Quarkonium studies at LHCb

Vanya Belyaev (ITEP,Moscow) on behalf of LHCb collaboration

Quarkonium studies at LHCb

… highly incomplete list

- ~~Production of J/ψ, $\psi(2S)$, Υ using $\mu^+\mu^-$~~
- ~~Production of $\chi_c(1P)$, $\chi_b(1,2,3P)$ using $(\mu^+\mu^-)\gamma$ and $(\mu^+\mu^-)\gamma_{conv}$~~
- ~~Production of η_c, χ_c,… using $p\bar{p}$ and $\phi\phi$~~
- ~~Quarkonia production in pA, AA, AA', …~~
- Precise measurement of η_c, $\eta_c(2S)$ parameters with $p\bar{p}$ and $\phi\phi$
- Precise measurement of χ_{c1},χ_{c2} parameters with $J/\psi\mu^+\mu^-$ and $\phi\phi$
- Precise measurement of $B(\psi(2S)\to\mu^+\mu^-)$
- Near threshold $D\bar{D}$ spectroscopy:
  - Observation of a new charmonium state
  - Precise parameters of $\chi_{c2}(3930)$ and $\psi(3770)$

Hot!

The first $9 fb^{-1}$ result!

Precise charmonium studies @LHCb

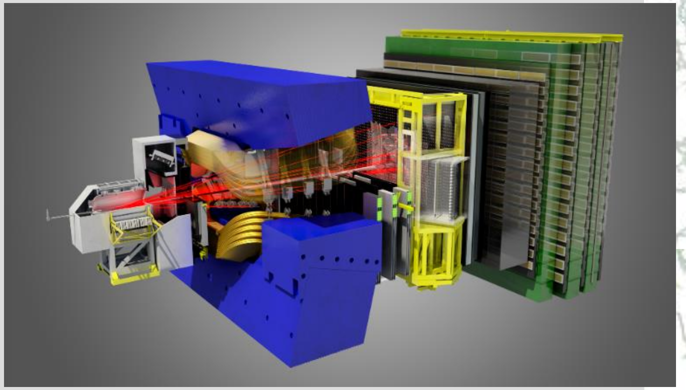
Why (precise) quarkonium studies?

- Many "*exotic*" states from 2002 with not-yet understood nature
  - previous presentations from Belle, BES-III, Belle II and LHCb
- Theory is very prolific in prediction of even more strange objects
  - Various kinds of tetraquarks, moleculas, hadrocharmonia, …
  - "Mixtures" of quarkonia with new beasts, e.g. molecular
- Precise measurements are crucial for interpretation
  - $\chi_{c1}(3872)$ mass (and shape)
- Some states expected in Quark Model are not found yet
  - Crucial and vital issue!
- Without complete and well understood quarkonium basic it is very difficult to judge on the nature of exotic states
- Important for precise B-physics, e.g. understanding of $D\bar{D}$ dynamics (e.g. $\psi(3770)$ shape) for $B \rightarrow D\bar{D}K$ decays (and study of CP violation)

… full list of arguments is "*too large to fit in the margin*"

LHCb is universal detector

... well suited for charmonium studies



- Huge $c\bar{c}$ cross-section:
  - both open and hidden charm
- Powerful trigger:
  - Not only dimuon final state
  - High efficiency for open charm hadrons
    - $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$ and many others
  - for (detached) fully hadronic inclusive b-hadron decays
    - e.g. $b \rightarrow (X \rightarrow p\bar{p})X$ or $b \rightarrow (X \rightarrow \phi\phi)X$, ...
- Particle identification with superb $\pi \leftrightarrow K \leftrightarrow p$ separation
  - crucial for reconstruction of hadronic states

$D\bar{D}$ near-threshold spectroscopy

The first 9fb^{-1} result!

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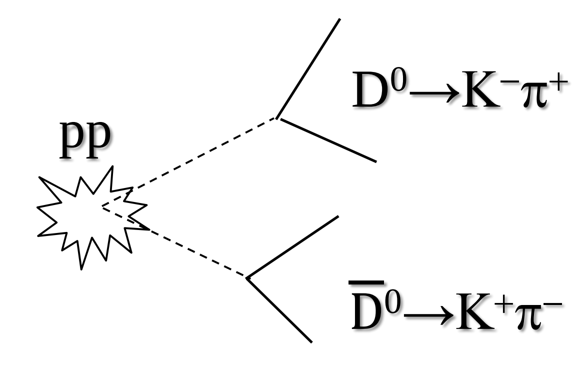


