Spectroscopy of exotic states (Experimental aspects)

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OUTLINE

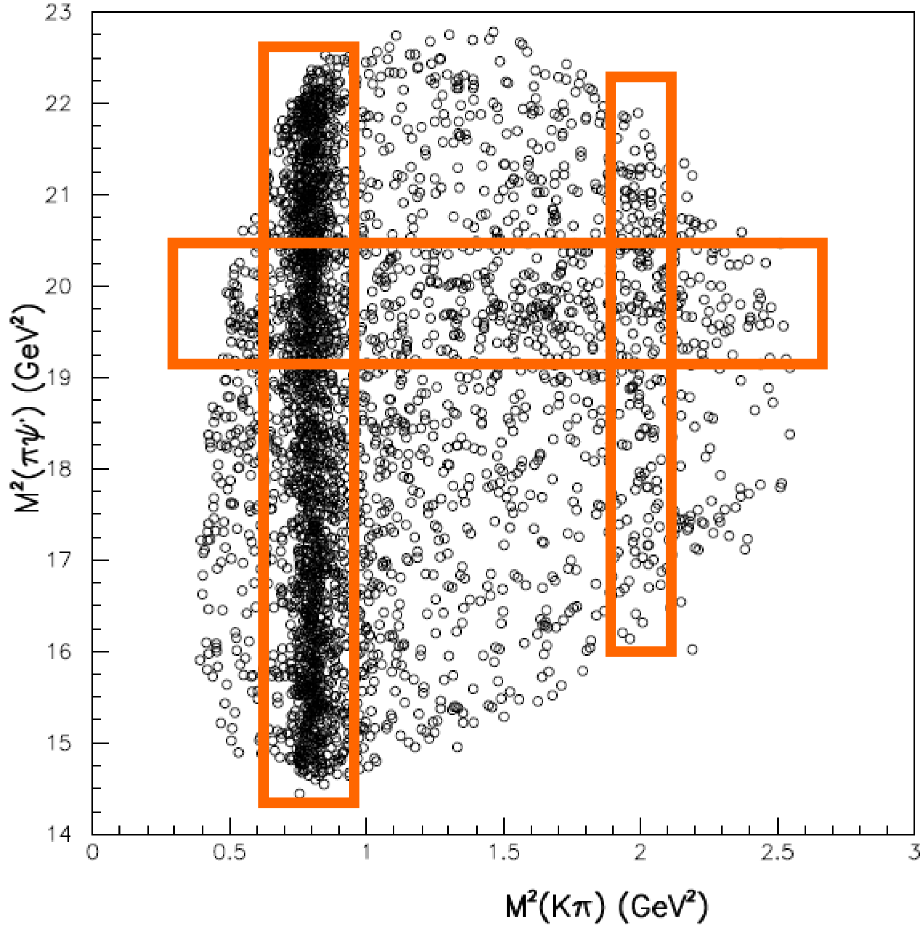
- Lecture 1: The Past and Present
  - How it all began (on a parking lot)
  - The X, the Y and the Z
  - What is „beam constraint“?
- Lecture 2: The Future
  - Dalitz formalism: how to „see“ quantum numbers
  - (Bottomonium: recoil mass, kinematic reflections $\rightarrow$ BACKUP)
  - Belle II (ready to take data ?)
  - Panda, an X factory! („detailed balance“)

Lecture 2

$B^0 \rightarrow K^+ \psi' \pi^-$

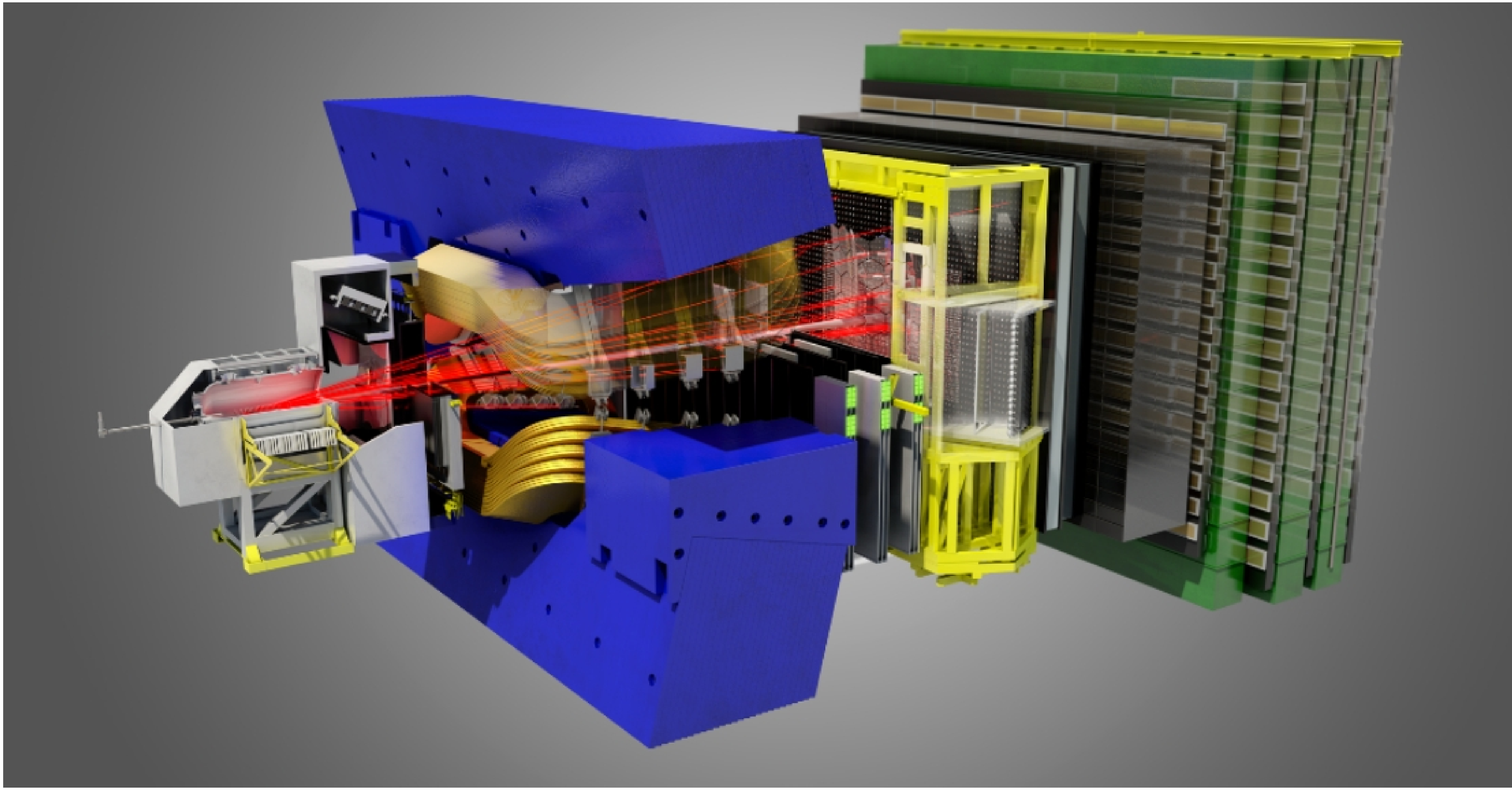
$\psi' \rightarrow J/\psi \ \pi^+ \pi^-$

K*(892) **K*(1430)**



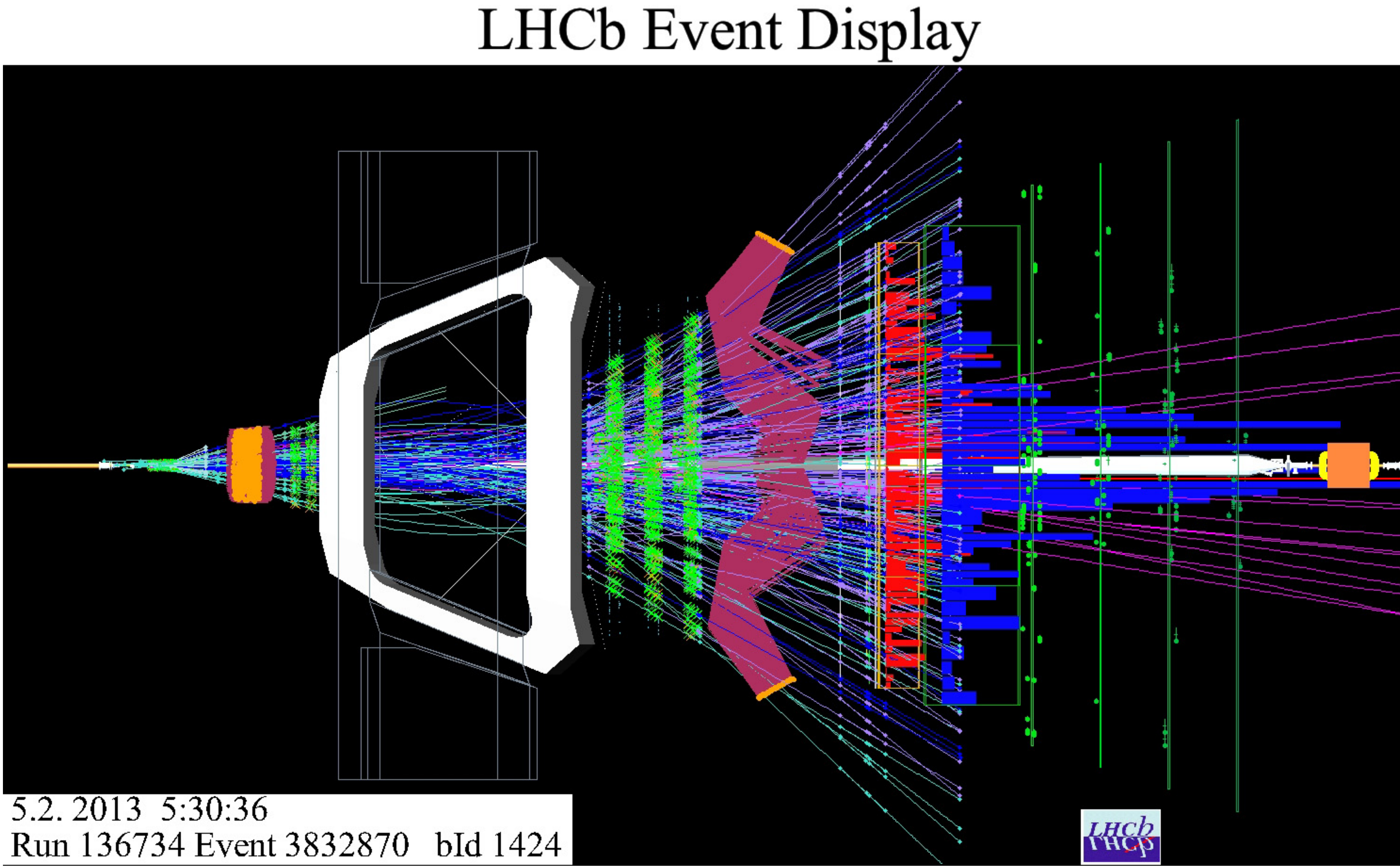
Confirmation of the $Z(4430)^+$ at LHCb

LHCb



Velo RICH1 MAGNET RICH2 MUON System
Tracking Stations Calorimeters

X(3872) event

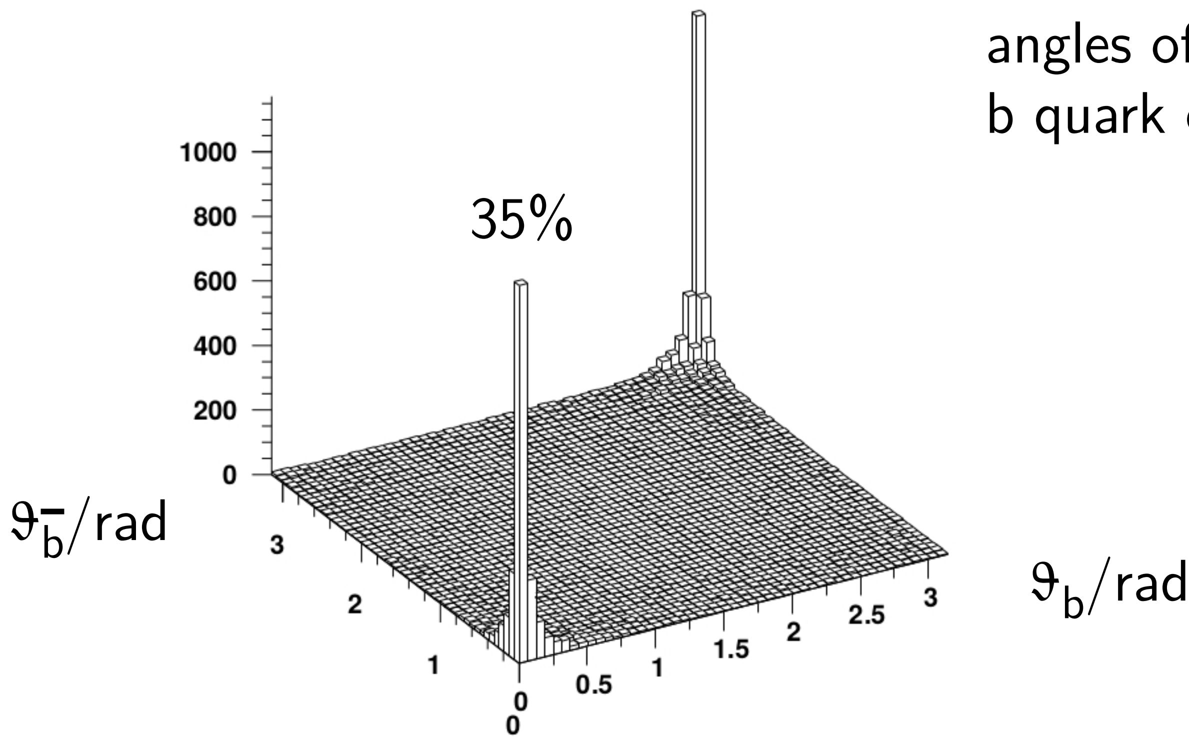

LHCb Event Display
5.2. 2013 5:30:36
Run 136734 Event 3832870 bId 1424
LHCb

Why forward boost?

Is it a fixed target experiment?

N.B. the precessor experiment, HERA-B, was fixed target with wire targets, moved into the beam.

No!
It is a pp interaction.
So, why is LHCb „peaked forward"?

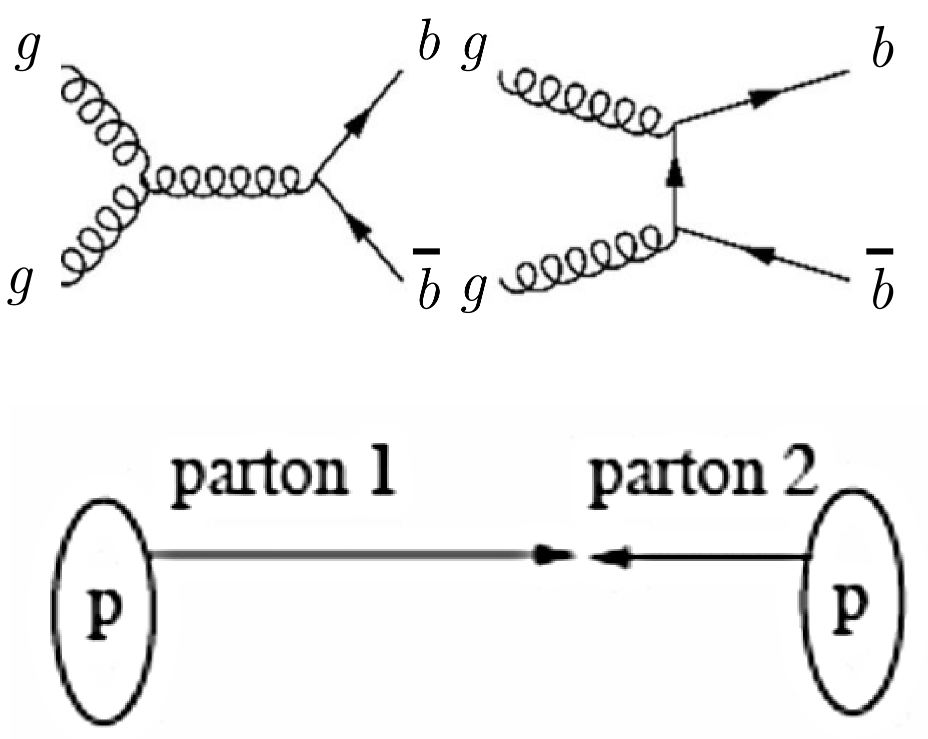


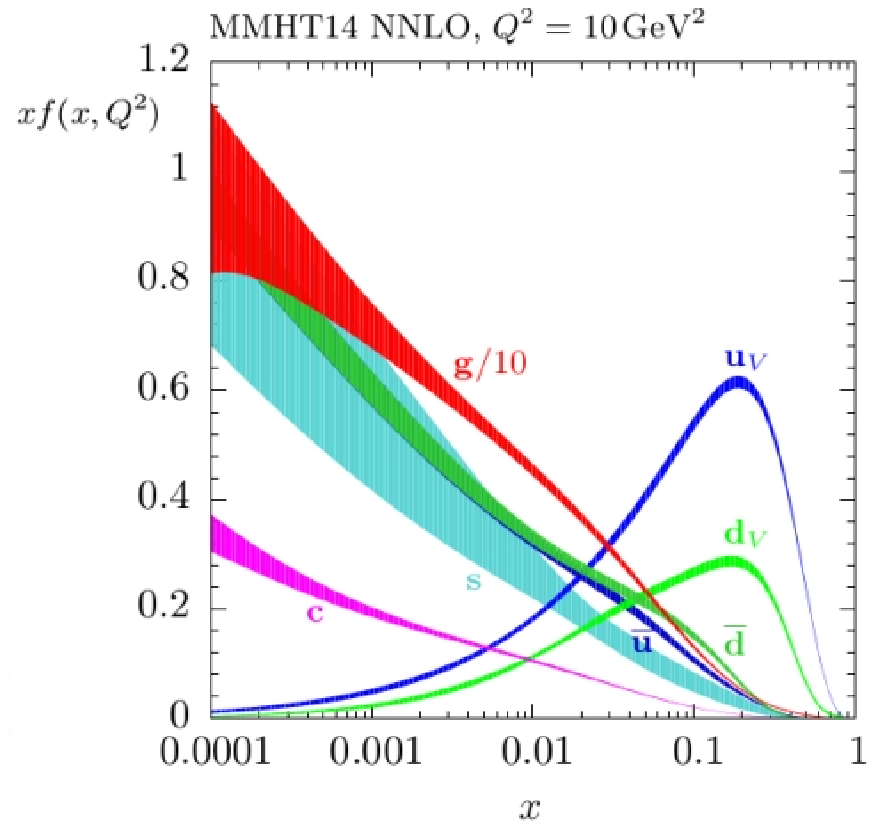
angles of the
b quark emission

b quark production at LHCb is dominated by gluon gluon fusion

$\sqrt{s'} = x_1\, x_2\, \sqrt{s}$, average product is 0.1

prefers asymmetric parton momentum fractions





LHCb

Cross sections at 14 TeV:

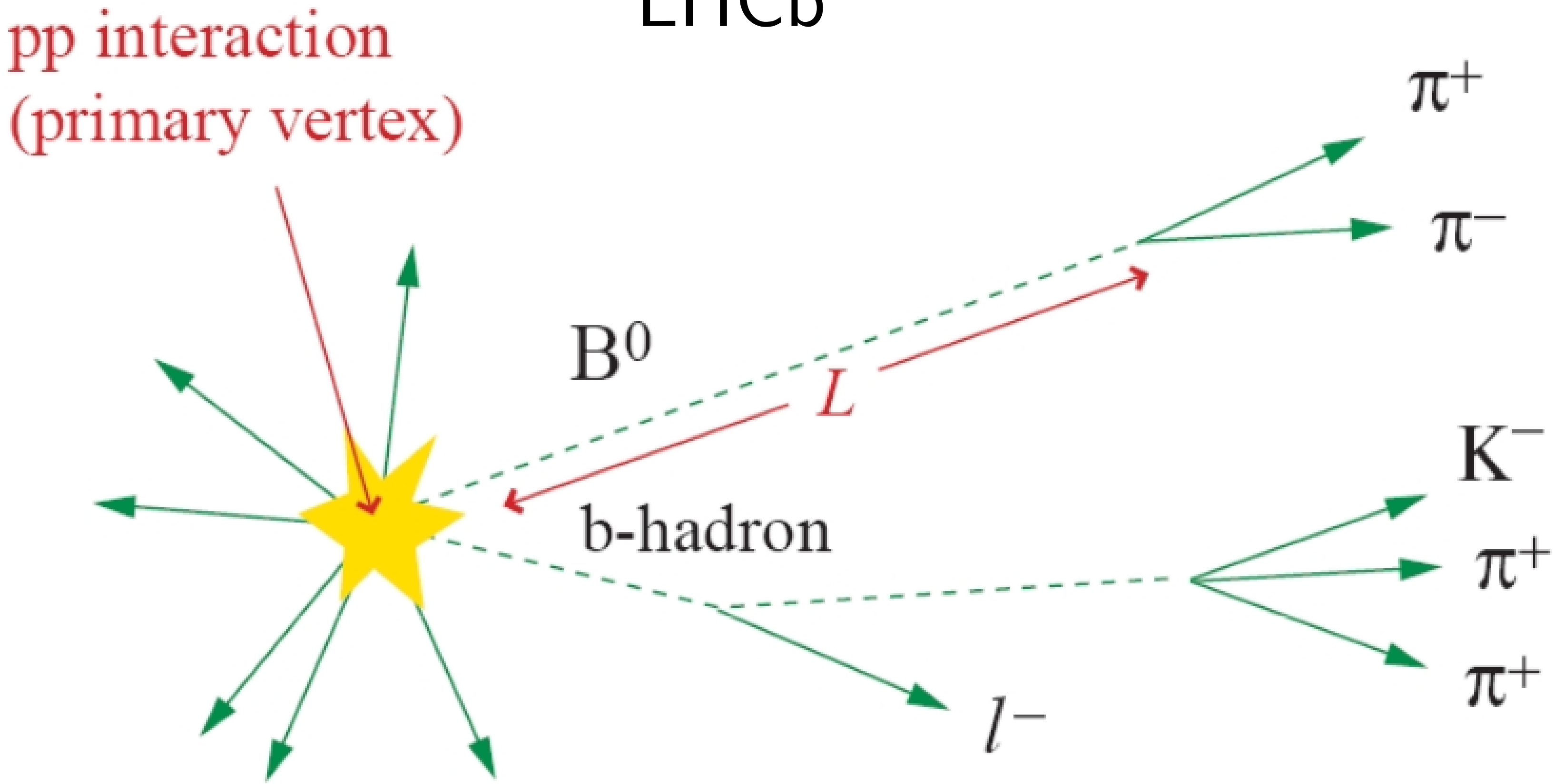
Total	100 mb
Inelastic	80 mb
$c\bar{c}$	3.5 mb
$b\bar{b}$	500 μb

remember Belle: 1.2 nb

In 1 in every 200 collisions a bb pair is produced

needs a clever trigger („High level trigger“)

LHCb

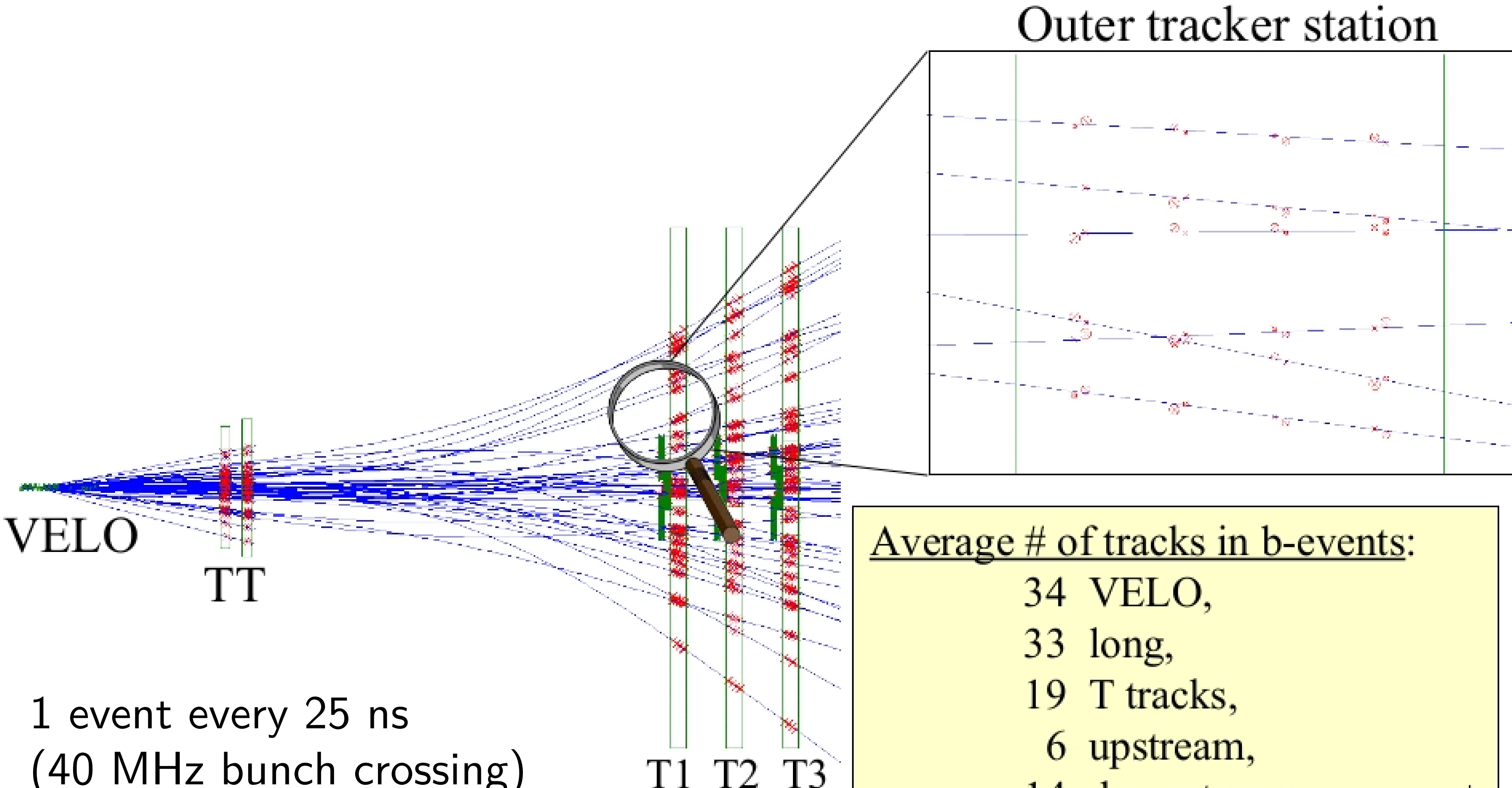


- Typical decay length of *B* hadron ~ 7 mm
- Decay products with p ~ 1 – 200 GeV

Advantage: high momentum
detector materials don‘t have to be very thin!

Belle
~200 um
1-4 GeV

LHCb



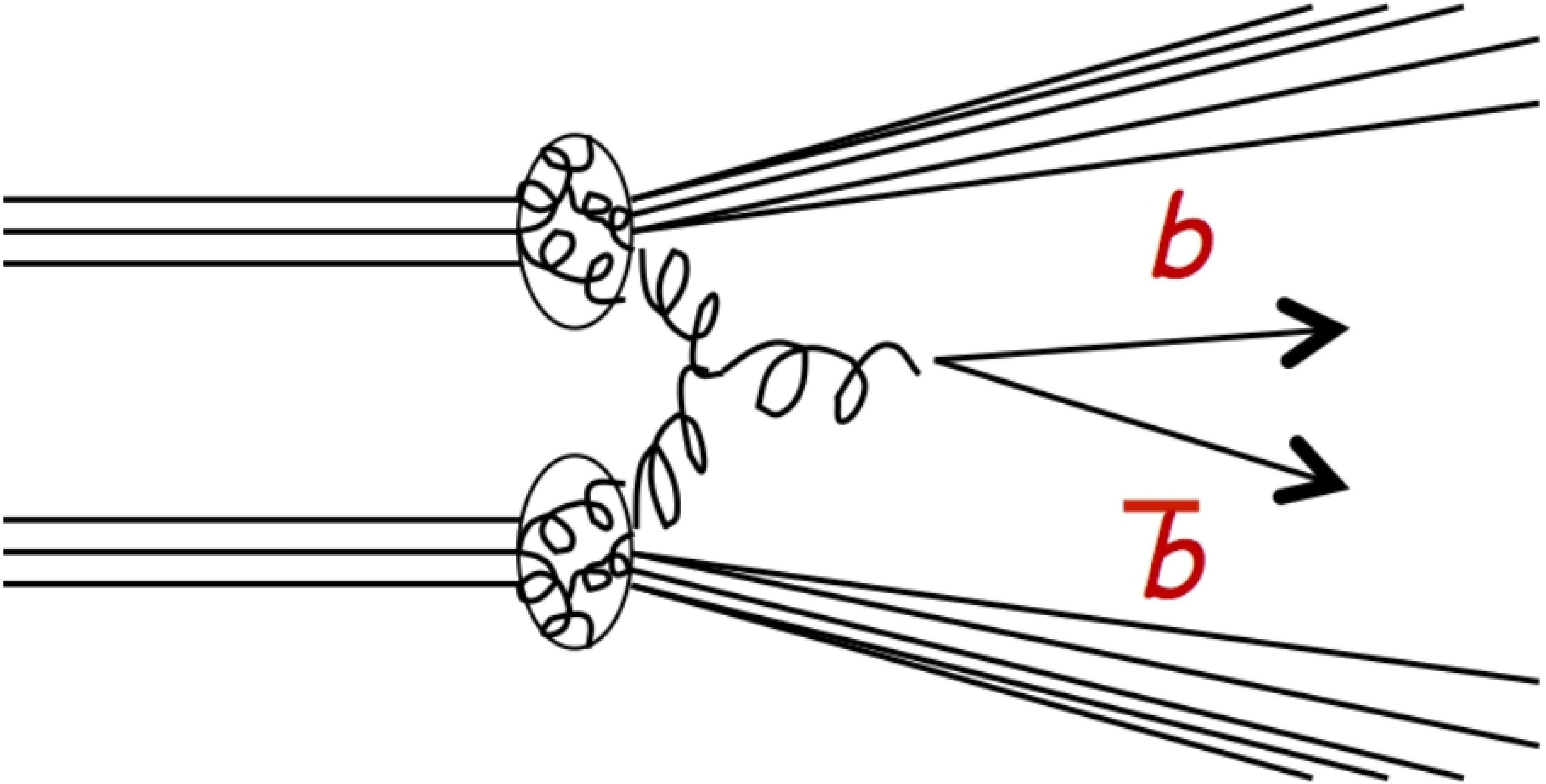
Average # of tracks in b-events:

	34	VELO,
	33	long,
	19	T tracks,
	6	upstream,
	14	downstream +
Total	106	reconstructed tracks

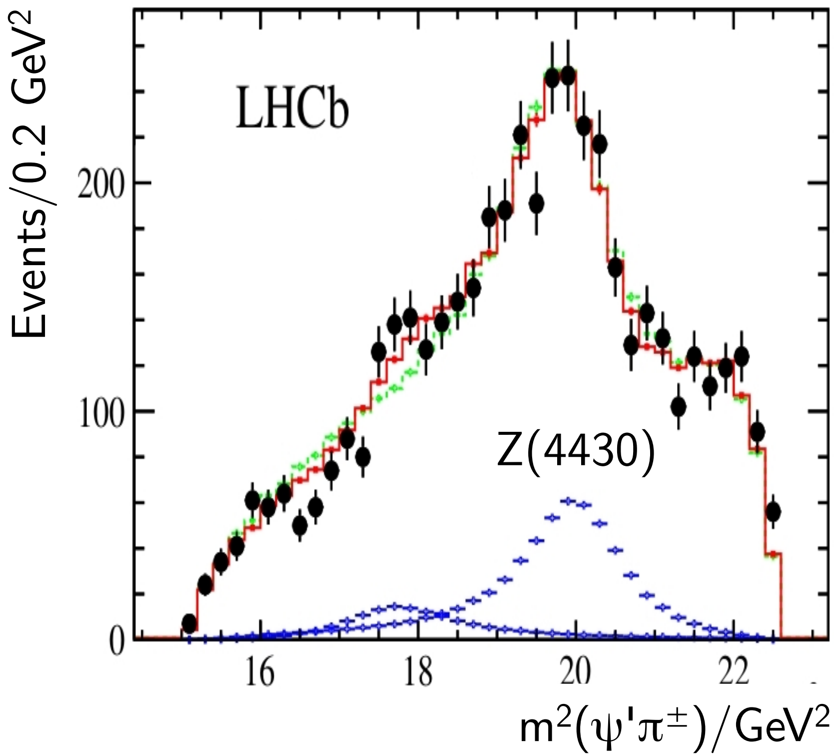
1 event every 25 ns
(40 MHz bunch crossing)

Uli Uwer, Heidelberg

Why so many tracks at LHCb ?


