LHCb and
Tetra- and Penta-Quark candidates

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Nov 4, 2015
at

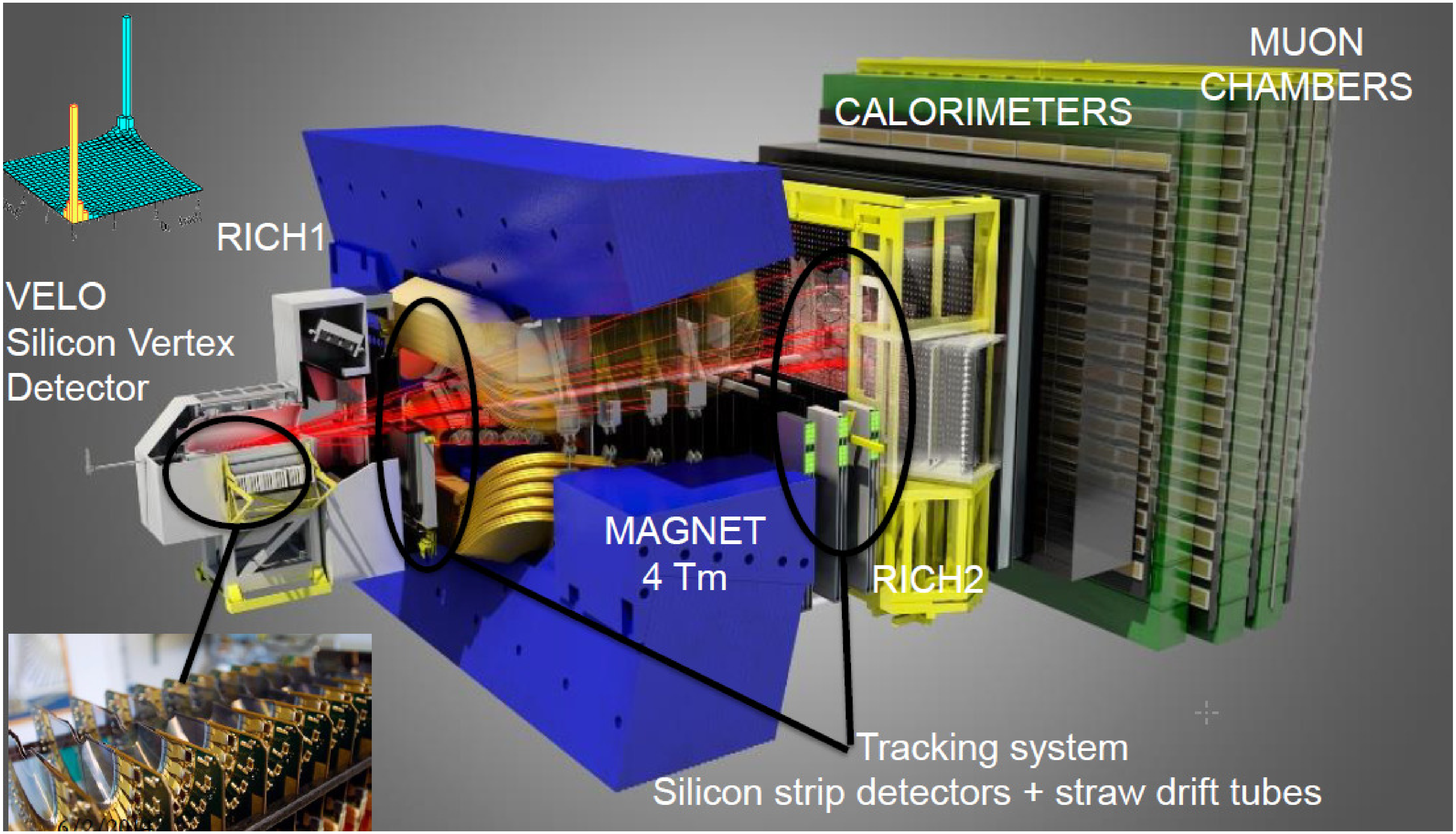
INSTITUTE for
NUCLEAR THEORY

Modern Exotic Hadrons
(INT 15-60W)

Outline

- LHCb present and future capabilities in exotic hadron spectroscopy
- LHCb results on exotic hadrons and some near future projects

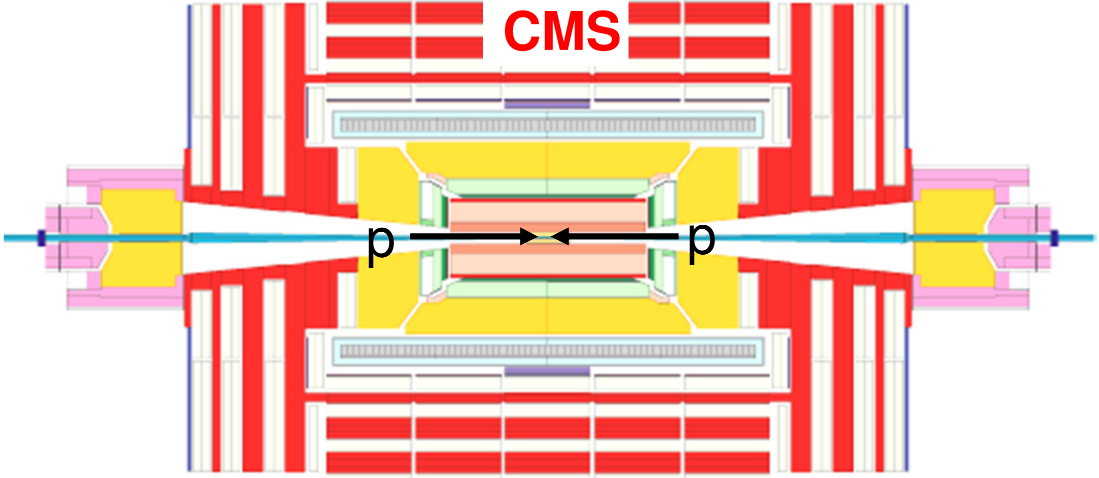
LHCb detector



- pp collider experiment with “fix target layout”

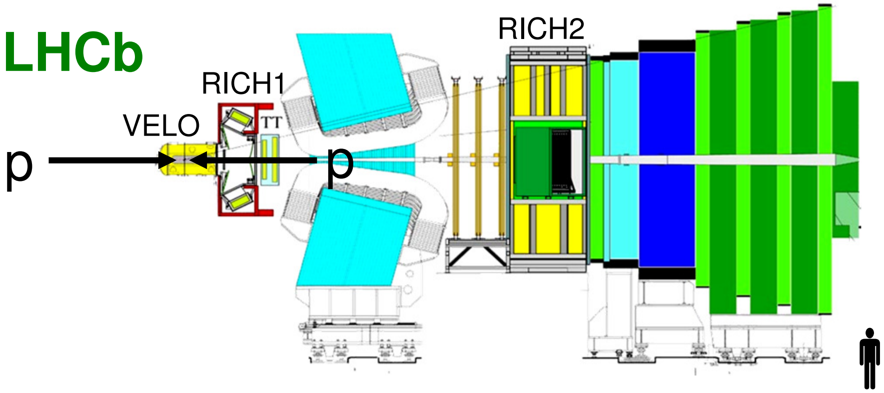
LHCb: first dedicated b (c) detector at hadronic collider

- Typical hadronic collider experiment optimized for high-p_T physics:
  - CMS and ATLAS at LHC, CDF and D0 at Tevatron
  - “central detector” (less bkg from beam fragments)
  - run at highest luminosity available: high p_T thresholds in trigger, not efficient for b decays
  - large detector volume: $$$$, large events size→limited trigger bandwidth to storage (~500 Hz in Run I)
  - b triggers via dimuon pairs (e.g. $b \to J/\psi X$, $J/\psi \to \mu^+\mu^-$)
  - heavy flavor physics is a very low priority; very low trigger bandwidth allocation (~5 Hz)
  - no hadron ID (no K,p identification), large backgrounds in exclusive b-hadron decays



LHCb:

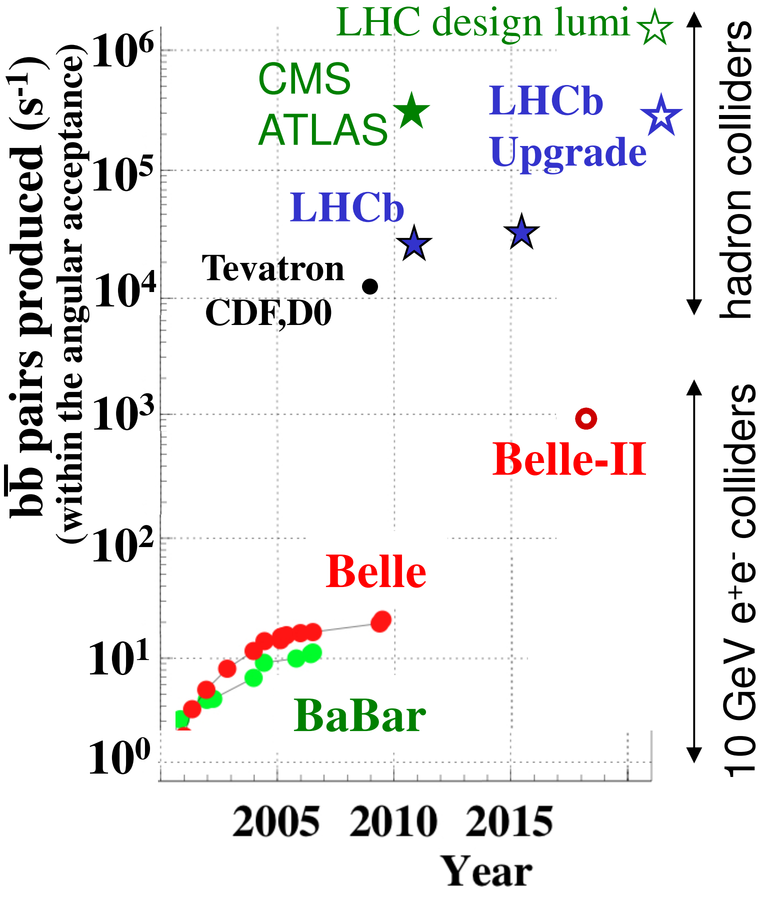
- First of a kind
- “forward detector” (can catch b and $\bar{b}$ in small-volume detector)
- run at diluted luminosity: low p_T thresholds in trigger, efficient for b decays
- hadron ID via RICH detectors; low backgrounds in b-hadron decays



- small detector volume: $, small events size→large trigger bandwidth to storage (5 kHz in Run I)
- b triggers via dimuon pairs and detached vertices even without muons (trigger on selected c decays too)
- heavy flavor physics is the top priority; takes almost all trigger bandwidth

Colliders and $b\bar{b}$ rates

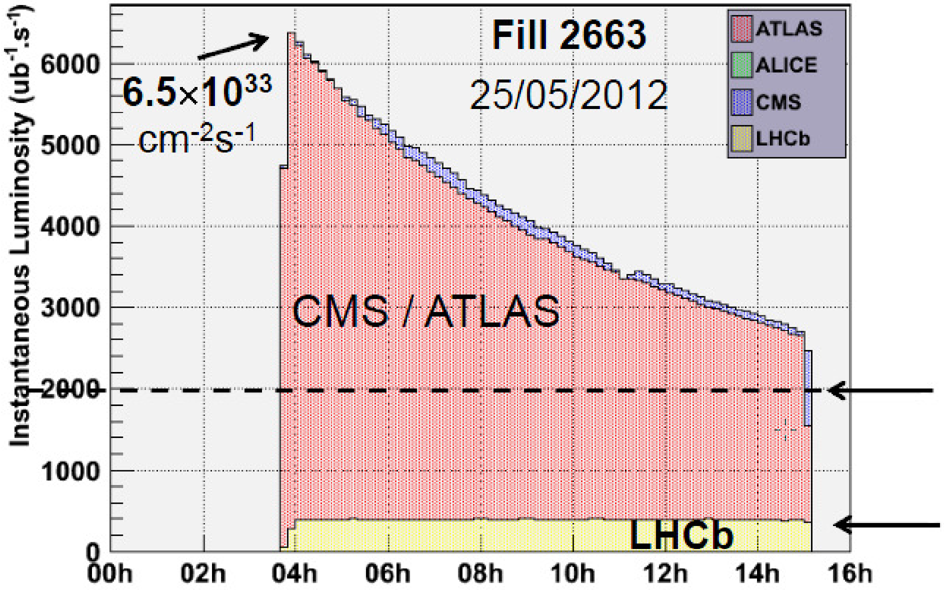
Previously a lot of results on exotic hadron spectroscopy with heavy quarks came from e^+e^- B-factories (also from e^+e^- charm factory – BES III)



- Tremendous rate potential at hadron colliders
  - **physics reach determined by the detector capabilities not by the machine**
- Collect all b-hadron species at the same time:
  - **additional gain by a factor of ~10-100 in integrated B_s rates at hadronic colliders**
  - **also get Λ_b, B_c which are out of reach for the 10 GeV e^+e^- factories**
- Charm rates factor of 10 higher than beauty rates:
  - **nuisance and physics opportunity at the same time**

LHCb luminosity and its upgrade

- Maximal value of luminosity for safe LHCb operations ~ 4×10^{32} $cm^{-2}s^{-1}$
- Beams are intentionally misaligned at LHCb to stay below this limit.
- Luminosity is “leveled” over run duration.



ATLAS & CMS lumi
limited by the LHC;
falls off exponentially

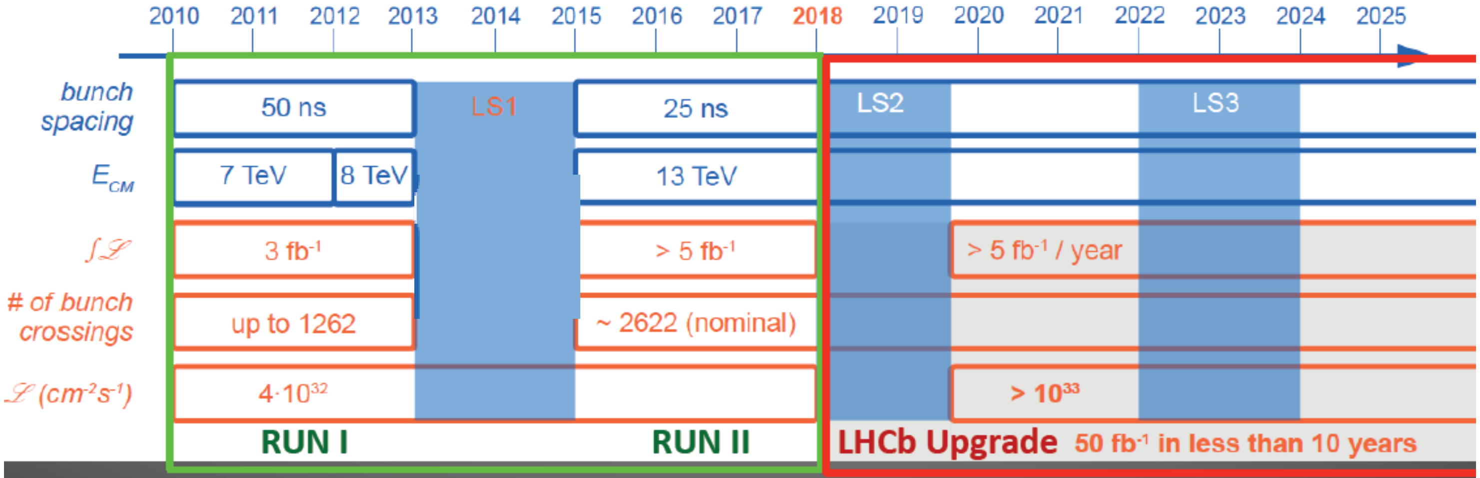
2×10^{33} LHCb upgrade

4.1×10^{32}

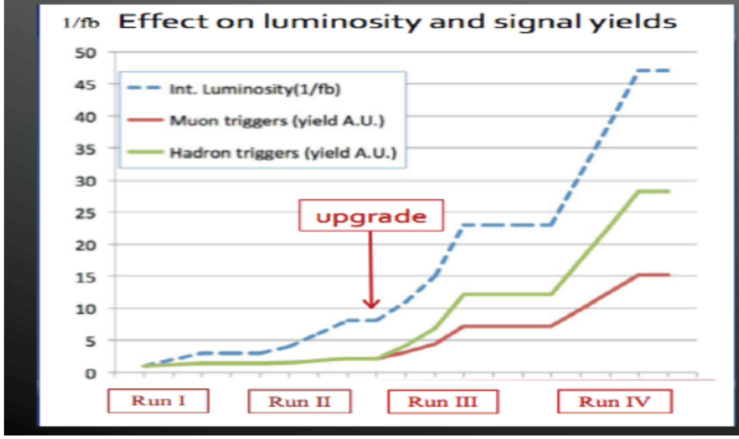
LHCb lumi
limited by the LHCb design
‘leveled’ continuously

- The main luminosity limitation comes from 1MHz L0 bandwidth imposed by the readout speed.
- **upgrade: (2020-)** instantaneous luminosity up to ~ 20×10^{32} $cm^{-2}s^{-1}$
  - Readout all detectors at 40 MHz. Do all triggering in the computer farm. Increase output bandwidth to 20-30 kHz to cope with the increased physics rate
  - Factor of ~2 improvement in hadronic trigger efficiencies. Muon trigger efficiencies stay the same.

LHCb present and future data samples



	RUN I		RUN II		LHCb Upgrade 50 fb^{-1} in less than 10 years	
bunch spacing	50 ns	LS1	25 ns	LS2		LS3
E_{CM}	7 TeV 8 TeV		13 TeV			
$\int\mathscr{L}$	3 fb^{-1}		> 5 fb^{-1}		> 5 fb^{-1} / year	
# of bunch crossings	up to 1262		~ 2622 (nominal)			
$\mathscr{L}$ (cm^{-2}s^{-1})	$4{\cdot}10^{32}$				> 10^{33}	



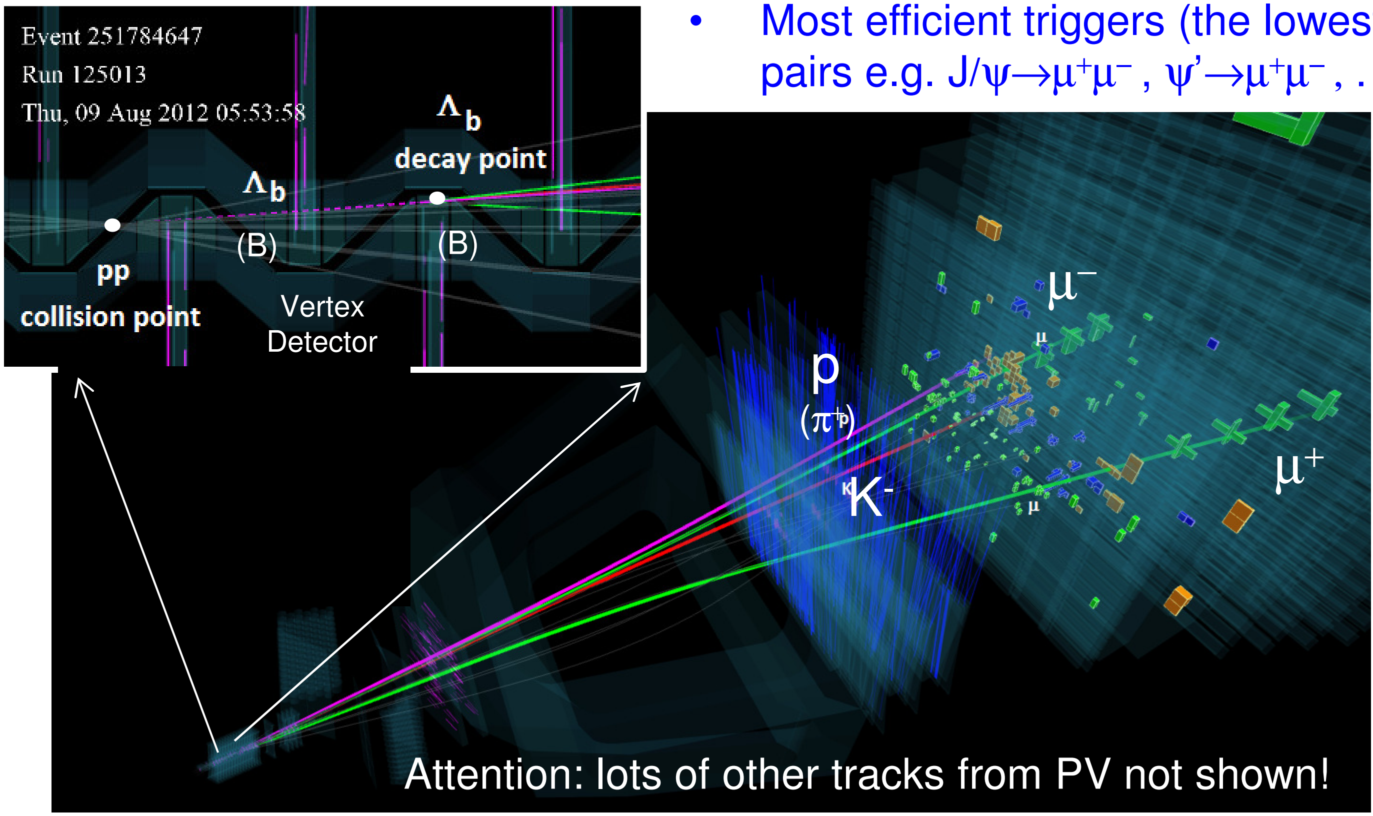
LHCb Integrated luminosities profile:

- RUN I: ~3 fb^{-1}
- RUN II: ≥ 5 fb^{-1}
- Upgrade: ≥ 50 fb^{-1}

- Increase in data statistics by a factor of:
  - ~ 3 by 2018
  - ~10 by 2026 (with a new detector)
  - ~17 by 2030

Triggering in LHCb

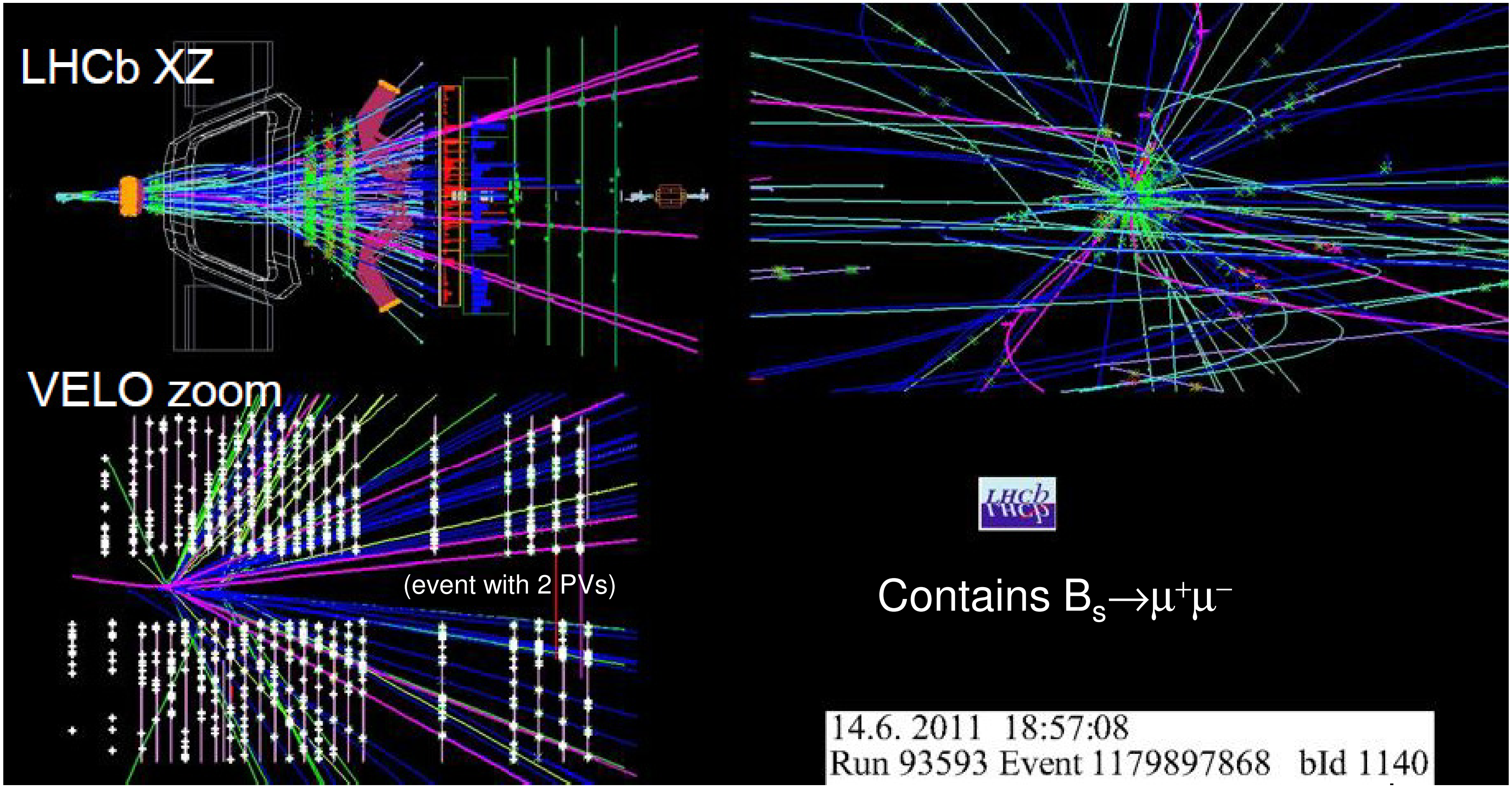
- Collision rate at LHC is up to 40 MHz, our trigger rate to storage was 5 kHz in Run I (20 kHz in Run II): live or die by trigger performance
- Tons of particles coming out of PV i.e. primary pp interaction point (mostly π, some K,p, very little μ)
- Most of our triggers rely on long visible lifetime of the lightest b- (and c-) hadrons: weak decays, lifetime prolonged by significant forward momentum
- Reconstruction of b or c decay vertex, detached from PV, also important for suppression of backgrounds in offline analysis (eliminate combinatorics from PV)
- Most efficient triggers (the lowest p_T thresholds) on dimuon pairs e.g. $J/\psi \to \mu^+\mu^-$, $\psi' \to \mu^+\mu^-$, …



Attention: lots of other tracks from PV not shown!

- We do trigger on purely hadronic detached vertices, but with lower efficiency (higher p_T thresholds) – unique feature at LHC!
- We have $J/\psi \to \mu^+\mu^-$ and $\Upsilon \to \mu^+\mu^-$ triggers with no detached vertex requirement; we can do promptly produced channels with them

Rare but typical LHCb event



Contains $B_s \rightarrow \mu^+\mu^-$

Efficiencies and backgrounds in LHCb

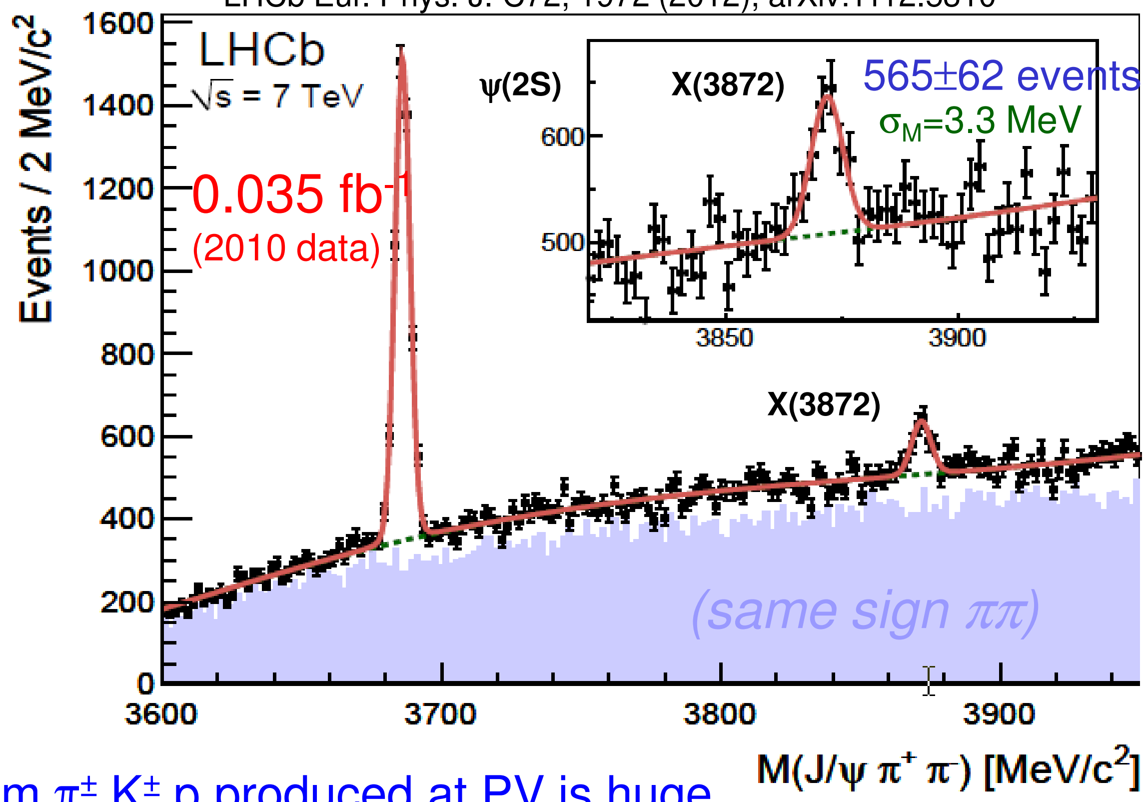
- Assuming the final state is triggered on!
- The detector works the best for all-charged final states ($\pi^{\pm}$,$K^{\pm}$,p,$\overline{p}$,$\mu^{\pm}$):
  - absolute reconstruction efficiency per track lower than at e^+e^- B-factories; lose efficiency faster when increasing final state multiplicity
  - channels with dimuons cleaner than without them
  - channels with kaons (to lesser extent with protons) cleaner than without them
- Efficiency penalty for $K^0_s \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$:
  - forward boost is not helping in detecting them; they live too long:
  - once they decay beyond the vertex detector, momentum resolution is poor, combinatorics larger
  - we reconstruct only a fraction of them, $K^0_s/K^{\pm}$ penalty is ~ 1/10 (much smaller penalty at e^+e^- B-factories)
  - can't trigger on them
- Efficiency & background penalty for γ, π^0, η:
  - we do have electromagnetic calorimeter, but its granularity is very coarse for busy forward direction at a hadronic collider, energy resolution not great (cheap technology, lots of radiation length in front of it)
  - efficiency drops quickly with energy (difficult to do π^0 from high multiplicity decay)
  - difficult to detect more than one
  - $\pi^0/\pi^{\pm}$ efficiency penalty ~ 1/10 or more
  - backgrounds are high and increase with decreasing energy
- No K^0_L, n:
  - we do have a very crude hadron calorimeter, but used only in low level trigger, no hadronic clusters in offline
  - perhaps could do them as a "missing particle", reconstruction ambiguities and large backgrounds
- e not as useful as μ (lose them to bremsstrahlung in the tracker)

Data mining

- Offline analysis includes “stripping”:
  - large reduction in data volume before accessible for physics analysis.
  - essentially a software trigger run in offline:
    - however, unlike online trigger it can be redone.
    - occasional restriping with refined offline software and possibly new stripping criteria
  - inclusive “stripping lines” $J/\psi\to\mu^+\mu^-$, $\psi'\to\mu^+\mu^-$, $\Upsilon^{(n)}\to\mu^+\mu^-$
    - when J/ψ, ψ' are detached then much lower p_T cut-offs (better efficiency)
    - all event info (all particles) in the event accessible in offline analysis (“full DST”)
    - we can easily mine $\mu^+\mu^-$ + hadrons final states
  - exclusive “stripping lines” for everything else:
    - only selected final state particles are accessible in offline analysis (“micro DST”)
    - pretty tight “bandwidth” limitations per channel: have to decide on most important cuts based on simulations and small test samples (for bkgs)
    - to select a new channel, must write a new stripping line, test it, get it approved by Working Group, wait for next stripping campaign (often many months)

Prompt signals

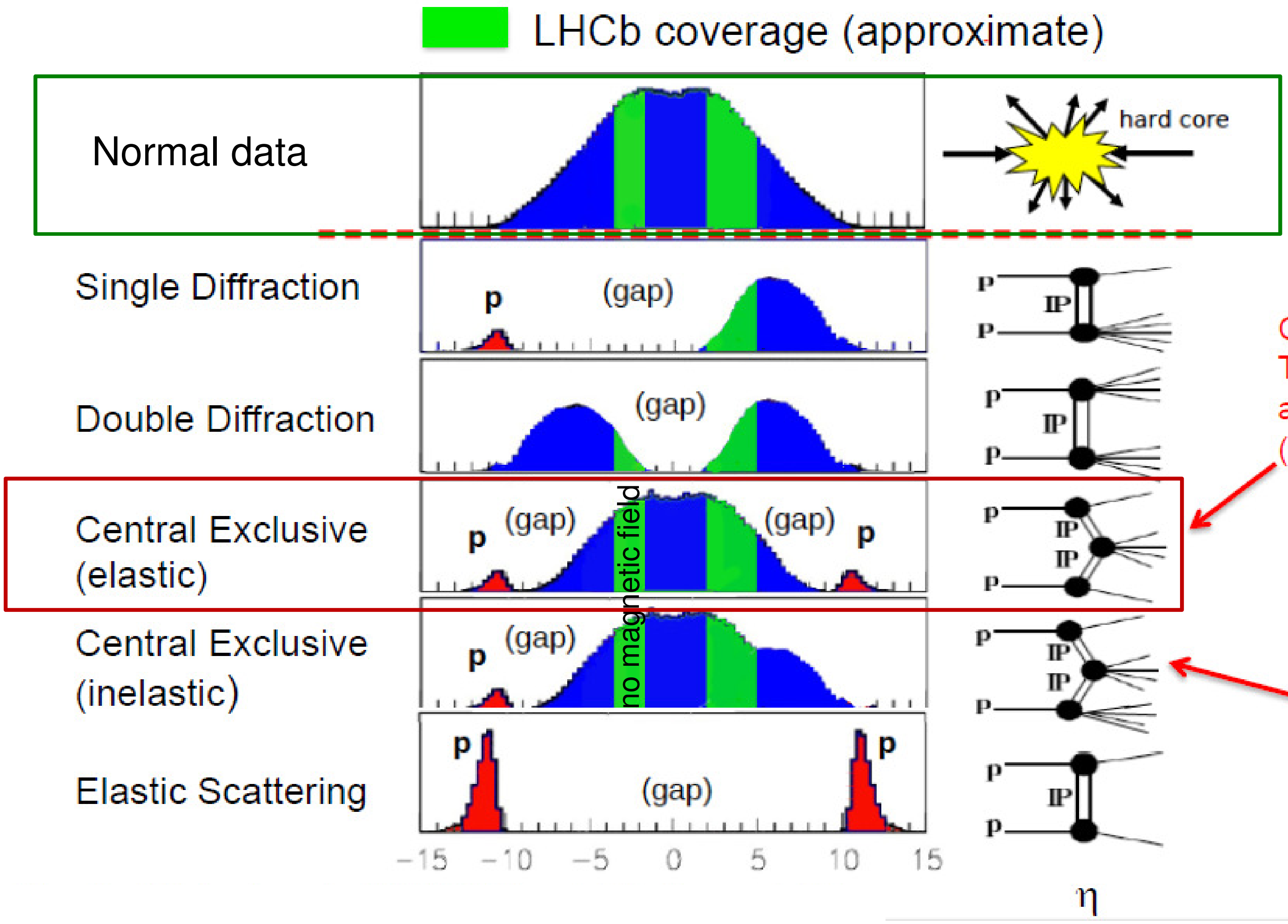
LHCb Eur. Phys. J. C72, 1972 (2012), arXiv:1112.5310



- Prompt signal are hard at LHC:
  - we only trigger on prompt $J/\psi\to\mu^+\mu^-$,$\psi'\to\mu^+\mu$,$\Upsilon\to\mu^+\mu^-$,$\Upsilon'\to\mu^+\mu^-$,$\Upsilon''\to\mu^+\mu^-$
- Combinatorial background from $\pi^\pm$,$K^\pm$,p produced at PV is huge
  - the only exotic candidate we have been able to see in prompt production so far is X(3872) $\to\pi^+\pi^-J/\psi$
  - backgrounds are much higher for $\pi^+\pi^-\Upsilon$; even $\Upsilon'\to\pi^+\pi^-\Upsilon$ is barely doable (Υs are heavier → softer transition pions → higher backgrounds)
  - we have tried and failed to see any Z_b^+ states
- D0 has recently claimed observation of prompt production of X(4140) $\to\phi J/\psi$ at Tevatron. This is very doable in LHCb.

Central Exclusive Production

- Various types of pp collisions at LHC:



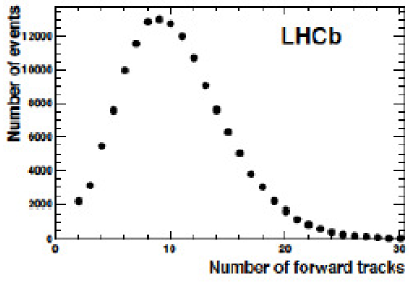
CEP events:
Trigger on and reconstruct a handful of particles (muons, hadrons, photons..)

CEP backgrounds:
reject events with additional particles, usually very forward

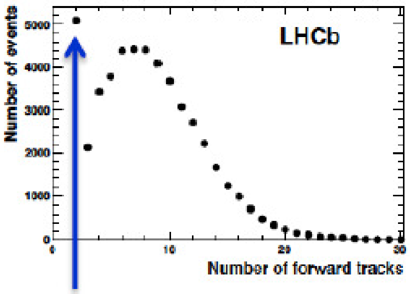
CEP triggers

Di-μ triggered events

Backward tracks>0

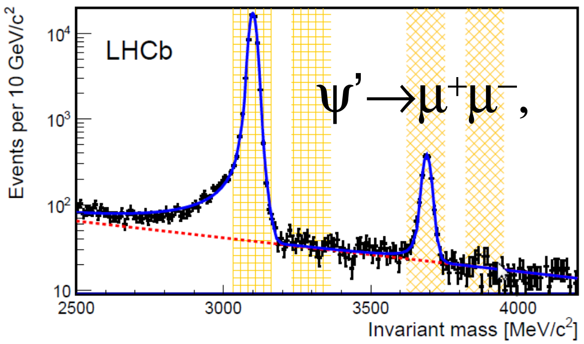


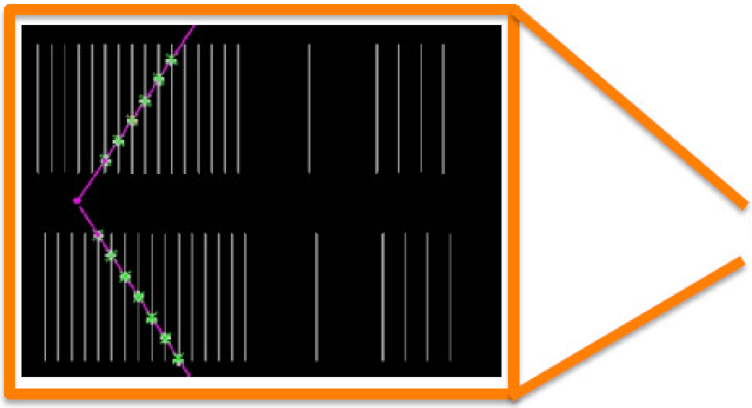
Backward tracks=0



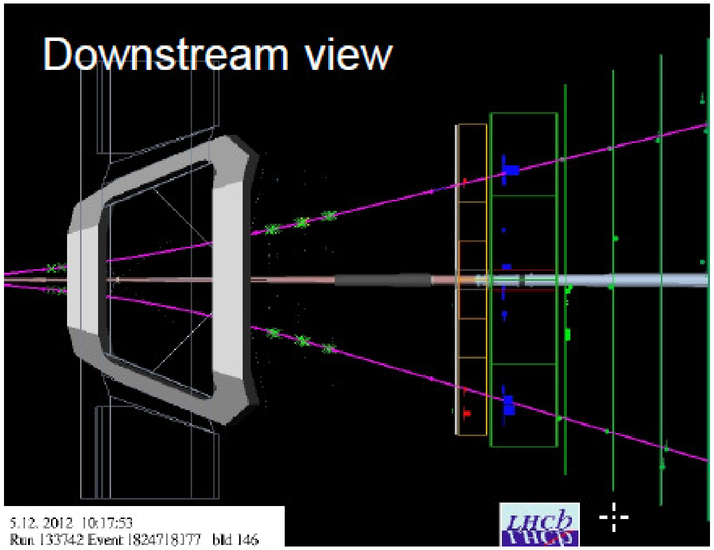
CEP candidates

$J/\psi \to \mu^+\mu^-$





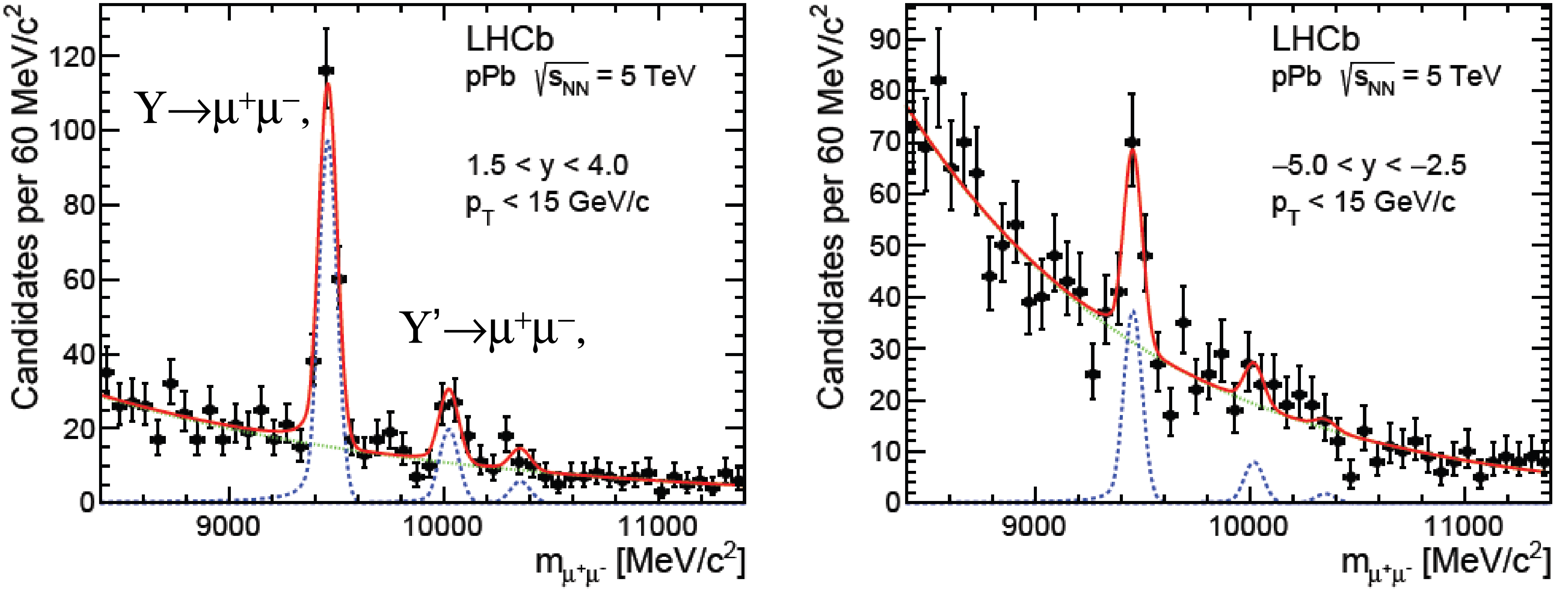
VELO RZ view



- Special low-multiplicity no-backwards-tracks dimuon triggers were deployed for part of Run I
  - Can do exclusive $\pi^+\pi^-J/\psi$, look e.g. for X(3872)
- Later also extended to dihadron lines ($\chi_{c0} \to K^+K^-,\pi^+\pi^-$)
  - Plan to study charmonia decays to 2-4 body final states
- More opportunities in Run II (but not after the upgrade; too many pp interactions per crossing)

