Higgsstrahlung and Beam size choice

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Outline

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Why optimization of the beam size?

- Beam-beam forces lead to the emission of beamstrahlung photons and a degradation of the luminosity spectrum.
- Degradation is controlled by the choice of the horizontal beam size.
- A reduction of this parameter would increase the luminosity but also the beamstrahlung: $n_\gamma \propto \frac{1}{\sigma_x+\sigma_y}$ with $\sigma_x \gg \sigma_y$.
- A good compromise between luminosity and beamstrahlung needs to be found.
- CLIC has chosen a default beam size based on the generic aim to have 60% of the luminosity above 99% of the nominal c-o-m energy. ILC used similar considerations.
- However, this beam size choice should be confirmed with detailed studies of the most relevant physics channels.
- The horizontal beam size corresponding to the best precision on the cross section measurement for Higgsstrahlung process at 380 GeV is determined.

How?

- Vary horizontal beam size.
- Run GUINEA-PIG to simulate the initial energy spread and the beamstrahlung effect and to produce luminosity file.
- Run WHIZARD to simulate ISR and generate events.
- Perform the analysis.
- 40 cases from $S_x = 0.1$ to $S_x = 10$ and each case analyzed separately.
- Find optimum for the best cross section uncertainty: $\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{\tilde{N}_s + \tilde{N}_b}}{\tilde{N}_s} \cdot 100\%$.

Higgsstrahlung process

- At 380 GeV, it is the dominant process for Higgs boson production.
- It allows to measure the Higgs couplings in a model independent manner.
- Events can be identified from the Z boson alone and no assumptions on the Higgs decay are necessary.
- The energy and momenta of the two final state particles from the Z decay allow to reconstruct the recoil mass of Higgs boson:

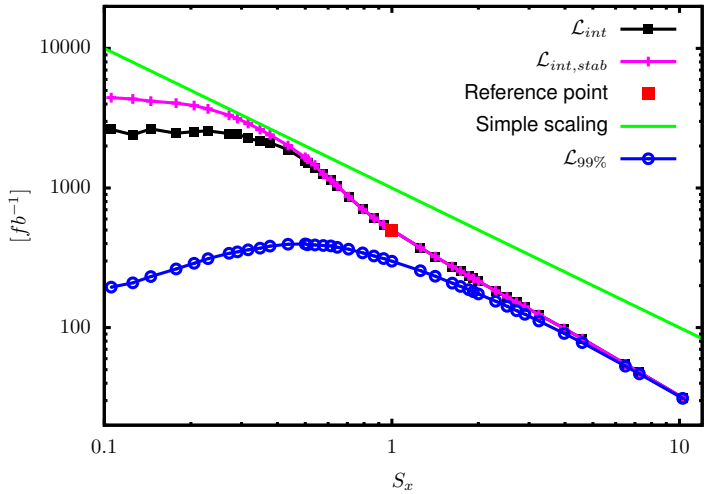
$$m^2_{rec} = s + m^2_Z - 2 \cdot \sqrt{s} \cdot E_Z.$$

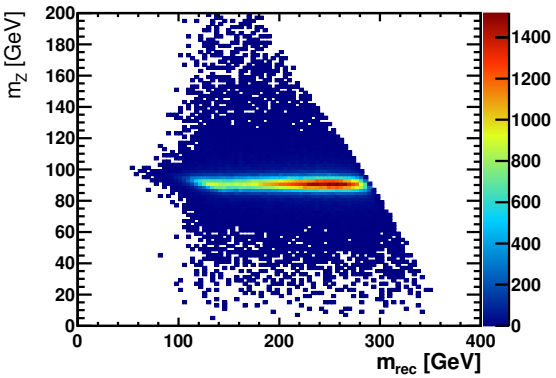
- Sensitive to beamstrahlung effect: the nominal c-o-m energy is assumed in the recoil mass calculation.
- The jet energy resolution R_j of a detector at CLIC is simulated using:

$$E_{j,sm} = E_j + E_j \cdot R_j \cdot G_j \qquad \text{where } G_j\text{=rand.Gaus(0,1).}$$

