Lepton Universality at Z pole

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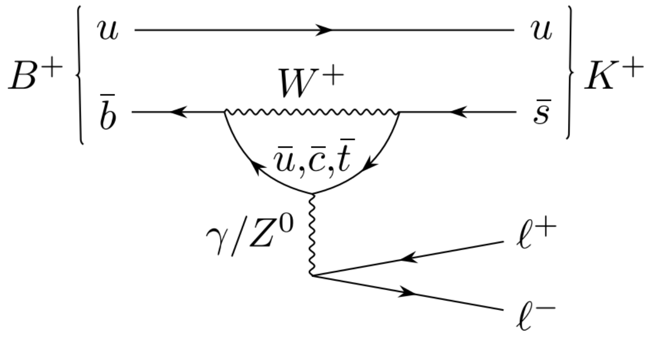
LFU evidence in LHCb

Lepton Universality:

- In the SM, the couplings of leptons to the gauge boson are independent with their flavour except for the phase space difference.
- LHCb collaboration just report a results of evidence of Lepton non-universality with LHC data in $B^+ \to K^+ \ell\ell$



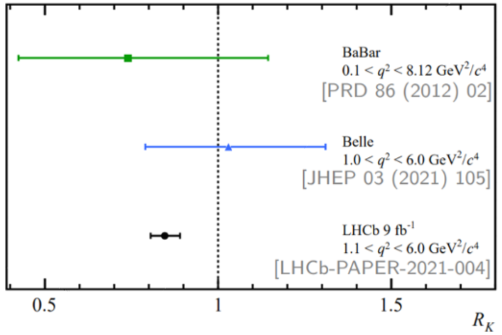
$$R_K = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathrm{d}q^2} \mathrm{d}q^2}{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathrm{d}q^2} \mathrm{d}q^2} \stackrel{\mathrm{SM}}{=} 1 \pm \mathcal{O}(10^{-2}) \text{ EM correction}^1$$

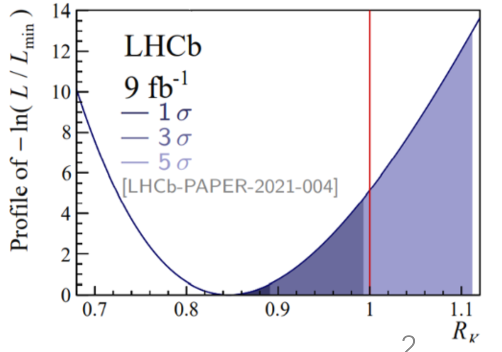
R_K with full Run 1 and Run 2 LHCb data

The measured value of R_K is:

