MAX-PLANCK-GESELLSCHAFT

Belle II

TCPV in Radiative decays:
$B \rightarrow Ks\, \pi^0\, \gamma\ ,\ \rho\, \gamma$

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Flavour Physics with High-Luminosity Experiments

MIAPP, Garching – October 26th 2016

Photon polarization

Radiative B decays, with $b \rightarrow s \gamma$ transitions, dominated by loop (penguin) diagrams
New physics could enter at same order (1-loop) as Standard Model

Standard Model makes definite prediction of photon helicity
(D. Atwood et al., Phys. Rev. Lea. 79, 185 (1997)):

- $B^0 \rightarrow X_s \gamma_R$
- $\overline{B}^0 \rightarrow X_s \gamma_L$

If a helicity flip occurs, the photon will also flip its helicity, producing $B^0 \rightarrow X_s \gamma_L$

- Rate ~ m_s/m_b at the leading contribution (P. Ball and R. Zwicky, Phys. Lea. B 642, 478 (2006))
- Corrections can increase this value

No common final state for B^0 and $\overline{B}^0$

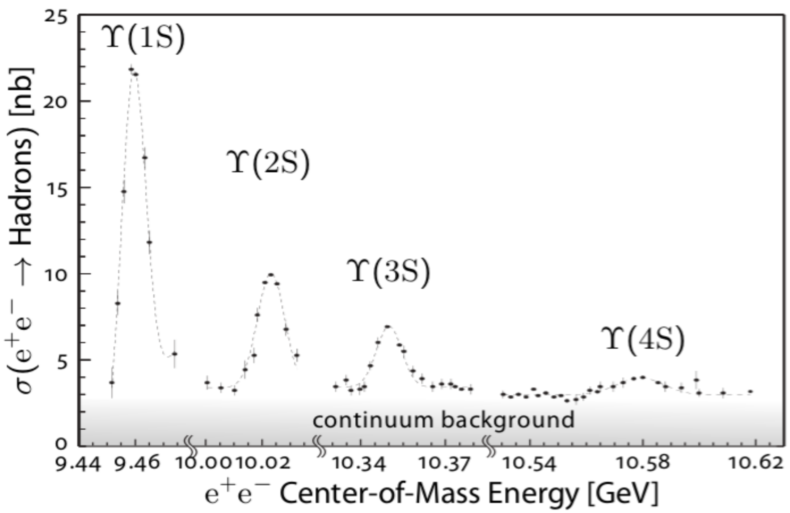
- Suppression of asymmetry S due to interference between B^0 mixing and decay diagrams (TD CP asymmetry)

$$\mathcal{S}^{\mathrm{SM}} = -\sin 2\phi_1 \frac{m_s}{m_b} \left[2 + \mathcal{O}(\alpha_s)\right] + \mathcal{S}^{\mathrm{SM}, s\gamma g}$$

C < 0.01 (direct CP violation) (Greub at al., Nucl. Phys B 434, 39 (1995))

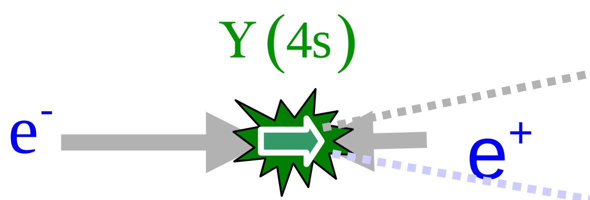
- TD CP asymmetry measurements give an indirect measurement of photon polarization

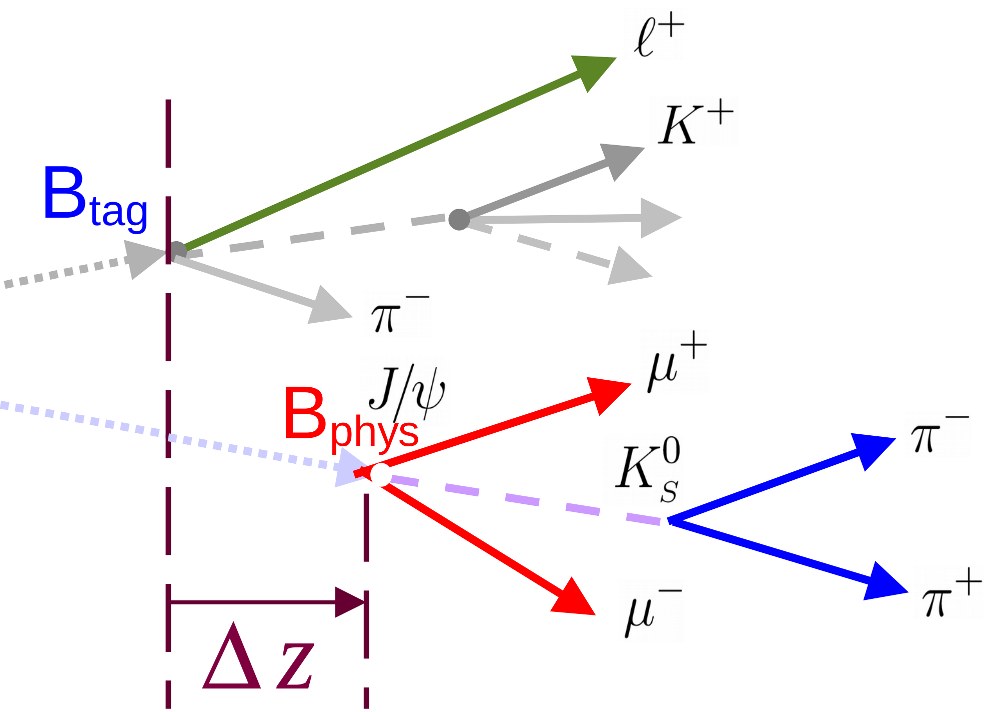
Time dependent measurements

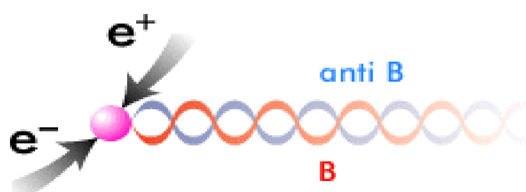


- Y(4S) is the first resonance just above the $B\overline{B}$ production threshold
- Only $B\overline{B}$ pairs are produced, and are at rest in the Y(4S) frame

$$\Delta t = \frac{\Delta z}{\beta \gamma c}$$







Resolution on Δt will be dominated by the resolution of the tagging side vertex

Coherent B meson pair production

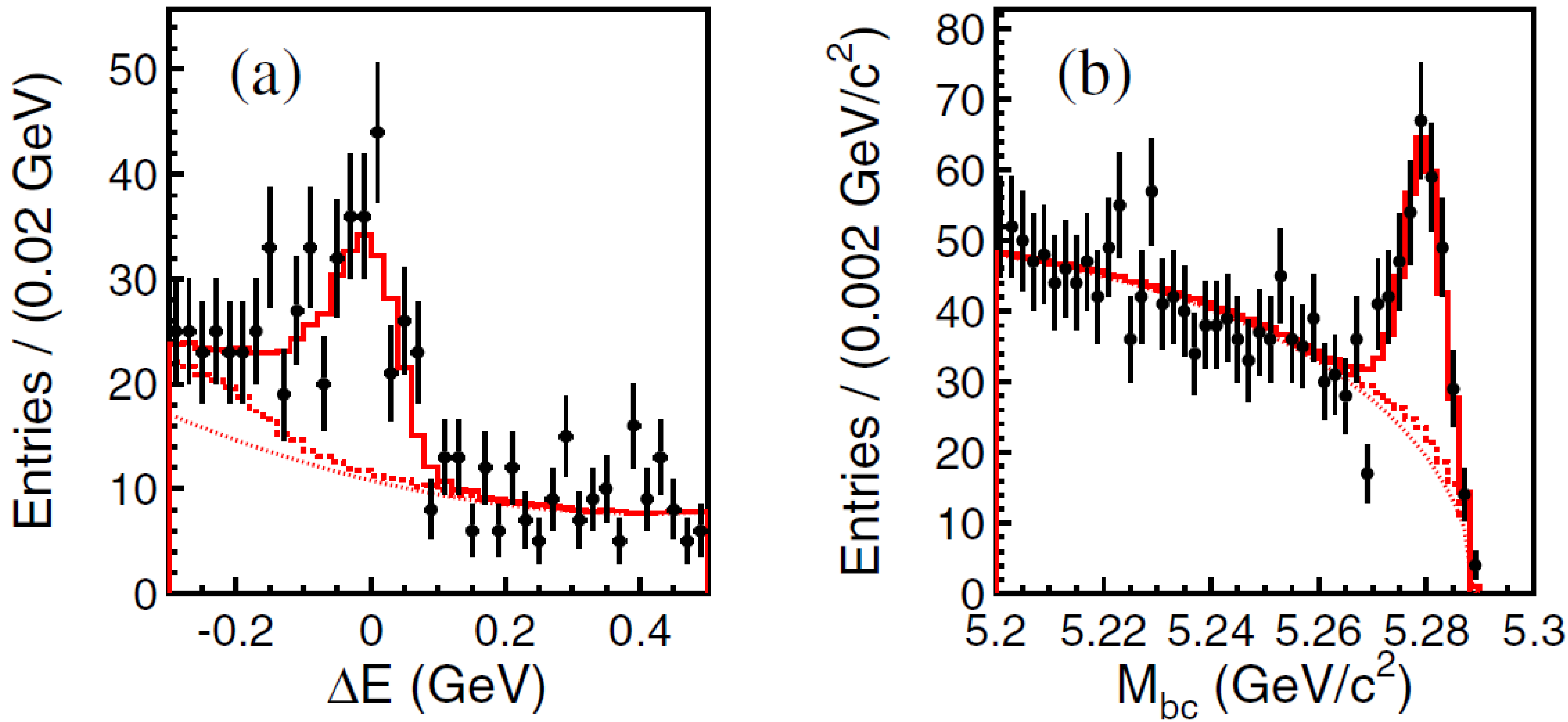
Belle ~ 200 μm
Belle II ~ 130 μm

Δt probability parametrization $\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q\left(\mathcal{A}_{CP}\cos\Delta m_d \Delta t + \mathcal{S}_{CP}\sin\Delta m_d \Delta t\right)\right]$

$B^0 \rightarrow Ks\ \pi^0\ \gamma$: Belle

Phys. Rev. D 74, 111104(R) (2006)

$$\Delta E = E_B^* - E_{beam}^* \qquad M_{bc} = \sqrt{E_{beam}^{*} - P_B^{*}}$$

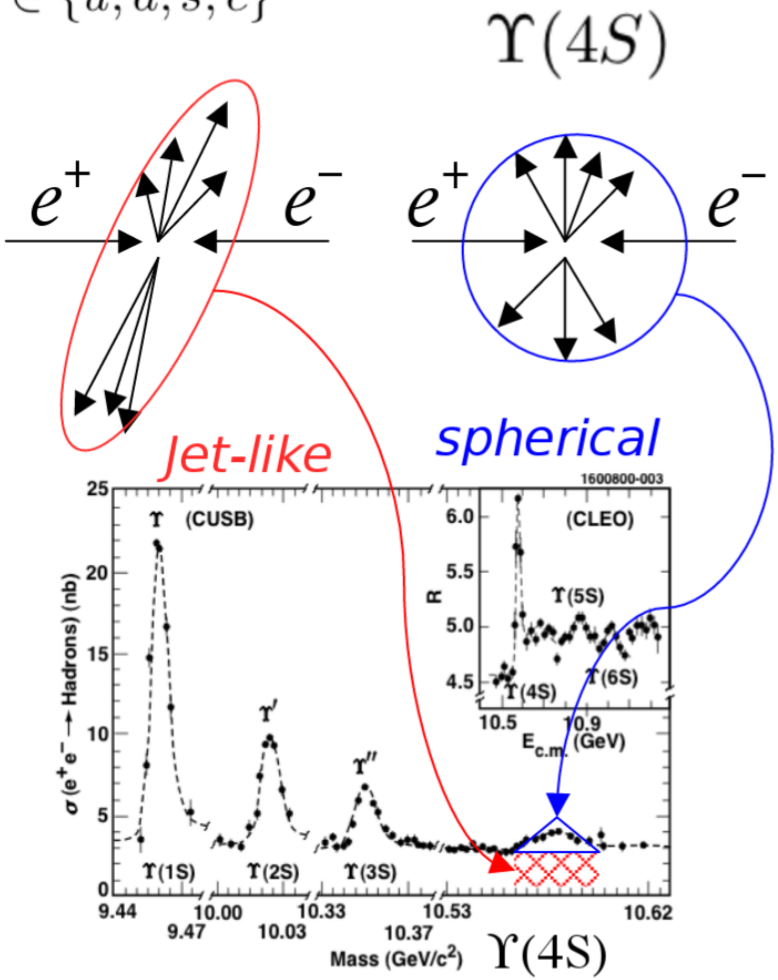


Three $M(Ks\ \pi^0)$ regions

- $0.8\ GeV/c^2 < M(Ks\ \pi^0) < 1.0\ GeV/c^2$: N = 112.5 ± 12.0 S/N =1.91
- $1.3\ GeV/c^2 < M(Ks\ \pi^0) < 1.55\ GeV/c^2$: N = 28.7 ± 7.1 S/N =0.81
- $1.55\ GeV/c^2 < M(Ks\ \pi^0) < 1.8\ GeV/c^2$: N = 35.2 ± 10.0 S/N =0.35

Selection

$$e^+e^- \rightarrow q\bar{q}$$
$$q \in \{u, d, s, c\}$$



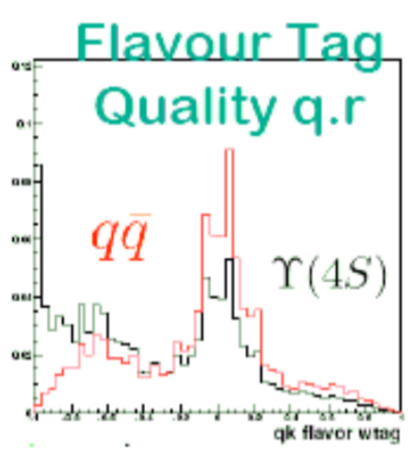
Continuum supression:

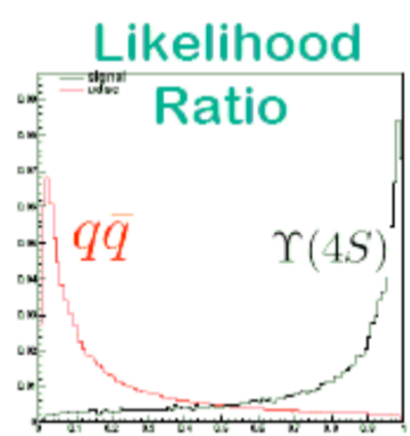
Likelihood constructed from

- Modified Fox-Wolfram moments (Event Shape)
- $\cos(\theta_B)$
- Helicity in $K_S\pi^0$ system for three different $M(K_S\,\pi^0)$ regions

Flavor tag quality

Likelihood cuts

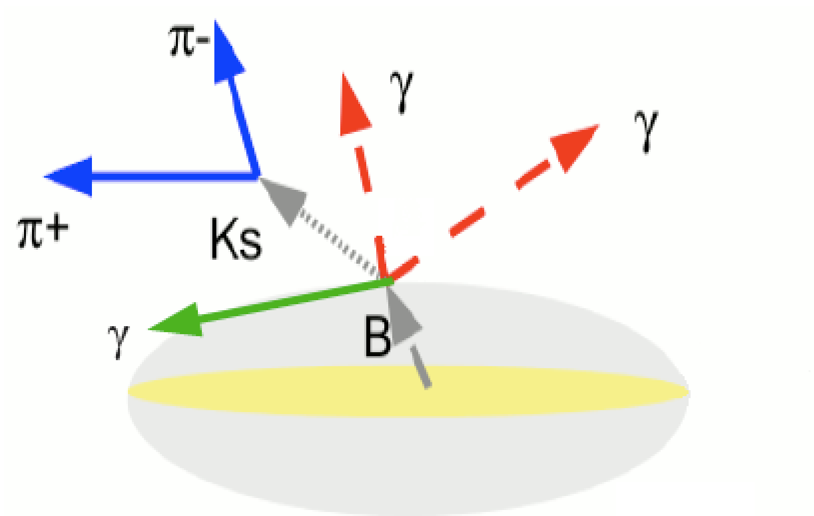


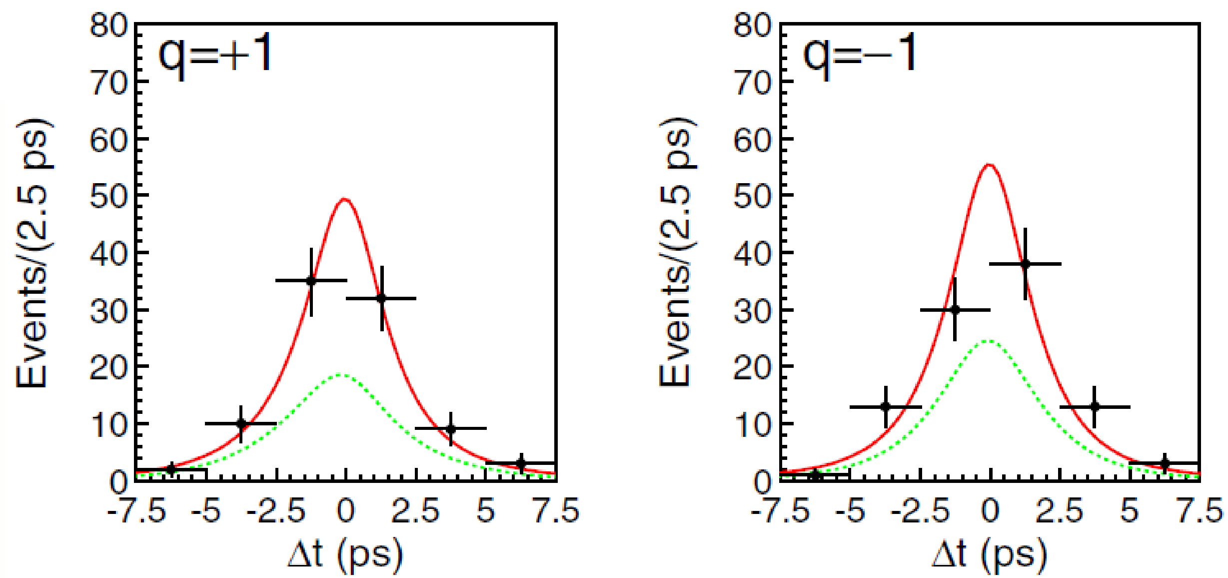


Time dependent analysis

Phys. Rev. D 74, 111104(R) (2006)

