Recent LHCb results on charm and charmonium spectroscopy

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on behalf of the LHCb collaboration

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High Energy Physics and Quantum Field Theory
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Outline

- The LHCb detector
- Recent results
  - Charmed baryons lifetime measurement: Ω_c^0, Λ_c^+, Ξ_c^+ and Ξ_c^0 [Run I: $3fb^{-1}$]
  - Charmonia and charmonium-like exotics:
    - Near threshold $D\bar{D}$ spectroscopy:
      new charmonium state $X(3842)$ compatible with $\psi_3(1^3D_3)$ [Run I+II: $9fb^{-1}$]
    - Update of the analysis of $\Lambda_b^0 \to J/\psi\, pK^-$:
      3 narrow pentaquark candidates: $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ [Run I+II: $9fb^{-1}$]
    - Evidence for an $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)K^+\pi^-$ decays [Run I+II: $4.7fb^{-1}$]
- Summary

For more LHCb results see talks by:

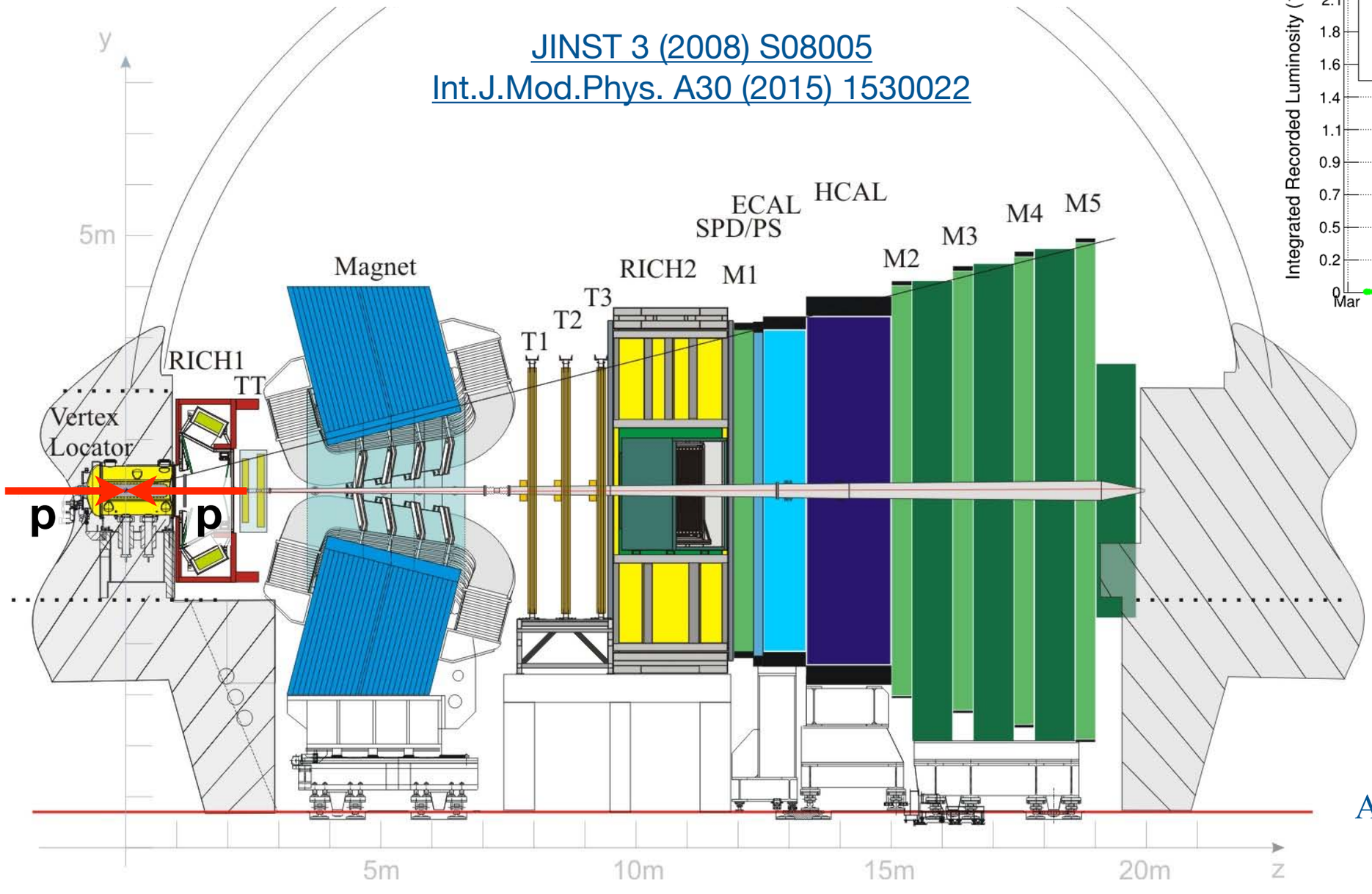
Vladimir Shevchenko, Dmitrii Pereima, Pavel Krokovny, Evgenii Kurbatov

The LHCb detector

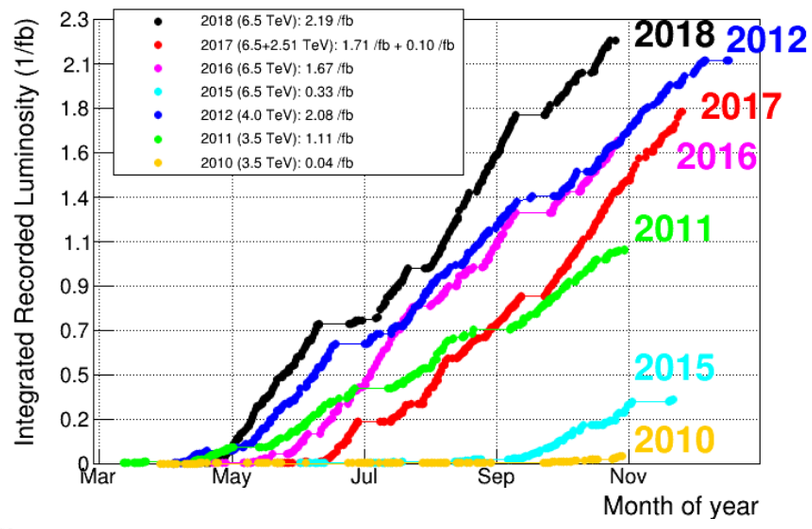
Details are given in the talk by Vladimir Shevchenko

- **VELO**: **impact parameter** resolution $(15 + 29/p_T[\mathrm{GeV}/c])$ μm, **decay time** resolution ~45 fs
- **Tracking stations, Magnet**: **momentum** resolution $\Delta p/p = 0.4\,\%$ at $5\ \mathrm{GeV}/c$, $1.0\,\%$ at $200\ \mathrm{GeV}/c$
- **PID efficiency**: for e^- ~90% with 5% $e \to h$ misID, for **K** ~95% with 5% $\pi \to$ K misID, for **μ** ~97% with 1-3% $\pi \to$ μ misID
- **Calorimetric system**: **ECAL** resolution ~$1\% \oplus 9\%/\sqrt{E[\mathrm{GeV}]}$, **HCAL** resolution ~$9\% \oplus 69\%/\sqrt{E[\mathrm{GeV}]}$
- **Trigger efficiency:** ~90% for **dimuon**, ~30% for multibody **hadronic**

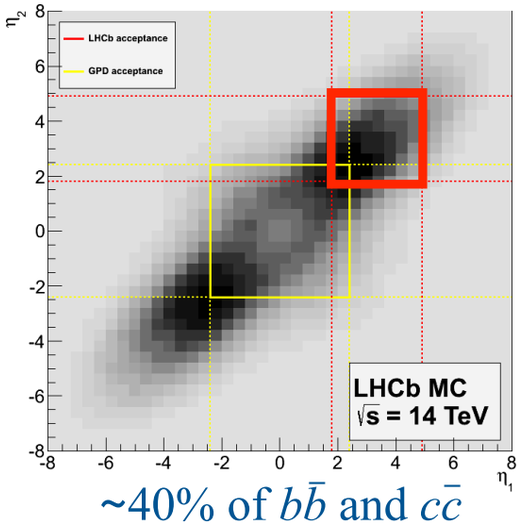
JINST 3 (2008) S08005
Int.J.Mod.Phys. A30 (2015) 1530022



LHCb integrated recorded luminosity in pp 2010-2018



Acceptance



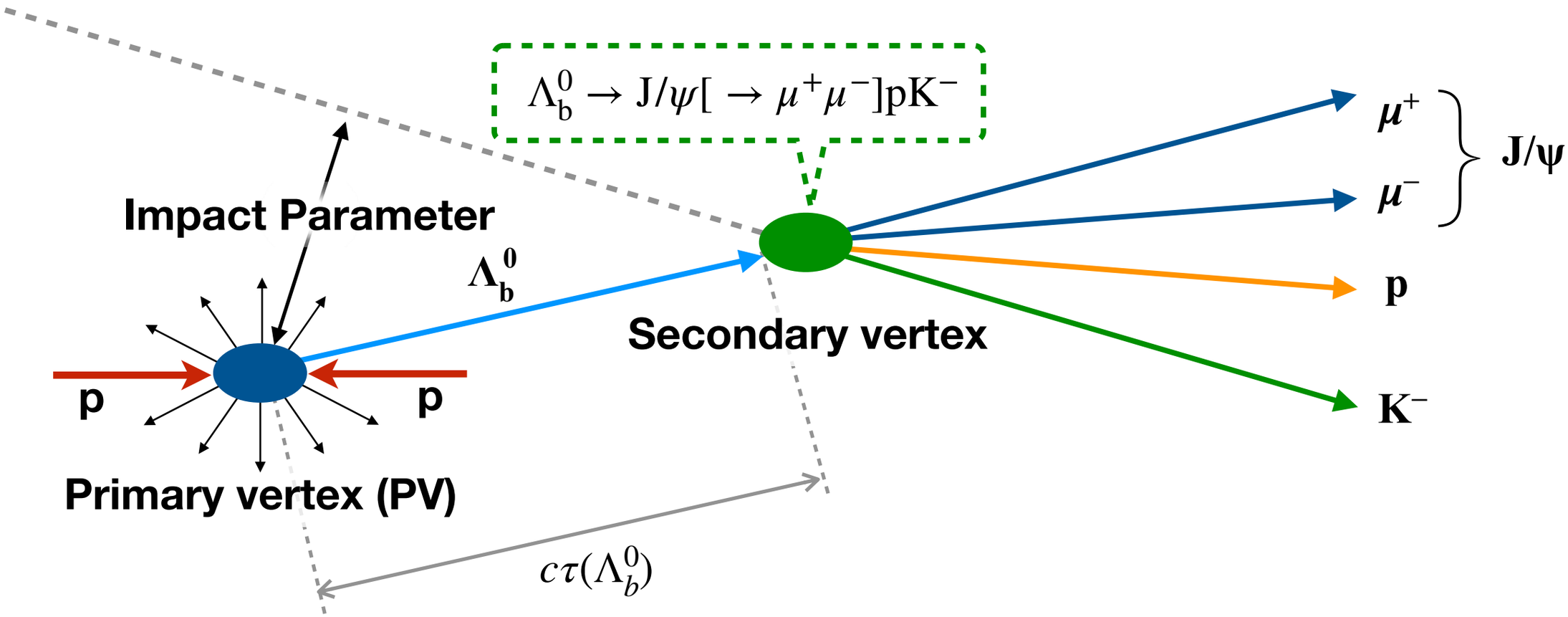
~40% of $b\bar{b}$ and $c\bar{c}$

Access to all species of b-hadrons

General analysis strategy

See talk by Dmitrii Pereima

- **Detached vertex method** (keep only **long-lived candidates**)



