Linear Collider Opportunities to Better Explore EW Physics

With emphasis on experimental issues and accelerator improvements

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- Physics demands an $\mathrm{e}^+\mathrm{e}^-$ collider to explore the Higgs and top quark in detail.
- LCs offer wide energy range, high luminosity, and selectable collisions (polarization).
- Key elements for EW are understanding of the center-of-mass energy, absolute integrated luminosity, differential luminosity, and polarization. Strategies are in hand.

Tried to join you: 48 hours at local airport/hotel. Now back home.

Introduction

With 48 hours spent stuck at the airport in an ice-storm/blizzard trying to get a flight out, my talk is very short on prep. time.

- An old more general talk (ICHEP2020) on LC EW possibilities is uploaded for reference that may be useful for those new to the field. Some numbers are too conservative, but the generalities are mostly accurate.
- The ILC Snowmass report is a relatively up-to-date reference for a wide-ranging view of the physics potential of linear colliders, (2203.07622).
- I will focus here on my recent work on exploring improving the ILC accelerator design for Z-pole running (arising as a by-product of beam-beam simulation studies investigating luminosity measurement biases at the Z). More generally, design changes may lead to improved potential for running near WW threshold, and also potentially higher energies.
- Thanks to Benno, Daniel Schulte, and Kaoru for encouraging feedback on accelerator implementation practicalities.
- The ILC concept and related design aspects have been around for a long time with different boundary conditions. Many of the perceived weaknesses belie the actual potential.

LC Misconceptions/FAQ

- *Circular colliders naturally have higher luminosity than linear colliders at the lower ECMs of interest.* No - or not always. See my favorite ReLiC counter-example (2203.06476). Depends on how much power is used/wasted. For the physics of interest, how much luminosity do you need before being systematics limited? For example, if luminosity uncertainty is limited to 10^{-4}, then absolute cross-sections don't benefit from more than 10^8 Z's.
- *But there is only one interaction region.* You can have 2 if affordable/desired. For ReLiC (recycling very high-luminosity linear collider): 2 IRs are natural.
- *Longitudinal polarization adds uncertainties with additional problematic nuisance parameters.* **NO**. Polarization allows one to avoid wasting the majority of the luminosity on uninteresting collisions, provides the best tool to explore the chiral nature of electroweak interactions, and when positrons are also polarized, in-situ measurements of polarization are very robust.
- *The center-of-mass energy can not be measured very well at a LC.* RDP is not available, but neither is it available at higher energy for a circular collider. Depends how well the tracker momentum scale is controlled. Precisions approaching 1 ppm can be envisaged. The ECM uncertainty likely subleading for m_{W} measurement. See 2209.03281 and 2308.10414.
- *250 GeV is not high enough energy*. Agreed. If higher energies follow, OK to start with 250 GeV. ILC initial energy was 500 GeV upgradable to 1 TeV.

- Recently, I have been looking at a new approach to forward calorimetry with a view to luminosity measurements targeting the 10^{-4} uncertainty level at the Z. See recent proceedings and talk at SLAC December Higgs factory workshop.
- One important aspect for Bhabha-based lumi. is to mitigate the issue of the electromagnetic deflection (EMD) of the outgoing Bhabha electron and positron caused by the EM field of the opposing bunch resulting in a bias in the luminosity estimate. Most concerning for Z running (more deflection at low momentum). See PLB 800 (2020) 135068 (Voutsinas et al.).
- Has led to exploring changes to the ILC machine design in this context and I happened across some scenarios that naively seem attractive in the more general context of luminosity optimization. See attached brief writeup.
- The key insight is that the beamstrahlung at the Z is relatively small and the half-width of the Z is substantial ($\Gamma_{\mathrm{Z}}/(2m_{\mathrm{Z}}) = 1.4$ %). One can therefore explore trading luminosity spectrum quality for more luminosity. While this is likely of most benefit at the lowest energies, there may be scope for a more aggressive embrace of higher luminosity at other energies.

