Prospects of Spectroscopy at Future Facilities

Simon Eidelman

Budker Institute of Nuclear Physics SB RAS
and Novosibirsk State University, Novosibirsk, Russia
and Lebedev Physical Institute RAS, Moscow, Russia

Outline

Instead of Introduction

S.L. Olsen, T. Skwarnicki, D. Zieminska, Rev.Mod.Phys. 90, 015003 (2018):

"This nearly total disconnect between the hadrons that we observe in experiments and the quarks and gluons that appear in the theory is a problem of large proportions in particle physics.[3] This is what we refer to as the "QCD dilemma." In addition to the intellectual dissatisfaction with a theory that is not directly applicable to the particles that are used and detected in experiments, there is also a practical problem in that many SM tests and searches for new physics (NP) involve strongly interacting hadrons in the initial and/or final states of the associated measurements."

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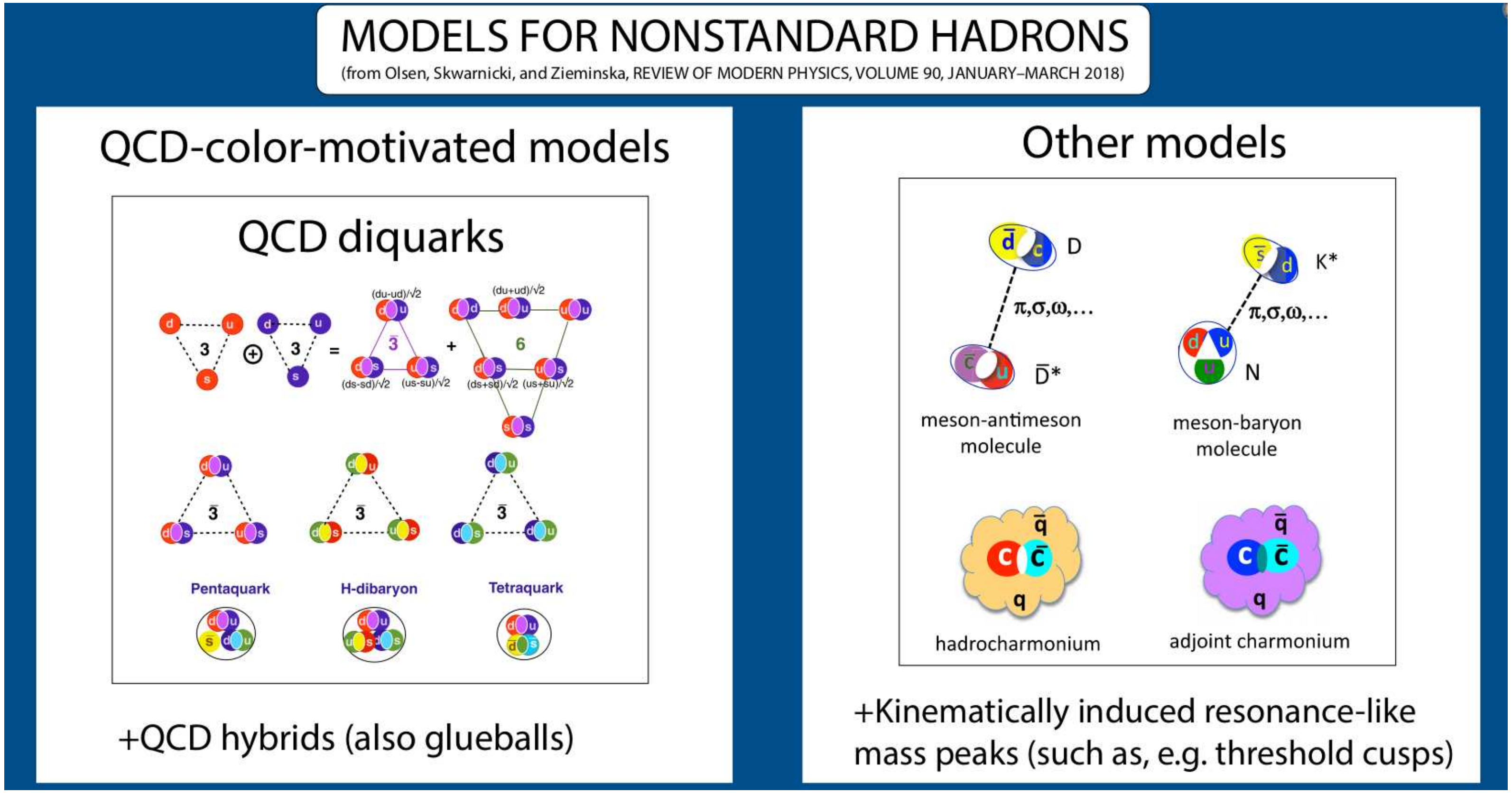
[3]As Frank Wilczek put it in a recent interview (Wilczek, 2016): "We have something called a standard model, but its foundations are kind of scandalous. We have not known how to define an important part of it mathematically rigorously,…"

Models of Hadron Production

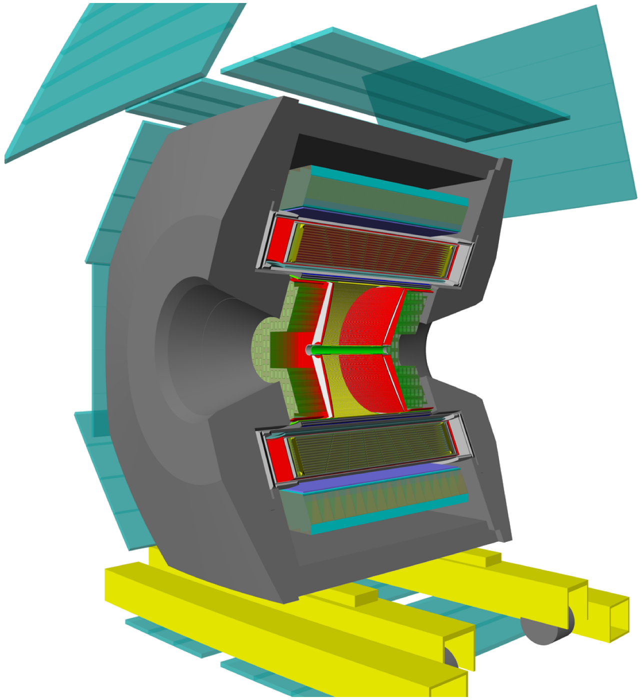


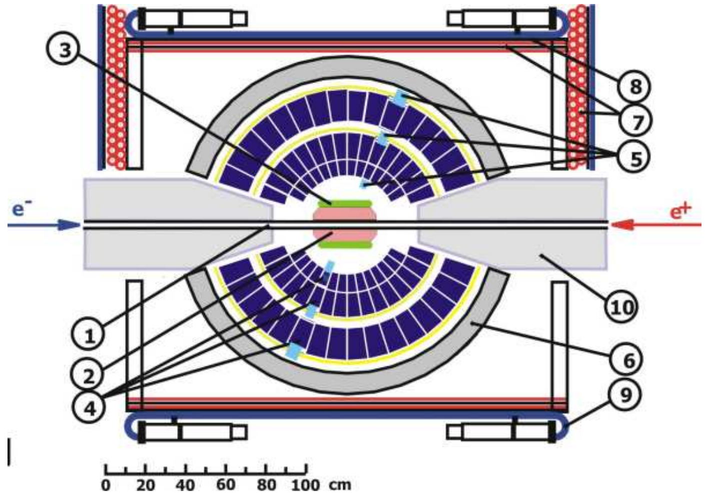
General

- What is behind the nice pictures above: how distinguish different possibilities experimentally - a question to theory?
- Strong interaction was deprived attention lately compared to CP violation, ν physics, astroparticle physics
- In the light meson sector:
  Many “extra” states (e.g. scalars), which of them are “exotic”?
  Mesons between 2 and 3 GeV, high-spin states
  Rather old (LASS) studies of strange mesons
- In the heavy meson sector a variety of new states with exotic properties among heavy quarkonia, but scarce knowledge of open-flavour mesons (D^{**}, D_{sJ}, B^{**}, B_{sJ})
- Situation with baryons is far from satisfactory

Hadrons with Light Quarks

e^+e^- Colliders – I





CMD-3 Detector SND detector

VEPP-2000 will run in the c.m. energy range 0.3-2 GeV for another 7-10 years

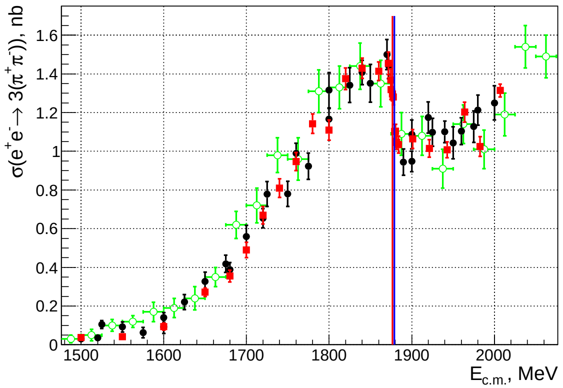
Cross sections of $e^+e^- \to$ hadrons as an input for the $(g-2)_\mu$ problem

Dynamics of multihadronic production of mesons

ρ, ω, ϕ and their excitations

Cross sections near the $N\overline{N}$ threshold

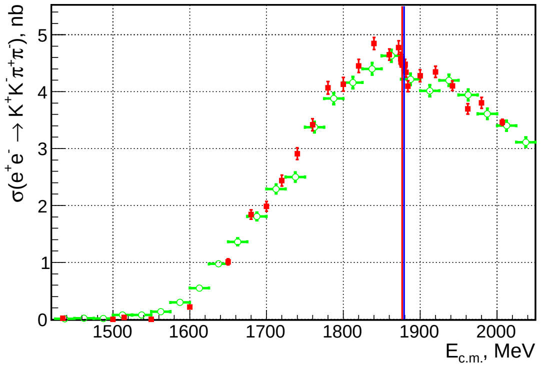
e^+e^- Colliders – II



CMD-3 - new

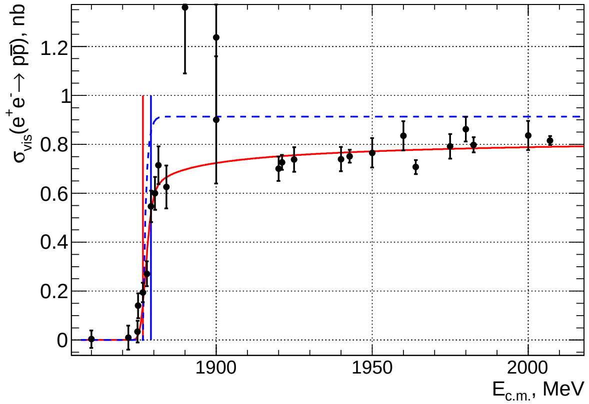
CMD-3 - old

BaBar



CMD-3 - new

BaBar



CMD-3

Strong interaction of nucleons in the Paris potential convolved with c.m. energy spread of 0.95 MeV and radiative corrections explains all σ's

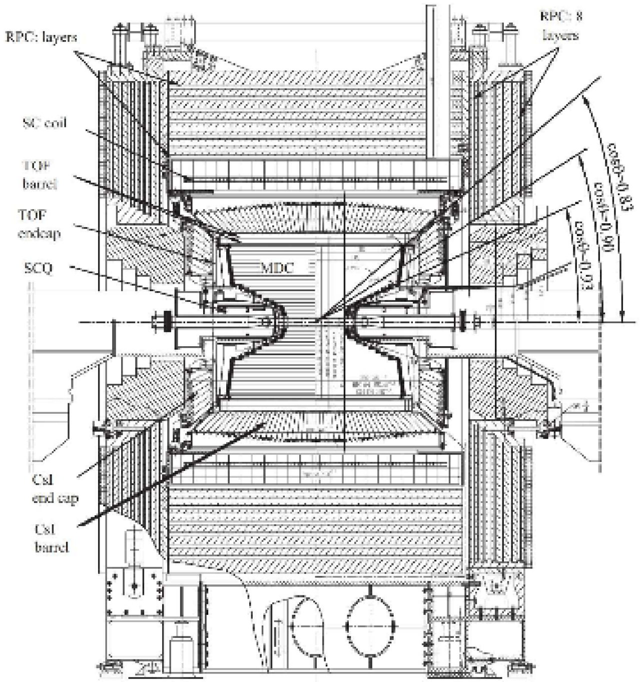
A.I. Milstein and S.G. Salnikov, Nucl. Phys. A977, 60 (2018)