b
b̄

Confirmation of the $Z_c(4430)^+$ in B meson decays



$$B^0 \to K^\pm \underbrace{\psi'\pi^\mp}_{\text{resonant state?}}$$

LHCb, PRL 112(2014)222002

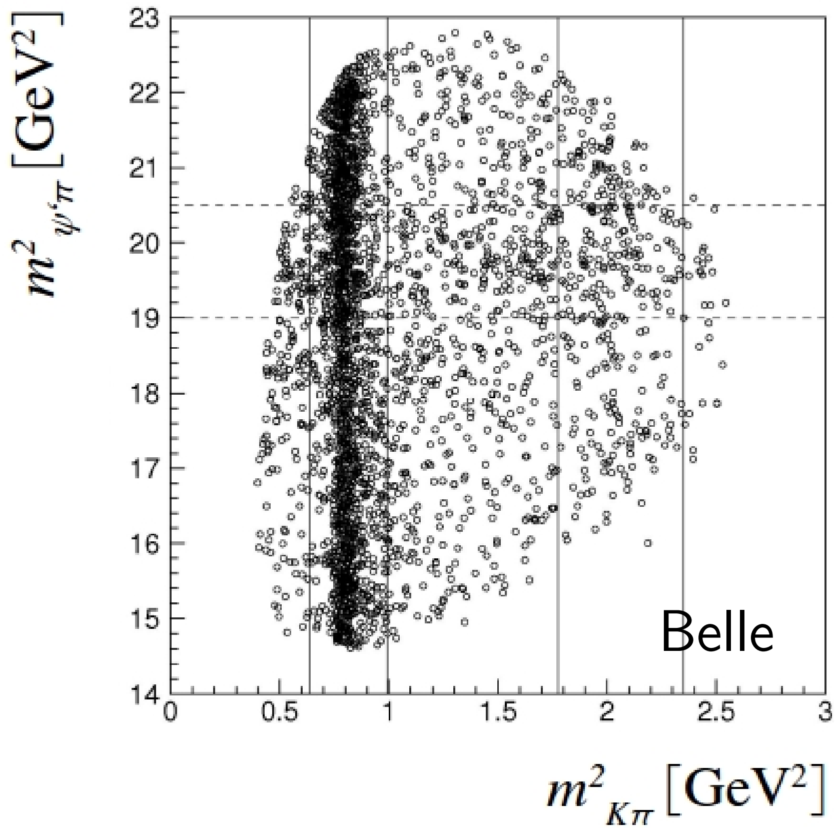
significance $\geq 13.9\sigma$

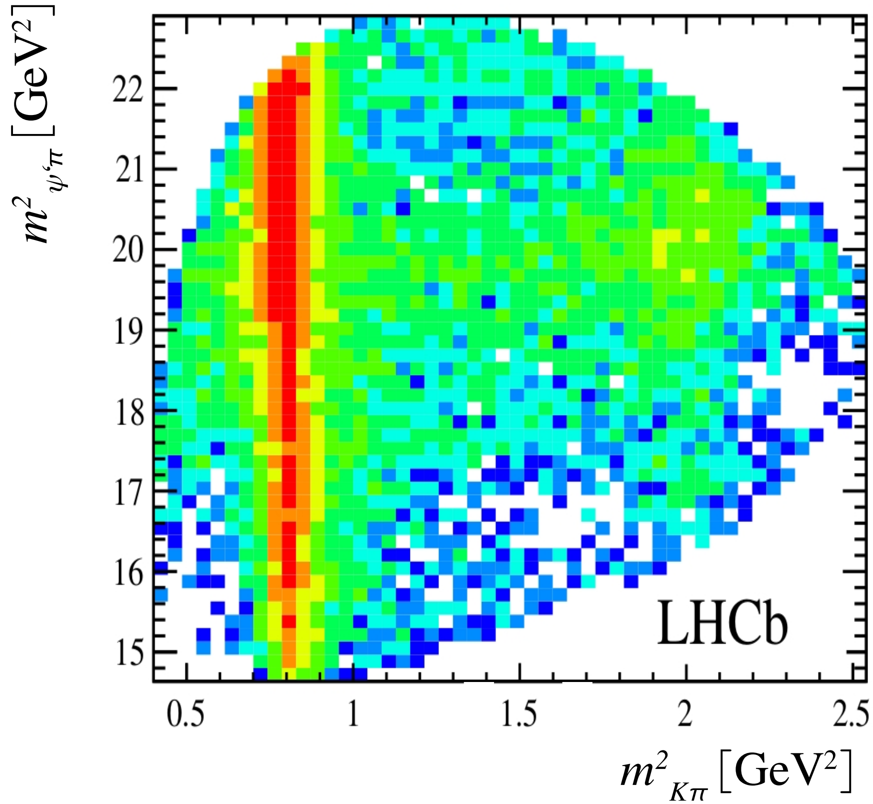
$J^P = \mathbf{1+}$ established
(other J^P rejected by $\geq 9.7\sigma$)

4-dim Dalitz Fit

$$\Phi = (M^2_{K\pi}, M^2_{J/\psi\pi}, \theta_{J/\psi}, \varphi)$$

Z(4430)

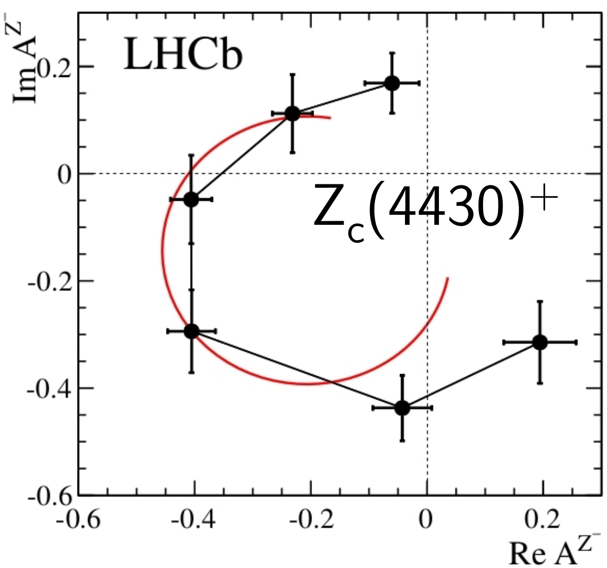




25176±174 events
factor 10 more than Belle

ARGAND PLOT: resonant character of Z^+ states

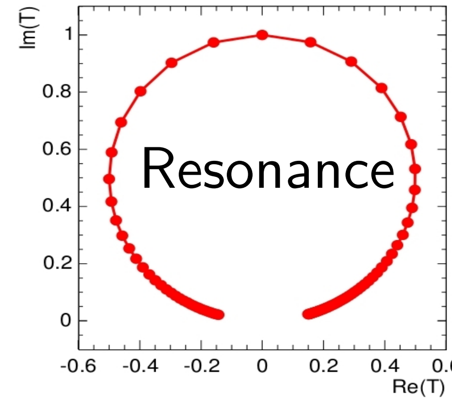
LHCb, PRL 112(2014)222002



$$\frac{m\Gamma}{s - m^2 - im\Gamma}$$

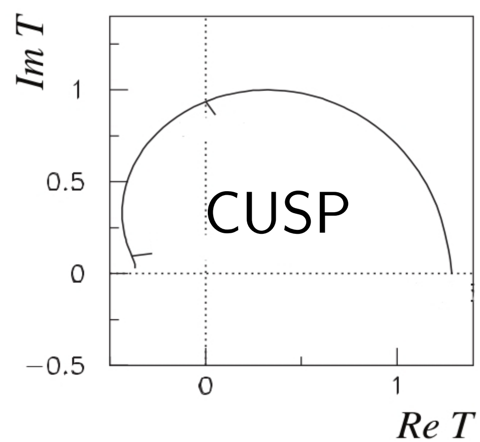
clockwise
or
counter-clockwise?

K. Peters, arXiv:hep-ph/0412069



phase motion 180°

D. Bugg, EPL 96(2011)11002



positive Im(T) only
phase motion not 180°

Why a Breit-Wigner has counter clockwise phase motion.

$$\frac{m\Gamma}{s - m^2 + im\Gamma} = \frac{m\Gamma s - m^3\Gamma}{(s-m^2)^2 + m^2\Gamma^2} - i\frac{m^2\Gamma^2}{(s-m^2)^2 + m^2\Gamma^2}$$

PDG convention

Belle and LHCb convention is minus

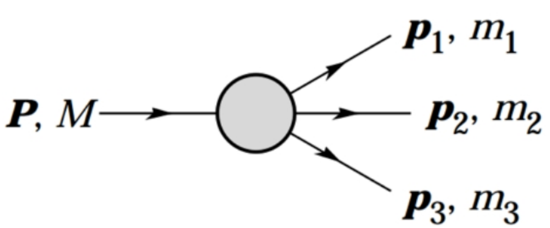
$$\mathscr{M}_{ba}^{\text{pole}}\Big|_{N=1} = -\frac{g_b\, g_a}{s - M_{\text{BW}}^2 + i\sqrt{s}\Gamma_{\text{BW}}}$$

PDG, Review „Resonances", 2016 version, p. 8

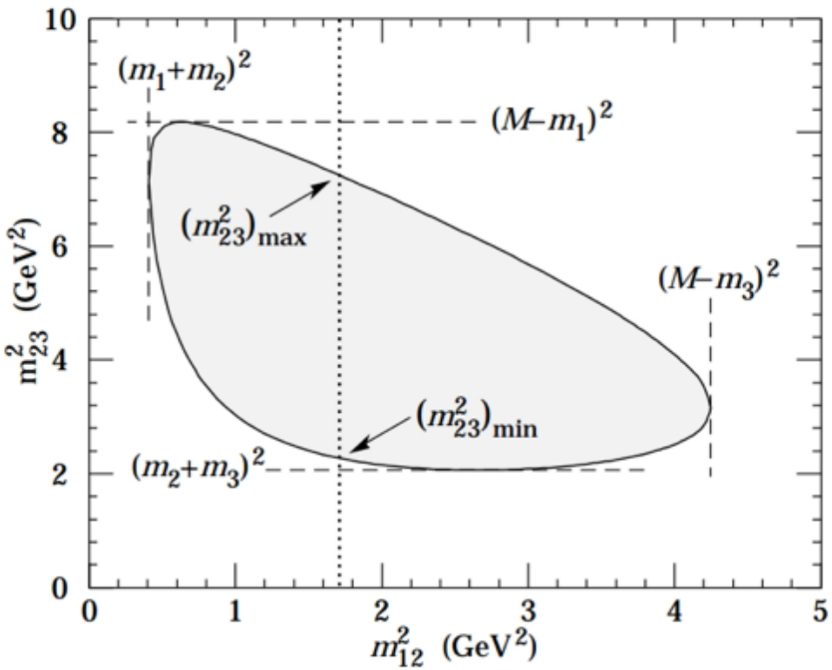
Howto determine the quantum number of the Z(4430) ?

DALITZ FORMALISM

Example: decay of a scalar to 3 scalars

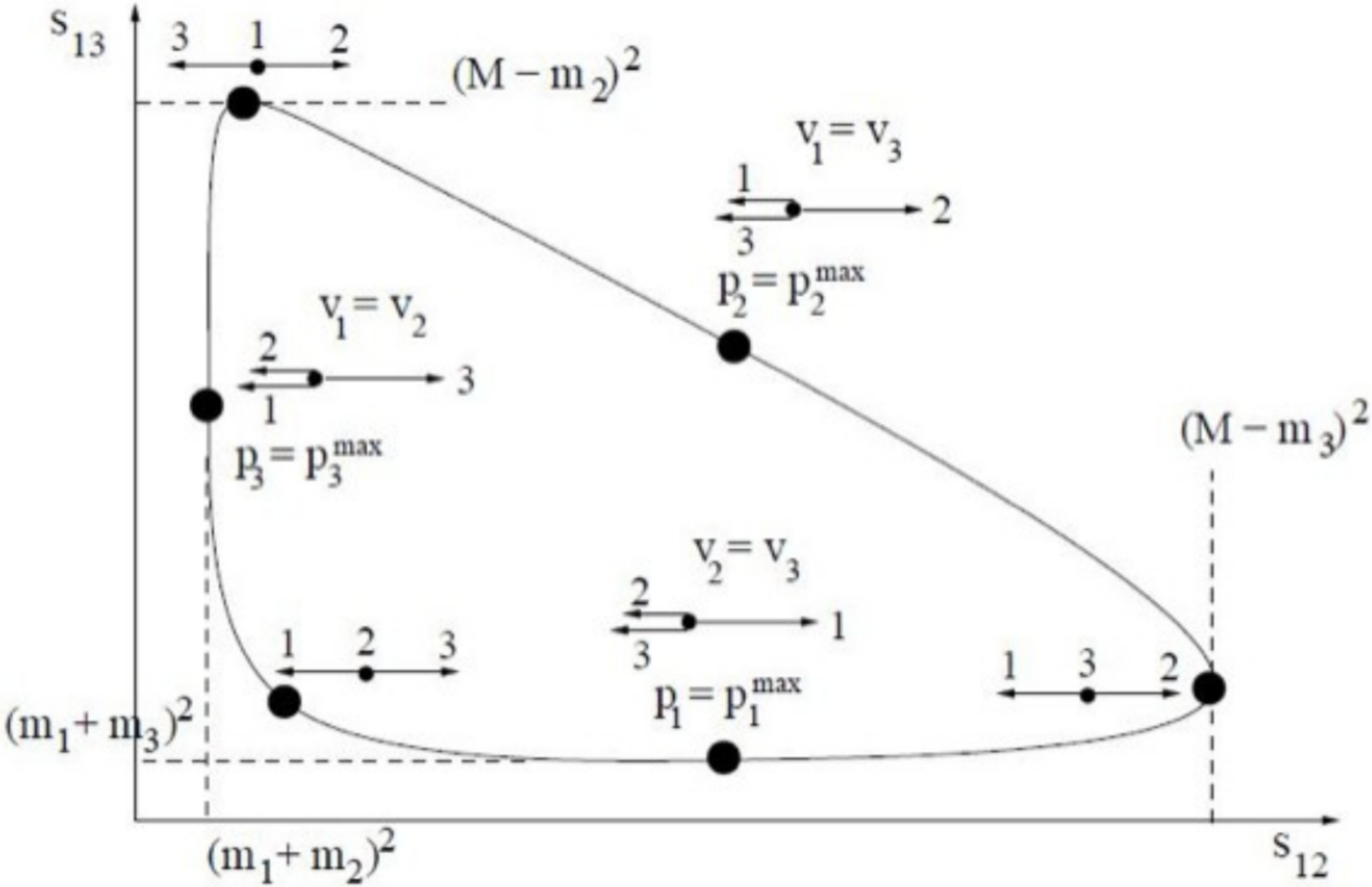


Constraint	**DOF**
3 four-vectors	12
masses m_1, m_2, m_3 fixed	−3
Energy and momentum conserved	−4
rotational invariance (Euler angles)	−3
	2

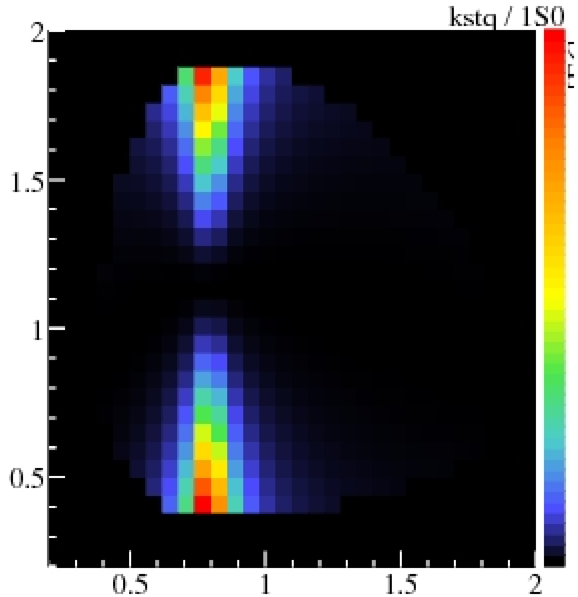


Kinematics fully determined by 2 variables!

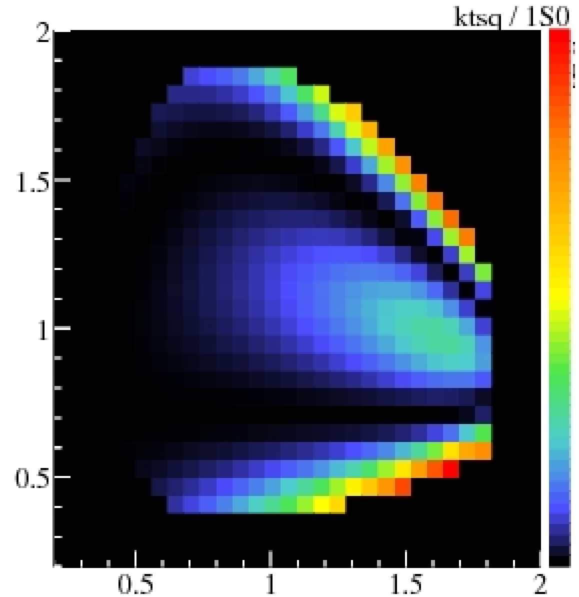
3-particle kinematics, mapped onto Dalitz space



Dalitz plot example: $p\bar{p} \to K K \pi$



K*(892)

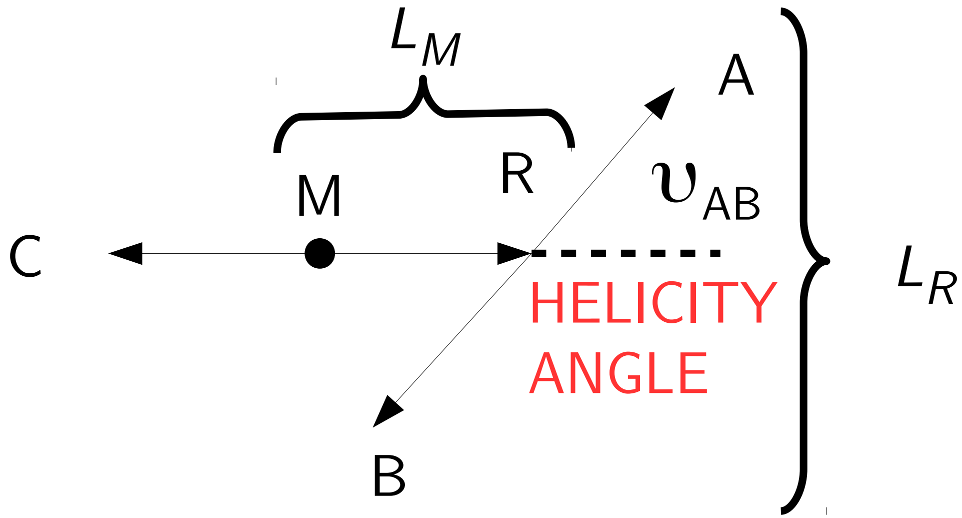


K_2*(1430)

J	L	l	Angular distribution
0	0	0	1
0	1	1	$\cos^2\theta$
0	2	2	$(\cos^2\theta - \frac{1}{3})^2$

M. T. Lakata, Ph. D. Thesis,
University of California Berkeley, 1998

Why do we „see“ angular distributions in m^2 distributions in a Dalitz plot?



$$f(m_{AB}, m_{BC}) = f_S(m_{AB}, m_{BC}) \times \varepsilon(m_{AB}, m_{BC}) + f_B(m_{AB}, m_{BC})$$

COMPLEX NUMBERS

$$f_S(m_{AB}, m_{BC}) = \sum_{\lambda} \left| \sum_{R} T_{fi}^{R,\lambda} \right|^2$$

signal density in Dalitz plot
(number of events in a bin)

Polarisations
e.g. λ=–1,0,1 for J=1

$$T_{fi}(m_{AB}, m_{BC}) = \frac{1}{m_R^2 - s_R - i m_R \Gamma_{tot}(s_R)}$$

$$\cdot F_M^{L_M} \cdot F_R^{L_R} \cdot \underbrace{\left(\frac{p_M}{m_M}\right)^{L_M} \cdot \left(\frac{p_R}{\sqrt{s_R}}\right)^{L_R}} \cdot T_\lambda \,.$$

Formfactors

Angular dependance

Momenta in the center-of-mass frames

Momentum dependance enters explicitely !

Formfactors

often: Blatt-Weisskopf barrier factors

$$F^0(z) = 1$$

$$F^1(z) = \frac{\sqrt{1+z_0}}{1+z}$$

$$F^2(z) = \frac{\sqrt{z_0^2+3z_0+9}}{z^2+3z+9}$$

$$F^3(z) = \frac{\sqrt{z_0^3+6z_0^2+45z_0+225}}{z^3+6z^2+45z+225}$$

Here $z{=}r^2p^2$ with a scale parameter representing the radius of the centrifugal barrier and usually set to $R{\simeq}1.6$ $(\mathrm{GeV/c})^{-1}$, which is $R{\simeq}$3-4 fm. For z_0 we use p_{R0} which is the R resonance daughters momentum calculated for the pole mass of R.

Width (in the Breit–Wigner Term)

$$\Gamma(s_R) = \Gamma_0\left(\frac{p_R}{p_{R0}}\right)^{2L_R+1}\frac{m_R}{\sqrt{s_R}} \cdot F_R^2$$

(again, using Blatt-Weisskopf)

Angular dependant term

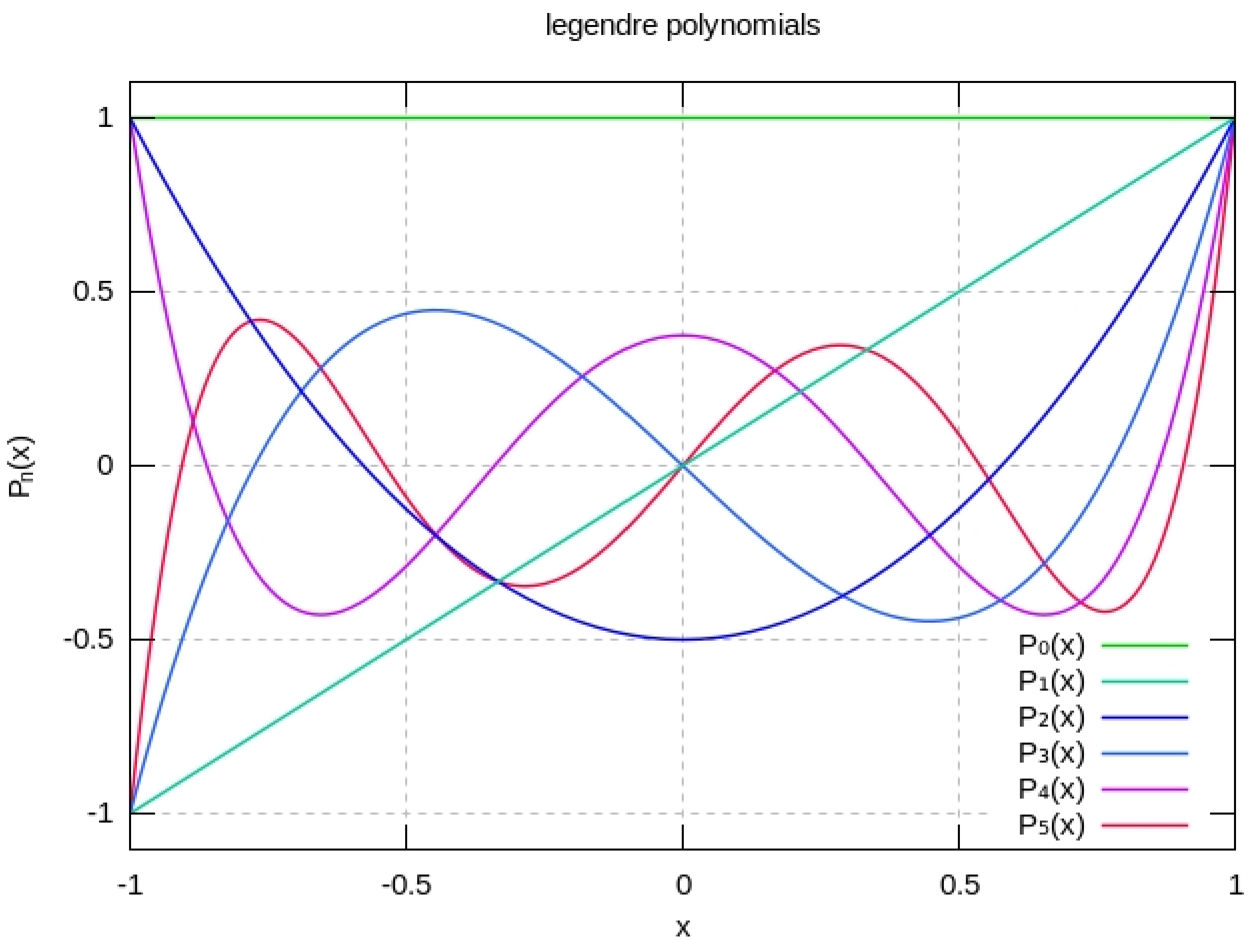
$$T_\lambda = d^J_{\lambda\lambda'}(\vartheta_{AB})$$

where J is the spin of the $R \rightarrow AB$ resonance and ϑ_{AB} its polar angle ("helicity angle"). $d^J_{\lambda\lambda'}$ are the Wigner D functions, which for $\lambda'=0$ can be expressed by the spherical harmonics

$$d^J_{\lambda 0} = \frac{4\pi}{2J+1}(-1)^\lambda Y_J^{-\lambda}$$

and for $\lambda=0$ and $\lambda'=0$ by the Legendre polynoms

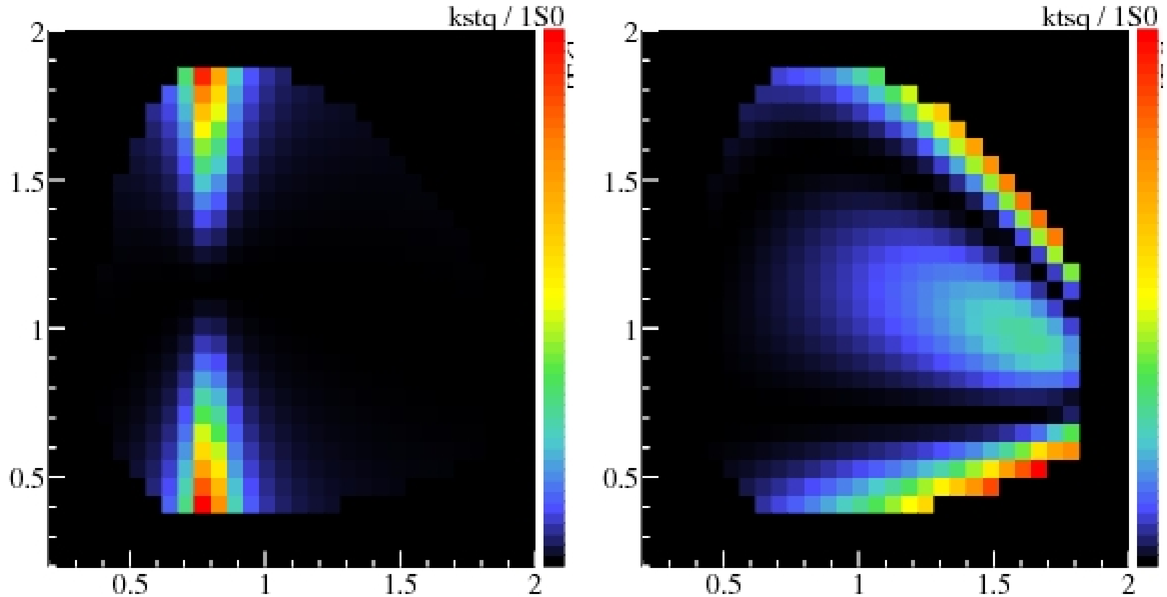
$$d^J_{00} = P_J(cos\vartheta_{AB}) \ .$$


legendre polynomials
1
0.5
0
-0.5
-1
$P_n(x)$
-1
-0.5
0
0.5
1
x
$P_0(x)$
$P_1(x)$
$P_2(x)$
$P_3(x)$
$P_4(x)$
$P_5(x)$

J is spin of resonance R

L_1	L_2	J	T_λ
0	0	0	1
1	1	0	$\cos^2(\vartheta_{AC})$
2	2	0	$(\cos^2(\vartheta_{AC})\text{-}1/3)^2$
1	0	1	1
0	1	1	1
1	1	1	$\sin^2(\vartheta_{AC})$
1	2	1	$\cos^2(\vartheta_{AC})+1/3$
2	1	1	$\cos^2(\vartheta_{AC})+1/3$
2	2	1	$(\cos(\vartheta_{AC})\sin(\vartheta_{AC}))^2$
2	0	2	1
0	2	2	1
1	1	2	$(\sin^2(\vartheta_{AC})+1/3)^2$
2	1	2	$\sin^2(\vartheta_{AC})$
2	2	2	$\cos^2(\vartheta_{AC})$

Dalitz plot example: $p\,\bar{p} \rightarrow K\,K\,\pi$



K*(892) $\qquad$ K_2*(1430)

J	L	1	Angular distribution
0	0	0	1
0	1	1	$\cos^2\theta$
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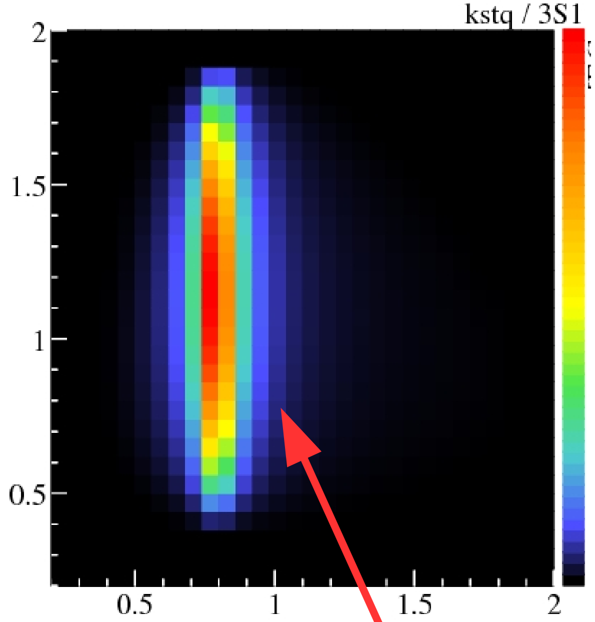
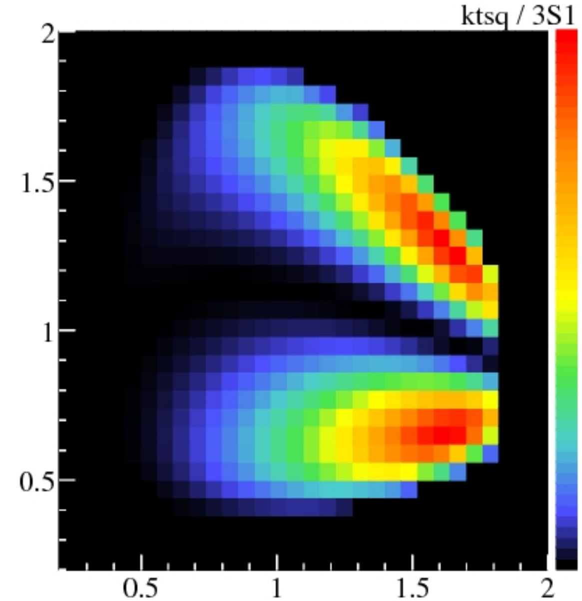
M. T. Lakata, Ph. D. Thesis,
University of California Berkeley, 1998

If J_{total}=1, then distributions change



K*(892)



K_2^*(1430)

we reach K* by L=0

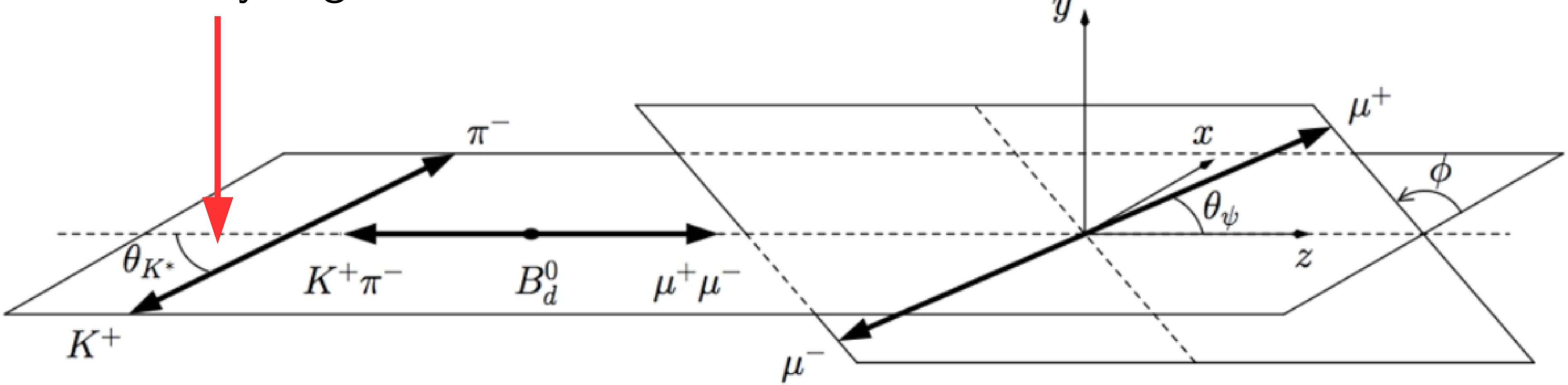
$B \rightarrow \psi' \; K \; \pi$

(search for Z(4430) is [$\psi \;\; \pi'$])

scalar → vector scalar scaler

Constraint	DOF
3 four-vectors	12
masses m_1, m_2, m_3 fixed	–3
energy and momentum conserved	–4
rotational invariance (Euler angles)	–3
vector helicity	2
	4

a helicity angle



requires 4-dim analysis!

If more than 2 variables: Dalitz plot shape becomes a function of the 3rd or 4th variable ...

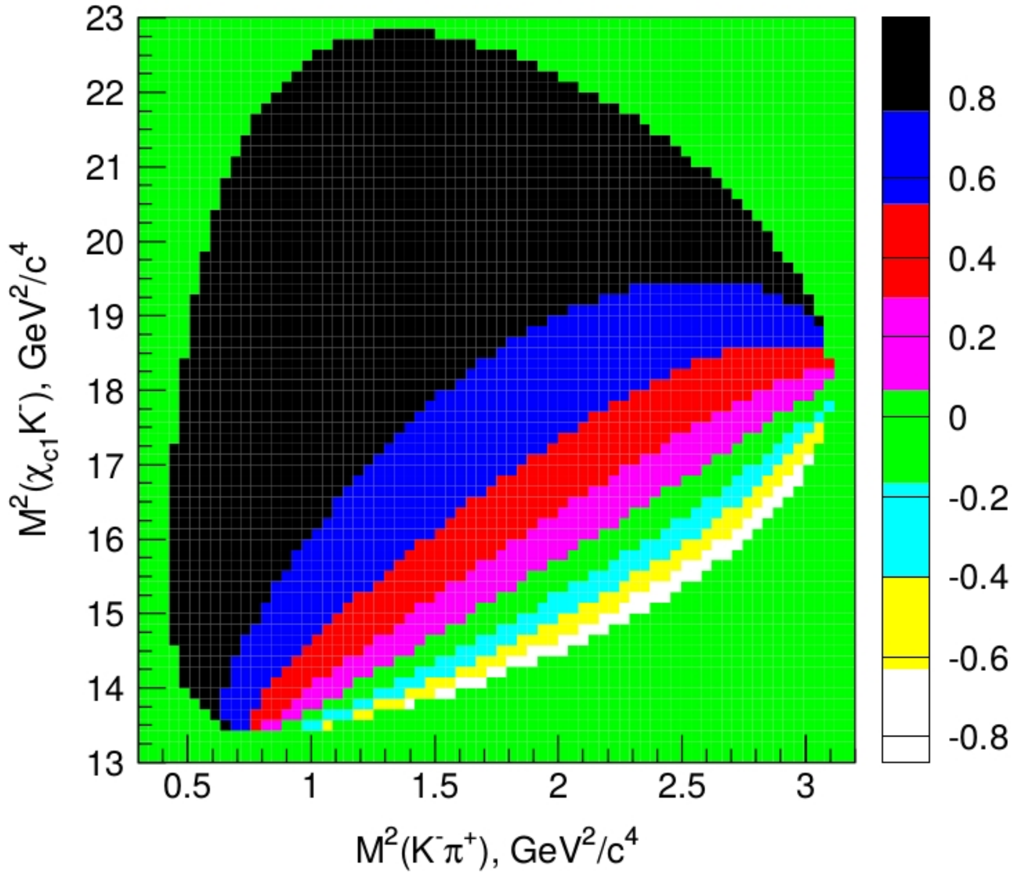


FIG. 5: $\cos\theta$ as a function of the Dalitz plot variables, where θ is the angle between the helicity axes for $K\pi$ and $\pi\chi_{c1}$ intermediate resonances.

