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A thousand* recipes to use up dimuon events at the FCC-ee

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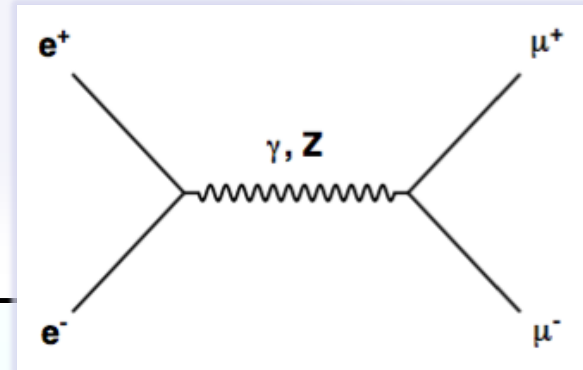
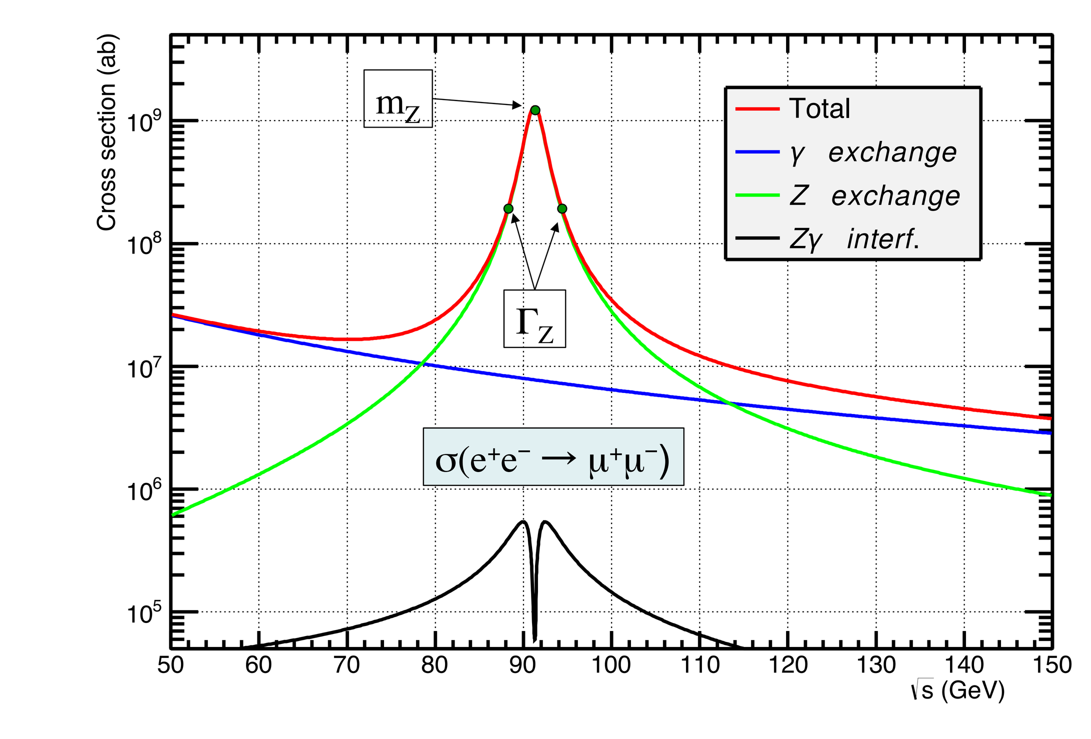
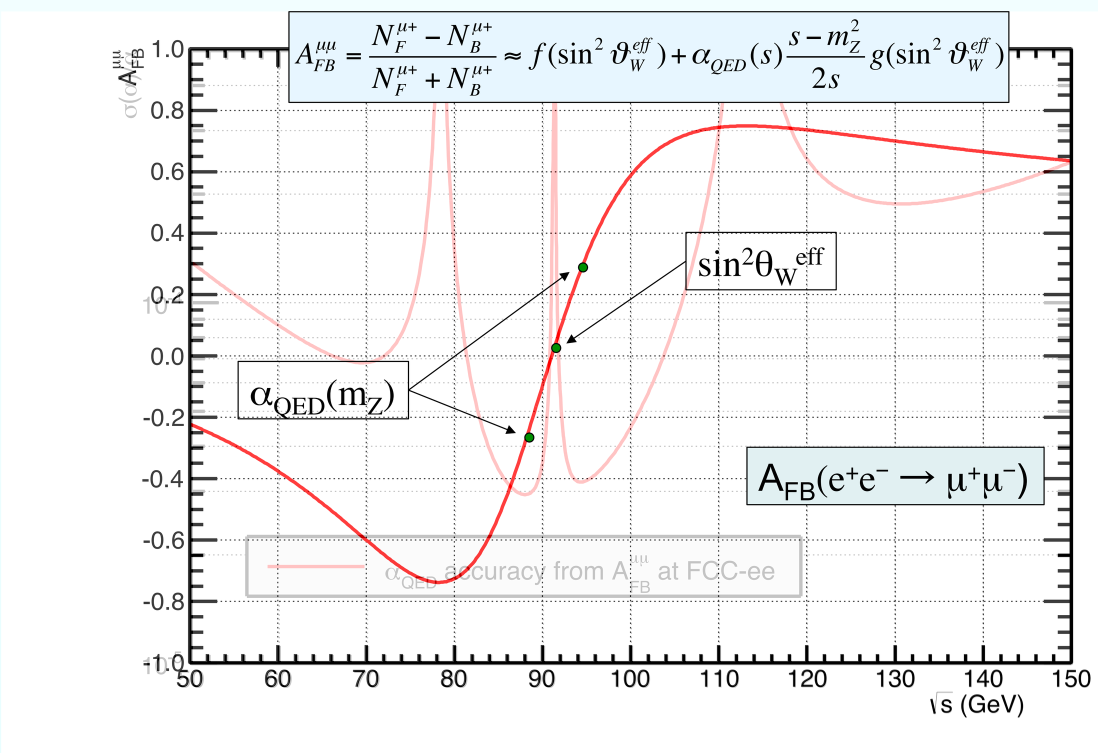
FCC week, 9-13 April 2018, Beurs van Berlage

