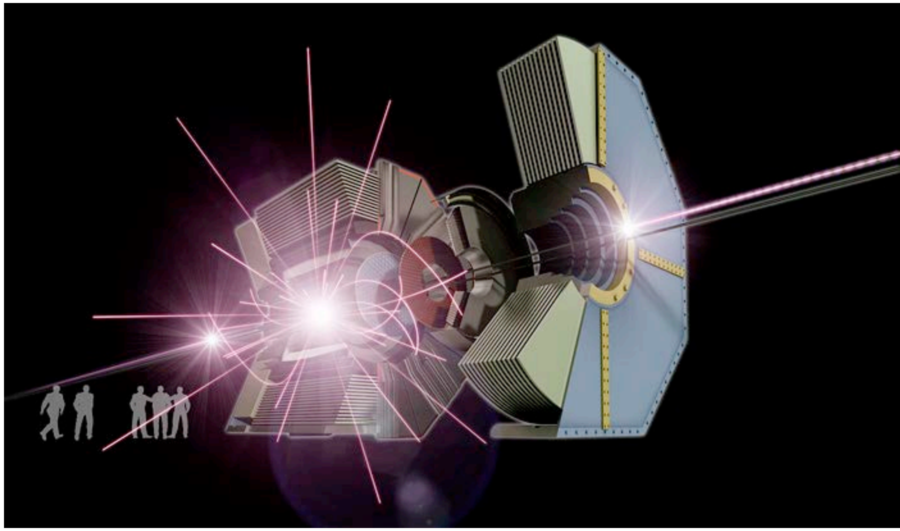
54th International Winter Meeting on Nuclear Physics

25-29 January 2016 Bormio (Italy)

The Belle II Experiment



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Bormio, January 29, 2016

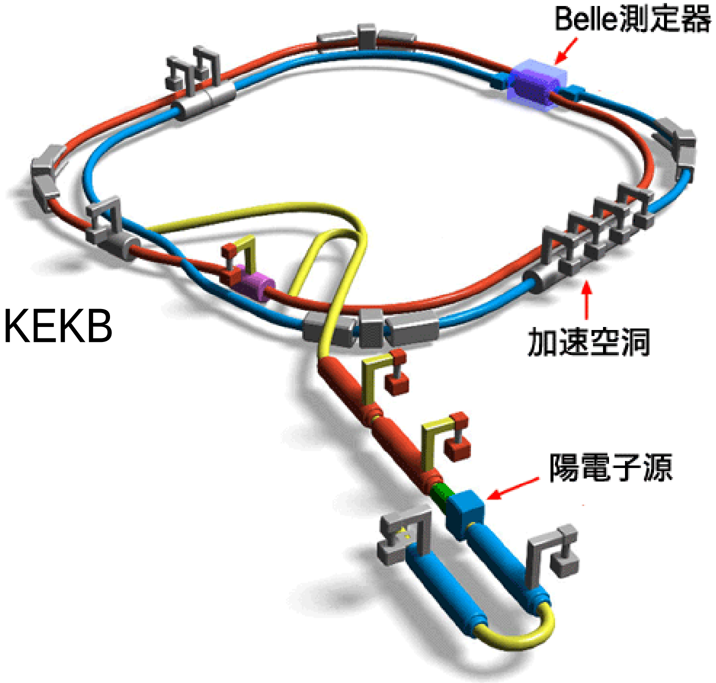
University of Ljubljana

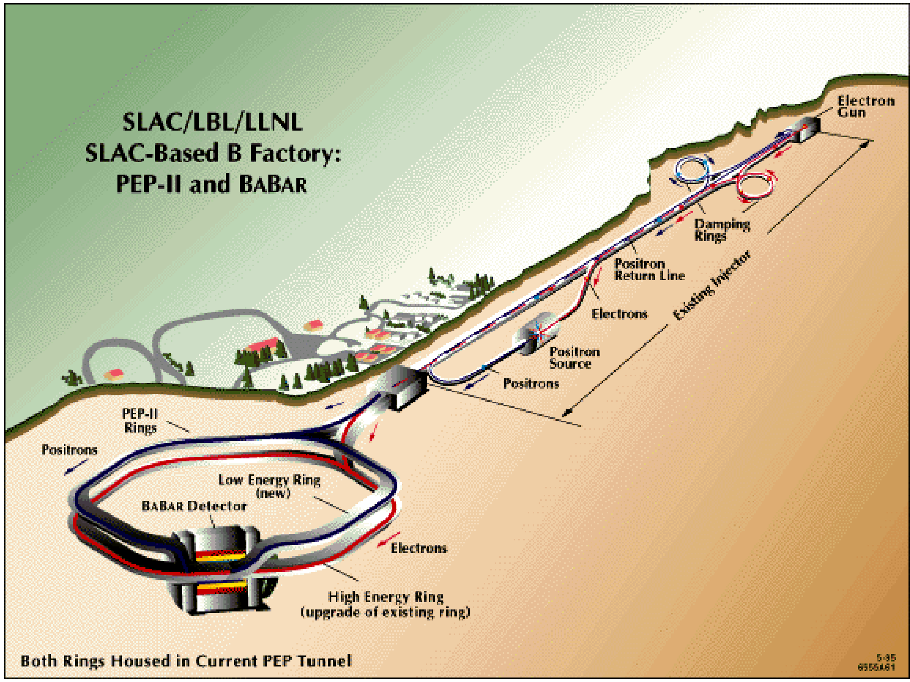
“Jožef Stefan” Institute

Contents

- Super B factory: motivation
- Super B factory: accelerator and detectors
- Summary: status and outlook

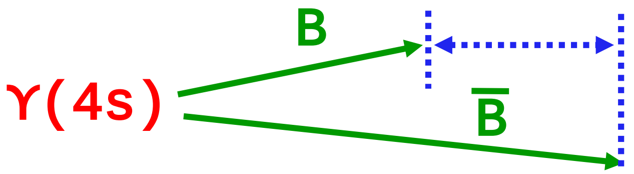
Asymmetric B factories: flavour physics at the luminosity frontier





$\sqrt{s}=10.58$ GeV

$$e^{+} \longrightarrow \Upsilon(4s) \longleftarrow e^{-}$$



$$\Delta z \sim c\beta\gamma\tau_B \sim 200\mu m$$

BaBar	$p(e^-)=9$ GeV	$p(e^+)=3.1$ GeV	$\beta\gamma=0.56$
Belle	$p(e^-)=8$ GeV	$p(e^+)=3.5$ GeV	$\beta\gamma=0.42$

To a large degree shaped flavour physics in the previous decade

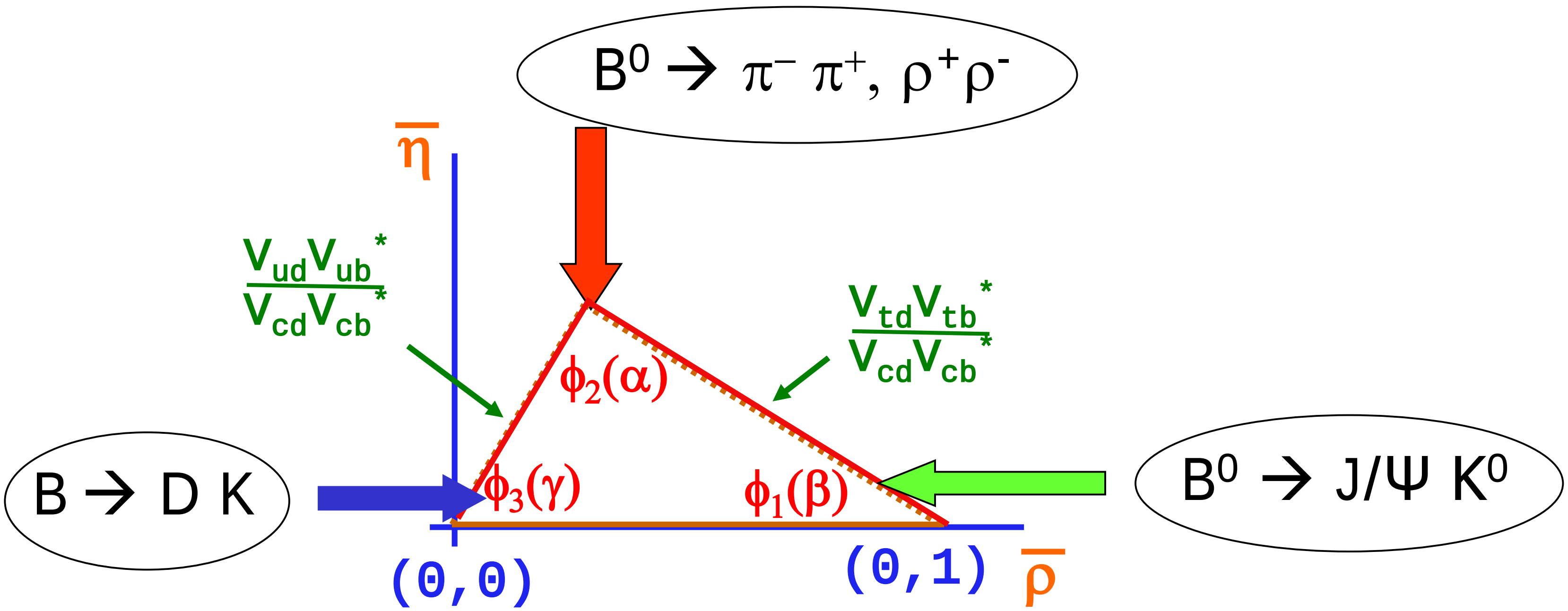
Comparison of **energy** /**intensity** frontiers

To observe a large ship far away one can either use **strong binoculars** or observe **carefully the direction and the speed of waves** produced by the vessel.

Energy frontier (LHC)

Luminosity frontier - (super) B factories

CP violation in the B system and unitarity triangle



$B^0 \rightarrow \pi^- \pi^+, \rho^+\rho^-$

$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$

$\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}$

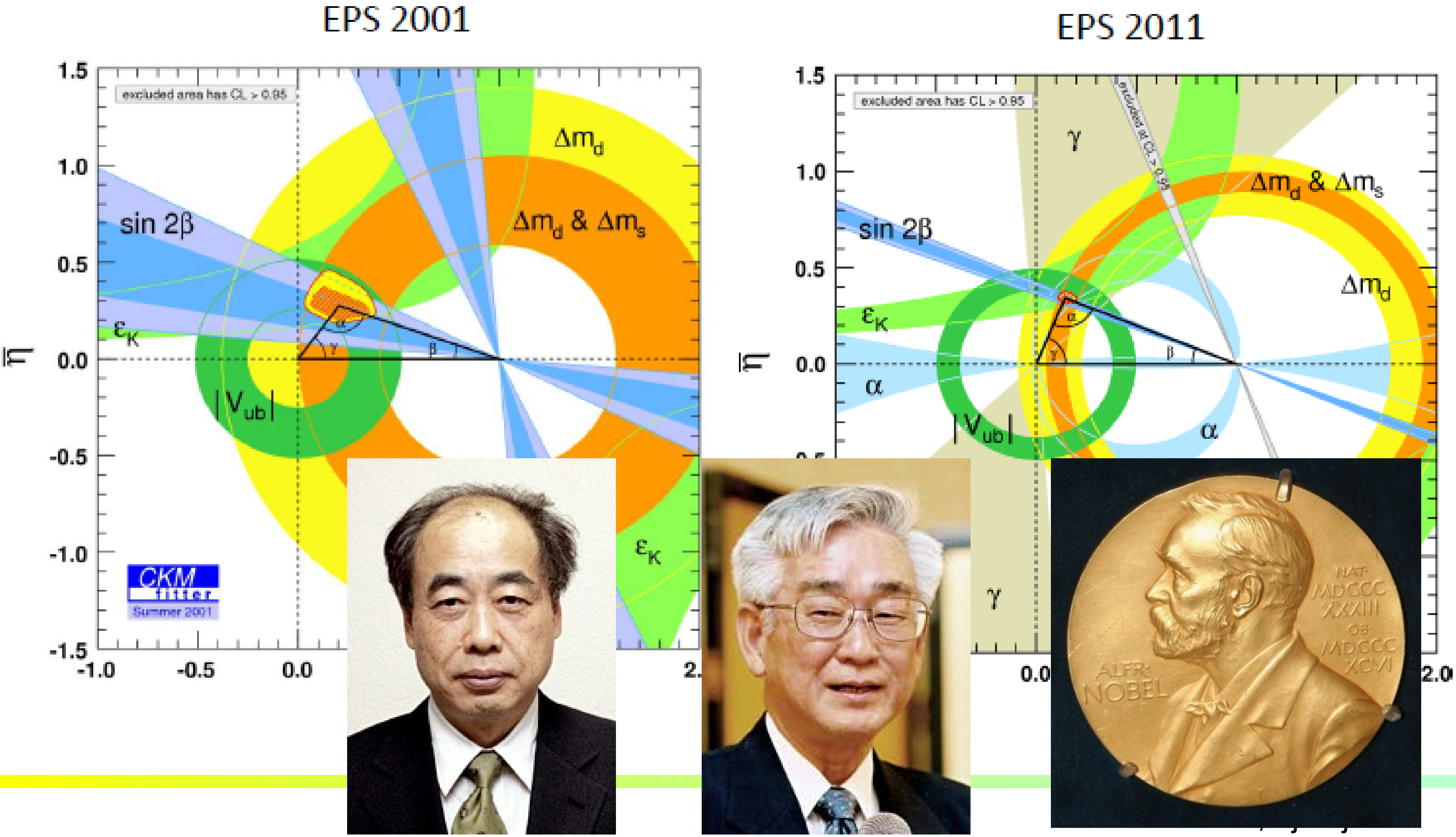
$B \rightarrow D\ K$

$B^0 \rightarrow J/\Psi\ K^0$

→ More: talk by Marcel Merck yesterday

B factories: CP violation in the B system

CP violation in the B system: from the discovery (2001) to a precision measurement (2011).


EPS 2001

EPS 2011

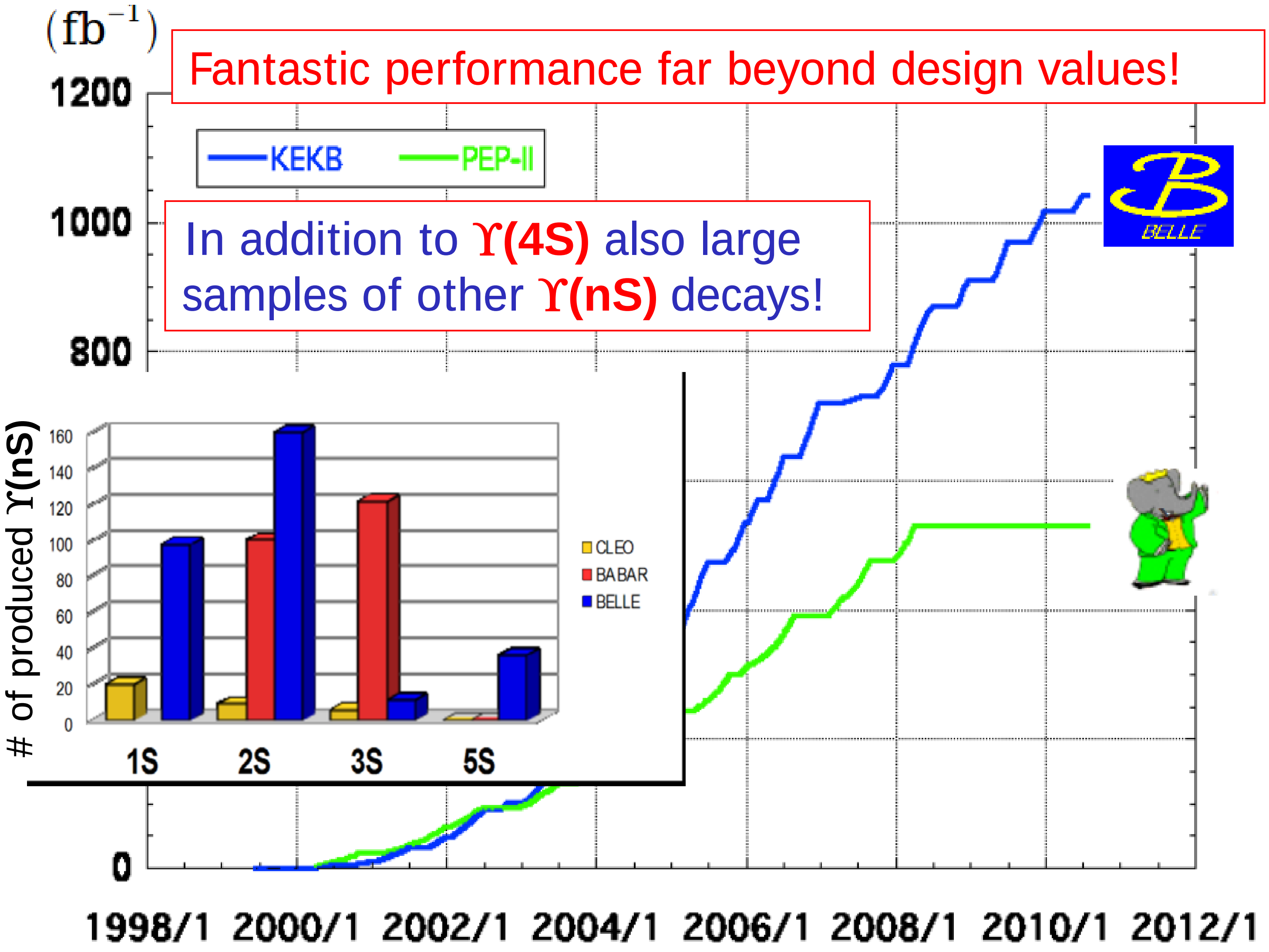
B factories: a success story

- Measurements of CKM matrix elements and angles of the unitarity triangle
- Observation of direct CP violation in B decays
- Measurements of rare decay modes (e.g., $B \rightarrow \tau\nu$, $D\tau\nu$)
- $b \rightarrow s$ transitions: probe for new sources of CPV and constraints from the $b \rightarrow s\gamma$ branching fraction
- Forward-backward asymmetry (A_{FB}) in $b \rightarrow sl^+l^-$
- Observation of D mixing
- Searches for rare τ decays
- Discovery of exotic hadrons including charged charmonium- and bottomonium-like states

Integrated luminosity at B factories

Fantastic performance far beyond design values!

In addition to **Υ(4S)** also large samples of other **Υ(nS)** decays!



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

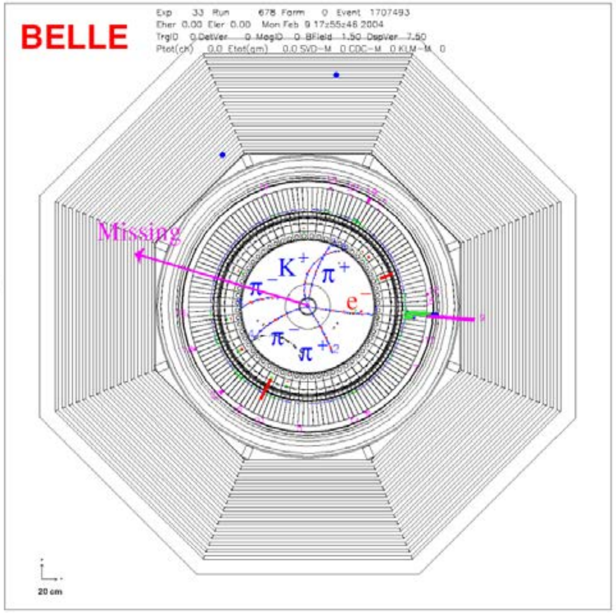
$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

Advantages of a B factory in the LHC era

$$B^+ \to D^0\pi^+$$
$$\quad(\to K\pi^-\pi^+\pi^-)$$
$$B^- \to \tau(\to e\nu\bar{\nu})\nu$$



Unique capabilities of a B factory:

→ Exactly two B mesons produced (at Υ(4S))

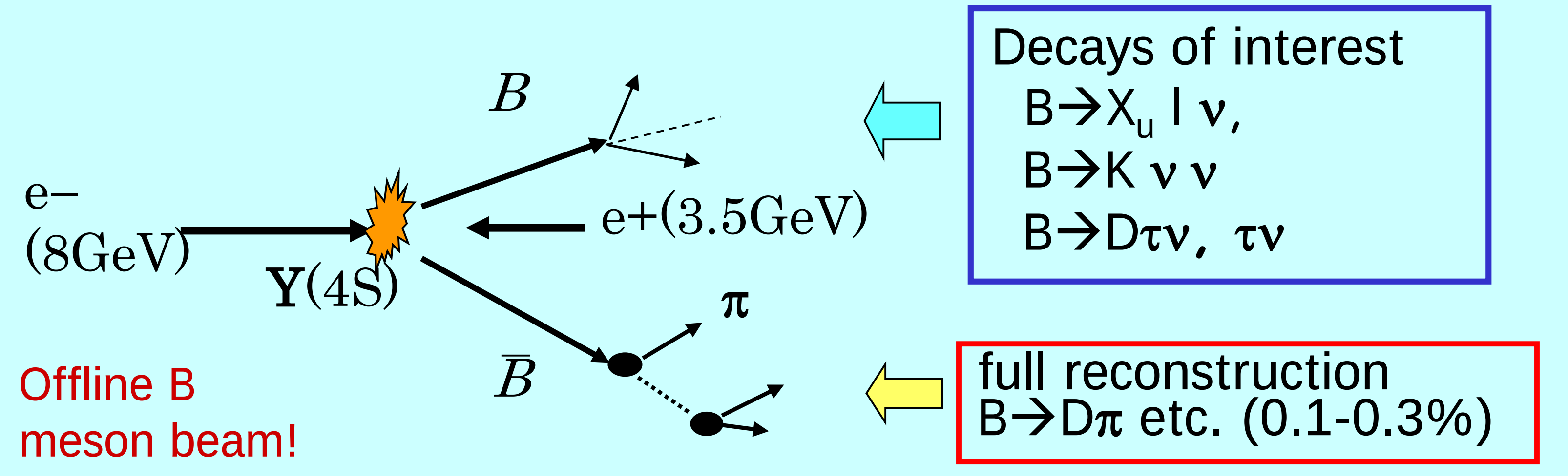
→ High flavour tagging efficiency

→ Detection of gammas, π^0s, K_Ls

→ Very clean detector environment (can observe decays with several neutrinos in the final state!)

Full reconstruction tagging

An example of the power of a B factory: fully reconstruct one of the B's to tag B flavor/charge, determine its momentum, and exclude decay products of this B from further analysis (exactly two B's produced in Υ(4S) decays)



Decays of interest

- $B \rightarrow X_u\, l\, \nu$,
- $B \rightarrow K\, \nu\, \nu$
- $B \rightarrow D\tau\nu$, $\tau\nu$

full reconstruction
$B \rightarrow D\pi$ etc. (0.1-0.3%)

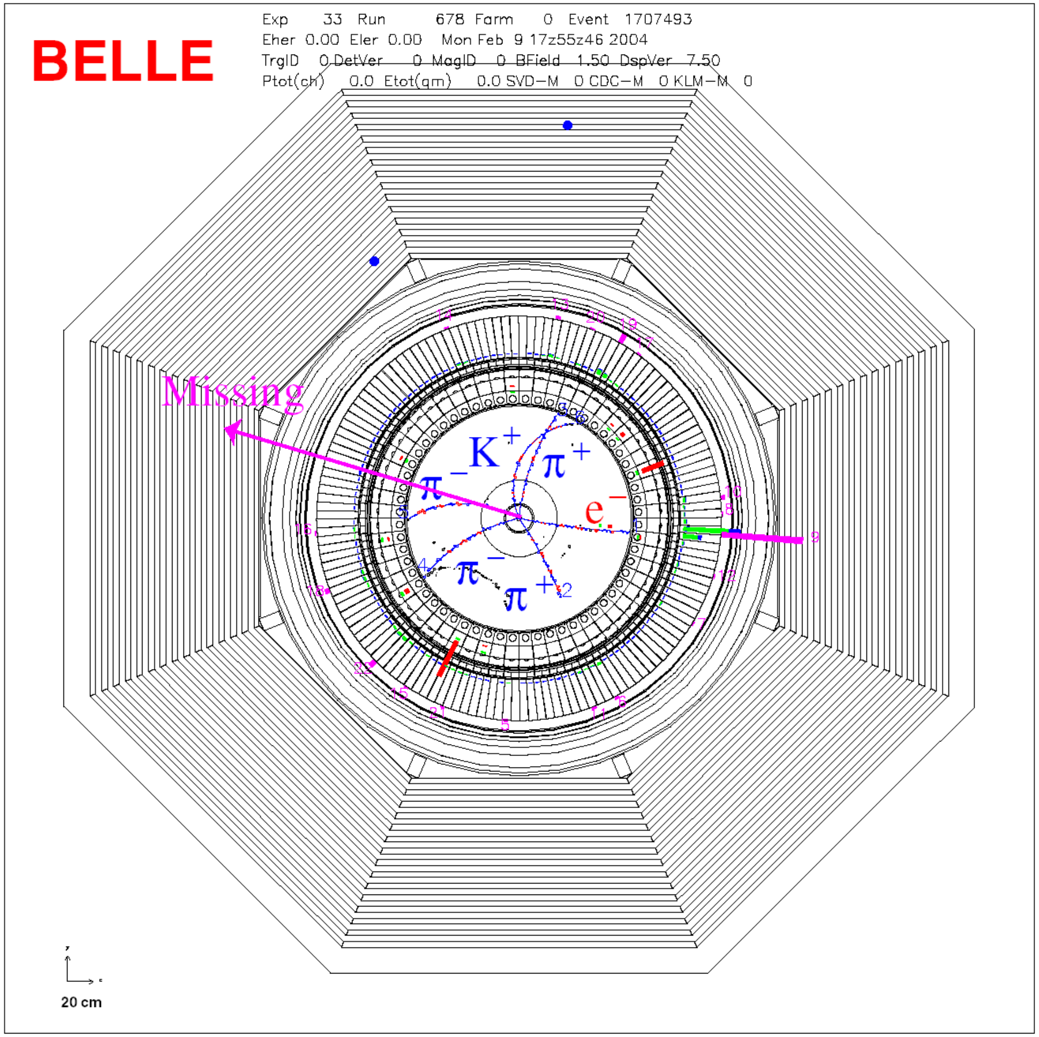
Offline B meson beam!

Powerful tool for B decays with neutrinos, used in several analyses

→unique feature at B factories

$B^- \rightarrow \tau^- \nu_\tau$

Example of a missing energy decay

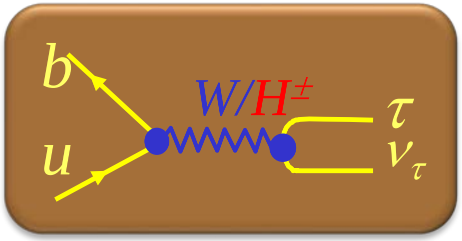


$$B^+ \rightarrow D^0\pi^+$$

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

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

Charged Higgs limits from B $\rightarrow \tau^- \nu_\tau$



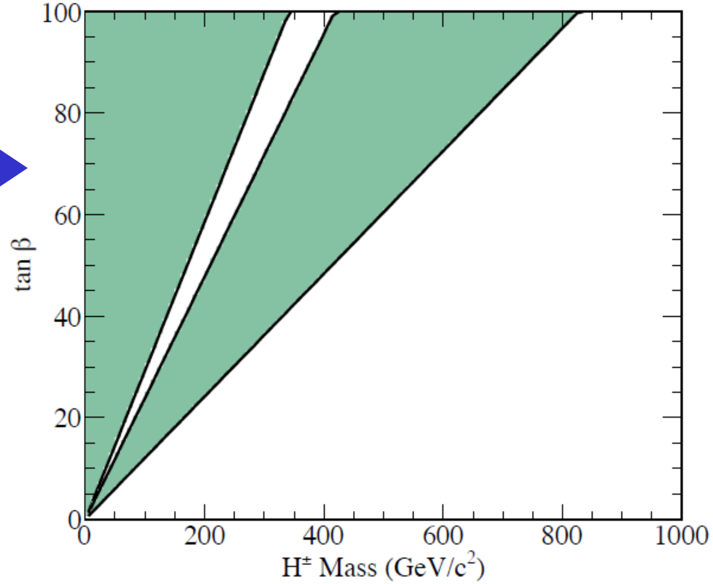
Measured value

$$r_H = \frac{BF(B \rightarrow \tau\nu)}{BF(B \rightarrow \tau\nu)_{SM}} = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

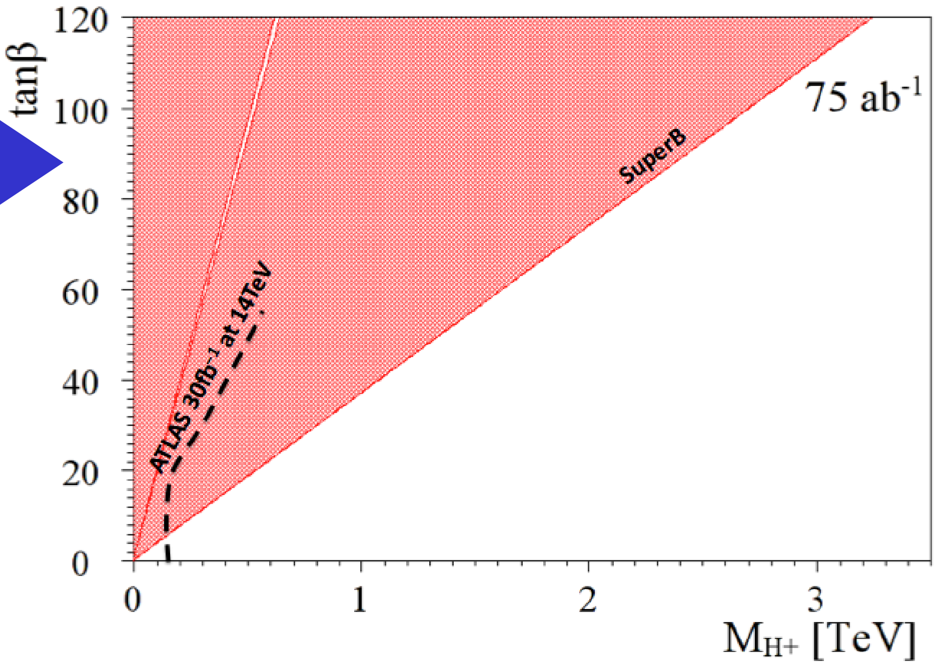
→ limit on charged Higgs mass vs. tanβ

(for type II 2HDM)

B factories: Exclusion plot

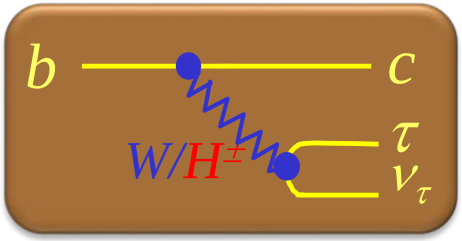


Super B factory: Discovery plot: very much competitive with LHC!