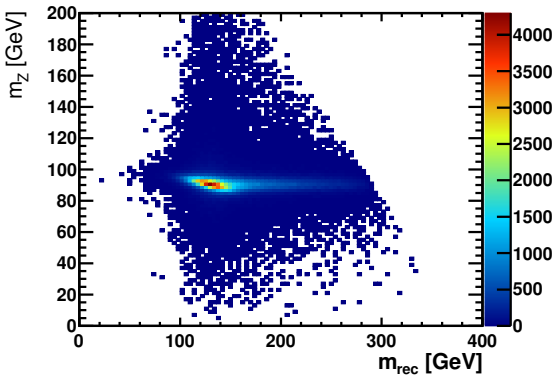
- The smeared momentum of the jet is calculated from its smeared energy keeping its mass unchanged.

From the machine to the results

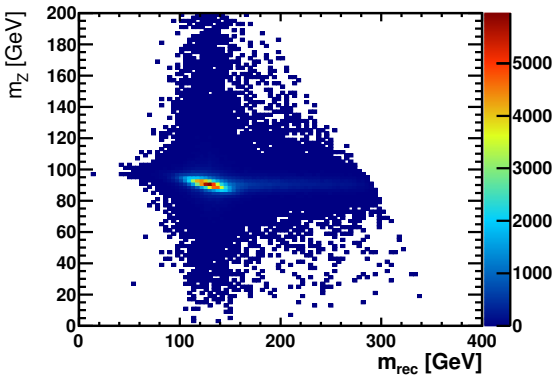




(a) $S_x = 0.1$



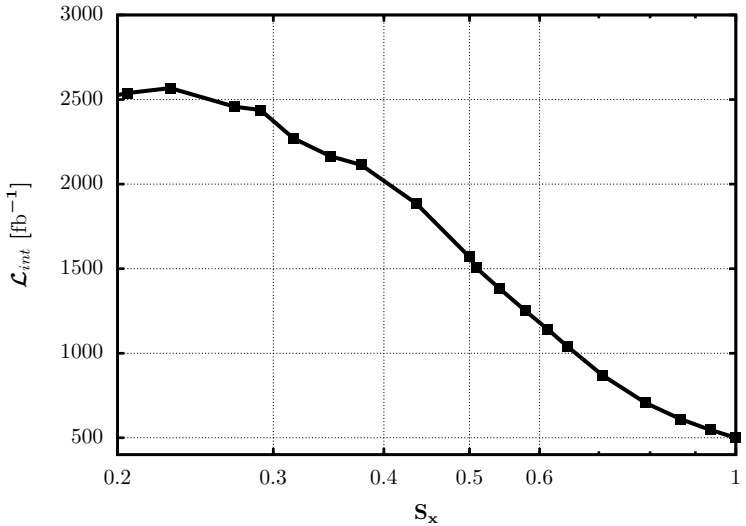
(b) $S_x = 1.0$

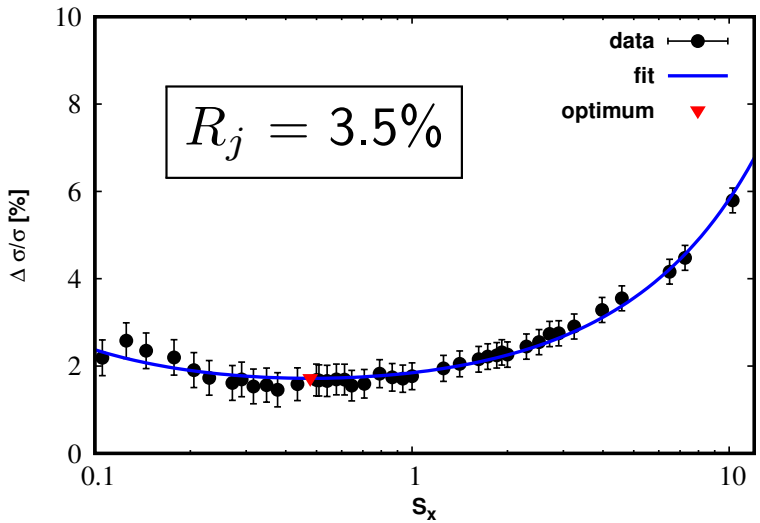


(c) $S_x = 10.2$

- At large beam size: smaller beamstrahlung effect (sharp peak) but poor luminosity.
- Reducing the size of the beam shifts the Higgs recoil mass to higher values.
- Compromise in the middle.