Belle, Phys. Rev. D78(2008)072004

Legendre decomposition of Z(4430)+ data („model independent“)

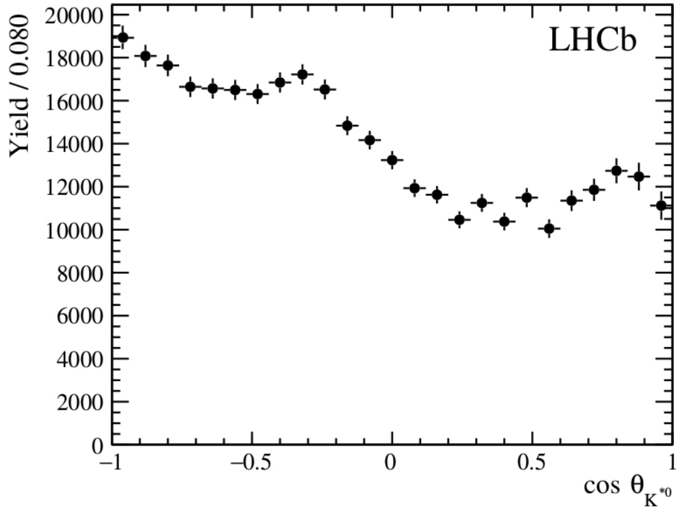
LHCb, Phys. Rev. D 92(2015)112009

$$\frac{dN}{d\cos\theta_{K^{*0}}} = \sum_{j=0}^{l_{\max}} \langle P_j^U \rangle P_j(\cos\theta_{K^{*0}})$$

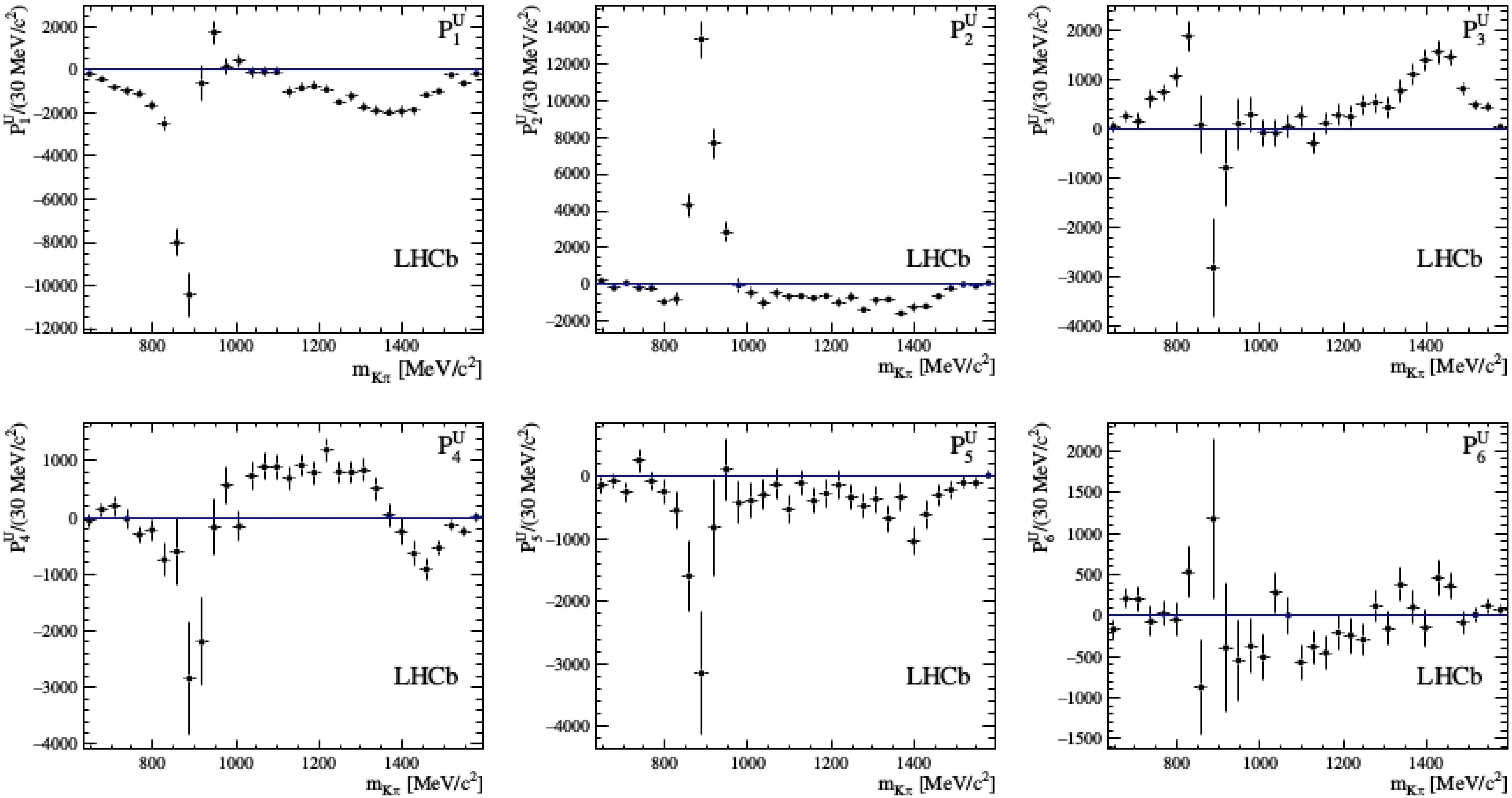
„moments“

select a certain bin in $m(K\pi)$

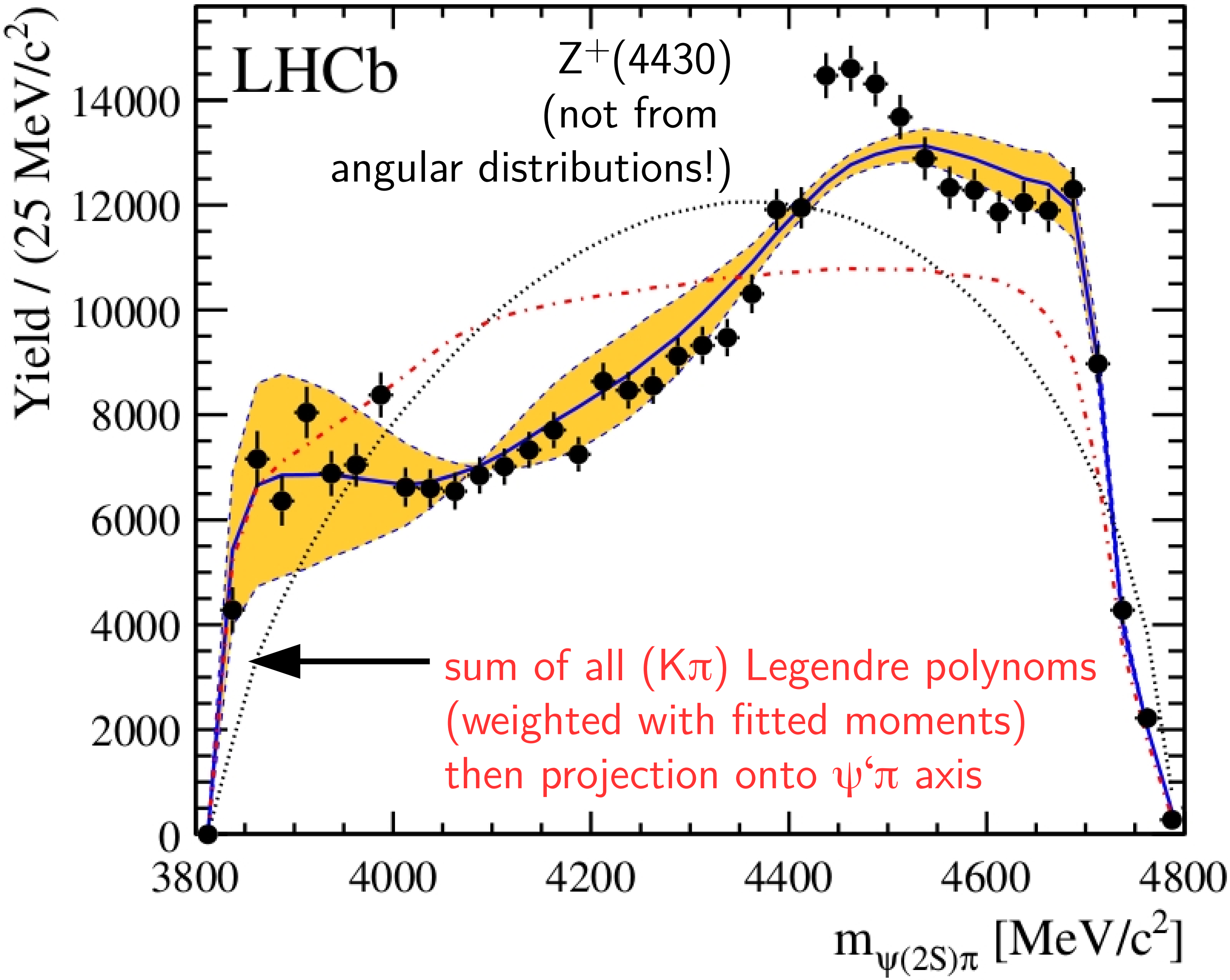
find the decomposition in Legendre polynomials in $\cos(\theta_{K*})$



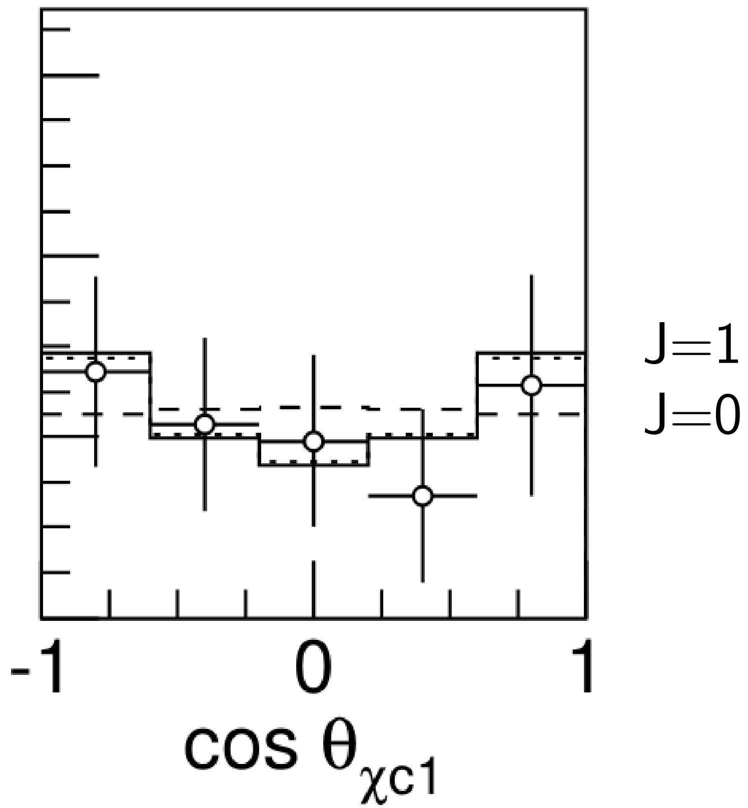
this works, because it is an orthogonal system



LHCb, Phys. Rev. D 92(2015)112009


LHCb
Z⁺(4430)
(not from
angular distributions!)
sum of all (Kπ) Legendre polynoms
(weighted with fitted moments)
then projection onto ψ'π axis
Yield / (25 MeV/c²)
14000
12000
10000
8000
6000
4000
2000
0
3800
4000
4200
4400
4600
4800
m_ψ(2S)π [MeV/c²]

Let's assume, we established J=1 for a charged Z state by Legendre polynomes in the angular distribution here: Belle, PRD 78, 072004 (2008)



How to determine, that the Z state has $J^P = 1^+$? (positive parity)

B $\rightarrow$ K Z(4430)

0– $\rightarrow$ 0– 1($+$ or $-$)

is a weak decay.

Parity may be violated!

Solution:

$B \to K\ Z(4430)$ is a <u>weak</u> decay

but

$Z(4430) \to \psi\pi$ is a <u>strong</u> decay

parity conserving !

need to check the angular distribution

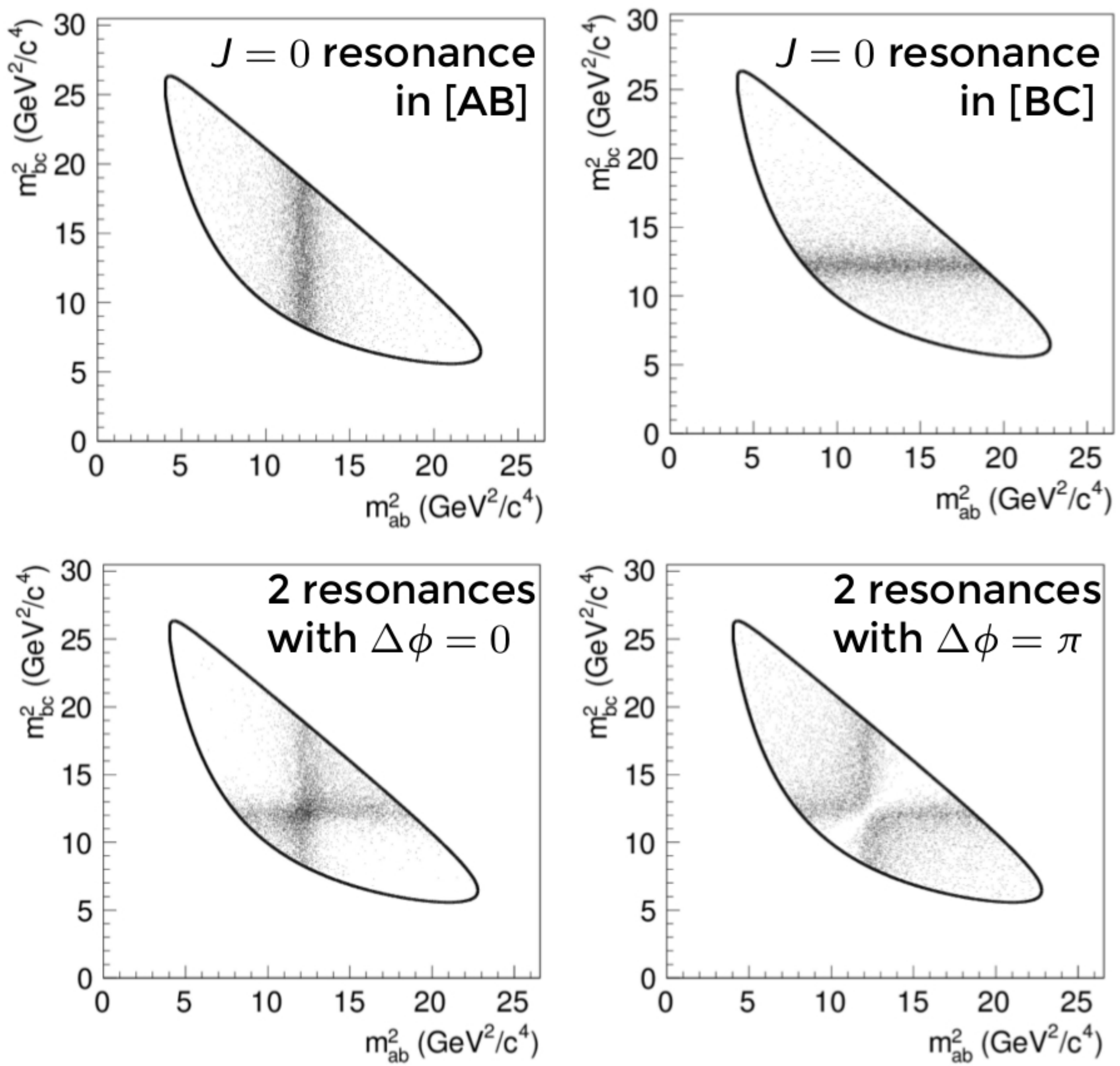
of the ψ (or the π)

in the rest frame of the Z state

1– 0– in S-wave $\to$ 1+

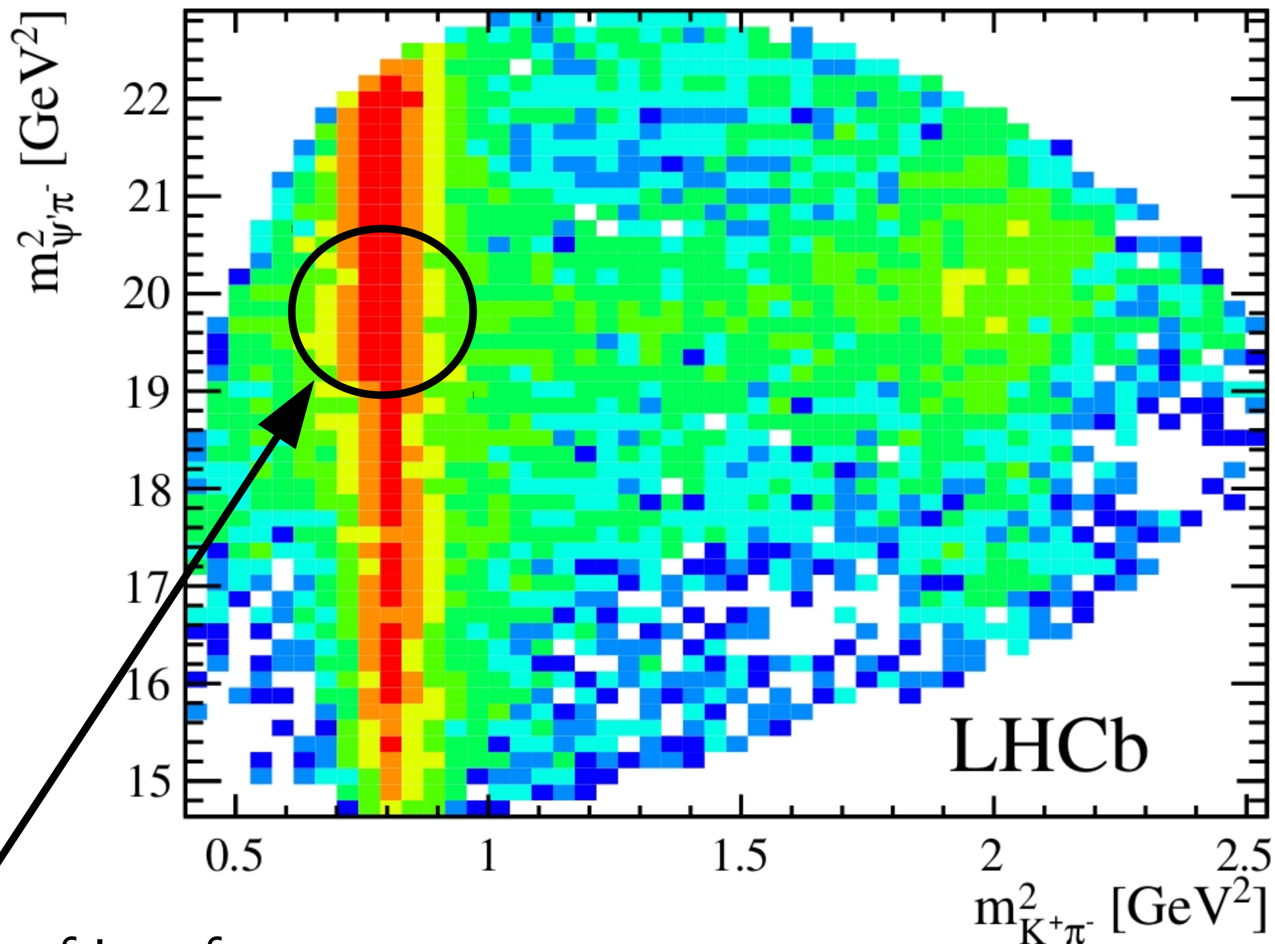
1– 0– in P-wave $\to$ 1– (or 0– or 2–)

Interlude: interference in a Dalitz plot



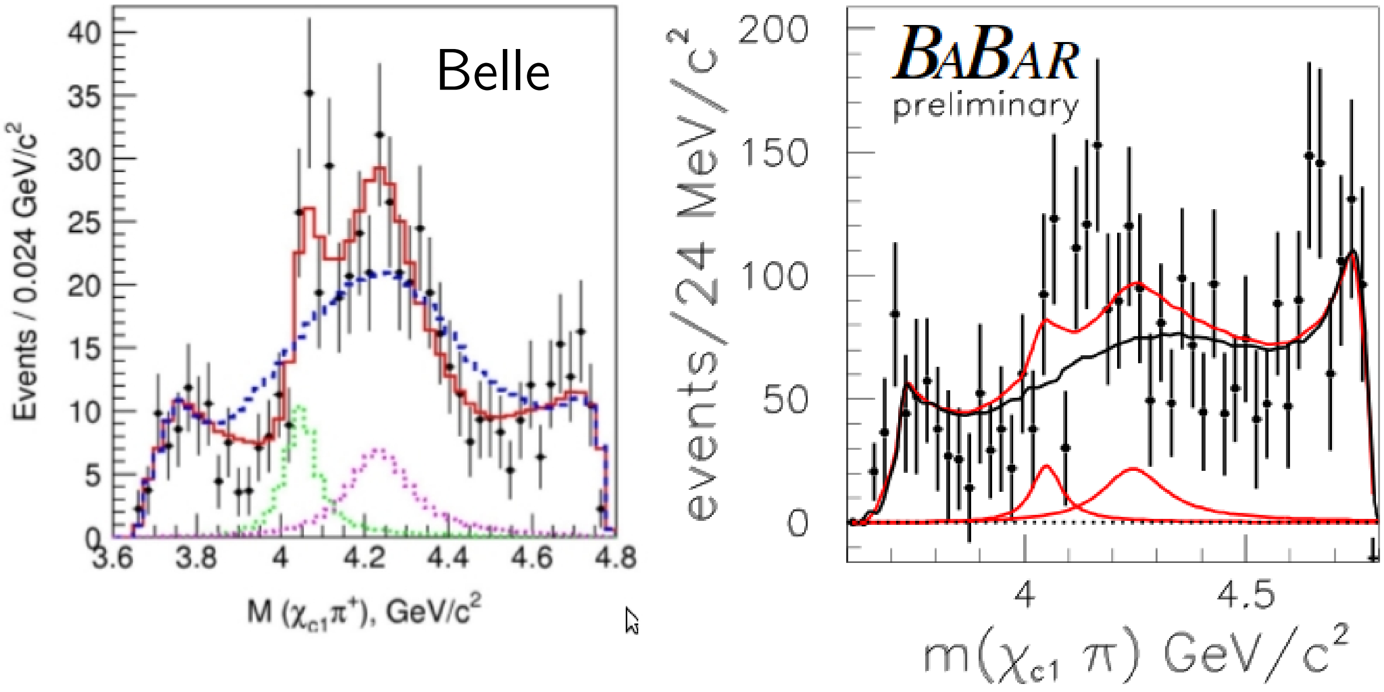
plots by
A. Palano,
S. Neubert
see also book
„Physics of the
B factories“

An easy way to see that the Z(4430) is 1+.



No sign of interference.
We know that the K* is 1–.
If the Z(4430) is J=1 and there is no interference, then 1+ !

Interference plays an important role: significance is higher, if destructive interference is allowed in the fit



A final remark about Breit-Wigner

relativistic

$$A = \frac{m\Gamma}{s - m^2 + im\Gamma}$$

PDG convention

non-relativistic

$$A = \frac{\Gamma/2}{\sqrt{s} - m + i\Gamma/2}$$

$$\sigma = A^2 = \frac{m^2\Gamma^2}{(s - m^2)^2 + m^2\Gamma^2}$$

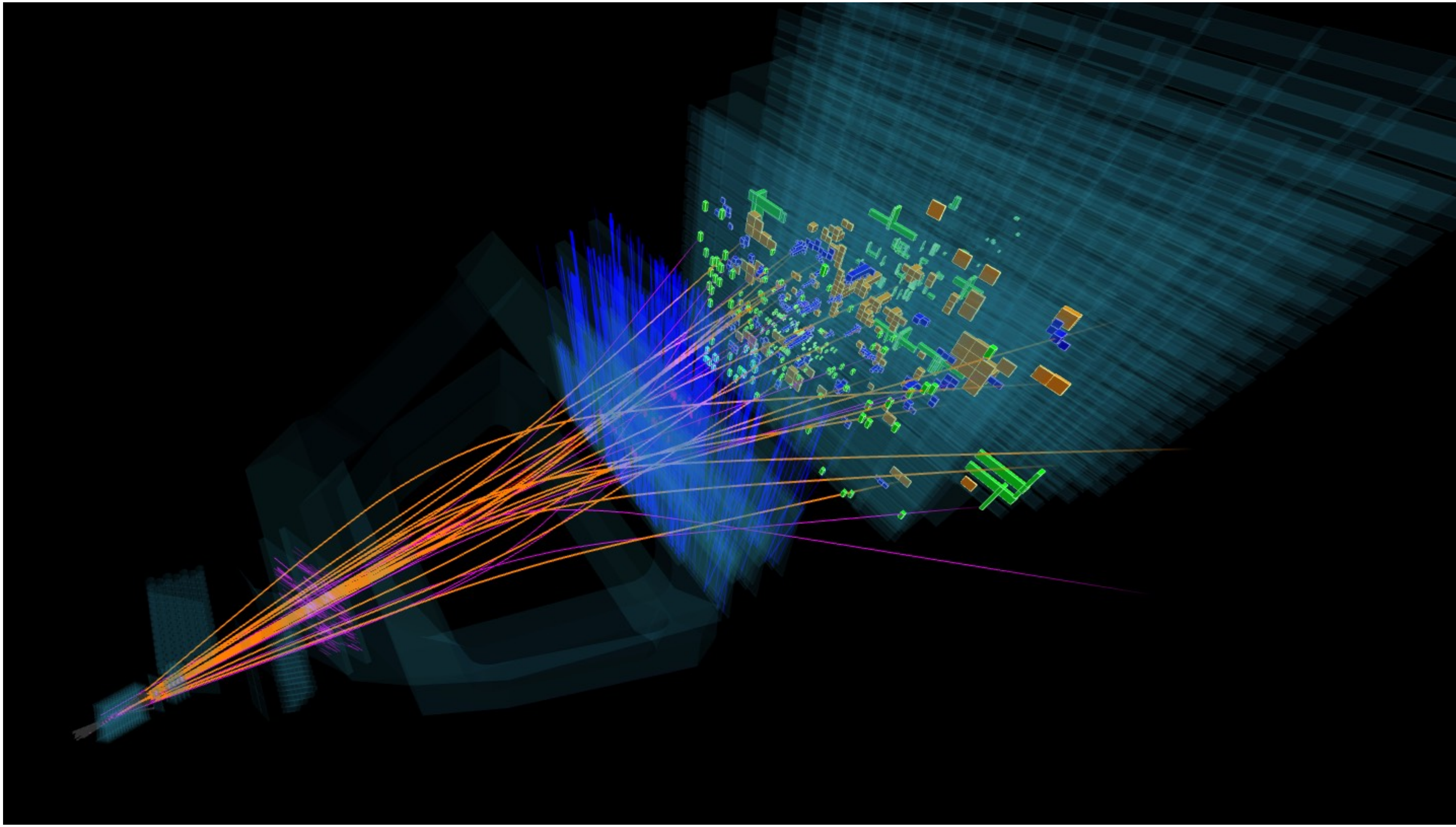
$$\sigma = \frac{\Gamma^2/4}{(\sqrt{s} - m)^2 + \Gamma^2/4}$$

not Lorentz invariant,
but sufficient in many cases

Almost all the observed, narrow Z states are $J^P = 1^+$

Why?

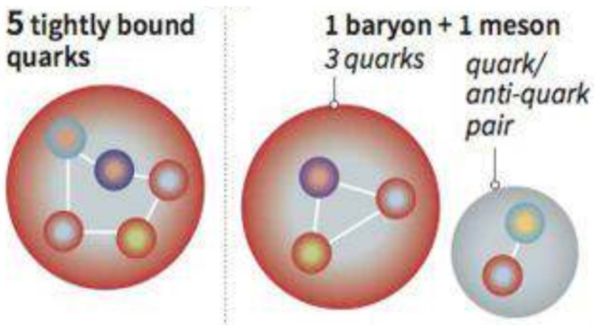
Pentaquark decay

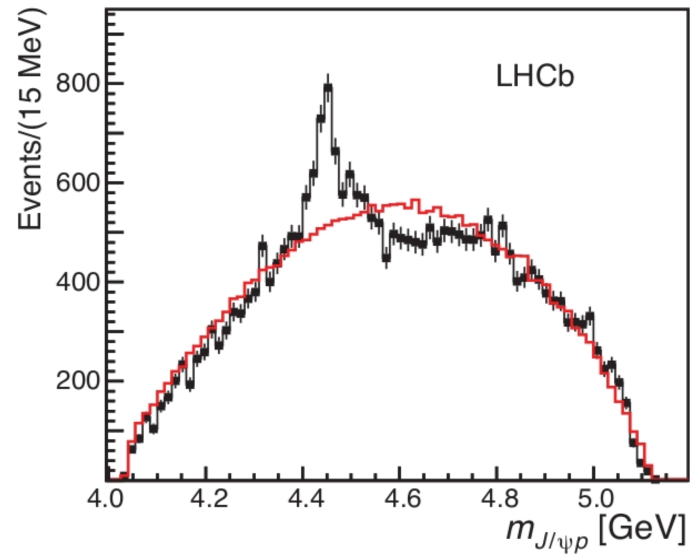


The P(4450) pentaquark

LHCb, arXiv:1507.03414

Phys. Rev. Lett. 115(2015)072001





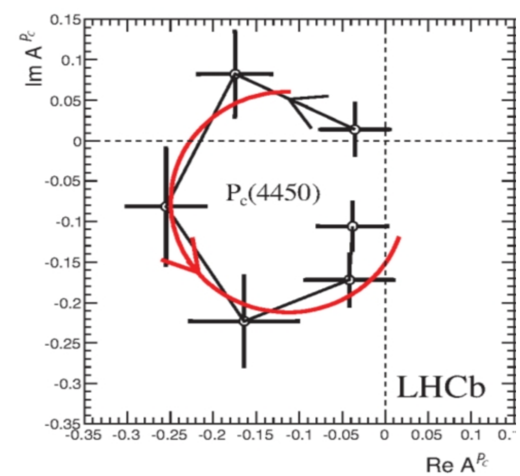
26007±166 Λ_b candidates

$\Lambda_b \to$ K [J/ψ p]

[MeV]	$P_c(4450)^+$
Mass	$4449.8 \pm 1.7 \pm 2.5$
$\chi_{c1}(1P)p$	4448.93 ± 0.07
$\Lambda_c^{+*}\overline{D}^0$	4457.09 ± 0.35
$\Sigma_c\overline{D}^{0*}$	4459.9 ± 0.5
$\Sigma_c\overline{D}^0\pi^0$	4452.7 ± 0.5

several thresholds in the vicinity

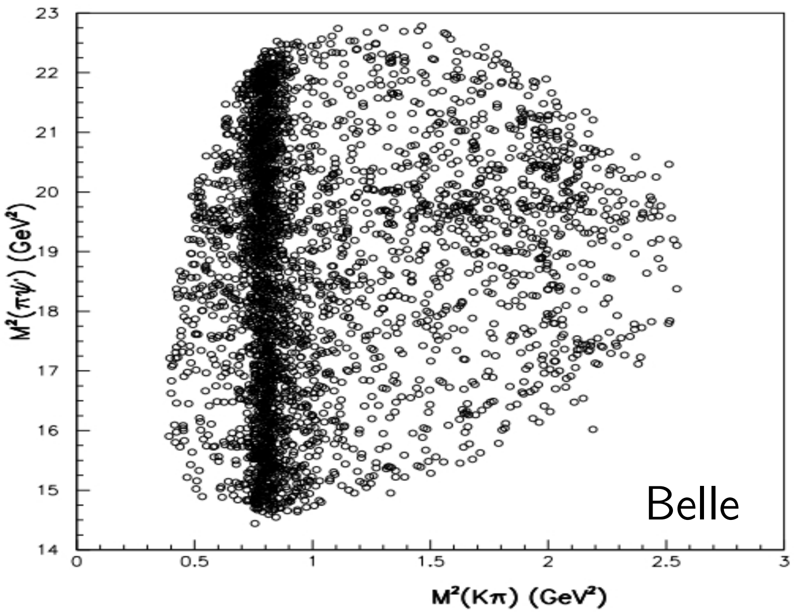
resonant character

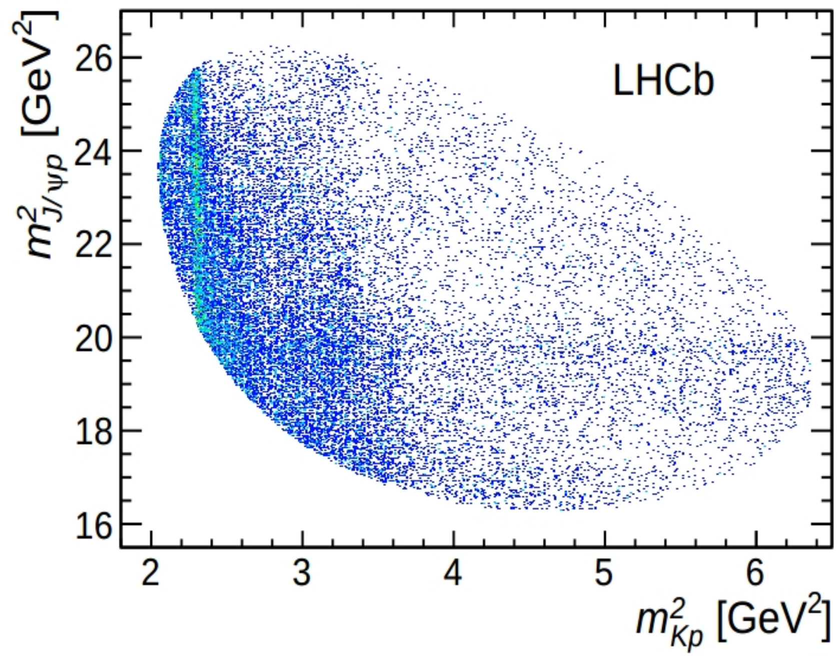


Similarities of „tetraquark“ and „pentaquark“

$B^0 \to K^- \psi' \pi^+$
Phys. Rev D80(2009)031104

$\Lambda_b{}^0 \to K^- J/\psi\ p$
Phys. Rev. Lett. 115(2015)072001





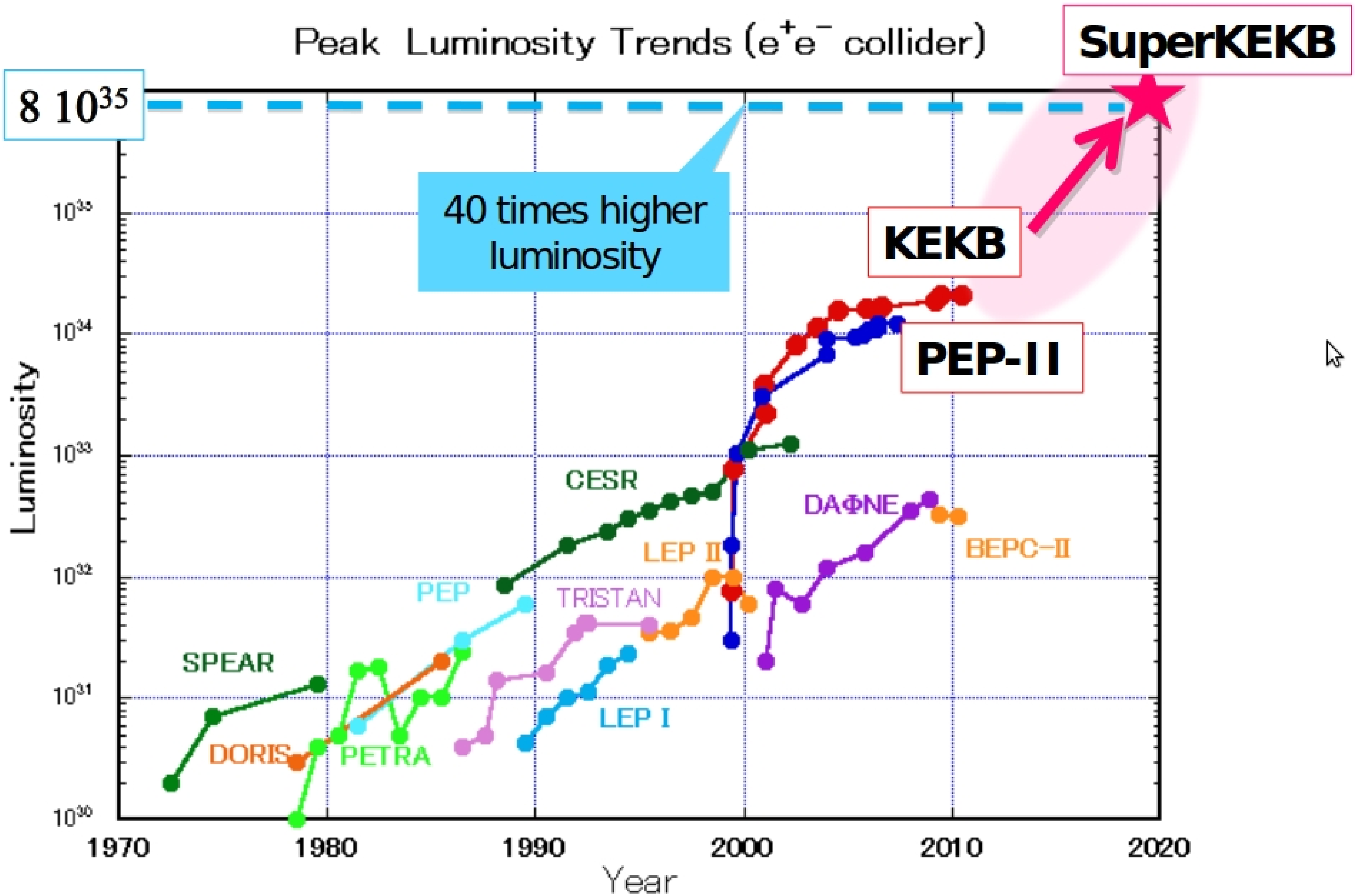
$c\ \bar{c}\ u\ \bar{d}$ (minimal content) $\to$ Z(4430)$^+$
c c u u d (minimal content) $\to$ P(4450)$^+$
similar mass (?)

