Newly-observed X(3960) and Puzzle of the $\chi_{c0}(2P)$ state

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Outline

Based on

Amplitude Analysis: arXiv: 2210.15153, PRL Editors' Suggestion
Branching Fraction: arXiv: 2211.05034, PRD Editors' Suggestion

Experimental results

- $X(3960)$: the $D_s^+ D_s^-$ near-threshold enhancement
- $X_0(4140)$: a resonant structure or $J/\psi\phi$ rescattering effect ?
- Upper limits on $\Gamma[\chi_{c0}(4500)/\chi_{c0}(4700) \to D_s^+ D_s^-]$

Discussion on its nature

Personal views

- A new hadron: $D_s^+ D_s^-$ molecule, $[cs][\bar{c}\bar{s}]$, mixture of molecule and tetraquark, …
- The same as $\chi_{c0}(3915)$: $c\bar{c}$ (or mixed with $D_s^+ D_s^-$), $D_s^+ D_s^-$ molecule, $[cq][\bar{c}\bar{q}]$, …
- $\chi_{c0}(2P)$ candidates: $\chi_{c0}(3860)$ or $\chi_{c0}(3915)$?

First measurement of $B^+ \to D_s^+ D_s^- K^+$ decay

$\bar{b} \to \bar{c}c\bar{s}$

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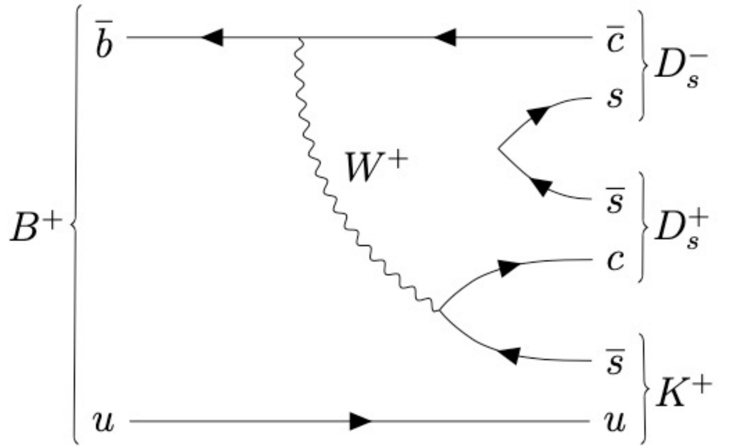
Amplitude Analysis: arXiv: 2210.15153, PRL Editors' Suggestion

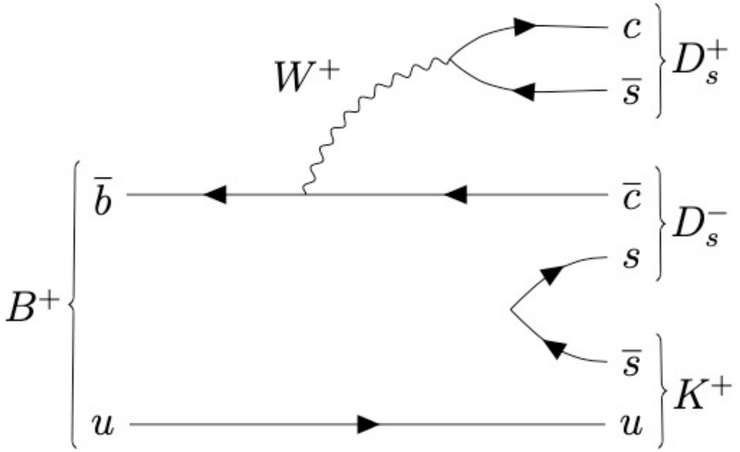
Branching Fraction: arXiv: 2211.05034, PRD Editors' Suggestion



- ❖ Cabibbo favoured $\bar{b} \to \bar{c}c\bar{s}$ transition only focus on $D^{(*)}\bar{D}^{(*)}$ before, while decays involving $D_s^{(*)+}D_s^{(*)-}$ pairs have never been explored.

- ❖ Such decays provide an excellent laboratory for investigations of open- and hidden-charm meson spectroscopy, covering (exotic) hadrons.

- ❖ Offer information to theoretical calculations of the charm-loop contributions to $\bar{b} \to \bar{s}l^+l^-$ processes that are sensitive to new physics [JHEP09(2010)089].

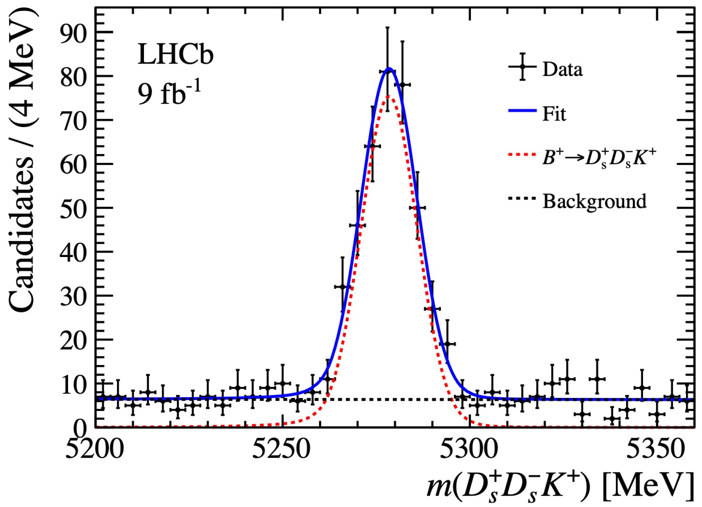


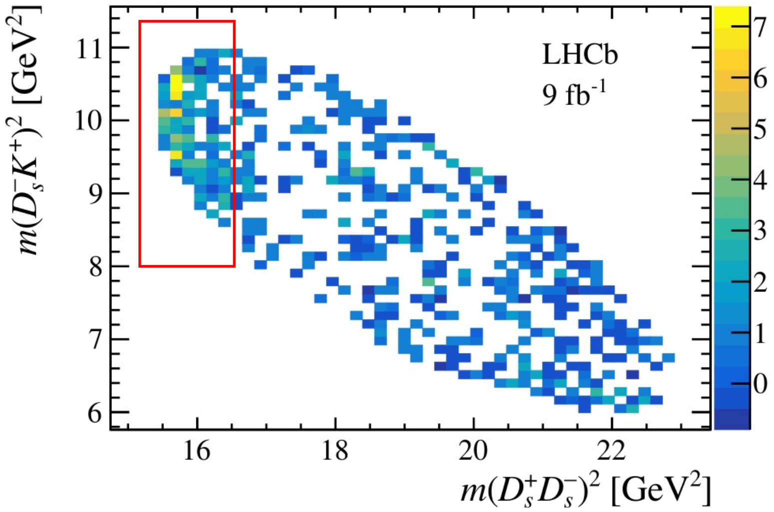
Note: charge-conjugate processes are always included.

Yields and distributions

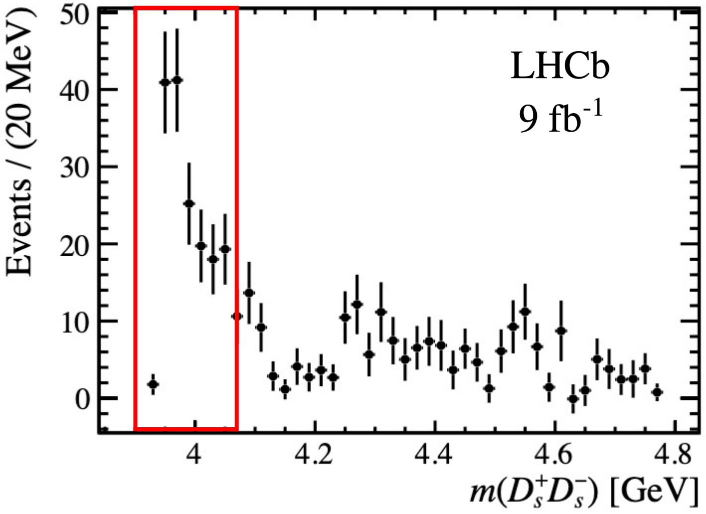
$\bar{b} \to \bar{c}c\bar{s}$

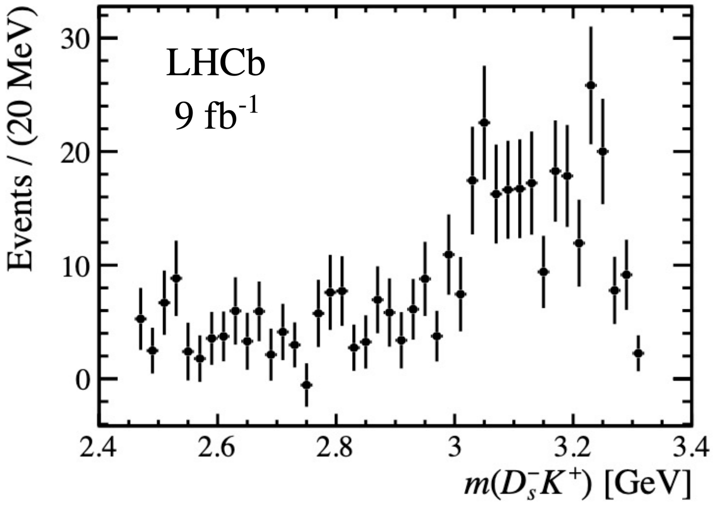
- Full data set, 9 fb^{-1}
- $D_s^+ \to K^+K^-\pi^+$
- Gradient BDT
- Purity of 84.4% within ± 20 MeV
- 360 B^+ signal candidates

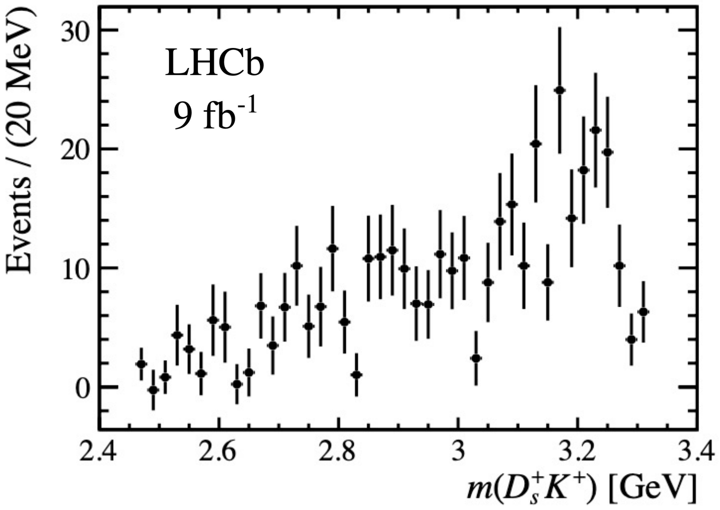




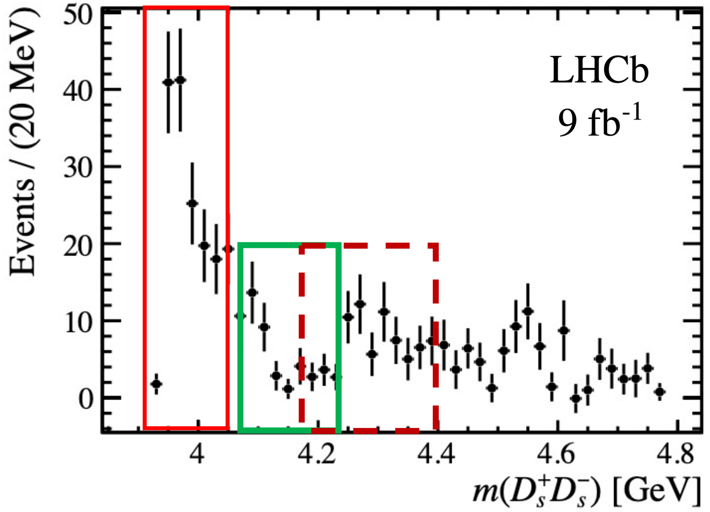
Threshold enhancement at $D_s^+D_s^-$

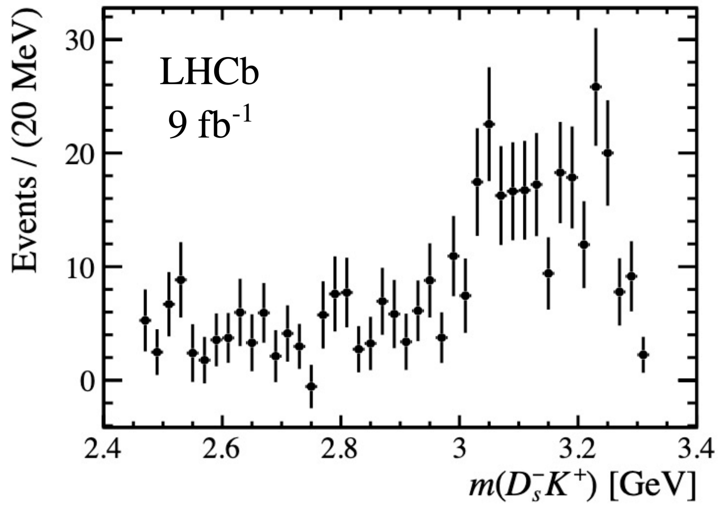






Considered components



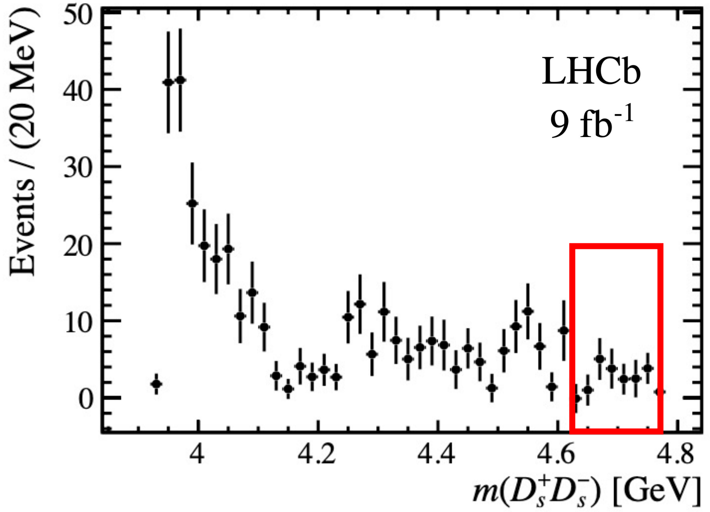


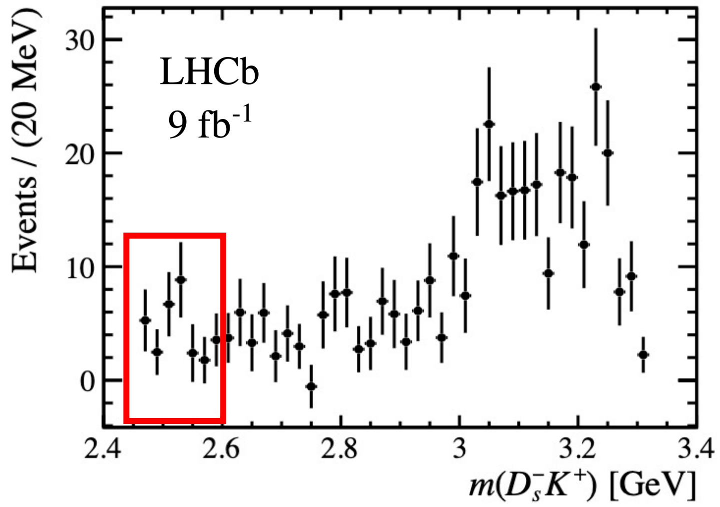
Need a state to describe the dip around 4140 MeV!

