Background and Machine Detector Interface

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Abstract

The compact linear collider study aims to establish the feasibility of constructing a linear electron positron collider with multi-TeV centre-of-mass energy. Due to the high energy and luminosity beam-beam effects at the interaction point are important. A short introduction is given into the beam-beam interaction and the dependence on beam parameters and the consequences for the parameter choice is discussed. The different constraints are detailed for the crossing angle between the two beam lines. Further the different background generation mechanisms are investigated and their impact on the detector design is detailed.

Acknowledgements

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Background and Machine Detector Interface

D. Schulte

- Luminosity and Spectrum
- Crossing Angle
- Background
- Masks etc.

- Lots of work had been done for the CLIC Physics Report

  need to get dust of different tools

  will put more emphasis on new calculations on demand

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Basic Parameters

- CLIC aims to achieve a luminosity similar to the ILC level at much higher energy

		CLIC	ILC	NLC
E_{cms}	$[TeV]$	3.0	0.5	0.5
f_{rep}	$[\mathrm{Hz}]$	50	5	120
N	$[10^9]$	3.7	20	7.5
ϵ_y	$[nm]$	20	40	40
L_{total}	$10^{34} cm^{-2} s^{-1}$	5.9	2.0	2.0
$L_{0.01}$	$10^{34} cm^{-2} s^{-1}$	2.0	1.45	1.28
n_γ		2.2	1.30	1.26
$\Delta E/E$		0.29	0.024	0.046

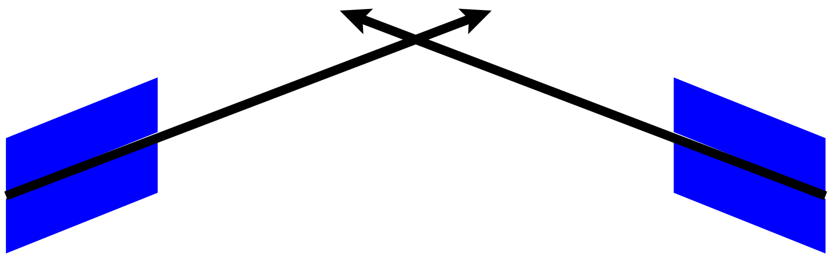
- Luminosity is delivered in 50 pulses per second
- Each pulse lasts about $150\,\mathrm{ns}$, contains 312 bunches spaced by $0.5\,\mathrm{ns}$
- In ILC luminosity is delivery by pulses with 5 Hz
- Each pulse is about $1\,\mathrm{ms}$ long

$\Rightarrow$ Very different regime

- event reconstruction
- background conditions

- High energy also affect background level

Interaction Point Layout



- Distance L^* between final quadrupole and interaction point can be chosen
  - below $3.5\,\mathrm{m}$ luminosity is compromised (R. Tomas)
  - $4.3\,\mathrm{m}$ and $3.5\,\mathrm{m}$

  yield similar luminosity

- Design of final doublet is challenging
  - high gradient required
  - support needs to be very stable

    detectors can be quite noisy
  - a permanent magnet design has been done (S. Russenschuck et al.)
  - but energy adjustment of beam delivery system is limited
  - superconducting quadrupoles are very though

    in particular stability
  - but would allow energy adjustment
  - maybe a combined approach is possible

Luminosity and Luminosity Spectrum

- Four main sources of energy spread at the IP

  - initial state radiation

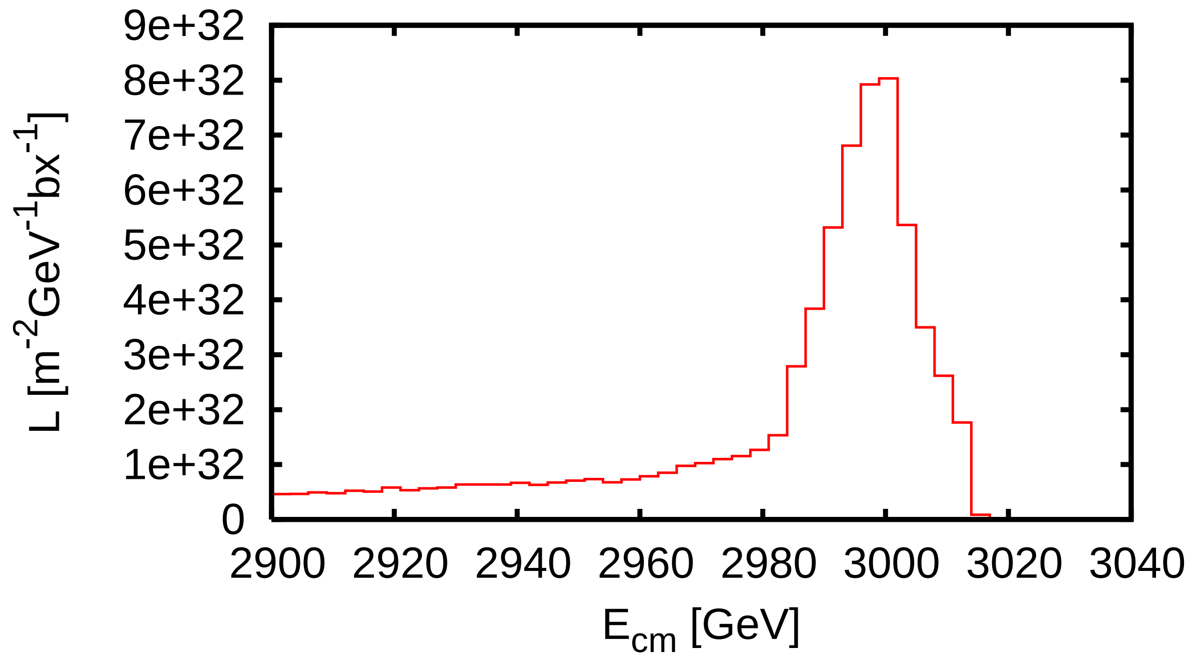
    $\Rightarrow$ unavoidable

    $\Rightarrow$ has sharp peak

  - beamstrahlung

    $\Rightarrow$ similar shape as ISR

    $\Rightarrow$ can be reduced by reducing luminosity



- single bunch energy spread

  due to single-bunch beam loading and RF curvature

  $\Rightarrow$ part cannot be avoided

  $\Rightarrow$ helps in stabilising the linac

  $\Rightarrow$ $\mathcal{O}(1\,\%)$ (better for ILC)

  $\Rightarrow$ now included in simulation

- bunch-to-bunch and pulse-to-pulse variations

  $\Rightarrow$ $\mathcal{O}(0.1\,\%)$

Impact of Luminosity Spectrum

- Reduced production in a resonance

  $\Rightarrow$ effectively reduced luminosity
- Impact on threshold scans

  $\Rightarrow$ modified effective cross section, step is less steep
- Two-peak separation

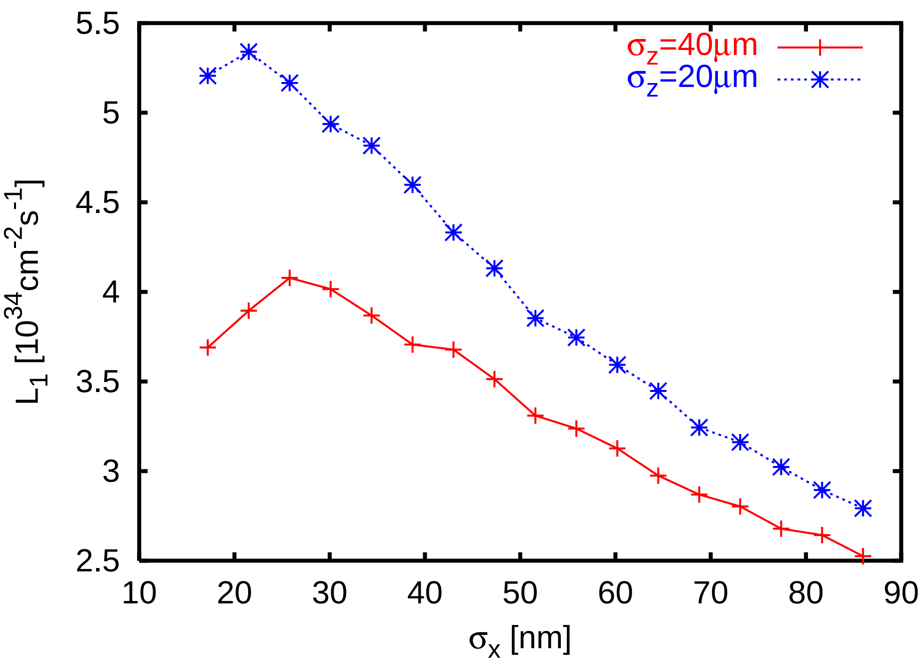
  $\Rightarrow$ mainly due to single bunch energy spread
- Missing mass analysis

  $\Rightarrow$ initial conditions are wrong
- Impact on constraint fits

  $\Rightarrow$ initial conditions are wrong
- Difficulty in spectrum reconstruction

