XYZ states at Belle and Belle II

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EMMI Workshop and International Workshop L
on Gross Properties of Nuclei and Nuclear Excitations:
"Strong interaction physics of heavy flavors"

Hirschegg, 18.01.2024

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Bundesministerium für Bildung und Forschung
ErUM-FSP T09 Belle II
BELLE
Belle II

Outline

- Status of Belle II
- Tetraquark flavor landscape
- X(3872) lineshape
- T_{cc}
- T_{cs}
- Absolute branching fractions

Nomenclature

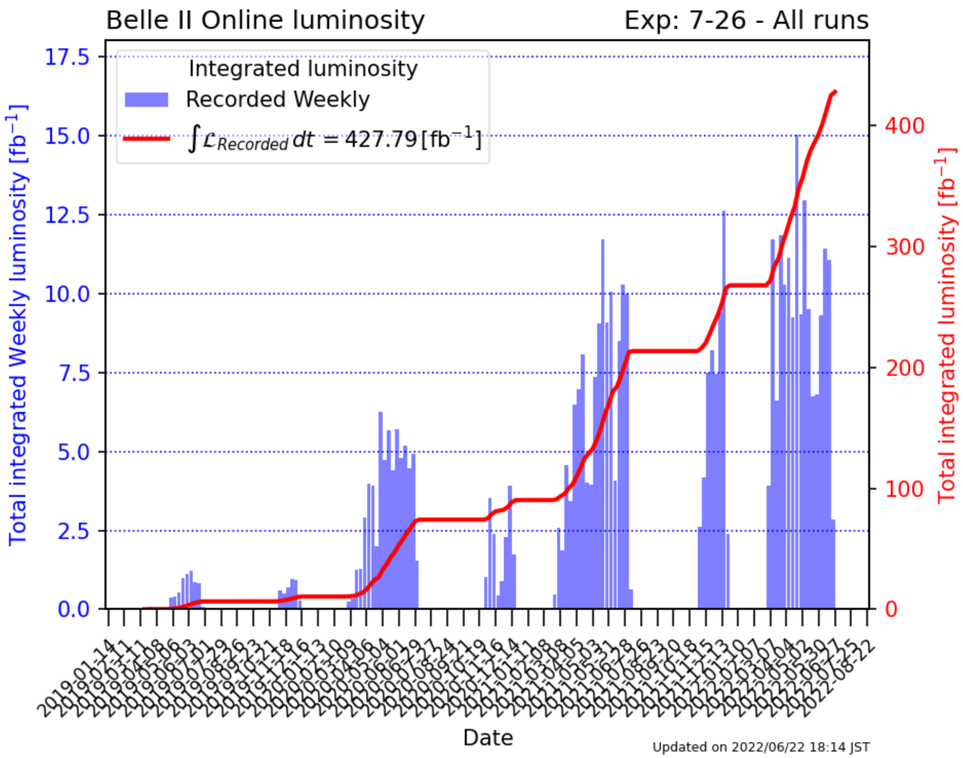
→ X(3872)	(historic)
$\chi_{c1}(3872)$	PDG 2022
although decay to $\chi_{c1}\pi\pi$ not observed	
T_{ψ}^{f}	LHCb proposal (if tetraquark)
→ $T_{c\bar{c}}^{0}$	PDG proposal (if tetraquark)

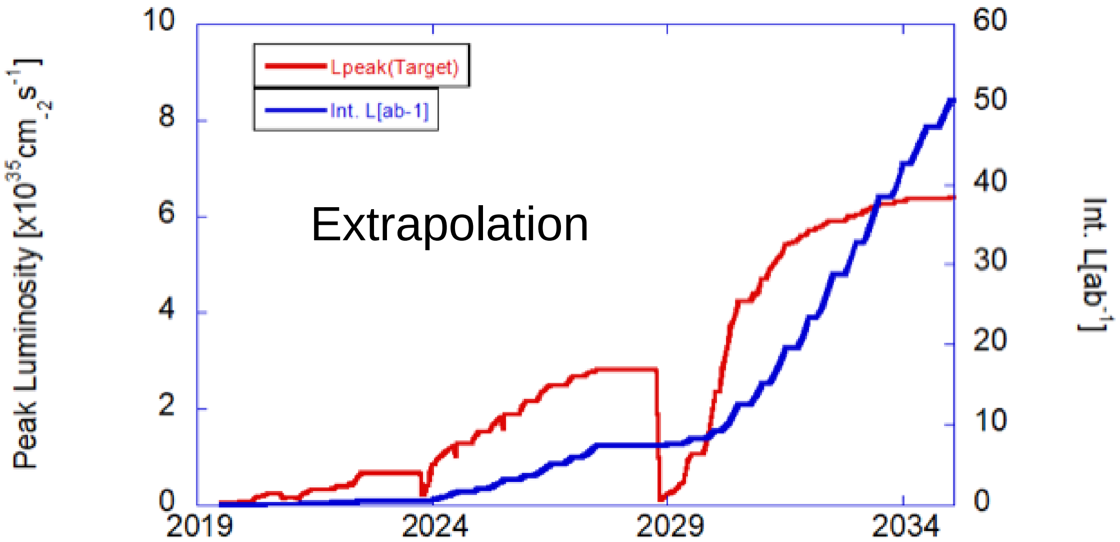
- Focus of this talk:
  - charmonium-like states, in particular in B decays,
  - For bottomonium-like states and $c\bar{c}s\bar{s}$ states, in particular in continuum and initial state radiation (ISR) production, see talk by Elisabetta Prencipe

Status of Belle II

Status and plan of Belle II data taking

- Belle II collected data 428 fb^{-1}
  362 fb^{-1} for B mesons
  (~50% of Belle, ~85% of BaBar)
  1 fb^{-1} is about 1.1 Mill. $B\bar{B}$ pairs
- Peak luminosity reached
  4.7 x 10^{34} cm^{-2} s^{-1}
  - Factor 2+ higher than previous world record by KEKB
  - Factor 4+ higher than KEKB design luminosity
- 89.5% data taking efficiency during pandemic situation
- Long shutdown (LS1) in 2022/23 completed, new pixel detector
- Plan: 50 ab^{-1}





Belle II plan for 2024

- Run stably at 10^{35} cm^{-2} s^{-1}
  (corresponding to ~1 Belle or ~2 BaBar per year)
- Squeeze β_y^* to 0.6 mm
  (still factor 2 higher than design)
- Increase* beam currents x factor 2
  (plus: modified injection,
  new Linac accelerating structures installed)
- Exceed 1 ab^{-1} integrated luminosity
  (2 ab^{-1} Belle and Belle II combined data set would enable new analyses, sensitivity estimates existing)
- 50 ab^{-1} planned by 2035
  (~50 Belle and ~100 BaBar)

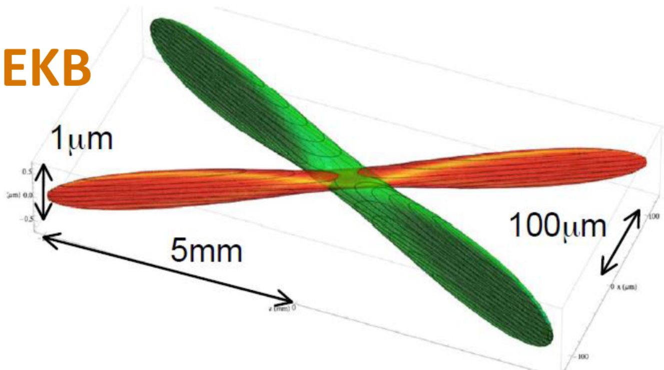
$$\mathcal{L} \sim \frac{I}{\beta_y^*}$$

I beam current
β_y^* vertical β function

Gaussian width of a single beam near the IP

$$\sigma_y \propto \sqrt{\beta_y^*}$$

SuperKEKB

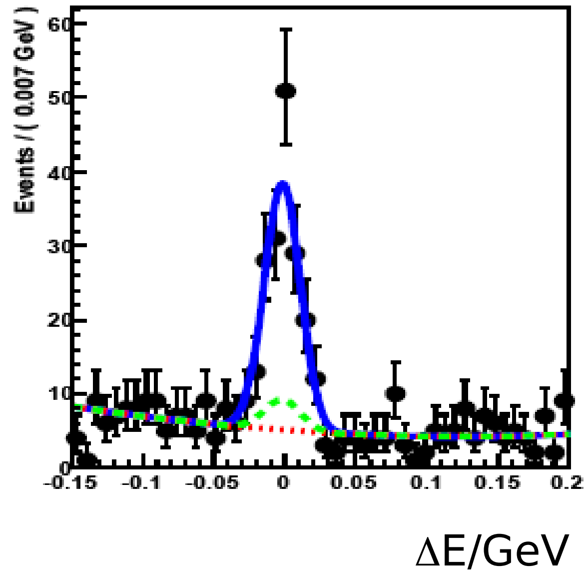


KEKB	100 µm (horizontal) × 2 µm (vertical)
SuperKEKB	10 µm (horizontal) × 59 nm (vertical) NANOBEAM

*Reminder: beam current at both KEKB and SuperKEKB up to now ≥1 A, at PEPII ≥2A

Belle (II) characteristics for XYZ

$$\Delta E \equiv E_B^{\mathrm{cms}} - E_{\mathrm{beam}}^{\mathrm{cms}}$$



Belle, X(3872) in B decays

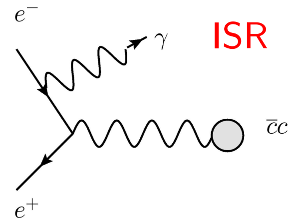
Phys. Rev. D84 (2011) 05200

- Different from hadron collisions:
  - e^+e^- initial state fixed, no pile-up
  - Beam energy is known to precision 0.1 MeV

    beam-constrained variables: B meson mass, ΔE (improve resolution)
  - $\Upsilon(4S) \rightarrow B\bar{B}$

    thus other side B meson can be used (absolute branching fractions can be measured)
- High efficiency for neutral particles

  γ, π^0, η (e.g. $D_{sJ}(2317)$ or neutral Z states for isospin triplets)



- Unique at Belle (II) and BESIII:

  Y states, e.g. Y(4260) in ISR
- Unique at Belle (II):

  $\Upsilon(5S)$ and Z_b states

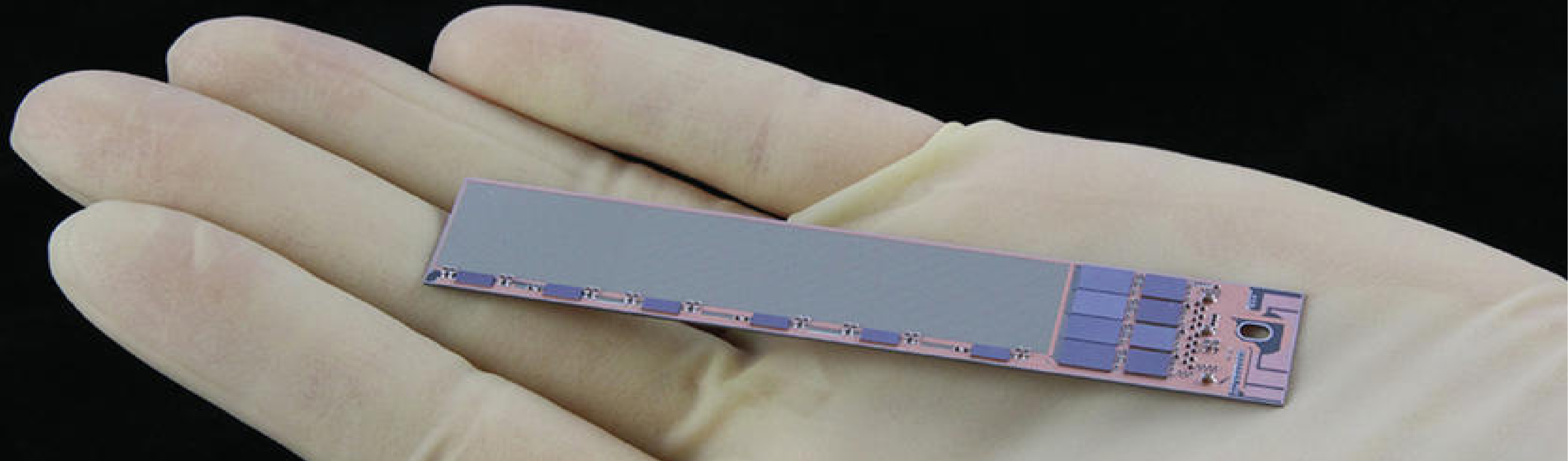
  Z states accessible at threshold and in B decays (far from threshold)

Extrapolated yield for 50 ab^{-1}:

State	Production and decay	N
$X(3872)$	$B \rightarrow KX(3872)$, $X(3872) \rightarrow J/\Psi\pi^+\pi^-$	$\simeq$14.000
$Y(4260)$	ISR, $Y(4260) \rightarrow J/\Psi\pi^+\pi^-$	$\simeq$29.600
$Z(4430)$	$B \rightarrow K^{\mp}Z(4430)$, $Z(4430) \rightarrow J/\Psi\pi^{\pm}$	$\simeq$10.200

Belle II DEPFET Pixel Detector

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



Monolithic type

Radius 1.4, 2.2 cm (very close to interaction point)

Pixel size 50 × (55-85) μm^2

Sensor 75 µm thickness, 0.2% X_0 per 1 layer

Radiation 2 MRad/year (factor ~3 less than at LHC)

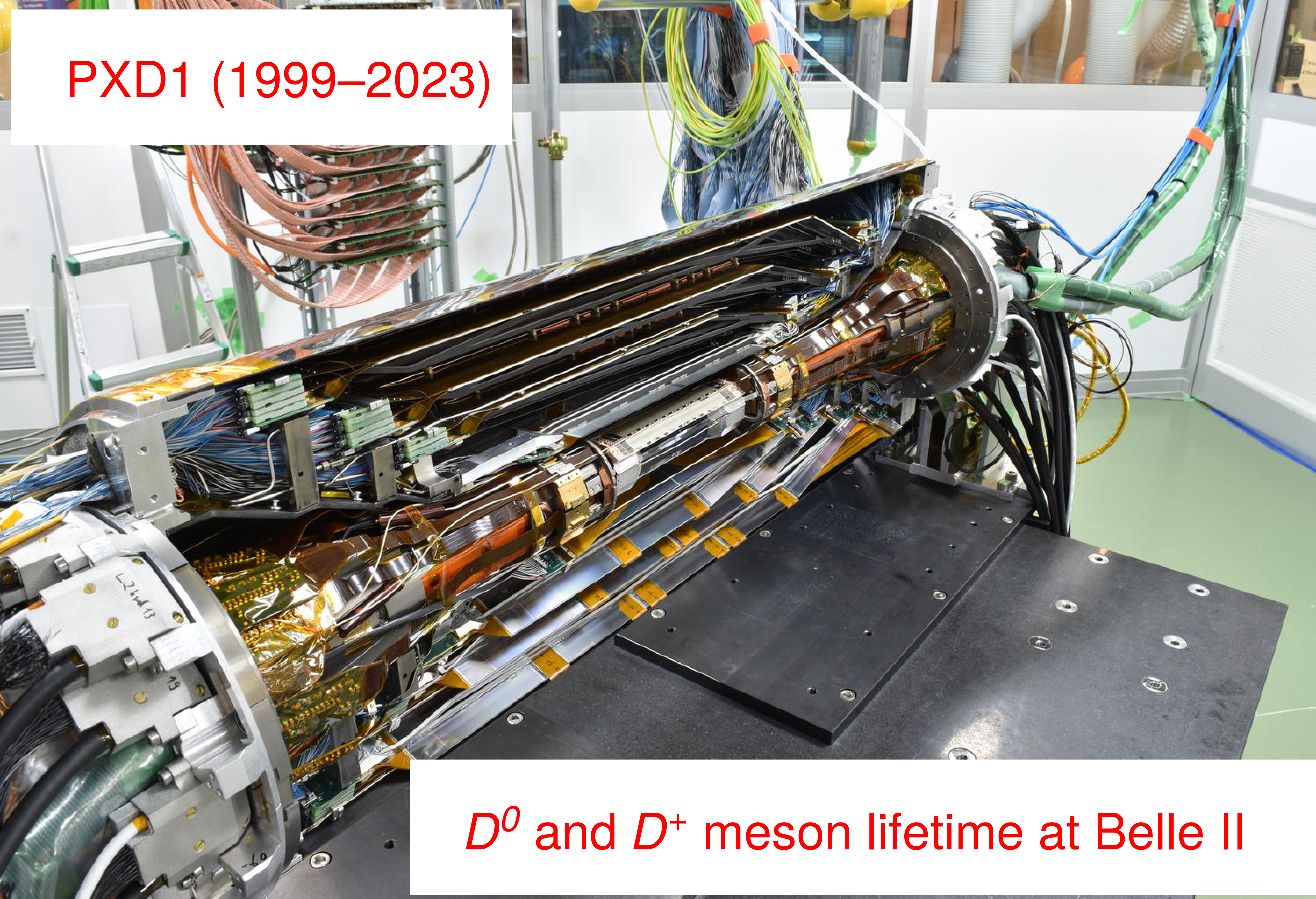
JENNIFER

Belle II

Bundesministerium
für Bildung
und Forschung

An MSCA-RISE project funded by European Union under grant n.644294

PXD1 (1999–2023)