$X_0(4140) \neq \mathrm{X}(4140)$ in the $J/\psi\phi$ system

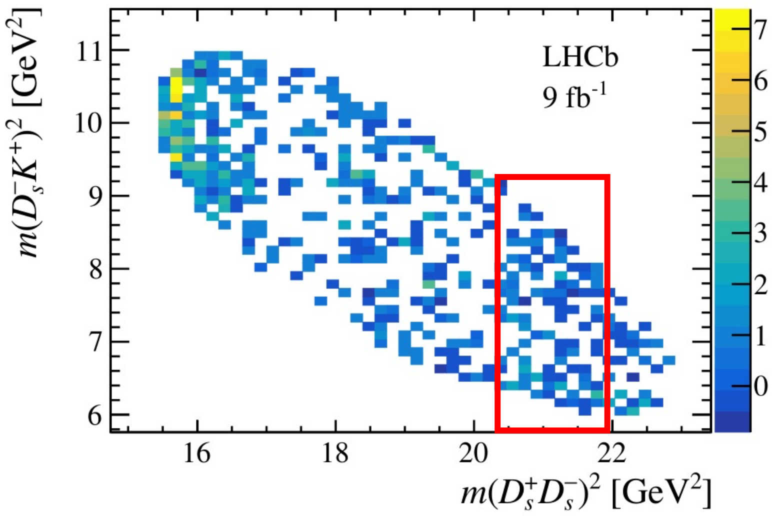
$D_s^+ D_s^-$	$X(3960)$	0^{++}	$> 14\sigma$
	$X_0(4140)$	0^{++}	$\sim 4\sigma$
	$\chi_{c0}(4500)$	0^{++}	
	$\chi_{c0}(4700)$	0^{++}	
	$\psi(4040)$	1^{--}	
	$\psi(4160)$	1^{--}	
	$\psi(4260)$	1^{--}	
	$\psi(4415)$	1^{--}	
	$\chi_{c2}(3930)$	2^{++}	
$D_s^- K^+$	$\overline{D}_0^*(2300)^0$	0^+	
	$\overline{D}_1^*(2600)^0$	1^-	
	$\overline{D}_1^*(2760)^0$	1^-	
	$\overline{D}_2^*(2460)^0$	2^+	
3-body PHSP	NR	S-wave	$> 3\sigma$

Considered components

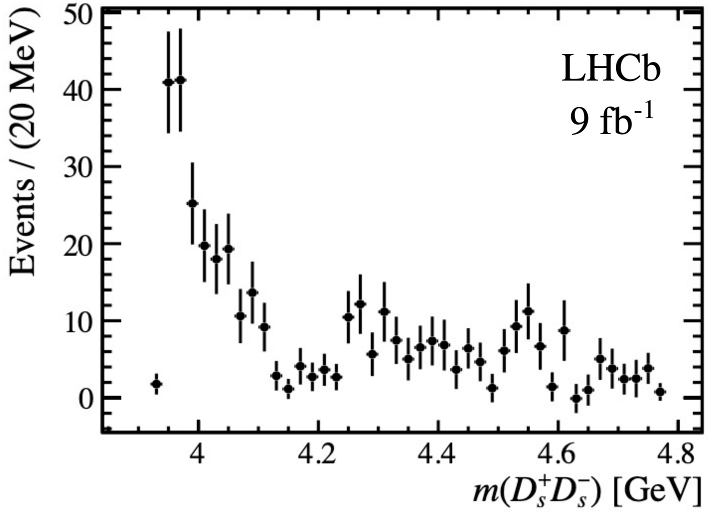


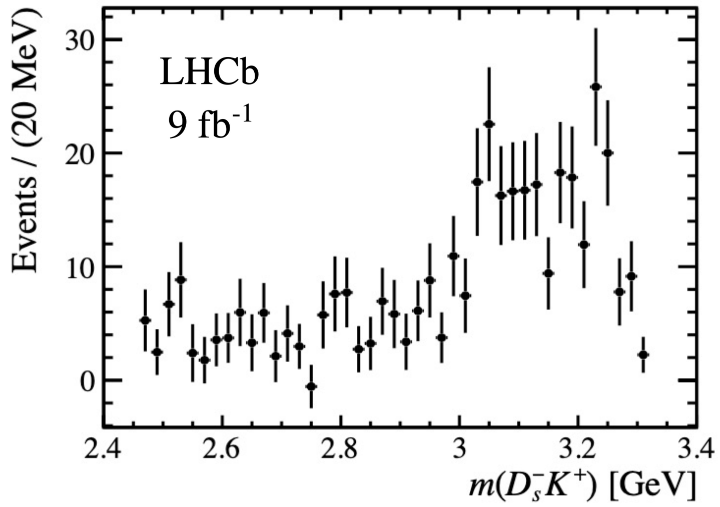


- Test $\bar{D}^*(2300)^0 \to D_s^- K^+$, failed
- From Dalitz and mass distributions, there may exist a $\psi(4660)$ satete.



Considered components





$D_s^+D_s^-$	$X(3960)$	0^{++}	$> 14\sigma$
	$X_0(4140)$	0^{++}	$\sim 4\sigma$
	$\chi_{c0}(4500)$	0^{++}	
	$\chi_{c0}(4700)$	0^{++}	
	$\psi(4040)$	1^{--}	
	$\psi(4160)$	1^{--}	
	$\psi(4260)$	1^{--}	$> 3\sigma$
	$\psi(4415)$	1^{--}	
	$\psi(4660)$	1^{--}	$> 3\sigma$
	$\chi_{c2}(3930)$	2^{++}	
$D_s^-K^+$	$\overline{D}_0^*(2300)^0$	0^+	
	$\overline{D}_1^*(2600)^0$	1^-	
	$\overline{D}_1^*(2760)^0$	1^-	
	$\overline{D}_2^*(2460)^0$	2^+	
3-body PHSP	NR	S-wave	$> 3\sigma$

Adding $\psi(4600)$

$\mathcal{S}$(others) $< 2\sigma$

Helicity-based amplitude analysis

- Helicity formulism

$$\mathcal{M}(m_{P_1P_2},\theta_X) = \sum_n \mathcal{H}^{X_n} d^{J_{X_n}}_{0,0}(\theta_X)\, p^{L_B} F_{L_B}(pd)\, q^{L_{X_n}} F_{L_{X_n}}(qd)\, \mathcal{A}(m_{P_1P_2})$$

Helicity coupling constants

Wigner-D function

Resonance terms

$\mathcal{A}(m_{P_1P_2})$: RBW, Flatte, K matrix

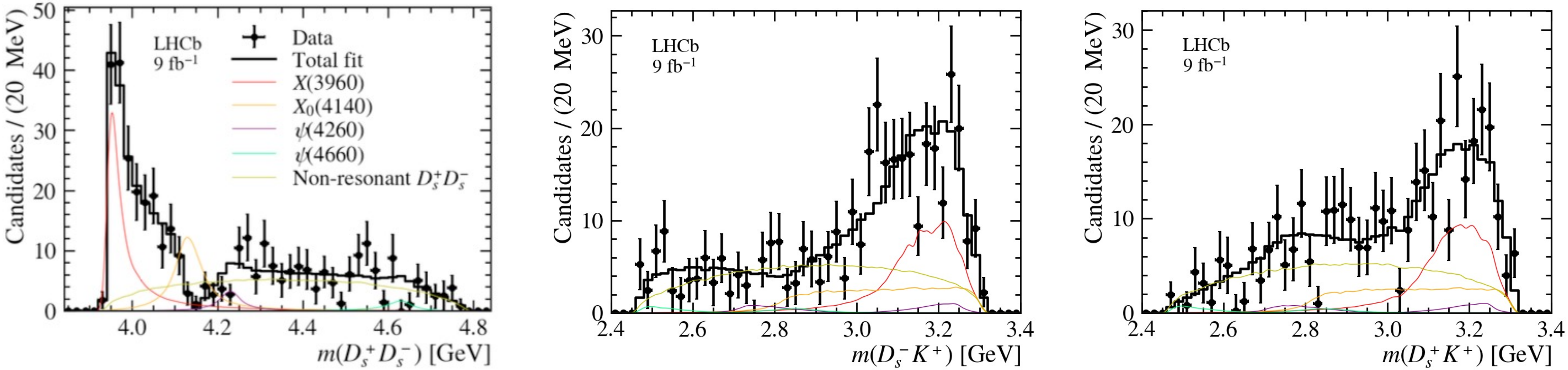
- Unbinned fit with background statistically subtracted using sPlot method

- Significance calculation

$$p = \mathrm{TMath::Prob}(2\Delta\mathcal{L}, \Delta\mathrm{ndf})$$

$$\mathcal{S} = \mathrm{RooStats::PValueToSignificance}(p/2)$$

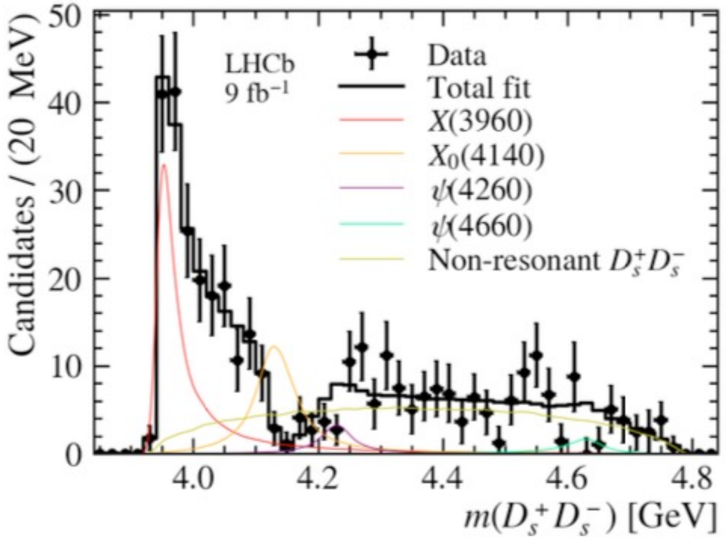
Baseline amplitude fit



$X(3960)$: significant $X_0(4140)$ and ψ states: need to be confirmed in future

Component	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	$\mathcal{F}$ (%)	$\mathcal{S}$ (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 11$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 8.0$	12.6 (14.3)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 11$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 7.5$	3.7 (3.9)
$\psi(4260)$	1^{--}	4230	55	$3.6 \pm 0.4 \pm 3.0$	3.1 (3.3)
$\psi(4660)$	1^{--}	4633	64	$2.2 \pm 0.2 \pm 0.5$	2.9 (3.2)
NR	S-wave	-	-	$46.1 \pm 13.2 \pm 11.1$	3.1 (3.4)

Baseline amplitude fit



State	J^P preference	$\mathcal{S}(\sigma)$
$X(3960)$	0^+ over $1^-/2^+$	>9.3
$X_0(4140)$	0^+ over $1^-/2^+$	>3.5

$\mathcal{F}$: fit fraction

$\mathcal{S}$: significance (numbers in brackets don't include sys. effects)

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$X(3960)$	0^{++}	$3956 \pm 5 \pm 11$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 8.0$	12.6 (14.3)
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Treat $X(3960)$ and $\chi_{c0}(3930)$ as same state

$T_{\psi\phi}^{f}$ or $\chi_{c0}(2P)$

$D_s^+ D_s^-$ threshold: 3936.7 MeV

Resonances	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	Decays	References
$X(3960)$	0^{++}	$3956 \pm 5 \pm 11$	$43 \pm 13 \pm 8$	$D_s^+ D_s^-$	This work
$\chi_{c0}(3930)$	0^{++}	$3923.8 \pm 1.5 \pm 0.4$	$17.4 \pm 5.1 \pm 0.8$	$D^+ D^-$	PRD102.112003(2020)
$\chi_{c0}(3915)$	$0^{++}/2^{++}$	3921.7 ± 1.8	18.8 ± 3.5	$D^+ D^-, J/\psi\omega, \gamma\gamma$	PDG 2022

$$\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^-)} = \frac{\mathcal{B}^{(1)} \mathcal{F}_X^{(1)}}{\mathcal{B}^{(2)} \mathcal{F}_X^{(2)}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08, \; <1.0$$

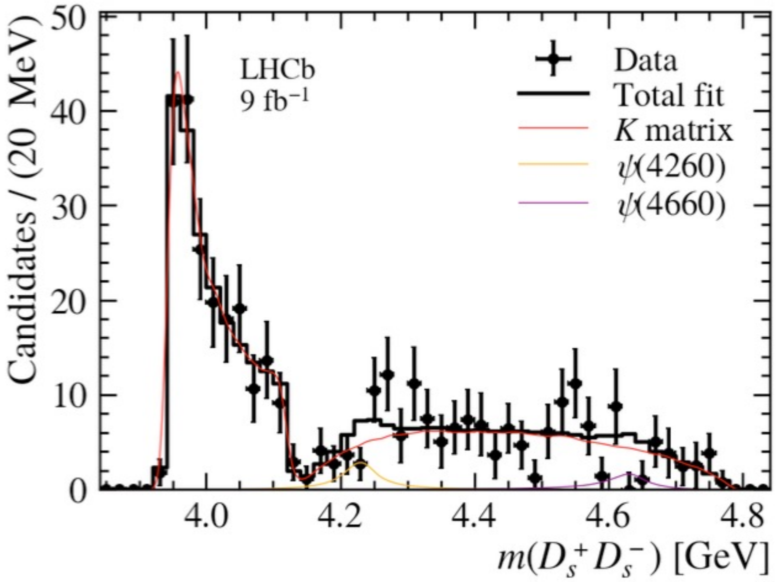
- **It is harder to excite an $s\bar{s}$ pair from vacuum compared with $u\bar{u}(d\bar{d})$**
- **Phase space of $X \to D_s^+ D_s^-$ is much smaller than $X \to D^+ D^-$**

This X state seems not to be a pure charmonium!

Alternative K-matrix model for $X_0(4140)$

New state ?

- Dip around 4140 MeV near the $J/\psi\phi$ threshold
- A simple K-matrix with an explicit resonance and two coupled channels ($D_s^+ D_s^-$ and $J/\psi\phi$)



$$\begin{pmatrix} \mathcal{M}_{D_s^+ D_s^- \to D_s^+ D_s^-} & \mathcal{M}_{D_s^+ D_s^- \to J/\psi\phi} \\ \mathcal{M}_{J/\psi\phi \to D_s^+ D_s^-} & \mathcal{M}_{J/\psi\phi \to J/\psi\phi} \end{pmatrix} \equiv \begin{pmatrix} \mathcal{K}_{11} & \mathcal{K}_{12} \\ \mathcal{K}_{21} & \mathcal{K}_{22} \end{pmatrix}$$

$$\mathcal{K}_{ba}(m) = \sum_R \frac{g_b^R g_a^R}{M_R^2 - m^2} + f_{ba} \qquad \mathcal{P}_b(m) = \sum_R \frac{\beta_R g_b^R}{M_R^2 - m^2} + \beta_b$$

$$\mathcal{M}_a = \sum_b (I - i\rho\mathcal{K})^{-1}_{ab} \mathcal{P}_b$$

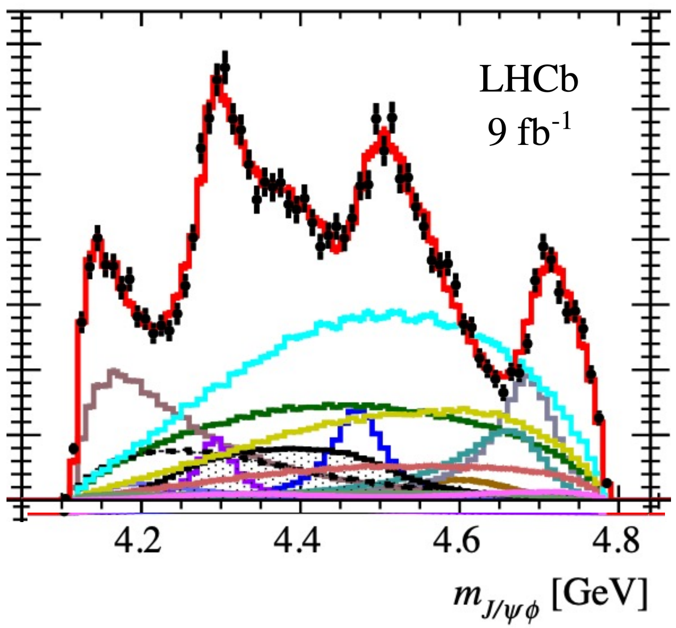
The dip can also be described by the $J/\psi\phi \leftrightarrow D_s^+ D_s^-$ reaction.