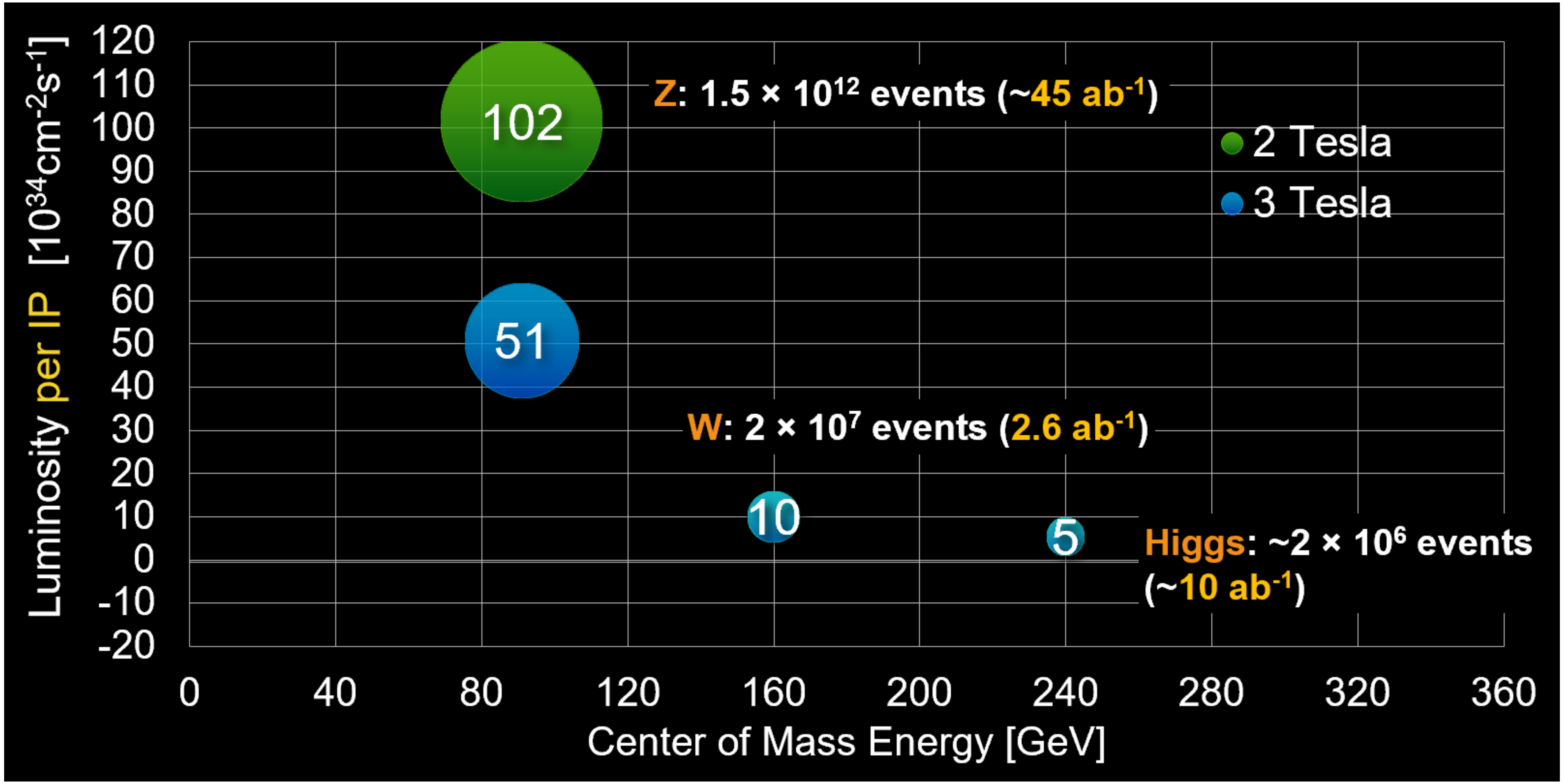
$$R_K = 0.846 \, {}^{+0.042}_{-0.039} \, (\text{stat.}) \, {}^{+0.013}_{-0.012} \, (\text{syst.})$$

- dominant systematic effect: fit model
  - effects such as calibration of trigger & kinematics are at permille-level
- p-value under SM hypothesis: 0.0010
- significance: $3.1\,\sigma$ (evidence for LFU violation in $B^+ \to K^+ \ell^+ \ell^-$ decays)