Results

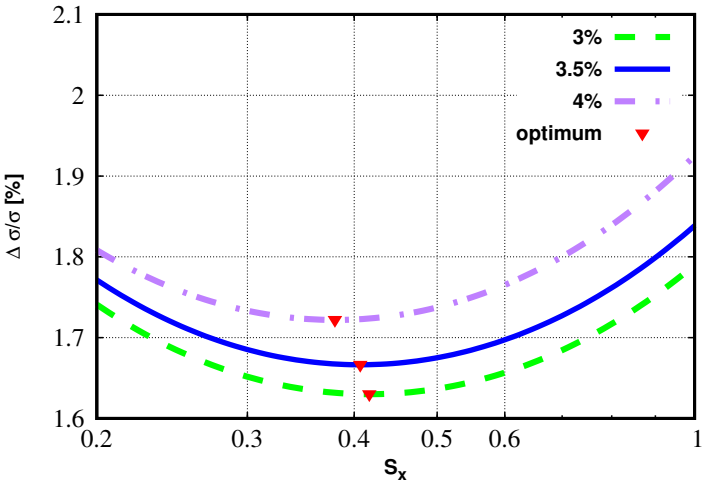




Variables	Unit	Signal	Background
ϵ_x	$[\mu$m$]$	0.950	0.950
σ	[fb]	81.794	36,532
N_{exp}	-	40,897	18,265,900
η	[%]	25.98	0.13
$\tilde{N}_{s,b}$	-	10,627	24,641
$\Delta\sigma/\sigma$	[%]	1.767	

- Good precision at nominal value of S_x.
- Very close to the fractional uncertainty on the total cross section from the full simulation at 350 GeV at CLIC [1][2]: $\Delta\sigma(HZ) = \pm 1.8\%$.
- Expect more beamstrahlung at 380 GeV: a bit competitive.
- Precision at optimum value: even better.
- 3 times higher integrated luminosity at optimum but more luminosity means more beam-beam background.

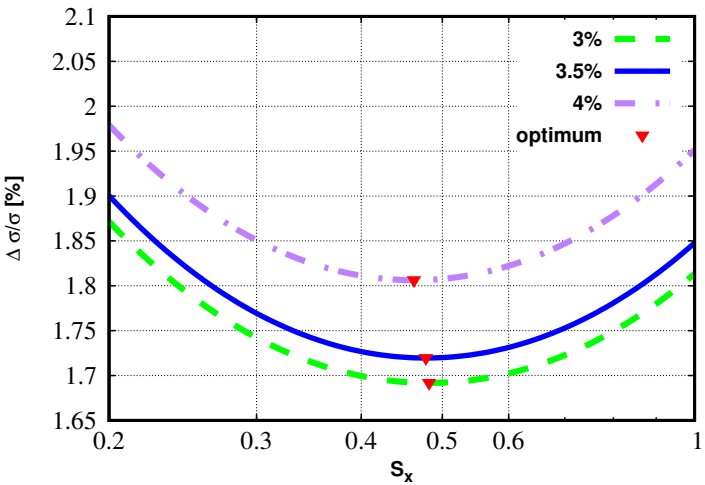
Results



With collision stabilization

R_j [%]	$S_{x,opt}$	$\Delta\sigma/\sigma$ [%]
0.0	0.6453	1.323
3.0	0.4166	1.630
3.5	0.4065	1.666
4.0	0.3797	1.722

A bit smaller optimum value but higher precision.



