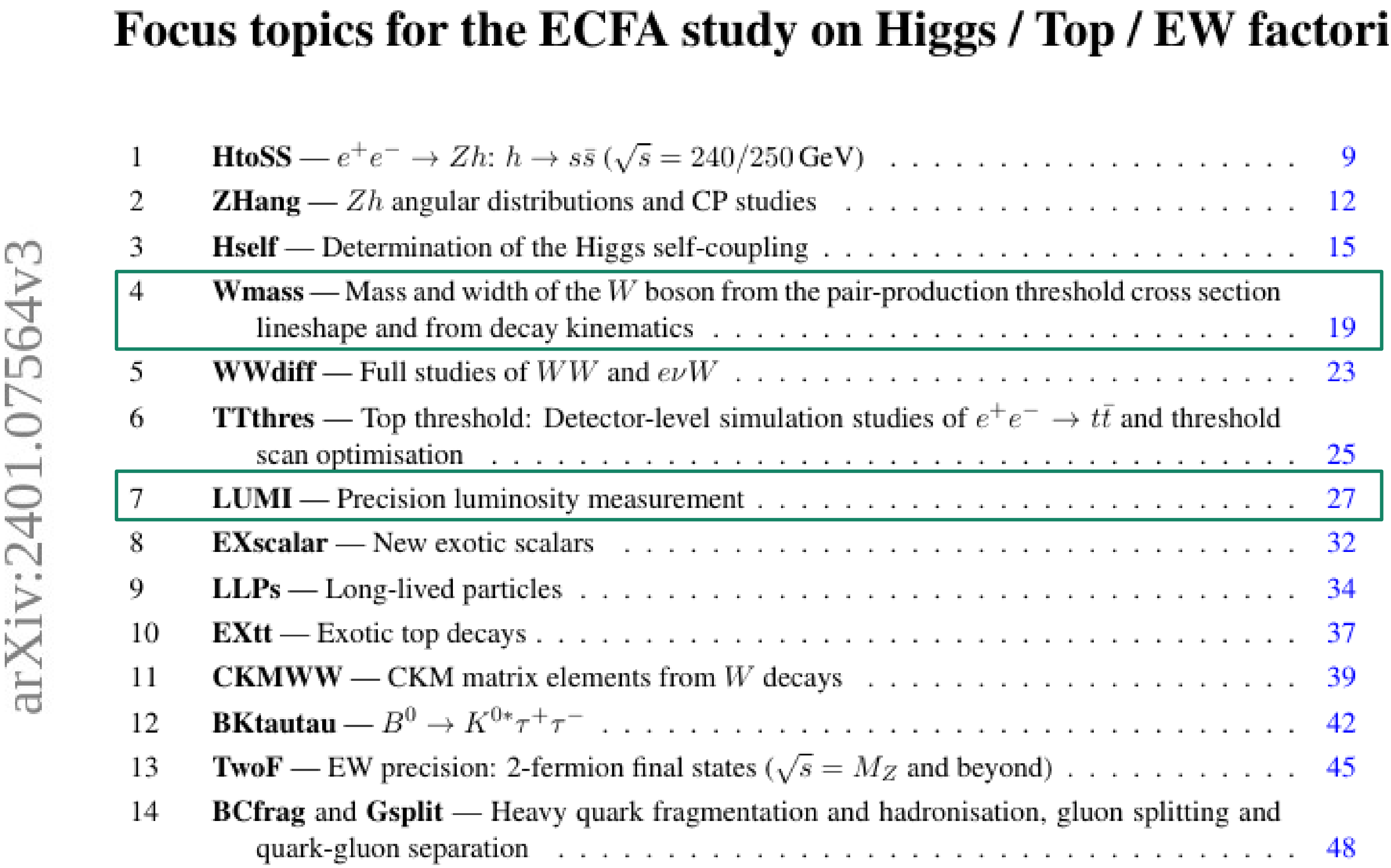


Focus topics for the ECFA study on Higgs / Top / EW factories

arXiv:2401.07564v3

A. Freitas
(U. Pittsburgh)

LUMI – Precision luminosity measurement

Expert team: P. Azzurri, I. Bozovic, M. Dam, A. Freitas, A. Irles, A. Meyer
F. Piccinini, W. Płaczek, A. Sailer, M. Skrzypek, G. Wilson

- Gitlab wiki
- Sign up for egroup: ECFA-WHF-FT-LUMI@cern.ch
- Email WG1 PREC conveners: ecfa-whf-wg1-prec-conveners@cern.ch

Slide materials from M. Dam, S. Jadach, G. Wilson

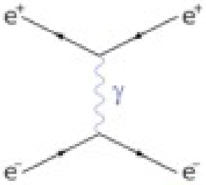
Overview

- Luminosity calibration important for total cross-section and line-shape measurements (**Z pole**, WW, HZ, …)
- Absolute calibration, goal $< 10^{-4}$
- Point-to-point precision, goal $< 10^{-5}$
- Requirements for Lumi calibration process(es):
  - Large rate / low backgrounds
  - Good control of exp. systematics
  - Reliable, high-precision theory prediction, negligible BSM influence

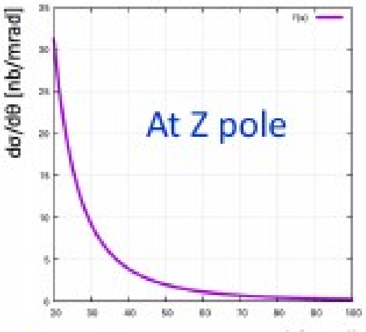
Exploit well known QED reference processes with no (or weak) dependence on EW parameters

Small angle Bhabha scattering

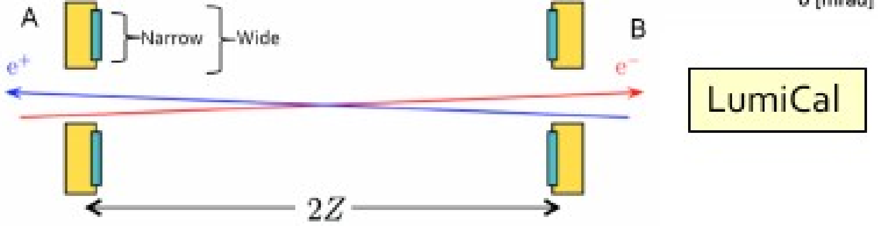
- Very strongly forward peaked
- Dominated by *t*-channel γ exchange



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



- Measured in very forward calorimetrers centered around outgoing beams



- Important systematics from acceptance definition ($\theta_{\min}$)

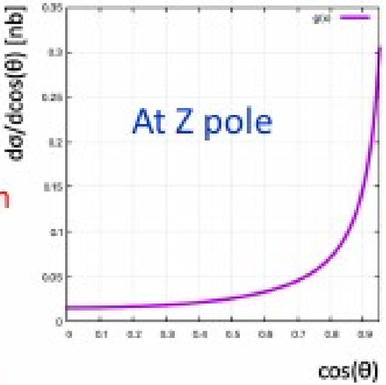
$$\frac{\delta\sigma^{\text{acc}}}{\sigma^{\text{acc}}} \simeq \frac{2\delta\theta_{\min}}{\theta_{\min}} = 2\left(\frac{\delta R_{\min}}{R_{\min}} \oplus \frac{\delta z}{z}\right)$$

Large angle γγ production

- Forward peaked

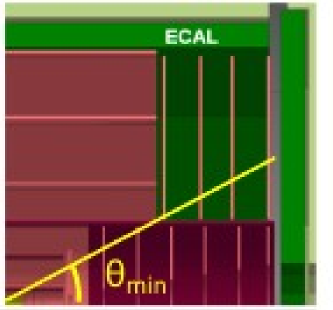
$$\sigma(e^+e^- \to \gamma\gamma) = \frac{2\pi\alpha^2}{s}\left\{\ln\frac{1+\cos\theta_{\min}}{1-\cos\theta_{\min}} - \cos\theta_{\min}\right\}$$

($\theta_{\min}$ defines the ECAL acceptance)



- Measured in main calorimeter system from minimum angle $\theta_{\min}$ (to 90°)
- Rate larger than physics rates everywhere except at Z pole
  - Example $\theta_{\min} = 20°$ ($\cos\theta < 0.94$)

Energy	Process	Cross Section	Large angle $e^+e^- \to \gamma\gamma$
90 GeV	$e^+e^- \to Z$	40 nb	0.039 nb
160 GeV	$e^+e^- \to W^+W^-$	4 pb	15 pb
240 GeV	$e^+e^- \to ZH$	0.2 pb	5.6 pb
350 GeV	$e^+e^- \to tt$	0.5 pb	2.6 pb