Upper limits on $X_0(4500)/X_0(4700) \to D_s^+ D_s^-$

Exotic nature ?

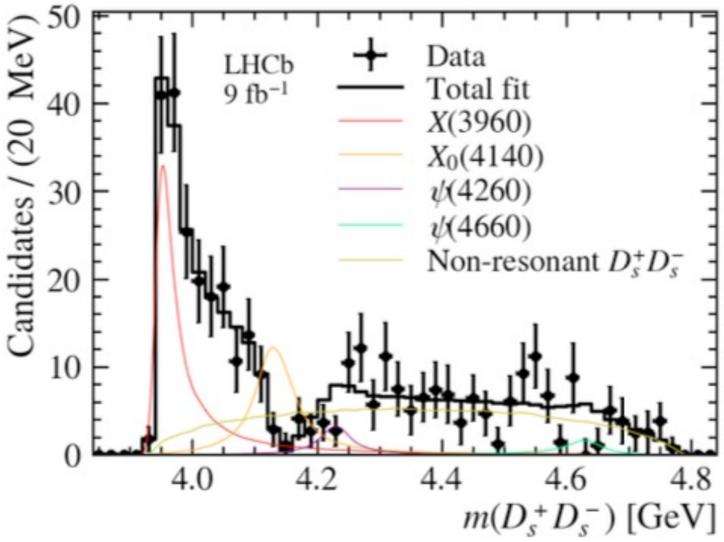
- $X_0(4500)$ and $X_0(4700)$ are observed in $J/\psi\phi$ mass via $B \to J/\psi\phi K$ [PRL127, 082001 (2021), 2301.04899]

- No significant excess in $D_s^+ D_s^-$ system,
  $\mathcal{F}(X(4500) \to D_s^+ D_s^-) = (0.6 \pm 1.0)\%$
  $< 3.5\%$ at 90% C.L.
  $\mathcal{F}(X(4700) \to D_s^+ D_s^-) = (2.4 \pm 1.8)\%$
  $< 6.7\%$ at 90% C.L.



Assuming average eff. for each track in $B^+ \to J/\psi\phi K^+$ equals approximately that in $B^+ \to D_s^+ D_s^- K^+$, then

$\Gamma(X(4500) \to D_s^+ D_s^-)/\Gamma(X(4500) \to J/\psi\phi) < 1.0$
$\Gamma(X(4700) \to D_s^+ D_s^-)/\Gamma(X(4700) \to J/\psi\phi) < 1.1$



On the nature of X(3960) and Puzzle of the $\chi_{c0}(2P)$ candidate

- $X(3960)$ as a new hadron
- $X(3960)$ as the same as $\chi_{c0}(3915)$
- Puzzle of $\chi_{c0}(2P)$

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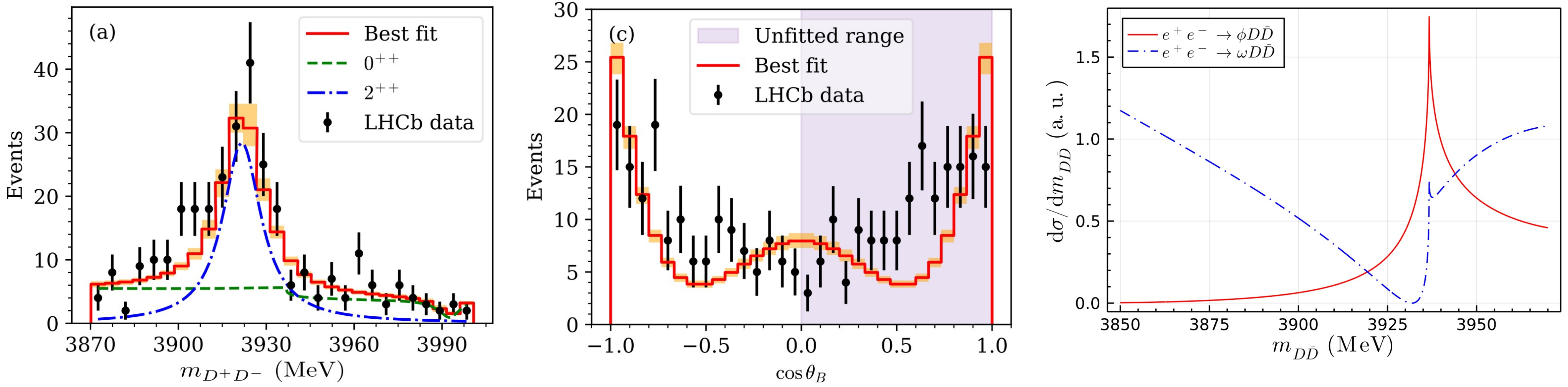
$X(3960)$ as a new 0^{++} hadron

1. a) $D_s^+ D_s^-$ molecule [Feng-Kun Guo, Bing-Song Zou et al., Sci.Bull. 68 (2023) 688]

- 0^{++} component in $B^+ \to D^+ D^- K^+$ derives from $X(3960)$, which has a mass around 3.94 GeV
- Predict a peak in $M(D\bar{D})$ via $e^+e^- \to \phi D\bar{D}$ while a dip via $e^+e^- \to \omega D\bar{D}$ at $E = 5.4$ GeV



b) Other molecular $D_s^+ D_s^-$ interpretations [Fang-Zheng Peng, Mao-Jun Yan, M.P. Valderrama, 2304.13515; Halil Mutuk, EPJC 82 (2022) 1142]

$X(3960)$ as a new 0^{++} hadron

2. a) Tetraquark $[cs][\bar{c}\bar{s}]$ state [S.S. Agaev et al., 2211.14129, 2303.02457]

- QCD two-point sum rules, $M_X = 3976 \pm 85$ MeV, $\Gamma_X = 42.2 \pm 8.3$ MeV
- Patrial widths, $\Gamma(X \to D_s^+ D_s^-) = (34.0 \pm 11.9)$ MeV, $\Gamma(X \to \eta\eta_c) = (5.2 \pm 1.1)$ MeV, $\Gamma(X \to \eta'\eta_c) = (3.0 \pm 0.7)$ MeV

$$M \approx 3975\ MeV \geq m_{th}(D_s^+ D_s^-)$$

b) Tetraquark $c\bar{c}s\bar{s}$ configuration

- Extended recoupling model, $M_X = 3970$ MeV, $\Gamma_X = 45 \pm 5$ MeV [A.M. Badalian and Yu.A. Simonov, 2301.13597]
- Improved chromomagnetic interaction model, $M_X = 3976.5$ MeV ($M_{X_0'} = 4195.1$ MeV) [Tao Guo et al. 2211.10834]
- QCD sum rule, $M_X = 3.98 \pm 0.10$ GeV [Qi Xin, Zhi-Gang Wang, Xiao-Song Yang, AAPPS Bull. 32 (2022) 37]

$X(3960)$ as a new 0^{++} hadron

3. $D_s^+ D_s^-$ (19%)+$D_s^{*+} D_s^{*-}$ (18%) + $T(c\bar{c}s\bar{s})$ (56%) [Jialun Ping et al. 2303.15388]

- Complex-scaling range of a chiral quark model, $\mathrm{M_{pole}} = 3995 + 6.4i$ MeV

$$M > m_{th}(D_s^+ D_s^-)$$

4. $D_{(s)}^{(*)}\overline{D}_{(s)}^{(*)}$ charmoniumlike resonance [Rui Chen, Qi Huang, 2209.05180]

- One-boson-exchange model with the S−D wave mixing effects considered, mass from the $D_s^+ D_s^-$ threshold to ~3980 MeV.

5. Others ... (很抱歉未能列全所有相关参考文献！)

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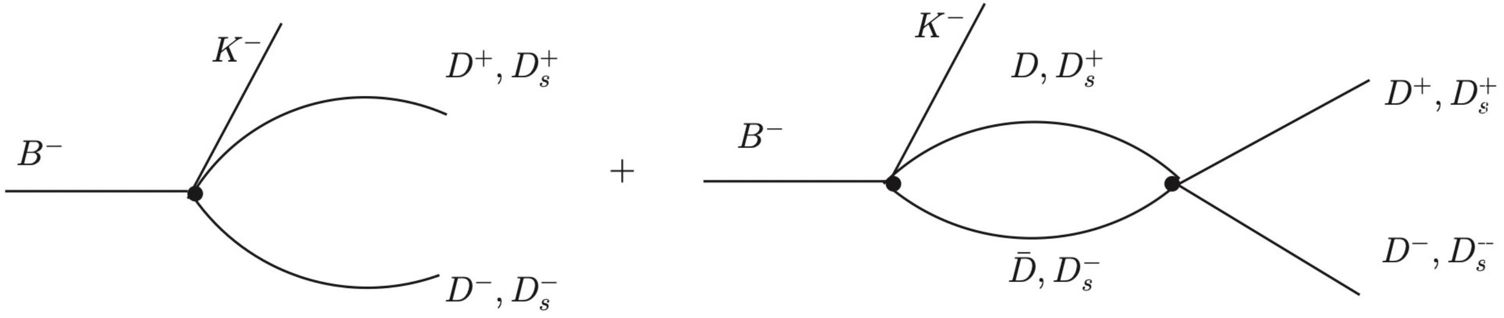
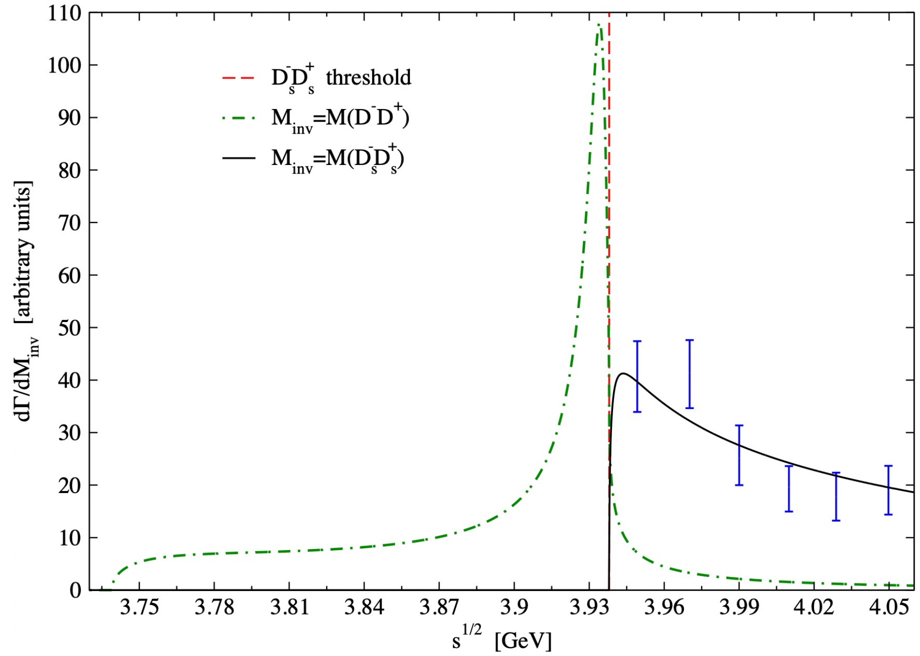
1. $D_s^+ D_s^-$ bound state [M. Bayar, A. Feijoo, E. Oset, PRD 107 (2023) 034007]

- $D_s^+ D_s^- - D\bar{D}$ coupled-channel dynamics





Need to be confirmed

in future high statistics !

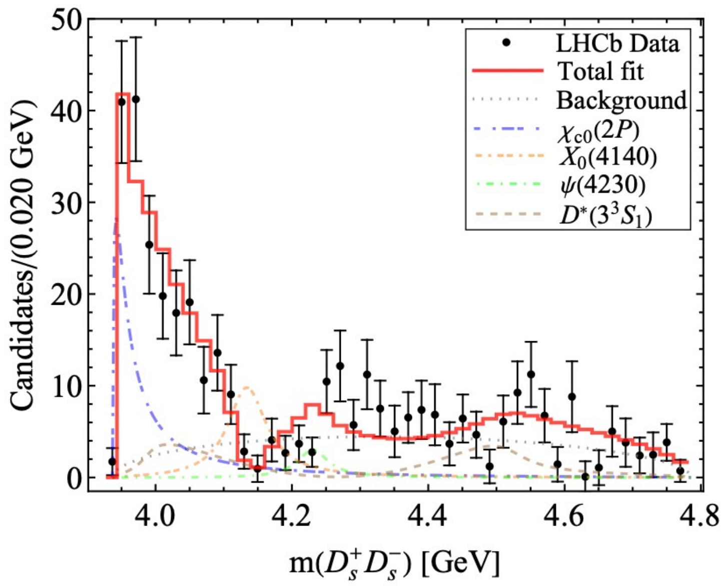
$X(3960)$ and $\chi_{c0}(3915)$ are the same $D_s^+ D_s^-$ bound state.

