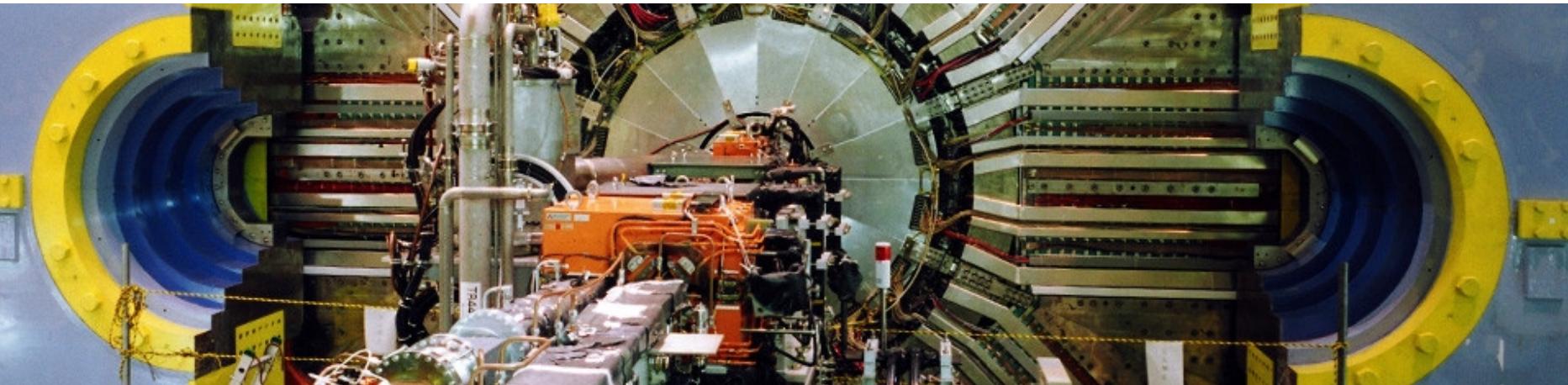


Towards a Precision Measurement of the Muon Pair Asymmetry in e^+e^- Annihilation at Belle and Belle 2



15th Meeting of the Radio Monte CarLow Working Group, Mainz

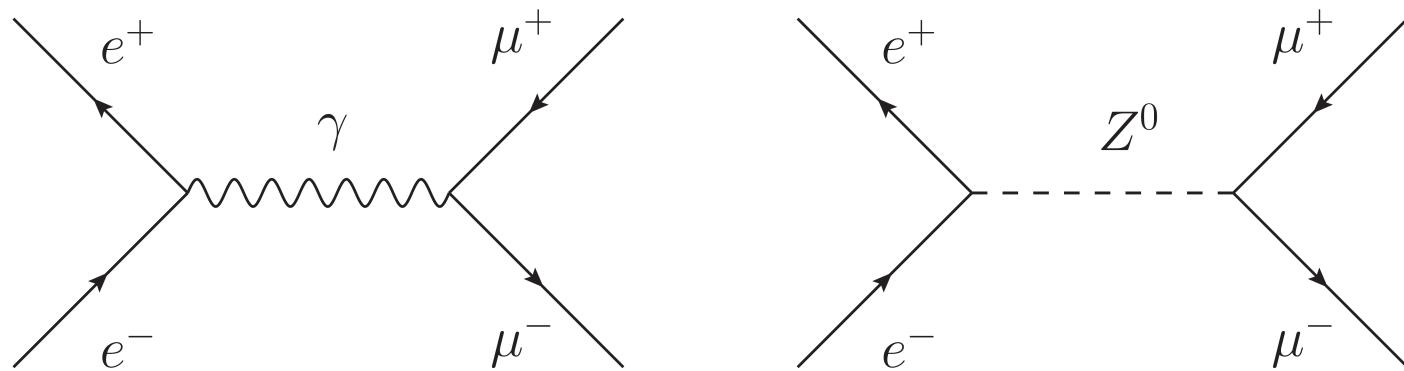
Torben Ferber (torben.ferber@desy.de)

11.04.2014

Outline

- Motivation: $e^+e^- \rightarrow \mu^+\mu^-$
- Basics: Belle at KEKB
- Event selection and backgrounds
- Experimental challenges
- Generator and theory status and needs

Motivation: $e^+e^- \rightarrow \mu^+\mu^-$ at Belle



➤ Typical observables for $e^+e^- \rightarrow \mu^+\mu^-$:

- Total and/or differential cross section
- Forward-backward charge asymmetry A_{FB}

➤ At Belle: $\sim 1\text{ab}^{-1}$ (@ $\sim 10.58\text{GeV}$) = $10^9 \mu\mu$

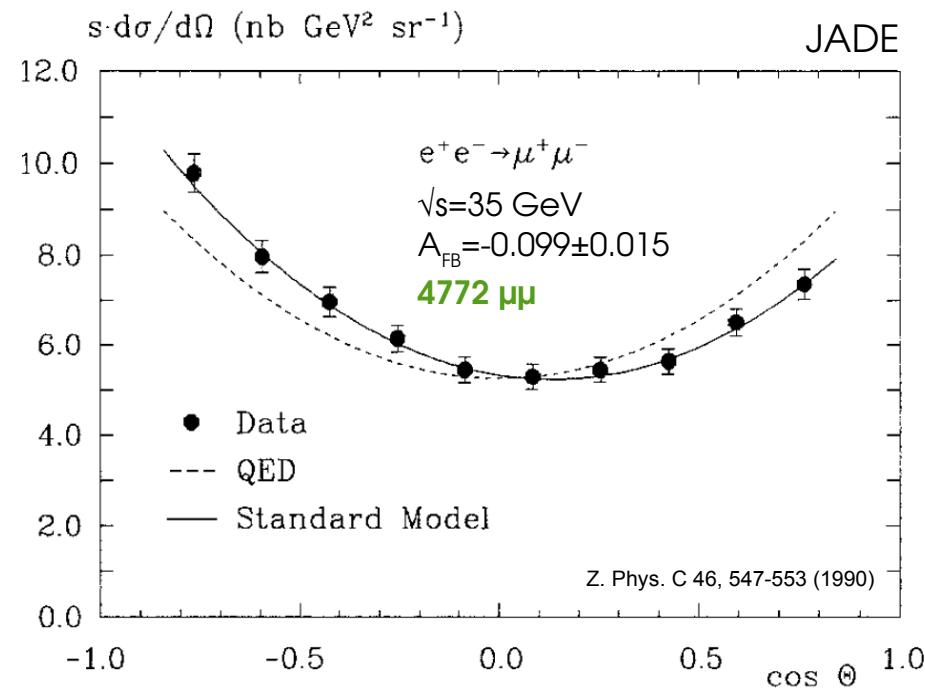
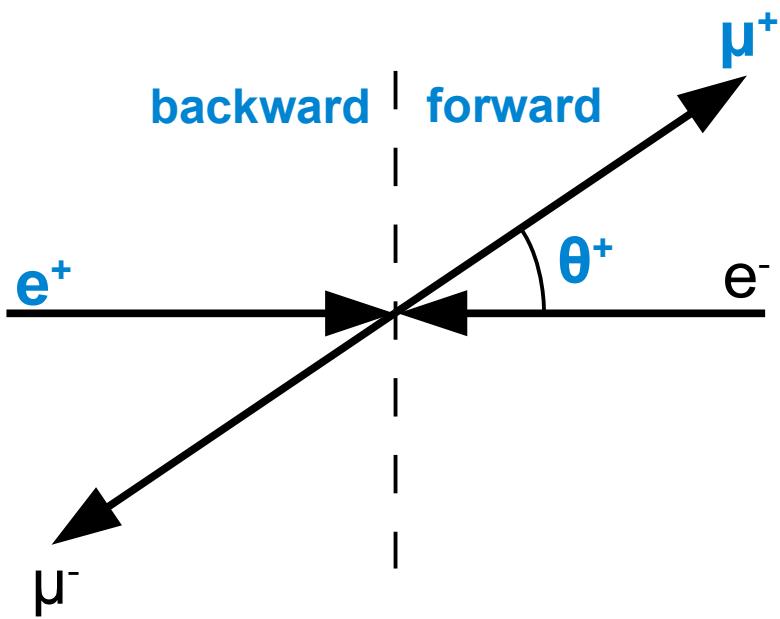
➤ At Belle2: 50ab^{-1} by 2023 = $50 \times 10^9 \mu\mu$

