Luminosity Measurement at e+e- Colliders

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General

The luminosity $\mathcal{L}$ is a key quantity of each collider

For a process with a cross section σ holds:

$\dot{N}$ = σ x $\mathcal{L}$

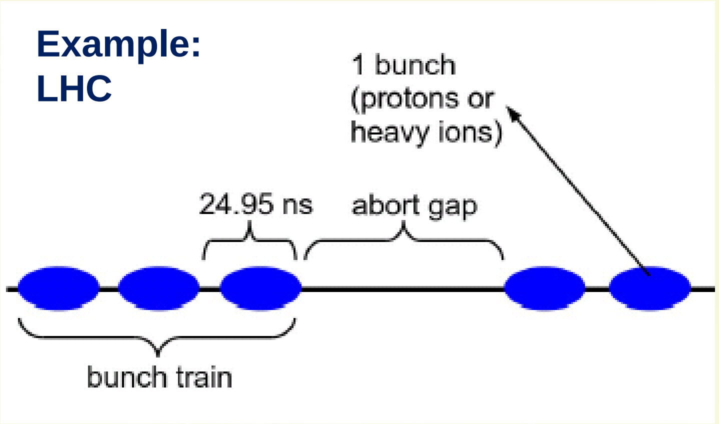
$\dot{N}$: Number of events of the process recorded per unit time

As larger the luminosity as more events of a given process you may collect in a certain time!

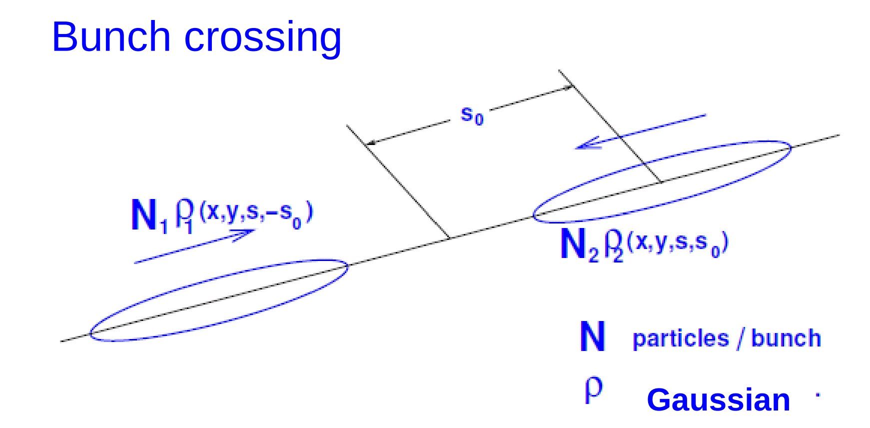
However, to measure cross sections precisely, also a precise measurement of the luminosity $\mathcal{L}$ is necessary.

General

In a Collider particles are accelerated in bunches, with N_b particles



$$\mathcal{L} = \frac{f_{rev} N_1 N_2 n_b}{4\pi\sigma_x\sigma_y} F;$$

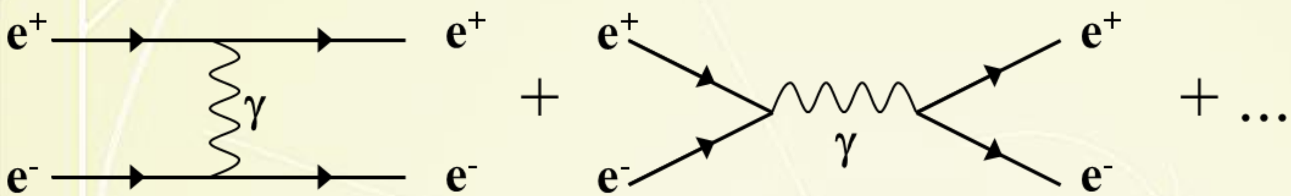


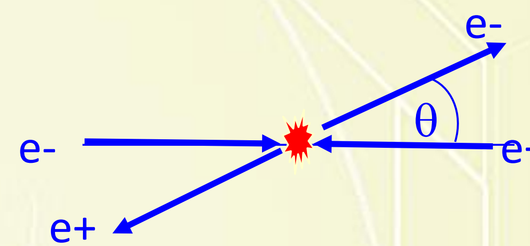
f_{rev} : revolution frequecy
n_b : number of bunches
σ_x, σ_y: Gaussian widths
F : impact of a crossing angle, at e^+e^- linear collider also a luminosity enhancement factor.

e^+e^- collider

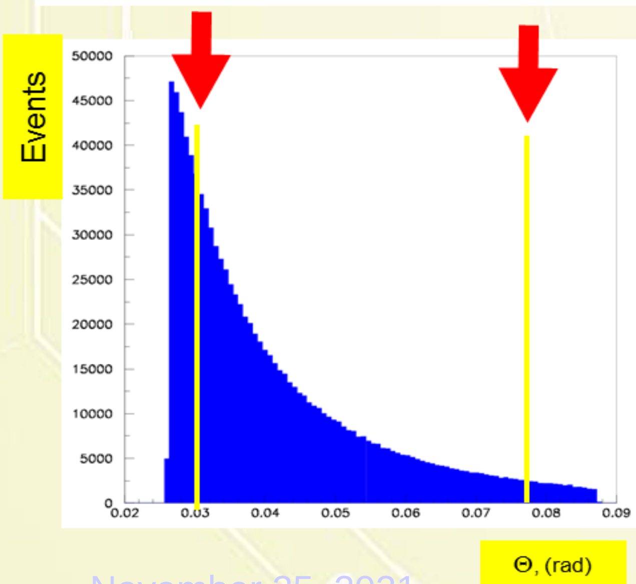
Bhabha scattering at low polar angles is used as a gauge process