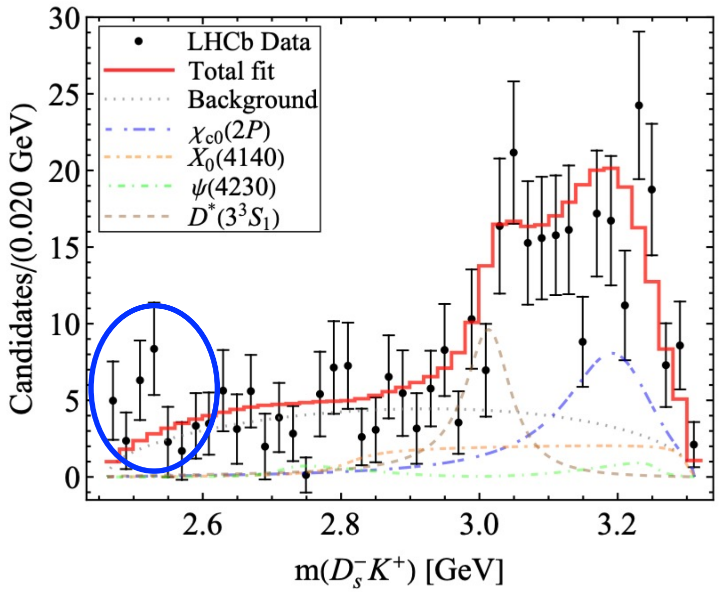
$X(3960)$ as the same as $\chi_{c0}(3915)$

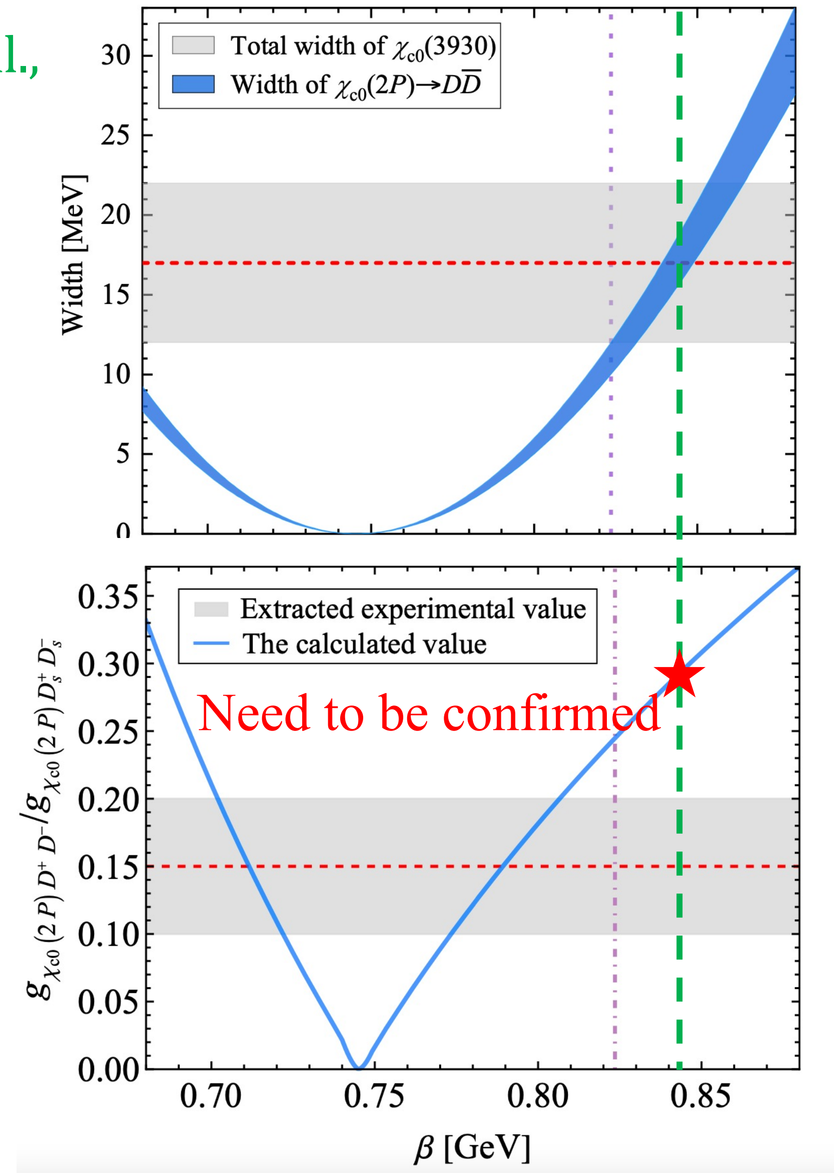
$\chi_{c0}(2P)$

2. Conventional $\chi_{c0}(2P)$ state [Dian-Yong Chen, Xiang Liu, et al., PRD 106 (2022) 094037]

- Quark pair creation model
- Considering node effect of spatial wave function of $\chi_{c0}(2P)$
- Expected to calculate partial widths !



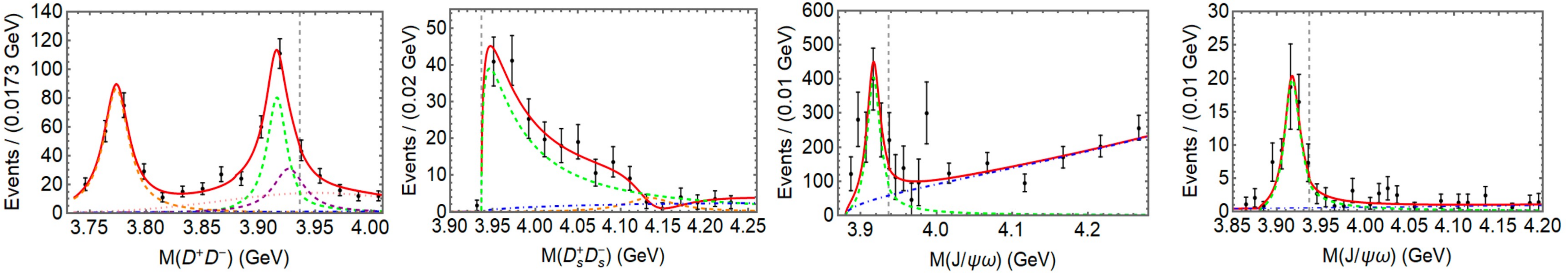




$X(3960)$ as the same as $\chi_{c0}(3915)$

3. $c\bar{c} + D_s^+ D_s^-$ mixture [Han-Qing Zheng et al., 2302.06278]

- K-matrix approach of $D_{(s)}\bar{D}_{(s)}$ four-point contact interactions → applied pole counting rule, only one pole on Sheet II, $\sqrt{s} = 3.9207 - 0.0129i$, tends to be $D_s^+ D_s^-$ molecule.
- Flatte-like parameterizations → pole counting rule, two ploes on Sheets III and VII, $\sqrt{s} = 3.9163 - 0.0107i$, $3.8986 - 0.0108i$, tends to be confining state
- Spectral density function sum rule $\mathcal{Z} \sim 0.5$ → may be a mixture of $c\bar{c} + D_s^+ D_s^-$ (but large errs. of g_i)



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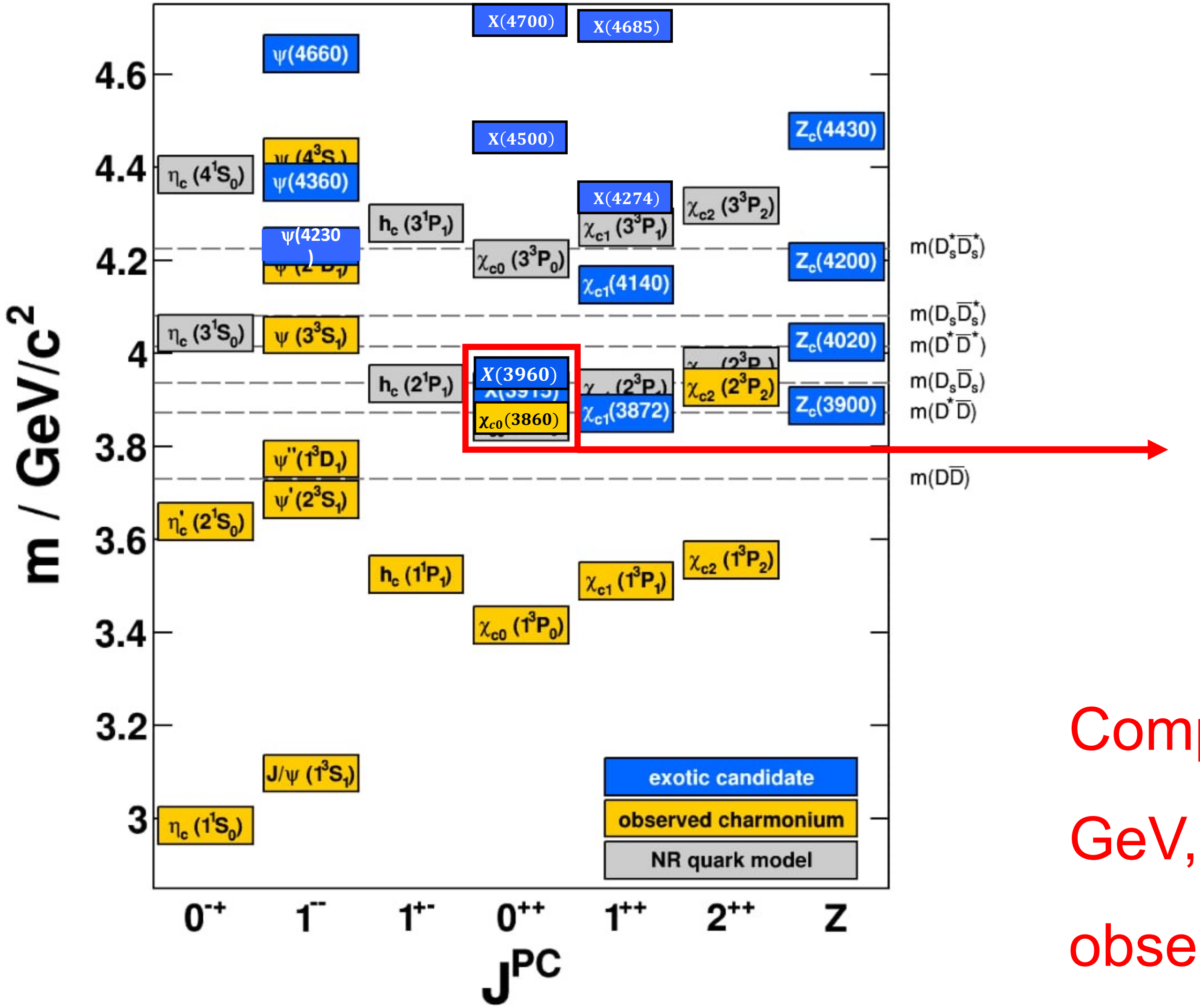
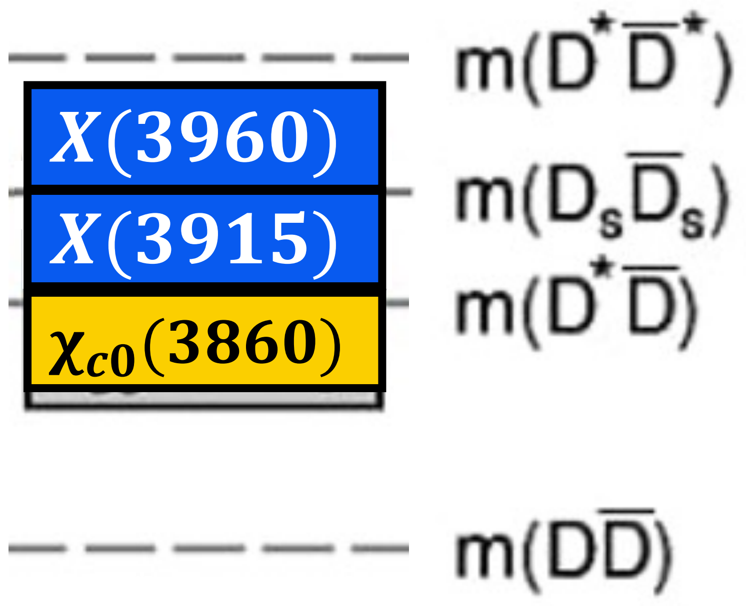
Charmonium spectroscopy

$c\bar{c}$





Complex charmonium spectra around 3.9 GeV, who is the real $\chi_{c0}(2P)$? Is the new-observed $X(3960)$ the $\chi_{c0}(2P)$ candidate?

Potential models for ^3P_J spectroscopy

$\chi_{cJ}(nP)$

Table from arXiv: 2302.06278

State		EXP	GIM	CPM	nRM	RPM	RnPM	SPM	GEM
1^3P_0	$\chi_{c0}(1P)$	3414.71 ± 0.30	3445	3441	3424	3415.7	3415.2	3433	3430
1^3P_1	$\chi_{c1}(1P)$	3510.67 ± 0.05	3510	3520	3505	3508.2	3510.6	3510	3491
1^3P_2	$\chi_{c2}(2P)$	3556.17 ± 0.07	3550	3565	3556	3557.7	3556.2	3554	3523
2^3P_0	$\chi_{c0}(3860)$ $\chi_{c0}(3915)$	3862^{+48}_{-35} 3921.7 ± 1.8	3916	3915	3852	3843.7	3864.3	3842	3868
2^3P_1	$\chi_{c1}(3872)$	3871.65 ± 0.06	3953	3875	3925	3939.7	3950.0	3901	3911
2^3P_2	$\chi_{c2}(3930)$	3922.5 ± 1.0	3979	3966	3972	3993.7	3992.3	3937	3935
3^3P_0			4292		4202			4131	4172
3^3P_1			4317		4271			4178	4204
3^3P_2			4337		4317			4208	4222

- **Far away from the predicted $\chi_{c0}(3P)$ mass, $X(3960)$ shouldn't be $\chi_{c0}(3P)$.**

Potential models for the $\chi_{cJ}(2P)$ states

State		EXP	GIM	CPM	nRM	RPM	RnPM	SPM	GEM
	$\chi_{c0}(3860)$	3862^{+48}_{-35}							
2^3P_0	$\chi_{c0}(3915)$	3921.7 ± 1.8	3916	3915	3852	3843.7	3864.3	3842	3868
	$X(3960)$	3956 ± 12							
2^3P_1	$\chi_{c1}(3872)$	3871.65 ± 0.06	3953	3875	3925	3939.7	3950.0	3901	3911
2^3P_2	$\chi_{c2}(3930)$	3922.5 ± 1.0	3979	3966	3972	3993.7	3992.3	3937	3935

Coupled-channel and screened potential model

[Bai-Qing Li, Ce Meng, and Kuang-Ta Chao, PRD80 (2009) 014012]

In our calculation the contributions to the mass shifts from the $D_s^{(*)}\bar{D}_s^{(*)}$ channels are small mainly due to the small strange quark pair creation strength γ_s.

It is expected to recalculate ^3P_J charmonia with considering coupled-channel $D_s^{(*)}\bar{D}_s^{(*)}$ effects, as well as partial widths $(D\bar{D}, D_s^+D_s^-, \omega J/\psi, \eta^{(\prime)}\eta_c, \pi\pi\chi_{c0}, \ldots)$.

$X(3960)/\chi_{c0}(3915)$ as $\chi_{c0}(2P)$?

