PROSPECTS FOR HADRONIC PHYSICS AT BELLE II

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For the Belle II Collaboration

9/8/2017

OUTLINE

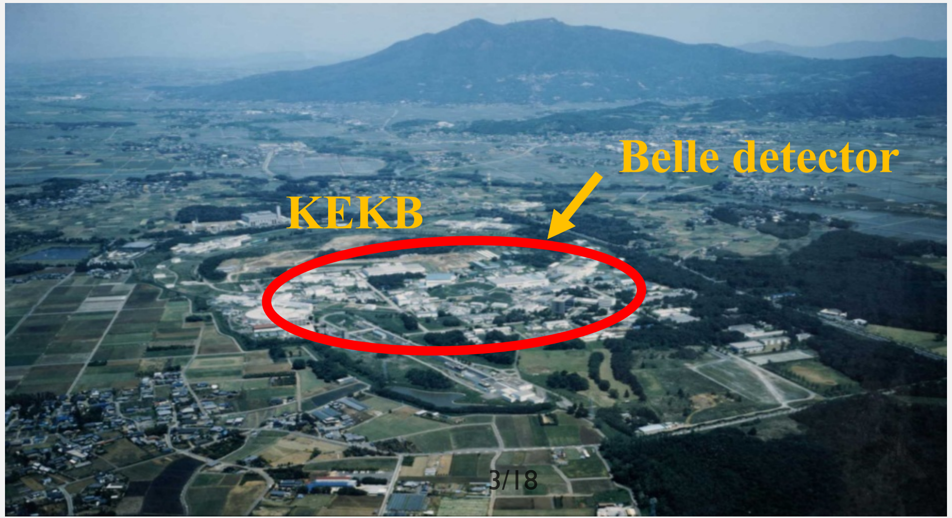
- Belle (I) Legacy
  - Quarkonium (like)
  - Hadronization (Fragmentation function measurements)
- SuperKEKB and Belle II
  - Upgrade
  - Status
  - Early Physics program
  - Outlook

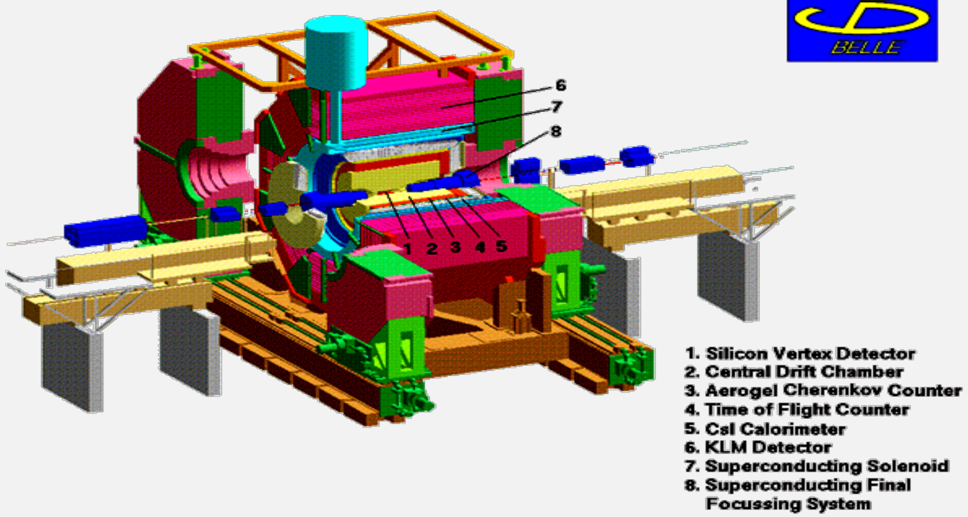
Before Belle II there was BELLE

- KEKB: asymmetric e^+ (3.5 GeV) e^- (8 GeV) collider:
  - $\sqrt{s}$ = **10.58 GeV,** $e^+e^- \rightarrow \Upsilon(nS) \rightarrow B/\bar{B}$ + continuum
  - $\sqrt{s}$ = 10.52 GeV, e+e-→ qqbar (u,d,s,c) 'continuum'
- Ideal (at the time) detector for high precision measurements:
  - tracking acceptance θ [17 °;150°]: Azimuthally symmetric
  - particle identification (PID): dE/dx, Cherenkov, ToF, EMcal, MuID
- Available data:
  - ~1 ab^{-1} total
  - ~1.8 $*10^9$ events at 10.58 GeV,
~220 $*10^6$ events at 10.52 GeV

Experiment	Scans/ Off. Res. fb^{-1}	$\Upsilon(5S)$ 10876 MeV fb^{-1}	10^6	$\Upsilon(4S)$ 10580 MeV fb^{-1}	10^6	$\Upsilon(3S)$ 10355 MeV fb^{-1}	10^6	$\Upsilon(2S)$ 10023 MeV fb^{-1}	10^6	$\Upsilon(1S)$ 9460 MeV fb^{-1}	10^6
CLEO	17.1	0.4	0.1	16	17.1	1.2	5	1.2	10	1.2	21
BaBar	54	R_b scan		433	471	30	122	14	99	–	
Belle	100	121	36	711	772	3	12	25	158	6	102

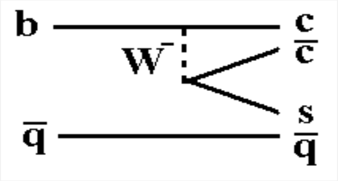
BELLE Detector (took data till 2010)



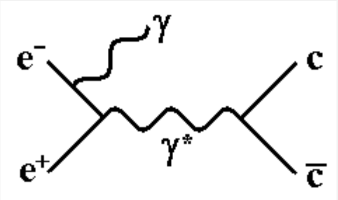


BELLE LEGACY IN HADRONIC PHYSICS – QUARKONIUM (-LIKE) PRODUCTION

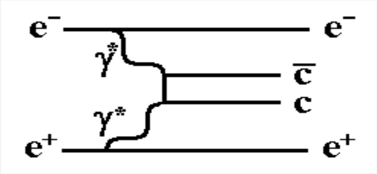
- B decays
  - Charmonium only
  - All quantum numbers available



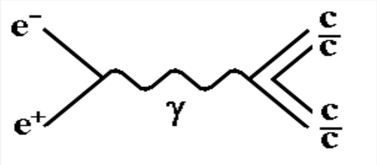
- Direct production / Initial State Radiation (ISR)
  - E_{CM} or below
  - $J^{PC}=1^{--}$



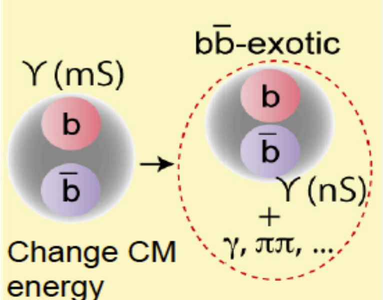
- Two-photon interaction
  - J^{PC} = 0-+, 0++, 2++



- Double charmonium production
  - Seen for $J^{PC}=1^{--}$ (J/ψ, $\psi(2S)$) plus J=0 states (C=1?)

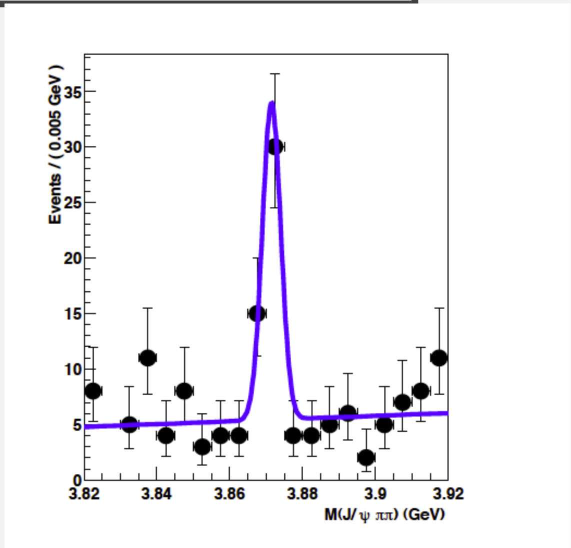


- Quarkonium transitions
  - Hadronic/radiative decays between states

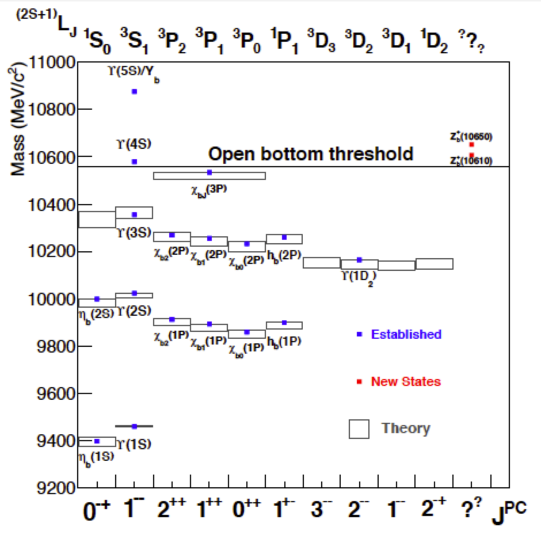


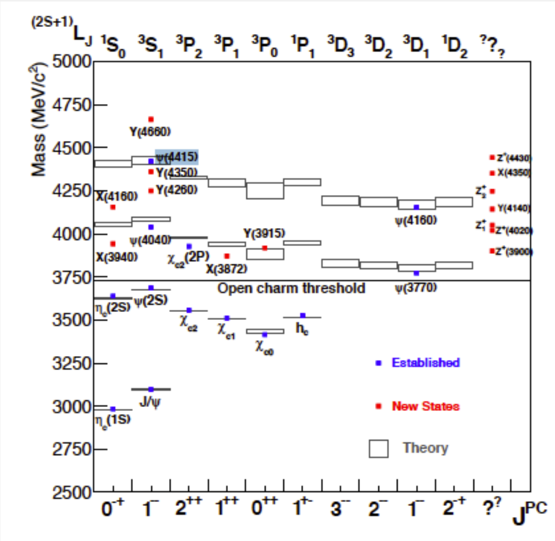
QUARKONIUM STUDIES AT BELLE II BUILD ON THE SUCCESSFUL BELLE PROGRAM

- XYZ revolution kicked off by discovery of X(3872) at Belle 2003
- Precision study of Charmonium: States above the DDbar threshold are a strongsuit of B factories → can access energy spectrum continuously)
- Precision studies of Bottomonium states and transitions



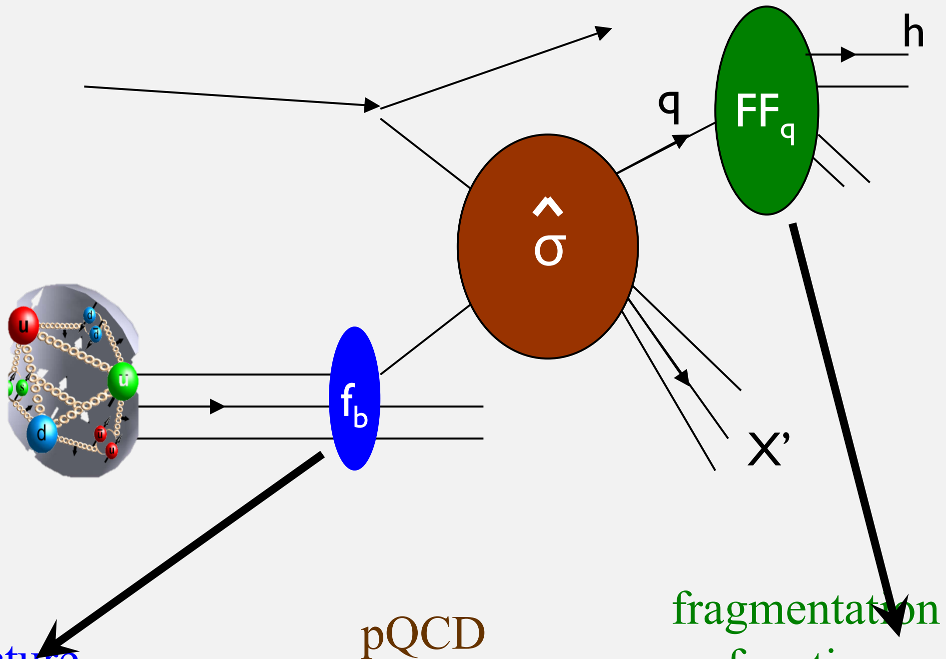
(Choi et al, PRL91 (26) 262001)





E+-E- CRUCIAL TO EXTRACT HADRONIZATION INFORMATION

- Fragmentation Functions appear almost always when accessing partonic structure of the nucleon
- Proton Structure extracted using QCD factorization theorem
- FFs contribute to virtually all processes
- Particular important for transverse spin structure



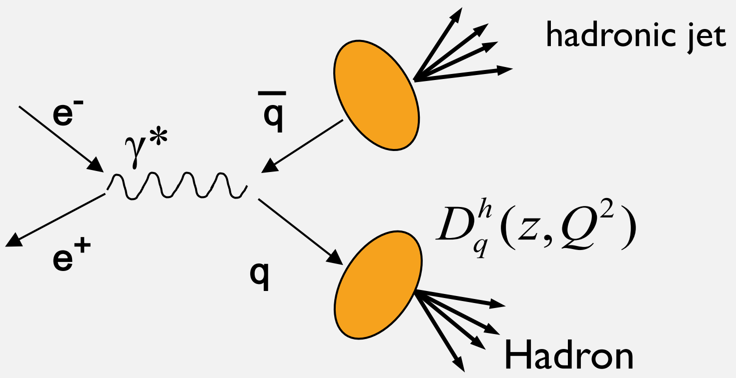
Proton Structure

pQCD

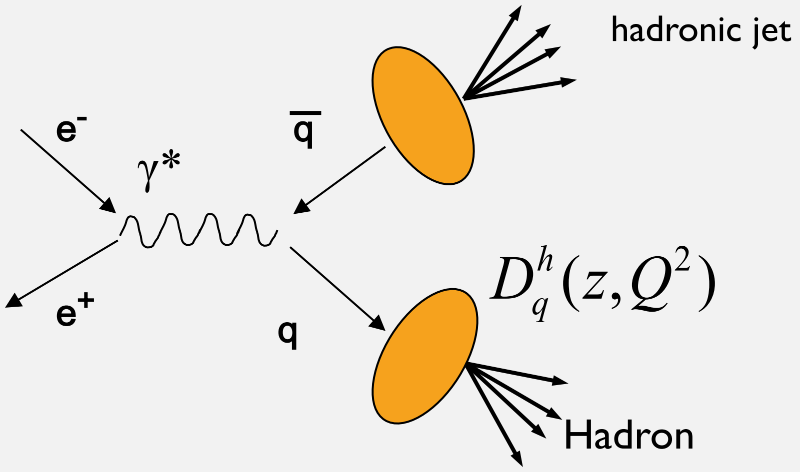
fragmentation function

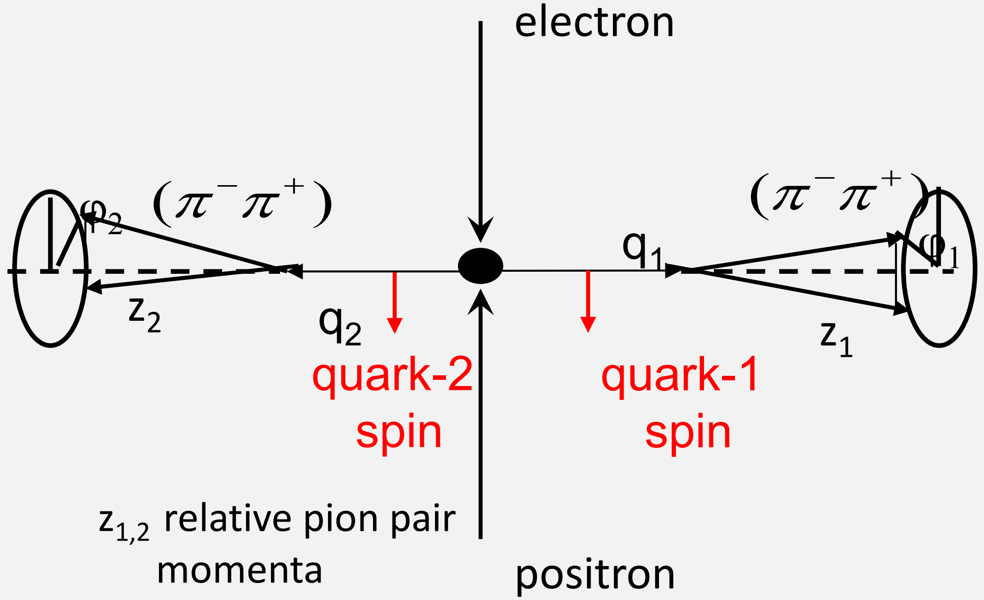
$$\frac{d^2\sigma(ep \to \pi X)}{dx\, dz} \propto q(x, k_T) \times \frac{d\sigma^2(e\, q \to e' q')}{dx} \times FF(z, p_T)$$