Why is LHCb better for the pentaquark than Belle II?

Reminder: decay to J/ψ p.

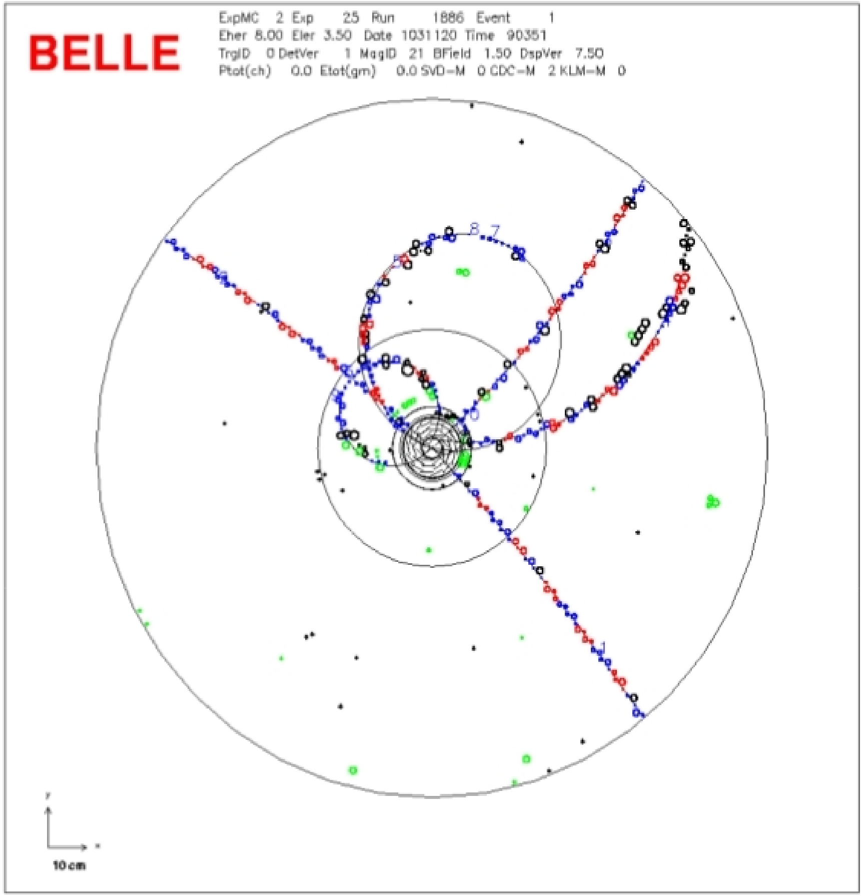

Belle II
P&H
UBE
70t10t
立入禁止
火気厳禁
Super
KEKB
BELLE
Belle II
Bundesministerium
für Bildung
und Forschung

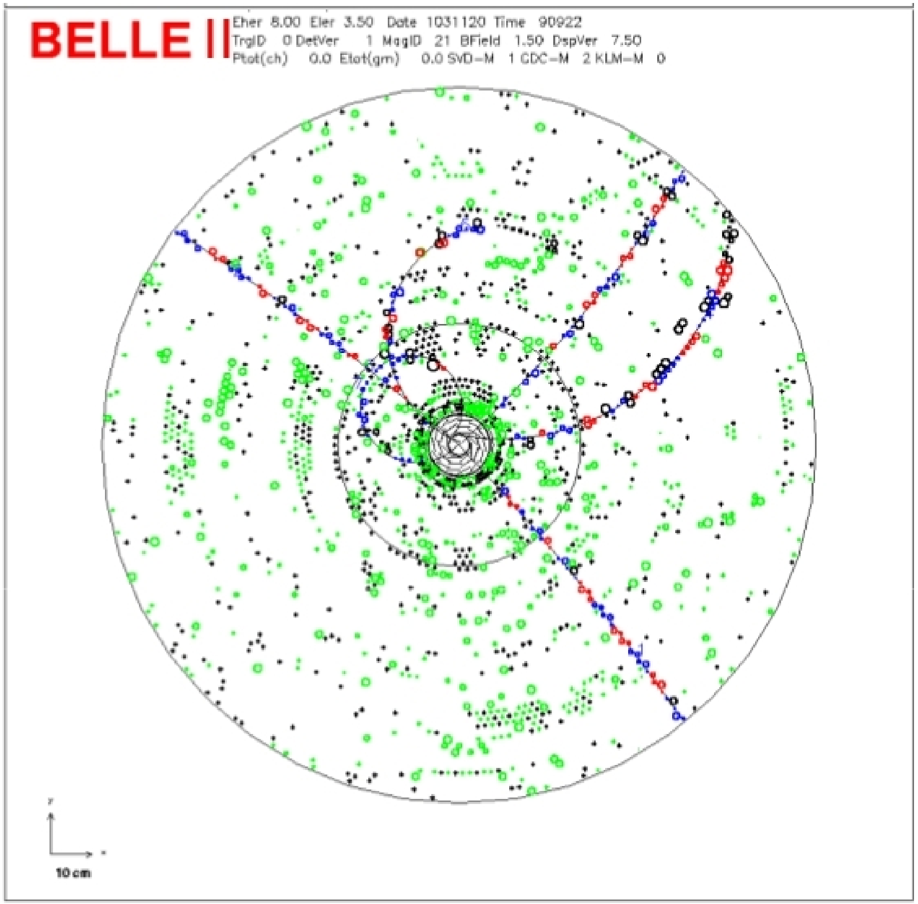
SuperKEKB asymmetric B meson factory, e+ e– $\rightarrow$ $B\bar{B}$
adjusted to Υ(4S) resonance, $\sqrt{s}$=10.6 GeV
different beam energies
8 GeV $\rightarrow$ 7 GeV (lower emittance)
3.5 GeV $\rightarrow$ 4 GeV (Touschek lifetime)
Upgrade: luminosity peak x40, integrated x50



Peak Luminosity Trends (e+e− collider)
SuperKEKB
8 10^35
40 times higher luminosity
KEKB
PEP-II
CESR
DAΦNE
LEP II
BEPC-II
PEP
TRISTAN
SPEAR
DORIS
PETRA
LEP I
Luminosity
Year
10^35
10^34
10^33
10^32
10^31
10^30
1970
1980
1990
2000
2010
2020

Background increase x factor 10–20





Trigger rate ~400 Hz (Belle) → 30.000 Hz (Belle II)

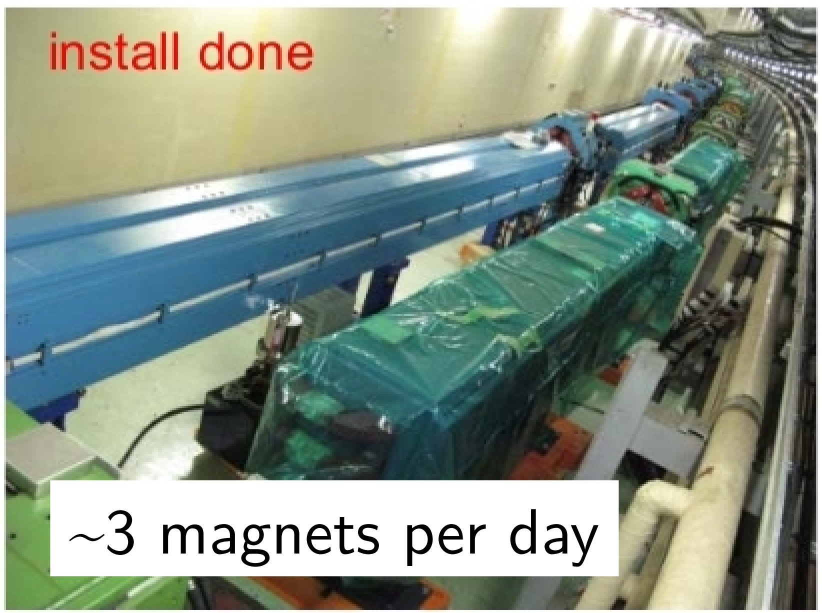
Installation of 100 new LER Dipole Magnets

field measurement

move into tunnel

Installation of 100 new LER bending magnets done

carry on an air-pallet

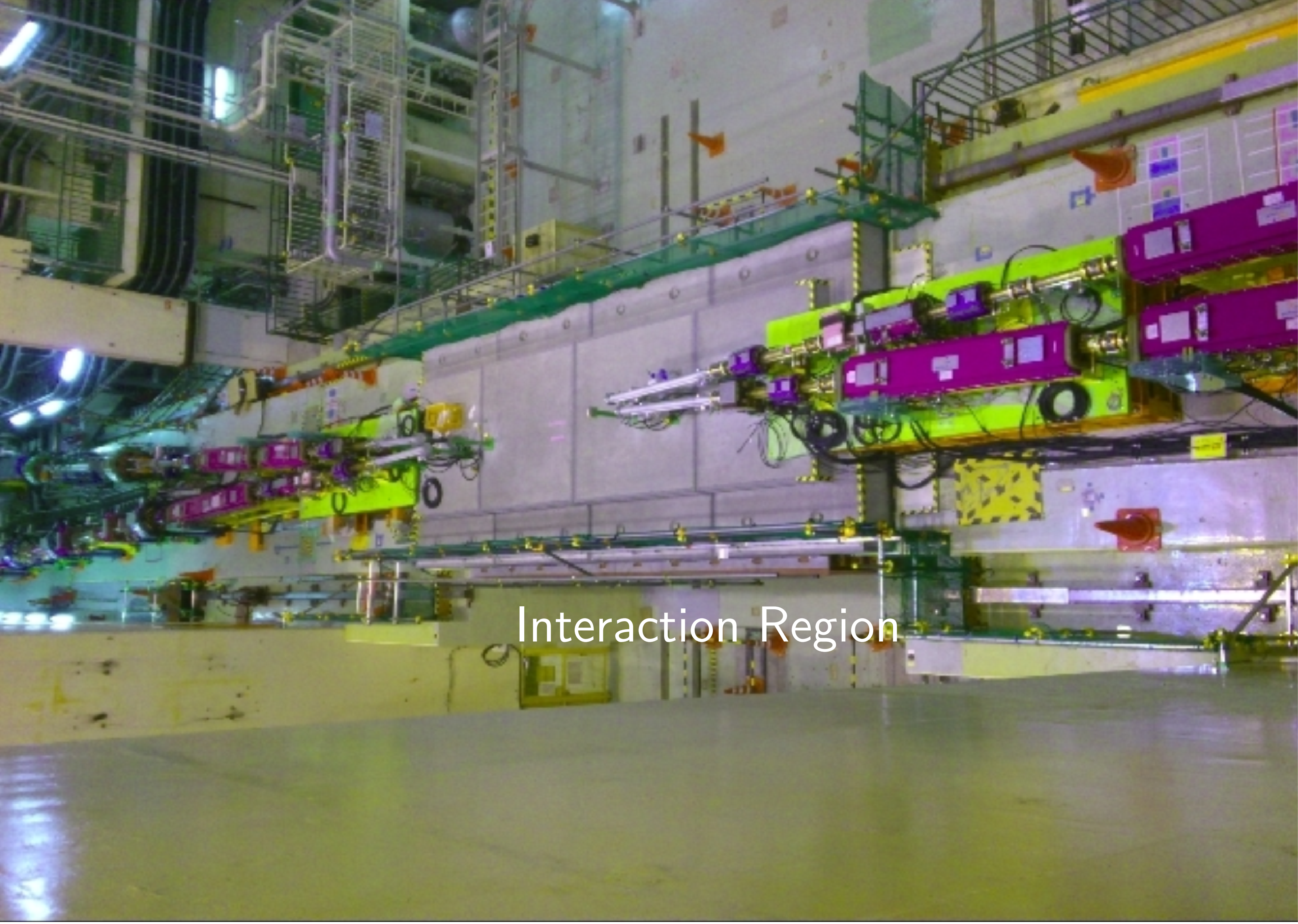


Install over HER magnets

~3 magnets per day

SuperKEKB Status, 7th BPAC, Mar. 11, 2013, K. Akai

19


Interaction Region

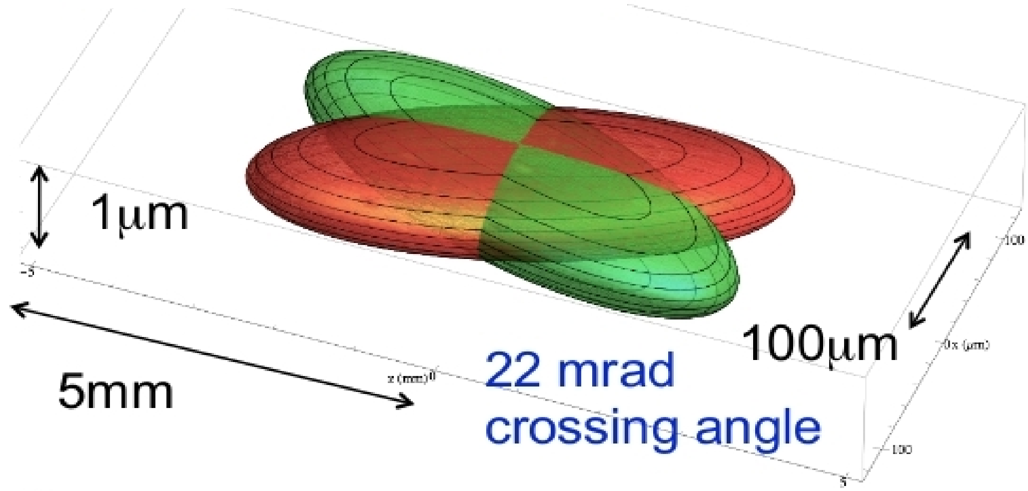
Nano-Beam Scheme

Belle → Belle II

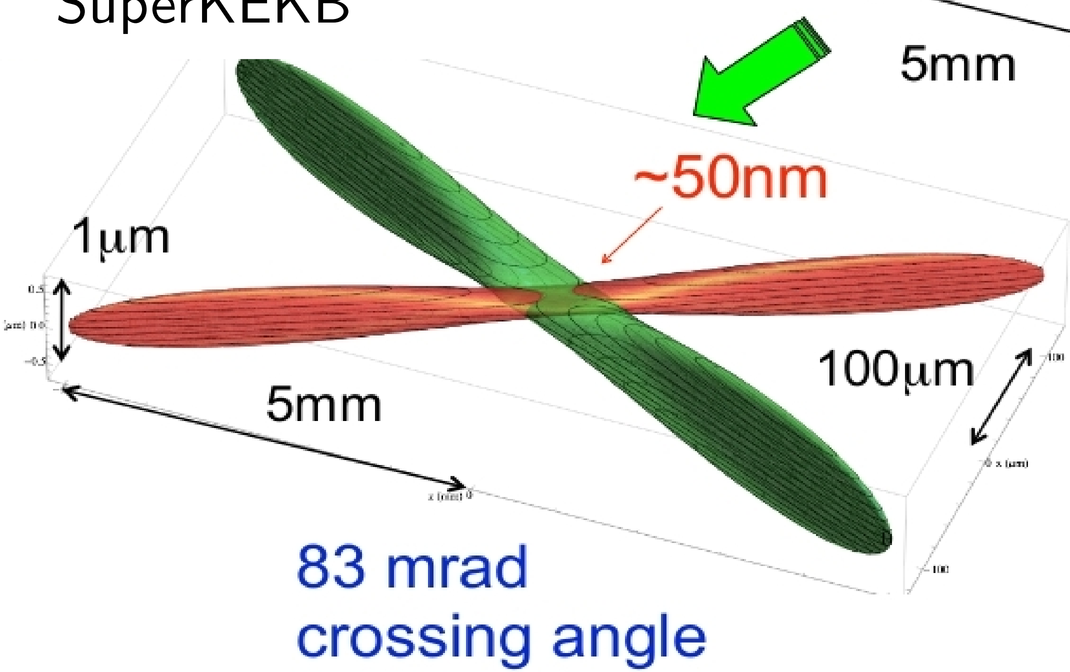
Luminosity x 40

$L \leq 0.8 \times 10^{36}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

KEKB *(without crab)*



SuperKEKB

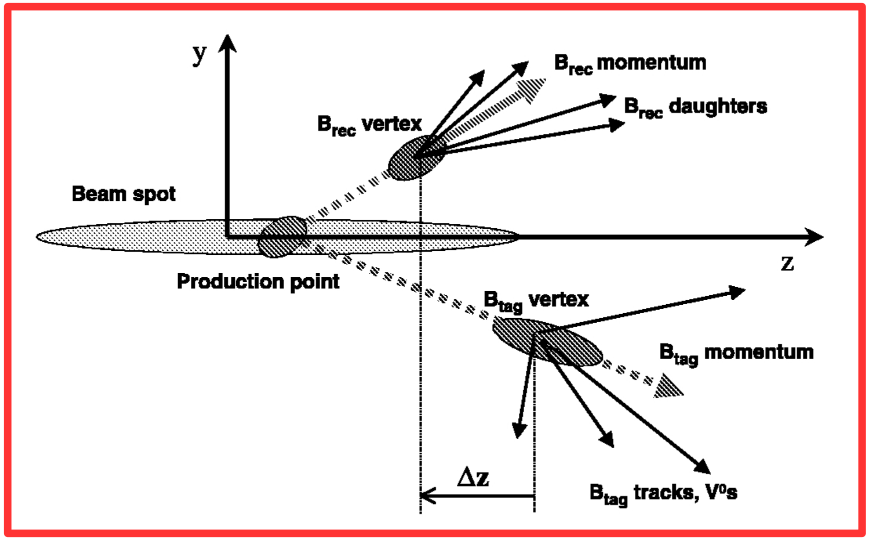


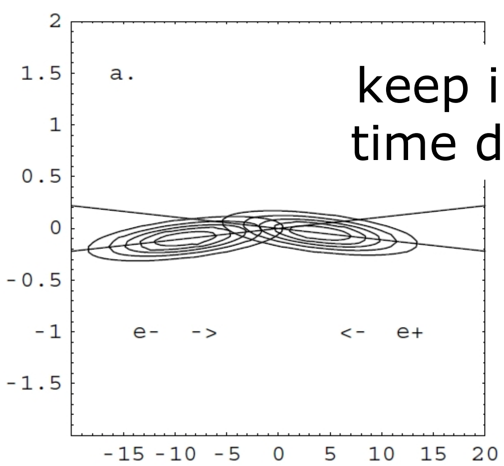
originally proposed for SuperB
by P. Raimondi (INFN)

graphics E. Paoloni (Pisa)

IP Profile for Belle and Belle II („nanobeam“)

100µm(H) x 2µm(V) →10µm(H) x 59nm(V)

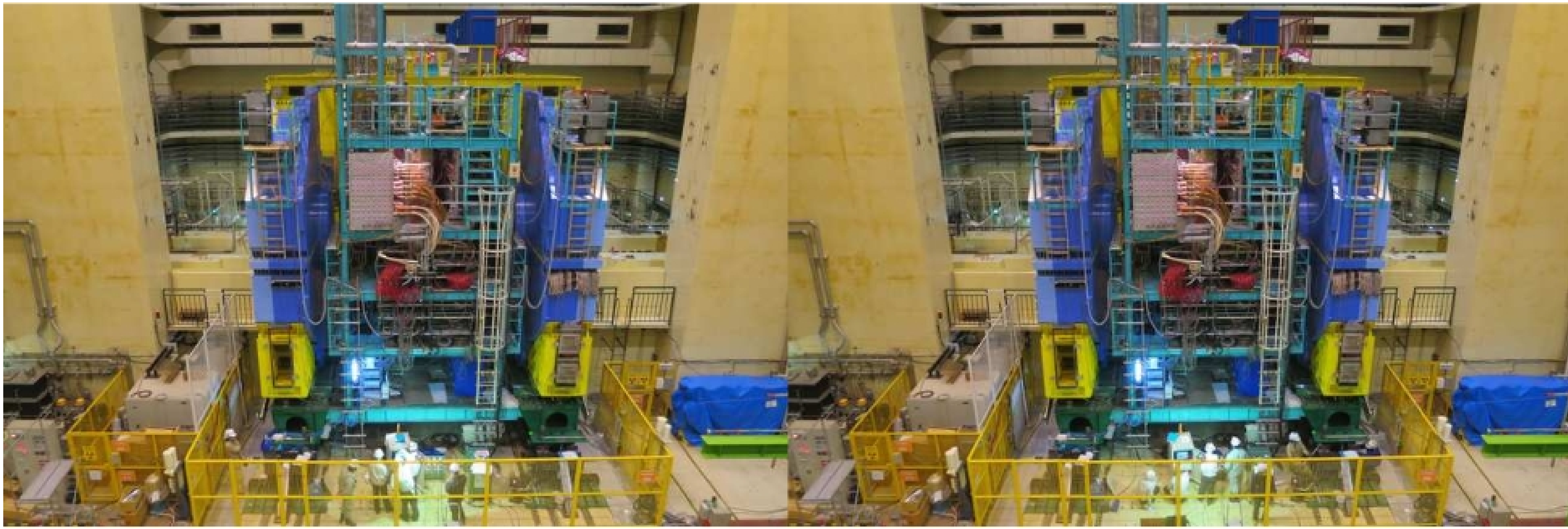




keep in mind:
time dependant evolution

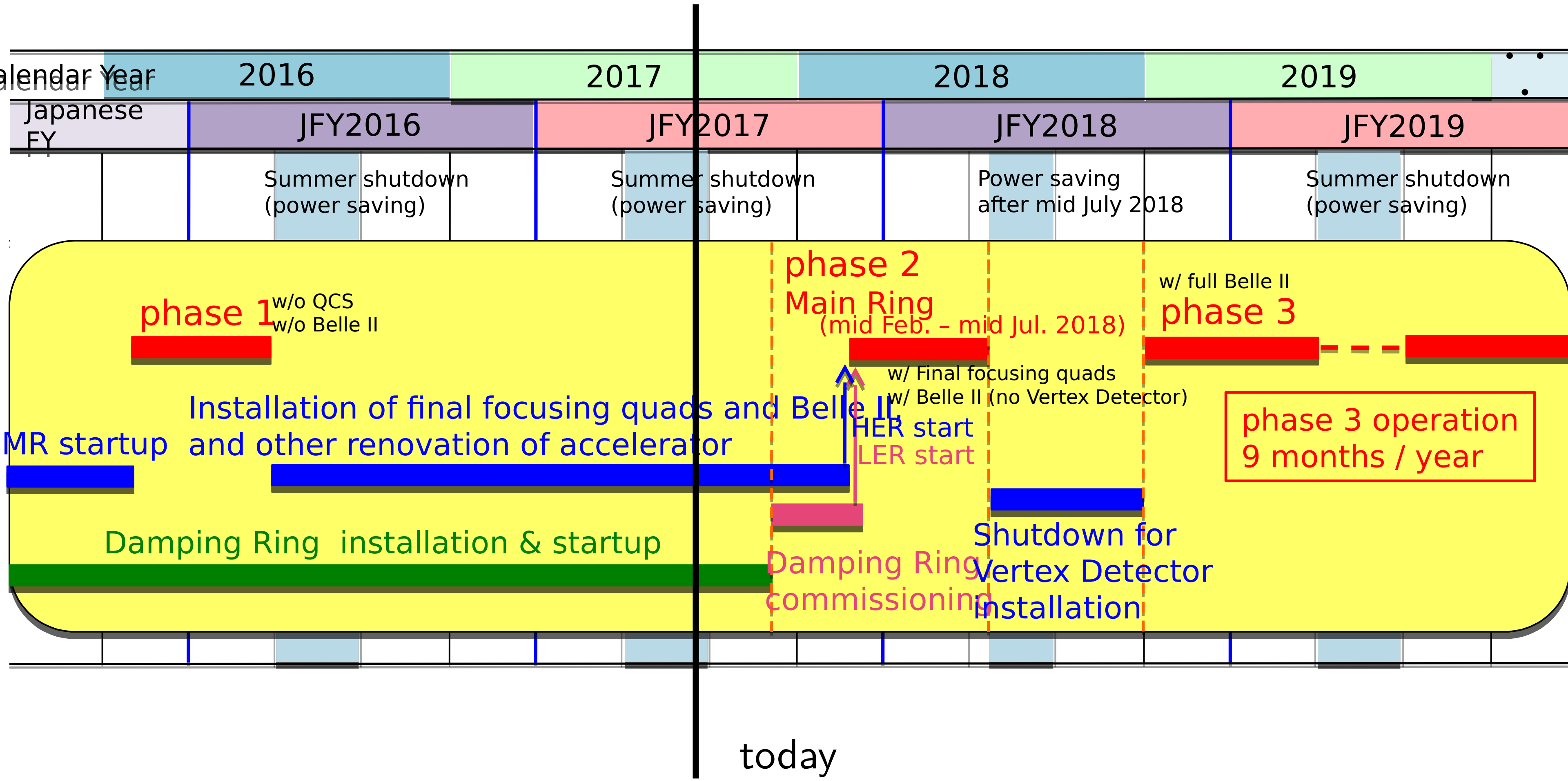
Belle Rotation 03/2013

for larger crossing angle 22 mrad $\rightarrow$ 83 mrad (nanobeam)



18.6 cm @ end of platform (accuracy 0.5 mm)

SuperKEKB/Belle II schedule



KEK Inter-University Research Institute Corporation
High Energy Accelerator Research Organization

Press Release

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

March 2nd, 2016

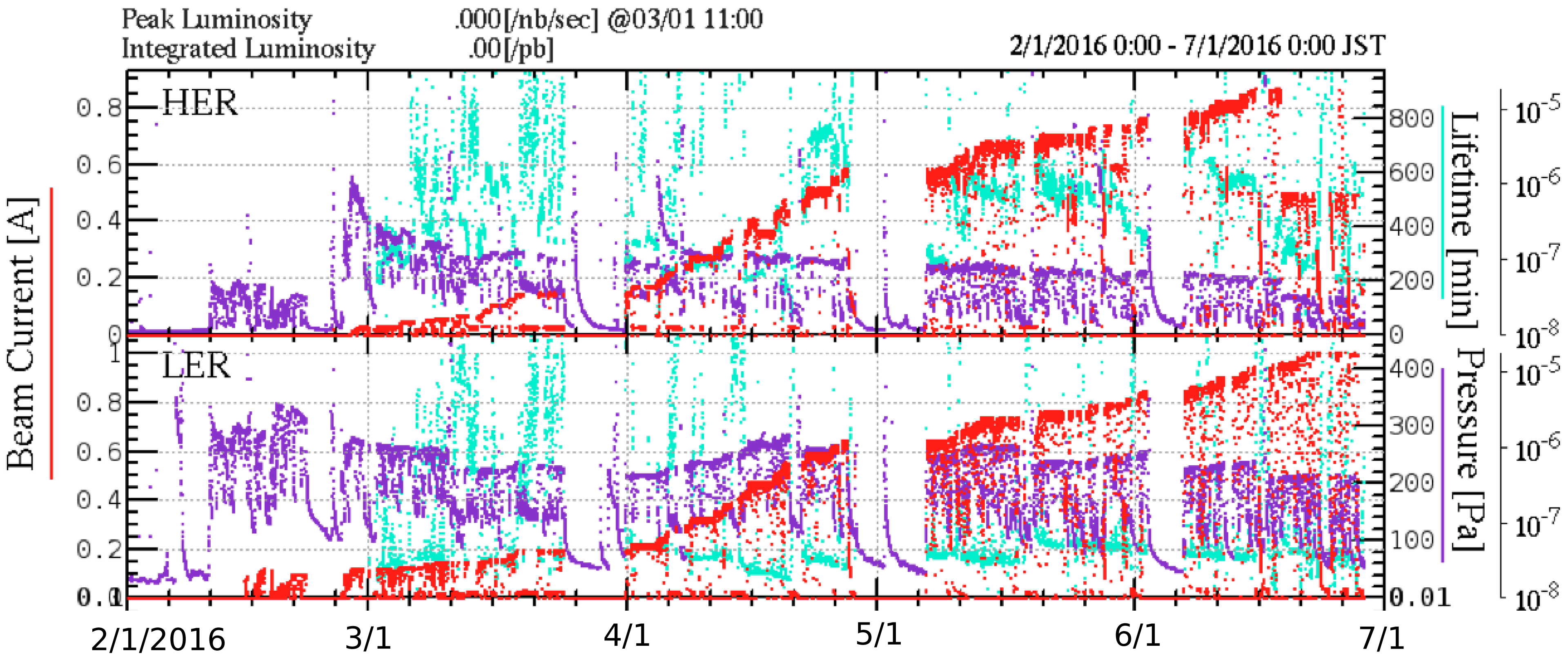
High Energy Accelerator Research Organization (KEK)

Phase I operation history

max. stored beam current 870 mA (HER), 1010 mA (LER)

