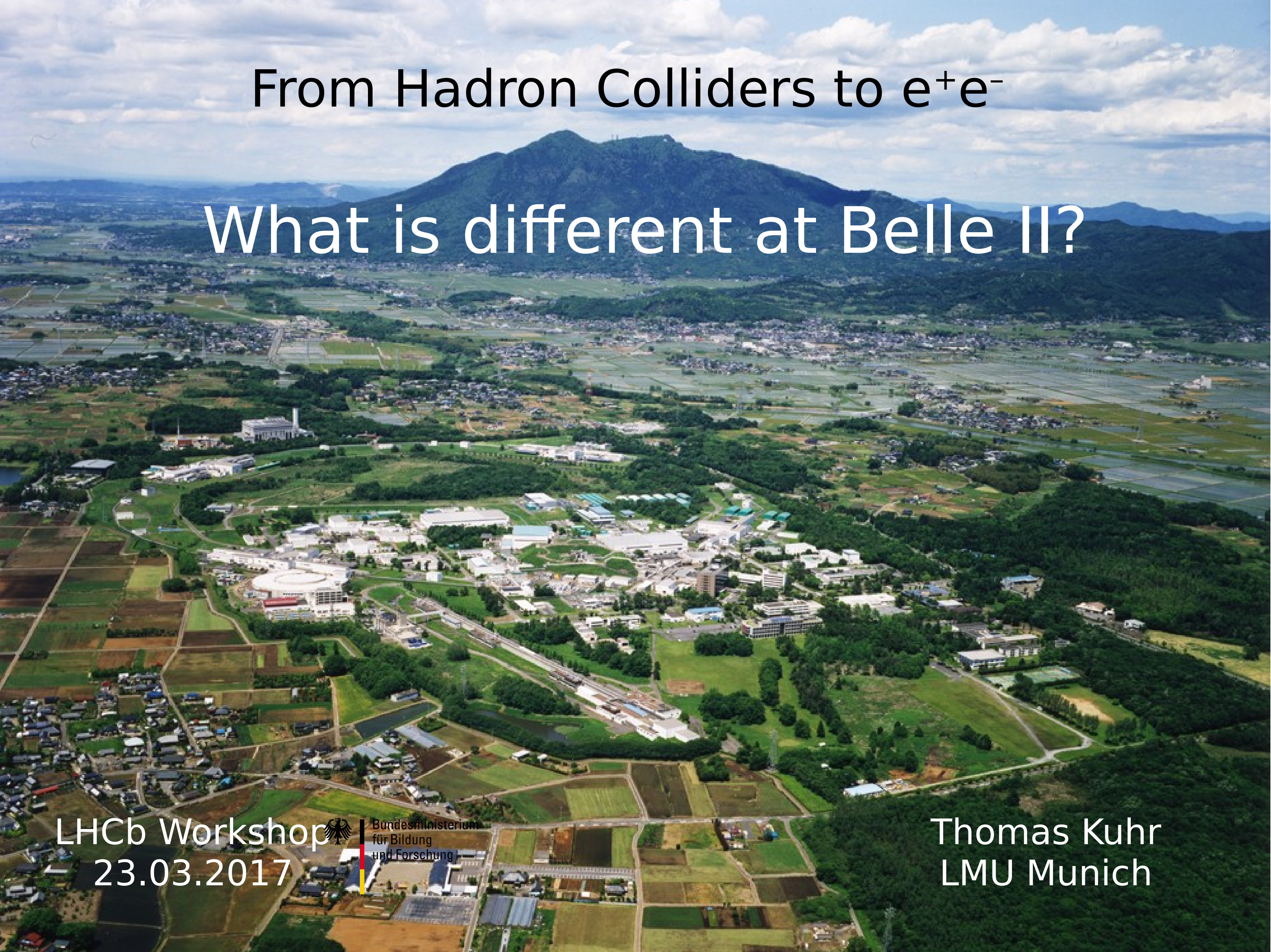


From Hadron Colliders to e^+e^-

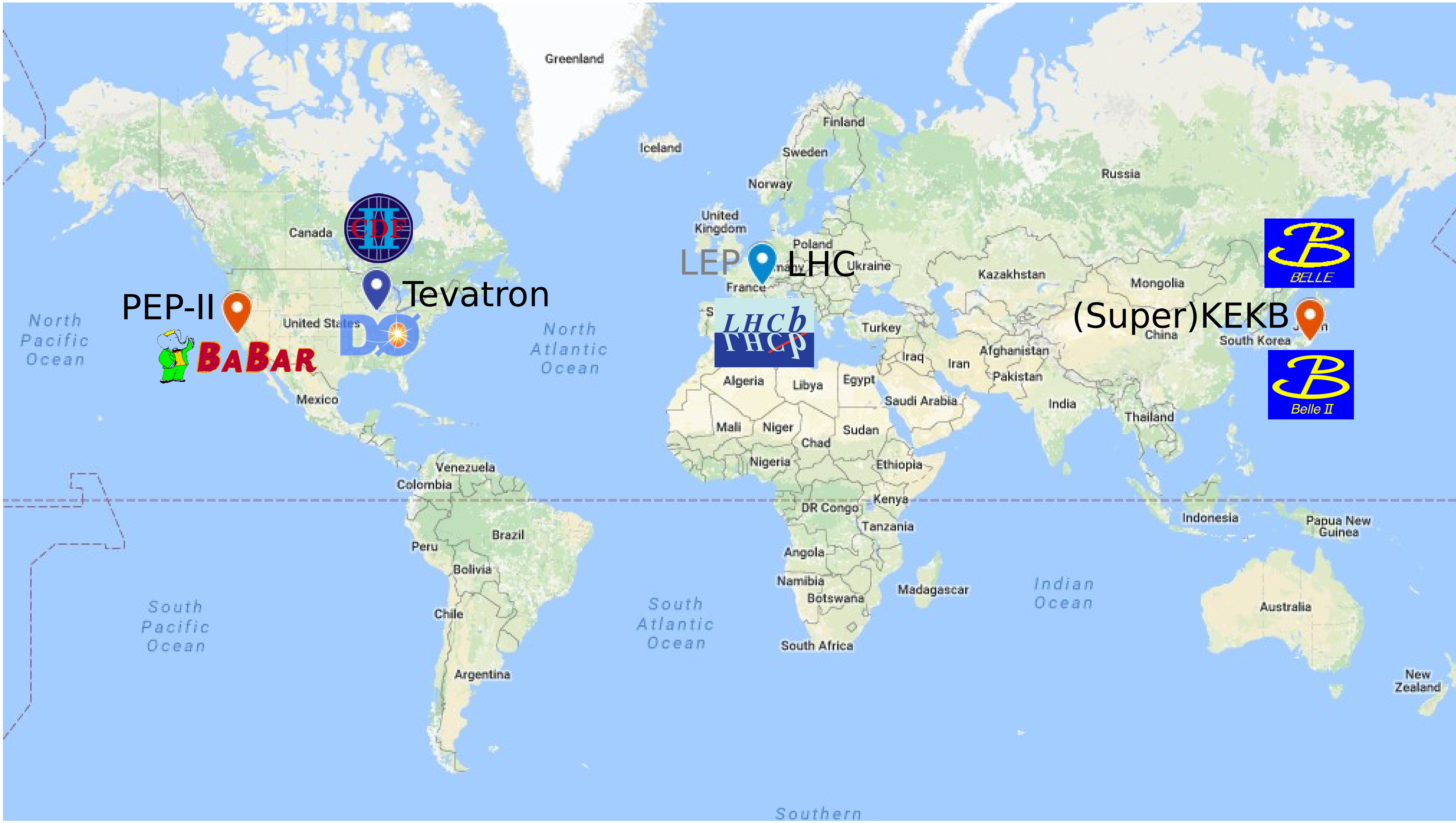
What is different at Belle II?

LHCb Workshop
23.03.2017

Bundesministerium für Bildung und Forschung

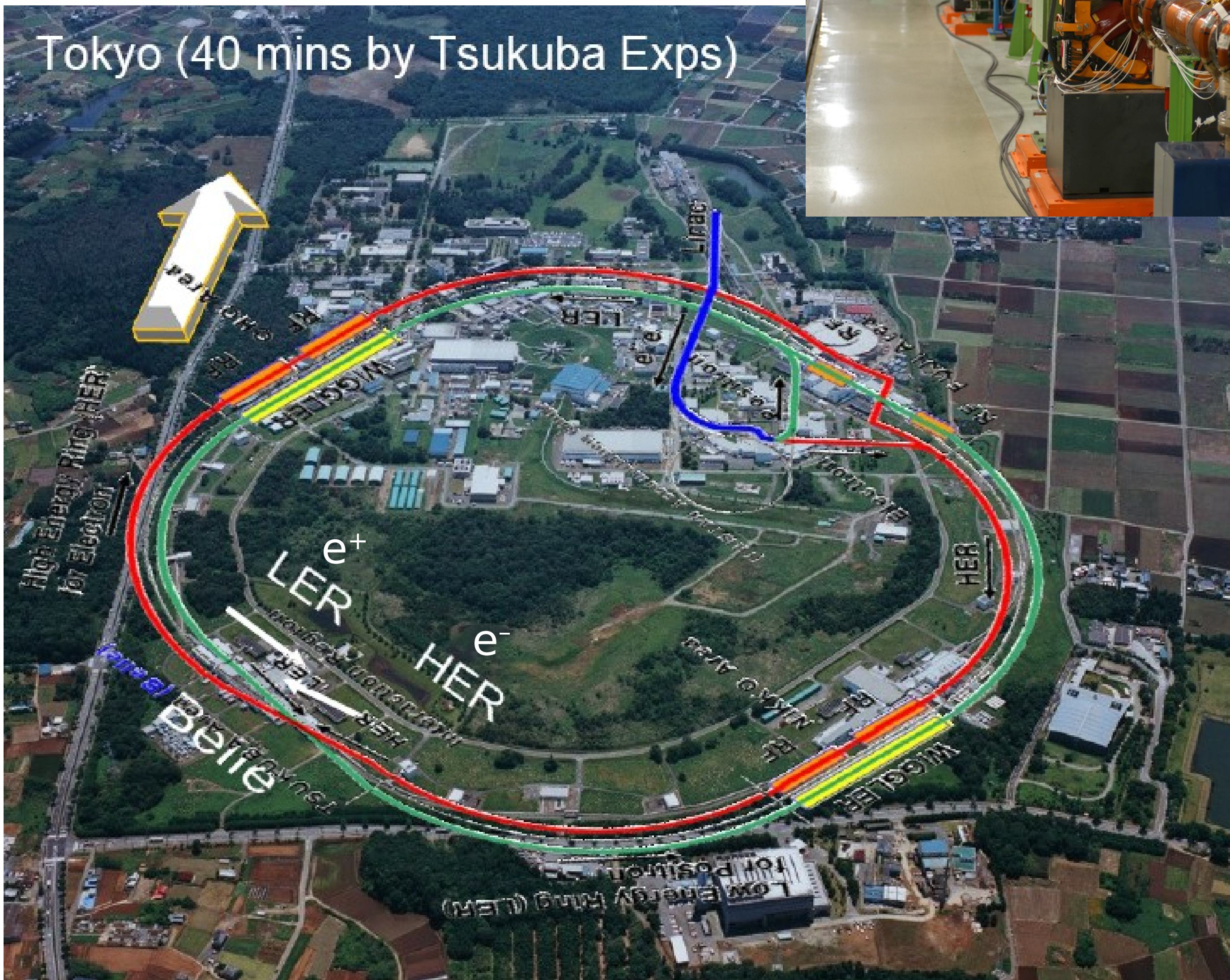
Thomas Kuhr
LMU Munich

Location

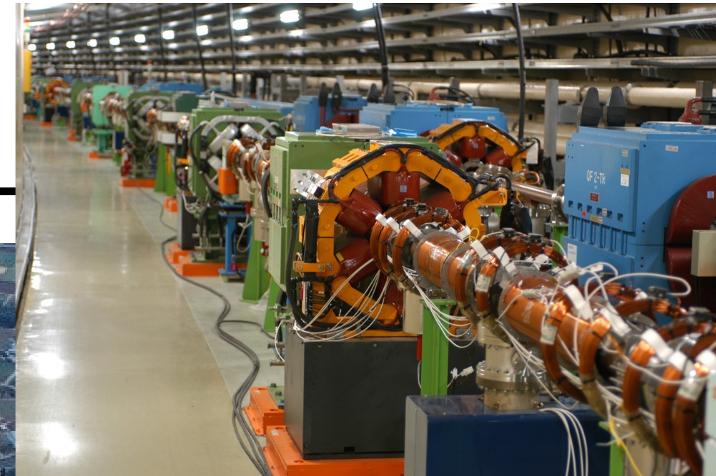


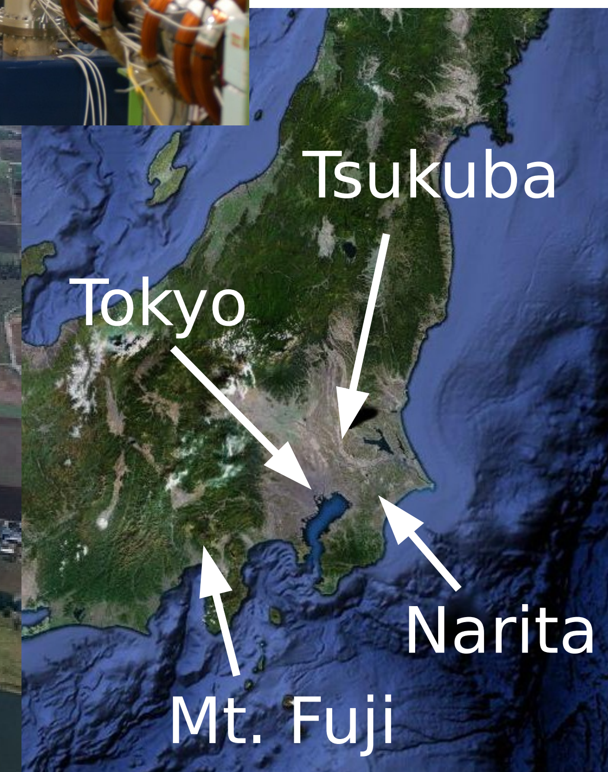
PEP-II
BaBar
Tevatron
LEP
LHC
LHCb
(Super)KEKB
BELLE
Belle II
Greenland
Iceland
Finland
Sweden
Norway
Russia
United Kingdom
Poland
Ukraine
France
Kazakhstan
Mongolia
Canada
United States
Mexico
North Pacific Ocean
North Atlantic Ocean
Turkey
Iraq
Iran
Afghanistan
Pakistan
China
South Korea
India
Thailand
Algeria
Libya
Egypt
Saudi Arabia
Mali
Niger
Chad
Sudan
Nigeria
Ethiopia
Venezuela
Colombia
Kenya
DR Congo
Tanzania
Indonesia
Papua New Guinea
Brazil
Peru
Bolivia
Angola
Namibia
Botswana
Madagascar
Indian Ocean
South Africa
Australia
South Pacific Ocean
South Atlantic Ocean
Chile
Argentina
New Zealand
Southern

KEK



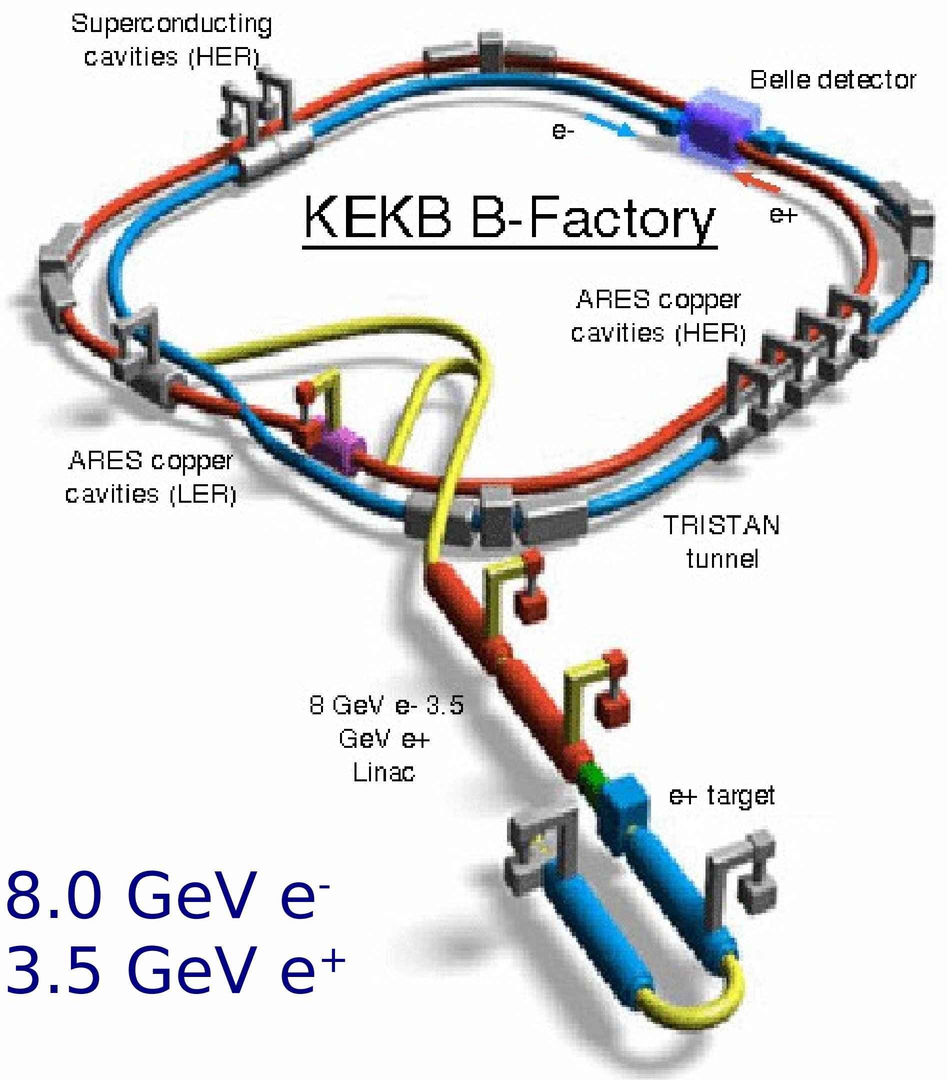
Tokyo (40 mins by Tsukuba Exps)
Linac
e+
LER
e-
HER
Belle



