# Centre-of-mass energy and Luminosity at FCC-ee

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FCC France Workshop, May 14, 2020

Most stringent requirements on the measurements of the luminosity and $\sqrt{s}$ set by the physics programme at the Z peak and the WW threshold.

Focus on these two energies. When not specified otherwise, numbers refer to the Z peak.

# Center-of-mass energy

For details, see :

“Polarization and center-of-mass energy calibration at FCC-ee”,
A. Blondel, P. Janot, J. Wenninger et al, arXiv:1909.12245

Talks at the FCC-week 2019 :
M. Koratzinos, ”Overview and status of CM uncertainties
P. Janot, "Measurements of beam-beam effects at the IP"

# Center of mass energy : requirements

- Goals of 100 keV on $M_Z$ : √s to 100 keV at the Z energy
- $M_W$ to 500 keV : √s to 300 keV at the WW threshold
- At higher energy : less stringent requirements, O( 10 – 20 ) MeV

Most important uncertainties for some key measurements :

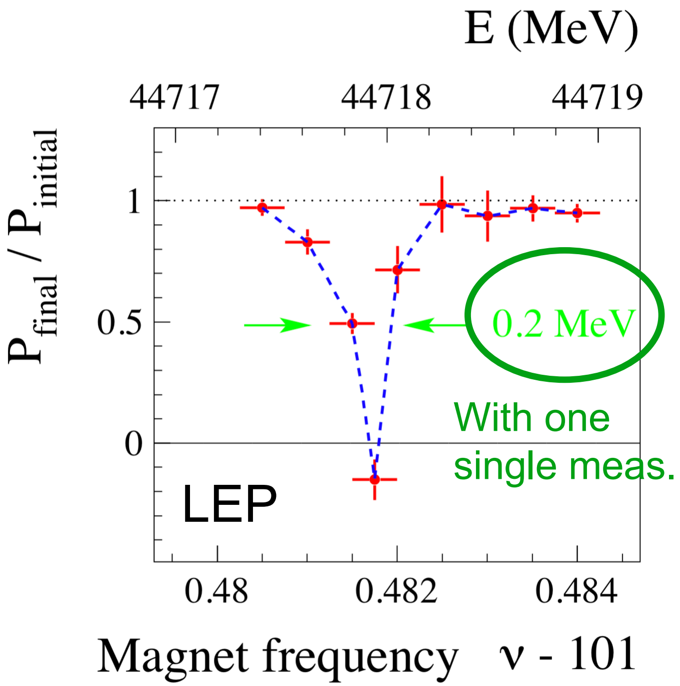
| | δ ( √s ) abs | δ ( √s ) ptp | δ ( energy spread) |
|---|---|---|---|
| **$m_Z$** | ++ | + | |
| **$\Gamma_Z$** | | ++ | ++ |
| **$\sin^2\theta_{eff}$ ( $A_{FB}^{\mu\mu}$)** | | ++ | |
| **$m_W$** | + | | |
| **$\Gamma_W$** | + | | |

$$\sqrt{s} = 2\sqrt{E_+E_-}\cos\alpha/2,$$

For δ ( √s ) = 100 keV, Need to know :

- The beam energies E+ and E- within O( 50 keV )
  - With a relative uncertainty of $10^{-6}$ at the Z peak
- The crossing angle $\alpha$ ( = 30 mrad) within < O( 0.1 mrad ), i.e. < 3 ‰

# Measurement of the beam energy



Basis of beam energy calibration (Z and WW) :
Resonant Depolarisation (RDP) :

Exploits the relation between the number of spin precessions per turn of transversely polarised e+/- and their energy

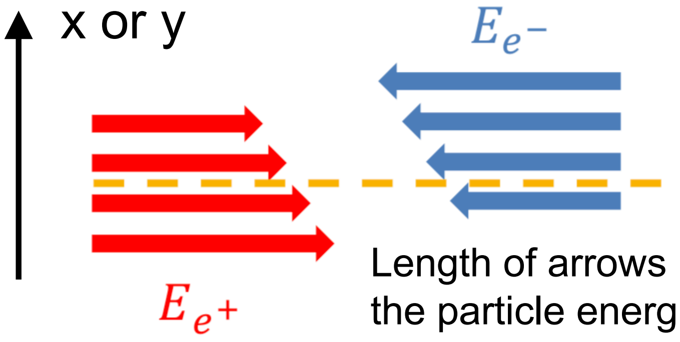
Improvement by a factor of 20 w.r.t. LEP1 thanks to a quasi-continuous calibration (one RDP measurement every 10-15 min), during normal data taking :

- made possible by having a few 100's of non-colliding $e^+$ and $e^-$ bunches devoted to RDP
- Allows tracking of all effects that cause variation of the beam energy (Earth tides, stray currents from railway line, bending field drifts, etc)
  - At LEP: extrapolation from measurements made at the end of fills largely dominated the systematic uncertainty

# Measurement of the beam energy

Many detailed studies performed to assess the corrections needed to go from $E_{RDP}$ to √s and the resulting systematic uncertainties, e.g.

- Average energy (measured by RDP) vs beam energies at the IP
  - E not constant along the ring (RFs, impedance losses)
- Potential shifts when going from the beam energies to √s, like :
  - Dispersion at the IP
    Combined with offset, can bias ECM.



√s lower than nominal

Length of arrows reflect the particle energies

In some cases, sizable correction. But small uncertainty on the correction factor.

