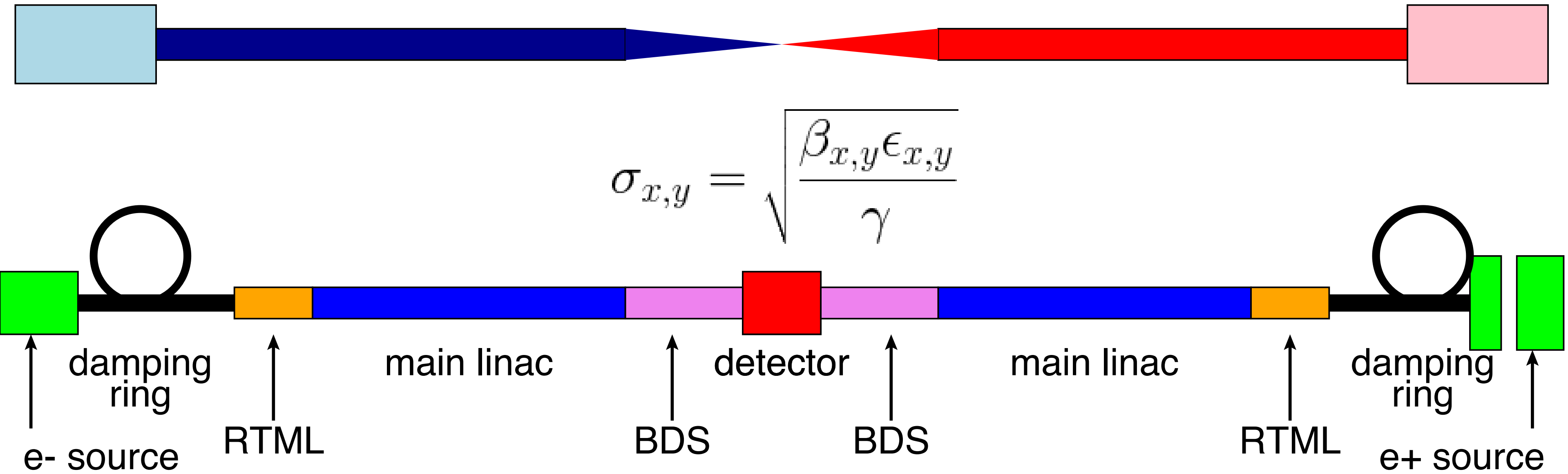
Note: ILC with β_y=0.24mm

Even stronger offset dependence for smaller beta-function



So in practice less gain than expected

Generic Linear Collider



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

Single pass poses luminosity challenge

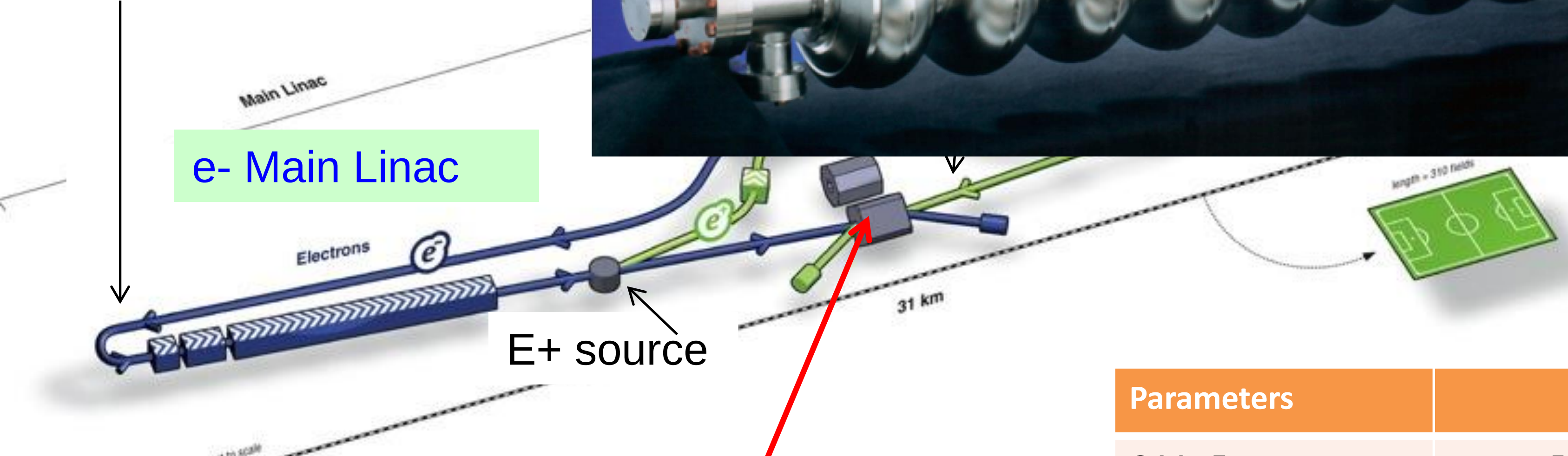
Low emittances are produced in the damping rings

They must be maintained with limited degradation

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

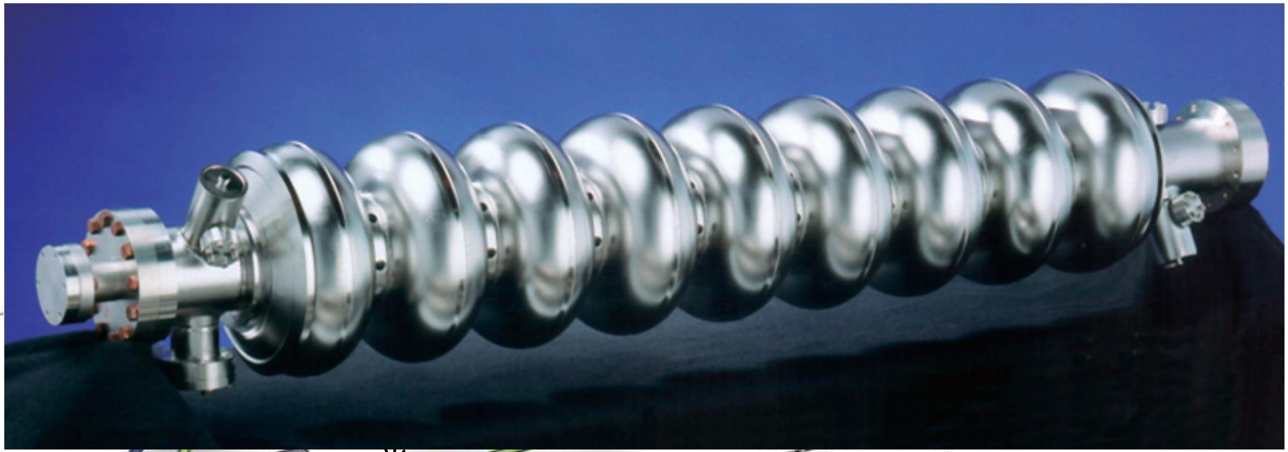
ILC

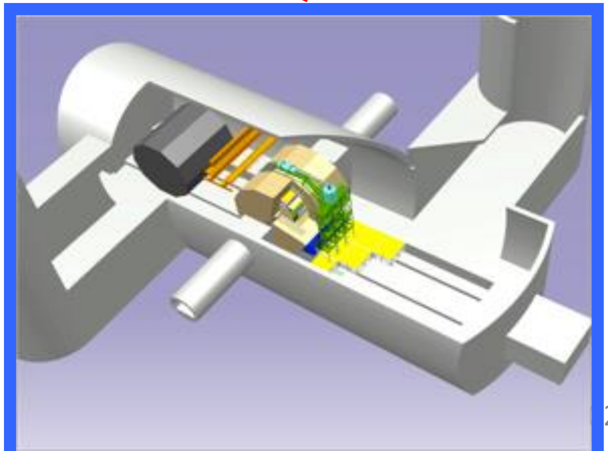
Ring to Main Linac (RTML)
(w. bunch compressors)