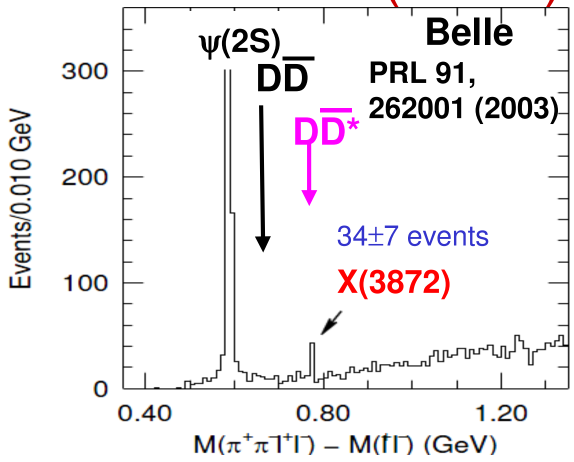
Heavy ions in LHCb

- In early 2013 LHCb collected 1.6 nb^{-1} of pPb and Pbp data ($s_{NN}^{1/2}$ = 5 TeV)



- Plan to take peripheral Pb+Pb collision data (multiplicity too high in head-on)
- Not clear if have any potential for exotics?

X(3872) – discovered in 2003



Belle
PRL 91, 262001 (2003)

$B \to X(3872)K$, $X(3872) \to J/\psi\rho^0$, $\rho^0 \to \pi^+\pi^-$, $J/\psi \to l^+l^-$

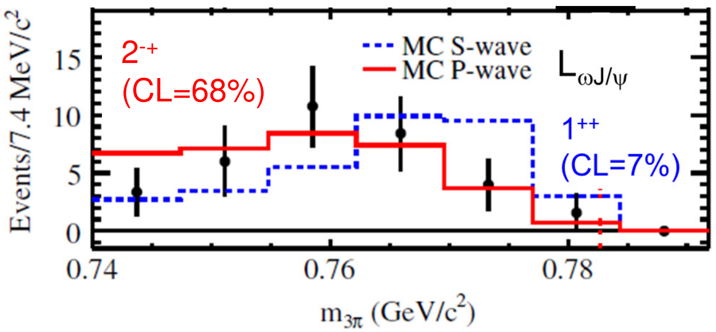
(isospin violating decays)

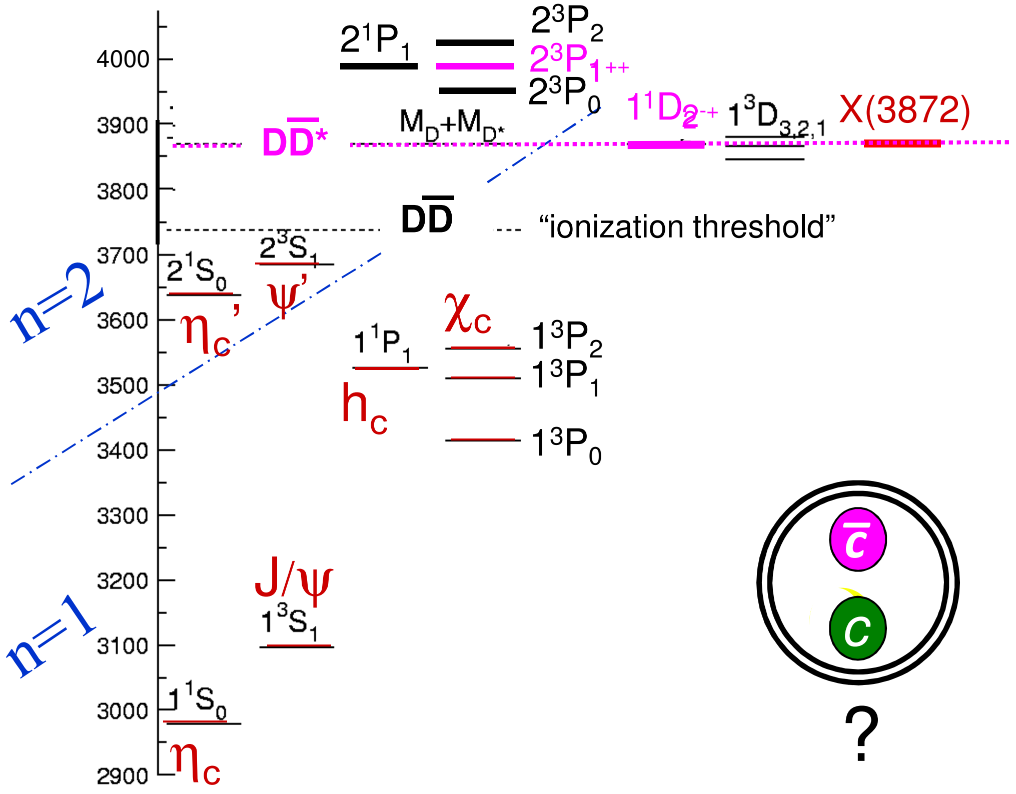
$\Gamma_{X(3872)} < 1.2$ MeV

very narrow

$B \to X(3872)K$, $X(3872) \to J/\psi\omega$, $\omega \to \pi^0\pi^+\pi^-$, $J/\psi \to l^+l^-$

BaBar
PR D82, 011101 (2010)





"ionization threshold" for states which cannot decay to $D\overline{D}$: 1^{++},2^{-+}

$$M_{X(3872)} - [M_{D^0} + M_{D^{*0}}] = -0.11 \pm 0.19 \text{ MeV}$$

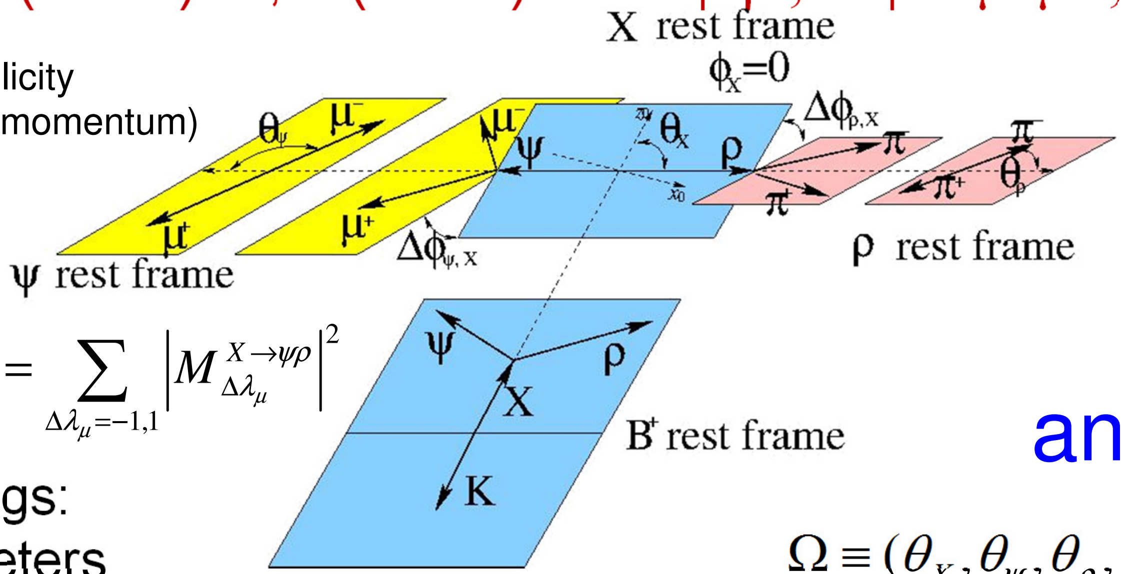
Mass indistinguishable from $D^0\overline{D}^{*0}$ thresholds

?

BaBar data preferred $J^P=2^{-+}$ (without ruling out 1^{++}) from the shape of $m_{3\pi}$ distribution → $\eta(1^1D_2)$ $c\overline{c}$ state?

Helicity amplitudes for $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\,\rho$, $J/\psi \to \mu^+\mu^-$, $\rho \to \pi^+\pi^-$

λ – particle helicity
(spin projection onto its momentum)



$$\left|M(\Omega \mid J_X, A^{J_X}_{\lambda_\psi,\lambda_\rho})\right|^2 = \sum_{\Delta\lambda_\mu=-1,1} \left|M^{X\to\psi\rho}_{\Delta\lambda_\mu}\right|^2$$

↑

Helicity couplings:
nuisance parameters

5D analysis

$$\Omega \equiv (\theta_X, \theta_\psi, \theta_\rho, \Delta\phi_{\psi,X}, \Delta\phi_{\rho,X})$$

$$M^{X\to\psi\rho}_{\Delta\lambda_\mu} = \sum_{\lambda_\psi=-1,0,1} \sum_{\lambda_\rho=-1,0,1} A^{J_X}_{\lambda_\psi,\lambda_\rho} D^{J_X}_{0,\lambda_\psi-\lambda_\rho}(0,\theta_X,0)^* D^1_{\lambda_\psi,\Delta\lambda_\mu}(\Delta\phi_{\psi,X},\theta_\psi,0)^* D^1_{\lambda_\rho,0}(\Delta\phi_{\rho,X},\theta_\rho,0)^*$$

$$A^{J_X}_{\lambda_\psi,\lambda_\rho} = \sum_L \sum_S B^{J_X}_{L,S} \left(\begin{array}{cc|c} J_\psi & J_\rho & S \\ \lambda_\psi & -\lambda_\rho & \lambda_\psi-\lambda_\rho \end{array}\right) \left(\begin{array}{cc|c} L & S & J_X \\ 0 & \lambda_\psi-\lambda_\rho & \lambda_\psi-\lambda_\rho \end{array}\right)$$

Clebsch-Gordan
coefficients

$|J_\psi - J_\rho| \le S \le J_\psi + J_\rho$

$S = 0,1,2$

$|J_X - S| \le L \le J_X + S$

$P_X = P_\psi P_\rho (-1)^L = (-1)^L$

(P-conservation
since strong decay)

Number of B_{LS} coupling equals number of independent $A_{\lambda\psi,\lambda\rho}$ couplings (1-5 depending on J_X) – no gain, unless high L values neglected

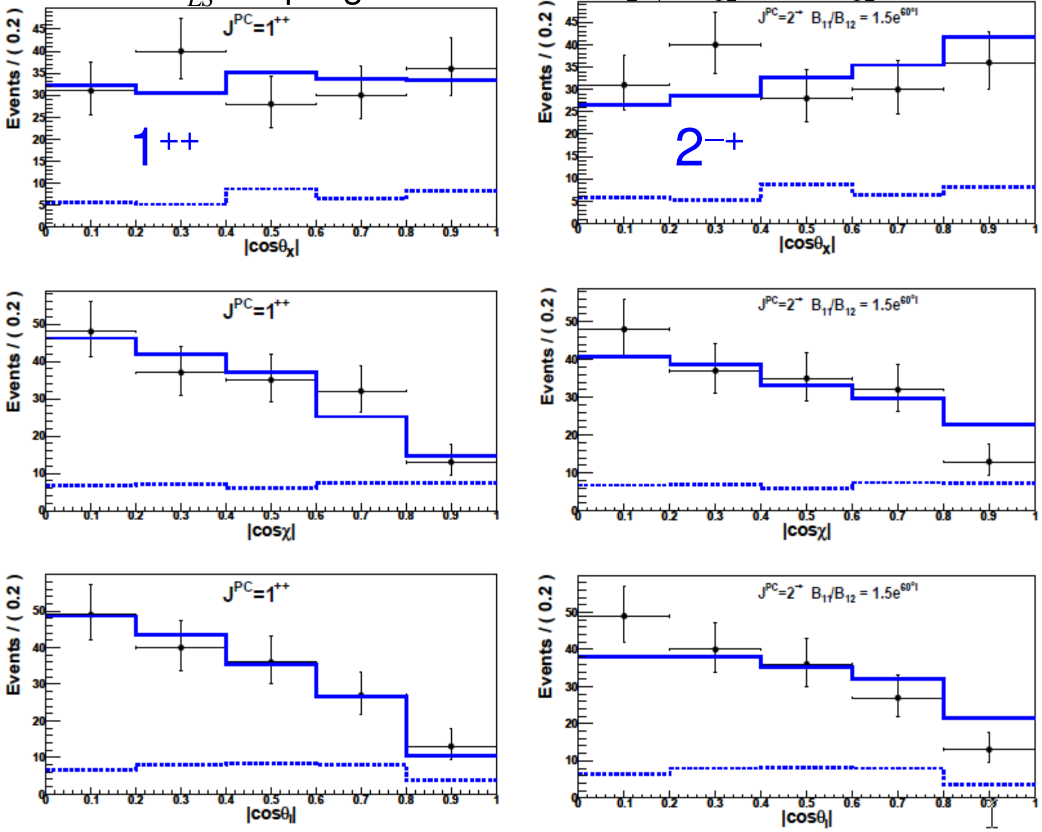
Determination of J^{PC} for X(3872)

Belle 711 fb^{-1}
173±16 events
PRD84(2011)052004

3 x 1D χ^2 analysis
$(L=L_{min})$

1^{++}: no B_{LS} couplings to fit

2^{-+}: $\alpha_{2-+}=B_{12}/(B_{11}+B_{12})=(0.64,0.27)$



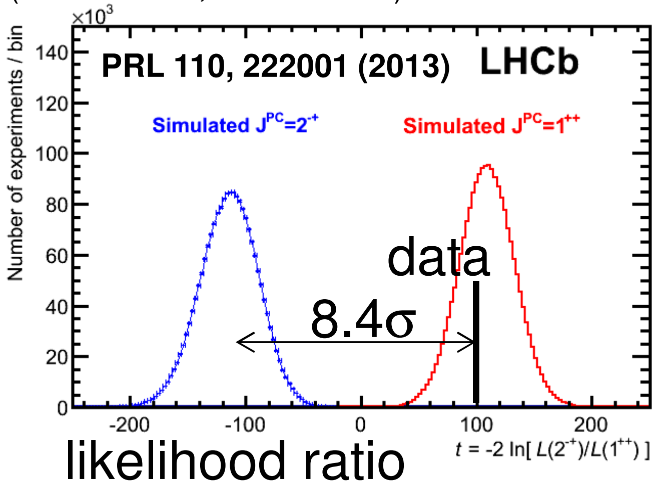
Could not distinguish between 1^{++} and 2^{-+}

LHCb 1 fb^{-1} (2011 data)
313±26 events

$\sqrt{313/173}=1.3$ small gain is statistical errors

5D unbinned likelihood ratio analysis

$\alpha_{2-+}=(0.671\pm0.046,\ 0.280\pm0.046)$

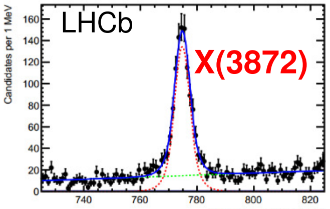


likelihood ratio

Very clear separation between 1^{++} and 2^{-+}
The data choose 1^{++}

- **It is important to analyze data in all sensitive dimensions simultaneously.** Angular correlations by far more powerful than 1D projections.

2015 update to X(3872) J^{PC} determination



LHCb 3 fb^{-1} (2011+2012 data)

1011±38 events

PRD92, 011102 (2015)

(all L values allowed)

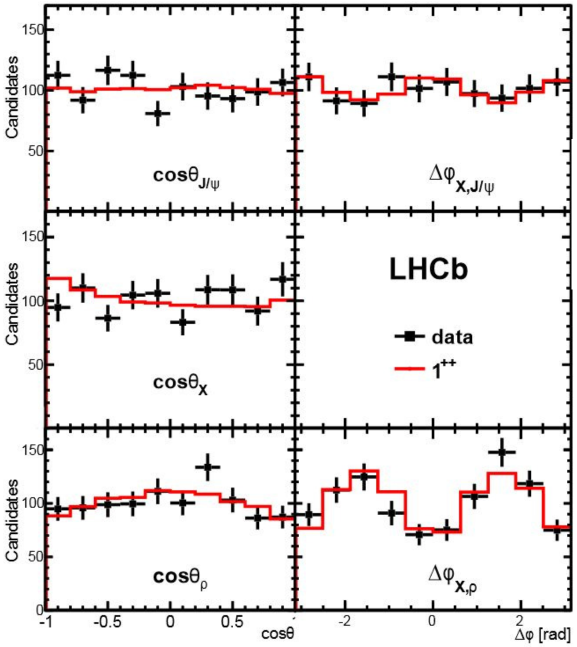
J^{PC}	B_{LS} all L	minimal L
0^{-+}	B_{11}	B_{11}
0^{++}	B_{00}, B_{22}	B_{00}
1^{-+}	$B_{10}, B_{11}, B_{12}, B_{32}$	B_{10}, B_{11}, B_{12}
1^{++}	B_{01}, B_{21}, B_{22}	B_{01}
2^{-+}	$B_{11}, B_{12}, B_{31}, B_{32}$	B_{11}, B_{12}
2^{++}	$B_{02}, B_{20}, B_{21}, B_{22}, B_{42}$	B_{02}
3^{-+}	$B_{12}, B_{30}, B_{31}, B_{32}, B_{52}$	B_{12}
3^{++}	$B_{21}, B_{22}, B_{41}, B_{42}$	B_{21}, B_{22}
4^{-+}	$B_{31}, B_{32}, B_{51}, B_{52}$	B_{31}, B_{32}
4^{++}	$B_{22}, B_{40}, B_{41}, B_{42}, B_{62}$	B_{22}