- Further selection to **suppress background**

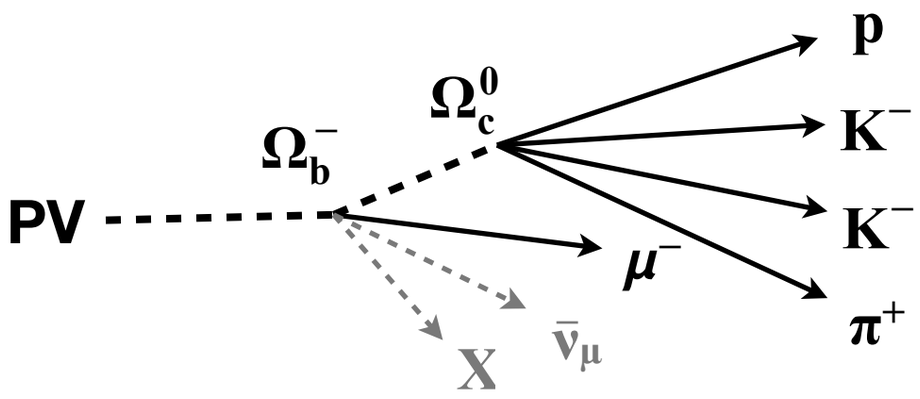
Lifetime of the charmed baryons

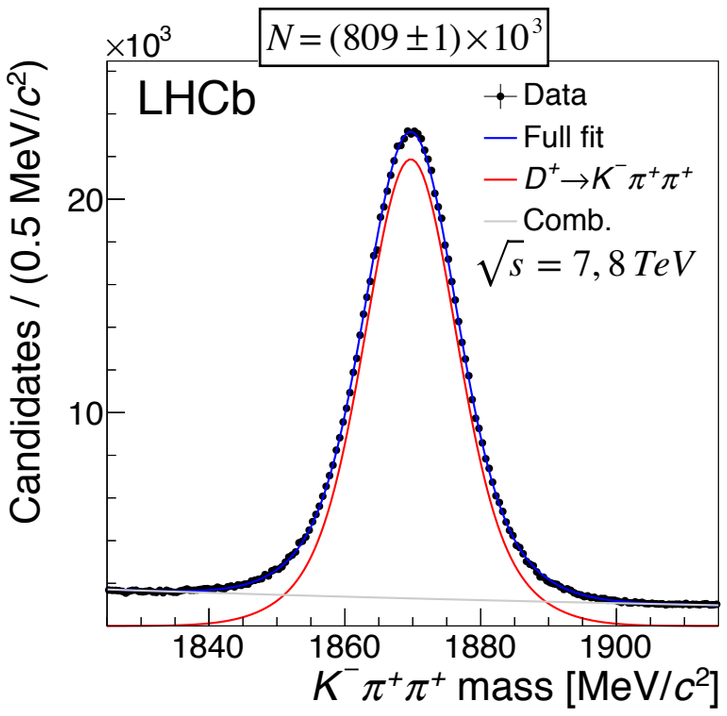
PRL 121 (2018) 092003
PRD (2019) 032001

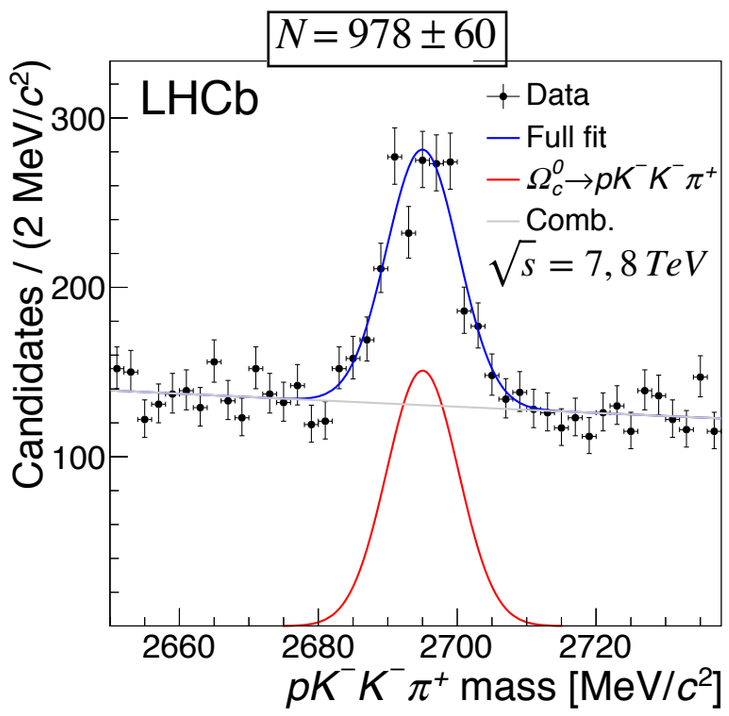
- Lifetime (τ) is useful to test theoretical approaches, i.e. Heavy Quark Expansion (HQE)
- For c-hadrons high-order terms relatively large (wrt b-hadrons)
- Lifetime hierarchy: $\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$ is predicted from HQE
- $\tau(\Omega_c^0)$ is considered the shortest due to large constructive interference between s-quark in $c \to s W^+$ transition and the spectator s-quark in the final state
- Lifetime of c-mesons (D^0, D^+, D_s^+) are well known with ~1% uncertainty level, whereas c-baryons lifetime with uncertainty up to 17%

New measurement for Ξ_c^+, Λ_c^+, Ξ_c^0, and Ω_c

- Signal channels:
  - $\Omega_b^- \to \Omega_c^0(\to pK^-K^-\pi^+)\mu^-\bar{\nu}_\mu X$, statistics is $\times 10$ wrt previous measurements (FOCUS, WA89, E687)
  - $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\bar{\nu}_\mu X$
  - $\Xi_b^- \to \Xi_c^0(\to pK^-K^-\pi^+)\mu^-\bar{\nu}_\mu X$
  - $\Xi_b^0 \to \Xi_c^+(\to pK^-\pi^+)\mu^-\bar{\nu}_\mu X$
- Control channel: $B \to D^+(\to K^-\pi^+\pi^+)\mu^-\bar{\nu}_\mu X$
  - only 10% of Run-II statistics







Lifetime of the charmed baryons

PRL 121 (2018) 092003
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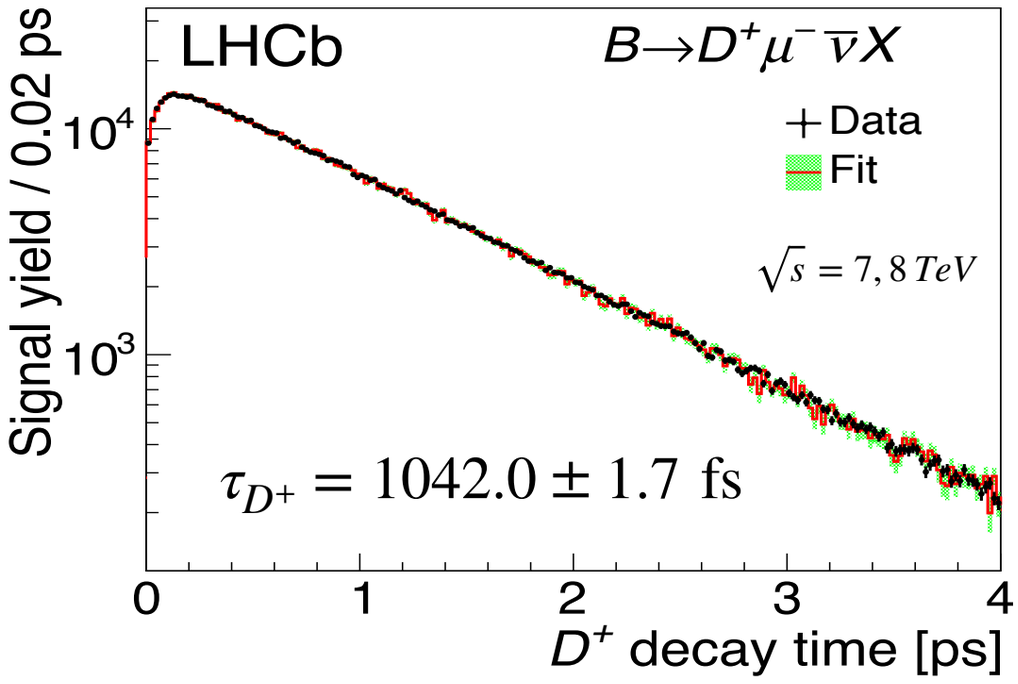
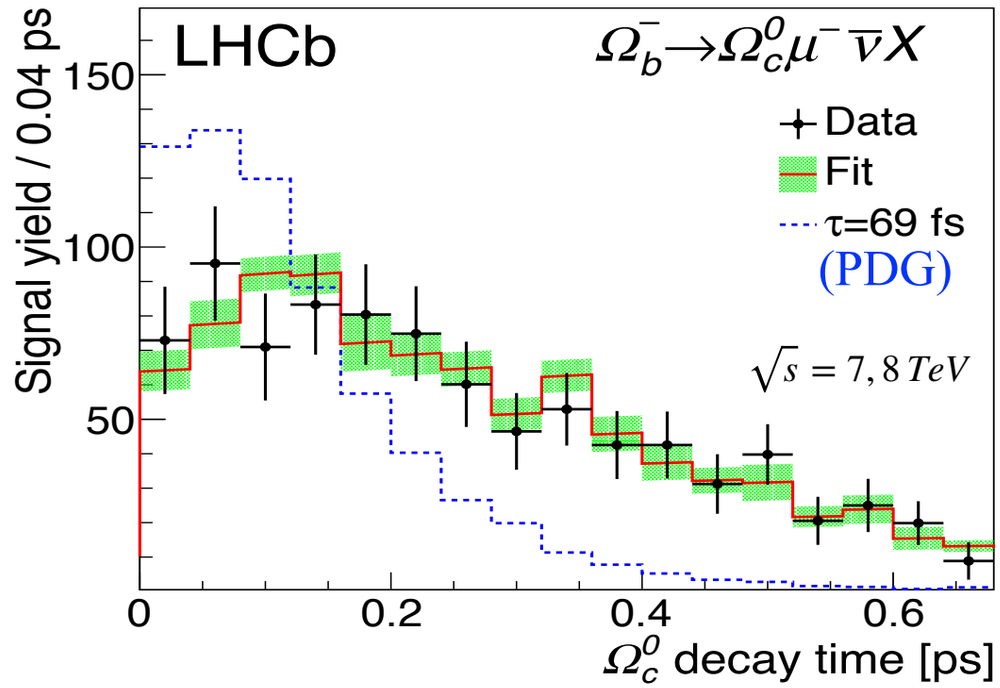
Examples of background subtracted distribution for

Normalisation D^+



Signal Ω_c^0



- Fit model: $S(t_{\rm rec}) = f(t_{\rm tec}) \times \exp(-\frac{t_{\rm rec}}{\tau_{\rm fit}} + \frac{t_{\rm rec}}{\tau_{\rm sim}}) \times \beta(t_{\rm rec})$

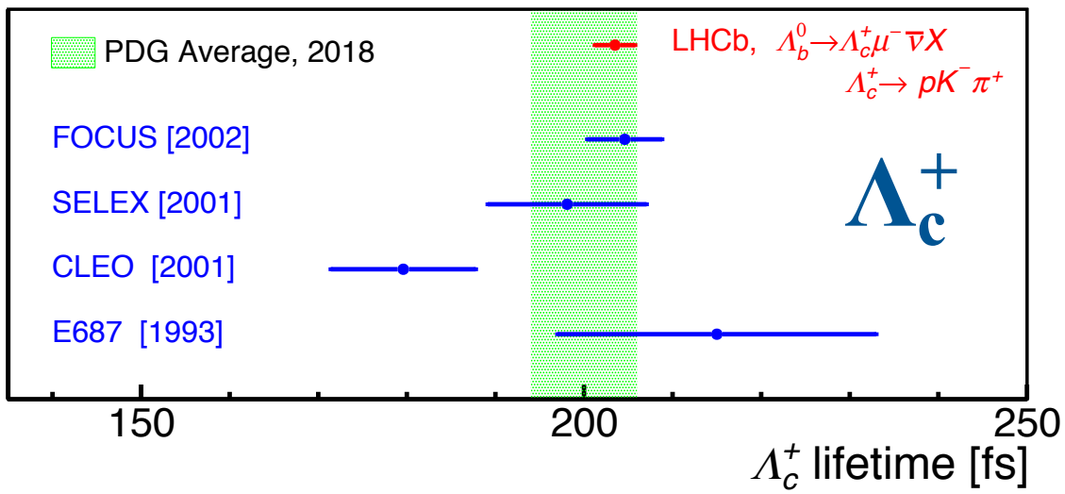
  Binned template from simulation; lifetimes used in simulation; tracking efficiency correction

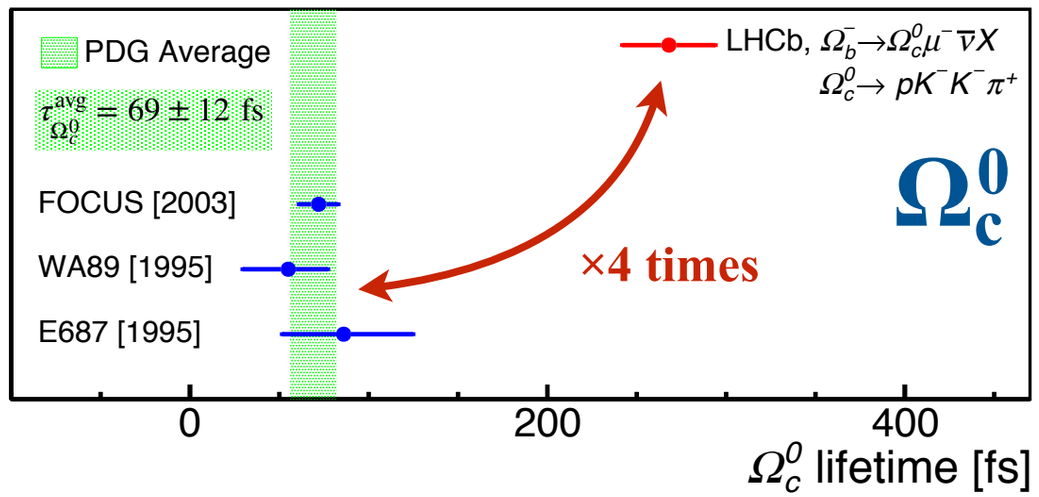
- Fit the background subtracted distributions
- Simultaneous fit of signal and normalisation samples
- Lifetimes are measured relative to that of the D^+ meson

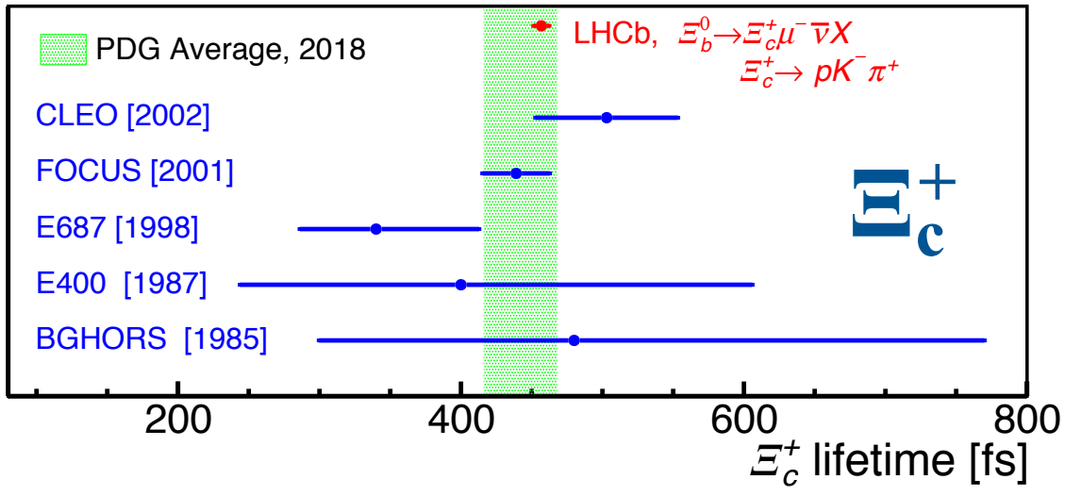
Lifetime of the charmed baryons

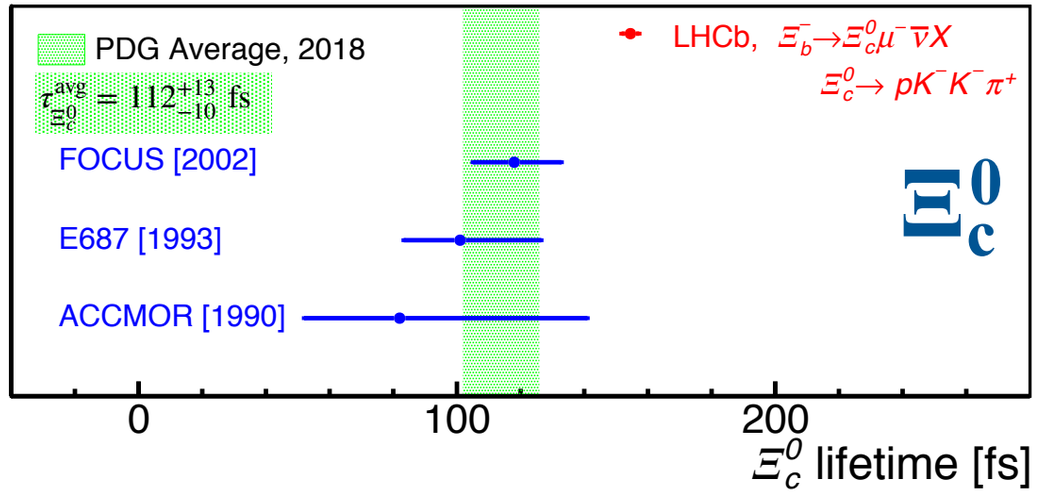
PRL 121 (2018) 092003
PRD (2019) 032001

Lifetime measurement results









$$\tau_{\Lambda_c^+} = 203.5 \pm 1.0 \pm 1.3 \pm 1.4(\tau_{D^+})\ \text{fs}$$
$$\tau_{\Xi_c^+} = 456.8 \pm 3.5 \pm 2.9 \pm 3.1(\tau_{D^+})\ \text{fs}$$