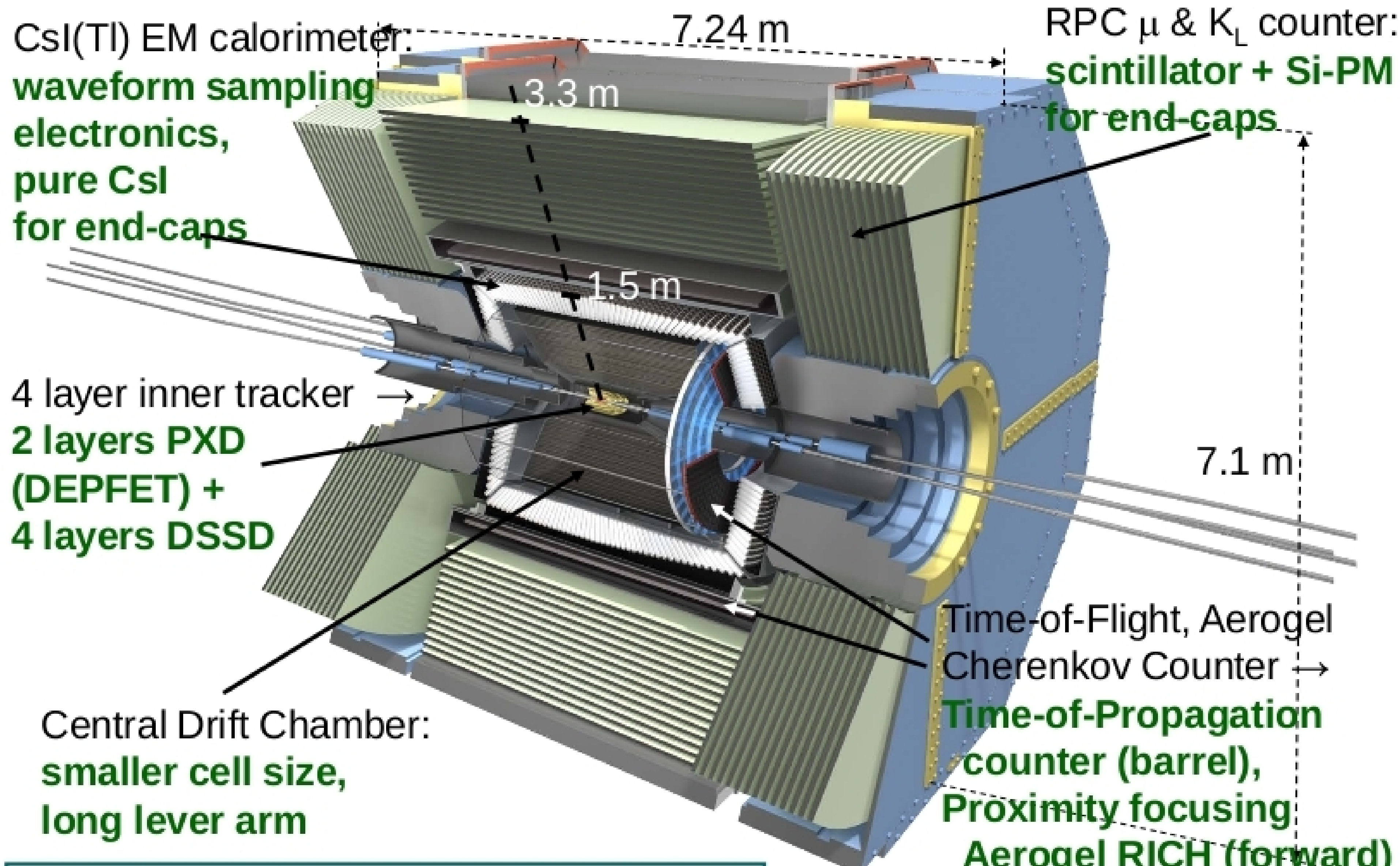
red: beam current

purple: vacuum pressure



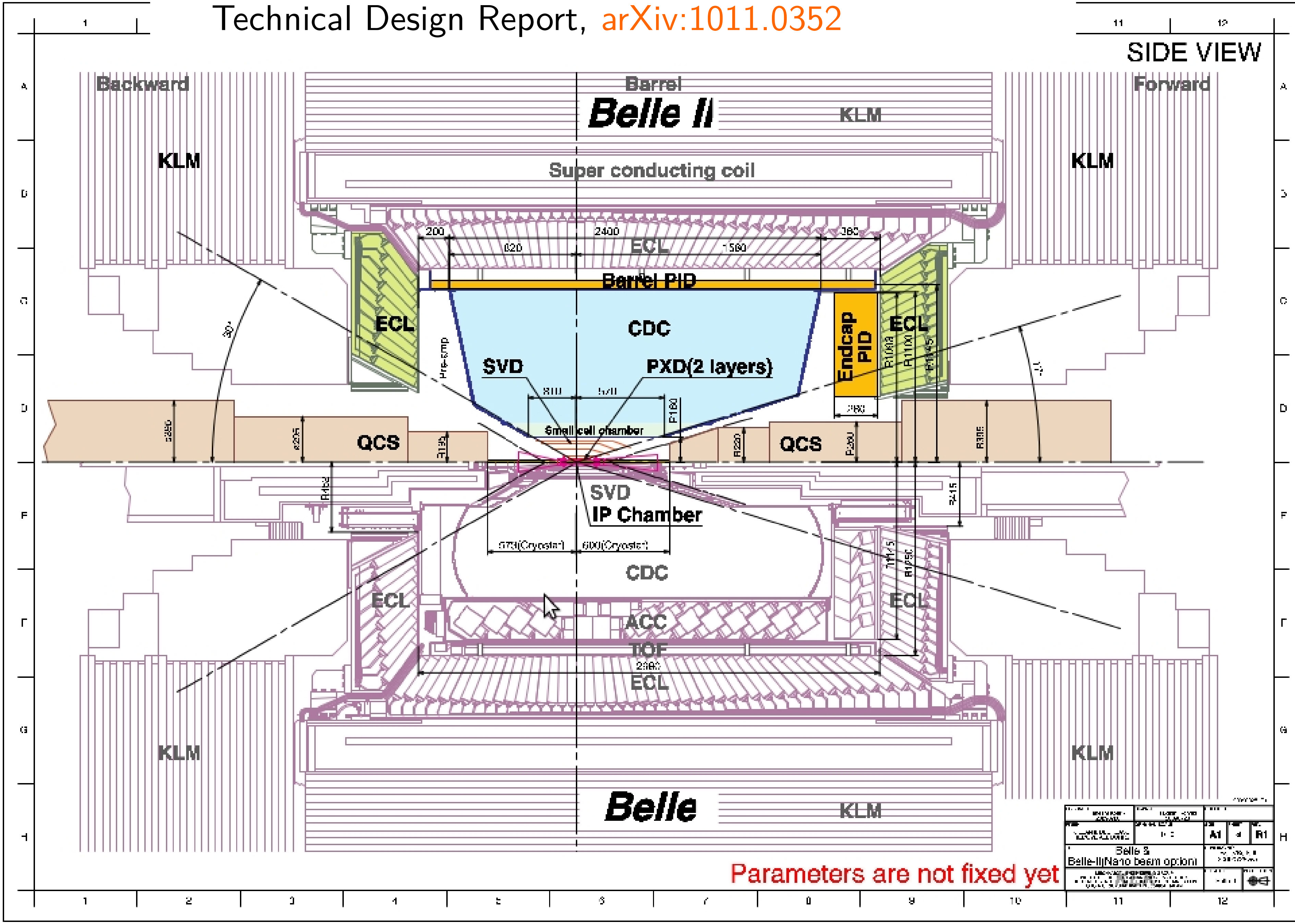
The Belle II Detector

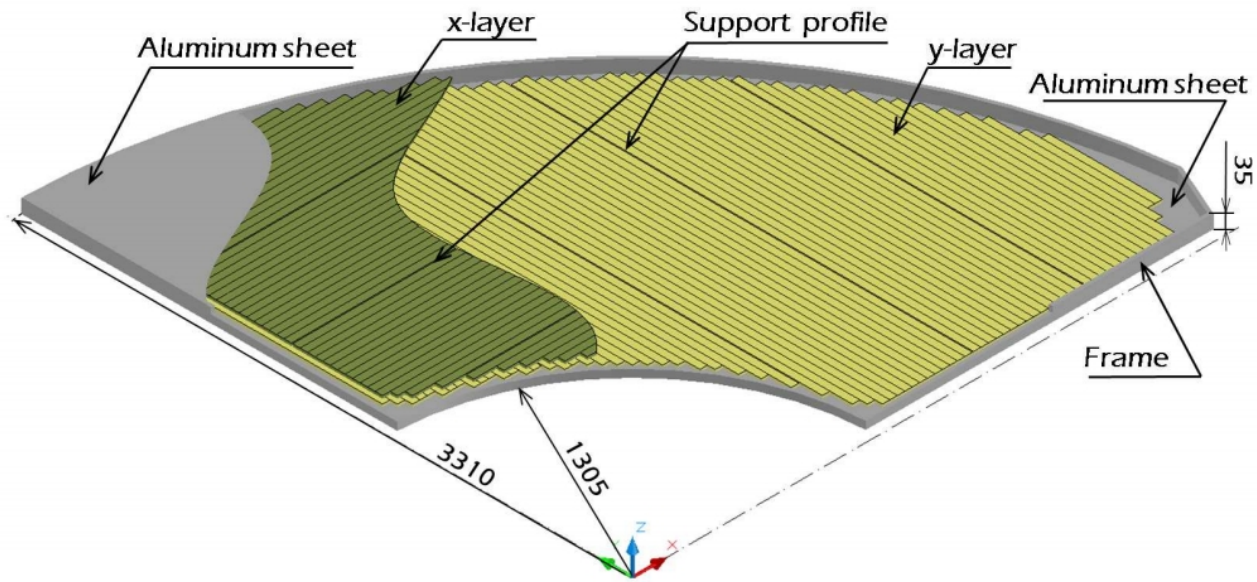
(Upgrade of the Belle Detector)



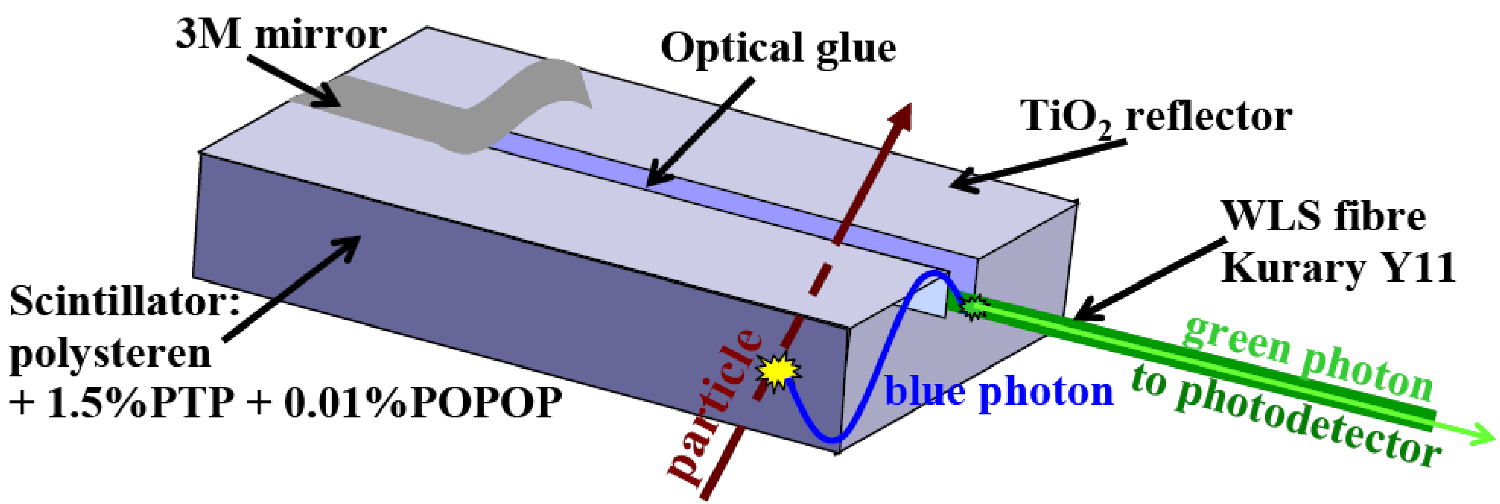
Belle II Technical Design Report: arXiv:1011.0352

Technical Design Report, arXiv:1011.0352





KLM
replace RPCs
by scintillators
total area ~1400 m2
16.800 readout fibres



B-KLM Installation

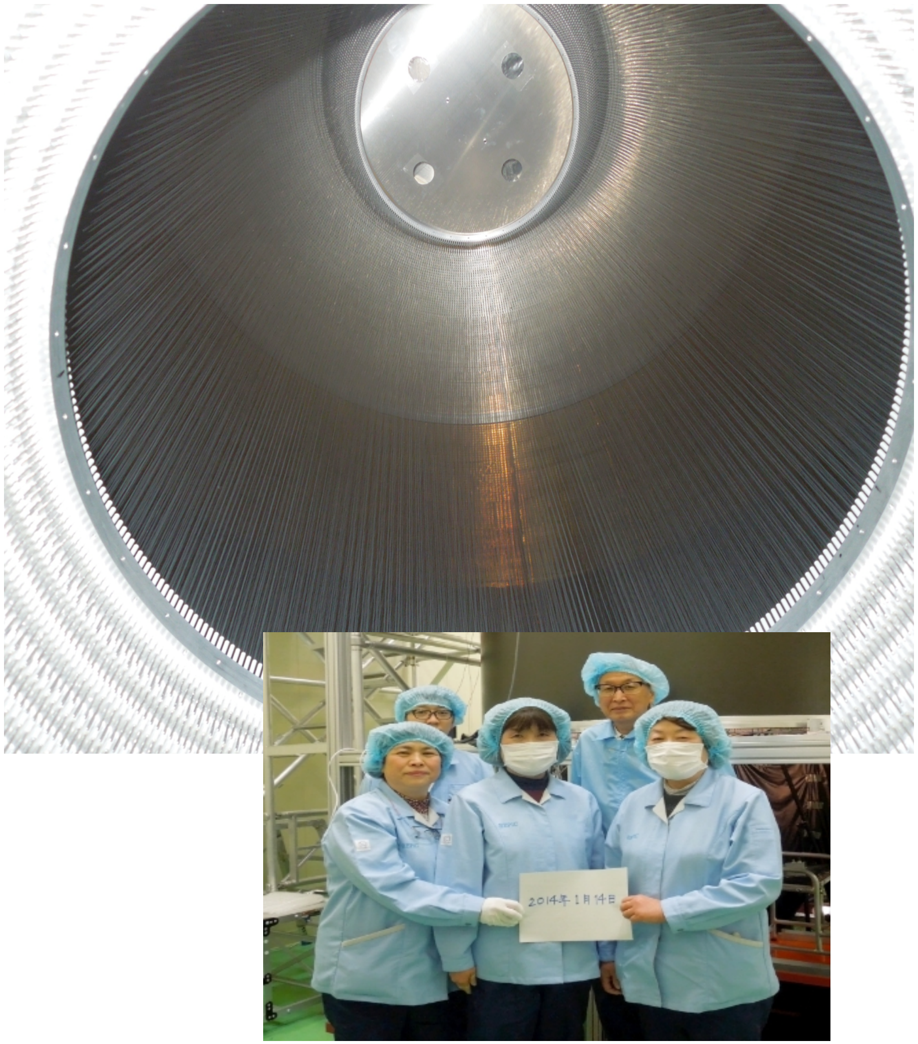
completed 11/2013
RPCs exchanged
by scintillator
in endcap and
2 inner layers in barrel

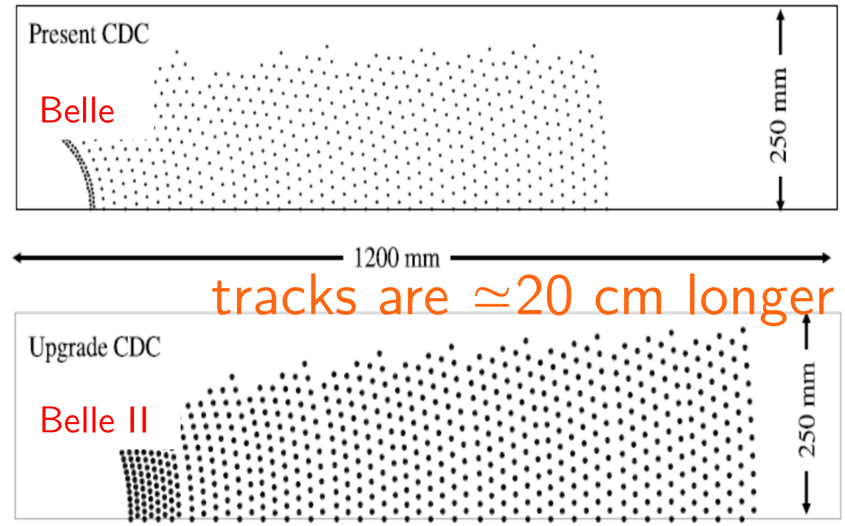
During installation, modules have been checked, found to be healthy.

The 1st New Detector Installed !!

CDC (Charged Drift Chamber)

wire stringing finished (01/2014), 51456 wires





Improved resolution:

$\sigma(p_T)/p_T =$

$0.19\ p_T \oplus 0.30/\beta$ (Belle)

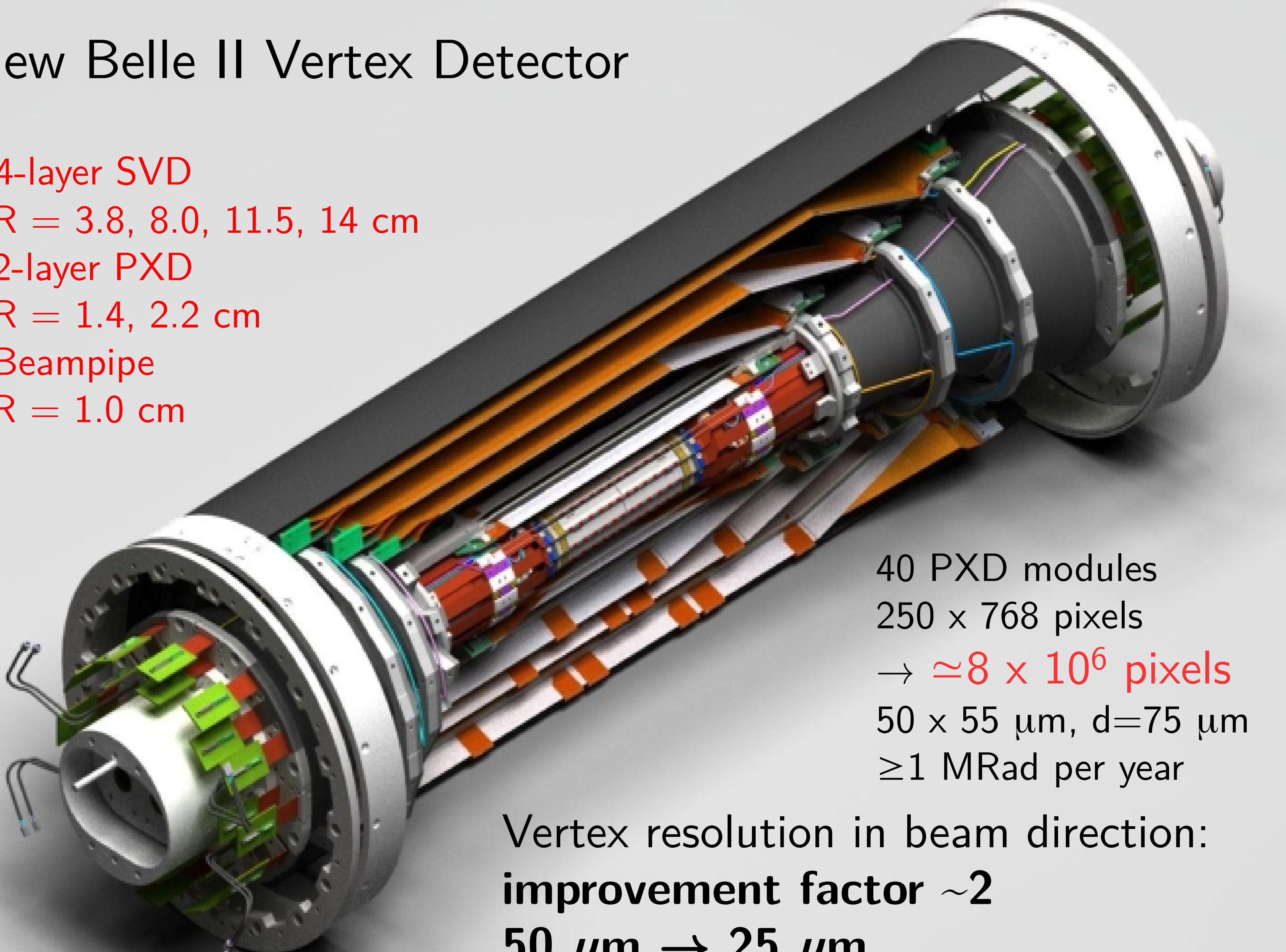
$0.11\ p_T \oplus\ 0.30/\beta$ (Belle II)

dE/dx 6.8% $\rightarrow$ 4.8%

CDC transport from Fuji Hall to Tsukuba Hall, 21.01.2015

New Belle II Vertex Detector

- 4-layer SVD
  R = 3.8, 8.0, 11.5, 14 cm
- 2-layer PXD
  R = 1.4, 2.2 cm
- Beampipe
  R = 1.0 cm

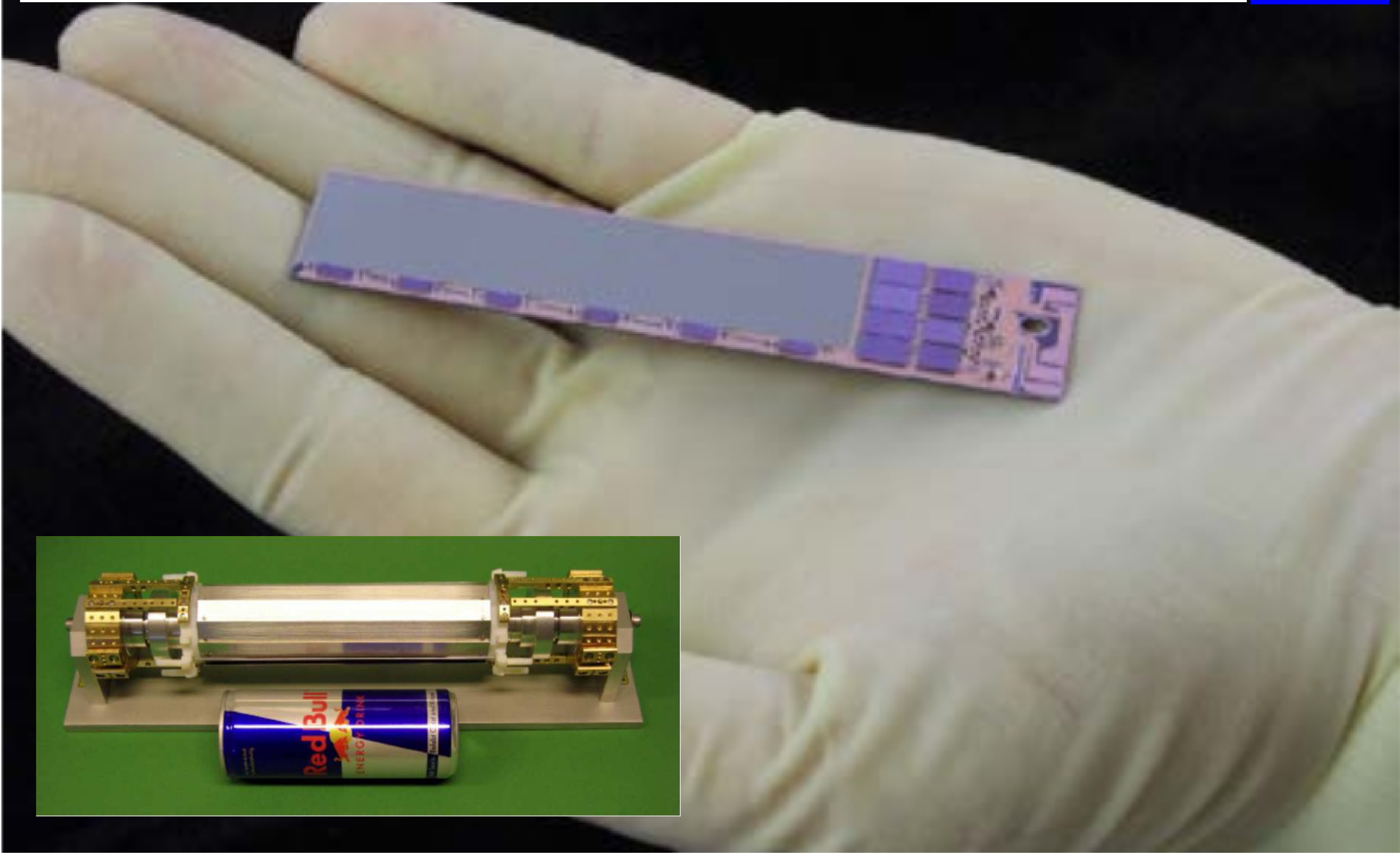


40 PXD modules
250 x 768 pixels
$\rightarrow \simeq 8 \times 10^6$ pixels
50 x 55 μm, d=75 μm
≥1 MRad per year

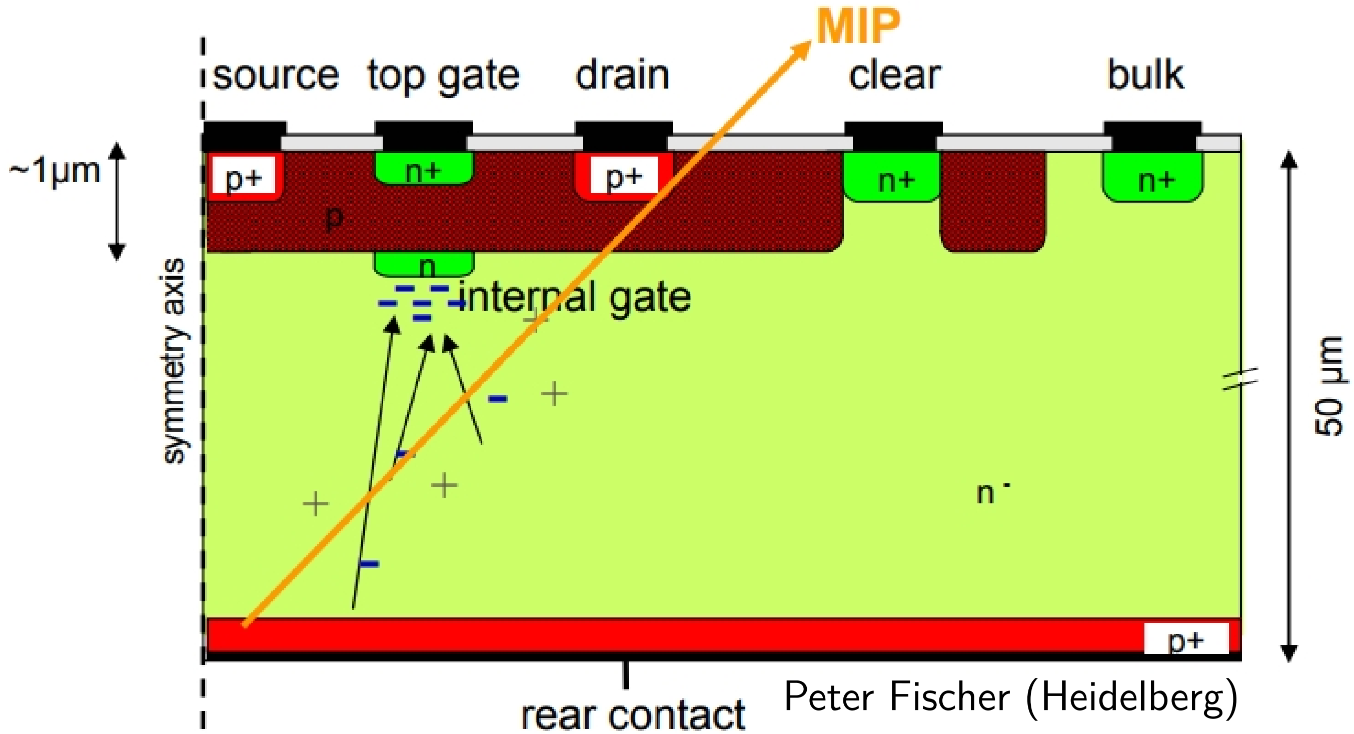
Vertex resolution in beam direction:
improvement factor ~2
50 μm → 25 μm

Belle II DEPFET Pixel Detector

Univ. Bonn, DESY, Univ. Giessen, Univ. Göttingen, Univ. Hamburg, Univ. Heidelberg, KIT Karlsruhe, Univ. Mainz, HLL München, MPI München, LMU München, TU München



DEPFET Principle

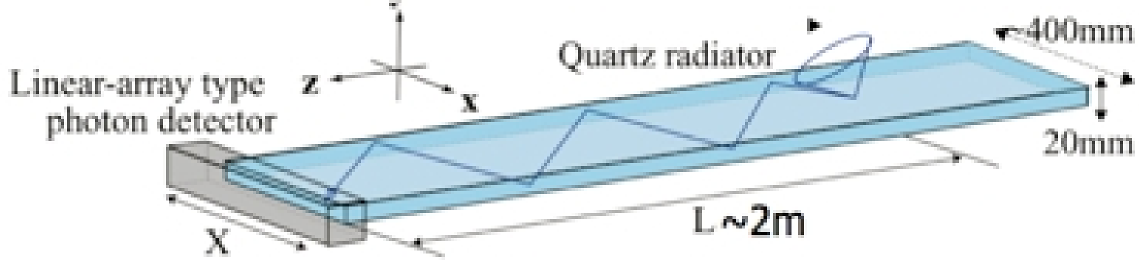


Peter Fischer (Heidelberg)

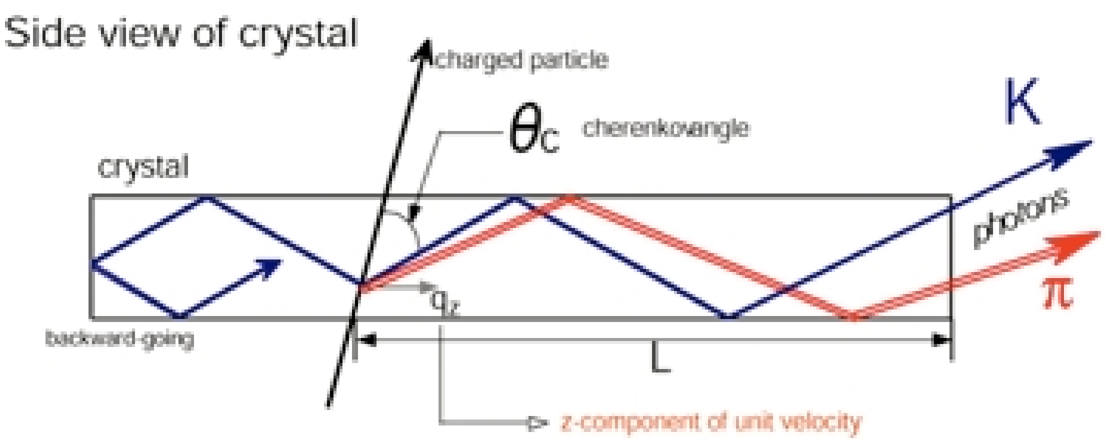
every pixel contains a p–FET (on n-substrate)
clear can be operated at high rates (30 kHz at Belle II)
then <u>current</u> flows to drain and is measured by an ADC (ASIC)
Belle II PXD has ~8 x 10^6 pixels

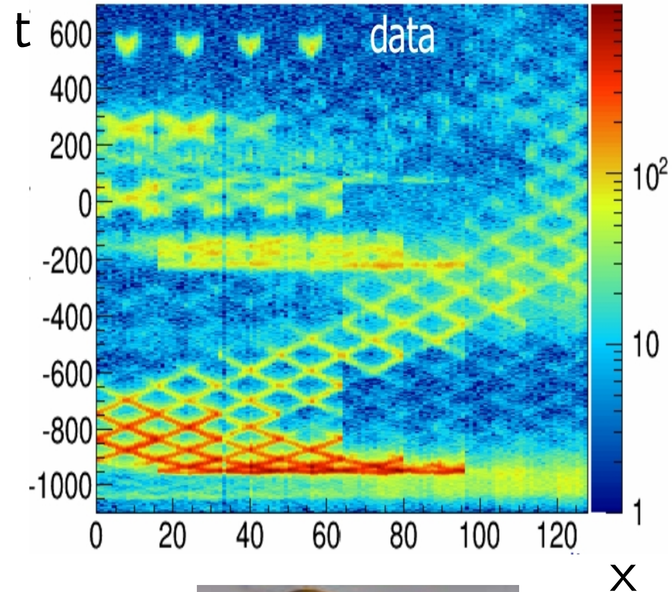
TOP (Time-of-Propagation Counter)

Radiator: Quartz



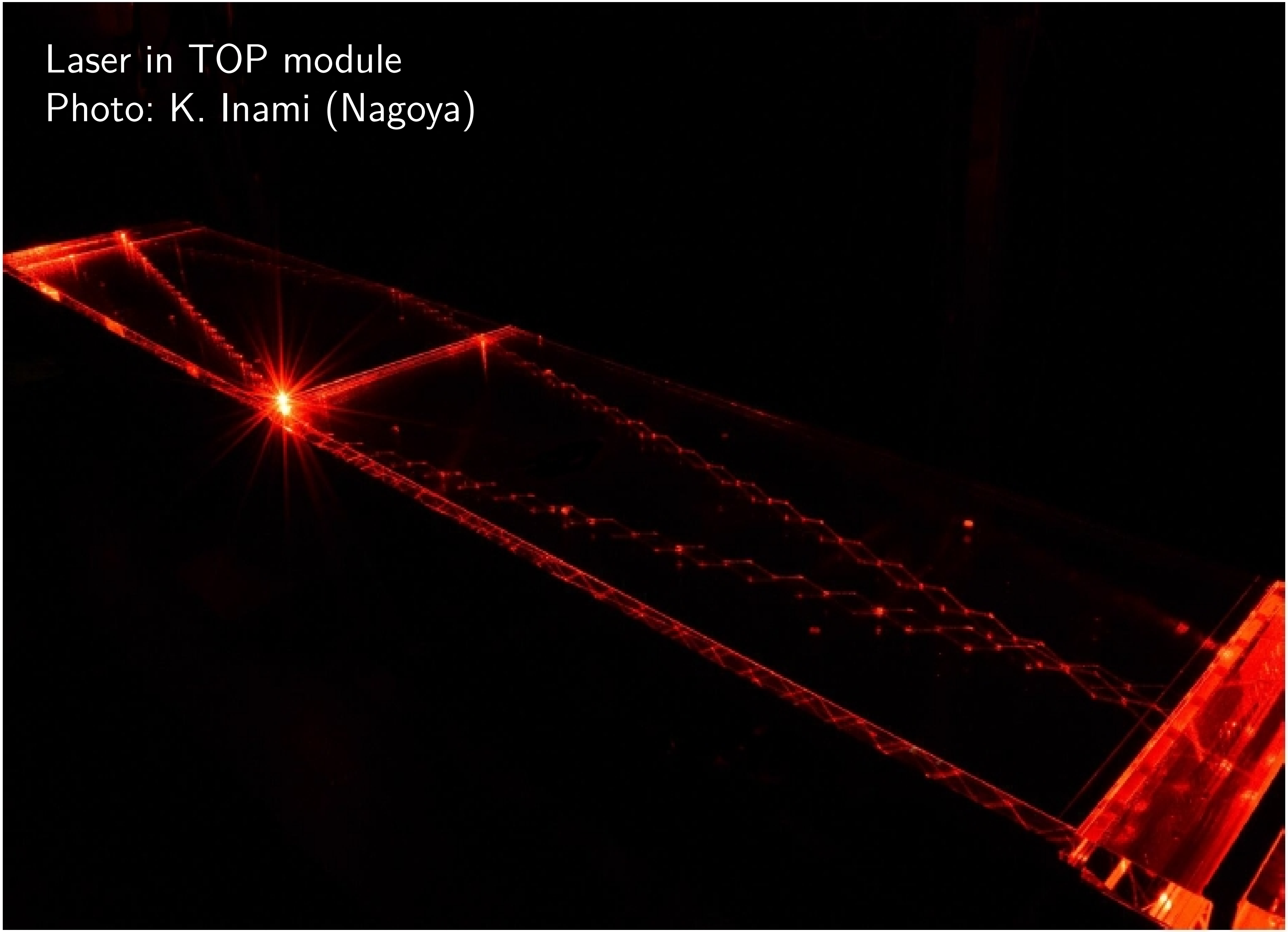
reconstruct Cherenkov angle from
- (X,Y)
- time of propagation