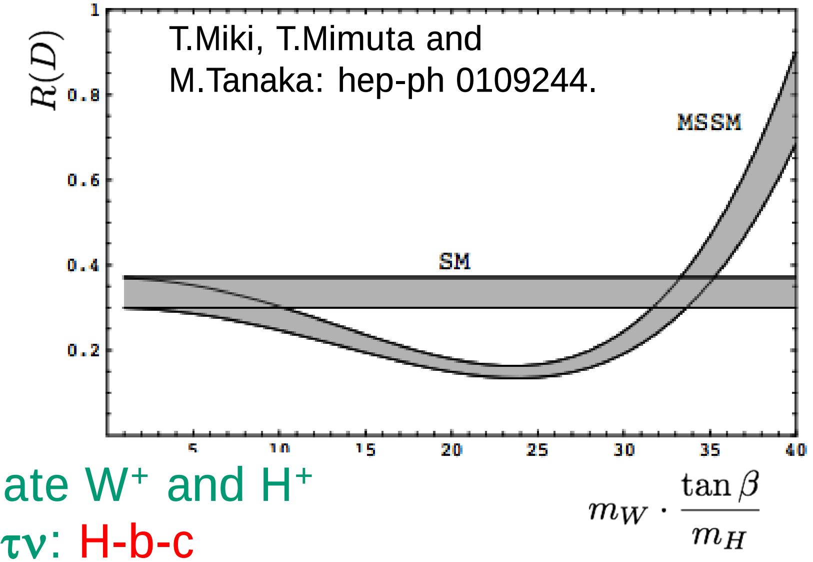


B → $D^{(*)}\tau\nu$ decays

Semileptonic decay sensitive to charged Higgs



$$R(D) \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}$$



T.Miki, T.Mimuta and M.Tanaka: hep-ph 0109244.

Complementary and competitive with B→τν

1.Smaller theoretical uncertainty of R(D)

2.Large Brs (~1%) in SM

3. Differential distributions can be used to discriminate W^+ and H^+
4. Sensitive to different vertex B→τ ν: H-b-u, B→Dτν: H-b-c

(LHC experiments sensitive to H-b-t)

First observation of B → $D^{*-}\tau\nu$ by Belle (2007)

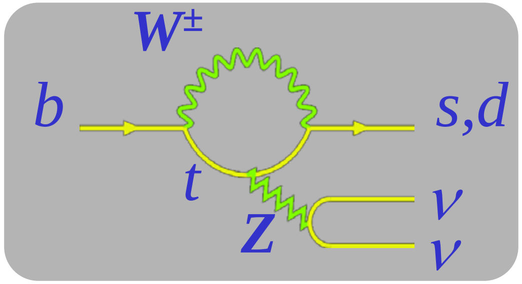
→ PRL 99, 191807 (2007)

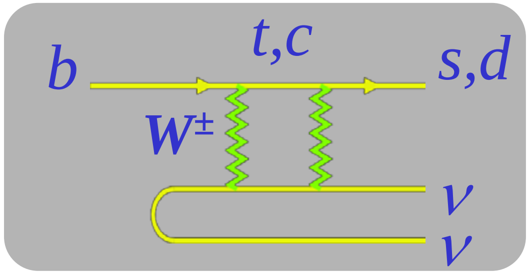
$B \rightarrow K^{(*)}\nu\bar{\nu}$

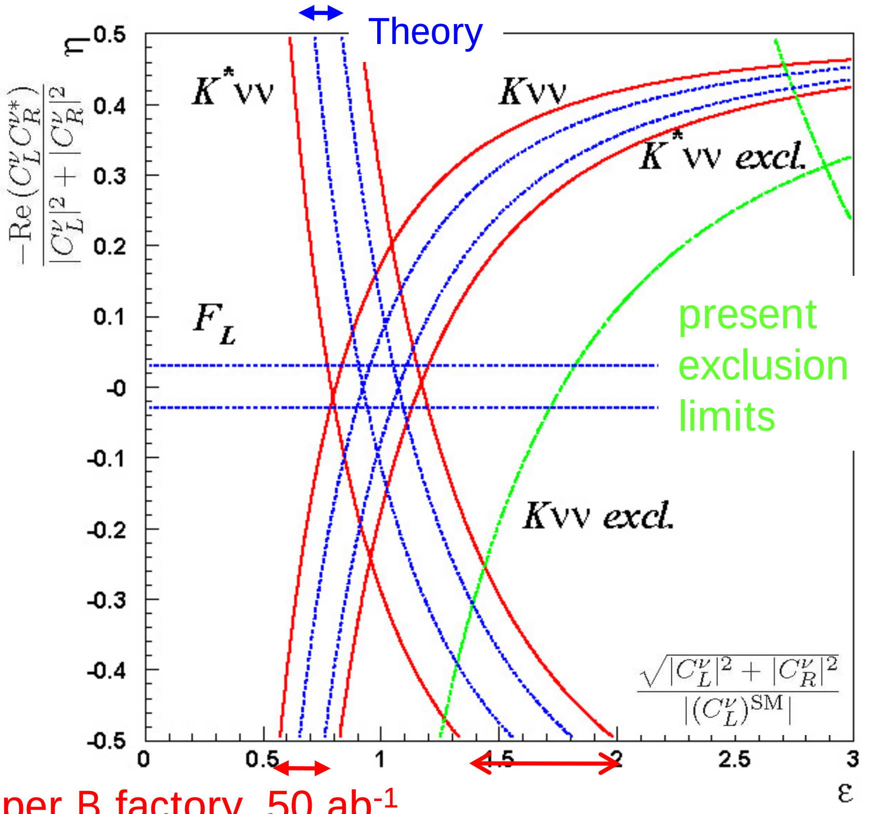
arXiv:1002.5012

adopted from W. Altmannshofer et al., JHEP 0904, 022 (2009)

SM: penguin + box diagrams



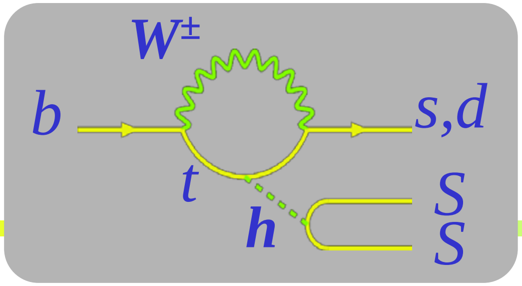


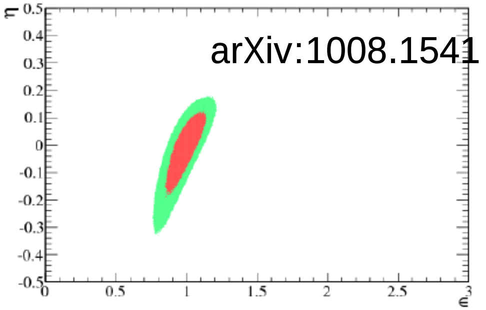


$B \rightarrow K\nu\nu$, $\mathcal{B} \sim 4{\cdot}10^{-6}$
$B \rightarrow K^*\nu\nu$, $\mathcal{B} \sim 6.8{\cdot}10^{-6}$

Look for deviations from the expected values → information on anomalous couplings C^ν_R and C^ν_L compared to $(C^\nu_L)^{SM}$

from, e.g.,

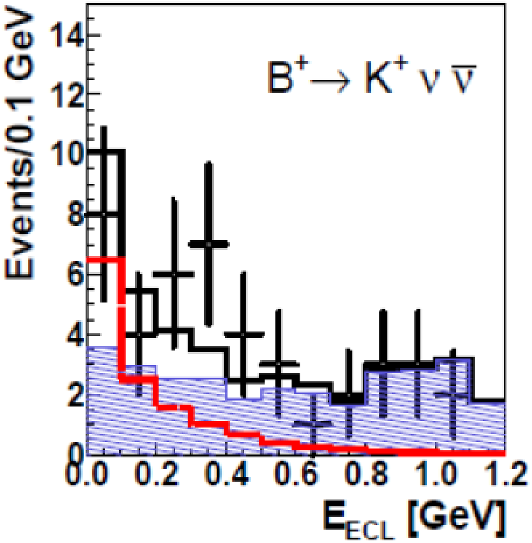




arXiv:1008.1541

$B \to h\nu\bar{\nu}$ decays

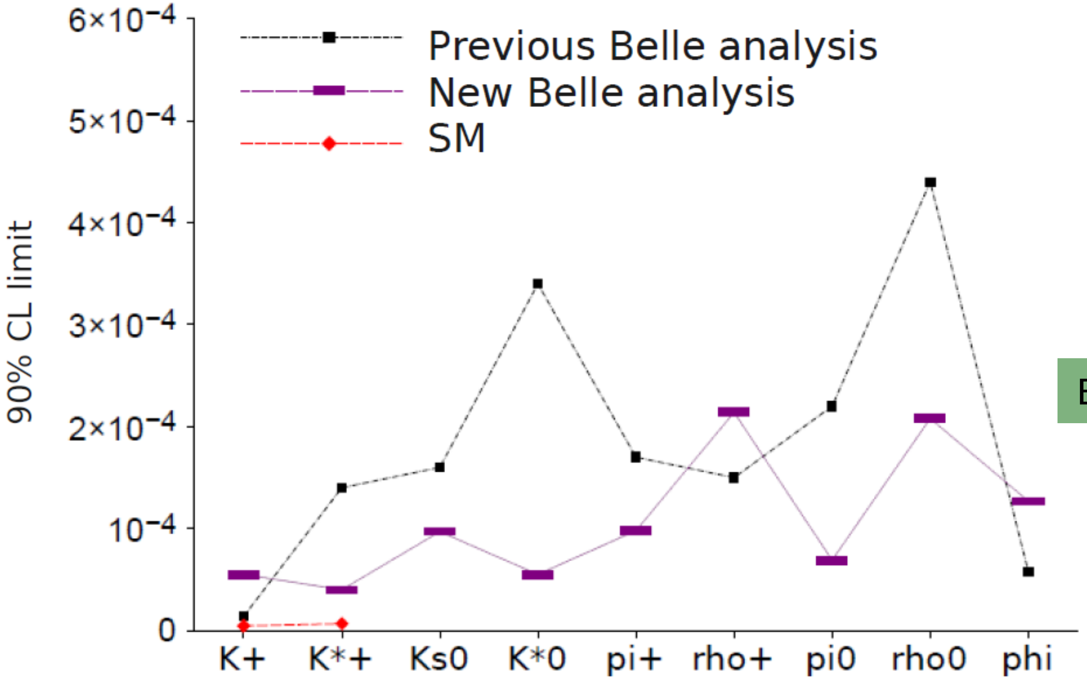
Method: again tag one B with full reconstruction, search for signal in the remaining energy in the calorimeter, at $E_{ECL} = 0$



$$N_{Sig} = 13.3^{+7.4}_{-6.6}(stat) \pm 2.3(syst)$$
$$S_{stat+syst} = 2.0\sigma$$

Belle, Phys. Rev. D 87, 111103(R) (2013)

Present status: recent update from Belle



Charm and τ physics

B factories = charm and τ factories

Charm and τ can be found in any "Y(nS) samples"

→ the integrated luminosity of the samples used for charm and τ studies is larger than for the B physics studies (Belle ~ 1 ab^{-1}, BaBar ~0.550 ab^{-1})

→ This will of course remain true for the super B factory

A few examples of the strengths of B factories:

- CP violation in charm at B factories (and super B factories) →can measure CPV separately in individual decay channels, $\pi^+\pi^-$, K^+K^-, $K_S\pi$,...
- $D\bar{D}$ pairs produced with very few light hadrons
- Full reconstruction of events →

Rare charm decays: tag with the other D

Again make use of the hermeticity of the apparatus!

Example: leptonic decays of D_s

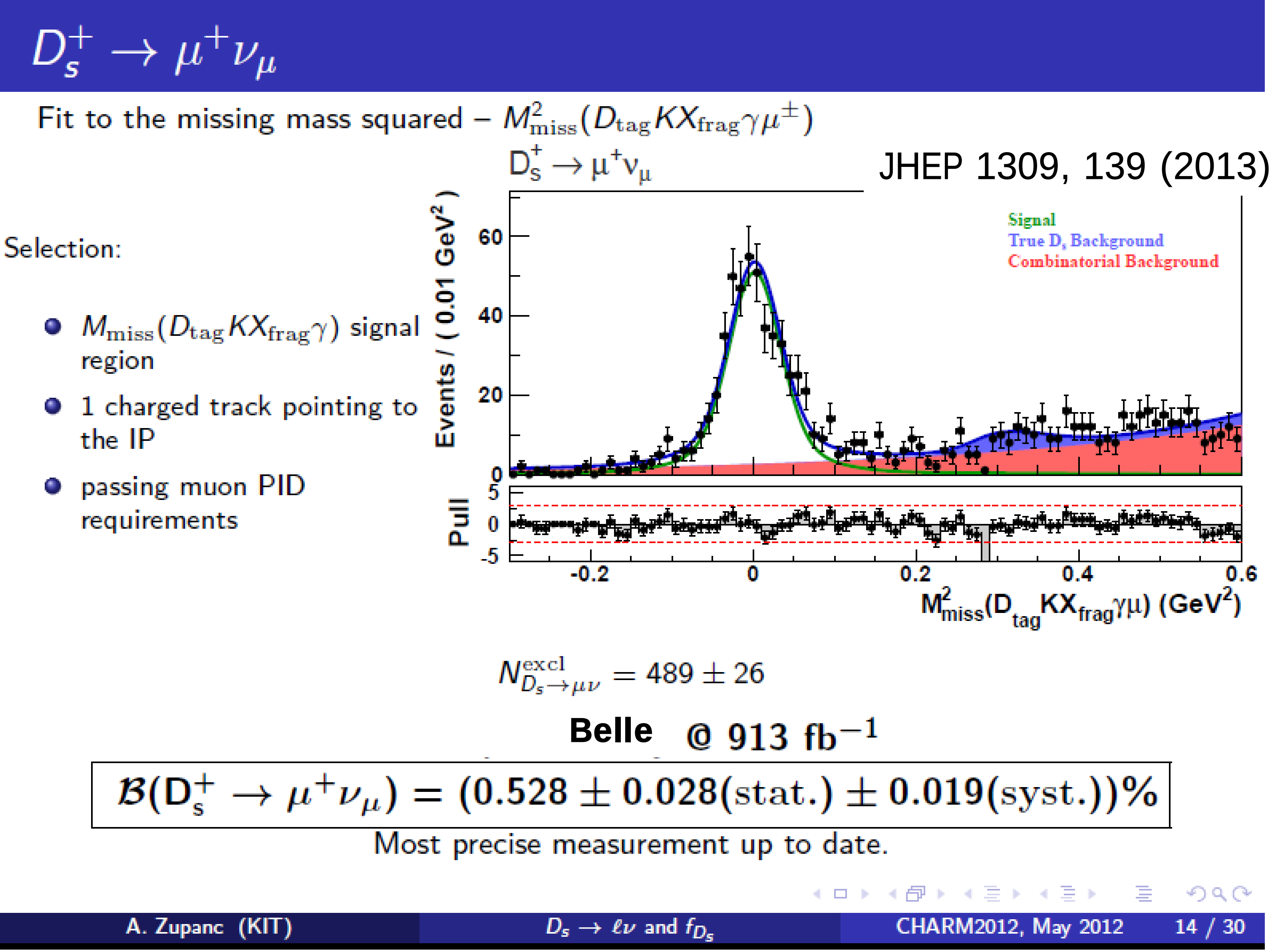
$$e^+e^- \to c\bar{c} \to \overline{D}_{\text{tag}} K X_{\text{frag}} D_s^{*+}$$

Recoil method in charm events:

- Reconstruct D_{tag} to tag charm, kaon to tag strangeness
- Additional light mesons (X_{frag}) can be produced in the fragmentation process (π, $\pi\pi$, ...)

2 step reconstruction:

- Inclusive reconstruction of D_s mesons for normalization (without any requirements upon D_s decay products)
- Within the inclusive D_s sample search for D_s decays
  - $D_s \to \mu\nu$: peak at $m_\nu^2 = 0$ in $M^2_{\text{miss}}(D_{\text{tag}} K X_{\text{frag}} \gamma \mu)$
  - $D_s \to \tau\nu$: peak towards 0 in extra energy in calorimeter



$D_s^+ \to \mu^+\nu_\mu$

Fit to the missing mass squared – $M^2_{\rm miss}(D_{\rm tag}KX_{\rm frag}\gamma\mu^\pm)$

Selection:

- $M_{\rm miss}(D_{\rm tag}KX_{\rm frag}\gamma)$ signal region
- 1 charged track pointing to the IP
- passing muon PID requirements

JHEP 1309, 139 (2013)

$$N^{\rm excl}_{D_s\to\mu\nu} = 489 \pm 26$$

Belle @ 913 $\rm fb^{-1}$

$$\boxed{\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.528 \pm 0.028(\text{stat.}) \pm 0.019(\text{syst.}))\%}$$

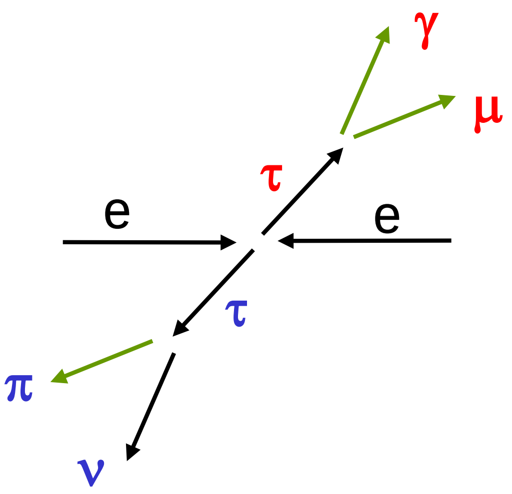
Most precise measurement up to date.

Extract f_{D_s} :

$$f_{D_s} = \frac{1}{G_F m_\ell \left(1 - \frac{m_\ell^2}{M_{D_s}^2}\right) |V_{cs}|} \sqrt{\frac{8\pi\mathcal{B}(D_s \to \ell\nu_\ell)}{M_{D_s}\tau_{D_s}}}$$

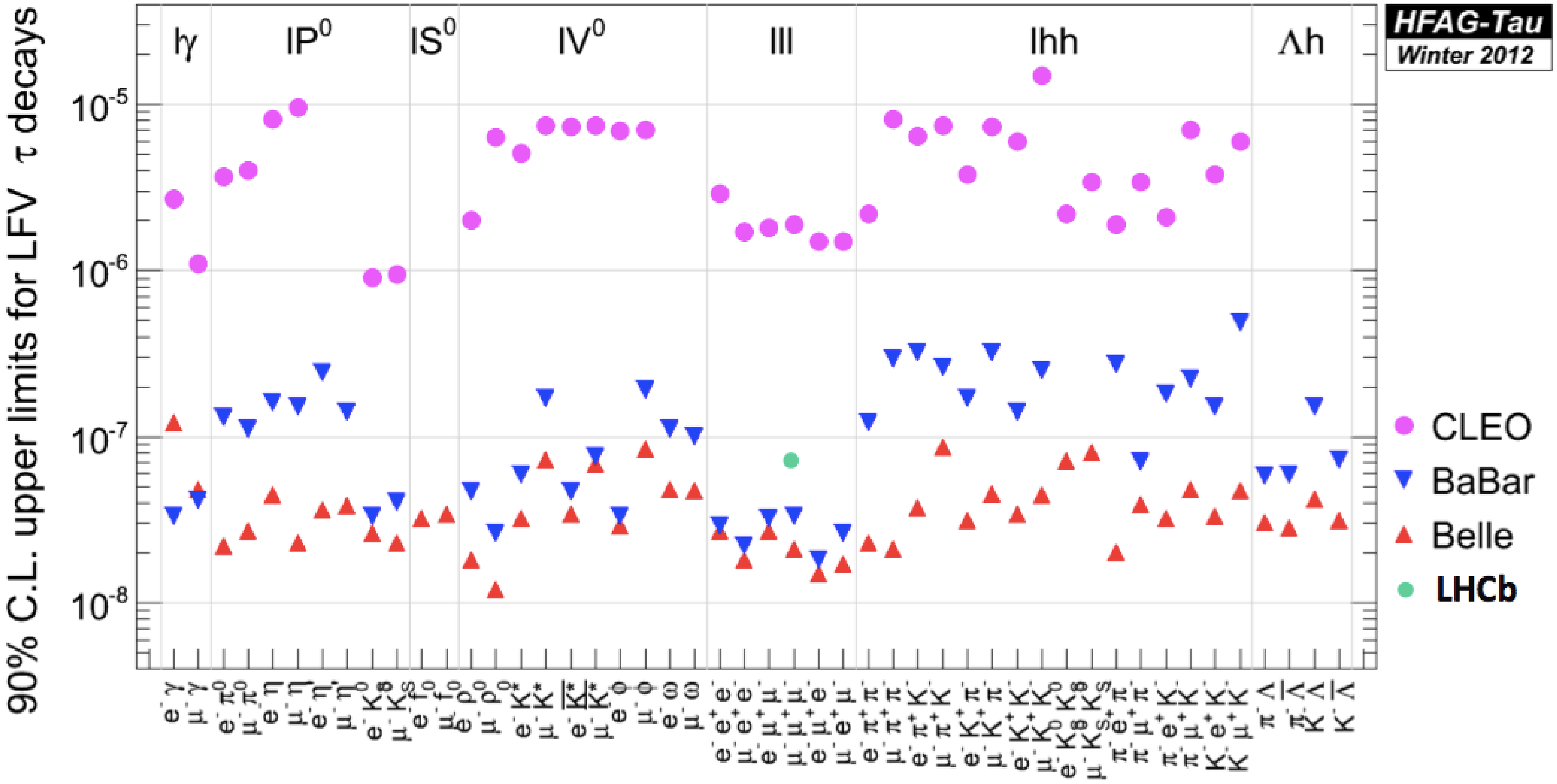
Rare τ decays

Example: lepton flavour violating decay $\tau \to \mu\,\gamma$



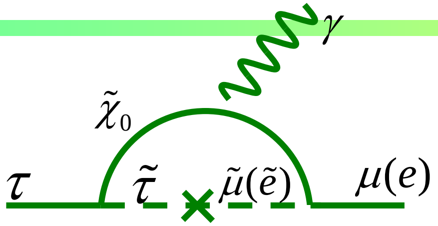
LFV in tau decays: present status

Lepton flavour violation (LFV) in tau decays: would be a clear sign of new physics



LFV and New Physics

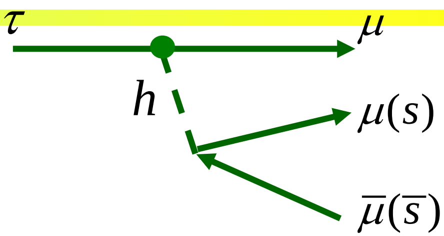
τ→lγ



- SUSY + Seasaw $(m^2_{\tilde{l}})_{23(13)}$
- Large LFV Br(τ→μγ)=O($10^{-7\sim9}$)

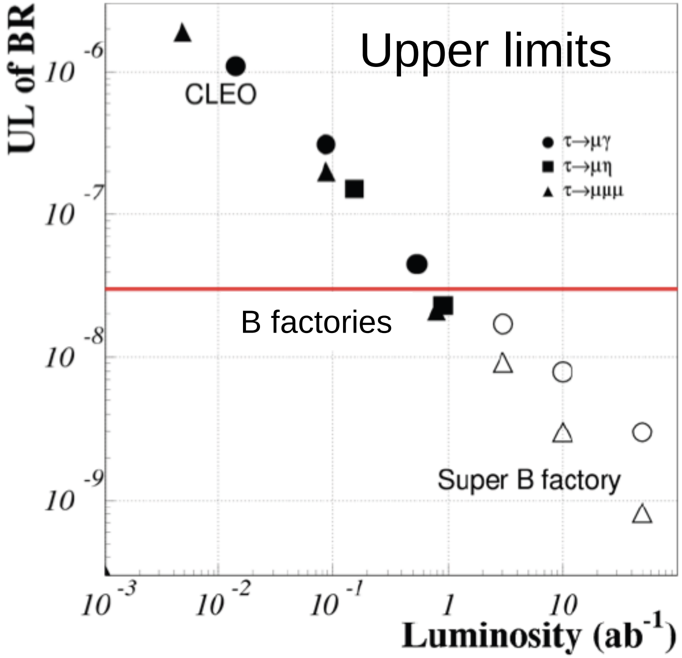
$$Br(\tau \to \mu\gamma) \simeq 10^{-6} \times \left(\frac{(m^2_{\tilde{L}})_{32}}{\bar{m}^2_{\tilde{L}}}\right)\left(\frac{1\,TeV}{m_{SUSY}}\right)^4 \tan^2\beta$$

τ→3l,lη



- Neutral Higgs mediated decay.
- Important when MSUSY >> EW scale.

$$Br(\tau \to 3\mu) = 4\times10^{-7} \times \left(\frac{(m^2_{\tilde{L}})_{32}}{\bar{m}^2_{\tilde{L}}}\right)\left(\frac{\tan\beta}{60}\right)^6\left(\frac{100GeV}{m_A}\right)^4$$



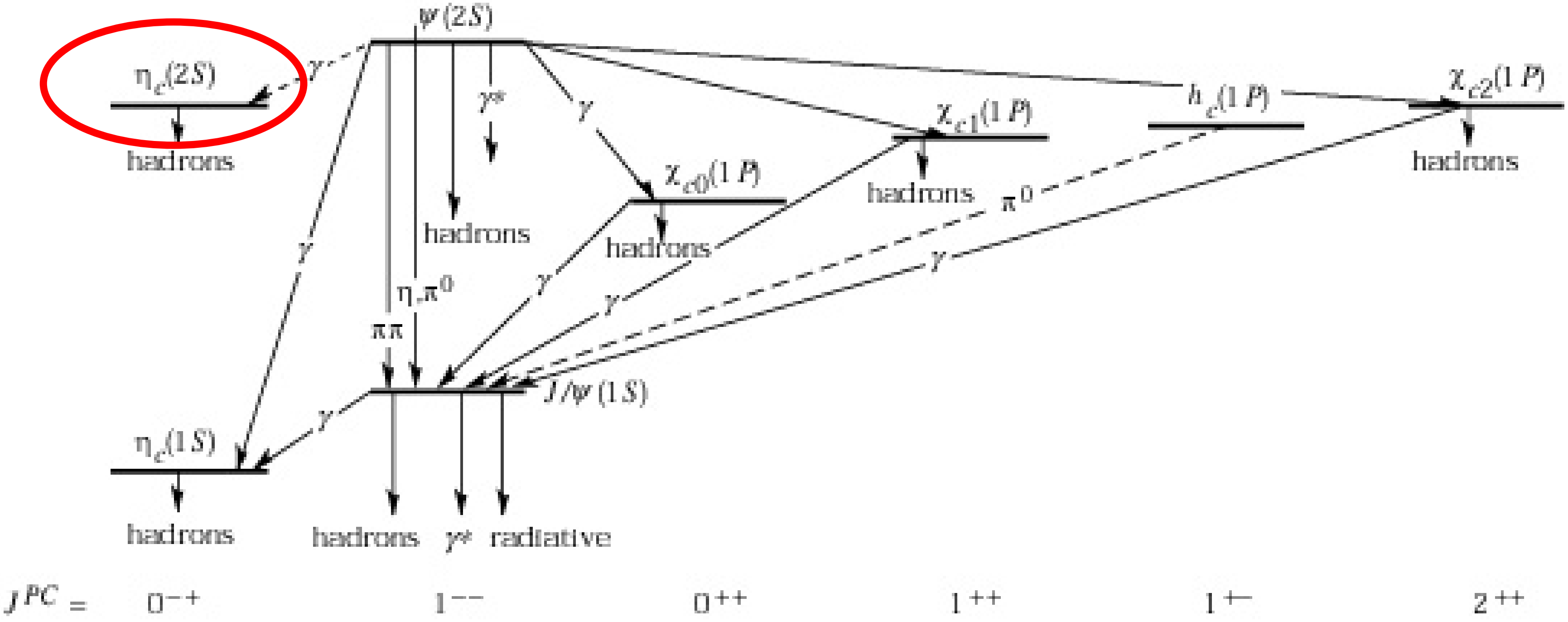
Integ. Lum.(ab^{-1})

model	Br(τ→μγ)	Br(τ→lll)
mSUGRA+seesaw	10^{-7}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-Universal Z’	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-7}

B factories and hadron spectroscopy

The series of discoveries started with the observation of the η_c' meson in $B \rightarrow K\ \eta_c'$ decays.