$$e^+e^- \longrightarrow e^+e^- (\gamma)$$





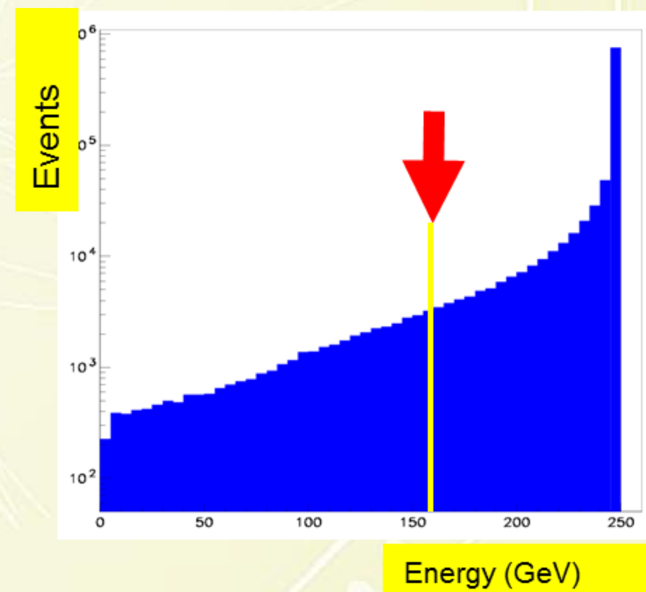
$$\frac{d\sigma_B}{d\theta} = \frac{2\pi\alpha_{em}^2}{s}\frac{\sin\theta}{\sin^4(\theta/2)} \approx \frac{32\pi\alpha_{em}^2}{s}\frac{1}{\theta^3}$$



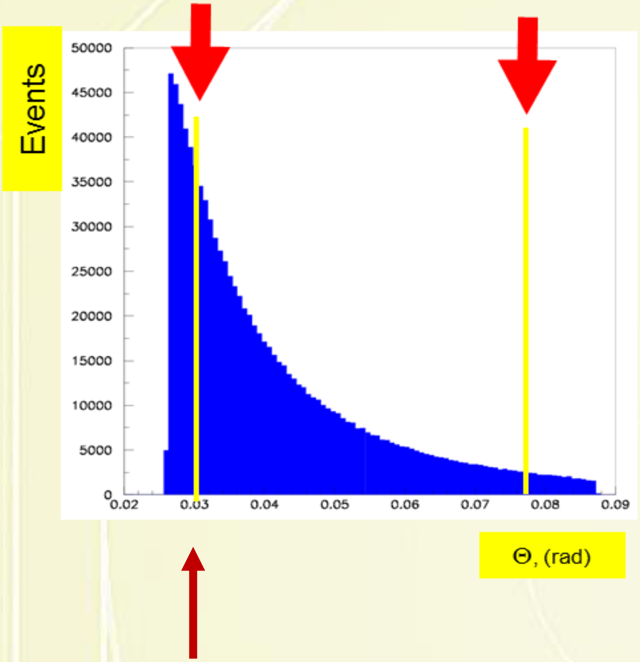
$\mathcal{L} = N / \sigma$

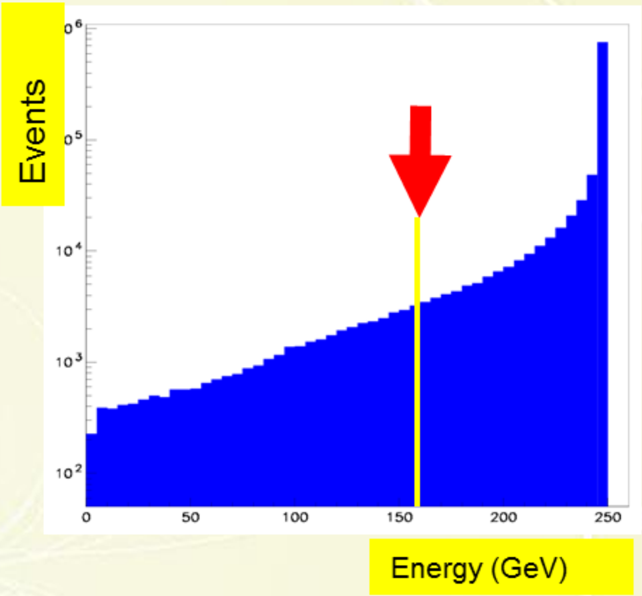
Count Bhabha events

From theory



e^+e^- collider





Essential is the control of the lower polar angle, or in a cylindrical calorimeter the inner radius

$\Delta\mathcal{L}/\mathcal{L} = 10^{-4}$ O(1μm)

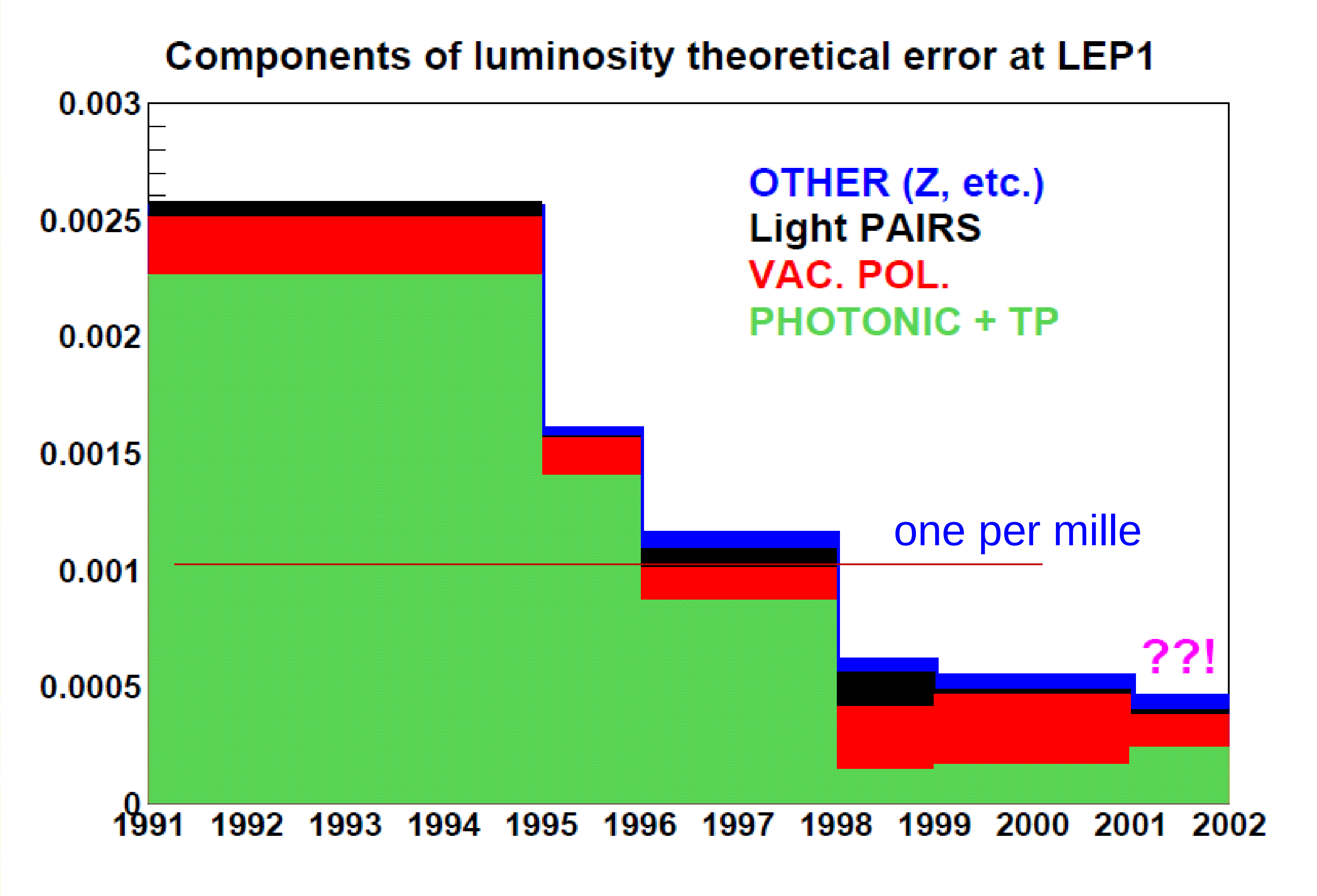
$\Delta\mathcal{L}/\mathcal{L} = 10^{-3}$ O(10μm)