LHCb 2015

Many more amplitudes to fit

CDF 2007

LHCb 2013

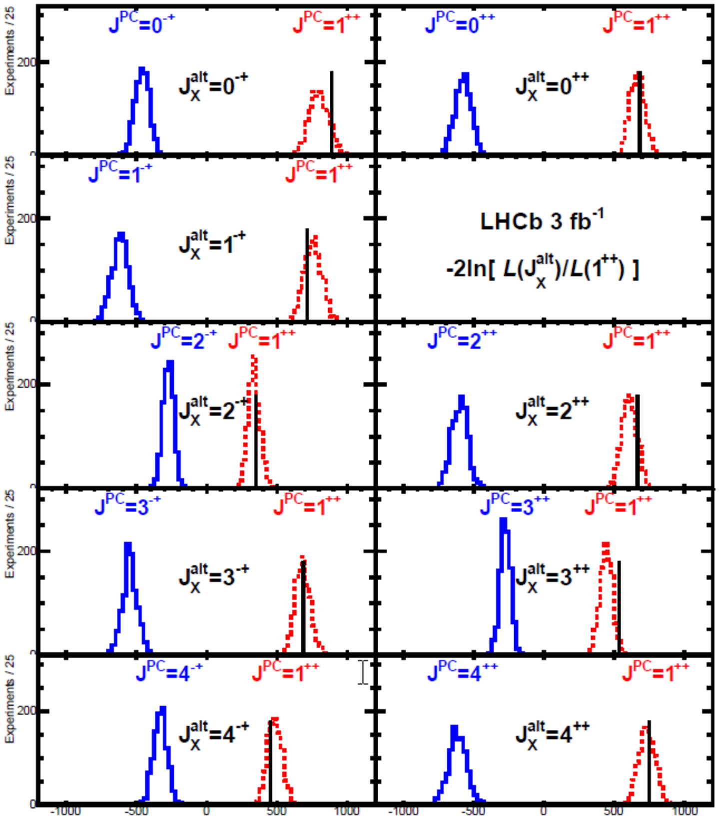


J^{PC} = 1^{++} at 16σ

$$f_D = \frac{\int |\mathcal{M}(\Omega)_D|^2 \, d\Omega}{\int |\mathcal{M}(\Omega)_{S+D}|^2 \, d\Omega}$$

<4% at 95% CL

Bin Gui
PhD
Syracuse
2014



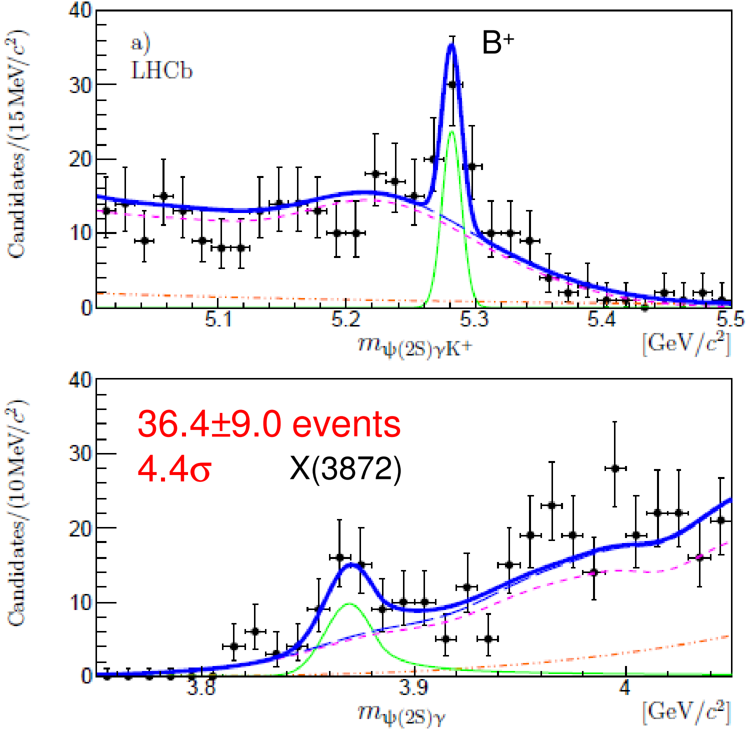
likelihood ratio

Radiative decays of X(3872) in LHCb

LHCb-PAPER-2014-008 arXiv:1404.0275 **Apr. 1, 2014**

Projections of 2D fit to $m_{\psi\gamma K+}$ vs $m_{\psi\gamma}$

$B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow \psi(2S)\gamma$

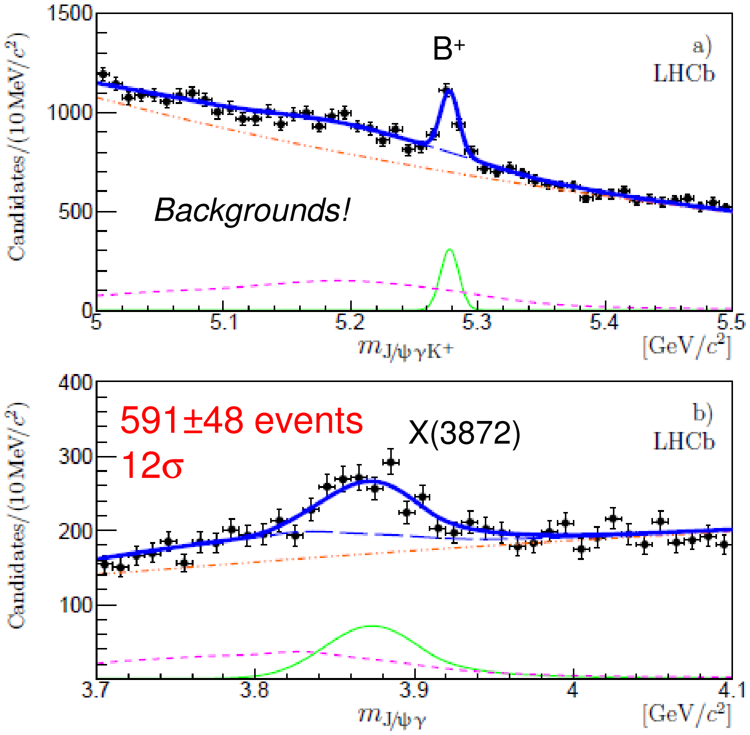

B+

36.4±9.0 events

4.4σ

X(3872)

$B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi\gamma$


B+

Backgrounds!

591±48 events

12σ

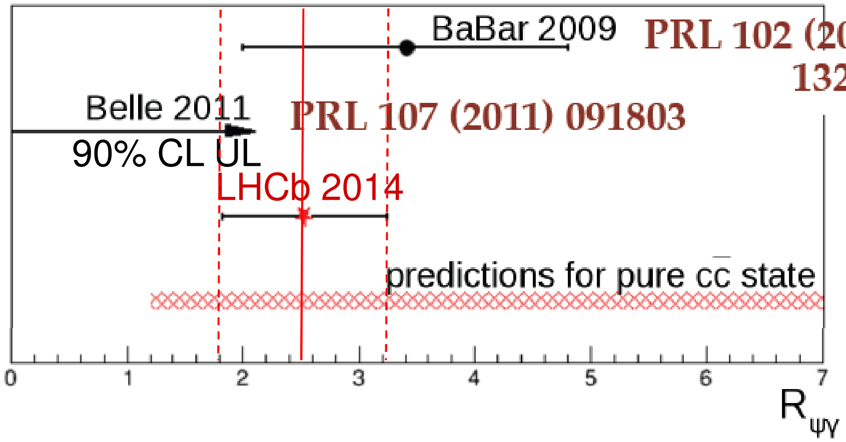
X(3872)

The most significant evidence for $X(3872) \rightarrow \psi(2S)\gamma$ to date!

efficiency($\psi(2S)\gamma$) / efficiency($J/\psi\gamma$) ~ 0.2

Detecting soft photons at hadronic collider is hard.

Radiative decays of X(3872) in LHCb



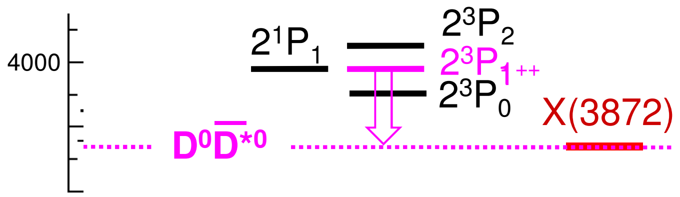
	Signal events: $B^+\to X(3872)K^+$, $X(3872)\to\psi(2S)\gamma$, $J/\psi\gamma$		Signal significance: $\psi(2S)\gamma$, $J/\psi\gamma$
PRL 102 (2009) 132001	25.4 ± 7.3,	23.0 ± 6.4	3.6σ, 3.5σ
PRL 107 (2011) 091803	$5.0^{+11.9}_{-11.0}$,	$30.0^{+8.2}_{-7.4}$	0.4σ, 4.9σ
LHCb	36.4 ± 9.0,	591.0 ± 48.0	4.4σ, 12σ

$BR(X(3872)\to\psi(2S)\gamma)/BR(X(3872)\to J/\psi\gamma)$

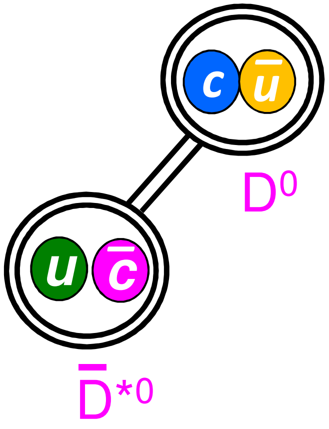
$= 2.48\pm0.64\pm0.29$

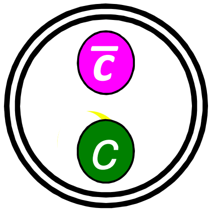
- The LHCb results are consistent with, but more precise than, the BaBar and Belle results:
  - LHCb can be competitive on simple final states with neutrals in spite of large backgrounds
- Consistent with the expectations for $\chi_{c1}(2^3P_1)$ state

X(3872) interpretation



$M_{X(3872)} - [M_{D0}+M_{D^*0}]$
$= -0.11\pm0.19$ MeV





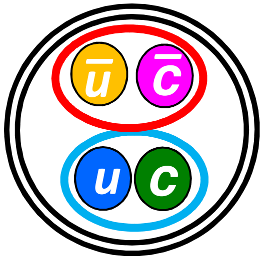
$\chi_c(2^3P_1)$ “attracted” by $D^0\bar{D}^{*0}$ threshold?

L=0

Meson-meson molecule?

essentially no binding energy?

mixture?



tightly bound tetraquark “attracted” by $D\bar{D}^*$ threshold ?

e.g. L. Maiani, F. Piccinini, A.D. Polosa, V. Riquer, PRD **89** (2014) 114010

$$[cu]_{S=1}\,[\bar{c}\bar{u}]_{S=0} + [cu]_{S=0}\,[\bar{c}\bar{u}]_{S=1}$$

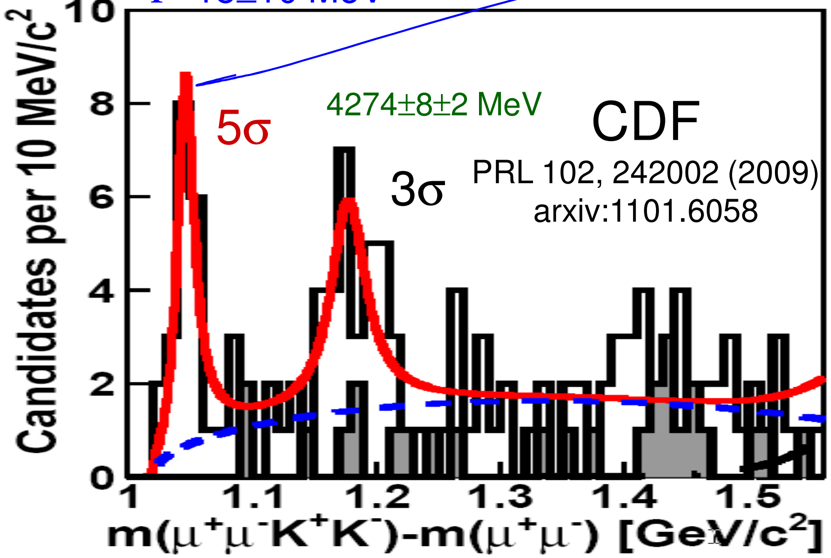
Future studies related to X(3872)

- We can have the best measurement of its mass, possibly the best limit on its width.
- Other modes with B→X(3872)+…, X(3872) $\rightarrow\pi^+\pi^- J/\psi$. Some may be worth amplitude analysis to see if contain exotic candidates decaying to X(3872).
- Other decay modes of X(3872) e.g. $\omega J/\psi$, $D\bar{D}^*$ (hard!)
- Production in CEP or heavy-ion data?

X(4140) in $B^+ \to J/\psi\phi K^+$

4143±3±1 MeV

Γ=15±10 MeV



5σ

4274±8±2 MeV

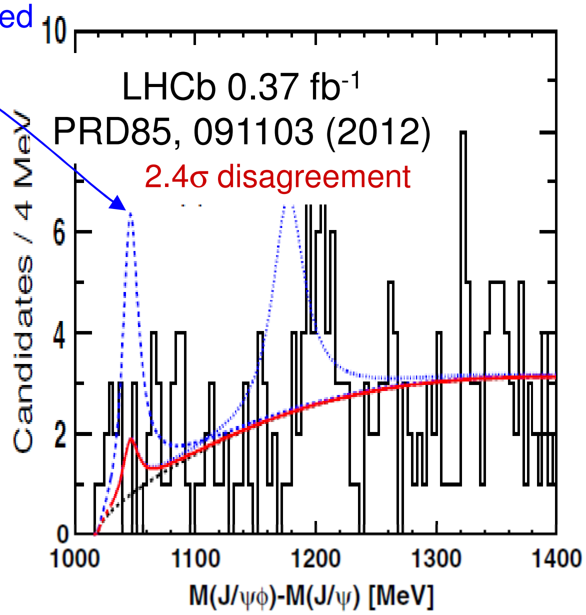
3σ

CDF

PRL 102, 242002 (2009)

arxiv:1101.6058

extrapolated



LHCb 0.37 fb^{-1}

PRD85, 091103 (2012)

2.4σ disagreement

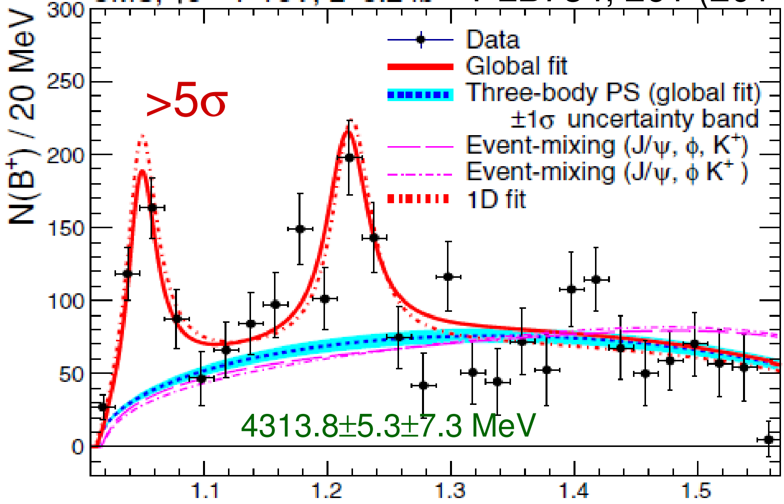
No evidence for the narrow X(4140) in early LHCb data (1/10th of our data)

4148.0±2.4±6.3 MeV

Γ=28±24 MeV

(background subtracted)

CMS, $\sqrt{s}$ = 7 TeV, L=5.2 fb^{-1} PLB734, 261 (2014)



>5σ

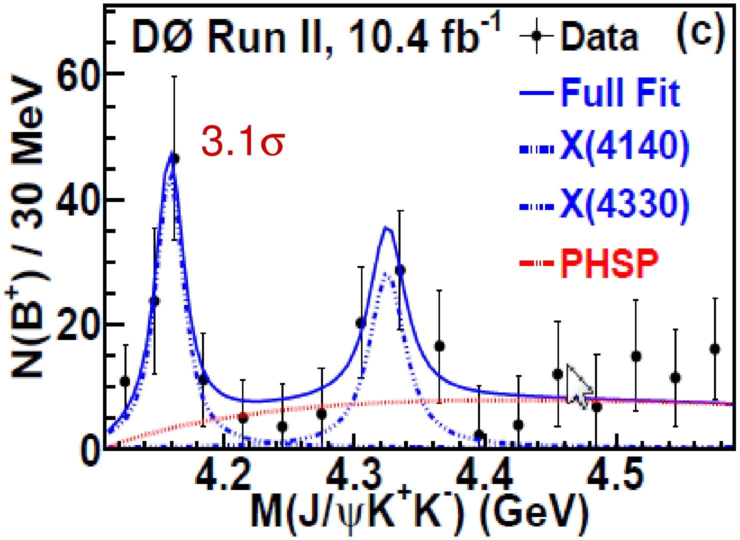
4313.8±5.3±7.3 MeV

3.5σ different from CDF!

4159.0±4.3±6.6 MeV

Γ=20±15 MeV

PRD89,012004(2014)

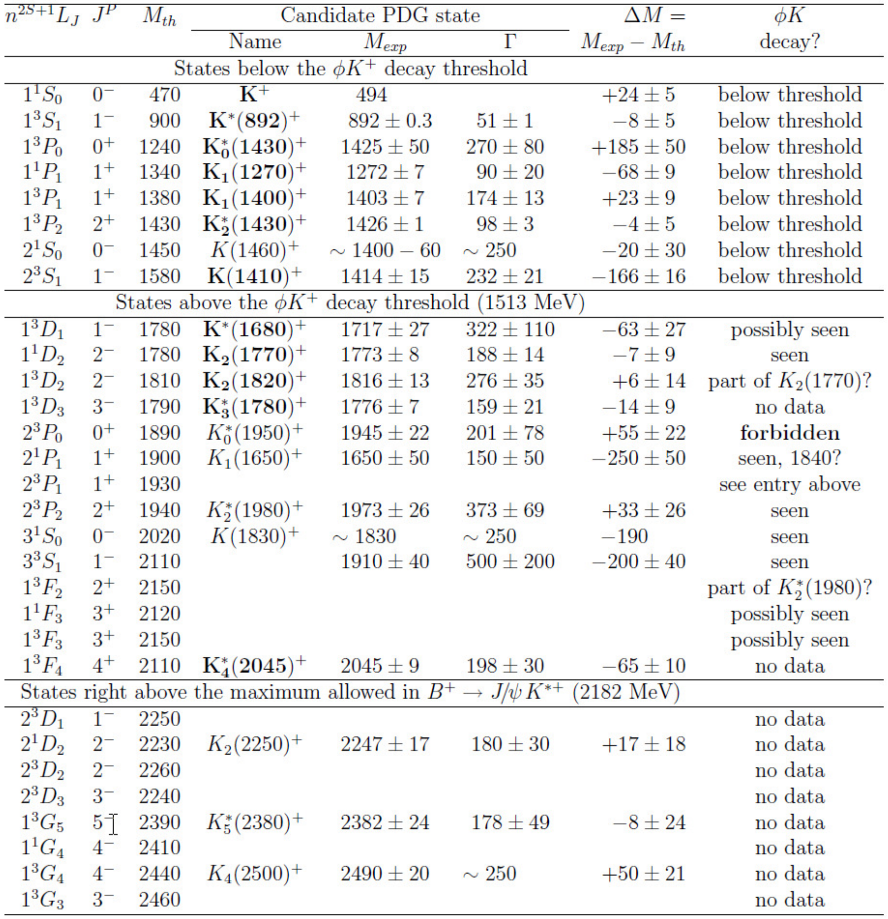


3.1σ

All these naïve analyses assume that non-X events conform to 3-body phase-space and do not study systematics of this assumption.

