Precise measurement of W mass

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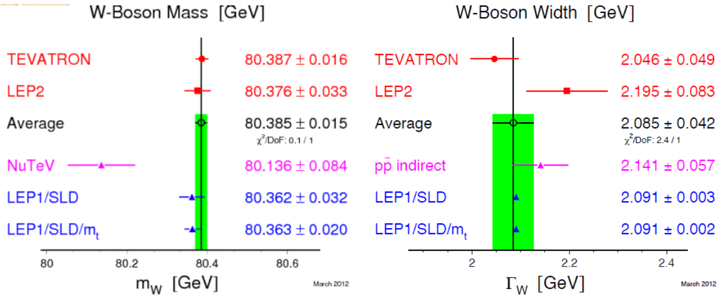
Motivation

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

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

  Improving the precision of m_W is important for testing the overall consistency of the SM.
- The direct measurement of m_W by reconstruction with its daughters suffer the large systematic uncertainty, such as the radiative correction, modeling of hadronization.
- The threshold scan method is more sensitive to the statistic of data and accelerator performance (this study).

Status and goal

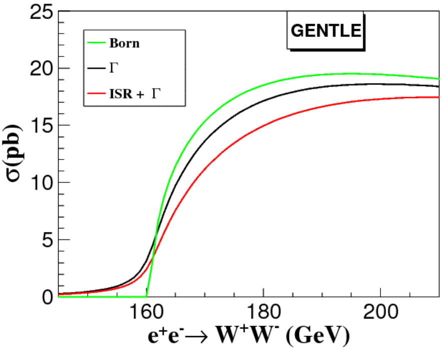


P.Azzurri (INFN & CERN)

★ Using the threshold scan method, **2.5 MeV** for total uncertainty for m_W 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 correction is also calculated by convoluting the Born cross section with ISR radiator, https://arxiv.org/abs/hep-ph/9910523v1 with the radiator up to order α^2 correction.



Statistic uncertainty for m_W

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

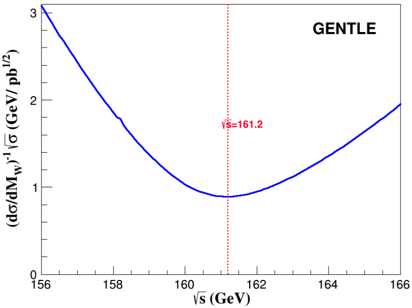
$$\begin{aligned}
\Delta\sigma_{W^+W^-} &= \sigma_{W^+W^-} \times \frac{\Delta N_{W^+W^-}}{N_{W^+W^-}} \\
&= \sigma_{W^+W^-} \times \frac{\sqrt{N_{W^+W^-} + N_{bkg}}}{N_{W^+W^-}} \\
&= \sqrt{\frac{\sigma_{W^+W^-}}{\mathcal{L}\epsilon P}} \qquad (P = \frac{N_{W^+W^-}}{N_{W^+W^-} + N_{bkg}})
\end{aligned}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

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

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

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

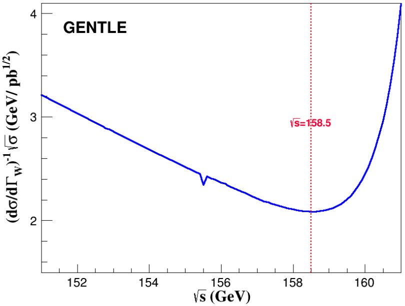
- With $\mathcal{L} = 500\ \text{fb}^{-1}$, $\epsilon = 0.8$, $P = 0.9$:
  $$\Delta M_W = \left(\frac{\partial\sigma_{W^+W^-}}{\partial M_W}\right)^{-1} \times \sqrt{\frac{\sigma_{W^+W^-}}{\mathcal{L}\epsilon P}} \approx 1.5\text{MeV}.$$



Max stat. sensitivity at $\sqrt{s} \sim 2m_W + 0.4$ GeV

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

- With $\mathcal{L} = 500$ 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.



Max stat. sensitivity at $\sqrt{s} \sim 2m_W - 3.3$ GeV

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 $\sqrt{s} = 161.2$ GeV, $\Delta M_W \approx 1.5$ MeV
- Two or three points around $\sqrt{s} = 161.2$ GeV, ΔM_W does't change much.
- $\Delta M_{W\pm}$ increases when there are more than four points.

Systematic uncertainty for m_W

Beam energy spread

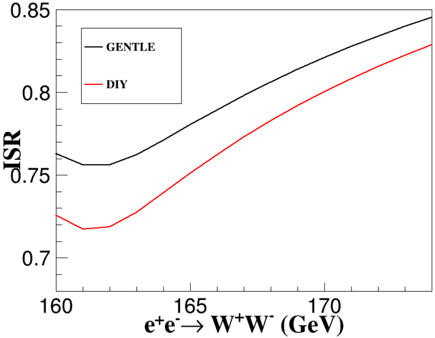
With the beam energy spread, the $\sigma_{W^+W^-}$ becomes:

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

Δ (%)	Δm_W (MeV)
2	0.11
1	0.07
0.16	0.06

ISR factor $(1+\delta)$

- The ISR factor is calculated by convoluting the Gentle's results (no ISR) and ISR radiator.
- Actually, the difference between the results from Gentle (with ISR) and our 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 $\mathcal{L}$

For fake data, $\mathcal{L} = G(\mathcal{L}_0, \Delta\mathcal{L}_0)$. For fit, χ^2 is defined as

$$\chi^2 = \sum_i \frac{(y_i - h \cdot x_i)^2}{\delta_i^2} + \frac{(h-1)^2}{\delta_c^2} \tag{7}$$

Here, y_i, x_i are the true and fit results at scan point i, h is a free parameter, δ_i and δ_c are the independent and correlated uncertainty, respectively. With $\delta\mathcal{L} = 0.1\%$, $\Delta m_W = 0.4$ MeV.