e- Main Linac

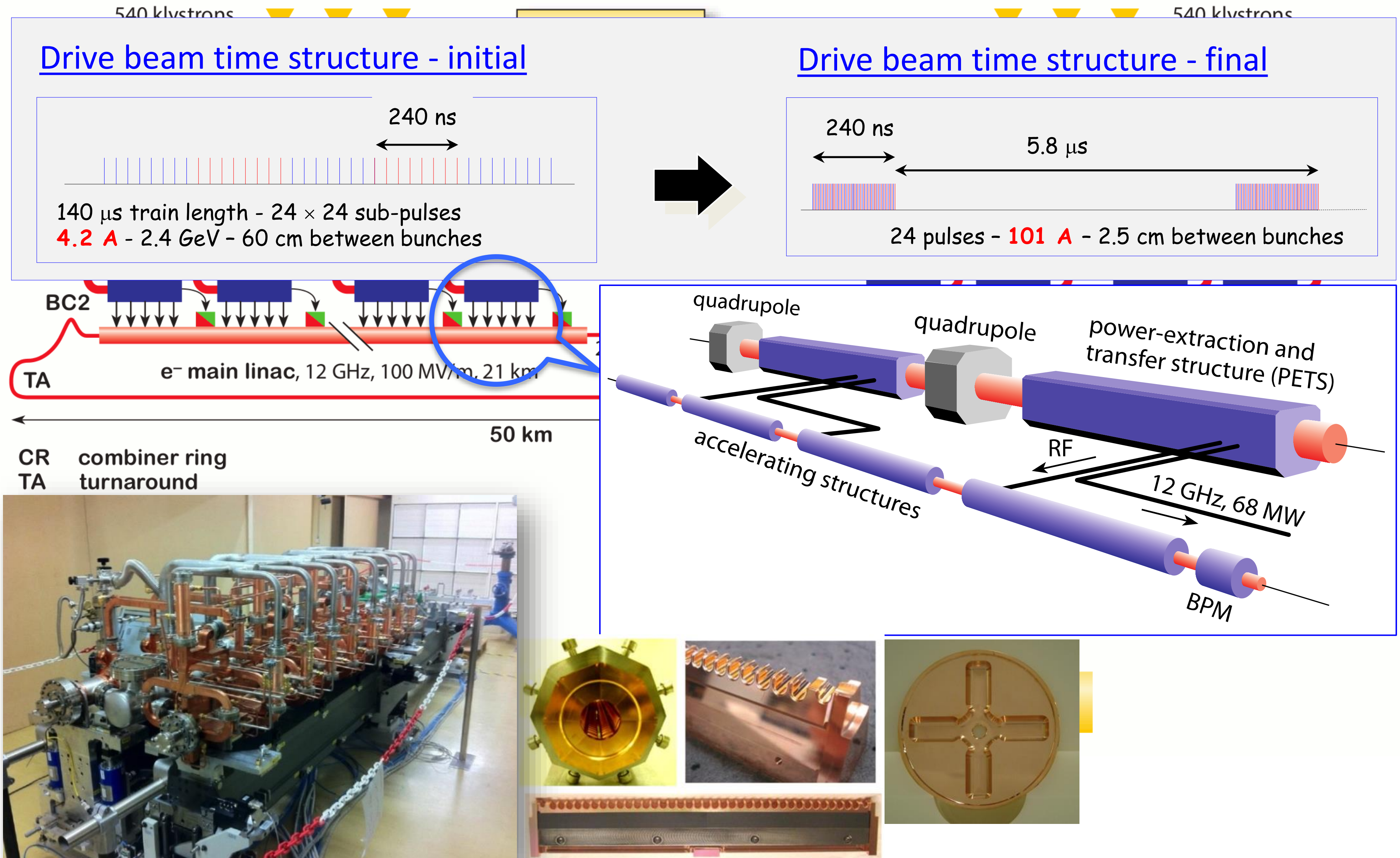
E+ source





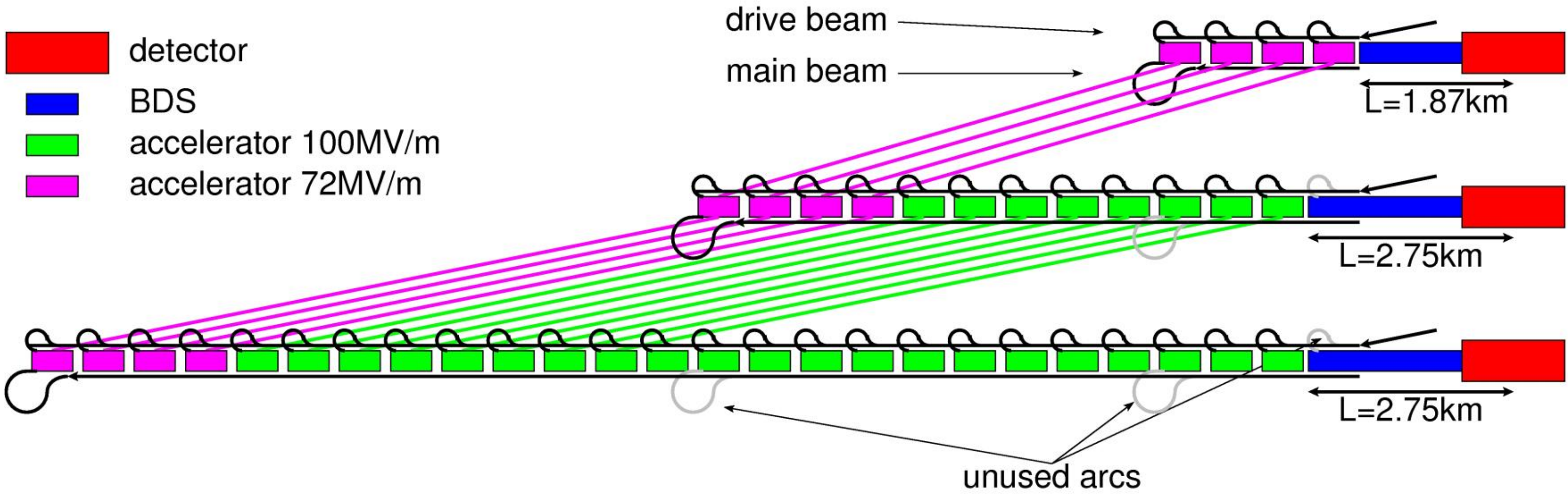
Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

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
quadrupole
quadrupole
power-extraction and transfer structure (PETS)
accelerating structures
RF
12 GHz, 68 MW
BPM

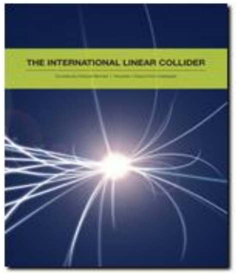
CLIC Staged Approach



- First stage: E_{cms}=380Gev, L=1.5x$10^{34}cm^{-2}s^{-1}$, $L_{0.01}/L>0.6$
- Second stage: E_{cms}=O(1.5TeV)
- Final stage: E_{cms}=3TeV, $L_{0.01}=2x10^{34}cm^{-2}s^{-1}$, $L_{0.01}/L>0.3$

Note: ILC TDR

Volume 1 - Executive Summary



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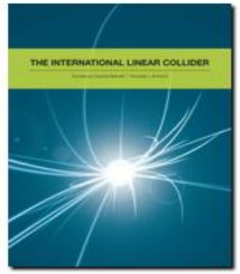
Volume 2 - Physics



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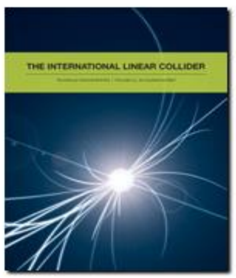
Volume 3 - Accelerator



Part I:
R&D in the Technical Design Phase

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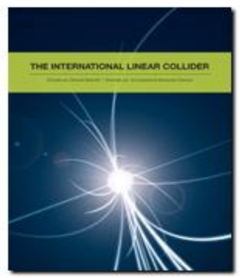
Volume 3 - Accelerator



Part II:
Baseline Design

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Volume 4 - Detectors

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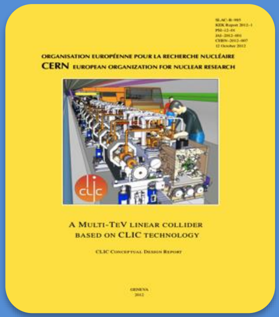
From Design to Reality

Download the pdf (5.5 MB)
Visit the web site

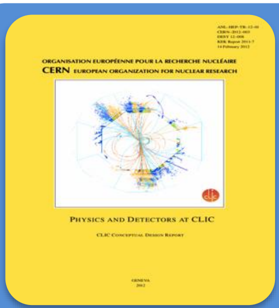
http://www.linearcollider.org/ILC/Publications/Technical-Design-Report

Note: CLIC CDR



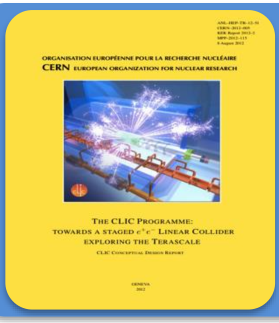
Vol 1: The CLIC accelerator and site facilities

- 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

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Luminosity and Parameter Drivers

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

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

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

Beam power

Luminosity spectrum

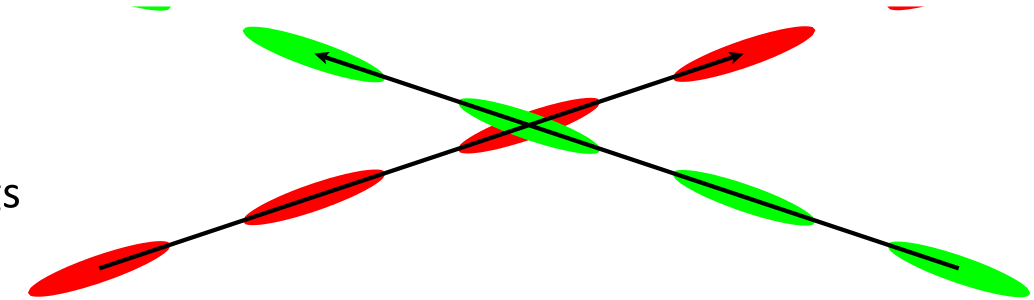
Beam Quality (+bunch length)

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

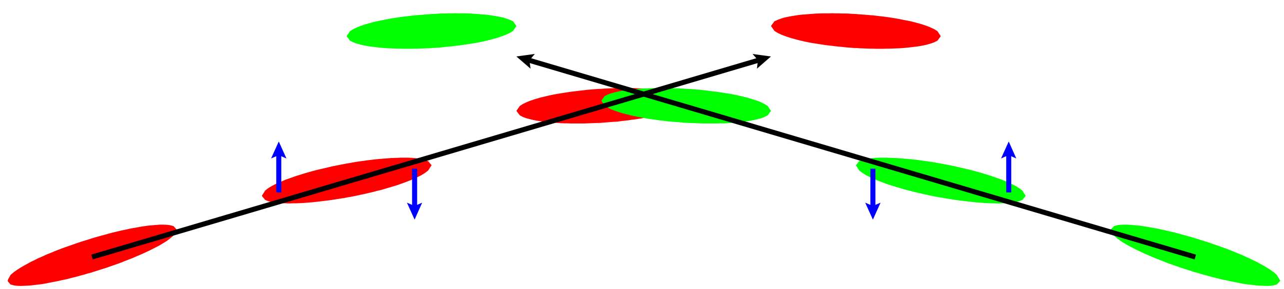


Luminosity with crossing angle

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

0.1-0.2

Use crab cavities:

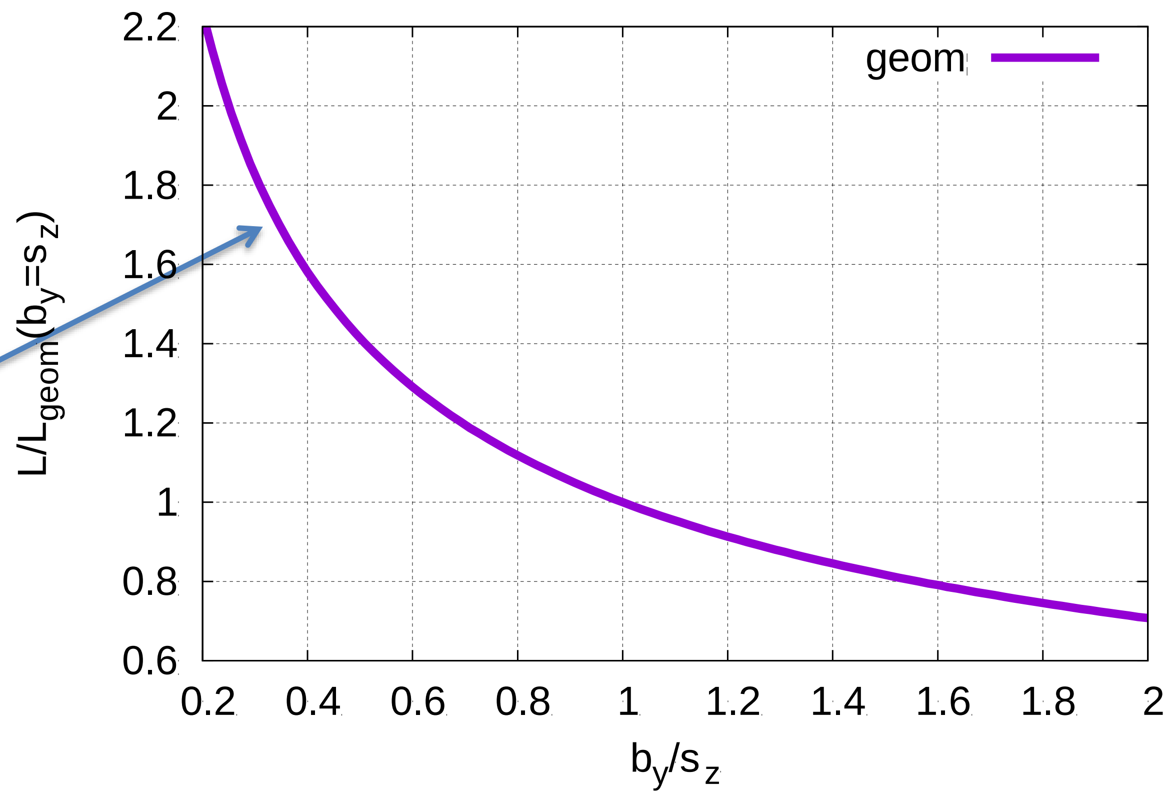


Can ignore crossing angle for beam-beam calculation
But not in detector design

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

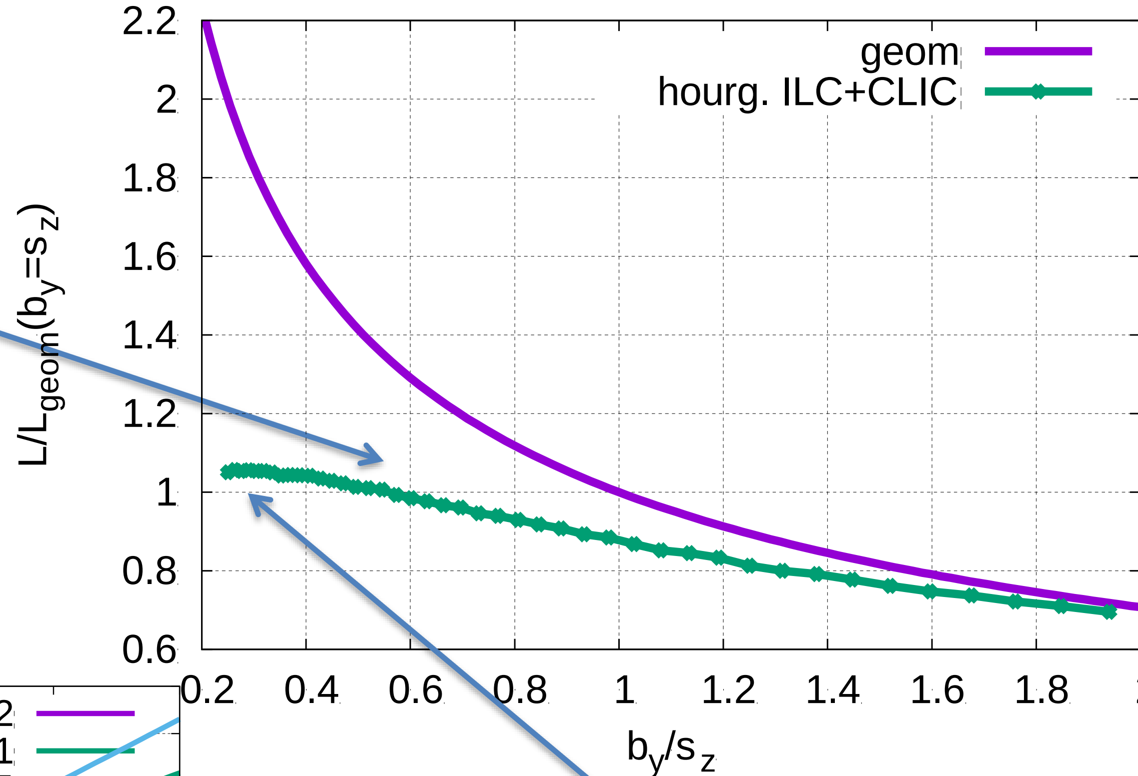
Not excluded that this can be improved but people worked on it for years

Luminosity actually increases not as predicted

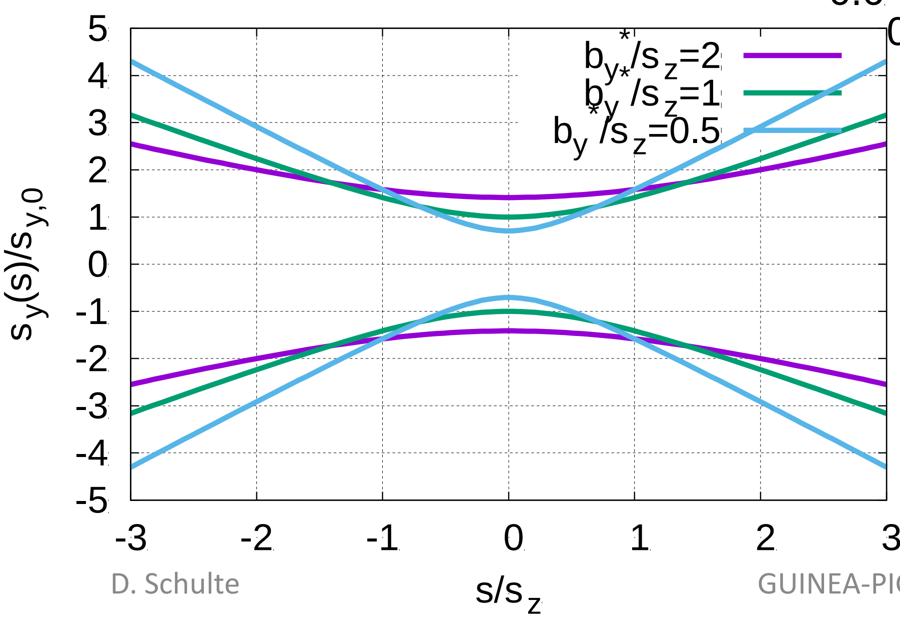
Hourglass Effect

Taking into account hourglass effect

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



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



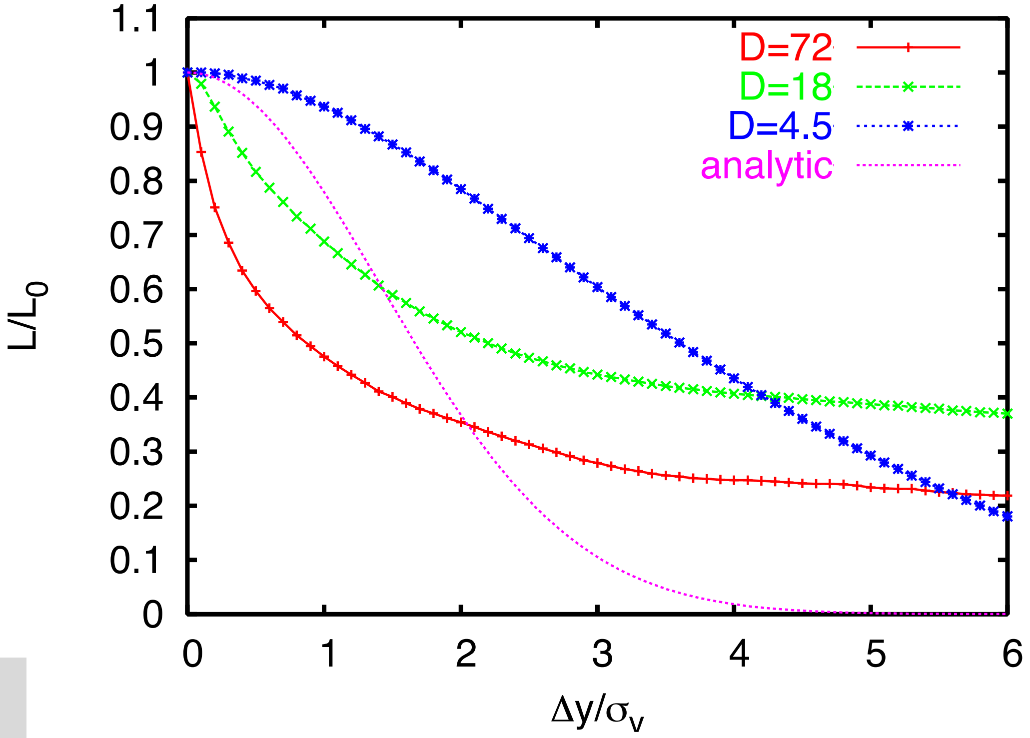
For flat beams, the optimum is around $\beta_y = 0.25 \times \sigma_z$

Note: This is different for round beams

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?