State		EXP	GIM	CPM	nRM	RPM	RnPM	SPM	GEM
	$\chi_{c0}(3860)$	3862^{+48}_{-35}							
2^3P_0	$\chi_{c0}(3915)$	3921.7 ± 1.8	3916	3915	3852	3843.7	3864.3	3842	3868
	$X(3960)$	3956 ± 12							
2^3P_1	$\chi_{c1}(3872)$	3871.65 ± 0.06	3953	3875	3925	3939.7	3950.0	3901	3911
2^3P_2	$\chi_{c2}(3930)$	3922.5 ± 1.0	3979	3966	3972	3993.7	3992.3	3937	3935

It will encounter troubles as follows

- Controversial $\chi_{c0}(2P)$'s mass
- Too small mass splitting, $M[\chi_{c2}(3930)] - M[X(3960)]$ <1 MeV, but theories > 60 MeV
- Huge OZI-suppressed partial wave (>1 MeV) [PRD86(2012) 091501]
- Awkward position of $\chi_{c0}(3860)$

Potential models for excited χ_{c0} states

$\chi_{c0}(2P)$

PRD95, 112003 (2017)

$\chi_{c0}(3860) \to D^+D^- + D^0\bar{D}^0$
in $e^+e^- \to J/\psi D\bar{D}$ decay

$M = 3862^{+26}_{-32}{}^{+40}_{-13}$ MeV

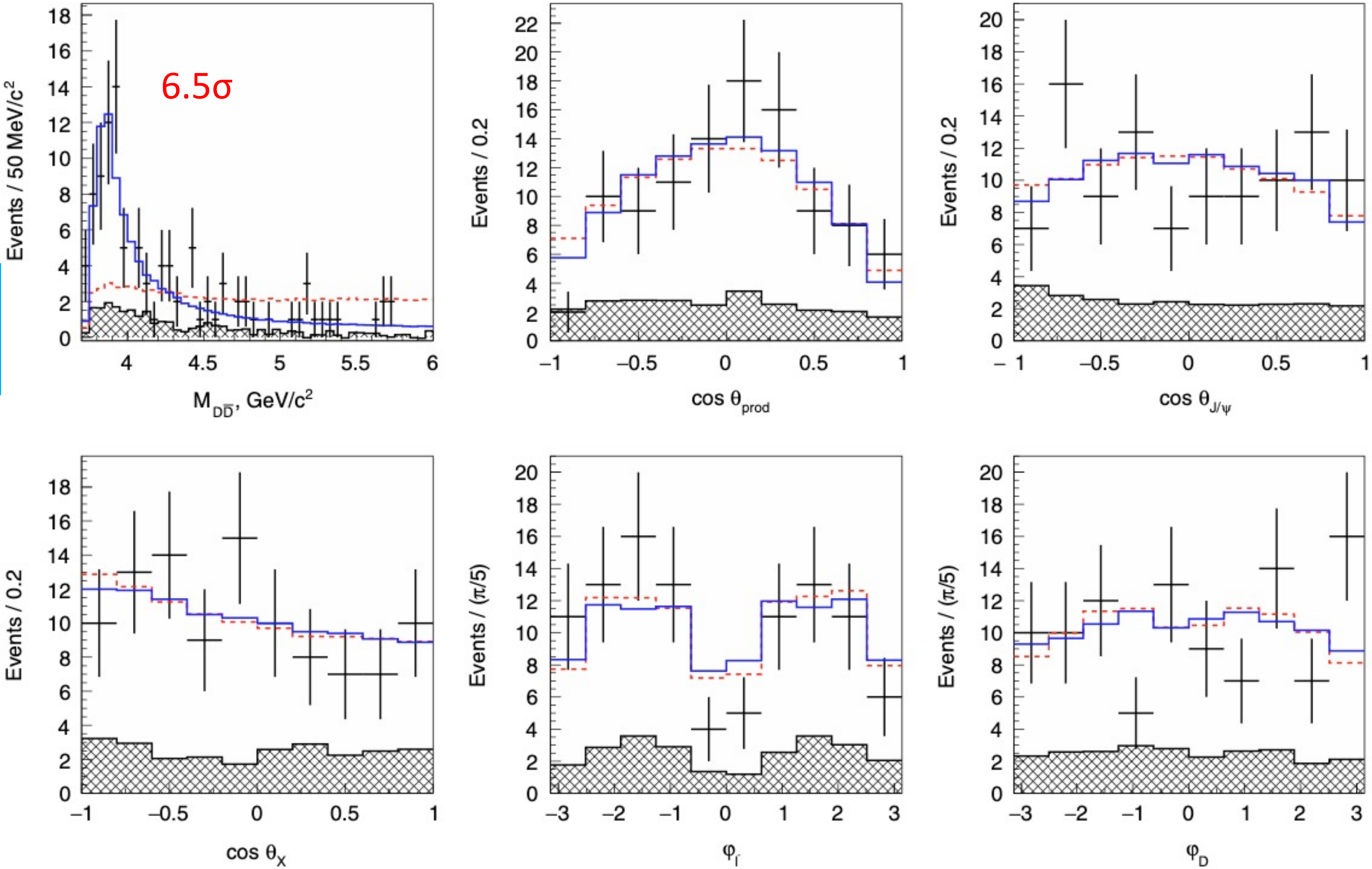
$\Gamma = 201^{+154}_{-67}{}^{+88}_{-82}$ MeV

0^{++} over 2^{++}, 2.5σ

Blue line: $\chi_{c0}(3860)$

Red dashed line: NR only

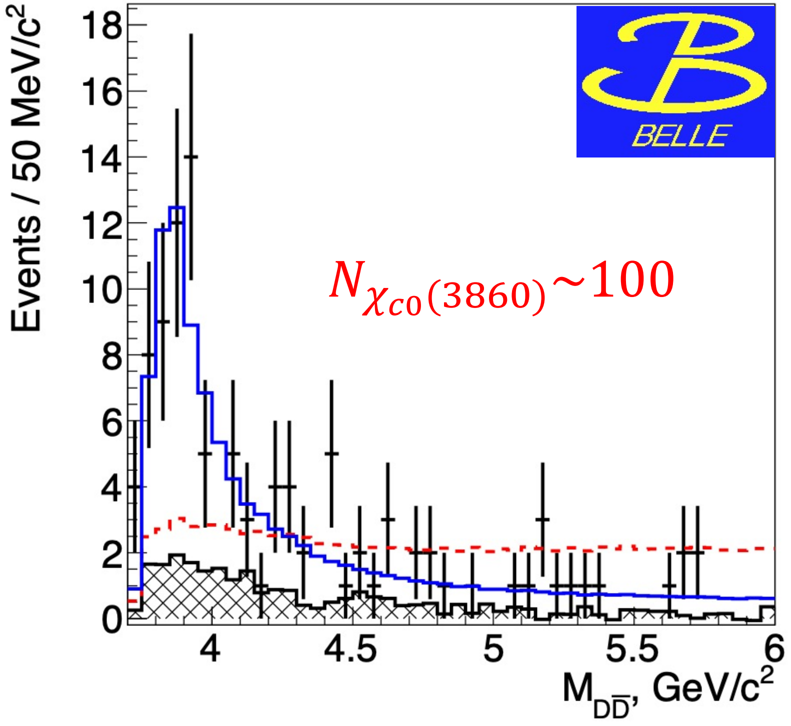
Need to be confirmed !



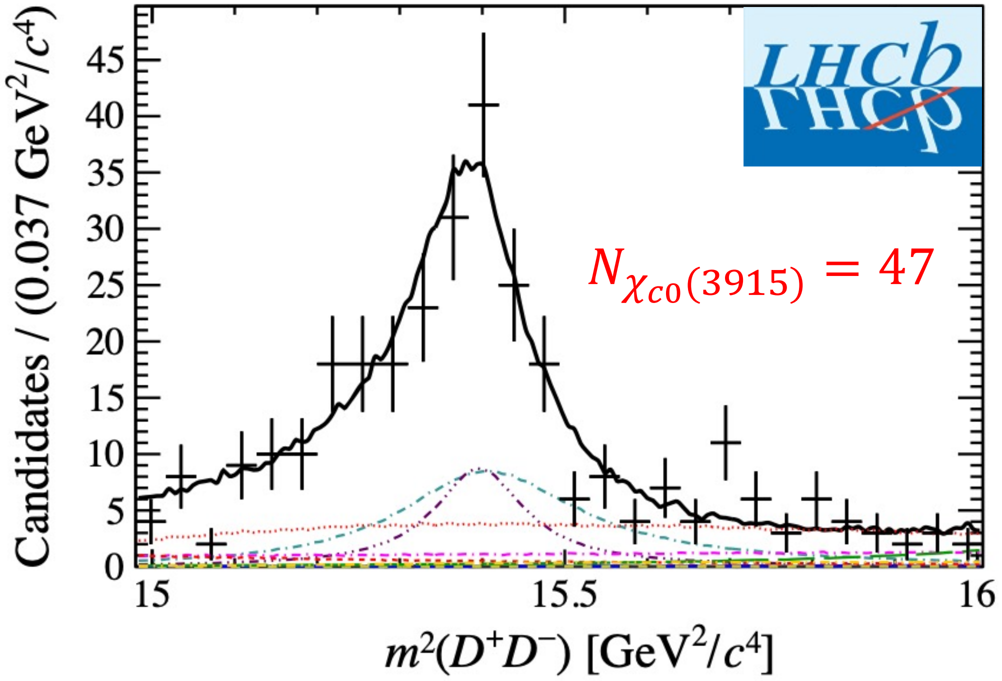
Potential models for excited χ_{c0} states

$\chi_{c0}(2P)$

PRD95, 112003 (2017)



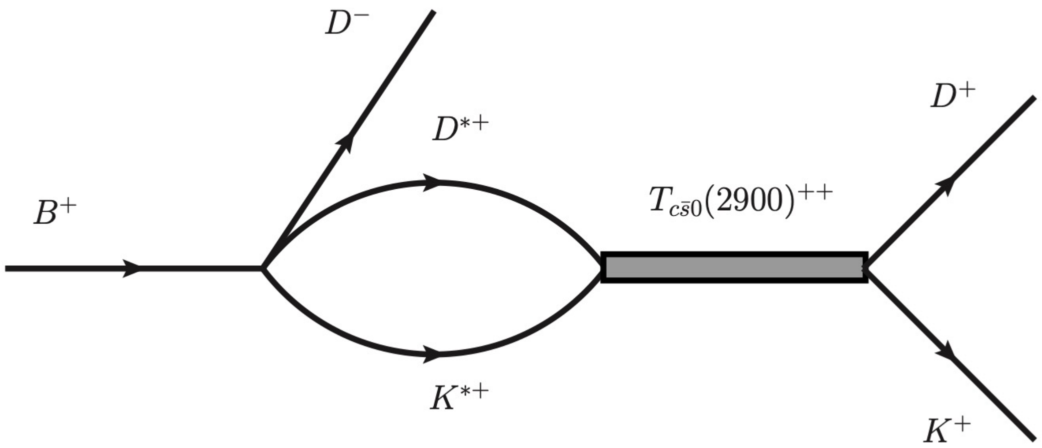
PRD 102, 112003 (2020)

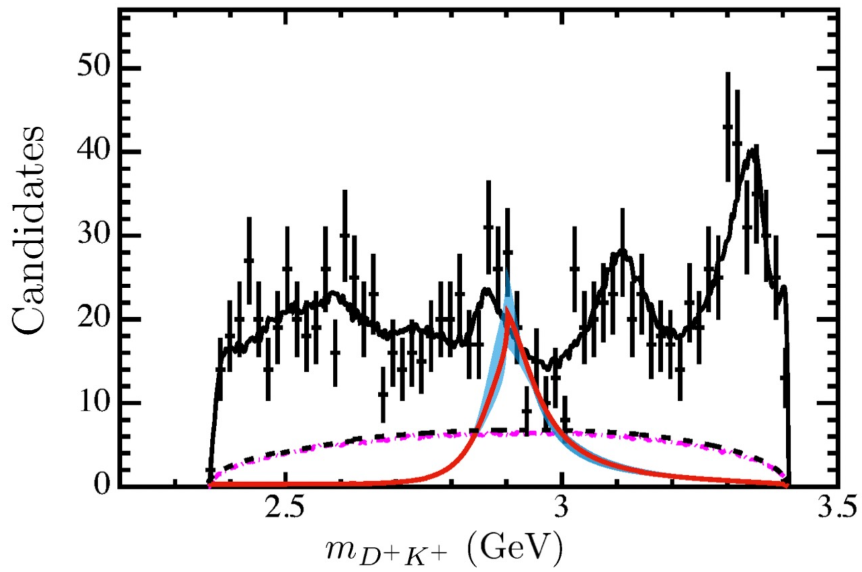


It is unreasonable to believe that the LHCb experiment with "high statistics" exclude the existence of $\chi_{c0}(3860)$!

Need to improve $\Gamma[\chi_{c0}(3915) \to D^+D^-]$

arXiv:2305.09436



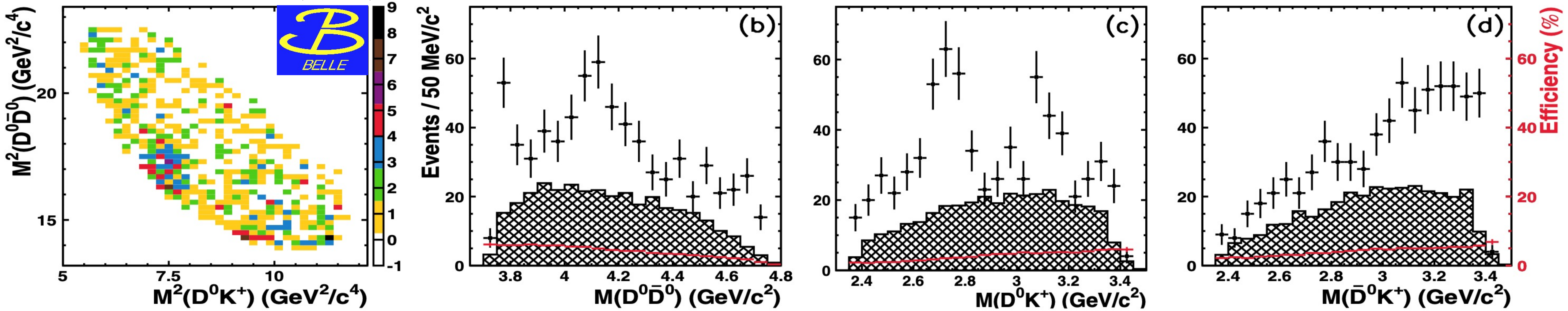


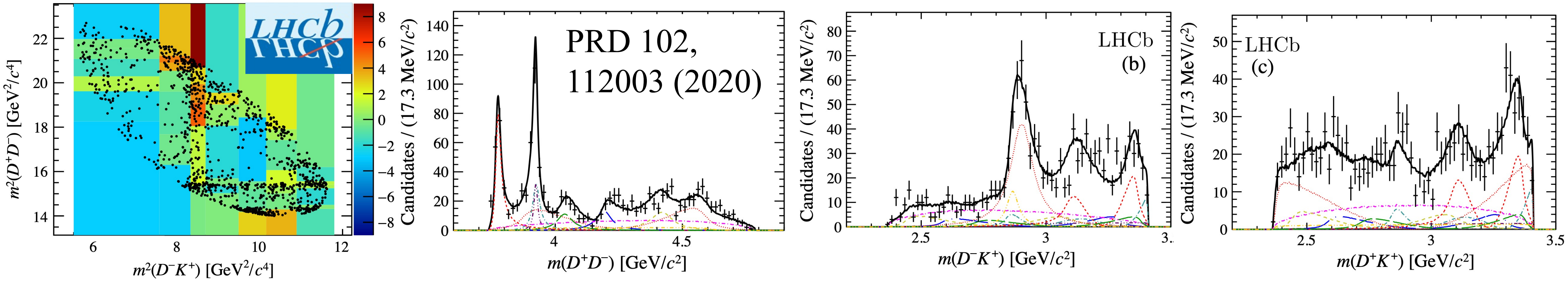
The fit fraction of $T_{c\bar{s}0}(2900)^{++} \to D^+K^+$ is estimated to be ~12.5%, so that the fit fractions of $\chi_{c0}(3915)$ and $\chi_{c2}(3930)$ would be much different !