  $\Rightarrow$ important value not directly measured, correlations are important

Beamstrahlung and Luminosity Optmisation

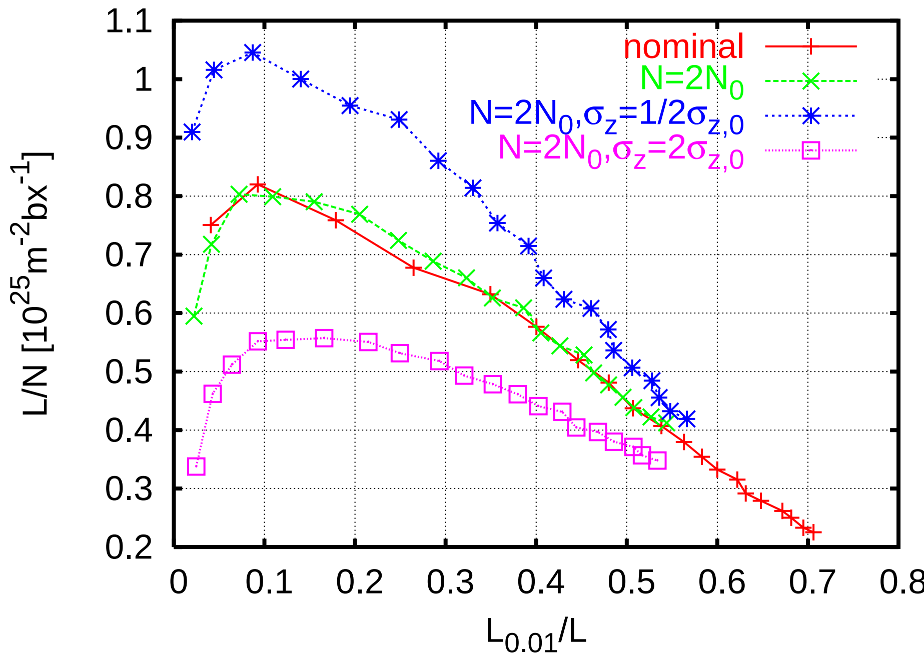


Total luminosity for $\Upsilon \gg 1$

$$\mathcal{L} \propto \frac{N}{\sigma_x}\frac{\eta}{\sigma_y} \propto \frac{n_\gamma^{3/2}}{\sqrt{\sigma_z}}\frac{\eta}{\sigma_y}$$

large $n_\gamma \Rightarrow$ higher $\mathcal{L} \Rightarrow$ degraded spectrum

$$\mathcal{L}_{0.01} \propto \frac{(1-\exp(-n_\gamma))^2}{\sqrt{n_\gamma}}\frac{\eta}{\sqrt{\sigma_z}\sigma_y}$$



chose n_γ, e.g. maximum $L_{0.01}$ or $L_{0.01}/L = 0.4$ or ...

$$\mathcal{L}_{0.01} \propto \frac{\eta}{\sqrt{\sigma_z}\sigma_y}$$

Reduction of Incoming Energy Spread

- Bunch-to-bunch and pulse-to-pulse variations should be limited to about 0.1% RMS

  $\Rightarrow$ already difficult to achieve

  $\Rightarrow$ a reduction would have enormous impact on machine design

- Intra-bunch energy spread can be reduced by reducing the bunch charge

  $\Rightarrow$ change is always relative to the optimum choice for a given accelerating structure

- Currently optimise for 0.35% RMS energy spread

  $\Rightarrow$ seem to be able to reach 0.1% with $N = 0.5N_0$

  $\Rightarrow$ full test of beam stability required

  - luminosity L_1 is reduced to about 30%

  - beamstrahlung is also reduced

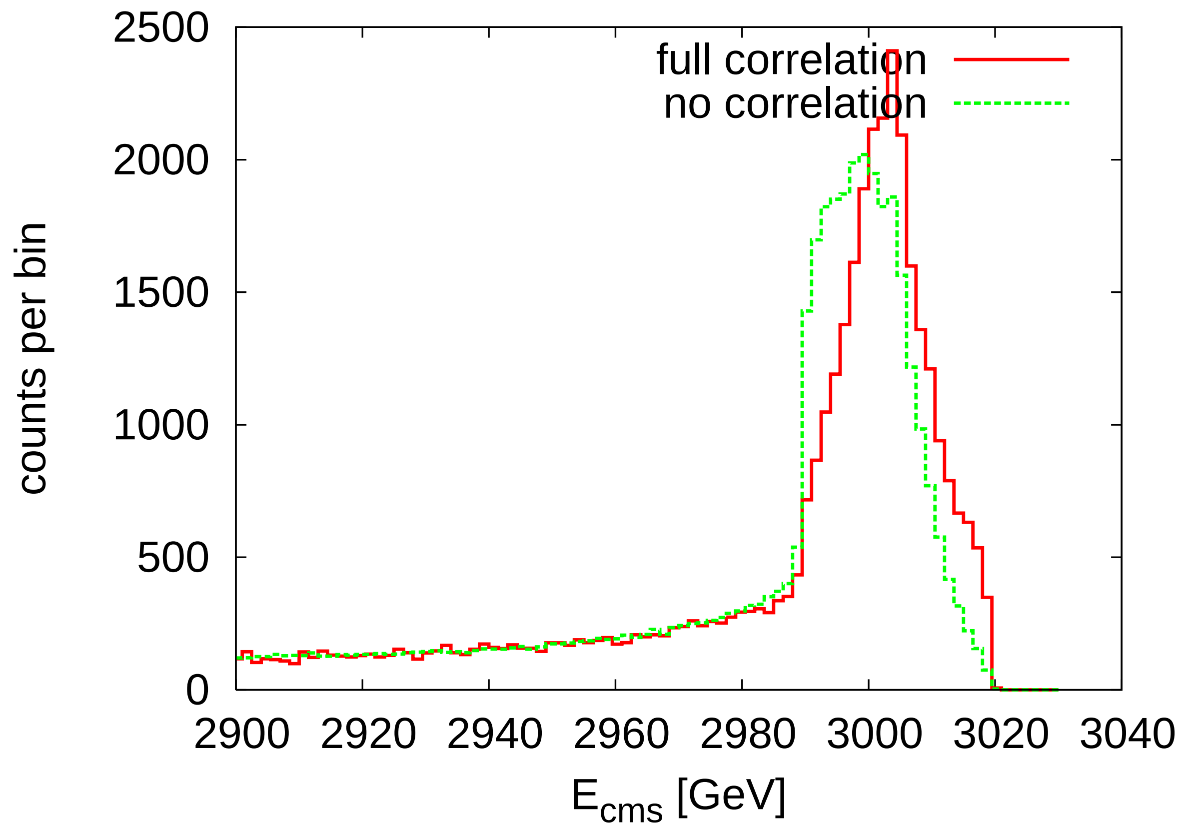
Luminosity Spectrum Reconstruction

- Luminosity Spectrum reconstruction is a challenging task
- One proposed method is to measure Bhabha angles

$$p_{\perp,1} = -p_{\perp,2} \quad \Rightarrow \quad \frac{p_1}{p_2} = \frac{\sin\theta_2}{\sin\theta_1}$$

- Initial transverse momenta could be different
  - is noticeable in ILC

  $\Rightarrow$ needs to be studied for CLIC



- Need model to seperate the beams
- Simple test remix colliding beam particle energies

  $\Rightarrow$ different spectrum

  $\Rightarrow$ correlations are important

$\Rightarrow$ Further study needed

Background Sources

- Machine produced background before IP

  beam tails from linac

  synchrotron radiation

  muons

  beam-gas, beam-black body radiation scattering (linac+BDS)