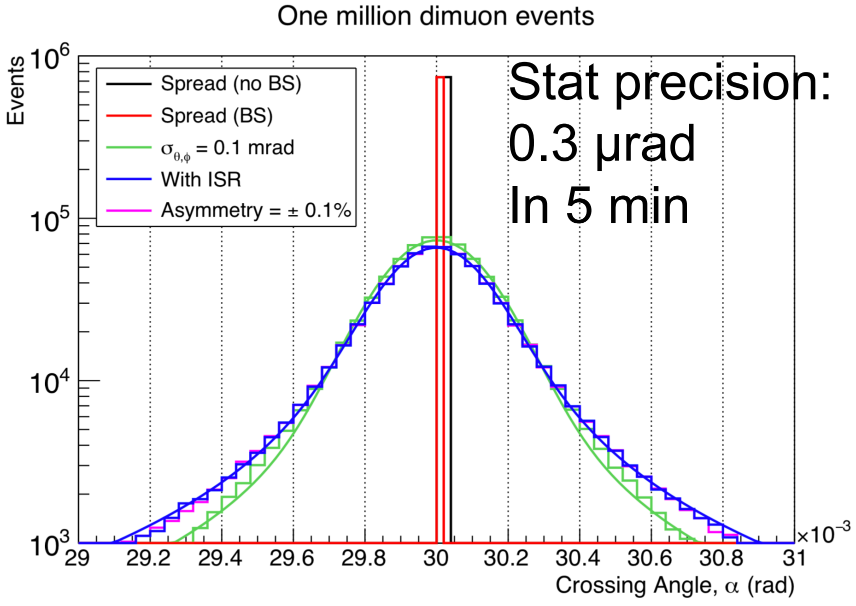
The target of δ( √s ) of 100 keV at the Z peak and 300 keV at WW is within reach.

# Measurement of the crossing angle

- Beam Position Monitors placed on the quads close to the IP measure $\alpha$
  - But expected precision not better than O ( 0.1 ) mrad
  - At the Z peak, corresponds to O ( 100 keV ) on √s

- $\alpha$ can be measured much better by the experiment using the constrained kinematics of dimuon events

$$\alpha = 2\arcsin\left[\frac{\sin(\varphi^- - \varphi^+)\sin\theta^+\sin\theta^-}{\sin\varphi^-\sin\theta^- - \sin\varphi^+\sin\theta^+}\right]$$

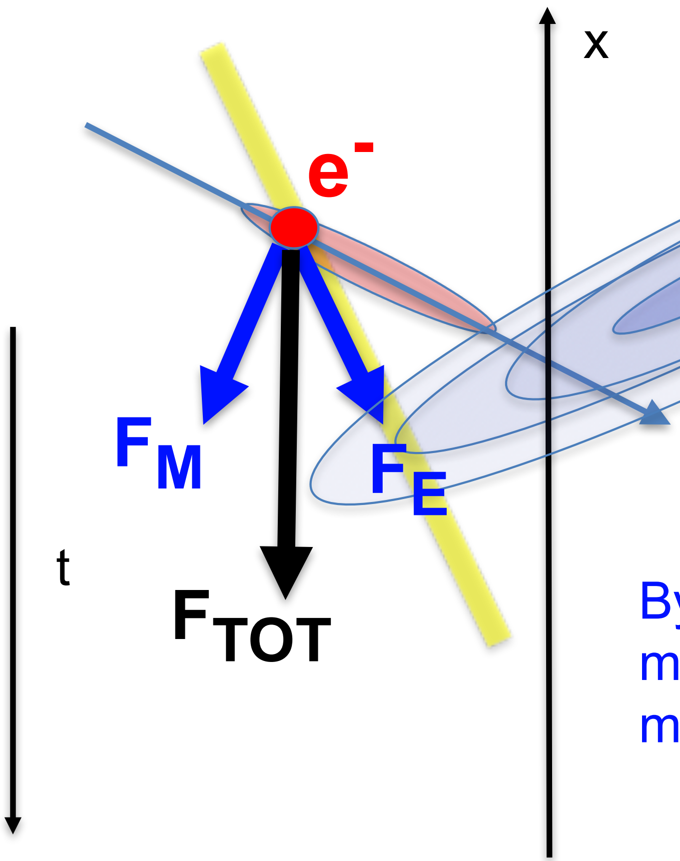

One million dimuon events

Stat precision:
0.3 µrad
In 5 min

Syst. uncertainty of O ( 0.1 µrad )
Negligible contribution to δ( √s )

NB: the same events also allow the energy spread to be determined in-situ

# Complication: Beam-beam effects



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”

→ Energy increases

→ Crossing angle increases: $\Delta(\alpha/2) = \text{Kick} / E_e$

No effect on $p_z$, hence no effect on $\sqrt{s} = 2\sqrt{(p_z^+ p_z^-)} = 2E_e \cos \alpha/2$ : exact compensation of :

- The increase of Ee ( 60 keV )
- The increase of $\alpha$ ( $\Delta\alpha$ = 0.17 mrad, i.e. $\Delta\alpha / \alpha \sim 0.5\%$ )

# Correction of beam-beam effects

However these effects can not be ignored, because :

$$\sqrt{s} = 2\sqrt{E_+^0 E_-^0}\cos\alpha_0/2 = 2\sqrt{E_+E_-}\cos\alpha/2,$$

E in absence of BB effects, measured with RDP

??