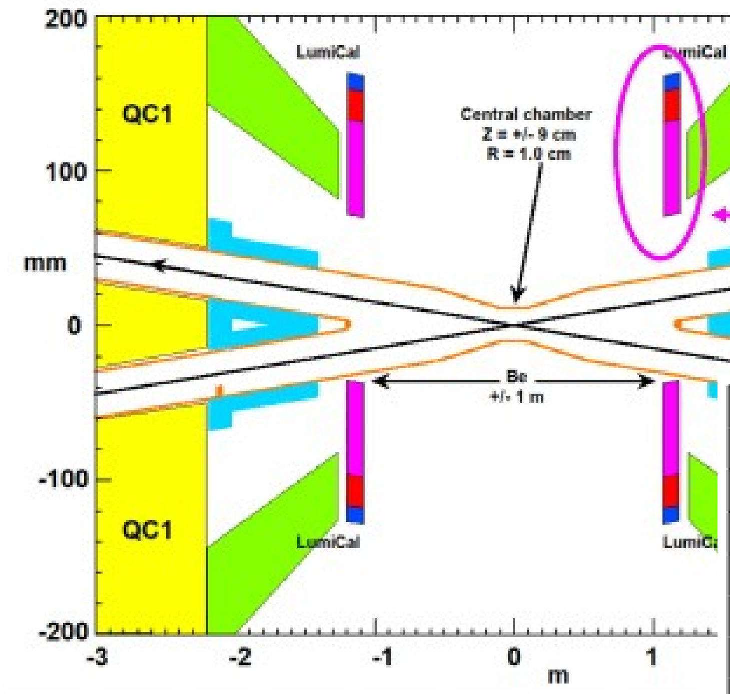
Small-angle Bhabha scattering

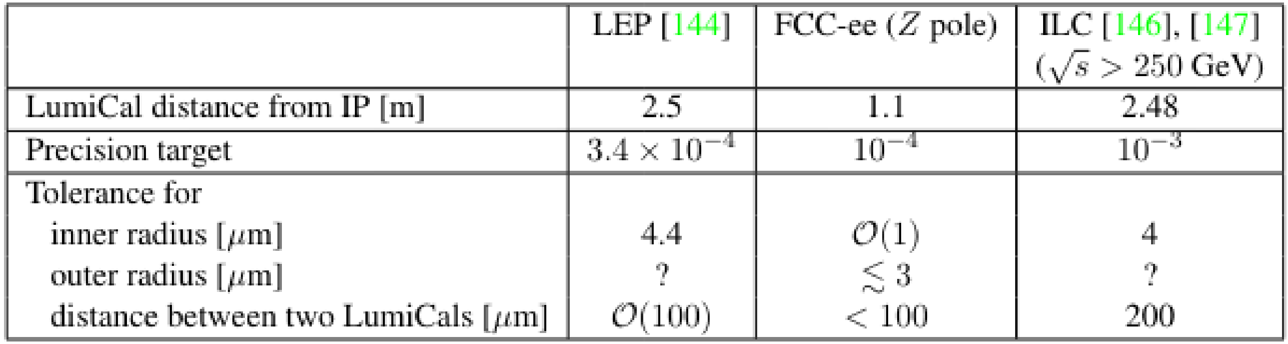
- Experimental challenges:
    - Metrology (geometrical acceptance)
    - Beam parameters
    - Energy calibration and background from beamstrahlung (for LCs)
- Theory challenges:
    - Photon vacuum polarization
    - Pair production
    - NLO electroweak corrections

LumiCals @ FCC-ee

Challenge:

- MDI region is very busy, LumiCals pushed far inside main detector volume
- Not much space + increased requirements to precision

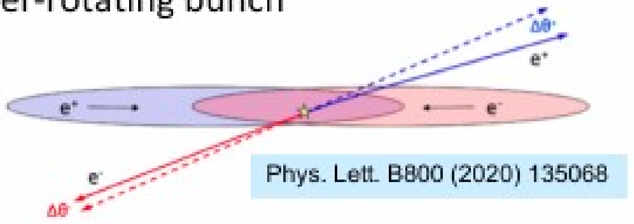




	LEP [144]	FCC-ee (Z pole)	ILC [146], [147] ($\sqrt{s} > 250$ GeV)
LumiCal distance from IP [m]	2.5	1.1	2.48
Precision target	3.4×10^{-4}	10^{-4}	10^{-3}
Tolerance for			
inner radius [μm]	4.4	$\mathcal{O}(1)$	4
outer radius [μm]	?	$\lesssim 3$	?
distance between two LumiCals [μm]	$\mathcal{O}(100)$	< 100	200

LumiCal effects: Focussing of final state particles

- Small angle final state particles feel focussing effect while traversing through counter-rotating bunch
  - Effect was present already at LEP but only corrected for in 2019
  - LEP Bhabha cross sectins were overestimated by about 0.1%
    - Integrated luminosities were underestimated
  - cross sections were overestimated by about 0.1%
    - Number of neutrino generations was underestimated by 0.26%

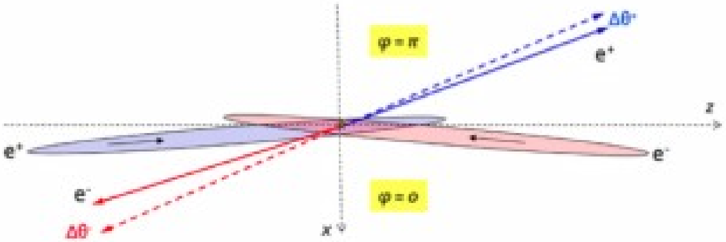


Phys. Lett. B800 (2020) 135068

$$\boxed{N_\nu = 2.9840 \pm 0.0082} \Rightarrow \boxed{N_\nu = 2.9918 \pm 0.0081}$$

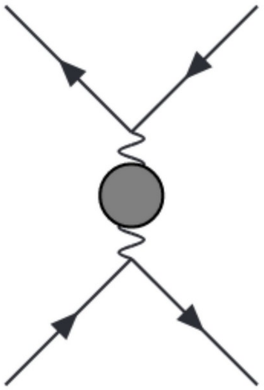
- At FCC-ee, situation more complicated due to finite beam-crossing angle
  - Detailed Guinea-Pig simulation studies
    - Average angular focussing of 41 μrad @ 45.6 GeV and @ 64 mrad
    - Aceptance effect of the same magnitude as at LEP
      - **0.19%**
      - ~20 times luminosity accuracy goal !!
  - Focussing effect is reflected in also acollinerity angle distribution of Bhabha events
    - Allows a correction to be done to an estimated 10^{-4} accuracy