ACCESS TO FRAGMENTATION FUNCTIONS IN E^+E^-



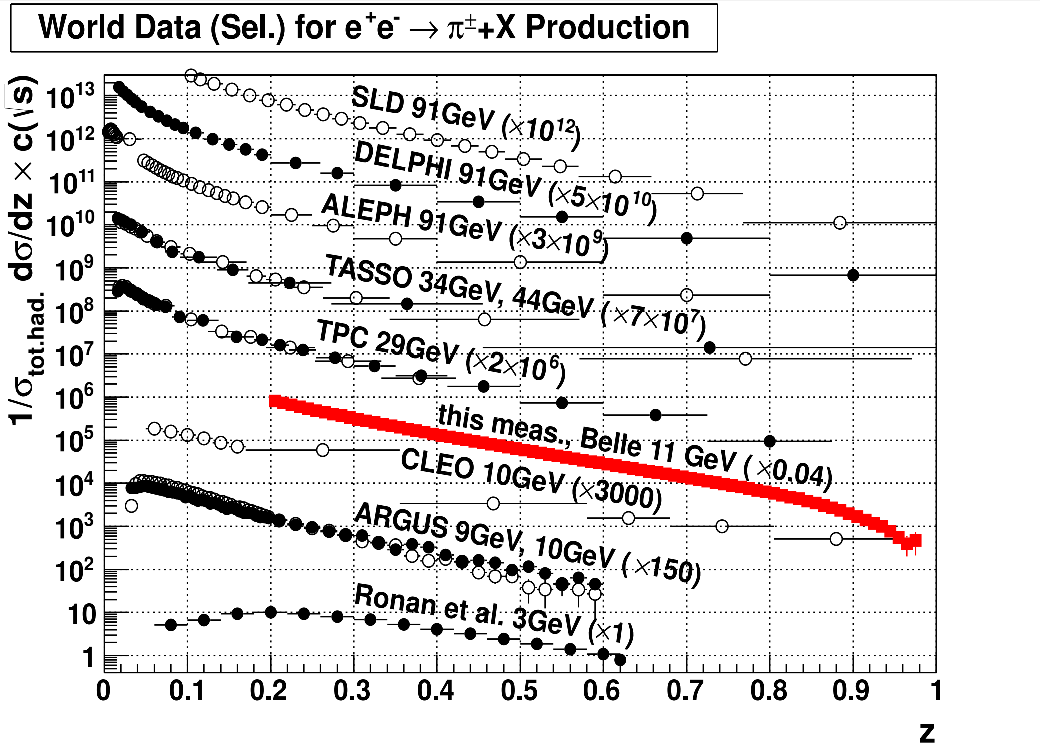
ACCESS TO FRAGMENTATION FUNCTIONS IN E+E-





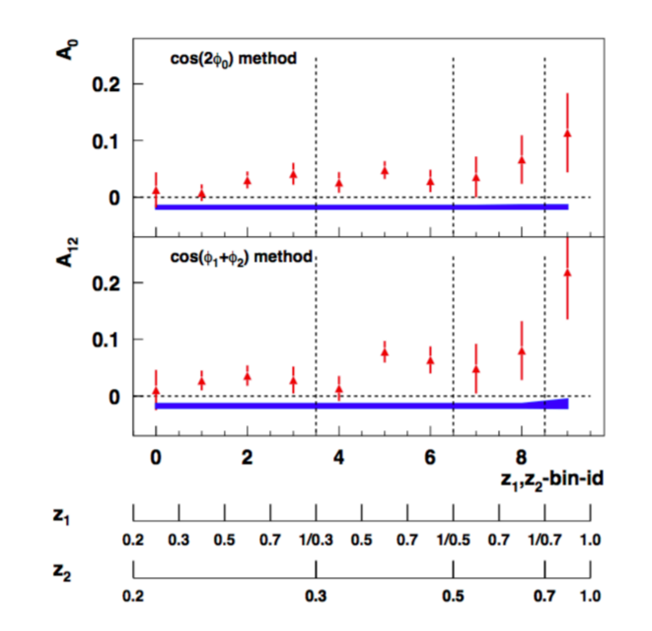
- Polarized FFs can be extracted from back-to-back production

B-FACTORIES: A NEW ERA FOR THE STUDY OF FRAGMENTATION FUNCTIONS



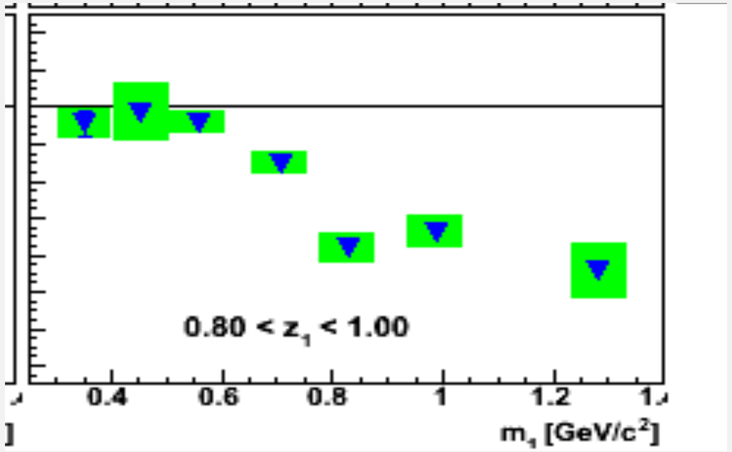
EXAMPLES OF FF 'FIRSTS' AT BELLE

Phys.Rev.Lett. 96 (2006) 232002



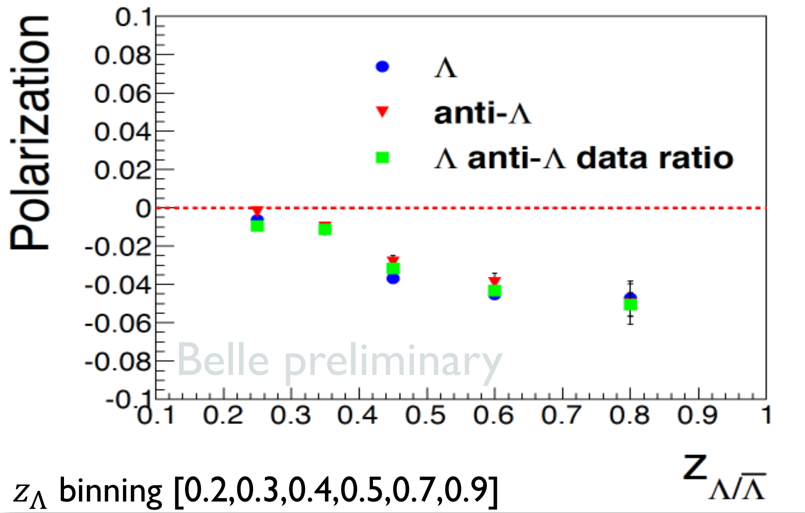
- First observation of Collins effect in back-to-back hadrons

Phys.Rev.Lett. 107 (2011) 072004



- First access to polarization dependent di-hadron FFs

BELLE-CONF-1611, arXiv:1611.06648

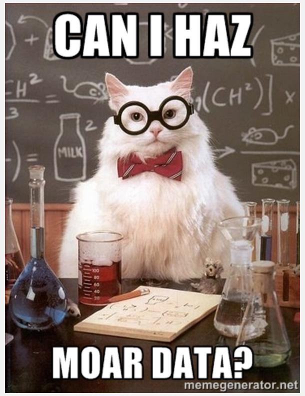


- First observation of transverse Λ polarization in e+-e-
  - Learn about Baryon spin structure in hadronization

AND THERE IS MORE BELLE HADRONIC PHYSICS

- Exclusive hadronic x-sections (see talk by Griessinger on Wed. on BaBar results)
- Transition form factors
- ….

WISHLIST



- **More data will help Quarkonium and Fragmentation Fct! studies!**
  - Map out resonances
  - More data at/above Υ(4S)→search molecular structures near open bottom thresholds
  - Experimental information of charmonium > Ddbar threshold very incomplete,
  - More data below Y(4S) →test predictions for unobserved bottomium states
  - Determine transitions and quantum numbers
  - More differential access to fragmentation functions
  - Precision back-to-back correlations of less copious hadrons (e.g. Λ)
  - Precision should be on par with anticipated SIDIS data from JLab12
- State of the Art Detector
  - PID: increase efficiency of e.g. multi kaon final states
  - Vertexing: More efficient charm rejection for FF studies

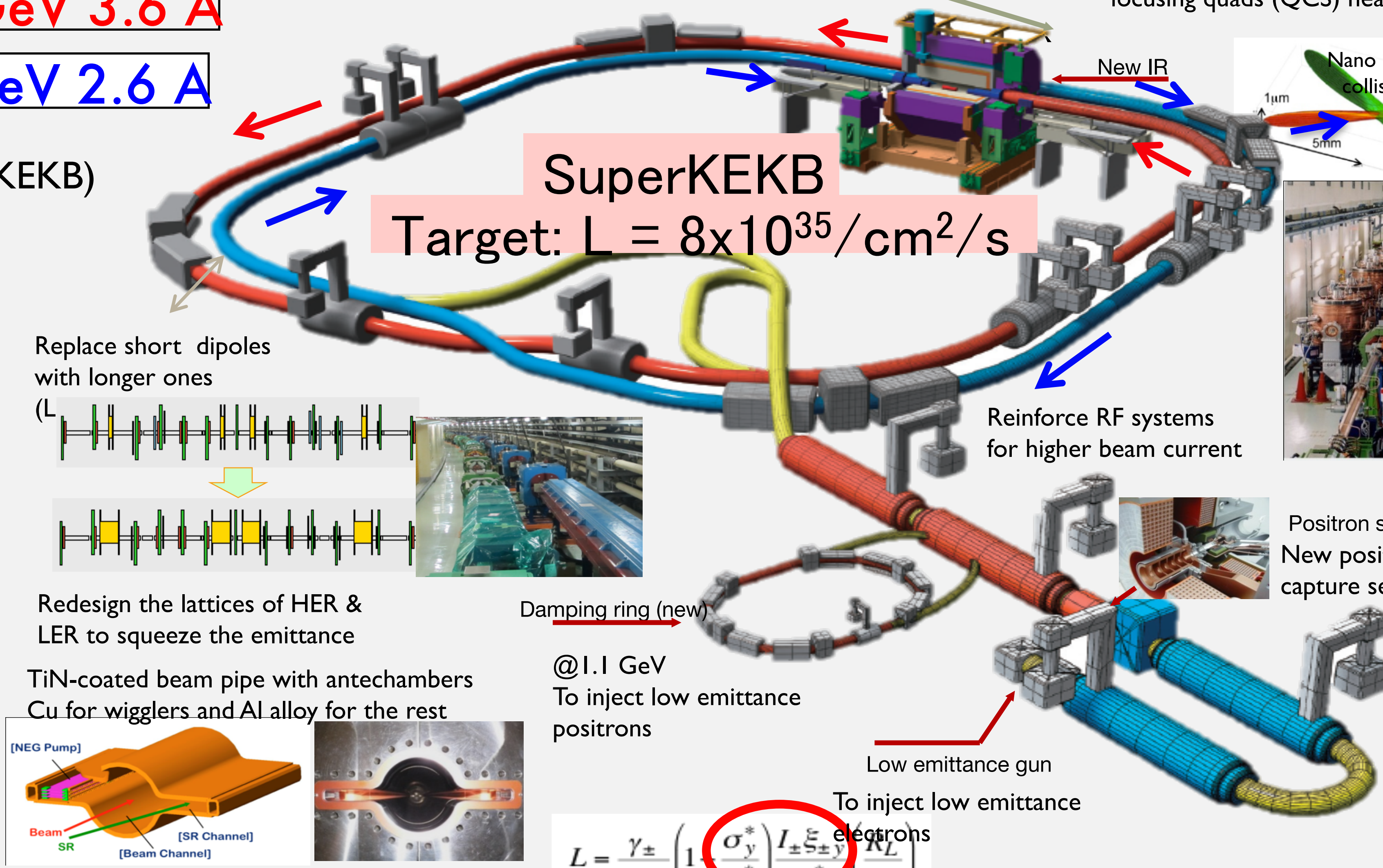
KEKB →SUPERKEKB: DELIVER INSTANTANEOUS LUMI X 40

Belle II

e^+ 4GeV 3.6 A

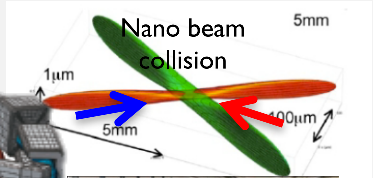
e^- 7GeV 2.6 A

(~2x KEKB)



