Experimental environment at FCC-ee

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for the FCC-ee MDI team

FCC Workshop, CERN, January 13, 2020

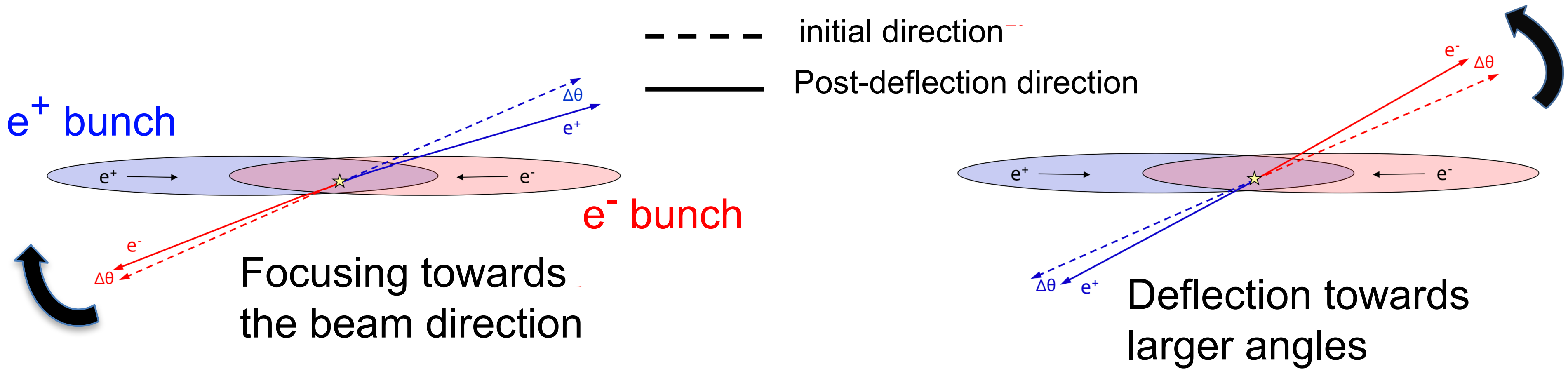
- Beam related backgrounds and impact in the detectors
- Beam-induced effects on the luminosity measurement

Most of what is covered here is a consequence of the large electromagnetic fields induced by the bunches. E.g. at the Z: up to 10 T equivalent in the lab frame.

Consequences of these strong fields at the IP [relevant or this talk]

- Beamstrahlung
  - Photons created in the interaction region
  - Low energy (<E> = 2 MeV at the Z peak), leave the IR in the beam-pipe ($< \theta > \approx 80$ μrad w.r.t. the beam direction)
  - Contribute (a bit) to the pair-production background, $\gamma^{(*)}\gamma^{(*)} \longrightarrow$ e+e-

- Particles in the final state feel the fields of the bunches – especially at small angles



- Because of the crossing angle : the particles in the bunches are accelerated along x, by the opposite charge bunch, until they reach the IP (see backup). Increase of the effective crossing angle, by about 0.5% at the Z peak.

The Guinea-Pig program (D. Schulte) allows all these effects to be simulated.

Background sources at FCC-ee

- Synchrotron radiation : see Helmut and Manuela's talks

  masks & shielding of the beam-pipe : SR-induced background in the detector is brought down to a sub-leading level (with baseline beam-pipe R = 1.5 cm in the central region).

- Beam losses due to interactions well upstream of the IR :

  A beam e+/- that looses an energy fraction $\Delta E/E > 2\%$ will be lost at some point. Losses more likely around the IR since smaller aperture.

  - Interaction with thermal photons (warm BP)
  - Beam-gas (elastic of inelastic)
  - Beamstrahlung
  - Radiative Bhabha at small ΔE

  } Process at IP1, loss at IP2 (or at IP1 after > 1 turn)

  See MDI overview by Manuela

  Lost e+/- usually have high energy. Need to track the particles through the lattice for many turns. Collimators can in principle be used to limit bckgd in the detectors.

- Background interactions at the IP

  - Especially $\gamma\gamma$ interactions

  Low energy bckgd particles. Simulation as for a "signal" process, does not require the lattice. Can not be shielded !

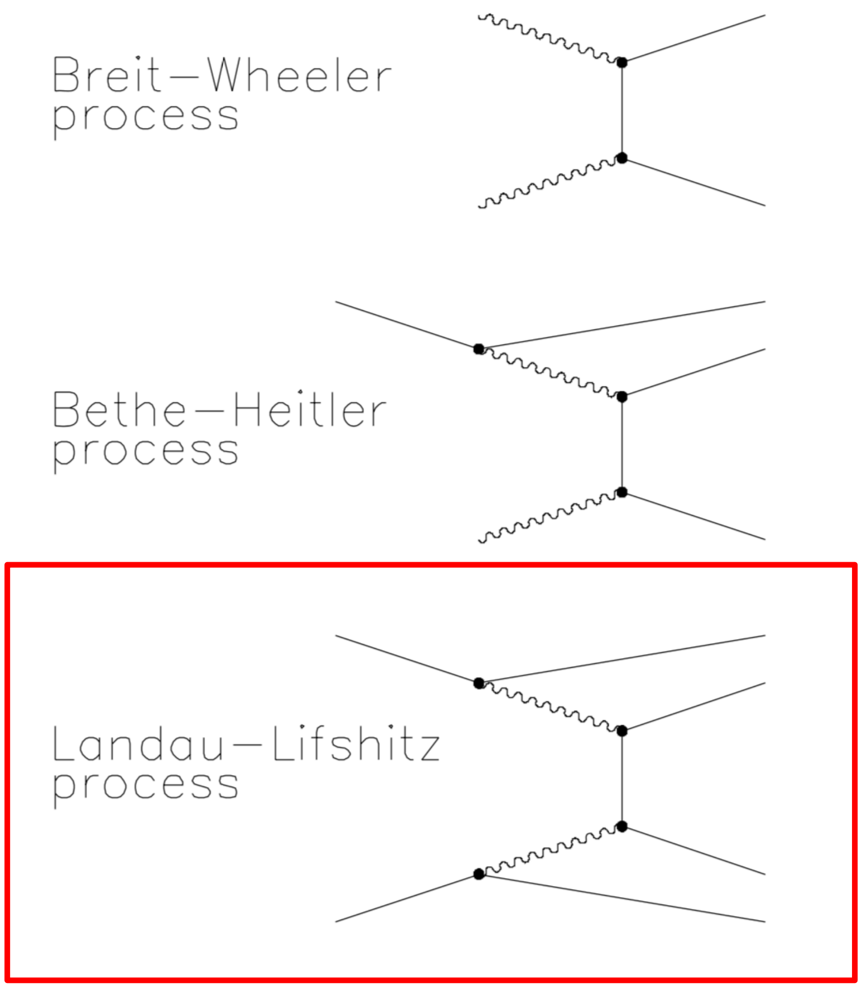
  Main focus in this talk.

Pair-production background

Dominated by incoherent pair production (IPC) : $\gamma\gamma \rightarrow$ e+ e-

At FCC : about 80% of the pairs created (and of the energy they carry) come from the LL process. Beamstrahlung photons contribute to the remaining 20%.

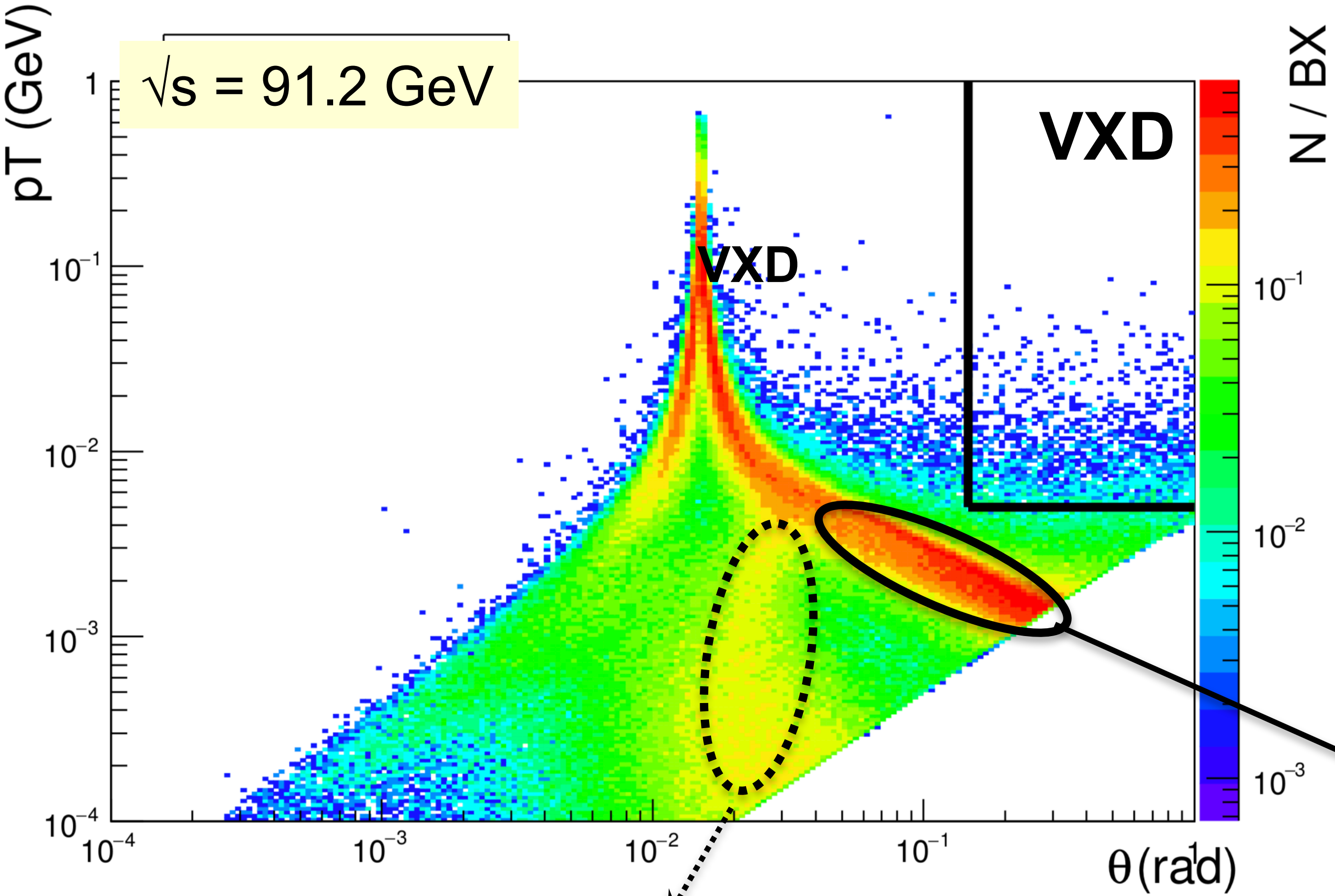
(at CLIC or ILC, the contribution of Beamstrahlung photons, via the Bethe-Heitler process, is larger)