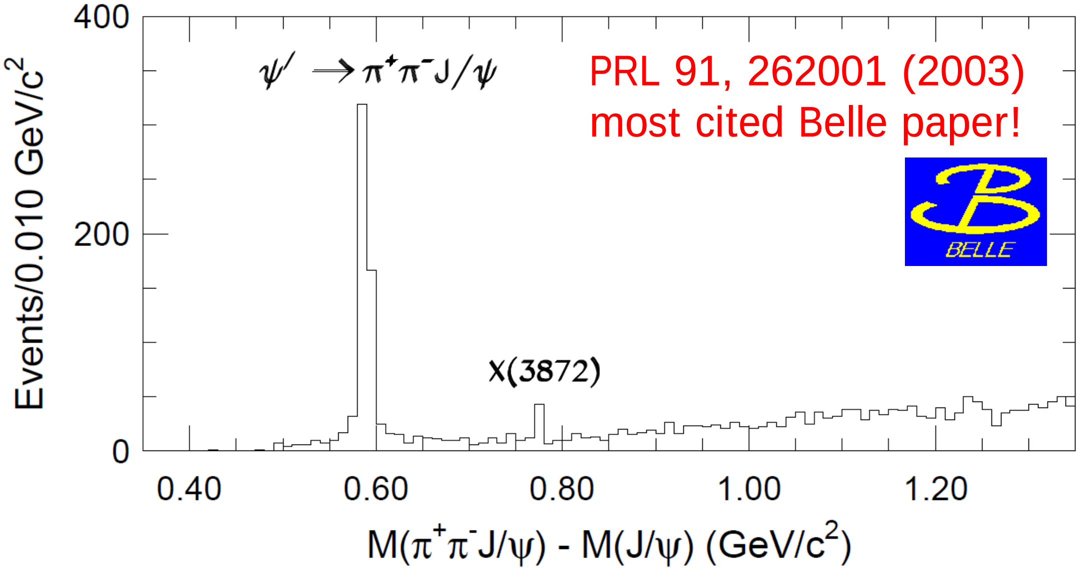
$\eta_c' = \eta_c(2S)$ the first radially excited state of para-charmonium



B factories and hadron spectroscopy

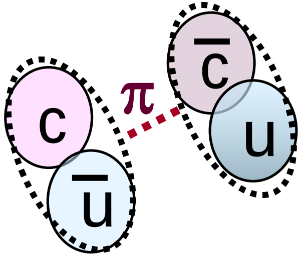
The series of discoveries started with the observation of the η_c' meson in B → K η_c' decays. →

The first exotic state was X(3872) – again found in B → K X(3872) decays

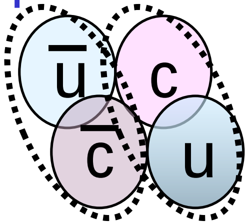


PRL 91, 262001 (2003)
most cited Belle paper!

Molecular state?

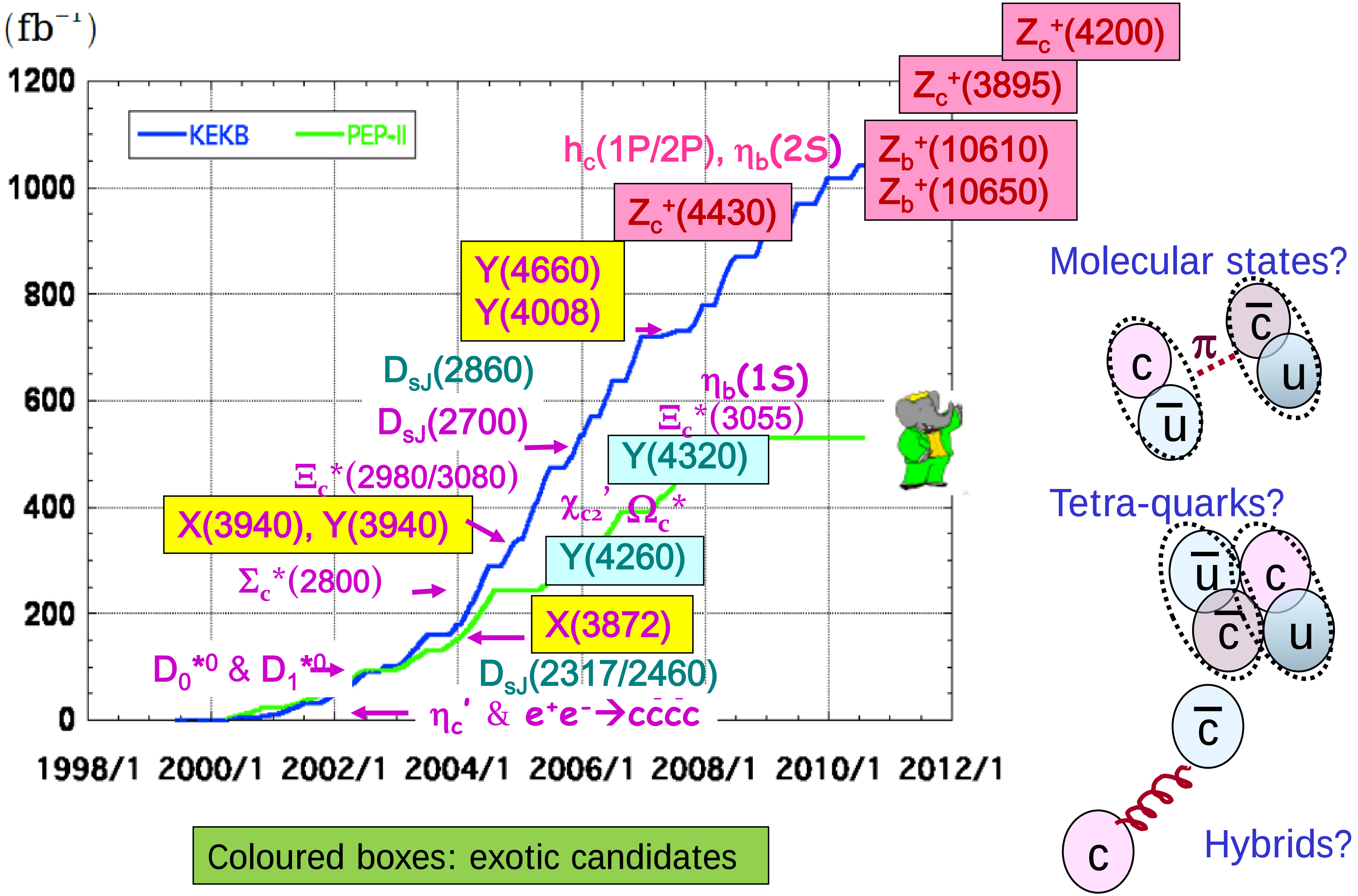


Tetra-quark?



It turned out that we have just opened a door to a gold mine!

New hadrons at B-factories



Molecular states?

Tetra-quarks?

Hybrids?

Coloured boxes: exotic candidates

Advantages in searches for new hadrons

Clean environment:

- Can look for new states in an inclusive way (e.g. $Y(5S) \to h_b\, \pi\, \pi$)

→

- Can reconstruct one resonance, look for the recoiling system (e.g. $e^+ e^- \to J/\psi + X$)

→

- Detection of gammas, π^0s

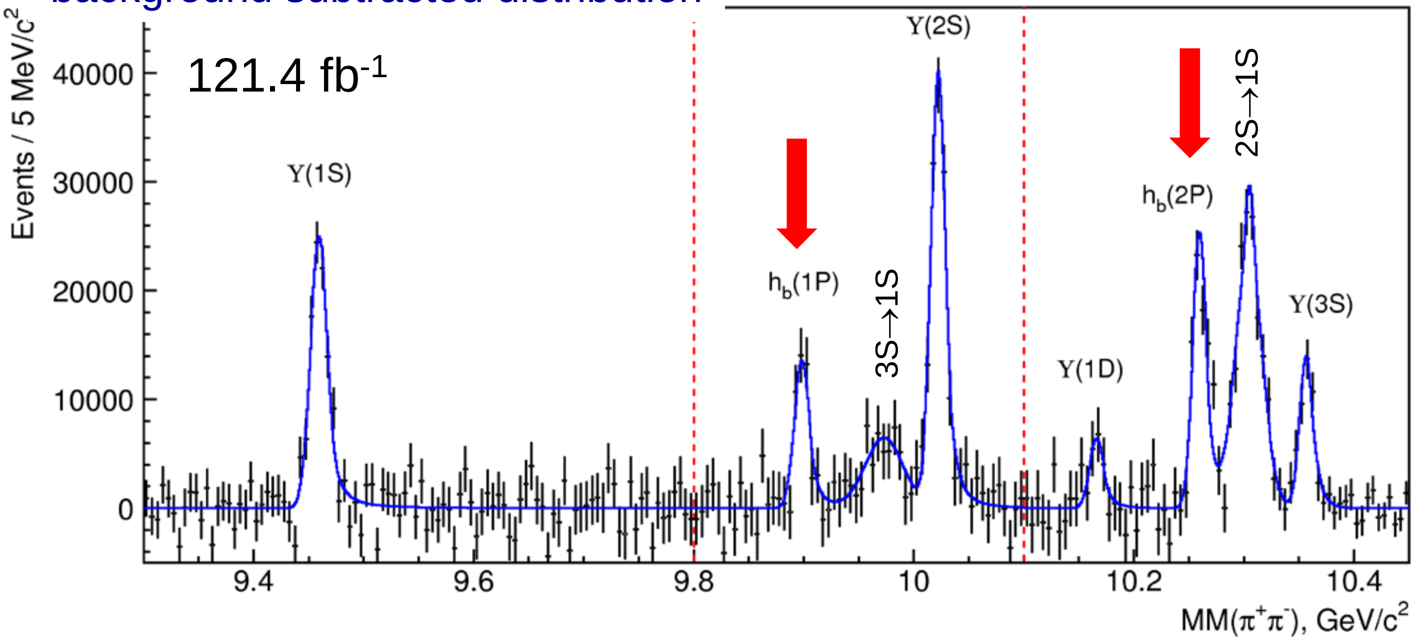
Observation of $h_b(nP)$ in $\Upsilon(5S)$ decays

$h_b(nP)$: $(b\bar{b})$, $S=0$, $L=1$, $J^{PC}=1^{+-}$

Inclusive search in $\boxed{\Upsilon(5S)} \rightarrow \boxed{\pi+\pi-}$ …. ← Only two charged pions used

$$MM(\pi+\pi-) = \sqrt{(P_{\Upsilon(5S)} - P_{\pi+\pi-})^2}$$

background subtracted distribution



Significance
w/ systematics

h_b(1P)	5.5σ
h_b(2P)	11.2σ

PRL108, 032001

h_b production is enhanced (despite of the spin flip between Υ(5S) and h_b)
→ the mechanism of production is exotic → look for resonances in **π h_b**

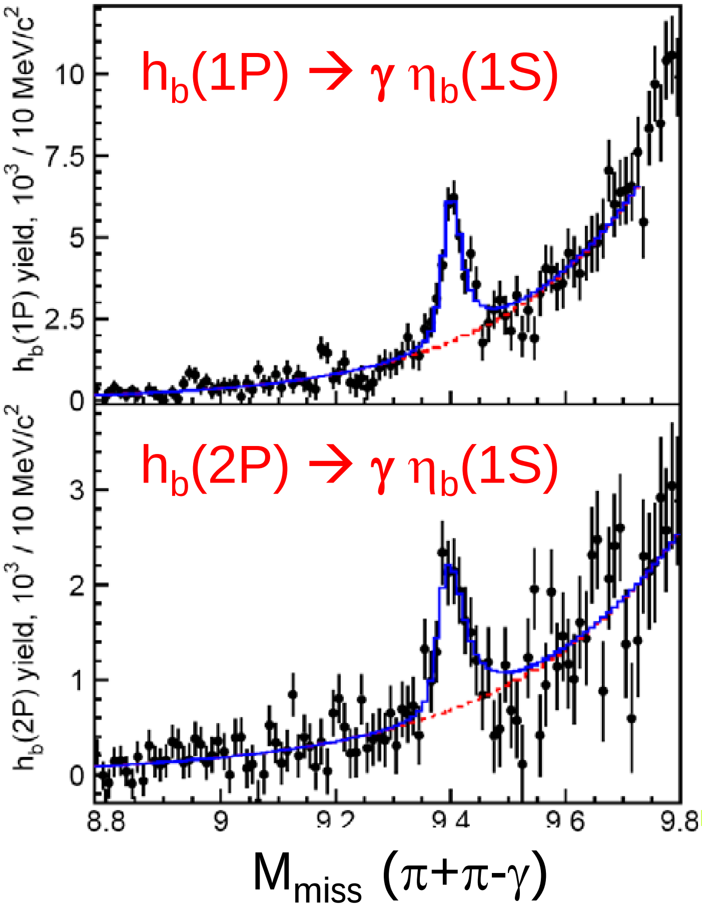
Observation of $\eta_b(nS)$ in h_b decays

Inclusive search in $\boxed{\Upsilon(5S)} \rightarrow \boxed{\pi^+\pi^- \gamma}$ ....

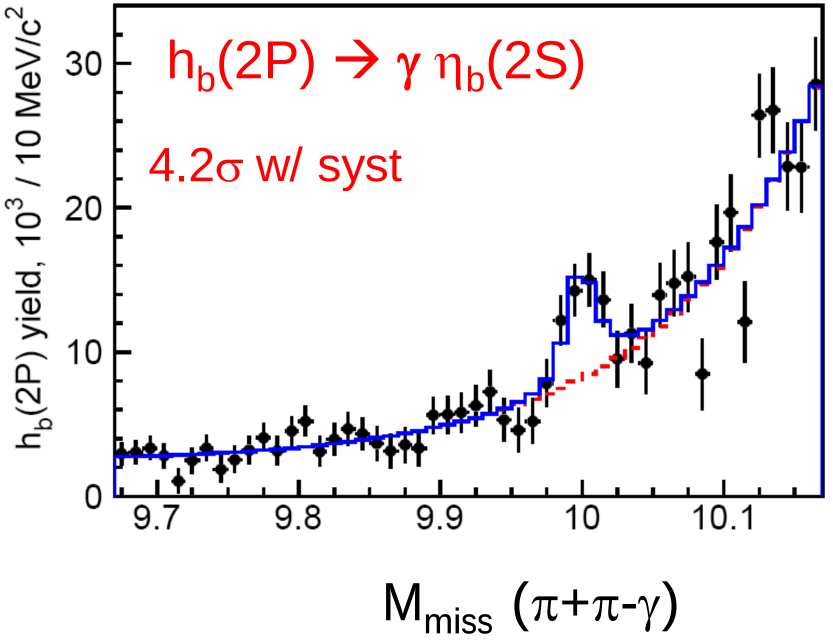
Use only two charged pions and a gamma

para-bottomonium
$\eta_b(nS)$: $(b\bar{b})$, S=0, L=0, $J^{PC}=0^{-+}$

$\Upsilon(5S) \rightarrow h_b(nP)\ \pi\ \pi$,
$h_b(nP) \rightarrow \gamma\ \eta_b(n'S)$

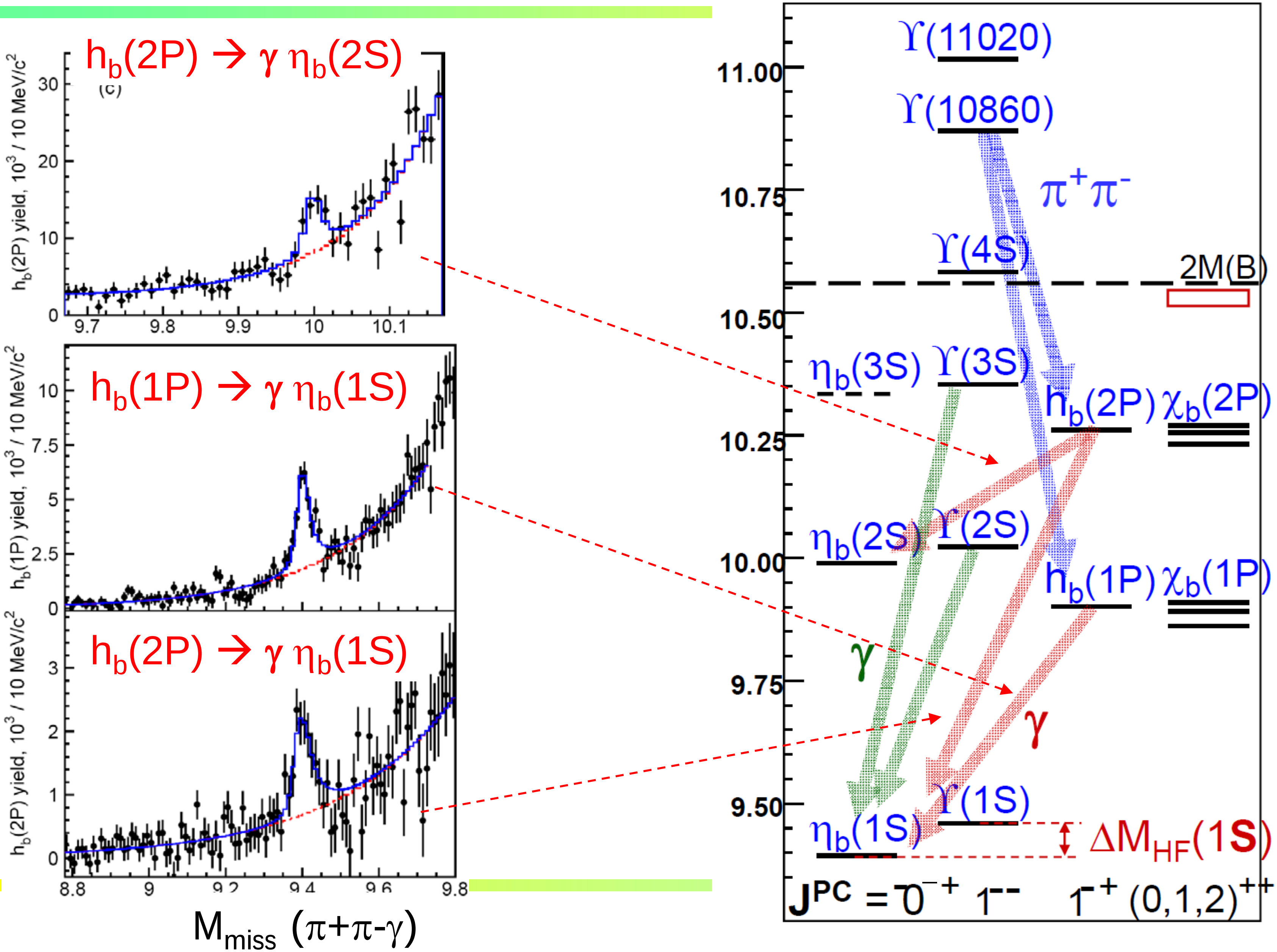


First evidence for $\eta_b(2S)$



Mizuk et al. Belle PRL 109 (2012) 232002

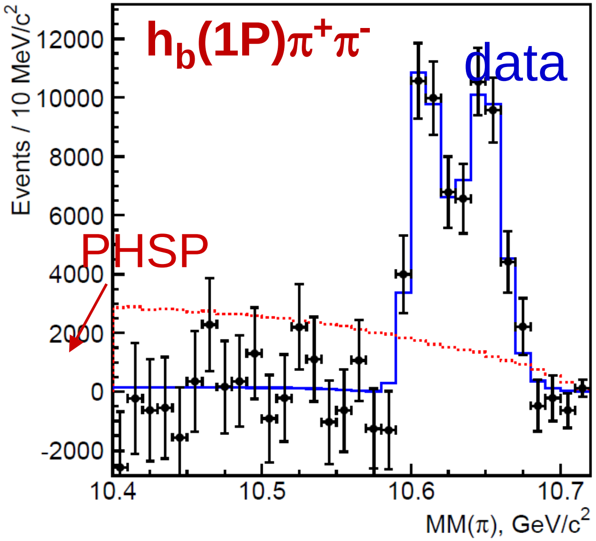
Observation of η_b(nS) in h_b decays



Observation of charged Z_b states: resonant substructure in $\Upsilon(5S) \rightarrow h_b(nP)\,\pi^+\pi^-$

Inclusive search in $M(h_b\pi^+) = MM(\pi^-)$

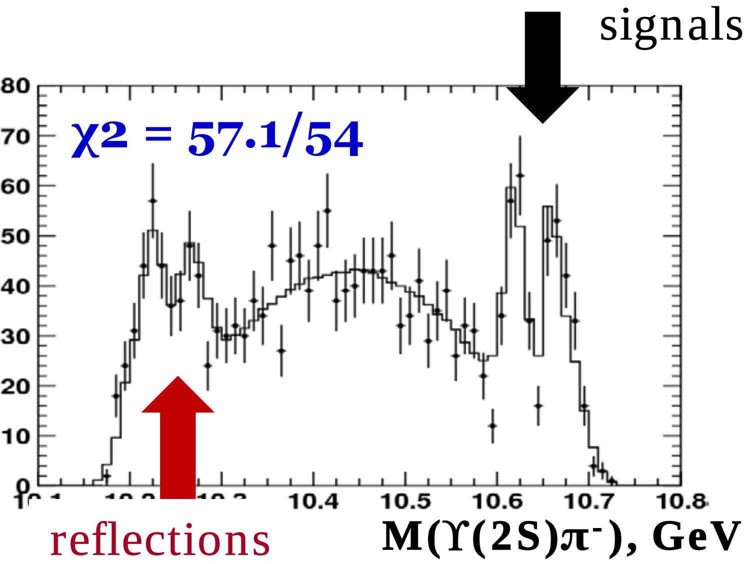
measure $\Upsilon(5S) \rightarrow h_b\pi\pi$ yield in bins of $MM(\pi)$



PRL 108, 122001 (2012)

Exclusive searches:

Observed in $\Upsilon(5S) \rightarrow$ **$\Upsilon(1S)$** $\pi+\pi-$, **$\Upsilon(2S)$** $\pi+\pi-$ and **$\Upsilon(3S)$** $\pi+\pi-$



$Z_b(10610)$	M = 10608.1 ± 1.7 MeV Γ = 15.5± 2.4 MeV
$Z_b(10650)$	M = 10653.3 ± 1.5 MeV Γ = 14.0 ± 2.8 MeV

Seen in 5 different final states, parameters are consistent

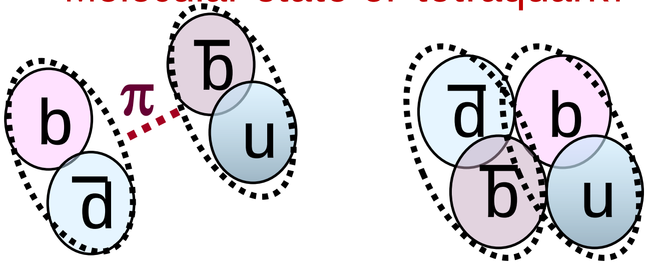
$J^P=1^+$ in agreement with data; other J^P are excluded

PRD 91, 072003 (R) (2015)

Z_b^+ properties

Must be an exotic state (a charged bottomonium-like state must at least have the $b\bar{b}u\bar{d}$ content)

Molecular state or tetraquark?



- $Z_b^+(10610)$: mass very close to the BB* threshold
- $Z_b^+(10650)$: mass very close to the B*B* threshold

Analysis of angular distributions suggests $J^P=1^+$ for both states.

Observation of dominant Z_b decays to BB* and B*B*

- $Z_b^+(10610) \to BB^*$, BR = (82.6 +- 3.7)%
- $Z_b^+(10650) \to B^*B^*$, BR = (70.6 +- 8.6)%   arXiv:1512.07419 (submitted to PRL)

consistent with a molecular nature of the charged bottomonia (Bondar, Garmash, Milstein, Mizuk, Voloshin, PRD84 054010)

Observation of a neutral partner of Z(10610) in

- $Z_b^0 \to \Upsilon \pi^0$ decays with 6.5 sigma significance

PRD 88, 052016 (2013)   (arXiv:1308.2646)

Charmonium-like vs bottomonium like

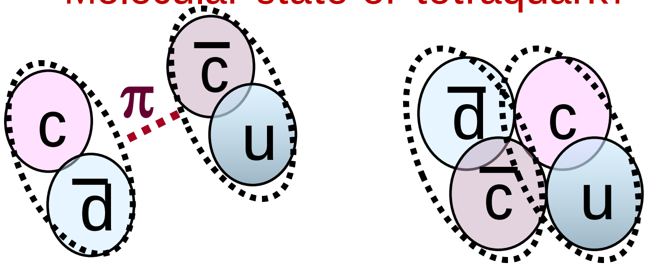
Interesting to compare the observed exotic charmonium-like states with bottomonium-like states.

If the molecular interpretation is right, the spectra close to the open charm and beauty thresholds should be similar.

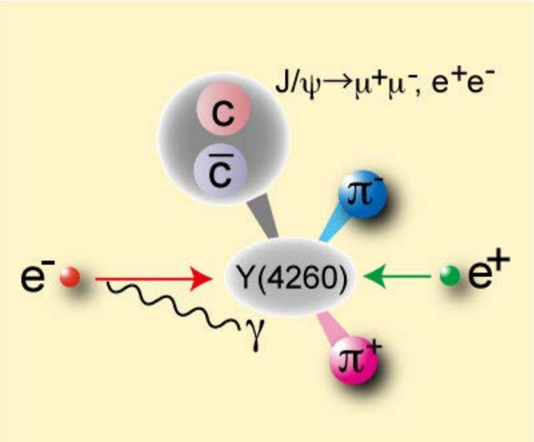
→ Investigate charged charmonia

... again have to be exotic (such a state must at least have the $c\bar{c}u\bar{d}$ content)

Molecular state or tetraquark?

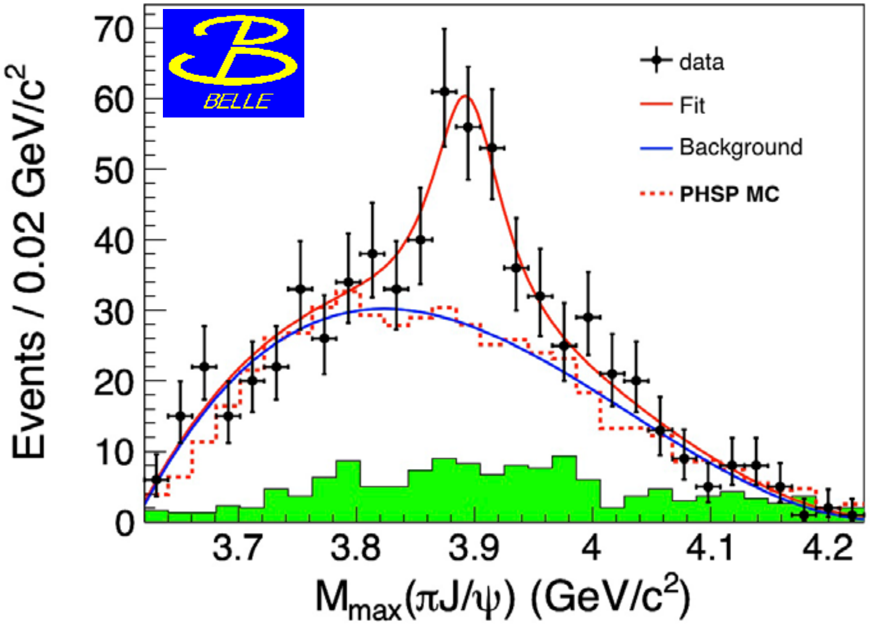


Charged charmonium in Y(4260) → $J/\psi\ \pi^+\pi^-$



Y(4260) produced via ISR (Initial State Radiation)

Look for a resonance in $J/\psi\ \pi^+$



Found! → $Z_c^+(3895)$

PRL110, 252002 (2013)

Observed also by BES III.
They also found a peak in $(DD^*)^+$ at 3885 MeV
PRL110, 252001 (2013)
PRL112, 022001 (2014)

very similar to
$\Upsilon(5S) \to Z_b^+\ \pi^- \to \Upsilon(1s)\ \pi^+\ \pi^-$

Several more states, no time to discuss...

Charged charmonia in B → charmonium + π + K

More charged charmonium-like states!