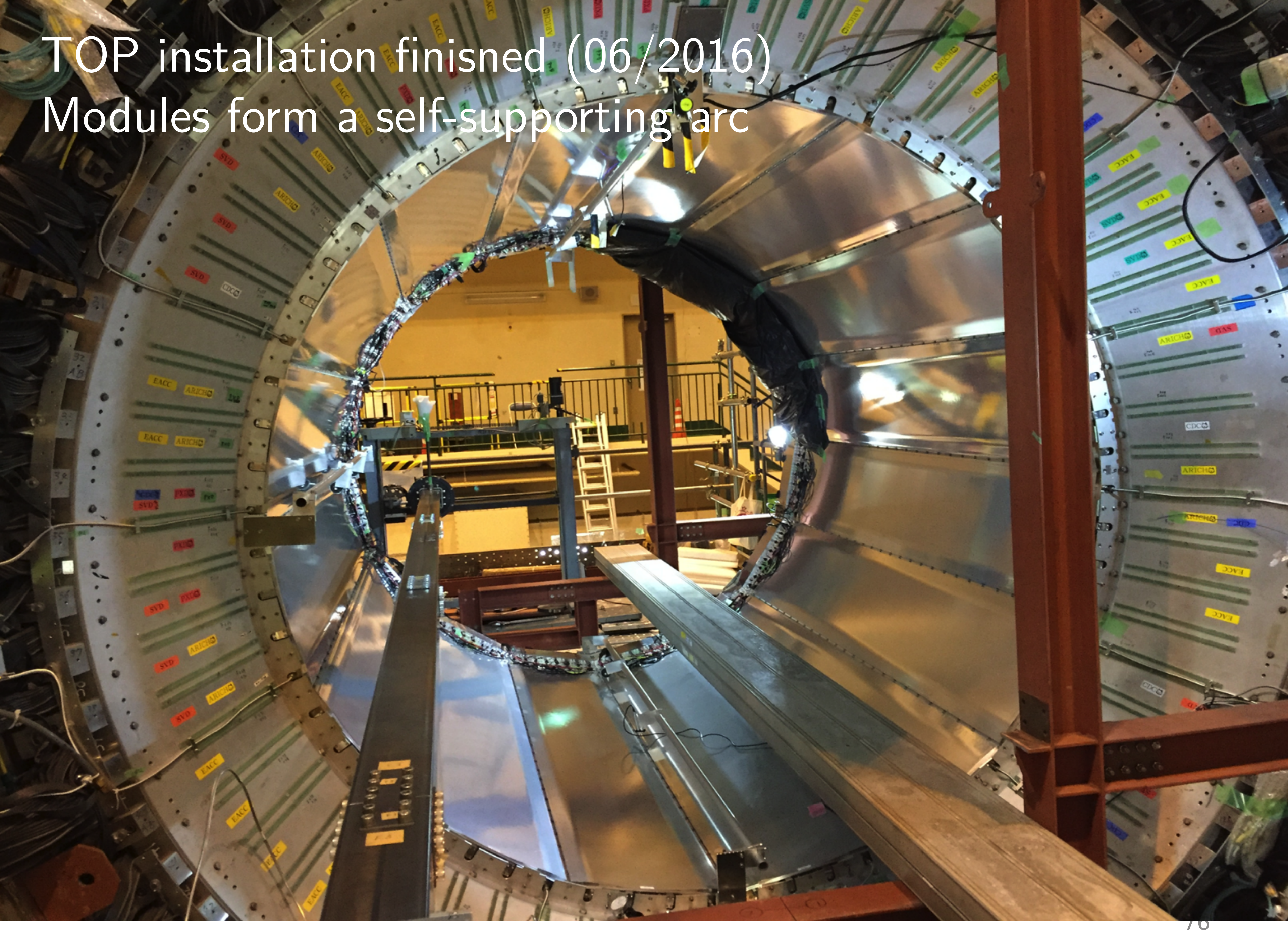
- Photon detector: Hamamatsu SL10 MCP-PMT
  - $\Delta t \leq 50$ ps
  - single photon sensitivity
  - operated in B=1.5 T field
- Estimated kaon fake rate factor 2-5 smaller than Belle (@ 95% kaon efficiency)

TOP Assembly of 1st Module


Laser in TOP module
Photo: K. Inami (Nagoya)

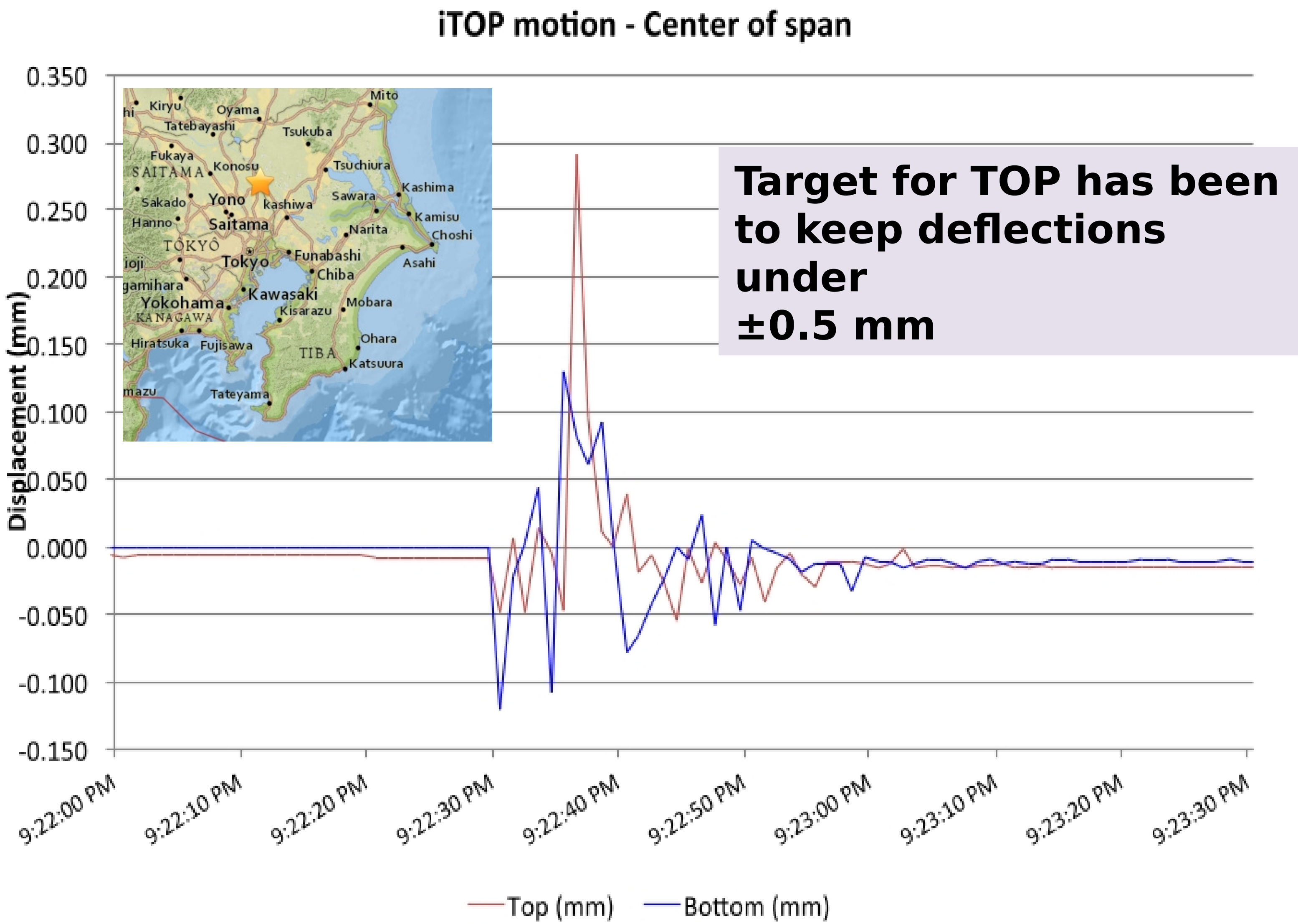
TOP installation finisned (06/2016)

Modules form a self-supporting arc



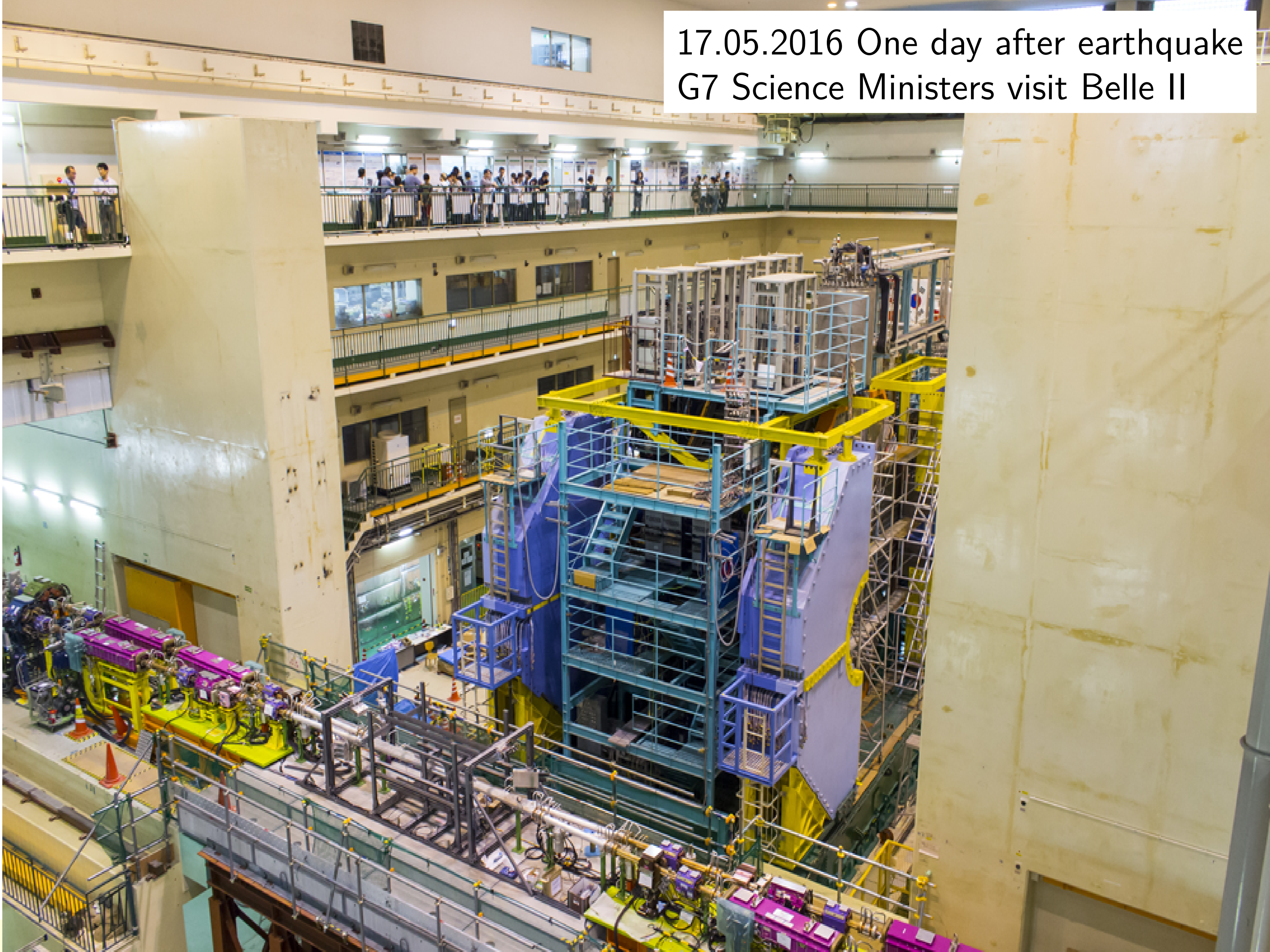
16.05.2016 First night after „strongback“ support were removed $\rightarrow$ a M5.4 earthquake with epicenter in Ibaraki prefecture !

http://earthquake.usgs.gov/earthquakes/eventpage/us10005hqy#executive

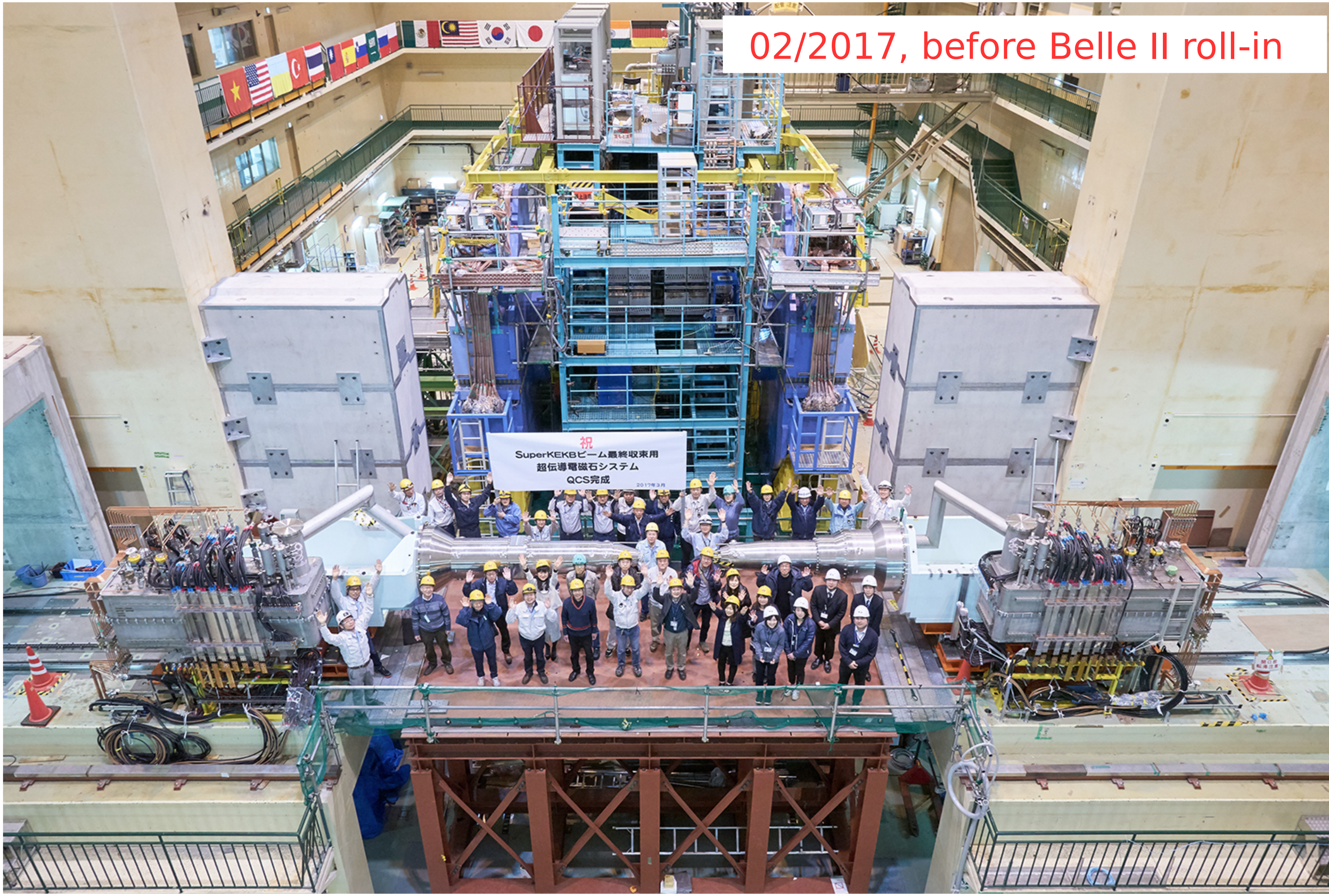


Target for TOP has been to keep deflections under ±0.5 mm

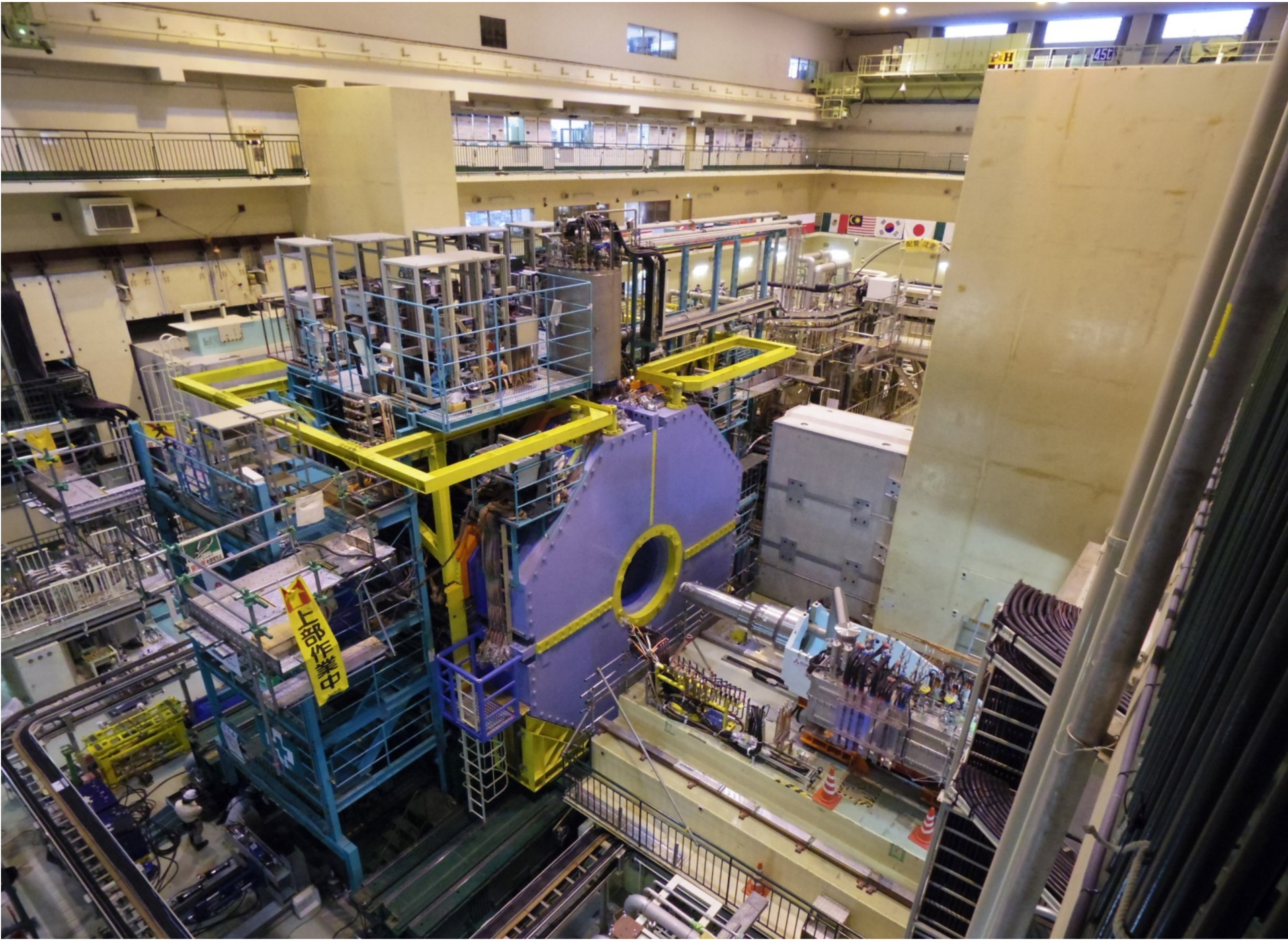
17.05.2016 One day after earthquake
G7 Science Ministers visit Belle II

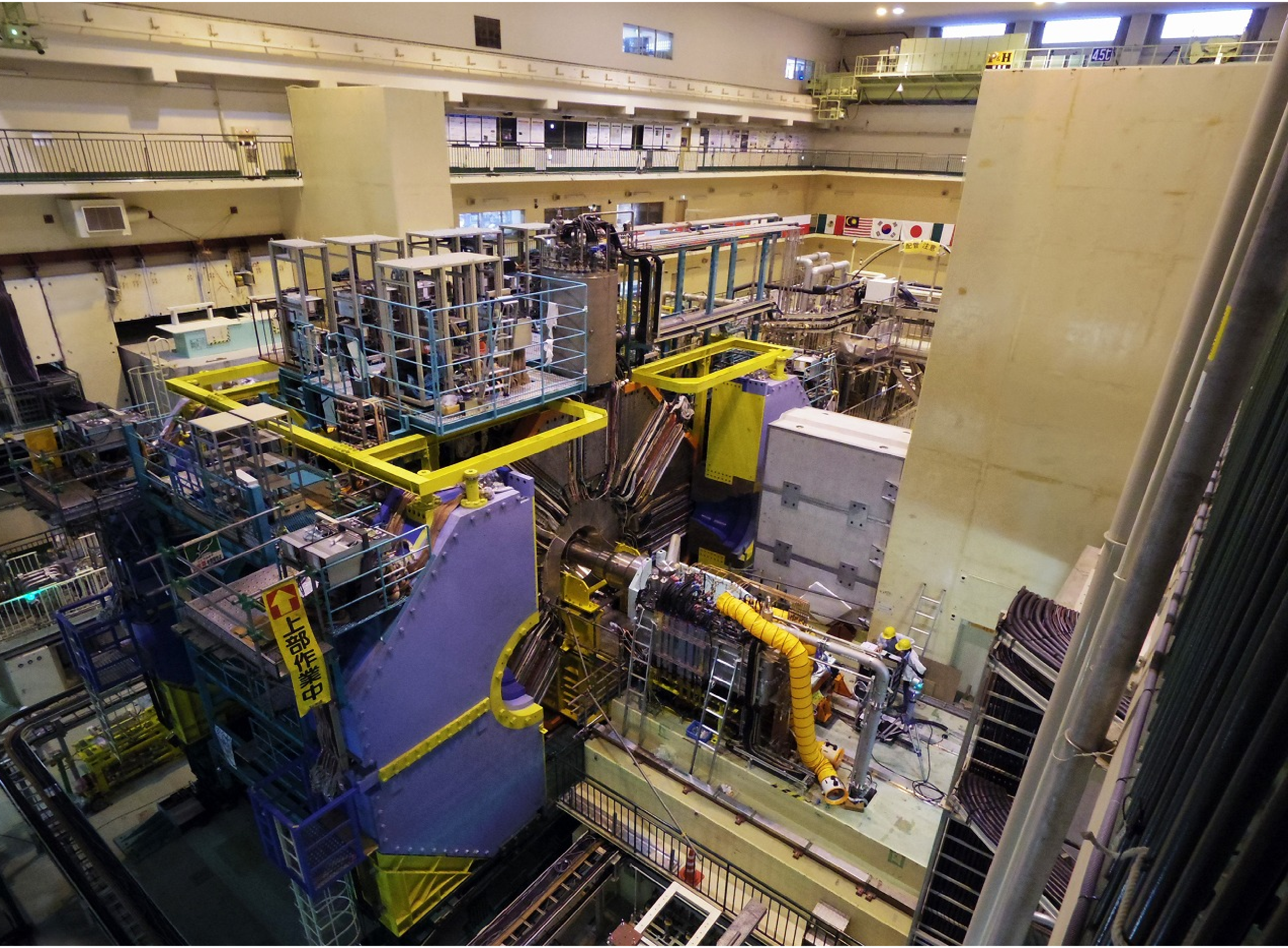


Final focusing quadrupoles (QCS) installed at IR, 55 superconducting coils, 2 cryostats



ROLL-IN, 11.04.2017


上部作業中

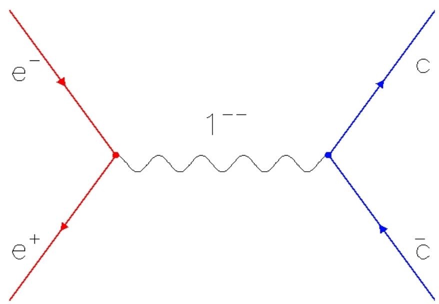

上部作業中
45t

$\overline{\text{P}}\text{ANDA}$

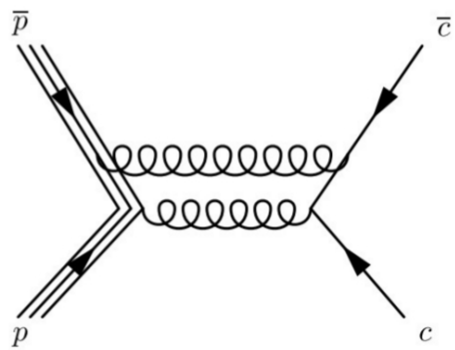
X(3872) factory

Charmonium(-like) Production in $\bar{p}p$ collisions

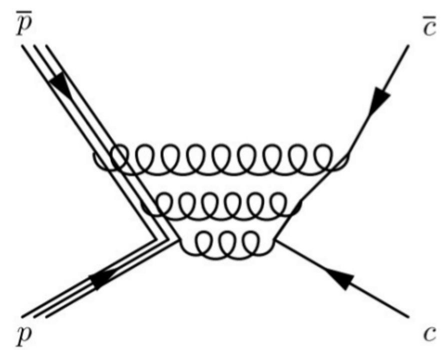
- X(3872) has 1^{++} (C=+)
- In e^+e^- collisions only $J^{PC}=1^{--}$ can be produced directly in $\bar{p}p$ collisions any quantum number



2 gluons: 0^{-+}, 0^{++}, 2^{++}



3 gluons: 1^{--}, 1^{+-}

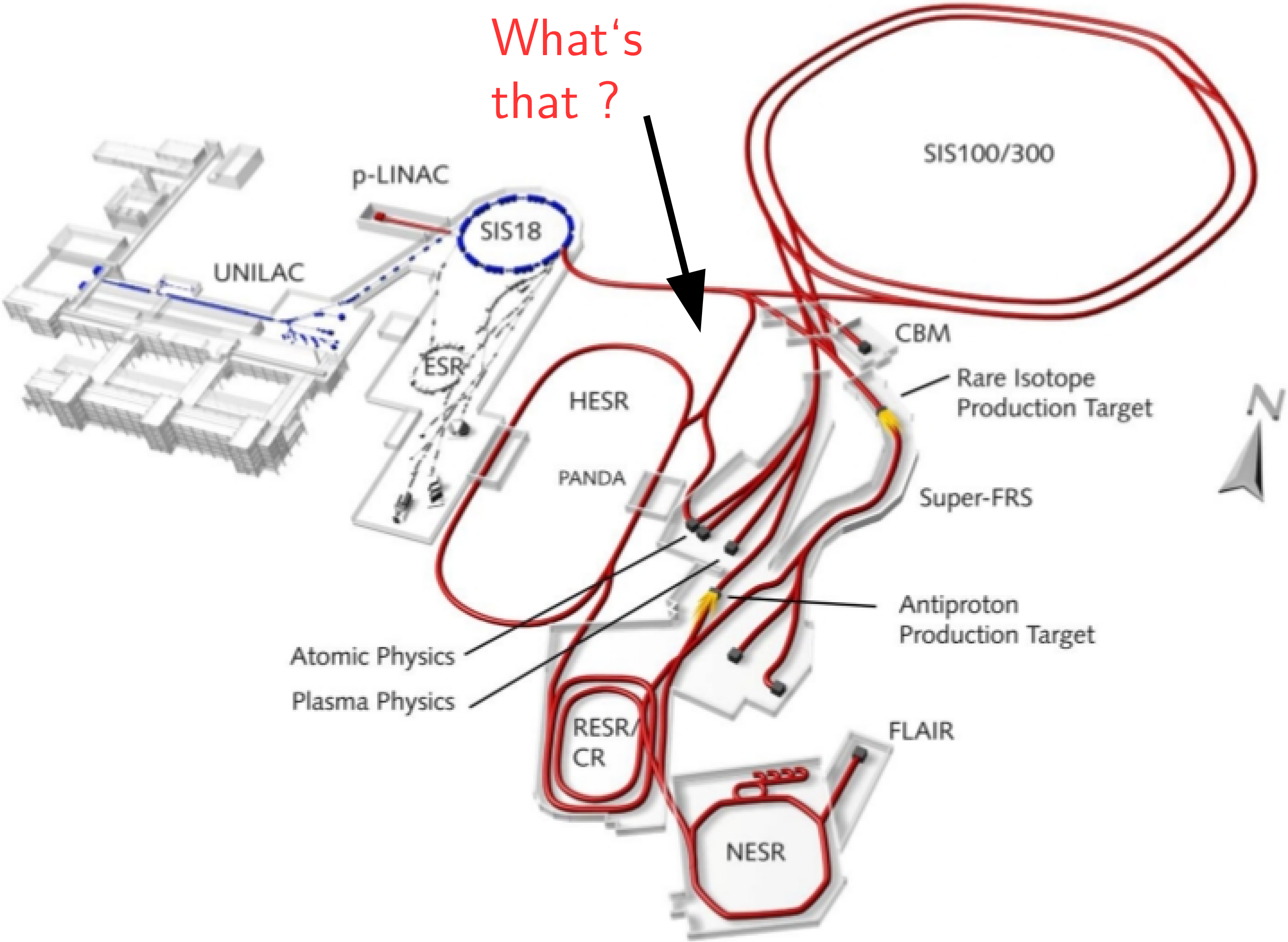


- 2 mechanisms:

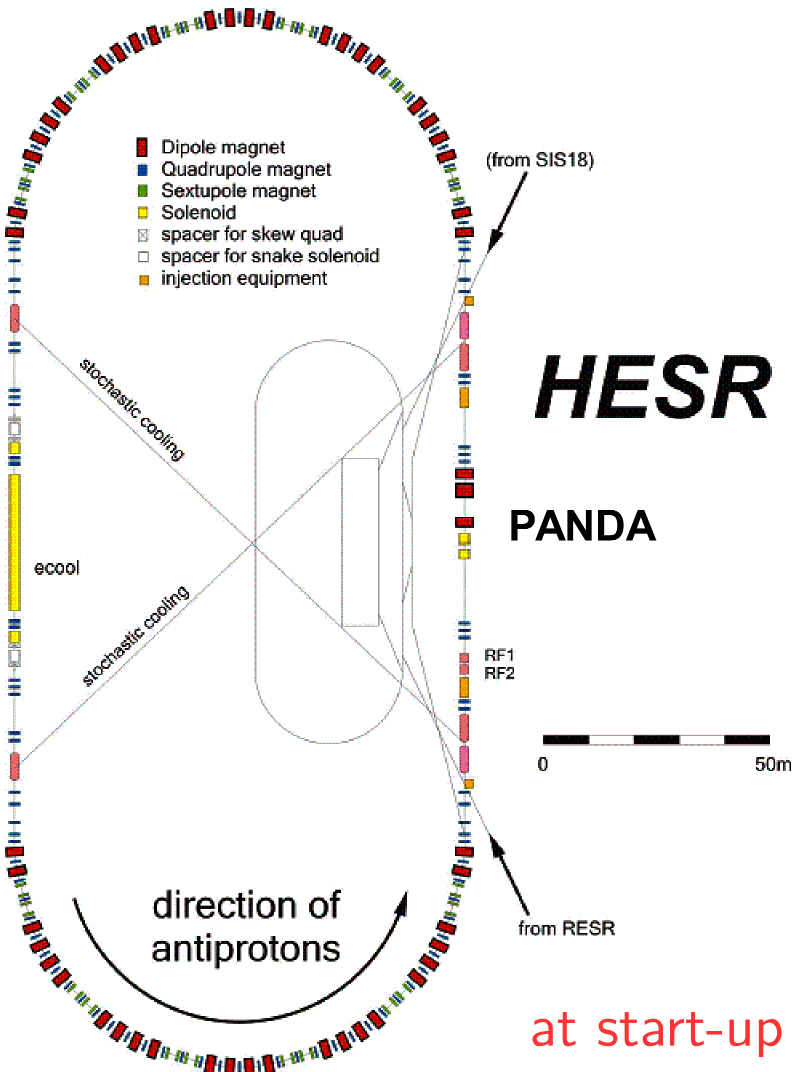
Formation $\bar{p}\underline{p} \rightarrow X(3872)$
Production $pp \rightarrow X(3872)$ + meson(s) @ higher energy

(no parking lot)

FAIR (Facility for Anti-Proton and Ion Research)
Helmholtz Center GSI Darmstadt (Germany)



HESR (High Energy Storage Ring)



For Anti-Protons

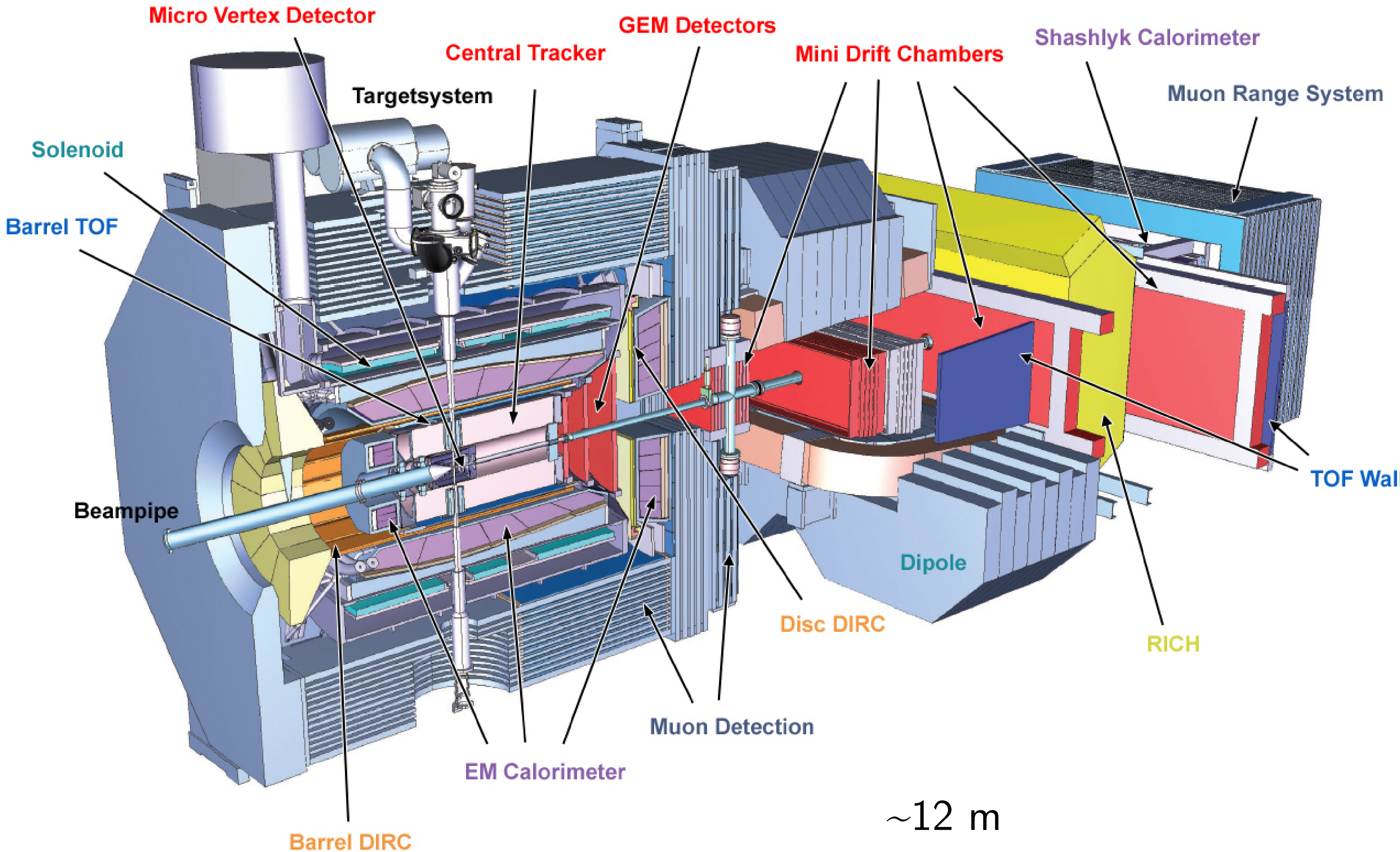
High intensity mode
- $10^{11}\ \bar{p}$
- $\delta p/p \approx 10^{-4}$ (stochastic cooling)

High resolution mode
- $10^{10}\ \bar{p}$
- $\delta p/p \approx 10^{-5}$ (e^- cooling)

Internal targets
- $\mathcal{L} = 2 \times 10^{32}\ cm^{-2}\ s^{-1}$
- H_2 Pellets
- Cluster jet
- Nuclei: Be, C, Si, Al

at start-up planned
$L = 1 \times 10^{31}\ cm^{-2}\ s^{-1}$

Question:
what‘s that large dipole magnet behind Panda good for?