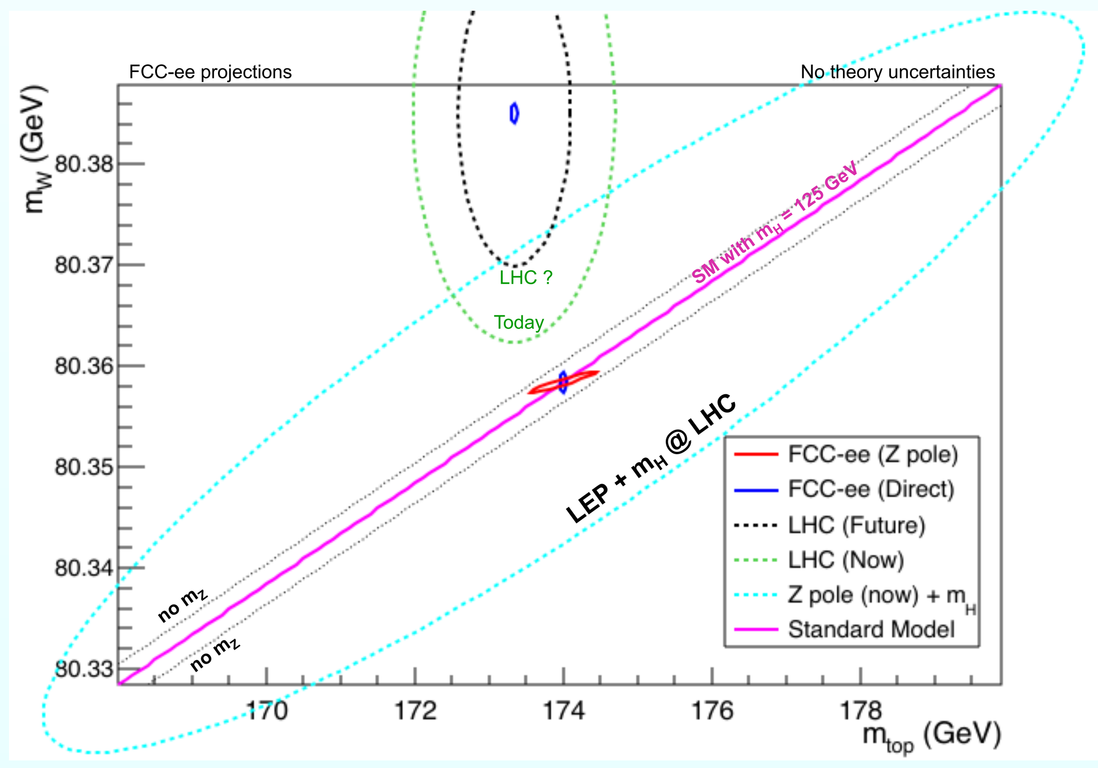


Precision measurements of the Z properties

Dimuons are the simplest events at the FCC-ee, with a μ^+ and a μ^- almost back-to-back, both easily identifiable with a track in the tracker and the muon chambers, and almost no interaction within the calorimeters. Their momenta and directions can be measured with high accuracy, typically 50 MeV and 100 μrad, respectively, for 45 GeV muons. Dimuon events are therefore used routinely used for measurements that require extreme precision. The measurement of the Z mass and the Z width can be performed "just" by counting the numbers of such events at the Z pole ($\sqrt{s}$ ≈ 91.2 GeV) and around it ($\sqrt{s}$ ≈ 88 and 94 GeV). The FCC-ee not only offers a statistical precision of a few keV on m_Z and Γ_Z, but even more importantly a way – unique to circular colliders – to calibrate the beam energy in situ with a 50 keV accuracy, with "continuous" resonant depolarization of monitoring bunches, turning to a target precision better than 100 keV on m_Z and Γ_Z. The ratio of the number of dimuons to that of hadronic Z decays enables a measurement of the strong coupling constant $\alpha_S(m_Z)$ with a precision of 0.0002 or better. Because of the parity-violating couplings of the Z to the muons, μ^+'s (μ^-'s) tend to be produced forward (backward). The forward-backward asymmetry at the Z pole depends solely on the weak mixing angle, $\sin^2\theta_W^{eff}$. Around the Z pole, a dependence on the electromagnetic coupling constant $\alpha_{QED}(m_Z)$ arises from the interference with the photon exchange. With over 10^{11} dimuons, an experimental precision of 5×10^{-6} (dominated by the beam energy accuracy) is obtained on $\sin^2\theta_W^{eff}$, and a statistics-dominated relative precision of 3×10^{-5} on $\alpha_{QED}(m_Z)$ can be contemplated if the beam energy spread is known to a few per mil. In the standard model, these precision measurements allow m_W, m_{top}, and m_{Higgs} to be predicted with great accuracy and be compared to their direct measurements at the FCC-ee for new physics discovery.

