HUGS 2021 Lectures on:
Experimental Meson Spectroscopy

Ryan Mitchell
Senior Scientist
Indiana University
(remitche@indiana.edu)

Table 3: Major experiments in the past, present, and future of heavy-quark exotics studies.

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Belle	$X(3872)$ [4] $Y(3940)$ [106] $X(3915)$ [166] $Z_c(4430)$ [30, 136, 137] $Z_b(10610)$, $Z_b(10650)$ [160, 162, 163] $Y_b(10888)$ [151, 152]	KEKB	1998–2010	KEK (Tsukuba, Japan)	
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COMPASS	photoproduction [181] $a_1(1420)$ [182]	SPS	2002-2011		μ/π beam on N target ($p_{beam} \approx 160$, 200 GeV) $\pi N \to XN$ $\gamma N \to XN$
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GlueX	Beginning (searches for light quark hybrid mesons)	CEBAF	2016–	Jefferson Lab (Newport News, Virginia, USA)	γ beam on p target ($E_{beam} \leq 11$ GeV): $\gamma p \to Xp$
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Progress in Particle and Nuclear Physics 93 (2017) 143–194

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Heavy-quark QCD exotica

Richard F. Lebed [a,*], Ryan E. Mitchell [b], Eric S. Swanson [c]

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VA. Detectors

VB. Hadron Colliders

VC. e^+e^- Colliders

* B Factories

* τ/c Factories

VD. Fixed Targets

VE. New Possibilities

VF. Outlook

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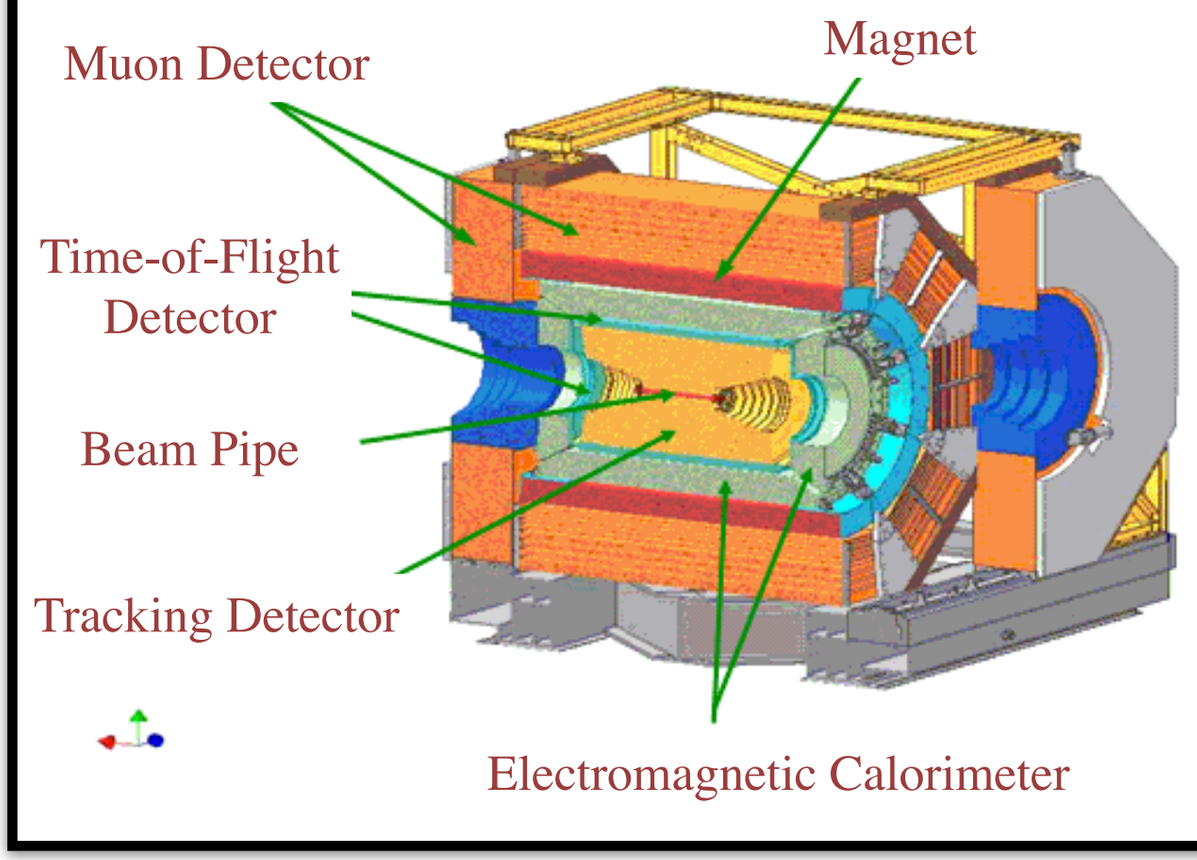
The **BESIII Experiment** *(Beijing Spectrometer)*
at **BEPCII** *(Beijing Electron Positron Collider)*
at **IHEP** *(Institute for High Energy Physics)* in Beijing, China

BESIII Detector *(a standard high-energy physics experiment)*

(1) Tracking detector ⇒ *charged particle momentum*

(2) Time-of-Flight (TOF) ⇒ *charged particle mass*

(3) Calorimeter ⇒ *photon energy and direction*



Measure the four-vectors of final-state particles ($\gamma, e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm}, p, \bar{p}$) and detached vertices ($K_S, \Lambda, \ldots$)

e^+e^- collisions at $E_{\rm CM}$ between 2.0 and 4.9 GeV

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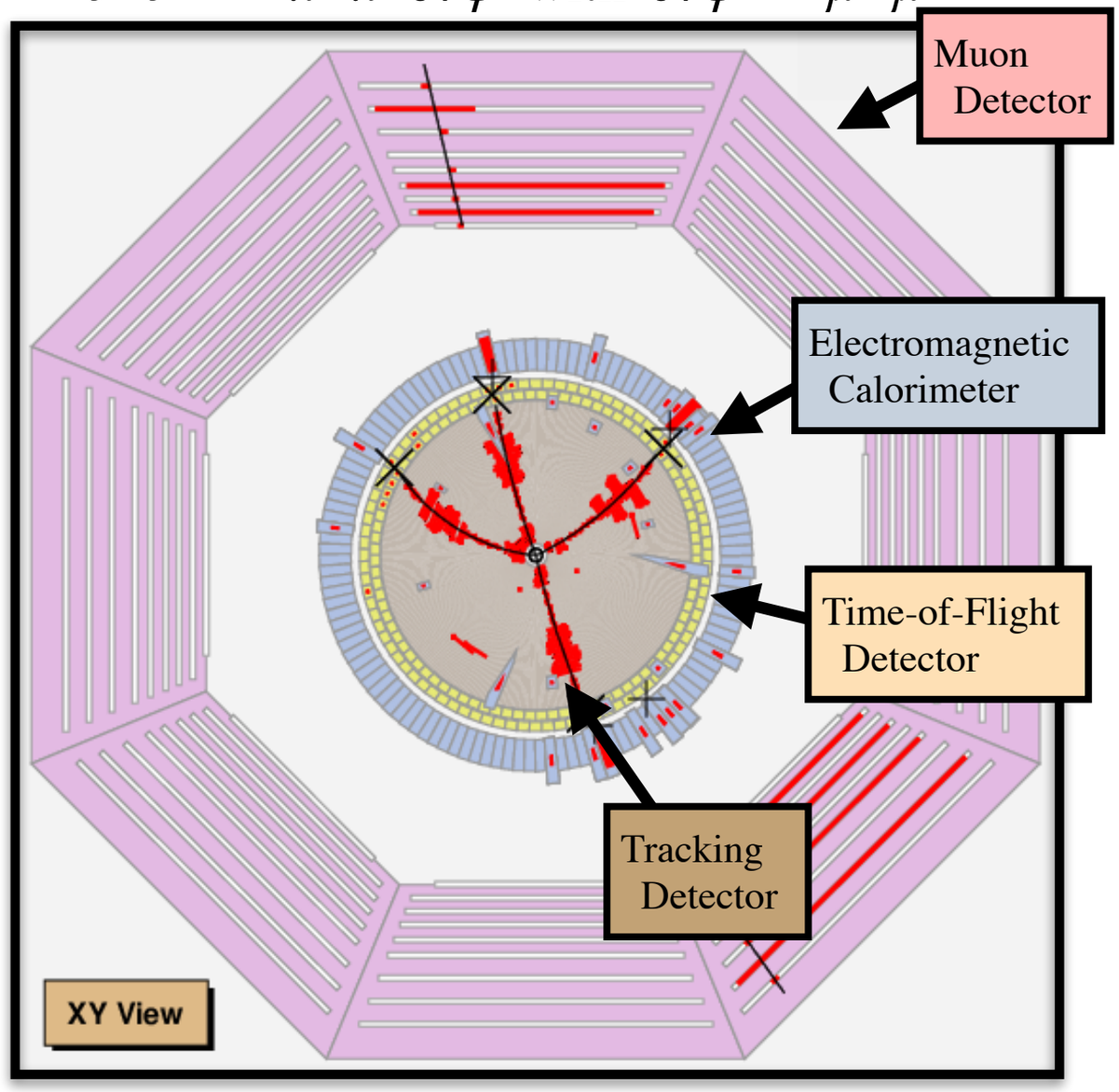
$e^+e^- \to \pi^+\pi^- J/\psi$ with $J/\psi \to \mu^+\mu^-$



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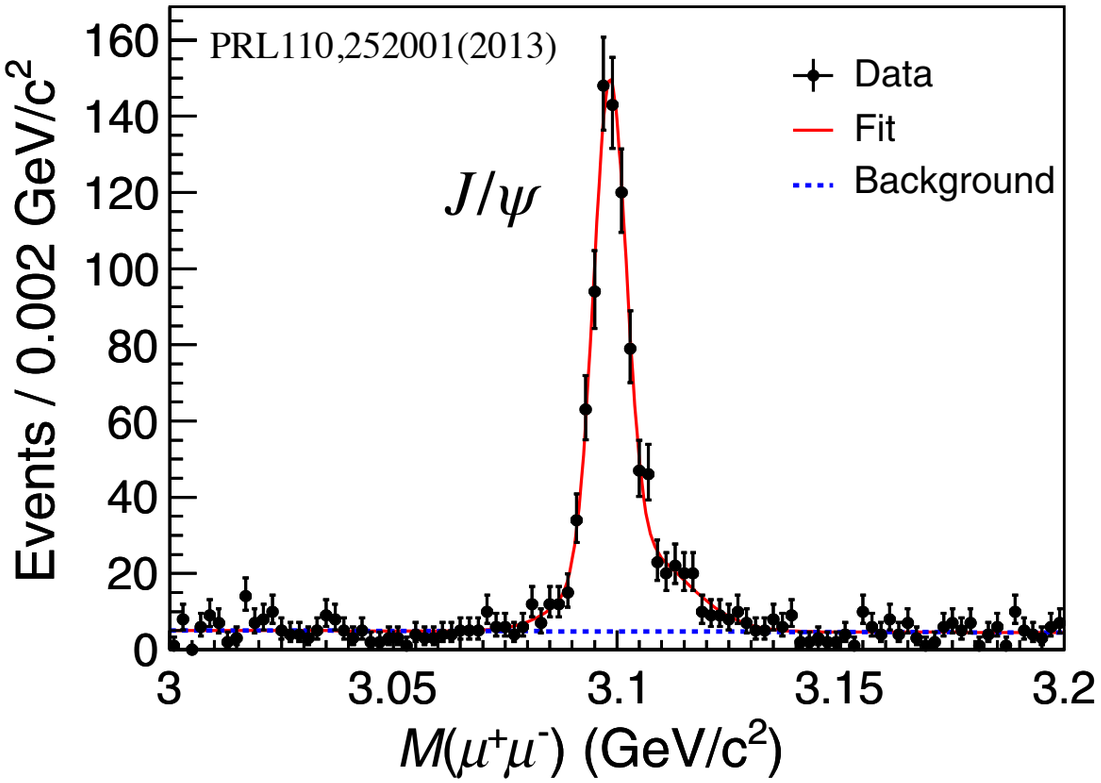

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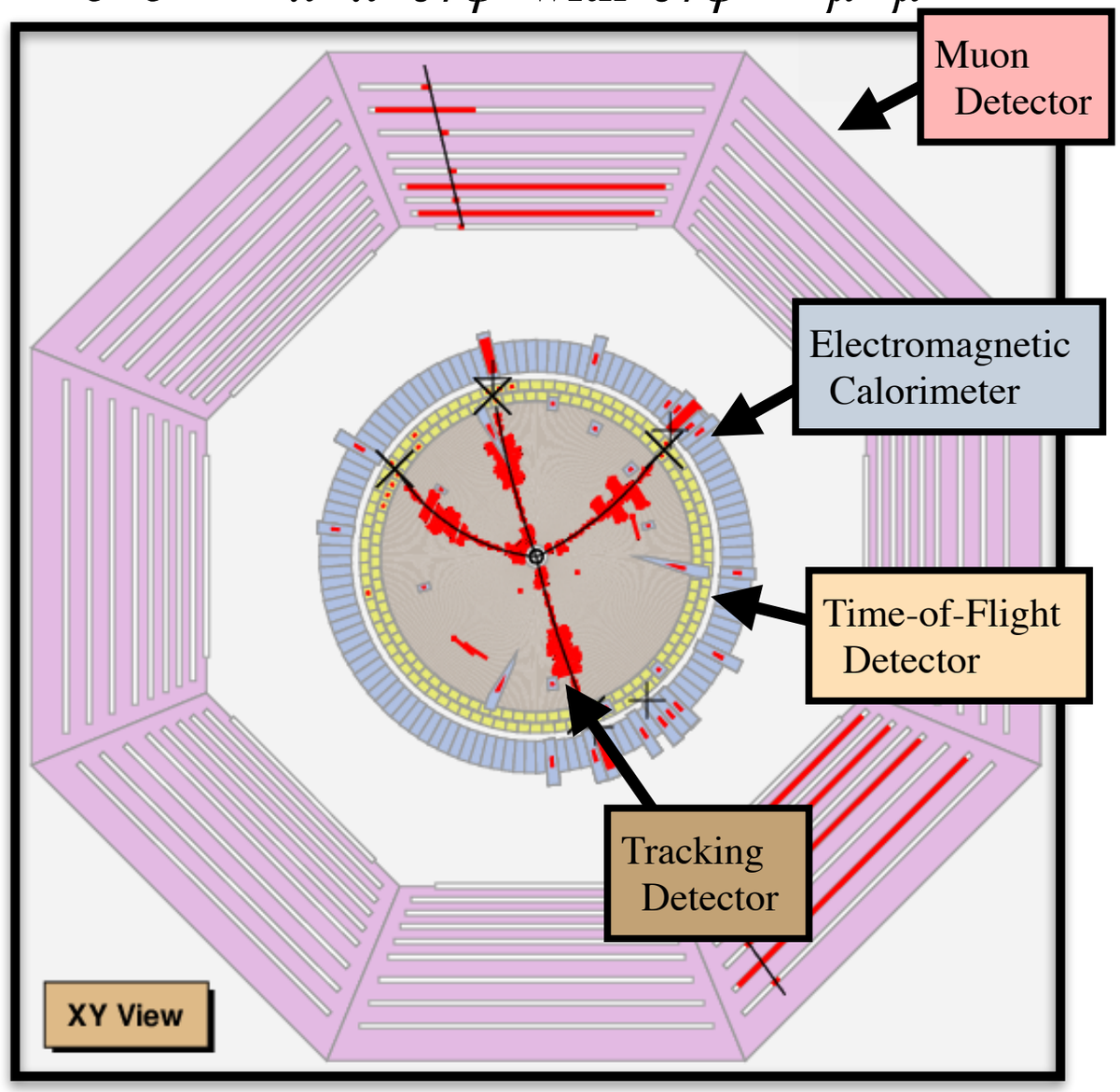
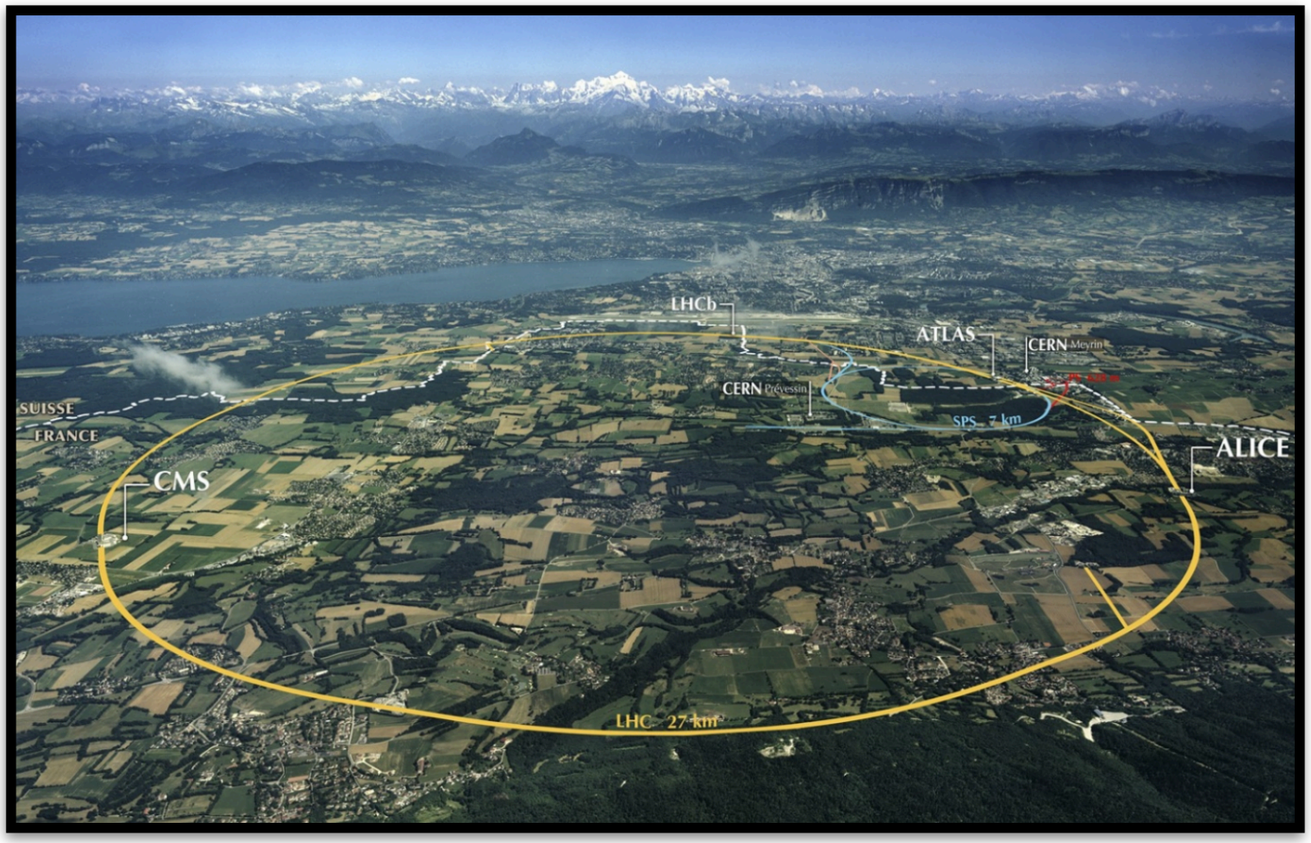
$e^+e^- \to \pi^+\pi^- J/\psi$ with $J/\psi \to \mu^+\mu^-$

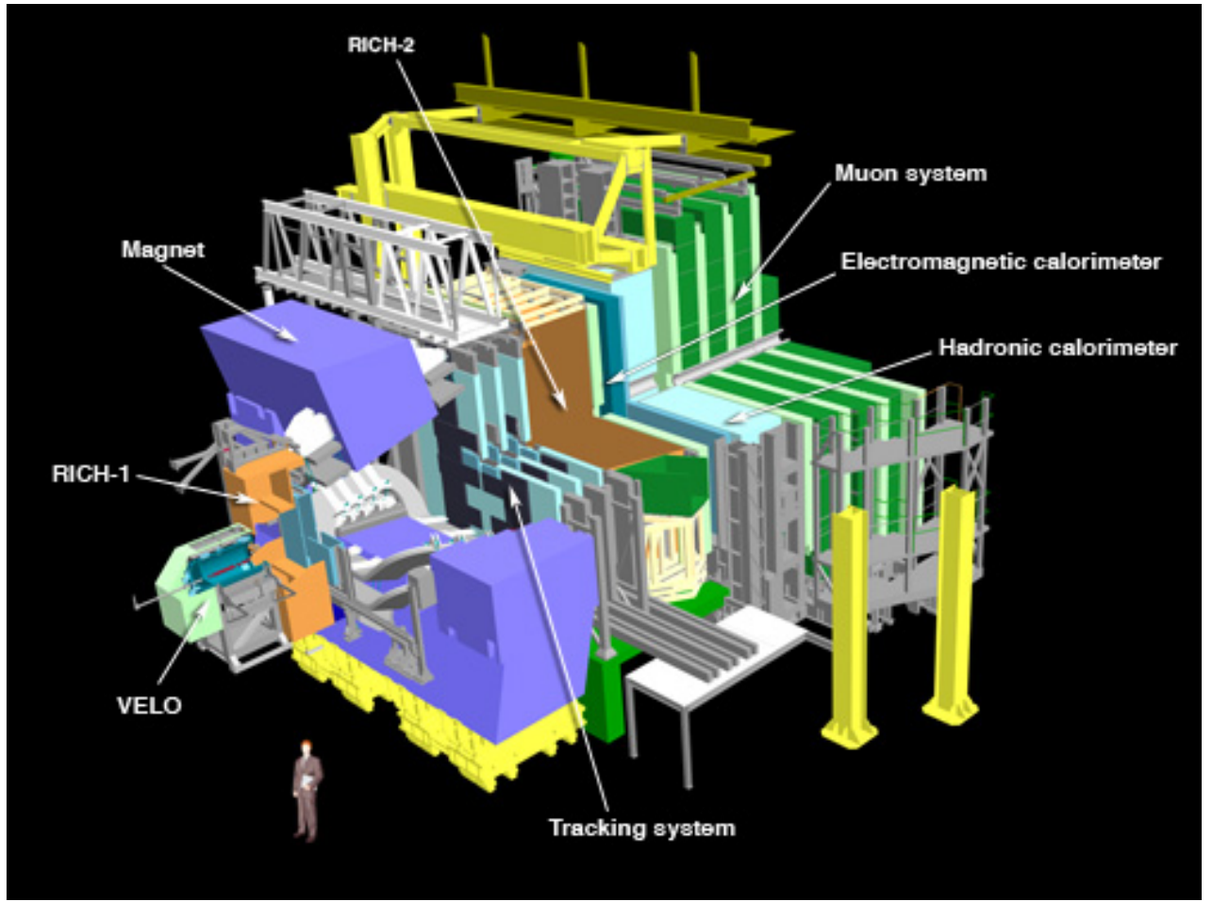


e^+e^- collisions at $E_{\rm CM}$ between 2.0 and 4.9 GeV

VA. Detectors

The **LHCb Experiment**
at the **LHC** *(Large Hadron Collider)*
at **CERN** *(European Council for Nuclear Research)* in Geneva, Switzerland





Measure the four-vectors of final-state particles ($\gamma, e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm}, p, \bar{p}$) and detached vertices ($K_S, \Lambda, \ldots, D, \Lambda_c, \ldots B, \Lambda_b, \ldots$)

pp collisions between 7 and 14 TeV

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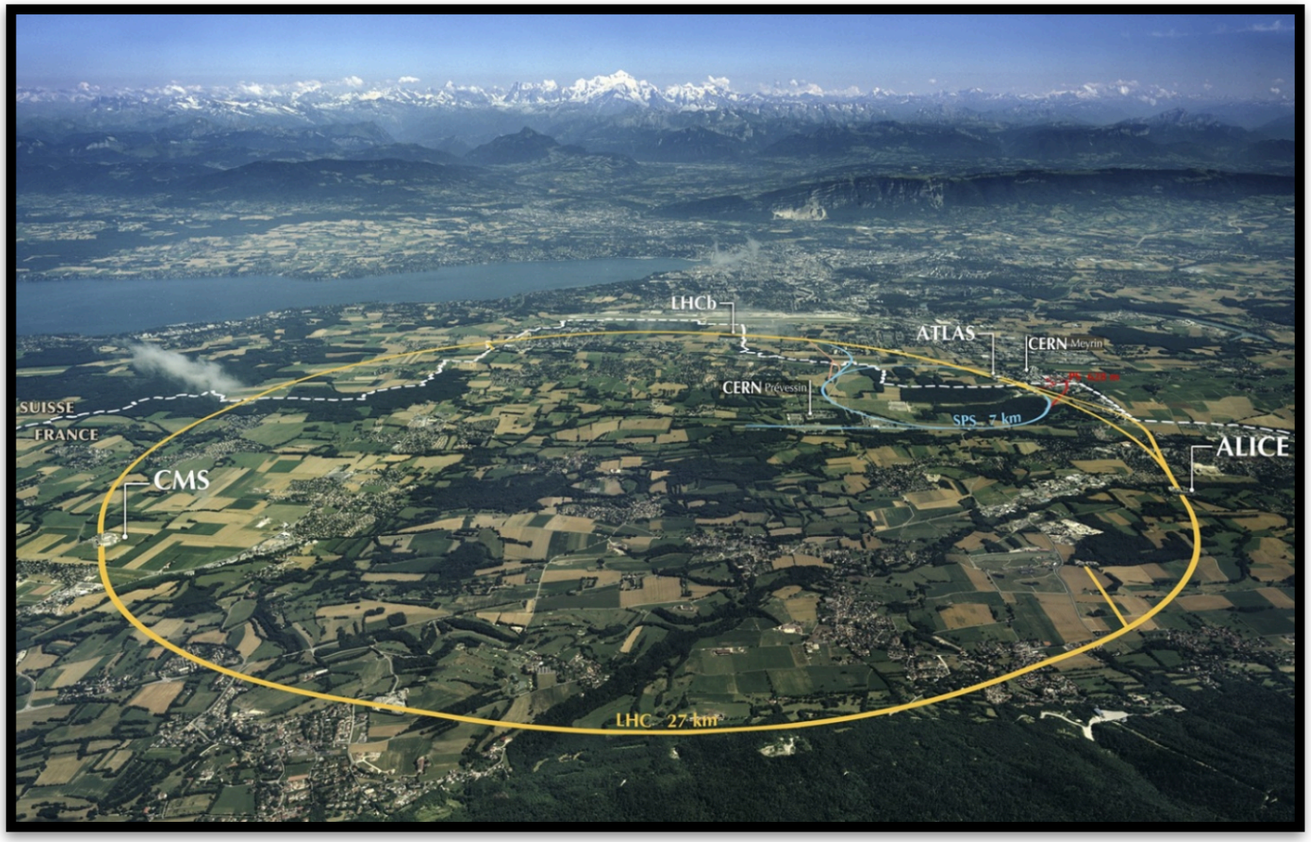

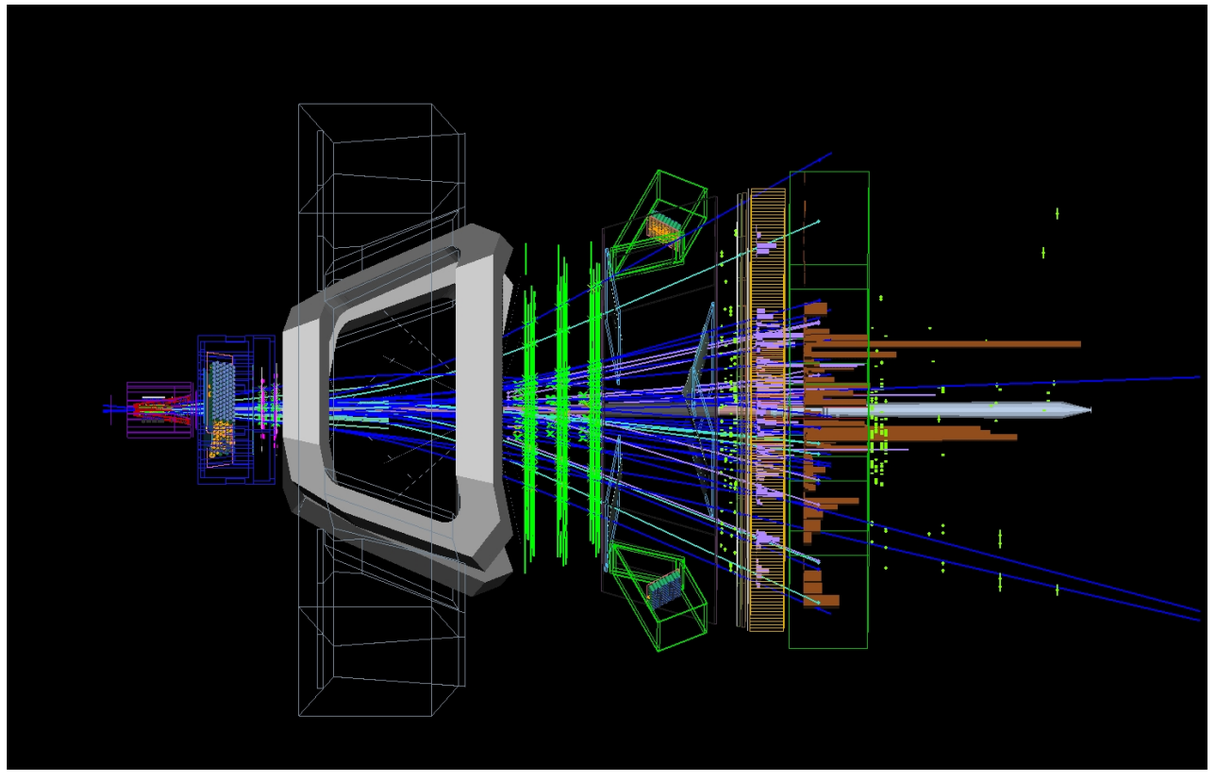

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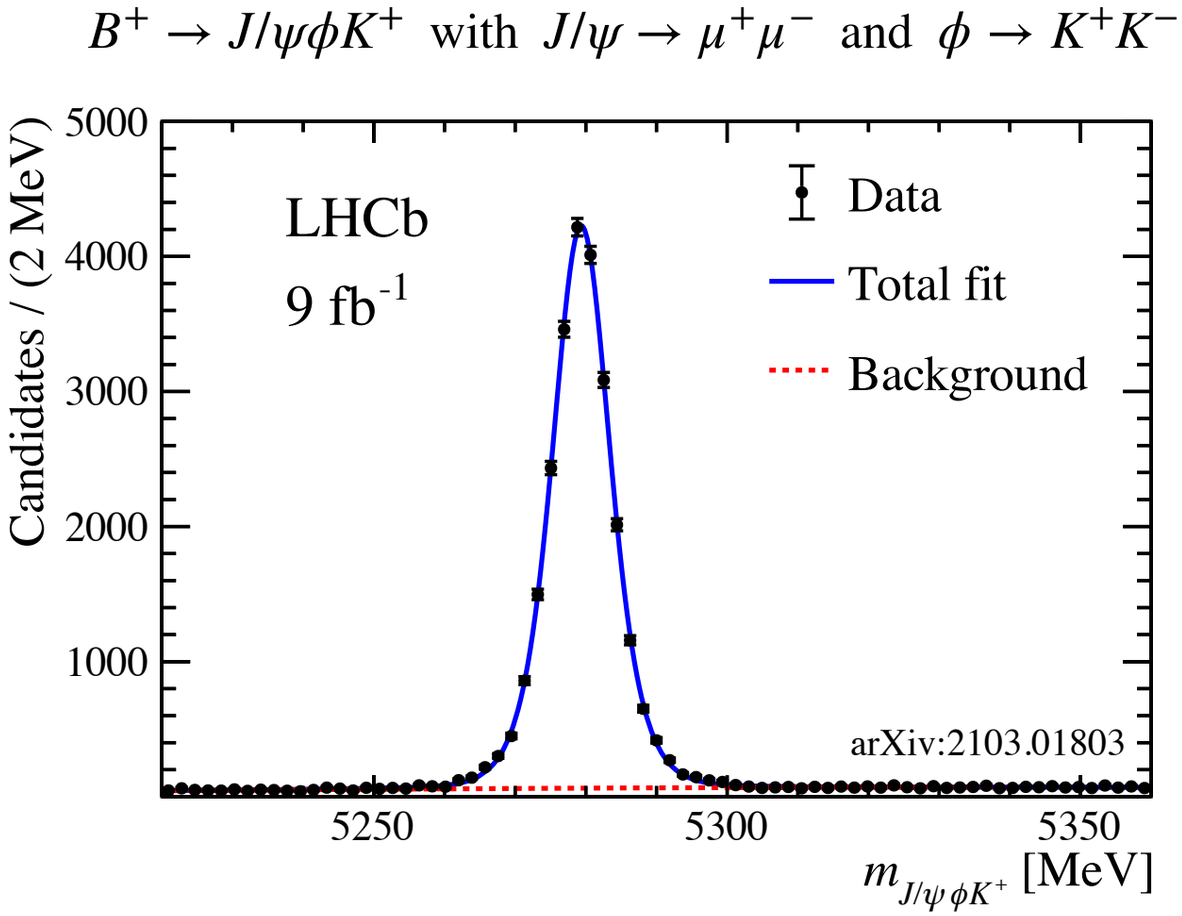