Motivation: A_{FB}

► Define observable:
Forward-backward asymmetry

$$A_{FB} = (F - B) / (F + B), F = \cos(\theta^{+/-}) > 0, B = \cos(\theta^{+/-}) < 0$$

center of mass system



Motivation: Improved Born below Z-pole

$$\begin{aligned} \frac{2s}{\pi} \frac{d\sigma}{d\cos(\theta)} (\text{e}^+ \text{e}^- \rightarrow \mu^+ \mu^-) = \\ \underbrace{|\alpha(s)|^2 (1 + \cos^2(\theta))}_{\sigma^\gamma} \\ + \underbrace{8\Re(\alpha^*(s)\chi(s)(\mathcal{G}_{ve}\mathcal{G}_{v\mu}(1 + \cos^2(\theta)) + 2\mathcal{G}_{ae}\mathcal{G}_{a\mu}\cos(\theta)))}_{\sigma^{\gamma-Z}} \\ + 16|\chi(s)|^2((|\mathcal{G}_{ve}|^2 + |\mathcal{G}_{ae}|^2)(|\mathcal{G}_{v\mu}|^2 + |\mathcal{G}_{a\mu}|^2)(1 + \cos^2(\theta)) \\ + \underbrace{8\Re(\mathcal{G}_{ve}\mathcal{G}_{ae}^*)\Re(\mathcal{G}_{v\mu}\mathcal{G}_{a\mu}^*)\cos(\theta))}_{\sigma^Z}, \end{aligned}$$

with

$$\chi(s) = \rho \frac{G_F m_Z^2}{8\pi\sqrt{2}} \frac{s}{s - m_Z^2 + is\Gamma_Z/m_Z},$$

Motivation: Improved Born below Z-pole

$$\frac{2s}{\pi} \frac{d\sigma}{d\cos(\theta)} (e^+ e^- \rightarrow \mu^+ \mu^-) =$$
$$\underbrace{|\alpha(s)|^2 (1 - \cos(\theta))}_{\sigma^\gamma} \text{ symmetric}$$
$$+ 8\Re \left(\alpha^*(s)\chi(s) (\mathcal{G}_{ve}\mathcal{G}_{v\mu}(1 - \cos(\theta)) + 2\mathcal{G}_{ae}\mathcal{G}_{a\mu} \cos(\theta)) \right) \text{ symmetric}$$
$$+ 16|\chi(s)|^2 ((|\mathcal{G}_{ve}|^2 + |\mathcal{G}_{ae}|^2) (|\mathcal{G}_{v\mu}|^2 + |\mathcal{G}_{a\mu}|^2) (1 + \cos^2(\theta))$$
$$+ 8\Re \left(\chi(s) (\mathcal{G}_{v\mu}\mathcal{G}_{a\mu}^* + \mathcal{G}_{a\mu}\mathcal{G}_{v\mu}^*) \cos(\theta) \right), \text{ negligible at } \sqrt{s} < m_Z$$
$$\underbrace{\sigma_Z}_{\sigma^\gamma - Z}$$

with

$$\chi(s) = \rho \frac{G_F m_Z^2}{8\pi\sqrt{2}} \frac{s}{s - m_Z^2 + is\Gamma_Z/m_Z},$$

Motivation: Improved Born below Z-pole

$$\frac{2s}{\pi} \frac{d\sigma}{d\cos(\theta)} (e^+ e^- \rightarrow \mu^+ \mu^-) =$$

$|\alpha(s)|^2 (1 - \chi(s))$

symmetric

interference term

$$+ 8\Re (\alpha^*(s)\chi(s)(G_{ve}G_{v\mu}(1 - \chi(s)) + 2G_{ae}G_{a\mu}\cos(\theta)))$$

$\sigma \gamma - Z$

symmetric

$$+ 16|\chi(s)|^2((|G_{ve}|^2 + |G_{ae}|^2)(|G_{v\mu}|^2 + |G_{a\mu}|^2)(1 + \cos^2(\theta))$$

negligible at $\sqrt{s} < m_Z$

$$+ 8\Re (\alpha^*(s)v_\mu G_{a\mu}^*)\cos(\theta)),$$

σZ

with

$$\chi(s) = \rho \frac{G_F m_Z^2}{8\pi\sqrt{2}} \frac{s}{s - m_Z^2 + is\Gamma_Z/m_Z},$$

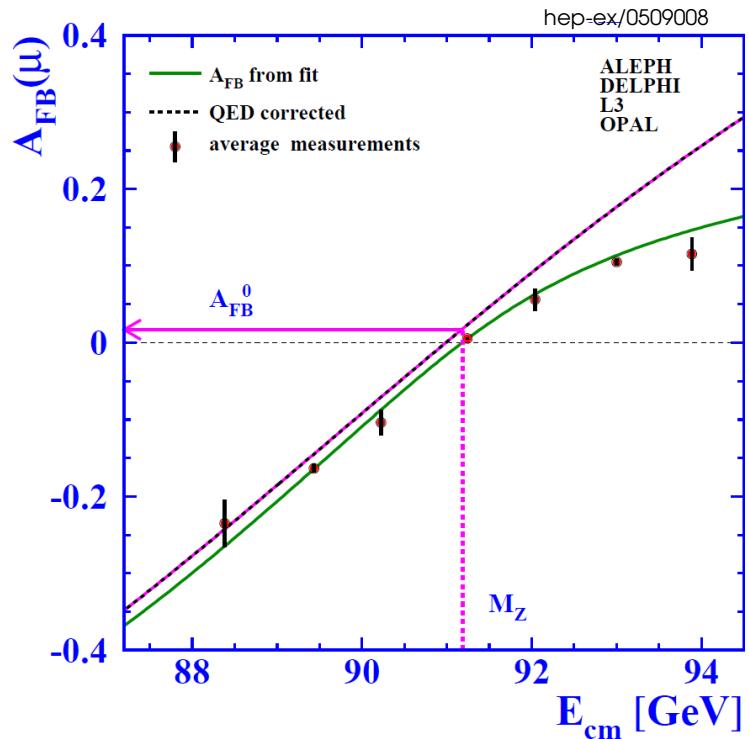
Motivation: The past

► at the Z-pole:

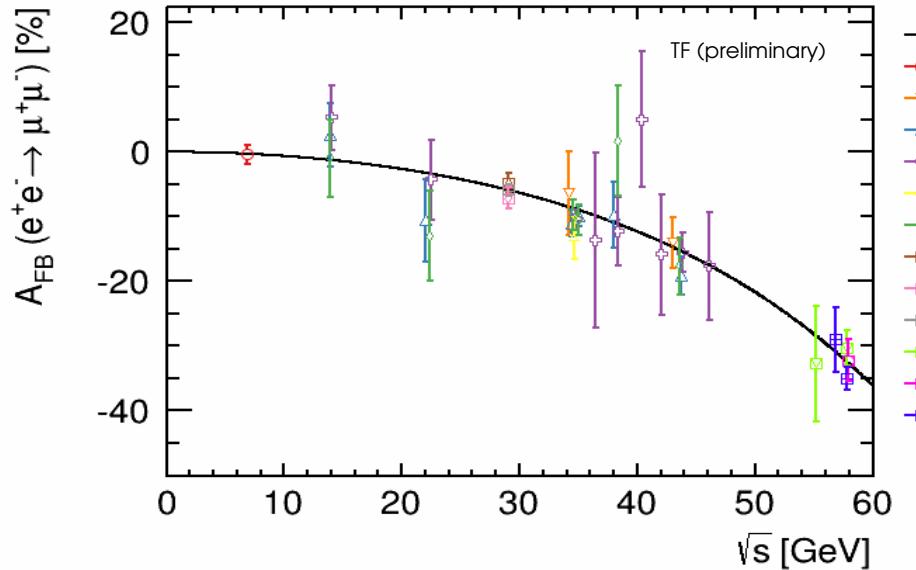
- $A_{FB} \sim g_V^2 g_A^2 / (g_V^2 + g_A^2)^2$
(i.e. the “Z-term” of
the Born cross section)

► below the Z-pole:

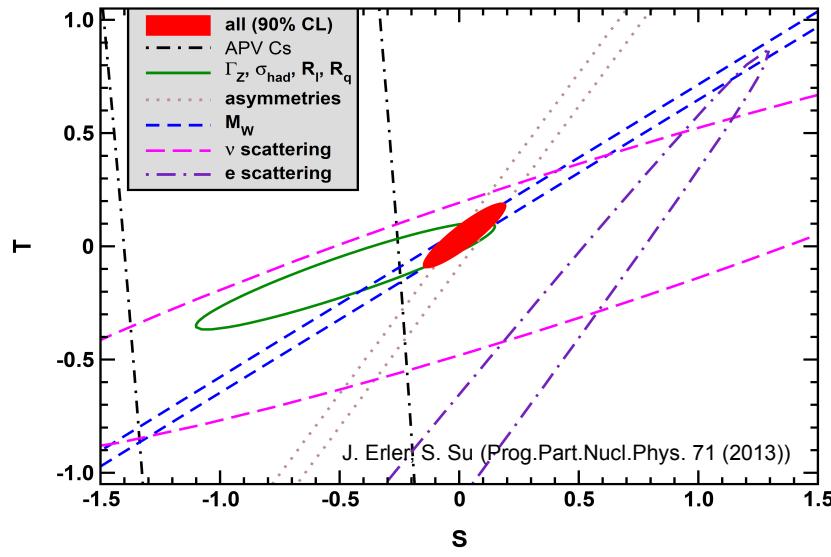
- $A_{FB} \sim \rho g_A g_A$ (interference term)
- Typical rel. unc. 10%, down to ~5% at ~58GeV (VENUS@TRISTAN)
- Typical backgrounds ~1%
- “Traditional” tension between A_{FB} and total cross section



