Future Relevant Experiments

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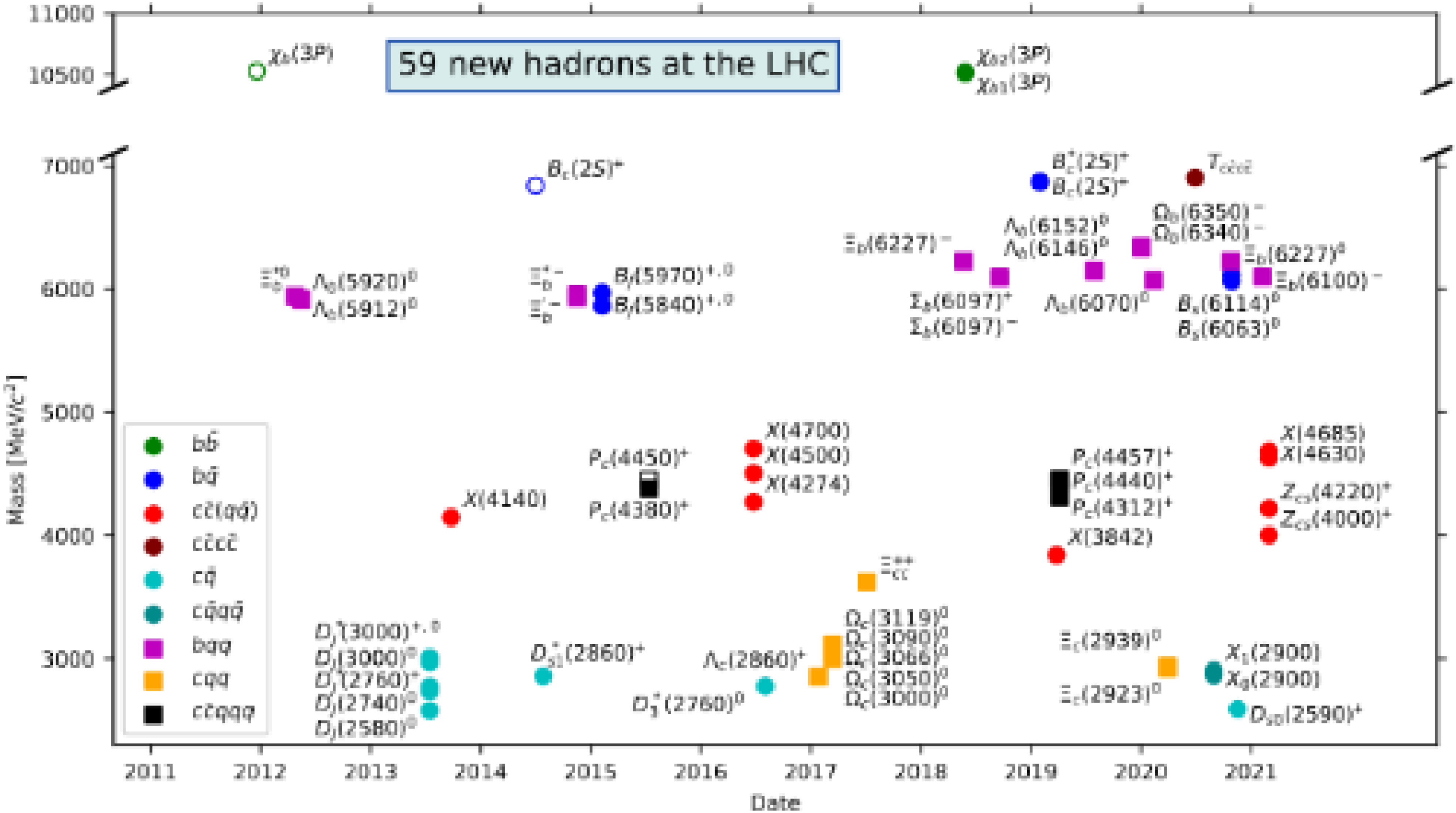
OUTLINE

1. New era
2. Existing and future measurements
3. Super-charm-tau factory
4. Conclusions

New era – I

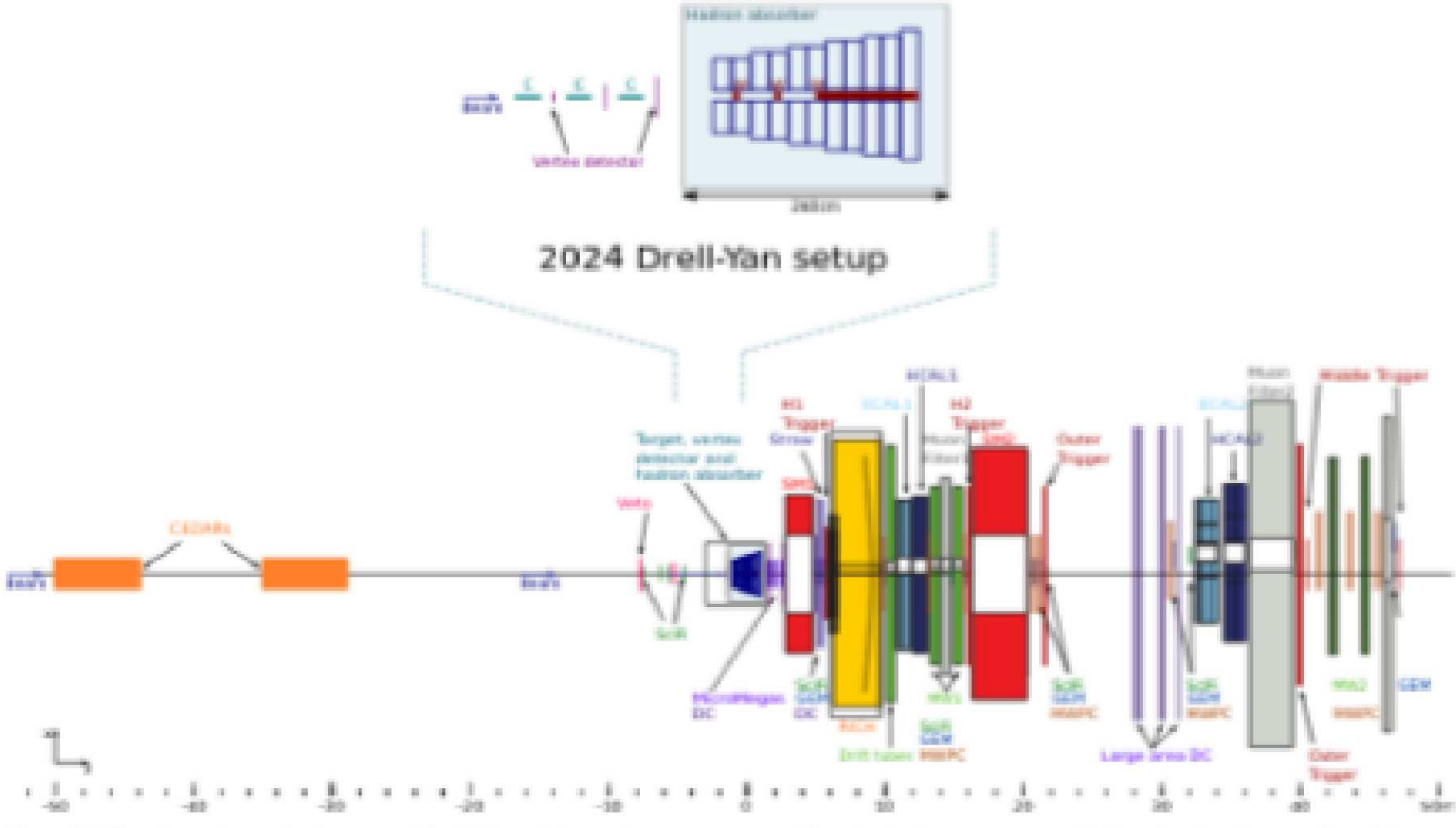

59 new hadrons at the LHC
Mass [MeV/c²]
Date
11000
10500
7000
6000
5000
4000
3000
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
bb̄
bq̄
cc̄(qq̄)
cc̄cc̄
cq̄
cq̄qq̄
bqq
cqq
cc̄qqq
χb(3P)
χb2(3P)
χb1(3P)
Bc(2S)+
Bc*(2S)+
Tcc̄cc̄
Λb(5920)0
Λb(5912)0
Bj(5970)+,0
Bj(5840)+,0
Ξb(6227)−
Λb(6152)0
Λb(6146)0
Ωb(6350)−
Ωb(6340)−
Ξb(6227)0
Ξb(6100)−
Σb(6097)+
Σb(6097)−
Λb(6070)0
Bs(6114)0
Bs(6063)0
X(4700)
X(4500)
X(4274)
X(4140)
Pc(4450)+
Pc(4380)+
Pc(4457)+
Pc(4440)+
Pc(4312)+
X(3842)
X(4685)
X(4630)
Zcs(4220)+
Zcs(4000)+
Ξcc++
Ωc(3119)0
Ωc(3090)0
Ωc(3066)0
Ωc(3050)0
Ωc(3000)0
Λc(2860)+
DJ*(3000)+,0
DJ(3000)0
DJ*(2760)+
DJ(2740)0
DJ(2580)0
Ds1*(2860)+
D3*(2760)0
Ξc(2939)0
Ξc(2923)0
X1(2900)
X0(2900)
Ds0(2590)+

New era – II

- Many new states with unusual properties observed in both charmonium and bottomonium sectors
- Their interpretation involves tetra- and pentaquarks, molecules, hadroquarkonium, mixture with regular quarkonium, various kinematic/dynamic effects (threshold, cusp, rescattering etc.)
- Where are glueballs and hybrids?
- Theorists suggest fancy models, sometimes even with predictions while experiments extract results using rather complicated methods
- Data samples often insufficient despite huge $\int L\, dt$
- My personal opinion about what can be expected: future experiments and relevant physics

AMBER at CERN – I

COMPASS found evidence for the $\tilde{X}(3872)$ - a C=-1 X(3872) partner?
CERN approved a new experiment COMPASS++ or AMBER.