B vertex reconstruction





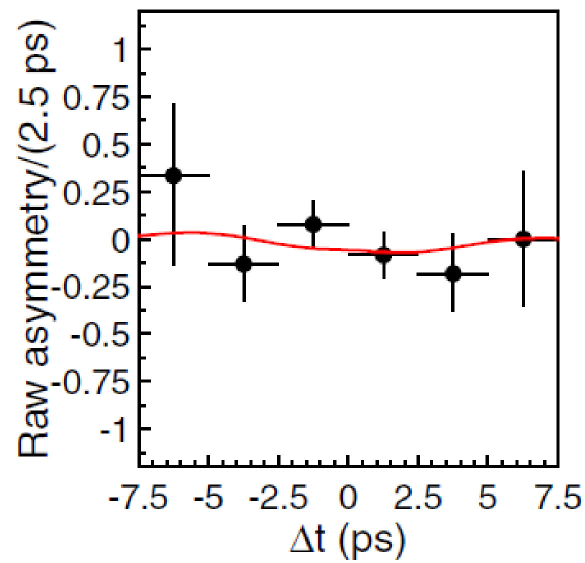
$$\mathcal{S}_{K_S^0\pi^0\gamma} = -0.10 \pm 0.31(\mathrm{stat}) \pm 0.07(\mathrm{syst}),$$

$$\mathcal{A}_{K_S^0\pi^0\gamma} = -0.20 \pm 0.20(\mathrm{stat}) \pm 0.06(\mathrm{syst}),$$

No significant CP asymmetry

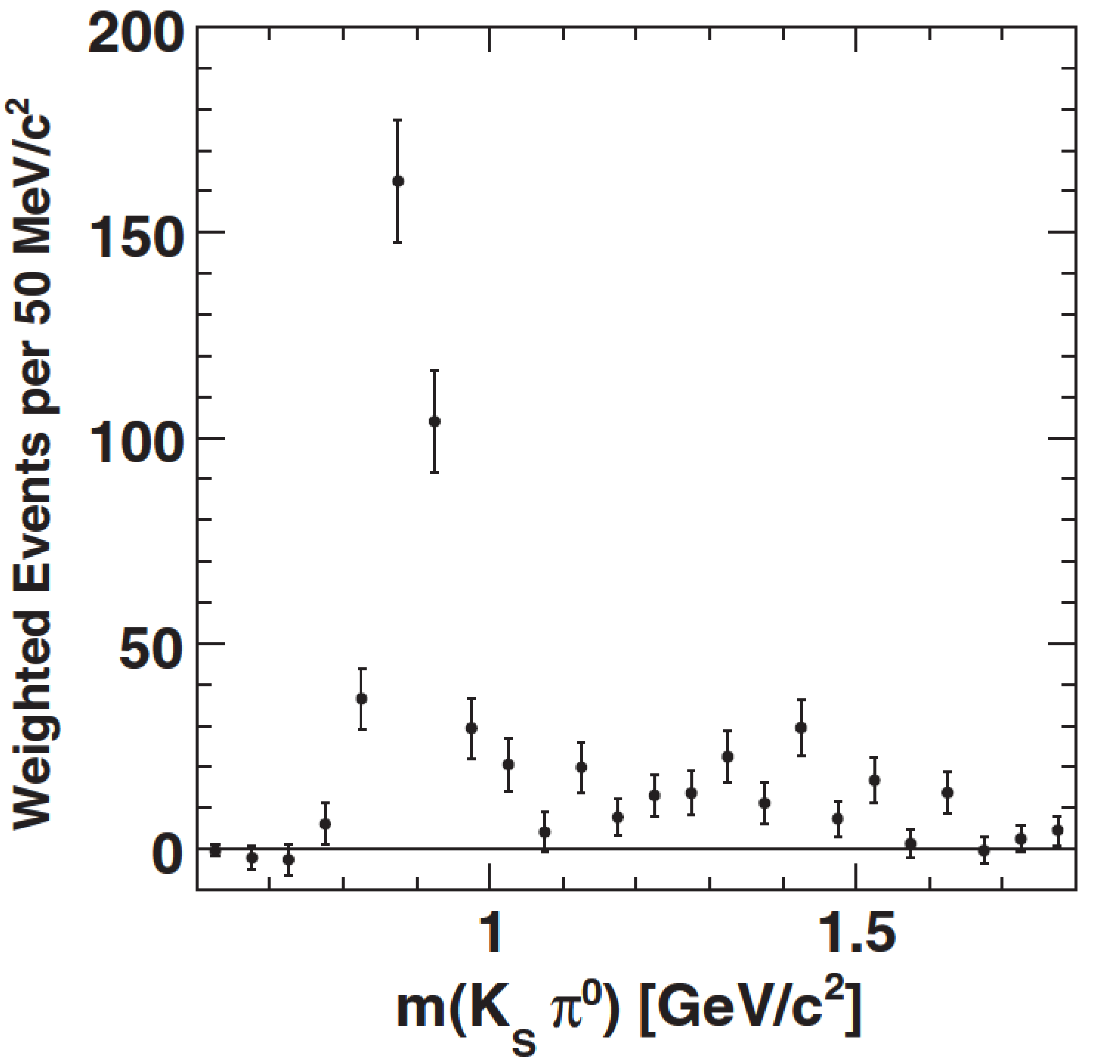
$$\mathcal{S}_{K^{*0}\gamma} = -0.32^{+0.36}_{-0.33} \pm 0.05$$

$$\mathcal{A}_{K^{*0}\gamma} = -0.20 \pm 0.24 \pm 0.05$$



$B^0 \to Ks\, \pi^0\, \gamma$: BaBar

Phys. Rev. D 78, 071102 (2008)



Two M(Ks π^0) regions

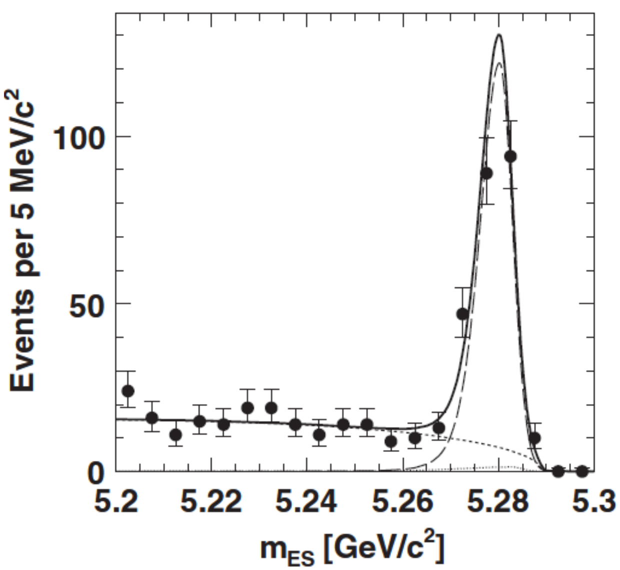
- 0.8 GeV/c^2 < M(Ks π^0) < 1.0 GeV/c^2
- 1.1 GeV/c^2 < M(Ks π^0) < 1.8 GeV/c^2

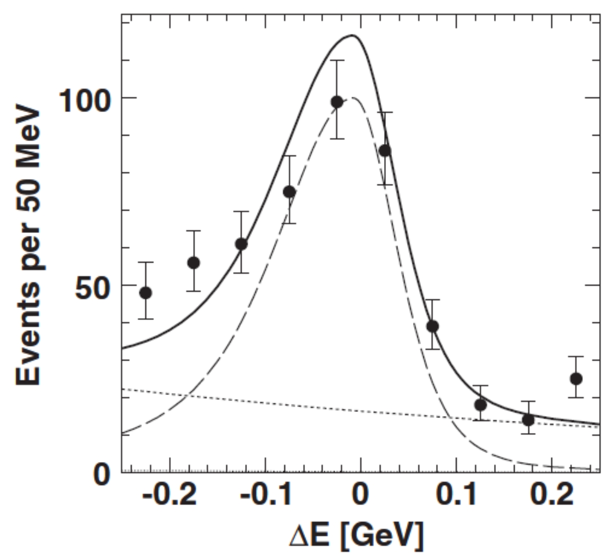
Two different fits

K* region

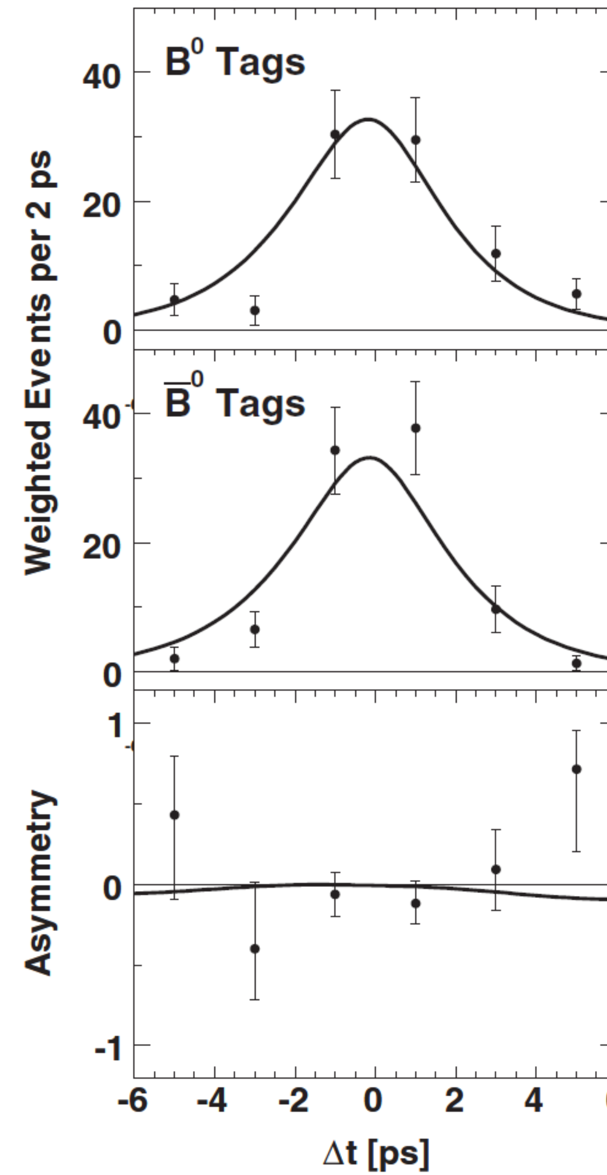
339 ± 24 (stat) signal events

$S = -0.03 \pm 0.29(\text{stat}) \pm 0.03(\text{syst})$
$C = -0.14 \pm 0.16(\text{stat}) \pm 0.03(\text{syst})$





Phys. Rev. D 78, 071102 (2008)

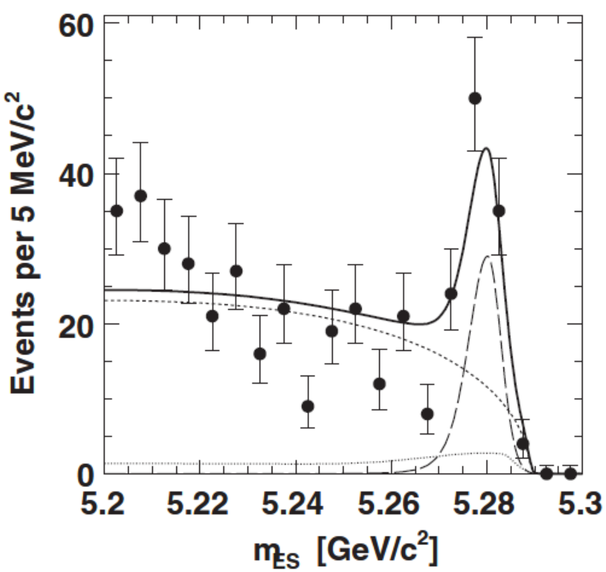


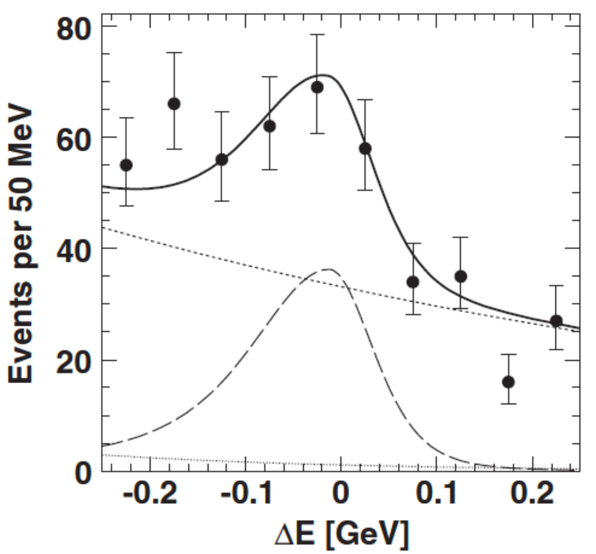
Non K* region

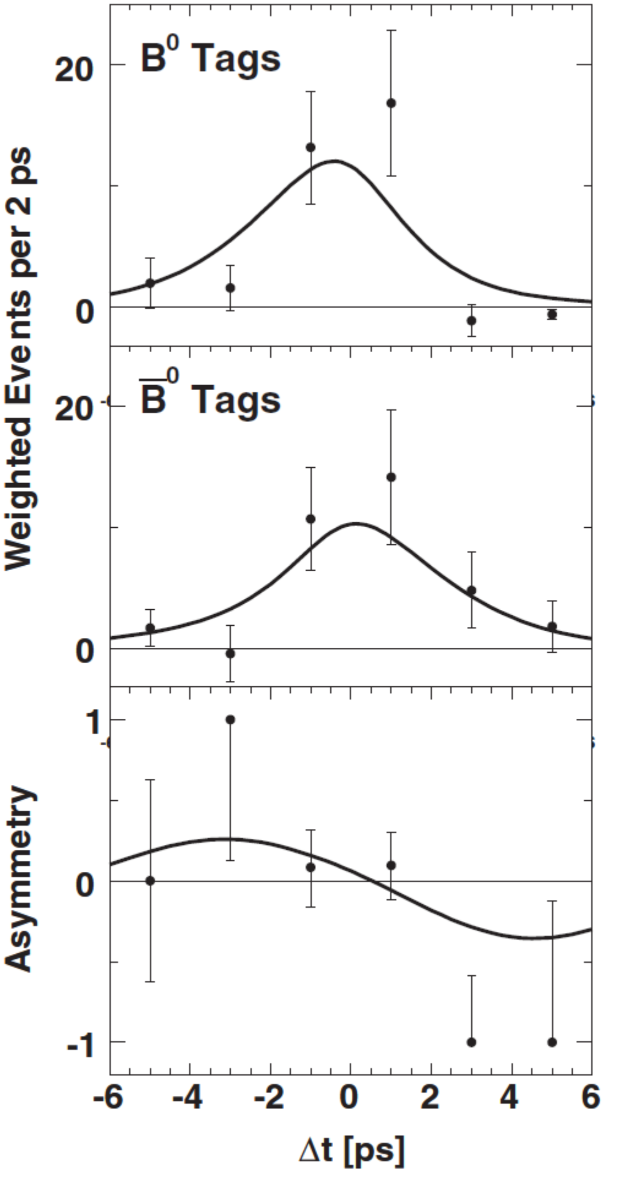
Phys. Rev. D 78, 071102 (2008)