No collision stabilization

R_j [%]	$S_{x,opt}$	$\Delta\sigma/\sigma$ [%]
0.0	0.7162	1.355
3.0	0.4820	1.692
3.5	0.4777	1.720
4.0	0.4624	1.806

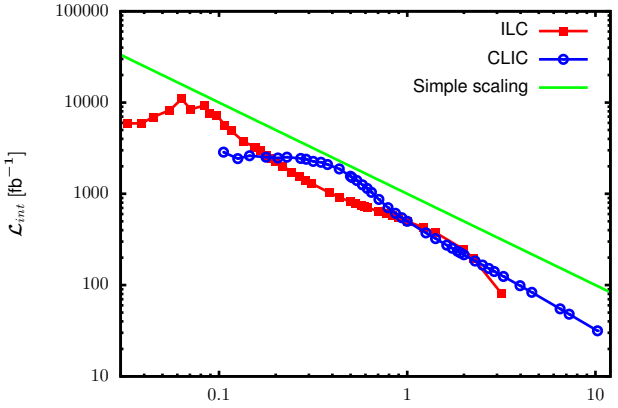
A bit higher optimum value but lower precision.

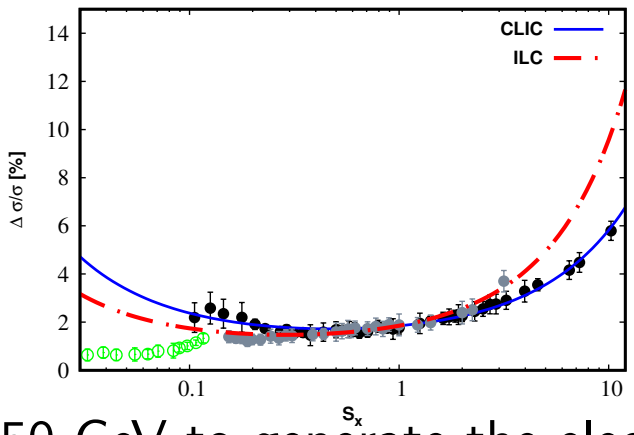
- Four values of R_j: the higher the R_j, the higher is the S_x optimum value.
- A lower R_j requires a lower S_x to maintain the quality of Higgs event reconstruction.
- From $R_j = 4\%$ to $R_j = 3\%$, one can improve approximately 6% in the precision.

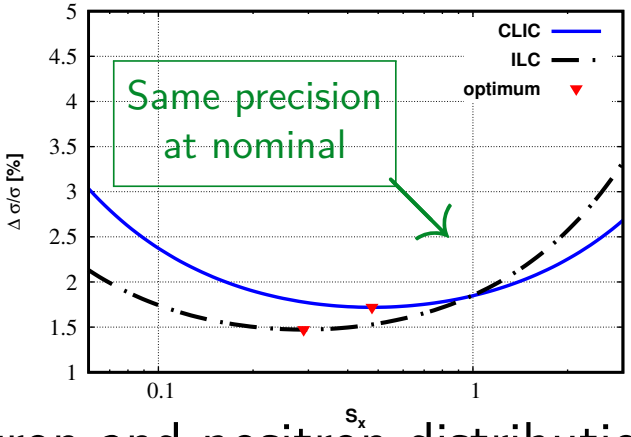
Impact on the design choice

- Optimum at around one quarter of $\epsilon_{x,nom}$.
- Only 7.4% improvement in the precision at optimum.
- Making the beam size smaller is non-trivial: many risks and difficulties.
- The improvement in the precision: small and might be canceled by the effect of more $\gamma\gamma \to hadrons$ events at lower S_x on the jet reconstruction.
- The $e^{\pm}$ pair background rises up in number and their angle slightly increases.
- The systematic uncertainty due to the knowledge of the luminosity spectrum might be larger for smaller S_x.
- If CLIC would fail to maintain the actual beam size and considers to enlarge the $\epsilon_{x,nom}$ twice, it would lose only 8% in precision.

Comparison with the ILC parameters







- Lattice for the ILC at 350 GeV to generate the electron and positron distributions through MAD-X; 200-500 GeV baseline parameters.
- Different nominal horizontal emittance: $\epsilon_{0,CLIC} = 0.95$ μm and $\epsilon_{0,ILC} = 10$ μm so that for both, it corresponds to $S_x = 1$.
- $\mathcal{L}_{int}$ is almost similar for CLIC and ILC.
- ILC affected by the collision instability much since it has a larger bunch length. Affected green data points are then ignored during fitting to show optimum.
- ILC has a bit lower optimum value compared to CLIC but the cross section uncertainty at the nominal value of S_x is similar.
- Consistent with the results from full simulation for ILC at 350 GeV: the precision achievable at CLIC and ILC is almost the same [2].

