Heavy Flavor Physics and Hadron Spectroscopy

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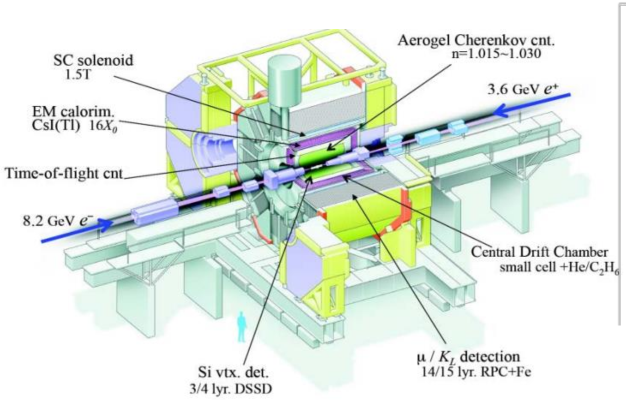
Syracuse University

A very broad topic – cover only new highlights!

More on spectroscopy in talks on Tuesday by:
Roberta Cardinale, Liang Yan, Yuji Kato

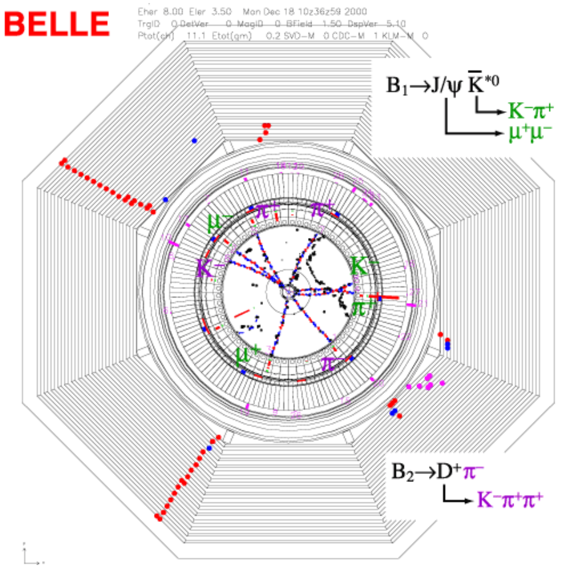
The XXVII International Workshop on Deep Inelastic Scattering and Related Subjects (DIS2019)
Torino, Italy, from April 8 to April 12, 2019

New results: experimental actors



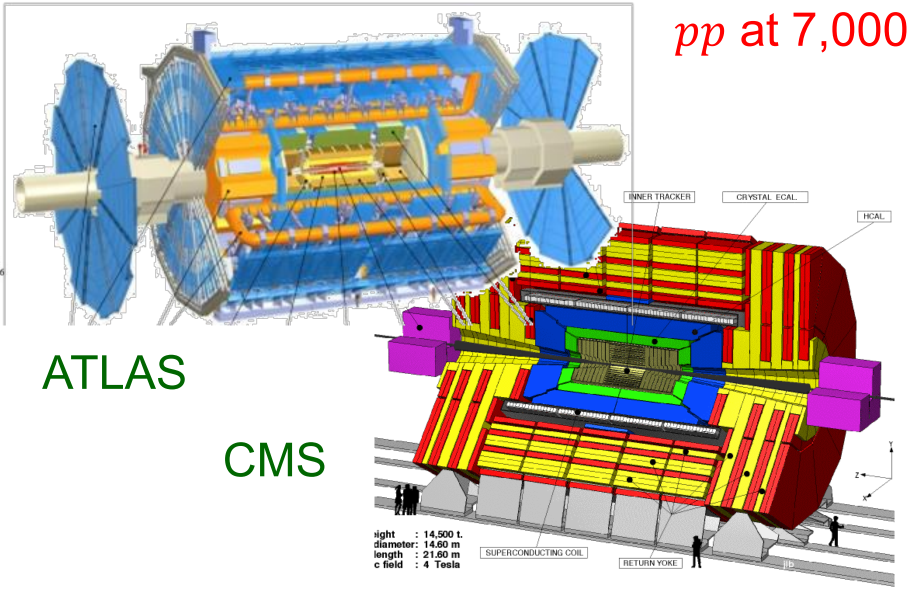
e^+e^- at 10 GeV

BELLE

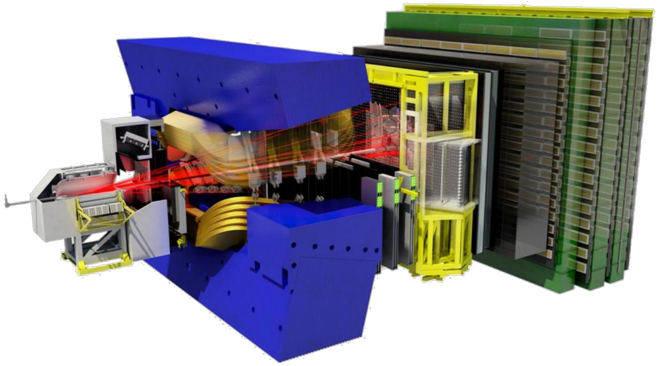


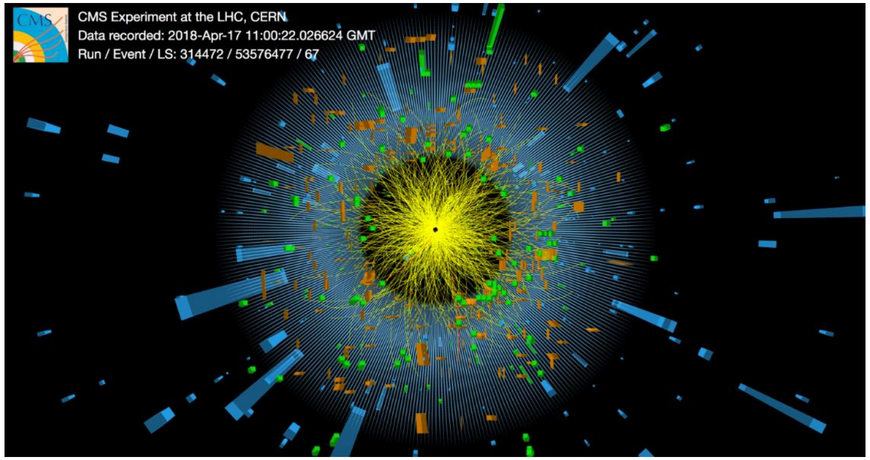
clean environment, low cross-section

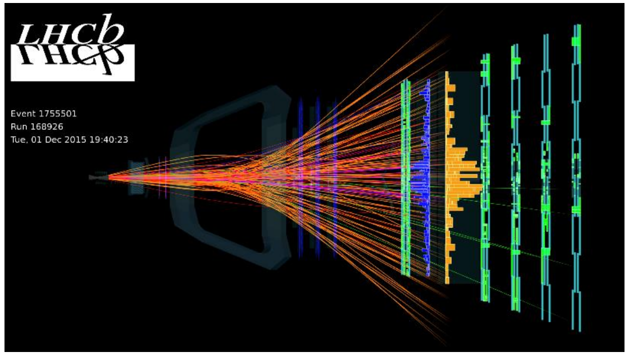
pp at 7,000-13,000 GeV



LHCb



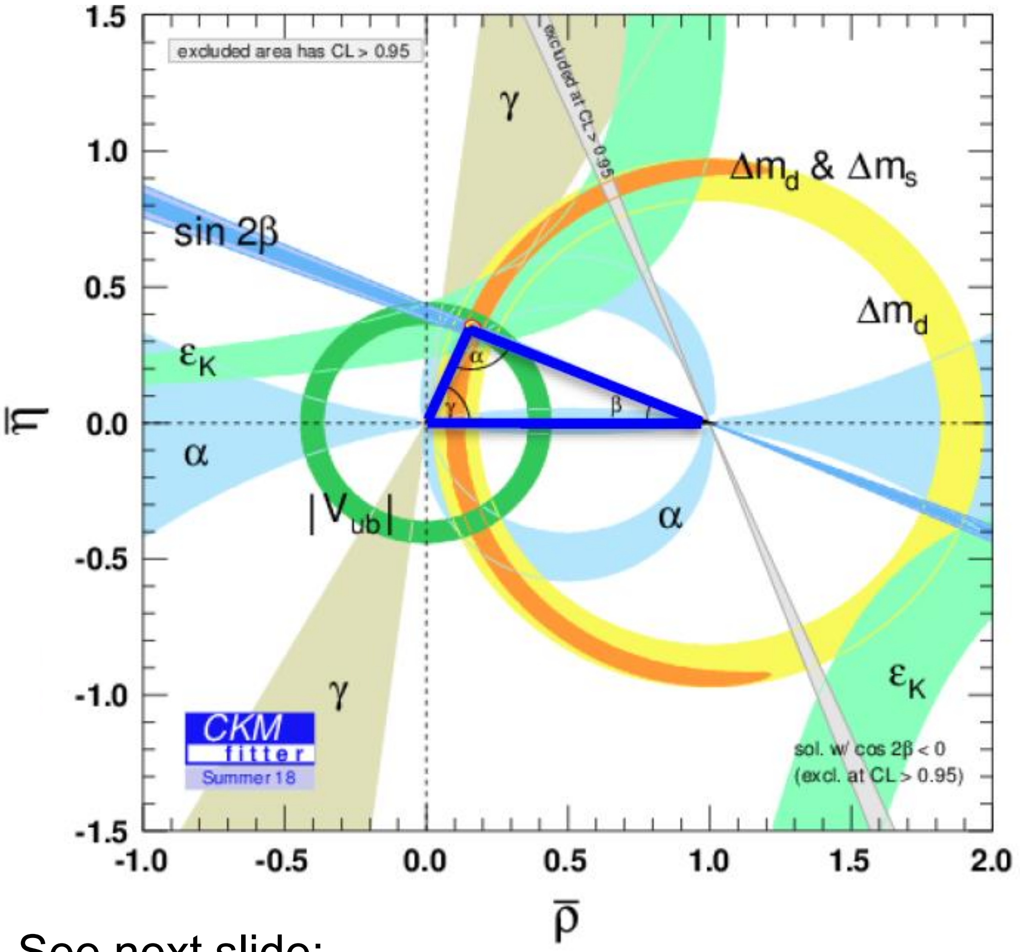




busy environment, high cross-section

Quark flavor transitions – unitarity triangle

Unitarity triangle



- Tremendous success of the CKM paradigm!
  - All available measurements agree with it to the current level of precision

Kobayashi & Maskawa
Nobel Prize 2008

- The game now is looking for BSM physics in corrections to the CKM picture

See next slide:

$\tilde{\varrho} = \rho(1-\lambda^2/2)$

$\tilde{\eta} = \eta(1-\lambda^2/2)$

Trees: γ, V_{ub}

Loops: everything else

Quark flavor transitions – CKM matrix

- Described by CKM matrix in Standard Model
- A complex phase in 3-generation matrix gives a rise to CPV. BSM physics likely to contribute additional CPV phases.
- Wolfenstein's parameterization depicts the measured structure of CKM well

$$\begin{array}{cc} & \begin{array}{ccc} \mathrm{d} & \mathrm{s} & \mathrm{b} \end{array} \\ \begin{array}{c} \mathrm{u} \\ \mathrm{c} \\ \mathrm{t} \end{array} & V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta V \end{array}$$

Good to λ^3~1%

$$\delta V = \begin{pmatrix} 0 & 0 & 0 \\ -iA^2\lambda^5\eta & 0 & 0 \\ A\lambda^5(\rho+i\eta)/2 & -A\lambda^4(1/2-\rho-i\eta) & 0 \end{pmatrix}$$

Complex phase η

mostly in V_{td}, V_{ub} (λ^3)

then a bit in V_{ts} (λ^4)

even less in V_{cd} (λ^5)

$\lambda^0 = 1$

$\lambda^1 = 0.23$

$\lambda^2 = 0.051$

$\lambda^3 = 0.012$

$\lambda^4 = 0.0026$

$\lambda^5 = 0.0006$

λ=0.226±0.001 (sinθ_C)

A=0.81±0.02

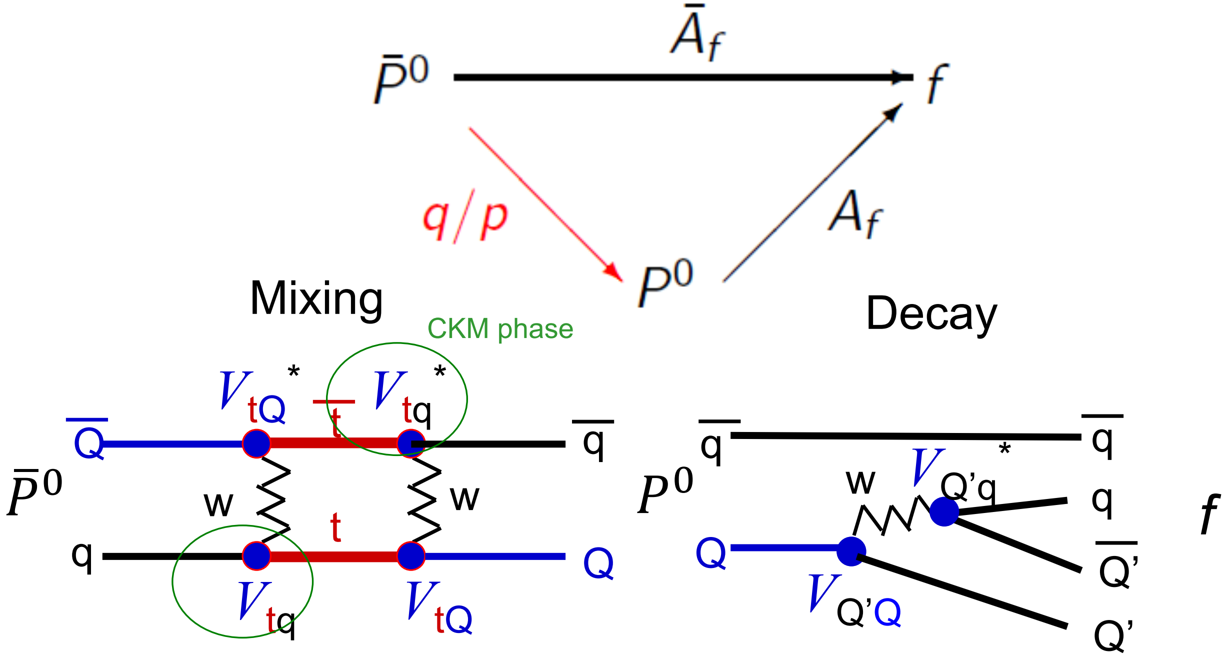
ρ,η depicted on the previous slide

Search for BSM in CP violation and mixing in neutral mesons

Flavour eigenstates

$$|P_{L,H}\rangle = p|P^0\rangle \pm q|\bar{P}^0\rangle$$

Mass eigenstates



Extra phases from BSM particles in the loop?