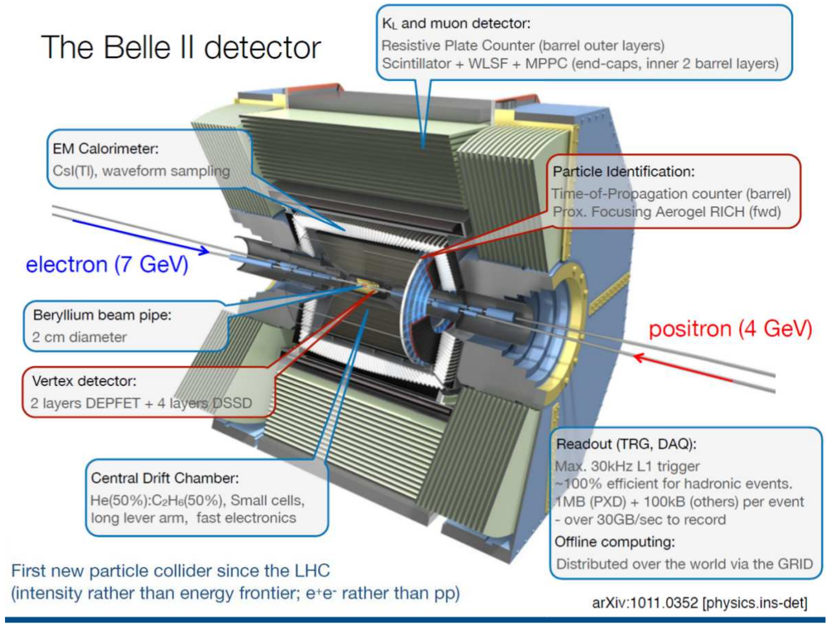
R.R. Akhmetshin et al., Phys. Lett. B794, 64 (2019)

Is the effect $\propto \mathcal{B}$ in $p\bar{p}$ annihilation?

The effect of strong interaction of $N\overline{N}$ near threshold is common for e^+e^-, J/ψ, D and B decays

e^+e^- Colliders – III



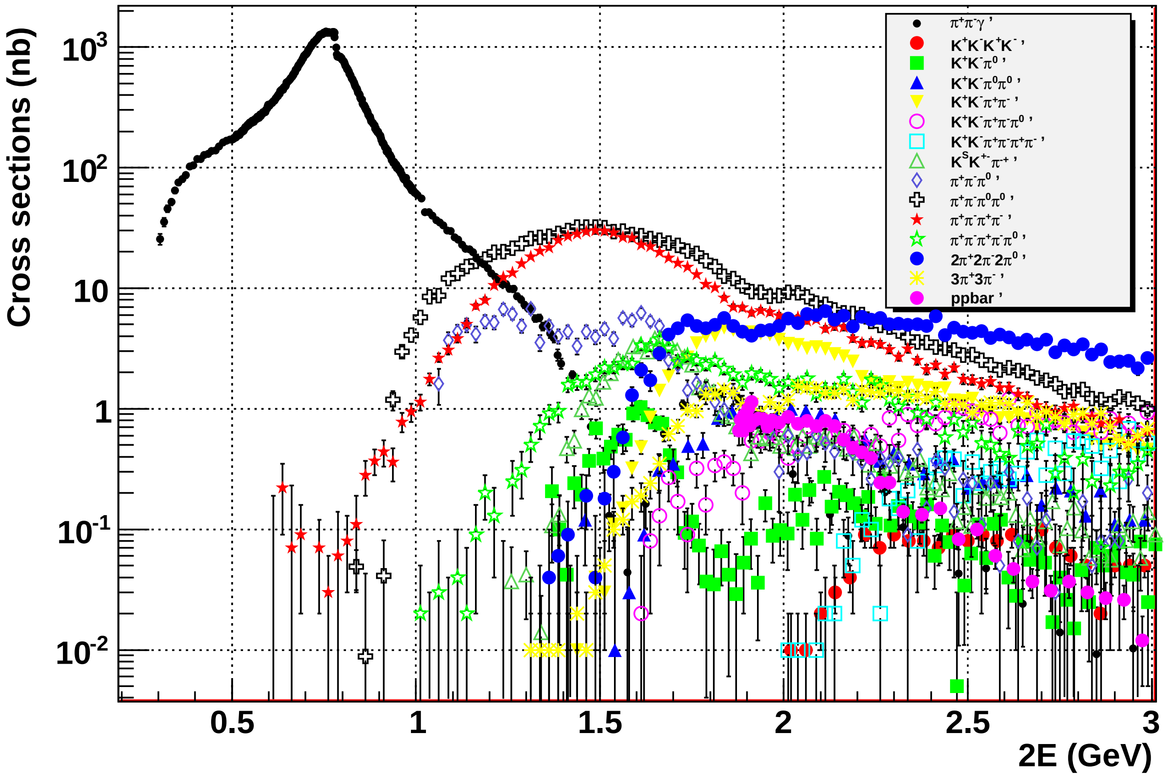


BESIII Detector

The c.m.energy range: 2-4.6(4.9) for BESIII, 9-11.02 (?) for BelleII

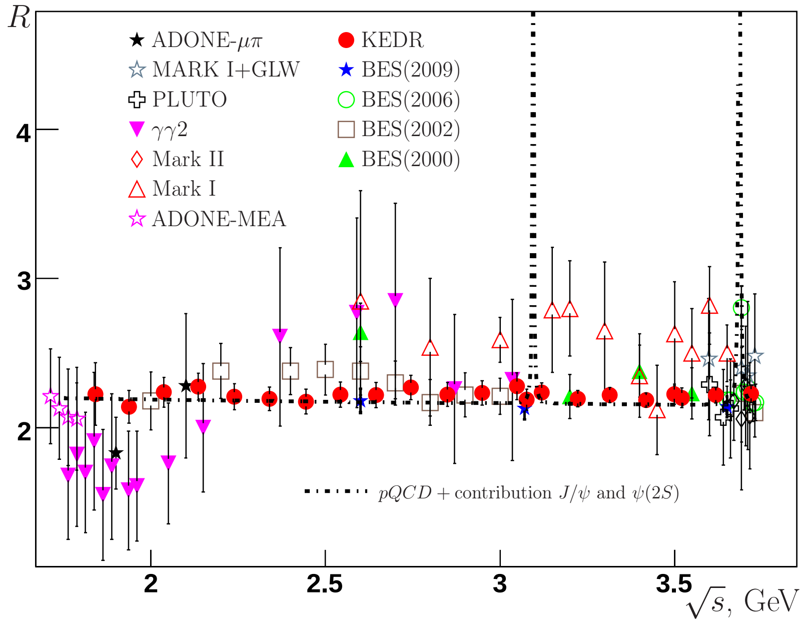
Study of dynamics in multihadronic processes using ISR, vector meson decays in the ψ and Υ families, baryons of light quarks, some baryons with charm

e^+e^- Colliders – IV



BelleII and BESIII will strogly improve the BaBar measurements

e^+e^- Colliders – V (R measurement at KEDR)



1.84-3.05 GeV $R = 2.225 \pm 0.020 \pm 0.047$ ($R_{\rm pQCD} = 2.18 \pm 0.02$)

V.V. Anashin et al., Phys. Lett. B770, 174 (2017)

3.05-3.72 GeV $R_{\rm uds} = 2.204 \pm 0.013 \pm 0.030$ ($R_{\rm pQCD} = 2.16 \pm 0.01$)

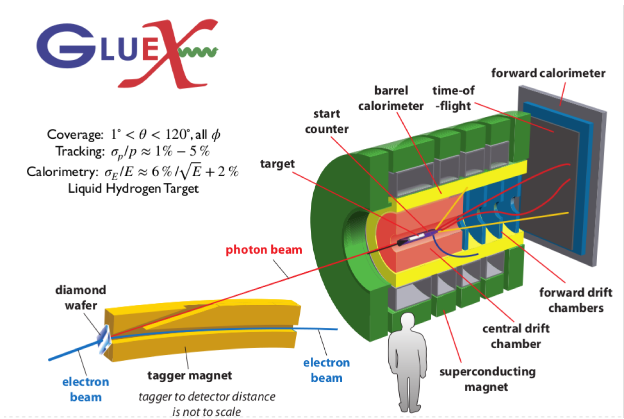
V.V. Anashin et al., Phys. Lett. B753, 533 (2016); B788, 42 (2019)

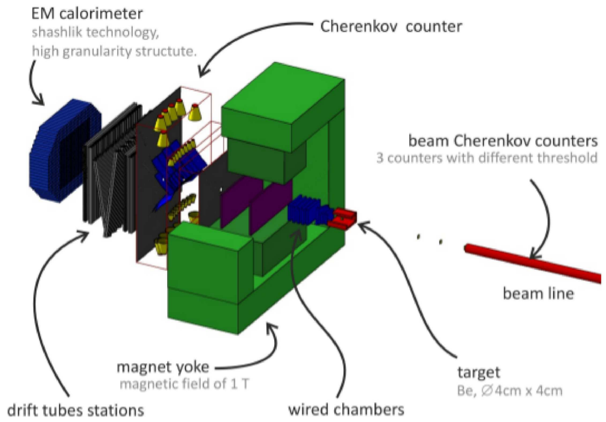
Total (syst. error) 3.9% (2.4%) at low, 2.6% (1.9%) at high $\sqrt{s}$

R measurement from 5 to 7 GeV in progress

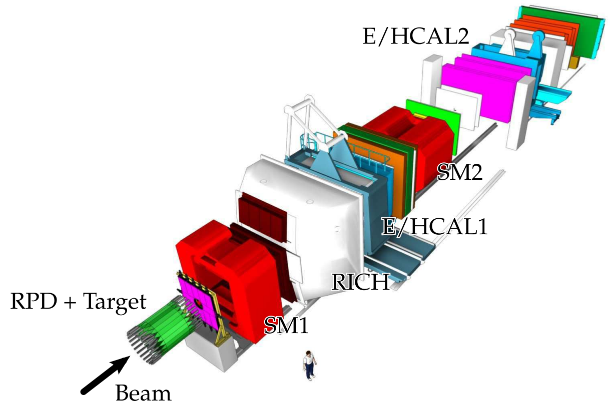
Confirmation by BESIII awaited impatiently

Lepto- and Hadroproduction





VES



COMPASS

τ lepton as a Source of Resonances

- A pure laboratory to test Standard Model
- All three basic interactions are probed:
  electromagnetic production in $e^+e^- \to \tau^+\tau^-$, weak decay,
  strong form factors in hadronic decays
- Low decay multiplicity $\Rightarrow$ smaller combinatorial BG
- Each hadronic decay is saturated by a single resonance:
  $2\pi,\ 4\pi,\ \eta\pi\pi - \rho + \rho' + \ldots$, $3\pi - a_1(1260) + a_1'$ etc.
- At $\Upsilon(4S)$ $\sigma(e^+e^- \to \tau^+\tau^-) \approx$0.9 nb, so 1 ab^{-1} gives $\approx 10^9$ $\tau^+\tau^-$ pairs
- BelleII will collect a data sample
  3 orders of magnitude higher than CLEO