Luminosity Measurement Introduction

Two predominantly QED processes considered for $\mathrm{e^+e^-}$ collider abs. luminosity measurements at the 10^{-4} level (target especially for Z running for improving N_ν). Both can be under very good theoretical control.

1. **Bhabha Scattering**, $\mathrm{e^+e^- \to e^+e^-}$. Used at LEP/SLC with small-angle Si/W-based calorimeters to restrict to the pure t-channel contribution. Current ILC and FCC-ee LumiCal designs follow this approach. $d\sigma/d\theta \sim 1/\theta^3$. Prone to systematics from knowledge of θ_{min} and EMD bias.
2. **Pair Annihilation into Photons**, $\mathrm{e^+e^-} \to \gamma\gamma$. A pure QED process. $d\sigma/d\theta \sim 1/\theta$. Less sensitive to θ_{min} systematic. No θ_{max}. Lower event rate.

Integrated cross-sections are approximately:

$\sigma_{\mathrm{e^+e^-}} = 1040\ \mathrm{nb}\ (\theta_{\mathrm{min}}^{-2} - \theta_{\mathrm{max}}^{-2})/\ s[\mathrm{GeV}^2]$.

$\sigma_{\gamma\gamma}(\theta > \theta_{\mathrm{min}}) = 130\ \mathrm{nb}\ \ (1 - P_{\mathrm{e^-}} P_{\mathrm{e^+}})\,(\log_{\mathrm{e}}(\frac{1+\cos\theta_{\mathrm{min}}}{1-\cos\theta_{\mathrm{min}}}) - \cos\theta_{\mathrm{min}})/\ s[\mathrm{GeV}^2]$

For $\theta_{\mathrm{min}} = 31.3$ mrad and $\theta_{\mathrm{max}} = 51.6$ mrad (OPAL LEP1), the cross-sections are **81 nb** (Bhabhas) and **115 pb** ($\gamma\gamma$ unpolarized) at $\sqrt{s} = 91.2$ GeV.

My Take

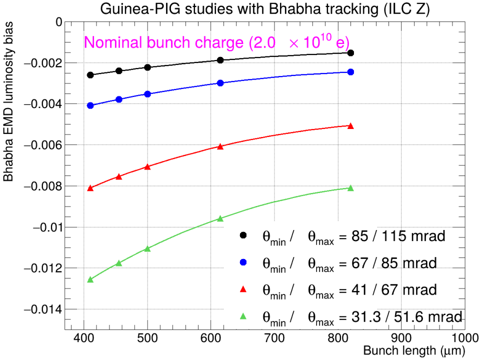
- Use Bhabhas for relative luminosity (especially for polarized beams).
- $\mathrm{e^+e^-} \to \gamma\gamma$ can reach 10^{-4} statistical (at Z) with 1 ab^{-1} and $\theta_{\mathrm{min}} = 1.8^\circ$.
- Precision **absolute** lumi. is experimentally easier with $\gamma\gamma$ cf Bhabhas.

Reducing the Bhabha EMD Luminosity Bias

Two methods - besides reducing the bunch charge (and luminosity) come to mind

1. Changing the fiducial acceptance (wider angles - less deflection). Reduces the Bhabha counts. Bias reduction of factor of 3 for factor 7.5 loss in statistics (blue).
2. Longer bunches (reducing the bunch compression). Lower charge density so less deflection. Higher disruption, modest lumi. increase, smaller energy spread (σ_E/E).

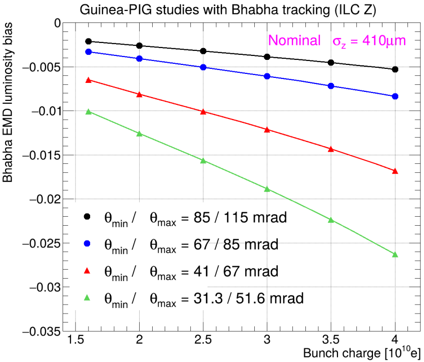
ILC-Z nominal bunch length: 410 μm.