$\alpha$ with BB effects, measured with dimuons

To go to √s: one needs to know $\alpha_0$, i.e. in addition to $\alpha$, the xing angle increase $\Delta\alpha = \alpha - \alpha_0$. Can be determined since :

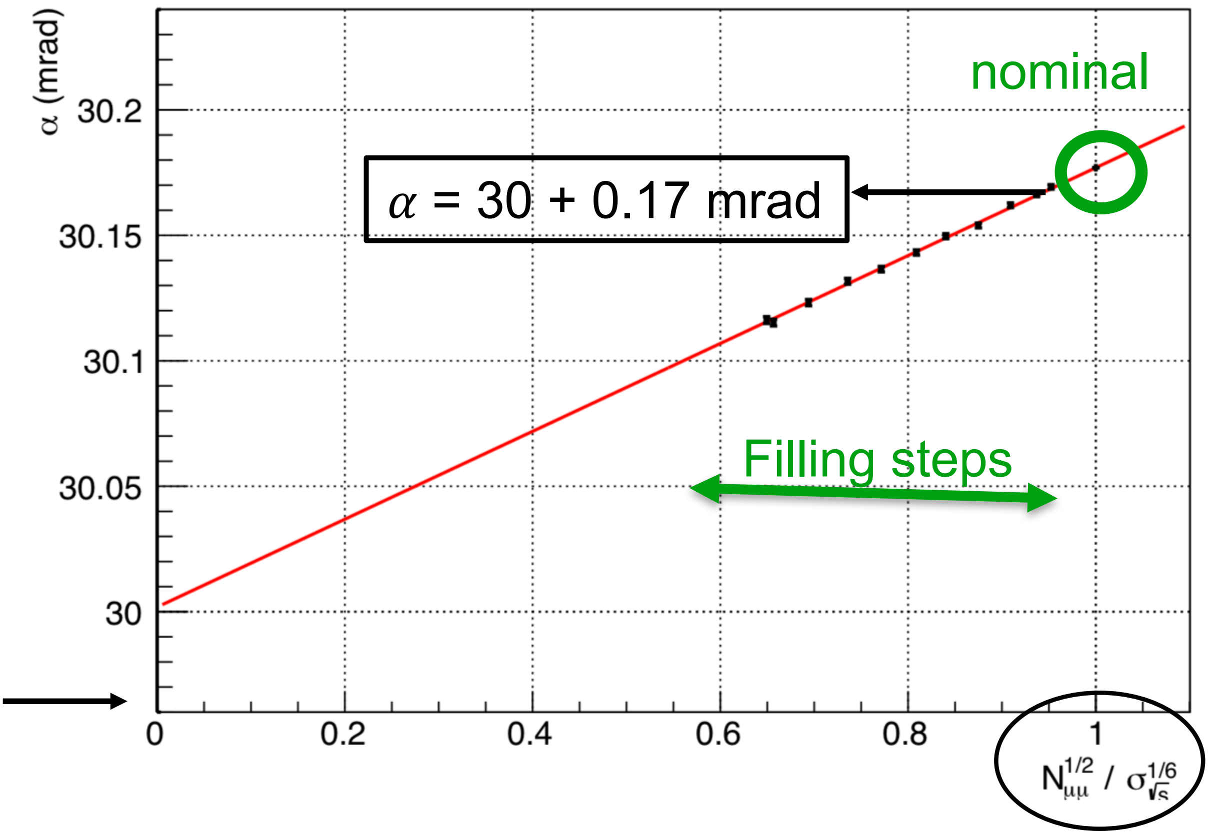
- We know how $\Delta\alpha$ varies with the bunch intensity N
  - Beam-beam effects grow linearly with N when everything else is equal

- 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 !

# Correction of beam-beam effects

Illustration:

- O( 10 ) filling steps
- For each step: calculate $\Delta\alpha$ from a multi-turn simulation
- $\Delta\alpha$ grows indeed linearly with intensity (*)



nominal

$\alpha$ = 30 + 0.17 mrad

Filling steps

The intercept of a linear fit gives $\alpha_0$.

$\alpha_0$ = 30 mrad

With an intensity ramp of O(10) steps, each of 40 sec each : can determine $\alpha_0$ with a precision of about 3 μrad ( and $\Delta\alpha$ within 2%)

Roughly N / Nnominal, measured by the experiment

i.e. δ ( $\alpha$ ) negligible ( a few keV) to δ ( √s )

(*) simplification here, see the paper. What matters is that the scaling variable on the x-axis can be measured

# To conclude on $\sqrt{s}$

- 100 keV on the absolute scale of $\sqrt{s}$ at the Z peak is challenging but appears feasible

- Point-to-point uncertainty can be controlled via :
  - Endpoint of scattered $e^{\pm}$ spectrum in the polarimeters
  - Direct measurement of M(μμ) by the experiments
    - O(40 keV)
    - Need to ensure the long-term stability of the magnetic field in the detector

- Energy spread can be controlled via :
  - Bunch length measurement (beam instrumentation) : to ~ 2%
  - Dimuon events -> distribution of the reconstructed longitudinal imbalance gives $\sigma(\sqrt{s})$ with a ‰ precision
    - Leads to a small increase of the error on $\Gamma_Z$

# Measurement of the luminosity

For details, see :

Overview of luminosity measurement: Talk Mogens Dam, FCC week 2019

"Beam-beam effects on the luminosity measurement at FCC-ee",
G. Voutsinas, E. Perez, M. Dam, P. Janot, JHEP 10 (2019) 225

See also "Beam-beam effects on the luminosity measurement at LEP and the number of light neutrino species", idem, Phys.Lett.B 800 (2020) 135068

# Luminosity at FCC-ee

Precision measurements programme requires very precise normalisation, most stringent requirements for the Z and WW energies.