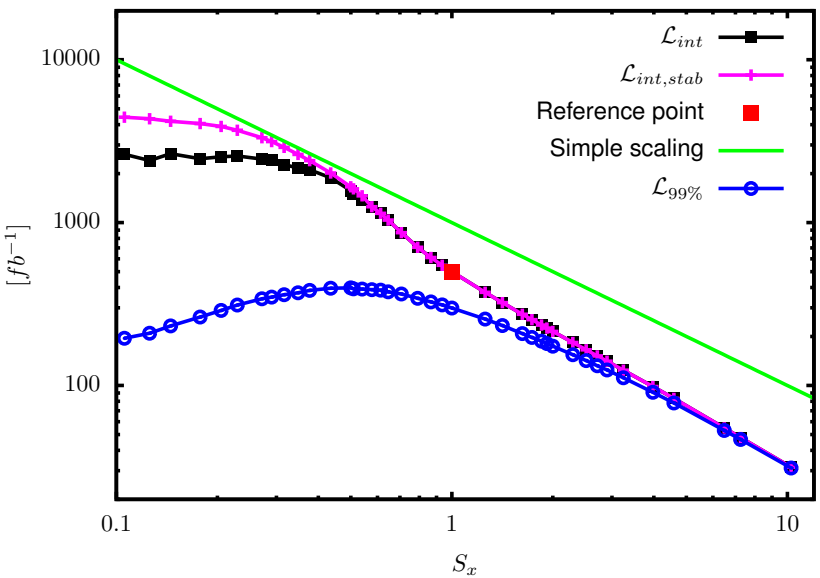
Conclusion

- Using a specific scaling parameter, the effect of beamstrahlung on the Higgsstrahlung process analysis has been studied.
- This work presents a first evaluation of the optimum value for the trade-off between luminosity and beamstrahlung for the cross section measurement of the Higgsstrahlung process at CLIC.
- The optimum is at $S_{x,opt} \approx 0.5$ which corresponds approximately to one quarter of $\epsilon_{x,nom}$ for 3.5% jet energy resolution.
- However, this optimum provides only 7.4% improvement in the precision which is small. It is much harder to achieve such a beam size.
- Beam-beam backgrounds would be much larger at the smaller beam size, in particular $\gamma\gamma \rightarrow hadrons$ and e^-e^+ pairs. This might reduce the gain further.
- The choice of the actual beam parameters at CLIC is confirmed to be reasonable from the physics analysis point of view.
- For the ILC, a similar result is found with a slightly larger gain at optimum. This is despite of the difference between the beam size and bunch length.
- In the present work, only the Higgsstrahlung process at 380 GeV has been evaluated. Similar studies with full simulation, with multiple beam parameters and with other processes at 3 TeV should be addressed.

BACKUP

Collision stabilization

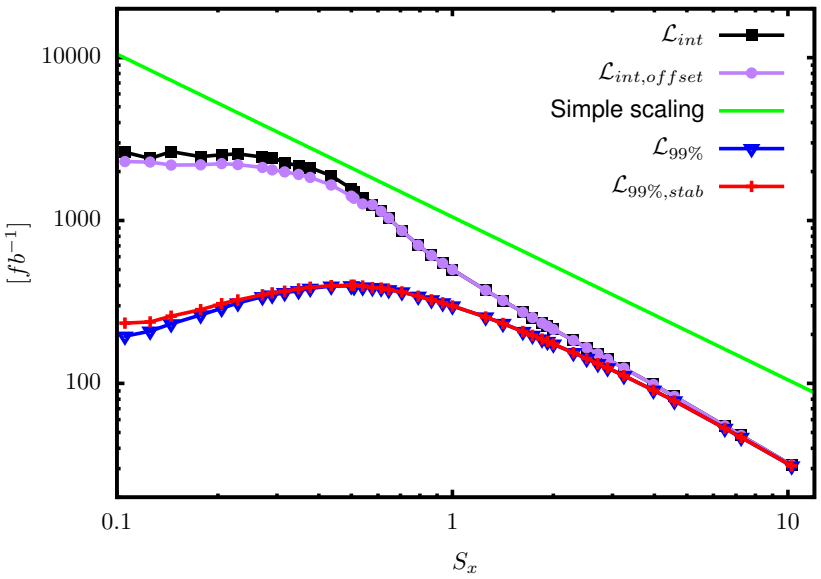
- For smaller S_x (<0.5): collision not stable
- To stabilize collision in this regime: set force symmetric which models the beam to be up-down and left-right symmetric.
- This significantly enhances the luminosity for a very small beam size.