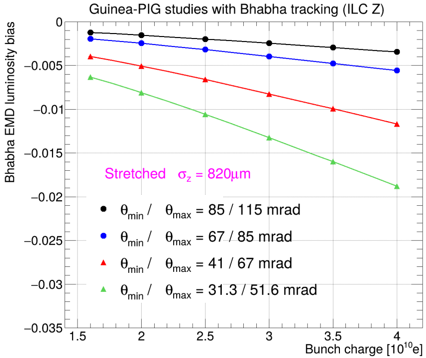


- Bhabha cross-sections at the Z: 80.7 / 46.5 / 10.6 / 7.8 nb
- Compared with $\sigma_{\rm had} = 31$ nb.

What about **Increasing** the Bunch Charge (N)?

ILC nominal bunch charge is 2×10^{10}e with sources designed with 50% margin.

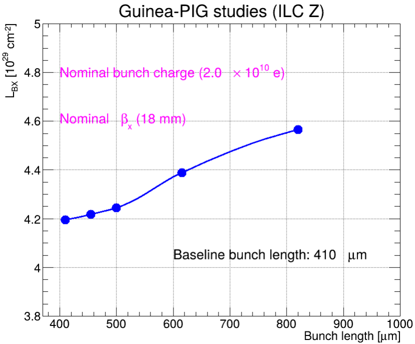


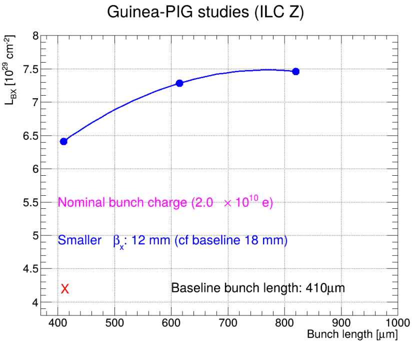


- As expected the bias increases substantially with N. The lumi. per bunch crossing increases by a factor of 7.7 from nominal to doubled bunch charge and doubled bunch-length (this talk ...) - much more than the factor of 4 in geometric lumi.
- Longer bunches helpful for EMD mitigation presuming this can be integrated into the accelerator design. Two reasons: less deflection, easier z_{vtx} diagnostics.
- When targeting 10^{-4} lumi. precision with Bhabhas, should plan on understanding a 1% bias to 1 part in 300. If feasible: need excellent diagnostics.

ILC-Z Luminosity Optimization Study I

Baseline is the ILC250 Z running described in Yokoya, Kubo, Okugi (1908.08212).





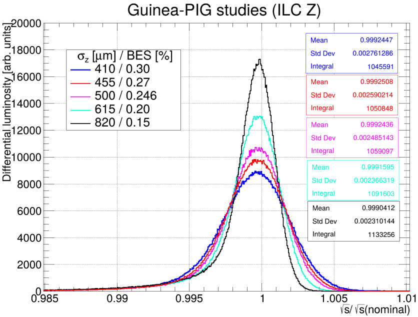
Compress the bunches less..

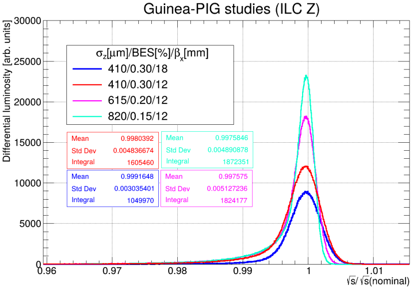
1. Leads to smaller beam energy spread (BES).
2. Modest lumi. gain.
3. Less EMD, longer beam spot.

Looks attractive.

Red cross = ILC-Z baseline. Explore smaller β_x^* (Daniel Schulte suggestion). ILC250 uses 13 mm. Detector backgrounds will be bigger with smaller horizontal collimation depth of $5\sigma_x$ for $\beta_x^* = 12$ mm. What about lumi spectrum for both plots?