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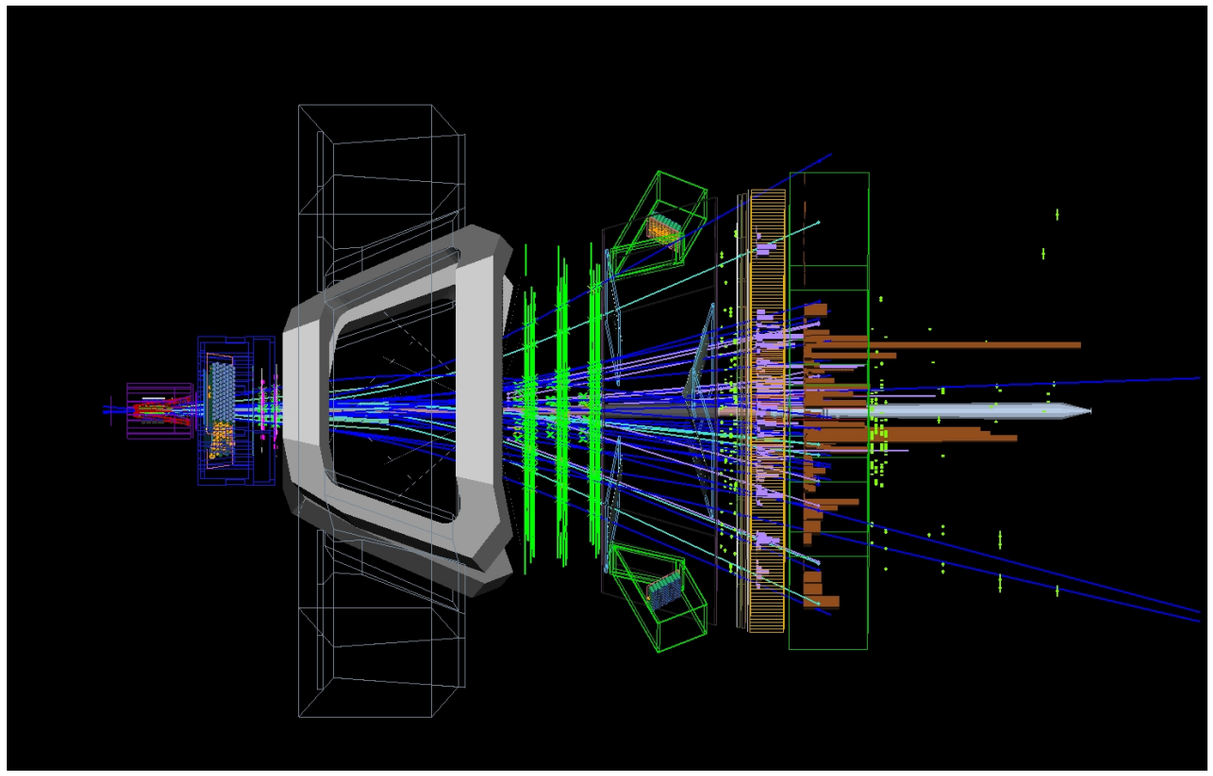
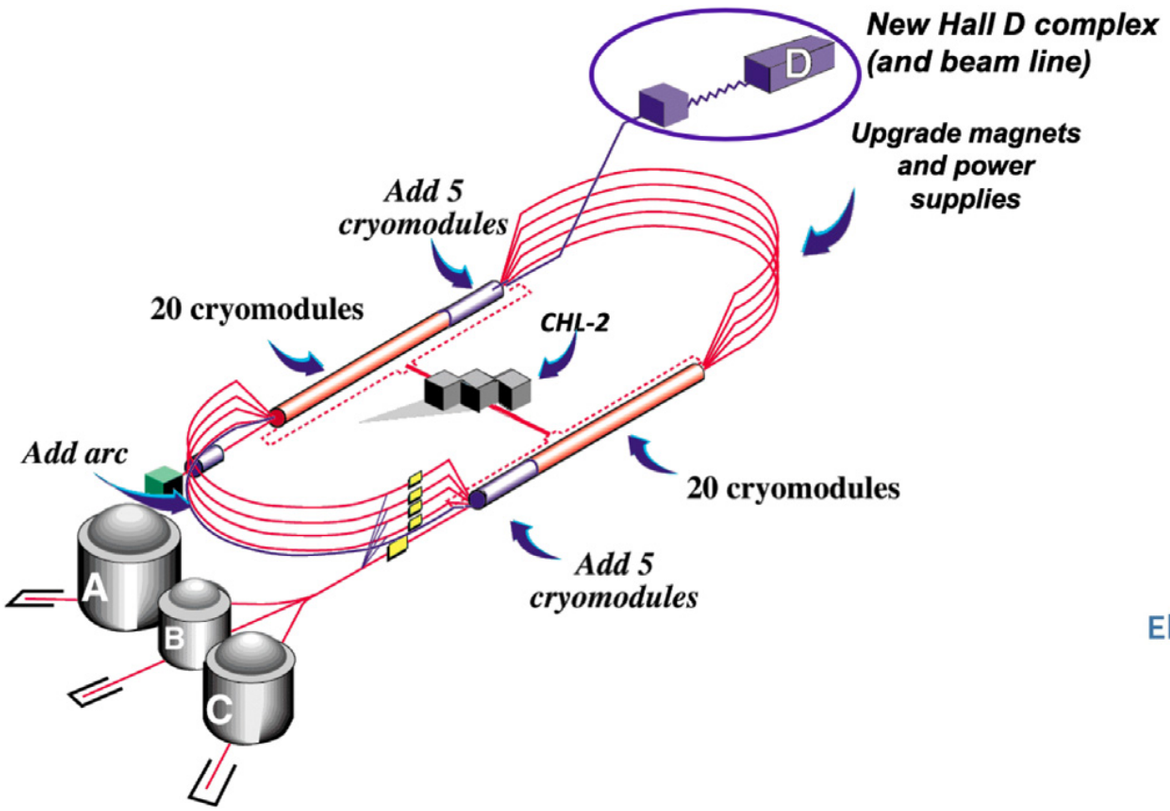


pp collisions between 7 and 14 TeV

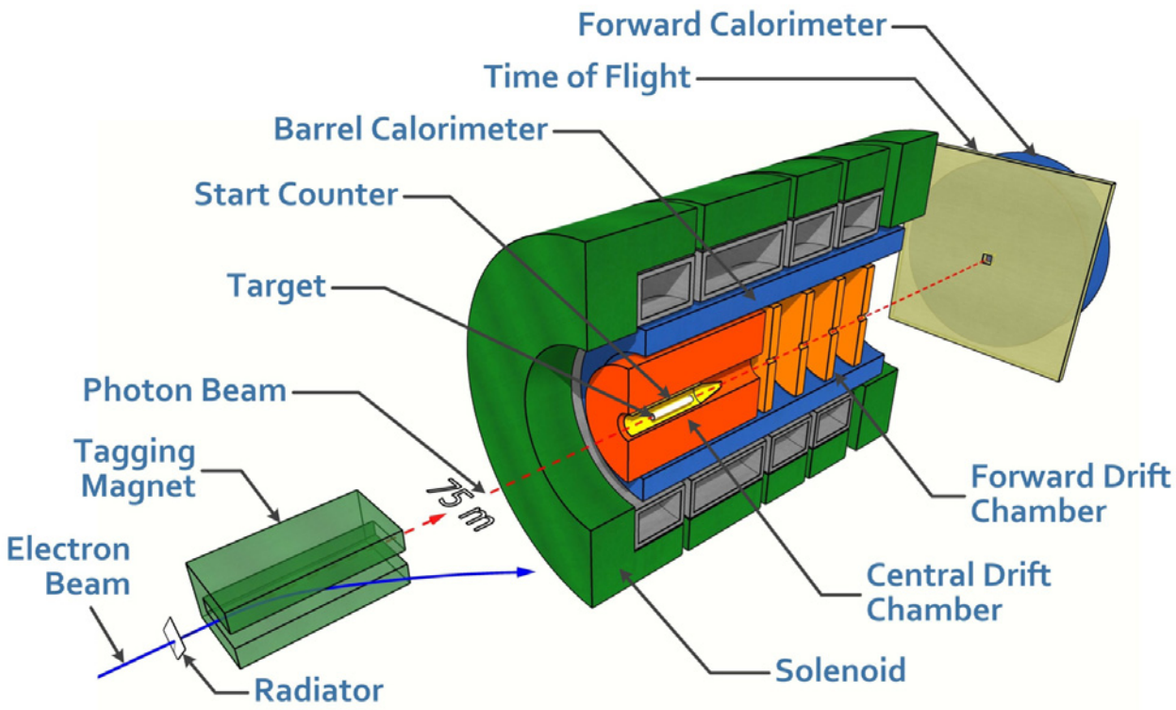
VA. Detectors

The **GlueX Experiment** *(Gluon Excitations)* at **CEBAF** *(Continuous Electron Beam Accelerator Facility)* at **JLab** *(Jefferson Lab)* in Newport News, Virginia



Nuclear Inst. and Methods in Physics Research, A 987 (2021) 164807

The GlueX beamline and detector



Measure the four-vectors of final-state particles ($\gamma, e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm}, p, \bar{p}$) and detached vertices ($K_S, \Lambda, \ldots$) and photon beam polarization.

γp photoproduction with $E_{\text{beam}} \approx 9$ GeV

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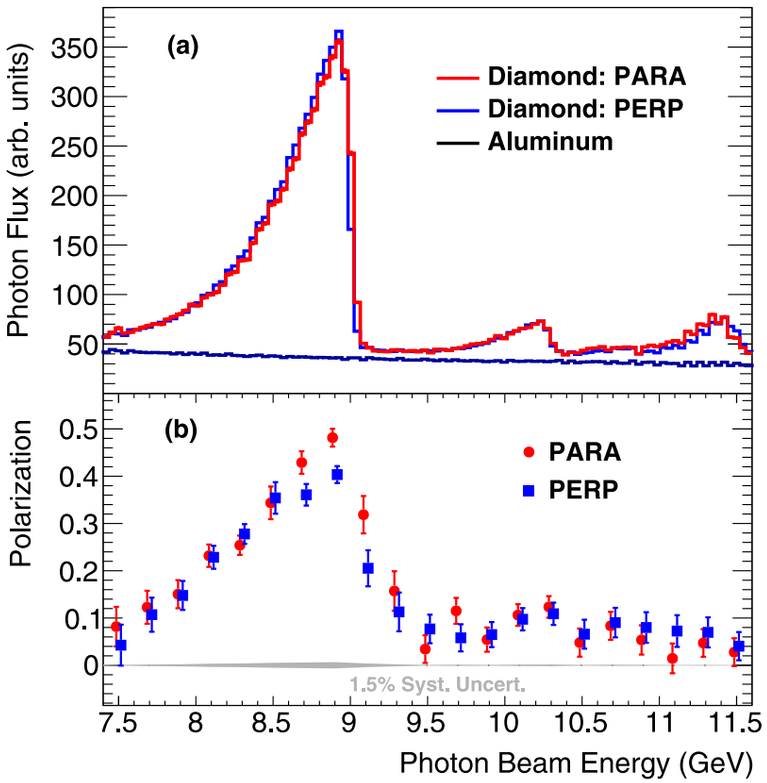

Nuclear Inst. and Methods in Physics Research, A 987 (2021) 164807

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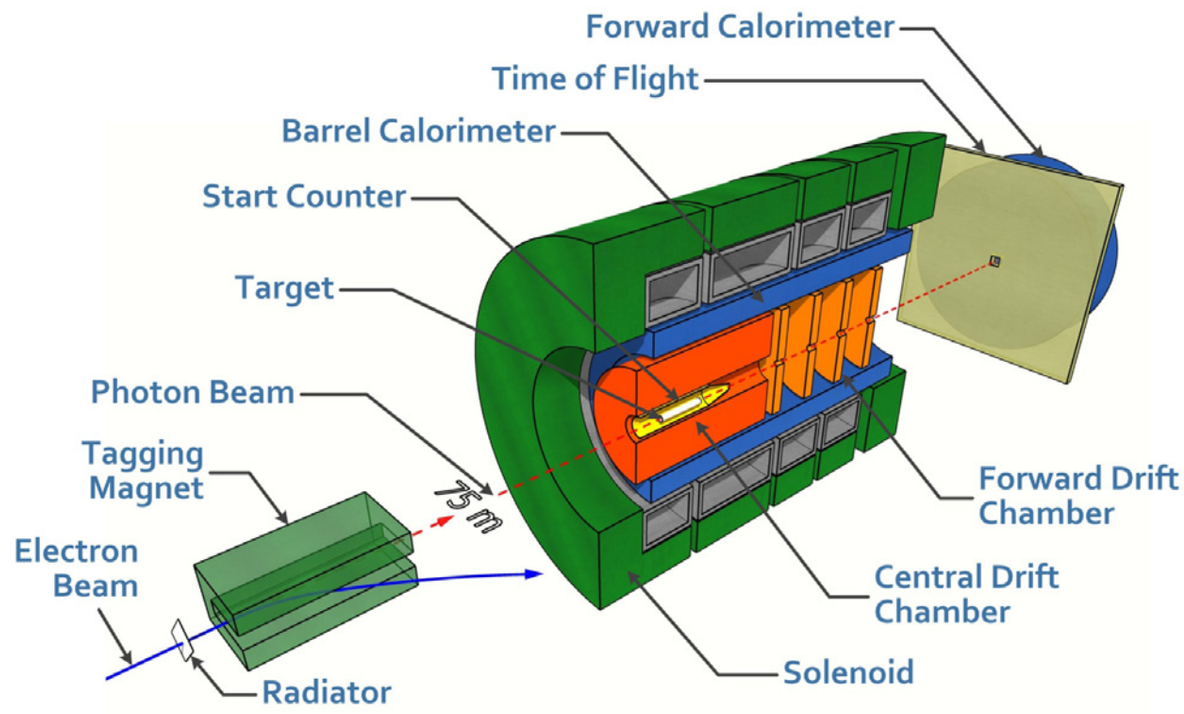

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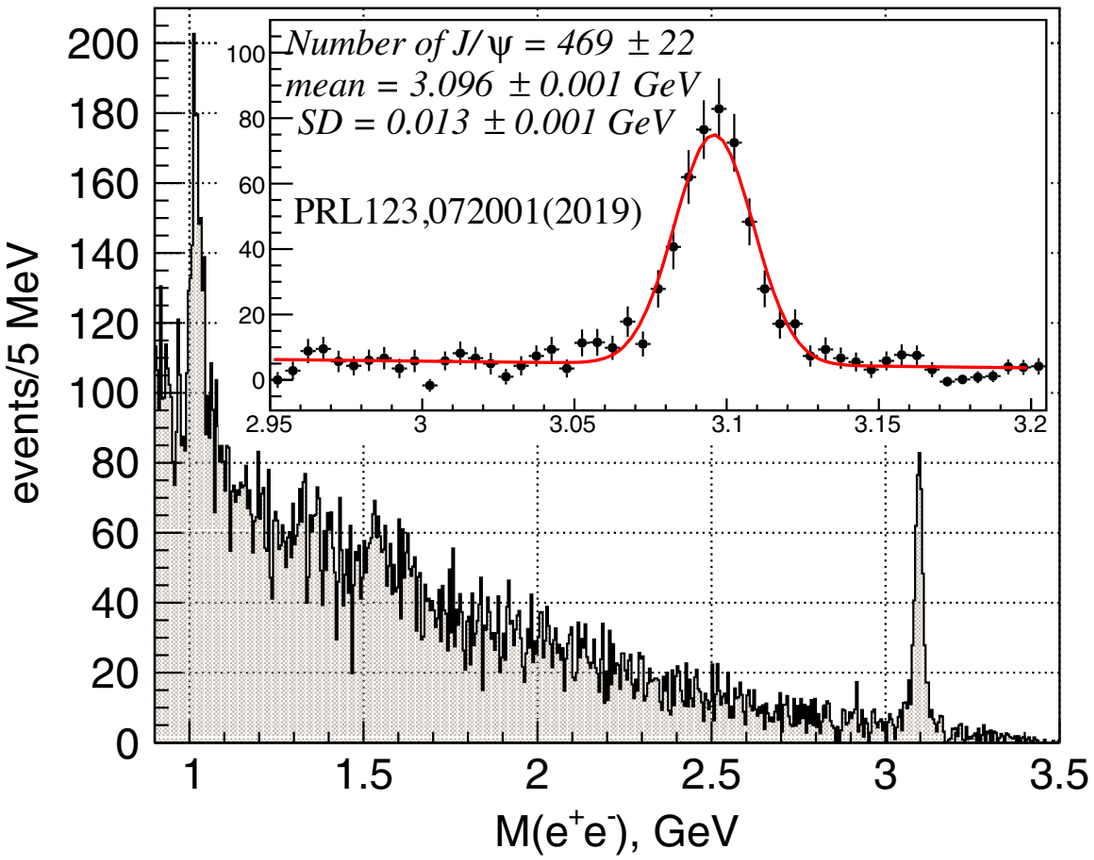
VA. Detectors

The **GlueX Experiment** *(Gluon Excitations)*
at **CEBAF** *(Continuous Electron Beam Accelerator Facility)*
at **JLab** *(Jefferson Lab)* in Newport News, Virginia

$\gamma p \to J/\psi p$ with $J/\psi \to e^+e^-$



Measure the four-vectors of final-state particles ($\gamma, e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm}, p, \bar{p}$) and detached vertices ($K_S, \Lambda, \ldots$) and photon beam polarization.

Nuclear Inst. and Methods in Physics Research, A 987 (2021) 164807

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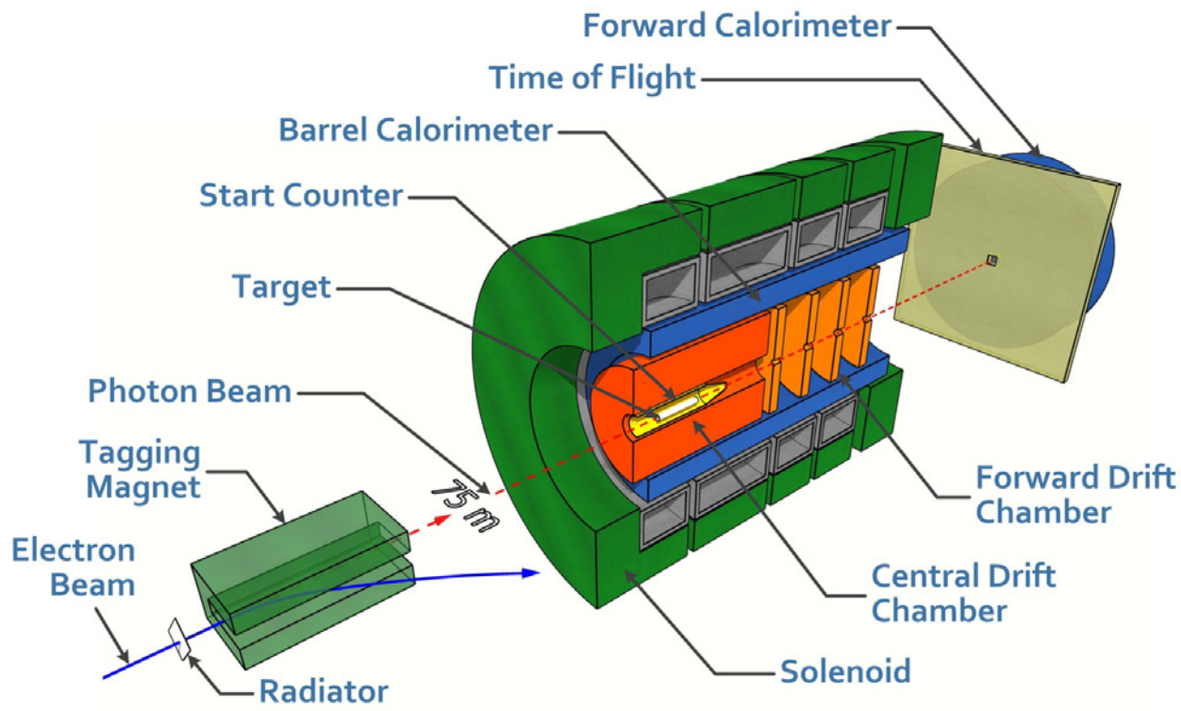


γp photoproduction with $E_{\text{beam}} \approx 9$ GeV

Table 3: Major experiments in the past, present, and future of heavy-quark exotics studies.

Experiment	Highlights	Accelerator	Years	Institute	Production
BaBar	$Y(4260)$ [29] $Y(4360)$ [108]	PEP-II	1999–2008	SLAC (Menlo Park, California, USA)	e^+e^- annihilation ($E_{\rm CM} \approx 10$ GeV): $e^+e^- \to B\bar{B}$; $B \to KX$ $e^+e^- \to Y_b$ $e^+e^- \to \pi Z_b$ $e^+e^-(\gamma_{\rm ISR}) \to Y$ $e^+e^-(\gamma_{\rm ISR}) \to \pi Z_c$ $e^+e^- \to J/\psi + X$ $\gamma\gamma \to X$
Belle	$X(3872)$ [4] $Y(3940)$ [106] $X(3915)$ [166] $Z_c(4430)$ [30, 136, 137] $Z_b(10610)$, $Z_b(10650)$ [160, 162, 163] $Y_b(10888)$ [151, 152]	KEKB	1998–2010	KEK (Tsukuba, Japan)	
Belle II	Upcoming continuation of Belle	SuperKEKB	2018–		
CLEO-c	$Y(4260)$ [142] $\pi^+\pi^- h_c$ [177]	CESR-c	2003–2008	Cornell U. (Ithaca, New York, USA)	e^+e^- annihilation ($E_{\rm CM} \approx 4$ GeV): $e^+e^- \to Y$ $e^+e^- \to \pi Z$ $e^+e^- \to \gamma X$
BESIII	$Z_c(3900)$ [22, 154] $Z_c(4020)$ [156, 158] $Y(4230)$ [149] $X(3872)$ [52]	BEPCII	2008–	IHEP (Beijing, China)	
CDF	$Y(4140)$ [126] $Y(4274)$ [132] $X(3872)$ [178, 179, 172]	Tevatron	1985–2011	Fermilab (Batavia, Illinois, USA)	$p\bar{p}$ collisions ($E_{\rm CM} \approx 2$ TeV): $p\bar{p} \to X$ + any $p\bar{p} \to B$ + any; $B \to KX$
D0	$X(3872)$ [171] $Y(4140)$ [174] $X(5568)$ [175]				
ATLAS	$\chi_b(3P)$ [180]	LHC	2010–	CERN (Geneva, Switzerland)	pp collisions ($E_{\rm CM} = 7$, 8, 13 TeV): $pp \to X$ + any $pp \to B$ + any; $B \to KX$ $pp \to \Lambda_b$ + any; $\Lambda_b \to KP_c$
CMS	$X(3872)$ [28] $Y(4140)$, $Y(4274)$ [130]				
LHCb	$Z_c(4430)$ [138, 139] $X(3872)$ [109] $P_c(4380)$, $P_c(4450)$ [35] $Y(4140)$, $Y(4274)$ [125, 131]				
COMPASS	photoproduction [181] $a_1(1420)$ [182]	SPS	2002-2011		μ/π beam on N target ($p_{beam} \approx 160$, 200 GeV) $\pi N \to XN$ $\gamma N \to XN$
$\bar{\rm P}$ANDA	Upcoming	HESR		GSI (Darmstadt, Germany)	$\bar{p}$ beam on p target ($p_{beam} \approx 1.5$–15 GeV): $p\bar{p} \to X$ $p\bar{p} \to X$ + any
GlueX	Beginning (searches for light quark hybrid mesons)	CEBAF	2016–	Jefferson Lab (Newport News, Virginia, USA)	γ beam on p target ($E_{beam} \leq 11$ GeV): $\gamma p \to Xp$
CLAS12					

Progress in Particle and Nuclear Physics 93 (2017) 143–194

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Heavy-quark QCD exotica

Richard F. Lebed [a,*], Ryan E. Mitchell [b], Eric S. Swanson [c]

LECTURE V. Current and Future Experiments

VA. Detectors

VB. Hadron Colliders

VC. e^+e^- Colliders

* B Factories

* τ/c Factories

VD. Fixed Targets

VE. New Possibilities

VF. Outlook

VB. Hadron Colliders

Highlights from Hadron Colliders

(1) hadron production

(2) the Tevatron and the LHC

(3) breakthroughs at the LHC

- $B_c(2S)$ and $B_c^*(2S)$
- $X(3842)$ (or $\psi_3(3842)$)
- $X(2900)$
- $T_{c\bar{c}c\bar{c}}$
- Ω_c states
- P_c pentaquarks

(4) the future of the LHC

Production mechanisms at hadron colliders:

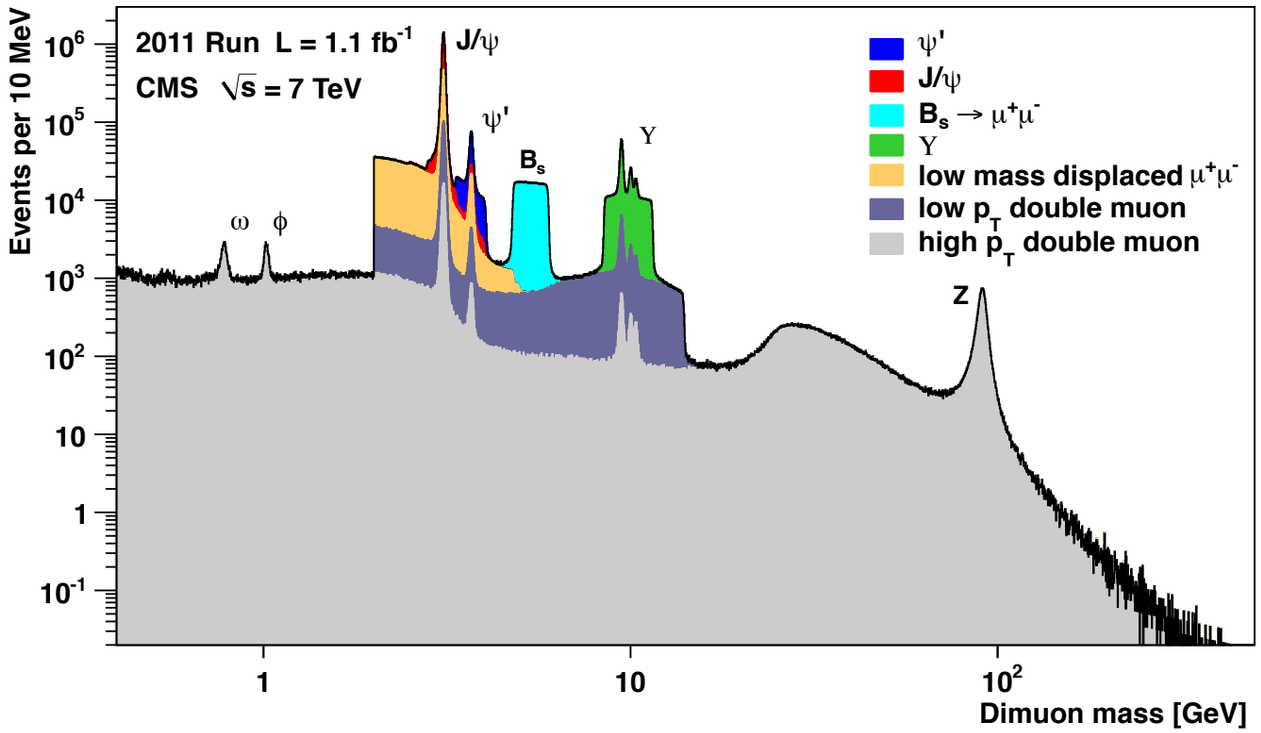
pp (or $p\bar{p}$) $\rightarrow X$ + anything (prompt)

pp (or $p\bar{p}$) $\rightarrow B$ (Λ_b) + anything (non-prompt)

High rates mean triggers play an important role:

2017 JINST 12 P01020

The CMS trigger system



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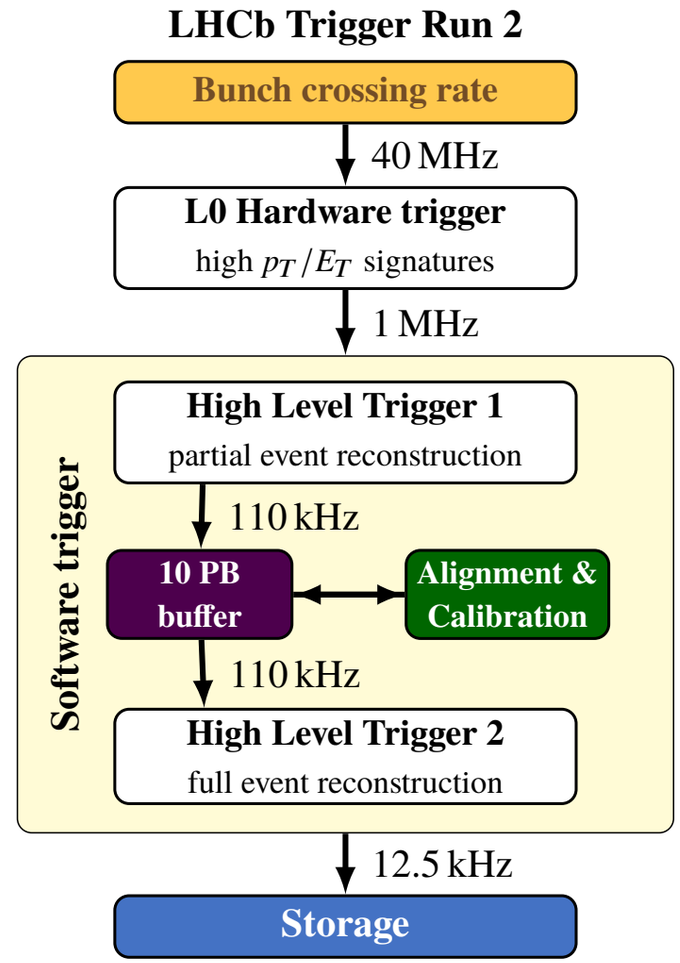

2019 JINST 14 P04013

Design and performance of the LHCb trigger and full real-time reconstruction in Run 2 of the LHC

The LHCb collaboration

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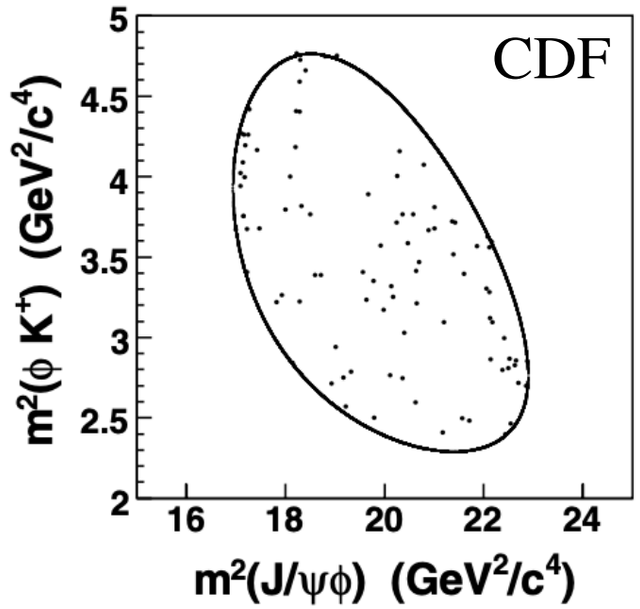
(4) the future of the LHC

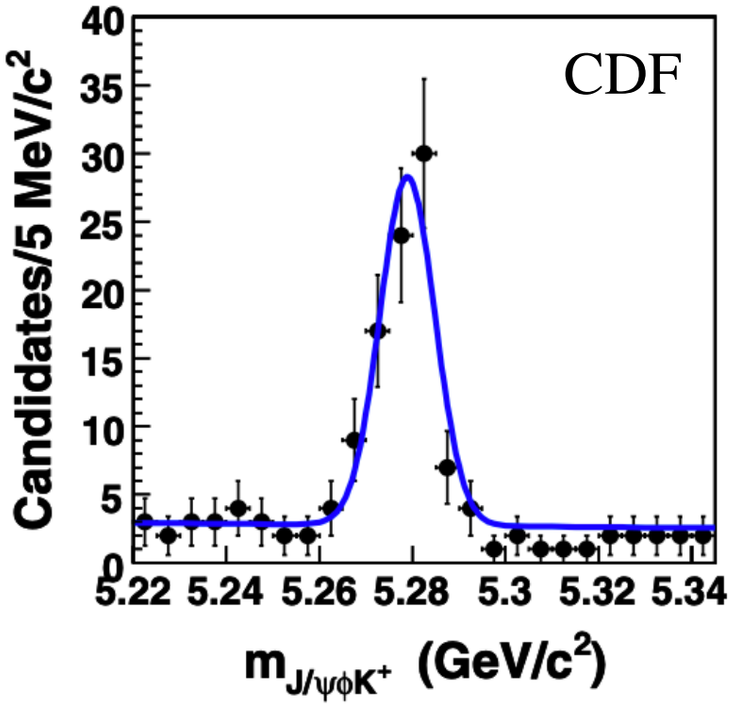
PRL **102,** 242002 (2009) PHYSICAL REVIEW LETTERS week ending 19 JUNE 2009

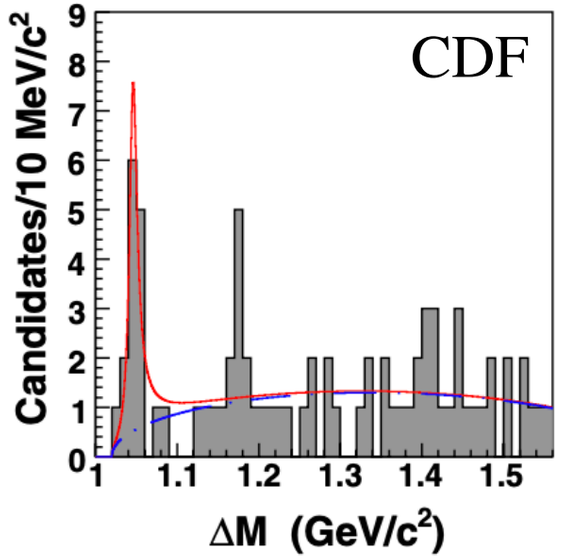
Evidence for a Narrow Near-Threshold Structure in the $J/\psi\phi$ Mass Spectrum in $B^+ \to J/\psi\phi K^+$ Decays

(CDF Collaboration)

The first study of $B \to K\phi J/\psi$ was at the Tevatron…







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Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$

arXiv:2103.01803v1 [hep-ex] 2 Mar 2021

LHCb collaboration†

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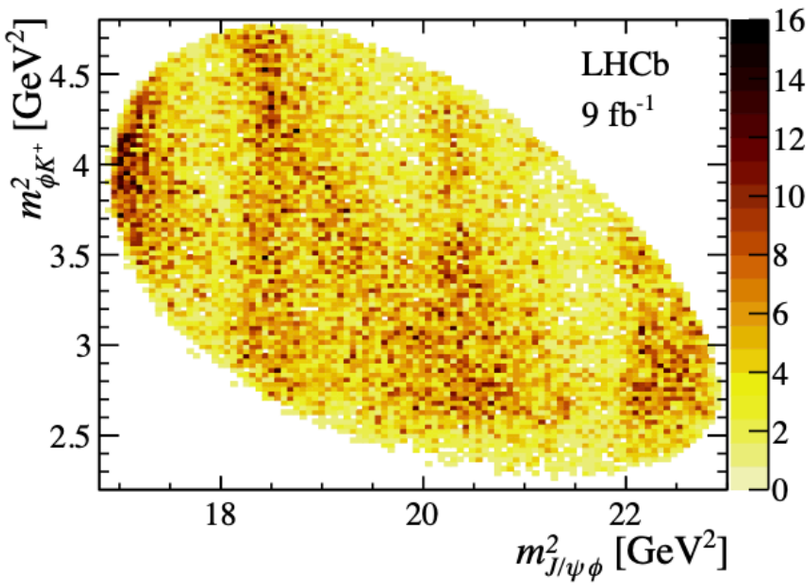
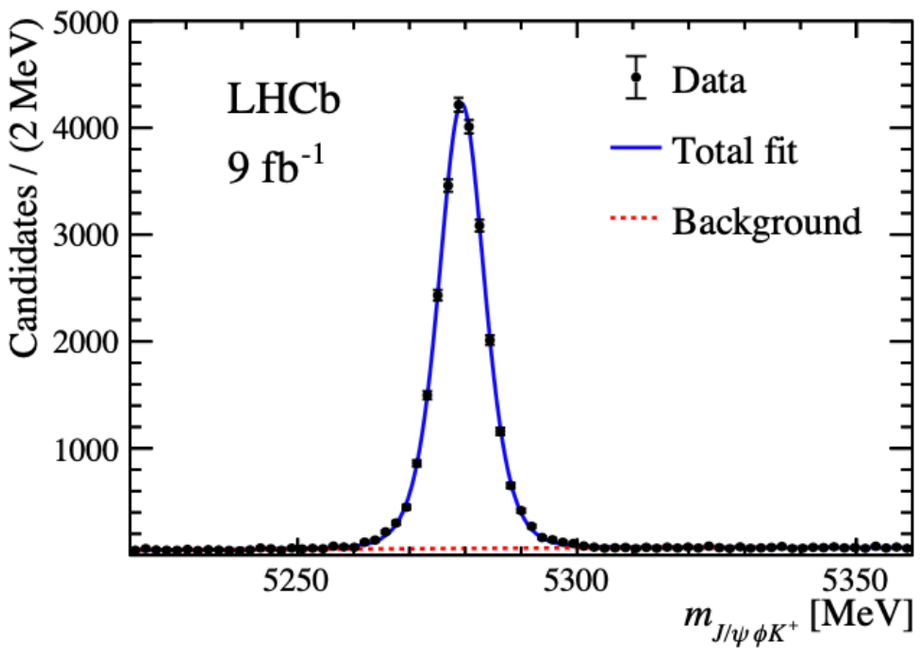
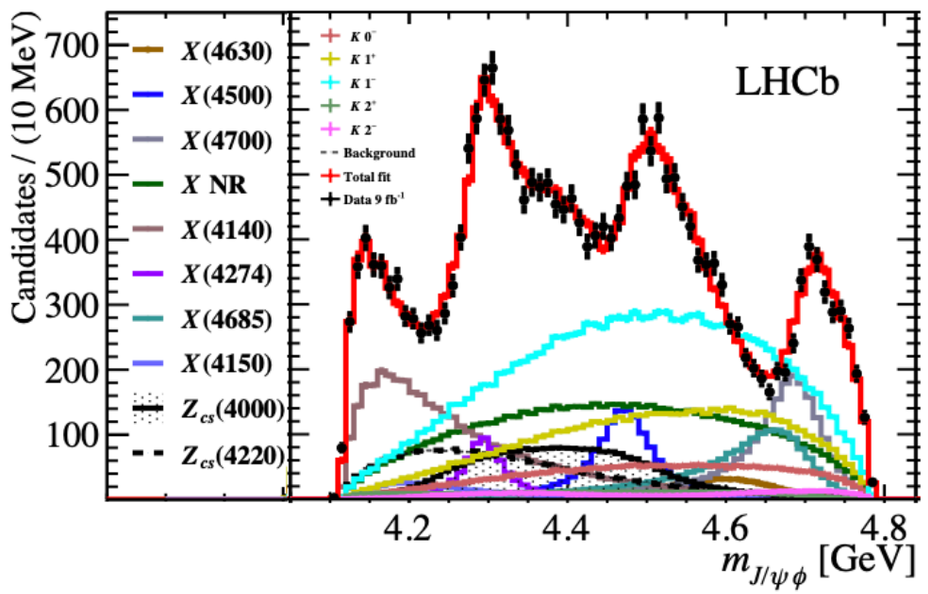
… but the statistics at the LHC are now overwhelming.







