Luminosity Measurement at FCC-ee

FCC-Week, Roma
11-15 April 2016

Mogens Dam
Niels Bohr Institute
Copenhagen, Denmark

Luminosity Measurement

- Normalization of cross section of physics process *i* to a standard "lumi" process with known cross section:

$$\sigma_i = \frac{N_i}{L} \qquad \text{with} \qquad L = \frac{N_{\text{lumi}}}{\sigma_{\text{lumi}}}$$

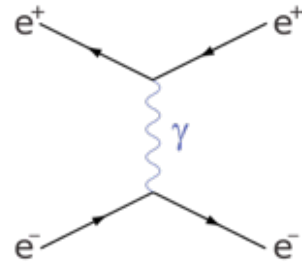
- Requirements for lumi process
  - Must have ***calculable cross section*** with minimal model dependence
    - Basically QED dominated
  - Should provide ***sufficient statistics*** to not dominate uncertainty

$$N_{\text{lumi}} \gg N_i \qquad \Rightarrow \qquad \sigma_{\text{lumi}} \gg \sigma_i$$

- Main FCC-ee physics processes:

Energy	Process	Cross Section	Statistics
90 GeV	$e^+e^- \rightarrow Z$	40 nb	10^{12}
160 GeV	$e^+e^- \rightarrow W^+W^-$	4 pb	10^8
240 GeV	$e^+e^- \rightarrow ZH$	200 fb	10^6
350 GeV	$e^+e^- \rightarrow tt$	500 fb	10^6

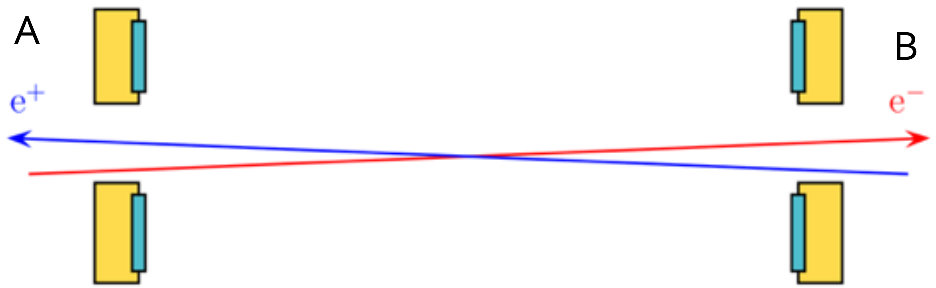
Lumi processes (i)

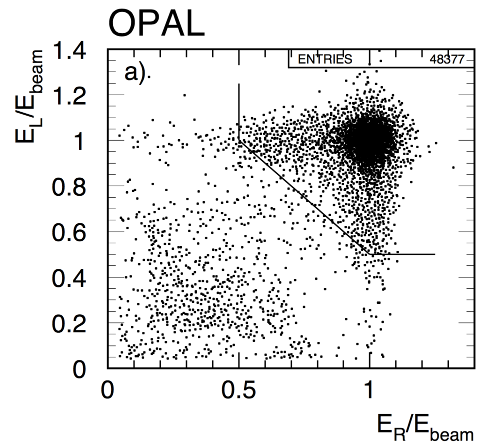


- Standard lumi process is small angle elastic e⁺e⁻ (Bhabha) scattering
  - Dominated by t-channel photon exchange
  - Very strongly forward peaked

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

  - Measured with set of two calorimeters; one at each side of the IP





    - Typically between θ_{min} = 30-50 mrad and θ_{max} = 50 – 100 mrad ; σ ≃ O(50 nb) @ 90 GeV
    - Minimize dependence on beam parameters: define **loose and tight fiducial volumes**

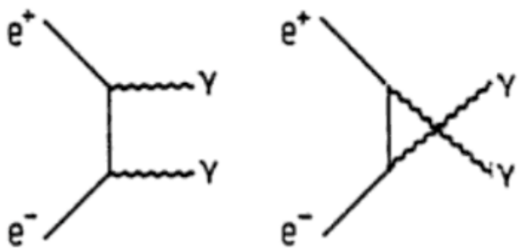
$$\mathrm{acceptance} = \mathrm{tightA} \cap \mathrm{looseB} + \mathrm{tightB} \cap \mathrm{looseA}$$

    - With finite beam crossing angle: Center **acceptances around outgoing beam lines**
  - Important systematics from acceptance definition: *minimum scattering angle*

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

Lumi processes (ii)

- Possible alternative lumi process: Large angle photon-pair production
  - Only "one" graph at lowest order – very poor literature at NNLO and beyond



H.-U. Martyn, Adv.Ser.Direct.High Energy Phys. 7 (1990) 92-161

$$\sigma(e^+e^- \to \gamma\gamma) = \frac{2\pi\alpha^2}{s}\left\{\ln\frac{1+\cos\theta_{min}}{1-\cos\theta_{min}} - \cos\theta_{min}\right\}$$

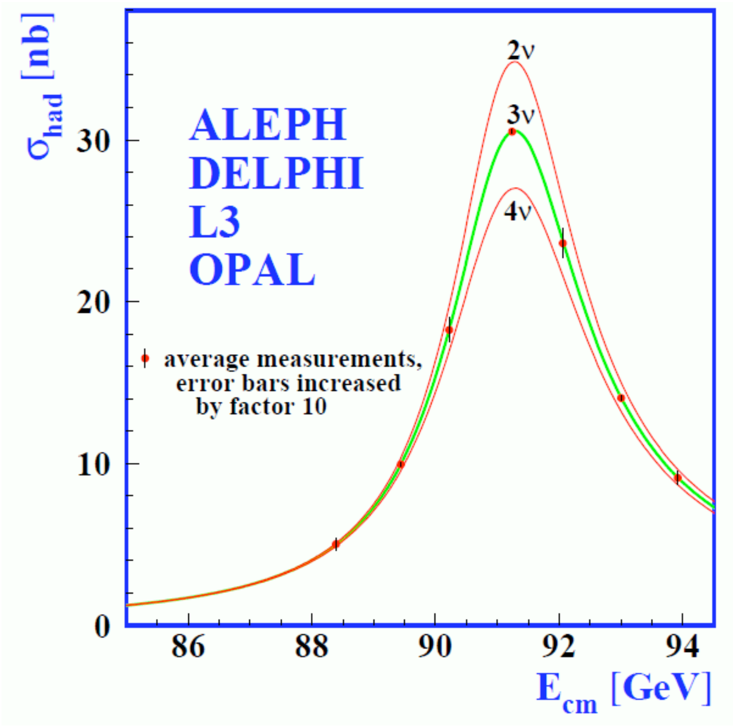
(θ_{min} defines the ECAL acceptance)