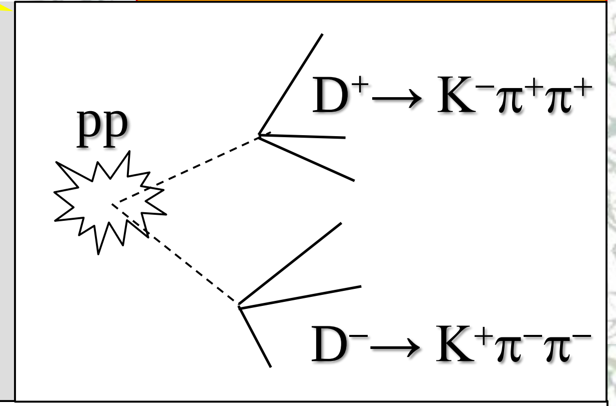
Full LHCb dataset

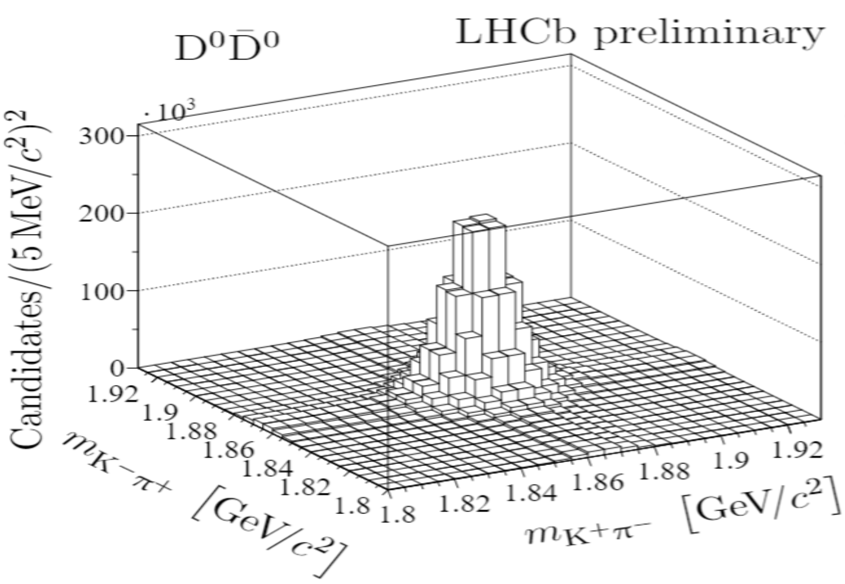
2011-2018 Run I+II 9fb^{-1}

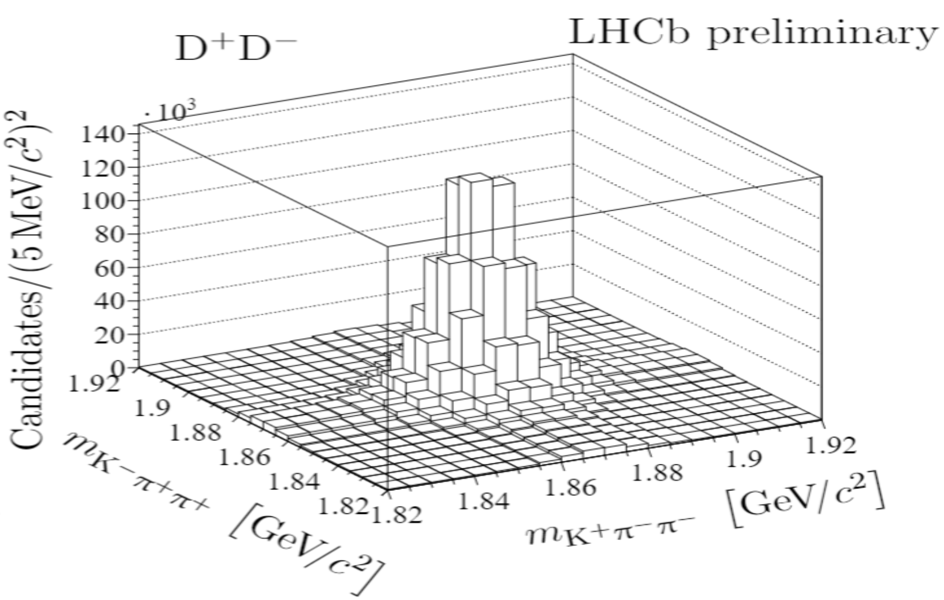
$\sqrt{s}$=7,8&13TeV

3.6M $D^0\bar{D}^0$

2.0M D^+D^-







$D\bar{D}$ mass spectra

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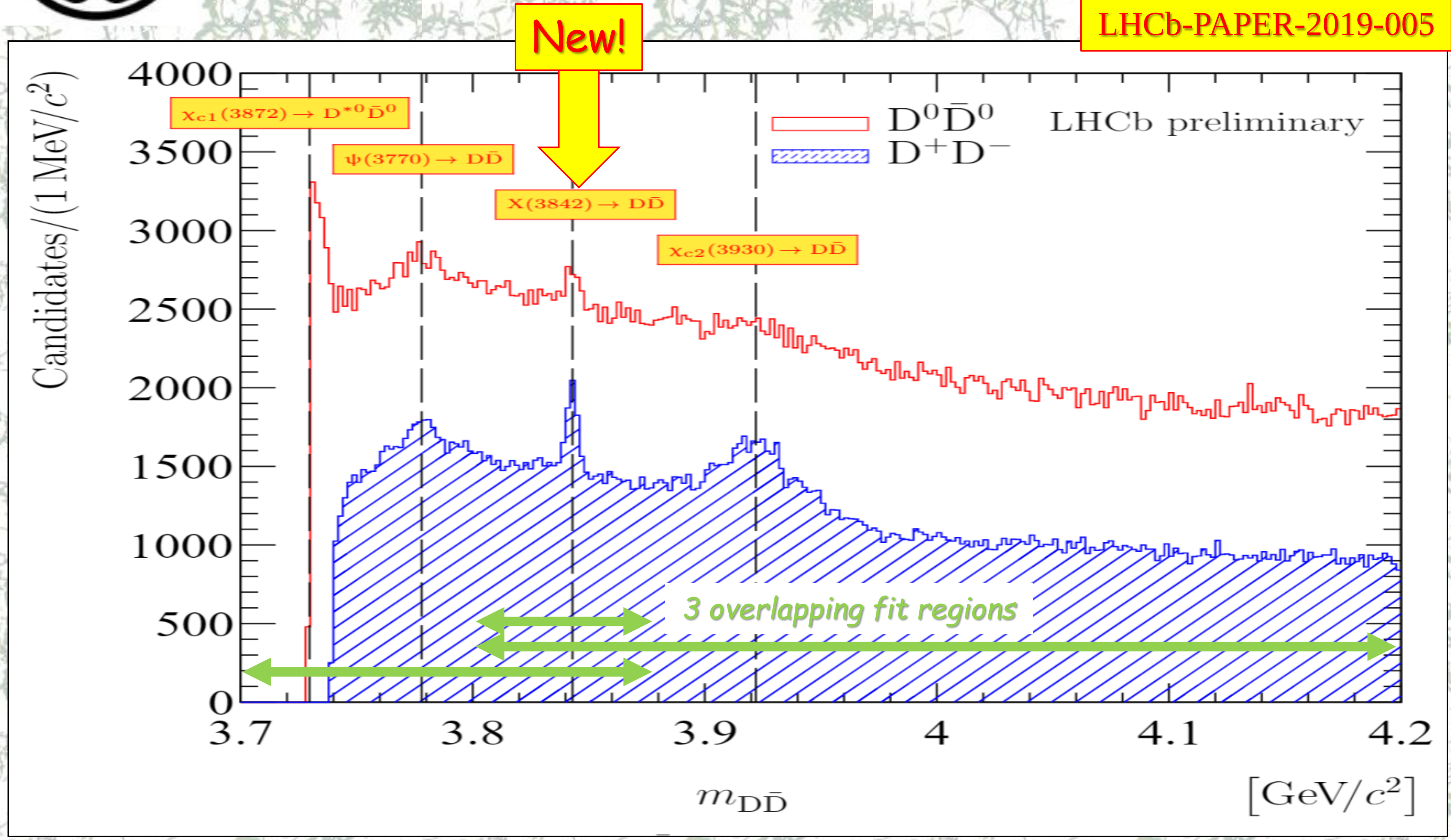

$3.80 < m(D\bar{D}) < 3.88\ \mathrm{GeV}/c^2$

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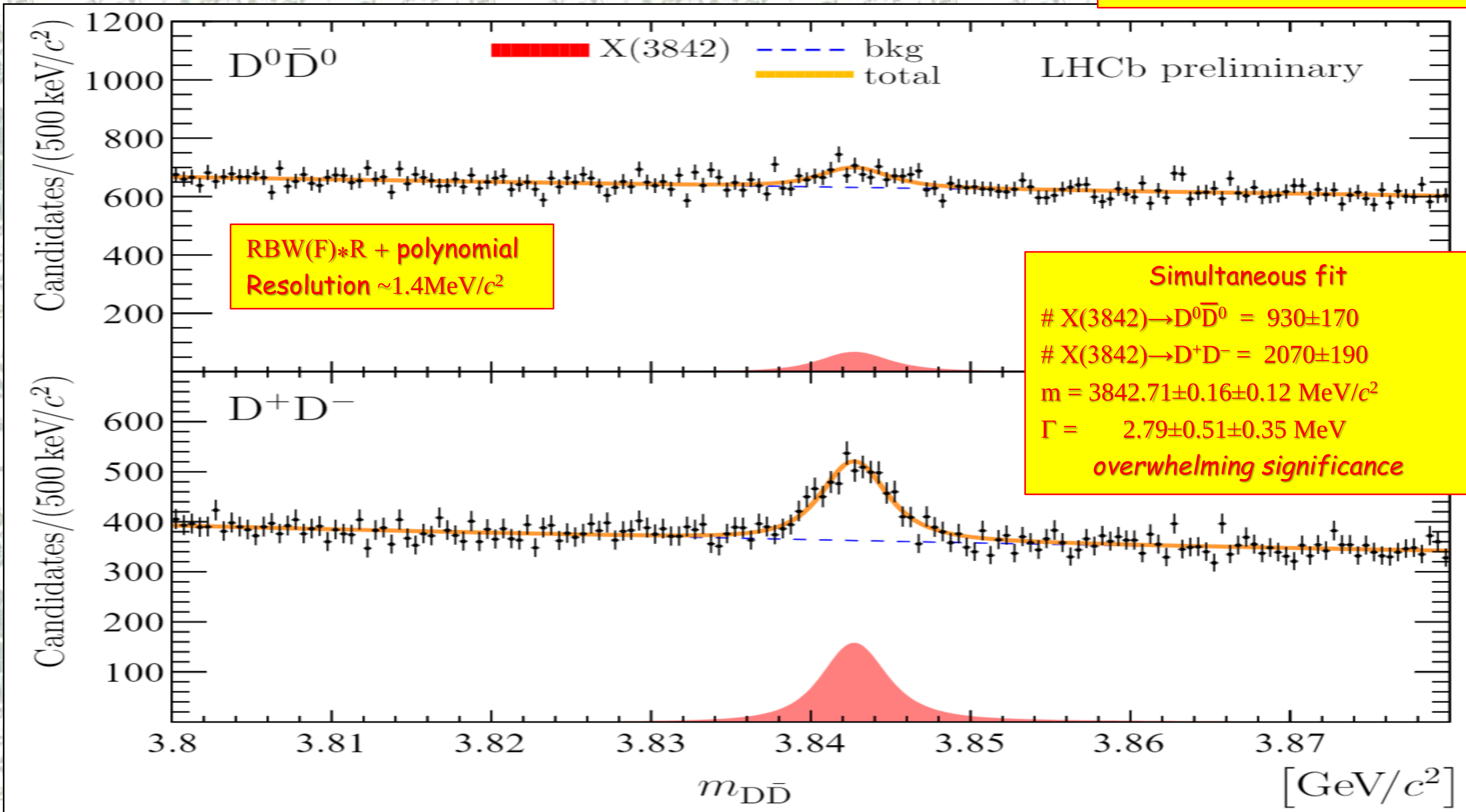