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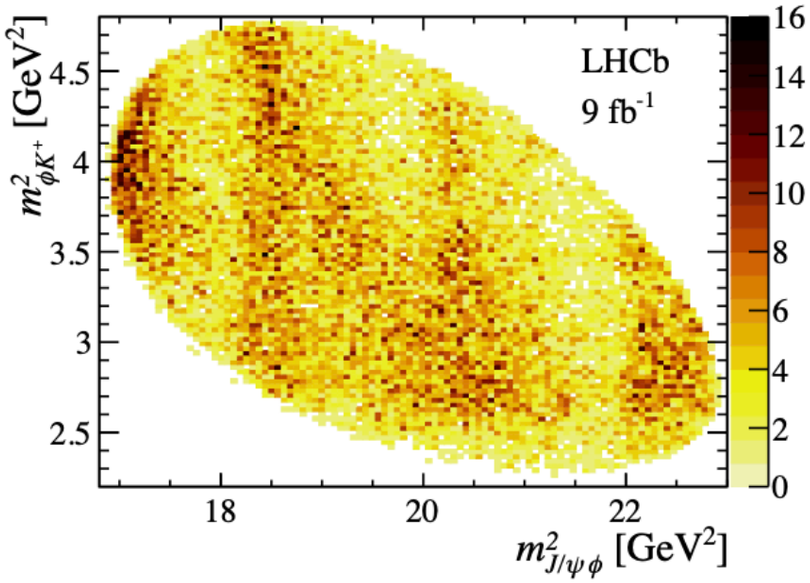

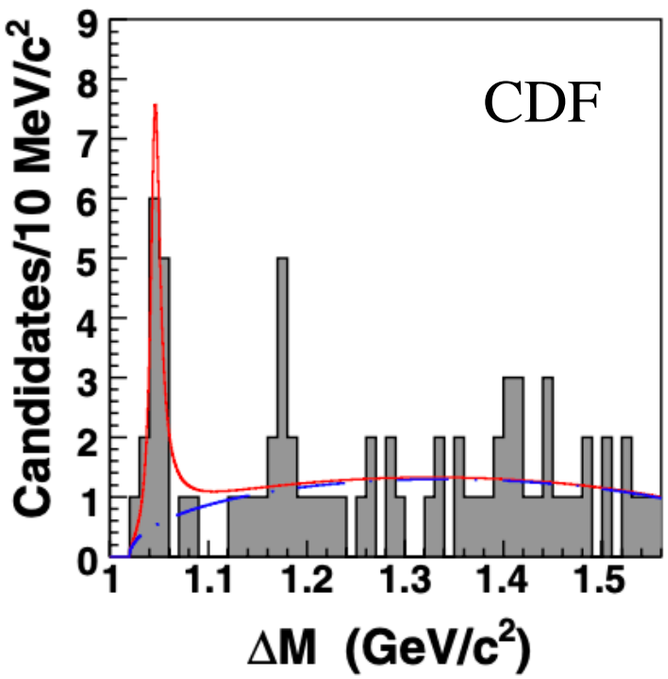

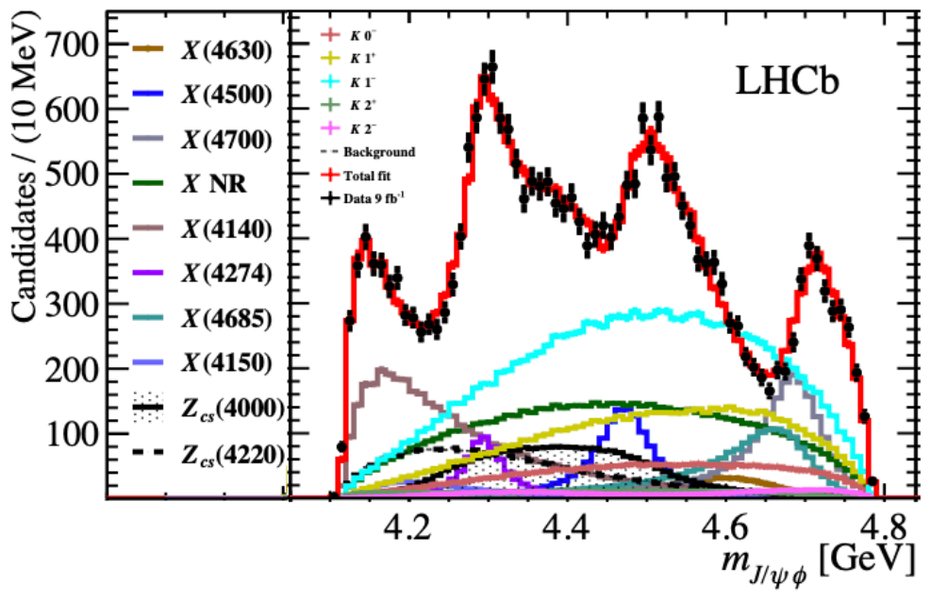

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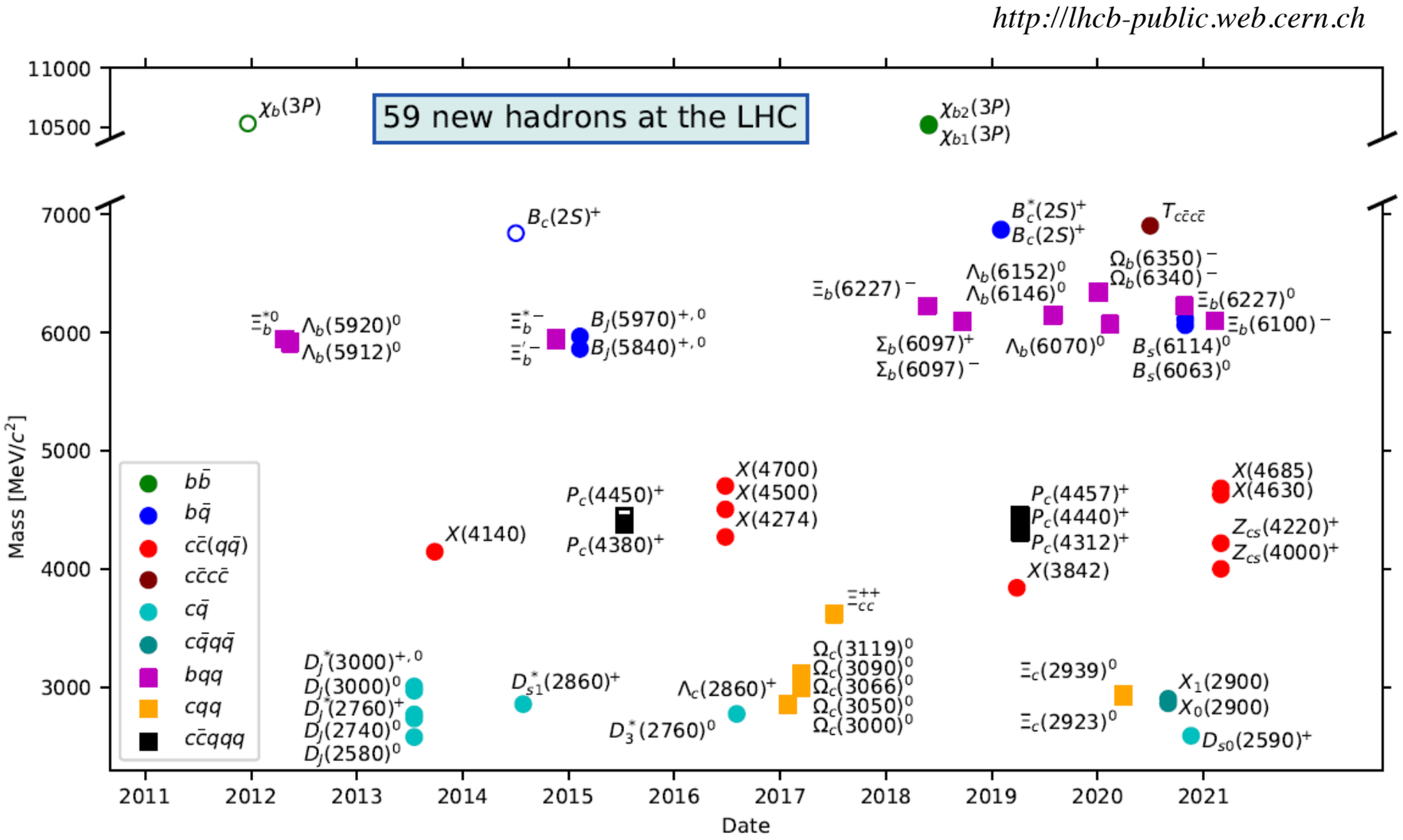

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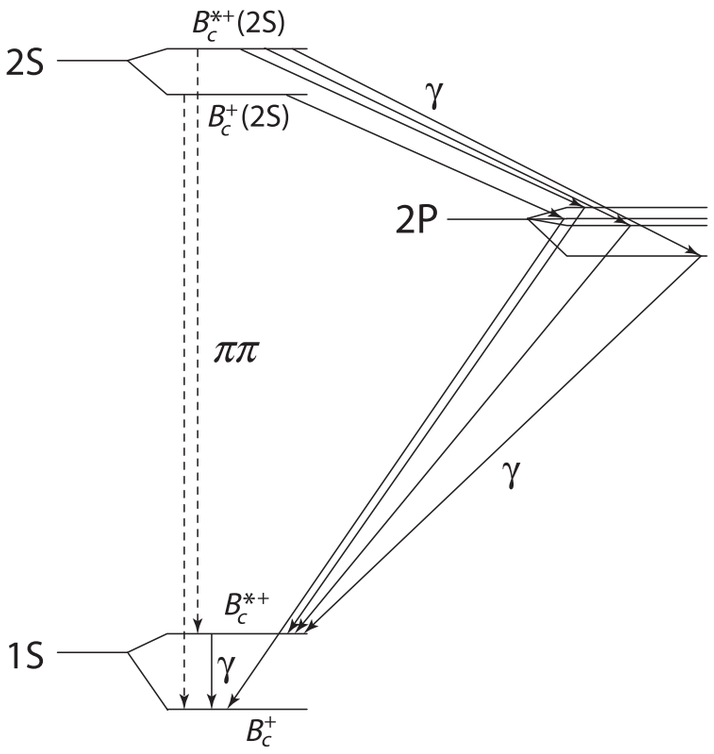
PHYSICAL REVIEW LETTERS **122,** 132001 (2019)

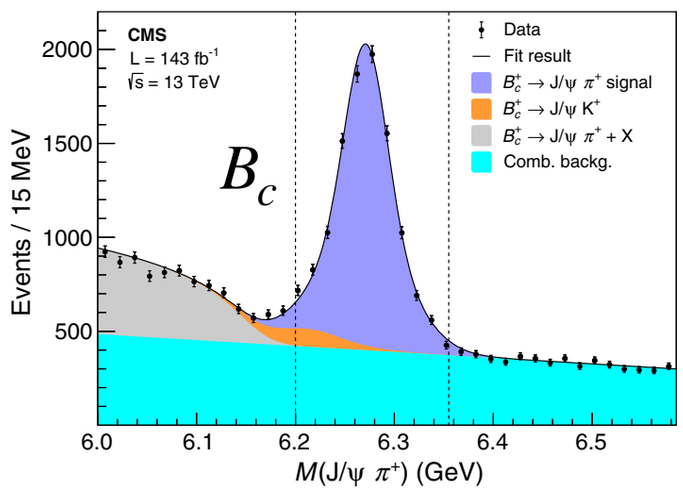
Editors' Suggestion | Featured in Physics

Observation of Two Excited B_c^+ States and Measurement of the $B_c^+(2S)$ Mass in pp Collisions at $\sqrt{s} = 13$ TeV

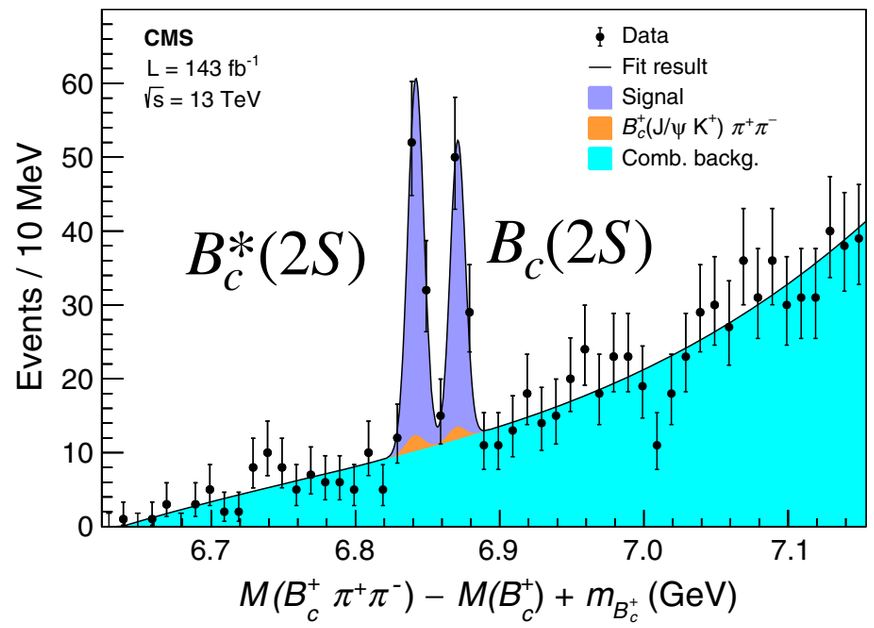
A. M. Sirunyan *et al.*[*]
(CMS Collaboration)



Find $B_c \to J/\psi\pi^+$:



Add two more pions:



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(4) the future of the LHC

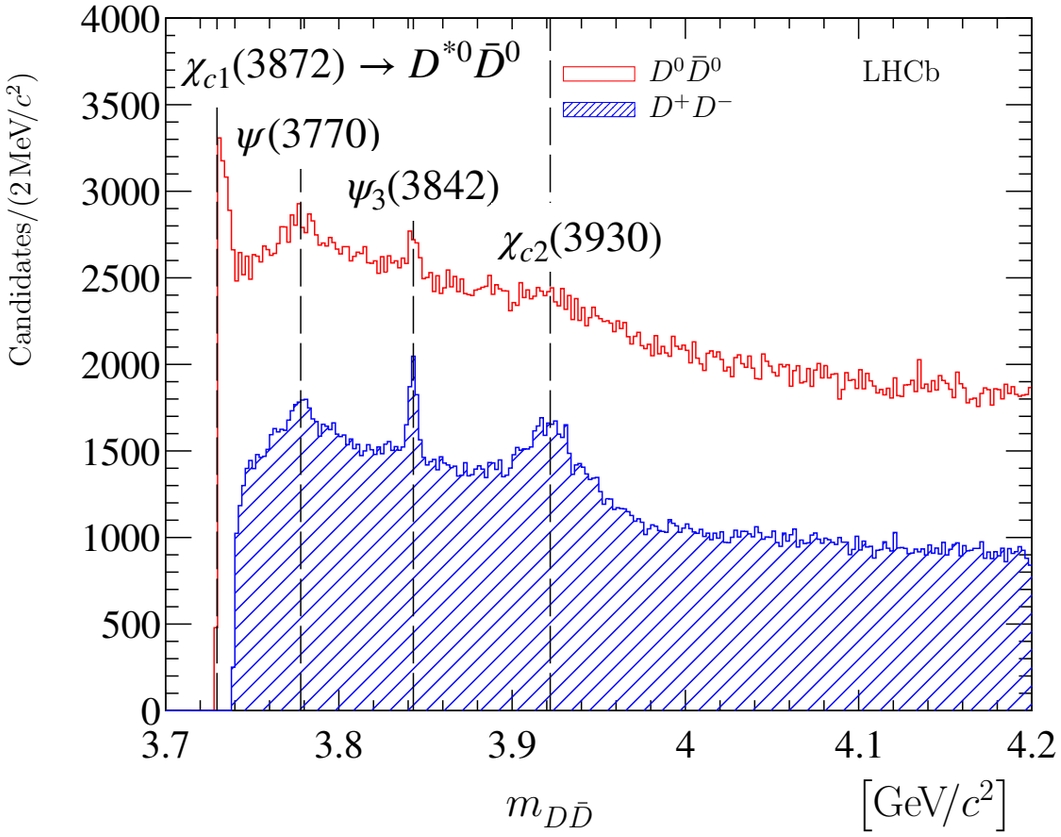
JHEP07(2019)035

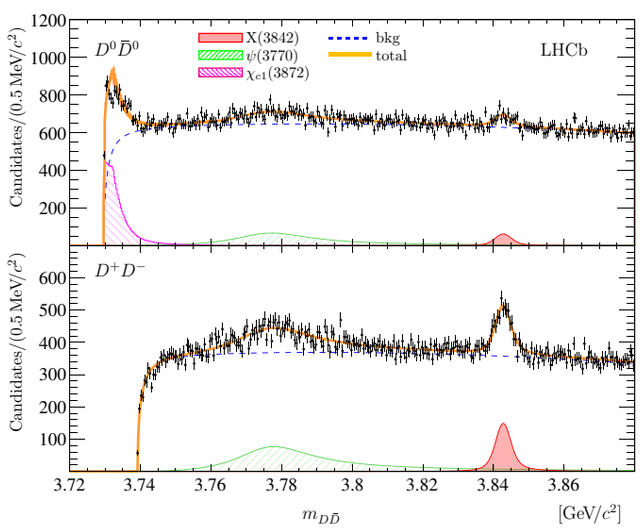
Near-threshold $D\bar{D}$ spectroscopy and observation of a new charmonium state

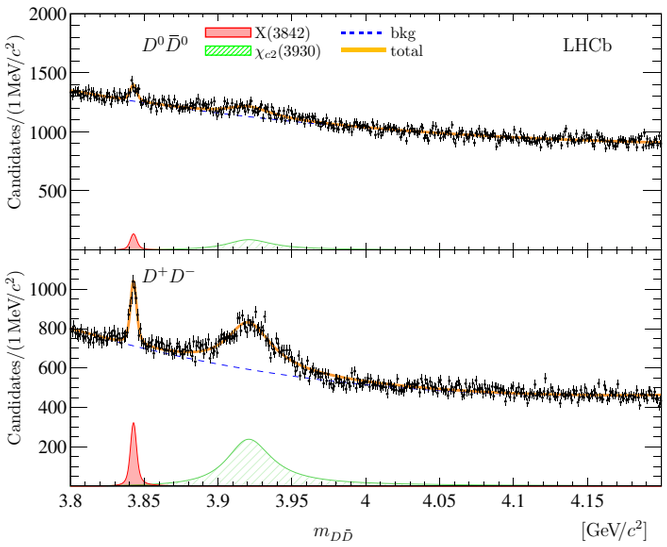
The LHCb collaboration

Find $D^0 \to K^-\pi^+$ and $\bar{D}^0 \to K^+\pi^-$, plot $M(D^0\bar{D}^0)$.

Find $D^+ \to K^-\pi^+\pi^+$ and $D^- \to K^+\pi^-\pi^-$, plot $M(D^+D^-)$.







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(4) the future of the LHC

JHEP07

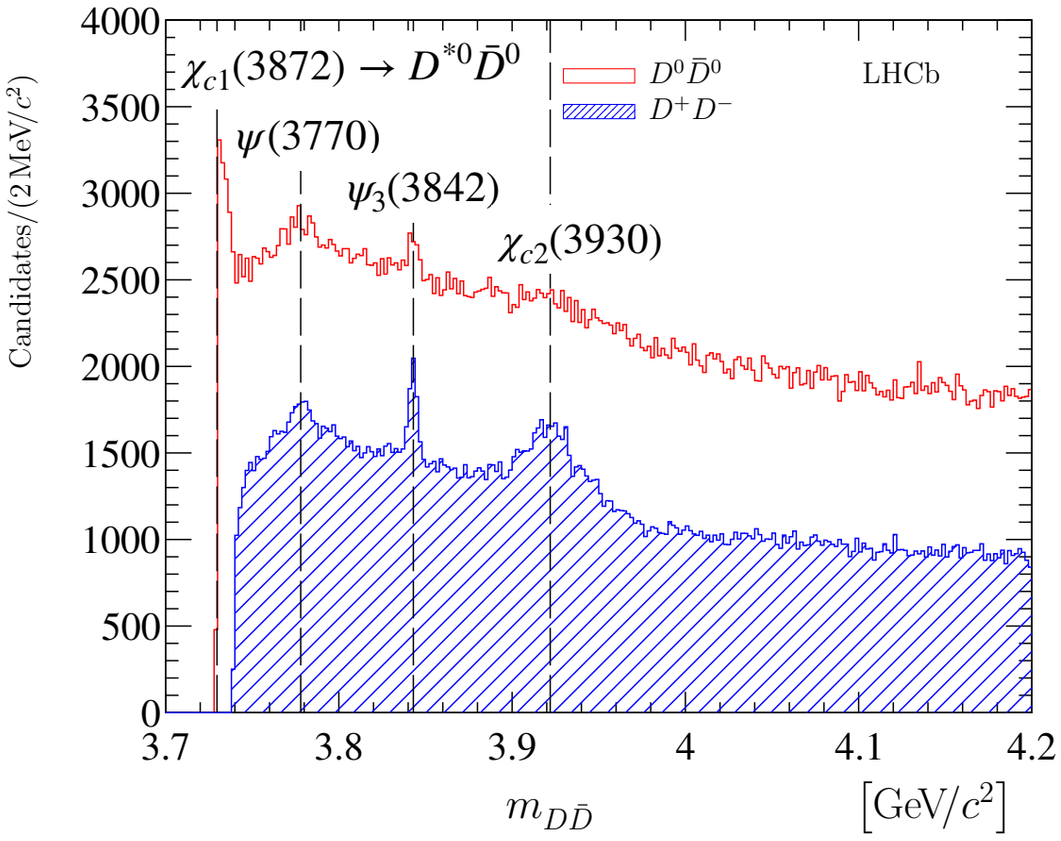
Near-threshold $D\bar{D}$ spe

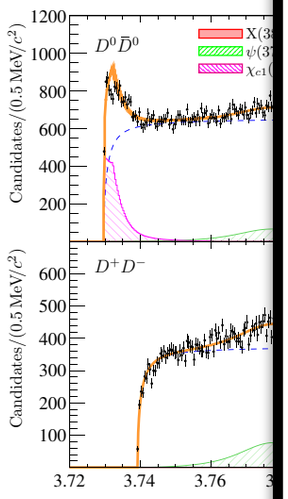
new charmonium state

The LHCb collaboration

Find D^0 –

Find D^+ –





(α_s, b, m_c, σ) = (0.5461, 0.1425 GeV^2, 1.4794 GeV, 1.0946 GeV)

Multiplet	State	Expt.	Input (NR)	Theor. NR	Theor. GI
1S	$J/\psi(1^3S_1)$	3096.87 ± 0.04	3097	3090	3098
	$\eta_c(1^1S_0)$	2979.2 ± 1.3	2979	2982	2975
2S	$\psi'(2^3S_1)$	3685.96 ± 0.09	3686	3672	3676
	$\eta_c'(2^1S_0)$	3637.7 ± 4.4	3638	3630	3623
3S	$\psi(3^3S_1)$	4040 ± 10	4040	4072	4100
	$\eta_c(3^1S_0)$			4043	4064
4S	$\psi(4^3S_1)$	4415 ± 6	4415	4406	4450
	$\eta_c(4^1S_0)$			4384	4425
1P	$\chi_2(1^3P_2)$	3556.18 ± 0.13	3556	3556	3550
	$\chi_1(1^3P_1)$	3510.51 ± 0.12	3511	3505	3510
	$\chi_0(1^3P_0)$	3415.3 ± 0.4	3415	3424	3445
	$h_c(1^1P_1)$	see text		3516	3517
2P	$\chi_2(2^3P_2)$			3972	3979
	$\chi_1(2^3P_1)$			3925	3953
	$\chi_0(2^3P_0)$	???		3852	3916
	$h_c(2^1P_1)$			3934	3956
3P	$\chi_2(3^3P_2)$			4317	4337
	$\chi_1(3^3P_1)$			4271	4317
	$\chi_0(3^3P_0)$			4202	4292
	$h_c(3^1P_1)$			4279	4318
1D	$\psi_3(1^3D_3)$			3806	3849
	$\psi_2(1^3D_2)$			3800	3838
	$\psi(1^3D_1)$	3769.9 ± 2.5	3770	3785	3819
	$\eta_{c2}(1^1D_2)$			3799	3837
2D	$\psi_3(2^3D_3)$			4167	4217
	$\psi_2(2^3D_2)$			4158	4208
	$\psi(2^3D_1)$	4159 ± 20	4159	4142	4194
	$\eta_{c2}(2^1D_2)$			4158	4208

+ 1F, 2F, 1G

Highlights from Hadron Colliders

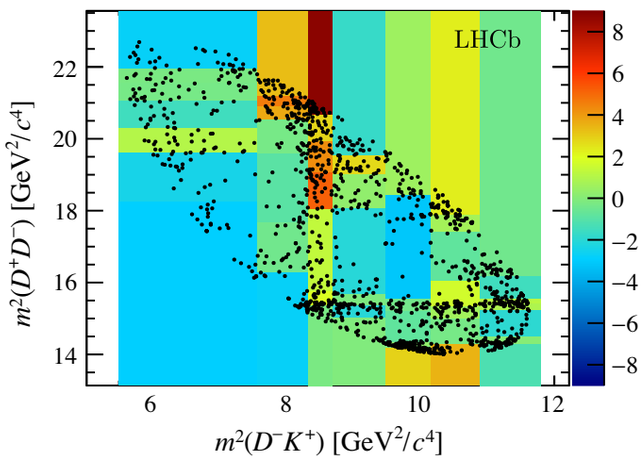
(1) hadron production

(2) the Tevatron and the LHC

(3) breakthroughs at the LHC

- $B_c(2S)$ and $B_c^*(2S)$
- $X(3842)$ (or $\psi_3(3842)$)
- $X(2900)$
- $T_{c\bar{c}c\bar{c}}$
- Ω_c states
- P_c pentaquarks

(4) the future of the LHC

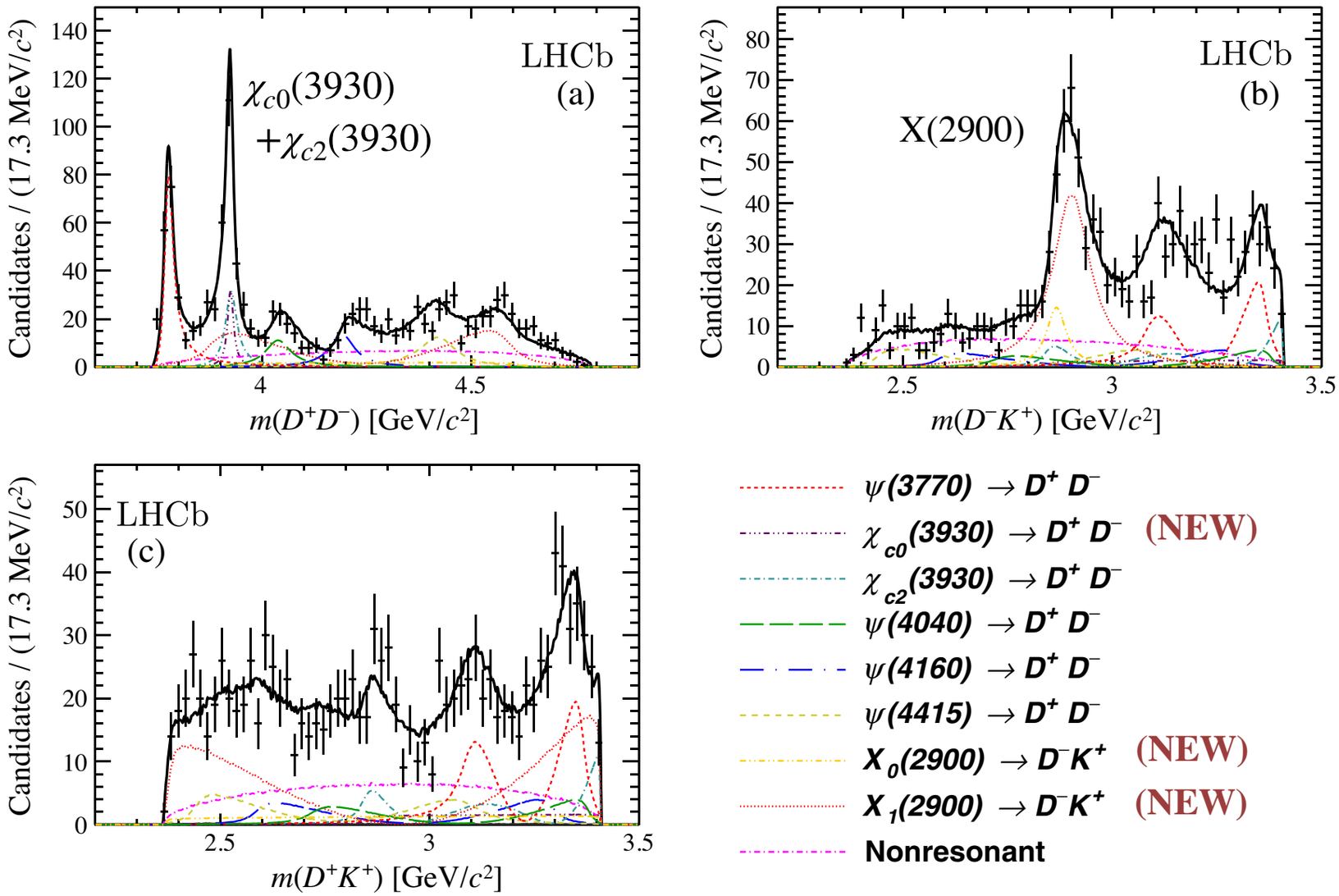


PHYSICAL REVIEW D **102,** 112003 (2020)

Editors' Suggestion

Amplitude analysis of the $B^+ \to D^+D^-K^+$ decay

(LHCb Collaboration)



VB. Hadron Colliders

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(4) the future of the LHC

Science Bulletin 65 (2020) 1983–1993

Contents lists available at ScienceDirect

Science Bulletin

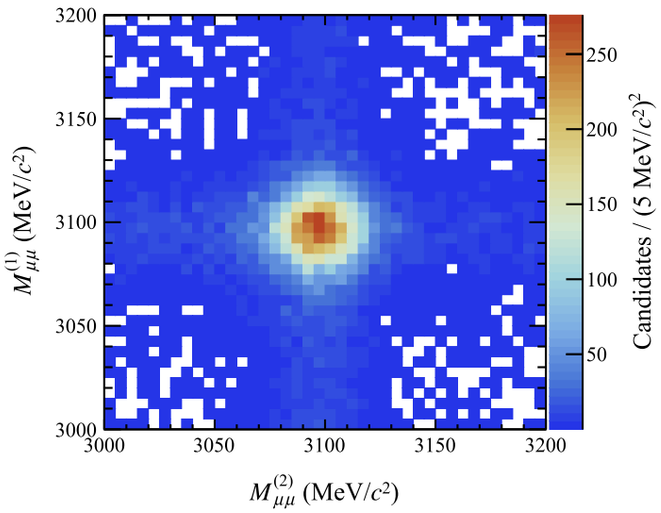
journal homepage: www.elsevier.com/locate/scib

Article

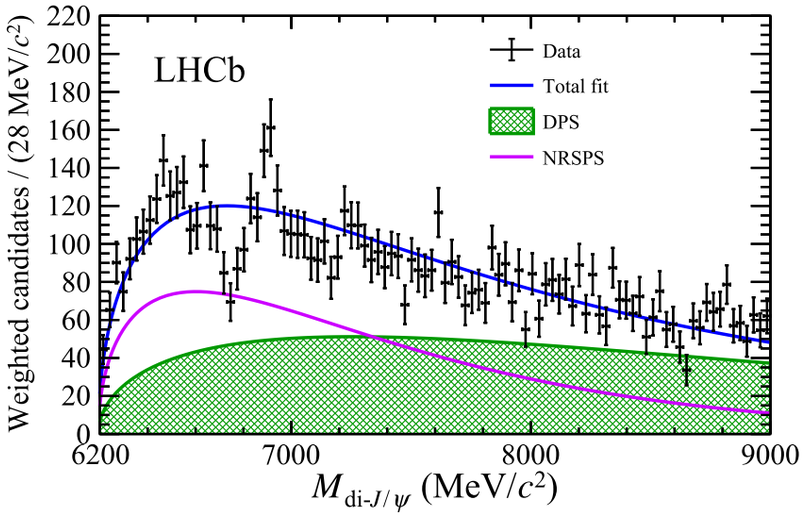
Observation of structure in the J/ψ-pair mass spectrum

LHCb collaboration [1]

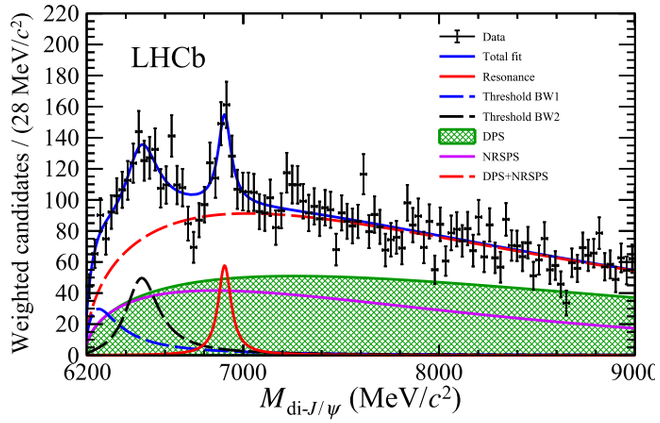
Select $J/\psi J/\psi$:

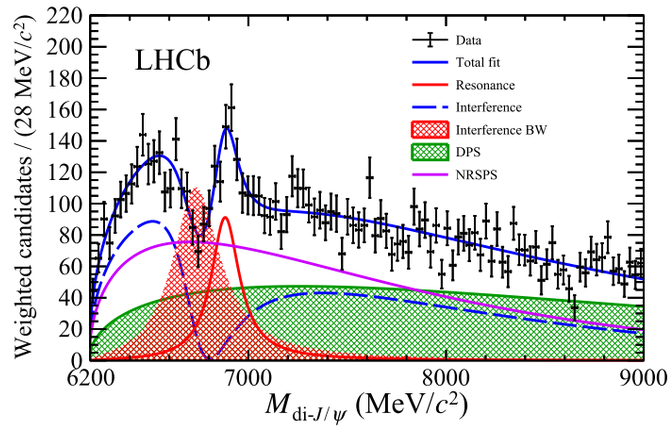


Try to fit $M(J/\psi J/\psi)$:



Need a state at 6900 MeV?