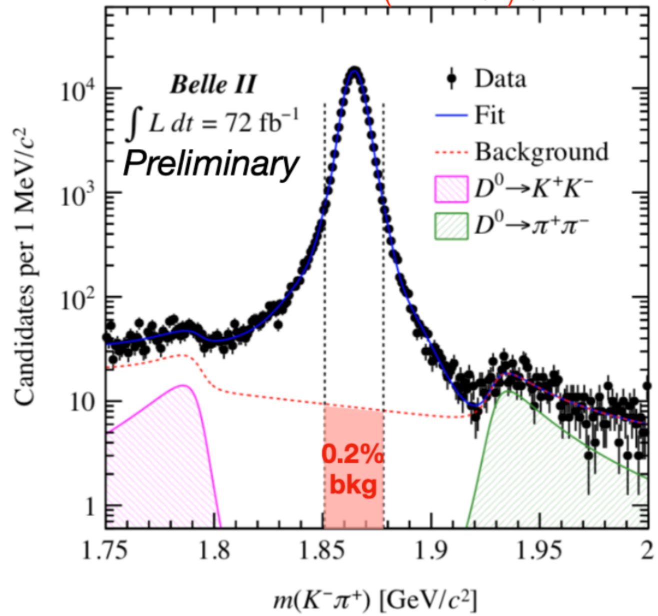
D^0 and D^+ meson lifetime at Belle II

D^0 and D^+ meson lifetime at Belle II

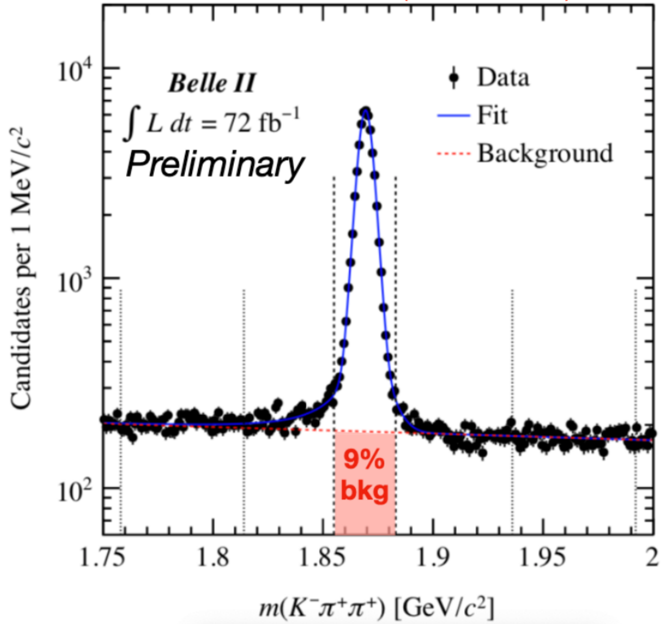
Phys Rev. Lett. 127 (2021) 211801

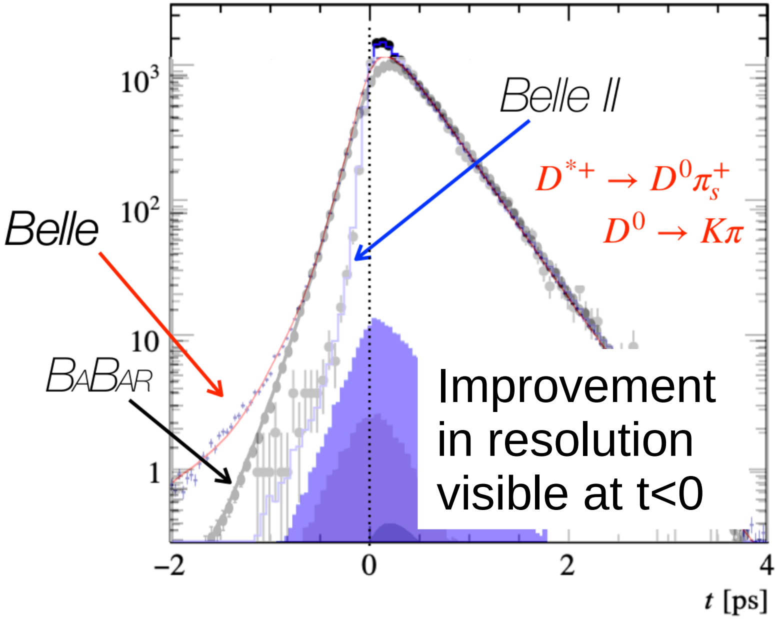
- D^* tagging
- Unbinned fit to (t,σ_t)
- Resolution ~60-70 *fs*
- Largest systematic error: alignment
  0.72 *fs* (D^0), 1.70 *fs* (D^+)

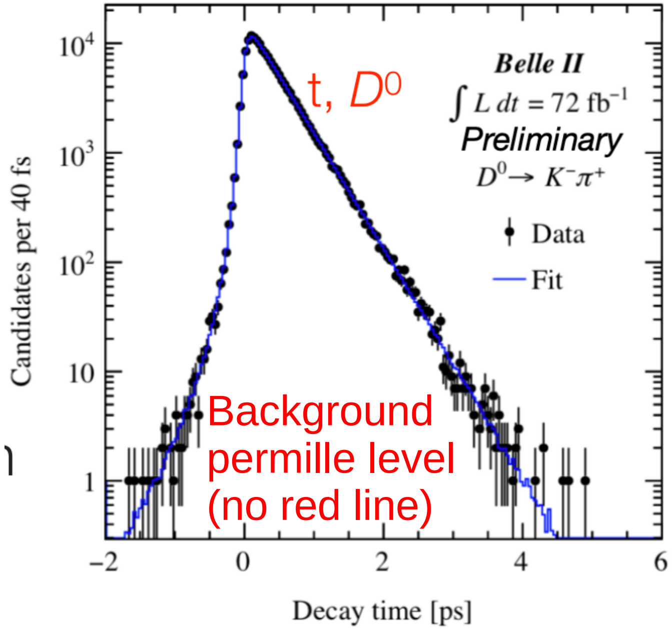
~171k $D^{*+}\to D^0(\to K^-\pi^+)\pi^+$

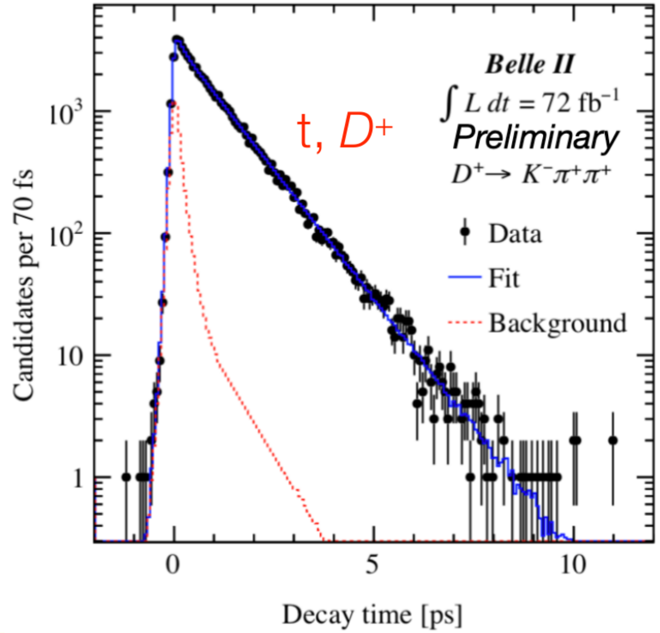


~59k $D^{*+}\to D^+(\to K^-\pi^+\pi^+)\pi^0$

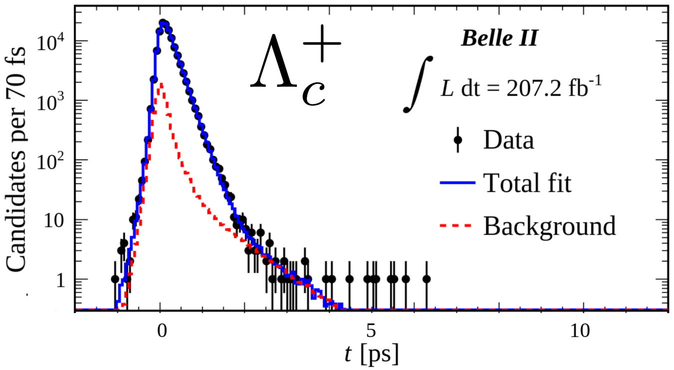


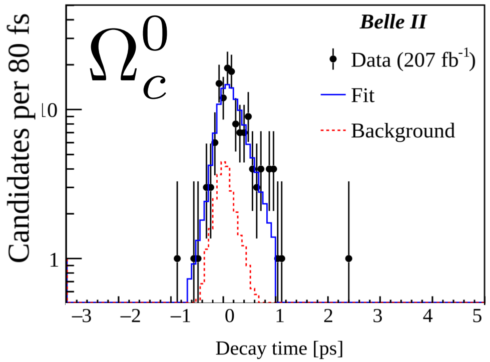


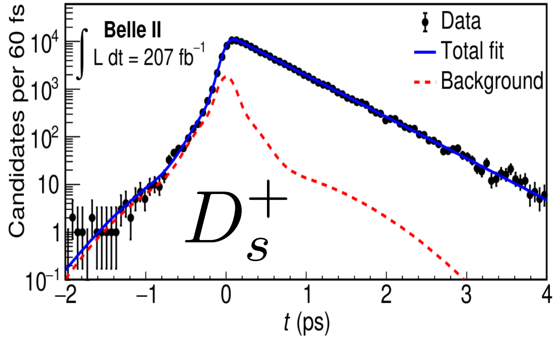




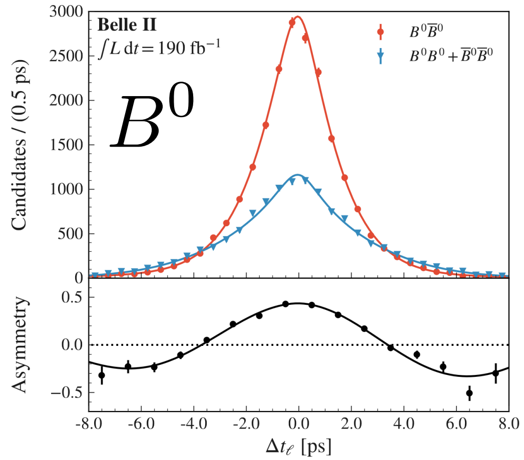
Meson lifetime results achieved with PXD1 (1999–2022)







Particle	Measured lifetime	Reference
Λ_c^+	$203.2 \pm 0.9 \pm 0.8$ fs	Phys. Rev. Lett 130 (2023) 071802
Ω_c^0	$243 \pm 48 \pm 11$ fs	Phys. Rev. D 107 (2023) L031103
D^0	$410.5 \pm 1.1 \pm 0.8$ fs	Phys. Rev. Lett. 127 (2021) 211801
D^+	$1030.4 \pm 4.7 \pm 3.1$ fs	Phys. Rev. Lett. 127 (2021) 211801
D_s^+	$499.5 \pm 1.7 \pm 0.9$ fs	Phys. Rev. Lett. 131 (2023) 171803
B^0	$1499 \pm 13 \pm 8$ fs	Phys. Rev. D 107 (2023) L091102



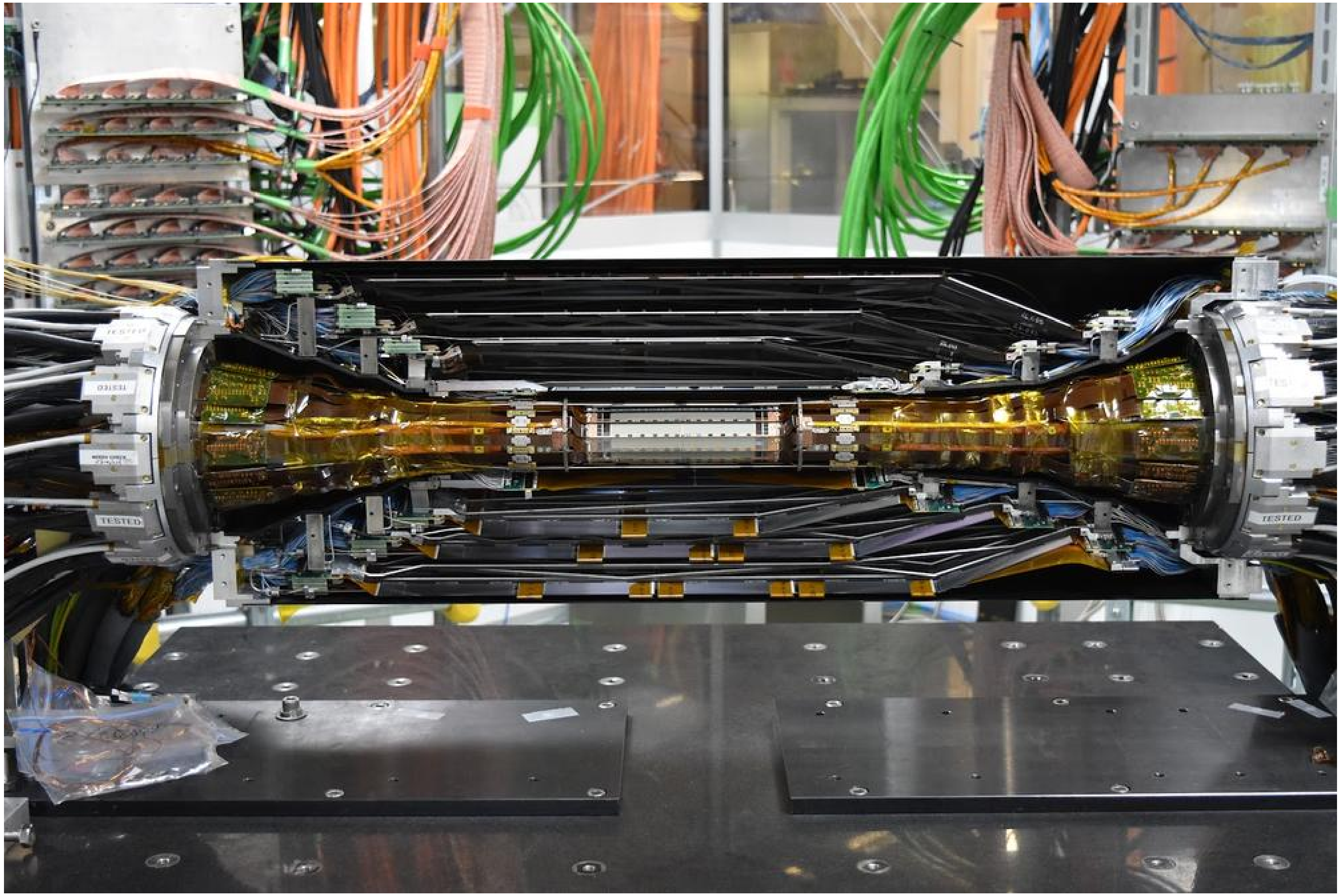
Resolution in beam direction $\Delta z \geq 25\mu m$ (factor $\simeq$2 better than Belle).

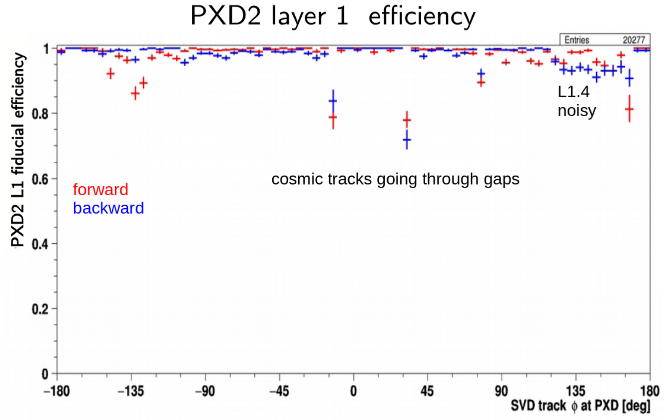
Belle II confirms surprising LHCb observation: contrary to the expectation by HQET, lifetime of Ω_c is larger than that of the Λ_c.

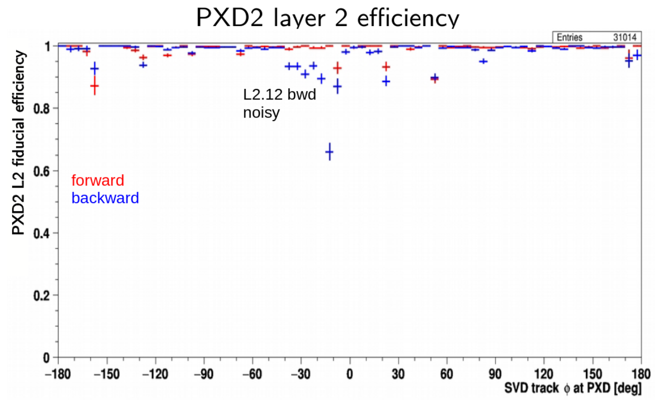
Precision propagates into reconstruction of e.g. $X(3872) \to D^{*0}\overline{D}^0$.

PXD2 (2023)

Both hit efficiency and hit purity ~20% higher than PXD1.