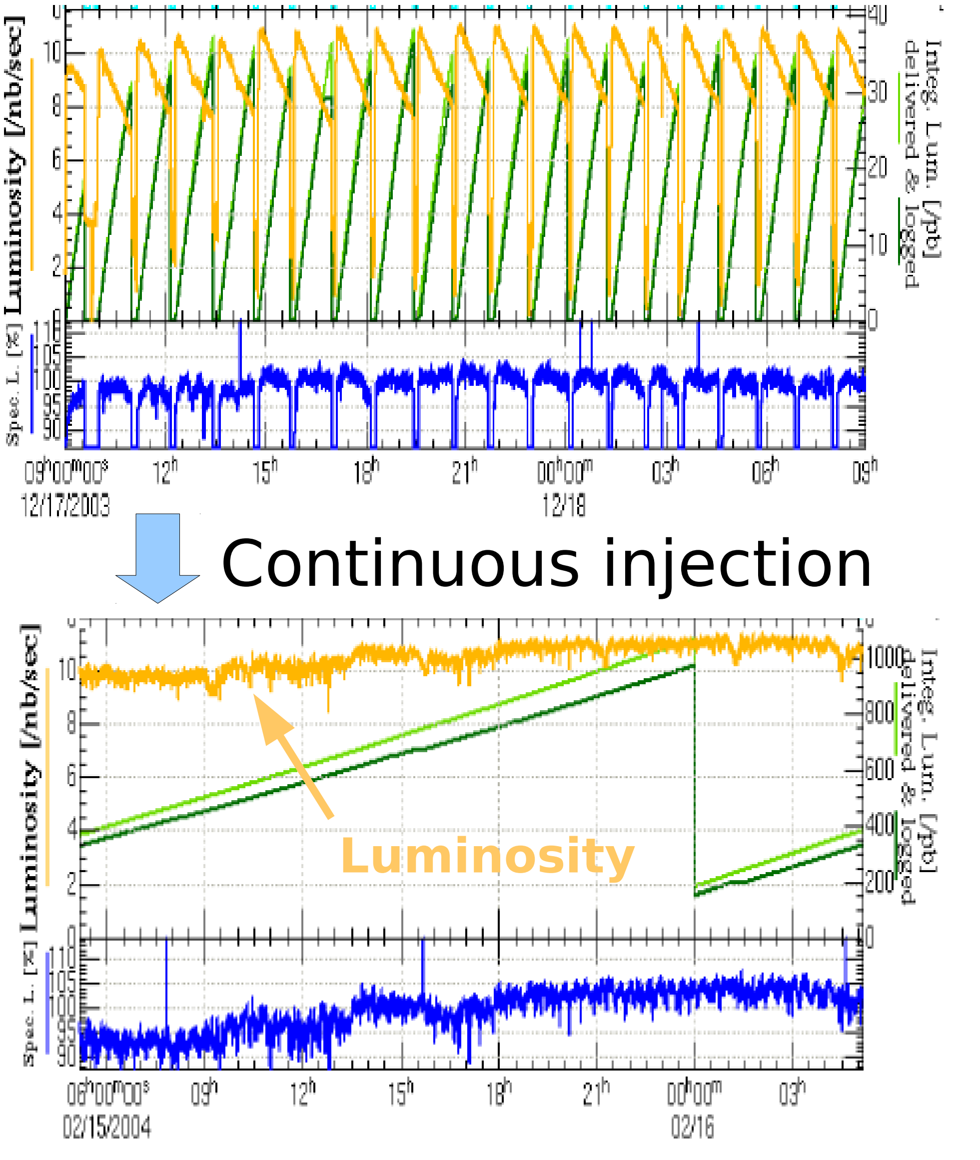


Tsukuba
Tokyo
Narita
Mt. Fuji

KEKB Accelerator

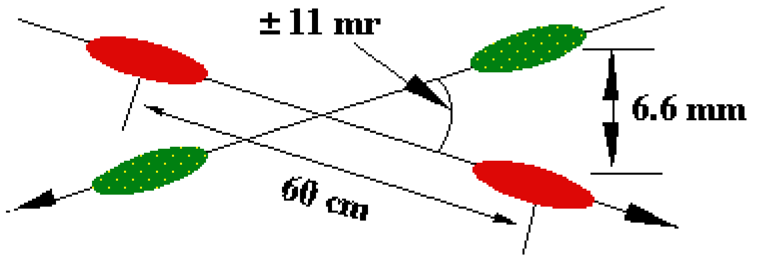


8.0 GeV e^-
3.5 GeV e^+

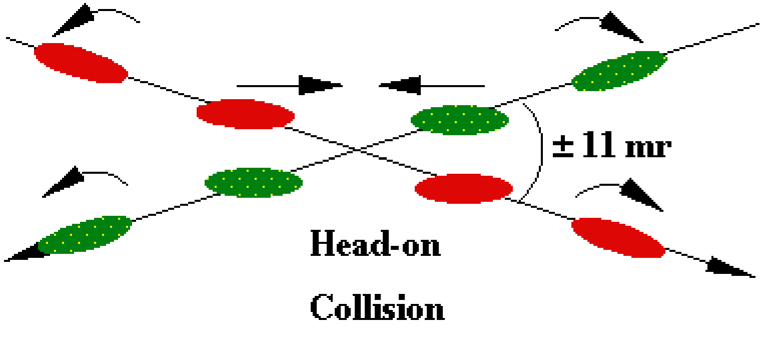


Crab Cavities

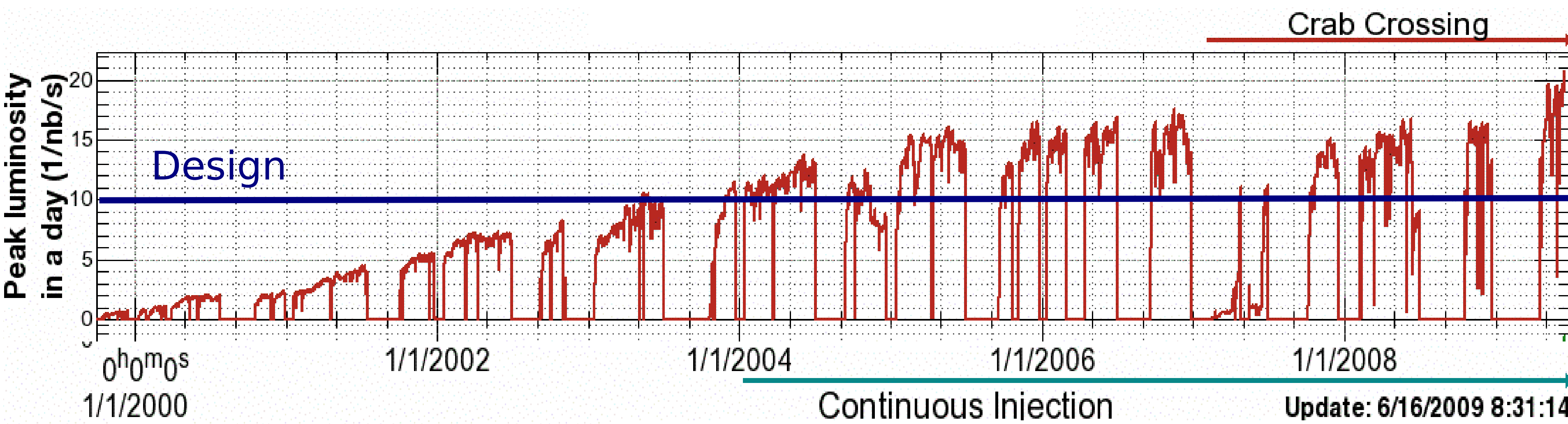
- 22 mrad crossing angle between beams



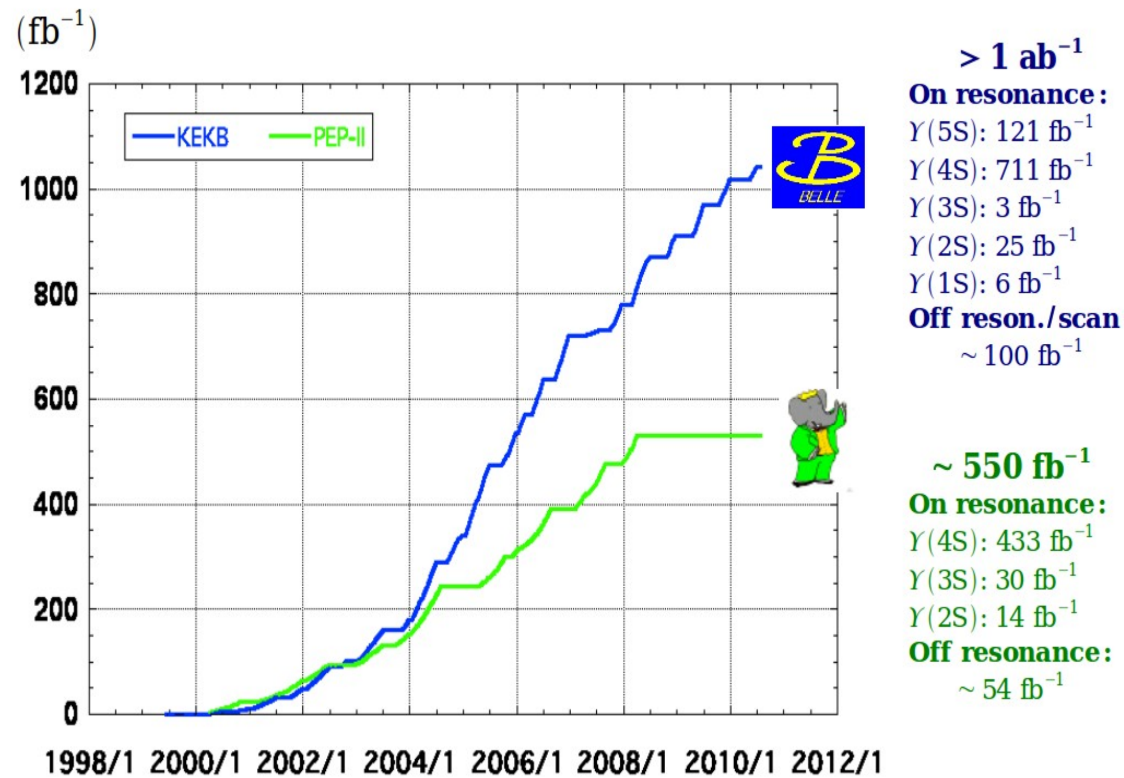
- Rotate bunches to have head-on collisions



KEKB Performance

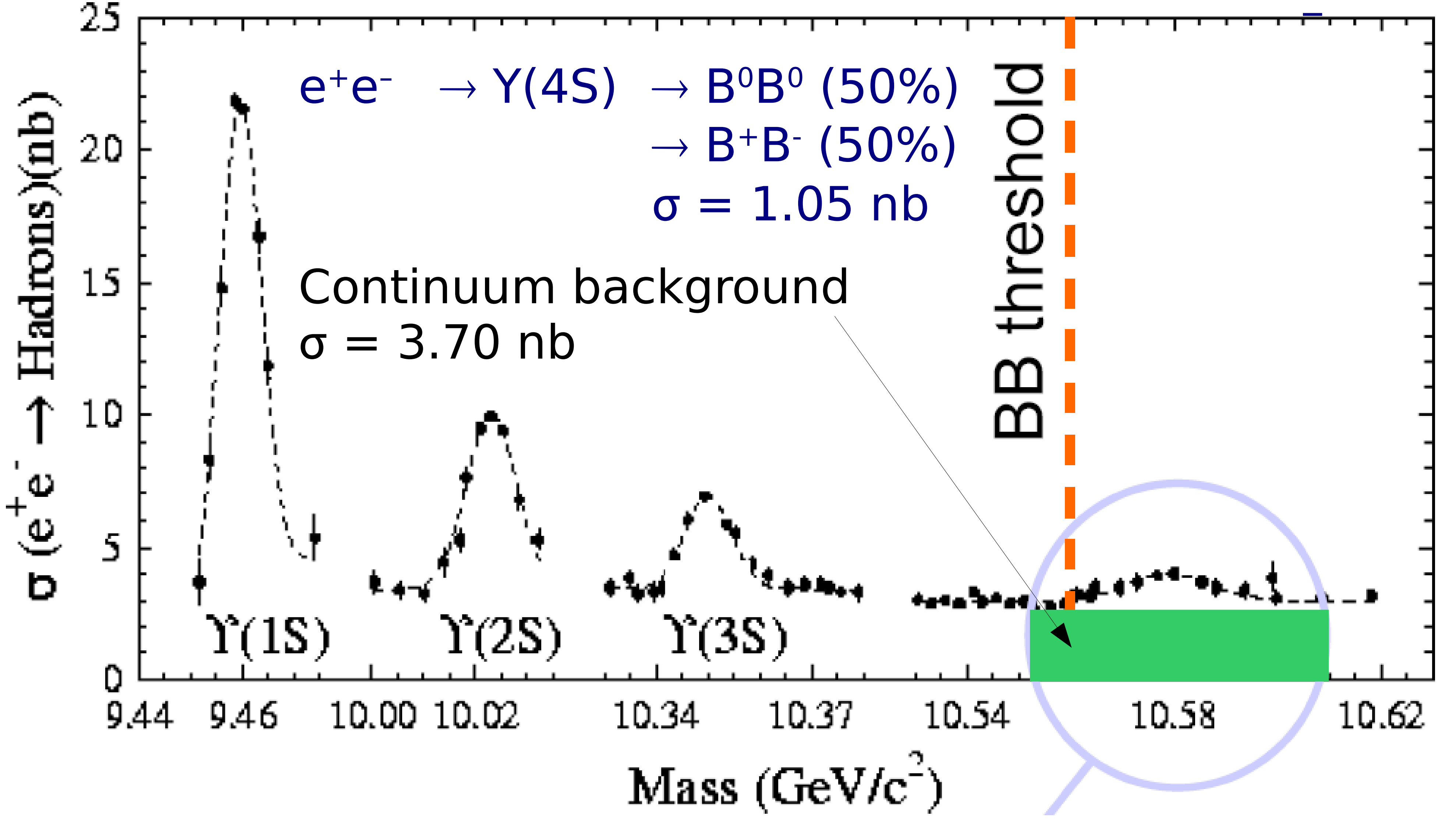


- World record luminosity: $2.1 \times 10^{34}\ cm^{-2}s^{-1}$ → Twice design
- 1 ab^{-1} of integrated luminosity



World Record Luminosity

B Factory

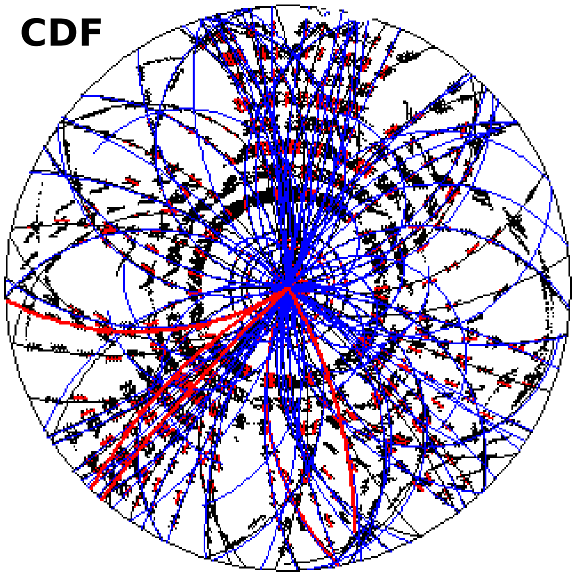


e+e- → Υ(4S) → B0B0 (50%)
→ B+B- (50%)
σ = 1.05 nb
BB threshold
Continuum background
σ = 3.70 nb
Υ(1S)
Υ(2S)
Υ(3S)
σ (e+e- → Hadrons)(nb)
Mass (GeV/c2)
0
5
10
15
20
25
9.44
9.46
10.00
10.02
10.34
10.37
10.54
10.58
10.62

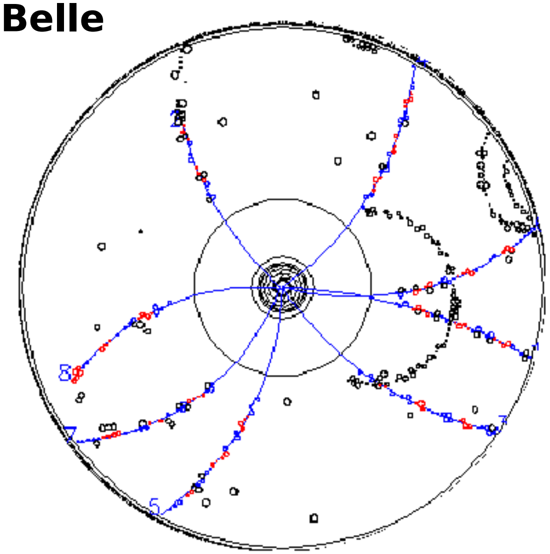
Production of B Mesons

Hadron-Collider:
pp, $p\bar{p}$

CDF



Belle



B Factory:
e^+e^-

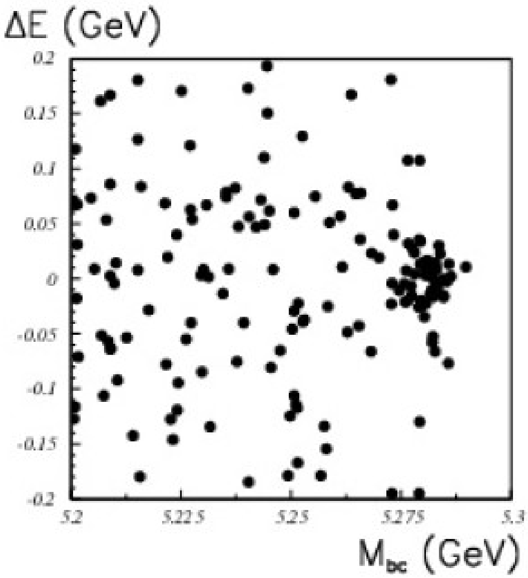
Strong interaction of quarks/gluons in hadrons:

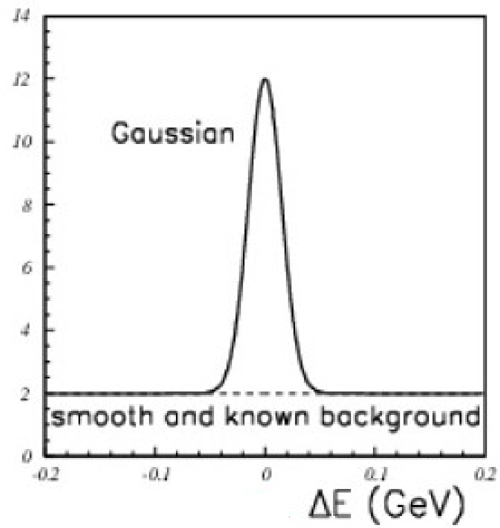
- ✔ High rate
- ✔ Production of all kinds of b hadrons in fragmentation

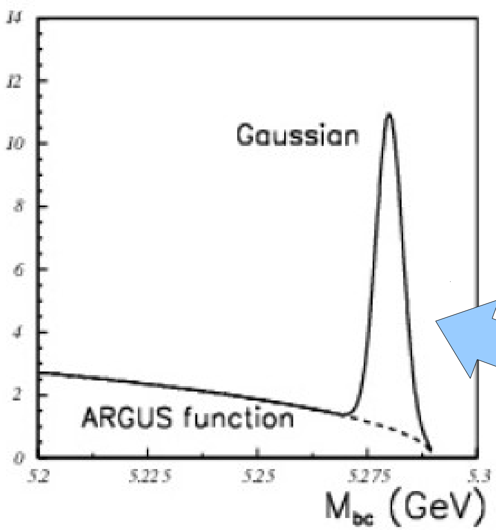
Electromagnetic interaction of elementary particles:

- ✔ Known kinematics
- ✔ $B\bar{B}$ events from Υ(4S) decays without background tracks

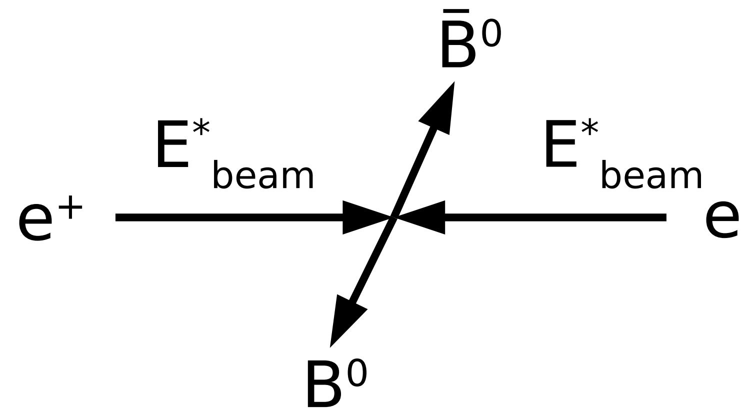
B^0 Reconstruction







In Y(4S) CMS:

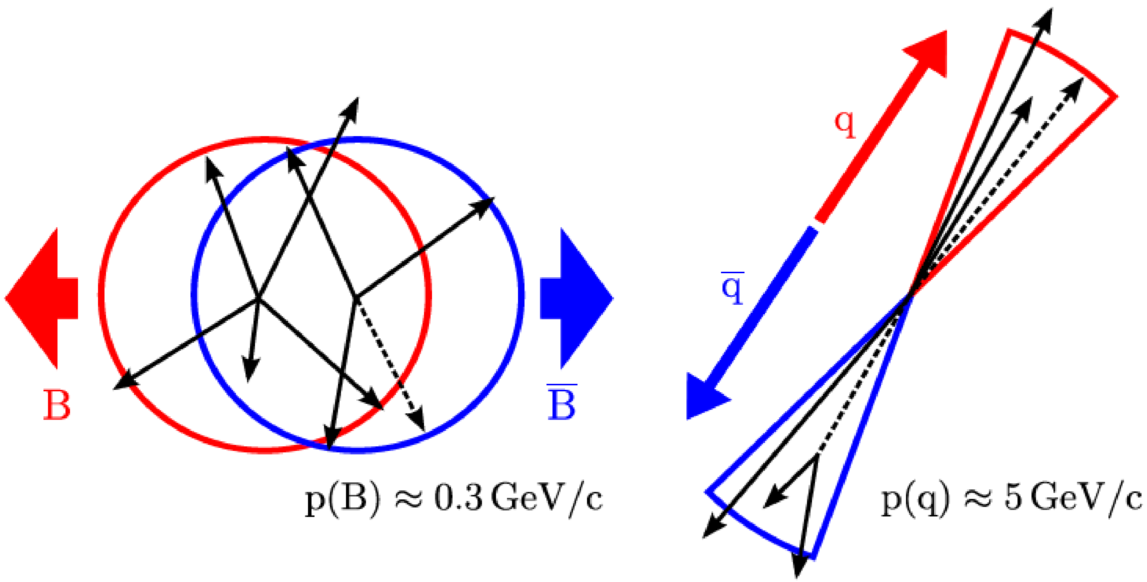


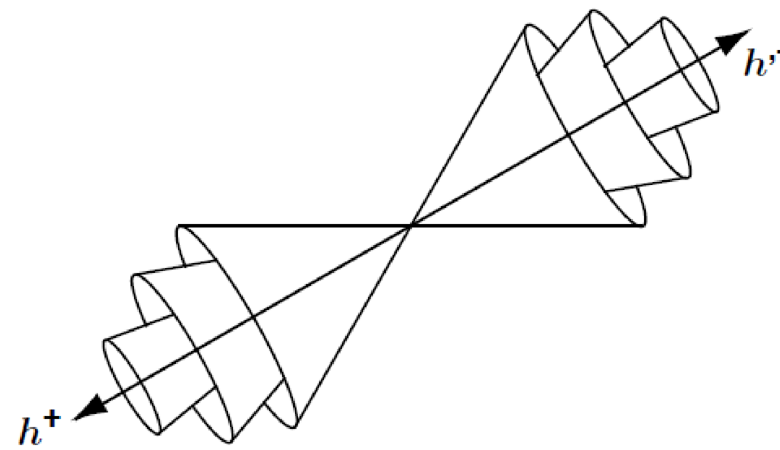
$$\Delta E = \left(\sum_{\text{daughters}} E_i^\star \right) - E_{beam}^\star$$

$$M_{bc} = \sqrt{{E_{beam}^\star}^2 - \left(\sum_{\text{daughters}} \vec{p}_i^\star \right)^2}$$

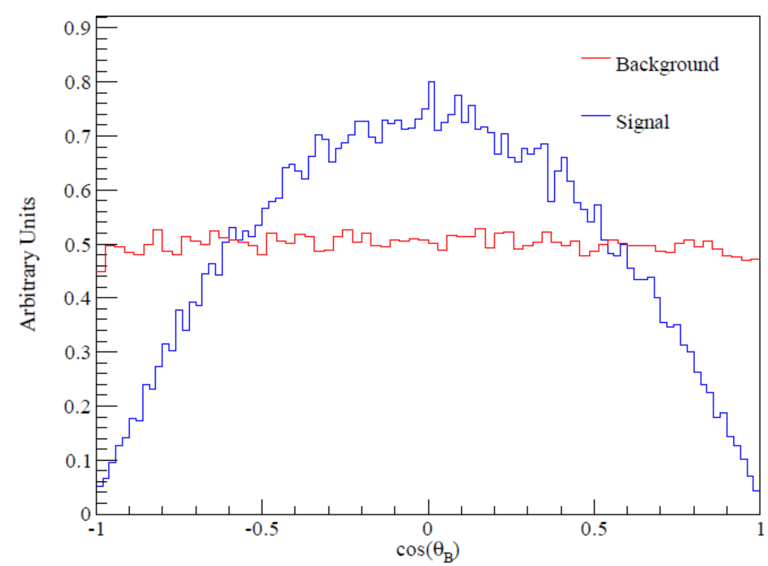
Energy and momentum of B mesons determined by beam energy

Continuum Suppression





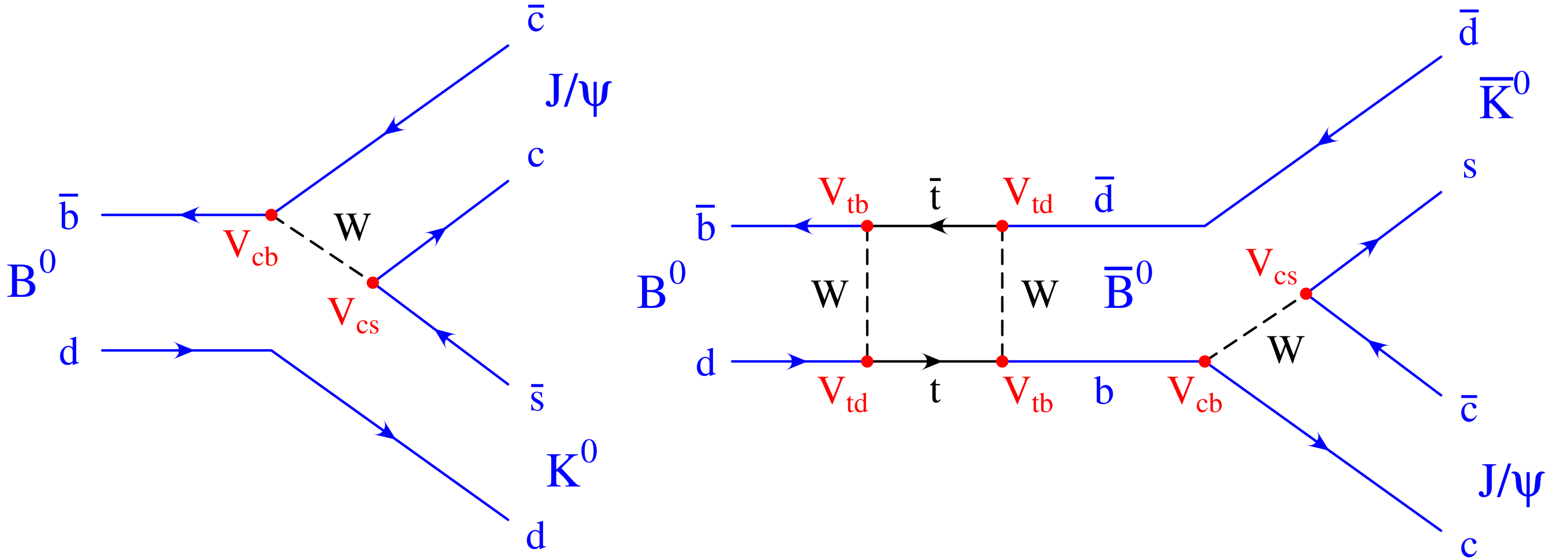
$e^+e^- \to \Upsilon(4S) \to B\overline{B}$ $e^+e^- \to q\overline{q} \quad (q \in \{u, d, s, c\})$



- Fox-Wolfram moments:
  $H_k = \Sigma_{ij}\ |p_i|\ |p_j|\ P_k(\cos\theta_{ij})$, P_k: Legendre pol.
- Cleo cones
- B momentum/thrust direction
- Vertex separation Δz

Measurement of CP Violation

- Golden Mode: $B^0 \to J/\psi\, K^0$



➢ Time dependent asymmetry measurement:

$$a_f(t) = \frac{\Gamma(\bar{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to f) + \Gamma(B^0 \to f)} \approx -\xi_f \sin(2\phi_1) \sin(\Delta m t)$$