← In agreement with PDG

$$\tau_{\Xi_c^0} = 154.5 \pm 1.7 \pm 1.6 \pm 1.0(\tau_{D^+})\ \text{fs}$$

← 3.3σ deviation wrt PDG

$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2(\tau_{D^+})\ \text{fs}$$

← ×4 times wrt PDG

Lifetime hierarchy updated:

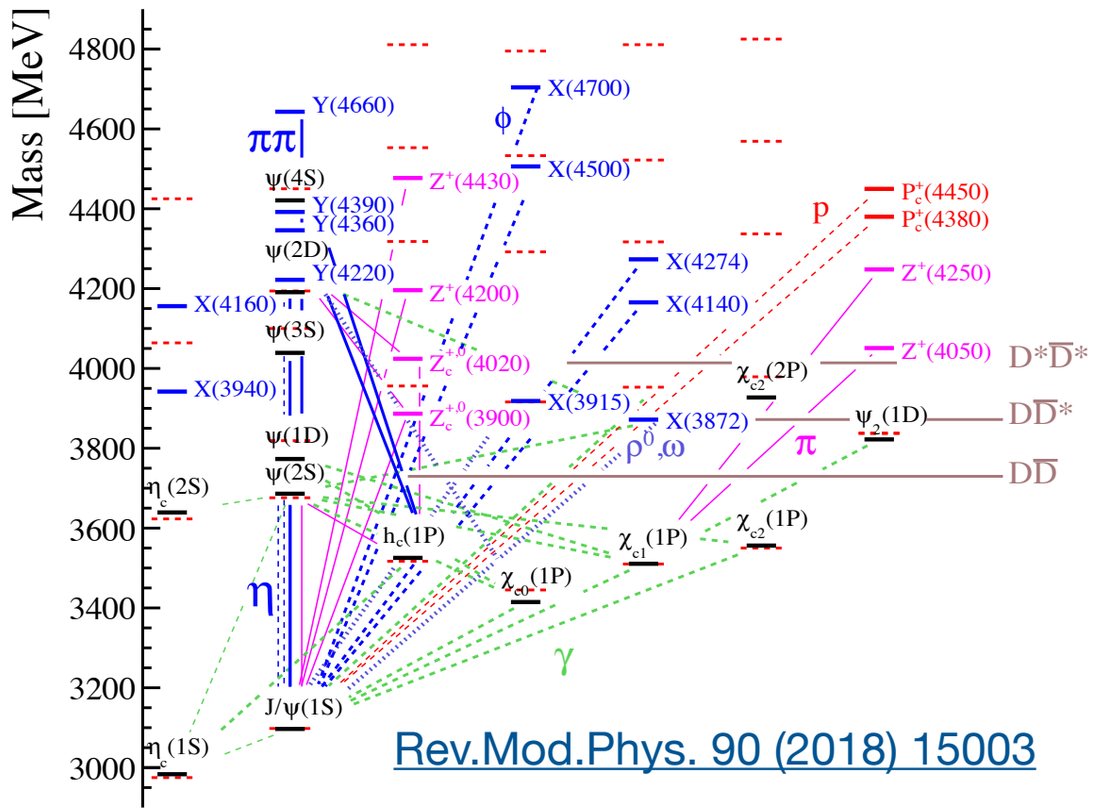
$$\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$$

HQE allows inverted hierarchy depending on treatment of higher order terms [arXiv:hep-ph/9311331]

Charmonium spectrum status

- Charmonium spectrum and properties well described by potential models but there are many not yet observed states above the $D^0\overline{D}^0$ threshold.
- A lot of exotic hadrons (X, Y, Z) which doesn't fit into conventional charmonium spectrum
- Many theoretical interpretations in discussion
- Precise measurements are crucial for interpretation of exotic states

Charmonium-like states



Rev.Mod.Phys. 90 (2018) 15003

Highlights from LHCb

Conventional:

- Production of J/ψ, $\psi(2S)$ with $\mu^+\mu^-$
  [arXiv:1908.03099, JHEP 10 (2013) 115]
- Production of χ_{c1} and χ_{c2} with $(\mu^+\mu^-)\gamma$ [PLB 714 (2012) 215]
- Precise measurement of parameters of
  - η_c and $\eta_c(2S)$, with $p\bar{p}$ and $\phi\phi$
    [EPJ C75 (2015) 311, PLB 769 (2017) 305, EPJ C77 (2017) 609]
  - χ_{c1} and χ_{c2}, with $J/\psi\mu^+\mu^-$ and $\phi\phi$
    [PRL 119 (2017) 221801, EPJ C77 (2017) 609]
- And many more …

Exotics:

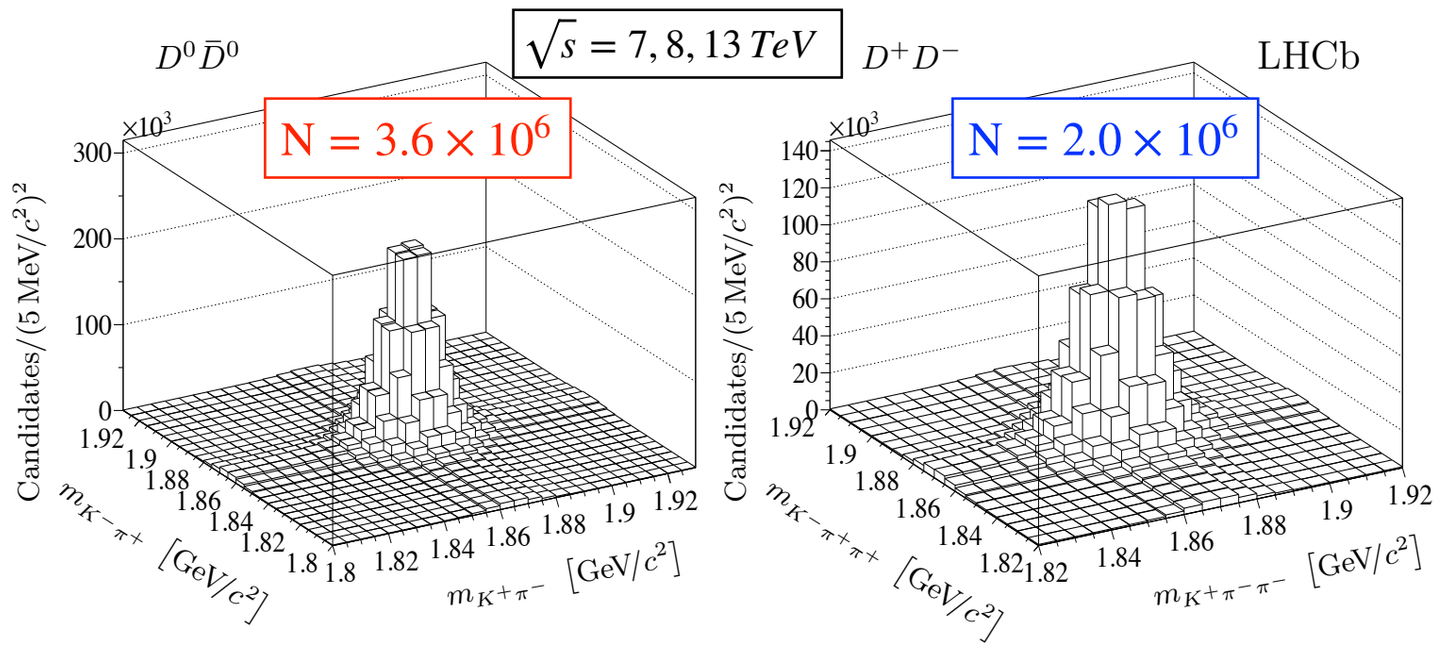
- Study of $\chi_{c1}(3872)$ (production, J^{PC}, new decay modes)
  [EPJ C72 (2012) 1972, PRL 110 (2013) 222001, Nucl.Phys. B886 (2013) 665]
- $Z(4430)^+$ resonance confirmation [PRL 112 (2014) 222002, PRD 92 (2015) 112009]
- Observation of $P_c(4380)^+$ and $P_c(4450)^+$
  [PRL 115 (2015) 072001, PRL 117 (2016) 082002]
- $X(4140)$ and $X(4274)$ resonance confirmation
  [PRL 118 (2017) 022003, PRD 95 (2017) 012002]
- Exotic contributions to the $B^0 \to J/\psi K^+\pi^-$ [PRL 122 (2019) 152002]
- And many more…

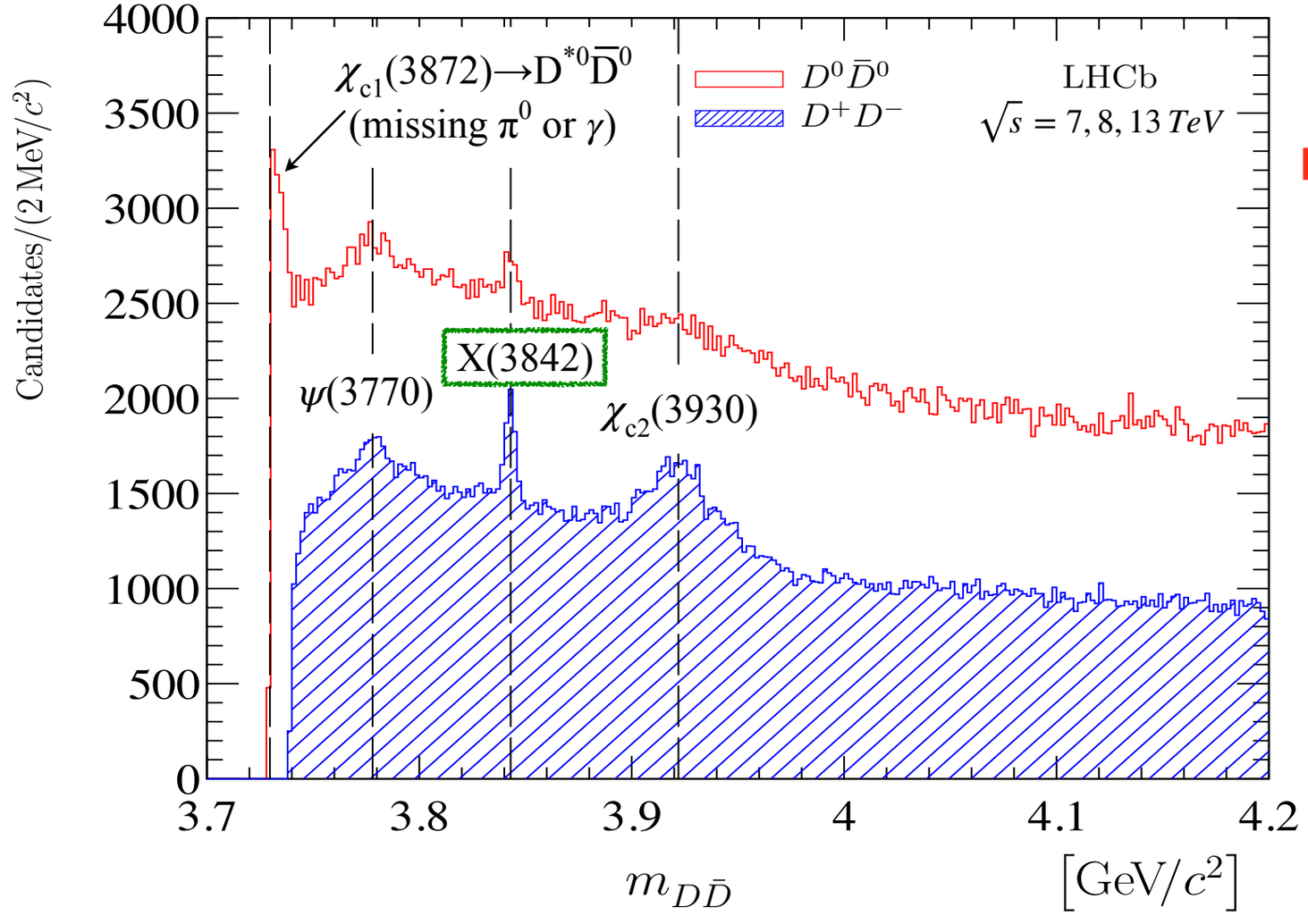
Further search for charmonium states and determine their properties