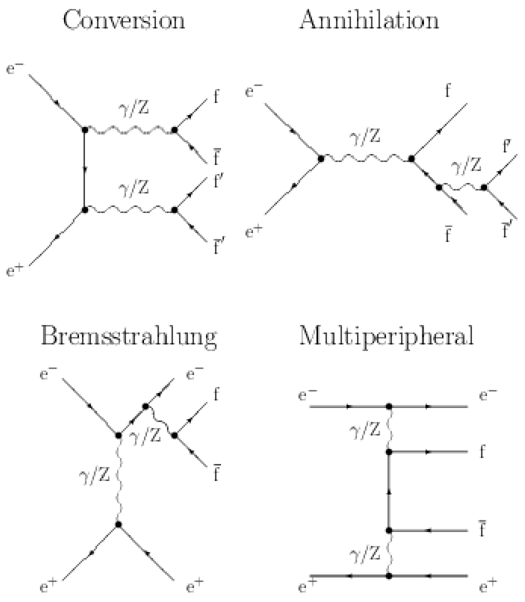
JHEP 10 (2019) 225



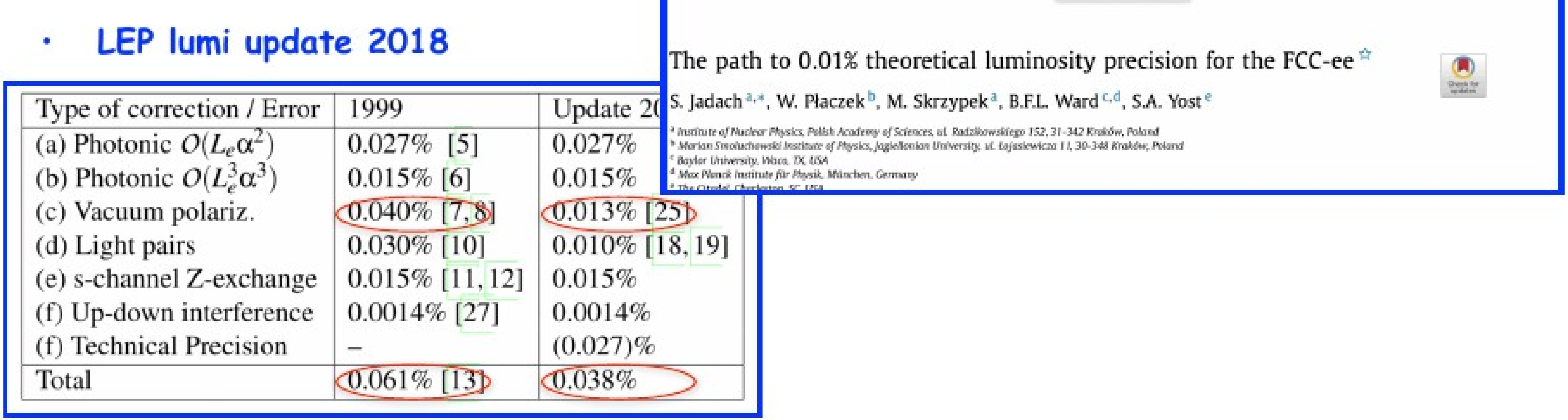
Bhabha theory uncertainties

- Mostly QED process -> controlled calculation of h.o. corr.
- Implementation in MC framework is complex task, but not fundamental obstacle
- Challenge 1: fermion pair production
- Challenge 2:
hadronic vacuum
polarization
(non-perturbative,
from data or lattice)





- LEP lumi update 2018



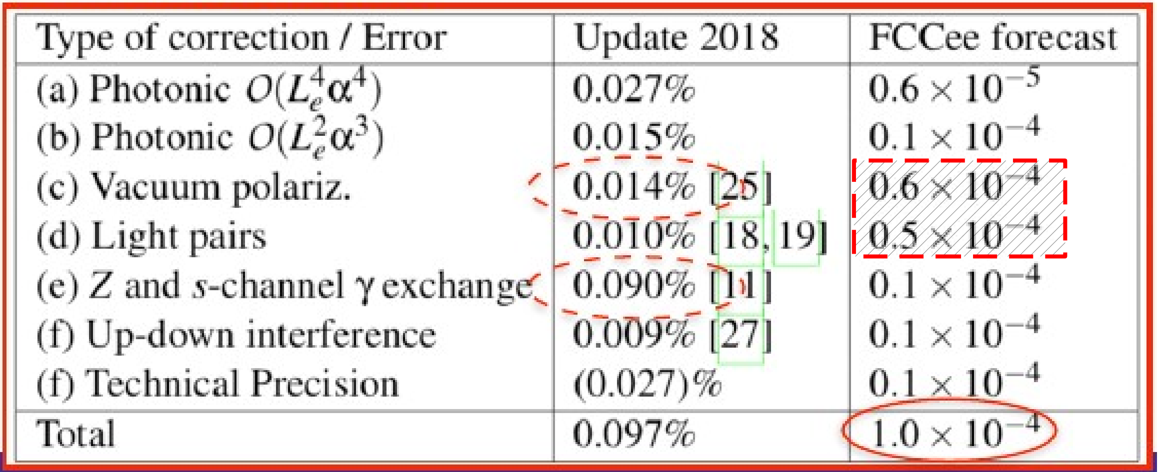
Type of correction / Error	1999	Update 20
(a) Photonic $O(L_e\alpha^2)$	0.027% [5]	0.027%
(b) Photonic $O(L_e^3\alpha^3)$	0.015% [6]	0.015%
(c) Vacuum polariz.	0.040% [7, 8]	0.013% [25]
(d) Light pairs	0.030% [10]	0.010% [18, 19]
(e) s-channel Z-exchange	0.015% [11, 12]	0.015%
(f) Up-down interference	0.0014% [27]	0.0014%
(f) Technical Precision	–	(0.027)%
Total	0.061% [13]	0.038%

The path to 0.01% theoretical luminosity precision for the FCC-ee ☆

S. Jadach [a,*], W. Płaczek [b], M. Skrzypek [a], B.F.L. Ward [c,d], S.A. Yost [e]

[a] Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Kraków, Poland
[b] Marian Smoluchowski Institute of Physics, Jagiellonian University, ul. Łojasiewicza 11, 30-348 Kraków, Poland
[c] Baylor University, Waco, TX, USA
[d] Max Planck Institute für Physik, München, Germany
[e] The Citadel, Charleston, SC, USA

- By the time of FCC-ee VP contribution will be merely 0.006%
- QED corrections and Z contrib. come back to front!
- Z contrib. easy (?) to master
- Improvements on photonics cors. will be difficult, new MC will be needed!
- Our FCC-ee forecast is 0.01% provided QED m.e. and VP are improved.



Type of correction / Error	Update 2018	FCCee forecast
(a) Photonic $O(L_e^4\alpha^4)$	0.027%	0.6×10^{-5}
(b) Photonic $O(L_e^2\alpha^3)$	0.015%	0.1×10^{-4}
(c) Vacuum polariz.	0.014% [25]	0.6×10^{-4}
(d) Light pairs	0.010% [18, 19]	0.5×10^{-4}
(e) Z and s-channel γ exchange	0.090% [11]	0.1×10^{-4}
(f) Up-down interference	0.009% [27]	0.1×10^{-4}
(f) Technical Precision	(0.027)%	0.1×10^{-4}
Total	0.097%	1.0×10^{-4}

Bhabha theory uncertainties

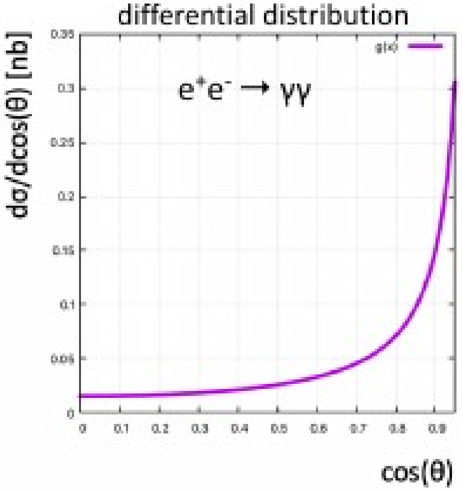
- Challenge 1: fermion pair production
  - Technology for e+e- → 4f @ NLO exists [Denner, Dittmaier, Roth, Wieders, 2015]
- Challenge 2: hadronic vacuum polarization
  - Factor 2 improvement expected from new data/calculations, but beyond that unclear [Jegerlehner 2019]
- EW (NLO+) corrections missing in existing tools, but straightforward to implement

Di-photon production

- Experimental challenges:
  - Statistical precision
    - Z-pole: 5×10^{-5} for 10 ab^{-1}
    - 250 GeV: 4×10^{-4} for 5 ab^{-1}
  - Background from Bhabha (100x larger)

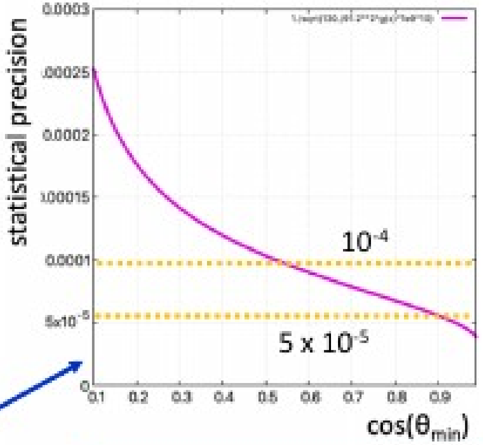
    (for 10^{-4} precision need 10^{-6} suppression, i.e. 10^{-3} per track – doable in central tracking region)
  - Acceptance

Normalisation via $e^+e^- \rightarrow \gamma\gamma$ - Acceptance



Example:

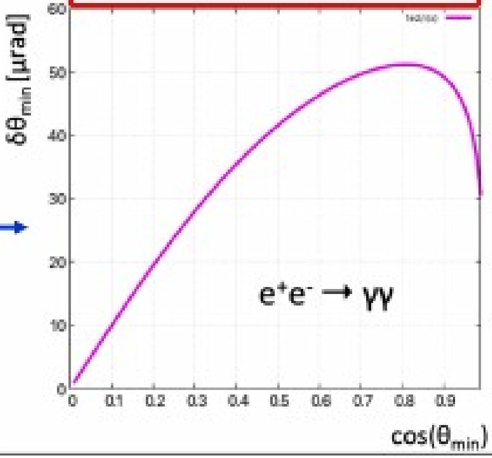
For 10 ab^{-1} sample → 1/15'th of full Z sample