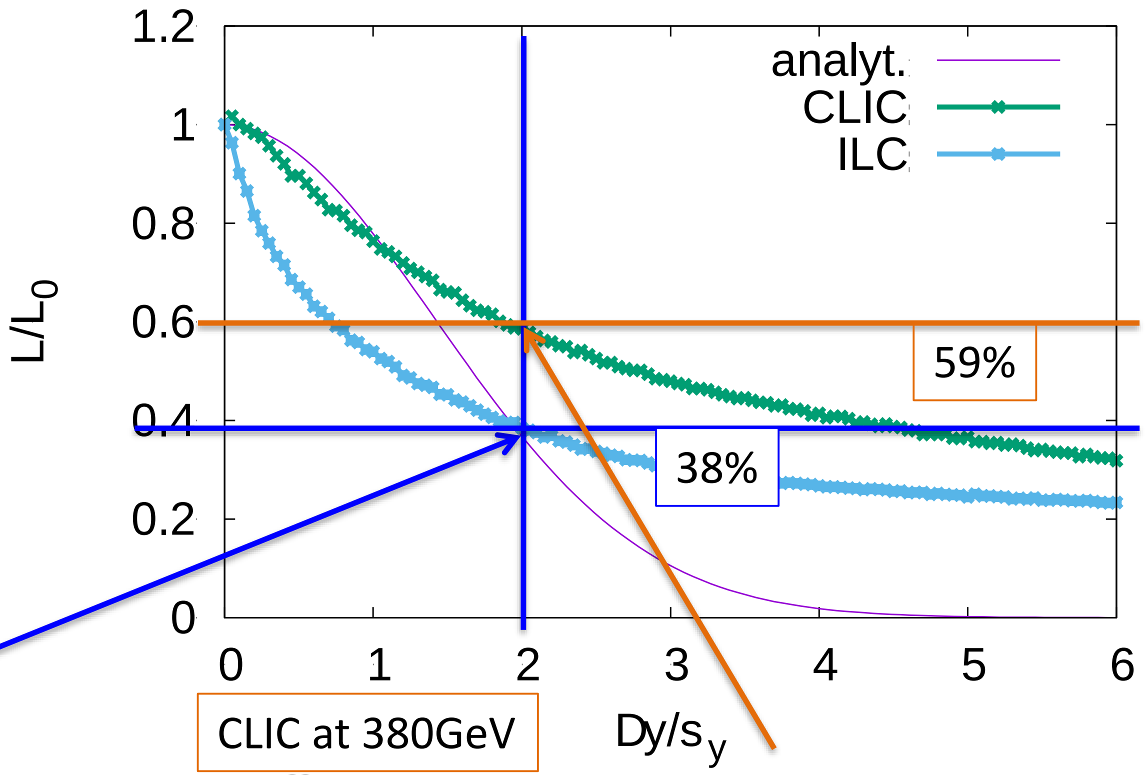
Luminosity and Offset

Luminosity loss for beam offsets depends strongly on disruption parameter

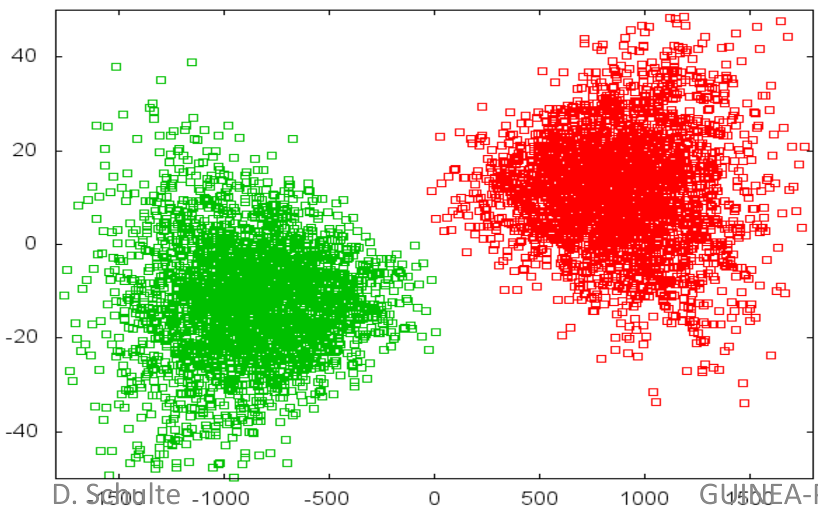
$\Delta y = 2\ \sigma_y$

$L = 0.38\ L_0$

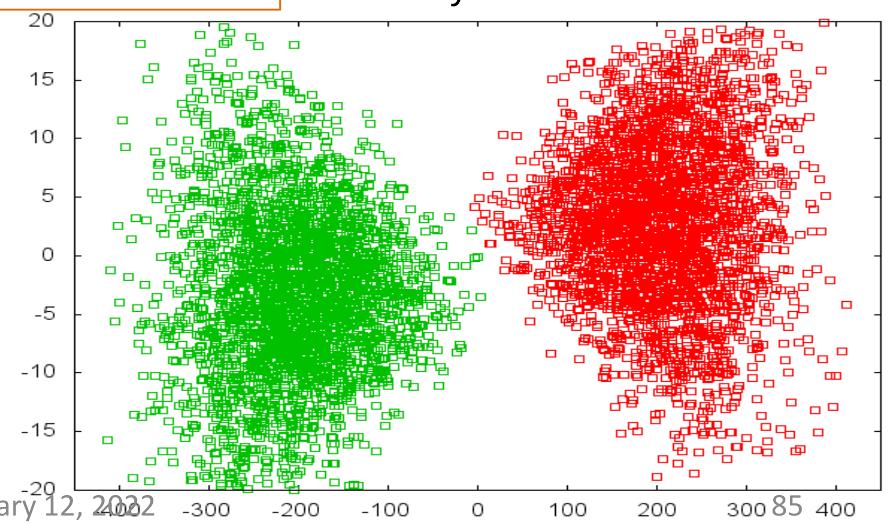
$L = 0.59\ L_0$



ILC



CLIC at 380GeV

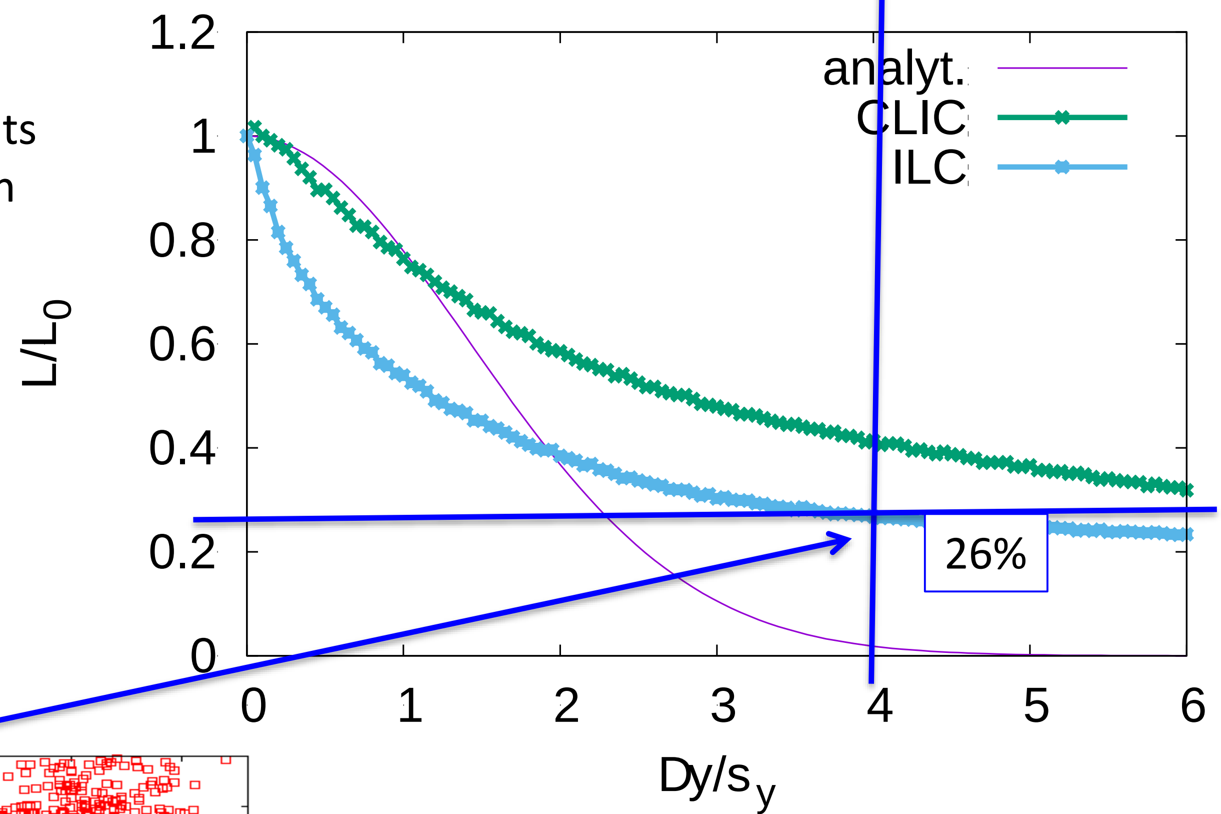


Luminosity and Offset

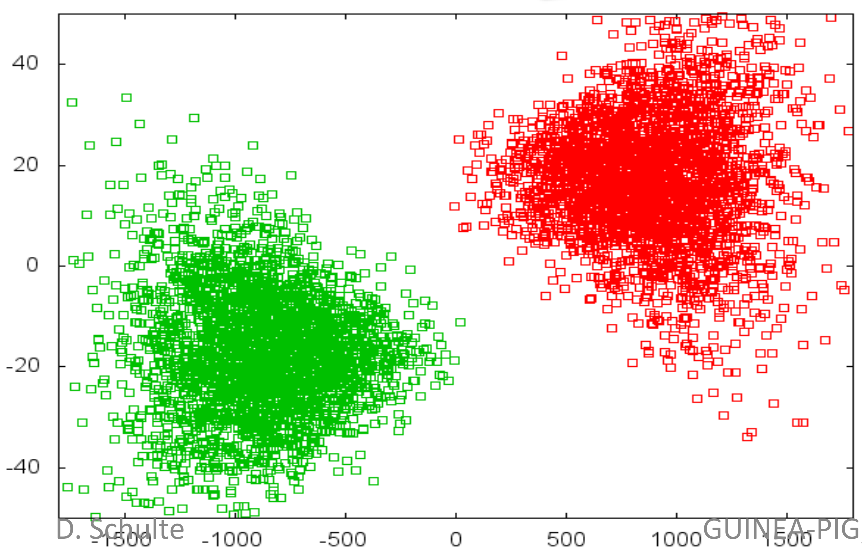
Luminosity loss for beam offsets depends strongly on disruption parameter