low PT particles, may enter (many times) in the vertex detector.
Or can make showers in material in the fwd region (e.g. Lumi monitor), leading to secondaries that can backscatter into the main detector.

Incoherent pair production

Events generated with Guinea-Pig. (pT, θ) distribution in detector frame :



With B = 2 T :
Only part. with pT > 5 MeV and θ > 8 deg reach the first layer of the VXD detector.

Red region = potentially dangerous.

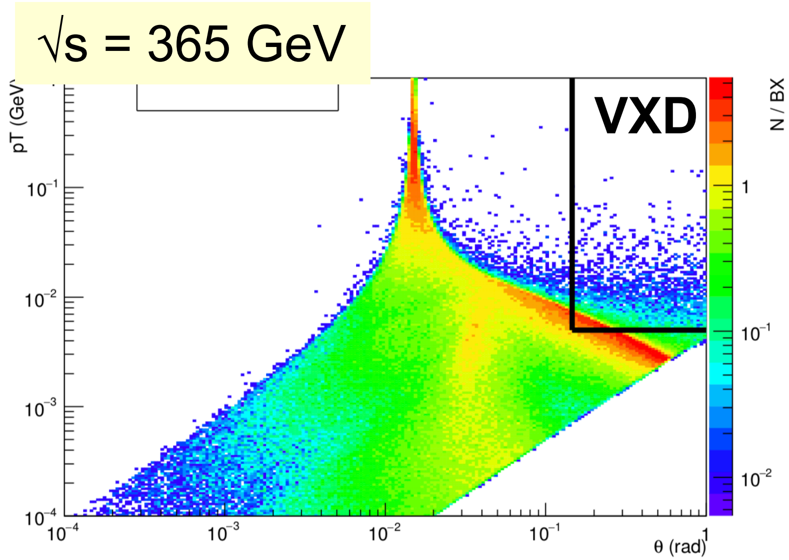
e^+/ e^- are deflected towards larger angles by the oncoming bunch, and shifted to larger pT.

e+(e-) are focused towards smaller angles / lower pT by the EM force created by the e- (e+) bunch.

Pair production and $\gamma\gamma \longrightarrow$ hadrons background

Per BX :

$e^{\pm}$ pairs		
$\sqrt{s}$ [GeV]	91.2	365
Total particles	~ 800	~ 6200
Total E (GeV)	~ 500	~ 9250
$p_{\mathrm{T}} \geq 5\ MeV$ and $\theta \geq 8^{\circ}$	~ 6	~ 292



Large # of particles created, that carry up to 9 TeV. But few particles reach the detector, even at the highest energy.

hadrons		
$\sqrt{\hat{s}_{\min}}$ [GeV]	evts Z	evts Top
2	0.00063	0.0078
5	0.00029	0.0043
10	0.00015	0.0027

$\gamma\gamma \longrightarrow$ hadrons background negligible at both energies.

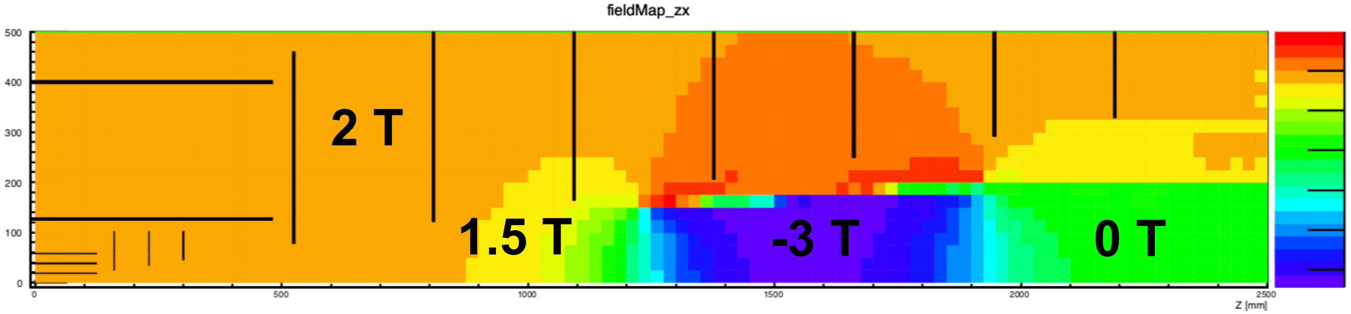
Backgrounds with full detector simulation

For a realistic estimation of the background in the detector : need a full simulation (interaction of e+/- with the beam-pipe, secondaries, backscattering).

Full GEANT-based Monte-Carlo simulation:

- Two detector models : CLD and IDEA
  - See detailed dedicated talks this afternoon
- Detailed interaction region (LumiCal, compensating & screening solenoids, split of the beam pipe, etc)

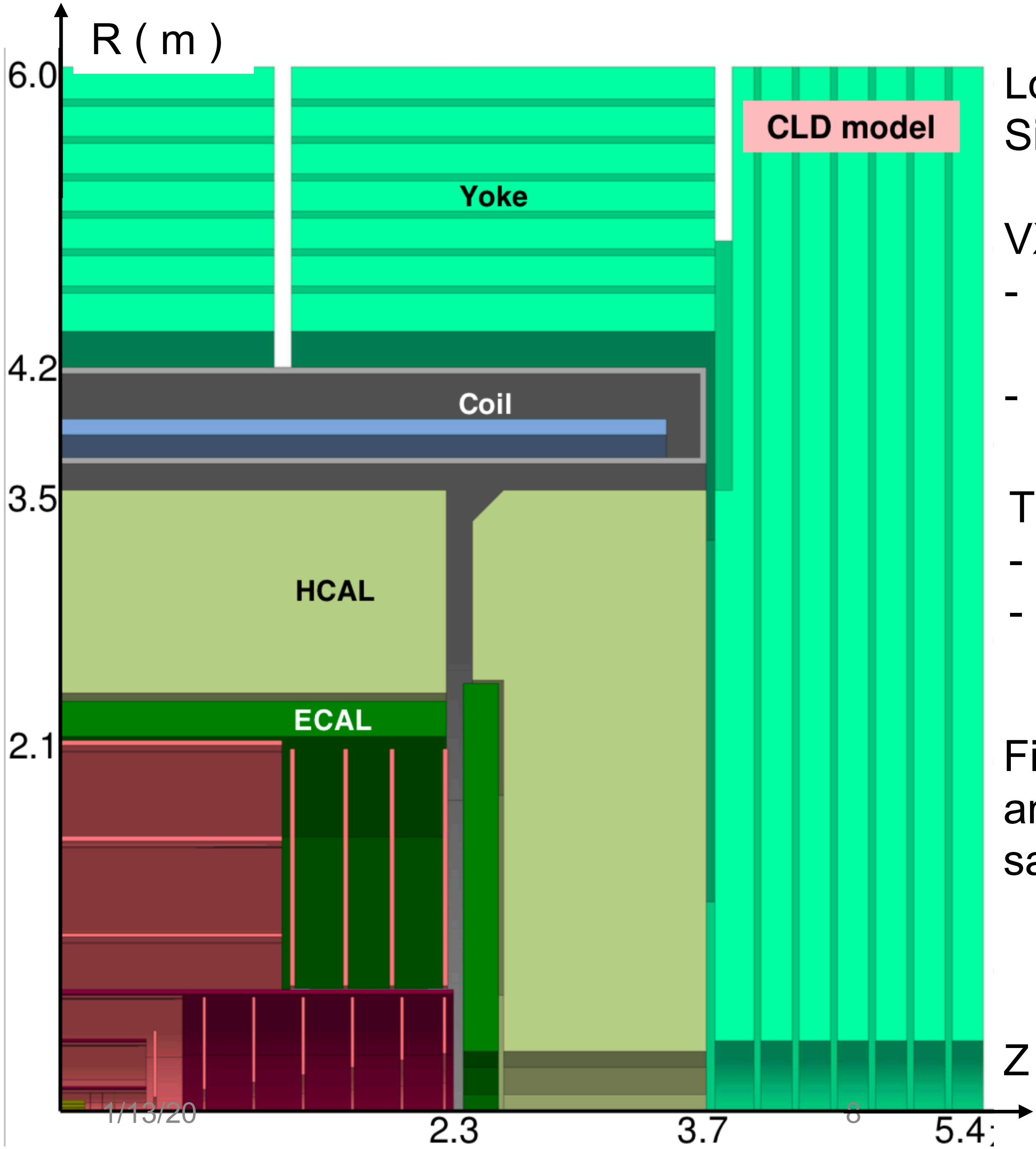
- Realistic magnetic field map (main solenoid and compensating scheme)



- DD4HEP for the geometry
- Studies made with the ddsim / ILC framework and/or the FCC software framework

Bz-field map in (R , z) used in the simulation. R from 0 to 50 cm, z from 0 to 2.5 m.
Black lines = VXD and Si-Tk layers.