B → K X: an excellent tool for production of charmonia and charmoniumlike states; essential in observation of η_c' and X(3872)

Belle observed 4 charged peaks in B decays to charmonium + π + K

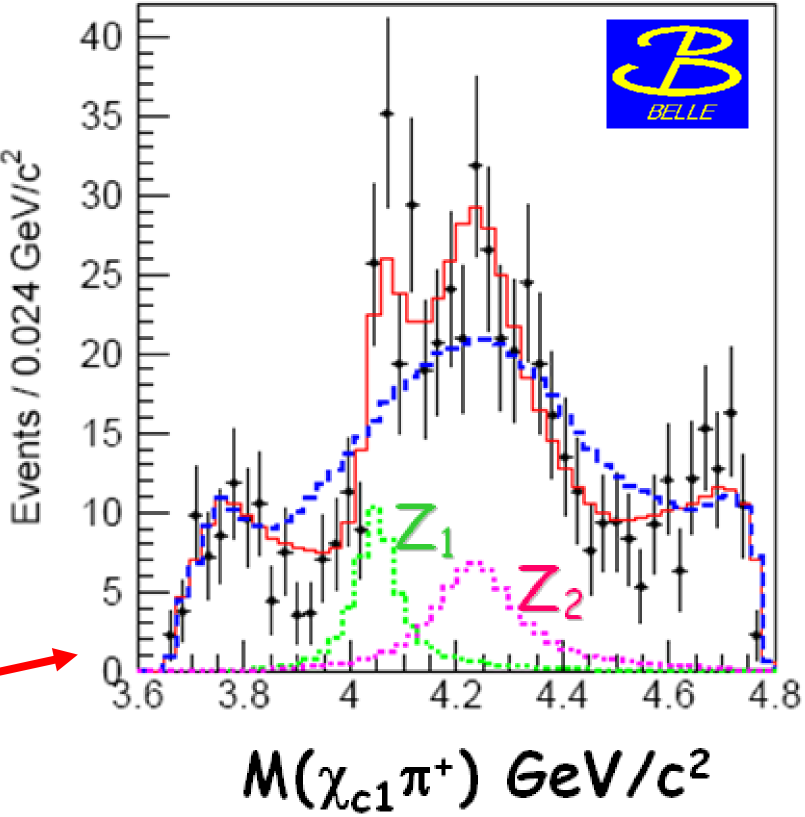
cc=J/Ψ → $Z_c^+(4200)$

cc=Ψ' → $Z_c^+(4430)$

cc=χ_{c1} → $Z_c^+(4050)$, $Z_c^+(4250)$

=Z_1 =Z_2

$Z_c^+(4430)$ confirmed by LHCb.



R. Mizuk et al. (Belle) PRD 78, 072004

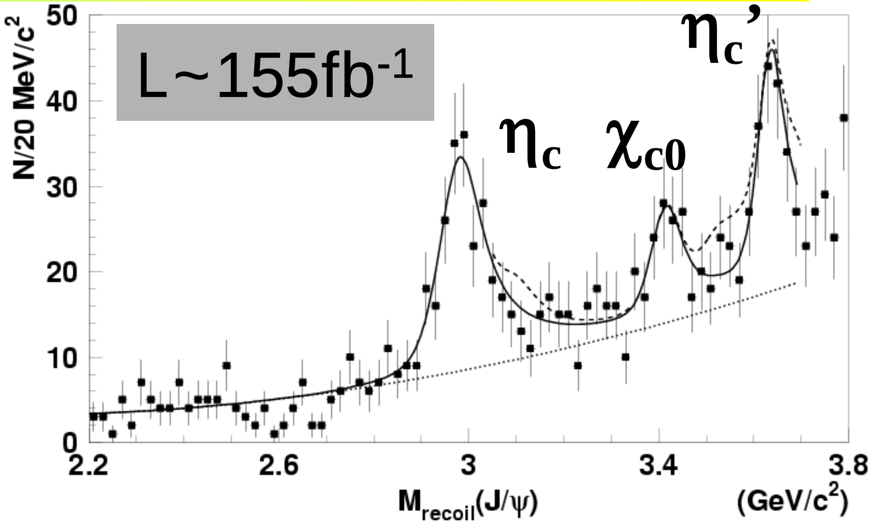
J/ψ recoil method

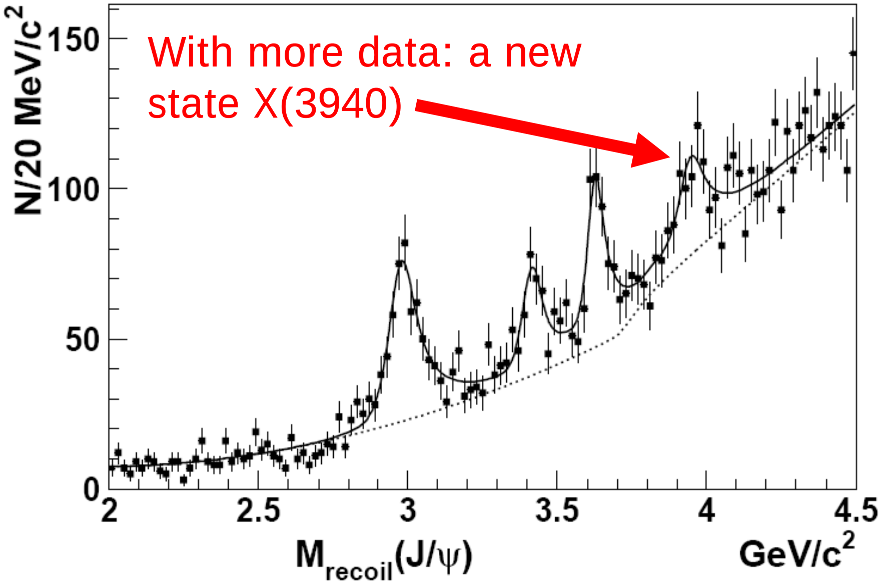
The idea: reconstruct J/ψ, calculate the mass of the recoiling system.

First used in the discovery of an unexpectedly large double charmonium production in $e^+e^- \rightarrow c\bar{c}c\bar{c}$

In the recoil mass spectrum, Belle observed the peaks of charmonium C=0 states and discovered X(3940).

This reaction challenged our understanding of perturbative QCD. Leading order prediction was O(0.1) of the observed value. NLO calculations 'almost' solved the discrepancy.





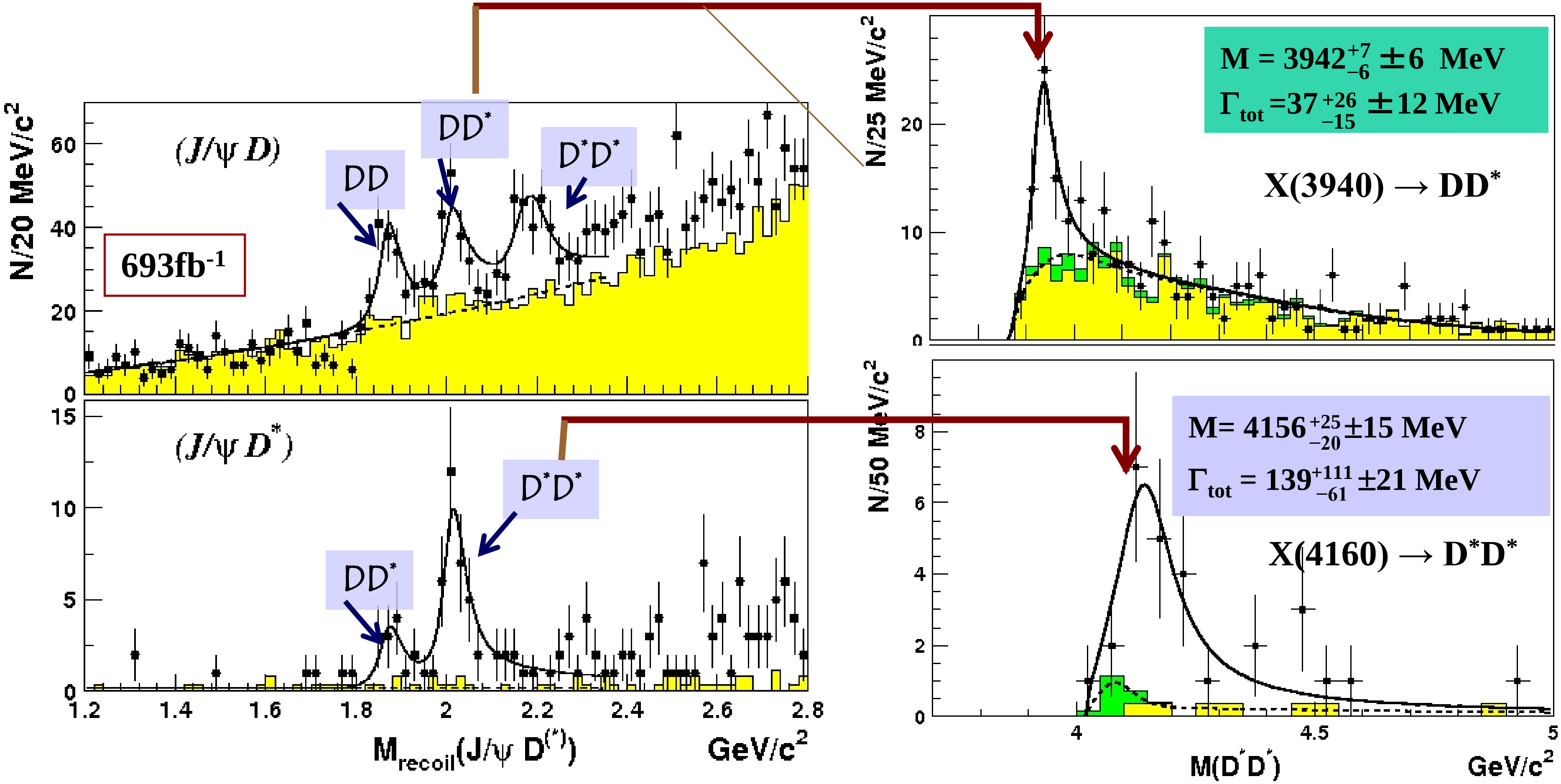
With more data: a new state X(3940)

N.B. Such a study can only be done at a B factory!

$e^+e^- \to J/\psi\ D^{(*)}\ D^{(*)}$

Reconstruct J/ψ and D or D*, calculate the mass of the recoiling system.

→ Confirmed X(3940) and found one more state at 4156 MeV.



Future prospects at Belle-II: Full reconstruction of χ_c or η_c will allow to exploit the recoil technique and scan the charmonium(-like) C=-1 states.

What next?

Next generation: Super B factories → Looking for New Physics

→ Need much more data (almost two orders!)

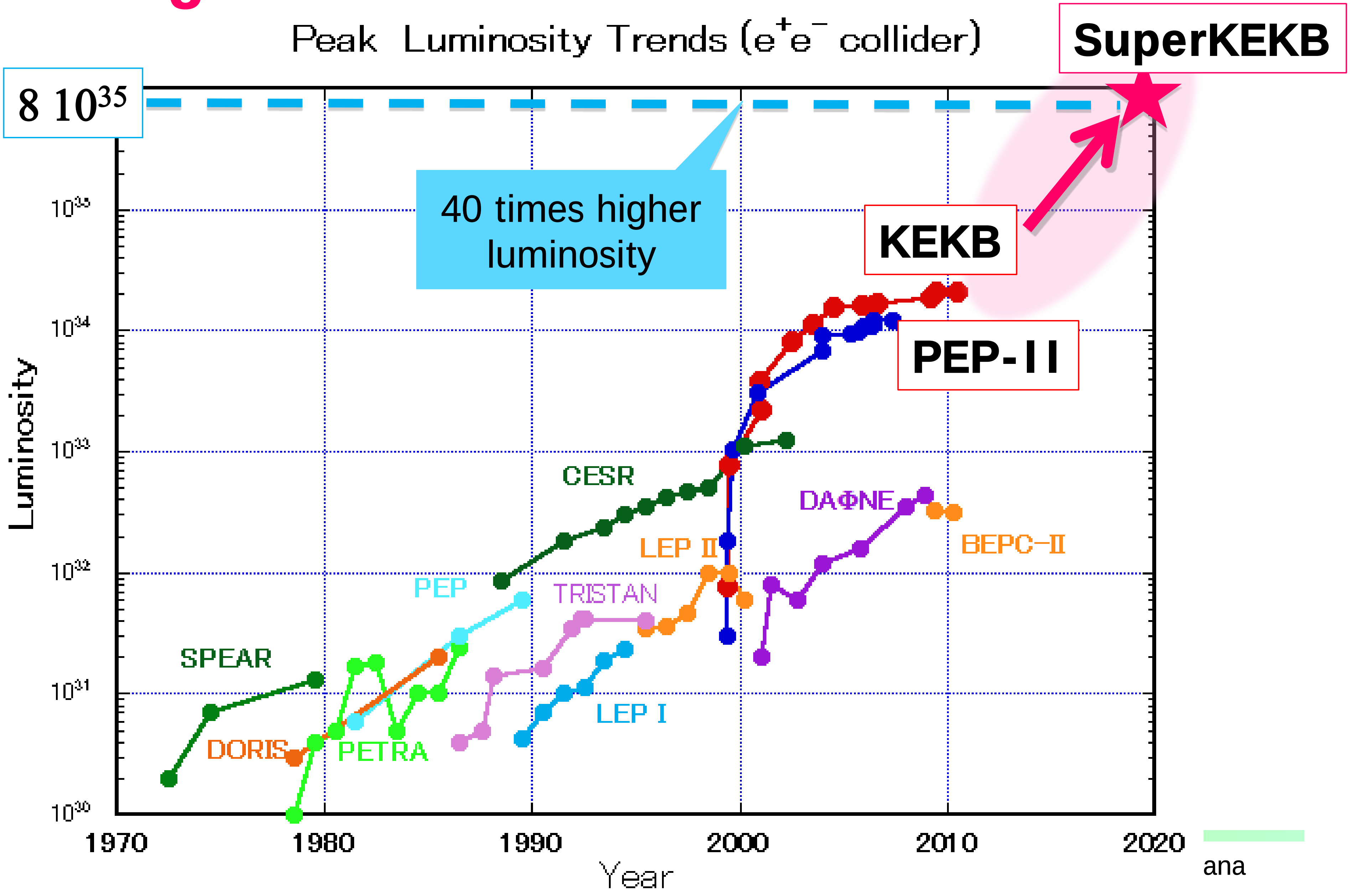
Super B factory: also an excellent tool for studies of exotic hadrons

A new feature: very strong competition from LHCb and BESIII

Still, e^+e^- machines running at (or near) Υ(4s) will have considerable advantages in several classes of measurements, and will be complementary in many more

→ Physics at Super B Factory, arXiv:1002.5012 (Belle II)
→ SuperB Progress Reports: Physics, arXiv:1008.1541 (SuperB)

Need O(100x) more data →Next generation B-factories



8 10^{35}

SuperKEKB

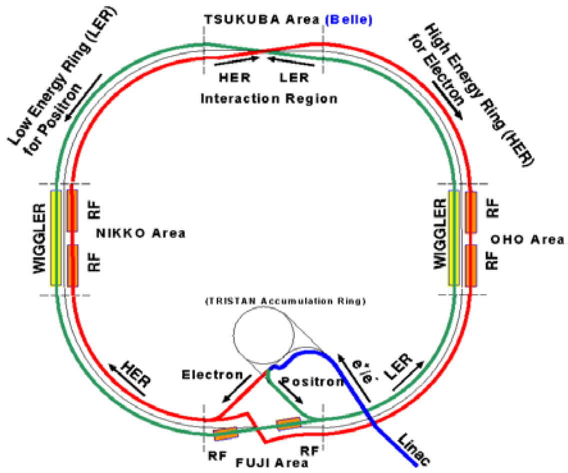
40 times higher luminosity

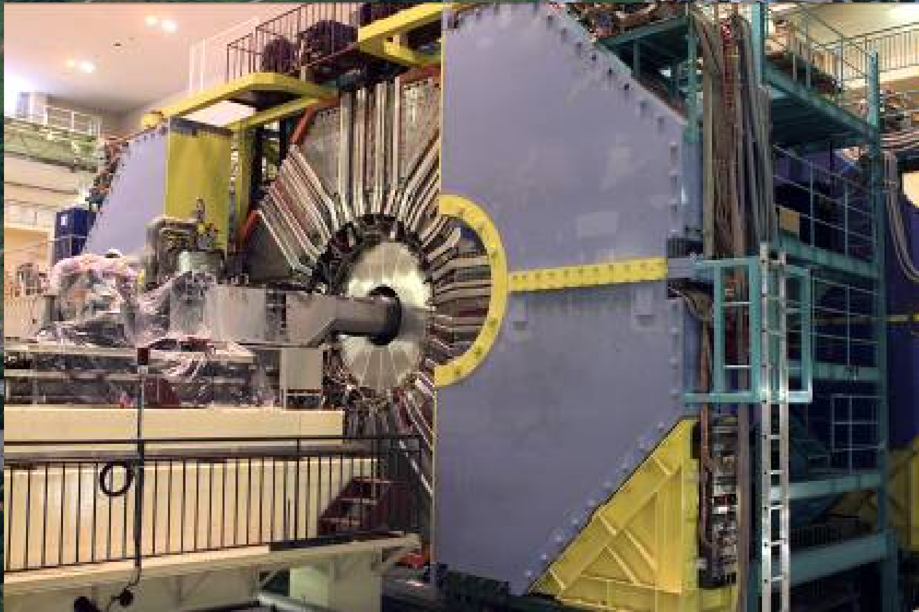
KEKB

PEP-II

How to do it?
→ upgrade the existing KEKB and Belle facility

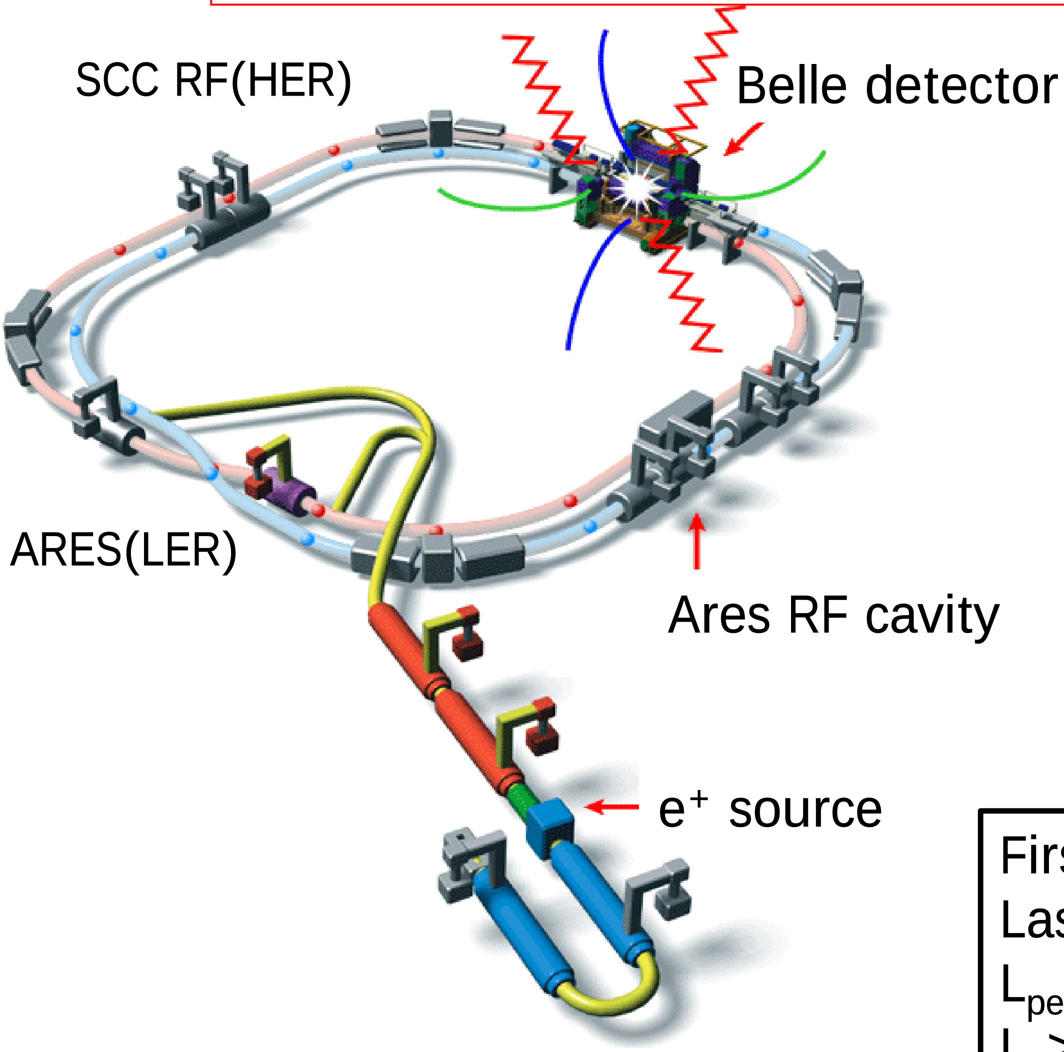
KEKB → SuperKEKB
Belle → Belle II





The KEKB Collider

Fantastic performance far beyond design values!



- e^- (8 GeV) on e^+(3.5 GeV)
  - $\sqrt{s} \approx m_{\Upsilon(4S)}$
  - Lorentz boost: $\beta\gamma=0.425$
- 22 mrad crossing angle

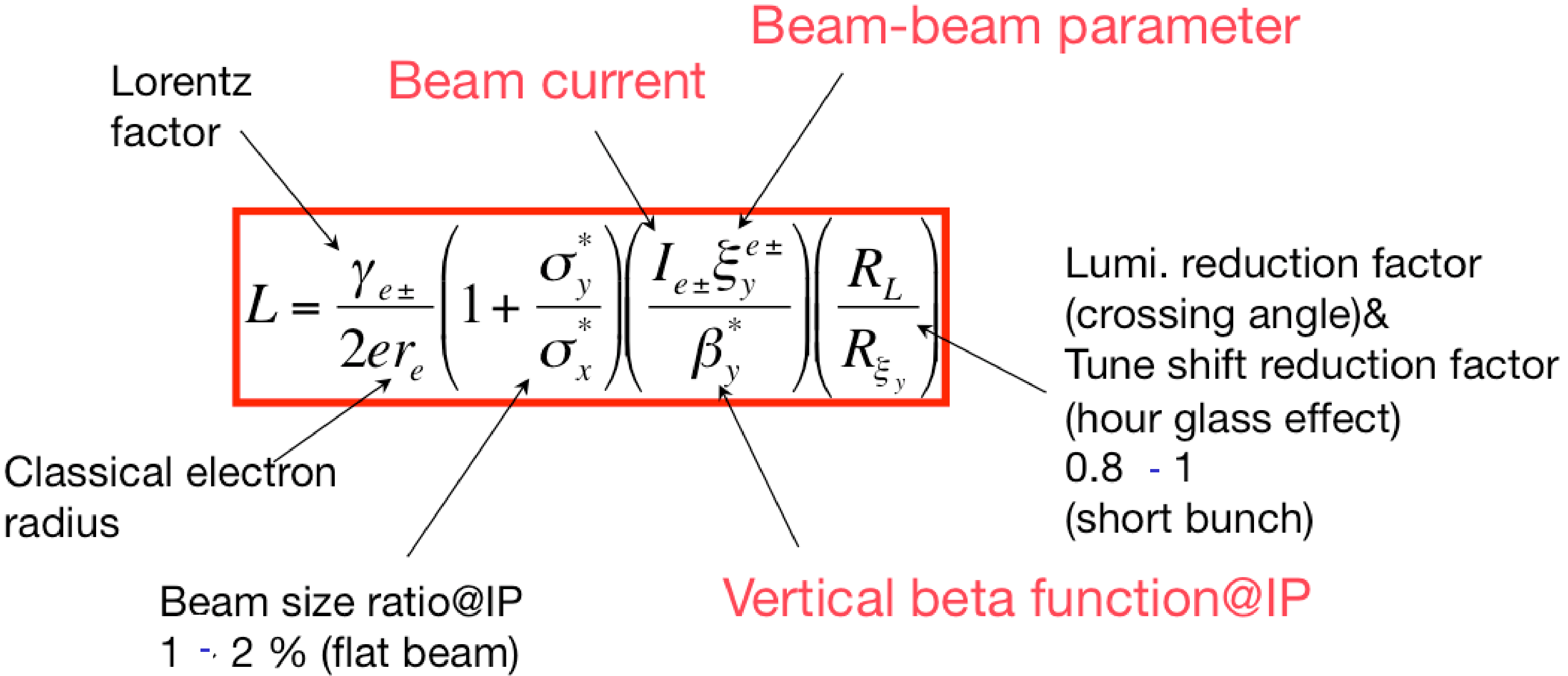
Peak luminosity (WR!) :

2. 1 x 10^{34} $cm^{-2}s^{-1}$

=2x design value

First physics run on June 2, 1999
Last physics run on June 30, 2010
L_{peak} = 2.1x10^{34}/cm^2/s
L > $1ab^{-1}$

How to increase the luminosity?



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

Lorentz factor

Beam current

Beam-beam parameter

Classical electron radius

Beam size ratio@IP
1 - 2 % (flat beam)

Vertical beta function@IP

Lumi. reduction factor
(crossing angle)&
Tune shift reduction factor
(hour glass effect)
0.8 - 1
(short bunch)

(1) Smaller β_y^*

(2) Increase beam currents

(3) Increase ξ_y

"Nano-Beam" scheme

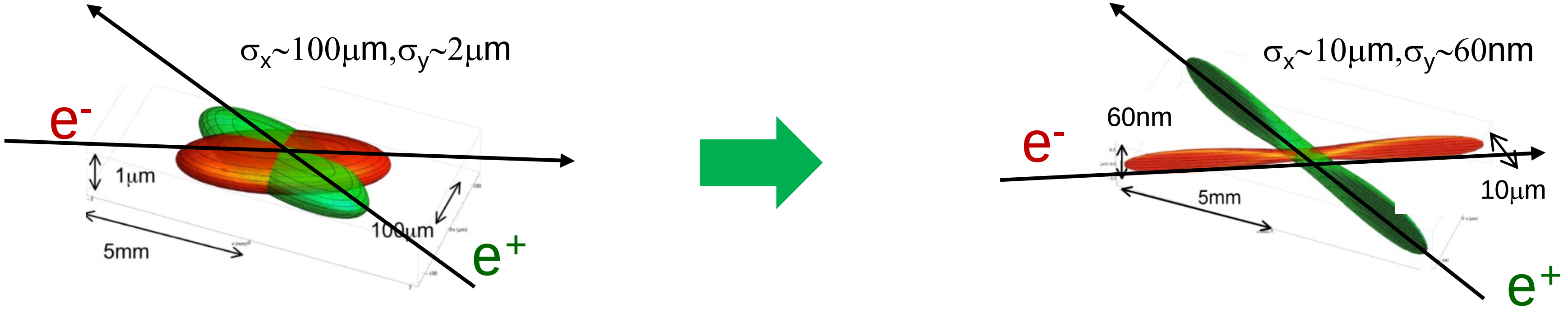
Collision with very small spot-size beams

Invented by Pantaleo Raimondi for SuperB

How big is a nano-beam ?

How to go from an excellent accelerator with world record performance – KEKB – to a 40x times better, more intense facility?

In KEKB, colliding electron and positron beams are much thinner than a human hair…



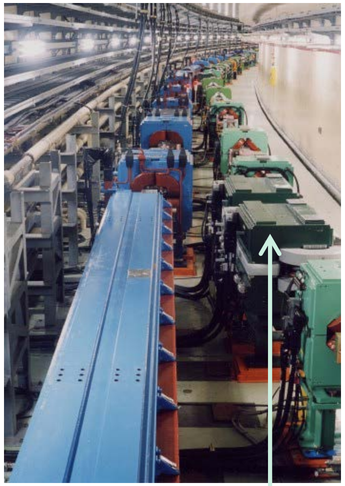
… For a 40x increase in intensity you have to make the beam as thin as a few x100 atomic layers!