  - Pure QED process with few radiative corrections between initial legs and propagator
  - Cross section is much smaller than small angle Bhabha, but adequate everywhere but at Z-pole running
  - Main experimental background: Large angle Bhabha scattering ($e^+e^- \to e^+e^-$)
  - Example: $\theta_\gamma > 20^o$ ($\cos\theta_\gamma < 0.94$) with respect to the beam axis:

Energy	Process	Cross Section	$e^+e^- \to \gamma\gamma$	$e^+e^- \to e^+e^-$
90 GeV	$e^+e^- \to Z$	40 nb	0.039 nb	2.9 nb
160 GeV	$e^+e^- \to W^+W^-$	4 pb	15 pb	301 pb
240 GeV	$e^+e^- \to ZH$	200 fb	5600 fb	134000 fb
350 GeV	$e^+e^- \to tt$	500 fb	2600 fb	60000 fb

Tera-Z Luminosity Measurement

- Let's set aside the higher energy running points, where large angle $e^+e^- \to \gamma\gamma$ production could be the way to go, and concentrate for the time being on Tera-Z
- Types of luminosity measurement
  - **Absolute:** Determination of peak cross section; Number of neutrino species
  - **Relative point-to-point:** Determination of line-shape parameters M_Z and Γ_Z

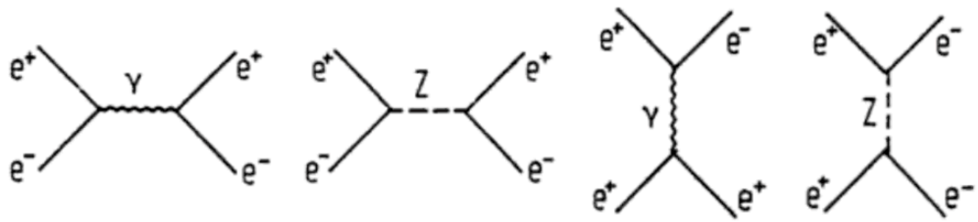


Tera-Z Absolute Normalisation (i)

- After much effort, precision on absolute luminosity at LEP was dominated by theory (example OPAL):

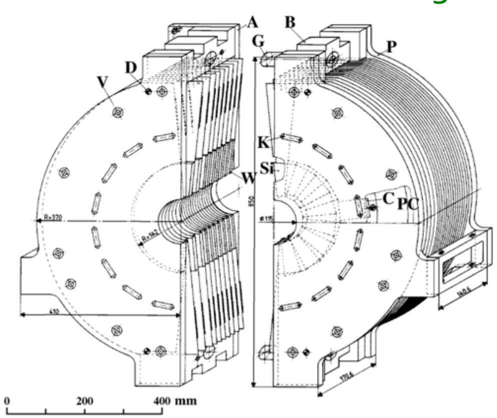
  Theory: 5.4×10^{-4} **Experiment: 3.4×10^{-4}**

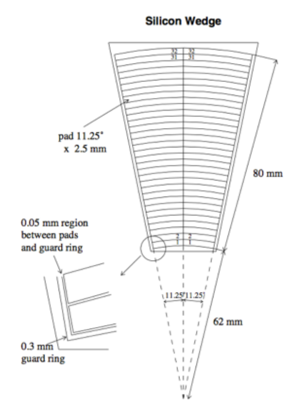
- Ambitious FCC-ee goal: Total uncertainty to precision of order **10^{-4}**
  - Will require major effort within **theory**
    - Four graphs already at lowest order



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

Opal luminosity calorimeter
Tungsten/silicon





Tera-Z Absolute Normalisation (ii)

- With 10^{12} Zs, will have 10^9 $e^+e^- \rightarrow \gamma\gamma$ events
  - Statistical precision of 3×10^{-5}
  - Systematic precision?
    - Theoretical situation of the $e^+e^- \rightarrow \gamma\gamma$ will need to be reviewed
    - Have to control the 100 times larger large angle Bhabha scattering cross section background to a relative precision of $O(10^{-7})$
      - Electron/photon separation controlled to $O(10^3 - 10^4)$
      - Remember that large angle Bhabha scattering has large Z dependence
  - Possibly $e^+e^- \rightarrow \gamma\gamma$ is our best bet to get precise **absolute** normalisation ??
    - To be pursued…

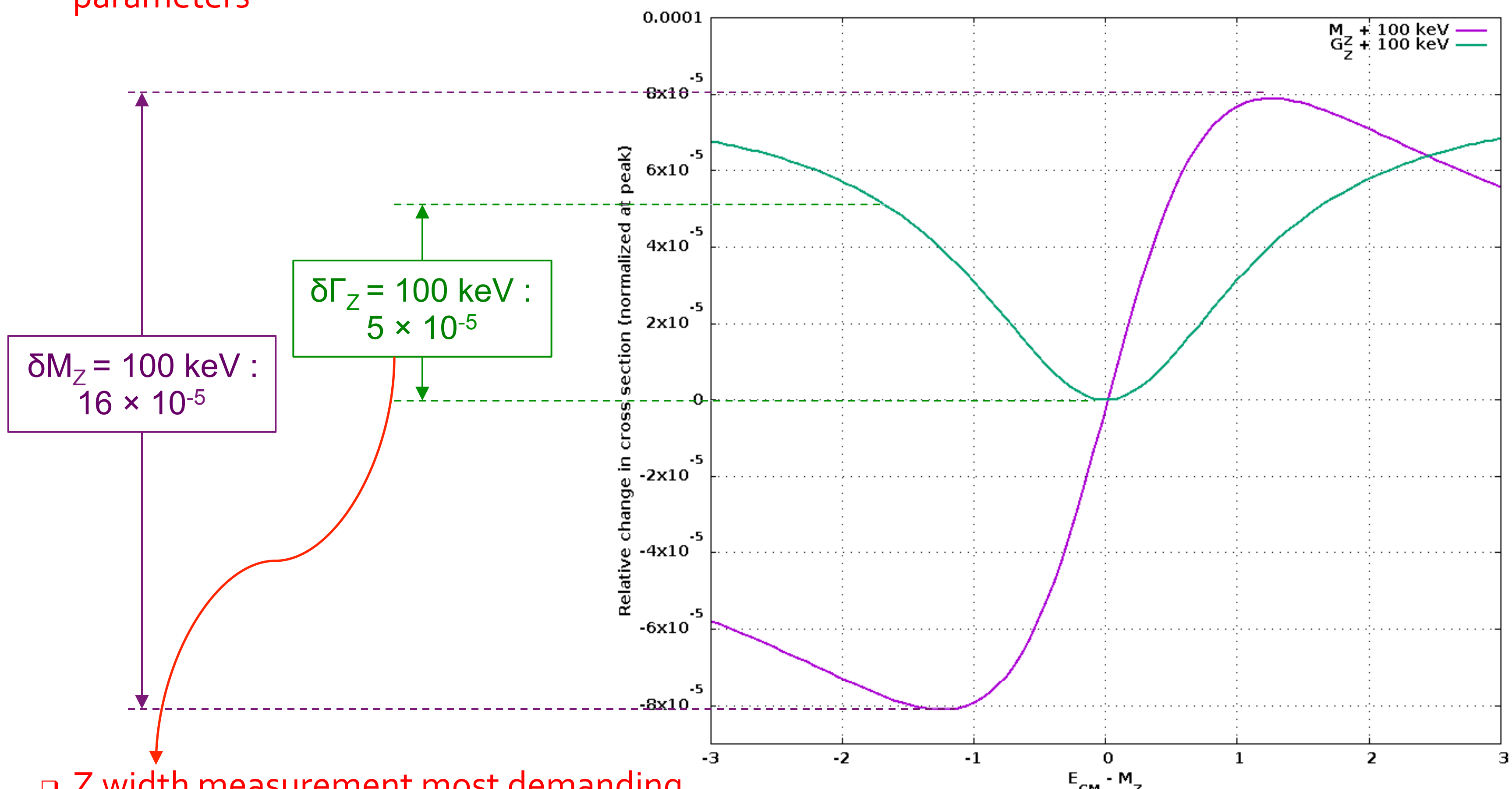
- But we still need relative normalisation…