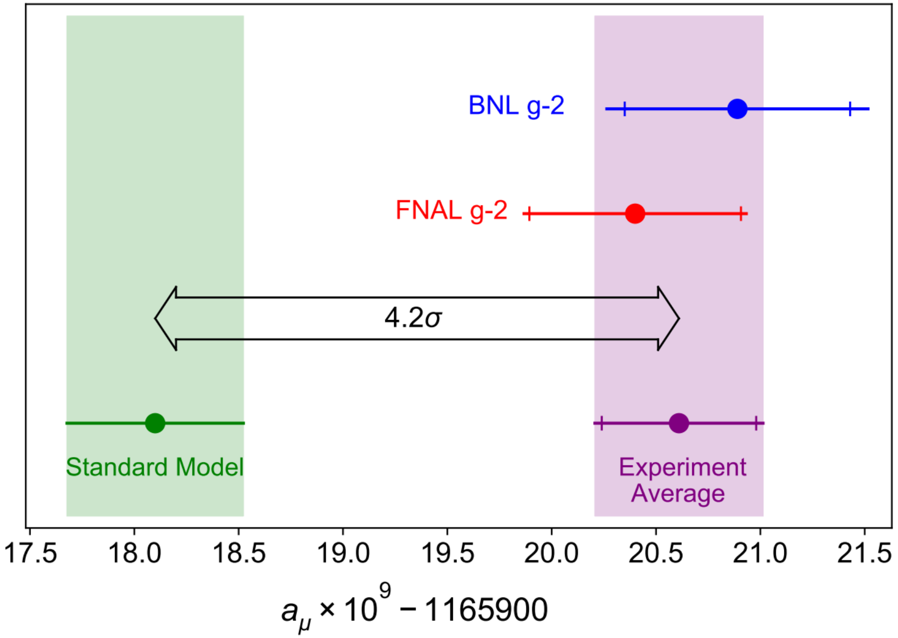


CEPC opportunities

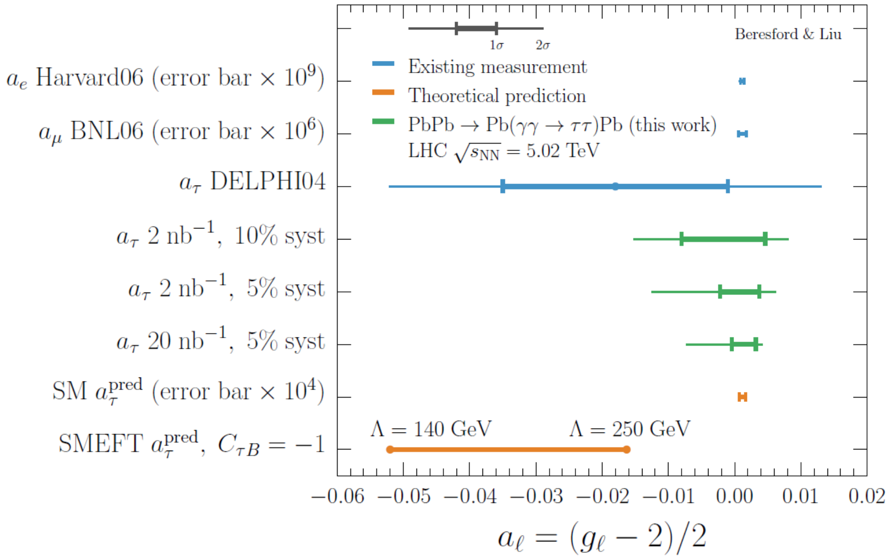


With 10E12 Z bosons produced, it's great opportunity to explore Lepton Flavour Universality.
LFU test in flavour physics reported by Lingfeng Li

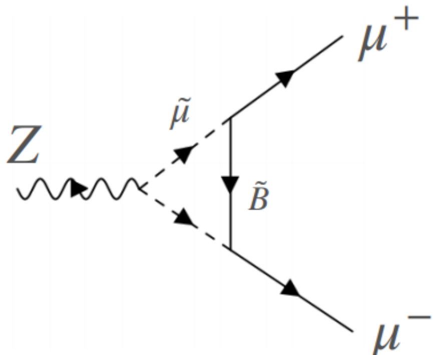
Directly LFU measure in Z⟶ℓℓ



Phys. Rev. Lett. 126, 141801 (2021)



- Precise measure of Br(Z⟶ℓℓ) is a test on mu g-2 new physics
- Potential explore tau g-2 as well



$$\frac{\delta\Gamma_\mu}{\Gamma_\mu} \sim 10^{-4} - 10^{-5}$$

Z→ℓℓ (results from LEP and LHC)

$$\frac{\Gamma_{\mu\mu}}{\Gamma_{\rm ee}} = \frac{B(\mathrm{Z}\to\mu^+\mu^-)}{B(\mathrm{Z}\to \mathrm{e}^+\mathrm{e}^-)} = 1.0009 \pm 0.0028$$

$$\frac{\Gamma_{\tau\tau}}{\Gamma_{\rm ee}} = \frac{B(\mathrm{Z}\to\tau^+\tau^-)}{B(\mathrm{Z}\to \mathrm{e}^+\mathrm{e}^-)} = 1.0019 \pm 0.0032$$

