

Hadron Physics at Charm & B factories and JLab – Presence and Perspectives

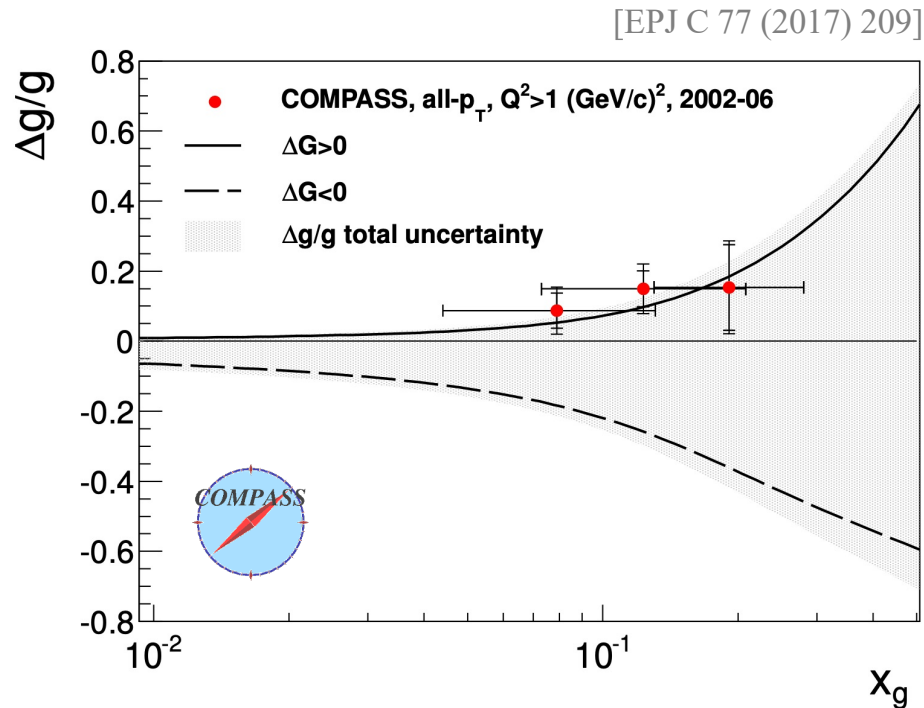
Frank Nerling
HFHF, Campus Frankfurt

KHuK Annual Meeting 2021
2021, Dec 9th - 10th

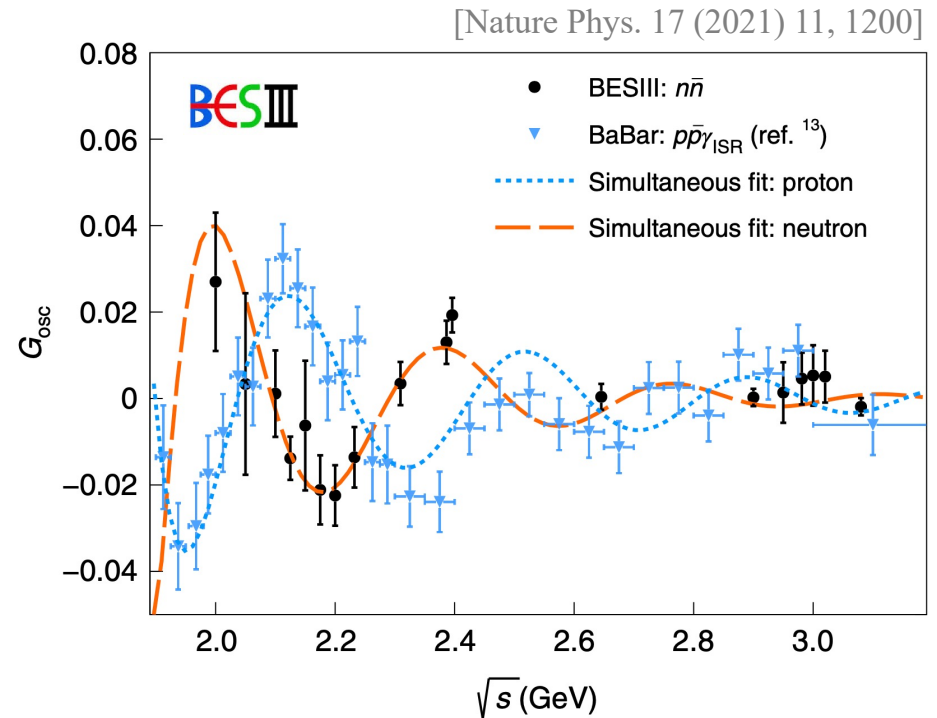
Outline

- **Introduction & motivation**
- **A selection of recent highlight results**
 - Supernumerary vector Y states
 - Manifestly exotic Z_c states
- **Overview & outlook**
 - Involvement of german groups
 - Future opportunities
- **Summary**

Hadron Structure



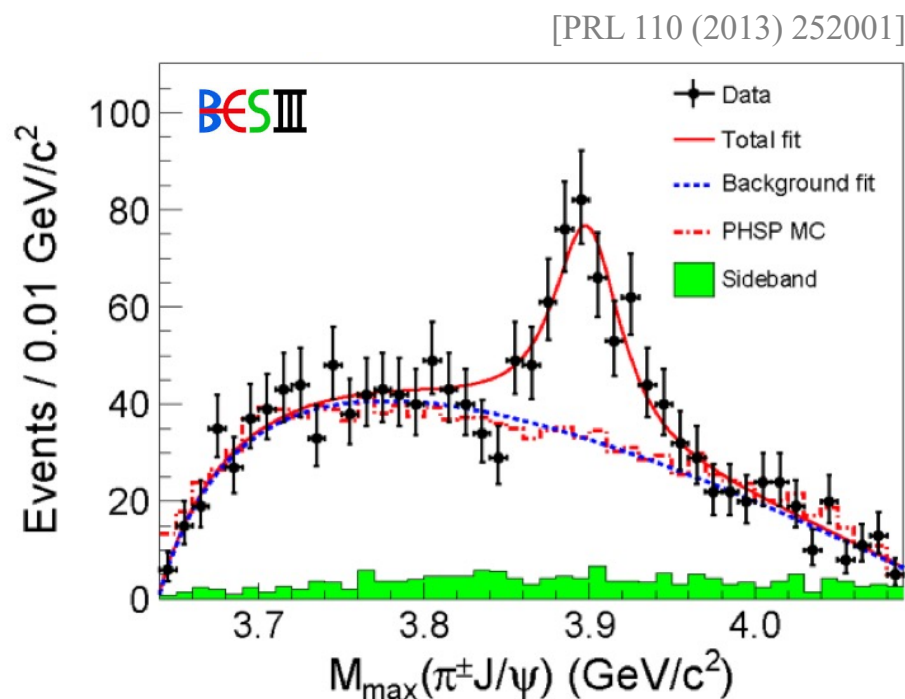
**proton spin $\frac{1}{2}$
not yet understood**



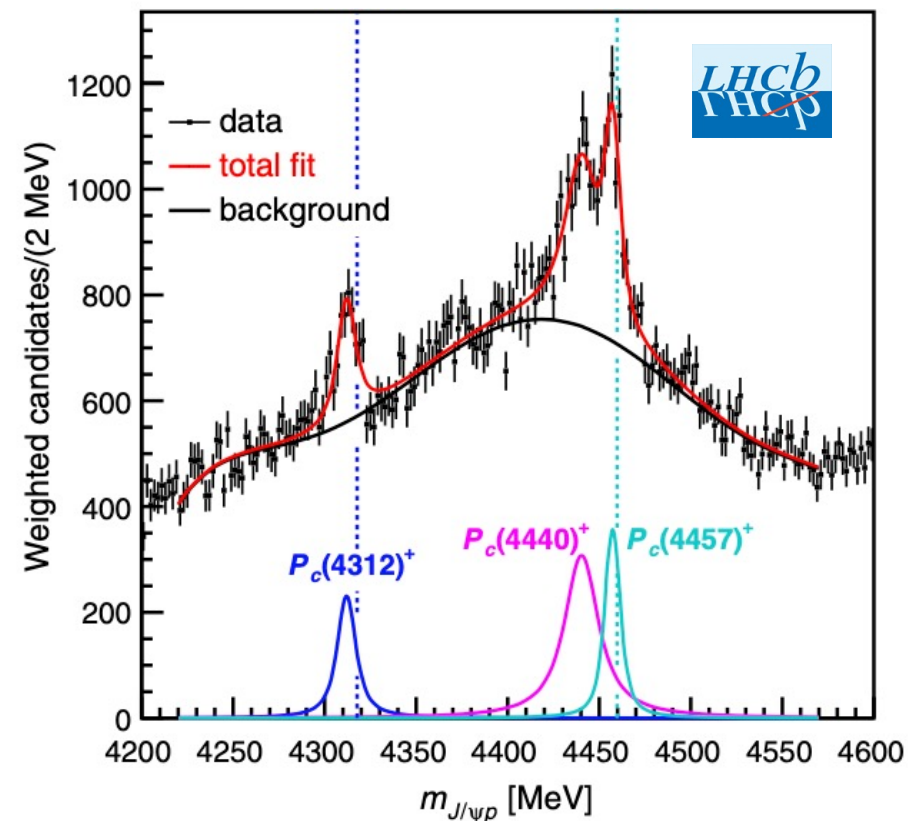
**oscillating features of
neutron structure**

Hadron Spectroscopy

[PRL 122 (2019) 222001]



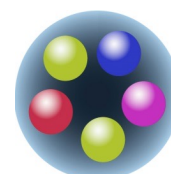
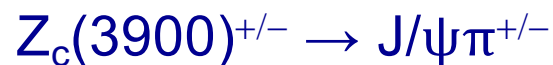
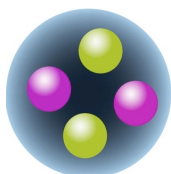
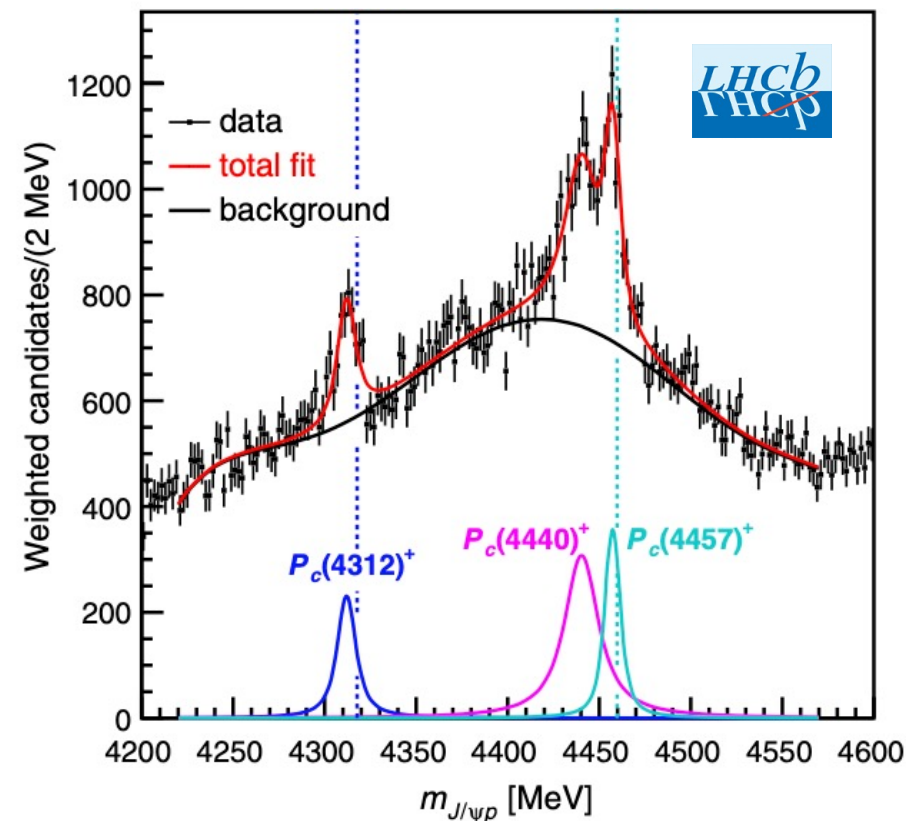
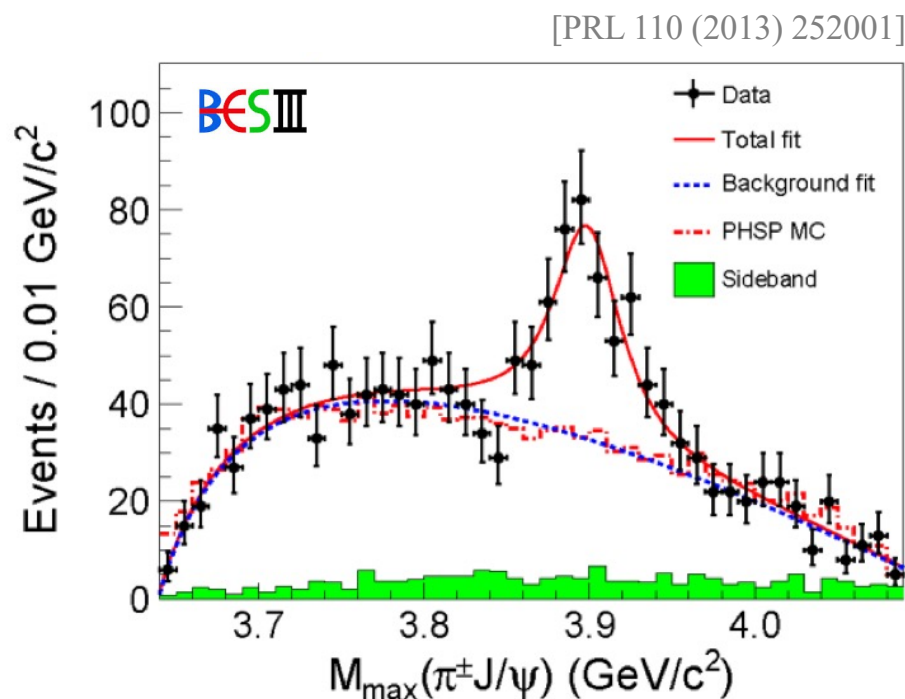
$$Z_c(3900)^{+/-} \rightarrow J/\psi \pi^{+/-}$$