Motivation: Oblique parameter T

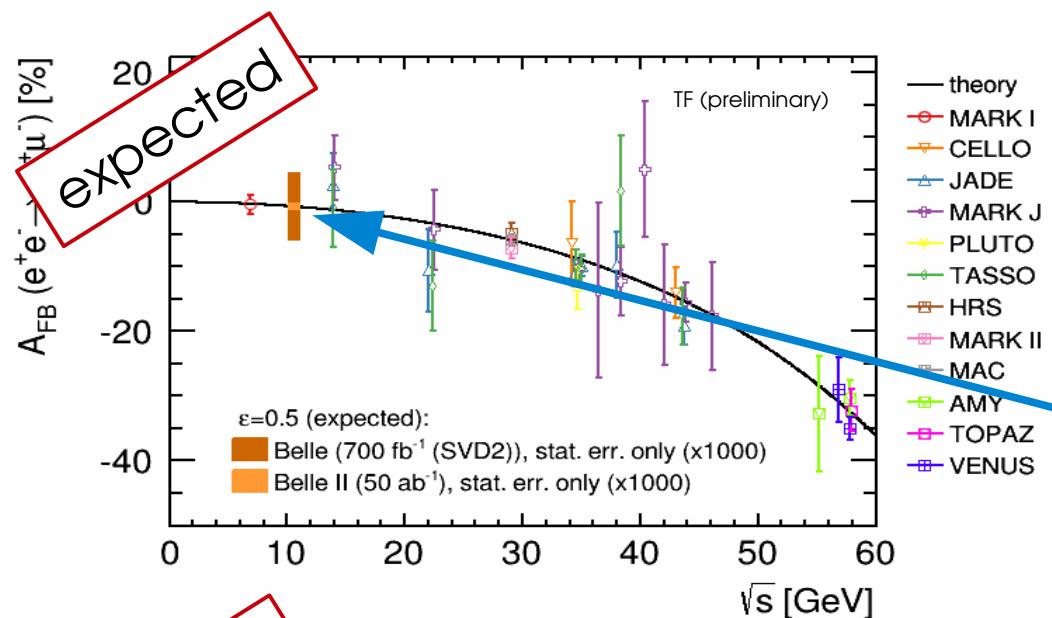


$$\mathcal{A}_{FB}(s) \approx \rho \frac{3G_F}{4\sqrt{2}\pi\alpha} \frac{sM_Z^2}{s - M_z^2} g_A^e g_A^\mu$$



$$\Delta\rho^{\text{new}} = \frac{\hat{\Pi}_{WW}^{\text{new}}(0) - \hat{c}_Z^2 \hat{\Pi}_{ZZ}^{\text{new}}(0)}{M_W^2(1 - \Delta\hat{r}_W)} \equiv \frac{\alpha T}{1 - \Delta\hat{r}_W} \approx \hat{\alpha}_Z T$$

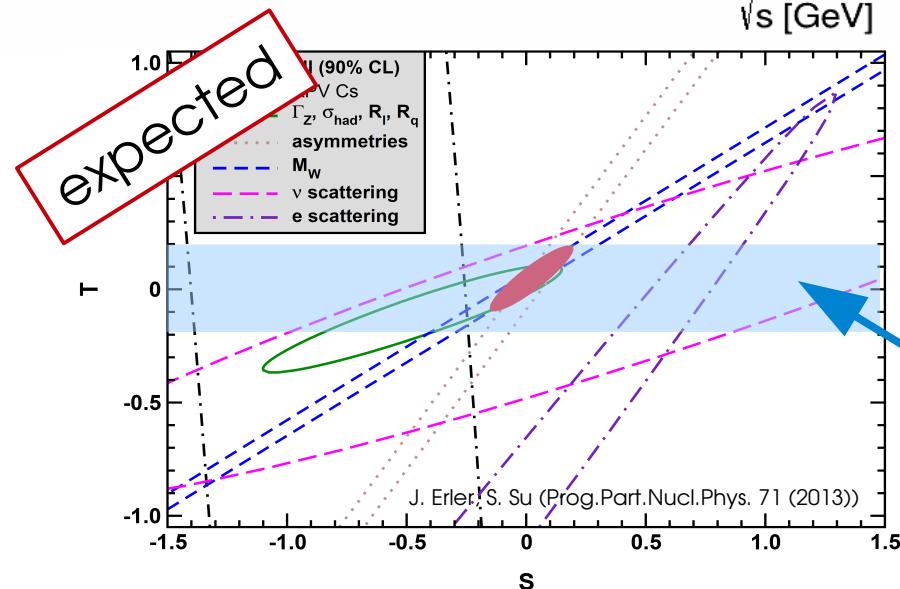
Motivation: Oblique parameter T



$$\mathcal{A}_{FB}(s) \approx \rho \frac{3G_F}{4\sqrt{2}\pi\alpha} \frac{sM_Z^2}{s - M_z^2} g_A^e g_A^\mu$$

Belle: $A_{FB} \approx -0.75\%$

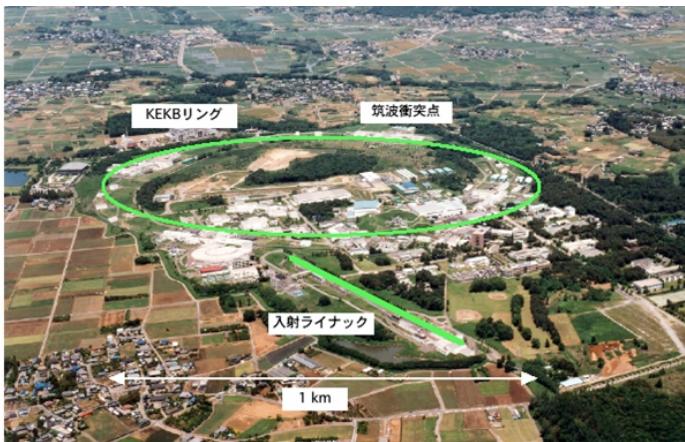
$\sigma_{\text{stat}}(A_{FB})/A_{FB} \approx 1\%$



$$\Delta\rho^{\text{new}} = \frac{\hat{\Pi}_{WW}^{\text{new}}(0) - \hat{c}_Z^2 \hat{\Pi}_{ZZ}^{\text{new}}(0)}{M_W^2(1 - \Delta\hat{r}_W)} \equiv \frac{\alpha T}{1 - \Delta\hat{r}_W} \approx \hat{\alpha}_Z T$$