Br(Z→ℓℓ)

$\mathrm{e}^+\mathrm{e}^-$	3.3632 ± 0.0042
$\mu^+\mu^-$	3.3662 ± 0.0066
$\tau^+\tau^-$	3.3696 ± 0.0083

PR 427 (2006) 257
(a combined measurement from LEP)

SM: $\mathcal{O}(10^{-9})$

$$R_Z = \frac{\sigma^{\rm fid,e}_{Z\to ee}/E^{\rm e}_Z}{\sigma^{{\rm fid},\mu}_{Z\to\mu\mu}/E^{\mu}_Z} = \frac{\sigma^{\rm fid}_{Z\to ee}}{\sigma^{\rm fid}_{Z\to\mu\mu}} = \frac{BR(Z\to ee)}{BR(Z\to\mu\mu)}$$
$$= 1.0026 \pm 0.0013\,({\rm stat}) \pm 0.0048\,({\rm syst})$$
$$= 1.0026 \pm 0.0050\,.$$

Eur. Phys. J. C 77 (2017) 367
(measurement from ATLAS)

$$\frac{\sigma^{8\,\rm TeV}_{pp\to Z\to\tau^+\tau^-}}{\sigma^{8\,\rm TeV}_{pp\to Z\to\mu^+\mu^-}} = 1.01 \pm 0.05 \quad , \quad \frac{\sigma^{8\,\rm TeV}_{pp\to Z\to\tau^+\tau^-}}{\sigma^{8\,\rm TeV}_{pp\to Z\to e^+e^-}} = 1.02 \pm 0.06\,,$$

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LHCb measurement

Z→ℓℓ (CEPC prospective)

- LFU test highly related to the measurement of Br(Z→ℓℓ)

	1993 peak f	$\Delta f/f$ (%)
Monte Carlo		
$e^+e^- \to e^+e^-$ Monte Carlo	1.0056	0.02
Acceptance Correction		
Electromagnetic energy	1.0009	0.10
Electron identification	1.0025	0.08
Acceptance definition	1.0000	0.09
Low multiplicity	1.0001	0.01
Other Corrections		
Four-fermion events	1.0000	0.02
Signal Correction	1.0091	0.16
Backgrounds		
$e^+e^- \to \tau^+\tau^-$	0.9968	0.06
$e^+e^- \to \gamma\gamma$	0.9999	0.01
$e^+e^- \to q\bar{q}$	0.9999	0.02
$e^+e^- \to e^+e^-\ell^+\ell^-$	1.0000	0.01
Background Correction	0.9966	0.06
Total Correction Factor	1.0057	0.17

σ(pp→ee)=1.0064 ± 0.0109 nb

	1993 peak f	$\Delta f/f$ (%)
Monte Carlo		
$e^+e^- \to \mu^+\mu^-$ Monte Carlo	1.0955	0.07
s' cut correction	0.9990	–
Initial/final state interference	1.0002	–
Acceptance Correction		
Tracking losses	1.0046	0.06
Track multiplicity cuts	1.0007	0.04
Muon identification	1.0000	0.05
Acceptance definition	1.0000	0.10
Other Corrections		
Trigger efficiency	1.0006	0.02
Four-fermion events	1.0011	0.01
Signal Correction	1.1022	0.15
Backgrounds		
$e^+e^- \to \tau^+\tau^-$	0.9914	0.02
$e^+e^- \to e^+e^-\mu^+\mu^-$	0.9995	0.01
Cosmic rays	0.9998	0.02
Background Correction	0.9907	0.03
Total Correction Factor	1.0920	0.16