Mixing observables

- $\Delta m \equiv (m_H - m_L)$, $x = \Delta m/\Gamma$
- $\Gamma \equiv (\Gamma_L + \Gamma_H)/2$, $y = \Delta\Gamma/2\Gamma$
- $\Delta\Gamma \equiv \Gamma_L - \Gamma_H$

CPV in decay: $\left|\bar{A}_{\bar{f}}/A_f\right| \neq 1$ (“direct”)

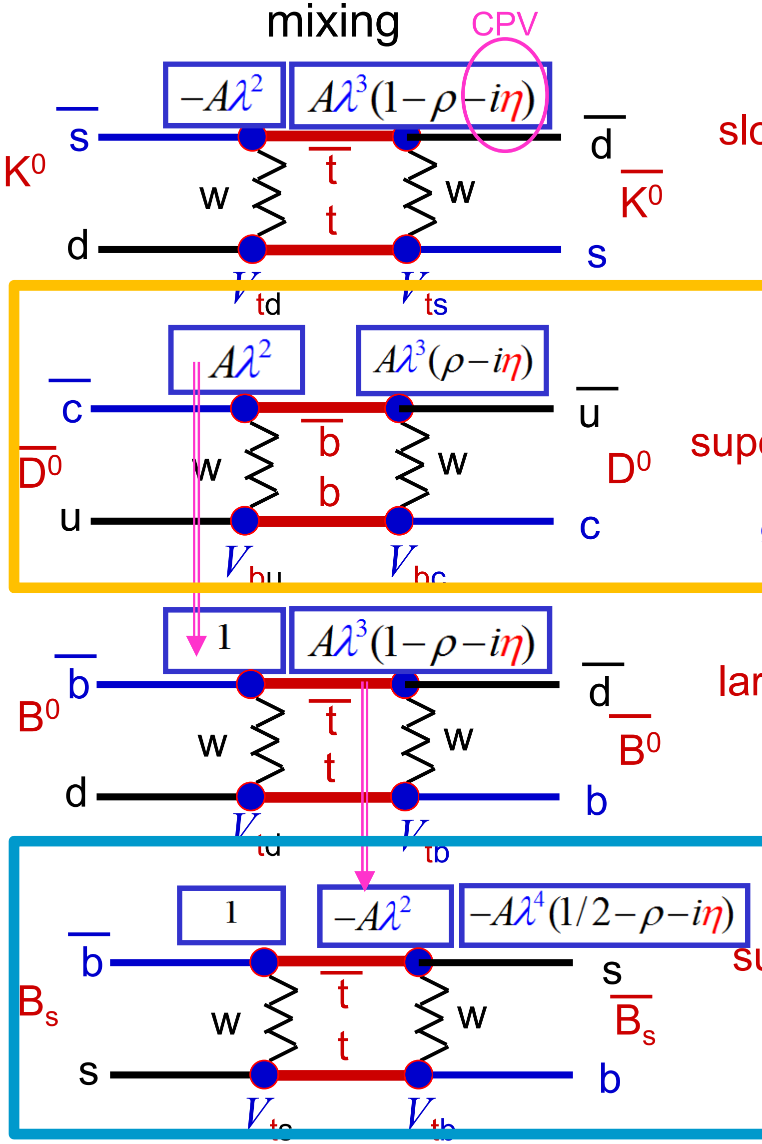
CPV in mixing: $|q/p| \neq 1$

CPV in interference between mixing and decay: $\phi \equiv \arg\left\{\frac{q}{p}\frac{A_f}{\bar{A}_f}\right\}$ (“indirect”)

CP violation and mixing in neutral mesons

mixing

dominant decay (lifetime)



slow mixing, small CPV

CPV discovery
KM hypothesis

super slow mixing, very small CPV

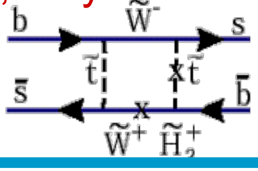
long distance diagrams can come into play;
good place to look for large non-SM CPV
but SM “background” not well predicted

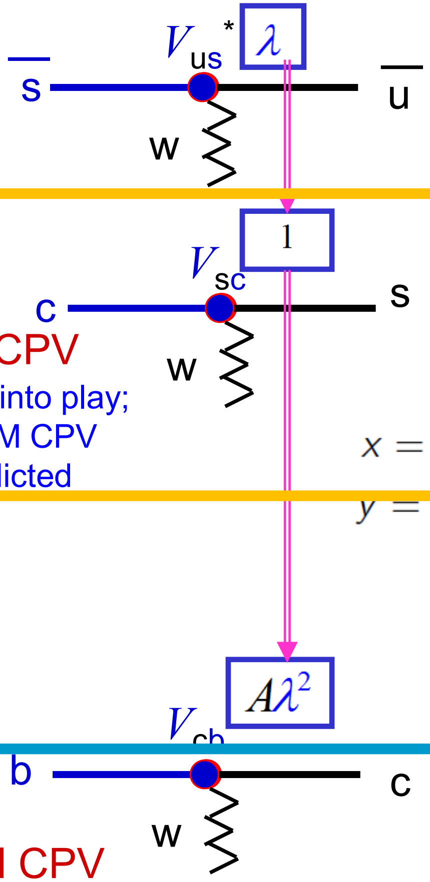
large mixing, large CPV

good place
to test SM CPV

super fast mixing, very small CPV

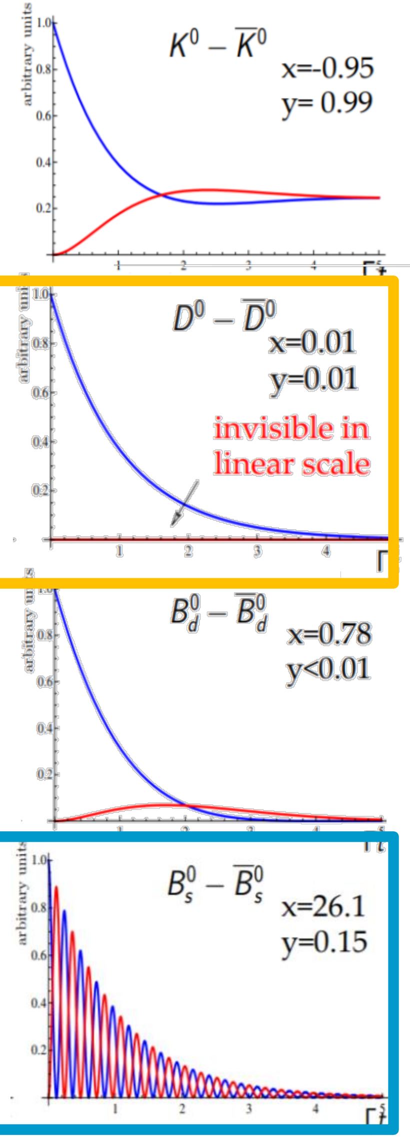
good place
to look for
non-SM CPV



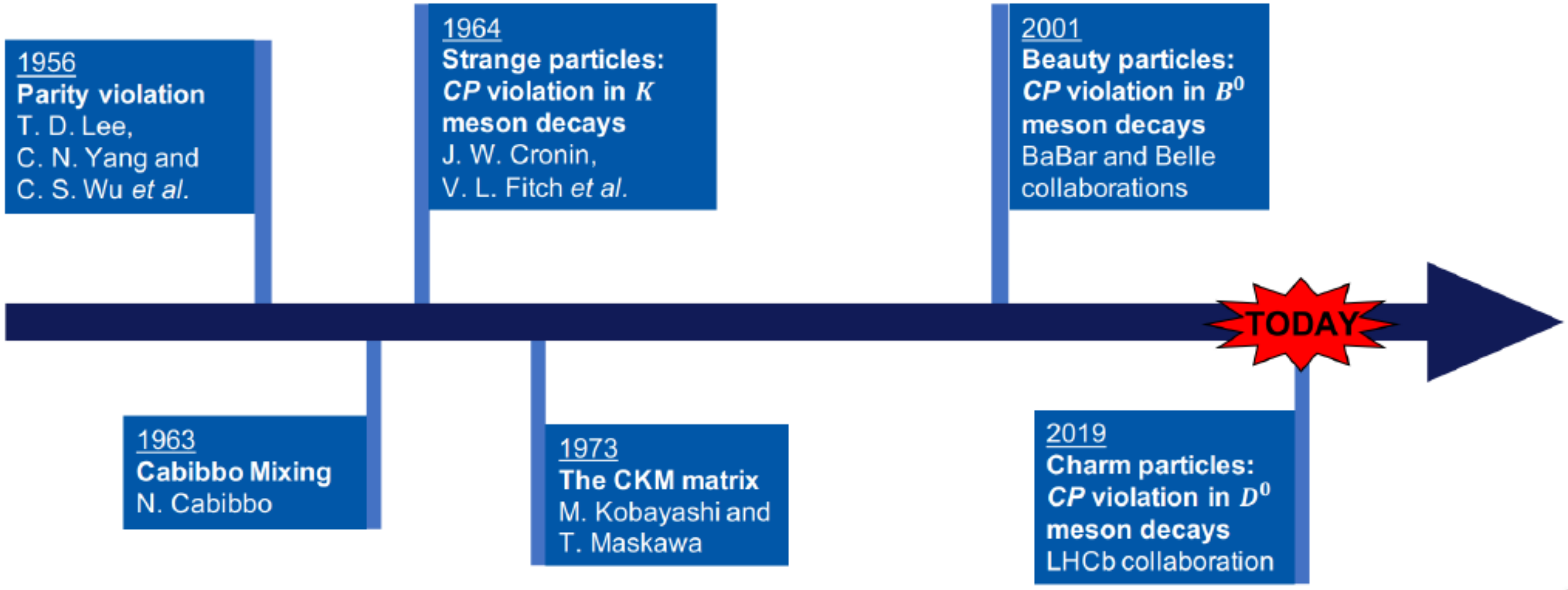


$x = \Delta m/\Gamma$

$y = \Delta\Gamma/2\Gamma$



Observation of CP violation in charm



1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
CP violation in K
meson decays
J. W. Cronin,
V. L. Fitch *et al.*

1973
The CKM matrix
M. Kobayashi and
T. Maskawa

2001
Beauty particles:
CP violation in B^0
meson decays
BaBar and Belle
collaborations

2019
Charm particles:
CP violation in D^0
meson decays
LHCb collaboration

LHCb Run 2, 6 fb^{-1}, 13 TeV [arXiv:1903.08726]

Observation of CP violation in charm

LHCb Run 2, 6 fb^{-1}, 13 TeV [arXiv:1903.08726]

- Run-2 results:
  - Well compatible with previous LHCb results and world average

$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$

$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

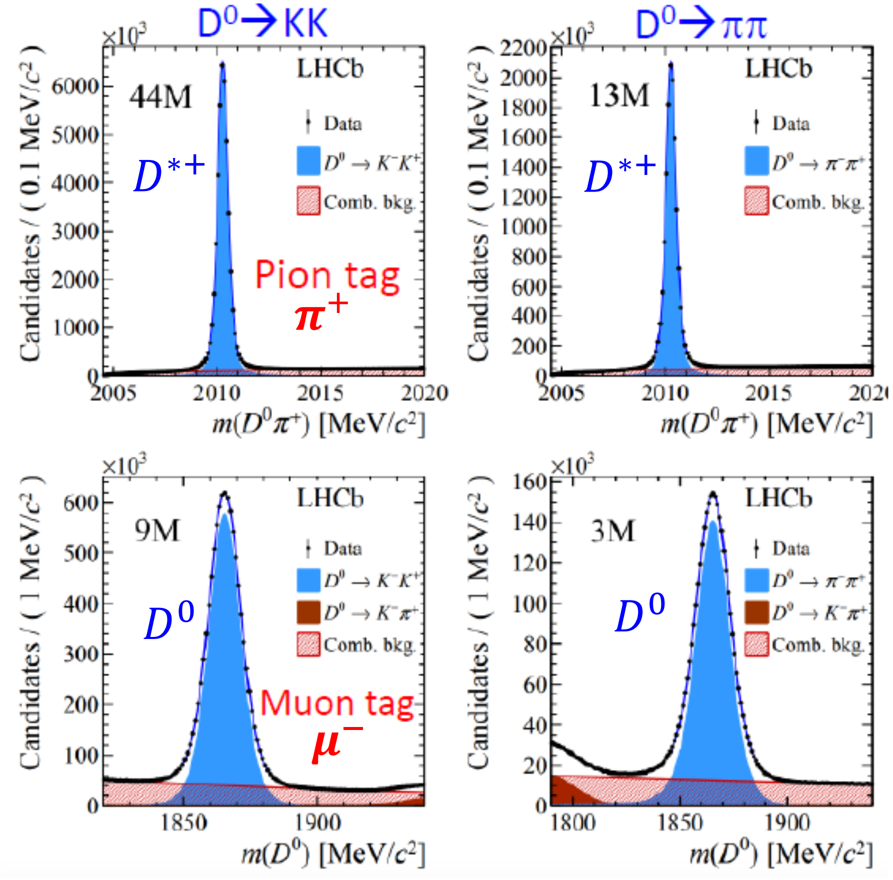
$D^{*+} \to D^0\pi^+$

$\bar{B} \to D^0\mu^-\nu_\mu X$

- Combination of Run-1 and Run-2 data gives

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

- CP violation observed at 5.3σ!
- Roughly compatible with the SM, which however is way more uncertain than data

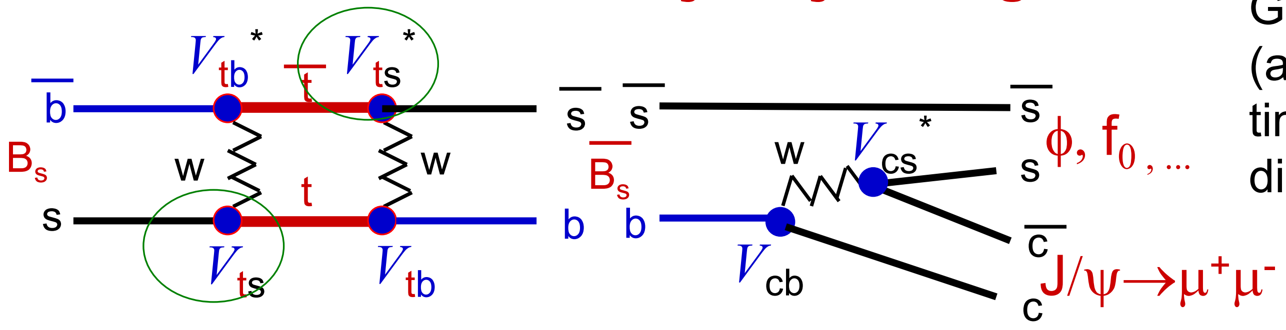


$$A_{raw} = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)}$$

$$\Delta A_{CP} = A_{raw}(KK) - A_{raw}(\pi\pi)$$
$$\cong A_{CP}(KK) - A_{CP}(\pi\pi)$$

Production and detection asymmetries cancel (after kinematical reweighting)

Phase of $B_s - \overline{B}_s$ mixing



Golden mode $B_s \to J/\psi\phi, \phi \to K^+K^-$ (analog of $B^0 \to J/\psi K_s$), but requires decay-time dependent angular analysis to disentangle CP even and odd contributions.