- $\mathcal{L}_{int}$: the integrated luminosity before collision stabilization.
- $\mathcal{L}_{int,stab}$: the integrated luminosity after collision stabilization.

Disruption effects

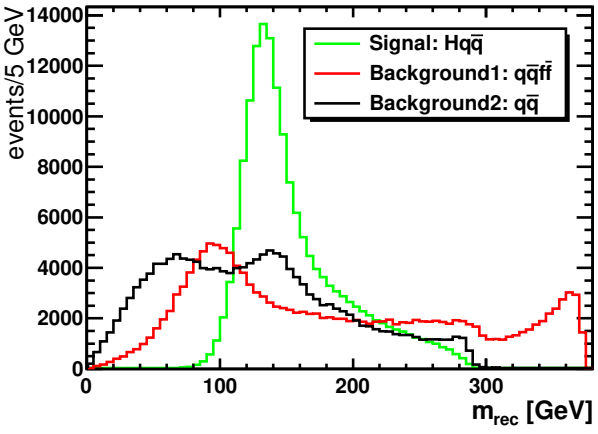
- For a very small beam size, disruption is one of the major sources of collision instability.
- Due to the attractive force that the two colliding bunches exert on each other causing luminosity enhancement. It can be saturated.
- $\mathcal{L}_{int}$ not sensitive to beam offset and a very small effect of instability for the peak luminosity.



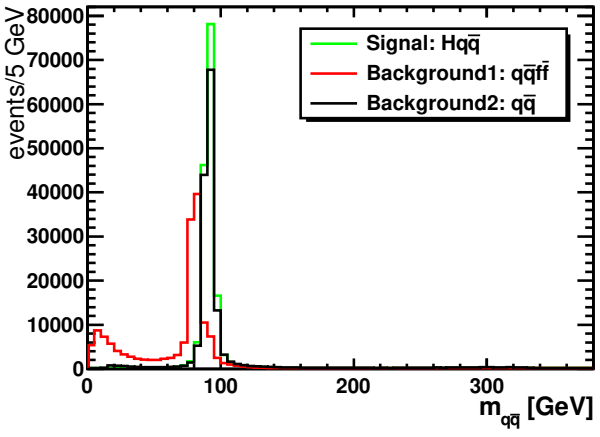
- $D_y = \frac{2r_e N\sigma_z}{\gamma\sigma_y(\sigma_x+\sigma_y)}$
- $\mathcal{L}_{int,offset}$: the integrated luminosity after adding 0.1 offset for each beam
- $\mathcal{L}_{99\%,stab}$: the peak luminosity after collision stabilization.

$\Rightarrow$ $\mathcal{L}_{int}$(collision stabilization) should give a better representation of the luminosity expectation as a function of the beam size.