Belle 2: $\sigma_{\text{stat}}(A_{FB})/A_{FB} \approx 0.1\%$

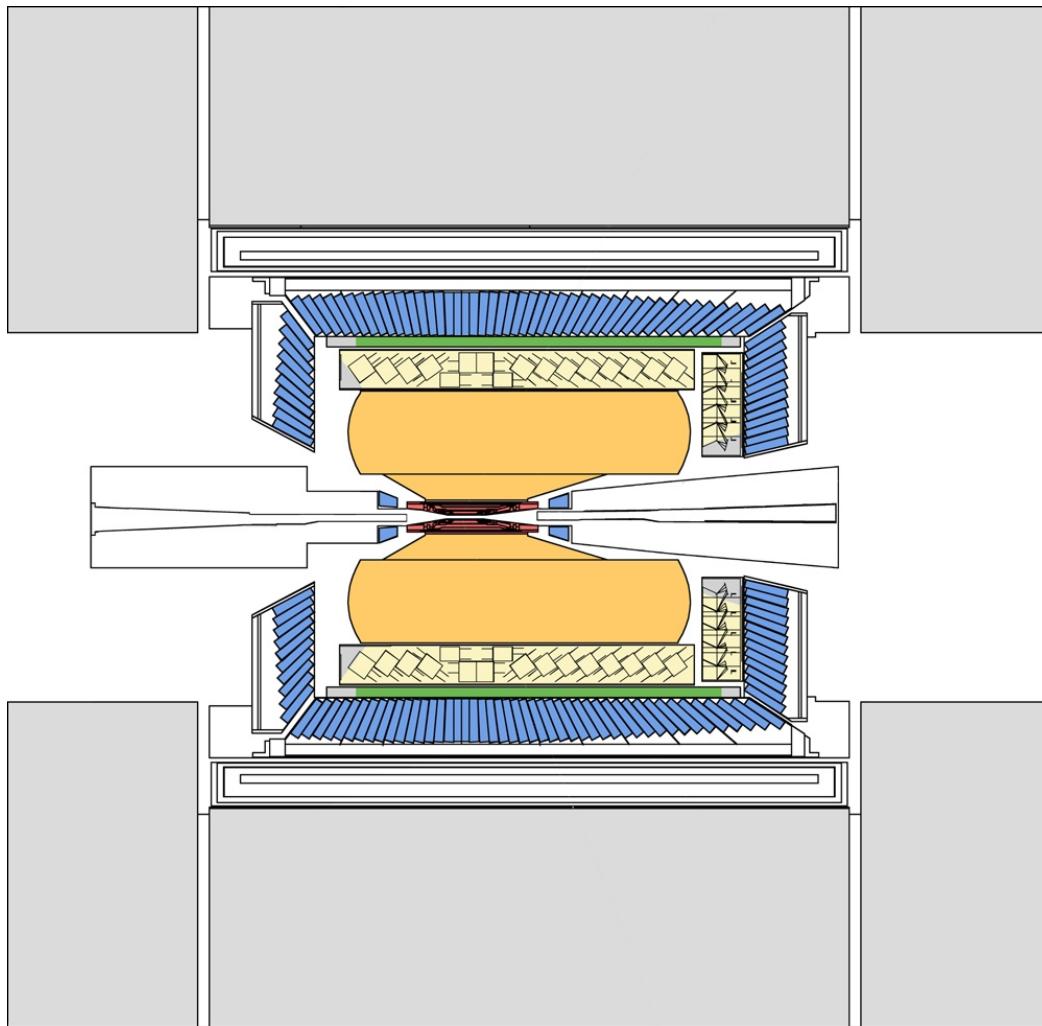
Belle at KEKB in Japan



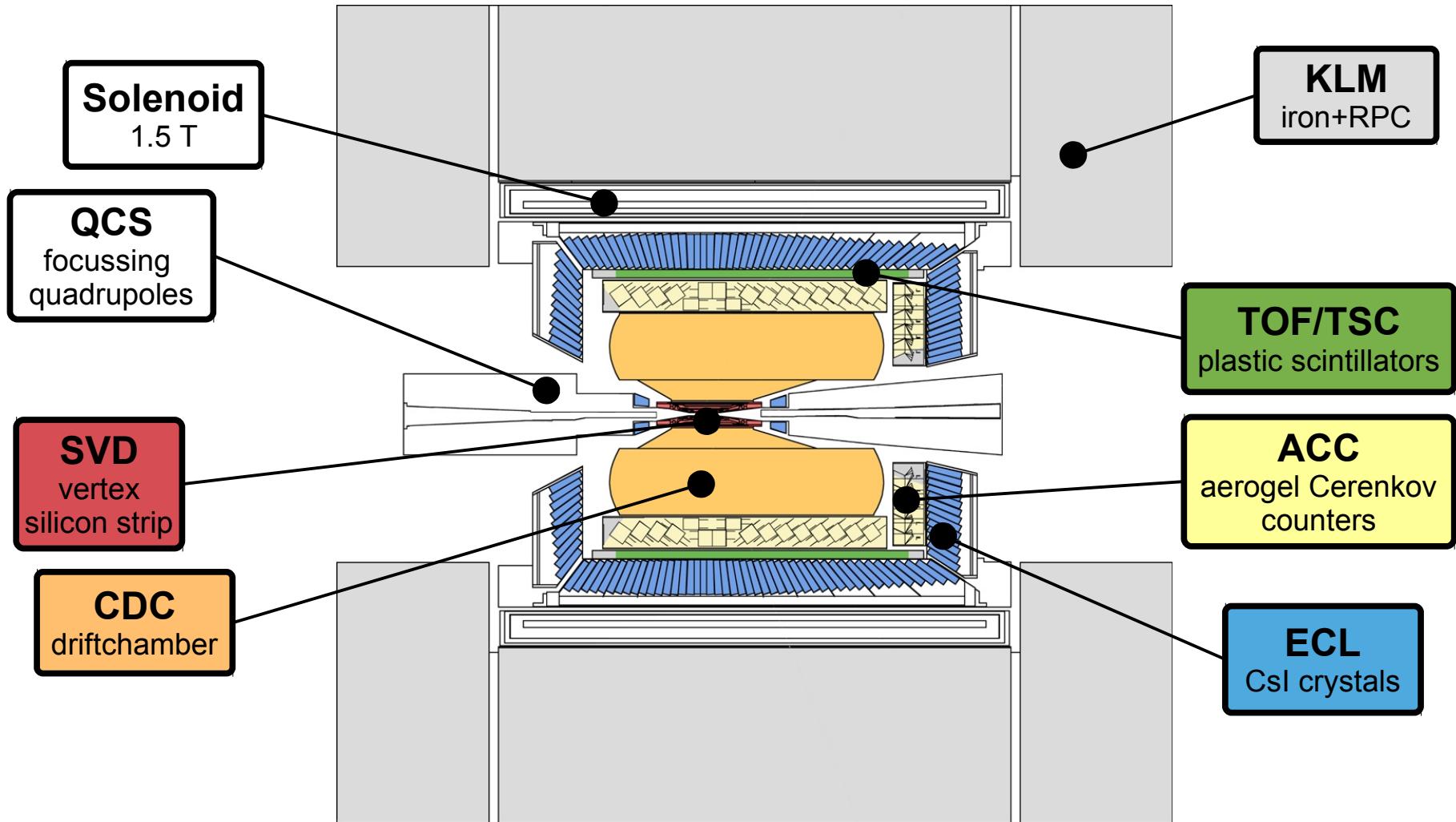
- Asymmetric (3.5GeV/8GeV) e^+e^- collider at KEK (Japan)
- Data taking until 2010
- Main physics:
rare decays and CPV (B, D)
- Integrated luminosity: $\sim 1\text{ab}^{-1}$
 - $770 \times 10^6 B\bar{B}$ pairs at $\Upsilon(4S)$
 - $1100 \times 10^6 \mu\bar{\mu}$ pairs



The Belle detector



The Belle detector



Experimental strategy

$$\mathcal{A}_{FB}^{\text{visible}} = \mathcal{A}_{FB}^{\text{EW}} + \Delta\mathcal{A}_{FB}^{\text{QED}} + \Delta\mathcal{A}_{FB}^{\text{detector}} + \Delta\mathcal{A}_{FB}^{\text{background}}$$

Event selection for $e^+e^- \rightarrow \mu^+\mu^-$

Using the full unskimmed SVD2 Belle data set ($\sim 0.7\text{ab}^{-1}$, 150TB@DESY)!

$$\mathcal{A}_{FB}^{\text{visible}} = \mathcal{A}_{FB}^{\text{EW}} + \Delta\mathcal{A}_{FB}^{\text{QED}} + \Delta\mathcal{A}_{FB}^{\text{detector}} + \Delta\mathcal{A}_{FB}^{\text{background}}$$

- Acollinearity
- Invariant mass (s')
- Acceptance $|\cos(\theta)|$

- Avoid edges
- Uniform trigger
- Uniform PID

- Remove Bhabha
- Remove cosmics
- Two photon
- $\tau^+\tau^-$



Event selection for $e^+e^- \rightarrow \mu^+\mu^-$

➤ $2 \leq n_{\text{tracks}} \leq 4$ with CDC hits

- $dz < 5\text{cm}$, $dr < 0.5\text{cm}$, no vertexfit

➤ $p^{\text{CM}} > 0.5 E_{\text{beam}}$

➤ Opposite charge

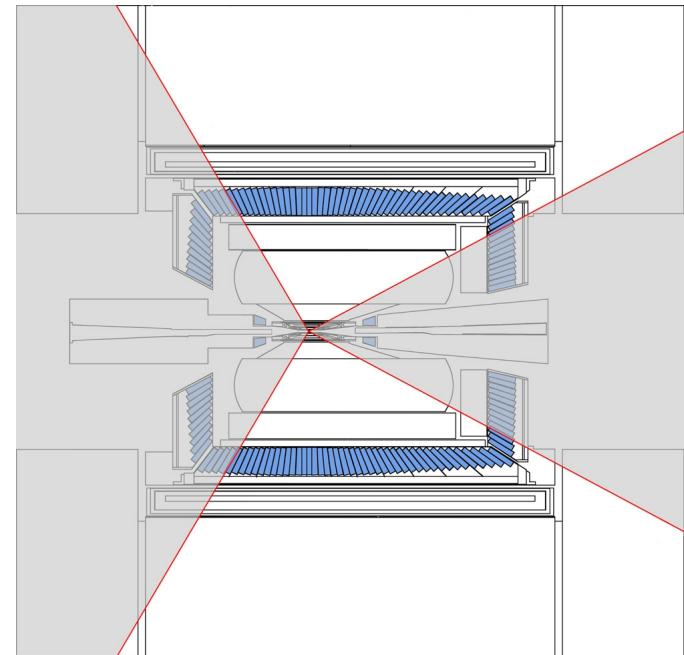
➤ Acollinearity^{CM} $< 10^\circ$

➤ $| \cos(\theta) | < 0.75$

➤ PID: ECL, dE/dx and KLM

➤ $\Delta\text{TOF} < 5\text{ns}$ (if available)

→ Signal efficiency: 43% (tight PID)



Experimental strategy

$$\mathcal{A}_{FB}^{\text{visible}} = \mathcal{A}_{FB}^{\text{EW}} + \Delta\mathcal{A}_{FB}^{\text{QED}} + \Delta\mathcal{A}_{FB}^{\text{detector}} + \Delta\mathcal{A}_{FB}^{\text{background}}$$

Backgrounds

> cosmic muons

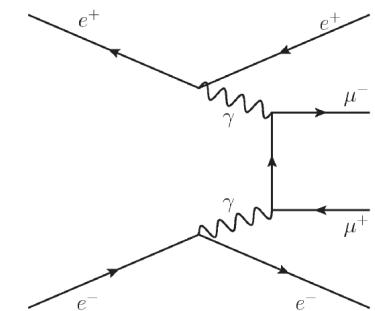
- $A_{FB}(\text{Cosmics})=0$

> $e^+e^- \rightarrow \tau^+\tau^-$ with $\tau \rightarrow \mu\nu\nu$

- $A_{FB}(\tau^+\tau^-)$ the same as $A_{FB}(\mu^+\mu^-)$ in the SM, possible selection bias