SuperKEKB
Target: $L = 8\times10^{35}/cm^2/s$

New superconducting final focusing quads (QCS) near the IP



Replace short dipoles with longer ones
(L

Reinforce RF systems for higher beam current

Positron source
New positron target / capture section

Redesign the lattices of HER & LER to squeeze the emittance

@1.1 GeV
To inject low emittance positrons

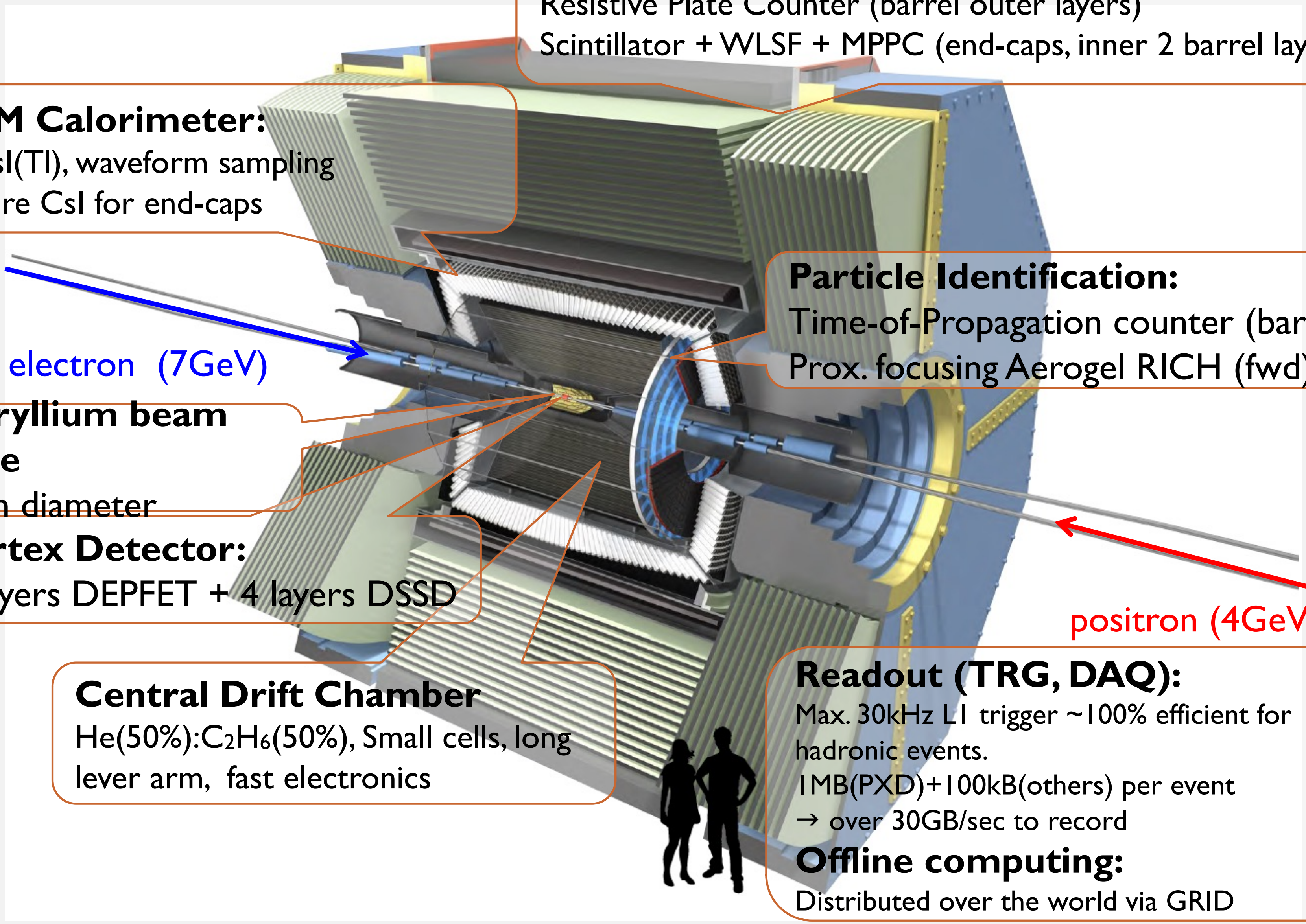
TiN-coated beam pipe with antechambers
Cu for wigglers and Al alloy for the rest

[NEG Pump]
Beam
SR
[SR Channel]
[Beam Channel]

Low emittance gun
To inject low emittance electrons

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

CUT VIEW OF BELLE II DETECTOR



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

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

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

electron (7GeV)

Beryllium beam pipe
2cm diameter

Vertex Detector:
2 layers DEPFET + 4 layers DSSD

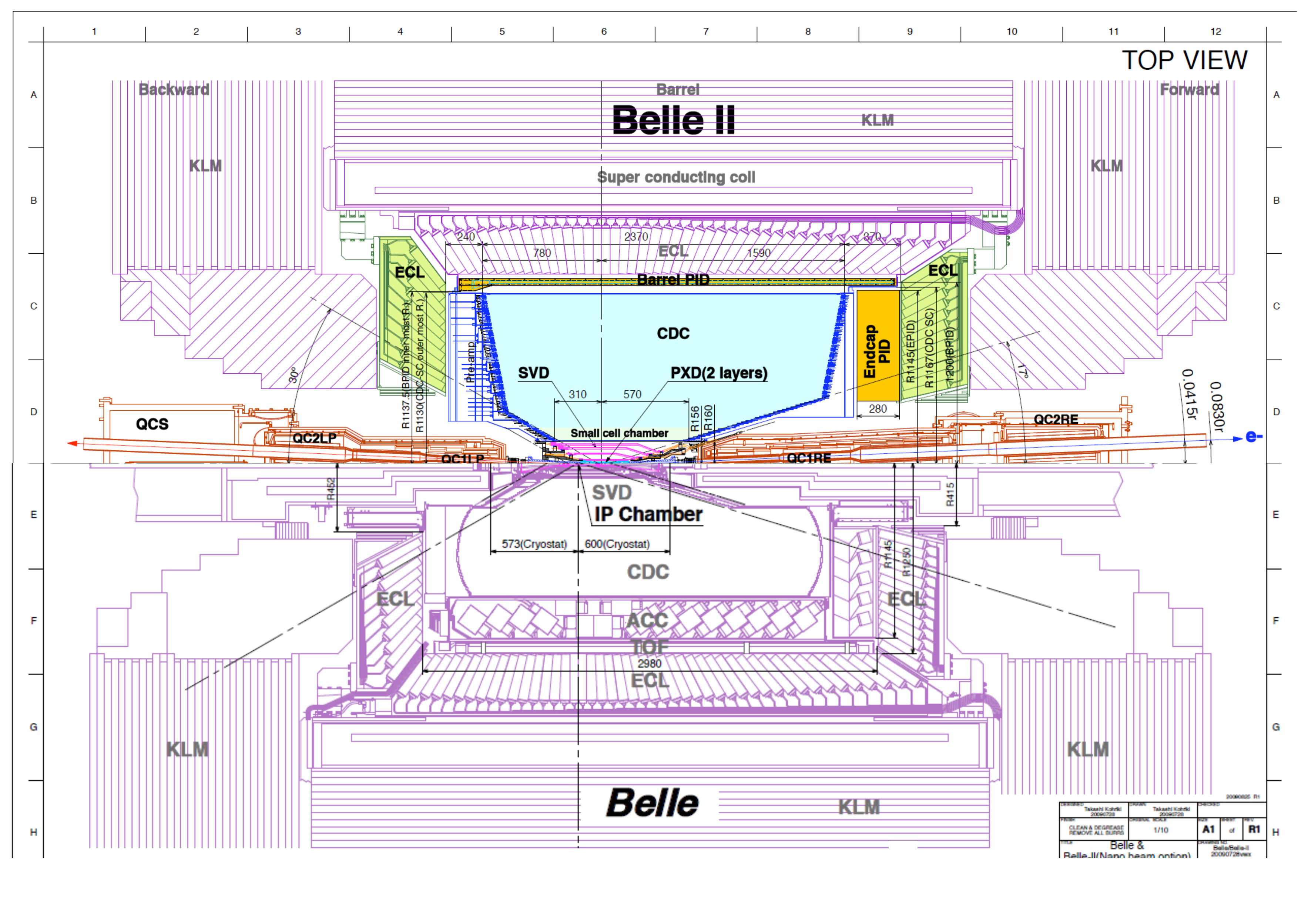
positron (4GeV)

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

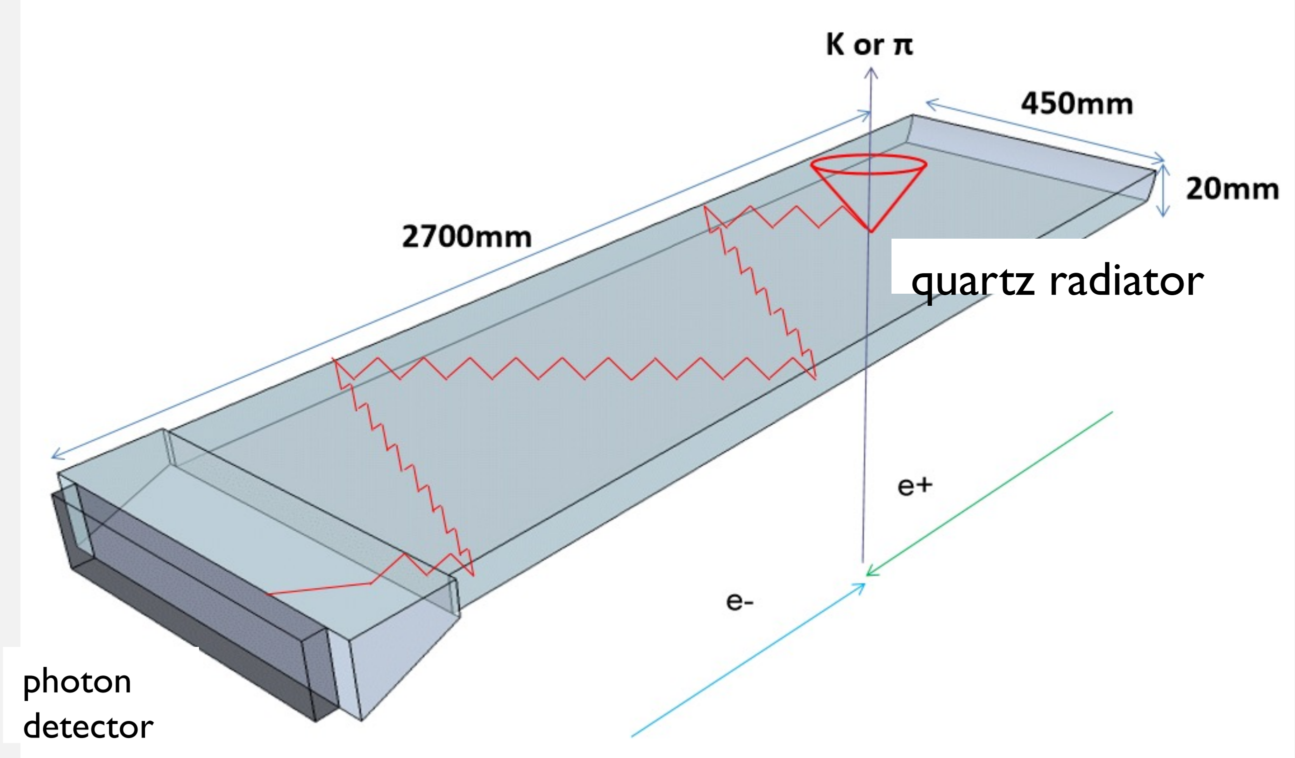
Readout (TRG, DAQ):
Max. 30kHz L1 trigger ~100% efficient for hadronic events.
1MB(PXD)+100kB(others) per event
→ over 30GB/sec to record

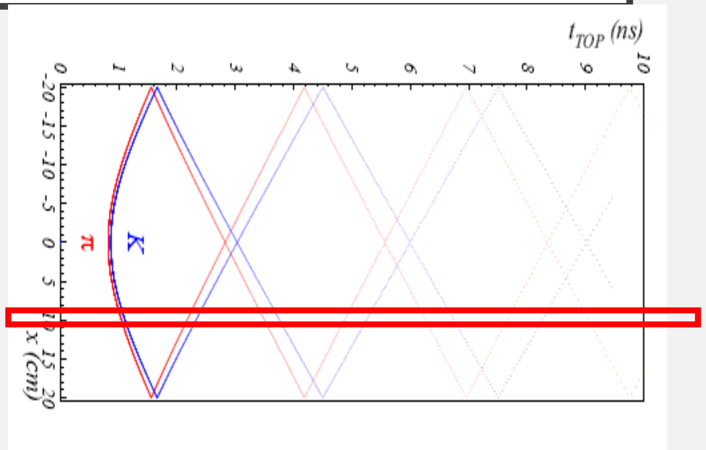
Offline computing:
Distributed over the world via GRID

BELLE II DETECTOR (COMP. TO BELLE)