Phase-difference ϕ_s between the two diagrams, precisely predicted in the SM to be:

$$\phi_s = -2\lambda^2\eta = -0.0374 \pm 0.007 \text{ rad}$$

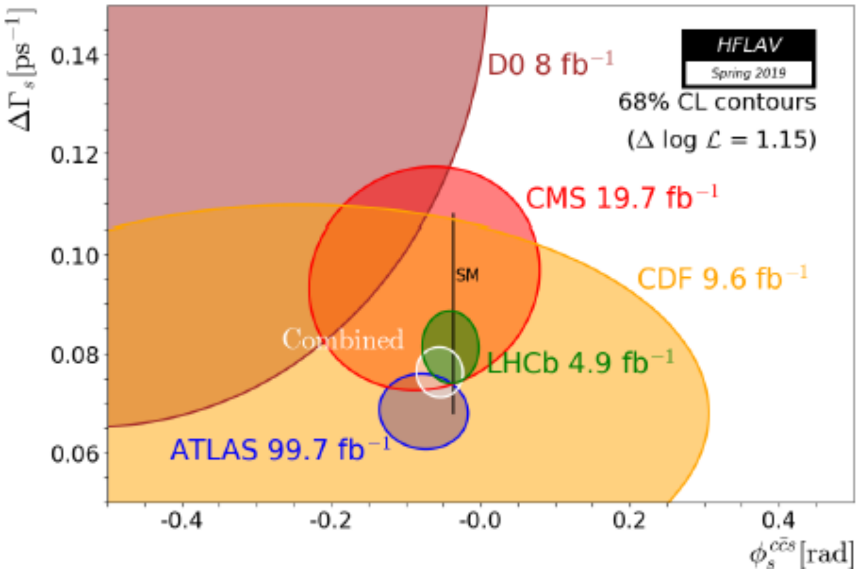
thus, very small. It can receive sizeable contributions from BSM particles in the loop.

- New measurement by ATLAS using B_s→J/ψϕ and by LHCb using B_s→J/ψϕ and B_s→J/ψππ
  - ATLAS: 80.5 fb^{-1}, 13 TeV [ATLAS-CONF-2019-009]
  - LHCb: 1.9 fb^{-1}, 13 TeV [LHCb-PAPER-2019-013]
    1.9 fb^{-1}, 13 TeV [arXiv:1903.05530]

(subsets of Run 2)

- The combination of Run-1 and Run-2 data gives
  - ATLAS: $\phi_s = -0.076 \pm 0.034(stat) \pm 0.019(syst)$ rad
  - LHCb: $\phi_s = -0.040 \pm 0.025$ rad

New average for ϕ_s



(preliminary)

New HFLAV average

$$\phi_s = -0.0544 \pm 0.0205$$

- Approaching the sensitivity to observe a nonzero value
- Eagerly waiting for analyses with full Run-2 data and CMS results

Lepton Flavor Universality tests in $b \to s l^+ l^-$

- Measure the double ratio

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

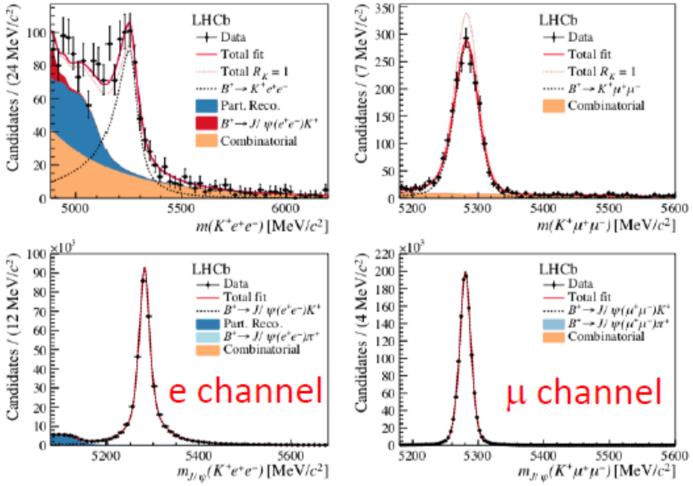
Theoretically very clean.
Observation of $R_K \neq 1$ would be a clear sign of new physics!

- New measurement of R_K by LHCb in the dilepton mass-squared range $1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$
  - Adding 2 fb^{-1} of Run-2 data to 3 fb^{-1} of Run-1 data
  - Statistics of previous measurement doubled

3 fb^{-1} at 7/8 TeV + 2 fb^{-1} at 13 TeV [arXiv:1903.09252]

Non-resonant
e^+e^-, $\mu^+\mu^-$

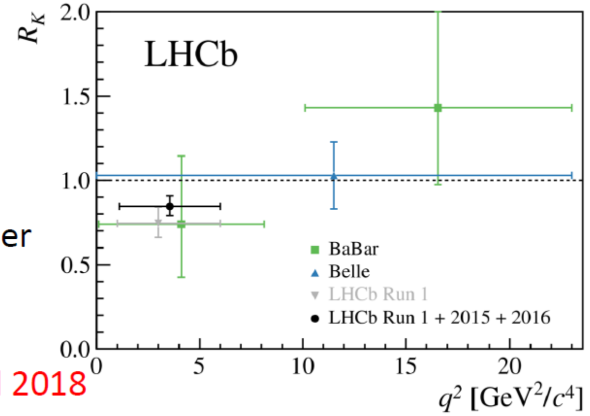
Resonant
$J/\psi \to e^+e^-$, $\mu^+\mu^-$



$$R_K = 0.846\,^{+0.060}_{-0.054}\,^{+0.016}_{-0.014}$$

2.5σ from the SM

- Situation practically unchanged after the new measurement
  - Reduced uncertainty but central value closer to the SM
- Outlook
  - Inclusion of 2017 and 2018 data doubles statistics

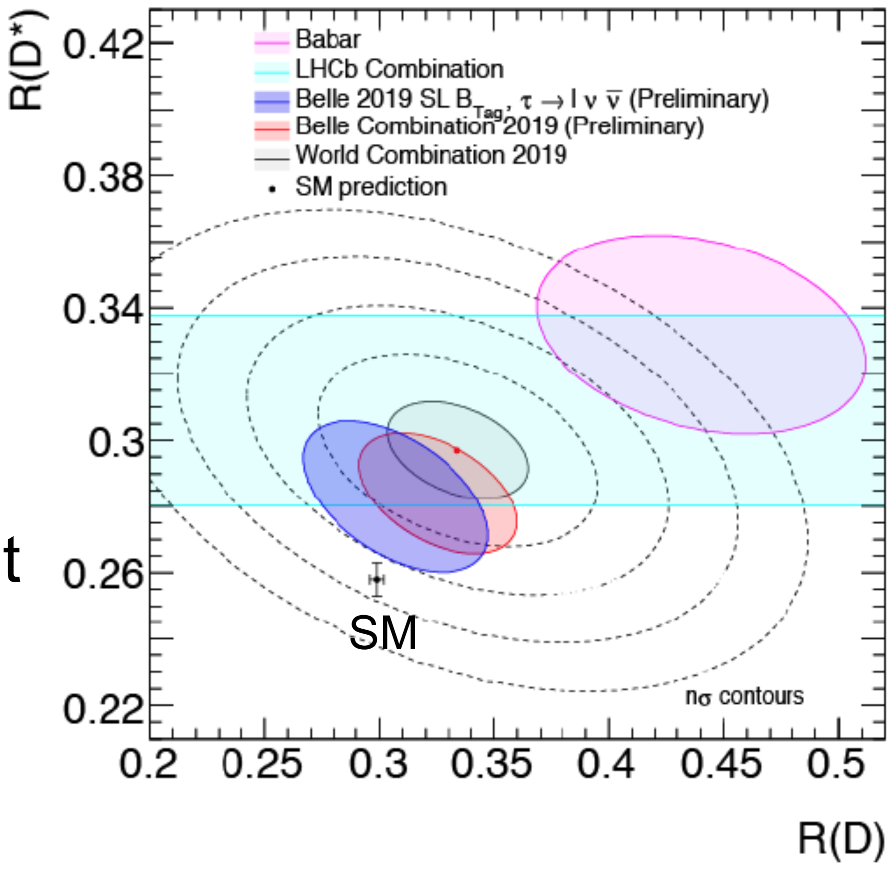


Lepton Flavor Universality tests in $B \to D^{(*)}\tau\nu$

- New Belle measurement presented at Moriond EW

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

- Most precise measurement of *R*(*D*) and *R*(*D**) to date and first *R*(*D*) measurement performed with semileptonic tag
- Compatible with SM at 1.2σ



combined significance ~~$\sim 3.8\sigma$~~ 3.1σ

Charmonium spectroscopy

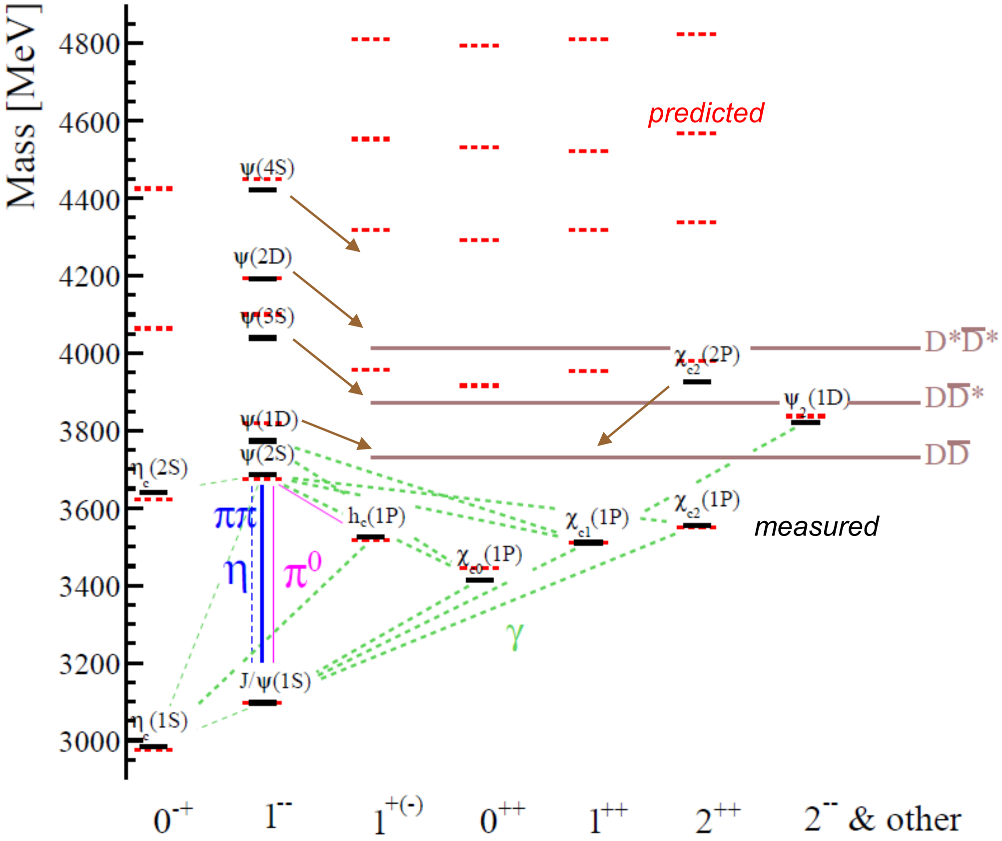
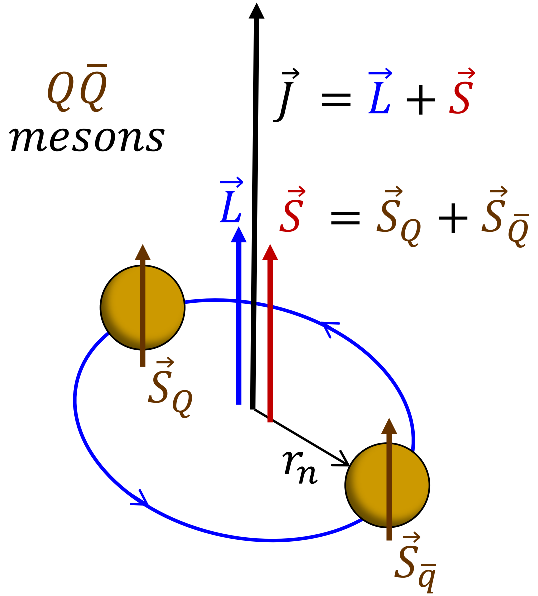


Figure from Olsen,Skwarnicki,Zieminska
Rev.Mod.Phys. 90, 015003 (2018); arXiv:1708.04012

Mesons as $(Q\bar{Q})$ bound states.