133 ± 20 (stat) signal events

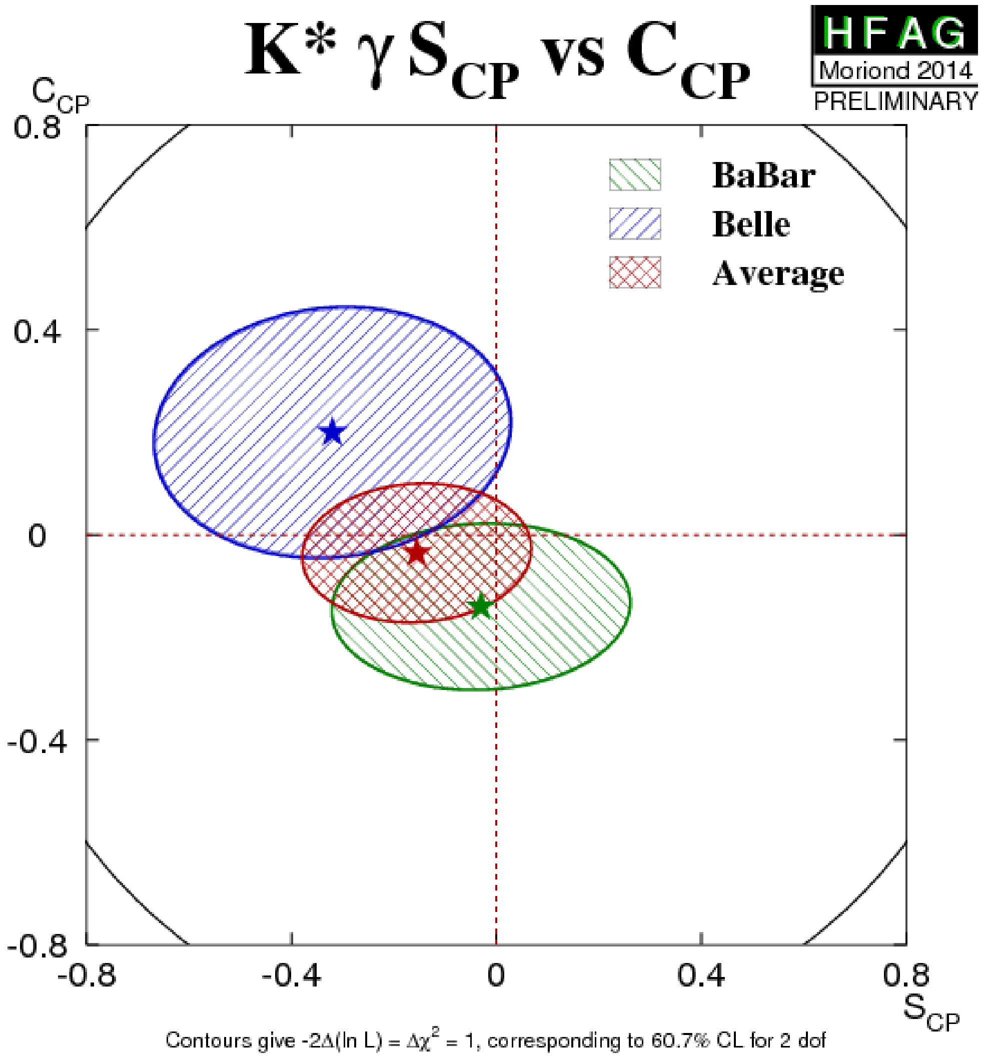
$S = -0.78 \pm 0.59(\text{stat}) \pm 0.09(\text{syst})$
$C = -0.36 \pm 0.33(\text{stat}) \pm 0.04(\text{syst})$

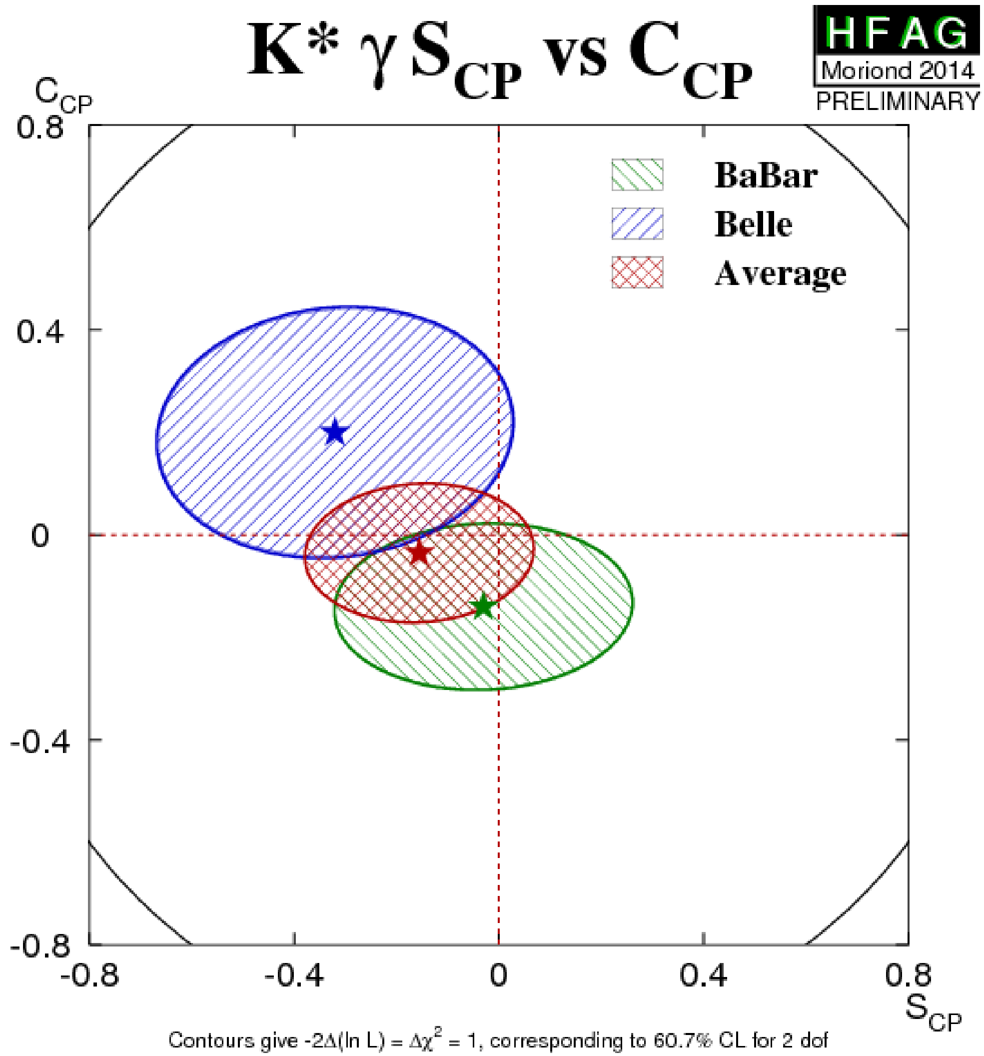






HFAG averages





We need more data

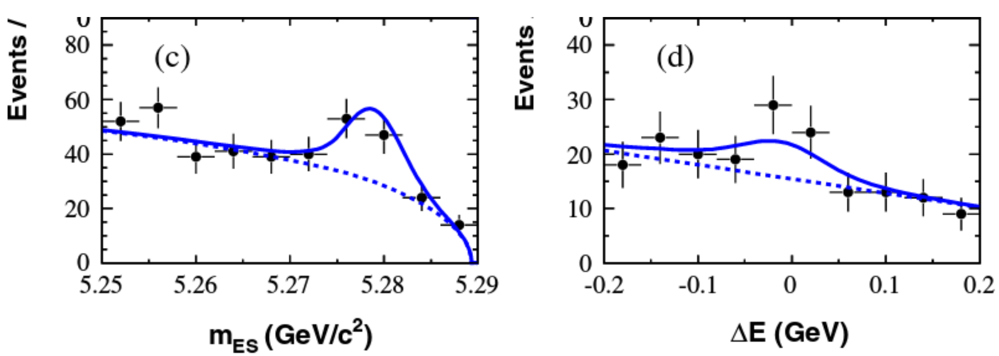
$B^0 \to K_S \eta \gamma$: BaBar

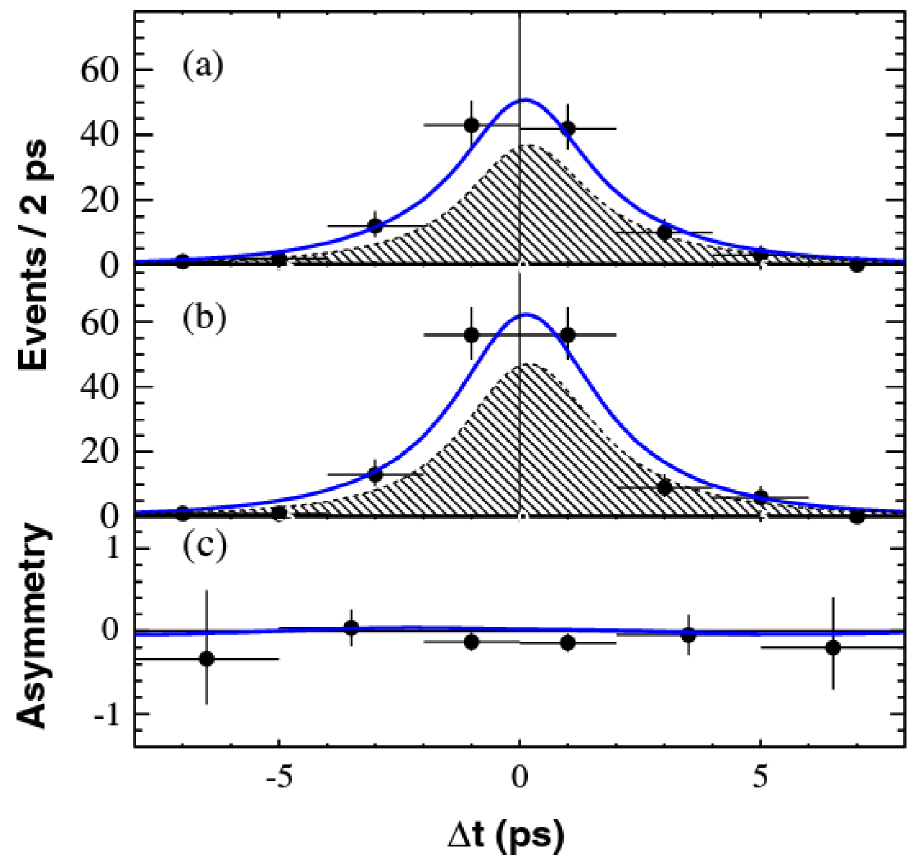
Phys. Rev. D 79, 011102 (2009)

82 ± 23 (stat) signal events (Br = $(7.1^{+2.1}_{-2.0}$(stat) ± 0.4(syst)) × 10^{-6})

$S = -0.18^{+0.49}_{-0.46}$(stat) ± 0.12(syst)

$C = -0.32^{+0.40}_{-0.39}$(stat) ± 0.07(syst)



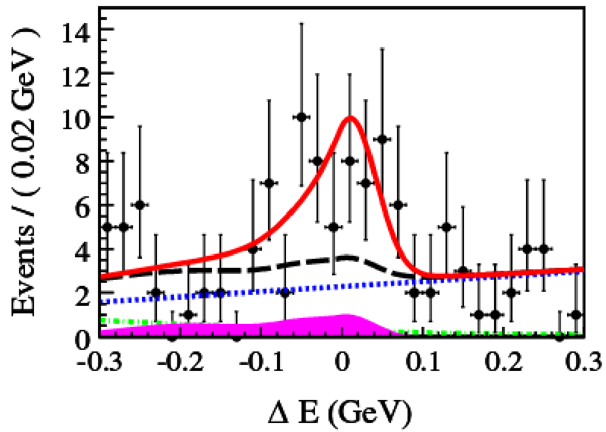


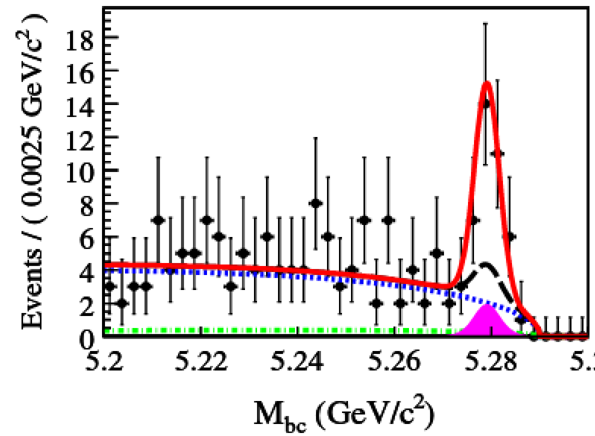
$B^0 \rightarrow Ks\ \phi\ \gamma$: Belle

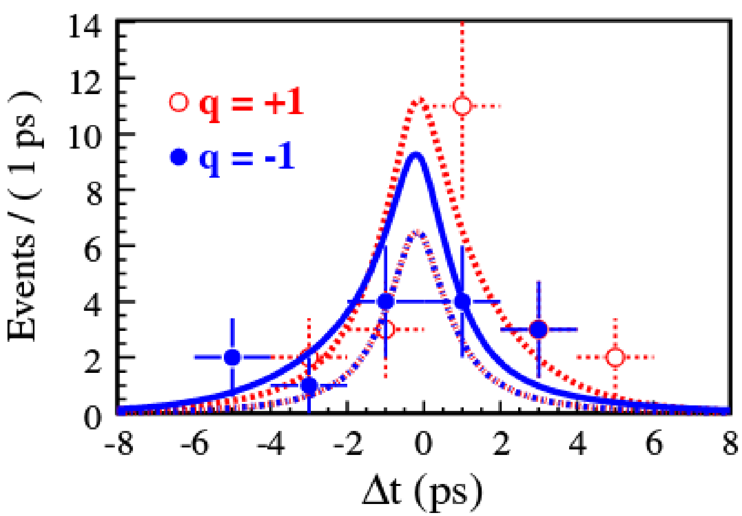
Phys. Rev. D 84 071101 (2011)

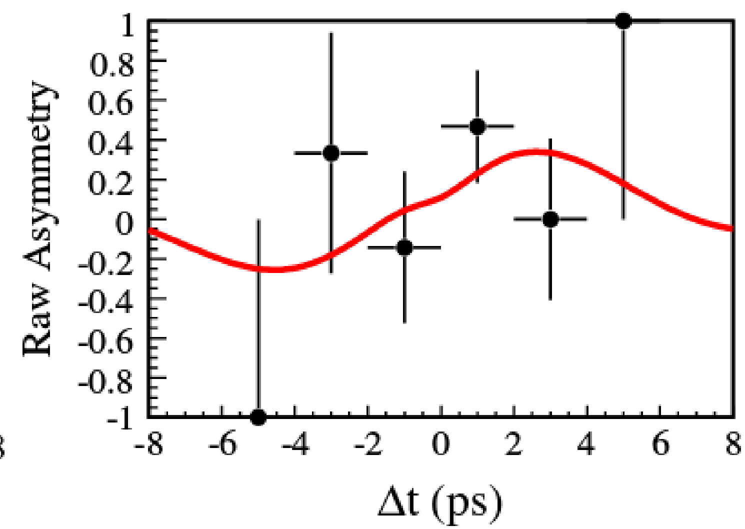
37 ± 8 (stat) signal events

Br = (2.74 ± 0.60 (stat) ± 0.32(syst)) $\times 10^{-6}$









$S = 0.74^{+0.72}_{-1.05}(\text{stat})\ ^{+0.10}_{-0.24}\ (\text{syst})$

$A = 0.35 \pm 0.58(\text{stat})^{+0.23}_{-0.10}(\text{syst})$

$B^0 \rightarrow Ks\ \rho^0\ \gamma$: Belle

PRL 101, 251601 (2008)

212 ± 17 (stat) signal events

$S(Ks\ \rho^0\ \gamma) = 0.11 \pm 0.33(stat)\ ^{+0.005}_{-0.09}(syst)$

$A(Ks\ \pi^+\ \pi^-\ \gamma) = 0.05 \pm 0.18(stat) \pm 0.06(syst)$

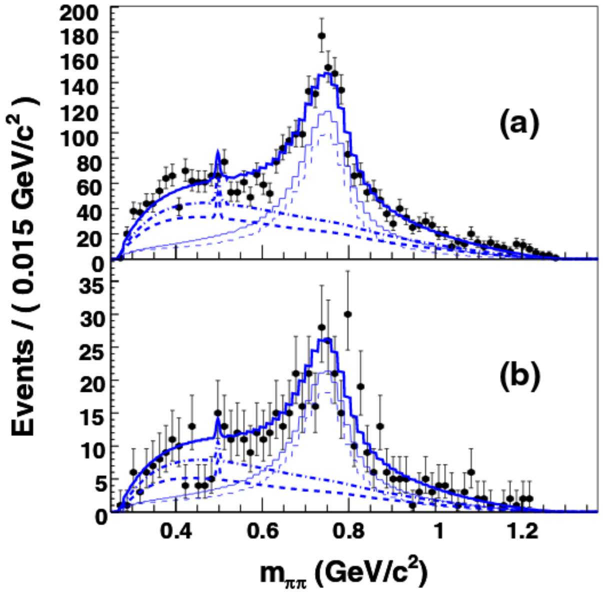


FIG. 3 (color online). $m_{\pi\pi}$ distributions for (a) $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ and (b) $B^0 \rightarrow K^0_S\pi^+\pi^-\gamma$. The curves follow the convention in Fig. 1. The thin dashed curve is the correctly reconstructed $B \rightarrow K_1(1270)\gamma$ signal component.

