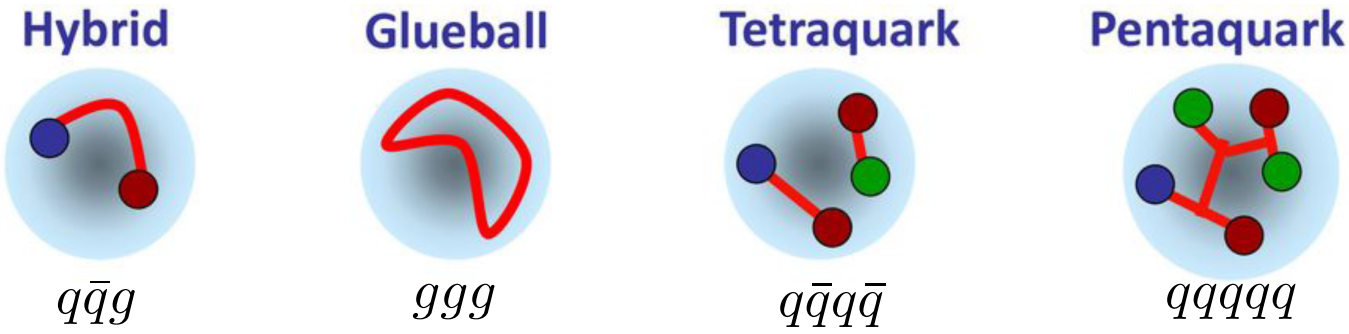
(Heavy flavored) exotic hadrons at LHCb

Biplab Dey

Jefferson Lab User Organization 2020 Annual Meeting

Exotics in the light quark sector?

- Exotics: beyond conventional mesons ($q\bar{q}$) and baryons (qqq)



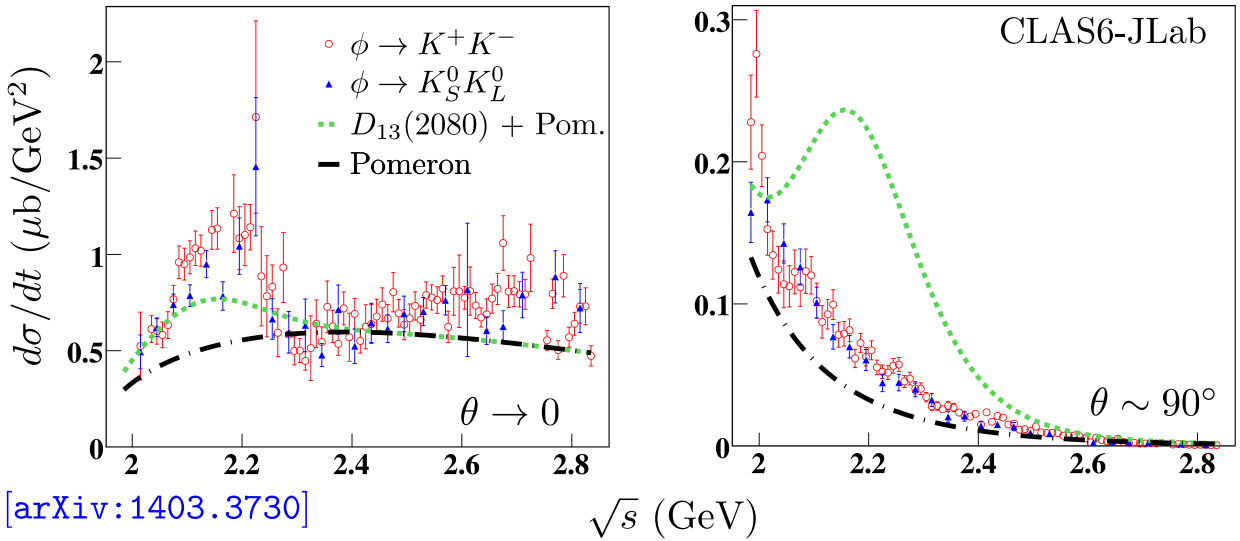
- $f_0(500)$, $a_0(980)$, $f_0(980)$ surmised to be $\pi\pi$ or $K\bar{K}$ tetraquarks or molecules. Difficult to establish.
- $S = +1$ baryon: *manifestly* exotic $\Theta(1540)^+ \to nK^+$
- Historically, very hard to establish in the light quark (u, d, s) sector...

[RPP 2019] ... of the best known candidate from that period, $\Theta(1540)^+$, the 2006 Particle Data Group listing [7] included a statement: "The conclusion that pentaquarks in general, and that Θ^+, in particular, do not exist, appears compelling." which well reflected the prevailing mood in the particle physics community until a study of $\Lambda_b^0 \to J/\psi p K^-$ ($J/\psi \to \mu^+\mu^-$) decays by LHCb [8]

Structure in $\gamma p \to \phi p$ at CLAS6

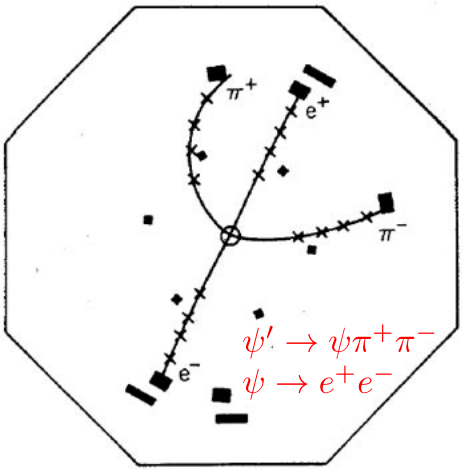
B. Dey, JLab-Thesis-2011
Phys.Rev.C89, 055208
arXiv:1403.3730

- The strange quark is not *that* light: $\mathcal{O}(\frac{m_s}{\Lambda_{\rm QCD}}) \sim 1$
- Detailed data from CLAS6 from near-threshold till $\sqrt{s} \sim 2.8$ GeV.



- Data sees $\sqrt{s} \sim 2.1$ GeV "bump" only at forward angles (t-channel)
- Re-scattering effects? Resonance at kinematic endpoint? (Lebed'15)

The November Revolution in 1974

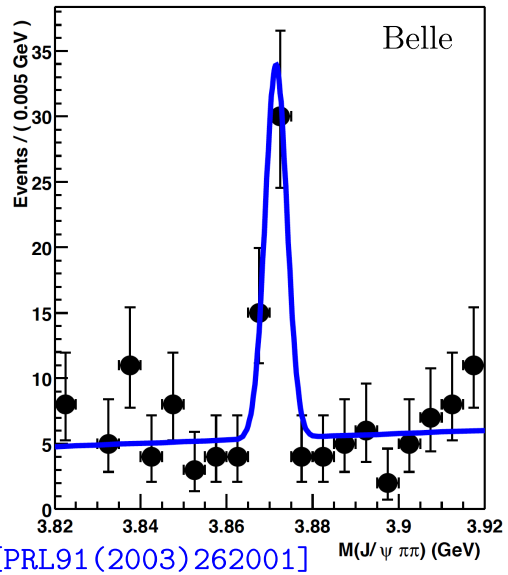


- Heavy charm discovery at SLAC/BNL in Nov'74. Narrow $J/\psi \to e^+e^-$ peak.
- $m_c \gg \Lambda_{\rm QCD}$ means that $\alpha_s(q^2 = m_c^2) \sim 0.3$, instead of $\mathcal{O}(1)$ for light quarks.
- Charm climbs out of the "QCD brown muck" and allows for simple non-relativistic models

- Cornell potential for heavy quarkonium successfully describes $c\bar{c}$, $b\bar{b}$ spectrum, BFs, ...

$$V(r) = -\frac{k\alpha_s}{r} + br$$

Belle 2003 discovery of the $X(3872)$ [aka $\chi_{c1}(3872)$]



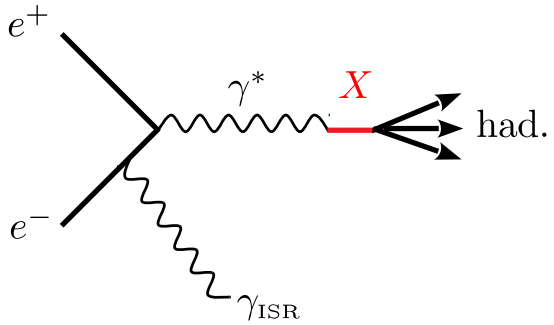
[PRL91(2003)262001]

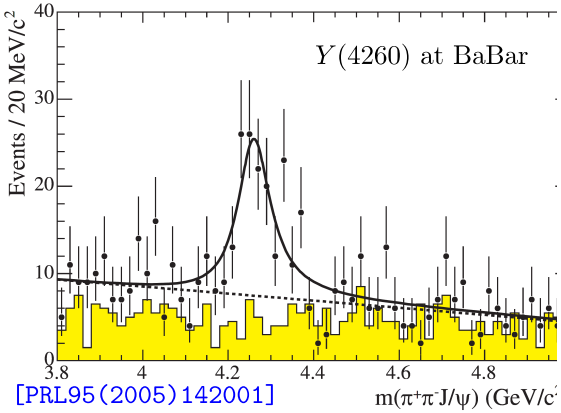
- Belle "accidentally" discovers the $X(3872)$ in $B^+ \to J/\psi \pi^+ \pi^- K^+$. X = unknown.
- $J^{PC} = 1^{++}$ [from LHCb-2014 PRL112, 222002 (2014)], mass many 10's of MeV lower than nearest $c\bar{c}$ candidate, $\chi_{c1}(2P)$.
- Very narrow and mass right at $D^0\overline{D}^{*0}$ threshold.
- Most cited (1785) Belle paper! Seen in many other experiments and production/decay modes, since.

- Detailed lineshape studies recently from LHCb: 2005.13419, 2005.13422
- $X(3872)$ remains first concrete proof of non-$q\bar{q}$ states!

The neutral $Y(4260)$ in 2005 from *BABAR*

- 2003, same year as $\Theta(1540)^+$ claim from LEPS. Many novel ideas from the B-factories to look for exotics.

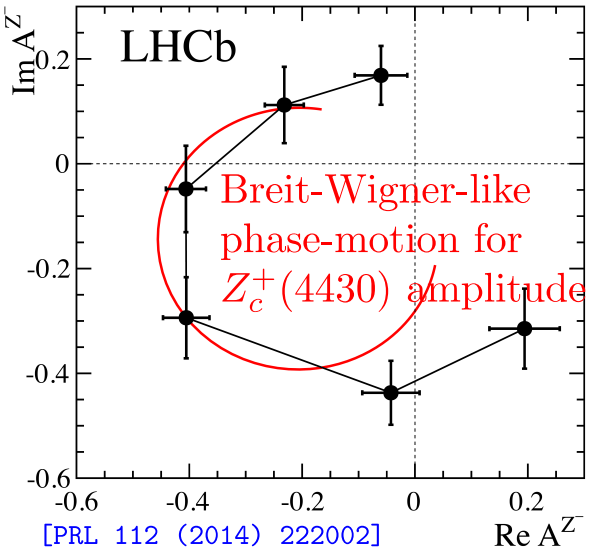




- ISR technique at Belle/*BABAR*: an initial photon is radiated so that $\gamma^* \to$ hadrons allows scanning a continuous spectrum.
- Look for $\gamma^* \to X(3872) \to J/\psi\,\pi^+\pi^-$. Would fix the $J^{PC} = 1^{--}$, same as the photon.
- New $Y(4260)$ state, not seen in B-decays. non-$c\bar{c}$, hybrid candidate.

