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Beam-beam effects on luminosity measurement

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Introduction

Required precision in luminosity measurement ($\sqrt{s}$ 91.2 GeV): $\Delta L/L = 10^{-4}$

- It is expected to match theoretical precision by the time FCCee will be running

Small angle Bhabha scattering is the standard option for luminosity measurement

- Alternatively, large angle γ pair production is considered → to be further investigated

Very challenging task

- Various sources of systematics
- Focus on beam – beam effects
  - expected to introduce a bias 15-20 times larger than the required precision
  - A correction with a relative precision of 5% is required!

Beam – induced effects on Bhabhas

Beam induced effects on the L measurement were first studied in ILC*

However the situation in FCCee is considerably different

- In FCCee the crab waist scheme is used
  - Bunches collide under a large crossing angle

We can divide the beam – beam effects into 2 categories

1) Prior to interaction

All events receive a Px "kick" due to the crossing angle

2) Final state effects

The Bhabha final state leptons are focussed by the field of the opposite bunch

*C. Rimbault et al, 'Impact of beam-beam effects on precision luminosity measurementsat the ILC' JINST 2 P09001, September 2007

Outline

In the following slides we will describe these effects

- And suggest realistic corrections

The main tool for the study is Guinea Pig code (GP)

- Where we insert bhabha-files (either single electrons/positrons or BHWIDE generated)

In principle, if one knows very precisely the beam parameters, and fully trusts the simulations, could use GP to infer a correction factor

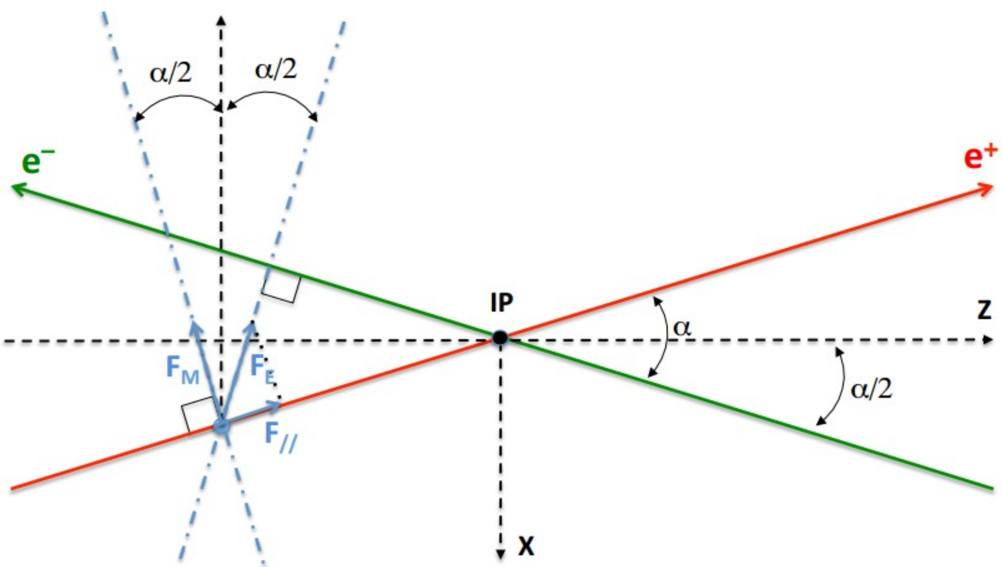
However, the beam-beam effects have a strong dependence on the beam parameters

- Which may vary from bunch to bunch or from fill to fill

Additionally, these effects haven't been observed yet

- Any handles to corroborate experimentally the simulations are very useful
- Ways to infer the correction factor with reduced dependence on simulations are proposed

Prior to interaction (Px kick)

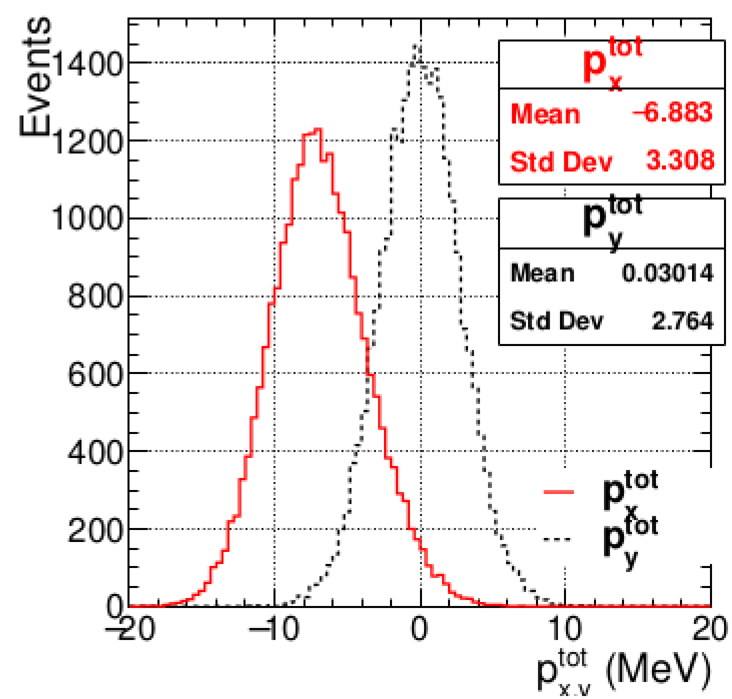


Particles from one bunch feel the electric and magnetic force from the opposite bunch

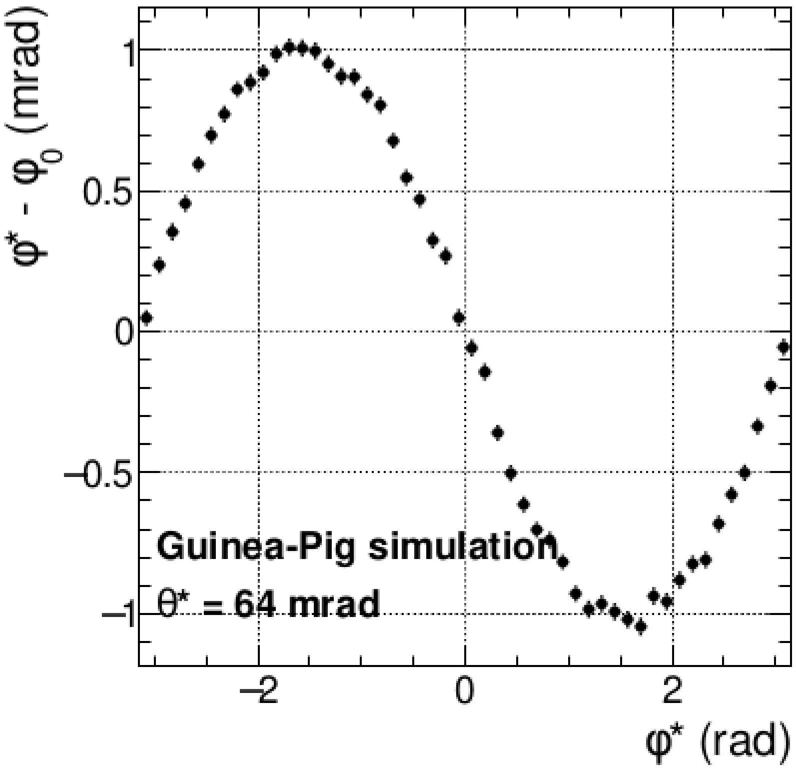
- Results to a force paraller to x-axis
  - Before IP particles are accelerated
  - After IP they are deccelarated
- Overall effect is 0
- However, by the time the interaction happens, the overall effect is positive