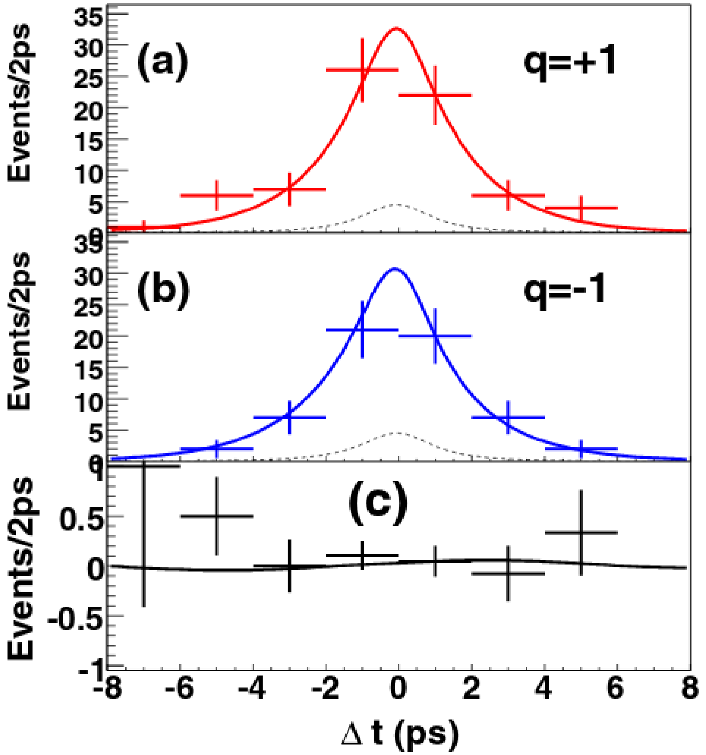


FIG. 2 (color online). (a) $q = +1$ yield, (b) $q = -1$ yield, and (c) raw asymmetry as a function of Δt for events with $r > 0.5$. The raw asymmetry is defined as $(N_+ - N_-)/(N_+ + N_-)$ where N_+ (N_-) is the event yield with $q = +1(-1)$. The solid curves are the fits while the dashed curves show the background contributions.

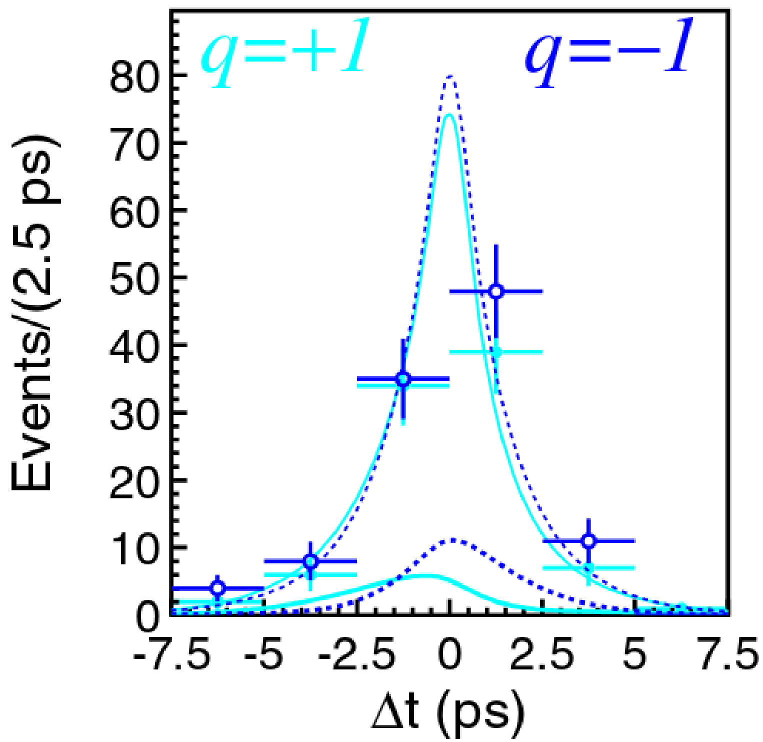
$B^0 \to \rho^0 \gamma$: Belle

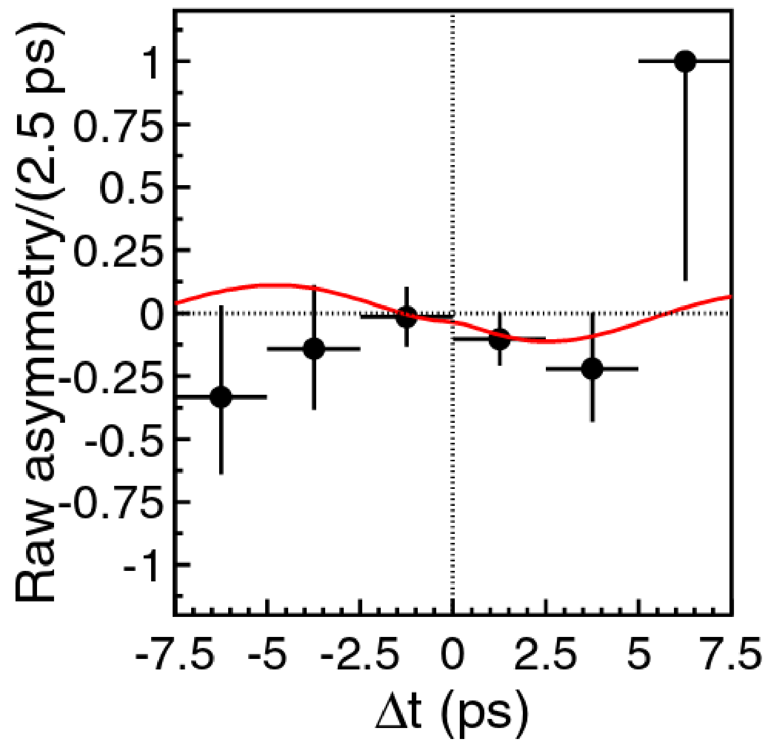
Phys. Rev. Lett. 100, 021602 (2008)

First measurement of CP asymmetry parameters in a $b \to d \gamma$ process

$$\mathcal{S}_{\rho^0\gamma} = -0.83 \pm 0.65(\mathrm{stat}) \pm 0.18(\mathrm{syst})$$
$$\mathcal{A}_{\rho^0\gamma} = -0.44 \pm 0.49(\mathrm{stat}) \pm 0.14(\mathrm{syst})$$

Consistent with no CP violation





Summary

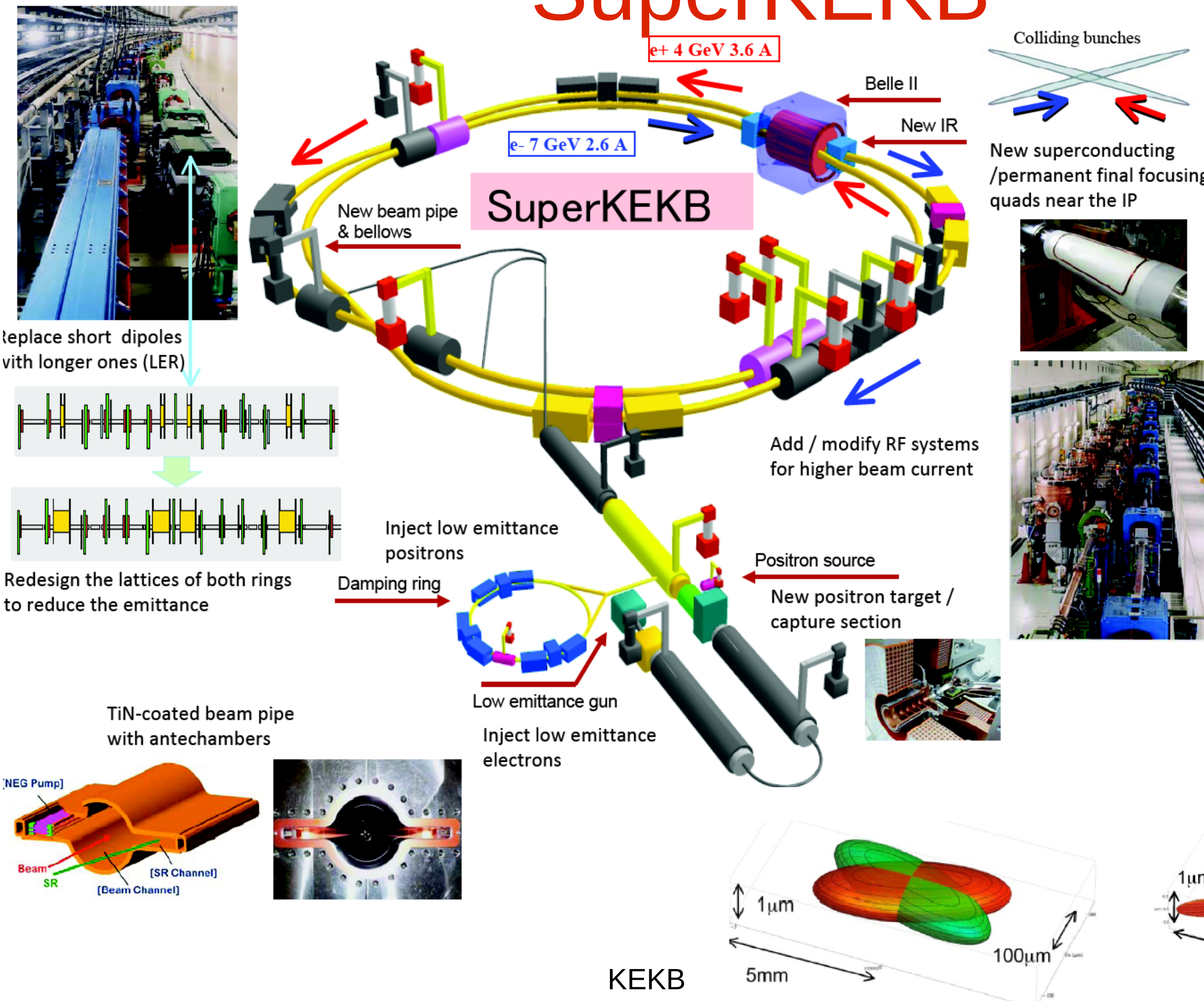
Eur. Phys. J. C74 (2014) 3026

	BaBar	Belle	Average
$\mathcal{S}(K^{*0}\gamma)$	$-0.03 \pm 0.29 \pm 0.03$	$-0.32 \pm 0.35 \pm 0.05$	-0.17 ± 0.20
$\mathcal{C}(K^{*0}\gamma)$	$-0.14 \pm 0.16 \pm 0.03$	$0.20 \pm 0.24 \pm 0.05$	0.00 ± 0.13
$\mathcal{S}(K^0_S\pi^0\gamma)$	$-0.78 \pm 0.59 \pm 0.09$	$-0.10 \pm 0.31 \pm 0.07$	-0.40 ± 0.25
$\mathcal{C}(K^0_S\pi^0\gamma)$	$-0.36 \pm 0.33 \pm 0.04$	$0.20 \pm 0.20 \pm 0.06$	0.00 ± 0.16
$\mathcal{S}(K^0_S\eta\gamma)$	$-0.18 \pm 0.48 \pm 0.12$		-0.18 ± 0.50
$\mathcal{C}(K^0_S\eta\gamma)$	$-0.32 \pm 0.40 \pm 0.07$		-0.32 ± 0.41
$\mathcal{S}(K^0_S\phi\gamma)$		$0.74 \pm 0.90 \pm 0.20$	0.74 ± 0.91
$\mathcal{C}(K^0_S\phi\gamma)$		$-0.35 \pm 0.58 \pm 0.20$	-0.35 ± 0.61
$\mathcal{S}(K^0_S\rho^0\gamma)$		$0.11 \pm 0.33 \pm 0.07$	0.11 ± 0.35
$\mathcal{C}(K^0_S\pi^+\pi^-\gamma)^\dagger$		$0.05 \pm 0.18 \pm 0.06$	0.05 ± 0.20
$\mathcal{S}(\rho^0\gamma)$		$-0.83 \pm 0.65 \pm 0.18$	-0.83 ± 0.68
$\mathcal{C}(\rho^0\gamma)$		$0.44 \pm 0.49 \pm 0.14$	0.44 ± 0.53

† For $m_{K\pi\pi} < 1.8\,\mathrm{GeV}/c^2$ and $m_{\pi\pi} \in [0.6, 0.9]\,\mathrm{GeV}/c^2$.

We need more data

SuperKEKB



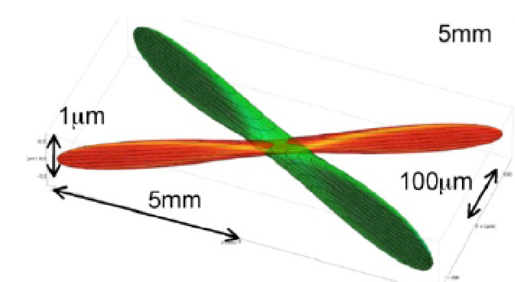
Peak luminosity

- KEKB = 2.11×10^{34} cm^{-2} s^{-1}
- SuperKEKB = 8×10^{35} cm^{-2} s^{-1}

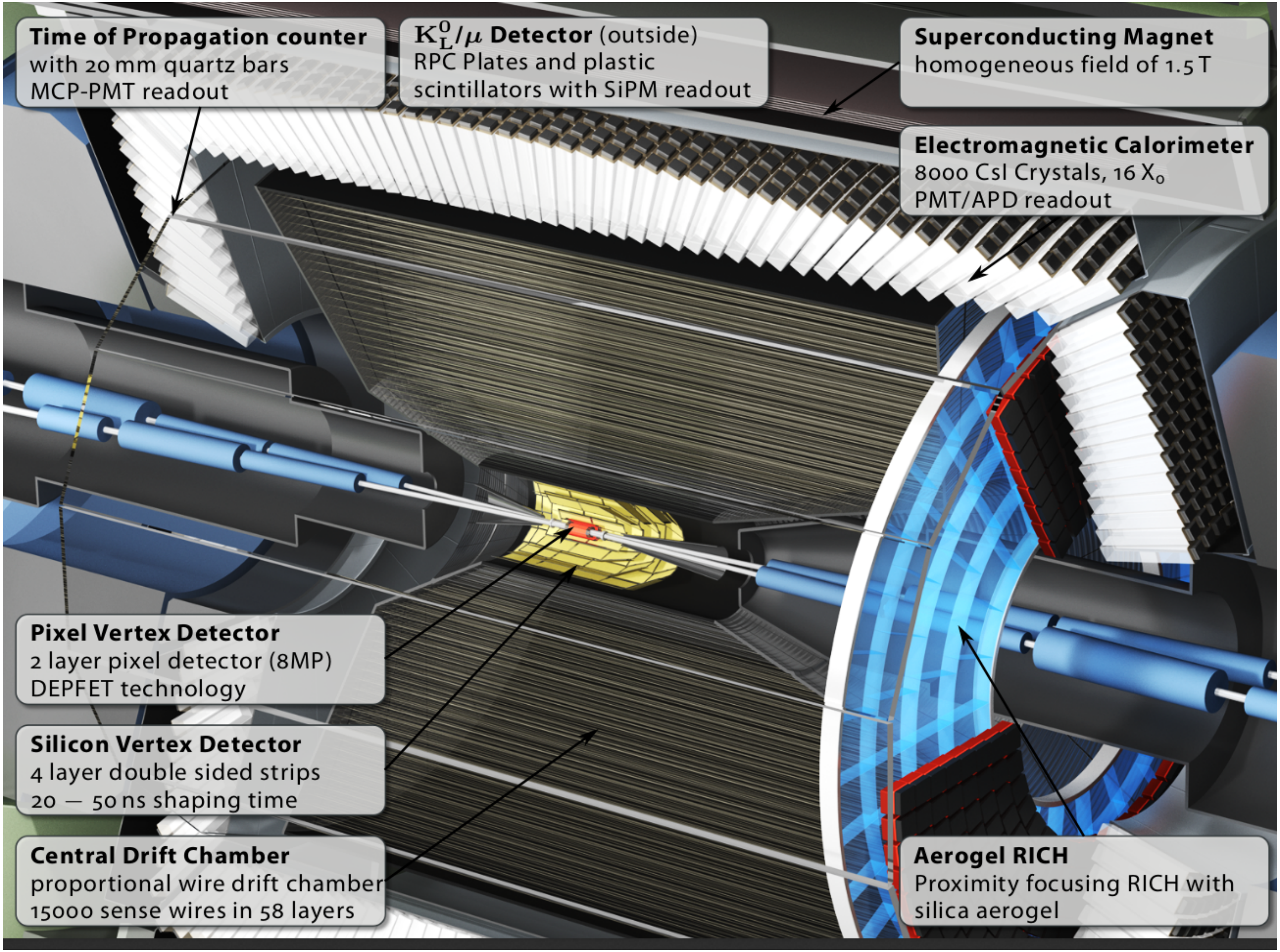
e^+e^- beams energy

- KEKB = 8 GeV / 3.5 GeV
- SuperKEKB = 7 GeV / 4 GeV

SuperKEKB Nanobeam

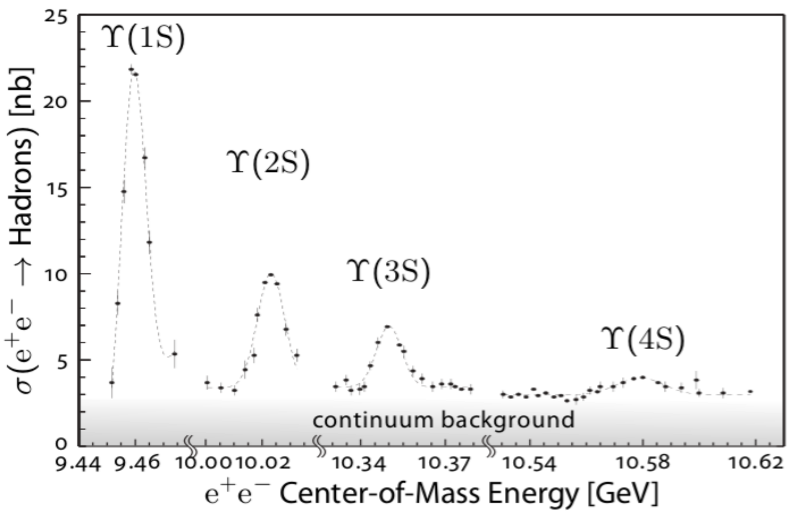


Belle II



Time of Propagation counter
with 20 mm quartz bars
MCP-PMT readout
K_L^0/μ Detector (outside)
RPC Plates and plastic
scintillators with SiPM readout
Superconducting Magnet
homogeneous field of 1.5 T
Electromagnetic Calorimeter
8000 CsI Crystals, 16 X_0
PMT/APD readout
Pixel Vertex Detector
2 layer pixel detector (8MP)
DEPFET technology
Silicon Vertex Detector
4 layer double sided strips
20 — 50 ns shaping time
Central Drift Chamber
proportional wire drift chamber
15000 sense wires in 58 layers
Aerogel RICH
Proximity focusing RICH with
silica aerogel