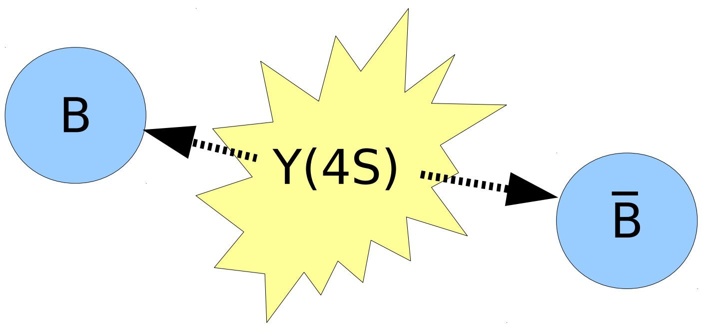
Measurement of time-dep. CP Violation

- Flavor of initial state, time of decay

- m(Υ(4S)) = 10.58 GeV, 2 x m(B) = 10.56 GeV

➔ $p^*(B) \approx 300$ MeV

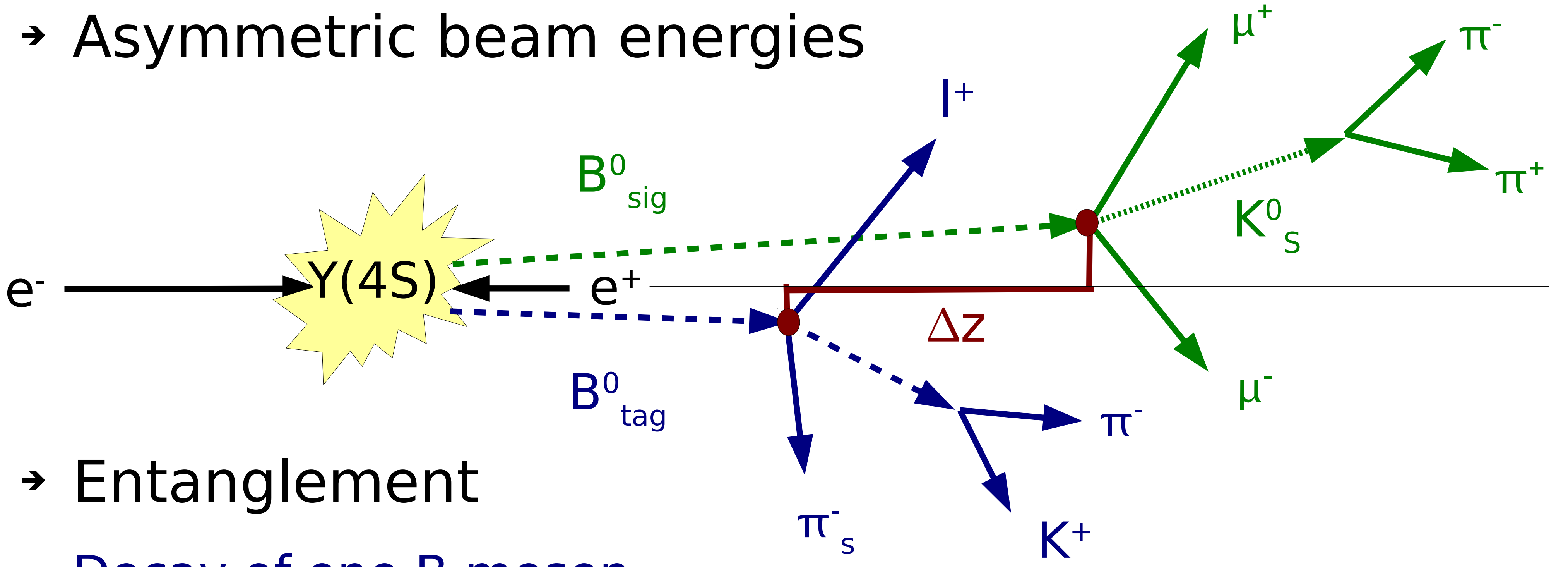
➔ B mesons almost at rest in center of mass system (CMS)



➔ B meson flight distance in CMS too small for a time measurement

Measurement of time-dep. CP Violation

➔ Asymmetric beam energies

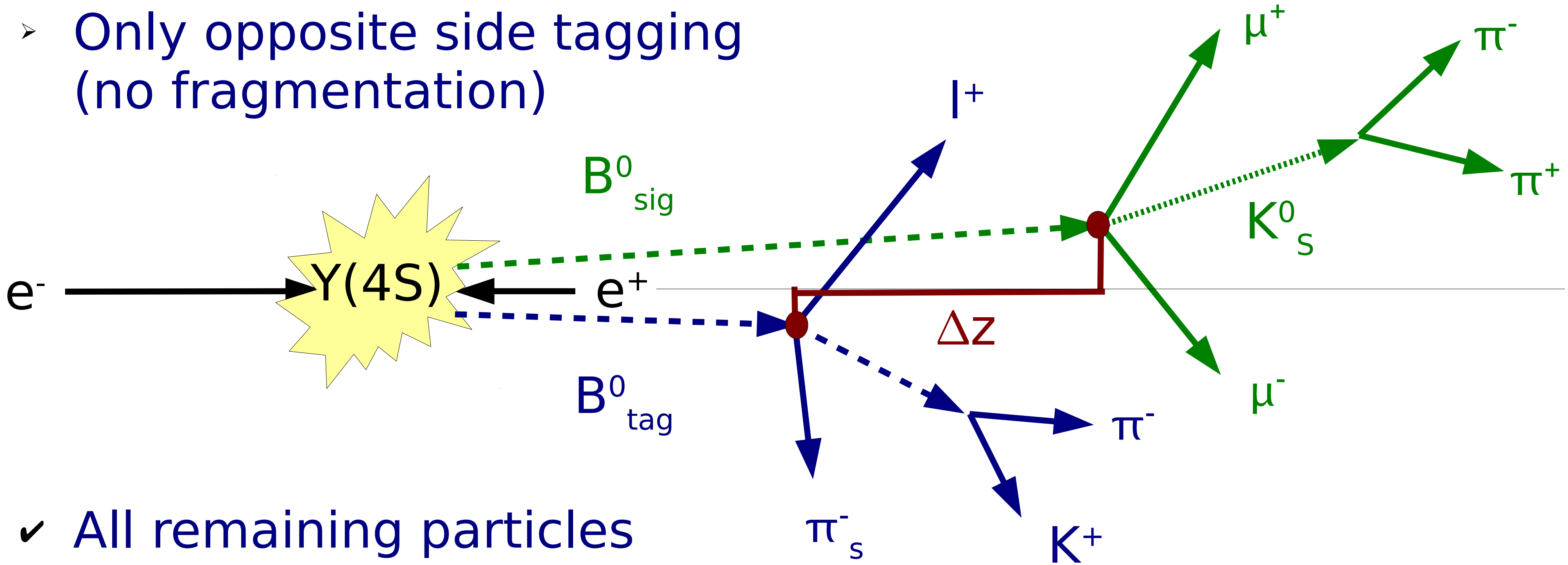


➔ Entanglement

- Decay of one B meson at time t_{tag} in flavor eigenstate Q → tagging
- Other B meson is at time t_{tag} in flavor eigenstate $\overline{Q}$
- Time measurement: $\Delta t = t_{sig} - t_{tag} = \Delta z / c\beta\gamma$

Flavor Tagging

- Only opposite side tagging (no fragmentation)

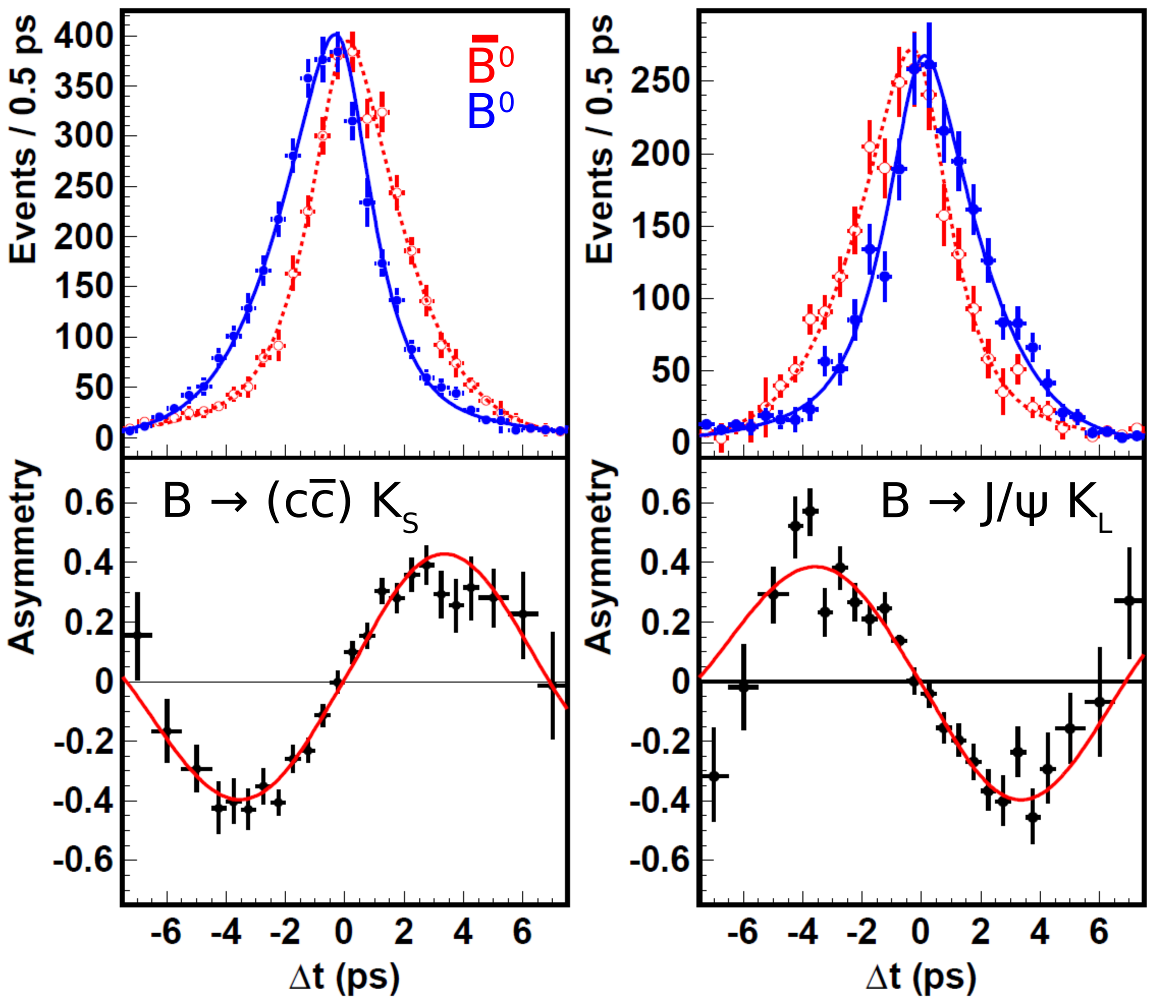


- ✔ All remaining particles are from the tag B meson
- Leptons, high momentum particles, kaons, Lambdas, slow pions (from D^*)
- ➔ Tagging power: $\varepsilon D^2 \approx 30\%$, D = 1-2w, w: wrong tag fraction

Observation of CP Violation

PRL 108,171802 (2012)

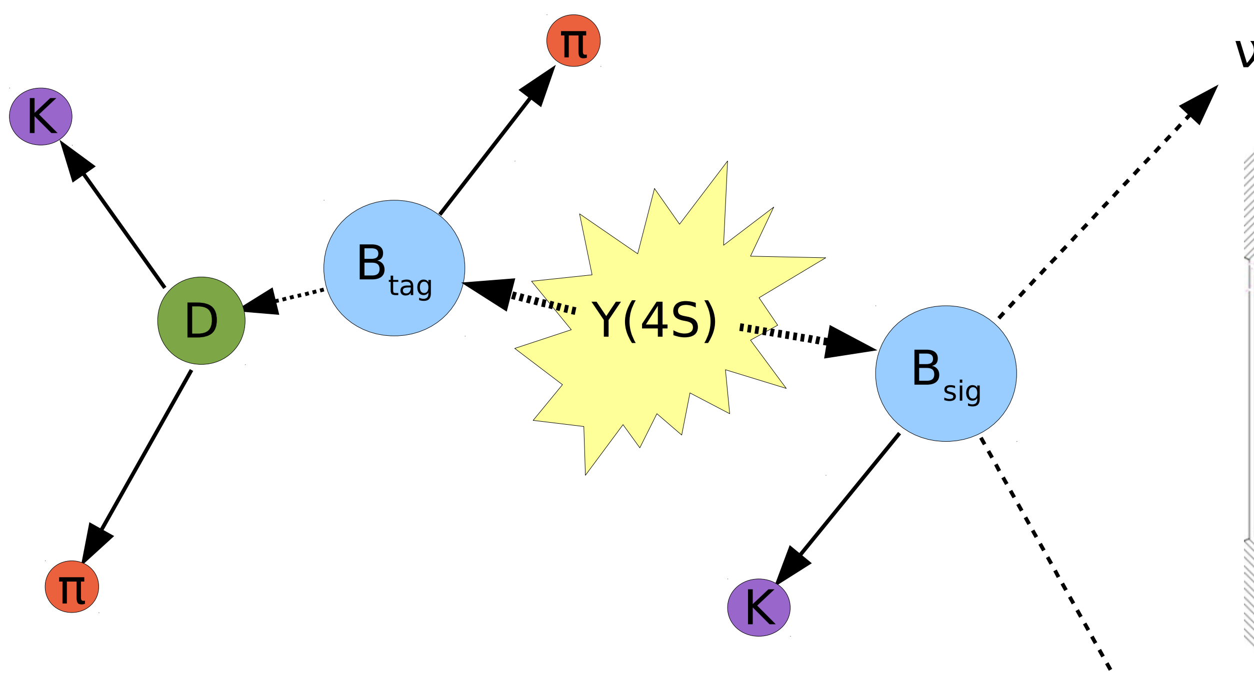
772×10^6 BB



$$A(\Delta t) = \frac{N_{\mathrm{sig}}(\bar{B}^0_{\mathrm{tag}}, \Delta t) - N_{\mathrm{sig}}(B^0_{\mathrm{tag}}, \Delta t)}{N_{\mathrm{sig}}(\bar{B}^0_{\mathrm{tag}}, \Delta t) + N_{\mathrm{sig}}(B^0_{\mathrm{tag}}, \Delta t)}$$

- ➢ Observation of mixing-induced CP violation in B^0 system
- ✔ Confirmation of KM mechanism of ~~CP~~ in the Standard Model

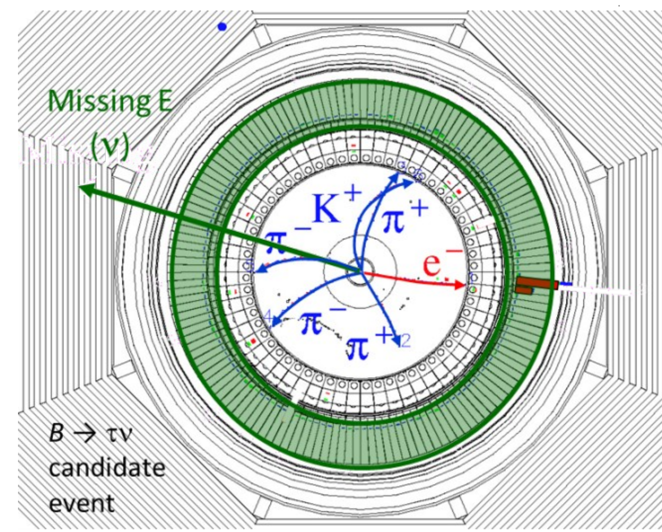
Full Reconstruction



$B^+ \rightarrow D^0\pi^+$

$(\rightarrow K\pi^-\pi^+\pi^-)$

$B^- \rightarrow \tau(\rightarrow e\nu\bar{\nu})\nu$



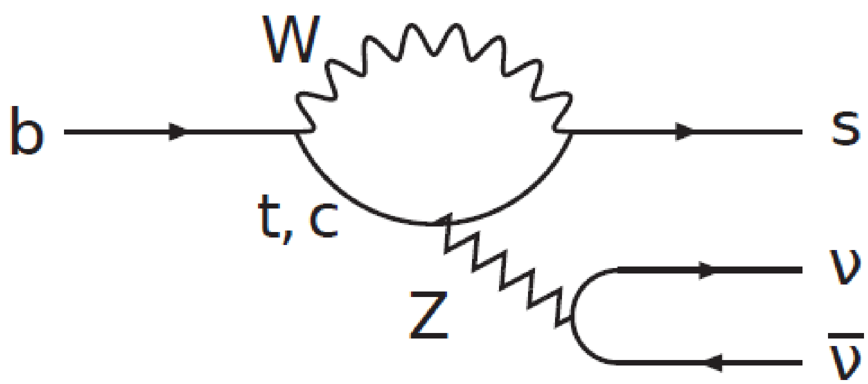
- Full reconstruction of one hadronically decaying B meson

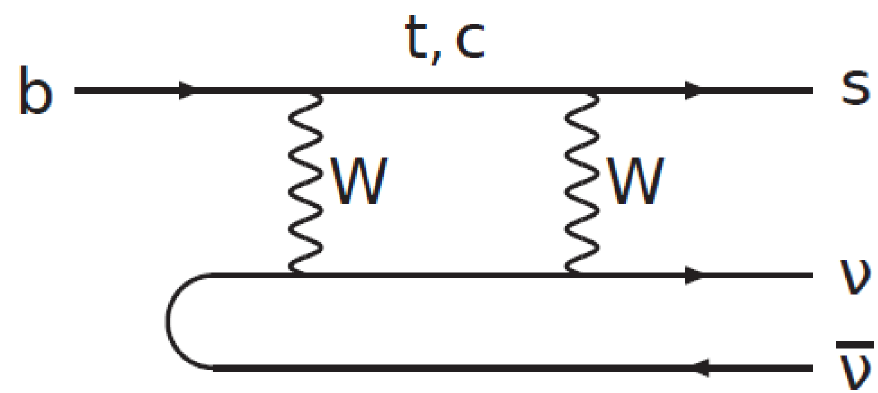
➔ Momentum and charge of signal B meson known

➔ All remaining particles belong to signal B meson

➢ Reconstruction of decays with neutrinos

$B \rightarrow K^{(*)}\nu\bar{\nu}$





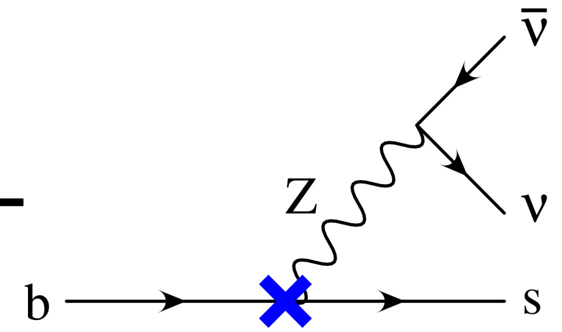
- Rare FCNC decay without long range effects (→ no direct CPV)

- Theoretically reliable SM prediction:
  $BR(B^+ \rightarrow K^+\nu\nu) = (4.0 \pm 0.5) \times 10^{-6}$
  $BR(B^0 \rightarrow K^{*0}\nu\nu) = (9.2 \pm_{1.1} 1.0) \times 10^{-6}$

Buras *et al.*,
JHEP 1502, 184 (2015)

➢ Sensitive to new physics

New Physics in $B \to K^{(*)}\nu\bar{\nu}$

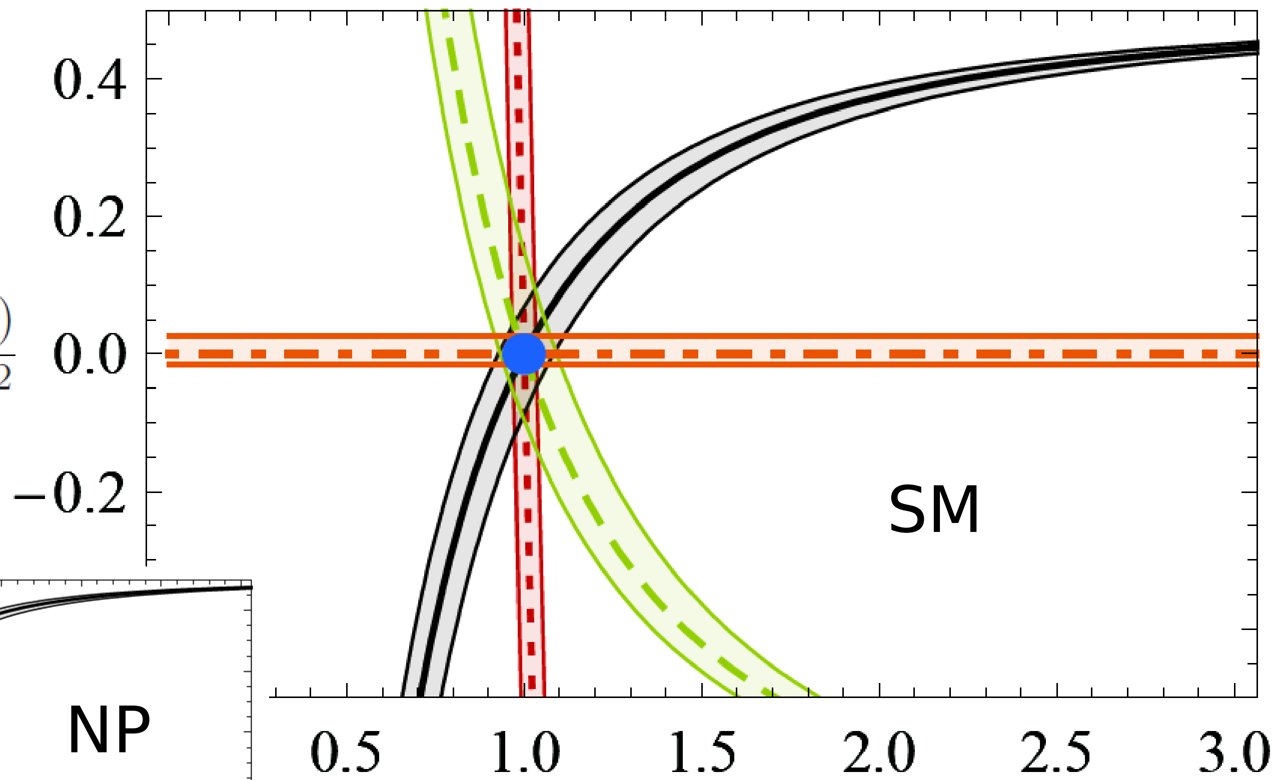


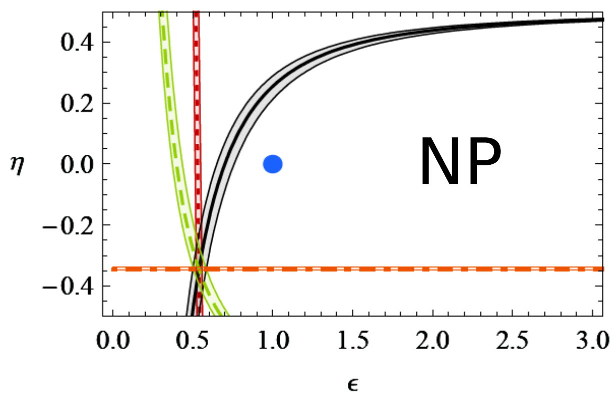
$C^{\nu}_{L/R}$:
left/right handed Coupling

$B \to K^{*}\nu\bar{\nu}$ $B \to X_s\nu\bar{\nu}$

$B \to K\nu\bar{\nu}$

$$\eta = \frac{-\mathrm{Re}\,(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}$$





F_L

Fraction of longitudinal K^* polarization

$$\epsilon = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|(C_L^\nu)^{\mathrm{SM}}|}$$