Detector concept #1 : CLD detector – based on the CLIC detector



Low mass vertex and tracker, both Si detectors

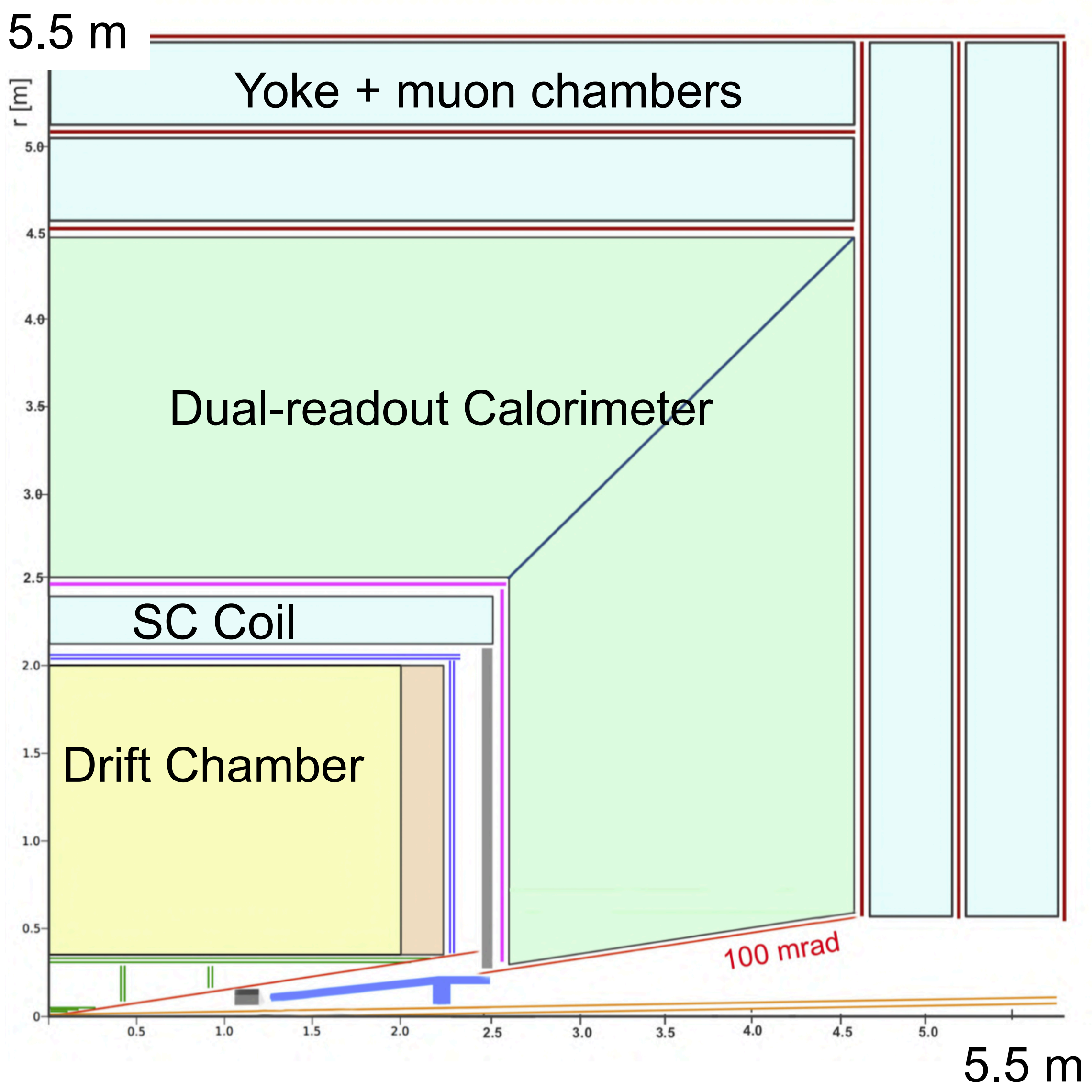
VXD: double-layers of pixels
- 3 barrel (Rin = 17.5 mm), 3 disks in endcap)
- 0.6% X0 per double-layer

Tracker: pixels and micro-strips
- 6 barrel layers, 11 endcap disks
- 1.1 – 1.6% X0 per layer

Fine granularity ECAL (tungsten-Si) and HCAL (scintillator-Steel) sampling calorimeters
- optimised for particle flow reco

Detector concept #2 : the IDEA detector

" International Detector for Electron-positron Accelerators "



- VXD : MAPS sensors
- Ultra-light drift chamber with PID
  - 1.6% X0
- Dual readout calorimeter
- Si disks between DCH and DR

Drift chamber :

L = 400 cm, R = 35-200
Gas: 90% He - 10% iC_4H_{10}
Drift length: 1 cm → drift time: 350 ns

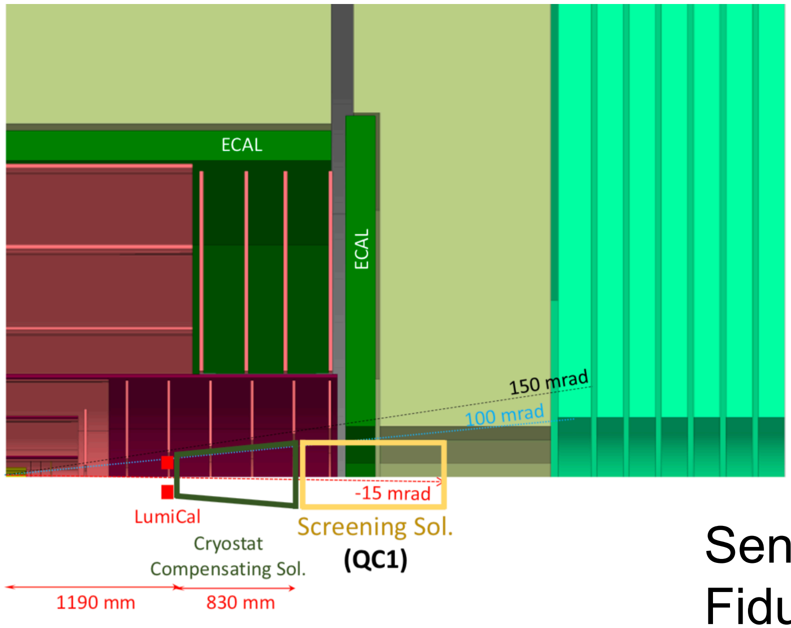
Spatial res: $\sigma_{xy} < 100$ µm, $\sigma_z < 1000$ µm
56448 squared drift cells of 12 - 13.5 mm
112 layers (stereo)

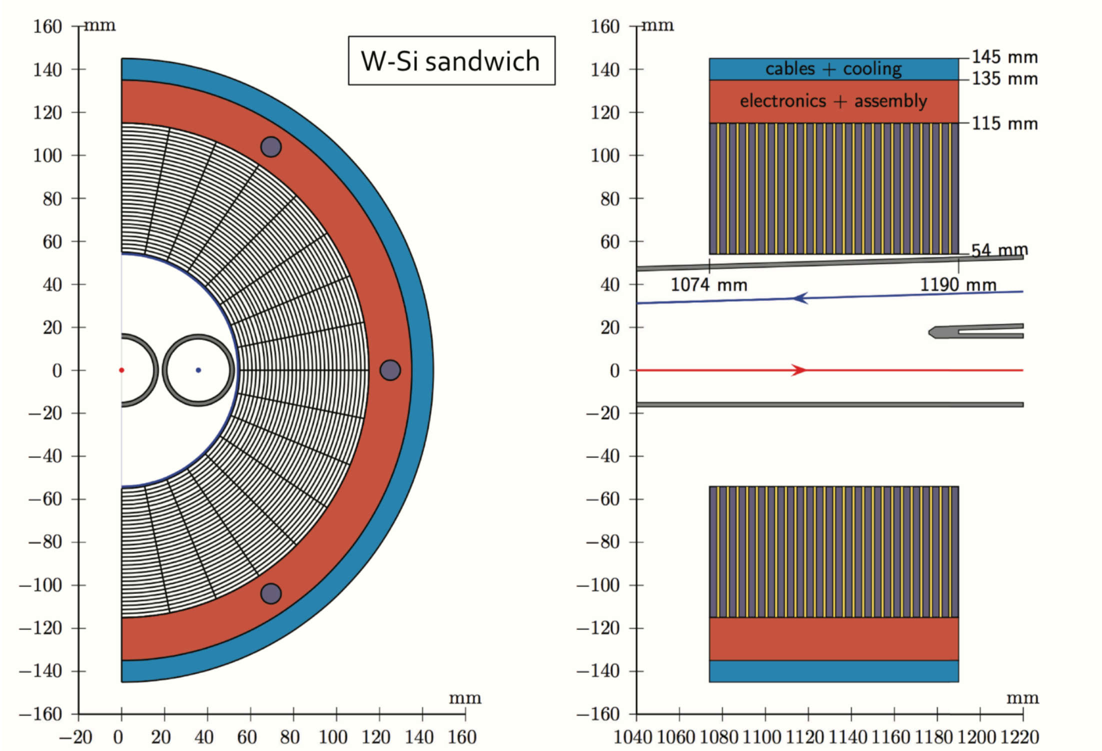
Detector concept for the luminometer

Determine the luminosity from the rate of Bhabha events, measured in two forward calorimeters centered around the outgoing beam-pipes.

