Measurements of W mass and Study $e^+e^- \to \gamma_{ISR}q\bar{q}$

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Motivation

- The W boson mass has played a central role in precision EW measurements and in constraints on the SM model through global fit.

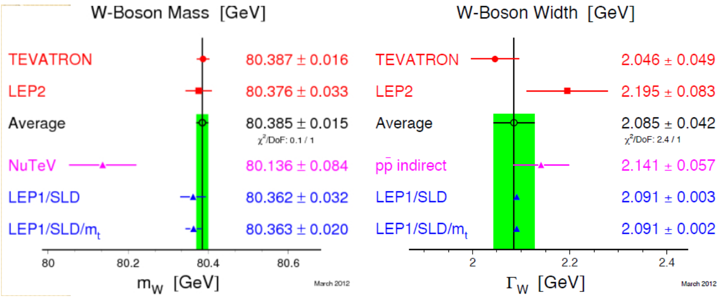
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r) \quad (1)$$

  Improving the precision the m_W is importance for testing the overall consistency of the SM.

- The narrow mesons, such as $\omega(782), \phi(1020), J/\psi, \Upsilon(1S), \Upsilon(2S)$..., can be used to calibrate physical events in CEPC. So study the rate of production for these mesons via ISR processes is useful.

I. Measurement of m_W

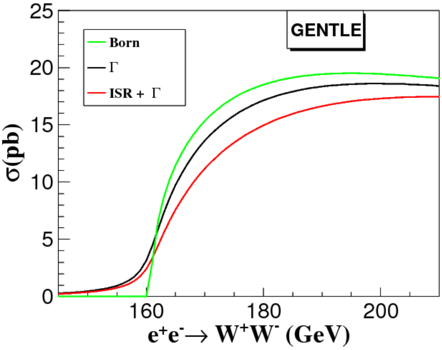
Status and goal



★ Using the threshold scan method, **2.5 MeV** can be achieved with **500 fb^{-1}** integrated luminosity at CEPC (Pre-CDR).

Theoretical tool

- The $\sigma_{W^+W^-}$ is a function of $\sqrt{s}, M_W, \Gamma_W$, which is calculated with the GENTLE package in this study.
- The ISR factor is also calculated with DIY method, with the radiator up to order α^2. https://arxiv.org/abs/hep-ph/9910523v1



Statistic uncertainty for m_W

$\Delta\sigma_{W^+W^-}, \Delta M_W, \Delta\Gamma_W$ (Stat.)

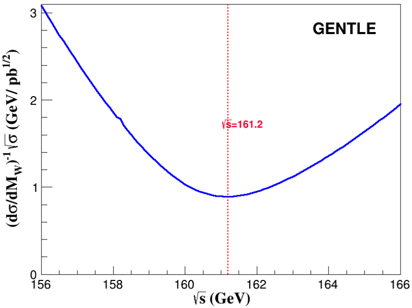
$$\begin{aligned} \Delta\sigma_{W^+W^-} &= \sigma_{W^+W^-} \times \frac{\Delta N_{W^+W^-}}{N_{W^+W^-}} \\ &= \sigma_{W^+W^-} \times \frac{\sqrt{N_{W^+W^-} + N_{bkg}}}{N_{W^+W^-}} \\ &= \sqrt{\frac{\sigma_{W^+W^-}}{\mathcal{L}\epsilon P}} \qquad (P = \frac{N_{W^+W^-}}{N_{W^+W^-} + N_{bkg}}) \end{aligned} \tag{2}$$

$$\Delta M_W = (\frac{\partial\sigma_{W^+W^-}}{\partial M_W})^{-1} \times \sqrt{\frac{\sigma_{W^+W^-}}{\mathcal{L}\epsilon P}} \tag{3}$$

$$\Delta\Gamma_{W^\pm} = (\frac{\partial\sigma_{W^+W^-}}{\partial\Gamma_W})^{-1} \times \sqrt{\frac{\sigma_{WW}}{\mathcal{L}\epsilon P}} \tag{4}$$

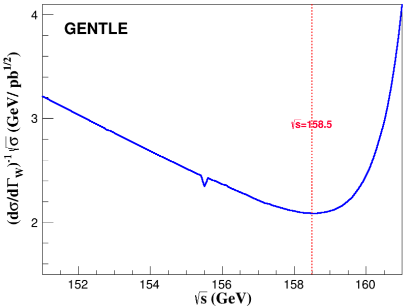
$\Delta\sigma_{W^+W^-}, \Delta M_W, \Delta\Gamma_W$ (Stat.)