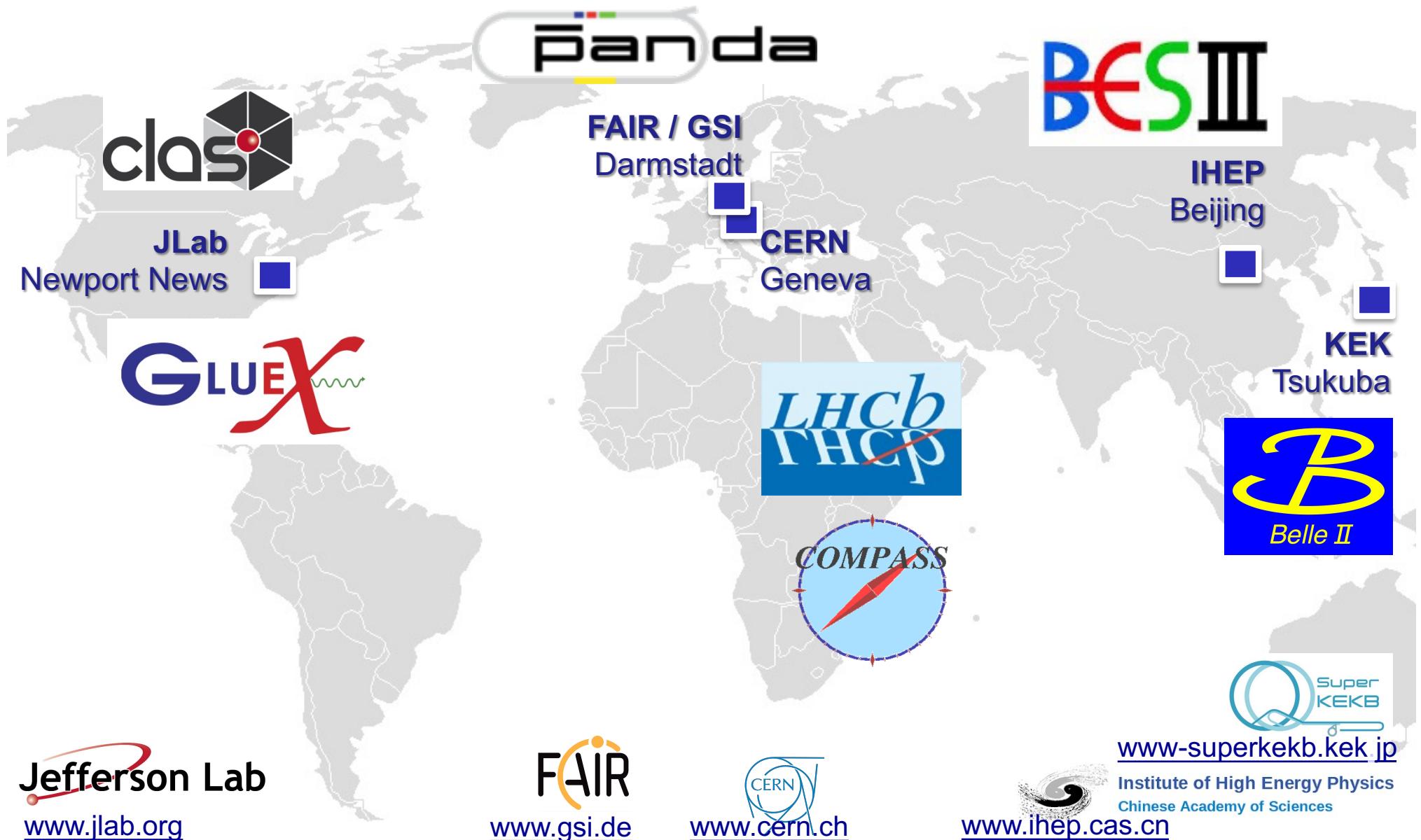


$$P_c(4xxx)^+ \rightarrow J/\psi p \text{ (incl. c.c.)}$$

Hadron Spectroscopy

[PRL 122 (2019) 222001]



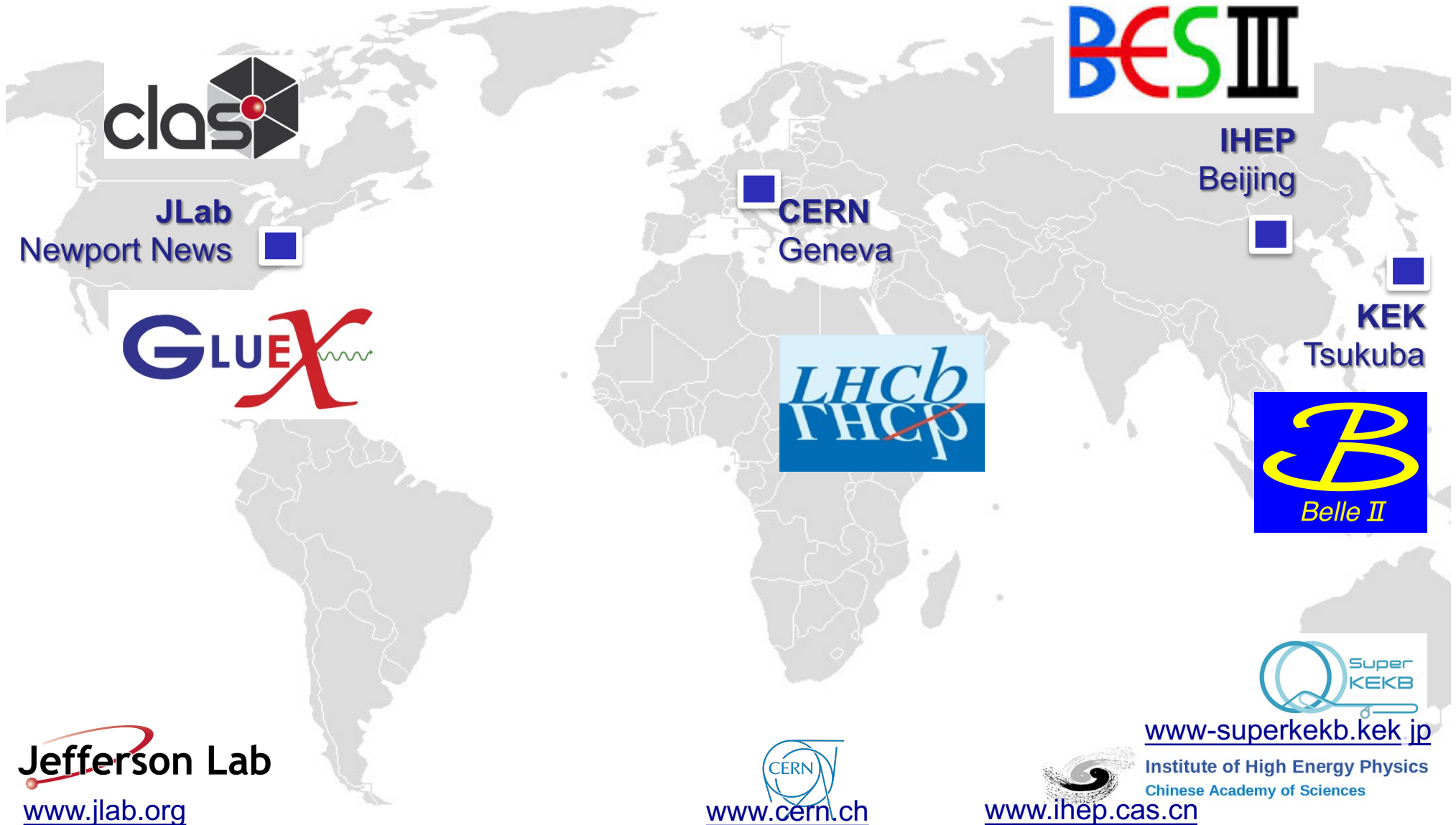


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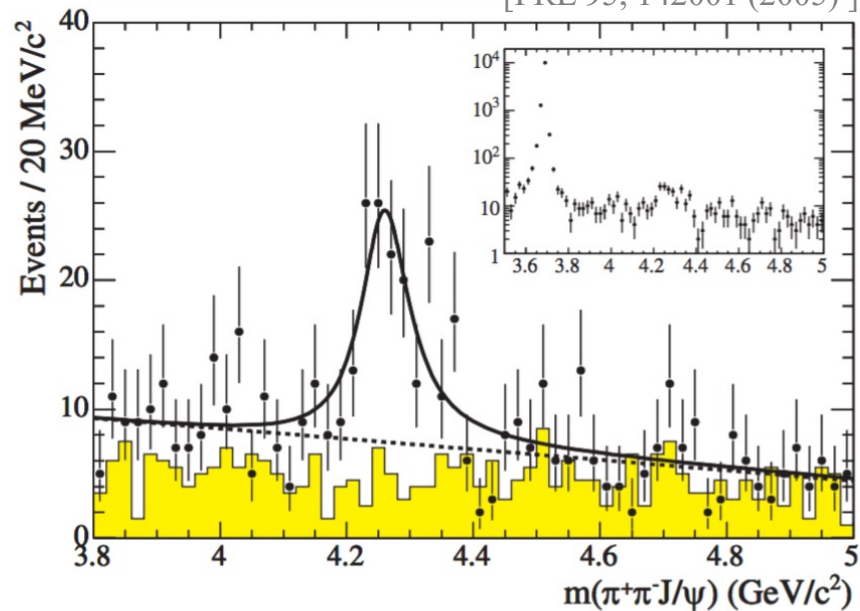
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The $Y(4260)$ and further supernumerary vector states

Some history:

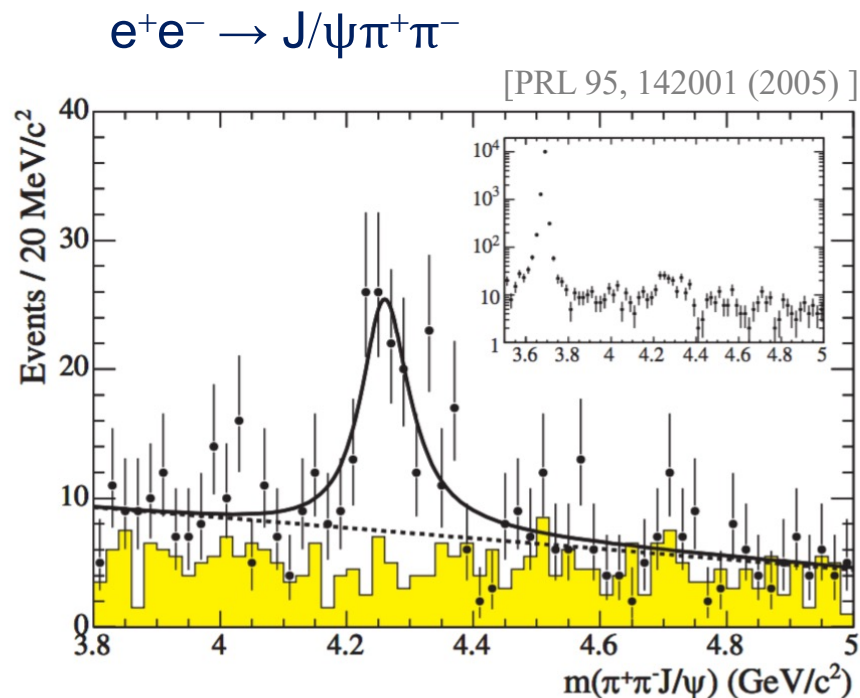
$$e^+e^- \rightarrow J/\psi\pi^+\pi^-$$

[PRL 95, 142001 (2005)]

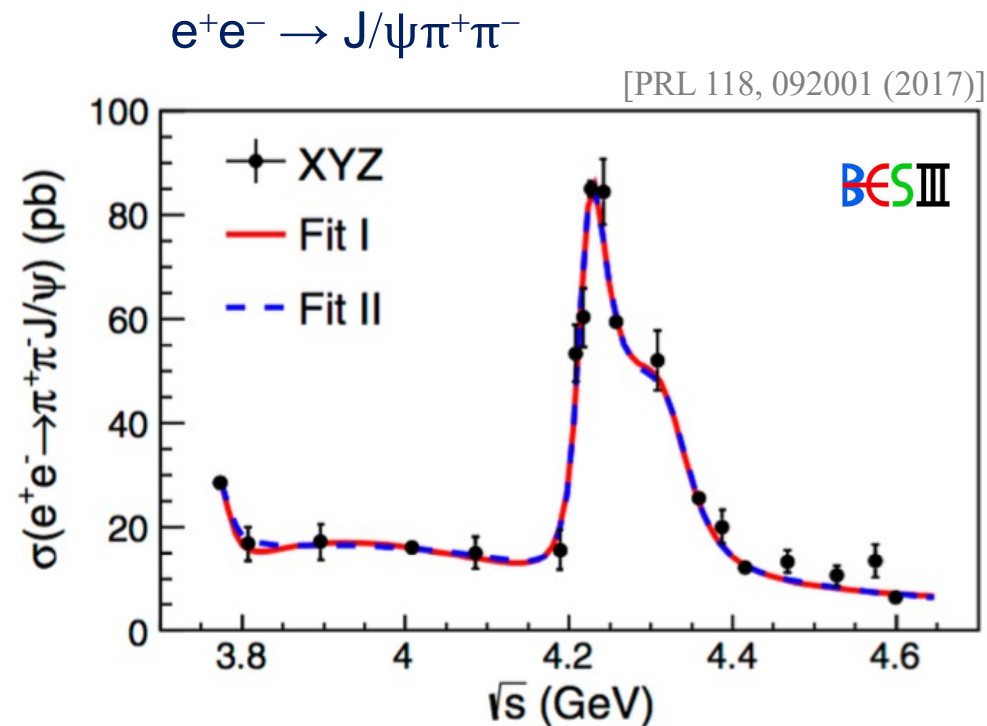


- Discovery of the $Y(4260)$ using ISR by BaBar in $J/\psi\pi^+\pi^-$

Some history:



BESIII result:

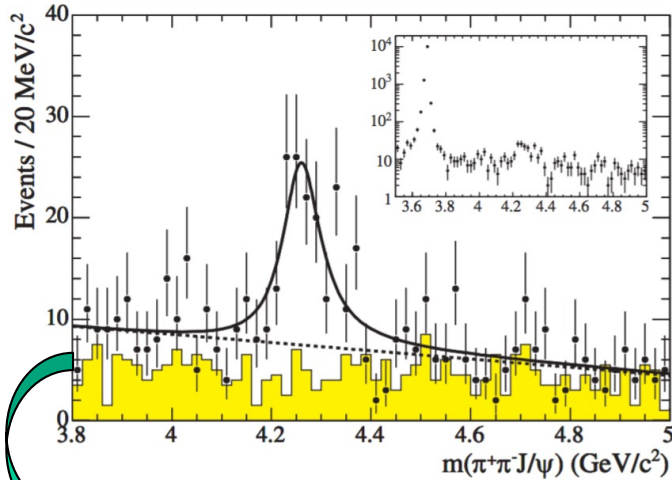


- Discovery of the $Y(4260)$ using ISR by BaBar in $J/\psi\pi^+\pi^-$

- Cross-section inconsistent with the single resonance $Y(4260)$!
 - Two favoured over one by $>7\sigma$

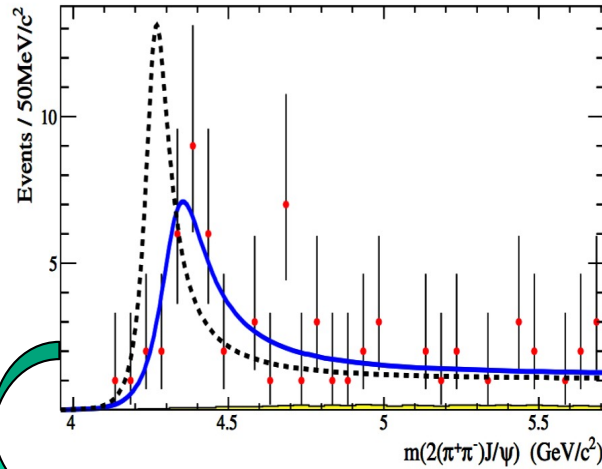
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[BaBar, PRL 95, 142001 (2005)]

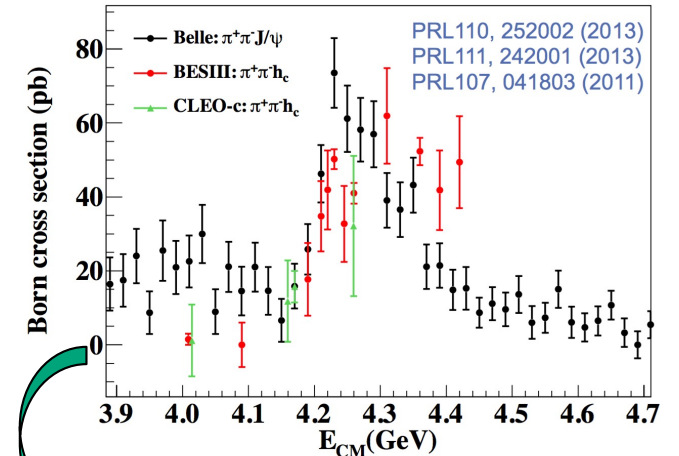


$$e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$$

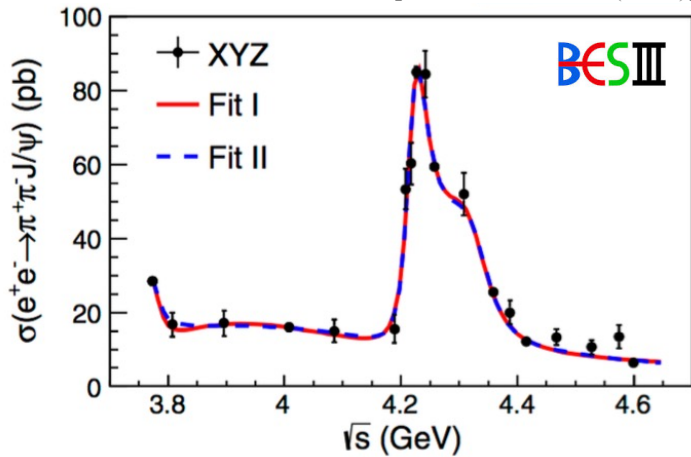
[BaBar, PRL 98, 212001 (2007)]



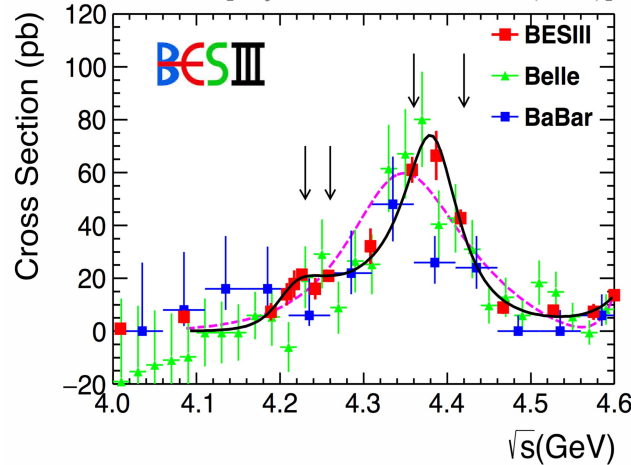
$$e^+e^- \rightarrow h_c\pi^+\pi^-$$



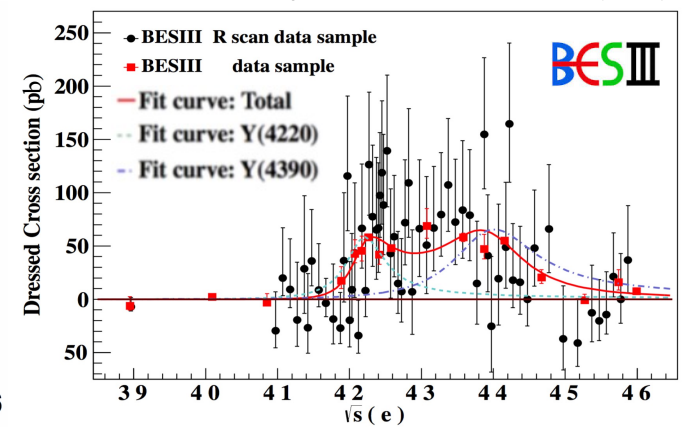
[PRL 118, 092001 (2017)]



[Phys. Rev. D 96, 032004 (2017)]



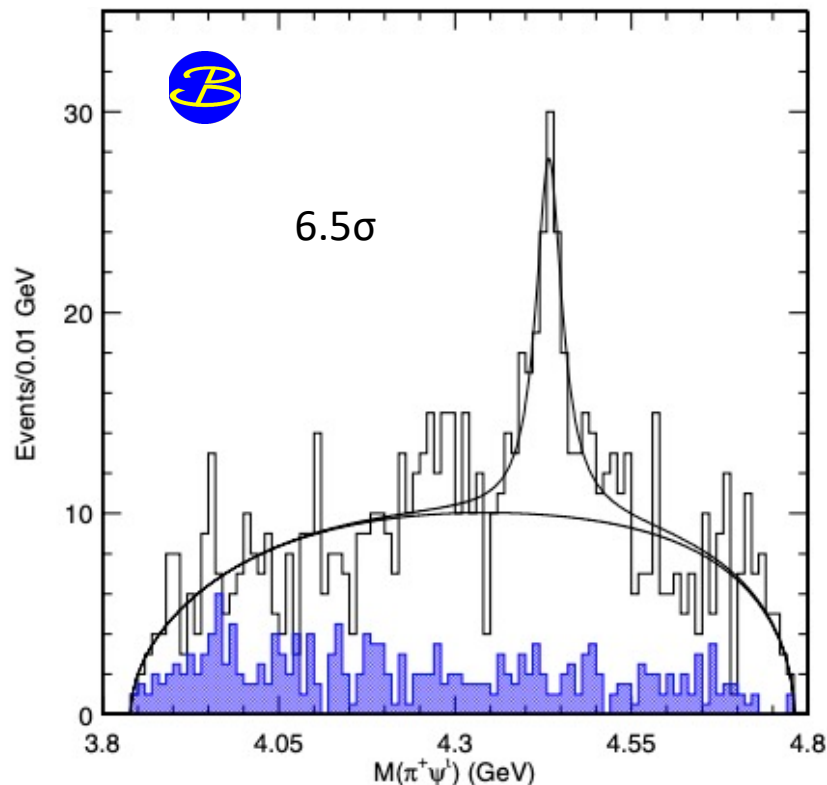
[Phys. Rev. Lett. 118 092002 (2017)]