Goal: Reach an experimental uncertainty of :

- $10^{-4}$ (absolute)
  - for a precise determination of $\sigma^0_{had}$ and $N_\nu$
  - match the anticipated theo. precision
  - OPAL reached (exp.) 3.4 x $10^{-4}$

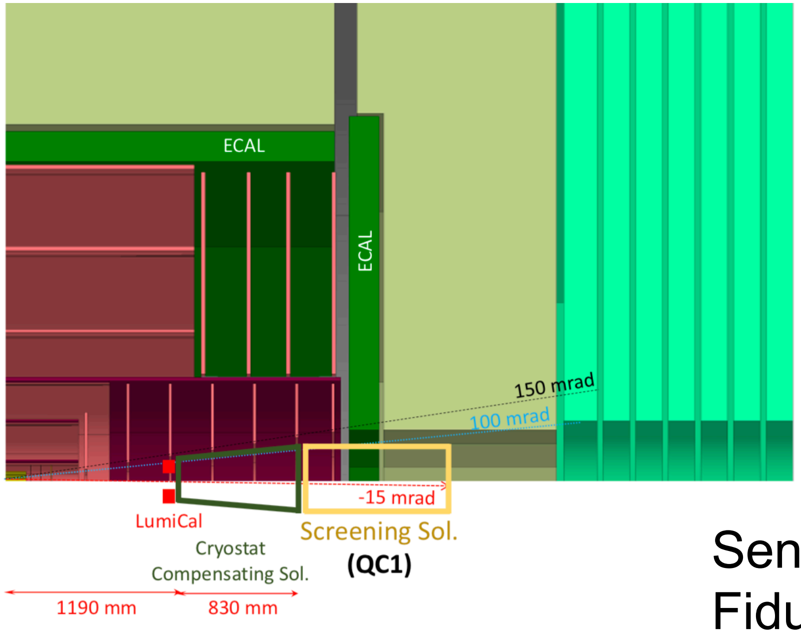
- a few $10^{-5}$ (relative, line-shape scan)
  - Needed to determine $\Gamma_Z$ to 100 keV

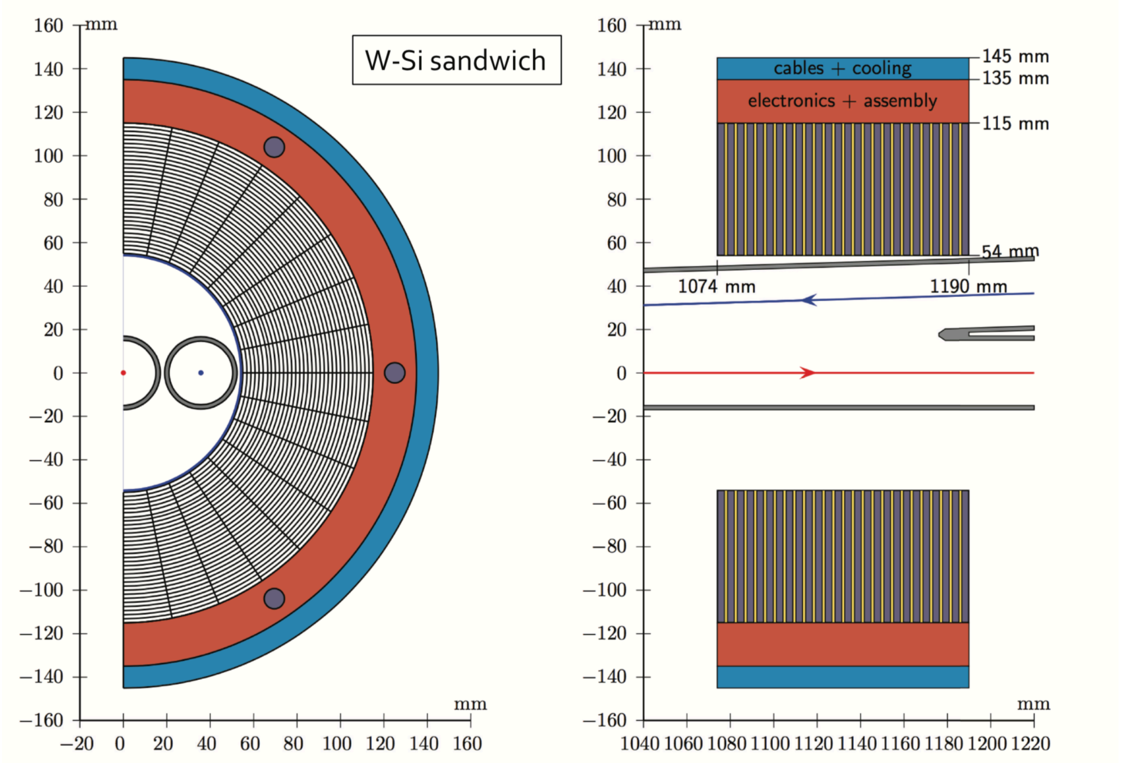
# Detector concept for the luminometer

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.

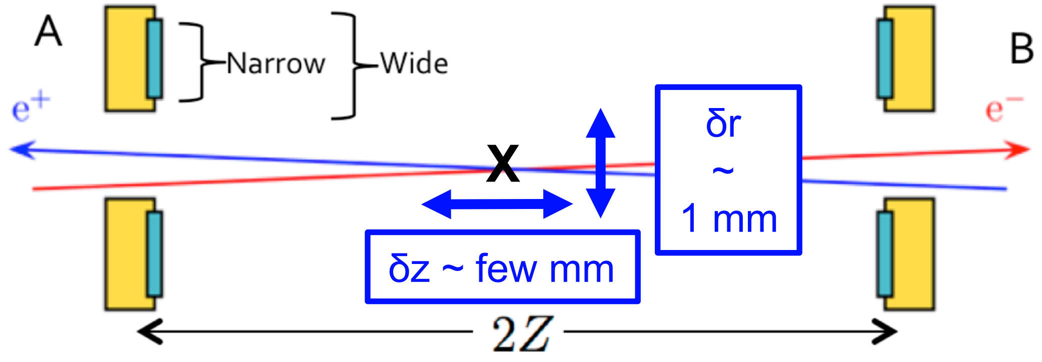




Sensitive region: 55 < R < 115 mm
Fiducial volume for the measurement: 64 – 86 mrad,
σ(Bhabha) = 14 nb at √s = 91.2 GeV

# Definition of and precision on the acceptance

Method of "asymmetric acceptance" :



Events are selected if :
e- in Narrow and e+ in Wide
or
e+ in narrow and e- in Wide

Largely reduces the dependence of A on:

- radial or longitudinal displacements of the IP wrt lumi system.
- Any displacement of the vertex (e.g. ISR)

With θ( Wide ) = θ ( Narrow ) +/- 2 mrad :

$$\boxed{\frac{\Delta A}{A} \approx -\left(\frac{\delta z}{6\,\mathrm{mm}}\right)^2 \times 10^{-4}}$$

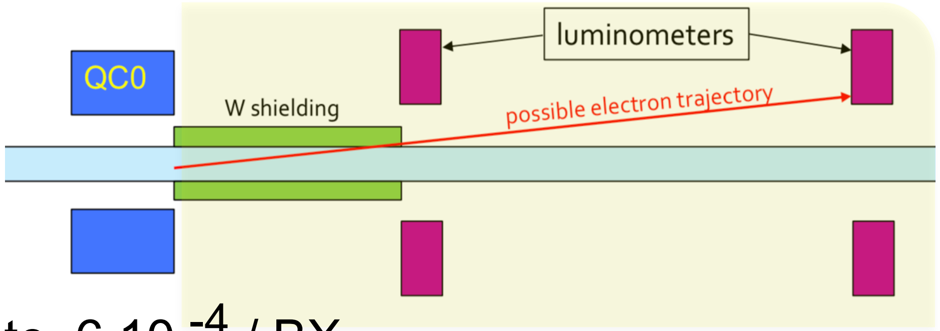
$$\boxed{\frac{\Delta A}{A} \approx +\left(\frac{\delta r}{0.6\,\mathrm{mm}}\right)^2 \times 10^{-4}}$$

- Inner (outer) radius of the luminometer: must be known to 1.6 ( 3.8 ) µm
  - OPAL achieved $\Delta R_{in} \approx 5$ µm
  - Compact detector: each Si sensor from one wafer only. Vertical assembly of the two halves will drive $\Delta R_{in}$
- Distance 2Z between the two arms: must be known to ~ 100 µm

# Impact of backgrounds on the luminosity measurement

- Synchrotron radiation: negligible except at the top energy
- Pair production background : impact checked with a full simulation. Small energy deposit (350 MeV / BX at the Z peak) and easy to shield (at the rear of the calorimeter).
- Beam-gas: 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 BG + extrapolation of the trajectory of the part, that are lost in | z | < 2.1 m :
Rate of coincidence per BX = 2 $10^{-5}$



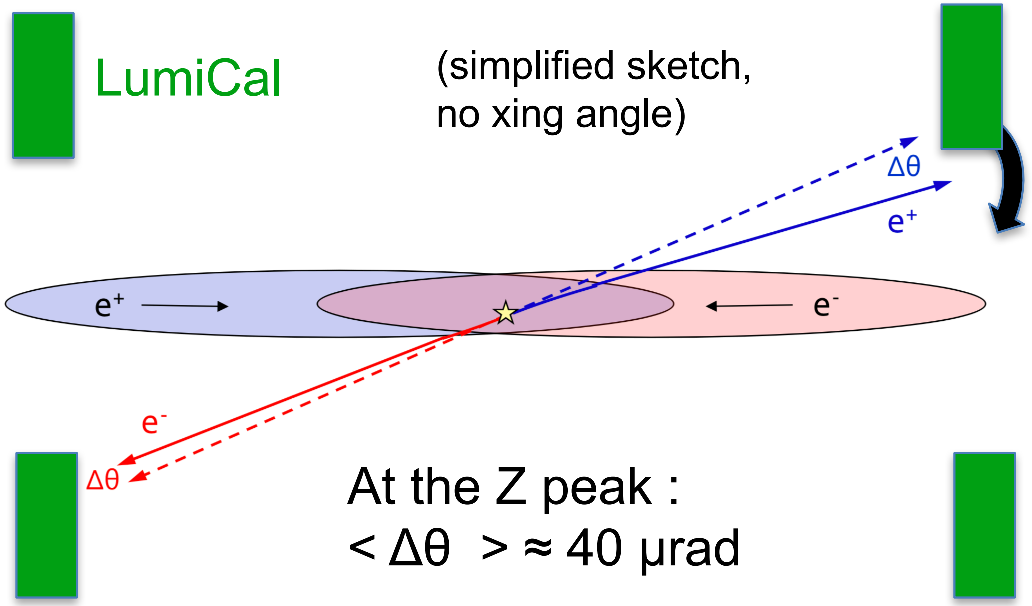
Already small compared to the Bhabha rate, 6 $10^{-4}$ / BX

> 95% of them leave the BP early and will be stopped by the tungsten shielding.
Estimation of coincidence rate : < $10^{-7}$ before any energy / angular cut.

From the current studies: backgrounds are not expected to be an issue.

# Beam-induced effects on the acceptance

The e+/- in the final state of the Bhabha interaction feel the EM fields from the bunches !



(simplified sketch, no xing angle)

At the Z peak :
$< \Delta\theta > \approx 40$ μrad

Focusing of the Bhabha $e^{\pm}$ by the beam force :

The # of $e^{\pm}$ 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.