ILC-Z Luminosity Optimization Study II





Black is much better than blue (baseline). Sharper peak - more lumi. Implementable?

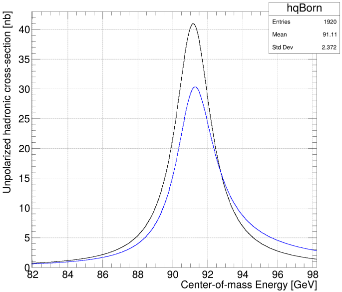
Again longest bunch option looks good. Improvement exceeds expected geometric factor of $\sqrt{3/2}$.

Note the ability to resolve the peak from the tail likely is important rather than simply the moment values. These plots suggest that these potential lumi improvements are OK physics wise.

Z Observable Sensitivity Tests (WIP)

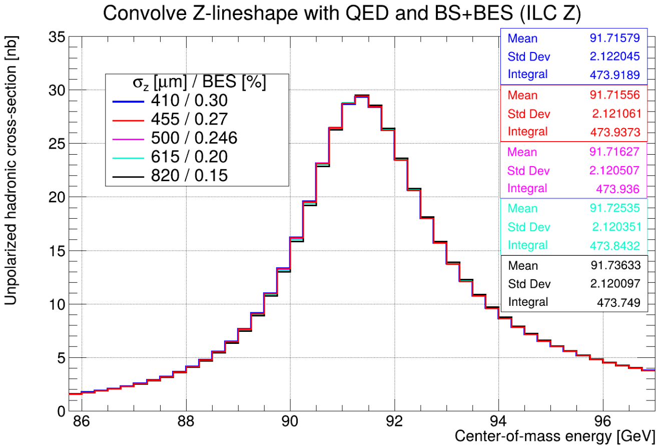
Implemented a two-step procedure (thanks Michael for initial Mathematica nb).

1. Convolve the theoretical Z lineshape with the QED radiative corrections using an ISR radiator function (going from the black Breit-Wigner resonance to the physical blue measurable cross-section) using numerical integration.
   The integration limit is set at $s'/s = 0.4$.
2. Convolve the quadratically-interpolated physical cross-section (25 MeV bins) with each luminosity spectrum using random sampling of the lumi. spectrum histogram for $\sqrt{s}/\sqrt{s}_{\mathrm{nom}} > 0.6$. Report observable cross-sections for 45 scan points with 0.25 GeV spacings.



- It should be feasible to fit the observable cross-sections for lineshape parameters and see how much degradation there is, and assess sensitivity to knowledge of the lumi spectrum. Also can test A_{LR} with this setup.
- Next slides illustrate qualitatively/semi-quantitatively the results so far.

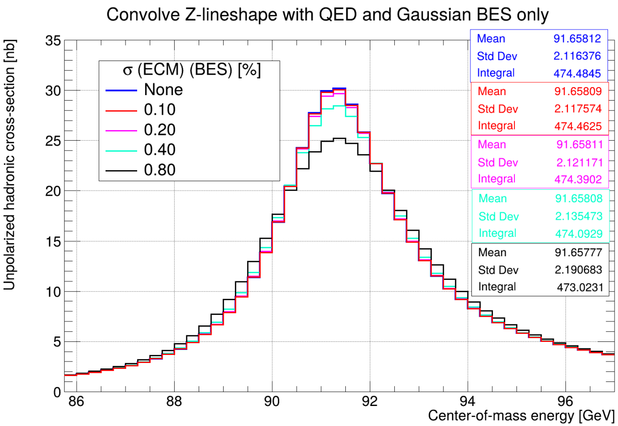
Z lineshape for σ_z modifications



Seems like very marginal differences. Note the small change in the std. dev. of the distributions.