AMBER at CERN – II

AMBER (NA66) @ CERN

Emergence of hadron mass

Phase-I

- Proton radius measurement with muon beam and TPC as active target
- Pion-induced Drell-Yan and charmonia production with both π^+ and π^- to access pion PDFs
- Antiproton production yield — input for astrophysical search for Dark Matter

Already approved and starts in 2022

Phase-II

- Kaon-induced Drell-Yan charmonia and prompt photon production with RF-separated kaon beam to access kaon PDFs
- Kaon spectroscopy
- Kaon-induced Primakoff reactions, kaon polarizability
- Kaon form-factor and kaon radius in K-e elastic scattering

2025+

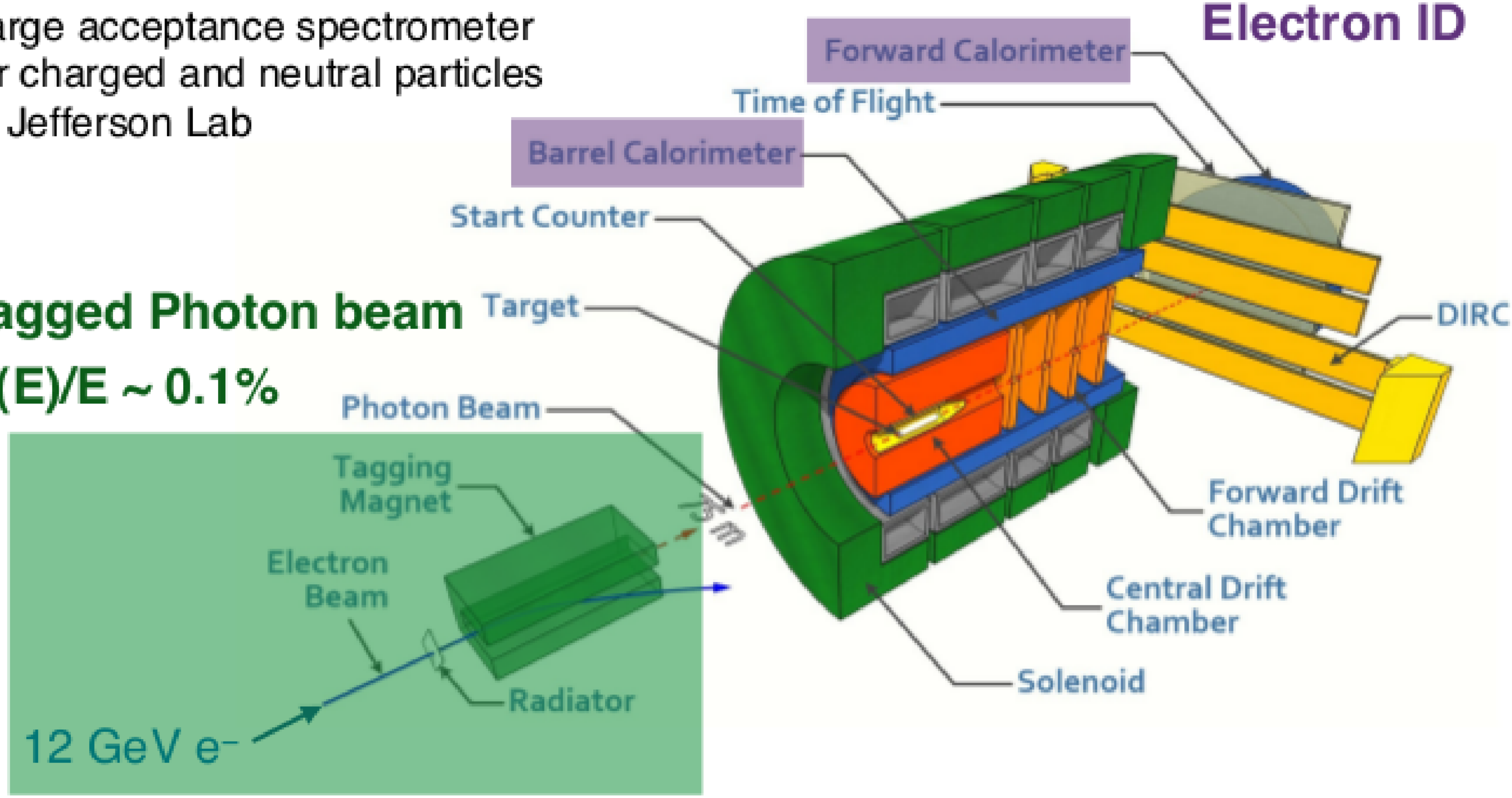
GlueX at JLAB – I

Large acceptance spectrometer for charged and neutral particles at Jefferson Lab

Tagged Photon beam

$\sigma(E)/E \sim 0.1\%$

Electron ID

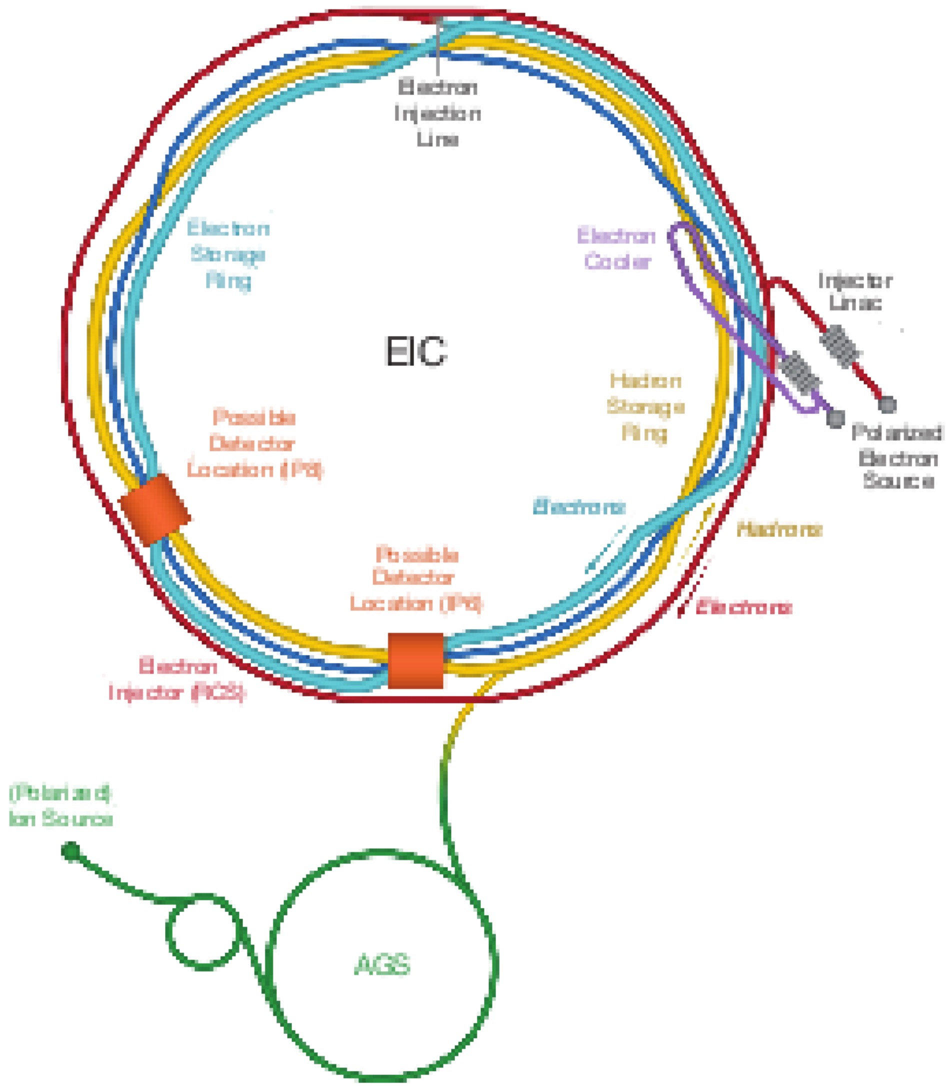


- **GlueX-I** (2017–2018): $E_\gamma > 8$ GeV, $L = 330\ pb^{-1}$
- **GlueX-II** (2020–): expect 3-4x GlueX-I

GlueX at JLAB – II

- With 6-8k J/ψ measure the differential cross section of photoproduction and do more detailed searches for the Pc states
- First studies of $\psi(2S)$ and χ_{cJ} photoproduction
- Searches for hybrid mesons in η_c decays to light mesons
- With the full GlueX-II data (improved pi/K PID) make measurements of open charm production
- Photoproduction of the XYZ states will have to wait for EIC, or an upgrade of the electron accelerator at JLAB