- With $\mathcal{L} = 500\ \text{fb}^{-1}$, $\epsilon = 0.8$, $P = 0.9$:
  $\Delta M_W = (\frac{\partial \sigma_{W+W-}}{\partial M_W})^{-1} \times \sqrt{\frac{\sigma_{W+W-}}{\mathcal{L}\epsilon P}} \approx 1.5$ MeV.



$\Delta\sigma_{W^+W^-}, \Delta M_W, \Delta\Gamma_W$ (Stat.)

- With $\mathcal{L} = 500\ \text{fb}^{-1}$, $\epsilon = 0.8$, $P = 0.9$:
  $\Delta\Gamma_W = (\frac{\partial\sigma_{W+W-}}{\partial\Gamma_W})^{-1} \times \sqrt{\frac{\sigma_{W+W-}}{\mathcal{L}\epsilon P}} \approx 3.5$ MeV.



Data taken for the measurement of M_W

If we just consider the M_W, with Γ_W fixed to PDG value:

- One point at $\sqrt{s} = 161.1(161.2)$ GeV, $\Delta M_{W^\pm} \approx 1.5$ MeV
- Two or three points around $\sqrt{s} = 161.2$ GeV, it's been almost stable.
- $\Delta M_{W^\pm}$ increases when there are more than four points.

So, only one point enough!

Systematic uncertainty for m_W

Beam energy spread

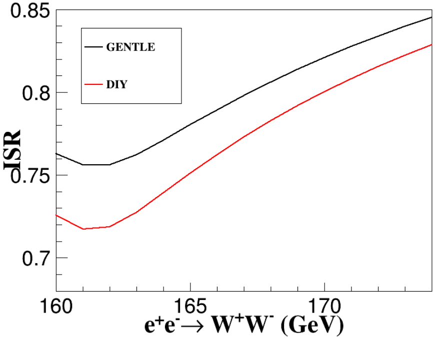
With the beam energy spread, the $\sigma_{W^+W^-}$ becomes:

$$\sigma_{W^+W^-}(E) = \int_0^{\infty} \sigma(E') \times G(E, E') dE' \approx \int_{E-6\sqrt{2}\Delta\cdot E}^{E+6\sqrt{2}\Delta\cdot E} \sigma(E') \times \frac{1}{\sqrt{2\pi}\sqrt{2}\Delta\cdot E} e^{\frac{-(E-E')^2}{2(\sqrt{2}\Delta\cdot E)^2}} dE' \tag{5}$$

Here, $\sqrt{2}\Delta \cdot E$ is the energy spread, and Δ is 0.16% (preCDR). To save compute time, we use the region $[E - 6\sqrt{2}\Delta \cdot E, E + 6\sqrt{2}\Delta \cdot E]$.
The fit results show that the effect from beam energy spread is negligible.

ISR factor $(1+\delta)$

- The ISR factor is calculated by combining the Gentle's results (no ISR) and DIY radiator, and 0.1% is taken as the error.
- Actually, the difference between the results from Gentle (with ISR) and our DIY method will not contributes to Δm_W, but the accuracy of radiator we used does.



Luminosity $\mathcal{L}$

Considering the $\Delta\mathcal{L}$, the luminosity becomes :

$$\mathcal{L} \sim G(\mathcal{L}_0, \Delta\mathcal{L}) \tag{6}$$

If just taking data at one energy point, we simulate data with $\mathcal{L}$ and use $\mathcal{L}_0$ in fit. By 500 samplings, the $\Delta m_W \propto \Delta\mathcal{L}$:

$\mathcal{L}$ (‰)	Δm_W (MeV)
1.0	1.70
0.5	0.80
0.1	0.16

So corresponding Δm_W is very large if just taking data at one energy point. Instead, the contribution from $\Delta\mathcal{L}$ can be added in the χ^2 construction when there are more than one energy point.