- beam-beam background at IP

  beamstrahlung

  coherent pair creation

  incoherent pair creation

  hadron production

  neutrons

- spent beam background

  backscattering of particles

  especially neutrons

Crossing Angle

- Three main constraints on crossing angle exist
  - extraction of the spent beams without excessive losses
    lower limit
  - multi-bunch kinck instability
    lower limit
  - synchrotron radiation emission in the detector solenoid field
    upper limit
- Simplified simulations of the effect of synchrotron radiation in a detector field of $B_z = 4\,\mathrm{T}$ required (F. Zimmermann)

$$\theta_c \leq 20\,\mathrm{mradian}$$

$\Rightarrow$ this study needs to be repeated with more realistic fields

- The multi-bunch kinck instability is given by

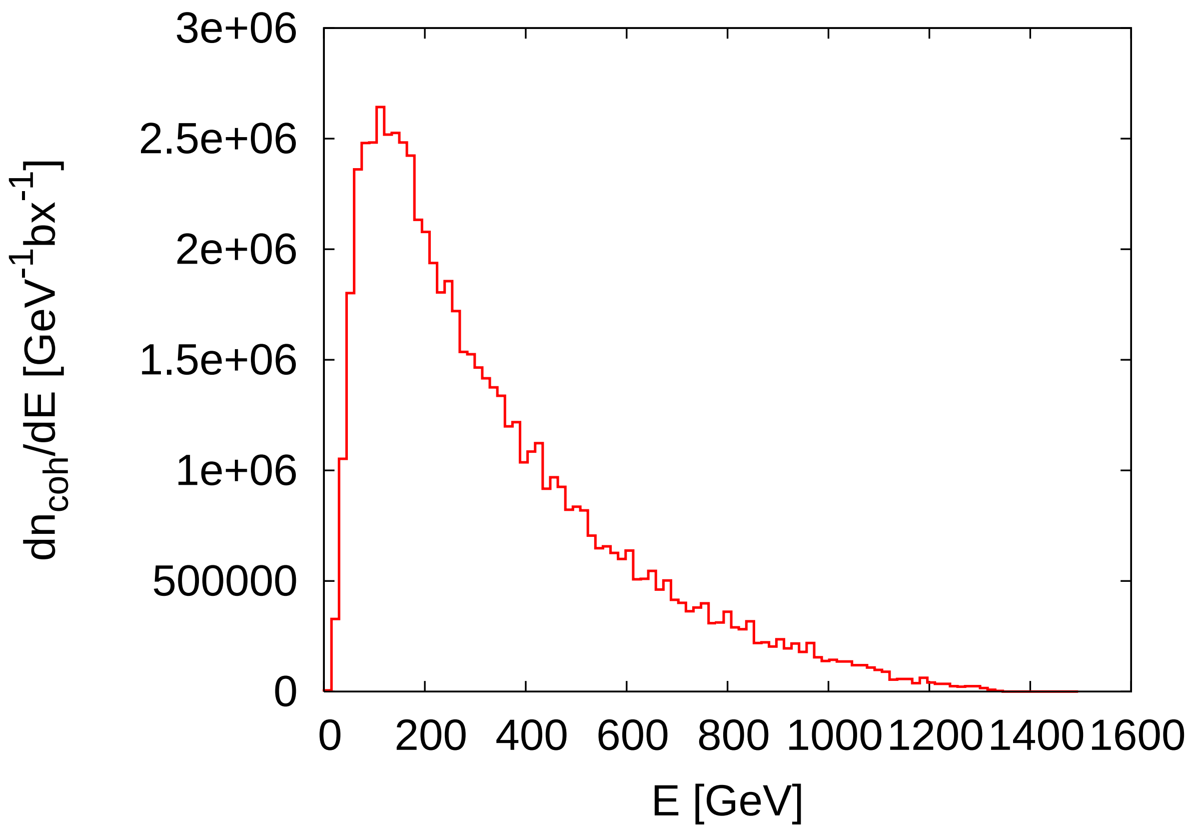
$$\Delta y = \frac{\Delta y_0}{1 - n_c \frac{4 N r_e}{\gamma \theta_c^2} \frac{\delta y'}{\delta \Delta y_0}}$$

Coherent Pairs

- Coherent pairs are generated by a photon in a strong electro-magnetic field
- Cross section depends exponentially on the field

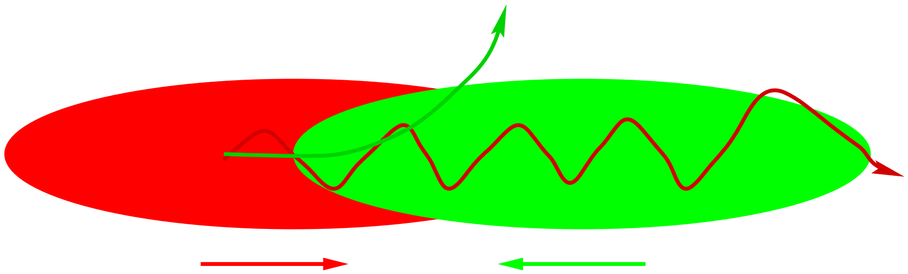
⇒ Rate of pairs is small for centre-of-mass energies below $1\,\mathrm{TeV}$

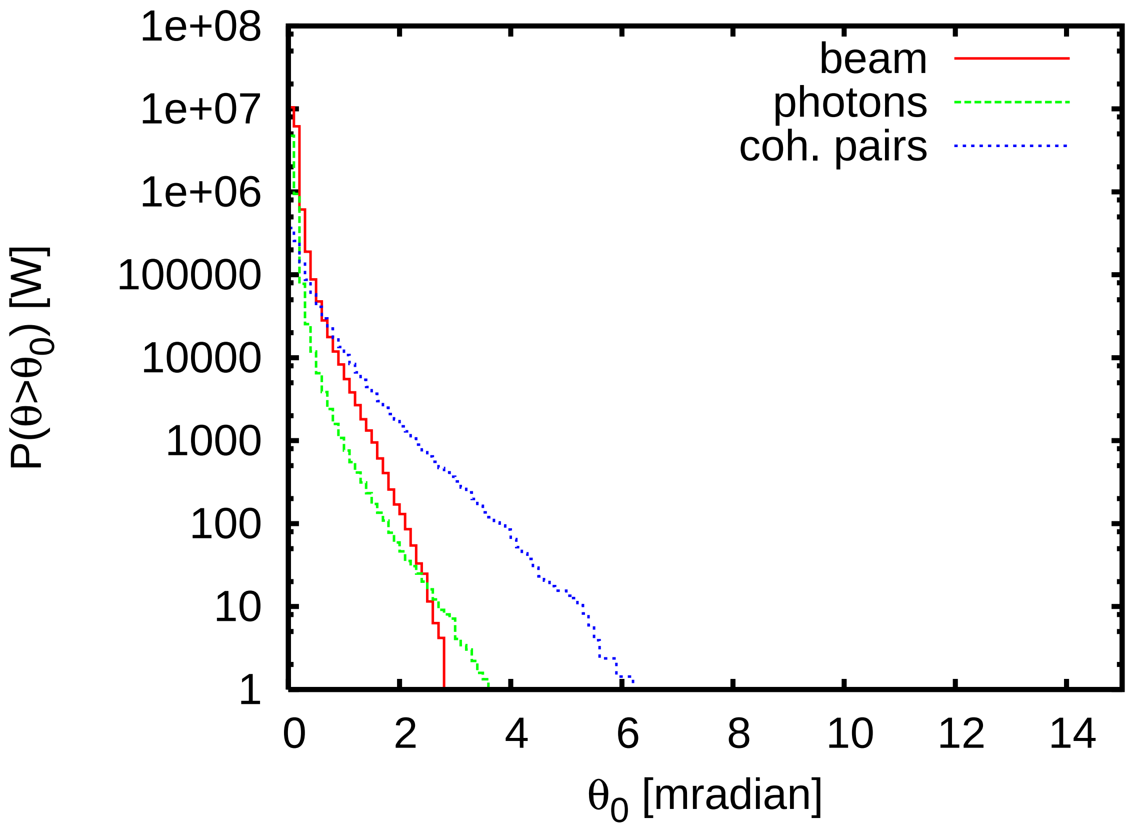
⇒ In CLIC, rate is substantial



Need to foresee large enough exit hole (about 10mradian)

Spent Beam and Crossing Angle





- Crossing angle needs to be large enough to extract spent beam
- For new parameters we need 10mradian angle
  - plus space for quadrupole (2cm in an old design)