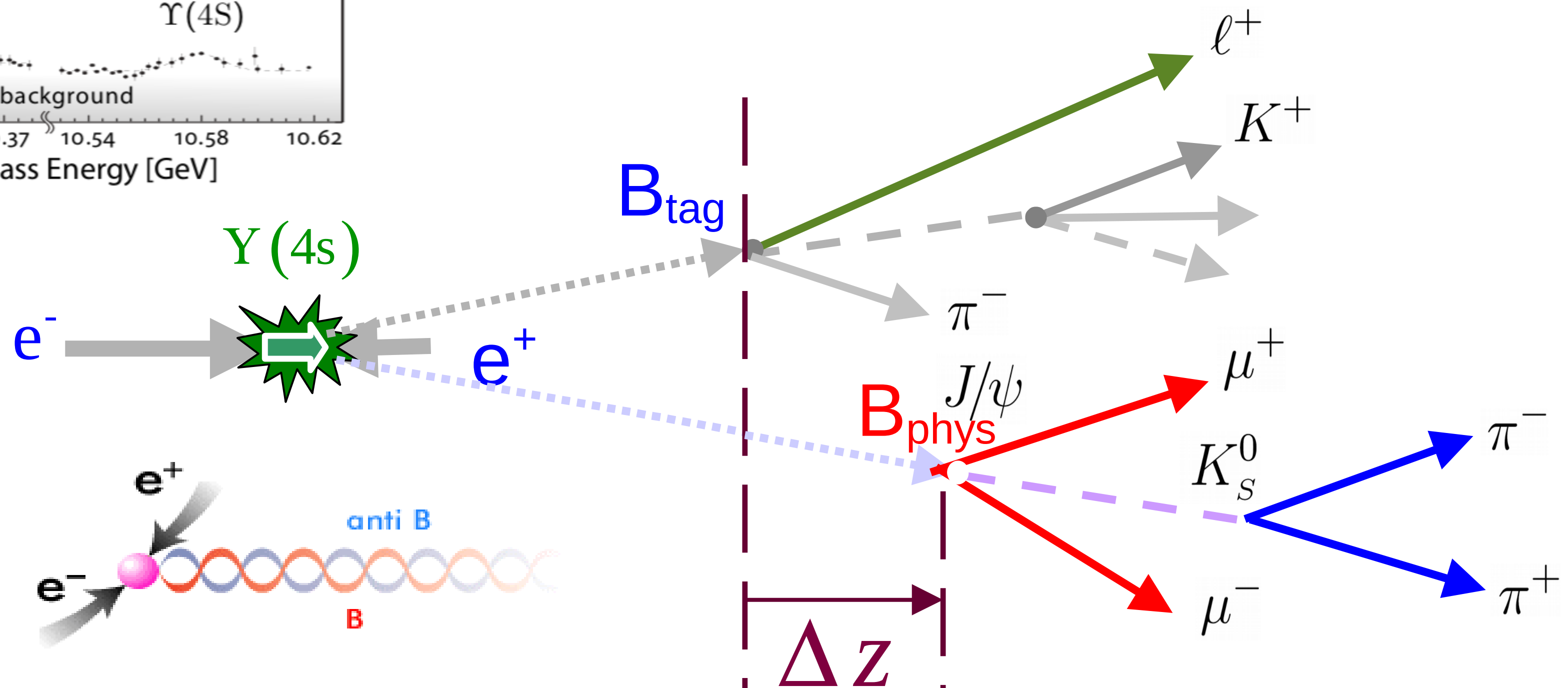
Time dependent measurements



- Y(4S) is the first resonance just above the $B\bar{B}$ production threshold
- Only $B\bar{B}$ pairs are produced, and are at rest in the Y(4S) frame

$$\Delta t = \frac{\Delta z}{\beta \gamma c}$$

Resolution on Δt will be dominated by the resolution of the tagging side vertex



Coherent B meson pair production

Belle ~ 200 μm
Belle II ~ 130 μm

Δt probability parametrization $\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q\left(\mathcal{A}_{CP}\cos\Delta m_d \Delta t + \mathcal{S}_{CP}\sin\Delta m_d \Delta t\right)\right]$

Belle II Pixel Vertex Detector

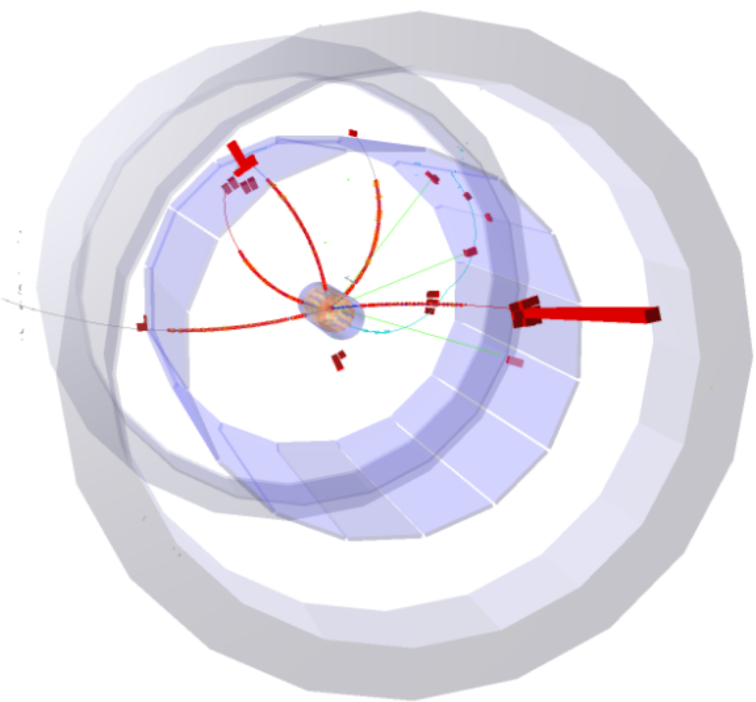
- 40 times increase of luminosity → higher background
- Lower boost → smaller separation between the B mesons

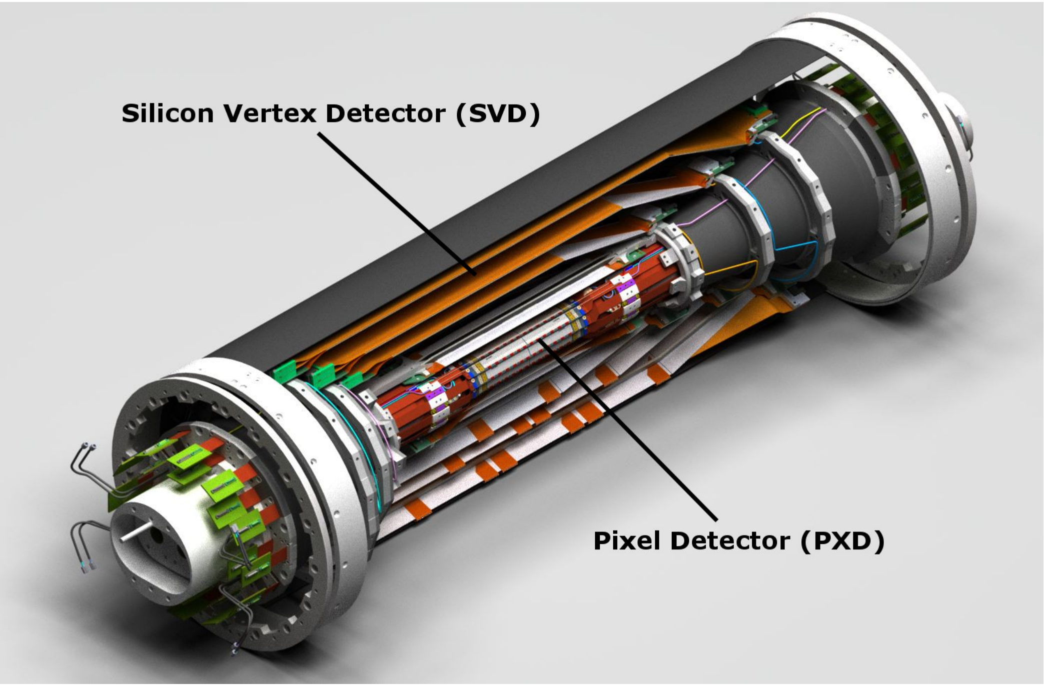
→ Pixel detector needed

Most suited technology : DEPFET

- Innermost detector system as close as possible to IP
- Highly granular pixel sensors provide most accurate 2D position information

- Reconstruction of primary and secondary vertices of short-lived particles
- Decay of particles is typical in the order of 100μm from the IP

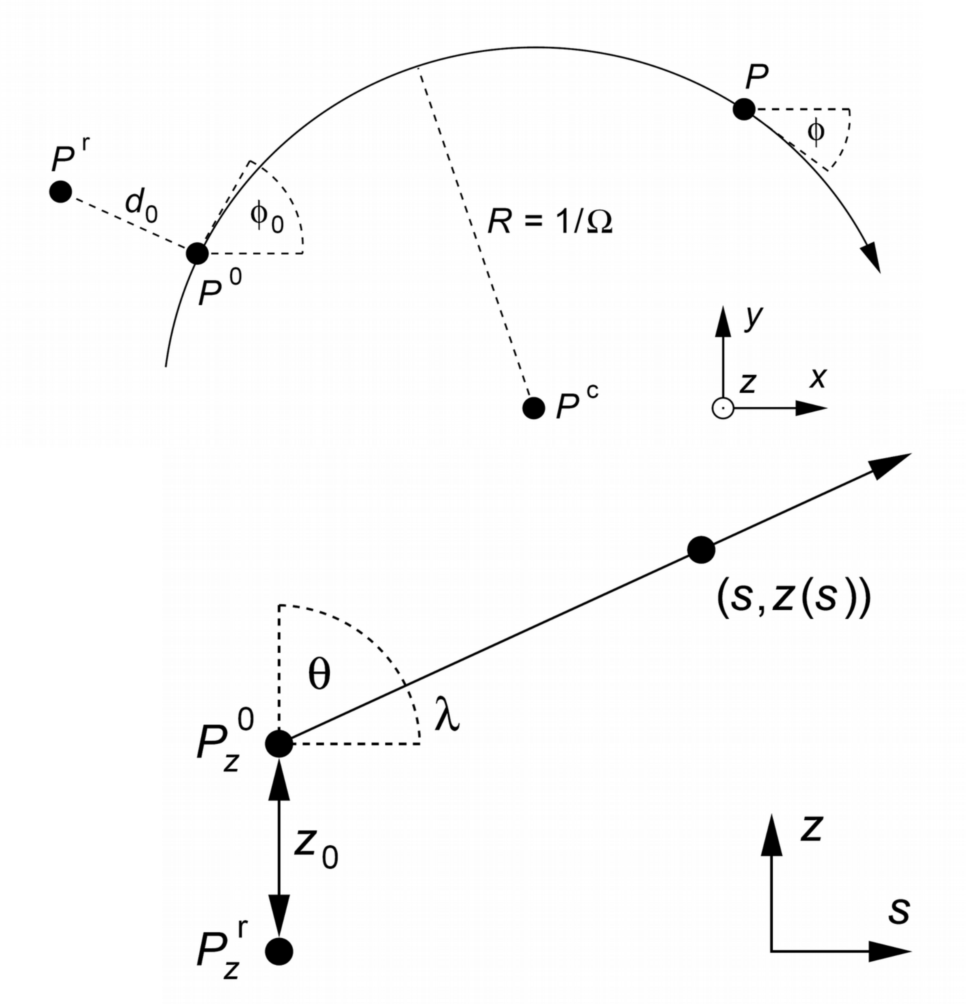


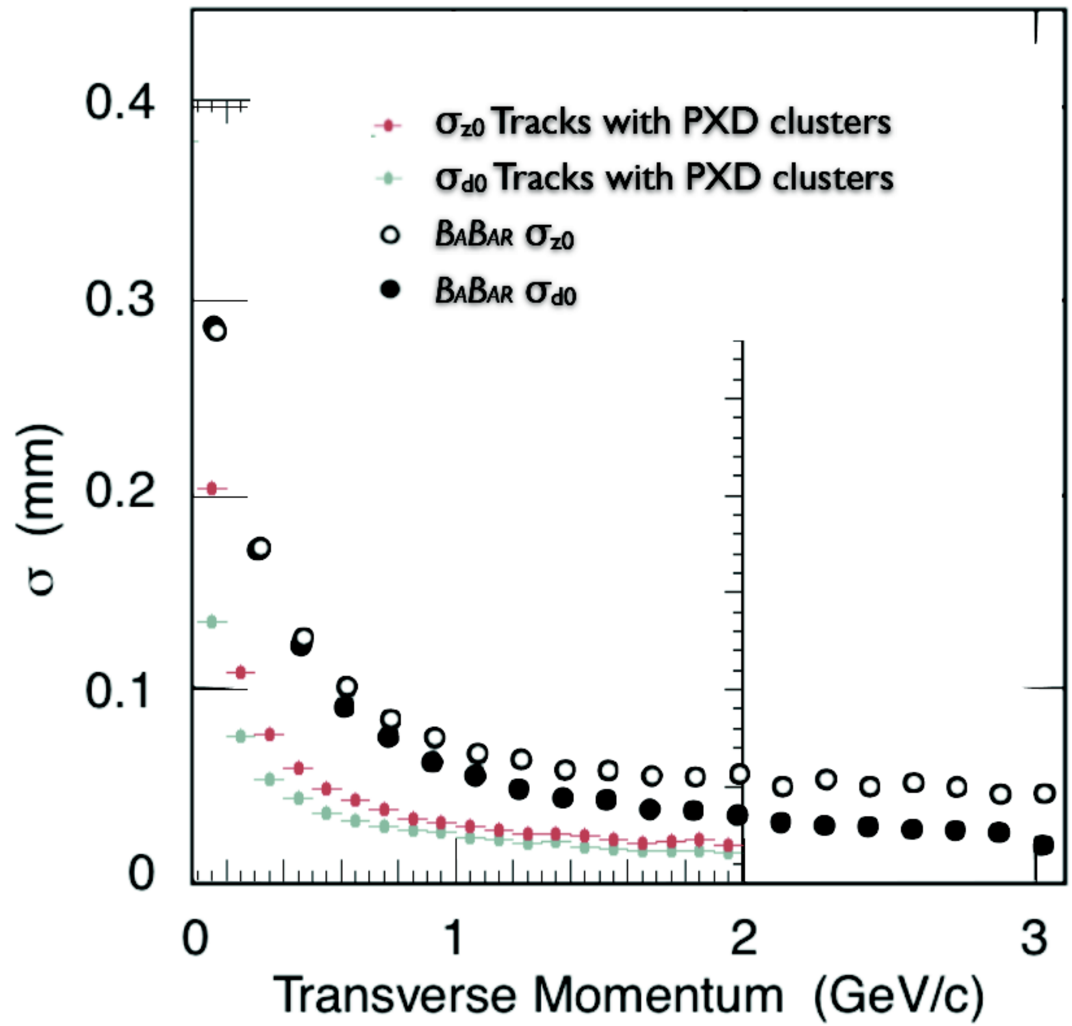


The impact parameter

The impact parameters: d_0 and z_0

- defined as the projections of distance from the point of closest approach to the origin
- good measure of the overall performance of the tracking system
- used to find the optimal tracker configuration





