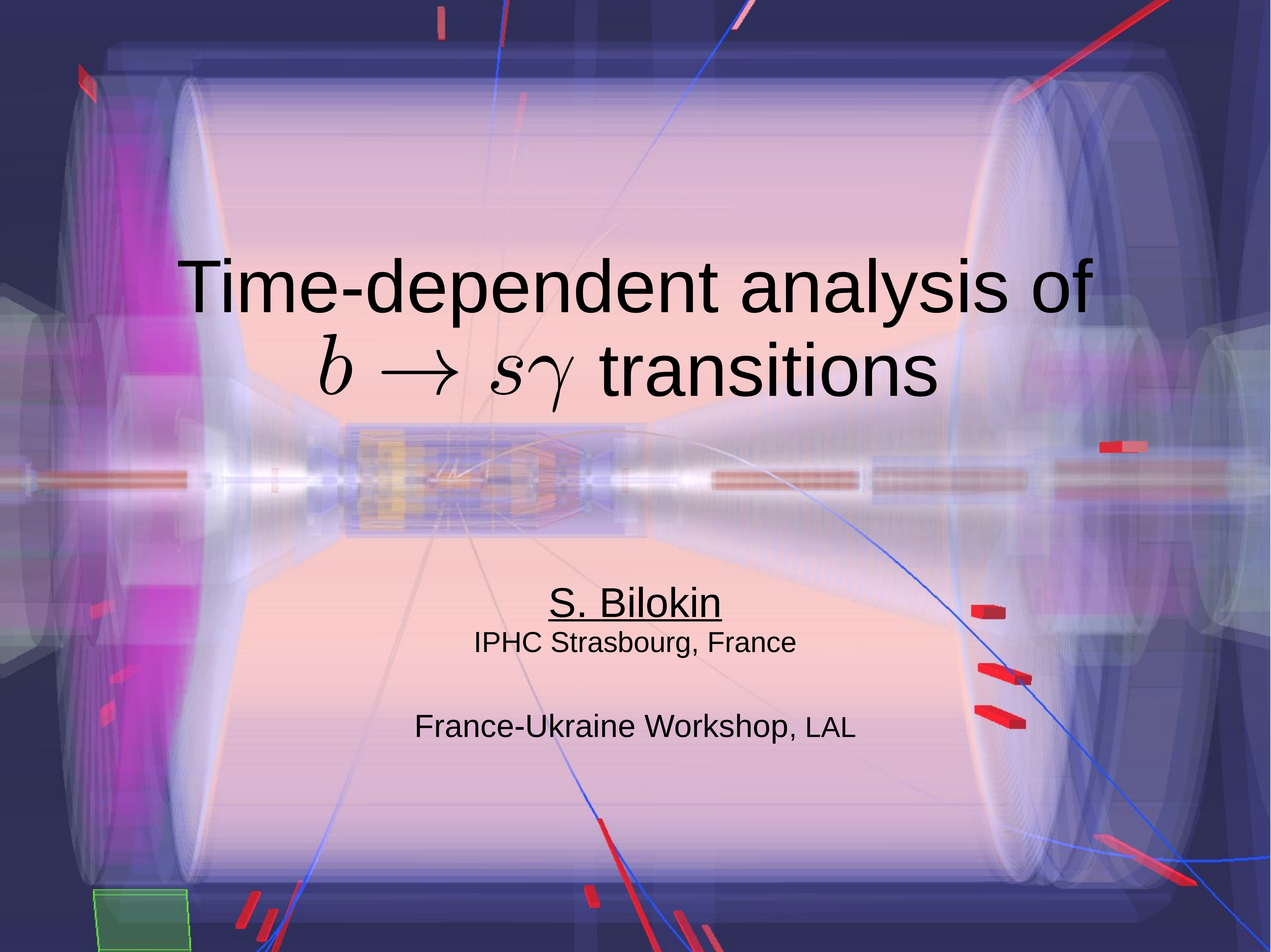

# Time-dependent analysis of $b \to s\gamma$ transitions


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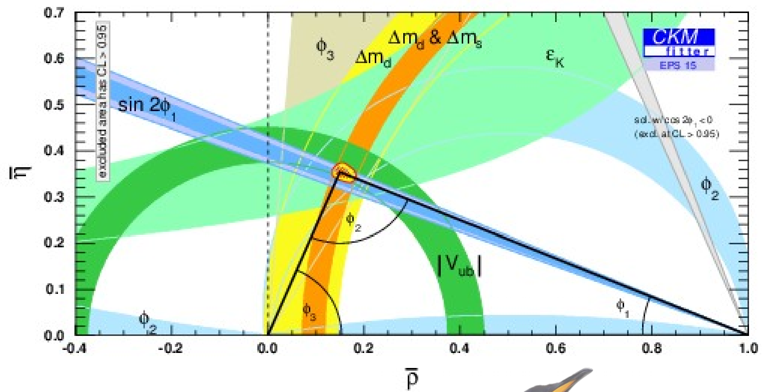
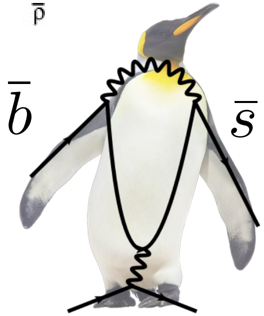
France-Ukraine Workshop, LAL

# Scientific motivation

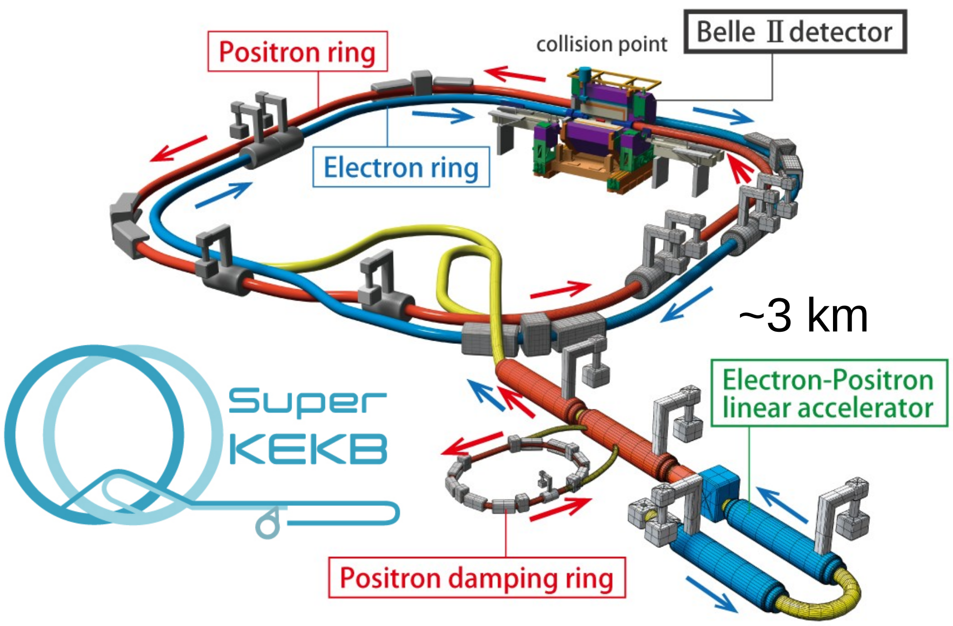
- Belle II @ SuperKEKB is the new $e^+e^-$ facility at intensity frontier, which studies properties of rare B meson decays – **b-factory**
  - Successor of **Belle @ KEKB** and **BaBar @ PEP II**
  - Rich physics program
    - Direct searches of BSM
      - Dark matter, axions, exotics ...
    - Indirect searches
      - **B physics (CKM, EW penguins, <u>radiative decays</u>)**
      - Charm physics
      - Tau physics
    - Quarkonium and QCD studies