Precision spectroscopy below open flavor threshold(s)

Charmonium spectroscopy above $D\bar{D}$ threshold

LHCb-PAPER-2019-005
arXiv:1903.12240

Run 1 + Run 2
9 fb^{-1}

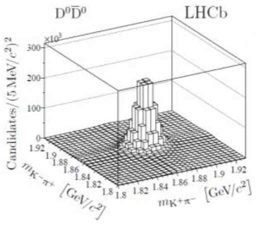
PLB 769, 187 (2017)

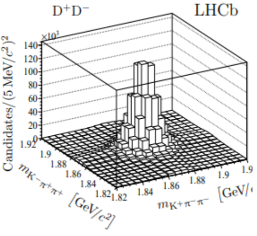
	$m_{\psi(3770)}$ [MeV/c^2]
Shamov and Todyshev	3779.8 ± 0.6
PDG average	3778.1 ± 1.2
PDG fit	3773.13 ± 0.35
This analysis	3778.13 ± 0.70 ± 0.63

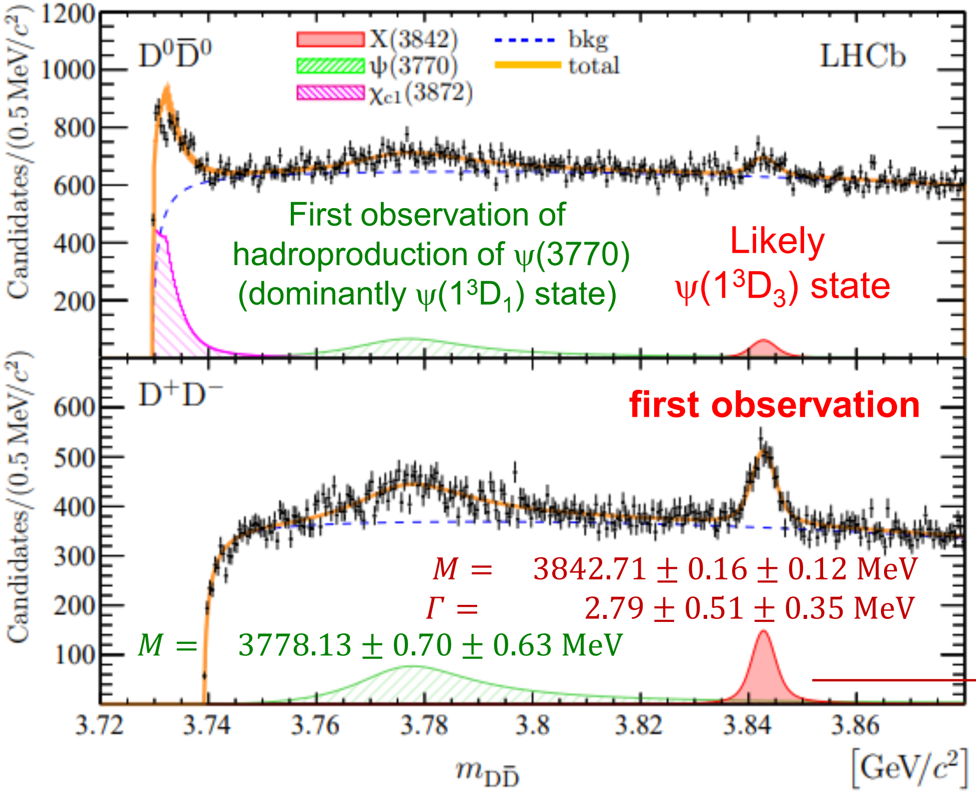
PRL 96, 082003 (2006)
PRD 81, 092003 (2010)

	$m_{\chi_{c2}(3930)}$ [MeV/c^2]	$\Gamma_{\chi_{c2}(3930)}$ [MeV]
Belle	3929 ± 5 ± 2	29 ± 10 ± 2
BaBar	3926.7 ± 2.7 ± 1.1	21.3 ± 6.8 ± 3.6
This analysis	3921.90 ± 0.55 ± 0.19	36.64 ± 1.88 ± 0.85

Purely hadronic final states!







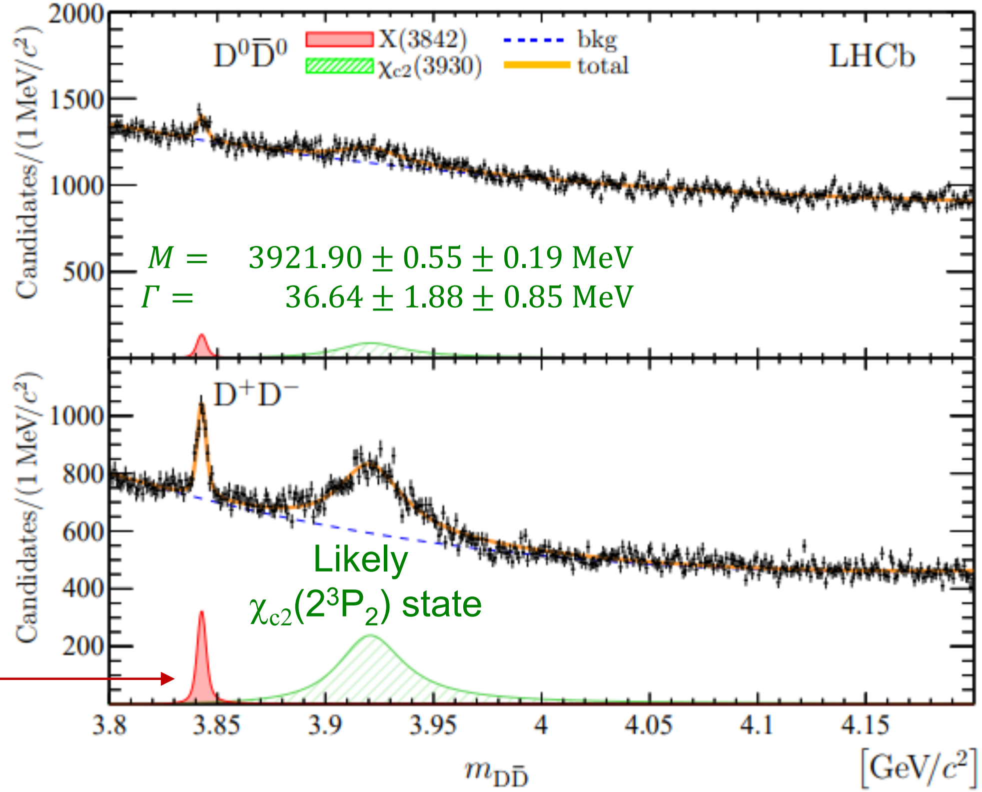
First observation of hadroproduction of ψ(3770) (dominantly ψ(1^3D_1) state)

Likely ψ(1^3D_3) state

first observation

M = 3842.71 ± 0.16 ± 0.12 MeV
Γ = 2.79 ± 0.51 ± 0.35 MeV

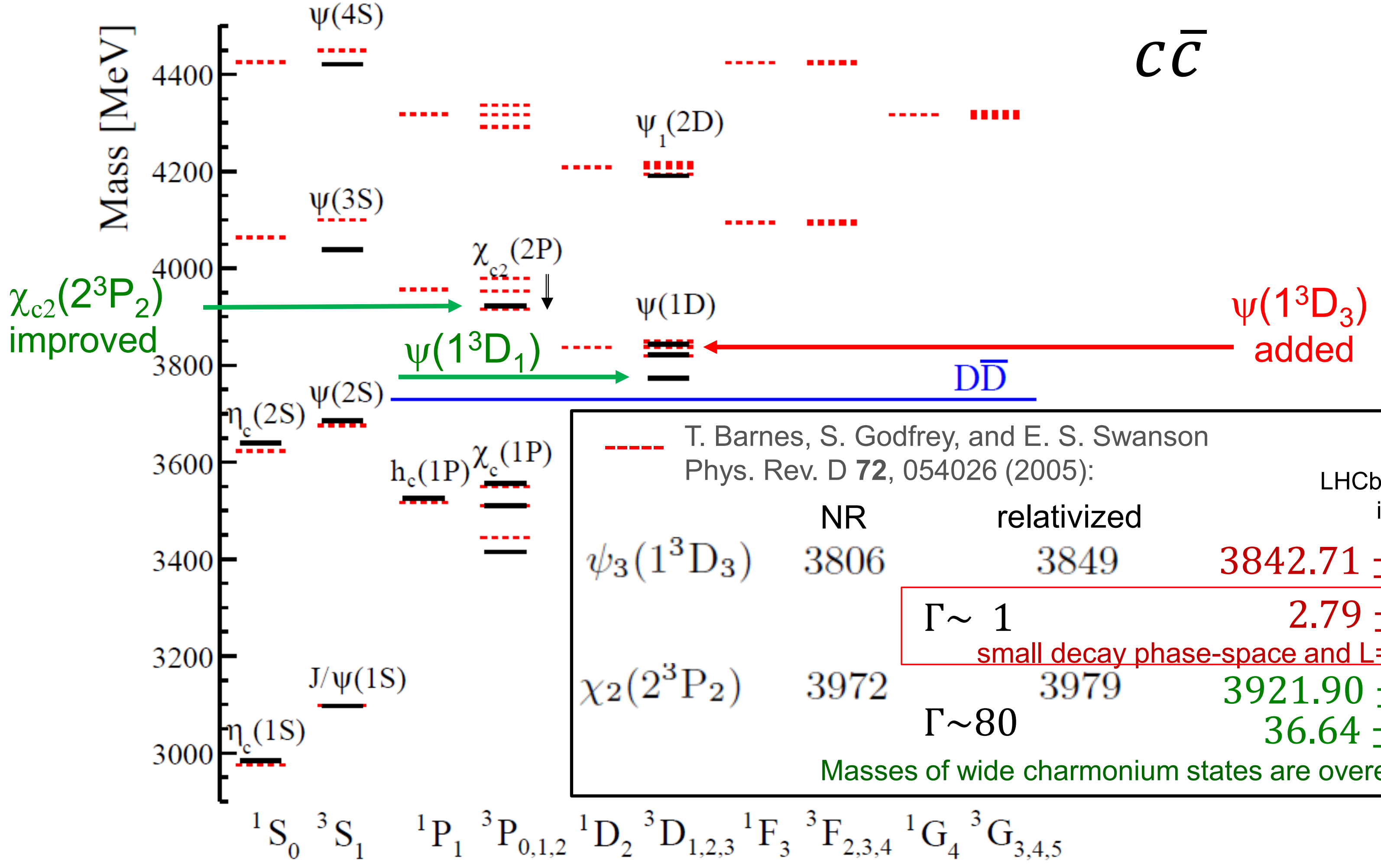
M = 3778.13 ± 0.70 ± 0.63 MeV



M = 3921.90 ± 0.55 ± 0.19 MeV
Γ = 36.64 ± 1.88 ± 0.85 MeV

Likely $\chi_{c2}(2^3P_2)$ state

Update to charmonium spectroscopy



------ T. Barnes, S. Godfrey, and E. S. Swanson Phys. Rev. D **72**, 054026 (2005):

	NR	relativized	LHCb-PAPER-2019-005 in preparation
$\psi_3(1^3D_3)$	3806	3849	$3842.71 \pm 0.16 \pm 0.12$ MeV
	$\Gamma \sim 1$		$2.79 \pm 0.51 \pm 0.35$ MeV
$\chi_2(2^3P_2)$	3972	3979	$3921.90 \pm 0.55 \pm 0.19$ MeV
	$\Gamma \sim 80$		$36.64 \pm 1.88 \pm 0.85$ MeV

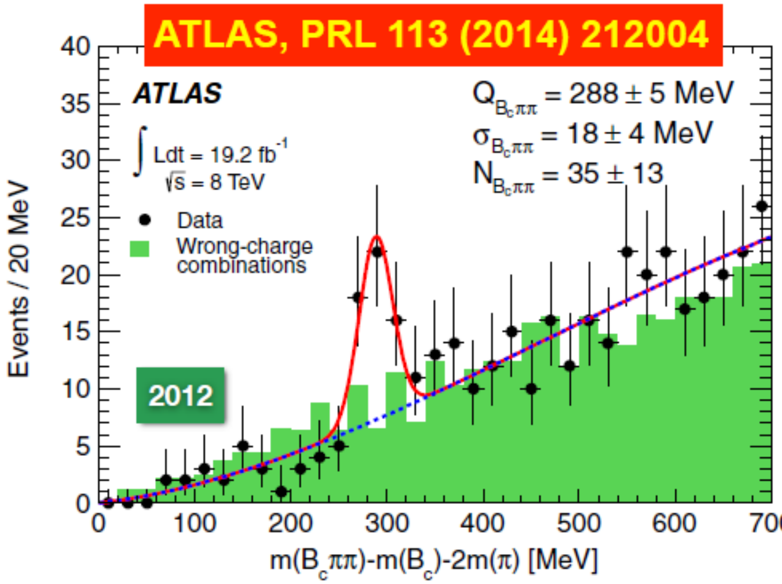
small decay phase-space and L=3 centrifugal barrier!

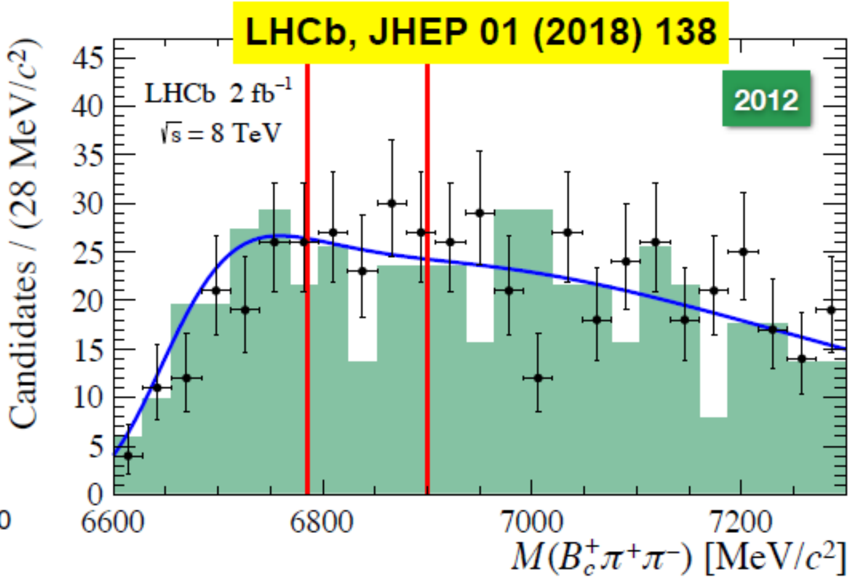
Masses of wide charmonium states are overestimated in potential approaches.