W+Si sandwich
25 layers, total 25 X0

In front of the compensating solenoid. 10 cm long. Front face at ~ 1m from the IP.

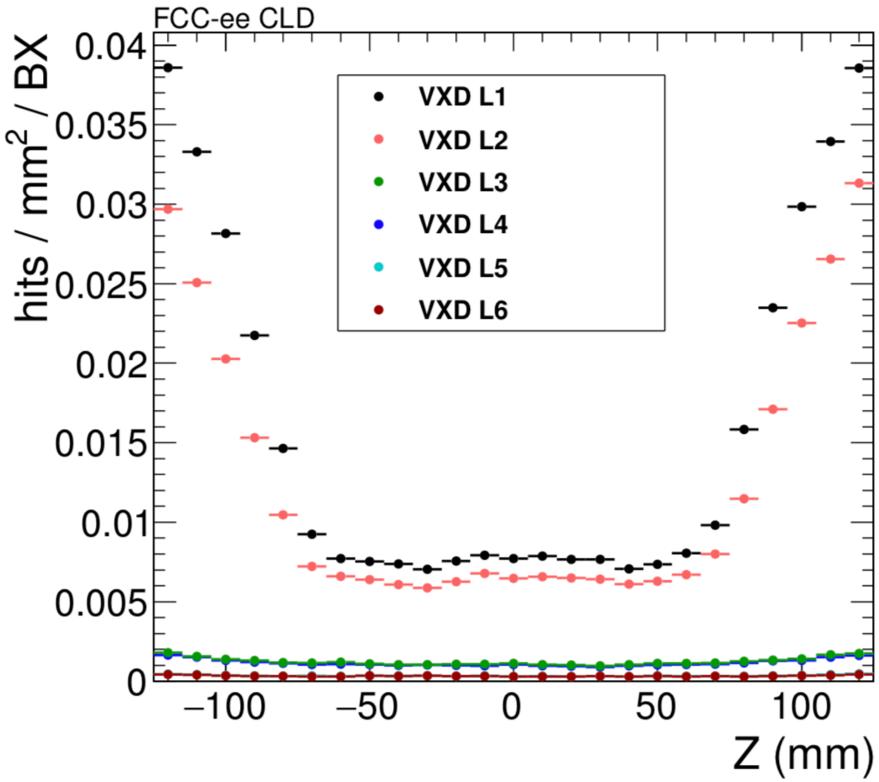




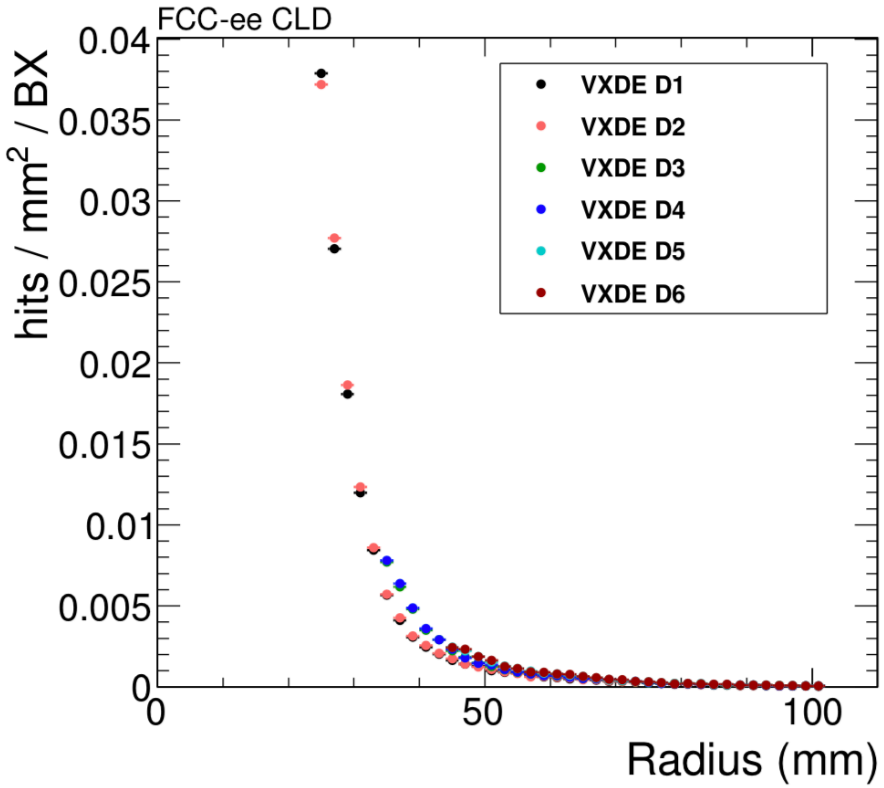
Sensitive region: 55 < R < 115 mm
Fiducial volume for the measurement: 64 – 86 mrad,
σ(Bhabha) = 14 nb at √s = 91.2 GeV

Pair production & Sync Radiation background: hit densities

- Example: hit densities (IPC) in the CLD vertex detector, at √s = 365 GeV :



Barrel



Endcap

- Sync. Radiation: hit densities at 365 GeV are O(5) lower than those from IPC.

Background occupancies (IPC + SR) in the VXD / Si tracker

Derived from the hit densities using :

- Pixel (strip) size of 25 μm x 25 μm (50 μm x 0.3 mm)
- “cluster size” (charge sharing) of 3
- Safety factor of 5

√s [GeV]	**365 [1 BX]**	**91.2 [1 BX]**	**91.2 [1 μs = 50 BX]**
VXD	~ $4\ 10^{-4}$	~ $8\ 10^{-6}$	~ $4\ 10^{-4}$
Tracker	~ $5\ 10^{-4}$	~ $2\ 10^{-5}$	~ $1\ 10^{-3}$

Bunch spacing : Δt = 3396 ns at √s = 365 GeV, but only ~ 20 ns at √s = 91.2 GeV.
At 91.2 GeV : the readout electronics of the Si sensors will integrate many BXs !
- e.g. assuming a readout of 1 μs : 50 BX

Even with a conservative assumption : using ALICE ITS technology, r/o = 10 μs = 500 BX (3 BX) at 91.2 GeV (365 GeV). The occupancies remain low :

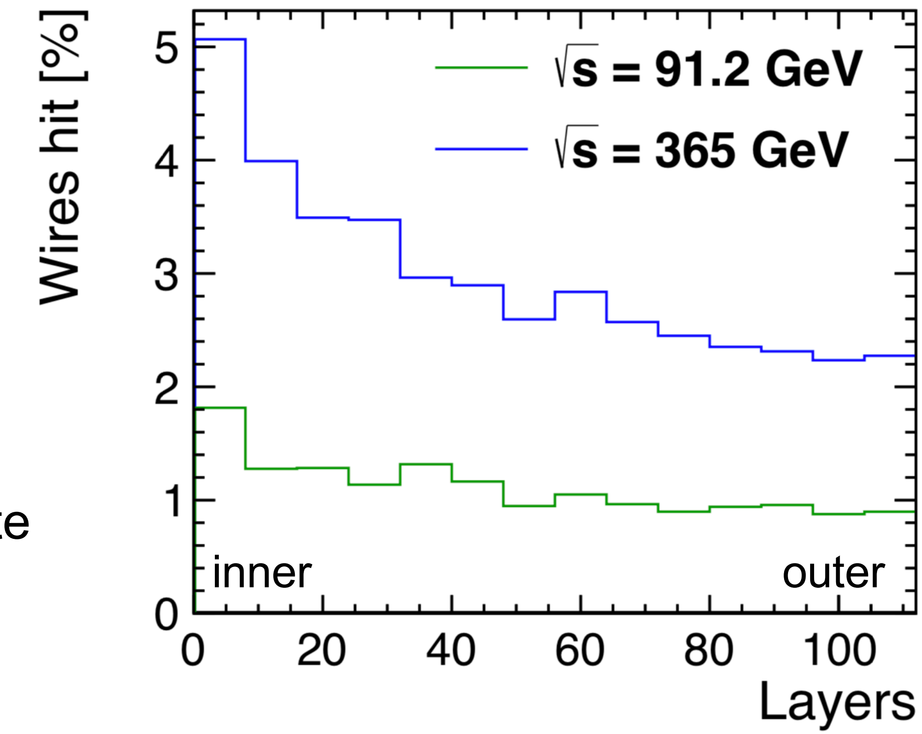
VXD : ~ 0.4% (~ 0.1%).
Tracker : less than 1% (less than 0.15%)

IPC background : occupancies in the Drift Chamber (IDEA)

Only a few of the primary e+/- particles have a pT that is large enough to reach the DCH.