$B^+ \to J/\psi \phi K^+$

- 6D amplitude analysis of 4289±151 events 3 fb^{-1} in progress
- Difficulty: dealing with high mass region of K* resonances



$n^{2S+1}L_J$	J^P	M_{th}	Candidate PDG state			$\Delta M =$	ϕK
			Name	M_{exp}	Γ	$M_{exp} - M_{th}$	decay?
States below the ϕK^+ decay threshold							
1^1S_0	0^-	470	$\mathbf{K^+}$	494		$+24 \pm 5$	below threshold
1^3S_1	1^-	900	$\mathbf{K^*(892)^+}$	892 ± 0.3	51 ± 1	-8 ± 5	below threshold
1^3P_0	0^+	1240	$\mathbf{K_0^*(1430)^+}$	1425 ± 50	270 ± 80	$+185 \pm 50$	below threshold
1^1P_1	1^+	1340	$\mathbf{K_1(1270)^+}$	1272 ± 7	90 ± 20	-68 ± 9	below threshold
1^3P_1	1^+	1380	$\mathbf{K_1(1400)^+}$	1403 ± 7	174 ± 13	$+23 \pm 9$	below threshold
1^3P_2	2^+	1430	$\mathbf{K_2^*(1430)^+}$	1426 ± 1	98 ± 3	-4 ± 5	below threshold
2^1S_0	0^-	1450	$K(1460)^+$	$\sim 1400 - 60$	~ 250	-20 ± 30	below threshold
2^3S_1	1^-	1580	$\mathbf{K(1410)^+}$	1414 ± 15	232 ± 21	-166 ± 16	below threshold
States above the ϕK^+ decay threshold (1513 MeV)							
1^3D_1	1^-	1780	$\mathbf{K^*(1680)^+}$	1717 ± 27	322 ± 110	-63 ± 27	possibly seen
1^1D_2	2^-	1780	$\mathbf{K_2(1770)^+}$	1773 ± 8	188 ± 14	-7 ± 9	seen
1^3D_2	2^-	1810	$\mathbf{K_2(1820)^+}$	1816 ± 13	276 ± 35	$+6 \pm 14$	part of $K_2(1770)$?
1^3D_3	3^-	1790	$\mathbf{K_3^*(1780)^+}$	1776 ± 7	159 ± 21	-14 ± 9	no data
2^3P_0	0^+	1890	$K_0^*(1950)^+$	1945 ± 22	201 ± 78	$+55 \pm 22$	**forbidden**
2^1P_1	1^+	1900	$K_1(1650)^+$	1650 ± 50	150 ± 50	-250 ± 50	seen, 1840?
2^3P_1	1^+	1930					see entry above
2^3P_2	2^+	1940	$K_2^*(1980)^+$	1973 ± 26	373 ± 69	$+33 \pm 26$	seen
3^1S_0	0^-	2020	$K(1830)^+$	~ 1830	~ 250	-190	seen
3^3S_1	1^-	2110		1910 ± 40	500 ± 200	-200 ± 40	seen
1^3F_2	2^+	2150					part of $K_2^*(1980)$?
1^1F_3	3^+	2120					possibly seen
1^3F_3	3^+	2150					possibly seen
1^3F_4	4^+	2110	$\mathbf{K_4^*(2045)^+}$	2045 ± 9	198 ± 30	-65 ± 10	no data
States right above the maximum allowed in $B^+ \to J/\psi K^{*+}$ (2182 MeV)							
2^3D_1	1^-	2250					no data
2^1D_2	2^-	2230	$K_2(2250)^+$	2247 ± 17	180 ± 30	$+17 \pm 18$	no data
2^3D_2	2^-	2260					no data
2^3D_3	3^-	2240					no data
1^3G_5	5^-	2390	$K_5^*(2380)^+$	2382 ± 24	178 ± 49	-8 ± 24	no data
1^1G_4	4^-	2410					no data
1^3G_4	4^-	2440	$K_4(2500)^+$	2490 ± 20	~ 250	$+50 \pm 21$	no data
1^3G_3	3^-	2460					no data

(bold font – well established PDG states)

Mass range visible in this analysis

Thomas Britton

Z(4430)$^+$ discovery and its importance

Phys.Rev.Lett. 100, 142001 (2008)

Observation of a resonance-like structure in the $\pi^{\pm}\psi'$ mass distribution in exclusive $B \to K\pi^{\pm}\psi'$ decays

Press Release

>Top >PressRelease >this page

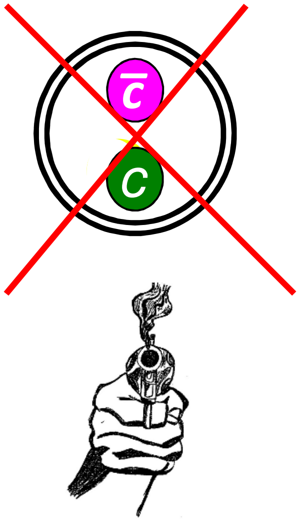
last update: 07/11/13

Press Release

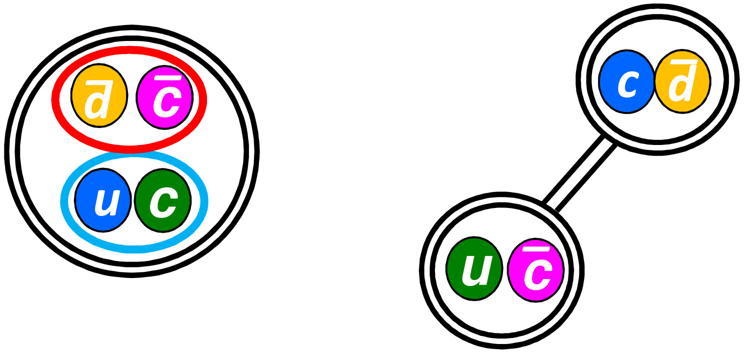
Belle Discovers a New Type of Meson

November 13, 2007
High Energy Accelerator Research Organization (KEK)

neutral



charged



$Z(4430)^-$ previous measurements

[ψ' ≡ ψ(2S)]

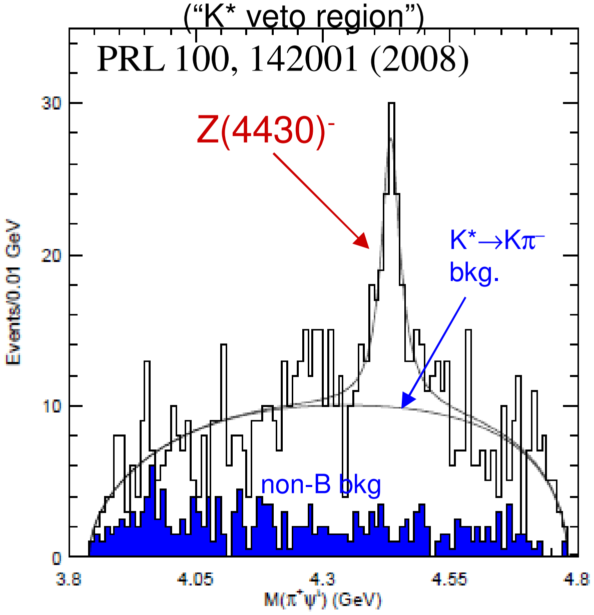
Z^- K^*

B→ψ'π⁻K

Belle 2008

1D M(ψ'π⁻) mass fit

("K* veto region")



$M(Z) = 4433 \pm 4 \pm 2$ MeV

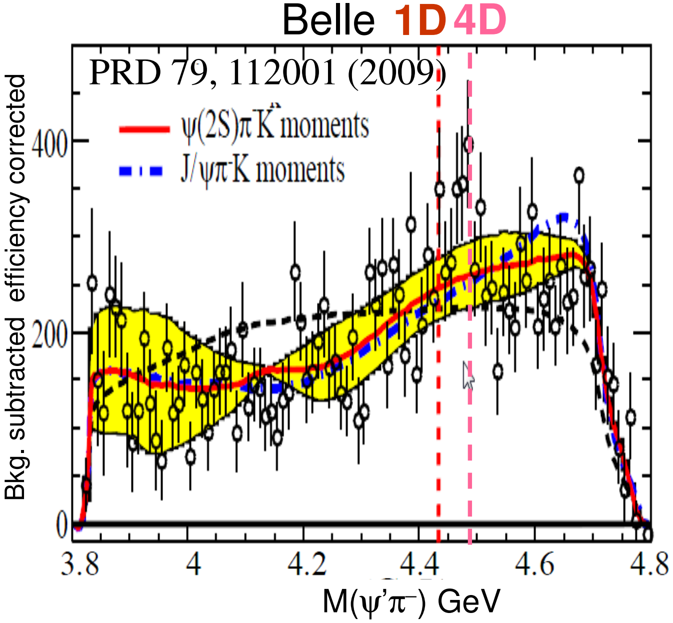
$\Gamma(Z) = 45^{+18}_{-13}{}^{+30}_{-13}$ MeV

significance 6.5σ

Ad hoc assumption about the K*→Kπ⁻ background shape.

BaBar 2009

Harmonic moments of K*s (2D) reflected to M(ψ'π⁻)



BaBar did not confirm $Z(4430)^-$ in B sample comparable to Belle.

Did not numerically contradict the Belle results.

Almost **model independent** approach to K*→Kπ⁻ backgrounds.

Belle 2013

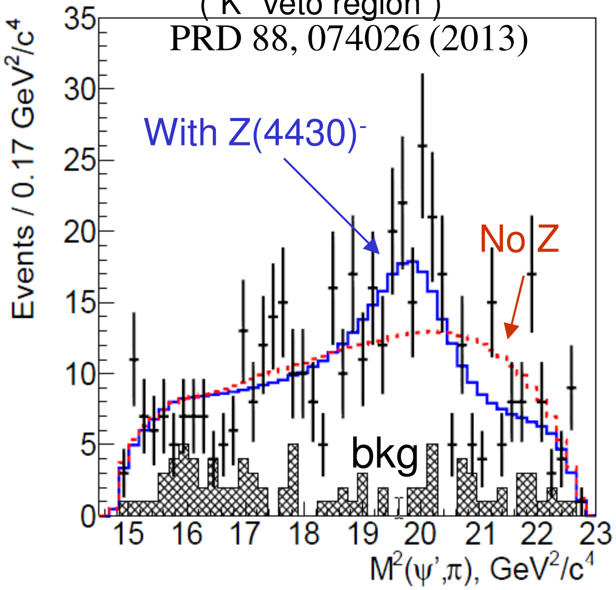
(2D amplitude fit in 2009)

4D amplitude fit

(subsample with $\psi' \to l^+l^-$)

$0.996\ \mathrm{GeV}/c^2 < M(K,\pi) < 1.332\ \mathrm{GeV}/c^2$

("K* veto region")



$M(Z) = 4485^{+22}_{-22}{}^{+28}_{-11}$ MeV

$\Gamma(Z) = 200^{+41}_{-46}{}^{+26}_{-35}$ MeV

6.4σ (5.6σ with sys.)

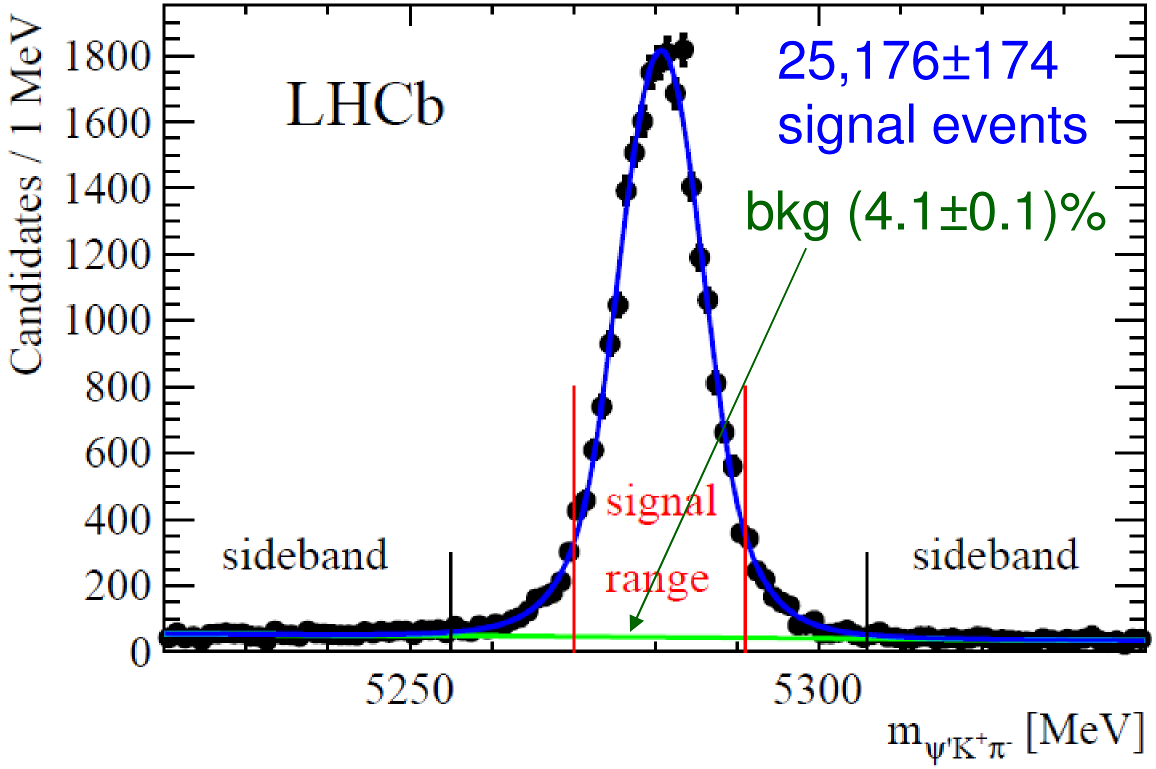
$J^P=1^+$ preferred by $>3.4\sigma$

Model dependent approach to K*→Kπ⁻ backgrounds. Higher statistical sensitivity.

$Z(4430)^+$ in LHCb

LHCb-PAPER-2014-014 **PRL 112, 222002 (2014)**

- $B^0 \to \psi' K^+ \pi^-$, $\psi' \to \mu^+ \mu^-$ (3 fb^{-1})



25,176±174 signal events

bkg (4.1±0.1)%

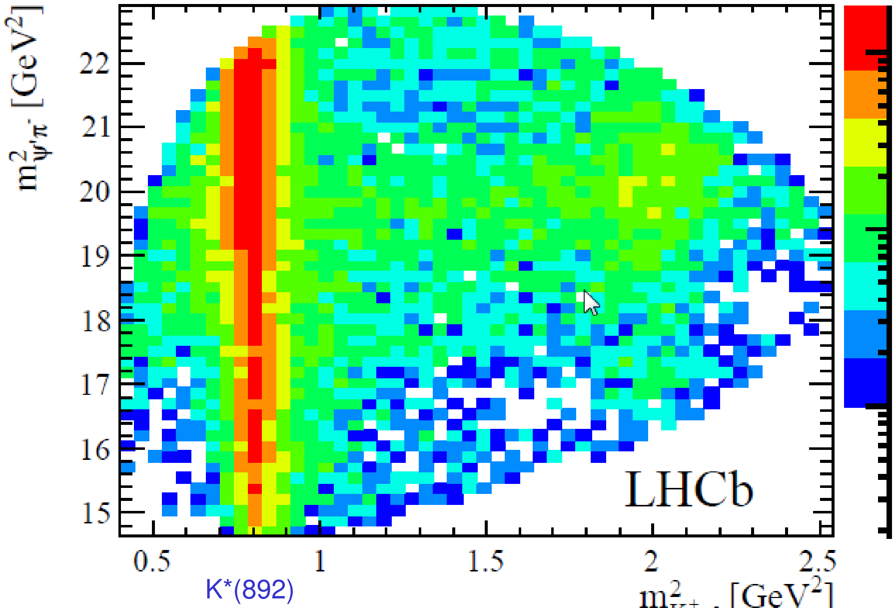
vs
Belle: 2,010±50
BaBar: 2,021±53

vs. bkg in Belle: 7.8%

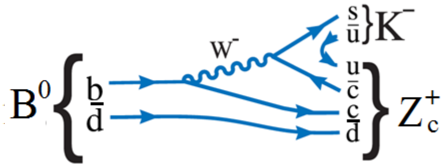
An order of magnitude larger signal statistics than in Belle or BaBar thanks to hadronic production of b-quarks at LHC.

Even smaller non-B background than at the e^+e^- experiments thanks to excellent performance of the LHCb detector (vertexing, PID)

$B^0 \to \psi'\pi^+K^-$



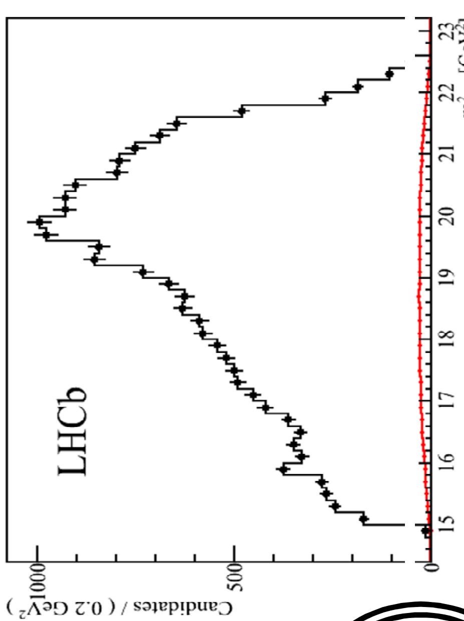
K*(892)
J=1



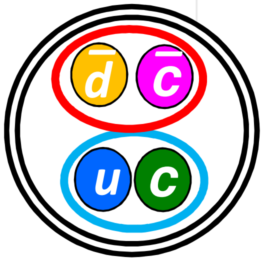
← $Z_c(4430)^+$ →

$\to J/\psi\pi^+$

?

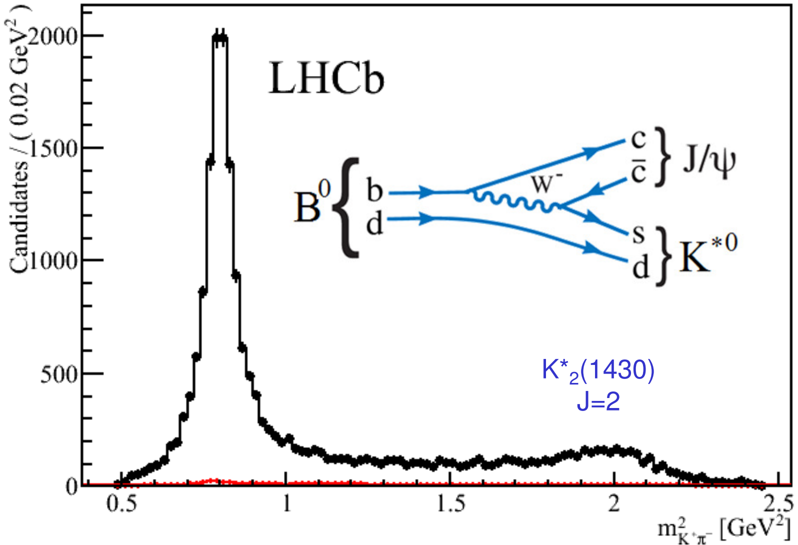


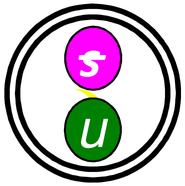
Tetraquark



Is it a reflection of interfering K^*'s $\to \pi^+K^-$?

Proper amplitude analysis necessary to check





Kaon excitations

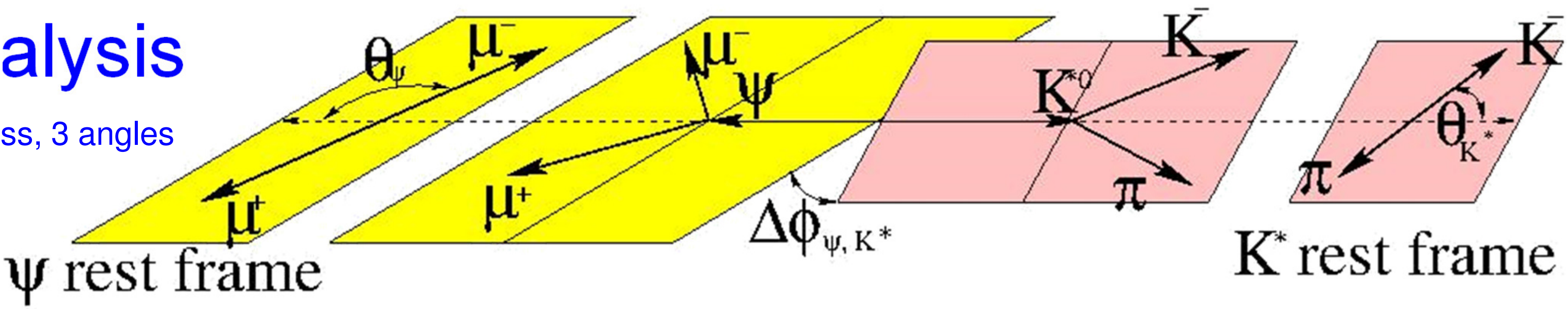
Amplitude Analysis of $B^0 \to \psi'\pi^+K^-$, $\psi' \to \mu^+\mu^-$

$$\left| M\left(\mathrm{m}_{K\pi}, \Omega \mid A_{\lambda_\psi}^{B\to\psi K_n^*}\right) \right|^2 = \sum_{\Delta\lambda_\mu=-1,1} \left| M_{\Delta\lambda_\mu}^{K^*} \right|^2$$

$$\Omega \equiv (\theta_{K^*}, \theta_\psi, \Delta\phi_{\psi,K^*})$$

4D analysis

1 mass, 3 angles



$$M_{\Delta\lambda_\mu}^{K^*} = \sum_n \sum_{\lambda_\psi=-1,0,1} A_{\lambda_\psi}^{B\to\psi K_n^*} D_{\lambda_\psi,0}^{J_{K^*}}(0,\theta_{K^*},0)^* R(m_{K\pi} \mid M_{K_n^*}, \Gamma_{K_n^*}) D_{\lambda_\psi,\Delta\lambda_\mu}^{1}(\Delta\phi_{\psi,K^*}, \theta_\psi, 0)^*$$

1-3 independent **complex** helicity couplings per K_n^* resonance

Breit-Wigner amplitude:

$$R(m \mid M_X, \Gamma_X) = \frac{B'_{L_B}(p,p_0,d)\left(\frac{p}{M_B}\right)^{L_B} B'_{L_X}(q,q_0,d)\left(\frac{q}{m}\right)^{L_X}}{M_X^2 - m^2 - iM_X\Gamma(m)} \qquad \Gamma(m) = \Gamma_X \left(\frac{q}{q_0}\right)^{2L_X+1} \frac{M_X}{m} B'_{L_X}(q,q_0,d)^2$$