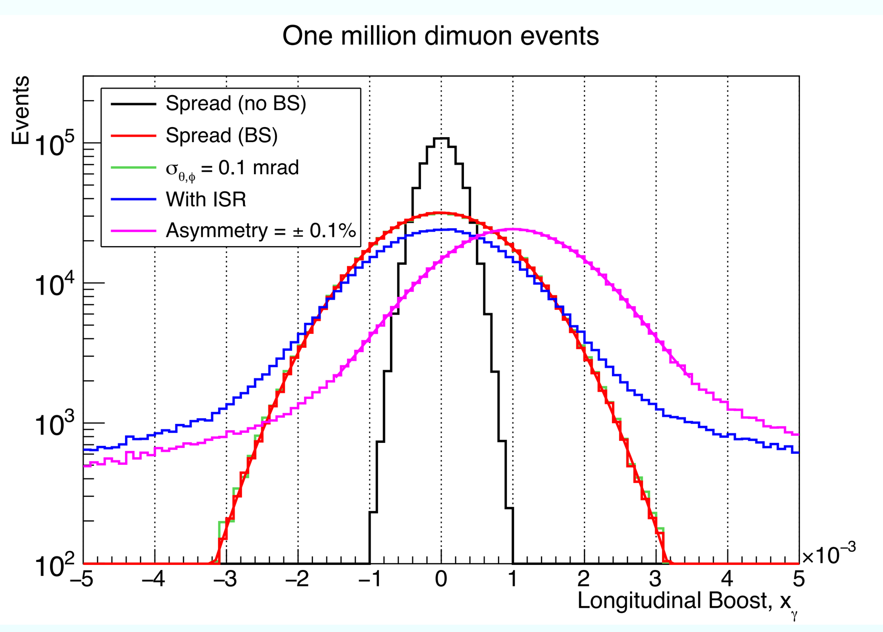






Beam energy spread and asymmetry; Beam energy and number of neutrinos

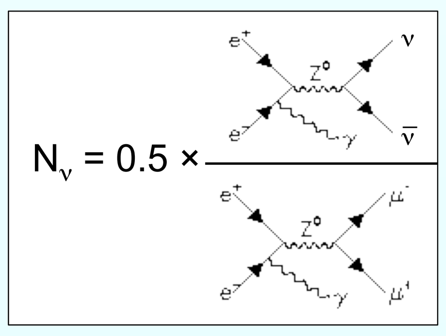
At the FCC-ee, beamstrahlung is pushed at its limits to maximize the luminosity, which causes a large beam energy spread, from 60 MeV at the Z pole to 350 MeV at the top energies. Because the pertaining biases to the measurements of Γ_Z and α_{QED} are two-to-three orders of magnitude larger than their target precisions, the beam energy spread must be measured to a few per mil. Dimuon events are instrumental for this purpose, too. The effect of energy spread is to slightly boost the two muons along the "beam axis" and modify their directions – in a way similar to the radiation of a photon (ISR) by one of the two incoming particles. This "longitudinal" boost x_γ (in unit of $\sqrt{s}$) can be determined with the help of (E, **p**) conservation from the muon polar and azimuthal angles, $\theta^\pm$ and $\varphi^\pm$, and the beam crossing angle α. The mean value and shape of the x_γ distribution give the difference between the e± beam energies and the relative centre-of-mass energy spread, after unfolding ISR effects, with the necessary precision in a few minutes.



$$x_\gamma = -\frac{x_+\cos\theta^+ + x_-\cos\theta^-}{\cos(\alpha/2) + |x_+\cos\theta^+ + x_-\cos\theta^-|} \quad \text{with} \quad x_\pm = \frac{\mp\sin\theta^\mp\sin\varphi^\mp}{\sin\theta^+\sin\varphi^+ - \sin\theta^-\sin\varphi^-}$$

Pseudo Observable	Γ_Z			$\alpha_{QED}(m_Z^2)$		Γ_W	Γ_{top}
Acceptable error	35 keV			10^{-5}		0.5 MeV	9 MeV
$\sqrt{s}$ (GeV)	87.9	91.2	93.8	87.9	93.8	161	350
$\sigma(\delta E)/\delta E$	0.8%	0.2%	0.8%	0.7%		7%	15%
$N_{e^+e^-\to\mu^+\mu^-}$	$5\,10^4$	$8\,10^5$	$5\,10^4$	$6.5\,10^4$		650	150
L (10^{34}cm^{-2}s^{-1})	230					32	1.8
$\sigma_{\mu\mu}$ (pb)	185	1450	460	185	460	4.0	0.8
Dimuon rate (Hz)	425	3325	1050	425	1050	1.3	0.015
Time needed	2 min	4 min	< 1 min	3 min	1 min	8 min	2 h 30