Charged hidden charm tetraquarks

- Host of $Z_c^+ \to J/\psi\pi^+$ states seen since 2008. Manifestly non-$q\bar{q}$ since valence quark configuration is $|c\bar{c}u\bar{d}\rangle$. No $Z_{cs}^+ \to J/\psi K^+$ seen yet.
- $Z_c^+(4430)$ most famous, couples to $\psi(2S)\pi^+$, instead of $J/\psi\pi^+$

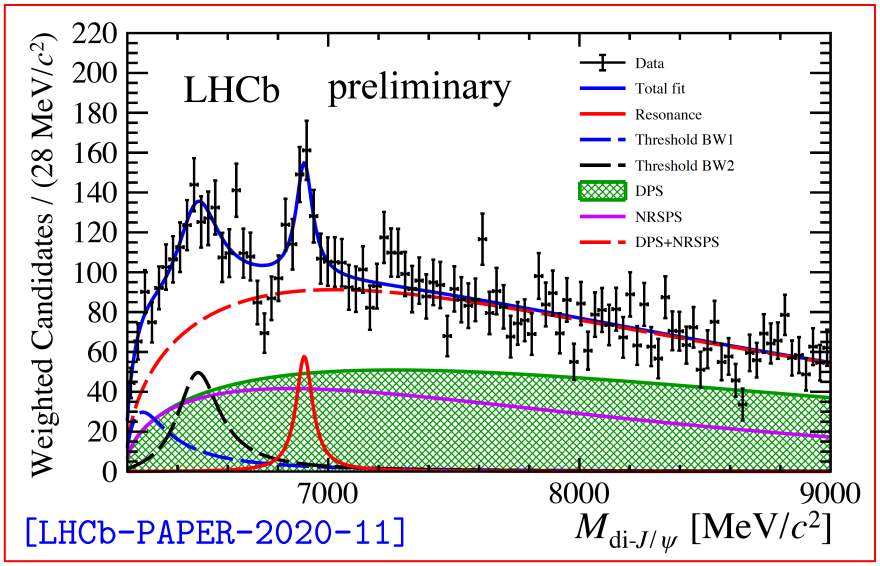


- LHCb-2014 paper w/ full multi-dimensional fit to $B^0 \to \psi(2S)\pi^- K^+$
- LHCb sees $Z_c^-(4200)$ and $Z_c^-(4600)$ in the $B^0 \to J/\psi\pi^- K^+$ mode [PRL122(2019),152002 B. Dey *et al.*]

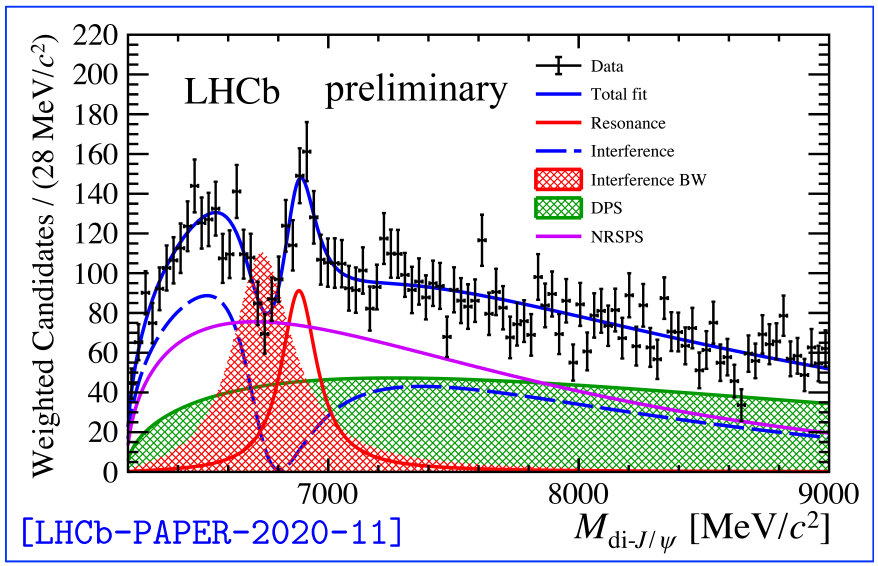
Evidence for $T_{cc\bar{c}\bar{c}}$ (new!)

[LHCb-PAPER-2020-011] (in preparation)

- $T_{QQ\bar{Q}\bar{Q}}$, $Q \in \{c, b\}$, in many QCD models [1803.02522, 1911.00960]
- $T_{bb\bar{b}\bar{b}}$ searched at LHCb [JHEP10(2018),086] and CMS [2002.06393]
- LHCb: prompt di-J/ψ search shows clear evidence of structures. Peak at $\sim$ 6.9 GeV with possible $T_{cc\bar{c}\bar{c}}$ interpretation.
- Mass fit models: include interference with NR process or not...



$m_0 \sim 6905$ MeV, $\Gamma \sim 80$ MeV, $N_{\text{sig}} \sim 252$



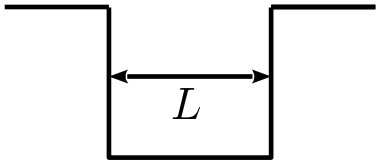
$m_0 \sim 6886$ MeV, $\Gamma \sim 168$ MeV, $N_{\text{sig}} \sim 784$

Takeaways from tetraquarks

- Non-$q\bar{q}$ states ubiquitous in charm, compared to light quark systems

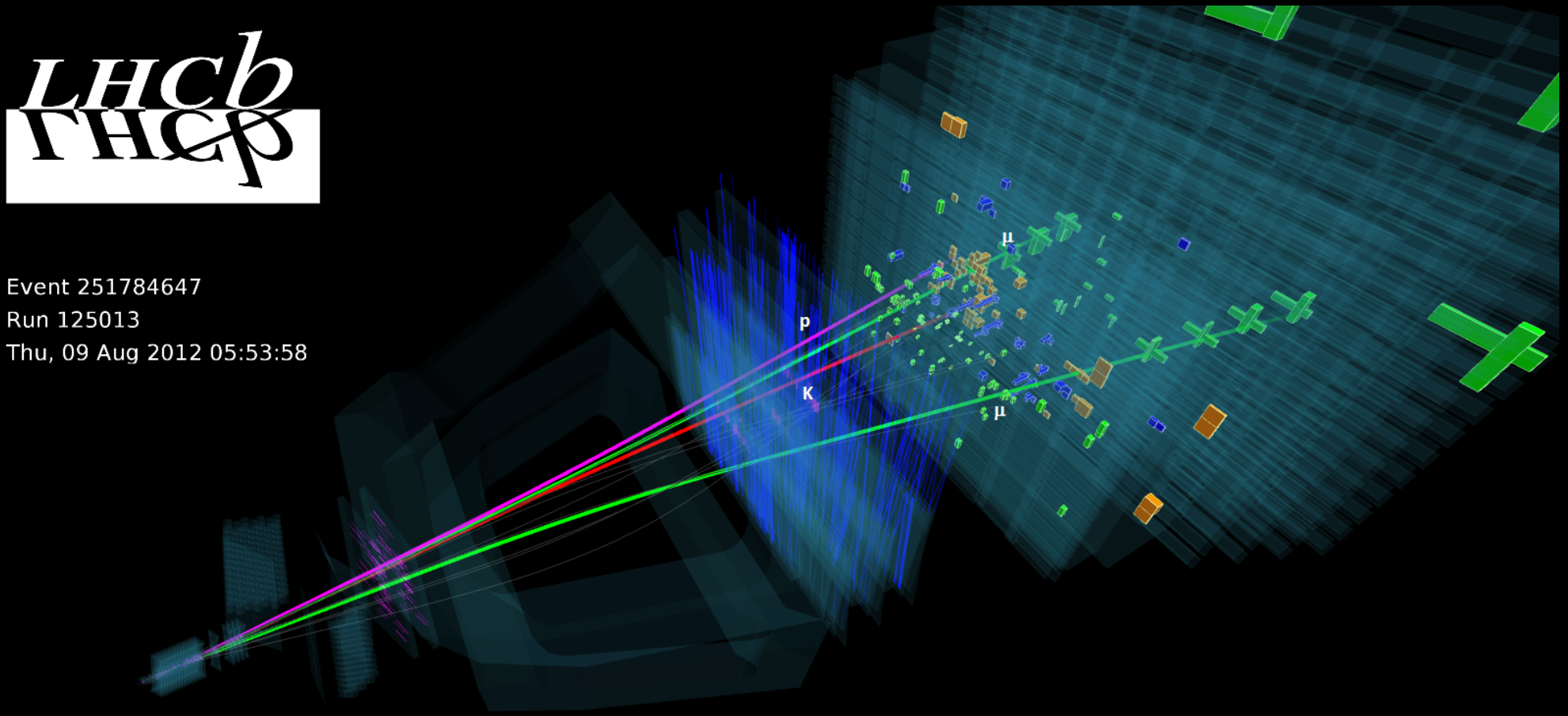
$$p_n \sim \frac{n}{L}$$

$$\text{KE} = \frac{p^2}{2m_q}$$



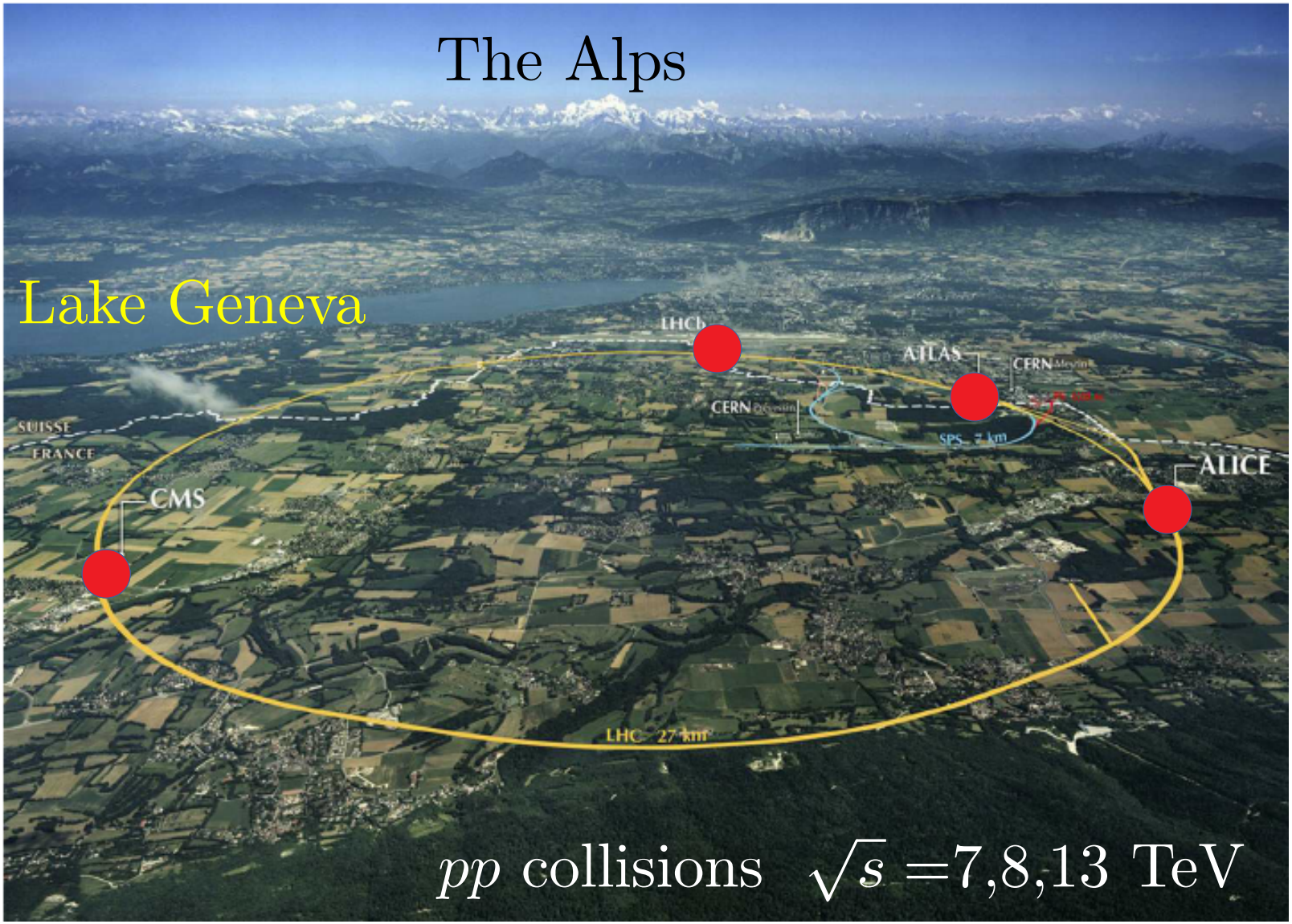
- Simple square-well potential picture illustrative.
- Heavy quark helps in better binding

- Production mechanisms clearly vary case-by-case. Those seen in B decays don't always appear in e^+e^-, and vice versa.



