Studies of hadron spectroscopy and nuclear matter at LHCb

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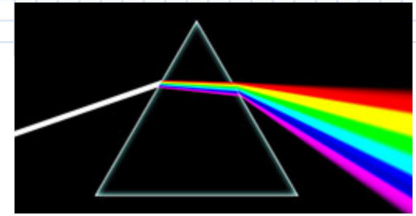
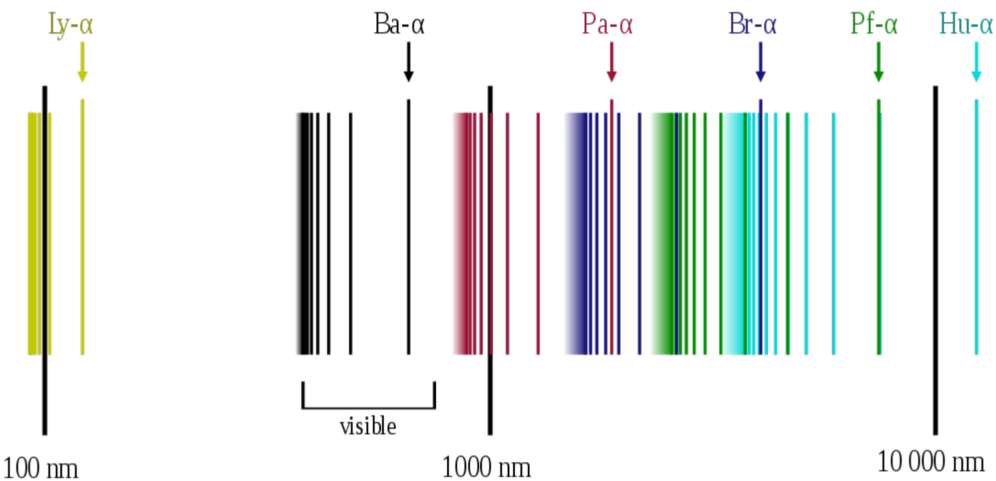
IHEP Seminar, 26/06/2018

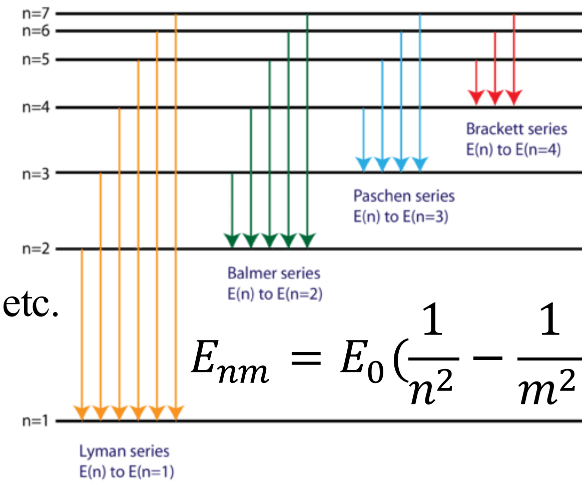
Spectroscopy



- Important in history of science and now
  - ➢ Establishment of quantum mechanics
    The famous hydrogen system

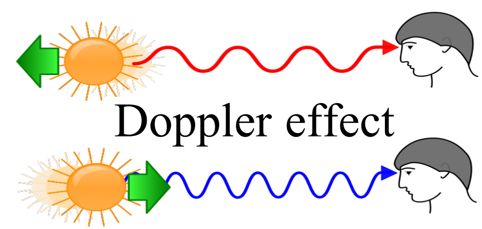


N. Bohr etc.



$$E_{nm} = E_0\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

  - ➢ Help to understand quantum electromagnetic interactions
    - ❑ Spin-orbital, spin-spin: fine structure, hyperfine structure
  - ➢ Measurement of faraway star properties
    - ❑ Absorption lines → chemical composition
    - ❑ light Doppler shift → speed of galaxies
  - ➢ Characteristic X-ray for element identification



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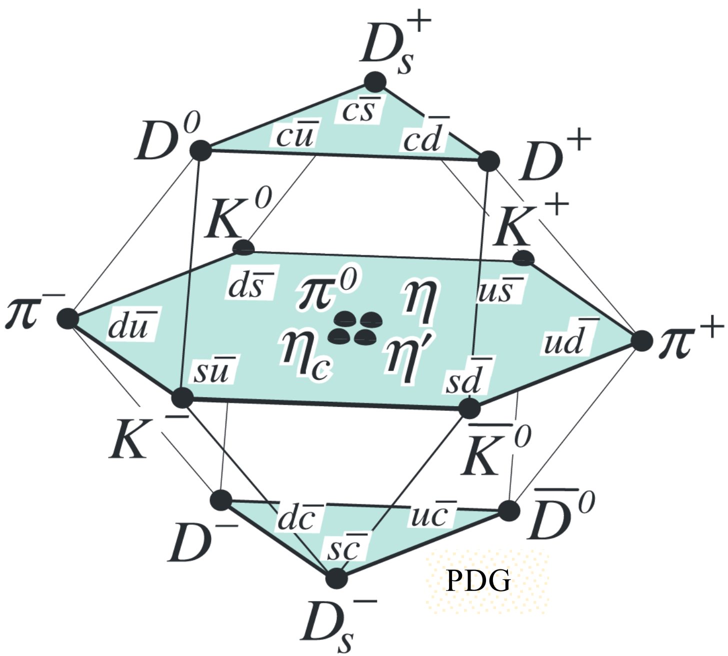
Spectroscopy II

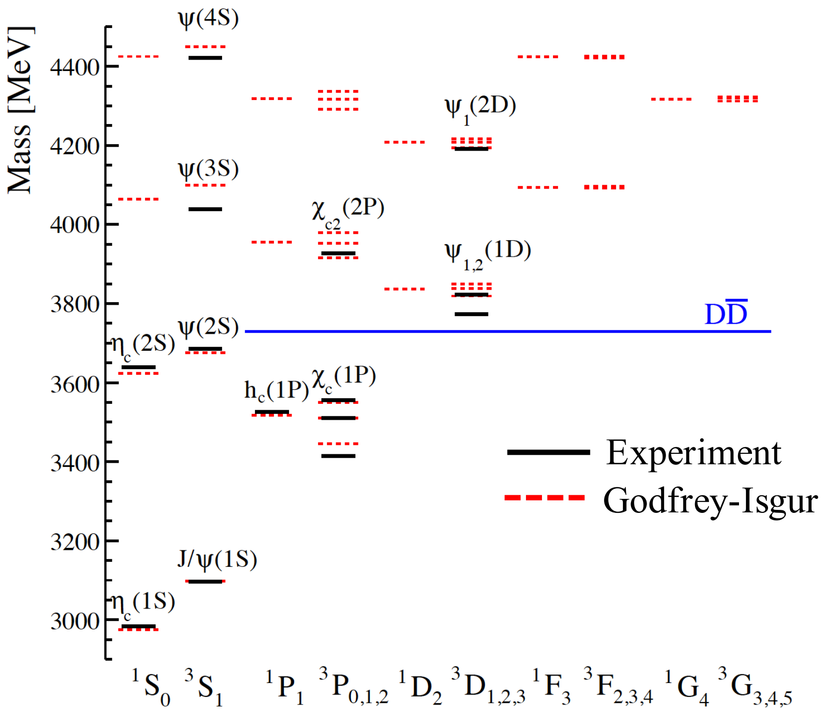
Atomic spectrum	↔	EM interaction (QED)
Hadron spectrum	↔	Strong interaction (QCD)

➢ Two examples of QCD bound state systems

Quark model



Excited states



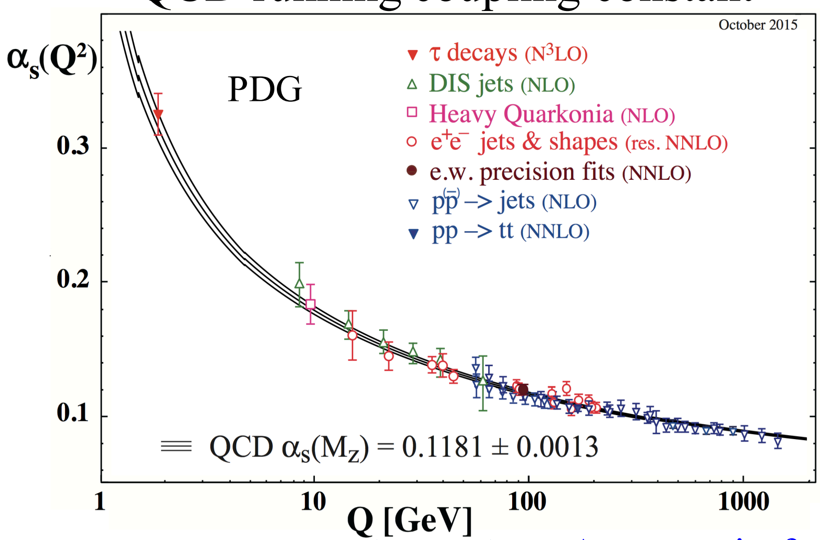
Spectroscopy III

Atomic spectrum ⟷ EM interaction (QED)

Hadron spectrum ⟷ Strong interaction (QCD)

Non-perturbative regime of QCD:
Test QCD-based phenomenological models and computing tools (LQCD)

QCD running coupling constant



Confinement ⟷ Asymptotic free

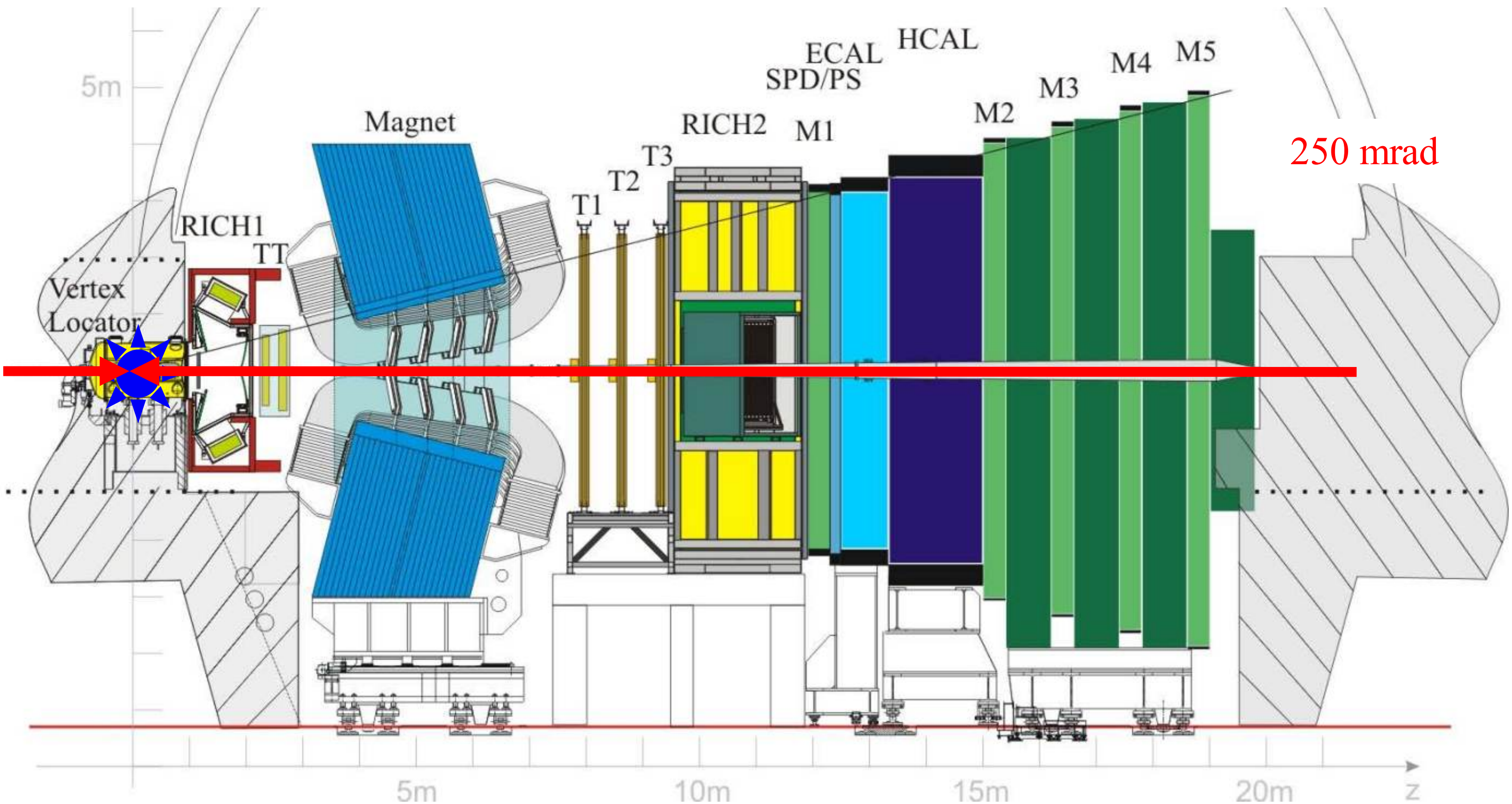
The LHCb experiment

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

LHCb experiment

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

Aiming for precision measurements in b, c flavor sectors
Acceptance: $2 < \eta < 5$

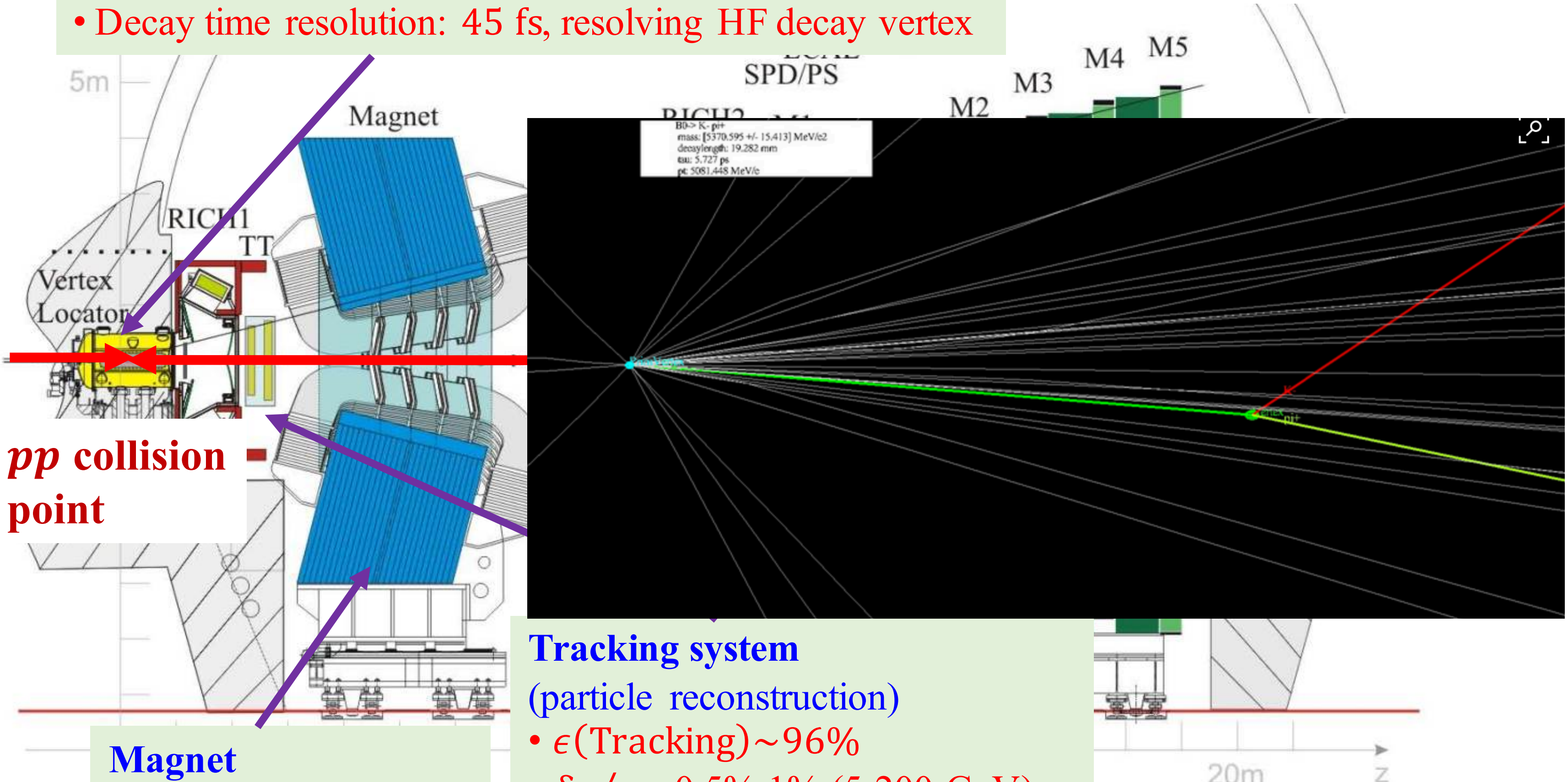


LHCb experiment

$\tau(H_b) \sim 1.5$ ps, $\tau(H_c) \sim 0.1 - 1$ ps

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

Vertex Locator (vertex reconstruction)
- Impact parameter resolution: 20μm
- Decay time resolution: 45 fs, resolving HF decay vertex



***pp* collision point**

Tracking system
(particle reconstruction)
- ϵ(Tracking)~96%
- $\delta p/p$ ~0.5%-1% (5-200 GeV)
- $\sigma(m_{B\to hh}) \approx 22$ MeV

Magnet
Bending power: 4 Tm

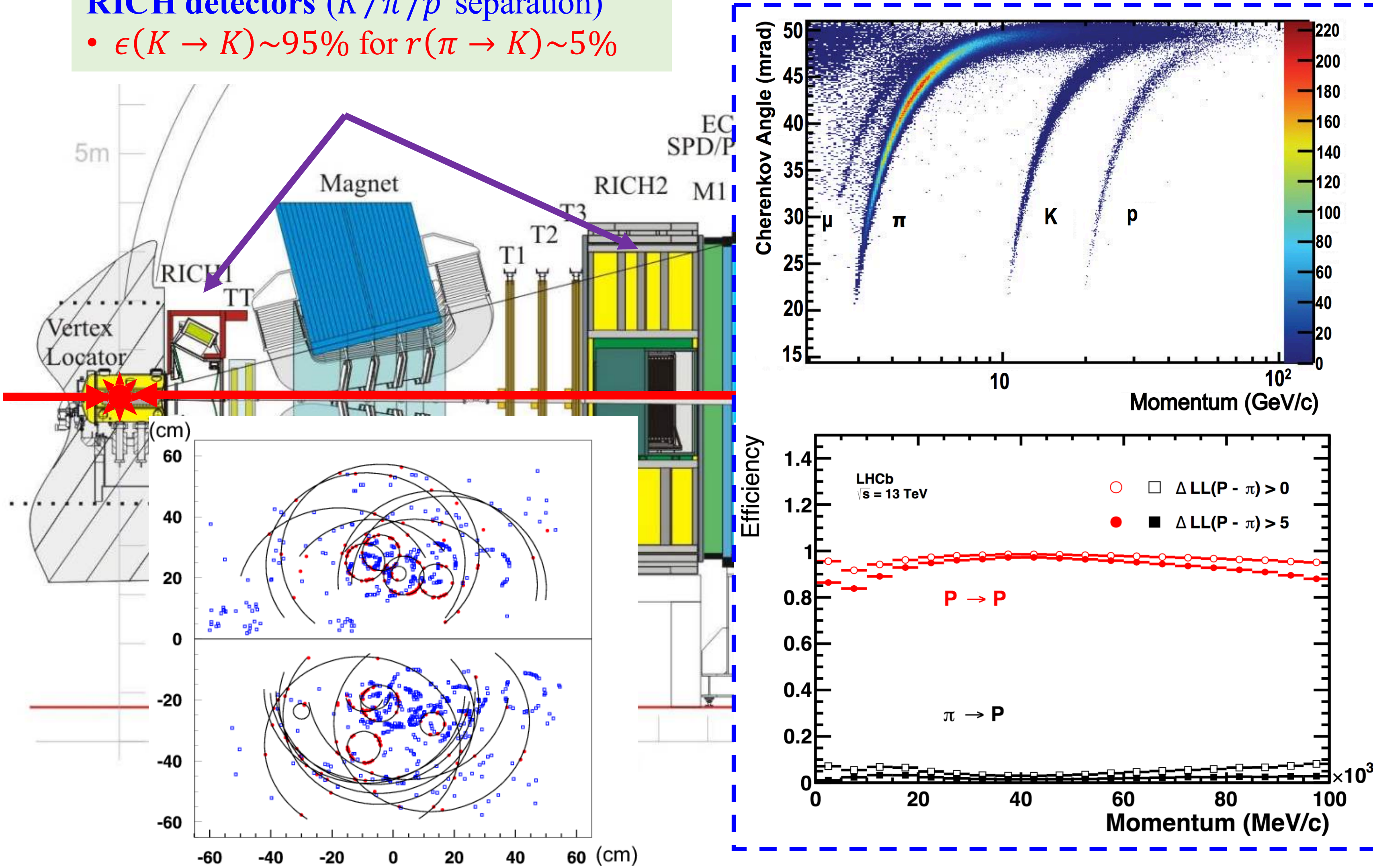
LHCb experiment

Decays: $b \to c \to s\ (K^{\pm})$; Baryon → proton

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

RICH detectors ($K/\pi/p$ separation)

- $\epsilon(K \to K) \sim 95\%$ for $r(\pi \to K) \sim 5\%$

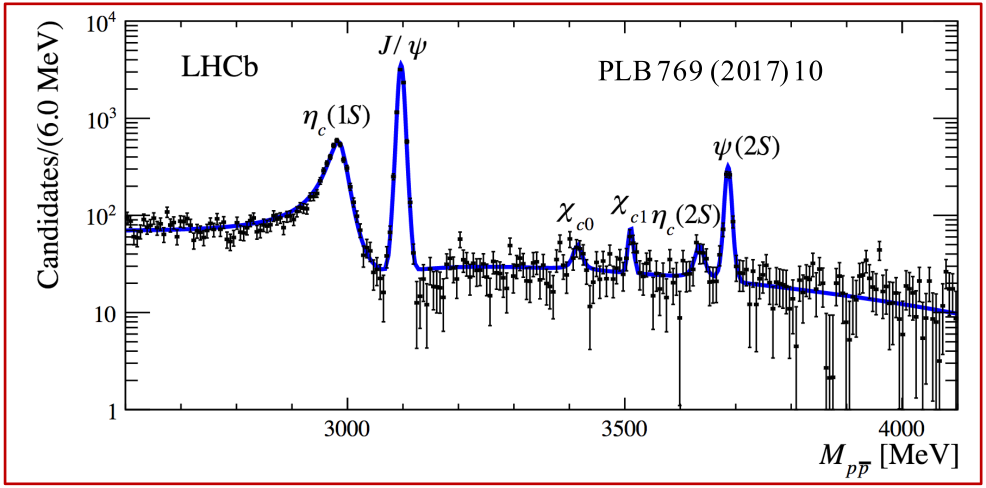


Why LHCb

- Large luminosity: $L \sim 8\ \mathrm{fb}^{-1}$
- Large production rate: $\sigma(b\bar{b}) \sim 500$ μb @ 13 TeV
- All possible species: $B^+, B^0, B_s^0, B_c^+, \Lambda_b^0, \Xi_b^{+,0}, \Omega_b^- + \cdots +$ excited states
- Efficient signal reconstruction
  - Tracking, particle ID, Vertex reconstruction for b, c
- Flexible (dedicated) trigger

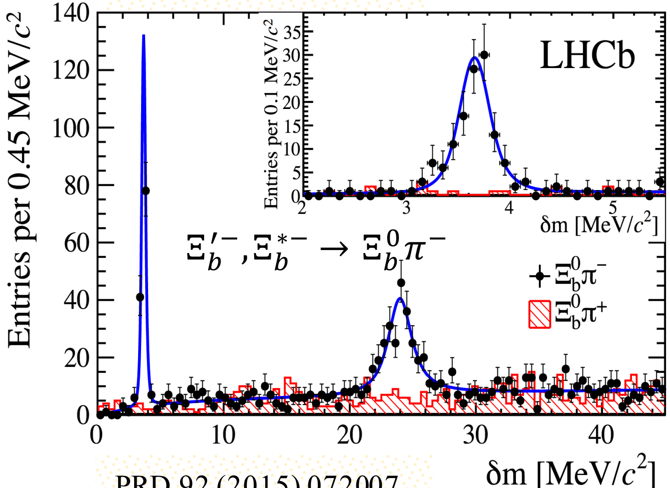
Prefer to have weakly decaying particle, challenging to study "prompt production and strong (EM) decays" ($X \to \Upsilon p$)

