Experimental status of Z pole and W measurements

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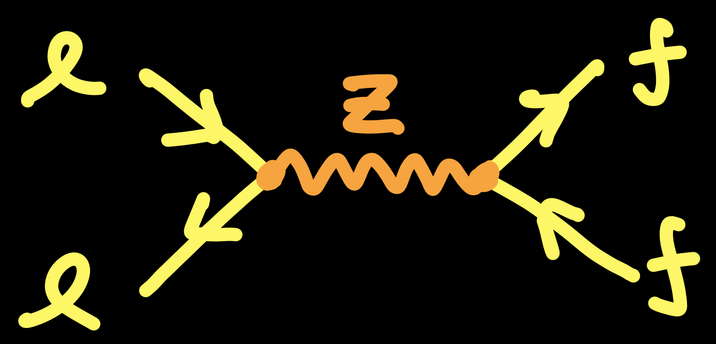
Updated CEPC collider parameters since CDR

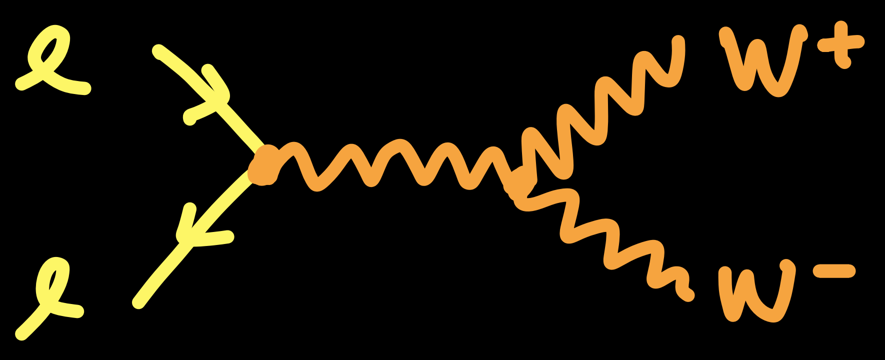
	Higgs		Z (2T)	
	CDR	Updated	CDR	Updated
Beam energy (GeV)	120	-	45.5	-
Synchrotron radiation loss/turn (GeV)	1.73	1.68	0.036	-
Piwinski angle	2.58	3.78	23.8	33
Number of particles/bunch N_e (10^{10})	15.0	17	8.0	15
Bunch number (bunch spacing)	242 (0.68μs)	218 (0.68μs)	12000	15000
Beam current (mA)	17.4	17.8	461.0	1081.4
Synchrotron radiation power /beam (MW)	30	-	16.5	38.6
Cell number/cavity	2	-	2	1
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.33/0.001	0.2/0.001	-
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.89/0.0018	0.18/0.0016	-
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	17.1/0.042	6.0/0.04	-
Bunch length σ_z (mm)	3.26	3.93	8.5	11.8
Lifetime (hour)	0.67	0.22	2.1	1.8
Luminosity/IP L (10^{34} cm^{-2}s^{-1})	2.93	5.2	32.1	101.6

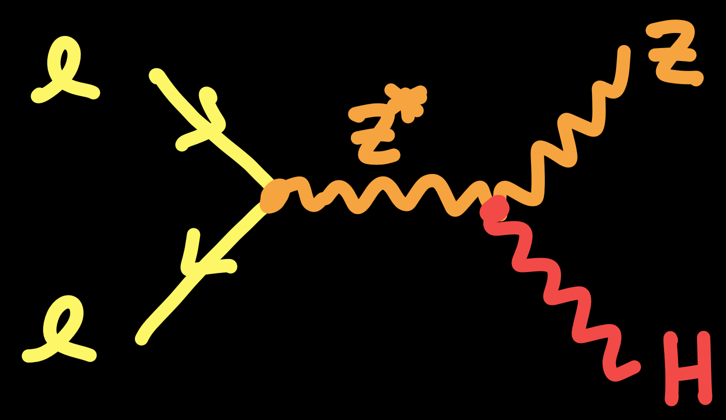
Luminosity increase factor: × 1.8 × 3.2

The CEPC Program

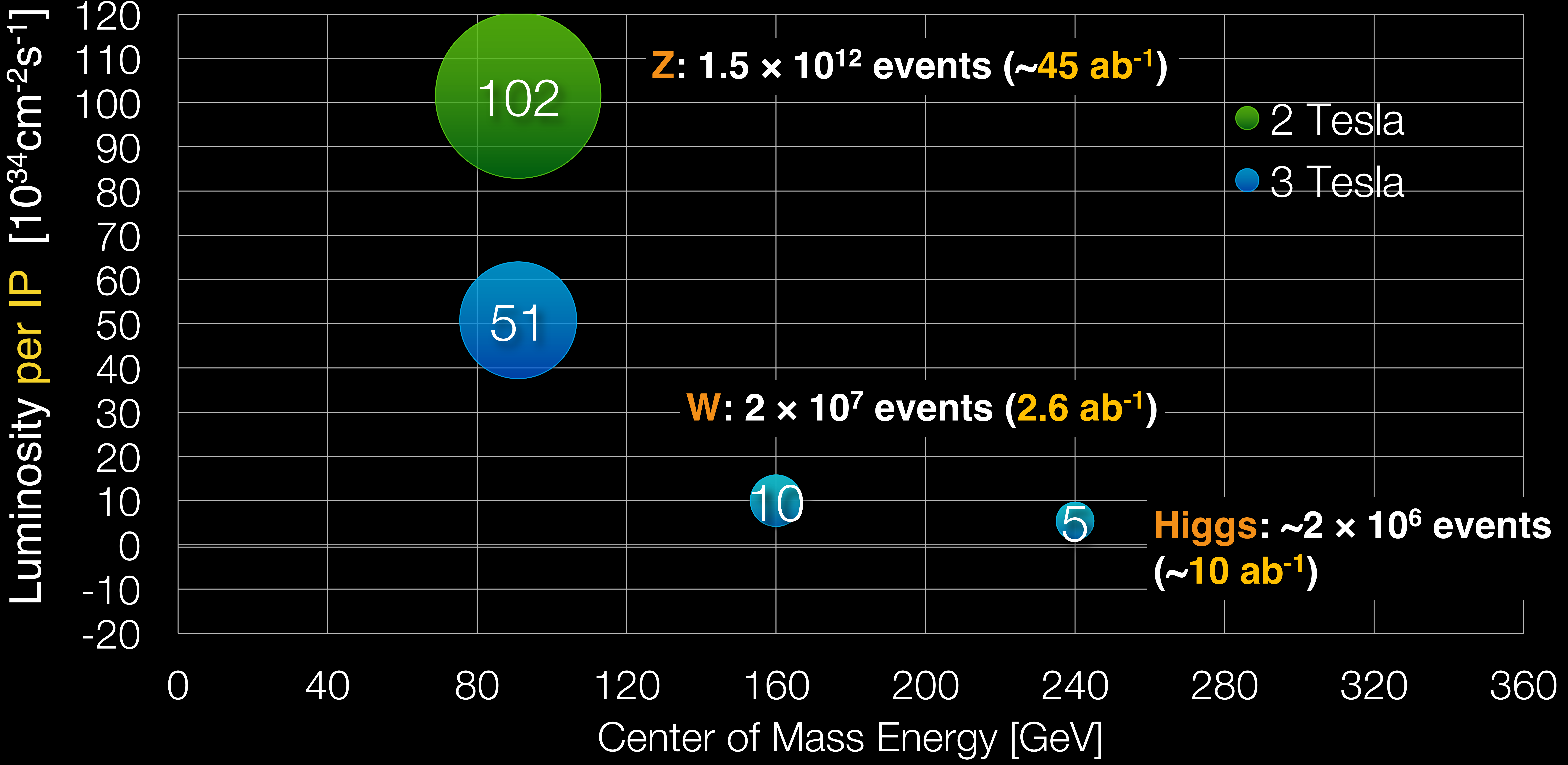
100 km e^+e^- collider







2 IPs



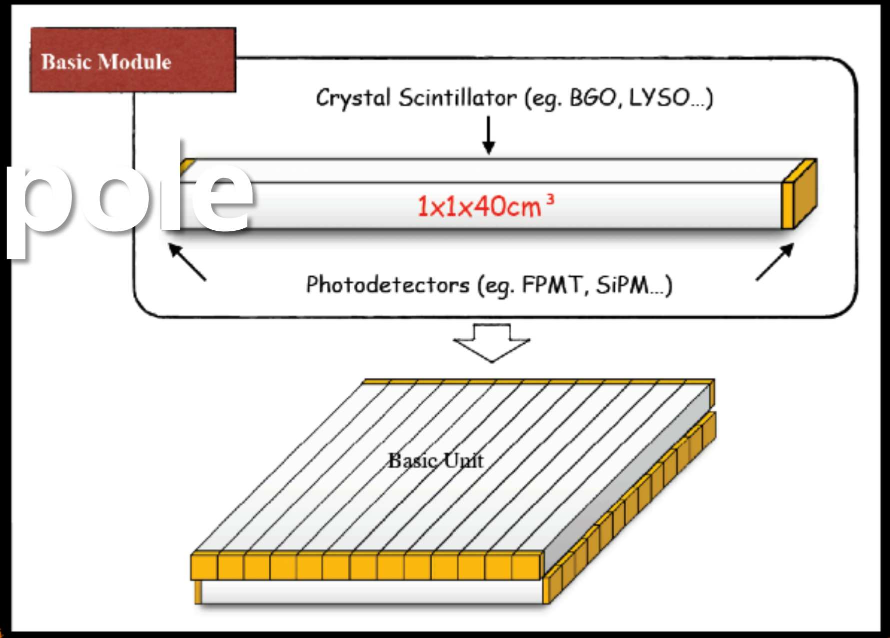
CEPC: Detector Concepts

CEPC plans for 2 interaction points

- ➢ New ! Crystal calorimeter concept is being studied.
- ☐ Higher precision on EM energy scale
- ☐ Useful for precision measurements
- ☐ More in Calorimetry section tomorrow

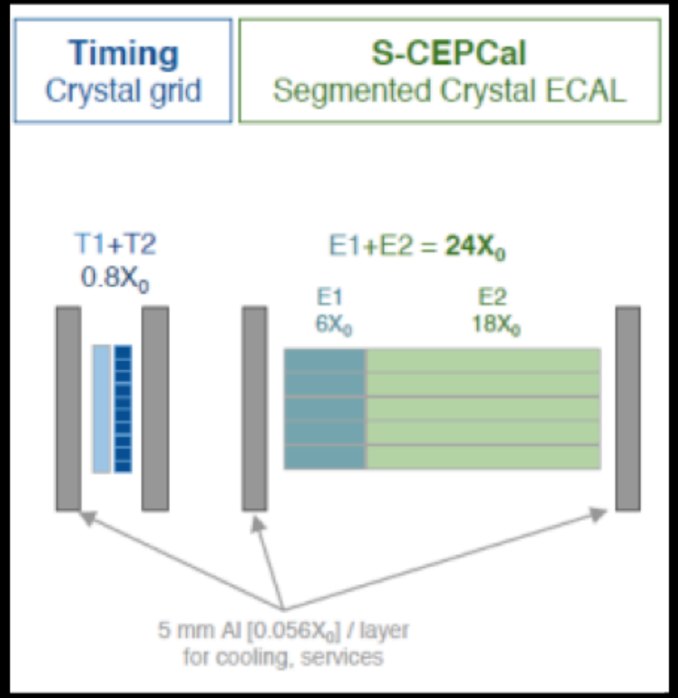
Long crystal bars with optical readout at both ends

Yuexin Wang (IHEP), et al



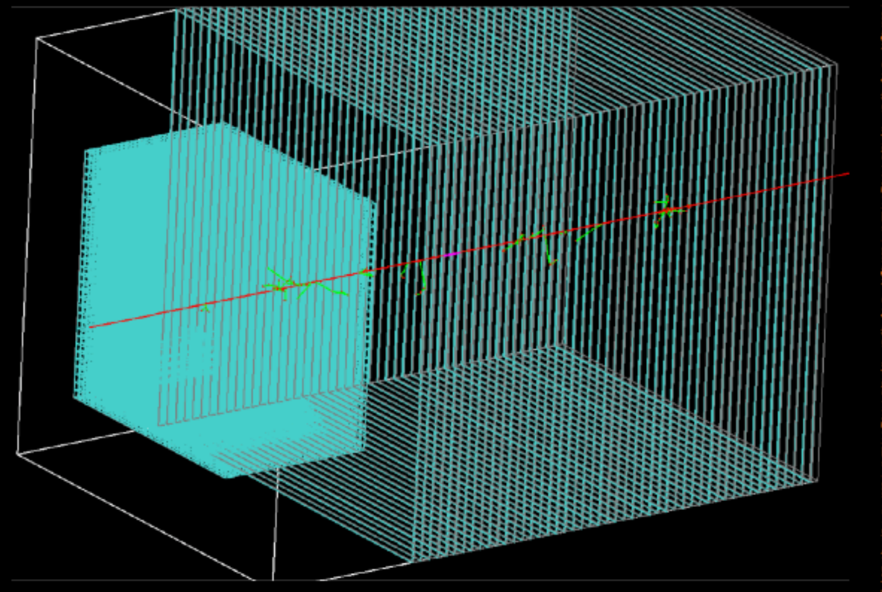
Long crystal bars with optical readout at single ends

Tully (Princeton), Eno (UMD), et al



Thin crystal tiles with optical readout at single ends

Yong Liu (IHEP), et al

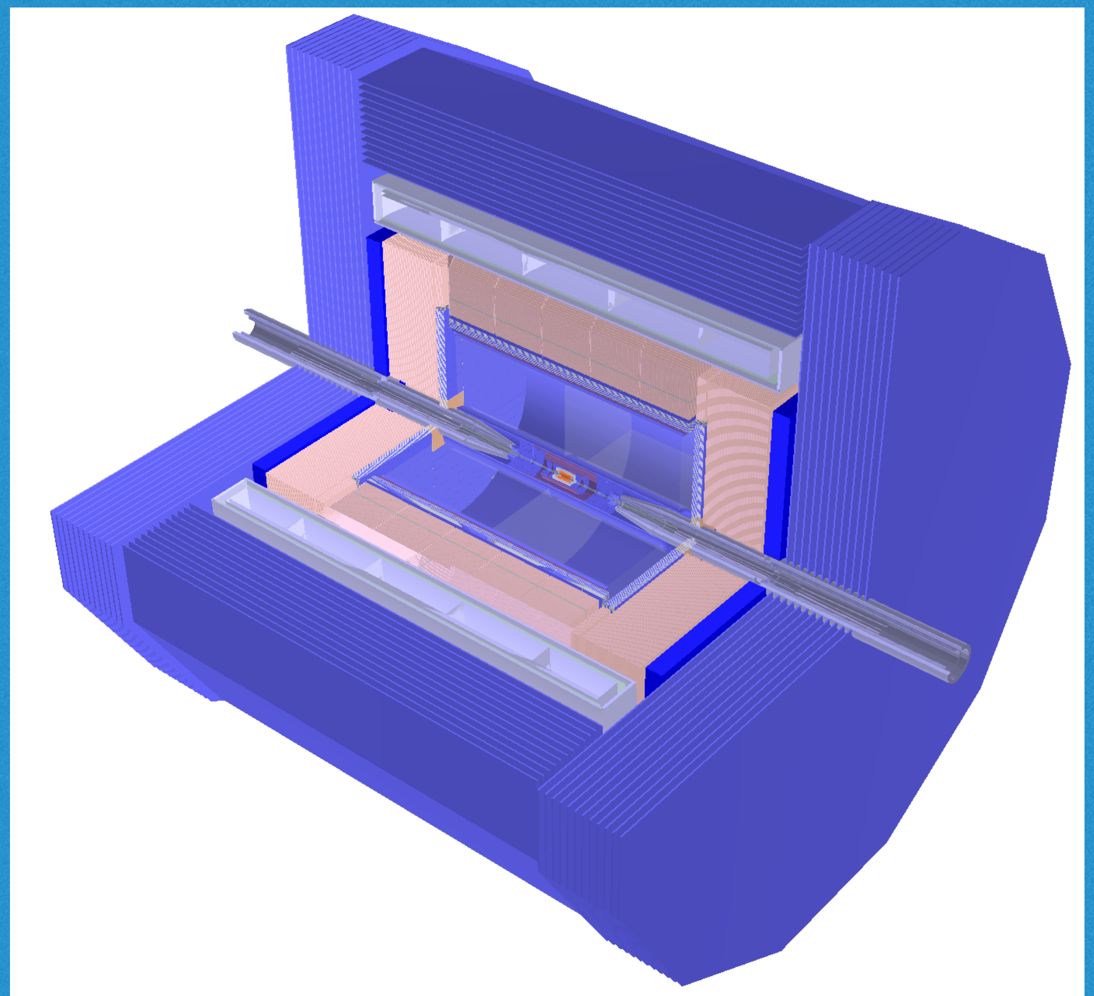


ECAL: 30 layers

- ➢ Tracking p2Tesla magnetic field @ Z pole
- ➢ erformance to be revised

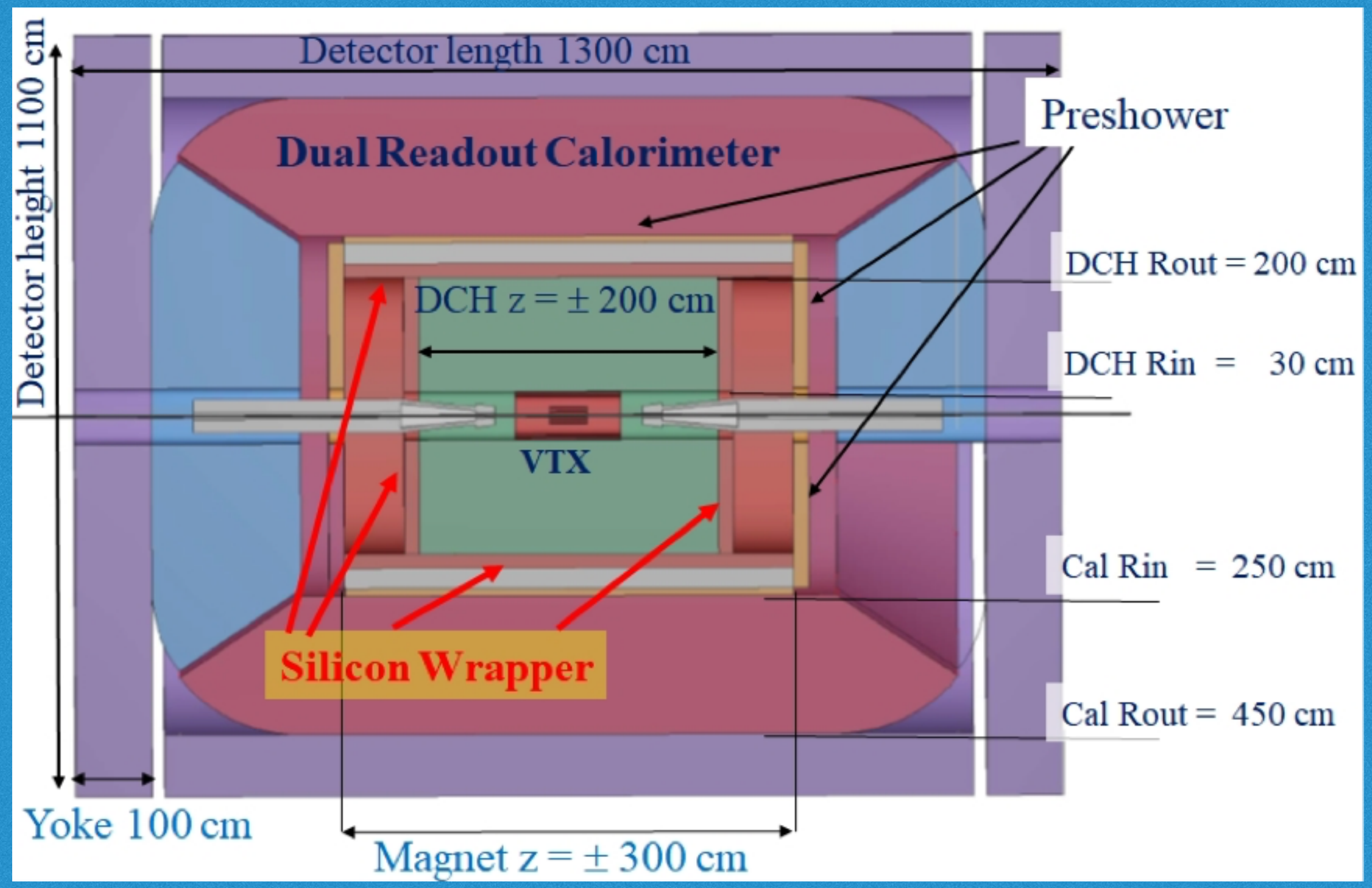
Particle Flow Approach

Baseline detector
ILD-like
(3 Tesla)



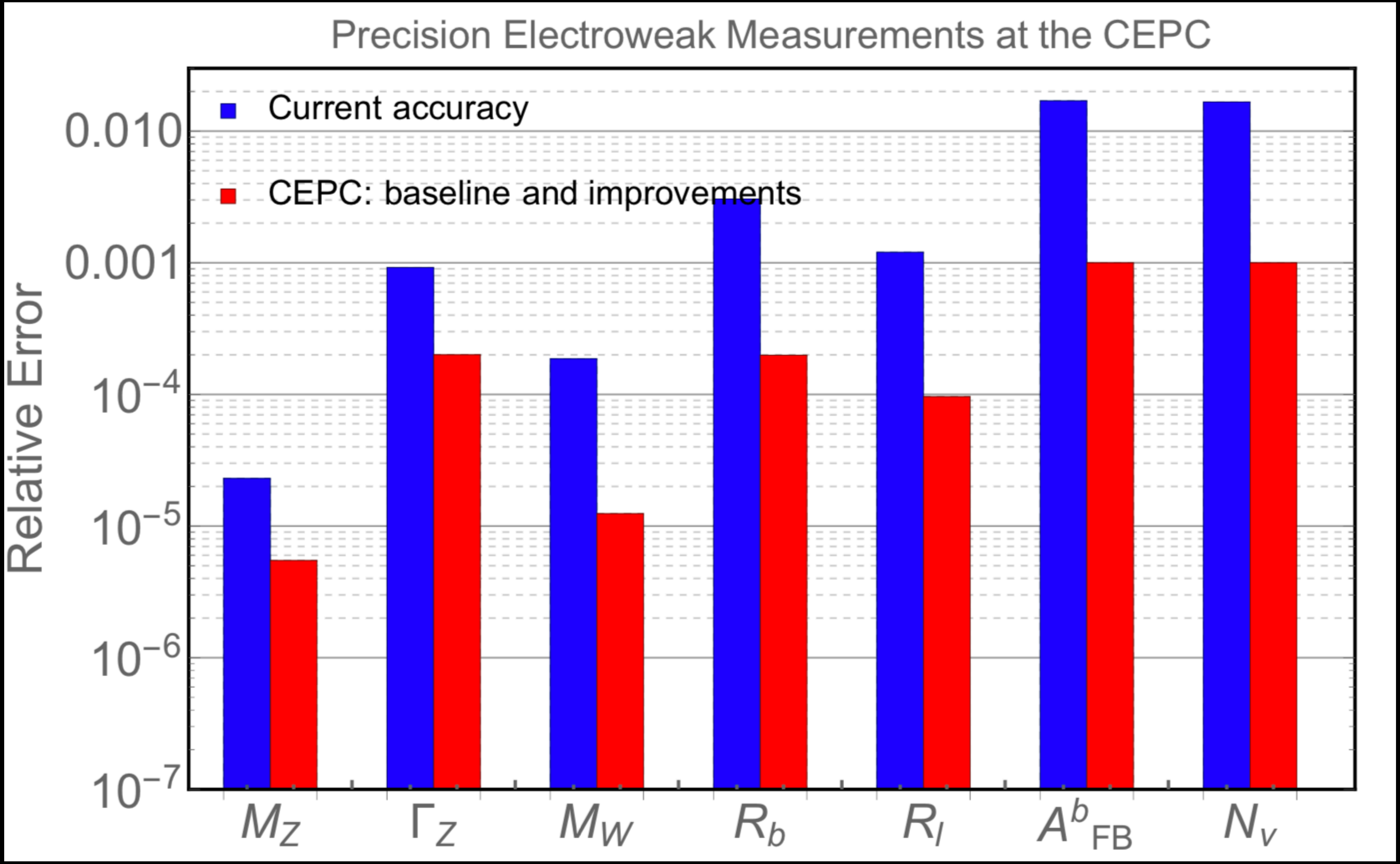
IDEA Concept

Low magnetic field concept
(2 Tesla)