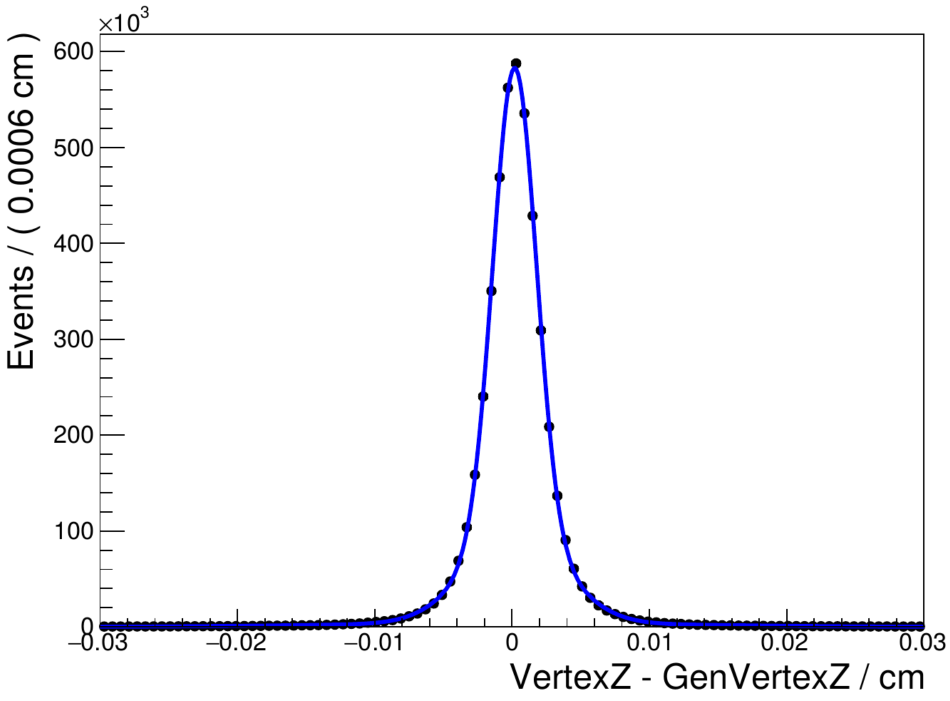
Almost a factor 2 improvement respect to BaBar

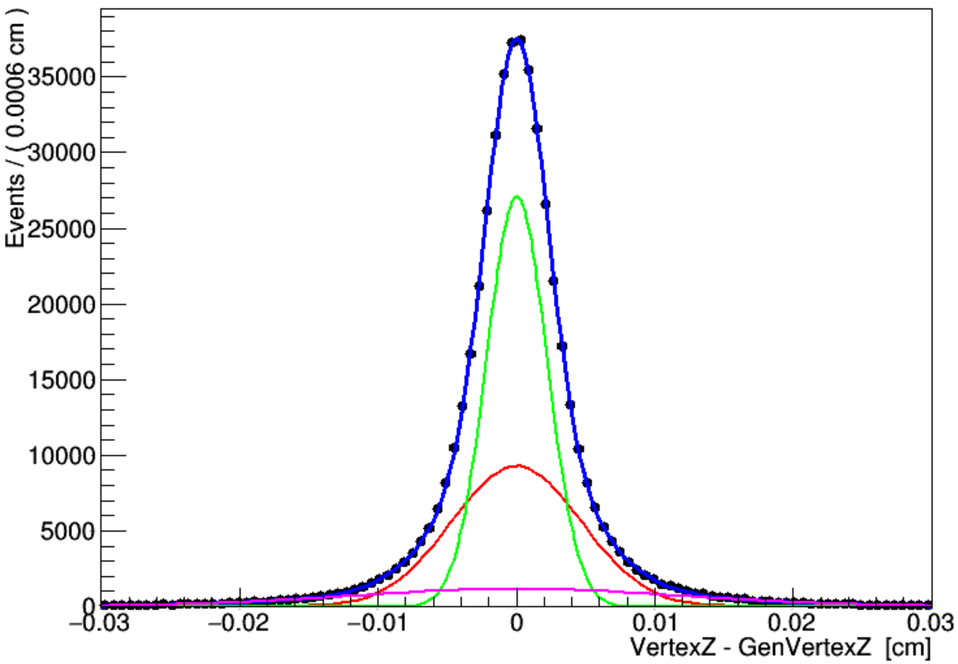
Vertex fit: Breco side

Two vertex fitters used in Belle II for kinematic vertex fits

- Kfit : used in Belle
- RAVE: a CMS tool, see https://rave.hepforge.org/)

$J/\psi \rightarrow \mu\ \mu$





Belle II

- Bias = 2.0 μm
- Resolution = 25.6 μm

Belle MC + basf2

- Bias = 0.17 μm
- Resolution = 43 μm

Rave: Adaptive Vertex Fitter

Down-weights outliers dynamically, instead of using hard cutoffs (important for 3+ track vertices).

Minimization of the weighted least sum of squares

Journal of Physics G, 34:N343–N356, 2007.

square of the standardized residual

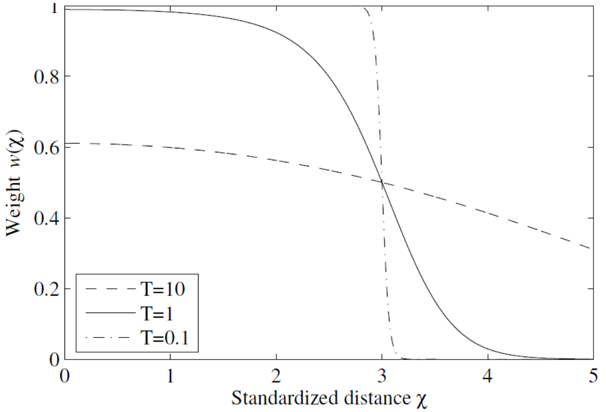
$$w_i\left(\chi_i^2\right) = \frac{\exp(-\chi_i^2/2T)}{\exp(-\chi_i^2/2T) + \exp(-\sigma_{\mathrm{cut}}^2/2T)}$$

Weight

"temperature" parameter
"softness" of the weight function

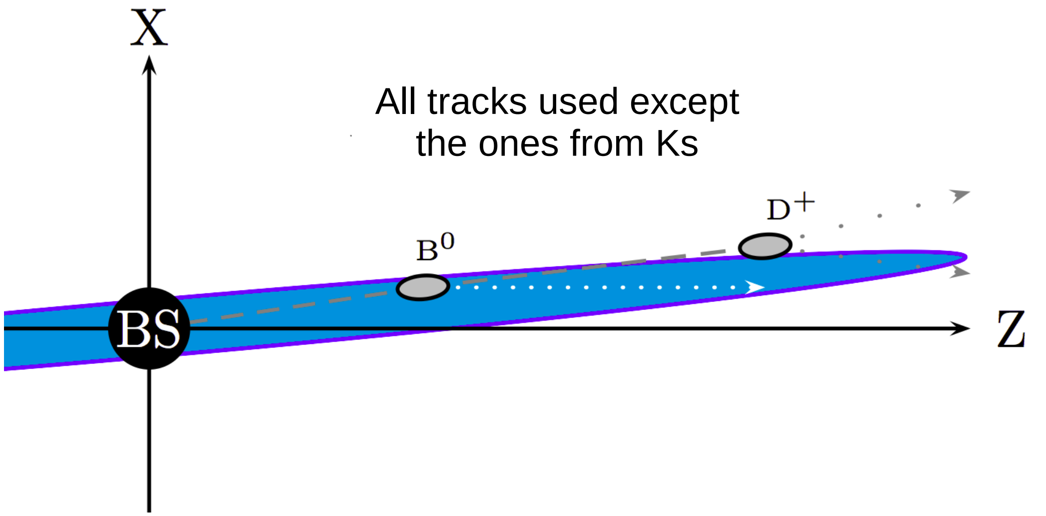
cutoff parameter

in each iteration step
the temperature parameter is lowered



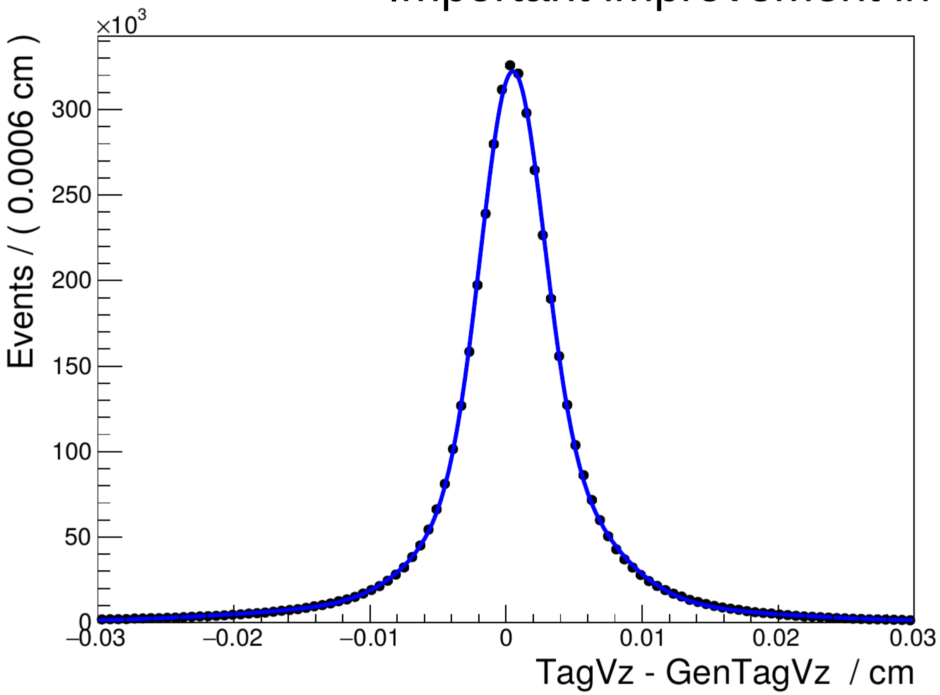
$$T_i = 1 + r \cdot (T_{i-1} - 1)$$

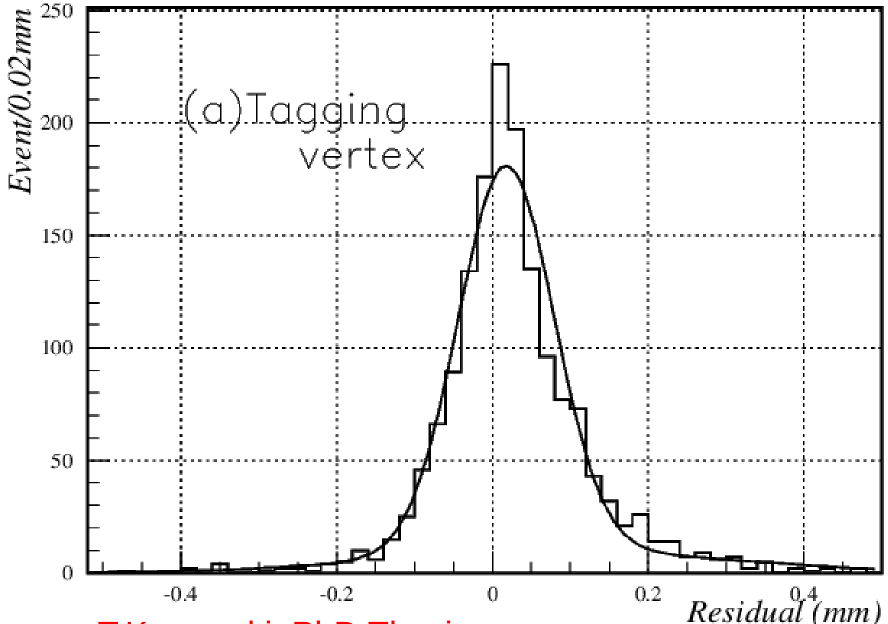
0<r<1



Tag side vertex resolution

Important improvement in the tag side vertex resolution

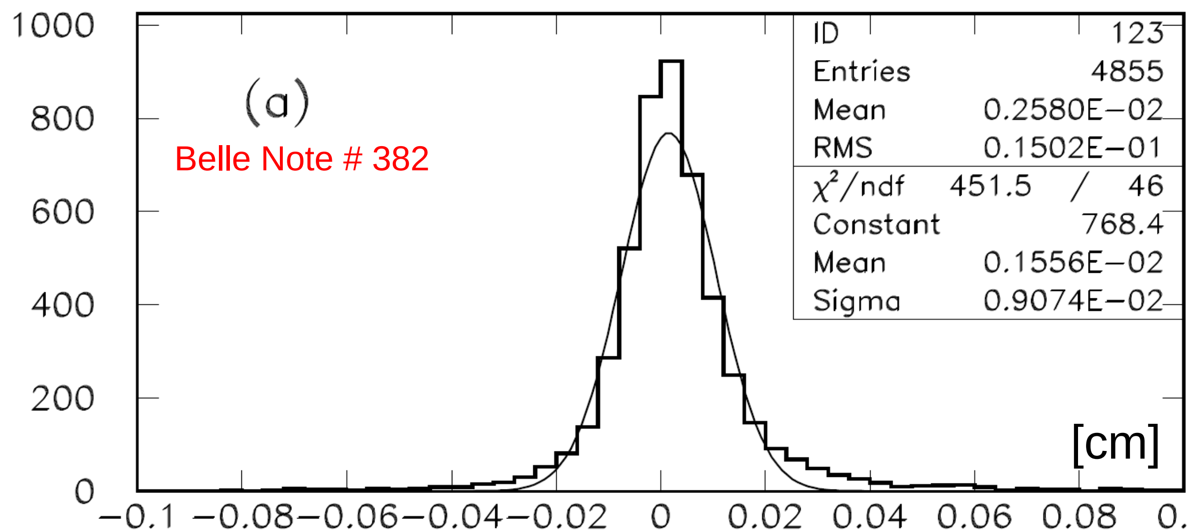




T.Kawasaki, PhD Thesis

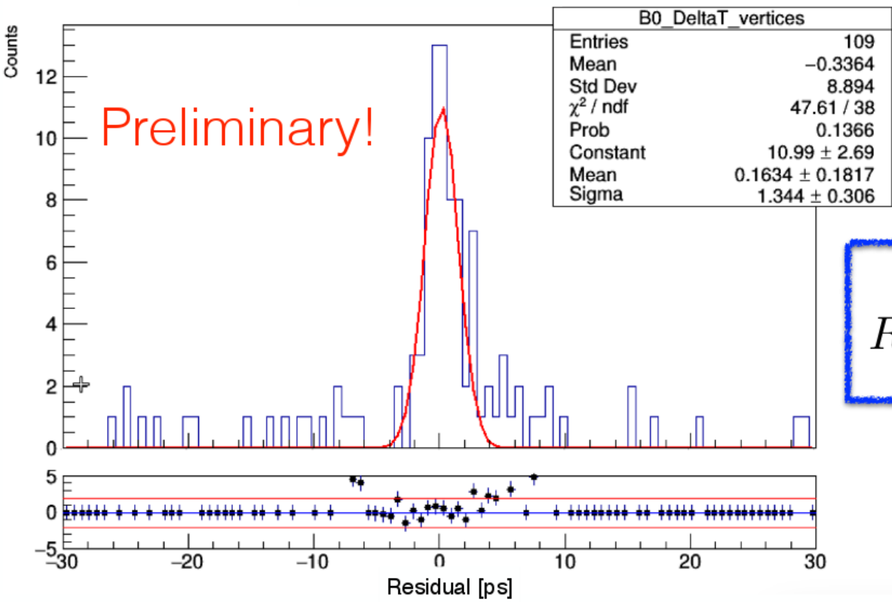
Belle II
- Shift = 5.9 μm
- Resolution = 53 μm