$\Rightarrow$ 20 $\mathrm{mradian}$ seems OK

- Somewhat smaller angles seem feasible
  - maybe 14 $\mathrm{mradian}$

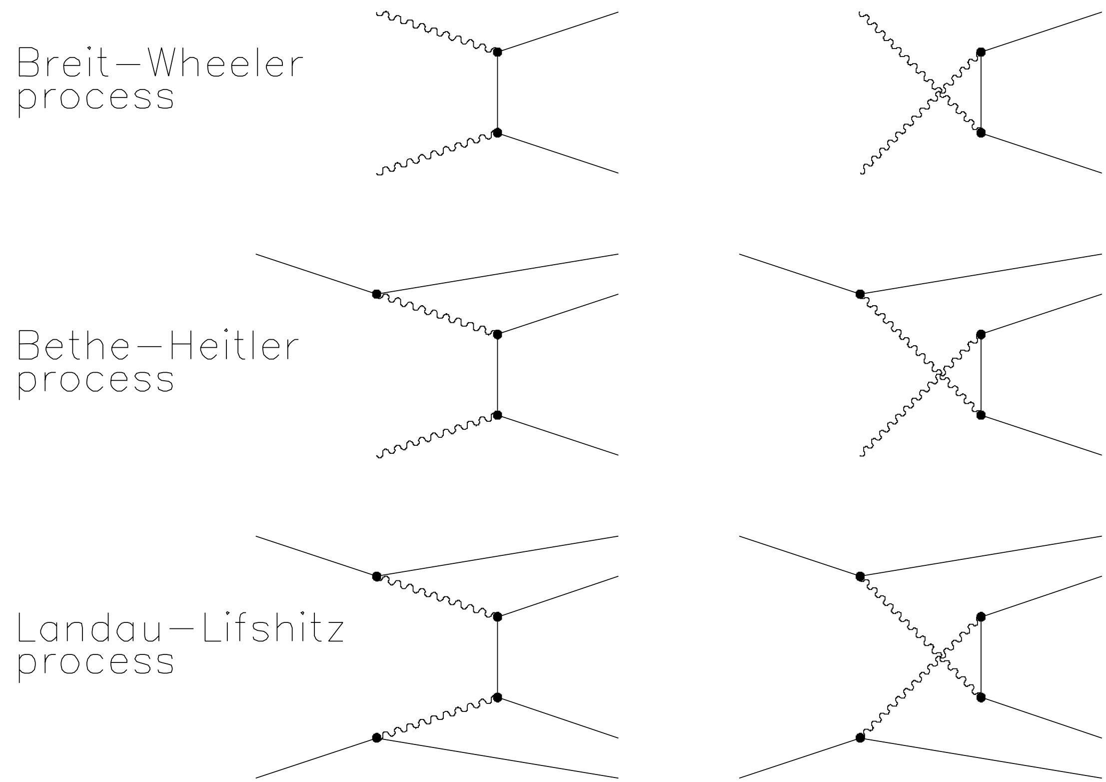
Incoherent Pair Production

Three different processes are important

- Breit-Wheeler
- Bethe-Heitler
- Landau-Lifshitz

The real photons are beamstrahlung photons

The processes with virtual photons can be calculated using the equivalent photon approximation and the Breit-Wheeler cross section



Deflection by the Beams

Most of the produced particles have small angles

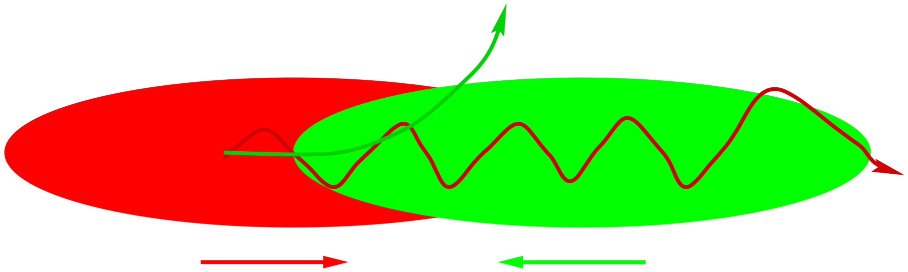
The forward or backward direction is random

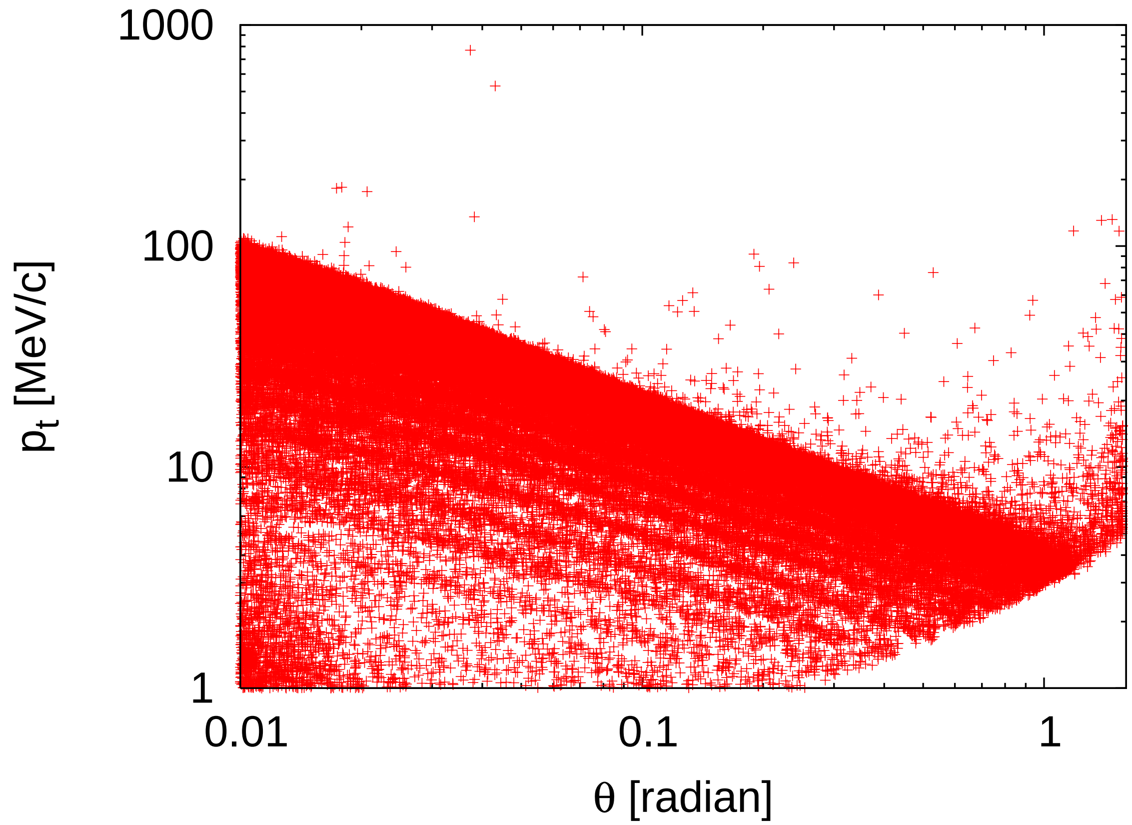
The pairs are affected by the beam

$\Rightarrow$ some are focused some are defocused

Maximum deflection

$$\theta_m = \sqrt{4\frac{\ln\left(\frac{D}{\epsilon}+1\right) D\sigma_x^2}{\sqrt{3}\epsilon\sigma_z^2}}$$





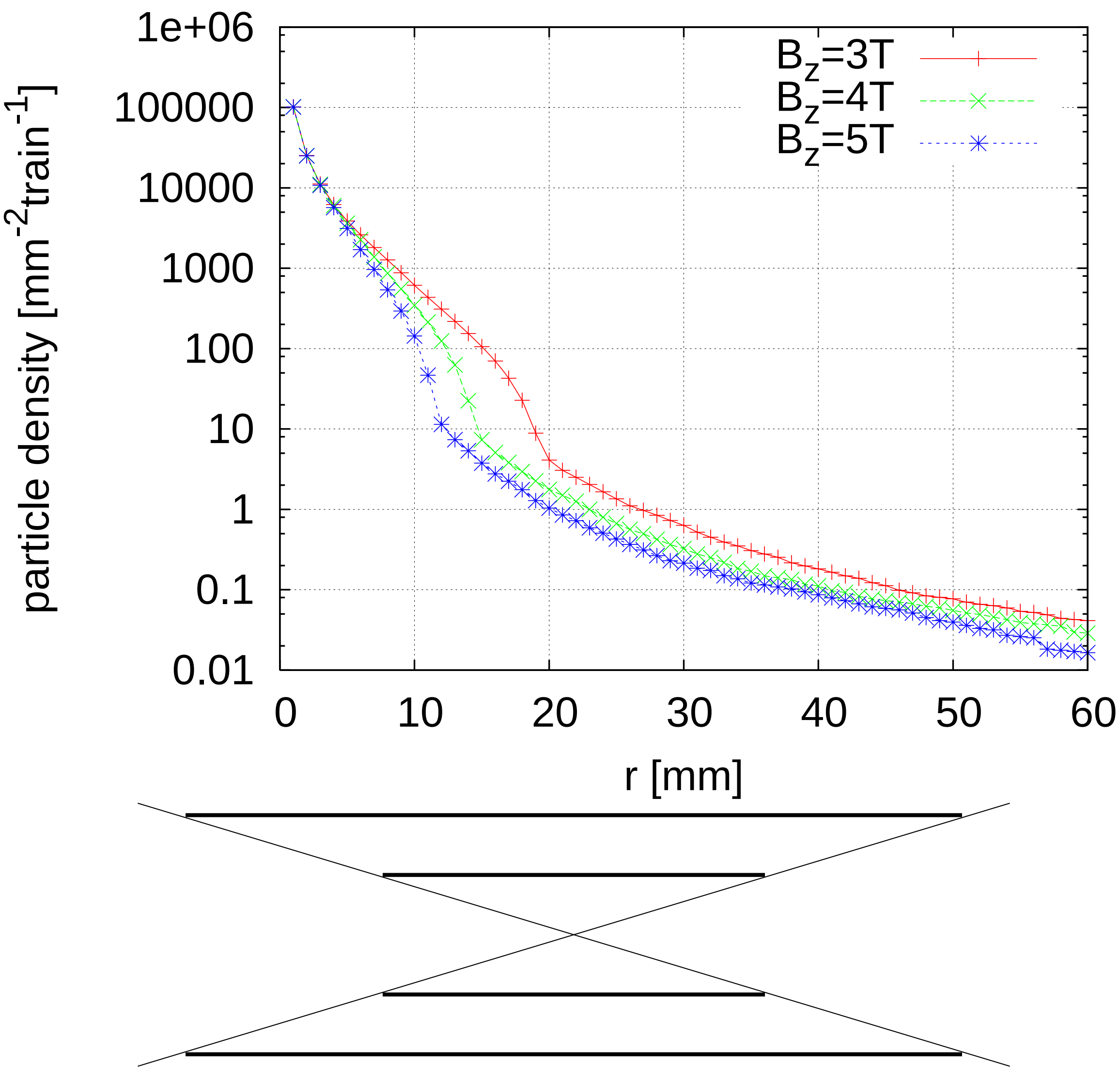
Impact of the Pairs on the Vertex Detector