B_c spectroscopy ($b\bar{c}$)

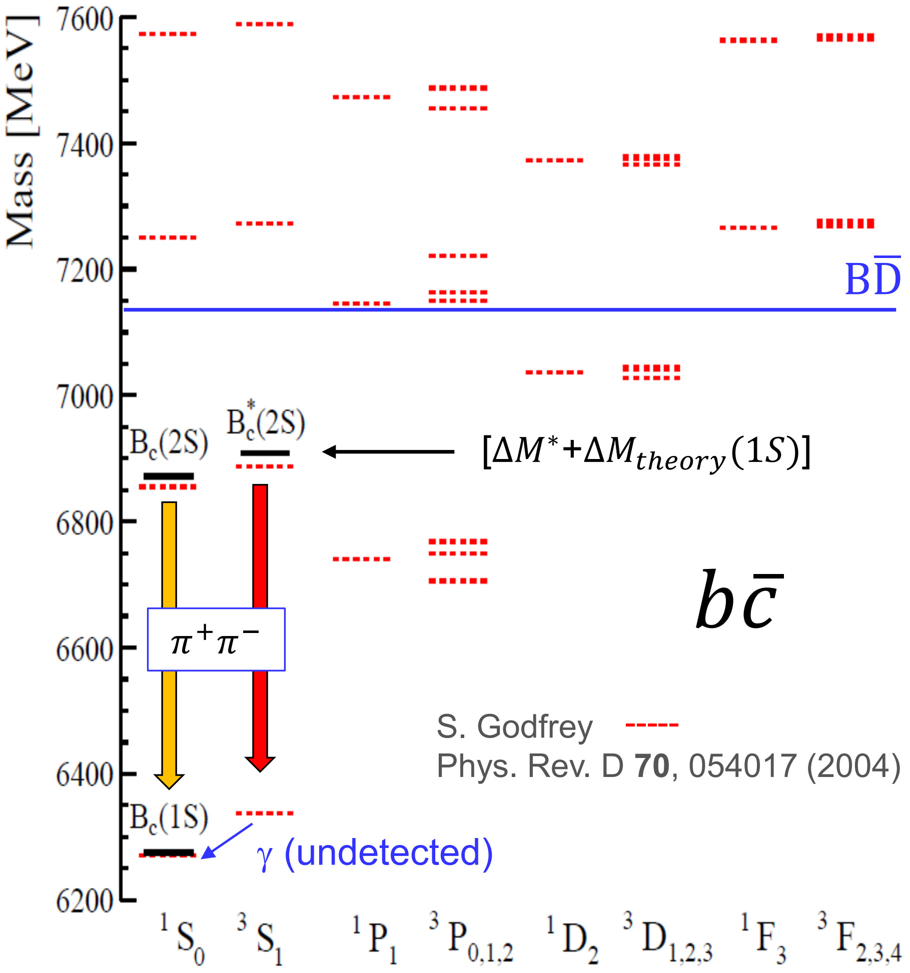
- Like heavy quarkonium, with masses in between $c\bar{c}$ and $b\bar{b}$, but no gluon or photon annihilations, thus states below open flavor threshold must all decay to the ground state (B_c!) via photon and light hadron (cascade) transitions. B_c decays weakly.
- Controversy over the only excitation seen up to recently:

★ **Seen by ATLAS at 5.2σ; not confirmed by LHCb in 8 TeV data**


ATLAS, PRL 113 (2014) 212004


LHCb, JHEP 01 (2018) 138

Observations of an excited B_c^+ states

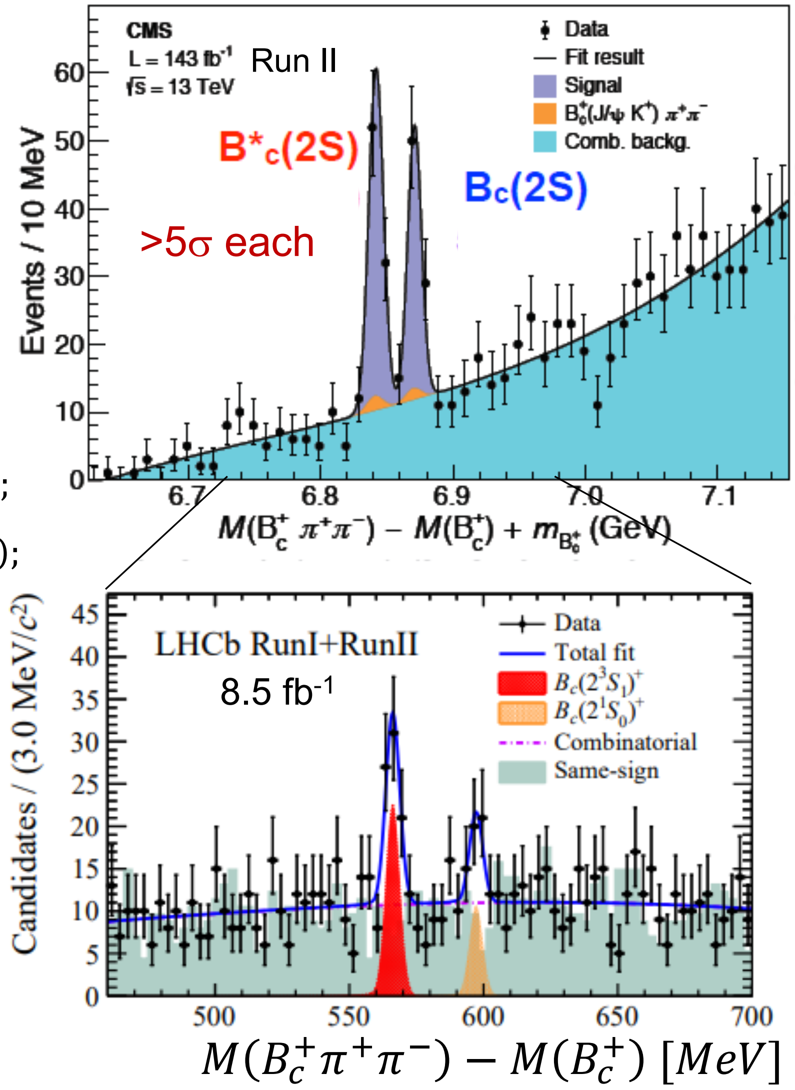


S. Godfrey -----
Phys. Rev. D **70**, 054017 (2004)

CMS
arxiv:1902.00571

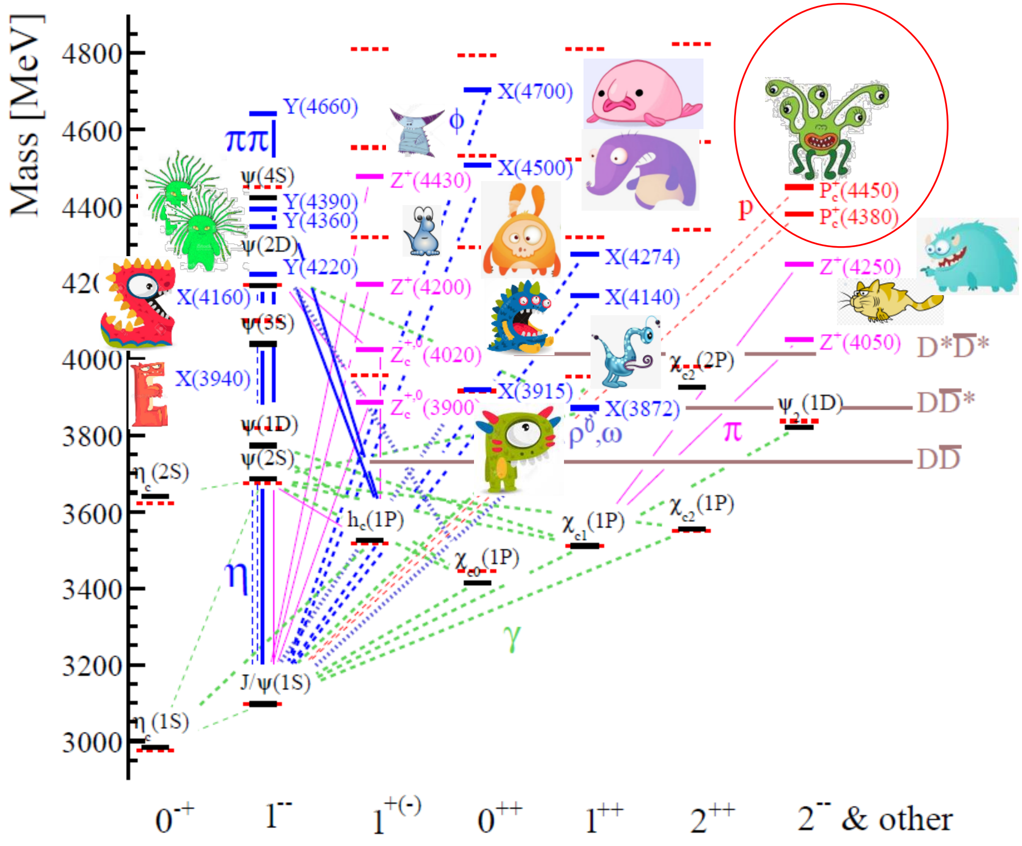
Determine $M(2^1S_0)$ and
$\Delta M^* = M(2^3S_1) - \Delta M(1S)$;
$\Delta M(1S) = M(1^3S_1) - M(1^1S_0)$;

LHCb-PAPER-2019-007
arxiv:1904.00081



Charmonium-like states

Above the flavor threshold: More exotic states than $c\bar{c}$ states!

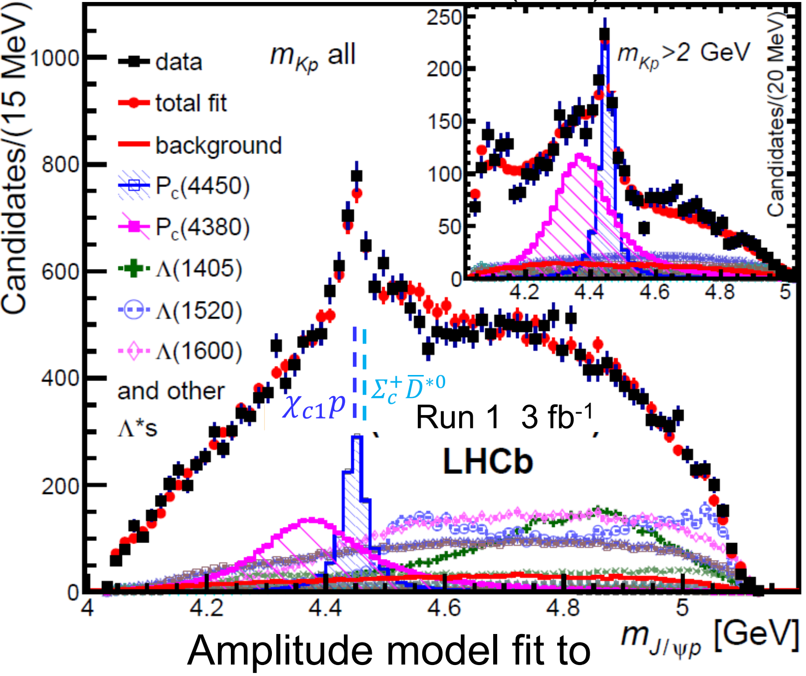


A lot of “freak” $c\bar{c}q\bar{q}$ ($c\bar{c}qqq$) states above open flavor thresholds

- Tightly-bound tetraquark (pentaquark) states?
- Meson-meson (meson-baryon) states/interactions?
- Interplay of both?

Run 1 evidence for $P_c^+ \to J/\psi p$ pentaquarks in $\Lambda_b \to J/\psi p K^-$

PRL 115, 072001 (2015)



Amplitude model fit to masses and decay angles

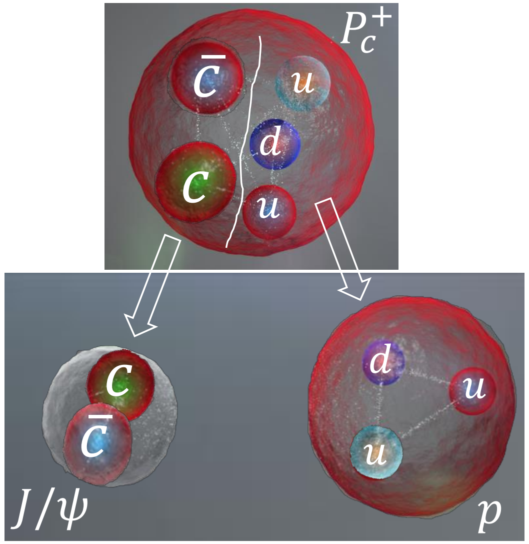
P$_c$(4450)$^+$ $M = 4450 \pm 2 \pm 3$ MeV
$\Gamma = 39 \pm 5 \pm 19$ MeV
$F.F. = 4.1 \pm 0.5 \pm 1.1$ %

P$_c$(4380)$^+$ $M = 4380 \pm 8 \pm 29$ MeV
$\Gamma = 205 \pm 18 \pm 86$ MeV
$F.F. = 8.4 \pm 0.7 \pm 4.2$ %

27k $\Lambda_b \to J/\psi p K^-$ signal events
5.4% background

Tightly-bound pentaquark

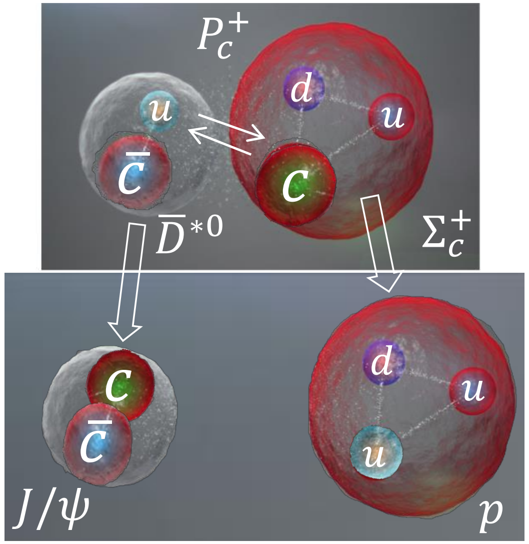
$M_{P_c^+} = M_{J/\psi} + M_p + \sim 400$MeV