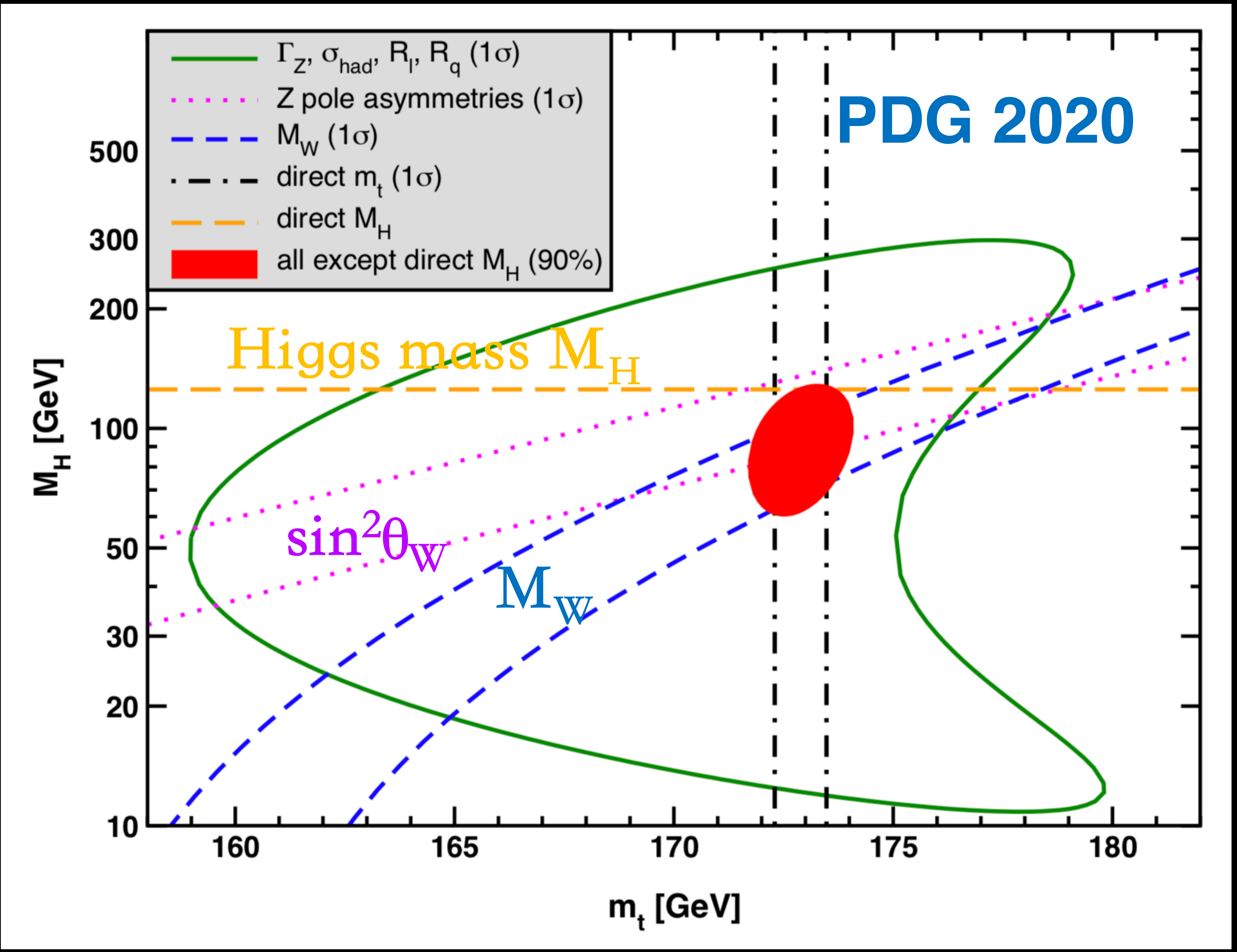
Prospect of CEPC EWK physics

Expect to have 1~2 order of magnitude better than current precision



The status of electroweak global fit

- 7 key observables in electroweak global fit
  - Consistency study of the standard model electroweak section
  - Small conflict in Higgs mass (2σ) between direct measurement and EWK fit.
  - Need CEPC Z pole and WW runs : Precise measurements on EWK observables.



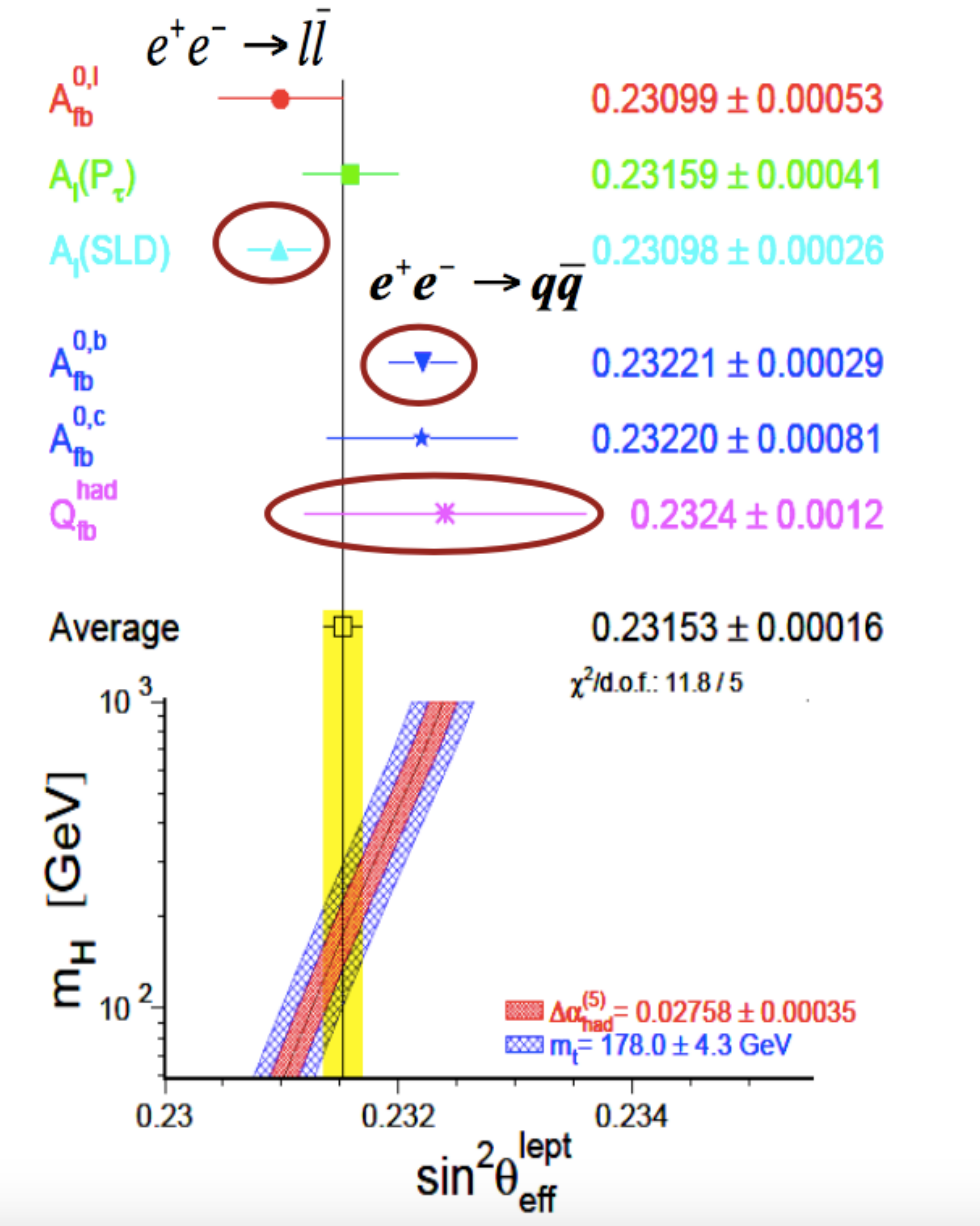
Fundamental constant	δx/x	measurements
$\alpha = 1/137.035999139\ (31)$	1×10^{-10}	$e^{\pm}\ g_2$
$G_F = 1.1663787\ (6) \times 10^{-5}\ \mathrm{GeV}^{-2}$	1×10^{-6}	$\mu^{\pm}$ lifetime
$M_Z = 91.1876 \pm 0.0021$ GeV	1×10^{-5}	LEP
$M_W = 80.379 \pm 0.012$ GeV	1×10^{-4}	LEP/Tevatron/LHC
$\sin^2\theta_W = 0.23152 \pm 0.00014$	6×10^{-4}	LEP/SLD
$m_{top} = 172.74 \pm 0.46$ GeV	3×10^{-3}	Tevatron/LHC
$M_H = 125.14 \pm 0.15$ GeV	1×10^{-3}	LHC

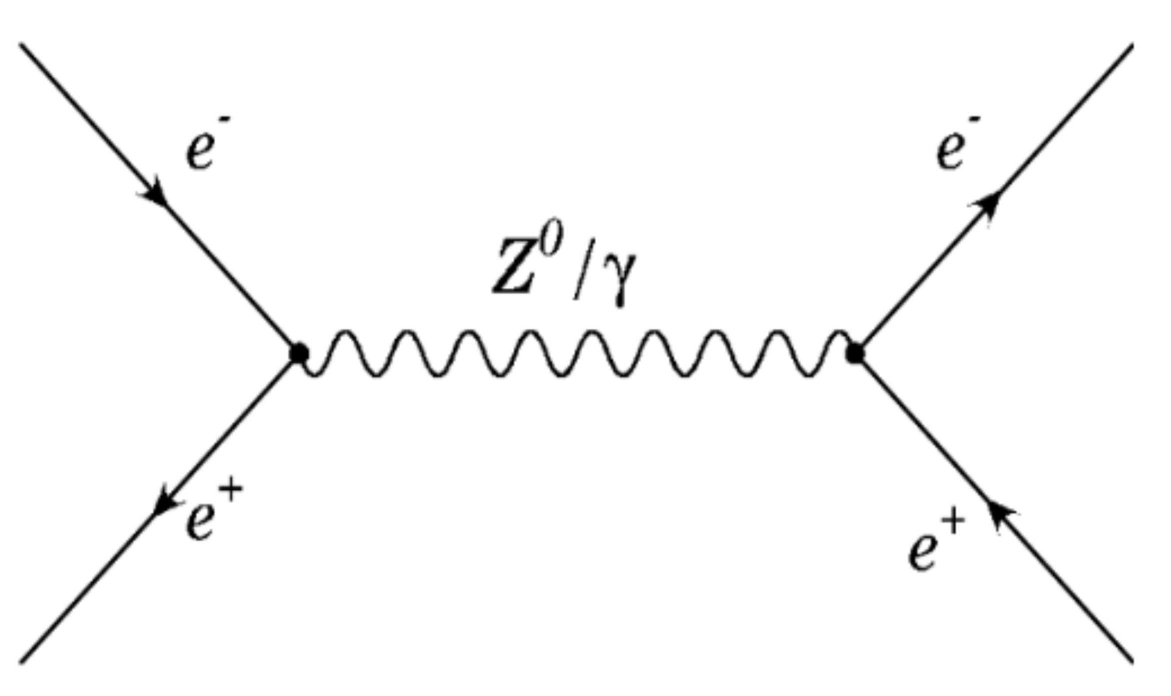
Weak mixing angle measurements ($\sin^2\theta_W$)

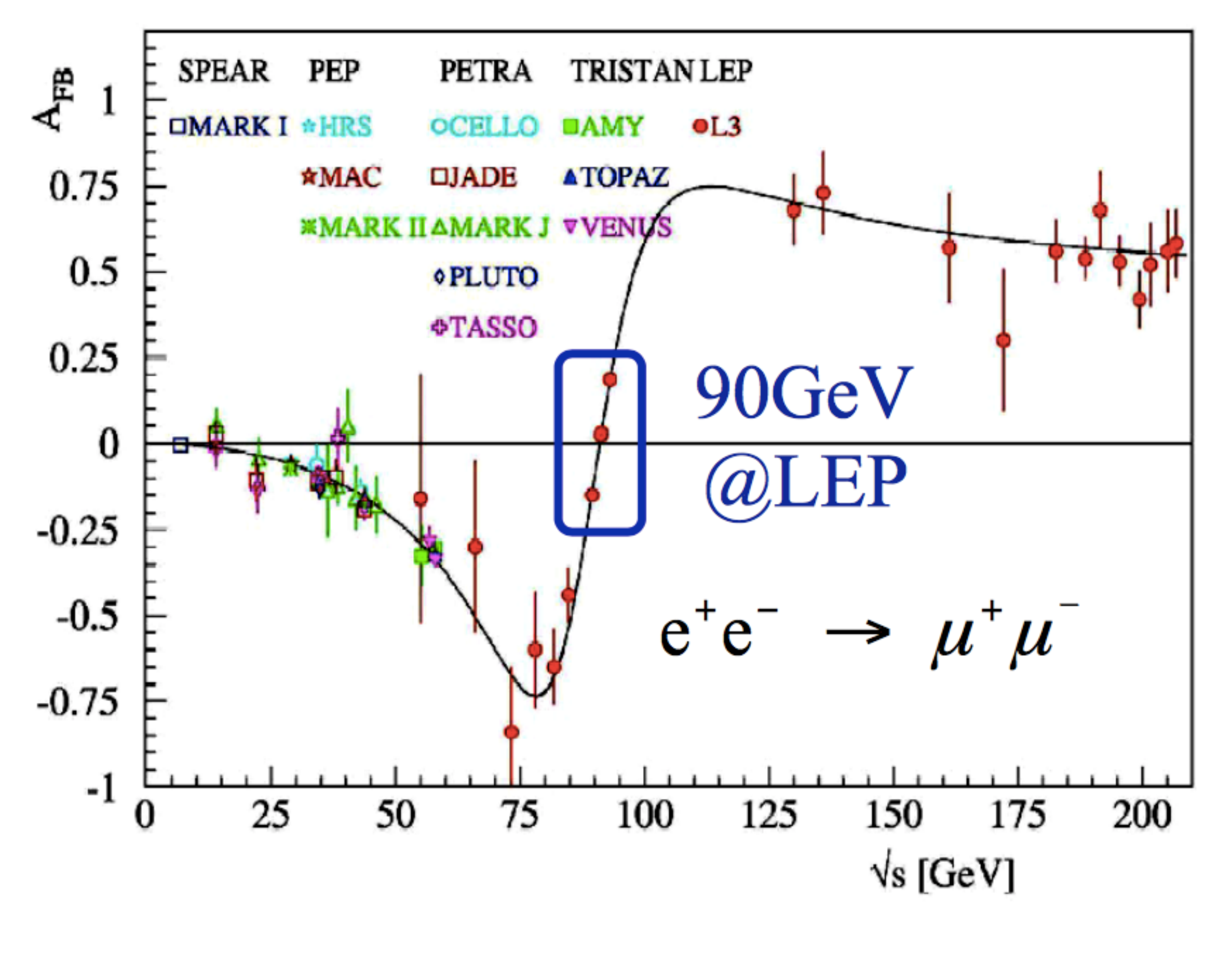
- Weak mixing angle measurement is well motivated
  - ~3σ tension between LEP and SLC measurements
  - Experimental syst. much larger than theory syst.

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \neq 0$$

	$\sin^2\theta_W$
LEP	0.23221 ± 0.00029
SLC	0.23098 ± 0.00026
Theory	0.23121 ± 0.00004







Weak mixing angle measurements ($\sin^2\theta_W$)

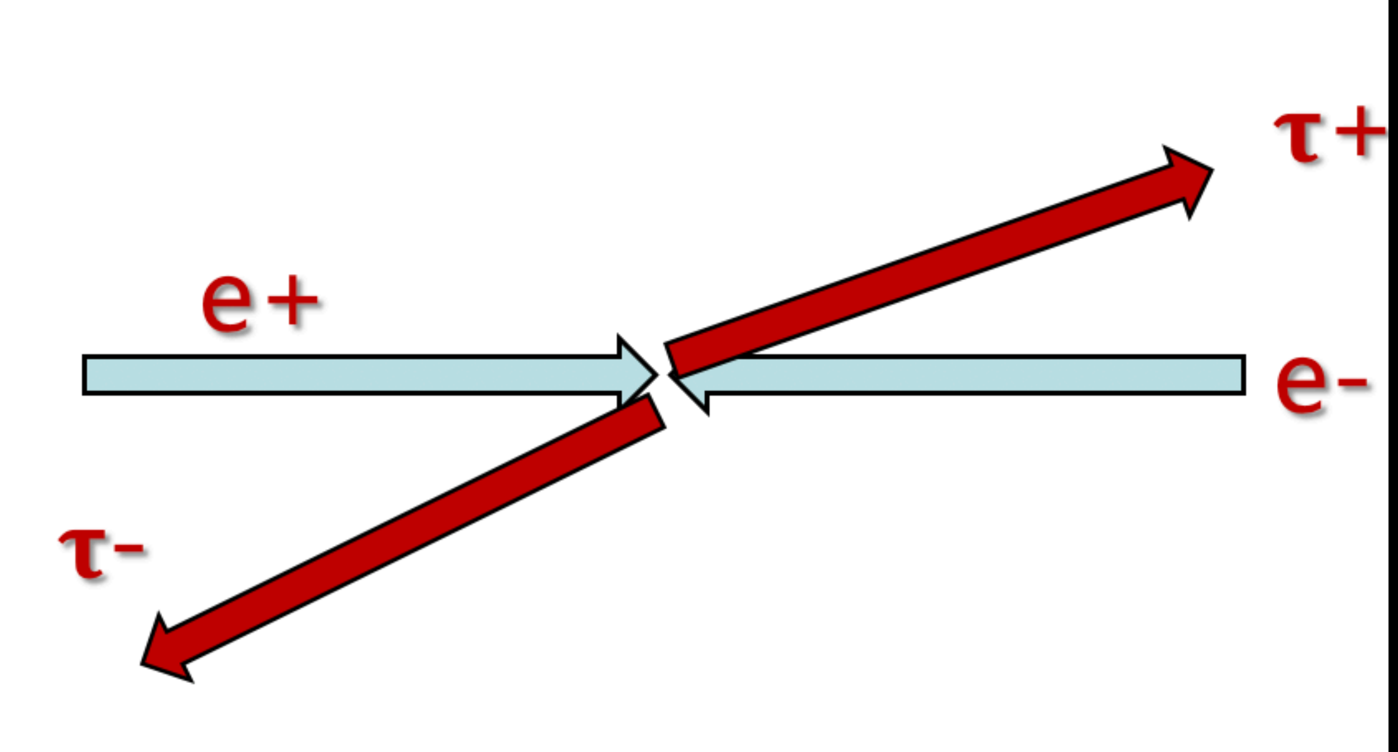
- Stat. Unc. dominated in LEP and Tevatron measurements
- Syst. Unc. (PDF) will become dominated systematics for LHC measurements
- CEPC has potential to improve $\sin^2\theta_W$ by two order of magnitudes
- Theory unc. is about 4×10^{-5} level with two loop calculation

Experiment	Stat. (10^{-5})	Syst. (10^{-5})	Theory unc. (PDF+QCD) (10^{-5})	Total unc. (10^{-5}) $\delta\sin^2\theta_W$
LEP	29	~ 1	~0	29
Tevatron	27	5	18	33
LHC 8TeV	36	18	35	53
LHC 13TeV By Projection	~15	> 20	> 25	~ 20
CEPC	~0.2	~0.2	4	~0.3

Weak mixing angle measurements

- $\sin^2\theta_W$ can be extracted very precisely from A_e and A_τ using tau polarization
- Major systematics of A_e precisely:

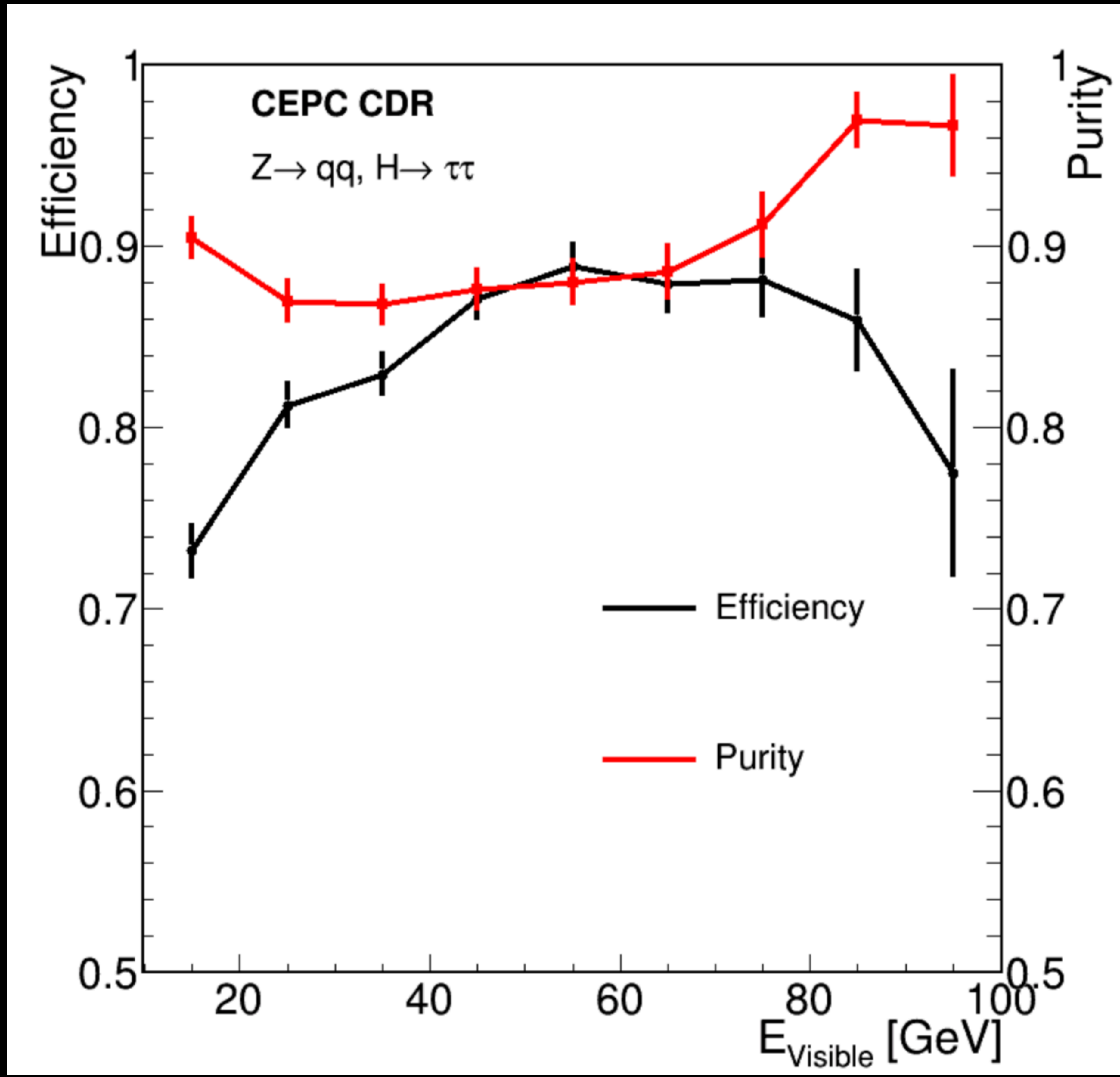
□ Tau ID efficiency and fake rate (expected to be comparable to stat. unc.)



$$
\begin{aligned}
A_{\mathrm{FB}} &= \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}} \\
A_{\mathrm{LR}} &= \frac{\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}}}{\sigma_{\mathrm{L}} + \sigma_{\mathrm{R}}} \frac{1}{\langle|\mathcal{P}_{\mathrm{e}}|\rangle} \\
A_{\mathrm{LRFB}} &= \frac{(\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}})_{\mathrm{L}} - (\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}})_{\mathrm{R}}}{(\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}})_{\mathrm{L}} + (\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}})_{\mathrm{R}}} \frac{1}{\langle|\mathcal{P}_{\mathrm{e}}|\rangle}
\end{aligned}
$$

Tau purity was already very good in LEP
even better at CEPC with better tau performance

τ decay mode	Number selected decays	Purity of the samples (%)
$\tau \to e\nu_e\nu_\tau$	18434	89.4 ± 0.1
$\tau \to \mu\nu_\mu\nu_\tau$	19811	94.3 ± 0.1
$\tau \to \pi/K\nu_\tau$	14850	73.2 ± 0.1
$\tau \to \rho\nu_\tau$	26548	75.4 ± 0.1
$\tau \to a_1\nu_\tau$	9446	53.2 ± 0.2



Branching ratio (R^b): motivation

$$\frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to had)}$$

- At LEP measurement 0.21594 ±0.00066
- CEPC aim to improve the precision by a factor 10~20 (0.02%)
- R^b measurement is sensitive to New physics models (SUSY)
  - SUSY predicts corrections to Z→ bb vertex
  - Through gluino and chargino loop …