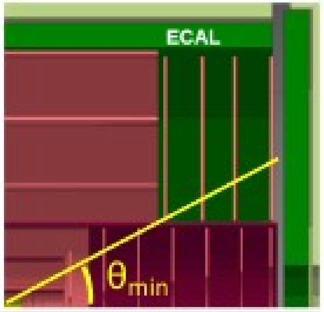
To exploit statistical power, include forward region up to cosθ-values of 0.8-0.9 or higher (37°-25° or lower)

Reaching 10^{-4} level precision on the acceptance requires knowledge of θ_{min} to **50 μrad** or better

required accurary on θ_{min} for 10^{-4} accuracy on acceptance

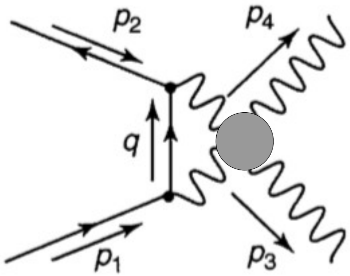


- In practice, probably advantageous to go forward to something like $\cos(\theta_{min}) = 0.94$ (20°)
  - Higher rate
  - May be easier to control $\delta\theta_{min}$ at lower θ_{min} values?
- For $\cos(\theta_{min}) = 0.94$, $\delta\theta_{min} = 46$ μrad is required
  - At $z_{ref} = 2.25$ m, this corresponds to
    - Acceptance inner radius: $r_{min} = 0.82$ m
    - Inner acceptance radius to be known to better than $\delta r_{min} = 100$ μm, *if* z_{ref} *perfectly known*
    - z_{ref} to better than 300 μm, *if* r_{min} *perfectly known*
- All other contributions have to be kept very low
  - No holes, no cracks …



Di-photon production

- Theory challenges:
  - Photon vacuum polarization only at NNLO (no problem), but there are also (very uncertain) light-by-light contributions
  - Large angle requirement ($\cos\theta \lessapprox 0.9$) → relatively large impact of EW corrections
  - Not much MC development



LUMI: Summary / Open Questions

- ee→γγ promising for absolute calibration
- Bhabha still important for point-to-point calibration
  (higher statistics)
- No full study for ee→γγ has been done
  (backgrounds, acceptance, theory uncertainties, ...)
- Need detailed design for LumiCal
- Impact of beamstrahlung?
  (from simulation? from in-situ lumi spectrum measurement?)
- MC tools need to be upgraded: fermion-pair prod., ...

Wmass – Mass and width of the W boson

Expert team: P. Azzurri, J. Bendavid, M. Beneke, J. de Blas, S. Dittmaier,
A. Freitas, A. Irles, A. Meyer, S. Plätzer, M. Schott,
R. Ströhmer, G. Wilson

- Gitlab wiki
- Sign up for egroup: ECFA-WHF-FT-WMASS@cern.ch
- Email WG1 PREC conveners: ecfa-whf-wg1-prec-conveners@cern.ch

Slide materials from P. Azzurri

future e+e- mW digest

1. from WW **threshold** cross sections at $E_{CM} \simeq 157.5$-162.5 GeV

→Δm_W=0.3 MeV [10/ab]

Syst : Theory calculations / E_{CM} / acceptance / background

2. from decay **kinematics** mostly at $E_{CM} \simeq 240$ GeV **and** E_{beam} (LEP2)

→Δm_W= 1-0.5 MeV (stat) [2-5/ab] **: 2-5 MeV (syst) ?**

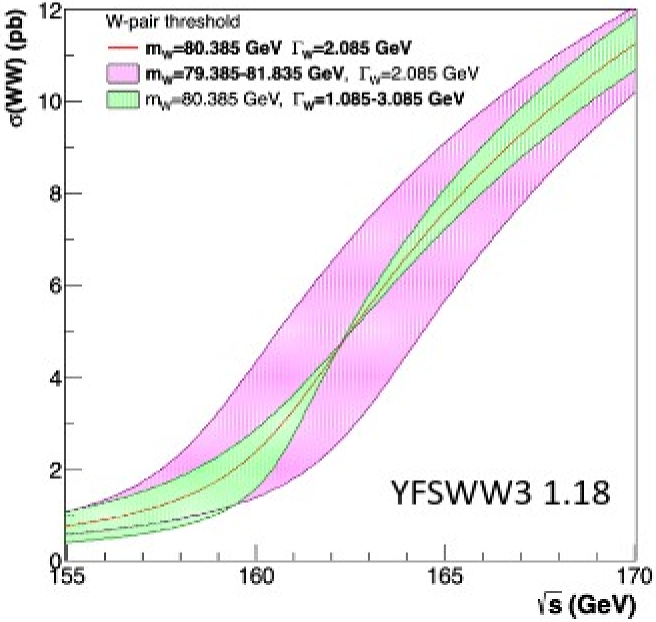
Syst : Theory modeling (NP QCD) / E_{CM} / det calibration /

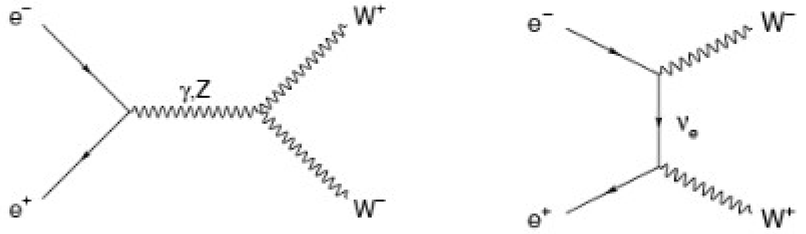
3. from **lepton decay kinematics** and hadronic decays **without** E_{beam}

→Δm_W= 2 MeV (stat**) : 2-5 MeV (tot) ?**

Syst : det calibration / Theory modeling (NP QCD)

The WW threshold lineshape and the W mass



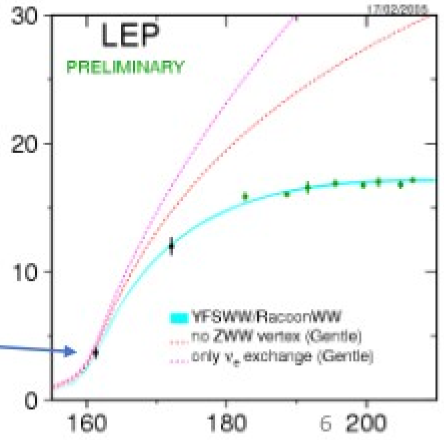


WW cross section rise $\beta = \sqrt{1 - 4m_W^2/s}$ driven by t-channel production

Extract the W mass inverting the m_W dependence

$$\sigma(m_W, E) \qquad\qquad m_W = \sigma^{-1}(E)$$

$$\boxed{\Delta m_W = \left(\frac{d\sigma}{dm_W}\right)^{-1} \Delta\sigma}$$



ALEPH Phys.Lett.B 401 (1997) 347 with 10/pb $m_W = 80.14 \pm 0.34$ GeV

stat extrapolation to 10/ab $\Longrightarrow$ $\Delta m_W = 0.34$ MeV

WW threshold : W mass precision requirements

Conditions to achieve Δm_W(syst)< Δm_W(stat) = **0.3 MeV**
with a single point WW threshold measurement

current theory precision
$\Rightarrow \boldsymbol{\Delta m_W}$ = 3 MeV

$$\Delta m_W(B) = \left(\frac{d\sigma}{dm_W}\right)^{-1}\left(\frac{\Delta\sigma_B}{\varepsilon} \oplus \Delta\sigma_{TH}\right)$$

Background and Theory

$\Delta\sigma_{TH} < \mathbf{1fb}$ $(\Delta\sigma_{TH}/\ \sigma_{TH} < 2\cdot 10^{-4})$
$\Delta\sigma_B/\varepsilon < \mathbf{1fb}$ $(\Delta\sigma_B/\ \sigma_B < 4\cdot 10^{-3})$

$$\Delta m_W(\varepsilon) = \sigma\left(\frac{d\sigma}{dm_W}\right)^{-1}\left(\frac{\Delta\varepsilon}{\varepsilon} + \frac{\Delta L}{L}\right)$$

Acceptance and Luminosity

$\left(\frac{\Delta\varepsilon}{\varepsilon} \oplus \frac{\Delta L}{L}\right) < \mathbf{2\cdot 10^{-4}}$