Belle
- Shift = 29 μm
- Resolution = 89 μm



$B^0 \rightarrow K_s\ \pi^0\ \gamma$: Δt resolution

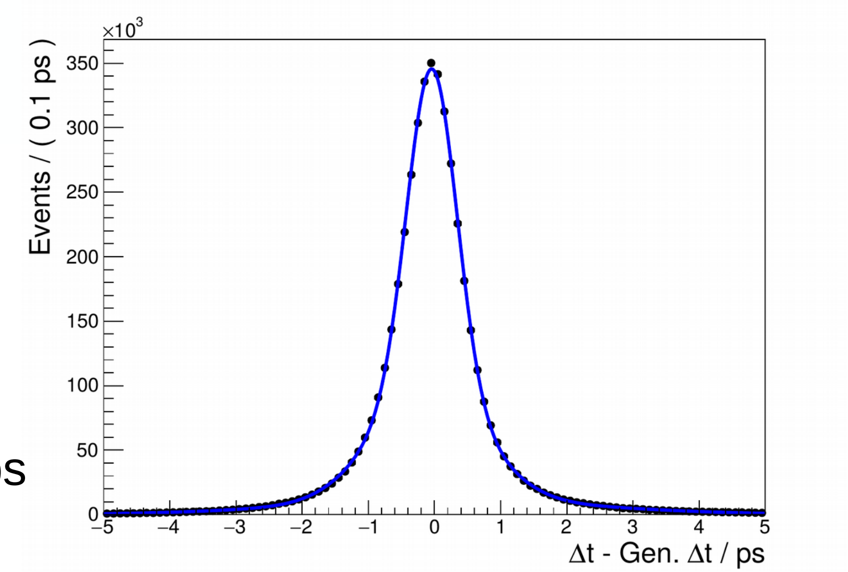
Δt distribution



Δt residual distribution:

$$Residual = \Delta t_{reco} - \Delta t_{truth}$$

$B^0 \rightarrow J/\psi\ K_s$



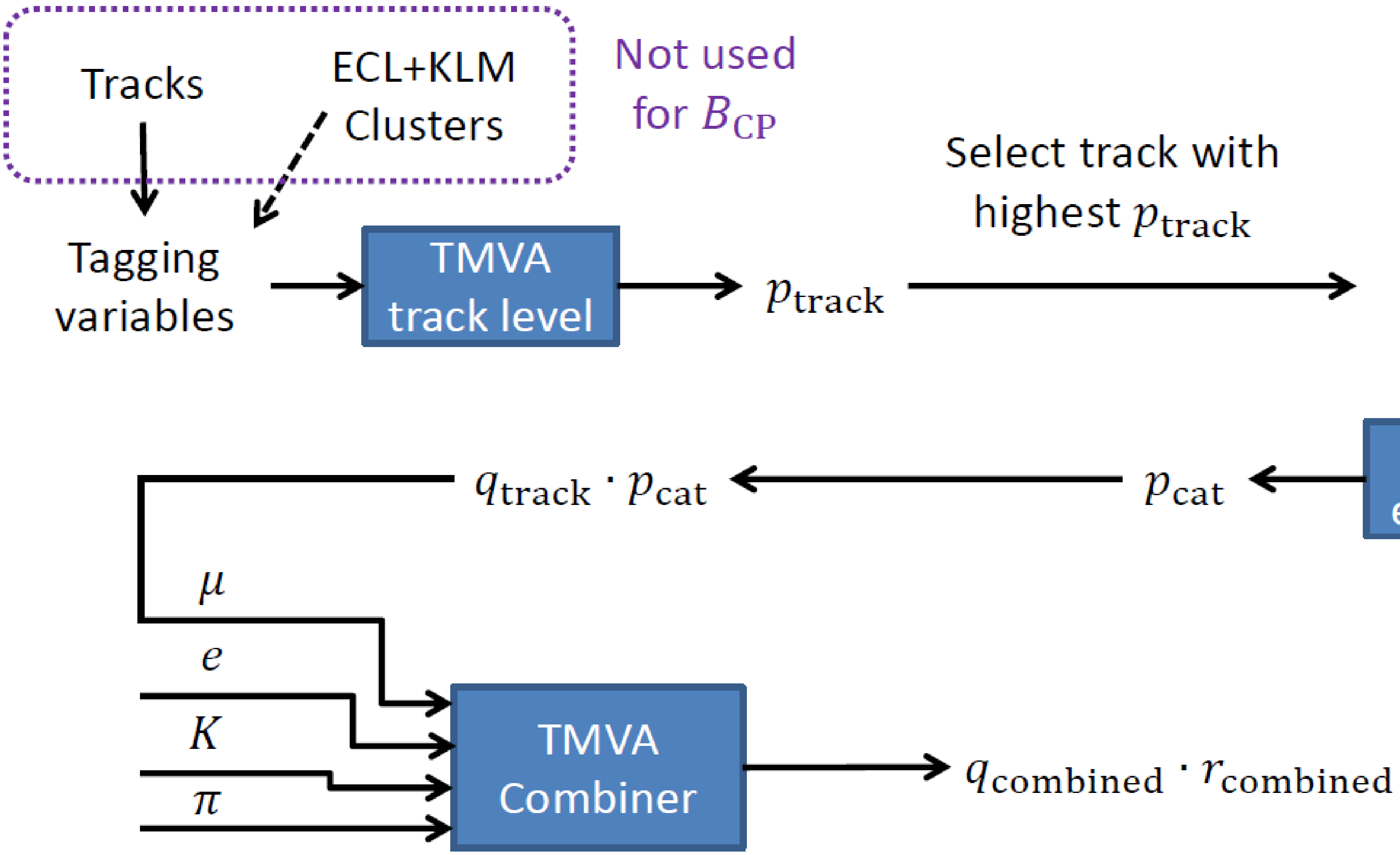
No bias observed on Δt distribution
Δt resolution ≃ 1.3 ps

Belle II
- Bias = -0.003 ps
- Resolution = 0.77 ps

Belle
- Bias = 0.2 ps
- Resolution = 0.92 ps

Flavour tagging

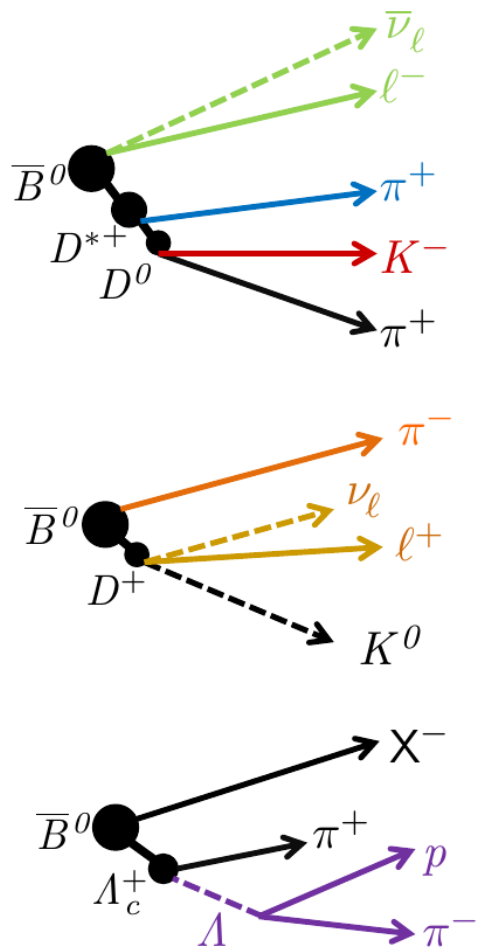
Based on multivariate methods

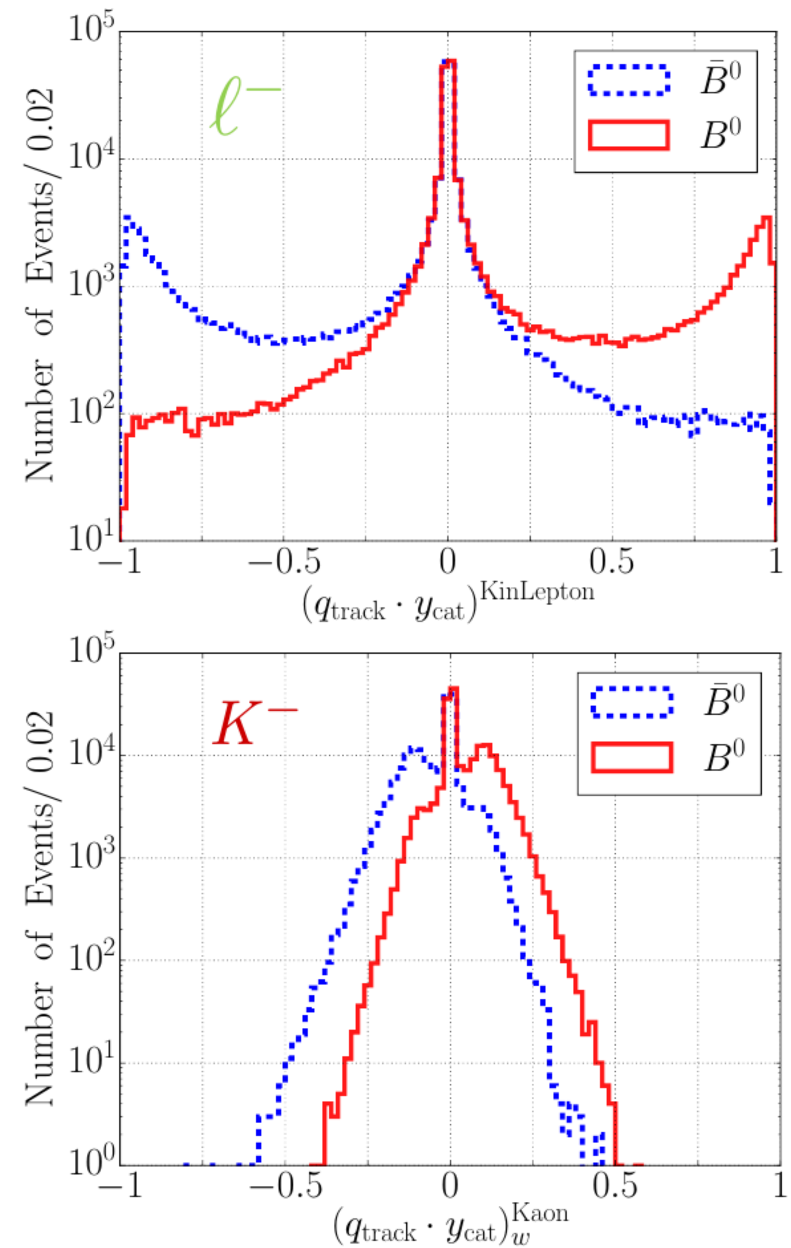


Categories and variables

Categories based on different signatures

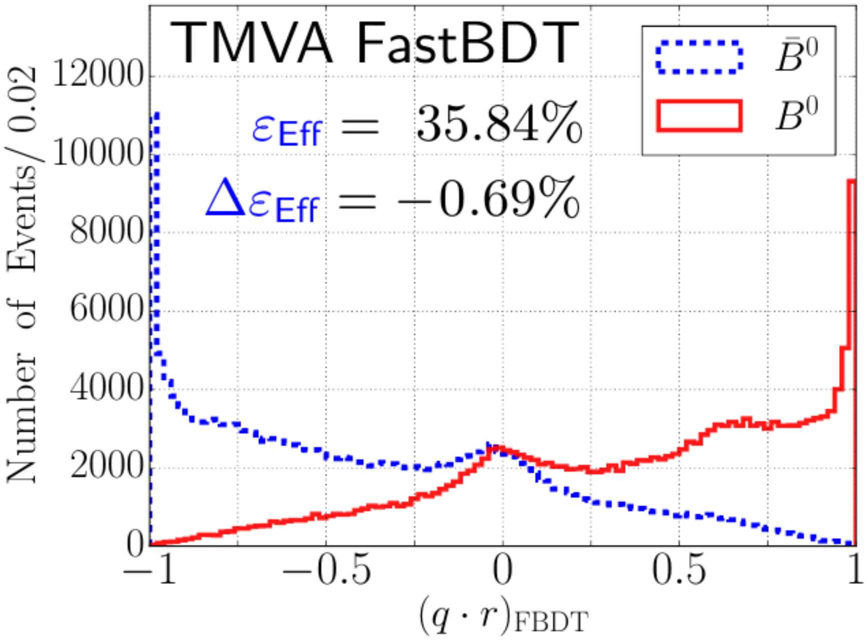
Categories	Targets
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
KinLepton	e^-
Intermediate KinLepton	ℓ^+
Kaon	K^-
KaonPion	K^-, π^+
SlowPion	π^+
FastPion	π^-
MaximumP	ℓ^-, π^-
FSC	ℓ^-, π^+
Lambda	Λ
Total= 13	