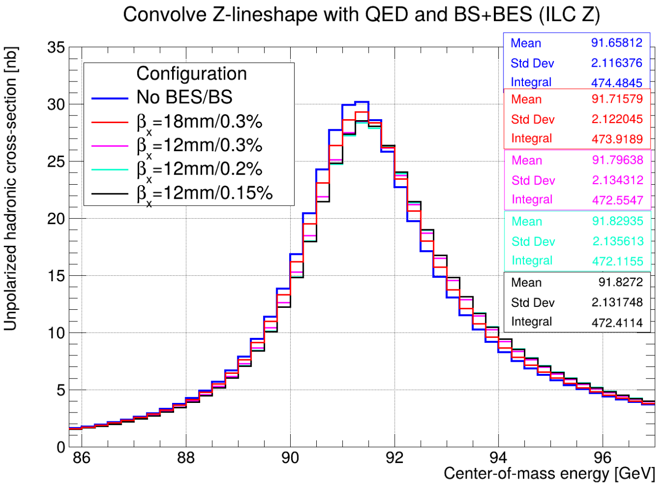
Z lineshape toy models

Here the luminosity spectrum is chosen as a Gaussian with std. dev. in the center-of-mass energy as specified. (ILC-Z nominal from BES is about 0.2% (magenta))



Note how the mean is stable when the lumi spectrum is symmetric.

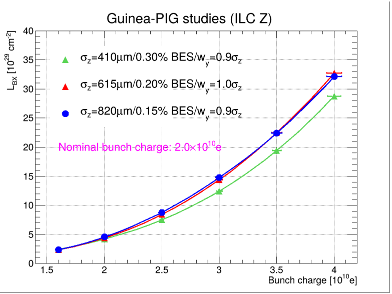
Z lineshape for β_x^* modifications



Observable differences between $\beta_x^* = 18\text{mm}$ (ILC-Z baseline) and 12mm. But expect the 80% lumi increase to win the day decisively presuming this will be acceptable for detector backgrounds.

ILC-Z luminosity optimization III

What about increasing the bunch charge (N)? ILC nominal bunch charge is 2×10^{10}e with sources designed with 50% margin. Expect $L \sim N^2$ if purely geometric (but also pinch effect).

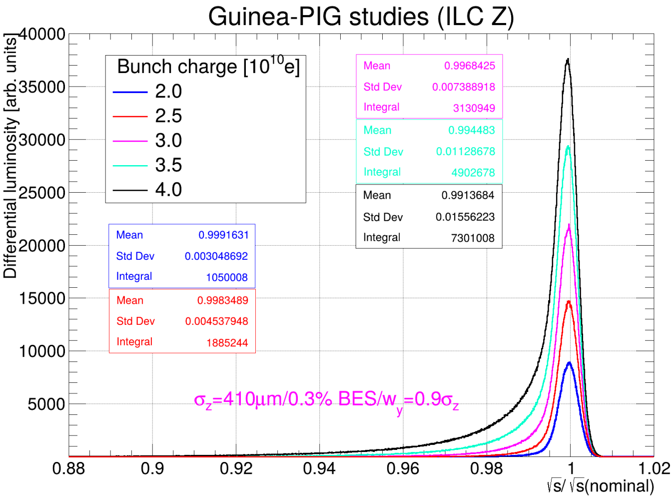


Note that while L_{BX} may increase by a factor of around 8 by doubling the bunch charge and bunch length, the realistic increase is only a factor of 4 for constant power, where one would need to halve the rate of bunch collisions ($f_{\mathrm{rep}} n_{\mathrm{b}}$).