Electron-Ion Collider – I

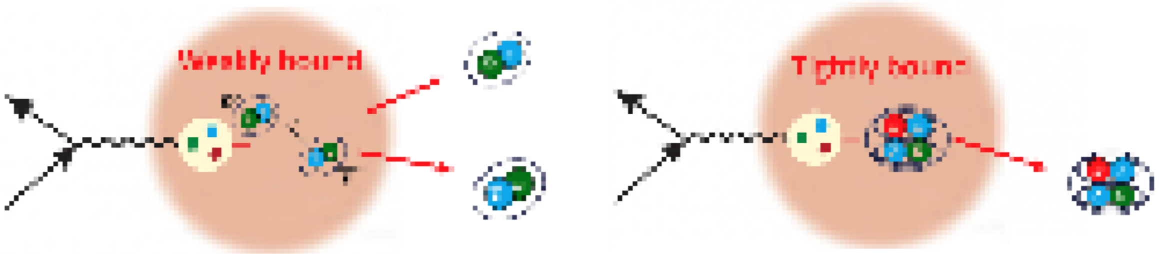


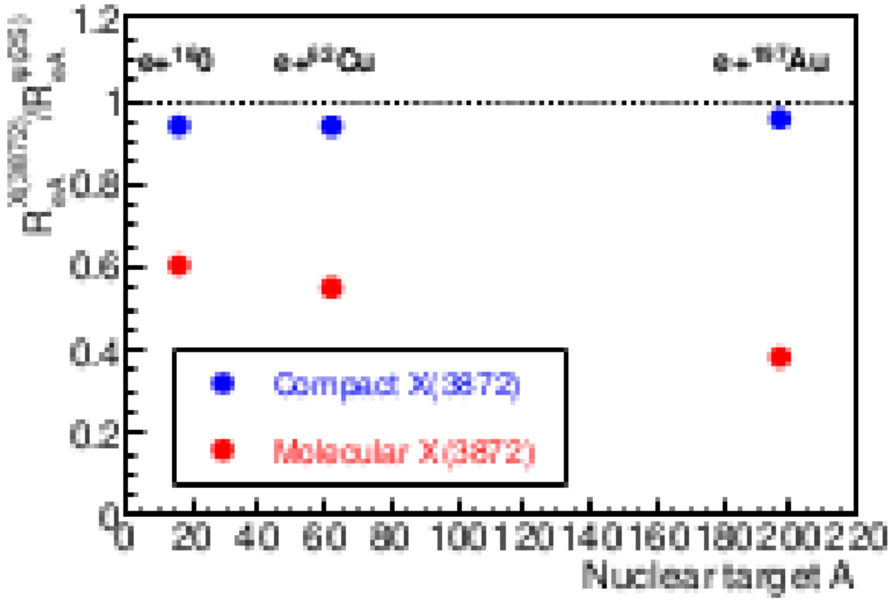
Electron-Ion Collider – II

The main features:

- Highly polarized electron (70%) and proton (70%) beams
- Ion beams from deuterons to heavy nuclei (gold, lead or uranium)
- Variable $e + p$ center-of-mass energies from 20 to 100 GeV, upgradable to 140 GeV
- High collision electron-nucleon luminosity 10^{33}-10^{34} cm^{-2}s^{-1}
- More than one interaction region

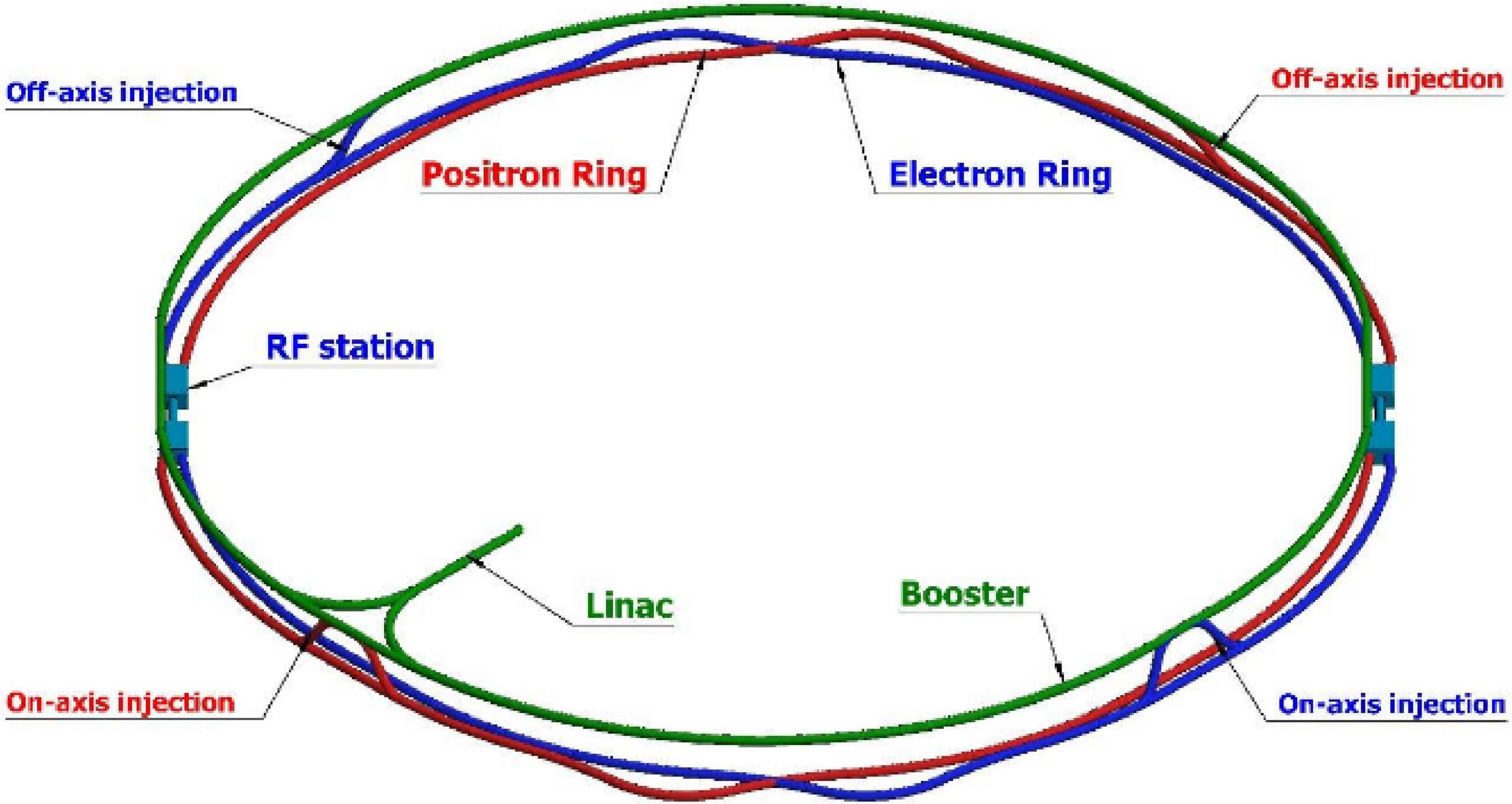
Electron-Ion Collider – III





$R_{eA}(X)$ – the nuclear modification factor for a particle X

CEPC – I


Off-axis injection
Positron Ring
Electron Ring
Off-axis injection
RF station
Linac
Booster
On-axis injection
On-axis injection

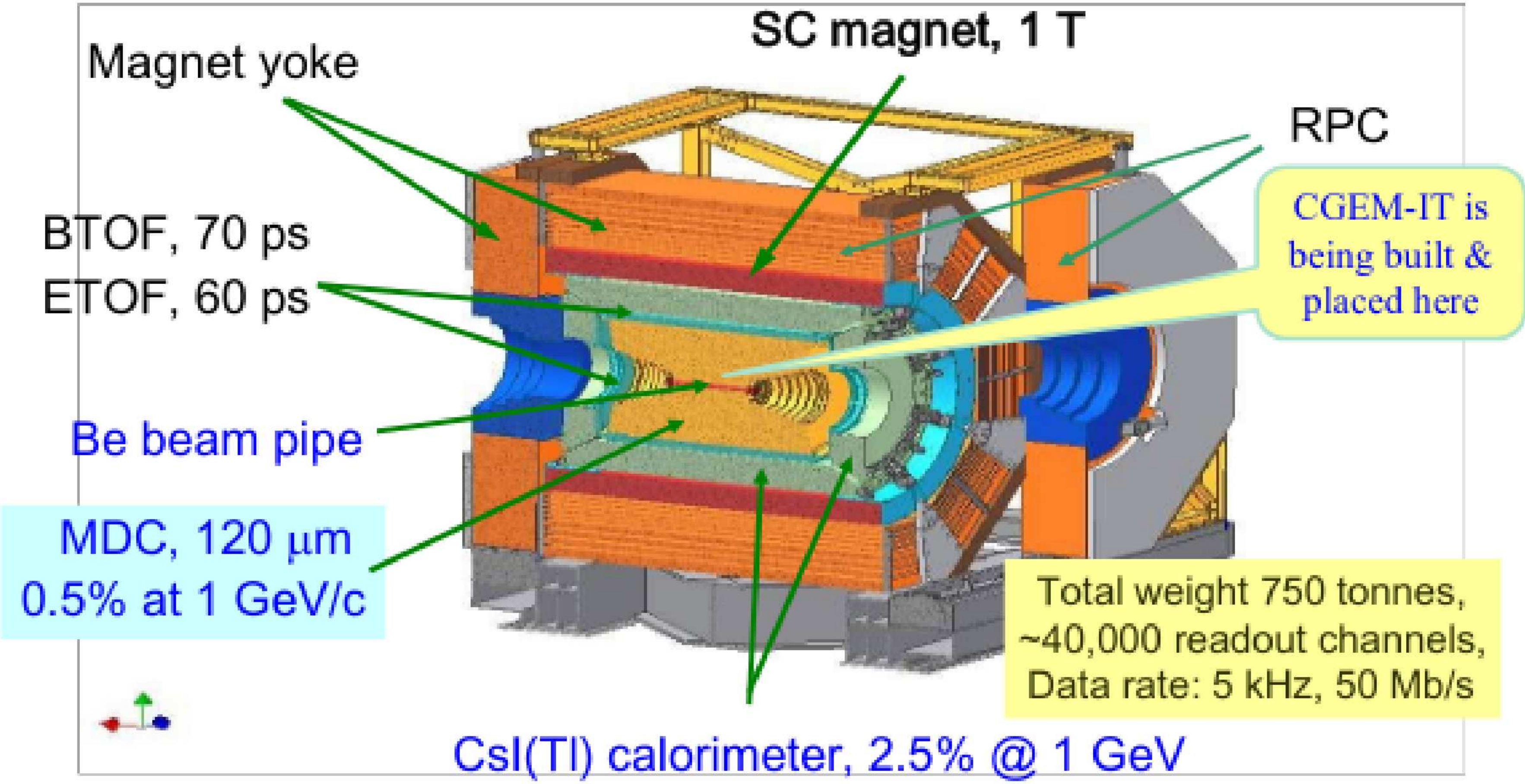
CEPC – II

Mode	H	Z	W^+W^-
$\sqrt{s}$, GeV	240	91	160
L, 10^{34} cm^{-2}s^{-1}	3	17	10
Years	7	2	1
$\int L\ dt$, ab^{-1}	5.6	16	2.6
Number	10^6	7×10^{11}	2×10^7