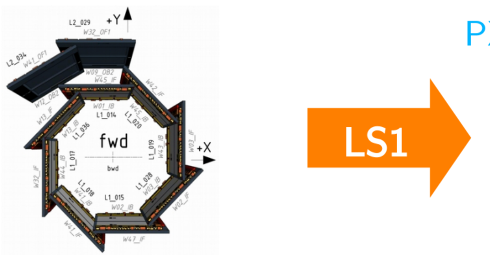


Efficiency

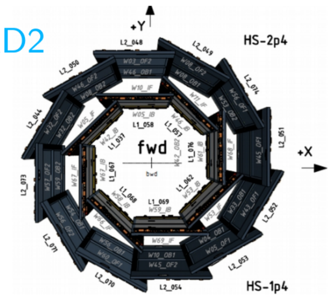
from cosmic data taking

in 09/2023

PXD1



PXD2

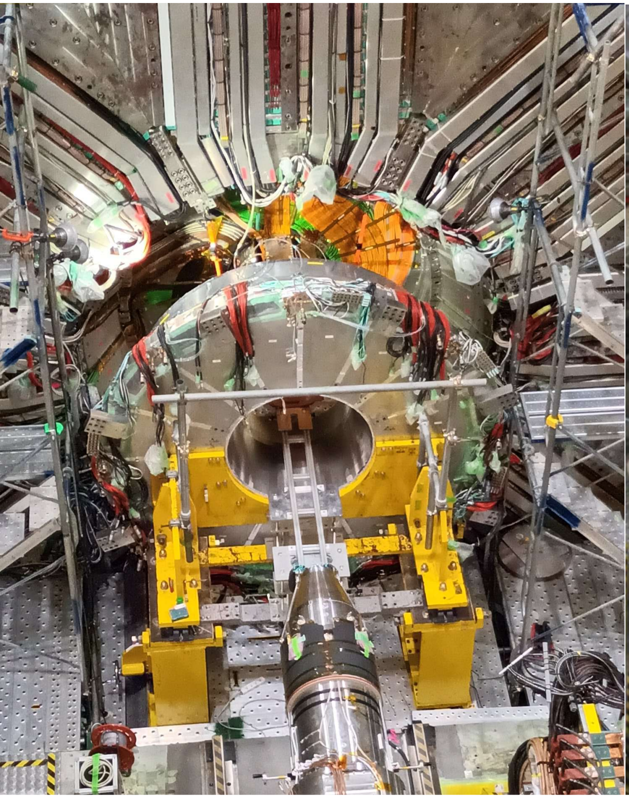


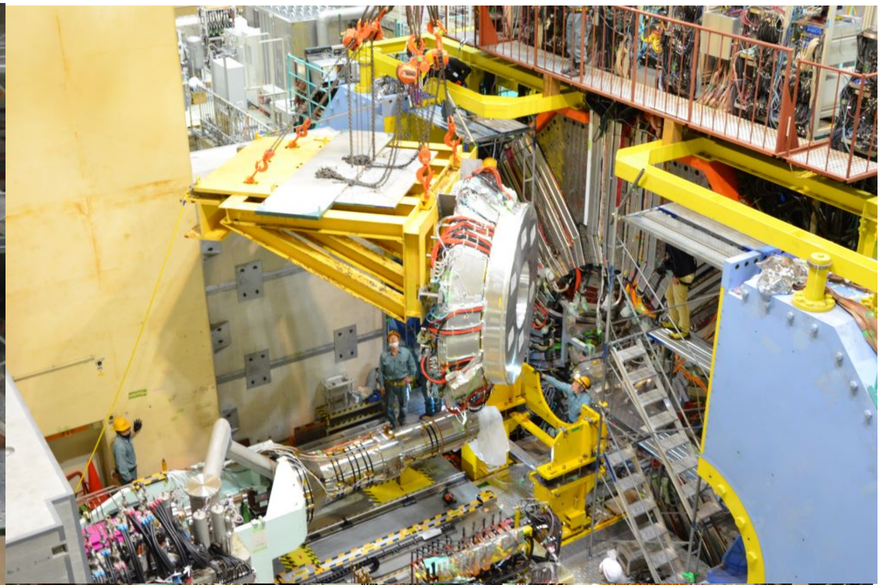
~8 Million pixels

(factor 2 more than PXD1)

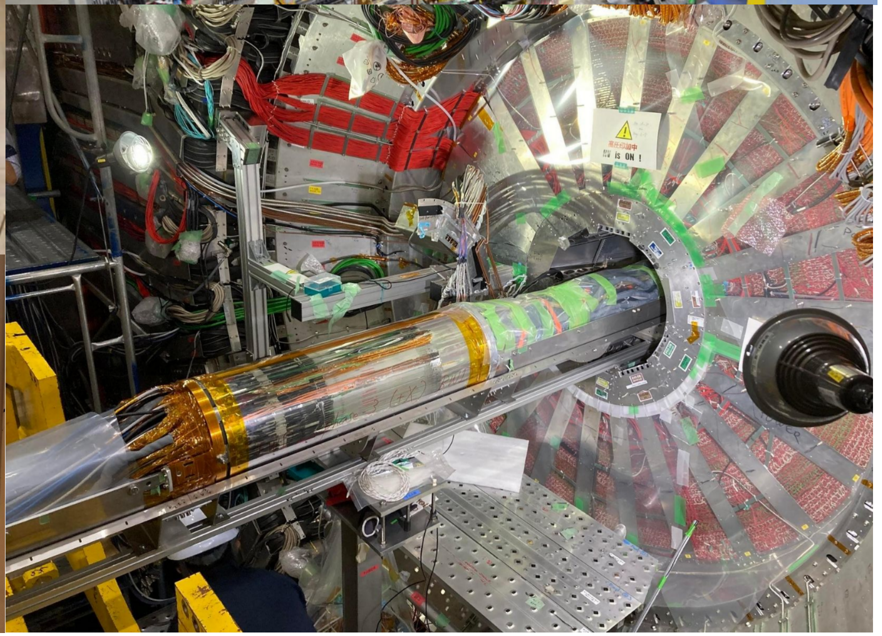
PXD2 installation (2023)

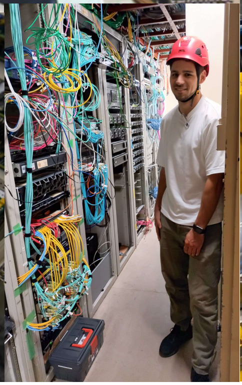
"Tsukuba action"





QCS (final focusing quadrupole) for nanobeam operation



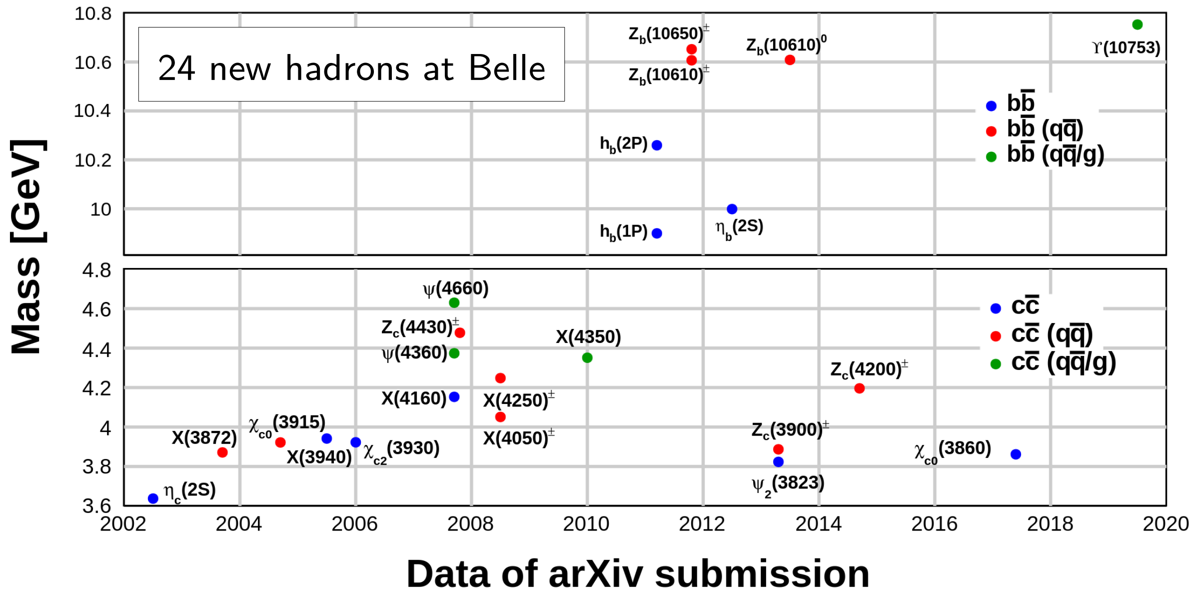


Fotos: KEK (official), B. Spruck, K. Trabelsi, S.L.

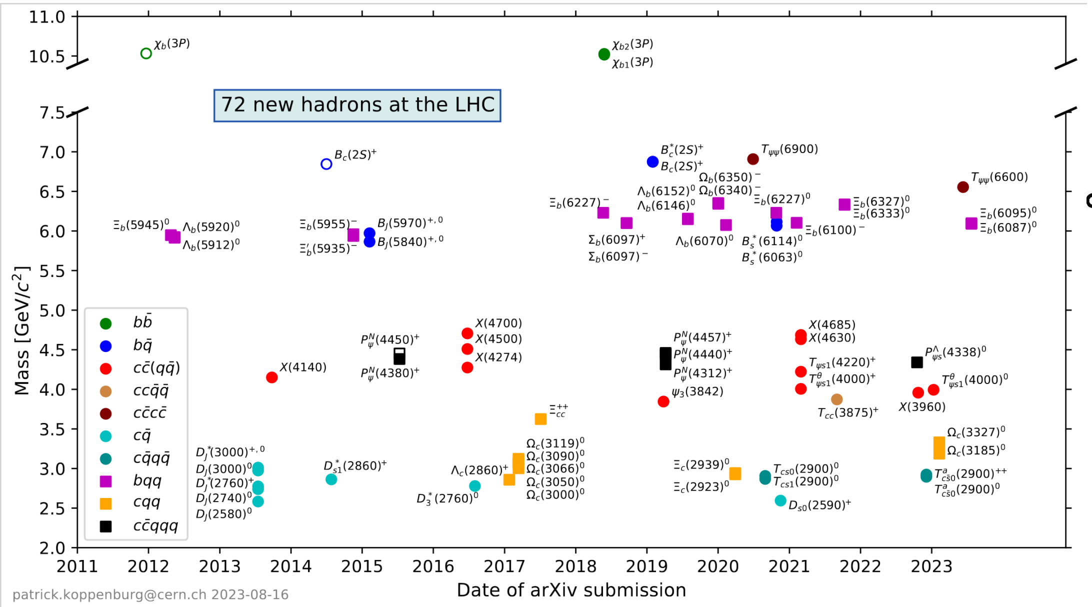
Present view of the Tetraquark flavor landscape: which combinations are missing?

Here: only charmonium-like states

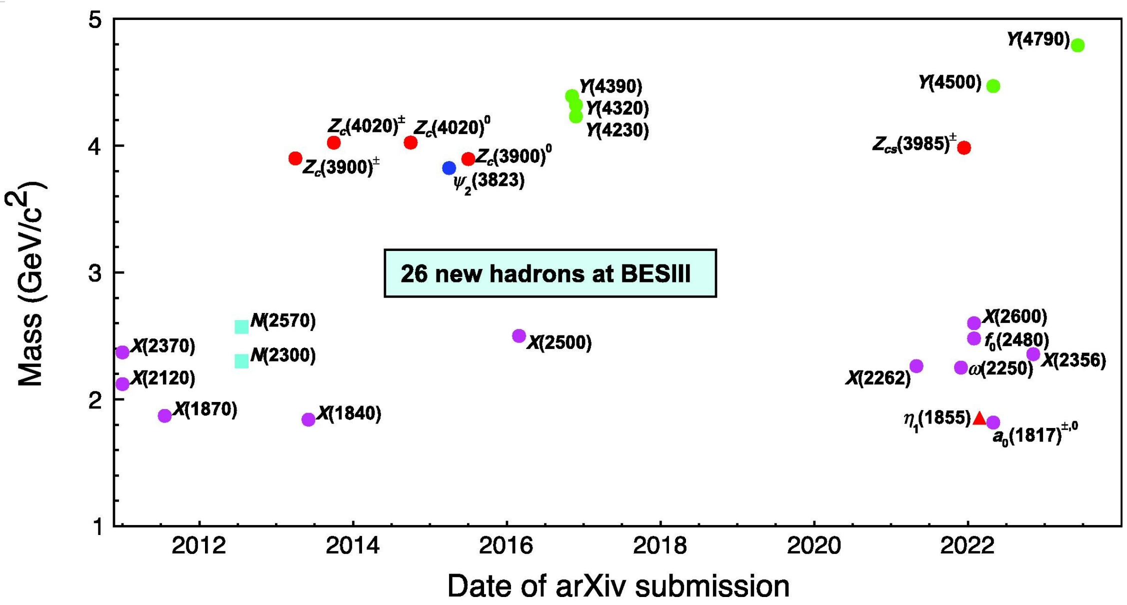
New hadrons found at Belle, BESIII, LHC



https://qwg.ph.nat.tum.de/exoticshub/belle.php

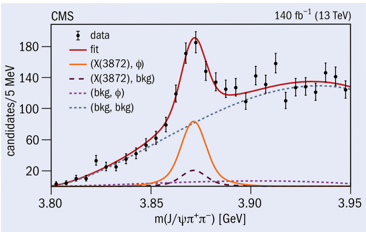


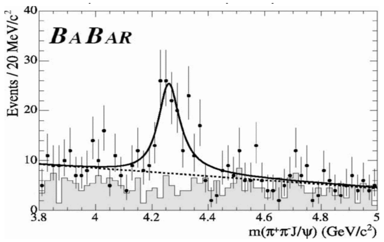
https://www.nikhef.nl/~pkoppenb/particles.html

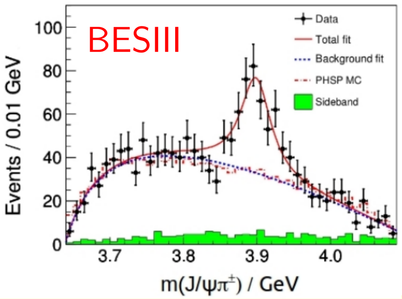


https://doi.org/10.1016/j.scib.2023.08.025

Historic XYZ states (2000–2010)







$c\bar{c}c\bar{c}$	~~$c\bar{s}c\bar{c}$~~	~~$c\bar{u}c\bar{c}$~~	~~$c\bar{d}c\bar{c}$~~	$c\bar{c}s\bar{c}$	~~$c\bar{s}s\bar{c}$~~	~~$c\bar{u}s\bar{c}$~~	~~$c\bar{d}s\bar{c}$~~
$c\bar{c}c\bar{s}$	$c\bar{s}c\bar{s}$	~~$c\bar{u}c\bar{s}$~~	~~$c\bar{d}c\bar{s}$~~	$c\bar{c}s\bar{s}$	$c\bar{s}s\bar{s}$	~~$c\bar{u}s\bar{s}$~~	~~$c\bar{d}s\bar{s}$~~
$c\bar{c}c\bar{u}$	$c\bar{s}c\bar{u}$	$c\bar{u}c\bar{u}$	~~$c\bar{d}c\bar{u}$~~	$c\bar{c}s\bar{u}$	$c\bar{s}s\bar{u}$	$c\bar{u}s\bar{u}$	~~$c\bar{d}s\bar{u}$~~
$c\bar{c}c\bar{d}$	$c\bar{s}c\bar{d}$	$c\bar{u}c\bar{d}$	$c\bar{d}c\bar{d}$	$c\bar{c}s\bar{d}$	$c\bar{s}s\bar{d}$	$c\bar{u}s\bar{d}$	$c\bar{d}s\bar{d}$

$c\bar{c}u\bar{c}$	~~$c\bar{s}u\bar{c}$~~	~~$c\bar{u}u\bar{c}$~~	~~$c\bar{d}u\bar{c}$~~	$c\bar{c}d\bar{c}$	~~$c\bar{s}d\bar{c}$~~	~~$c\bar{u}d\bar{c}$~~	~~$c\bar{d}d\bar{c}$~~
$c\bar{c}u\bar{s}$	$c\bar{s}u\bar{s}$	~~$c\bar{u}u\bar{s}$~~	~~$c\bar{d}u\bar{s}$~~	$c\bar{c}d\bar{s}$	$c\bar{s}d\bar{s}$	~~$c\bar{u}d\bar{s}$~~	~~$c\bar{d}d\bar{s}$~~
$c\bar{c}u\bar{u}$	$c\bar{s}u\bar{u}$	$c\bar{u}u\bar{u}$	~~$c\bar{d}u\bar{u}$~~	$c\bar{c}d\bar{u}$	$c\bar{s}d\bar{u}$	$c\bar{u}d\bar{u}$	~~$c\bar{d}d\bar{u}$~~
X, Y				Z			
$c\bar{c}u\bar{d}$	$c\bar{s}u\bar{d}$	$c\bar{u}u\bar{d}$	$c\bar{d}u\bar{d}$	$c\bar{c}d\bar{d}$	$c\bar{s}d\bar{d}$	$c\bar{u}d\bar{d}$	$c\bar{d}d\bar{d}$
Z				X, Y			

Molecular and compact states

see talk by
Elisabetta Prencipe

$c\bar{c}c\bar{c}$	~~$c\bar{s}c\bar{c}$~~	~~$c\bar{u}c\bar{c}$~~	~~$c\bar{d}c\bar{c}$~~	$c\bar{c}s\bar{c}$	~~$c\bar{s}s\bar{c}$~~	~~$c\bar{u}s\bar{c}$~~	~~$c\bar{d}s\bar{c}$~~
$c\bar{c}c\bar{s}$	$c\bar{s}c\bar{s}$	~~$c\bar{u}c\bar{s}$~~	~~$c\bar{d}c\bar{s}$~~	$c\bar{c}s\bar{s}$			
$c\bar{c}c\bar{u}$	$c\bar{s}c\bar{u}$	$c\bar{u}c\bar{u}$	~~$c\bar{d}c\bar{u}$~~	$c\bar{c}s\bar{u}$	$c\bar{s}s\bar{u}$	$c\bar{u}s\bar{u}$	~~$c\bar{d}s\bar{u}$~~
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$c\bar{c}u\bar{s}$	$c\bar{s}u\bar{s}$	~~$c\bar{u}u\bar{s}$~~	~~$c\bar{d}u\bar{s}$~~	$c\bar{c}d\bar{s}$	$c\bar{s}d\bar{s}$	~~$c\bar{u}d\bar{s}$~~	~~$c\bar{d}d\bar{s}$~~
$c\bar{c}u\bar{u}$	$c\bar{s}u\bar{u}$	$c\bar{u}u\bar{u}$	~~$c\bar{d}u\bar{u}$~~	$c\bar{c}d\bar{u}$	$c\bar{s}d\bar{u}$	$c\bar{u}d\bar{u}$	~~$c\bar{d}d\bar{u}$~~
$c\bar{c}u\bar{d}$	$c\bar{s}u\bar{d}$	$c\bar{u}u\bar{d}$	$c\bar{d}u\bar{d}$	$c\bar{c}d\bar{d}$	$c\bar{s}d\bar{d}$	$c\bar{u}d\bar{d}$	$c\bar{d}d\bar{d}$

No isospin, often called "compact"
but e.g. η-exchange possible
Karliner, Rosner, Nucl. Phys. A 954 (2016) 365

u, d-quark substructure
Molecule-type potentials with isospin term possible

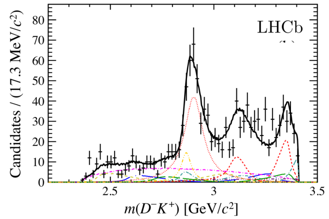
Pion substructure
cc or $c\bar{c}$, and $u\bar{u}, u\bar{d}, d\bar{u}, d\bar{d}$

T_{cs}

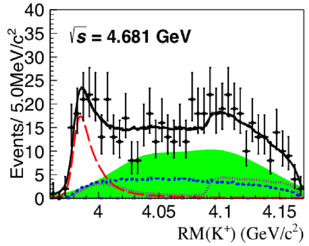
Example (not observed yet)
[Ds+K–]

Neutral (and doubly charged) Ds not possible in meson model.