Energy resolution

$$\frac{\sigma_E}{E} = \frac{20\%}{\sqrt{E}}$$

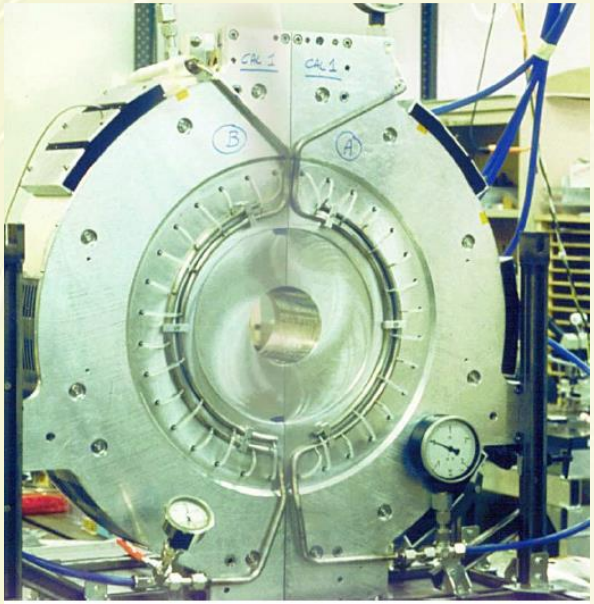
e^+e^- collider

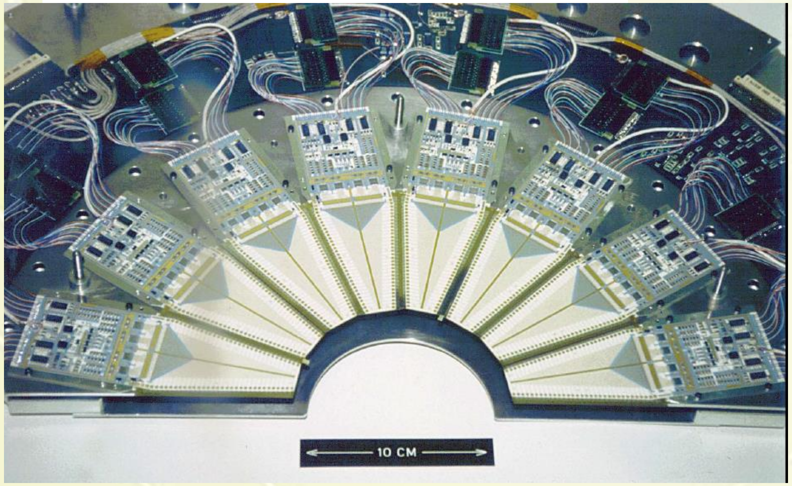
Theory uncertainties in the Bhabha cross section at LEP1 $\sqrt{s} \approx 91$ GeV (S. JADACH, FCAL workshop Cracow 2006):