It is a clean experiment for weak decays

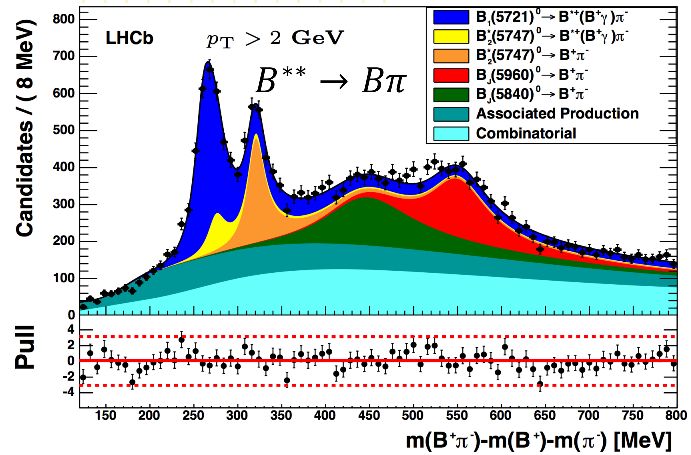


LHCb spectroscopy

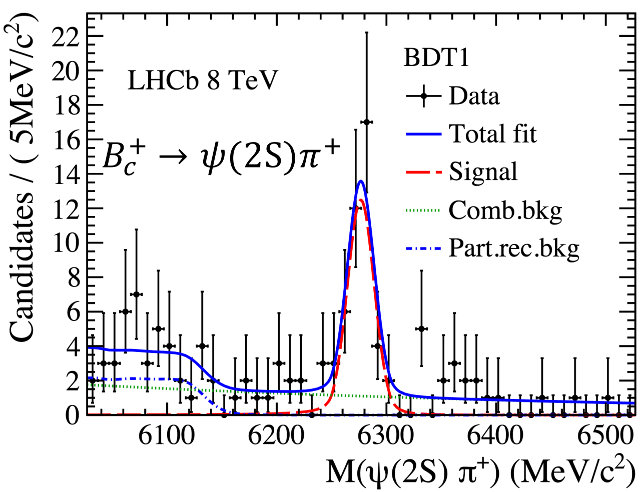
PRL 114 (2015) 062004



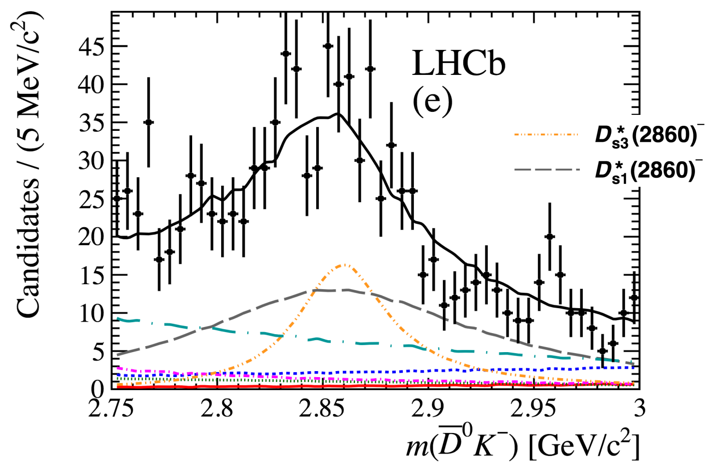
JHEP 1504 (2015) 024



PRD 92 (2015) 072007



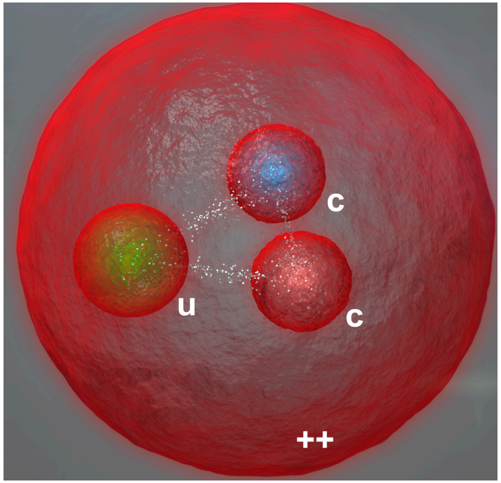
PRL 113 (2014) 162001



$X(3872), X \to J/\psi\phi, Z_c^+(4430), D_q^{**}$ states, b, c baryons, $Q\bar{Q}$, B_c^+ …

PRL 119 (2017) 112001 [arXiv:1707.01621]

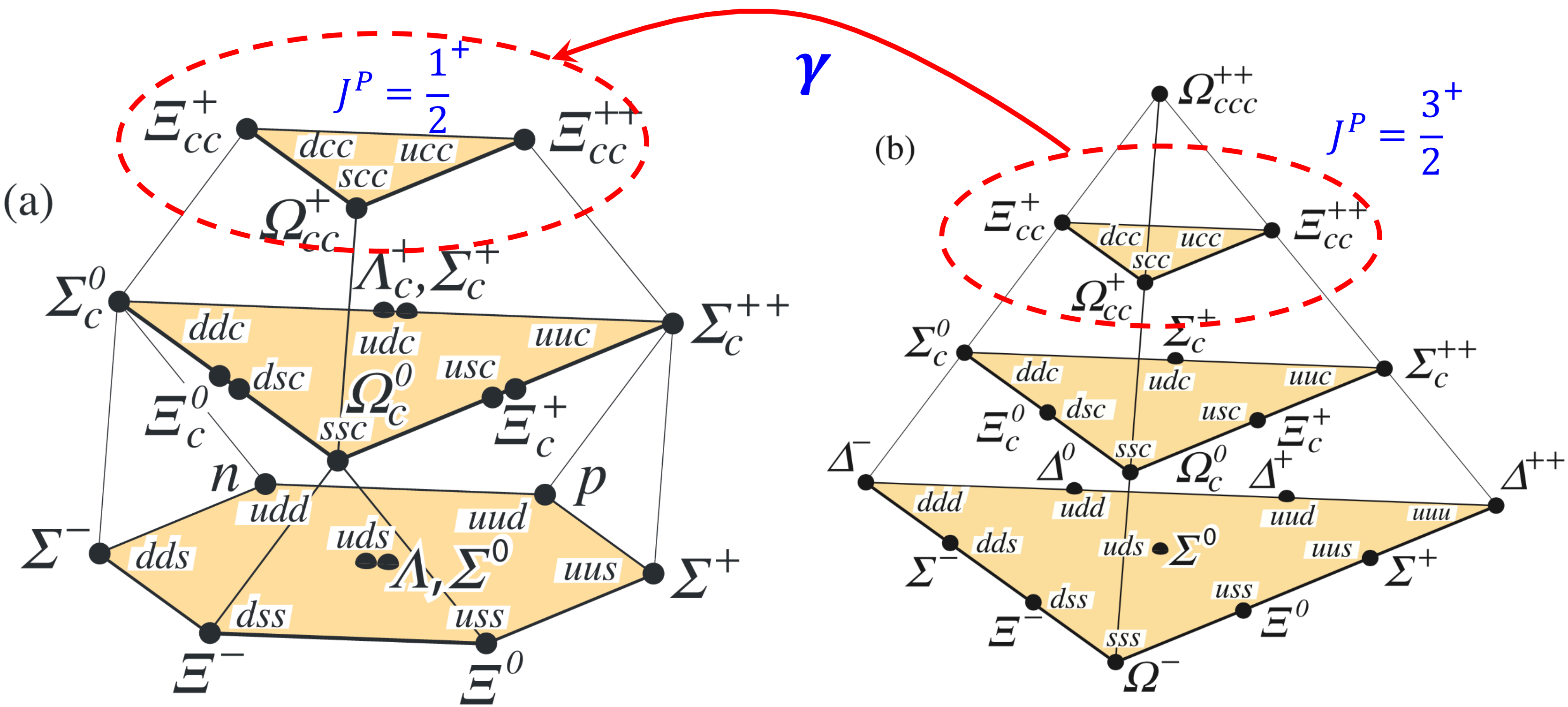
Observation of the doubly charmed baryon Ξ_{cc}^{++} (ccu)



Ξ_{cc}^{++}: ccu

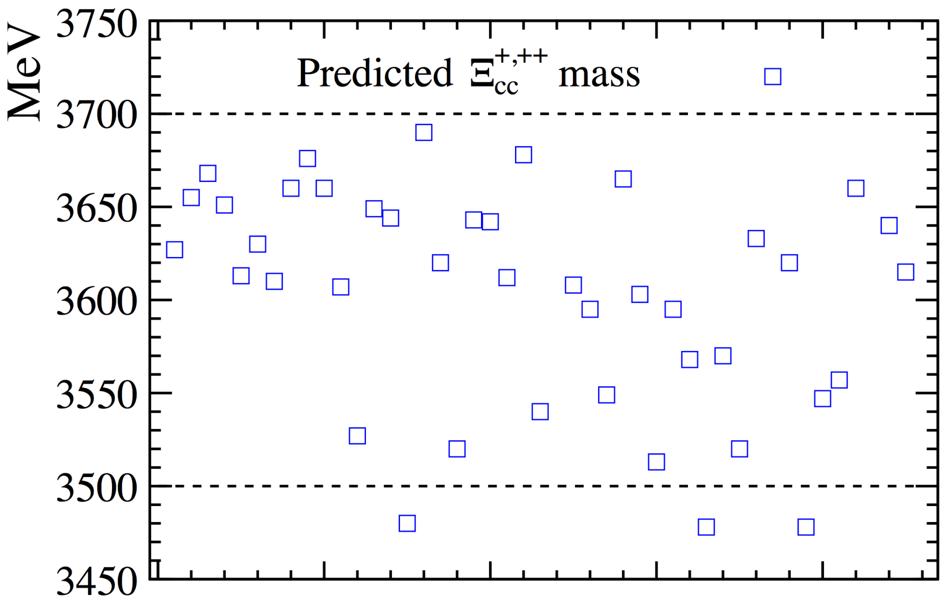
The doubly charm baryons

- Two SU(4) baryon 20-plets with $J^P = 1/2^+$ or $J^P = 3/2^+$, each contains a SU(3) triplet with two charm quarks: $\Xi_{cc}^{+}(ccd),\ \Xi_{cc}^{++}(ccu),\ \Omega_{cc}^{+}(ccs)$
- $3/2^+$ states expected to decay to $1/2^+$ states via electromagnetic interaction
- $1/2^+$ states decay weakly with a c quark transformed to lighter quarks



Masses (before 2017)

- Many models have been applied to determine masses of ground state and excitations: (non-) relativistic QCD potential models, triple harmonic-oscillator potential model, QCD sum rules, bag model or quark model …
  - ➢ Predicted $\Xi_{cc}^{+,++}$ masses in range 3.5 − 3.7 GeV, $M(\Omega_{cc}^{+}) \approx M(\Xi_{cc}) + 0.1$ GeV



Experimental studies far behind theories

A point = one prediction

- Lattice QCD computations:

$M(\Xi_{cc}) \approx 3.6$ GeV, $M(\Omega_{cc}^{+}) \approx 3.7$ GeV, $\sigma \sim 10$ MeV

Lifetimes of ½⁺ states

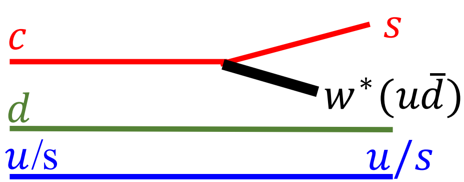
Particle	τ (ps)
D^0	0.410 ± 0.002 PDG
D_s^+	0.500 ± 0.007
D^+	1.040 ± 0.007
$D_b^+(B_c^+)$	0.507 ± 0.009
$\Lambda_c^+(cud)$	0.200 ± 0.006
$\Xi_c^0\,(csd)$	0.112 ± 0.012
$\Xi_c^+(csu)$	0.442 ± 0.026
$\Omega_c^0\,(css)$	0.069 ± 0.012

- Heavy quark decay spectator model predicts almost equal lifetimes
  - ➢ True for bottom hadrons: 1.5 ps $\pm$ 10%
  - ➢ True for charm semi-leptonic decay width:

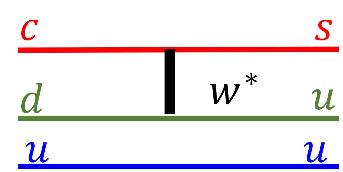
$$\Gamma(H_c \to l\nu_l X) = \frac{\mathrm{Br}(H_c \to l\nu_l X)}{\tau_{H_c}} \approx 0.3\ \mathrm{ps}^{-1}$$

- But charm hadron lifetimes known to vary a lot
  - ❑ Explained by Pauli interference and non-spectator decays, qualitatively
    - ➢ Destructive/constructive interference ($\Gamma_s^{-/+}$): $cuq/csq \to suq/ssq\,(u\bar{d})$
    - ➢ W-exchange process (enhancement): $cdq \to suq$

Spectator (Γ_s)



W-exchange (W)



➢ Expectation: $\tau(\Xi_{cc}^{++}(ccu)) \gg \tau(\Xi_{cc}^{+}(ccd))$

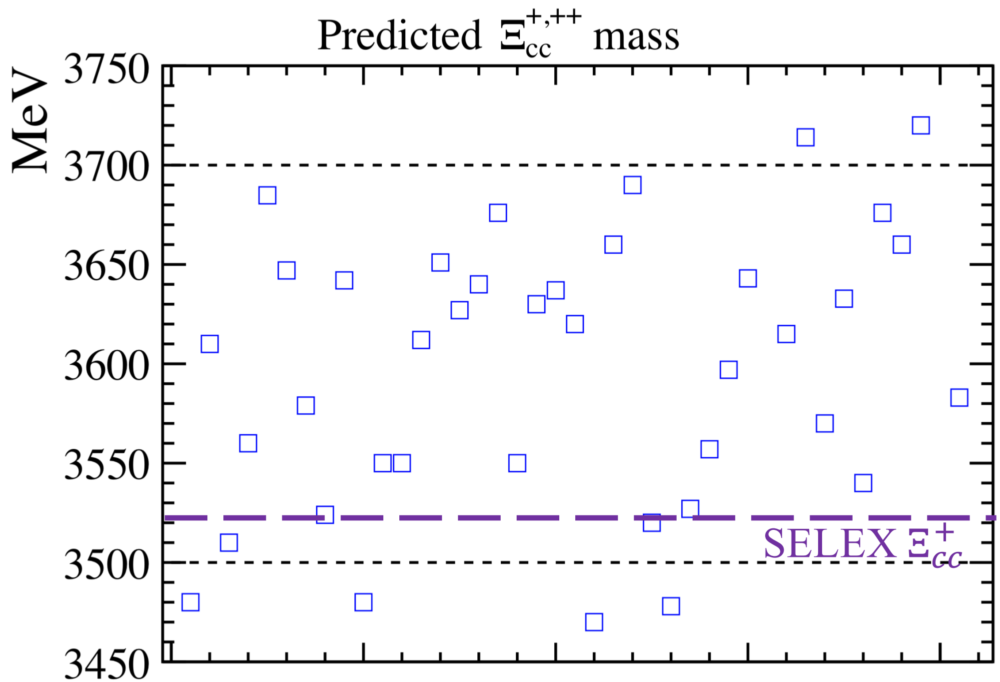
- Model calculations give $\tau(\Xi_{cc}^{++}) \in [\,200 - 700]$ fs

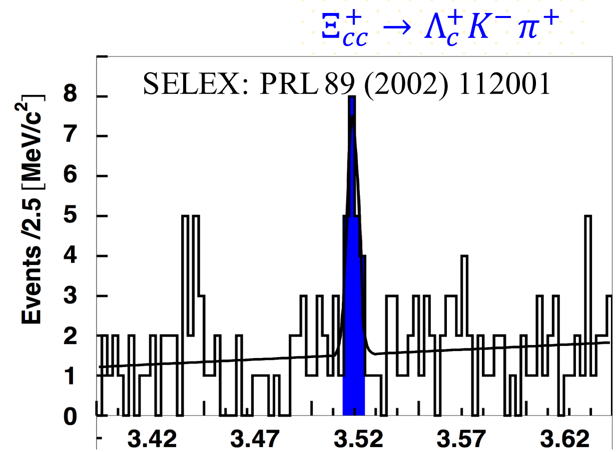
$$\tau(\Xi_c^+)/2 \approx \tau^{++} \approx \tau(D_s^+, B_c^+)/2, \qquad \tau(\Xi_c^0)/2 < \tau^+ < \tau(\Lambda_c^+)/2$$

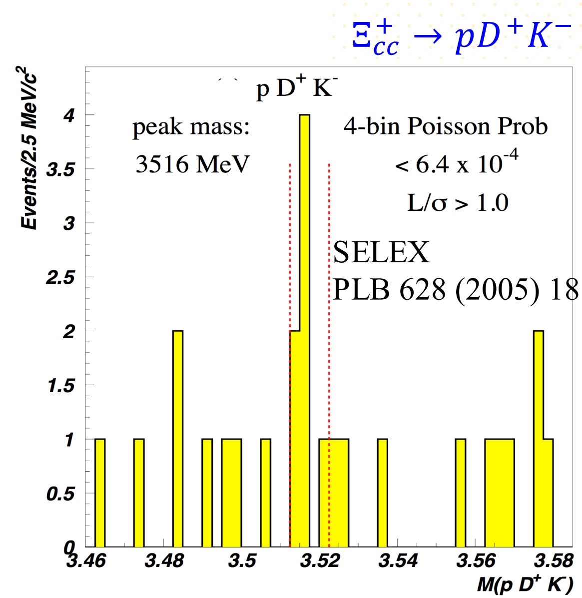
$\tau^{++} \approx 0.25$ ps
$\tau^{+} \approx 0.075$ ps

Ξ_{cc} in the past

- $\Xi_{cc}^{+}(ccd)$ reported by SELEX $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^{+} \to p D^+ K^-$ decays
  - **Signal yields**: 15.9 ($\Lambda_c^+ K^- \pi^+$) and 5.62 ($p D^+ K^-$)
  - **Short lifetime**: $\tau(\Xi_{cc}^{+}) < 33$ fs @90% CL, but not zero
  - **Large production:** $R = \frac{\sigma(\Xi_{cc}^{+}) \times \mathrm{BF}(\Xi_{cc}^{+} \to \Lambda_c^+ X)}{\sigma(\Lambda_c^+)} \sim 20\%$
  - **Mass (combined):** 3518.7 ± 1.7 MeV



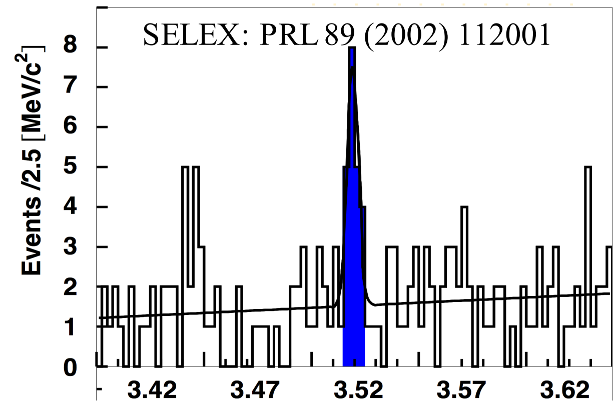




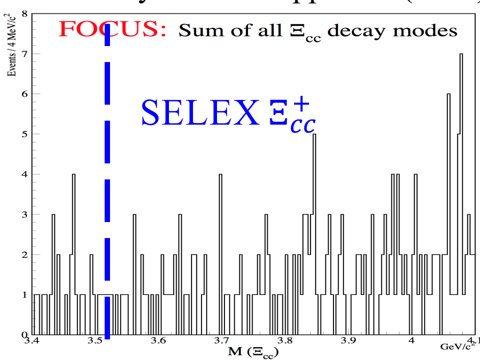
Ξ_{cc} in the past

- $\Xi_{cc}^{+}(ccd)$ reported by SELEX $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ and $\Xi_{cc}^{+} \to p D^{+} K^{-}$ decays
  - **Signal yields**: 15.9 ($\Lambda_c^{+} K^{-} \pi^{+}$) and 5.62 ($p D^{+} K^{-}$)
  - **Short lifetime**: $\tau(\Xi_{cc}^{+}) < 33$ fs @90% CL, but not zero
  - **Large production:** $R = \frac{\sigma(\Xi_{cc}^{+}) \times \mathrm{BF}(\Xi_{cc}^{+} \to \Lambda_c^{+} X)}{\sigma(\Lambda_c^{+})} \sim 20\%$
  - **Mass (combined):** 3518.7 ± 1.7 MeV
- Not seen by others with larger Λ_c^{+} samples

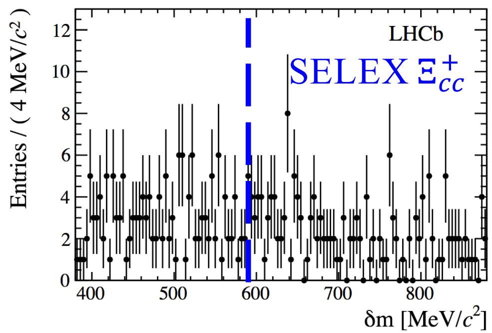
$\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$



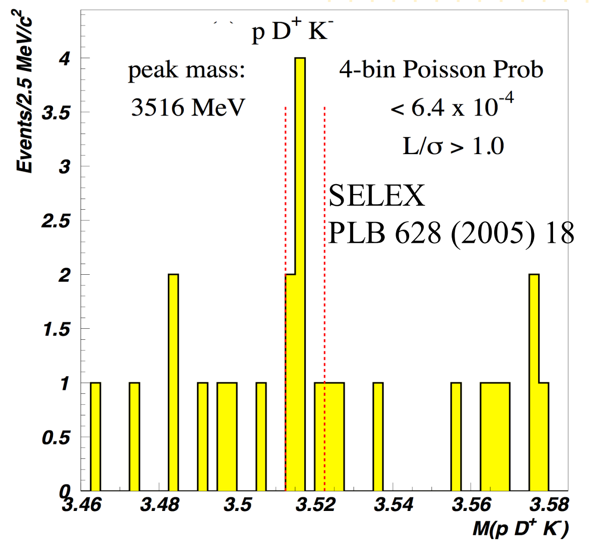
Nucl. Phys. Proc. Suppl. 115 (2003) 33



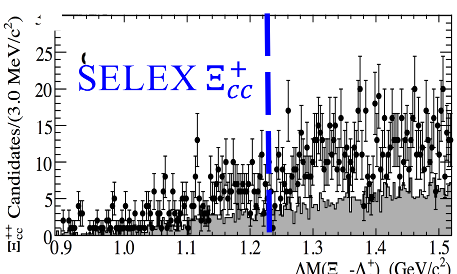
LHCb: JHEP 12 (2013) 090



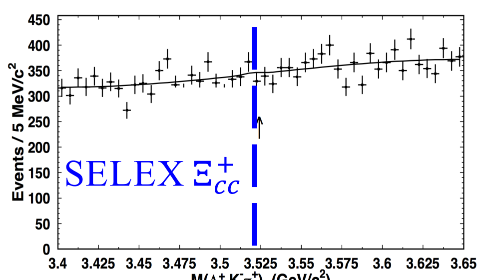
$\Xi_{cc}^{+} \to p D^{+} K^{-}$



BaBar: PRD 74 (2006) 011103

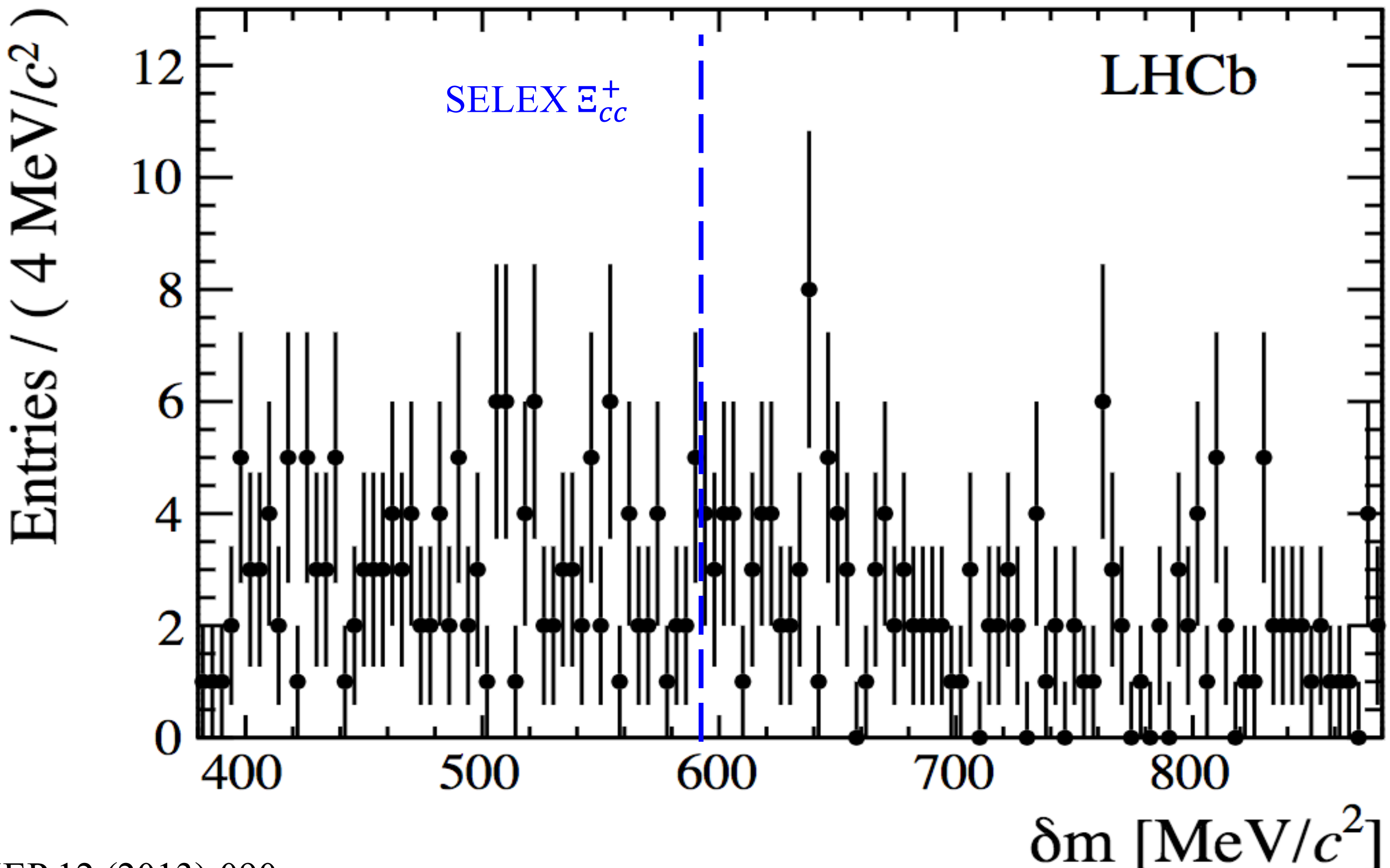


Belle: PRL 97 (2006) 162001



$\Xi_{cc}^{+}(ccd)$ search at LHCb

- $\Xi_{cc}^{+} \to K^{-}\pi^{+}\Lambda_{c}^{+}$, with $\Lambda_{c}^{+} \to pK^{-}\pi^{+}$ (no evidence of signal)