A rough estimate gives 3×10^6 X(3872) produced from $Z \to b\bar{b}$

How many promptly produced X's can be expected?

BESIII Experiment at BEPC2 – I

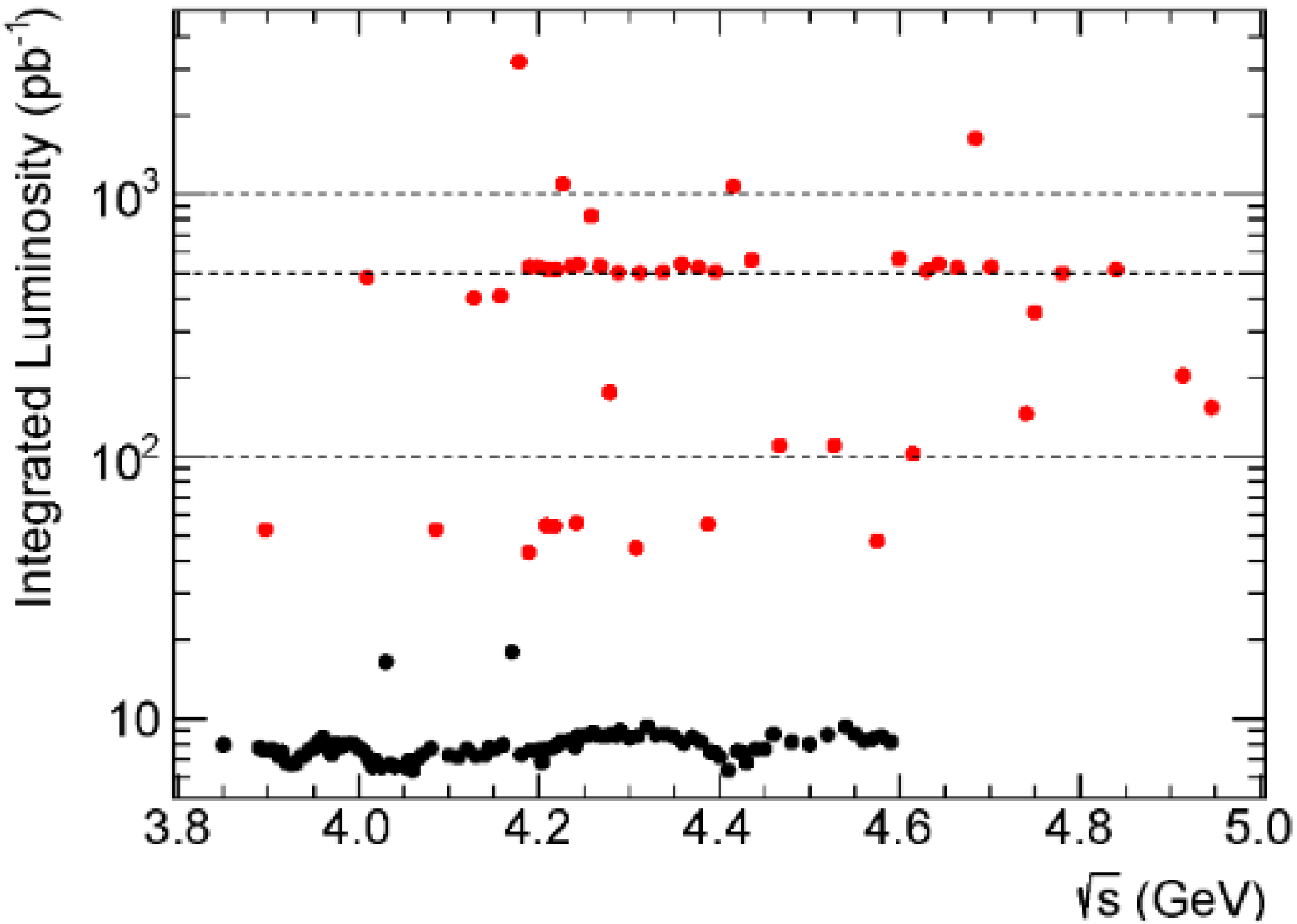


Has been in full operation since 2008, all subdetectors are in very good status!

BESIII Experiment at BEPC2 – II

BESIII

Data for XYZ study

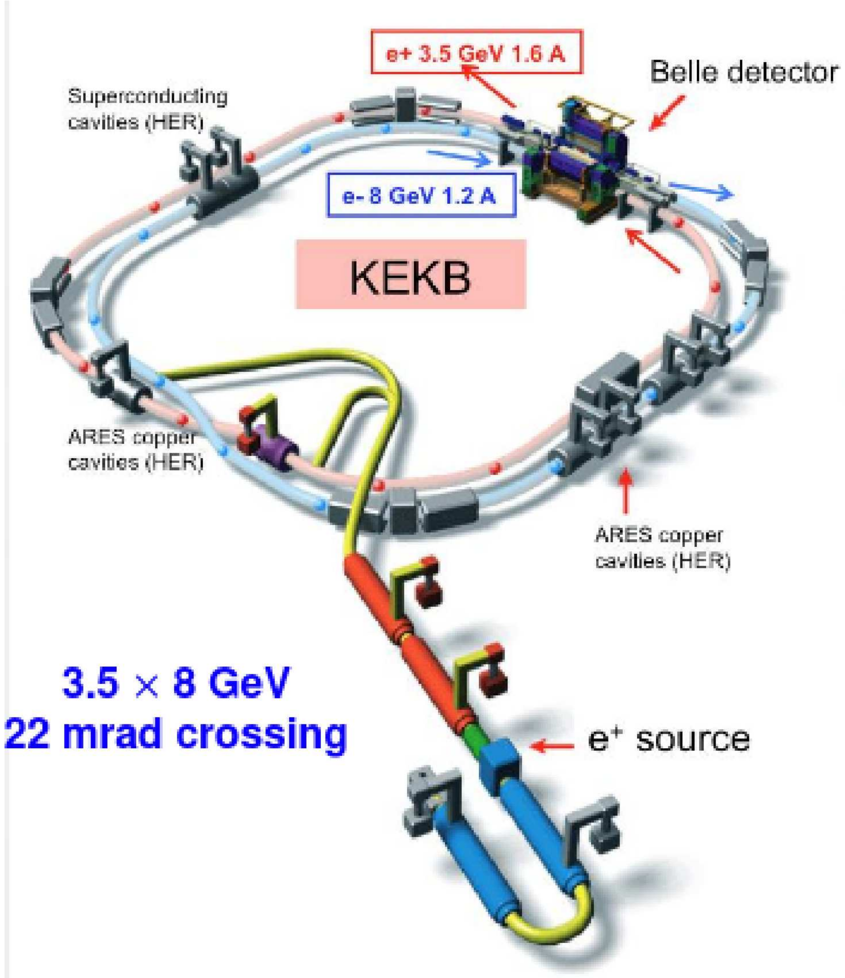


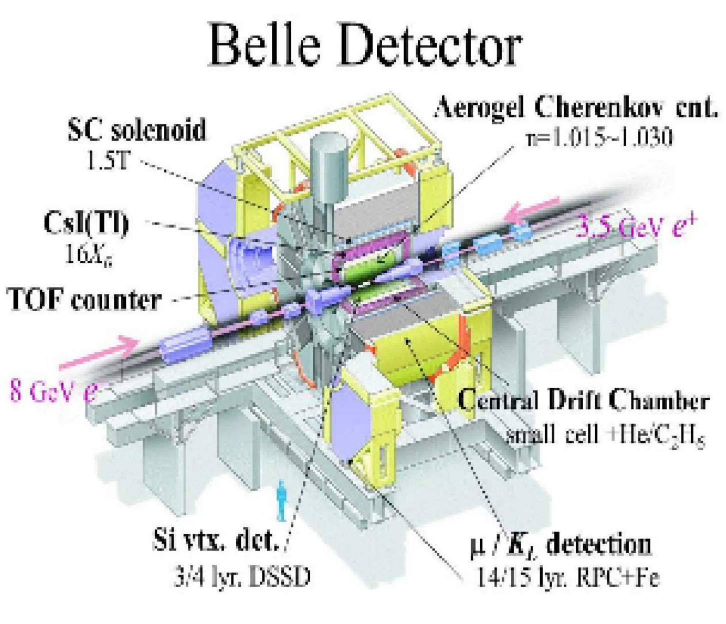
Plans of BESIII

For the next 10 years

1. 2021-2023 (not for XYZ)
   - $3 \times 10^9\ \psi(2S)$ events
   - 20 fb^{-1} at $\psi(3770)$
2. BEPCII $\Rightarrow$ BEPCIII
   - New SCQ magnets and new RF cavities, E_{beam} increased to 2.8 GeV
   - Luminosity after the upgrade:
     $1.2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 2-2.5 GeV
     $(0.5 - 0.8) \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 2.5-2.8 GeV
   - 3 years for preparation and installing
   - Applied for funding (200M)
   - Detector upgrade discussed