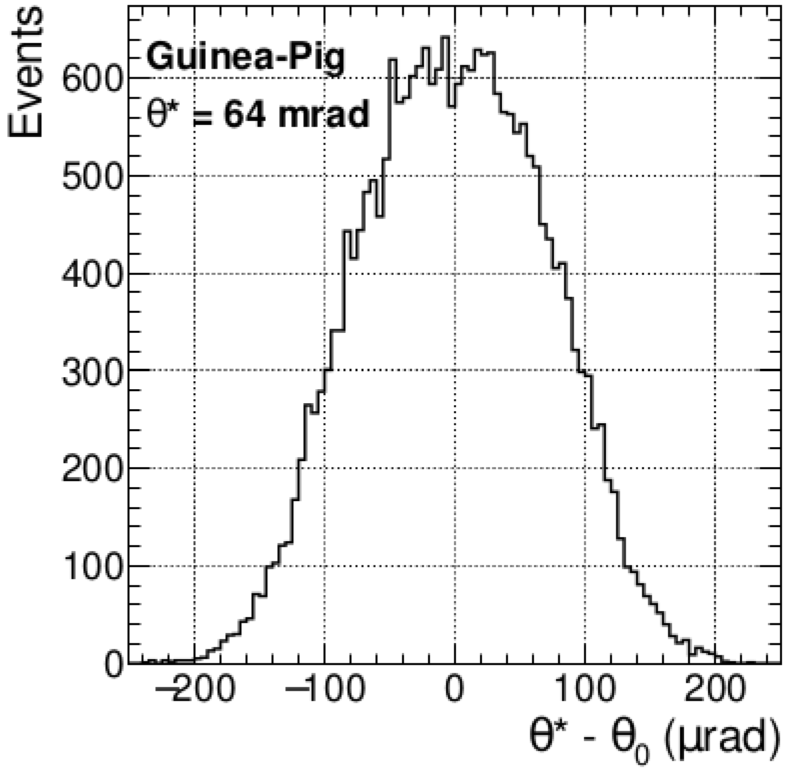
This leads to a boost along X (Px kick)

- On average ~ 3.5 MeV per particle
- It is visible in all final states, not only bhabhas
- Both θ, φ are modified



Prior to interaction II





The px kick, averaged over φ, does not bias the θ mean

- It does not introduce a bias in the luminosity measurement
- But it can be used in order to evaluate this bias
  - As it will be explained in slide 8

Final state effects (EM deflection)

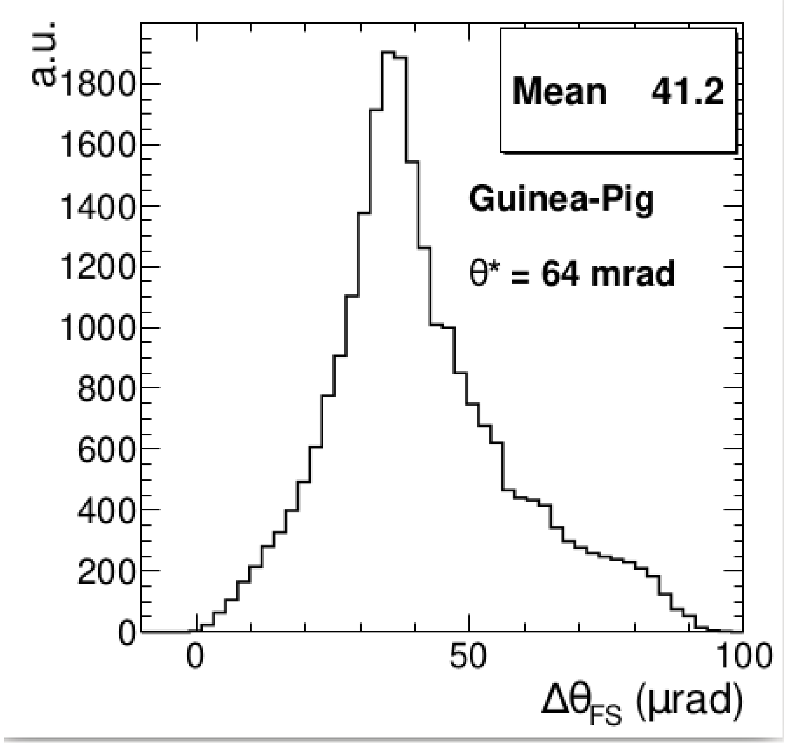
The particles are focussed by the field of the opposite bunch