RBW(F)∗R + polynomial
Resolution ~1.4MeV/c^2

Simultaneous fit

\# $X(3842)\to D^0\bar{D}^0$ = 930±170

\# $X(3842)\to D^+D^-$ = 2070±190

m = 3842.71±0.16±0.12 MeV/c^2

Γ = 2.79±0.51±0.35 MeV

overwhelming significance

3.8 <m($D\bar{D}$)< 4.2 GeV/c^2

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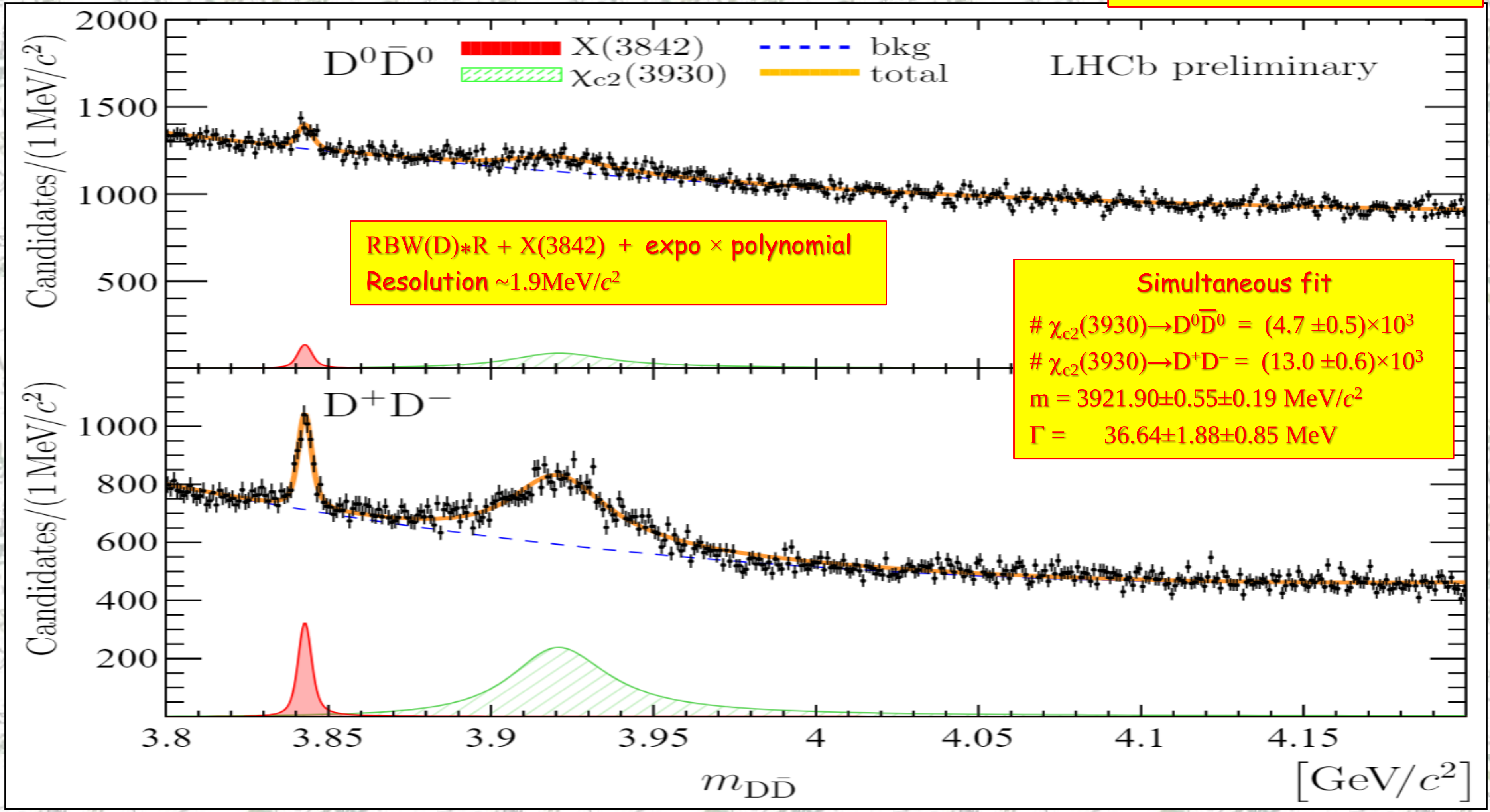

m(D$\bar{D}$)< 3.88 GeV/c^2

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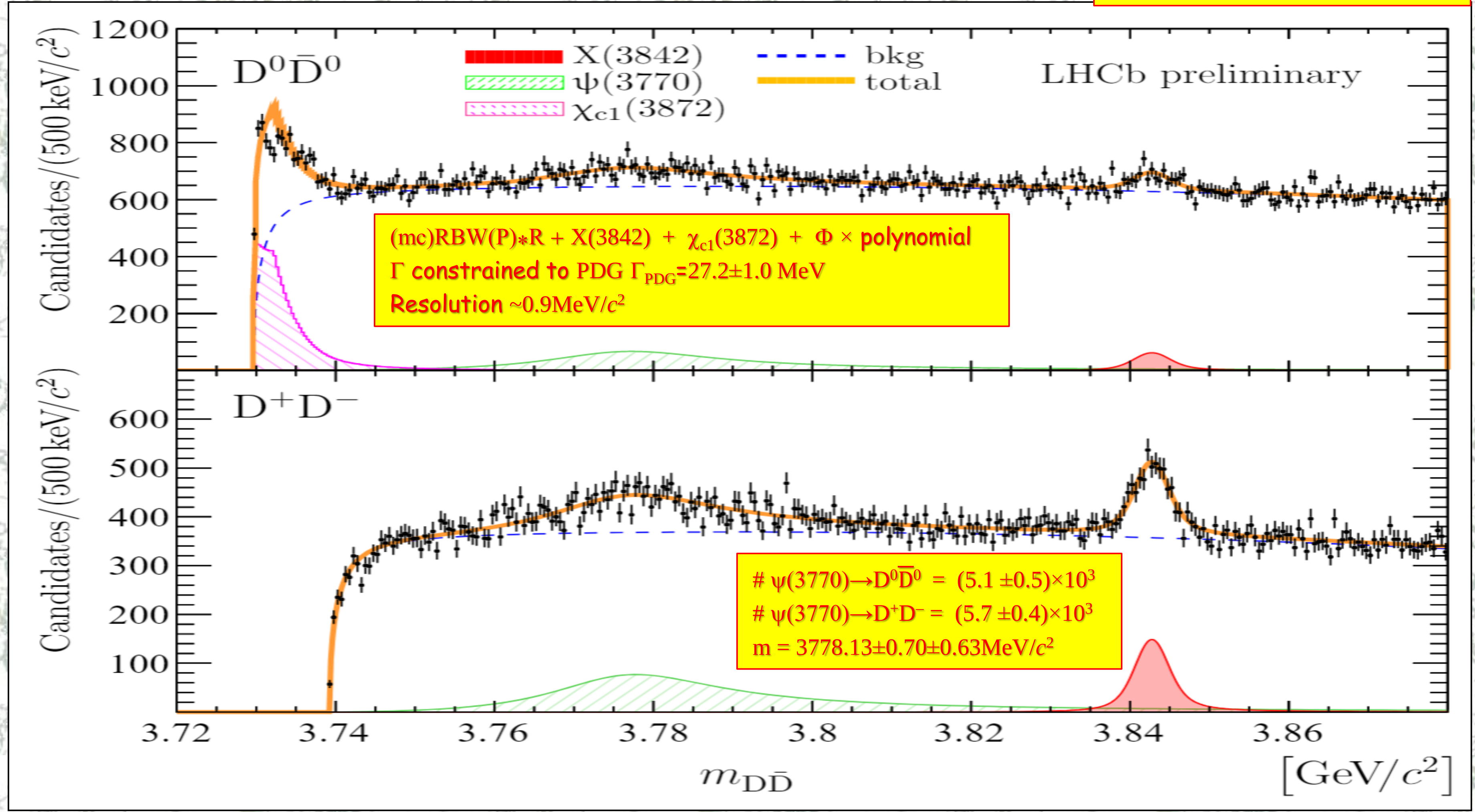

Systematic [MeV/c^2 or MeV]

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Source	X(3842) σ_μ [MeV/c^2]	X(3842) σ_Γ [MeV]	χ_{c2}(3930) σ_μ [MeV/c^2]	χ_{c2}(3930) σ_Γ [MeV]	ψ(3770) σ_μ [MeV/c^2]
Signal model	0.02	0.02	0.01	0.15	0.62
Resolution		0.31		0.20	
Background model		0.13	0.15	0.81	0.03
Momentum scale	0.07	—	0.05	—	
D meson mass	0.10	—	0.10	—	0.10
Sum in quadrature	0.12	0.35	0.19	0.85	0.63

For all measured quantities systematic is smaller than statistical uncertainty

$D\bar{D}$ near-threshold spectroscopy

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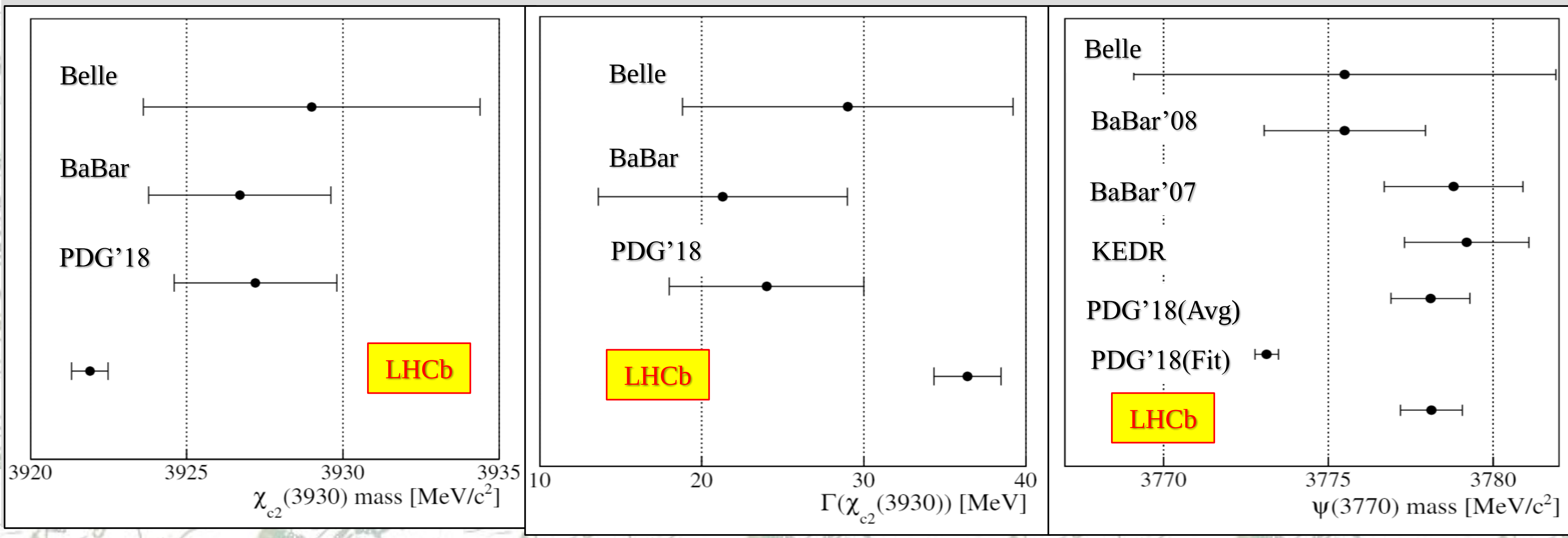
- New narrow state X(3842) is observed