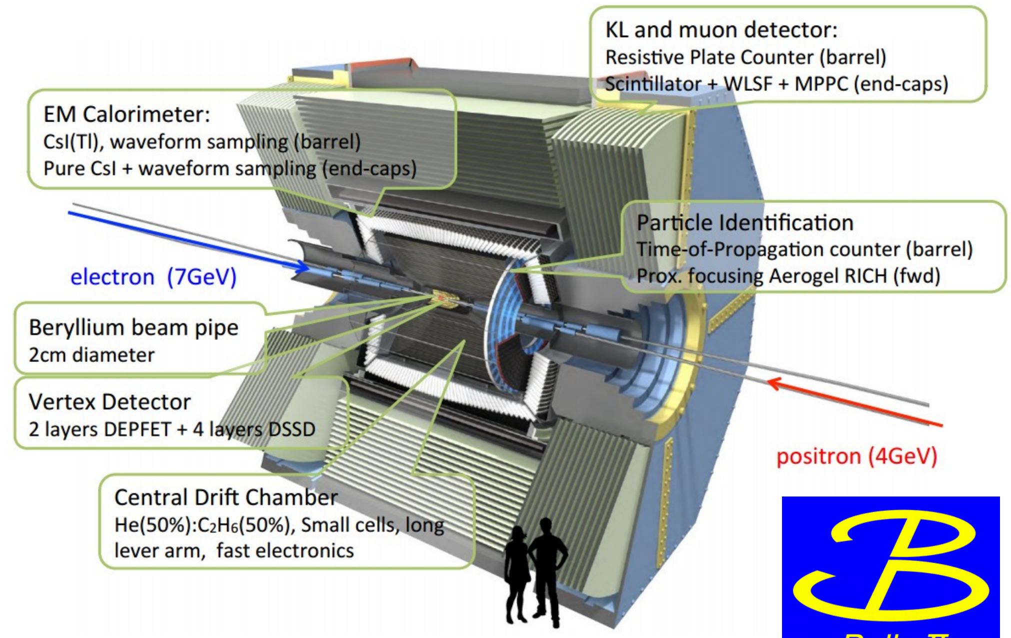



- No New Physics (NP) particles have been discovered at the LHC yet
  - Importance of the indirect searches is rising
  - Belle II can reach beyond the energy frontier sensitivity
- Constructive complementarity & competition with LHC

# Belle II at SuperKEKB




- Most of the data will be taken at the Y(4S) resonance
  - $E(e^-) = 7\,GeV$, $E(e^+) = 4\,GeV$
- Nano-beam scheme and doubling the beam current
  - Vertical beam size is 50nm
  - Higher beam background
- $\mathcal{L} = 8 \cdot 10^{35} \mathrm{cm}^{-2} \mathrm{s}^{-1} (\mathrm{KEKB\ x\ 40})$

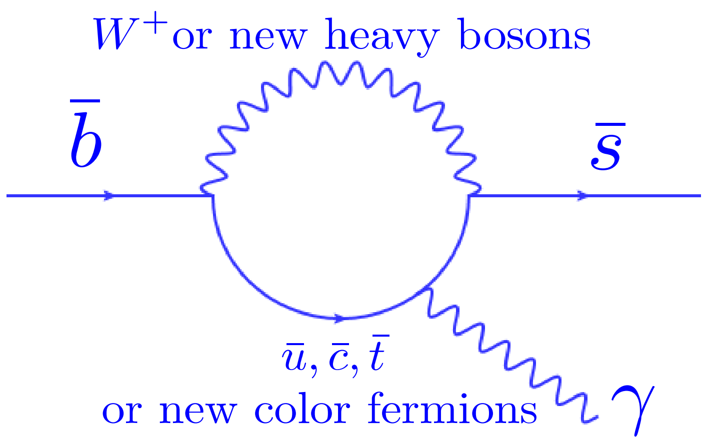
Belle II TDR - arXiv:1011.0352

- Improved vertex resolution, PID, tracking, etc...
- High detection efficiency $\gamma, \pi^0, K^0_{S,L}$
- **Detector commissioning has started and full Belle II will be next year**

**Plan to collect 50 $ab^{-1}$ by 2025**

# Introduction

- We are interested in time-dependent CP analysis of $b \to s\gamma$ transitions
  - In Standard Model
    no time-dependent CP violation (TDCPV)
    is expected due to its V-A structure
    and photon polarization
  - Sensitive to New Physics effects




- We are studying two channels:
  - $B^0 \to K_S^0 \pi^0 \gamma$ $\quad$ $B^0 \to K_S^0 \pi^+ \pi^- \gamma$
  - BR: $9.5 \times 10^{-6}$ $\quad$ $7 \times 10^{-6}$ $(\text{with } K_S^0 \to \pi^+\pi^-)$

- These processes go through several resonances $K^{*0}$ and higher $K_1^0$, $K_2^0$, … etc, often called $\mathbf{X_{sd}}$
  - $B^0 \to K_S^0 \pi^0 \gamma$ goes through $K^{*0}$ and $X_{sd}$
  - $B^0 \to K_S^0 \pi^+ \pi^- \gamma$ only through higher resonances $X_{sd}$

# Results by the previous experiments

arXiv:hep-ex/0608017
arXiv:0806.1980v1

arXiv:0807.3103
arXiv:1512.03579

$$B^0 \to K_S^0 \pi^0 \gamma$$

~ 0.48 ab$^{-1}$

$$\mathcal{S}_{K^{*0}\gamma} = -0.32^{+0.36}_{-0.33}(\mathrm{stat}) \pm 0.05$$
$$\mathcal{A}_{K^{*0}\gamma} = -0.20 \pm 0.24(\mathrm{stat}) \pm 0.05$$
$$\mathcal{S}_{K_S^0\pi^0\gamma} = -0.10 \pm 0.31(\mathrm{stat}) \pm 0.07$$
$$\mathcal{A}_{K_S^0\pi^0\gamma} = -0.20 \pm 0.20(\mathrm{stat}) \pm 0.06$$