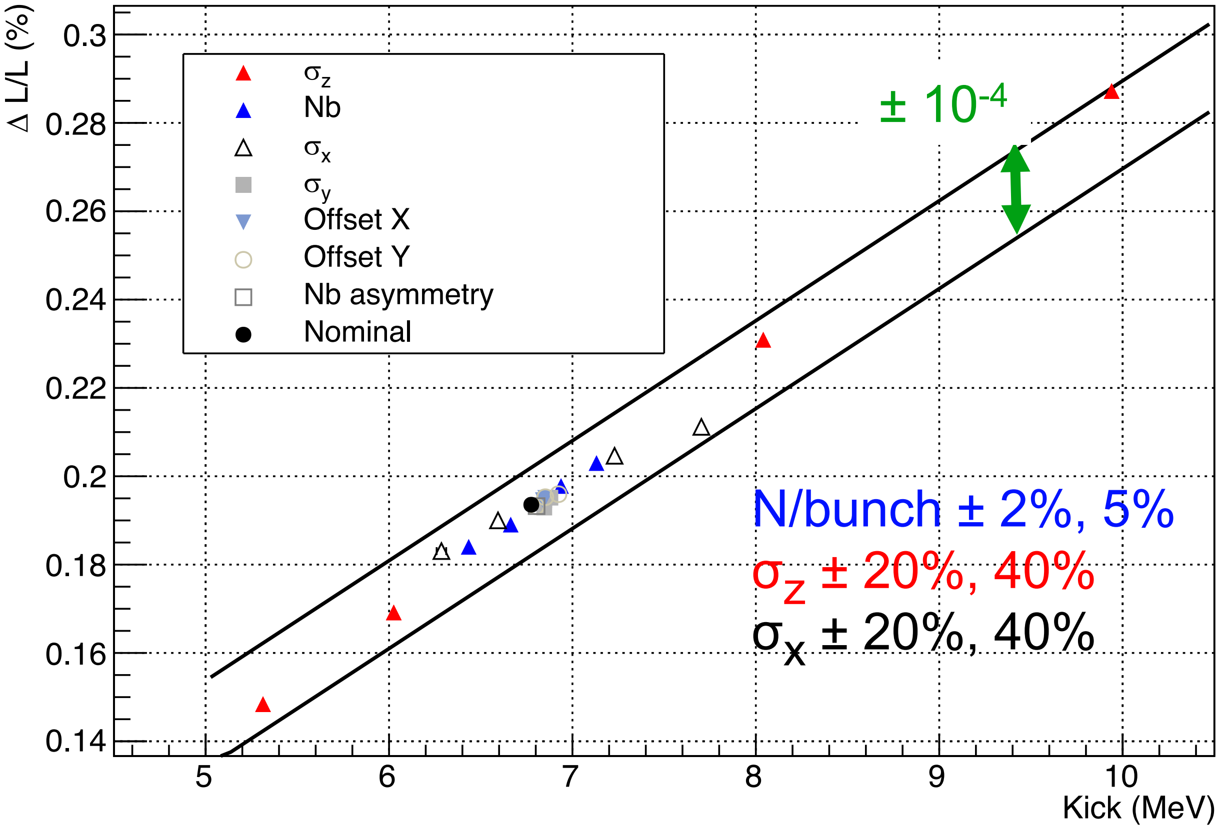
# The px kick gives the luminosity correction !

Very strong correlation between the luminosity bias and the px kick induced by beam-beam interactions (proportional to the crossing angle increase, see earlier)

Plot : simulations with several variations of the beam parameter around the nominal settings.

Expected : ΔL is due to the “EM focusing” of the final state Bhabhas. The kick is very much the same effect, but applied to the initial state instead of to the final state.

( NB: it is | ΔL | / L that is shown )



Hence: the per-cent level measurement of the px-kick, as can be obtained from dimuon events, provides a determination of the bias within the target precision.

# To conclude on the luminosity

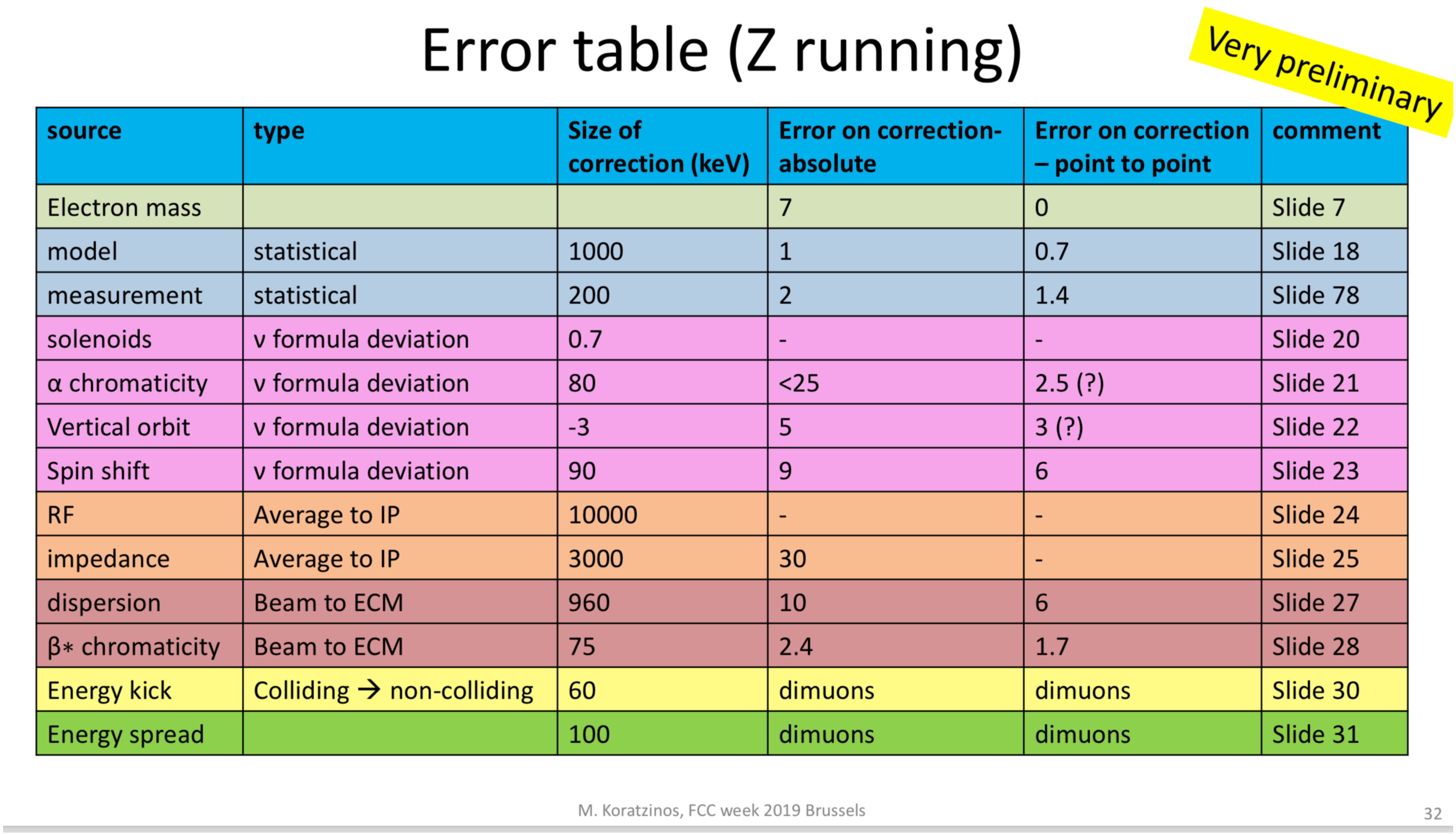
Measurement of the luminosity to $10^{-4}$ is challenging but appears within reach provided that :