σ(pp→μμ)=1.4563 ± 0.0142 nb

	1993 peak f	$\Delta f/f$ (%)
Monte Carlo		
$e^+e^- \to \tau^+\tau^-$ Monte Carlo	1.3302	0.09
s' cut correction	0.9992	–
Initial/final state interference	1.0004	–
Acceptance Correction		
Multiplicity cuts	1.0017	0.16
Acollinearity and cone cuts	1.0002	0.23
Definition of $\lvert\cos\theta_\tau\rvert$	1.0000	0.10
$e^+e^- \to e^+e^-$ rejection	1.0038	0.26
$e^+e^- \to \mu^+\mu^-$ rejection	0.9997	0.08
$e^+e^- \to e^+e^-\ell^+\ell^-$ rejection	1.0018	0.11
Cosmic ray cuts	1.0001	0.01
Combinations of cuts	1.0000	0.08
Other Corrections		
Trigger efficiency	1.0002	0.01
Tau branching ratios	1.0000	0.05
Four-fermion events	1.0013	0.04
Signal Correction	1.3414	0.45
Backgrounds		
$e^+e^- \to e^+e^-$	0.9966	0.07
$e^+e^- \to \mu^+\mu^-$	0.9902	0.11
$e^+e^- \to q\bar{q}$	0.9960	0.11
$e^+e^- \to e^+e^-\ell^+\ell^-$	0.9948	0.07
Four-fermion	0.9994	0.02
Cosmic rays	0.9997	0.02
Background Correction	0.9768	0.19
Total Correction Factor	1.3105	0.48

σ(pp→ττ)= 1.5048 ± 0.0158 nb

- **LEP results are dominated by statistical uncertainty**
  - With~10^{12} Z produced, statistical uncertainty will be neglected
- Modeling play important role on systematics uncertainty, expected to be improved at CEPC era.
- Momentum/Energy calibration and lepton identification (~0.1%)
- Tau reconstruction and selection (~0.2-0.3%)

All the quoted cross sections are fiducial cross sections

Eur.Phys.J.C 19 (2001) 587-651 (OPAL measurement)

Z→ee (OPAL selection)

- Low multiplicity: $$2 \leq N_{\mathrm{track}} \leq 8 \text{ and } 2 \leq N_{\mathrm{cluster}} \leq 8,$$
- High energy clusters: $$E_1 > 0.2\sqrt{s} \text{ and } E_2 > 0.1\sqrt{s}.$$
- Total electromagnetic energy: $$E_{\mathrm{total}} \equiv \sum E^i_{\mathrm{cluster}} > 0.80\sqrt{s}.$$
- Two electrons

High energy cluster associated with a track is treated with electron candidate。

- Geometrical and kinematic acceptance: (e^- direction is measured from calorimeter)

$$|\cos\theta_{e^-}| < 0.70 \text{ and } \theta_{acol} < 10°,$$

Particle flow algorithm to improve

Improve from **Track reconstruction** and **high granularity calorimeter** in CEPC

Better energy resolution

Noval Lepton indentification, like LICH

	1993 peak f	1993 peak $\Delta f/f$ (%)
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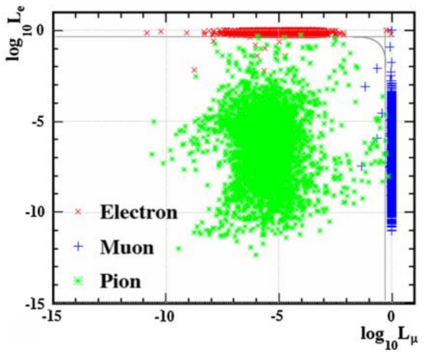

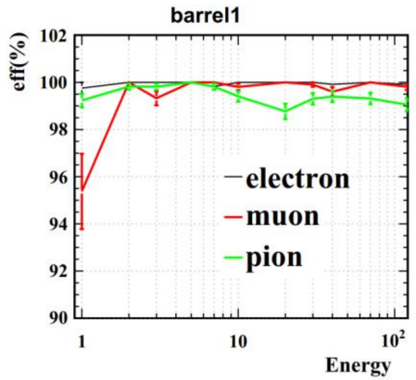

Eur. Phys. J. C (2017) 77 :591

We may expect a 1-2 magnitude lower than LEP for systematics, comparable with statistical ~10^{-4} - 10^{-5} (Current LEP ~10^{-3})

* θ_{acol} is the acollinearity angle of the e+e− pair, defined as 180° − α, where α is the opening

$$\phi_{acop} \equiv ||\phi_{e^-} - \phi_{e^+}| - 180°|$$

Z→μμ (OPAL selection)