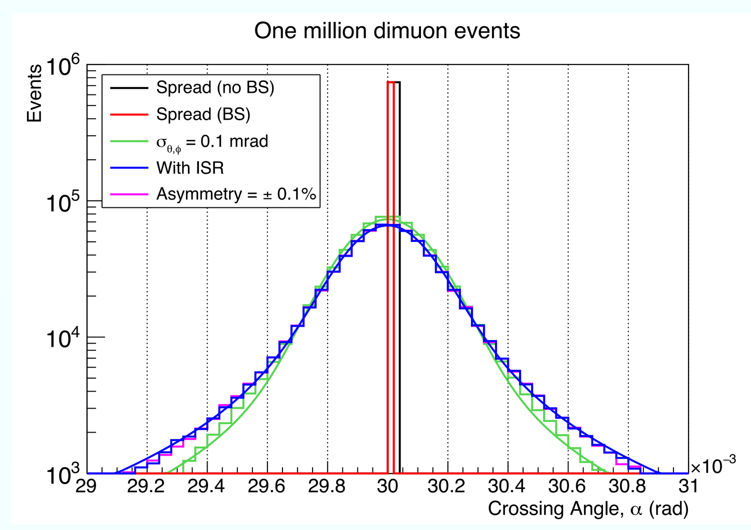
At centre-of-mass energies above the WW threshold, the resonant depolarization method is not available to measure the beam energy. The distribution of $\sqrt{(1-2x_\gamma)}$, however, presents a pronounced peak around $m_Z/\sqrt{s}$, from the radiative return to the Z resonance. The precise measurement of m_Z at the Z pole allows in turn the determination of $\sqrt{s}$ at higher energies. This method can be calibrated at the WW threshold, where resonant depolarization can be concurrently used. Radiative returns to the Z selected with an energetic photon in the detector acceptance are also instrumental for the measurement of the number of light neutrino species with a precision of 0.0008.



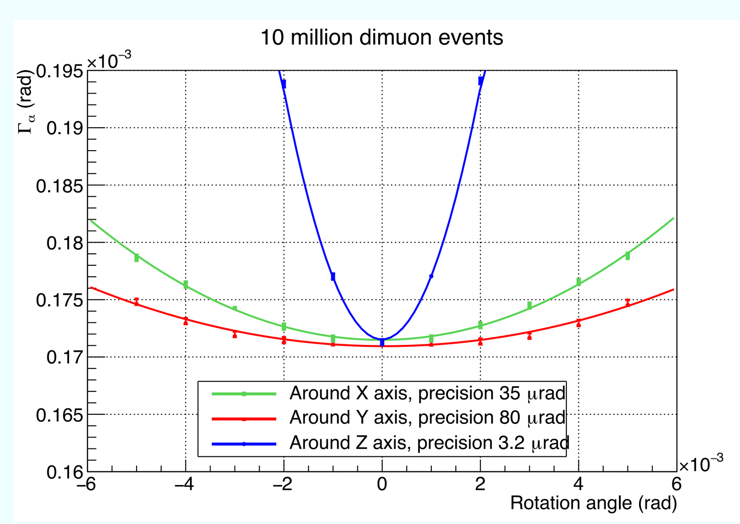
Detector vs beam absolute alignment

The measurement of the beam energy spread requires an absolute knowledge of the beam crossing angle and of the two muon directions with respect to the natural reference frame, in which the z axis is the bissector of the two beam directions, the (x,z) plane contains the two beams, and the y axis points upwards perpendicularly to that plane. The beam crossing angle α can be determined from the muon directions and (E, **p**) conservation, with a precision of 0.3 μrad within 5 minutes at the Z pole.