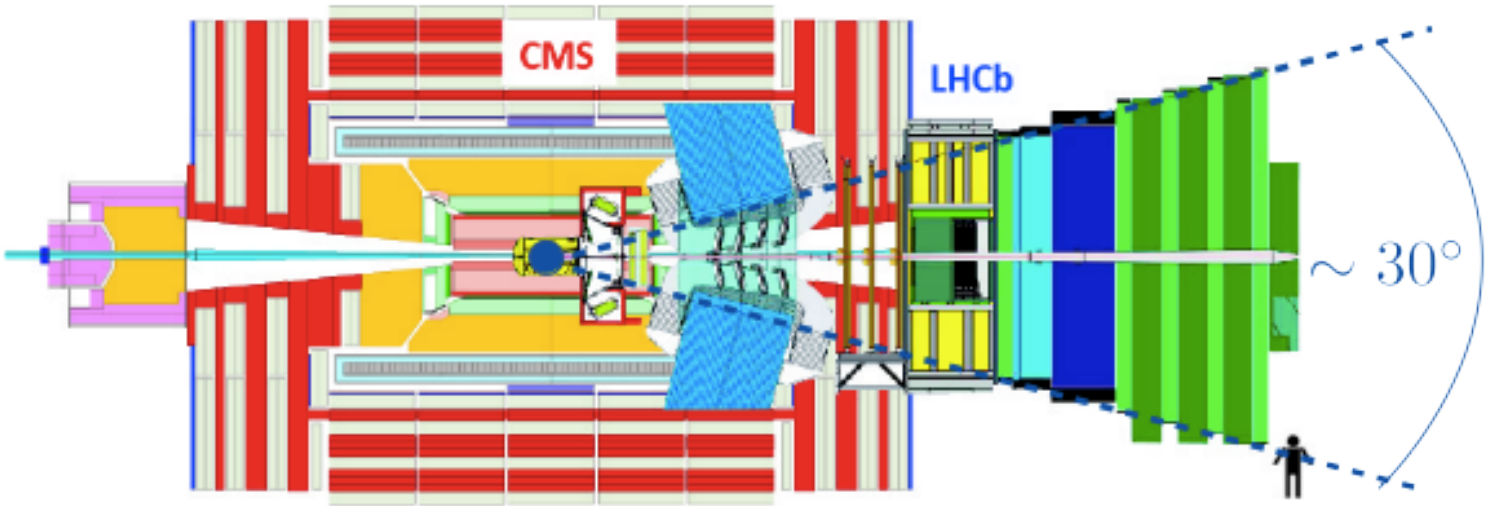
Pentaquarks at LHCb

The LHC at CERN



LHCb, the LHC B-factory

- ATLAS/CMS interested in heavy objects (Higgs, TeV-scale new particles), while b-particles are relatively light ($m_B \sim 5.29$ GeV).
- The b-particles from pp collisions are highly boosted. LHCb is a forward spectrometer. New Physics in CP-violation and rare b-decays

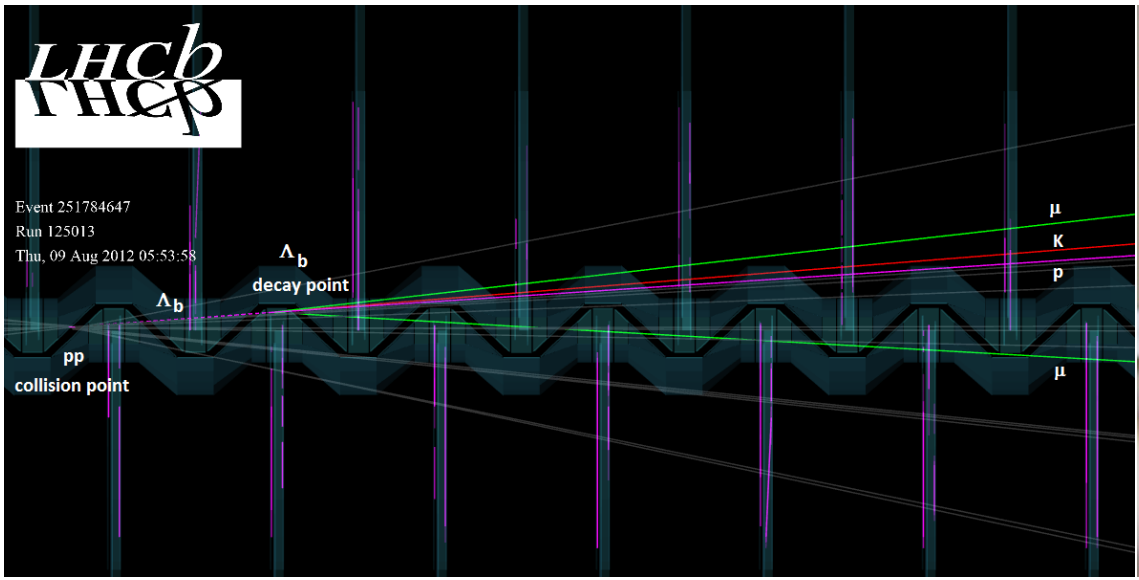


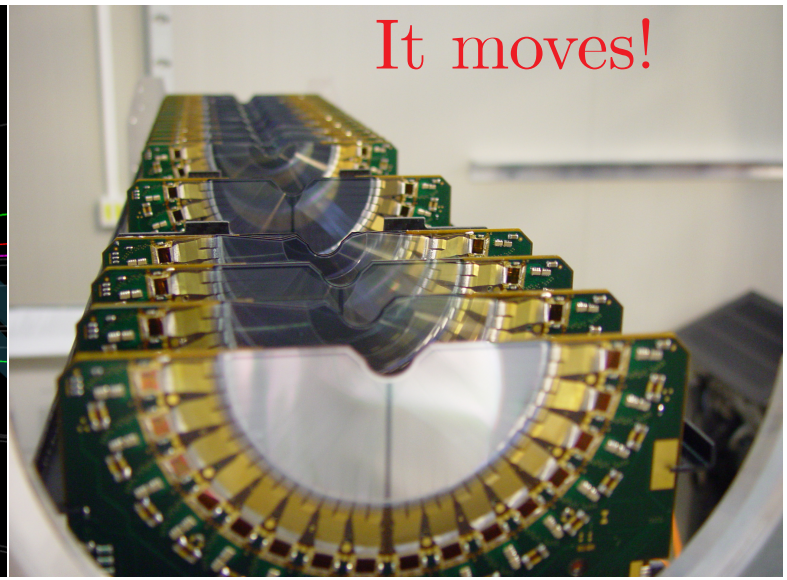
- Compared to e^+e^- colliders (*BABAR*, Belle, BES), huge $b\bar{b}/c\bar{c}$ xsections, but ensuing background. Triggering is critical!

LHCb: precise vertexing

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

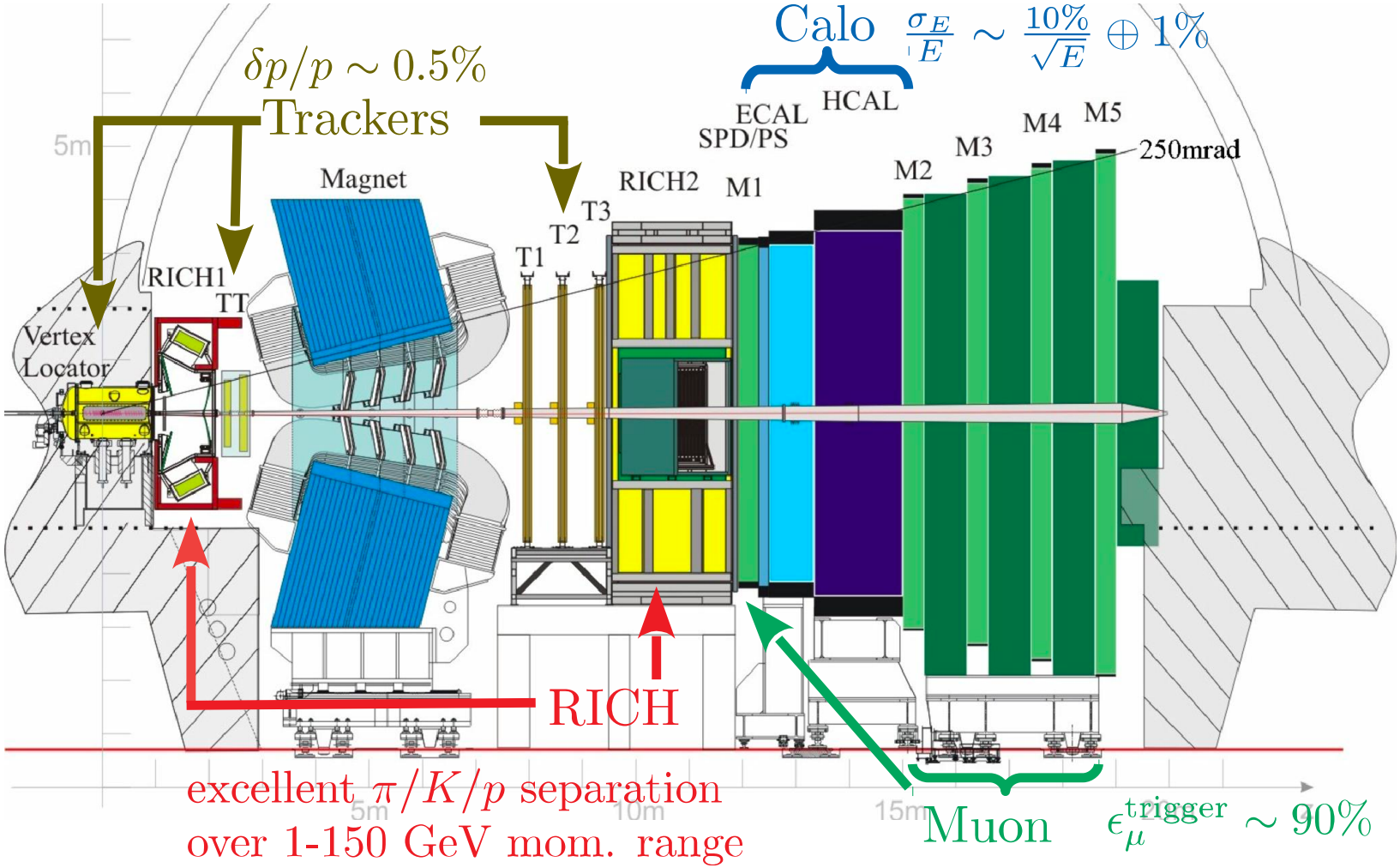
- The weakly-decaying (boosted) b-particles fly $\sim$ cm. Locating the displaced b-decay vertex separates signal from background.
- Innermost Si vertex detector (VeLo) surrounds the collision point. Inserts in to around 8 mm after stable beam. $\sigma_{\rm IP} \sim 15\mu m$.