- Simplified study using simple cylinder without mass
  - coverage is down to $200\,\mathrm{mradian}$
- Simulating number of particles that hit at least once
  - experience indicates that number of hits is three per particle
  - but needs to be done with real detector parameters

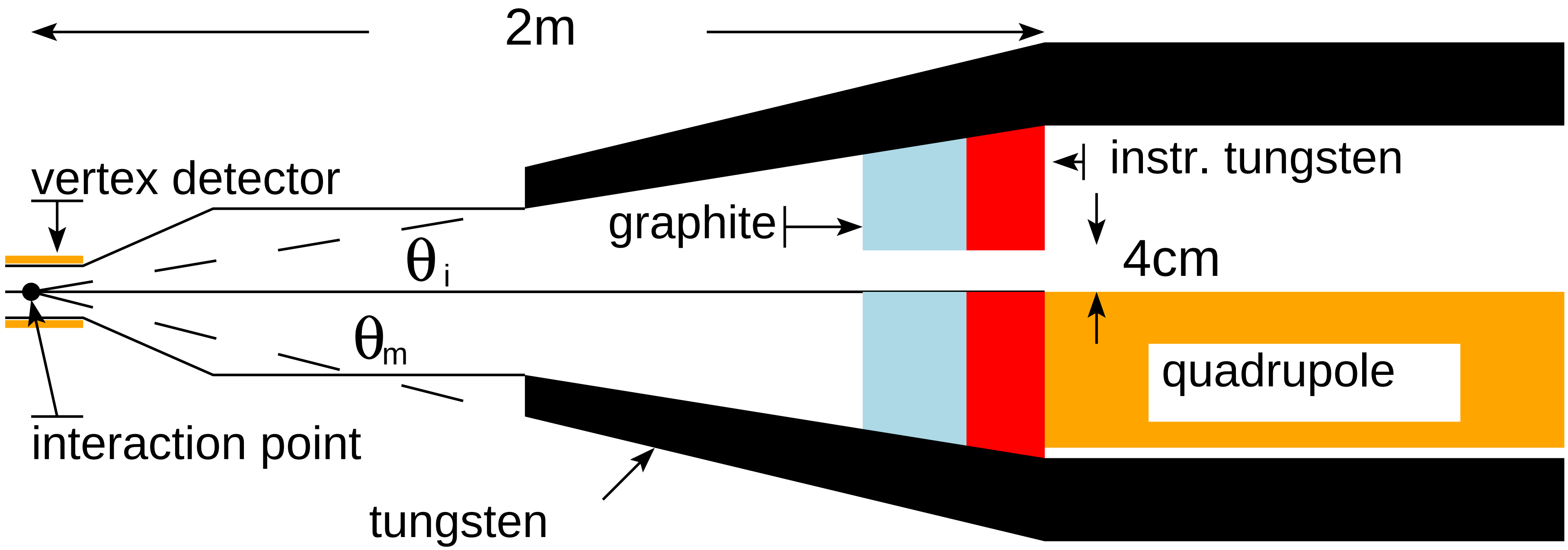
⇒ At $r_1 \approx 30\,\mathrm{mm}$ expect 1 hit per train and mm^2

⇒ Detector should be a bit larger

  - but depends on technology



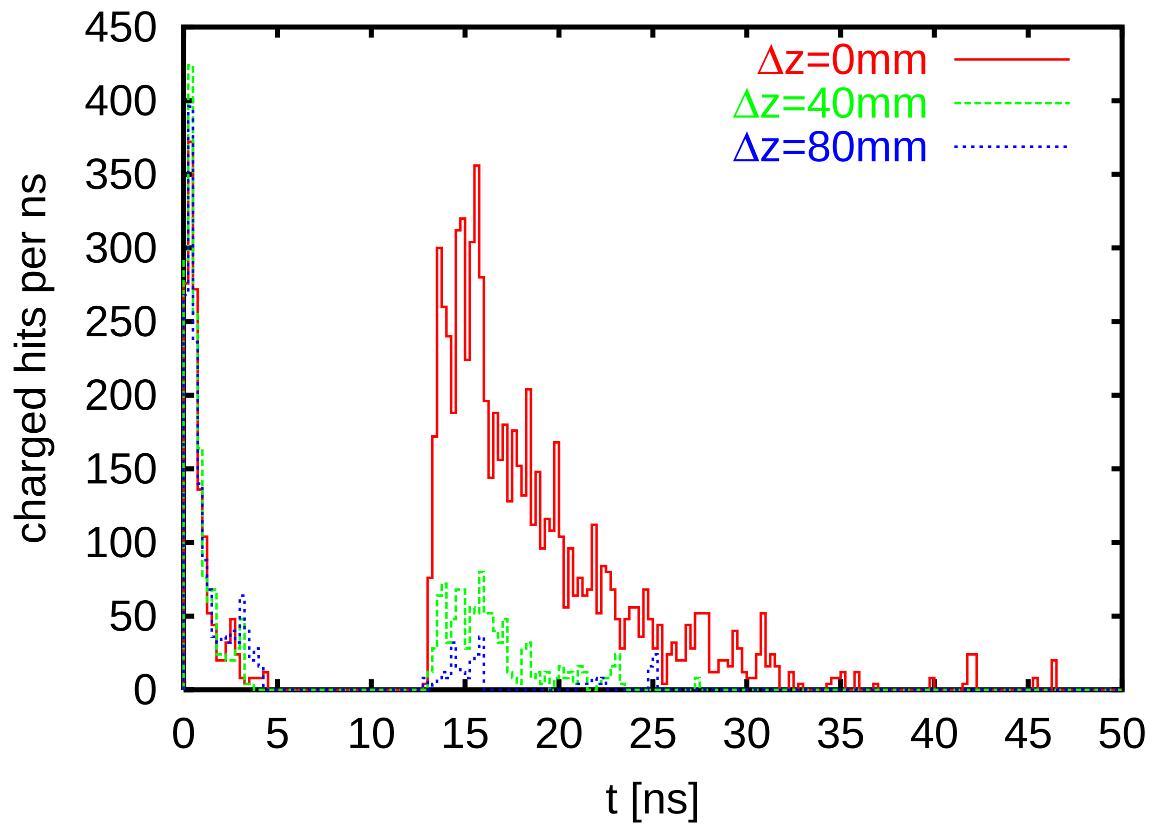
Mask Design



- Current CLIC design corresponds to old TESLA design
  - improvement is possible
  - quadrupole can be further out
- Outer mask suppresses backscattered photons
  - maybe less coverage would be sufficient
- Inner mask prevents backscattering of charged particles
  - distance needs to be small enough that exit hole is smaller than vertex detector

Inner Mask

- Low-Z material reduces backscattering
  - it allows electrons and positrons to penetrate with small probability of scattering
  - it reduces energy of backscattered charged particles via ionisation
- Required thickness is about $10\,\mathrm{cm}$

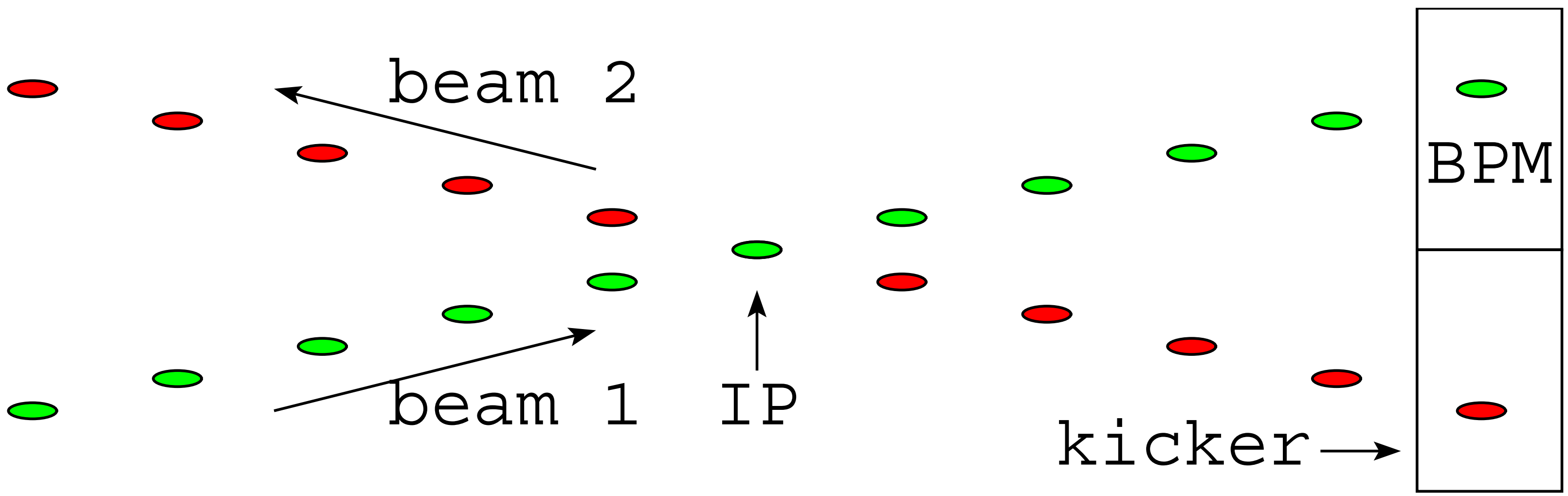


- But hole overlaps with vertex detector

$\Rightarrow$ could have backscattering through the hole, if not careful

Intra-Pulse Interaction Point Feedback

- Reduction of jitter is dominated by feedback latency
  - IP to BPM
  - electronics
  - Kicker to IP
- Assuming 40 ns one can hope for about a factor 2
- Only cures offsets