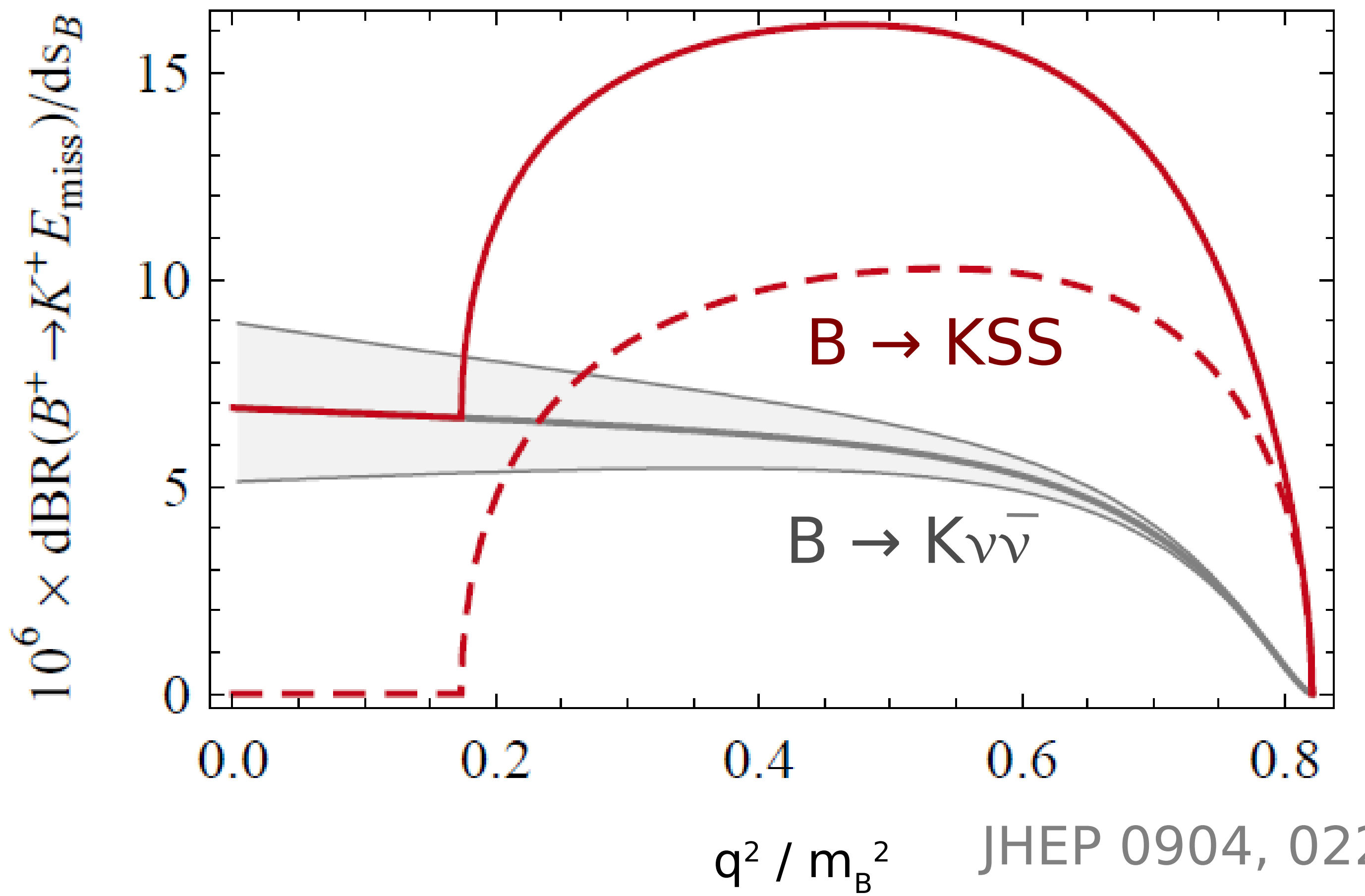
Altmannshofer et al, JHEP 0904, 022

Search for New Invisible Particles

- Same experimental signature of $B \to K^{(*)}\nu\bar{\nu}$ and $B \to K^{(*)}$ + invisible particles (S)

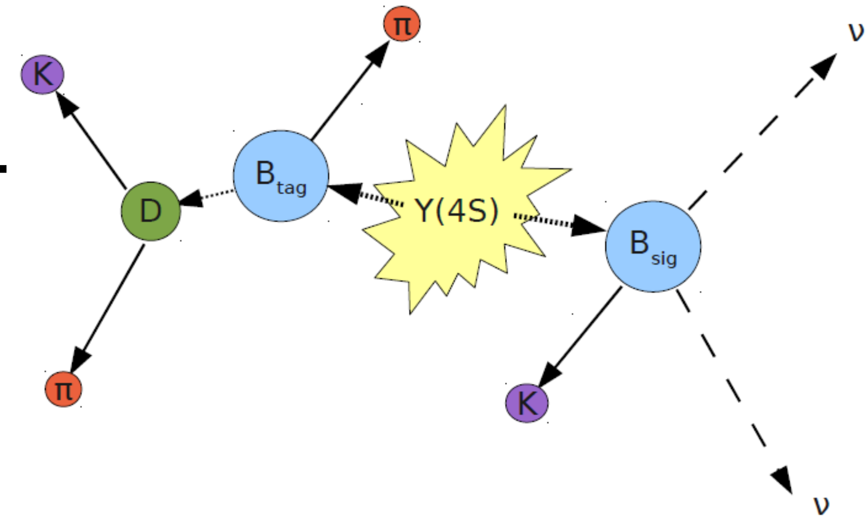
  - Can be distinguished from $K\nu\bar{\nu}$ if new particles have mass

  - Requires measurement of $q^2 = m^2(\nu\bar{\nu})$



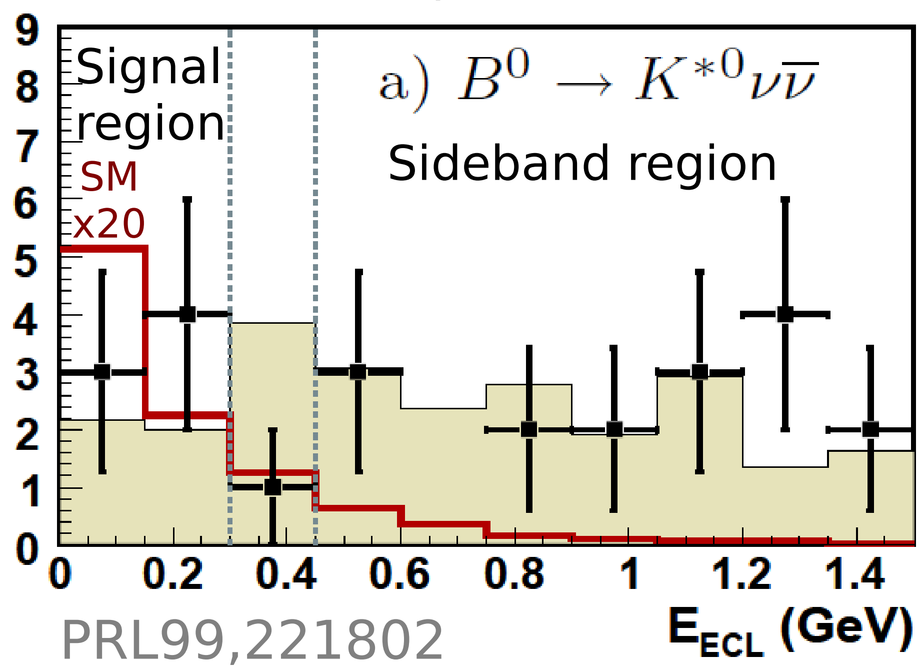
JHEP 0904, 022

Analysis Technique



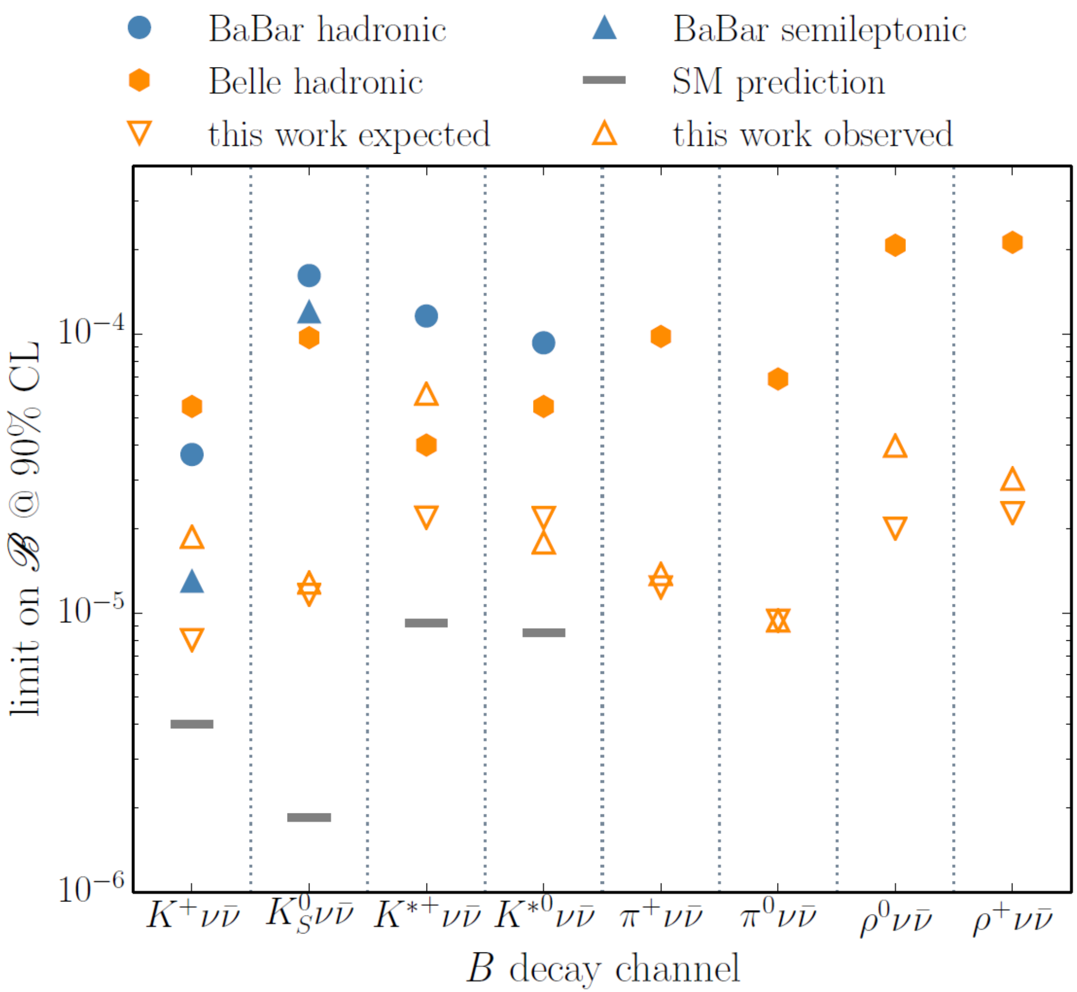
- Reconstruction of hadron + other B meson
- hadronic or semileptonic or inclusive tag
- ➔ nothing else in the detector
- ➢ No further energy in the calorimeter
  - E_{ECL}, E_{extra} = sum of clusters energies not assigned to hadron or tag B

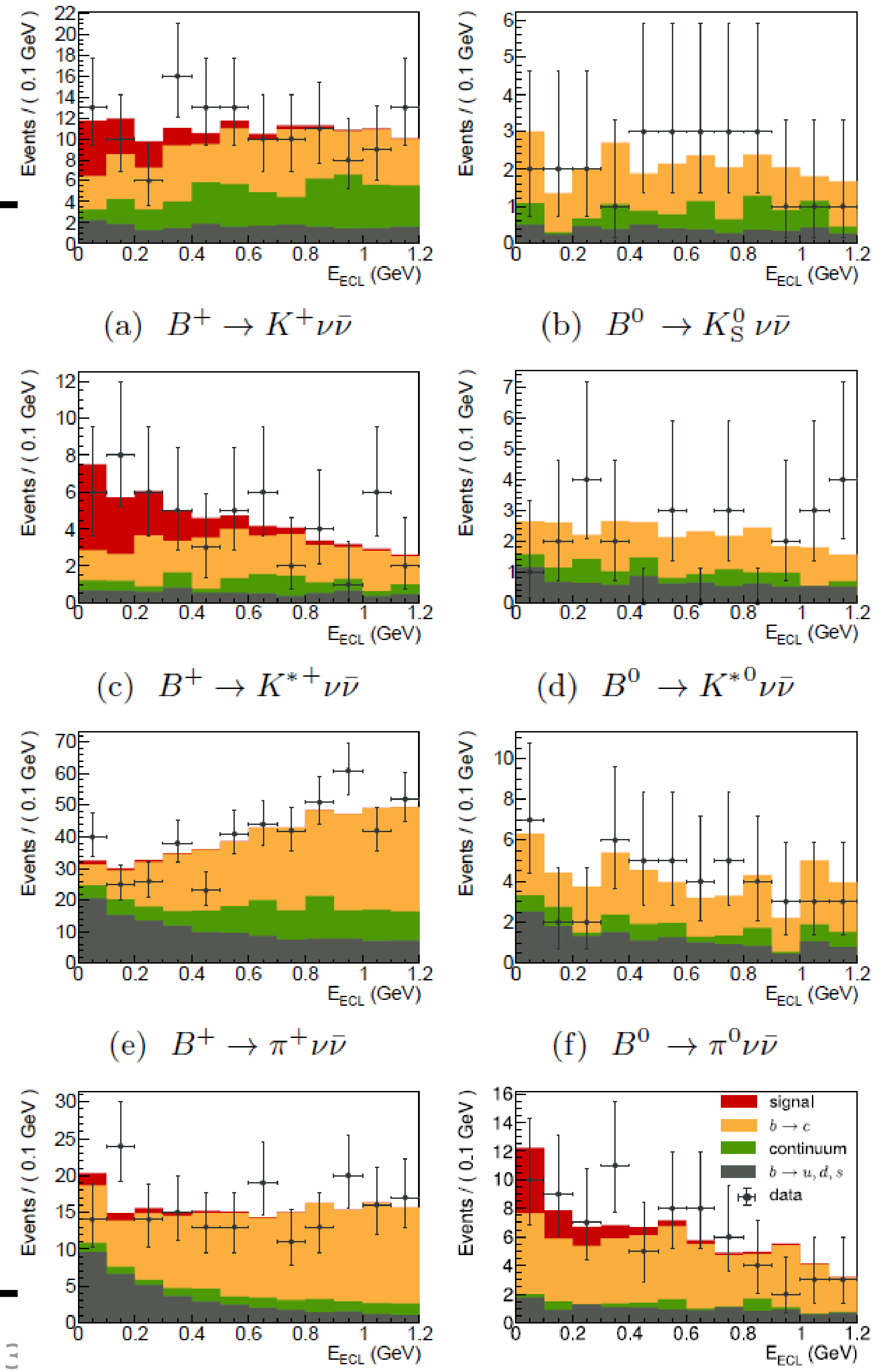
← extrapolation with MC



PRL99,221802

B → $K^{(*)}\nu\nu$ Results





(a) $B^+ \to K^+\nu\bar{\nu}$
(b) $B^0 \to K_S^0\nu\bar{\nu}$
(c) $B^+ \to K^{*+}\nu\bar{\nu}$
(d) $B^0 \to K^{*0}\nu\bar{\nu}$
(e) $B^+ \to \pi^+\nu\bar{\nu}$
(f) $B^0 \to \pi^0\nu\bar{\nu}$
(g) $B^+ \to \rho^+\nu\bar{\nu}$
(h) $B^0 \to \rho^0\nu\bar{\nu}$