ISR factor $(1+\delta)$ and luminosity $\mathcal{L}$

The number of simulated data is:

$$N_{dt} = \mathcal{L}\sigma_{W^+W^-}(1+\delta)\epsilon \tag{7}$$

Since the uncertainties of $\mathcal{L}$ and $(1+\delta)$ affect the Δm_W in same way, we consider them together. For fake data, $\mathcal{L} = G(\mathcal{L}_0, \sqrt{2}\Delta\mathcal{L}_0)$. For fit, χ^2 is defined as

$$\chi^2 = \sum_i \frac{(y_i - h \cdot x_i)^2}{\delta_i^2} + \frac{(h-1)^2}{\delta_c^2} \tag{8}$$

Here, y_i, x_i are the true and fit results at scan point i, h is a free parameter, δ_i is the Stat. uncertainty, and δ_c is the total Syst. uncertainty from ISR and $\mathcal{L}$. The corresponding is about 0.6 MeV (assuming 0.1% for $\delta\mathcal{L}$ and $\delta(1+\delta)$).

Beam energy uncertainty ΔE

With the ΔE, the total energy becomes:

$$E = G(E_p, \Delta E) + G(E_m, \Delta E) \quad (9)$$

By 500 samplings, the corresponding $\Delta M_{W^\pm}$ is:

ΔE (MeV)	$\Delta M_{W^\pm}(MeV)$
2.0	1.54
1.5	1.03
1.0	0.74
0.5	0.36

So, if we just consider the uncertainties above, $\Delta M_W < 2.0$ MeV can be achieve at 2 data points, 161 and 162 GeV, with $\mathcal{L} = 500\ \text{fb}^{-1}$ and $\epsilon = 0.72$.

MC simulation and Event selection ($\mu\nu_\mu qq$)

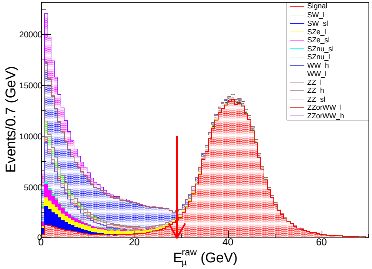
MC samples

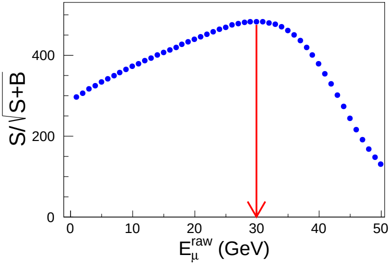
		N_G	N_P	N_S	Scale Factor
Signal		300857	300202	272251	1.00
Bkg.	ZZ_l	5000000	120292	14932	0.11
	ZZ_{sl}	614909	300454	13299	0.41
	WW_l	100000	15367	14366	0.50
	SZe_l	693376	36559	1847	0.46
	$ZZ(WW)_l$	200000	4877	548	0.35
	ZZ_h	400000	86214	497	0.16
	SZe_{sl}	200000	19841	121	0.46
	$SZnu_l$	200000	3295	89	0.30
	SW_l	200000	107	82	0.48
	WW_h	823843	111109	41	0.28
	$SZnu_{sl}$	200000	19001	14	0.05
	$ZZ(WW)_h$	393463	35280	3	1.00
	SW_{sl}	285715	13498	2	1.00

Here, the N_G is the generated number of events, N_P and N_S are the ones passing preliminary and final event selections.

Event selection

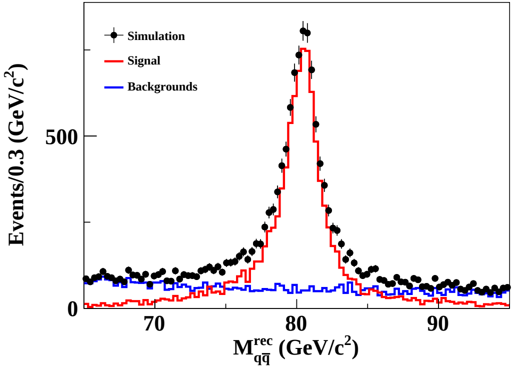
- The signal events are selected with one lepton (μ), two jets, and one missing neutrino.
- To reject backgrounds, the $E_\mu^{\mathrm{raw}} > 30$ GeV is performed. This cut is optimized with: $S/\sqrt{S+B}$, where S and B are the number of signal and background events.