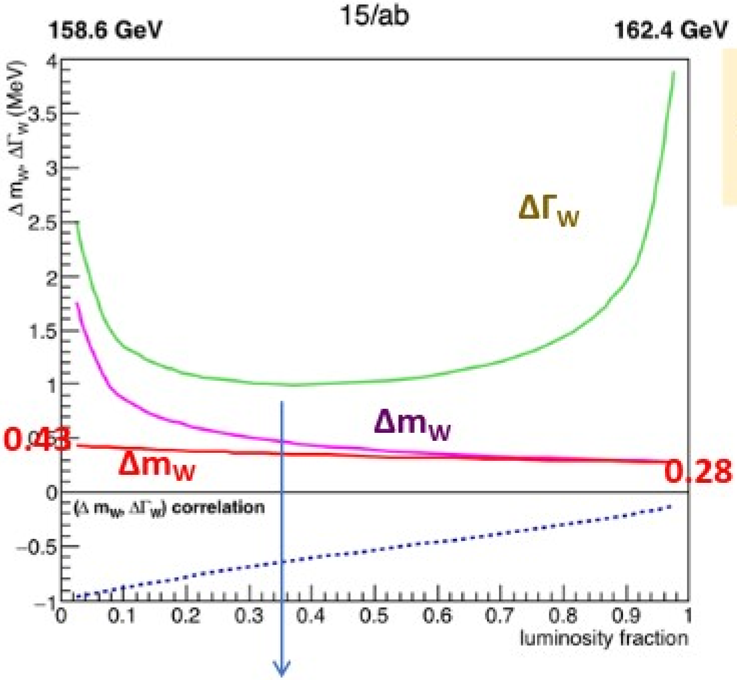
$$\Delta m_W(E) = \left(\frac{d\sigma}{dm_W}\right)^{-1}\left(\frac{d\sigma}{dE}\right)\Delta E \leq \frac{1}{2}\Delta E$$

Collision energy

$\Delta E_b < 0.3\ MeV$ $(\Delta E_b/\ E_b < 4\cdot 10^{-6})$

WW threshold : W mass and width

Scans of possible E_1 E_2 data taking energies and luminosity fractions f (at the E_2 point)



Δm_W =0.45 MeV , $\Delta\Gamma_W$=1 MeV (r=-0.6)

Δm_W=0.35 MeV

A -minimum of **$\Delta\Gamma_W$=0.91 MeV** with **Δm_W=0.55 MeV**
taking data at E_1=**156.6** GeV E_2=**162.4** GeV f=**0.25**
yields **Δm_W=0.47 MeV** (as single par)

B- minimum of **Δm_W=0.28 MeV** **$\Delta\Gamma_W$=3.3 MeV** with
E_1=**155.5** GeV E_2=**162.4** GeV f=**0.95**
yields **Δm_W=0.28 MeV** (as single par)

C- minimum of **$\Delta\Gamma_W$=0.96 MeV** **+Δm_W=0.41 MeV** with
E_1=**157.5** GeV E_2=**162.4** GeV f=**0.45**
yields and **Δm_W=0.37 MeV** (as single par)

Δm_W , $\Delta\Gamma_W$: error on W mass and width from fitting both

Δm_W : error on W mass from fitting only m_W

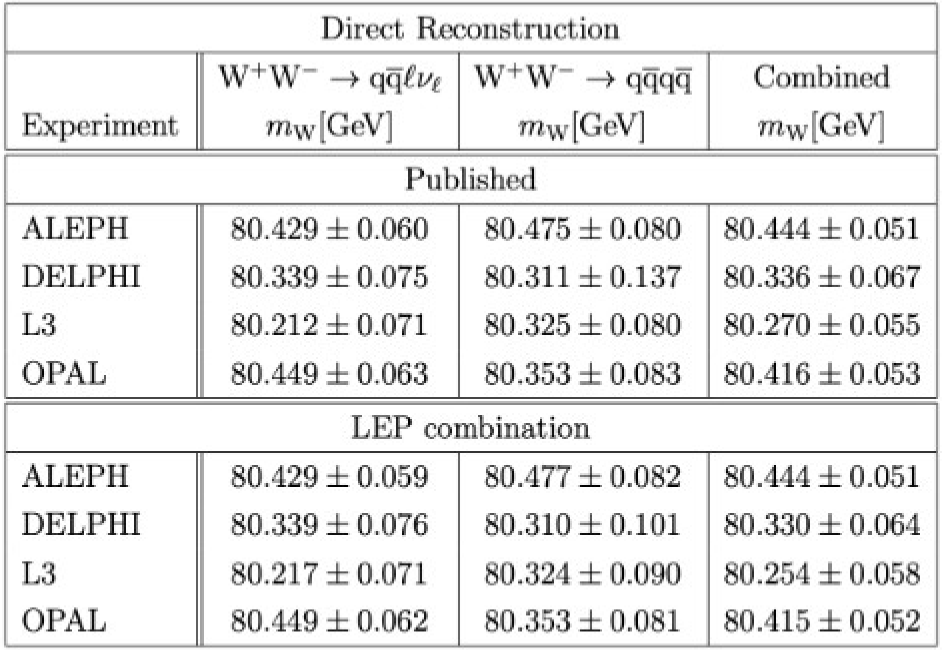
WW threshold uncertainties

- Energy calibration:
  - $O(10^{-6})$ precision from resonant depolarization at circ. colliders
  - Comparable precision may be achievable from $K_S^0 \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$ decays [ref]
- Theory challenges:
  - Factorization of WW production and W decay not adequate near threshold
  - For $\Delta m_W \sim 1$ MeV need e+e- → 4f at NNLO (!)
  - Alternatively, use EFT framework with NNLO and N3LO building blocks [see arXiv:1906.05379 for more details]
  - More precise treatment of initial-state QED radiation

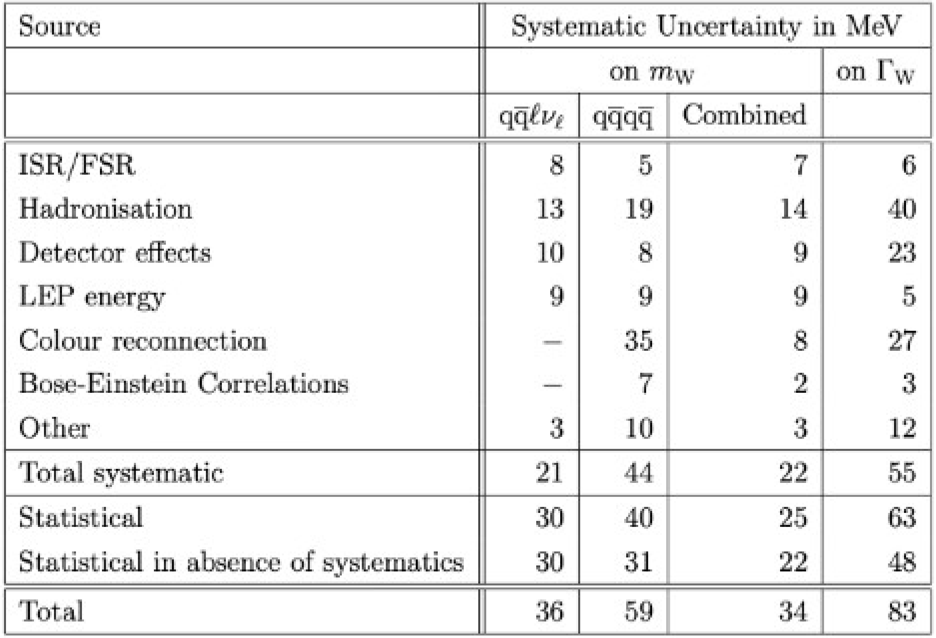
W mass from decay kinematics

- Kinematic reconstruction of *ℓνqq* and *qqqq* final states:
  - ~1 MeV stat. prec. for m_W and Γ_W
  - Beam energy constraint overcomes jet energy scale uncertainty
  - Jet physics and hadronization are still dominant syst. err. (color reconnection for *qqqq*)
  - Excellent detector efficiency (even for low-E hadrons) can help to control hadron/QCD uncertainties
- Fully leptonic differential observables:
  - Lepton energy spectrum and pseudomass [OPAL, hep-ex/0203026]
  - Higher stat. err. but lower syst. err.