τ Decay to Three Pions and $a_1(1260)$

- Current values of mass and width show a high scatter of values caused by different parameterizations
- Determination of decay dynamics ($\rho\pi$, $\sigma\pi$, KK^*, $\ldots$)
- More light on $a_1(1420)$ and possible a_1' at 1640 MeV

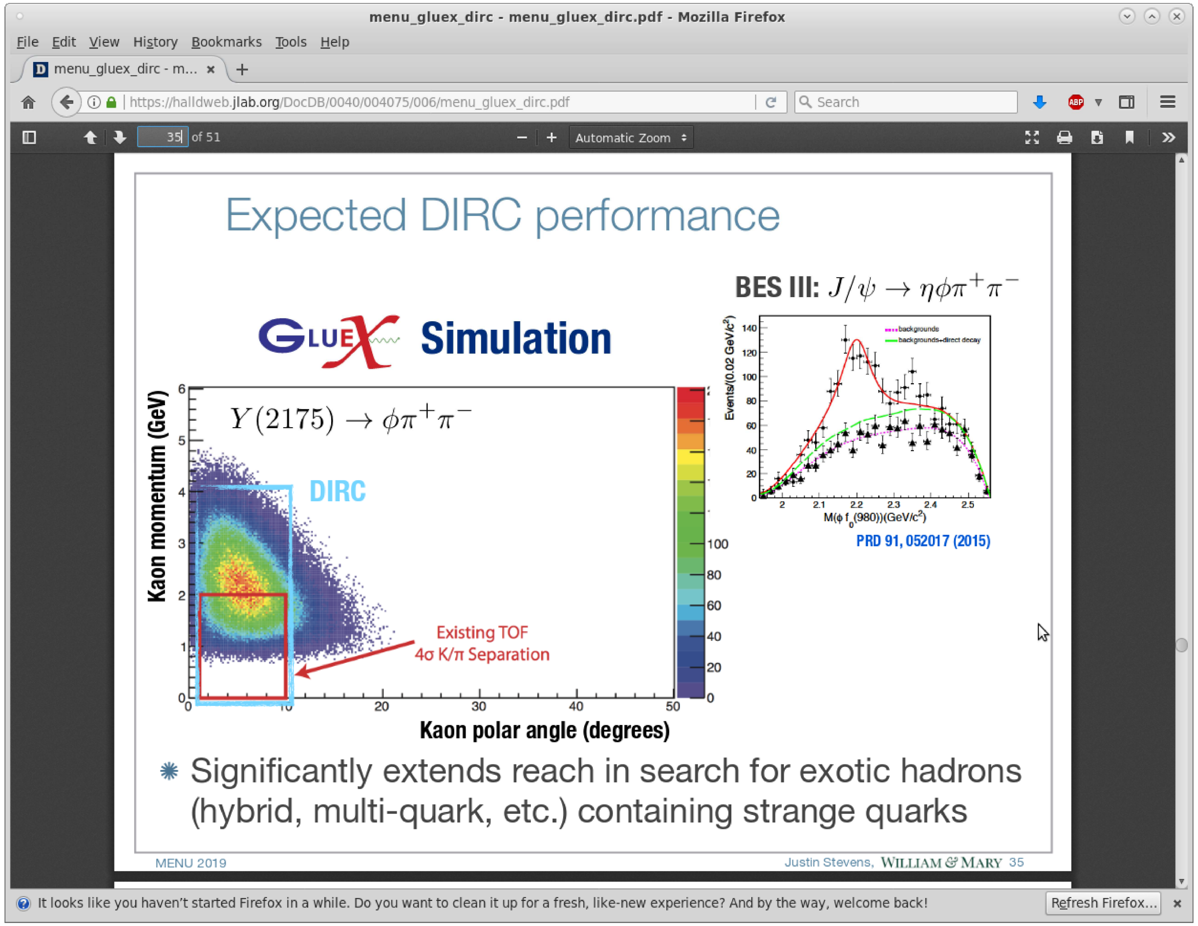
$\pi_1(1600)$, $\eta\pi$, $\eta'\pi$

- Only single 1^{-+}-wave pole required to describe peaks at 1.4 and 1.6 GeV/c^2
  - $m_0 = (1564 \pm 24_{\text{stat.}} \pm 86_{\text{sys.}})$ MeV/c^2
  - $\Gamma_0 = (492 \pm 54_{\text{stat.}} \pm 102_{\text{sys.}})$ MeV/c^2
  - Consistent with $\pi_1(1600)$
  - First measurement of pole parameters of $\pi_1(1600)$
- Raises doubts about existence of $\pi_1(1400)$

Rodas et al., Phys.Rev.Lett. 122, 042002 (2013)

What can be learned about the $\eta\pi$ and $\eta'\pi$ systems from the combined analysis of the $\eta(\eta')\pi^+\pi^-$ system in e^+e^- (CMD-3, SND, BESIII), photoproduction (GlueX) and τ decays (BelleII)?

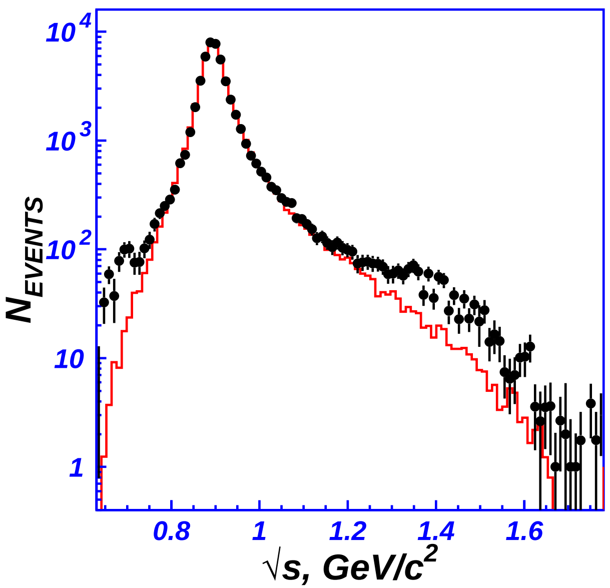
Vectors

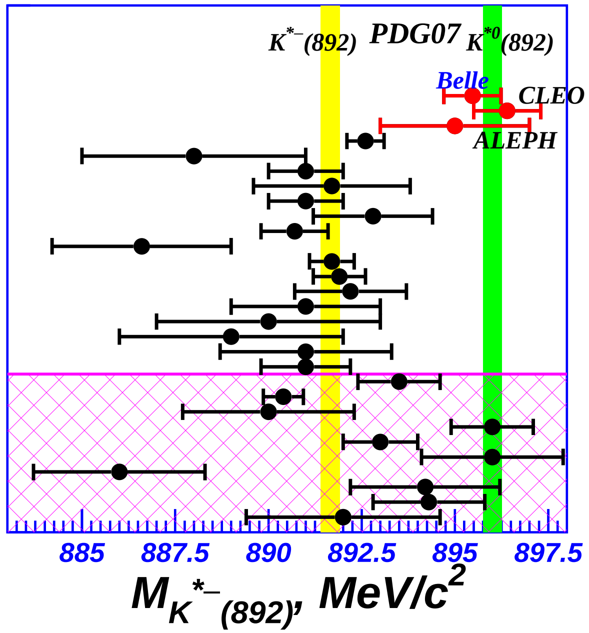


Properties of excited vector mesons (ρ', ω', ϕ') are known badly

Strong evidence for the ρ' at 2.2 GeV, Is $\phi(2170)$ normal? ω'

$K_S\pi$ Mass Spectrum at Belle





The $M_{K\pi}$ spectrum is well described by
the $K^*(892)$, $K_0^*(700)$ (κ) and $K_0^*(1430)$ (or $K^*(1410)$)

$$M(K^*(892)^-) = (895.47 \pm 0.20 \pm 0.44 \pm 0.59)\ \mathrm{MeV}$$

$$\Gamma(K^*(892)^-) = (46.2 \pm 0.6 \pm 1.0 \pm 0.7)\ \mathrm{MeV}$$

Are masses of $K^{*\pm}$ and K^{*0} different?

D. Epifanov et al., Phys. Lett. B 654, 65 (2007)

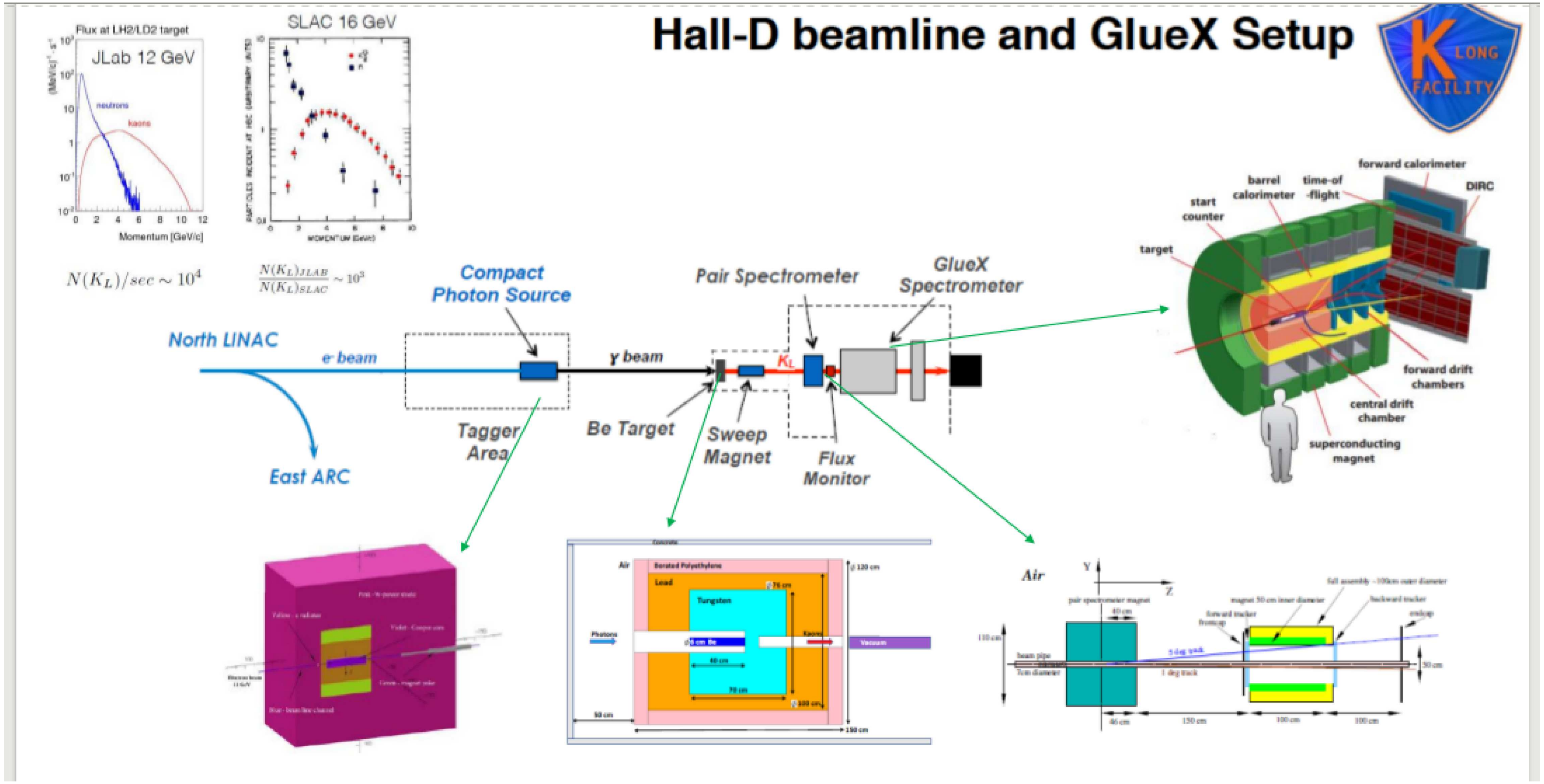
Spectroscopy of K^*'s

About 3.5% of τ decays are with kaons

State	J^P	Mass, MeV	Width, MeV	Decays
$K_0^*(700)(\kappa)$	0^+	824 ± 30	470 ± 50	$K\pi$
$K^*(892)$	1^-	891.66 ± 0.26	50.8 ± 0.9	$K\pi$
$K_1(1270)$	1^+	1272 ± 7	90 ± 20	$K\pi\pi$
$K_1(1400)$	1^+	1403 ± 7	174 ± 13	$K\pi\pi$
$K^*(1410)$	1^-	1414 ± 15	232 ± 21	$K\pi\pi,\ K\pi$
$K_0^*(1430)$	0^+	1425 ± 50	270 ± 80	$K\pi$
$K_2^*(1430)$	2^+	1425.6 ± 1.5	98.5 ± 2.9	$K\pi,\ K\pi\pi$
$K(1460)$	2^+	$1482.40 \pm 3.58 \pm 15.22$	$335.60 \pm 6.20 \pm 8.65$	$K^*\pi,\ K\rho$
$K_2(1580)$	2^-	≈ 1580	≈ 110	$K^*\pi,\ K_2^*(1430)\pi$
$K_1(1650)$	1^+	1650 ± 50	150 ± 50	$K\phi$
$K^*(1680)$	1^-	1718 ± 18	322 ± 110	$K\pi,\ K\rho,\ K^*\pi$