$\Delta y = 4\,\sigma_y$

$L = 0.26\,L_0$



ILC

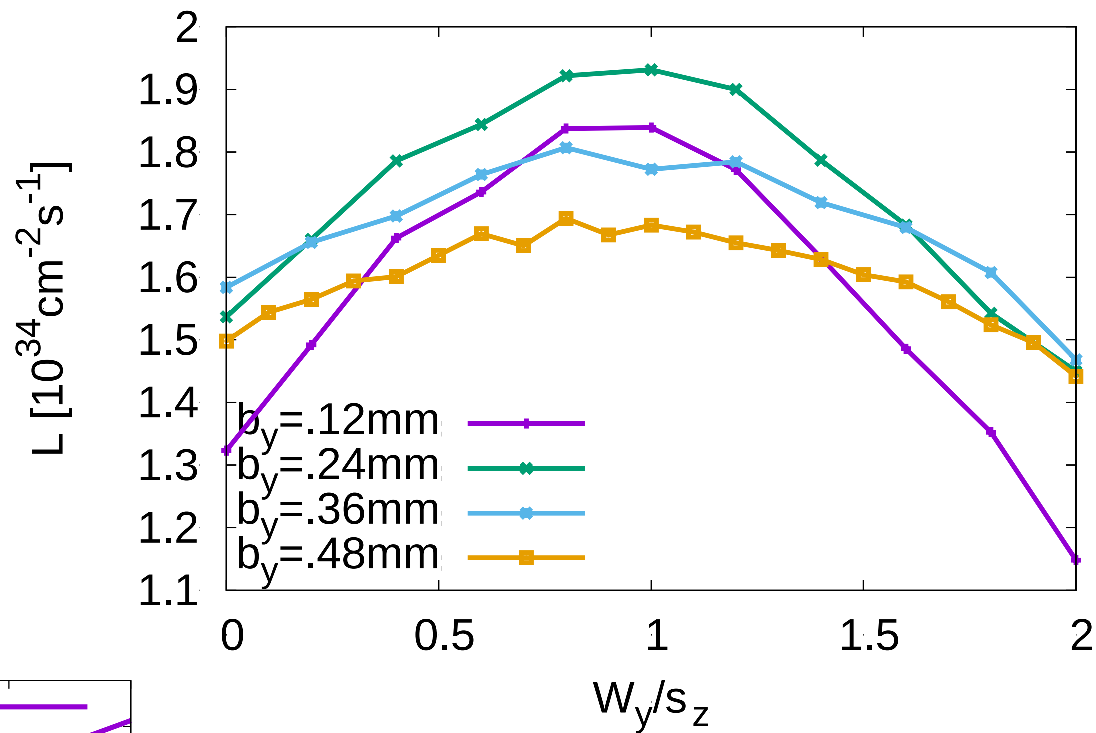


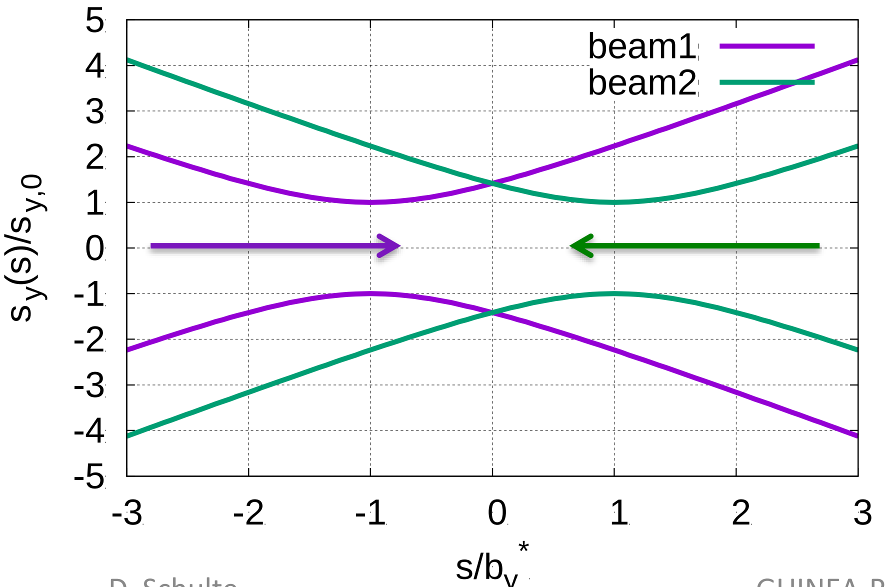
Note: ILC Full Optimisation

For ILC could consider smaller vertical beta-functions

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

Would gain 15% luminosity





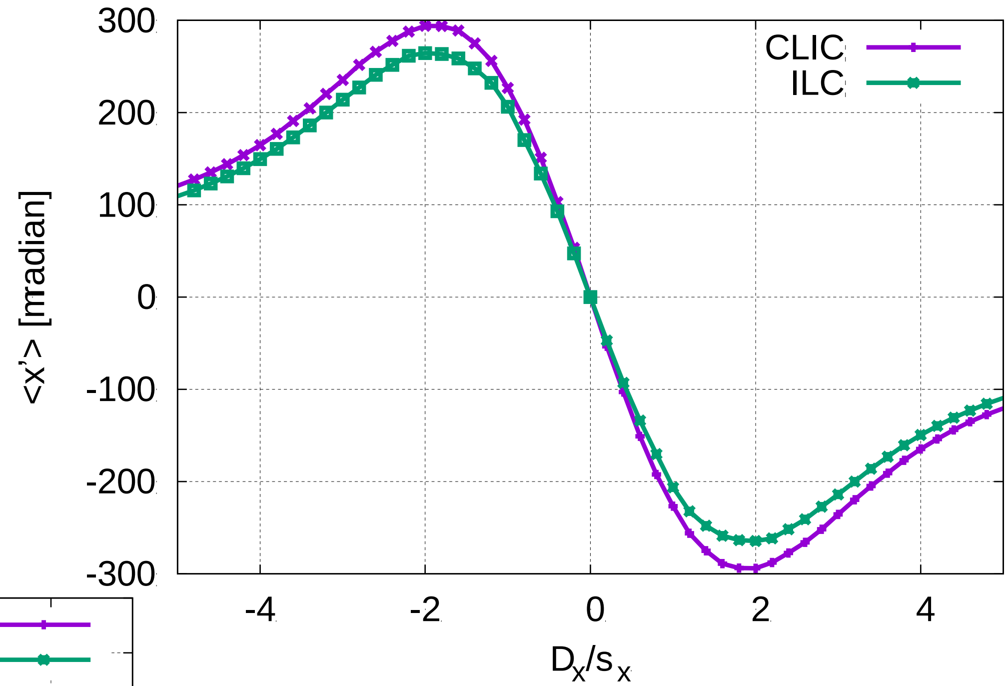
But still more difficult to produce (larger divergence)
And tolerances become tighter

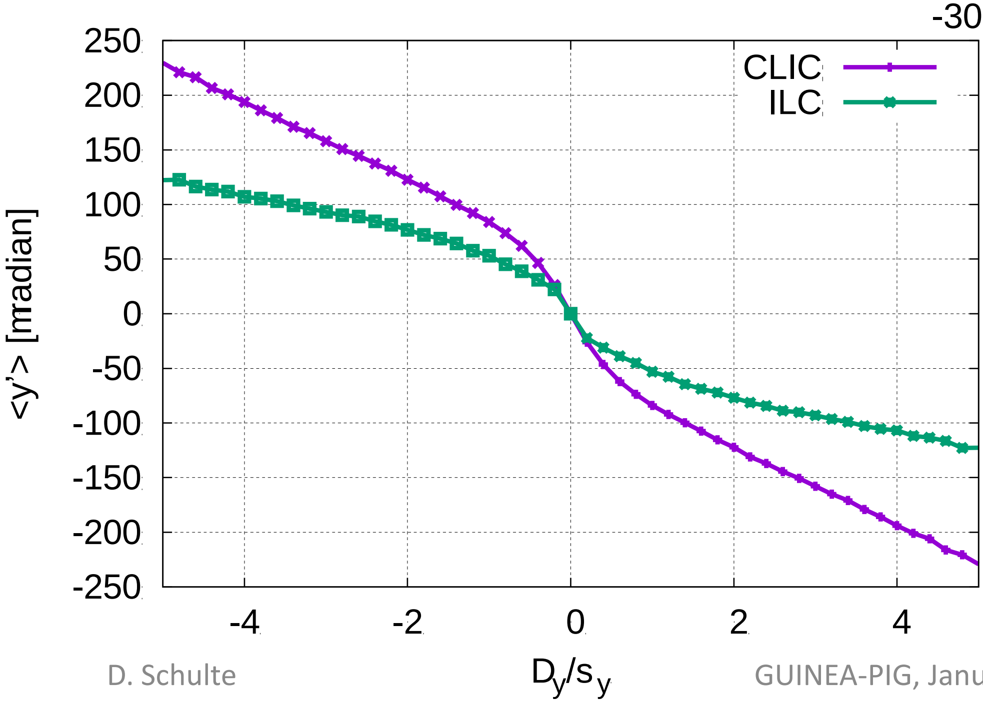
Beam-beam Deflection

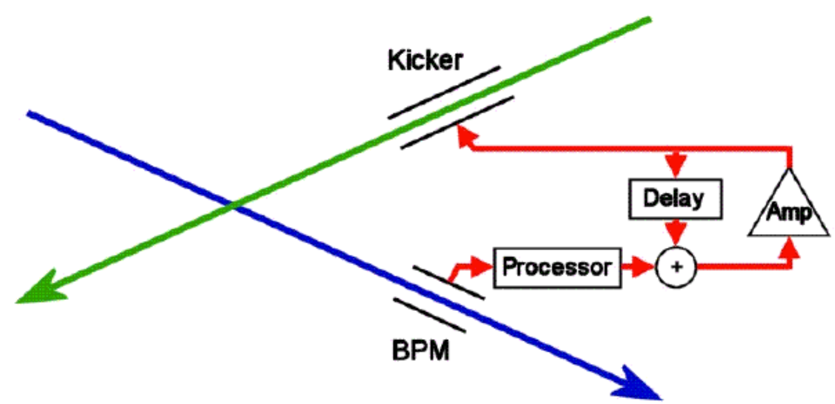
Strong deflection allows to easily measure and correct offset