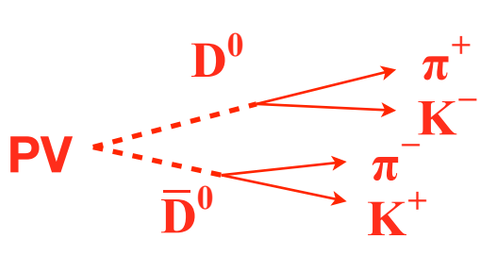
Near threshold $D\bar{D}$ spectroscopy

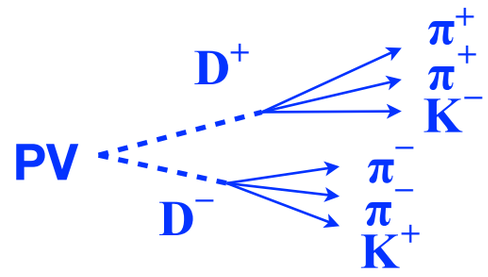
JHEP 07 (2019) 035

- First analysis to make use of full Run-I + Run-II data: ~9fb^{-1}
- Prompt D^+D^- and $\bar{D}^0D^0$, where $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$
- Displaced D-vertices







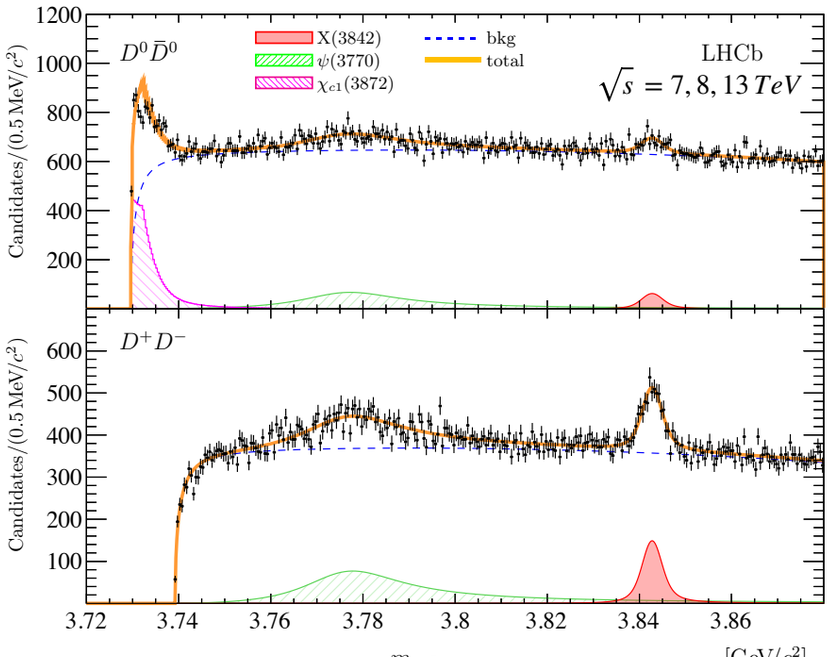


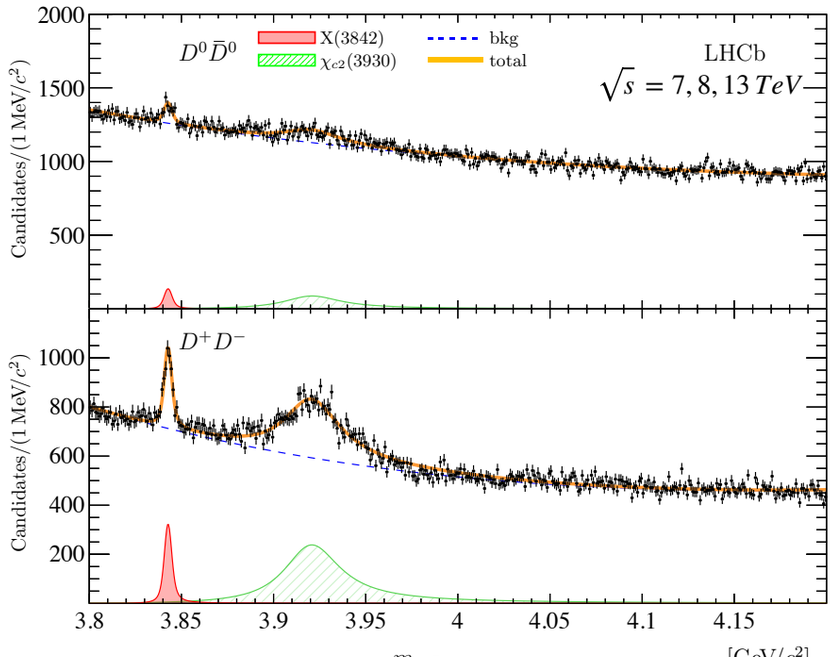
- D candidates mass within ±20 MeV (approximately ±3σ) of the PDG value
- Purity ~88% for $D^0\bar{D}^0$, ~90% for D^+D^-
- To improve $D\bar{D}$ resolution: D mass constrained to the known values
- Fits in three different mass region

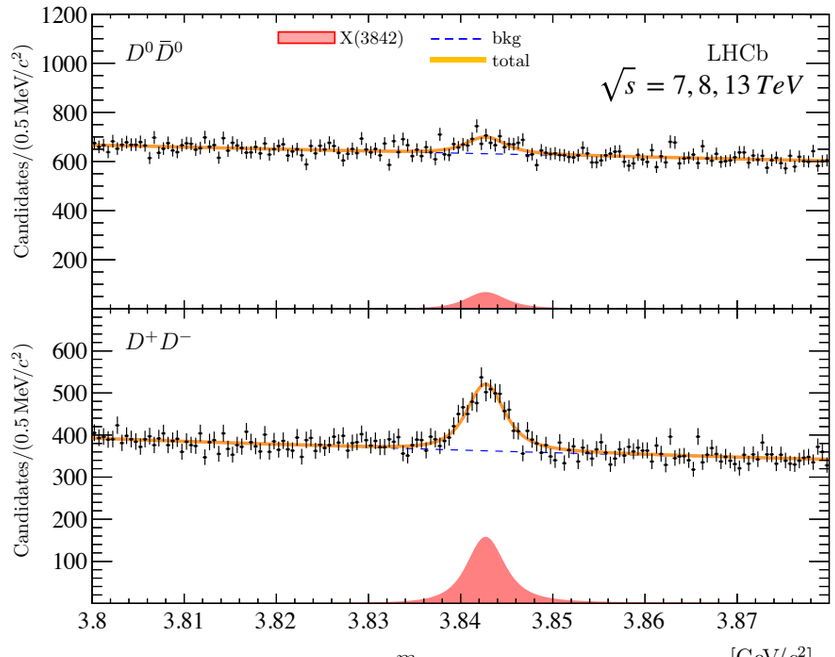
Near threshold $D\bar{D}$ spectroscopy

JHEP 07 (2019) 035

Simultaneous fit for D^+D^- and $D^0\bar{D}^0$ candidates

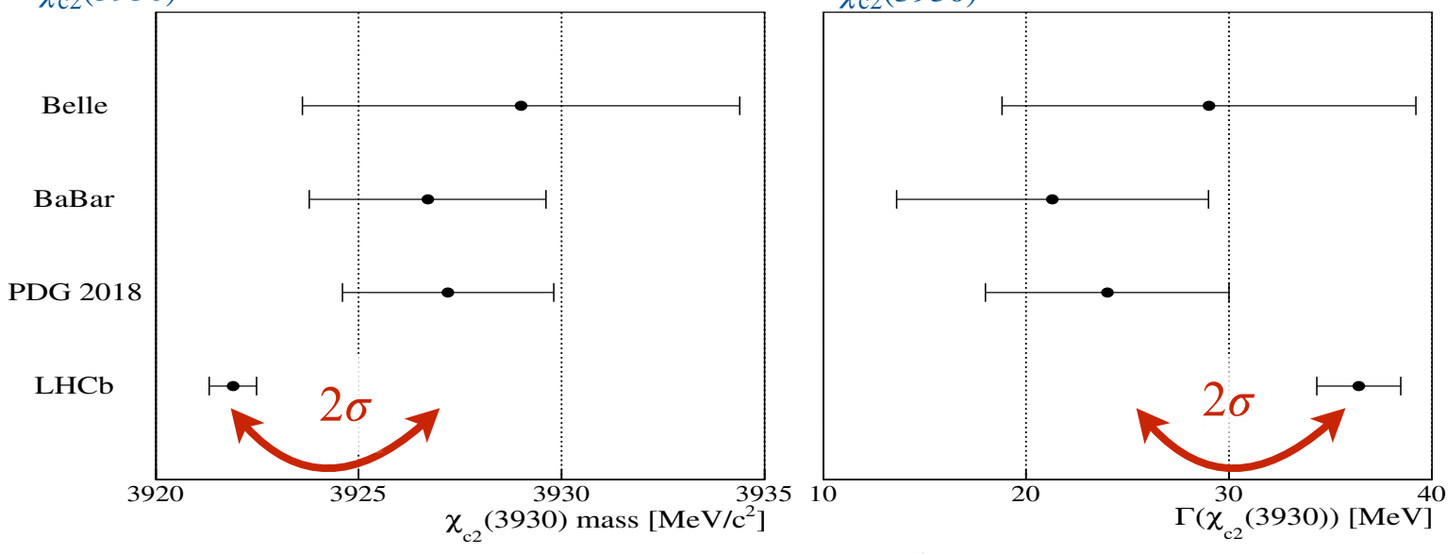




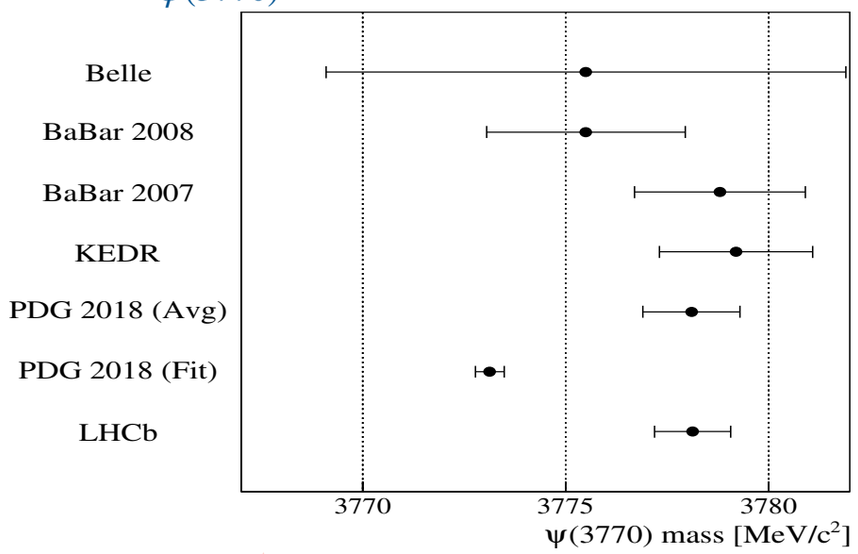


- Observation of X(3842) — new narrow charmonium state with measured parameters:
  $m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12\ \text{MeV}/c^2$; $\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35\ \text{MeV}$
- Mass and width are compatible with $\psi_3(1^3D_3)$ charmonium with $J^{PC}=3^{--}$
- Prompt hadroproduction of the $\chi_{c2}(3930)$ and $\psi(3770)$ states is observed for the first time.
  The measured parameters:

$m_{\chi_{c2}(3930)} = 3921.9 \pm 0.6 \pm 0.2\ \text{MeV}/c^2$ $\Gamma_{\chi_{c2}(3930)} = 36.6 \pm 1.9 \pm 0.9\ \text{MeV}$