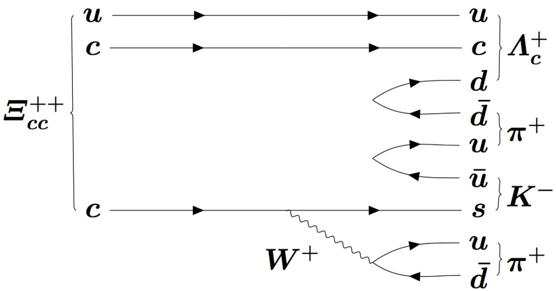


JHEP 12 (2013) 090

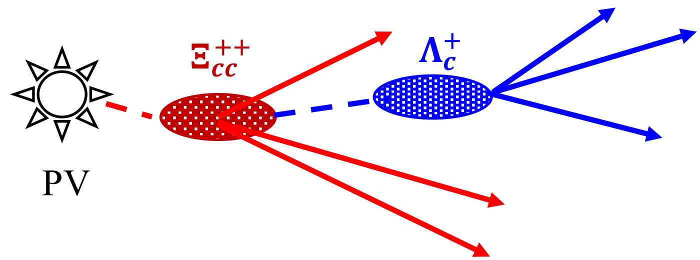
$\Xi_{cc}^{++}(ccu)$ search at LHCb

PRL 119 (2017) 112001

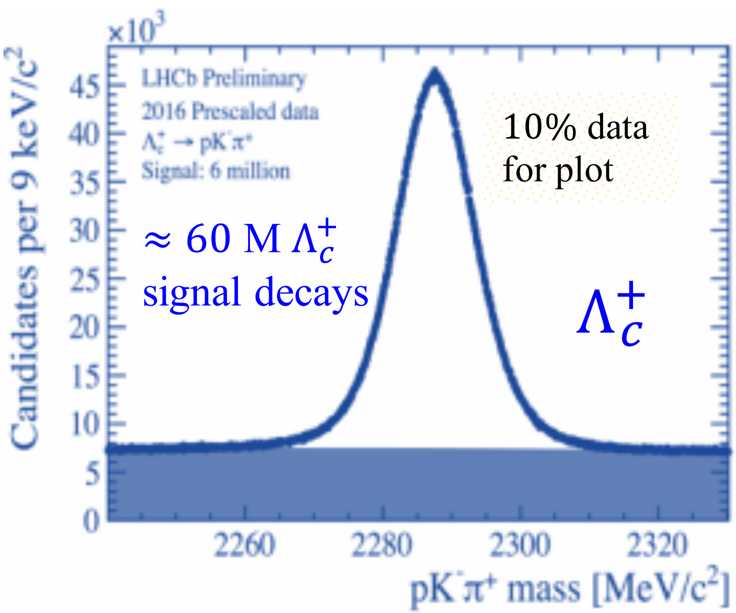
- $\Xi_{cc}^{++} \to K^-\pi^+\pi^+\Lambda_c^+$, with $\Lambda_c^+ \to pK^-\pi^+$



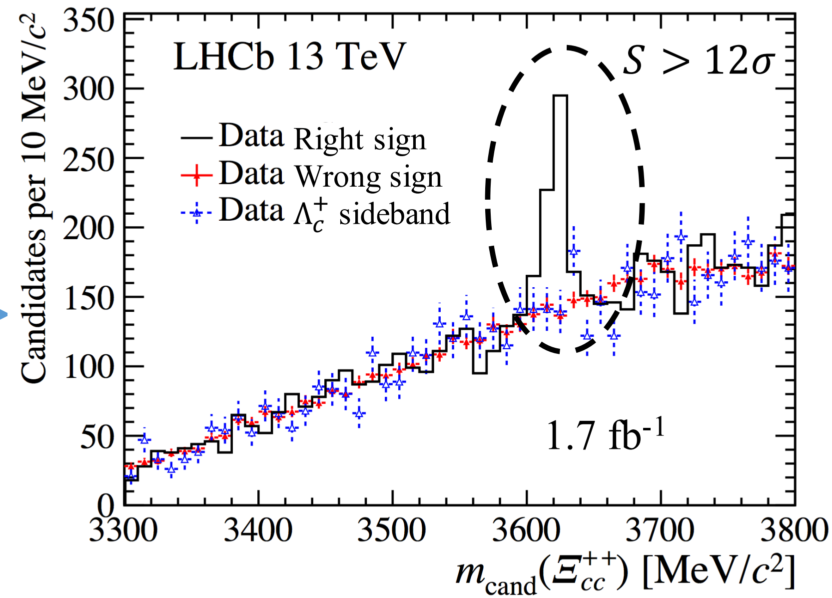
$\Xi_{cc}^{++} \to K^-\pi^+\pi^+\Lambda_c^+(\to pK^-\pi^+)$



- Selection requires a displaced Ξ_{cc}^{++} vertex, machine learning



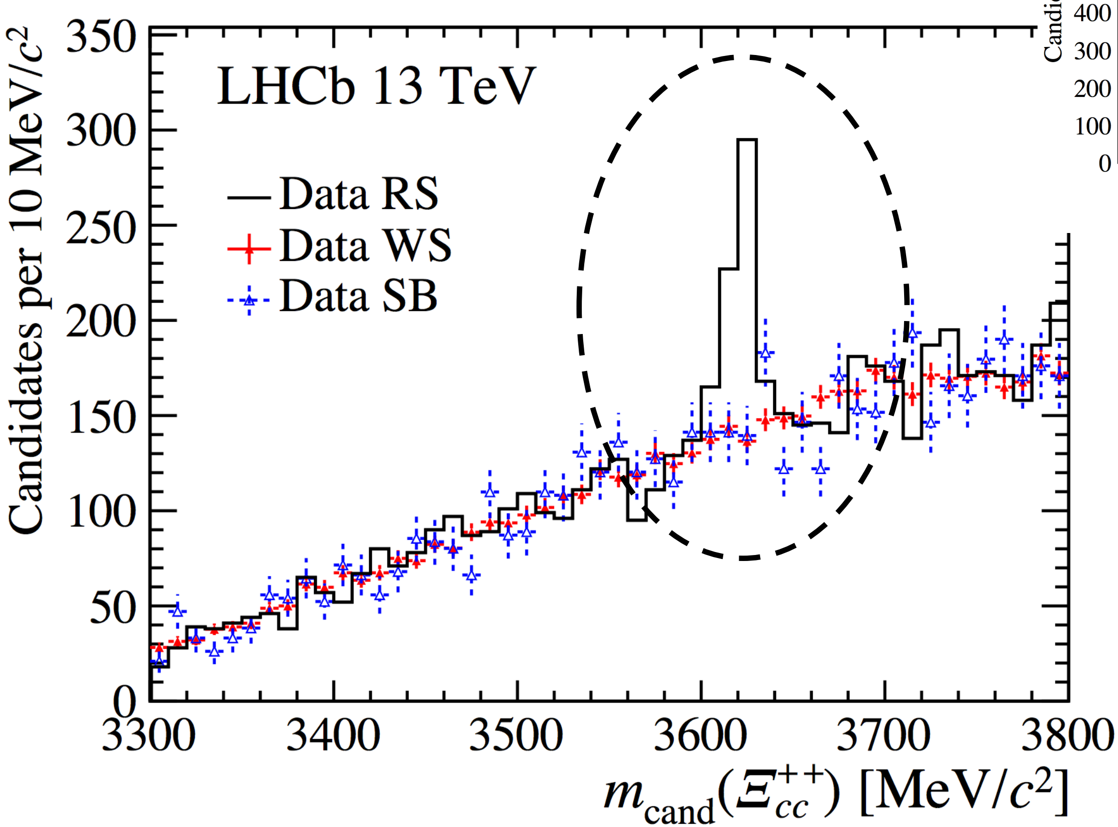
$+K^-2\pi^+$

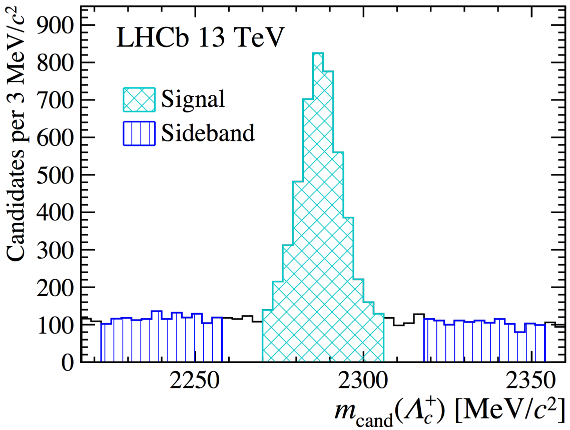


$\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum

PRL 119 (2017) 112001

- A significant structure in right sign (RS) combinations
- Not present in wrong sign (WS) combinations
- Not observed for Λ_c^+ background candidates
- Distributions similar except the peak in RS





The mass

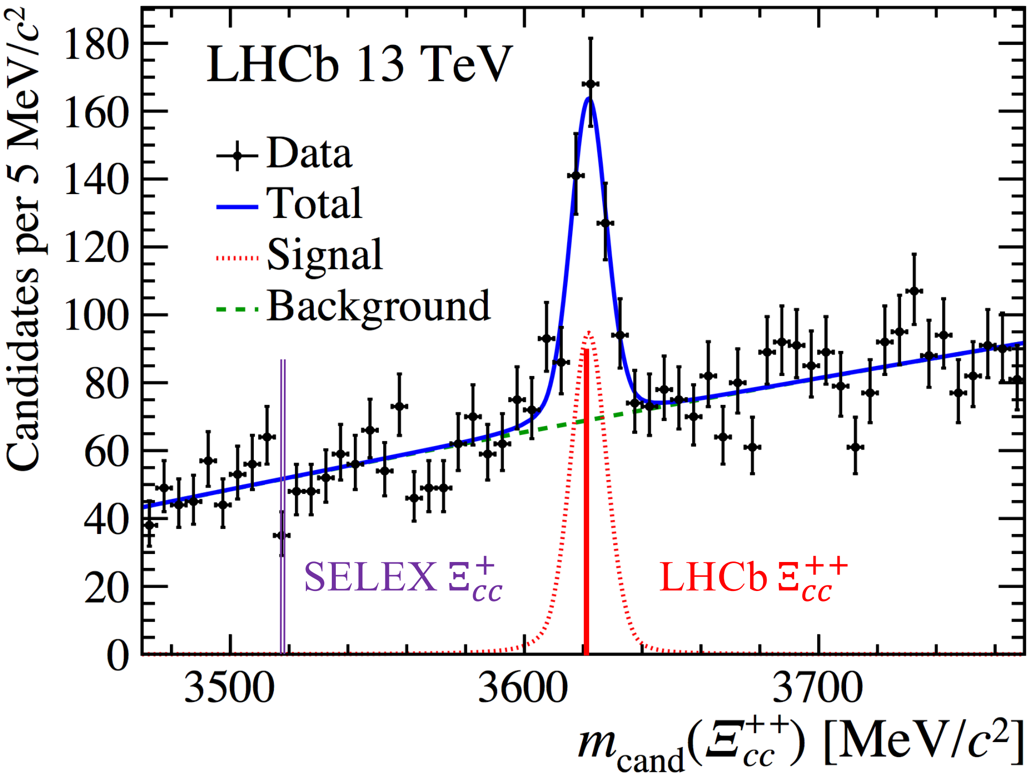
PRL 119 (2017) 112001

$M(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)$ MeV

$M(\Xi_{cc}^{++})_{\text{LHCb}} - M(\Xi_{cc}^{+})_{\text{SELEX}} = 103 \pm 2$ MeV

Unlikely to be isospin partners

$\Delta M = 2.16 \pm 0.20$ MeV [Science 347 (2015) 1452]



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PRL 119 (2017) 112001

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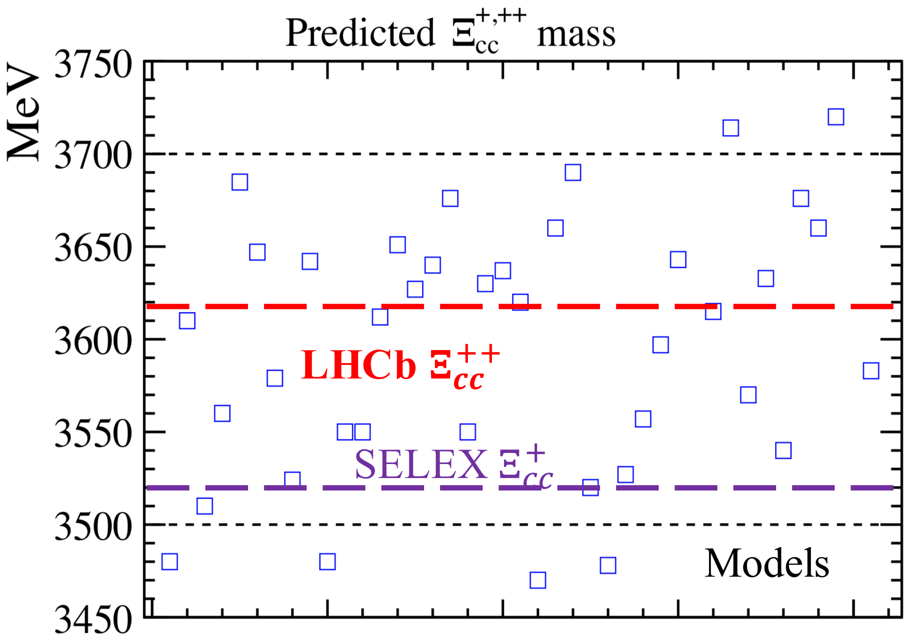

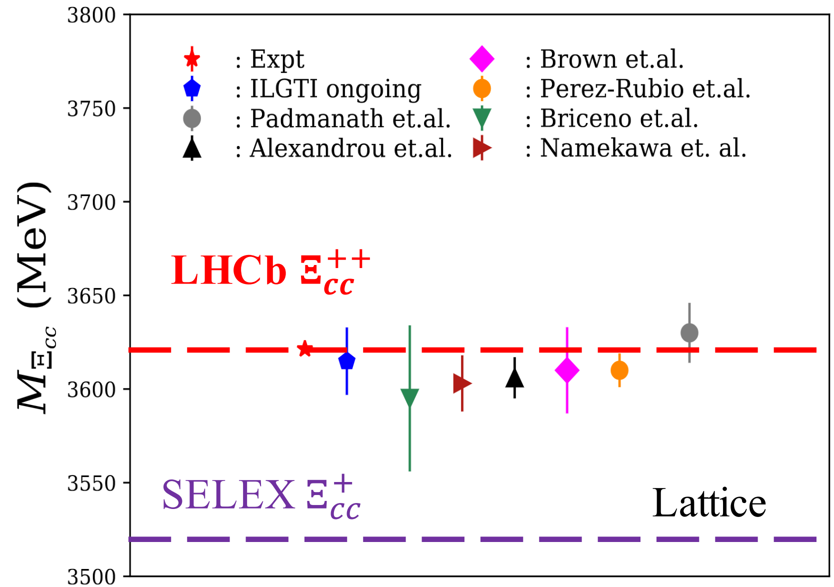

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PRL 119 (2017) 112001

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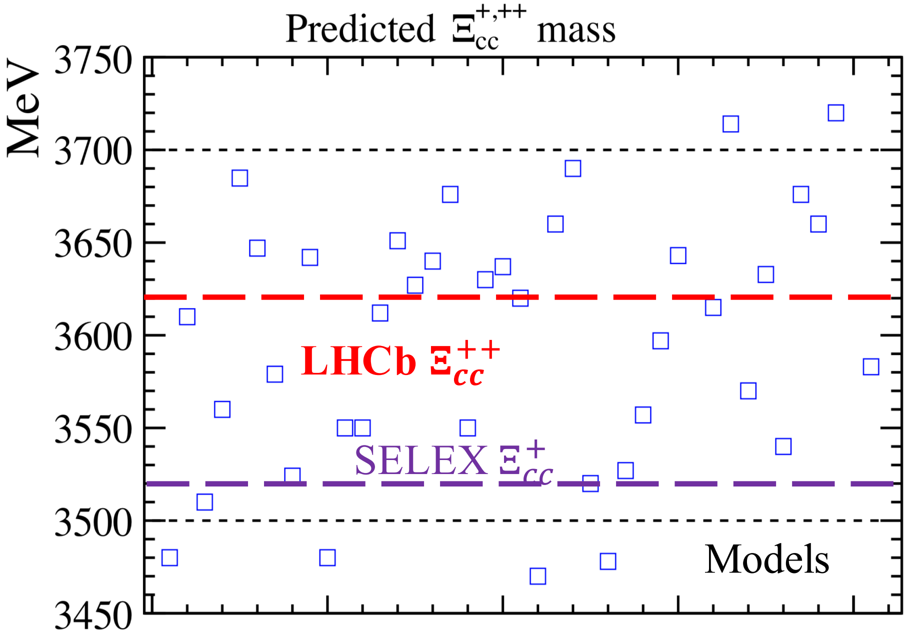
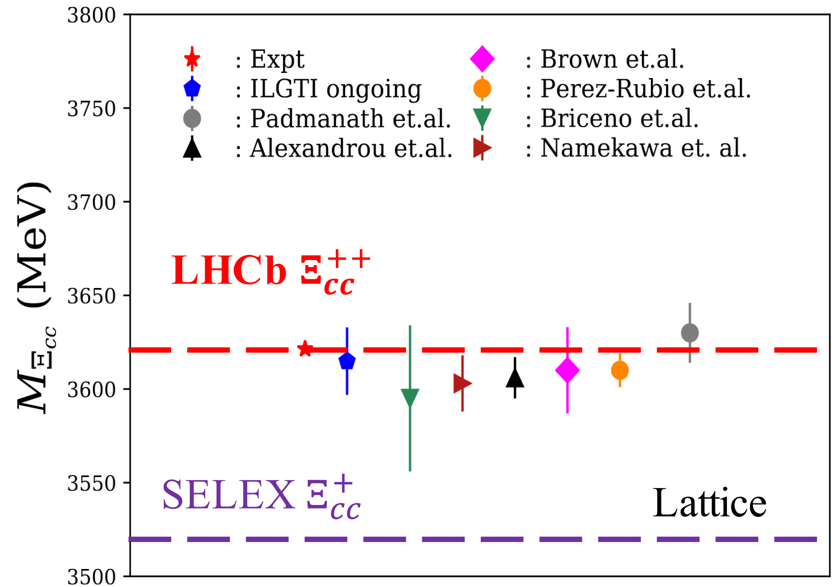


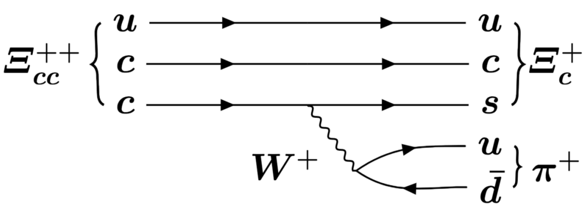


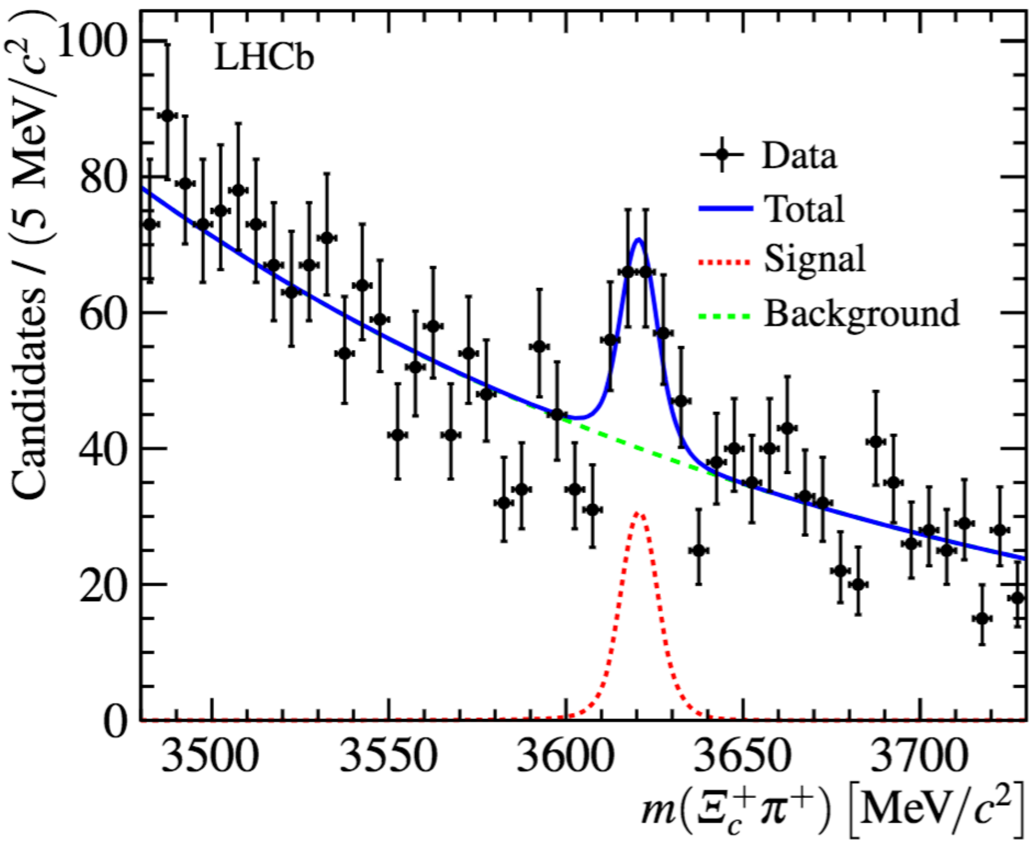
Production: $N(\Xi_{cc})/N(\Lambda_c^+)$ much smaller at LHCb, consistent with calculations

Another Ξ_{cc}^{++} decay

LHCb-PAPER-2018-026

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

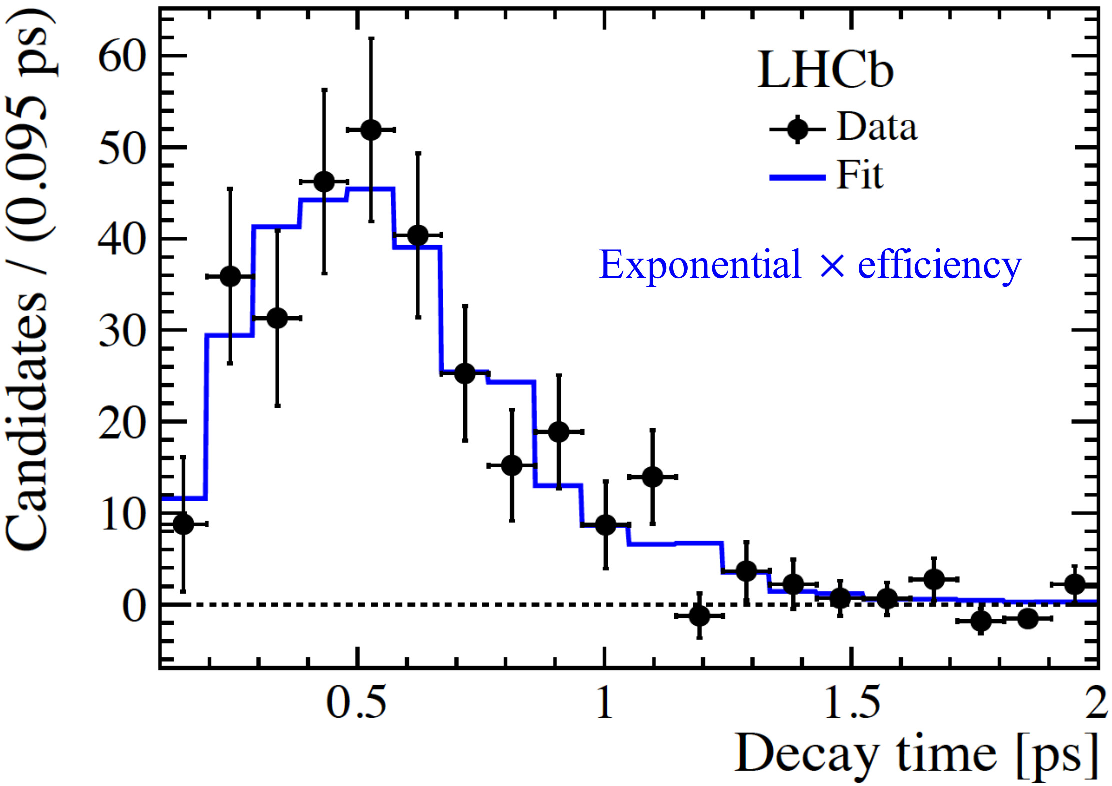




Mass consistent with $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decay

Ξ_{cc}^{++} lifetime

- Measured with $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, efficiency studied using $\Lambda_b^0 \to \Lambda_c^+ 3\pi$



$$t = \frac{L}{\gamma v} = \frac{L * m}{p} = \frac{(\boldsymbol{L} \cdot \boldsymbol{p}) * \boldsymbol{m}}{|p|^2}$$

Particle	τ (ps)
D^0	0.410 ± 0.002
D_s^+	0.500 ± 0.007
D^+	1.040 ± 0.007
$D_b^+(B_c^+)$	0.507 ± 0.009
$\Lambda_c^+(cud)$	0.200 ± 0.006
$\Xi_c^0\,(csd)$	0.112 ± 0.012
$\Xi_c^+(csu)$	0.442 ± 0.026
$\Omega_c^0\,(css)$	0.268 ± 0.026
$\Xi_{cc}^{++}\,(ccu)$	0.256 ± 0.026

$$\tau\left(\Xi_{cc}^{++}\right) = 0.256\,^{+0.024}_{-0.022}\,(\text{stat}) \pm 0.014\,(\text{syst})\ \text{ps}$$