Majority of hits observed are from secondary photons, E < 1 MeV.

Timing information can be used to separate signals from charged particles ("flow" of ionisation clusters) from those from photons (localised cluster) at DAQ level.



→ at 91.2 GeV : enough to integrate bckgd over 100 ns (5 BXs) to get the occupancy.
Average occupancies : ~ 1% at 91.2 GeV, ~ 3% at 365 GeV
[NB : no safety factor is applied here, in contrast to previous slide]

→ Timing offers an additional handle that will reduce the occupancies further, compared to what is shown in the plot.

Impact of background on reconstructed quantities in the main detector

Beyond these detector occupancies, the impact of these backgrounds on reconstructed quantities in the main detector has been studied in detail for the CLD detector.

- Full simulation and reconstruction
- Background events (IPC & SR) overlaid to physics events.

Very little effect on performances seen in the CLD studies :

- Small tracking efficiency loss (< 1%) at pT < 300 MeV
- Increased fake rate for the same pT range (remains < 4%)
- Slight degradation of jet energy resolution at 91 GeV, in the forward region

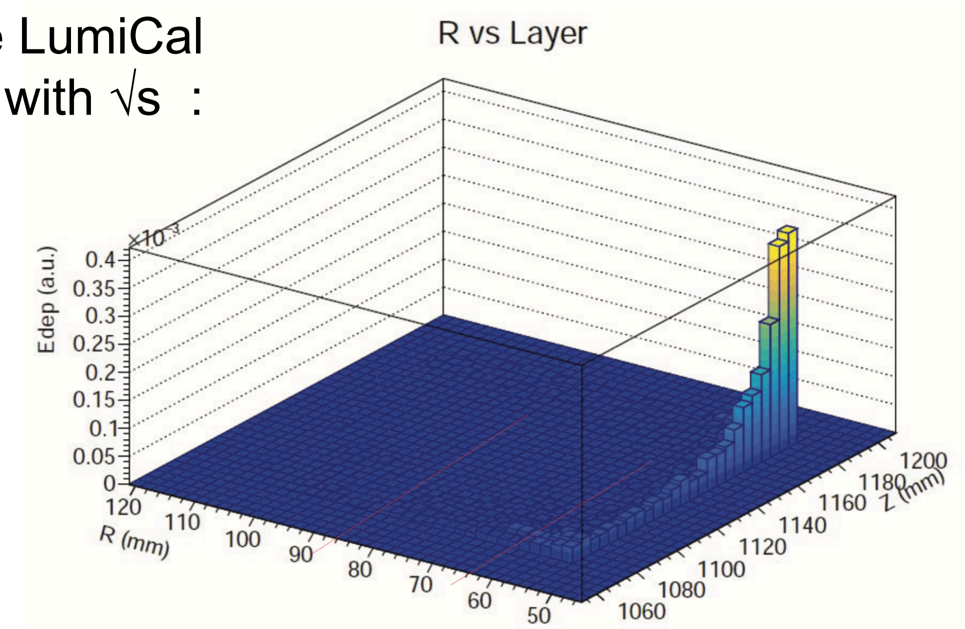
Details in the talk of Phillip Roloff this afternoon.
and in arXiv:1911.12230

Impact of the IPC & SR backgrounds on the luminosity measurement

SR : at $\sqrt{s}$ = 365 GeV, energy in LumiCal is only 7 MeV with the BP shield (340 MeV without it).

IPC : number of pair particles that reach the LumiCal and the energy they deposit varies strongly with $\sqrt{s}$:

- Z pole : very low energy, 350 MeV / BX
- Top : in the GeV range



Energy mainly concentrated

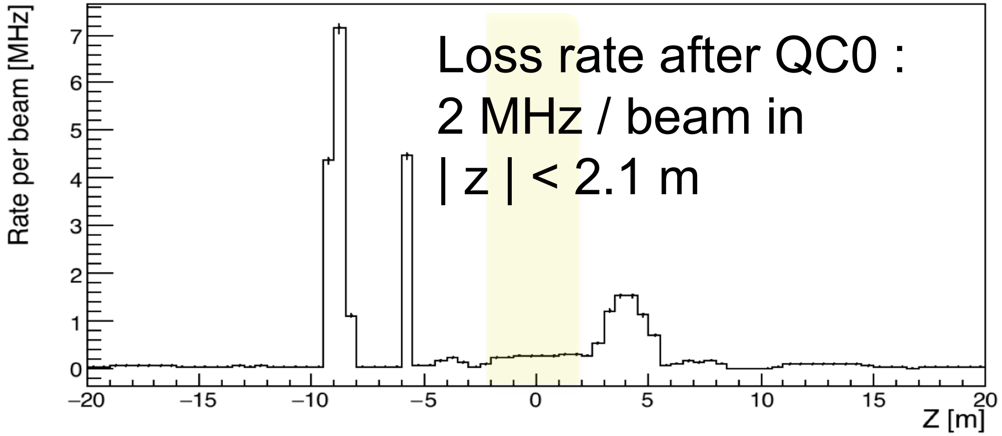
- at the inner radius, mostly outside the fiducial volume
- at the rear of the calorimeter: would be easy to shield

IPC and Synch Radiation backgrounds do not compromise the precision of the luminosity measurement.

Beam-gas background in the LumiCal

At LEP, coincidences of off-momentum particles from beam-gas scattering was the dominant background for the luminosity measurement : off-momentum particles deflected towards the LumiCal by the quadrupoles.

Loss map of inelastic beam-gas (Z peak, beam moving along +z): cf Manuela's talk

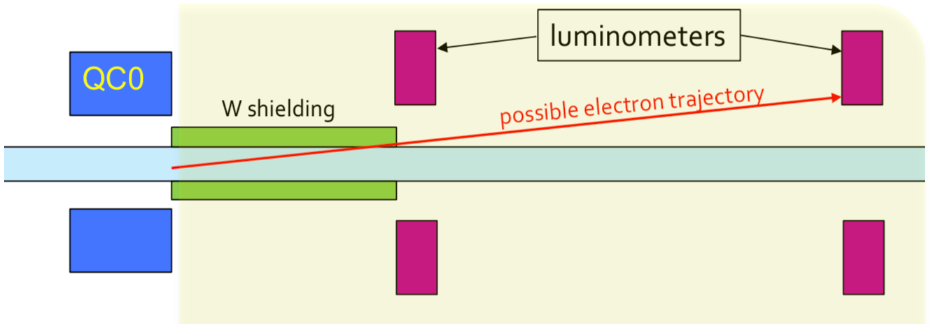


12% of these particles are deflected sufficiently by QC0 to point towards the LumiCal on the opposite side (simple extrapolation).

Rate of coincidences per BX :

$(12\% * 2 \text{ MHz} / 50 \text{ MHz})^2 = 2\ 10^{-5}$

Already small compared to the Bhabha rate, $6\ 10^{-4}$ / BX



> 95% of them leave the BP early and will be stopped by the 15mm tungsten shielding.

Estimation of coincidence rate : < 1E-7 before any energy / angular cut.

Seems to be negligible at FCC. To be confirmed with full sim.

Off-momentum particles (losses), more generally..

Background induced by lost particles should be checked with a full detector simulation (not only in LumiCal, secondaries…). This includes :

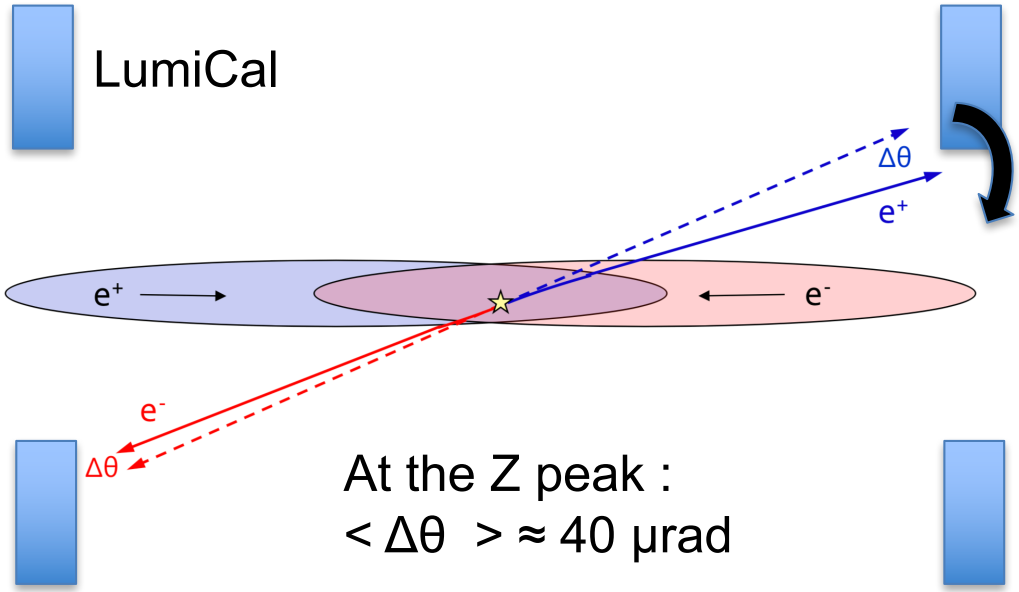
- Beam-gas : loss maps in the interaction region exist. Tracking into the detector can be done.
- Idem for interactions with thermal photons
- Radiative Bhabhas :
  - Z peak : losses all happen well before reaching the second IP
  - 365 GeV : a few losses in the vicinity of the second IR. Tracking into the detector (CLD) was done and checked that this bckgd is negligible.
  - Similar findings with CePC layout and IDEA detector.
- Beamstrahlung losses: to be pursued.