~ 0.42 ab$^{-1}$

$$S_{K^*\gamma} = -0.03 \pm 0.29\ (\mathrm{stat}) \pm 0.03$$
$$C_{K^*\gamma} = -0.14 \pm 0.16\ (\mathrm{stat}) \pm 0.03$$
$$S_{K_S^0\pi^0\gamma} = -0.78 \pm 0.59\ (\mathrm{stat}) \pm 0.09$$
$$C_{K_S^0\pi^0\gamma} = -0.36 \pm 0.33\ (\mathrm{stat}) \pm 0.04$$

$$B^0 \to K_S^0 \pi^+\pi^- \gamma$$

~ 0.6 ab$^{-1}$

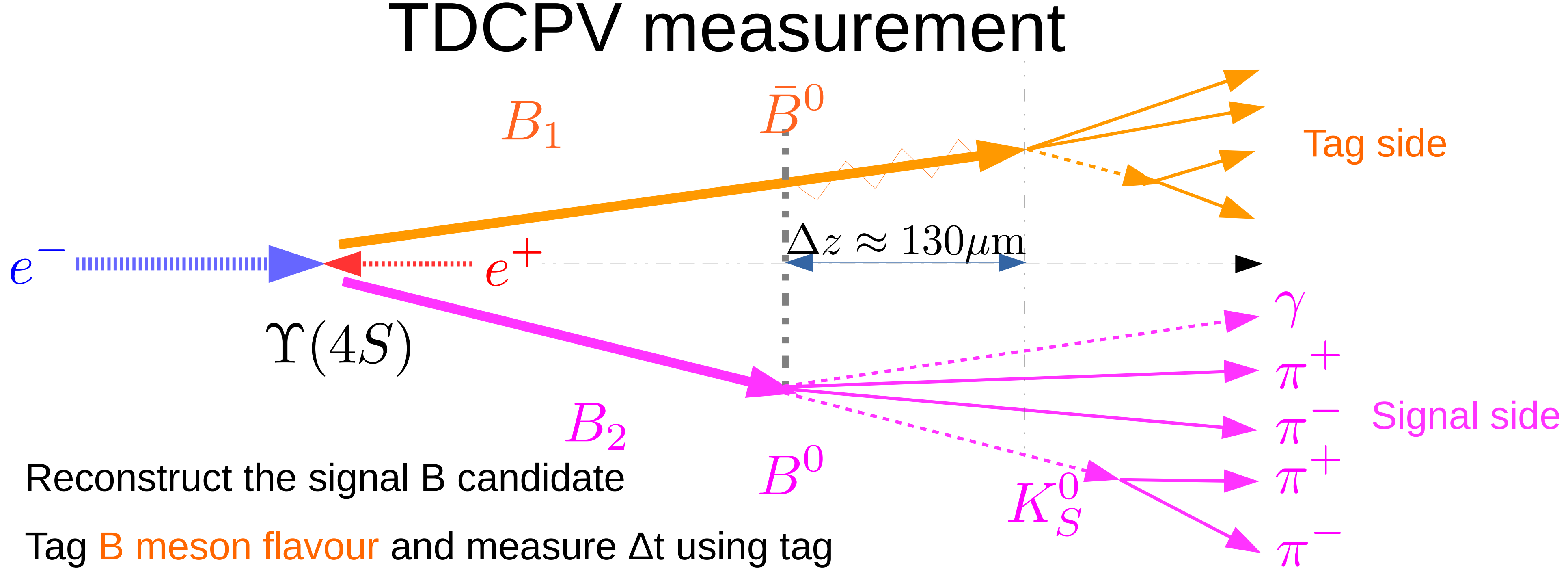
$$\mathcal{S}_{K_S^0\pi^+\pi^-\gamma} = 0.09 \pm 0.27^{+0.04}_{-0.07}$$
$$\mathcal{A}_{K_S^0\pi^+\pi^-\gamma} = 0.05 \pm 0.18 \pm 0.06$$

~ 0.43 ab$^{-1}$

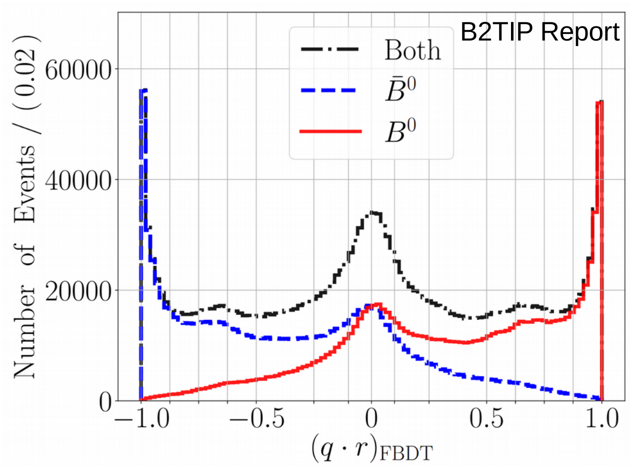
$$\mathcal{S}_{K_S^0\pi^+\pi^-\gamma} = 0.14 \pm 0.25 \pm 0.03,$$
$$\mathcal{C}_{K_S^0\pi^+\pi^-\gamma} = -0.39 \pm 0.20^{+0.03}_{-0.02}.$$

- **The results of the previous b-factories, Belle and BaBar are statistically limited → increase sensitivity ~x10 with Belle II**

# TDCPV measurement




- Reconstruct the signal B candidate
- Tag B meson flavour and measure Δt using tag side and signal side B candidate vertices
  - Effective flavour tagging efficiency is 33.6%
    - Detector improvement: +3%
    - Algorithm improvement: +3%
- Compute discriminating observables
- Build signal and background probability density functions (PDFs) models and extract S and A TDCPV parameters

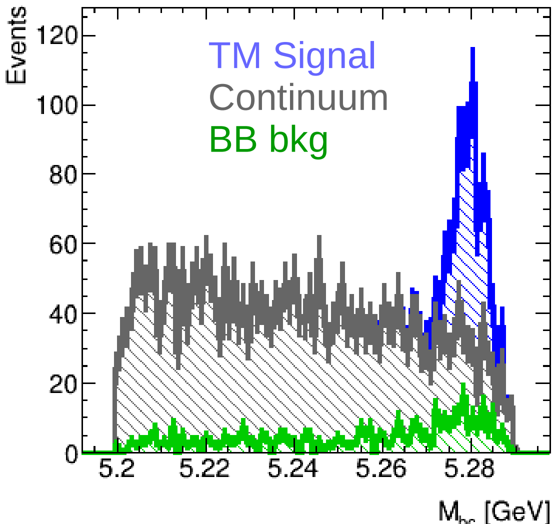


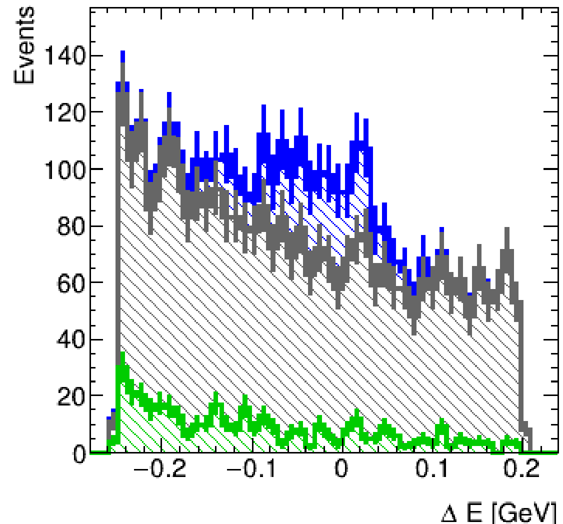

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 + q(S\sin(\Delta m \Delta t) + A\cos(\Delta m \Delta t))]$$

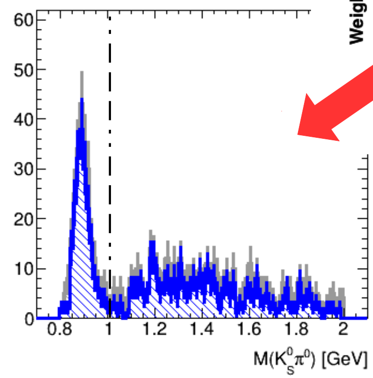
# Reconstruction quality

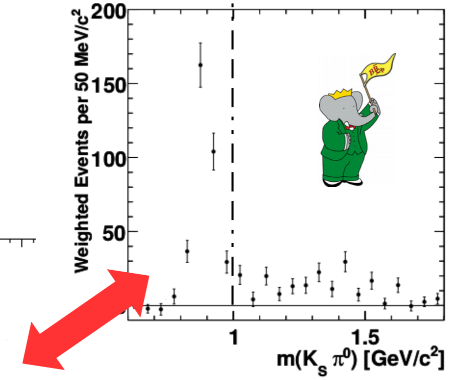
- Using full Belle II simulation sample 1 ab$^{-1}$:

$B^0 \to K_S^0 \pi^0 \gamma$ (all mass spectrum)



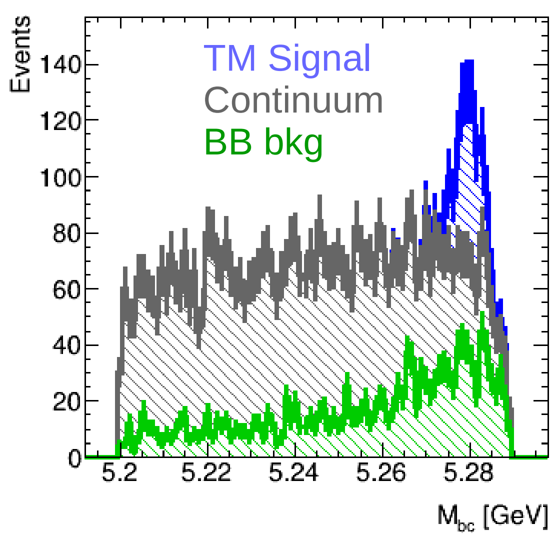



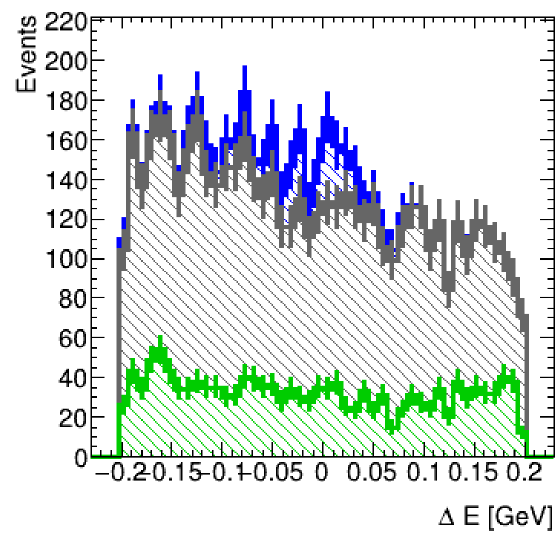

**~3.7% MC efficiency**

$B^0 \to K_S^0 \pi^+ \pi^- \gamma$

$$m_{bc} = \sqrt{(E_{beam}^{c.m.s.})^2 - (p_B^{c.m.s.})^2}$$

$$\Delta E = E_B^{c.m.s.} - E_{beam}^{c.m.s.}$$



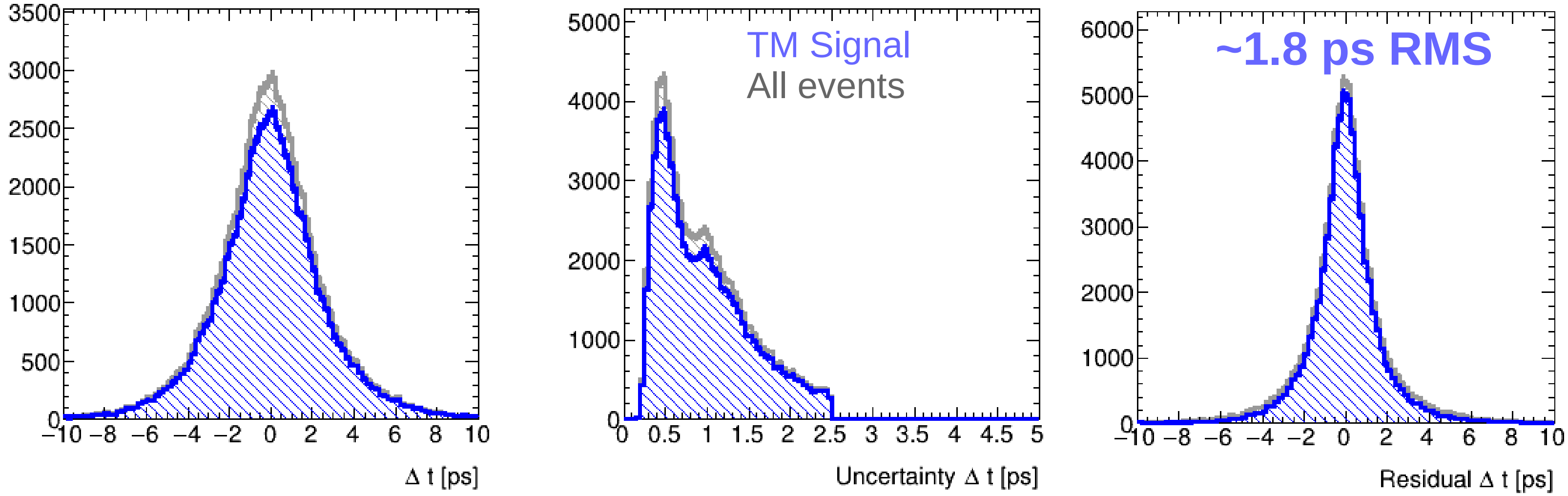




**~4.2% MC efficiency**

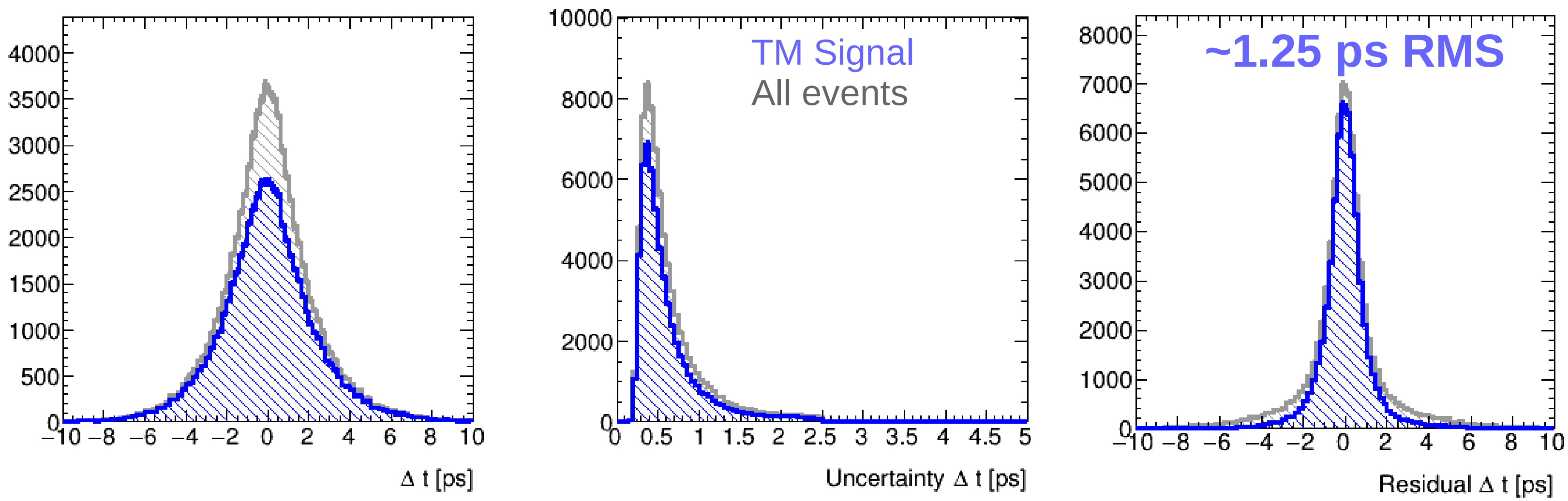
# Reconstruction quality

- Using full Belle II simulation signal samples:

$$B^0 \to K_S^0 \pi^0 \gamma$$

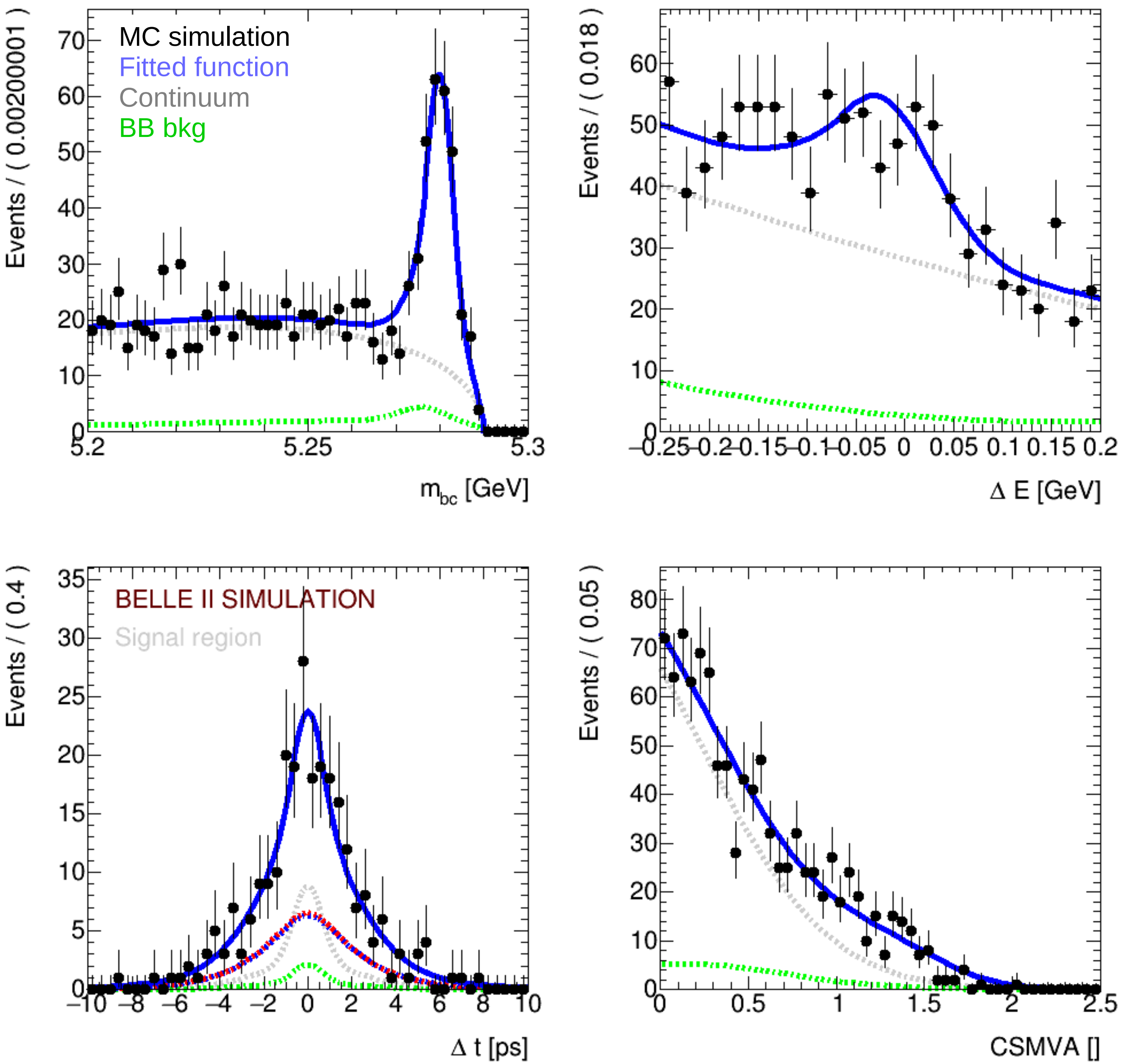



$$B^0 \to K_S^0 \pi^+ \pi^- \gamma$$



# Fit of $B^0 \to K_S^0 \pi^0 \gamma$

- Using MC sample of L = 1 $ab^{-1}$, **K* mass region**:




- 4D unbinned likelihood fit gives the precision on TDCPV parameters *A* & *S*
- 2 background models and 1 signal model
- Continuum bkg shape, signal fraction, A and S are determined from the fit

MC numbers:

- N(total) = 1029
- N(signal) = 203

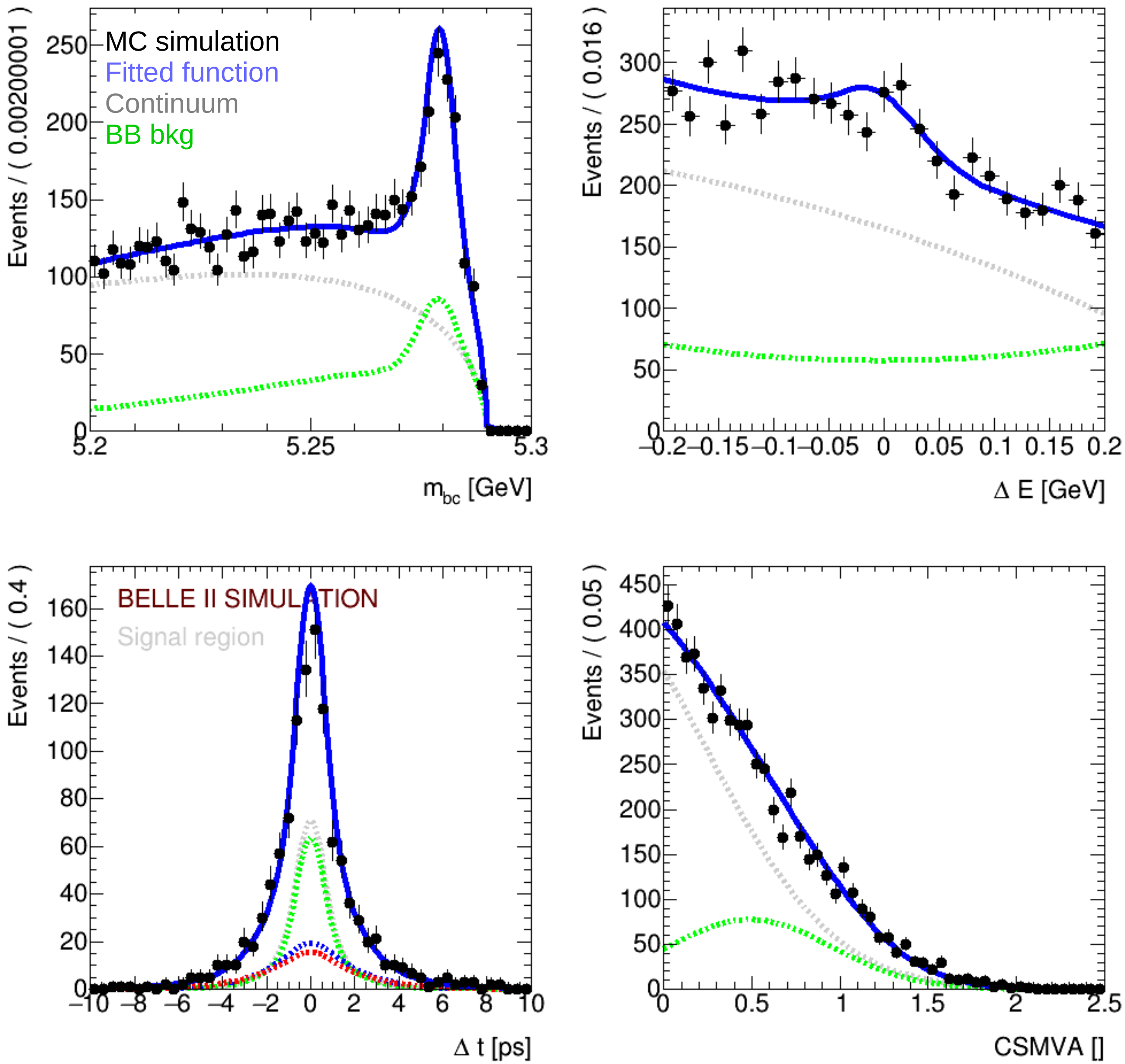
Fit results:

N(signal) =220±18

$$A = +0.03 \pm 0.19$$
$$S = +0.02 \pm 0.30$$

# Fit of $B^0 \to K_S^0 \pi^+ \pi^- \gamma$

- Using MC sample of L = 1 $ab^{-1}$:




- 4D unbinned likelihood fit gives the precision on TDCPV parameters *A* & *S*
- 2 background models and 1 signal model
- Continuum bkg shape, signal fraction, A and S are determined from the fit

MC numbers:

- N(total) = 6002
- N(signal) = 436

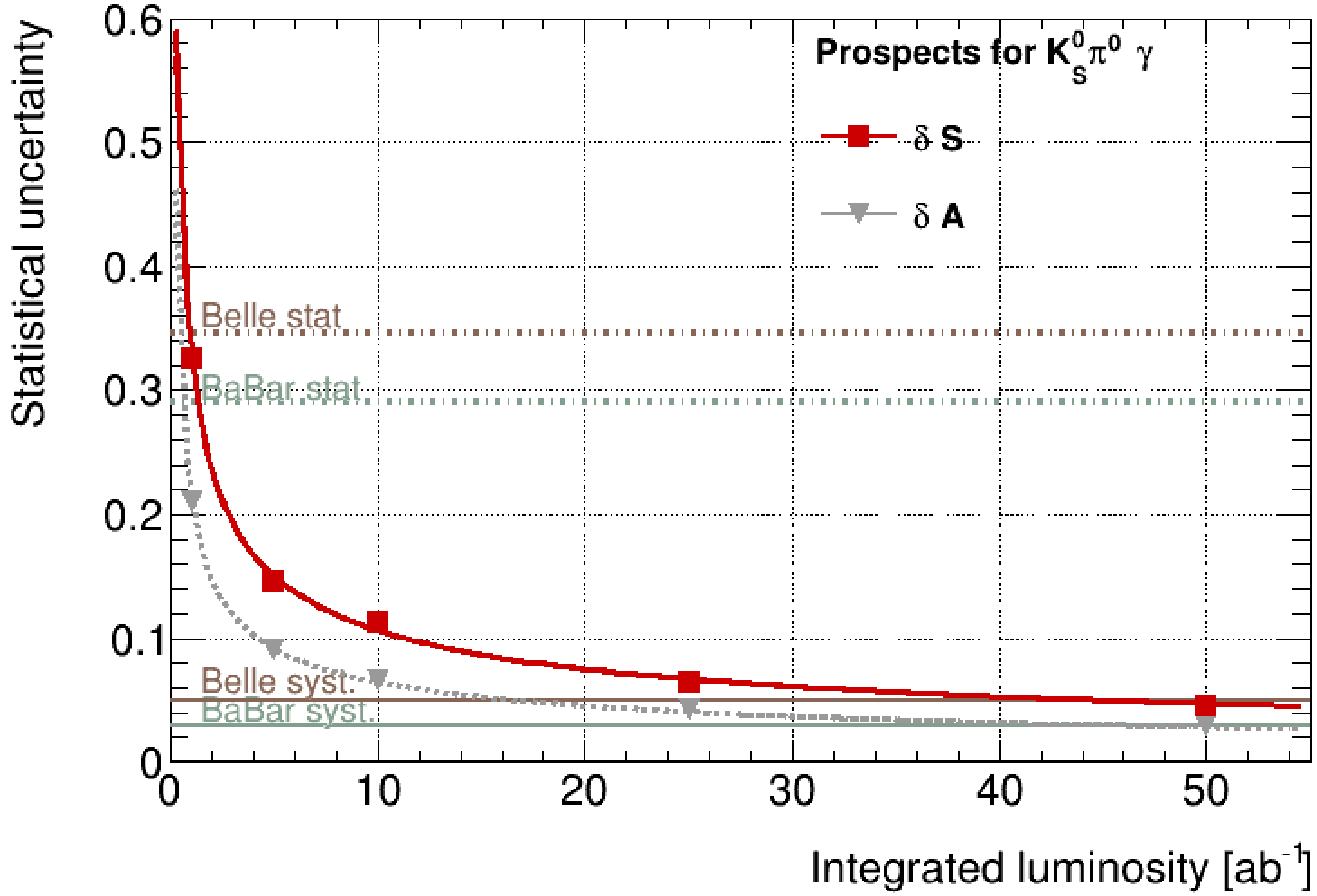
Fit results:

N(signal) = 428±29

$$A = -0.21 \pm 0.17$$
$$S = -0.09 \pm 0.20$$

# Preliminary prospects for $B^0 \to K_S^0 \pi^0 \gamma$

- 200 Toy MC experiments, **K*0 mass region**:

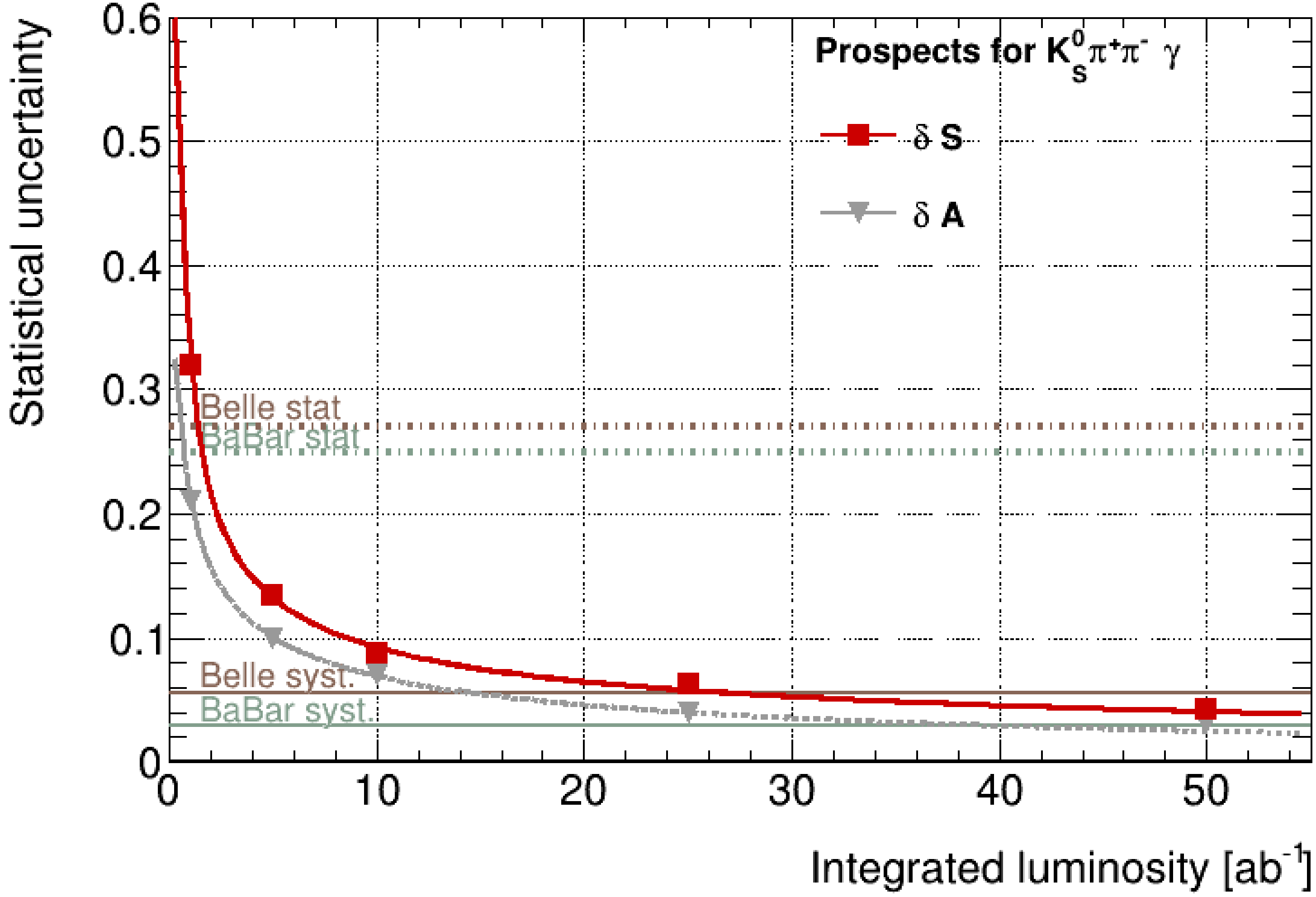



- The statistical error of full Belle II dataset is on the level of systematics

*Belle and BaBar errors are for S parameter

# Preliminary prospects for $B^0 \to K_S^0 \pi^+ \pi^- \gamma$

- 200 Toy MC experiments:




- Non CP eigenstates can dilute the precision on S by ~20%



*Belle and BaBar errors are for S parameter

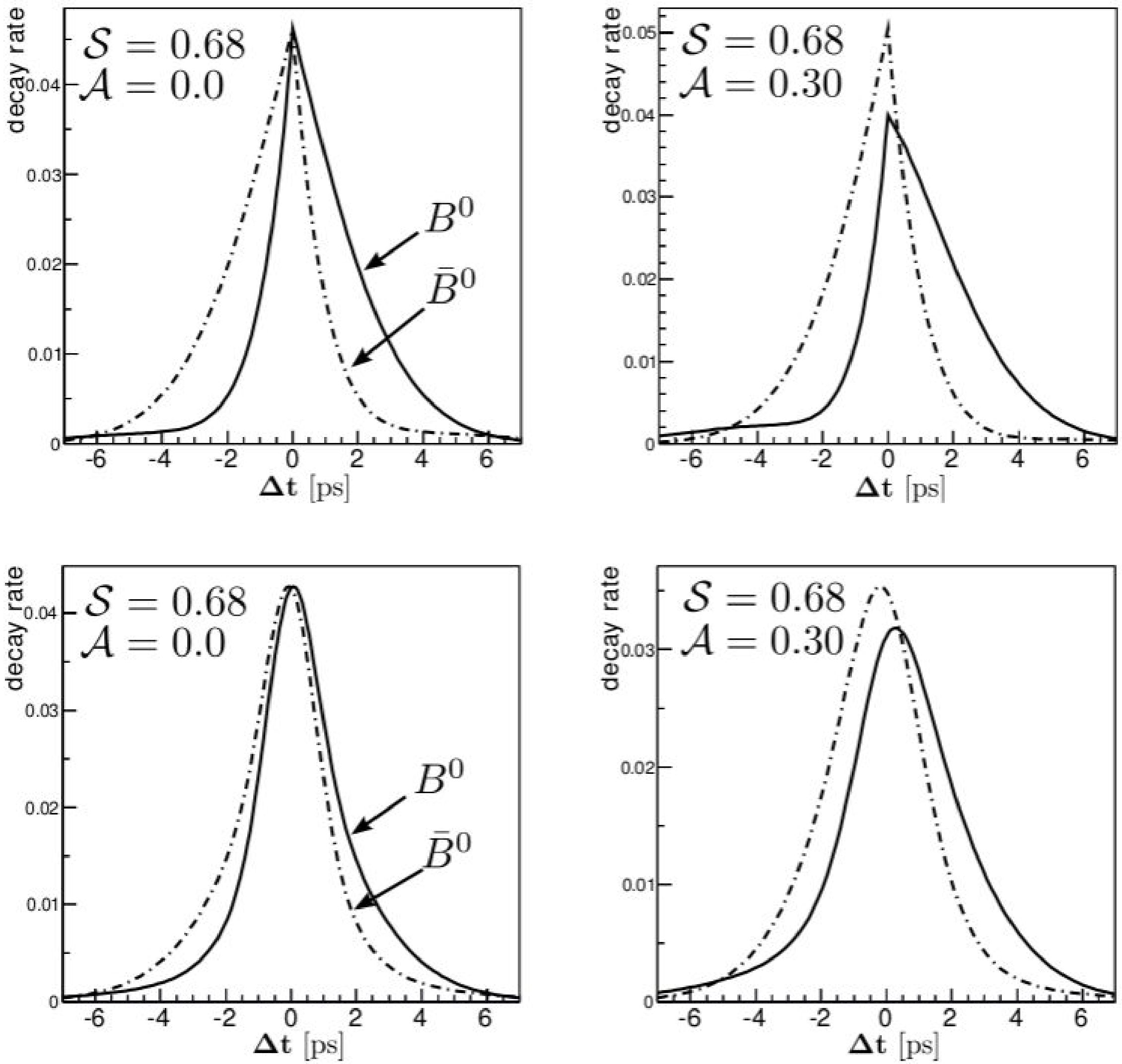
# Summary

- Radiative processes, like $b \to s\gamma$, are sensitive probes for New Physics
  - The e+e- collisions at Belle II is an excellent environment to study radiative processes
- For $B^0 \to K_S^0 \pi^+ \pi^- \gamma$ statistical uncertainty on δS ~ 0.043 is reachable
- Another channel $B^0 \to K_S^0 \pi^0 \gamma$ gives δS ~ 0.045, it is easier to interpret