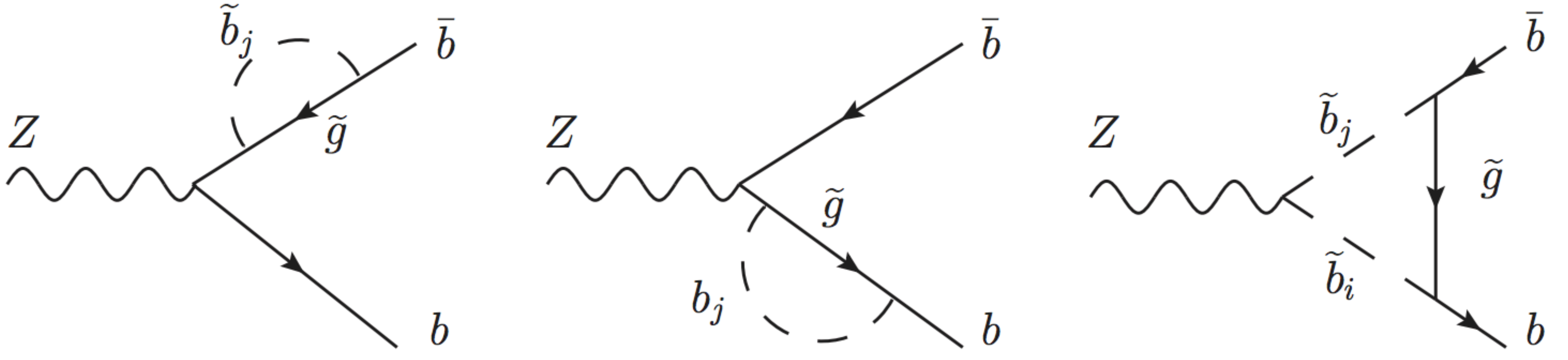


FIG. 1: One-loop Feynman diagrams of gluino correction to $Z \to \bar{b}b$

Arxiv:1601.07758v2

Branching ratio (R^b): systematics

Source	$\Delta\epsilon^c/\epsilon^c$ (%)	$\Delta\epsilon^{uds}/\epsilon^{uds}$ (%)	ΔR_b
Tracking resolution	1.24	4.0	0.00017
Tracking efficiency	0.80	4.0	0.00014
Silicon hit matching efficiency	0.82	2.8	0.00009
Silicon alignment	0.58	2.1	0.00008
Electron identification efficiency	1.11	0.5	0.00015
Muon identification efficiency	0.64	0.2	0.00009
c quark fragmentation	2.26	-	0.00028
c hadron production fractions	3.66	-	0.00046
c hadron lifetimes	0.55	-	0.00007
c charged decay multiplicity	1.09	-	0.00014
c neutral decay multiplicity	2.39	-	0.00030
Branching fraction $B(D \to K^0)$	1.20	-	0.00015
c semileptonic branching fraction	2.44	-	0.00031
c semileptonic decay modelling	2.34	-	0.00029
Gluon splitting to $c\bar{c}$	0.34	6.3	0.00018
Gluon splitting to $b\bar{b}$	0.50	9.3	0.00027
K^0 and hyperon production	-	0.3	0.00001
Monte Carlo statistics (c, uds)	0.66	2.5	0.00010
Subtotal $\Delta\epsilon^c$ and $\Delta\epsilon^{uds}$	6.65	13.3	0.00090
Electron identification background			0.00039
Muon identification background			0.00041
Efficiency correlation ΔC^b			0.00066
Event selection bias			0.00033
Total			0.00129

$$\frac{\Delta R_b}{R_b} = -0.059\frac{\Delta\epsilon^c}{\epsilon^c} - 0.010\frac{\Delta\epsilon^{uds}}{\epsilon^{uds}} + \frac{\Delta C^b}{C^b}$$

Tracker resolution and efficiency(~0.1%)

Lepton identification (~0.1%)

Charm modeling (~0.4%)

Gluon splitting (~0.1%)

Background (~0.2%)

b-tagging corrections (~0.3%)

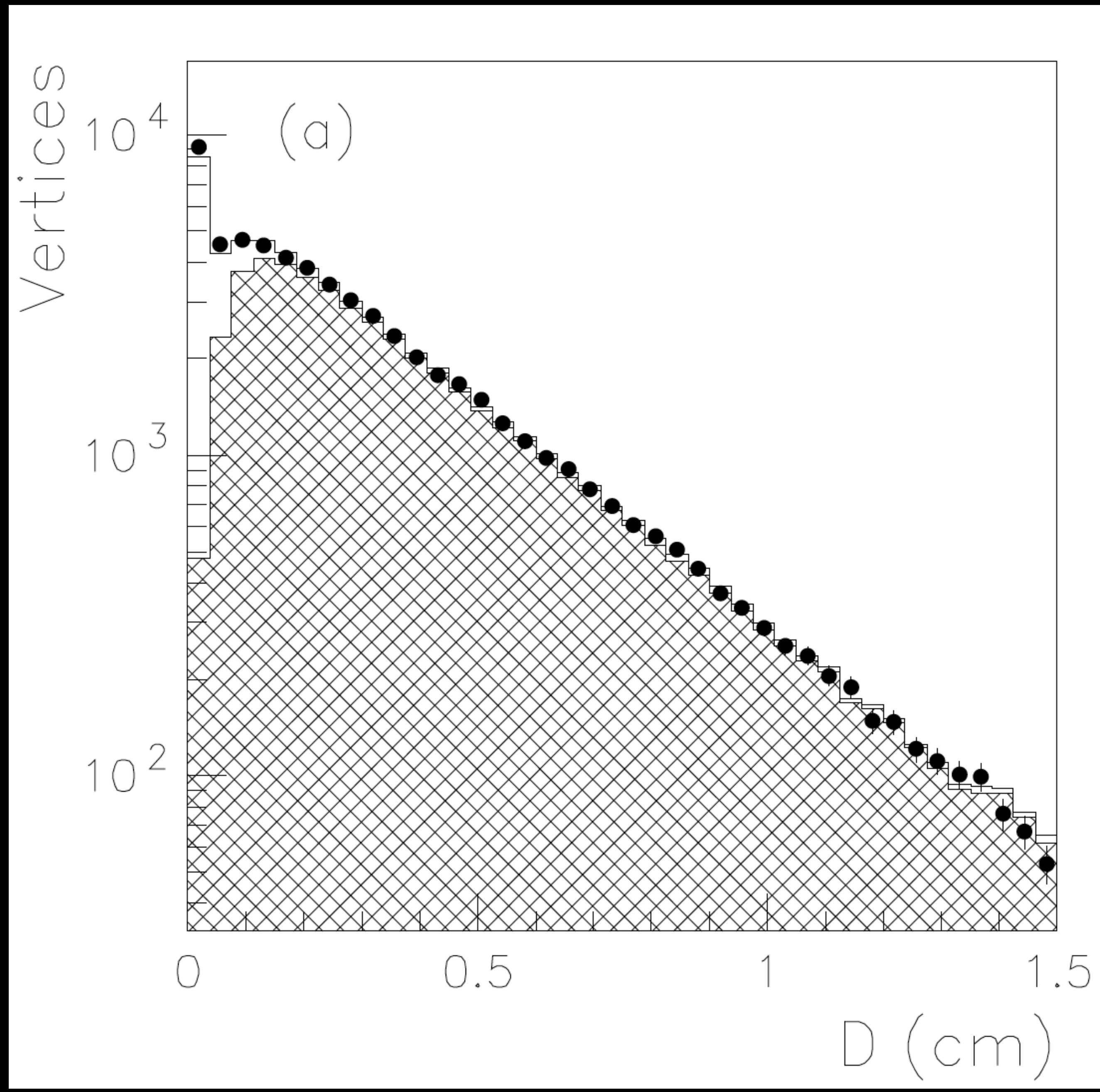
OPAL collaboration, Eur.Phys.J.C8:217-239,1999

Branching ratio (R^b): detector requirement

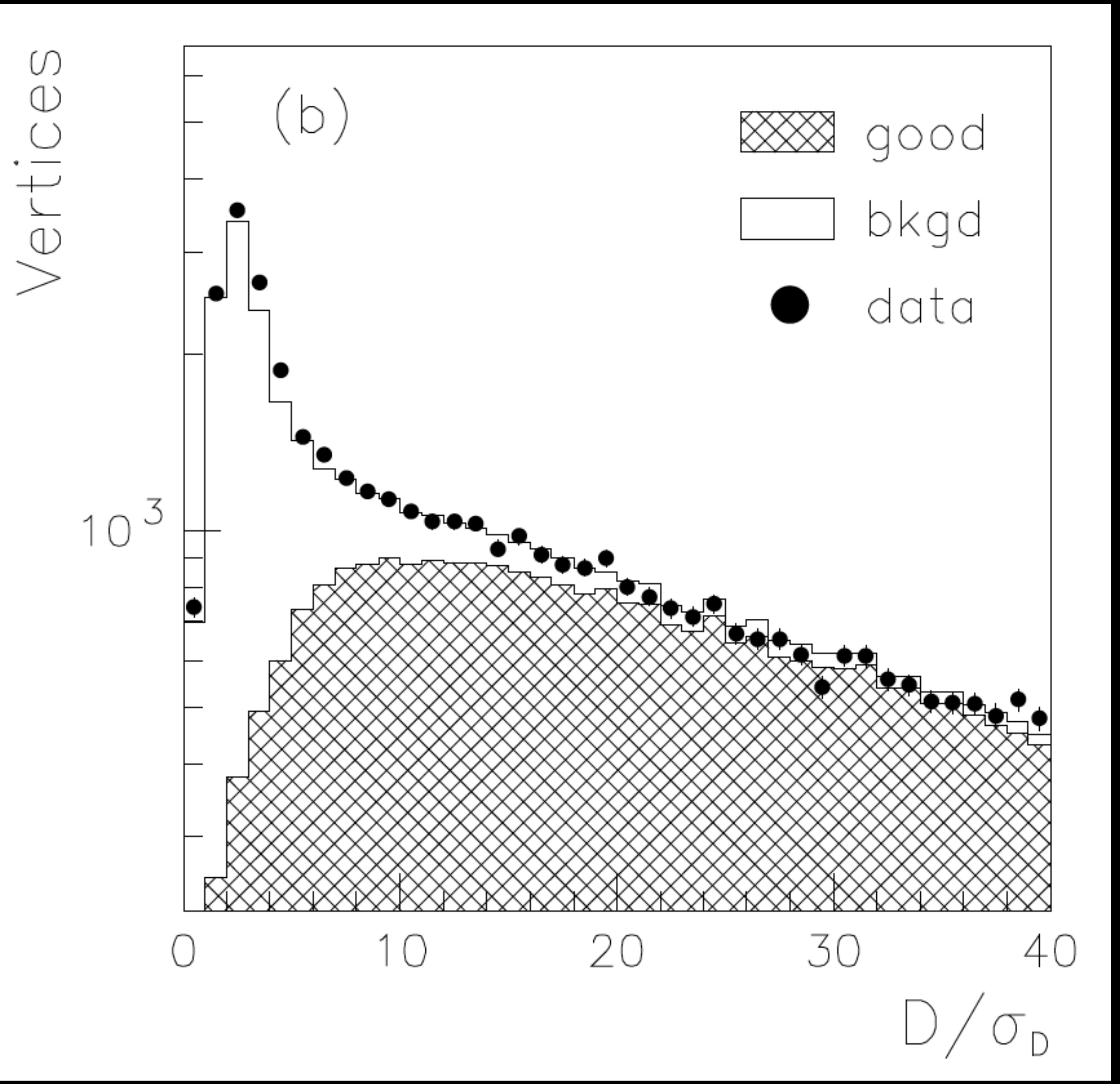
$$\frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to had)}$$

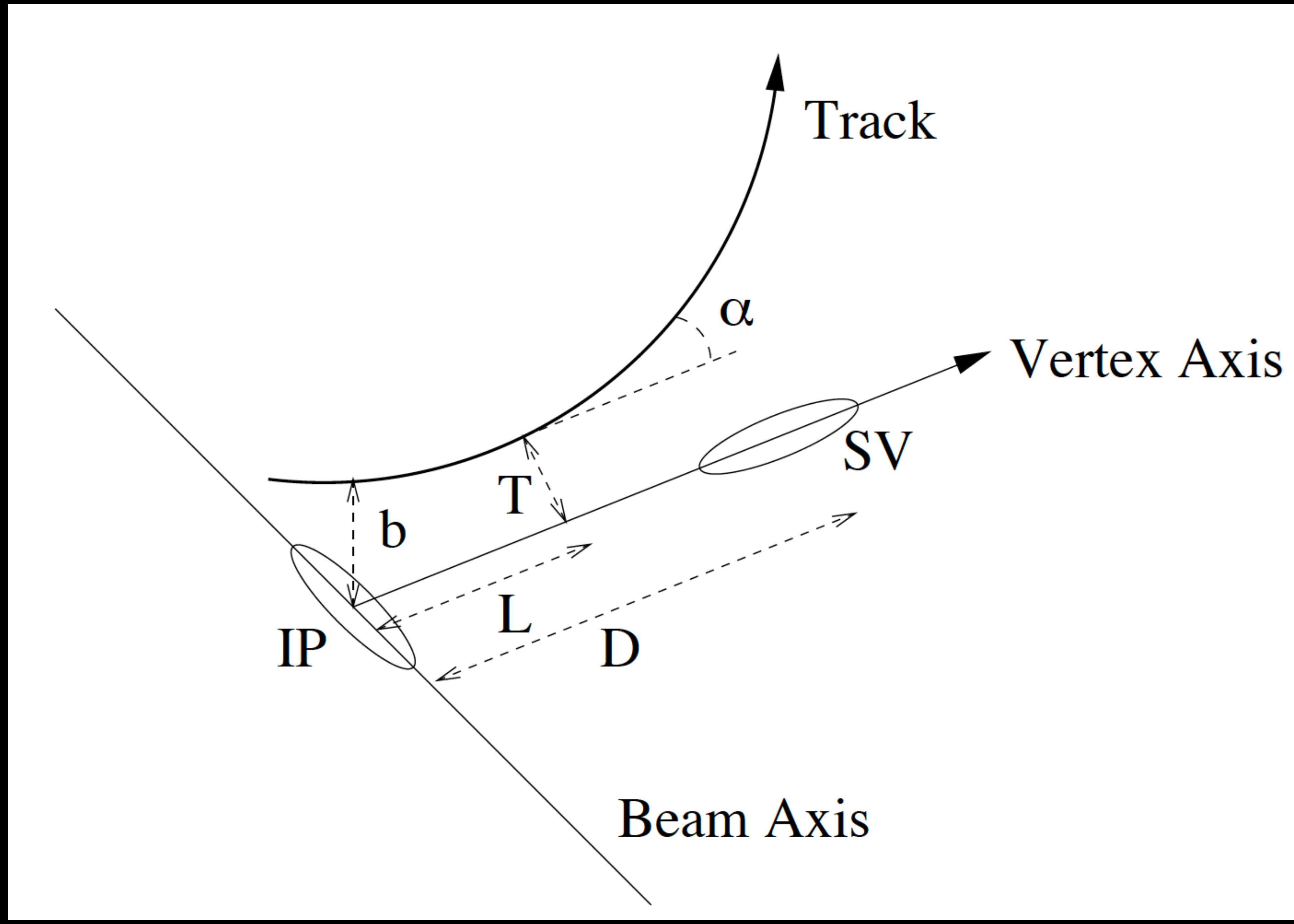
- Two ways to tag the b quarks in Z->qq events
  - Secondary Vertex tag (Average decay length of b meson of 2mm level at Z pole)
    - ➢ Multi-variant analysis : Impact parameter in R/φ and Z , mass of vertex …
  - Lepton tag
  - ➢ High momentum Electron and muon with pT>1GeV in a jet …

Vertex distance to IP



Vertex distance significance





SLD, Ann.Rev.Nucl.Part.Sci.46:395-469,1996

R^b: b tagging hemisphere correlations

- Hemisphere is taken to be tagged
  - if it is tagged by either one or both of the secondary vertex and lepton tags.
- Major systematics: hemisphere correlations
  - The tagging efficiency correlation between the two hemispheres in one event:
    - ➢ Angular effects : due to inefficient regions of detector
    - ➢ QCD effects (g->bb)
    - ➢ Vertex effects : due to vertex fitting

$$C_b = \frac{\varepsilon_{2jet-tagged}}{(\varepsilon_{1jet-tagged})^2}$$

Single (N_t) and double tagged events (N_{tt})

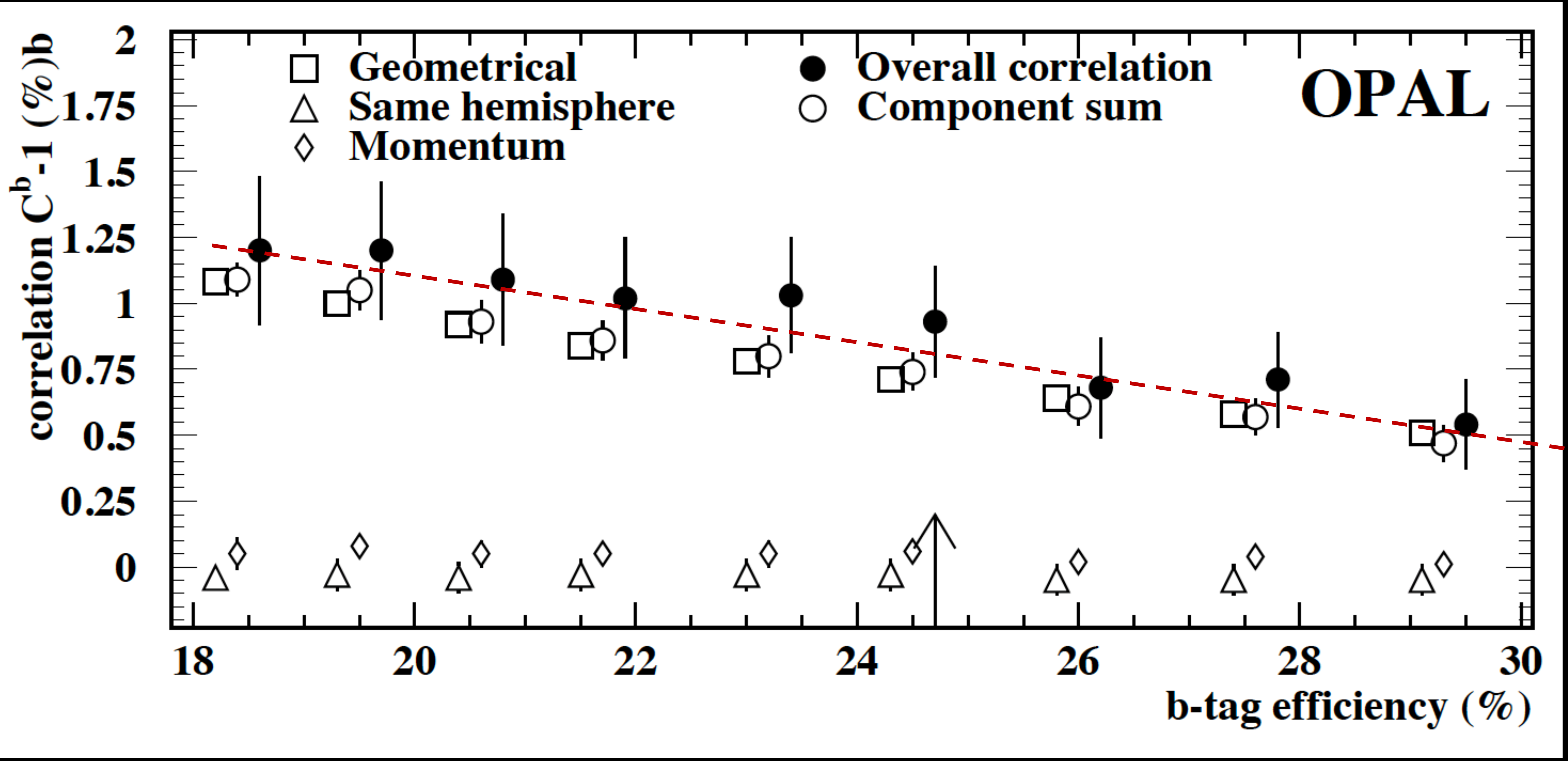
- $$\begin{aligned} N_{\rm t} &= 2N_{\rm had}\{\epsilon^{\rm b}\ R_{\rm b}\ + \epsilon^{\rm c}\ R_{\rm c}\ + \epsilon^{\rm uds}\ (1 - R_{\rm b} - R_{\rm c})\}, \\ N_{\rm tt} &= N_{\rm had}\{C^{\rm b}\ (\epsilon^{\rm b})^2\ R_{\rm b} + C^{\rm c}(\epsilon^{\rm c})^2\ R_{\rm c}\ + C^{\rm uds}(\epsilon^{\rm uds})^2\ (1 - R_{\rm b} - R_{\rm c})\}, \end{aligned}$$

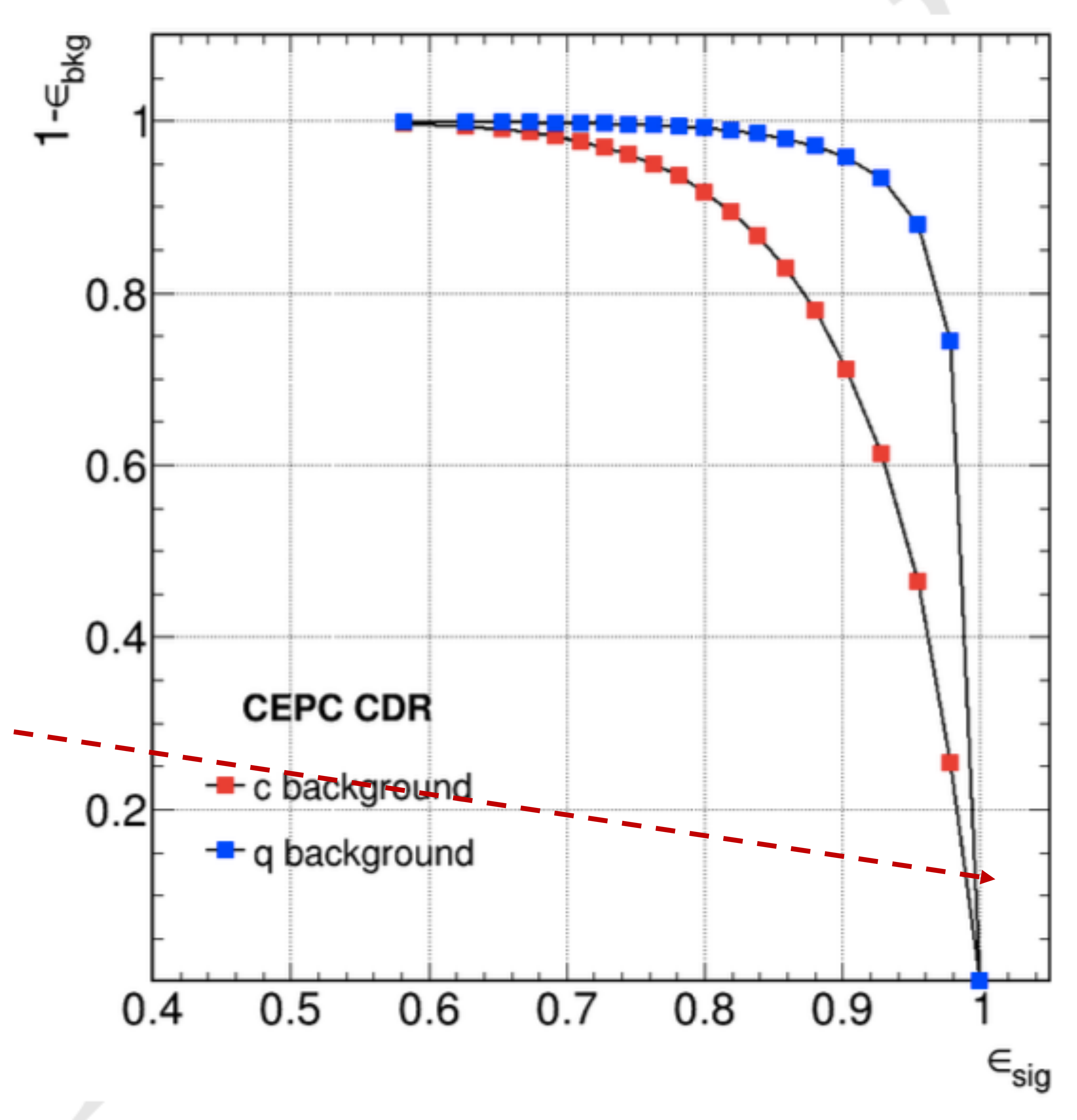
R^b: b tagging hemisphere correlations

$$C_b = \frac{\varepsilon_{2jet-tagged}}{(\varepsilon_{1jet-tagged})^2}$$

- Hemisphere correlations depends on b tagging efficiency
  - with 95% purity working points efficiency> 70% in CEPC
  - This systematics will not be dominated