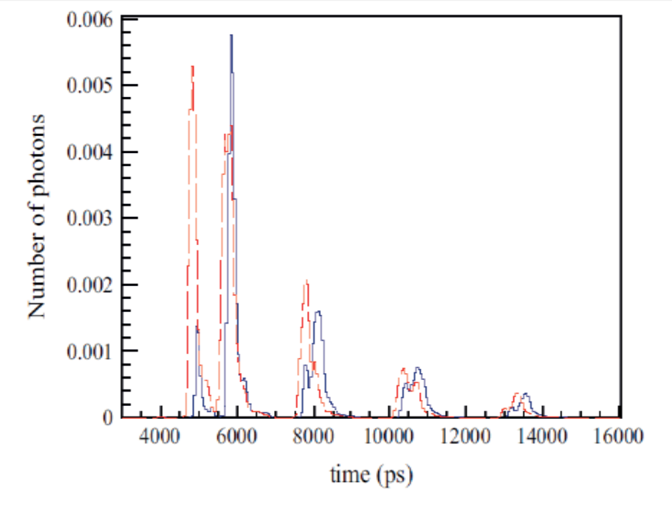


NEW PARTICLE ID DEVICE THAT SAMPLES CHERENKOV LIGHT DISTRIBUTION WITH PICO-SECOND TIMING



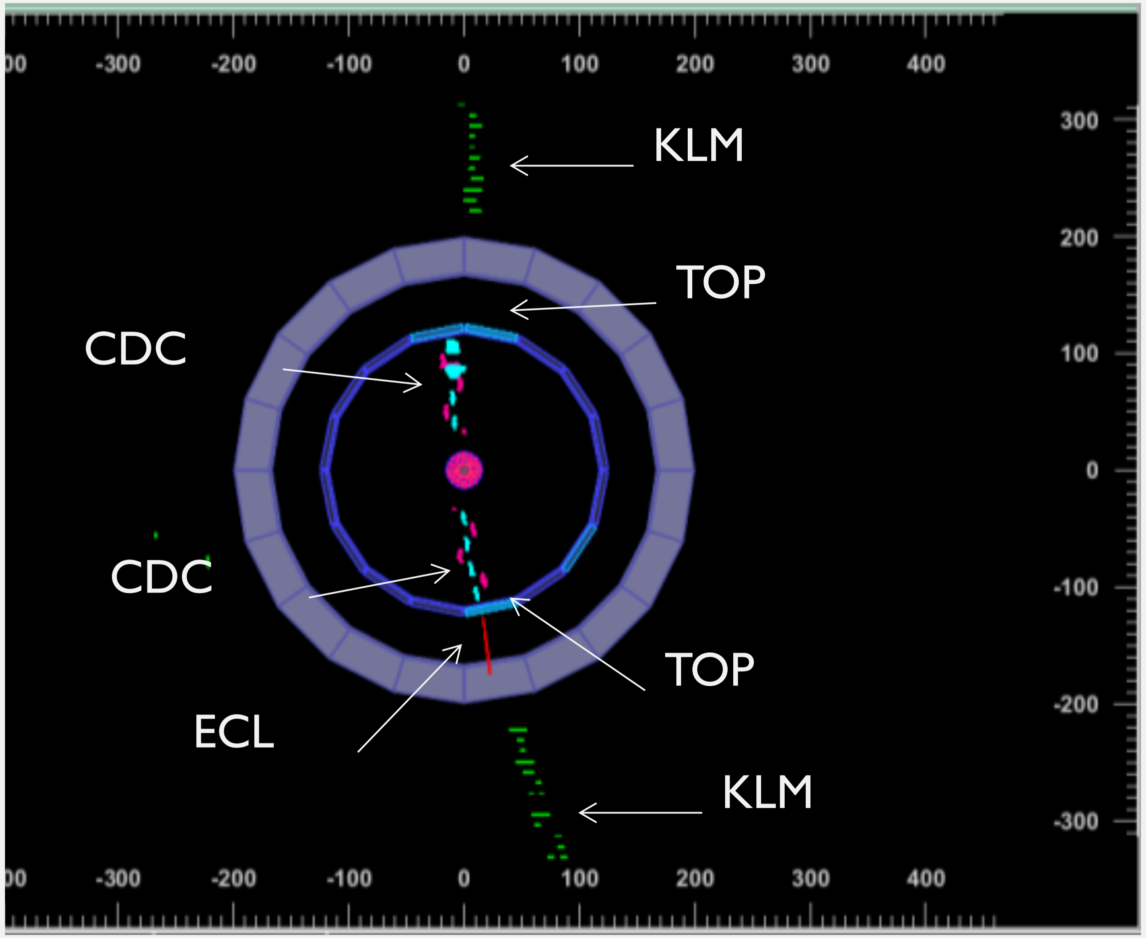


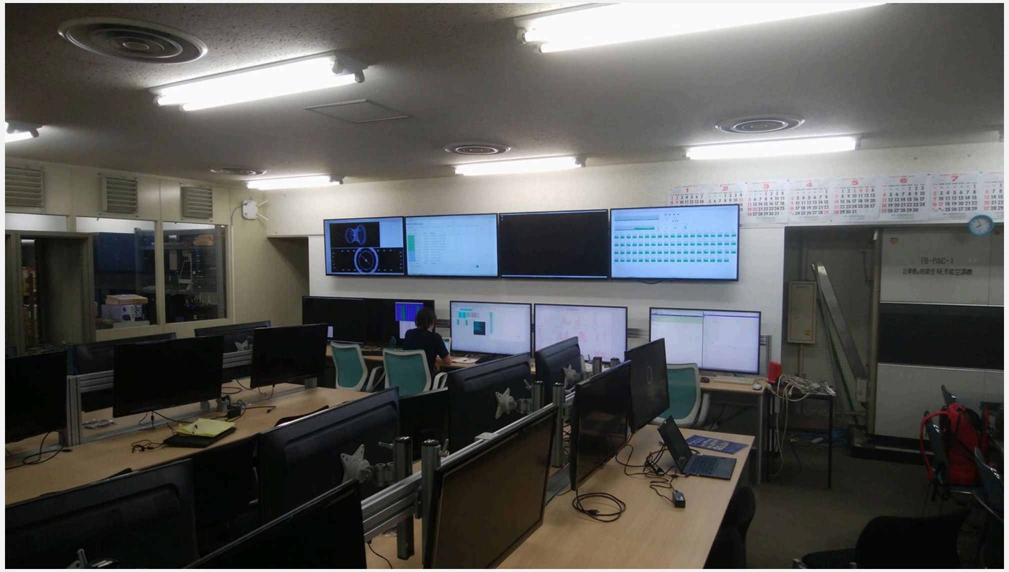
Patterns for π and K



- Mainly TOP detector: goal of resolution < 40ps
- Kaon ID Efficiency >95% over large part of phase space compared with 85% at Belle

READOUT INTEGRATION



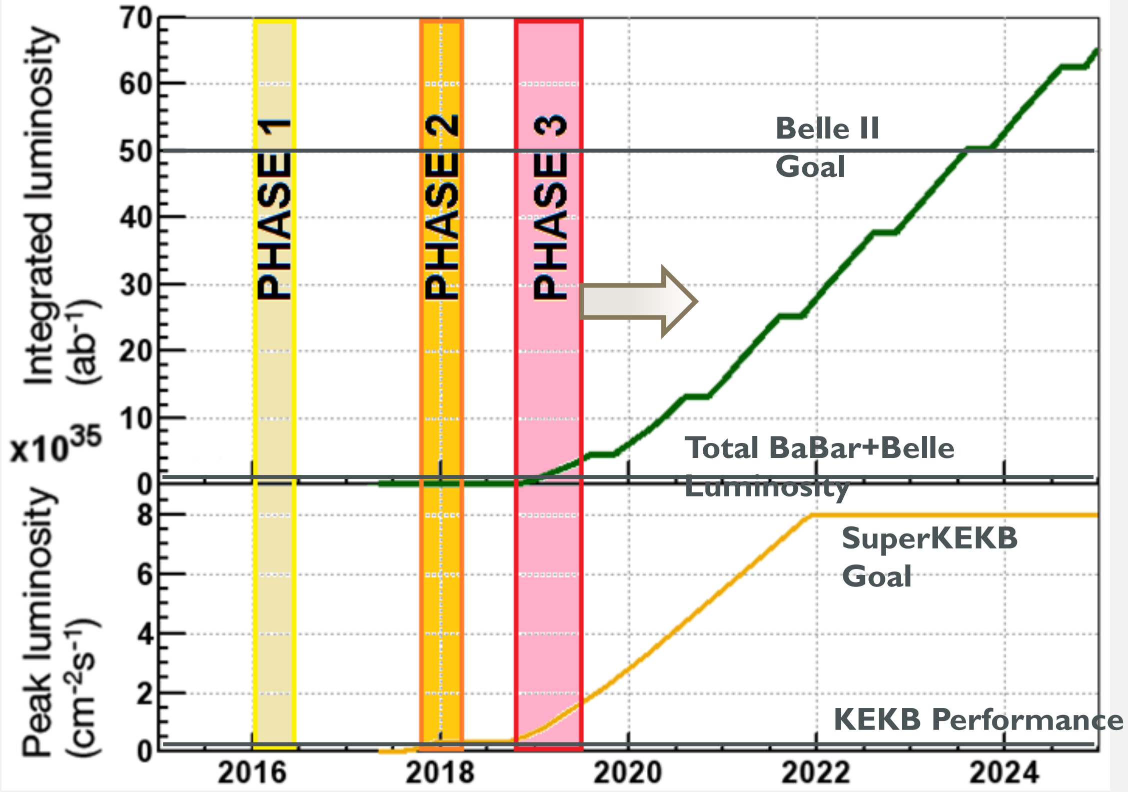


Belle II Control Room

- Readout integration of installed sub-detectors and central DAQ is in progress.
- Combined data taking established in cosmic running

CURRENT STATUS AND SCHEDULE

- Phase 1 (complete)
  - Accelerator commissioning
- Phase 2 (early 2018)
  - First collisions (20±20 fb^{-1})
  - Partial detector
  - Background study
  - Physics possible
- Phase 3 ("Run 1", early 2019)
  - Nominal Belle II start
- **Ultimate goal: 50 ab^{-1}**



- **Search for New Physics via precision measurements**
  - CPV, (semi-)leptonic/penguin decays, LFV, dark sector, …

BELLE II EARLY PHYSICS PROSPECTS

- Existing B-Factories ~1.5 ab^{-1}: **opportunity for other results in Phase 2/3?**

Experiment	Scans/ Off. Res.	$\Upsilon(5S)$ 10876 MeV		$\Upsilon(4S)$ 10580 MeV		$\Upsilon(3S)$ 10355 MeV		$\Upsilon(2S)$ 10023 MeV		$\Upsilon(1S)$ 9460 MeV	
	fb^{-1}	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6
CLEO	17.1	0.4	0.1	16	17.1	1.2	5	1.2	10	1.2	21
BaBar	54	R_b scan		433	471	30	122	14	99	–	
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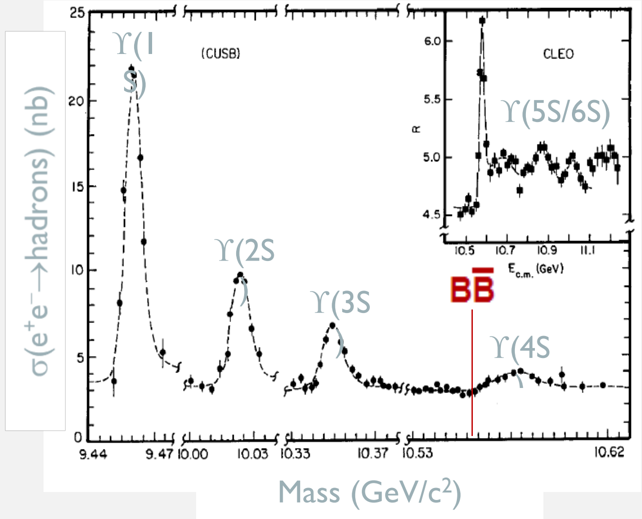
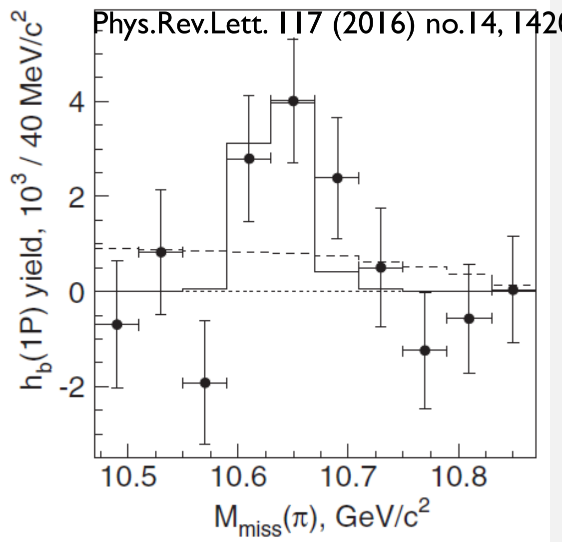
Potential impact with O(10-100) fb^{-1}



- Phase 2: Above $\Upsilon(4S)$
  - Study of Υ(nS) states in (hadronic) transitions
  - Study of exotic four-quark states (e.g. Z_b at Υ(6S))
    →Study possible with limited tracking resolution



Z_b

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Phys.Rev.Lett.102:012001,2009, (Babar)
PRD 82, 091106 (2010). 0810.3829. (Belle)

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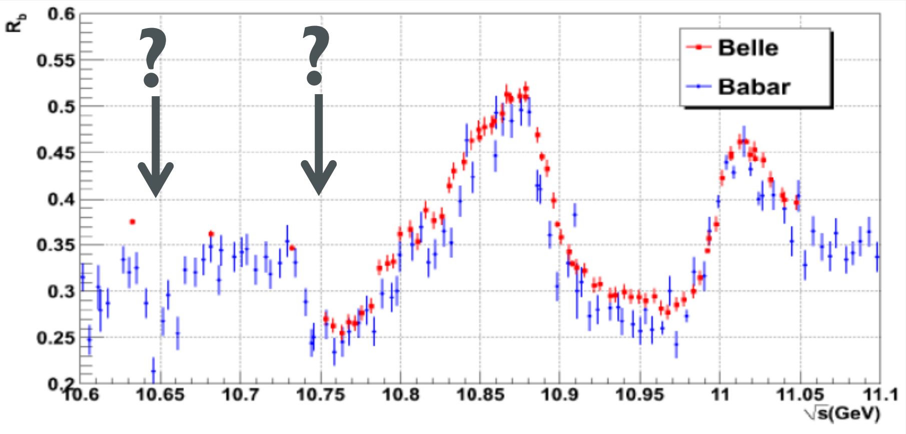
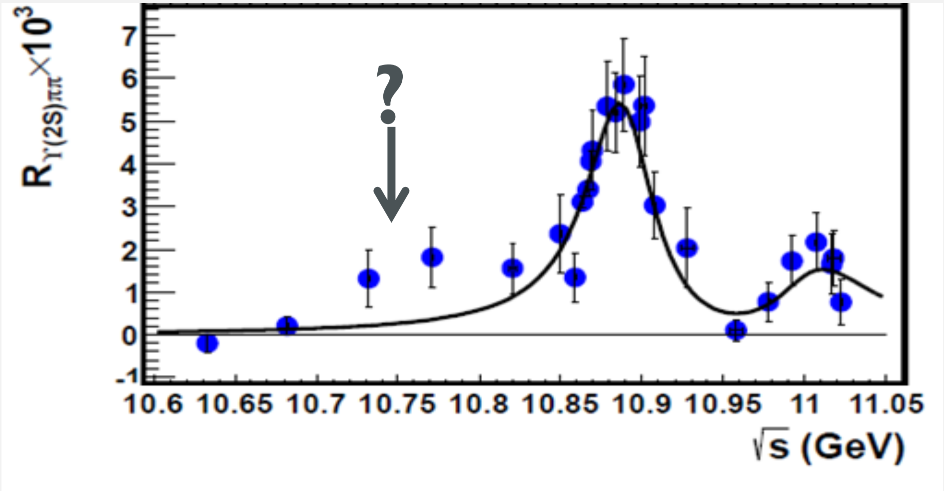
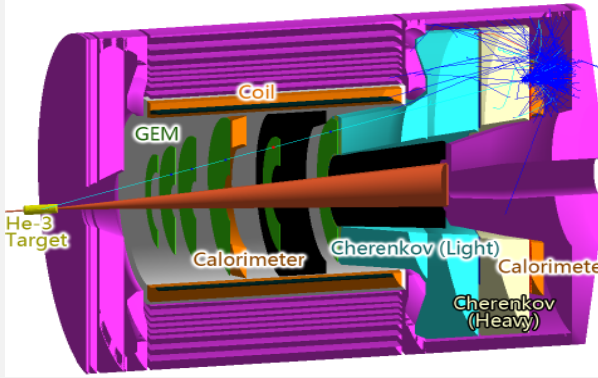