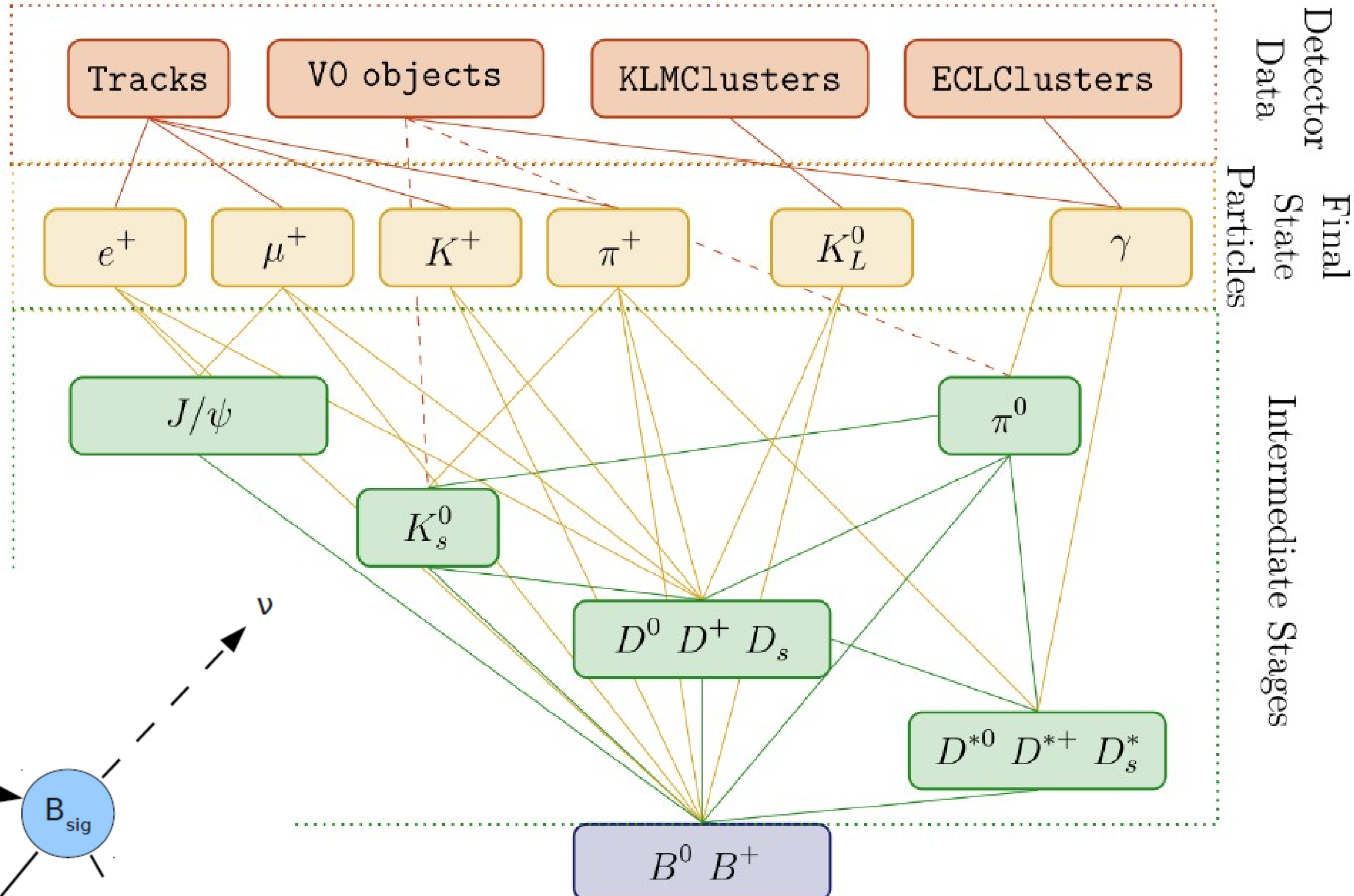
arXiv:1702.0322
4

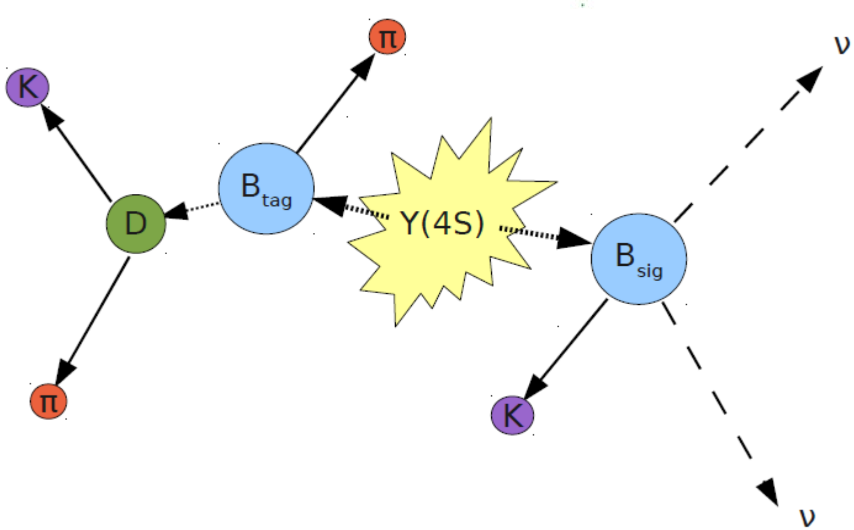
Full Event Interpretation

- Huge number of B meson decay modes

→ Hierarchical reconstruction

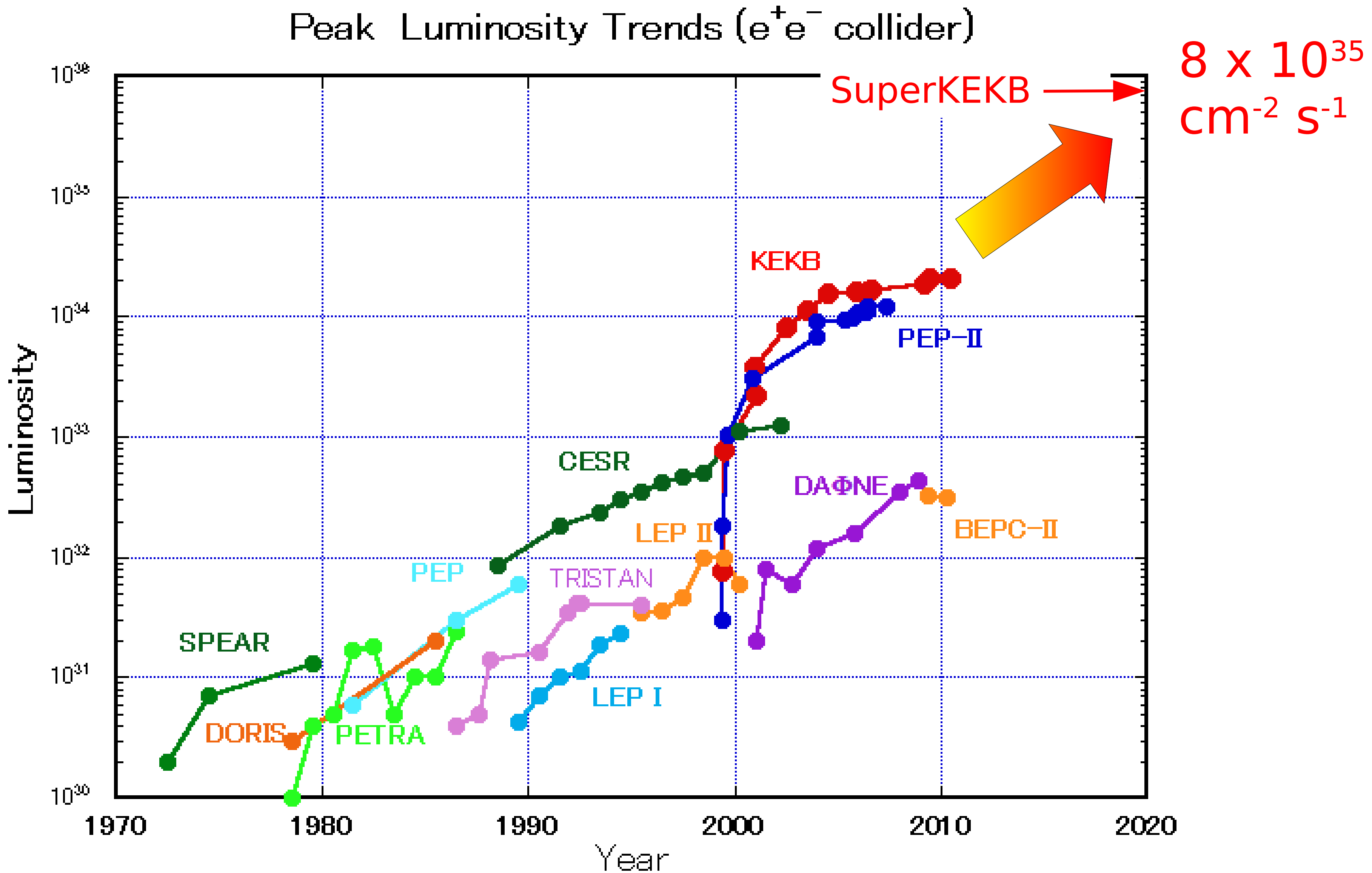
→ Multivariate classifiers





→ Per mill level efficiency

Belle II: Aim For 50 ab^{-1}



Accelerator Design: Nano Beam Scheme

Invented by Pantaleo Raimondi for SuperB

Beam-Beam parameter $\xi_y \propto \sqrt{(\beta_y^*/\varepsilon_y)}$

Lorentz factor

Beam current

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

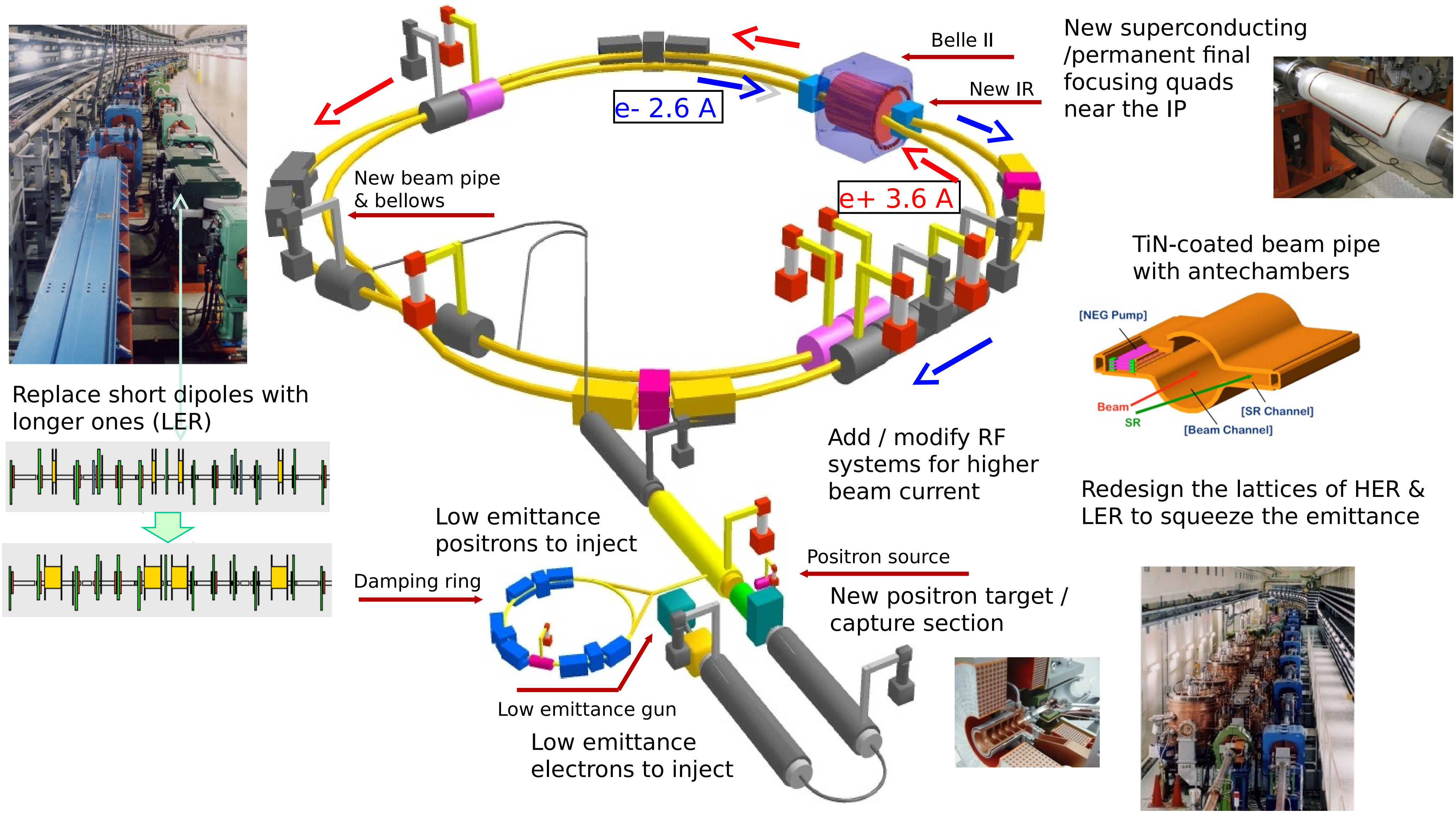
Geometrical reduction factors (crossing angle, hourglass effect)

Beam aspect ratio at IP

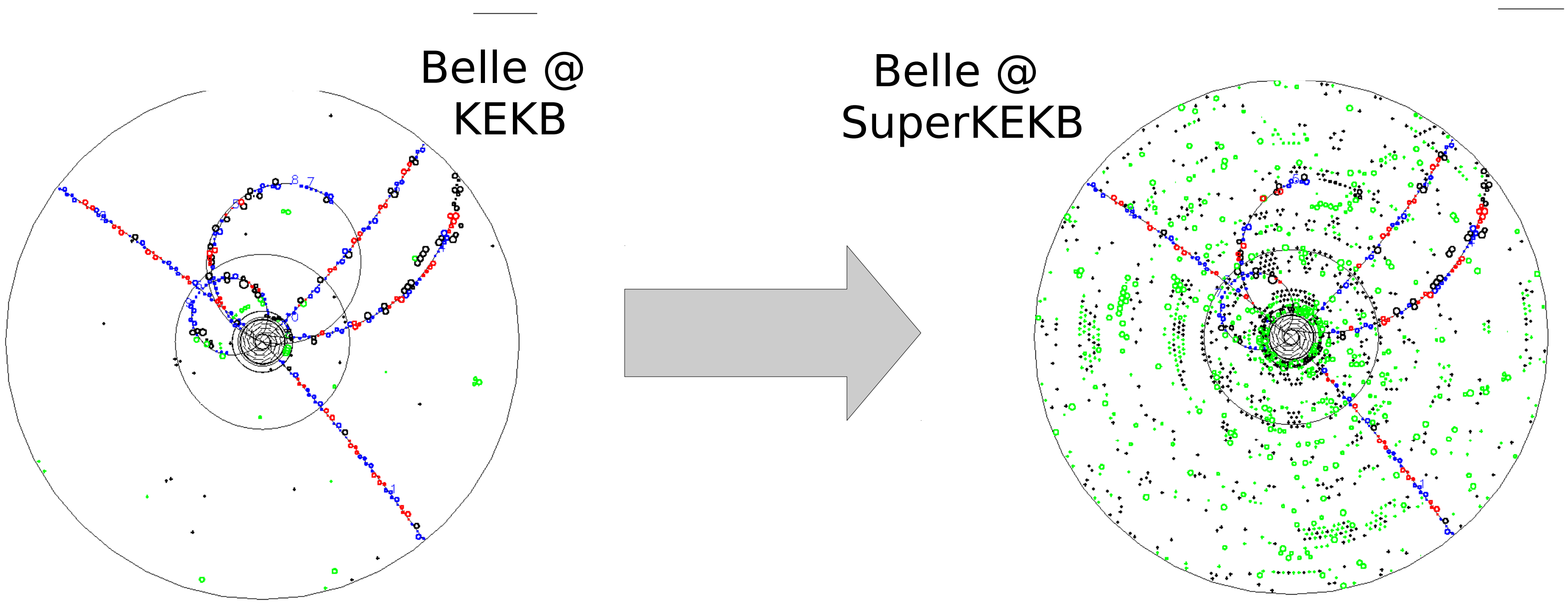
Vertical beta function at IP

	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

SuperKEKB Upgrade



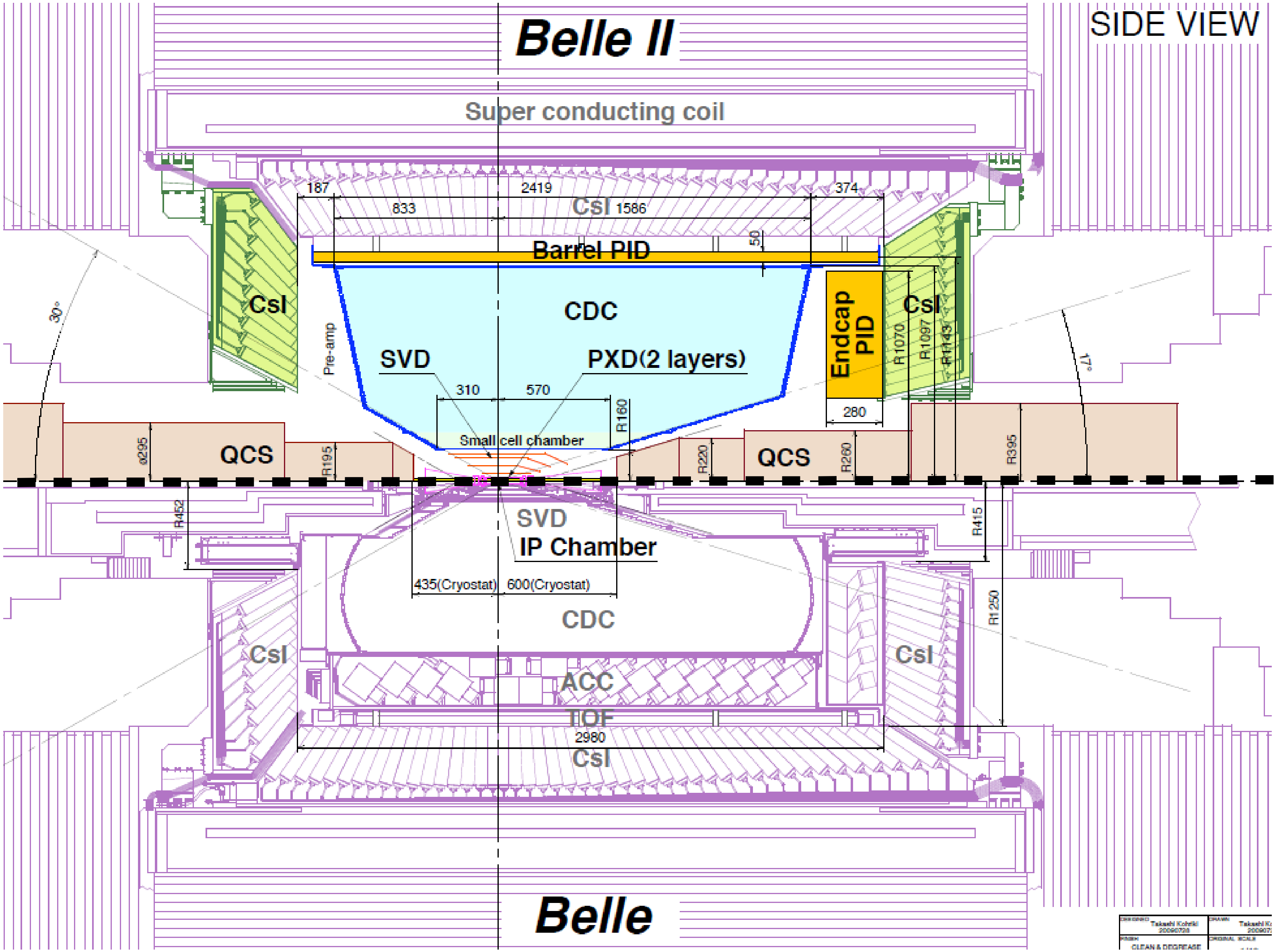
Belle II Detector Challenges



- Higher background → radiation damage, occupancy
- Higher event rate → trigger, DAQ, computing
- Low momentum particle reconstruction and ID, hermeticity

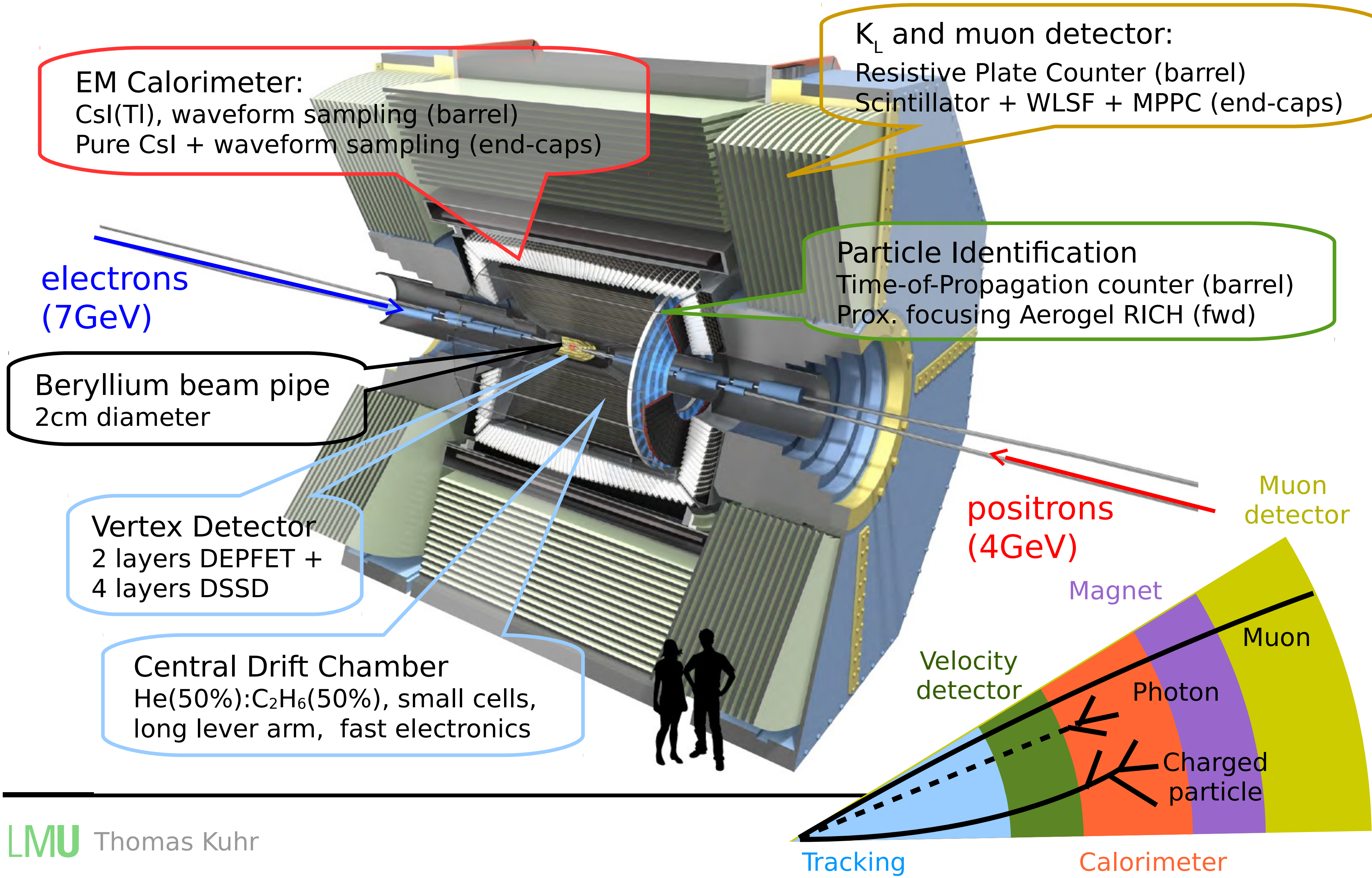
→ Detector has to be upgraded for SuperKEKB conditions to achieve equal or better performance than at KEKB

Belle II Detector Compared with Belle

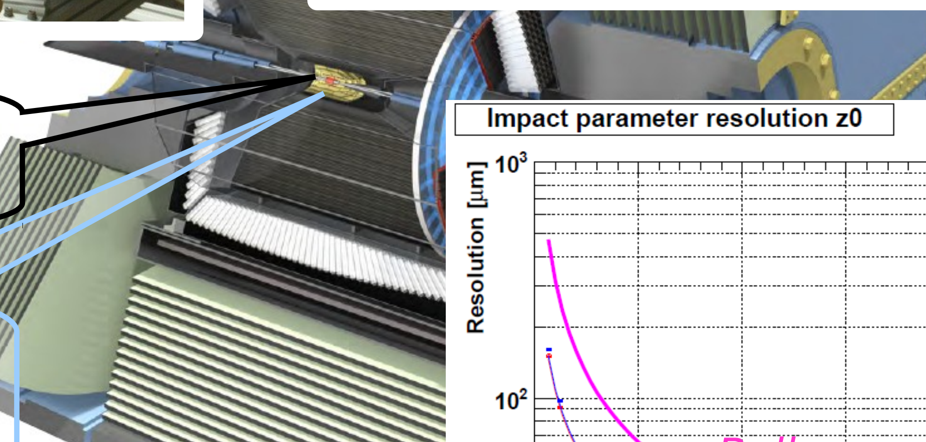


Belle II Detector

TDR: arXiv:1011.0352

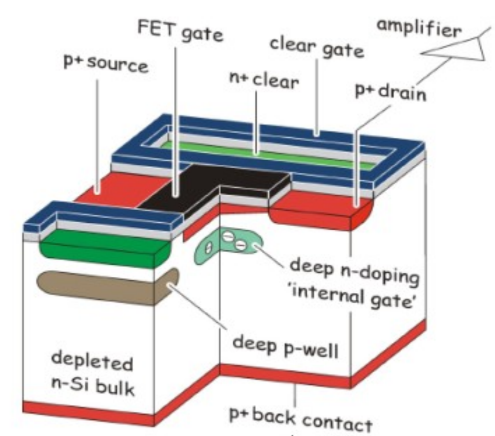


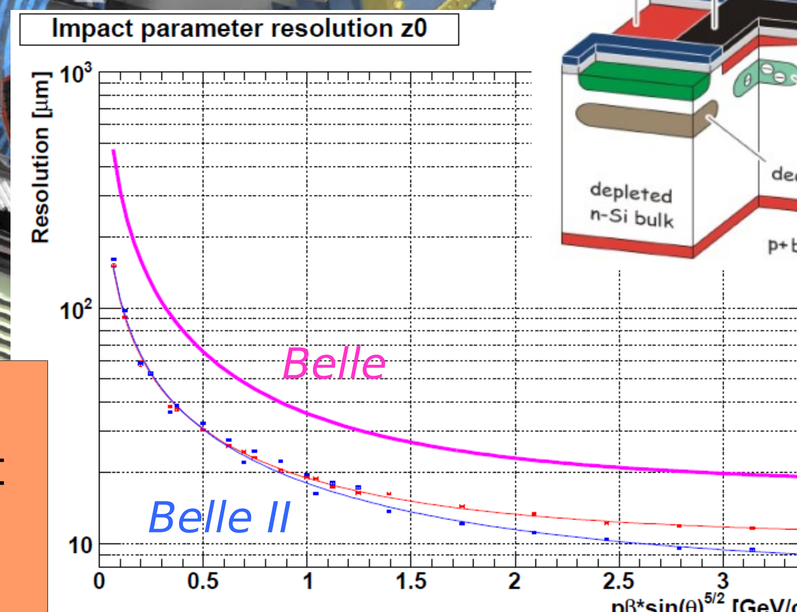
Beam Pipe and Pixel Detector



Beryllium beam pipe
r = 1.0 cm

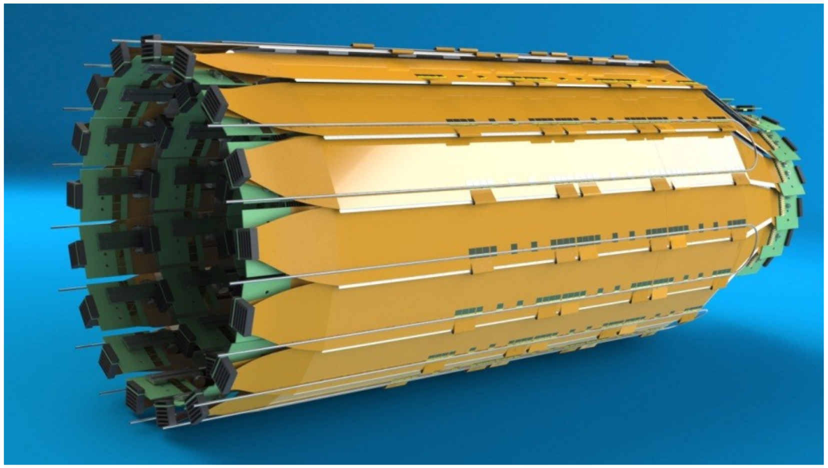
Vertex Detector
2 layers DEPFET
r = 1.4 and 2.2 cm

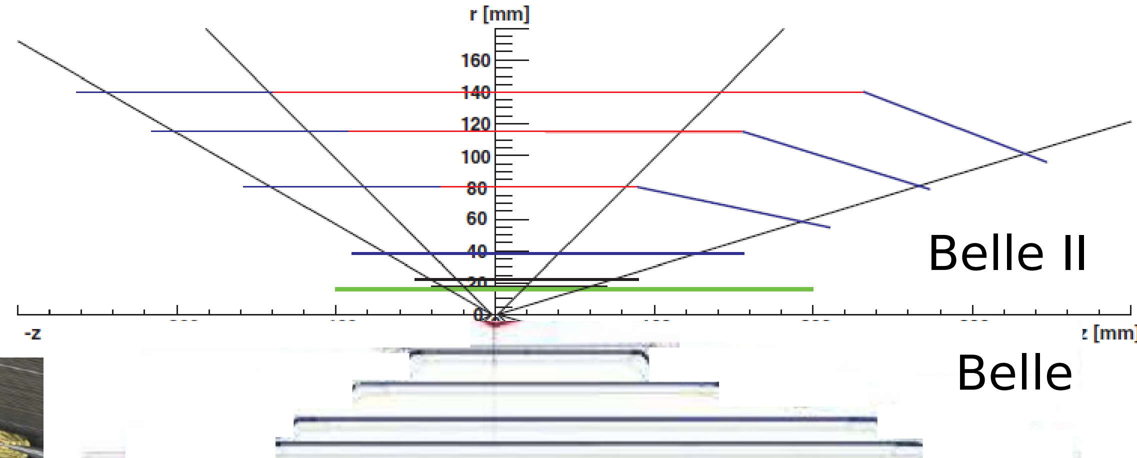


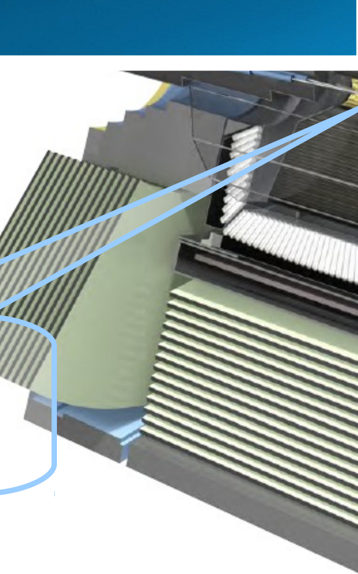


Significant improvement in vertex resolution

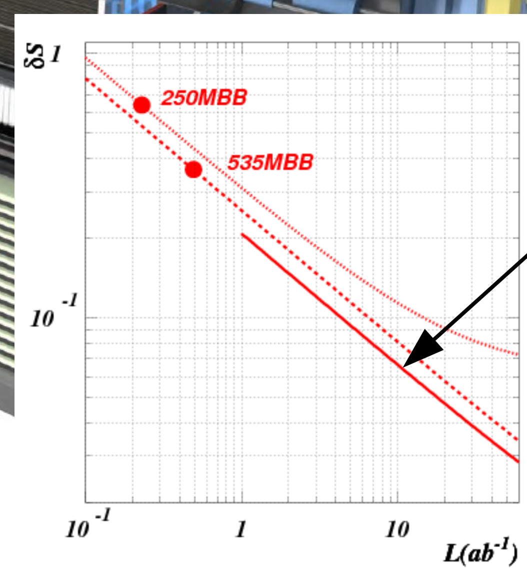
Silicon Strip Detector





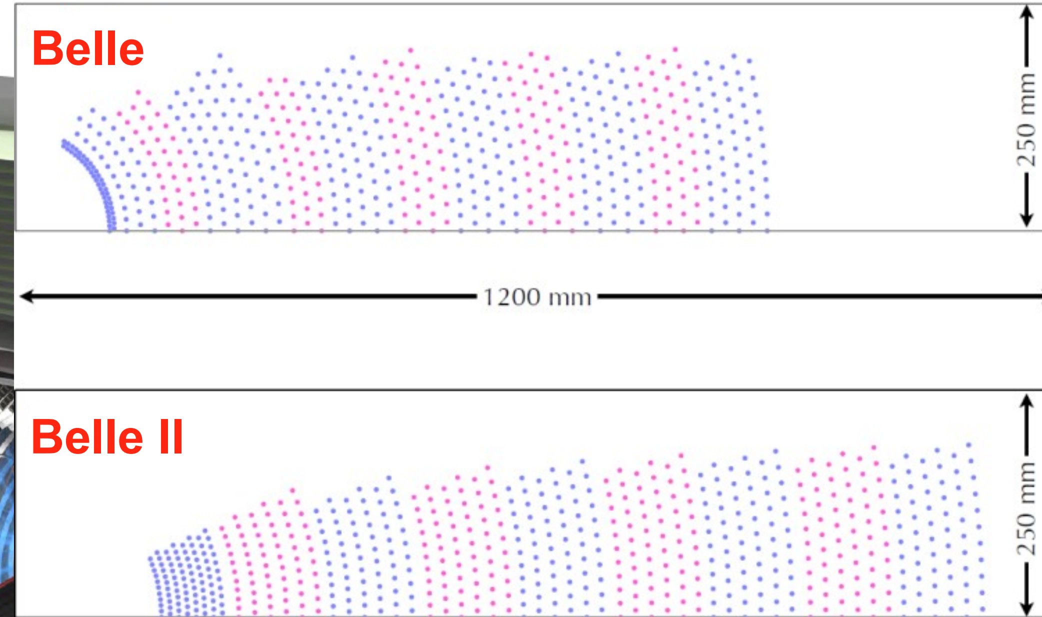


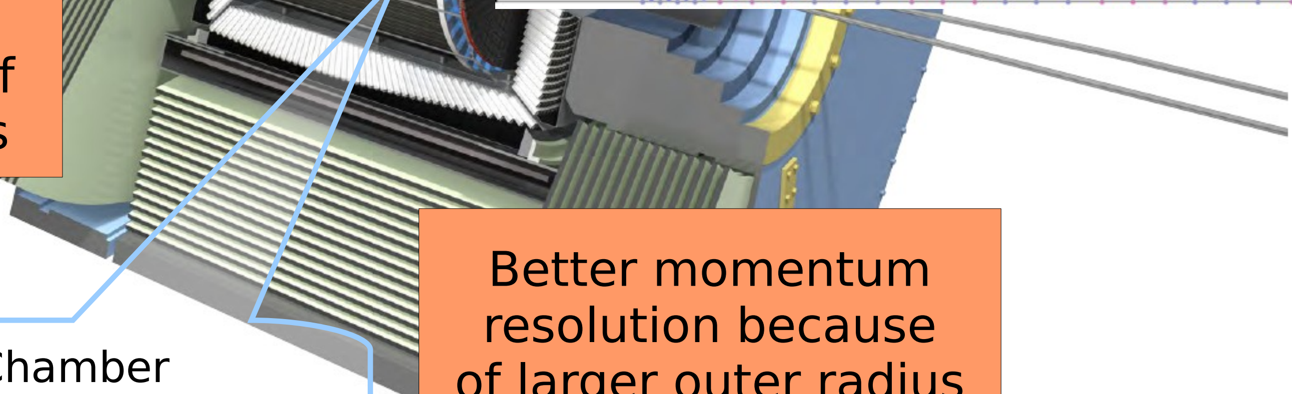
Vertex Detector
4 layers DSSD
r = 3.8 – 14.0 cm