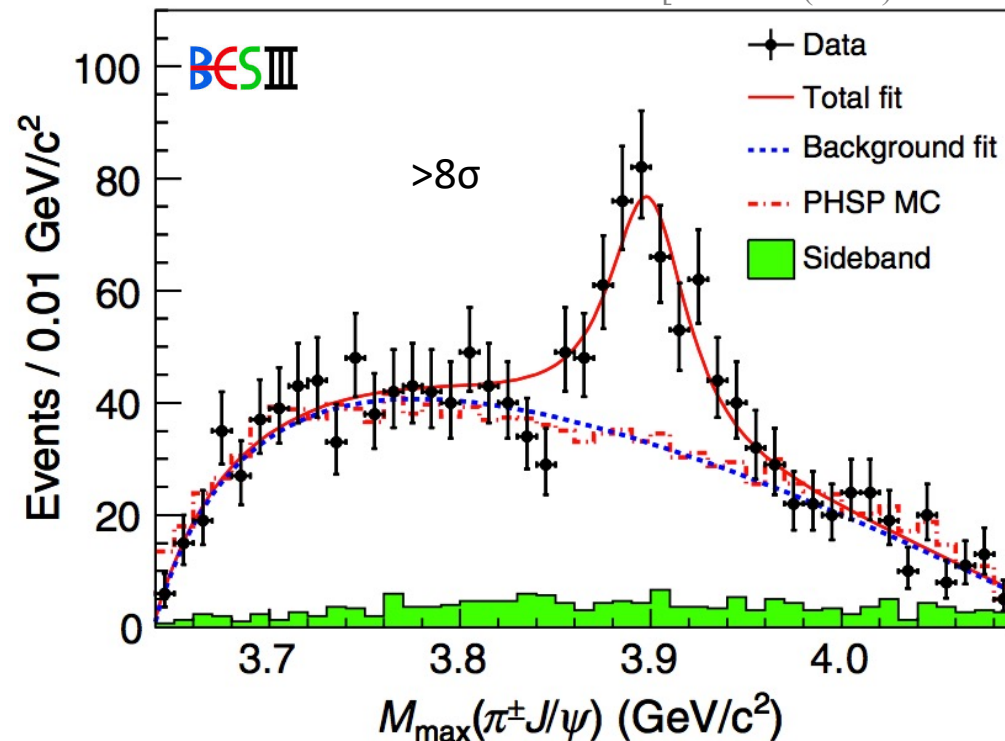
Two structures now resolved: $Y(4260) \rightarrow Y(4220)$, $Y(4360) \rightarrow Y(4390)$?

The $Z_c(3900)$ and further (charged) Z_c states

[Phys. Rev. Lett., 100 (2008) 142001]



[PRL 110 (2013) 252001]

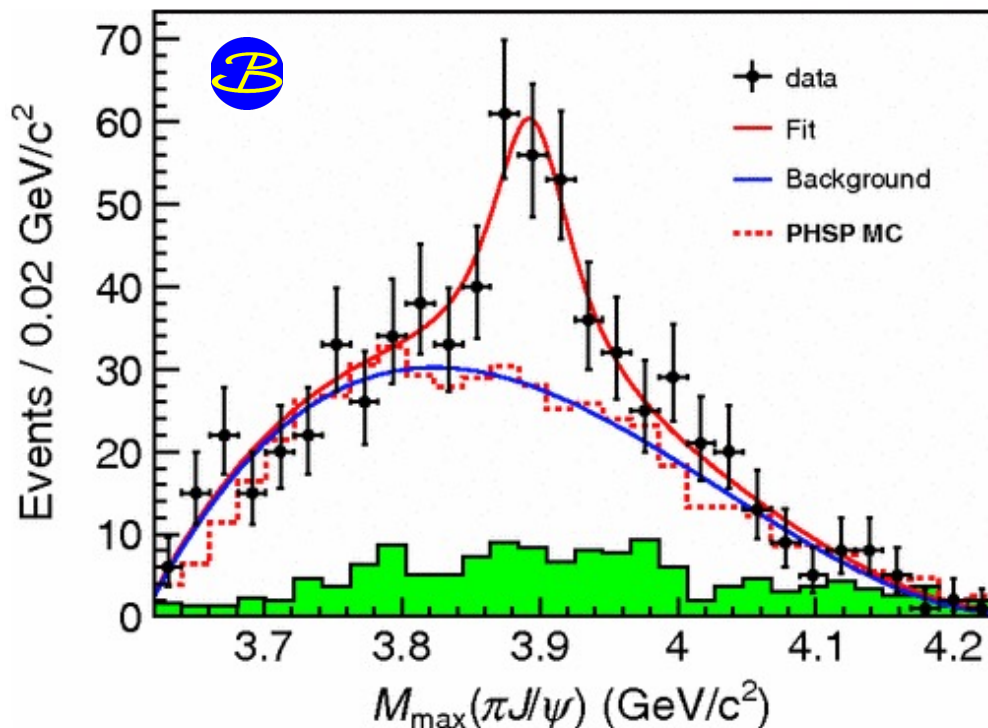


- First observed by Belle in 2008
 - not confirmed by BaBar, but LHCb
 - first charged charmonium-like state

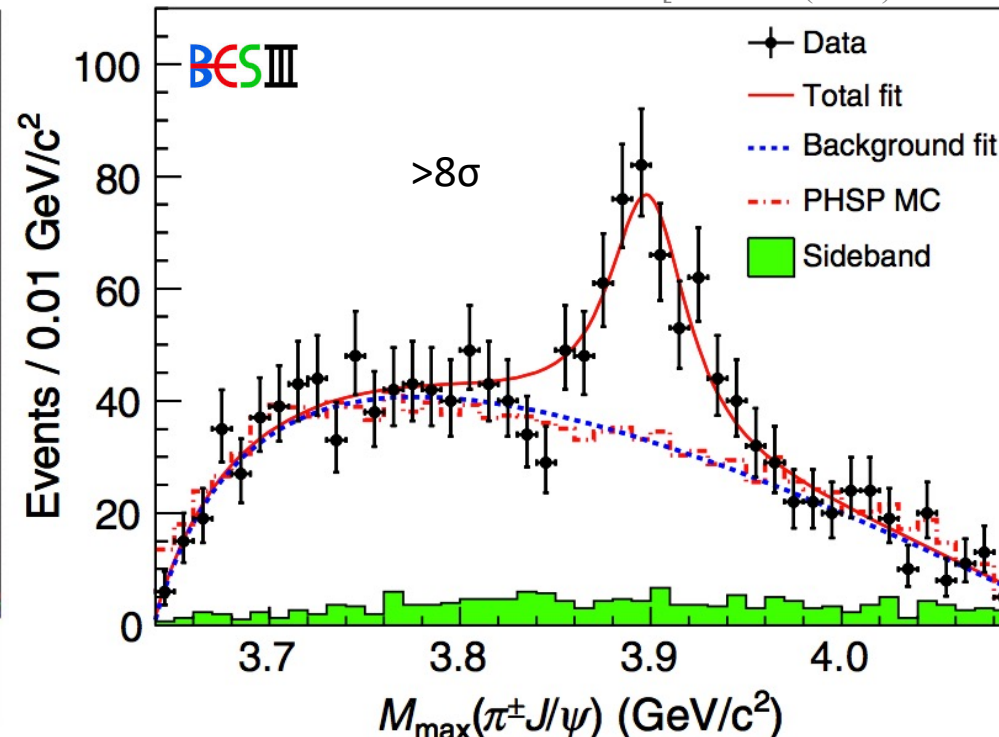
- Discovery of $Z_c(3900)$ by BESIII
 - decays to $J/\psi \Rightarrow$ contains $c\bar{c}$
 - electrical charged \Rightarrow contains $u\bar{d}$

\Rightarrow Minimal quark content [$c\bar{c}u\bar{d}$]: First observation of manifestly exotic 4-quark states

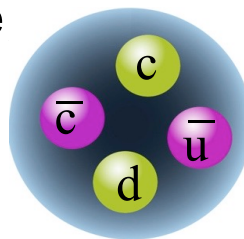
[Phys. Rev. Lett., 111 (2013) 019901]



[PRL 110 (2013) 252001]



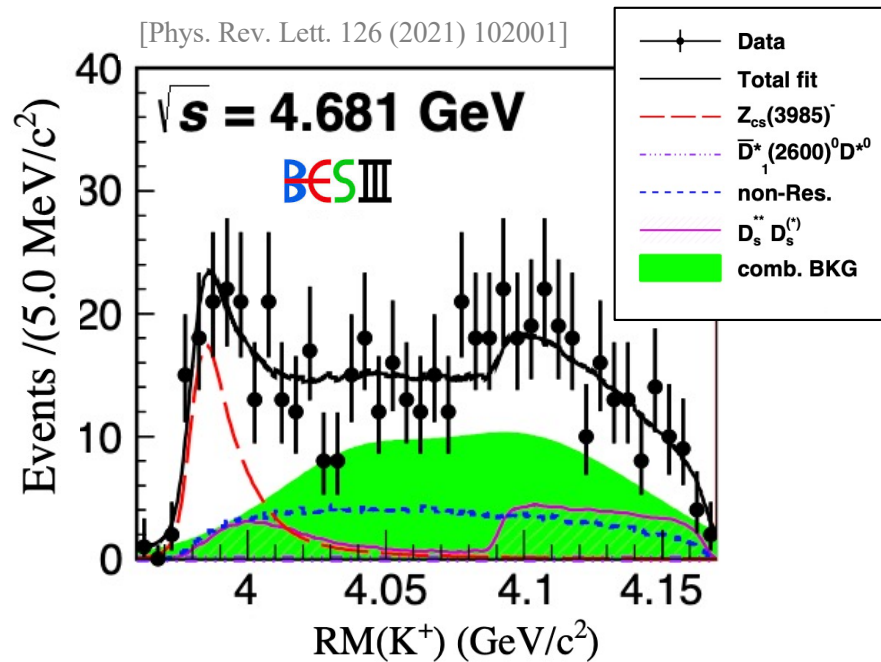
- Shortly after confirmed by Belle
 - including neutral partner state
 - isospin triplet established



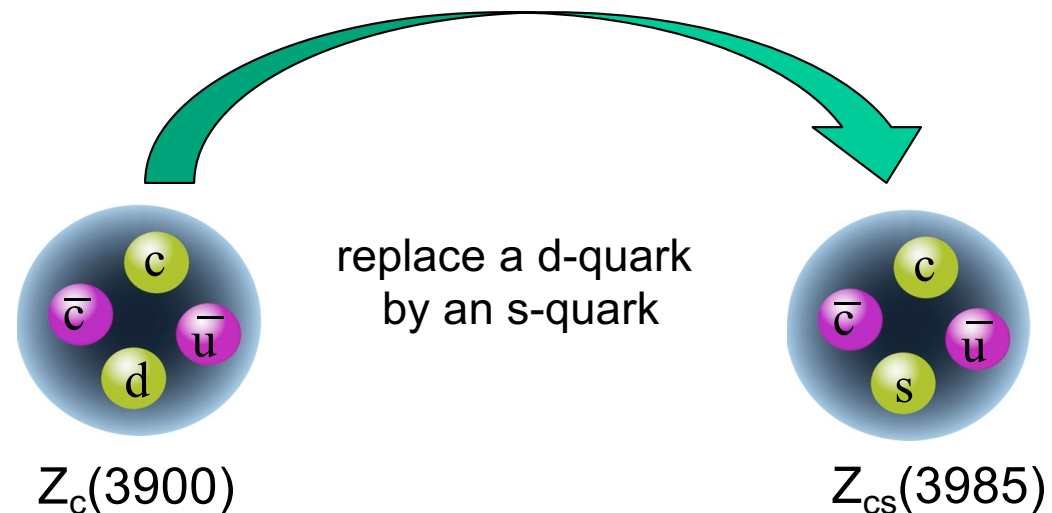
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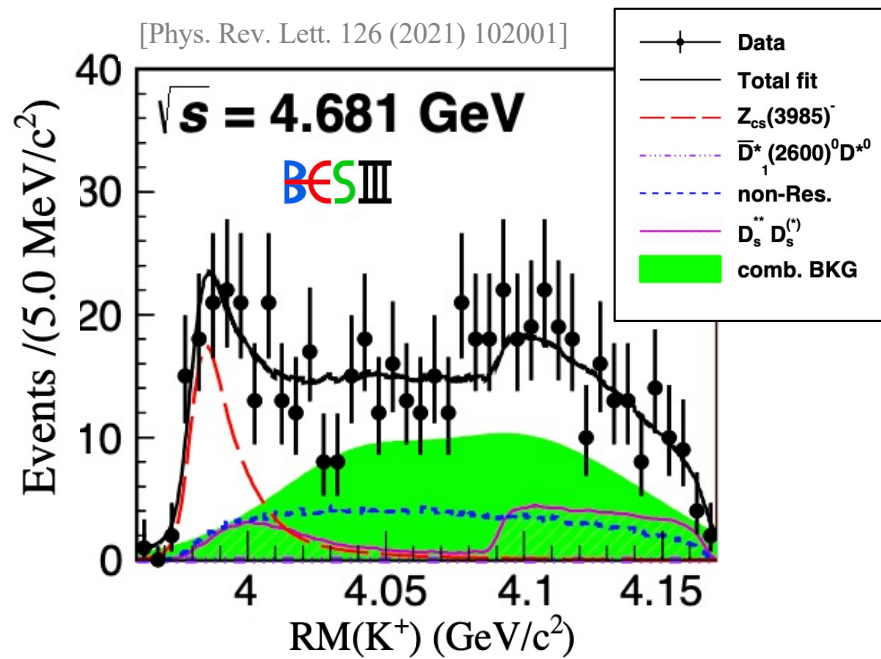
First Z_{cs} candidates reported