Tera-Z Relative Normalisation (i)

- FCC-ee goal: Determine Z parameters to precisions:

$\delta M_Z = 100$ keV ; $\delta\Gamma_Z = 100$ keV

  - Plot shows relative change in cross section across Z resonance for variation of this size in these parameters



  - Z width measurement most demanding
    - Need **relative** normalisation to about **2 × 10^{-5}**

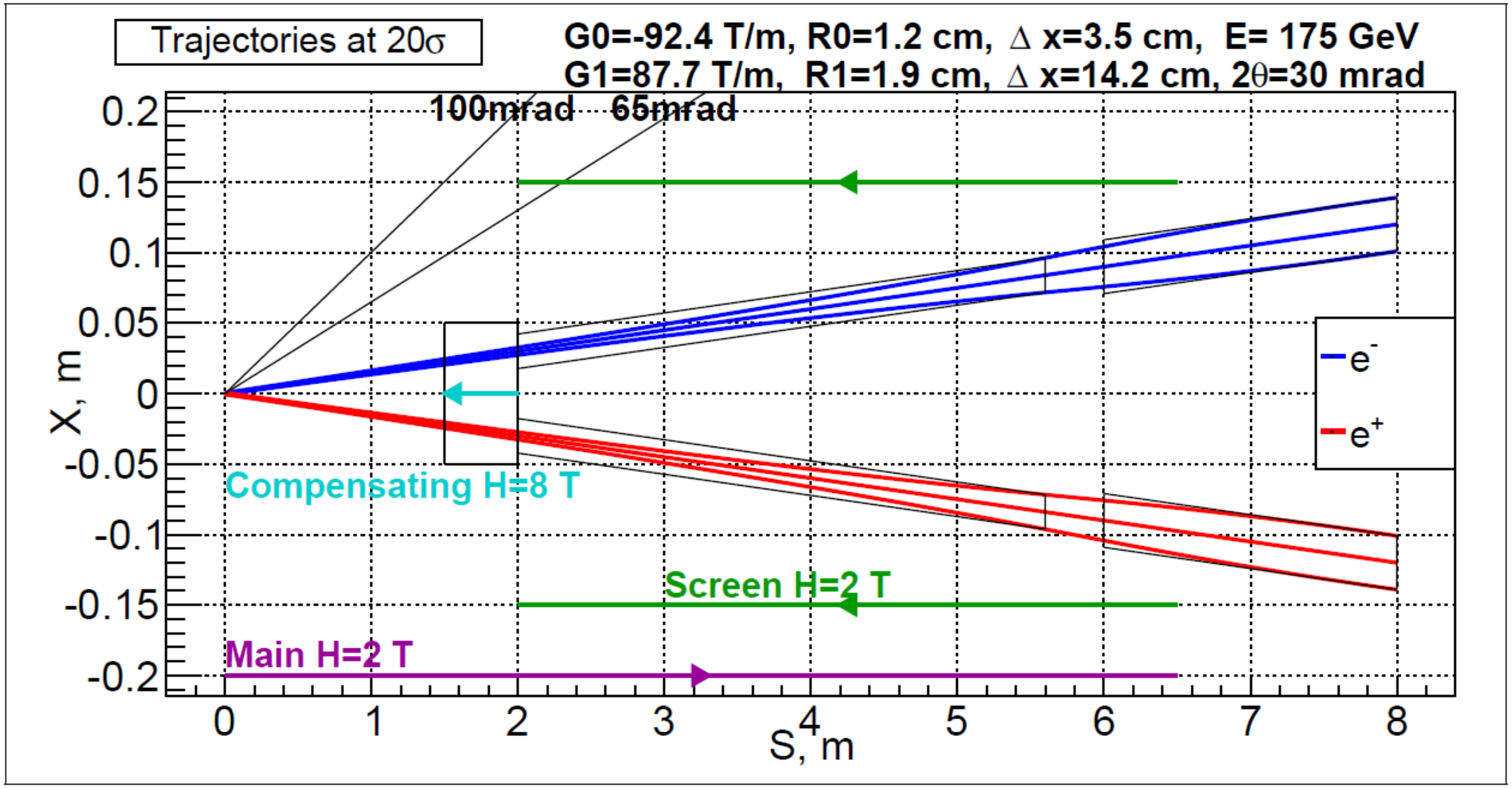
Tera-Z Relative Normalisation (ii)

- Relative normalisation to 2×10^{-5}
  - Need statistics of order $10^9 - 10^{10}$
  - To optimize sensitivity of off-peak running, aim for cross section ≳ Z production; i.e ≳ 15 nb
  - We are back to small angle Bhabha scattering

- Let's take a look at the experimental situation…

IR Layout (i)