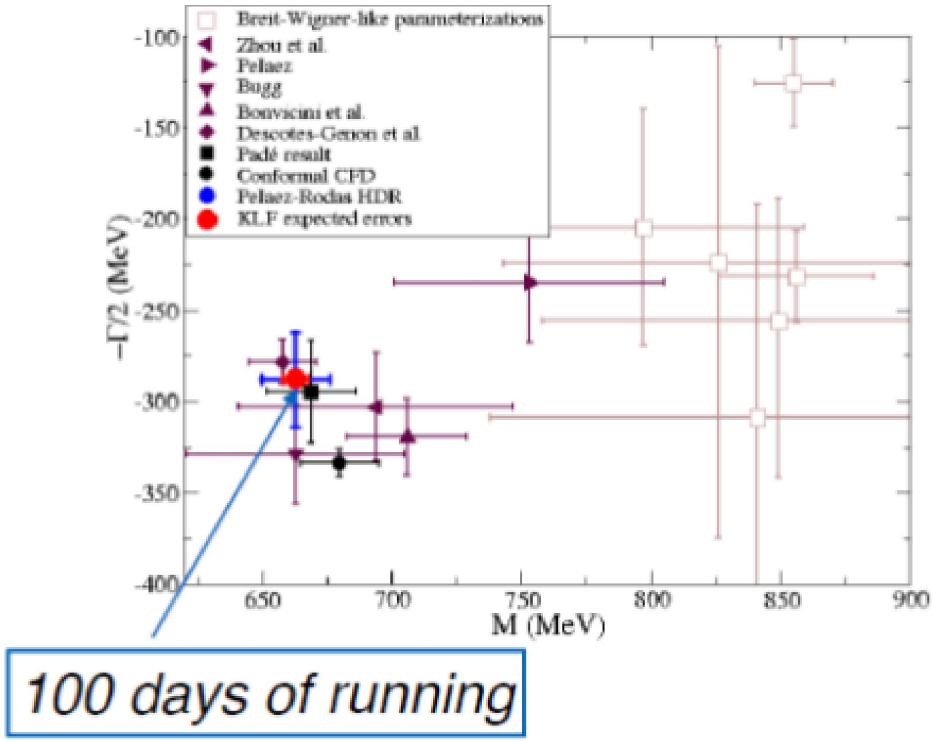
12 more resonances from 1780 to 3100 MeV are badly studied

K_L^0 Factory (KLF) at JLAB



κ properties at KLF

Mass and width of the $K_0^*(700)$ (κ)



Measurement with KLF will reduce:

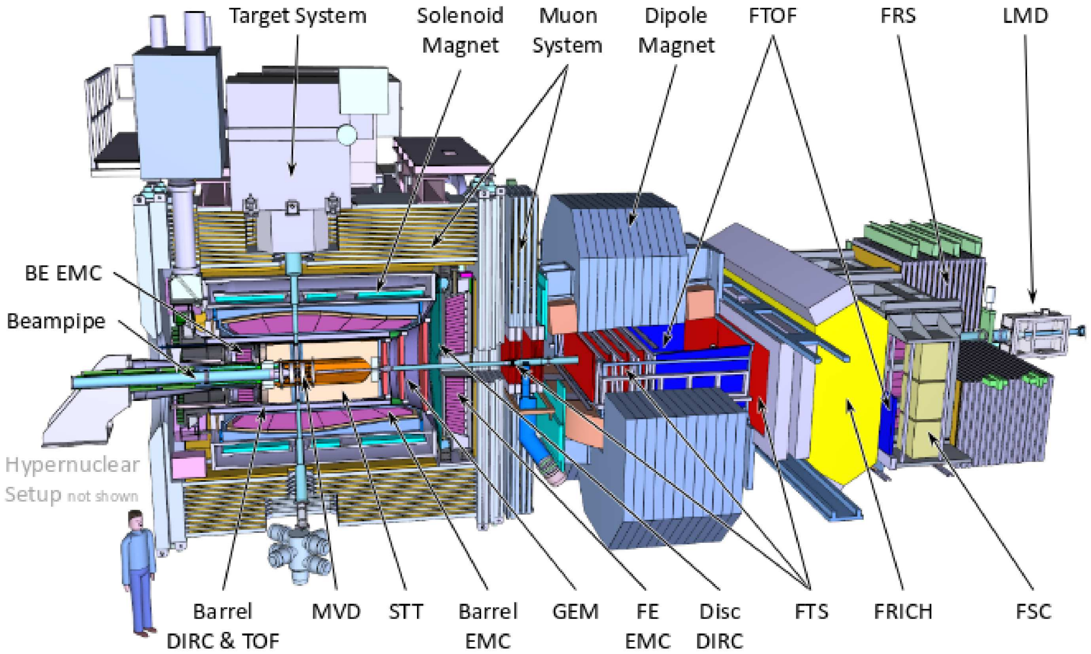
Uncertainty in the mass by a factor of two!

Uncertainty in the width by a factor of five!

Hadrons with Heavy Quarks

Main Players

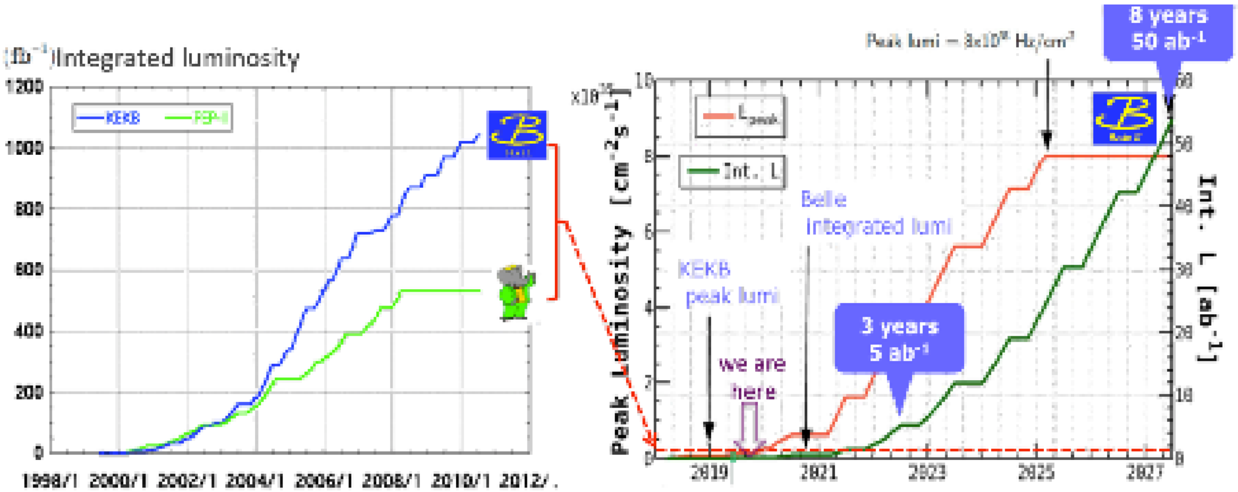
In addition to BESIII, Belle/BelleII, LHCb, ATLAS and CMS, there are also Super-c-τ factories and PANDA



$p\bar{p} \to c\bar{c}$ has high potential (all J^P accessible)

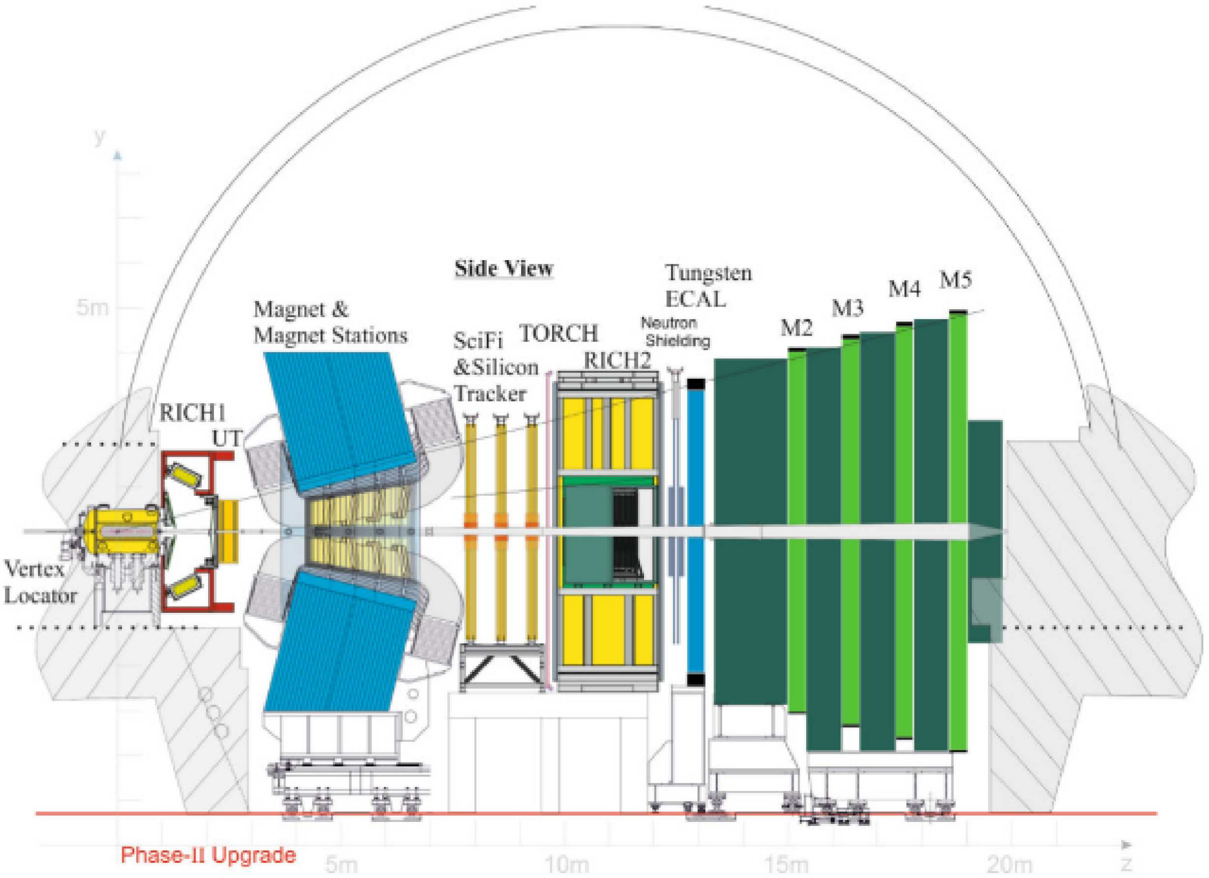
Two difficulties – one should know the precise mass of a narrow state, and PANDA can start too late (close to 2030?) after BelleII and LHCb