CEPC b tagging ROC curve

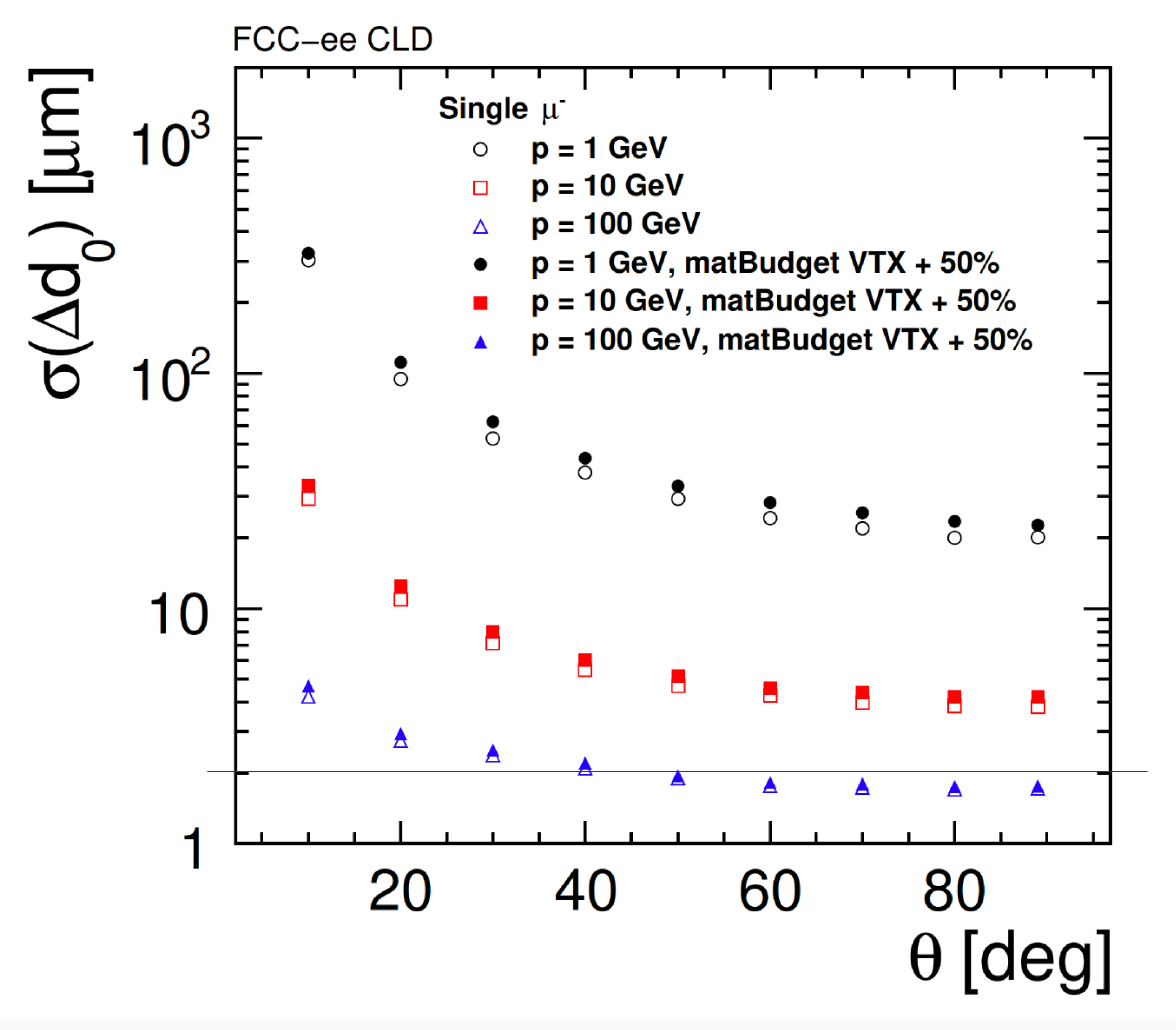




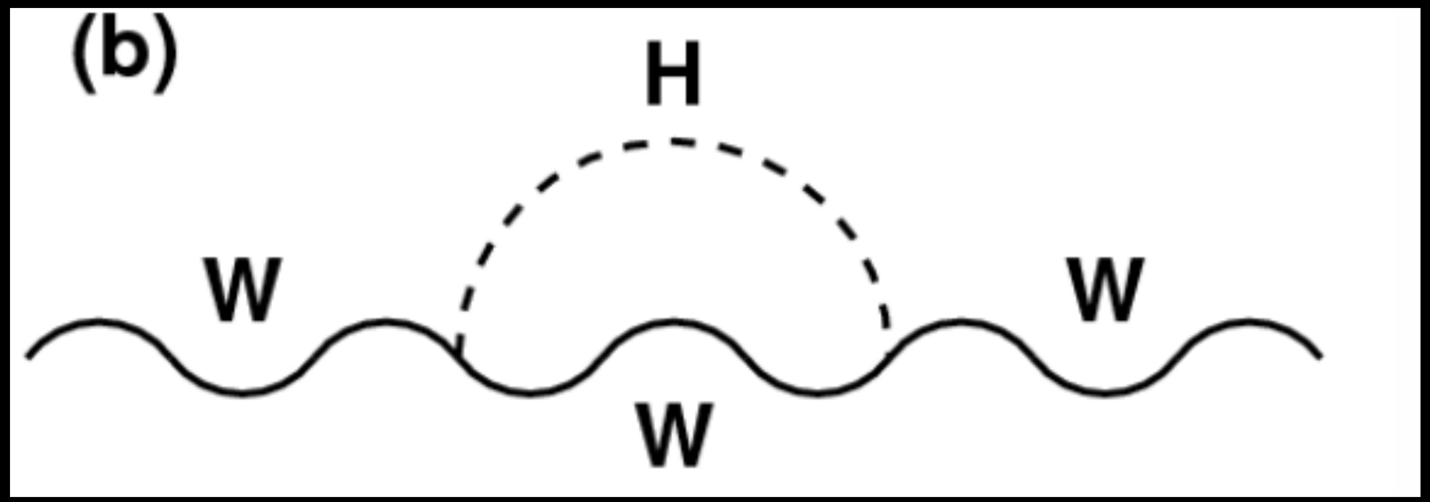
OPAL collaboration, Eur.Phys.J.C8:217-239,1999

R^b: tracker systematics

- Alignment systematics:
  - LEP study : 20µm mis-alignment → 0.04% systematics
  - CEPC aim for 2um mis-alignment (at least 5µm) → <0.005% syst.
- Hit Efficiency :
  - LEP study 1% syst. → 0.007% syst. In R^b
  - CEPC <0.5% syst. → 0.003% syst. In R^b
- Lepton efficiency
  - LEP: 3% syst. → 0.03% systematics in R^b
  - CEPC: 0.5% syst→ 0.005% syst. in Rb

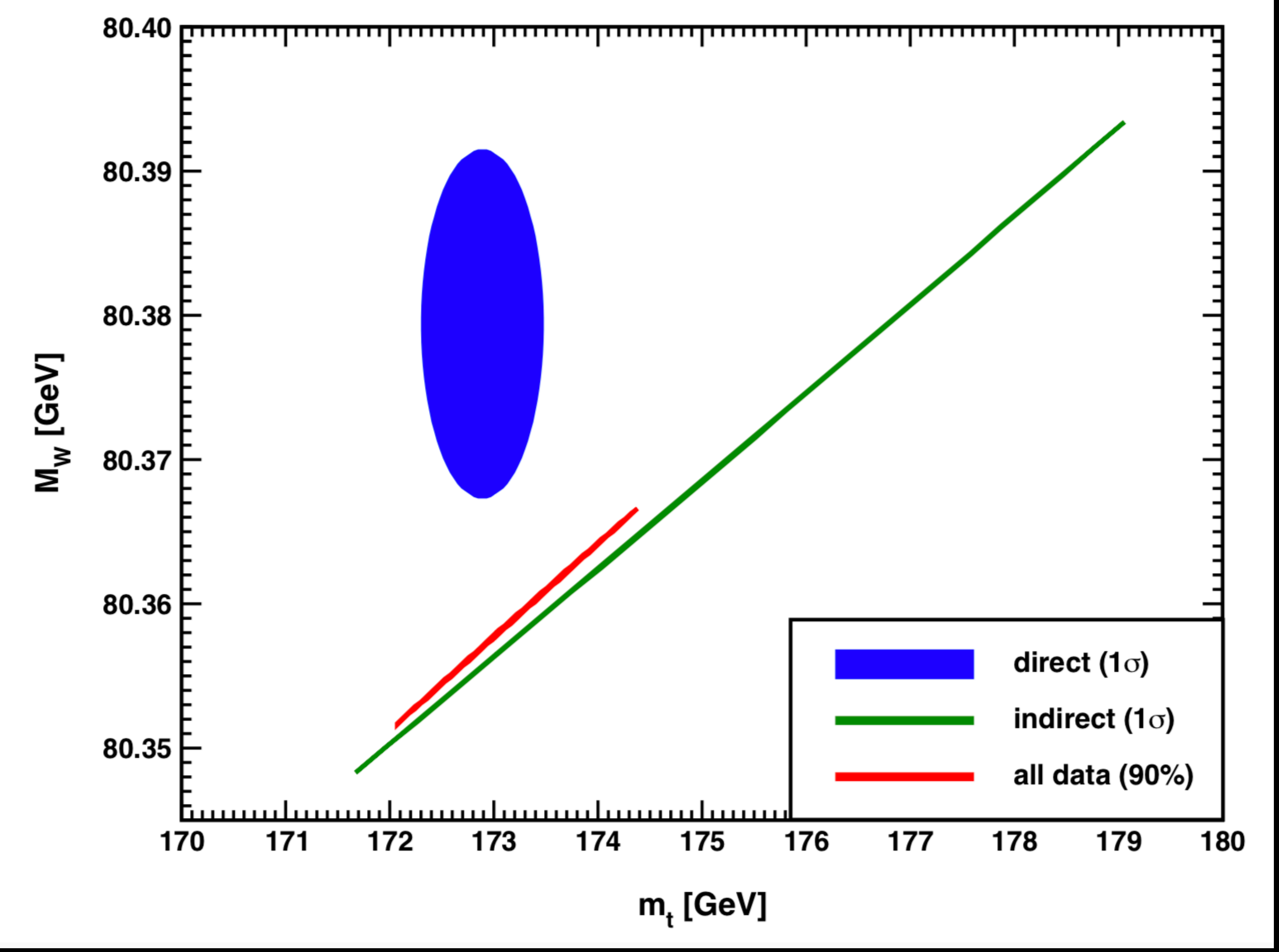


W mass measurements

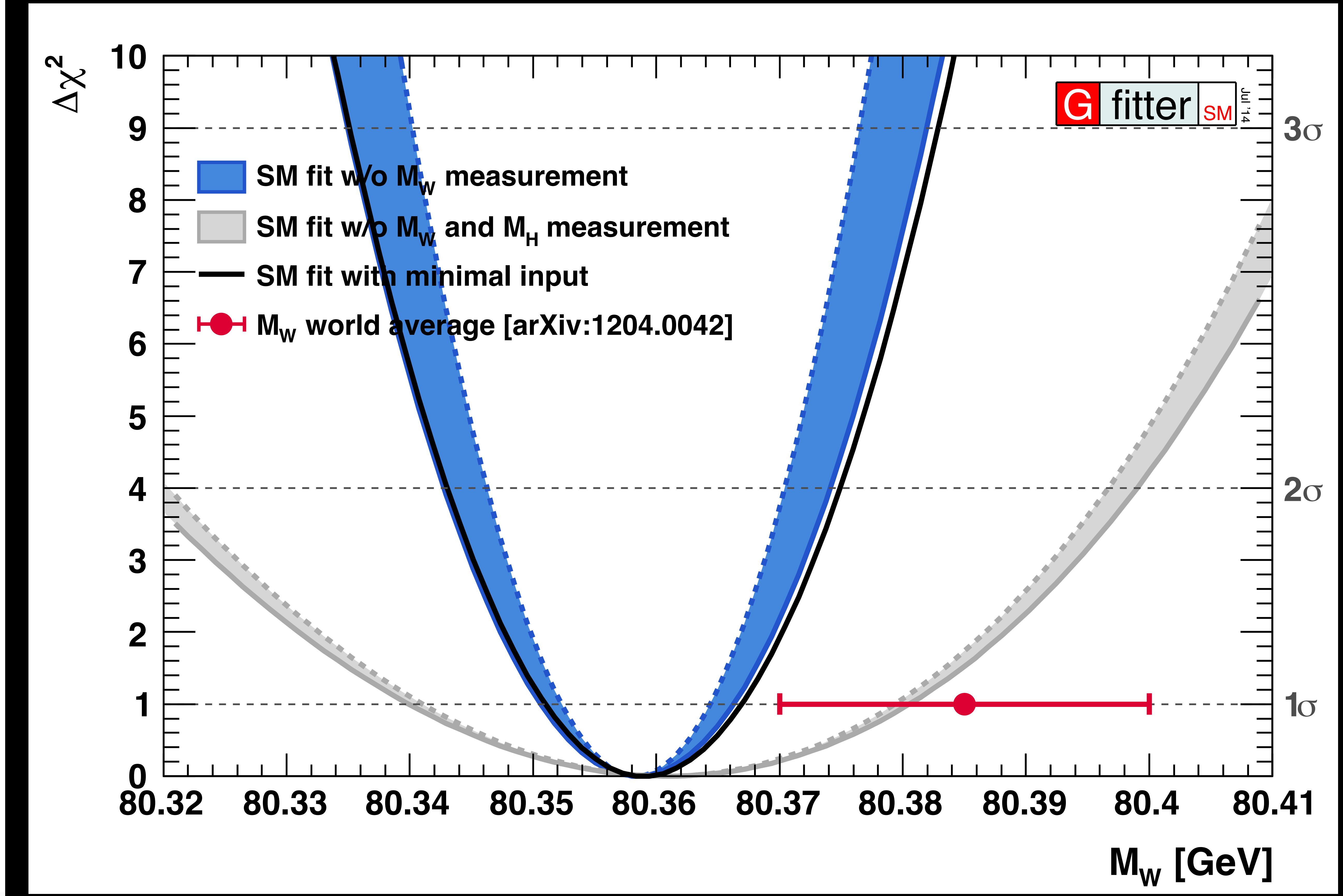


- W mass measurement is well motivated
  - ~2σ tension between direct measurements and EWK global fit
  - Indirect search for new physics

W mass (m_W) vs Top mass (m_t)



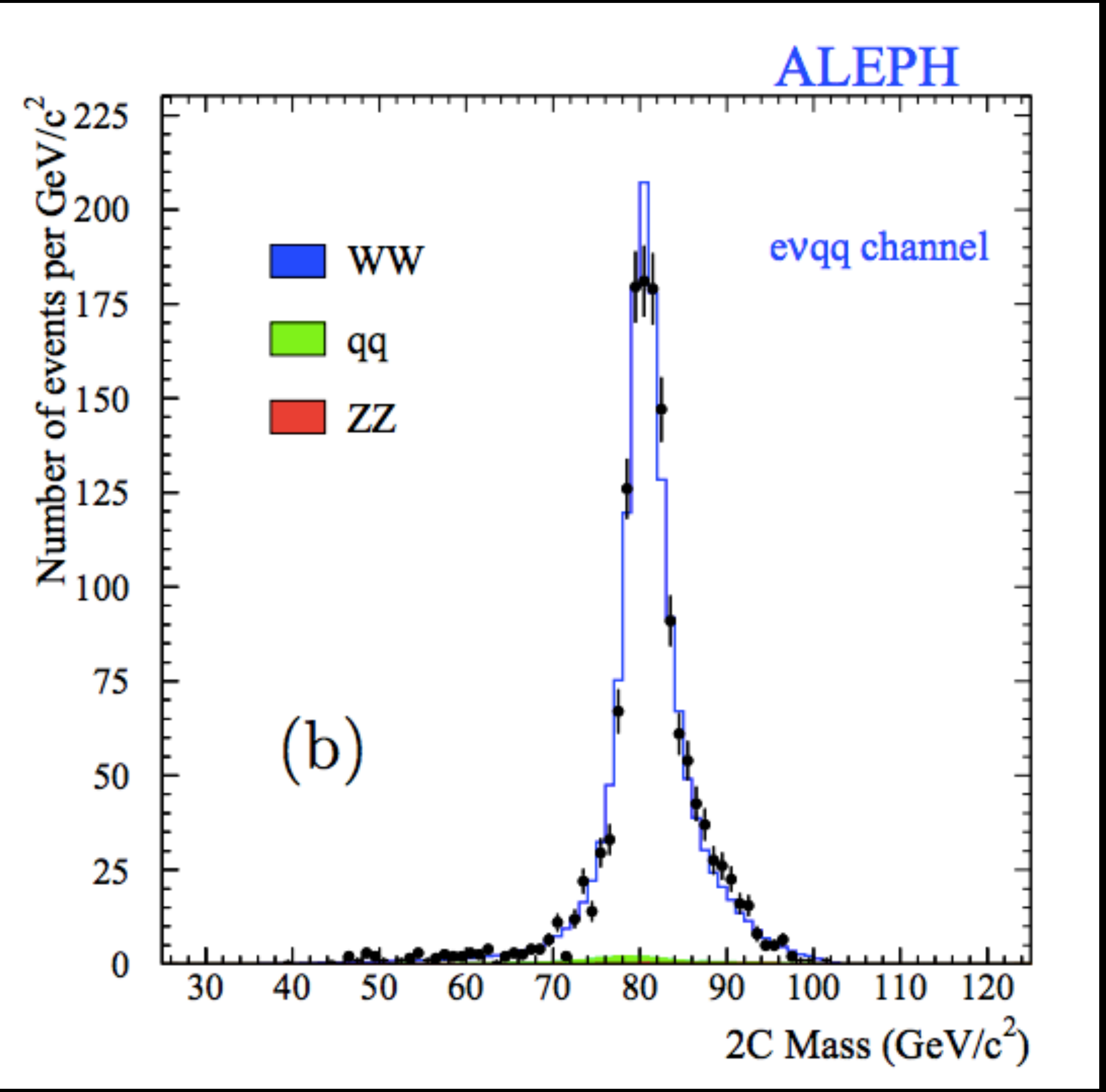
Chi2 distribution of W mass in EWK fit



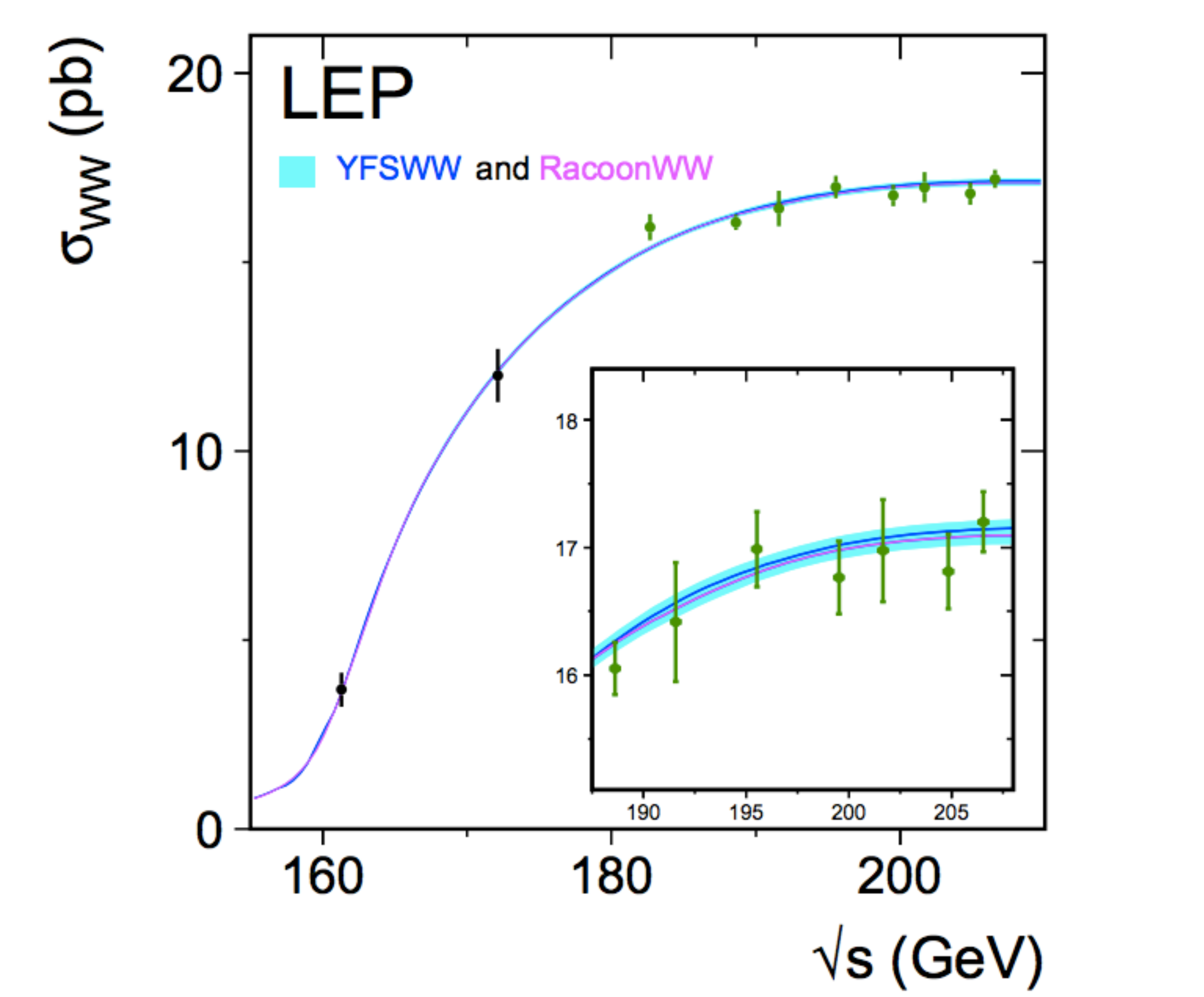
W mass measurement in lepton collider

➢ **Two approaches to measure W mass at lepton collider （developed by LEP)**

Direct measurement
performed in ZH runs (240GeV)
Precision 2~3MeV



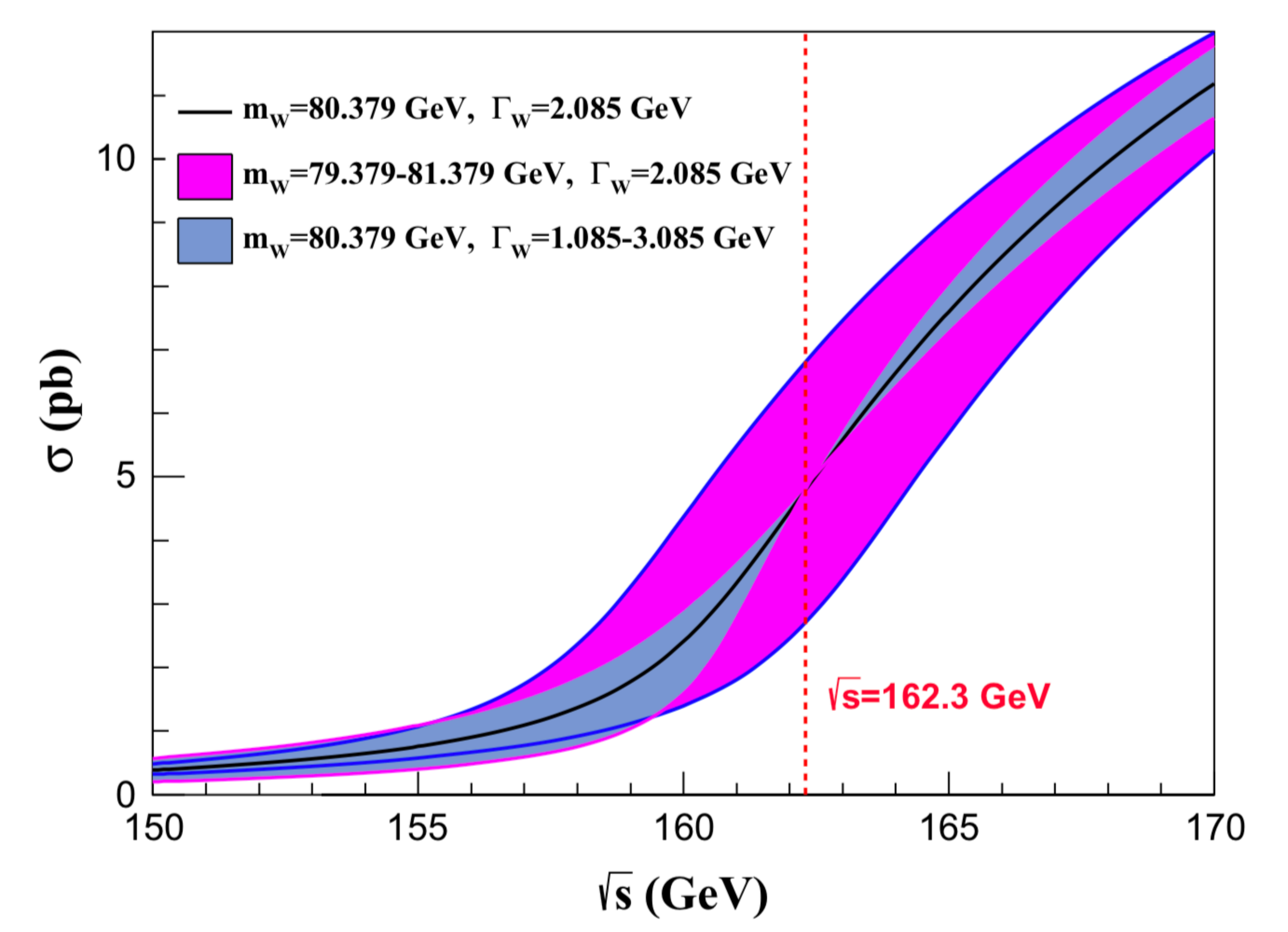
WW threshold scan
WW threshold runs (157~172GeV)
Expected Precision 1MeV level