- Geometrical precision of construction and metrology to 1 µm level
- Support and alignment to order of 100 micron precision

(Large) bias induced by the EM focusing of the Bhabha electrons can be corrected for.

- Scan around the Z peak : systematic uncertainty on the correction factor largely correlated between energy points (full correlation if the scan is made during one consistent data taking period).

# Backup slides



# Error table (Z running)

Very preliminary

| source | type | Size of correction (keV) | Error on correction-absolute | Error on correction – point to point | comment |
|---|---|---|---|---|---|
| Electron mass | | | 7 | 0 | Slide 7 |
| model | statistical | 1000 | 1 | 0.7 | Slide 18 |
| measurement | statistical | 200 | 2 | 1.4 | Slide 78 |
| solenoids | ν formula deviation | 0.7 | - | - | Slide 20 |
| α chromaticity | ν formula deviation | 80 | <25 | 2.5 (?) | Slide 21 |
| Vertical orbit | ν formula deviation | -3 | 5 | 3 (?) | Slide 22 |
| Spin shift | ν formula deviation | 90 | 9 | 6 | Slide 23 |
| RF | Average to IP | 10000 | - | - | Slide 24 |
| impedance | Average to IP | 3000 | 30 | - | Slide 25 |
| dispersion | Beam to ECM | 960 | 10 | 6 | Slide 27 |
| β∗ chromaticity | Beam to ECM | 75 | 2.4 | 1.7 | Slide 28 |
| Energy kick | Colliding → non-colliding | 60 | dimuons | dimuons | Slide 30 |
| Energy spread | | 100 | dimuons | dimuons | Slide 31 |

M. Koratzinos, FCC week 2019 Brussels

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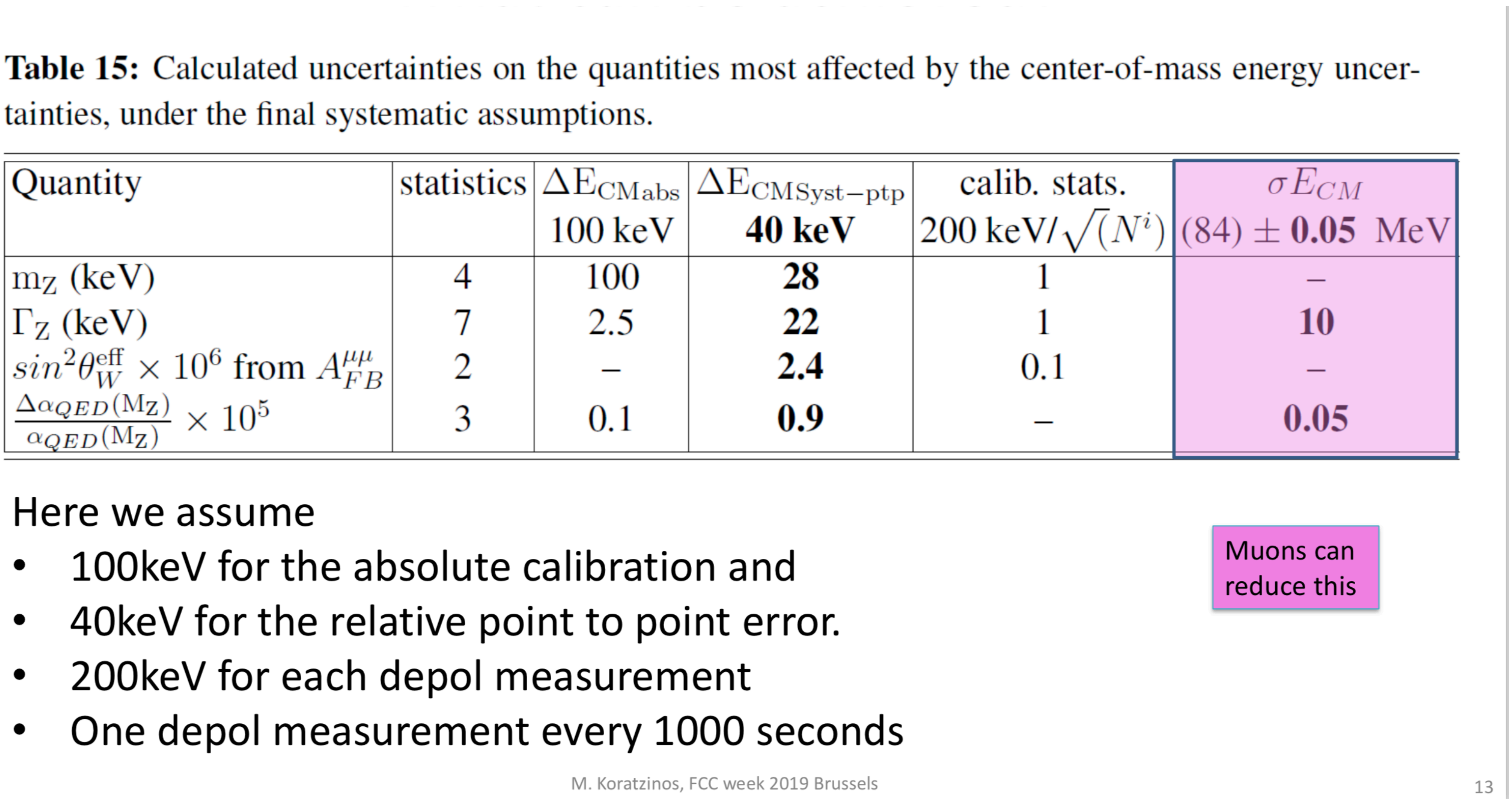