Improvement in $\delta S(K_S\pi^0\gamma)$ because of larger K_S acceptance (by ~30%)

Drift Chamber





Reduced dead time because of new electronics

1-2 µs → 200 ns

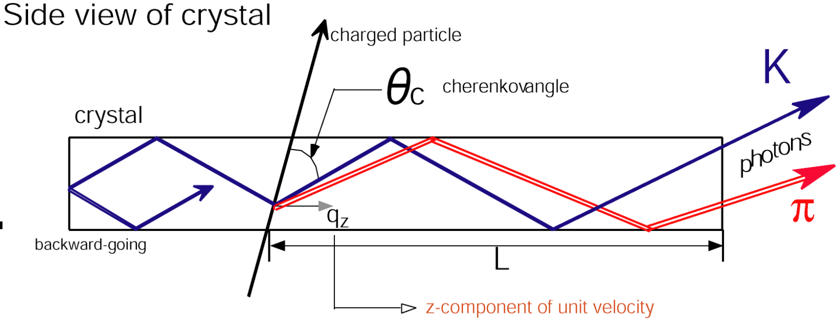
Central Drift Chamber
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics

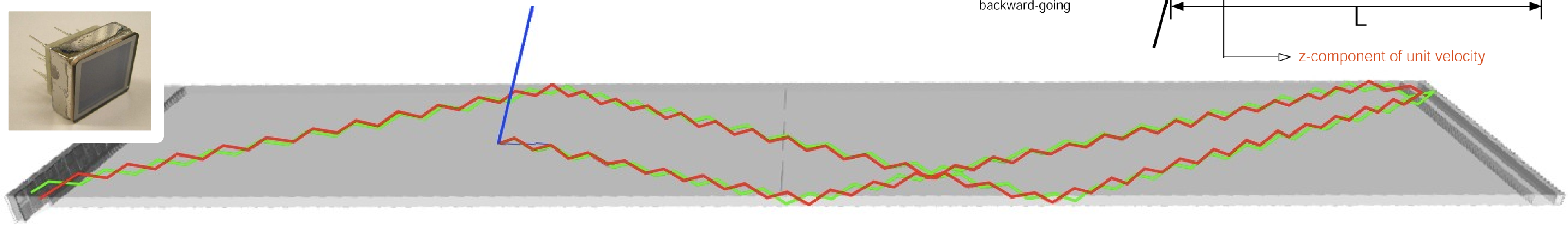
Better momentum resolution because of larger outer radius

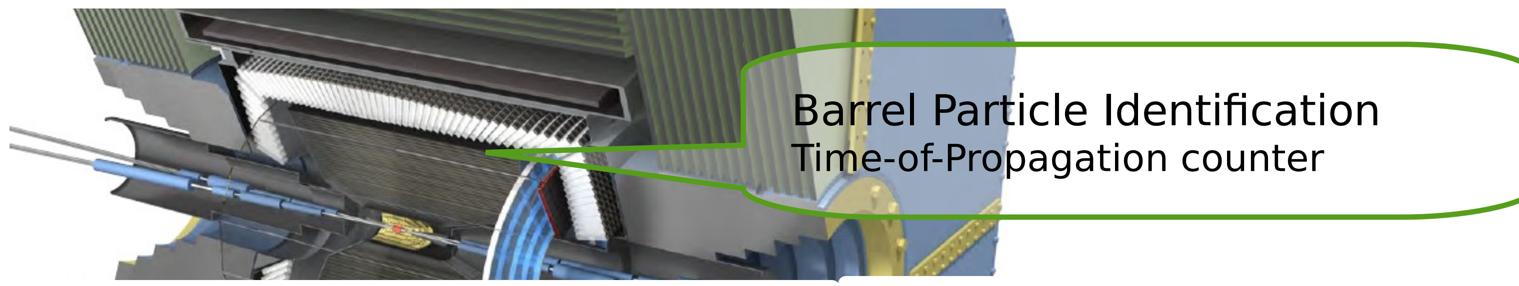
$$\sigma_{p_t}/p_t = \sqrt{(0.2\% p_t)^2 + (0.3\%/\beta)^2}$$

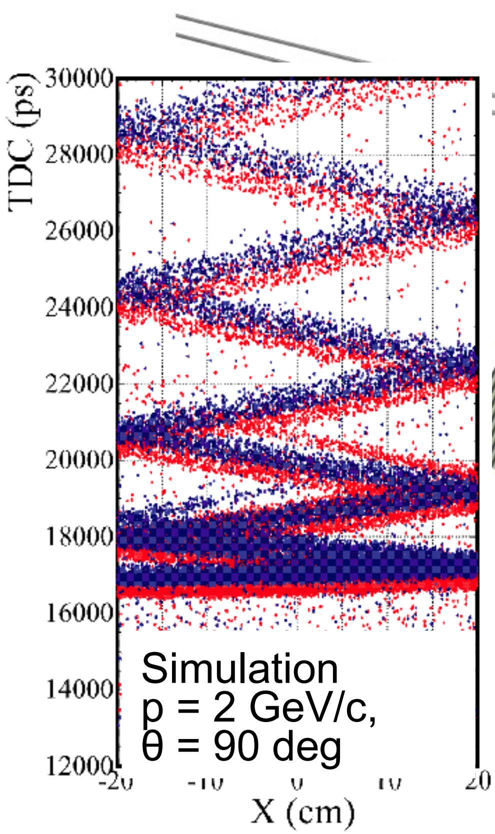
Barrel Particle ID

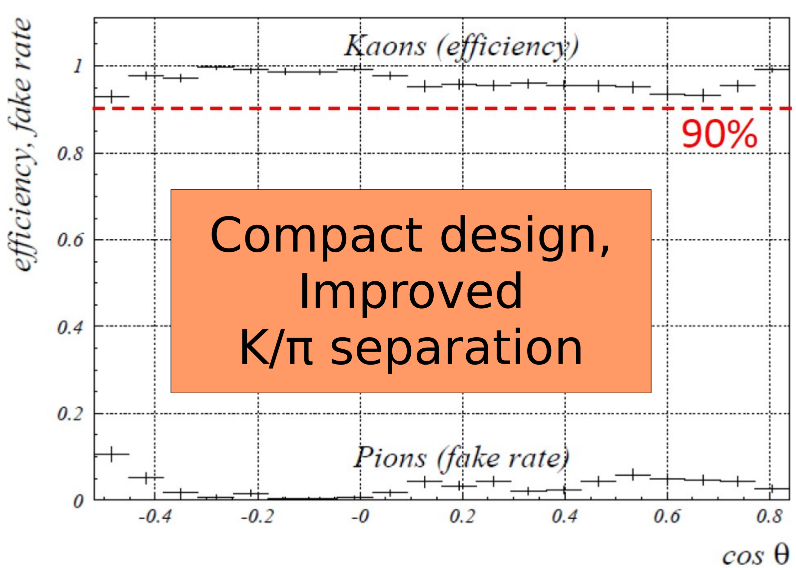
Side view of crystal

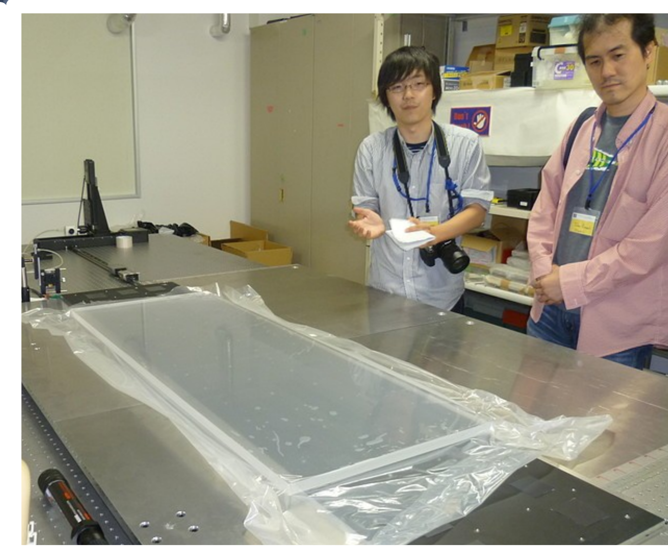




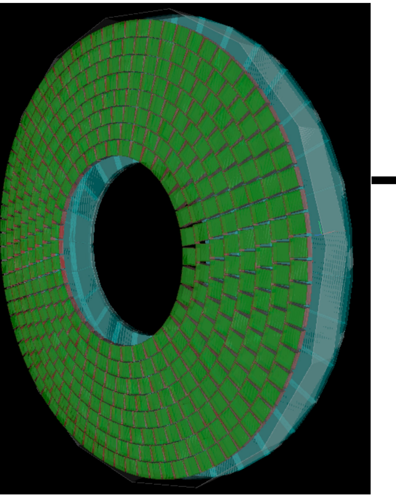


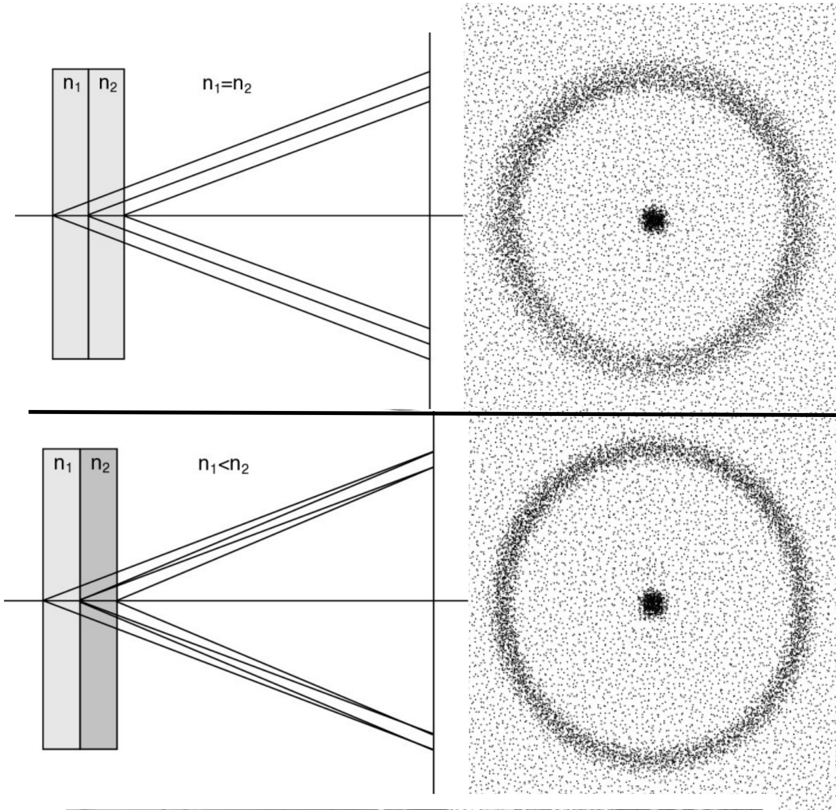


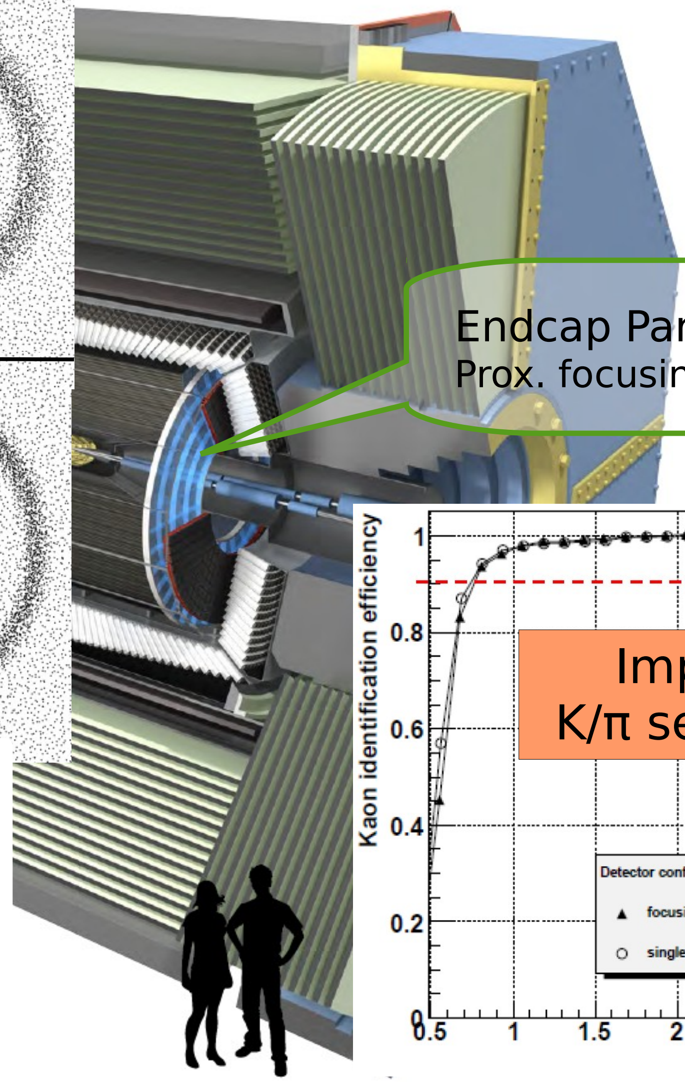




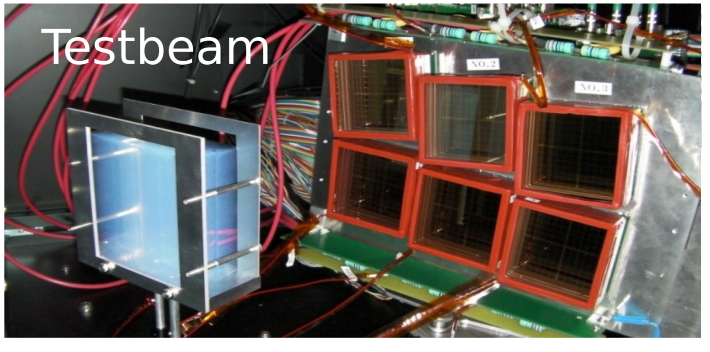
Endcap Particle Identification

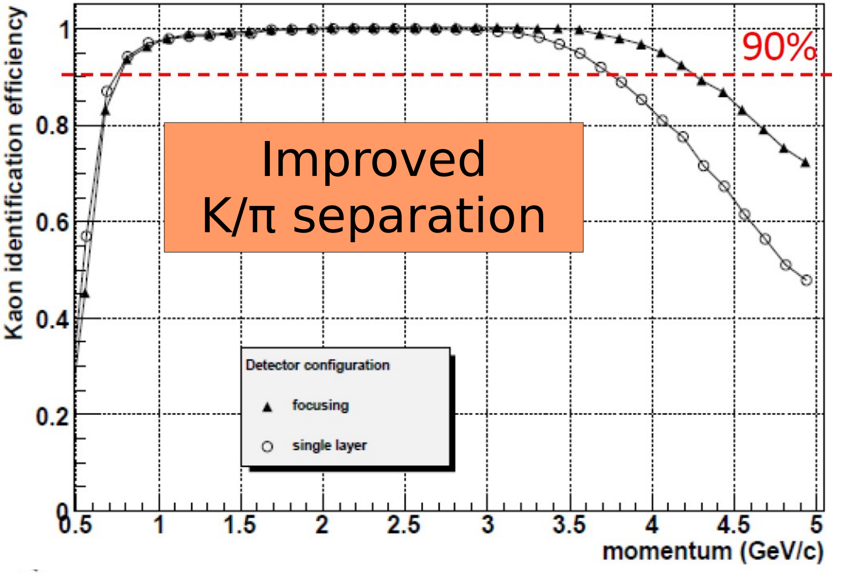






Endcap Particle Identification
Prox. focusing Aerogel RICH

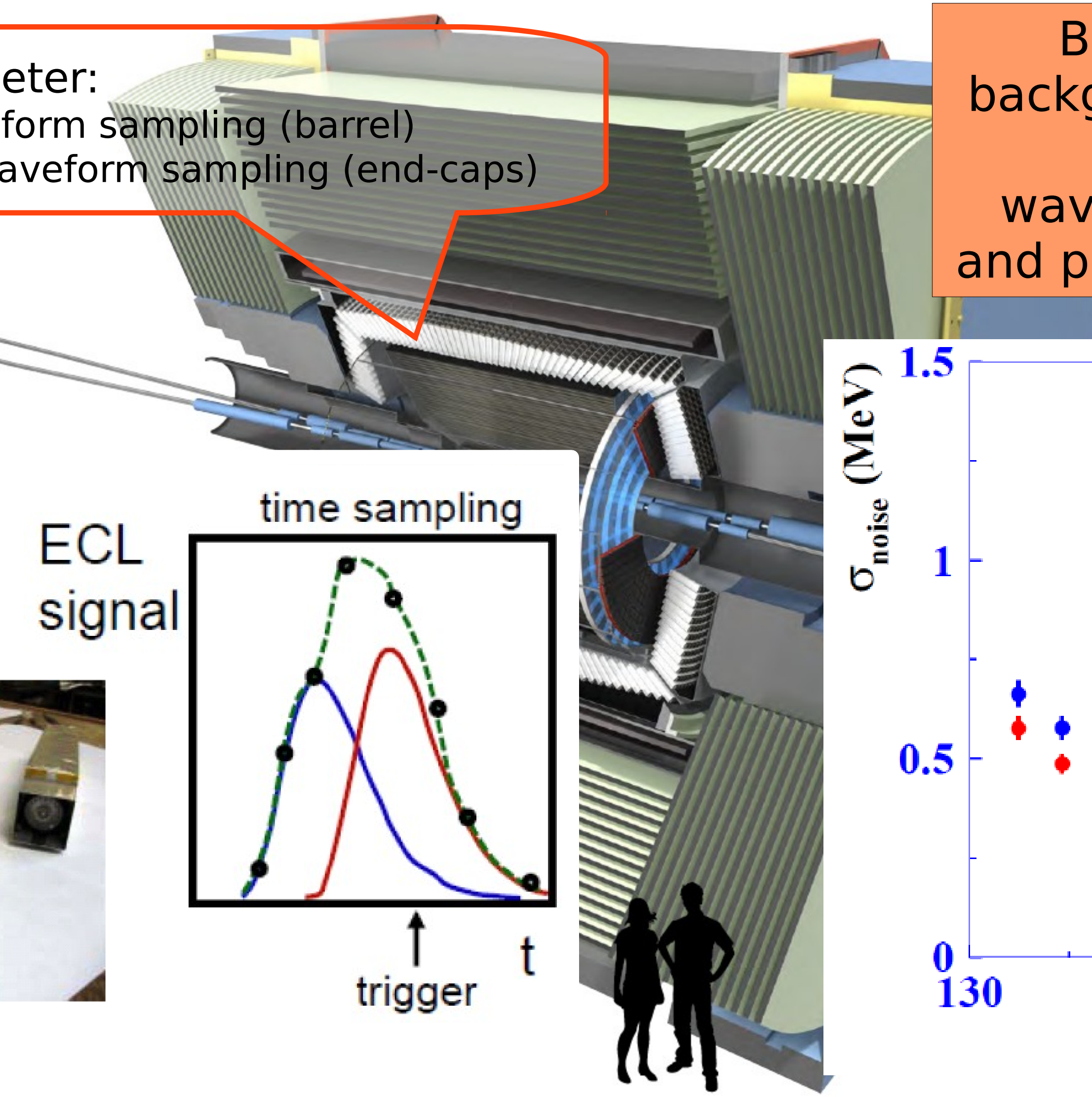


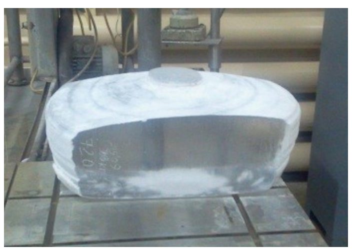


EM Calorimeter

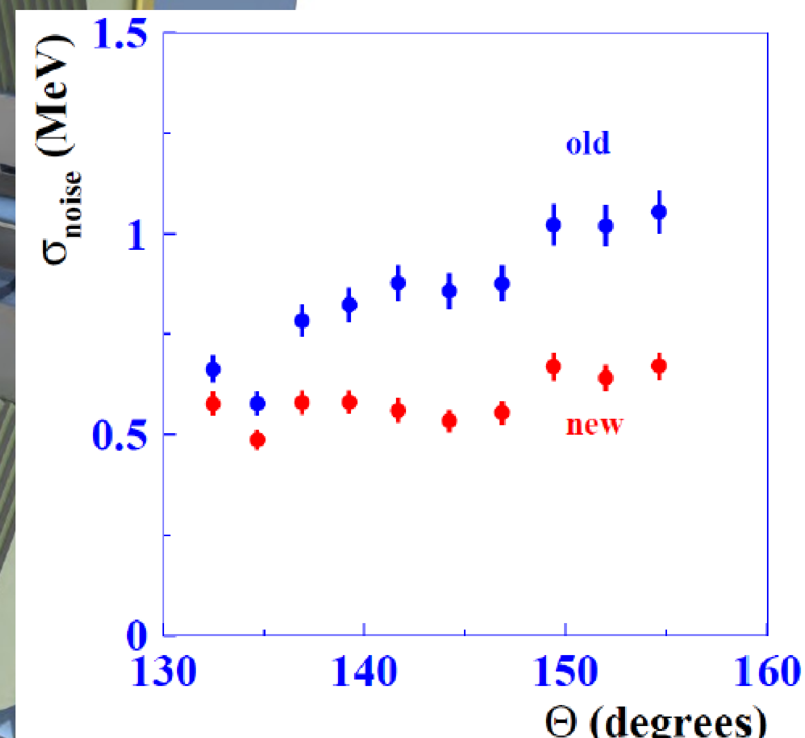
EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