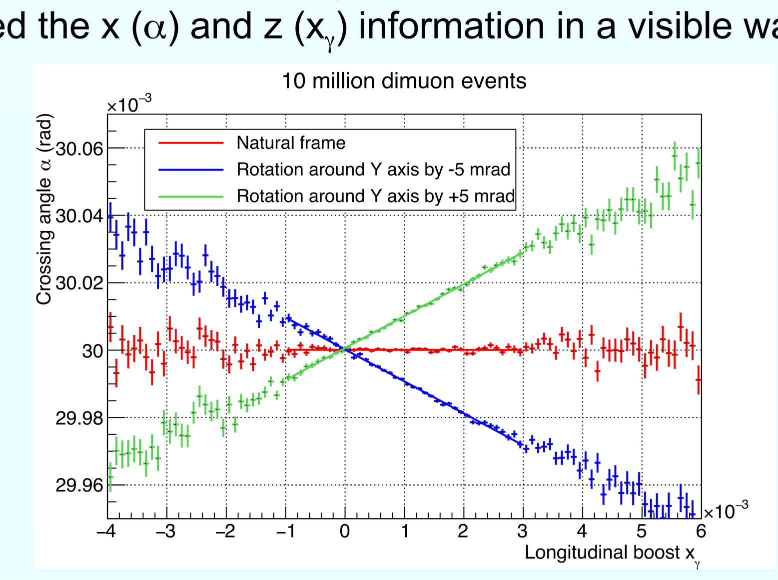
$$\alpha = 2\arcsin\left[\frac{\sin(\varphi^- - \varphi^+)\sin\theta^+\sin\theta^-}{\sin\varphi^-\sin\theta^- - \sin\varphi^+\sin\theta^+}\right]$$



The spread of the α distribution from dimuon events is smallest when the z axis (used to determine $\theta^\pm$) and the x axis (used to determine $\varphi^\pm$) are perfectly known. The alignment of the detector with respect to these axes can therefore be achieved with a minimization of this spread. Precisions of 3.2 (35) μrad on the Euler rotation angles around the x (z) axes need only one hour at the Z pole.



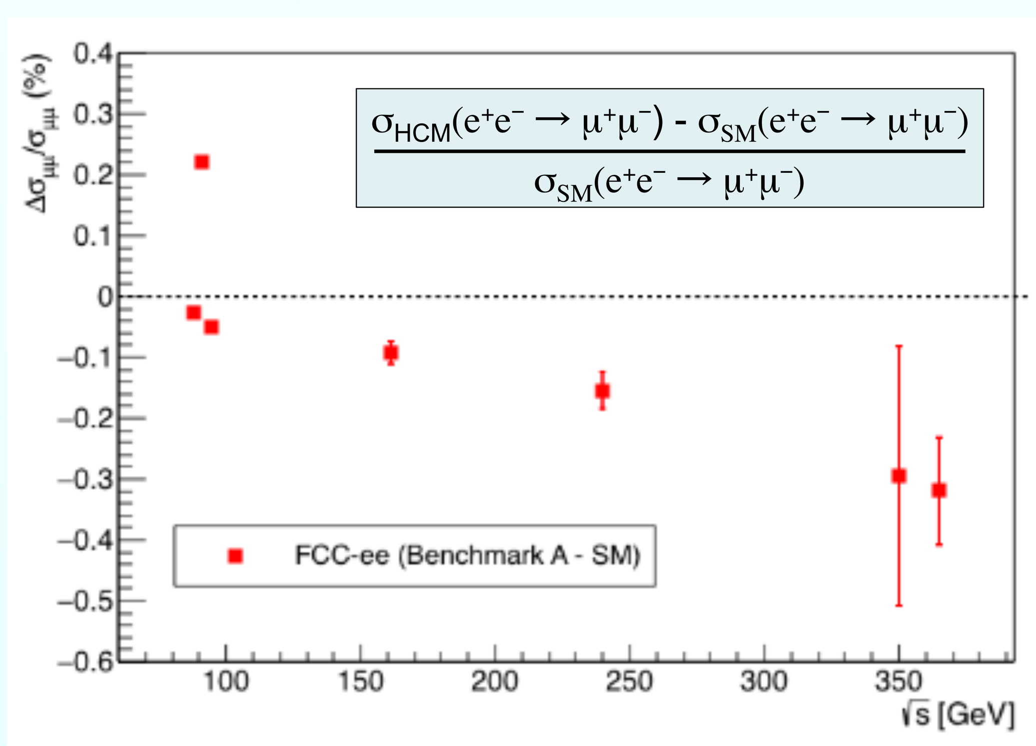
The precision on the Euler rotation angle around the y axis improves from 80 to 18 μrad (in one hour at the Z pole) by also minimizing the correlation between α and x_γ: such a rotation with respect to the natural frame mixes indeed the x (α) and z (x_γ) information in a visible way:



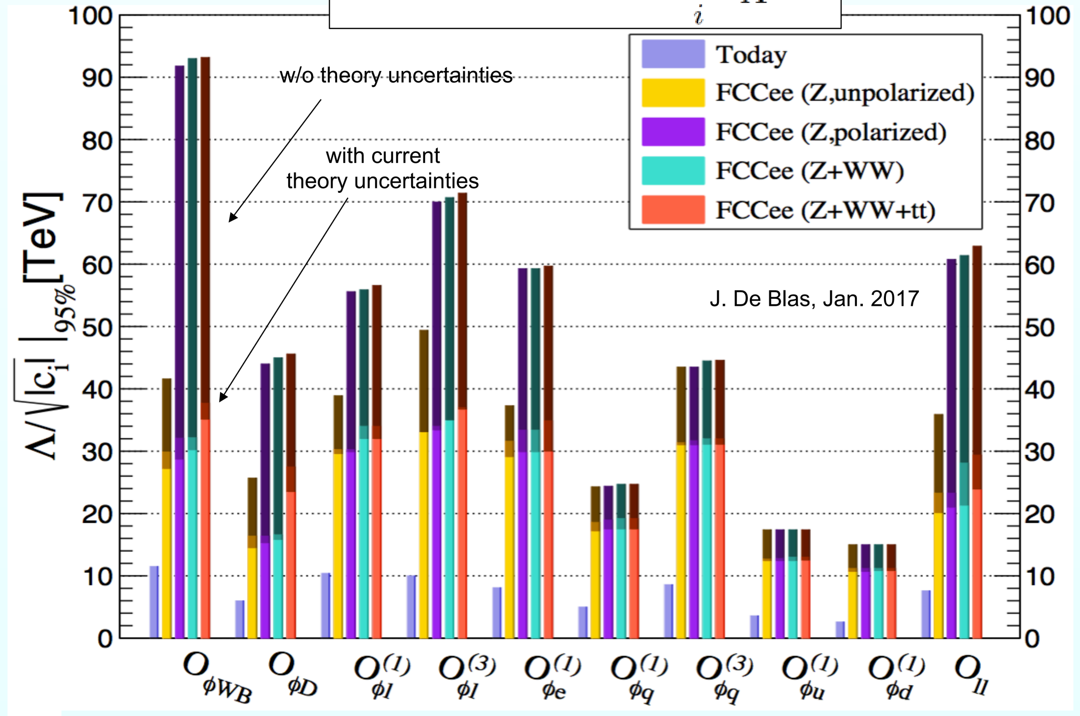
Sensitivity to heavy new physics

The precision measurements from dimuons at the Z pole may be found not to fit either with the standard model or with the direct measurements of m_W, m_{top}, and m_{Higgs}, or with both. Such an observation would mean that new weakly-coupled physics (and particles) exist. This new physics is often generically parameterized in terms of effective dimension six operators, whose effects become predominant above a certain energy scale Λ. Provided that the precision of theory predictions improves up to matching the FCC-ee experimental accuracy, a sensitivity to new physics scales of 10 to 100 TeV is at hand.

A correlated pattern of deviations between sets of measurements at all FCC-ee centre-of-mass energies may also provide direct hints of the specific underlying new physics. In composite Higgs models, for example, the interference with an extra neutral gauge boson with mass $m_{Z'}$ ~ 3 TeV and width ~ 600 GeV, which would have be unnoticed at LEP and about which HL-LHC cannot say much, would modify the dimuon cross section in such a way that FCC-ee would be able to determine all gauge sector parameters of the model (including the Z' mass) to 5%.



$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$



EP department

* Due to lack of space, only sixteen recipes are given above. The 984 others are on the back.