Machine design parameters

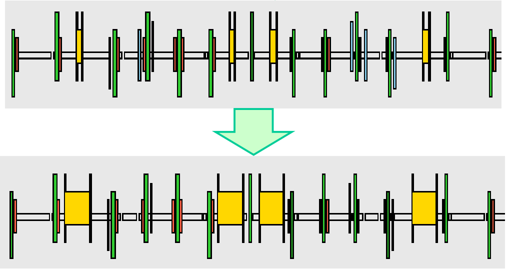
parameters		KEKB		**SuperKEKB**		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7	GeV
Half crossing angle	φ	11		41.5		mrad
Horizontal emittance	ε_x	18	24	3.2	4.6	nm
Emittance ratio	κ	0.88	0.66	0.37	0.40	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
Beam currents	I_b	1.64	1.19	3.60	2.60	A
beam-beam parameter	ξ_y	0.129	0.090	0.0881	0.0807	
Luminosity	**L**	**2.1 x 10^{34}**		**8 x 10^{35}**		**$cm^{-2}s^{-1}$**

- **Nano-beams and a factor of two more beam current** to increase luminosity
- **Large crossing angle**
- **Change beam energies** to solve the problem of short lifetime for the LER

KEKB → SuperKEKB

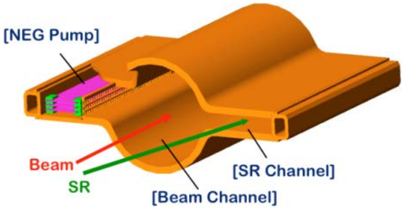


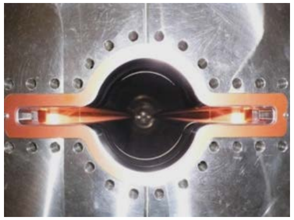
Replace short dipoles with longer ones (LER)

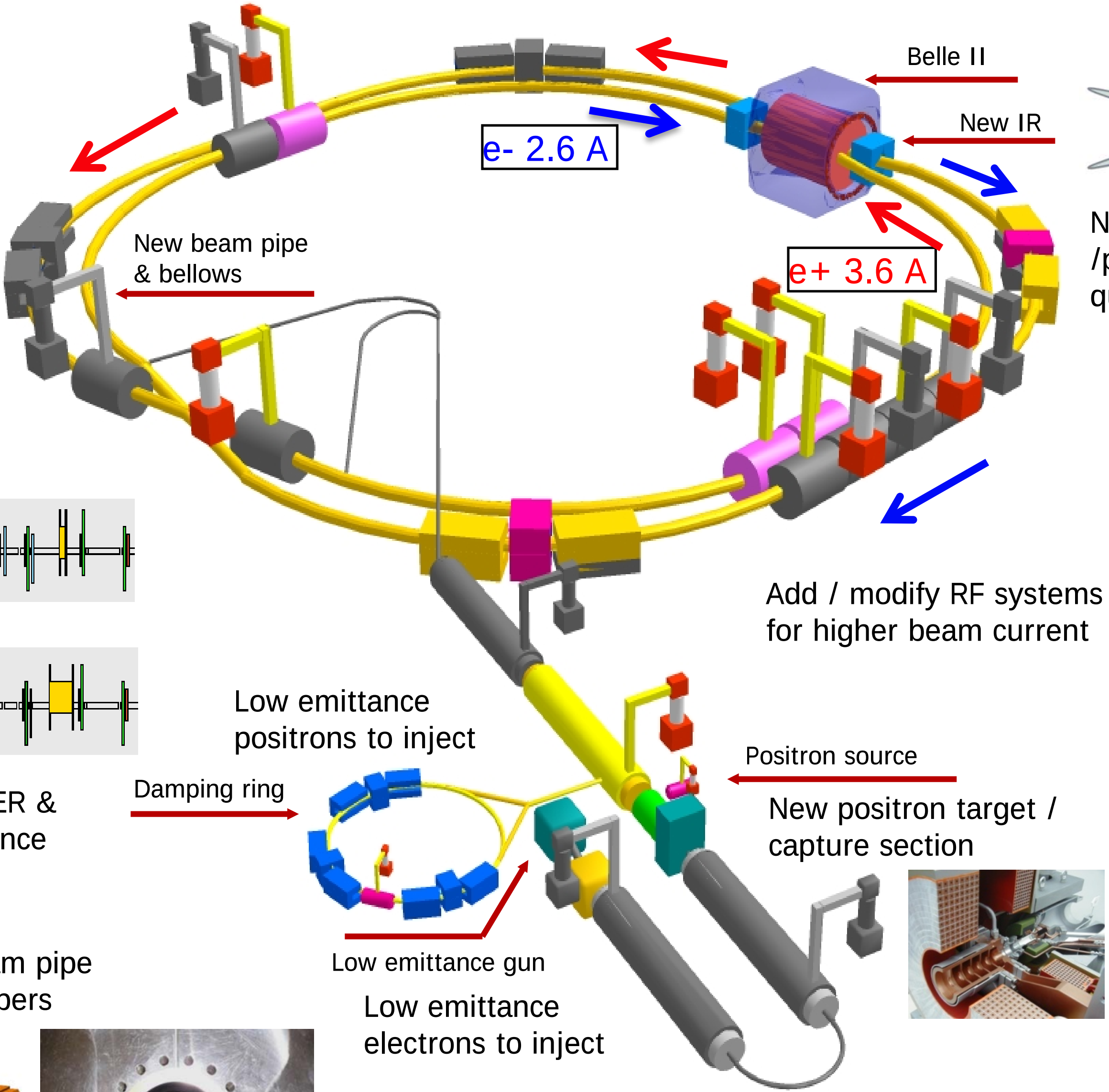


Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers



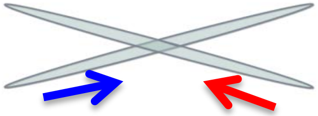




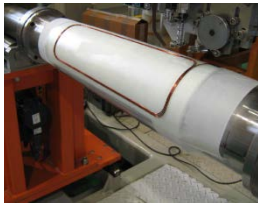
Low emittance positrons to inject

Low emittance electrons to inject

Colliding bunches



New superconducting /permanent final focusing quads near the IP

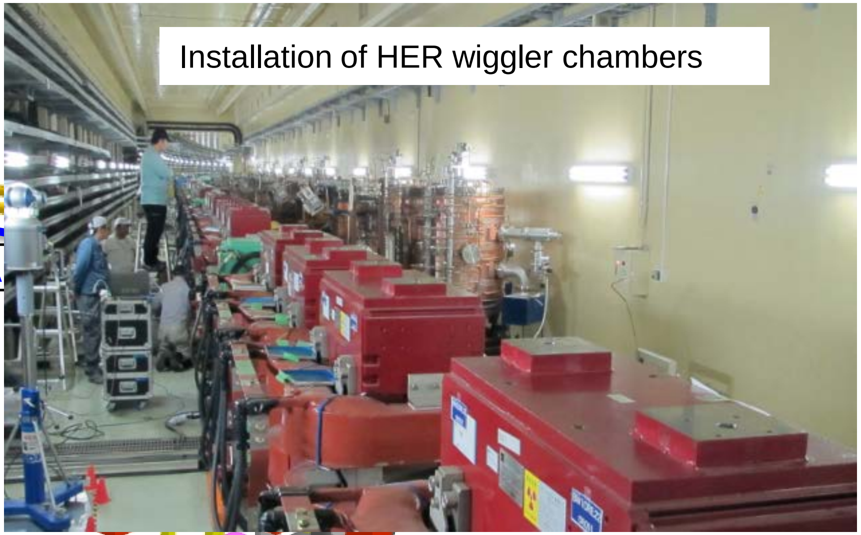


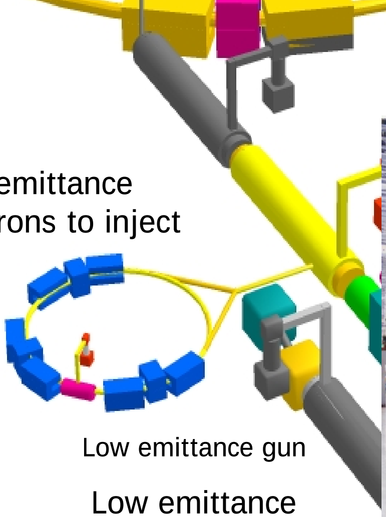
Add / modify RF systems for higher beam current

New positron target / capture section

To get x40 higher luminosity


Installation of 100 new long LER bending magnets

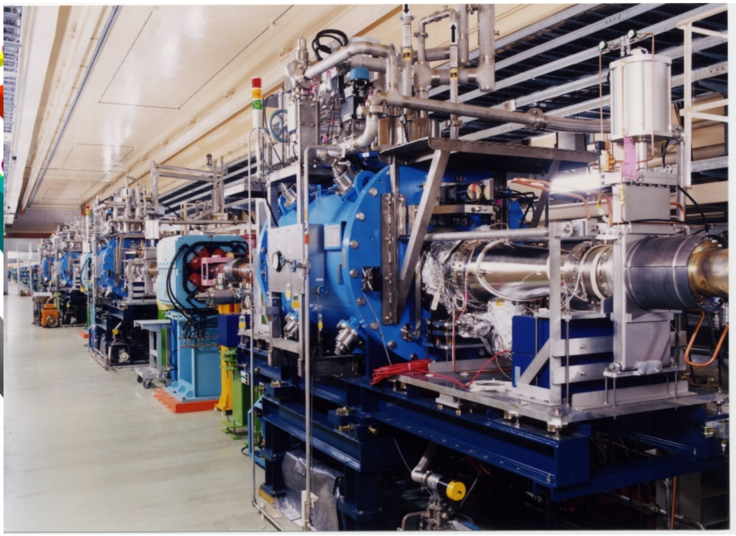

Installation of HER wiggler chambers


Low emittance positrons to inject

Low emittance gun

Low emittance electrons to inject

Add / modify RF systems for higher beam current




Damping ring tunnel

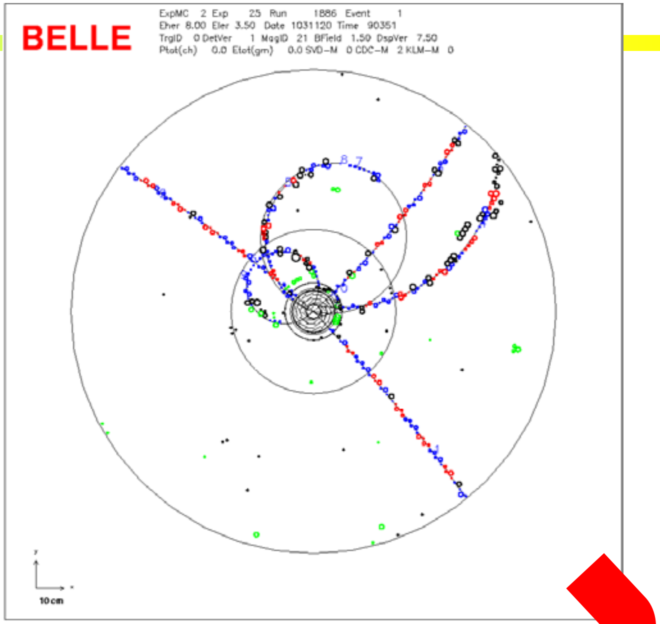
Requirements for the Belle II detector

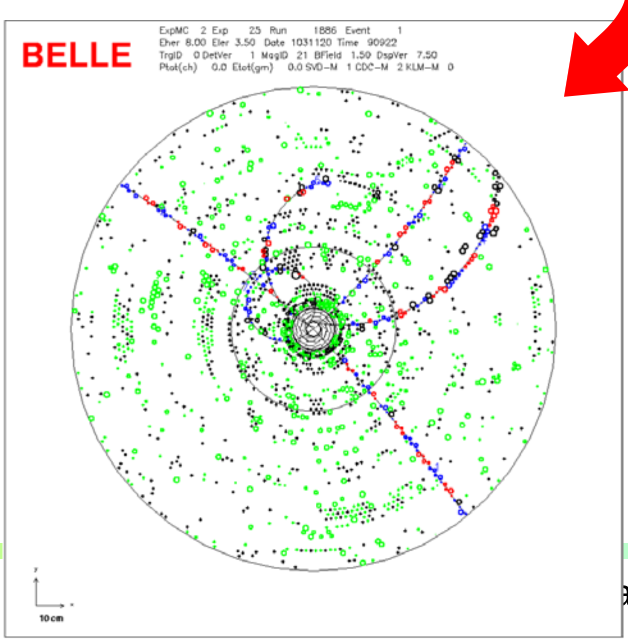
Critical issues at L= 8 x 10^{35}/cm^2/sec

- **Higher background (×10-20)**
  - radiation damage and occupancy
  - fake hits and pile-up noise in the EM
- **Higher event rate (×10)**
  - higher rate trigger, DAQ and computing
- **Require special features**
  - low *p* μ identification ← sμμ recon. eff.
  - hermeticity ← ν “reconstruction”

Solutions:

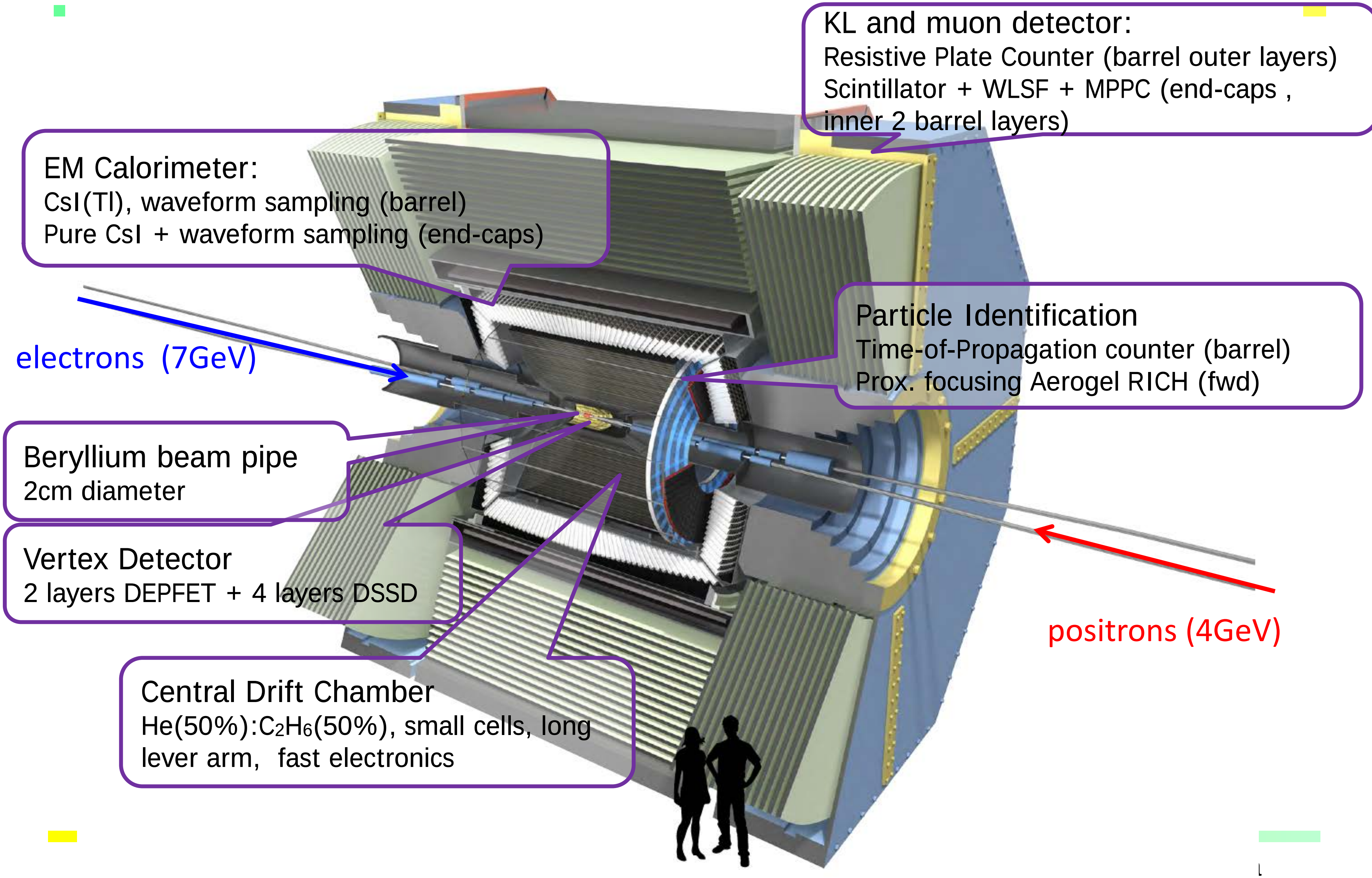
- Replace inner layers of the vertex detector with a pixel detector.
- Replace inner part of the central tracker with a silicon strip detector.
- Better particle identification device
- Replace endcap calorimeter crystals
- Faster readout electronics and computing system.





Belle II TDR, arxiv:1011.0352v1[physics.ins-det]

Belle II Detector



KL and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps , inner 2 barrel layers)

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

electrons (7GeV)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

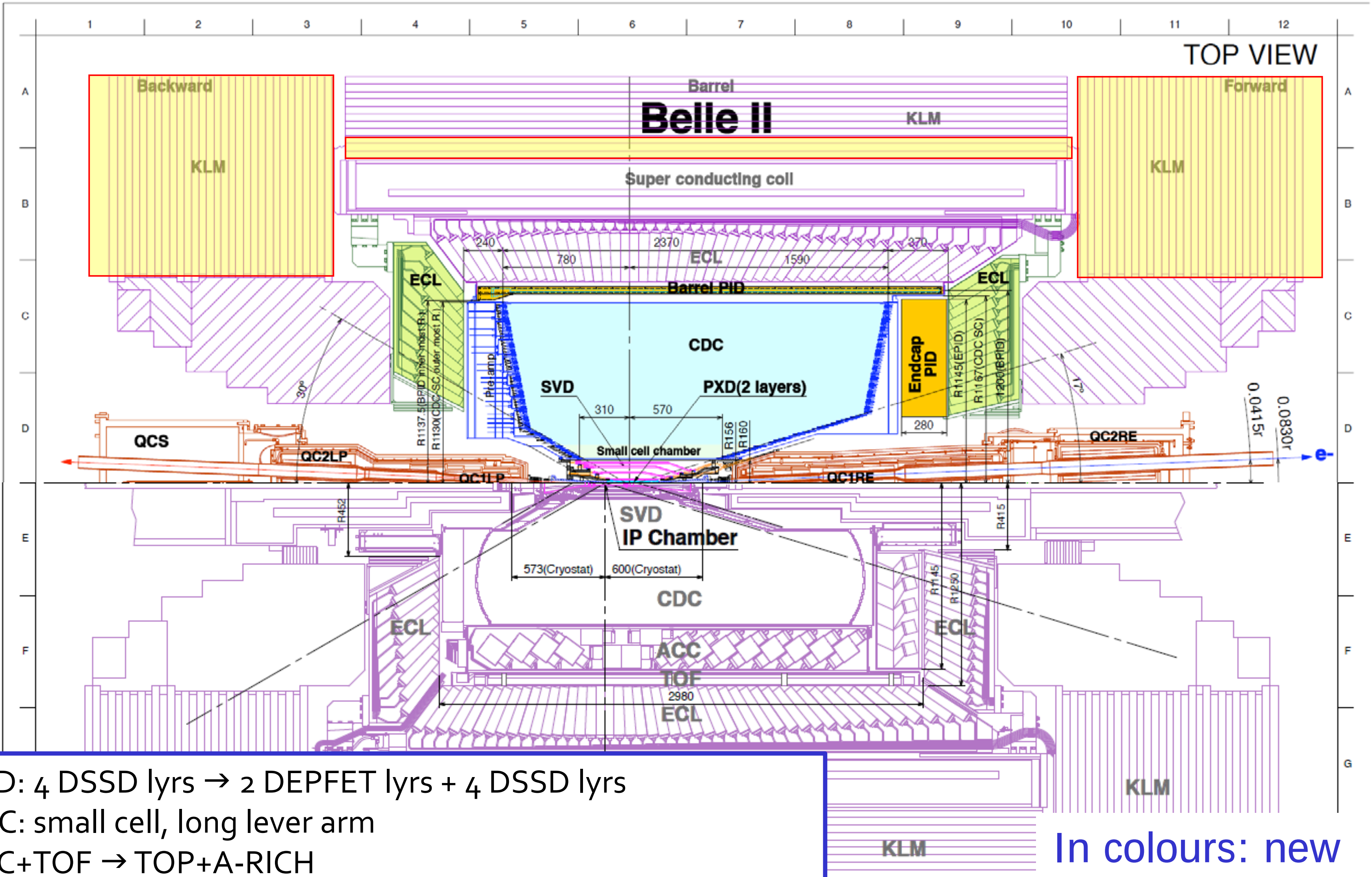
Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

positrons (4GeV)

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

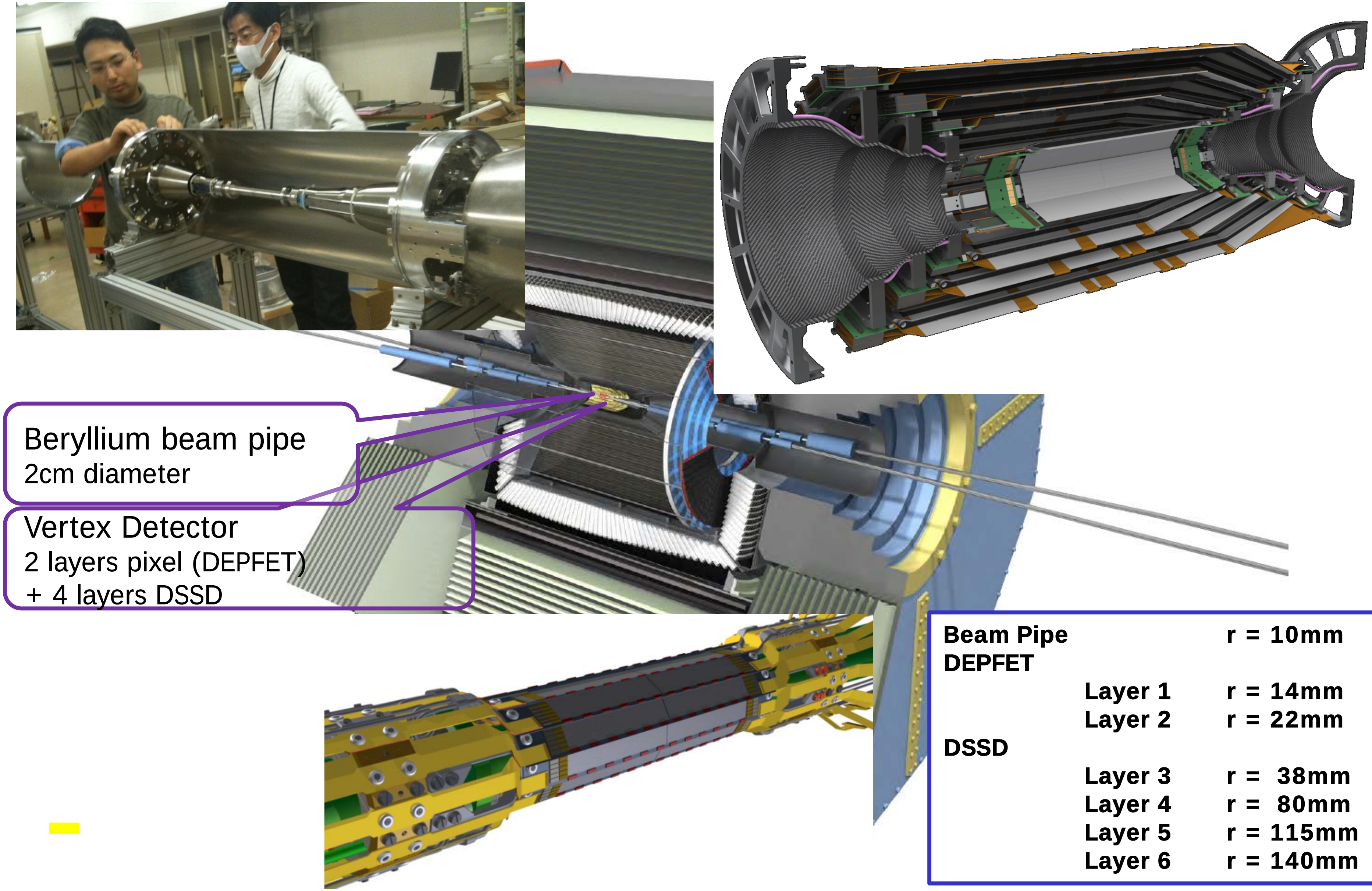
Belle II Detector (compared to Belle)



SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

In colours: new components

Belle II Detector – vertex region



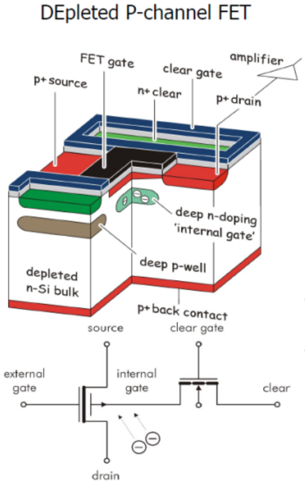
Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers pixel (DEPFET)
+ 4 layers DSSD

Beam Pipe		**r = 10mm**
DEPFET		
	Layer 1	**r = 14mm**
	Layer 2	**r = 22mm**
DSSD		
	Layer 3	**r = 38mm**
	Layer 4	**r = 80mm**
	Layer 5	**r = 115mm**
	Layer 6	**r = 140mm**

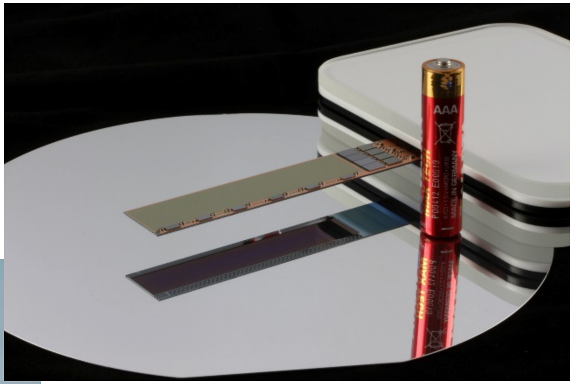
Pixel detector: 2 layers of DEPFET sensors

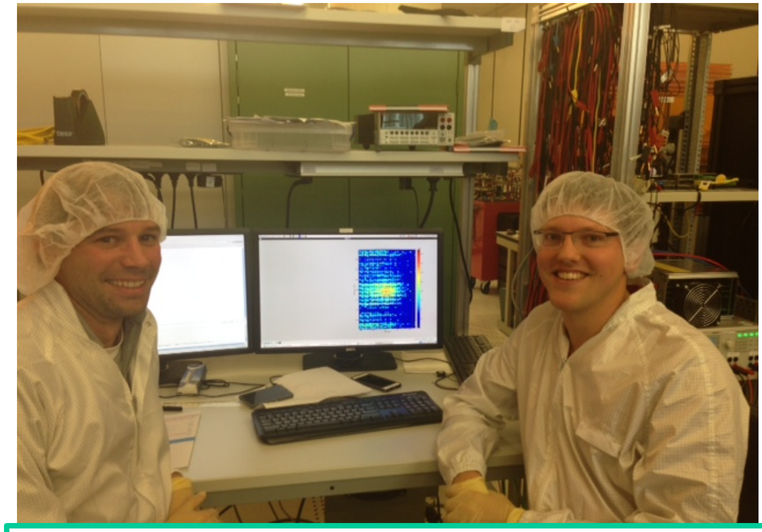
Mechanical mockup of the pixel detector

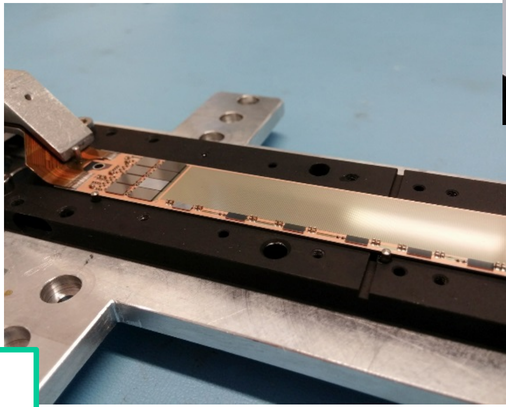


DEPFET sensor: developed at MPI Munich, produced at HLL

http://aldebaran.hll.mpg.de/twiki/bin/view/DEPFET/WebHome

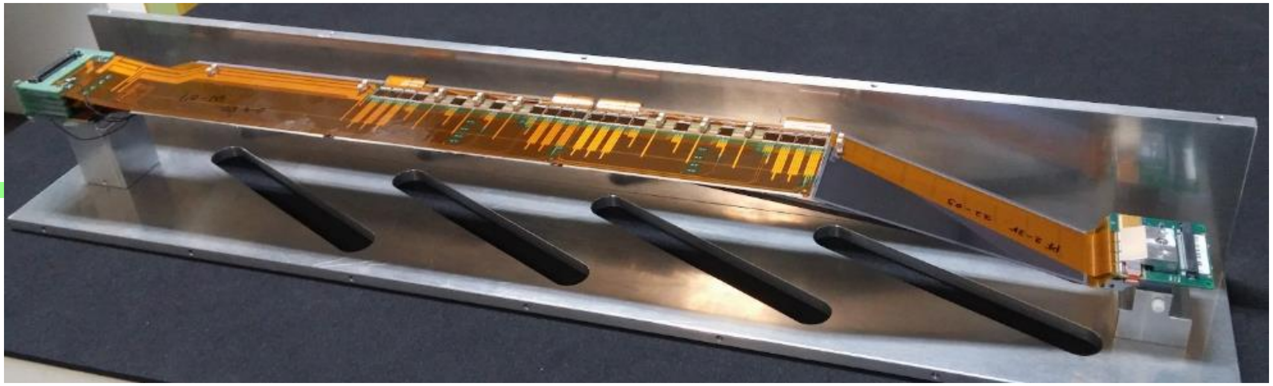




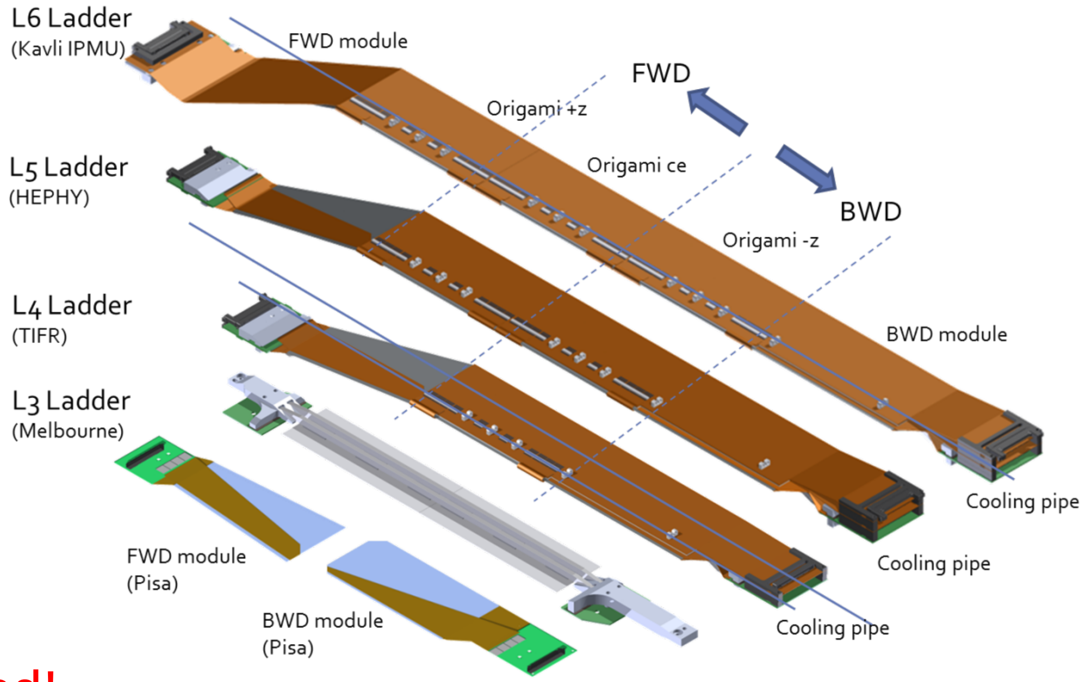


→Talk by Dima Levit

First laser light observed with the full size sensor

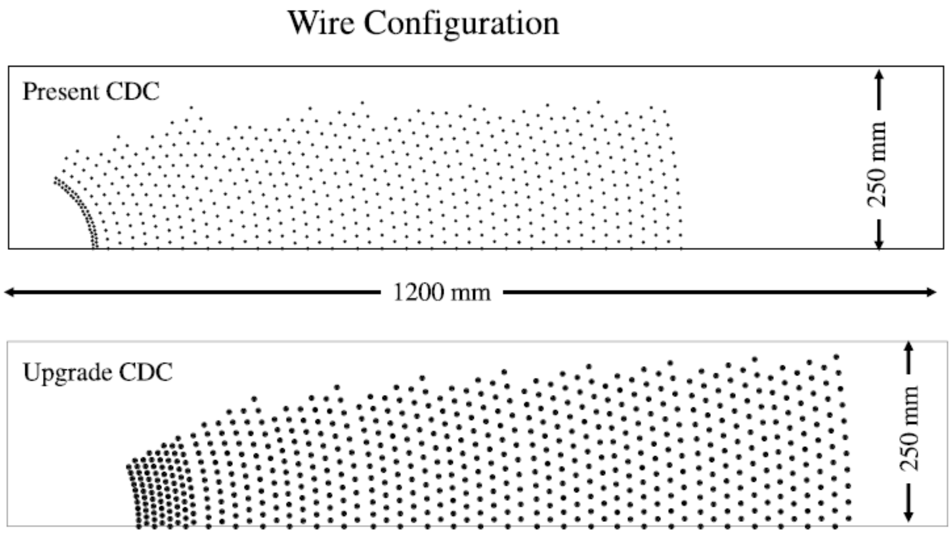


SVD: four layers of silicon microstrip detectors.