$m_{\psi(3770)} = 3778.1 \pm 0.7 \pm 0.6\ \text{MeV}/c^2$

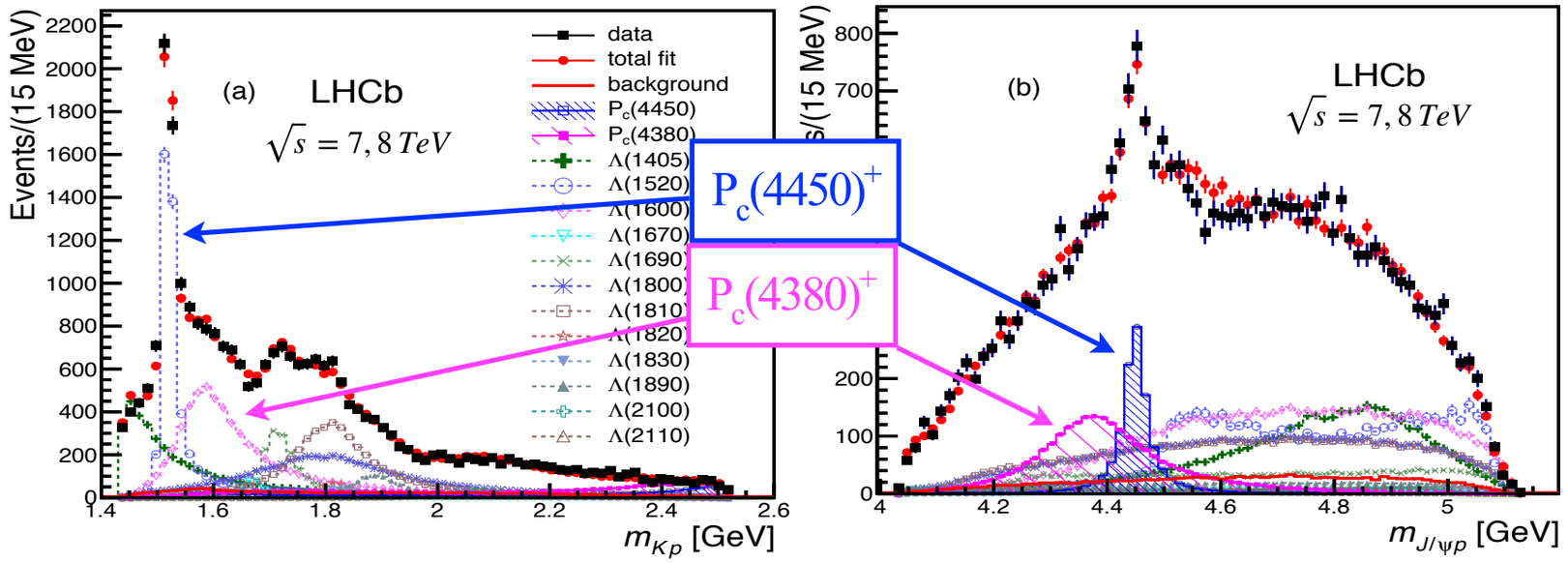


Exotics in $\Lambda_b^0 \to J/\psi\, pK^-$ decay

Previous analysis of $\Lambda_b^0 \to J/\psi\, pK^-$ with Run-I

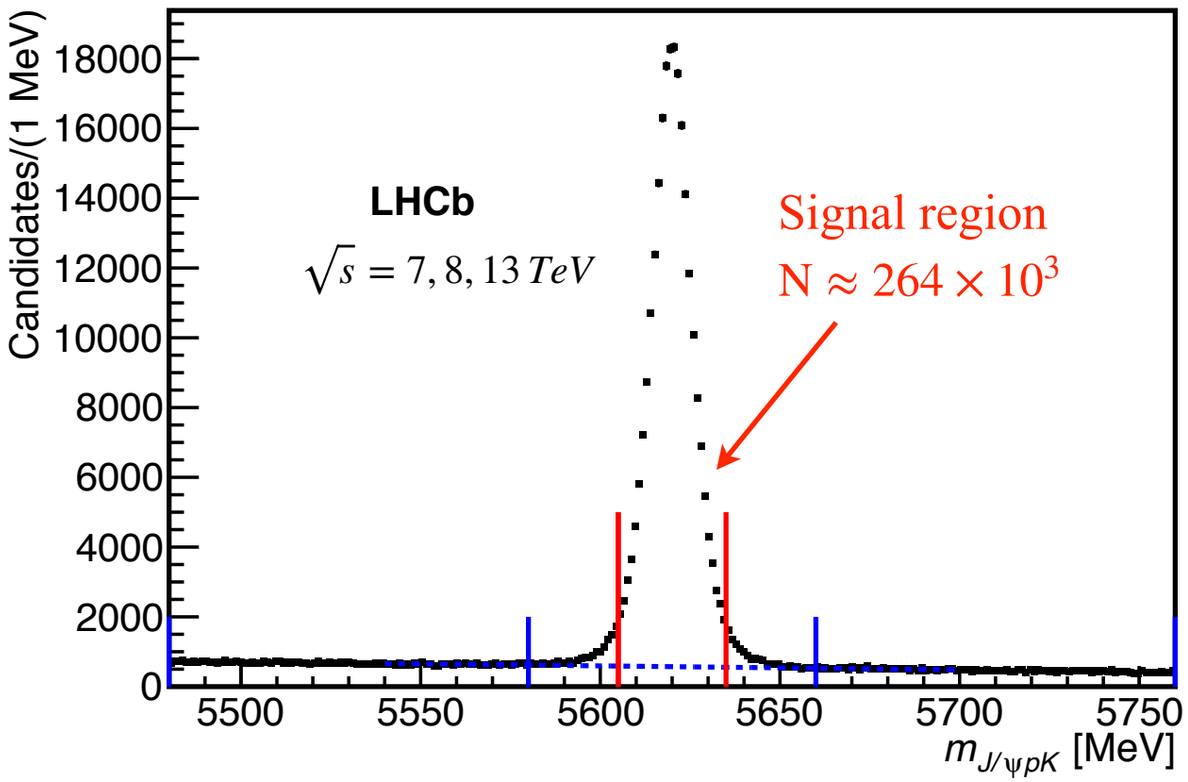
PRL 115 (2015) 072001

- In 2015 the exotic contributions $P_c(4380)^+$ and $P_c(4450)^+$ decaying to $J/\psi p$ observed by means of full amplitude analysis
- Model independent analysis reject non-exotic contributions model at the level of $>9\sigma$ [PRL 117 (2016) 082002]



Update of $\Lambda_b^0 \to J/\psi\, pK^-$ analysis with Run-I + Run-II

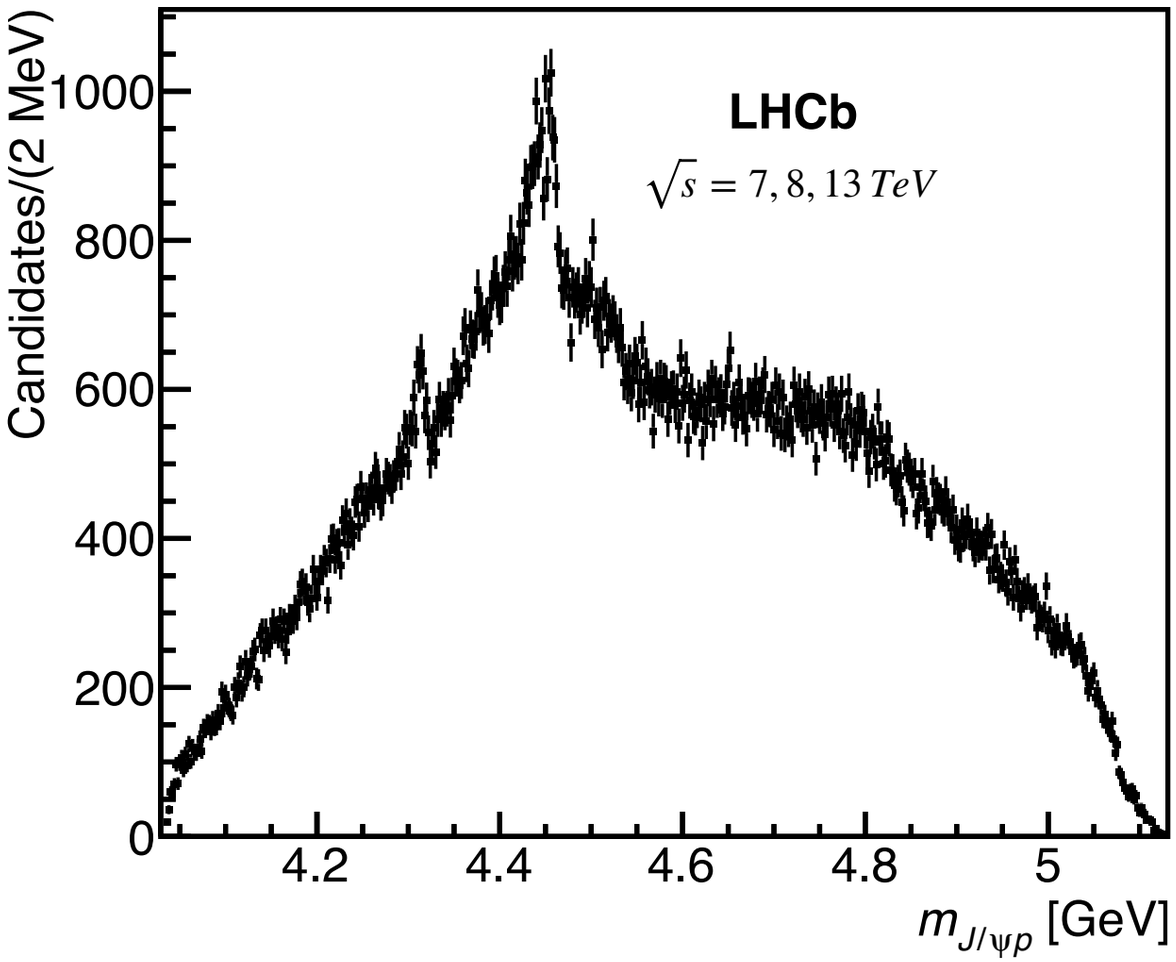
PRL 122 (2019) 222001

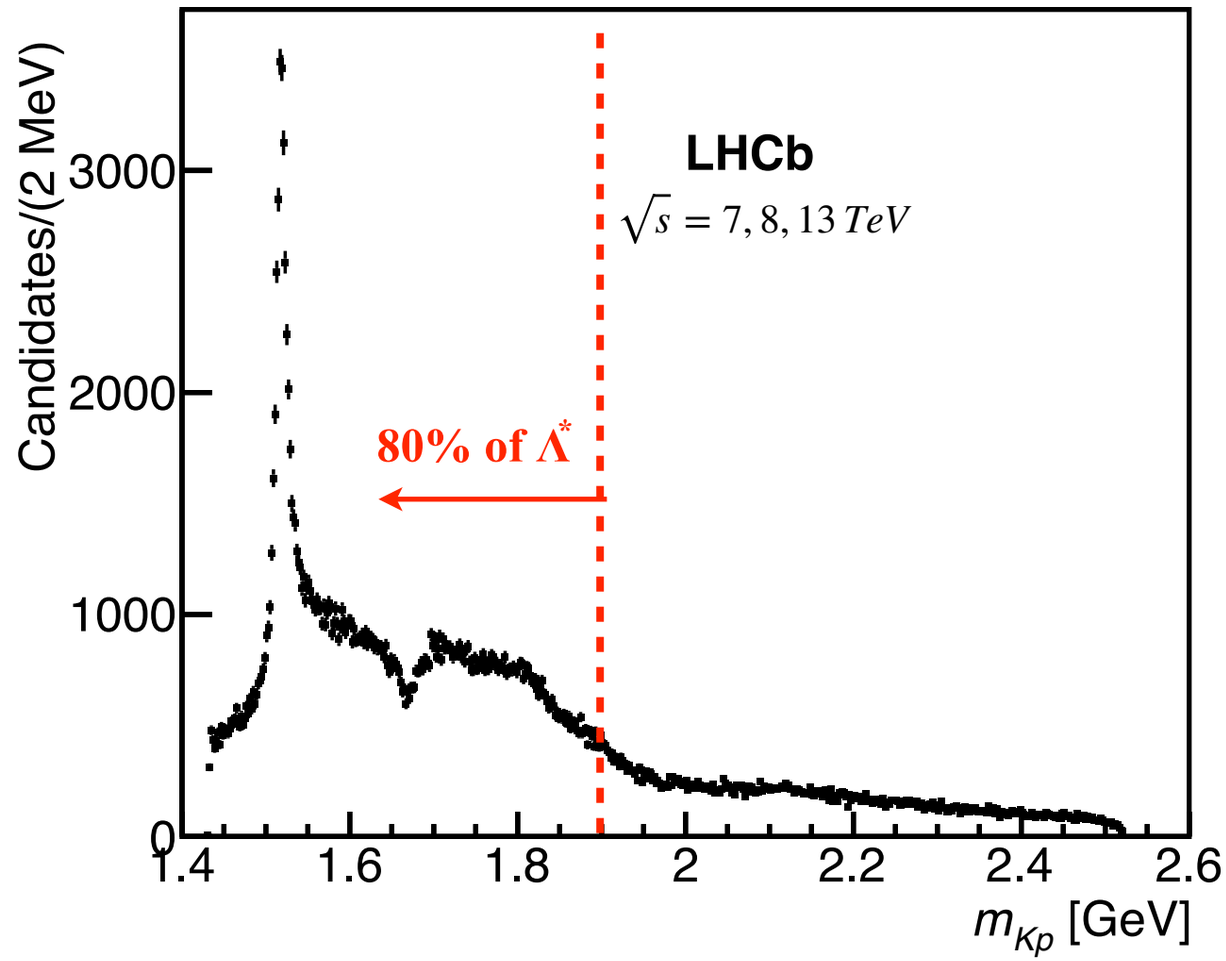


- Enhancement of statistics wrt Run1 only:
  - $\times 2$ (improved selection)
  - $\times 3$ (integrated luminosity)
  - $\times 1.5$ (increased cross-section at $\sqrt{s} = 13\text{TeV}$)
- In total **$\times 9$ larger dataset**

Exotics in $\Lambda_b^0 \to J/\psi\, pK^-$ decay

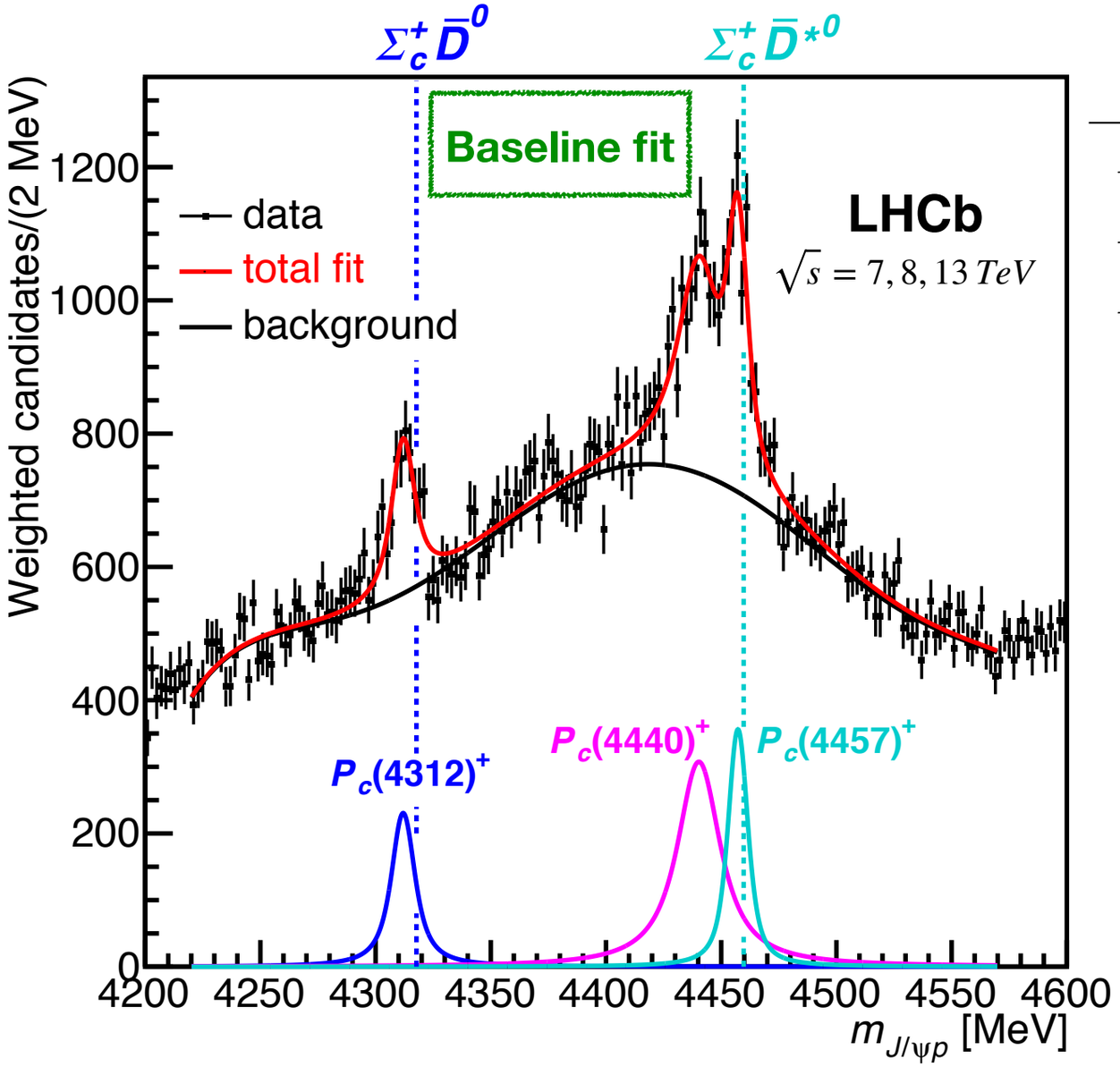
PRL 122 (2019) 222001





- Peaking structure at $4450\ \mathrm{MeV}$ confirmed (resolved in two narrow structures)
- A new peak (previously one-bin bump) seen
- Amplitude analysis faces challenge and takes time
- Simplified approach: 1D fits of $\mathrm{m(J/\psi p)}$ distribution
- To suppress Λ^* contribution:
  - apply cut $\mathrm{m(J/\psi p)} > 1.9\ \mathrm{MeV}$
  - apply weights according to the inverse Λ^* background density (as a function of $\cos(\theta_{\mathrm{Pc}})$)