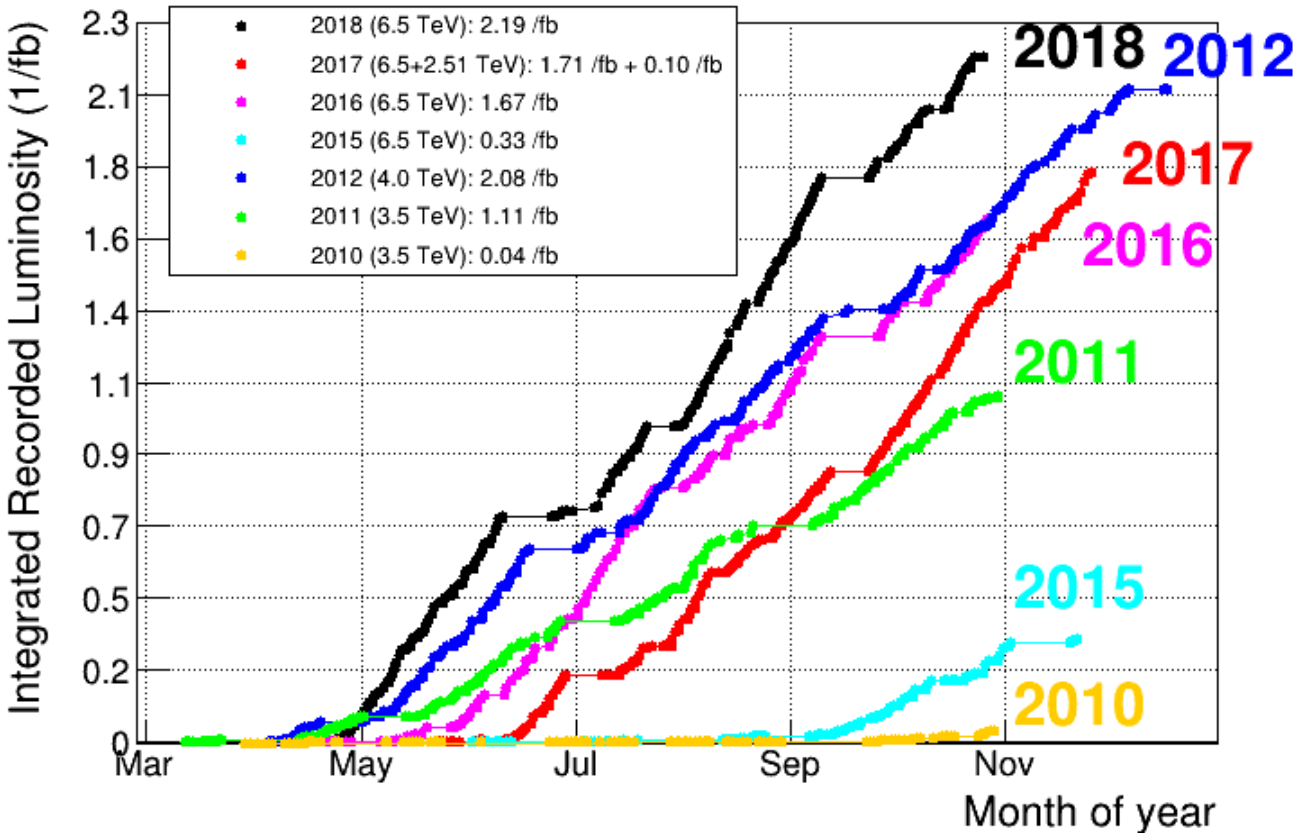
Primed for flavor physics

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



- RICH, VeLo systems unique at the LHC. No RICH for ATLAS/CMS.

Integrated luminosities at LHCb

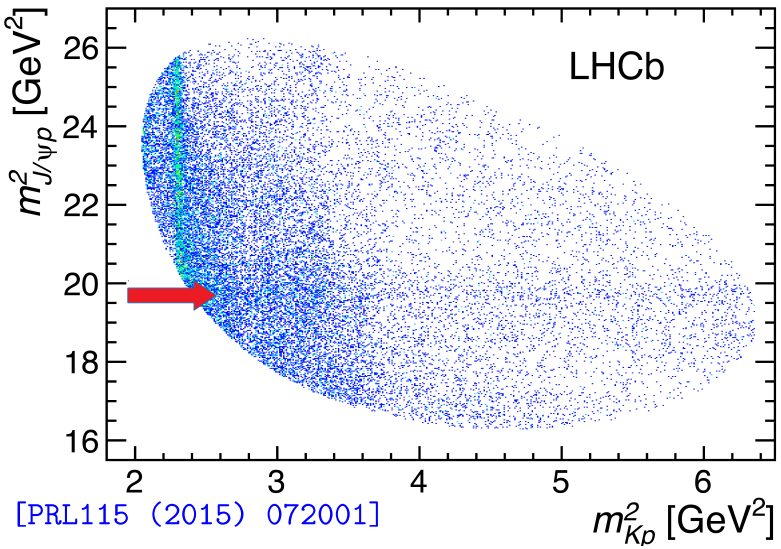


- Recorded around 9/fb of data: Run 1 (2011-12) and Run 2 (2015-18)

Pentaquarks: a serendipitous discovery

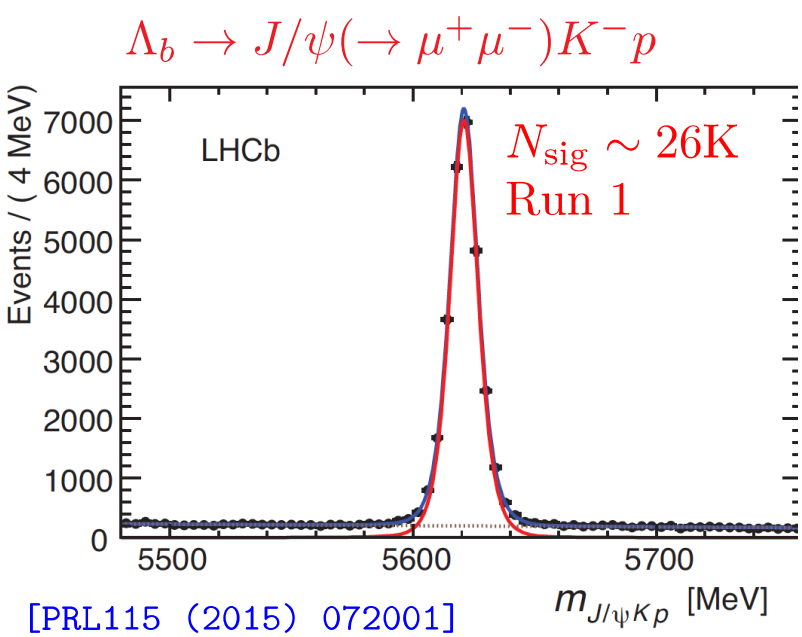
- LHCb was investigating a completely different problem: Λ_b^0 lifetime.
- Heavy quark symmetry: all b-hadron species have comparable lifetimes, while Tevatron measurements: $\tau_{\Lambda_b^0}/\tau_{\overline{B}} \sim 0.8$
- 2014 LHCb paper [PLB, 734, (2014) 122] resolved the issue ultimately. $\tau_{\Lambda_b^0}/\tau_{\overline{B}} = 0.974 \pm 0.006 \pm 0.004$, consistent with HQS.

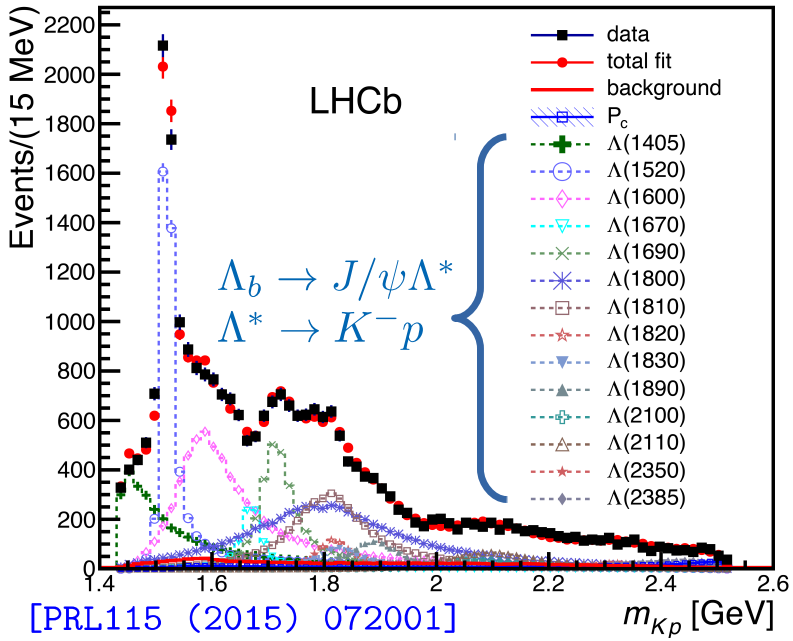
- Analysis used $\Lambda_b^0 \to J/\psi K^- p$
- "Band" seen in $m(J/\psi p)$. Reflection?
- Need angular analysis instead of bump-hunting.



The 2015 analysis

- Very clean Λ_b^0 signal
- Problem is the dominant background from conventional Λ^* states

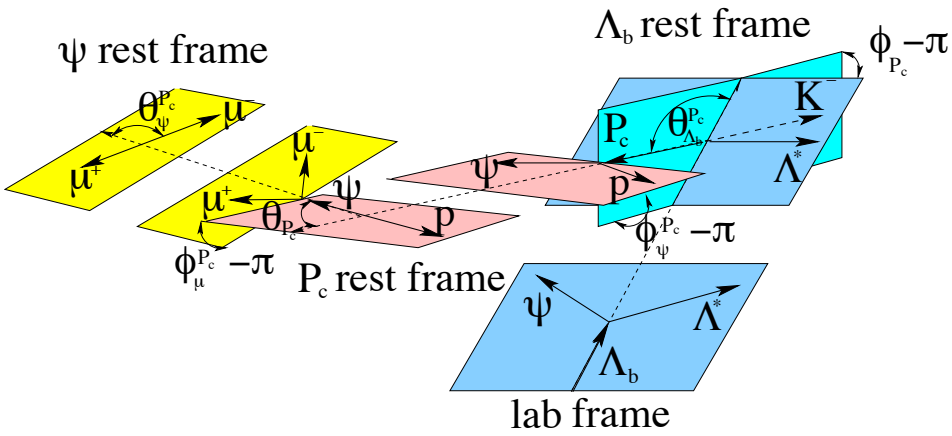




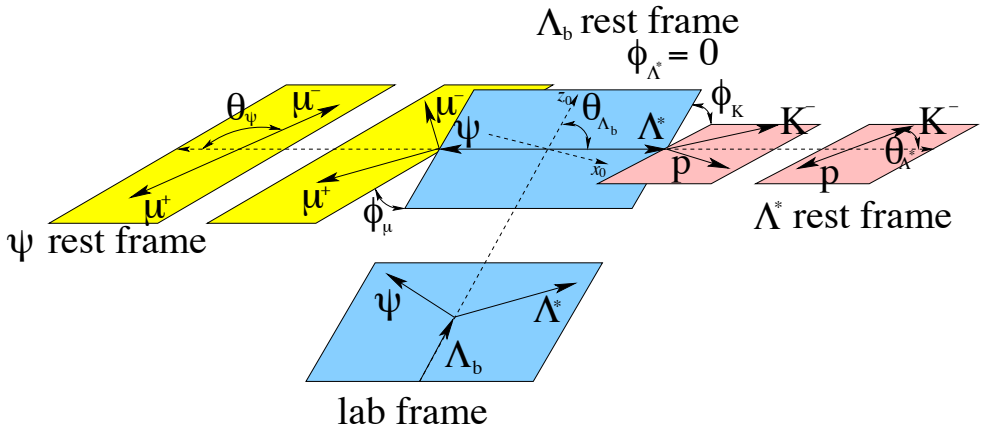
Angular analysis setup

- Full 6-dimensional angular analysis in the helicity formalism, allowing a polarised Λ_b^0.