  $m = 3842.71 \pm 0.16 \pm 0.12$ MeV/c^2

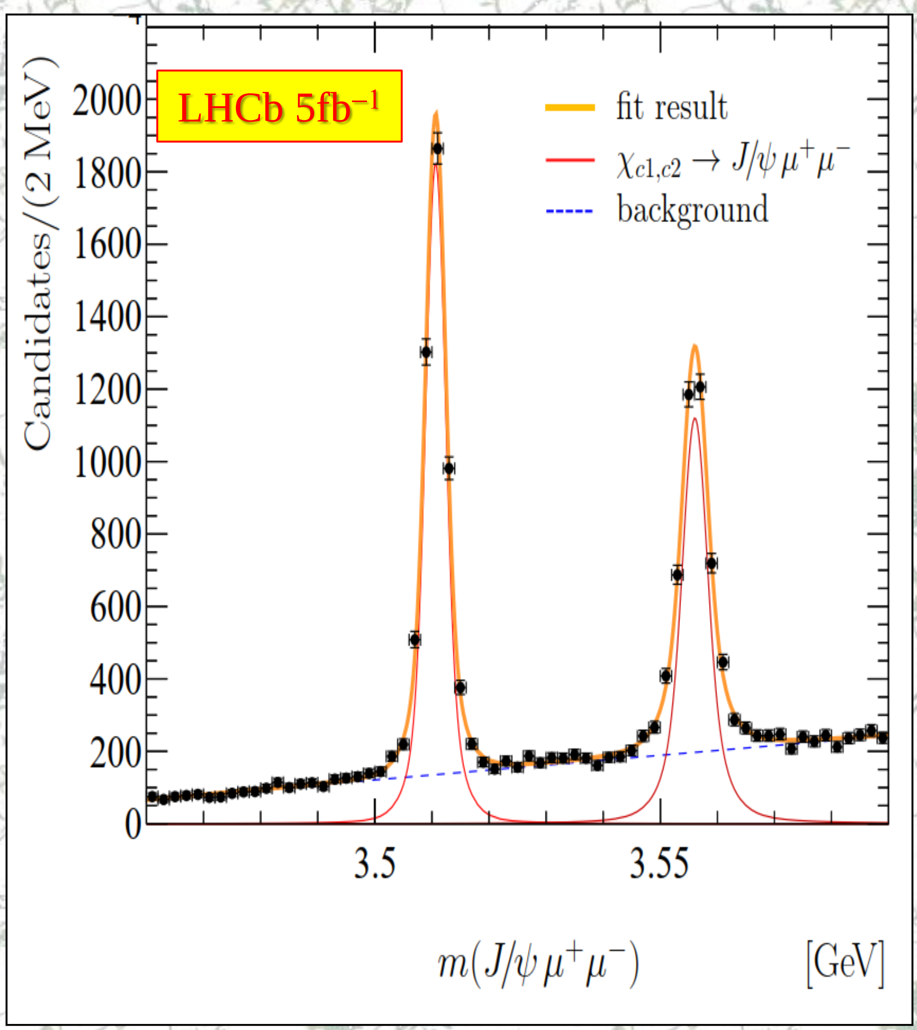
  $\Gamma = 2.79 \pm 0.51 \pm 0.35$ MeV

  - Consistent with expected 1^3D_3 state $\psi_3(1D)$ with $J^{PC}=3^{--}$
- Precise measurements for $\chi_{c2}(3930)$ and $\psi(3770)$ parameters

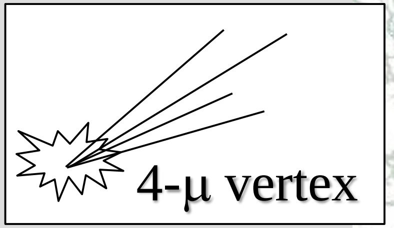


Precise χ_{c1} & χ_{c2} parameters using $\chi_{c1,2} \to J/\psi\, \mu^+\mu^-$

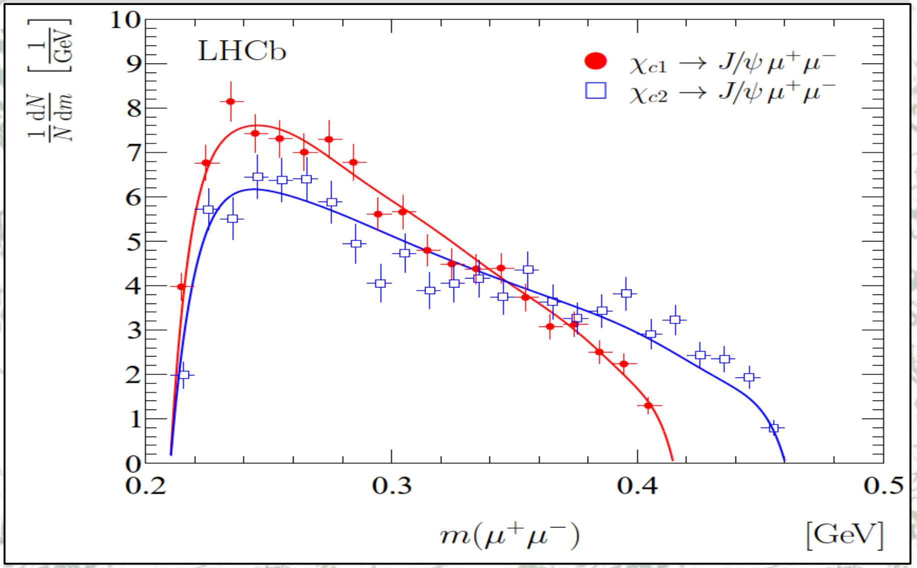
PRL119(2017) 221801



- 4-muon final state: ideal for hadronic machines
  - 5k $\chi_{c1} \to J/\psi\mu^+\mu^-$
  - 4k $\chi_{c2} \to J/\psi\mu^+\mu^-$



- Opens possibility for precise measurement of form factors



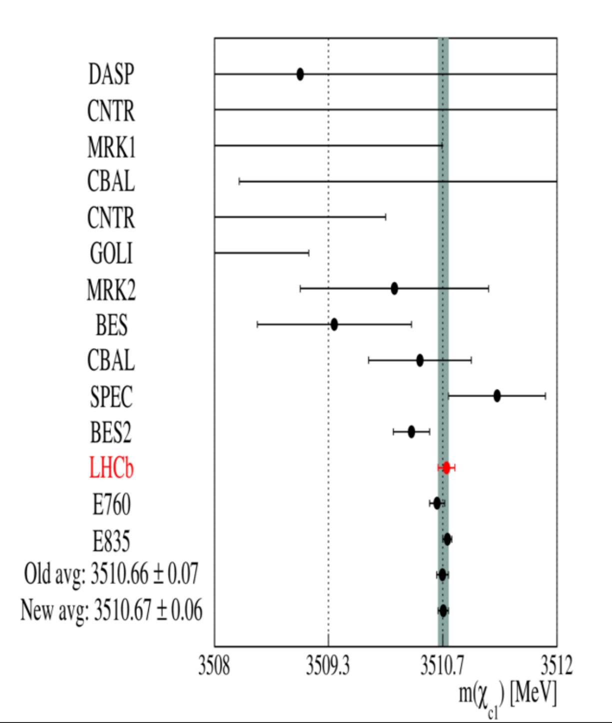
Precise χ_{c1} & χ_{c2} parameters using $\chi_{c1,2} \to J/\psi\, \mu^+\mu^-$