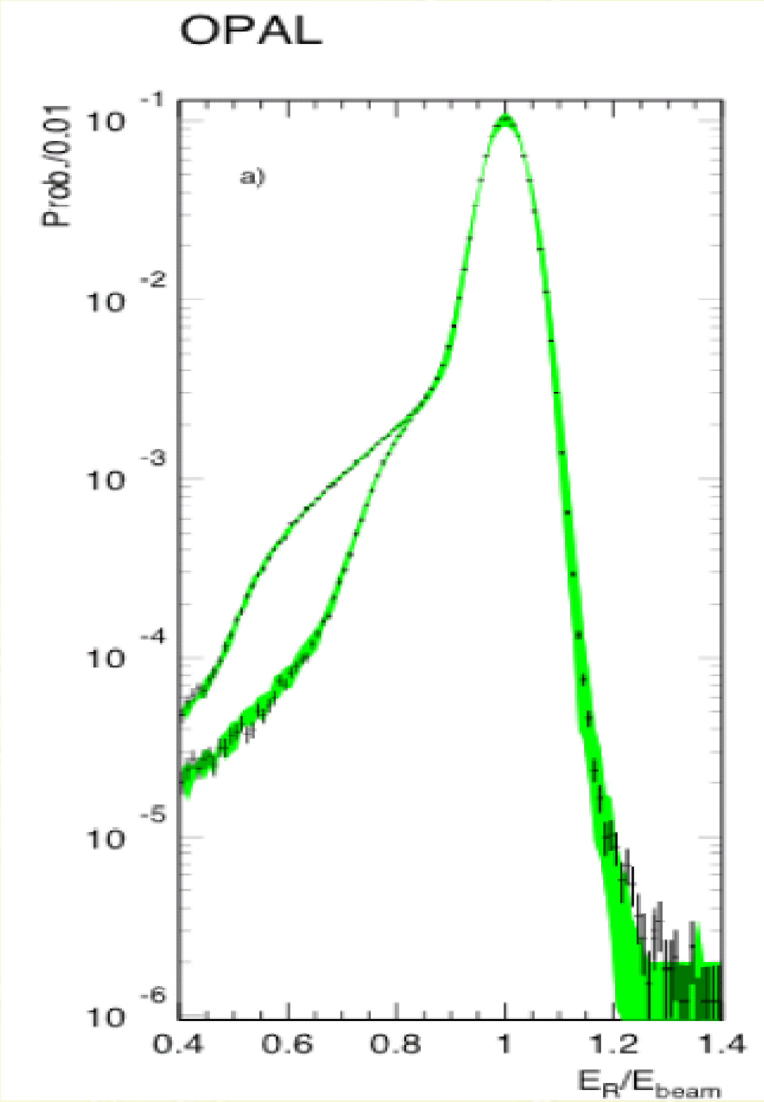


e^+e^- collider

Example of a measurement at LEP (OPAL):

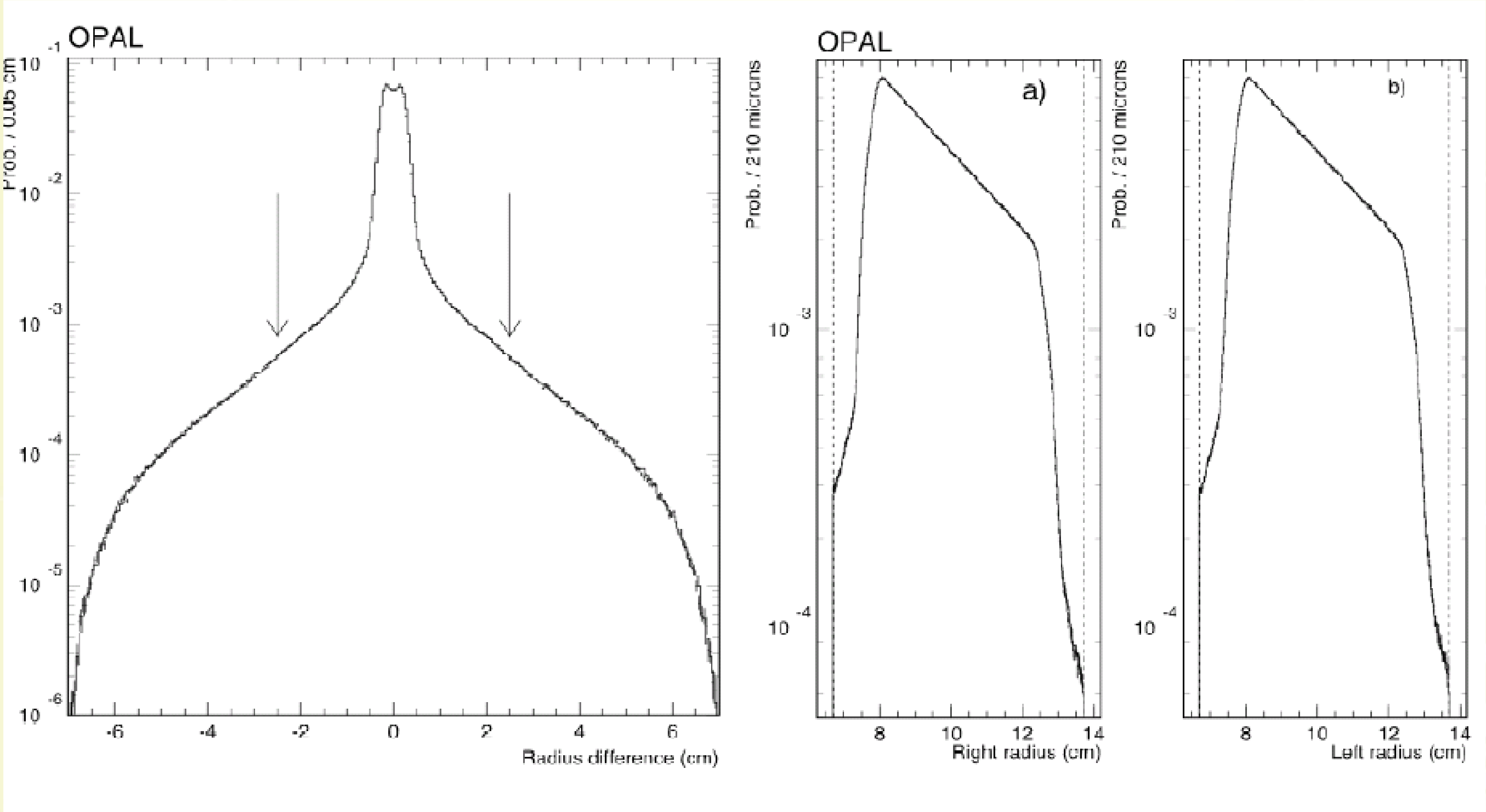






Excellent agreement between experiment and BHLUMI MC

e^+e^- collider



Experimental precision (OPAL): $\Delta\mathcal{L}/\mathcal{L} = 3.4 \times 10^{-4}$

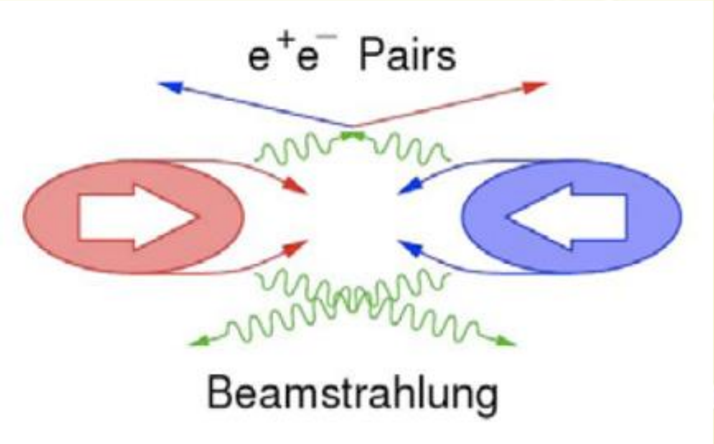
Theory precision : $\Delta\mathcal{L}/\mathcal{L} = 5.4 \times 10^{-4}$