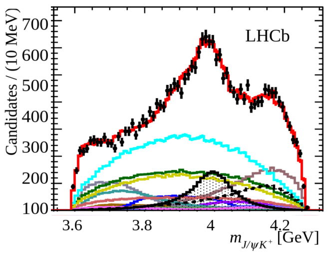
$c\bar{c}c\bar{c}$	~~$c\bar{s}c\bar{c}$~~	~~$c\bar{u}c\bar{c}$~~	~~$c\bar{d}c\bar{c}$~~	$c\bar{c}s\bar{c}$	~~$c\bar{s}s\bar{c}$~~	~~$c\bar{u}s\bar{c}$~~	~~$c\bar{d}s\bar{c}$~~
$c\bar{c}c\bar{s}$	$c\bar{s}c\bar{s}$	~~$c\bar{u}c\bar{s}$~~	~~$c\bar{d}c\bar{s}$~~	$c\bar{c}s\bar{s}$	$c\bar{s}s\bar{s}$	~~$c\bar{u}s\bar{s}$~~	~~$c\bar{d}s\bar{s}$~~
$c\bar{c}c\bar{u}$	$c\bar{s}c\bar{u}$	$c\bar{u}c\bar{u}$	~~$c\bar{d}c\bar{u}$~~	$c\bar{c}s\bar{u}$	$c\bar{s}s\bar{u}$	$c\bar{u}s\bar{u}$	~~$c\bar{d}s\bar{u}$~~
$c\bar{c}c\bar{d}$	$c\bar{s}c\bar{d}$	$c\bar{u}c\bar{d}$	$c\bar{d}c\bar{d}$	$c\bar{c}s\bar{d}$	$c\bar{s}s\bar{d}$	$c\bar{u}s\bar{d}$	$c\bar{d}s\bar{d}$
						X0 X1	
$c\bar{c}u\bar{c}$	~~$c\bar{s}u\bar{c}$~~	~~$c\bar{u}u\bar{c}$~~	~~$c\bar{d}u\bar{c}$~~	$c\bar{c}d\bar{c}$	~~$c\bar{s}d\bar{c}$~~	~~$c\bar{u}d\bar{c}$~~	~~$c\bar{d}d\bar{c}$~~
$c\bar{c}u\bar{s}$	$c\bar{s}u\bar{s}$	~~$c\bar{u}u\bar{s}$~~	~~$c\bar{d}u\bar{s}$~~	$c\bar{c}d\bar{s}$	$c\bar{s}d\bar{s}$	~~$c\bar{u}d\bar{s}$~~	~~$c\bar{d}d\bar{s}$~~
Zcs+				Zcs0			
$c\bar{c}u\bar{u}$	$c\bar{s}u\bar{u}$	$c\bar{u}u\bar{u}$	~~$c\bar{d}u\bar{u}$~~	$c\bar{c}d\bar{u}$	$c\bar{s}d\bar{u}$	$c\bar{u}d\bar{u}$	~~$c\bar{d}d\bar{u}$~~
					Tcs0		
$c\bar{c}u\bar{d}$	$c\bar{s}u\bar{d}$	$c\bar{u}u\bar{d}$	$c\bar{d}u\bar{d}$	$c\bar{c}d\bar{d}$	$c\bar{s}d\bar{d}$	$c\bar{u}d\bar{d}$	$c\bar{d}d\bar{d}$
	Tcs++						



D–K+ LHCb

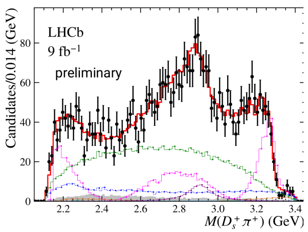


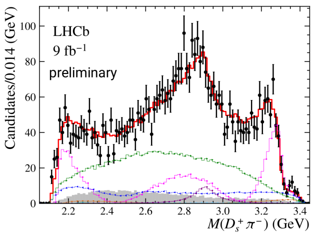
Ds+ D*– BESIII



LHCb J/Psi K+

LHCb





Ds+pi–

ISOSPIN PARTNERS

Ds+pi+ LHCb

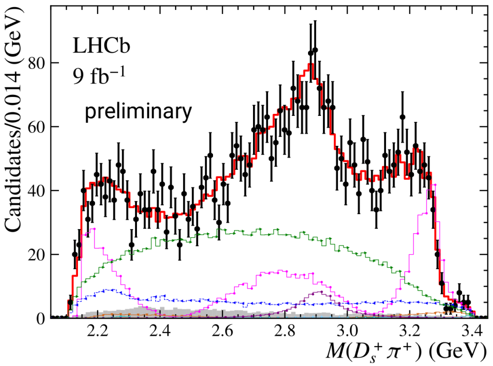
Doubly charged states

Not possible

in meson model.

5 states

not observed yet



LHCb

Only state

observed yet

$c\bar{c}c\bar{c}$	~~$c\bar{s}c\bar{c}$~~	~~$c\bar{u}c\bar{c}$~~	~~$c\bar{d}c\bar{c}$~~	$c\bar{c}s\bar{c}$	~~$c\bar{s}s\bar{c}$~~	~~$c\bar{u}s\bar{c}$~~	~~$c\bar{d}s\bar{c}$~~
$c\bar{c}c\bar{s}$	$c\bar{s}c\bar{s}$	~~$c\bar{u}c\bar{s}$~~	~~$c\bar{d}c\bar{s}$~~	$c\bar{c}s\bar{s}$	$c\bar{s}s\bar{s}$	~~$c\bar{u}s\bar{s}$~~	~~$c\bar{d}s\bar{s}$~~
	++						
$c\bar{c}c\bar{u}$	$c\bar{s}c\bar{u}$	$c\bar{u}c\bar{u}$	~~$c\bar{d}c\bar{u}$~~	$c\bar{c}s\bar{u}$	$c\bar{s}s\bar{u}$	$c\bar{u}s\bar{u}$	~~$c\bar{d}s\bar{u}$~~
$c\bar{c}c\bar{d}$	$c\bar{s}c\bar{d}$	$c\bar{u}c\bar{d}$	$c\bar{d}c\bar{d}$	$c\bar{c}s\bar{d}$	$c\bar{s}s\bar{d}$	$c\bar{u}s\bar{d}$	$c\bar{d}s\bar{d}$
	++		++				
$c\bar{c}u\bar{c}$	~~$c\bar{s}u\bar{c}$~~	~~$c\bar{u}u\bar{c}$~~	~~$c\bar{d}u\bar{c}$~~	$c\bar{c}d\bar{c}$	~~$c\bar{s}d\bar{c}$~~	~~$c\bar{u}d\bar{c}$~~	~~$c\bar{d}d\bar{c}$~~
$c\bar{c}u\bar{s}$	$c\bar{s}u\bar{s}$	~~$c\bar{u}u\bar{s}$~~	~~$c\bar{d}u\bar{s}$~~	$c\bar{c}d\bar{s}$	$c\bar{s}d\bar{s}$	~~$c\bar{u}d\bar{s}$~~	~~$c\bar{d}d\bar{s}$~~
	++						
$c\bar{c}u\bar{u}$	$c\bar{s}u\bar{u}$	$c\bar{u}u\bar{u}$	~~$c\bar{d}u\bar{u}$~~	$c\bar{c}d\bar{u}$	$c\bar{s}d\bar{u}$	$c\bar{u}d\bar{u}$	~~$c\bar{d}d\bar{u}$~~
$c\bar{c}u\bar{d}$	$c\bar{s}u\bar{d}$	$c\bar{u}u\bar{d}$	$c\bar{d}u\bar{d}$	$c\bar{c}d\bar{d}$	$c\bar{s}d\bar{d}$	$c\bar{u}d\bar{d}$	$c\bar{d}d\bar{d}$
	++		++				

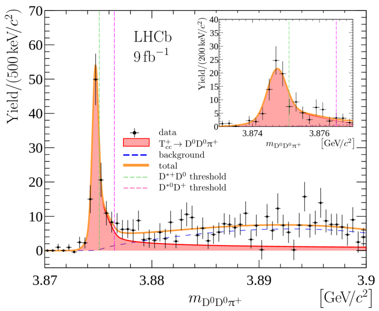
T_{cc}

8 states

not observed yet

D0 D0 pi+

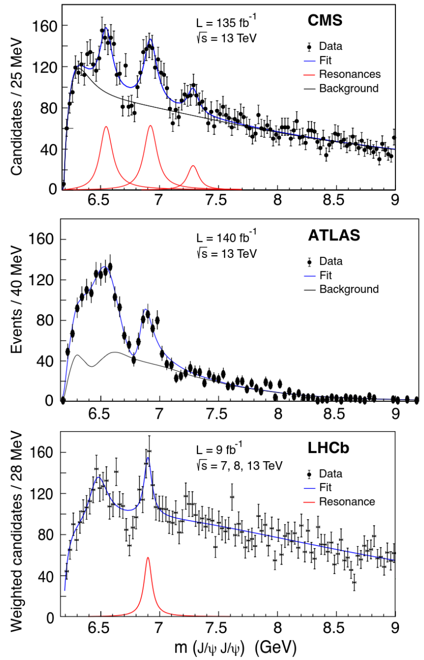
LHCb



$c\bar{c}c\bar{c}$	~~$c\bar{s}c\bar{c}$~~	~~$c\bar{u}c\bar{c}$~~	~~$c\bar{d}c\bar{c}$~~	$c\bar{c}s\bar{c}$	~~$c\bar{s}s\bar{c}$~~	~~$c\bar{u}s\bar{c}$~~	~~$c\bar{d}s\bar{c}$~~
Tcc0							
$c\bar{c}c\bar{s}$	$c\bar{s}c\bar{s}$	~~$c\bar{u}c\bar{s}$~~	~~$c\bar{d}c\bar{s}$~~	$c\bar{c}s\bar{s}$	$c\bar{s}s\bar{s}$	~~$c\bar{u}s\bar{s}$~~	~~$c\bar{d}s\bar{s}$~~
$c\bar{c}c\bar{u}$	$c\bar{s}c\bar{u}$	$c\bar{u}c\bar{u}$	~~$c\bar{d}c\bar{u}$~~	$c\bar{c}s\bar{u}$	$c\bar{s}s\bar{u}$	$c\bar{u}s\bar{u}$	~~$c\bar{d}s\bar{u}$~~
$c\bar{c}c\bar{d}$	$c\bar{s}c\bar{d}$	$c\bar{u}c\bar{d}$	$c\bar{d}c\bar{d}$	$c\bar{c}s\bar{d}$	$c\bar{s}s\bar{d}$	$c\bar{u}s\bar{d}$	$c\bar{d}s\bar{d}$
		Tcc+					
$c\bar{c}u\bar{c}$	~~$c\bar{s}u\bar{c}$~~	~~$c\bar{u}u\bar{c}$~~	~~$c\bar{d}u\bar{c}$~~	$c\bar{c}d\bar{c}$	~~$c\bar{s}d\bar{c}$~~	~~$c\bar{u}d\bar{c}$~~	~~$c\bar{d}d\bar{c}$~~
$c\bar{c}u\bar{s}$	$c\bar{s}u\bar{s}$	~~$c\bar{u}u\bar{s}$~~	~~$c\bar{d}u\bar{s}$~~	$c\bar{c}d\bar{s}$	$c\bar{s}d\bar{s}$	~~$c\bar{u}d\bar{s}$~~	~~$c\bar{d}d\bar{s}$~~
$c\bar{c}u\bar{u}$	$c\bar{s}u\bar{u}$	$c\bar{u}u\bar{u}$	~~$c\bar{d}u\bar{u}$~~	$c\bar{c}d\bar{u}$	$c\bar{s}d\bar{u}$	$c\bar{u}d\bar{u}$	~~$c\bar{d}d\bar{u}$~~
$c\bar{c}u\bar{d}$	$c\bar{s}u\bar{d}$	$c\bar{u}u\bar{d}$	$c\bar{d}u\bar{d}$	$c\bar{c}d\bar{d}$	$c\bar{s}d\bar{d}$	$c\bar{u}d\bar{d}$	$c\bar{d}d\bar{d}$

J/Psi J/Psi

LHCb, ATLAS, CMS



Quantum numbers J^{PC} (whereever determined)

$c\bar{c}c\bar{c}$	~~$c\bar{s}c\bar{c}$~~	~~$c\bar{u}c\bar{c}$~~	~~$c\bar{d}c\bar{c}$~~	$c\bar{c}s\bar{c}$	~~$c\bar{s}s\bar{c}$~~	~~$c\bar{u}s\bar{c}$~~	~~$c\bar{d}s\bar{c}$~~
??+							
$c\bar{c}c\bar{s}$	$c\bar{s}c\bar{s}$	~~$c\bar{u}c\bar{s}$~~	~~$c\bar{d}c\bar{s}$~~	$c\bar{c}s\bar{s}$	$c\bar{s}s\bar{s}$	~~$c\bar{u}s\bar{s}$~~	~~$c\bar{d}s\bar{s}$~~
				1+,0+			
$c\bar{c}c\bar{u}$	$c\bar{s}c\bar{u}$	$c\bar{u}c\bar{u}$	~~$c\bar{d}c\bar{u}$~~	$c\bar{c}s\bar{u}$	$c\bar{s}s\bar{u}$	$c\bar{u}s\bar{u}$	~~$c\bar{d}s\bar{u}$~~
$c\bar{c}c\bar{d}$	$c\bar{s}c\bar{d}$	$c\bar{u}c\bar{d}$	$c\bar{d}c\bar{d}$	$c\bar{c}s\bar{d}$	$c\bar{s}s\bar{d}$	$c\bar{u}s\bar{d}$	$c\bar{d}s\bar{d}$
		1+				1+,1−	
$c\bar{c}u\bar{c}$	~~$c\bar{s}u\bar{c}$~~	~~$c\bar{u}u\bar{c}$~~	~~$c\bar{d}u\bar{c}$~~	$c\bar{c}d\bar{c}$	~~$c\bar{s}d\bar{c}$~~	~~$c\bar{u}d\bar{c}$~~	~~$c\bar{d}d\bar{c}$~~
$c\bar{c}u\bar{s}$	$c\bar{s}u\bar{s}$	~~$c\bar{u}u\bar{s}$~~	~~$c\bar{d}u\bar{s}$~~	$c\bar{c}d\bar{s}$	$c\bar{s}d\bar{s}$	~~$c\bar{u}d\bar{s}$~~	~~$c\bar{d}d\bar{s}$~~
1+							
$c\bar{c}u\bar{u}$	$c\bar{s}u\bar{u}$	$c\bar{u}u\bar{u}$	~~$c\bar{d}u\bar{u}$~~	$c\bar{c}d\bar{u}$	$c\bar{s}d\bar{u}$	$c\bar{u}d\bar{u}$	~~$c\bar{d}d\bar{u}$~~
1++, 1−				1+, 1−			
$c\bar{c}u\bar{d}$	$c\bar{s}u\bar{d}$	$c\bar{u}u\bar{d}$	$c\bar{d}u\bar{d}$	$c\bar{c}d\bar{d}$	$c\bar{s}d\bar{d}$	$c\bar{u}d\bar{d}$	$c\bar{d}d\bar{d}$
1+, 1−				(1++)			

X(3872)

Lineshape of X(3872)

New 2023, Belle, Phys. Rev.D 107 (2023) 112011
Hikari Hirata and team (Nagoya)

- $X(3872) \to D^0\overline{D}^{*0}$ (not $X(3872) \to J/\psi\pi^+\pi^-$)
- Neutral and charged B decays
- 711 fb^{-1} (total Belle Y(4S) data set, but no Belle II data)
- Two fit approaches:
  Breit-Wigner and Flatté (as closeby threshold distorts simple Breit-Wigner)

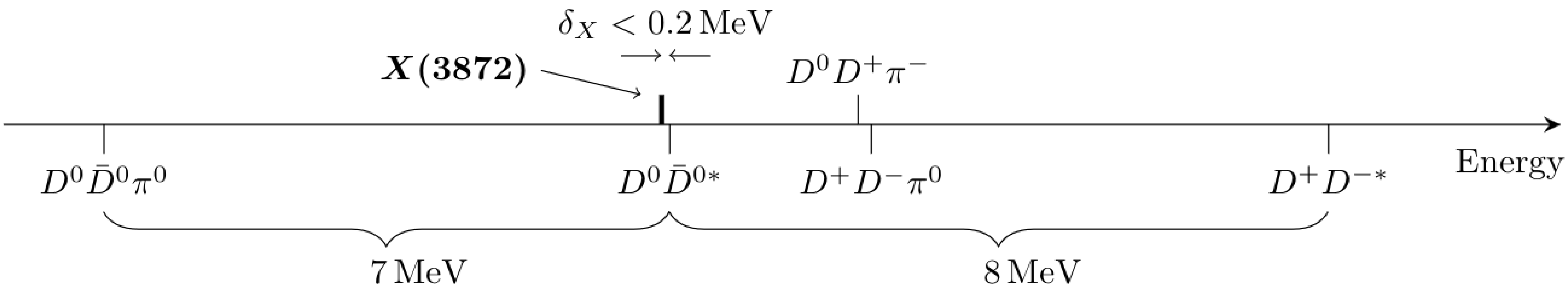


Figure 1: Thresholds close to the $X(3872)$ (to scale, anti-particle states omitted).