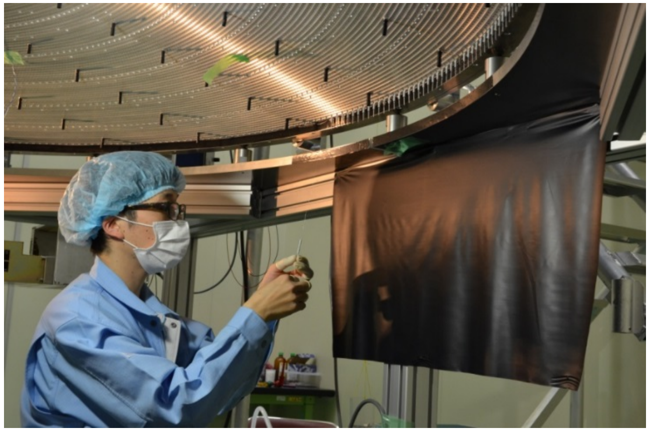


Production started!

Belle II CDC

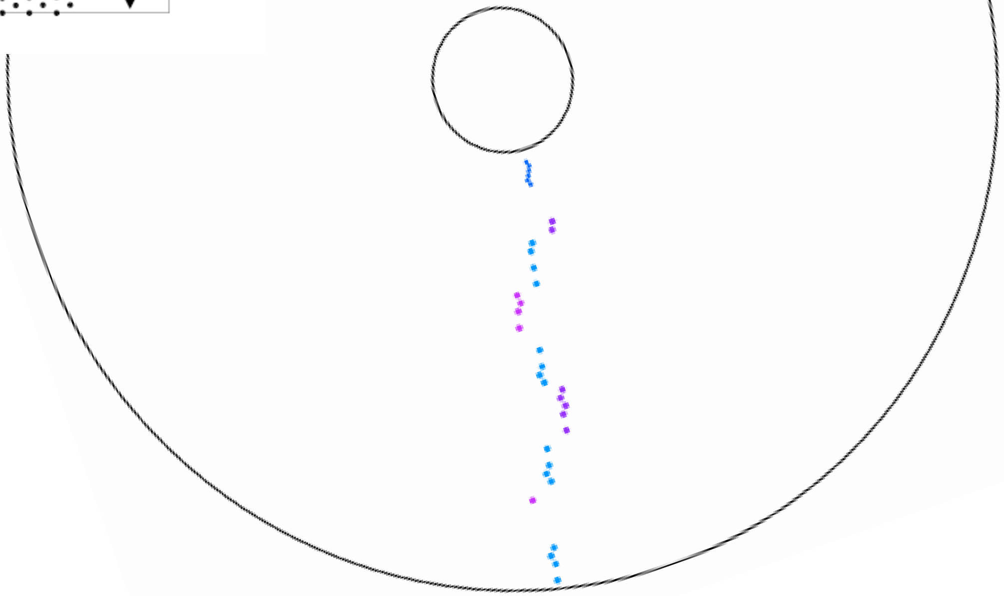


Much bigger than in Belle!



Wire stringing in a clean room

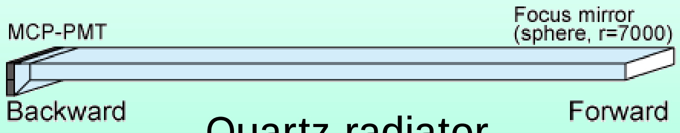
- thousands of wires,
- 1 year of work...



Being commissioned with cosmic rays.

Particle Identification Devices

Barrel PID: Time of Propagation Counter (TOP)



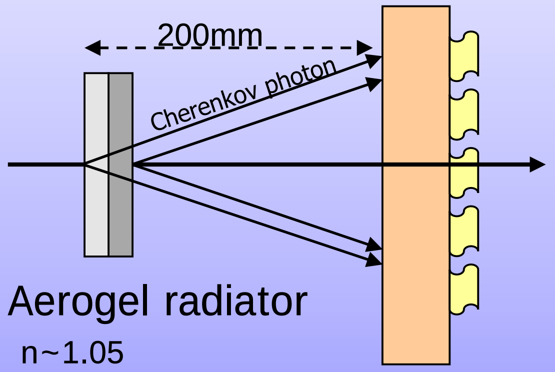
Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

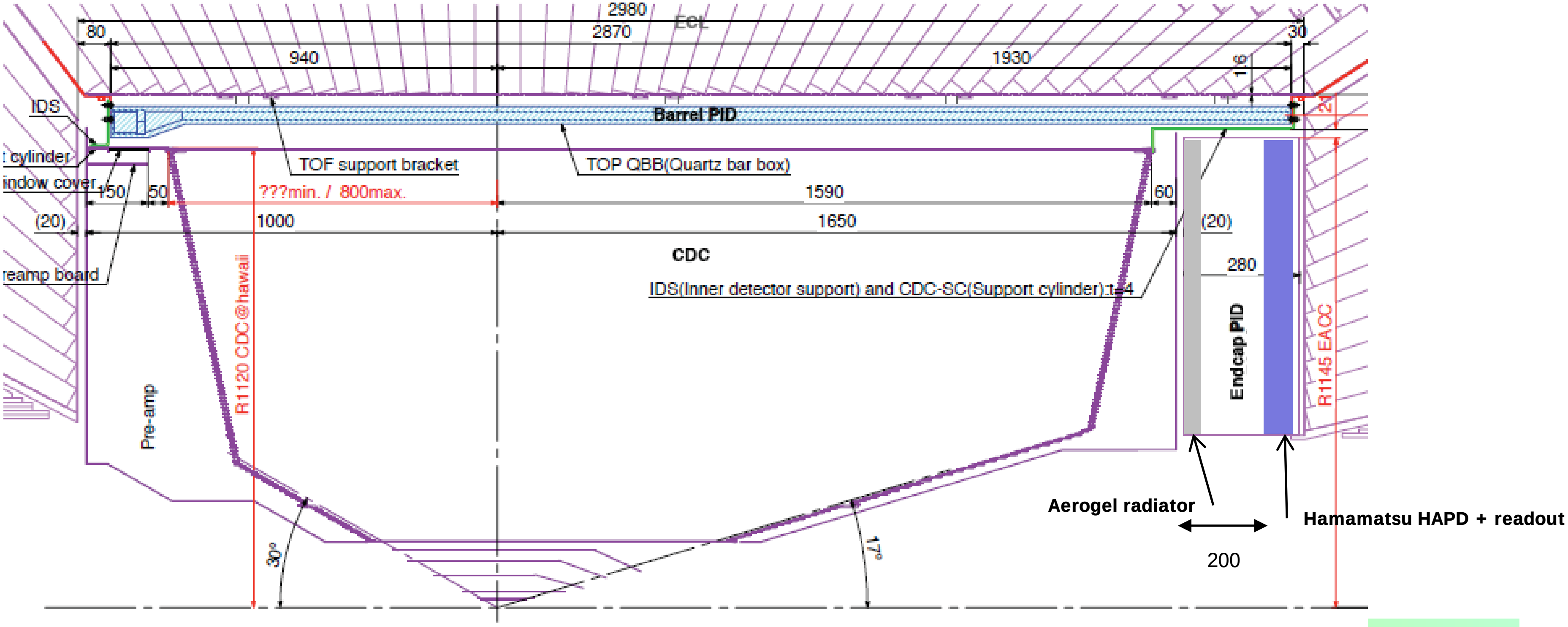
Endcap PID: Aerogel RICH (ARICH)



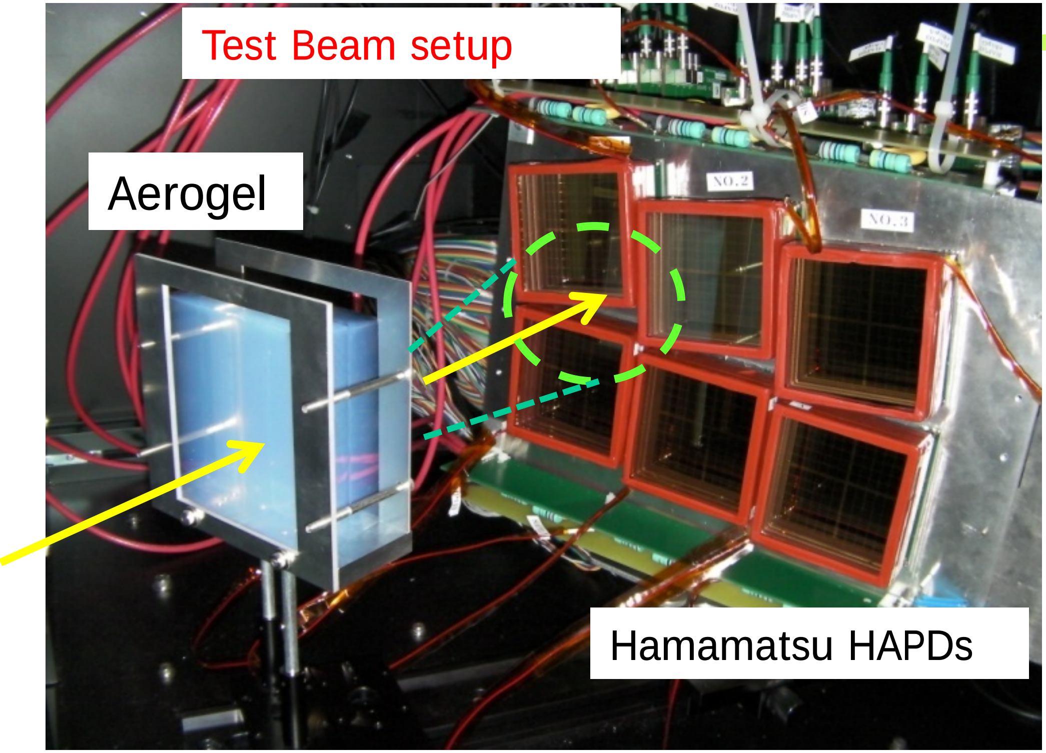
Aerogel radiator

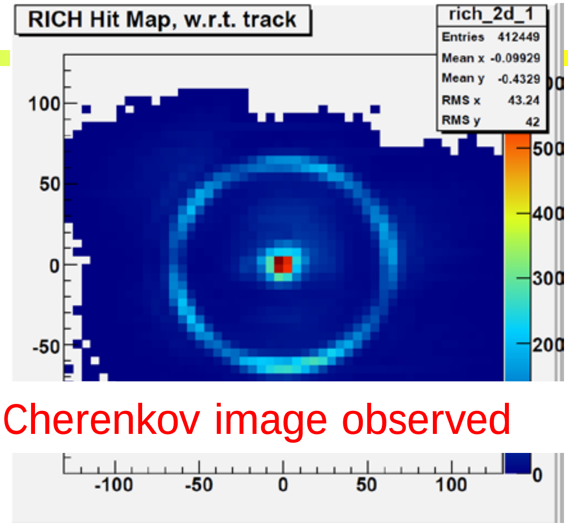
n~1.05

Hamamatsu HAPD



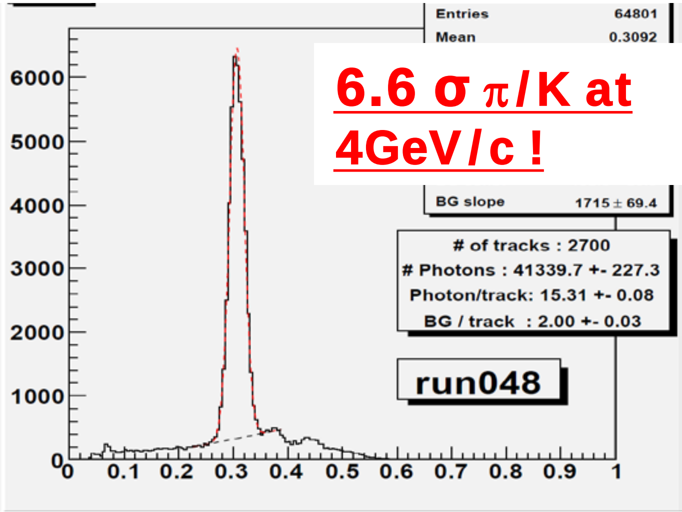
Aerogel RICH (endcap PID)


Test Beam setup



Clear Cherenkov image observed

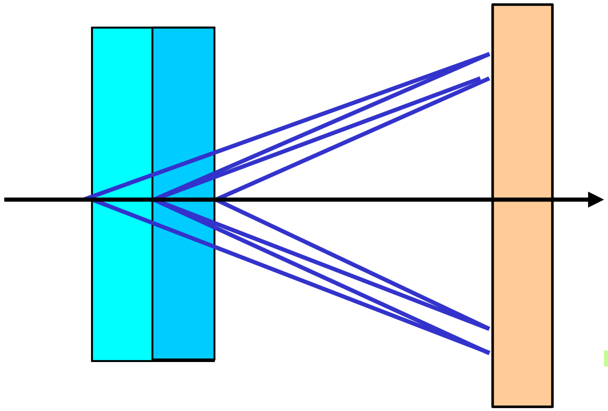
Cherenkov angle distribution



6.6 σ π / K at 4GeV / c !

RICH with a novel "focusing" radiator – a two layer radiator

Employ multiple layers with different refractive indices→ Cherenkov images from individual layers overlap on the photon detector.

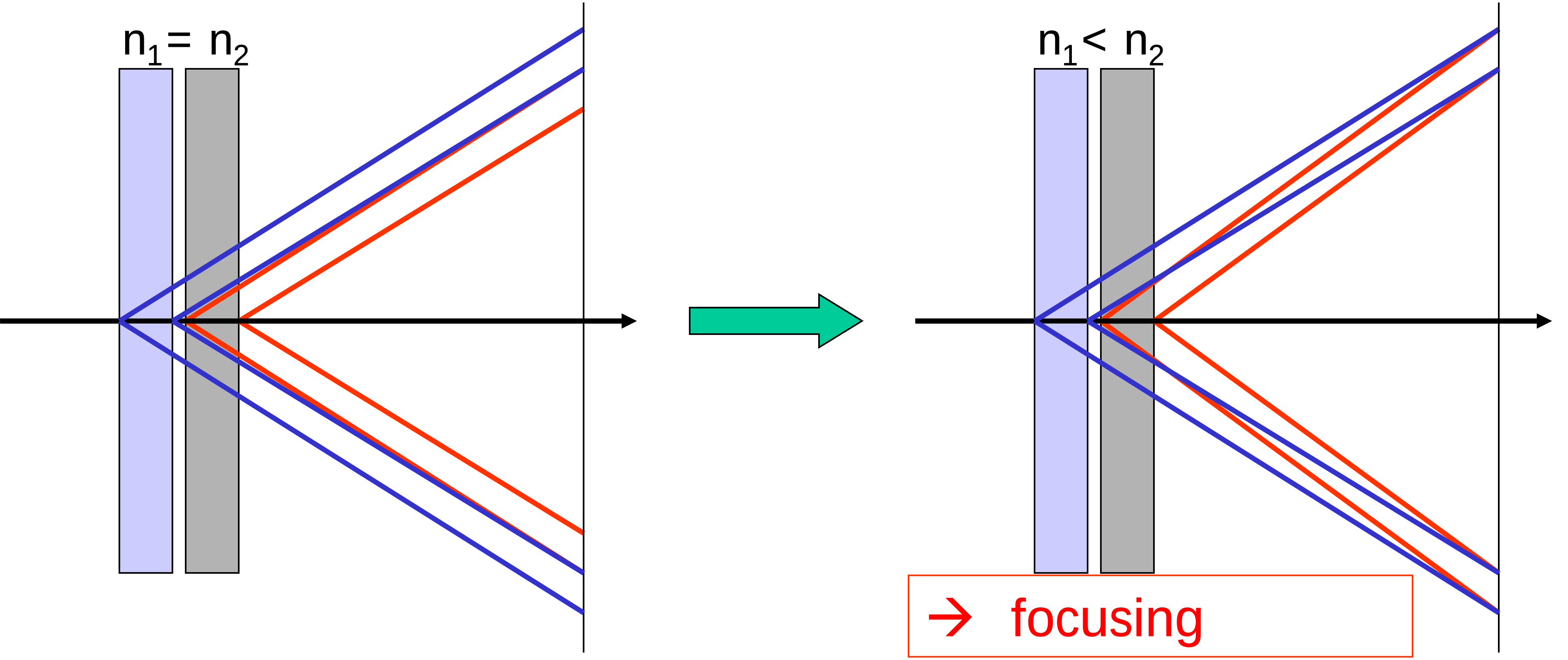


Radiator with multiple refractive indices

How to increase the number of photons without degrading the resolution?

normal

→ stack two tiles with different refractive indices: “focusing” configuration



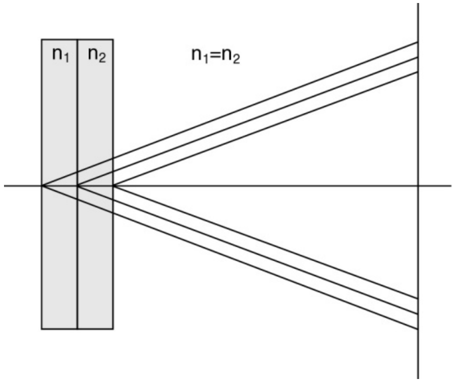
→ focusing

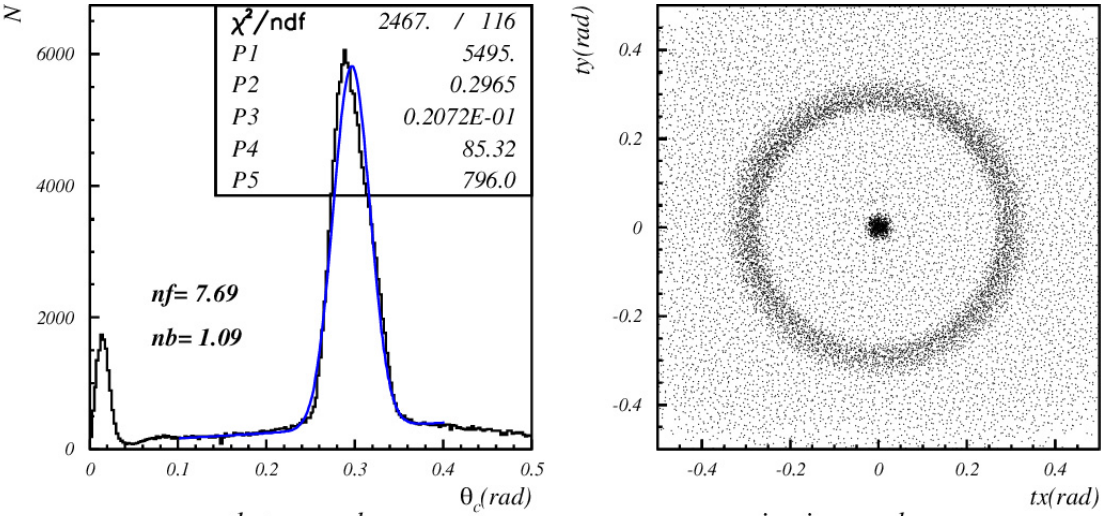
Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.13.

Focusing configuration – data

Increases the number of photons without degrading the resolution

4cm aerogel single index

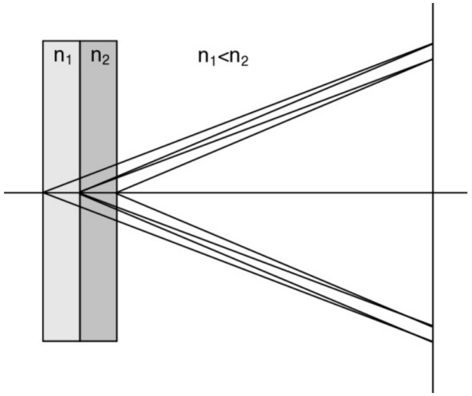


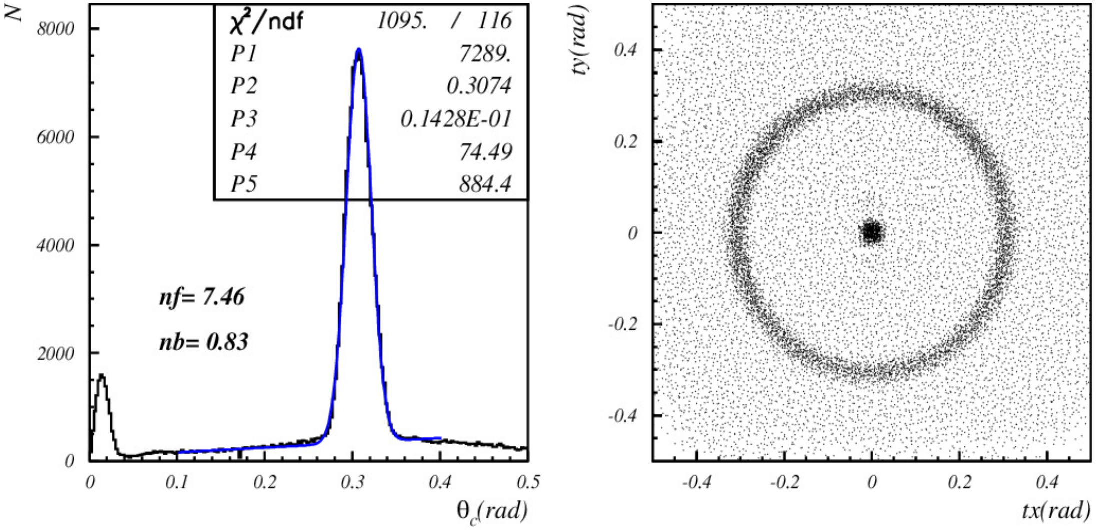


theta cerenkov

ring in cerenkov space

2+2cm aerogel

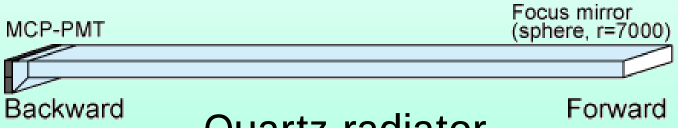




→NIM A548 (2005) 383

Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



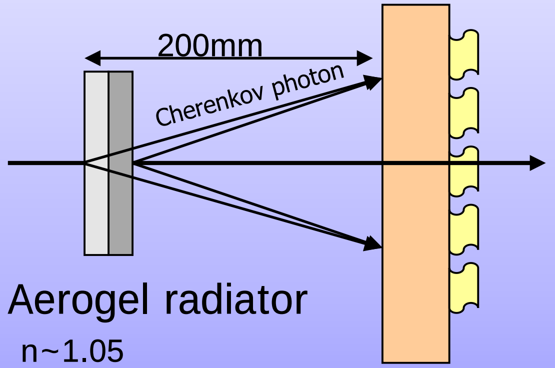
Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

Endcap PID: Aerogel RICH (ARICH)