Signal and backgrounds

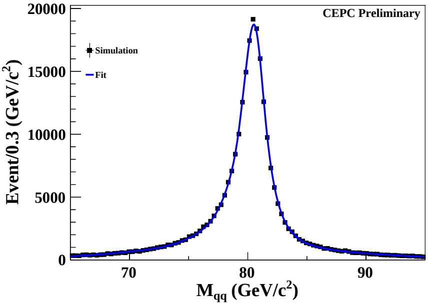
The distributions of signal and backgrounds after the E_μ^{raw} cut:



In the plot above, the signal is scaled with 0.04 to see backgrounds clearly.

Signal yields

Signal yields are obtained with maximum likelihood fit, where the signal PDF is the signal shape (RooKeysPdf) and the background is described by 2-nd Chebychev function.



Input: $N_{sig} = 259570$, $N_{out} = 5762$

Fit: $N_{sig} = 259573.0 \pm 695.0$, $N_{out} = 5758.4 \pm 470.6$

II. Study of $e^+e^- \to \gamma_{ISR} q\bar{q}$

$e^+e^- \to \gamma_{ISR} q\bar{q}$

The observed cross section is:

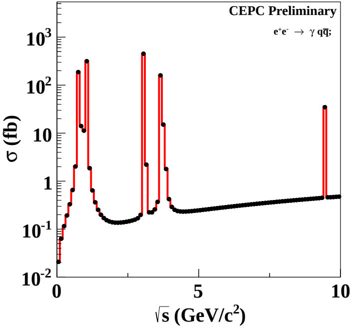
$$\sigma_{\mathrm{obs}}(s) = \int \sigma_B(s(1-x)) \cdot W(s,x)dx \tag{10}$$

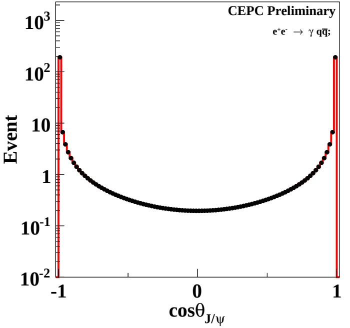
The $W(s,x)$ is the radiator, $\sigma_B(s)$ is the Born cross section. For the narrow resonance, the $\sigma_B(s)$ is given by the standard Breit-Wigner formula:

$$\sigma_0(s) = \frac{12\pi m^2 \Gamma_{ee}^2}{(s-m^2)^2 + m^2\Gamma^2}, \tag{11}$$

where m and Γ are the mass and width of resonance, Γ_{ee} is the partial width to e^+e^-.

Distributions for σ and polar angle





Formula for polar angle of γ_{ISR}

The polar angle distribution for γ_{ISR}:

$$P(\theta) = \frac{\sin^2\theta - \frac{x^2\sin^4\theta}{2(x^2-2x+2)} - \frac{m_e^2}{E^2}\frac{(1-2x)\sin^2\theta - x^2\cos^4\theta}{x^2-2x+2}}{(\sin^2\theta + \frac{m_e^2}{E^2}\cos^2\theta)^2}, \quad (12)$$

where $s = 4E^2$, E is the beam energy, m_e is the electron mass, $x = E_\gamma / E$.
The probability for the hard photon inside the opening angle θ_m

$$P(0 \le \theta \le \theta_m) = \frac{h(\theta_m)}{h(\pi)}, h(\theta_m) = \int_0^{\theta_m} P(\theta)\sin\theta d\theta, \quad (13)$$

where

$$h(\theta) = \frac{L-1}{2} + \frac{m_e^2}{2E^2}\frac{\cos\theta}{\sin^2\theta + \frac{m_e^2}{E^2}\cos^2\theta} - \frac{1}{2}\ln\frac{1+\sqrt{1-\frac{m_e^2}{E^2}}\cos\theta}{1-\sqrt{1-\frac{m_e^2}{E^2}}\cos\theta}$$