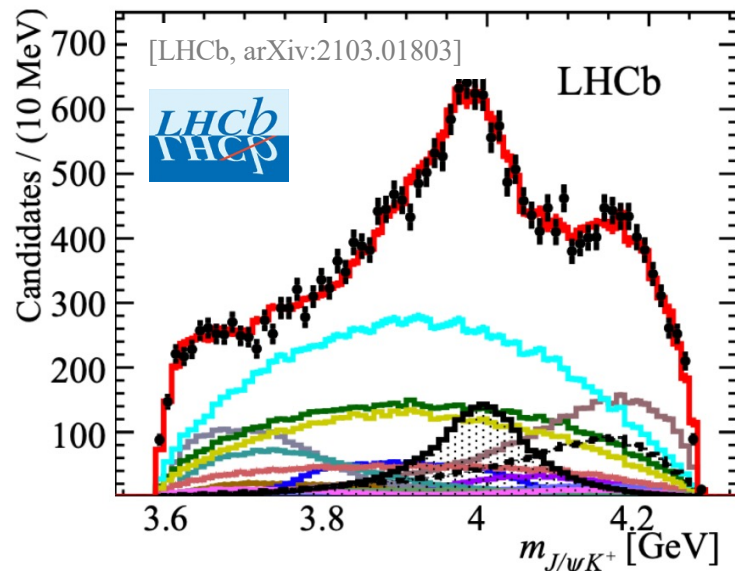
- Search for **strange partner** of $Z_c(3900)$
 - Containing s quark in open charm decay
 - $Z_{cs}(3985)$, in $e^+e^- \rightarrow K^+(D_s D^*/D_s^* D)^-$
 - **Narrow** threshold enhancement (5.3σ)
 - $M = (3982.5_{-2.6}^{+1.8} \pm 2.1) \text{ MeV}/c^2$,
 - $\Gamma = (12.8_{-4.4}^{+5.3} \pm 3.0) \text{ MeV}$
 - Minimal **quark content** => $[c\bar{c}s\bar{u}]$



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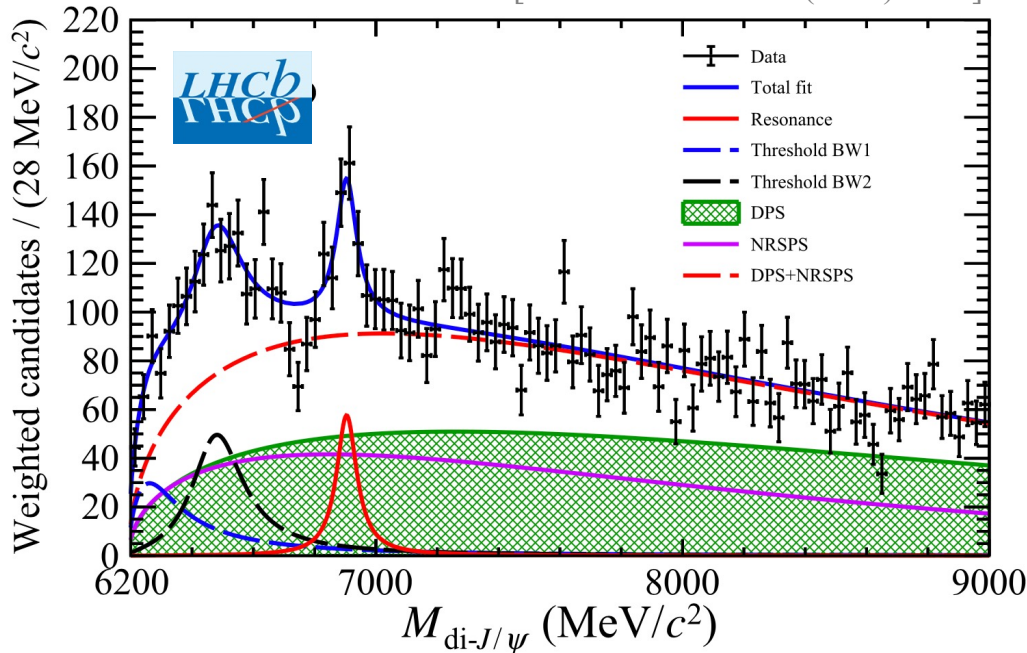


- LHCb reports a $Z_{cs}(4000)$ in $B \rightarrow \phi(J/\psi K^+)$
 - $M = (4000.3 \pm 6_{-14}^{+4}) \text{ MeV}/c^2$,
 - $\Gamma = (131 \pm 15 \pm 26) \text{ MeV}$
 - $J^P = 1^+$, hidden charm final state
 - 10x broader ...

=> Same state observed in different decays (open/hidden charm) at two experiments?

$T_{cc\bar{c}\bar{c}}$: X(6900) $> 5\sigma$

[Science Bulletin 65 (2020) 1983]

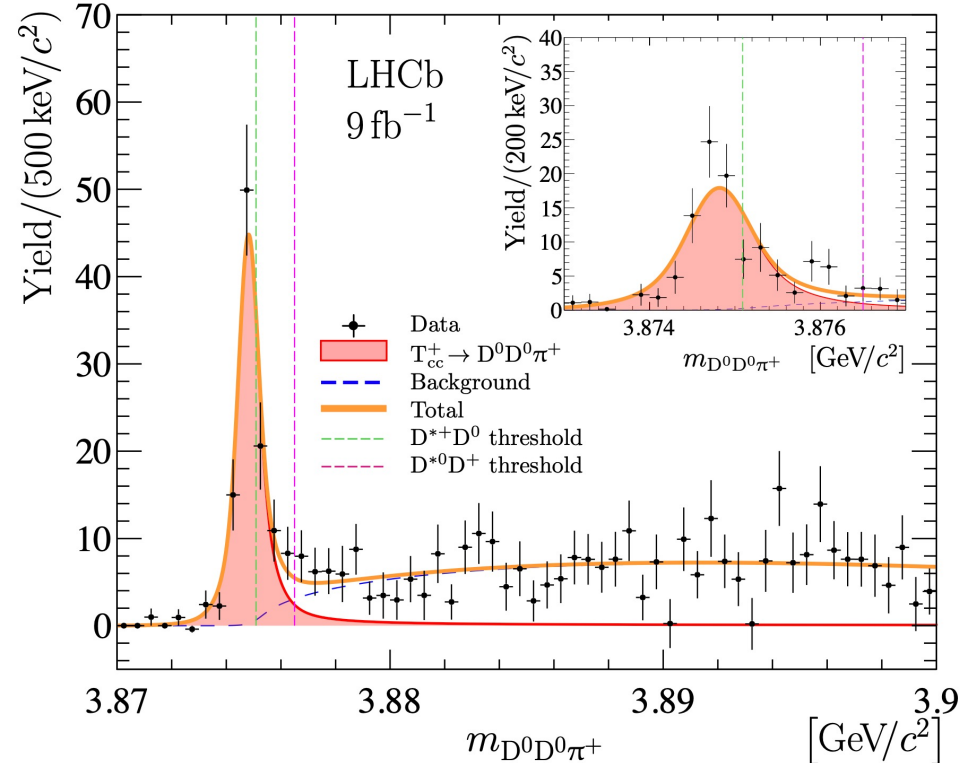


First hidden doubly charmed tetraquark candidate reported

- $m = 6905 \pm 11 \pm 7 \text{ MeV}/c^2$
- $\Gamma = 80 \pm 19 \pm 33 \text{ MeV}$ (Model I)

T_{cc^+} $> 22\sigma$

[LHCb-Paper-2021-032 (2021)]

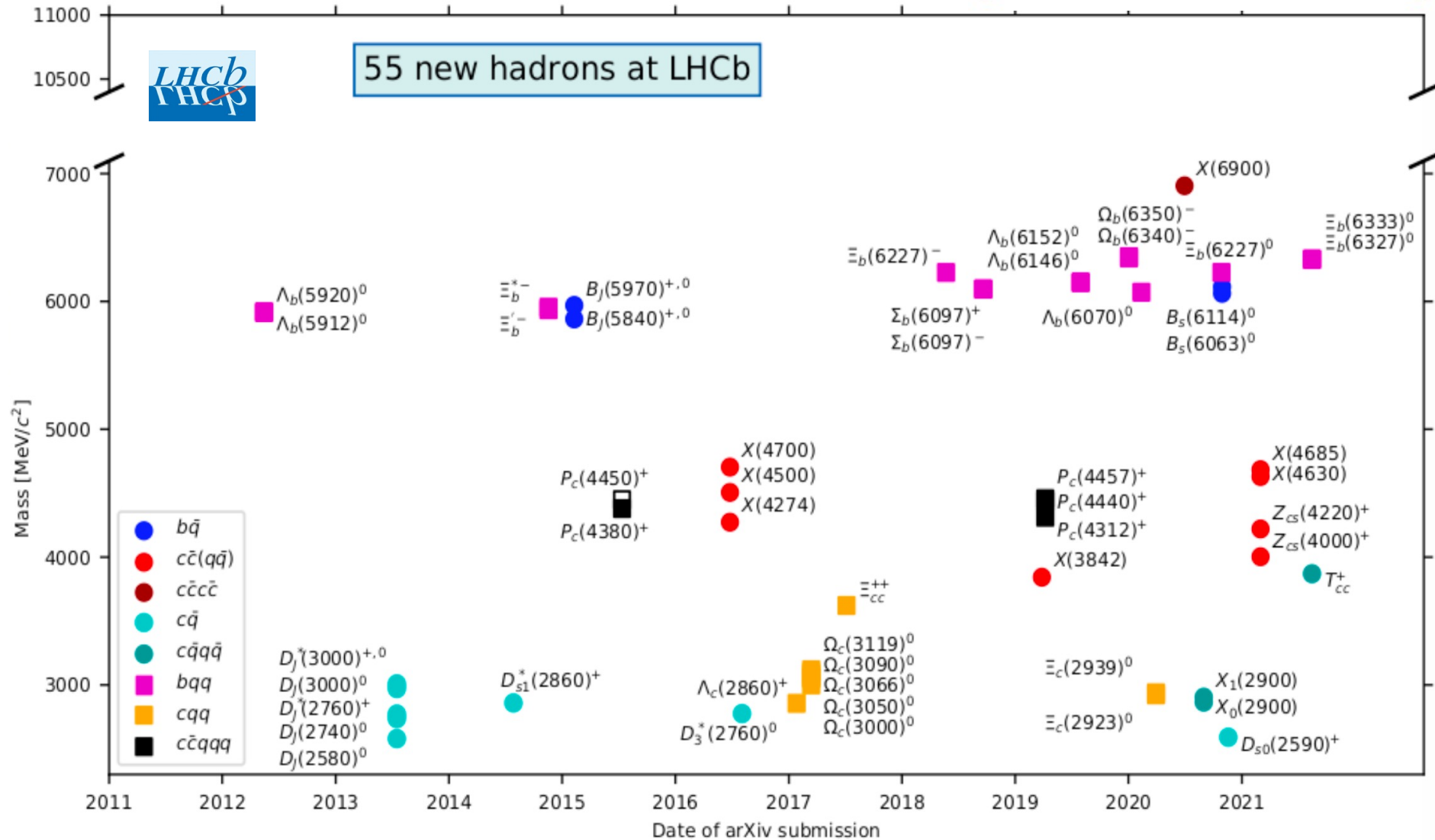


First same signed doubly charmed tetraquark candidate reported

- Minimal quark content $\Rightarrow [cc\bar{u}\bar{d}]$
- $m_{BW} = 3875 \text{ MeV} (\pm 61 \pm 5_{-14}^{+11} \text{ keV}/c^2)$
- $\Gamma_{BW} = 410 \pm 165 \pm 43_{-38}^{+18} \text{ keV}$

Again a zoo of new (exotic) hadrons ...