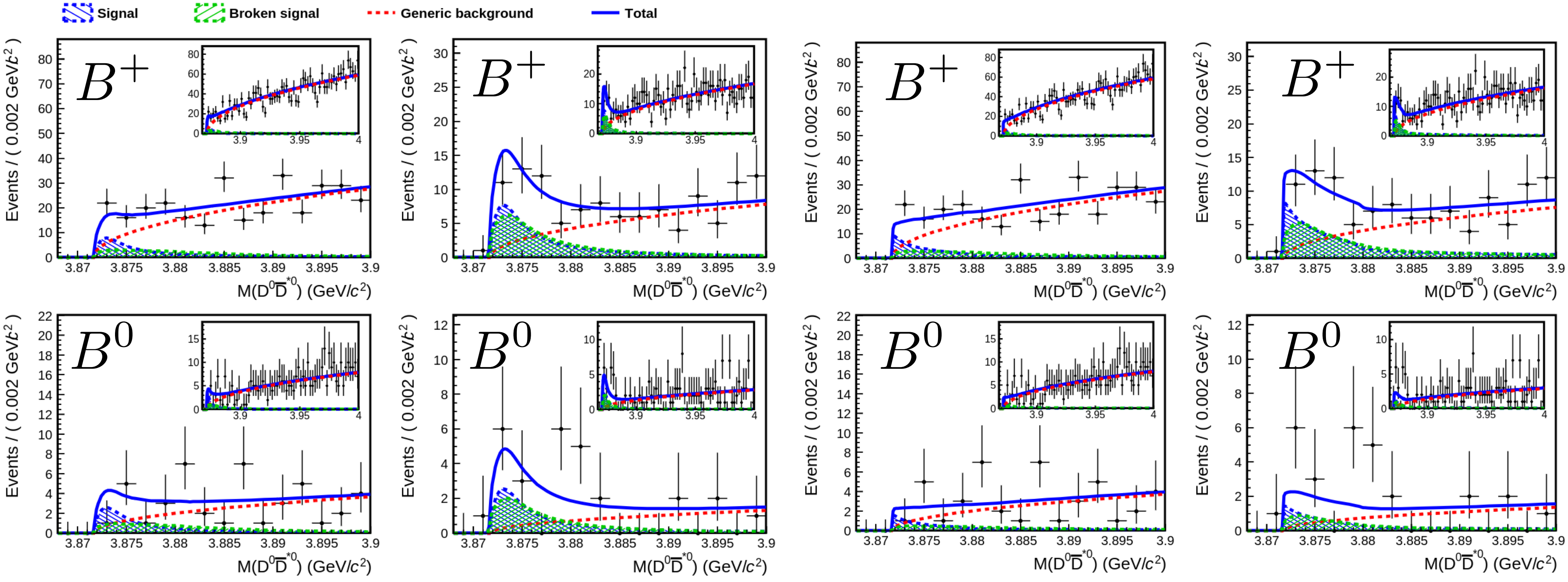
Schmidt, Jansen Hammer, Phys. Rev. D 98 (2018) 014032 (2018)

B → D*D in B meson decays

New 2023

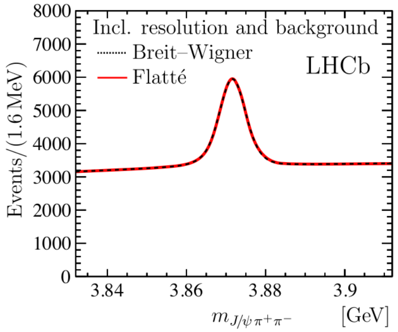
Belle, Phys. Rev.D 107 (2023) 112011

Breit-Wigner fit | Flatté fit



$D^{0*} \to D^0\gamma$ | $D^{0*} \to D^0\pi^0$ | $D^{0*} \to D^0\gamma$ | $D^{0*} \to D^0\pi^0$

LHCb,
Phys. Rev. D 102 (2020) 092005



$$f_{\mathrm{BW}}(M) = \frac{m_{\mathrm{BW}} M \Gamma(M)}{(M^2 - m_{\mathrm{BW}}^2)^2 + m_{\mathrm{BW}}^2 \Gamma(M)^2}$$

$$f_{\mathrm{Flatte}}(E) = \frac{g k_{D^0\overline{D}^{*0}}}{|D(E)|^2}$$

$$D(E) = \begin{cases} E - E_f - \frac{1}{2} g \kappa_{D^+D^{*-}} + \frac{i}{2}[g k_{D^0\overline{D}^{*0}} + \Gamma(E)] & \text{for } 0 < E < \delta, \\ E - E_f + \frac{i}{2}[g(k_{D^0\overline{D}^{*0}} + k_{D^+D^{*-}}) + \Gamma(E)] & \text{for } E > \delta, \end{cases}$$

Yield $70.5^{+13.6}_{-11.5}$ events (BW)

Significance 7.5σ(BW)

Flatté formalism

The Flatté-inspired parametrization is defined as follows using the energy from the $D^0\overline{D}^{*0}$ threshold, $E = M - (m_{D^0} + m_{D^{*0}})$ [22, 27, 43]:

$$f_{\text{Flatte}}(E) = \frac{g k_{D^0\overline{D}^{*0}}}{|D(E)|^2}, \tag{7}$$

$$D(E) = \begin{cases} E - E_f - \frac{1}{2} g \kappa_{D^+D^{*-}} + \frac{i}{2}[g k_{D^0\overline{D}^{*0}} + \Gamma(E)] \\ \qquad \text{for } 0 < E < \delta, \\ E - E_f + \frac{i}{2}[g(k_{D^0\overline{D}^{*0}} + k_{D^+D^{*-}}) + \Gamma(E)] \\ \qquad \text{for } E > \delta, \end{cases} \tag{8}$$

where $E_f = m_0 - (m_{D^0} + m_{D^{*0}})$ is the mass difference of this state (m_0) from the threshold, and g is the coupling constant for the DD^* channels; we assume the coupling constants for the D^0D^{*0} and D^+D^{*-} channels are the same due to isospin symmetry. The momenta k_a and κ_a for the channel a are measured in the rest frame of the $X(3872)$. They are expressed using the reduced mass μ as

$$\begin{aligned} k_{D^0\overline{D}^{*0}} &= \sqrt{2\mu_{D^0\overline{D}^{*0}} E}, \\ k_{D^+D^{*-}} &= \sqrt{2\mu_{D^+D^{*-}}(E - \delta)}, \\ \kappa_{D^+D^{*-}} &= \sqrt{2\mu_{D^+D^{*-}}(\delta - E)}, \\ \delta &= (m_{D^+} + m_{D^{*-}}) - (m_{D^0} + m_{D^{*0}}). \end{aligned} \tag{9}$$

The energy-dependent width $\Gamma(E)$ is defined by

$$\Gamma(E) = \Gamma_{J/\psi\rho}(E) + \Gamma_{J/\psi\omega}(E) + \Gamma_0, \tag{10}$$

where Γ_a is the partial width for the channel a. For the $J/\psi\rho$ and $J/\psi\omega$ channels, the dependence on E is defined as follows using the phase space and effective coupling constants, f_ρ and f_ω [27]:

$$\Gamma_{J/\psi\omega}(E) = f_\omega \int_{3m_\pi}^{M(E)-m_{J/\psi}} \frac{dm'}{2\pi} \frac{q(m', E)\Gamma_\omega}{(m' - m_\omega)^2 + \Gamma_\omega^2/4}, \tag{12}$$

where Γ_ρ and Γ_ω are total widths for the ρ and ω resonances, respectively. The upper bound of the integral is set by the difference between

$$M(E) = E + (m_{D^0} + m_{D^{*0}}) \tag{13}$$

and $m_{J/\psi}$. In each case, $q(m', E)$ is the momentum of the two- or three-pion system in the rest frame of the $X(3872)$:

$$\begin{aligned} q(m', E) = &\frac{1}{2M(E)} \sqrt{M^2(E) - (m' + m_{J/\psi})^2} \\ &\times \sqrt{M^2(E) - (m' - m_{J/\psi})^2}. \end{aligned} \tag{14}$$

Background function ($B\overline{B}$ and continuum)

$$\sqrt{M - (m_{D^0} + m_{D^{*0}})}$$

Flatté fit

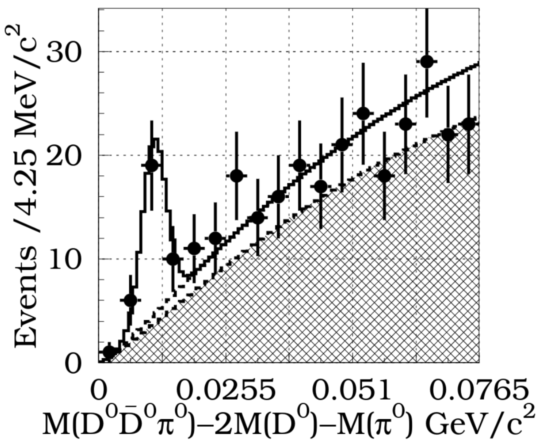
New 2023

Belle, Phys. Rev.D 107 (2023) 112011

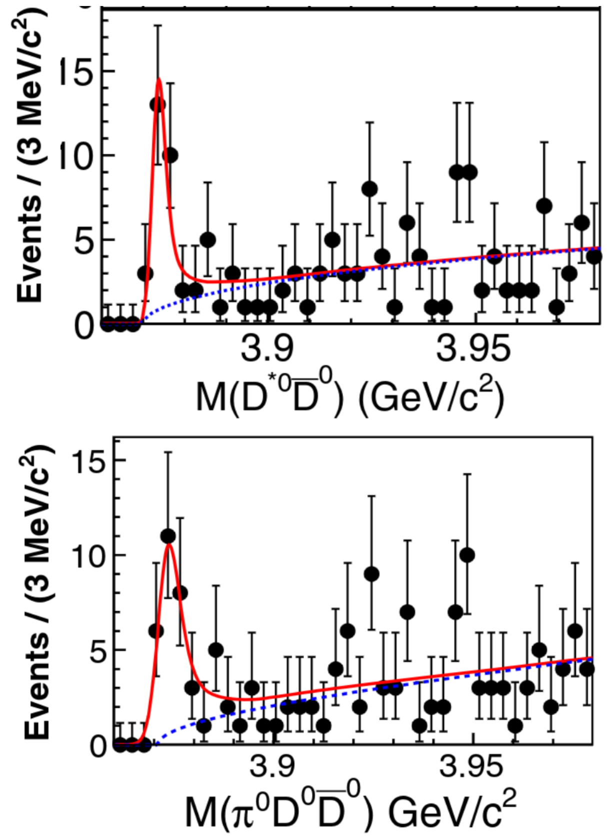
Based upon { Hanhart, Kalashnikova, Kudryavtsev, Nefediev Phys. Rev. D 76 (2007) 034007; Kalashnikova, Nefediev }

- unbinned maximum likelihood fit (simultaneous for B^+ and B^0)
- 5 free parameters: $E_f, g, f_\rho, f_\omega, \Gamma_0$
- 3 constraints:
  - $\mathcal{B}(D^+D^{*-}) = \mathcal{B}(D^{0*}\overline{D}^0)$
  - $\mathcal{B}(J/\psi\pi^+\pi^-) = \mathcal{B}(J/\psi\omega)$, fixes f_ω
  - Soft constraint on the ratio of $\mathcal{B}(J/\psi\pi^+\pi^-)$ vs. $\mathcal{B}(D^*D)$
- Mass constraint on $m(D^*)$ is applied
  - improves mass resolution from 2.72 MeV to 0.22 MeV
    Belle, Phys. Rev. Lett. 97 (2006) 162002
  - contribution from non-resonant $D\overline{D}\pi$ is negligible
    BESIII, Phys. Rev. Lett. 124 (2020) 242001
    1.3±0.7 events vs. 20.5±7.4 events $D^*\overline{D}$ in $D^* \to D\gamma$
    −0.5±2.3 vs. 36.1±7.7 events $D^*\overline{D}$ in $D^* \to D\pi^0$
  - however introduces a bias below threshold

BESIII, Phys. Rev. Lett. 97 (2006) 162002



BESIII, Phys. Rev. Lett. 124 (2020) 242001



Results from Flatté fit

- Values of Flatté energy parameter E_f close to $D^{*0}D^0$ threshold are disfavored; stable fits only for negative values of E_f (as also observed by LHCb)
- practical solution: fix $m_0 = 3864.5$ MeV corresponding to $E_f = -7.2$ MeV (adopted from LHCb)
- Result: scattering length is negative and large (larger than scale of strong interaction, ~1 fm) (weakly attractive interaction excluded, would be positive)

We search for the best lineshape fitted to the $M(D^0\bar{D}^{*0})$ distribution when the following ratios of parameters are fixed to the values measured at LHCb: dg/dE_f is fixed to -15.11 GeV^{-1}, and f_ρ/E_f and Γ_0/E_f are fixed based on the measurements $f_\rho = 1.8 \times 10^{-3}$ and $\Gamma_0 = 1.4$ MeV, and the assumption $E_f = -7.2$ MeV. Thus, only g is floated as a free parameter.

$$E_f = m_0 - (m_{D^0} + m_{D^{*0}})$$

TABLE V. Summary of the seven parameter sets used in the evaluation of lower limits on the coupling constant g, showing the g of the best fit, the g lower limits, and corresponding E_f upper limits. The parameter sets are the center values of dg/dE_f, Γ_0, and f_ρ measured at LHCb [26] (1), changing dg/dE_f by $+1\sigma$ (2), changing dg/dE_f by -1σ (3), changing Γ_0 by $+1\sigma$ (4), changing Γ_0 by -1σ (5), changing f_ρ by $+1\sigma$ (6), and changing f_ρ by -1σ (7). For the parameter set (7), no lower limit is determined, because no best fit is found in the range $g < 50$.

Parameter set	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dg/dE_f (GeV^{-1})	-15.11	-14.95 $(+1\sigma)$	-15.27 (-1σ)	-15.11	-15.11	-15.11	-15.11
Γ_0/E_f	-0.19	-0.19	-0.19	-0.29 $(+1\sigma)$	-0.09 (-1σ)	-0.19	-0.19
f_ρ/E_f (GeV^{-1})	-0.25	-0.25	-0.25	-0.25	-0.25	-0.38 $(+1\sigma)$	-0.12 (-1σ)
g of best fit	0.29	0.27	0.31	0.21	0.46	0.17	> 50
g lower limit at 90% C.L.	> 0.143	> 0.136	> 0.151	> 0.105	> 0.212	> 0.094	—
at 95% C.L.	> 0.113	> 0.108	> 0.119	> 0.082	> 0.167	> 0.075	—
E_f upper limit at 90% C.L. (MeV)	< -9.5	< -9.0	< -10.0	< -6.9	< -14.0	< -6.2	—
at 95% C.L. (MeV)	< -7.6	< -7.2	< -7.9	< -5.5	< -11.1	< -5.0	—

UPPER LIMIT

Results from Breit-Wigner fit

New 2023

Belle, Phys. Rev.D 107 (2023) 112011

$$m_{\rm BW} = 3873.71^{+0.56}_{-0.50}({\rm stat}) \pm 0.13({\rm syst})\ \text{MeV}$$

$$\Gamma_{\rm BW} = 5.2^{+2.2}_{-1.5}({\rm stat}) \pm 0.4({\rm syst})\ \text{MeV}$$

- reminder: in $D^{*0}\overline{D}^0$ mode only
- Pure *S*-wave assumed
  (limit on *D*-wave <4% at 95% C.L., LHCb Phys. Rev. D 92 (2015) 011102)
- Difference between $m_{\rm BW}$ and threshold

  $$2.02^{+0.56}_{-0.50}({\rm stat}) \pm 0.08({\rm syst})\ \text{MeV}$$

  significantly (2 MeV) higher than in $J/\psi\pi^+\pi^-$

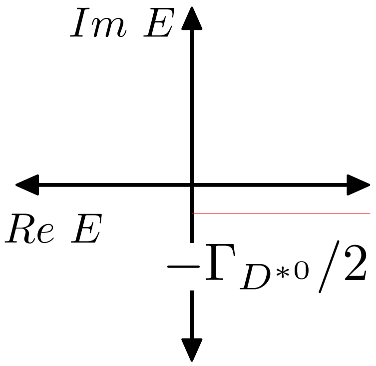
  (which was consistent with zero)
- Width is significantly larger than 1 MeV,
  weakens the anticipated impact of future sub-MeV experiments

Comparison of lineshape analyses of X(3872)

	Mass resolution (near peak)	Coupling g (from fit)
LHCb, Breit-Wigner, B decays $J/\psi\pi^+\pi^-$ only 3871.695 $\pm$ 0.067 $\pm$ 0.068 $\pm$ 0.010 MeV (BW, relativ to ψ') 1.39 $\pm$ 0.24 $\pm$ 0.10 (BW) Phys. Rev. D 102 (2020) 092005	2.4$-$3.0 MeV	
LHCb, Flatté, B decays $J/\psi\pi^+\pi^-$ only 3871.66 $^{+0.07}_{-0.06}$ $^{+0.11}_{-0.13}$ MeV (Flatté) 1.4 $\pm$ 0.4 $\pm$ 0.6 MeV (for m_0 fixed at $-$7.2 MeV) (Flatté) Phys. Rev. D 102 (2020) 092005 (2 poles, real part of energy +0.06 and $-$3.58 MeV)	2.4$-$3.0 MeV	$0.108 \pm 0.003^{+0.005}_{-0.006}$
BESIII, $e^+e^- \to \gamma X(3872)$ $DD\pi$ and $J/\psi\pi^+\pi^-$, coupled channel 3871.63 $\pm$ 0.13 $^{+0.06}_{-0.05}$ MeV (Flatté) 2.67 $\pm$ 1.77 $^{+8.01}_{-0.82}$ MeV (Flatté) arXiv:2309.01502 [hep-ex] (2 poles, real part of energy +0.26 and +7.04 MeV)	0.82 MeV ($DD\pi$) 1.90 MeV ($J/\psi\pi\pi$)	$0.16 \pm 0.10^{+1.12}_{-0.11}$
Belle, Breit-Wigner and Flatté, B decays D^*D only (mass constrained D^* fit) 3873.71 $^{+0.56}_{-0.50}$ $\pm$ 0.13 MeV (BW) 5.2 $^{+2.2}_{-1.5}$ $\pm$ 0.4 MeV (BW) Phys. Rev. D 107 (2023) 112011	0.22 MeV	$0.29^{+2.69}_{-0.15}{}^{+\infty}_{-0.029}$ (fit bias)