Not expected to cause problems in the detectors. But should be checked with a full simulation for the TDR.

Beam-induced effects on the luminosity measurement

Precision goal at the Z peak and WW :

- 10^{-4} (absolute), a few 10^{-5} (relative, line-shape scan)



Focusing of the Bhabha e+/- by the beam force :

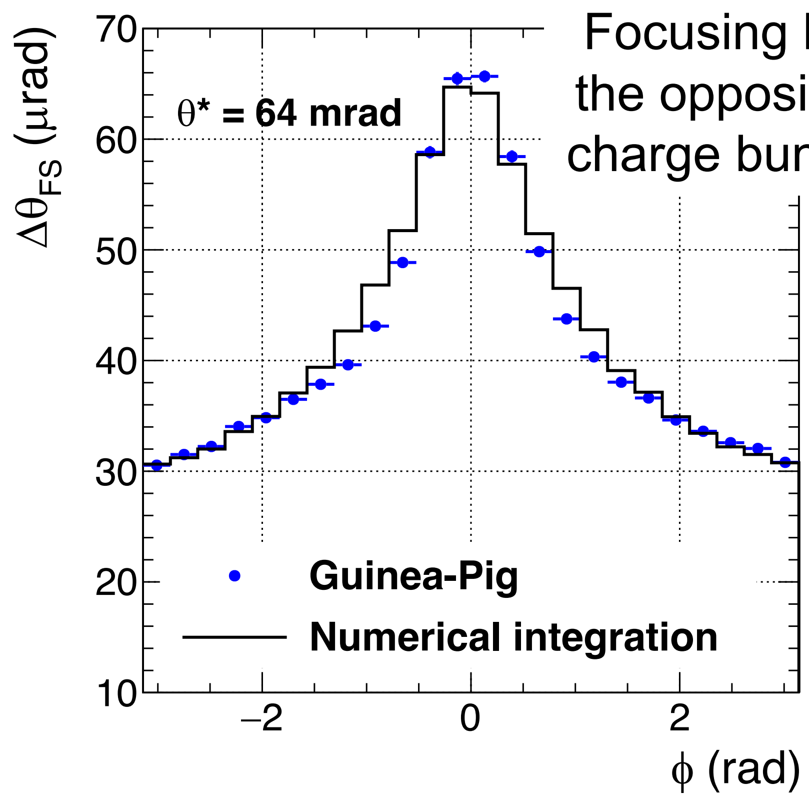
The # of e+/- that end up in the acceptance of the LumiCal is reduced: L measured < L true

Leads to $\Delta L / L \approx 0.2$ %
i.e. 20x larger than the target !

Needs to be corrected for. The precision on the correction factor should be about 5% to ensure a residual systematic below 10-4.
Correction can be calculated in principle... but desirable to determine it experimentally.

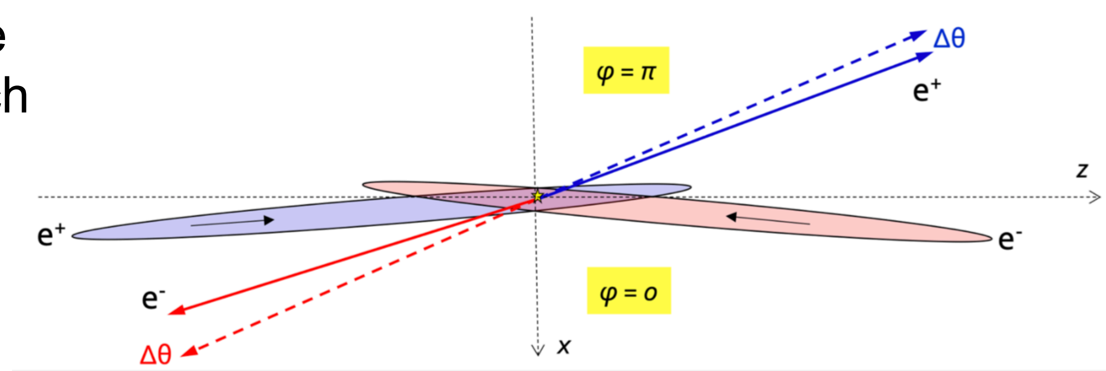
Two methods proposed in JHEP 10 (2019) 225 [arXiv:1908.01698]. Only one is described here.
Numbers refer to the Z peak.

Azimuthal dependence



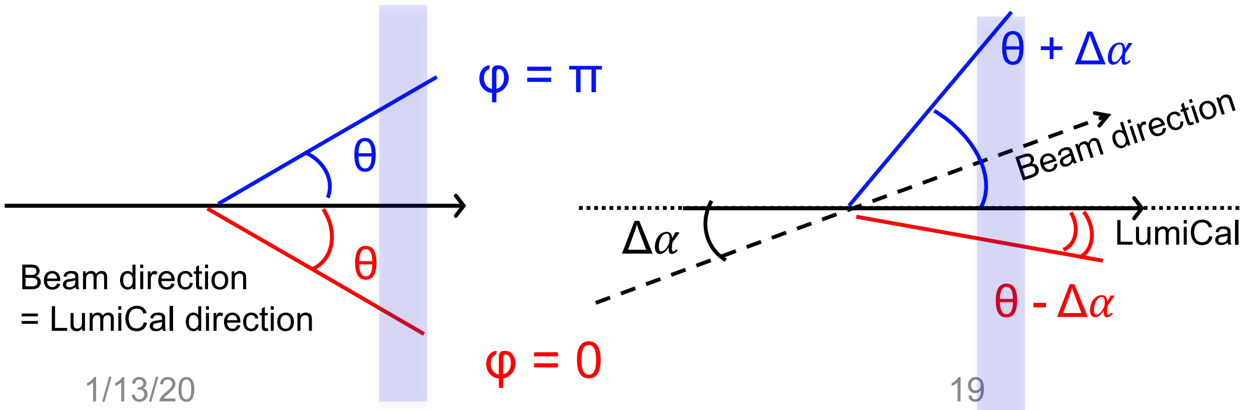
Focusing by the opposite charge bunch

Consequence of the crossing angle :



e- at φ = 0 feels a stronger force than the e+ at φ = π, since closer to the opposite bunch

In addition, the effective xing angle (30 mrad + $\Delta\alpha$) leads to a φ modulation of the θ 's:

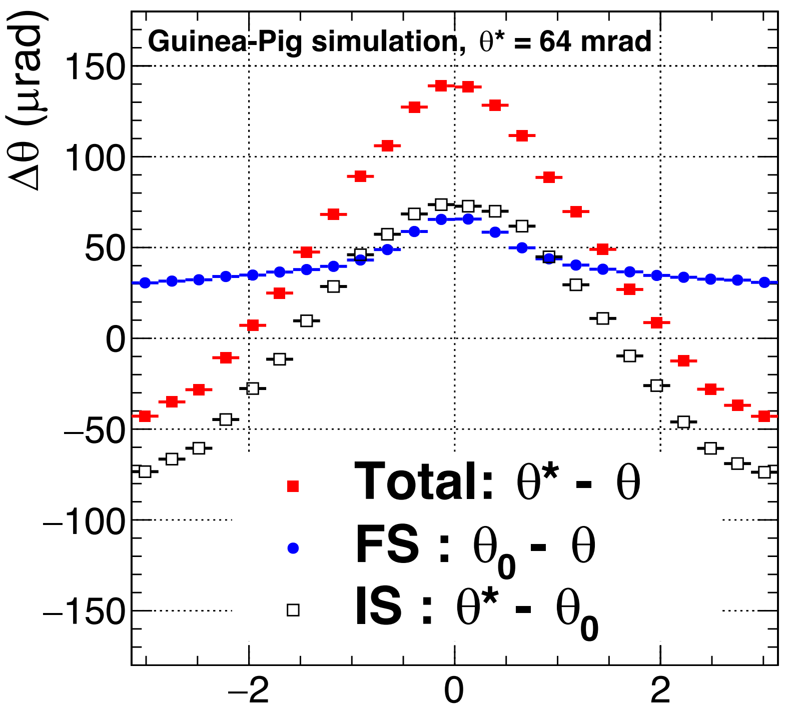


$$\theta' = \theta - \Delta\alpha \cos\varphi$$

$\Delta\alpha$ induced by beam-beam effects, about 0.5% of 15 mrad (see backup).