Expected to measure $\Gamma[\chi_{c0}(3915) \rightarrow D^0\bar{D}^0]$

$\chi_{c0}(3915)$

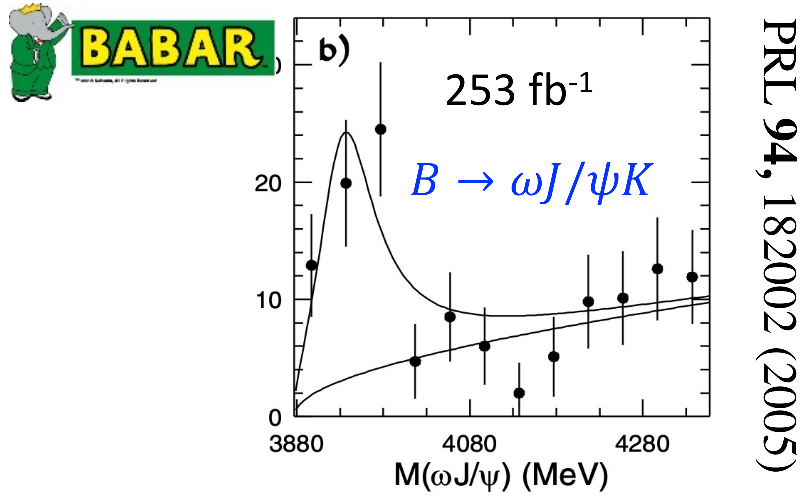
PRL 100, 092001 (2008)

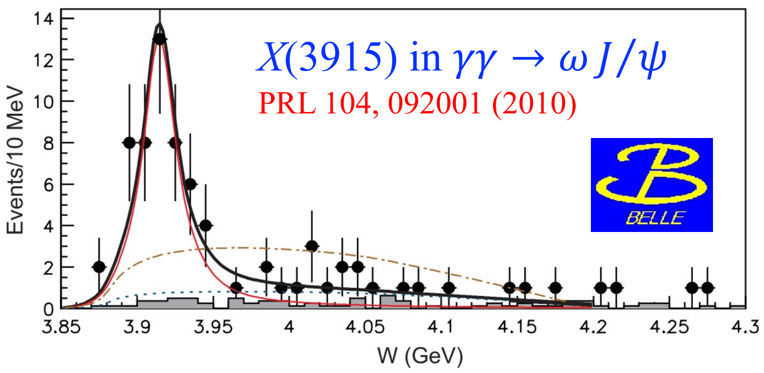


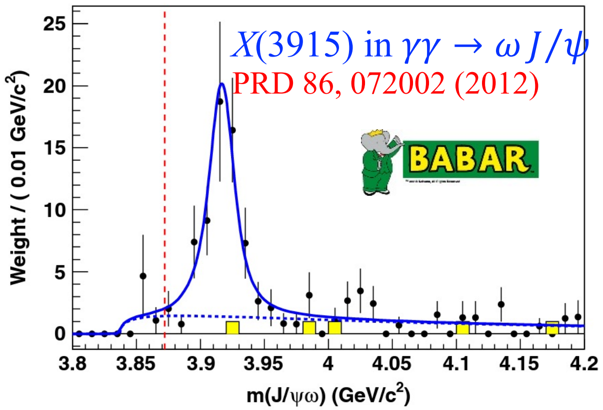


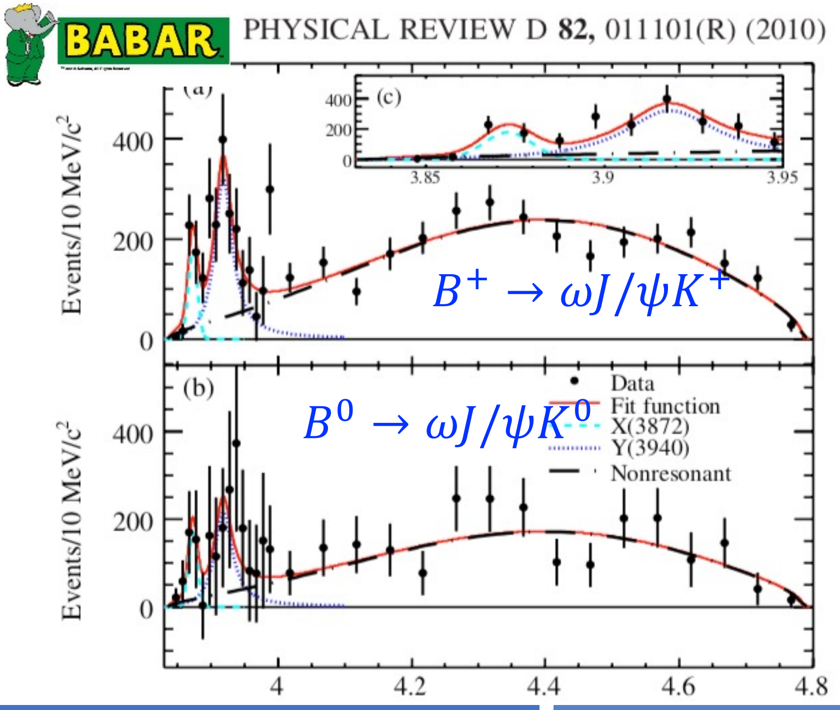
The mass distributions of between $B^+ \rightarrow D^0\bar{D}^0K^+$ and $B^+ \rightarrow D^+D^-K^+$ are different !

$\chi_{c0}(3915)$ and $\chi_{c2}(3930)$

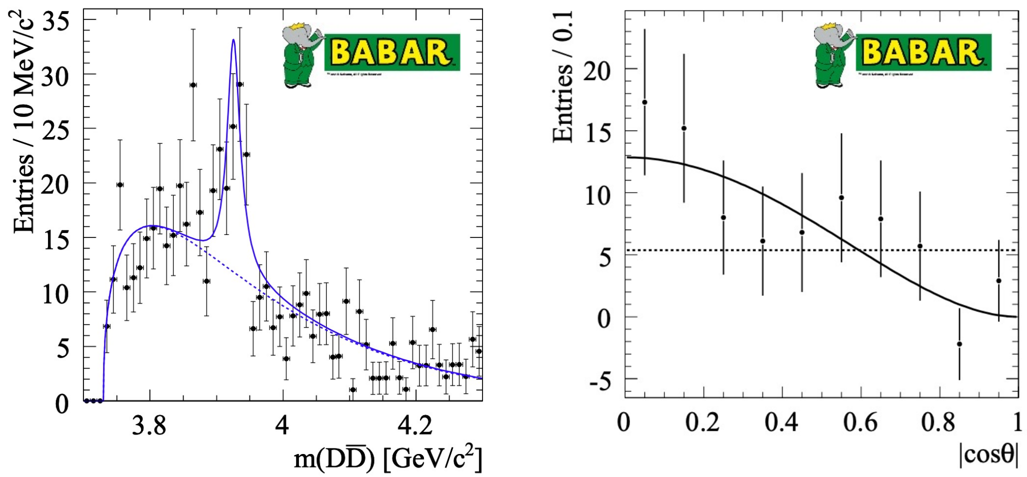






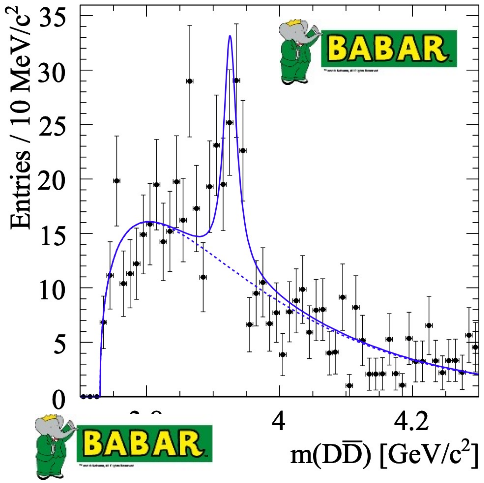


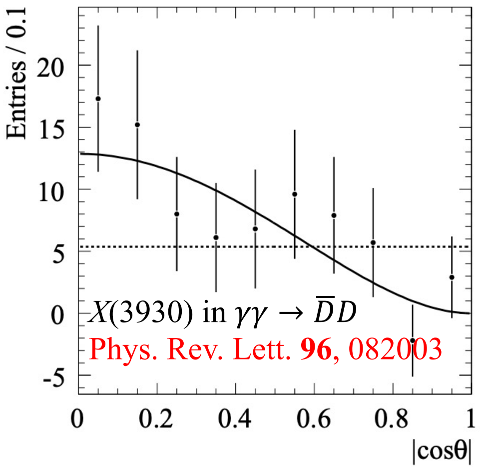
$X(3930)$ in $\gamma\gamma \to \bar{D}D$ [Phys. Rev. Lett. **96**, 082003]



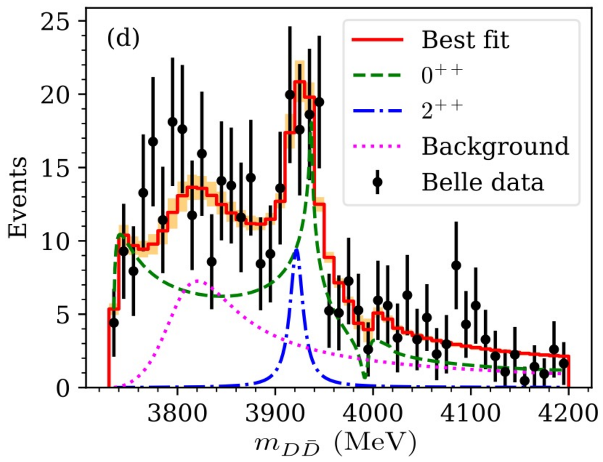
Why are $\chi_{c0}(3915)$ and $\chi_{c2}(3930)$ only observed in $\omega J/\psi$ and $D\bar{D}$ syetems, respectively? No $\chi_{c0}(3915)$ is in $D\bar{D}$ channel?

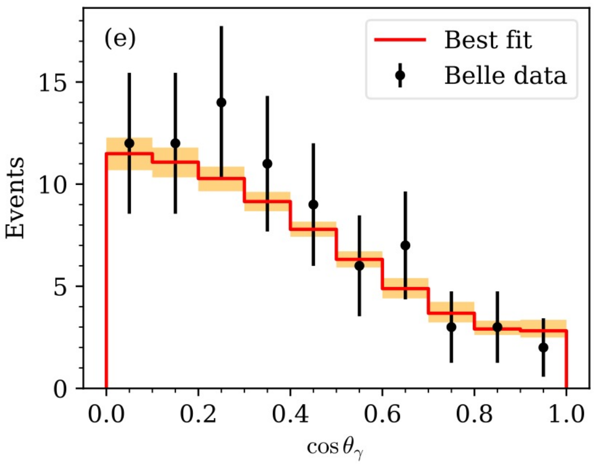
$\chi_{c0}(3915)$ and $\chi_{c2}(3930)$ — $\chi_{c0,2}{}'$





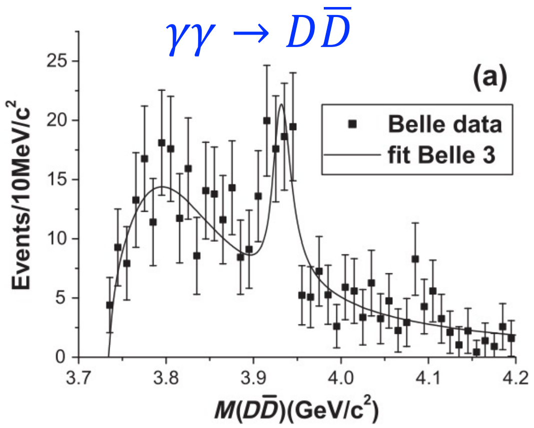
Feng-Kun Guo, Bing-Song Zou et al., Sci.Bull. 68 (2023) 688

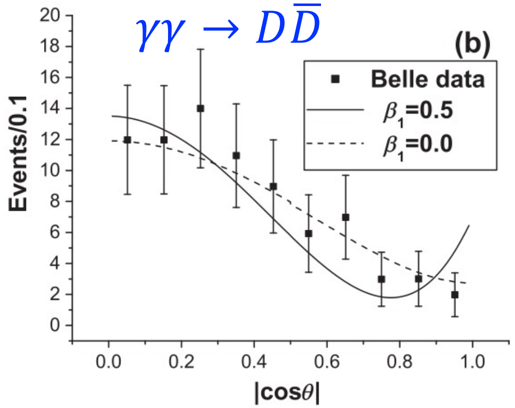


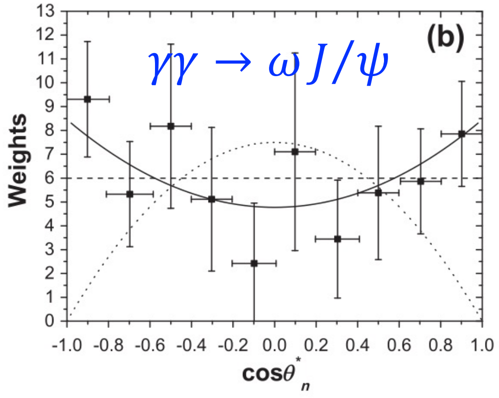


Zhi-Yong Zhou, Zhiguang Xiao, and Hai-Qing Zhou, PRL 115, 022001 (2015)

combined amplitude analysis of the $\gamma\gamma \to D\bar{D}$ and $\gamma\gamma \to J/\psi\omega$ data



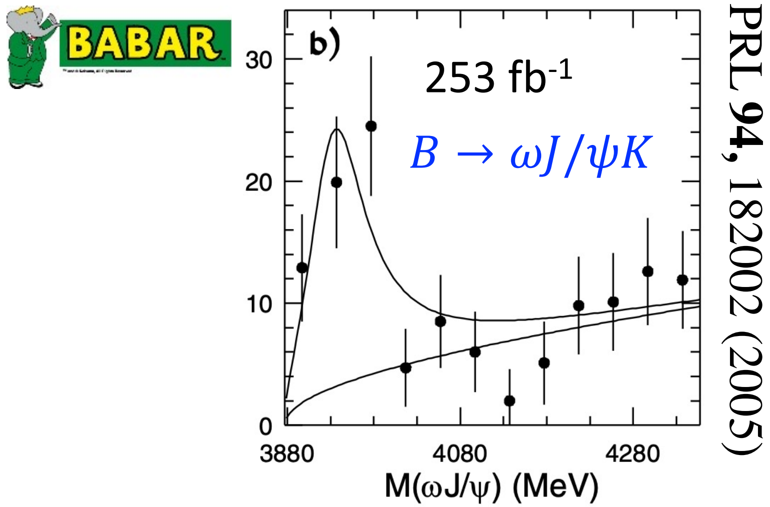


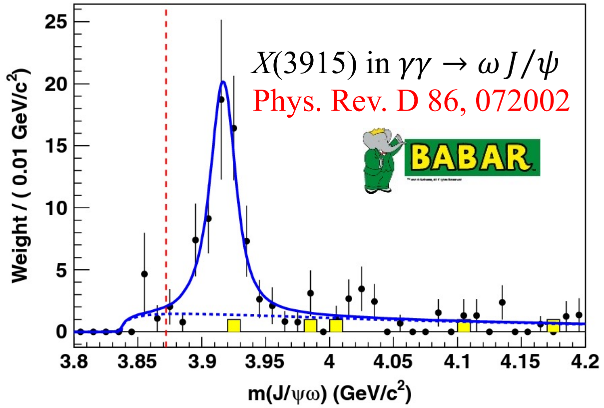


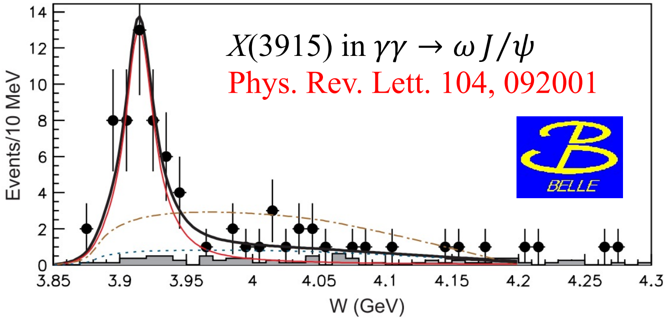
Both channels contain 0^{++} and 2^{++} contributions !

$X(3915)$ peak is a single 0^{++} particle?