> $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ (electrons untagged)

- A_{FB} not well described by our MC (AAFHB)

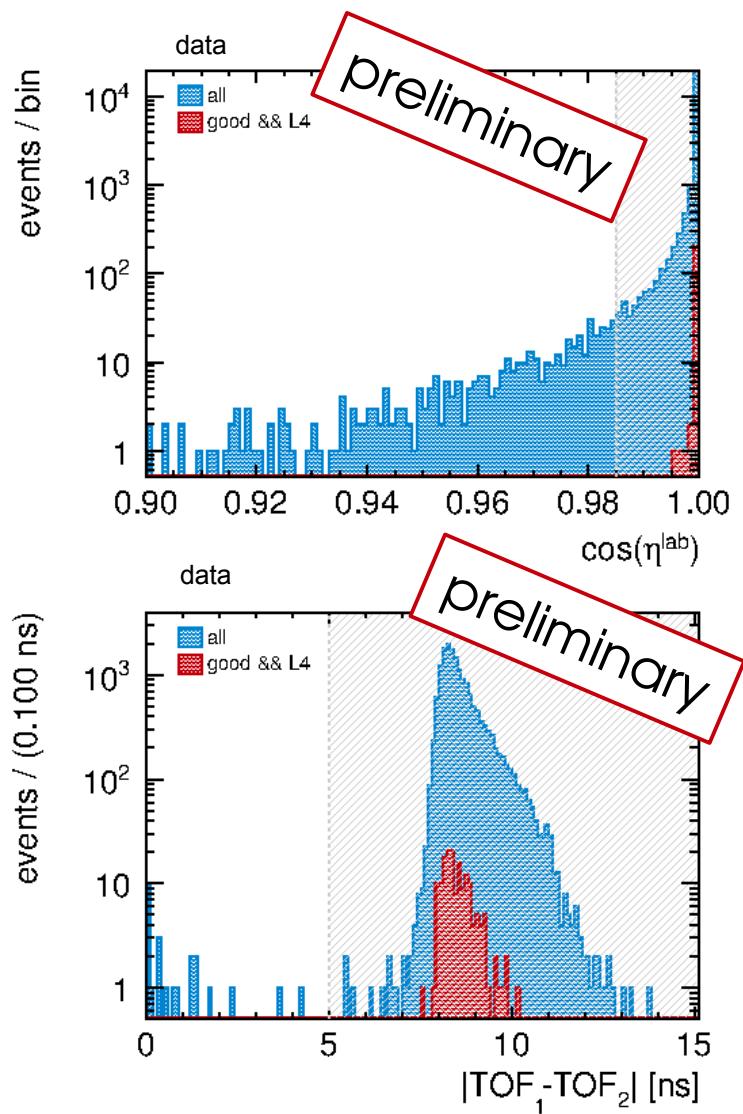
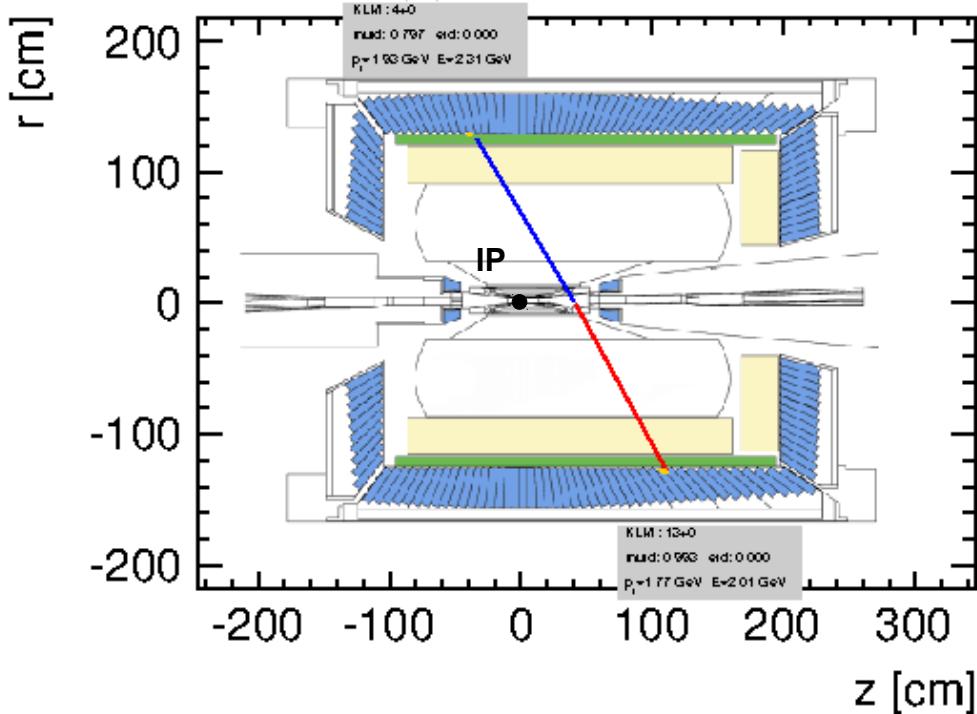


> $e^+e^- \rightarrow e^+e^-$ (Bhabha, electrons misidentified)

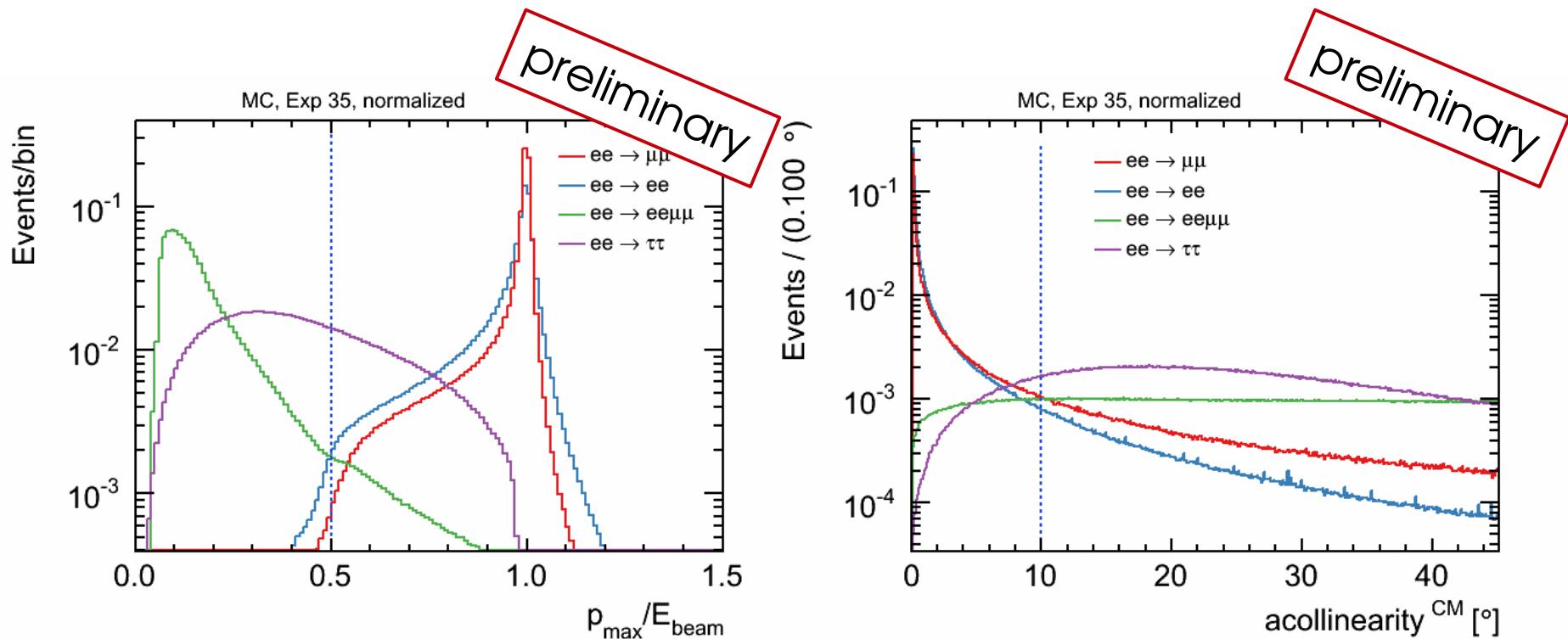
- huge A_{FB} dominated by t-channel QED contribution