$$\frac{x^2\cos\theta}{2(x^2-2x+2)}(1 - \frac{m_e^2}{E^2}\frac{1}{\sin^2\theta + \frac{m_e^2}{E^2}\cos^2\theta}), \qquad L = 2\ln\frac{\sqrt{s}}{m_e} \quad (14)$$

$$\propto A(\theta) + B(\theta)\frac{x^2}{x^2-2x+2}$$

Cross section and cut efficiency for $\cos\theta < 0.98$

Assuming the detection region is: $\cos\theta < \cos\theta_0$, the probability for the photon:

$$\begin{aligned} P &= 2(P(\frac{\pi}{2}) - P(\theta_0)) \\ &\propto \frac{L-1}{2} - A(\theta_0) - B(\theta_0)\frac{x^2}{x^2-2x+2} \end{aligned} \tag{15}$$

Here, $B(\theta_0)$ is a positive number. We can see that the radiative photon tends to along the beam direction when its energy large.

91.2 (GeV)	ω	ϕ	J/ψ	$\psi(2S)$	$\Upsilon(1S)$
σ_{obs} (fb)	178.5	318.8	452.5	159.0	16.3
ϵ (%)	15.59	15.59	16.60	16.61	16.83

The result is consistent with the conclusion from Eq. 15.

Summary

- Using the threshold scan method, we study the measurement of m_W.
- With 500 fb^{-1} integrated luminosity, a precision of 2 MeV can be achieved in CEPC with 2 energy points ($\Delta\mathcal{L} \leq 0.1\%$, $\Delta E \leq 1.5$ MeV, $\epsilon P = 0.72$).
- The process $e^+e^- \to W^+W^- \to \mu\nu_\mu qq$ is simulated, the event select efficiency is about 0.9.
- We estimate the cross sections and polar angle distributions of some narrow mesons produced via ISR processes. The production rates of there states are small when combining the acceptability of the detector.

Thank you!

backup

Luminosity

The fit method is also used to consider $\Delta\mathcal{L}$ (1%), the fit procedure and the corresponding result are similar as ISR: $\Delta M_W \sim 0.4$ MeV.
There are some questions below:

- 1. Using total sys. uncertainty or fit $\Delta\mathcal{L}, \Delta ISR$ simultaneously?

Energy spread

The effect of energy spread should be very small (compute precision). To check this, we use 100 times (10000 steps), the results are:

Mean (GeV)	80.3848	80.3849	80.3850	80.3851	80.3852
N	1	17	60	12	1

Theoretical error $\Delta\sigma_{WW}$

For ISR, the σ_{WW} is calculated with different options(different $O(\alpha^2)$).

For IZERO:

- $S = \frac{3}{4}\beta_e + \frac{\alpha}{\pi}(\frac{\pi^2}{3} - \frac{1}{2}) \times IZERO + \ldots$

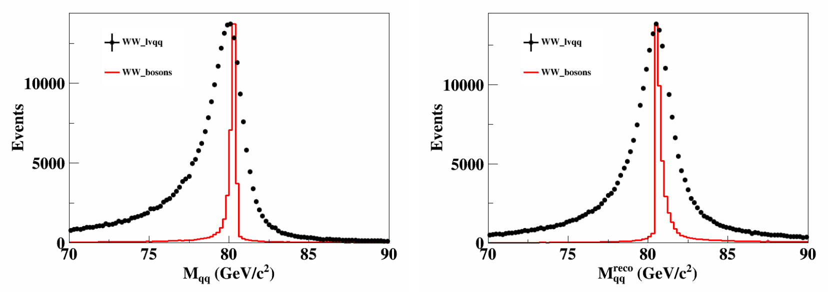
For IQEDHS:

- -1,$e^{O(\alpha)}$ - constant terms (a'la WWGENPV?)
- 0, $e^{O(\alpha)}$ + constant terms (a'la BBOR, universal?)
- 1, $e^{O(\alpha)} + L^2$ of $O(\alpha^2)$
- 2, $e^{O(\alpha)} + L^2 + L$ of $O(\alpha^2)$
- 3, $e^{O(\alpha)} + L^2 + L + 1$ of $O(\alpha^2)$ (recommended)

IZERO/IQEDHS	-1	0	1	2	3
0	4.105	4.456	4.438	4.443	4.443
1	4.105	4.483	4.465	4.470	4.469

ϵ, $\Delta\epsilon$

At 162 GeV, both the samples $WW_{l\nu qq}$ and WW_{boson} are the signal process, why the distributions are so different?