Blatt-Weisskopf functions

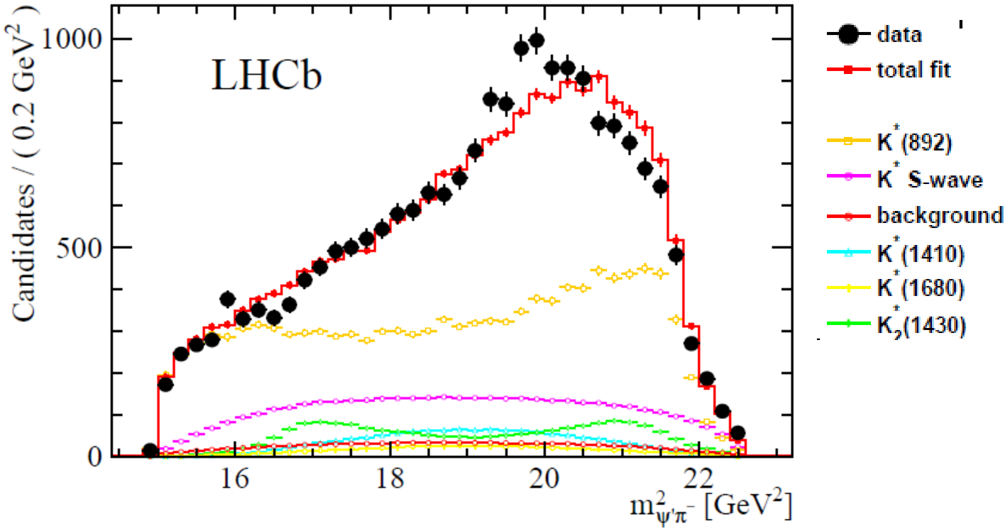
$$n = 0^+ : K_0^*(800), K_0^*(1430), NR; \quad 1^- : K^*(892), K^*(1410), K^*(1680) \quad 2^+ : K_2^*(1430) \quad (3^- : K_3^*(1780))$$

\# of fit parameters: 32

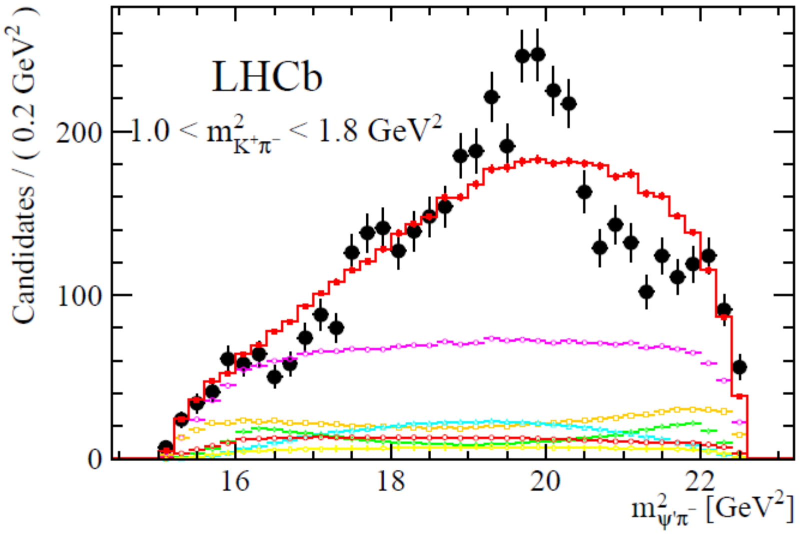
Amplitude fits without Z(4430)$^-$

of fit parameters: 32

("all data")



("K* veto region")



- The χ^2 p-value < 2×10^{-6}

⇩

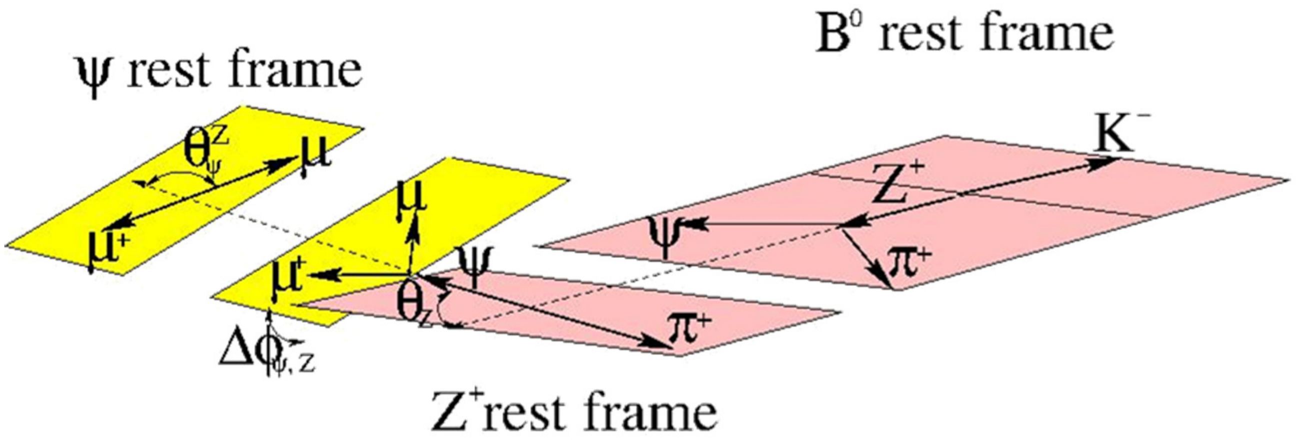
- The data cannot be adequately described with the J ≤ 3 K* contributions alone

Amplitude Analysis of $B^0 \to \psi'\pi^+K^-$, $\psi' \to \mu^+\mu^-$

$$\left| M(m_{K\pi},\Omega \,|\, M_Z,\Gamma_Z,J_Z,A^{Z\to\psi\pi}_{\lambda_\psi},\, A^{B\to\psi K^*_n}_{\lambda_\psi}) \right|^2 = \sum_{\Delta\lambda_\mu=-1,1} \left| M^{K^*}_{\Delta\lambda_\mu} + e^{i\Delta\lambda_\mu \alpha_\mu} M^{Z}_{\Delta\lambda_\mu} \right|^2$$

4D analysis

1 mass, 3 angles
all derivable from the K^* variables



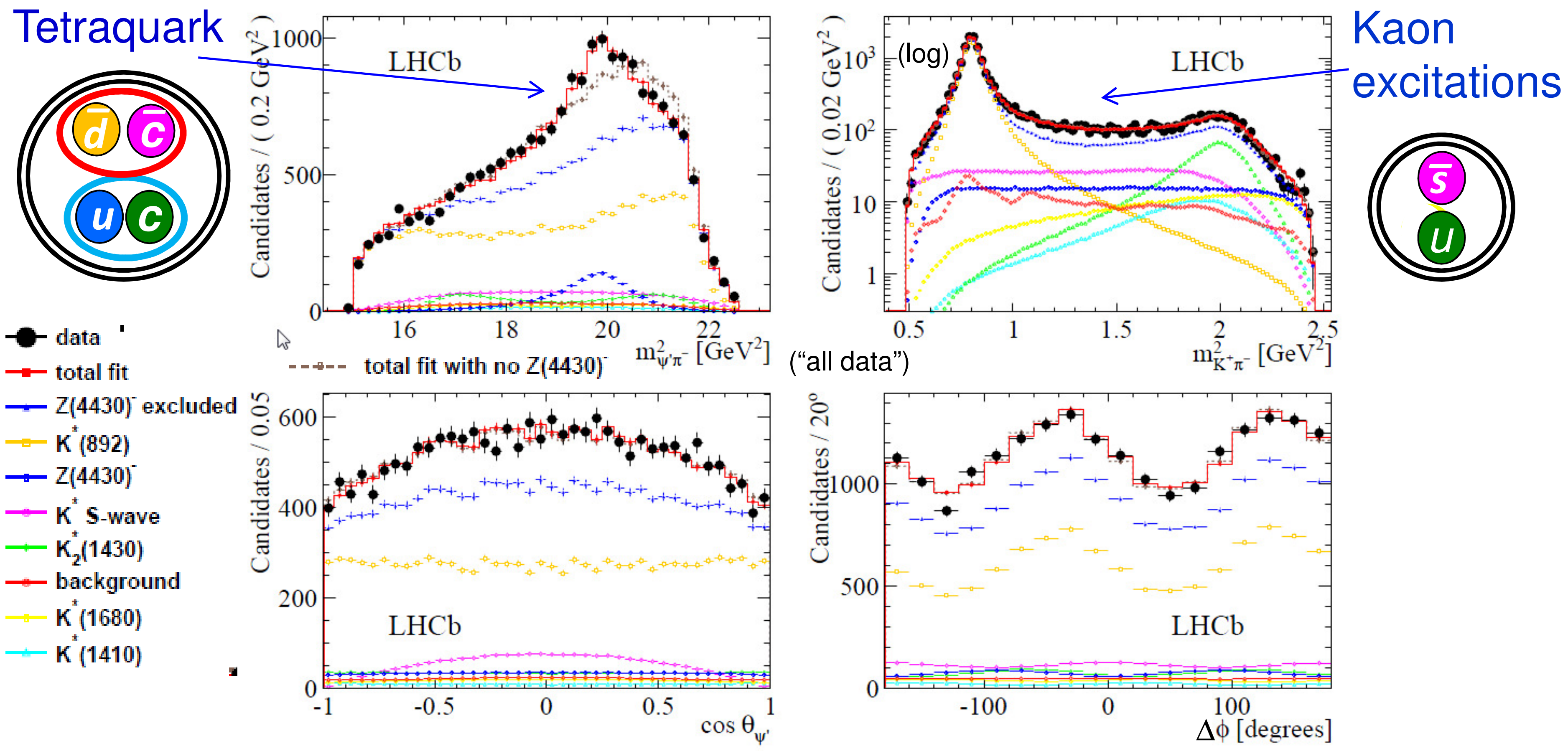
$$M^{Z}_{\Delta\lambda_\mu} = \sum_{\lambda_\psi=-1,0,1} A^{Z\to\psi\pi}_{\lambda_\psi} D^{J_Z}_{\lambda_\psi,\lambda_\psi}(0,\theta_Z,0)^* R(m_{\psi\pi} \,|\, M_Z,\Gamma_Z) D^{1}_{\lambda_\psi,\Delta\lambda_\mu}(\Delta\phi_{\psi,Z},\theta_\psi^{\,Z},0)^*$$

1 independent **complex** helicity
coupling after $L=L_{min}$

# of fit parameters: 32 + 4 = 36

Amplitude fits with $J^P=1^+$ Z(4430)$^+$

\# of fit parameters: 32 + 4 = 36

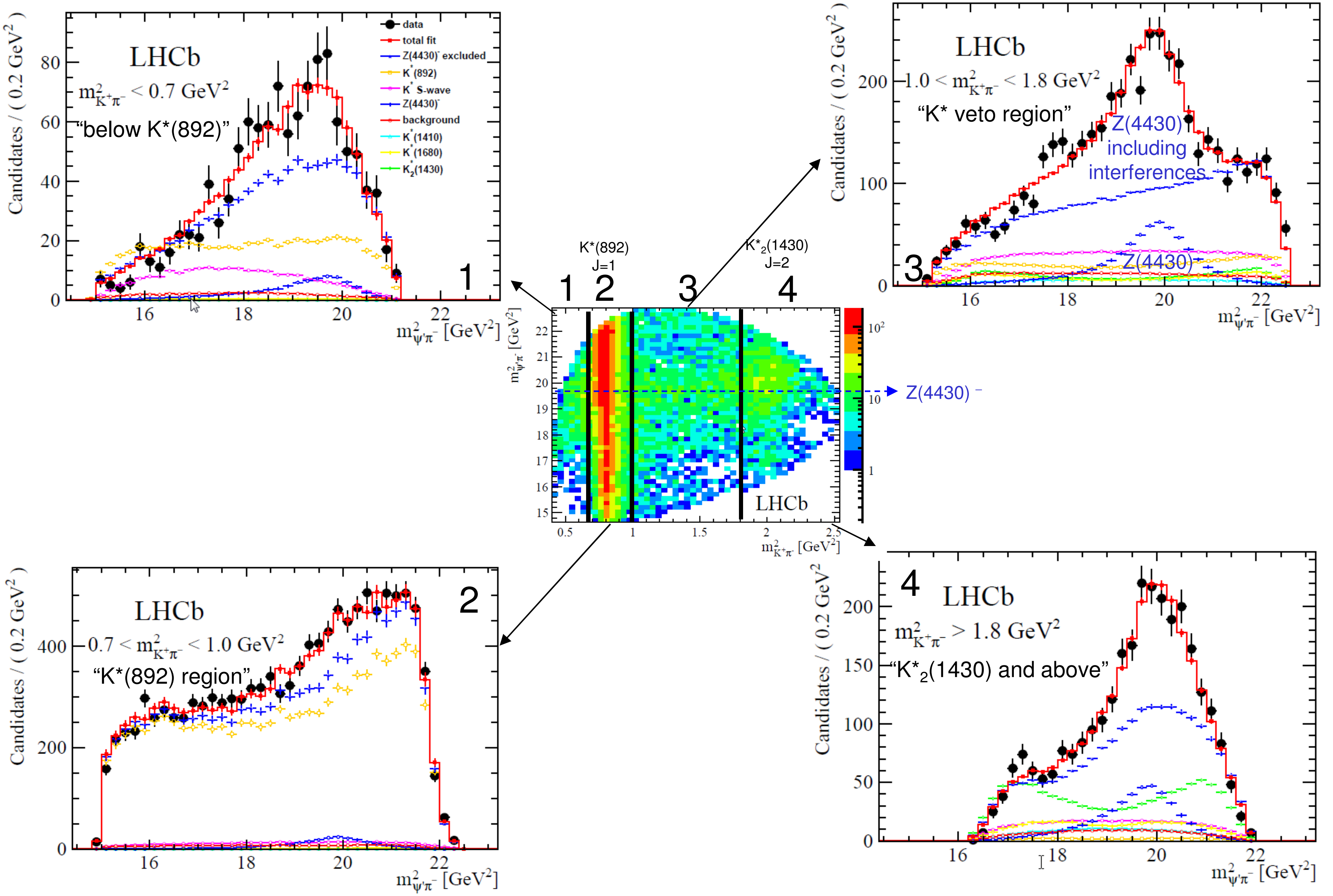


- The χ^2 p-value = 12%

⇩

- The data are well described when $J^P=1^+$ Z(4430)$^+$ is included in the fit
- Z(4430)$^+$ significances from $\Delta(-2\ln L)$ is 18.7σ (13.9σ with systematic variations)

Amplitude fits with $J^P=1^+$ Z(4430)$^-$



Z(4430)$^-$ parameters: LHCb vs Belle

	LHCb	Belle
$M(Z)$ [MeV]	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
$\Gamma(Z)$ [MeV]	$172 \pm 13^{+37}_{-34}$	$200^{+41}_{-46}{}^{+26}_{-35}$
f_Z [%]	$5.9 \pm 0.9^{+1.5}_{-3.3}$	$10.3^{+3.0}_{-3.5}{}^{+4.3}_{-2.3}$
f_Z^I [%] (with interferences)	$16.7 \pm 1.6^{+2.6}_{-5.2}$	
Significance	$> 13.9\sigma$	$> 5.2\sigma$

(new large systematic effect included by LHCb)

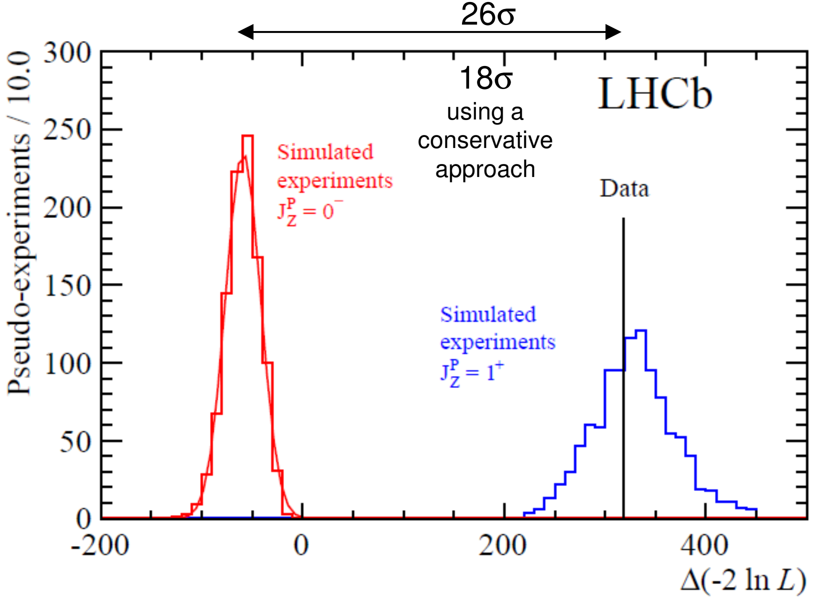
Amplitude fractions [%]
(statistical errors only)

Contribution	LHCb	Belle
S-wave total	10.8 ± 1.3	
NR	0.3 ± 0.8	
$K_0^*(800)$	3.2 ± 2.2	5.8 ± 2.1
$K_0^*(1430)$	3.6 ± 1.1	1.1 ± 1.4
$K^*(892)$	59.1 ± 0.9	63.8 ± 2.6
$K_2^*(1430)$	7.0 ± 0.4	4.5 ± 1.0
$K_1^*(1410)$	1.7 ± 0.8	4.3 ± 2.3
$K_1^*(1680)$	4.0 ± 1.5	4.4 ± 1.9
$Z(4430)^-$	5.9 ± 0.9	$10.3^{+3.0}_{-3.5}$

(not in the default fit $K^*_3(1780)$ 0.5 ± 0.2)

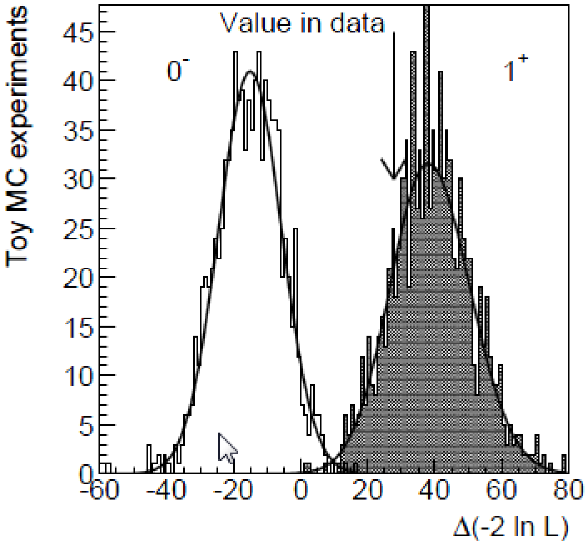
- Overall excellent consistency between LHCb and Belle
- Errors substantially improved

$Z(4430)^+$ spin-parity analysis



Belle

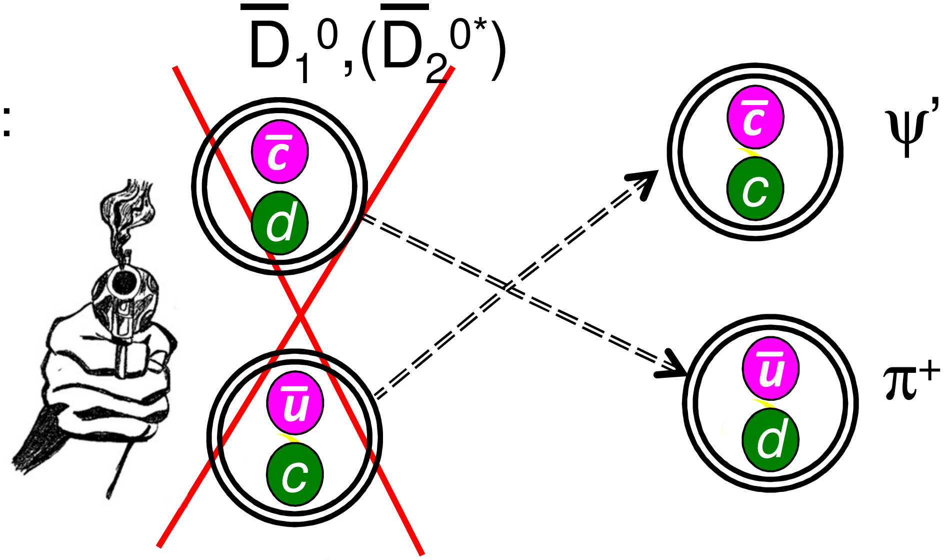
PRD 88, 074026 (2013)



Including systematic variations:

	Rejection level relative to 1^+	
Disfavored J^P	LHCb	Belle
0-	9.7σ	3.4σ
1-	15.8σ	3.7σ
2+	16.1σ	5.1σ
2-	14.6σ	4.7σ

- $J^P=1^+$ now established beyond any doubt



threshold cusp

$\bar{D}_1^0,(\bar{D}_2^{0*})$

D^{*+}

$J^P=0^-,1^-,2^-,(3^-)$

Hadronic resonances – Argand diagram

Forced harmonic oscillator:

Restoring force

Damping force:

Driving force

$$m\frac{d}{dt}\left(\frac{dx}{dt}\right) = -\ k\,x \quad - b\,\frac{dx}{dt} \quad - F_0\cos(\omega_{ext}t)$$

resonant frequency: $\omega_0 = \sqrt{\frac{k}{m}}$

dumping factor: $\gamma = \frac{b}{2m}$

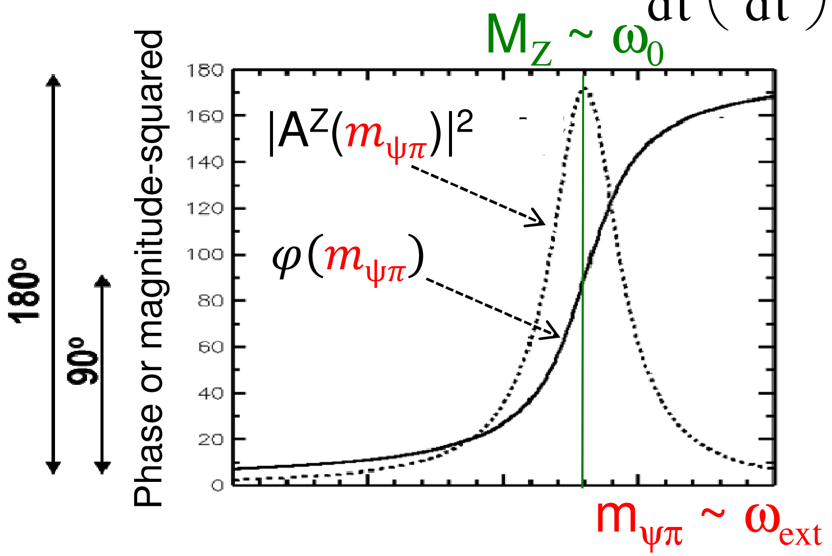
driving frequency

phase lag

$$x(t) \xrightarrow{t\to\infty} \frac{F_0/m}{\sqrt{(\omega_0^{\,2}-\omega_{ext}^{\,2})^2+(2\gamma\omega_{ext})^2}}\cos(\omega_{ext}t+\varphi)$$

$$\varphi = \mathrm{atan}\left(\frac{2\gamma\omega_{ext}}{\omega_0^{\,2}-\omega_{ext}^{\,2}}\right)$$

DEMO



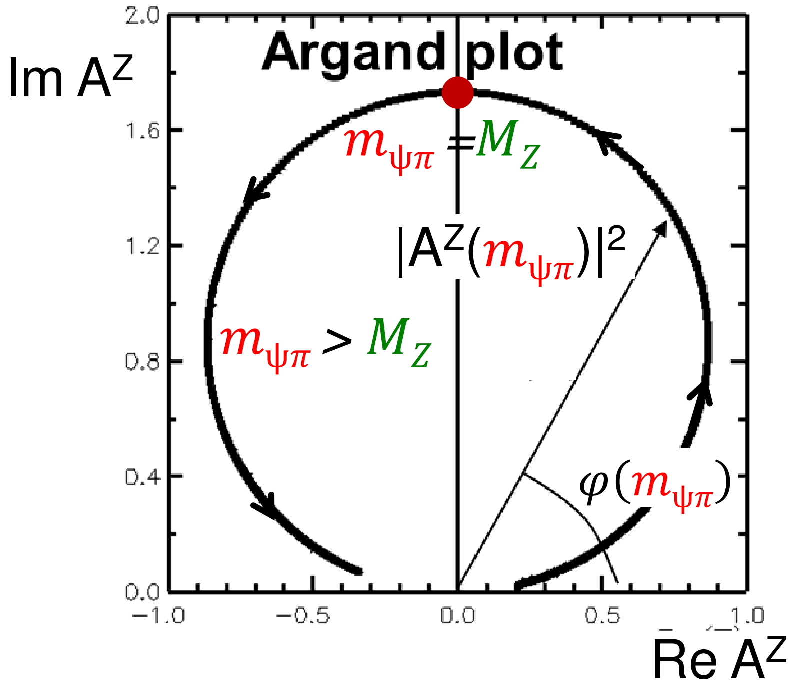
$$A^Z(m_{\psi\pi}) \sim \frac{1}{M_Z^{\,2}-m_{\psi\pi}^{\,2}-i\,M_Z\Gamma_Z} = |A^Z(m_{\psi\pi})|\,e^{i\varphi(m_{\psi\pi})}$$

$$|A^Z(m_{\psi\pi})|^2 \sim \frac{1}{(M_Z^{\,2}-m_{\psi\pi}^{\,2})^2+(M_Z\Gamma_Z)^2}$$

$$\varphi(m_{\psi\pi}) = \mathrm{atan}\left(\frac{M_Z\Gamma_Z}{M_Z^{\,2}-m_{\psi\pi}^{\,2}}\right)$$

Breit-Wigner amplitude

- $m_{\psi\pi} \sim \omega_{ext}$ driving frequency
- $M_Z \sim \omega_0$ resonance frequency
- $\Gamma_Z = \hbar/\tau_Z \sim \gamma/2$ dumping factor (mass indeterminacy)

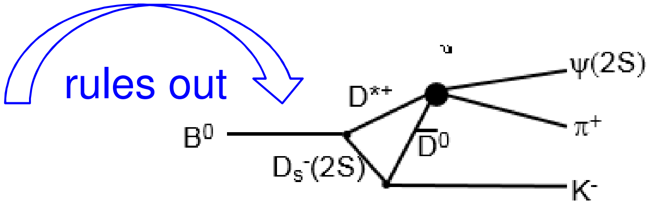


Argand diagram of Z(4430)$^+$

- Thanks to the large data statistics LHCb has been able to extract Argand diagram of Z(4430)$^+$ amplitude from its interference with the K* amplitudes:

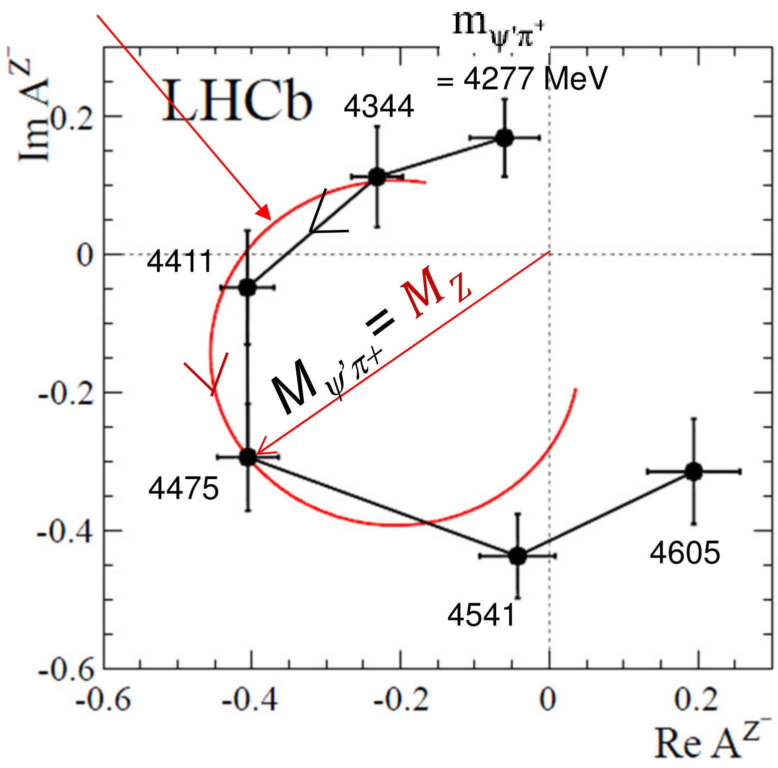
$$\frac{1}{M_Z^{\,2} - m_{\psi'\pi^+}^{\ \ 2} - i\,M_Z\Gamma_Z}$$

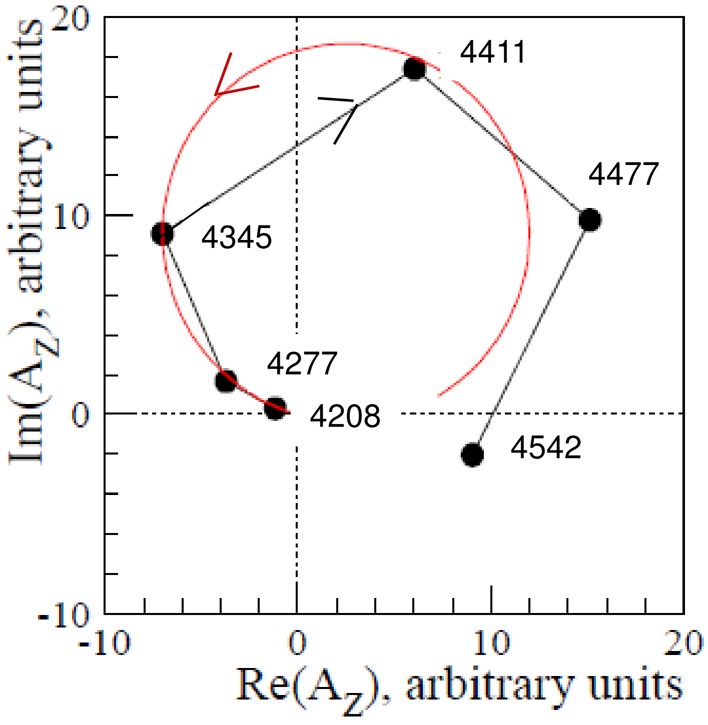
Breit-Wigner amplitude



rescattering model

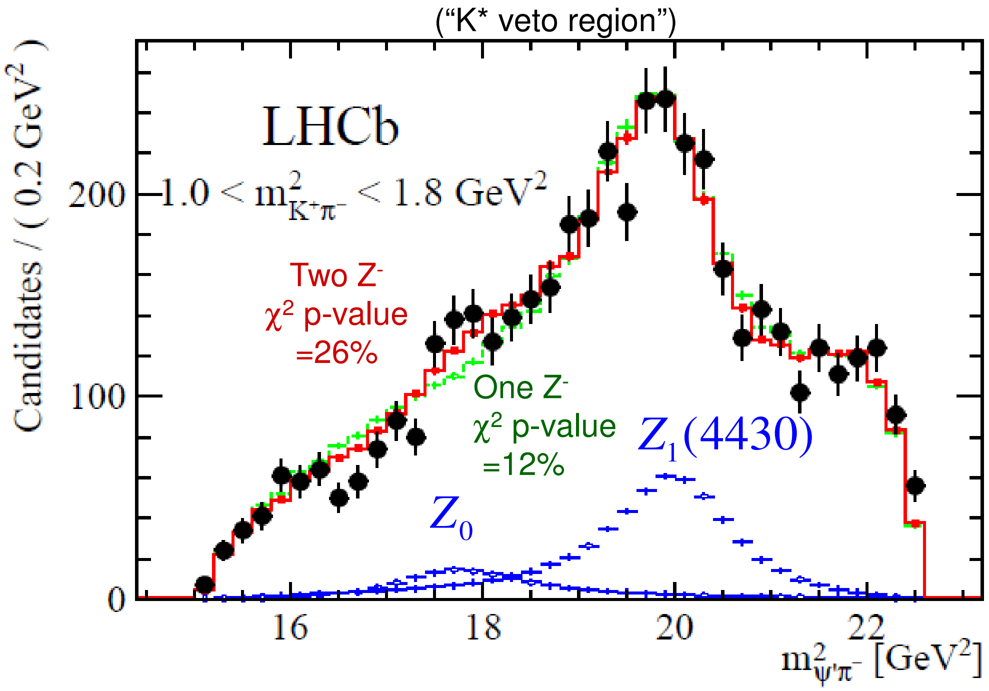
P. Pakhlov, T. Uglov
PL B748, 183 (2015)





More than one $Z^- \to \psi'\pi^-$?

LHCb-PAPER-2014-014, PRL 112 (2014) 222002



- Argand diagram for the Z_0 is inconclusive
- No evidence for the Z_0 in the model independent approach
- Need more data to clarify!

$$M(Z_0) = 4239 \pm 18^{+45}_{-10} \text{ MeV}$$

$$\Gamma(Z_0) = 220 \pm 47^{+108}_{-74} \text{ MeV}$$

$$f_{Z_0} = 1.6 \pm 0.5^{+1.9}_{-0.4} \%$$

$$f^I_{Z_0} = 2.4 \pm 1.1^{+1.7}_{-0.2} \%$$

6σ significane (with systematics)

$J^P(Z_0) = 0^-$ preferred

over $1^-, 2^+, 2^-$ by 8σ

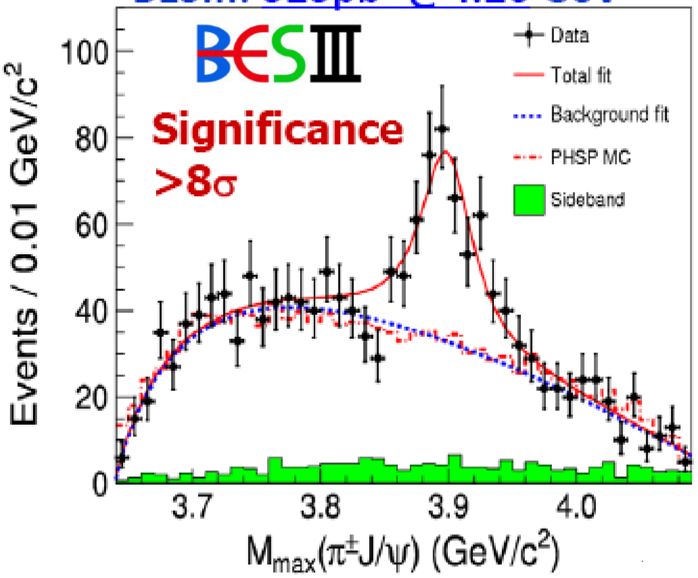
(660 ± 150 MeV wide 1^+

cannot be ruled out)

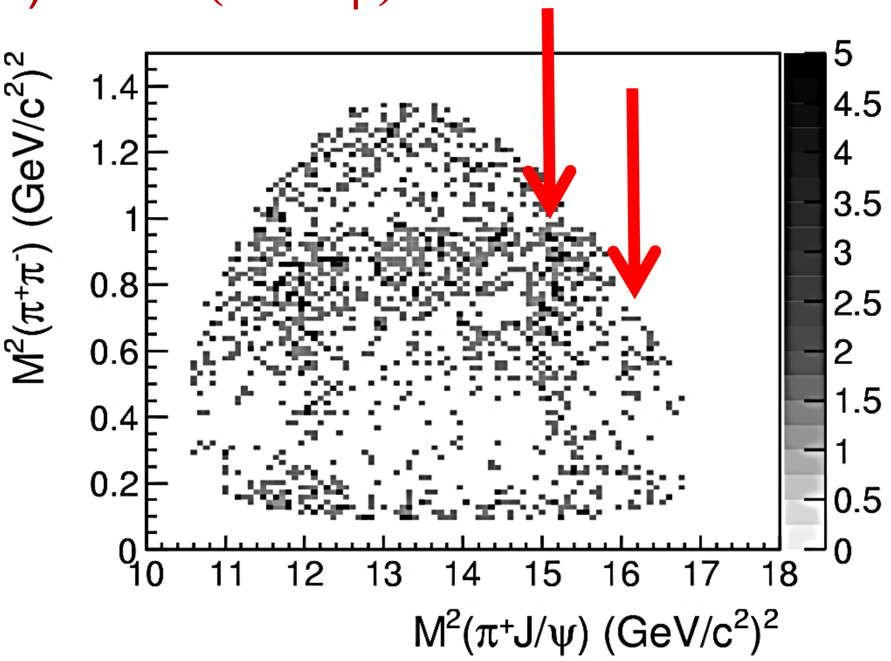
Previously confirmed Z_c^+ state: $Z_c(3900)^+$

$e^+e^- \rightarrow Y(4260) \rightarrow \pi^-(\pi^+ J/\psi)$

BESIII: 525pb^{-1}@4.26 GeV



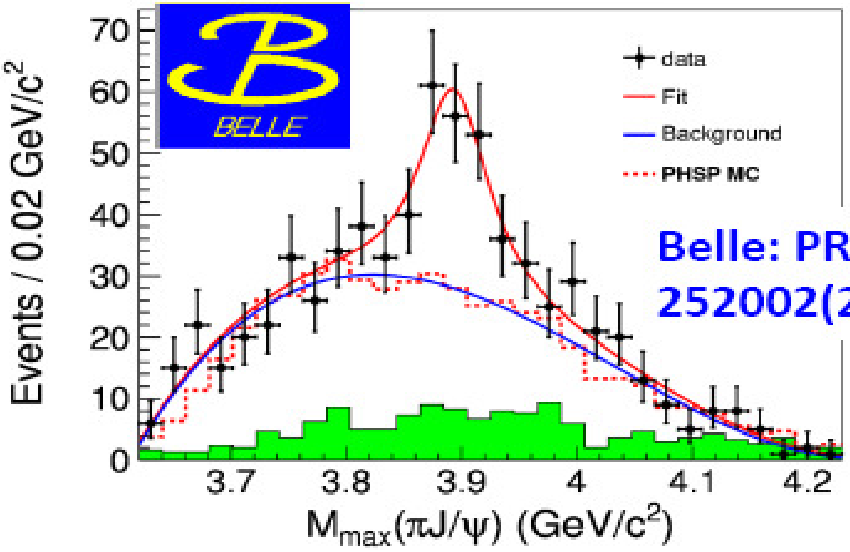
Significance >8σ



BESIII: PRL110, 252001 (2013)

- **M = 3899.0±3.6±4.9 MeV**
- **Γ = 46±10±20 MeV**
- **307 ± 48 events**

(no Argand diagram analysis)



Belle: PRL 11
252002(2013)

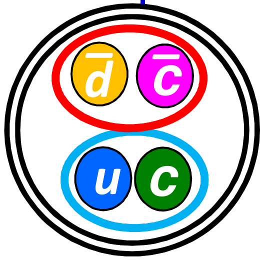
24±6 MeV above the $D\overline{D}^*$ threshold

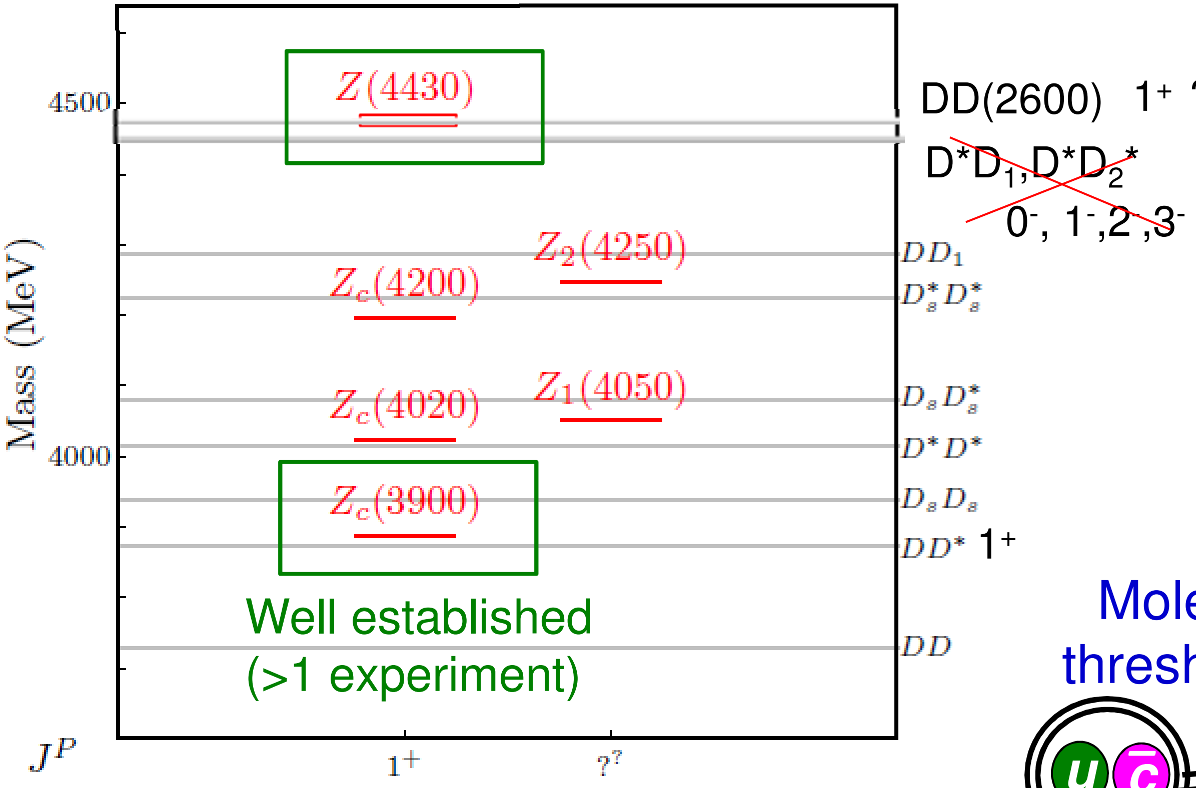
$Z(4430)^+$ and other Z_c^+ states

- The only threshold still at play for $Z(4430)^+$: DD(2600) if D(2600) exists (needs confirmation!) and if it is 1^- states (2^3S_1)
- Other charged Z_c^+,Z_b^+ states are near $D^{(*)}\bar{D}^{(*)}$, $B^{(*)}\bar{B}^{(*)}$ thresholds

Radial excitation of tightly bound tetraquark

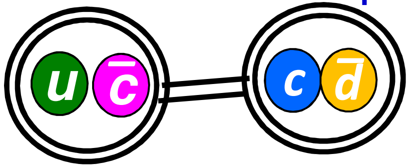
Tetraquark





Radial excitation of the $^3S_1$ meson inside meson molecule

Molecule or threshold cusp



Diquark states can be "attracted" towards the mesonic-pair threshold masses

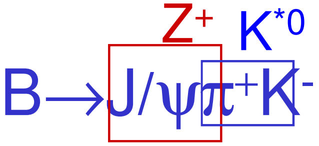
Meson molecules should be a few MeV below the threshold,
Meson-meson cusps alone should be exactly at the thresholds.