Hadronic Background

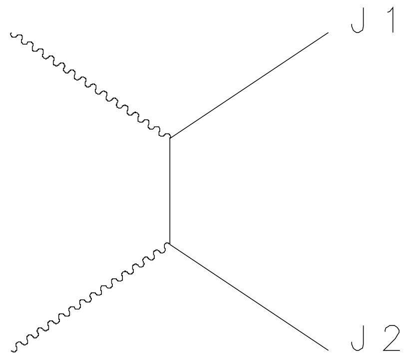
A photon can contribute to hadron production in two ways

- direct production, the photon is a real photon
- resolved production, the photon is a bag full of partons

Hard and soft events exist

e.g. “minijets”

a)



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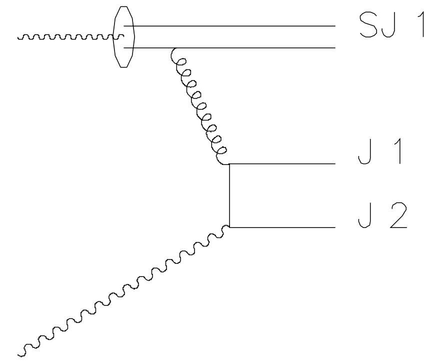

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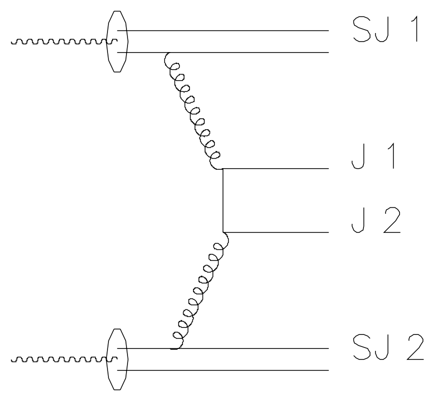
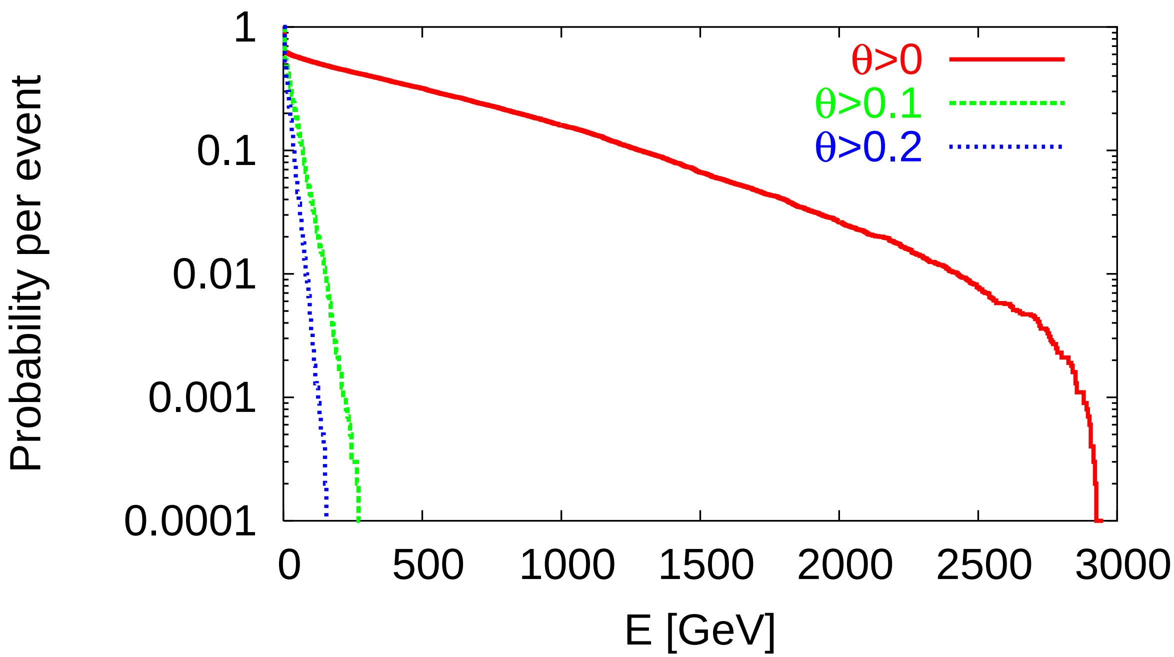


Hadronic Events

- Hadronic events with $W_{\gamma\gamma} \geq 5\,\mathrm{GeV}$
- Most energy is in forward/backward direction
  - $E_{vis} \approx 450\,\mathrm{GeV}$ per hadronic event for no cut
  - $E_{vis} \approx 23\,\mathrm{GeV}$ for $\theta > 0.1$
  - $E_{vis} \approx 12\,\mathrm{GeV}$ for $\theta > 0.2$
  - 20% from e^+e^- (cannot be reduced)



- Charged tracks from hadronic events add about 20% to the charged hits in the vertex detector
- Secondary nuetron flux can be noticeable

Low Energy Parameters

- First approach is to use $3\,\mathrm{TeV}$ performance assumptions
  - yields high performance
- Alternative is to assume already demonstrated performaces, where possible
  - more conservative first step
- One could reoptimise for lower energies

  $\Rightarrow$ would yield optimum performance

  $\Rightarrow$ but would need strong motivation by physics case

E_{cms}	$[\mathrm{TeV}]$	0.5	0.5	0.5	1.0	1.0	1.0
ϵ_x	$[\mu\mathrm{m}]$	4.0	4.0	0.66	4.0	4.0	0.66
ϵ_y	$[\mathrm{nm}]$	40	30	20	40	30	20
L_{total}	$[10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	0.26	0.305	1.12	0.515	0.62	2.25
$L_{0.01}$	$[10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	0.21	0.25	0.68	0.37	0.445	1.08

- Assumed $f_r = 50\,\mathrm{Hz}$

Luminosity and Background Values

		CLIC	CLIC	CLIC	CLIC(vo)	ILC	NLC
E_{cms}	$[TeV]$	0.5	1.0	3.0	3.0	0.5	0.5
f_{rep}	[Hz]	100	50	50	100	5	120
N	$[10^9]$	3.7	3.7	3.7	4.0	20	7.5
ϵ_y	$[nm]$	20	20	20	10	40	40
L_{total}	$10^{34}cm^{-2}s^{-1}$	2.2	2.2	5.9	10.0	2.0	2.0
$L_{0.01}$	$10^{34}cm^{-2}s^{-1}$	1.4	1.1	2.0	3.0	1.45	1.28
n_γ		1.2	1.5	2.2	2.3	1.30	1.26
$\Delta E/E$		0.08	0.15	0.29	0.31	0.024	0.046
N_{coh}	10^5	0.03	37.0	3.8×10^3	?	—	—
E_{coh}	$10^3 TeV$	0.5	1080	2.6×10^5	?	—	—
n_{incoh}	10^6	0.05	0.12	0.3	?	0.1	n.a.
E_{incoh}	$[10^6 GeV]$	0.28	2.0	22.4	?	0.2	n.a.
$n_\perp$		12.5	17.1	45	60	28	12
n_{had}		0.14	0.56	2.7	4.0	0.12	0.1

- Target is to have about one beamstrahlung photon per beam particle
  - similar effect to initial state radiation

  $\Rightarrow$ average energy loss is larger in CLIC than ILC
- Note: shorter bunches increase the photon energy but not the number