Exotics in $\Lambda_b^0 \to J/\psi\, pK^-$ decay



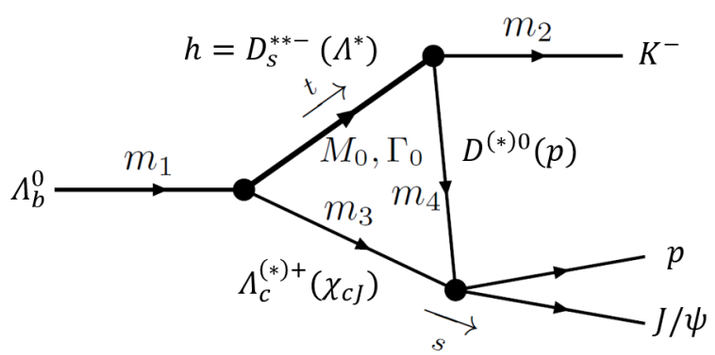
PRL 122 (2019) 222001

Fit results:

State	M [MeV]	Γ [MeV]	(95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)

- **7.3σ** for new $P_c(4312)^+$
- **5.4σ** for 2-peak structure ($P_c(4440)^+$ and $P_c(4457)^+$) wrt 1-peak hypothesis
- Large systematic uncertainty due to unknown interference terms
  - Established from the range of alternative fits including ones that take into account interference between BW amplitudes. No significant change to fit-quality with respect to incoherent sum of BW (baseline model)

- Near threshold masses and narrow resonances favour the hypothesis of baryon-meson molecule states
- $P_c(4457)^+$ could be generated by triangle diagrams, while it is unlikely for $P_c(4312)^+$ and $P_c(4440)^+$
- Full amplitude is in progress, but it turns to be quite complicated, therefore, requires more time



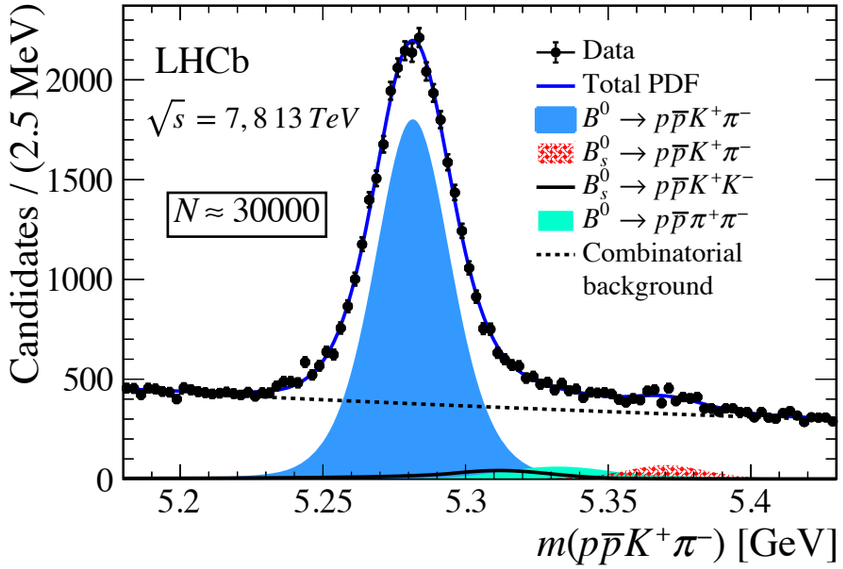
$\eta_c\pi^-$ resonance in $B^0 \to \eta_c K^+\pi^-$ decays

Eur.Phys.J. C78 (2018) 1019

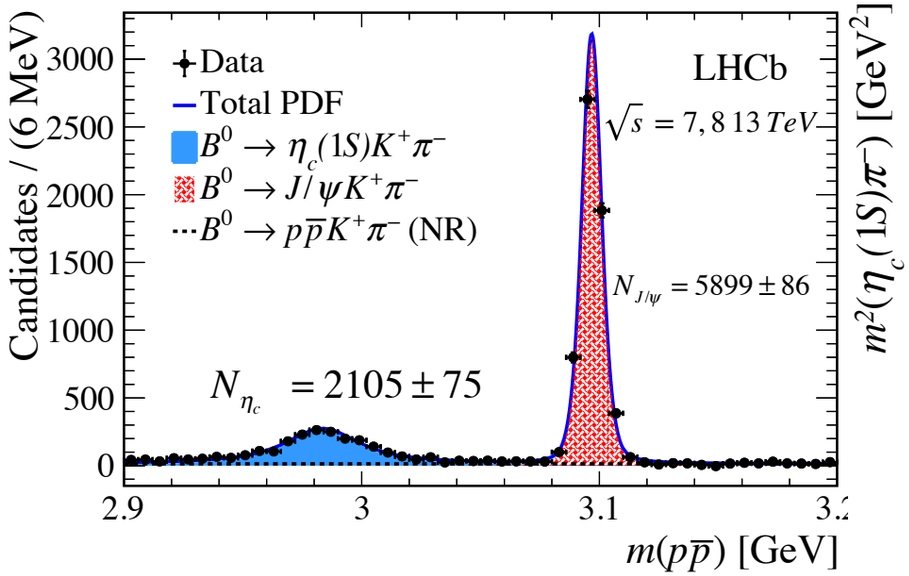
Exotics decaying to chromium:

- In $J/\psi p$, $J/\psi\pi^-$, $J/\psi\pi^+\pi^-$, $J/\psi\phi$, $J/\psi\gamma$, $\psi(2S)\pi^-$, $\psi(2S)\gamma$, $\chi_{c1}\pi^+$, system containing vectors J/ψ, $\psi(2S)$, χ_{c1}
- But what about the ground state charmonium $\eta_c(1S)$?
- The disadvantage is mostly hadronic decay modes ($p\bar{p}$ is one of them)

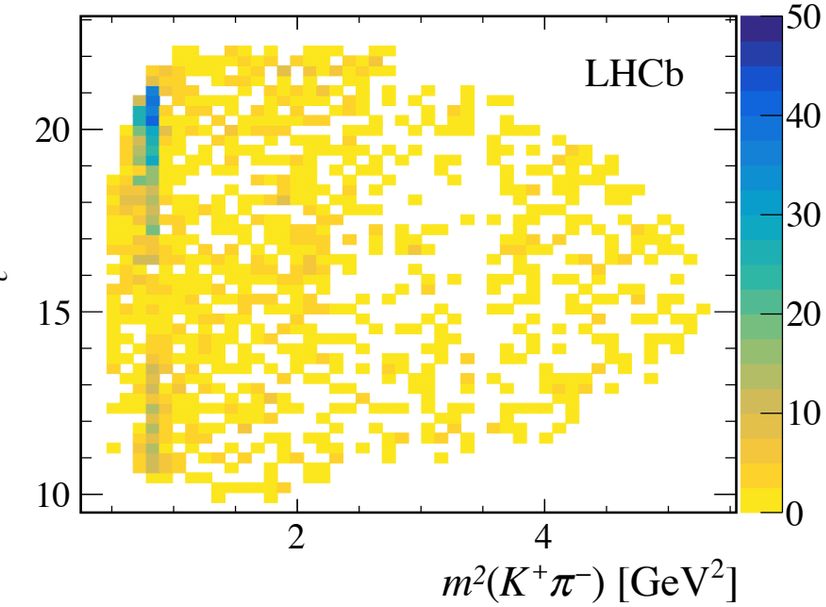
$B^0 \to p\bar{p}K^+\pi^-$



$B^0 \to c\bar{c}[\to p\bar{p}]K^+\pi^-$



Dalitz plot after *sPlot*



- $B^0 \to \eta_c[\to p\bar{p}]K^+\pi^-$ signal extracted via 2D fit of $m(p\bar{p}K^+\pi^-)$ and $m(p\bar{p})$

Dalitz plot analysis

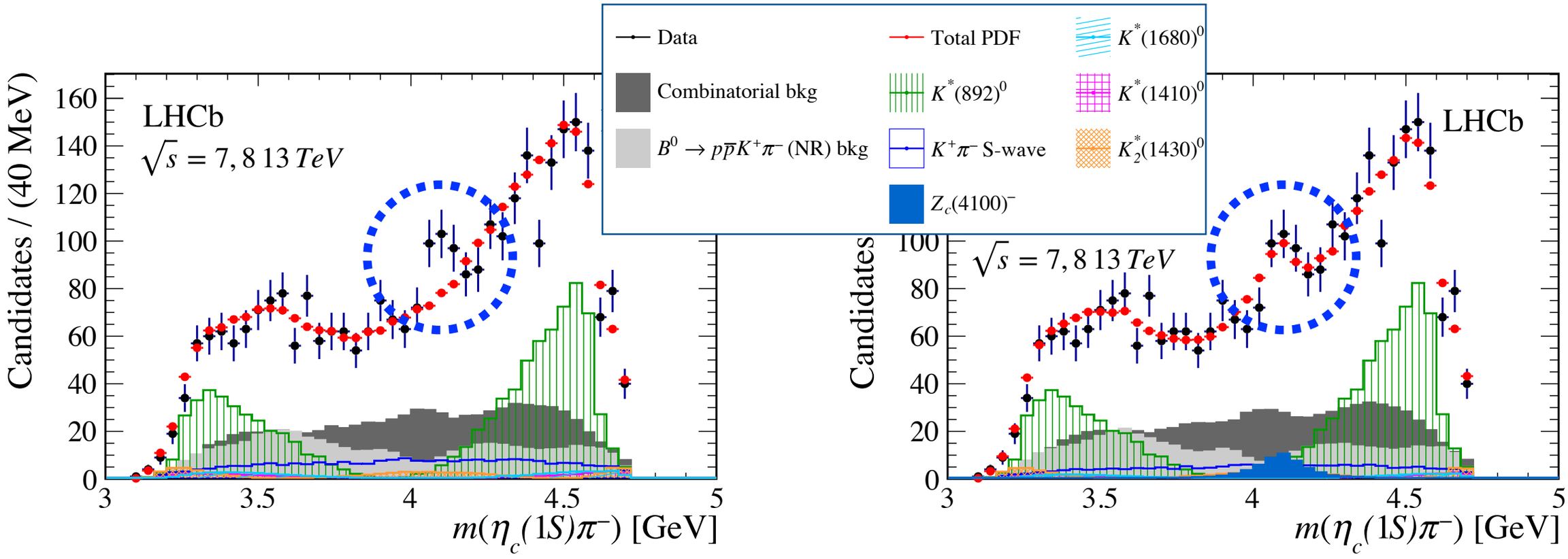
- Decay amplitude: sum of resonant $K^+\pi^-$ + non-resonant processes
- Six K^{*0} resonances give significant contributions
- Exotic $Z_c(4100)^- \to \eta_c\pi^-$ contribution added to improve the fit

$\eta_c\pi^-$ resonance in $B^0 \to \eta_c K^+\pi^-$ decays

Eur.Phys.J. C78 (2018) 1019

$K^+\pi^-$ only contributions

$K^+\pi^-$ and $\eta_c\pi^-$ contributions



- Good description is achieved by adding an exotic $Z_c(4100)^- \to \eta_c\pi^-$ component
- Evidence for exotic $Z_c(4100)^-$ resonance (3.4σ significance considering systematics)
- Both $J^P = 0^+$ and $J^P = 1^-$ are consistent with the data
- Mass and width are measured:

$$M = 4096 \pm 20^{+18}_{-22}\ \text{MeV}/c^2, \quad \Gamma = 152 \pm 58^{+60}_{-35}\ \text{MeV}$$

Conclusion

- The LHCb experiment provides a significant contribution to the knowledge of charm and charmonium spectroscopy:
  - Charmed baryons lifetime measurement: Ω_c^0, Λ_c^+, Ξ_c^+ and Ξ_c^0 [Run I: $3\,fb^{-1}$]
  - Charmonia and charmonium-like exotics:
    - New charmonium state $X(3842)$ compatible with $\psi_3(1^3D_3)$ [Run I+II: $9\,fb^{-1}$]
    - 3 narrow pentaquark candidates: $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ [Run I+II: $9\,fb^{-1}$]
    - Evidence for an $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)K^+\pi^-$ decays [Run I+II: $4.7\,fb^{-1}$]
- Looking forward for new results!