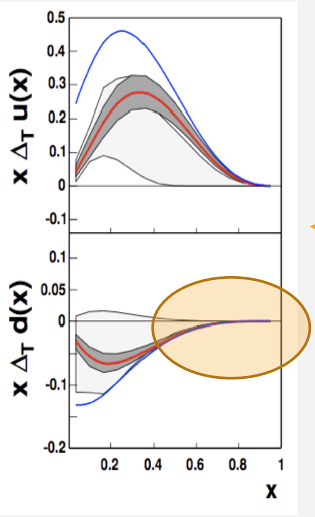
- Phase 2: Above $\Upsilon(4S)$
  - Study of exotic four-quark states (e.g. Zb at $\Upsilon(6S)$)
    →Study possible with limited tracking resolution
  - BB** threshold? : R_b dip versus $\pi\pi\Upsilon$ rise
  - <6fb^{-1} accumulated by Belle at $E_{CM}=\Upsilon(6S)$
  - Currently energies up to $\Lambda_b\Lambda_b$ threshold (11.24GeV)possible
- Early phase 3: Below $\Upsilon(4S)$
  - $\Upsilon(2S,3S)$ access to bottomonium
  - Scan for direct production of $\Upsilon(1^3D_J)$ triplet, $\eta_b(1S,2S)$ studies

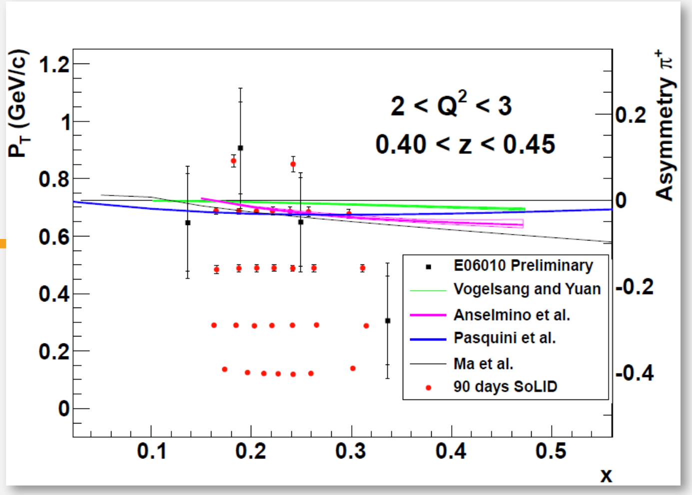


PRECISE KNOWLEDGE OF FRAGMENTATION FUNCTIONS NECESSARY FOR SUCCESSFUL SIDIS PROGRAM AT JLAB12



- JLab12 SIDIS program will have unprecedented precision
- →Need similar precision for Fragmentation functions
- Example: Precise measurement of p_T dependent Collins effect at SOLID
  - Needs precise measurement of Collins and spin averaged p_T dependent fragmentation functions!
- More advantages of Belle II for FF measurements:
  - Better Vertex resolution, increased MC statistics →lower systematics from charm contribution
  - Better PID: Multi-kaon final states

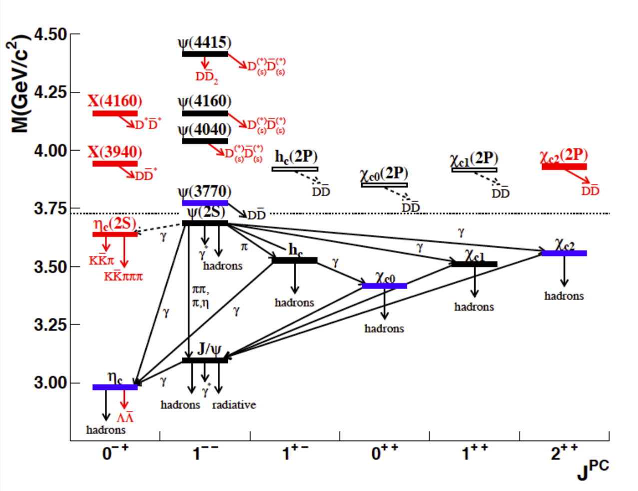




SUMMARY & OUTLOOK

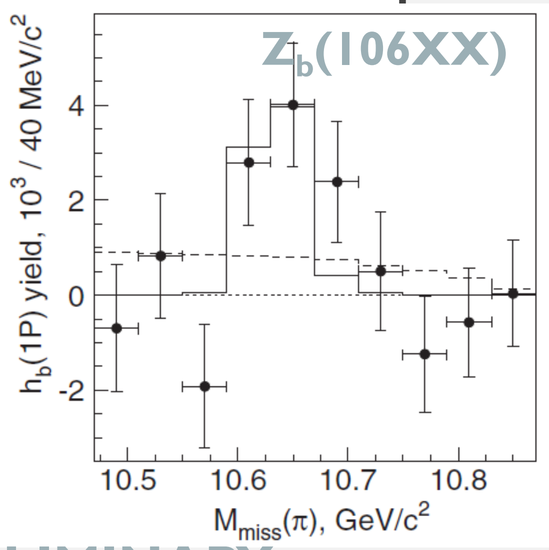
- Belle II will integrate 50x Belle luminosity (= 50 ab^{-1})over ~6 years
- State of the art detector
- Precision studies of Quarkonia, hadronization
- Physics program with first data focusing on E_{CM}>Υ(4S) already promising!
- Precision hadronization studies crucial for JLab12 SIDIS program

BACKUP


M(GeV/c^2)
4.50
4.25
4.00
3.75
3.50
3.25
3.00
ψ(4415)
ψ(4160)
ψ(4040)
X(4160)
X(3940)
h$_c$(2P)
χ$_{c0}$(2P)
χ$_{c1}$(2P)
χ$_{c2}$(2P)
ψ(3770)
ψ(2S)
η$_c$(2S)
h$_c$
χ$_{c0}$
χ$_{c1}$
χ$_{c2}$
J/ψ
η$_c$
hadrons
radiative
0^{-+}
1^{--}
1^{+-}
0^{++}
1^{++}
2^{++}
J^{PC}

ABOVE Υ(4S) / Υ(6S) RUNNING

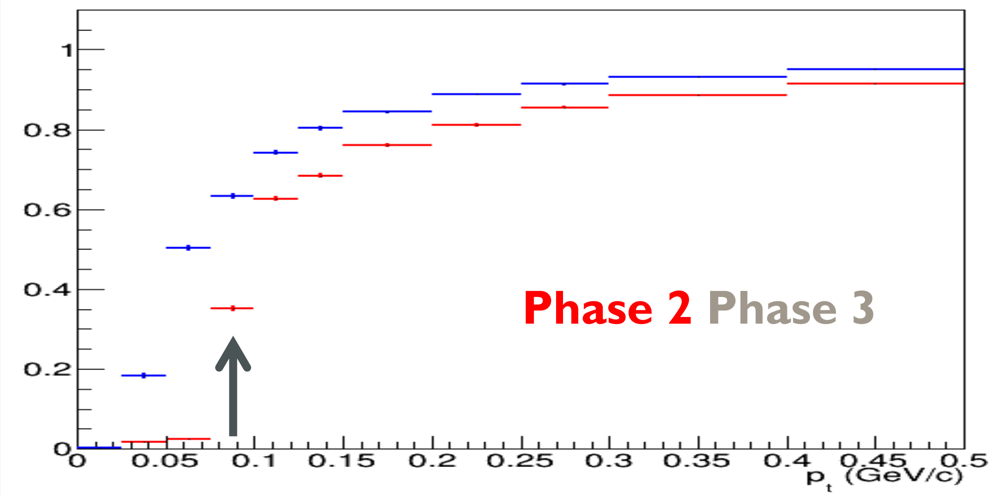
- Υ(6S) expectation from Υ(5S) and Y_c(4XXX)
  - Bottomonium: $\pi\pi h_b$(1,2,3?P), ππΥ(1,2,3S), ηΥ(1,2D)?
  - Resolve charged/four-quark intermediate states
  - Search for X_b("3872")?
  - Υ(6S) / BB threshold energy region behavior



- Phase 2 considerations
  - Low p_T track reconstruction
  - Rest of detector nominal
  - Existing Belle data <6fb^{-1}
- **Sufficient for Z_b study**

- Phase 3: 100 fb^{-1} sample?

PRELIMINARY

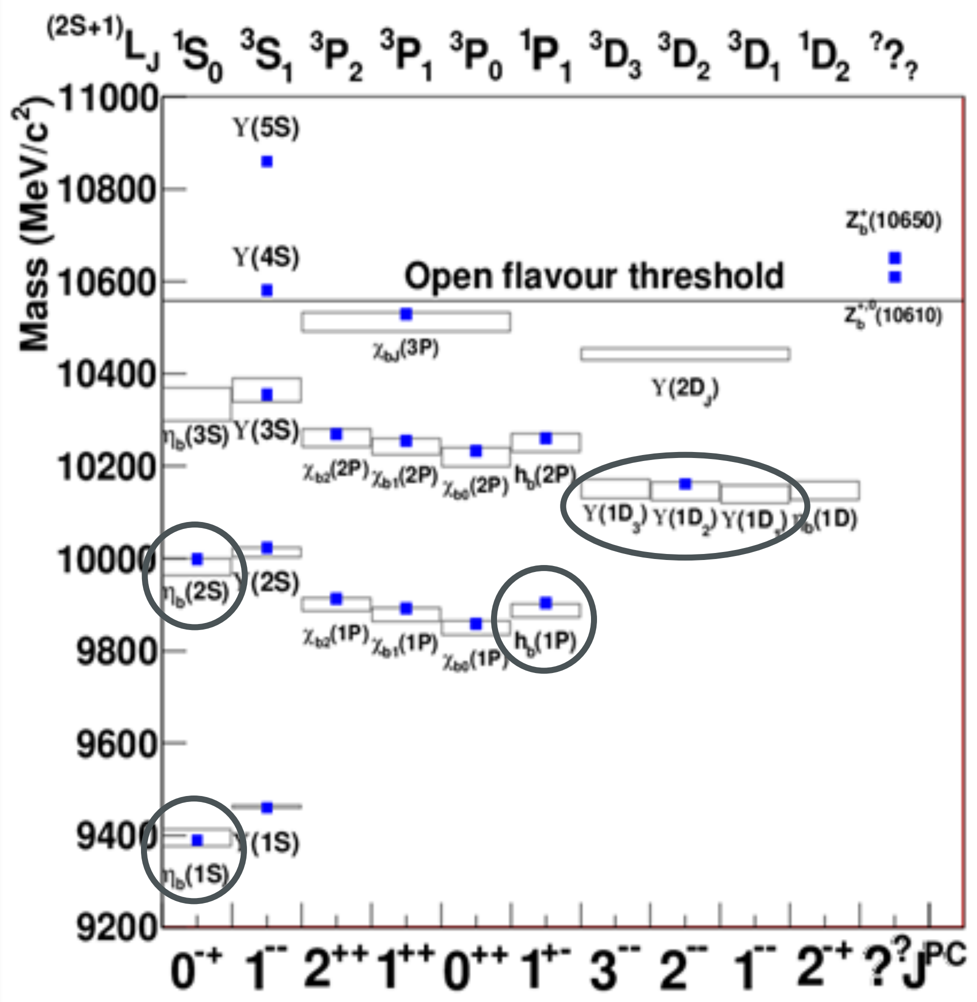


CONCLUSIONS

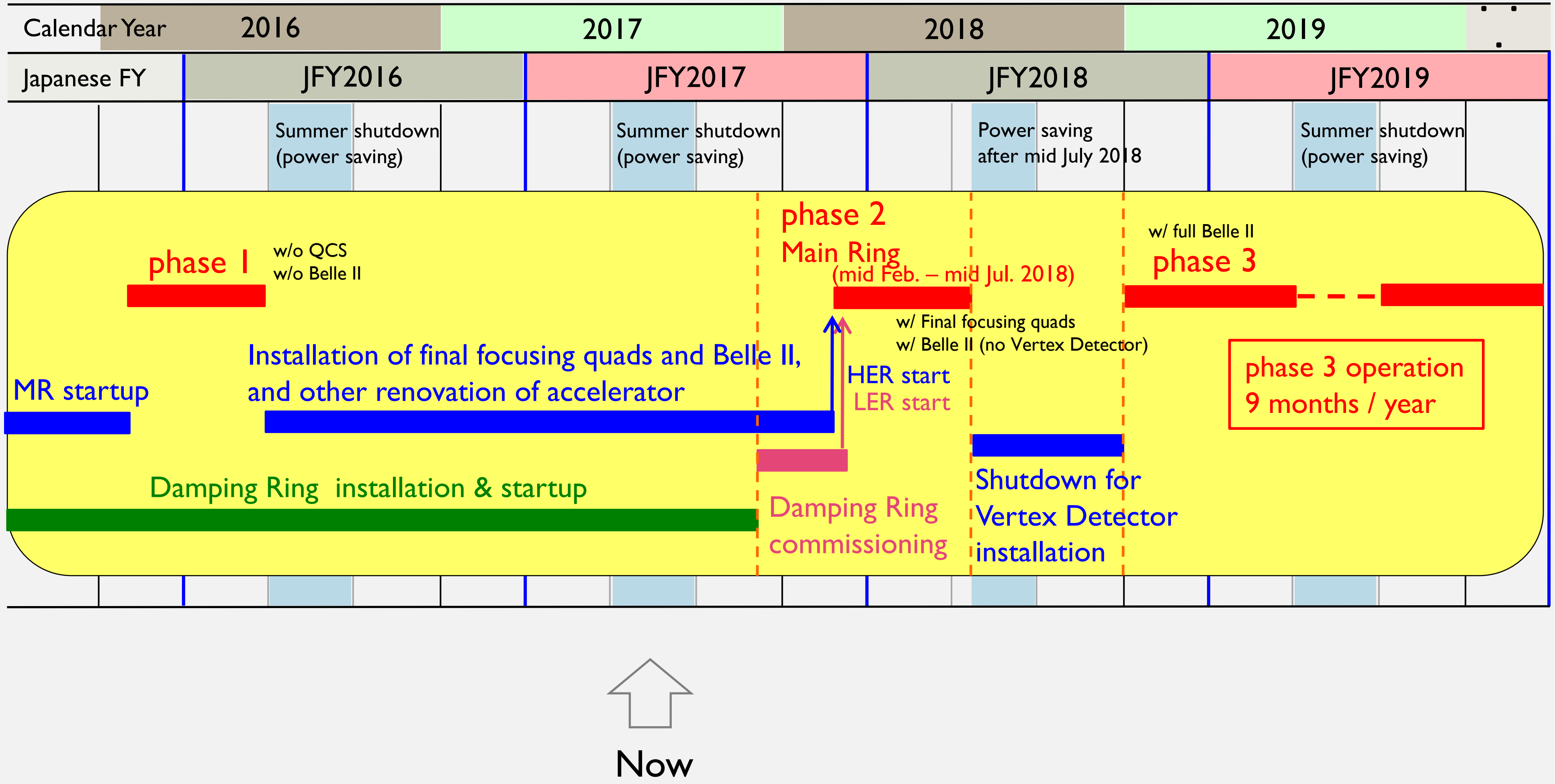
- The B-Factories discovered dozens of new, exotic hadrons (XYZ)
- Strong evidence of four-quark composition
- Many questions about their nature
  - Di-meson molecules? Tetraquarks? Something else?
  - Analogies between cc and bb (and light quark?) systems
- Belle-II is the next generation B-Factory
  - Collect 50x as much data over 2018-2025
  - Best chance to study and understand many of these
  - Plans for dedicated operations to study the XYZ states

Υ(3S) ON-RESONANCE: BOTTOMONIUM PHYSICS

- **200fb^{-1} ~7xBaBar (Phase 3+)**
- Focus on conventional $b\bar{b}$ physics
  - $\Upsilon(1^3D_J)$ triplet
    - J=1,3 yet to be discovered
  - η_b(1S,2S)
    - Confirm m(η_b(1S,2S))
  - Hadronic (π^0,$\pi^+\pi^-$,η,ω) decays
  - Radiative transitions
- Z_b^+ exotic states?