KEKB and Belle





Data taking: 1999 – 2010

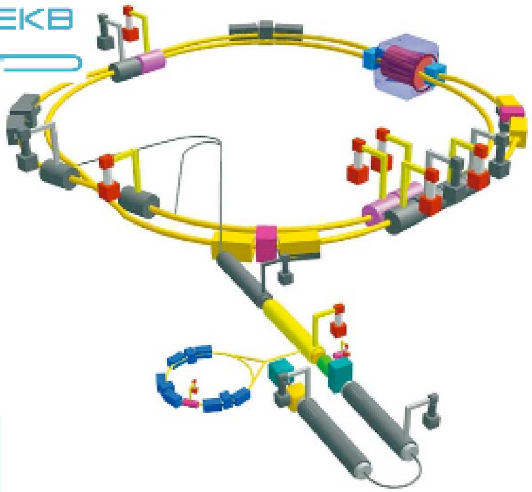
On/off/Scan $\Upsilon(nS)$ peaks

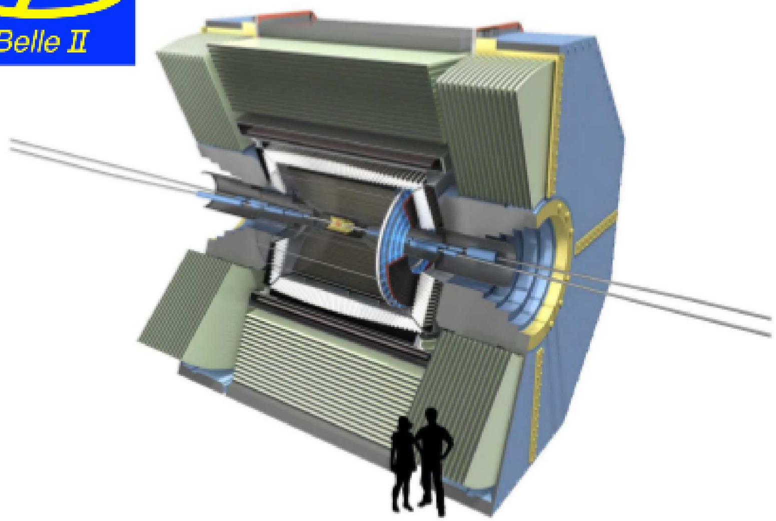
Total luminosity: 980 fb^{-1}

772M $B\bar{B}$ events @$\Upsilon(4S)$

$X(3872)$ was discovered by Belle in 2003, 1926 citations!

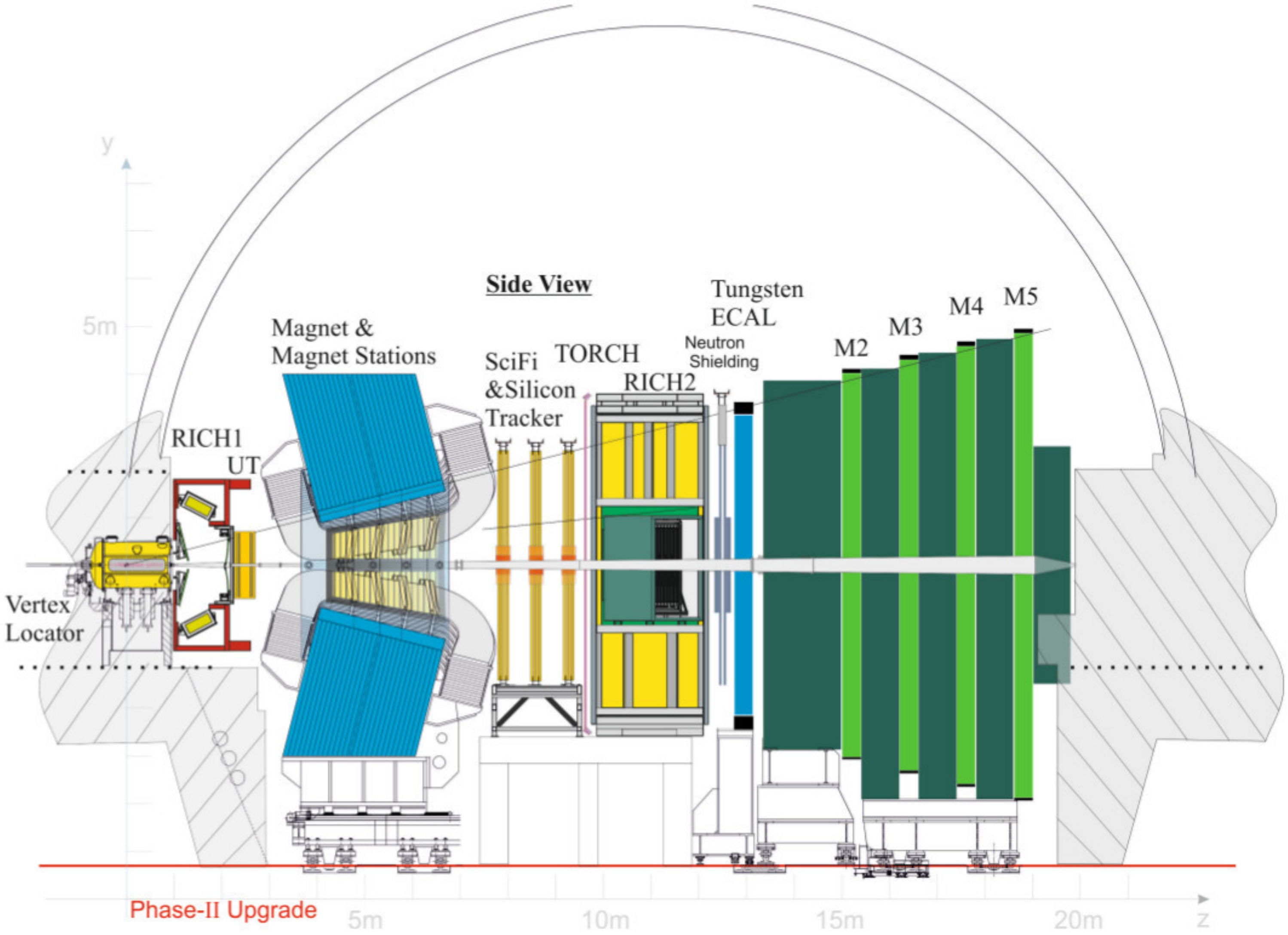
SuperKEKB and Belle II



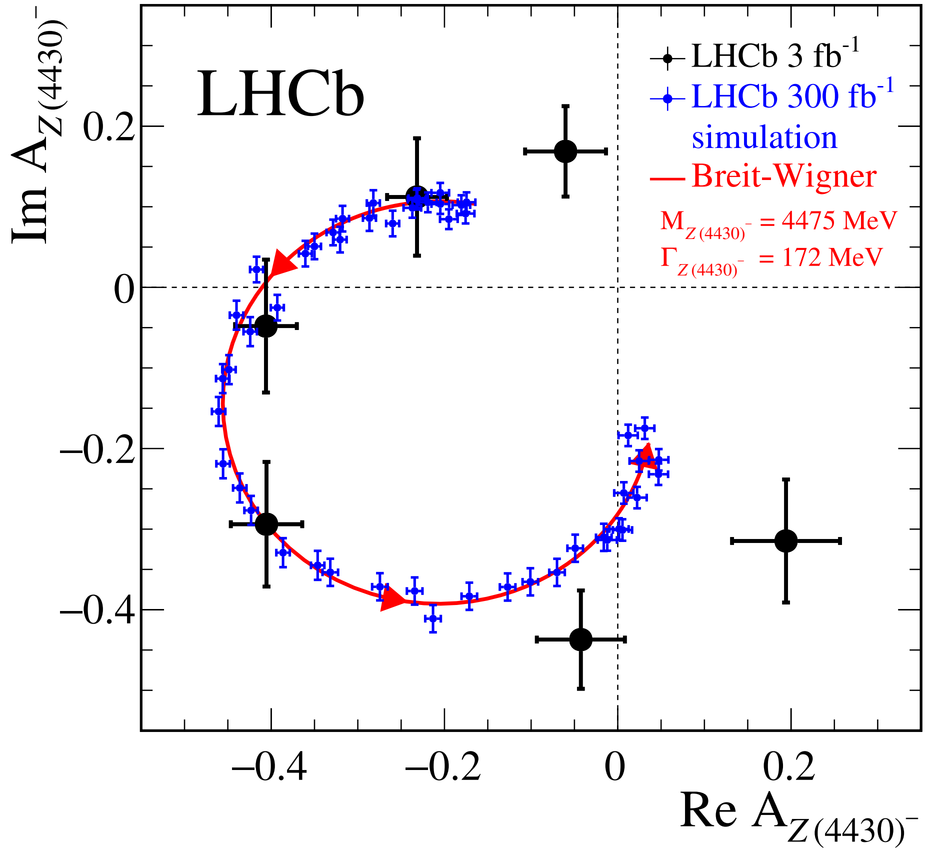


- Currently:
  $L_{\max} = 2.4 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  $\int L\ dt \approx 100\ \mathrm{fb}^{-1}$
- Planned by 2030:
  $L_{\max} = 6 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  $\int L\ dt = 50\ \mathrm{ab}^{-1}$
- 50 times more events of $c\bar{c}$ states
- Depending on $\sqrt{s}_{\max}$ (11,12 GeV?)
  What will we learn about $b\bar{b}$?