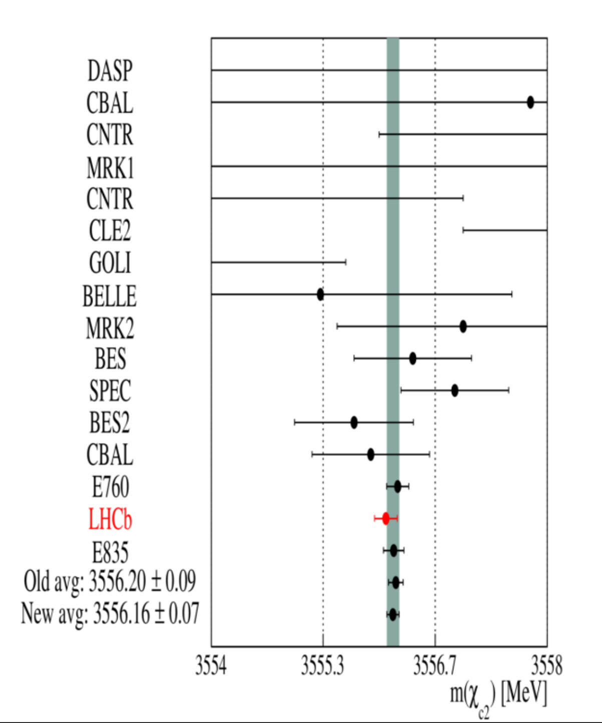
PRL119(2017) 221801

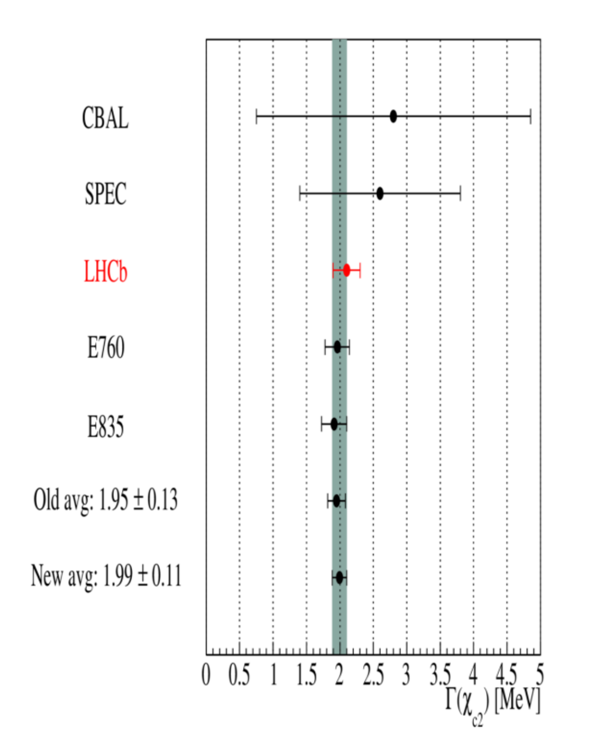
$$m(\chi_{c1}) = 3510.71 \pm 0.04\,(\text{stat}) \pm 0.09\,(\text{syst})\ \text{MeV}$$
$$m(\chi_{c2}) = 3556.10 \pm 0.06\,(\text{stat}) \pm 0.11\,(\text{syst})\ \text{MeV}$$

$$m(\chi_{c2}) - m(\chi_{c1}) = 45.39 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst})\ \text{MeV}\,.$$

$$\Gamma(\chi_{c2}) = 2.10 \pm 0.20\,(\text{stat}) \pm 0.02\,(\text{syst})\ \text{MeV}\,.$$





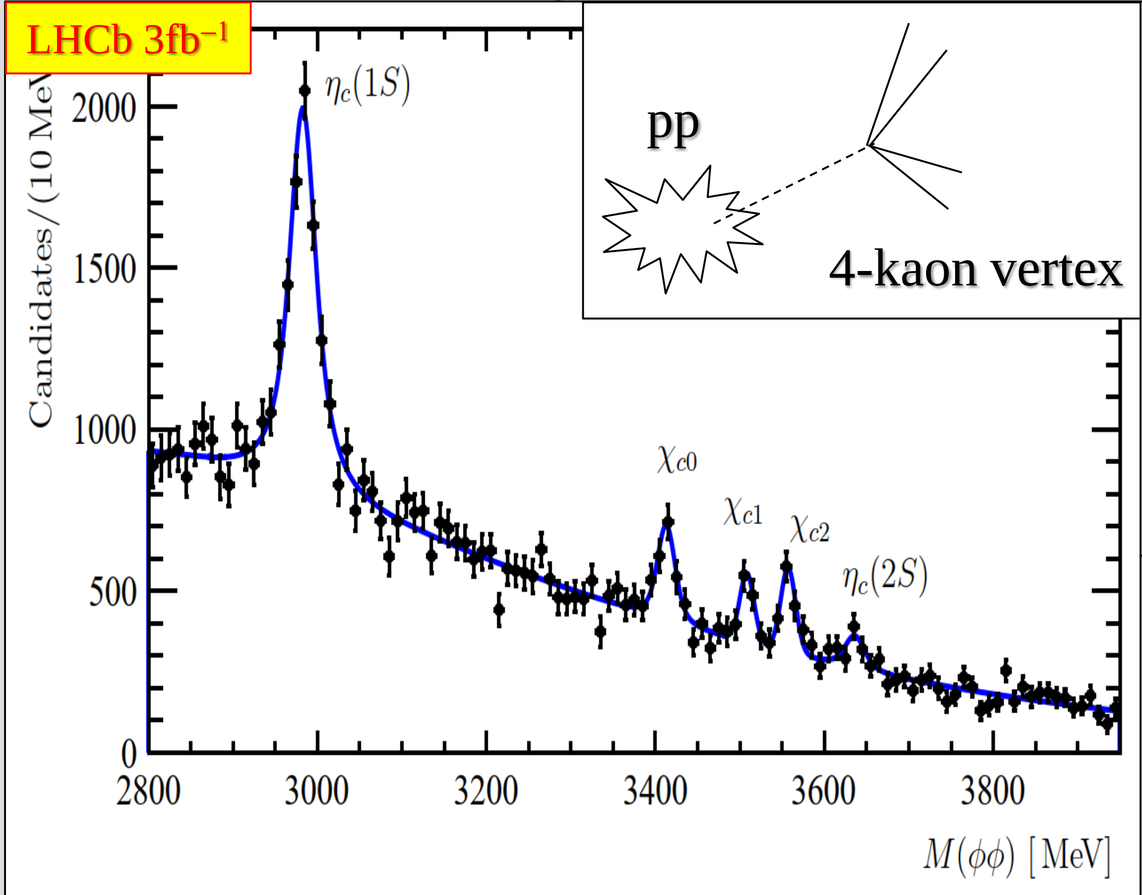


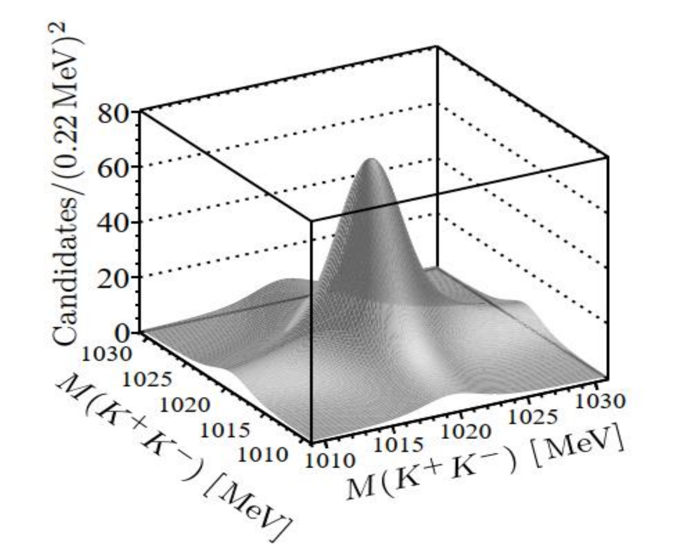
η_c, $\eta_c(2S)$, χ_c parameters using $b \to (X \to \phi\phi)X$

EPJC77(2017)609

- Detached $\phi\phi$-pairs. Excellent kaon ID is crucial

LHCb 3fb^{-1}





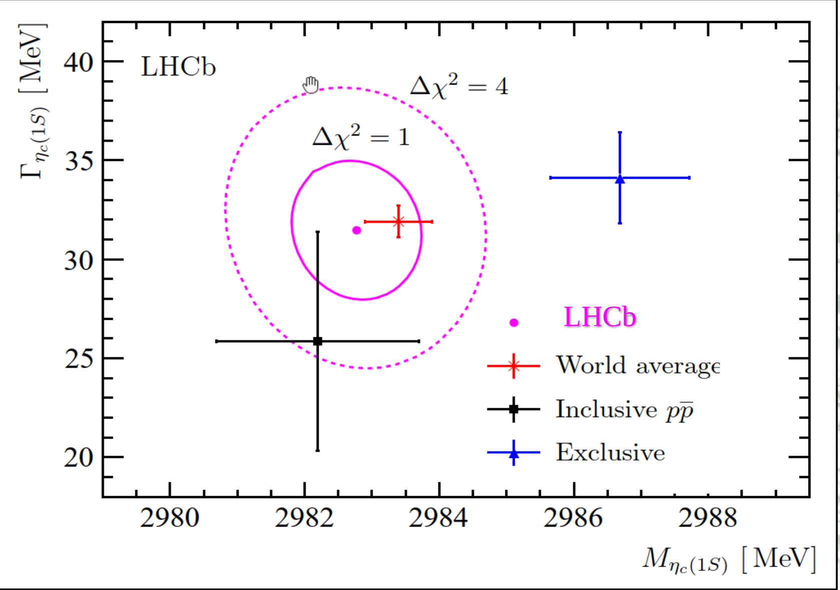
Resonance	Signal yield
$\eta_c(1S)$	6476 ± 418
χ_{c0}	933 ± 128
χ_{c1}	460 ± 89
χ_{c2}	611 ± 97
$\eta_c(2S)$	365 ± 100