Background: Cosmic muons

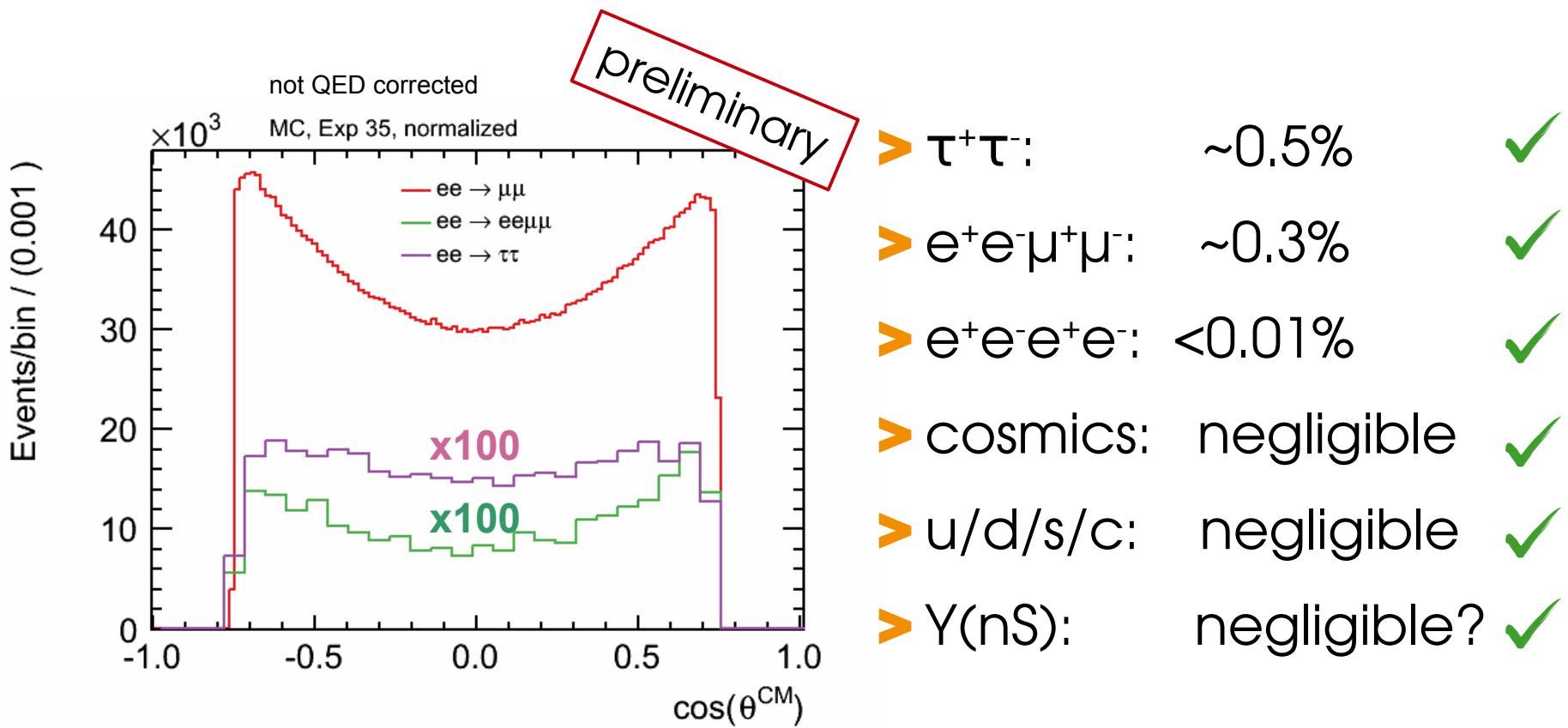
► Cosmic muons negligible after TOF and acollinearity cut



Background



Background

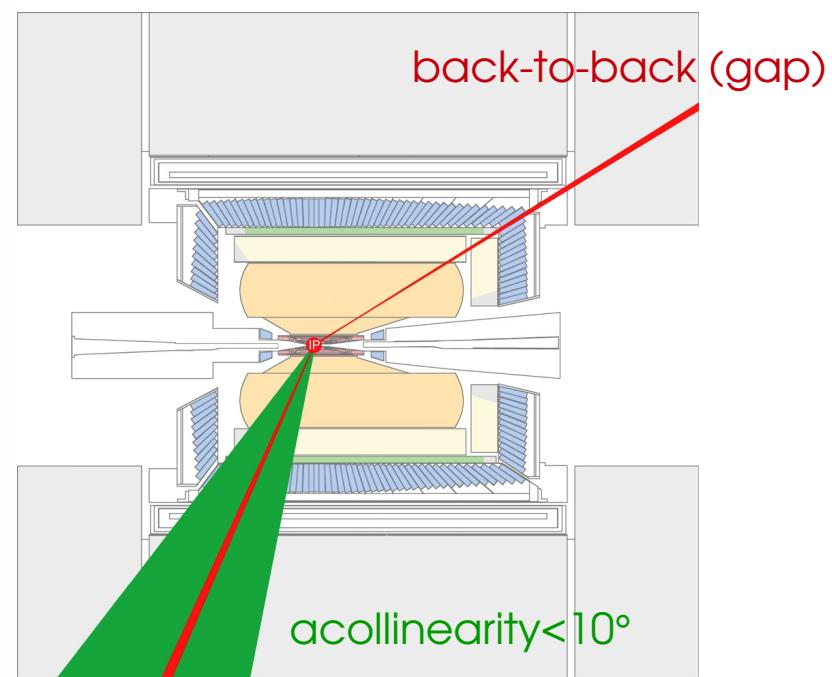
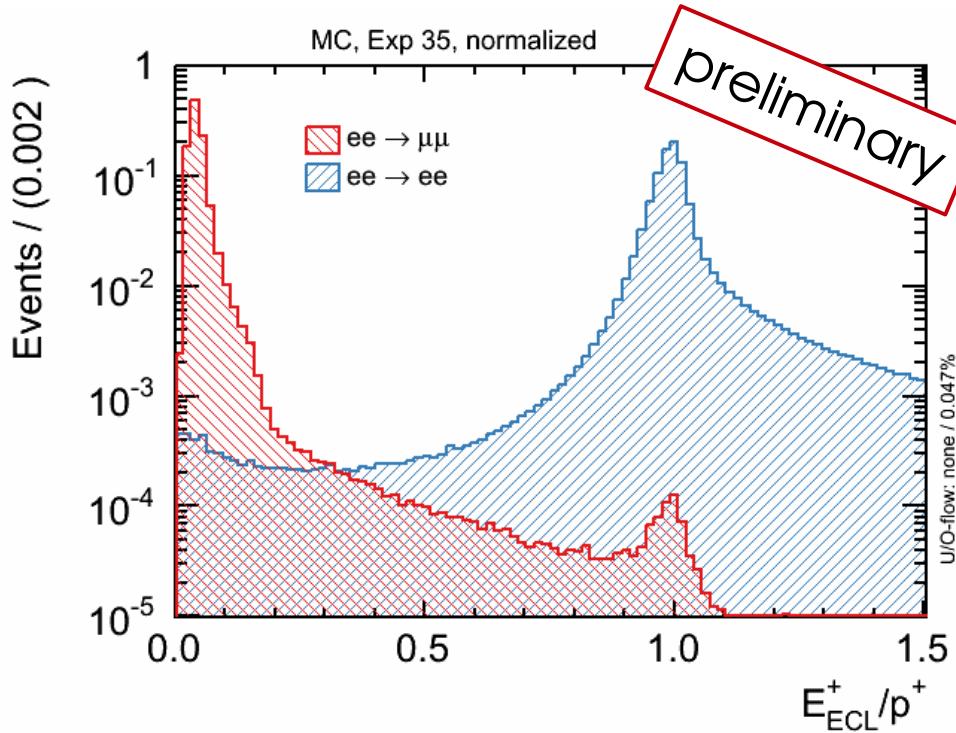


Background: $e^+e^- \rightarrow e^+e^-\gamma$ (Bhabha)