$\Lambda_b^0 \to P_c^+ K^-$ chain:



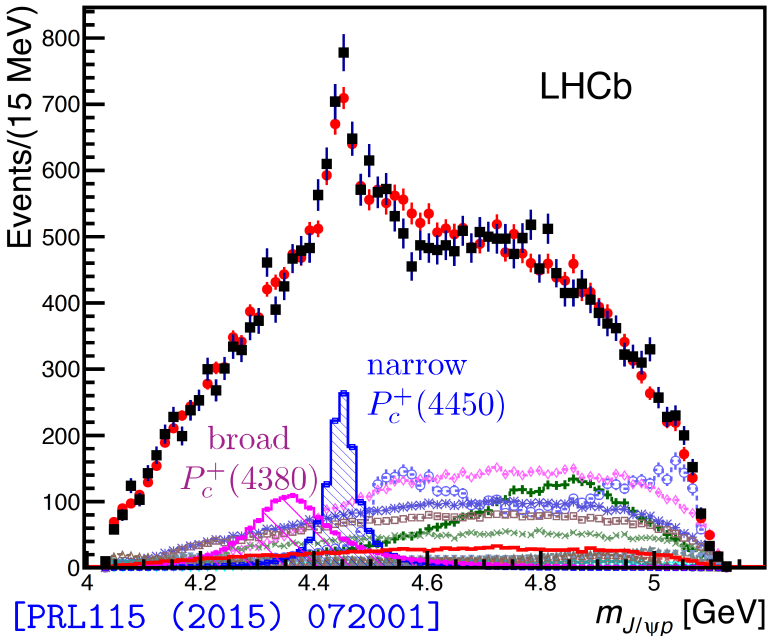
$\Lambda_b^0 \to J/\psi \Lambda^*$ chain:

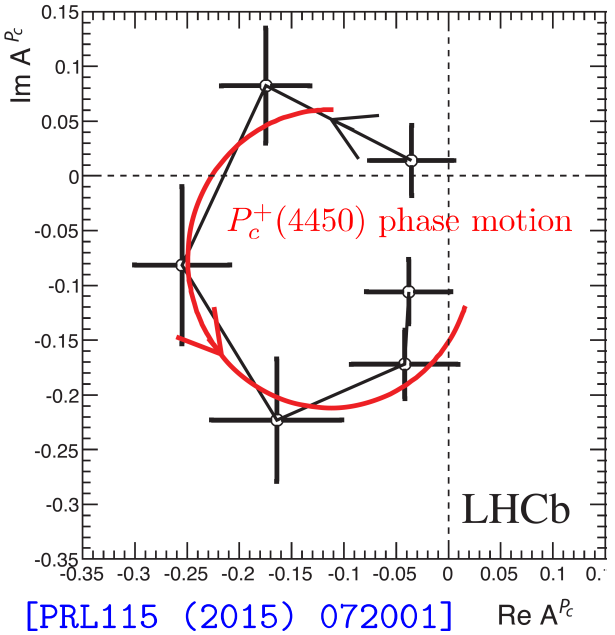


- Special care for final states with spins ($\mu^\pm$, p) when multiple chains occur.

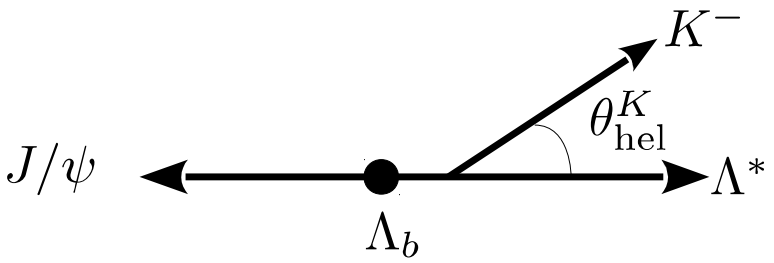
Status till 2015 (superseded now!)

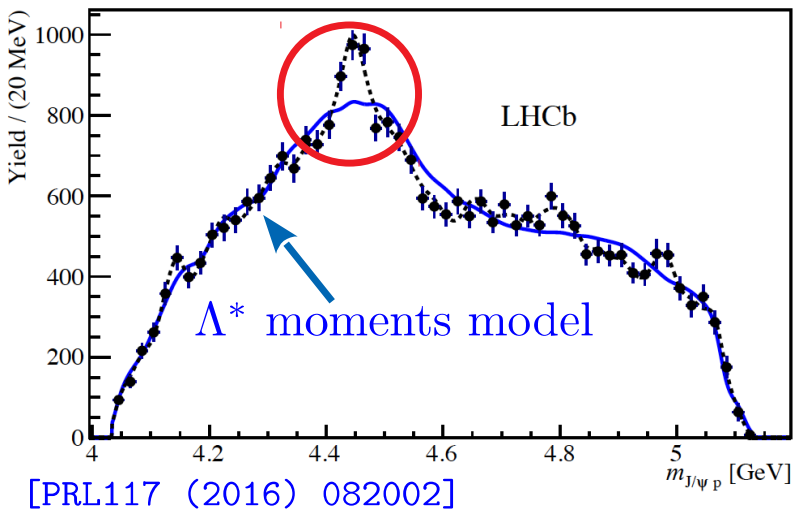
- Amplitude analysis signal two P_c^+ states with opposite parities. narrow $P_c^+(4450)$ and broad broad $P_c^+(4380)$
- Resonance-like phase-motion for the $P_c^+(4450)$ amplitude





Model-independent validation of exotics





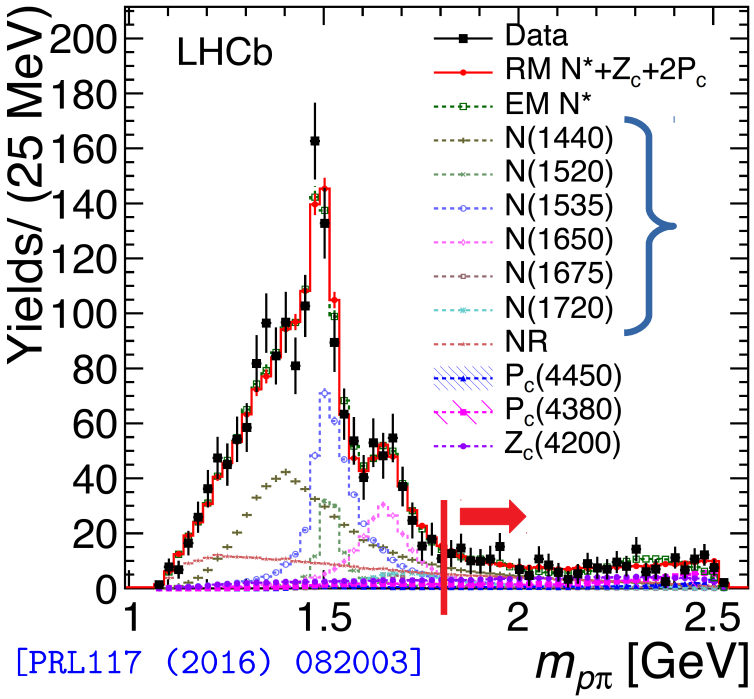
[PRL117 (2016) 082002]

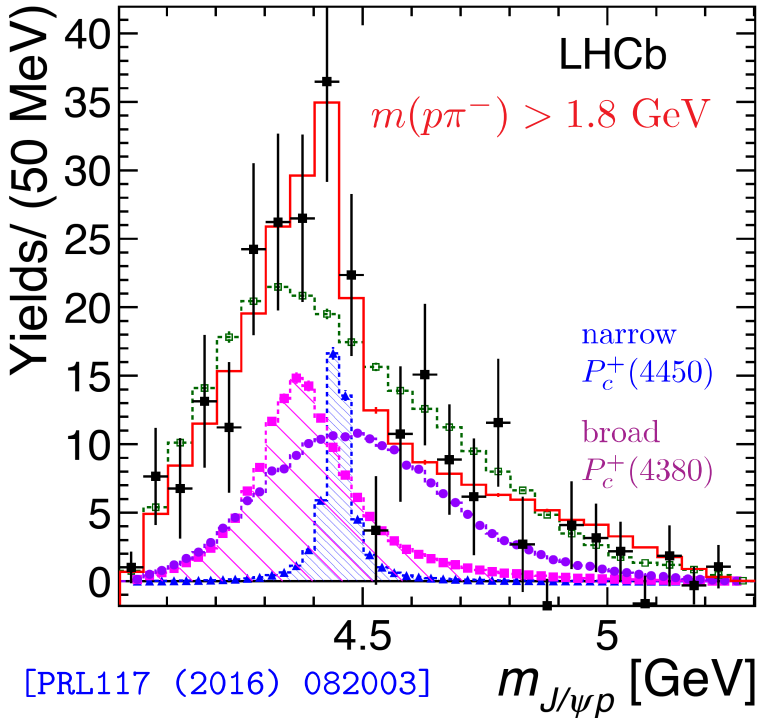
- Dominant and poorly understood Λ^* model a main systematic.
- Λ^* angular moments from data projected on to $m(J/\psi\, p)$
- Λ^*-only hypothesis rejected at $> 10\sigma$
- Same method used in Z_c^- searches in $B^0 \to \psi^{(\prime)} K^+ \pi^-$

  PRL122,152002 (2019), PRD92,112009 (2015)

Cabibbo-suppressed $\Lambda_b^0 \to J/\psi\, p\pi^-$ mode

- LHCb also looked at the Cabibbo-suppressed $\Lambda_b^0 \to J/\psi\, p\pi^-$

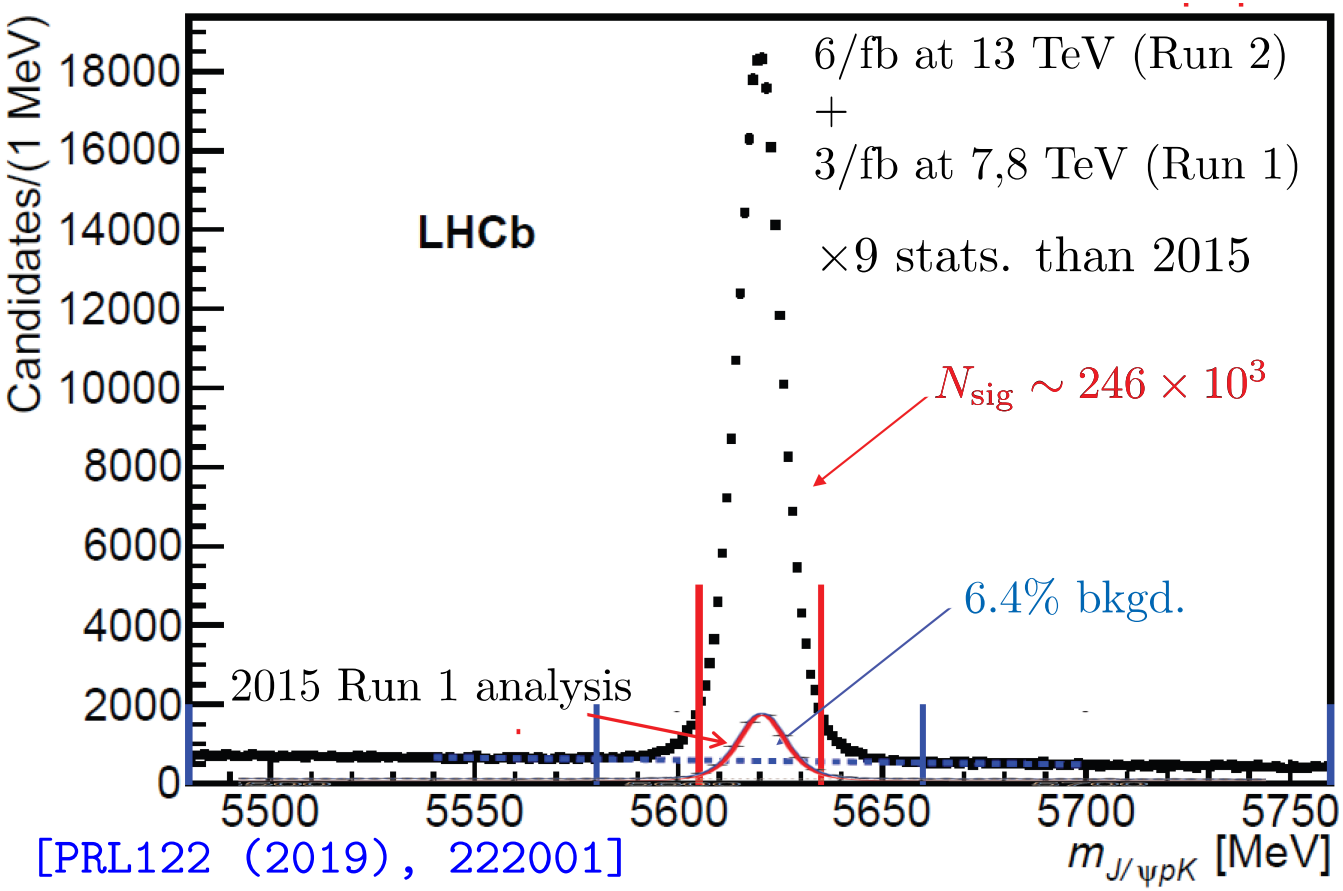




- Data consistent with the same P_c^+ presence, especially vetoing the N^* region as $m(p\pi^-) > 1.8$ GeV.