From Belle to BelleII

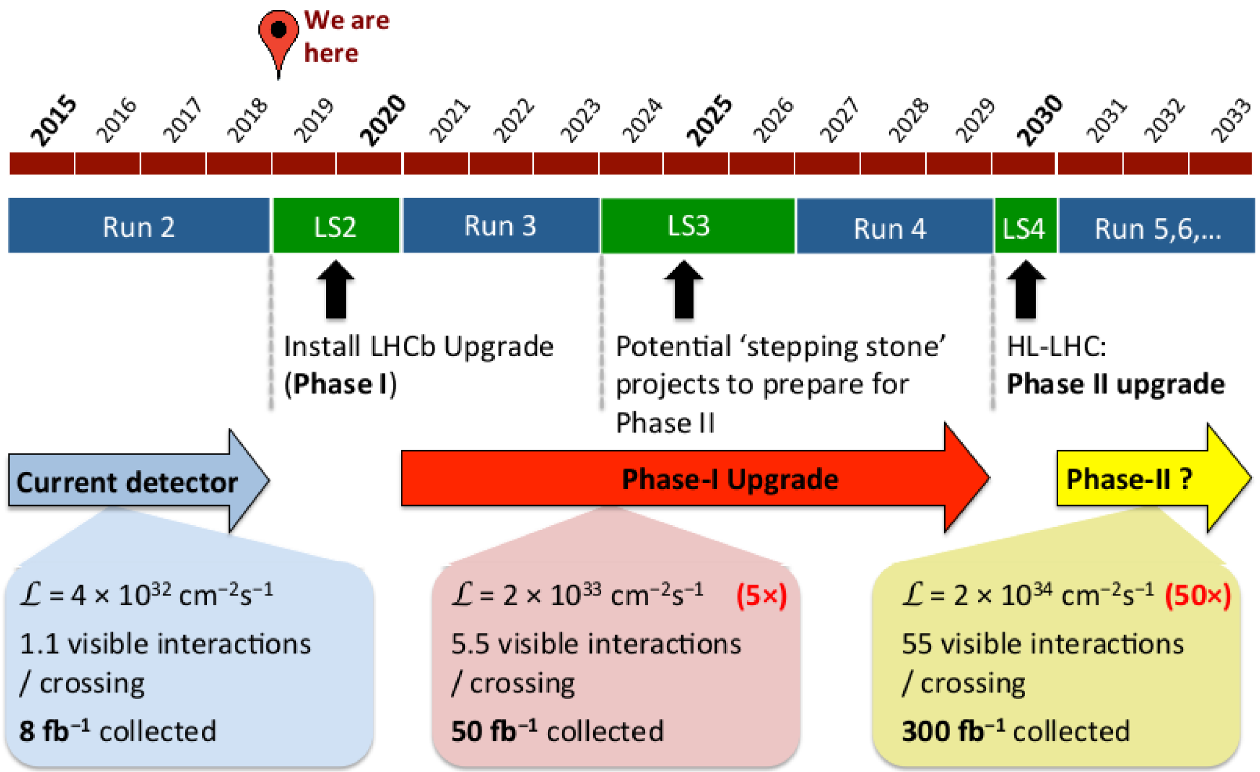


Analyses of the first data are in progress,
the first paper on luminosity measurement will be soon submitted to CPC

LHCb upgrade - I



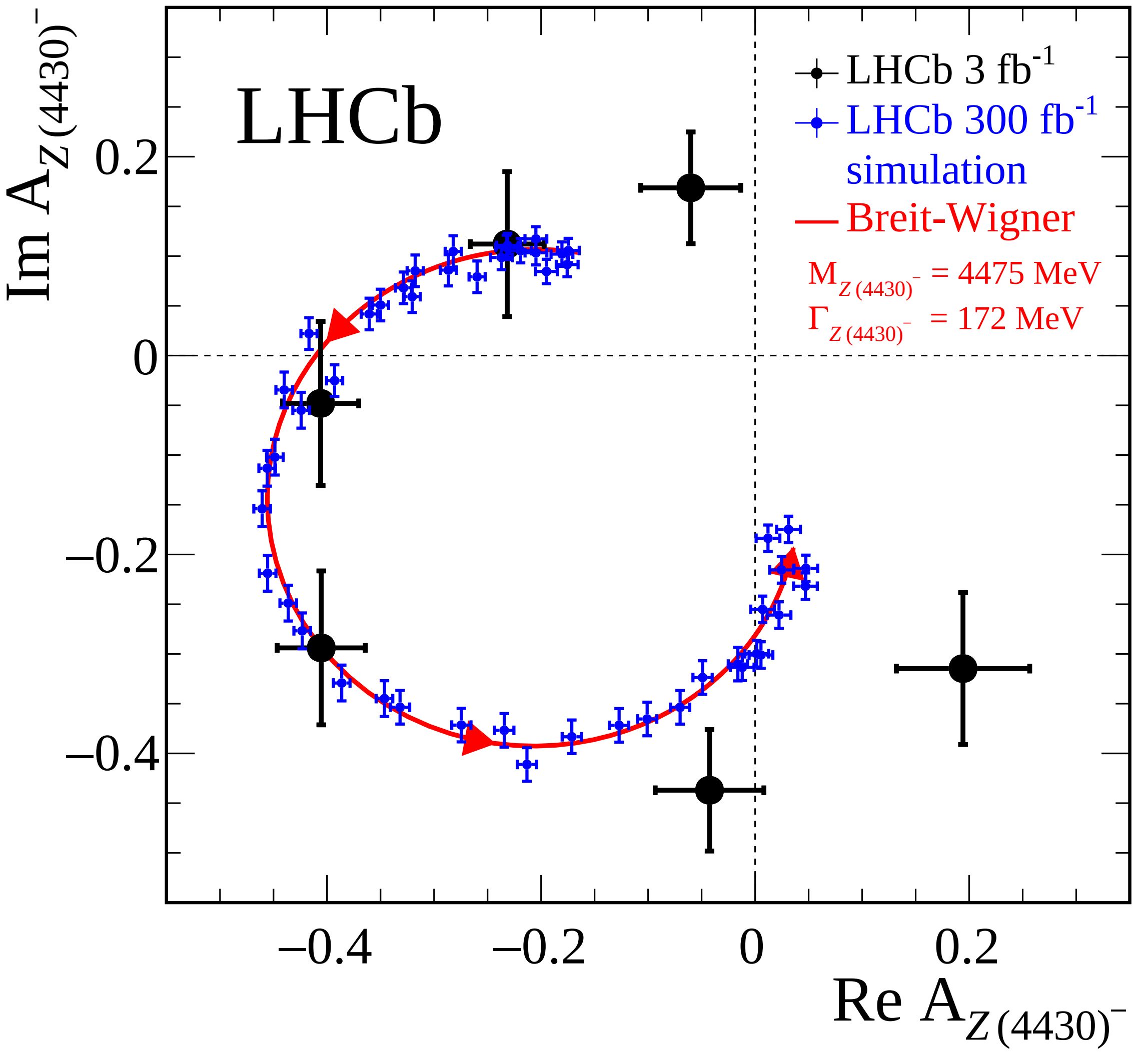
LHCb upgrade - II



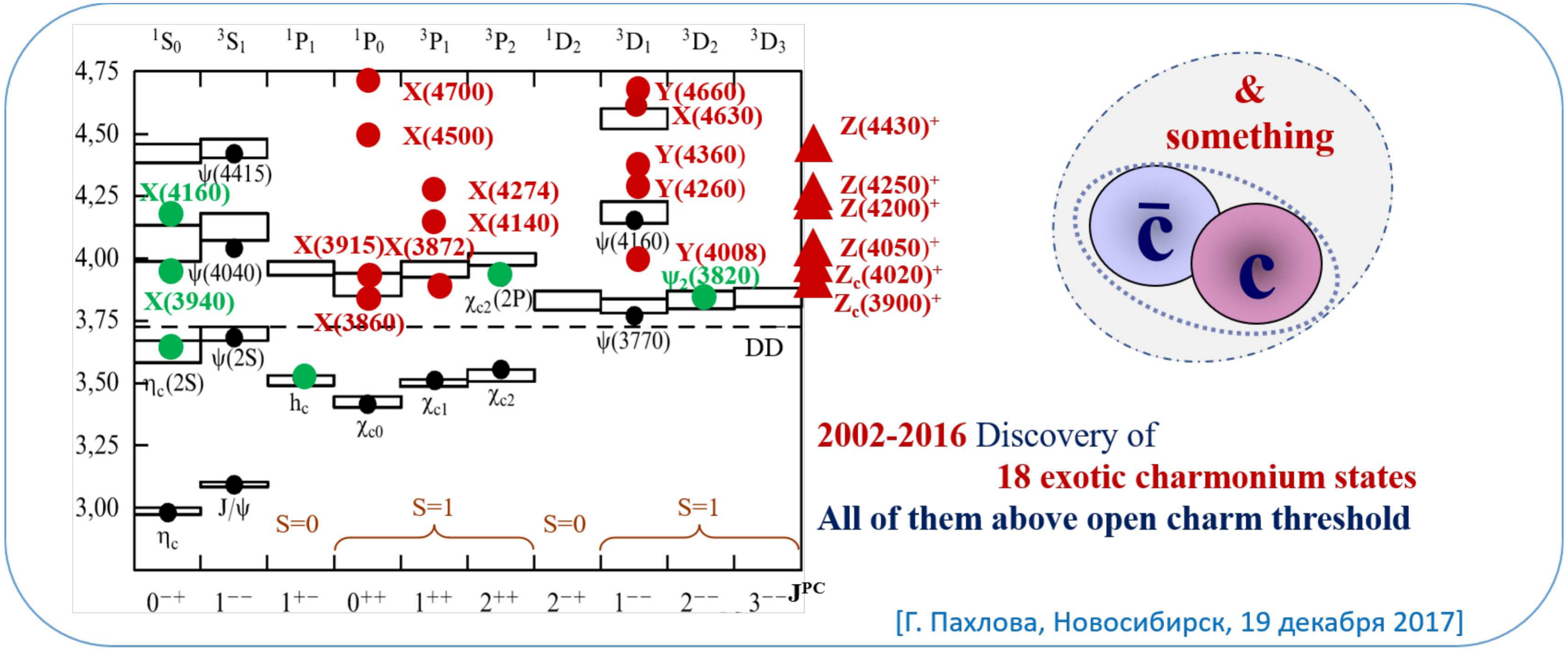
LHCb upgrade - III

Decay mode	LHCb 23 fb^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}
$B^+ \to X(3872)(\to J/\psi\,\pi^+\pi^-)K^+$	14k	30k	180k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100
$\Lambda_b^0 \to J/\psi\, pK^-$ [*]	680k	1.4M	8M
$\Xi_b^- \to J/\psi\,\Lambda K^-$	4k	10k	55k
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k
$\Xi_{bc}^+ \to J/\psi\,\Xi_c^+$	50	100	600