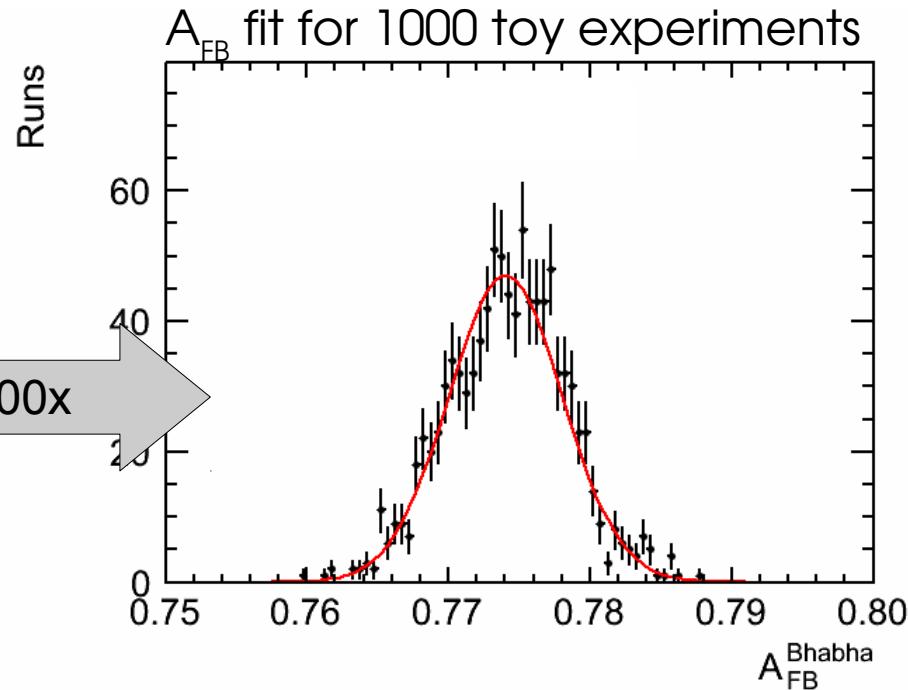
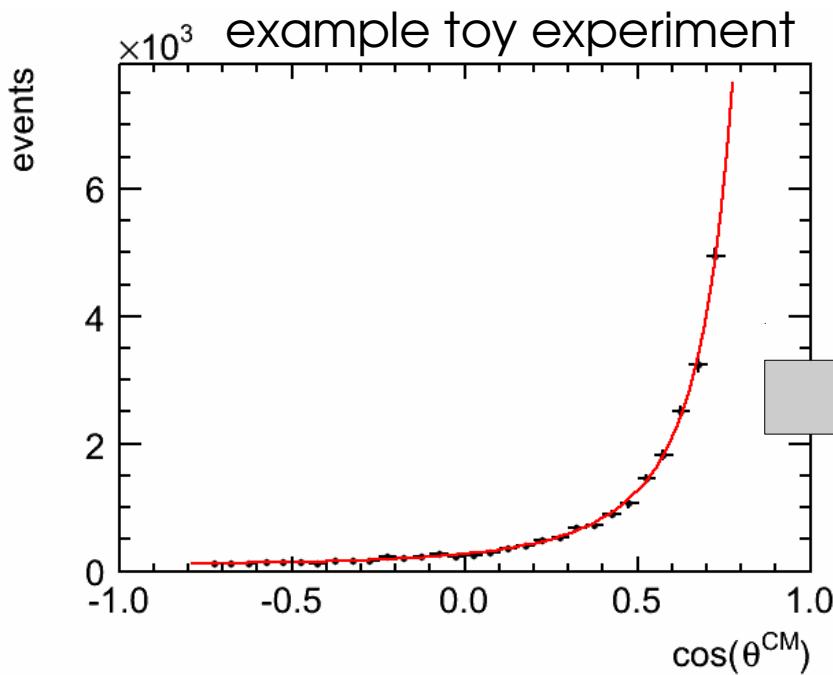
► $\sigma_{ee\gamma} = 125\text{nb}$ ($\theta^{\text{CM}} > 15^\circ$) (compare: $\sigma_{\mu\mu\gamma} = 1.115\text{ nb}$)

► PID $E_{\text{ECL}}/p_{\text{track}} < 0.2$ (both tracks):

- background fraction $w_{ee\gamma} = N_{ee\gamma}/N_{\mu\mu\gamma} = \sim 5 \times 10^{-5}$



Background: $e^+e^- \rightarrow e^+e^-\gamma$ (Bhabha)



Resulting A_{FB} bias from remaining Bhabha background:

$$\Delta A_{FB}(e^+e^- \rightarrow e^+e^-\gamma) = -3.8 \times 10^{-5}$$

$$\sigma(\Delta A_{FB}(e^+e^- \rightarrow e^+e^-\gamma)) = 2.3 \times 10^{-5} \text{ (MC stat.)}$$

$\sigma(\Delta A_{FB})$ currently dominated by uncertainty of background fraction w



Experimental strategy

$$\mathcal{A}_{FB}^{\text{visible}} = \mathcal{A}_{FB}^{\text{EW}} + \Delta\mathcal{A}_{FB}^{\text{QED}} + \Delta\mathcal{A}_{FB}^{\text{detector}} + \Delta\mathcal{A}_{FB}^{\text{background}}$$

Detector

► Mostly cancel (for Φ symmetry):

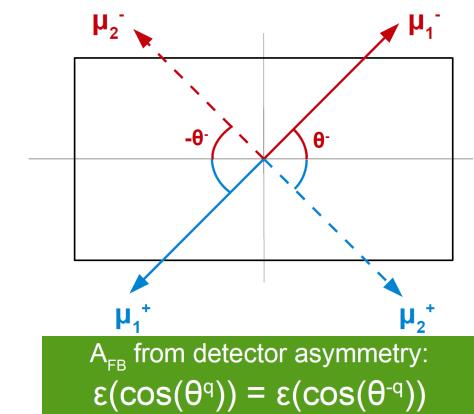
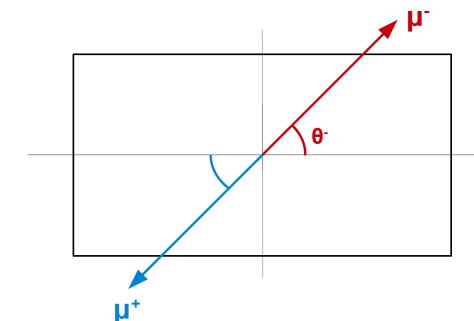
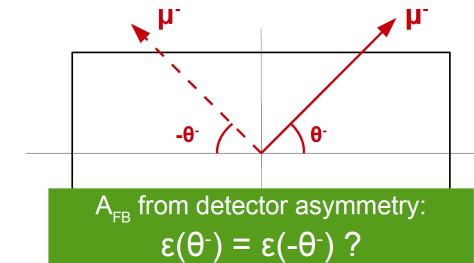
- Charge misidentification
- Tracking efficiency
- Trigger (L1, L3, L4)
- Particle ID

► Do not cancel (even for $\varepsilon^+ = \varepsilon^-$):

- Track resolution

► Other (systematics)

- Beam energy
- Beam energy spread
- Beam polarization



Experimental strategy

$$\mathcal{A}_{FB}^{\text{visible}} = \mathcal{A}_{FB}^{\text{EW}} + \Delta\mathcal{A}_{FB}^{\text{QED}} + \Delta\mathcal{A}_{FB}^{\text{detector}} + \Delta\mathcal{A}_{FB}^{\text{background}}$$

Electroweak radiative corrections

- Use **KKMC**+detector simulation to model acceptance
 - Correct for QED effects:
- $$\varepsilon_i^{QED} = \frac{D_i^{MC}}{D_i^{\text{improved Born}}}$$

Comput. Phys. Commun. 130 (2000) 260
Phys. Rev. D63 (2001) 113009

Feature	KORALB	KORALZ	$\mathcal{K}\mathcal{K}$ 4.13	$\mathcal{K}\mathcal{K}$ 2000+?
QED type	$\mathcal{O}(\alpha)$	EEX	CEEX, EEX	CEEX, EEX
CEEX(ISR+FSR)	none	none	$\{\alpha, \alpha L; \alpha^2 L^2, \alpha^2 L^1\}$	$\{\dots \alpha^2 L^1; \alpha^3 L^3\}$
EEX(ISR*FSR)	none	$\{\alpha, \alpha L, \alpha^2 L^2\}$	$\{\alpha, \alpha L, \alpha^2 L^2, \alpha^3 L^3\}$	$\{\dots \alpha^2 L^2, \alpha^3 L^3\}$
ISR-FSR int.	$\mathcal{O}(\alpha)$	$\mathcal{O}(\alpha)$	$\{\alpha, \alpha L\}_{\text{CEEX}}$	$\{\alpha, \alpha L\}_{\text{CEEX}}$
Exact brems.	1γ	$1, 2\text{coll. } \gamma$	$1, 2, 3\text{coll. } \gamma$	up to 3γ
Electroweak	No Z-res.	DIZET 6.x	DIZET 6.x	New version?



Electroweak radiative corrections: Tools

► (Semi)analytical tools: **topfit** and **ZFITTER**

→ with T. Riemann

hep-ph/0203220
hep-ph/0202109

Com.Phys.C. 133 (2001) 229-395
Com.Phys.C. 174 (2006) 728-758

- **topfit**: Complete electroweak one-loop radiative corrections incl. final state masses (+LoopTools2.10)
- **ZFITTER+DIZET**: A_{FB} (with cuts) at two-loop weak, final state masses only for kinematics

► MC tools: KORALB and **KKMC** (and PHOKHARA?)