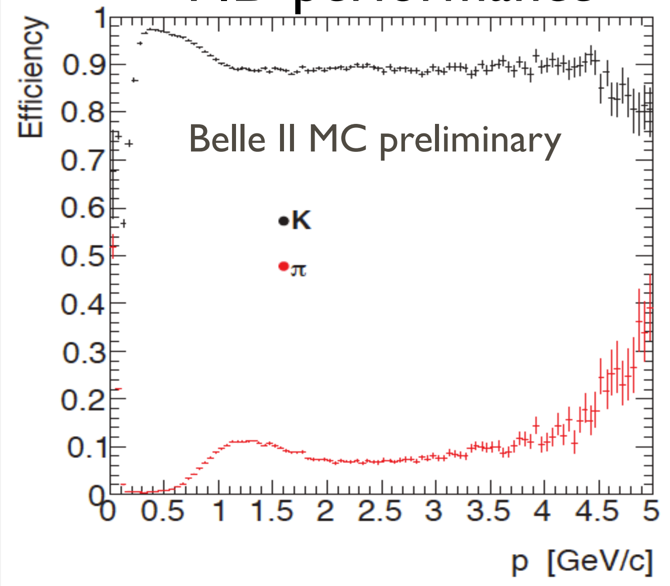
SUPERKEKB/BELLE II SCHEDULE

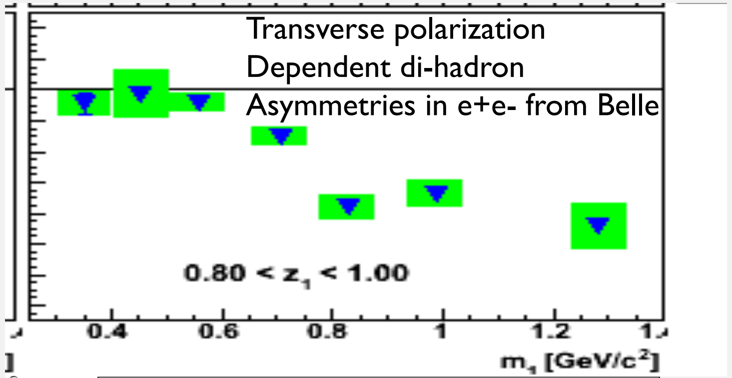


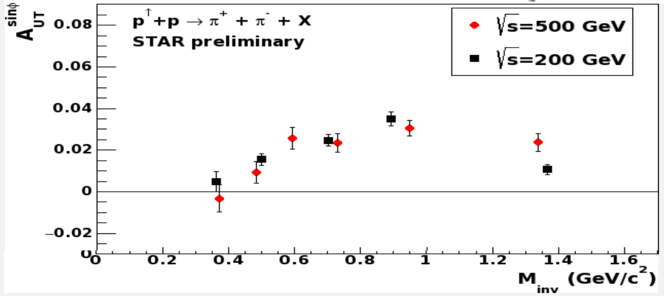
OTHER PERKS

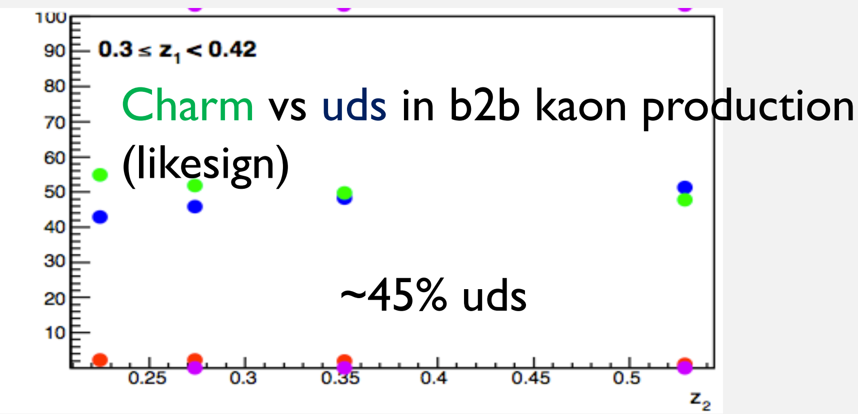
- More statistics and better vertexing will help with charm corrections
- Systematics will also be reduced since the main sources are dependent on MC statistics
- Better PID will help with multi-kaon final states

PID performance







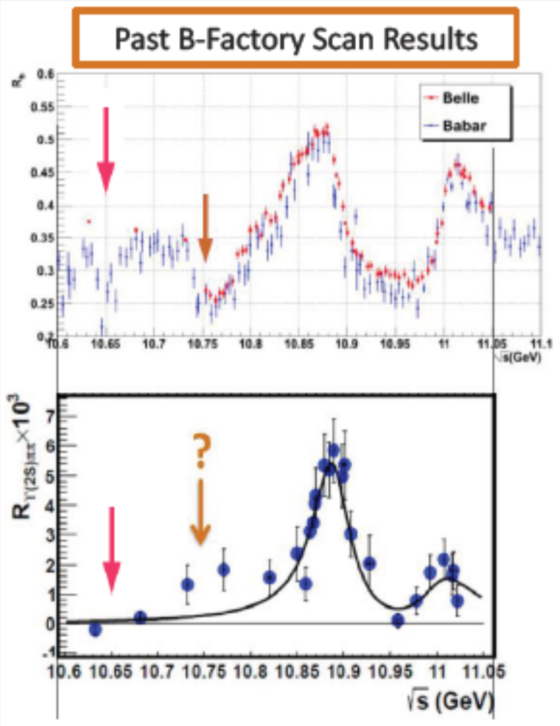


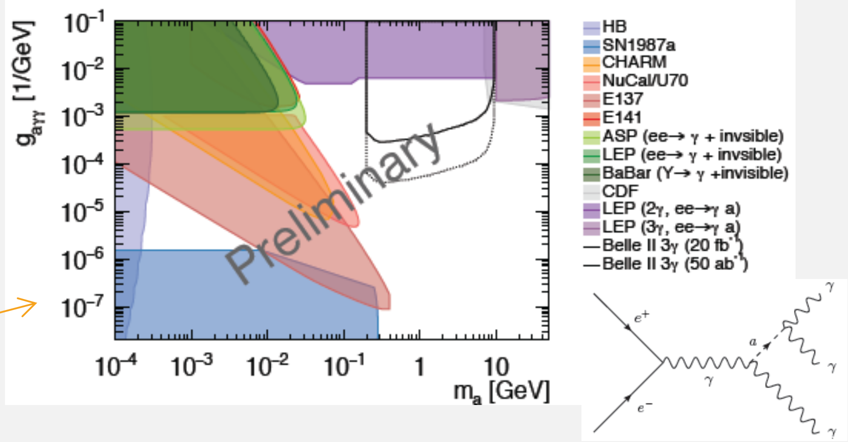
PHASE 2 PHYSICS PROGRAM

Under discussion

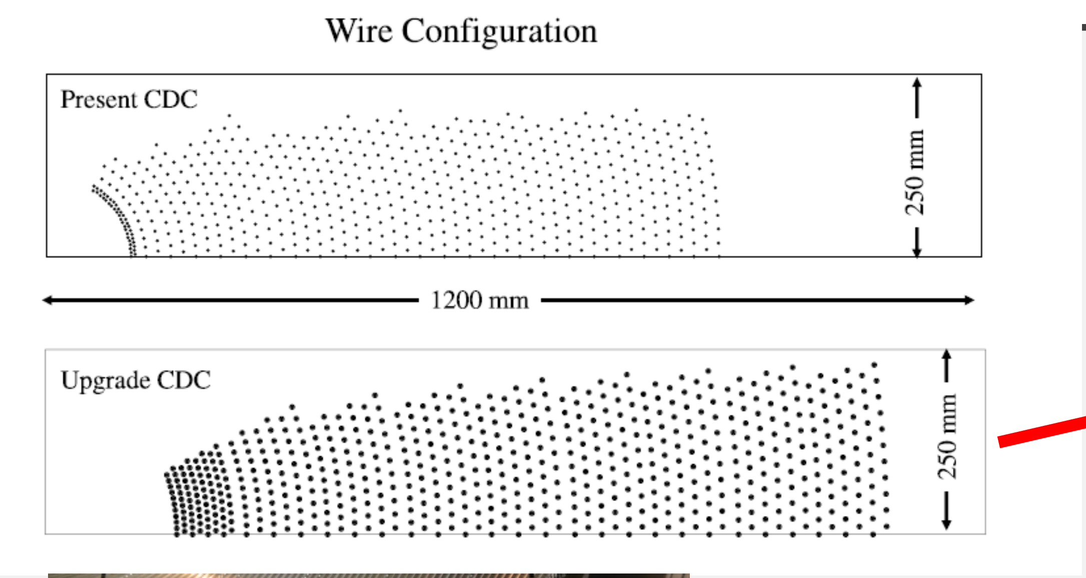
Only initial (low) performance, w/o Vertex Detector, but still there are interesting physics topics to do during phase 2.

WG	Mode	Description	Benchmark study or Unique measurement?
Semileptonic	B→X l v	Benchmark analysis in Y(4S)	Benchmark
Semileptonic	B(s)→X l v in Y(6S), Di-leptons	B and B_s counting in Y(6S)	Unique
EWP	B→K*γ	Benchmark analysis in Y(4S)	Benchmark
BtoCharm	B → Dπ. D*π, D → hh, K_S X	Benchmark analysis in Y(4S)	Benchmark
Bottomonium	Y(6S) → ππ + Y(nS)/hb	Zb substructure	Unique
Bottomonium	Y(6S) cross section, R_b	Cross section measurement and Rb decomposition at Y(6S)	Unique
Bottomonium	π π Y(pS)	ECM 10.75 GeV decay → π π Y(pS)	Unique
Low-multiplicity	ee → γ A', A'→ missing	Dark matter via dark photon	Unique
Low-multiplicity	ee → γ A'→ γ γ	Axion like dark sector for large A' masses (tri-photon final state)	Unique

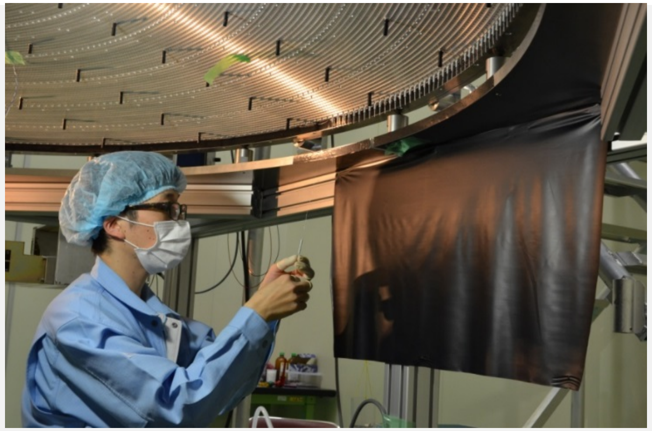




BELLE II CDC



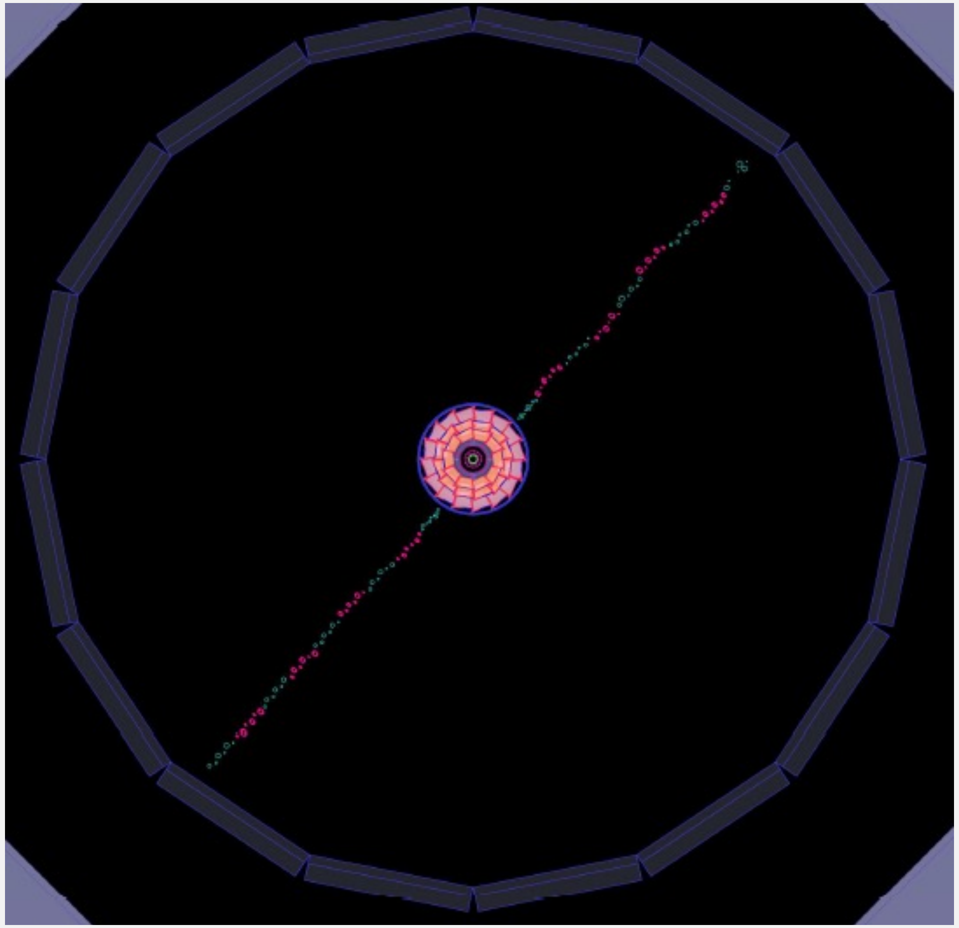
Much bigger than in Belle!