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

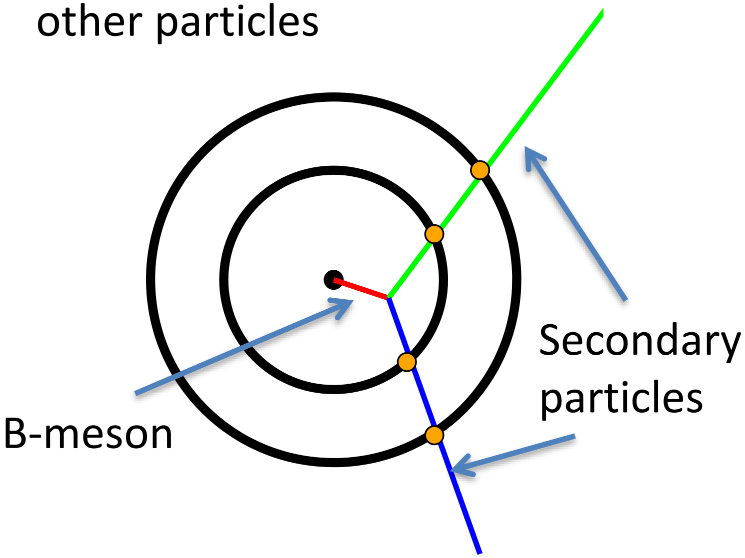


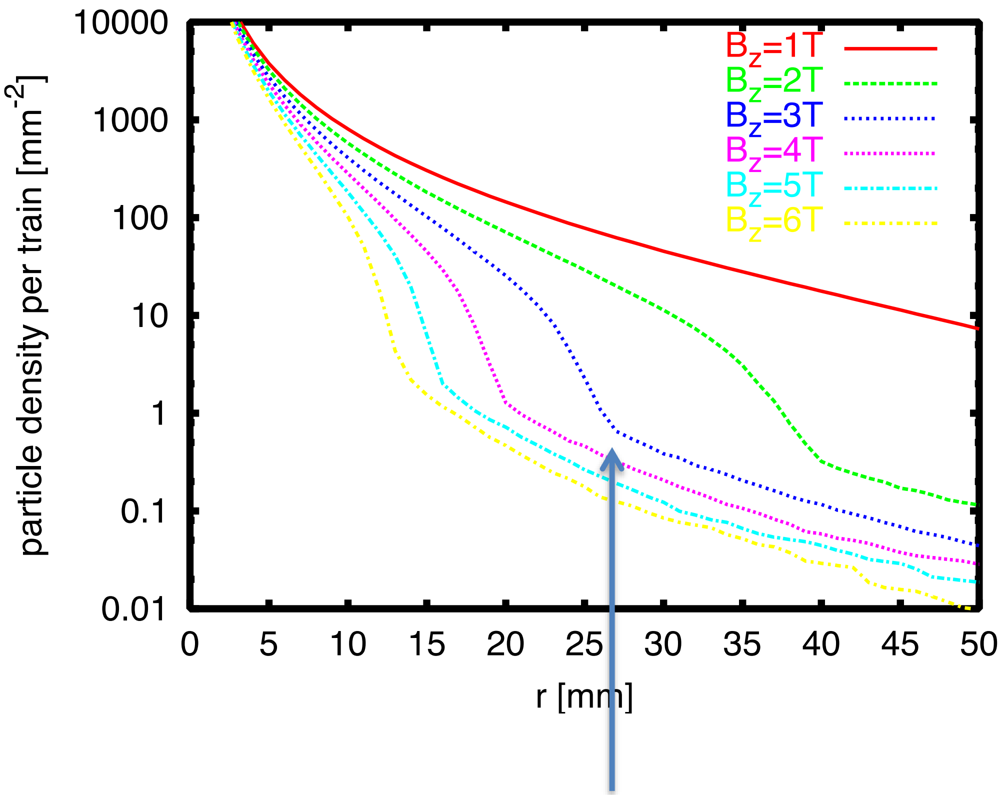




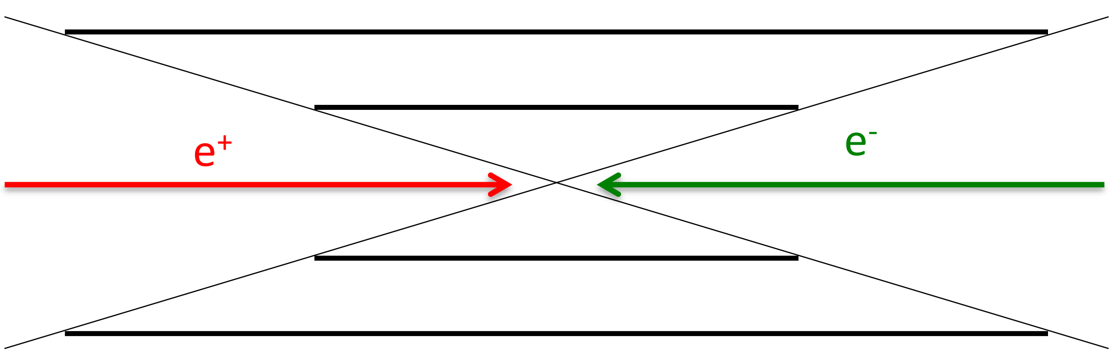
Impact on Vertex Detector

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





Need a certain angular coverage

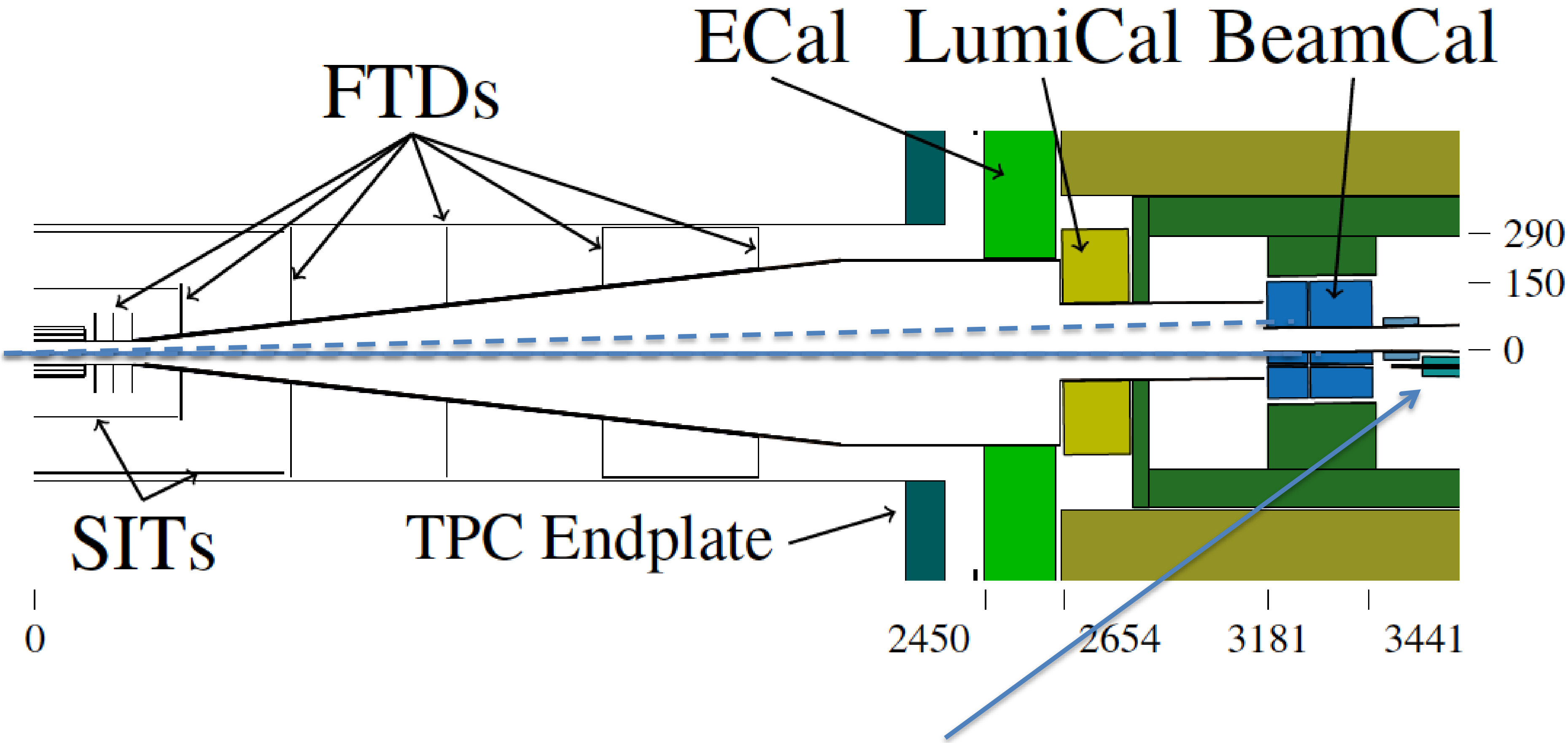


Hit density from pairs depends on radius and field

Edge is due to beam-beam deflection

Limit O(1mm^{-2})