η_c, $\eta_c(2S)$, χ_c parameters using $b \to (X \to \phi\phi)X$

LHCb 3fb^{-1}	EPJC77(2017)609

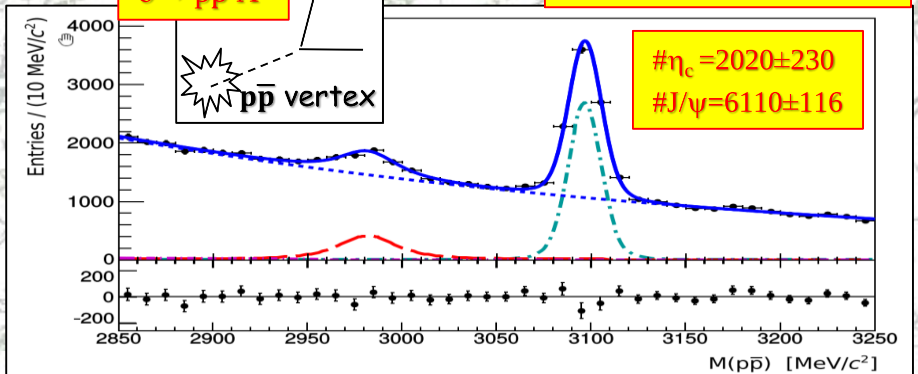
	Measured value	World average
$M_{\eta_c(1S)}$	$2982.8 \pm 1.0 \pm 0.5$	2983.4 ± 0.5
$M_{\chi_{c0}}$	$3413.0 \pm 1.9 \pm 0.6$	3414.75 ± 0.31
$M_{\chi_{c1}}$	$3508.4 \pm 1.9 \pm 0.7$	3510.66 ± 0.07
$M_{\chi_{c2}}$	$3557.3 \pm 1.7 \pm 0.7$	3556.20 ± 0.09
$M_{\eta_c(2S)}$	$3636.4 \pm 4.1 \pm 0.7$	3639.2 ± 1.2
$\Gamma_{\eta_c(1S)}$	$31.4 \pm 3.5 \pm 2.0$	31.8 ± 0.8
$\Gamma_{\eta_c(2S)}$	–	$11.3\,^{+3.2}_{-2.9}$

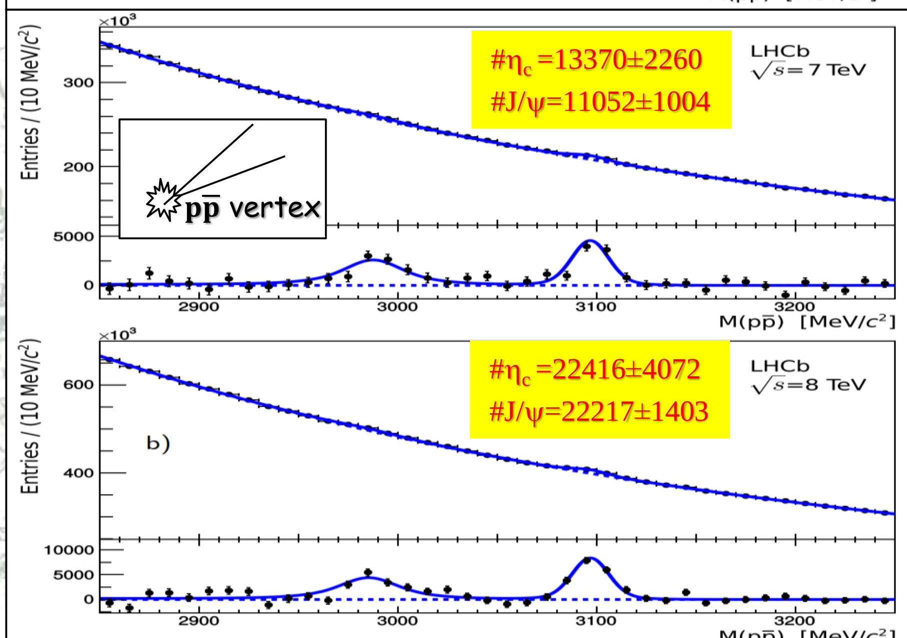
	Measured value	World average
$M_{\chi_{c1}} - M_{\chi_{c0}}$	$95.4 \pm 2.7 \pm 0.1$	95.91 ± 0.83
$M_{\chi_{c2}} - M_{\chi_{c0}}$	$144.3 \pm 2.6 \pm 0.2$	141.45 ± 0.32
$M_{\eta_c(2S)} - M_{\eta_c(1S)}$	$653.5 \pm 4.2 \pm 0.4$	655.70 ± 1.48



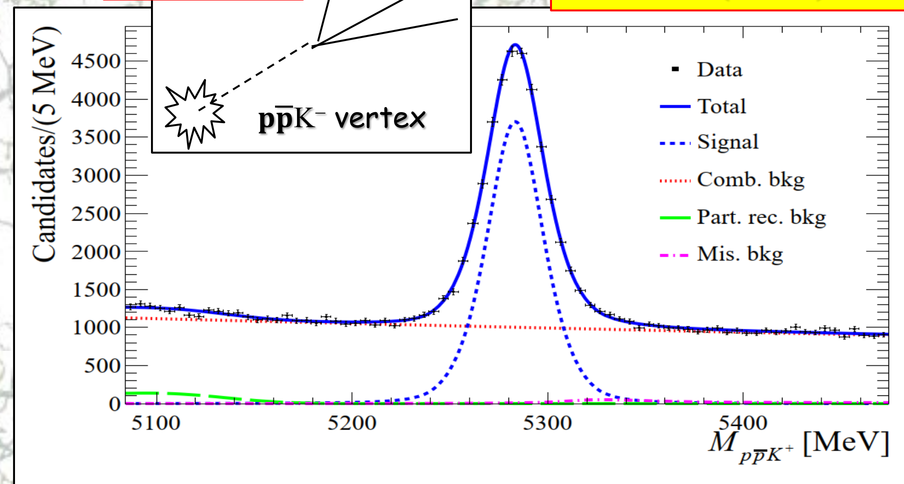
η_c parameters via $p\bar{p}$ decays

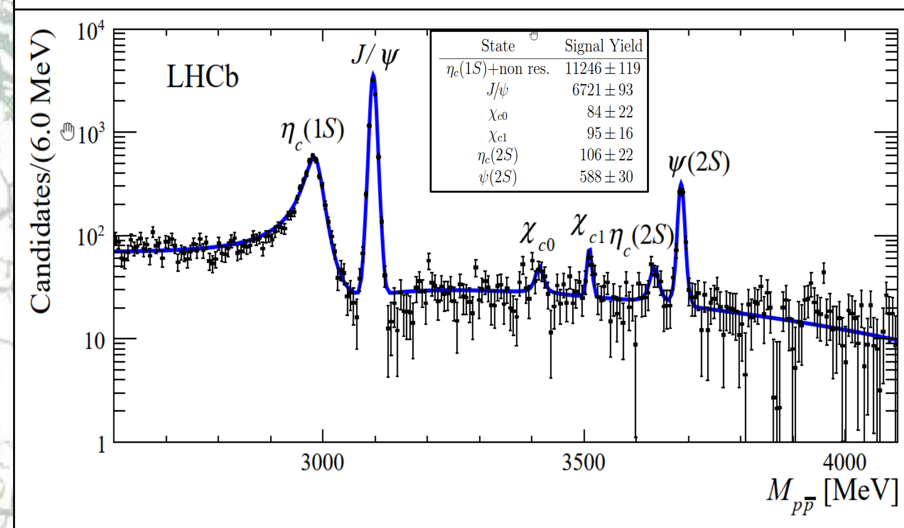
$b \to p\bar{p} X$ | LHCb 3fb^{-1} | EPJC75(2015)311





$B^- \to p\bar{p} K^-$ | LHCb 3fb^{-1} | PLB769(2017)305





η_c parameters via $p\bar{p}$ decays

PLB769(2017)305 | EPJC75(2015)311

- The precise mass/mass differences and η_c width are measured via exclusive $B^- \to p\bar{p} K^-$ decays

$$M_{J/\psi} - M_{\eta_c(1S)} = 110.2 \pm 0.5 \pm 0.9\,\text{MeV},$$
$$M_{\psi(2S)} - M_{\eta_c(2S)} = 52.5 \pm 1.7 \pm 0.6\,\text{MeV},$$
$$\Gamma_{\eta_c(1S)} = 34.0 \pm 1.9 \pm 1.3\,\text{MeV}.$$