LHCb upgrade - IV



Study of Charmonium-(like) States – I



Dots – good old guys, Dots – new states matching Quark Model

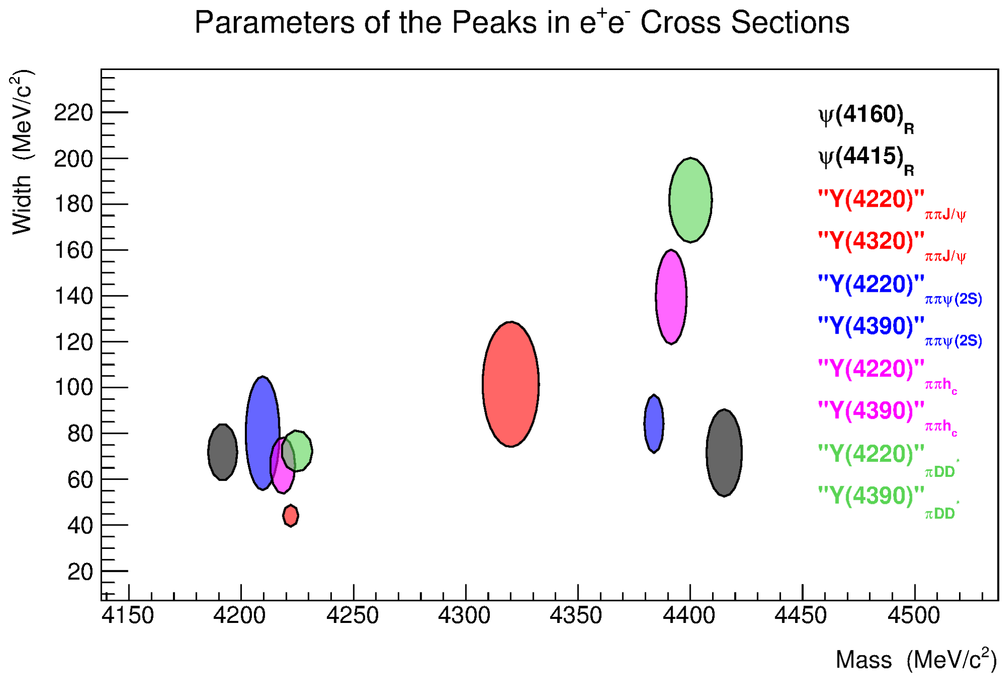
Dots – neutral, triangles – charged states, exotic?

Rectangulars – potential model predictions

Exotic because of the too large number of states with given $I^G J^{PC}$

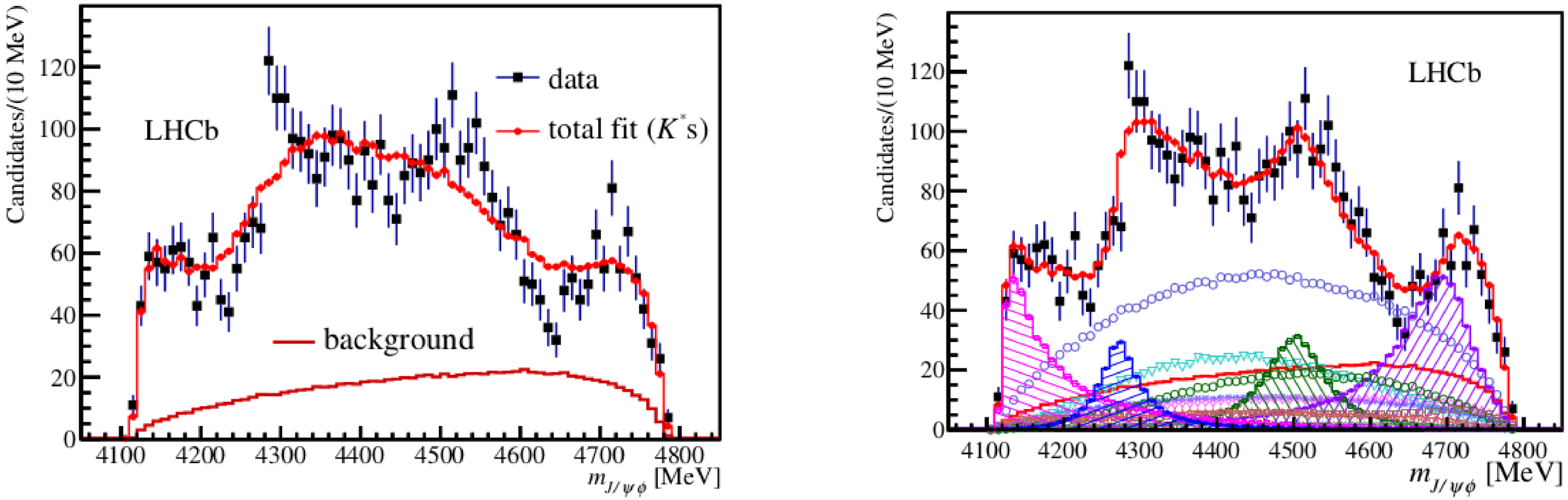
or unexpected decay pattern ($J/\psi\pi^+\pi^-$ instead of open charm)

Study of Charmonium-(like) States – II



Huge data samples needed to perform a coupled-channel analysis resulting in a consistent set of resonance parameters

LHCb – $J/\psi\phi$ system



From a controversial $Y(4140)$ of CDF to

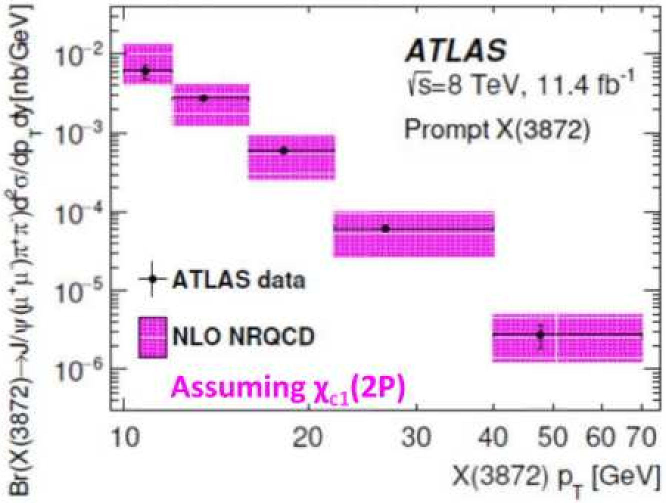
$\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c0}(4500)$, $\chi_{c0}(4700)$ of LHCb

Once again about importance of full amplitude analysis!

R. Aaij et al., Phys.Rev.Lett. 118, 022003 (2017)

$X(3872)$ Production at ATLAS

Cross section of prompt X(3872) in pp-collision (LHC experiment)



(JHEP01(2017)117)

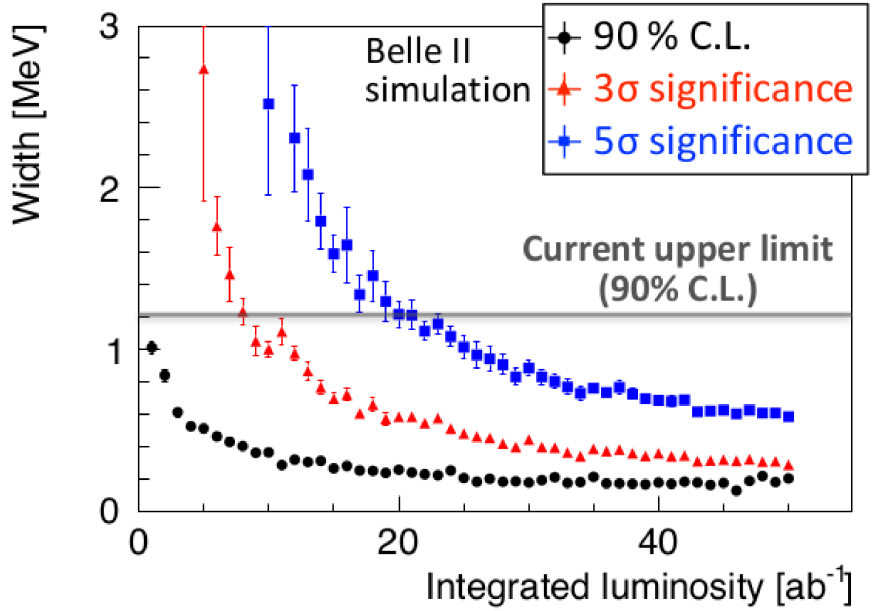
Inconsistent with pure molecular interpretation

- Support $D\bar{D}^* - \chi_{c1}(2P)$ mixture state.

  → Need further information about production and decay
- Current X(3872) total width:

$$\Gamma_{\rm tot} < 1.2\ {\rm MeV}$$

Determination of the $X(3872)$ Width at BelleII



With 50 ab^{-1} for $D^0\overline{D}^0\pi^0$ the toy-MC gives for $\Gamma_{\rm tot}$:

UL at 90%CL 180 keV

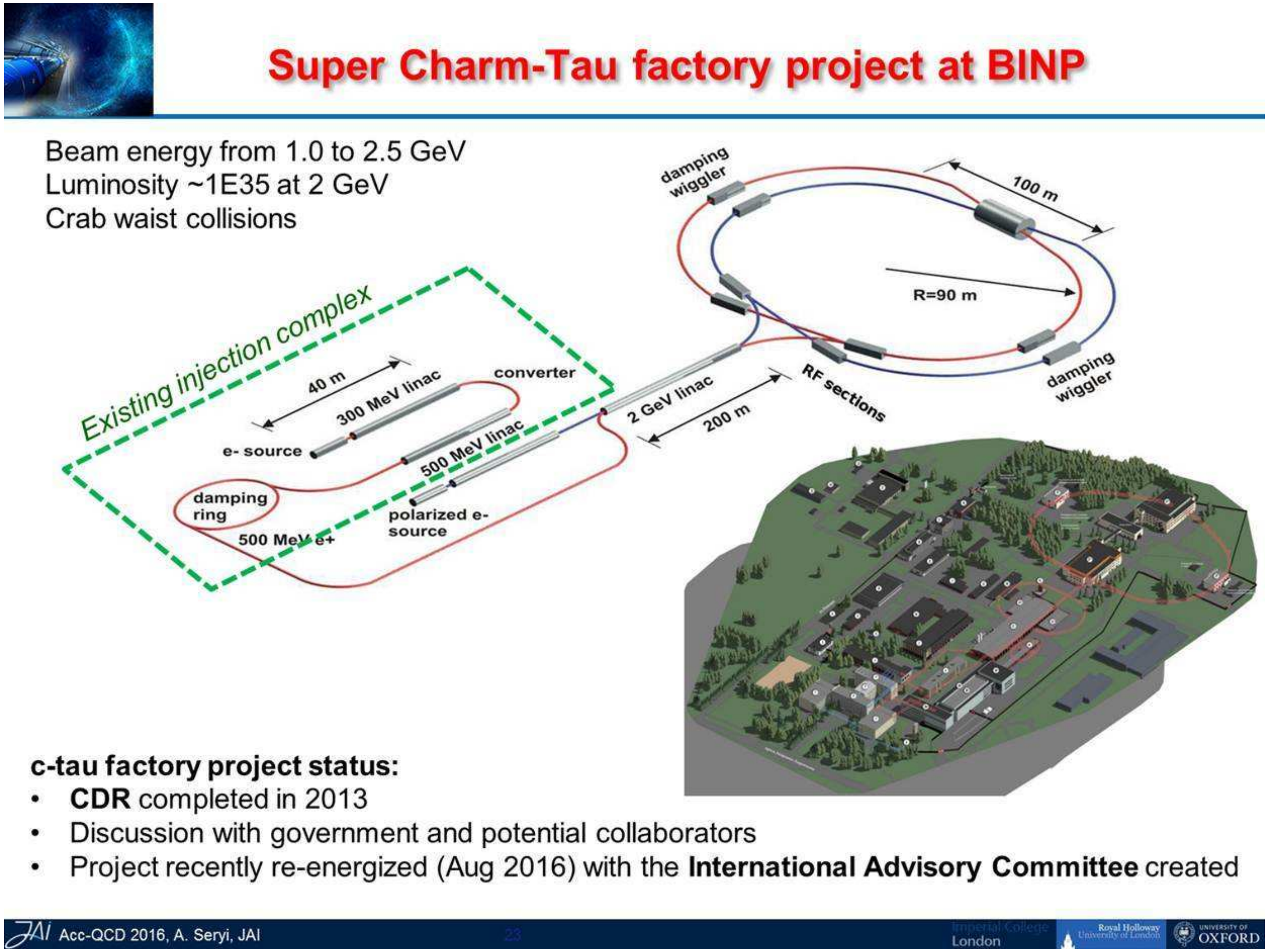
3σ sign. 280 keV

5σ sign. 570 keV

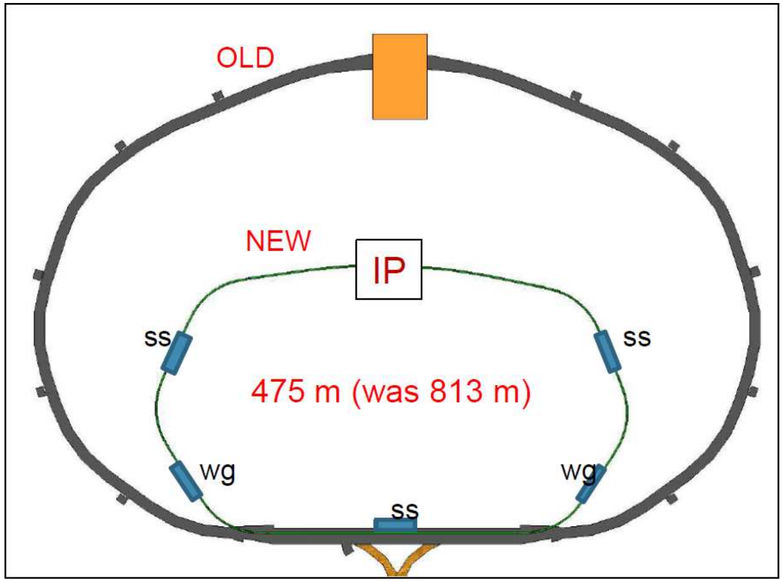
Talk of H. Hirata

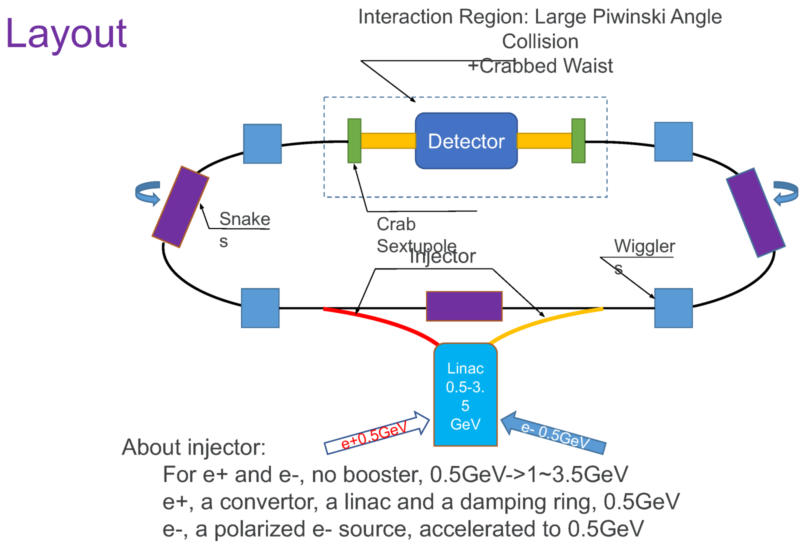
PANDA: $\Gamma/\Delta\Gamma > 5$ at $\Gamma > 50 \ldots 120$ keV

General View of the Novosibirsk c-τ Factory



Two projects of Super-charm-tau factories





Novosibirsk: 2-6 GeV, L from 0.63 (1 GeV) to 1 (4 GeV) $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

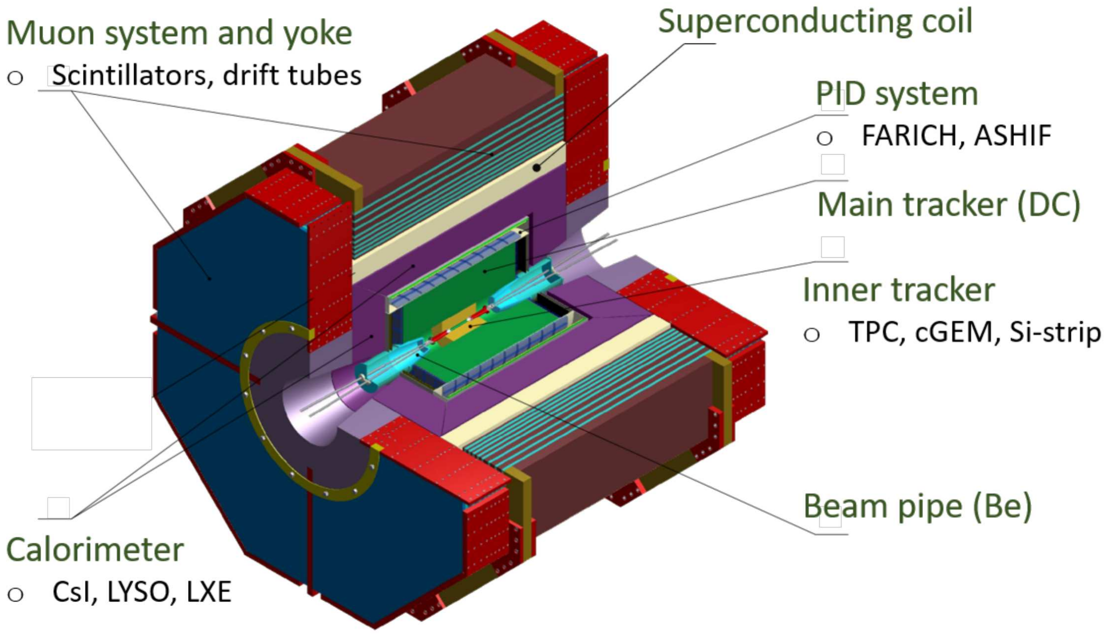
Hefei: 2-7 GeV, L from 0.5 (Phase I) to 1 (Phase II) $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Both have longitudinal polarization of the initial e^- beam

Detector for Novosibirsk SCTF

Counting rate 300 kHz Good energy and momentum resolution

High efficiency for soft tracks Very high identification quality



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 $\psi(2S)$ full decay pattern is unclear
- Is the $\psi(3770)$ a $D\overline{D}$ factory?
- 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
- Although believed to be conventional, these states are not well enough studied

Unconventional charmonia

- All $\psi(Y)$ states with $J^{PC} = 1^{--}$ will be directly produced at $\sqrt{s} = M_Y$: $\psi(4260/4230)$, $\psi(4360)$, $\psi(4660)$
- 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?

Mesons with open flavour

- 12 D^{**} are known
- 9 D_{sJ} are known, what are $D_{s0}^{*}(2317)$ and $D_{s1}(2460)$?
- 6 B^{**} are known
- Only 3 B_{sJ} observed,
  there is also $X(5568)$ decaying to $B_s\pi^{\pm}$ claimed by D0,
  but not seen by ATLAS, CDF, CMS and LHCb

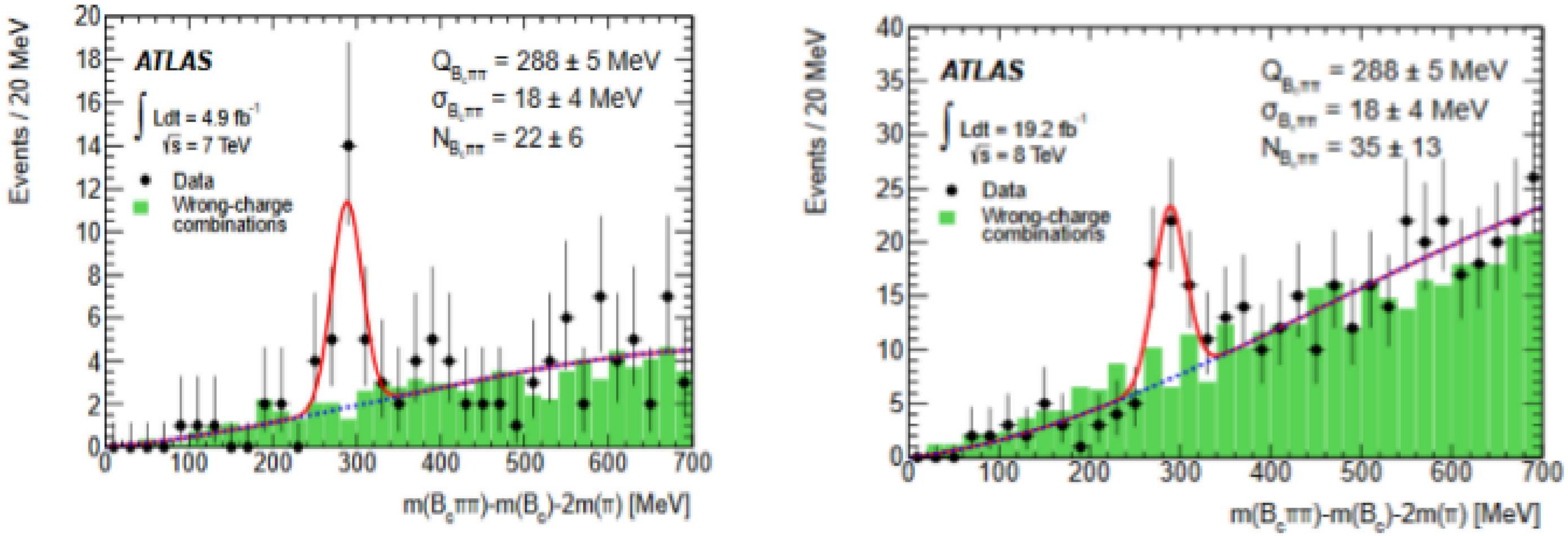
More efforts from both experiment and theory needed

B_c and its Excitations – I

The B_c is well established and its parameters are dominated by LHCb:

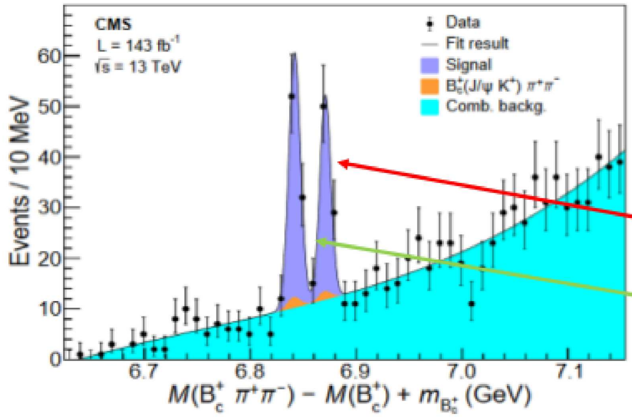
$M = 6274.9 \pm 0.8$ MeV, $\tau = (0.510 \pm 0.009) \times 10^{-12}$s

The $B_c(2S)$ decaying to $B_c\pi^+\pi^-$ is expected to be narrow.
ATLAS claims it at $6842 \pm 4 \pm 5$ MeV



B_c and its Excitations – II

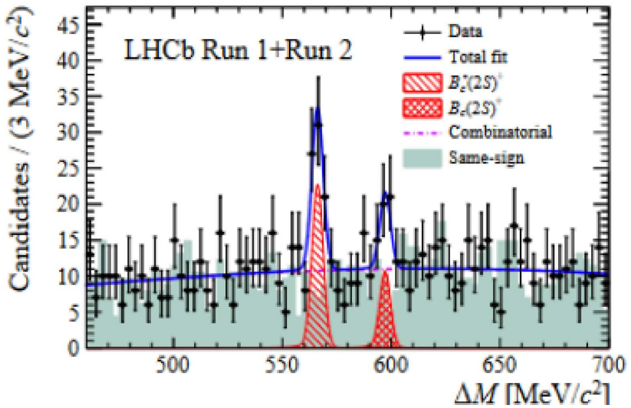
CMS and LHCb have consistent, more precise results at 29 MeV higher mass