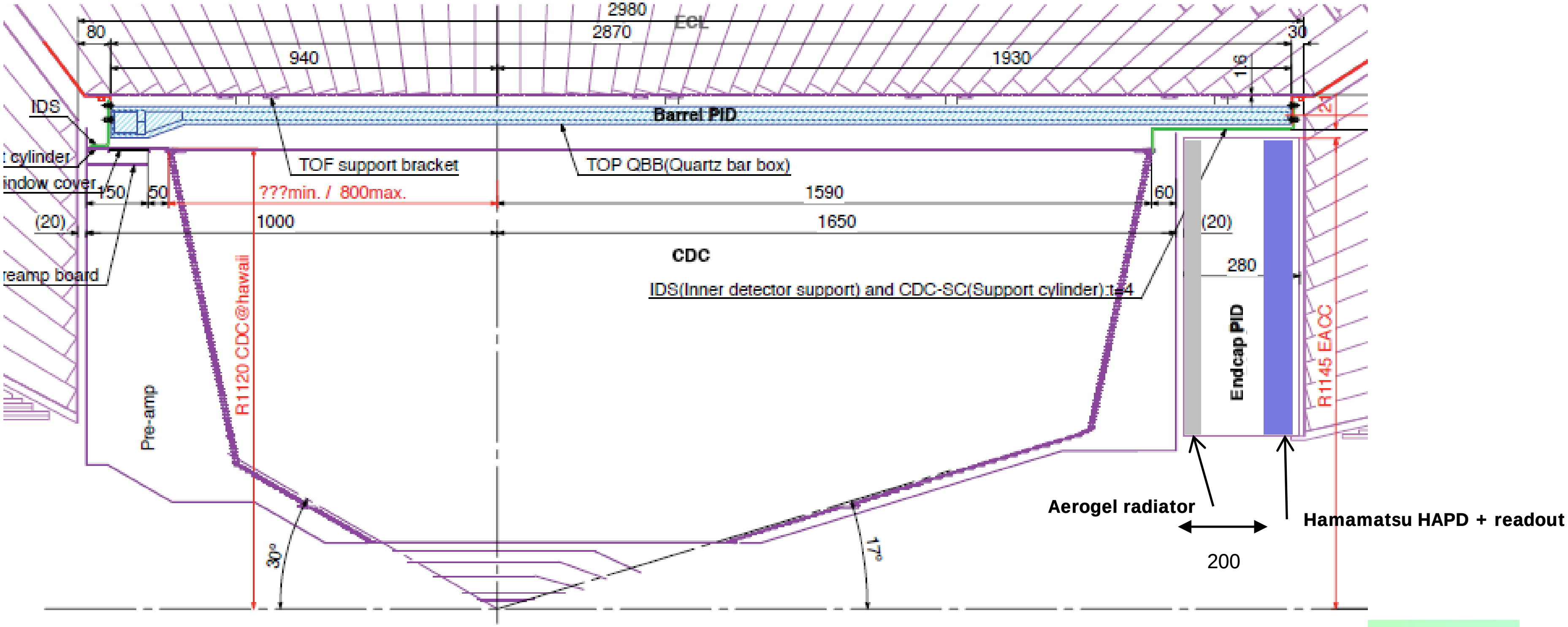


Aerogel radiator

n~1.05

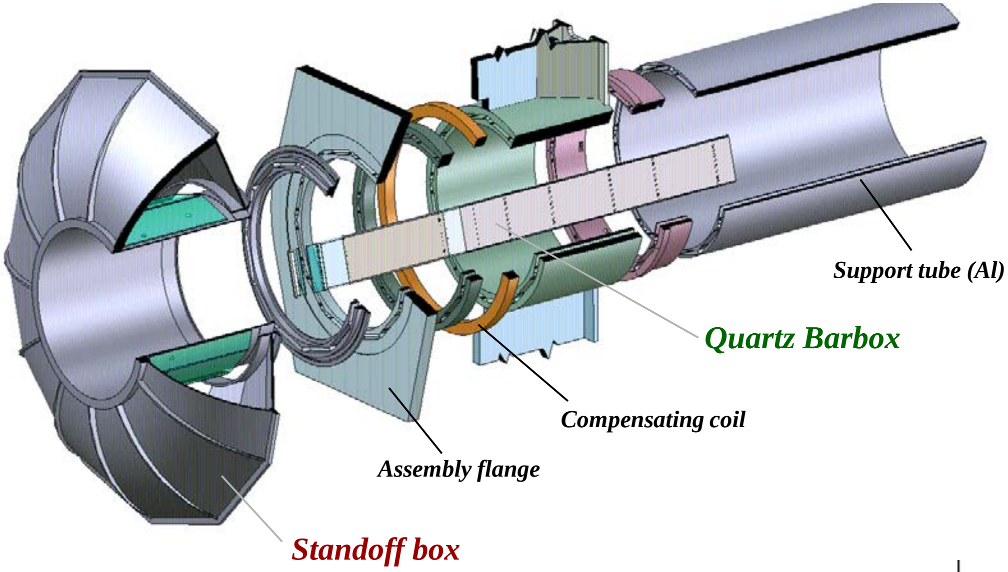
Hamamatsu HAPD

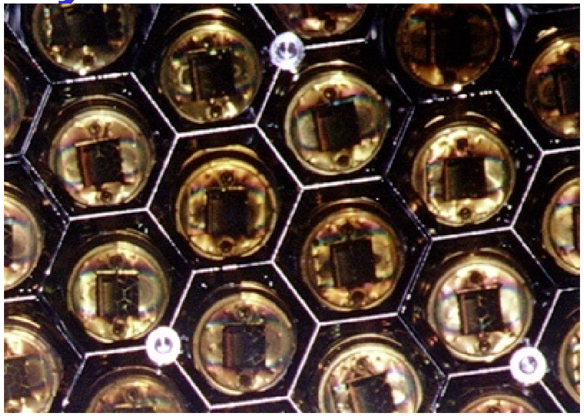
\+ new ASIC

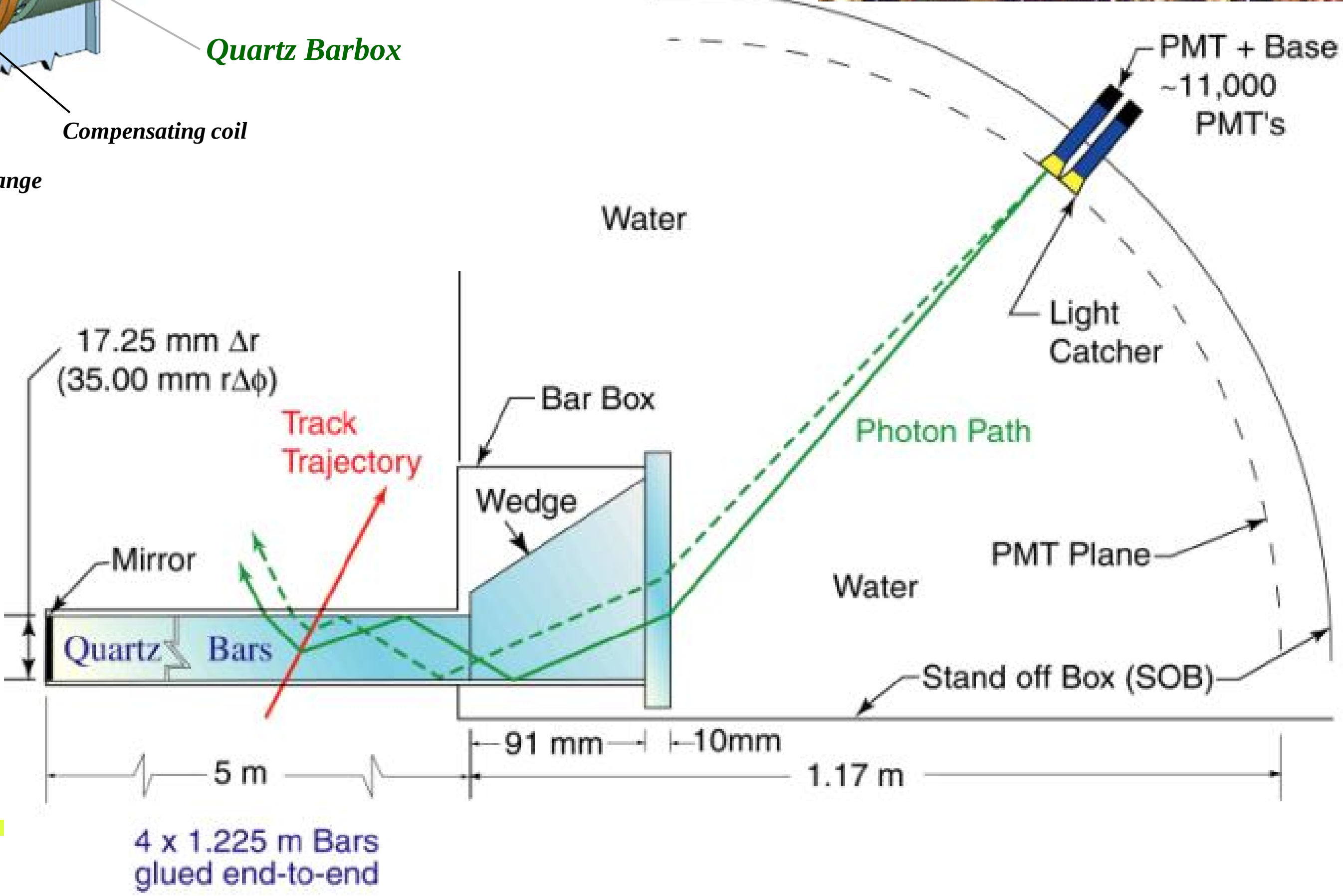


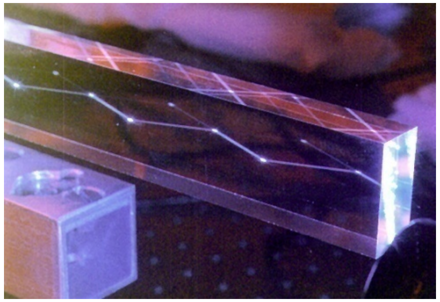
Peter Križan, Ljubljana

DIRC (@BaBar) - detector of internally reflected Cherenkov light

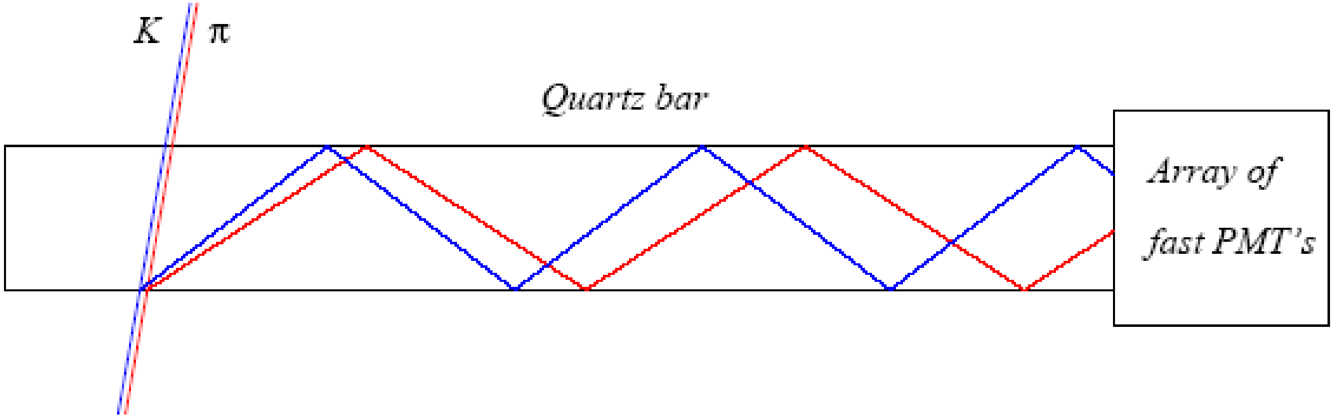


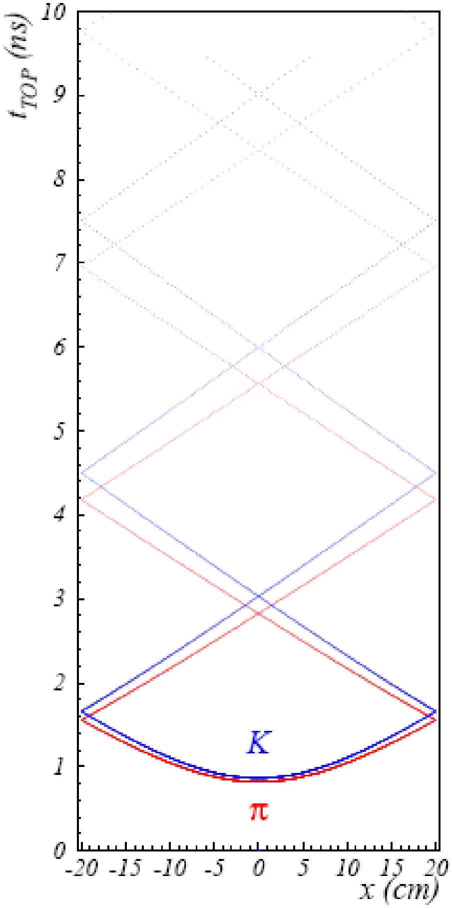






Belle II Barrel PID: Time of propagation (TOP) counter

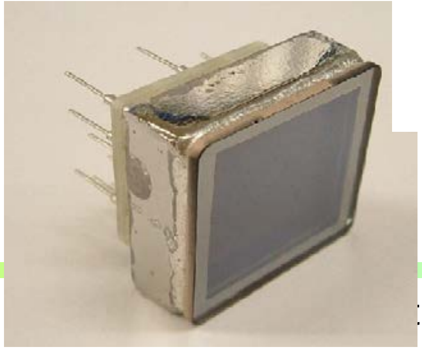




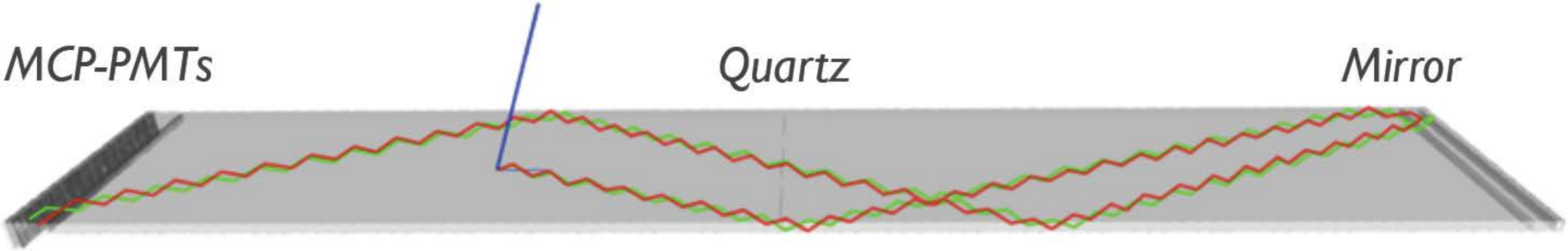
- Cherenkov ring imaging with precise time measurement.
- Uses internal reflection of Cherenkov ring images from quartz like the BaBar DIRC.
- Reconstruct Cherenkov angle from two hit coordinates and

the time of propagation of the photon

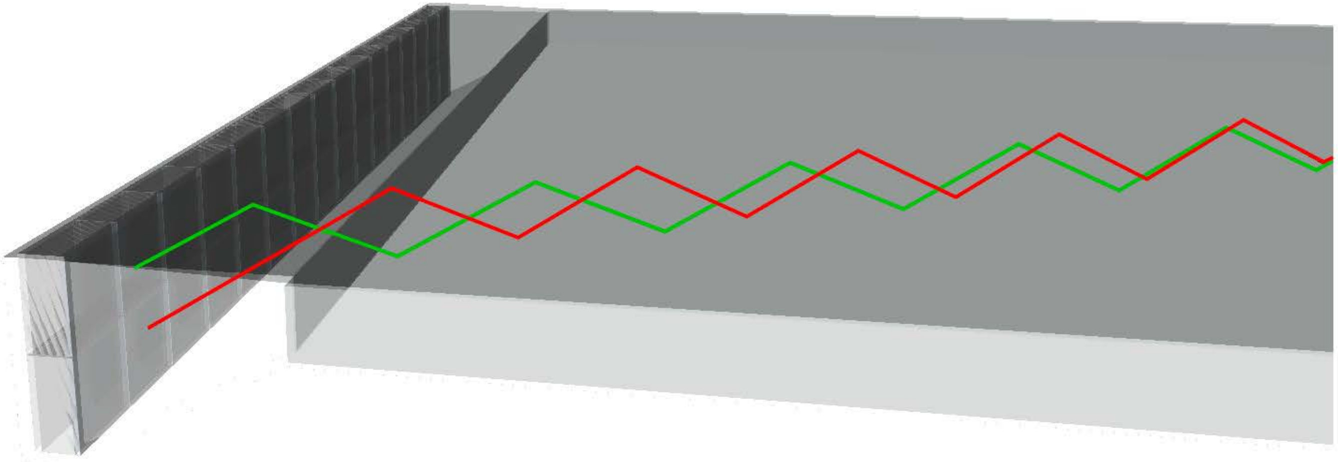
  - Quartz radiator (2cm thick)
  - Photon detector (MCP-PMT)
    - Excellent time resolution ~ 40 ps
    - Single photon sensitivity in 1.5



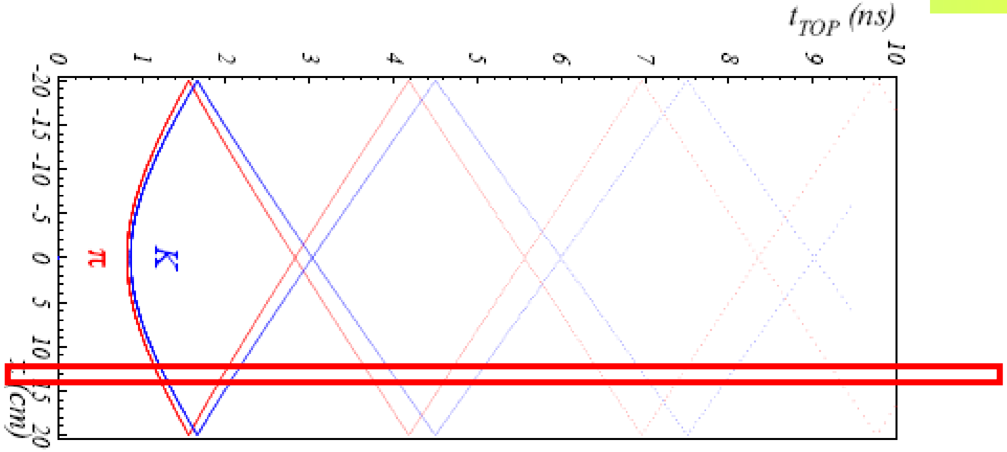
Barrel PID: Time of propagation (TOP) counter



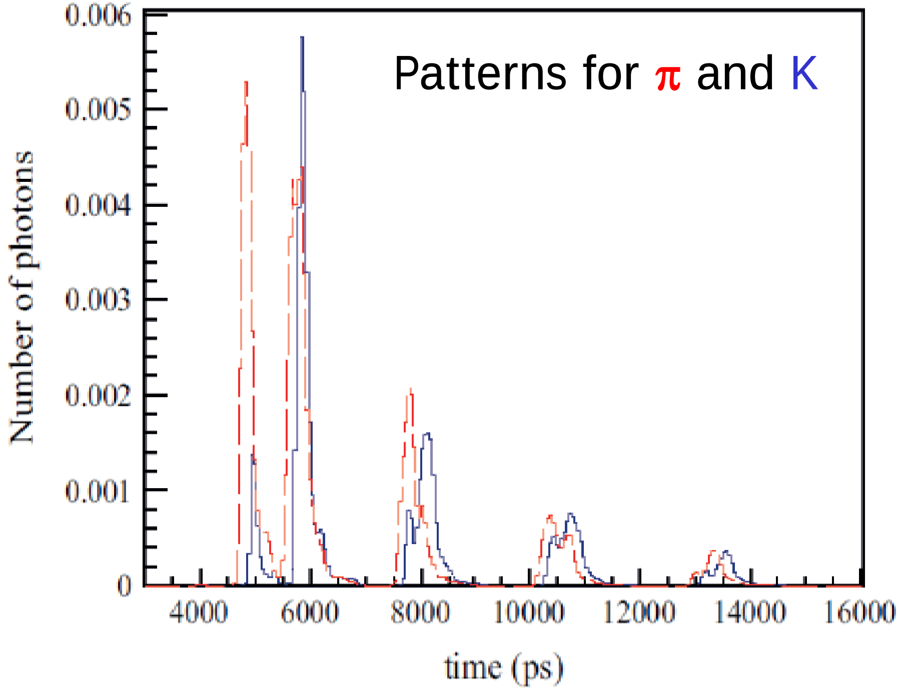
Example of Cherenkov-photon paths for 2 GeV/c $\pi^\pm$ and $K^\pm$.



TOP image

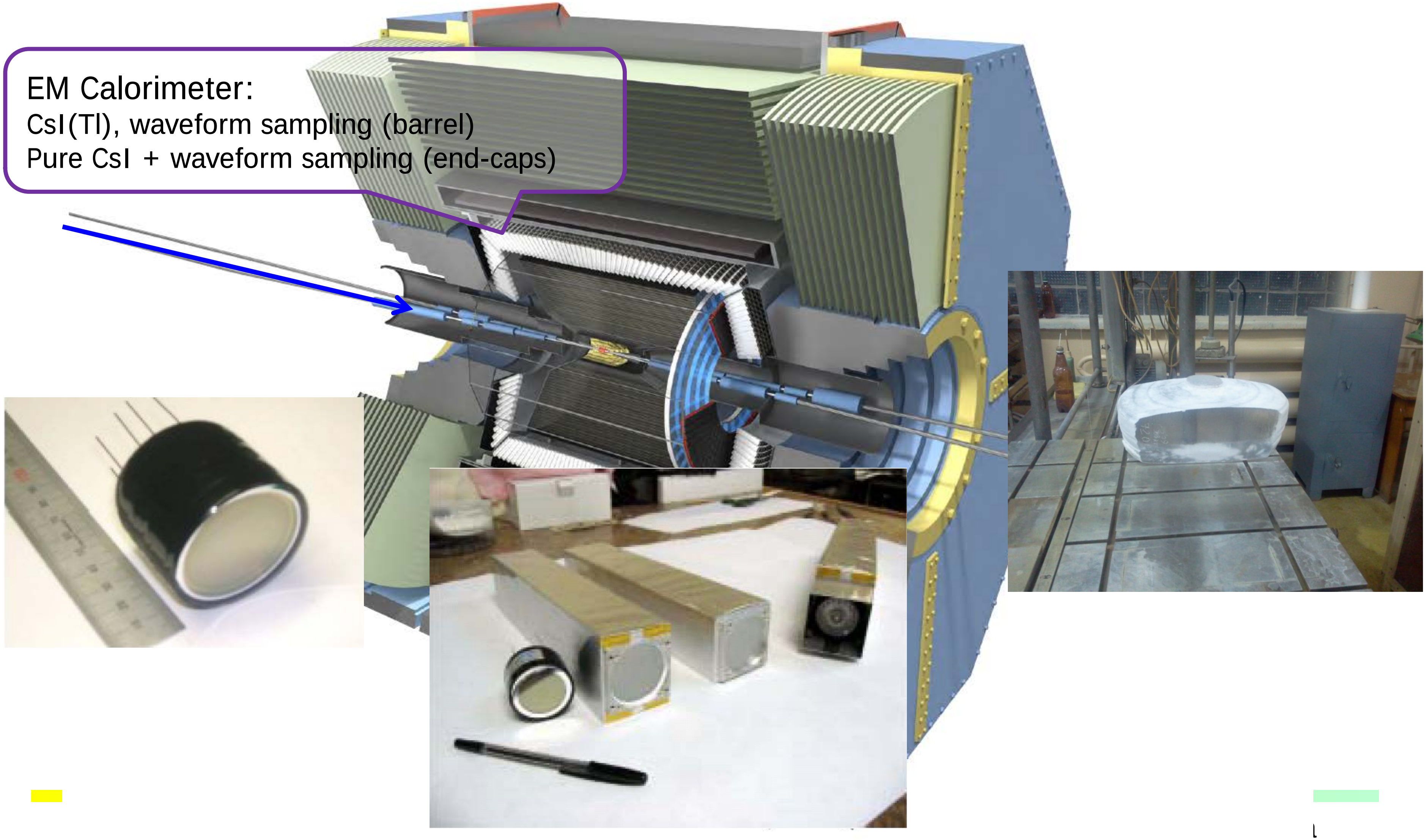


Pattern in the coordinate-time space ('ring') of a pion and kaon hitting a quartz bar



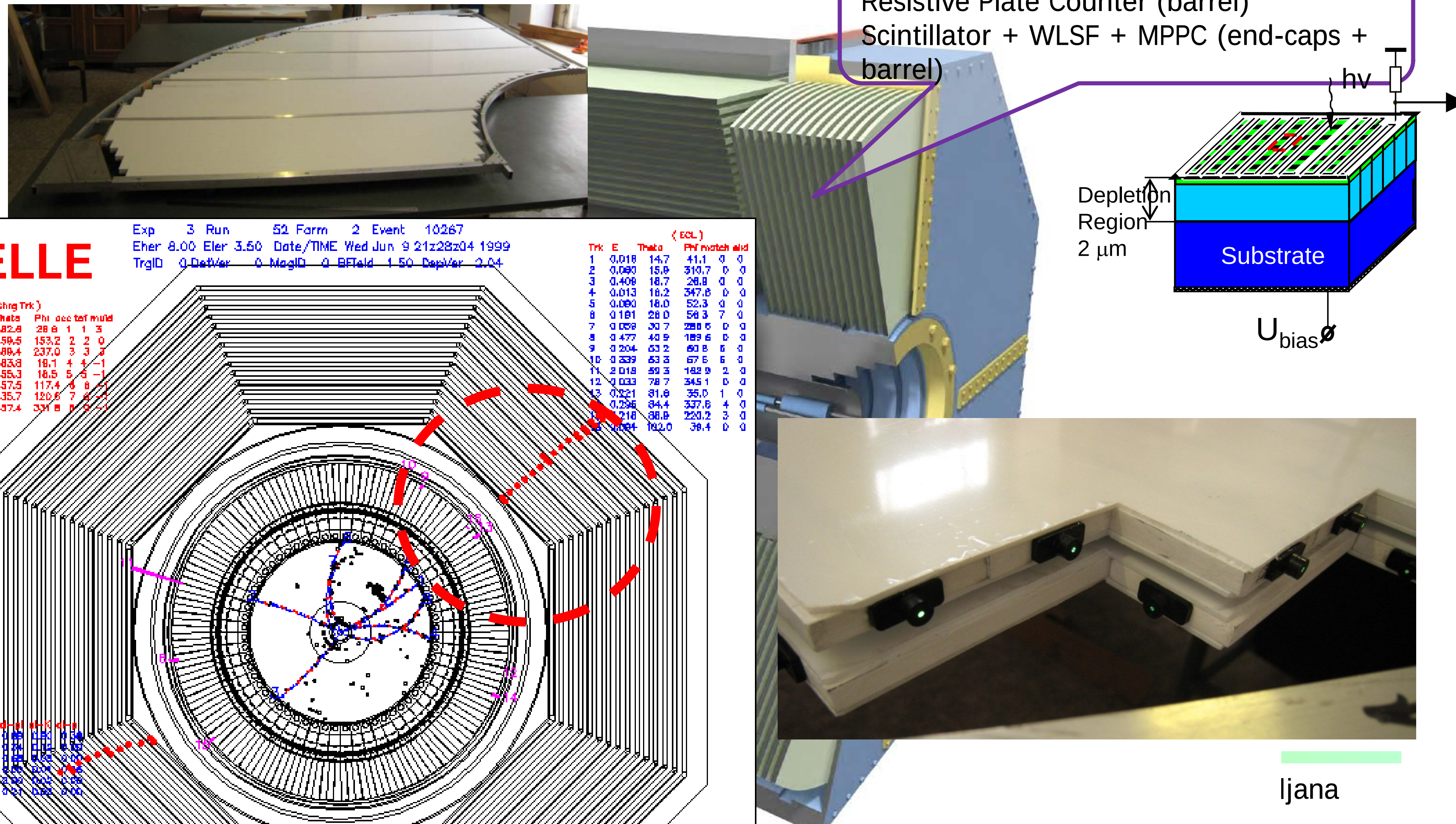
Time distribution of signals recorded by one of the PMT channels: different for π and K (~shifted in time)

EM calorimeter: upgrade needed because of higher rates (electronics → waveform sampling) and radiation load (endcap, replace some fraction of crystals CsI(Tl) → pure CsI)



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

Detection of muons and K_Ls: parts of the original RPC system have to be replace because they could not handle the high background rates (mainly neutrons)



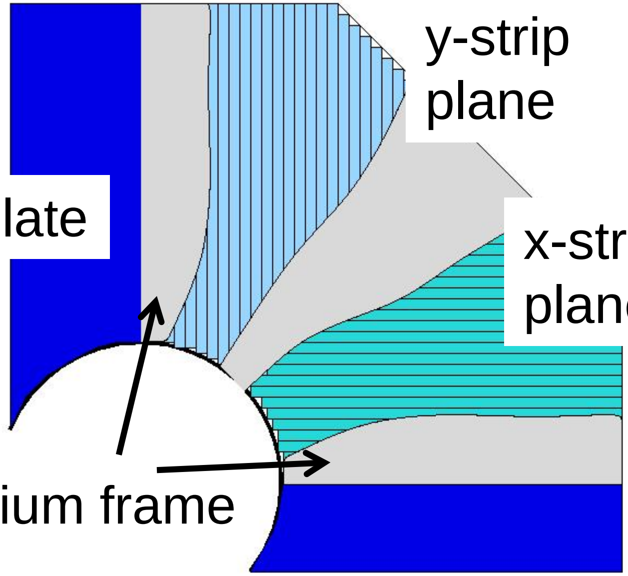
K_L and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps + barrel)

Ljana

Muon detection system upgrade in the endcaps

Scintillator-based KLM (endcap in inner layers of the barrell part)

- Two independent (x and y) layers in one superlayer made of orthogonal strips with WLS read out
- Photo-detector = avalanche photodiode in Geiger mode (SiPM)
- ~120 strips in one 90º sector
  (max L=280cm, w=25mm)
- ~30000 read out channels
- Geometrical acceptance > 99%



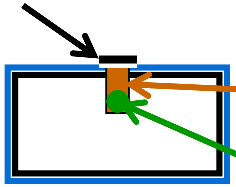
y-strip plane

Iron plate

x-strip plane

Aluminium frame

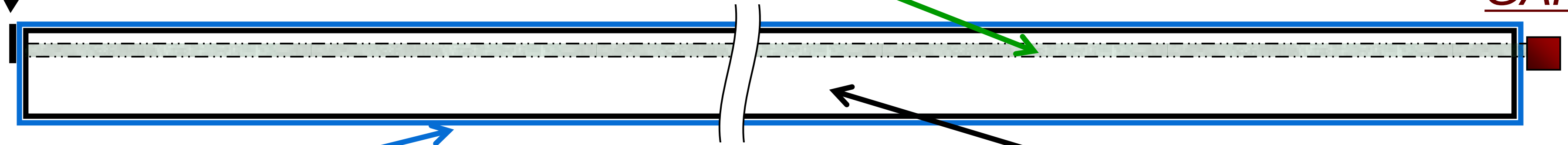
Mirror 3M (above groove & at fiber end)



Optical glue increase the light yield ~ 1.2-1.4)

WLS: Kurarai Y11 ∅1.2 mm

GAPD



Diffusion reflector (TiO_2)

Strips: polystyrene with 1.5% PTP & 0.01% POPOP

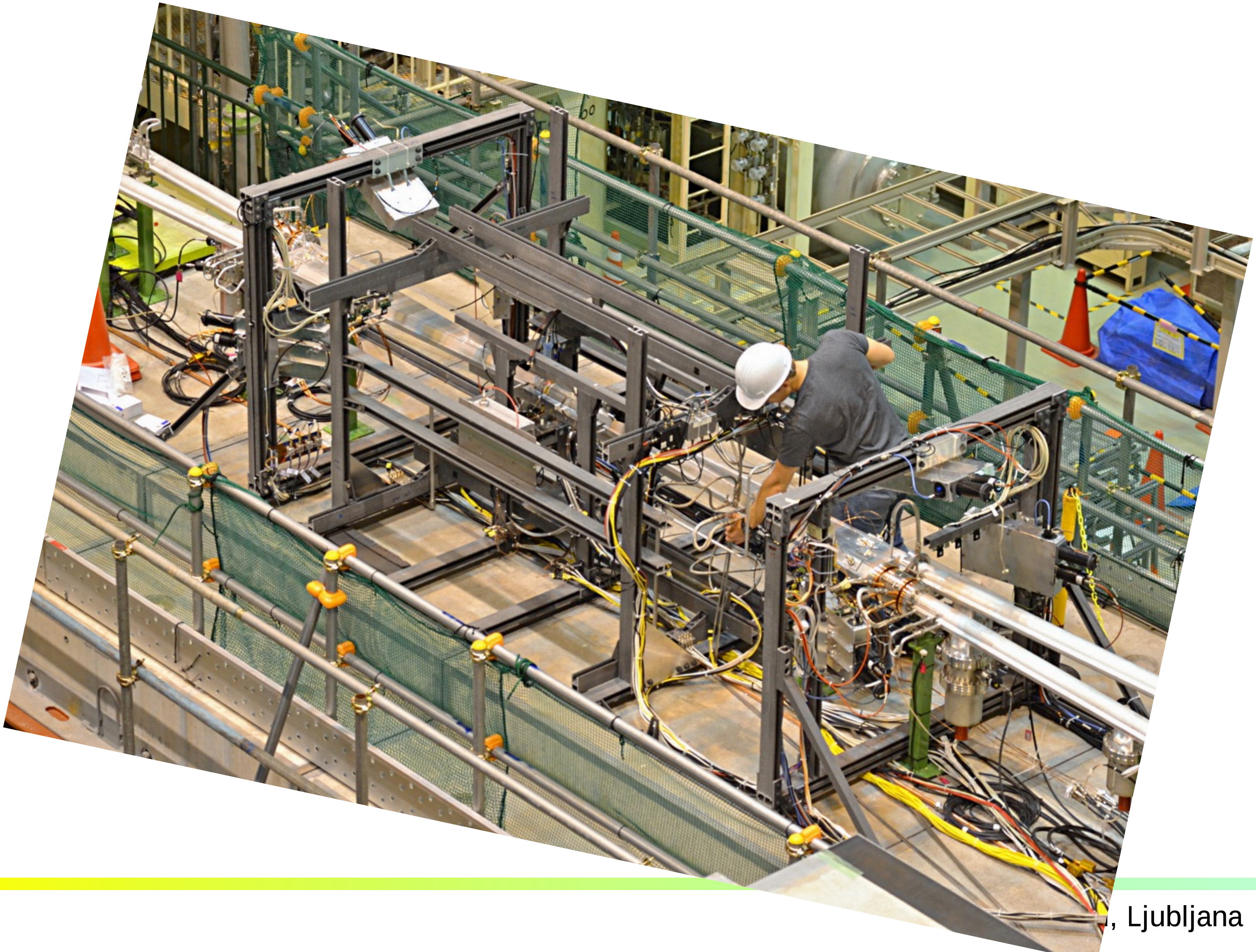
The Belle II Collaboration

A very strong group of ~680 highly motivated scientists!