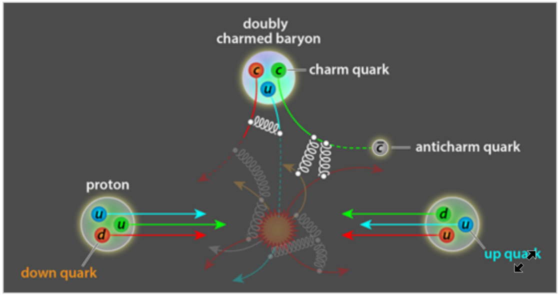
PRL 119 (2017) 112001

Viewpoint: A Doubly Charming Particle

Raúl A. Briceño, Department of Physics, Old Dominion University, Norfolk, VA 23529, USA
Jefferson National Accelerator Facility, Newport News, VA 23606, USA

September 11, 2017 • *Physics* 10, 100

High-precision experiments at CERN find a new baryon containing two charm quarks

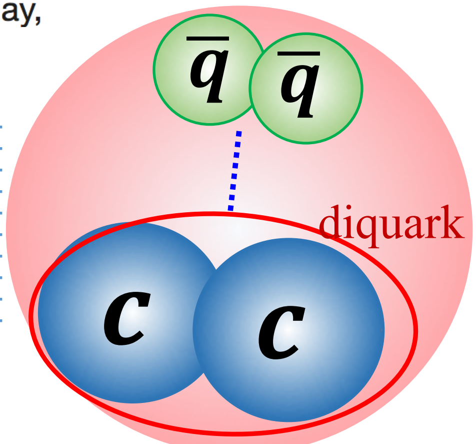


APS/Alan Stonebraker

words, would apply to both the Ξ_{cc}^{+} and the Ξ_{cc}^{++}). But the predictions from these studies were inconsistent with the measured mass of the putative Ξ_{cc}^{+} particle,

The LHCb's detection of the Ξ_{cc}^{++} has now resolved this conundrum: The previous theoretical studies had accurately predicted the mass of the Ξ_{cc}^{++}. In line with the recent trend in the field, this agreement provides yet another confirmation that we are entering an era where the physics of hadrons can be accurately predicted from QCD. Today,

Models predict absorptive potential between cc (diquark), like a heavy anti-quark, expecting existence of tetraquarks $cc\bar{q}\bar{q}$

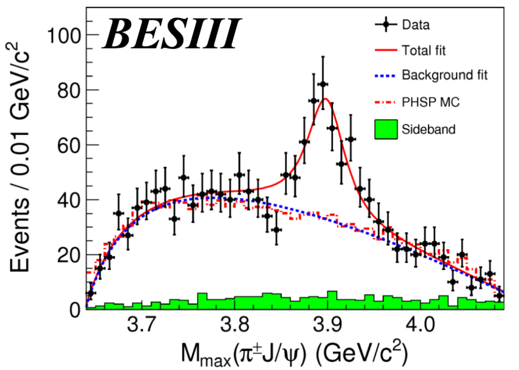


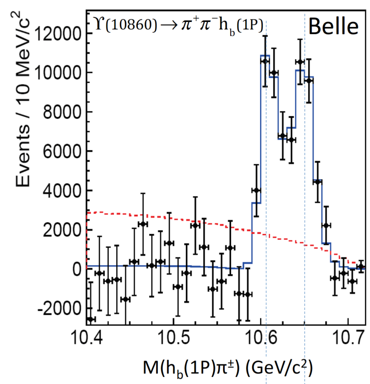
Pentaquark states $J/\psi p$ in Λ_b^0 decays

PRL 115 (2015) 072001 [arXiv:1507.03414]
PRL 117 (2016) 082003 [arXiv:1606.06999]

Exotic hadrons

- Many experimentally observed states not fitting in predicted spectrum
  - ➢ (Likely) states beyond 2 or 3 quark contents
  - ➢ Multi-quark states expected in constituent quark model, but not well predicted
- From e^+e^- collisions

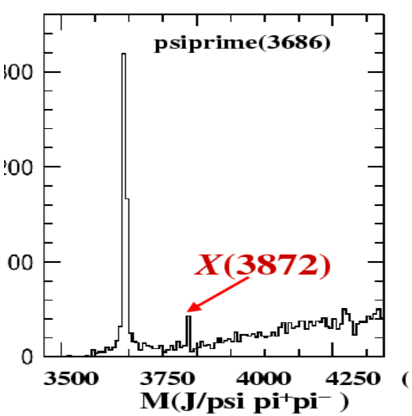


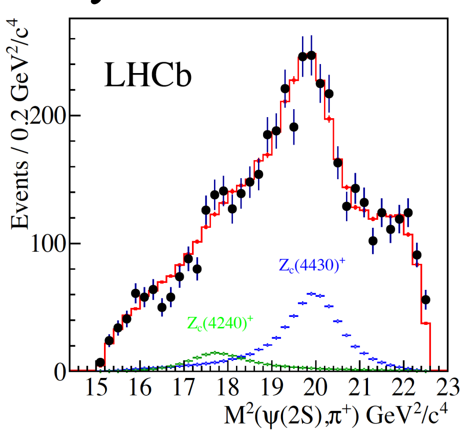


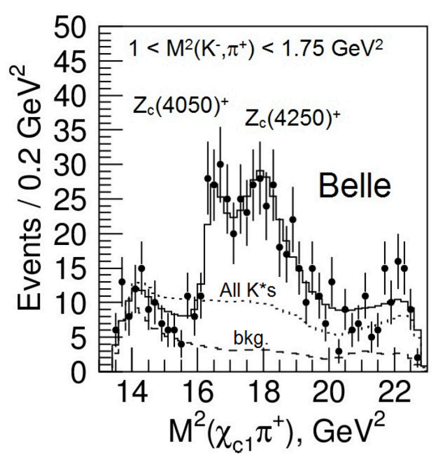
$+\cdots$

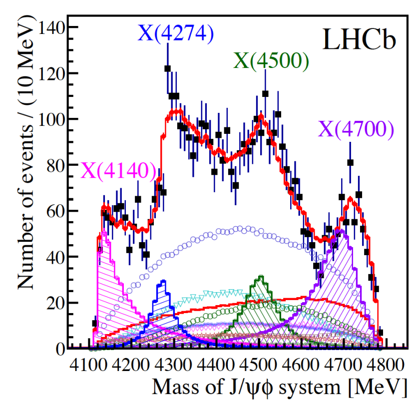
A nice review:
Rev. Mod. Phys. 90 (2018) 15003

- From b-hadron decays



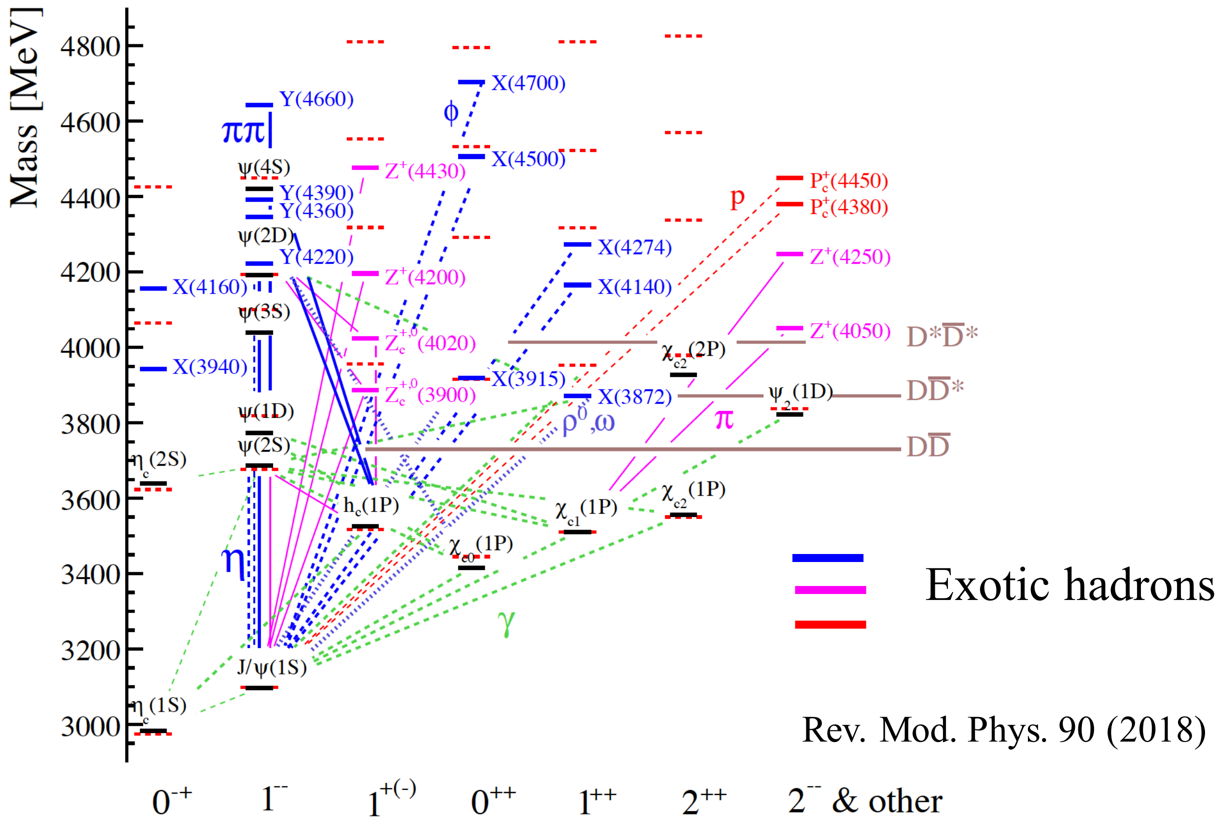






Exotic hadrons

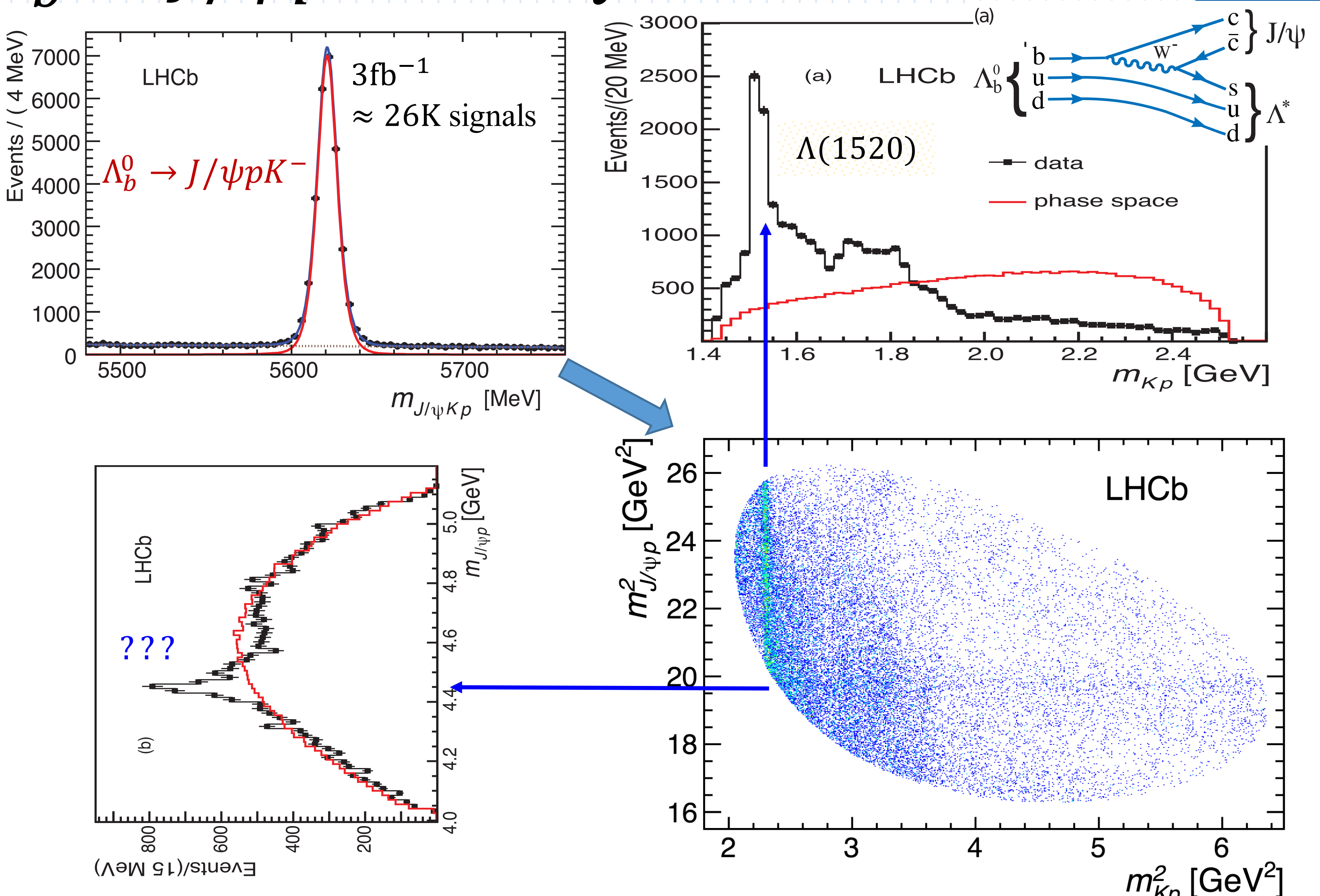
- Many experimentally observed states not fitting in predicted spectrum
  - ➢ (Likely) states beyond 2 or 3 quark contents
  - ➢ Multi-quark states expected in constituent quark model, but not well predicted
- **Making the spectrum a mess**



Rev. Mod. Phys. 90 (2018) 15003

$\Lambda_b^0 \to J/\psi p K^-$ decay

PRL 115 (2015) 072001



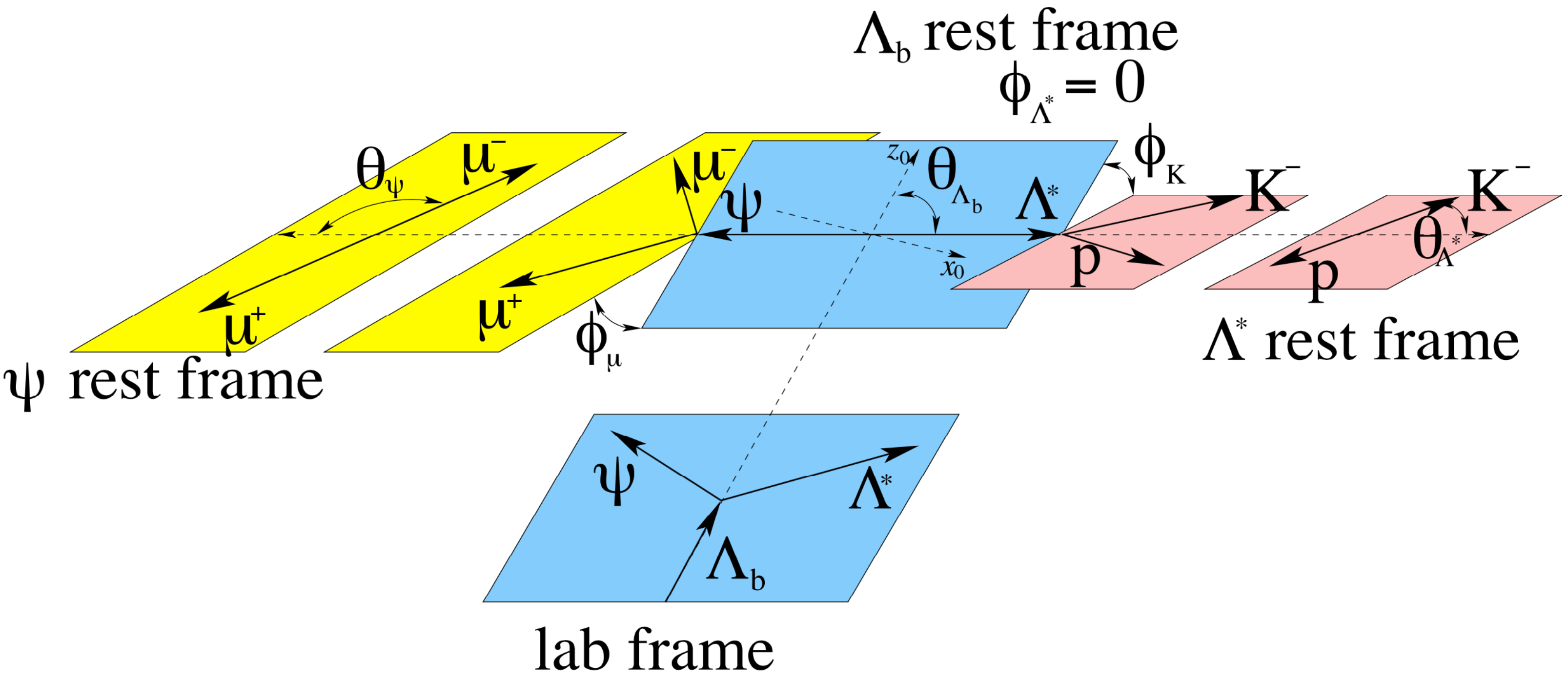
Amplitude fit

PRL 115 (2015) 072001

- Observables: $3\times(\cos\theta, \phi) + m_{pK}$, $\phi(J/\psi\Lambda^*) = 0$ with Λ_b^0 unpolarized

$$\Lambda_b^0 \to J/\psi\Lambda^*, \quad \Lambda^* \to pK^-, J/\psi \to \mu^+\mu^-$$

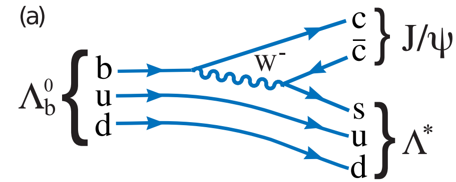
Helicity formulism

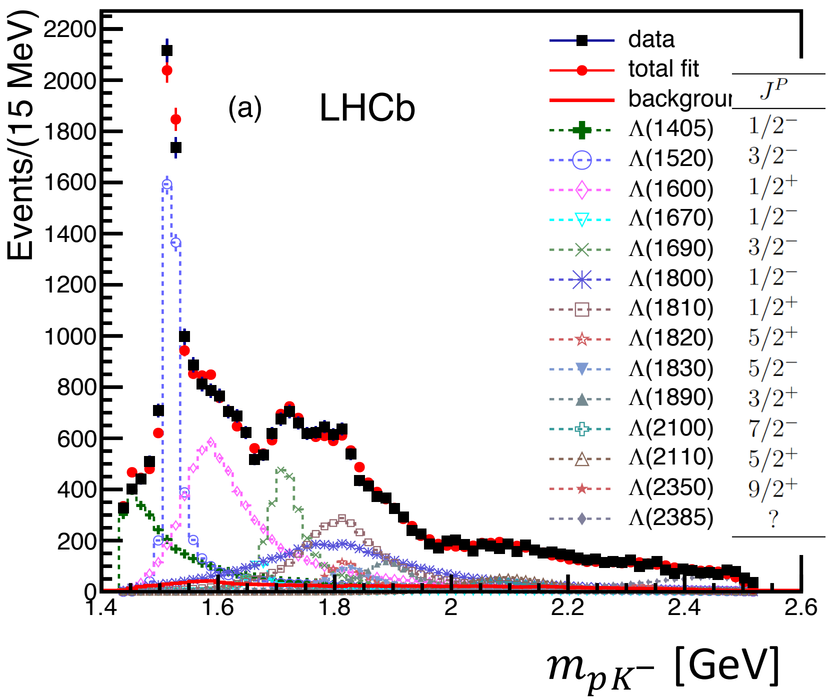


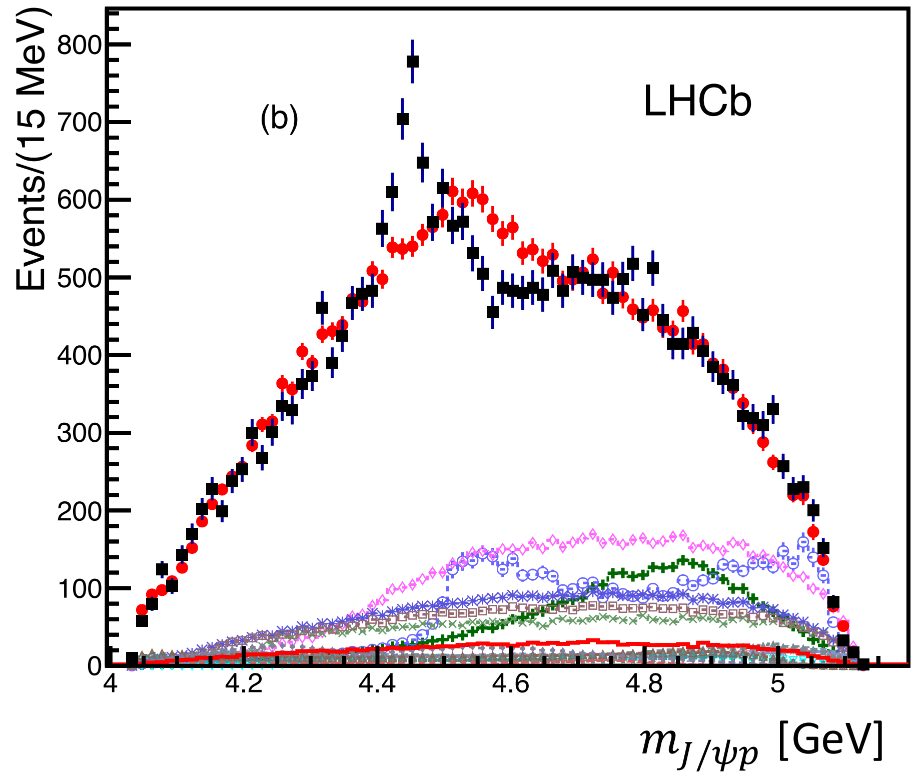
Amplitude fit with only Λ^*

PRL 115 (2015) 072001

$$\Lambda_b^0 \to J/\psi \Lambda^*, \quad \Lambda^* \to pK^-$$





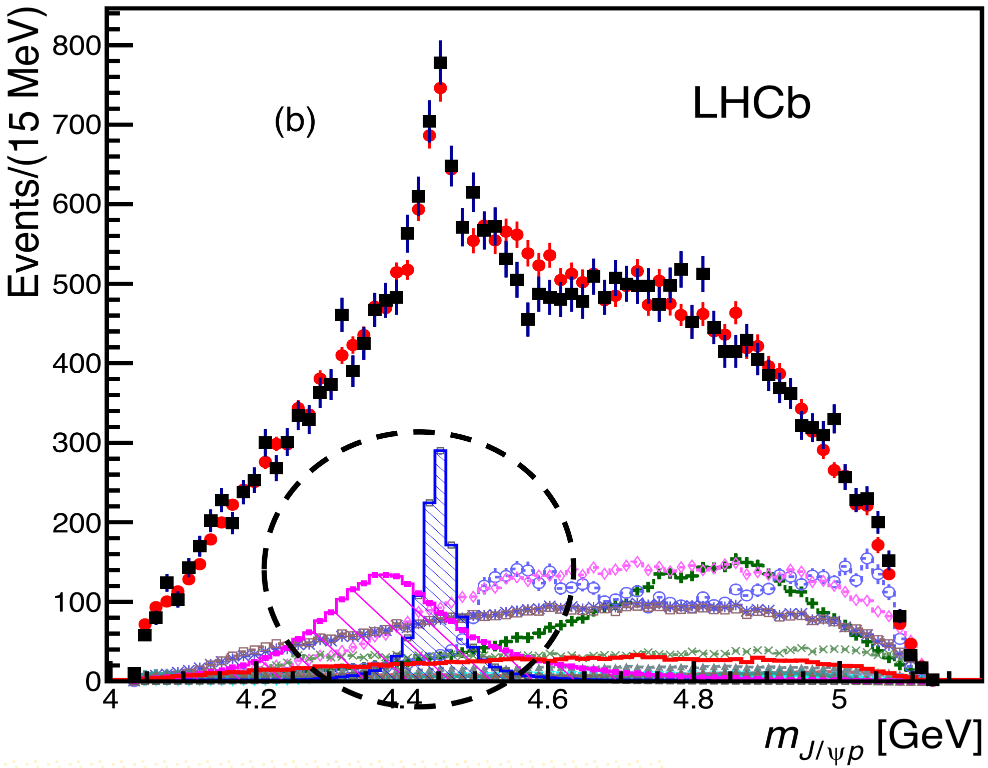


Λ^* resonances alone describes m_{pK^-} but not $m_{J/\psi p}$

$J/\psi p$ structures

PRL 115 (2015) 072001

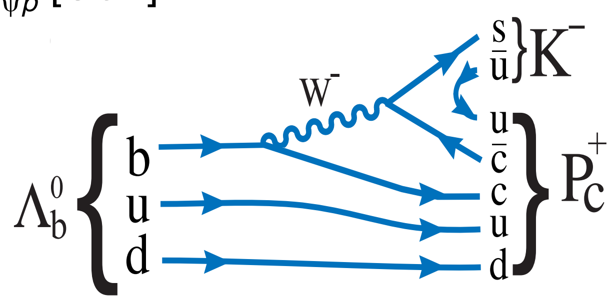
- Add two $P_c^+ \to J/\psi p$ resonances (one by one) to give satisfactory fit quality



Masses and widths:

$P_c(4380)^+$: $4380 \pm 8 \pm 29$ MeV
$205 \pm 18 \pm 86$ MeV

$P_c(4450)^+$: $4449.8 \pm 1.7 \pm 2.5$ MeV
$39 \pm 5 \pm 19$ MeV



$J/\psi p$ structures

PRL 115 (2015) 072001

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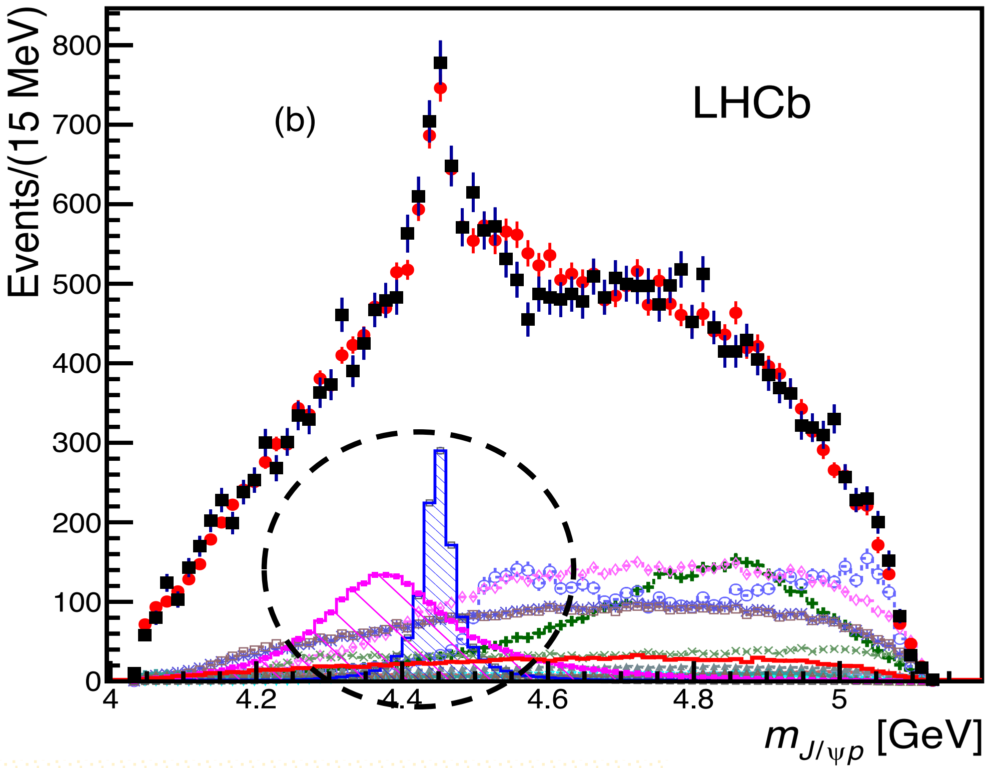

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$205 \pm 18 \pm 86$ MeV

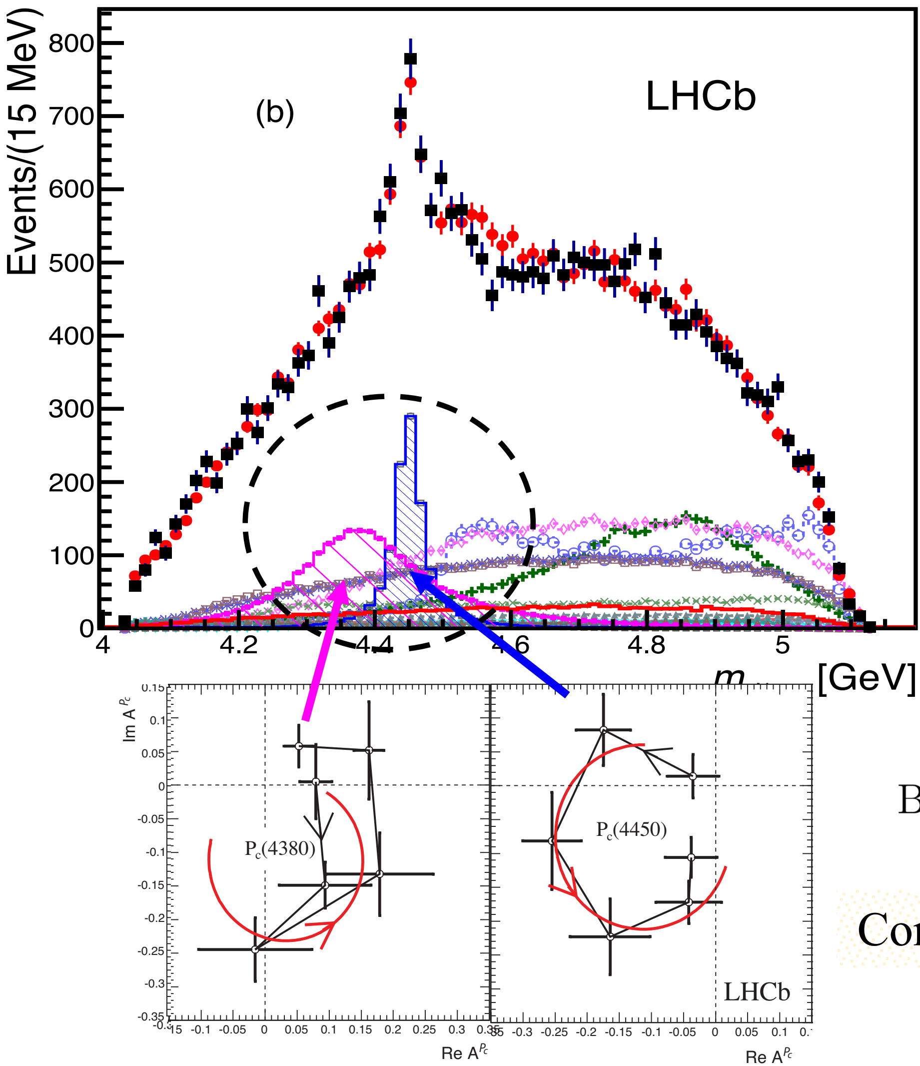
$P_c(4450)^+$: $4449.8 \pm 1.7 \pm 2.5$ MeV
$39 \pm 5 \pm 19$ MeV

$J^P = (3/2^-, 5/2^+)$
aso possible $(3/2^+, 5/2^-)$, $(5/2^+, 3/2^-)$

$J/\psi p$ structures

PRL 115 (2015) 072001

- Add two $P_c^+ \to J/\psi p$ resonances (one by one) to give satisfactory fit quality



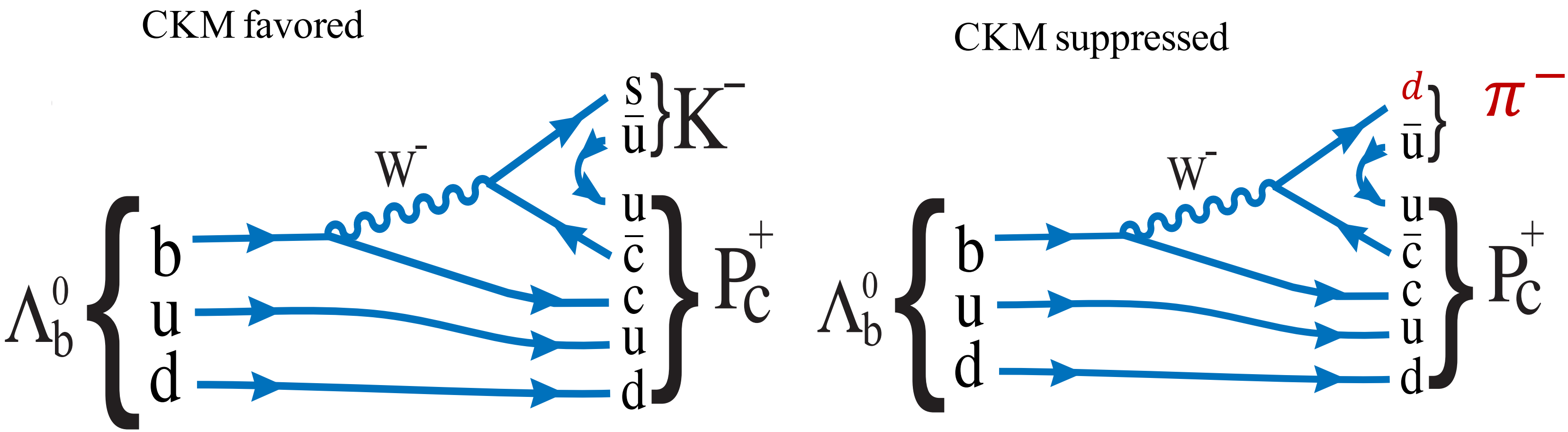
Argand phase evolution: $-\Gamma_0 \to \Gamma_0$

$$\mathrm{BW}(m|M_{0X},\Gamma_{0X}) = \frac{1}{{M_{0X}}^2 - m^2 - iM_{0X}\Gamma(m)}$$

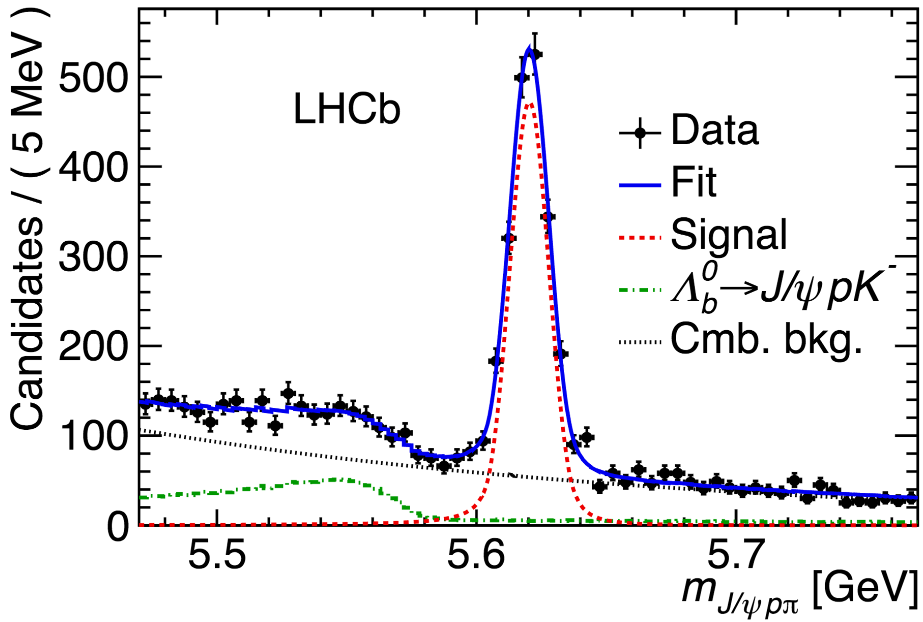
Consistent with resonance picture with $c\bar{c}uud$

$\Lambda_b^0 \rightarrow J/\psi p \pi^-$ decay

PRL 117 (2016) 082003



≈ 2K signal decays



$\Lambda_b^0 \to J/\psi p \pi^-$ amplitude fit

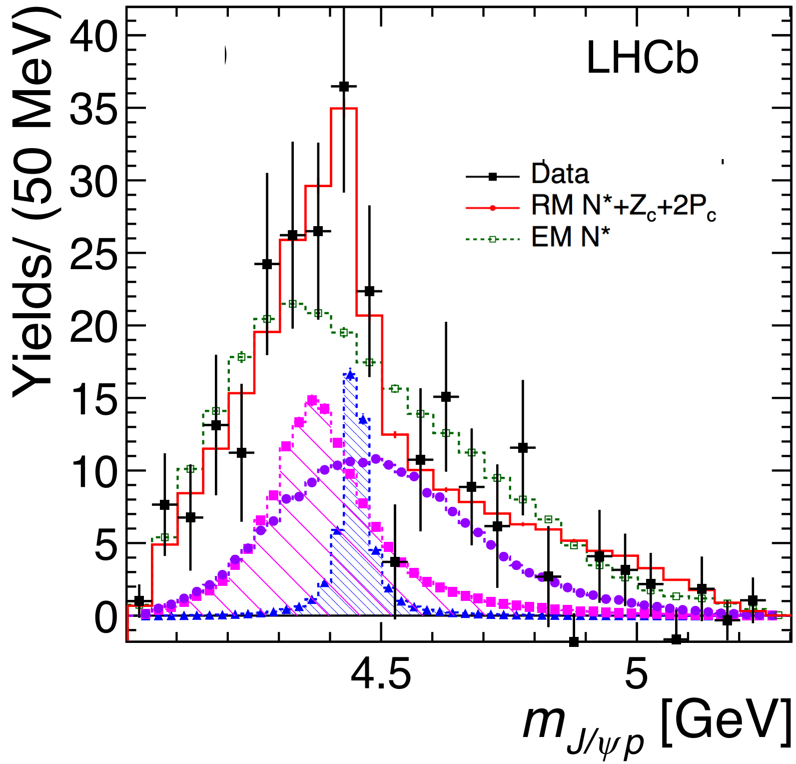
PRL 117 (2016) 082003

- A similar amplitude analysis, using N^* resonances w/ or w/o exotic hadrons

Fit quality improves by including exotics $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^+$ on top of N^* resonances

Combined significance $> 3\sigma$

$\frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ \pi^-)}{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)} \sim 5\%$ consistent with CKM suppression



$Z_c(4200)^+$: Belle [PRD 90 (2014)112009]

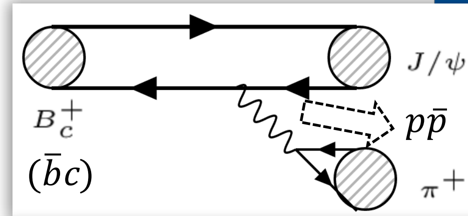
$M_0 = 4196^{+31+17}_{-29-13}$ MeV, $\Gamma_0 = 370 \pm 70^{+70}_{-132}$ MeV

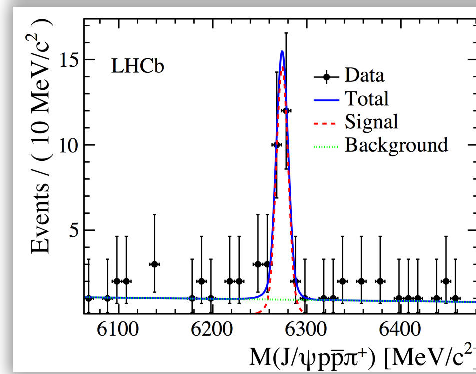
Updating with new data

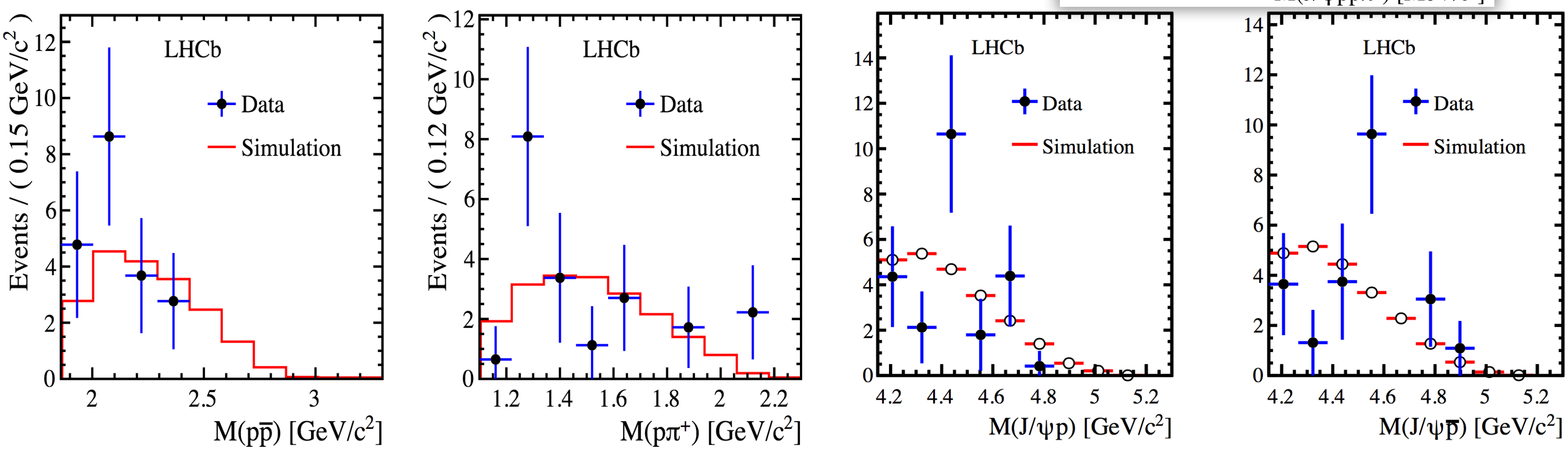
Baryons in B_c^+ decay

PRL 113 (2014)152003

- Large phase space for decay $B_c^+ \to J/\psi p\bar{p}\pi^+$
  - ➢ Low production rate of B_c^+
- First B_c^+ baryonic decay observed with 7.3σ
- Resonance structures
  - ➢ Hint of $J/\psi p$ enhancements, will be explored with more data







Pentaquarks

- First observation caught a lot of attention

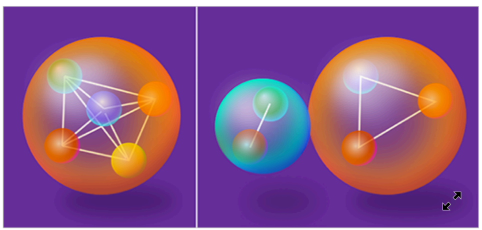
Viewpoint: Elusive Pentaquark Comes into View

Kenneth Hicks, Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA

August 12, 2015 • *Physics* 8, 77

PRL 115 (2015) 072001

A new type of particle containing five quarks has been observed by the LHCb experiment.



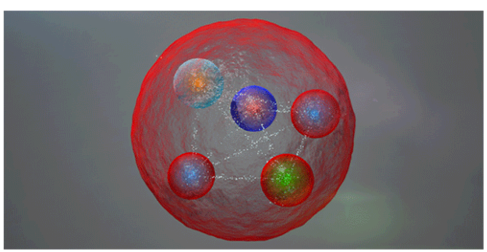
APS/Carin Cain

Synopsis: Pentaquark Discovery Confirmed

PRL 117 (2016) 082003

August 18, 2016

New results from the LHCb experiment confirm the 2015 discovery that quarks can combine into groups of five.



CERN

nature International weekly journal of science

NATURE | NEWS

Forsaken pentaquark particle spotted at CERN

Exotic subatomic particle confirmed at Large Hadron Collider after earlier false sightings.

Matthew Chalmers

14 July 2015 | Updated: 14 July 2015

PRL 115 (2015) 072001

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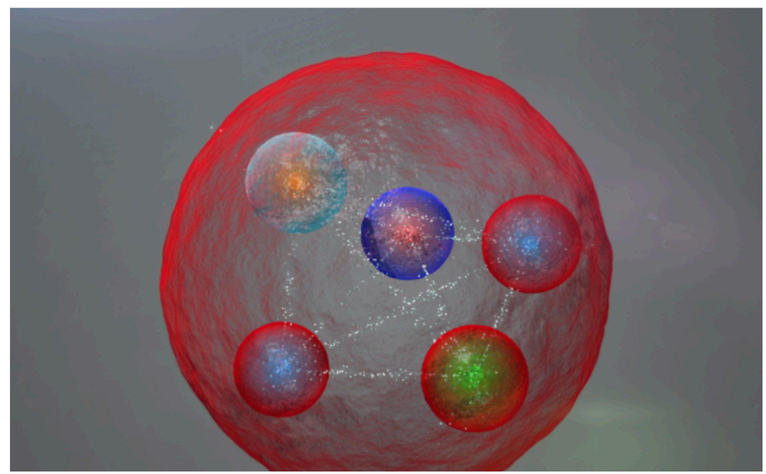
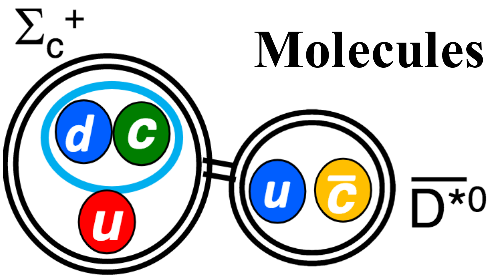


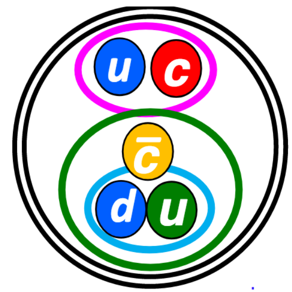
Pentaquarks

- First observation caught a lot of attention, however the internal structure is a mystery
- Possible explanations

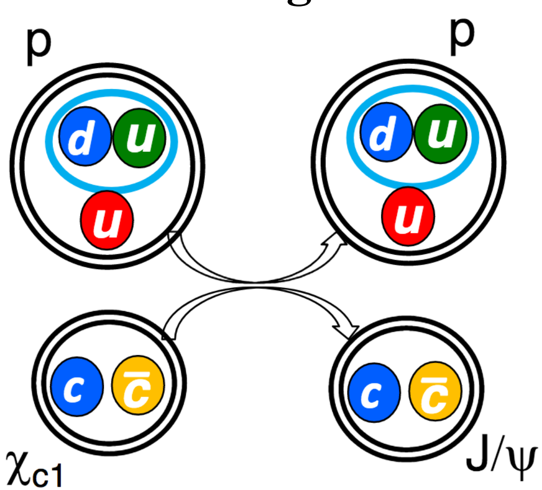
Molecules



Tightly-bound pentaquark



Rescattering effects



Puzzles:

- Two states with large spin, opposite parity
- $P_c(4380)^+$ has large width

Can only be resolved with more experimental studies

The zoo

- Exotic states studied in $\mathrm{H_b} \to [c\bar{c}]\, K^-\pi^+/p$ decays
  - $Z(4430)^-, Z(4240)^- \to \psi'\pi^-$ in $B^0 \to \psi' K^+\pi^-$ decay: [PRL 100 (2008)142001]
  - $Z(4050)^-, Z(4250)^- \to \chi_{c1}\pi^-$ in $B^0 \to \chi_{c1}K^+\pi^-$ decay: [PRD 78 (2008) 072004] [LHCb]
  - $Z(4200)^- \to J/\psi\pi^-$ in $B^0 \to J/\psi K^+\pi^-$ decay: [PRD 90 (2014) 112009][LHCb]
  - $P_c(4380)^+, P_c(4450)^+ \to J/\psi p$ in $\Lambda_b \to J/\psi p\pi^-$ decay: [PRL 115 (2015) 072001]
  - $X \to J/\psi\phi$ in $B^+ \to J/\psi\phi K^+$ decays: [PRL 118 (2017) 022003]
  - $X \to \eta_c\pi^+$ in $B^0 \to \eta_c K^+\pi^-$ decays [LHCb]
  - $X \to \eta_c/\chi_{c1,2}p$, in $\Lambda_b^0 \to \eta_c/\chi_{c1,2}pK^+$ decays, $X \to J/\psi\Lambda$ from Ξ_b^+ decays [LHCb]
  - $X \to \chi_{c0}p$ in $\Lambda_b^0 \to \chi_{c0}pK^-$ decay [LHCb]
  - $X \to \chi_{c0}\phi$ in $B^+ \to \chi_{c0}\phi K^+$ decay [LHCb]
  - $X \to \chi_{c0}\pi^+$ in $B^0 \to \chi_{c0}\pi^+K^-$ decay [LHCb]

Can we build connections among them, like $c\bar{c}$ spectrum? Find the missing states!