LEP combined results



	Direct Reconstruction		
Experiment	$W^+W^- \to q\bar{q}\ell\nu_\ell$ m_W[GeV]	$W^+W^- \to q\bar{q}q\bar{q}$ m_W[GeV]	Combined m_W[GeV]
	Published		
ALEPH	80.429 ± 0.060	80.475 ± 0.080	80.444 ± 0.051
DELPHI	80.339 ± 0.075	80.311 ± 0.137	80.336 ± 0.067
L3	80.212 ± 0.071	80.325 ± 0.080	80.270 ± 0.055
OPAL	80.449 ± 0.063	80.353 ± 0.083	80.416 ± 0.053
	LEP combination		
ALEPH	80.429 ± 0.059	80.477 ± 0.082	80.444 ± 0.051
DELPHI	80.339 ± 0.076	80.310 ± 0.101	80.330 ± 0.064
L3	80.217 ± 0.071	80.324 ± 0.090	80.254 ± 0.058
OPAL	80.449 ± 0.062	80.353 ± 0.081	80.415 ± 0.052



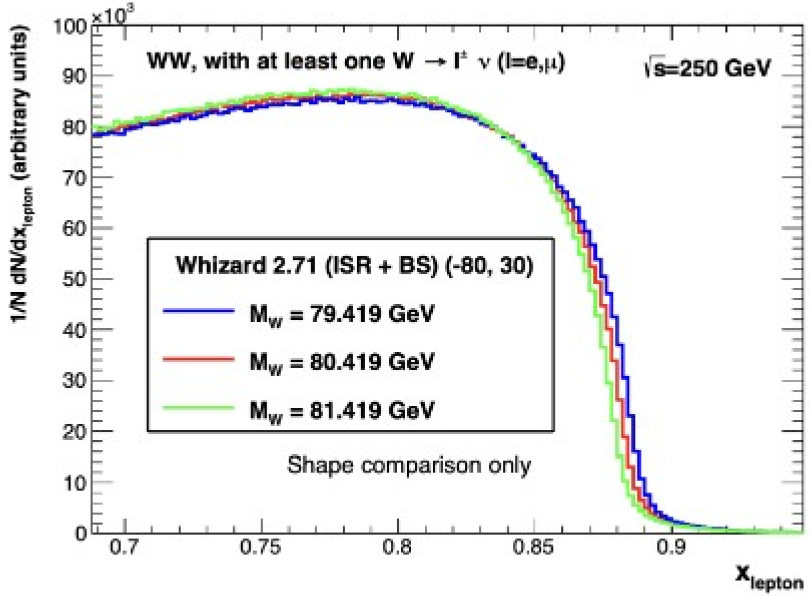
Source	Systematic Uncertainty in MeV			
	on m_W			on Γ_W
	$q\bar{q}\ell\nu_\ell$	$q\bar{q}q\bar{q}$	Combined	
ISR/FSR	8	5	7	6
Hadronisation	13	19	14	40
Detector effects	10	8	9	23
LEP energy	9	9	9	5
Colour reconnection	–	35	8	27
Bose-Einstein Correlations	–	7	2	3
Other	3	10	3	12
Total systematic	21	44	22	55
Statistical	30	40	25	63
Statistical in absence of systematics	30	31	22	48
Total	36	59	34	83

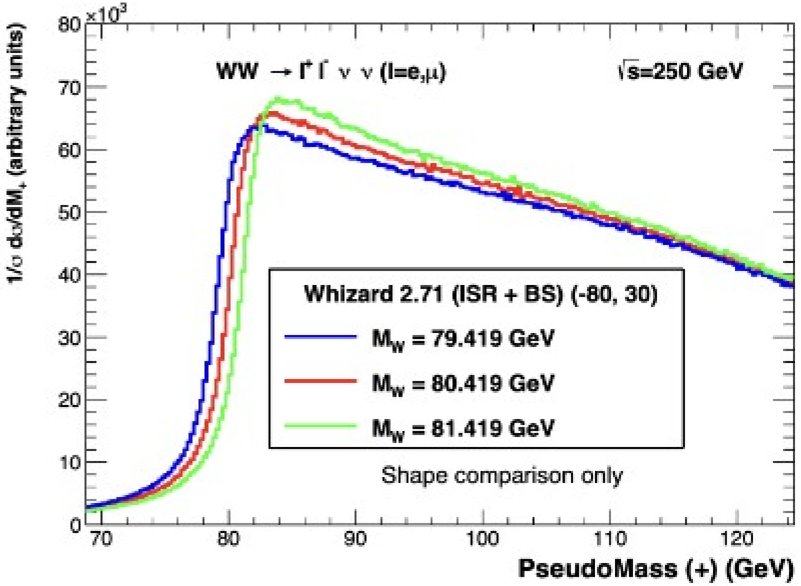
arXiv:2203.07622

G.Wilson CERN precision workshop June 10 2022

W mass from lepton Energy and Pseudomass

Endpoints in the lepton (or jet) energy a
$E_\ell = E_{CM}(1 \pm \beta)$ where β is the W velocity





expected statistical Δm_W =4.4 MeV with 2/ab@250 GeV
experimental syst from lepton energy calibration

Wmass: Summary / Open Questions

WW threshold scan:

- Study Multi-point (n>3) scans to reduce/cancel syst. err. from acceptance, luminosity, background
- Updated studies with modern generators and methods to evaluate uncertainties
- Higher-order (~NNLO) corrections

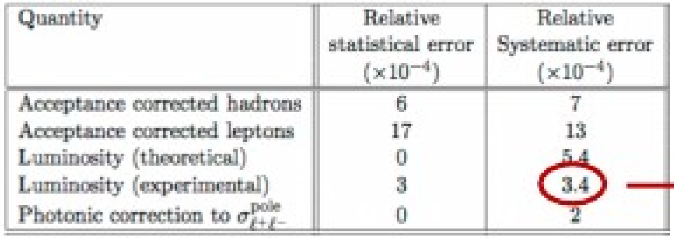
W decay kinematics:

- Impact of different CoM energies and syst. err.
- Explore combined analysis of WW, ZZ, Zγ to cancel exp./th. syst. errs
- Modeling of hadronization, color reconnection

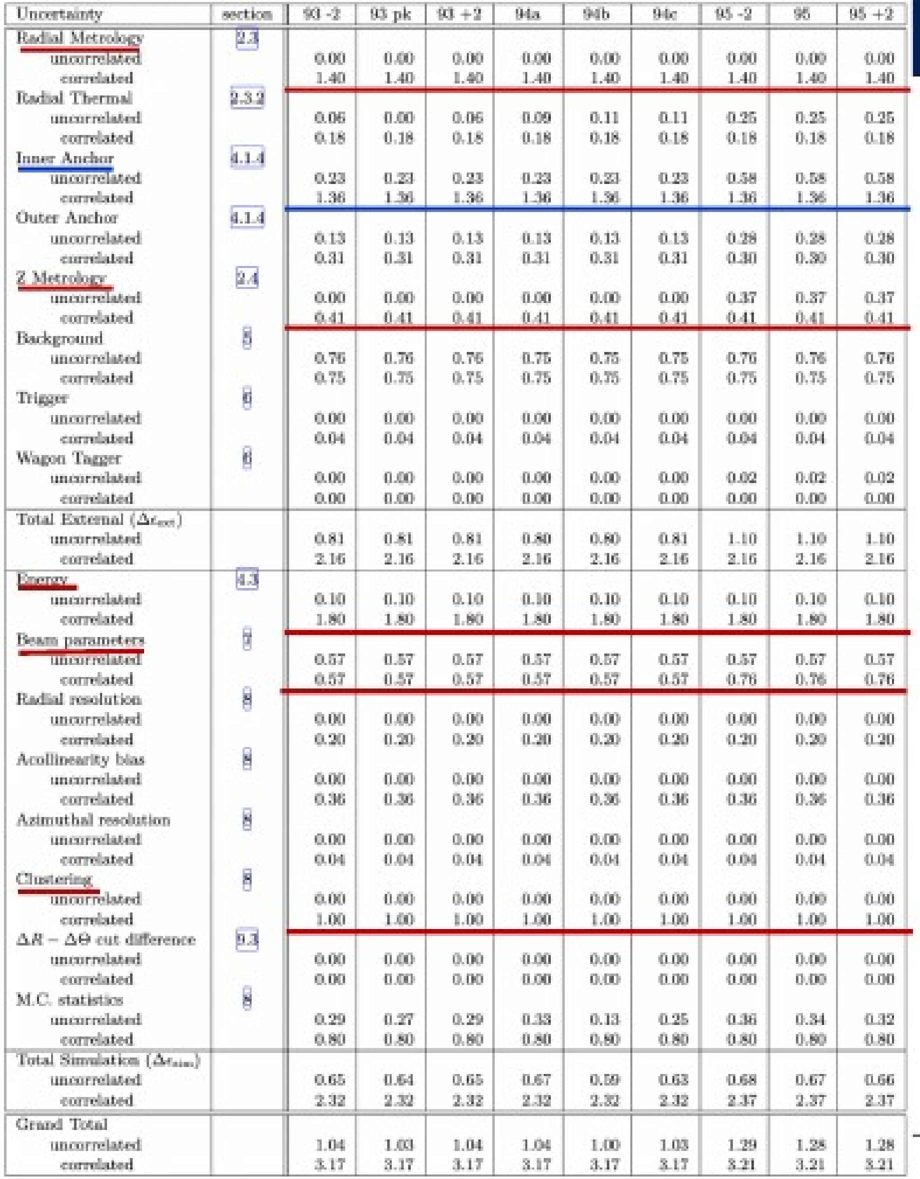
Backup

OPAL Summary of Systematics

$\times 10^{-4}$



Quantity	Relative statistical error ($\times 10^{-4}$)	Relative Systematic error ($\times 10^{-4}$)
Acceptance corrected hadrons	6	7
Acceptance corrected leptons	17	13
Luminosity (theoretical)	0	5.4
Luminosity (experimental)	3	3.4
Photonic correction to $\sigma^{\text{pole}}_{\ell^+\ell^-}$	0	2