- Two tracks with:

$$p_{\rm track} > 6~{\rm GeV}, \quad |\cos\theta| < 0.95,$$

- Azimuthal separation $\cos(\Delta\phi) < 0.95,$

- Muon identification:
  - At least two muon chamber hits are associated with the track
  - At least four hadronic calorimeter strips associated with track
  - Track has pT>15 GeV and isolated

- Visiable energy: scaler sum of two tracks momentum and the energy of highest energy cluster found in the EM calo. (reject ee→ττ and two-photon interaction events)

$$E^{\mu}_{\rm vis} > 0.6\sqrt{s},$$

A better tracking efficiency in CEPC, and better momentum/angular measurement (*especially in forward region where OPAL uses muon chamber, a better control of acceptance uncertainty expected in CEPC*)

LICH algorithm

LICH algorithm and new tau reconstruction

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Expect to reduce systematics by a order of magnitude, resulting XS measure at level 10^{-4}-10^{-5}, a $R_{mm/ee}$ at level of 10^{-5} .
With PFO for both electron and muon, some systematic can be correlated and cancelled out.

Z→ττ (OPAL selection)

- Multiplcity cuts: $2 \leq N_{\text{track}} \leq 6 \quad \text{and } N_{\text{track}} + N_{\text{cluster}} \leq 15.$
- ee→ττ event topology: event are reconstructed with a cone jet-finding algorithm with cone half-angle of 35°, Each cone must have summed energy>0.1 beam energy. Exactly two clusters reconstructed.
- ee→ττ acollinearity: $\theta_{\text{acol}} < 15°$
- Geometrical acceptance $|\cos\theta_\tau| < 0.9.$

Noval tau reconstruction algorithm

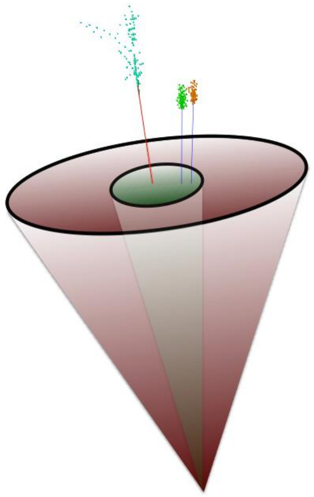
- Orthogonal with ee→μμ events
- Reject ee →ee events with:

$$E_{\text{total}} \equiv \sum E^i_{\text{cluster}} < 0.8\sqrt{s}, \quad |\cos\theta_\tau| < 0.7$$

$$E^\tau_{\text{vis}} < 1.05\sqrt{s} \quad \text{or} \quad E_{\text{total}} < 0.25\sqrt{s}, \ \cos\theta_\tau| > 0.7$$

- Reject non-resonance ee→eeℓℓ

$$E^\tau_{\text{vis}} > 0.18\sqrt{s}.$$



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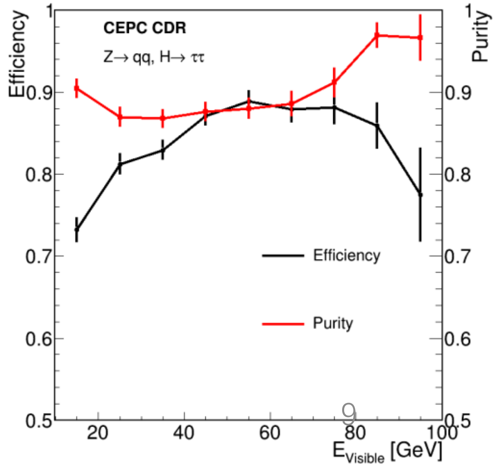

Expect to reduce factor of 5-10 for systematics uncertainty, resulting a 10^{-5} for ratio.

Summary

- Propose measurements of Br($Z\to\ell\ell$) in CEPC at Z pole
  - Results can test LFU with a unprecedented precision with an simple estimation
  - A complimentary result for LHCb measurement
  - Also sensitive to potential new physics related to muon/tau g-2
- Next step will run on full/fast simulated samples