Systematics: natural D* width and branching constraint

- For the D^* mass, $m_{true} - m_{rec}$ is 4.8 MeV for $D\gamma$ mode, 0.8 MeV for $D\pi^0$ mode much larger than natural width (impact on line shape negligible)
  however, influence on $[DD^*]$ pair is investigated for systematics
  two MC sets: natural width 61.0 keV or 65.5 keV
  (a) mass difference and (b) interference of $X(3872) \to D^0\overline{D}^{*0},\ \overline{D}^0 D^{*0}$
  one D^* fixed (true mass), one D^* reconstructed



- BESIII D^{*0} 55.9 keV, $D^{*\pm}$ 83.4 keV, 50-70 keV for uncertainties

- LHCb 65.5 ± 15.4 keV (measured width of $D^{*\pm}$, then inserted into k_1')
  impact on pole position observed

$$k_1'(E) = \sqrt{-2\mu(E - E_R + i\Gamma_{D^{*0}}/2)}$$

Belle

$$\mathcal{B}(B \to X(3872)K) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$$
$$= \frac{\int_{m(D^0)+m(D^{*0})}^{m(B)-m(K)} f_{\text{Flatte}}(M(J/\psi\pi^+\pi^-))dM(J/\psi\pi^+\pi^-)}{\int_{m(D^0)+m(D^{*0})}^{m(B)-m(K)} f_{\text{Flatte}}(M(D^0\bar{D}^{*0}))dM(D^0\bar{D}^{*0})}$$
$$\times \mathcal{B}(B \to X(3872)K) \times \mathcal{B}(X(3872) \to D^0\bar{D}^{*0})$$
$$= \begin{cases} (8.61 \pm 0.32) \times 10^{-6} & \text{for the } B^+ \text{ mode} \\ (4.1 \pm 1.1) \times 10^{-6} & \text{for the } B^0 \text{ mode} \end{cases}$$

LHCb

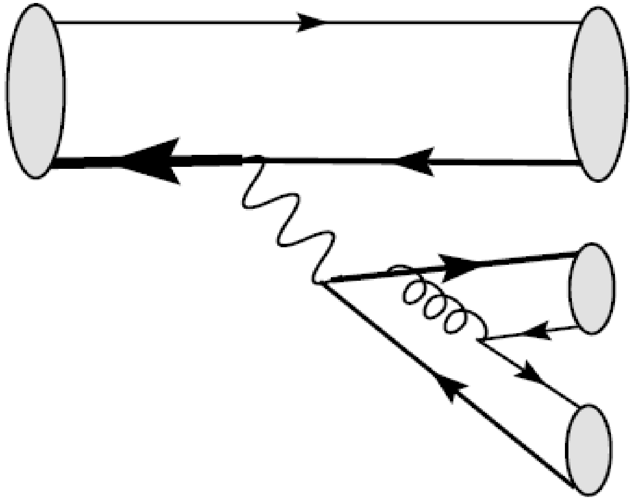
$$\frac{\Gamma(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{\Gamma(\chi_{c1}(3872) \to D^0\bar{D}^{*0})} = 0.11 \pm 0.03$$

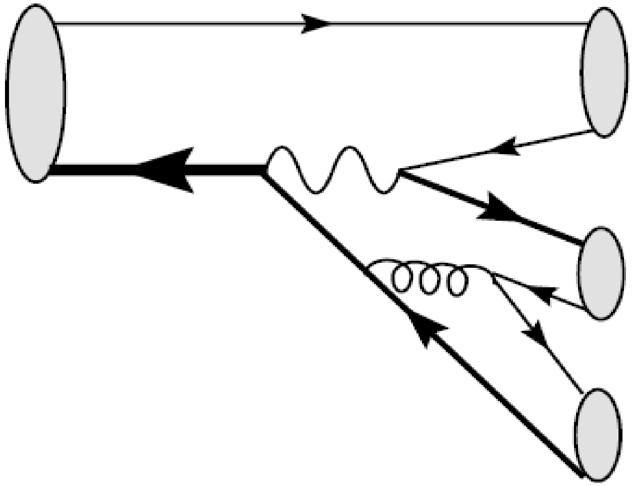
BESIII

$$\frac{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)}{\Gamma(X(3872) \to D^0\bar{D}^{*0})} = 0.05 \pm 0.01^{+0.01}_{-0.02}$$

B^+ and B^0 decays are different

Swanson, Phys. Rept. 429 (2006) 243





Color enhanced graph

$B^0 \to K^+$
$B^0 \to K^0$
$B^+ \to K^+$
$B^+ \to K^0$

any combination possible

Color suppressed graph

$B^+ \to K^+$
$B^0 \to K^0$
(charge sign changes by W,
and changes back,
$\to$ same charge for B and K)

(color is locked by spectator quark)

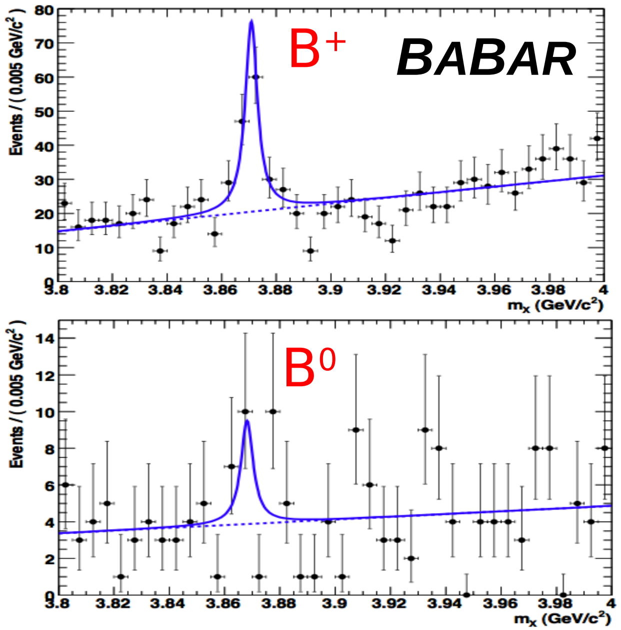
X(3872) → $J/\psi\pi^+\pi^-$, charged vs. neutral B mesons

BELLE II

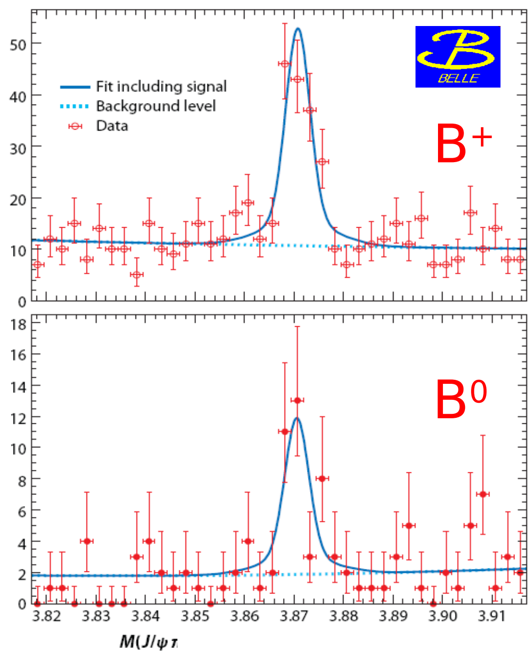
Phys. Rev. D 77(2008)111101, 413/fb

arXiv:0809.1224, 605/fb
(ICHEP 2008)

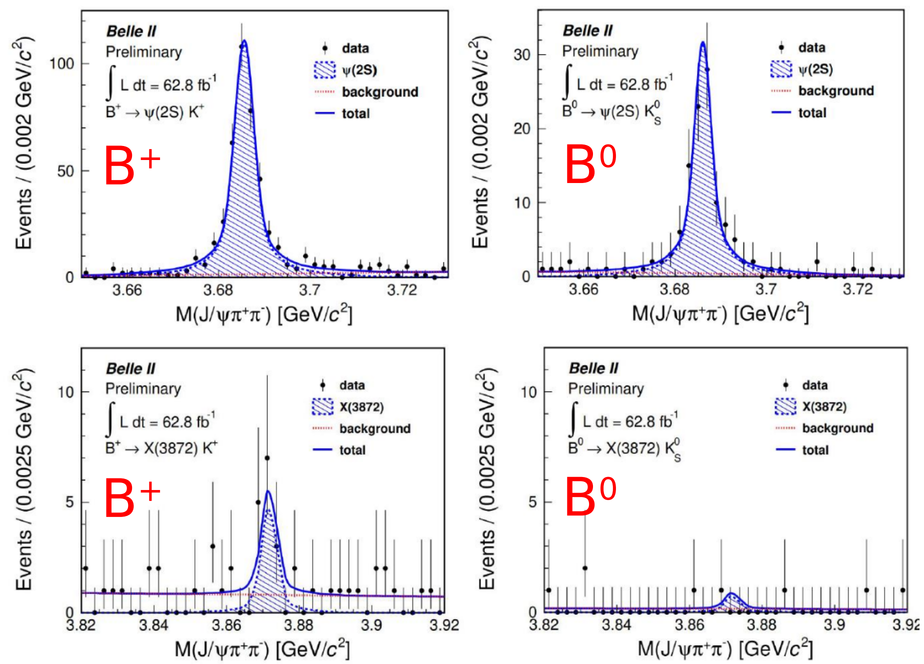
BELLE2–NOTE–PL–2021–002



$m_{J/\psi\pi+\pi-}$ / GeV



$m_{J/\psi\pi+\pi-}$ / GeV



$m_{J/\psi\pi+\pi-}$ / GeV

Presently factor ~7 more data on tape, but no reanalysis yet

https://docs.belle2.org/record/2277/files/BELLE2-NOTE-PL-2021-002.pdf?version=2

X(3872), charged vs. neutral B mesons

Ratio B^0/B^+ is a test of isopin.

- If X(3872) has no isospin (charmonium, hybrid), ratio large ($\simeq 1$)

$$\frac{\mathcal{B}(B^0 \to K^0 J/\psi)}{\mathcal{B}(B^+ \to K^+ J\psi)} = 0.873 \pm 0.026 \text{ (PDG 2023)}$$

$$\frac{\mathcal{B}(B^0 \to K^0 \psi')}{\mathcal{B}(B^+ \to K^+ \psi')} = 0.929 \pm 0.085 \text{ (PDG 2023)}$$

  Limit $= 1$, for $m(B^0)$=$m(B^+)$, $m(K^+)$=$m(K^0)$, and only constituent charm quarks

- If X(3872) is a $D^*\overline{D}$ molecule, ratio should be small (<0.1)
  B^0, K^0 contain d quarks
  B^+, K^+ contain u quarks
  D^0, D^{*0} contain u quarks
  precise calculation see Braaten, Lu, Phys. Rev. D77 (2008) 014029

- Present world average (PDG 2023), dominated by $J/\psi\pi\pi$

$$\frac{\mathcal{B}(B^0 \to K^0 X(3872))}{\mathcal{B}(B^+ \to K^+ X(3872))} = 0.500 \pm 0.246$$

X(3872) → D*D, charged vs. neutral B mesons

$$\frac{\mathcal{B}(B^0 \to X(3872)K^0)}{\mathcal{B}(B^+ \to X(3872)K^+)} = 1.34^{+0.47}_{-0.40}(\text{stat})^{+0.10}_{-0.12}(\text{syst})$$

Efficiency is a result of the BW fit (varies near threshold)

Mode	$\mathcal{B}_{\overline{D}^{*0}} \sum \epsilon_{ij} \times \mathcal{B}_{ij}$
Combined	8.70×10^{-4}
$X(3872)K^+$	6.92×10^{-4}
$X(3872)K^0$	1.78×10^{-4}

factor ~4 (between $X(3872)K^+$ and $X(3872)K^0$)

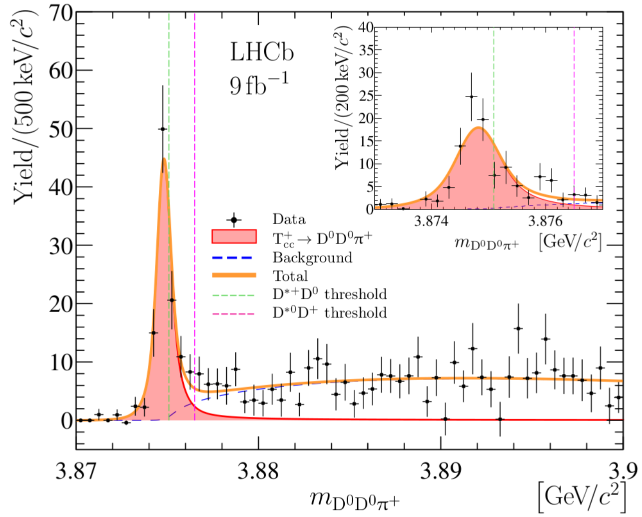
- Reminder: branching fraction of X(3872) to D^*D is factor $\simeq$10$-$20 larger than to $J/\psi\pi^+\pi^-$
- Conclusion: ratio of B^0/B^+ is very different: $\simeq$0.5 in $J/\psi\pi^+\pi^-$ vs. $\simeq$1.3 in D^*D
- Confirms former observation from Belle, Phys. Rev. D81 (2010) 031103

$$\frac{\mathcal{B}(B^0 \to X(3872)K^0)}{\mathcal{B}(B^+ \to X(3872)K^+)} = 1.26 \pm 0.65 \pm 0.06$$

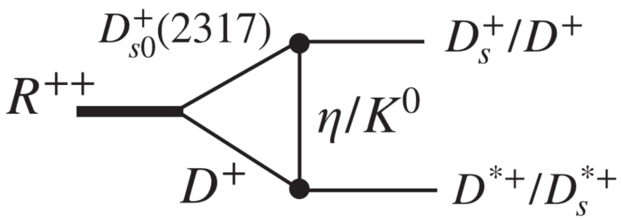
T_{cc}

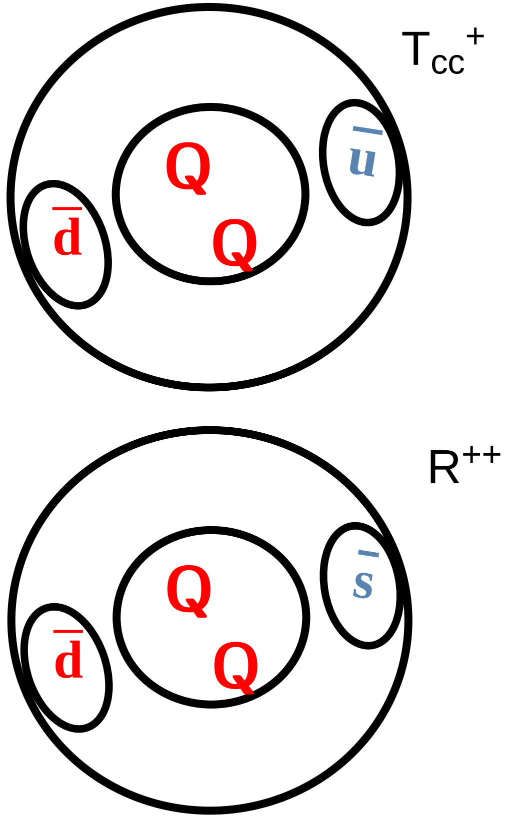
Search for R^{++}

LHCb, Nature Phys. 18 (2022) 751



- Remember T_{cc}^+, as $[D^0D^{*+}]$ state at LHCb
- $[D^+D_{s0}^{*+}(2317)]$
  predicted [DDK] molecular state by kaon exchange
  Sanchez Sanchez et al., Phys. Rev. D 98 (2018) 054001
  5-15 MeV binding energy
  mass 4.13–4.17 GeV
- Double charge (exotic nature obvious)
- $D_{s0}^{*+}(2317)$ decay to DK kinematically forbidden,
  but decay to $[D^+D_s^{*+}]$ possible by triangle diagram
- Needs two charm quarks,
  thus also two anti-charm quarks
  $\Upsilon(nS) \to cc\bar{c}\bar{c}X$
  kinematically not accessible in B decays





- → take $\Upsilon(1S)$ and $\Upsilon(2S)$ decays
  and inclusive production in e+e-
  at three energies (continuum, $\Upsilon(4S)$ and $\Upsilon(5S)$)
  Belle, Phys. Rev. D 102 (2020) 112001

R++

$c\bar{c}c\bar{c}$	~~$c\bar{s}c\bar{c}$~~	~~$c\bar{u}c\bar{c}$~~	~~$c\bar{d}c\bar{c}$~~
$c\bar{c}c\bar{s}$	$c\bar{s}c\bar{s}$	~~$c\bar{u}c\bar{s}$~~	~~$c\bar{d}c\bar{s}$~~
$c\bar{c}c\bar{u}$	$c\bar{s}c\bar{u}$	$c\bar{u}c\bar{u}$	~~$c\bar{d}c\bar{u}$~~
$c\bar{c}c\bar{d}$	$c\bar{s}c\bar{d}$	$c\bar{u}c\bar{d}$	$c\bar{d}c\bar{d}$

$c\bar{c}s\bar{c}$	~~$c\bar{s}s\bar{c}$~~	~~$c\bar{u}s\bar{c}$~~	~~$c\bar{d}s\bar{c}$~~
$c\bar{c}s\bar{s}$	$c\bar{s}s\bar{s}$	~~$c\bar{u}s\bar{s}$~~	~~$c\bar{d}s\bar{s}$~~
$c\bar{c}s\bar{u}$	$c\bar{s}s\bar{u}$	$c\bar{u}s\bar{u}$	~~$c\bar{d}s\bar{u}$~~
$c\bar{c}s\bar{d}$	$c\bar{s}s\bar{d}$	$c\bar{u}s\bar{d}$	$c\bar{d}s\bar{d}$