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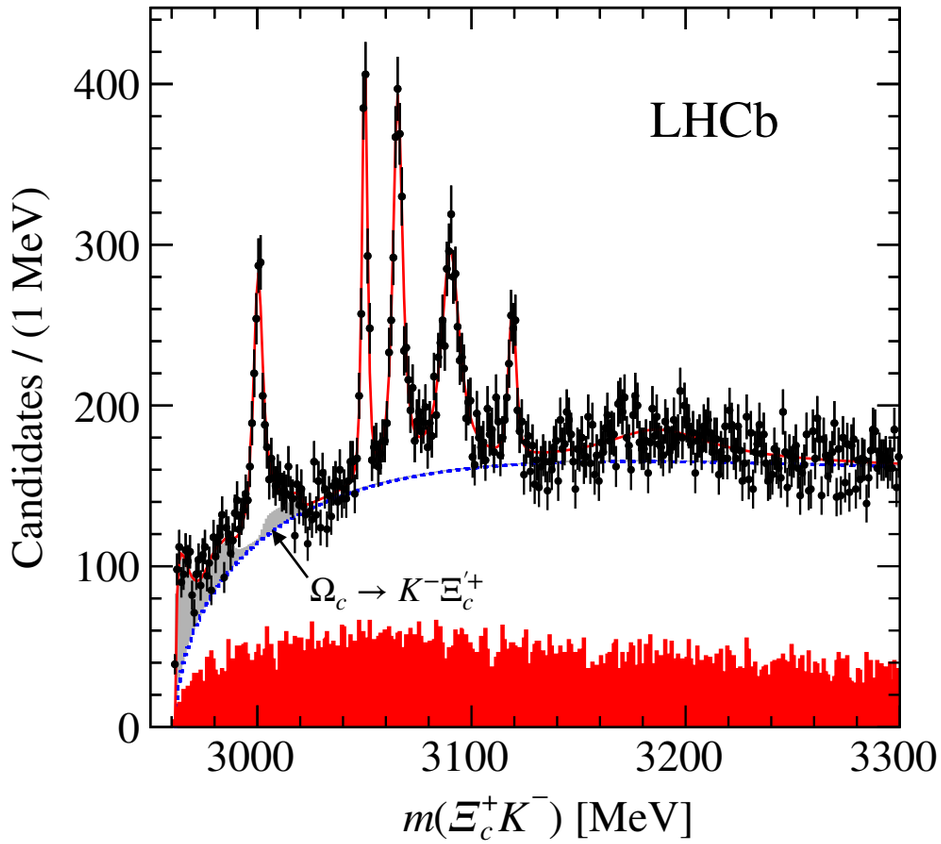
(4) the future of the LHC

PRL **118,** 182001 (2017) PHYSICAL REVIEW LETTERS week ending 5 MAY 2017

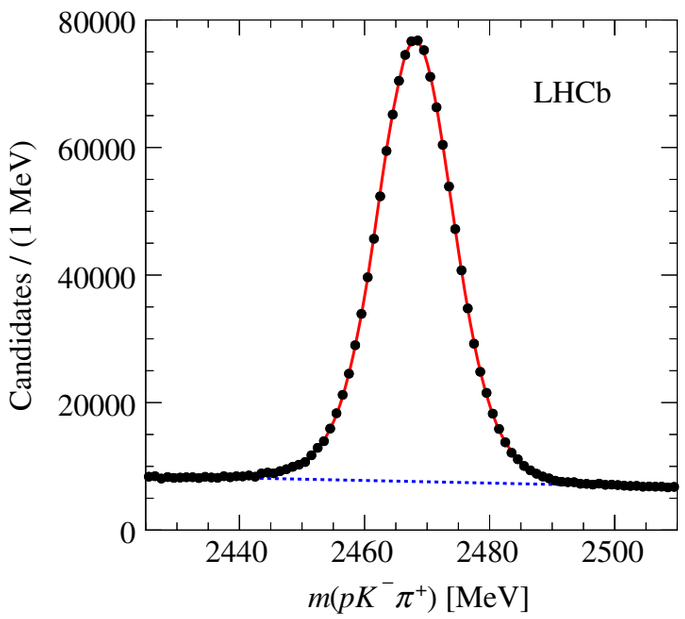
Observation of Five New Narrow Ω_c^0 States Decaying to $\Xi_c^+ K^-$

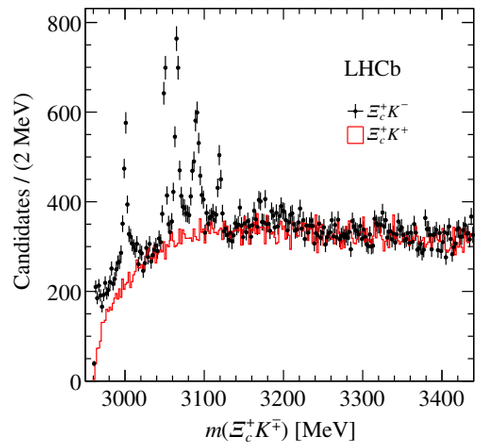
R. Aaij *et al.*[*]
(LHCb Collaboration)

Combine the Ξ_c^+ with a K^-:



Find $\Xi_c^+ \to pK^-\pi^+$:





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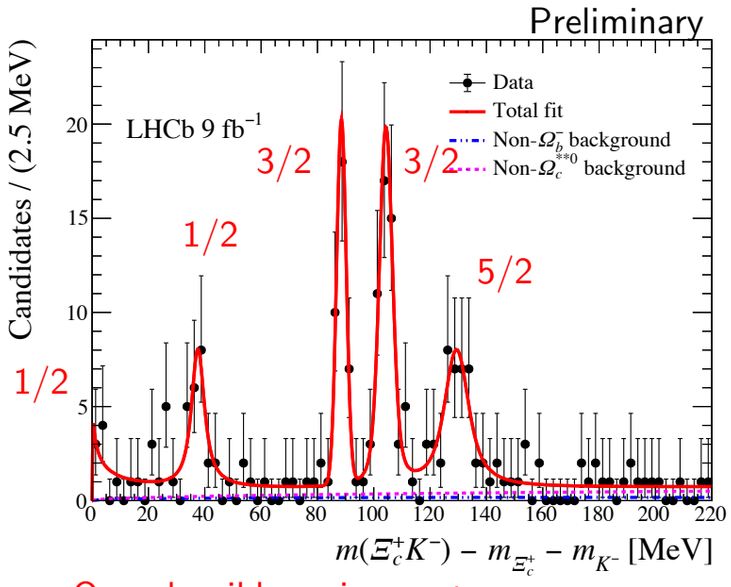
(4) the future of the LHC

From Mikhail Mikhasenko at CHARM2021 (June 1, 2021):

Start with $\Omega_b^- \to (\Xi_c^+ K^-)\pi^-$:

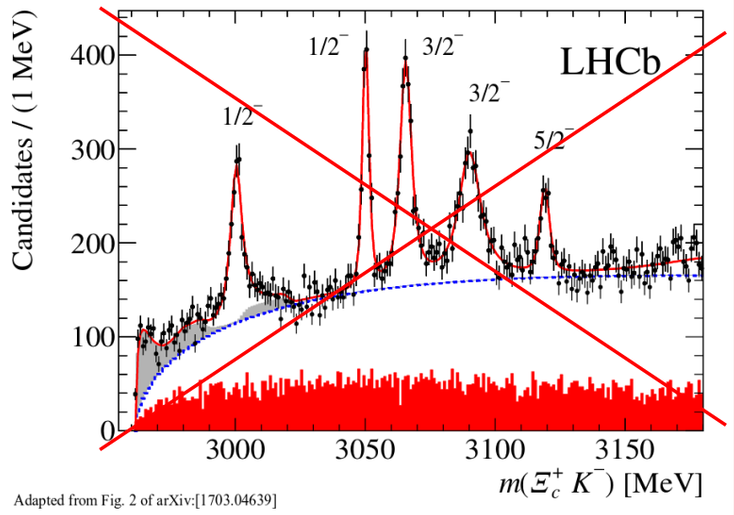
Combined spin test

[LHCb-PAPER-2021-012, in preparation]



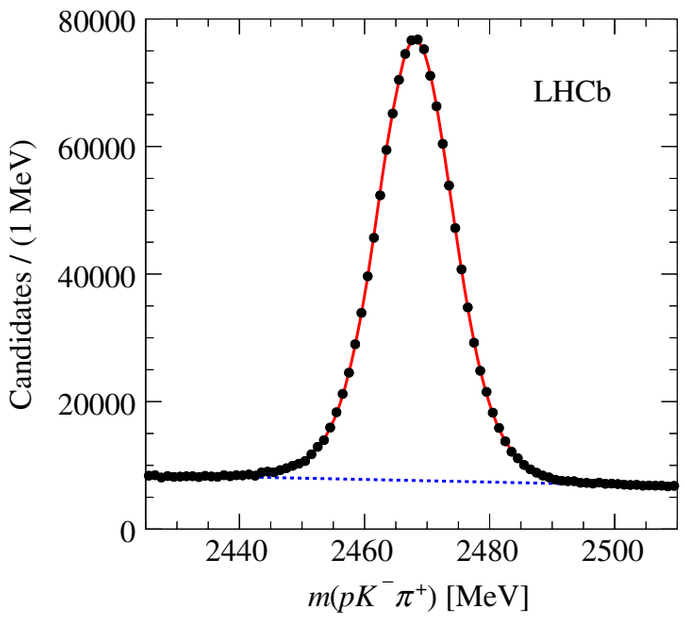
One plausible assignments

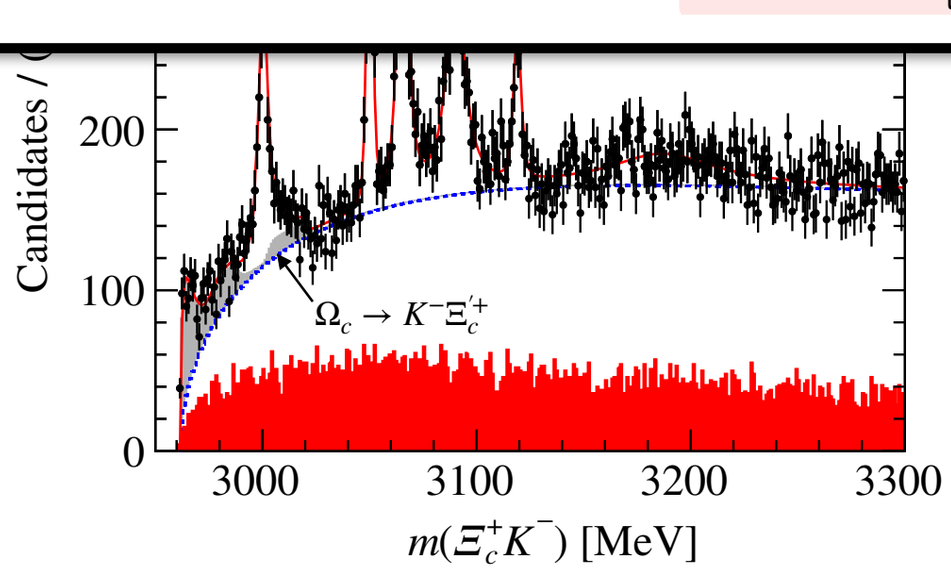
Excluded by 3.6σ

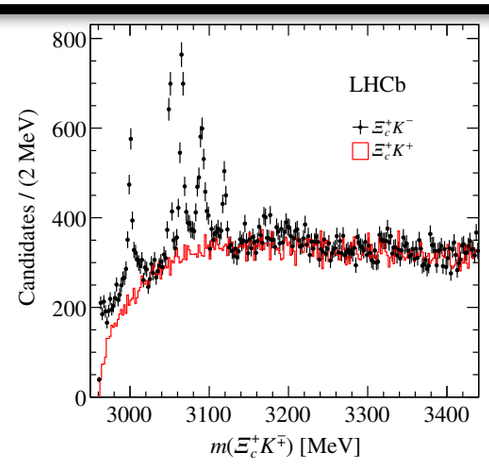


to be revisited!

Find $\Xi_c^+ \to pK^-\pi^+$:







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(4) the future of the LHC

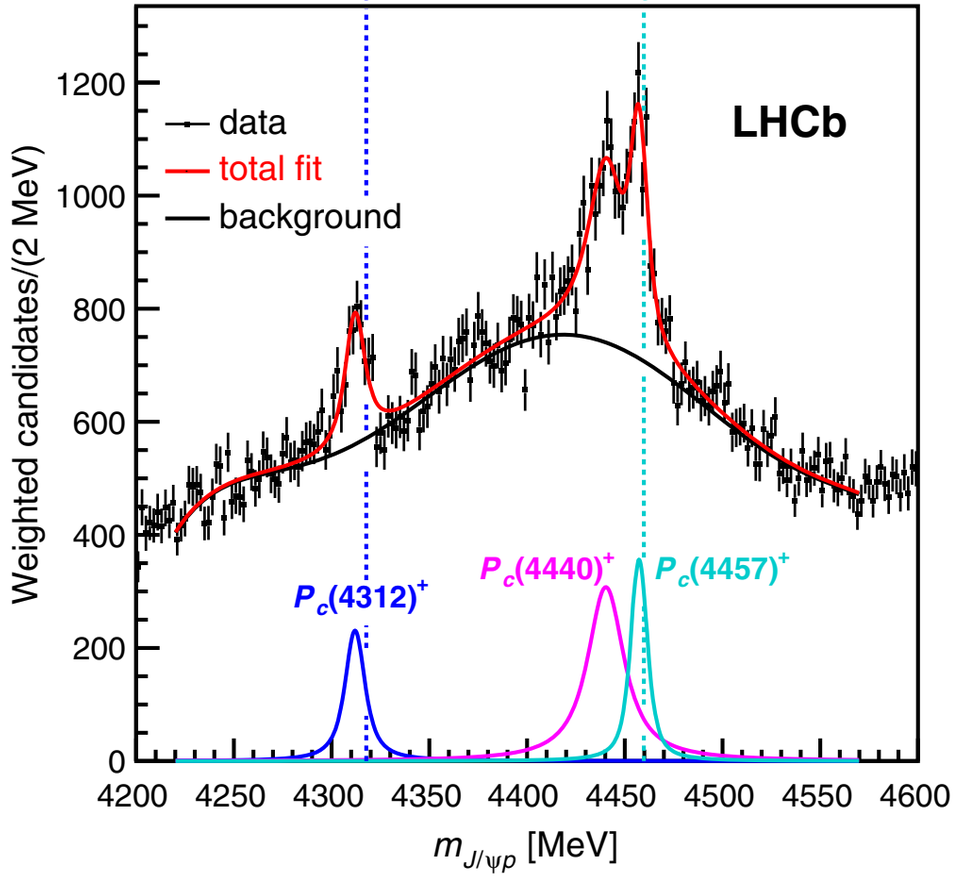
PHYSICAL REVIEW LETTERS **122,** 222001 (2019)

Editors' Suggestion | Featured in Physics

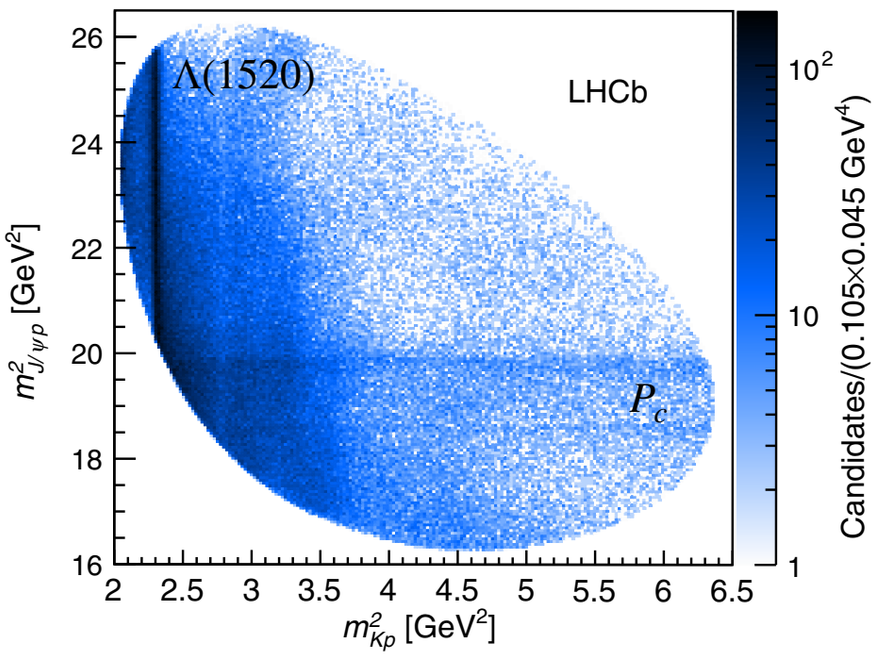
Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of the Two-Peak Structure of the $P_c(4450)^+$

R. Aaij *et al.*[*]
(LHCb Collaboration)

Observe structure in $M(J/\psi p)$:



Dalitz plot for $\Lambda_b^0 \to pK^-J/\psi$:



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(4) the future of the LHC

https://hilumilhc.web.cern.ch

Table 3: Major experiments in the past, present, and future of heavy-quark exotics studies.

Experiment	Highlights	Accelerator	Years	Institute	Production
BaBar	$Y(4260)$ [29] $Y(4360)$ [108]	PEP-II	1999–2008	SLAC (Menlo Park, California, USA)	e^+e^- annihilation ($E_{\rm CM} \approx 10$ GeV): $e^+e^- \to B\bar{B}$; $B \to KX$ $e^+e^- \to Y_b$ $e^+e^- \to \pi Z_b$ $e^+e^-(\gamma_{\rm ISR}) \to Y$ $e^+e^-(\gamma_{\rm ISR}) \to \pi Z_c$ $e^+e^- \to J/\psi + X$ $\gamma\gamma \to X$
Belle	$X(3872)$ [4] $Y(3940)$ [106] $X(3915)$ [166] $Z_c(4430)$ [30, 136, 137] $Z_b(10610)$, $Z_b(10650)$ [160, 162, 163] $Y_b(10888)$ [151, 152]	KEKB	1998–2010	KEK (Tsukuba, Japan)	
Belle II	Upcoming continuation of Belle	SuperKEKB	2018–		
CLEO-c	$Y(4260)$ [142] $\pi^+\pi^- h_c$ [177]	CESR-c	2003–2008	Cornell U. (Ithaca, New York, USA)	e^+e^- annihilation ($E_{\rm CM} \approx 4$ GeV): $e^+e^- \to Y$ $e^+e^- \to \pi Z$ $e^+e^- \to \gamma X$
BESIII	$Z_c(3900)$ [22, 154] $Z_c(4020)$ [156, 158] $Y(4230)$ [149] $X(3872)$ [52]	BEPCII	2008–	IHEP (Beijing, China)	
CDF	$Y(4140)$ [126] $Y(4274)$ [132] $X(3872)$ [178, 179, 172]	Tevatron	1985–2011	Fermilab (Batavia, Illinois, USA)	$p\bar{p}$ collisions ($E_{\rm CM} \approx 2$ TeV): $p\bar{p} \to X$ + any $p\bar{p} \to B$ + any; $B \to KX$
D0	$X(3872)$ [171] $Y(4140)$ [174] $X(5568)$ [175]				
ATLAS	$\chi_b(3P)$ [180]	LHC	2010–	CERN (Geneva, Switzerland)	pp collisions ($E_{\rm CM} = 7$, 8, 13 TeV): $pp \to X$ + any $pp \to B$ + any; $B \to KX$ $pp \to \Lambda_b$ + any; $\Lambda_b \to KP_c$
CMS	$X(3872)$ [28] $Y(4140)$, $Y(4274)$ [130]				
LHCb	$Z_c(4430)$ [138, 139] $X(3872)$ [109] $P_c(4380)$, $P_c(4450)$ [35] $Y(4140)$, $Y(4274)$ [125, 131]				
COMPASS	photoproduction [181] $a_1(1420)$ [182]	SPS	2002-2011		μ/π beam on N target ($p_{beam} \approx 160$, 200 GeV) $\pi N \to XN$ $\gamma N \to XN$
$\bar{\rm P}$ANDA	Upcoming	HESR		GSI (Darmstadt, Germany)	$\bar{p}$ beam on p target ($p_{beam} \approx 1.5$–15 GeV): $p\bar{p} \to X$ $p\bar{p} \to X$ + any
GlueX	Beginning (searches for light quark hybrid mesons)	CEBAF	2016–	Jefferson Lab (Newport News, Virginia, USA)	γ beam on p target ($E_{beam} \leq 11$ GeV): $\gamma p \to Xp$
CLAS12					

Progress in Particle and Nuclear Physics 93 (2017) 143–194

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Heavy-quark QCD exotica

Richard F. Lebed [a,*], Ryan E. Mitchell [b], Eric S. Swanson [c]

LECTURE V. Current and Future Experiments

VA. Detectors

VB. Hadron Colliders

VC. e^+e^- Colliders

*** B Factories**

* τ/c Factories

VD. Fixed Targets

VE. New Possibilities

VF. Outlook

VC. e^+e^- Colliders: B Factories

Highlights from B Factories

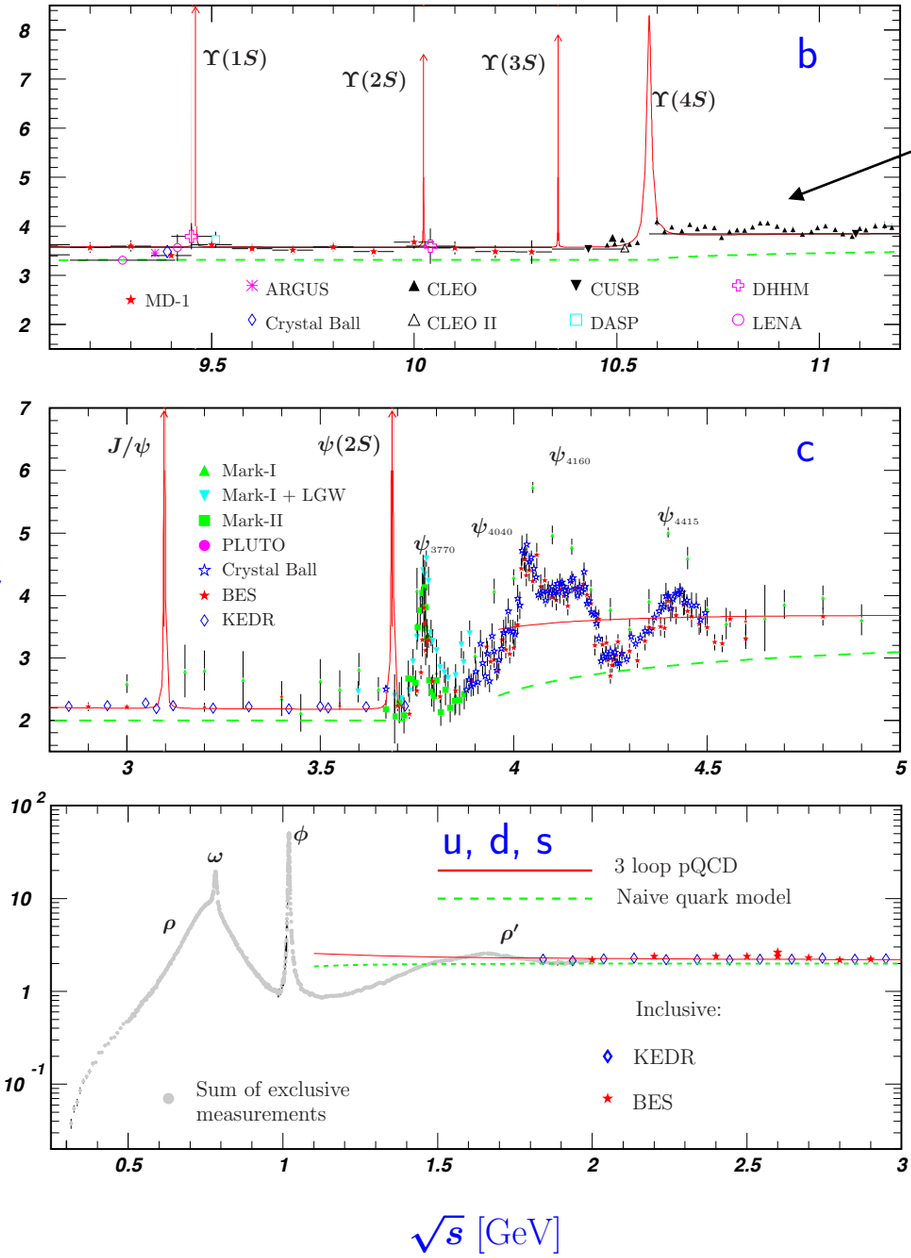
(1) production mechanisms

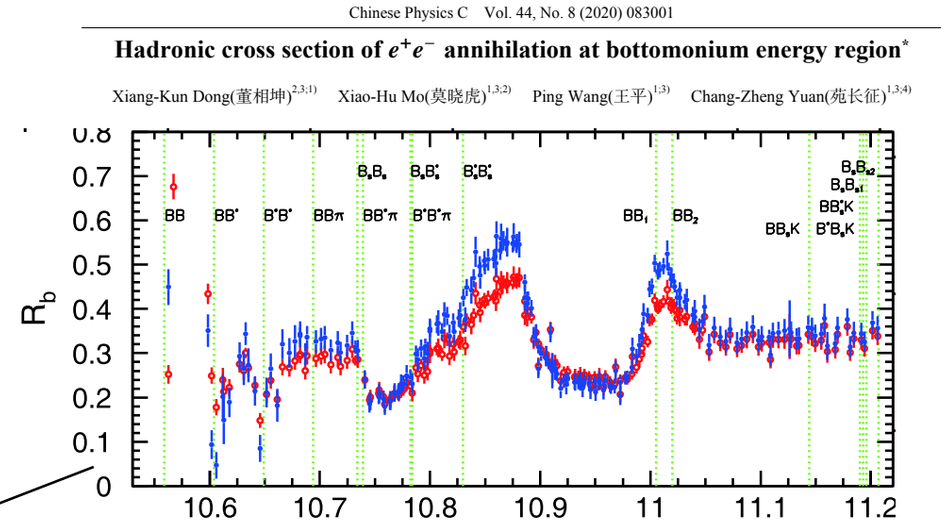
(2) B decays

(3) ISR production of charmonium

(4) ISR production of light quarks

(5) status of Belle II





(i) $e^+e^- \to \Upsilon(4S) \to B\bar{B}$

$\Longrightarrow$ flavor physics

$\Longrightarrow B \to KX_{c\bar{c}}$

(ii) $e^+e^- \to Y_b$

$\Longrightarrow Y_b \to (\pi\pi, \eta, \omega, \ldots)X_{c\bar{c}}$

$\Longrightarrow Y_b \to \pi Z_c$

(iii) $e^+e^- \to \Upsilon(1S,2S,3S)$

$\Longrightarrow$ bottomonium transitions

(iv) $e^+e^- \to J/\psi + X_{c\bar{c}}$

$\Longrightarrow$ further access to charmonium

(v) $e^+e^-(\gamma_{\rm ISR}) \to \psi$

$\Longrightarrow$ coverage of whole charmonium region

(vi) $e^+e^-(\gamma_{\rm ISR}) \to \rho, \omega, \phi, \ldots$

$\Longrightarrow$ coverage of whole light quark region

(vii) $e^+e^- \to e^+e^-X_{q\bar{q}}$

$\Longrightarrow$ two-photon collisions

VC. e^+e^- Colliders: B Factories

Highlights from B Factories

(1) production mechanisms

(2) *B* decays

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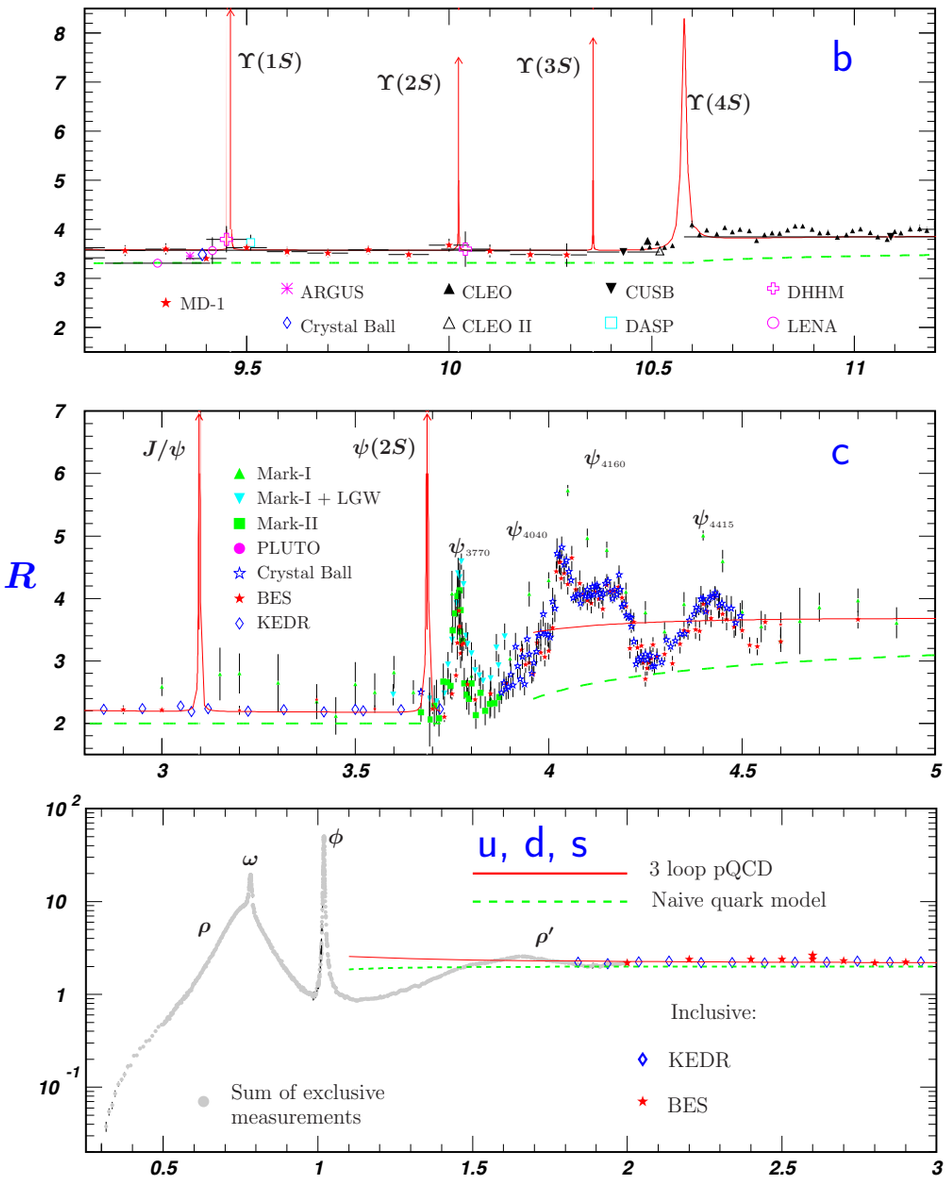
$e^+e^- \to \Upsilon(4S) \to B^+B^-$