[LHCb-FIGURE-2021-001]

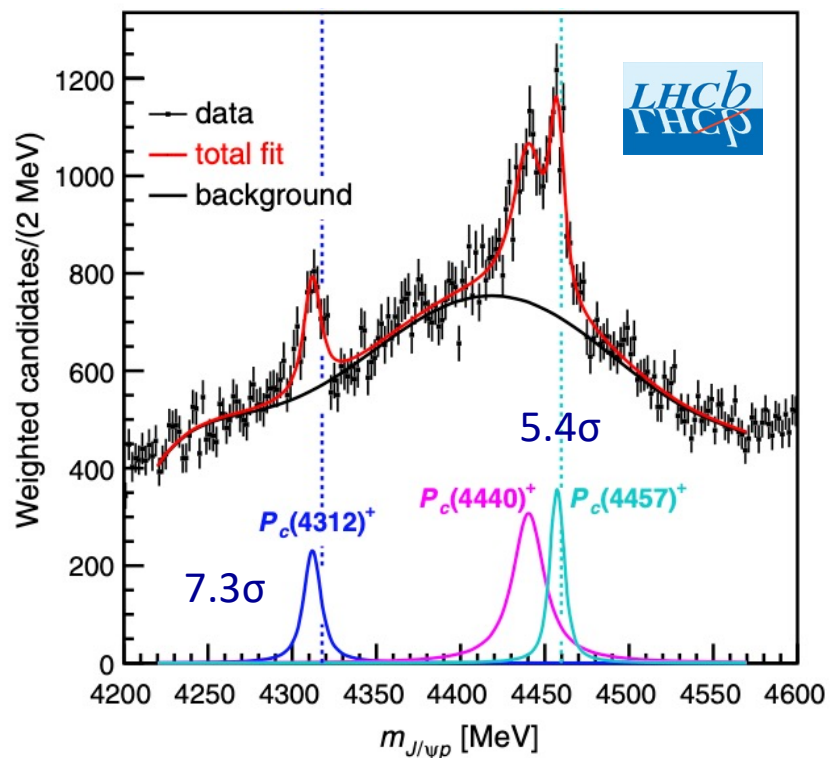


[Polyakov, EPS-HEP-2021]

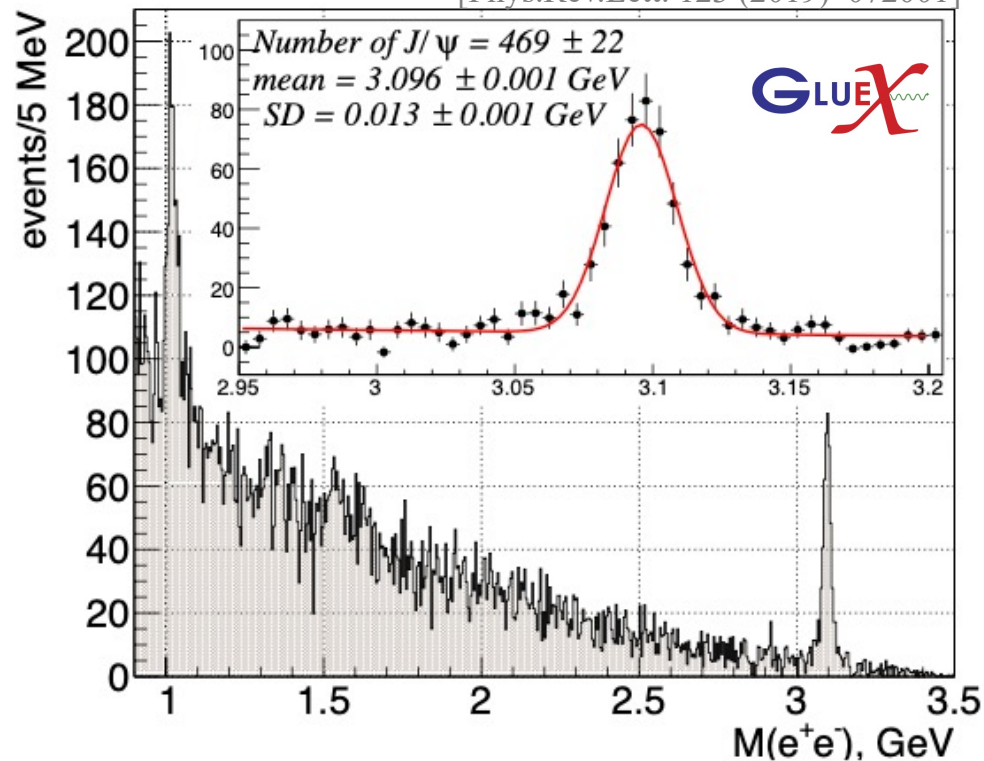
$$P_c(4xxx)^+ \rightarrow J/\psi p \text{ (c.c. incl.)}$$

$$\gamma + p \rightarrow J/\psi p$$

[PRL 122 (2019) 222001]



[Phys.Rev.Lett. 123 (2019) 072001]

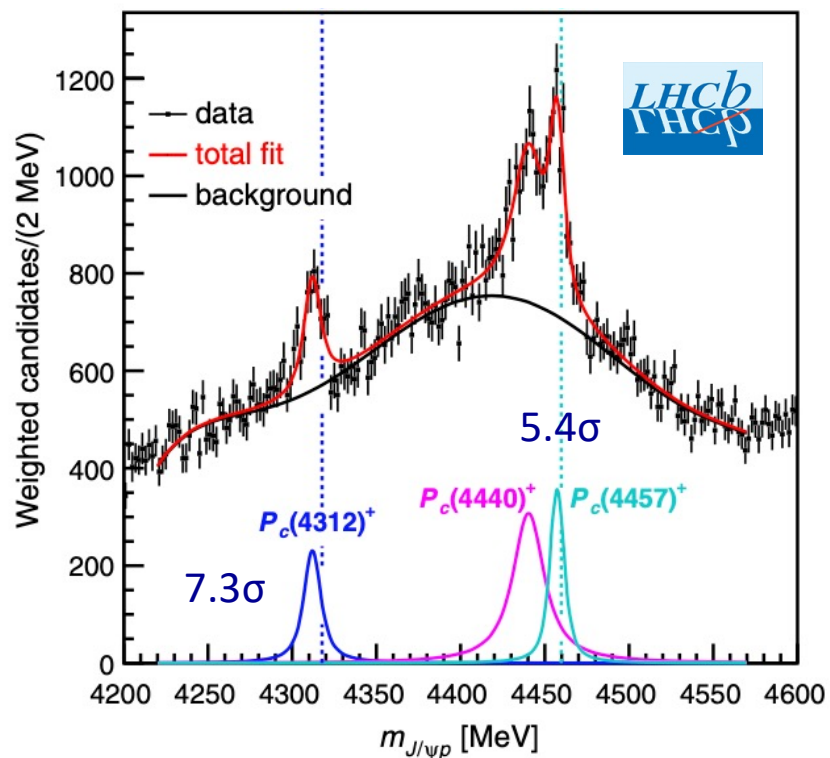


- Revival of pentaquark states
 - Five-quark states reported by LHCb
 - $P_c(4312)$, $P_c(4440)$, $P_c(4457)$,

- Clear J/ψ peak in photoproduction
 - Search for pentaquark states reported by LHCb

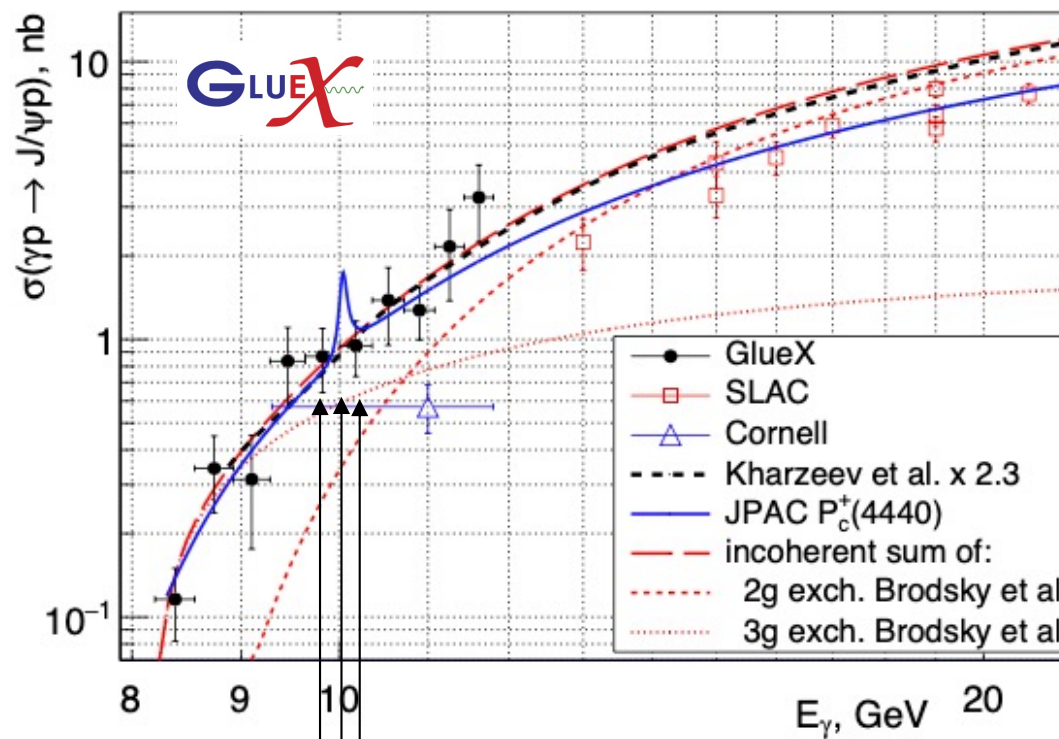
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[PRL 122 (2019) 222001]