e^+e^- collider

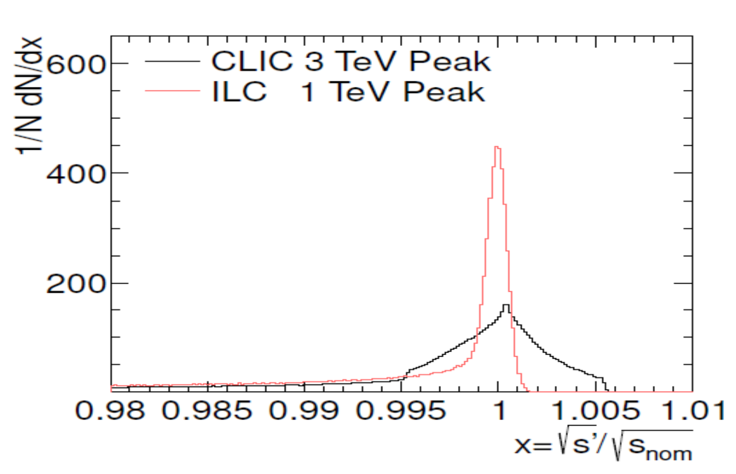
Theory uncertainties at higher energies at ILC/CLIC (S. JADACH, FCAL workshop Cracow 2006):

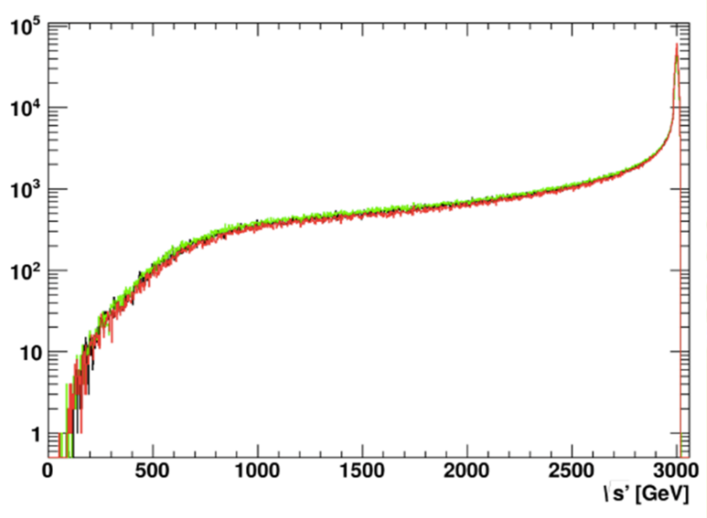
in the range of polar angles 25 – 100 mrad:

- Hadronic vacuum polarisation
- QED photonic corrections
- EW corrections to Z (t-channel)
- Light fermion pairs



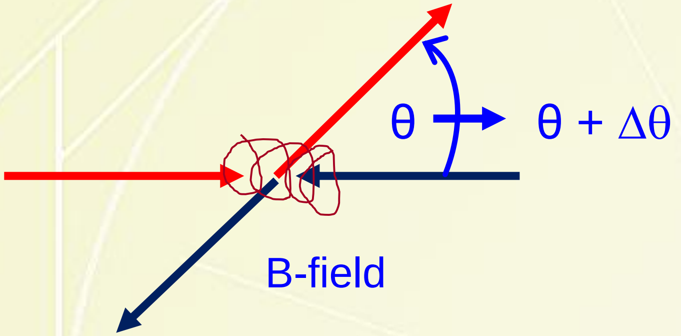
Other challenges: Beamstrahlung – luminosity spectrum

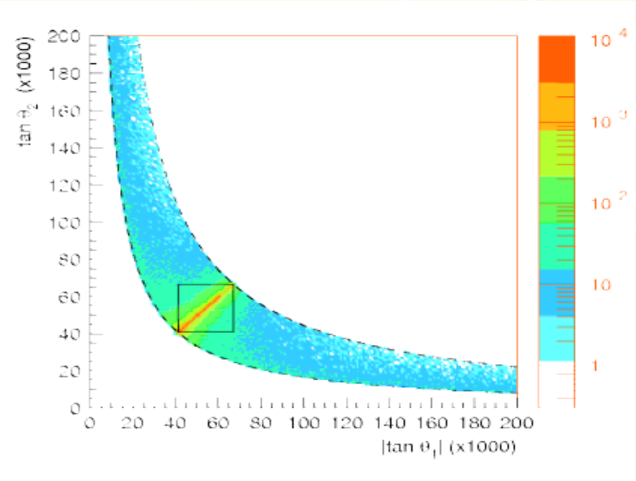




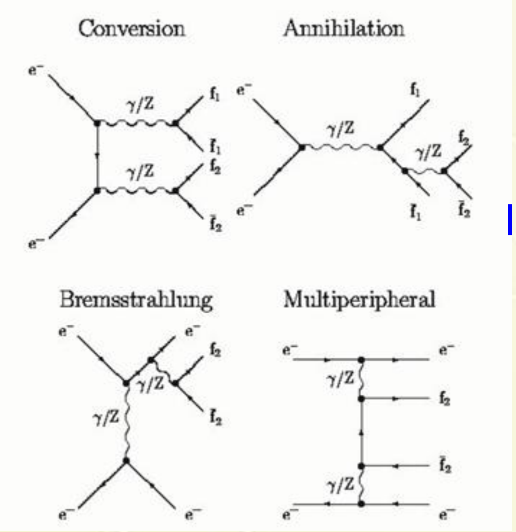
e^+e^- collider

Deflection of the scattered electron/positron in the bunch magnetic field

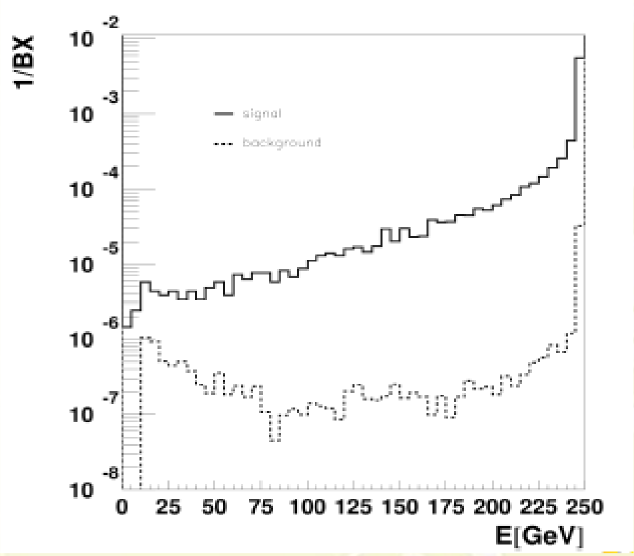




Physics background: four-fermion processes



not easy to calculate-
likely need to be measured



e^+e^- collider

Precision needed at ILC ($\sqrt{s}$ = 500 GeV) $\Delta\mathcal{L}/\mathcal{L} = 10^{-3}$