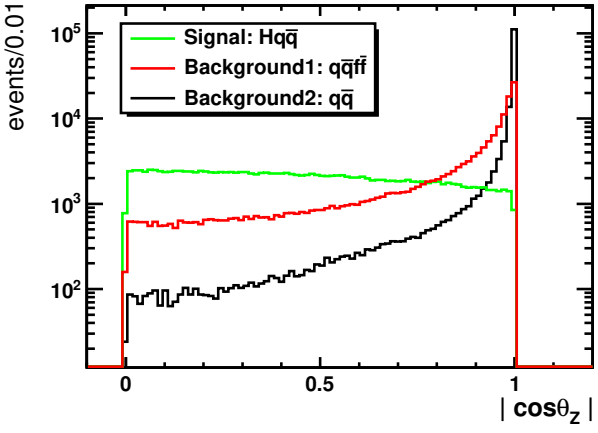
Reconstruction approach



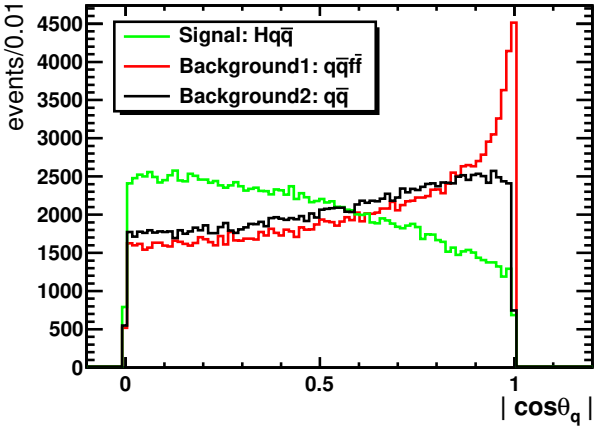
(g) the recoil mass



(h) the reconstructed Z mass



(i) the polar angle of the Z

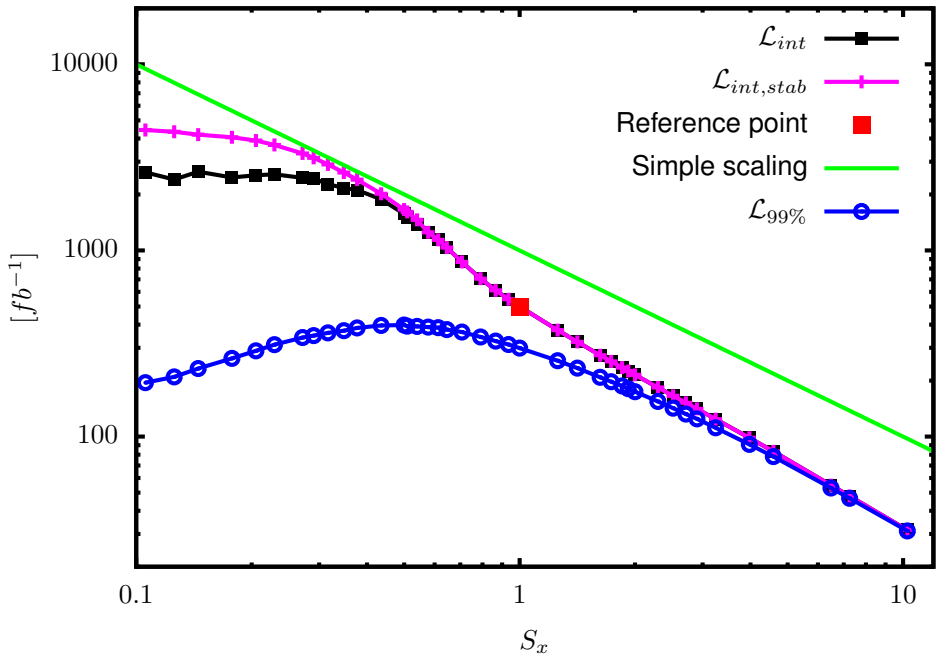


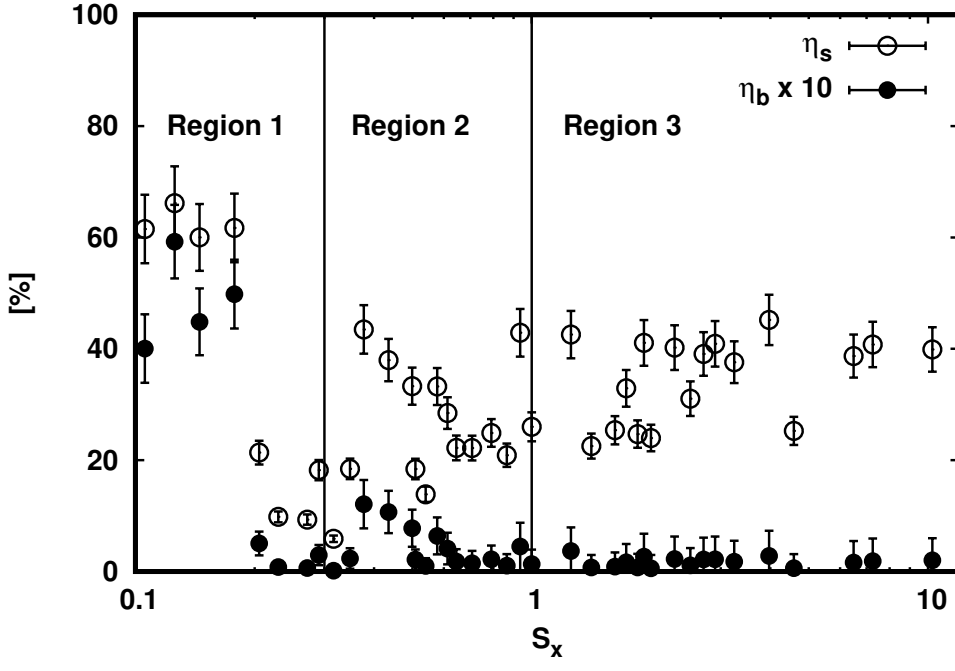
(j) the angle of quarks

- More realistic way to perform such an optimization study.
- A Boosted Decision Tree (BDT) classifier as implemented in the Multivariate Analysis Tool (TMVA): used to suppress the backgrounds.

It uses four variables:

1. the recoil mass,
2. the reconstructed Z mass,
3. the polar angle of the Z and
4. the angle of the quarks form the Z decay relative to its flight direction in the Z rest frame.





- Both the background efficiency and the signal efficiency become larger at smaller S_x.
- This means that TMVA hardly suppresses unwanted events for smaller beam size.
- Need more backgrounds in Region 1.
- Cross section uncertainty:

where

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{\tilde{N}_s + \tilde{N}_b}}{\tilde{N}_s} \cdot 100\%$$

$$\tilde{N}_s = \eta_s \cdot \sigma_s \cdot \mathcal{L}_{int}$$
$$\tilde{N}_b = \eta_b \cdot \sigma_b \cdot \mathcal{L}_{int}$$

Impact on the design choice

Fraction of $\epsilon_{x,nom}$	S_x	$\Delta\sigma/\sigma$ [%]	Improvement [%]
1/4($\simeq \epsilon_{x,opt}$)	0.500	1.720	7.4
1/3	0.577	1.728	6.9