- Decay by fall-apart:
  - **Wide states?**
  - What slows it down to make P$_c$(4450)$^+$ narrow? L between **diaquarks**?
  - P$_c$(4380)$^+$ S=1,L=0 broad, P$_c$(4450)$^+$ S=0,L=1 narrow
- Spectrum (**confining potential**)
  - Many states expected (n,L,S)

L. Maiani, A. D. Polosa, V. Riquer, PL B749 (2015) 289
R. F. Lebed, PL, B749 (2015) 454
V.V. Anisovich, M.A. Matveev, J. Nyiri, A.V. Sarantsev PL,. B749 (2015) 454
and others

Loosely-bound pentaquark



$M_{P_c^+} = M_{\bar{D}^{*0}} + M_{\Sigma_c^+} - \sim$few MeV
Fast fall-apart prevented

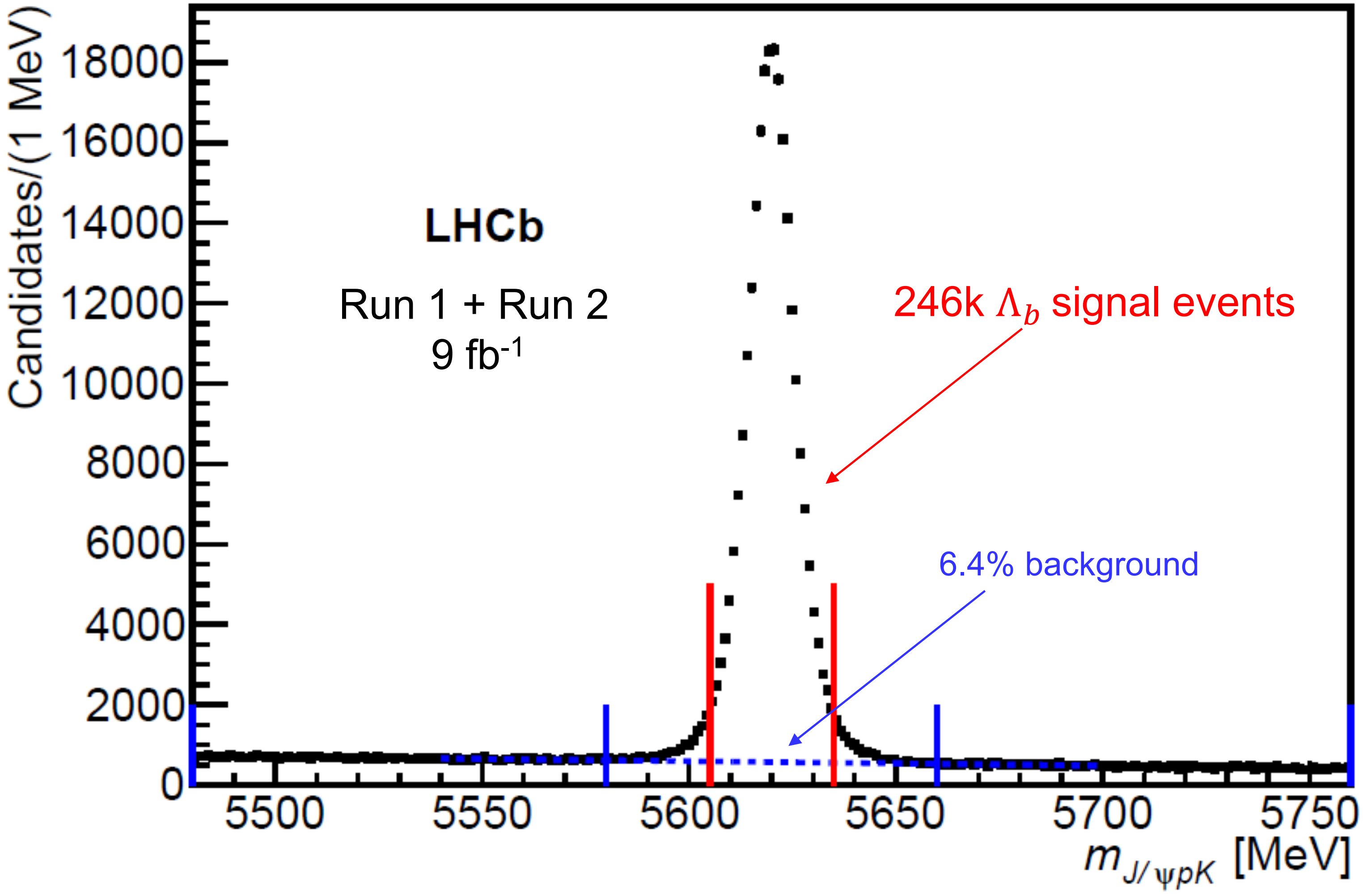
- Decay by heavy quarks changing confinement partners, then fall-apart:
  - **All states narrow**
- Spectrum (**shallow potential well**)
  - n=0,L=0 between hadron
  - Very few states expected (S)
  - Weak binding: masses a few MeV below the related baryon-meson thresholds
- Only $\Sigma_c^+\bar{D}^{(*)0}$ expected to bind:
  - P$_c$(4450)$^+$ = $\Sigma_c^+\bar{D}^{*0}$ molecule?
- Peaking at $\Lambda_c^+\bar{D}^{(*)0}$,$\chi_{cJ}p$ thresholds possible from triangle diagram processes:
  - P$_c$(4450)$^+$ = $\chi_{c1}p$ threshold?

Wu,Molina,Oset,Zou, PRL105 (2010) 232001
Wang,Huang,Zhang,Zou, PR C84 (2011) 015203
Karliner,Rosner, PRL 115 (2015) 122001
and others

Guo,Meissner,Wang,Yang, PRD92 (2015) 071502

New $\Lambda_b \rightarrow J/\psi p K^-$ data sample

9x more than used in the Run 1 2015-2016 papers



246k Λ_b signal events

6.4% background

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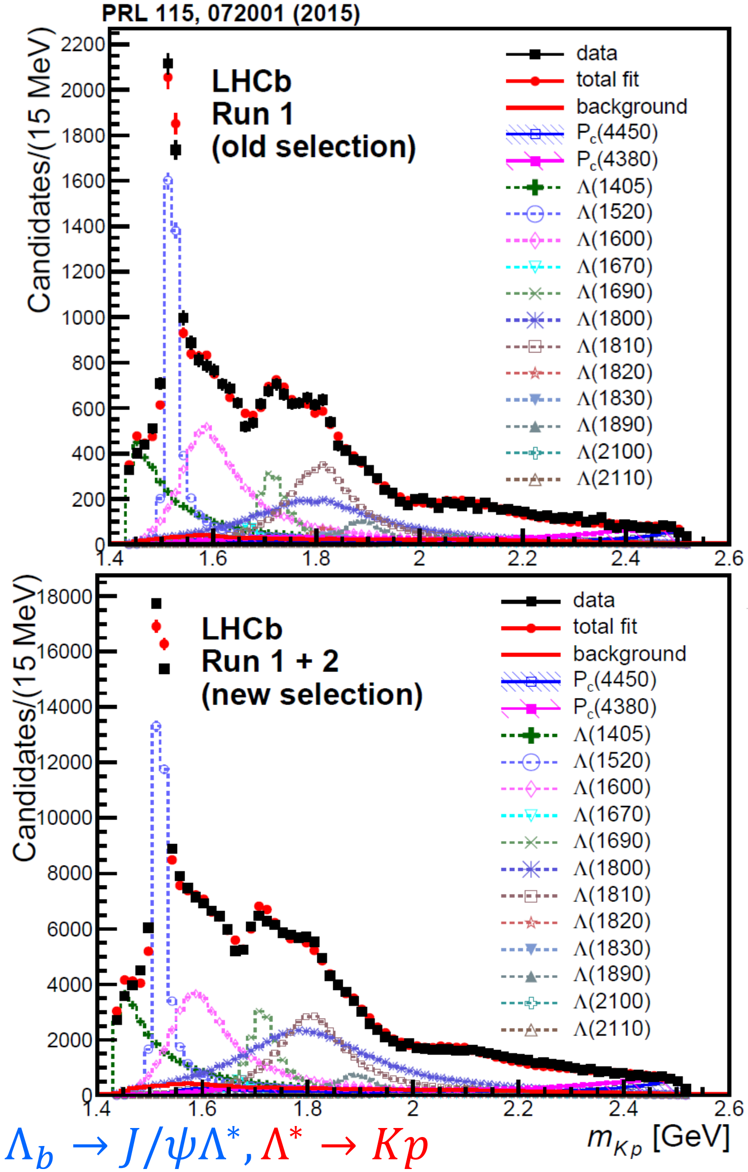
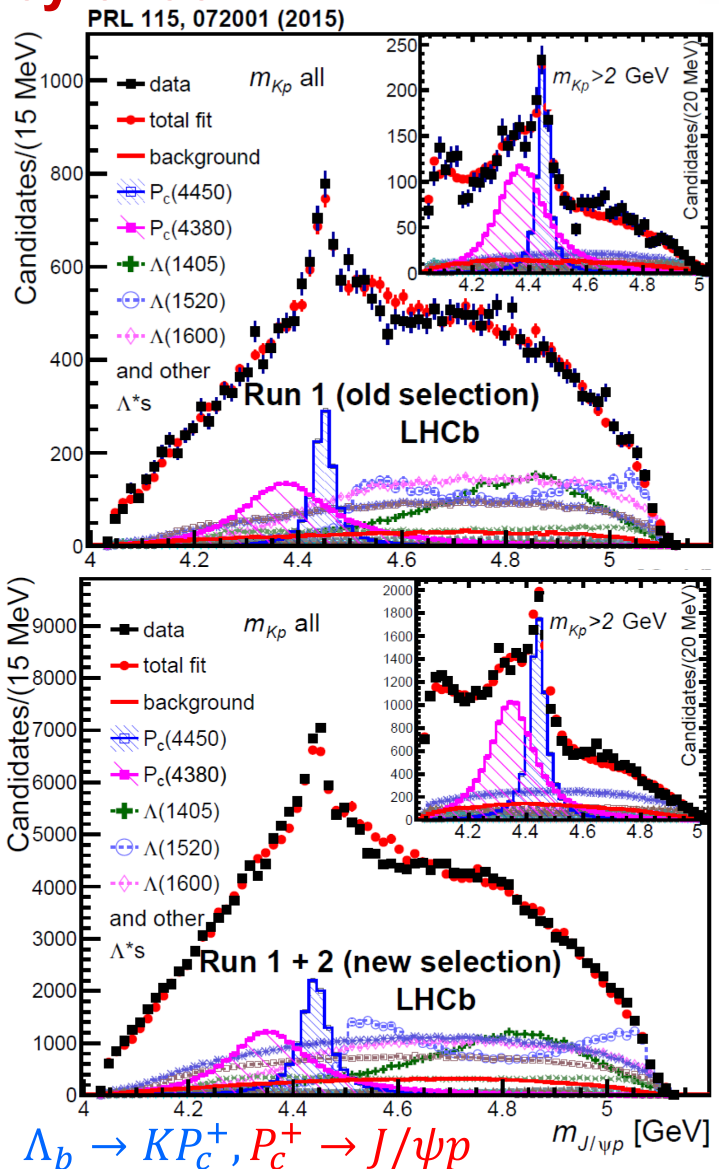
Improvements in the data selection (x 2), integrated luminosity (x 3) and cross-section ($\sqrt{s}$ =13 TeV vs 7-8 TeV)

Data consistency check



$\Lambda_b \to J/\psi \Lambda^*, \Lambda^* \to Kp$



$\Lambda_b \to K P_c^+, P_c^+ \to J/\psi p$

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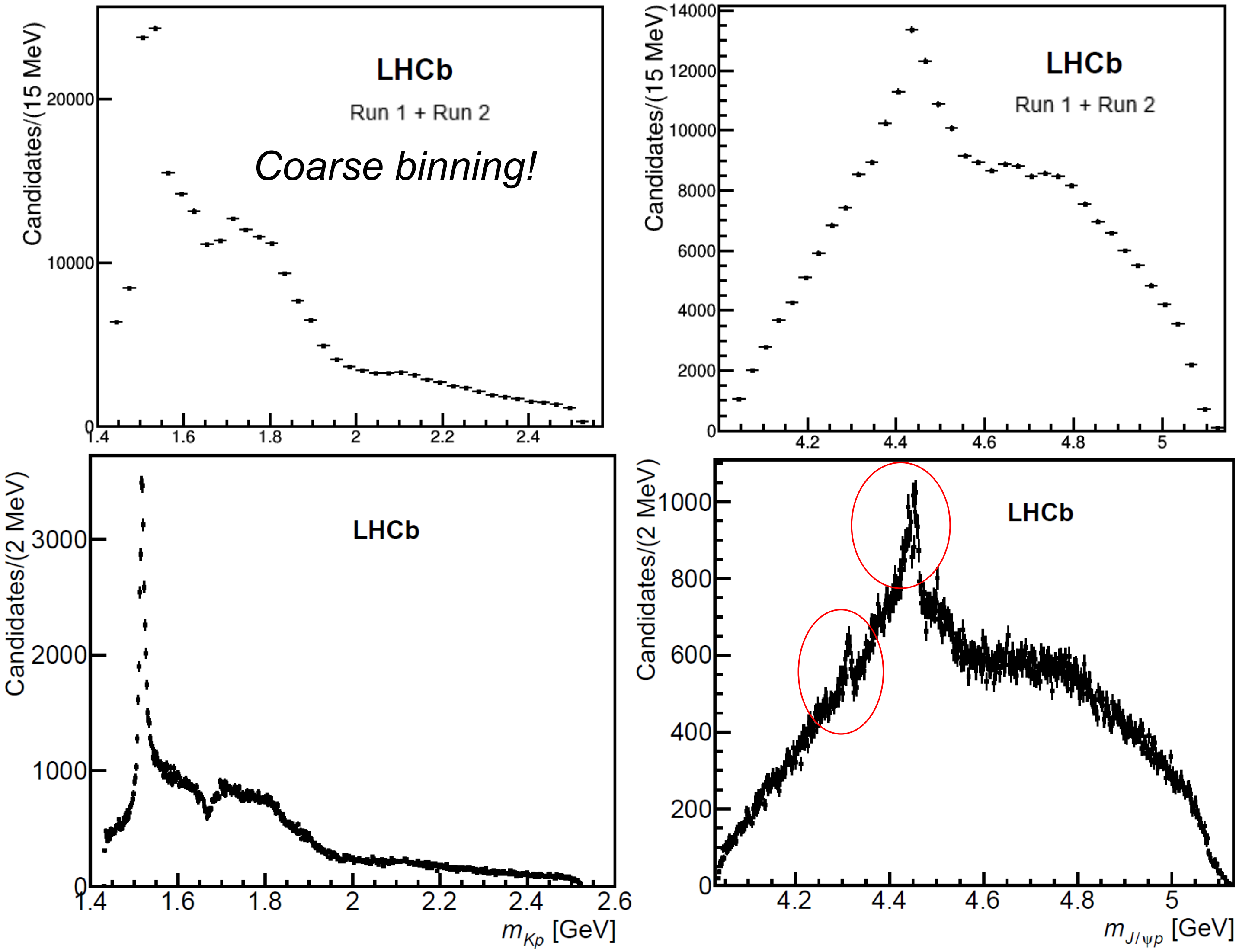
6D amplitude model
fit to masses and decay angles