No problem with statistical precision
Systematics:

Table 2: Systematic uncertainties in the ILC luminosity measurement.

Source of uncertainty	$\Delta L/L$ (10^{-3}) 500 GeV	1 TeV
Bhabha cross section [63]	0.54	0.54
Polar-angle resolution [5]	0.16	0.16
Polar-angle bias [5]	0.16	0.16
Energy resolution [5]	0.1	0.1
Energy scale [5]	1	1
Beam polarization [5]	0.19	0.19
Physics background [62]	2.2	0.8
Beam-beam effects [59]	0.9	1.5
Total	2.6	2.1

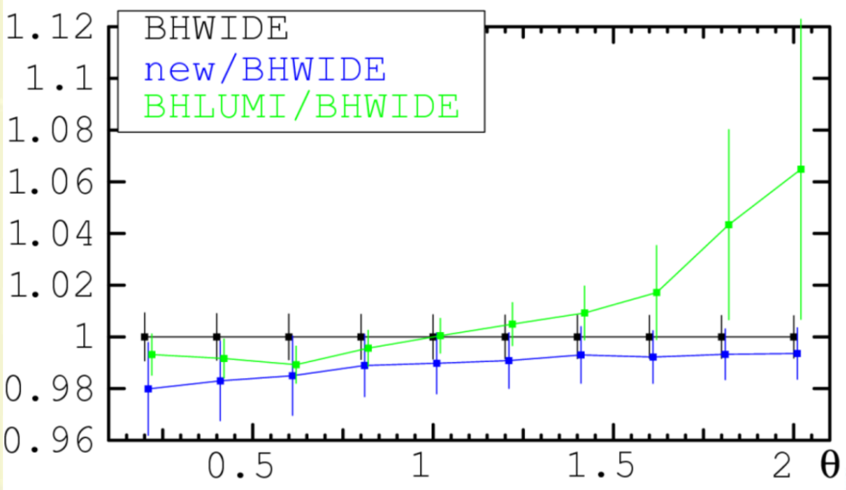
Likely underestimated

Precision needed at CLIC ($\sqrt{s}$ = 3 TeV) $\Delta\mathcal{L}/\mathcal{L} = 10^{-2}$

More detailed studies needed

e^+e^- collider

V. Makarenko made comparison of different codes (JINR 2016):



- BHWIDE for wide angle scattering
  S. Jadach, W. Placzek, Z. Was et al., *Comp.Phys.Comm. 102 (1997) 229-251*
  Precision: 0.1 – 0.5% (depending on c.m.s. energy);
- BHLUMI for forward region ($\sim 20 mrad$)
  S. Jadach, W. Placzek et al., *Phys.Lett. B390 (1997) 298-308*
  Precision: up to 0.06% (at LEP1 energy).

- The NLO generator allows to achieve only about 1% precision.
  - The error imposed by using of BHWIDE is of the same size.

Second order corrections

The complete $\mathcal{O}\left(\alpha^2 L\right)$ analytic result was first received in A.A., V. Fadin, E. Kuraev, L. Lipatov, N. Merenkov, L. Trentadue [Nucl.Phys.B '1997]

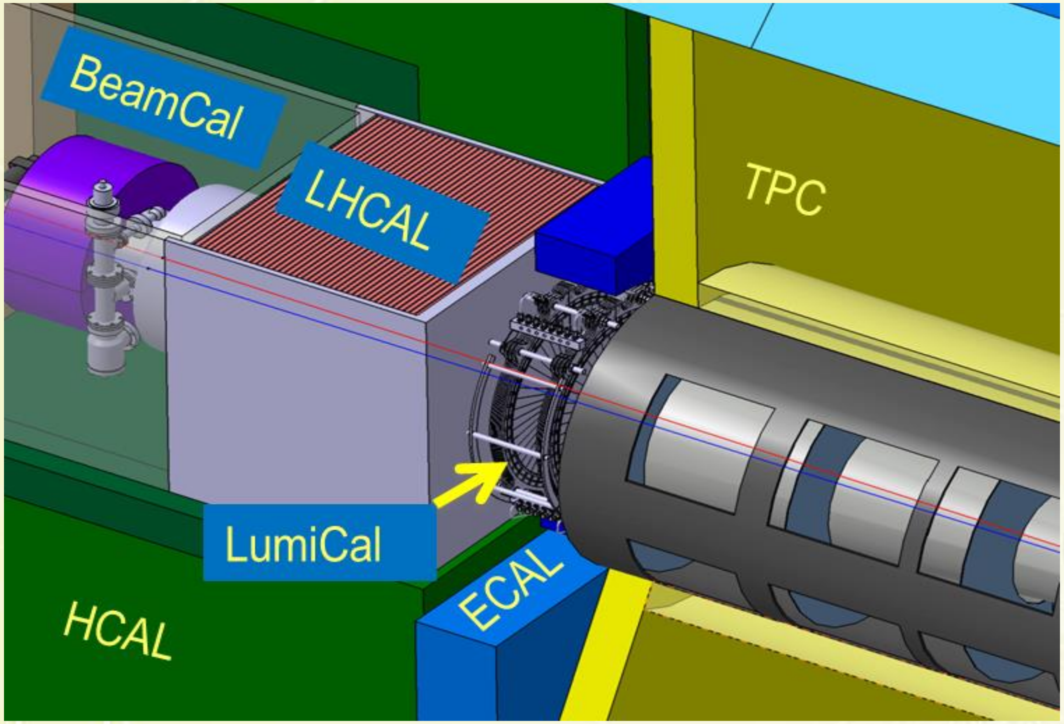
Two-loop virtual pure QED RC were computed by A. Penin [PRL'2005, NPB'2006]