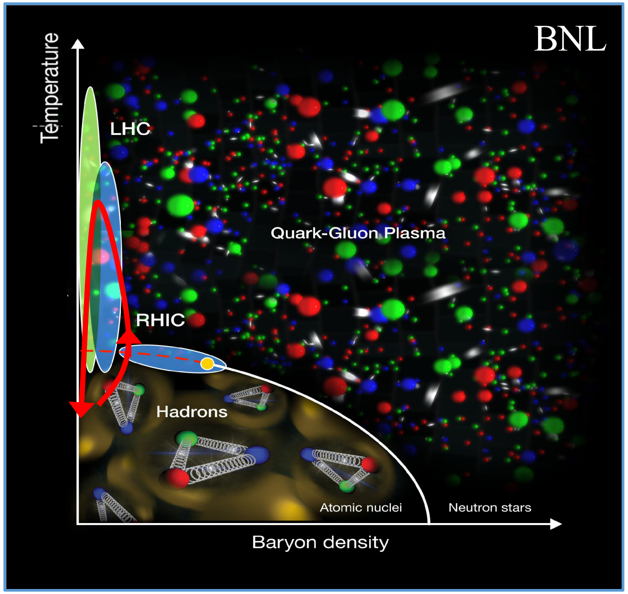
Nuclear matter

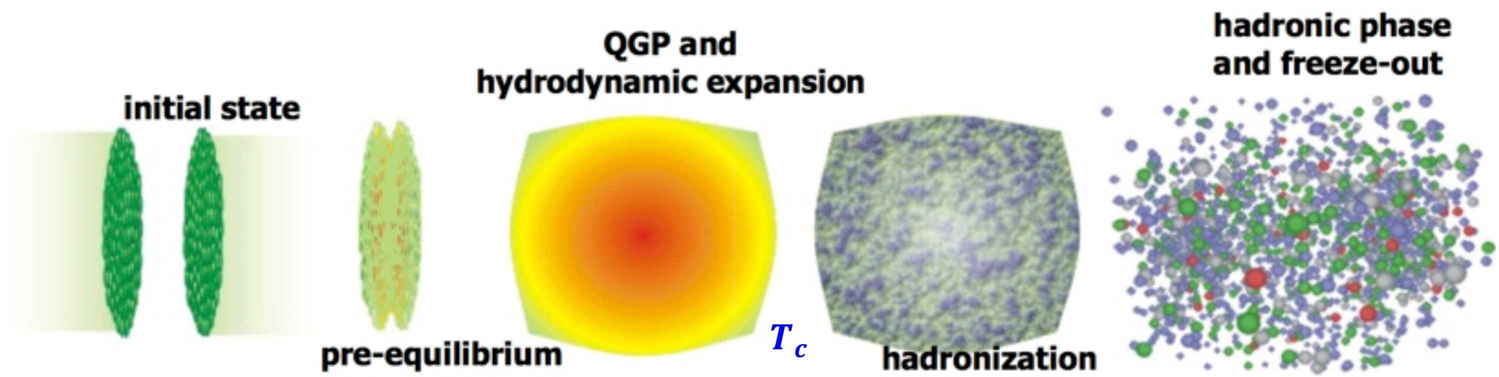
JHEP 03 (2016) 133 [arXiv:1601.07878]
PLB774 (2017) 159 [arXiv:1706.07122]
JHEP 1710 (2017) 090 [arXiv:1707.02750]

Quark gluon plasma (QGP)

- System of deconfined colored objects
  - ➢ High temperature hot medium
  - ➢ Statistical ensemble: spin, color, flavor degrees of freedom; temperature, net baryon number

    Hadron systems: color degrees of freedom frozen
  - ➢ Strongly interacting fluid: hydrodynamics
- Present in heavy-ion collisions at $\tau \sim \mathrm{fm}/c$
  - ➢ Enough energy density in space to melt hadrons
  - ➢ Phase transition temperature at LHC: $T_c \approx 150$ MeV





Hydrodynamics

Hadronic gas

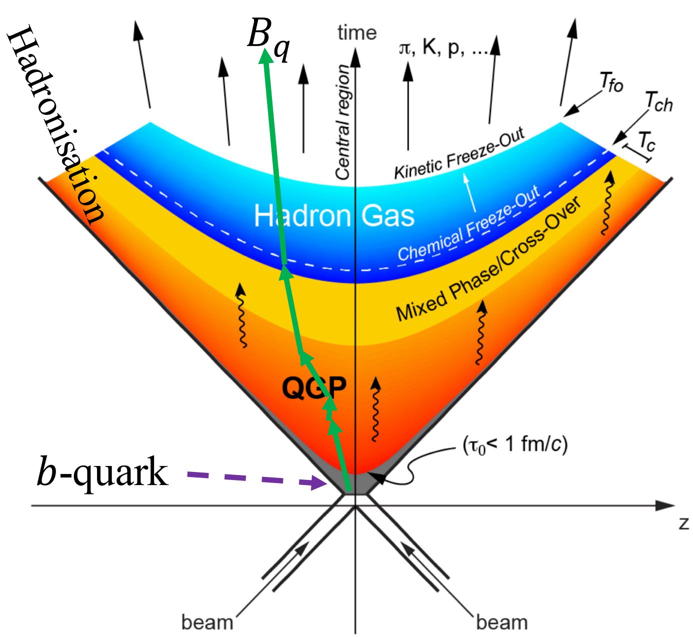
$\tau \sim 0\ \mathrm{fm}/c$ $\tau \sim 1\ \mathrm{fm}/c$ $\tau \sim 10\ \mathrm{fm}/c$

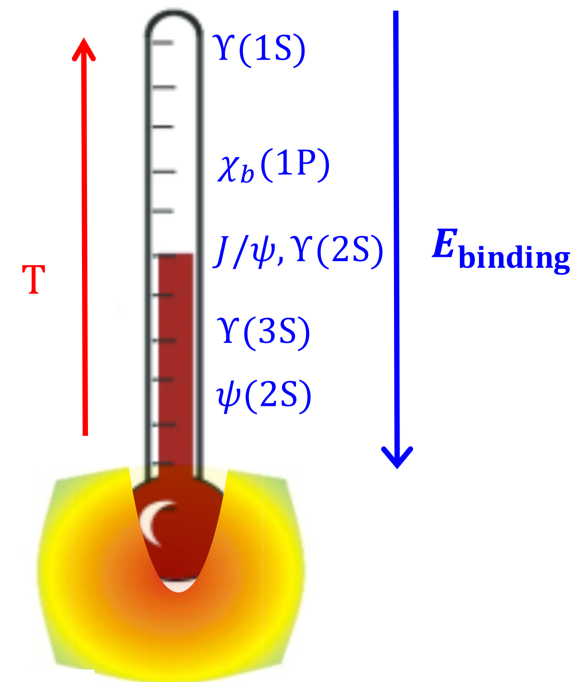
Phys.Scripta T158 (2013)014004

Heavy flavour/quarkonia in QGP

- Heavy flavour produced before QGP: $\tau_P \ll 1\ \mathrm{fm}/c$
  - ➢ Microscopic interactions with constituents of medium: QGP characterization
- Quarkonium: bound state of QCD
  - ➢ QCD potential strongly modified in QGP: color screening. States disassociated, in-medium survival probability depends on binding energy and temperature

Excited states easier (at lower T) to melt than ground state→ sequential suppression

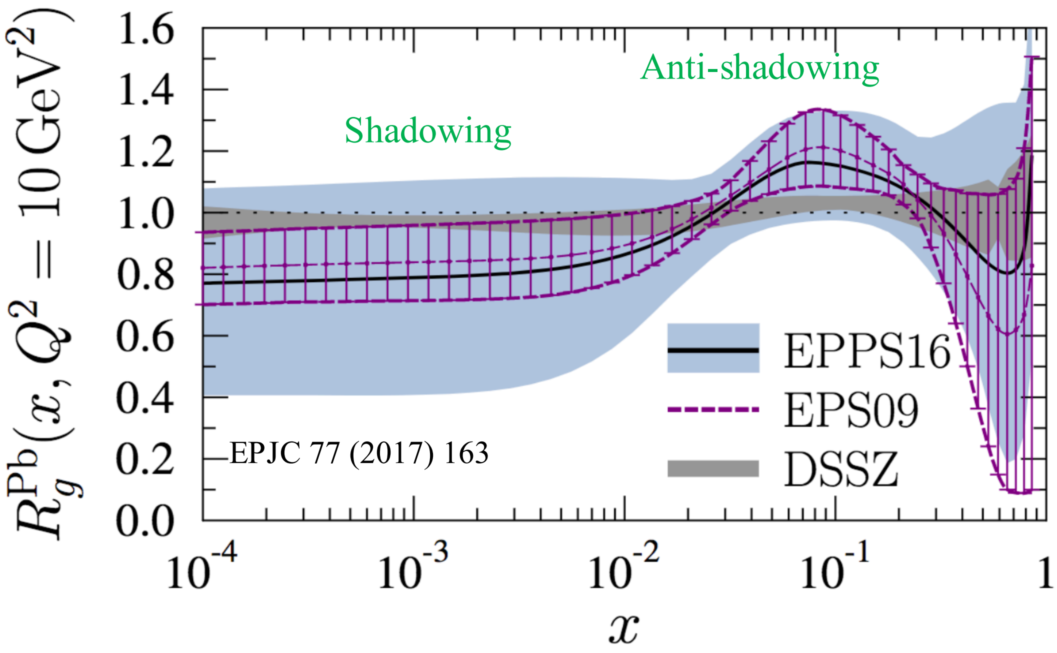




Cold nuclear matter effects

- Effects present in heavy ion collisions, but not due to QGP formation
  - ➢ Modification of gluon PDF: $A = \sum(p,n)$, but $\mathrm{PDF}^{\mathrm{Pb}} \neq \mathrm{A} \times \mathrm{PDF}^{p}$

$\mathrm{PDF}^{\mathrm{Pb}}/\mathrm{PDF}^{p}/\mathrm{A}$



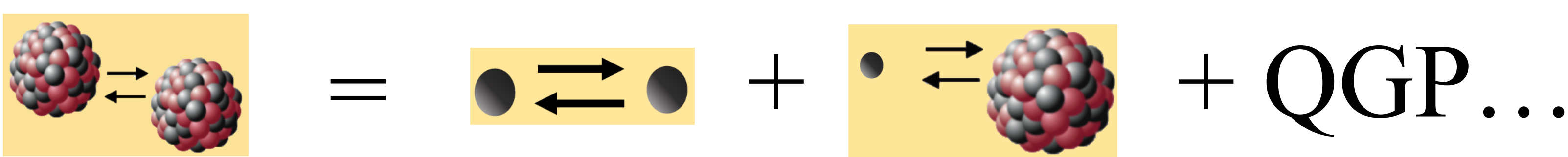
  - ➢ CGC, energy loss, co-movers …

Studying cold/hot nuclear matter effects

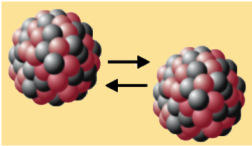
- pp collisions: references for pA and AA collisions
  - ➢ Control yields at production
  - ➢ test heavy flavor production mechanisms (pQCD, …)
- pA collisions: baseline to study cold nuclear matter effects, QGP not expected in pA collisions
- AA collisions: study hot QGP
- Nuclear modification factor:

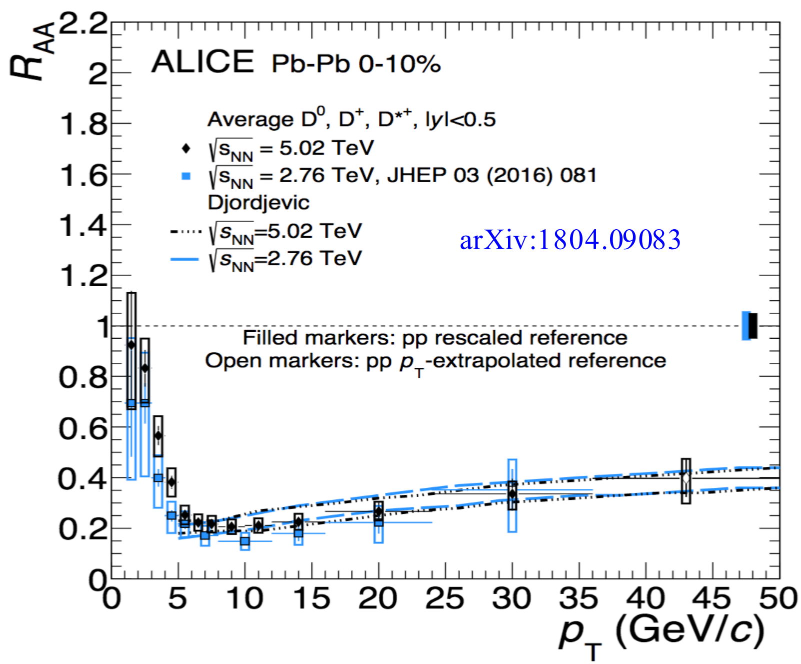
$$R_{pA} = \frac{\sigma_{pA}}{A\sigma_{pp}}$$

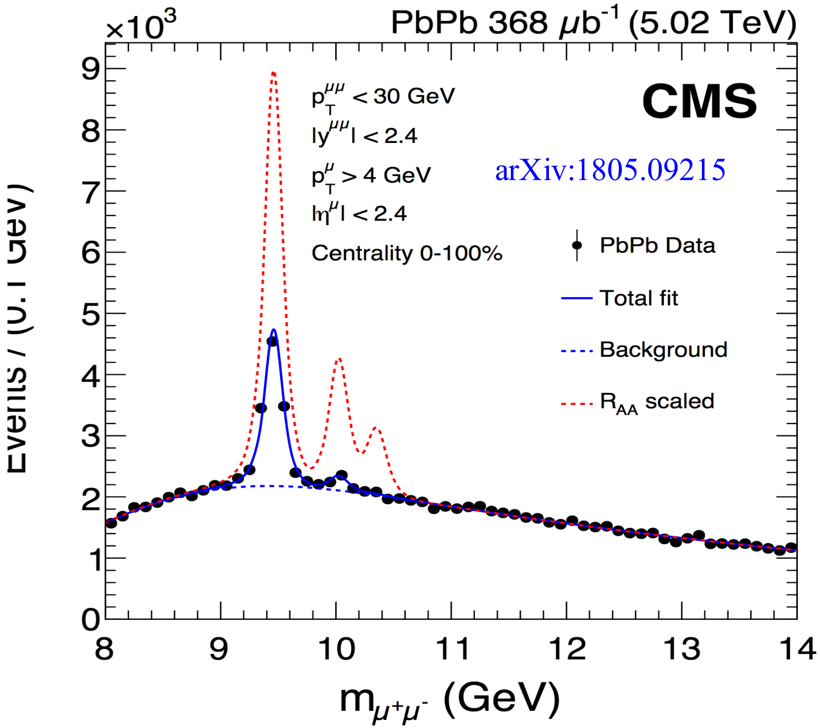
$$R_{AA} = \frac{N_{AA}}{< T_{AA} > \sigma_{pp}}$$



Heavy flavor in PbPb collisions







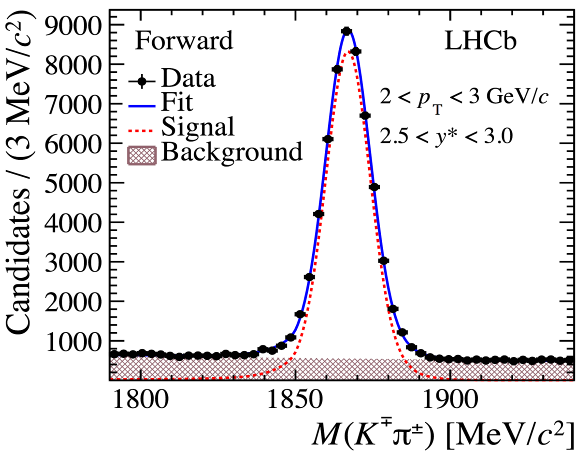
- *D* mesons strongly suppressed in PbPb collisions: *c*-quark loses energy by collisions and gluon radiations. Described by transport models
- Excited quarkonia more suppressed compared to lower states → sequential suppression

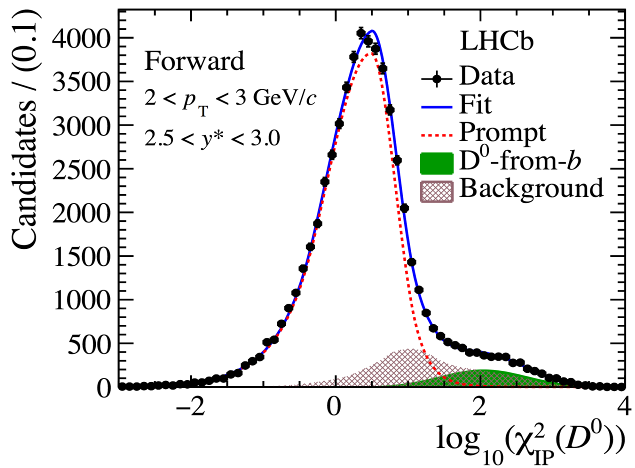
Other data also suggest formation of hot QGP in heavy ion collisions

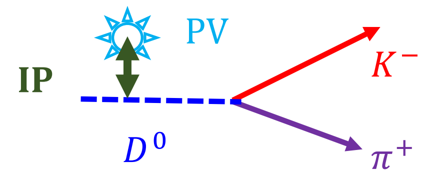
Probing cold nuclear effect with D^0

JHEP 1710 (2017) 090

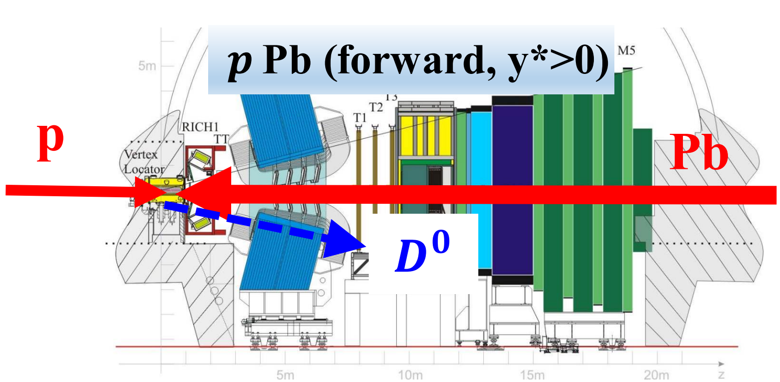
- Measuring D^0 cross-section in pPb collisions
  - ➢ Remove D^0 from b-hadron using impact parameter

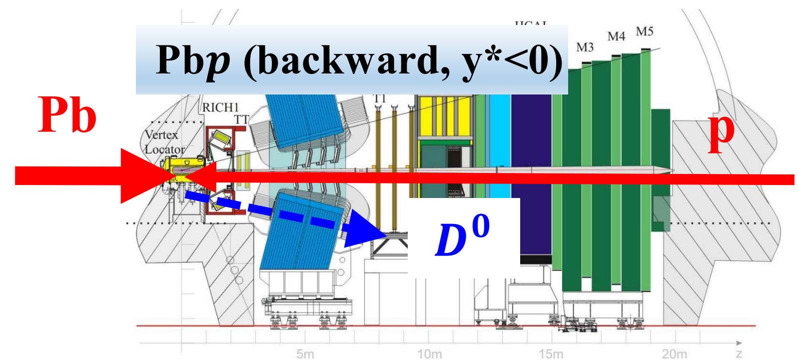






- Forward (p-direction) and backward (Pb direction): different PDF in Pb

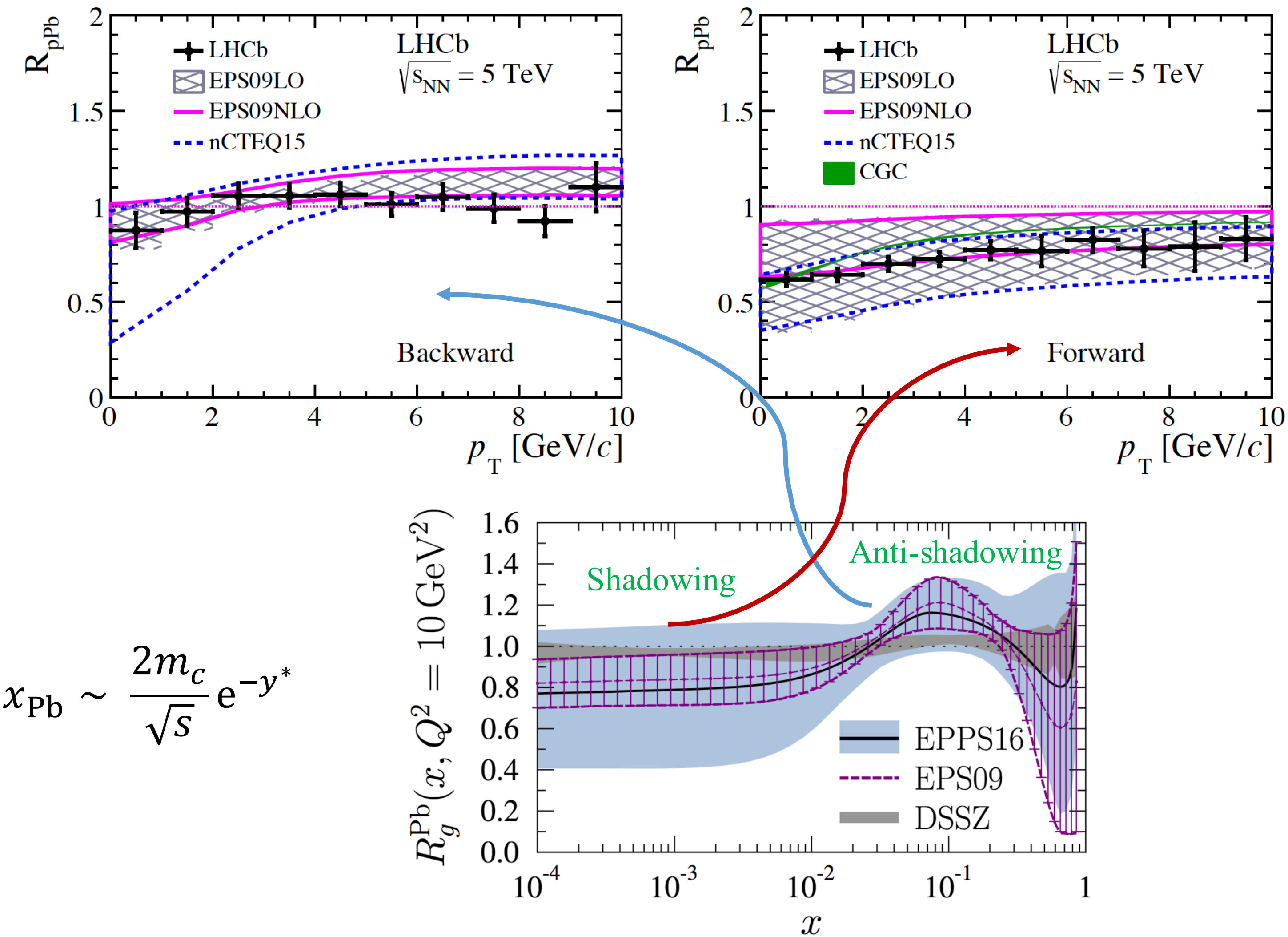




Cold nuclear effect with prompt D^0

- Nuclear modification factors (R_{pA})

JHEP 1710 (2017) 090

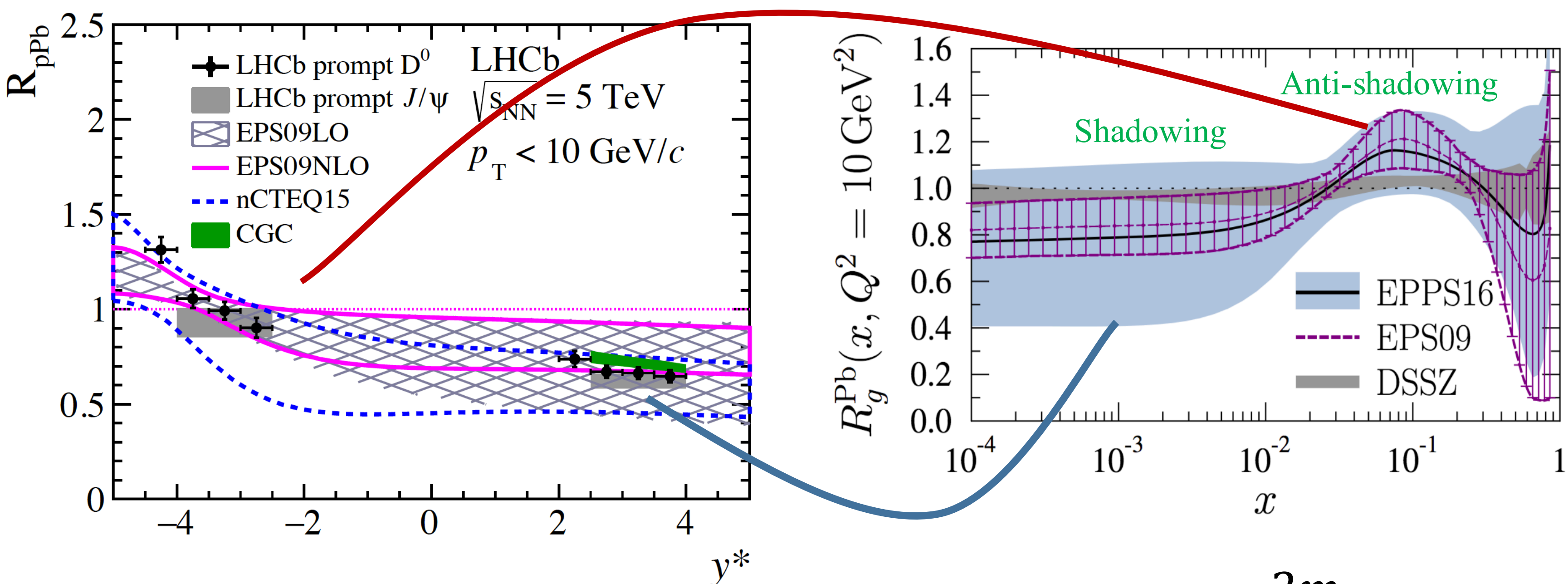


$$x_{Pb} \sim \frac{2m_c}{\sqrt{s}} e^{-y^*}$$

Cold nuclear effect with prompt D^0

- Nuclear modification factors (R_{pA})

JHEP 1710 (2017) 090



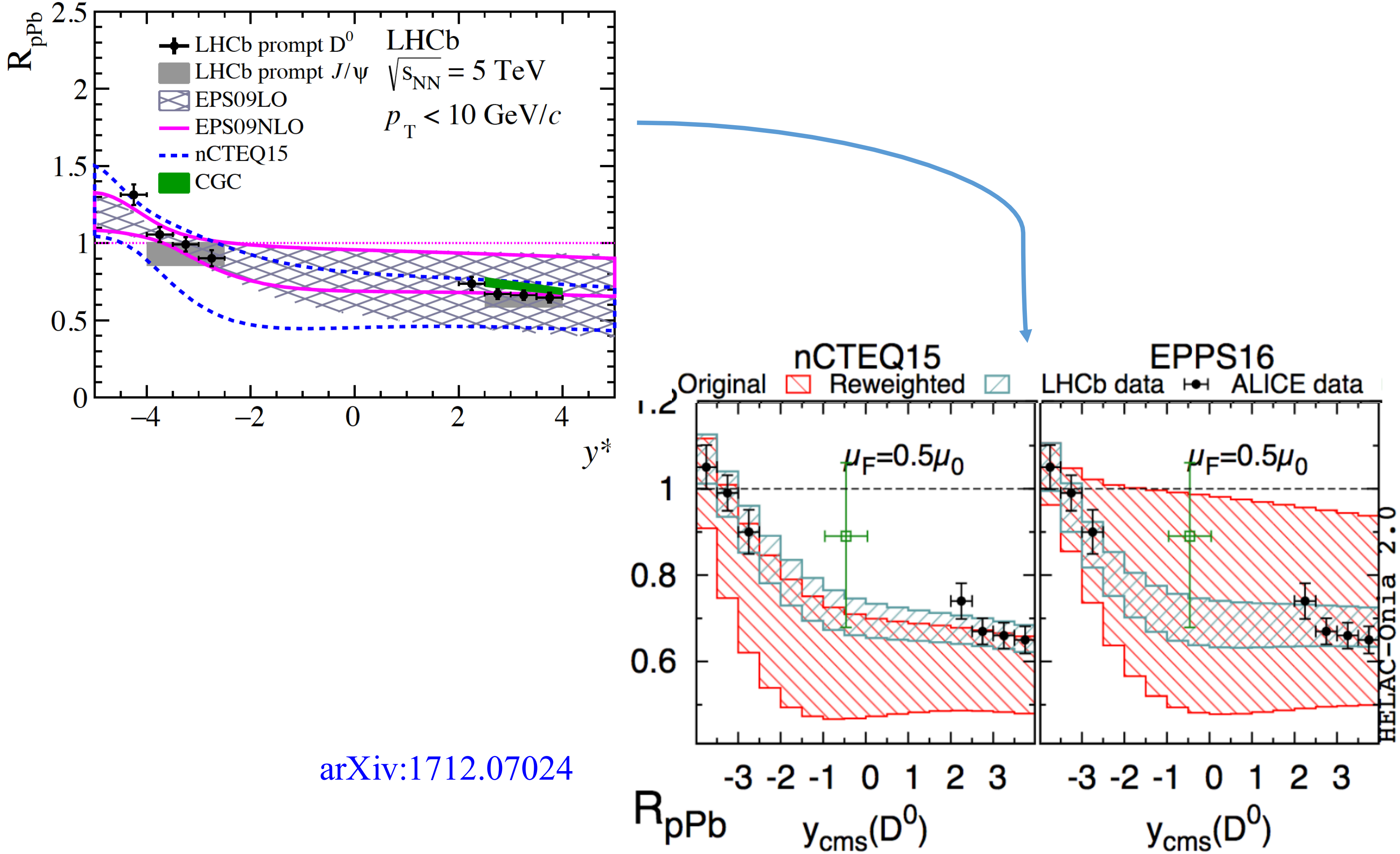
$$x_{\mathrm{Pb}} \sim \frac{2m_c}{\sqrt{s}} e^{-y^*}$$