For more LHCb results see talks by:

Vladimir Shevchenko, Dmitrii Pereima, Pavel Krokovny, Evgenii Kurbatov

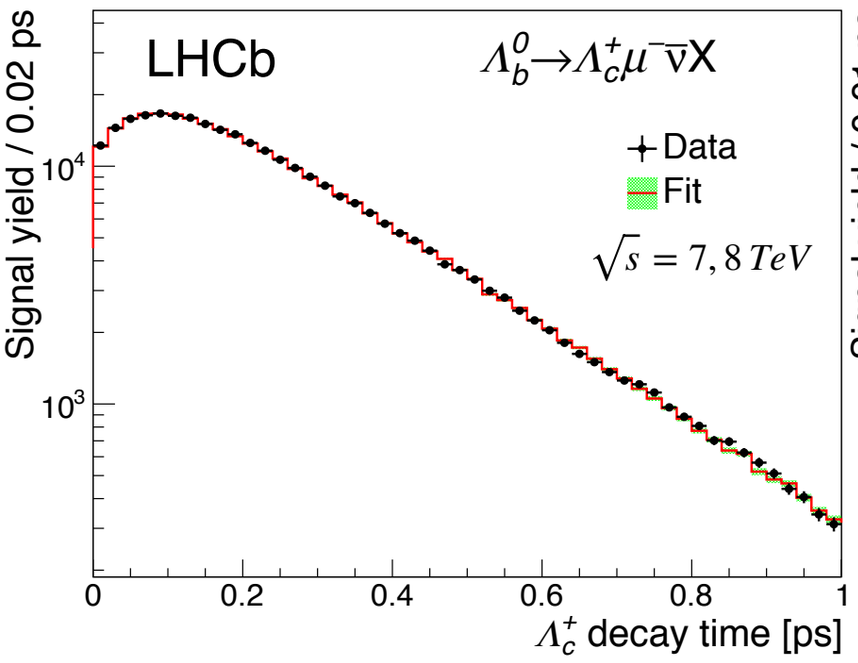
Backup slides

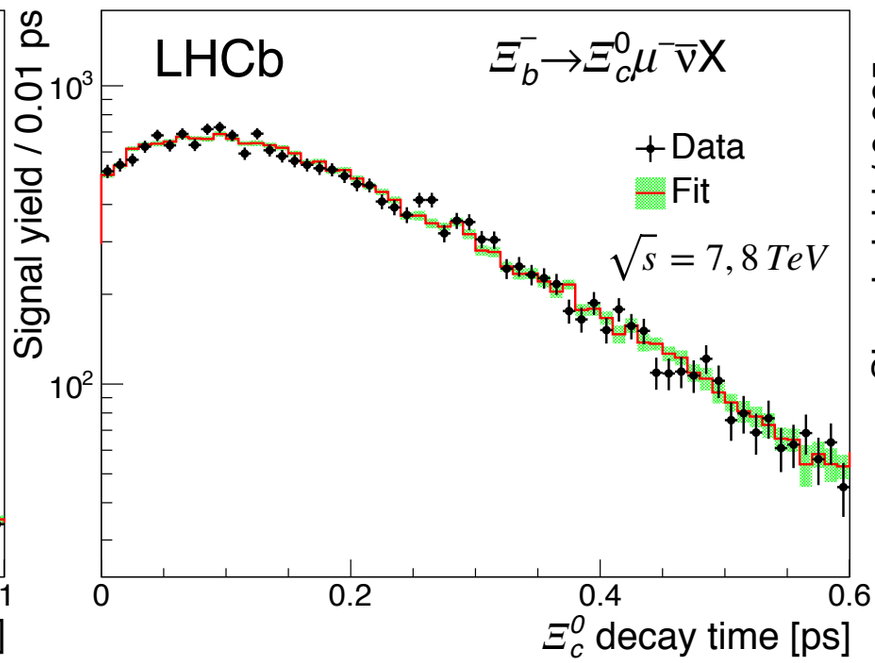
Lifetime of the charmed baryons

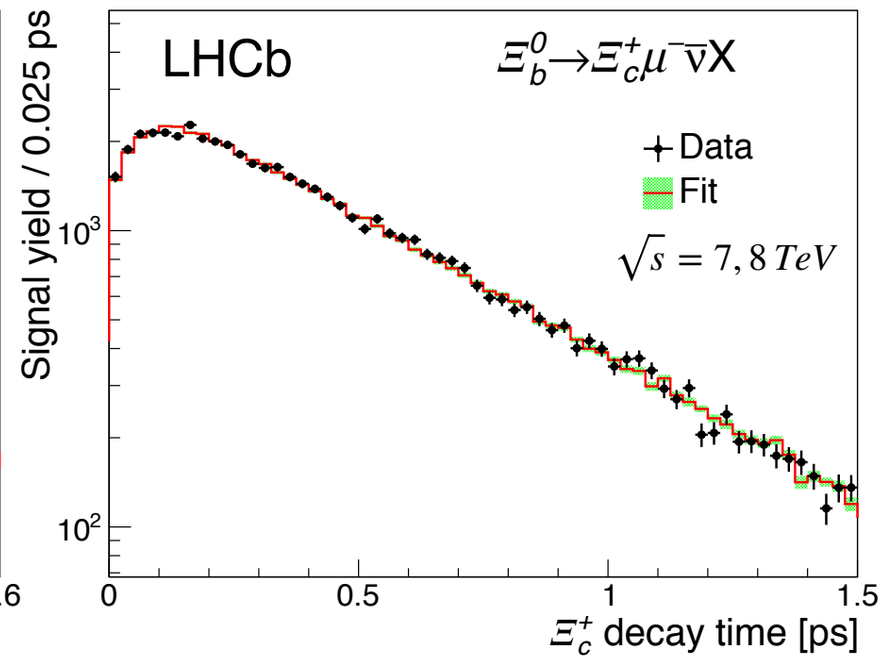
PRL 121 (2018) 092003
PRD (2019) 032001

Fits of lifetime distributions

$\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\bar{\nu}_\mu X$ $\Xi_b^- \to \Xi_c^0(\to pK^-K^-\pi^+)\mu^-\bar{\nu}_\mu X$ $\Xi_b^0 \to \Xi_c^+(\to pK^-\pi^+)\mu^-\bar{\nu}_\mu X$







Lifetime measurement results

$\tau_{\Lambda_c^+} = 203.5 \pm 1.0 \pm 1.3 \pm 1.4(\tau_{D^+})$ fs

$\tau_{\Xi_c^+} = 456.8 \pm 3.5 \pm 2.9 \pm 3.1(\tau_{D^+})$ fs

← In agreement with PDG

$\tau_{\Xi_c^0} = 154.5 \pm 1.7 \pm 1.6 \pm 1.0(\tau_{D^+})$ fs

$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2(\tau_{D^+})$ fs

← 3.3σ deviation wrt PDG

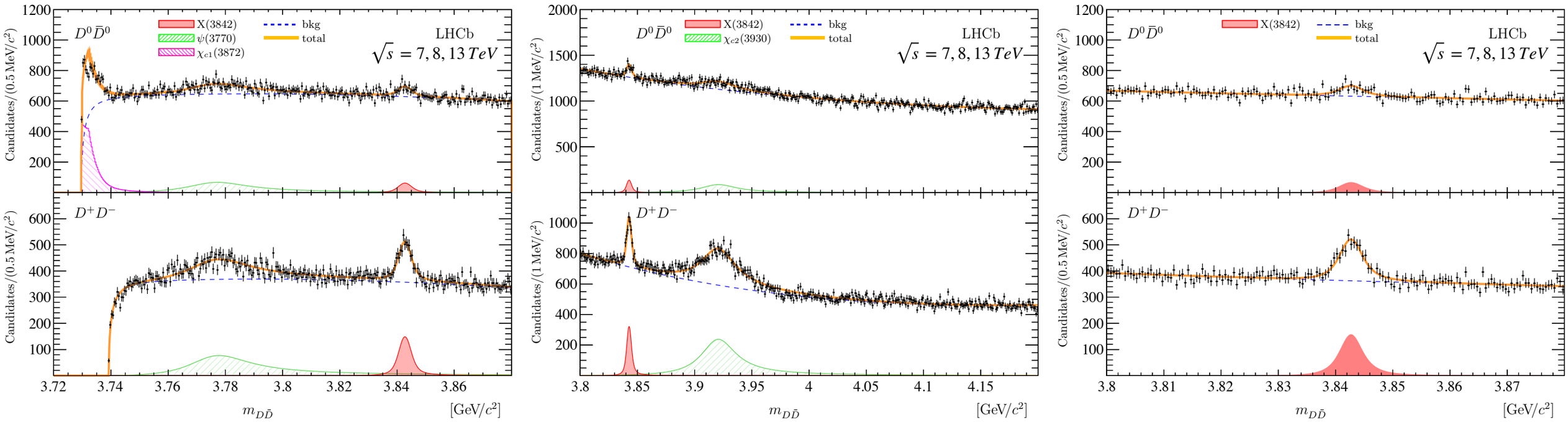
Lifetime hierarchy confirmed:

$\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$

Near threshold $D\bar{D}$ spectroscopy

JHEP 07 (2019) 035

Simultaneous fit for D^+D^- and $D^0\bar{D}^0$ candidates



- Observation of X(3842) — new narrow charmonium state

$$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12\,\text{MeV}/c^2; \qquad \Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35\,\text{MeV}$$

- Mass and width are compatible with $\psi_3(1^3D_3)$ charmonium with $J^{PC}=3^{--}$
- Prompt hadroproduction of the $\chi_{c2}(3930)$ and $\psi(3770)$ states is observed for the first time.

The measured parameters:

$$\left.\begin{aligned} m_{\psi(3770)} &= 3778.1 \pm 0.7 \pm 0.6\,\text{MeV}/c^2 \\ m_{\chi_{c2}(3930)} &= 3921.9 \pm 0.6 \pm 0.2\,\text{MeV}/c^2; \\ \Gamma_{\chi_{c2}(3930)} &= 36.6 \pm 1.9 \pm 0.9\,\text{MeV} \end{aligned}\right\}$$

2σ tension

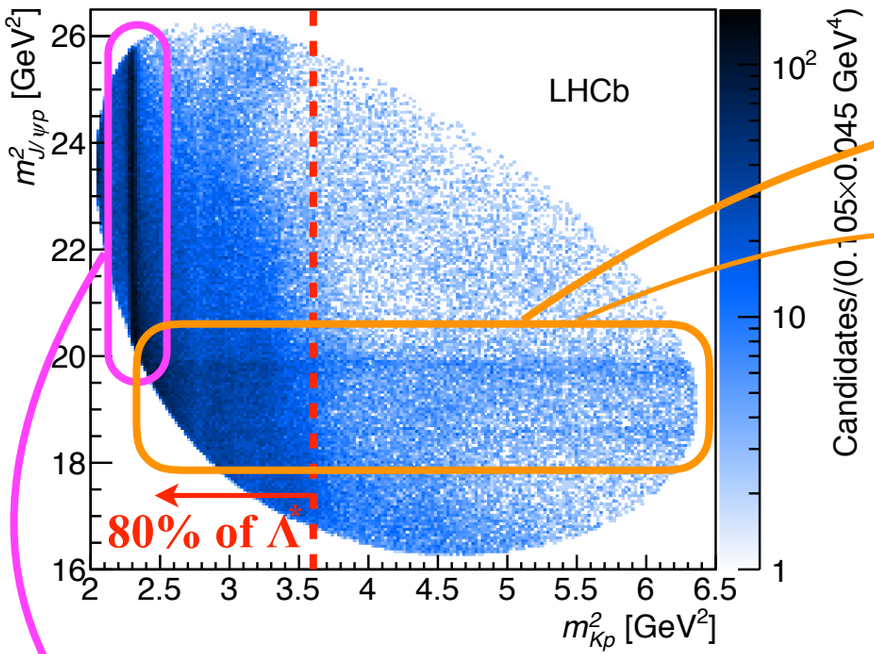
PDG:

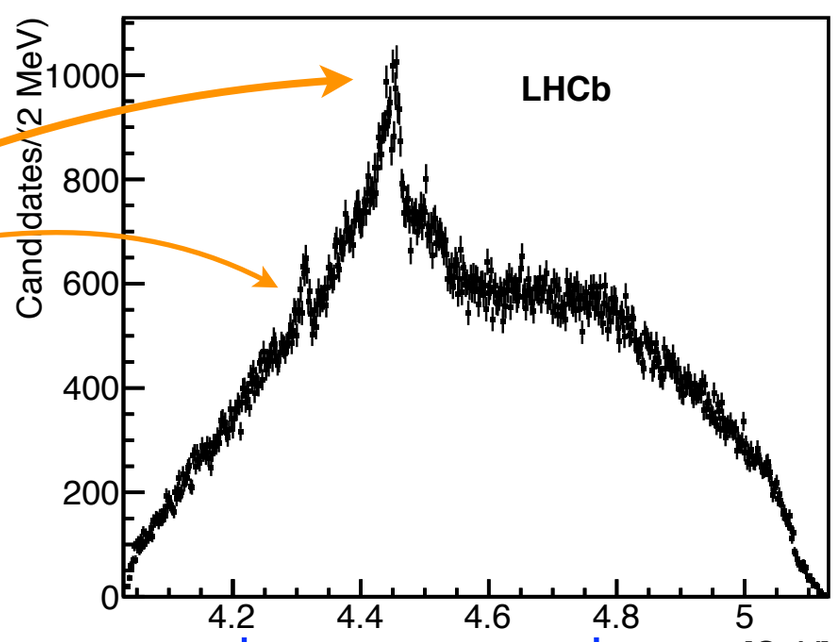
$$\left\{\begin{aligned} m_{\chi_{c2}(3930)} &= 3927.2 \pm 2.6\,\text{MeV}/c^2; \\ \Gamma_{\chi_{c2}(3930)} &= 24 \pm 6\,\text{MeV} \end{aligned}\right.$$