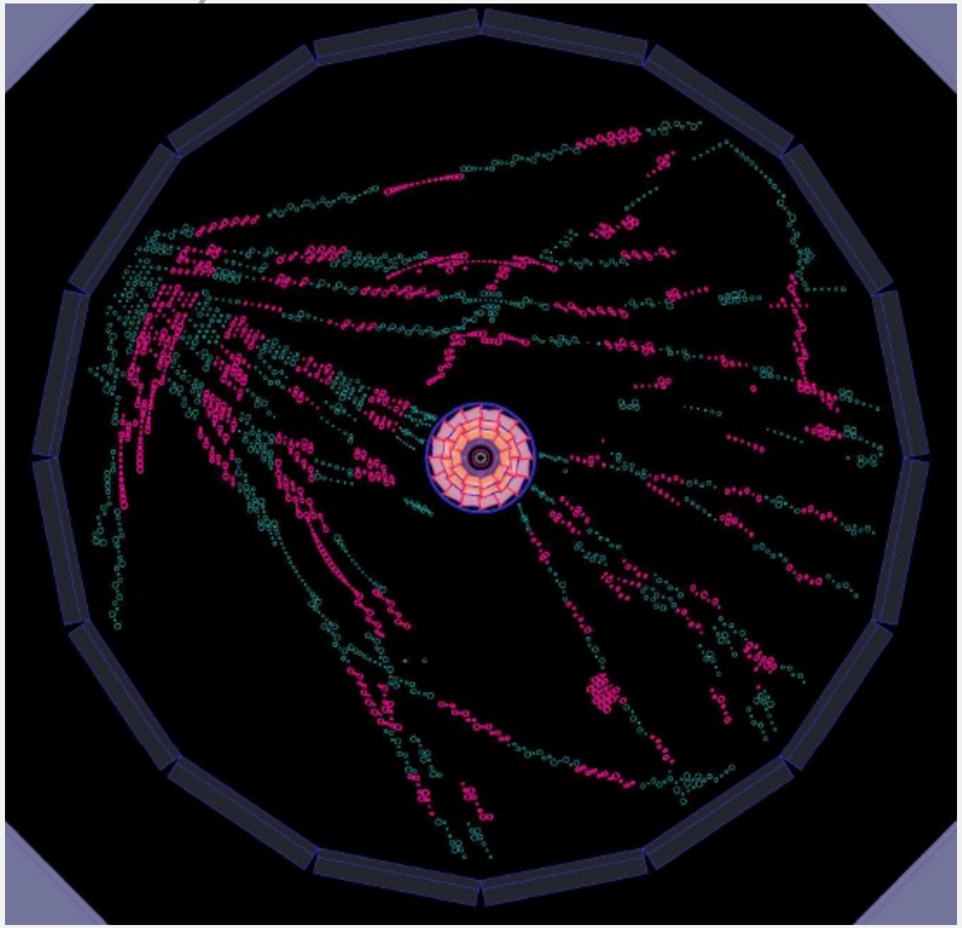
Wire stringing in a clean room

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

CDC EVENT DISPLAYS (WITH FULLY INSTRUMENTED READOUT)



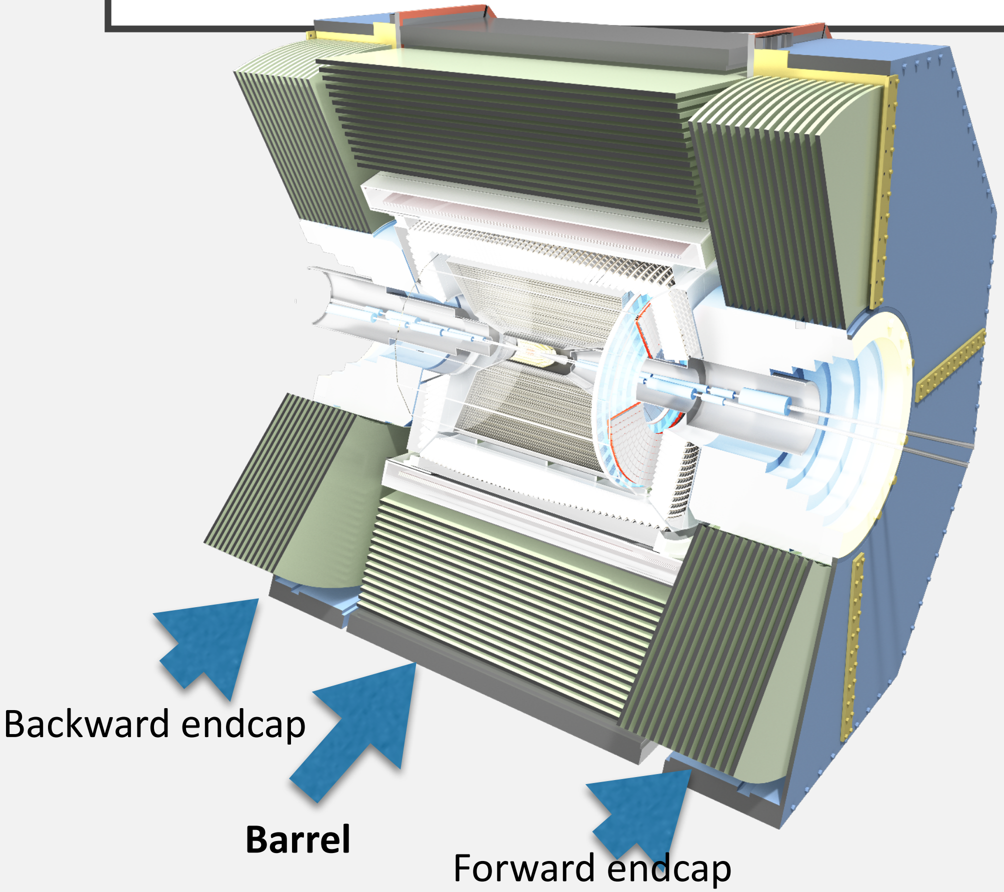
Single cosmic ray track

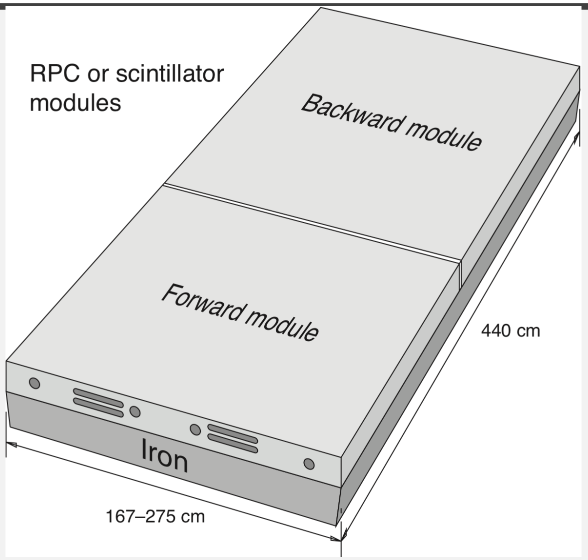


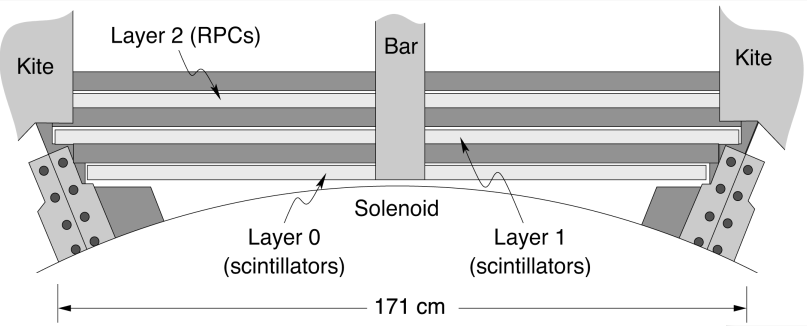
Multiple tracks
(showering cosmic ray event)

→ talk by N. Taniguchi

THE KLM ("K_L–MUON DETECTOR")

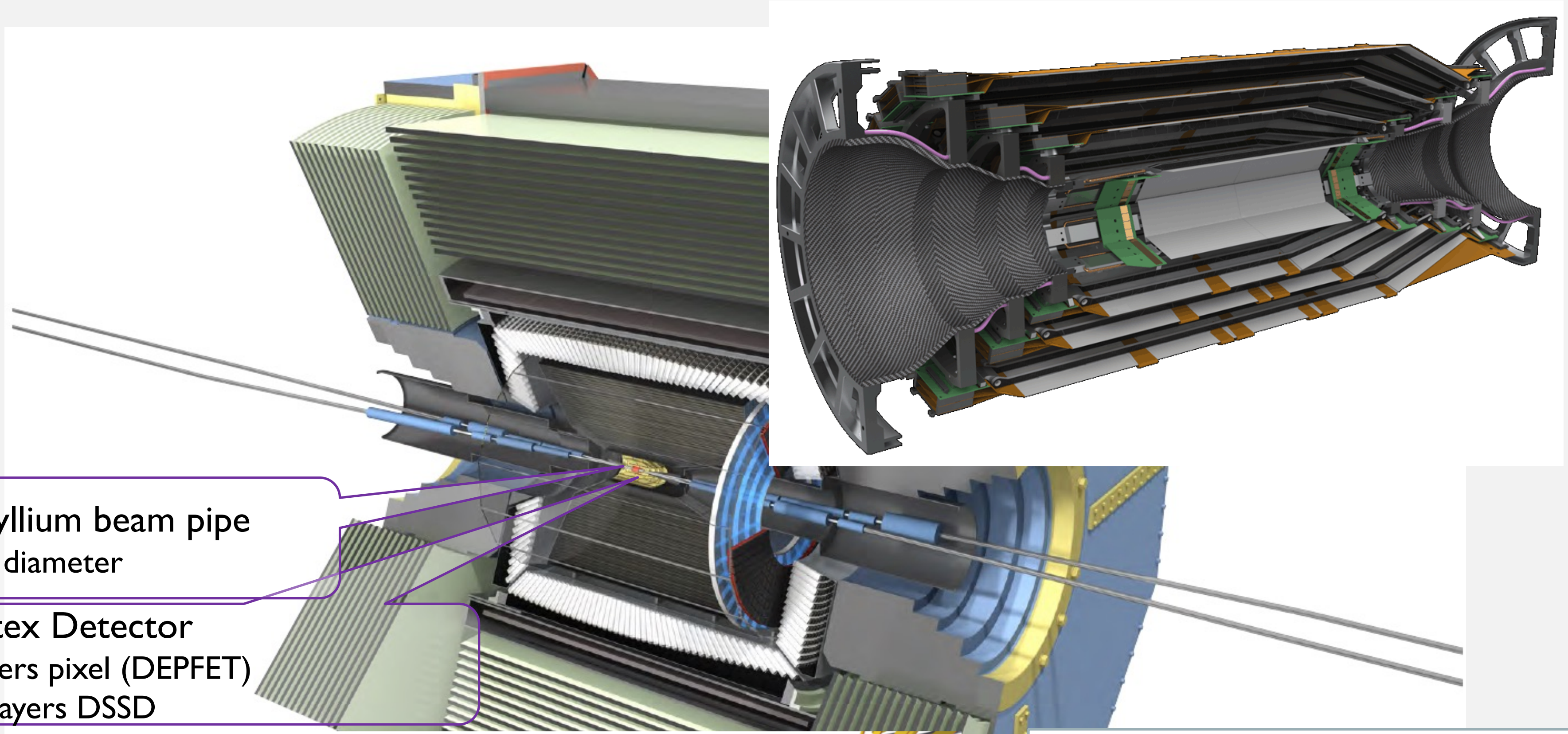


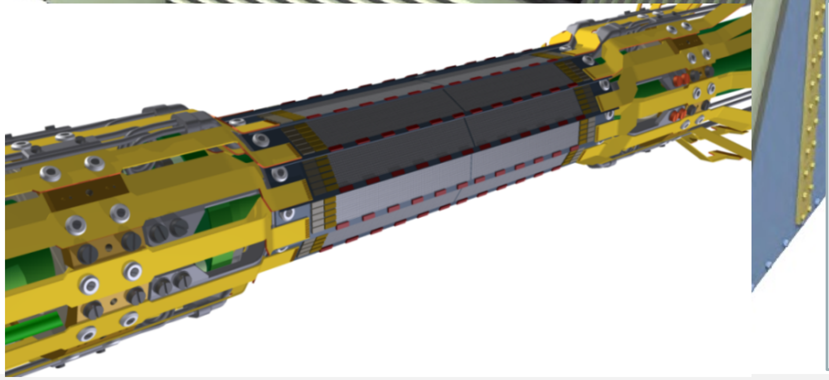




- **Barrel KLM** (US-responsibility) consists of 15 active interleaved with the iron plates of the 1.5T solenoid's flux return yoke.
- 13 outer layers: legacy Resistive Plate Chambers (RPCs)
- 2 inner layers: Scintillator (NEW)
  - Robust wrt neutron flux from beam background/shields subsequent RPC layers

BELLE II DETECTOR – VERTEX REGION

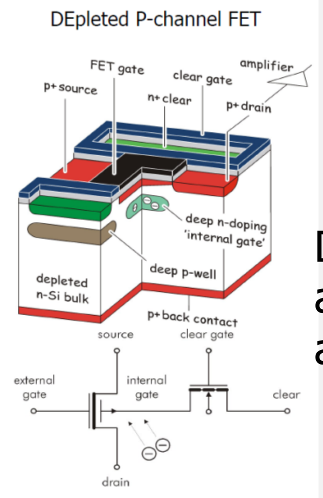




Beam Pipe		**r = 10mm**
DEPFET		
	Layer 1	**r = 14mm**
	Layer 2	**r = 22mm**
DSSD		
	Layer 3	**r = 39mm**
	Layer 4	**r = 80mm**
	Layer 5	**r = 115mm**
	Layer 6	**r = 140mm**

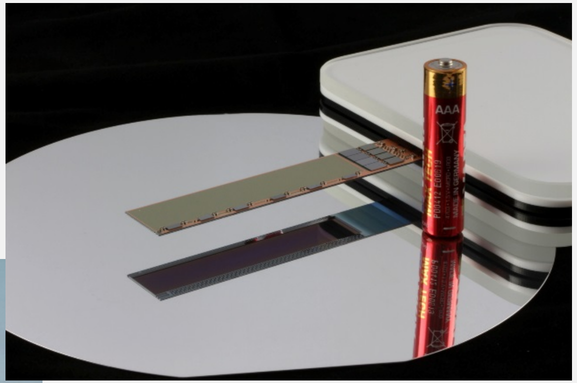
PIXEL DETECTOR: 2 LAYERS OF DEPFET SENSORS