$B^\mp \to$ exclusive

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

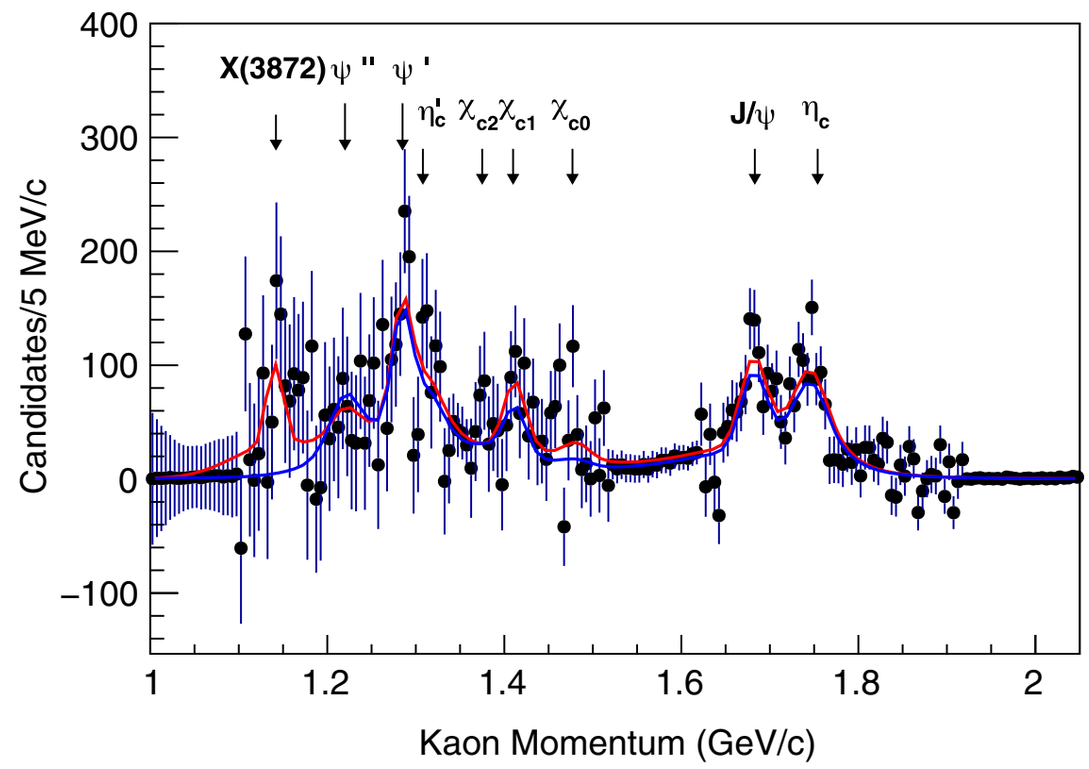


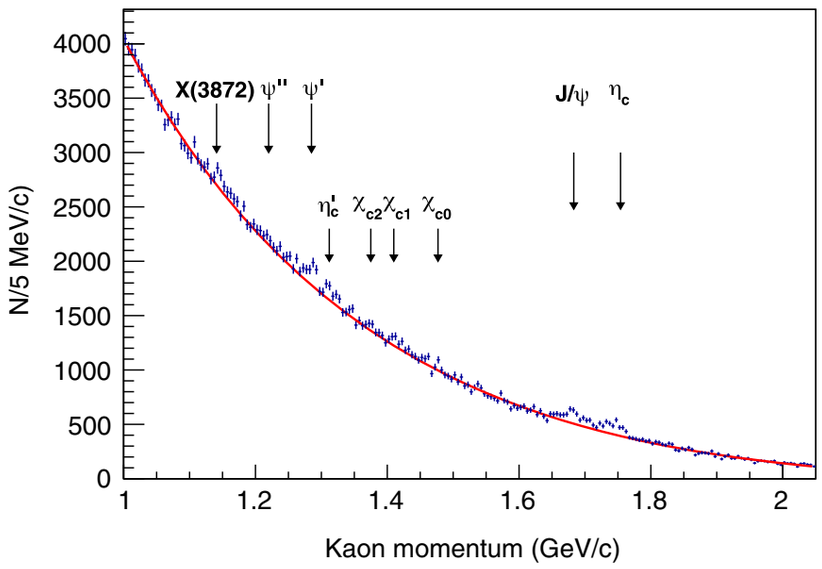
$\Longrightarrow$ *absolute branching fractions for the X(3872)*

PHYSICAL REVIEW LETTERS **124,** 152001 (2020)

Measurements of the Absolute Branching Fractions of $B^\pm \to K^\pm X_{c\bar{c}}$

(*BABAR* Collaboration)





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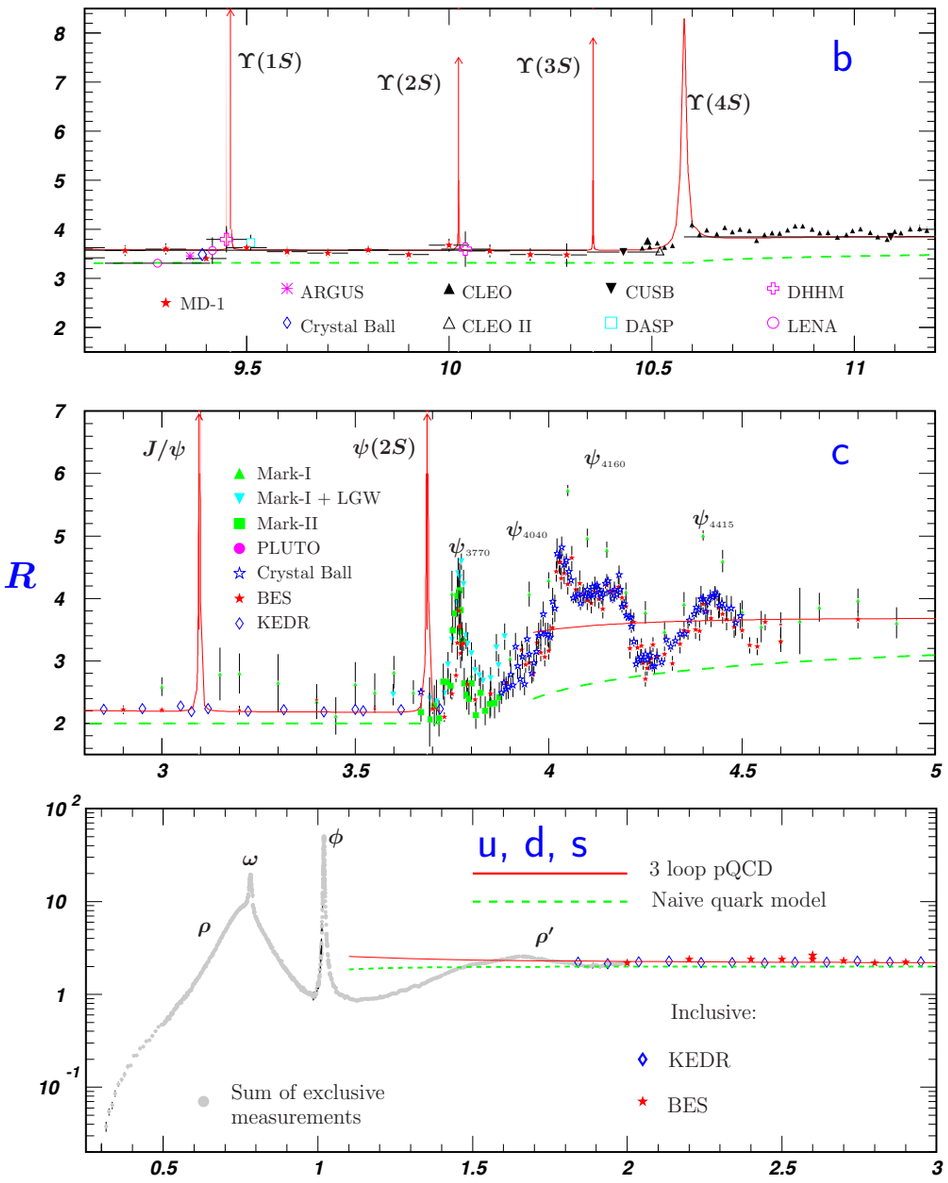
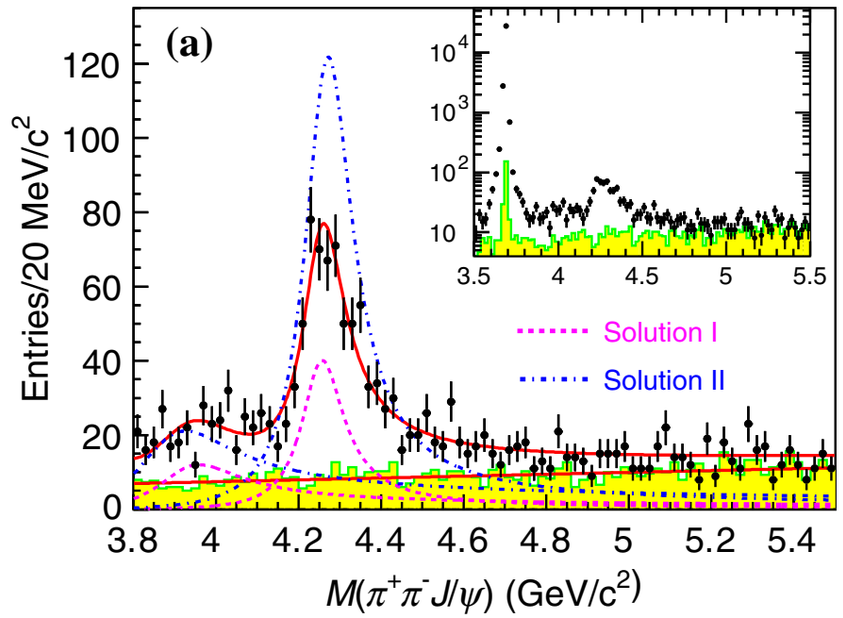
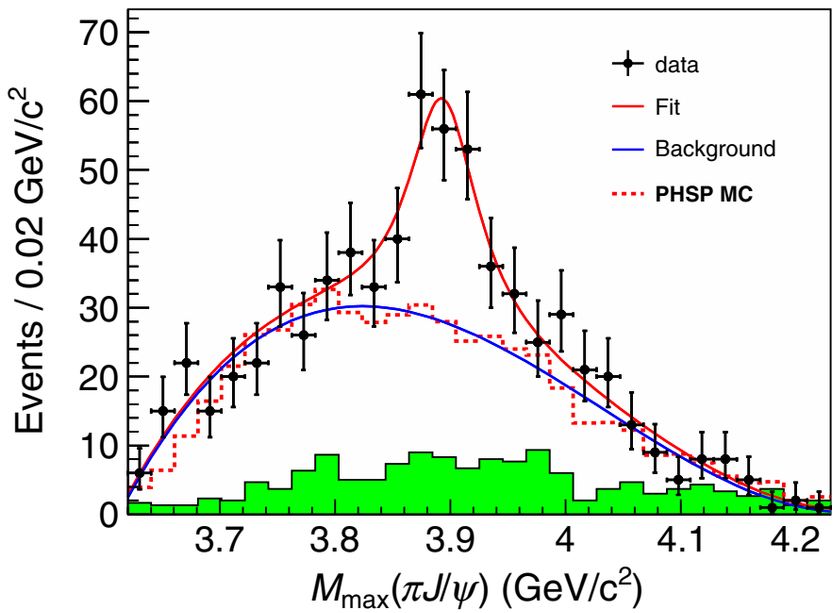


PRL **110,** 252002 (2013) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 21 JUNE 2013

Study of $e^+e^- \to \pi^+\pi^- J/\psi$ and Observation of a Charged Charmoniumlike State at Belle

(Belle Collaboration)





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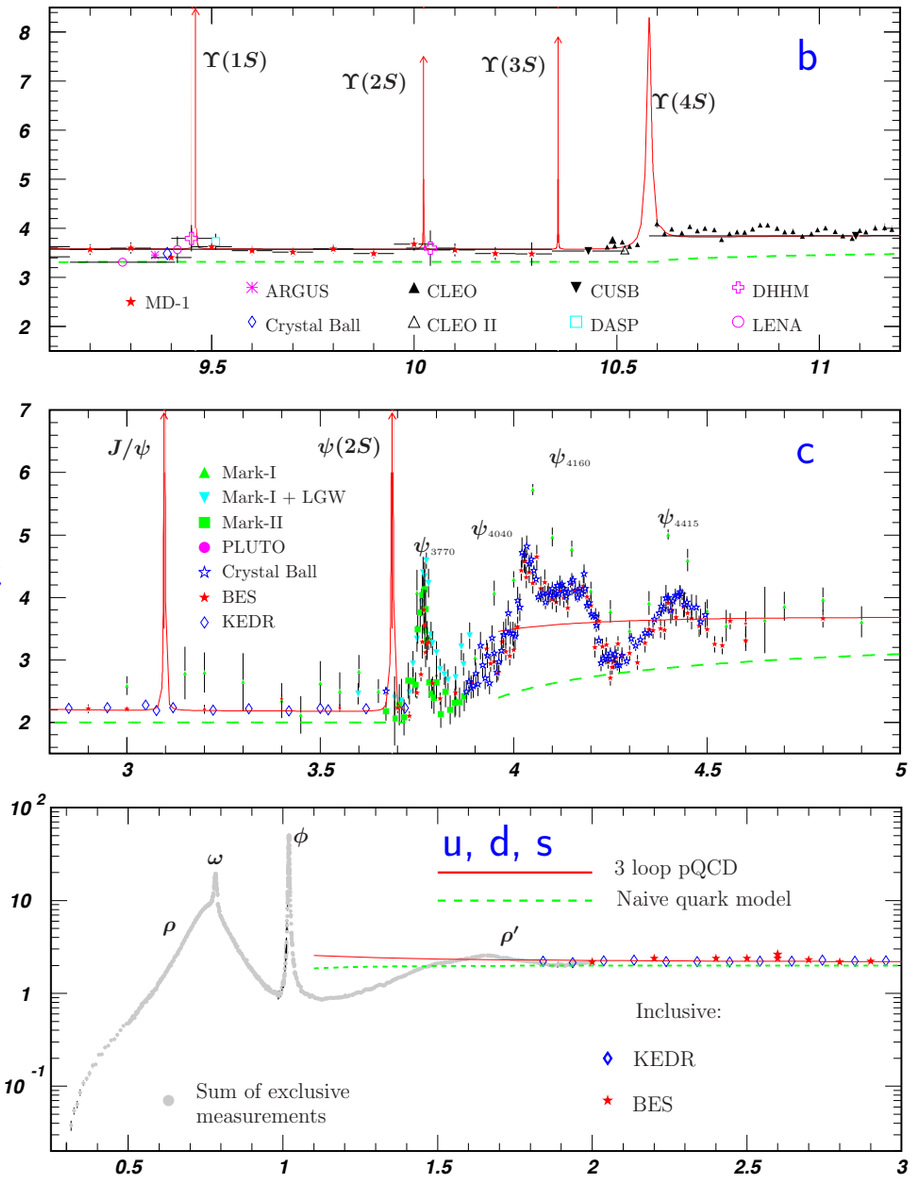

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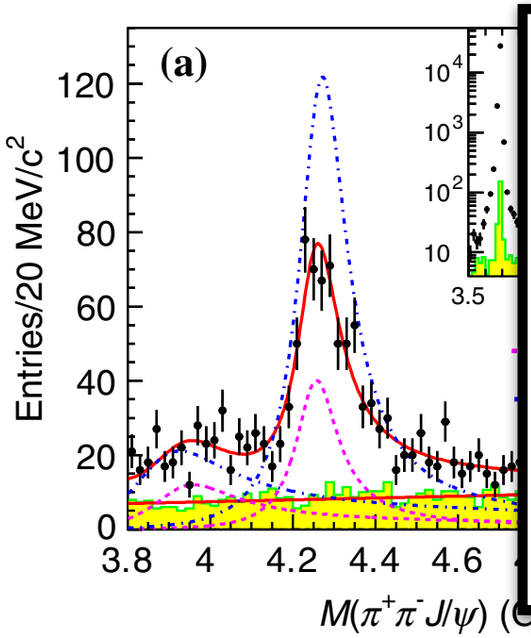
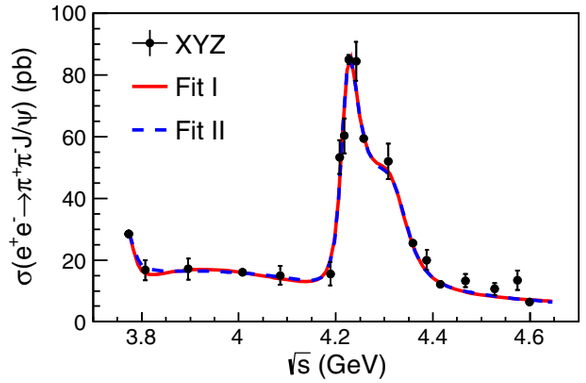
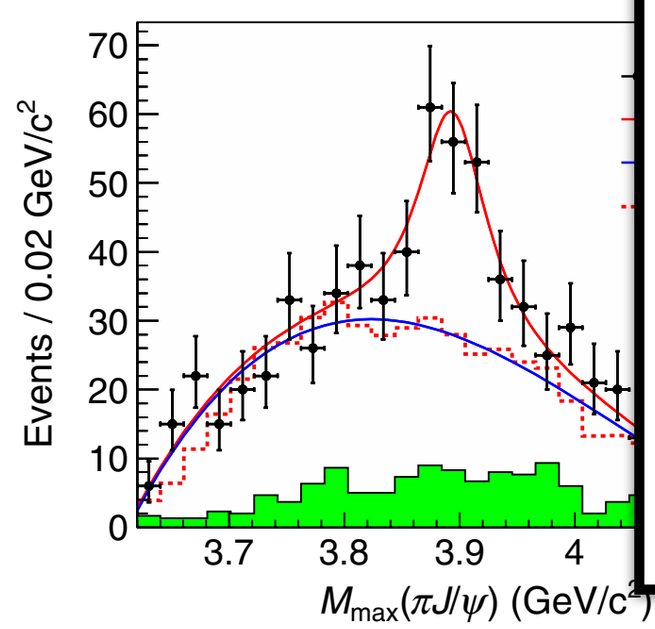


PRL **118,** 092001 (2017) — PHYSICAL REVIEW LETTERS — week ending 3 MARCH 2017

Precise Measurement of the $e^+e^- \to \pi^+\pi^- J/\psi$ Cross Section at Center-of-Mass Energies from 3.77 to 4.60 GeV

(BESIII Collaboration)

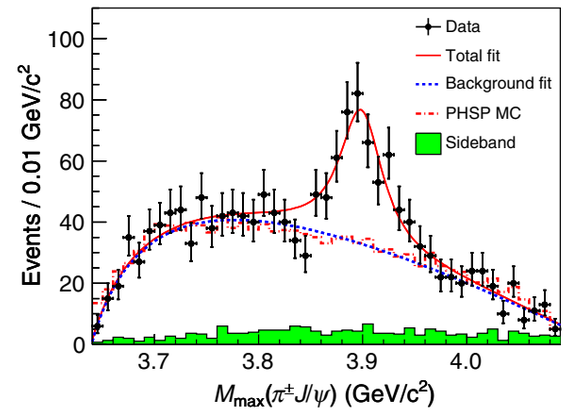




Selected for a Viewpoint in *Physics* — PRL **110,** 252001 (2013) — PHYSICAL REVIEW LETTERS — week ending 21 JUNE 2013

Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV

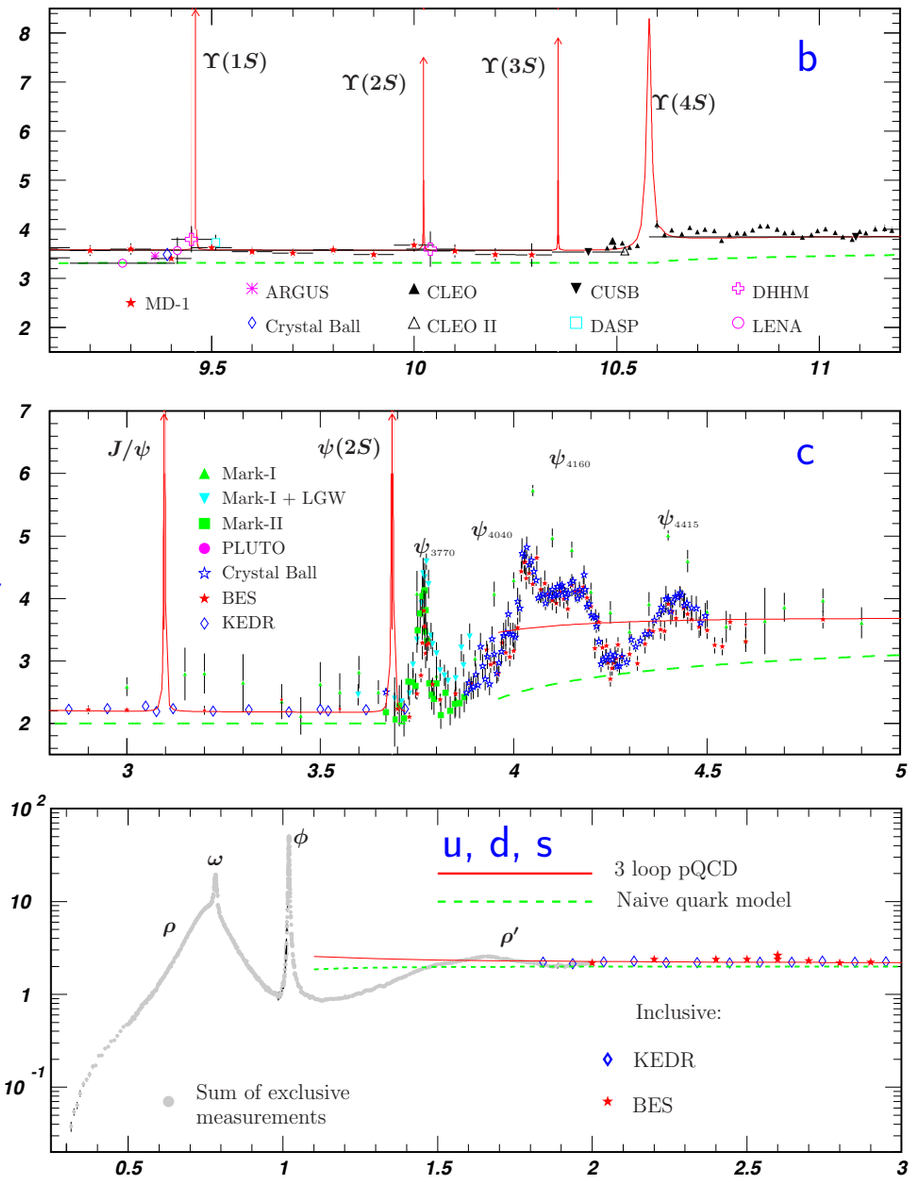
(BESIII Collaboration)



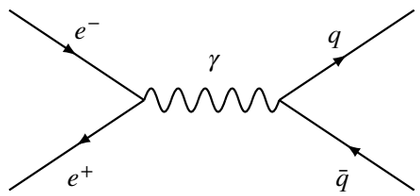
VC. e^+e^- Colliders: B Factories

Highlights from B Factories

(1) production mechanisms
(2) *B* decays
(3) ISR production of charmonium
(4) ISR production of light quarks
(5) status of Belle II

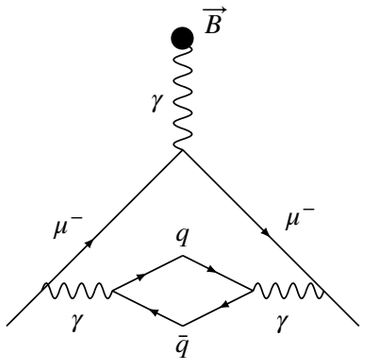


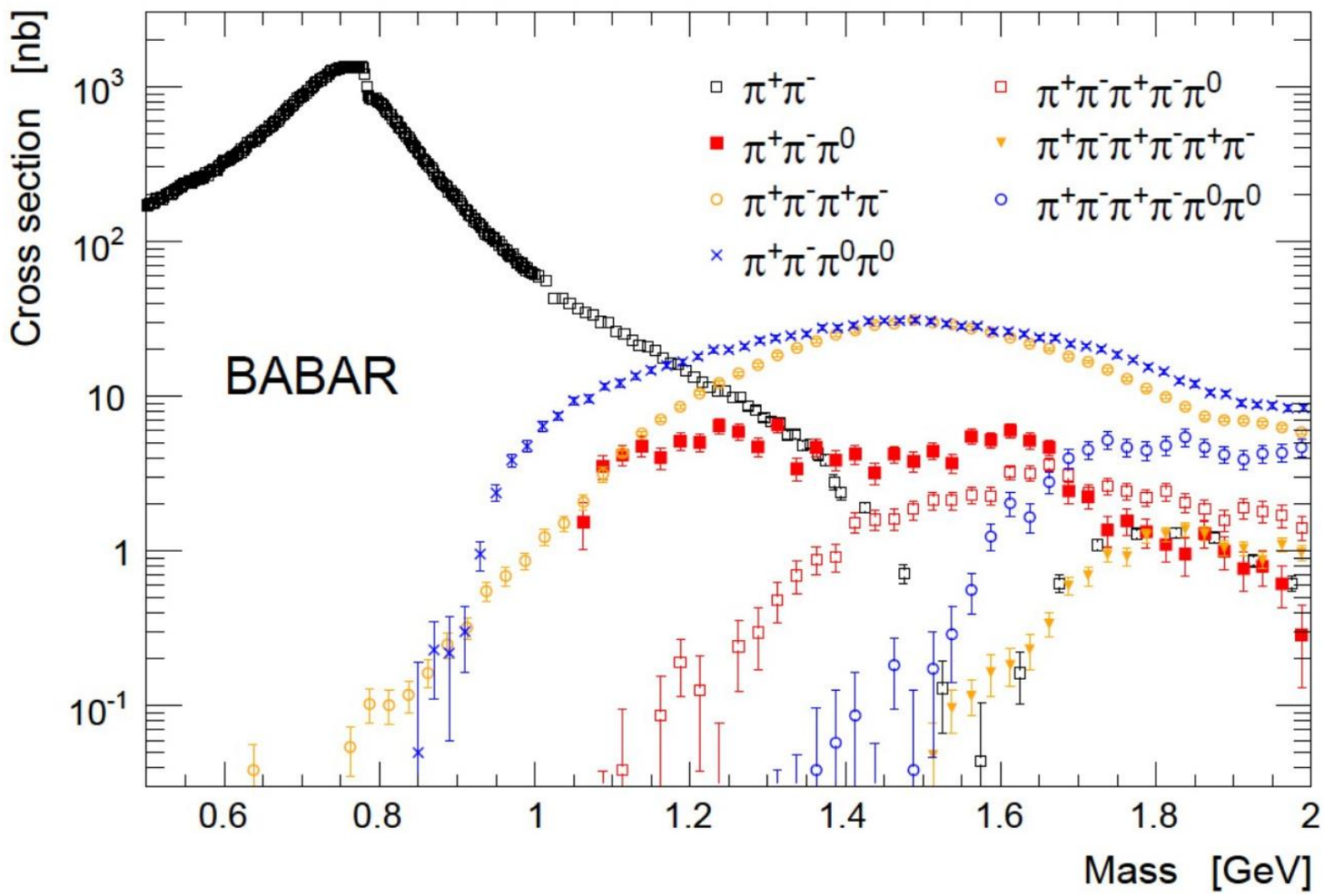
e^+e^- results from BABAR and implications for the muon g-2



Michel Davier (LAL – Orsay)

g-2 Theory Initiative
FermiLab, 3-6 June 2017





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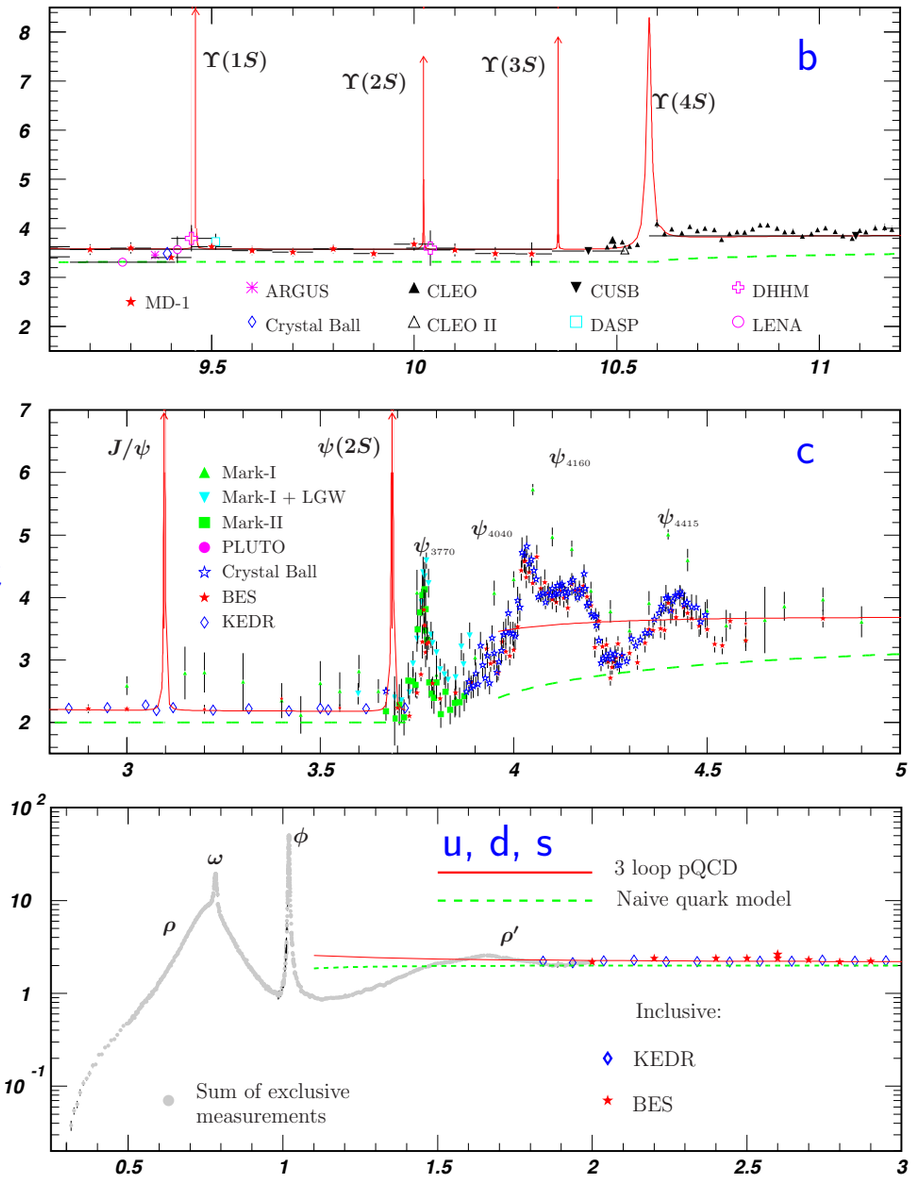
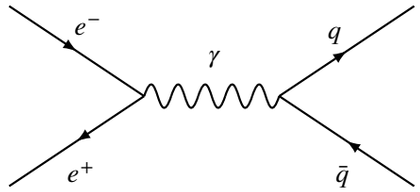


e^+e^- results from BABAR and implications for the muon g-2



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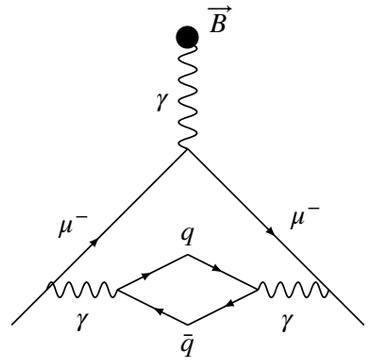
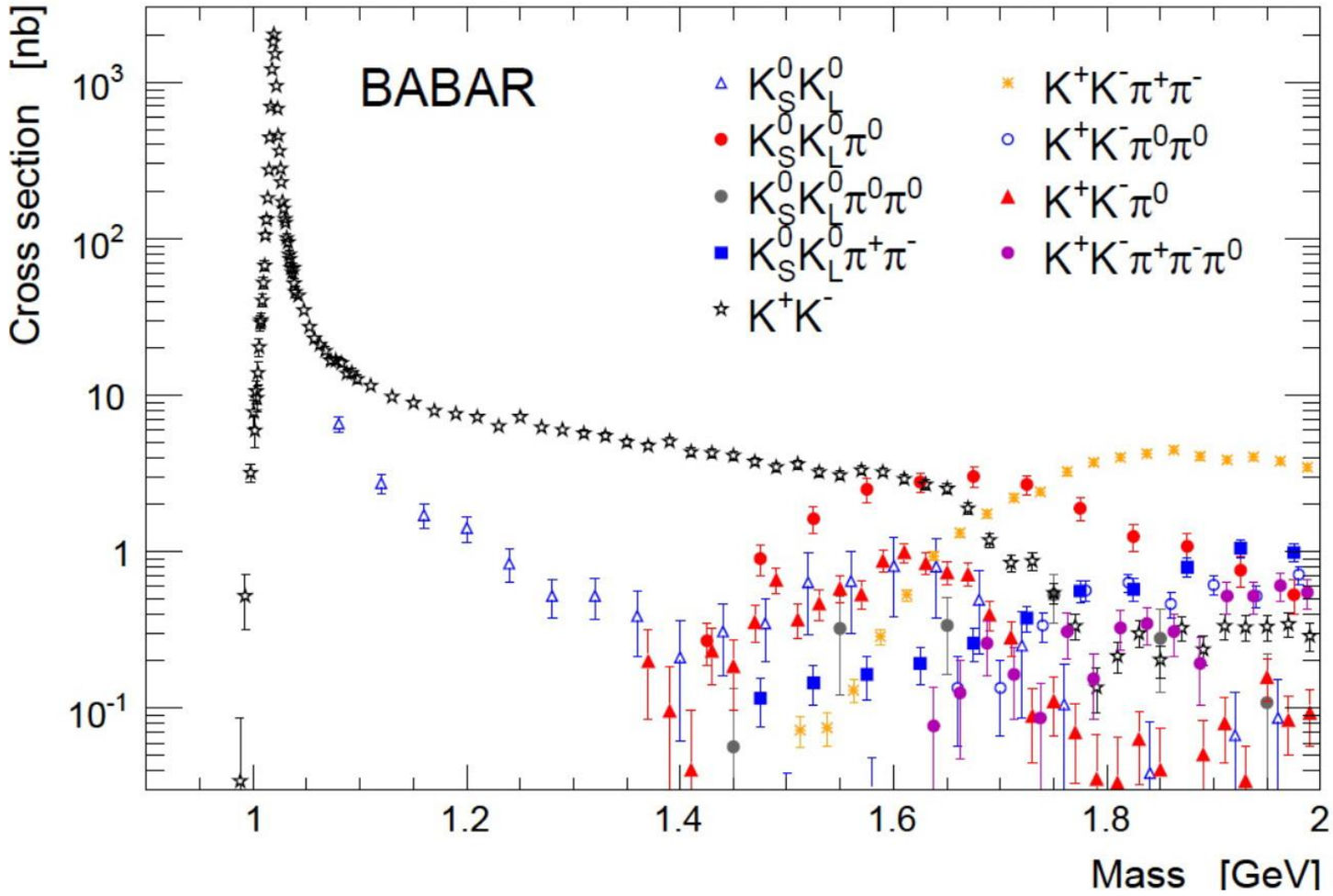
g-2 Theory Initiative
FermiLab, 3-6 June 2017