- **Belle II will provide enough data to have statistical uncertainties comparable to the systematic ones for the radiative TDCPV studies**

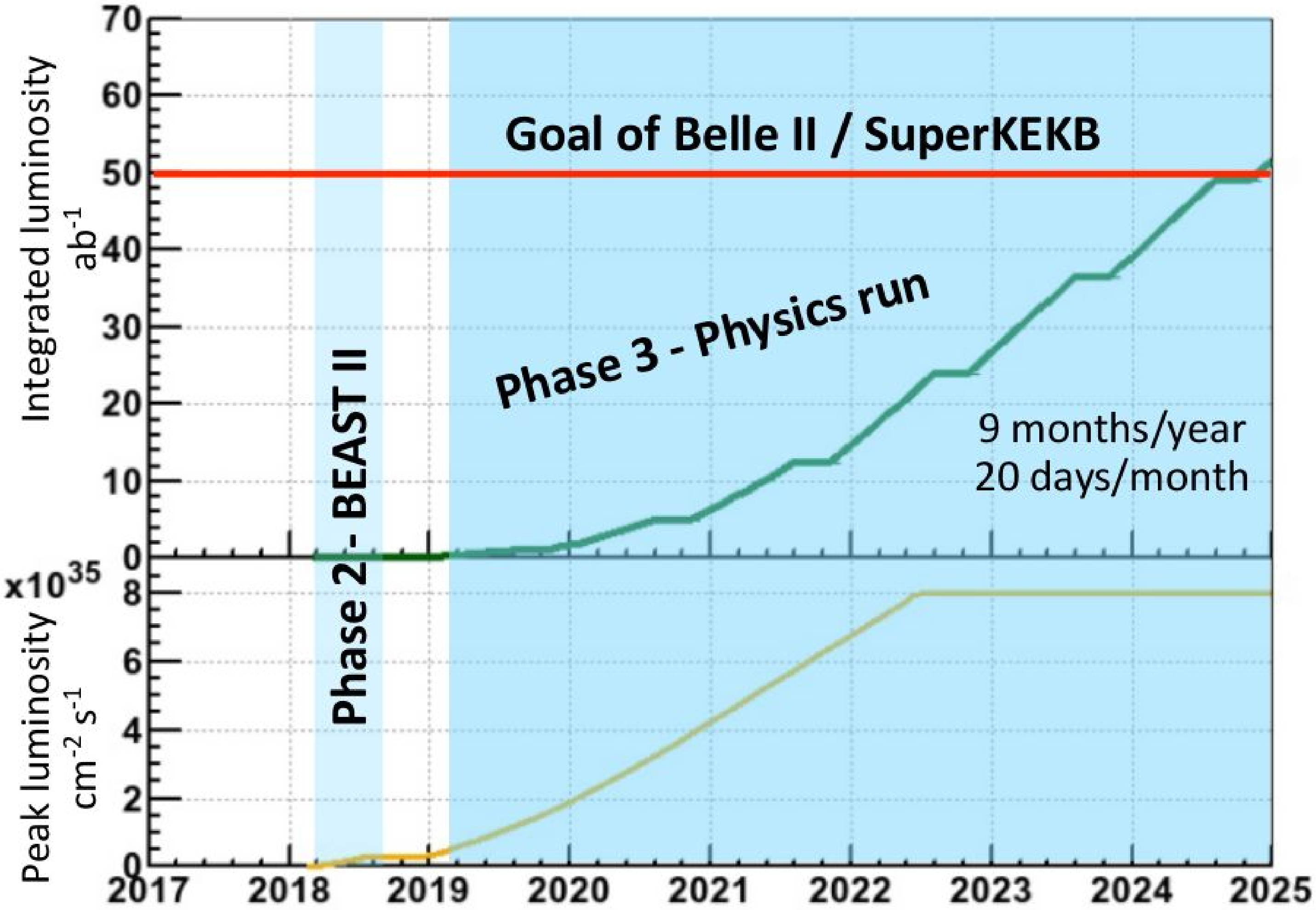
Thank you!

# Delta T




- Change of S and A parameters and influence of experimental resolution

# Initial SuperKEKB planning



# Belle II parameters

| Component | Type | Configuration | Readout | Performance |
|---|---|---|---|---|
| Beam pipe | Beryllium double-wall | Cylindrical, inner radius 10 mm, 10 $\mu$m Au, 0.6 mm Be, 1 mm coolant (paraffin), 0.4 mm Be | | impact parameter resolution $\sigma_{z_0} \sim 20\ \mu$m (PXD and SVD) |
| PXD | Silicon pixel (DEPFET) | Sensor size: $15\times100$ (120) mm$^2$ pixel size: $50\times50$ (75) $\mu$m$^2$ 2 layers: 8 (12) sensors | 10 M | |
| SVD | Double sided Silicon strip | Sensors: rectangular and trapezoidal Strip pitch: 50(p)/160(n) - 75(p)/240(n) $\mu$m 4 layers: 16/30/56/85 sensors | 245 k | |
| CDC | Small cell drift chamber | 56 layers, 32 axial, 24 stereo r = 16 - 112 cm $-83 \leq z \leq 159$ cm | 14 k | $\sigma_{r\phi} = 100\ \mu$m, $\sigma_z = 2$ mm $\sigma_{p_t}/p_t = \sqrt{(0.2\%p_t)^2 + (0.3\%/\beta)^2}$ $\sigma_{p_t}/p_t = \sqrt{(0.1\%p_t)^2 + (0.3\%/\beta)^2}$ (with SVD) $\sigma_{dE/dx} = 5\%$ |
| TOP | RICH with quartz radiator | 16 segments in $\phi$ at $r \sim 120$ cm 275 cm long, 2 cm thick quartz bars with 4x4 channel MCP PMTs | 8 k | $N_{p.e.} \sim 20$, $\sigma_t = 40$ ps K/$\pi$ separation : efficiency $> 99\%$ at $< 0.5\%$ pion fake prob. for $B \to \rho\gamma$ decays |
| ARICH | RICH with aerogel radiator | 4 cm thick focusing radiator and HAPD photodetectors for the forward end-cap | 78 k | $N_{p.e.} \sim 13$ K/$\pi$ separation at 4 GeV/$c$: efficiency 96% at 1% pion fake prob. |
| ECL | CsI(Tl) (Towered structure) | Barrel: $r = 125$ - 162 cm End-cap: $z =$ -102 cm and +196 cm | 6624 1152 (F) 960 (B) | $\frac{\sigma E}{E} = \frac{0.2\%}{E} \oplus \frac{1.6\%}{\sqrt[4]{E}} \oplus 1.2\%$ $\sigma_{pos} = 0.5\ \text{cm}/\sqrt{E}$ (E in GeV) |
| KLM | barrel: RPCs | 14 layers (5 cm Fe + 4 cm gap) 2 RPCs in each gap | $\theta$: 16 k, $\phi$: 16 k | $\Delta\phi = \Delta\theta = 20$ mradian for $K_L$ $\sim 1$ % hadron fake for muons |
| | end-caps: scintillator strips | 14 layers of $(7-10) \times 40$ mm$^2$ strips read out with WLS and G-APDs | 17 k | $\Delta\phi = \Delta\theta = 10$ mradian for $K_L$ $\sigma_p/p = 18\%$ for 1 GeV/$c$ $K_L$ |