Uncertainty	section	93 -2	93 pk	93 +2	94a	94b	94c	95 -2	95	95 +2
Radial Metrology	2.3									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
correlated		1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40
Radial Thermal	2.3.2									
uncorrelated		0.06	0.00	0.06	0.09	0.11	0.11	0.25	0.25	0.25
correlated		0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Inner Anchor	4.1.4									
uncorrelated		0.23	0.23	0.23	0.23	0.23	0.23	0.58	0.58	0.58
correlated		1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36
Outer Anchor	4.1.4									
uncorrelated		0.13	0.13	0.13	0.13	0.13	0.13	0.28	0.28	0.28
correlated		0.31	0.31	0.31	0.31	0.31	0.31	0.30	0.30	0.30
Z Metrology	2.4									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.37	0.37
correlated		0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
Background	5									
uncorrelated		0.76	0.76	0.76	0.75	0.75	0.75	0.76	0.76	0.76
correlated		0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Trigger	6									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
correlated		0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Wagon Tagger	6									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02
correlated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total External ($\Delta\epsilon_{\text{ext}}$)										
uncorrelated		0.81	0.81	0.81	0.80	0.80	0.81	1.10	1.10	1.10
correlated		2.16	2.16	2.16	2.16	2.16	2.16	2.16	2.16	2.16
Energy	4.3									
uncorrelated		0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
correlated		1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Beam parameters	7									
uncorrelated		0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
correlated		0.57	0.57	0.57	0.57	0.57	0.57	0.76	0.76	0.76
Radial resolution	8									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
correlated		0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Acollinearity bias	8									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
correlated		0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
Azimuthal resolution	8									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
correlated		0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Clustering	8									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
correlated		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\Delta R - \Delta\Theta$ cut difference	9.3									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
correlated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
M.C. statistics	8									
uncorrelated		0.29	0.27	0.29	0.33	0.13	0.25	0.36	0.34	0.32
correlated		0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Total Simulation ($\Delta\epsilon_{\text{sim}}$)										
uncorrelated		0.65	0.64	0.65	0.67	0.59	0.63	0.68	0.67	0.66
correlated		2.32	2.32	2.32	2.32	2.32	2.32	2.37	2.37	2.37
Grand Total										
uncorrelated		1.04	1.03	1.04	1.04	1.00	1.03	1.29	1.28	1.28
correlated		3.17	3.17	3.17	3.17	3.17	3.17	3.21	3.21	3.21

Table 24: This table summarizes the experimental systematic uncertainties on the absolute L_{RL} luminosity measurement for the nine data samples. The lines labeled correlated and uncorrelated refer to errors correlated and uncorrelated among the samples. All errors are in units of 10^{-4}.

LumiCal Geometrical Tolerances

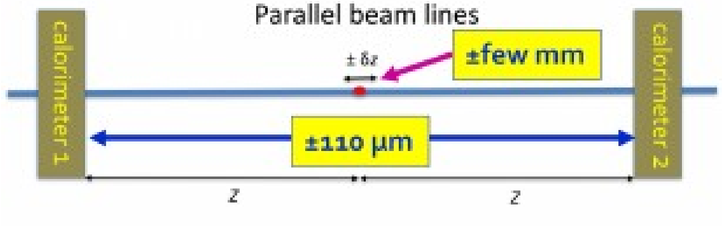
- Acceptance depends on **inner and outer radius** of acceptance definition

$$\boxed{\frac{\Delta A}{A} \approx -\frac{\Delta R_{\rm in}}{1.6\,\mu{\rm m}} \times 10^{-4}} \quad \text{and} \quad \boxed{\frac{\Delta A}{A} \approx +\frac{\Delta R_{\rm out}}{3.8\,\mu{\rm m}} \times 10^{-4}}$$

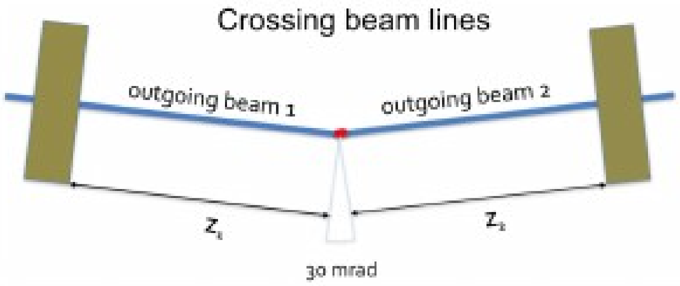
  - ❑ **Aim for construction and metrology precision of 1 µm**

- Acceptance depends on (half) **distance between the two luminometers**

$$\boxed{\frac{\Delta A}{A} \approx +\frac{\Delta Z}{55\,\mu{\rm m}} \times 10^{-4}}$$



  - ❑ Situation is somewhat more complicated due to the crossing beam situation
  - ❑ Now, it is the sum of distances, **$Z_1 + Z_2$**, which has **to be known to 110 µm**



Precision goal: 1×10^{-4}

LEP (OPAL):

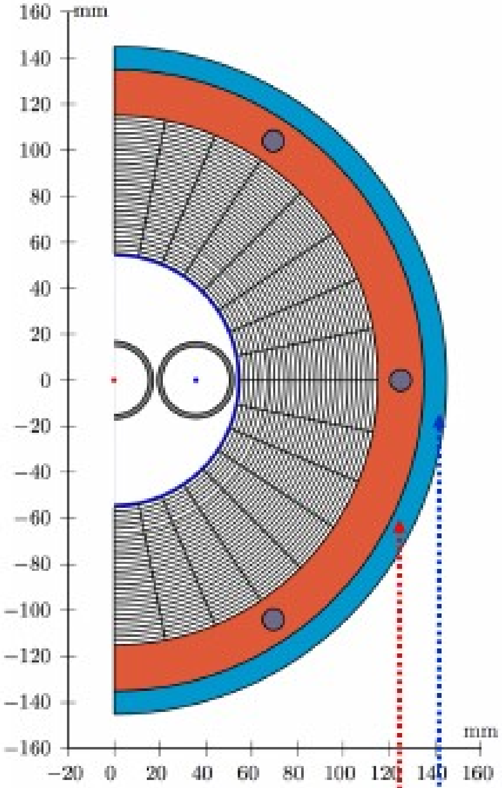
- inner/outer radius 2.5 µm and 11 µm
- z-position: 123 µm
- achieved lumi prec.: 3.4×10^{-4}

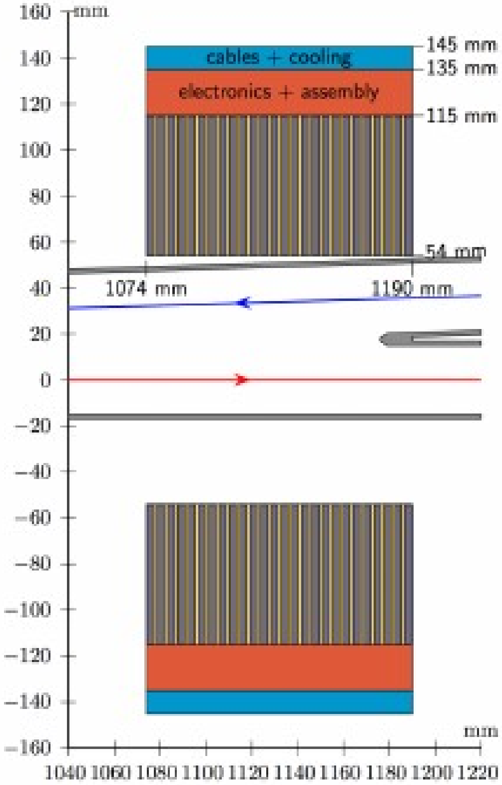
For FCC-ee:

- factor ~2 improvem. for same precision
- additonal factor 4 for precision goal 10^{-4}

LumiCal CDR Design

- W+Si sandwich: 3.5 mm W + Si sensors in 1 mm gaps
  - Effective Molière 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 Molière 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?)