SuperKEKB/Belle II Status

- Commisioning (Phase 1) of the main ring (without final quads) starts Feb 1, 2016 - next week! Interaction point detector: instead of Belle II, a commissioning detector – Beast II. →
- Add final quads in summer 2016
- Belle II: installation of outer detectors: spring/early summer 2016
- Belle II (without the vertex detector) roll in autumn 2016, cosmic rays
- Phase 2 commissioning autumn 2017 – spring 2018 (+ first physics runs)
- Install vertex detector summer 2018
- Full detector operation autumn 2018 (Phase 3)

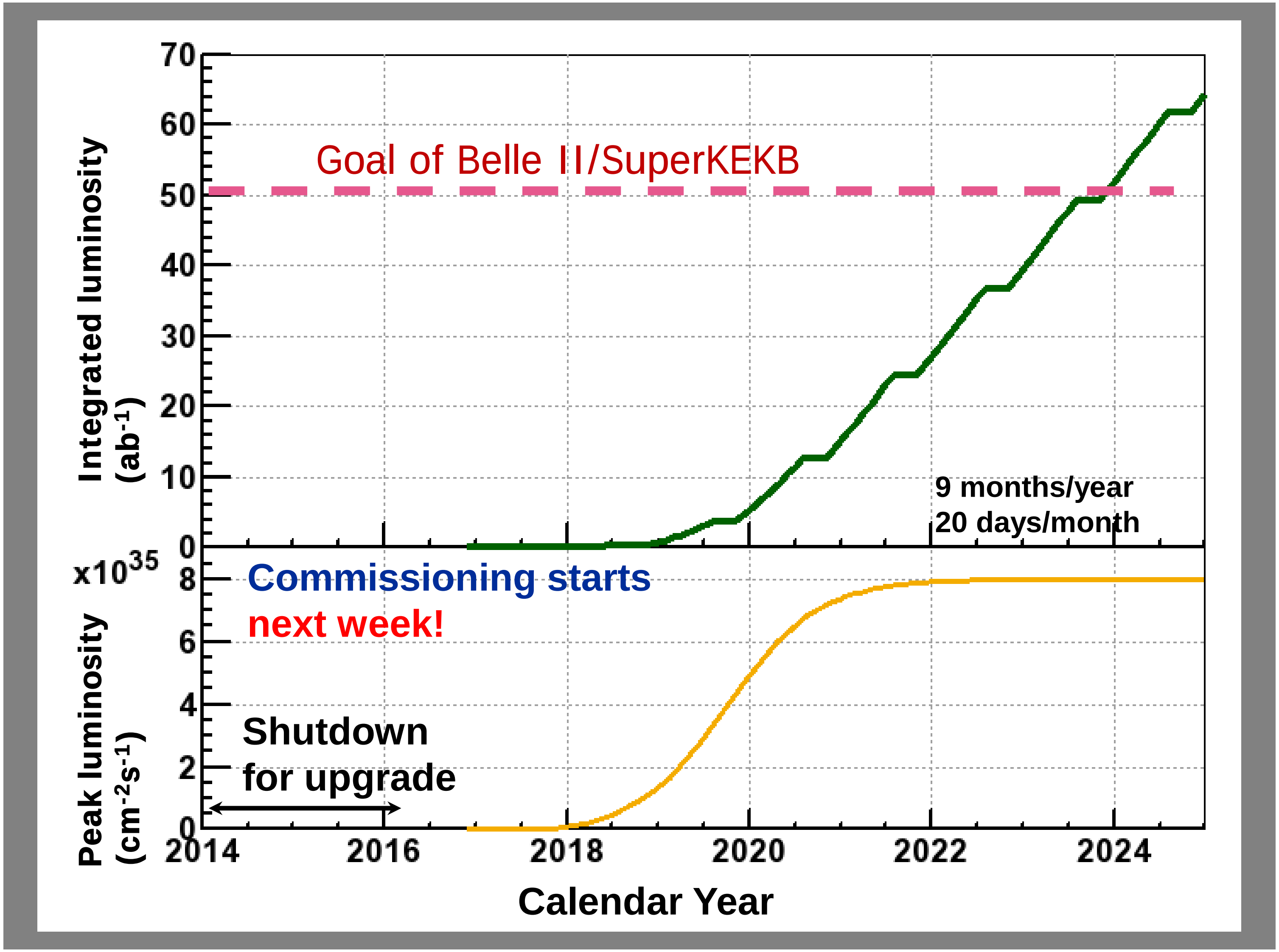
Beast II: the commissioning detector



Outer Detector Installation

A platform for the TOP detector practice installation

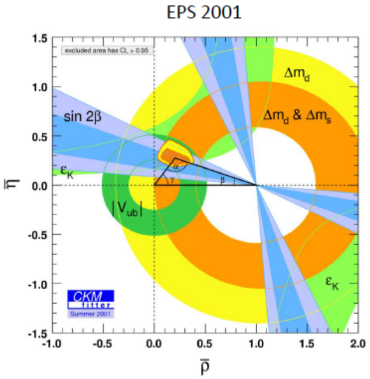
SuperKEKB luminosity projection

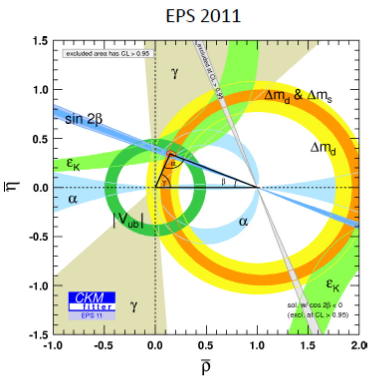


Commissioning starts next week!

Shutdown for upgrade

Summary





- B factories have proven to be an excellent tool for flavour physics as well for searches for new hadronic states, with reliable long term operation, constant improvement of the performance, achieving and surpassing design performance
- Super B factory at KEK under construction 2010-15 → SuperKEKB+Belle II, L x40, construction at full speed
- Expect a new, exciting era of discoveries, and a friendly competition and complementarity with LHCb and BESIII

Belle II

Super
KEKB
uest for BSM

Additional slides

B(*)B* molecular interpretation

Bondar, Garmash, Milstein, Mizuk, Voloshin
PRD84 054010 (arXiv:1105.4473)

$$|Z_b'\rangle = \frac{1}{\sqrt{2}} 0^{-}_{bb} \otimes 1^{-}_{Qq} - \frac{1}{\sqrt{2}} 1^{-}_{bb} \otimes 0^{-}_{Qq}$$

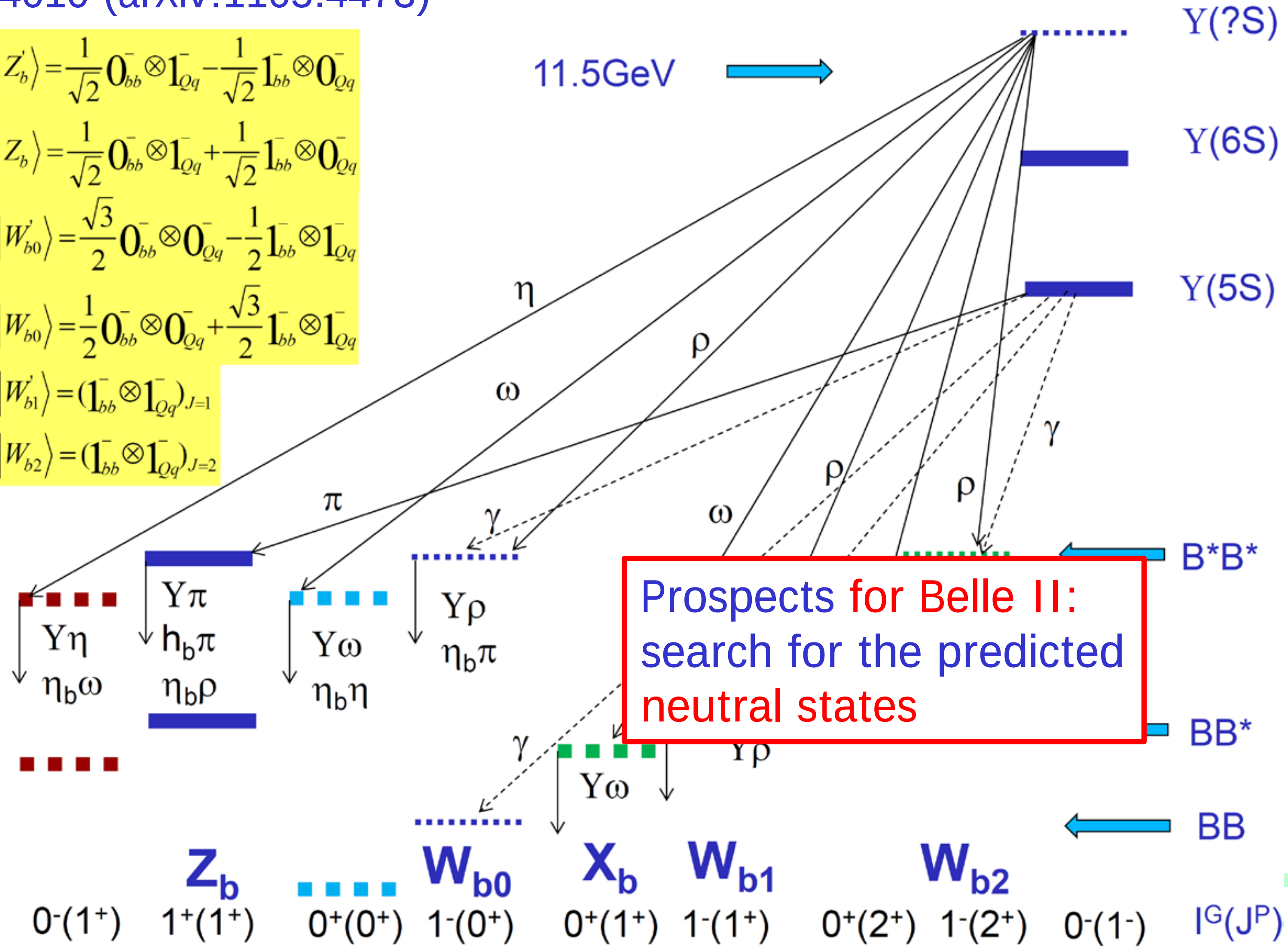
$$|Z_b\rangle = \frac{1}{\sqrt{2}} 0^{-}_{bb} \otimes 1^{-}_{Qq} + \frac{1}{\sqrt{2}} 1^{-}_{bb} \otimes 0^{-}_{Qq}$$

$$|W_{b0}'\rangle = \frac{\sqrt{3}}{2} 0^{-}_{bb} \otimes 0^{-}_{Qq} - \frac{1}{2} 1^{-}_{bb} \otimes 1^{-}_{Qq}$$

$$|W_{b0}\rangle = \frac{1}{2} 0^{-}_{bb} \otimes 0^{-}_{Qq} + \frac{\sqrt{3}}{2} 1^{-}_{bb} \otimes 1^{-}_{Qq}$$

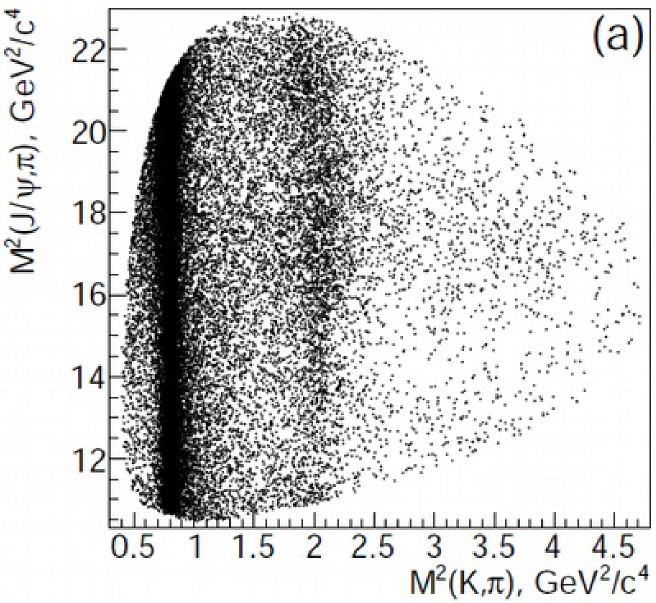
$$|W_{b1}'\rangle = (1^{-}_{bb} \otimes 1^{-}_{Qq})_{J=1}$$

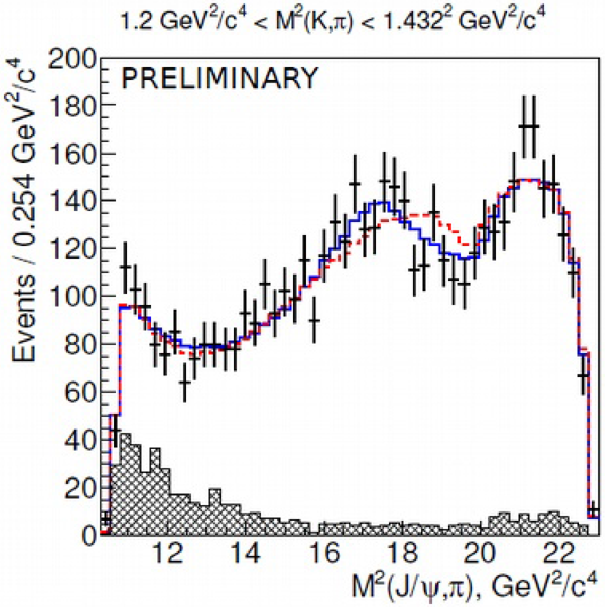
$$|W_{b2}\rangle = (1^{-}_{bb} \otimes 1^{-}_{Qq})_{J=2}$$

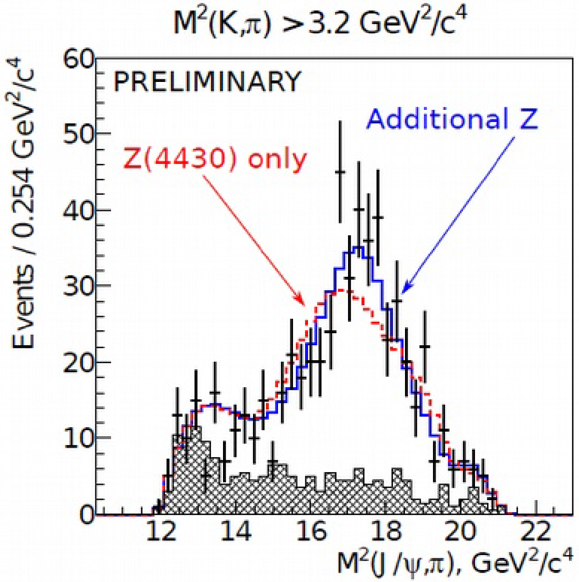


Prospects for Belle II: search for the predicted neutral states

A new charged charmonium in $B \to J/\psi\, \pi^+ K$







- 4D amplitude analysis
- 10 K* resonances, $Z^+(4430)$, $Z^+(4200)$ → new
- 6.6σ significance
- M = 4196 $^{+31}_{-29}$ $^{+17}_{-13}$ MeV/c2
- Γ = 370 ± 70 $^{+70}_{-132}$ MeV
- $J^P = 1^+$

K. Chilikin, R. Mizuk, PRD 90, 112009 (2014)

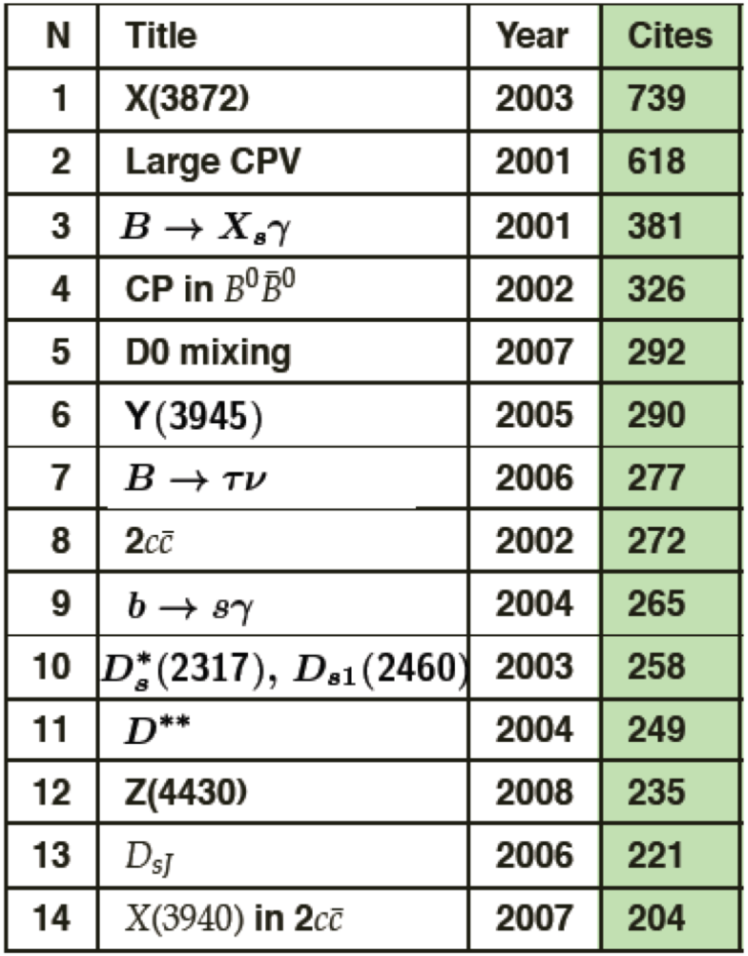
B factories and hadron spectroscopy

B factories have found most of the still missing pieces in bottomonium and charmonium spectra.

Belle, Babar, BES-III and LHCb are studying a plethora of new states, the so called XYZ mesons, which require a spectroscopy with new degrees of freedom (tetraquarks, molecules, hybrids).

Many new questions arose from unexpected states near the open charm/beauty thresholds.

A lot more to be explored with considerably larger data sets!

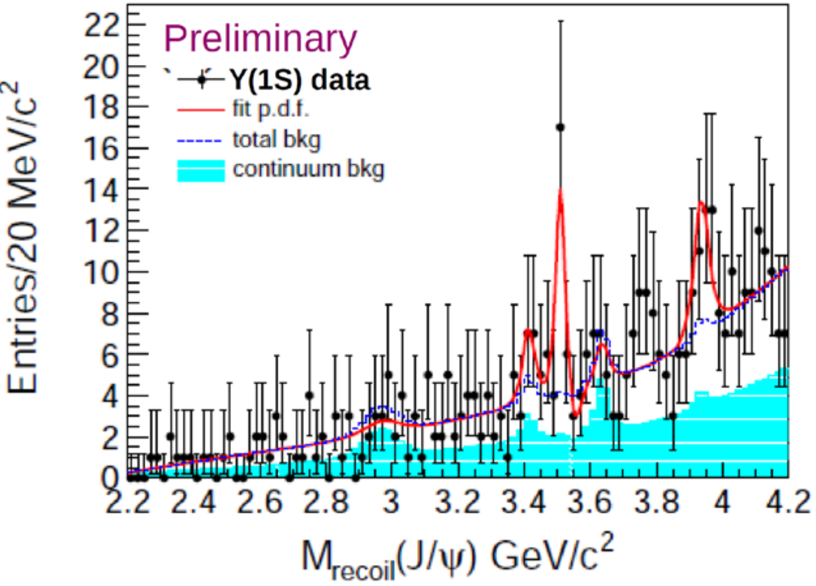


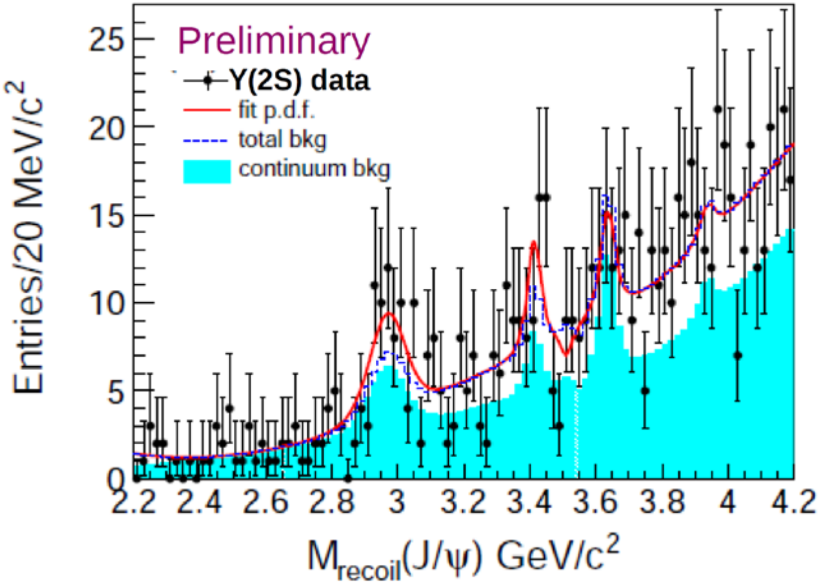
N	Title	Year	Cites
1	X(3872)	2003	739
2	Large CPV	2001	618
3	$B \to X_s\gamma$	2001	381
4	CP in $B^0\bar{B}^0$	2002	326
5	D0 mixing	2007	292
6	Y(3945)	2005	290
7	$B \to \tau\nu$	2006	277
8	$2c\bar{c}$	2002	272
9	$b \to s\gamma$	2004	265
10	$D_s^*(2317)$, $D_{s1}(2460)$	2003	258
11	D^{**}	2004	249
12	Z(4430)	2008	235
13	D_{sJ}	2006	221
14	X(3940) in $2c\bar{c}$	2007	204

8 out of 14 most cited Belle papers are spectroscopy related

N.B. Table needs updating...

Double-charmonium production in Υ(1,2S) decays





- Reconstruct J/ψ, look at the recoil mass
- One significant channel observed
- In good agreement with theory (NRQCD)

Channels	N_{fit}	$\Sigma\,(\sigma)$	$\mathcal{B}_R(\times 10^{-6})$	$\mathcal{B}_{th}(\times 10^{-6})$
$\Upsilon(1S) \to J/\psi + \eta_c$	-5.0 ± 6.3	–	< 2.2	$3.9^{+5.6}_{-2.3}$
$\Upsilon(1S) \to J/\psi + \chi_{c0}$	6.0 ± 5.6	1.3	< 3.4	1.3
$\Upsilon(1S) \to J/\psi + \chi_{c1}$	19.9 ± 6.2	4.6	$3.98 \pm 1.24 \pm 0.22$	4.9
$\Upsilon(1S) \to J/\psi + \chi_{c2}$	-3.2 ± 4.0	–	< 1.4	0.20
$\Upsilon(1S) \to J/\psi + \eta_c'$	-2.1 ± 6.0	–	< 2.2	$2.0^{+3.4}_{-1.4}$
$\Upsilon(1S) \to J/\psi + X(3940)$	19.0 ± 8.7	2.8	< 5.4	–
$\Upsilon(1S) \to \psi' + \eta_c$	-5.0 ± 3.9	–	< 3.6	$1.7^{+2.4}_{-1.0}$
$\Upsilon(1S) \to \psi' + \chi_{c0}$	2.1 ± 4.1	0.6	< 6.5	–
$\Upsilon(1S) \to \psi' + \chi_{c1}$	0.2 ± 3.6	0.1	< 4.5	–
$\Upsilon(1S) \to \psi' + \chi_{c2}$	-6.7 ± 2.3	–	< 2.1	–
$\Upsilon(1S) \to \psi' + \eta_c'$	-5.7 ± 3.3	–	< 3.2	$0.8^{+1.4}_{-0.6}$
$\Upsilon(1S) \to \psi' + X(3940)$	-5.9 ± 4.0	–	< 2.9	–
$\Upsilon(2S) \to J/\psi + \eta_c$	16.3 ± 11.9	1.9	< 5.4	$2.6^{+3.7}_{-1.6}$
$\Upsilon(2S) \to J/\psi + \chi_{c0}$	7.8 ± 9.5	1.1	< 3.4	1.1
$\Upsilon(2S) \to J/\psi + \chi_{c1}$	-4.4 ± 6.6	–	< 1.2	4.1
$\Upsilon(2S) \to J/\psi + \chi_{c2}$	2.1 ± 7.4	0.4	< 2.0	0.17
$\Upsilon(2S) \to J/\psi + \eta_c'$	-3.8 ± 10.8	–	< 2.5	$1.3^{+2.1}_{-0.9}$
$\Upsilon(2S) \to J/\psi + X(3940)$	0.7 ± 12.1	0.0	< 2.0	–
$\Upsilon(2S) \to \psi' + \eta_c$	-0.4 ± 7.9	–	< 5.1	$1.1^{+1.6}_{-0.7}$
$\Upsilon(2S) \to \psi' + \chi_{c0}$	2.6 ± 5.7	0.6	< 4.7	–
$\Upsilon(2S) \to \psi' + \chi_{c1}$	-2.8 ± 4.2	–	< 2.5	–
$\Upsilon(2S) \to \psi' + \chi_{c2}$	-13.3 ± 4.8	–	< 1.9	–
$\Upsilon(2S) \to \psi' + \eta_c'$	-3.0 ± 5.9	–	< 3.3	$0.5^{+0.9}_{-0.4}$
$\Upsilon(2S) \to \psi' + X(3940)$	-0.3 ± 7.1	–	< 3.9	–