CLIC Inner Detector Layout

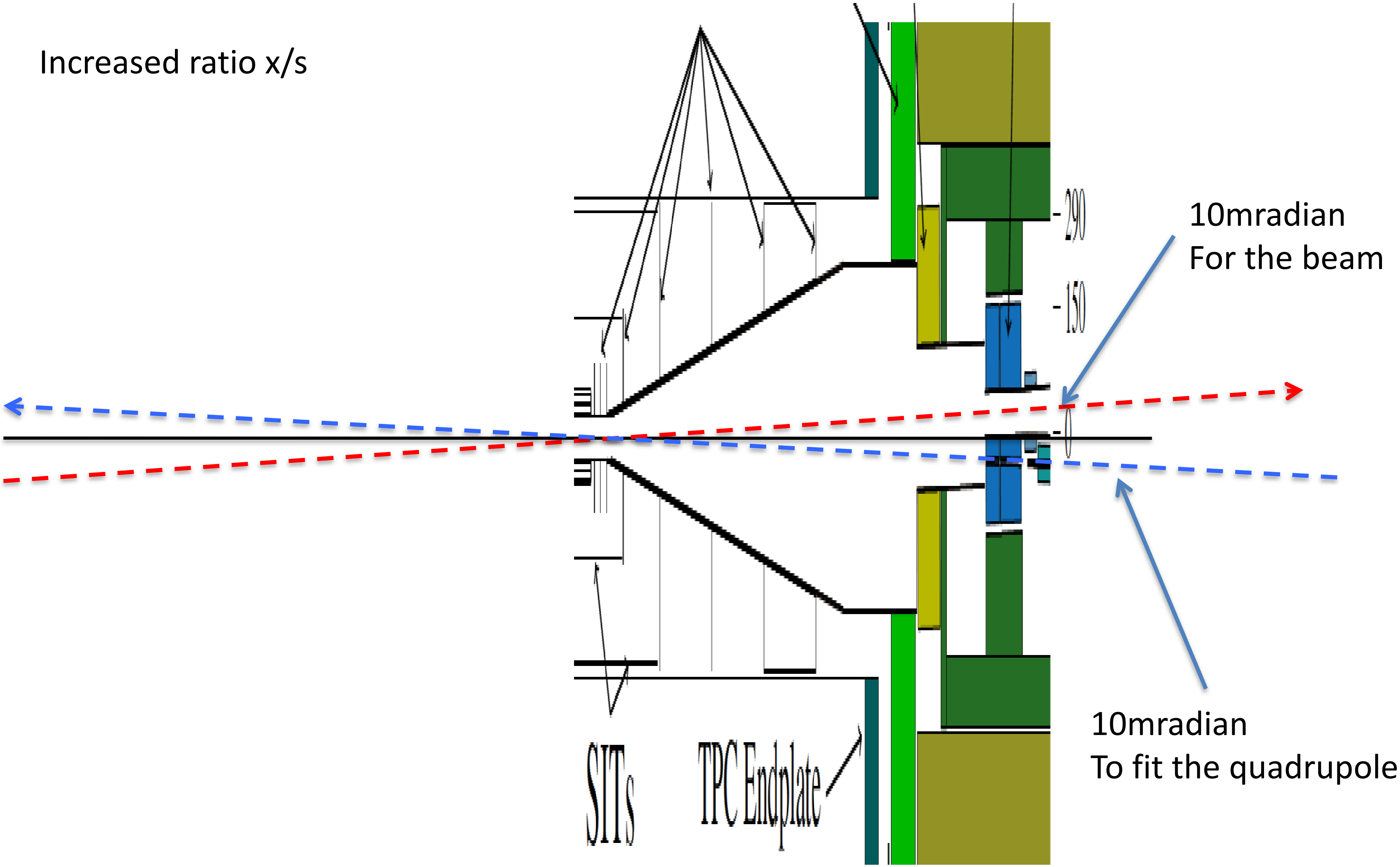


The last focusing magnet of the machine is inside of the detector

A. Seiler

CLIC Inner Detector Layout

Increased ratio x/s



ILC and CLIC Main Parameters

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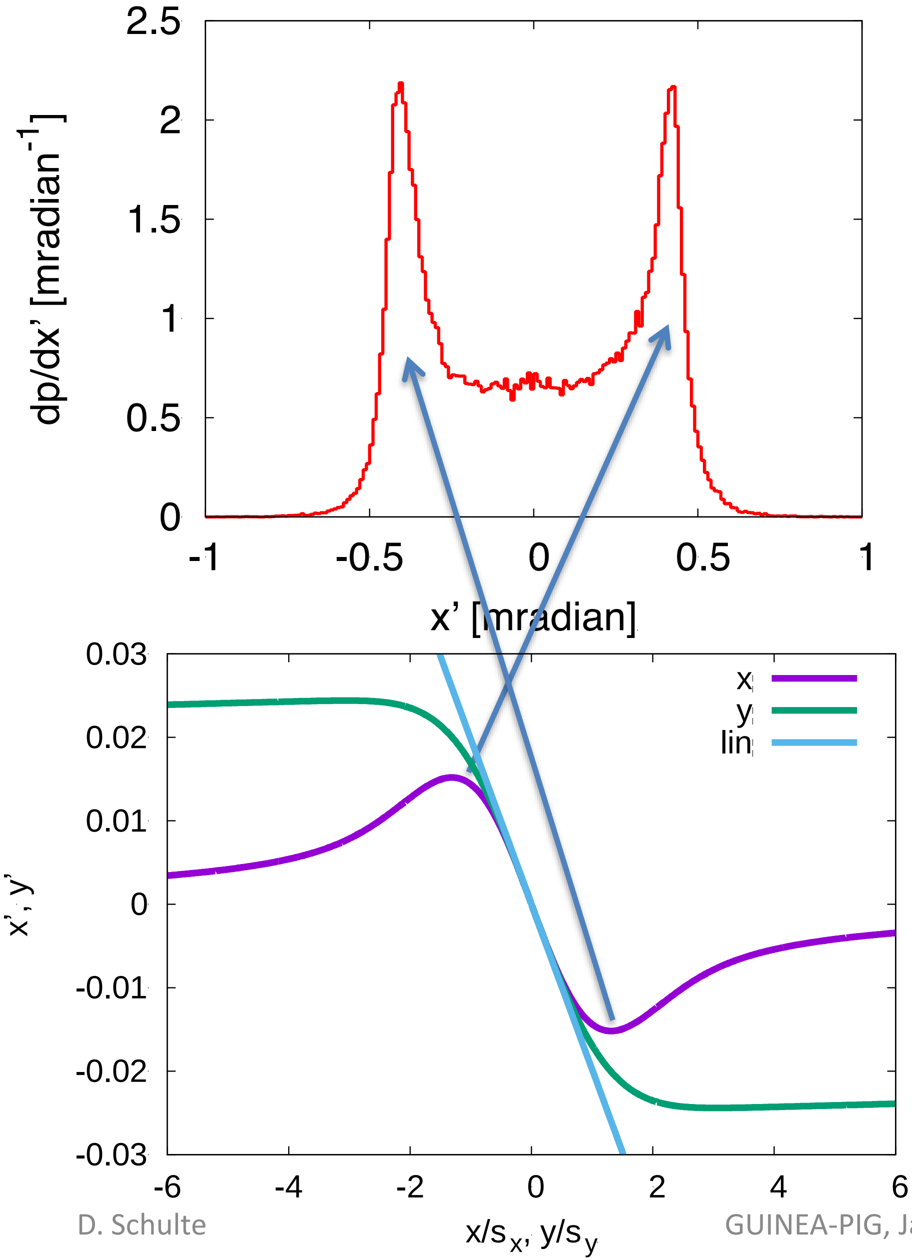
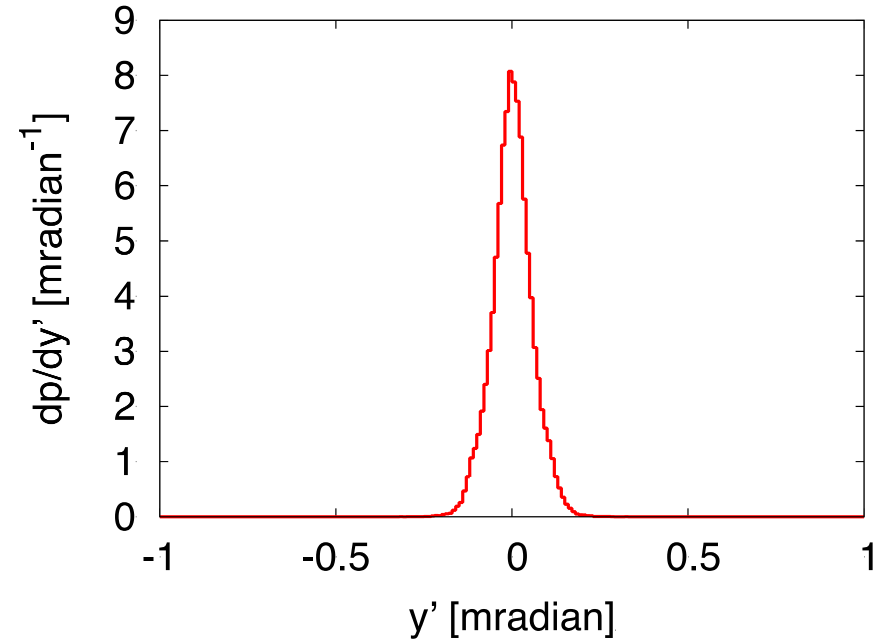
Particles per bunch	N [10^9]	20	5.2	3.72
Bunch length	σ_z [μm]	300	70	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	474/5.9	149/2.9	40/1
Vertical emittance	$\varepsilon_{x,y}$ [nm]	35	40	20
Photons per beam particle	n_γ	1.9	1.5	2.1
Average photon energy	$\langle E_\gamma/E_0 \rangle$ [%]	2.4	4.5	13
Coherent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