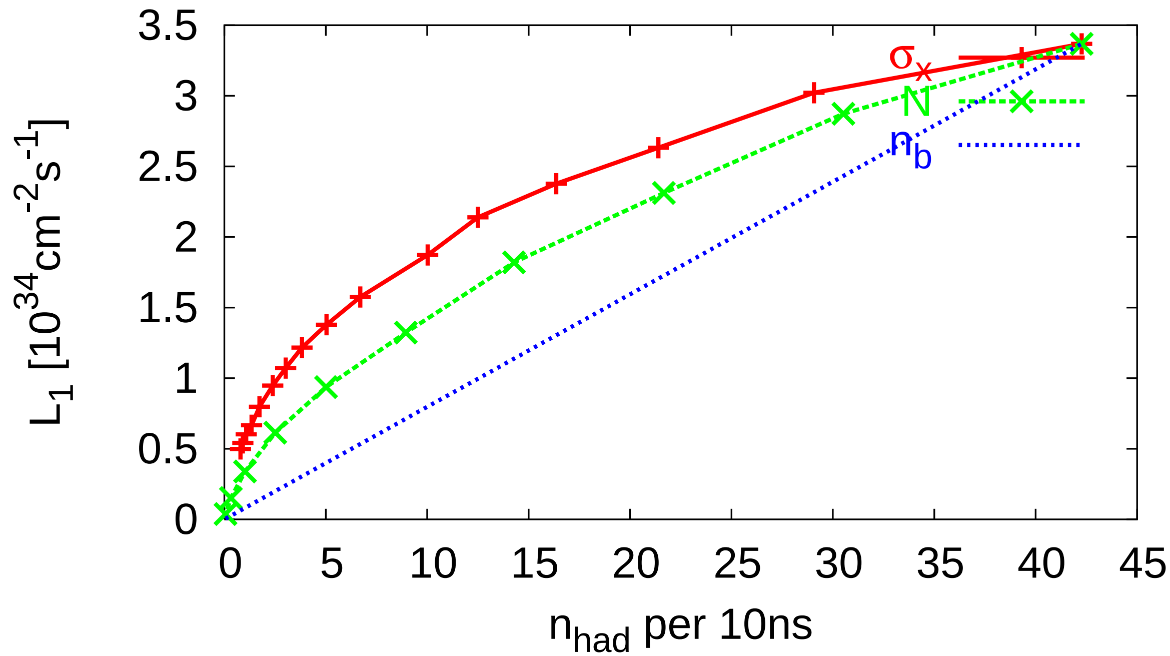
Background Reduction/Spectrum Improvement

- Larger distance Δz between bunches
  - $\Rightarrow L_{0.01} \propto 1/\Delta z \propto B(\delta t)$
  - $\Rightarrow B_{bx}$, $L_{0.01}/L_{total}$ remain constant
- Larger horizontal beam size σ_x
  - $\Rightarrow L_{0.01} \propto 1/\sigma_x$
  - $\Rightarrow B_{bx}$, $L_{0.01}/L_{total}$ improve
  - $\Rightarrow$ may ease focusing, but effect is likely small
- Reduced bunch charge N
  - $\Rightarrow L_{0.01} \propto N^2$
  - $\Rightarrow B_{bx}$, $L_{0.01}/L_{total}$ improve, better coverage
  - $\Rightarrow$ could improve beam dynamics
- Shorter pulse
  - $\Rightarrow L_{0.01} \propto n_b$
  - $\Rightarrow B_{bx}$, $L_{0.01}/L_{total}$ unchanged
  - $\Rightarrow$ reduces background per train

Hadronic Events

- Peak luminosity is shown as fuction of hadronic event rate in $10\,\mathrm{ns}$
- Older parameter set is being used

$\Rightarrow$ Best strategy is to increase horizonal beam size



Machine Background

Beam tails can produce background in the detector/ damage the machine

$\Rightarrow$ use collimation

synchrotron radiation before final doublet

$\Rightarrow$ collimation of photons

synchrotron radiation in final doublet

$\Rightarrow$ collimation of beam tails

muons due to beam loss (collimation)

$\Rightarrow$ distance

$\Rightarrow$ magnetised iron collimators

$\Rightarrow$ detector timing/granularity

beam scattering on black-body radiation

$\Rightarrow$ calculate (seems not a big problem sofar)

beam-gas scattering

$\Rightarrow$ improve vacuum (H. Burkhardt: $10^{-9}\,\mathrm{torr}$ to equal black body radiation)

Collimation System

- The collimation system removes particles with large transverse amplitudes or large energy errors
- It reduces the background in the detector and protects the machine
- To avoid that collimators are being destroyed a spoiler/absorber system is used
- The transverse collimation is determined by synchrotron radiation emission in the final doublet
- The design strategy has been
  - to make the energy collimation be failsafe
  - but not the betatron collimation
- This is based on the assumption that
  - energy errors can occour from pulse to pulse without a warning
  - betatron oscillations are mainly due to megnet failure which can be interlocked
- Large transverse kicks due to RF breakdowns in the main linac could create a problem

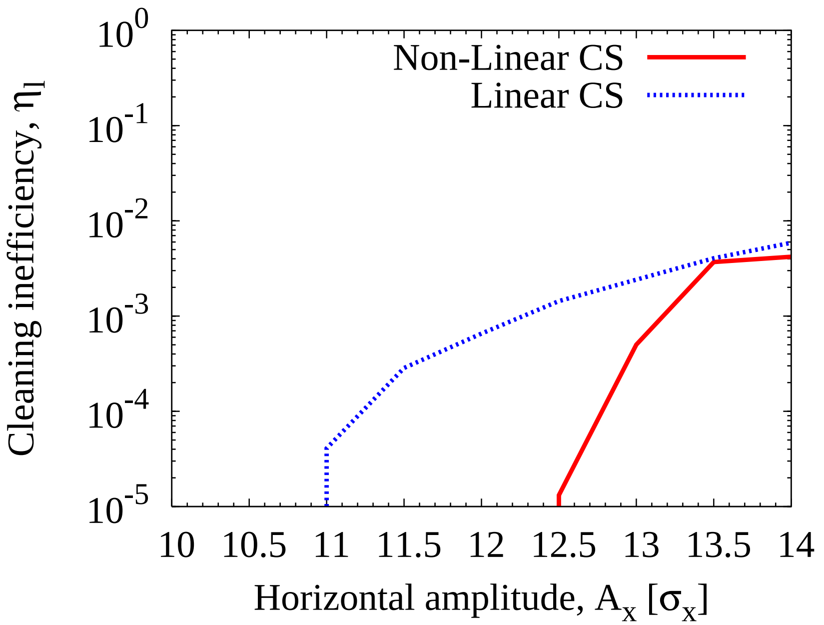
Collimation System Design

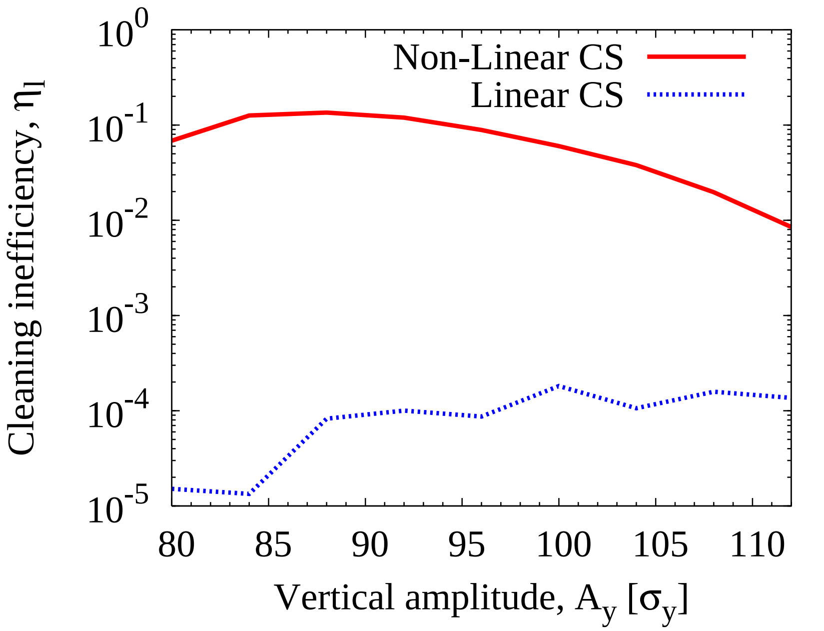
- Two systems have been studied (J. Resta Lopez)