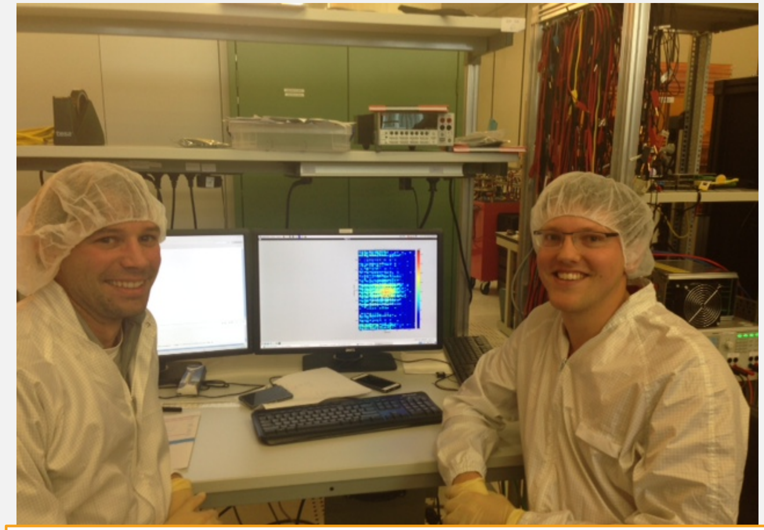
Mechanical mockup of the pixel detector

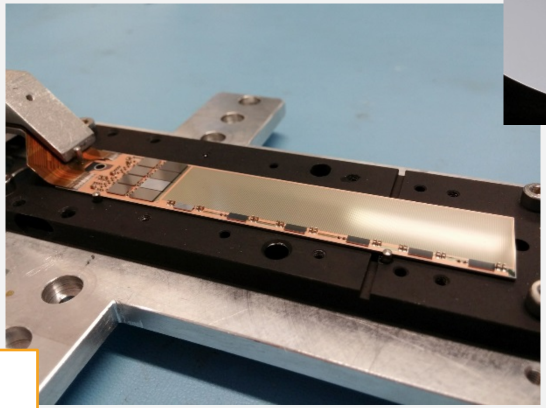


DEPFET sensor: developed at MPI Munich, produced at HLL

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

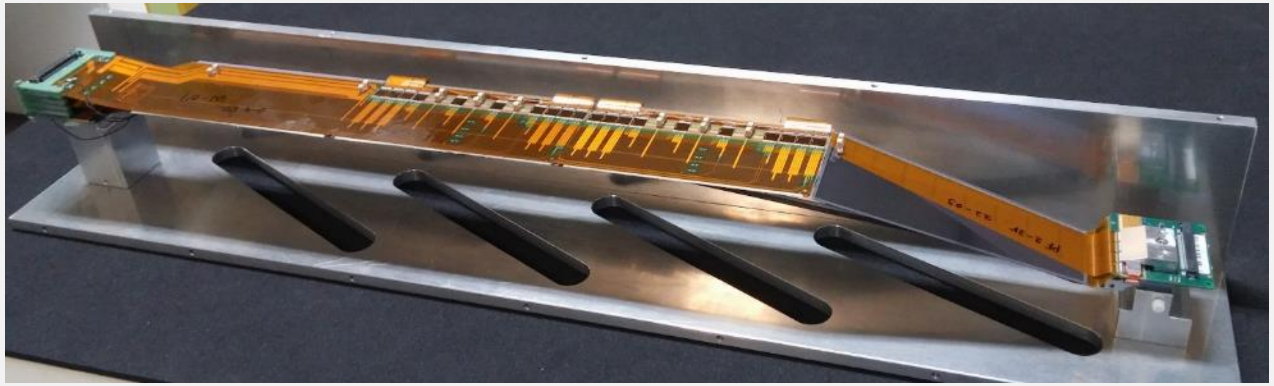




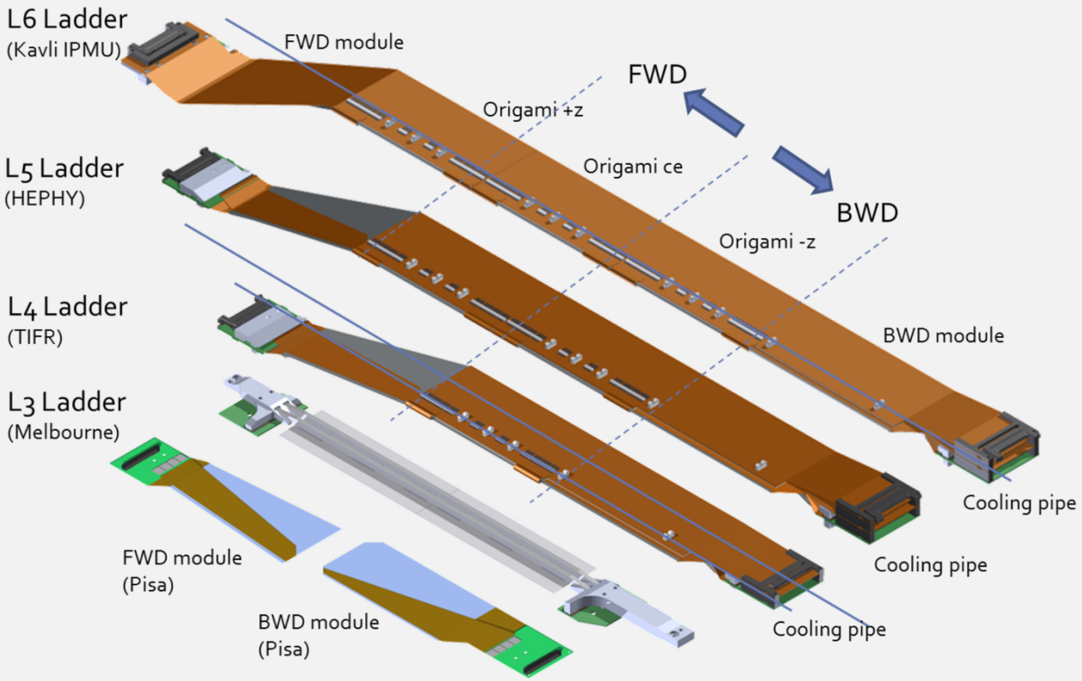


First laser light observed with the full size sensor

→ talk K. Lautenbach



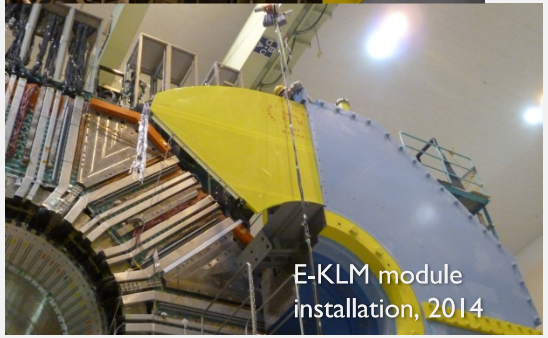
SVD: FOUR LAYERS OF SILICON MICROSTRIP DETECTORS.

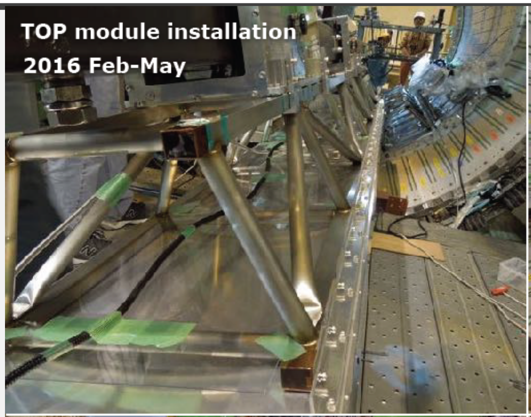


A truly worldwide effort…

INSTALLATION OF SUB-DETECTORS


B-KLM module installation, 2013

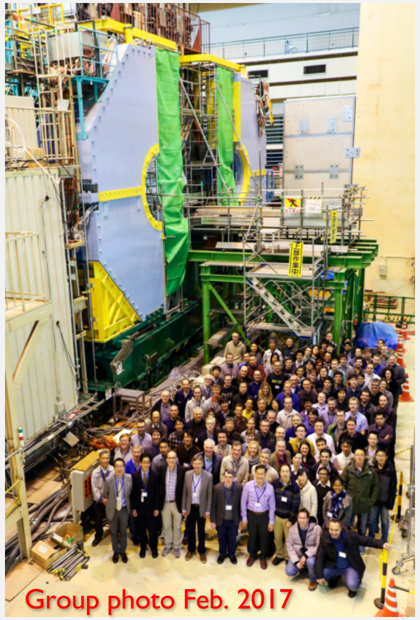

E-KLM module installation, 2014


TOP module installation 2016 Feb-May


B field measurement by CERN mapper 2016 June-July


CDC installation 2016 Oct-Dec

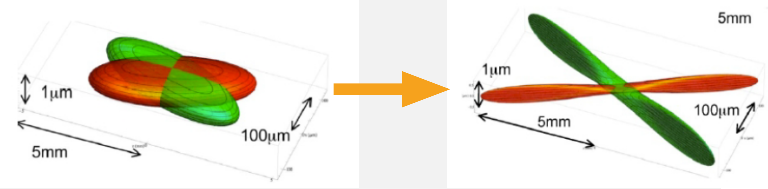

BWD end-cap installation 2017 Jan-Feb


Group photo Feb. 2017


Group photo Apr. 2017

SUPERKEKB NANOBEAMS

To get 40x luminosity of Belle



Reduce beam size to a few 100 atomic layers!

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

Lorentz factor

Beam current

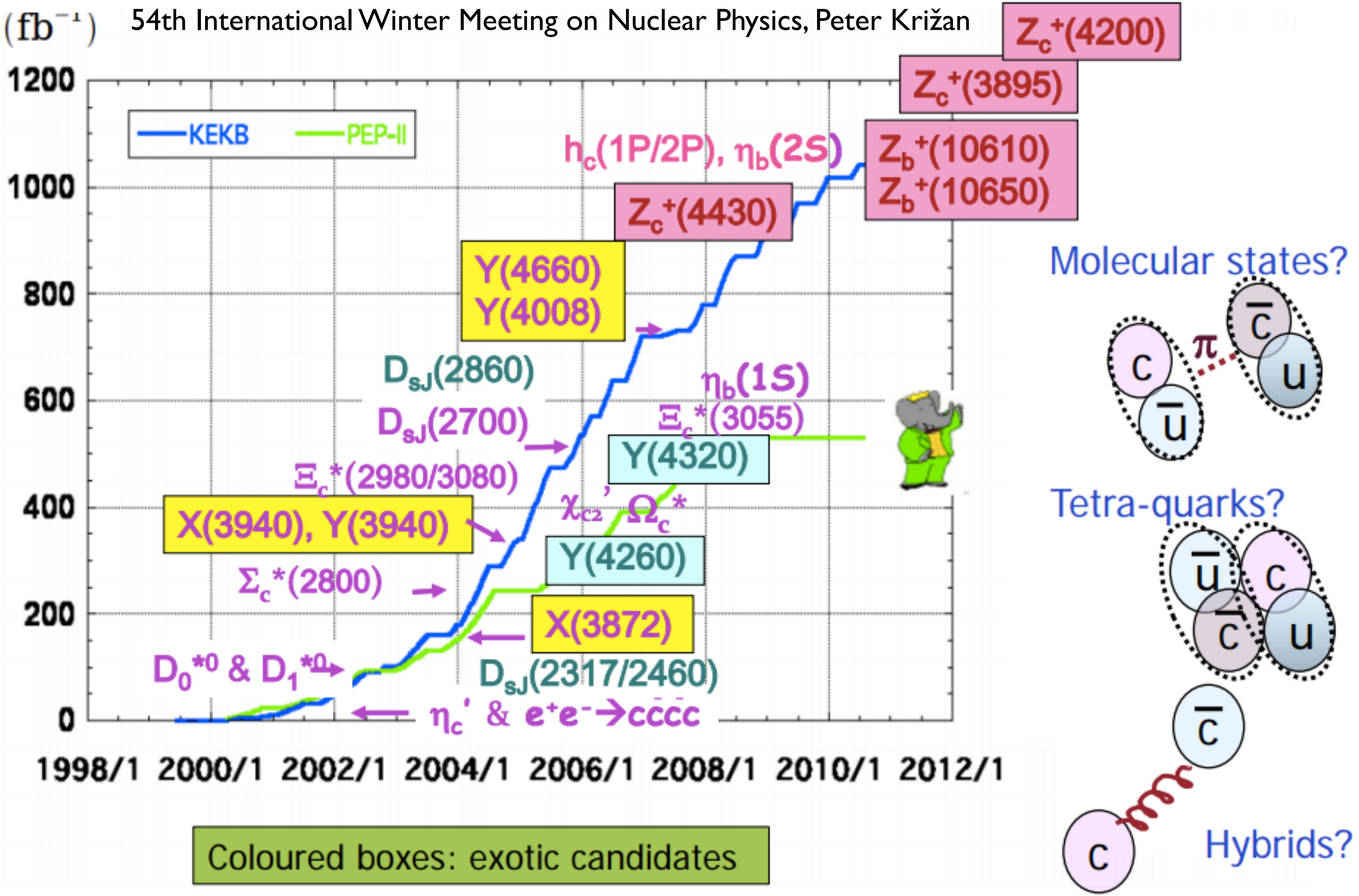
Beam-Beam parameter

Geometrical reduction factors (crossing angle, hourglass effect)

Beam aspect ratio at IP

Vertical beta function at IP

Parameter		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
beam energy	E_b	3.5	8	4	7	GeV
CM boost	$\beta\gamma$	0.425		0.28		
half crossing angle	ϕ	11		41.5		mrad
horizontal emittance	εx	18	24	3.2	4.6	nm
beta-function at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam parameter	ξ_y	0.129	0.090	0.0881	0.0807	nm
beam size at IP	σ_x^*/σ_y^*	100/2		10/0.059		µm
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$



(fb⁻¹)
1200
1000
800
600
400
200
0
1998/1 2000/1 2002/1 2004/1 2006/1 2008/1 2010/1 2012/1
KEKB
PEP-II
$Z_c^+(4200)$
$Z_c^+(3895)$
$h_c(1P/2P)$, $\eta_b(2S)$
$Z_b^+(10610)$
$Z_b^+(10650)$
$Z_c^+(4430)$
Y(4660)
Y(4008)
$D_{sJ}(2860)$
$\eta_b(1S)$
$D_{sJ}(2700)$
$\Xi_c^*(3055)$
Y(4320)
$\Xi_c^*(2980/3080)$
χ_{c2}', Ω_c^*
X(3940), Y(3940)
Y(4260)
$\Sigma_c^*(2800)$
X(3872)
D_0^{*0} & D_1^{*0}
$D_{sJ}(2317/2460)$
η_c' & $e^+e^- \to c\bar{c}c\bar{c}$
Molecular states?
c
$\bar{u}$
π
$\bar{c}$
u
Tetra-quarks?
$\bar{u}$
c
$\bar{c}$
u
$\bar{c}$
c
Hybrids?
Coloured boxes: exotic candidates