Since the uncertainties of $\mathcal{L}$ and ISR correction affect the Δm_W in same way, the situation for ISR correction is similar.

Beam energy uncertainty ΔE

With the ΔE, the total energy becomes:

$$E = G(E_p, \Delta E) + G(E_m, \Delta E) \tag{8}$$

By 500 samplings, the corresponding ΔM_W is:

ΔE (MeV)	$\Delta M_W (MeV)$
2.0	1.54
1.5	1.03
1.0	0.74
0.5	0.36

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

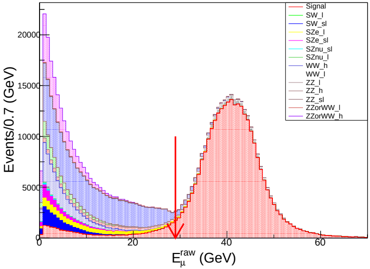
MC samples

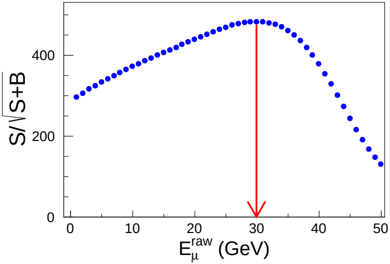
		N_G	N_P	N_S	Scale Factor
Signal		300857	300202	272251	1.00
Bkg.	ZZ_l	5000000	120292	14932	0.11
	ZZ_{sl}	614909	300454	13299	0.41
	WW_l	100000	15367	14366	0.50
	SZe_l	693376	36559	1847	0.46
	$ZZ(WW)_l$	200000	4877	548	0.35
	ZZ_h	400000	86214	497	0.16
	SZe_{sl}	200000	19841	121	0.46
	$SZnu_l$	200000	3295	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

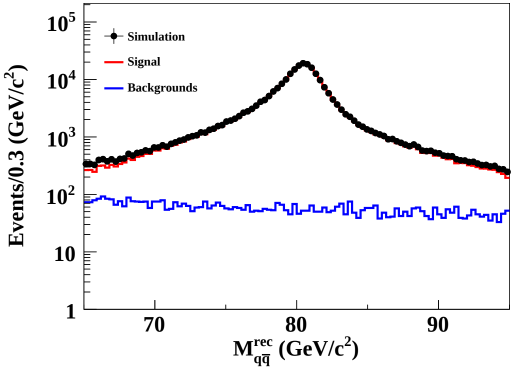
- The signal events are selected with one lepton (μ), two jets, and one missing neutrino.
- To reject backgrounds, the $E_\mu^{\text{raw}} > 30$ GeV is performed. This cut is optimized with: $S/\sqrt{S+B}$, where S and B are the number of signal and background events.



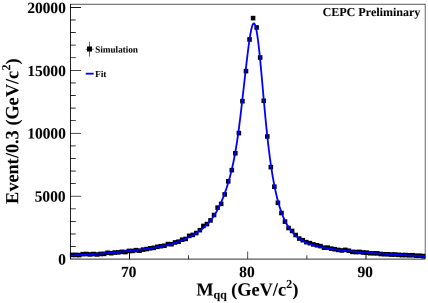


Signal and backgrounds

The distributions of $M_{q\bar{q}}^{rec}$ after the E_μ^{raw} cut:



Signal yields



Signal PDF: signal shape (RooKeysPdf)
Background PDF: 2-nd Chebychev function.
Input: $N_{sig} = 259570$, $N_{bkg} = 5762$
Fit: $N_{sig} = 259573.0 \pm 695.0$, $N_{bkg} = 5758.4 \pm 470.6$

Summary and Questions

- 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 event selection for process $e^+e^- \to W^+W^- \to \mu\nu_\mu qq$ is simulated, the event select efficiency is about 0.9.
- For theoretical uncertainty of σ_{WW}, we just consider the ISR correction. But how about others, *e.g.*, the modeling of hadronization?

Thank you!

backup

Backup

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

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:

$$\sigma_{W^+W^-}(E) = \int_0^\infty \sigma(E') \times G(E, E')dE' \approx \int_{E-6\sqrt{2}\Delta\cdot E}^{E+6\sqrt{2}\Delta\cdot E} \sigma(E') \times \frac{1}{\sqrt{2\pi}\sqrt{2}\Delta \cdot E} e^{\frac{-(E-E')^2}{2(\sqrt{2}\Delta\cdot E)^2}} dE' \quad (9)$$

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 $\Delta_{E_p}, \Delta_{E_m}$:

$$\sigma_{W^+W^-}(E_p, E_m) = \int_0^\infty \int_0^\infty \sigma(E_p^{'} + E_m^{'}) \times G_1(E_p, E_p^{'})dE_p^{'} \times G_2(E_m, E_m^{'})dE_m^{'} \tag{10}$$

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):

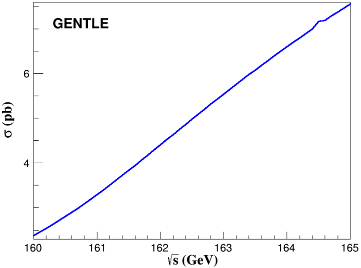
$$E = N(E_p, \Delta E^2) + N(E_m, \Delta E^2) \tag{11}$$

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 (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	...			