- When fit with the 2015 amplitude model, the full data sample gives the $P_c(4450)^+$ and $P_c(4380)^+$ parameters **consistent** with the 2015 results
- But…

New $\Lambda_b \to J/\psi p K^-$ data sample – narrow $P_c^+ \to J/\psi p$ peaks



The $J/\psi p$ mass resolution is 2.3-2.7 MeV (RMS) in 4.3-4.6 GeV region

(the excellent momentum resolution, vertexing and J/ψ and Λ_b mass constraints)

Observe narrow $J/\psi p$ structures which were insignificant with 1/9th of the present $\Lambda_b \to J/\psi p K^-$sample

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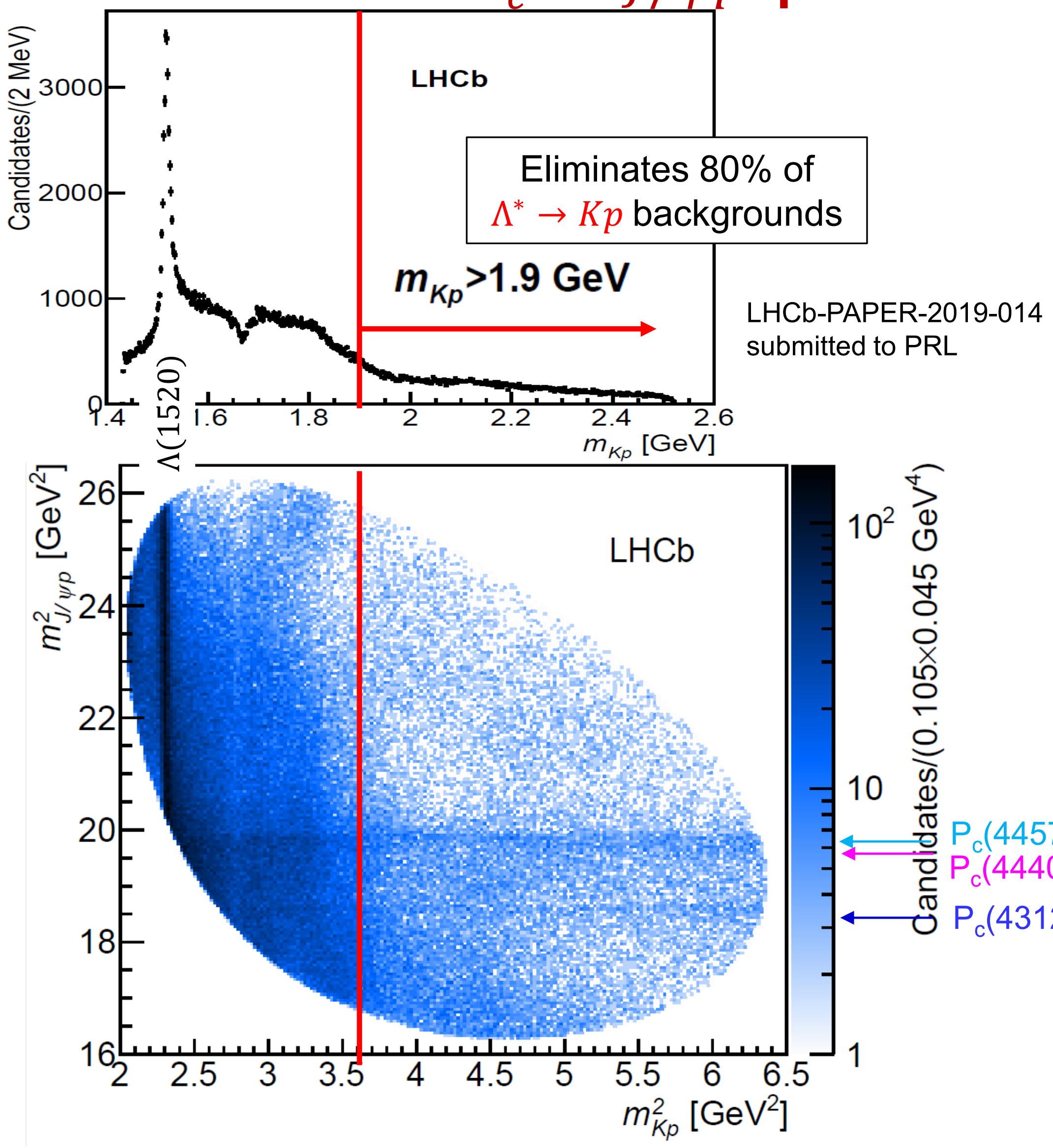
Narrow $P_c^+ \to J/\psi p$ peaks with Λ^* suppression



Eliminates 80% of $\Lambda^* \to Kp$ backgrounds

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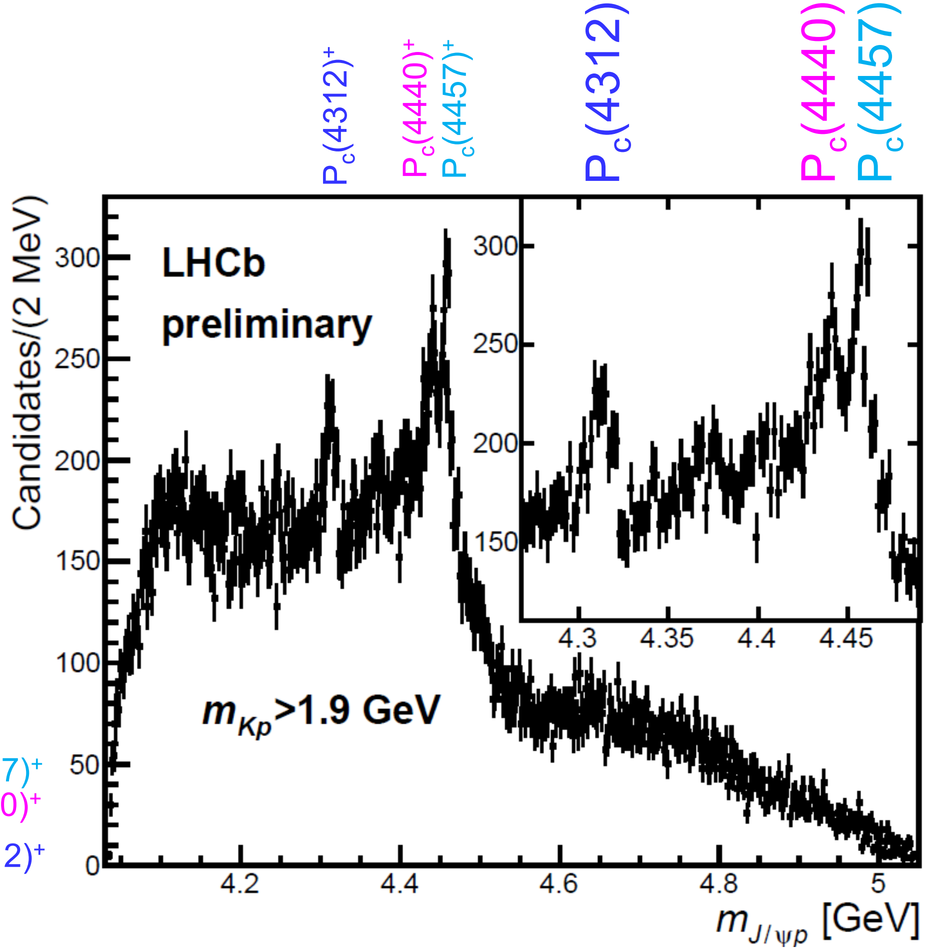
Mass resolution σ=2.3-2.7 (FWHM 5.4-6.4) MeV



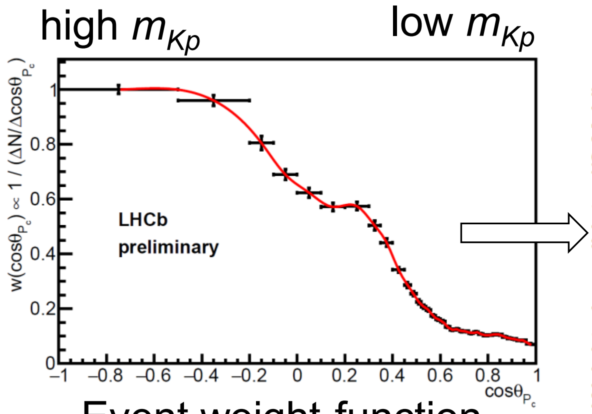
Proper amplitude analysis faces new challenges: must consider $m_{J/\psi p}$ resolution effects, large statistics and sub-percent precision in fit fractions required in the amplitude model – work in progress

Fits to $J/\psi p$ mass distributions

No need for amplitude analysis to prove that the **narrow** $J/\psi p$ peaks are not Λ^* reflections [see LHCb PRL **117**, 082002 (2016)].

Perform one-dimensional fits to $m_{J/\psi p}$ to characterize the narrow peaks.

The analysis is **not sensitive** to broad $J/\psi p$ contributions like $P_c(4380)^+$.

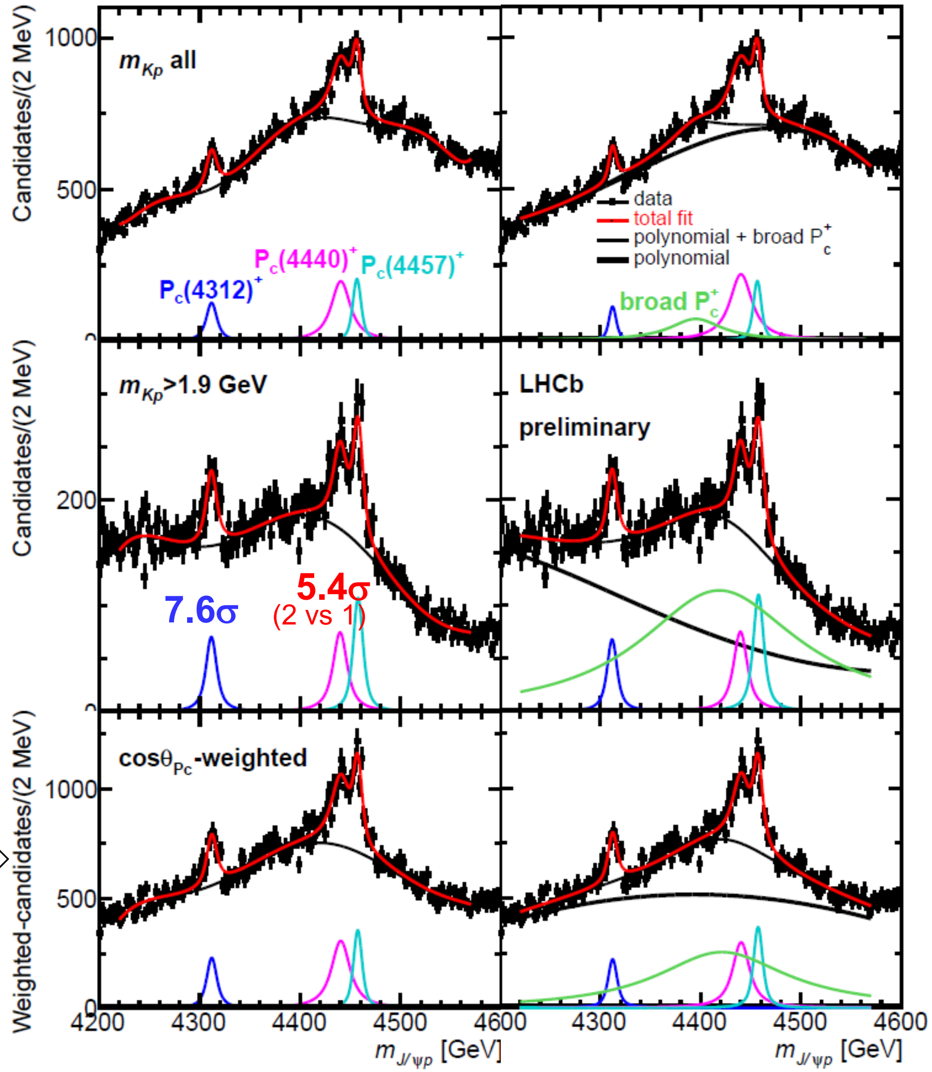


Event weight-function

Three narrow Breit-Wigner resonances +

high-order polynomial

low-order polynomial + broad P_c^+ as bkg.



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Different composition of Λ^* reflections. Tests systematic uncertainties.