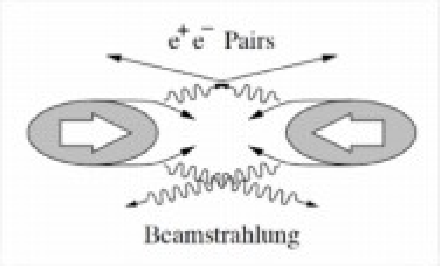




Precision goal: 1×10^{-4}

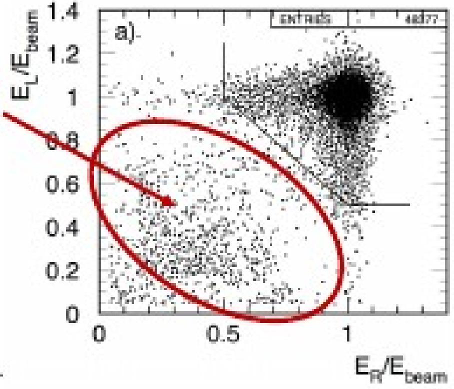
LumiCal effects: Backgrounds

- Synchrotron radiation:
  - Negligible
    - Largest effect at √s = 365 GeV, where beam-pipe shielding reduced deposit to $\mathcal{O}$(10 MeV) per LumiCal
- Beamstrahlung background – e^+e^- pairs
  - In general, (very) low energy particles – effectively focussed by detector magnet
  - GuineaPig simulation with parametrized magnetic field (helix extrapolation)



√s	# e± total	# e± LumiCal	Energy total	Energy LumiCal
91.2 GeV	400	0.3	250 GeV	0.06 GeV
365 GeV	3100	15	4500 GeV	3.2 GeV

    - Negligible at low √s
    - Strong energy dependence, at tt energy, starts to become important
- Beam-gas scattering
  - Coincidence of off-momentum particles from beam-gas scattering was main background process at LEP
    - 10^{-4} level after energy and angular cuts
  - At FCC-ee, ratio between æuminosity and beam current is far higher
    - Expected to be completely negligible
      - Supported by first study of sample of simulated off-momentum particle



$e^+e^- \to \gamma\gamma$ at $\sqrt{s} = 161$ GeV

Minimum polar angle (°)	$\sigma_{\gamma\gamma}$ (pb)
45	5.3
20	12.7
15	15.5
10	19.5
6	24.6
2	35.7

- Unpolarized Born cross-sections. Typical higher order effects 5 – 10% increase.
- Note not negligible electroweak box effects near WW threshold. (1.2% at widest angle).
- electron-photon discrimination can be aided by much better azimuthal measurements given the bending of the electrons in the B-field. Figure of merit: Bz_{LCAL}. Here ILD has 7.7 Tm. OPAL was 1.04 Tm.

W mass from kinematics with 4P fit (LEP2)

Formula for 2-jets final state from ee→Zγ→qqγ

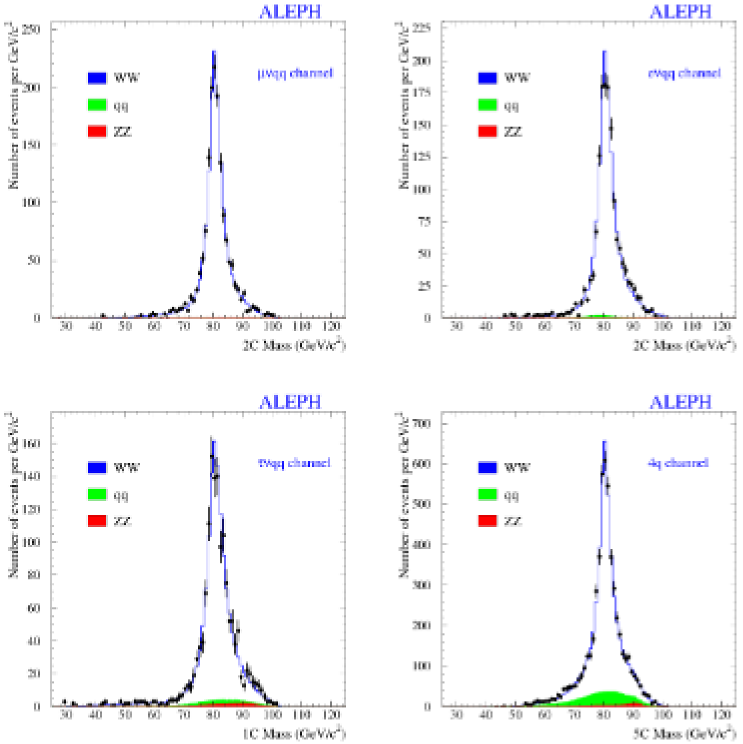
$$M_Z^2 = s\frac{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_2 - \beta_1\beta_2|\sin(\theta_1+\theta_2)|}{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_2 + \beta_1\beta_2|\sin(\theta_1+\theta_2)|}$$

E_{CM} is again a main ingredient: sets jet energy scale
other main ingredients are the jets (and lepton) **angles**
secondary ingredients are the **jet velocities** ($\beta=p/E$)

statistical uncertainties ALEPH LEP2→ FCCee extrapolated

Stat uncertainty	Δm_W	$\Delta\Gamma_W$
e**ν**qq	87 MeV → 0.9 MeV	200 MeV → 2 MeV
μνqq	82 MeV → 0.8 MeV	200 MeV → 2 MeV
τνqq	121 MeV → 1.2 MeV	320 MeV → 3.2 MeV
qqqq	70 MeV → 0.7 MeV	120 MeV → 1.2 MeV
combined	43 MeV → 0.4 MeV	90 MeV → 0.9 MeV

LEP2 (ALEPH) from ~10k WW @ E_{CM}=183-209 GeV



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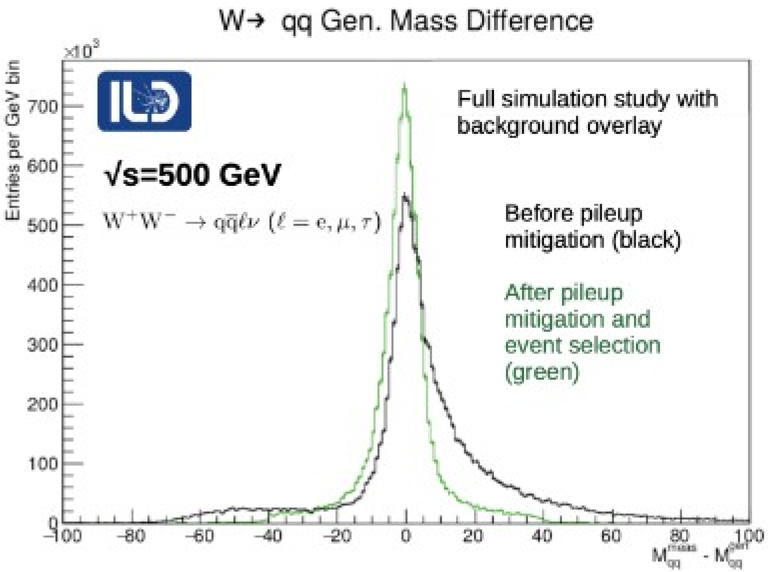
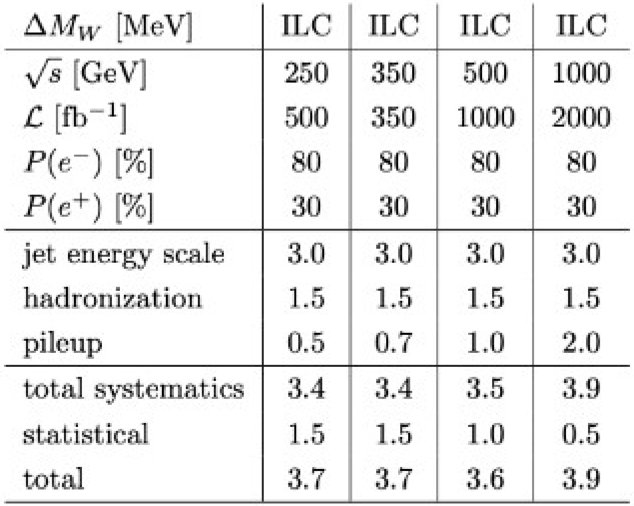
W mass from the hadronic mass



arXiv:2011.12451



ΔM_W [MeV]	ILC	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	250	350	500	1000
$\mathcal{L}$ [fb^{-1}]	500	350	1000	2000
$P(e^-)$ [%]	80	80	80	80
$P(e^+)$ [%]	30	30	30	30
jet energy scale	3.0	3.0	3.0	3.0
hadronization	1.5	1.5	1.5	1.5
pileup	0.5	0.7	1.0	2.0
total systematics	3.4	3.4	3.5	3.9
statistical	1.5	1.5	1.0	0.5
total	3.7	3.7	3.6	3.9

«.. dominated by the systematic uncertainties from the effective **jet energy scale** which is a challenging demand.. »