1/2	0.707	1.755	5.3
3/4	0.866	1.808	2.2
1 (nominal)	1.000	1.848	0.0
2	1.414	2.008	- 8.0
4	2.000	2.253	- 18.0

Summary of CLIC and ILC nominal beam parameters[3][4]

Parameter	Symbol	Unit	CLIC	ILC
Center-of-mass energy	$\sqrt{s}$	GeV	380	350
Normalized horizontal/vertical emittance	ϵ_x/ϵ_y	μm/nm	0.95/30	10/35
IP beam size	σ_x/σ_y	nm	149/2.9	683.5[a]/5.9[a]
Bunch length	σ_z	μm	70	300[a]
Horizontal/vertical IP beta function	β_x^*/β_y^*	mm	8.2/0.1	16/0.34
Bunch separation	Δt	ns	244	554
Charge per bunch	N	10^{10}	0.52	2
Number of bunch per train	n_b	-	352	1312
Repetition frequency	f_r	Hz	50	5
Total luminosity	$\mathcal{L}$	10^{34}cm^{-2}s^{-1}	1.5	1.0
Luminosity above 99% of $\sqrt{s}$	$\mathcal{L}_{99\%}$	10^{34}cm^{-2}s^{-1}	0.9	0.77

[a]RMS size

References

[1] H. Abramowicz, et al, Higgs Physics at the CLIC Electron-Positron Linear Collider, CLICdp-Pub-2016-001, arXiv:1608.07538.

[2] M. Thomson, Model-independent measurement of the $\sigma(e^+e^- \to HZ)$ cross section at a future e^+e^- linear collider using hadronic Z decays., Eur. Phys. J. C76, 72 (2016), arXiv:1509.02853.

[3] The CLIC, CLICdp collaboration, Updated baseline for a staged Compact Linear Collider, CERN-2016-004, arXiv:1608.07537.

[4] T. Behnke, et al., The International Linear Collider Technical Design Report, Volume 1: Executive Summary, ILC-REPORT-2013-040, arXiv:1306.6327, 2013.