VC. e^+e^- Colliders: B Factories

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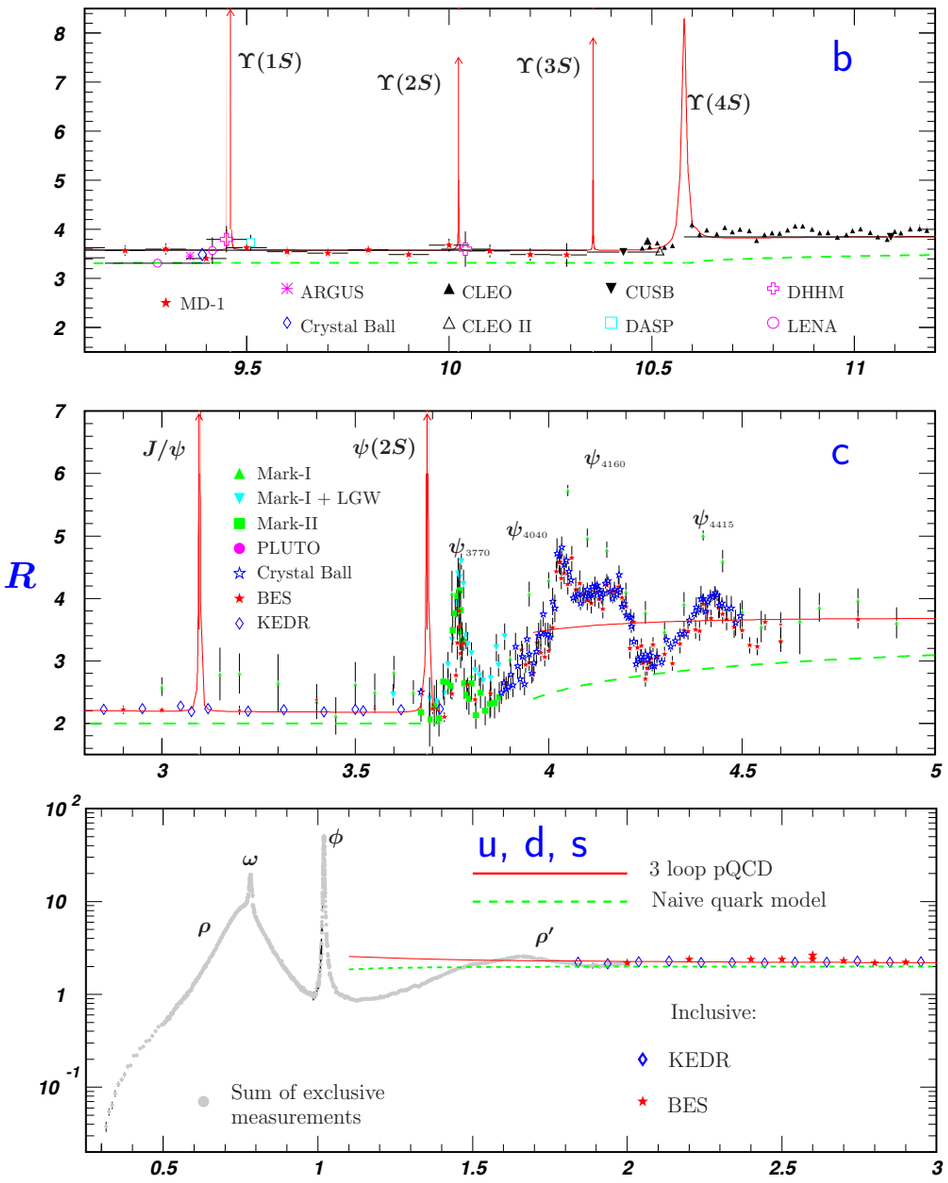
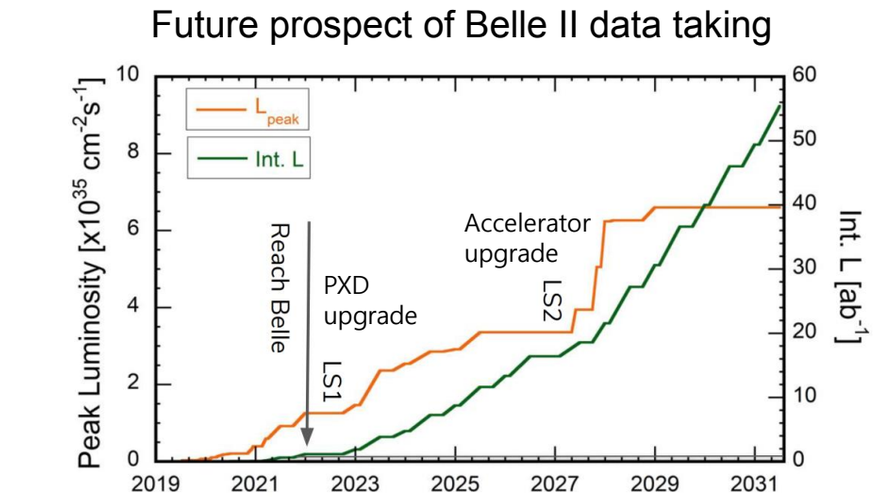


Rediscovery of X(3872) at Belle II Experiment

Youngmin Yook (yook@ihep.ac.cn) on behalf of Belle II Collaboration
Institute of High Energy Physics, Chinese Academy of Science

10th International Workshop on Charm Physics, June 3rd, 2021



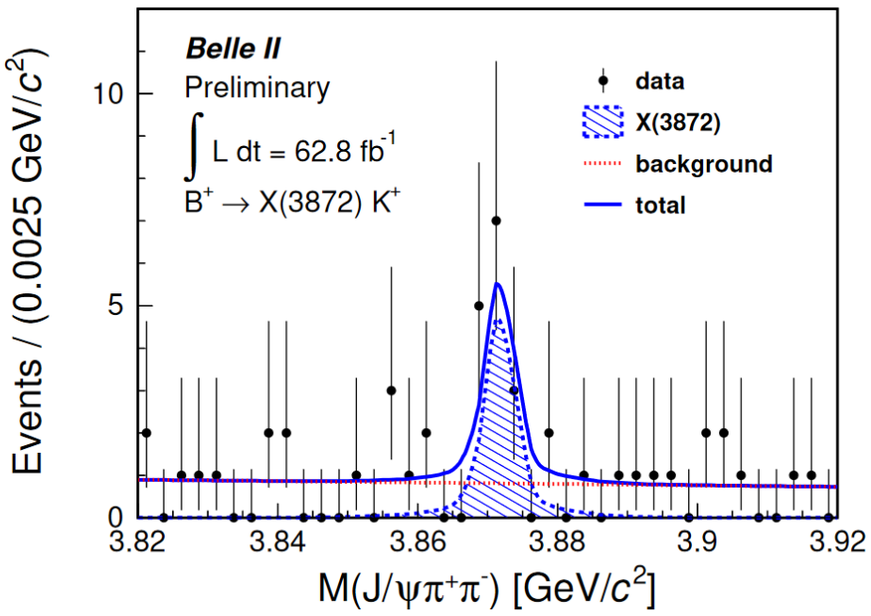


Table 3: Major experiments in the past, present, and future of heavy-quark exotics studies.

Experiment	Highlights	Accelerator	Years	Institute	Production
BaBar	$Y(4260)$ [29] $Y(4360)$ [108]	PEP-II	1999–2008	SLAC (Menlo Park, California, USA)	e^+e^- annihilation ($E_{\rm CM} \approx 10$ GeV): $e^+e^- \to B\bar{B}$; $B \to KX$ $e^+e^- \to Y_b$ $e^+e^- \to \pi Z_b$ $e^+e^-(\gamma_{\rm ISR}) \to Y$ $e^+e^-(\gamma_{\rm ISR}) \to \pi Z_c$ $e^+e^- \to J/\psi + X$ $\gamma\gamma \to X$
Belle	$X(3872)$ [4] $Y(3940)$ [106] $X(3915)$ [166] $Z_c(4430)$ [30, 136, 137] $Z_b(10610)$, $Z_b(10650)$ [160, 162, 163] $Y_b(10888)$ [151, 152]	KEKB	1998–2010	KEK (Tsukuba, Japan)	
Belle II	Upcoming continuation of Belle	SuperKEKB	2018–		
CLEO-c	$Y(4260)$ [142] $\pi^+\pi^- h_c$ [177]	CESR-c	2003–2008	Cornell U. (Ithaca, New York, USA)	e^+e^- annihilation ($E_{\rm CM} \approx 4$ GeV): $e^+e^- \to Y$ $e^+e^- \to \pi Z$ $e^+e^- \to \gamma X$
BESIII	$Z_c(3900)$ [22, 154] $Z_c(4020)$ [156, 158] $Y(4230)$ [149] $X(3872)$ [52]	BEPCII	2008–	IHEP (Beijing, China)	
CDF	$Y(4140)$ [126] $Y(4274)$ [132] $X(3872)$ [178, 179, 172]	Tevatron	1985–2011	Fermilab (Batavia, Illinois, USA)	$p\bar{p}$ collisions ($E_{\rm CM} \approx 2$ TeV): $p\bar{p} \to X$ + any $p\bar{p} \to B$ + any; $B \to KX$
D0	$X(3872)$ [171] $Y(4140)$ [174] $X(5568)$ [175]				
ATLAS	$\chi_b(3P)$ [180]	LHC	2010–	CERN (Geneva, Switzerland)	pp collisions ($E_{\rm CM} = 7$, 8, 13 TeV): $pp \to X$ + any $pp \to B$ + any; $B \to KX$ $pp \to \Lambda_b$ + any; $\Lambda_b \to KP_c$
CMS	$X(3872)$ [28] $Y(4140)$, $Y(4274)$ [130]				
LHCb	$Z_c(4430)$ [138, 139] $X(3872)$ [109] $P_c(4380)$, $P_c(4450)$ [35] $Y(4140)$, $Y(4274)$ [125, 131]				
COMPASS	photoproduction [181] $a_1(1420)$ [182]	SPS	2002-2011		μ/π beam on N target ($p_{beam} \approx 160$, 200 GeV) $\pi N \to XN$ $\gamma N \to XN$
$\bar{\rm P}$ANDA	Upcoming	HESR		GSI (Darmstadt, Germany)	$\bar{p}$ beam on p target ($p_{beam} \approx 1.5$–15 GeV): $p\bar{p} \to X$ $p\bar{p} \to X$ + any
GlueX	Beginning (searches for light quark hybrid mesons)	CEBAF	2016–	Jefferson Lab (Newport News, Virginia, USA)	γ beam on p target ($E_{beam} \leq 11$ GeV): $\gamma p \to Xp$
CLAS12					

Progress in Particle and Nuclear Physics 93 (2017) 143–194

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Heavy-quark QCD exotica

Richard F. Lebed [a,*], Ryan E. Mitchell [b], Eric S. Swanson [c]

LECTURE V. Current and Future Experiments

VA. Detectors

VB. Hadron Colliders

VC. e^+e^- Colliders

*** B Factories**

*** τ/c Factories**

VD. Fixed Targets

VE. New Possibilities

VF. Outlook

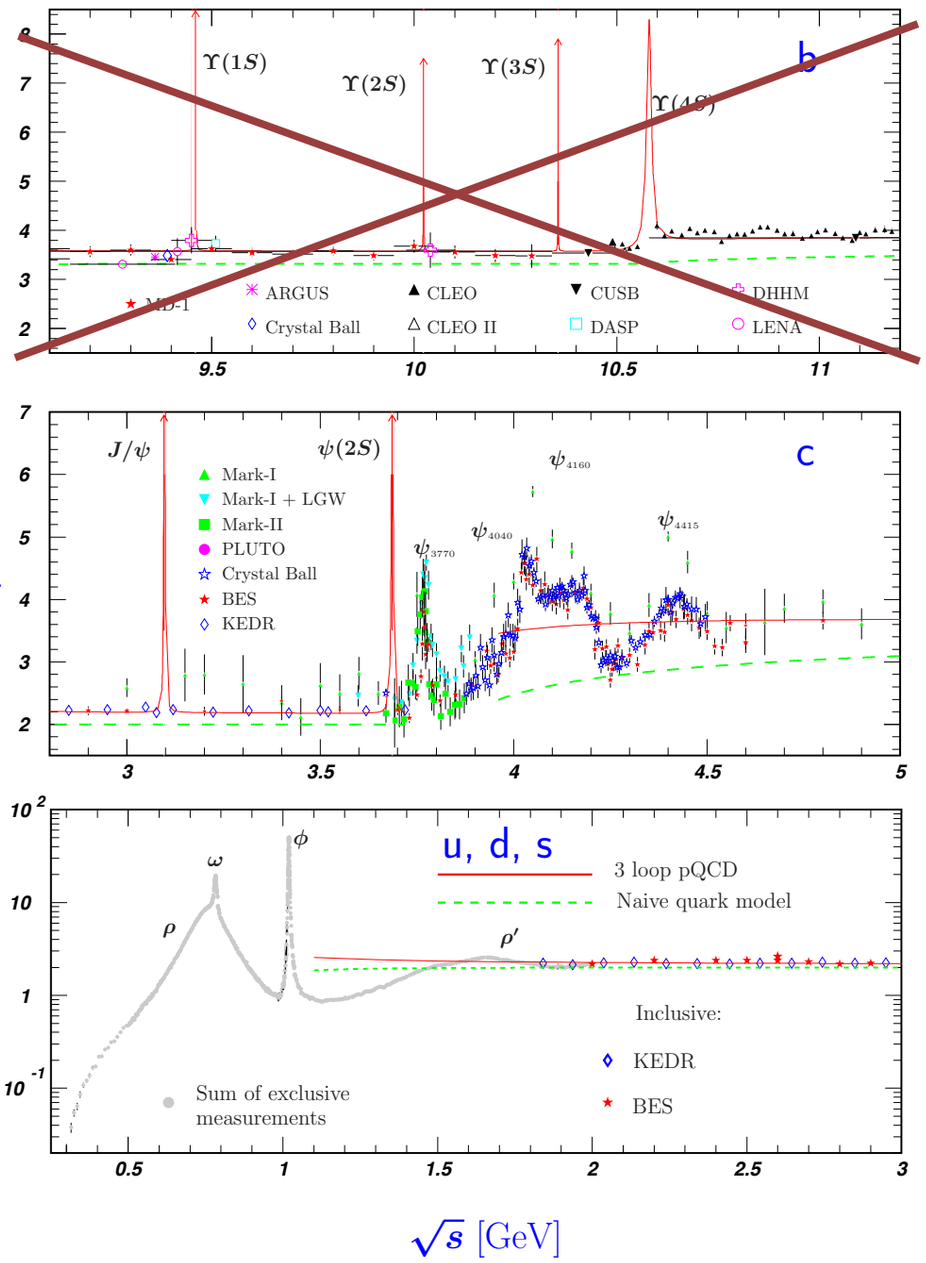
VC. e^+e^- Colliders: τ/c Factories

Highlights from tau-charm Factories

(1) production mechanisms

(2) J/ψ decays

(3) future τ/c factories?



Datasets at BESIII (superseding CLEO-c):

(i) large data sets between 4.0 and 4.9 ($+\epsilon$) GeV

$\Longrightarrow e^+e^- \to Y$

$\Longrightarrow Y \to (\pi\pi, \eta, \omega, \ldots)X_{c\bar{c}}$

$\Longrightarrow Y \to \gamma X_{c\bar{c}},\ \pi Z_c,\ K Z_{cs}, \ldots$

for XYZ physics

$\Longrightarrow e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-, \Sigma_c\bar{\Sigma}_c$

for flavor physics

(ii) large data set at 4.18 GeV

$\Longrightarrow e^+e^- \to D_s^+ D_s^{*-}$

for flavor physics

(iii) large data set at 3.77 GeV

$\Longrightarrow e^+e^- \to \psi(3770) \to D\bar{D}$

for flavor physics

(iv) 500M $\psi(2S)$ decays (soon to be 2.5B)

$\Longrightarrow$ charmonium transitions

(v) 10B J/ψ decays

$\Longrightarrow$ light quark spectroscopy

$\Longrightarrow$ glueball searches, etc.

(vi) data below the J/ψ

$\Longrightarrow$ light quark spectroscopy

$\Longrightarrow$ nucleon form factors, etc.

VC. e^+e^- Colliders: τ/c Factories

Highlights from tau-charm Factories

(1) production mechanisms

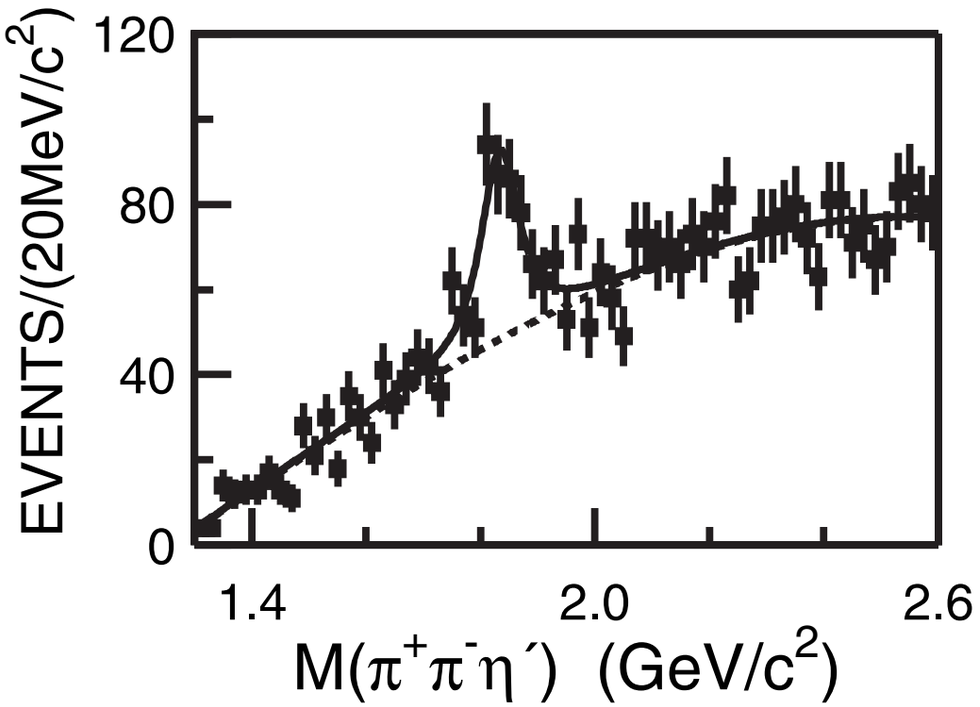
(2) J/ψ decays

(3) future τ/c factories?

PRL **95,** 262001 (2005) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2005

Observation of a Resonance $X(1835)$ in $J/\psi \to \gamma\pi^+\pi^-\eta'$

(BES Collaboration)



58M J/ψ decays

VC. e^+e^- Co

Highlights from tau-charm Factories

(1) production mechanisms

(2) J/ψ decays

(3) future τ/c factories?

PRL **95,** 262001 (2005) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER

Observation of a Resonance $X(1835)$ in $J/\psi \to \gamma\pi^+\pi^-\eta'$

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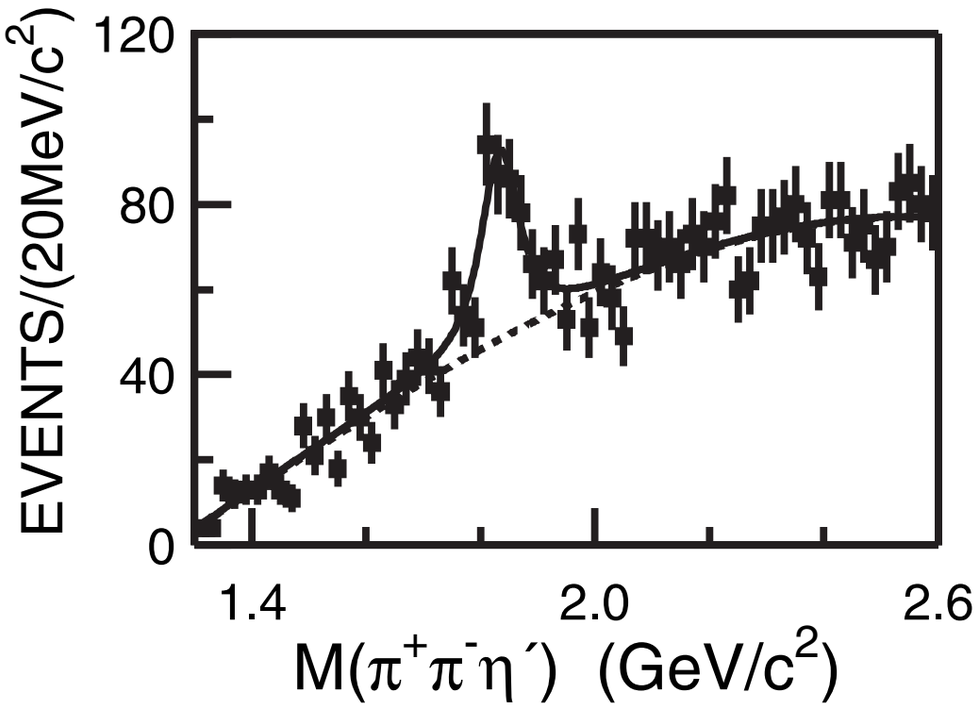
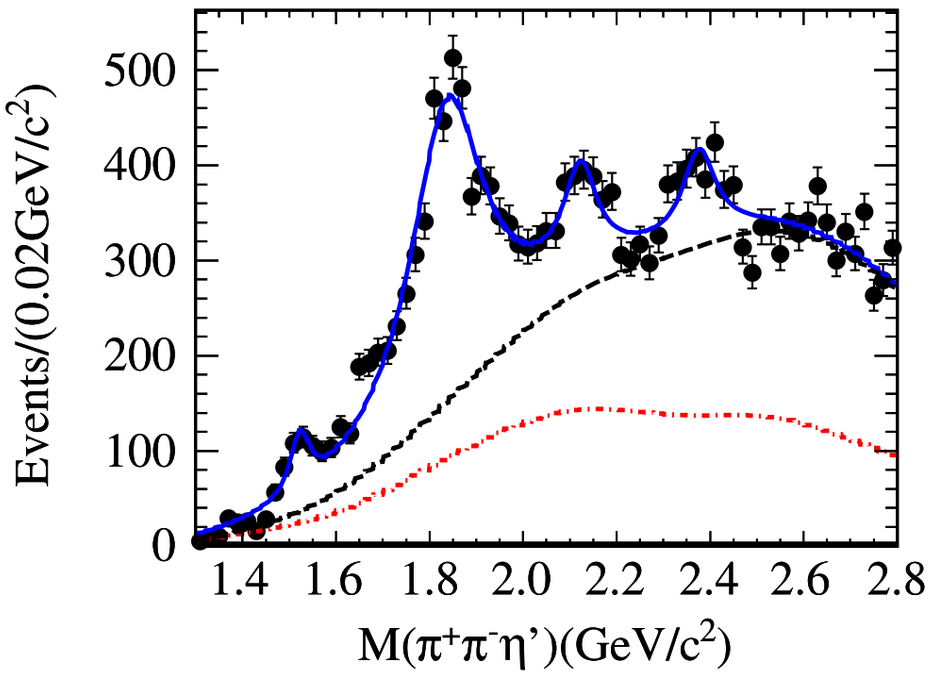


58M J/ψ decays

PRL **106,** 072002 (2011) PHYSICAL REVIEW LETTERS week ending 18 FEBRUARY 2011

Confirmation of the $X(1835)$ and Observation of the Resonances $X(2120)$ and $X(2370)$ in $J/\psi \to \gamma\pi^+\pi^-\eta'$

(BESIII Collaboration)



225M J/ψ decays

VC. e^+e^- Co

Highlights from tau-charm Factories

(1) production mechanisms

(2) J/ψ decays

(3) future τ/c factories?

PRL **95,** 262001 (2005) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER

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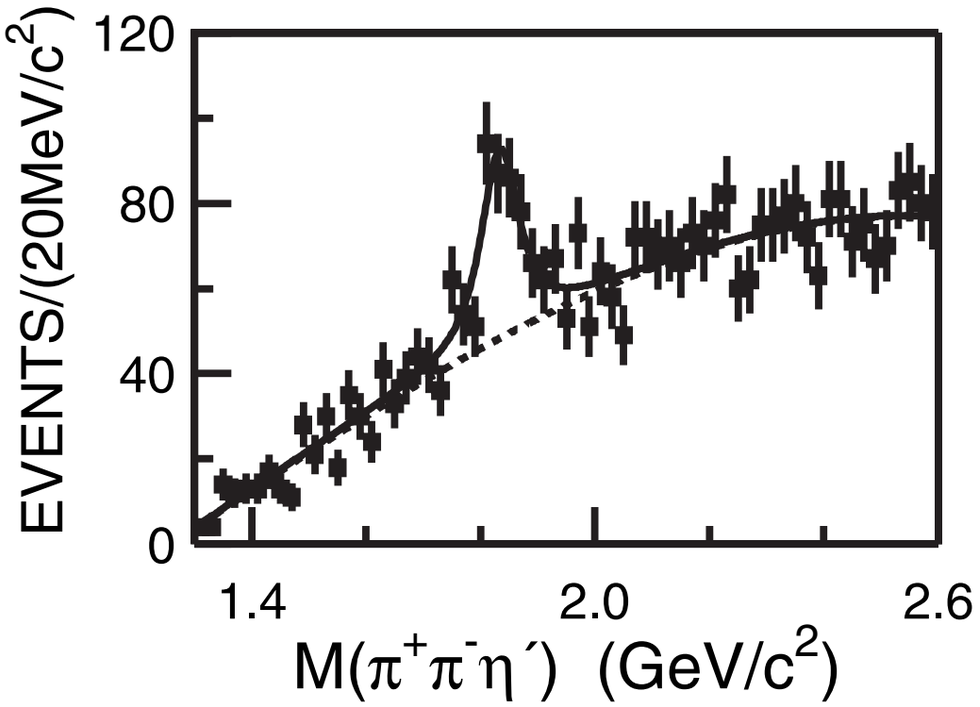
(BES Collaboration)



58M J/ψ decays

PRL **106,** 072002 (2011) PHYSICAL REVIEW LETTERS week ending 18 FEBRUARY 2011

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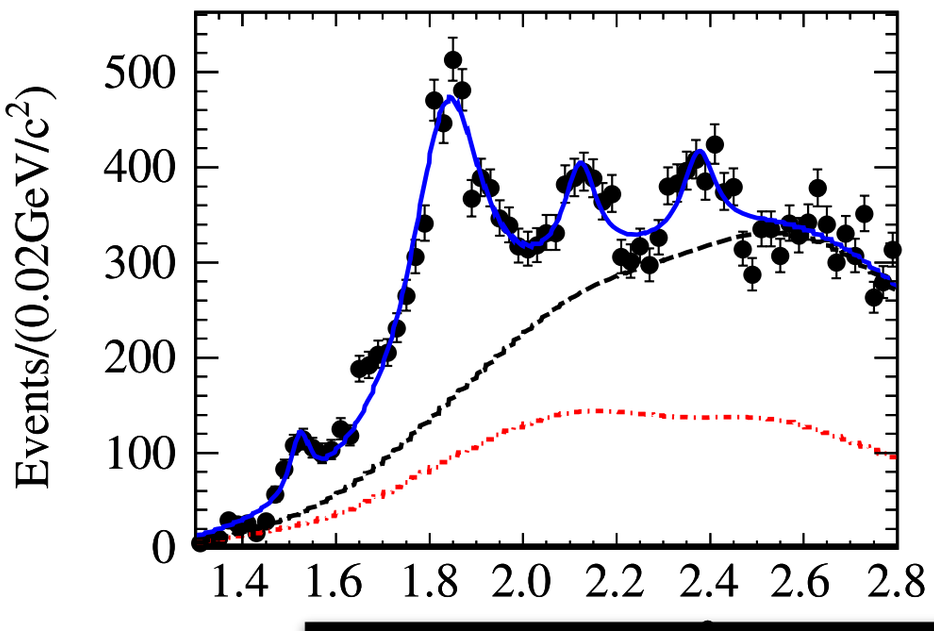
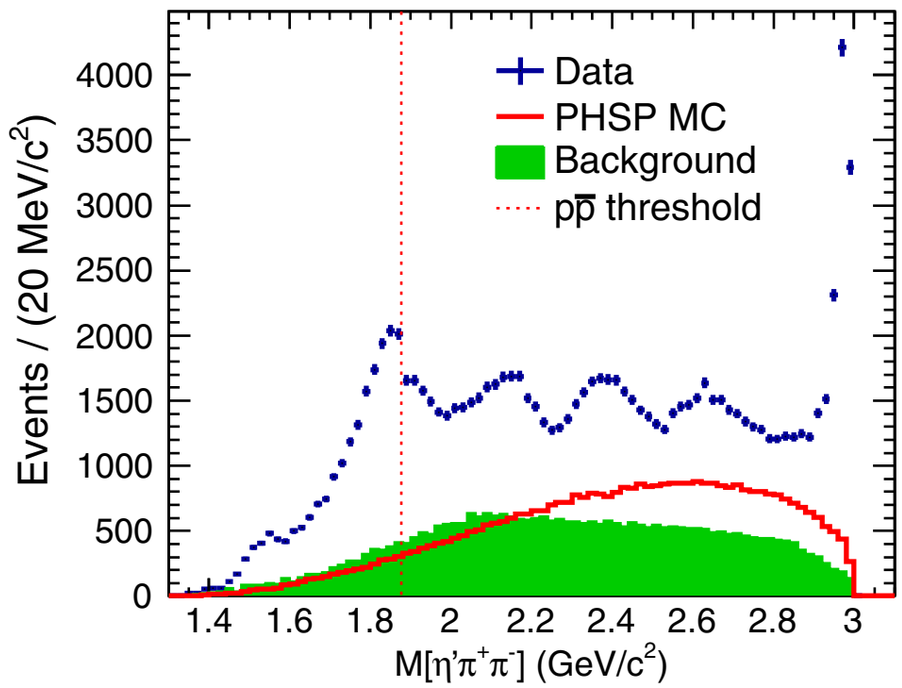


225M J/ψ decays

PRL **117,** 042002 (2016) PHYSICAL REVIEW LETTERS week ending 22 JULY 2016

Observation of an Anomalous Line Shape of the $\eta'\pi^+\pi^-$ Mass Spectrum near the $p\bar{p}$ Mass Threshold in $J/\psi \to \gamma\eta'\pi^+\pi^-$



1B J/ψ decays

With 10B J/ψ the distribution is even more interesting.

$\Longrightarrow$ Qualitatively different phenomena emerge with increasing statistics!

VC. e^+e^- Colliders: τ/c Factories

Highlights from tau-charm Factories

(1) production mechanisms

(2) J/ψ decays

(3) future τ/c factories?

Two possibilities exist for a tau-charm factor with 50× the luminosity of BESIII.

(Also, BESIII plans a 3× luminosity upgrade in summer 2024.)