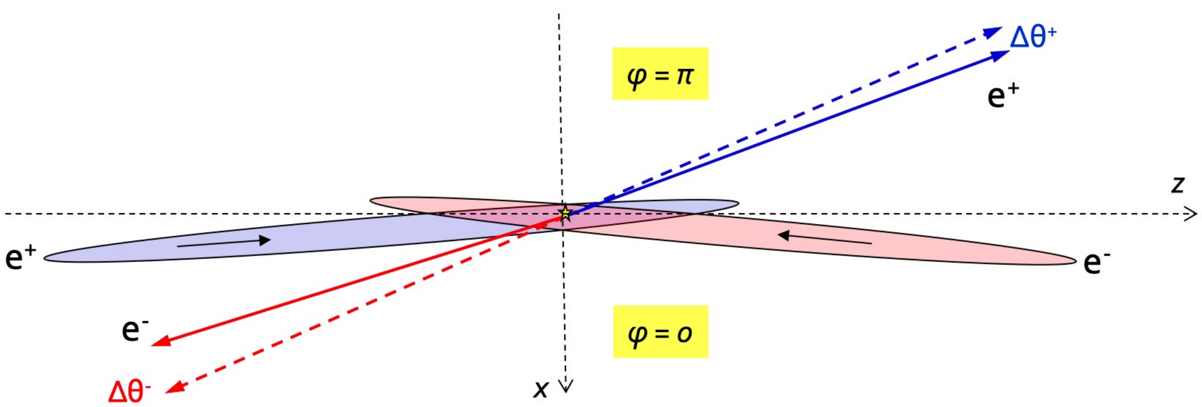
Their polar angle changes

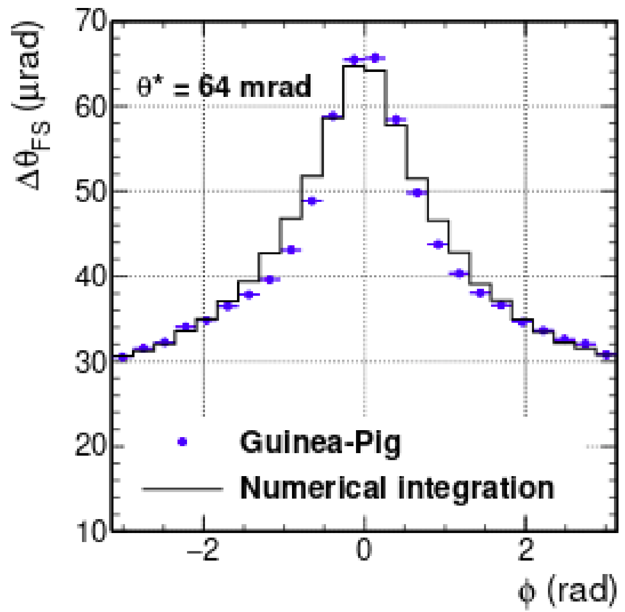
- Bias in L measurement
- Mean focussing angle ~ 41μrad
  - ΔL/L ~ 0.19%, 20x larger than required precision

The focussing is stronger along positive x-axis

- This is due to the crossing angle







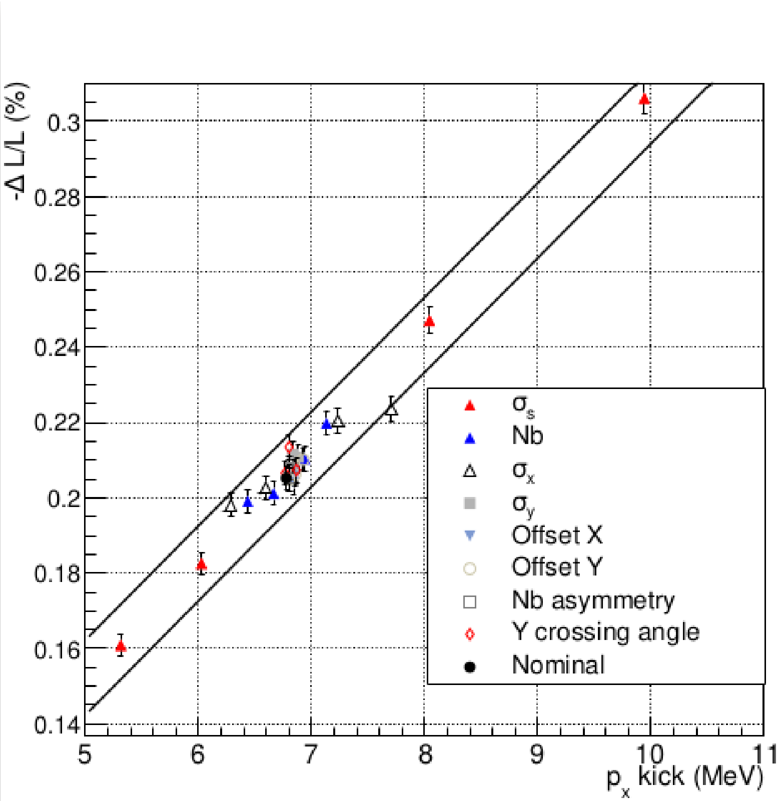
Correction using the central tracker

The Px kick is not the cause of the bias on the L measurement

- The cause is the EM deflection of the Bhabha final state leptons due to opposite bunch field

However there is a strong correlation between initial and final state effects

- Their source is the same
- To test that, several scenarios were examined in GP, where one of the beam parameters was varied
  - Magnitude of variations much larger than expected precision in the knowledge of the beam par.
- Luminosity bias plotted vs Px kick for each scenario



Variations

- Bunch population: ± 2 and 5 %
- Asymmetry between electron – positron populations: ± 2 and 5 %
- X,Y offsets : ± 20 and 40 % of $\sigma_{x,y}$
- Bunch length and transverse sizes: ± 20 and 40 %

Bias is a linear function of the kick

All scenarios remain within 10^{-4} distance from linear fit

➢ If we can measure the kick → we can estimate the bias

Correction using the central tracker II

The kick is an already known effect (see presentation by D. Shatilov at XIIthFCC-eeEnergy Calibration and Polarization WG meeting)

https://indico.cern.ch/event/687643/contributions/2821791/attachments/1575955/2488613/de_by_bs.pdf

It is expected to alter the crossing angle by a factor $\delta\alpha/\alpha$ ~0.5%

Factor $\delta\alpha$ is important to be measured in order to precisely know E_{cm}

A way to measure $\delta\alpha$ using $e^+e^- \rightarrow \mu^+\mu^-$ has been proposed by P. Janot*

A. Blondel et al., Polarization and Centre-of-mass Energy Calibration at FCC-ee,arXiv:1909.12245

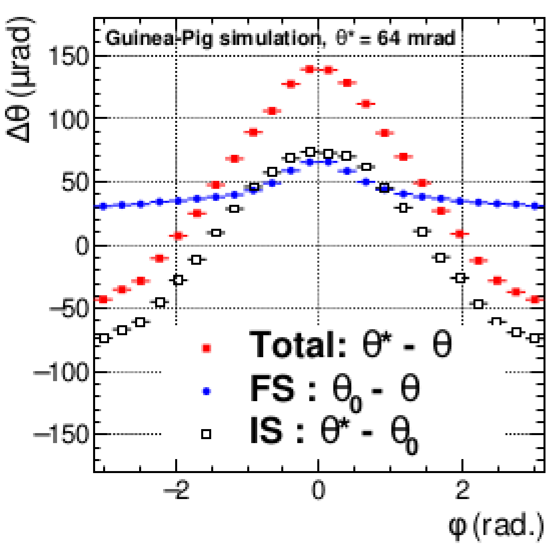
The kick is proportional to $\delta\alpha$ that can be measured with ~2% precision in the central tracker