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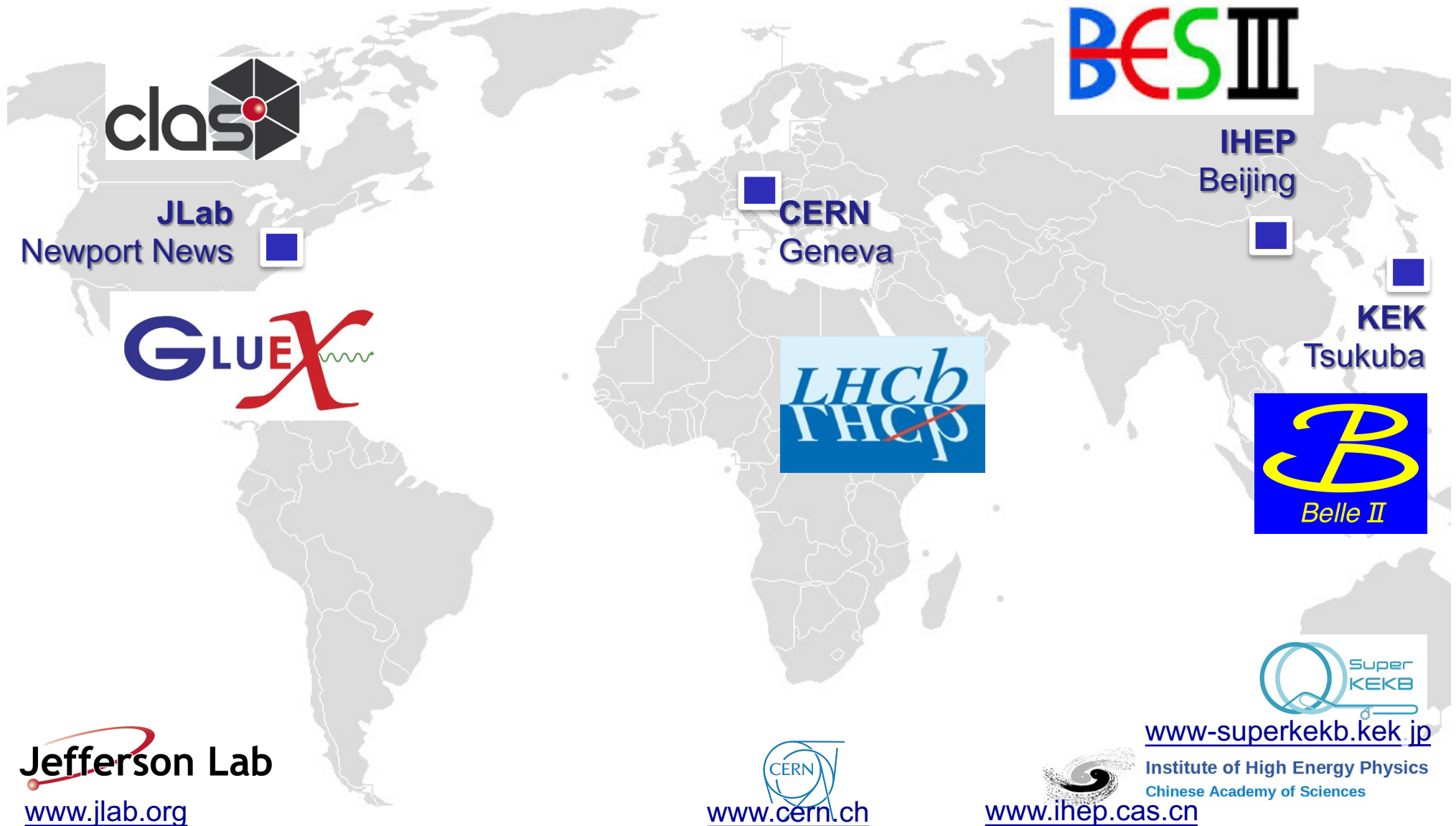
[Phys.Rev.Lett. 123 (2019) 072001]



- Revival of pentaquark states
 - Five-quark states reported by LHCb
 - $P_c(4312)$, $P_c(4440)$, $P_c(4457)$,

- No evidence for P_c 's in photoproduction
 - UL at 90% CL of 4.6, 1.8, and 3.9 nb for $P_c^+(4312)$, $P_c^+(4440)$, and $P_c^+(4457)$

German contributions



Jefferson Lab
www.jlab.org

CERN
www.cern.ch

SuperKEKB
www-superkekb.kek.jp
Institute of High Energy Physics
Chinese Academy of Sciences
www.ihep.cas.cn

Hadron Physics – Major labs & experiments overview on german groups involved

BESIII: 6 german institutes, 8 group leaders, 43 authors
 (RU Bochum, GSI Darmstadt, GU Frankfurt, HI Mainz, JGU Mainz, U Münster)



IHEP
Beijing

BelleII: 10 institutes, 7 group leaders, 41 authors (NB: < 1/3 hadron physics)
 (U Bonn, DESY Hamburg, U Göttingen, **JLU Gießen**, KIT Karlsruhe, JGU Mainz, LMU München,
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 (FZ Jülich, JLU Gießen)

GlueX: 2 institutes, 2 group leaders, 10 authors
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Tracking System (scintillating fibres), HD, TU D, RWTH AA
 Real-Time Analysis (real-time trigger, HD, TU D)

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(FZ Jülich, JLU) DIRC (Cherenkov detector, Expertise only, no funding), GSI

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BNL
long Island, NY



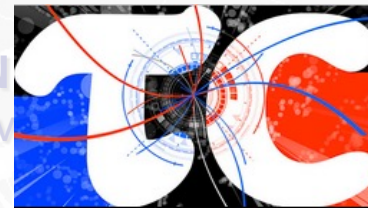
BNL+JLab Project: Electron Ion Collider



www.jlab.org

Frank Nerling

CERN
Geneve



future tau-charm factory

Budker Institute
Novosibirsk, Russia



NSC
Hefei, China



www-superkekb.kek.jp

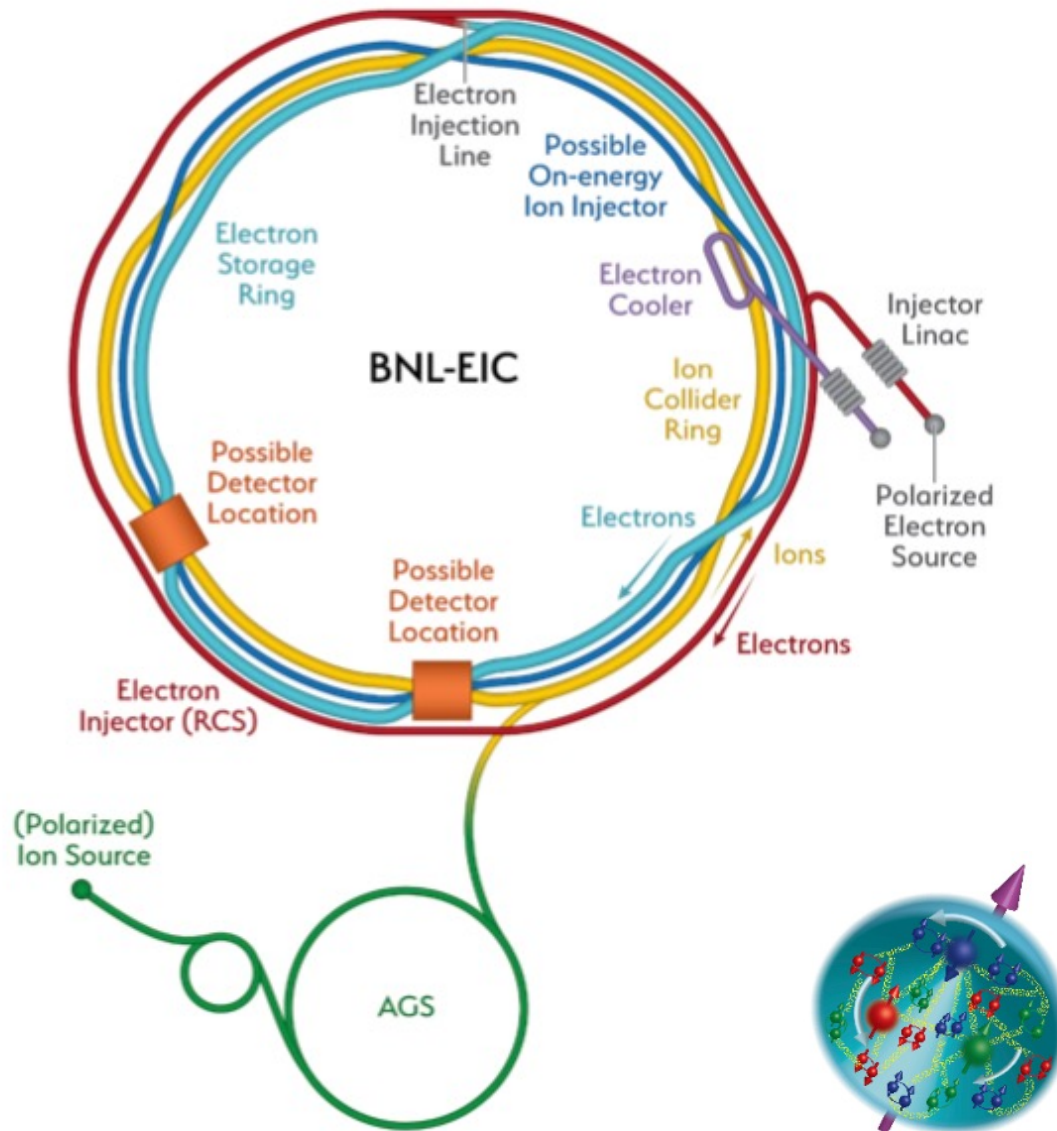
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- Versatile high-luminosity, polarised Electron-Ion-Collider (EIC)