Upgrade of LHCb



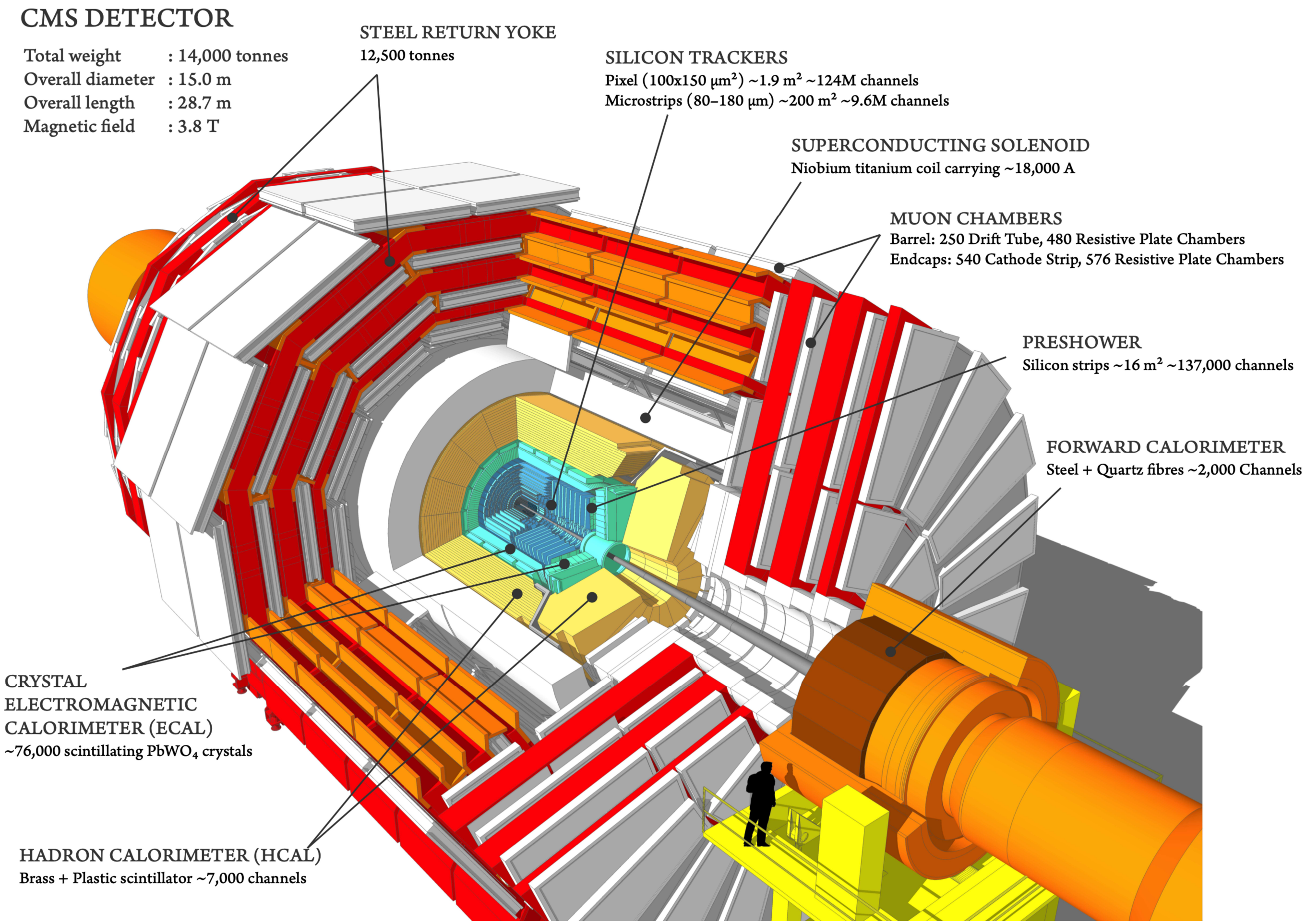
Future of XYZ at LHCb



From 3 to 300 fb^{-1}

Already a discovery machine with 9 fb^{-1} only

CMS



$\mathcal{B}(B^+ \to \psi(2S)\phi K^+) \approx 4 \times 10^{-6}$, a study of the $\psi(2S)\phi$ system

What is Super-Charm-Tau Factory?

A Super-Charm-Tau Factory is an (e^+e^- collider) complex for high-precision measurements between 2 and 6 (7) GeV with instantaneous luminosity up to $10^{35}\text{cm}^{-2}\text{s}^{-1}$ and longitudinal polarization of the initial e^- beam

Integrated luminosity of $\sim 10\ \text{ab}^{-1}$ could be collected in 10 years

General features

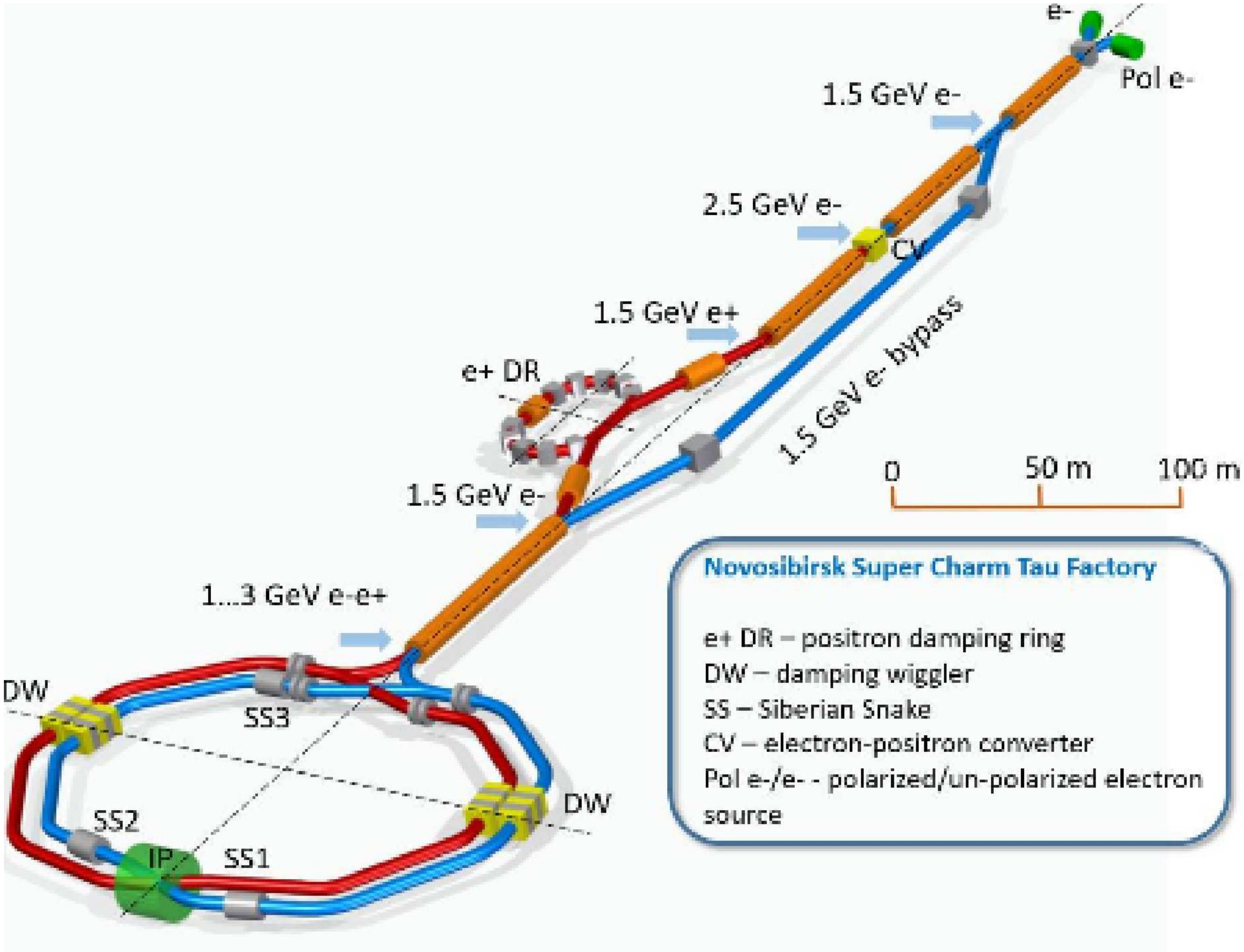
Strategic tasks of SCTF

- Non-perturbative QCD (f/f, hadron spectroscopy, multibody decays)
- Studies of weak interactions of leptons
  and quarks of the 1st and 2nd generations
- Searches for New Physics

Advantages of SCTF

- Pair production of τ, charm hadrons and baryons
  (double tagging $\Rightarrow$ measurement of absolute branchings)
- Longitudinal polarization of initial electrons
  (CP violation in decays of charm baryons and τ leptons)
- Coherent production of $D^0\bar{D}^0$ mesons (measurement of phases)
- Low multiplicity, threshold kinematics $\Rightarrow$ bkgd suppression