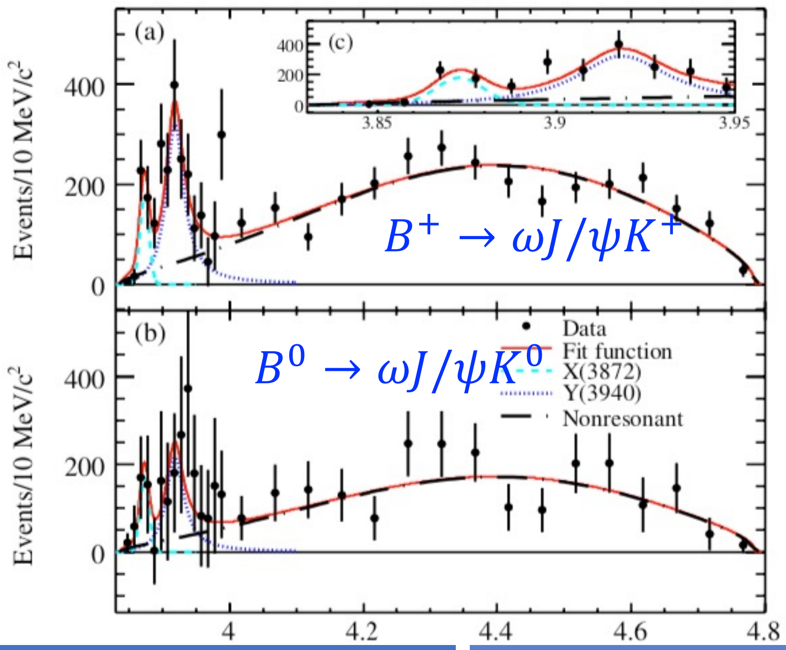
$\chi_{c0}(3915)$



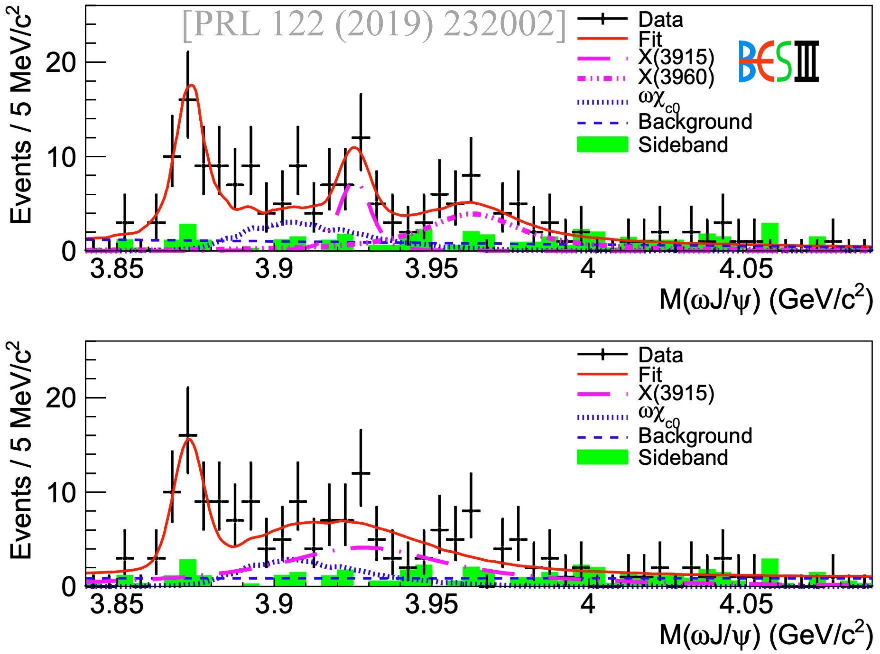




PHYSICAL REVIEW D 82, 011101(R) (2010)



$e^+e^- \to \gamma X$



Need to be confirmed whether or not the peak around 3.92 GeV is a single 0^{++} resonance?

What is nature of $X(3960)/\chi_{c0}(3915)$?

$T^{f}_{\psi\phi}$ or $\chi_{c0}(2P)$

- Hybrid state can be ruled out, due to too low mass for a QCD-hybrid candidate (the lightest 0^{++} charmonium hybrid around 4450 MeV)[1]. ✕

- Lightest $c\bar{c}s\bar{s}$ tetraquark, ~3920 MeV, is proposed by Lebed et al.[2]. The QCD sum rule[3] also favors $\chi_{c0}(3915)$ as a 0^{++} $cq\bar{c}\bar{q}$ or $cs\bar{c}\bar{s}$ tetraquark.

  favour

- Molecular $D_s^+D_s^-$ (virtual) state, is calculated in the quark delocalization color screening model [4]. The recent lattice QCD results[5] found a narrow 0^{++} $D_s^+D_s^-$ bound state. Some phenomenological studies[6] regard it as the molecular (virtual) state.

  favour

- $c\bar{c}$ mixed with exotic components, such as Ref.[7,8]

  favour

[1] arXiv:1204.5425. [2] arXiv:1602.08421, 2005.07100. [3]arXiv:1706.09731. [4] arXiv: 2103.12425.
[5] arXiv:2011.02542, 2111.02934. [6]arXiv: 1503.04431, 2101.01021. [7]arXiv: 2302.06278. [8]arXiv:2303.15388.

What is nature of $X(3960)/\chi_{c0}(3915)$?

$\chi_{c0}(2P)$ puzzle

	nature	mass	(partial) width	OZI rule	Other
$X(3960)$ as a new hadron	$D_s^+ D_s^-$ molecule	✓	**?**	✓	N/A
	$c\bar{c}s\bar{s}$ tetraquark	**?**	?	✓	N/A
$X(3960)$ = $\chi_{c0}(3915)$	hybrid	X	?	?	N/A
	$D_s^+ D_s^-$ molecule	✓	?	?	N/A
	$c\bar{c}q\bar{q}$ tetraquark	?	?	✓	N/A
	charmoninum $\chi_{c0}(2P)$	**?**	**?**	X	$\chi_{c0}(3860)'s$ problem
	$c\bar{c} + D_s^+ D_s^-$	**?**	**?**	?	$\chi_{c0}(3860)'s$ problem

✓: **favor**
X: **disfavor**
? : **uncertain/unkown, need to be confirmed/observed**

$X(3960)/\chi_{c0}(3915)$ can be searched for or precisely studied:

$Br(B^+ \to XK^+)\times\Gamma(X \to D^+D^-) = (8.1 \pm 3.3)\times 10^{-6}$

$Br(B^+ \to XK^+)\times\Gamma(X \to D_s^+D_s^-) = 2.4\times 10^{-5}$

$Br(B^+ \to XK^+)\times\Gamma(X \to \omega J/\psi) = (3.0 \pm 0.9)\times 10^{-5}$

$X(3960)/\chi_{c0}(3915)$ →

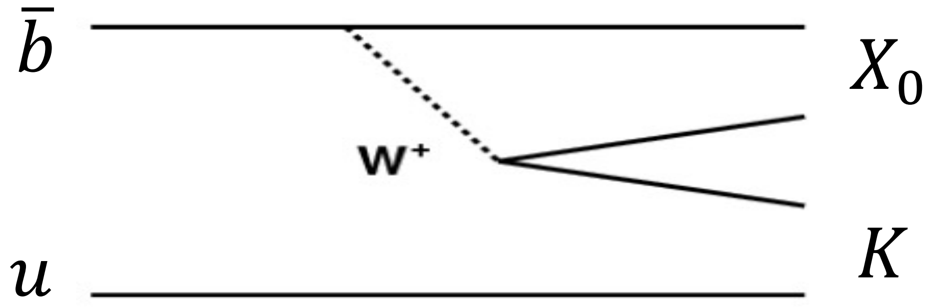
- $D^+D^- + D^0\bar{D}^0$
- $D_s^+D_s^-$
- $\omega J/\psi$ $\left(\Gamma_{\omega J/\psi} > 1\text{MeV}\right)$?
- $\eta^{(\prime)}\eta_c$
- $\pi\pi\chi_{c0}$
- $(\pi\pi)_2\chi_{c2}$
- $\gamma\psi \to [J/\psi, \psi(3686), \psi(3770)]$
- $\gamma D^{(*)}\bar{D}$
- $\gamma D_s^+D_s^-$

(first three channels: ~3 MeV?; D^+D^- through $\gamma\psi$: S wave; $\gamma D^{(*)}\bar{D}$, $\gamma D_s^+D_s^-$: P wave)

Calculations and measurements on partial widths are most important!

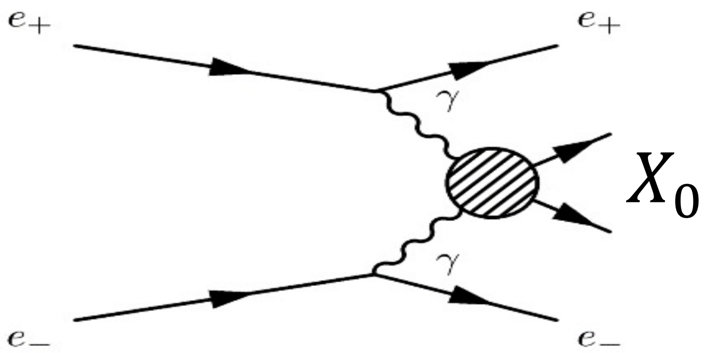
See also arXiv: 2302.06278.

From B decays:



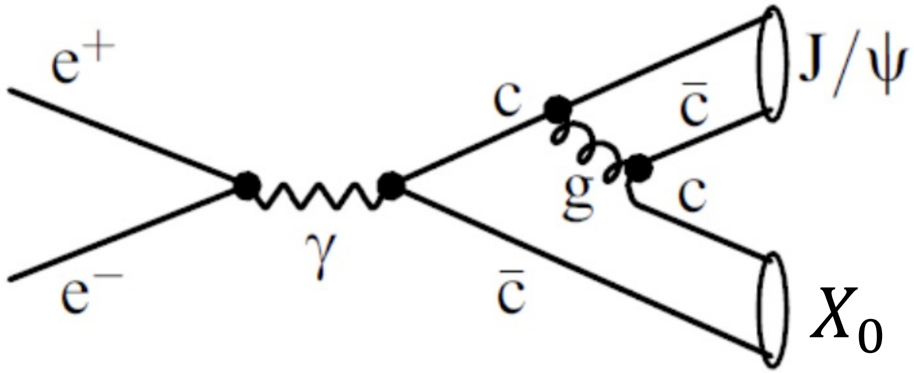
- $B^{+,0} \to D^+D^-K^{+,0}$ → $\chi_{c0}(3860)$, $\chi_{c0}(3915)/X(3960)$ [LHCb, Belle2]
- $B^{+,0} \to D^0\bar{D}^0K^{+,0}$ → Confirmed results from c.c. mode [LHCb, Belle2]
- $B \to D_s^+D_s^-K$ → Precise M&Γ of $X(3960)$ [LHCb, Belle2]
- $B \to \omega J/\psi K$ → J^{PC} of X_0, $\Gamma(\omega J/\psi)/\Gamma(D_{(s)}\bar{D}_{(s)})$ [LHCb, Belle2]
- $B \to \pi\pi\chi_{c0,2}K$ → First search for these states [LHCb, Belle2]
- $B \to \gamma\psi K$ → First search for these states [LHCb, Belle2]

From two-photon processes:



$\gamma\gamma \to D\bar{D}$	$\to \chi_{c0}(3860), \chi_{c0}(3915)/X(3960)$	[Belle2]
$\gamma\gamma \to D_s^+ D_s^-$	$\to$ Search for $X(3960), X_0(4140)$	[Belle2]
$\gamma\gamma \to \omega J/\psi$	$\to \chi_{c0}(3860), \chi_{c0}(3915)/X(3960)$	[Belle2]
$\gamma\gamma \to \eta^{(\prime)}\eta_c$	$\to$ First search for these states	[Belle2]
$\gamma\gamma \to \pi\pi\chi_{c0,2}K$	$\to$ First search for these states	[Belle2]
$\gamma\gamma \to \gamma\psi$	$\to$ (First) search for these states	[Belle2]

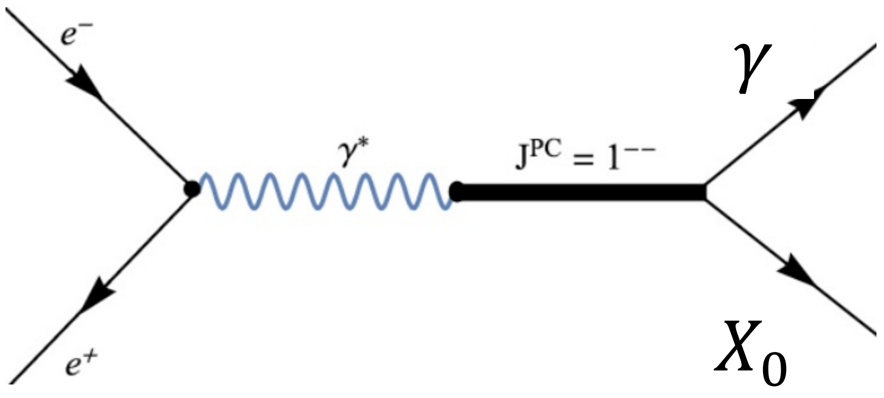
From double $c\bar{c}$ production:



- $e^+e^- \to J/\psi D\bar{D}$ → $\chi_{c0}(3860)$, $\chi_{c0}(3915)/X(3960)$ [Belle2]
- $e^+e^- \to J/\psi D_s^+ D_s^-$ → Search for $X(3960)$, $X_0(4140)$ [Belle2]
- $e^+e^- \to J/\psi\pi\pi\chi_{c0,2}$ → First search for these states [Belle2]
- $e^+e^- \to J/\psi\eta^{(\prime)}\eta_c$ → First search for these states [Belle2]
- $e^+e^- \to J/\psi\psi\gamma$ → First search for these states [Belle2]
- $e^+e^- \to J\psi\gamma DD_{miss}^{(*)}$ → First search for these states [Belle2]

From (ISR) radiative processes:

BESIII / Belle2



$$e^+e^- \to \begin{pmatrix} \gamma \\ \omega \\ \phi \\ 3\pi \\ K^*\bar{K} \end{pmatrix} \times \begin{pmatrix} D\bar{D} \\ D_s^+D_s^- \\ J/\psi\omega \\ \pi\pi\chi_{c0,2} \\ \eta^{(\prime)}\eta_c \\ \gamma\psi \\ \gamma D^{(*)}\bar{D} \\ \gamma D_s^+D_s^- \end{pmatrix}$$

Summary of $X(3960)$

◆ Branching fraction ratio

- First observation of the $B^+ \to D_s^+ D_s^- K^+$ decay
- Relative branching fraction is measured

$$\mathcal{R} = \frac{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)}{\mathcal{B}(B^+ \to D^+ D^- K^+)} = 0.525 \pm 0.033\,(\text{stat}) \pm 0.027\,(\text{syst}) \pm 0.034\,(\text{ext})$$

◆ Amplitude analysis

- First observation of the $D_s^+ D_s^-$ near-threshold structure, named $X(3960)$
- Favor exotic $c\bar{c}s\bar{s}$ state, disfavor $\chi_{c0}(2P)/\chi_{c0}(3P)$; if confirmed, should name $T_{\psi\phi}^{f}(3960)$
- New X(3960) : $M_0 = 3956 \pm 5 \pm 11$ MeV, $\Gamma_0 = 43 \pm 13 \pm 8$ MeV , $\mathcal{S} > 12\sigma$