State	Signal Yield
$\eta_c(1S)$+non res.	11246 ± 119
J/ψ	6721 ± 93
χ_{c0}	84 ± 22
χ_{c1}	95 ± 16
$\eta_c(2S)$	106 ± 22
$\psi(2S)$	588 ± 30

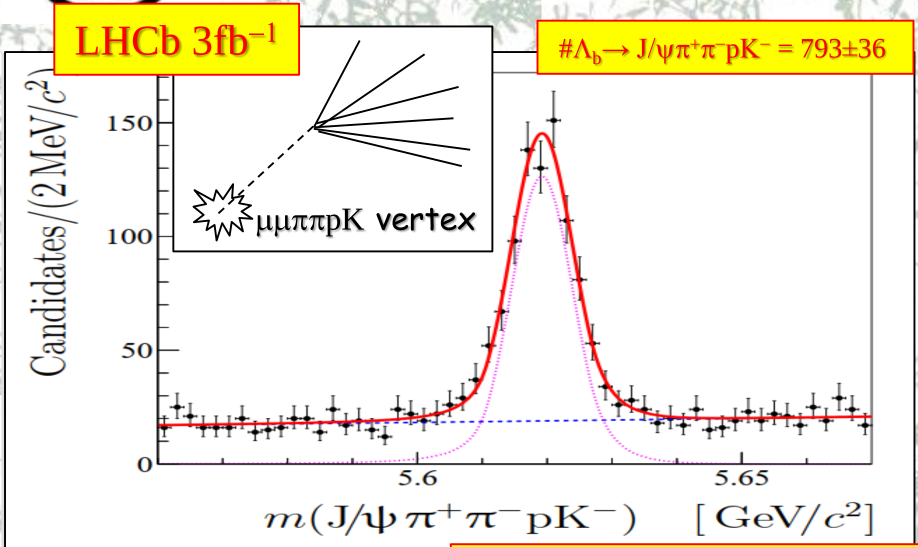
- Mass differences via inclusive $b \to p\bar{p}X$

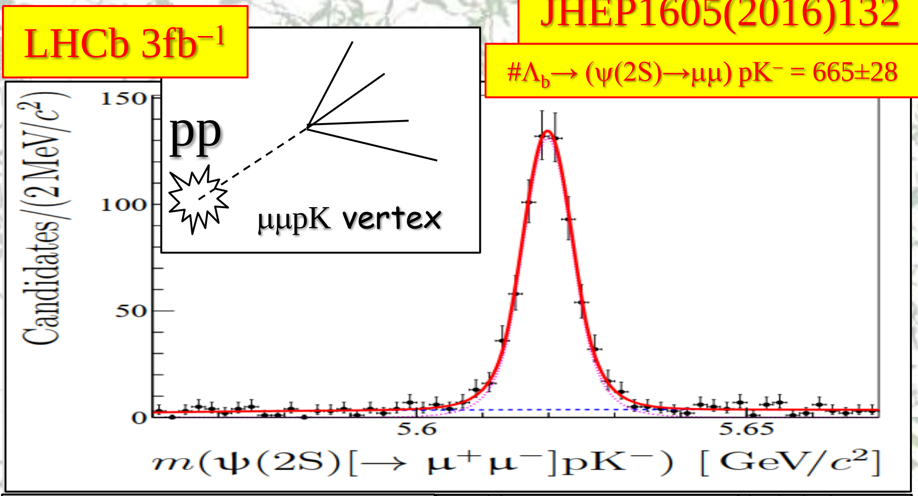
$$\Delta M_{J/\psi,\,\eta_c(1S)} = 114.7 \pm 1.5 \pm 0.1\ \text{MeV}/c^2.$$

$\#\eta_c = 2020 \pm 230$
$\#J/\psi = 6110 \pm 116$

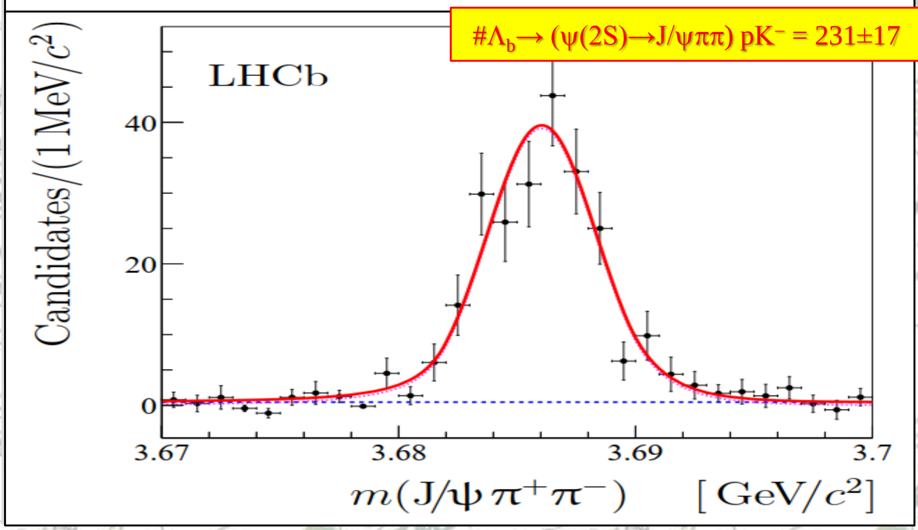
$Br(\psi(2S)\to\mu^+\mu^-)$ via $\Lambda_b\to\psi(2S)pK^-$

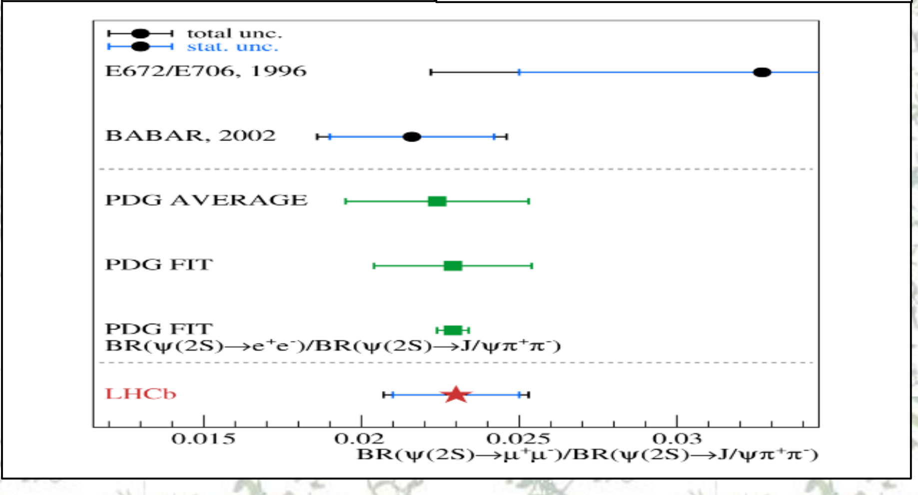
JHEP1605(2016)132





$$\frac{\mathcal{B}(\psi(2S)\to\mu^+\mu^-)}{\mathcal{B}(\psi(2S)\to J/\psi\,\pi^+\pi^-)} = (2.30\pm0.20\pm0.12\pm0.01)\times10^{-2}$$





Summary

- LHCb is a universal detector
  - well suited for *precise measurements* of conventional charmonia in *leptonic*, *hadronic* and *open charm final states*
- A lot of results with Run-I ($3\mathrm{fb}^{-1}$) and (part of) Run-II ($6\mathrm{fb}^{-1}$) data
- *New results started to appear with the full dataset* $9\mathrm{fb}^{-1}$
- Near-threshold $\mathrm{D\overline{D}}$ spectroscopy:
  - Observation of X(3842): $\psi_3(1D)$ candidate, 1^3D_3
    - The first *spin–3* charmonium state, $J^{PC} = 3^{--}$
  - Precise measurement of $\chi_{c2}(3930)$, $\psi(3770)$
- Precise measurement of χ_{c1}, χ_{c2}, η_c, $\eta_c(2S)$, …
- "Parasitic measurements" can be interesting and have interesting precision