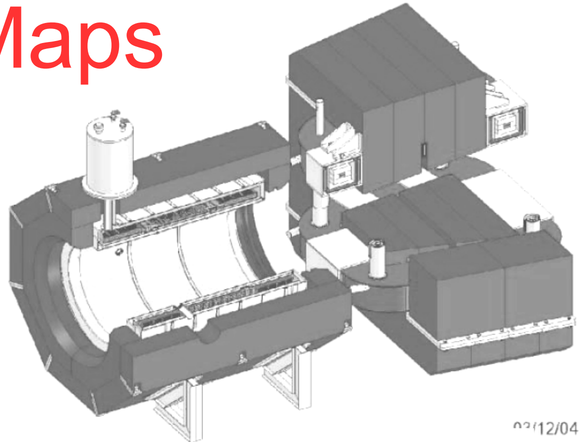


~12 m

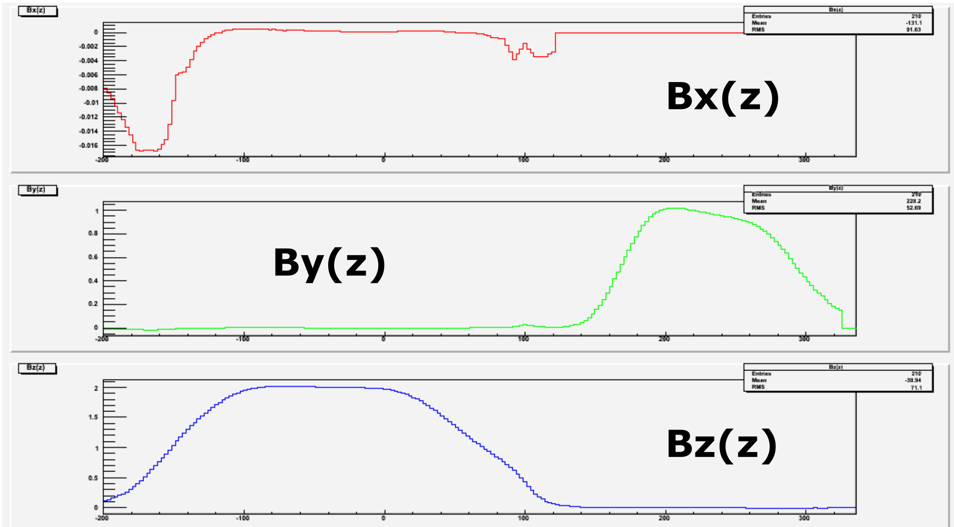
Target spectrometer
Bz = 2 T

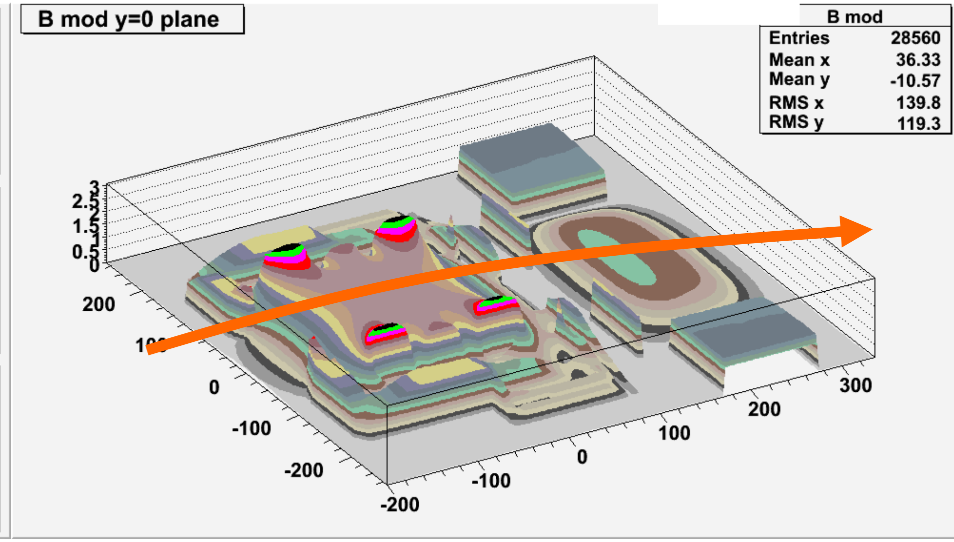
Forward spectrometer
Dipole B·L = 2 Tm

Panda B Field Maps



B field in kG



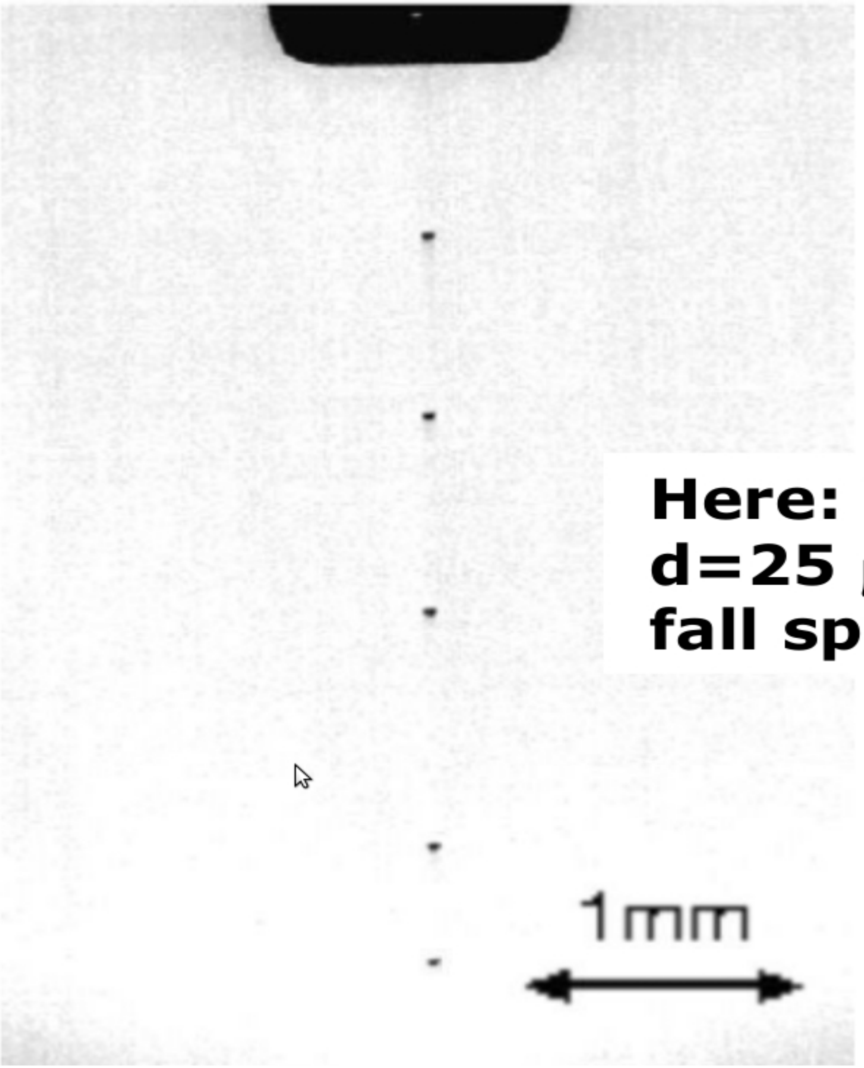


-200 0 +300
z/cm

→beam deflection for p_{beam}=15 GeV/c
4.2 cm @ z=6m (end of dipole)

Question:
why is the HESR an „accelerator“ and not (only) a „storage ring“ ?

The Panda Pellet Target



Here: WASA Target
d=25 μm
fall speed $\geq$ 60 m/s

Anti-proton beam momentum p≤15 GeV/c
$\rightarrow$ √s≤5.5 GeV
access to states higher than 5 GeV !
not available in Belle II (B decays) neither at BesIII

B=2 T (high!)

fixed target
$\rightarrow$ high p_z of tracks (boosted)

NO TRIGGER
full reconstruction online
with interaction rate 2 x 10^7 /s

Panda is a fixed target experiment

$$\sqrt{s} = \sqrt{2m_p^2 + 2m_p\sqrt{p_{beam}^2 + m_p^2}}$$

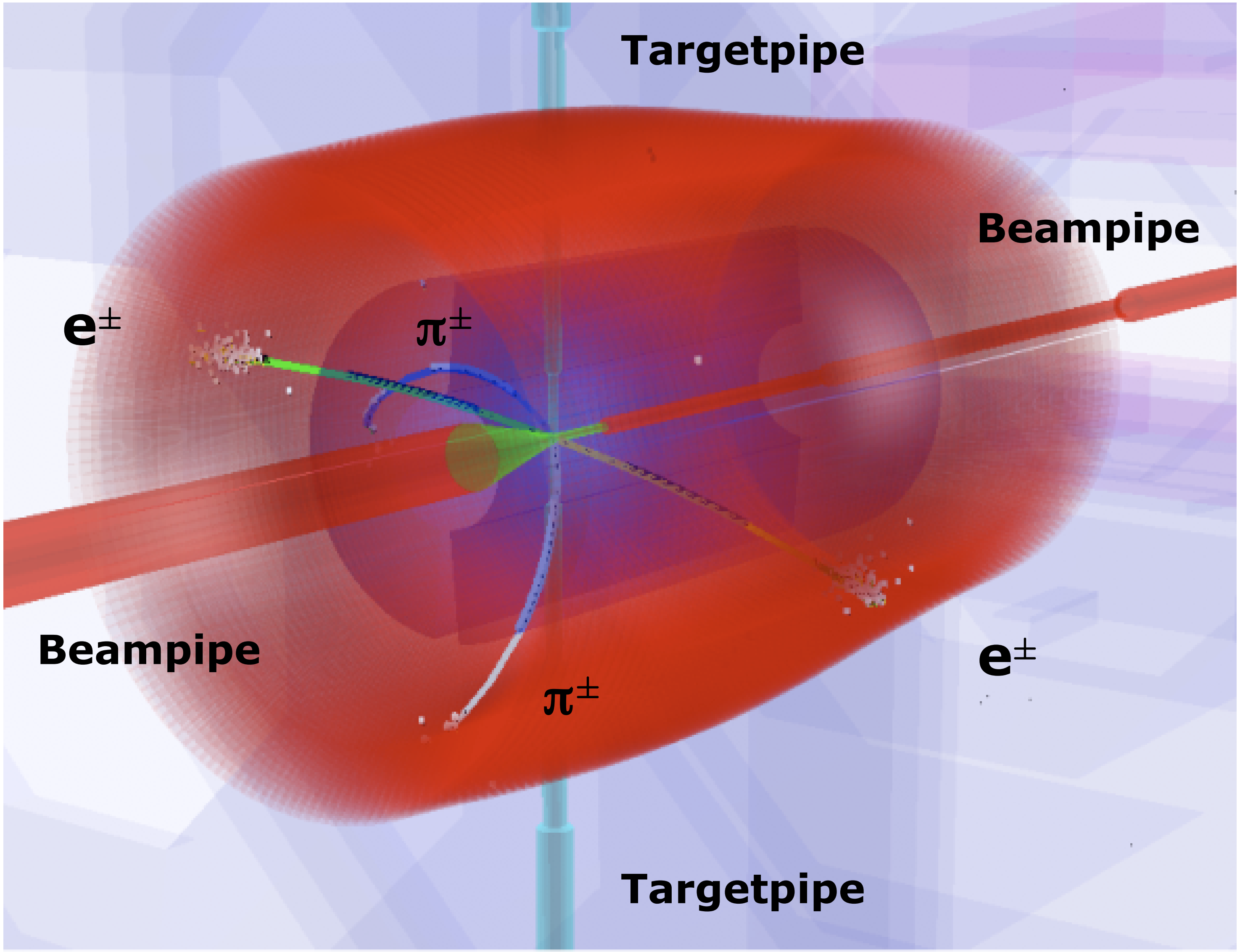
Homework

p_{beam} / GeV/c	$\sqrt{s}$ / GeV	Resonance
4.064	3.096	J/ψ
6.234	3.686	ψ'
6.571	3.770	ψ''
6.991	3.872	X(3872)
7.277	3.940	Y(3940)
7.705	4.040	ψ'''
8.685	4.260	Y(4260)

β_{cms}=0.89 (very high!)
$\beta\gamma$=1.95
$\beta\gamma$=0.43 (Belle), 0.28 (Belle II)

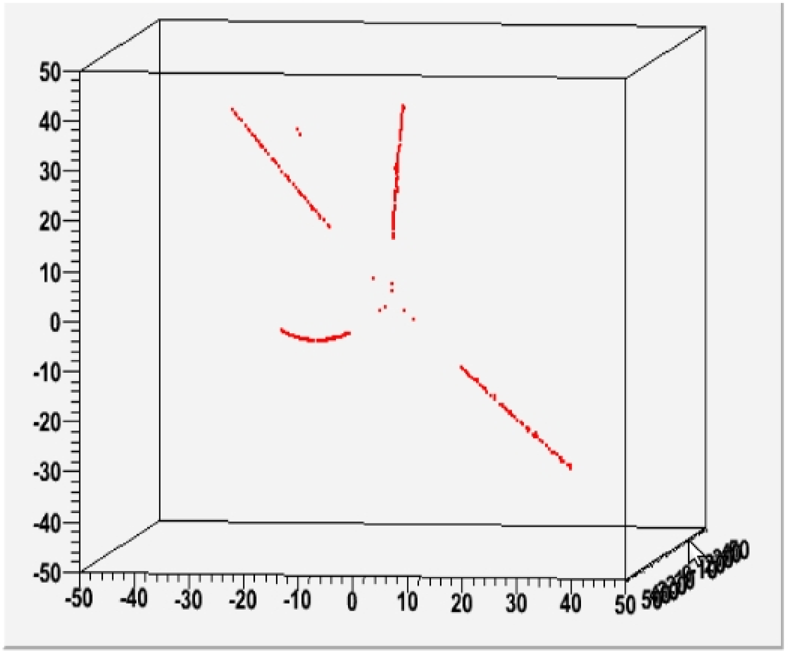
Beam operators „tune“ antiproton momentum energy (for resonance scan) is a non-linear function

X(3872)→ J/ψ π⁺ π⁻ Event, PandaRoot Simulation

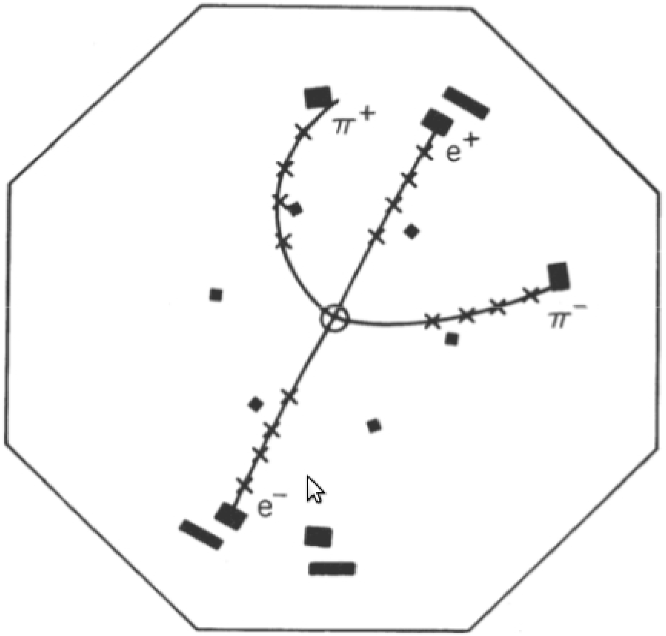


PandaRoot Framework Simulation
X(3872) $\rightarrow$ J/ ψ π^+ π^-
TPC digitization,
MVD Silicon Tracker digitization

XYZ coordinates / cm



ψ' $\rightarrow$ J/ ψ π^+ π^-
Mark II, 1973



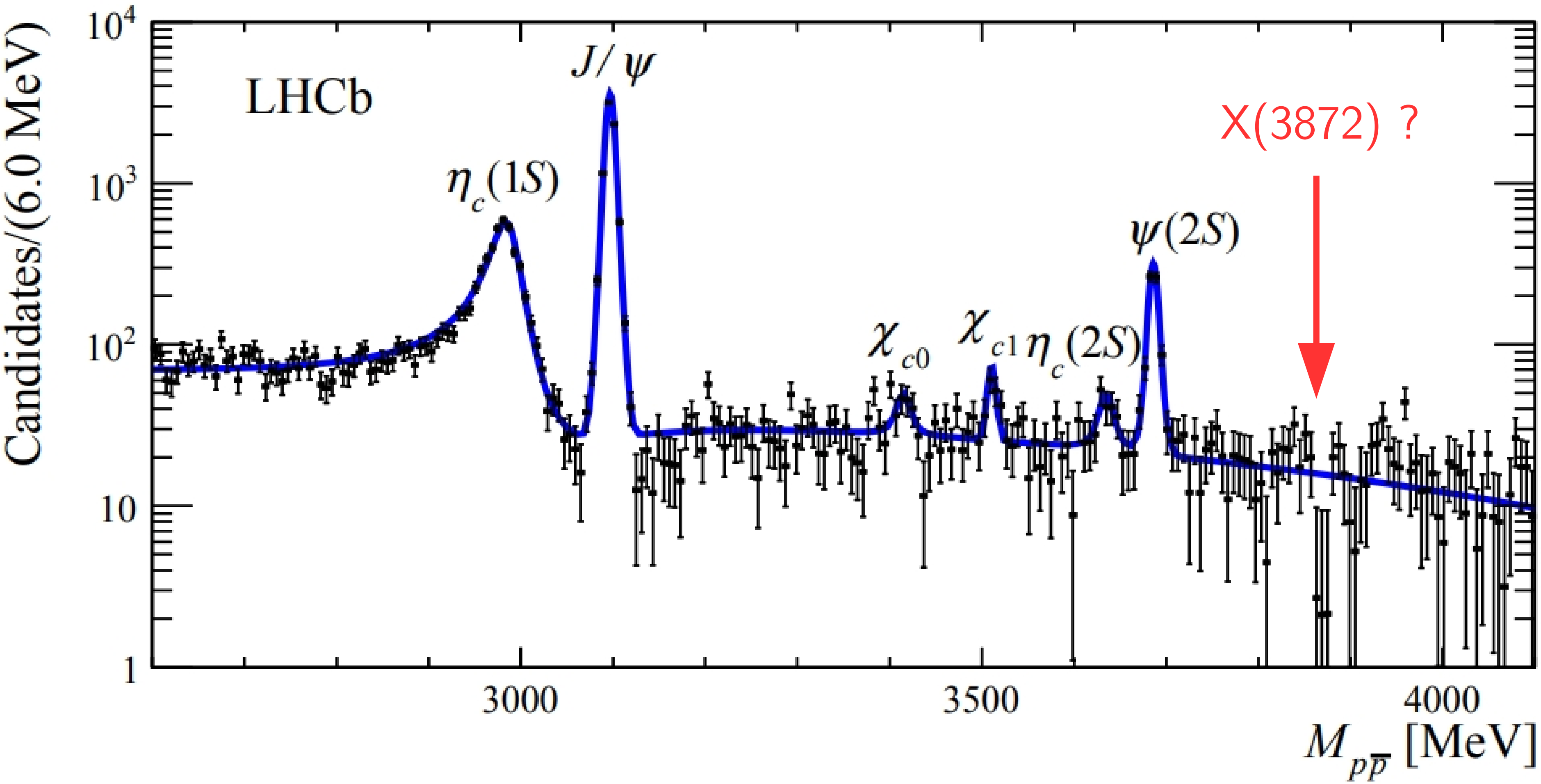
How can we estimate cross sections at PANDA ?

DETAILED BALANCE.

$B^+ \to$ [charmonium]K^+ decays, with [charmonium]$\to p\bar{p}$

LHCb, arXiv:1303.7133 [hep-ex], Eur. Phys. J. C73 (2013) 2462

LHCb, arXiv:1607.06446 [hep-ex], Phys.Lett. B769 (2017) 305



Remember Breit–Wigner?

From PDG,
Review Section „Kinematics“

This is SQUARED
(there is no „i“ anymore)

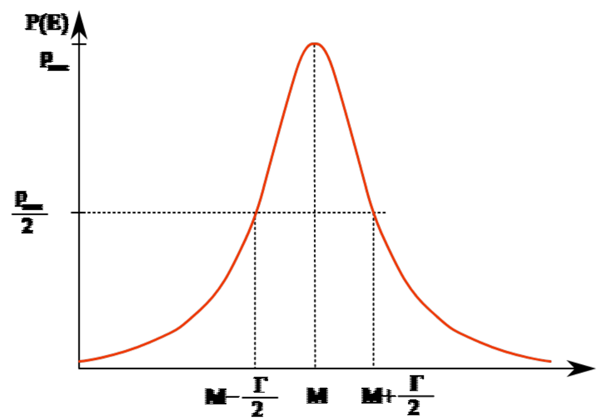
The spin-averaged Breit-Wigner cross section for a spin-J resonance produced in the collision of particles of spin S_1 and S_2 is

$$\sigma_{BW}(E) = \frac{(2J+1)}{(2S_1+1)(2S_2+1)} \frac{\pi}{k^2} \frac{B_{\rm in} B_{\rm out} \Gamma_{\rm tot}^2}{(E-E_R)^2 + \Gamma_{\rm tot}^2/4} , \qquad (46.55)$$

where k is the c.m. momentum, E is the c.m. energy, and $B_{\rm in}$ and $B_{\rm out}$ branching fractions of the resonance into the entrance and exit channels. The $2S+1$

k is wave number,
for a matter wave

$$k \equiv \frac{2\pi}{\lambda} = \frac{p}{\hbar} = \frac{\sqrt{2mE}}{\hbar}$$



The (squared) Breit-Wigner formula
relates the cross section
and the branching fraction.

N.b. this is more a „coupling strength“
but time-reversed it gives a
branching fraction.

Cross section for p p -> X(3872)

spin X(3872)

Branching fraction X(3872) -> ppbar

Branching fraction of X(3872) as detected in Panda

$$\sigma_{BW}(E_{cm}) = \frac{(2J+1)}{(2S_1+1)\cdot(2S_2+1)} \cdot \frac{\pi}{k^2} \cdot \frac{\mathcal{B}_{in}(i)\cdot\mathcal{B}_{out}(f)\cdot{\Gamma_R}^2}{(E_{cm}-M_R)^2+{\Gamma_R}^2/4}$$

spin proton

spin antiproton

width of X(3872) unknown! (we need a trick)

$$k = \sqrt{\frac{{E_{cm}}^2 - 4m_p^2}{4}}$$

How do we know cross sections @ $\overline{\text{P}}$ANDA ?
$\rightarrow$ Detailed Balance

Production
@ Panda

$$\sigma[p\bar{p} \rightarrow X(3872)] = \sigma_{BW}[p\bar{p} \rightarrow X \rightarrow \text{all}](m_{X(3872)})$$

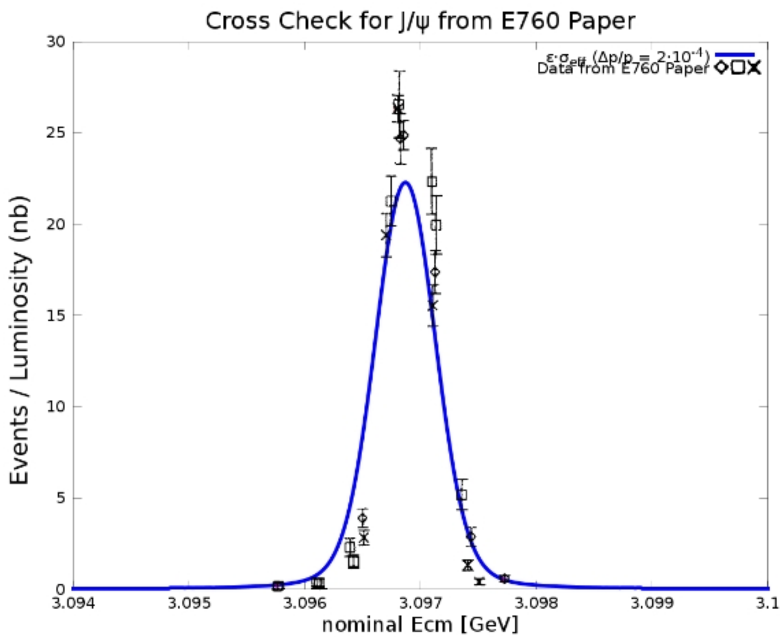
$$= \frac{(2J+1)\cdot 4\pi}{m^2_{X(3872)} - 4m_p^2} \cdot \frac{\mathcal{B}(X(3872) \rightarrow p\bar{p}) \cdot \overbrace{\mathcal{B}(X(3872) \rightarrow f)}^{=1} \cdot \Gamma^2_{X(3872)}}{\underbrace{4(m_{X(3872)} - m_{X(3872)})^2}_{=0} + \Gamma^2_{X(3872)}}$$

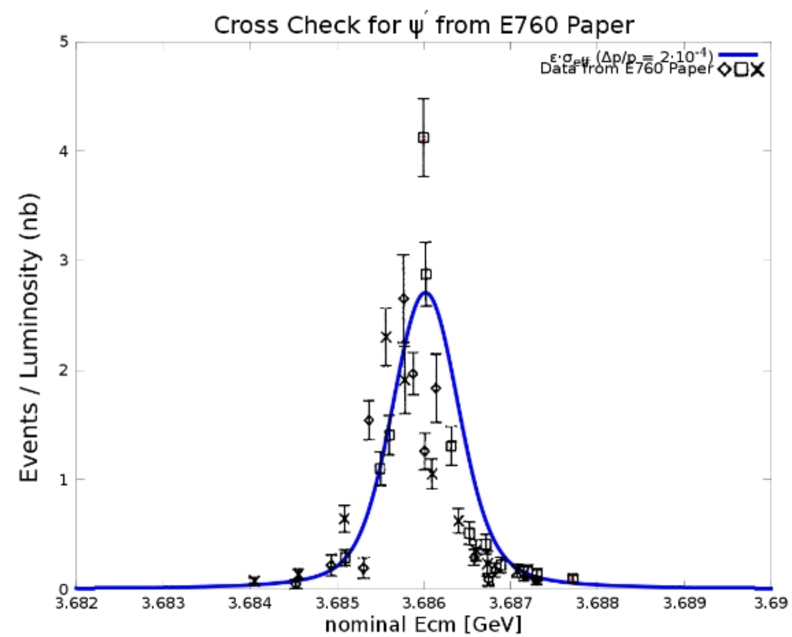
$$\stackrel{(J=1)}{=} \frac{3 \cdot 4\pi}{m^2_{X(3872)} - 4m_p^2} \cdot \mathcal{B}(X(3872) \rightarrow p\bar{p})$$

Decay
@ Belle, BaBar, Bes3, LHCb

Trick: if sitting on the resonance, the width cancels out

Crosscheck of detailed balance with data from E760





Data points from E760, Phys. Rev. D47 (1993) 772
blue curves from detailed balance (LHCb as input)
M. Galuska (Giessen)

Table: Peak cross sections $\sigma^{\text{peak}}_{[p\bar{p}\to R]}$ for $p\bar{p} \to R$ assuming Breit Wigner distributions with constant small width Γ_R.

Res. R	J	Mass m [MeV]	$\mathcal{B}(R \to p\bar{p})$	$\sigma^{\text{peak}}_{[p\bar{p}\to R]}$ ±err. fr. $\mathcal{B}(R \to p\bar{p})$± err. fr. m_R
$J/\psi(1S)$	1	3096.916 ± 0.011	$(2.17 \pm 0.07) \cdot 10^{-3}$	$5.25 \pm 0.17 \pm 0.00\ \mu b$
$\psi(2S)$	1	$3686.109^{+0.012}_{-0.014}$	$(2.76 \pm 0.12) \cdot 10^{-4}$	$402 \pm 18 \pm 4$ nb
$\eta_c(1S)$	0	2981.0 ± 1.1	$(1.41 \pm 0.17) \cdot 10^{-3}$	$1.29 \pm 0.16 \pm 0.00\ \mu b$
$\eta_c(1S)$	0	2981.0 ± 1.1	$(1.32 \pm 0.19) \cdot 10^{-3}$	$1.21 \pm 0.17 \pm 0.00\ \mu b$
$\eta_c(2S)$	0	3638.9 ± 1.3	$(1.85 \pm 1.26) \cdot 10^{-4}$	$93 \pm 63 \pm 0$ nb
$\eta_c(2S)$	0	3638.9 ± 1.3	$(3.12 \pm 1.65) \cdot 10^{-4}$	$< 157 \pm 83 \pm 0$ nb (95% CL)
$\chi_{c0}(1P)$	0	3414.75 ± 0.31	$(2.23 \pm 0.13) \cdot 10^{-4}$	$134.1 \pm 7.8 \pm 0$ nb
$h_c(1P)$	1	3525.41 ± 0.16	$(8.95 \pm 5.21) \cdot 10^{-4}$	$1.47 \pm 0.86 \pm 0\ \mu b$
$h_c(1P)$	1	3525.41 ± 0.16	$(1.68 \pm 0.05) \cdot 10^{-3}$	$< 2776 \pm 87 \pm 0$ nb (95% CL)
$X(3872)$	1	3871.68 ± 0.17	$(5.31 \pm 0.00) \cdot 10^{-4}$	$< 68.0 \pm 4.0 \pm 0.0$ nb (95% CL)
$X(3915)$	?	3917.5 ± 2.7	$(27 \pm 10) \cdot 10^{3}$	not isolated

Let's assume 50 nb (conservative)

Cross sections at $\overline{\text{P}}$ANDA

L $=$ 1 x 10^{31} cm^{-2} s^{-1} (start-up phase)
1 nb $=$ 1 x 10^{-9} x 10^{-24} cm^2
1 nb^{-1} $=$ 10^{33} cm^{-2}

L$=$0.01 collisions per nanobarn and per second

for 1 nb production cross section
0.01 * 3600 * 24 $=$ 864 events per 1 day

for X(3872): estimate 50 nb
43.500 per 1 day
Decay into $J/\psi\pi\pi$ (assume 5% branching fraction)
$\rightarrow$ 2160 events per day (in Panda start–up phase!)
Belle recorded ~150 events in ~10 years

End of Lecture 2

Thank you!

Backup Slides

Bottomonium-like States

RECOIL MASS

$$m_B = \sqrt{E_B^{*2} - \vec{p}_B^{*2}} \qquad (1)$$

where $*$ indicates the center-of-mass system.

In a two-body system: $\vec{p}_A^* = -\vec{p}_B^*$ and $E_A^* + E_B^* = \sqrt{s}$.