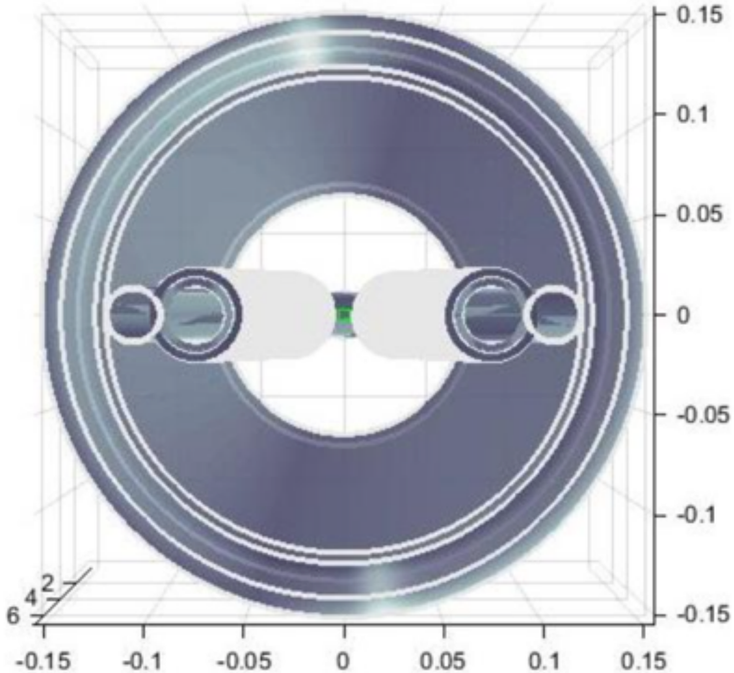
Anton Bogomyagkov

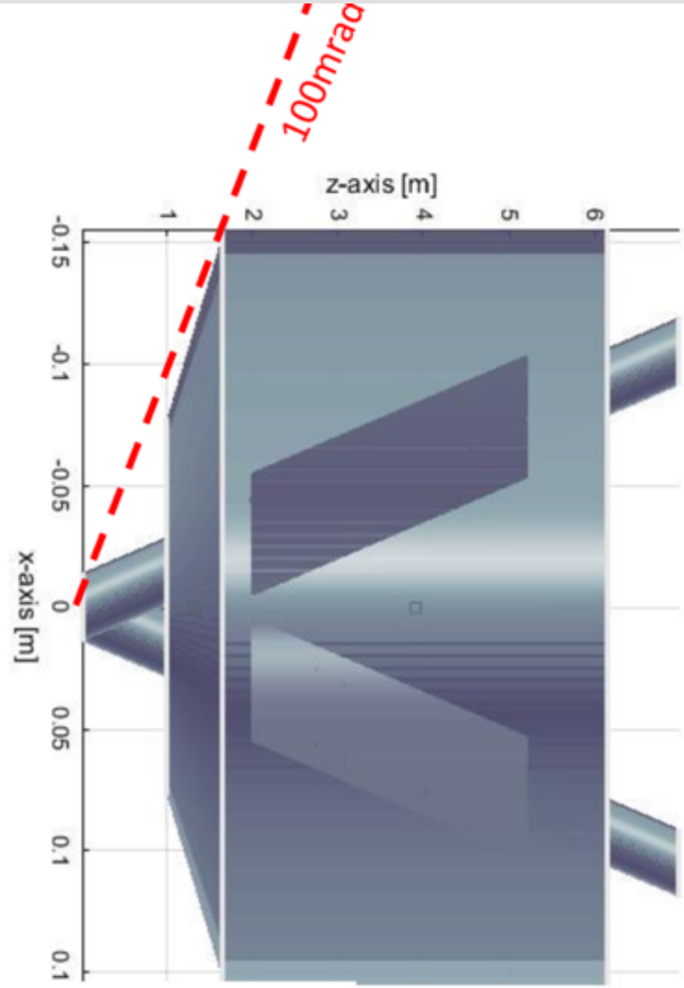


- Beams cross at an angle of 30 mrad
- Quadrupoles are close to IP: $L^* \approx 2$ m
- Need compensation for detector solenoid due to non-zero crossing angle

IR Layout (ii)