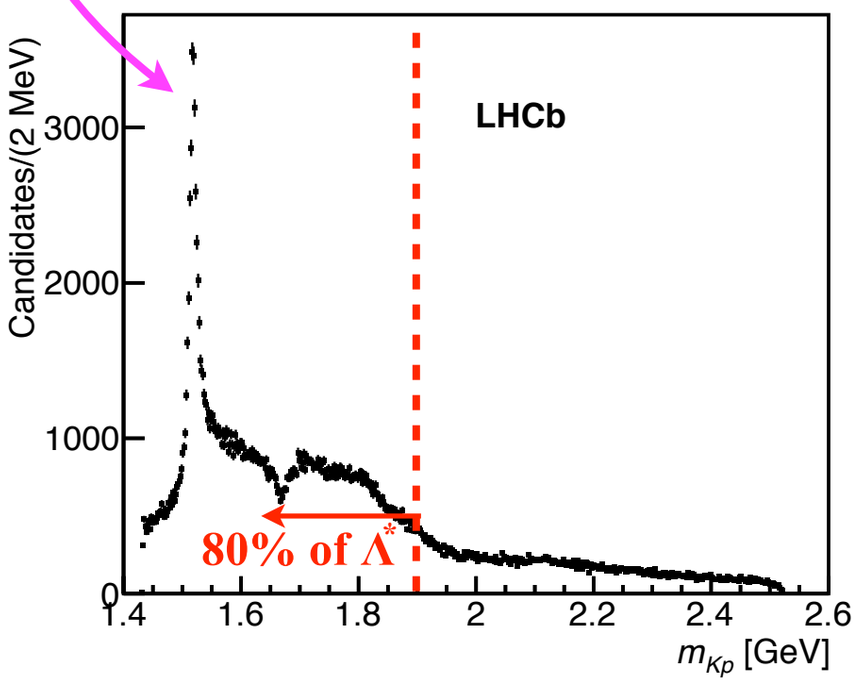
Exotics in $\Lambda_b^0 \to J/\psi\, pK^-$ decay

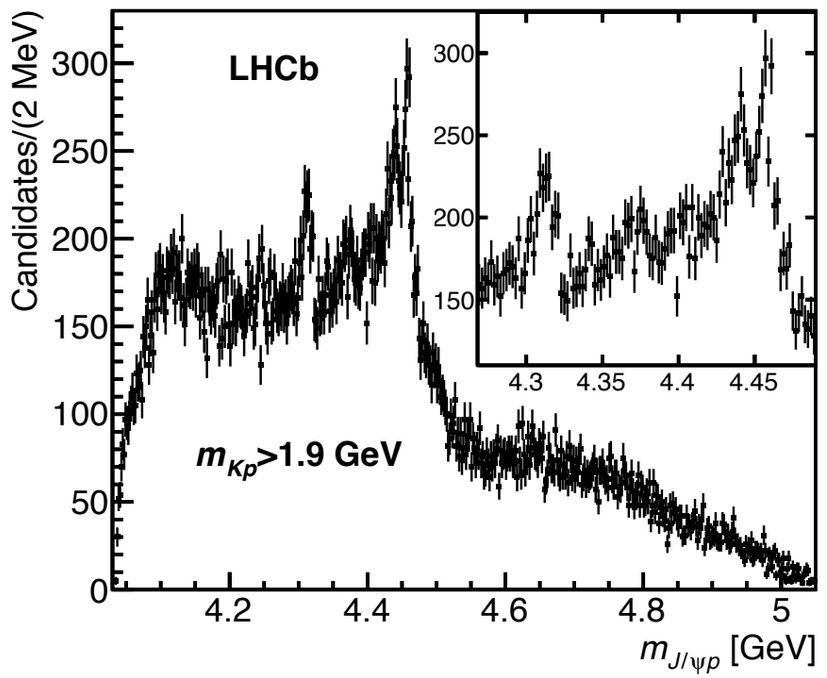
PRL 122 (2019) 222001

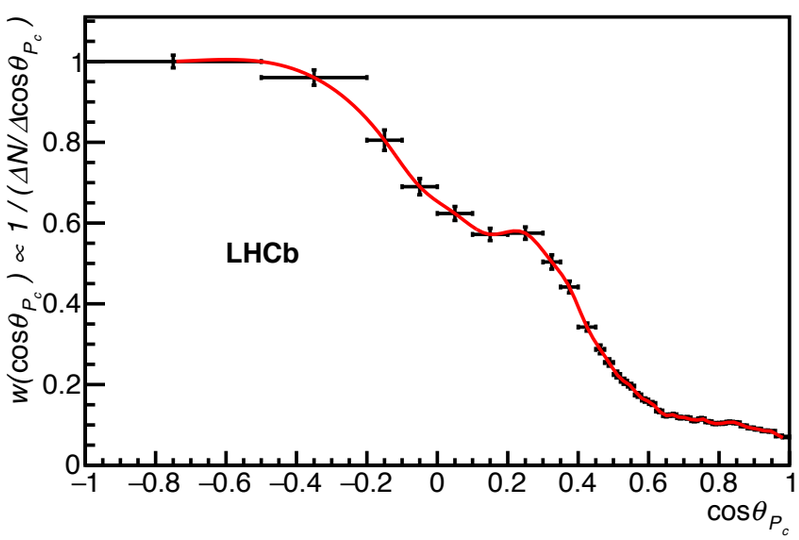
- Peaking structure at 4450 MeV confirmed (resolved in two narrow structures)
- A new peak (previously one-bin bump) seen
- Amplitude analysis faces challenge and takes time
- Simplified approach: 1D fits of m(J/ψp) distribution
- To suppress Λ^* contribution:
  - apply cut m(J/ψp) > 1.9 MeV
  or
  - apply weights according to the inverse Λ^* background density:





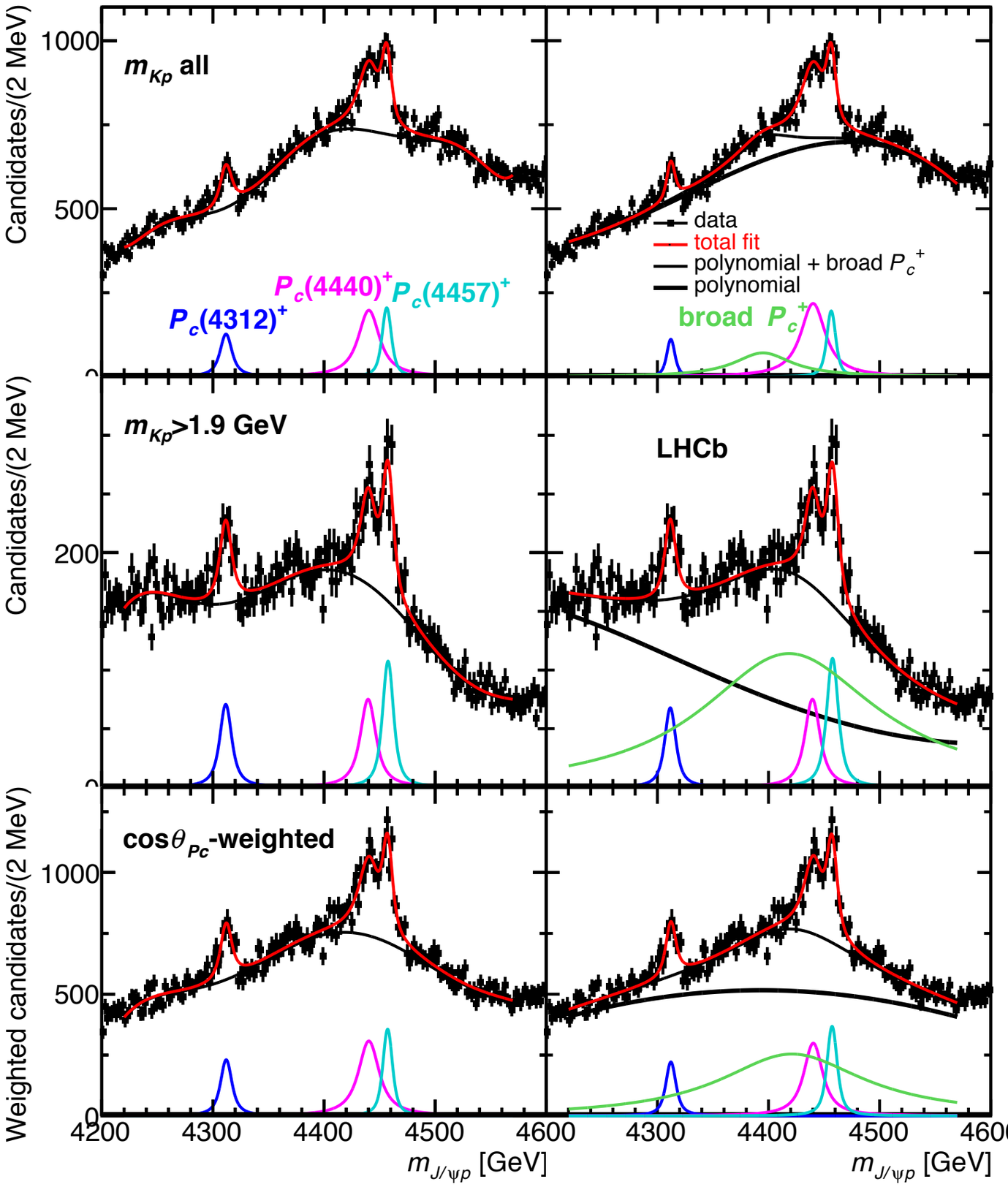






Exotics in $\Lambda_b^0 \to J/\psi\, pK^-$ decay

PRL 122 (2019) 222001



Full range

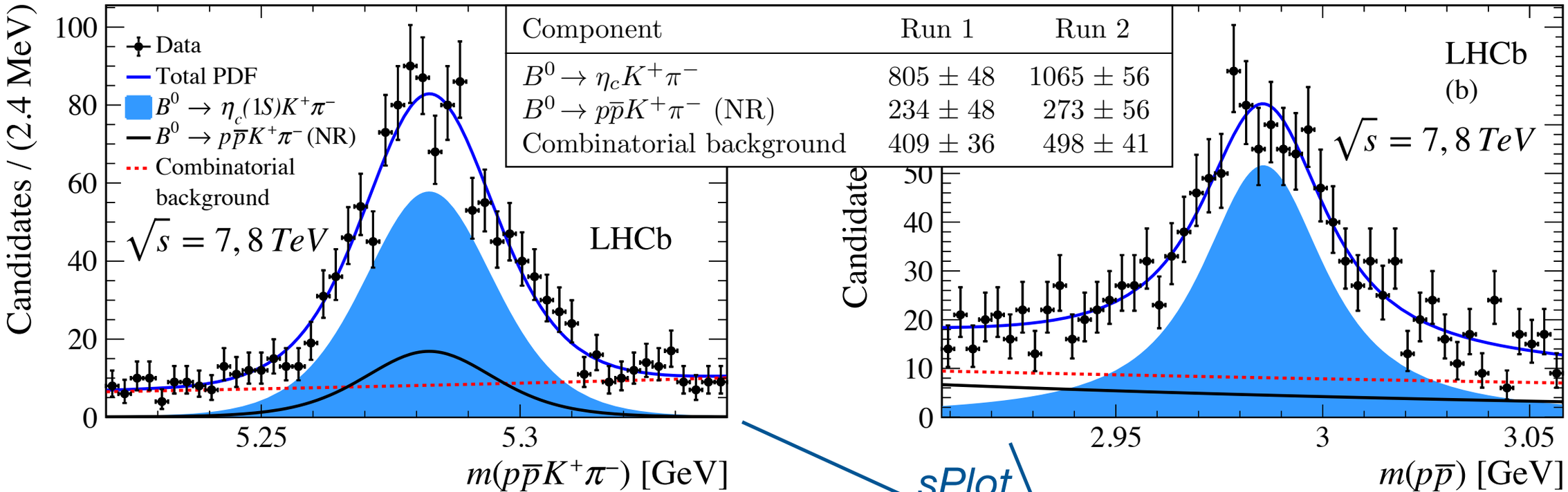
After cut $m(J/\psi p) > 1.9$ MeV

Weighted on $\cos(\theta_{Pc})$

$\eta_c\pi^-$ resonance in $B^0 \to \eta_c K^+\pi^-$ decays

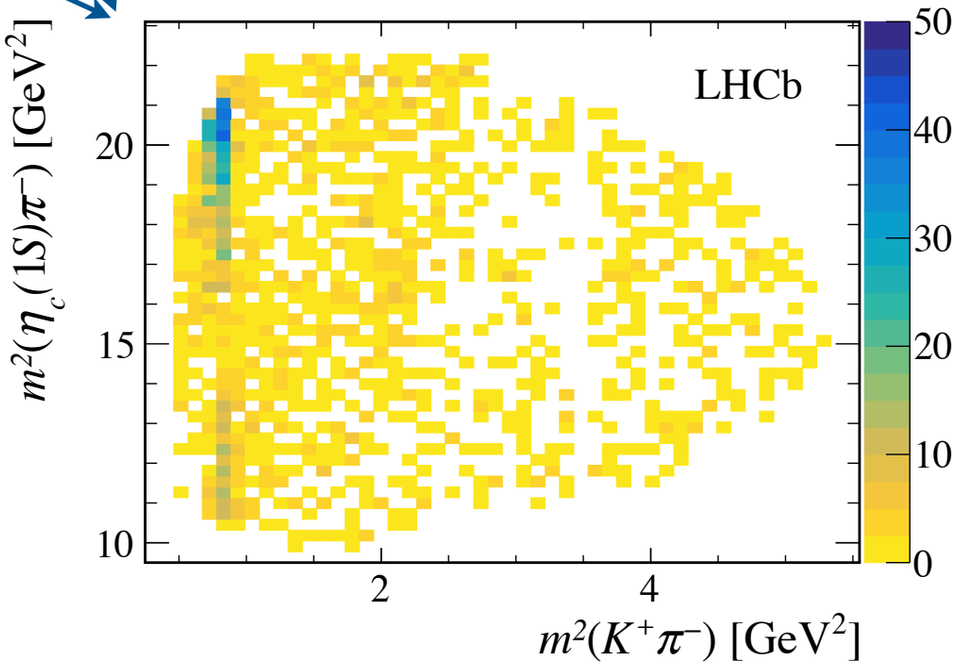
Eur.Phys.J. C78 (2018) 1019

2D fit $m(p\bar{p}K^+\pi^-)$-$m(p\bar{p})$ for Run-I and Run-II



Component	Run 1	Run 2
$B^0 \to \eta_c K^+\pi^-$	805 ± 48	1065 ± 56
$B^0 \to p\bar{p}K^+\pi^-$ (NR)	234 ± 48	273 ± 56
Combinatorial background	409 ± 36	498 ± 41

sPlot



Dalitz plot analysis

- Decay amplitude: sum of resonant $K^+\pi^-$ + non-resonant processes
- Six K^{*0} resonances give significant contributions
- Exotic $Z_c(4100)^- \to \eta_c\pi^-$ contribution added to improve the fit