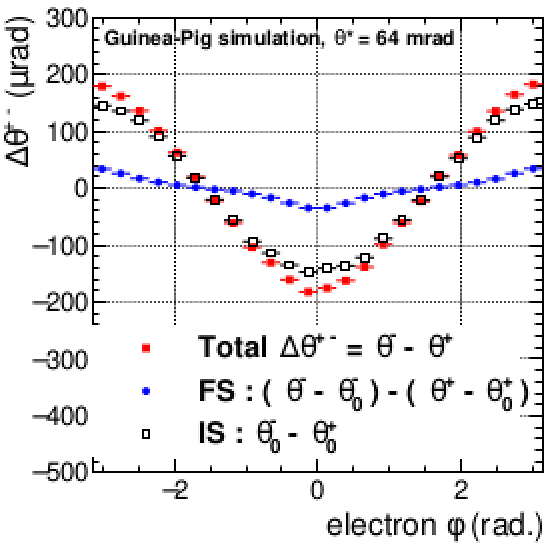
- Directly translates to 2% accuracy for the Px kick
  - The luminosity bias correction factor can be inferred with 2% precision
  - Well within the specification of 5%

Correction using the LumiCal

An alternative way to estimate the L bias using only the LumiCal is proposed:

- That takes advantage of the φ modulation of the beam – beam effects
  - Which leads to an acollinearity $\Delta\theta = \theta^{-} - \theta^{+}$
    - Amounts to ~200μrad, for particles in LumiCal acceptance
- Polar angle reconstruction uncertainty of ~ 140μrad
- RMS of Acol. distribution ~ 100μrad
- Few hundred events enough to measure Acol ~ 5% precision





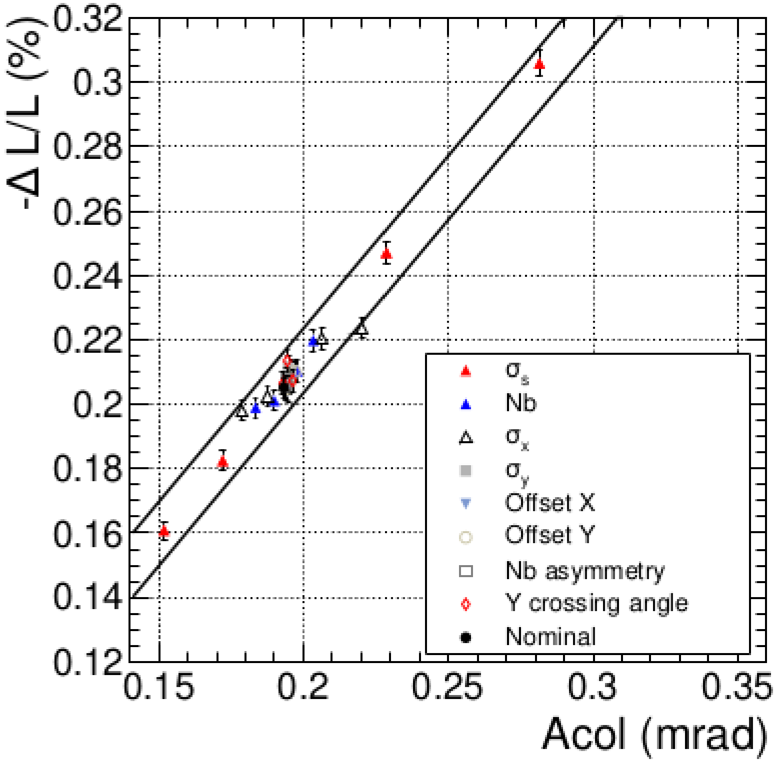
Correction using the LumiCal II

We performed similar exercise as with the Px kick

Strong correlation between beam-beam effects & acollinearity is observed

Again, All scenarios remain within 10^{-4} distance from linear fit

- Therefore, the L bias can be estimated with the required precision by measuring the acollinearity using the LumiCal



But this idea assumes that the only sources of azimuthal asymmetry in LumiCal rate are the beam – beam effects

- Not true!

Misalignment along X axis causes similar modulation with Px kick

$Acol^{meas} = Acol^{kick} + Acol^{EMD} + Acol^{misalignment}$

- An alignment precision of 5μm is required. Is it achievable?
- If not, how can we disentangle between misalignment and beam – beam effects?

1. Using the filling of the machine

Inspired by the method of measurement of the x-angle increase $\delta\alpha$ due to the kick

During the filling of the machine, half intensity is injected in the bunches

- they are then topped up by steps of 10%, till nominal intensity is reached
- 1 measurement for each step (+1 for nominal intensity)

The method can be used since β function is nominal during the fill (we will have collisions)

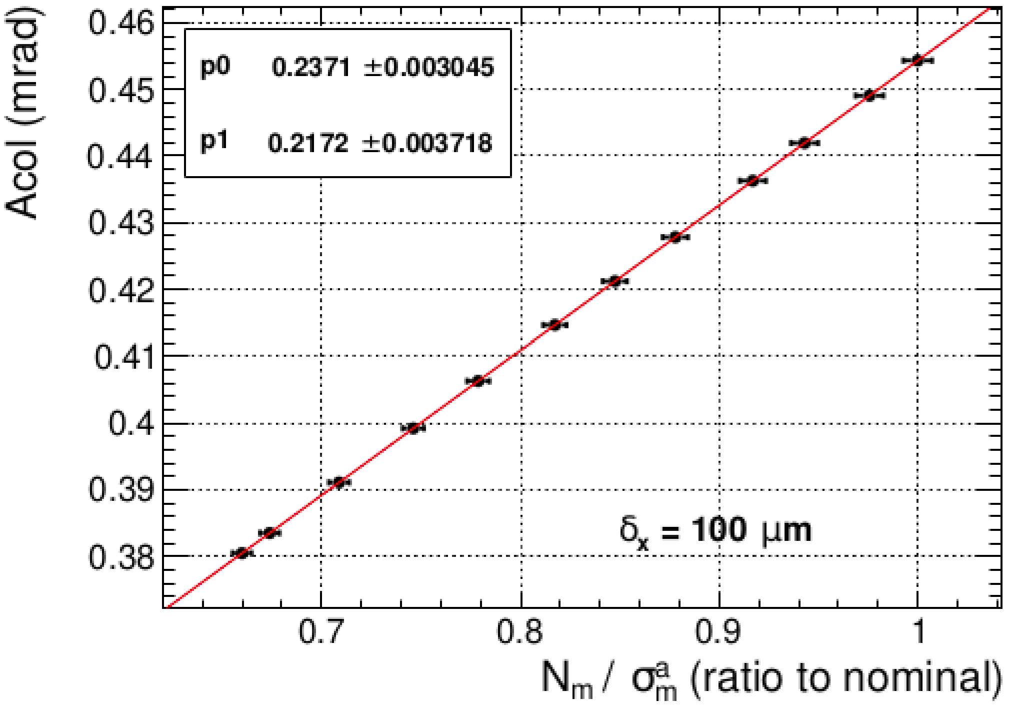
- No luminosity loss!