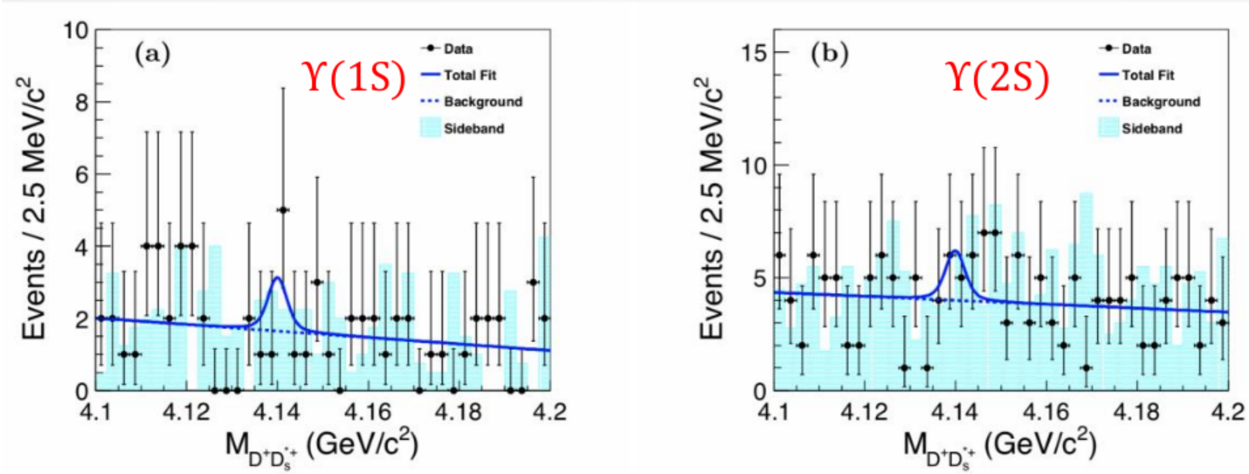
$c\bar{c}u\bar{c}$	~~$c\bar{s}u\bar{c}$~~	~~$c\bar{u}u\bar{c}$~~	~~$c\bar{d}u\bar{c}$~~
$c\bar{c}u\bar{s}$	$c\bar{s}u\bar{s}$	~~$c\bar{u}u\bar{s}$~~	~~$c\bar{d}u\bar{s}$~~
$c\bar{c}u\bar{u}$	$c\bar{s}u\bar{u}$	$c\bar{u}u\bar{u}$	~~$c\bar{d}u\bar{u}$~~
$c\bar{c}u\bar{d}$	$c\bar{s}u\bar{d}$	$c\bar{u}u\bar{d}$	$c\bar{d}u\bar{d}$

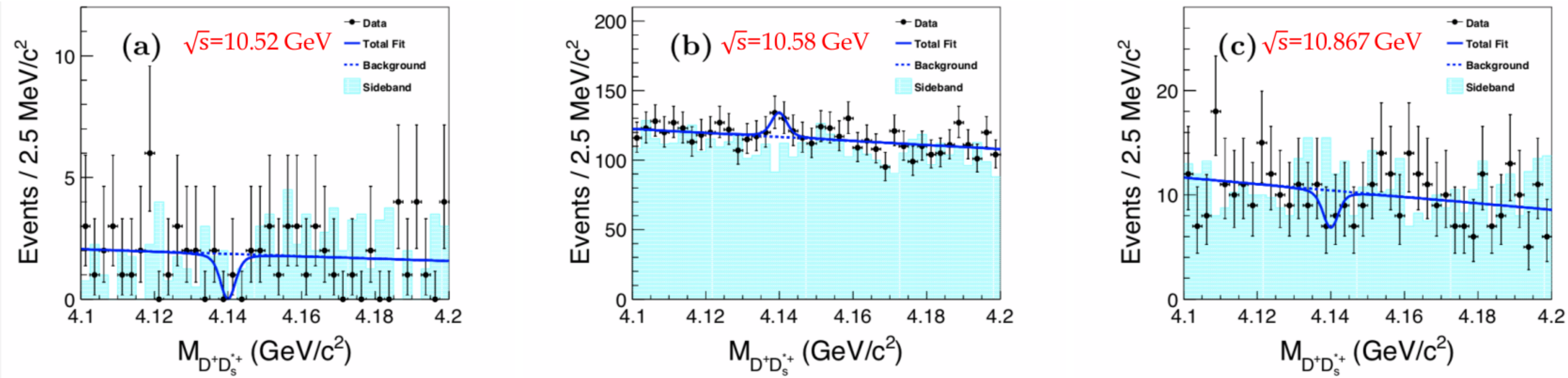
$c\bar{c}d\bar{c}$	~~$c\bar{s}d\bar{c}$~~	~~$c\bar{u}d\bar{c}$~~	~~$c\bar{d}d\bar{c}$~~
$c\bar{c}d\bar{s}$	$c\bar{s}d\bar{s}$	~~$c\bar{u}d\bar{s}$~~	~~$c\bar{d}d\bar{s}$~~
$c\bar{c}d\bar{u}$	$c\bar{s}d\bar{u}$	$c\bar{u}d\bar{u}$	~~$c\bar{d}d\bar{u}$~~
$c\bar{c}d\bar{d}$	$c\bar{s}d\bar{d}$	$c\bar{u}d\bar{d}$	$c\bar{d}d\bar{d}$

Search for R^{++}

Belle, Phys. Rev. D 102 (2020) 112001

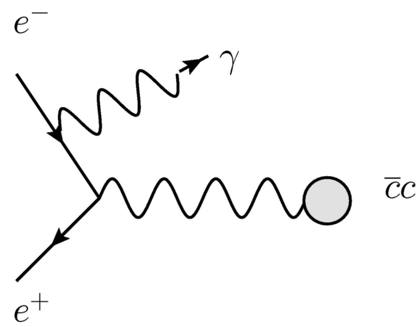
Fit examples for fixed mass 4.14 GeV/c^2 and fixed width 2 MeV





No signal observed. Upper limits on cross sections are small (order of few fb)

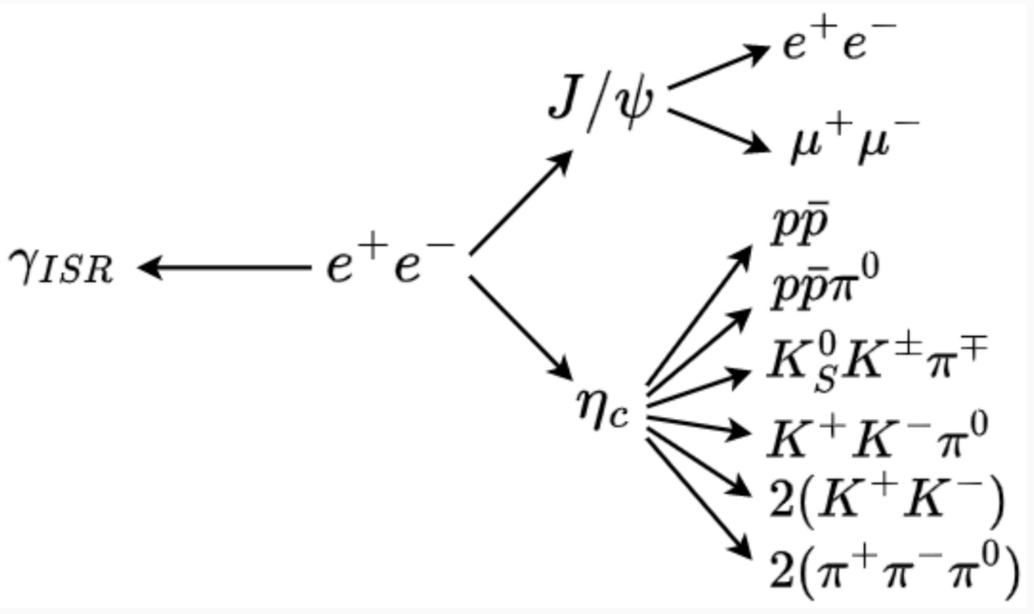
Search for Y_{cc}



NEW 2023
Belle, JHEP 08 (2023) 121
Junhao Yin and team
(Korea University)

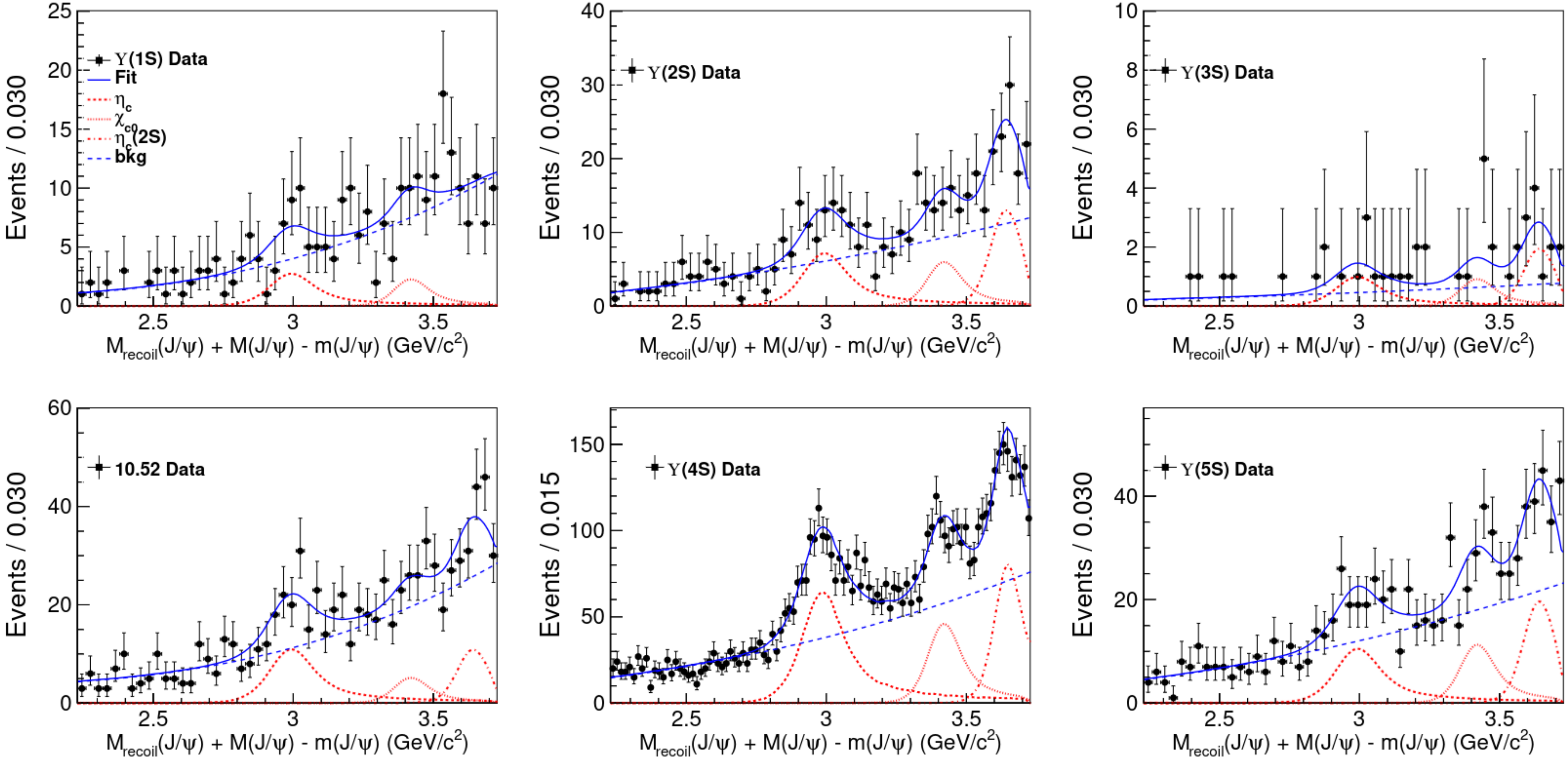
- Search for T_{cc} $[c\bar{c}c\bar{c}]$, but in ISR
  $\rightarrow$ vector state Y_{cc}
- $[J\psi\eta_c]$ threshold is 6081 MeV
  $J^{PC} = 1^{--}$ can be reached by P-wave (L=1), suppressed by (2L+1)
- $[h_c\eta_c]$ threshold is 6509 MeV
  $J^{PC} = 1^{--}$ can be reached by S-wave (L=0)
  decay to $J\psi\eta_c$ is open
- $\Upsilon(nS)(n$=1−5) and 10.52 GeV (off-resonance)
  955 fb^{-1} (total Belle data set)

exclusive analysis: J/ψ reconstructed η_c reconstructed $\leq$3 extra tracks
inclusive analysis (J/ψ or $J/\psi\gamma_{ISR}$): J/ψ reconstructed ISR photon $E\gamma \geq$1 GeV $\geq$4 tracks
suppress $B\overline{B}$ by $R_2 \geq 0.13$



Search for Y_{cc}

NEW 2023
Belle, JHEP 08 (2023) 121

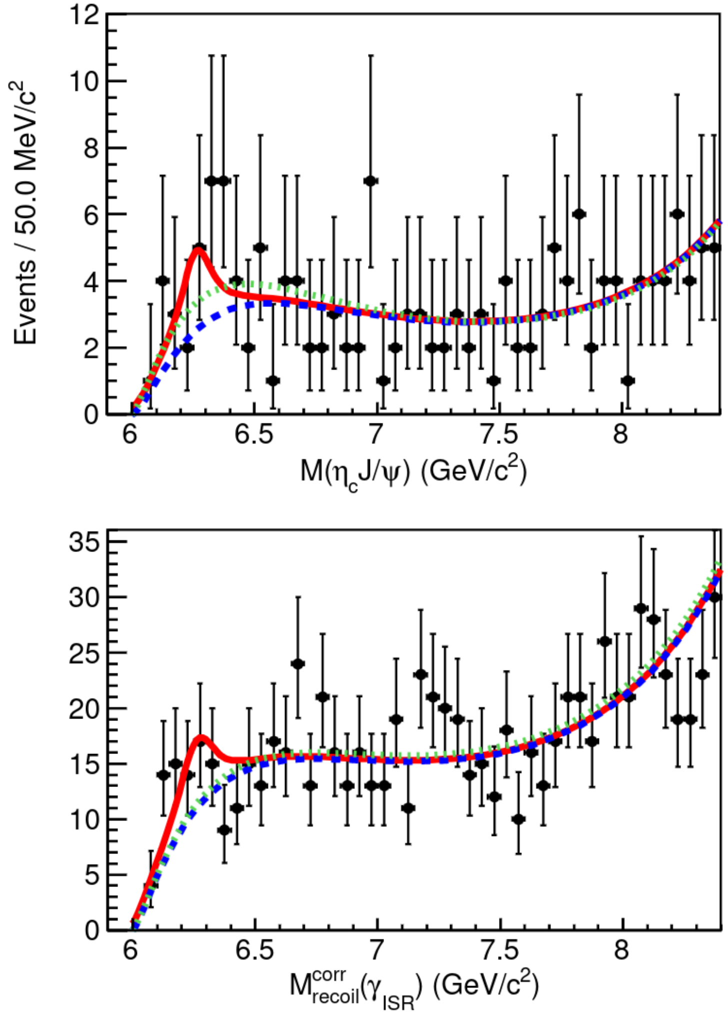


$$\mathrm{M_{recoil}}(J/\psi) \equiv \sqrt{|p_{e^+e^-} - p(J/\psi)|^2}$$

subtracting resolution by using PDG mass m(J/ψ)

Search for Y_{cc}

NEW 2023
Belle, JHEP 08 (2023) 121



Simultaneous unbinned maximum likelihood fit for $[J/\psi\eta_c]$ invariant mass and γ_{ISR} recoil mass

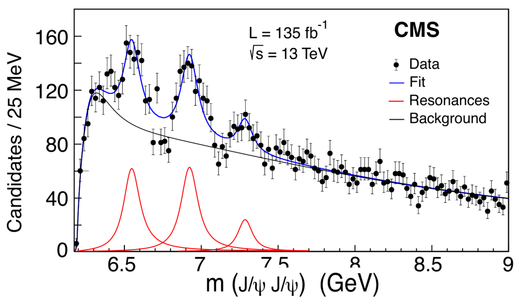
- Signal shape: Breit-Wigner, free mass and width, convolved with Gaussian from resolution study
- Background shape: ARGUS function, parameters from fit to the η_c and J/ψ sideband
- Signal-yield fractions fixed from signal MC