W mass measurement in lepton collider

- **Optimization of data taking strategy in WW threshold scan**
- **Assuming one year data taking in WW threshold (2.6 ab^{-1})**
- **Four energy scan points:**
- 157.5, 161.5, 162.5(W mass, W width measurements)
- 172.0 GeV (α_{QCD} (m_W) measurement, Br (W->had) , CKM |Vcs|)
- 14M WW events in total(400 times larger than LEP2 comparing WW runs)

E_{cm} (GeV)	Lumiosity (ab^{-1})	Cross section (pb)	Number of WW pairs (M)
157.5	0.5	1.25	0.6
161.2	0.2	3.89	0.8
162.3	1.3	5.02	6.5
172.0	0.5	12.2	6.1



W mass measurements

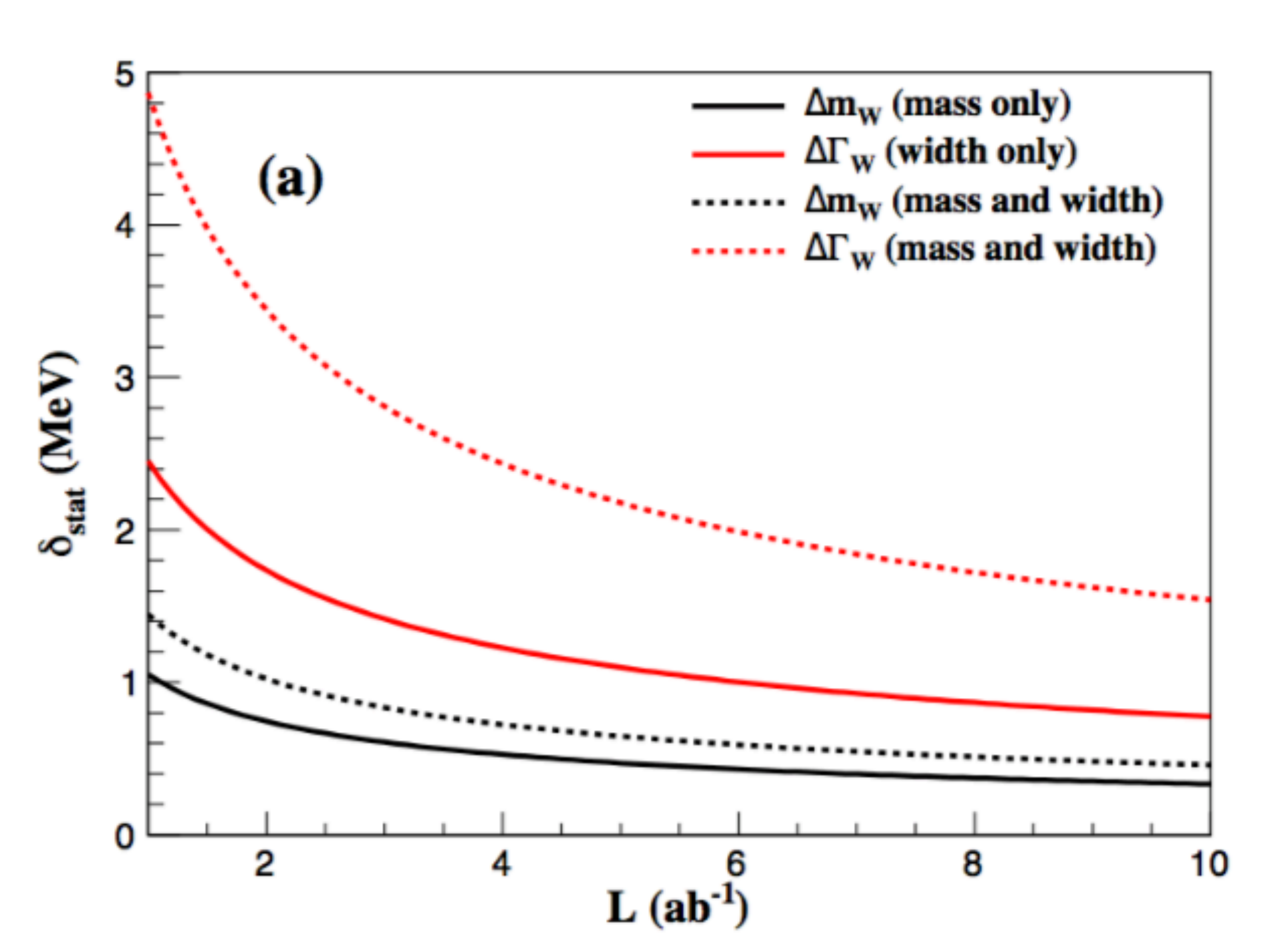
- **Expect to reach 1MeV precision on W mass (12 MeV unc. in PDG fit in PDG2020)**
- **Four energy scan points:**
- 157.5, 161.5, 162.5(W mass, W width measurements)
- 172.0 GeV (α_{QCD} (m_W), Br (W->had) , CKM |Vcs|)

- 14M WW events in total
- 400 times larger than LEP2 WW runs)

P.X.Shen, P.Azzuri , G.Li et,al, Eur.Phys.J.C 80 (2020) 1, 66

Joint study of CEPC/Fcc-ee

Observable	m_W	Γ_W
Source	Uncertainty (MeV)	
Statistics	0.8	2.7
Beam energy	0.4	0.6
Beam spread	–	0.9
Corr. syst.	0.4	0.2
Total	1.0	2.8



Snowmass 2021

- CEPC electroweak community is very active in Snowmass 2021
- One working group in snowmass (EF04) is for precision measurements

https://snowmass21.org/

Over the next year, the U.S. particle physics community will be engaged in Snowmass 2021, an in-depth process to define the most important questions for our field and to identify the most promising opportunities to address these questions in a global context. The process will have its roots in a series of preparatory meetings organized by Snowmass conveners, starting with a Snowmass Planning Meeting at Fermilab on November 4 - 6, 2020, and ending with a Snowmass Summer Study at the University of Washington, Seattle, on July 11 - 20, 2021.

To optimally engage all participants in the process, the Division of Particles and Fields **invites the international community to submit written documents** as described below. Given the increasing importance of interdisciplinary work in related fields such as astrophysics, cosmology, gravity, nuclear physics, accelerator physics, AMO, and materials science, members of the Divisions of Astrophysics, Gravitational Physics, Nuclear Physics, Physics of Beams and members of other units with a connection to particle physics are strongly encouraged to participate in this process.

Snowmass 2021

- **Submit five letter of intent (LOI) in snowmass 2021**
- **Weak mixing angle measurements at Z pole**
  - **More study with more realistic simulations**
  - **More detailed study on experimental and theory systematics**
- **High order EWK calculation (NNLO EWK corrections)**
- **aTGCs/QGCs in WW events**
- **Bounds in aQGCs**
- **Z->bb branching ratio**

CEPC LOI of $Sin^2\theta_W$

Snowmass2021 - Letter of Interest

Measurement of the leptonic effective weak mixing angle at CEPC

Thematic Areas: (check all that apply □/■)

□ (EF01) EW Physics: Higgs Boson properties and couplings
□ (EF02) EW Physics: Higgs Boson as a portal to new physics
□ (EF03) EW Physics: Heavy flavor and top quark physics
□ (EF04) EW Precision Physics and constraining new physics
□ (EF05) QCD and strong interactions: Precision QCD
□ (EF06) QCD and strong interactions: Hadronic structure and forward QCD
□ (EF07) QCD and strong interactions: Heavy Ions
□ (EF08) BSM: Model specific explorations
□ (EF09) BSM: More general explorations
□ (EF10) BSM: Dark Matter at colliders
□ (Other) *[Please specify frontier/topical group]*

Contact Information:
Name (Institution) [email]: Siqi YANG (University of Science and Technology of China)
Collaboration (optional):

Authors:
Manqi Ruan, Siqi Yang, Zhenyu Zhao, Liang Han

Abstract:
We present a study of the measurement of the leptonic effective weak mixing angle, $\theta^{\ell}_{\rm eff}$, at CEPC. Taking the advantage of the CEPC's high luminosity, the relative precision of $\sin^2\theta^{\ell}_{\rm eff}$ can be at least one order of magnitude better than $\mathcal{O}(0.1\%)$ which has been achieved at LEP, SLC and Tevatron. It will be the first time that experimental observation and the standard model theoretical calculation on the Z pole electroweak symmetry breaking can be directly compared at two-loop level. CEPC can also provide a $\mathcal{O}(0.1\%)$ precision on the comparison between $\sin^2\theta^{\ell}_{\rm eff}$ from different decay channels, including muon and electron, τ, heavy quarks (b and c), and light quarks (u and d). Besides, $\sin^2\theta^{\ell}_{\rm eff}$ can be measured at off-pole energy points, providing direct observations on the running effect of $\sin^2\theta^{\ell}_{\rm eff}$.

CEPC LOI : Z->bb

Snowmass2021 - Letter of Interest

[Measurement of R_b in hadronic Z decays at the CEPC]

Thematic Areas: (check all that apply □/■)

□ (EF01) EW Physics: Higgs Boson properties and couplings
□ (EF02) EW Physics: Higgs Boson as a portal to new physics
□ (EF03) EW Physics: Heavy flavor and top quark physics
■ (EF04) EW Precision Physics and constraining new physics
□ (EF05) QCD and strong interactions: Precision QCD
□ (EF06) QCD and strong interactions: Hadronic structure and forward QCD
□ (EF07) QCD and strong interactions: Heavy Ions
□ (EF08) BSM: Model specific explorations
□ (EF09) BSM: More general explorations
□ (EF10) BSM: Dark Matter at colliders
□ (Other) *[Please specify frontier/topical group]*

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Collaboration (optional):

Authors: Zhijun Liang, Bo Li, Bo Liu

Abstract: With an integrated luminosity of 45 ab^{-1} at $\sqrt{s}$ = 91.2GeV, more than 10^{12} Z bosons will be produced at the Circular Electron Positron Collider (CEPC). As a real Z boson factory, the precise study of Z boson physics can be achieved. The relative partial width, R_b, of Z boson into b quarks is measured on the CEPC Monte Carlo (MC) level. Based on the latest CEPC detector concept, the Z hadronic decay channel is simulated and reconstructed by the CEPC software framework. By using the double-tagging method, R_b can be solved from several equations referring to the ratios of b-tagged jet hemispheres in Z hadronic events. With the high performance of the b-tagging algorithm for CEPC, the precision of R_b measurement can be improved accordingly.

CEPC LOI : TGC in WW

Probing new physics with the measurements of $e^+e^- \to W^+W^-$ at CEPC with optimal observables

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Abstract: (maximum 200 words)

We propose to study the prospectives of the diboson ($e^+e^- \to W^+W^-$) measurements at the CEPC in the effective-field-theory framework. We plan to implement the method of optimal observables to extract useful information in the differential distributions and obtain the best possible reach on the coefficients of the corresponding dimension-six operators. The impact of systematic uncertainties due to detector resolutions and beamstrahlung effects will be thoroughly investigated.

CEPC LOI : unitarity

Positivity bounds on quartic-gauge-boson couplings

Snowmass letter of intent

Cen Zhang[1,2,3,*] and Shuang-Yong Zhou[4,5,†]

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Dim-8 Wilson coefficients in the Standard Model Effective Field Theory (SMEFT) are not allowed to take arbitrary values. By assuming that the SMEFT admits a UV completion that satisfies the fundamental principles of quantum field theory (QFT), including analyticity, unitarity, crossing symmetry, locality and Lorentz invariance, the so-called positivity bounds can be derived [1], determining the signs of certain linear combinations of dim-8 coefficients. Since the ultimate goal of the SMEFT is to determine its UV completion, one should restrict the search for operators only within these bounds, and optimize the search strategy accordingly. Alternatively, one might also use these bounds to experimentally test the fundamental principles of QFT [2]. In either case, as the LHC has started to probe the dim-8 SMEFT operators in many occasions, it has become increasingly important to understand the positivity bounds on their coefficients. A particular relevant topic at the LHC is the vector boson scattering (VBS) and the measurement of the quartic-gauge-boson couplings (QGCs). Searching for possible beyond the SM physics in the form of anomalous QGCs is one of the main goals of the current as well as the future electroweak program at the LHC and HL-LHC. These couplings can be measured in the VBS or the triboson production channels. Knowing their bounds from positivity will undoubtedly provide guidance for relevant future theoretical and experimental studies.

The conventional approach to derive positivity bounds makes use of the elastic 2-to-2 forward scattering amplitude. One can show that its second derivative w.r.t. s, the Mandelstem variable, is positive, and this leads to, at the tree level, a set of linear homogeneous inequalities for dim-8 coefficients. This approach has been adopted in Refs. [3–5], and the allowed parameter space of the Wilson coefficients has been reduced to only about 2%. However, these results are still far from complete. The reason is that the notion of elasticity depends on the particle basis, and therefore the scattering amplitudes between arbitrary superpositions of particle states should be explored, in order to obtain the full set of elastic positivity bounds. So far, this procedure has not been done systematically, and only a limited set of superposed states have been investigated in the literature.

Recently, we have proposed a new approach to extract positivity bounds [6]. This approach has the advantage that one is guaranteed to obtain the best bounds allowed by the fundamental QFT principles. Indeed, bounds tighter than the full set of elastic positivity bounds can be obtained in certain cases, and an explicit example has been presented in [6]. In this approach, instead of using elastic channels to probe the bounds, one essentially

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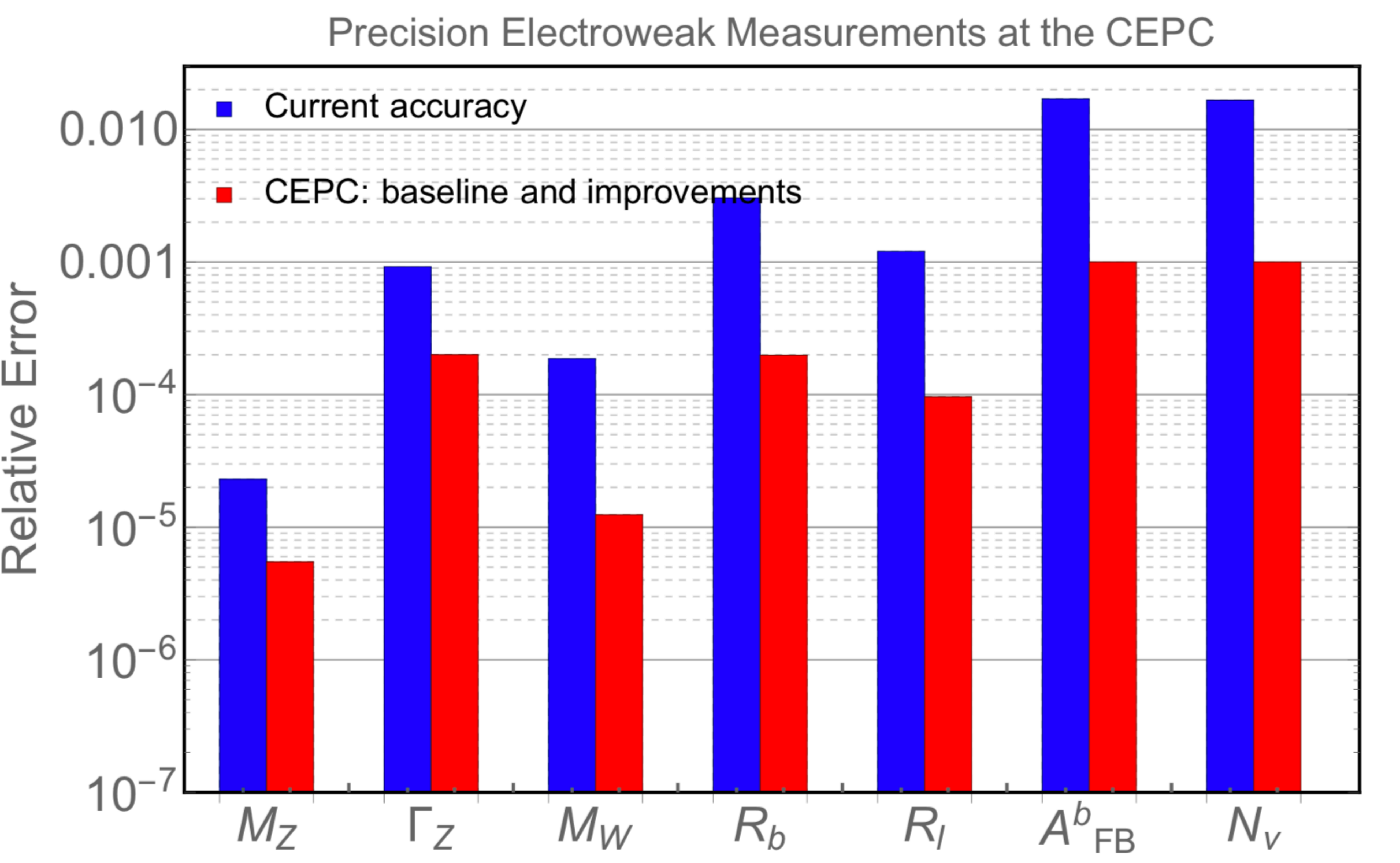
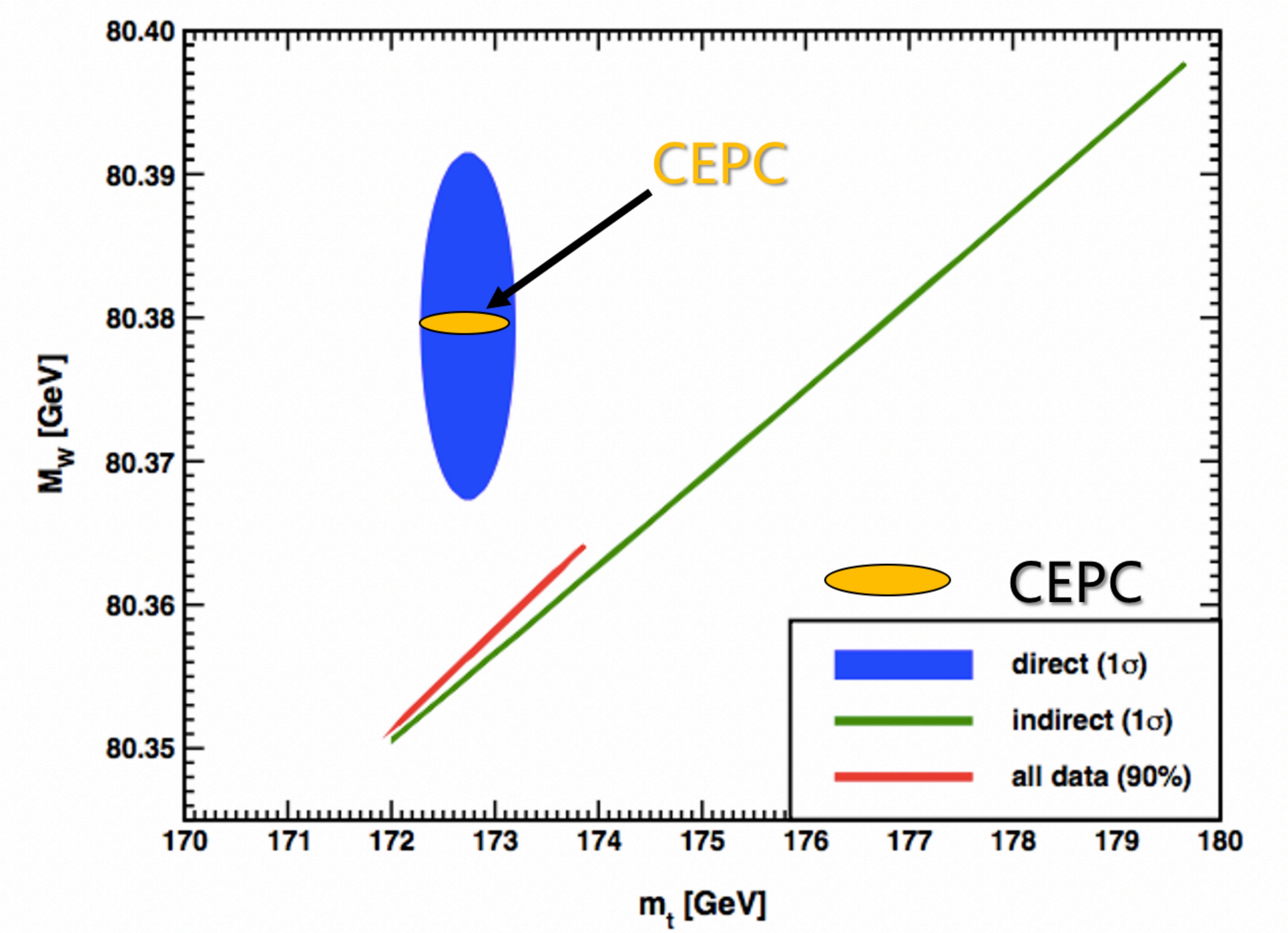
Summary

- Luminosity @ Z pole is now 3.2 times higher compared to CDR design
- ☐ Instant luminosity > $100*10^{34}cm^{-2}s^{-1}$
- ☐ >1.5 X10^{12} Z boson (Two year Z pole running)
- Potential of electroweak measurement at CEPC
- ☐ 1~2 order of magnitude better than current precision
- ☐ May solve the puzzle in W mass and $Sin^2\theta_W$





Weak mixing angle measurement at Z pole $\sin^2\theta_{eff}$ and A_{FB}

By Dr. Siqi Yang (USTC)

Snowmass2021 - Letter of Interest

Measurement of the leptonic effective weak mixing angle at CEPC

Thematic Areas: (check all that apply □/■)

□ (EF01) EW Physics: Higgs Boson properties and couplings
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Collaboration (optional):

Authors:
Manqi Ruan, Siqi Yang, Zhenyu Zhao, Liang Han

Abstract:
We present a study of the measurement of the leptonic effective weak mixing angle, $\theta^{\ell}_{\text{eff}}$, at CEPC. Taking the advantage of the CEPC's high luminosity, the relative precision of $\sin^2\theta^{\ell}_{\text{eff}}$ can be at least one order of magnitude better than $\mathcal{O}(0.1\%)$ which has been achieved at LEP, SLC and Tevatron. It will be the first time that experimental observation and the standard model theoretical calculation on the Z pole electroweak symmetry breaking can be directly compared at two-loop level. CEPC can also provide a $\mathcal{O}(0.1\%)$ precision on the comparison between $\sin^2\theta^{\ell}_{\text{eff}}$ from different decay channels, including muon and electron, τ, heavy quarks (b and c), and light quarks (u and d). Besides, $\sin^2\theta^{\ell}_{\text{eff}}$ can be measured at off-pole energy points, providing direct observations on the running effect of $\sin^2\theta^{\ell}_{\text{eff}}$.

I. Motivation and introduction

The leptonic effective weak mixing angle is the key parameter in the electroweak global fitting. It is important not only to the standard model global fitting, but also predictions in potential new physics. It is defined as an effective parameter which could absorb standard model or beyond standard model higher order effects. The experimental precisions of the $\sin^2\theta^{\ell}_{\text{eff}}$ measurements at the Z mass pole region are at $\mathcal{O}(0.1\%)$ level, including 0.23221 ± 0.00029 from the LEP combined $e^+e^- \to b\bar{b}$ results, 0.23098 ± 0.00026 from the SLC $e^+e^- \to e^+e^-$ polarization asymmetry observation, and 0.23179 ± 0.00033 from the combined D0 and CDF measurements, dominated by the light quark $q\bar{q} \to \ell^+\ell^-$ processes [1;2]. The theoretical uncertainty on $\sin^2\theta^{\ell}_{\text{eff}}$ can be reduced to 0.00005 around Z pole by performing complete two-loop level calculations[3]. As a conclusion, the $\sin^2\theta^{\ell}_{\text{eff}}$ related global fittings are now limited by the experimental precision in the past two decades. By the discovery of the Higgs boson in 2012, all parameters in the standard model predictions are experimentally fixed. As direct new physics searches have been going on for almost 10 years at the Large Hadron Collider but no obvious clue found, precise comparison between experiment and theoretical results in the global fitting becomes important. This requires significant improvements on the experimental measurements on $\sin^2\theta^{\ell}_{\text{eff}}$.