0 intensity $\rightarrow$ no beam – beam effects $\rightarrow$ y-intercept gives Acol due to no beam – beam (misalignment)

Slope will give Acol due to beam-beam effects

e.g. 100µm misalignment

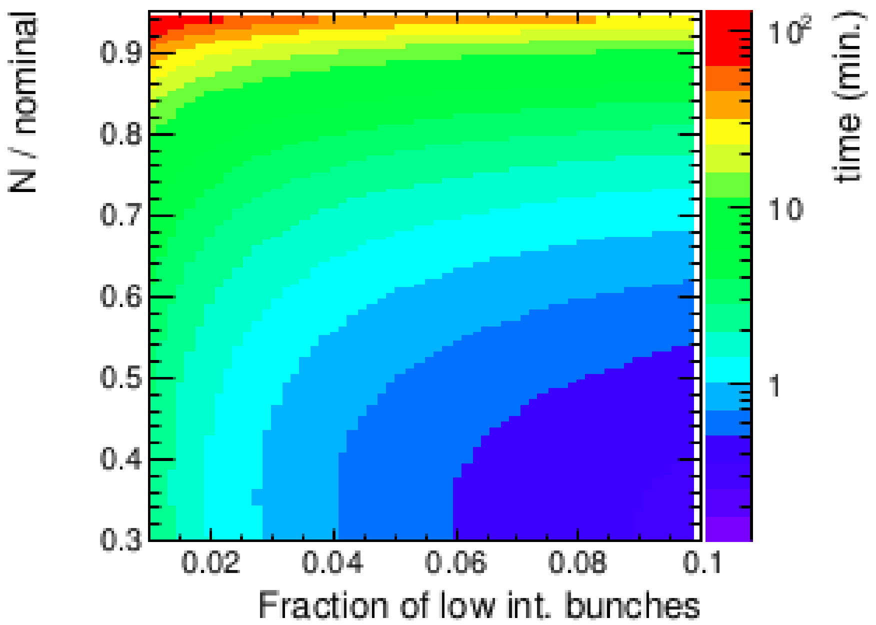
- ~ 2% precision in $Acol^{beam}$ by taking measurements at each step for 40s

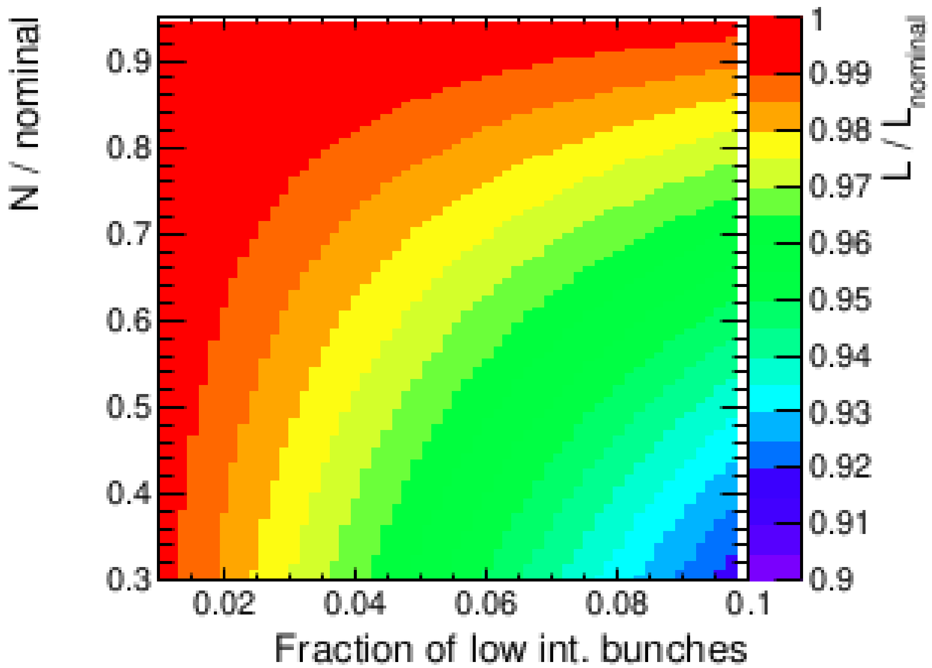


2. Using pilot bunches

Assuming that a fraction of bunches features lower intensity

- Want to minimize the luminosity loss, still allowing a measurement of Acol$^{beem\text{-}beam}$ on a time-scale << fill duration
- Low intensity : larger lever-arm... but low statistics !





E.g. we can measure the Acol$^{beem\text{-}beam}$ during 10min with the required precision of 5% if

- 2% of the bunches have 85% of the nominal intensity
- Resulting loss in luminosity: 0.5%

Beam – beam effects on the L measurement at LEP

In the context of the FCCee study, we realised that beam – beam effects affected the L measurement at LEP

- Created a bias of ~ 0.1%
  - Was not accounted for by the LEP experiments
  - Large compared to uncertainties reported by the experiments (e.g. OPAL reports 0.034% exp and 0.054% theory uncertainty)
  - It has an impact on the measurement of the number of light neutrino species

The bias was calculated for each LEP experiment and each year (1990 - 1995) at & around the Z pole using averaged beam parameters

- Tools: BHLUMI was used for the generation of Bhabha events, then fed to GP
- Used same selection criteria (E, N-W acceptance, acollinearity) for each experiment as the ones used during LEP times

Impact on N_ν

Number of light neutrino spedies reported from LEP: $N_\nu = 2.9840 \pm 0.0082$

When beam – beam effects are accounted for, N_ν moves by 0.95σ closer to 3

- $N_\nu = 2.9918 \pm 0.0081$

Moreover, beam – beam effects were found to have an impact in Γ_z and the Z peak hadronic cross section

- $\Gamma_z = 2.4955 \pm 0.0023$ GeV (+0.3MeV increase)
- $\sigma_{had}^0 = 41.500 \pm 0.0037$ nb (-40pb decrease)

The study has been documented here:

https://arxiv.org/abs/1908.01704

The paper has been accepted for publication at Phys. Let. B

Summary/Outlook

Beam – beam effects will cause a bias ~20 times larger than the required precision