Acollinearity of the final state in the LumiCal

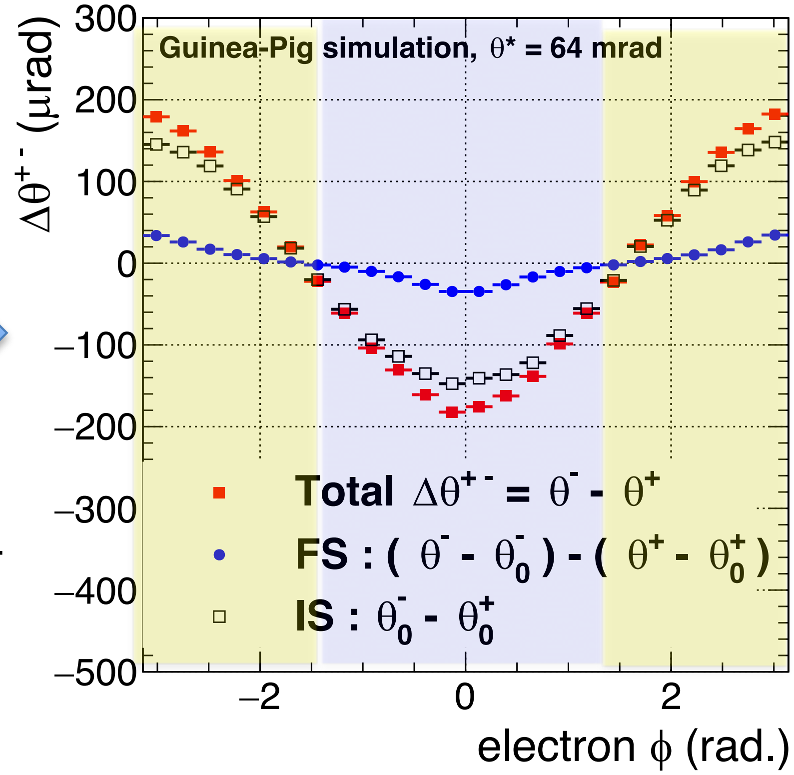
These two effects : for $\theta^* = 64$ mrad,
geom. angle in the LumiCal = 64 mrad – $\Delta\theta$:



at φ = 0: e± are focused
at φ = π: e± are deflected towards larger angles.

$$\Delta\theta^{\pm} = \theta^{-} - \theta^{+}$$

Acollinearity of the final state



$$\text{Acol} = \left\langle \Delta\theta^{+-} \right\rangle_{|\phi^-|>\pi/2} - \left\langle \Delta\theta^{+-} \right\rangle_{|\phi^-|<\pi/2}$$

Acol = about 220 μrad

Angular resolution of LumiCal :140 μrad

With only a few 100's of events : Acol can be measured within a few %.

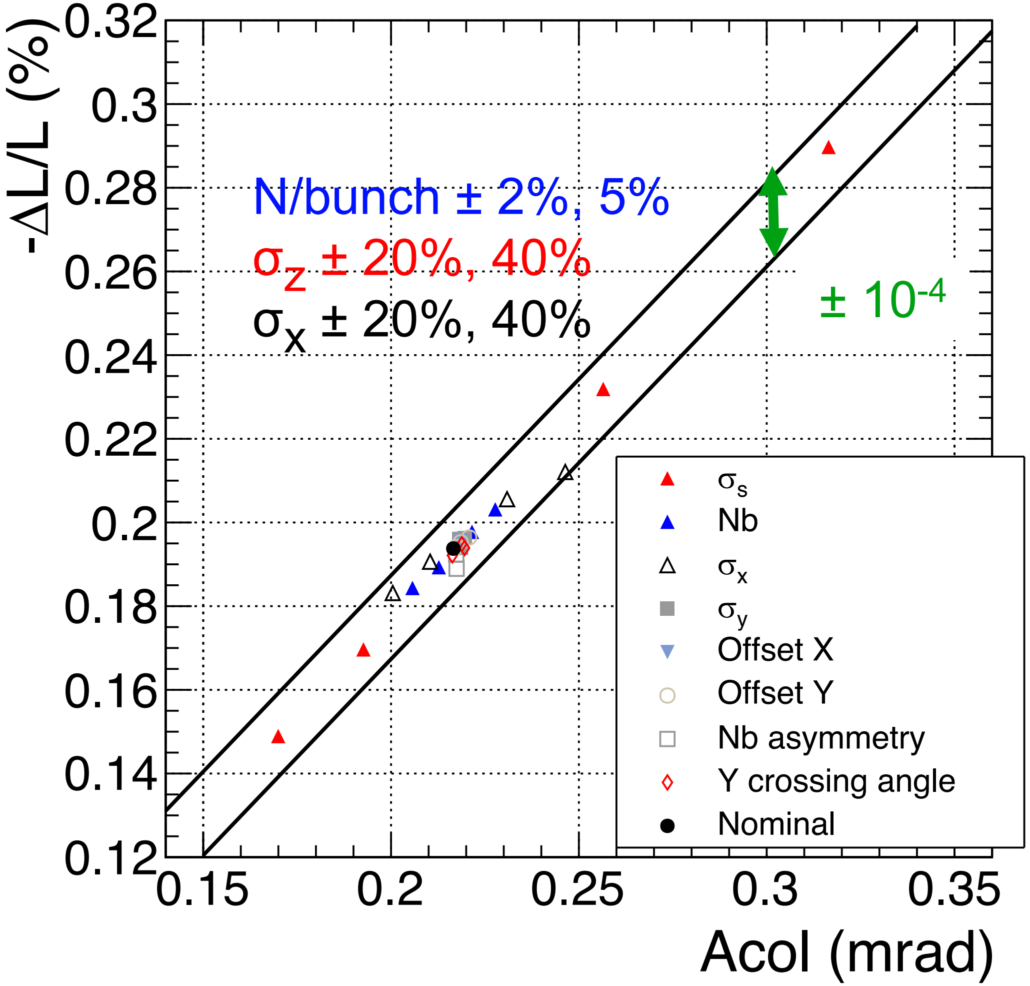
E.Perez

Acol and beam parameters

The size of Acol reflects the size of the beam-induced effects, hence the size of ΔL / L

Verification : several variations of the beam parameters around the nominal set, Guinea-Pig simulation for each; determine Acol and ΔL

→ the luminosity bias is indeed proportional to Acol



Hence :

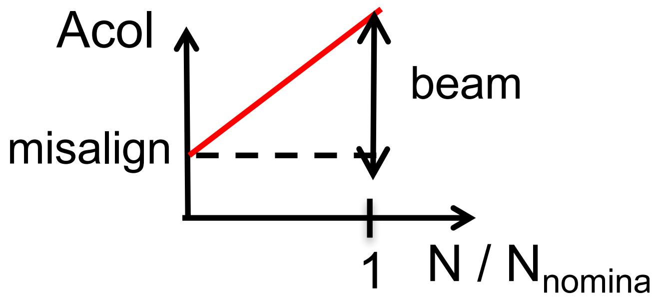
- Use GP simulations to map the bias & Acol
- An experimental measurement of Acol then gives the correction factor

< 1 sec of data taking provides the desired statistical accuracy on Acol.

Complication from misalignment effects & its solution

A misalignment of the luminometer system along the x direction also causes a non-zero acollinearity: $\mathrm{Acol} = \mathrm{Acol}_{\mathrm{beam}} + \mathrm{Acol}_{\mathrm{misalign}}$.

$\mathrm{Acol}_{\mathrm{beam}}$ induced by the beam effects, scale linearly with Npart / bunches.
$\mathrm{Acol}_{\mathrm{misalign}}$: independent of N/bunch.

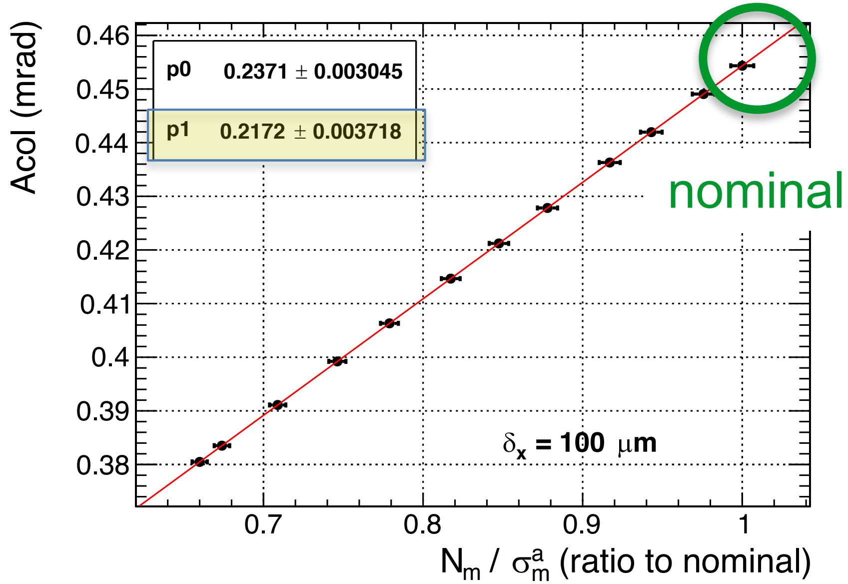


Measuring Acol in bunches with different Npart :
$\mathrm{Acol} = \mathrm{Acol}_{\mathrm{misalign}} + \mathrm{Acol}_{\mathrm{beam}} \times (N / N_{\mathrm{nominal}})$

Filling period of the machine, at the beginning of each fill : naturally offers collisions with bunches with N < nominal. N/bunch is gradually increased, starting from 50% of Nnominal, e.g. adding 10% of the nominal N per step. The beams do collide during this filling, and the **β*** is the nominal one !

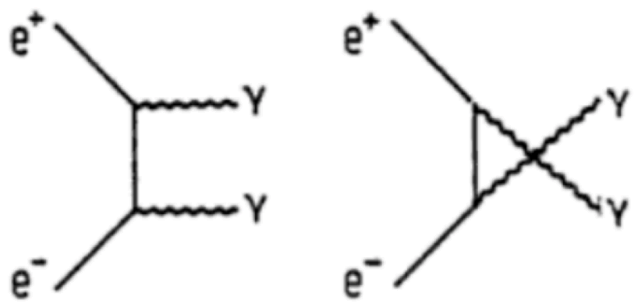
Illustration: 100 μm, 40 sec at each step.