R_{pA} consistent with nuclear PDF (nPDF) prediction

Constraining nPDF

JHEP 1710 (2017) 090

- Data much more precise than nPDF uncertainty, used to improve nPDF

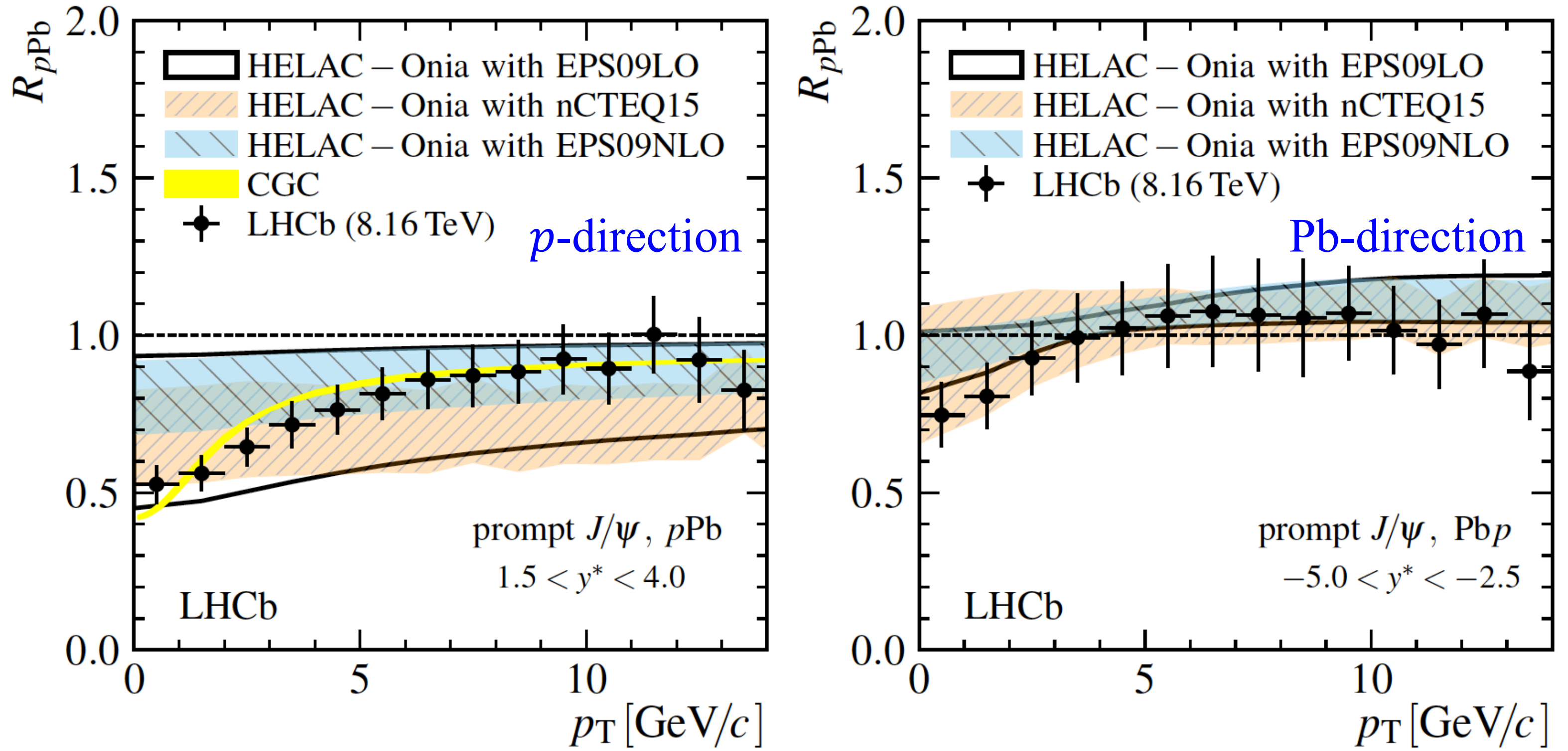


arXiv:1712.07024

Cold nuclear effect with J/ψ

- If nuclear effects dominated by nPDF, pQCD calculation predicts modification similar to D^0

$$R_{pA} = \frac{\sigma_X^{pA}}{A \times \sigma_X^{pp}}$$

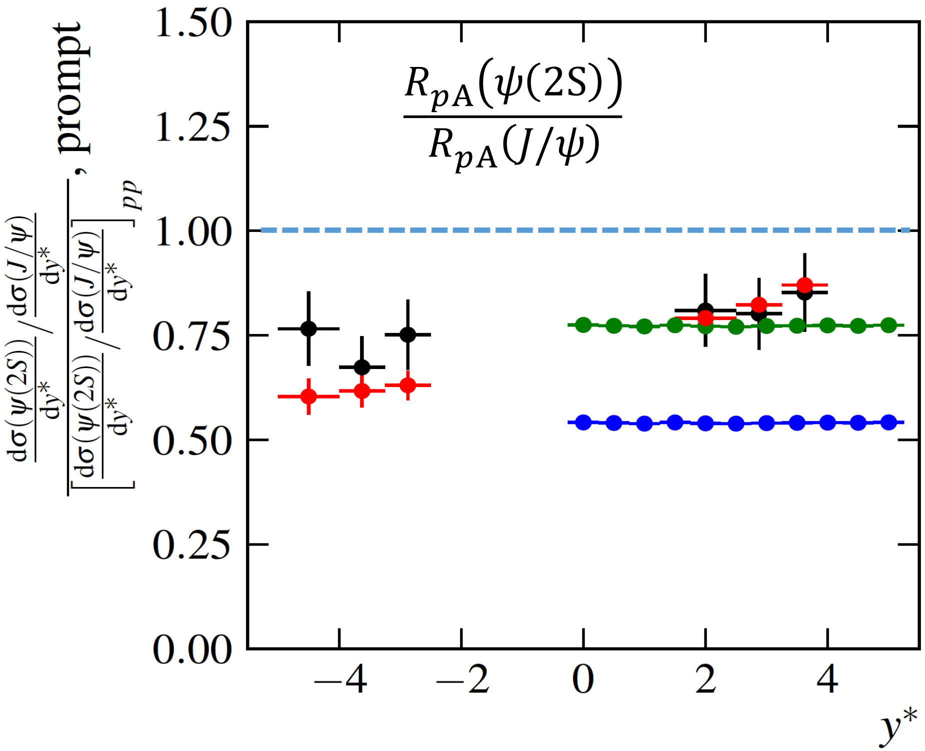


PLB774 (2017) 159

Nuclear effect with $\psi(2S)$

JHEP 03 (2016) 133

- pQCD also predicts $R_{pA}(J/\psi) \approx R_{pA}(\psi(2S))$, but in data $R_{pA}(\psi(2S)) < R_{pA}(J/\psi)$



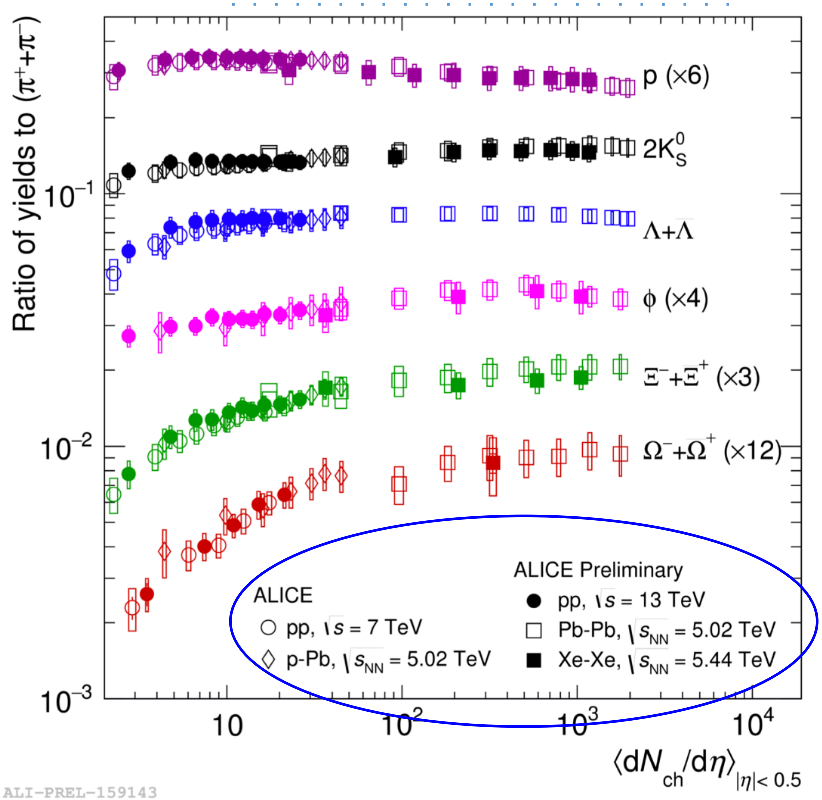
Explanations:

- co-movers (interactions with co-coming particles)
- gluon saturations
- Proposal of QGP in pPb collisions (QCD droplet), then sequential suppression

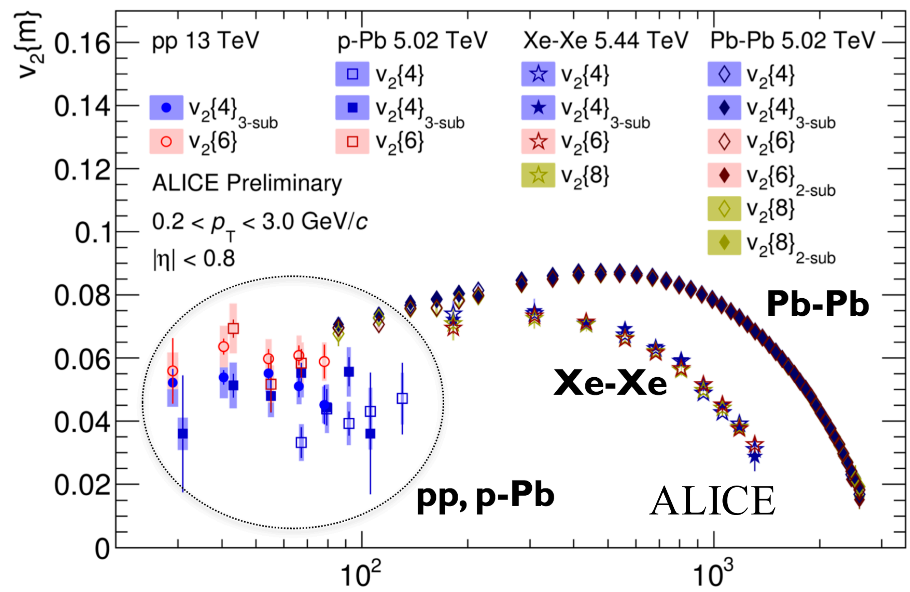
Small systems

- Evince of continuous evolution from *pp*, *p*Pb collisions to PbPb collisions

Soft particle production



Particle correlations

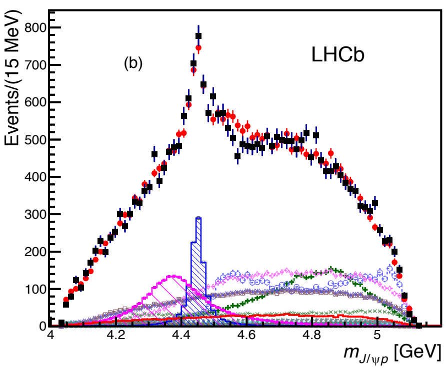


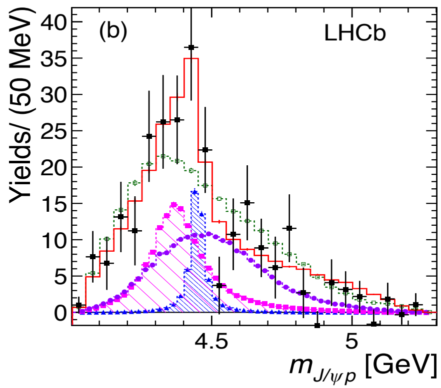
Observation in PbPb explained using QGP

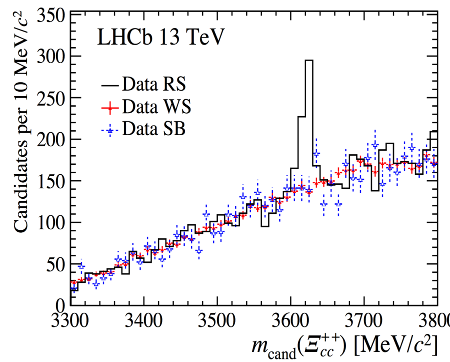
Is QGP also produced in *pp*, *p*Pb collisions?

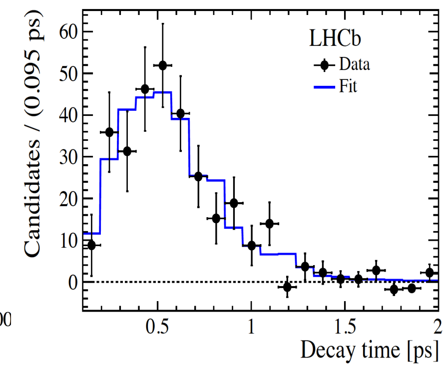
Summary

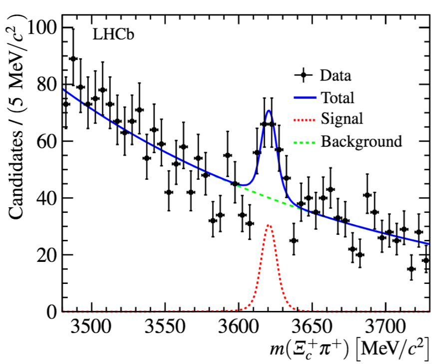
- LHCb plays an important roll for heavy quark spectroscopy
  - ➢ Hadron spectroscopy: Ξ_{cc}^{++} observation and properties
  - ➢ Exotic hadron spectroscopy: pentaquark states and prospects for other charmonium like exotic states → A pattern in the future?
- Unique contributions to studies of nuclear mater

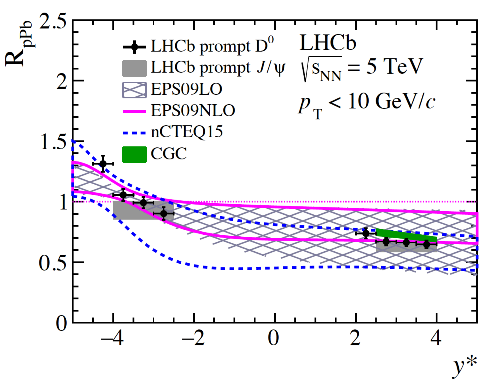


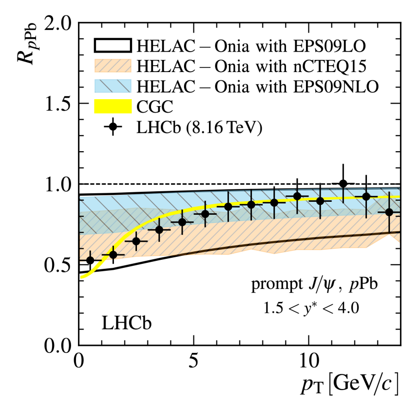


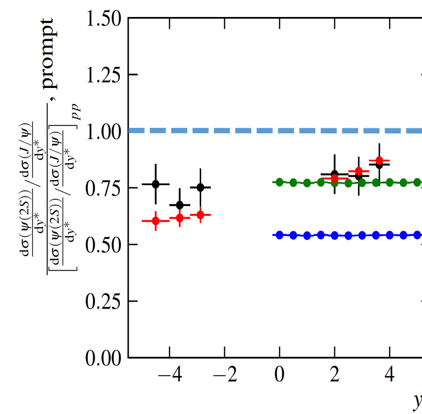








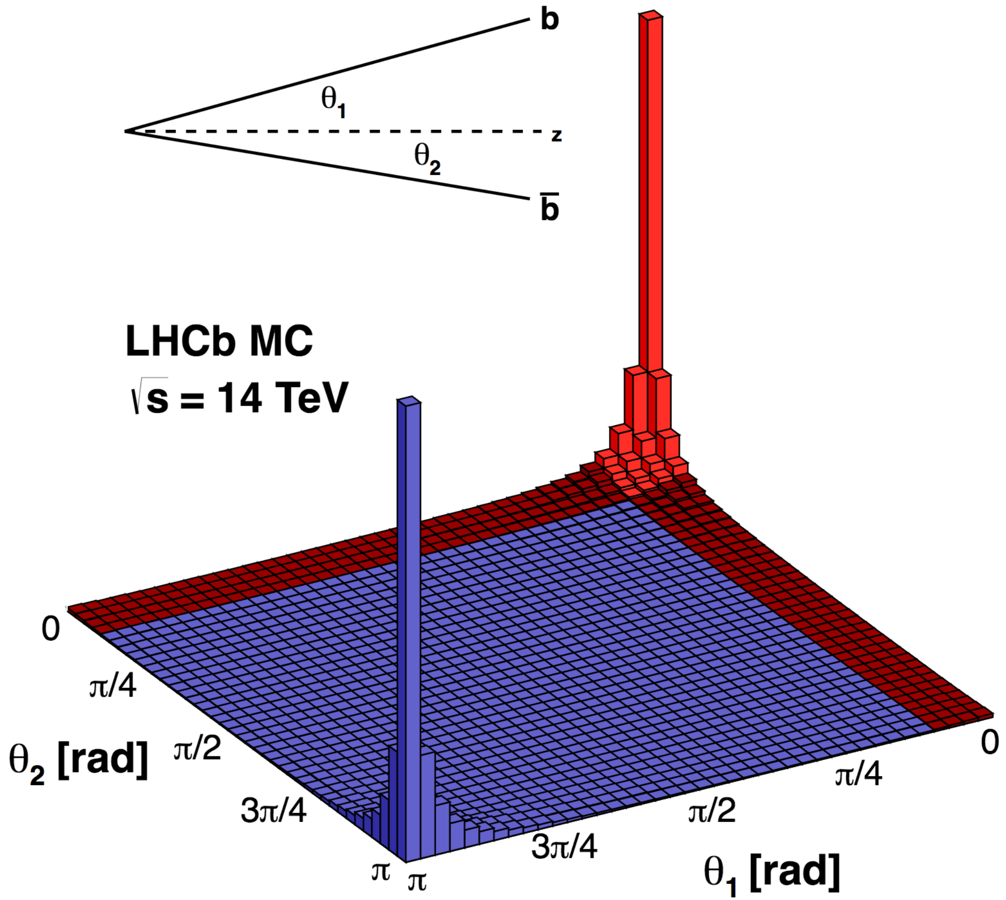




...

Backups

Bottom quark correlation



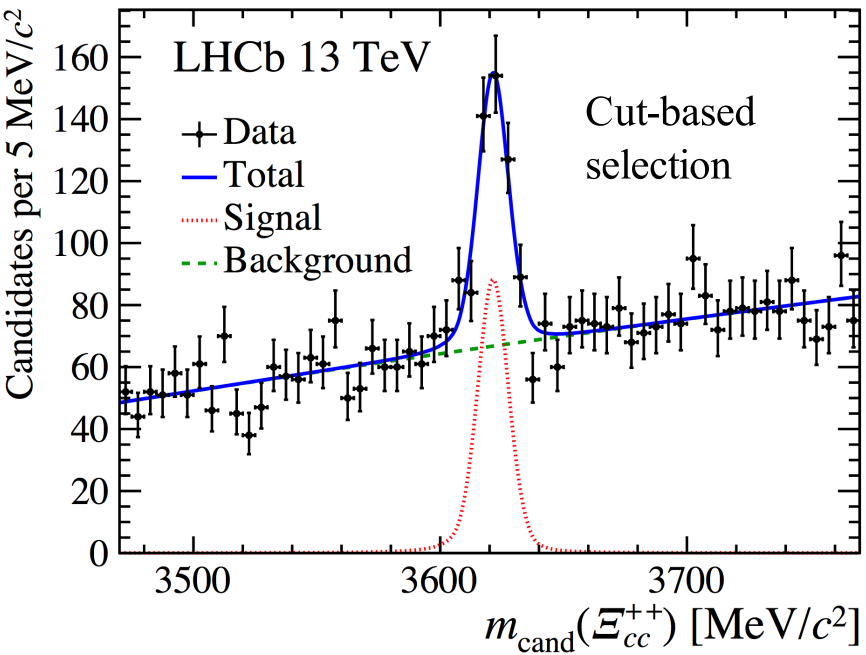
More tests

$\Xi_{cc}^{++} \to K^-\pi^+\pi^+\Lambda_c^+(\to pK^-\pi^+)$

1. Multiple candidates: not creating fake narrow structure
2. Checking combinations of tracks from Λ_c^+ and Ξ_{cc}^{++}: not peaking
3. MVA efficiency as a function of mass: very smooth
4. Varying threshold value of MVA selector: structure stays significant
5. Varying particle ID selections: no peaking structure emerging in WS combinations, structure stays in RS sample

arXiv: 1707.01621

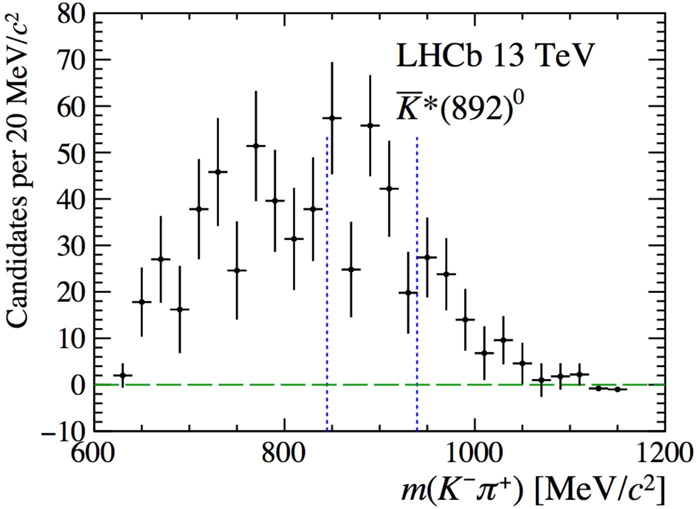
6. Using a cut based selection instead of using MVA, requiring good vertex fit quality, Ξ_{cc}^{++} vertex displaced and tracks are not produced from PV: peak significance $> 12\sigma$

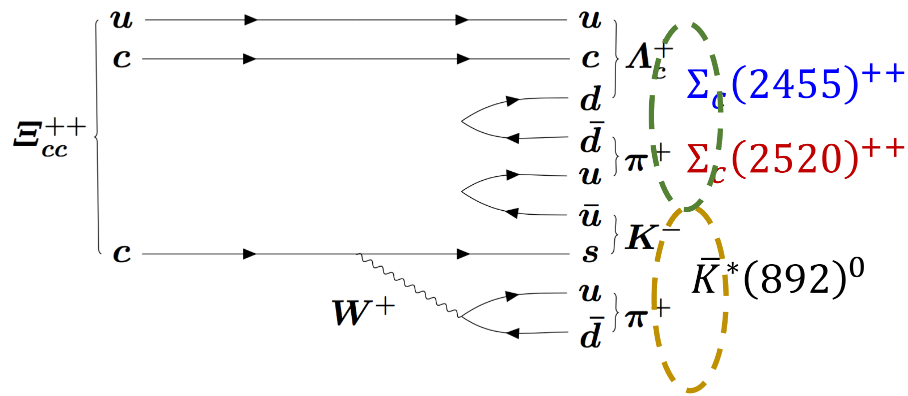


A series of decays

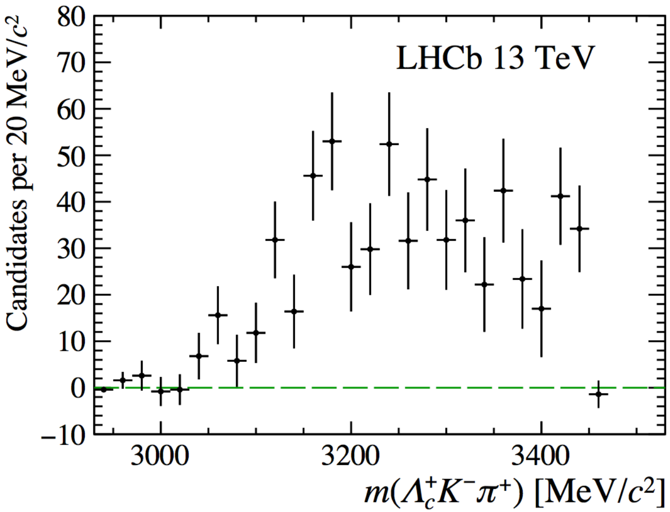
PRL 119 (2017) 112001

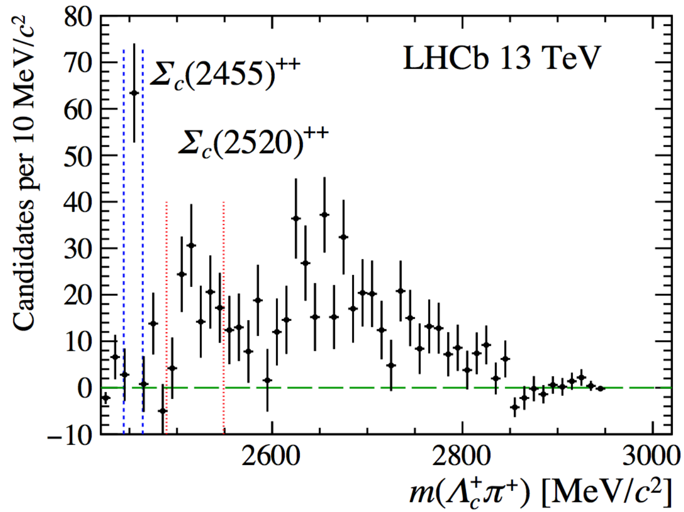
- Intermediate resonances: $\overline{K}^*(892)^0, \Sigma_c(2455)^{++}, \Sigma_c(2520)^{++}$





Quantify the branching fractions ($N\times$ data)!