Russia →

Super charm-tau factory in Russia

Vitaly Vorobyev, BINP

for the SCT Team

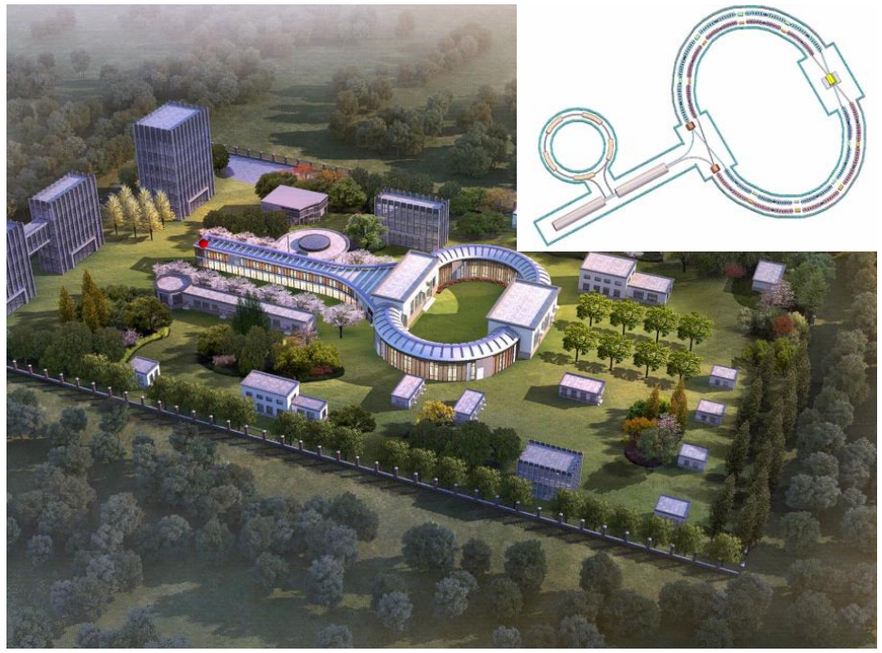
10th International Workshop on Charm Physics, Mexico, June 1st, 2021

China →

Experimental Program for Super Tau-Charm Facility

Xiaorong Zhou (On behalf of STCF working group)
State Key Laboratory of Particle Detection and Electronics
University of Science and Technology of China

10th International Workshop on Charm Physics (CHARM 2020)
2021.5.31-2021.6.4 (online)



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CLAS12					

Progress in Particle and Nuclear Physics 93 (2017) 143–194

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Review

Heavy-quark QCD exotica

Richard F. Lebed [a,*], Ryan E. Mitchell [b], Eric S. Swanson [c]

LECTURE V. Current and Future Experiments

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VB. Hadron Colliders

VC. e^+e^- Colliders

* B Factories

* τ/c Factories

VD. Fixed Targets

VE. New Possibilities

VF. Outlook

VD. Fixed Targets

Highlights from Fixed Targets

(1) production mechanisms

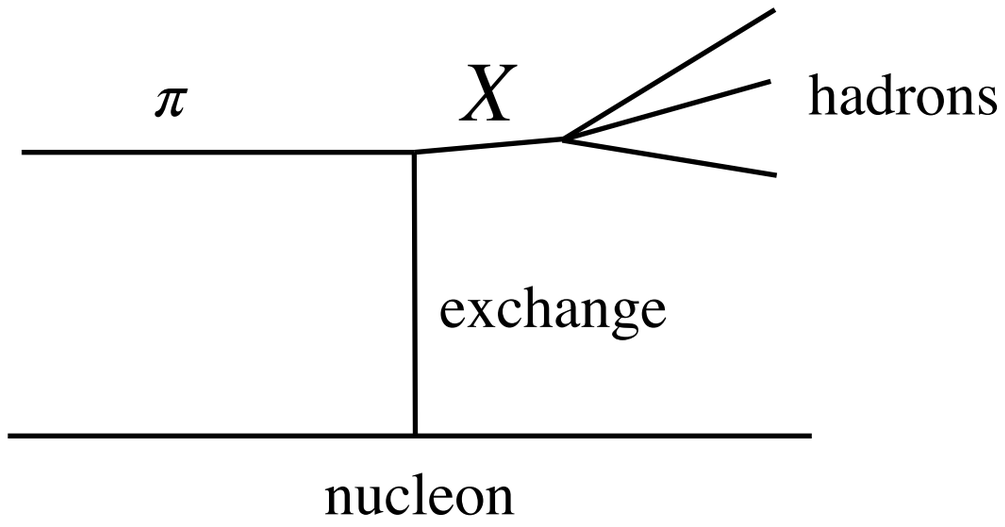
(2) COMPASS (pion beam) η

(3) GlueX (photon beam)

(4) photoproduction of charmonium

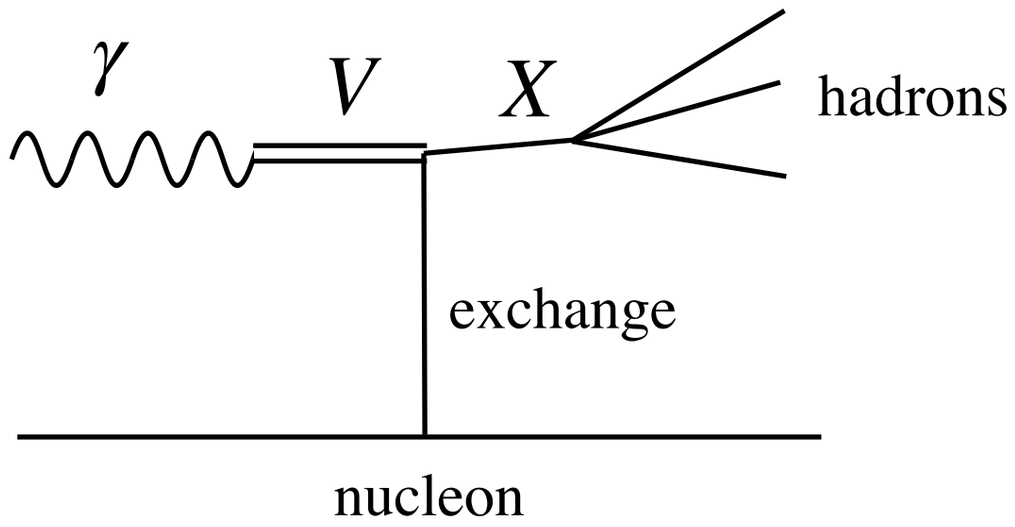
COMPASS (at CERN):

π^- beam with momentum 191 GeV/c



GlueX (at JLab):

γ beam with energy $\approx$ 9 GeV



complementary production mechanisms

VD. Fixed Targets

Highlights from Fixed Targets

(1) production mechanisms

(2) COMPASS (pion beam)

(3) GlueX (photon beam)

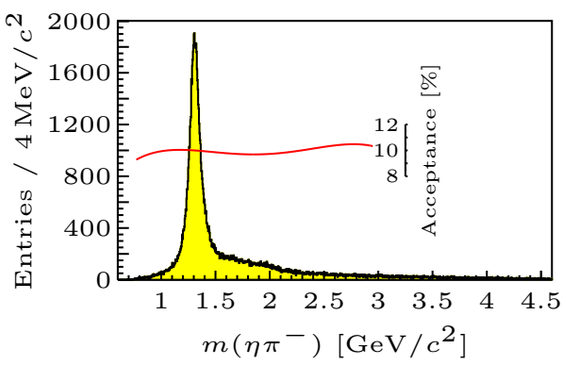
(4) photoproduction of charmonium

Best evidence for the exotic $\pi_1(1600)$ *(in my opinion)* …

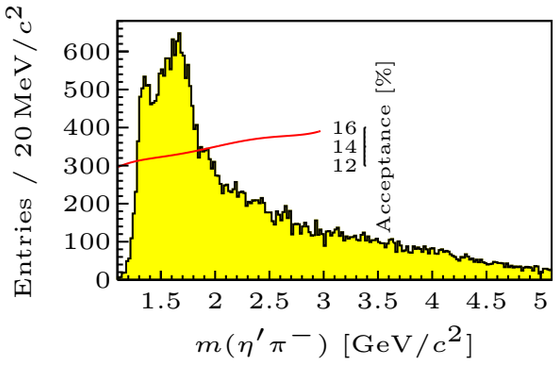
Physics Letters B 740 (2015) 303–311

Odd and even partial waves of $\eta\pi^-$ and $\eta'\pi^-$ in $\pi^- p \to \eta^{(\prime)}\pi^- p$ at 191 GeV/c

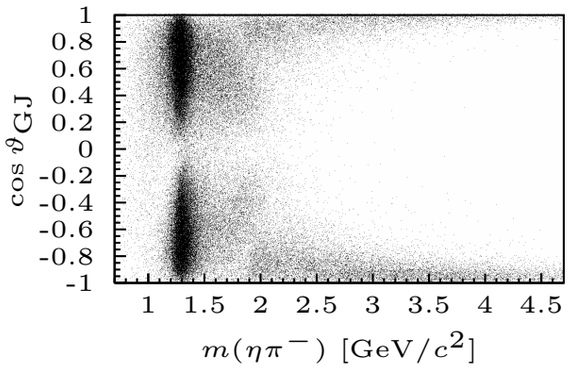
COMPASS Collaboration

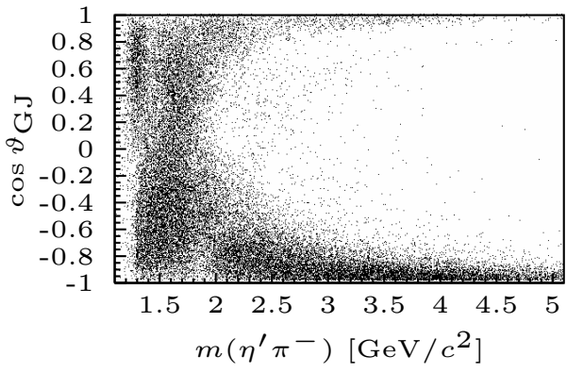


(a) $m(\eta\pi^-)$



(b) $m(\eta\pi^-)$





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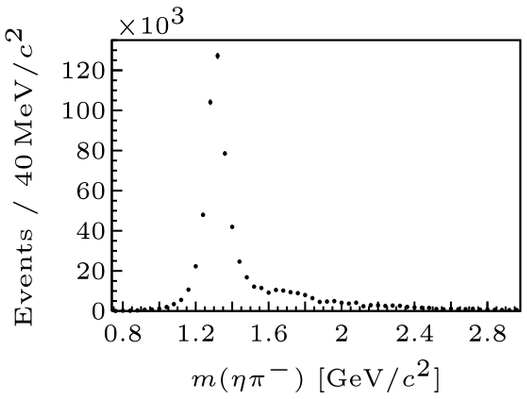
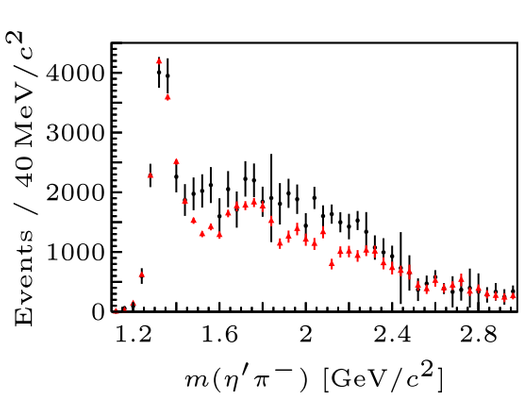
Odd and even partial waves of $\eta\pi^-$ and $\eta'\pi^-$ in $\pi^- p \to \eta^{(\prime)}\pi^- p$ at 191 GeV/c

COMPASS Collaboration



(b) D-wave, $L = 2$



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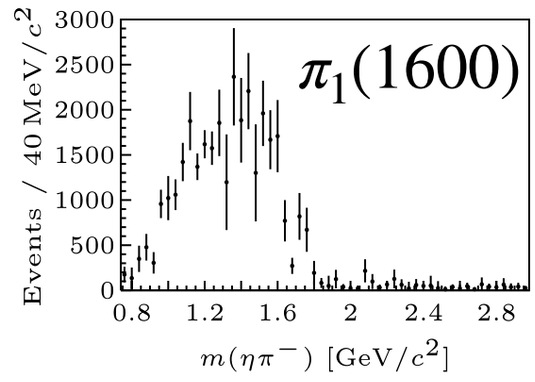
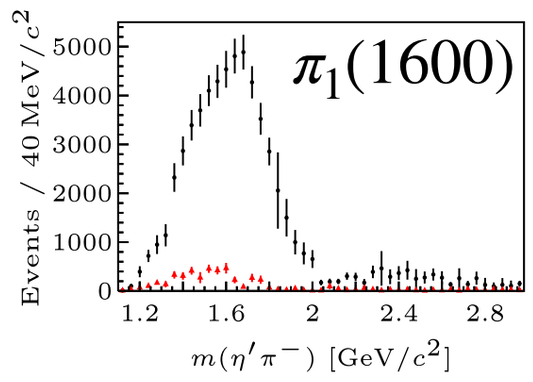


(a) P-wave, $L = 1$



(a) P-wave, $L = 1$

VD. Fixed Targets

Highlights from Fixed Targets

(1) production mechanisms

(2) COMPASS (pion beam)

(3) GlueX (photon beam)

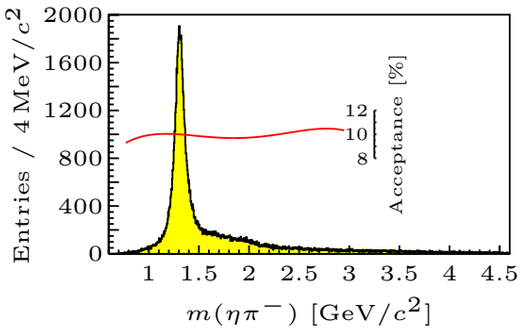
(4) photoproduction of charmonium

$$\pi^- p \to \eta\pi^- p$$

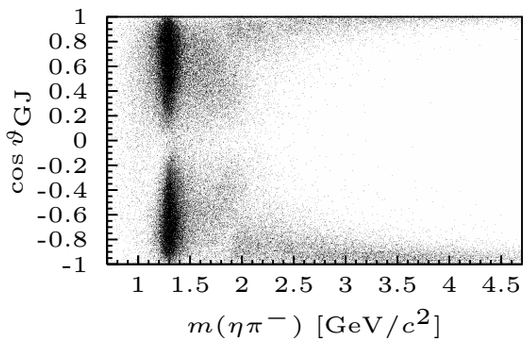
Physics Letters B 740 (2015) 303–311

Odd and even partial waves of $\eta\pi^-$ and $\eta'\pi^-$ in $\pi^- p \to \eta^{(\prime)}\pi^- p$ at 191 GeV/c

COMPASS Collaboration



(a) $m(\eta\pi^-)$



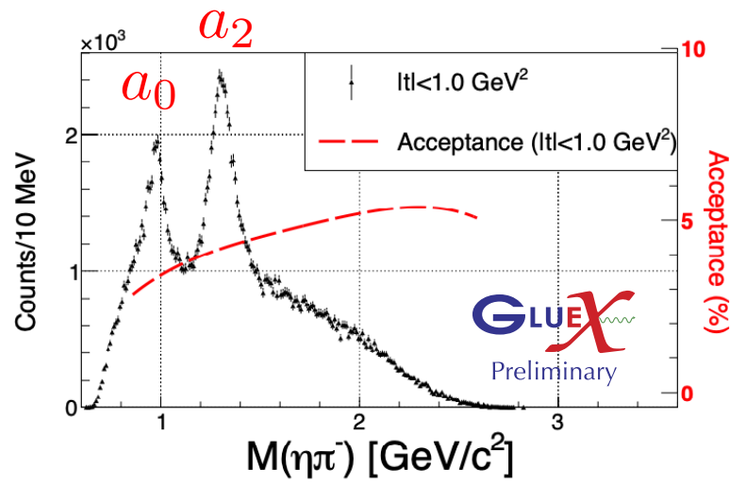
GlueX can build on these results!

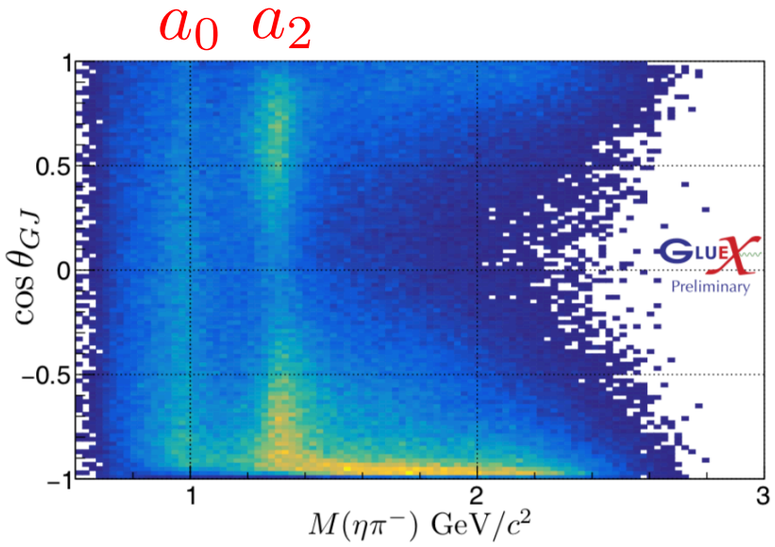
$$\gamma p \to \eta\pi^-\Delta^{++}$$

Early results from GlueX

Justin Stevens — William & Mary, Chartered 1693

April 2021 APS Meeting





VD. Fixed Targets

Highlights from Fixed Targets

(1) production mechanisms

(2) COMPASS (pion beam)

(3) GlueX (photon beam)

(4) photoproduction of charmonium

GlueX can build on these results! Many more final states are accessible.

$$\pi^- p \to \eta\pi^- p$$

Physics Letters B 740 (2015) 303–311

Odd and even partial waves of $\eta\pi^-$ and $\eta'\pi^-$ in $\pi^- p \to \eta^{(\prime)}\pi^- p$ at 191 GeV/c

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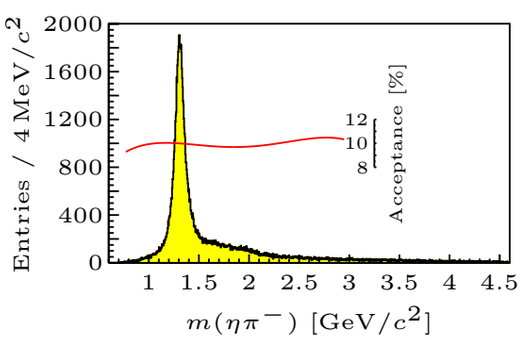

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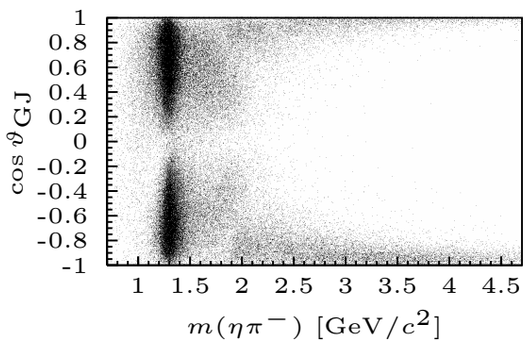

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Early results from GlueX

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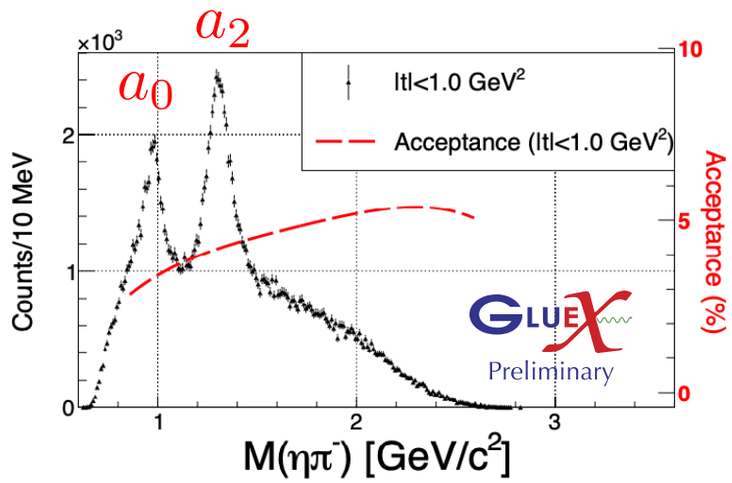
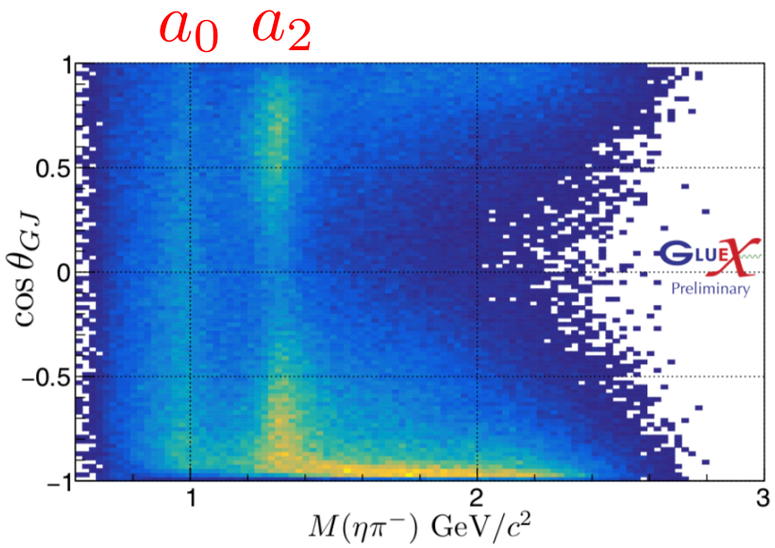
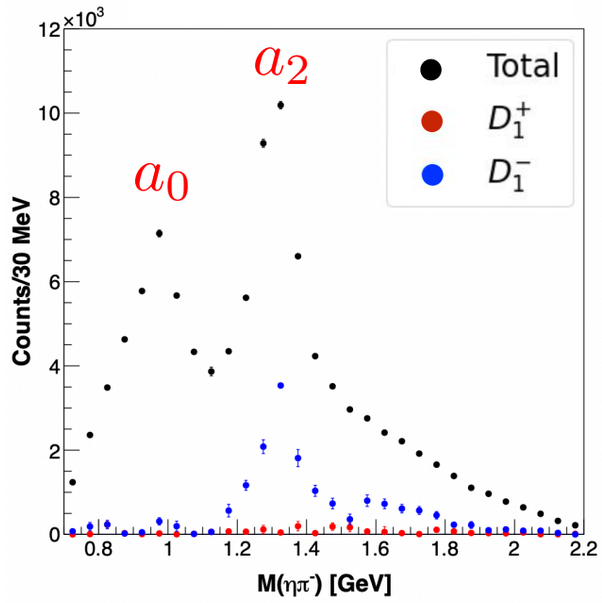
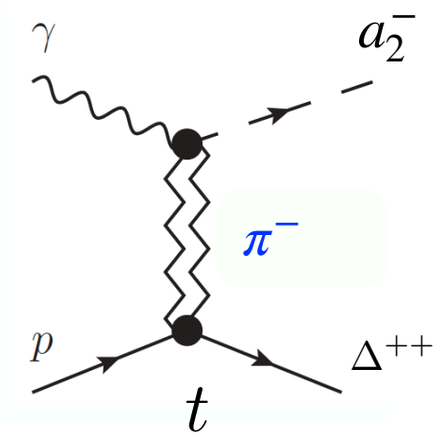




Preliminary angular analysis shows the $a_2(1320)$ is produced via π^- exchange, as expected.





VD. Fixed Targets

Highlights from Fixed Targets

(1) production mechanisms

(2) COMPASS (pion beam)

(3) GlueX (photon beam)

(4) photoproduction of charmonium

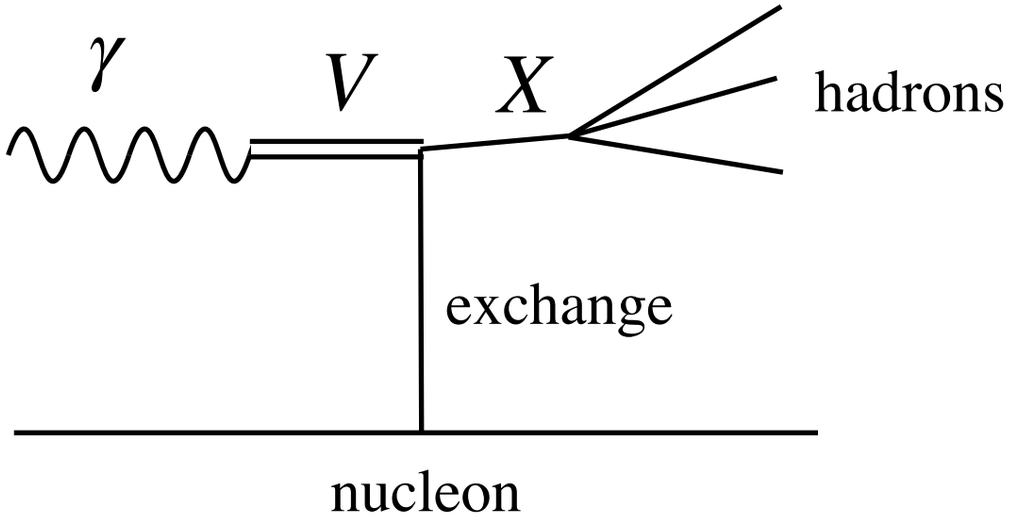
GlueX (at JLab):

γ beam with energy $\approx$ 9 GeV

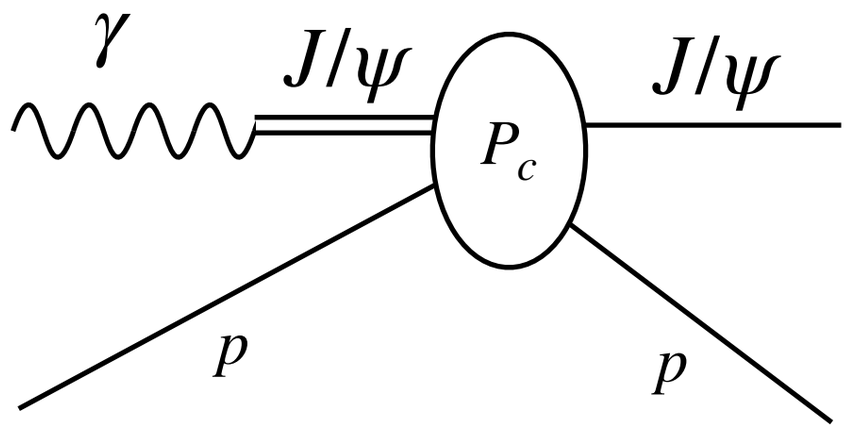
GlueX $M_{\gamma p}$ is just right to study P_c pentaquarks:

$$M_{\gamma p} = \left[(E_\gamma + m_p)^2 - E_\gamma^2\right]^{\frac{1}{2}} = \left[2E_\gamma m_p + m_p^2\right]^{\frac{1}{2}}$$

$$E_\gamma = 9 \text{ GeV} \implies M_{\gamma p} = 4.3 \text{ GeV}$$
$$E_\gamma = 11 \text{ GeV} \implies M_{\gamma p} = 4.8 \text{ GeV}$$



"t-channel"



"s-channel"

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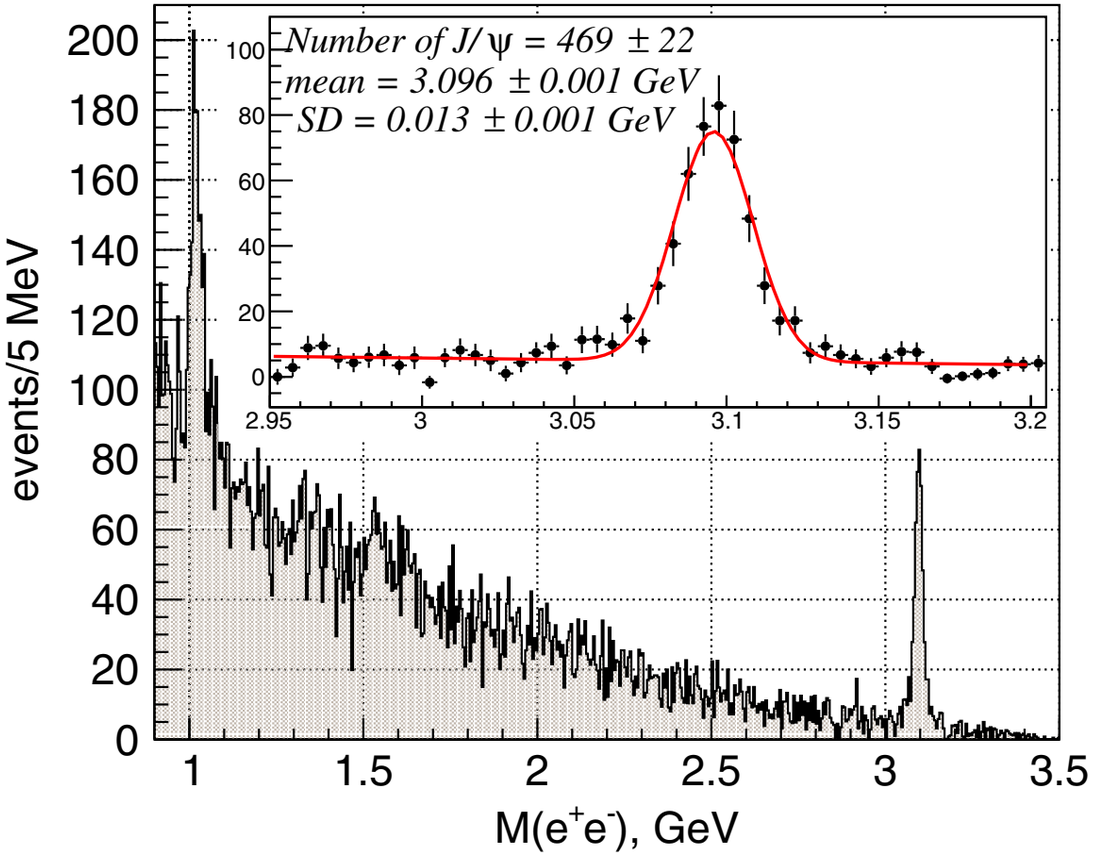
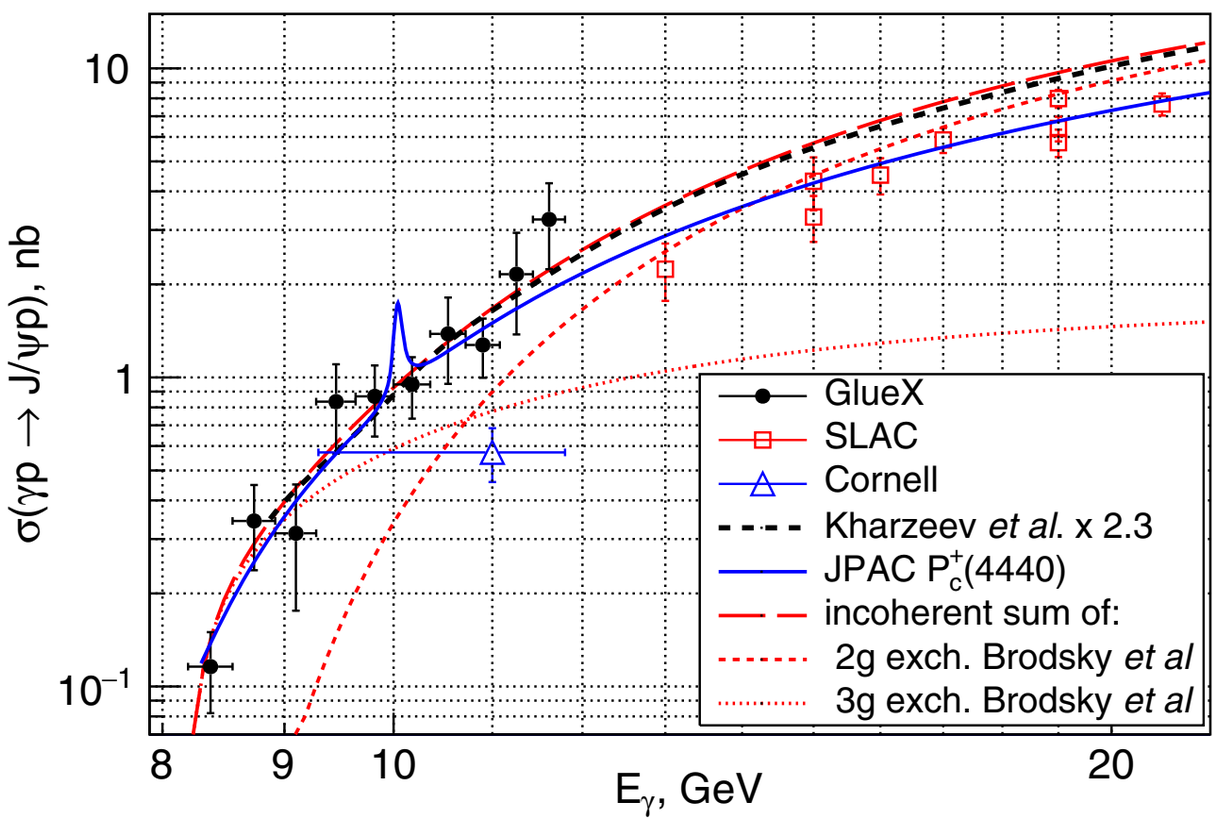
PHYSICAL REVIEW LETTERS **123,** 072001 (2019)

Editors' Suggestion

First Measurement of Near-Threshold J/ψ Exclusive Photoproduction off the Proton

(GlueX Collaboration)





$B(P_c \to J/\psi p) < 2 - 5\,\%$ *(model-dependent)*

Table 3: Major experiments in the past, present, and future of heavy-quark exotics studies.

Experiment	Highlights	Accelerator	Years	Institute	Production
BaBar	$Y(4260)$ [29] $Y(4360)$ [108]	PEP-II	1999–2008	SLAC (Menlo Park, California, USA)	e^+e^- annihilation ($E_{\rm CM} \approx 10$ GeV): $e^+e^- \to B\bar{B}$; $B \to KX$ $e^+e^- \to Y_b$ $e^+e^- \to \pi Z_b$ $e^+e^-(\gamma_{\rm ISR}) \to Y$ $e^+e^-(\gamma_{\rm ISR}) \to \pi Z_c$ $e^+e^- \to J/\psi + X$ $\gamma\gamma \to X$
Belle	$X(3872)$ [4] $Y(3940)$ [106] $X(3915)$ [166] $Z_c(4430)$ [30, 136, 137] $Z_b(10610)$, $Z_b(10650)$ [160, 162, 163] $Y_b(10888)$ [151, 152]	KEKB	1998–2010	KEK (Tsukuba, Japan)	
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COMPASS	photoproduction [181] $a_1(1420)$ [182]	SPS	2002-2011		μ/π beam on N target ($p_{beam} \approx 160, 200$ GeV) $\pi N \to XN$ $\gamma N \to XN$
$\bar{\rm P}$ANDA	Upcoming	HESR		GSI (Darmstadt, Germany)	$\bar{p}$ beam on p target ($p_{beam} \approx 1.5$–15 GeV): $p\bar{p} \to X$ $p\bar{p} \to X$ + any
GlueX	Beginning (searches for light quark hybrid mesons)	CEBAF	2016–	Jefferson Lab (Newport News, Virginia, USA)	γ beam on p target ($E_{beam} \leq 11$ GeV): $\gamma p \to Xp$
CLAS12					

Progress in Particle and Nuclear Physics 93 (2017) 143–194

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Review

Heavy-quark QCD exotica

Richard F. Lebed [a,*], Ryan E. Mitchell [b], Eric S. Swanson [c]

LECTURE V. Current and Future Experiments

VA. Detectors

VB. Hadron Colliders

VC. e^+e^- Colliders

* B Factories

* τ/c Factories

VD. Fixed Targets

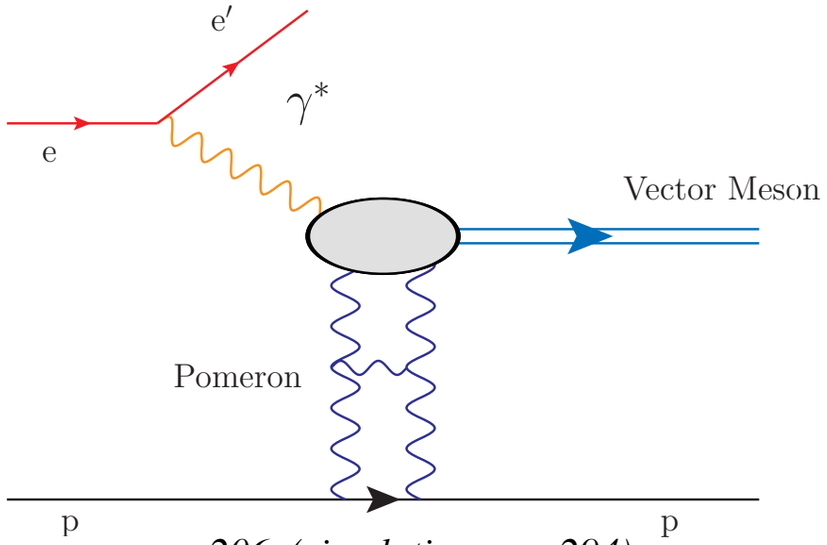
VE. New Possibilities (+ EIC!)

VF. Outlook

VE. New Possibilities (+EIC!)