Two independent correction approaches have been proposed

- Using the LumiCal
- Using the main tracker

The studies can be found here:

https://doi.org/10.1007/JHEP10(2019)225

First “application”: beam – beam effects created a ~0.1% bias in luminosity measurement in LEP

- 2σ deficit in N_ν is reduced to ~1σ

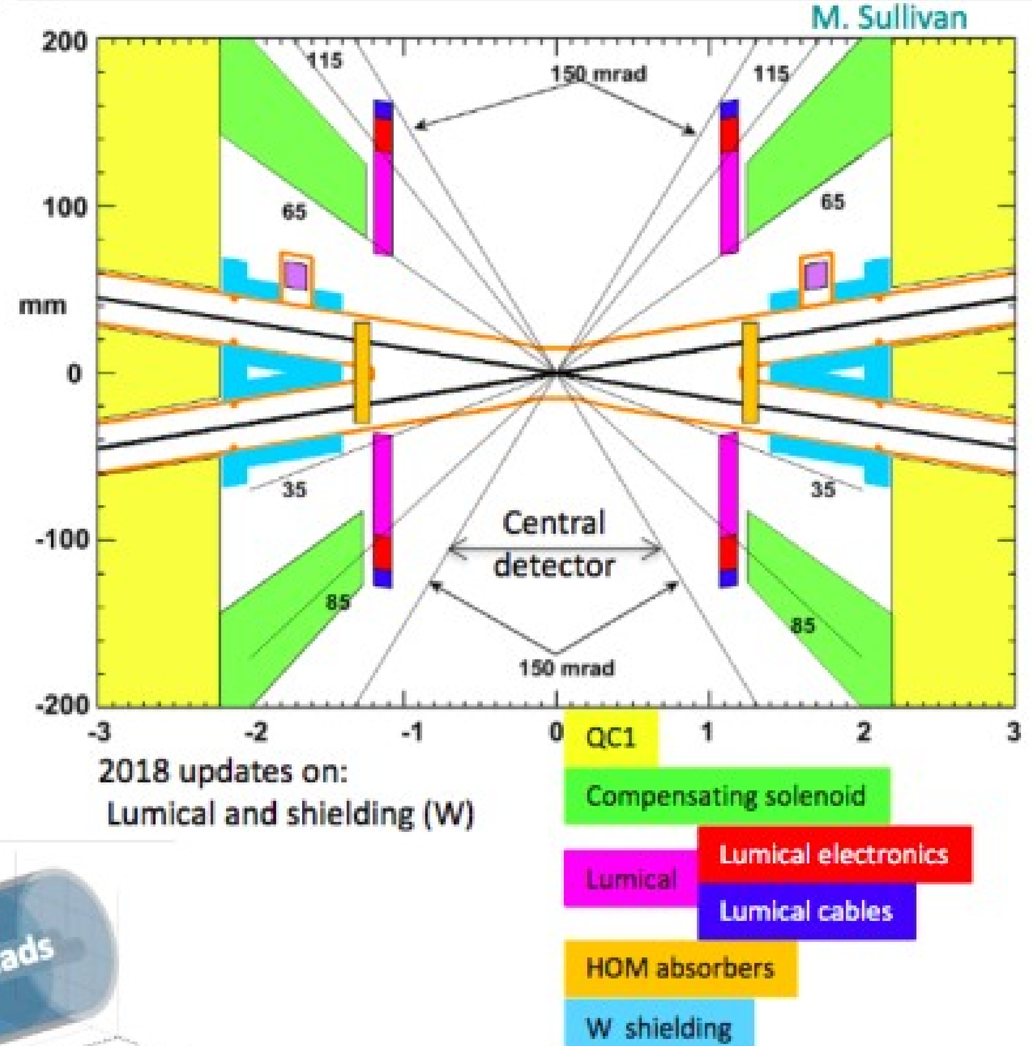
Outlook

- Crosschecks calculations are in principle possible using the LEP data
- Bias is proportional to the asymmetry in LumiCal’s counting rate wrt the Z vertex of the event
  - Could be of interest for a linear collider

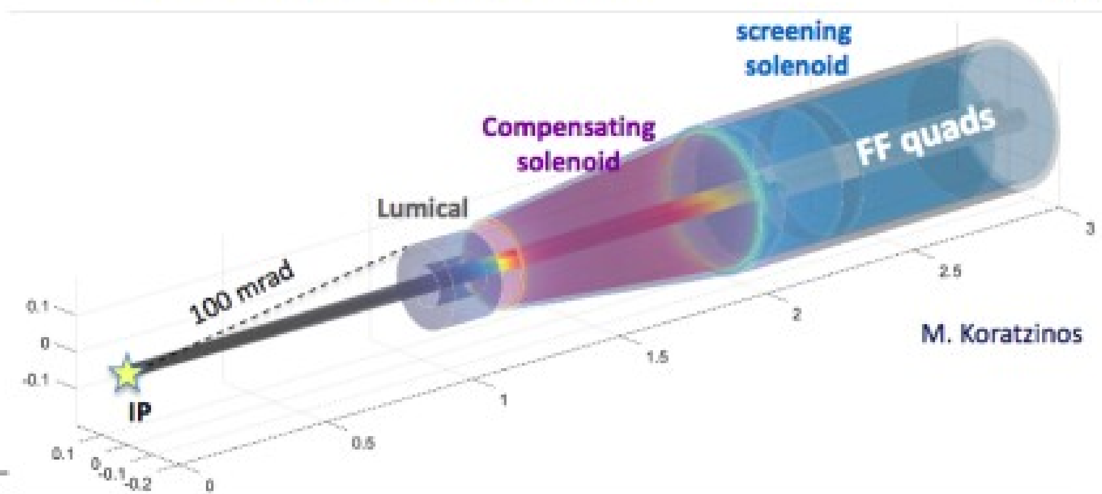
BACKUP

Interaction Region Layout

- Unique and flexible design at all energies
  - $L^* = 2.2$ m
    - Acceptance: 100 mrad
  - Solenoid compensation scheme
    - Reduce ε_y blow-up $\Rightarrow B_{Detector} \leq 2T$
  - Beam pipe
    - Warm, liquid cooled (~SuperKEKB)
    - Be in central region, then Cu
    - R = 15 mm in central region
      - 1st vertex detector layer 17 mm from IP
    - SR masks, W shielding
  - Mechanical design and assembly concept
    - Under engineering study