CEPC is an ideal collider to provide high precision measurements on $\sin^2\theta^{\ell}_{\text{eff}}$. It is planning a two-year run period around the Z pole, which can generate $3{\sim}6\times10^{11}$ single Z boson events. With such a large data sample, the statistical uncertainty, which is the dominant uncertainty in the LEP and SLC measurement, we can easily reduce the statistical uncertainty around 0.00001 on $\sin^2\theta^{\ell}_{\text{eff}}$. High precisions can be achieved independently in different decay channels, including muon and electron, τ, light quarks (u and d), and heavy quarks (b and c). The comparison channels is part of the standard model global test. The running effect on the translated $\sin^2\theta_W$ as a function of the energy scale is another physics interest. By now, there is no direct weak mixing angle measurement at an energy scale higher than the Z pole region. It would be very important to experimentally test the theoretical prediction that $\sin^2\theta_W$ would run to a higher value as the energy scale goes up.

LHC also has possibility to achieve a high precision on $\sin^2\theta^{\ell}_{\text{eff}}$, but would be very difficult. Uncertainties from parton distribution functions which models the initial state quark momentum are at $\mathcal{O}(0.1\%)$ level with respect to the $\sin^2\theta^{\ell}_{\text{eff}}$ value. Systematic uncertainties under high instantaneous luminosity collisions are expected to be same large with that from PDFs. In general, trying to measure $\sin^2\theta^{\ell}_{\text{eff}}$ at hadron colliders requires a series of long term studies. Besides, hadron colliders could not provide direct observations on τ and heavy quark couplings.

As a conclusion, CEPC could bring a relative precision of $\sin^2\theta^{\ell}_{\text{eff}}$ at $\mathcal{O}(0.01\%)$ level, and at $\mathcal{O}(0.1\%)$ level for comparison between different channels and for observation on the energy running effect.

II. Measurements and Expected precisions

The effective weak mixing angle can be observed from the forward-backward asymmetry (A_{FB}) via the $e^+e^- \to Z/\gamma^* \to f\bar{f}$ process. A_{FB} is defined as:

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B} \qquad (1)$$

R^b measurements

By Dr. Bo Li (Yantai U.)

Snowmass2021 - Letter of Interest

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1 Introduction

The Circular Electron Positron Collider (CEPC) is one of the next-generation e^+e^- colliders, that have been proposed to perform precision measurements of the Higgs boson properties. The CEPC will be hosted in China with a circumference of 100 km and two interaction points(IP)[1]. By operating at $\sqrt{s}$ = 240GeV, the CEPC is expected to produce approximately 10^6 Higgs bosons with an integrated luminosity of 5.6 ab^{-1} in about 7 years. The CEPC will also produce about more than 10^{12} Z bosons in about 2 years with an expected integrated luminosity of 45 ab^{-1} at $\sqrt{s} = 91.2$GeV[1]. With the high statistics of Z bosons, high-precision electroweak measurements of the Z boson properties can be achieved, such as the R_b measurement.

The relative decay width of $\mathrm{Z} \to \mathrm{b\bar{b}}$ in hadronic Z decays, $R_b = \Gamma(\mathrm{Z} \to \mathrm{b\bar{b}})/\Gamma(\mathrm{Z} \to \mathrm{hadrons})$, is a sensitive electroweak parameter to test the Standard Model (SM) and find new physics[2–4]. For example, the existence of stop-quarks or charginos in supersymmetry can result in a deviation between the measured R_b and the one in the SM[5]. The LEP and SLD collaborations have made accurate measurements of the R_b[6–10] with a combined value of $R_b = 0.21629 \pm 0.00066$[11]. The measurement of R_b at the CEPC is expected to be more precise owing to its high statistics of the Z boson and high performance of the b-tagging.

2 Monte Carlo simulation

The CEPC conceptual detector, following the Particle Flow Algorithm (PFA)[16], is composed of a silicon pixel vertex detector, a silicon tracking system, a TPC, an electromagnetic calorimeter and a hadronic calorimeter. The latest version of the conceptual detector is CEPC_v4[1], which has been updated and optimized from the preliminary conceptual detector CEPC_v1[17]. More information about the studies on the conceptual detector can be found in Ref.[18–22].

The Monte Carlo particles are generated from physics models by using Whizard[12] at the parton level and then interfaced with Pythia[13] for hadronization simulation. The MC particles are simulated by the detector simulation framework MokkaPlus[14] based on Geant4[15]. MokkaPlus is a simulation framework used for linear colliders and has been updated to match the CEPC detector concept.

The final physics objects, such as the lepton, photon and jet, are reconstructed by using a dedicated particle flow reconstruction framework Arbor[23;24]. A final state classification framework, FSClasser[25], is used for the reconstruction of the final physics events.

3 Analysis method

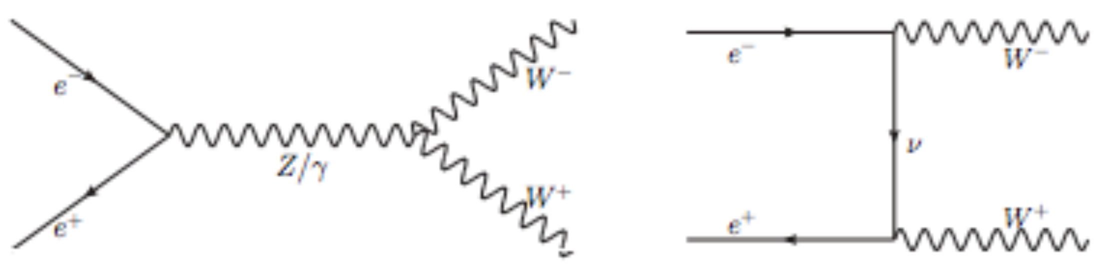
The R_b measurement is based on the double-tagging method. The procedure of the method is described as follows: The jets in the hadronic decay events are divided into two kinds of hemispheres, namely, hemisphere I and hemisphere J, according to the plane perpendicular to the thrust axis. By applying the b-tagging cuts on the two hemisphere samples separately, we can then retrieve two b-tagged hemispheres. The number of b-tagged hemisphere I samples is named N_t^I. For the opposite hemisphere J, the number of tagged samples is named N_t^J. For the two kinds of hemispheres, the b-tagging cut points can be applied differently. The number of events in which both hemispheres are tagged can be counted as $N_{tt}^{I,J}$. Three equations can

TGC with optimal observables

By jiaYing Gu,lingfeng Li
Dan Yu, Shuqi Li, Manqi, Zhijun

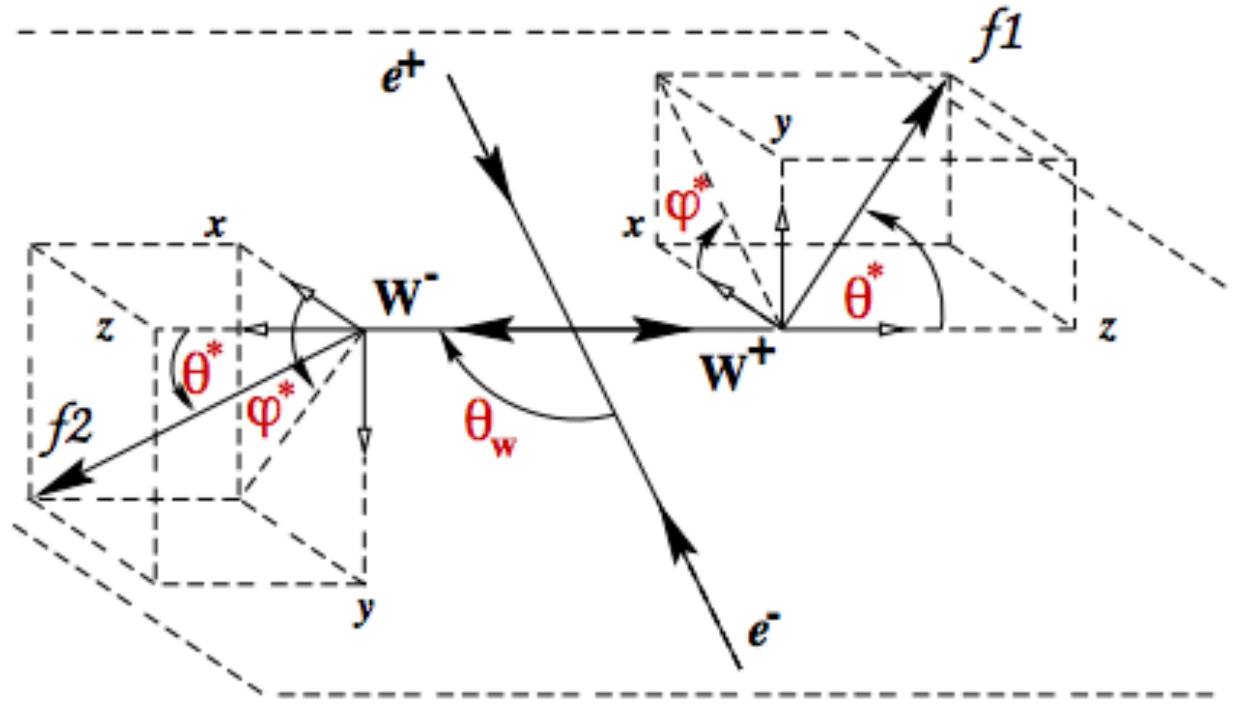
A refined TGC analysis using Optimal Observables

- TGCs are sensitive to the differential distributions!
  - Current method: fit to binned distributions of all angles.
  - Correlations among angles are ignored.



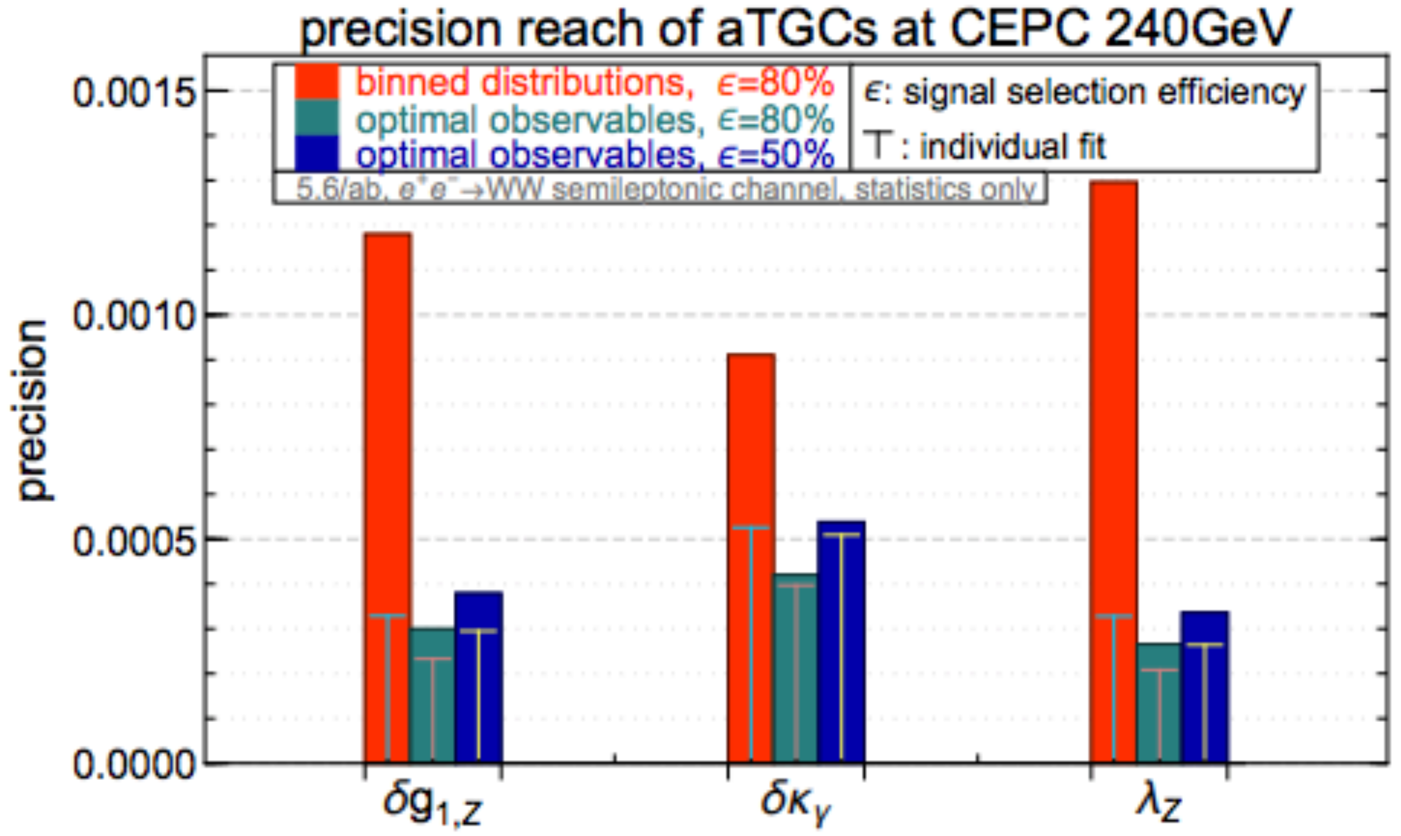
- What are optimal observables?

  (See *e.g.* Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)
  - For a given sample, there is an upper limit on the precision reach of the parameters.
  - In the limit of large statistics (everything is Gaussian) and small parameters (leading order dominates), this "upper limit" can be derived analytically!



$$\frac{d\sigma}{d\Omega} = S_0 + \sum_i S_{1,i}\, g_i\,,$$

- The optimal observables are given by $\mathcal{O}_i = \frac{S_{1,i}}{S_0}$, and are functions of the 5 angles.



TGC with optimal observables

By jiaYing Gu,lingfeng Li
Dan Yu, Shuqi Li, Manqi, Zhiju

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Abstract: (maximum 200 words)

We propose to study the prospectives of the diboson ($e^+e^- \to W^+W^-$) measurements at the CEPC in the effective-field-theory framework. We plan to implement the method of optimal observables to extract useful information in the differential distributions and obtain the best possible reach on the coefficients of the corresponding dimension-six operators. The impact of systematic uncertainties due to detector resolutions and beamstrahlung effects will be thoroughly investigated.

1 Background

The Circular Electron Positron Collider (CEPC) is a proposed future lepton collider based in China[1]. With runs at the Z-pole, WW threshold and around 240 GeV, it can reach unprecedented precisions for the measurements of the Higgs boson and the electroweak gauge bosons. For the electroweak gauge boson, the future prospectives of the measurements at the Z-pole and the WW threshold have already been studied in the conceptual design report[1]. Meanwhile, there is no projection for the set of observables in the diboson process, $e^+e^- \to W^+W^-$, at the CEPC. These observables are conventionally parameterized in terms of the anomalous triple Gauge couplings (aTGCs), and can be well measured at energies above the WW threshold, such as 240 GeV. They contain important information on the properties of the electroweak gauge bosons and provide crucial inputs for global effective-field-theory (EFT) analyses. A recent study[2] pointed out the importance of implementing the full EFT parameterization instead of the conventional three aTGC parameterization for the diboson process at future lepton colliders, and demonstrated the usefulness of the so-called *optimal observables*[3] for extracting information in the differential distributions of the diboson events. However, due to the absence of experimental inputs, Ref.[2] only performed a simplified diboson analyses based on statistical uncertainties. A more realistic analysis, which takes account of the systematics and detector effects, is desired to fully understand the potential of CEPC in probing the EFT parameters in the diboson measurements.

2 Proposed Study

We plan to focus on the semi-leptonic decay channel of the $e^+e^- \to W^+W^-$ process, which has a sizable branching fraction and good event reconstructions. While the optimal observable analysis in Ref.[2] gives an estimation on the precision reaches of the corresponding EFT parameters, our main focus will be on the investigation of the impacts of systematic uncertainties. This is a nontrivial task given the complicated nature of the optimal observables and their sensitivity to the differential distributions. In particular, the optimal observables at the parton level may be significantly different from those at detecter level, if the 4-momenta of the final state particles are not very well reconstructed. As such, it is important to understand the impacts of the resolutions of the jet energy and momentum, as well as the reconstruction of the missing momentum of the neutrino.

Our first step would be to compare the parton level and detector level results of the optimal observable analyses and understand the impact of systematics in terms of both the reconstructed central values of the EFT parameters (*i.e.* whether a bias can be induced by the systematics) and their uncertainties. In this comparison, we will also study the impacts of the selection cuts, such as the requirements on invariant mass that ensures the correct reconstruction of the W boson, on reducing the systematic uncertainties on the optimal observables. If the impacts of systematics are large and difficult to remove with selection cuts, we will also explore on the use of more sophisticated methods, such as machine learning techniques to estimate the precision reach on the EFT parameters and compare those with the ideal reach from the optimal observables.

3 Outlook

Our results on the optimal observable analyses of the diboson measurements will serve as a crucial component of a realistic global EFT analyses at the CEPC. It is also possible to generalize our analysis to include

Bounds in aQGCs (by Cen Zhang)

Positivity bounds on quartic-gauge-boson couplings

Snowmass letter of intent

Cen Zhang[1, 2, 3, *] and Shuang-Yong Zhou[4, 5, †]

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describes the allowed parameter space as a convex cone via the *extremal representation* of cones, and thus we will call it the extremal positivity approach. This approach is efficient because the extremal rays of the cone can be directly written down via group theoretical considerations. So far, this approach has been applied to the 4-W and the 4-H operator sets in Ref. [6]. More general applications of this approach are yet to be explored.

For Snowmass 21, we propose to study the full set of positivity bounds on aQGC operators in the SMEFT framework, by applying the new extremal positivity approach. We expect these results to unify and supersede all previous results in the literature. While providing guidance for future theoretical and experimental studies on VBS and relevant SMEFT fits, we also hope that this study will establish the general methodology for obtaining complete positivity bounds for dim-8 SMEFT operators.

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[5] G. N. Remmen and N. L. Rodd, JHEP **12**, 032 (2019), arXiv:1908.09845 [hep-ph].
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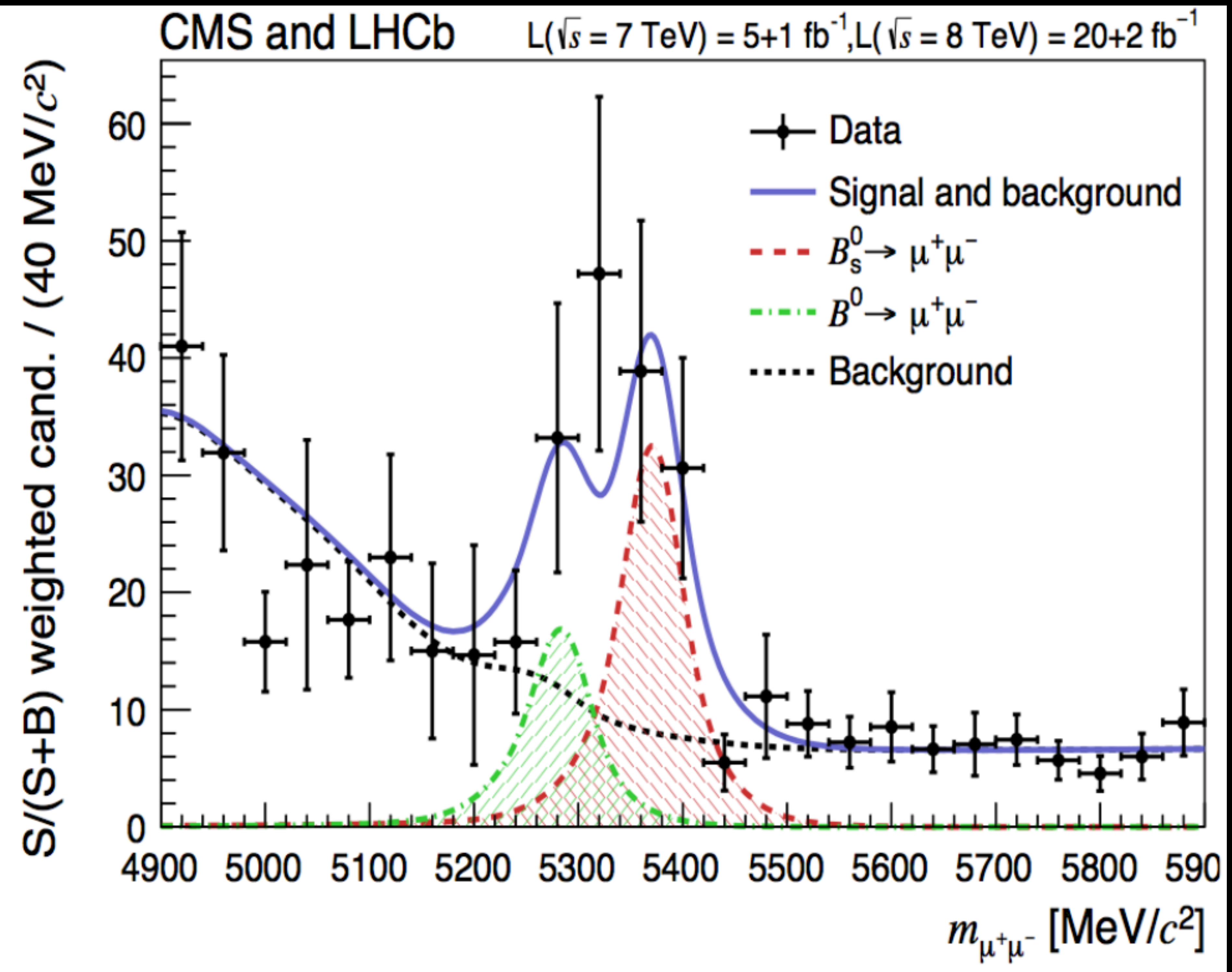
Backup: Track momentum resolution @ Z pole

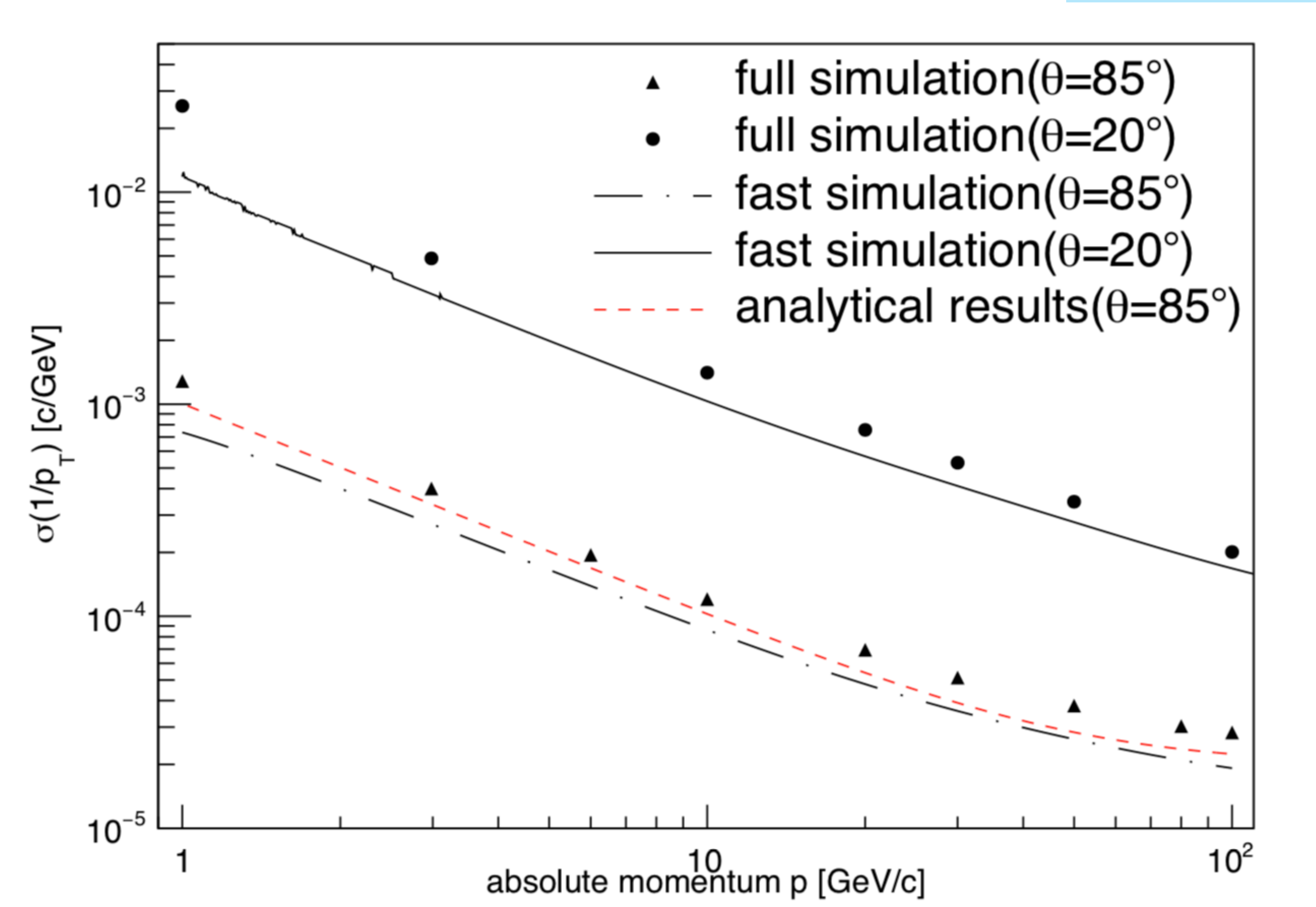
- Current optimization based on ZH runs @ 240GeV
- Most demanding case for low momentum track resolution is flavor physics
- Current design is good enough for EWK and flavor physics at Z pole

$$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\text{GeV}) \sin^{3/2}\theta}$$