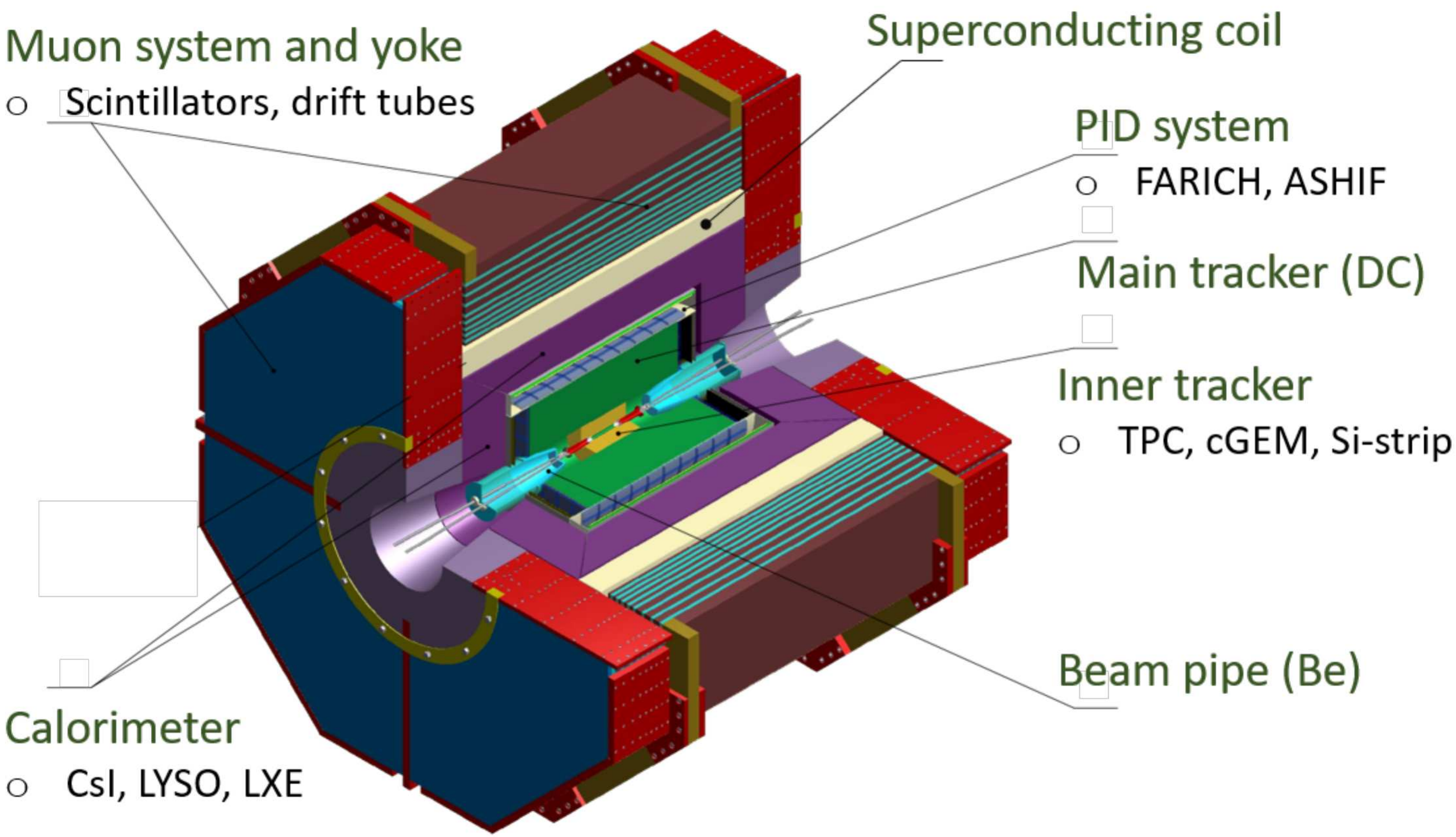
Super-charm-tau Factory in Novosibirsk



Parameters of Novosibirsk SCTF

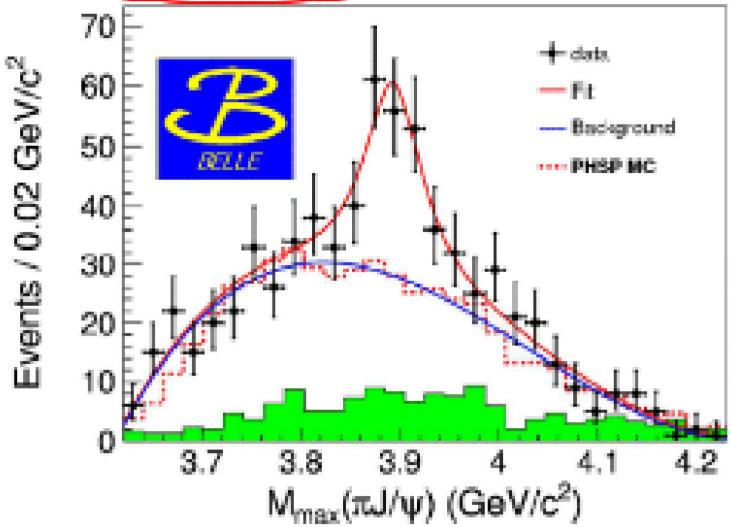
Circumference, m		622.7	
2θ, mrad		60	
β^*_x/β^*_y, mm		100/1	
F_{RF}, MHz		350	
E_{beam}, GeV	1.5	2	3
I, A	2	2	2
Bunches	323	431	259
$L, 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.8	1.3	1.1

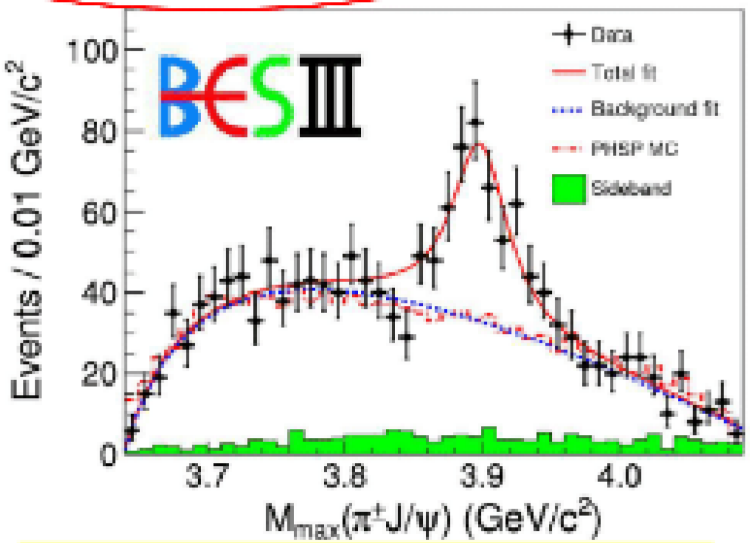
Detector for Novosibirsk SCTF



Comparison

Belle	BESIII
Belle with ISR: PRL110, 252002	BESIII at 4.260 GeV: PRL110, 252001
967 fb^{-1} in 10 years running time	0.525 fb^{-1} in one month running time





Belle:

- M = 3894.5±6.6±4.5 MeV
- Γ = 63±24±26 MeV
- 159 ± 49 events
- >5.2σ

BESIII:

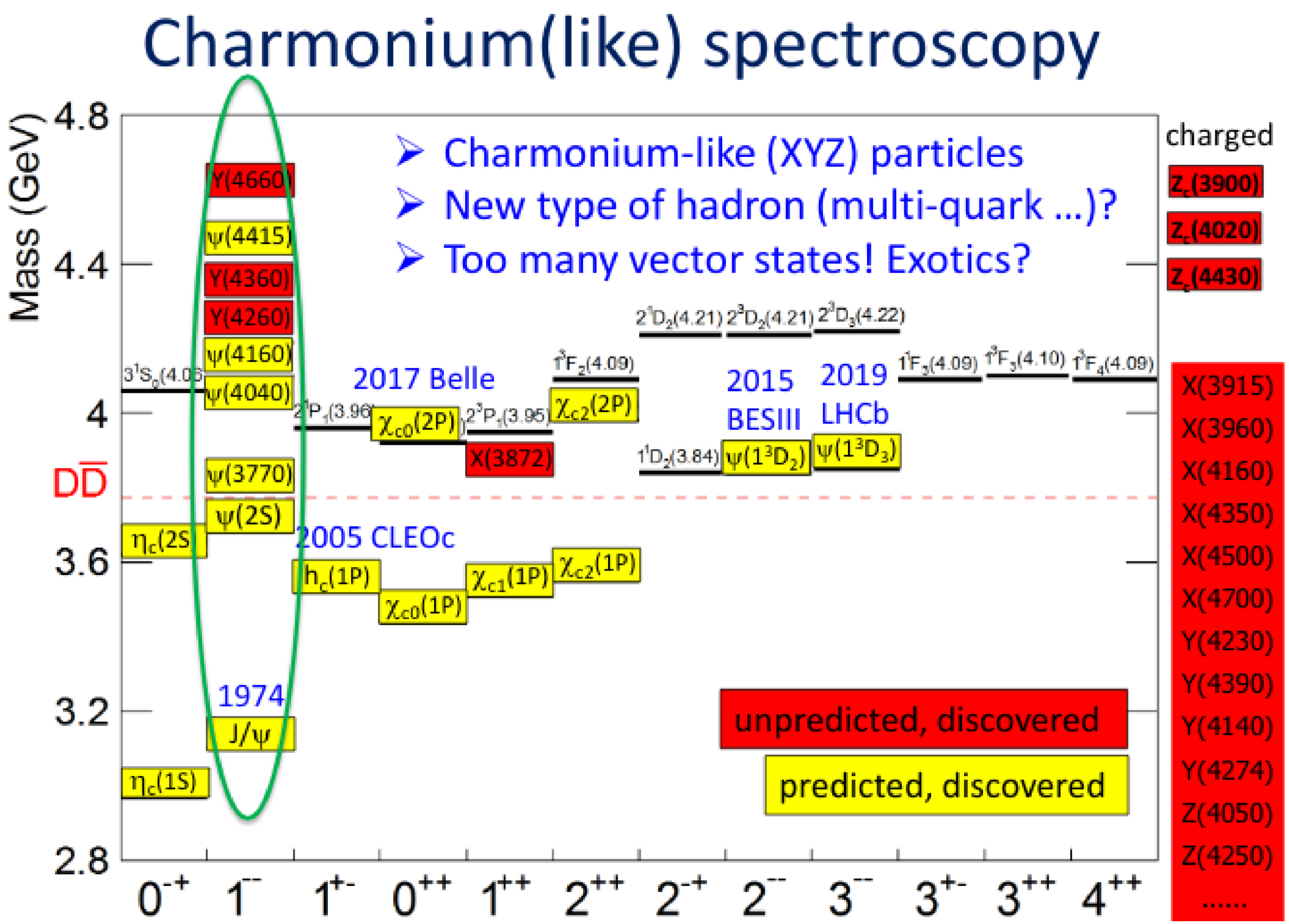
- M = 3899.0±3.6±4.9 MeV
- Γ = 46±10±20 MeV
- 307 ± 48 events
- >8σ