  - a linear one

  - a non-linear one

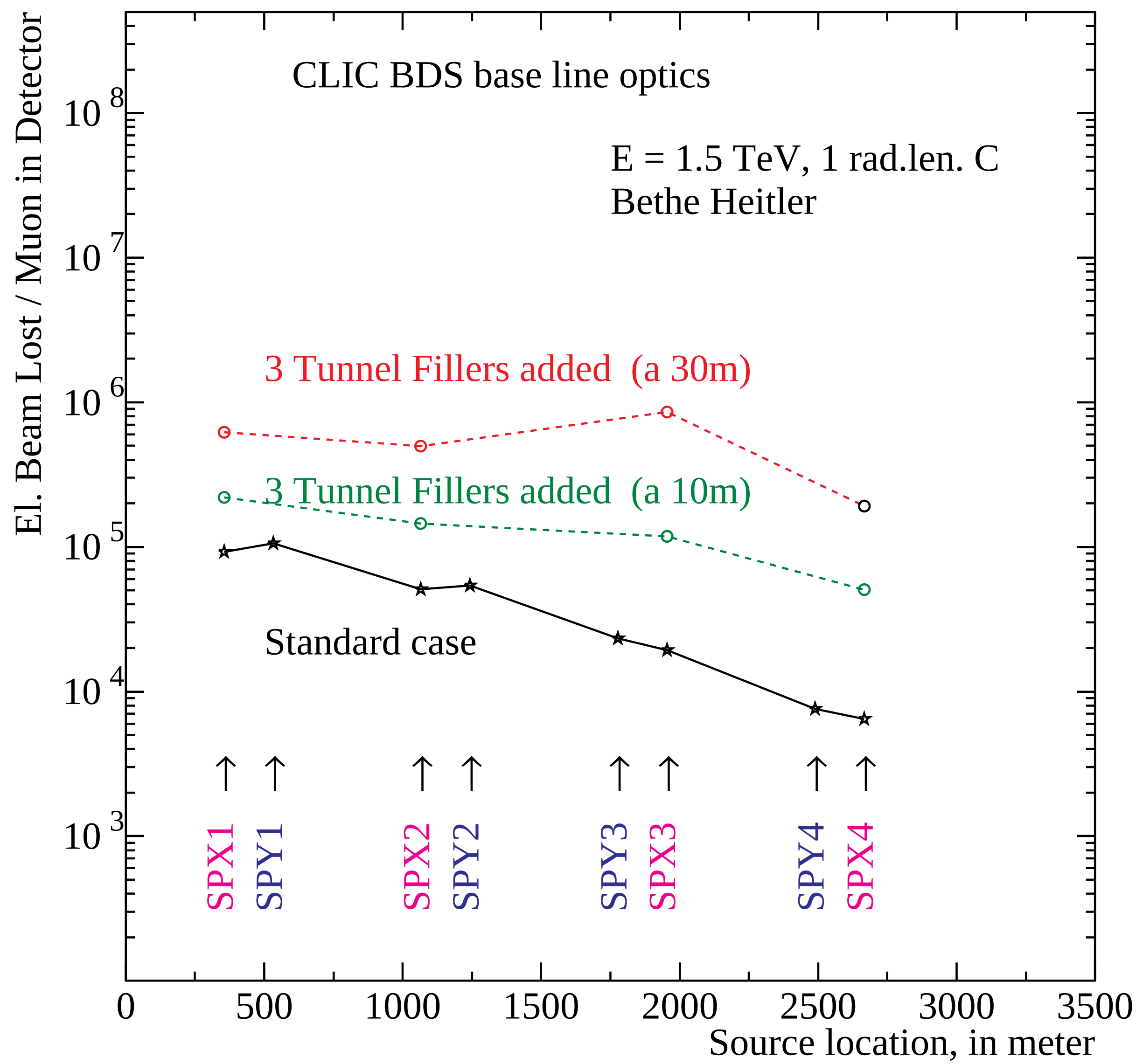
- Cleaning inefficiency can be quite good
- Linear system could be better than the non-linear one
- More detailed study of performance with imperfections appears useful





Muon Background

- Lost beam particles can generate secondary muons
  - Bethe-Heitler process (simulated)
  - production by photons in the shower
  - by hadronic processes
- Simulations performed with BDSIM (H. Burkhardt)
  - total muon rate expected to be twice larger
- Muons are hard to stop
- Potential means is use of tunnel fillers of magnetised iron
  - problems with tunnel access
  - high cost



Muon Rate

- Rate depends critically on assumption about beam halo
  - expect small values (some 10^{-4} for a vacuum pressure of $10\,\mathrm{ntorr}$, H. Burkhardt, needs more studies)
  - SLC experience has been bad (up to 0.01)
- For a beam halo of 10^{-3} we expect 5×10^4 muons per train in the detector
- Tunnel fillers can reduce this by an order of magnitude
- Better vacuum will help
  - beam stability requires very good vacuum
- But the detector will need to be able to cope with many muons
- Would follow ILC strategy
  - foresee place for tunnel fillers
  - but install them only if necessary

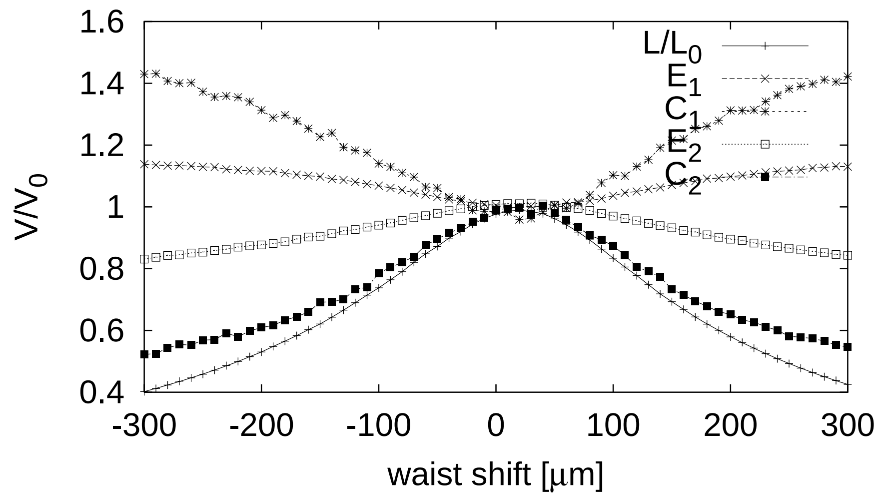
Tools

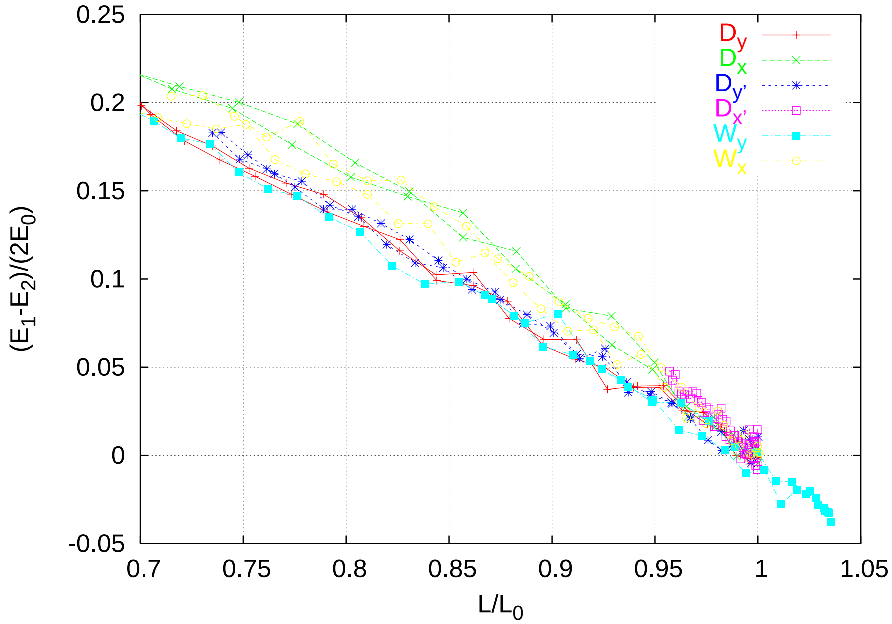
- Simulations
  - GUINEA-PIG: can generate luminosity spectra, electromagnetic and hadronic background, polarization to be included
  - CAIN: no hadronic background, polarization included
  - HTGEN: development of modules to simulate generation of beam halo and tails
  - BDSIM: to track beam halo and tails (GEANT based)
  - PLACET: to simulate realistic beam conditions
- Data bases (need to be updated for latest parameters)
  - CALYPSO: Beam particle collisions with full correlation
  - HADES: Hadronic background events, uses PYTHIA for generation (maybe something to improve)
  - files with pairs

Please Help

- Are the luminosity and background conditions OK?
  - first study has been positive
- Scenarios at lower energies
- Use luminosity and emittance tuning
  - no direct signal for luminosity that is fast
  - use signals to tune knobs (P. Eliasson, D.S.)
  - good candidate is beamstrahlung

  ⇒ instrumentation
- Precision you need for measurements
  - luminosity
  - energy
  - polarisation
- Integration of final quadrupoles





Conclusions

- Machine-detector interface considerations are vital for CLIC
- The luminosity has a pronounced spectrum
  - would aprreciate more feedback on relevance
  - need to investigate the spectrum reconstruction more
- Significant background exists
  - impacts detector design, e.g.
    - vertex detector
    - masking system
- Machine needs components in the detector
  - final quadrupoles
  - instrumentation
- We have a number of tools to study machine detector interface issues
  - we need more people to use them