Mass resolution ~15 MeV

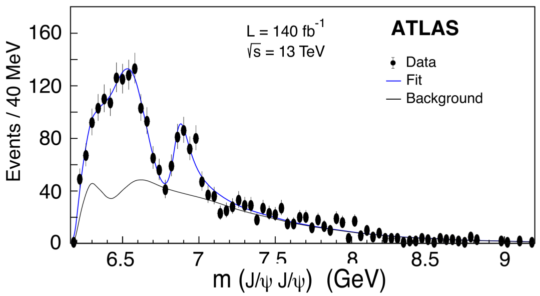
Signal efficiency ~4%

Reminder: yield in P-wave suppressed by factor 3

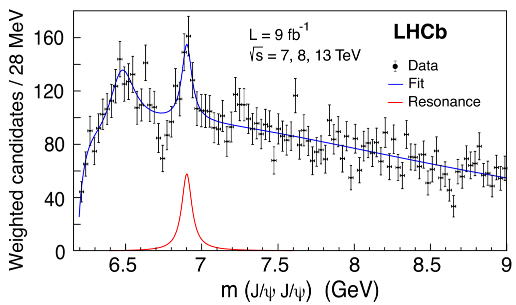
arXiv:2006.16957



arXiv:2304.08962



arXiv:2306.07164



Significance 2.1σ

Mass 6267 ± 43 MeV

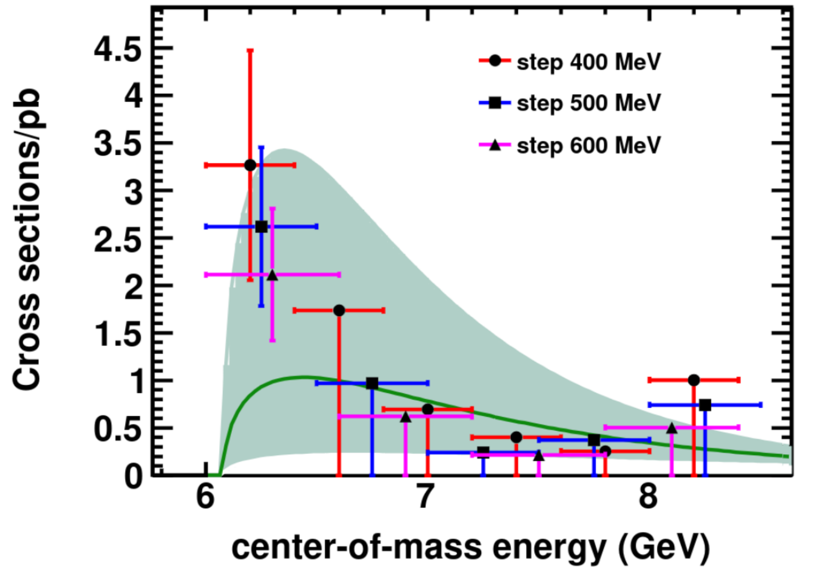
Width 121 ± 72 MeV

Search for Y_{cc}

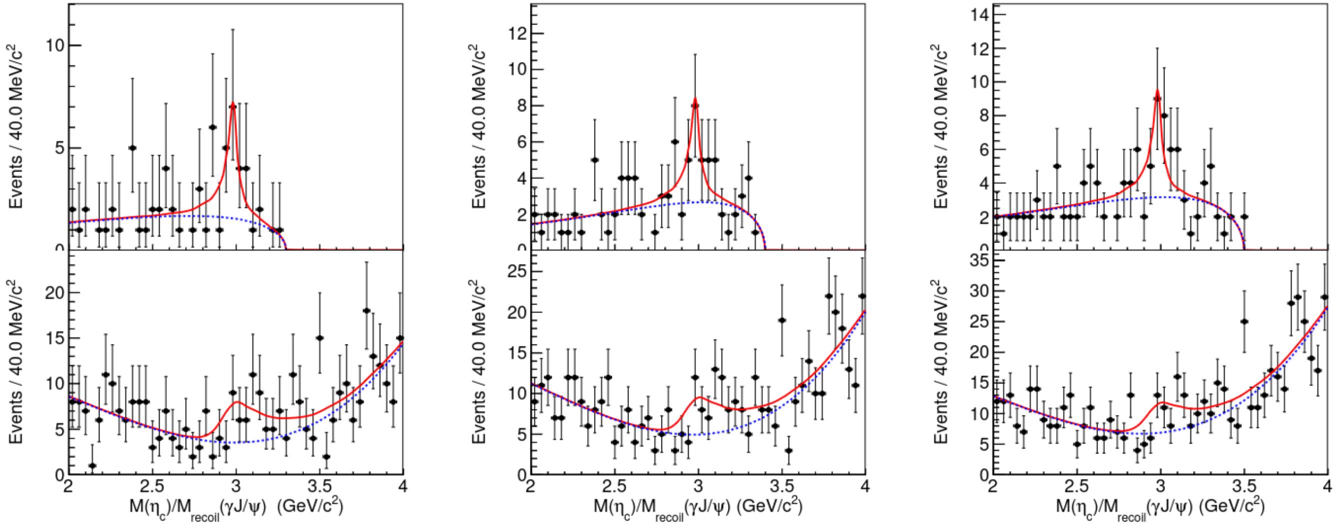
NEW 2023
Belle, JHEP 08 (2023) 121

Simultaneous unbinned maximum likelihood fit to reconstructed η_c mass and $[\gamma_{ISR} J/\psi]$ recoil mass

- Signal shapes: from MC (smoothed)
- Background shapes: ARGUS for exclusive, third-order-polynomial for inclusive analysis
- Signal-yield fractions fixed from signal MC



Statistical significance of enhancement near threshold 3.3σ



Fit curve $$\sigma = A \frac{\overbrace{\sqrt{2\mu\Delta M}}^{\text{Flatté – like } k \text{ factor}}}{\left(\frac{s}{s_0}\right)^n}$$

$$\mu = \frac{m(\eta_c)m(J/\psi)}{m(\eta_c)+m(J/\psi)}$$

$$\Delta M = \sqrt{s} - m(\eta_c) - m(J/\psi)$$

T_{cs}

T_{cs} searches at Belle

Neutral or doubly charged D_s must be exotic.

- B meson decay channel of $X_0(2900)$ $[cs\bar{u}\bar{d}]$ (J^P=0^+) and $X_1(2900)$ $[cs\bar{u}\bar{d}]$ (J^P=1^-) was investigated by BaBar PRD 83(2011)032004 and Belle PRL 93(2004)051803 :

  $B^+ \to K^+ D^+ D^-$

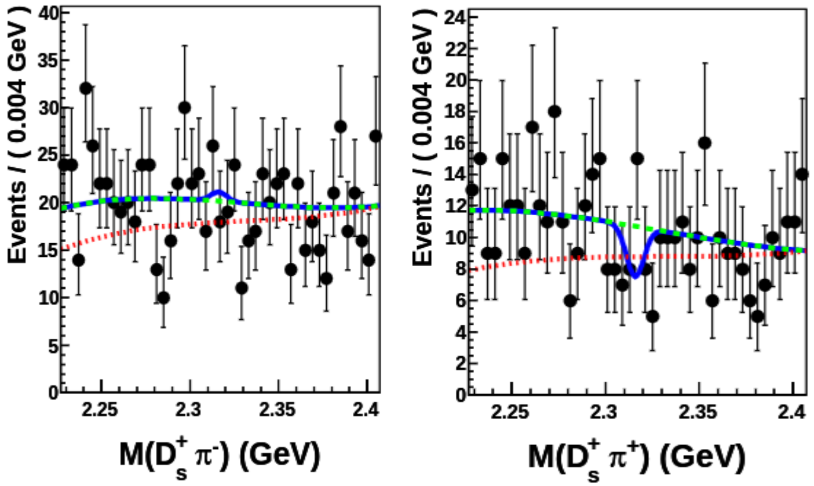
  $[D^- K^+]$ mass was not investigated.

- B meson decay channels of $T_{cs}^{++}(2900)$ $[c\bar{s}u\bar{d}]$ (J^P=0^+) and $T_{cs}^{0}(2900)$ $[c\bar{s}d\bar{u}]$ (J^P=0^+) were investigated by Belle PRD 91(2015)092011, as it contains $D_{s0}^*(2317)$:

  $B^0 \to \pi^- \overline{D}^0 D_s^+$

  $B^+ \to \pi^+ D^- D_s^+$

  $[D_s^+ \pi^\pm]$ mass was only investigated up to 2.4 GeV.



For other states with $D_s^{(*)}$ $D_s^{(*)}$,
see talk by Elisabetta Prencipe

ABSOLUTE BRANCHING FRACTION

PDG 2020

$\chi_{c1}(3872)$

$I^G(J^{PC}) = 0^+(1^{++})$

also known as $X(3872)$

Mass $m = 3871.69 \pm 0.17$ MeV
$m_{\chi_{c1}(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
Full width $\Gamma < 1.2$ MeV, CL = 90%

χ_{c1}(3872) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi^+\pi^- J/\psi(1S)$	> 3.2 %	650
$\omega J/\psi(1S)$	> 2.3 %	†
$D^0 \overline{D}^0 \pi^0$	> 40 %	117
$\overline{D}^{*0} D^0$	> 30 %	4
$\pi^0 \chi_{c1}$	> 2.8 %	319
$\gamma J/\psi$	$> 7 \times 10^{-3}$	697
$\gamma \psi(2S)$	> 4 %	181
$\pi^+\pi^- \eta_c(1S)$	not seen	745
$\pi^+\pi^- \chi_{c1}$	not seen	218
$p\overline{p}$	not seen	1693

100% ?

PDG 2021

$\chi_{c1}(3872)$

$I^G(J^{PC}) = 0^+(1^{++})$

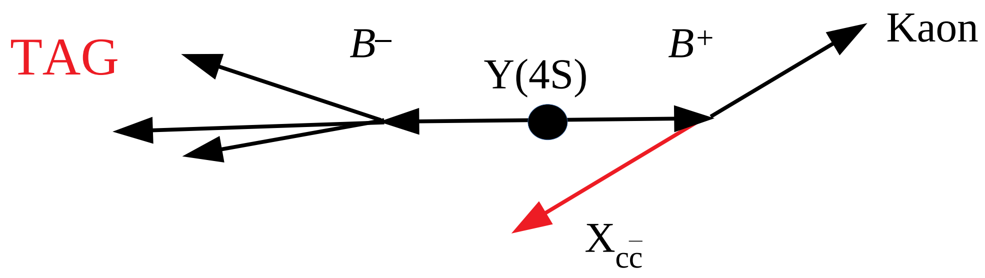
also known as $X(3872)$

Mass $m = 3871.65 \pm 0.06$ MeV
$m_{\chi_{c1}(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
Full width $\Gamma = 1.19 \pm 0.21$ MeV (S = 1.1)

χ_{c1}(3872) DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
e^+e^-	$< 2.8 \times 10^{-6}$	90%	1936
$\pi^+\pi^- J/\psi(1S)$	(3.8 ± 1.2) %		650
$\pi^+\pi^-\pi^0 J/\psi(1S)$	not seen		588
$\omega \eta_c(1S)$	< 33 %	90%	368
$\omega J/\psi(1S)$	(4.3 ± 2.1) %		†
$\phi\phi$	not seen		1646
$D^0 \overline{D}^0 \pi^0$	$(49 {}^{+18}_{-20})$ %		116
$\overline{D}^{*0} D^0$	(37 ± 9) %		†
$\gamma\gamma$	< 11 %	90%	1936
$D^0 \overline{D}^0$	< 29 %	90%	519
$D^+ D^-$	< 19 %	90%	502
$\pi^0 \chi_{c2}$	< 4 %	90%	273
$\pi^0 \chi_{c1}$	(3.4 ± 1.6) %		319
$\pi^0 \chi_{c0}$	< 70 %	90%	–
$\pi^+\pi^- \eta_c(1S)$	< 14 %	90%	745
$\pi^+\pi^- \chi_{c1}$	$< 7 \times 10^{-3}$	90%	218
$p\overline{p}$	$< 2.4 \times 10^{-5}$	95%	1693
Radiative decays			
$\gamma D^+ D^-$	< 4 %	90%	502
$\gamma \overline{D}^0 D^0$	< 6 %	90%	519
$\gamma J/\psi$	$(8 \pm 4) \times 10^{-3}$		697
$\gamma \chi_{c1}$	$< 9 \times 10^{-3}$	90%	344
$\gamma \chi_{c2}$	< 3.2 %	90%	303
$\gamma \psi(2S)$	(4.5 ± 2.0) %		181
***C*-violating decays**			
$\eta J/\psi$	< 1.8 %	90%	491

$B^+ \to K^+ X_{c\bar{c}}$

Particular situation at Υ(4S): $m(\Upsilon(4S)) = m_B + m_{\overline{B}}$
$\to B$ mesons at rest in cms system



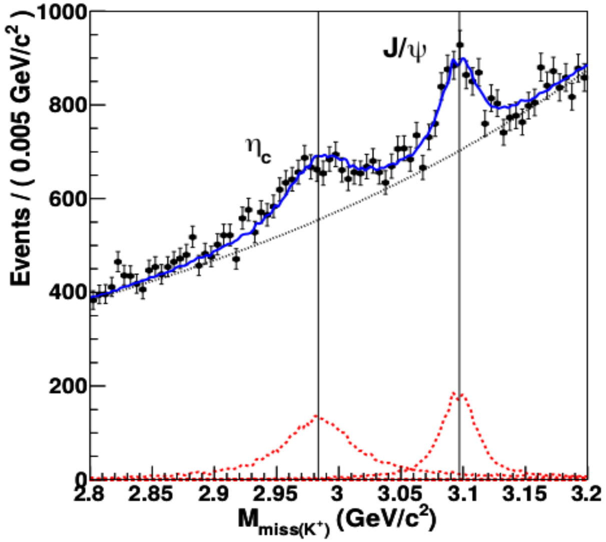
Hierarchical full reconstruction of 1104 hadronic decays
NeuroBayes neural-network package
M. Feindt, F. Keller, M. Kreps, T. Kuhr, S. Neubauer, D. Zander, A. Zupanc
Nucl. Instrum. Meth. A654 (2011) 432

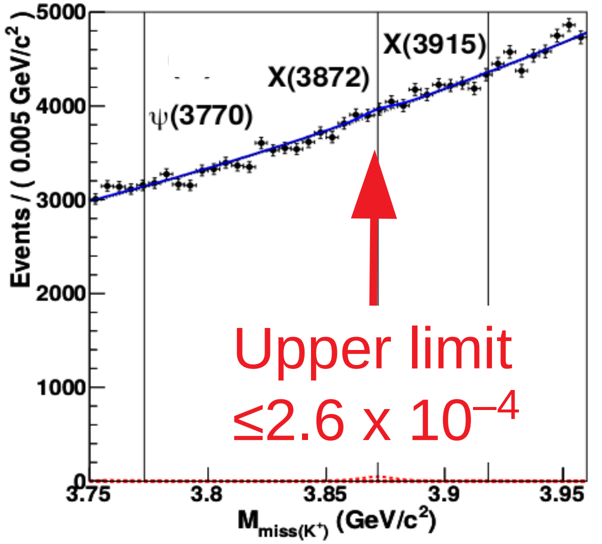
Disadvantage: reconstruction efficiency small (requires tag side)
$\varepsilon \leq 0.26$ %

Absolute branching fractions in $B^+ \to K^+ X_{c\bar{c}}$

Belle, Phys. Rev. D97 (2018) 012005

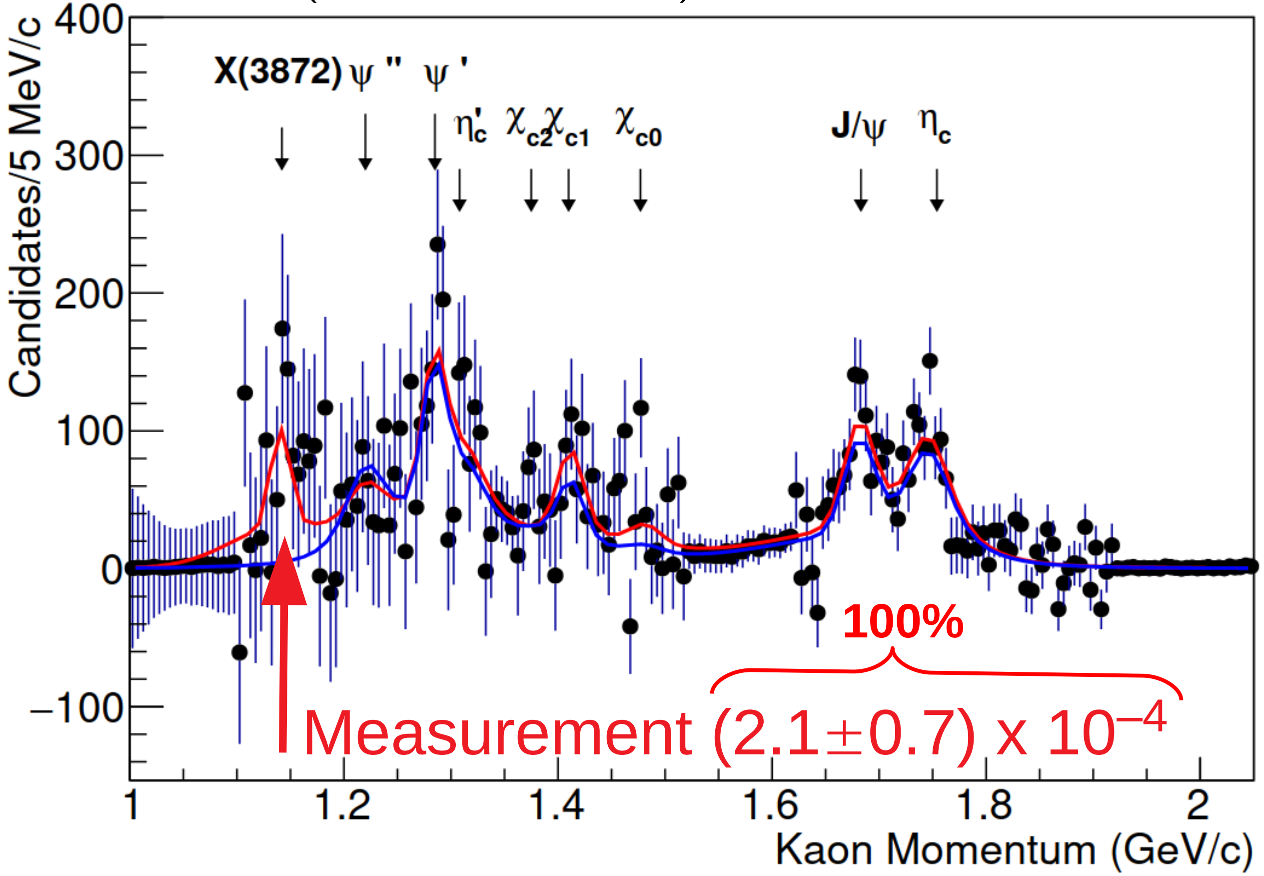
711 fb^{-1} (full Belle data set)





BaBar, Phys.Rev.Lett. 124 (2020) 152001

424 fb^{-1} (full BaBar data set)



p($K^\pm$) in the *B* meson rest frame

$$M_{\mathrm{miss(h)}} = \sqrt{(p^*_{\mathrm{e^+e^-}} - p^*_{\mathrm{tag}} - p^*_{\mathrm{h}})^2}/c$$

Belle II can improve error to ≤0.1 with 50 ab^{-1}

Conclusion and Outlook

- Long shutdown 1 sucessfully completed, next beams (start of run 2) planned for January 29, 2024
- New results in 2023:
  - X(3872) lineshape in $D^*\overline{D}$ (mass resolution 220 keV)
  - Search for T_{cc}
- Production modes: B decays, ISR, Υ decays, e^+e^- continuum, ... (different quantum numbers accessible)
- Cross sections carry surprising information, see e.g. X(3872)
- Target in 2024: 2 ab^{-1} combined Belle and Belle 2 data set ("2 x Belle")
- NUPECC Long Range Plan, Input from Belle II https://arxiv.org/abs/2212.09182