Conventional Charmonia

State	J/ψ	$\psi(2S)$	$\psi(3770)$	$\psi(4040)$
M, GeV	3.097	3.686	3.773	4.040
Γ, MeV	0.093	0.294	27	84
$\int Ldt, \mathrm{fb}^{-1}$	800	250	400	10
N	10^{12}	10^{11}	$2 \cdot 10^9$	10^8

- Even for the J/ψ and $\psi(2S)$ the full decay pattern is unclear, other states are not well enough studied
- 20 (25) fb^{-1} needed to produce 10^8 $\psi(4160)$ ($\psi(4415)$) mesons
- $\sim 10^{10}$ χ_{cJ} and $\eta_c(1S)$ in radiative decays of the J/ψ and $\psi(2S)$
- About 10^8 h_c mesons in $\psi(2S) \to h_c\pi^0$
- $\eta_c(2S)$ mesons can be produced in $\psi(2S) \to \eta_c(2S)\gamma$ or $\gamma\gamma$ collisions
- The huge $N(J/\psi)$ – a unique source of tagged $\bar{n}$, Λ, Σ as suggested recently by M. Karliner and C.Z. Yuan in arXiv:2103.06658

Study of Charmonium-(like) States – I

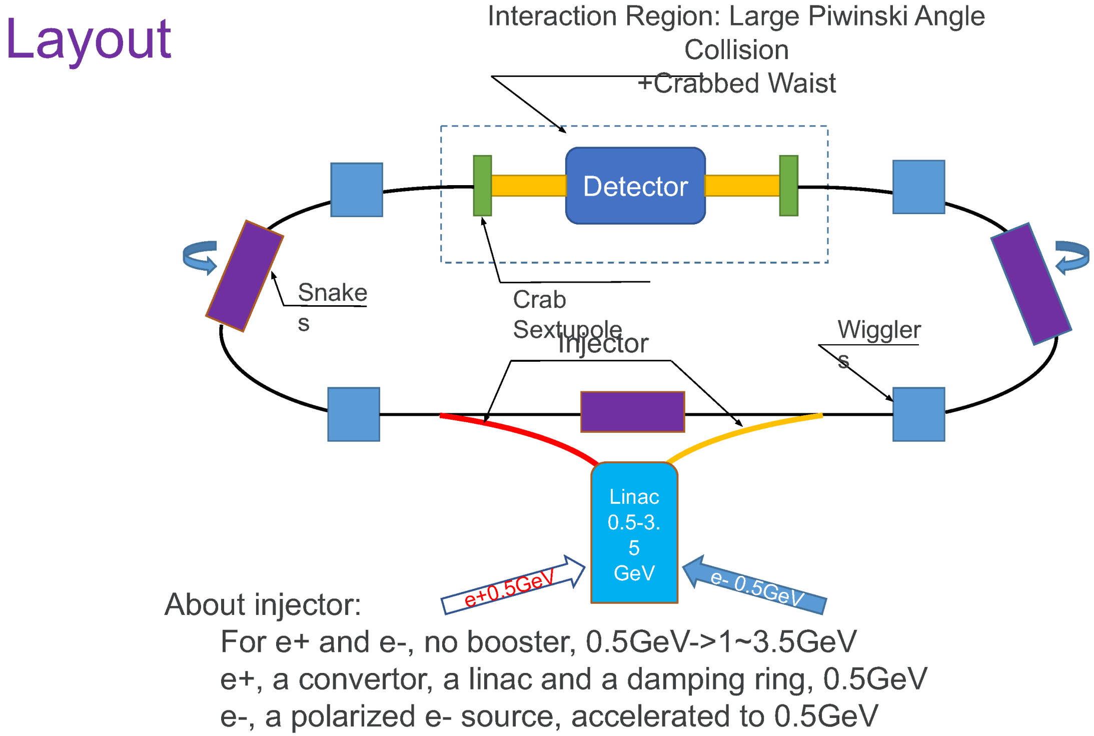


S. Godfrey and N. Isgur, Phys.Rev. D32, 189 (1985)

Study of Charmonium-(like) States – II

- All $\psi(Y)$ states with $J^{PC} = 1^{--}$ will be directly produced at $\sqrt{s} = M_Y$: $\psi(4260/4230)$, $\psi(4360)$, $\psi(4660)$, are there also $\psi(4320)$, $\psi(4390)$, ...?
  These and other quantum numbers are also accessible at PANDA
- Charged Z_c states can be produced by scanning the $\sqrt{s}$ range and studying the $J/\psi\pi\pi$, $h_c\pi\pi$, $D^{(*)}\bar{D}^{(*)}$ final states
- Neutral $c\bar{c}$ states with other quantum numbers can be studied in the recoil to $\pi\pi$, π^0, η, ω final states
- $C = +1$ states can be also produced in $\gamma\gamma$ collisions
- Between 6 and 7 GeV double $c\bar{c}$ production?

HIEPA – Layout



HIEPA - High Intensity Electron Positron Accelerator

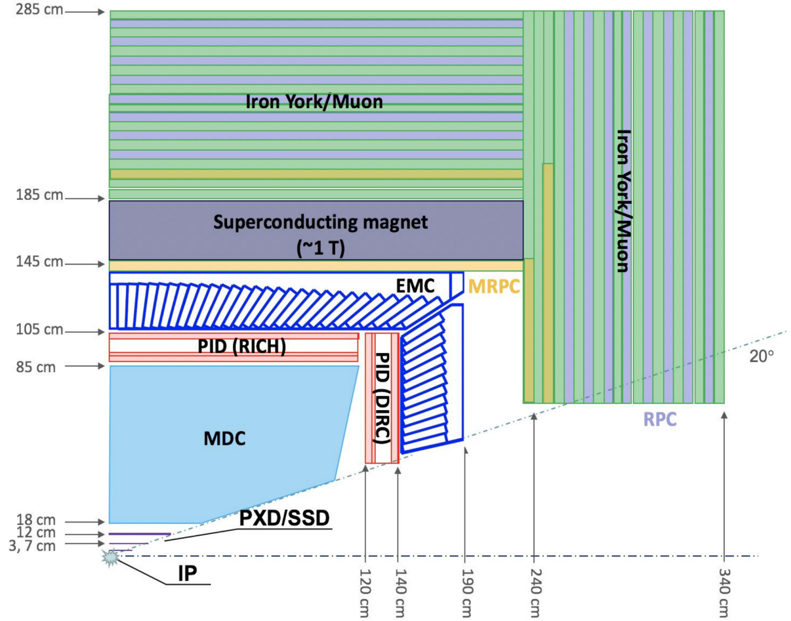
HIEPA is the project of SCTF in Hefei, China

HIEPA – Parameters

Parameter	Phase 1	Phase2
Circumference, m	600-800	600-800
Optimized beam energy, GeV	2	2
Current, A	1.5	2
Collision angle, mrad	60	60
Luminosity, 10^{35} cm^{-2} s^{-1}	0.5	1

HIEPA – Detector

A Detector Concept for STCF



PXD
- ~0.15%X_0/ layer
- σ_{xy}~50 μm

MDC
- σ_{xy}<~130 μm
- σ_p/p ~ 0.5% @ 1 GeV
- dE/dx~6%

PID
- π/K (and K/p) 3-4σ separation up to 2GeV/c

EMC
E range: 0.02-3.5GeV
σ_E(%) @ 1 GeV
Barrel: 2
Endcap: 4
Pos. Res. : ~ 5 mm

MUD
- Down to <~0.4GeV
- π suppression >10

Conclusions

- A lot of exciting experimental results,
  not many convincing interpretations
- Extensive development of theoretical models,
  experiments need clear recipees to distinguish them
- A good old Breit-Wigner started losing ground,
  once again experiments ask for wise input from theory
- New properties of charmonia produced from
  γ, μ, π, K at AMBER and GlueX
- Expecting new discoveries from
  PANDA, BESIII, LHCb, CMS, ATLAS, Belle and Belle II
- Super-charm-tau Factory badly needed to learn more about $c\bar{c}$
- Will high-energy facilities bring a new intrigue
  (EIC, CEPC, FCC, ILC. CLIC)?