- **KORALB**: Complete electroweak one-loop
 - debugging (A_{FB} wrong by a factor 2 for certain flags) and compilation with Z. Was (unfortunately: **KORALZ** EW part not working!)
- **KKMC+DIZET**: Default $\mu\mu$ and $\tau\tau$ generator at Belle
 - “same” weak corrections as **ZFITTER**, NLO QED+CEEX



Electroweak radiative corrections: Plan

- 1) Reproduce **topfit*** numbers for tau pairs at 500 GeV (12 digits)

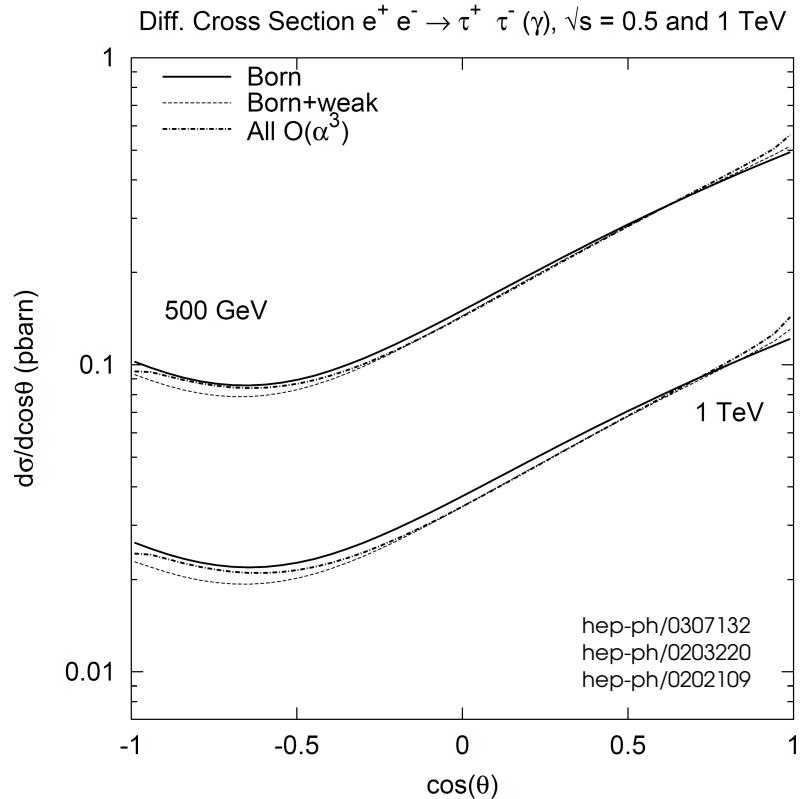
*unpublished private code

- 2) Produce **topfit** numbers for muon pairs at 10.58 GeV

- 3) Compare **topfit** to **ZFITTER** (one-loop): need final state mass?

- 4) Use **ZFITTER** to investigate systematics and control **KKMC**

10⁹ events (generator only):
~5000 CPU hours (NAF2.0)
~1TB disk (temp., on SONAS)
→ ~30h



Summary

- > A_{FB} is sensitive to the ρ -parameter at $Q=10.58 \text{ GeV}$
 - complementary to parity violation experiments
 - complementary to “LEP-era” precision physics
- > Belle: A_{FB} with a relative stat. precision of 1%
 - Understand detector effects and backgrounds at the $<10^{-4}$ level
 - No show-stoppers yet (but a painful way to go...)
- > Belle 2: A_{FB} with a relative stat. precision of 0.1%
 - Needs input from Belle to adjust low-multiplicity triggers, tracking, cosmic runs, background MC production, ...
- > Belle 2 will start physics run in 2016, 50ab^{-1} by the end of 2023

Questions

► PHOKHARA

- QED status to crosscheck the QED part of KKMC?
- Z-exchange in PHOKHARA?
- Y(1/2/3/4/5S) in PHOKHARA?

► Generator for $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$?

- AAFHB has no Z exchange and no higher order corrections

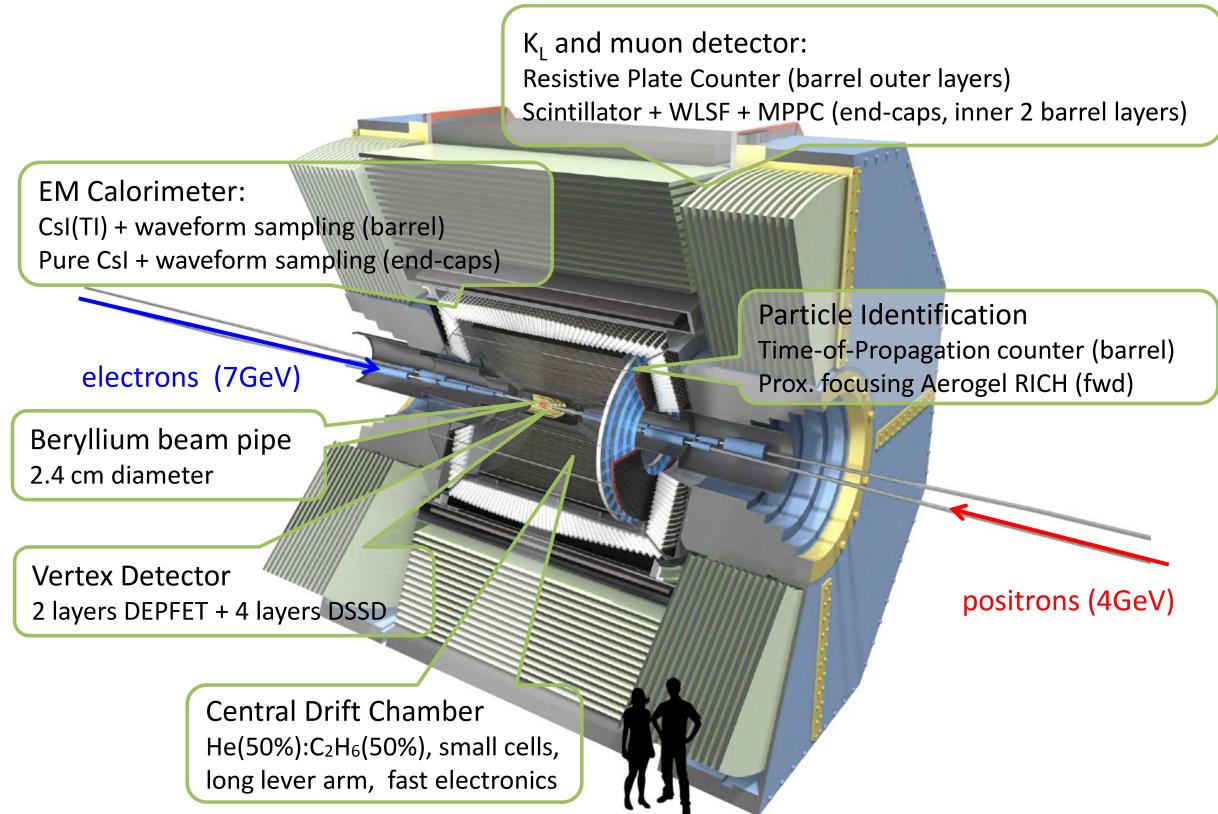
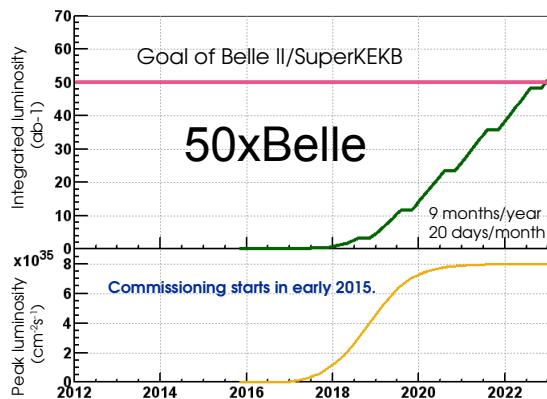
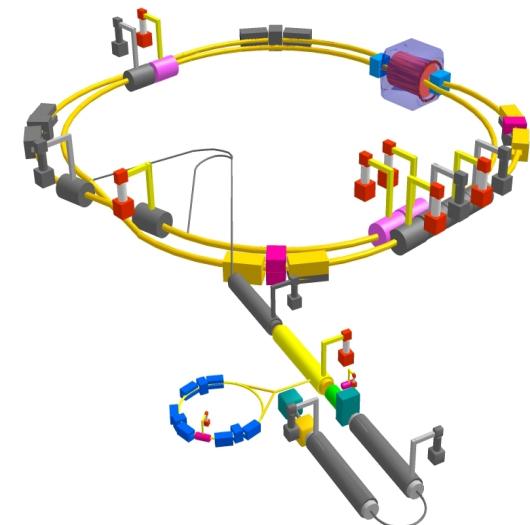
► What else can be done with sooo many muons?

- Exclusive $e^+e^- \rightarrow \mu^+\mu^-(1/2/3\gamma)$?
- Radiative return?
- $\alpha_{QED}(10.58 \text{ GeV})$?
- Try EW precision with Taus: Tau polarization and asymmetry?



Backup

Belle 2 at SuperKEKB



$$\text{Belle: } \sigma_{\text{stat}}(A_{\text{FB}})/A_{\text{FB}} \approx 1\% \rightarrow \text{Belle 2: } \sigma_{\text{stat}}(A_{\text{FB}})/A_{\text{FB}} \approx 0.1\%$$

Belle detector acceptance

detector	total	forward	barrel	backward
CDC	$17^\circ - 150^\circ$	—	$17^\circ - 150^\circ$	—
ACC	$17^\circ - 127^\circ$	$17^\circ - 34^\circ$	$34^\circ - 127^\circ$	—
ECL ^a	$12^\circ - 155.1^\circ$	$12^\circ - 31.4^\circ$	$32.2^\circ - 128.7^\circ$	$130.7^\circ - 155.1^\circ$
KLM (inner)	$25^\circ - 145^\circ$	$25^\circ - 51^\circ$	$51^\circ - 117^\circ$	$117^\circ - 145^\circ$
KLM (outer)	$17^\circ - 155^\circ$	$17^\circ - 51^\circ$	$51^\circ - 117^\circ$	$117^\circ - 155^\circ$
TOF	$34^\circ - 120^\circ$	—	$34^\circ - 120^\circ$	—

Tau polarization