2019 RE-ANALYSIS OF $\Lambda_b^0 \to J/\psi\, pK^-$ [PRL122(2019),222001]

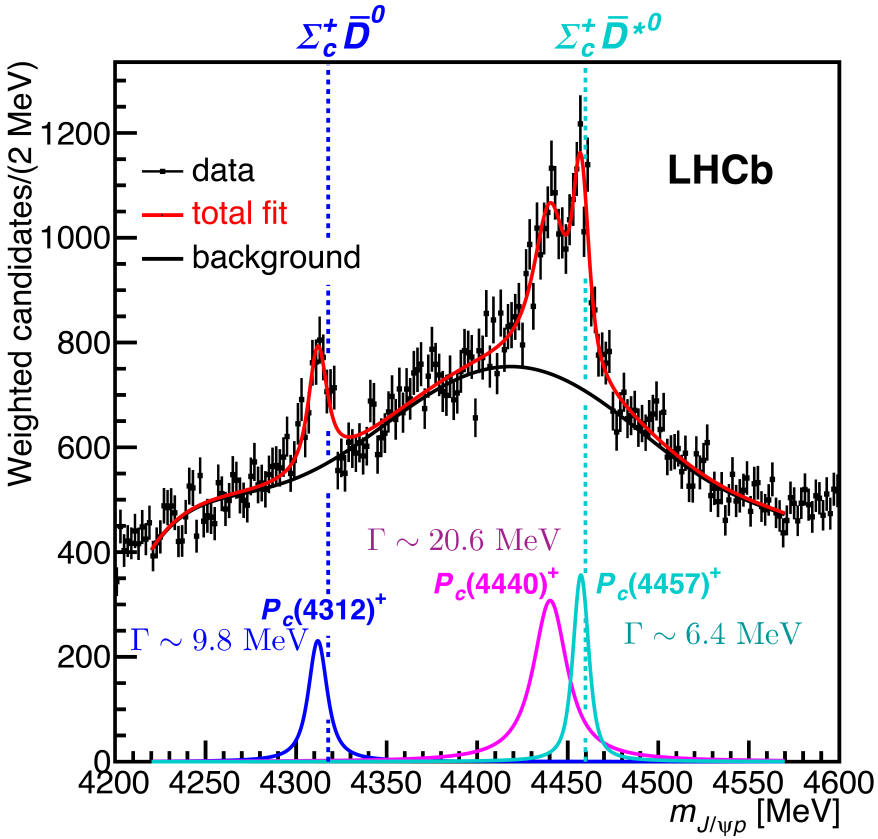
- Improved selections, additional lumi and higher xsection at 13 TeV
- Allows much finer binning to reveal P_c^+ substructures



New picture...

[PRL122(2019),222001]

- To suppress Λ^*, $m(pK) > 1.9$ MeV or weight by P_c^+ helicity angle.



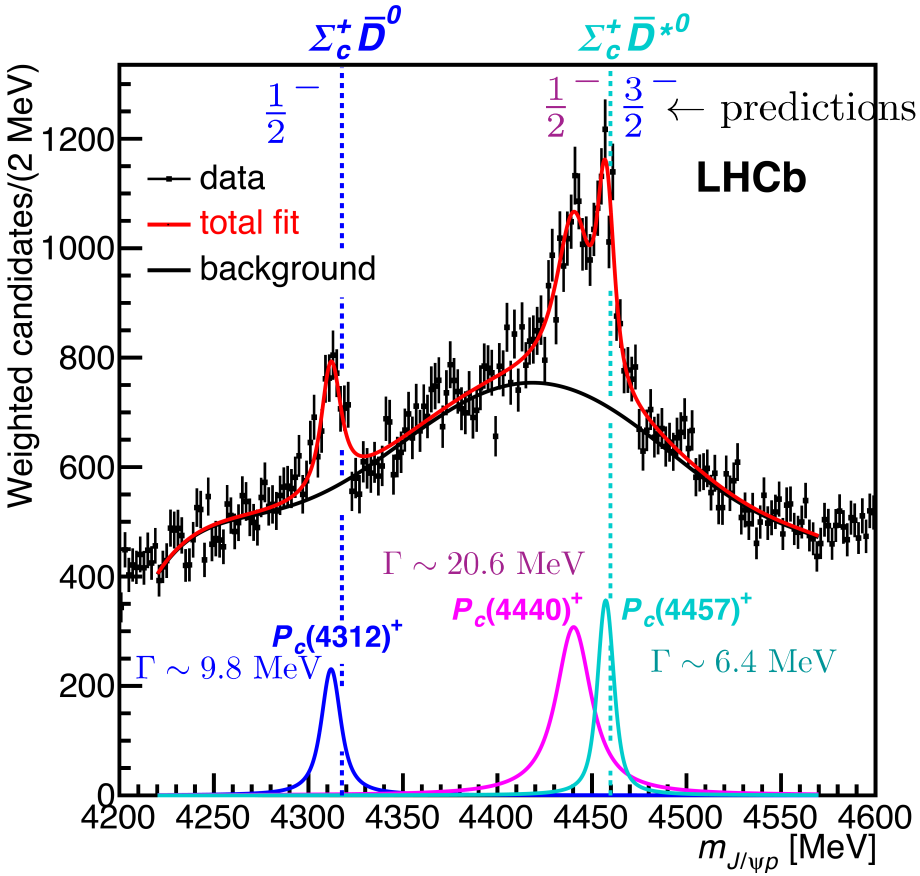
[PRL122 (2019), 222001]

- Three new narrow P_c^+'s
- New $P_c^+(4312)$ at 7.3 σ
- Old $P_c^+(4450)$ resolves into $P_c^+(4440)$ and $P_c^+(4457)$ at 5.4 σ
- 1-d fit not sensitive to broad $P_c^+(4380)$

Molecular states?

[PRL122(2019),222001]

- All three states close to to $\Sigma_c^+ \overline{D}^{0(*)}$ thresholds

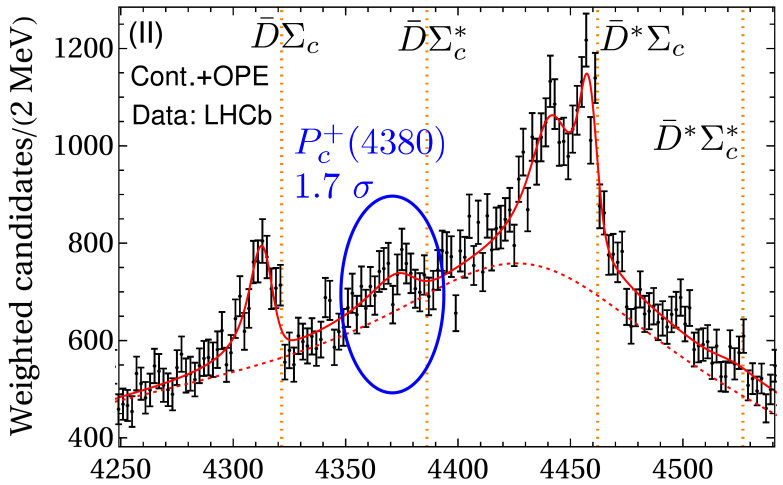


[PRL122 (2019), 222001]

- Loosely bound meson-baryon molecules predicted theoretically

Wang, Huang, Zhang, Zou, PRC84(2011) 015203
Yang, Sun, He, Liu, Zhu, Chin.Phys.C36:6-13,2012

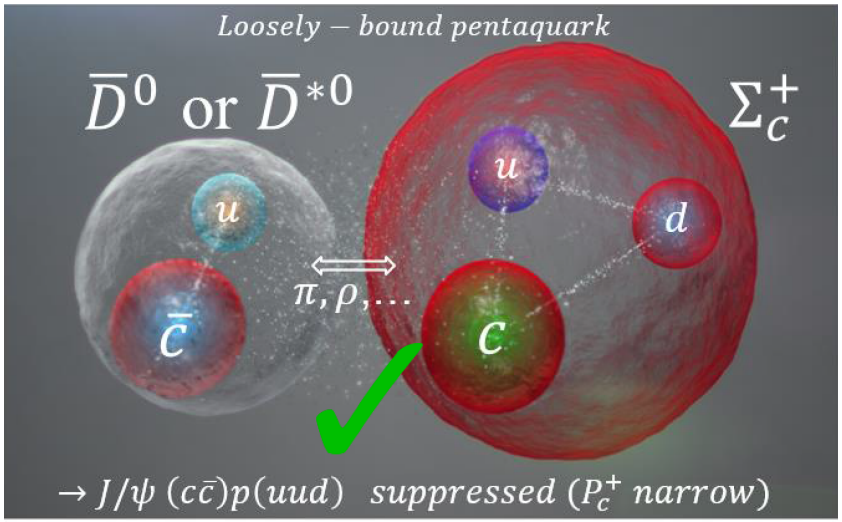
- Du *et al.* finds a narrow $P_c^+(4380)$

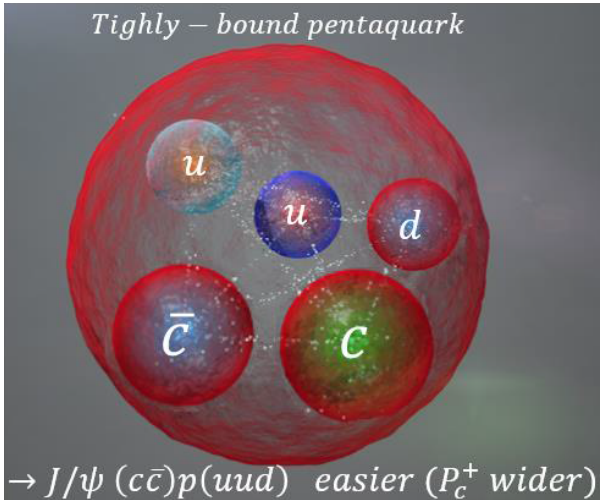


[PRL124 (2020) 072001]

More on the narrow widths...