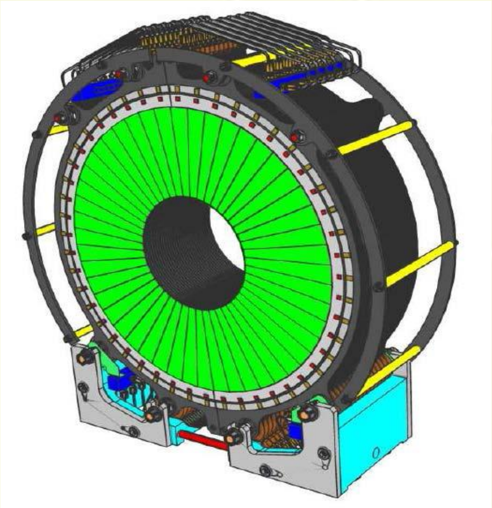
Emission of one or two real photons was also added, see e.g. C. Carloni Calame, H. Czyz, J. Gluza, M. Gunia, G. Montagna, O. Nicrosini, F. Piccinini, T. Riemann, M. Worek *NNLO leptonic and hadronic corrections to Bhabha scattering and luminosity monitoring at meson factories* JHEP 1107 (2011) 126

A. A. Penin and G. Ryan, *Two-loop electroweak corrections to high energy large-angle Bhabha scattering*, JHEP'2011

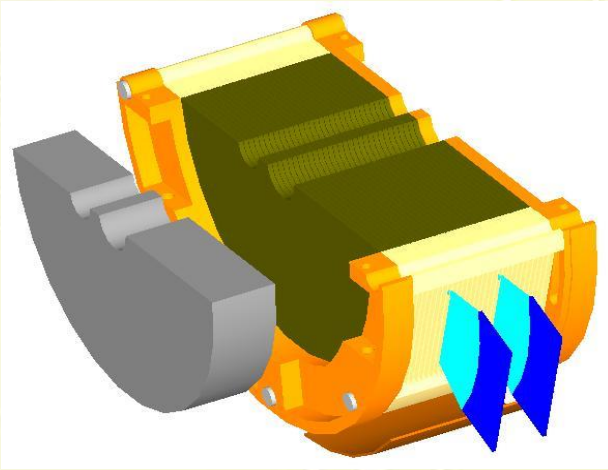
Summary given by A. Arbusov (FCAL workshop JINR 2016)

Luminometer





LumiCal



BeamCal

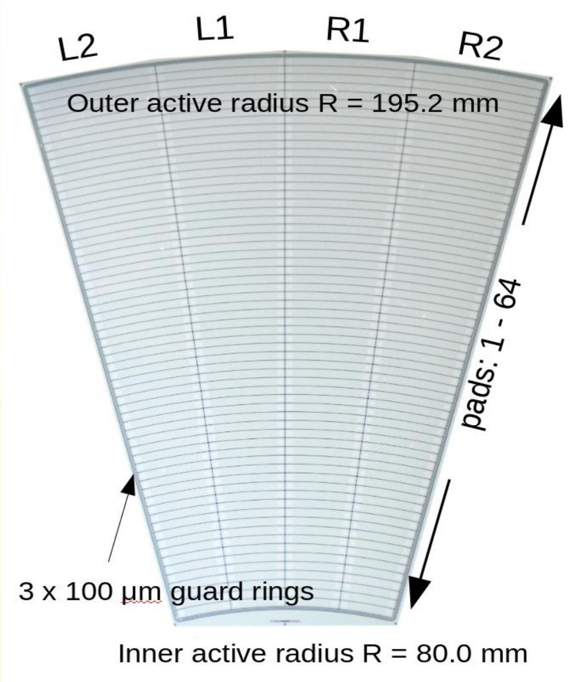
LumiCal and BeamCal:

- Si or GaAs/W sandwich calorimeters
- Compact (small Moliere radius)
- Thin detector planes
- W plates, 1 X0 thick, highly planar
- Dedicated FE, adapted to ILC timing (Marek will talk)

sensors

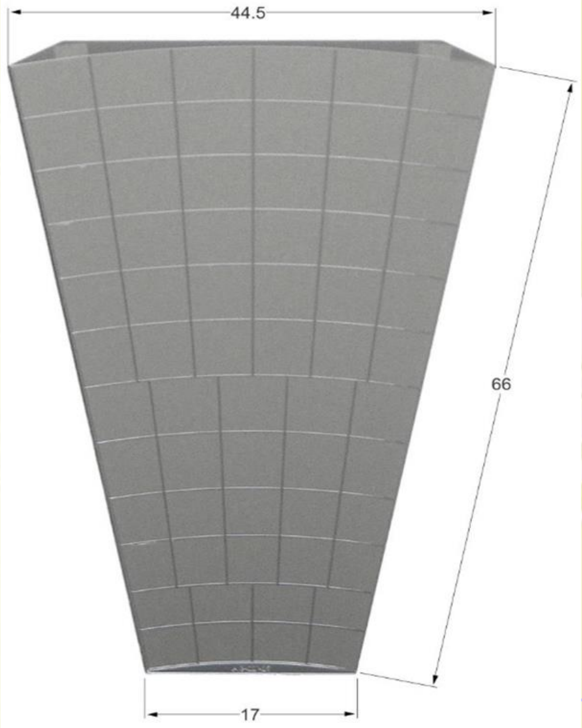
LumiCal sensor (Hamamatsu & INP (Cracow)

- Si, thickness 320 μm
- DC coupled with readout electronics
- p+ implants in n-type bulk
- 64 radial pads, pitch 1.8 mm
- 4 azimuthal sectors in one tile, each 7.5°
- 12 tiles make full azimuthal coverage