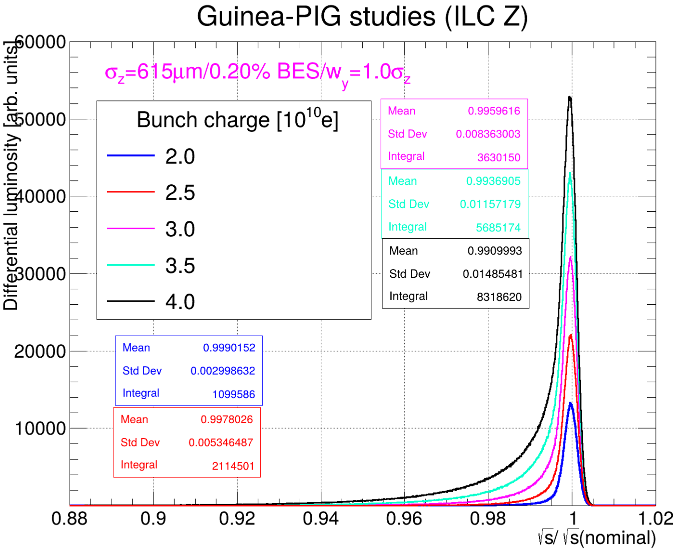
Many systems would need to be reviewed carefully. What were the main reasons for limiting N to 2×10^{10} e for ILC? Was it partly lumi spectrum quality?

Is higher N and especially $N = 4 \times 10^{10}$e acceptable physics wise at the Z?