B_s /B^0-> μ μ by CMS and LHCb



Momentum resolution in CEPC



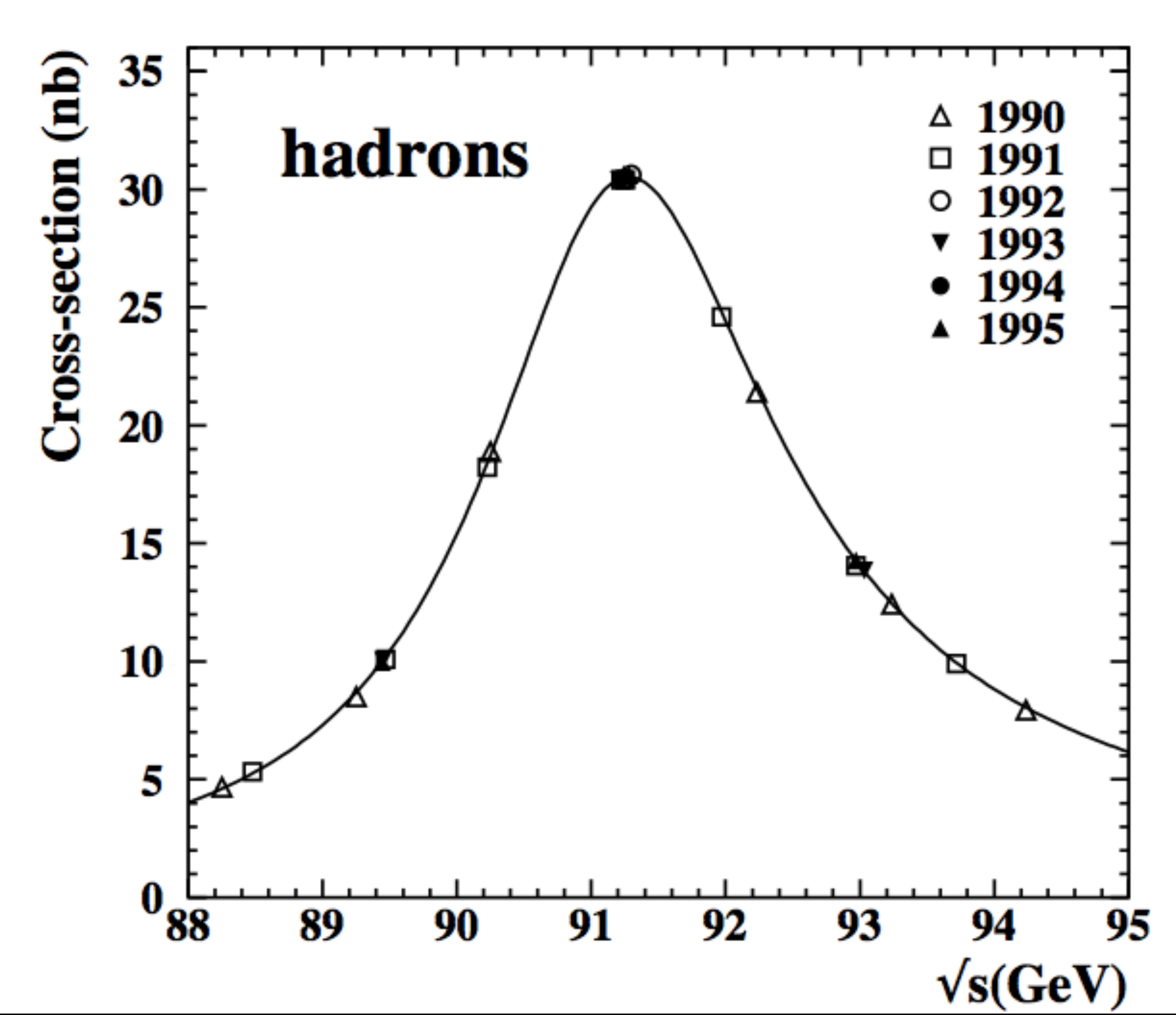
From CEPC CDR

Z mass measurement

- LEP precision : 91.1876±0.0021 GeV
- CEPC goal : 0.5 MeV (CDR) → 0.1MeV (TDR)

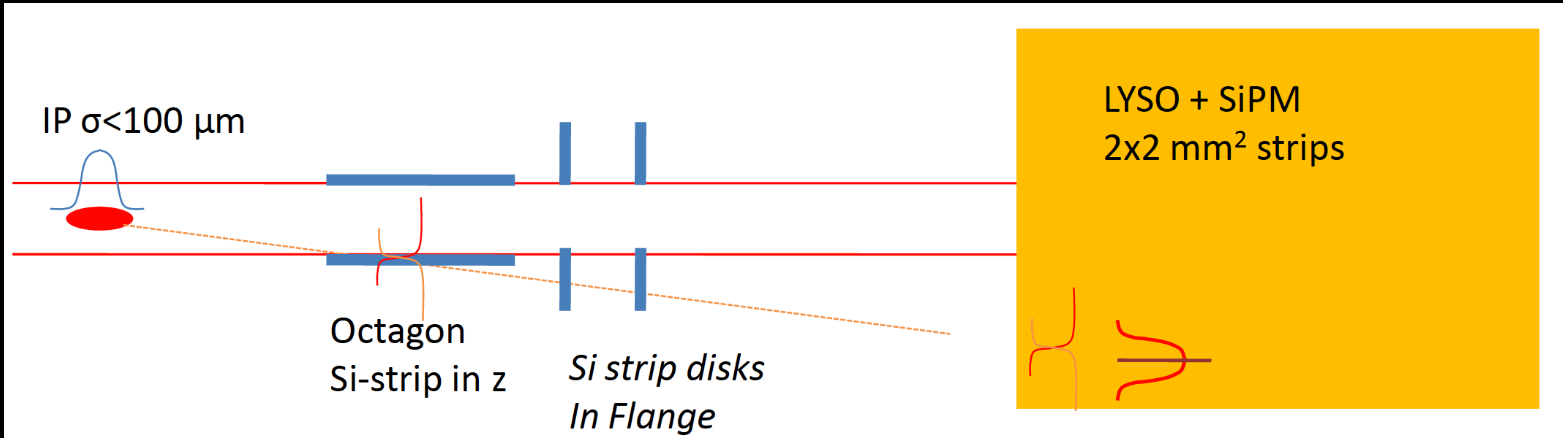
➢ Beam energy uncertainty is major systematics (0.1MeV)

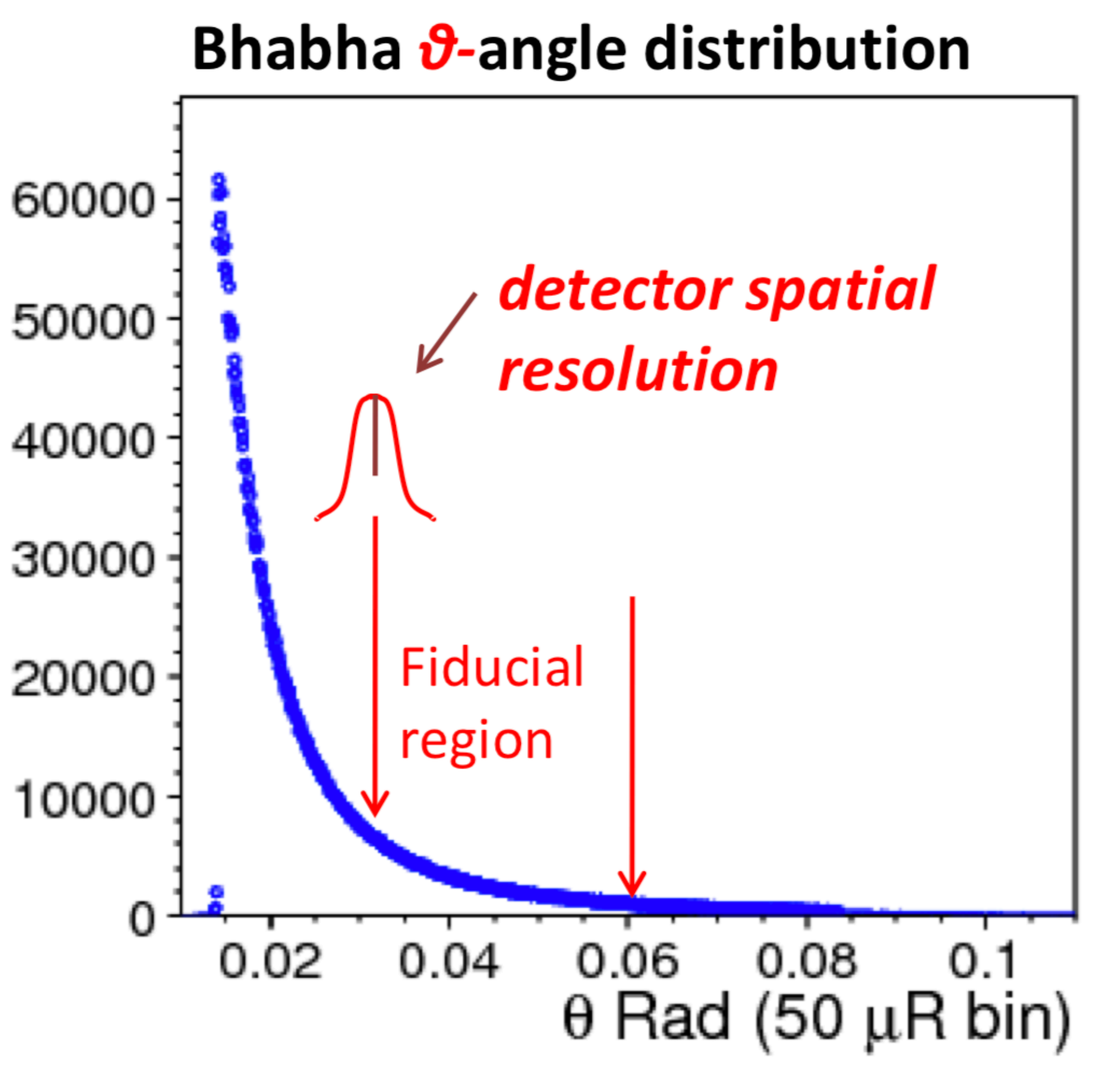
➢ Luminosity measurement



Luminosity measurement: Lumical detector

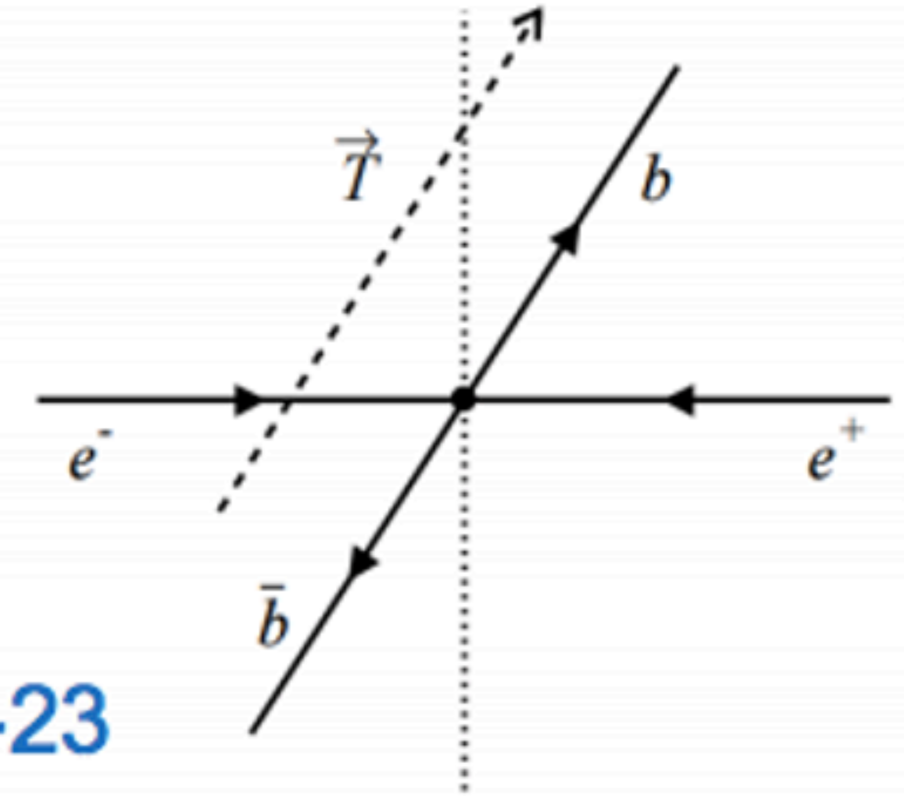
- **For luminosity δL/L = 10-4**
- 30 <θ <100 mRad
- Lumical : silicon strip disks + LYSO+SiPM calorimeter
- **strip Resolution dr = .75 μm**
- **Strip detetor resolution dz = 25 μm**





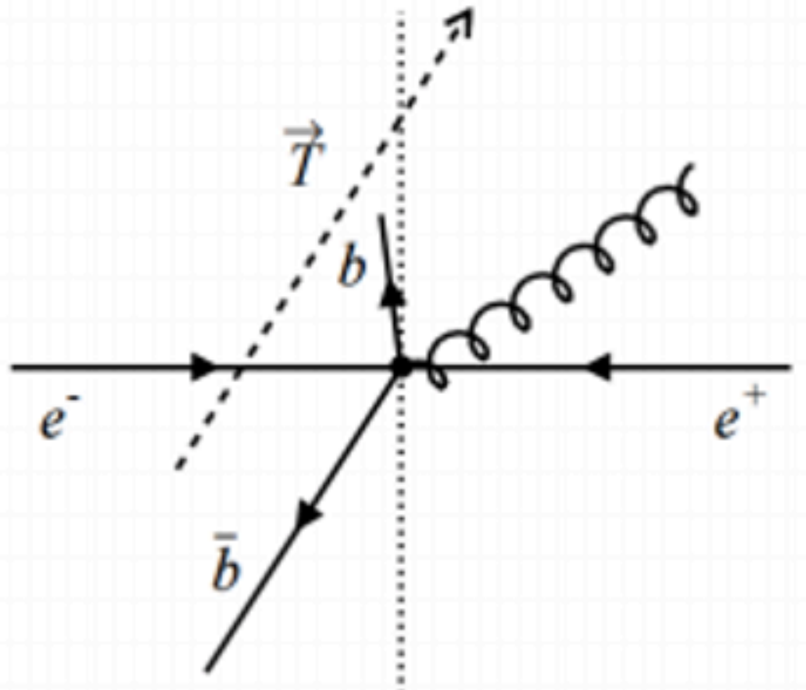
Branching ratio (R^b): theory systematics

- QCD related systematics
  - High order QCD corrections gives impact to hemisphere correlations
  - Impact to Backward-forward asymmetry



CERN-EP/98-23

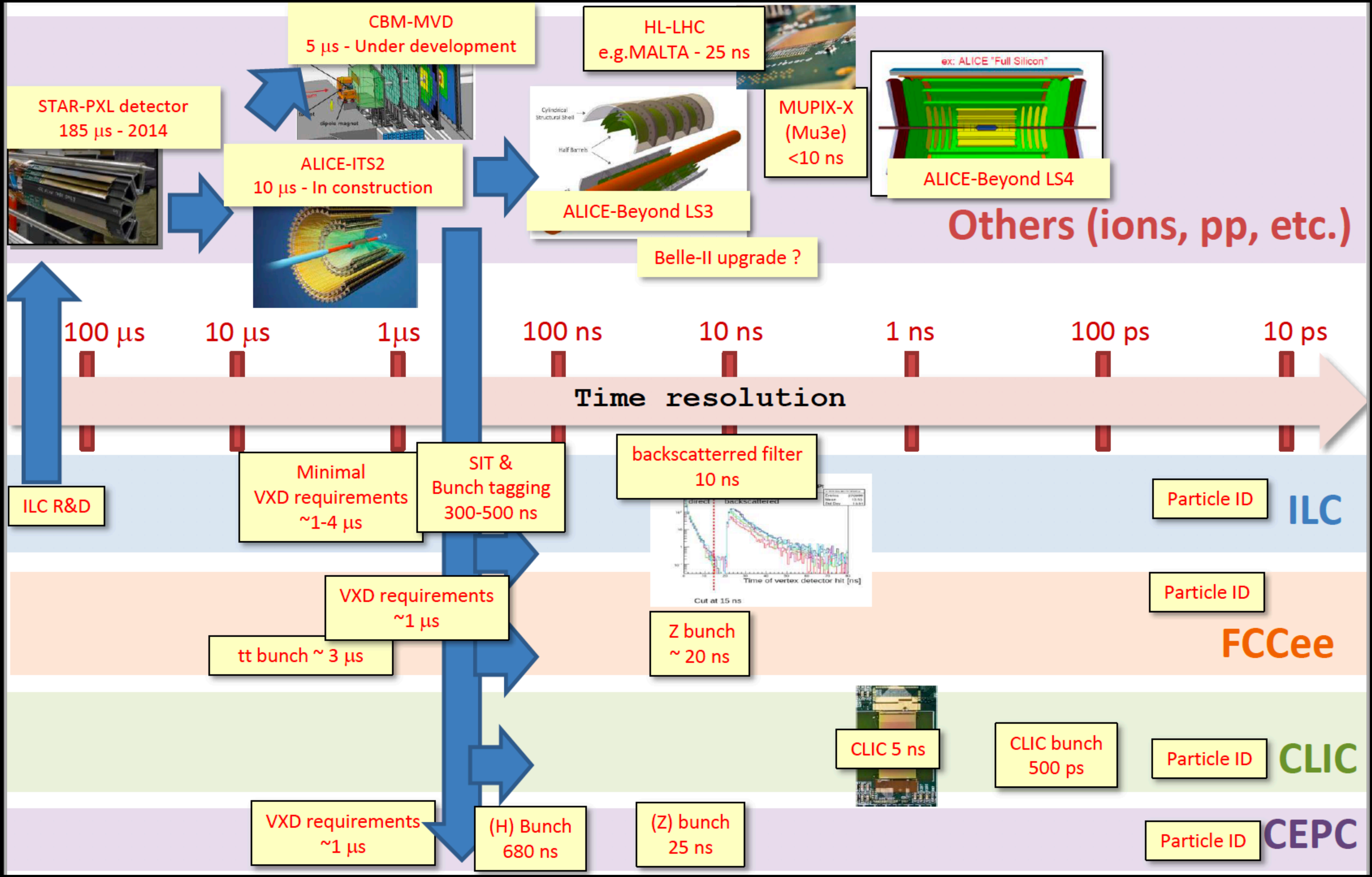
(a) No gluon



(d) Thrust forward, quark backward

Error source	C_{QCD}^{quark} (%)		$C_{QCD}^{part,T}$ (%)	
	$b\bar{b}$	$c\bar{c}$	$b\bar{b}$	$c\bar{c}$
Theoretical error on m_b or m_c	0.23	0.11	0.15	0.08
$\alpha_s(m_Z^2)$ (0.119 ± 0.004)	0.12	0.16	0.12	0.16
Higher order corrections	0.27	0.66	0.27	0.66
Total error	0.37	0.69	0.33	0.68

Timing of detector for Z pole running

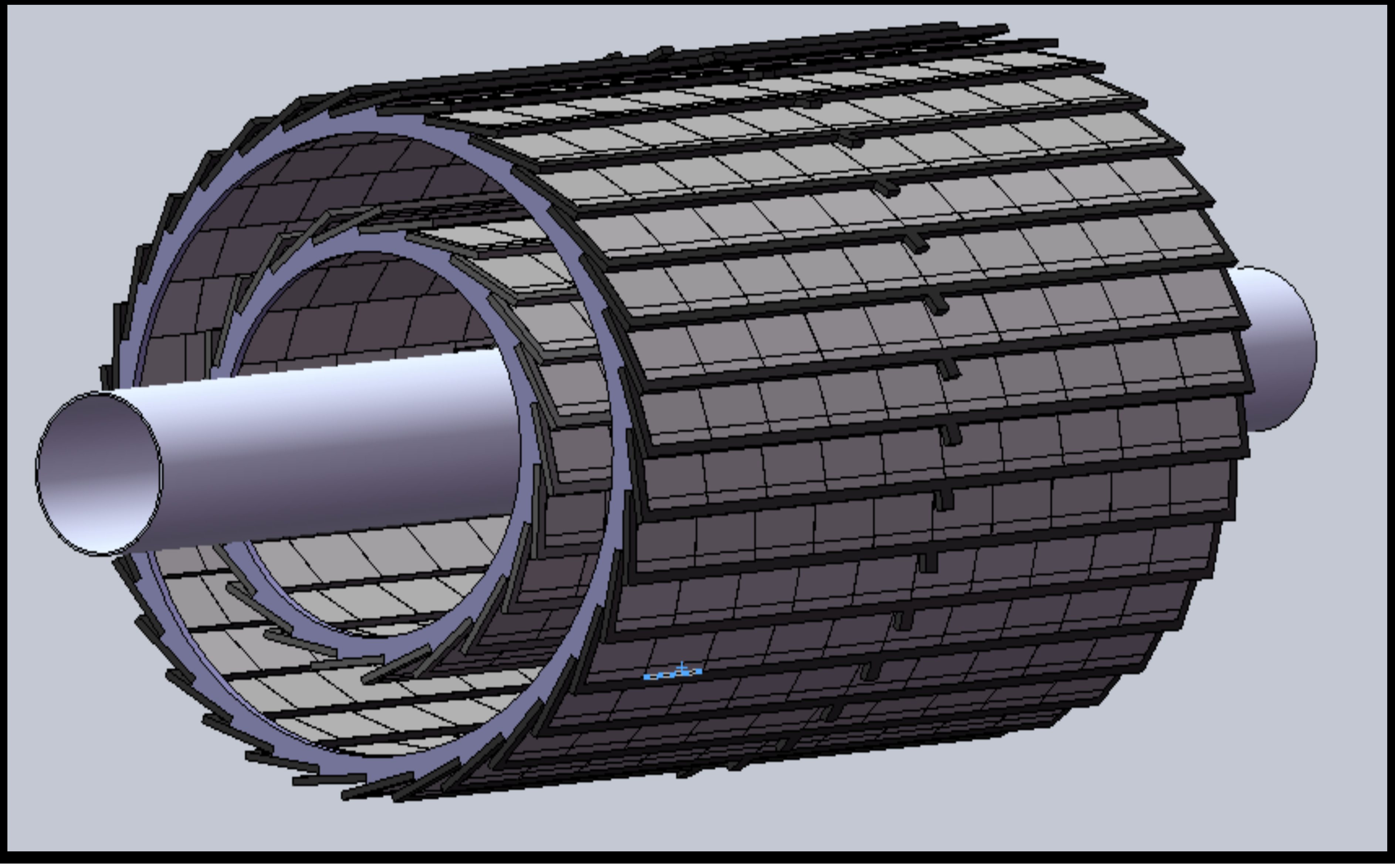


From Auguste Besson's talk in Fcc workshop

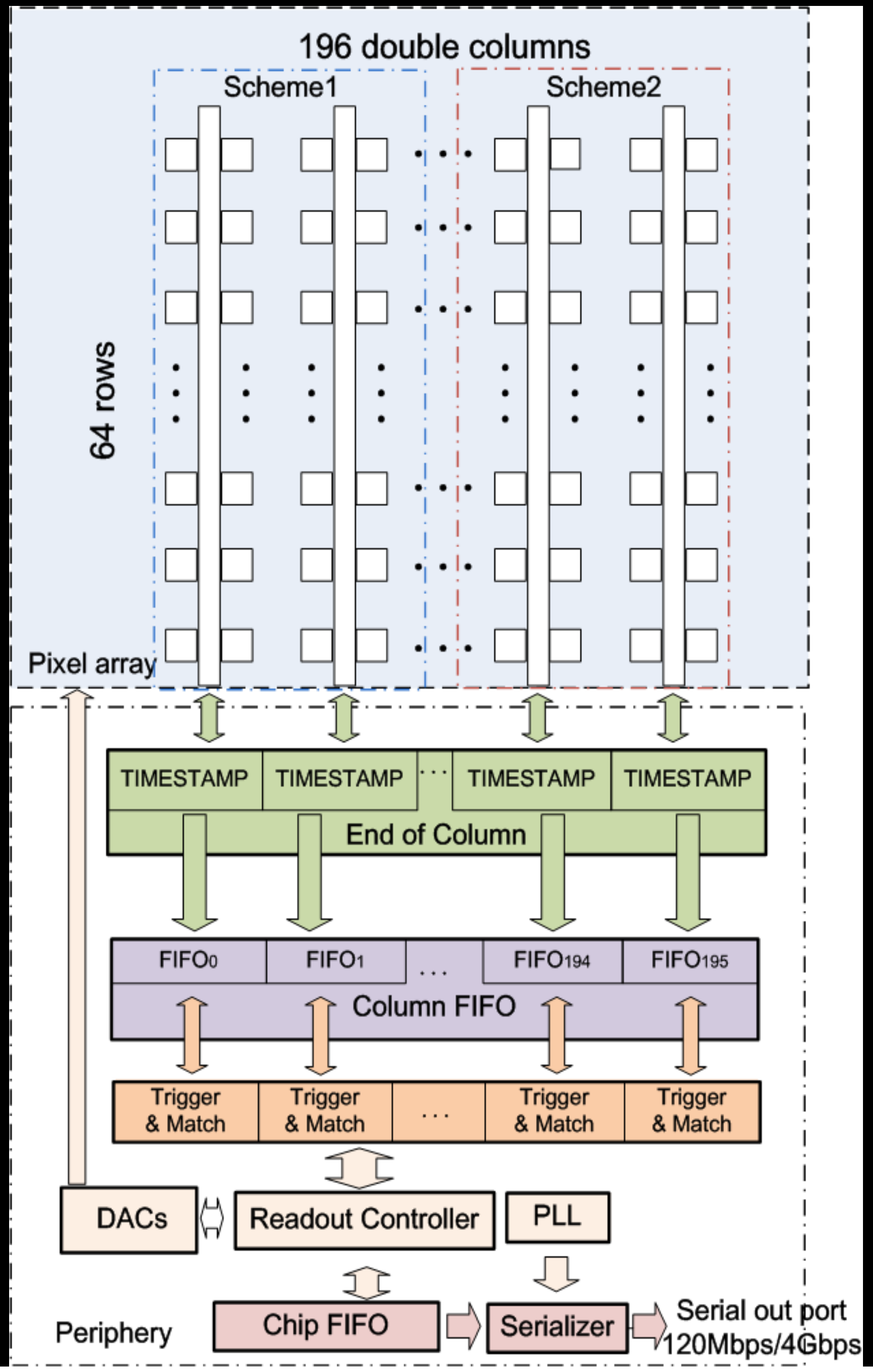
CEPC vertex prototype

- CEPC Vertex prototype R & D project, optimized for Z pole running
- Taichu sensor chip designed (based one standard CMOS MAPS tech.)
  - Readout time: 75ns~150ns
  - Consider to use Depleted CMOS