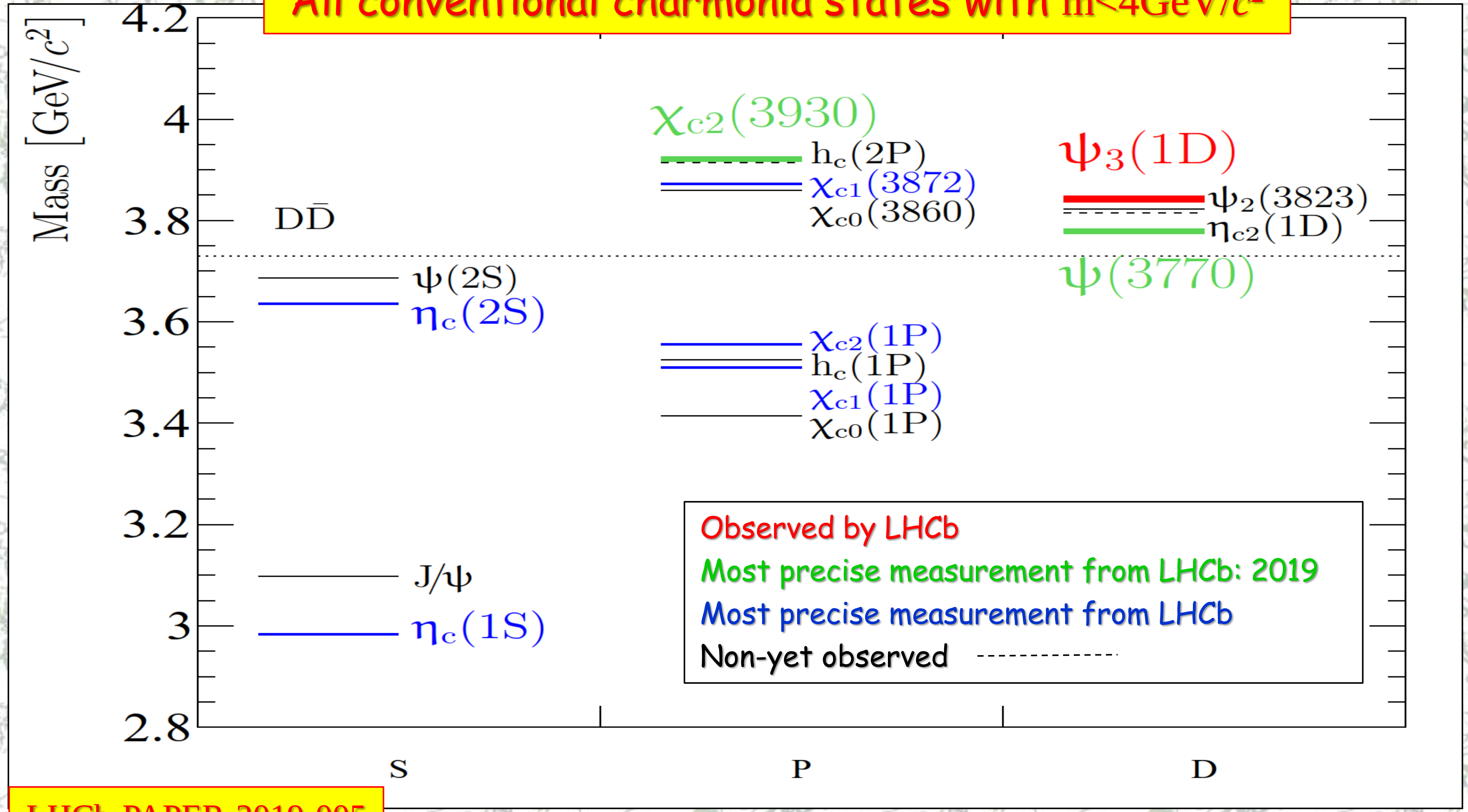
Hot!

The first $9\mathrm{fb}^{-1}$ result!

More in pipeline … … *Stay tuned!*

… doing well with charmonia

All conventional charmonia states with m<4GeV/c^2



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BACKUP

Theory predictions for $\psi_3(1^3D_3)$

Table 1.1: Predictions for the mass of the $^3D_3$ state.

Mass [MeV/c^2]
3844.8
3868.3
3849
3840
3884
3830
3815
3830

Typical theory uncertainty $O(20\text{MeV}/c^2)$ –

deduced from the difference between the predicted and the measured masses for other states

Almost all papers agree on the multiplet barycenter at 3815MeV/c^2

$\chi_{c2}(3930)$ at Belle & Babar

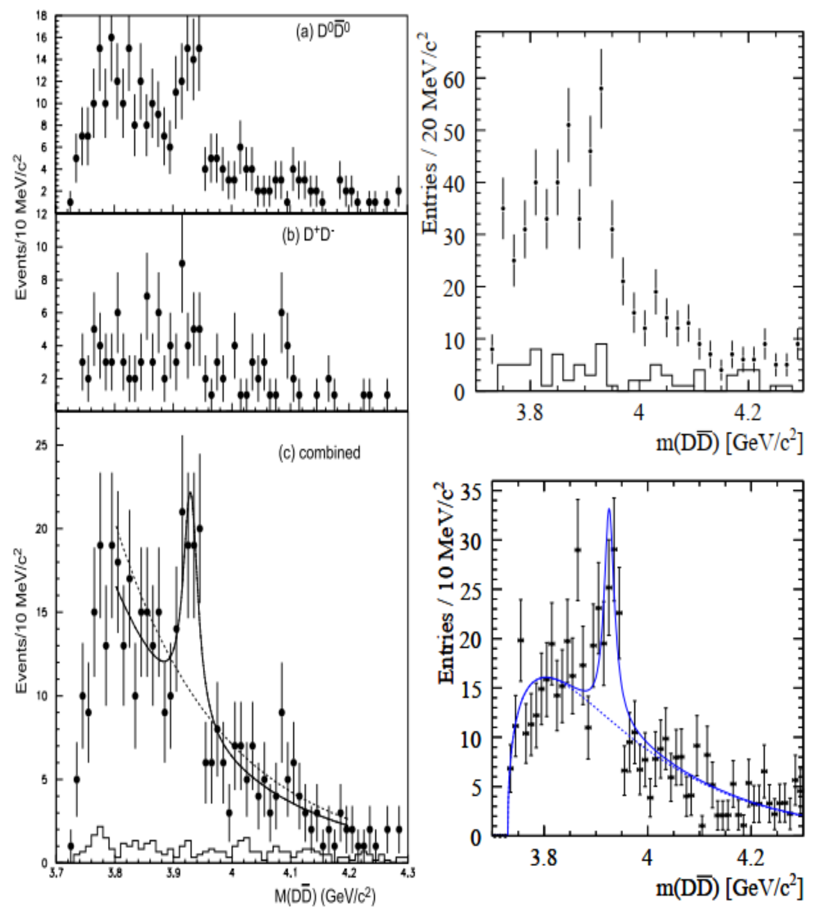

Figure F.1: The $\chi_{c2}(3930) \to D\bar{D}$ signals at (left) Belle [16], (right) BaBar [17]: (right-top) efficiency-non-corrected and (right-bottom) efficiency-corrected.

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$$\mu_{\chi_{c2}(3930)} = 3921.90 \pm 0.55 \pm 0.19\,\mathrm{MeV}/c^2\,,$$
$$\Gamma_{\chi_{c2}(3930)} = 36.64 \pm 1.88 \pm 0.85\,\mathrm{MeV}\,.$$

$\chi_{c2}(3930)$ MASS

INSPIRE search

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3927.2 ± 2.6	**OUR AVERAGE**				
3926.7 ±2.7 ±1.1	76 ±17	AUBERT	2010G	BABR	10.6 $e^+e^- \to e^+e^- D\bar{D}$
3929 ±5 ±2	64	UEHARA	2006	BELL	10.6 $e^+e^- \to e^+e^- D\bar{D}$

References:

AUBERT	2010G	PR D81 092003	Observation of the $\chi_{c2}(2P)$ Meson in the Reaction $\gamma\gamma \to D\bar{D}$ at BABAR
UEHARA	2006	PRL 96 082003	Observation of a χ'_{c2} Candidate in $\gamma\gamma D\bar{D}$ Production at Belle

$\chi_{c2}(3930)$ WIDTH

INSPIRE search

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
24 ± 6	**OUR AVERAGE**				
21.3 ±6.8 ±3.6	76 ±17	AUBERT	2010G	BABR	10.6 $e^+e^- \to e^+e^- D\bar{D}$
29 ±10 ±2	64	UEHARA	2006	BELL	10.6 $e^+e^- \to e^+e^- D\bar{D}$

ψ(3770) mass

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$$\mu_{\psi(3770)} = 3778.13 \pm 0.70 \pm 0.63\,\mathrm{MeV}/c^2$$

$\psi(3770)$ MASS

OUR FIT includes measurements of $m_{\psi(2S)}$, $m_{\psi(3770)}$, and $m_{\psi(3770)} - m_{\psi(2S)}$.

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3773.13 ± 0.35	**OUR FIT** Error includes scale factor of 1.1.				
3778.1 ± 1.2	**OUR AVERAGE**				
$3779.2\ ^{+1.8}_{-1.7}\ ^{+0.6}_{-0.8}$		[1] ANASHIN	2012A	KEDR	$e^+ e^- \to D\overline{D}$
$3775.5 \pm 2.4 \pm 0.5$	57	AUBERT	2008B	BABR	$B \to D\overline{D}K$
$3776 \pm 5 \pm 4$	68	BRODZICKA	2008	BELL	$B^+ \to D^0 \overline{D}^0 K^+$
$3778.8 \pm 1.9 \pm 0.9$		AUBERT	2007BE	BABR	$e^+ e^- \to D\overline{D}\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3779.8 ± 0.6		[2] SHAMOV	2017	RVUE	$e^+ e^- \to D\overline{D}$, hadrons
3772.0 ± 1.9		[3, 4] ABLIKIM	2008D	BES2	$e^+ e^- \to$ hadrons
$3778.4 \pm 3.0 \pm 1.3$	34	CHISTOV	2004	BELL	Sup. by BRODZICKA 2008