Mike Koratzinos:
Study of magnet compensation

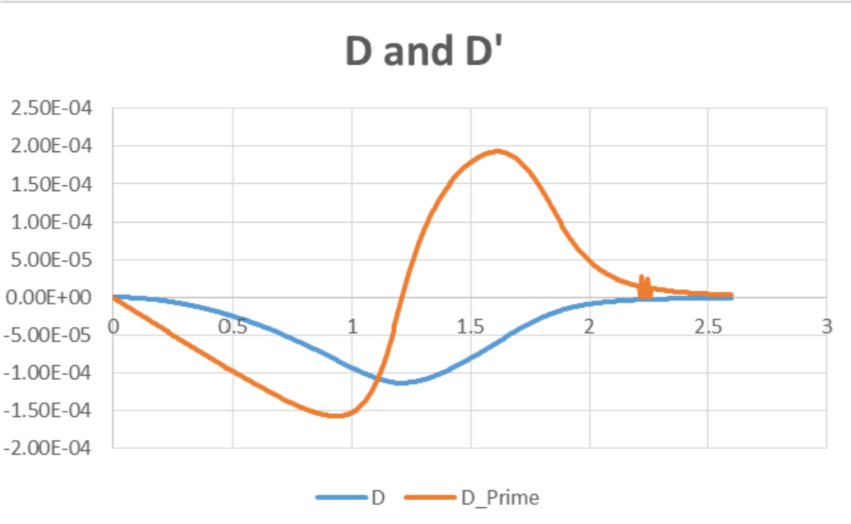


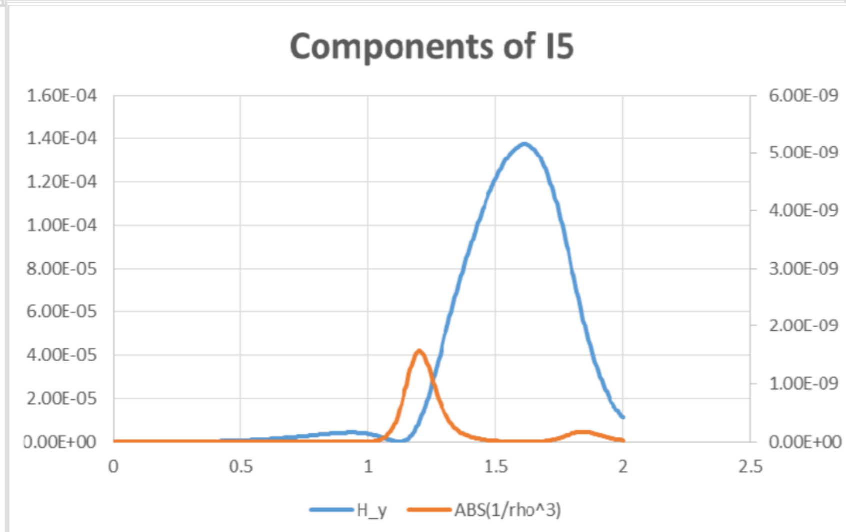


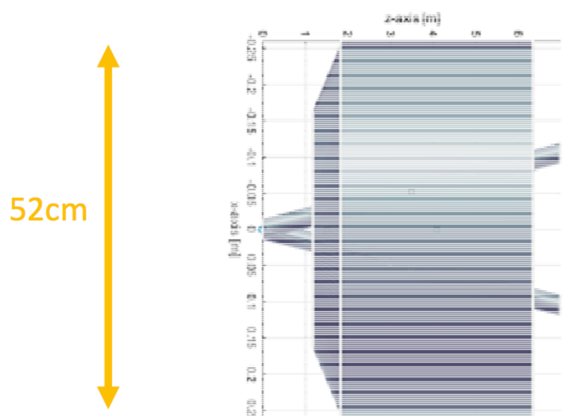
True proportions view

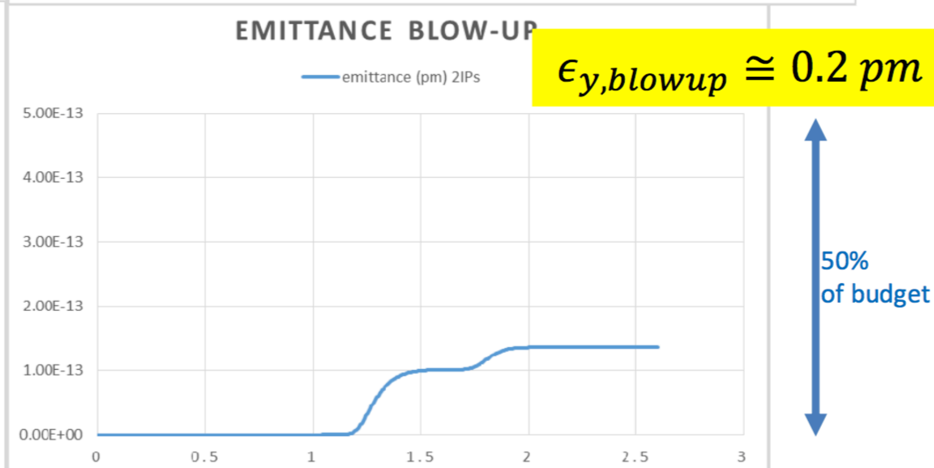
New proposal, 140mrad cone, solenoids start at 1.2m, 2 IPs