**Table 15:** Calculated uncertainties on the quantities most affected by the center-of-mass energy uncertainties, under the final systematic assumptions.

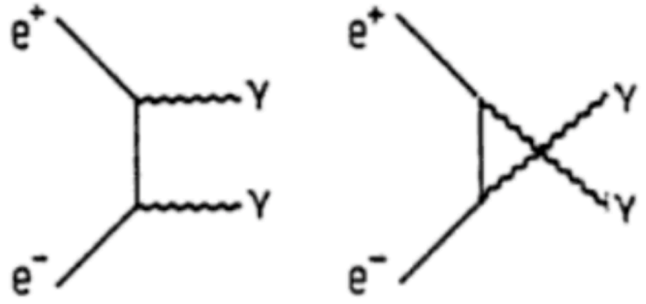
| Quantity | statistics | $\Delta E_{\mathrm{CMabs}}$ 100 keV | $\Delta E_{\mathrm{CMSyst-ptp}}$ **40 keV** | calib. stats. 200 keV/$\sqrt(N^i)$ | $\sigma E_{CM}$ (84) ± **0.05** MeV |
|---|---|---|---|---|---|
| $m_Z$ (keV) | 4 | 100 | **28** | 1 | – |
| $\Gamma_Z$ (keV) | 7 | 2.5 | **22** | 1 | **10** |
| $sin^2\theta_W^{\mathrm{eff}} \times 10^6$ from $A_{FB}^{\mu\mu}$ | 2 | – | **2.4** | 0.1 | – |
| $\frac{\Delta\alpha_{QED}(\mathrm{M_Z})}{\alpha_{QED}(\mathrm{M_Z})} \times 10^5$ | 3 | 0.1 | **0.9** | – | **0.05** |

Here we assume

- 100keV for the absolute calibration and
- 40keV for the relative point to point error.
- 200keV for each depol measurement
- One depol measurement every 1000 seconds

Muons can reduce this

# Alternative measurement of the luminosity : ee ⟶ $\gamma\gamma$ 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:
$\theta_{min}$ = 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/$\gamma$ separation ($\gamma$ conversions, e ⟶ $\gamma$ fake rate).

e.g. with $\varepsilon$ ( $\gamma$ id ) = 99% and fake(e ⟶ $\gamma$) = 1%, would need to know the $\gamma$ 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 ! )

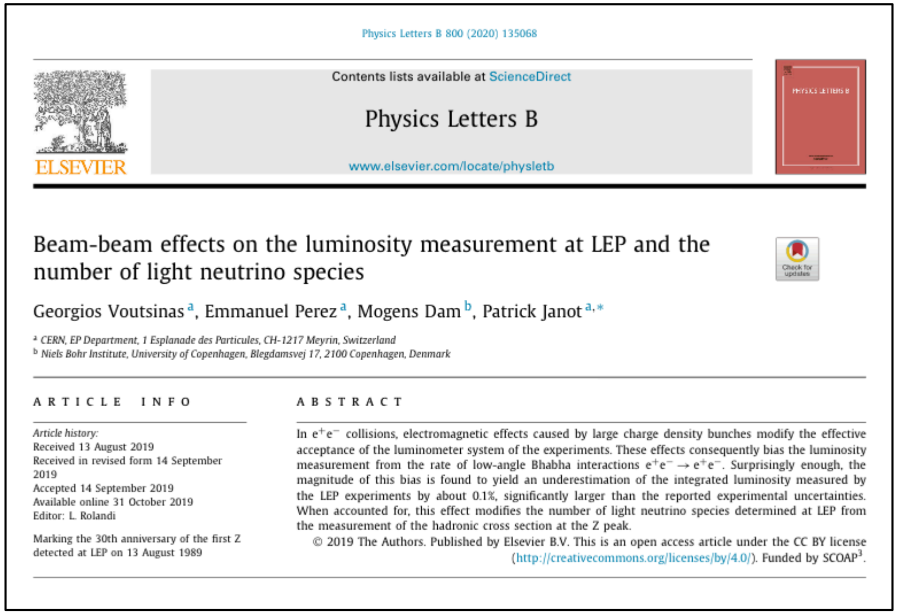
# Interesting by-product : beam-induced effects and the LEP luminosity

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.) )



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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.

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

Correcting for the bias leads to

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

# The revisited number of neutrinos

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

Correcting for the beam-induced effects :
Nv = 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 Nv .

Janot & Jadach, arXiv:1912.02067

Final results :

Nv = 2.9975 ± 0.0074 ( 0.3 σ away from 3 )

$\Gamma_Z$ = 2.4955 ± 0.0023 GeV ( 0.3 MeV increase )
$\sigma^0_{had}$ . = 41.4737 ± 0.0326 nb ( 70 pb decrease )