Best statistical sensitivity

Results

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b \to J/\psi p K^-)}$$

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

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Plausible theoretical interpretation

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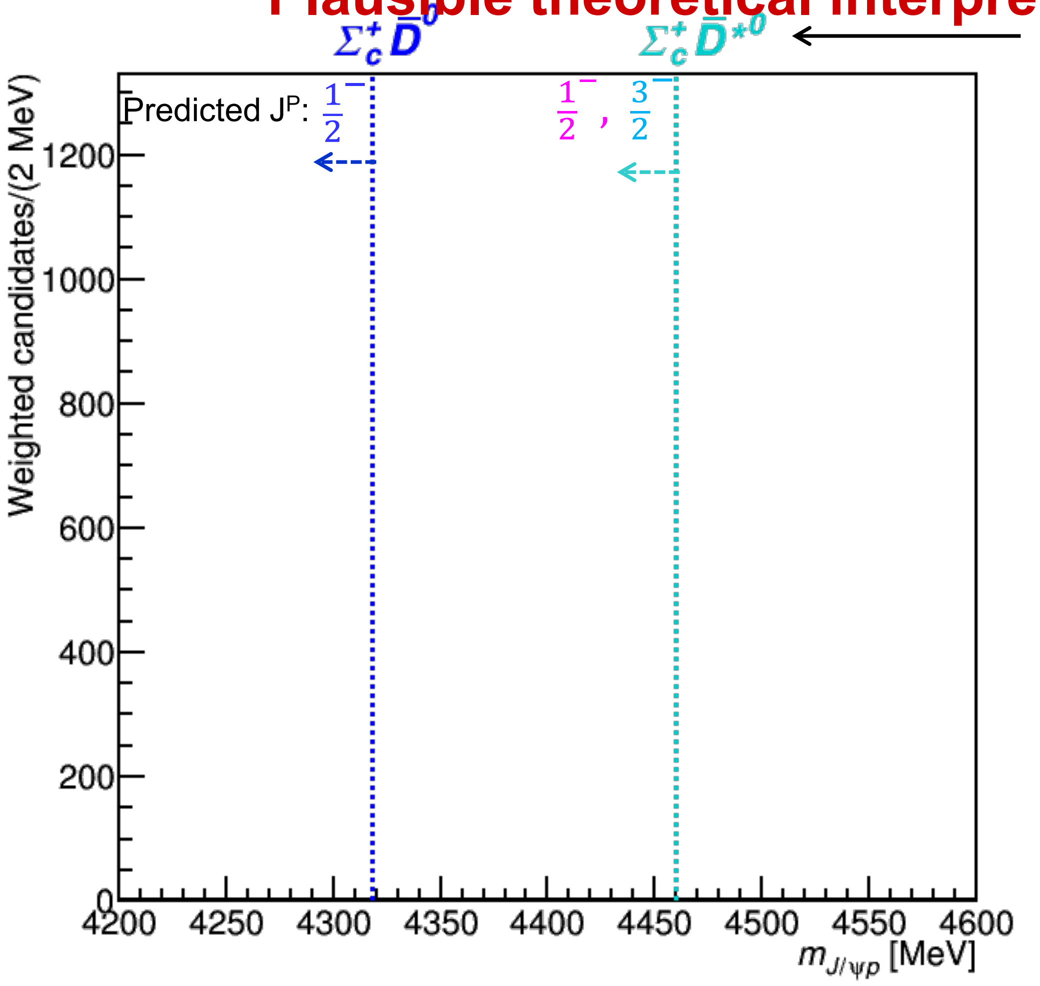

The **only** thresholds below which
molecular bound states
are expected in this mass range

Plausible theoretical interpretation

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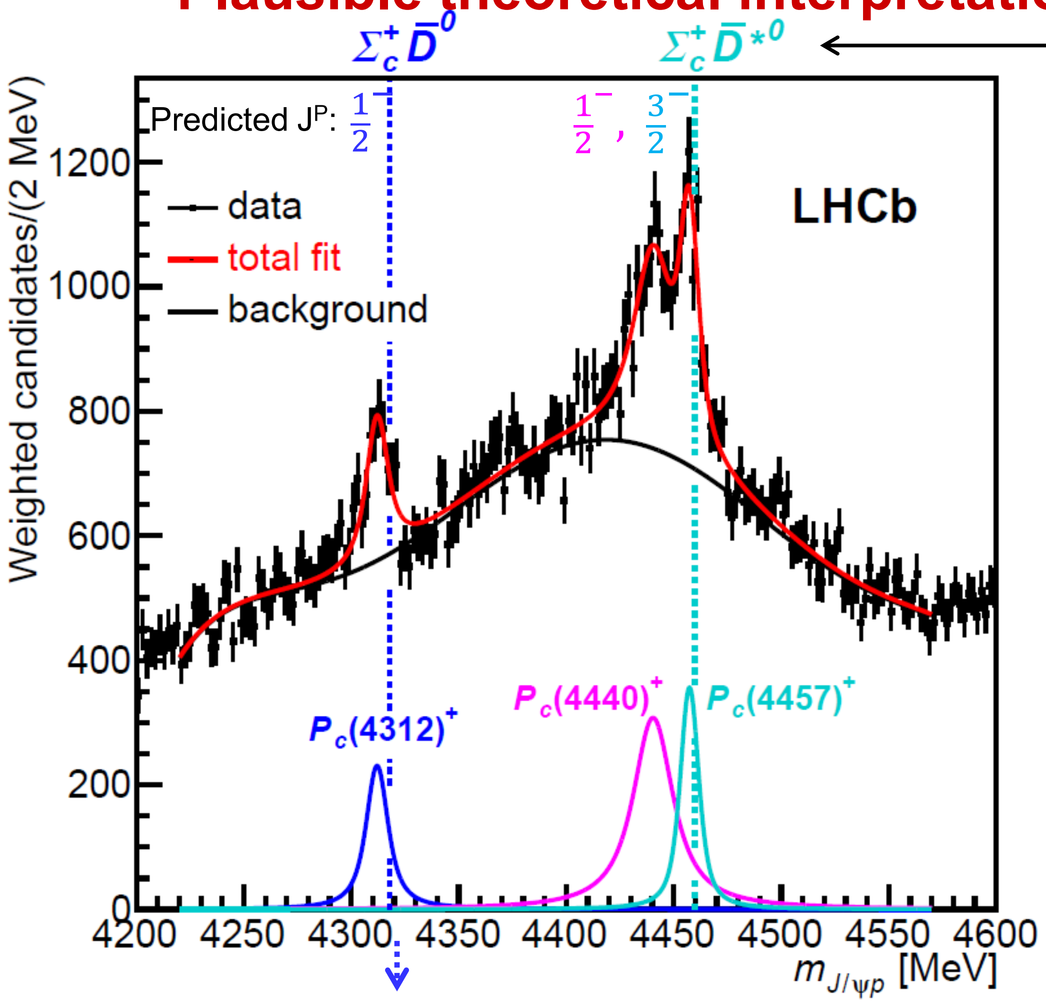
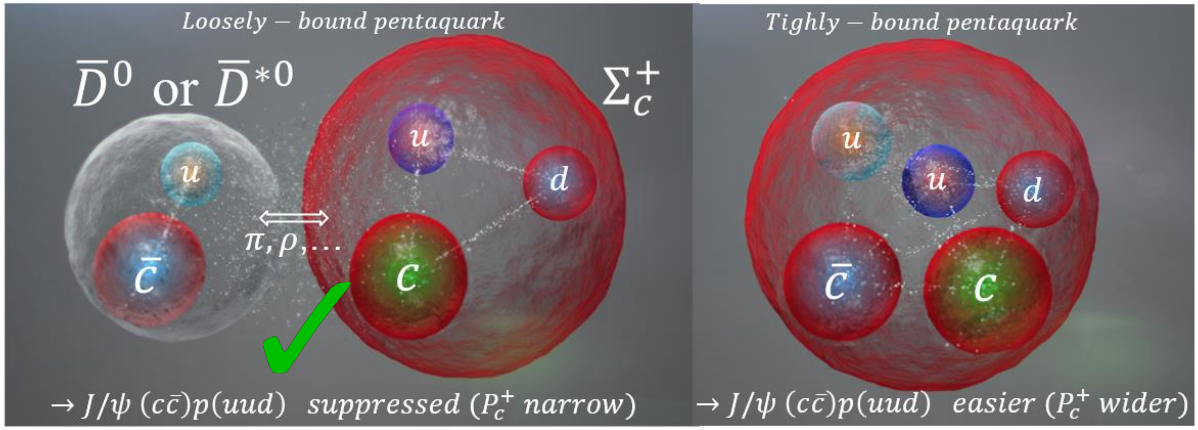


← The **only** thresholds below which molecular bound states are expected in this mass range

The near-threshold masses and the narrow widths of $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ favor "molecular" pentaquarks with meson-baryon substructure!



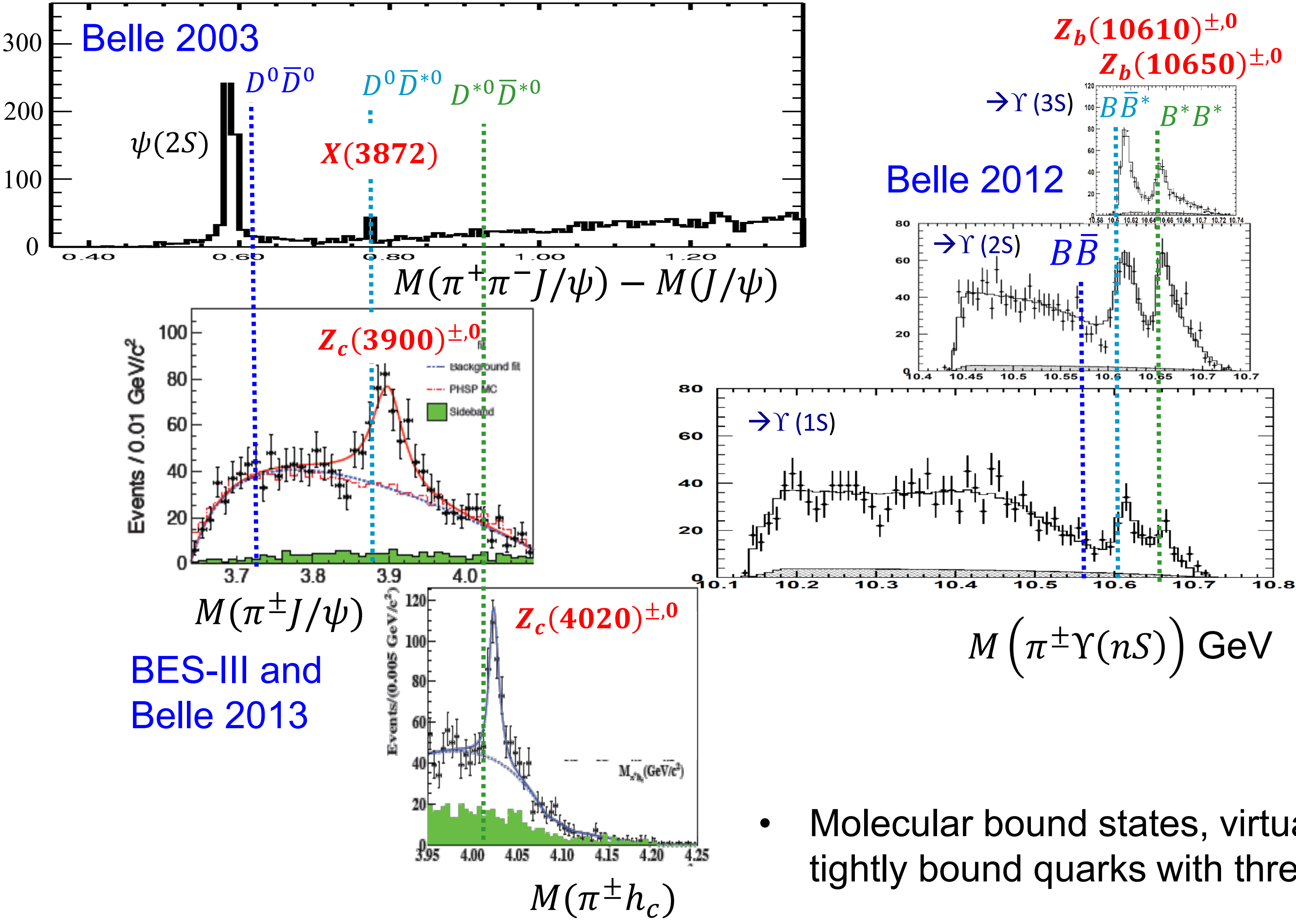
However, need to measure J^{P}s to confirm molecular hypothesis,
find isospin partners, …

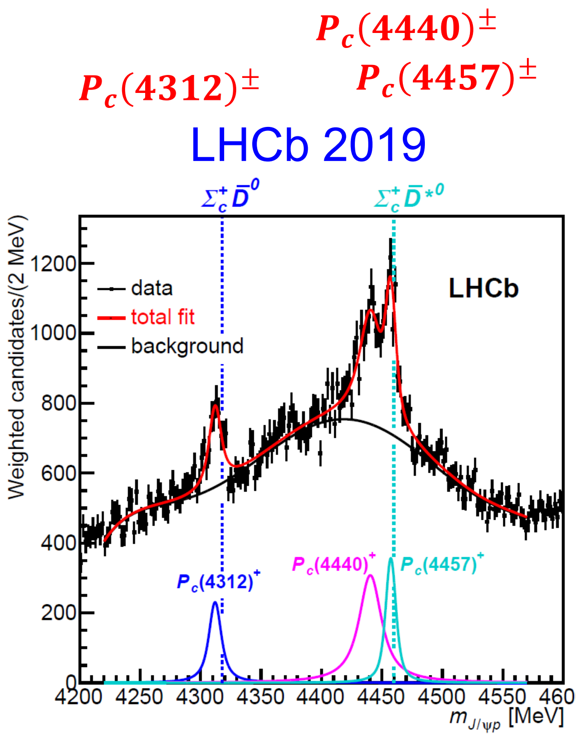
Can diquark substructure separated by a potential barrier [Maiani, Polosa, Riquer, PL,B778, 247 (2018)] produce width suppression?
Interplay of such states with thresholds?
This hypothesis is not ruled out

Existence of $\Sigma_c^+\bar{D}^0$ molecule would imply importance of ρ-exchange

$P_c(4312)^+$, $P_c(4440)^+$ not near triangle diagram thresholds, $P_c(4457)^+$ is.

Near threshold states





- Molecular bound states, virtual states or interplay of tightly bound quarks with thresholds ?

Summary of recent highlights

- New milestones reached in CPV studies (CPV observed in charm system), but the Standard Model is holding up:
  - Some measurements still statistics limited. BSM frontier is still open here.
- Tensions with SM in tests of Lepton Flavor Violation have not increased with the new measurements, but have not gone away either:
  - Lots more data available to analyze. Tune in.
- Progress in $c\bar{c}$ and $b\bar{c}$ spectroscopy:
  - New states have been just observed and fit the expectations
- Progress in exotic hadron spectroscopy:
  - New narrow $c\bar{c}uud$ pentaquark states observed
  - Their masses point to the importance of hadron-hadron thresholds in their dynamics, like many previous observations among tetraquark structures. More data needed to pin down exact nature of near-threshold spectroscopy.