Mike Koratzinos



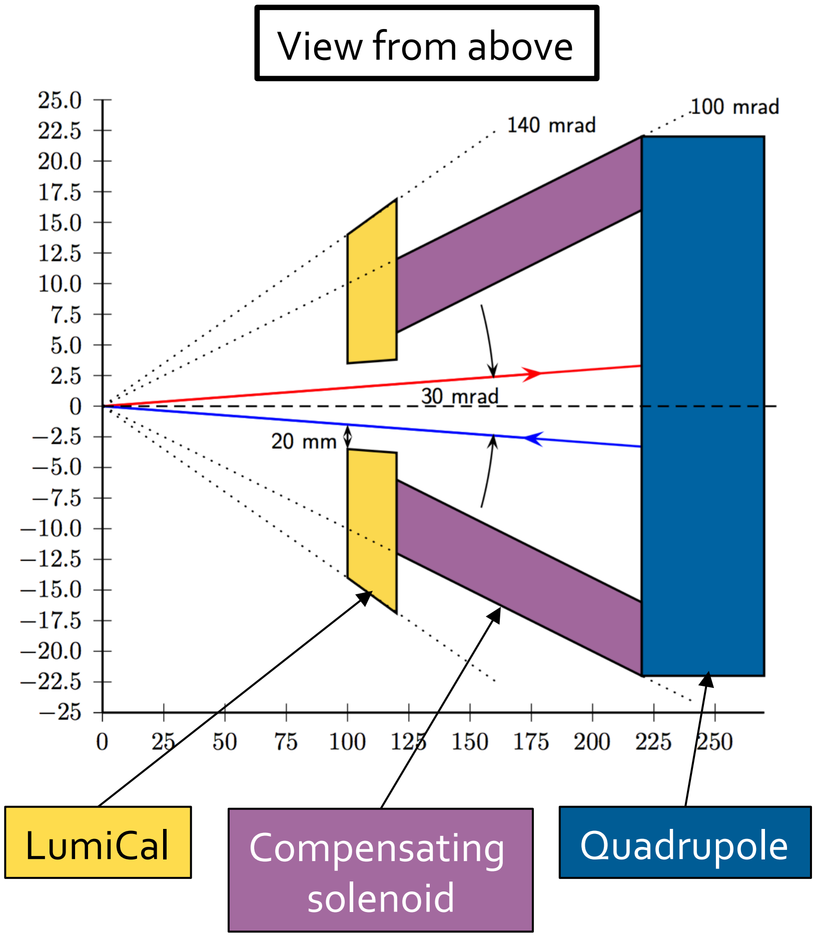


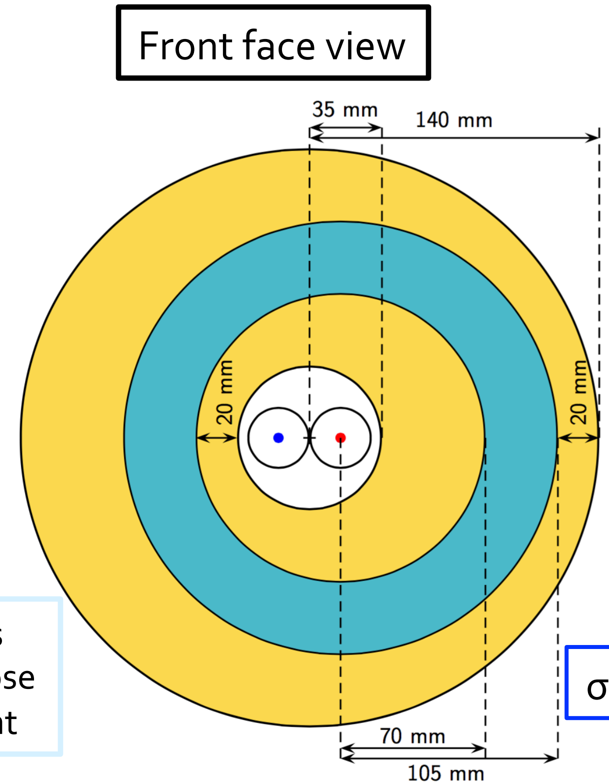




$\epsilon_{y,blowup} \cong 0.2\ pm$

Trying to *squeeze* in a LumiCal …





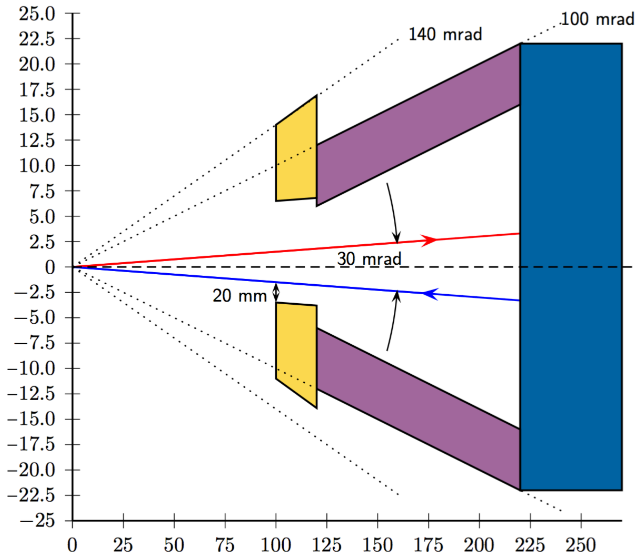
Acceptances
- Yellow: Loose
- Green: Tight

σ = 14 nb

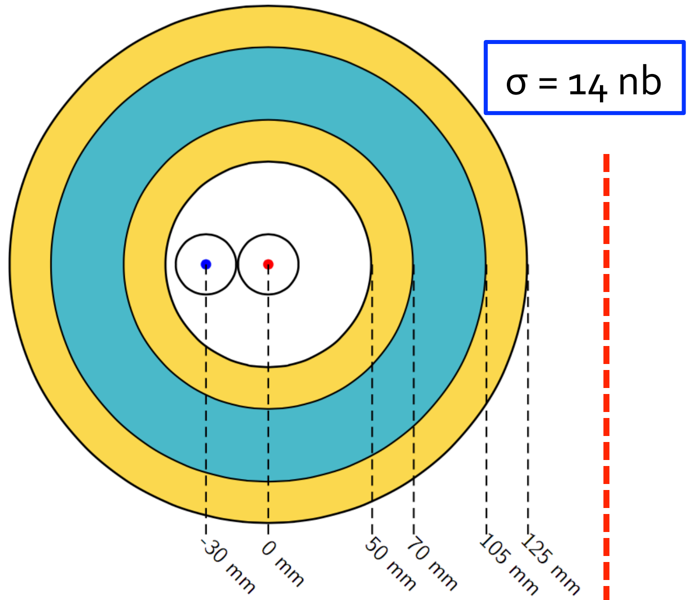
Here, have assumed that compensating solenoid stops at z=120 cm as proposed by M. Koratzinos

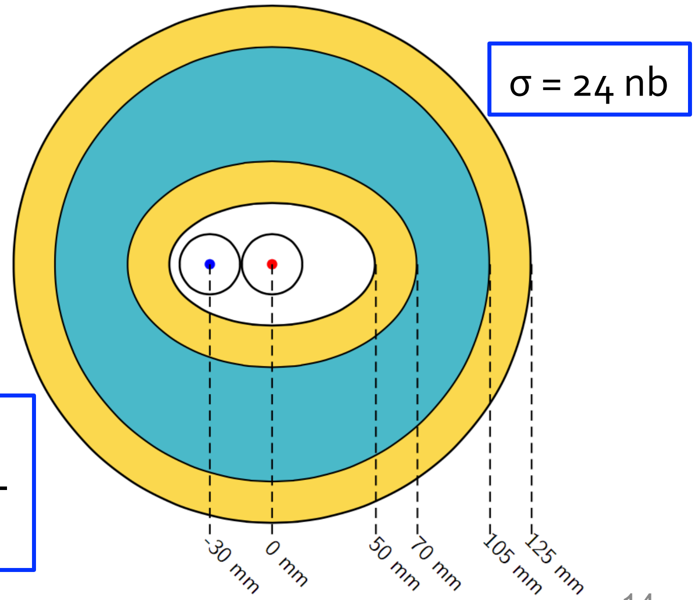
Here
- Lumical centered in detector system
- Tight acceptance centered around outgoing beam

Symmetric detector placed around outgoing beam



This gives asymmetric coverage in detector system

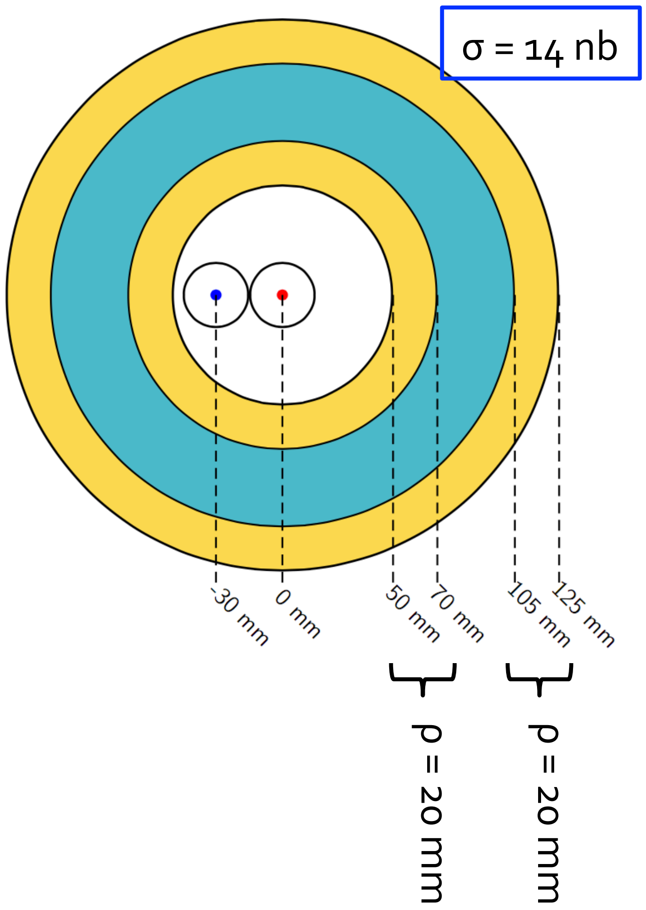




Can gain some cross section by going to non-circular acceptance

Fiducial volume

- Effective lumi cross section depends critically on ρ, the assumed difference between loose and tight fiducial volume
  - Here assumed ρ = 20 mm (20 mrad @ z = 100 cm)
    - Is this a safe tolerance?
    - OPAL used 100 mm (~40 mrad @ z = 240 cm)