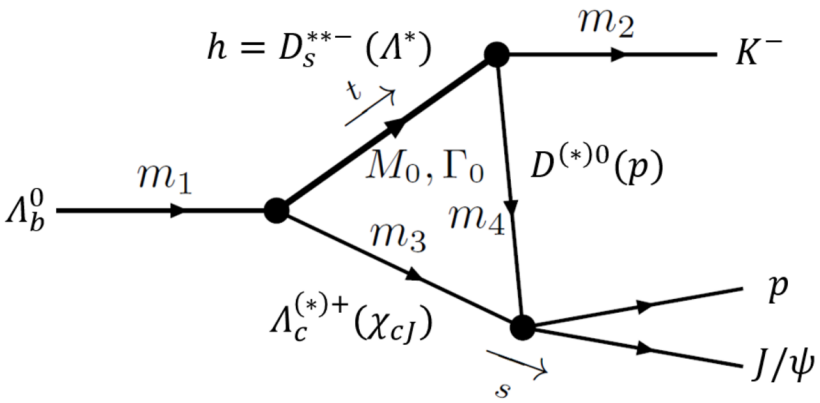
- Decay of the P_c^+ must be suppressed in some manner

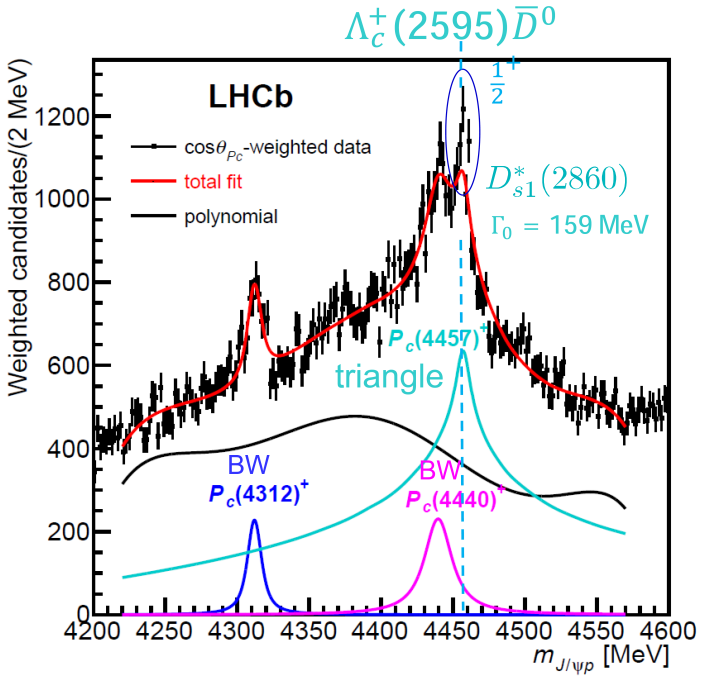




- c and $\bar{c}$ are separated
- c and $\bar{c}$ are close by. Easier to form the J/ψ

Cusps and triangle singularities



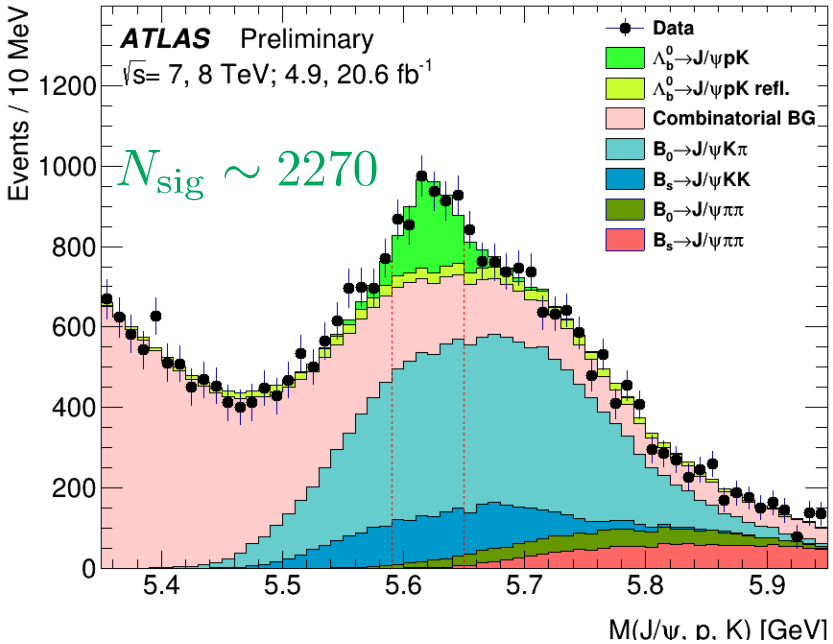


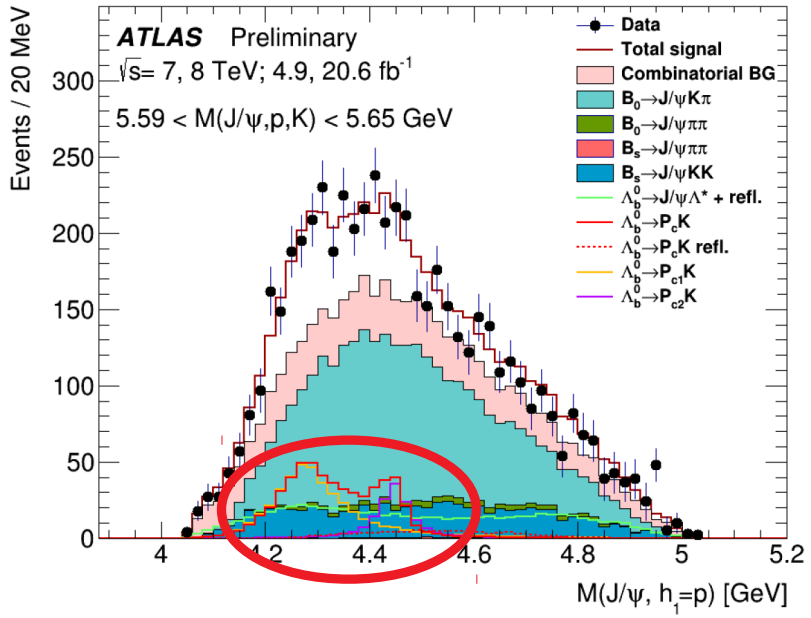
- All three legs must be on-shell.
- m_3 and m_4 rescatter to produce cusp at $(m_3 + m_4)$ mass.
- $P_c^+(4457)$ close to $\Lambda_c^+(2595)\bar{D}^0$ threshold.
- Reasonable fit if $D_{s1}^*(2860)^-$ is exchanged in the t-channel.

ATLAS Run I P_c^+ search

[ATLAS-CONF-2019-048]

- ATLAS has searched in $\Lambda_b^0 \to J/\psi\, pK^-$ as well (Run 1 only)
- Absence of p/K PID separation strongly impediments search

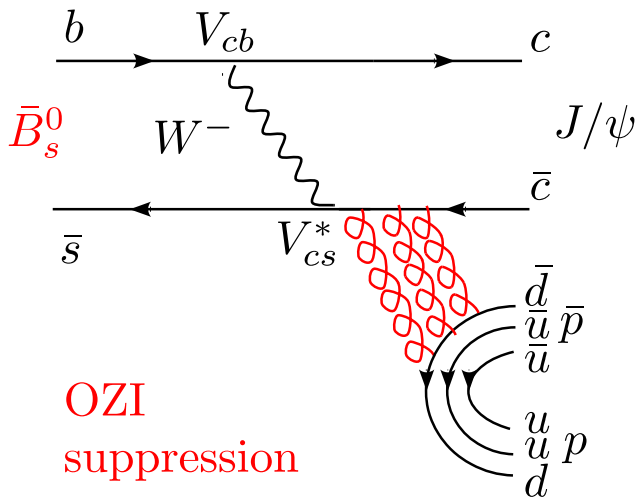


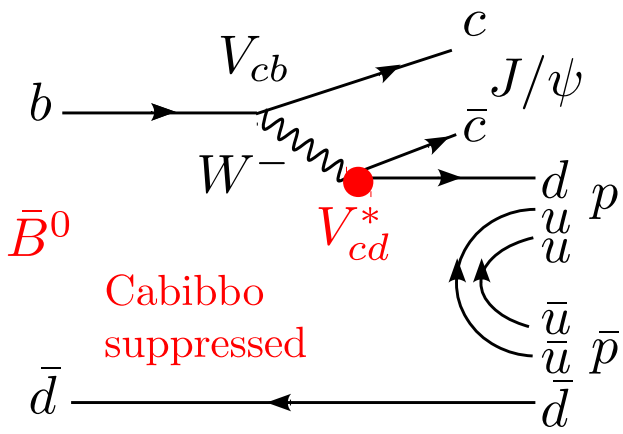


- p-values: with (24%) compared to without (0.009%) P_c^+ states, but data can't rule out null hypothesis.

Exotics searches in $B^0_{(s)} \to J/\psi\, p\bar{p}$

- "Rare" baryonic B-decays. Phase-space + Cabibbo/OZI suppressions:



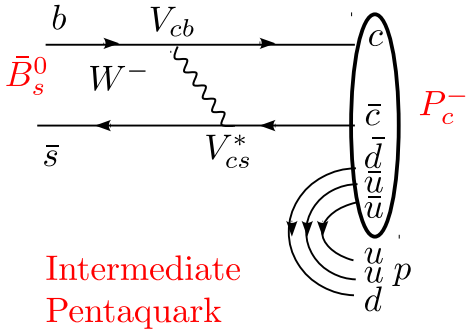


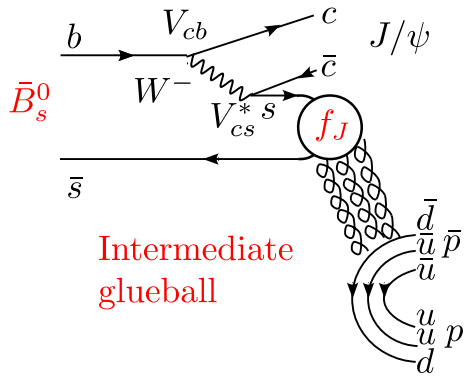
- Interesting "threshold enhancement" seen in many di-baryon B decays. Glueball in $p\bar{p}$? Pentaquark from a B-decay?

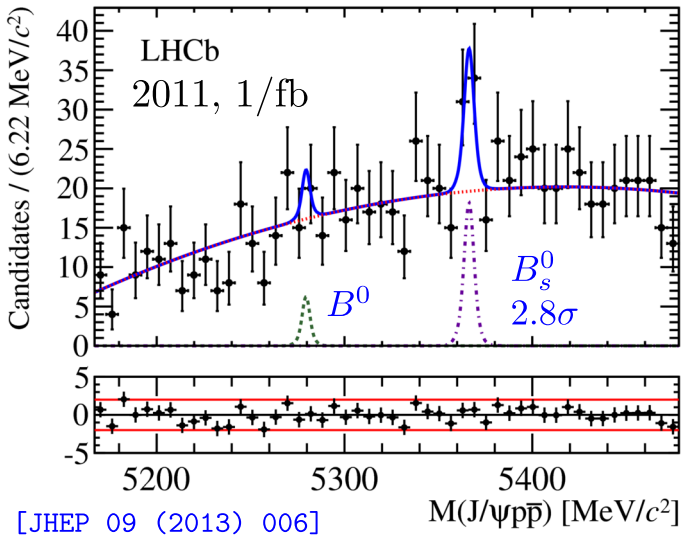
Exotics searches in $B^0_{(s)} \to J/\psi\, p\bar{p}$

- pQCD: $\mathcal{B}(B^0) > \mathcal{B}(B^0_s)$ (Hsiao [EPJC75, 101 (2015)])

- Suppression can be lifted by Pentaquark in $[J/\psi\, p]$ or glueball in $[p\bar{p}]$