Linear fit: the slope A_{beam} can be measured with a stat uncertainty of 1.7%, and a systematics of ~ 2%.
Well within the 5% target.



Concl: effect is well under control

Alternative measurement of the luminosity : ee $\longrightarrow \gamma\gamma$ at large angles



- Pure QED process (at LO)
- Well controlled theoretically

Much smaller σ than small angle Bhabhas, but statistics still adequate for a precision of 10^{-4}

Example:
θ_{min} = 20 deg

Huge contamination from $e^+e^- \longrightarrow e^+e^-$ before any id cut (20 - 100x signal)

Energy	Process	Cross Section	Large angle $e^+e^- \to \gamma\gamma$	Large angle $e^+e^- \to e^+e^-$
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	$e^+e^- \to ZH$	0.2 pb	5.6 pb	134 pb
350 GeV	$e^+e^- \to tt$	0.5 pb	2.6 pb	60 pb

Need a good control of the e/γ separation (γ conversions, e $\longrightarrow \gamma$ fake rate).

e.g. with ε (γ id) = 99% and fake(e $\longrightarrow \gamma$) = 1%, would need to know the γ id inefficiency to the % level and the fake rate to a few per-mille.

Worth to take a closer look – systematics completely different from small angle Bhabhas (and no beam induced effect !)

Interesting by-product : beam-induced effects and the LEP luminosity

Bhabha electrons at LEP were also affected by the beam-induced focusing !

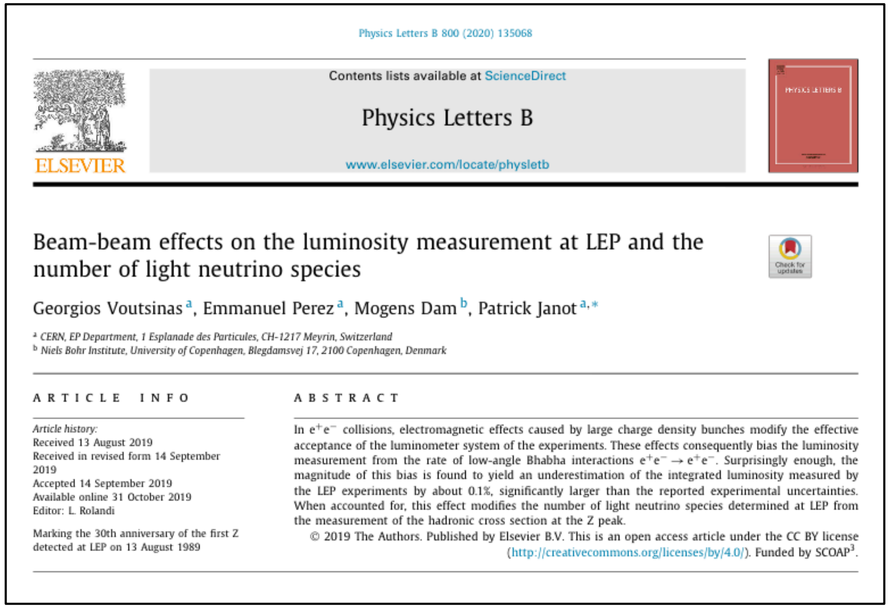
Voutsinas et al, arXiv:1908.01704

Typical focusing was O (10 μrad)
Leads to a bias on the luminosity of about 0.1 %

- Not accounted for by the experiments
- large compared to the quoted uncertainties (e.g. OPAL: 0.034% (exp), 0.056% (theo.))

The bias has been determined

- for each LEP 1 year, at and around the Z mass
- With the acceptance and selection cuts used by the experiments



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Beam-beam effects on the luminosity measurement at LEP and the number of light neutrino species

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Marking the 30th anniversary of the first Z detected at LEP on 13 August 1989

ABSTRACT

In e^+e^- collisions, electromagnetic effects caused by large charge density bunches modify the effective acceptance of the luminometer system of the experiments. These effects consequently bias the luminosity measurement from the rate of low-angle Bhabha interactions $e^+e^- \to e^+e^-$. Surprisingly enough, the magnitude of this bias is found to yield an underestimation of the integrated luminosity measured by the LEP experiments by about 0.1%, significantly larger than the reported experimental uncertainties. When accounted for, this effect modifies the number of light neutrino species determined at LEP from the measurement of the hadronic cross section at the Z peak.

Correcting for the bias leads to

- An increase of the luminosity w.r.t published
- A decrease of the measured peak cross-section σ^0_{had} .
- An increase of the number of light neutrino species derived from σ^0_{had}

The revisited number of neutrinos

Published : N_ν = 2.9840 +/- 0.0082 (2σ away from 3)

Correcting for the beam-induced effects :
N_ν = 2.9918 +/- 0.081 - the 2σ deficit is half-gone

Following this : the recent theoretical developments on the Bhabha cross-section, made for FCC, have been used to further correct N_ν .

Janot & Jadach, arXiv:1912.02067

Final results :

N_ν	=	2.9975	±	0.0074	(0.3 σ away from 3)
Γ_Z	=	2.4955	±	0.0023 GeV	(0.3 MeV increase)
σ^0_{had} .	=	41.4737	±	0.0326 nb	(70 pb decrease)

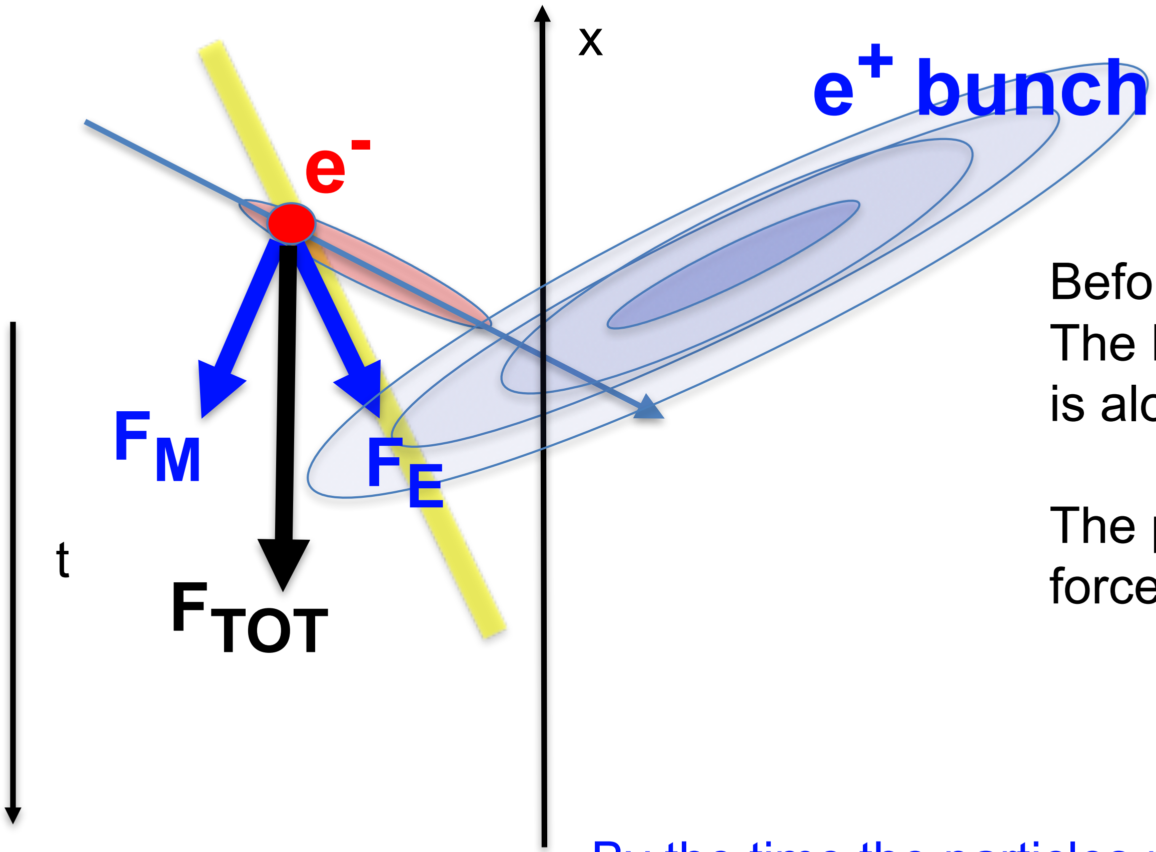
Conclusions

- Effect of IPC and SR background in the detector has been studied in full simulation. In general, negligible.
- Full simulations to be pursued for the backgrounds induced by beam losses (expected to be small).
- Beyond the baseline model: studies on-going to assess whether a smaller beam-pipe is possible (R = 1 cm instead of 1.5 cm)
  - IPC background remains acceptable

- It is possible to control the luminosity bias due to the EM focusing of the Bhabha electrons.

Backup

Beam-beam effects on the initial state particles



Before it reaches the IP :
The Lorentz force felt by the electron is along the x axis, pointing downwards.

The particle is accelerated by this force along -x, and it gains energy.

By the time the particles reach the IP and may interact, they have acquired a net momentum along (-) x.

≡ the “px-kick”