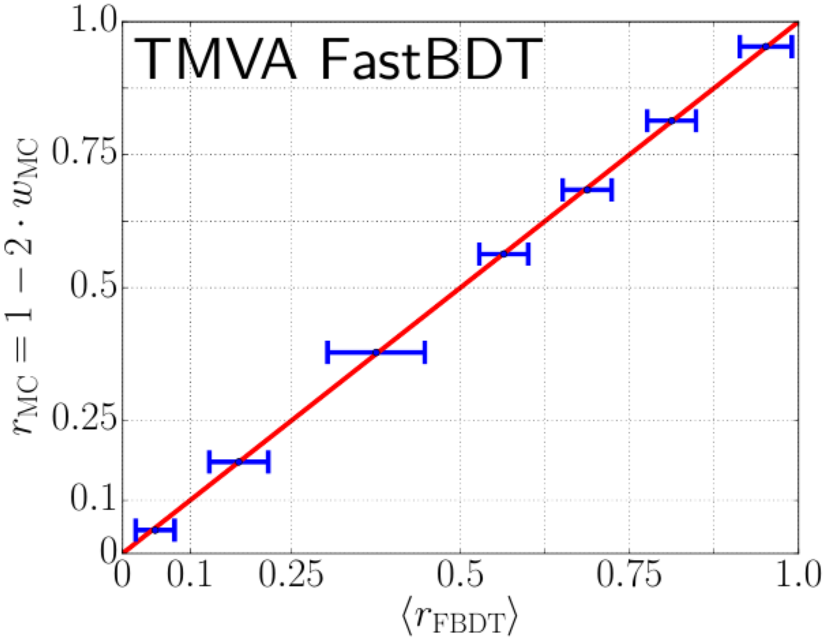


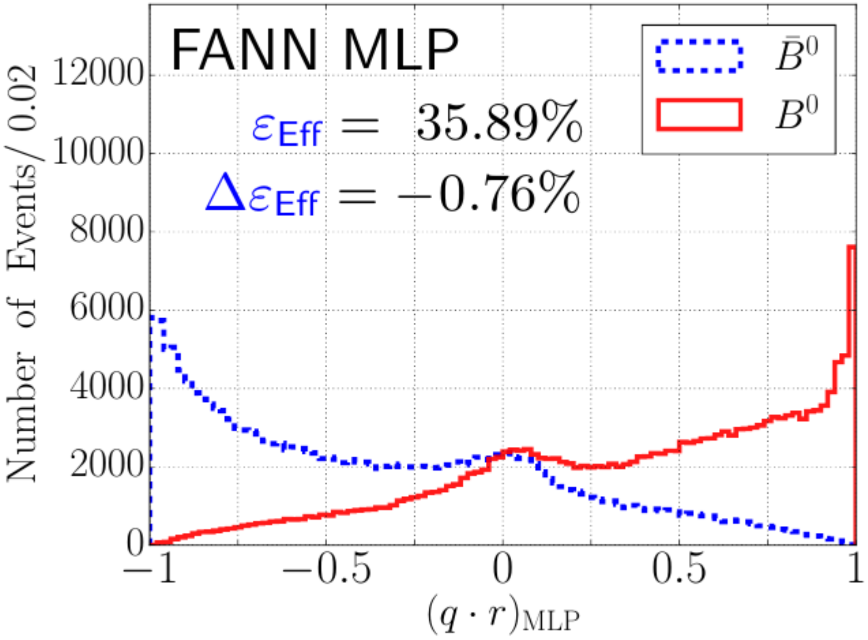


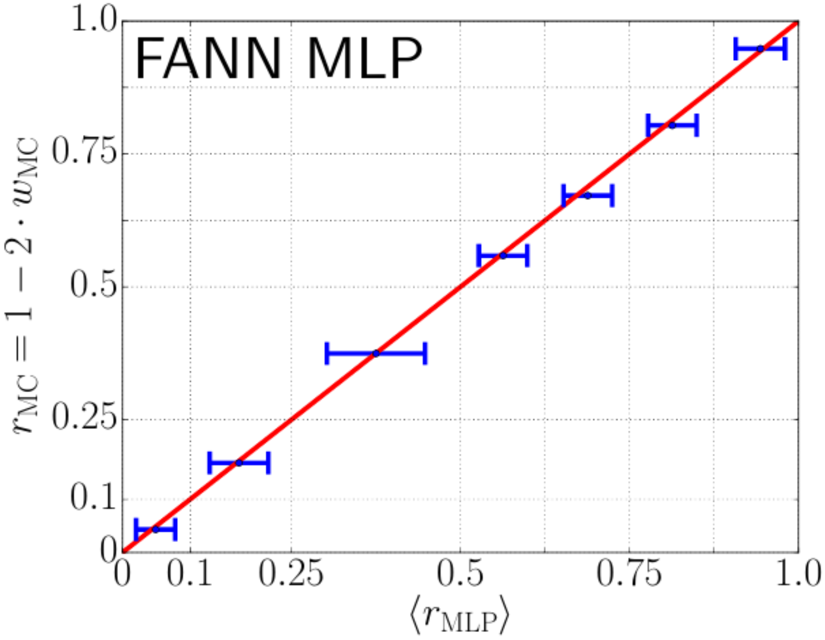
Combiner input

Combiner output

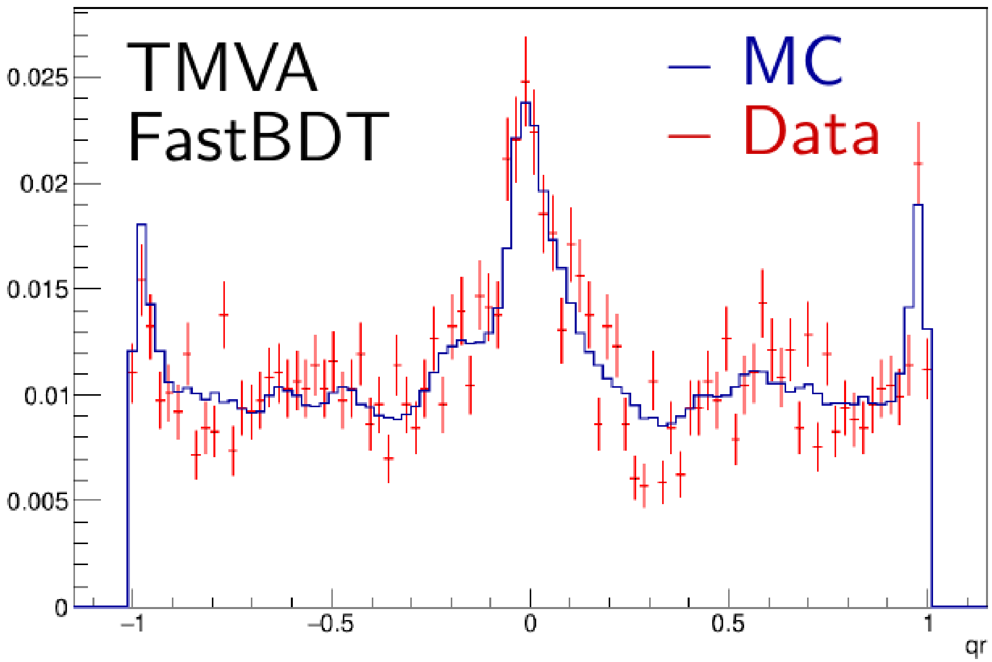








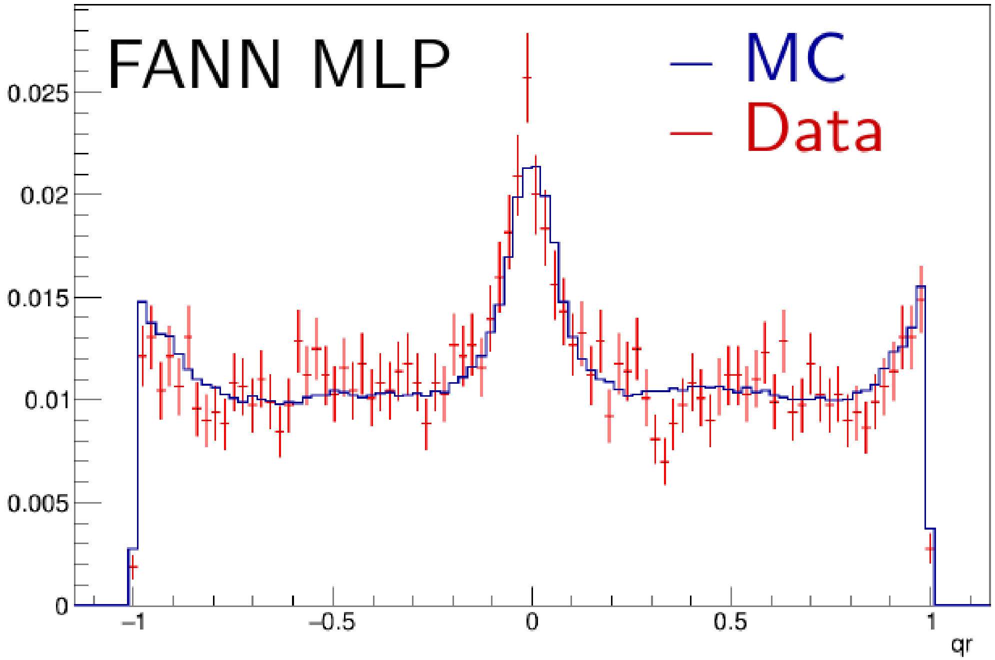
Belle Data – MC comparison



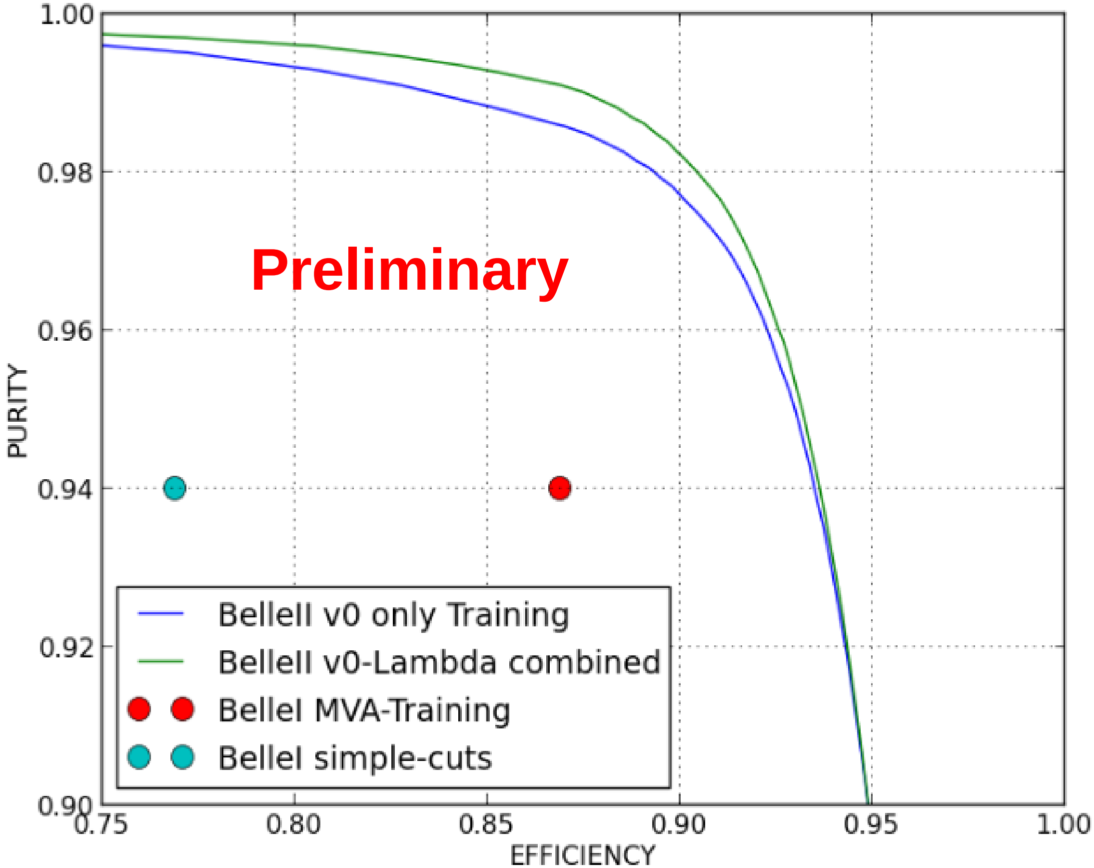
- Belle MC and data
- Belle II flavor tagging algorithm

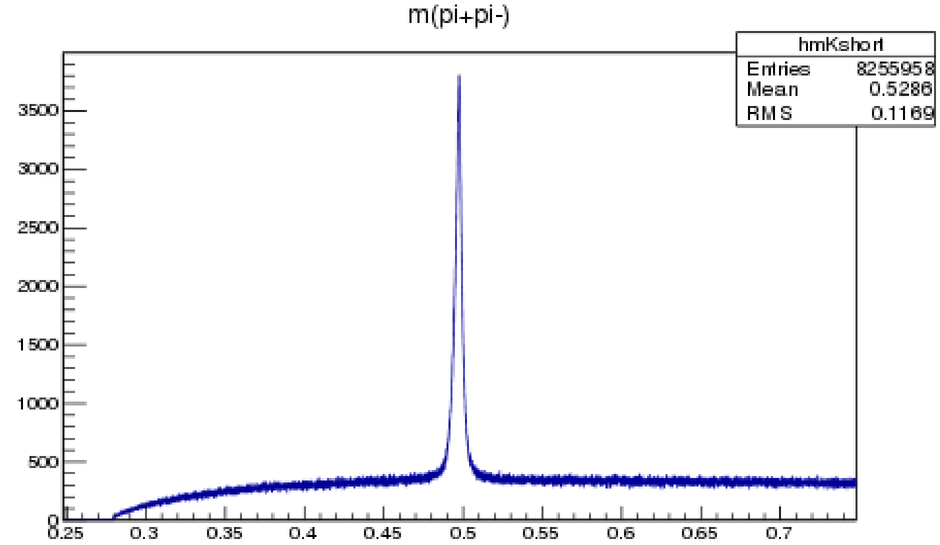
Efficiency

- Belle Converted MC = 32 %
- Belle = 29 %



Ks reconstruction





Training	ϵ	*purity*
b2-goodKS	93.6%	94%
b1-MVA	86.9%	94%
b1-cuts	76.9%	94%

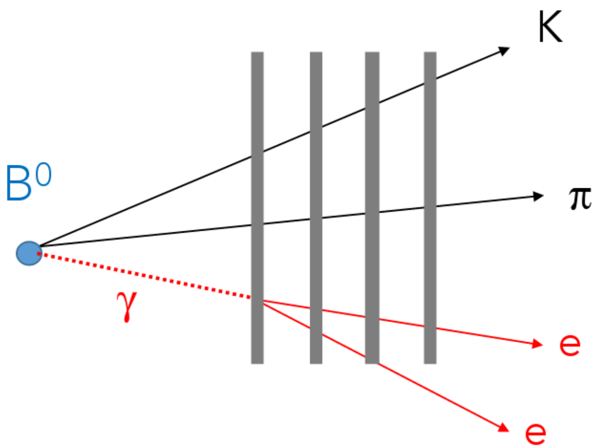
Ks efficiency improvement:

- Larger vertex detector acceptance
- New algorithm

$B^0 \rightarrow K^* \gamma$: converted γ

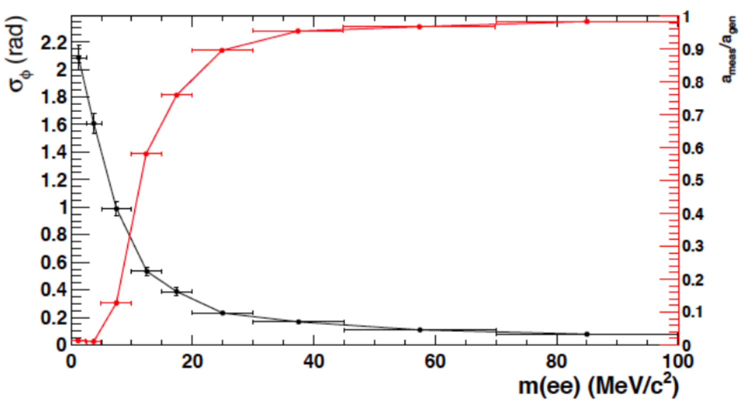
Martino Borsato CERN-THESIS-2015-219
Marie-Hélène Shune @ 4th B2TIP

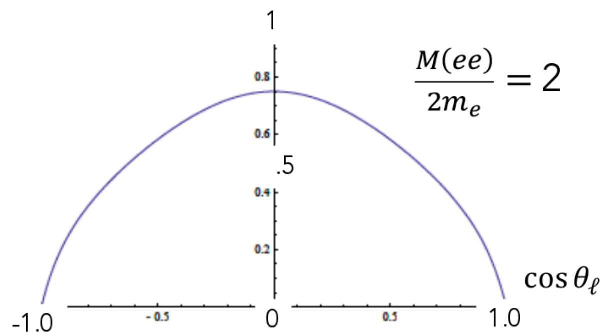
B→K*γ(→ ee) event in LHCb

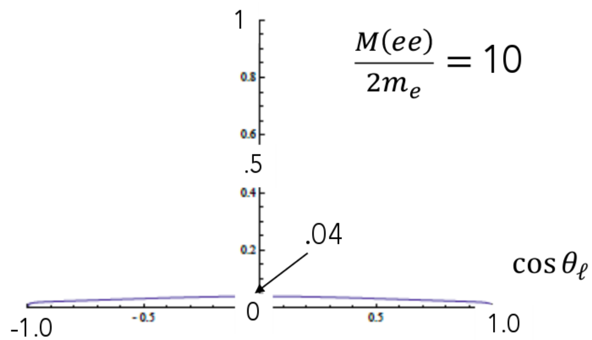


$$\frac{d\sigma}{d\phi} = A(1 + a\cos^2\phi)$$

- *a* gives the sensitivity to the photon polarisation
- Limited dependence with $\cos(\theta_\ell)$
- Strong dependence with M(ee)



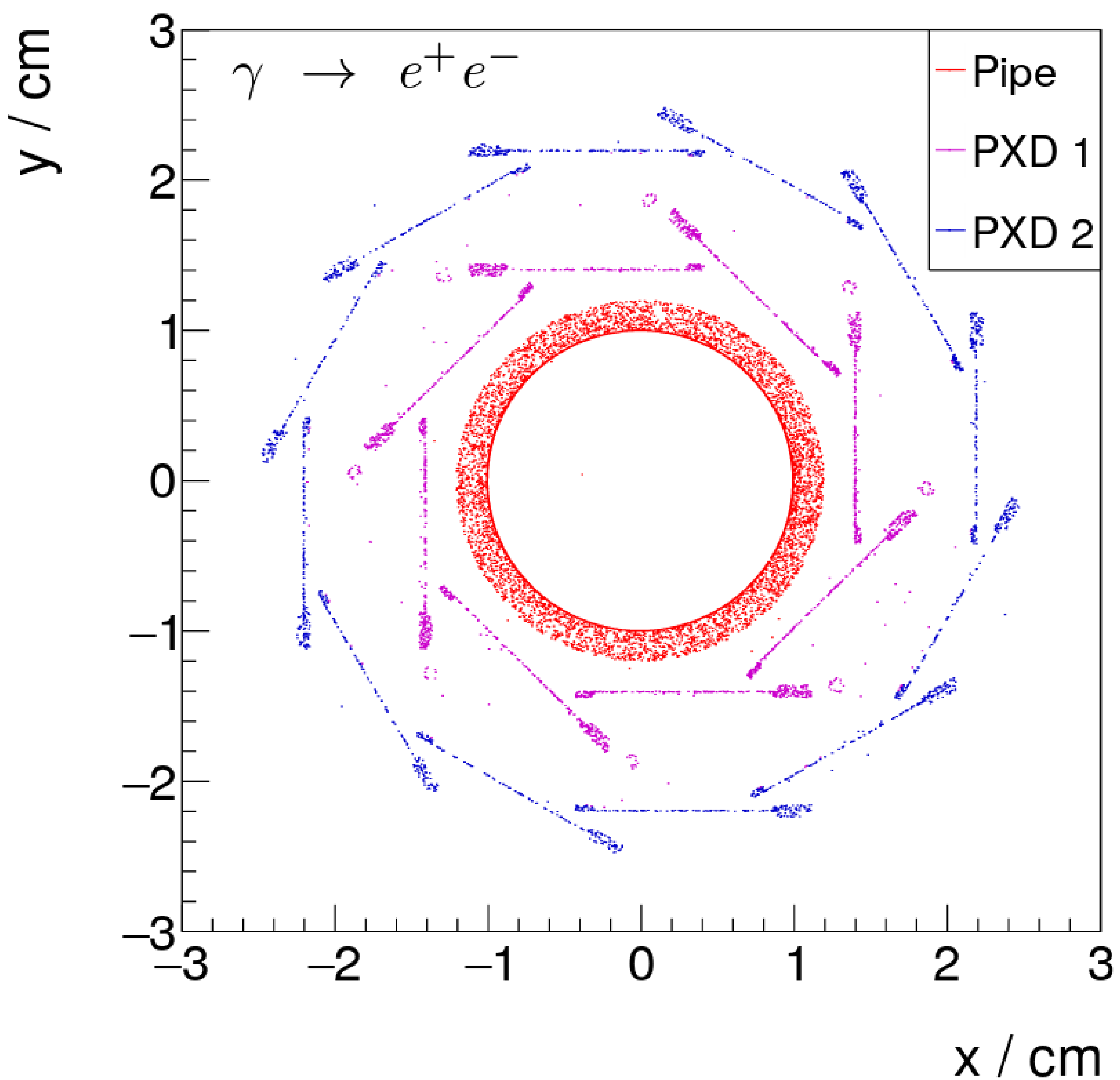




the sensitivity to the photon polarisation decreases as $1/M(ee)^2$

- For M(ee) < 10 MeV measurement dominated by multiple scattering
- Measurement very difficult with the LHCb detector

Belle II: converted γ



- Study of converted photons is at the beginning
- For $B^0 \rightarrow \pi^0 \pi^0$ ~ 3% of converted photons

Summary

- Radiative B decays, with $b \to s\, \gamma$ transitions are sensitive to New Physics
  - TD CP asymmetry measurements give an indirect measurement of photon polarization

- Present measurements dominated by the statistical errors. Scaling with luminosity:
  - $B^0 \to Ks\, \pi^0\, \gamma$: $\sigma(S)\sim0.04$, $\sigma(C)\sim0.02$
  - $B^0 \to \rho\, \gamma$: $\sigma(S)\sim0.08$, $\sigma(C)\sim0.06$

- With the upgrade of KEKB to SuperKEKB a new vertex detector is required for Belle II
  - Increase of background
  - Boost reduced
  - Maintenance of the same Belle vertex separation capability

- Expected better hardware/software performance then Belle considering the same integrated luminosity
  - Better Δt resolution
  - Higher flavour tagging efficiency
  - Higher Ks efficiency

- Feasibility of photon polarisation measurement using converted photons should be investigated at Belle II