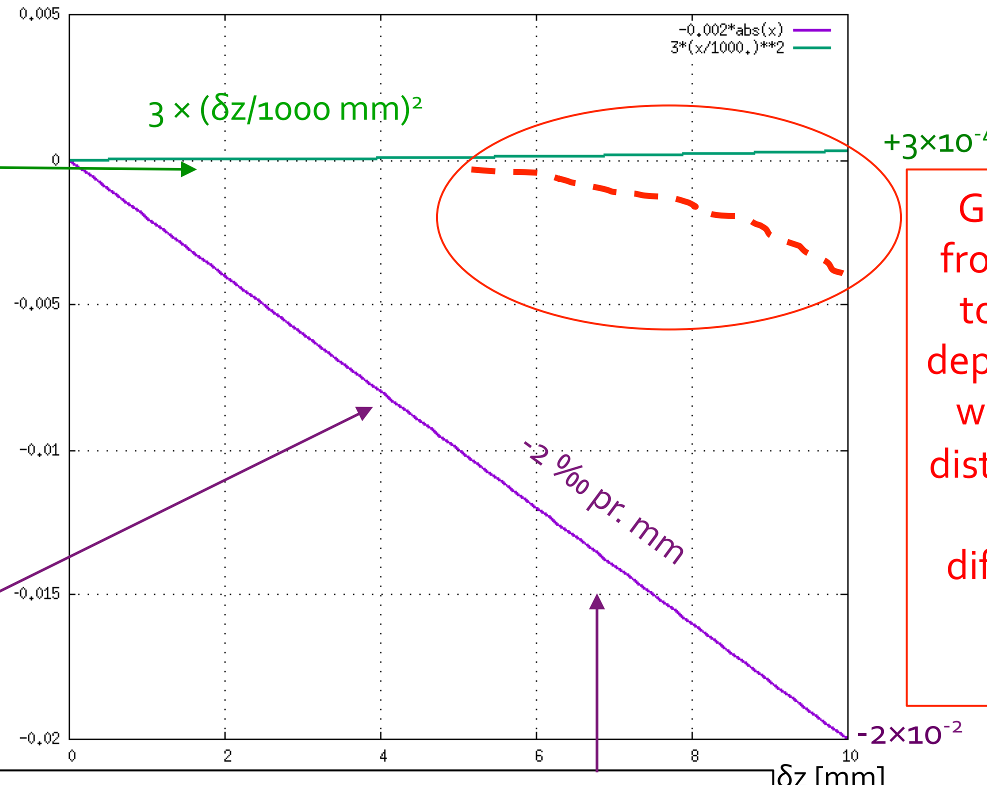


- Effects to take into account when choosing tolerance ρ
  1. Moliere radius of calorimeter (~14 mm)
     - Acceptance definition based also on precise energy measurment
  2. Possible displacements of IP w.r.t. nominal
  3. Bhabha event acollinearity distribution

Dependence on beam parameters

Example: Position of IP along z w.r.t. nominal

Weak 2^{nd} order dependence, when sufficient difference exists between tight and loose acceptance.



Strong 1^{st} order dependence if not using asymmetric acceptance [identical tight and loose acceptance]

Gradual transition from weak 2^{nd} order to strong 1^{st} order dependence, happens when acollinearity distributions starts to be cut off by difference between loose and tight acceptance

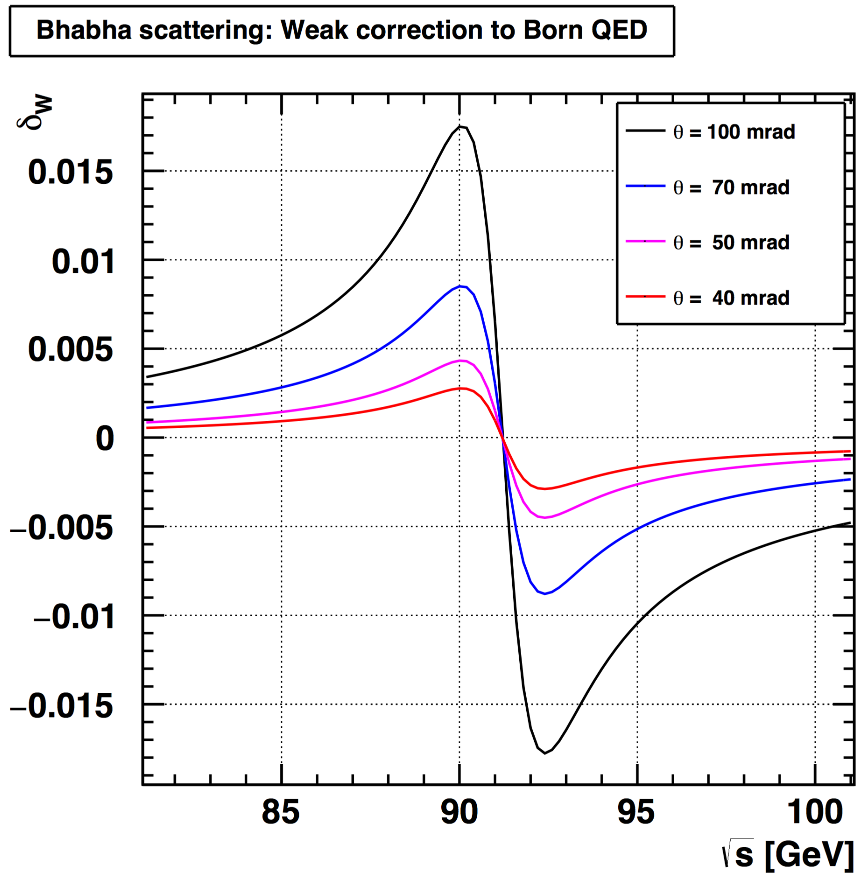
Similar picture for displacements in transverse plane: -2 ‰ pr. 50 μm

For relative normalisation, worry "only" about differences in beam parameters between energy points
Should attempt to stay away from strong 1^{st} order dependence