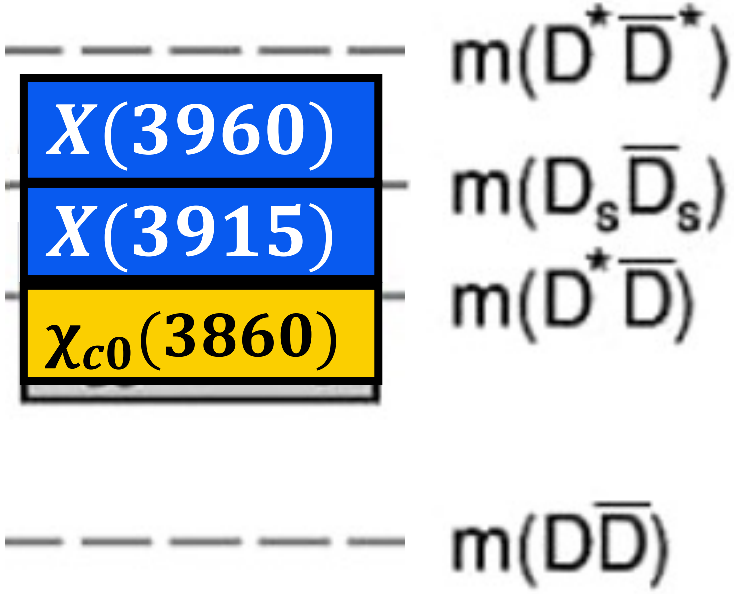
  $J^{PC} = 0^{++}$ over $1^{--}/2^{++}$, $\mathcal{S} > 9\sigma$
- New $X_0(4140)$: only a hint ($<4\sigma$), need to more statistics to confirm
- More experimental and theoretical efforts are needed to clarify the nature of states around 3.9 GeV

Light of Hope

JHEP 06 (2021) 035

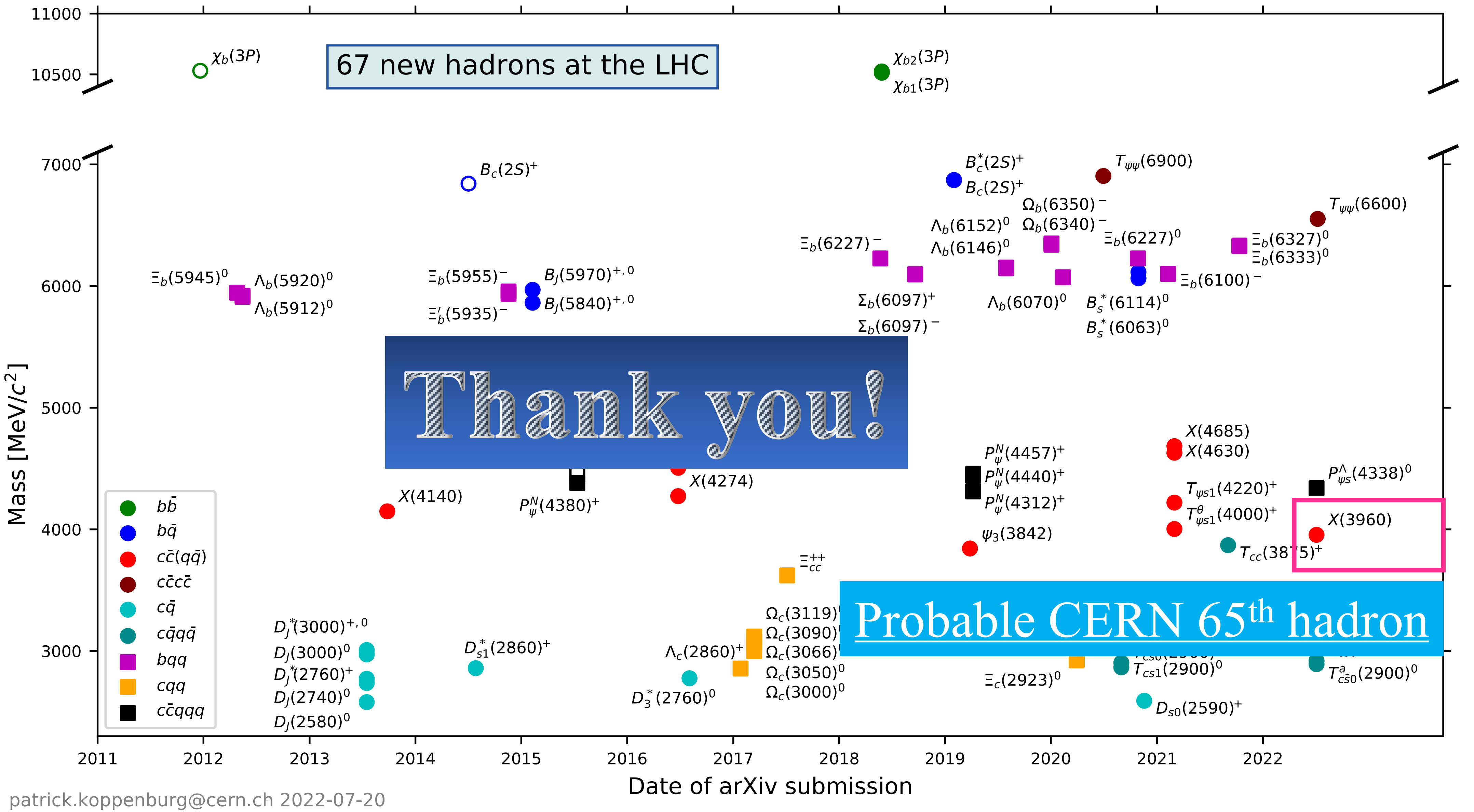
- Lattice QCD suggests existence of three 0^{++} charmonium-like states from $m(D\bar{D})$ and 4.13 GeV
  - $D\bar{D}$ bound state just below threshold
  - $D\bar{D}$ resonance likely related to $\chi_{c0}(3860)$
  - a narrow resonance below $D_s^+ D_s^-$ threshold

- But there are still two issues:
  - $D\bar{D}$ bound state is expected to be discovered
  - $\chi_{c0}(3915)$ and $X(3960)$ should be the same state in future high statistics



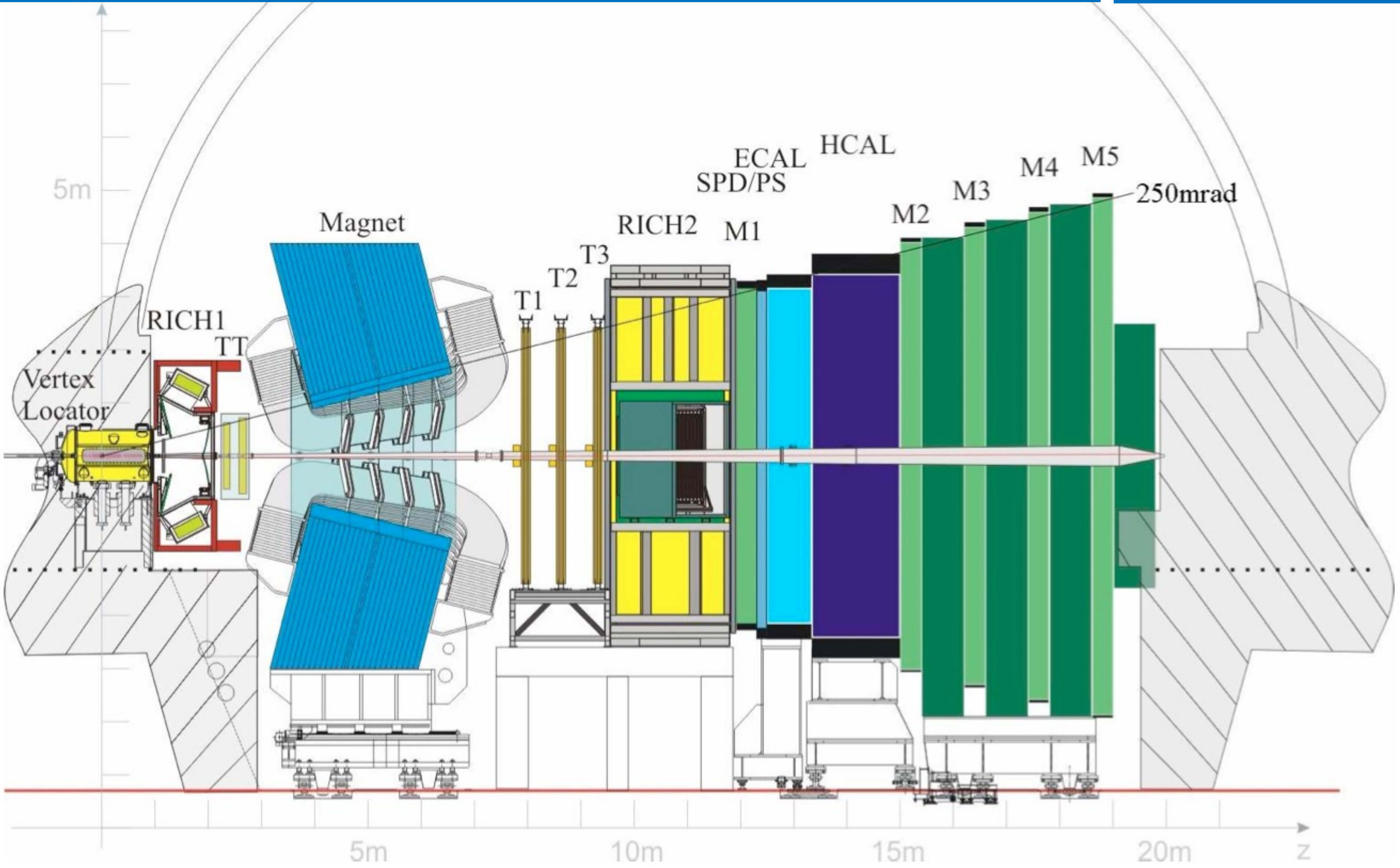
Painted eggshell

CERN 65th hadron



Back Up

LHCb detector



LHCb detector

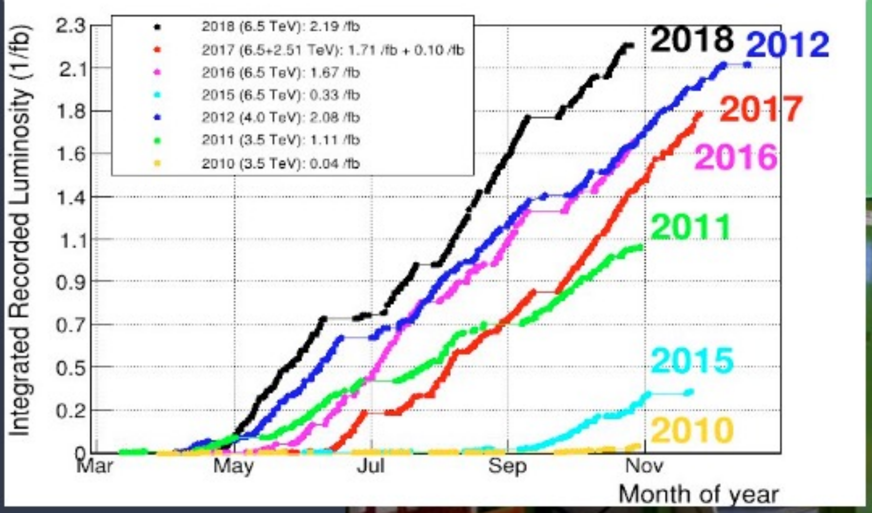
[JINST 3 (2008) S08005](#)
IJMP A 30, 1530022 (2015)

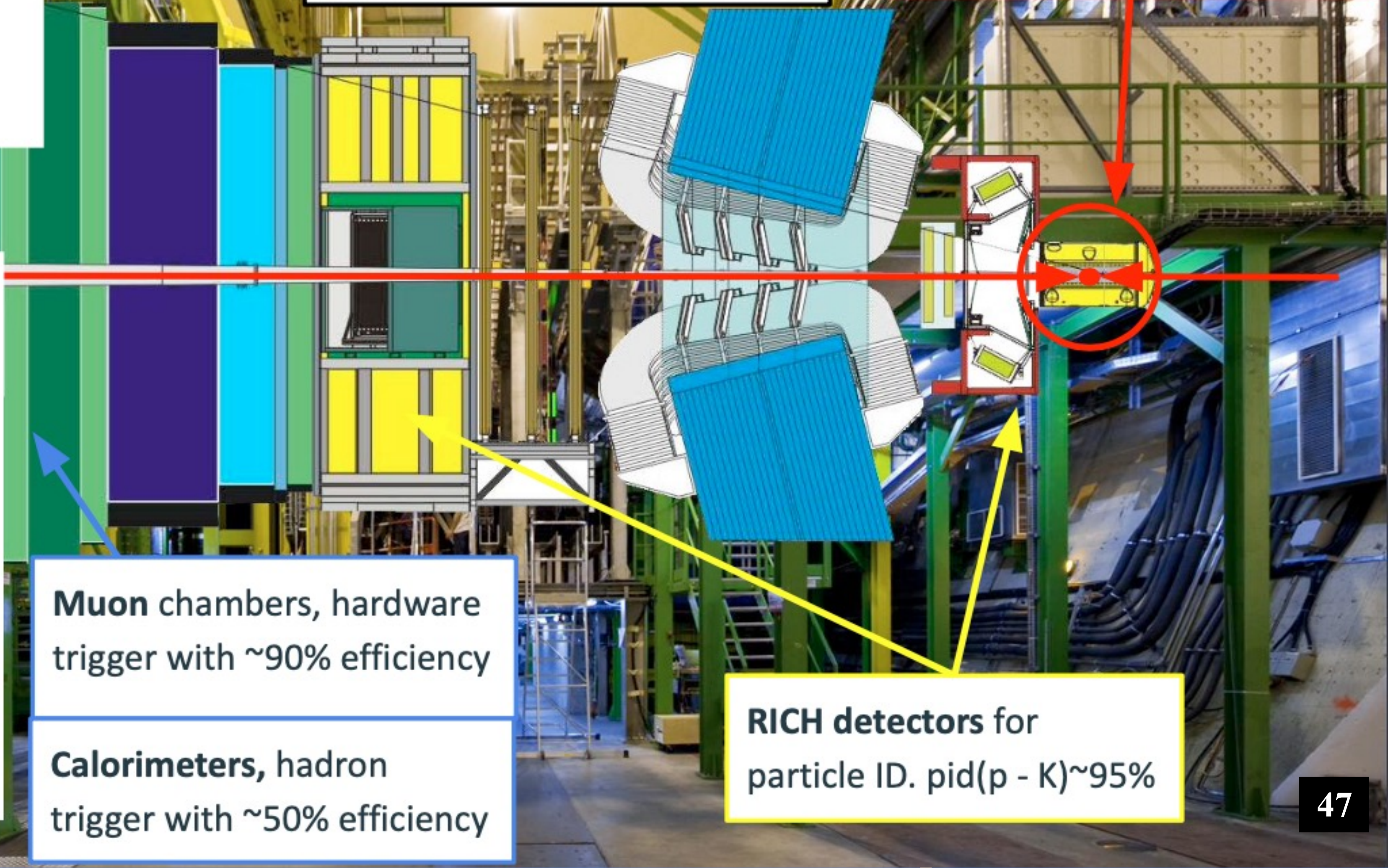
10 mrad to 250 (300) mrad (about 15°) in the vertical (horizontal)

The major player in spectroscopy thanks to its unique dedicated design

- high invariant mass resolution
- PID for separate K, π, p
- highly performant trigger

Luminosity:
Run 1 and Run 2: 9 fb^{-1}





Tracking: momentum resolution of $\sigma_p / p \sim 0{,}5 - 1\%$

VELO: vertex detector
IP resolution: ~25 μm

Muon chambers, hardware trigger with ~90% efficiency

Calorimeters, hadron trigger with ~50% efficiency

RICH detectors for particle ID. pid(p - K)~95%