Better signal to background separation because of wave form sampling and pure CsI in endcaps

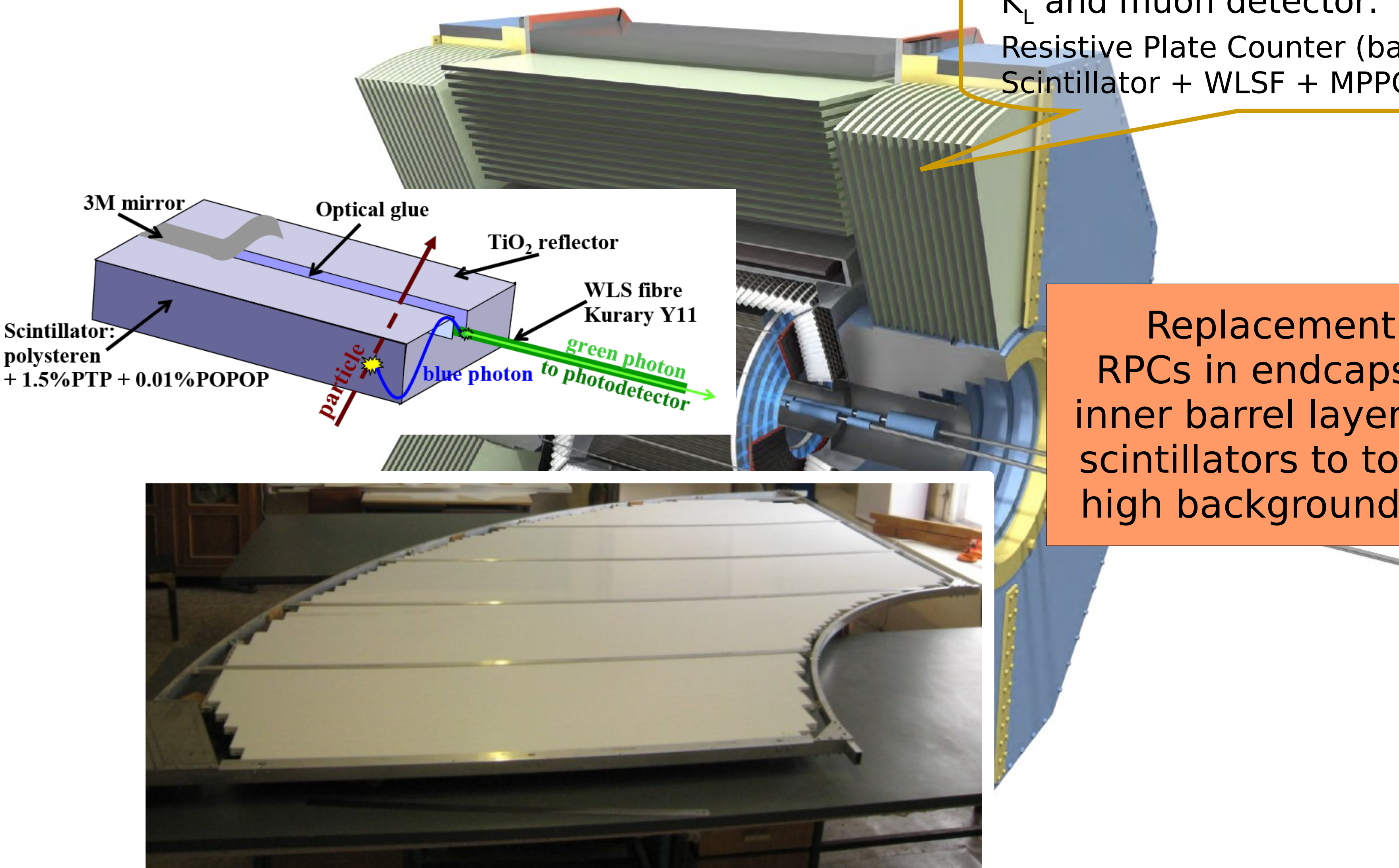




ECL signal



K_L and Muon Detector



K_L and muon detector:

Resistive Plate Counter (barrel)

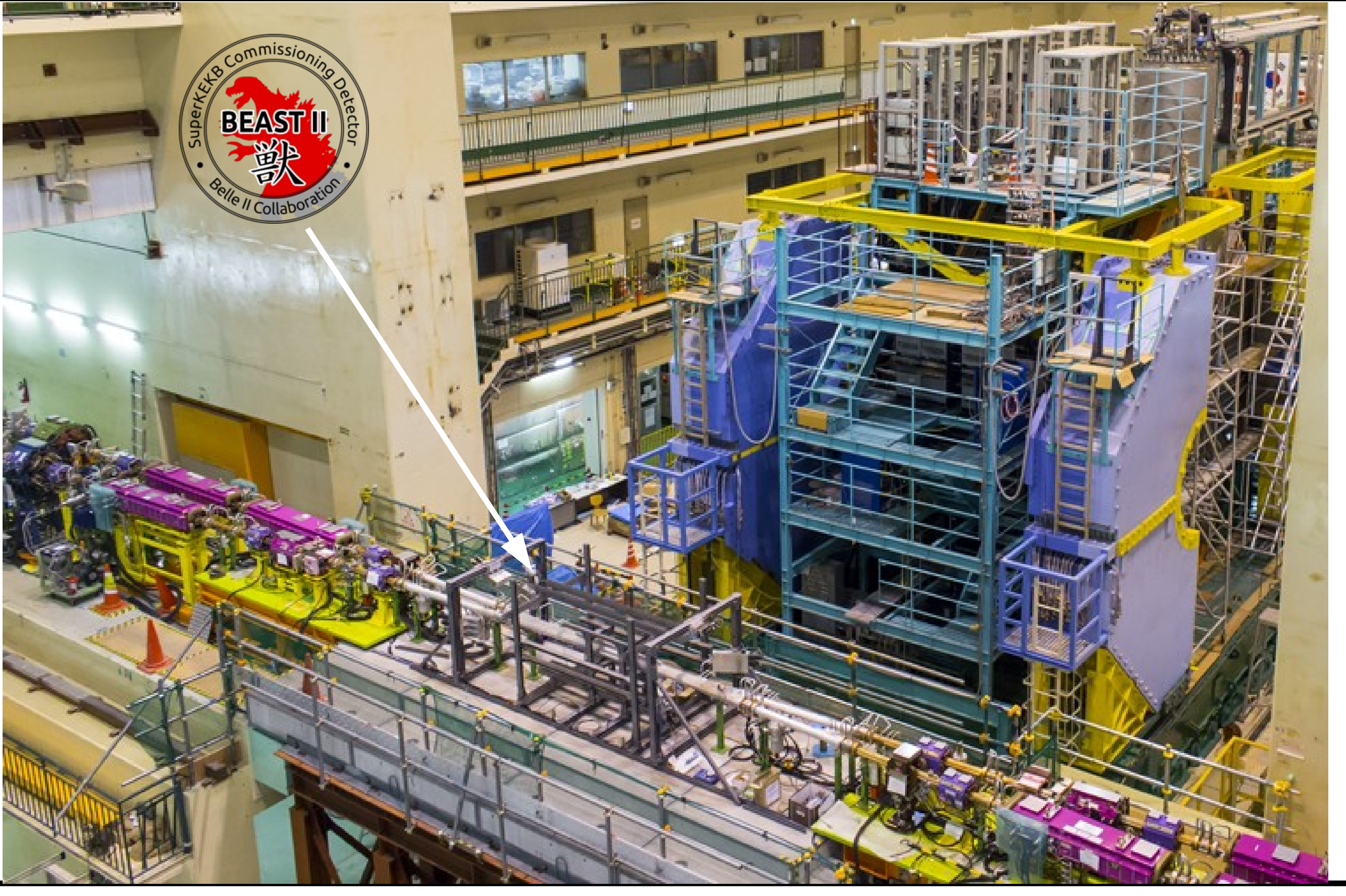
Scintillator + WLSF + MPPC (end-caps)

Replacement of RPCs in endcaps and inner barrel layers with scintillators to tolerate high background rates

Belle II Collaboration

~700 members
100 institutions
23 countries

BEAST II: Background Measurements



SuperKEKB First Turns

CERN COURIER

LATEST CERN COURIER ARTICLES

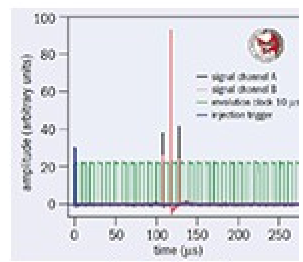
- Sommaire en français
- CMS updates its search for diphoton resonances
- World's most precise measurements and search for the
ca

CERN COURIER

Mar 18, 2016

'First turns' for SuperKEKB

On 10 February, the SuperKEKB electron-positron collider in Tsukuba, Japan, succeeded in circulating and storing a positron beam moving close to the speed of light through 1000 magnets in a narrow tube around the 3 km circumference of its main ring. And on 26 February, it succeeded in circulating and storing an



Signals from CLAWS

Physik Journal

Vierzigmal mehr Kollisionen

09. March 2016

Der Elektron-Positron-Beschleuniger SuperKEKB in Japan ist in Betrieb.

Am Forschungszentrum KEK in Tsukuba, Japan, hat der neue Elektron-Positron-Beschleuniger SuperKEKB nach fünfjähriger Aufbauphase seinen Betrieb aufgenommen. Am 10. Februar kreisten erstmals Positronen im Beschleunigerring; gut zwei Wochen später – am 26. Februar – gelang es, Elektronen in umgekehrter Richtung für mehr als hundert Umläufe zu speichern. In Zukunft sollen Elektronen und Positronen etwa vierzigmal häufiger kollidieren als an bisherigen Anlagen (KEKB in Japan und PEP-II in den USA) und dabei kurzlebige B-Mesonen und ihre Antiteilchen erzeugen. „Zusammen mit dem Detektor Belle II ist das eine Super-B-Mesonenfabrik", freut sich Sören Lange (Uni Gießen) als Sprecher der deutschen Sektion und Mitglied im Belle II Executive Board.

...enstrahlen ist bei SuperKEKB so gewählt, ...nti-B-Mesonen entstehen, sobald ein ...rt. Die Hochenergiephysiker wollen damit ... sich die Zerfallseigenschaften der ...nterscheiden. Diese Verletzung der ...echselwirkung wurde im B-Mesonen-...d LHCb beobachtet. Belle II soll einen ... CP-Verletzung jenseits des ...erletzung suchen. „Gegenüber dem ...n wir den Vorteil, dass wir die Kinematik und ...zustands genau kennen", sagt Sören ...it Belle II auch Zerfälle vollständig ...s auftreten, die der Detektor gar nicht

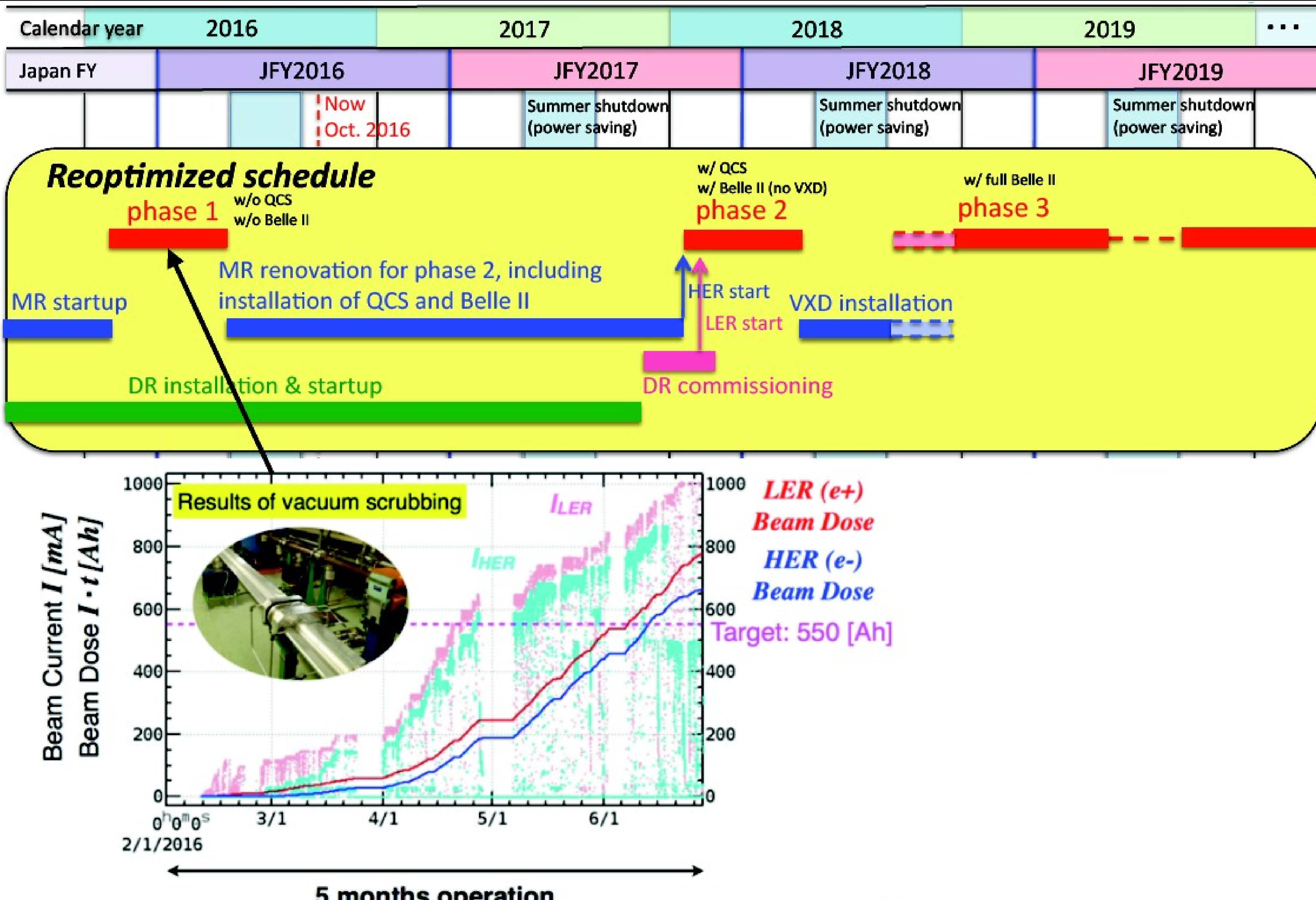
Press Release

First turns and successful storage of beams in the SuperKEKB electron and positron rings

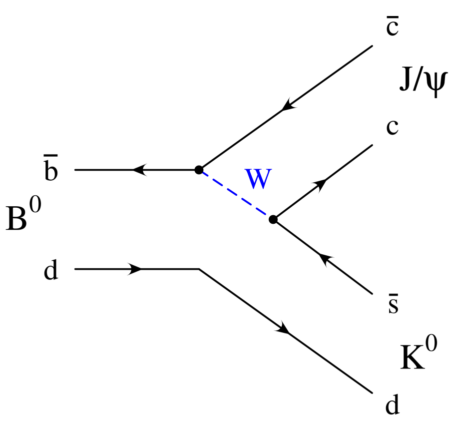
March 2nd, 2016

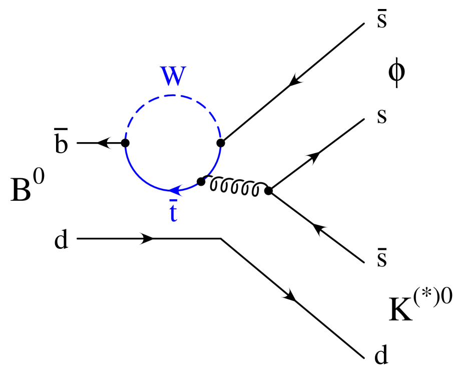
High Energy Accelerator Research Organization (KEK)