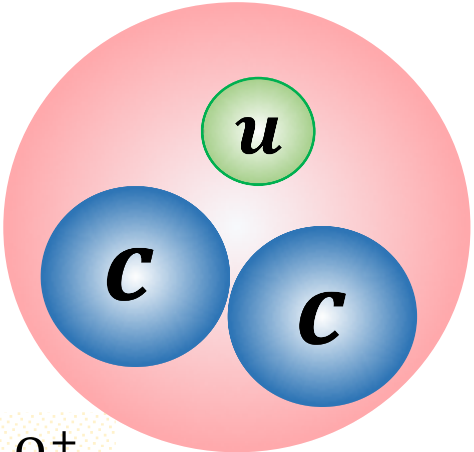




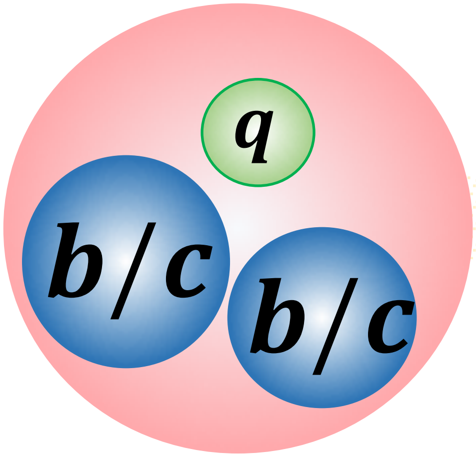
Many things to be done

Ξ_{cc}^{++}

- Other decay modes
- Lifetime
- Production
- Spin-parity



- Searching for Ξ_{cc}^{+}, Ω_{cc}^{+}

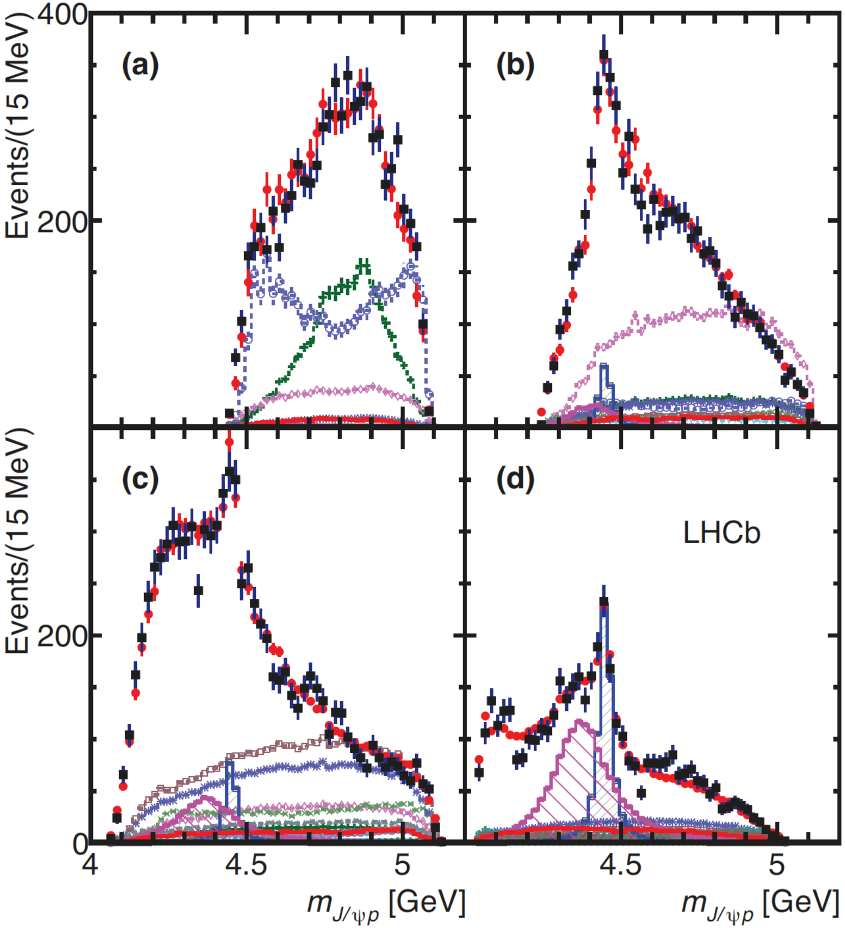


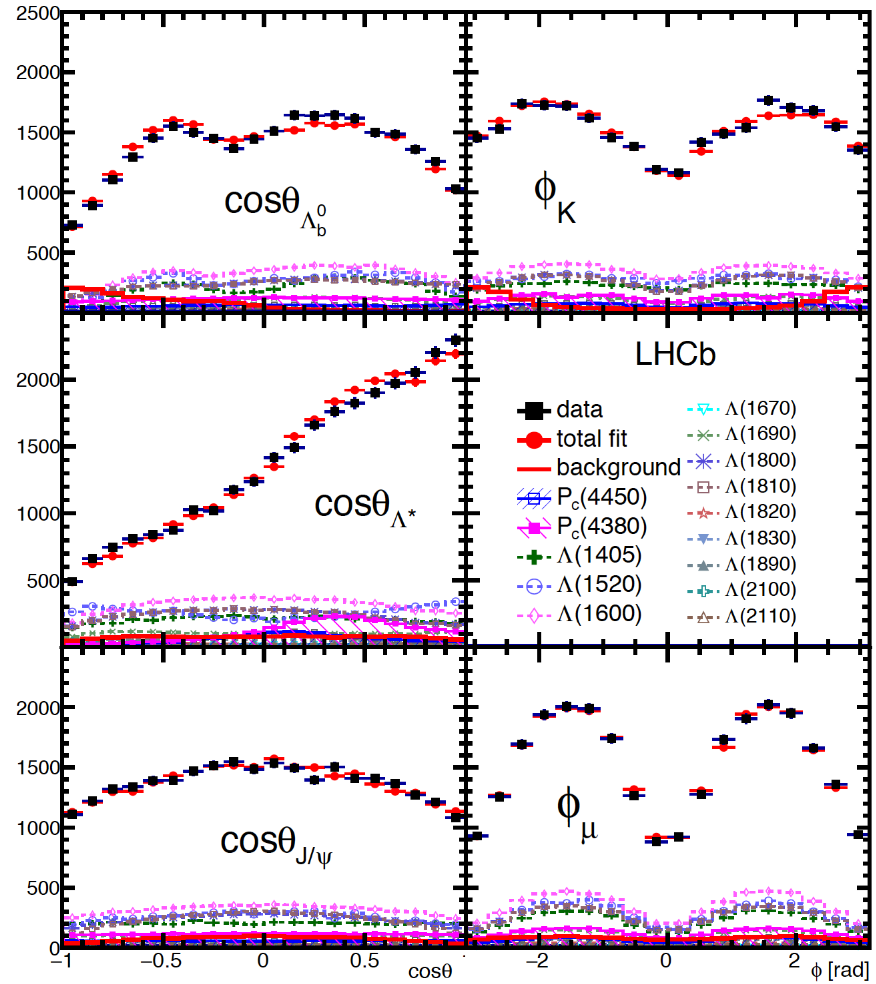
- Doubly heavy baryons with *b* quark(s)

- The excited states?
- New systems for CP violations
- Tetraquark states with a heavy diquark

PRL 119 (2017) 202001, PRL 119 (2017) 202002

Other variables

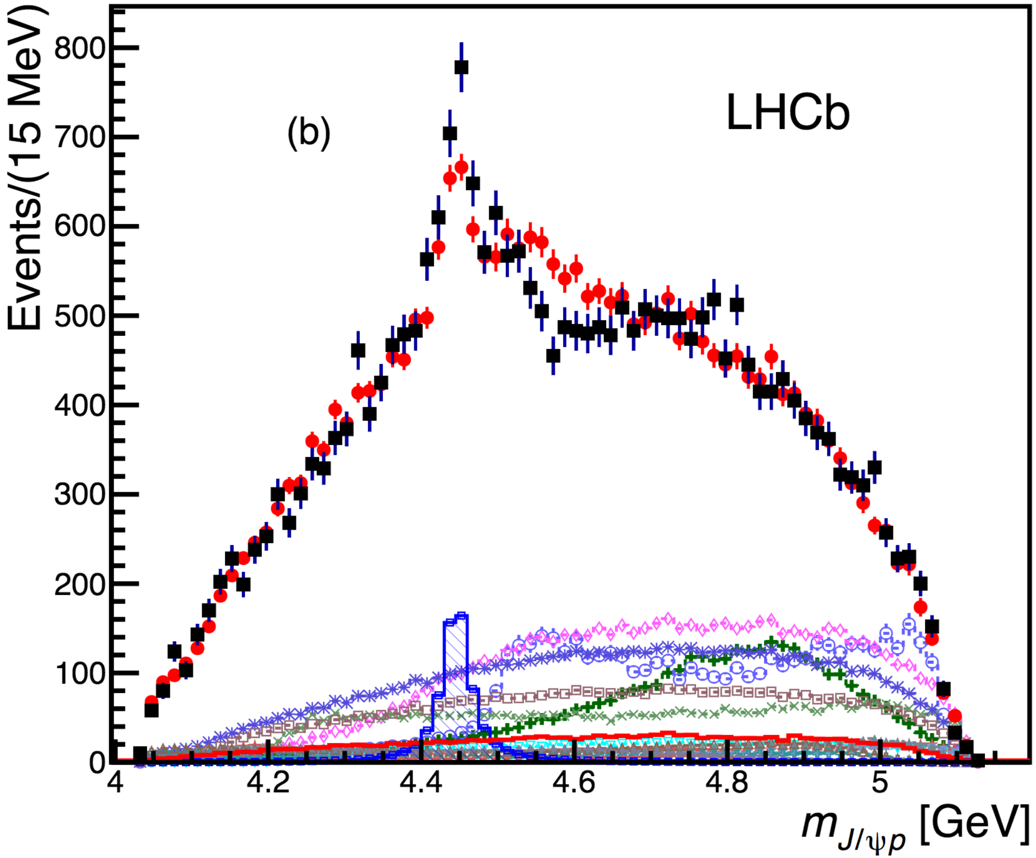


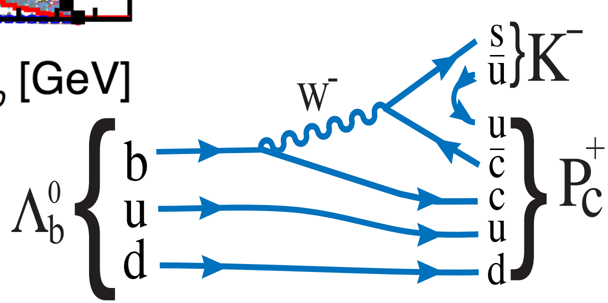


$J/\psi p$ structures

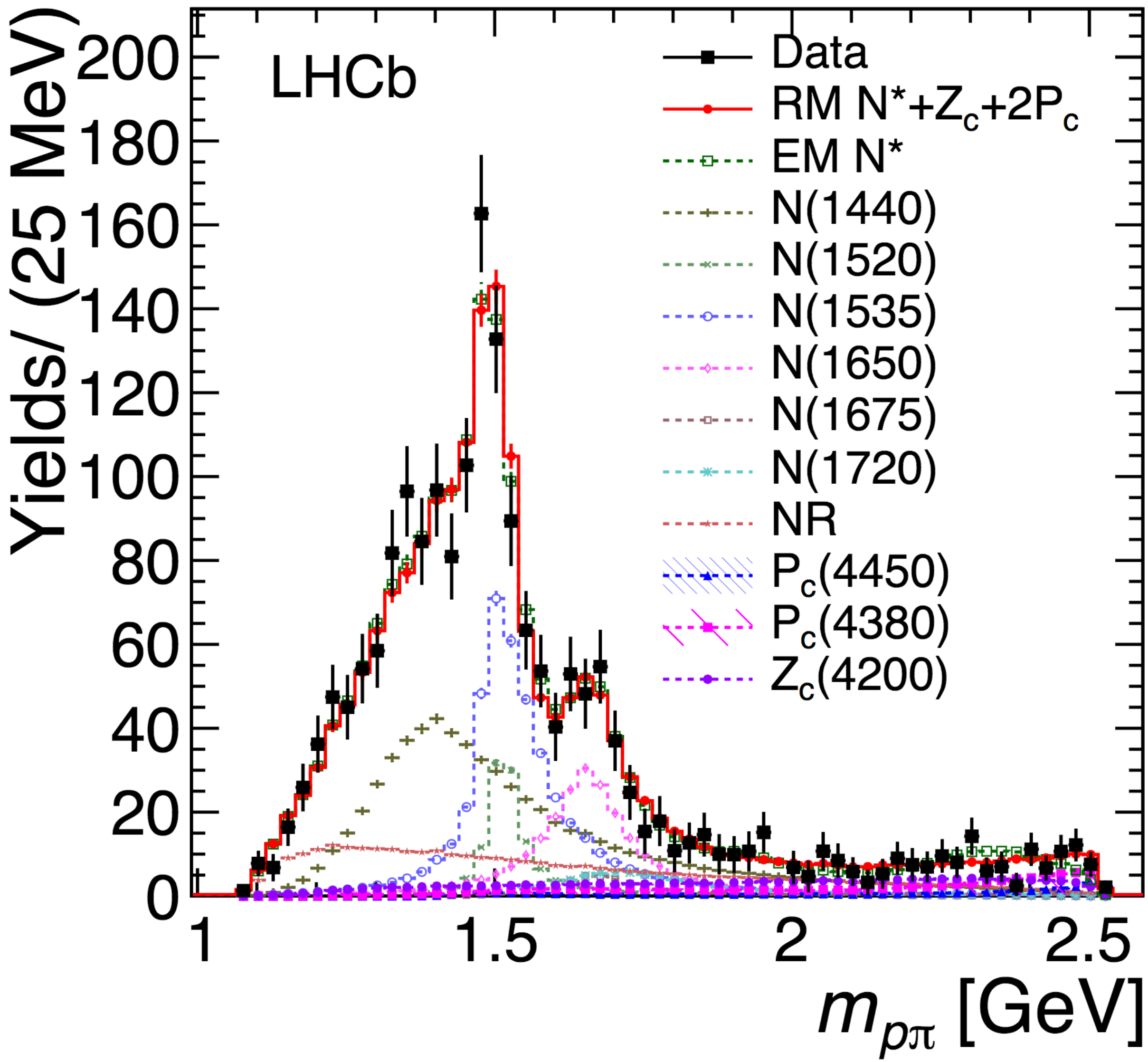
PRL 115 (2015) 072001

- Add one $P_c^+ \to J/\psi p$ resonances to give satisfactory fit quality

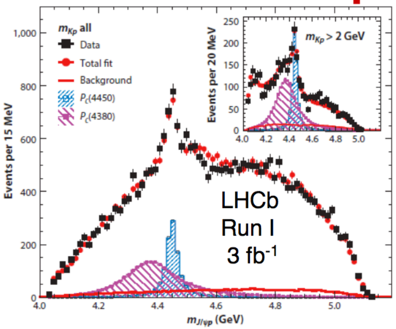




$\Lambda_b^0 \to J/\psi p \pi^-$ decay

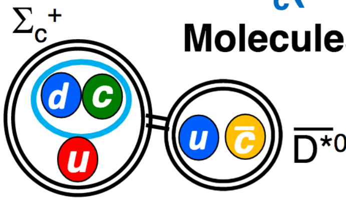


Interpretations of $P_c(4450)^+$, $P_c(4380)^+$?



LHCb-PAPER-2015-029

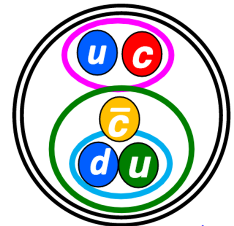
Molecules



No $\frac{5}{2}^{\pm}$ molecules in this mass range

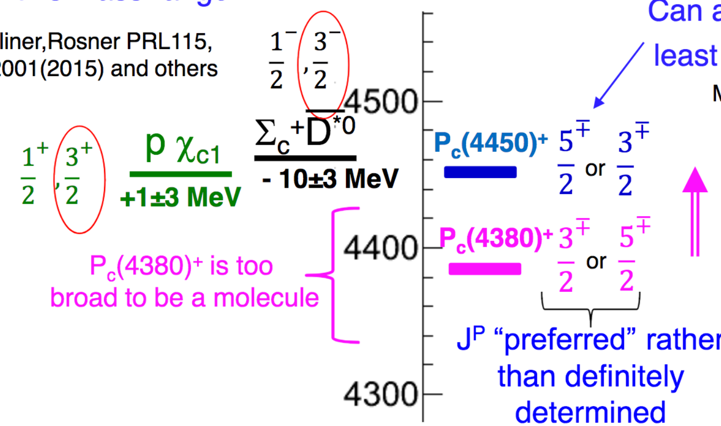
Karliner,Rosner PRL115, 122001(2015) and others

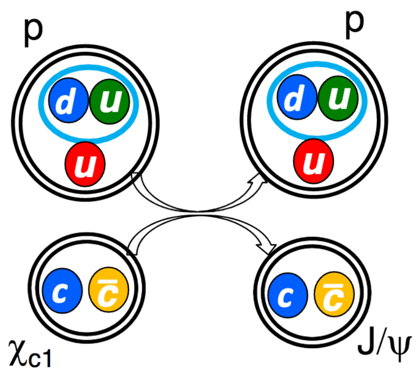
Tightly-bound penatquark



Can accommodate $\frac{5}{2}^{\pm}$ when at least one diquark in $S=1$ state

Maiani et al PLB749, 289 (2015) and many others





Realistic **rescattering mechanisms (cusps, triangle anomalies)** have the same J^P selection rules as realistic molecular models (must happen in S-wave)

	LHCb		U. Phase I	II
Decay mode	3 fb^{-1}	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$\Lambda_b \to J/\psi p K^-$	25k	0.13M	0.8M	5M

It is crucial to determine J^Ps!

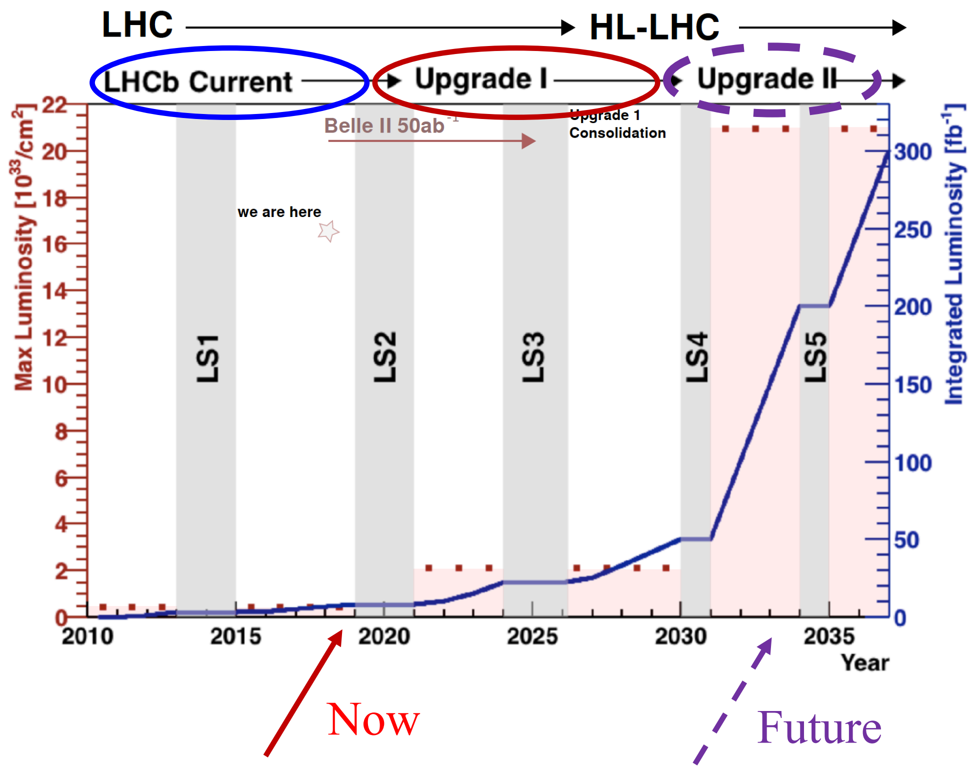
More robust verifications of resonant hypothesis.

Study related channels (see next).

LHCb upgrade II

- General purpose detector at large y, ~300 fb^{-1} (3000 fb^{-1} for ATLAS/CMS)

- CKM mechanism
  - ✓ $\gamma, \sin 2\beta, \phi_s$ mixing in B, D, rare decays
- Spectroscopy
  - ✓ Exotics, multiple heavy hadrons
- Heavy ion, nuclear matter
  - ✓ QGP, small systems
- EW, QCD, SM
  - ✓ $Z^0, W^{\pm}, h^0$
- Direct search for new physics

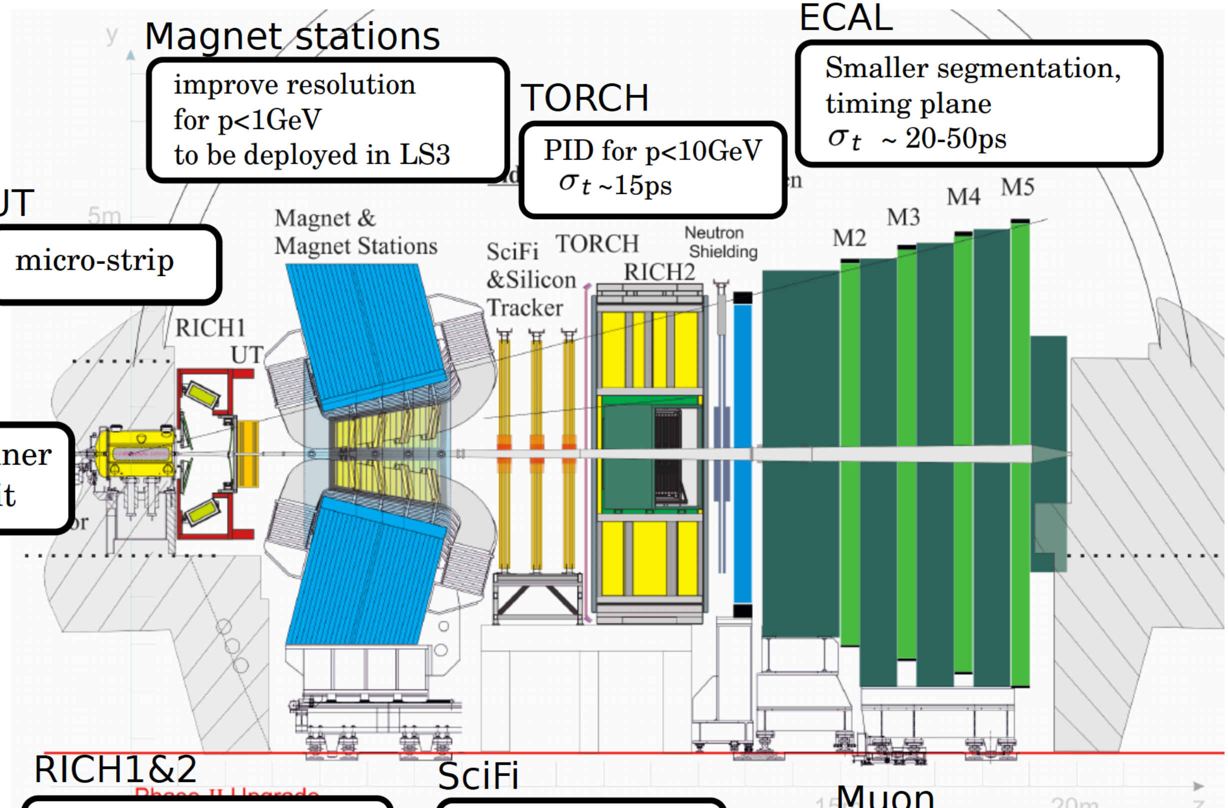


	LHCb	LHCb Upgrade I	LHCb Upgrade II
$\mathcal{L}_{instantaneous}$ $(cm^{-2}s^{-1})$	4×10^{32}	2×10^{33}	$\mathbf{2 \times 10^{34}}$
Pile-up	1	6	**60**

LHCb upgrade II

- Computing, software…

Being studied!



Magnet stations

improve resolution
for p<1GeV
to be deployed in LS3

TORCH

PID for p<10GeV
σ_t ~15ps

ECAL

Smaller segmentation,
timing plane
σ_t ~ 20-50ps

UT

micro-strip

Velo

Smaller, thinner
σ_t <200ps/hit

RICH1&2

higher occupancy
--> new photodetection
plane

SciFi

Add silicon detector
in the inner region

Muon

HCAL --> filter
inner chambers with
micro-resistive WELL