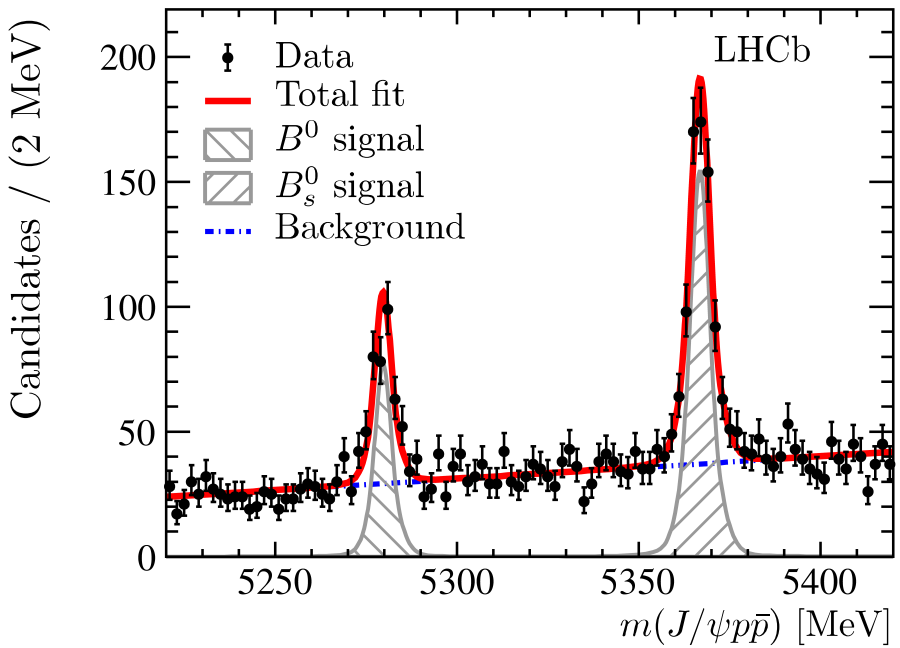
- LHCb has 1/fb upper limits at 90% CL: $\mathcal{B}(B^0) < 5.2 \times 10^{-7}$, $\mathcal{B}(B^0_s) < 4.8 \times 10^{-6}$

- Inverted hierarchy indicated by data, compared to naive expectation

5 fb^{-1} (2011-2016) results

[PRL122, 191804(2019)]
B. Dey *et al.*

- Powerful new multivariate classifier with proton PID + kinematic variables.
- First observation of these modes. with $\gg 10\sigma$.
- $N_{B^0_s} = 609 \pm 31$, $N_{B^0} = 256 \pm 26$.



$$\mathcal{B}(B^0 \to J/\psi\, p\bar{p}) = (4.51 \pm 0.40\ (\text{stat}) \pm 0.44\ (\text{syst})) \times 10^{-7}$$
$$\mathcal{B}(B^0_s \to J/\psi\, p\bar{p}) = (3.58 \pm 0.19\ (\text{stat}) \pm 0.33\ (\text{syst})) \times 10^{-6}$$

- Inverted $\mathcal{B}(B^0) < \mathcal{B}(B^0_s)$ confirmed in data, as opposed to Hsiao *et al.* theory expectations.

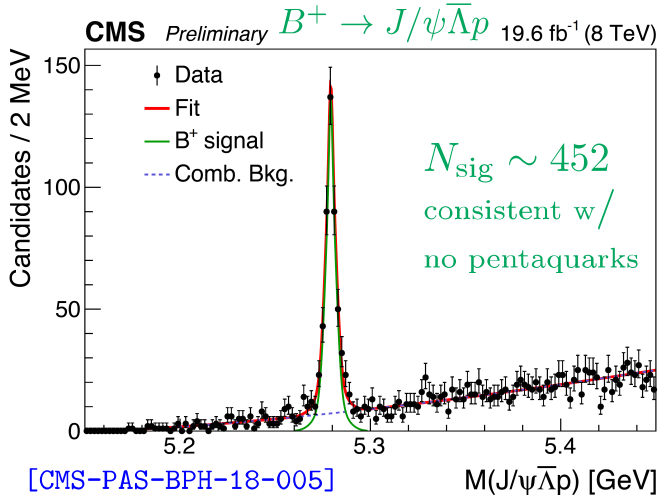
$B^0_{(s)} \to J/\psi\, p\bar{p}$ PROSPECTS

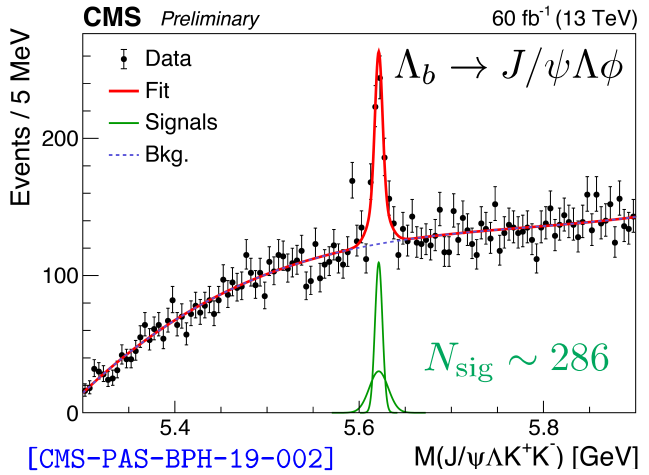
- Unlike $\Lambda_b^0 \to J/\psi\, pK^-$, production expected to be mostly phase-space. Pentaquark can dominate.
- Unique topology: pentaquark in both $J/\psi\, p$ and $J/\psi\, \bar{p}$ axes with interference in the Dalitz plane.
- Angular analysis on full Run 1+Run 2 ongoing.

Other P_c^+ searches at the LHC

LHCb:

- Update on $\Lambda_b^0 \to J/\psi\, p\pi^-$
- $B^+ \to J/\psi\, \overline{\Lambda} p$
- $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$
- Prompt P_c^+ production
- $\Lambda_b^0 \to \chi_{c1} p\pi^-$
- $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$

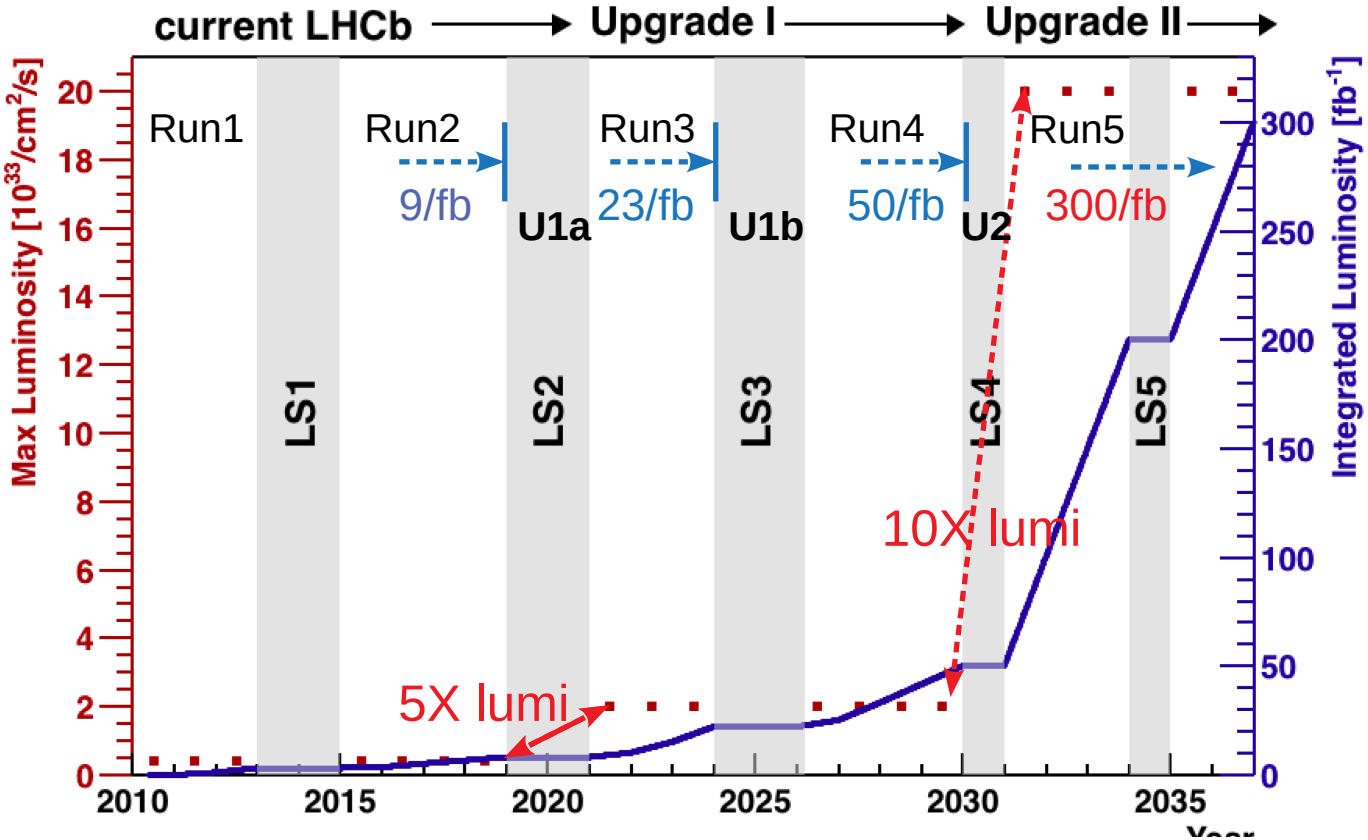




LOOKING AHEAD: LHCB UPGRADES

[CERN-LHCC-2017-003
LHCB-PUB-2018-009]

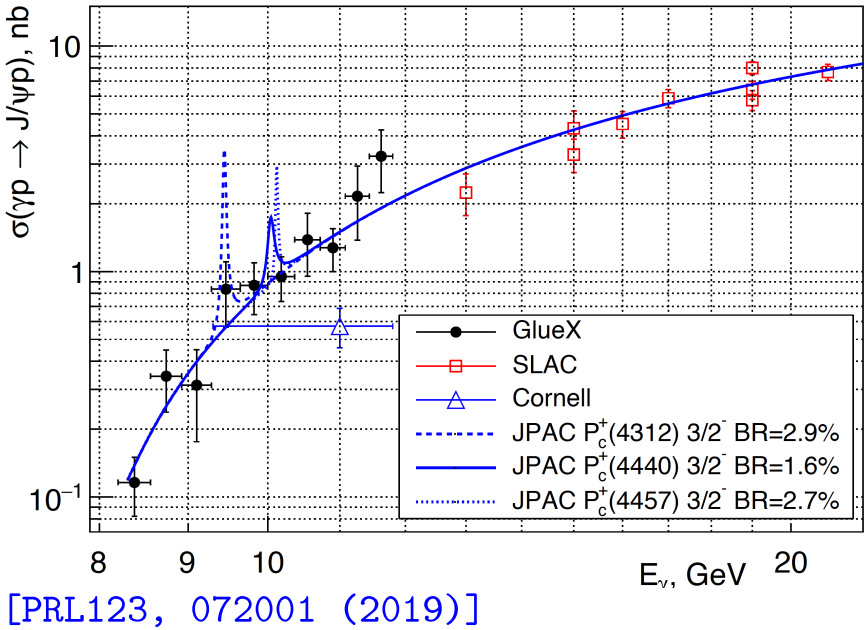
- Spectroscopy measurements still statistics limited. Aim to collect $\times 100$ data, improving upon 1-2 fb^{-1}/year.



- Staged upgrade towards 300 fb^{-1}
- Upgrade Ia(now)
- Entire detector R/O at 40MHz
- Versatile online s/w trigger

Summary and outlook

- Exotics appear to prefer heavy quark systems. LHCb continue to shape the field with both tetraquark and pentaquark discoveries.



[PRL123, 072001 (2019)]

- No reason same P_c^+'s as in *b*-decays will appear at JLab
- Full angular coverage, as in CLAS6 $\gamma p \to \phi p$ might be needed
- Can GlueX do $\gamma p \to J/\psi \pi^+(n)$?

- Looking forward to what JLab finds!