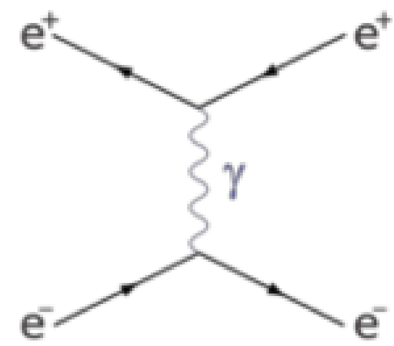
2018 updates on:
Lumical and shielding (W)



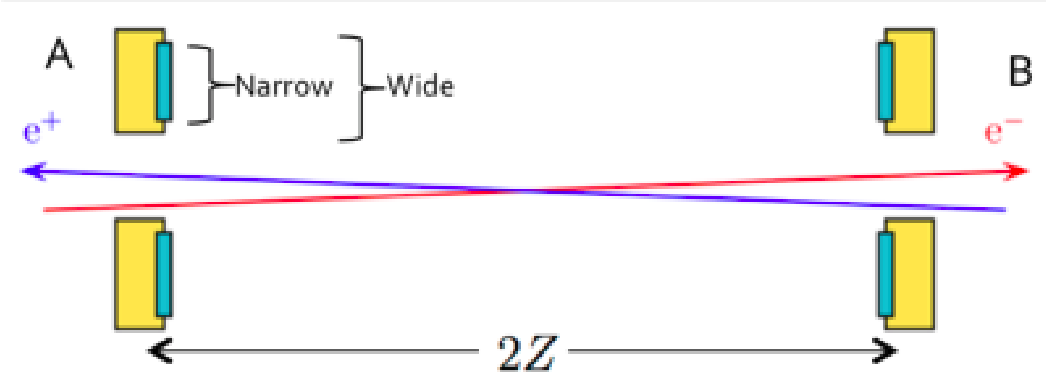
Luminosity Measurement

- Standard lumi process is small angle elastic e^+e^- (Bhabha) scattering
  - Dominated by *t*-channel photon exchange
  - Very strongly forward peaked

$$\sigma^{\text{Bhabha}} = \frac{1040 \text{ nb GeV}^2}{s}\left(\frac{1}{\theta^2_{\text{min}}} - \frac{1}{\theta^2_{\text{min}}}\right)$$



  - Measured with set of two calorimeters; one at each side of the IP
    - Crossing beams: Center monitors on outgoing beam lines



Two counting rates:
- SideA = NarrowA + WideB
- SideB = NarrowB + WideA

    - Minimize dependence on beam parameters and misalignment:
      - Average over two counting rates: **SideA + SideB**
  - Important systematics from acceptance definition: *minimum scattering angle*

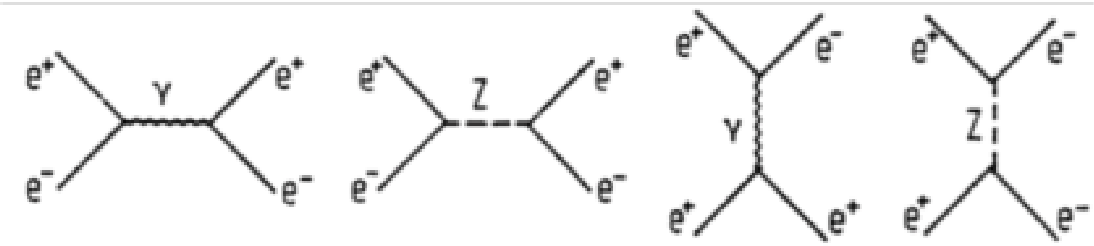
$$\frac{\delta\sigma^{\text{acc}}}{\sigma^{\text{acc}}} \simeq \frac{2\delta\theta_{\text{min}}}{\theta_{\text{min}}} = 2\left(\frac{\delta R_{\text{min}}}{R_{\text{min}}} \oplus \frac{\delta z}{z}\right)$$

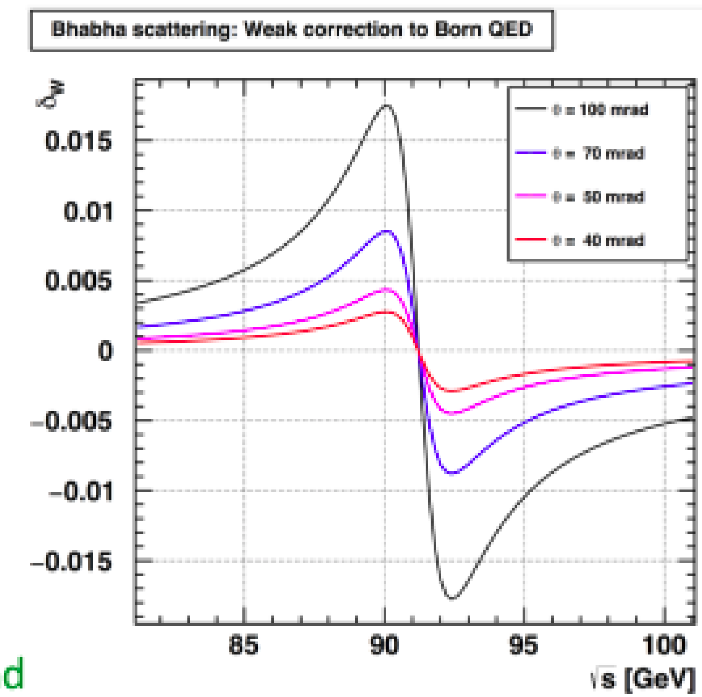
Normalisation to 10^{-4}

- The goal at FCC-ee is an absolute normalization to 10^{-4}
- After much effort, precision on absolute luminosity at LEP was dominated by theory
  - Example **OPAL** - most precise measurement at LEP:

    Theory: 5.4×10^{-4} **Experiment: 3.4×10^{-4}**

  - Since then, theory precision has improved to **3.8×10^{-4}** [Jadach et al, 1812.01004]
- Ambitious FCC-ee goal: Total uncertainty to precision of **10^{-4}**
  - Will require major effort within **theory**
    - Four graphs already at lowest order