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

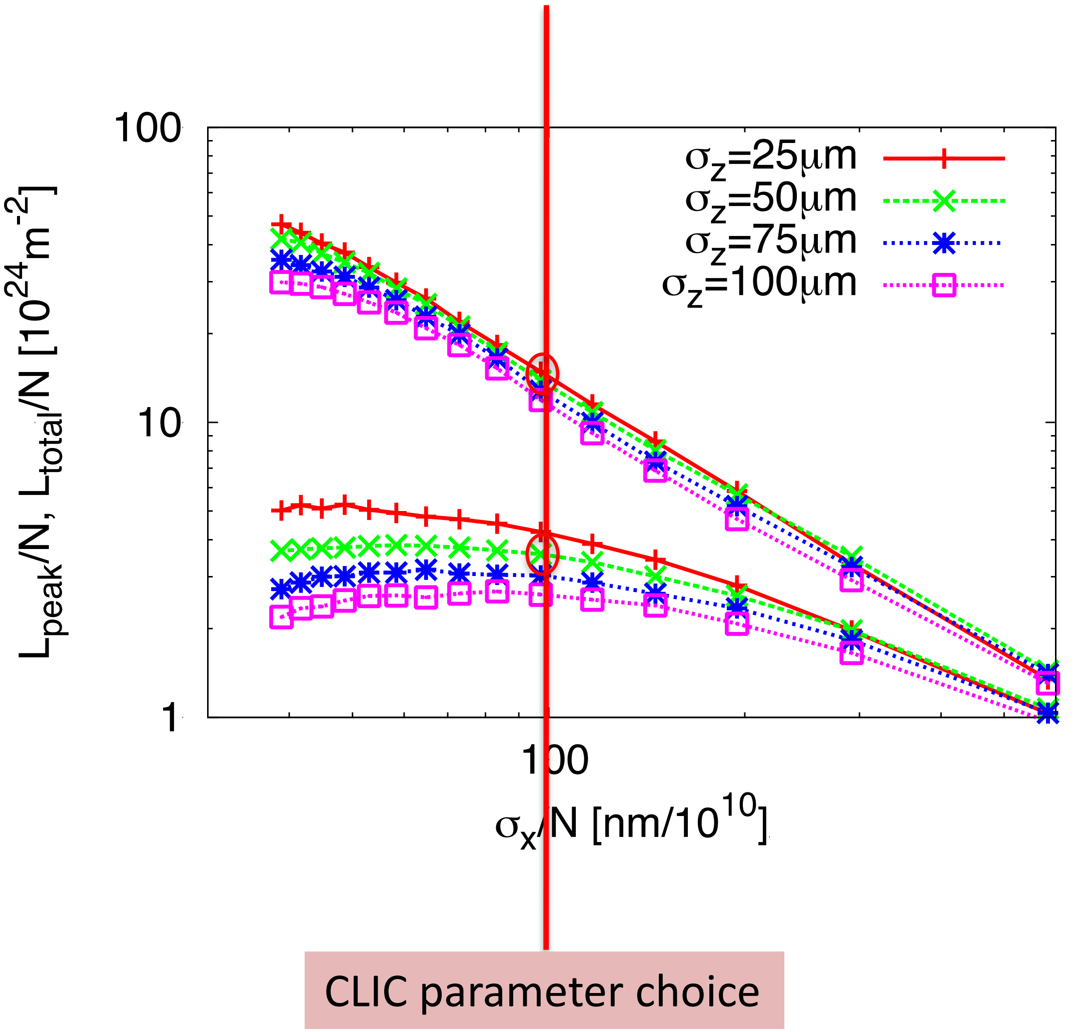
CLIC 3TeV Beamstrahlung

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

$$\Upsilon \gg 1$$

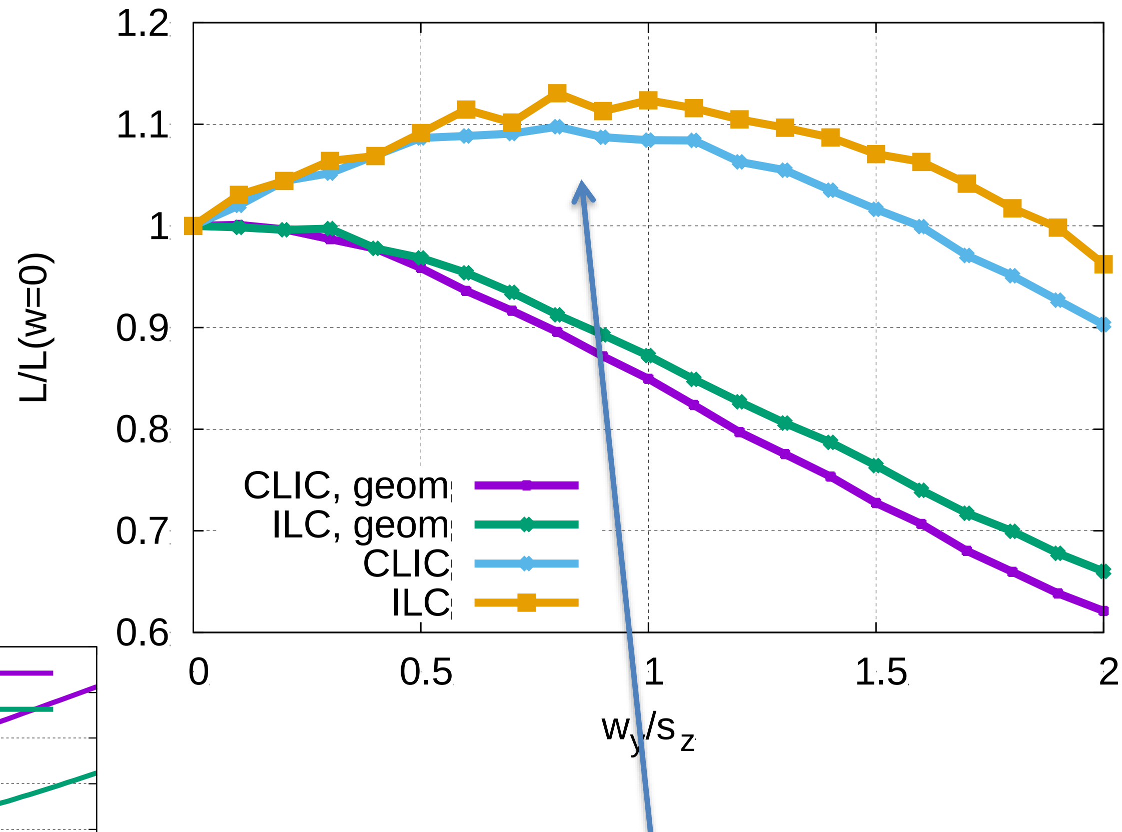
$$n_\gamma \propto \left(\frac{\sigma_z}{\gamma}\right)^{\frac{1}{3}} \left(\frac{N}{\sigma_x + \sigma_y}\right)^{\frac{2}{3}}$$

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

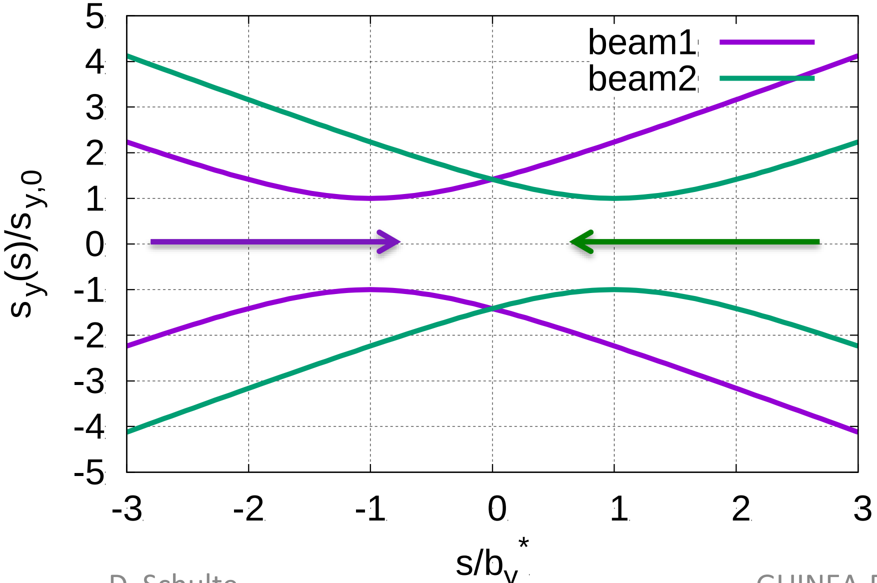


Waist Shift

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



For CLIC and ILC ~10% luminosity gain



FCC-eh

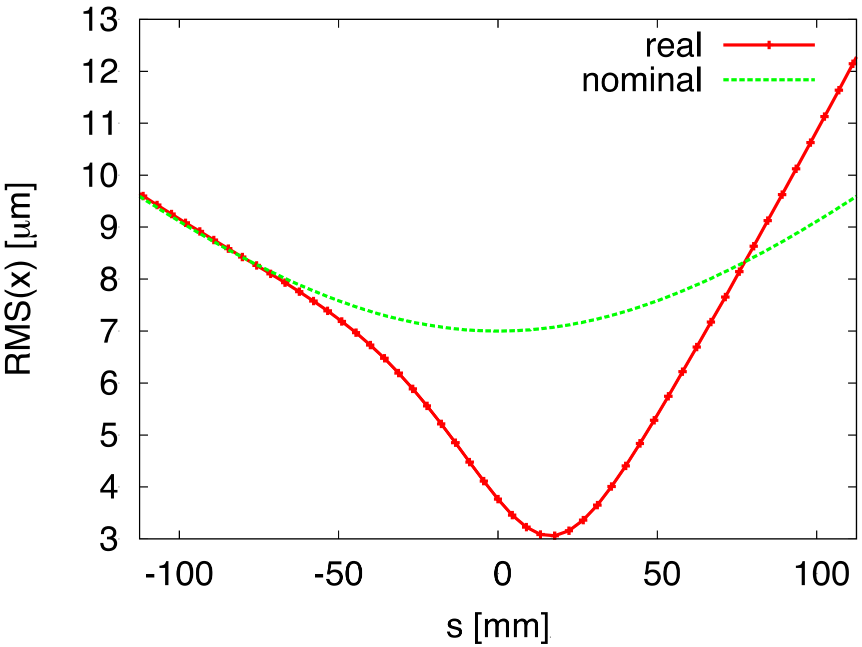
Do the electron and proton transverse beam sizes have to be matched?

In LHeC the sizes are not matched along the collision

- Strong pinching of electrons

⇒ Not obvious why beam sizes do need to match

⇒ Scan for optimum electron beam size and waist position



Electron beam shrinks during collision
Increases beam-beam tune shift for protons