- $\sqrt{s} = 20 - 141 \text{ GeV}$

- $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

- Start date: ~2030

- Physics programme

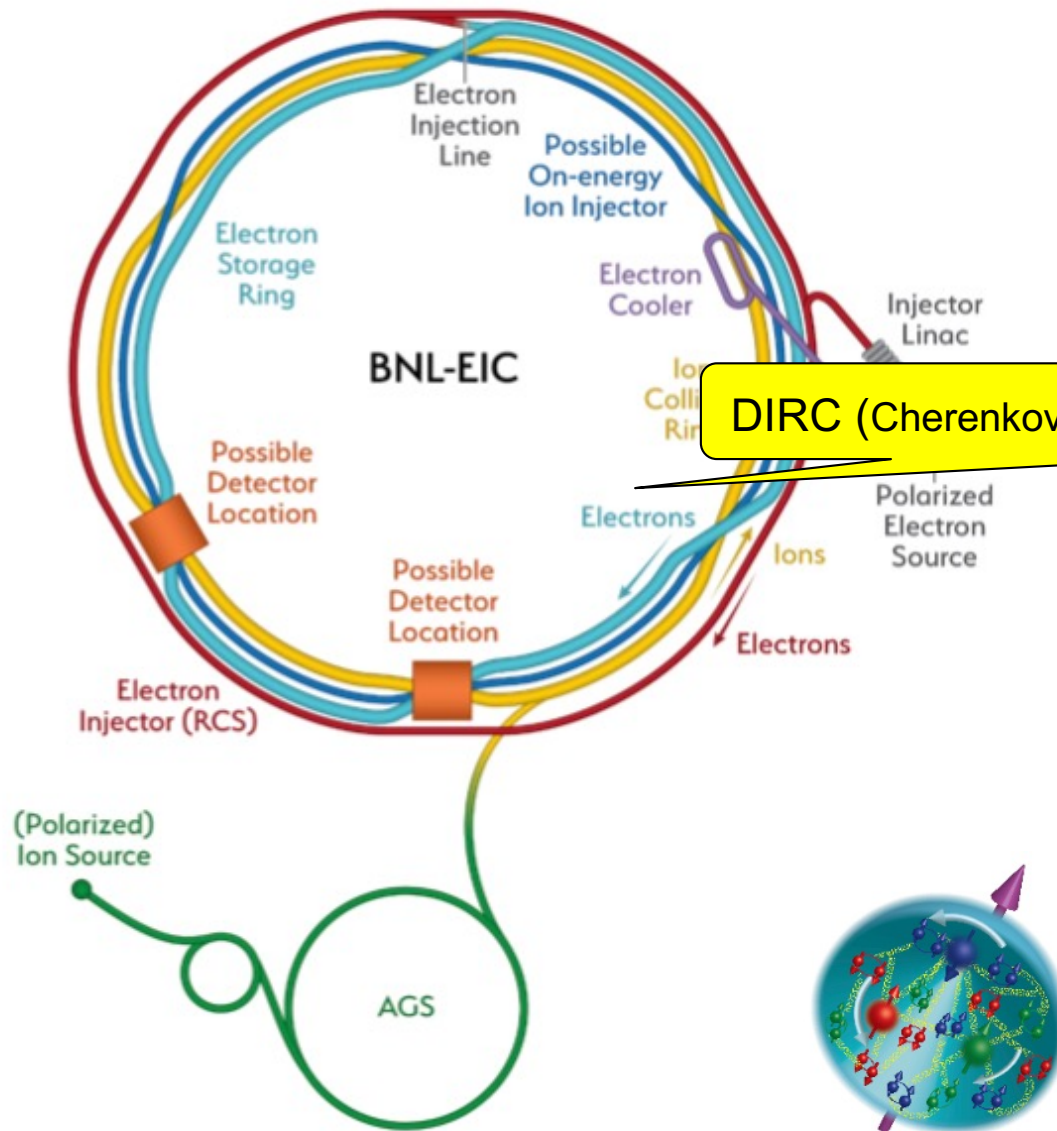
- (e + p, e + A) reactions

- Nucleon spin and 3D structure

- High gluon density and saturation

- Also spectroscopy programme

→ See talk by A. Schäfer



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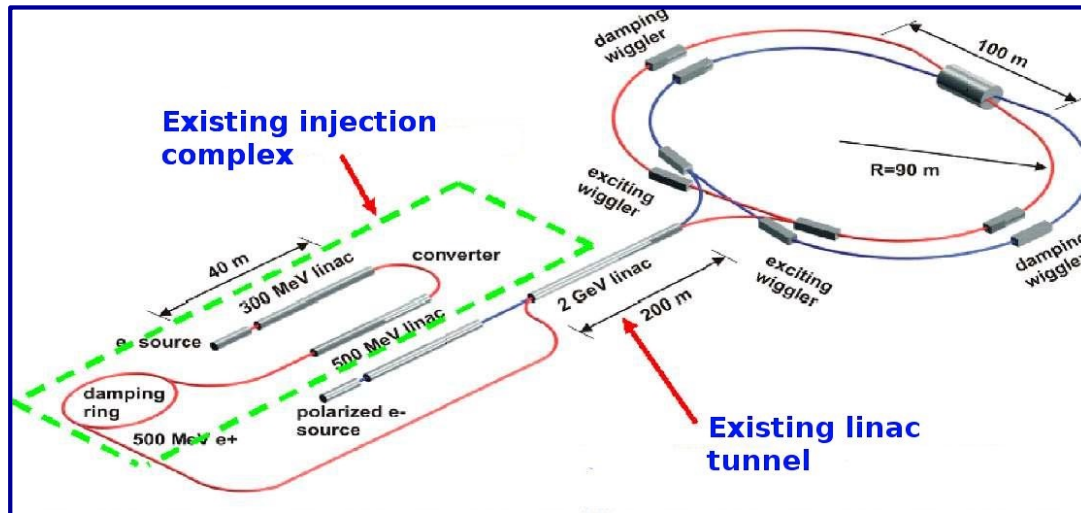
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→ See talk by A. Schäfer

Novosibirsk SCTF

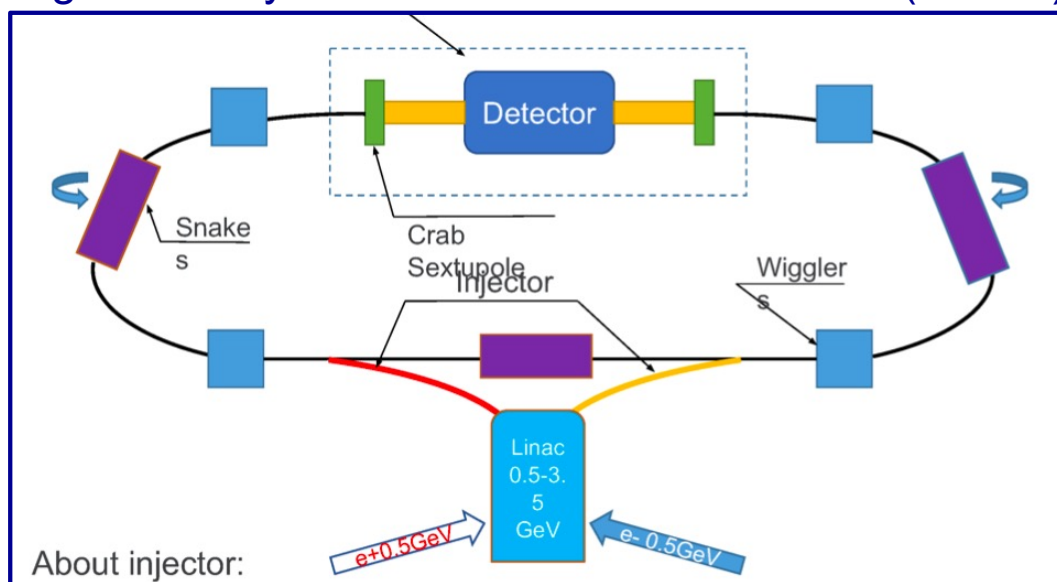


- SCTF Novosibirsk, Russia
 - $e^+ + e^-$ collider, $E_{cms} = 2 - 7 \text{ GeV}$
 - Luminosity up to $1 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
 - First proposal, 1-2 decades ago
 - Meanwhile: Close to Moscow (?)

- STCF Hefei (?), China
 - Natural extension and option for post-BEPCII project
 - $E_{cms} = 2 - 7 \text{ GeV}$, Luminosity: $1 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} = 4 \text{ GeV}$
 => $L = 2 \text{ ab}^{-1}/\text{year}$ (10 years of data taking competitive with BelleII: 50 ab^{-1})

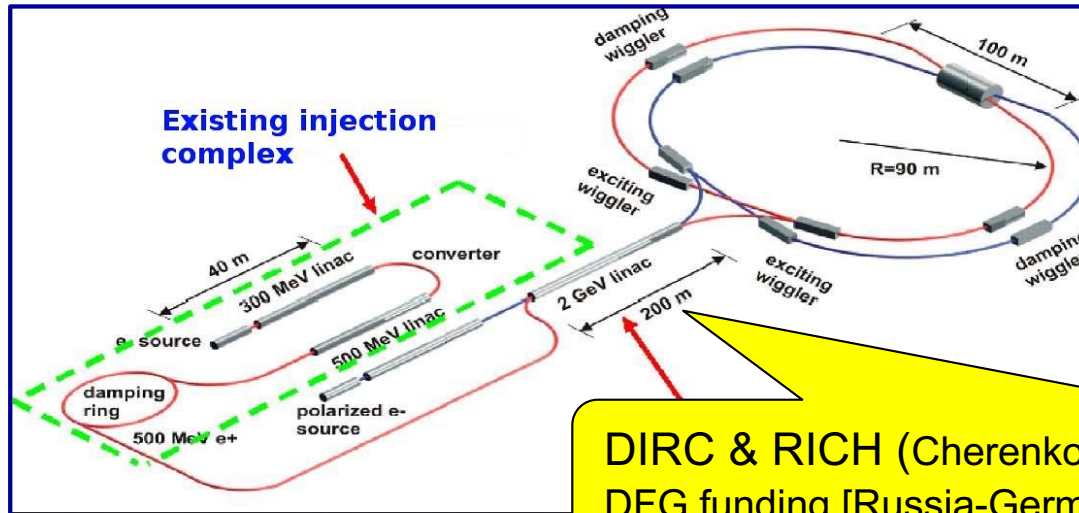
=> **Might** be merged to **one project**

High Intensity Electron Positron Accelerator (HIEPA)



- Physics programme
 - **Spectroscopy**, also structure ...

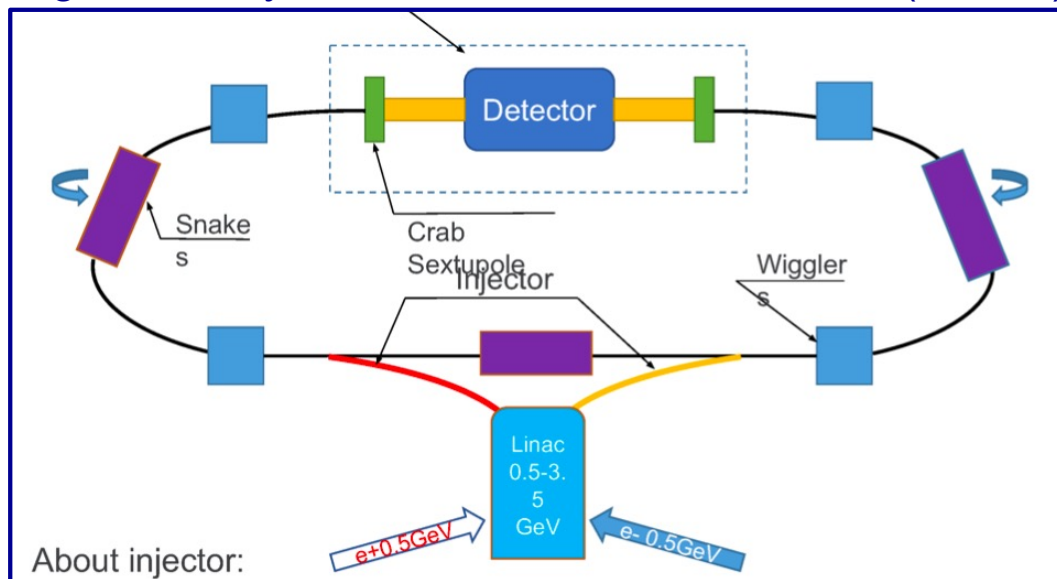
Novosibirsk SCTF



DIRC & RICH (Cherenkov detector, Expertise, R&D, application for DFG funding [Russia-Germany]), JLU Giessen & Budker Novosibirsk

- SCTF Novosibirsk, Russia
 - $e^+ + e^-$ collider, $E_{cms} = 2 - 7 \text{ GeV}$
 - Luminosity up to $1 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
 - First proposal, 1-2 decades ago
 - Meanwhile: Close to Moscow (?)

High Intensity Electron Positron Accelerator (HIEPA)



post-BEPC-II project

- $E_{cms} = 2 - 7 \text{ GeV}$, Luminosity: $1 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} = 4 \text{ GeV}$
 => $L = 2 \text{ ab}^{-1}/\text{year}$ (10 years of data taking competitive with BelleII: 50 ab^{-1})

=> **Might** be merged to **one project**

- Physics programme
 - Spectroscopy, also structure ...



BESIII Development (2022,23) Lumi.-Upgrade => factor 3 Further running (until 2030)
 Shutdown for installation (2024)

BelleII Since 2019 Phase-III: Physics data Lumi-Upgrade => factor 30-40 (w.r.t. Belle) Further running (until 2030)
 Shutdown (2023): Upgrade PXD Shutdown 2027/28

LHCb Run-III (2022-25), Shutdown, LS3 (2026-28) Run-IV (2029-3x?)
 LS2 (2019-20): Upgrade-I LS4 (203x?): Upgrade-II

GlueX GlueX-II (2020-24) KLF & GPDs (2025-29) GlueX-III: 2029-3x? GlueX++ (>2030) ?
 FCAL Upgrade (Fall`23)








CLAS12 Different targets (d,³He), (nuclear, C) High-lumi detector upgrade: JLab24 upgrade (>= 2030)
 => factor 10-100, CLAS24

PANDA PANDA P0 (2018-24), install. (2024-26), PANDA P1 (2027), ... Phase2 (2028-3?),
 first protons (2026), anti-protons (2027) expected

EIC Experiment start expected >= 2030

SCTF Experiment start expected >= 2030

Hadron physics, structure & spectroscopy an (qualitative) overview

Structure	Spectroscopy	
	BESIII	
	Belle II	
	LHCb	
	GlueX	
CLAS12		
	PANDA	
EIC		?
	STCF	?

- Hadron physics: Still hot topics and frequently new results, on both
 - Hadron Structure & Spectroscopy
 - Several discoveries of exotic multi-quark states

- New era started 2003: Discovery of the XYZ states
 - Many (exotic) XYZ states in the charmonium region
 - Manifestly exotic tetraquark states

- Revival of pentaquark states
 - Several candidates reported
 - => Need independent confirmation

Outlook:

- **BESIII**: Further data taking (and upgrades) for **10 more years** approved ...
- **BelleII**: In physics mode since 2019, 1/2 BaBar data on tape ($\sim 215 \text{ fb}^{-1}$).
- **LHCb**: A new discovery machine, looking forward to results based on Run-III
- **PANDA**: Complementary precision experiment coming **soon** ...
- **EIC/SCTF**: Future projects for structure & spectroscopy at the horizon

- Hadron physics: Still hot topics and frequently new results, on both
 - Hadron Structure & Spectroscopy
 - Several discoveries of exotic multi-quark states

- New era started 2003: Discovery of the XYZ states
 - Many (exotic) XYZ states in the charmonium region
 - Manifestly exotic tetraquark states

- Revival of pentaquark
 - Several candidates

Not discussed at all (time):
 also many exciting new spectroscopy results in B and light quark sector ...

Outlook:

- BESIII: Further data taking
- BelleII: In physics mode
- LHCb: A new discovery
- PANDA: Complementary
- EIC/SCTF: Future project

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