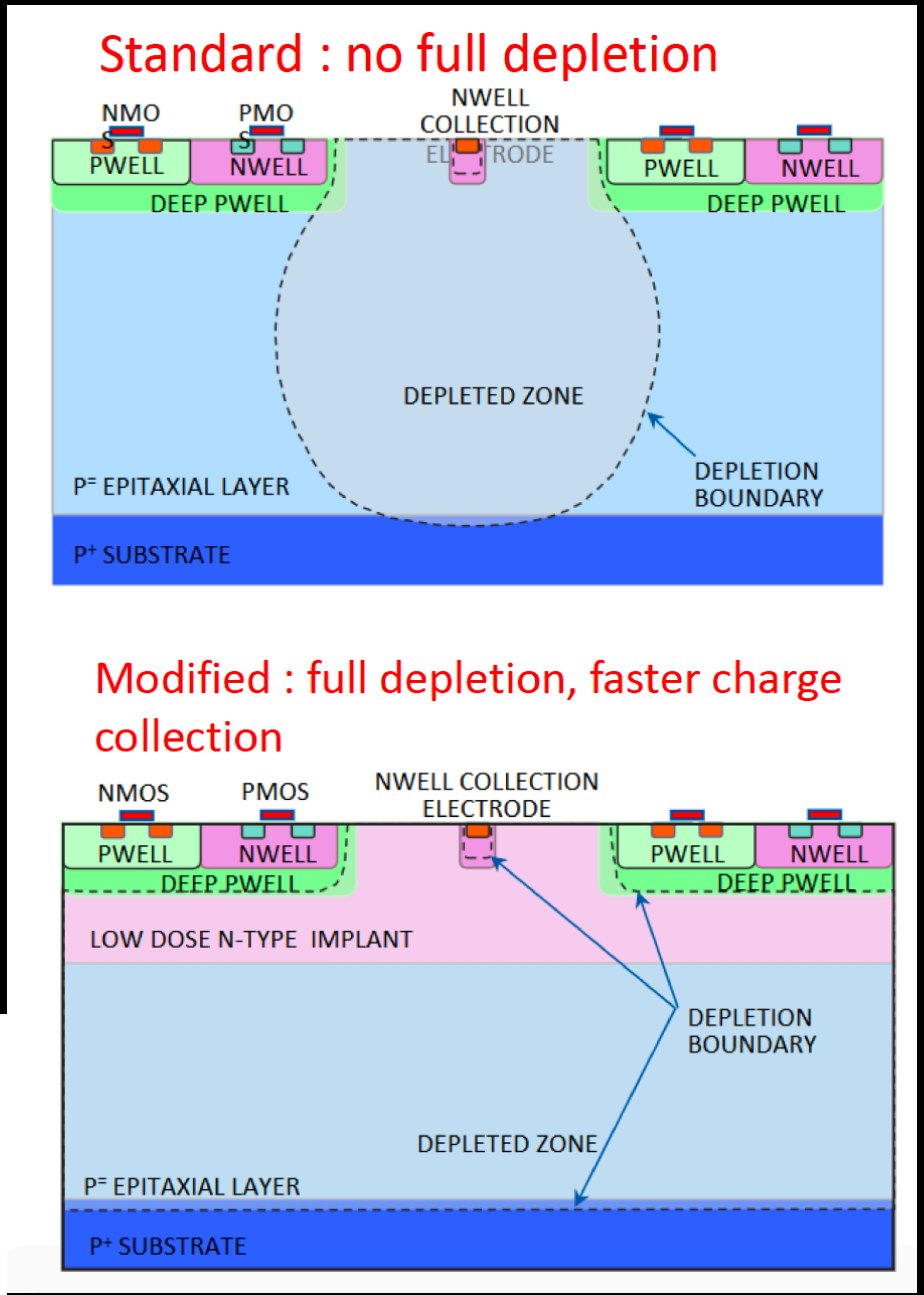
CEPC vertex detector prototype



Taichu chip readout



CMOS MAPS sensor

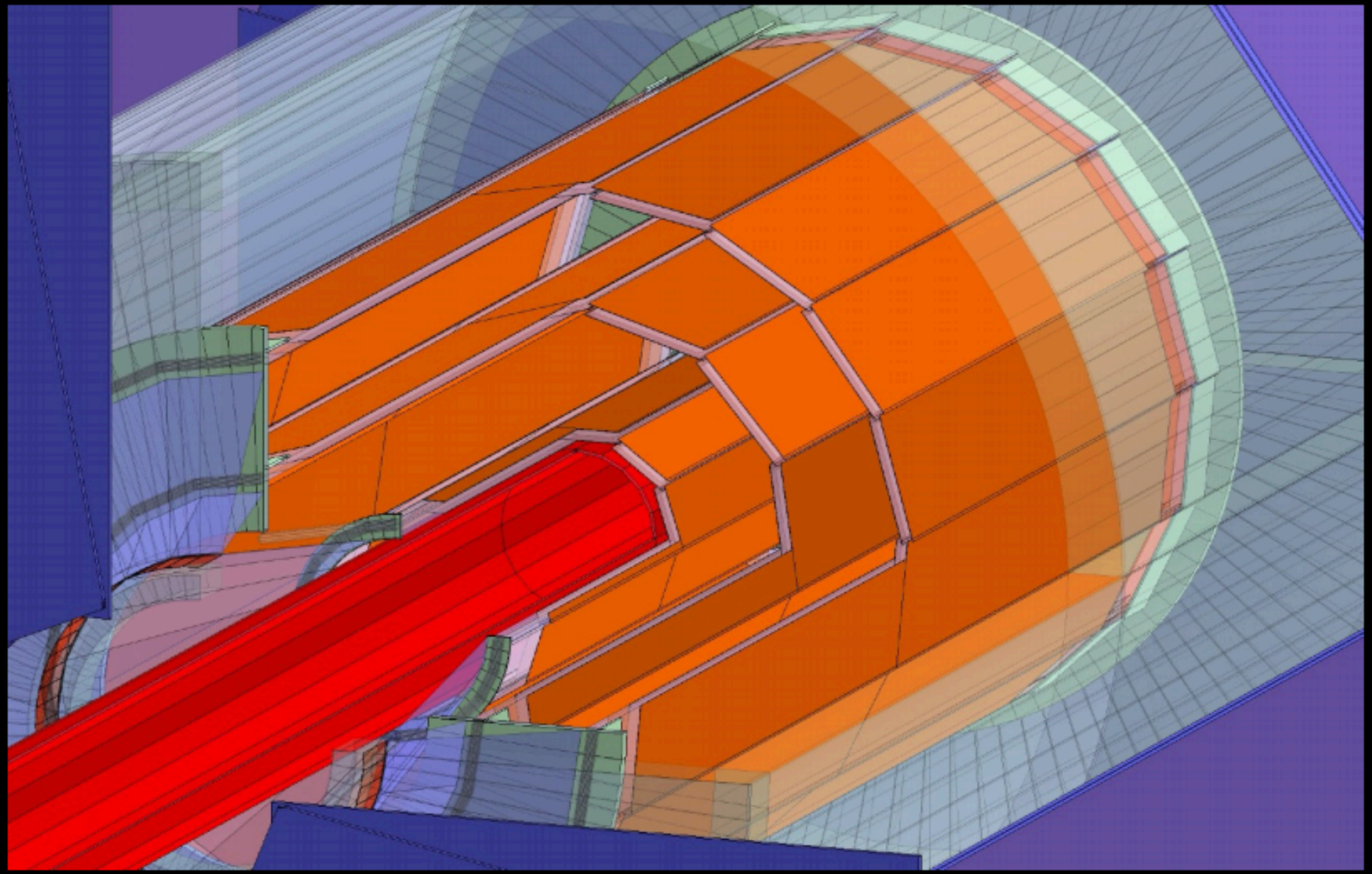


	Resolution	Readout Speed	TID	Power Consumption
Taichu-1 (TJ 180nm)	3~5μm	~50ns@40MHz Digital readout	Te be tested	100~200mW/cm2

Challenges in vertex detectors

Vertex detector design driven by needs of flavor tagging

- Extremely accurate/precise
- Extremely light



Large surfaces: ~ 1 m^2

Single point resolution
$\sigma < 3 - 5\ \mu m$
→ Pixel pitch
~ 16 – 25 μm

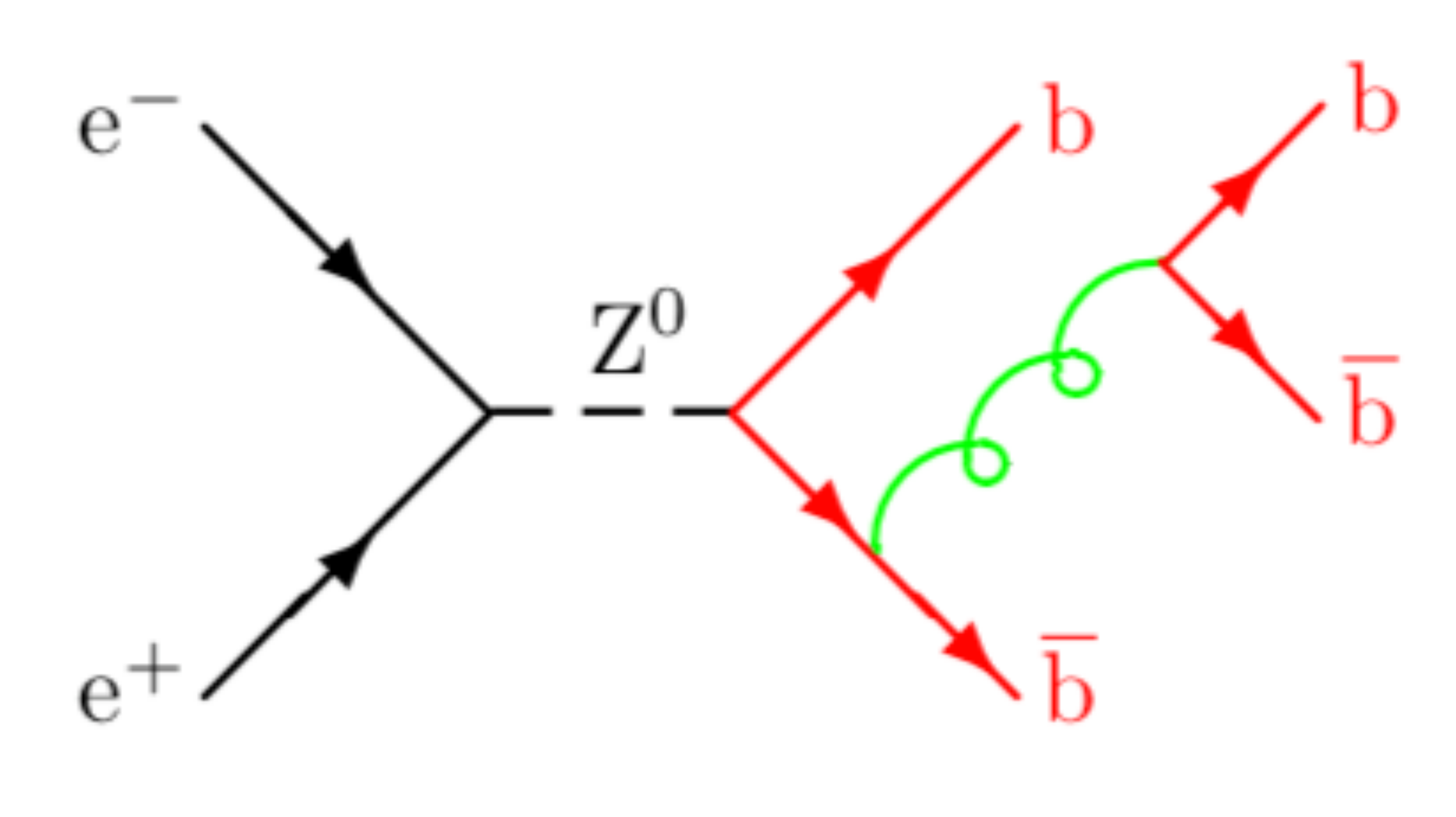
Low material budget
< 0.1 — 0.3% X_0 per layer
→ Thin sensors and ASICs
Light-weight support
→ Power pulsing (LC)
Air cooling
→ Low power dissipation
≤ 50 mW/cm^2

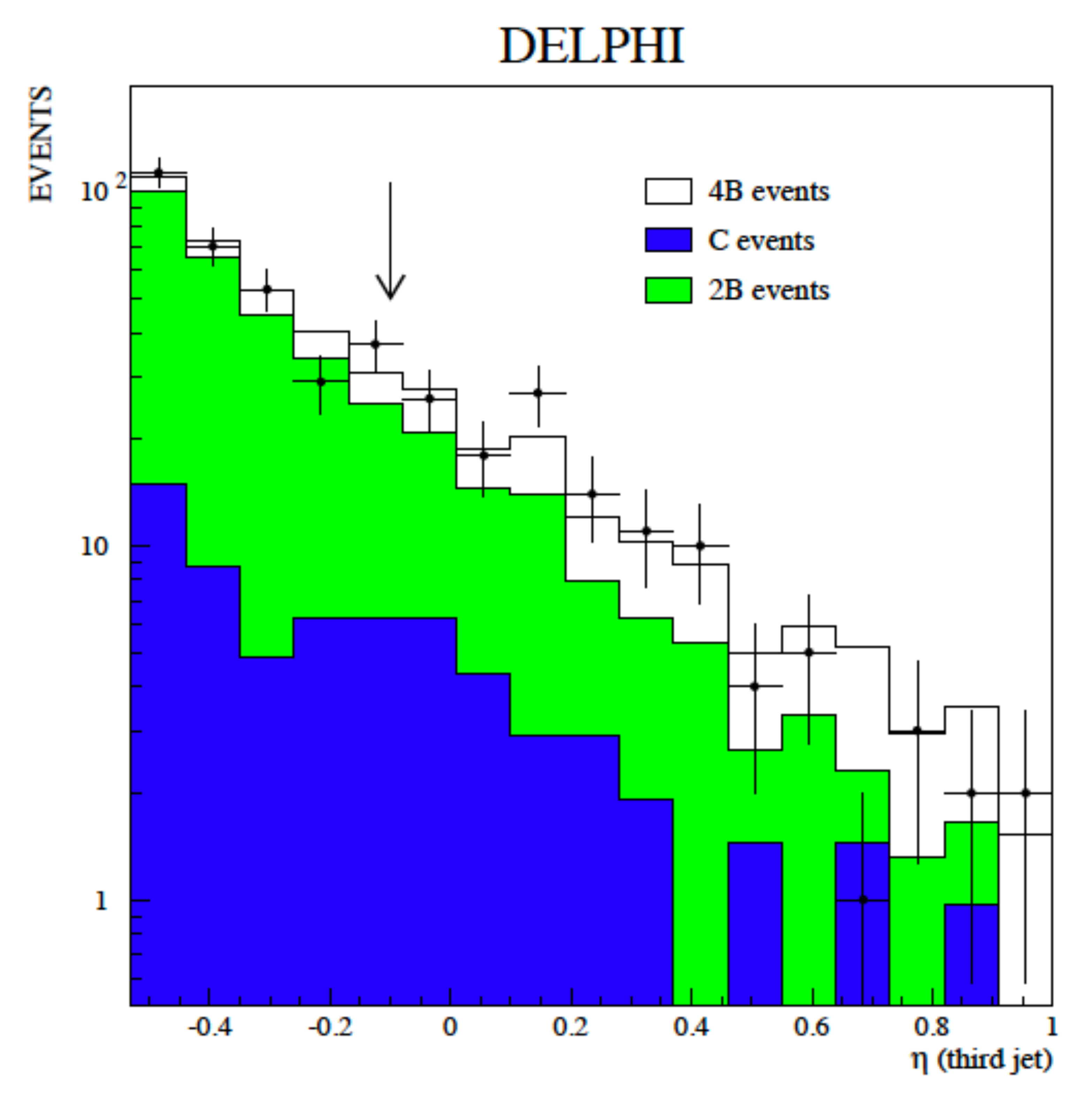
Time stamping
~10 ns (CLIC)
~300 ns — μs (ILC/CC)

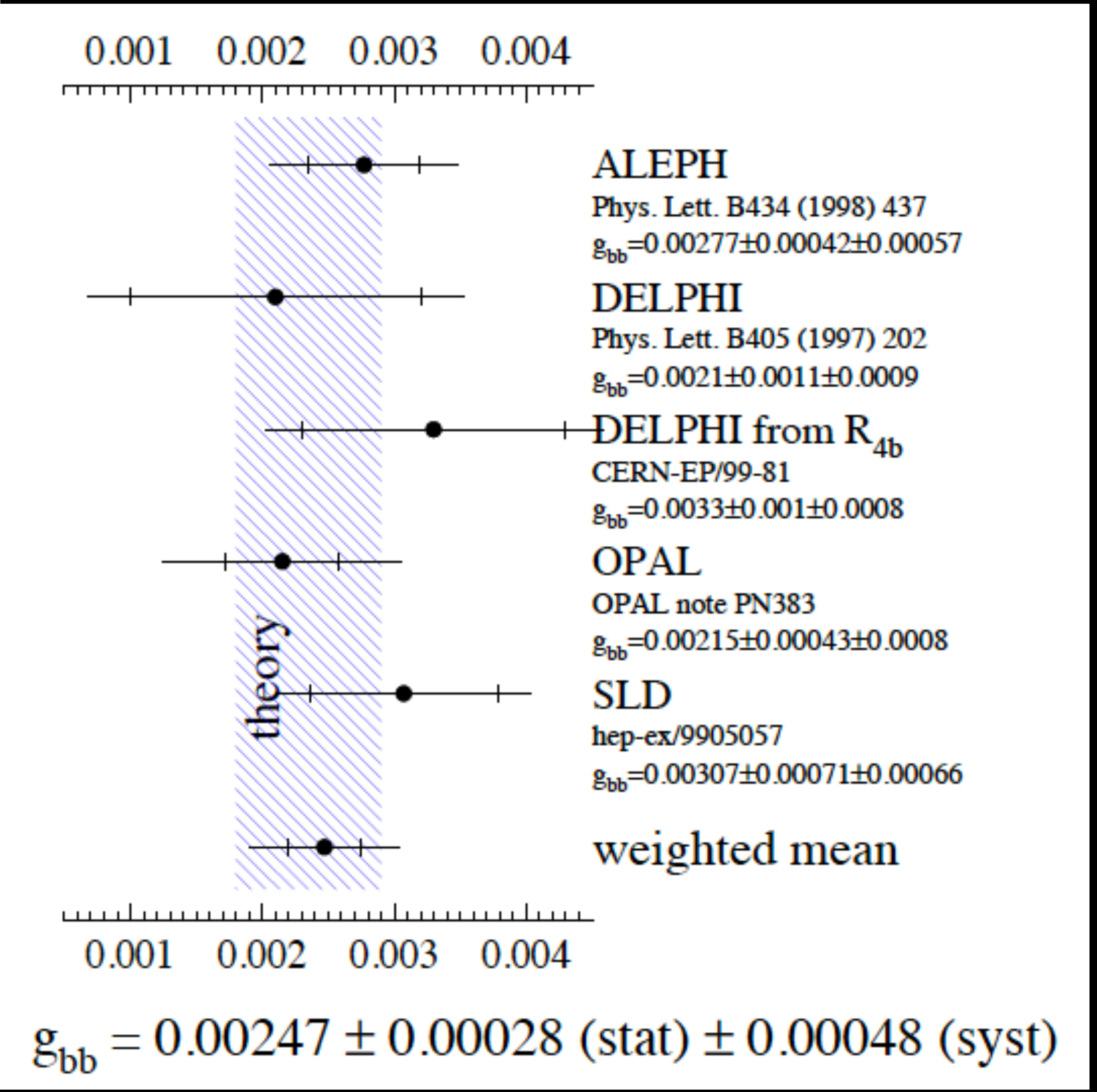
Circular colliders: continuous operation → more cooling → more material

R^b: gluon splitting

- Gluon splitting systematics is estimated by comparing data and MC simulation







DELPHI Z->4b analysis
Gluon splitting measurements

Detector requirement at Z pole

- Most of detector requirement is based on Higgs physics at ZH run
- New requirement for Z pole
  - Particle identification requested by flavor physics (k/π separation , π0/γ separation)
  - Detector timing (Z pole @40MHz collision)

Physics process	Measurands	Detector subsystem	Performance requirement	From CDR
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) =$ $2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$	Too tight?
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} =$ $5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta}(\mu\mathrm{m})$	Not enough?
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E =$ $3 \sim 4\%$ at 100 GeV	Too tight?
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E =$ $\frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$	Not enough?

R^b: charm modelling and lepton ID

- Charm modelling : depends on input from flavor experiments (BELLEII…)
  - C hadron fractions (factions of D^+, D^0, D^+_s) → 0.2% syst. In R^b
  - LEP: Tagging efficiency for D+ is three times higher than D0
  - Need more study to check D meson tagging efficiency in Fcc-ee/CEPC

Source	$\Delta\epsilon^c/\epsilon^c$ (%)	$\Delta\epsilon^{uds}/\epsilon^{uds}$ (%)	ΔR_b
c hadron production fractions	3.66	-	0.00046
c hadron lifetimes	0.55	-	0.00007
c charged decay multiplicity	1.09	-	0.00014
c neutral decay multiplicity	2.39	-	0.00030
Branching fraction $B(D \to K^0)$	1.20	-	0.00015
c semileptonic branching fraction	2.44	-	0.00031
c semileptonic decay modelling	2.34	-	0.00029