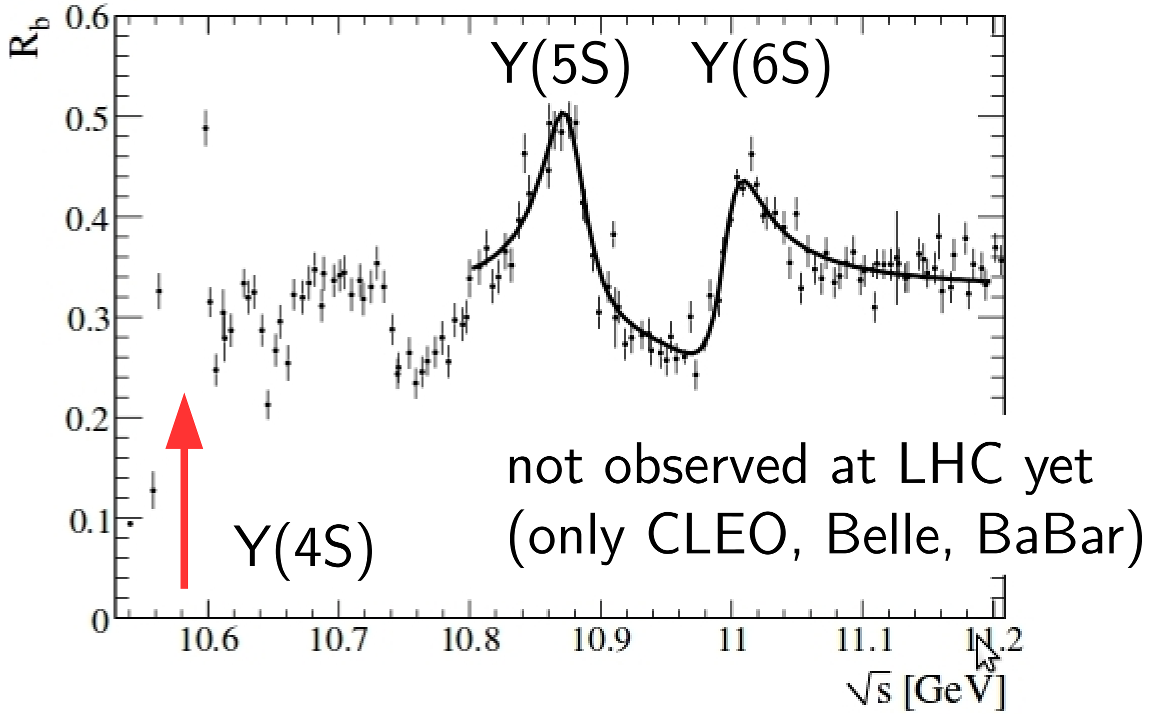
(back–to–back in cms)

$$m_B = \sqrt{(\sqrt{s} - E_A^*)^2 - p_A^{*2}} \qquad (2)$$

This implies: the mass of B can be calculated from measurements of A only. B does not need to be measured.

→ sometimes also refered to as „missing mass“

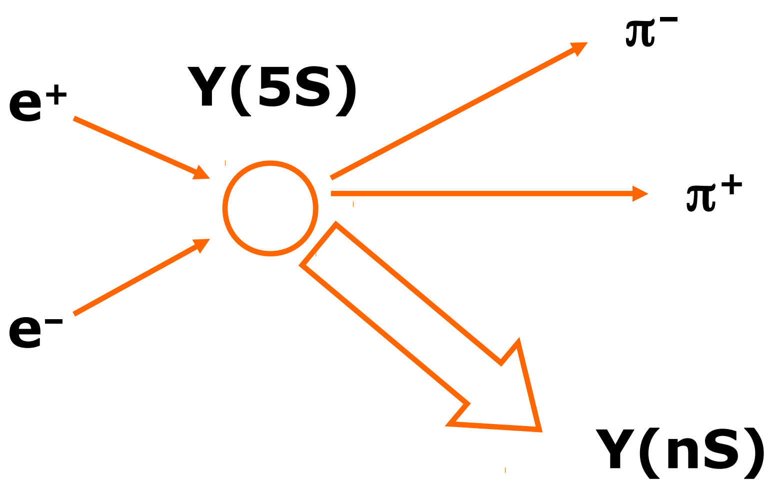
	$\Upsilon(10860)$	$\Upsilon(11020)$
mass (GeV)	10.876 ± 0.002	10.996 ± 0.002
width (MeV)	43 ± 4	37 ± 3
ϕ (rad)	2.11 ± 0.12	0.12 ± 0.07
PDG mass (GeV)	10.865 ± 0.008	11.019 ± 0.008
PDG width (MeV)	110 ± 13	79 ± 16



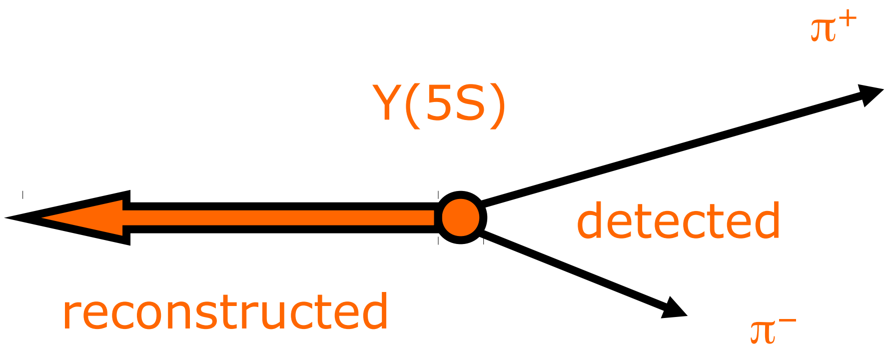
BaBar, 0809.4120[hep-ex], Phys. Rev. Lett. 102(2009)012001
Events „tagged“ with a B meson (N_{track}≥3, Evis>4.5 GeV, R_2<0.2)

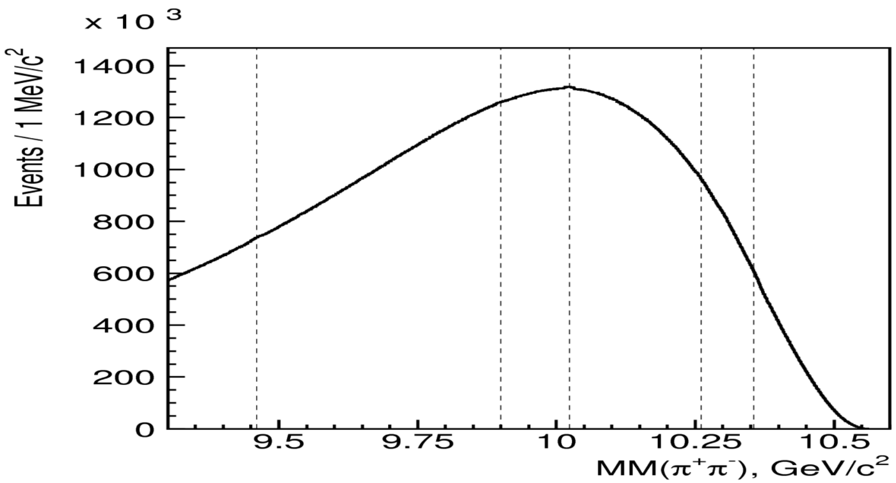
Υ(5S) data taking

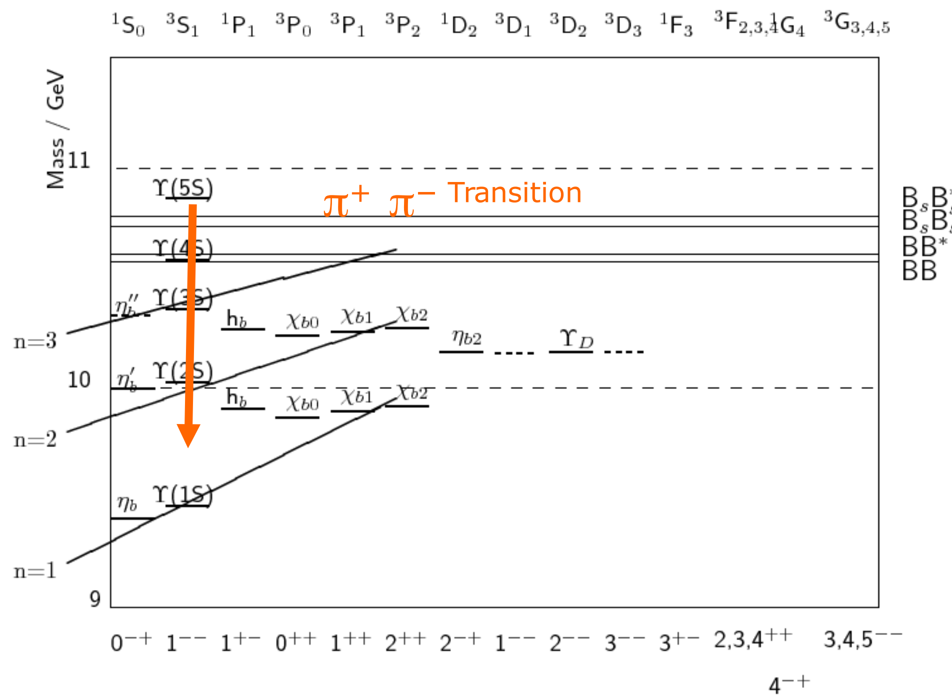
- KEK-B and Belle changed beam energy to Υ(5S)
- 22 points, 1 fb^{-1} per point, 5 MeV apart
  61 points, 0.5 fb^{-1} per point, 1 MeV apart
- investigate [vector $\rightarrow$ vector π π]
  as an analogy to Y(4260) $\rightarrow$ J/ψ π π



$\Upsilon(5S) \rightarrow X\, \pi^+\pi^-$ reconstruction







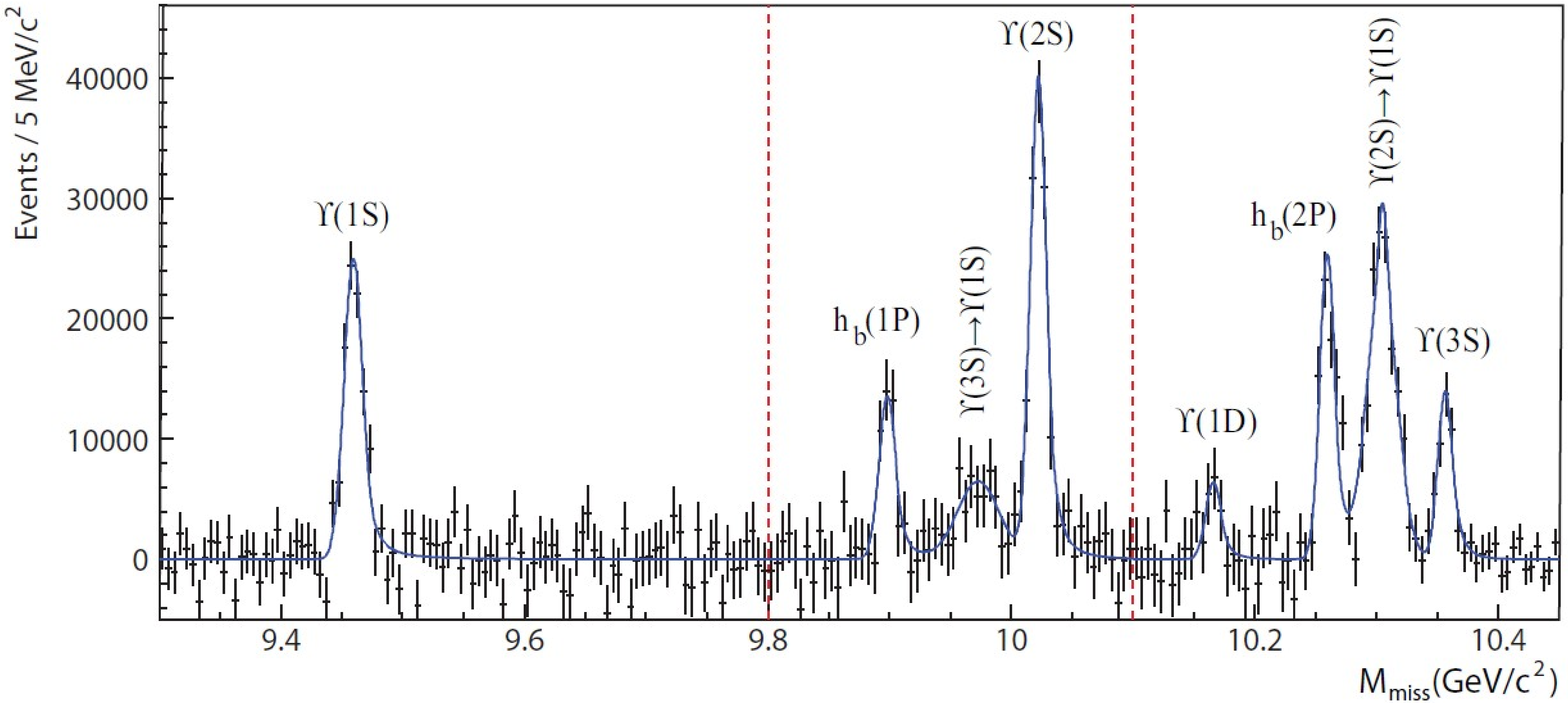
$$M_{\mathrm{miss}}(X) = \sqrt{(E_{\mathrm{c.m.}} - E^*_X)^2 - p^{*2}_X}$$

Υ(5S) Decays

$\pi^+ \pi^-$ missing mass

First observation of $h_b(1P)$ and $h_b(2P)$

Belle, 121.4 fb^{-1}
Phys. Rev. Lett 108(2011)032001
arXiv:1103.3419



Advantage of recoil mass technique:

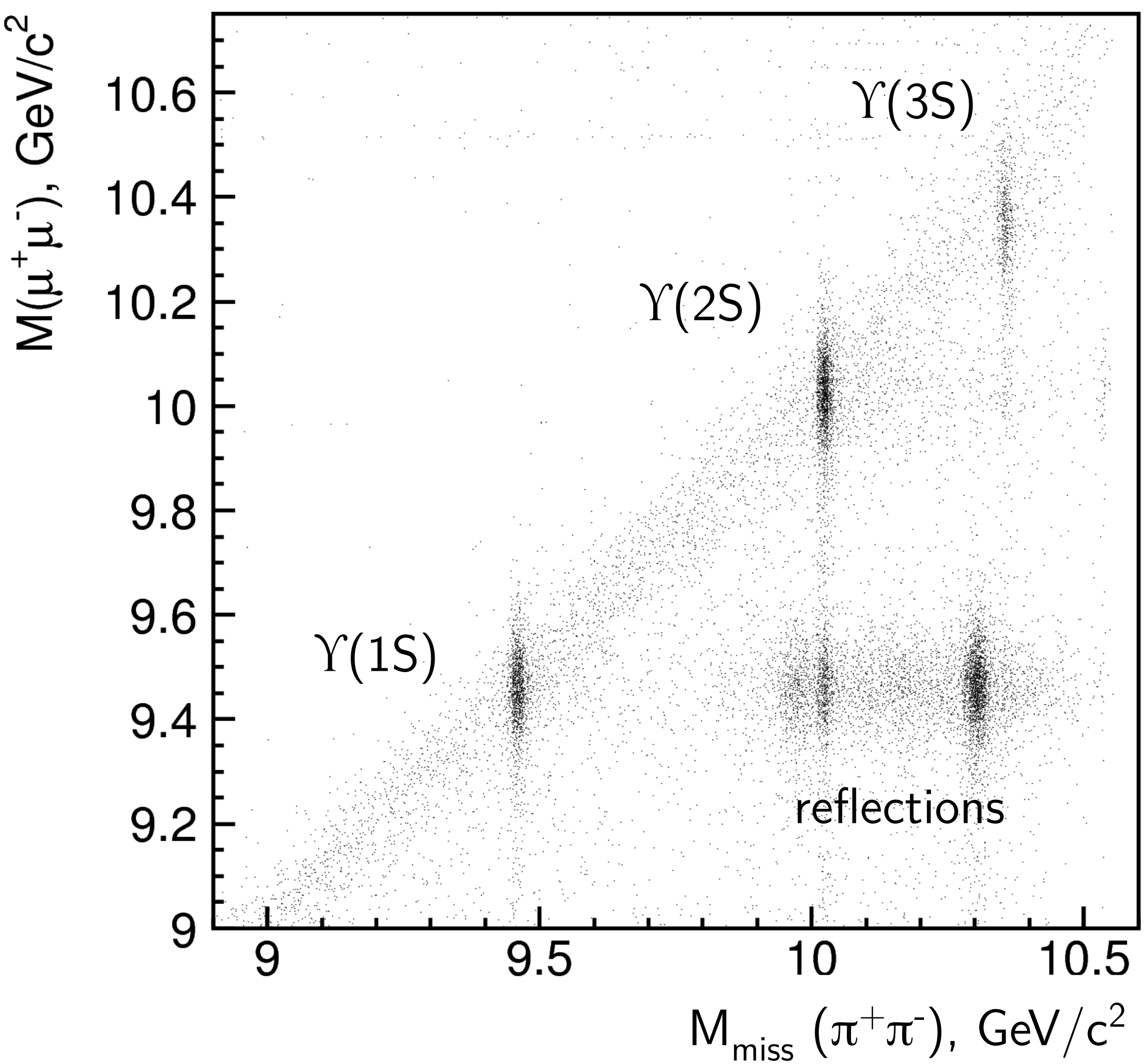
reconstruction of decay (final state particles) on recoil side not required
$\rightarrow$ 100% reconstruction efficiency

Resonant substructure of $\Upsilon(5S) \rightarrow \Upsilon(nS)\ \pi^+\pi^-$

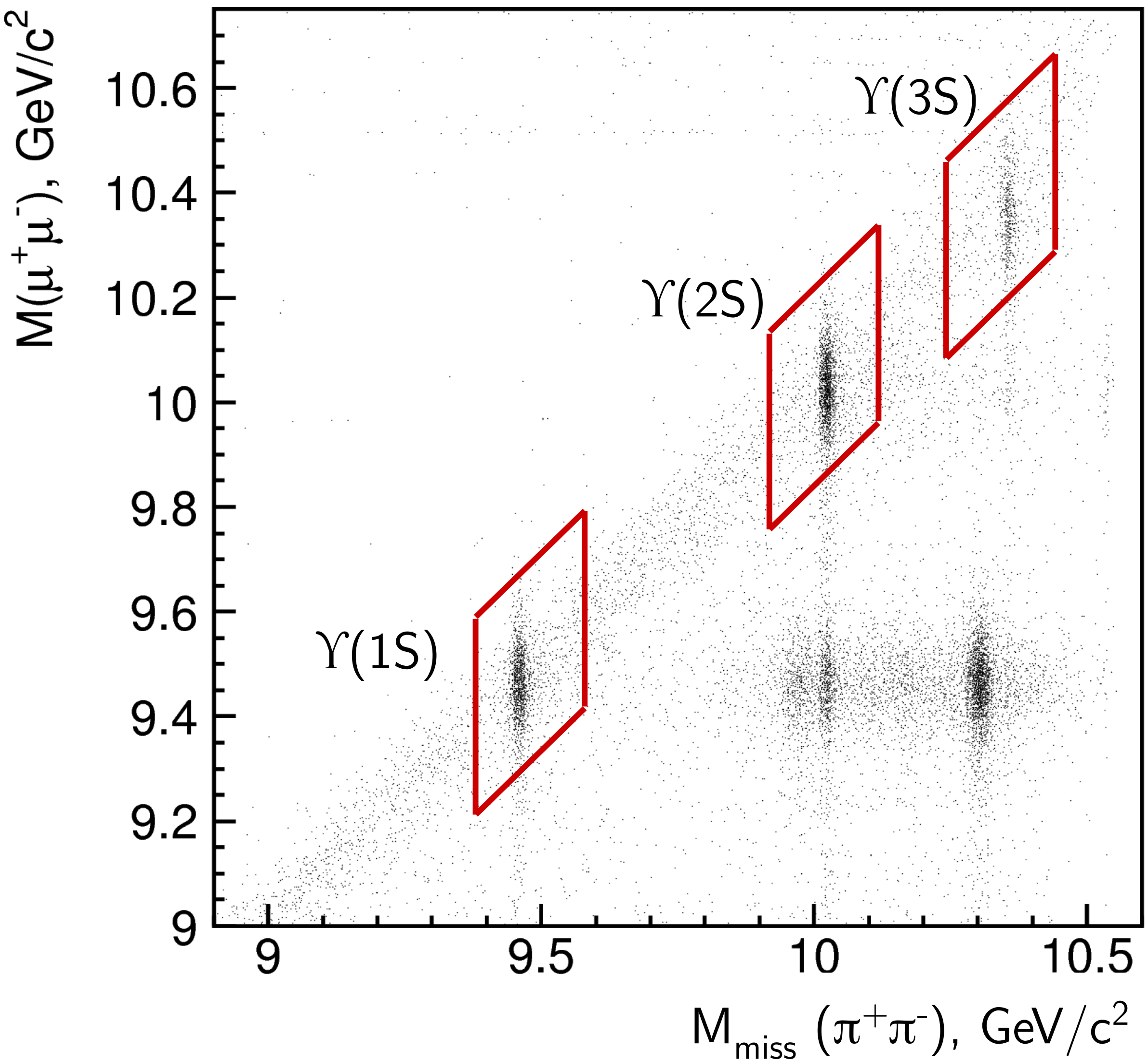
(n=1,2,3)

$\Upsilon(5S) \rightarrow \Upsilon(nS)\ \pi^+\pi^-$ (n = 1,2,3)

$\hookrightarrow \mu^+\mu^-$



$\Upsilon(5S) \rightarrow$ **$\Upsilon(nS)$** $\pi+\pi-$ (n = 1,2,3)
$\hookrightarrow \mu+\mu-$



Reflections
Y(5S)
$\rightarrow$ Y(2S,3S)$\pi\pi$
$\rightarrow$ Y(1S)$\pi\pi\pi\pi$

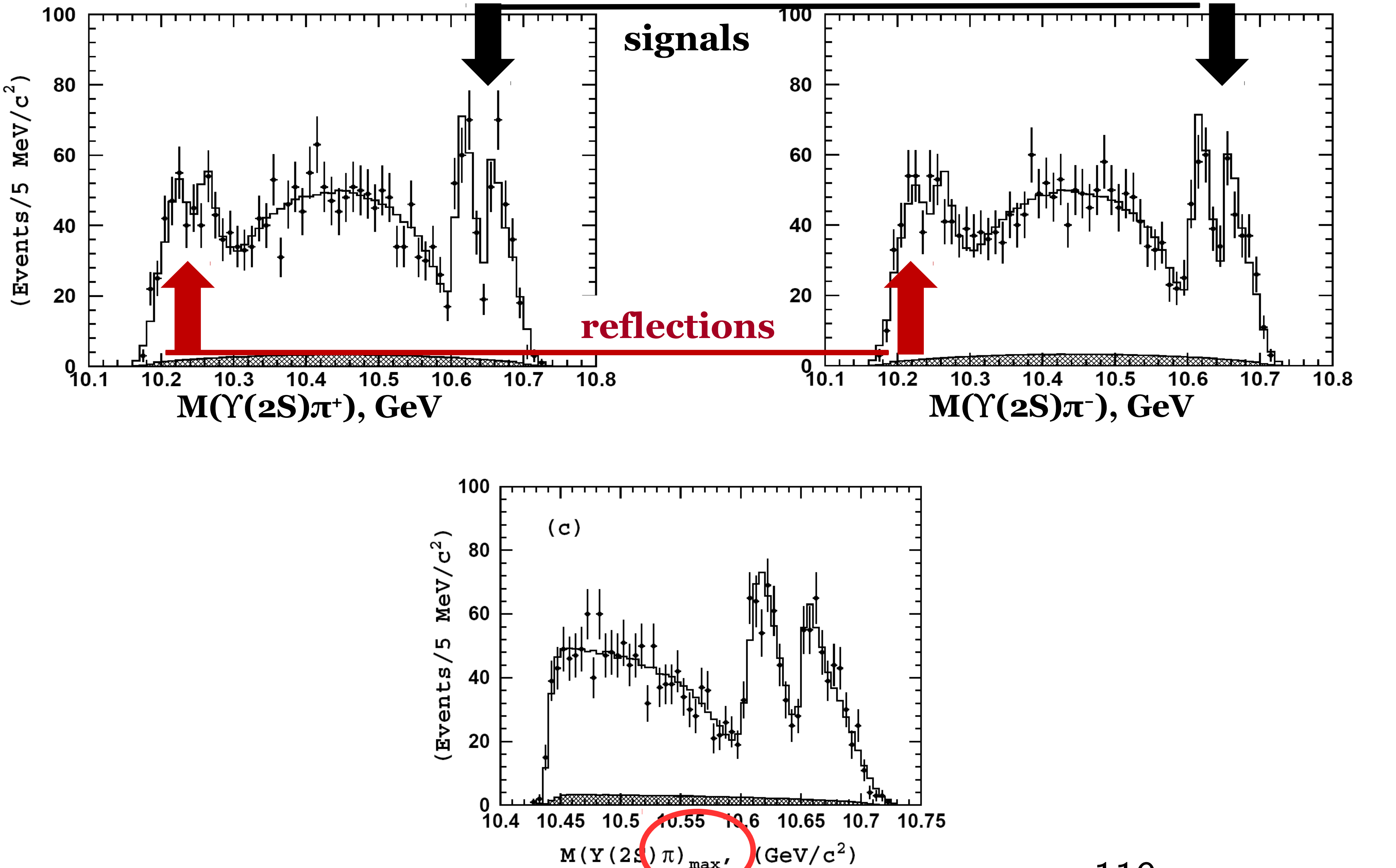
REFLECTION

$$\mathrm{Y}(5S) \to \mathrm{Y}(3S)\, \pi_1^+\, \pi_1^- \to \mathrm{Y}(1S)\, \underbrace{\pi_2^+\, \pi_2^-}_{\substack{\text{monoenergetic} \\ \mathrm{Y}(3S) \to \mathrm{Y}(1S)}}\, \underbrace{\pi_1^+\, \pi_1^-}_{\substack{\text{monoenergetic} \\ \mathrm{Y}(5S) \to \mathrm{Y}(3S)}}$$

Now we combine Y(1S) with $\pi_1^+\, \pi_1^-$

gives a (wrong) peak!

$\Upsilon(2S)\pi^+\pi^-$

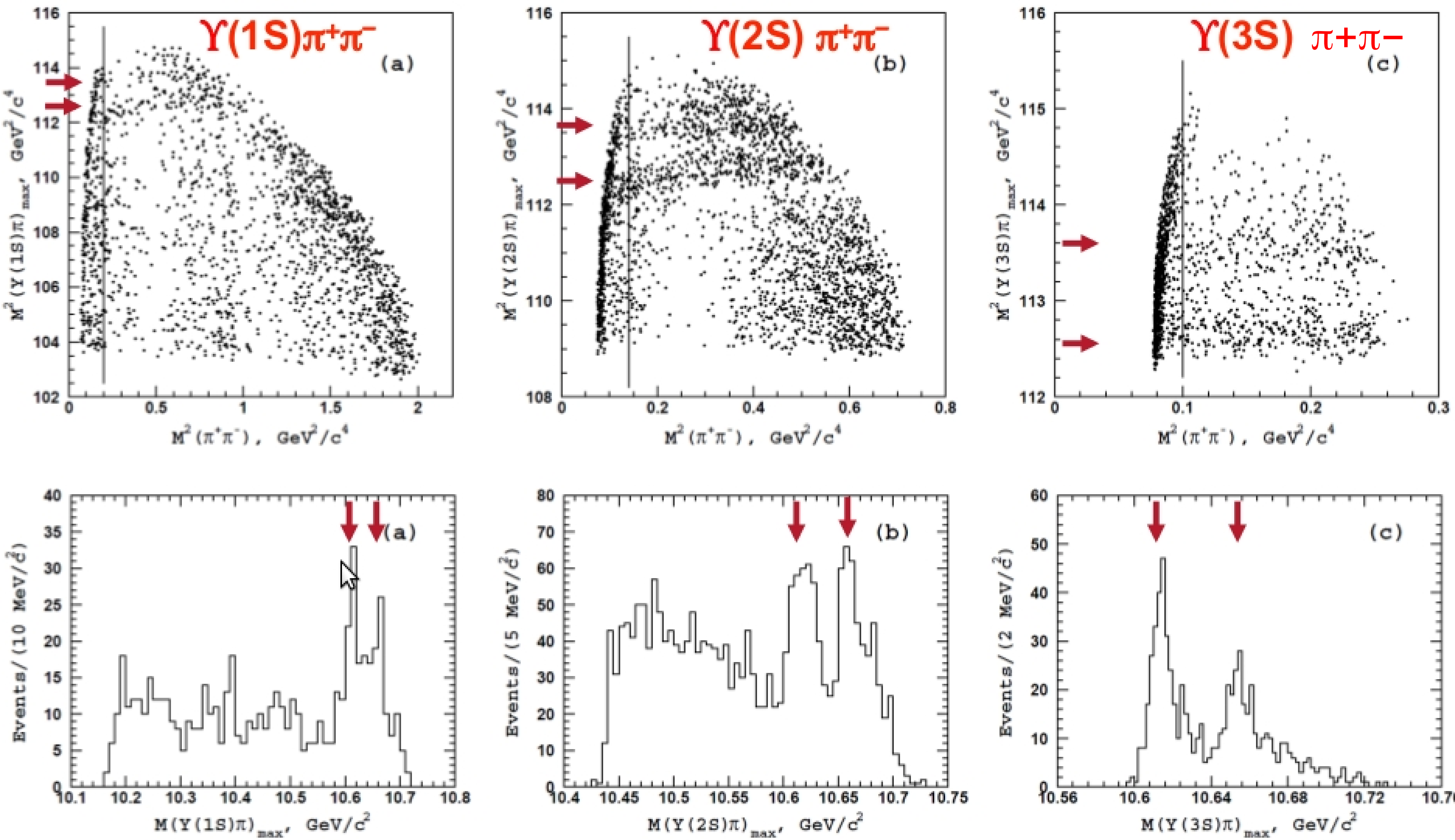


A different type of reflection

$$\begin{aligned} \Upsilon(5S) &\rightarrow \Upsilon(2S)\pi^+\pi^- \\ \Upsilon(5S) &\rightarrow Z^+\pi^- \\ Z^+ &\rightarrow \Upsilon(2S)\pi^+ \end{aligned} \qquad \begin{aligned} \Upsilon(5S) &\rightarrow \Upsilon(2S)\pi^+\pi^- \\ \Upsilon(5S) &\rightarrow Z^-\pi^+ \\ Z^- &\rightarrow \Upsilon(2S)\pi^- \end{aligned}$$

π^+ from Z^+ decay is monoenergetic (in Z rest frame),
because of two-body kinematics
π^+ from $\Upsilon(5S)$ decay in case of Z^- is monoenergetic,
because two-body decay and initial energy is fixed
$\rightarrow$ [$\Upsilon(2S)\pi^+$(from $\Upsilon(5S)$ decay)] combination gives a (wrong) peak
Solution: the one (the other) π^+ is high (low) momentum
$\rightarrow$ "identify" the pions (subsscript "max")
Side remark: the pure observation of these reflections tell us,
that there is a Z^+ and a Z^-

$\Upsilon(5S) \to \Upsilon(nS)\ \pi^+\pi^-$ Dalitz plots



$\to$ Signals of $Z_b(10610)$ and $Z_b(10650)$ CHARGED STATES

Summary of Z_b parameters

Thresholds (PDG)
BB* 10,604 GeV
B*B* 10,650 GeV

Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, MeV$/c^2$	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4\,^{+4.5+2.1}_{-3.9-1.2}$	$13\,^{+10+9}_{-8-7}$
$M[Z_b(10650)]$, MeV$/c^2$	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3\,^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)]$, MeV	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9\,^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7\,^{+11}_{-7}$
Rel. normalization	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. phase, degrees	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

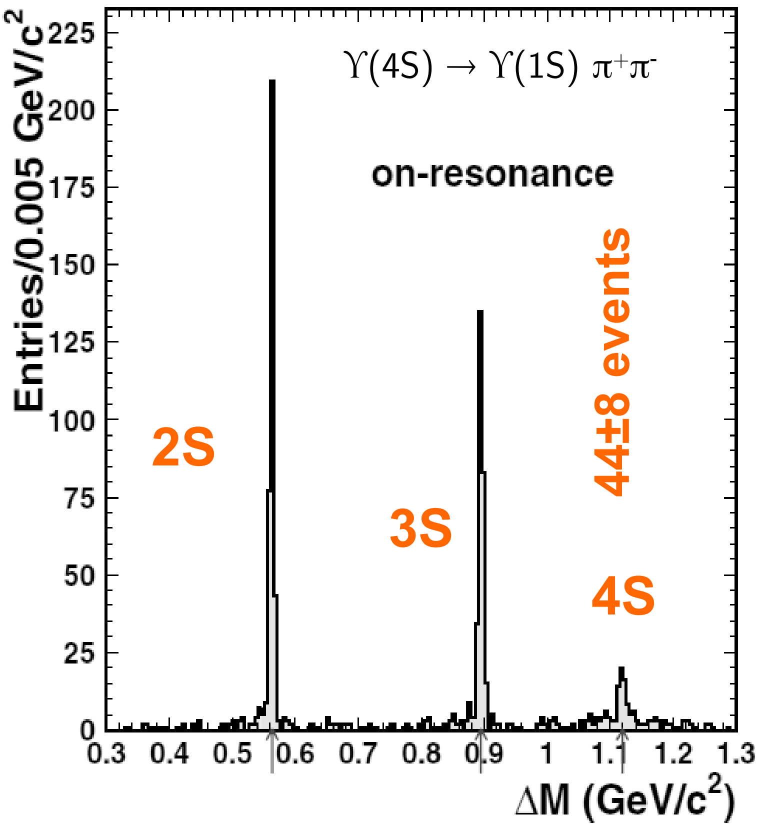
The two charged states are observed in 5 decays channels.

Reminder:

any of these results were only possible because of one reason: we have factor $\geq 10^3$ too many events ...

Γ[Y(5S)→ππY(nS)] is huge

Y(4S)→ππY(1S)
477 fb^{-1}

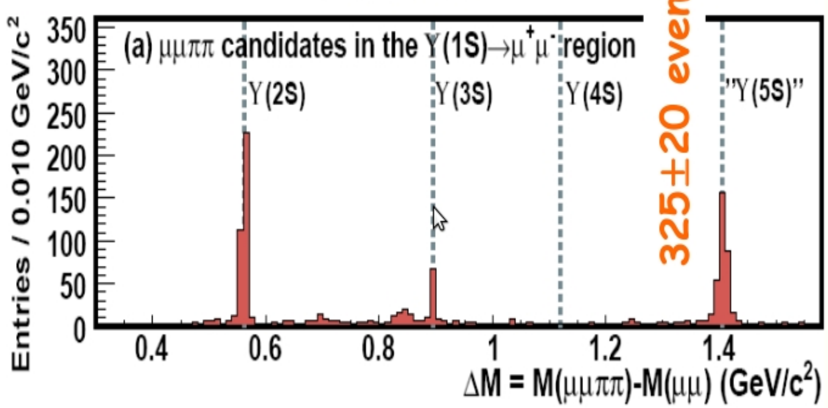


Phys. Rev. D75(2007)071103

8 times as many events integrated for Y(nS)

1/20 times the data & ~1/10th the crosssection

Y(5S)→ππY(1S)
21.7 fb^{-1}



Belle Phys. Rev. Lett. 100, 112001 (2008)

Not only Y(5S) → Y(1S)ππ is large, but also Y(5S)→ Y(2S)ππ