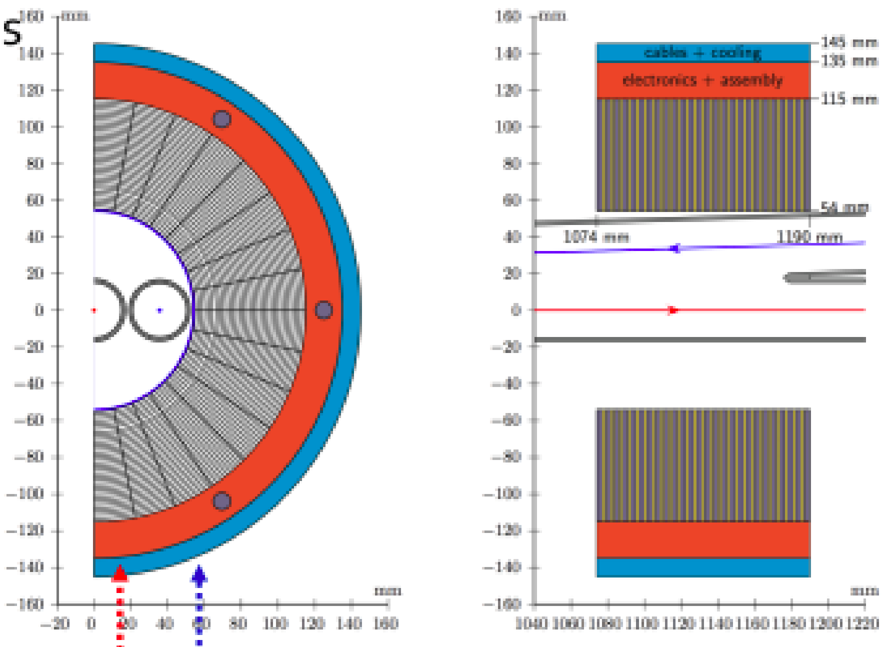




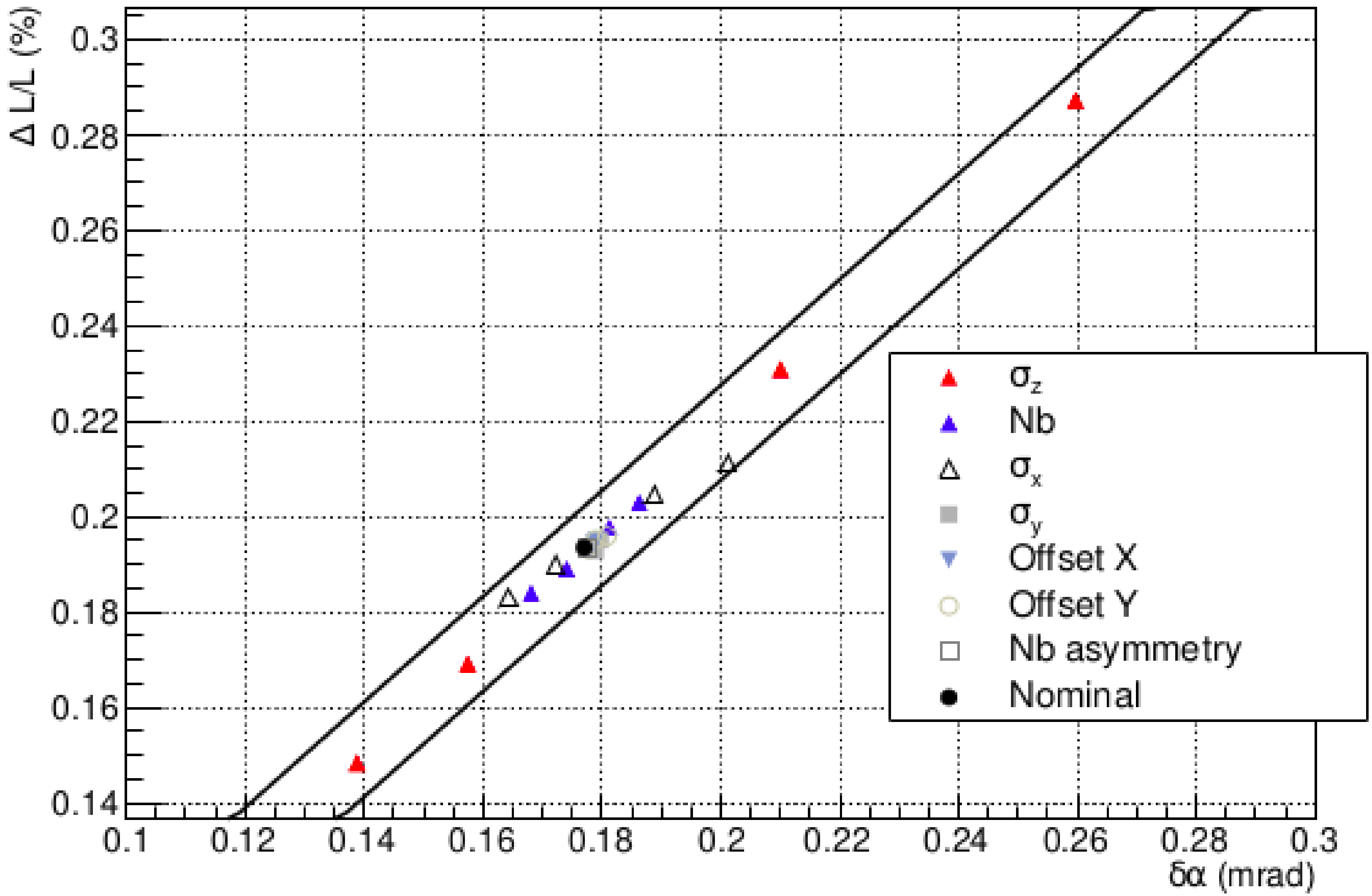
    - Dependence on Z parameters (increasing with angle)
    - Lots of radiative corrections between initial and final legs
  - Will require major effort **experimentally**
    - Second generation LEP luminosity monitors constructed and monitored to ***tolerances better than 5 μm***

LumiCal Design

- W+Si sandwich: 3.5 mm W + Si sensors in 1 mm gaps
  - Effective Moliere radius: ~15 mm
- 25 layers total: 25 X_0
- Cylindrical detector dimensions:
  - Radius: 54 < r < 145 mm
  - Along outgoing beam line: 1074 < z < 1190 mm
- Sensitive region:
  - 55 < r < 115 mm;
- Detectors centered on and perpendicular to outgoing beam line
- Angular coverage (>1 Moliere radius from edge):
  - Wide acceptance: 62-88 mrad
  - Narrow acceptance: 64-86 mrad
  - Bhabha cross section @ 91.2 GeV: 14 nb
- Region 115 < r < 145 mm reserved for services:
  - Red: Mechanical assembly, **read-out electronics**, cooling, equipment for alignment
  - Blue: Cabling of signals from front-end electronics to digitizers (behind LumiCals?)



Design inspired by LEP gen2 LumiCals and FCAL work (in particular Crakow group)


Δ L/L (%)
0.3
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0.26
0.28
0.3
δα (mrad)
σz
Nb
σx
σy
Offset X
Offset Y
Nb asymmetry
Nominal