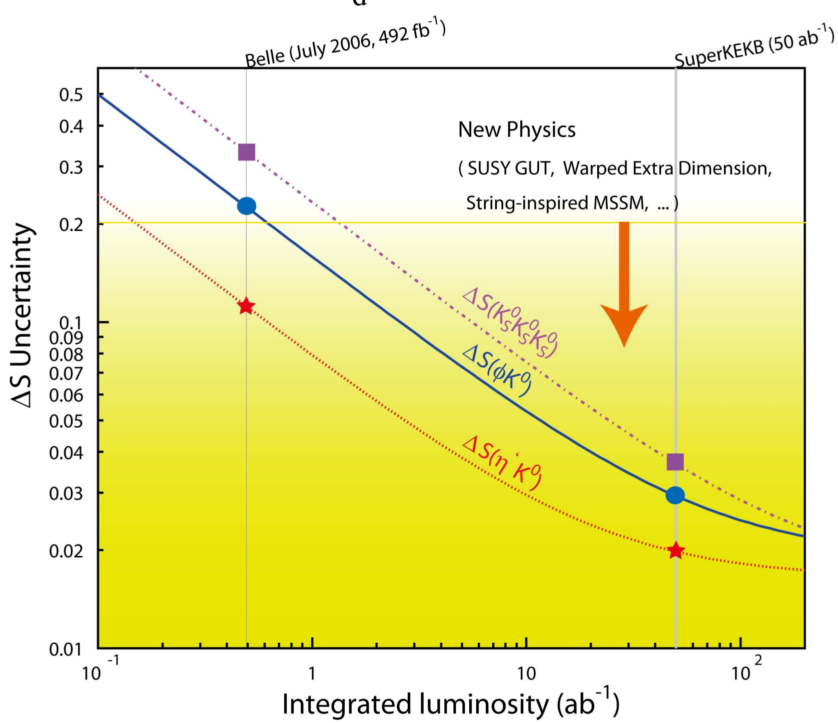
SuperKEKB / Belle II Schedule

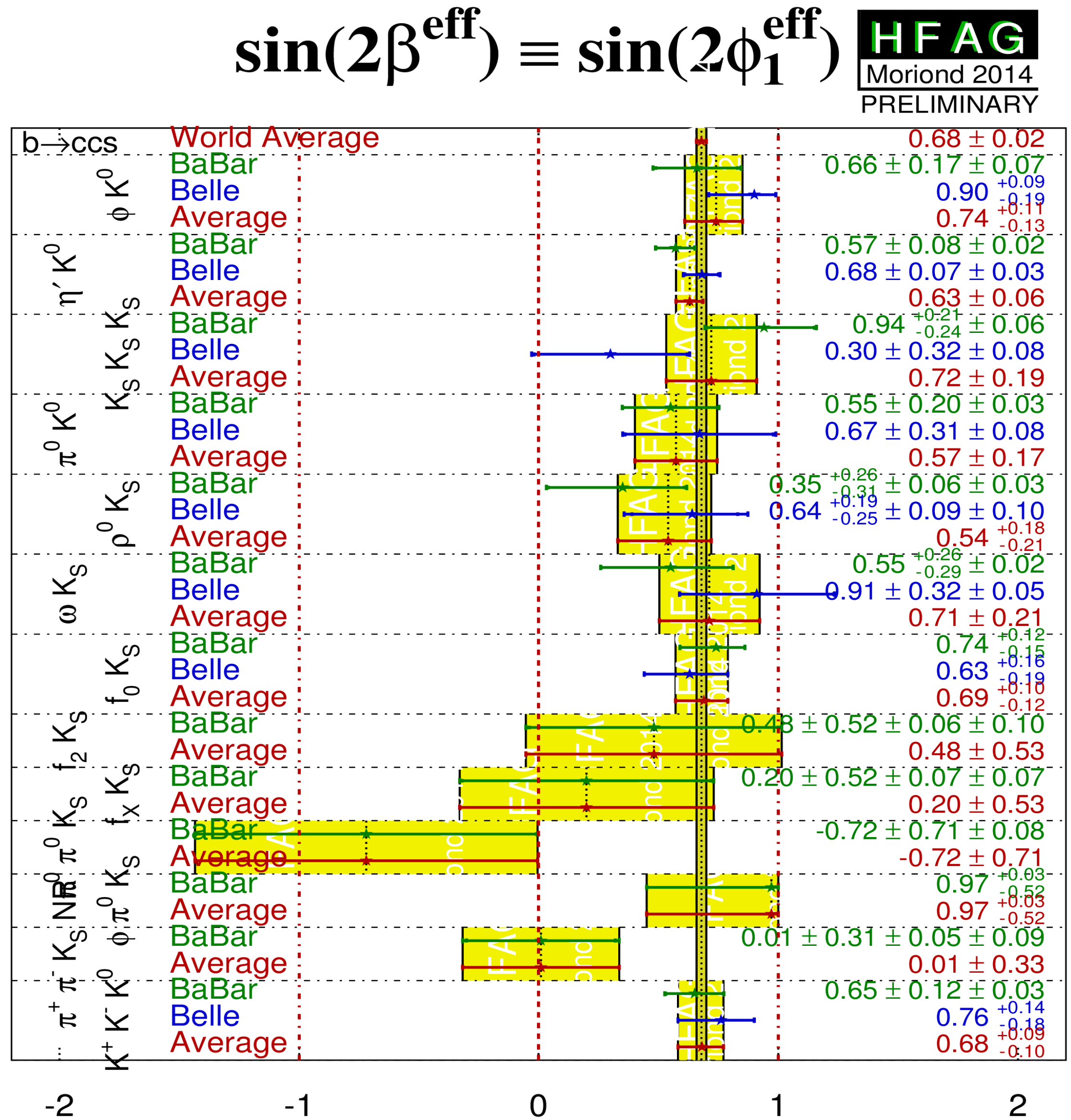


Search for New CP Violating Phases

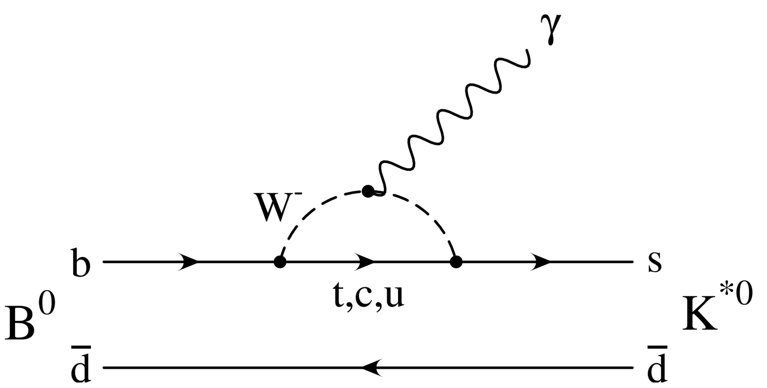








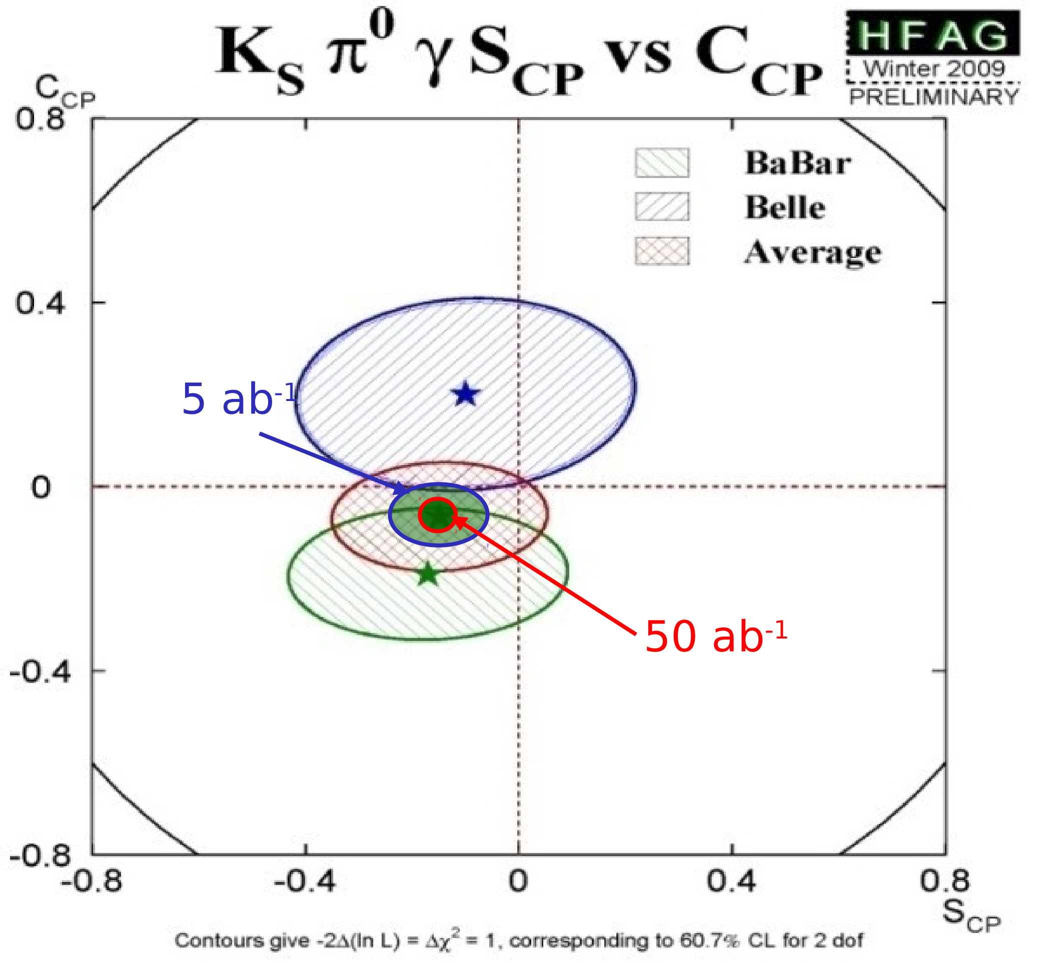
Search for Right-Handed Currents



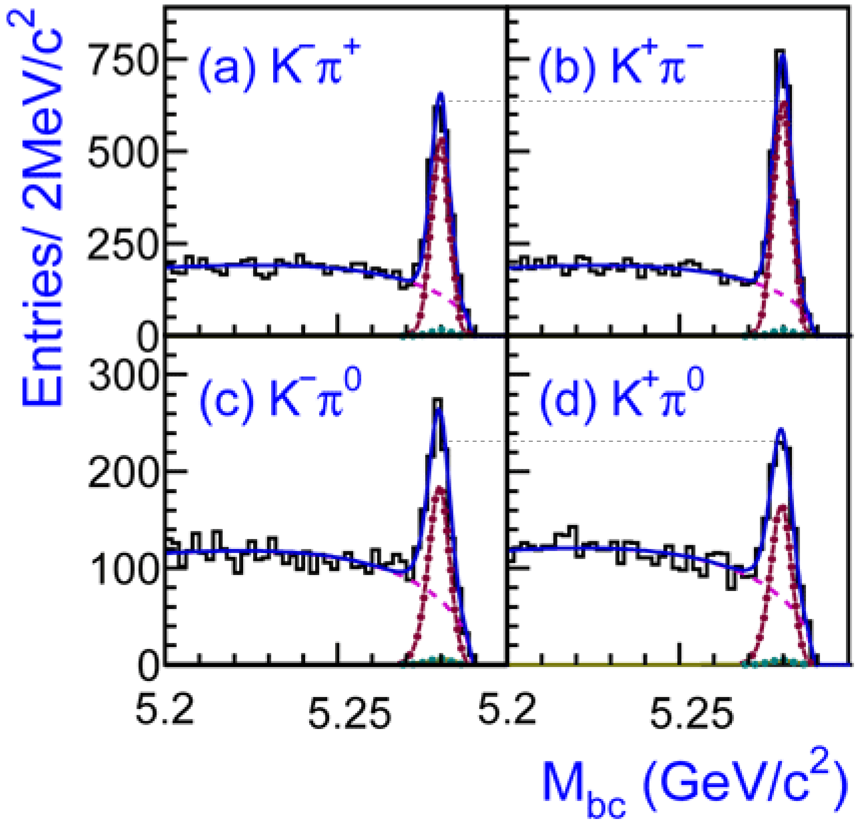
- $B^0 \to K^{*0} (\to K_S \pi^0) \gamma$

➔ SM:
$S_{CP} = 2 (m_s/m_b) \sin(2\phi_1)$

➢ Values up to $0.7 \sin(2\phi_1)$ possible in left-right symmetric NP models



Direct $\not{C}\!\not{P}$ in $B \to K\pi$

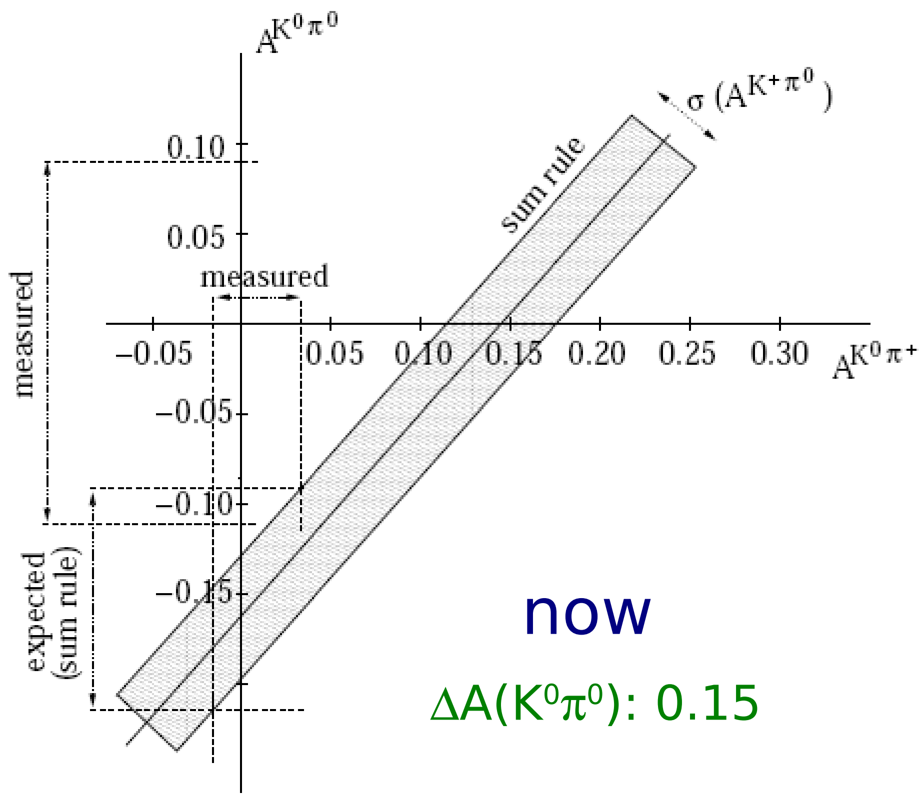


B^0 vs. $\bar{B}^0$

B^- vs. B^+

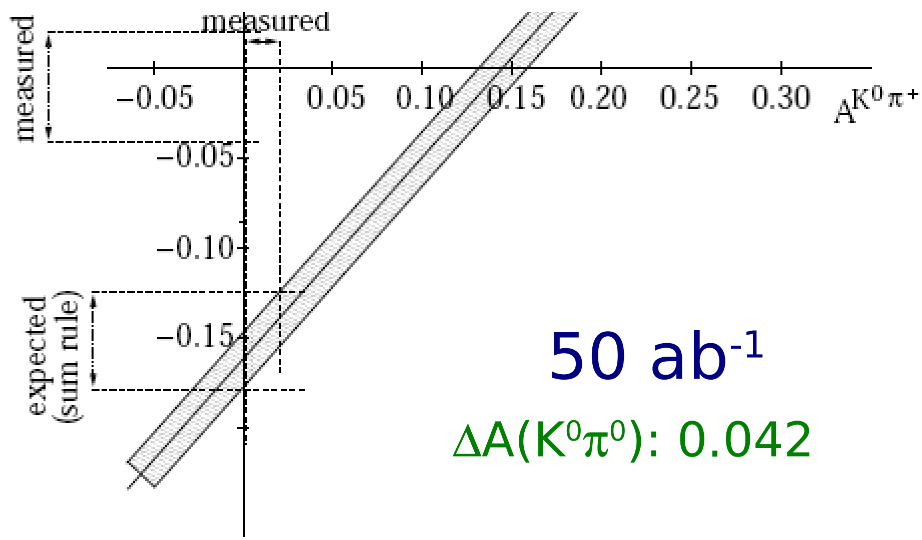
Sum rule:

$$\mathcal{A}_f(K^+\pi^-) + \mathcal{A}_f(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)\tau_{B^0}}{\mathcal{B}(K^+\pi^-)\tau_{B^+}} =$$
$$\mathcal{A}_f(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)\tau_{B^0}}{\mathcal{B}(K^+\pi^-)\tau_{B^+}} + \mathcal{A}_f(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}.$$



now

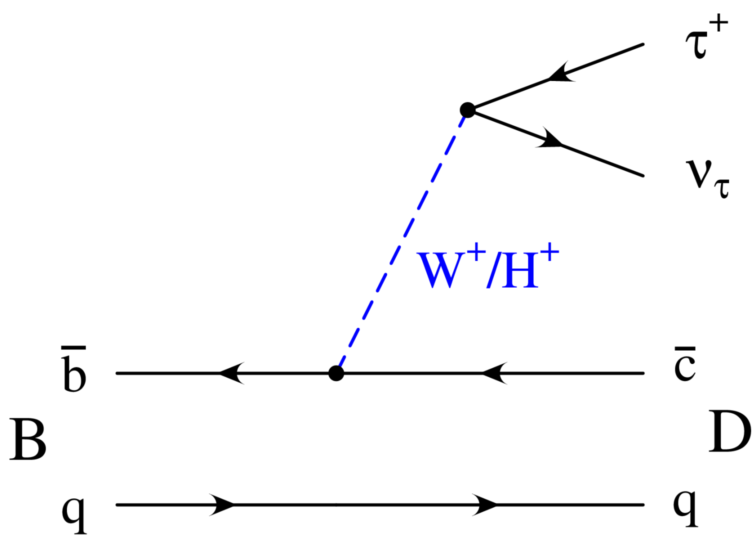
$\Delta A(K^0\pi^0)$: 0.15



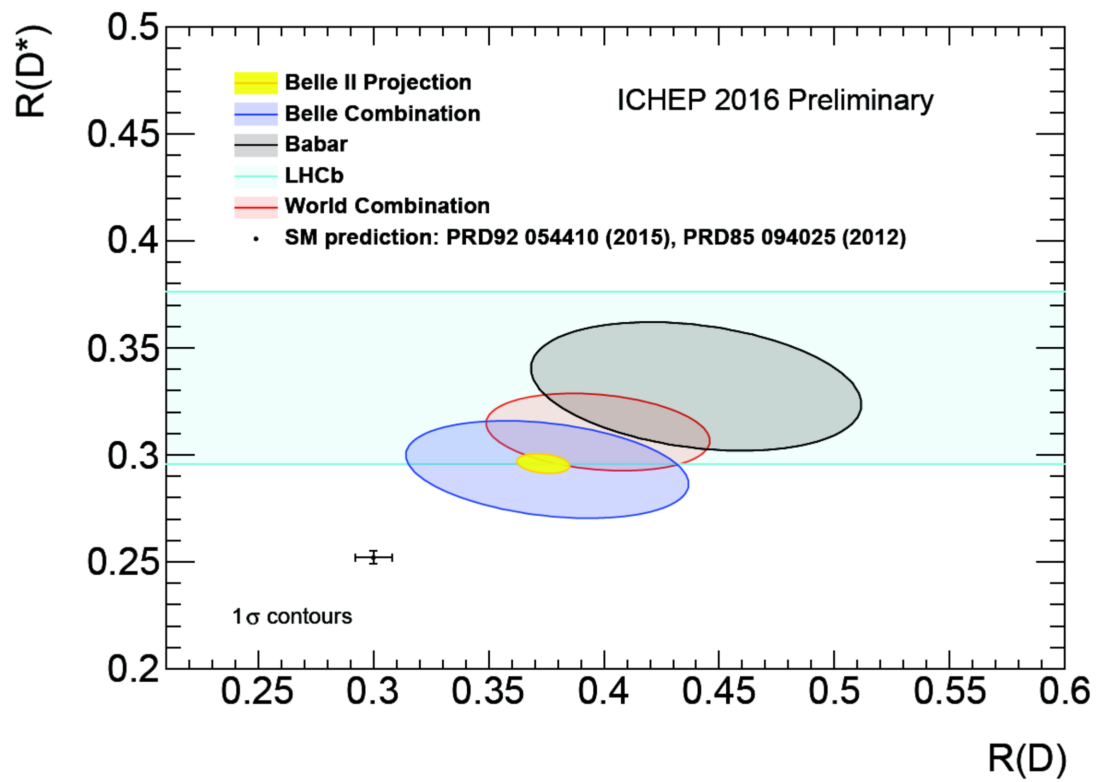
50 ab^{-1}

$\Delta A(K^0\pi^0)$: 0.042

Search for Multiple Higgs Bosons



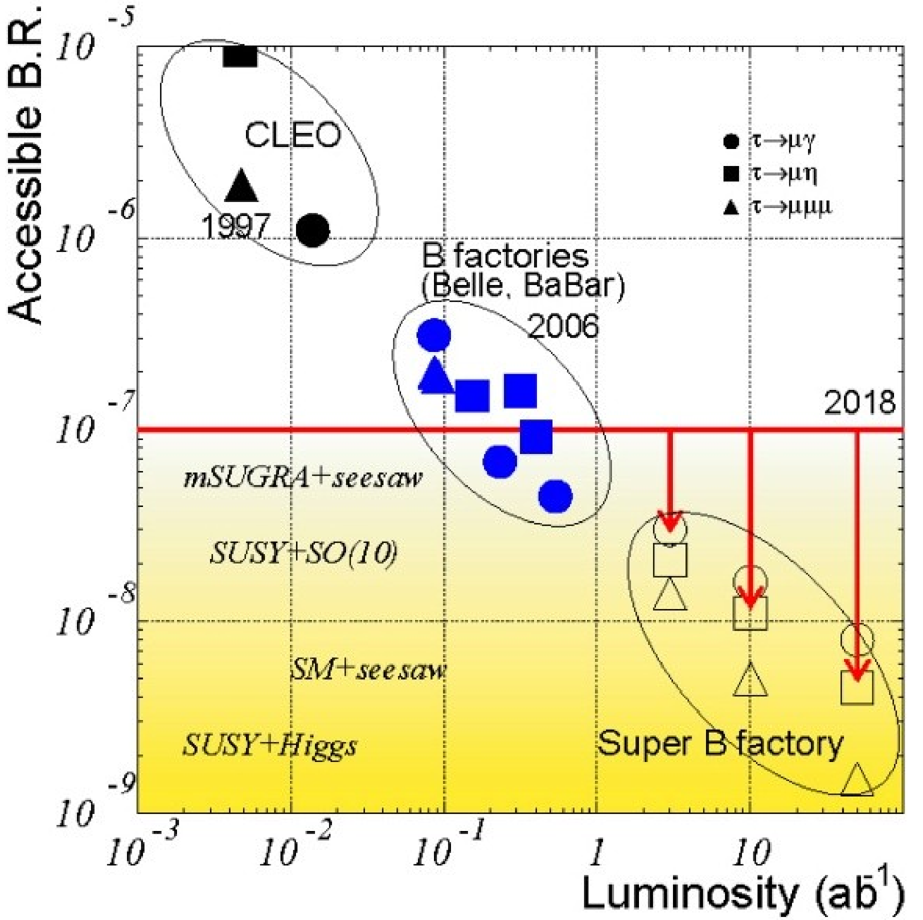
$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu_\tau)}{\mathrm{Br}(B \to D^{(*)}\ell\nu_\ell)}$$



- ➔ World average of R(D), R(D*) 4.0σ away from SM pred.
- ✗ Incompatible with 2HDM of type II

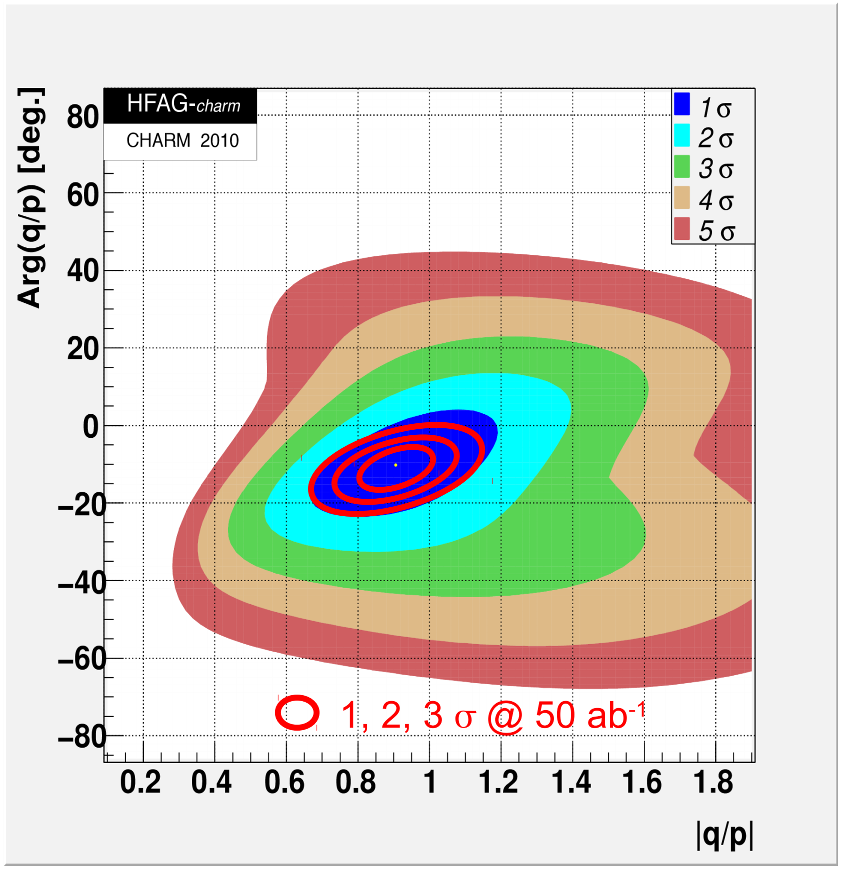
More New Physics Searches

Lepton flavor violation



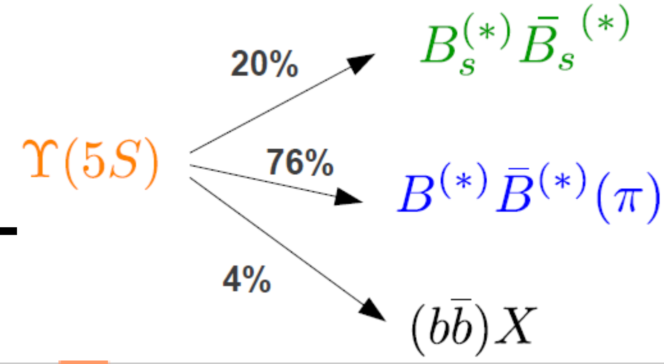
B(τ → μγ) 90% CL upper limit [10^{-9}]:
45 (~0.5 ab^{-1}) → 5 (50 ab^{-1})

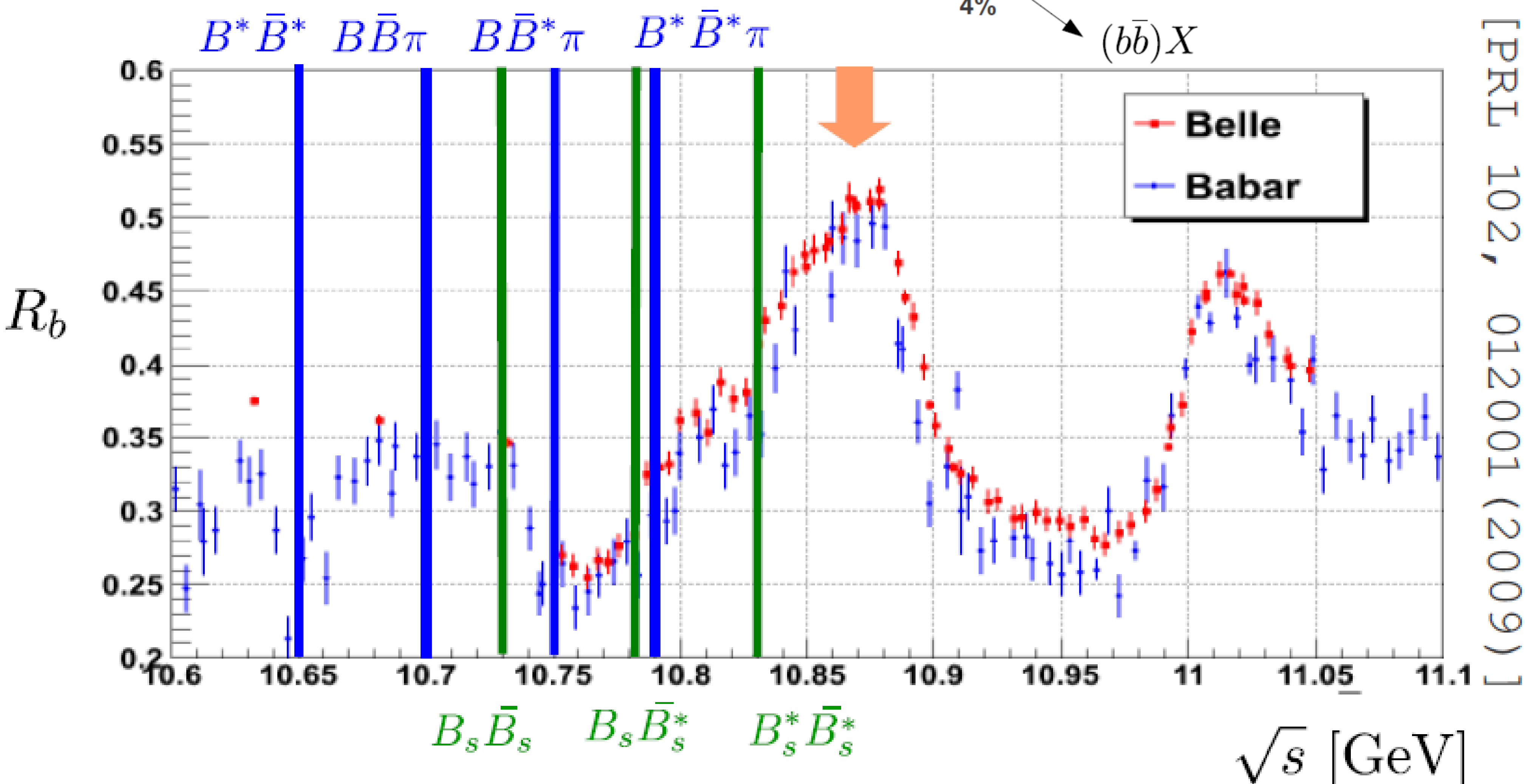
CP violation in D^0 mixing



Precision of |q/p|:
0.16 (~0.5 ab^{-1}) → 0.05 (50 ab^{-1})

Y(5S) Physics





→ Absolute B_s BRs, Spectroscopy (Z_b discovery)

Summary

Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\|V_{us}\|$ $[K \to \pi \ell \nu]$	**	0.1%	K-factory
$\|V_{cb}\|$ $[B \to X_c \ell \nu]$	**	1%	Belle II
$\|V_{ub}\|$ $[B_d \to \pi \ell \nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K_S^0]$	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		1.5°	Belle II
ϕ_3	***	3°	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K_S^0\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A_{SL}^d	***	0.001	LHCb
A_{SL}^s	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $A_{FB}(B \to K^*\mu\mu)$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\|q/p\|_D$	***	0.03	Belle II
$arg(q/p)_D$	***	1.5°	Belle II

$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

- em. interact.: ~1 nb
- Boost βγ ≈ 0.4
- ✔ Known kinematics
- ✔ No background tracks
- ✔ Good neutrals rec.
- ➔ Full event interpret.
- ➔ Decays with neutrals
- ➔ Inclusive decay rates
- ➔ Absolute BRs

Charm, τ, Υ(5S), spectroscopy

Isidori, Nir, Perez
Ann.Rev.Nucl.Part.Sci 60, 355 (2010)