CMS Experiment
PRL 122, 132001 (2019)

Thought to be $B_c(2S) \to B_c\pi^+\pi^-$

Thought to be
$B_c^*(2S) \to B_c^*\pi^+\pi^- \to B_c\gamma\pi^+\pi^-$



LHCb Experiment
PRL 122, 232001 (2019)

$M(B_s(2S)) = 6871.0 \pm 1.2 \pm 0.8 \pm 0.8$ MeV/c^2
$29 \pm 1.5 \pm 0.7$ MeV/c^2 CMS

$M(B_s(2S)) = 6871.1 \pm 1.3 \pm 0.1 \pm 0.8$ MeV/c^2
$31.0 \pm 1.4 \pm 0.0$ MeV/c^2 LHCb

LHCb second signal is weak (3.9σ)

It would be interesting to search for $B_c(nP)$ as well as $B_c^* \to B_c\gamma$

The "Last Meson" definitely deserves more attention

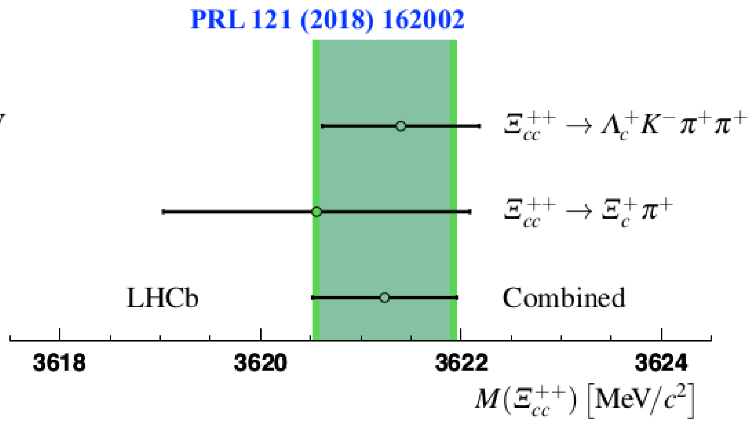
LHCb – doubly charm baryon

- Consistent mass measurements

$3621.40 \pm 0.72 \pm 0.27 \pm 0.14(\Lambda_c^+)$ MeV

$3620.56 \pm 1.5 \pm 0.4 \pm 0.3(\Xi_c^+)$ MeV

$3621.24 \pm 0.65 \pm 0.31$ MeV



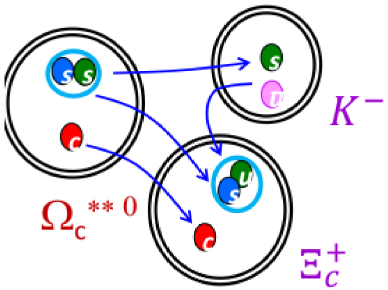
Mass difference: $m(\Xi_{cc}^{++})_{\text{LHCb}} - m(\Xi_{cc}^{+})_{\text{SELEX}} = 103 \pm 2$ MeV

➢ Inconsistent with being isospin partners

- $\tau_{\Xi_{cc}^{++}} = (256^{+24}_{-22} \pm 14)$ fs
- Confirms it is a weakly decaying $J = 1/2$ ground state
- A challenging search for Ξ_{cc}^{+} and Ω_{cc}^{++} in future

Ω_c

For the $\Omega_c(css)$ five narrow states are predicted with mass around 3000 MeV and splittings about 30 MeV, two $1/2^-$, two $3/2^-$ and one $5/2^-$

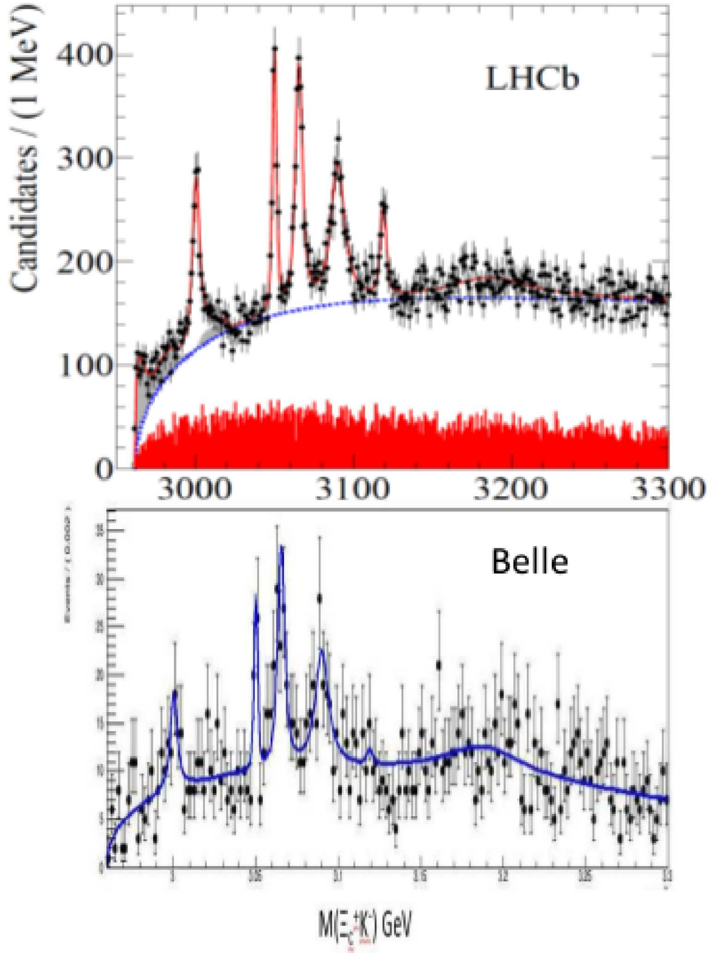


The $s\bar{s}$ diquark is ripped apart and made narrow

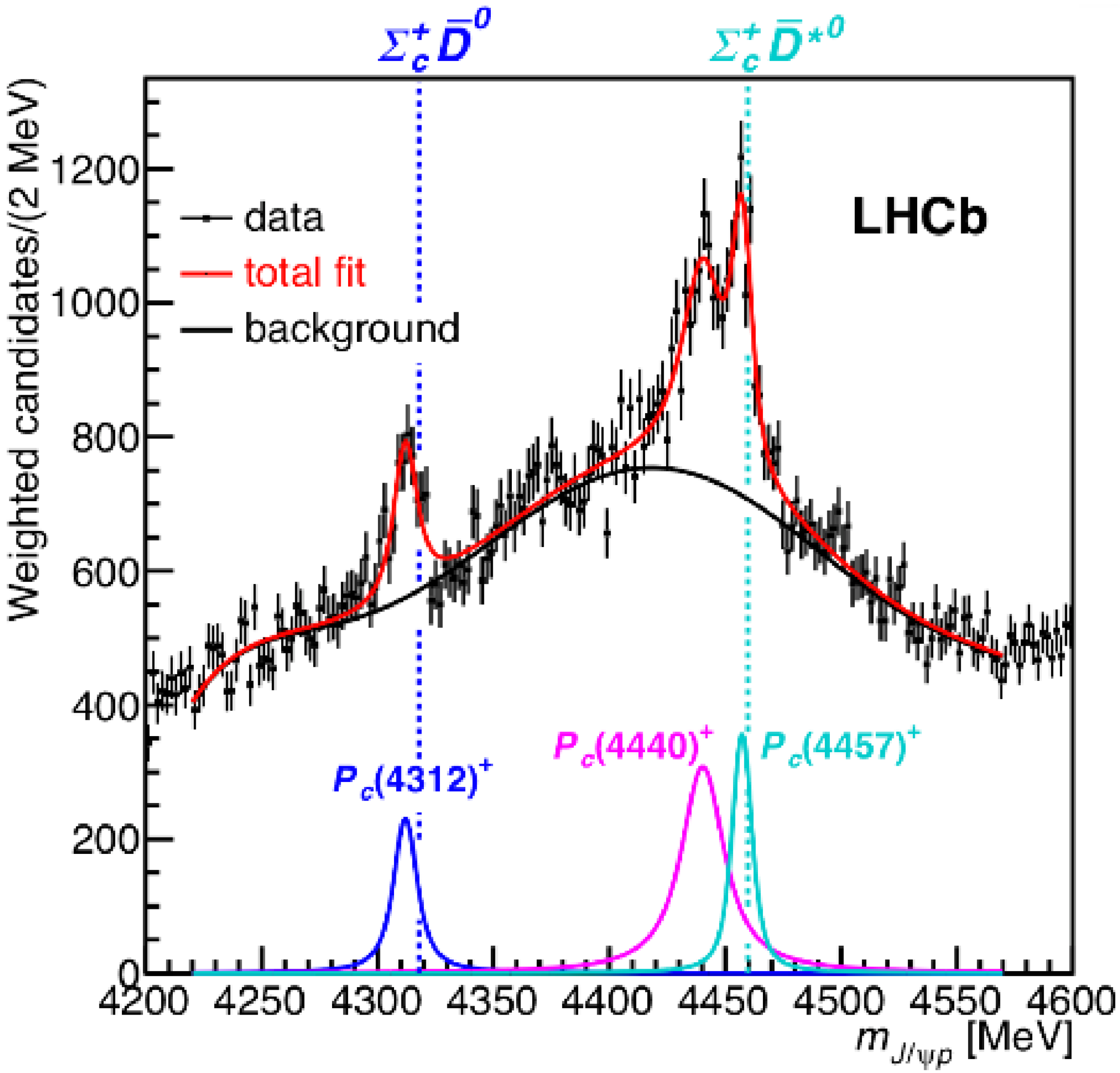
Not clear what is what

LHCb: R. Aaij et al., PRL 118, 182001 (2017)

Belle: J. Yelton et al., Phys. Rev. D97, 051102 (2018)



LHCb – Pentaquarks



R. Aaij et al., Phys.Rev.Lett. 122, 222001 (2019)

Searches for new baryons and maximum BelleII energy

Promising energy regions

Particles	Threshold, GeV/c^2
$B^{(*)}\bar{B}^{**}$	11.00 – 11.07
$B_s^{(*)}\bar{B}_s^{**}$	11.13 – 11.26
$\Lambda_b\,\bar{\Lambda}_b$	11.24
$B^{**}\bar{B}^{**}$	11.44 – 11.49
$B_s^{**}\bar{B}_s^{**}$	11.48 – 11.68
$\Lambda_b\,\bar{\Lambda}_b^{**}$	11.53 – 11.54
$\Sigma_b^{(*)}\,\bar{\Sigma}_b^{(*)}$	11.62 – 11.67
$\Lambda_b^{**}\,\bar{\Lambda}_b^{**}$	11.82 – 11.84

At the moment it is 11.02 GeV or slightly higher

Circular Electron Positron Collider (CEPC)

Unique number of hadrons produced under clean conditions,
a study of various correlations

Operation mode	Z factory	WW threshold	Higgs factory
$\sqrt{s}$ (GeV)	91.2	160	240
Run time (year)	2	1	7
Instantaneous luminosity ($10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	16–32	10	3
Integrated luminosity (ab^{-1})	8–16	2.6	5.6
Higgs boson yield	–	–	10^6
W boson yield	–	10^7	10^8
Z boson yield	10^{11}–10^{12}	10^8	10^8

Lepton Universality – How large is $\mathcal{B}(W^+ \to \tau^+ \nu_\tau)$?

Conclusions

Already now and more in close future there are excellent possibilities to study strong interactions

Complementarity of different approaches, both at the facility and analysis level, is crucial