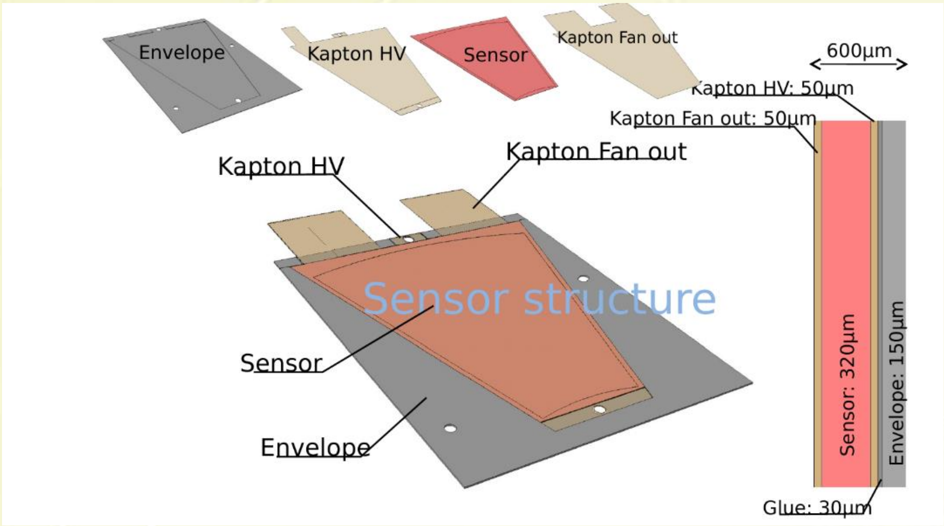


BeamCal Sensor (JINR & TSU)

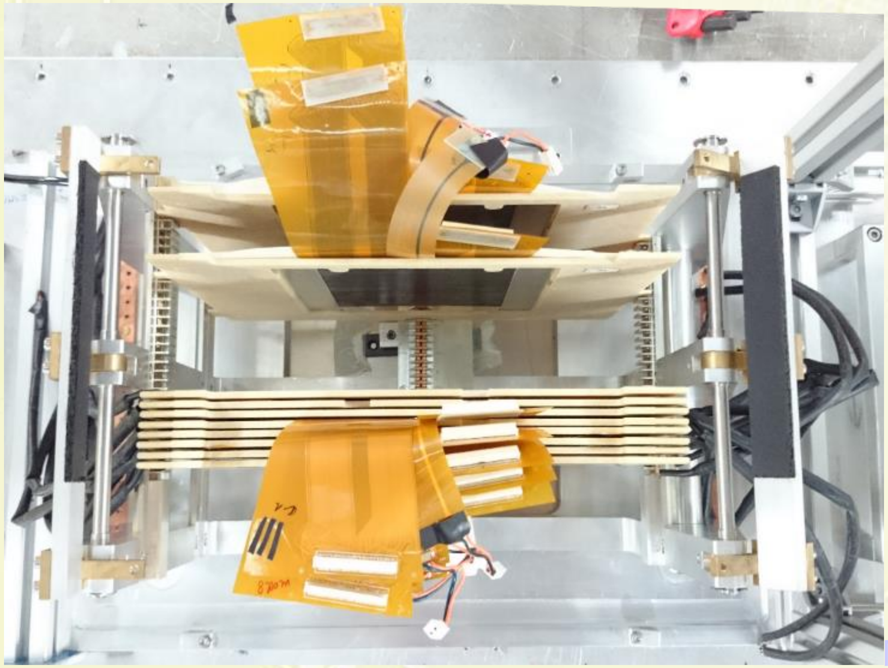
- GaAs, thickness 500 μm
- High resistivity (10^7 Ωm)
- Radiation hard
- S/N for MiPs ≈ 20

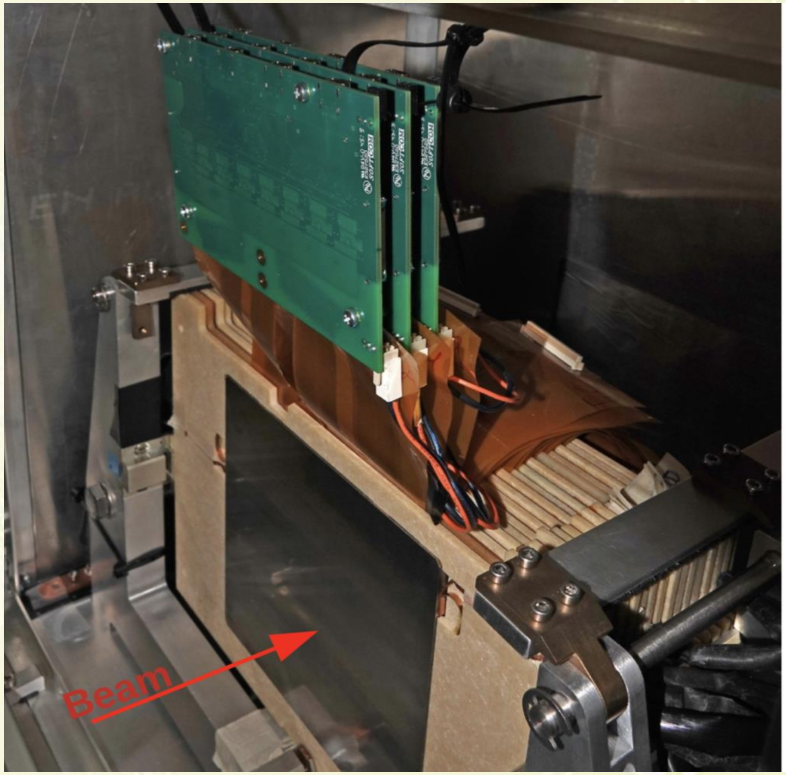


prototype LumiCal



Assembled detector plane





Prototype with FE ASICs on top

Summary

The luminosity $\mathcal{L}$ is a key quantity of each collider

- In e^+e^- collider at 90 GeV cms energy an accuracy $\Delta\mathcal{L}/\mathcal{L} = 3.4 \times 10^{-4}$ was reached at LEP (experimental) and $\Delta\mathcal{L}/\mathcal{L} = 5.4 \times 10^{-4}$ (theory)
- At future e^+e^- linear collider 10^{-3} and 10^{-2} is sufficient, however due to new phenomena at higher energy effort is needed, both from theory and R&D
- A partly assembled LumiCal prototype was studied in an 1-5 GeV electron beam, measurement of longitudinal and transversal shower development, Moliere radius, position resolution, published, and subject of a dedicated talk