What's new

- $\Delta M_W \propto$ Beam spead $\surd$
- $\Delta M_W \propto \mathrm{ISR}$ $\surd$
- $\Delta M_W \propto \Delta \mathcal{L}$ $\surd$
- $\Delta M_W \propto \Delta E_{beam}$ $\surd$
- $\Delta M_W \propto \Delta \epsilon \cdot P$

Energy spread (1-D)

To consider the effect of energy spread ($\Delta_{E_{tot}} = \sqrt{\Delta_{E_p} + \Delta_{E_m}} = \sqrt{2}\Delta$, ID assumption), the experimental $\sigma_{W^+W^-}$ become:

$$\sigma_{W^+W^-}(E) = \int_0^{\infty} \sigma(E^{'}) \times G(E, E^{'})dE^{'} \approx \int_{E-6\sqrt{2}\Delta\cdot E}^{E+6\sqrt{2}\Delta\cdot E} \sigma(E^{'}) \times \frac{1}{\sqrt{2\pi}\sqrt{2}\Delta \cdot E} e^{\frac{-(E-E^{'})^2}{2(\sqrt{2}\Delta\cdot E)^2}} dE^{'} \tag{16}$$

Here, $\sqrt{2}\Delta \cdot E$ is the energy spread, and Δ is 0.16% (preCDR). To save compute time, we use the region $[E - 6\sqrt{2}\Delta \cdot E, E + 6\sqrt{2}\Delta \cdot E]$.

Input (GeV)	80.385
Fit (GeV)	80.3851

Energy spread (2-D?)

The $\sigma_{W^+W^-}$ with the 2-D convolution with $\Delta_{E_p}, \Delta_{E_m}$:

$$\sigma_{W^+W^-}(E_p, E_m) = \int_0^\infty \int_0^\infty \sigma(E_p^{'} + E_m^{'}) \times G_1(E_p, E_p^{'}) dE_p^{'} \times G_2(E_m, E_m^{'}) dE_m^{'} \tag{17}$$

Do we need to use the 2-D formula? Very slow but without assumption!

Beam energy measurement uncertainty ΔE

Considering the ΔE, the total energy become (ID assumption):

$$E = N(E_p, \Delta E^2) + N(E_m, \Delta E^2) \tag{18}$$

By 500 samplings, the corresponding $\Delta M_{W^\pm}$ is:

ΔE (MeV)	$\Delta M_{W^\pm}(MeV)$
2.0	1.54
1.5	1.03
1.0	0.74
0.5	0.36

Uncertainty from luminosity ΔL (1 point)

Similarly, the Luminosity becomes :

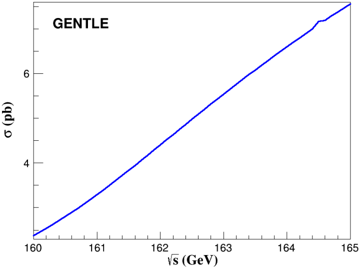
$$\mathcal{L} \sim N(\mathcal{L}, 2\Delta\mathcal{L}^2) \tag{19}$$

By 500 samplings, the $\Delta M_{W^\pm} \propto \Delta\mathcal{L}$:

$\mathcal{L}$ (‰)	$\Delta M_{W^\pm}(MeV)$
1.0	1.70
0.5	0.80
0.1	0.16

Uncertainty from luminosity ΔL (more points)

The cross sections around the most sensitive region are almost linear. So we take more points in this region (average luminosity).



Npt	1	2	3	4	5	6	7
$\Delta M_W(MeV)$	1.70	1.23	1.17	...			