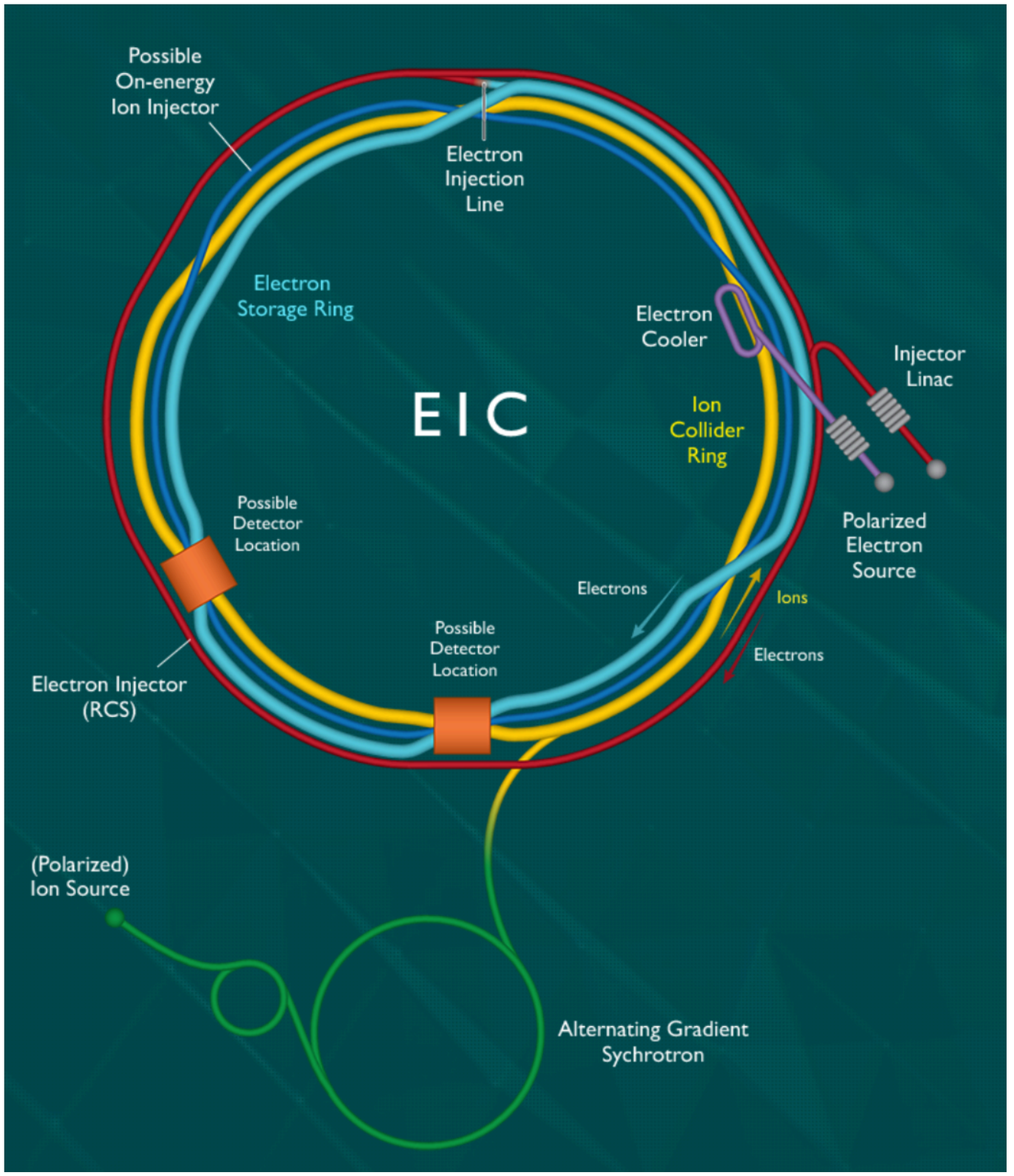
SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER

EIC Yellow Report



pg. 206 (simulations pg. 294)

$$\sqrt{s} = M_{ep} = 20 - 140 \text{ GeV}$$



https://www.bnl.gov/eic/

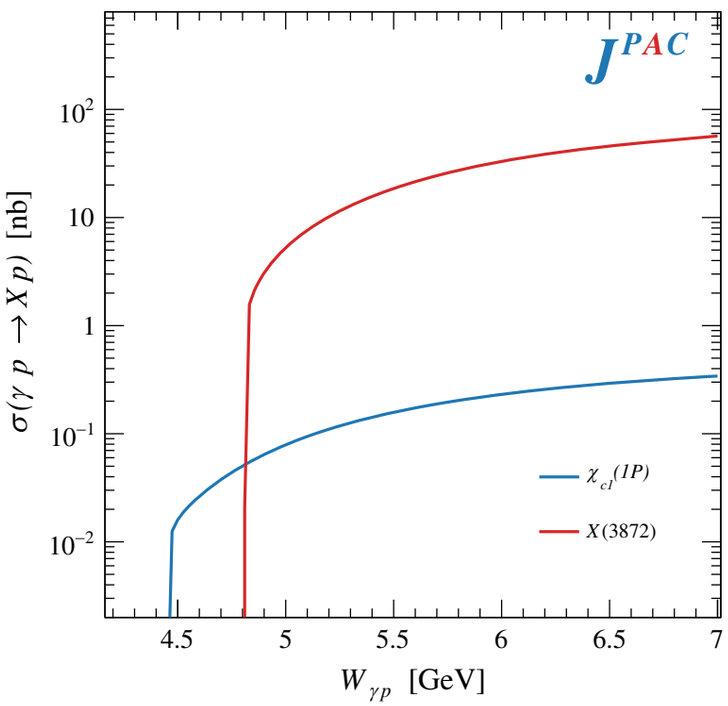
VE. New Possibilities (+EIC!)

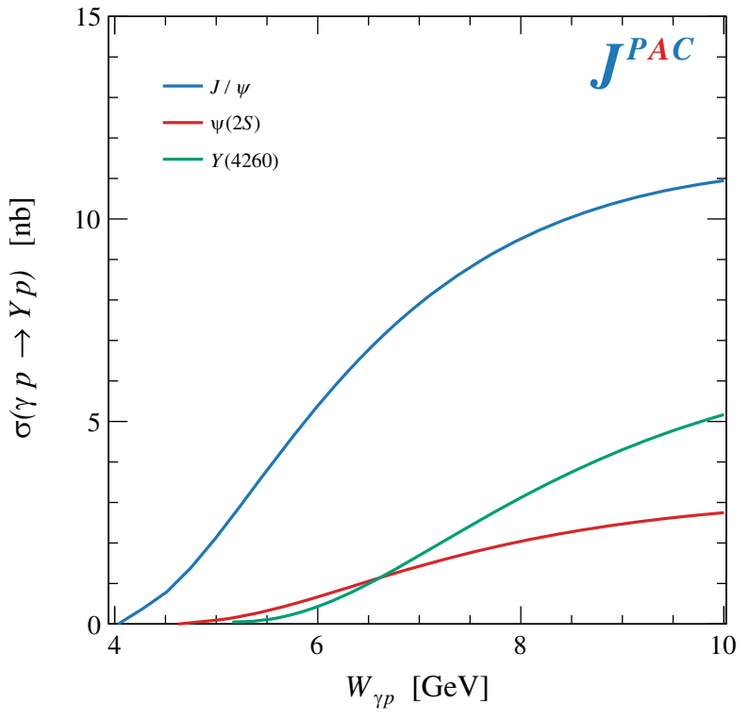
PHYSICAL REVIEW D **102,** 114010 (2020)

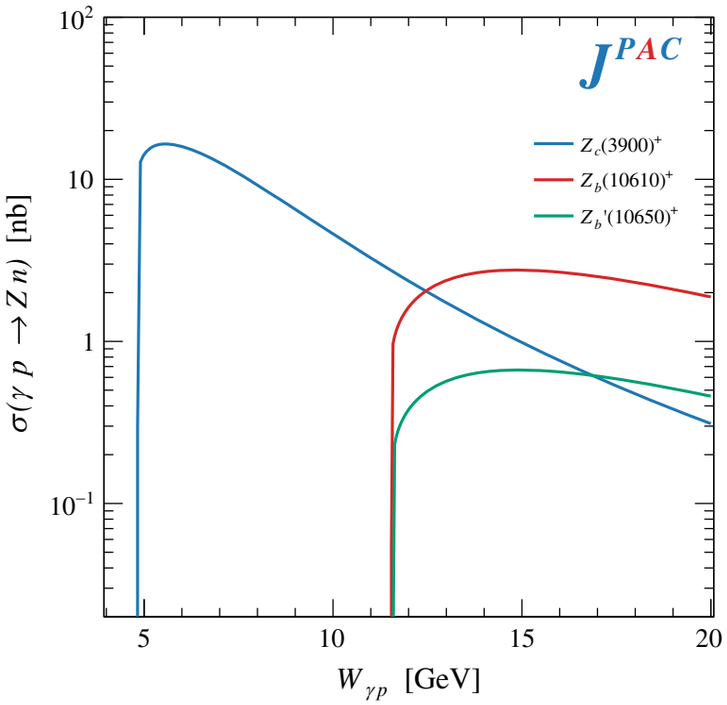
XYZ spectroscopy at electron-hadron facilities: Exclusive processes

M. Albaladejo,[1,*] A. N. Hiller Blin,[1,†] A. Pilloni,[2,3,4,‡] D. Winney,[5,6,§]
C. Fernández-Ramírez,[7] V. Mathieu,[8] and A. Szczepaniak[1,5,6]

(Joint Physics Analysis Center)







Note: Maximum $W_{\gamma p}$ at GlueX is ≈ 4.8 GeV.

Studying the XYZ at the EIC using photoproduction could work!

VE. New Possibilities: PANDA

Charm (-onium) physics at PANDA

Frank Nerling
HFHF, GSI Darmstadt
on behalf of the PANDA Collaboration

10th Intern. Workshop on Charm Physics
May 31st - June4th 2021

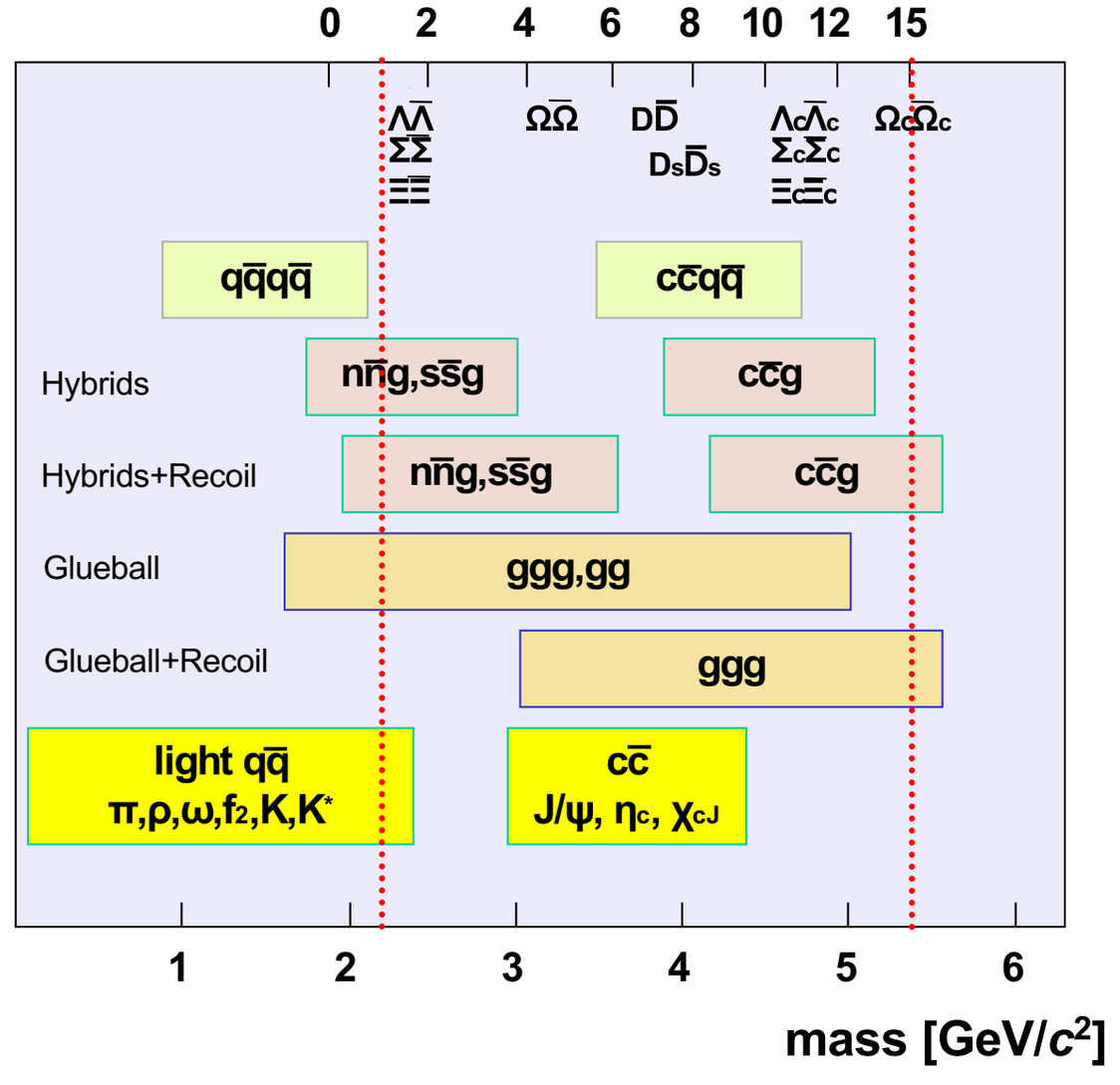
probe a variety of meson J^{PC} using:

$$\bar{p}p \to X$$
$$\bar{p}p \to X + \text{recoil}$$

Anti-Proton ANnihilation in DArmstadt

- **Meson spectroscopy**
  - Light mesons
  - Open charm
  - Charmonium
  - Exotic states:

    glue-balls, hybrids,
    molecules / multi-quarks
- **(Anti-) Baryon production**
- **Nucleon structure**
- **Charm in nuclei**
- **Strangeness physics**
  - hypernuclei,
  - S = -2 nuclear system



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* B Factories

* τ/c Factories

VD. Fixed Targets

VE. New Possibilities

VF. Outlook

VF. Outlook

Notes on the outlook for experimental meson spectroscopy:

1. There is a vibrant field in all meson sectors.

2. Novel opportunities are emerging for contact between theory, models, and experiment.

3. Statistical precision brings new surprises and challenges.

4. All experimental programs are continuing with major upgrades and new possibilities are planned.

VF. Outlook

Notes on the outlook for experimental meson spectroscopy:

1. Ther

2. Nove
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3. Stati

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   and

From Lecture 1:

QUARKS

ANTIQUARKS	d	u	s	c	b
$\bar{d}$	$\pi^0 \mid \eta \mid \eta'$	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{u}$	π^-	$\pi^0 \mid \eta \mid \eta'$	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	$\eta \mid \eta'$ / ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

- K^+ family *(weak decays, no mixing)*
- K^0 family *(weak decays, mixing)*
- π^0 family *(large electromagnetic decays)*
- J/ψ family *(strong decays, near or below open flavor threshold)*
- ρ family *(strong decays, above open flavor threshold)*
- $Z_c(3900)$ family *(exotic flavor quantum numbers)*

$J^{P(C)}$	$u\bar{d},\ u\bar{u},\ d\bar{d},\ s\bar{s}$			$c\bar{c}$	$b\bar{b}$	$d\bar{s},\ u\bar{s}$	$c\bar{u},\ c\bar{d}$	$c\bar{s}$	$d\bar{b},\ u\bar{b}$	$s\bar{b}$
$1^{-(-)}$	$\rho(1700)$	$\omega(1650)$	$\phi(1680)$	$\psi(3770)$	$\Upsilon(4S)$	$K^*(1680)$		$D_{s1}^*(2700)^+$		
$2^{+(+)}$	$a_2(1320)$	$f_2(1270)$	$f_2'(1525)$	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$K_2^*(1430)$	$D_2^*(2460)$	$D_{s2}^*(2573)^+$	$B_2^*(5747)$	$B_{s2}^*(5840)^0$
$1^{+(+)}$	$a_1(1260)$	$f_1(1285)$	$f_1(1420)$	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	$K_1(1400)$	$D_1(2430)$	$D_{s1}(2536)^+$		
$0^{+(+)}$	$a_0(1450)$	$f_0(1370)$	$f_0(1710)$	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$K_0^*(1430)$	$D_0^*(2300)$	$D_{s0}^*(2317)^+$		
$1^{+(-)}$	$b_1(1235)$	$h_1(1170)$	$h_1(1415)$	$h_c(1P)$	$h_b(1P)$	$K_1(1270)$	$D_1(2420)$	$D_{s1}(2460)^+$	$B_1(5721)$	$B_{s1}(5830)^0$
$1^{-(-)}$	$\rho(770)$	$\omega(782)$	$\phi(1020)$	$J/\psi(1S)$	$\Upsilon(1S)$	$K^*(892)$	$D^*(2007)^0 \mid D^*(2010)^+$	D_s^{*+}	B^*	B_s^{*0}
$0^{-(+)}$	π^0 π^+	$\eta \mid \eta'$	$\eta \mid \eta'$	$\eta_c(1S)$	$\eta_b(1S)$	K^0 K^+	D^0 D^+	D_s^+	B^0 B^+	B_s^0

excited states

ground state

$Z_c(4020)^+ \to \pi^+ h_c$	$Z_c(4430)^+ \to \pi^+ \psi(2S)$	$Z_b(10650)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$X(2900)^0 \to D^+ K^-$
$Z_c(3900)^+ \to \pi^+ J/\psi$	$Z_{cs}(4000)^+ \to K^+ J/\psi$	$Z_b(10610)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$T_{cc\bar{c}\bar{c}}(6900) \to J/\psi J/\psi$

VF. Outlook

Notes on the outlook for experimental meson spectroscopy:

1. There is a vibrant field in all meson sectors.

2. Novel opportunities are emerging for contact between theory, models, and experiment.

3. Statistical precision brings new surprises and challenges.

4. All experimental programs are continuing with major upgrades and new possibilities are planned.

VF. Outlook

Notes on the outlook for experimental meson spectroscopy:

1.

2.

3.

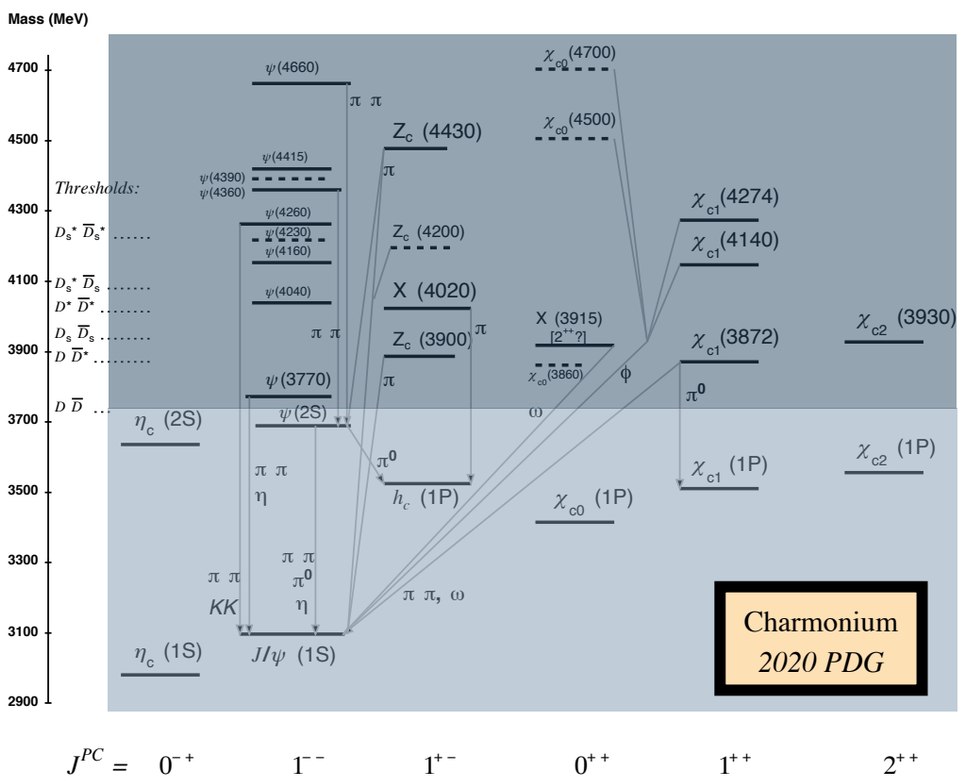
4.

From Lecture 3:

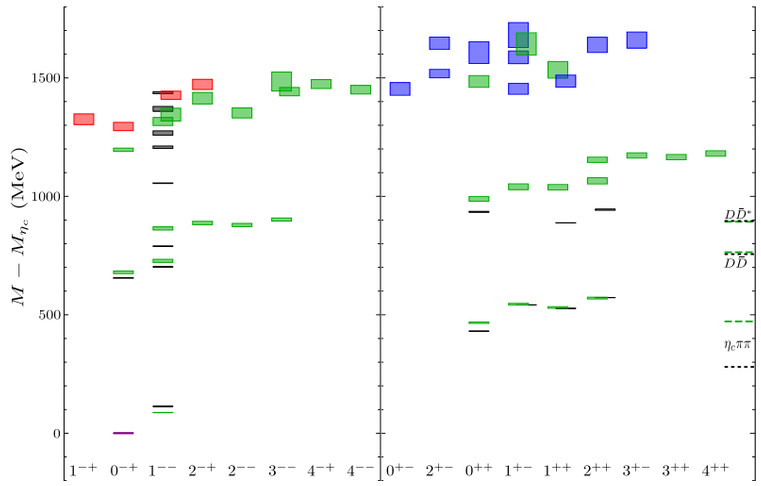
The goal of experimental meson (hadron) spectroscopy:

Uncover a broad set of physical phenomena
(including new meson states, their properties, decays patterns, etc.)
in order to build our understanding of the strong force.

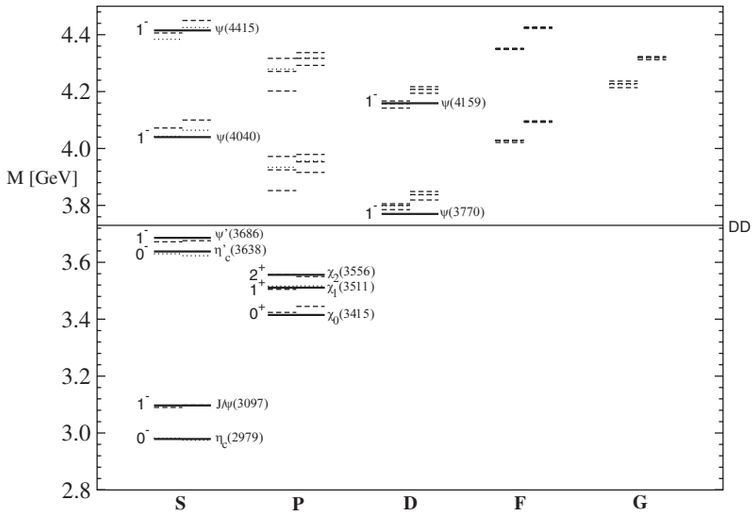
EXPERIMENT



THEORY



MODELS



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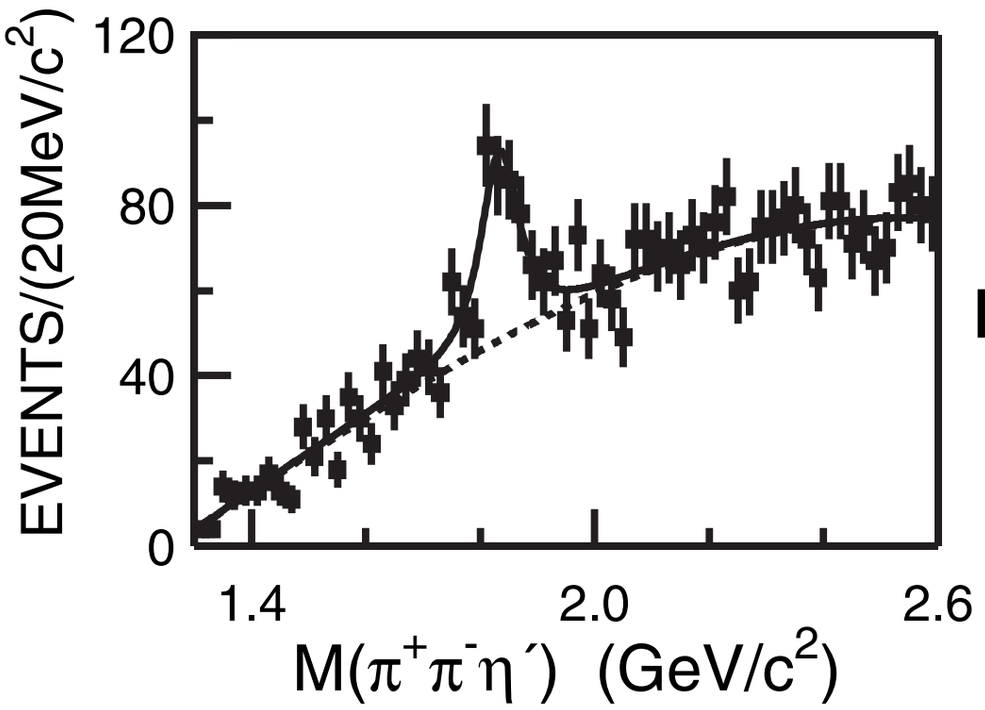
From Lecture 5:

PRL **95,** 262001 (2005) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2005

Observation of a Resonance $X(1835)$ in $J/\psi \to \gamma\pi^+\pi^-\eta'$

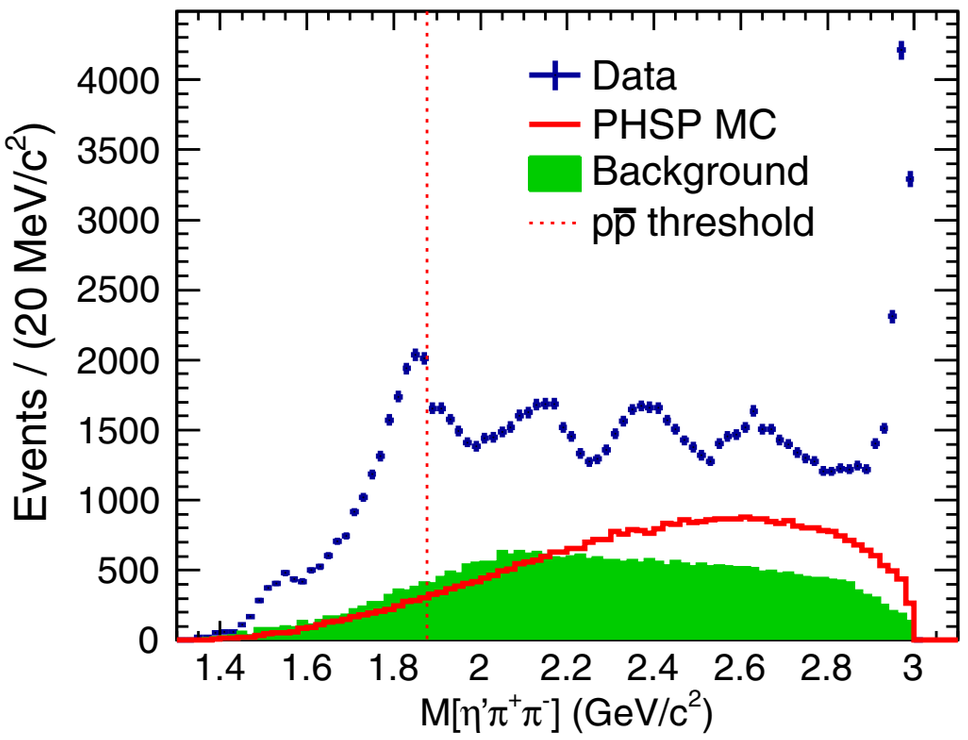
(BES Collaboration)



58M J/ψ decays

PRL **117,** 042002 (2016) PHYSICAL REVIEW LETTERS week ending 22 JULY 2016

Observation of an Anomalous Line Shape of the $\eta'\pi^+\pi^-$ Mass Spectrum near the $p\bar{p}$ Mass Threshold in $J/\psi \to \gamma\eta'\pi^+\pi^-$



1B J/ψ decays

VF. Outlook

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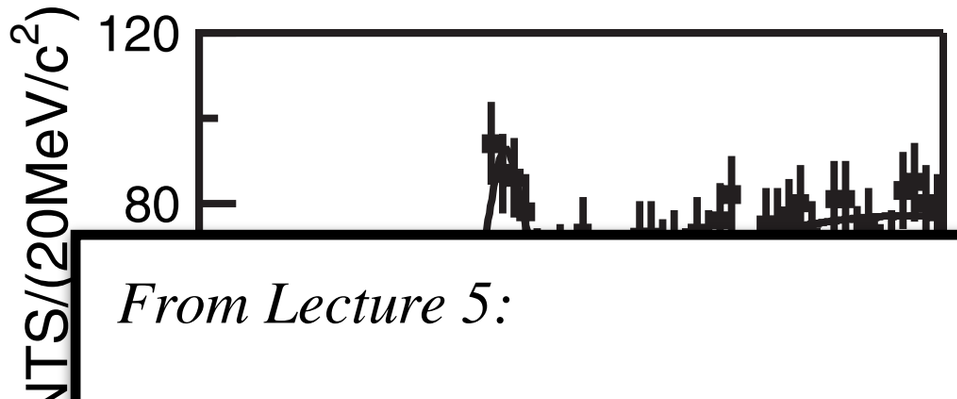

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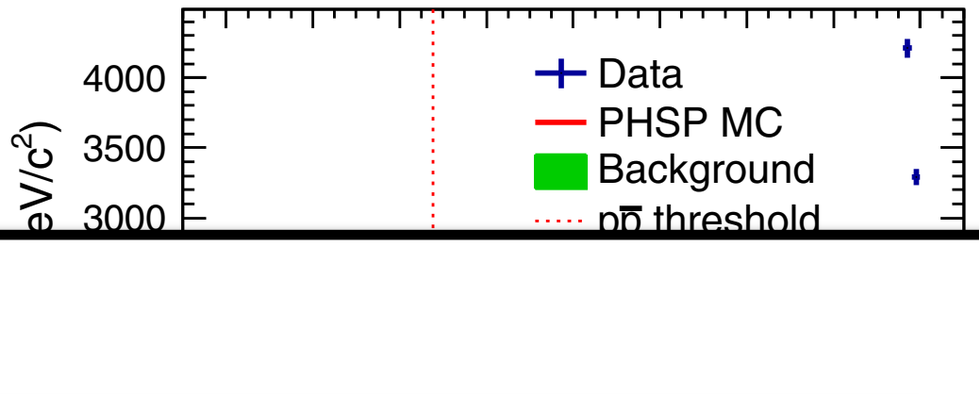
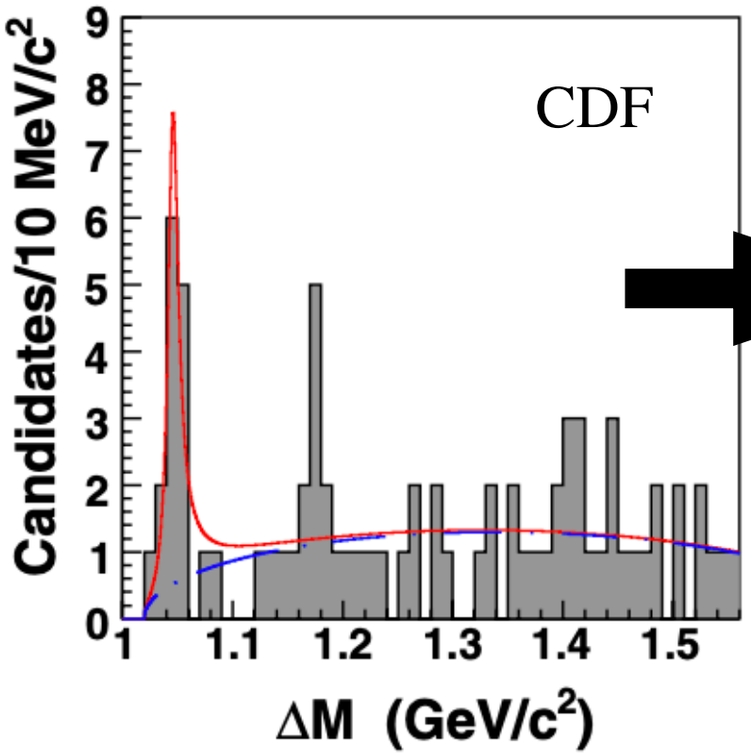
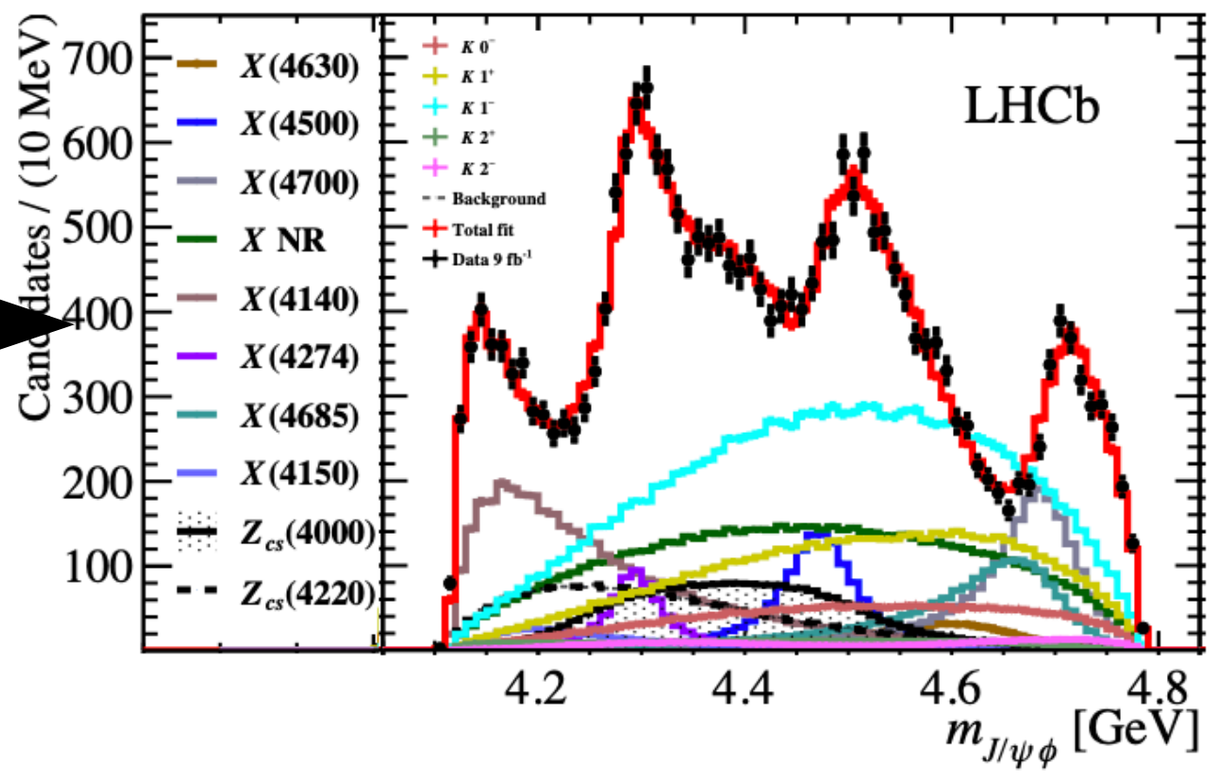


From Lecture 5:

58M





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Final thought:

By expanding the collection of known hadrons *("stamp collecting")*, we are steadily improving our understanding of the strong force and how it works to construct hadrons.