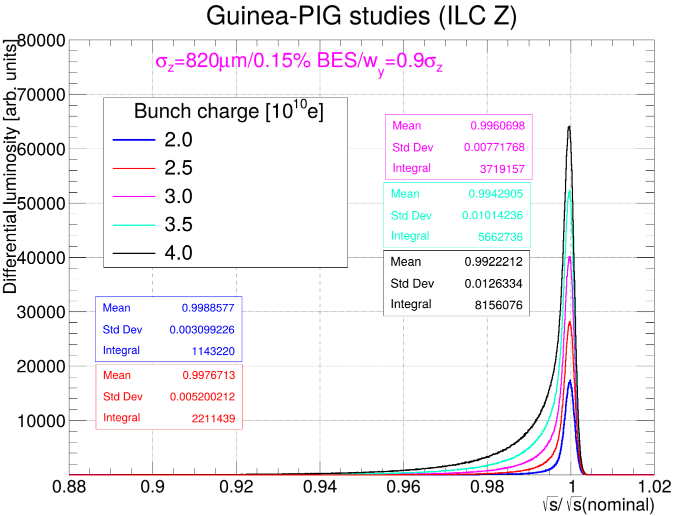
Luminosity Spectrum I



Luminosity Spectrum II

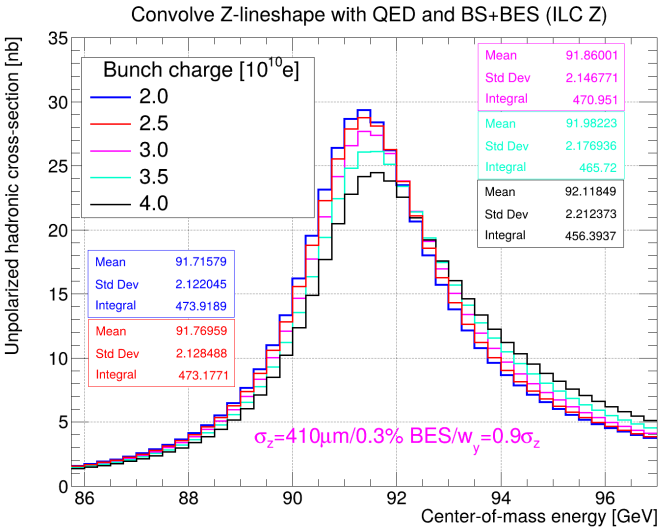


Luminosity Spectrum III



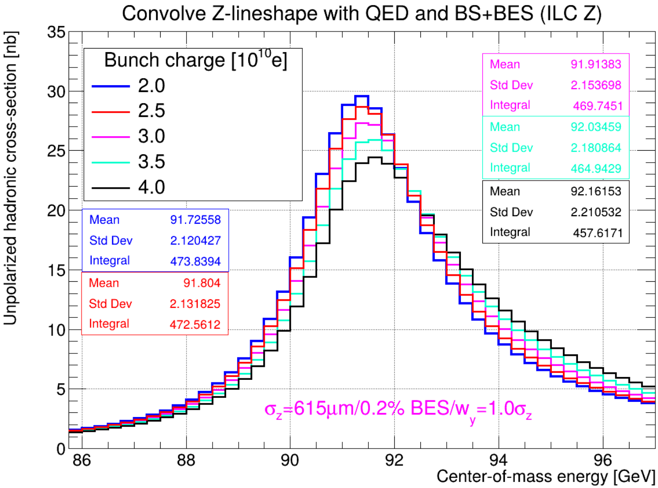
Some benefit from narrower energy spread. All spectra show increasingly prominent tail (as expected).

Z lineshape: increase bunch charge with standard σ_z



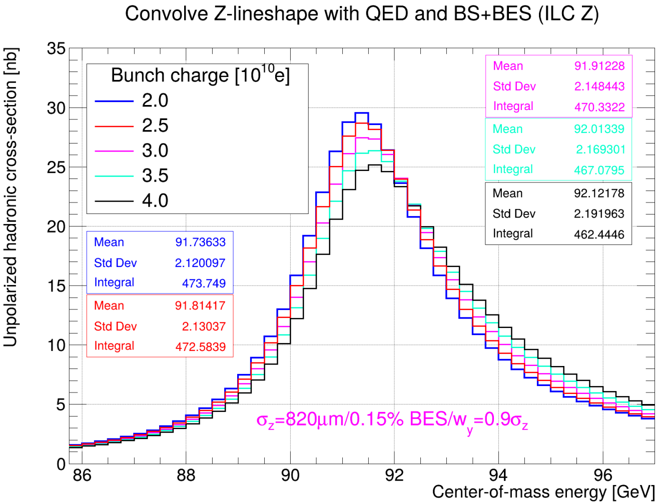
For the peak bin, $\mu_{\mathrm{BX}} = \sigma\, L_{\mathrm{BX}} = 0.0130$ (for $N = 2.0 \times 10^{10}$ e) and $\mu_{\mathrm{BX}} = 0.0799$ (for $N = 4.0 \times 10^{10}$ e)

Z lineshape: increase bunch charge with $\sigma_z = 615\mu m$



The reduction in peak event rate is real. Bear in mind that with a typical polarization scenario (assuming 80%/30% beam polarizations, the lumi weighted average hadronic cross-section is 20% higher than the unpolarized one).

Z lineshape: increase bunch charge with doubled σ_z



This is a little better. Again hard to argue with a factor of 8 in L_{BX} (4 in delivered lumi after halving the number of bunches to obey the power constraint).

Concluding Remarks

Beyond increasing $f_{\mathrm{rep}} n_{\mathrm{b}}$, have demonstrated 3 ways to increase luminosity for ILC-Z by tolerating more beamstrahlung: i) increased bunch-length, ii) decreased horizontal β function (β_x^*), iii) increased bunch charge.

- These range from a modest very plausible increase (8%), to a more substantive increase of 80% (combined), to an increase of a factor of about 4 (accounting for constant power) resp.. To do: check β_x^* + bunch charge.
- The changes look either OK for physics, probably OK - but increased detector background, or in need of more study, respectively.
- It may be that a more modest change in bunch charge is both attractive and more feasible (eg. $N = 3 \times 10^{10}$e).
- A higher gradient acceleration scheme will be better for emittance preservation. Should consider full gradient acceleration + main linac bypass.

Prospect for $\mathcal{L} > 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at Z-pole

Such changes need further consideration by accelerator experts. We do want to evaluate, informed by reasonable assumptions, what is acceptable for physics for the flagship measurements including A_{LR}, Z lineshape, m_{W}.

These studies focused on possibilities for ILC Z running. Physics reach of several LC-based accelerator concepts may benefit from more discussion on performance improvement in forums promoting collaboration across sub-disciplines. Eg. Higher poln.

Backup Slides