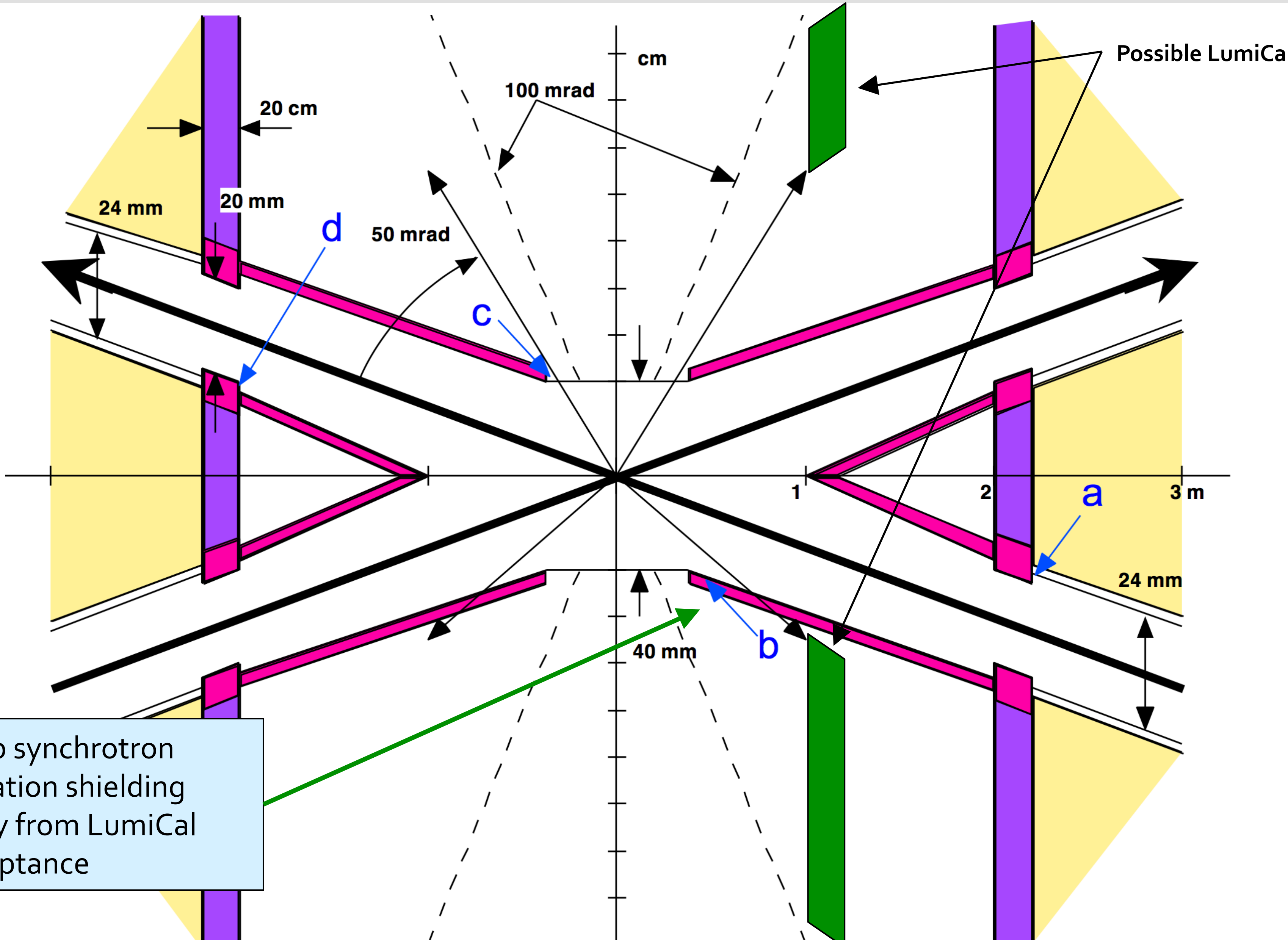
- Gut feeling: ρ=20 mm may be rather aggresive – need to increase ?
    - Need to fire up the bhlumi Bhabha event generator for study

Relative cross section measurement

- The weak correction to the Bhabha cross section is of order 1% for the small angle region considered here
- Have to understand this correction to a relative precision of ~10^{-3}
  - Probably ok, but should check…



SR shielding of beam pipe



Keep synchrotron radiation shielding away from LumiCal acceptance

Another reason to measure small angle Bhabha

Talk Tuesday:

It is stated, that by measuring Bhabha cross section at 3° (~50 mrad) to precision of 10^{-4} one can extract information on α_{QED}.

Need to normalize Bhabha by other process, e.g. large angle $e^+e^- \rightarrow \gamma\gamma$.

Observation: If there is interesting physics information in Bhabha scattering measured to 10^{-4}, then how can the same process be used to normalize to 10^{-4}

Measuring α_{em} in the spacelike region

C.M.C. Calame[1], F. Jegerlehner[2], M. Passera[3], L. Trentadue[4], G. Venanzoni[5]

$\Delta\alpha_{had}(-s_0)$ spacelike measurement at FCCee

Using Bhabha at small angle (to emphasize t-channel contribution) to extract $\Delta\alpha$:

$$\left(\frac{\alpha(t)}{\alpha(0)}\right)^2 \sim \frac{d\sigma_{ee\to ee}(t)}{d\sigma^0_{MC}(t)}$$

Where $d\sigma^0_{MC}$ is the MC prediction for Bhabha process with α(t)=α(0), and there are corrections due to RC…

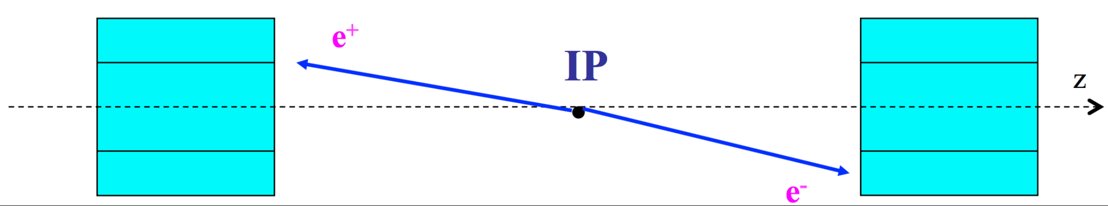
$$\Delta\alpha_{had}(t) = 1 - \left(\frac{\alpha(t)}{\alpha(0)}\right)^{-1} - \Delta\alpha_{lept}(t)$$

$\Delta\alpha_{lep}(t)$ theoretically well known!

$\delta\Delta\alpha_{had}(-(2\ \mathrm{GeV})^2)$ at 0.5% → $d\sigma(t)/d\sigma^0_{MC}(t) \sim 10^{-4}$!

Very challenging measurement (one order of magnitude improvement respect to date) for systematic error.

At Z peak small-angle detector needed (θ~3°)



Conclusion / Summary

- To match the fabulous statistics of FCC-ee need very precise normalisation
  - Absolute to 10^{-4}
  - Relative (point-to-point in energy scan) to few × 10^{-5}
- Available physics processes
  - Small angle Bhabha scattering
    - High rate: necessary for relative luminosity (at least on Z peak)
  - Large angle photon pairs
    - Rate exceeds that of WW, HZ, and tt
    - May also be interesting for absolute luminosity at Z pole
- Nevertheless, a small angle LumiCal remains extremely important
  - For relative normalisation at Z pole
  - Keep also as goal for precise absolute normalisation
  - Main problem is to get adequate space in forward busy region
- ...work to be done...