$Z_c(3900)^+$ is 24±6 MeV above the $D\bar{D}^*$ threshold (favors tetraquark picture)

Belle 4D fits to $B^0\to J/\psi\pi^+K^-$ $Z(4430)^+$ companion : $Z(4200)^+$

Belle

arXiv:1408.6457
Phys.Rev. D90 (2014) 112009


Z^+ K^{*0}
$B\to J/\psi\pi^+K^-$

$Z_c(4430)^+$	$(0.5^{+0.4}_{-0.1})\%$	5.1σ
$Z_c(4200)^+$	$(1.9^{+0.7}_{-0.5})\%$	8.2σ

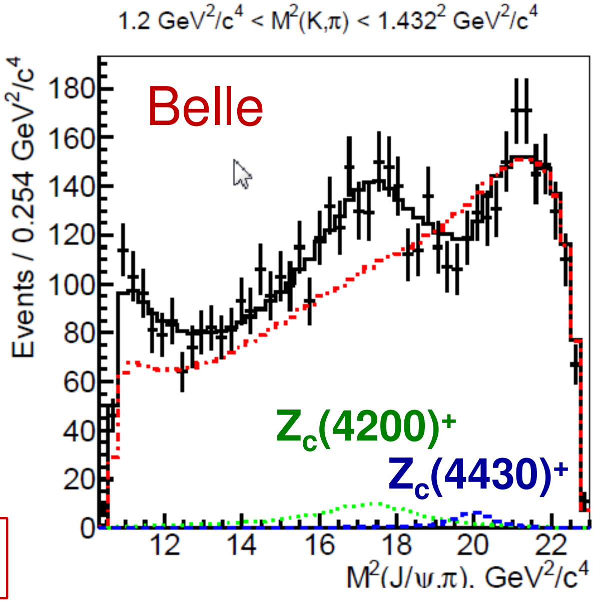
$J^P(4200)=1^+$ preferred by $>8.6\sigma$

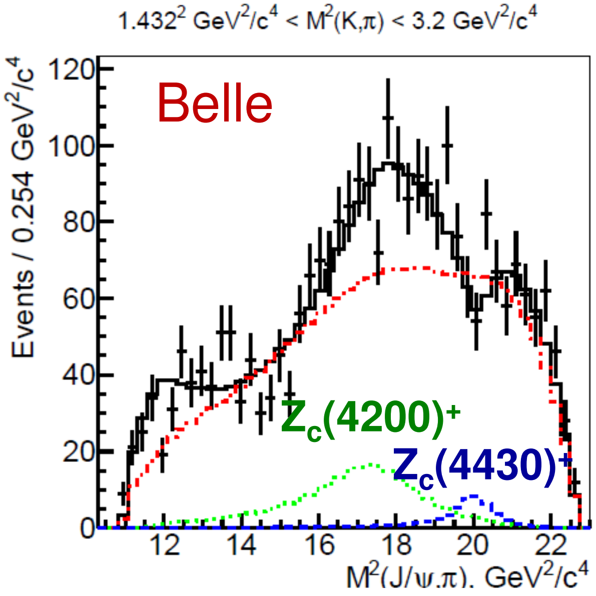
$$M(4200)=4196^{+31}_{-29}{}^{+17}_{-13}\ \text{MeV}$$

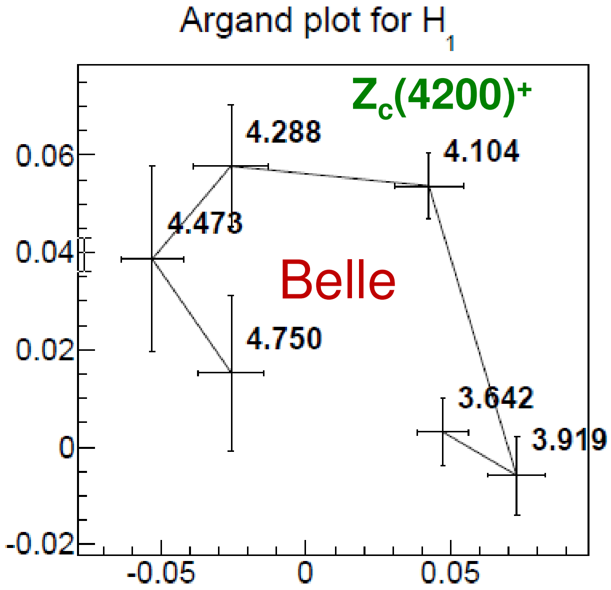
$$\Gamma(4200) = 370^{+70}_{-70}{}^{+70}_{-132}\ \text{MeV}$$

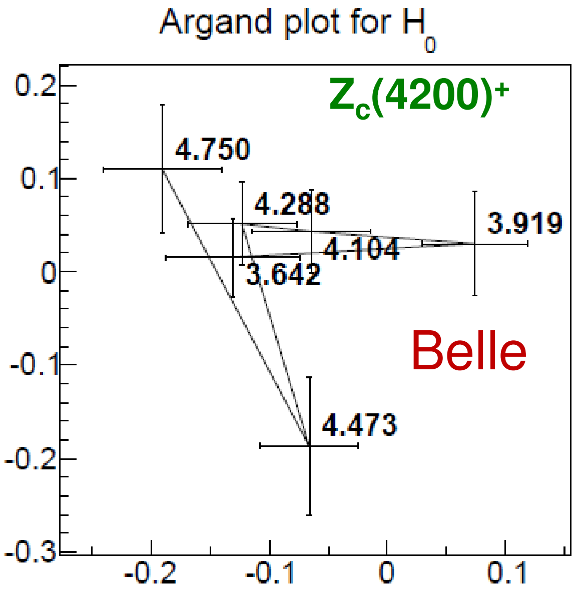
Observation of $Z(4430)^+$ in the 2nd B decay!

$Z(4430)^+$ mass and width fixed in these fits to the $B^0\to\psi'\pi^+K^-$ results









(In the LHCb fits, we neglect D-wave in $Z(1^+)$ decays: $H_1=H_0$)

Future studies of $Z(4430)^+$

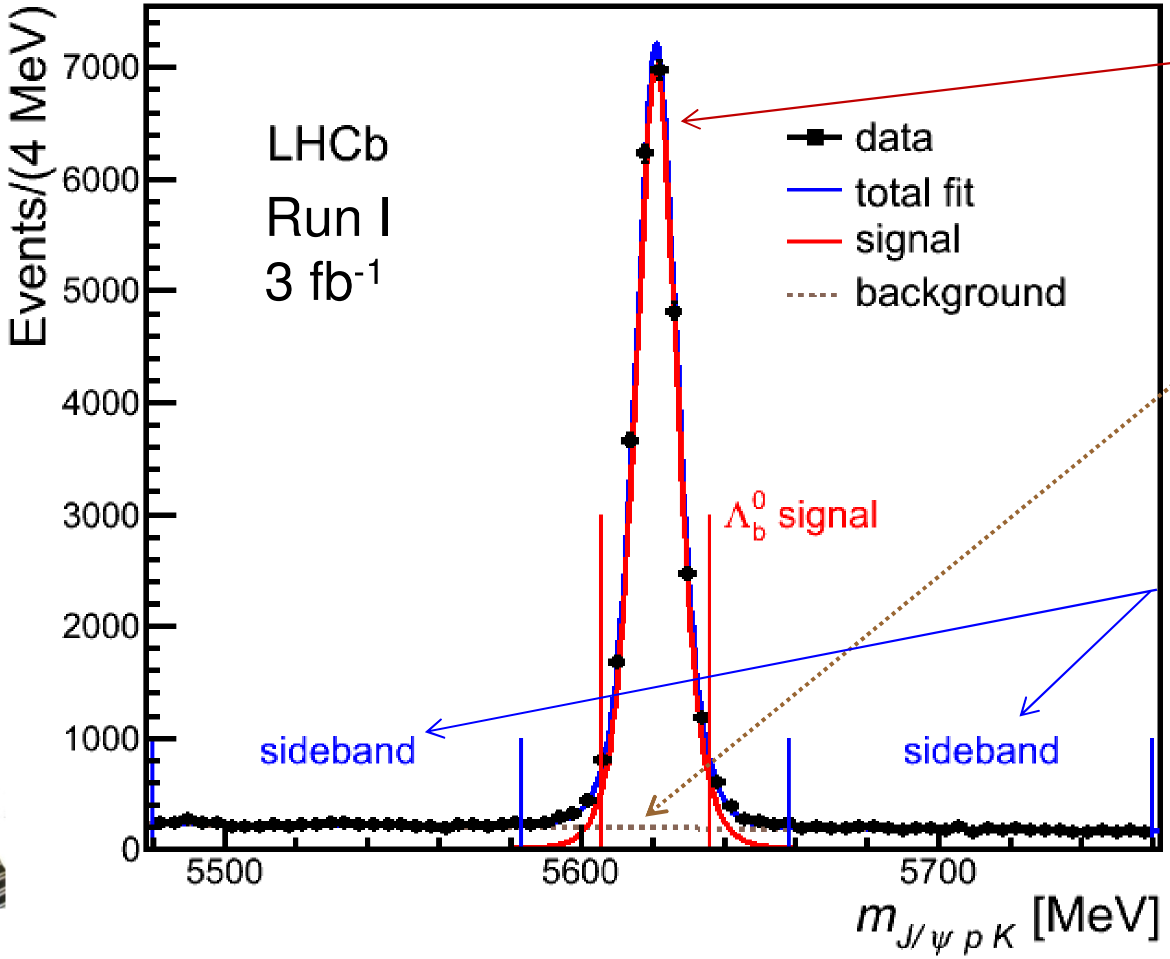
- We have 10 times more data than Belle for $B \rightarrow J/\psi\pi^+K^-$
  - We will analyze it to verify Belle's results
  - Possibly contribute to K* spectroscopy at high mass
  - Likely to be published together with reanalysis of $B \rightarrow \psi'\pi^+K^-$ (lower $\psi'\pi^+$ mass region?)
- We can improve $B \rightarrow \psi'\pi^+K^-$ results even without new data by adding $\psi' \rightarrow \pi^+\pi^- J/\psi$ (1/3 of the $\psi' \rightarrow \mu^+\mu^-$ sample), but is the complication worth the effort?

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

Nathan Jurik
will graduate
from Syracuse
in spring

Assist.Prof.
Liming Zhang
Tsinghua Univ.
(previously at
Syracuse)

LHCb-PAPER-2015-029, arXiv:1507.03414, PRL 115, 07201



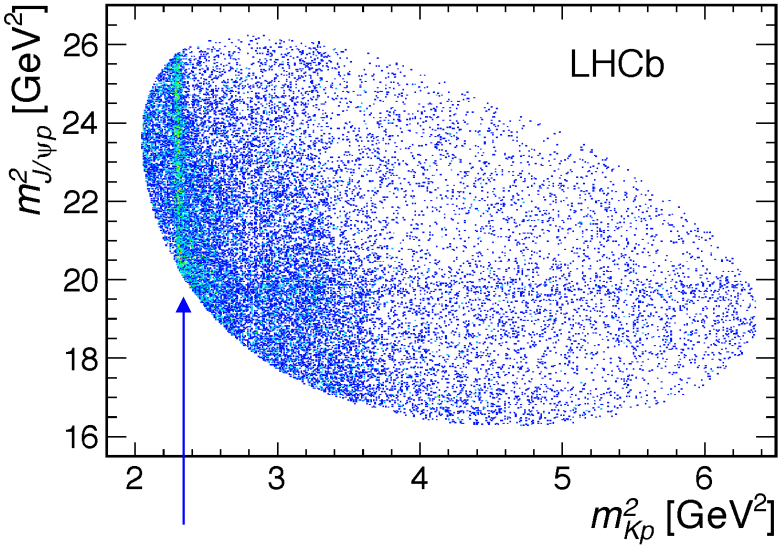
26,007±166
Λ_b^0 candidates

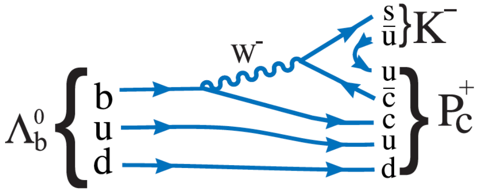
The background
is only 5.4% in
the signal region!

The sideband
distributions are flat
→ no major
reflections from the
other b-hadrons
after the selection

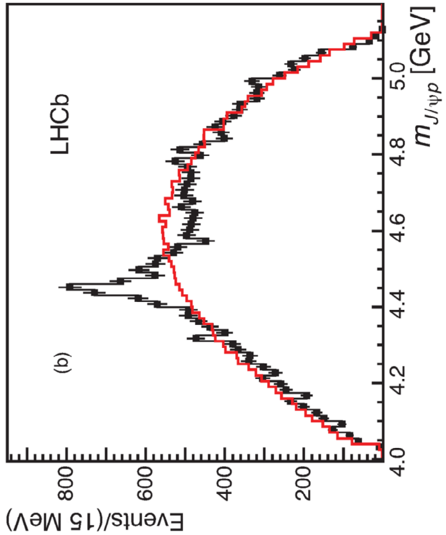
- The decay first observed by LHCb and used to measure Λ_b^0 lifetime (LHCb-PAPER-2013-032, PRL 111, 102003)

$\Lambda_b^0 \rightarrow J/\psi p K^-$: unexpected structure in $m_{J/\psi p}$



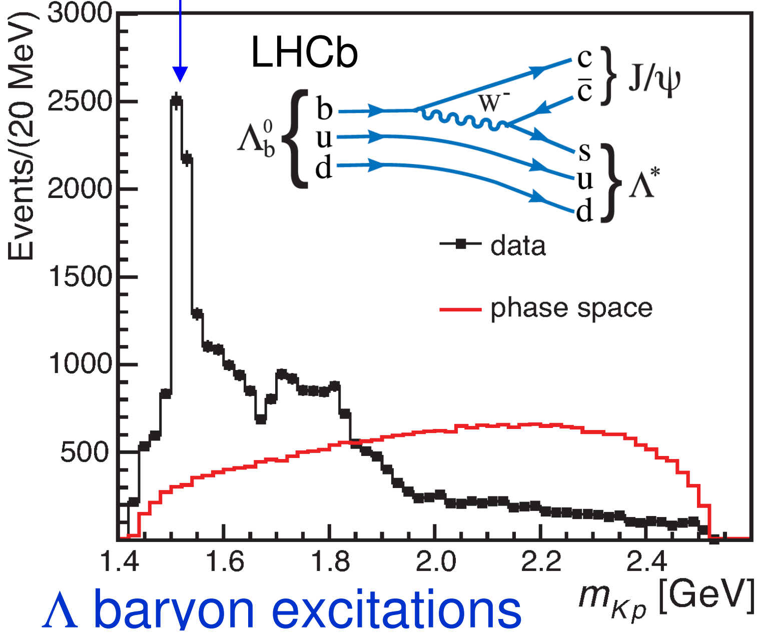


$P_c^+ \rightarrow J/\psi$ p
?



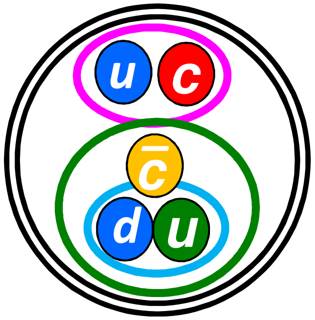
Exotic pentaquark

$\Lambda(1520)$ and other Λ^*'s $\rightarrow$ p K^-

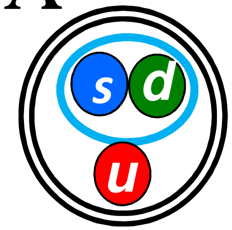


Λ baryon excitations

- Unexpected, narrow peak in $m_{J/\psi p}$
- Ignored in LHCb for more than 2 years. We, like almost everybody else, did not believe in pentaquarks:



Λ^*



assumed to be a reflection of interfering Λ^*'s $\rightarrow$ p K^- ?

Proper amplitude analysis absolutely necessary to check

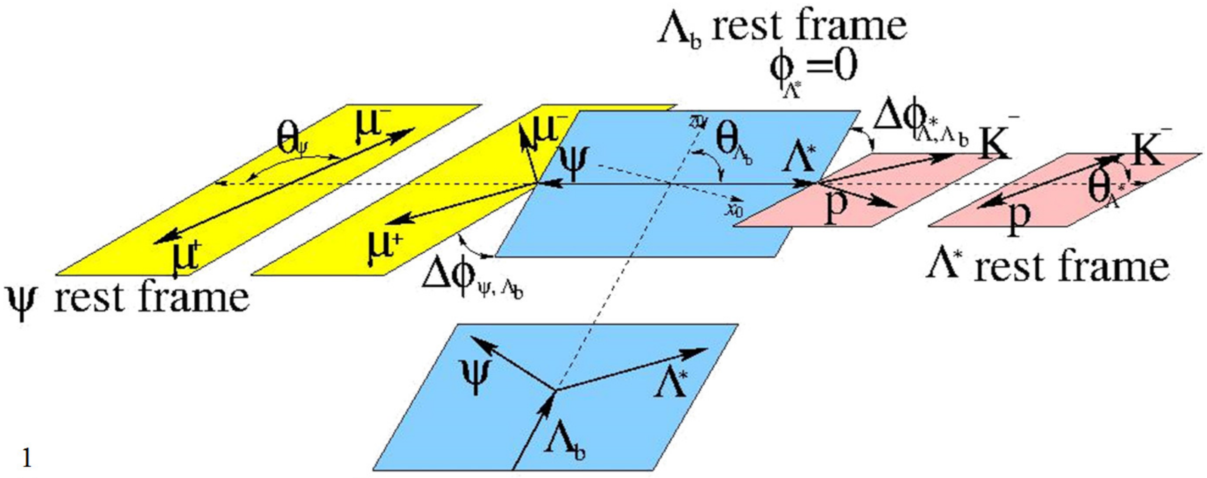
Amplitude Analysis of $\Lambda_b \to J/\psi p K^-$, $J/\psi \to \mu^+\mu^-$

$$\left| M\left(\mathrm{m}_{Kp}, \Omega \mid A^{\Lambda_b \to \psi \Lambda_n^*}_{\lambda_\psi, \lambda_{\Lambda^*}}, A^{\Lambda_n^* \to pK}_{\lambda_p}\right)\right|^2 = \sum_{\lambda_{\Lambda_b}=-1/2,+1/2} \sum_{\lambda_p=-1/2,+1/2} \sum_{\Delta\lambda_\mu=-1,1} \left| M^{\Lambda^*}_{\lambda_{\Lambda_b}, \lambda_p, \Delta\lambda_\mu} \right|^2$$

$$\Omega \equiv (\theta_{\Lambda_b}, \theta_{\Lambda^*}, \Delta\phi_{\Lambda^*, \Lambda_b}, \theta_\psi, \Delta\phi_{\psi, \Lambda_b})$$

6D analysis

1 mass, 5 angles



$$M^{\Lambda^*}_{\lambda_{\Lambda_b}, \lambda_p, \Delta\lambda_\mu} = \sum_n \sum_{\lambda_\Lambda} \sum_{\lambda_\psi=-1,0,1} A^{\Lambda_b \to \psi \Lambda_n^*}_{\lambda_\psi, \lambda_{\Lambda^*}} D^{\frac{1}{2}}_{\lambda_{\Lambda_b}, \lambda_{\Lambda^*} - \lambda_\psi}(0, \theta_{\Lambda^*}, 0)^*$$

$$A^{\Lambda_n^* \to pK}_{\lambda_p} D^{J_{\Lambda^*}}_{\lambda_{\Lambda^*}, \lambda_p}(\Delta\phi_{\Lambda^*, \Lambda_b}, \theta_{K^*}, 0)^* R(m_{Kp} \mid M_{\Lambda_n^*}, \Gamma_{\Lambda_n^*}) D^1_{\lambda_\psi, \Delta\lambda_\mu}(\Delta\phi_{\psi, \Lambda_b}, \theta_\psi, 0)^*$$

$\uparrow$

4-6 independent **complex** helicity couplings per Λ_n^* resonance

Λ^* resonance model

All known Λ^* states from KN scattering experiments

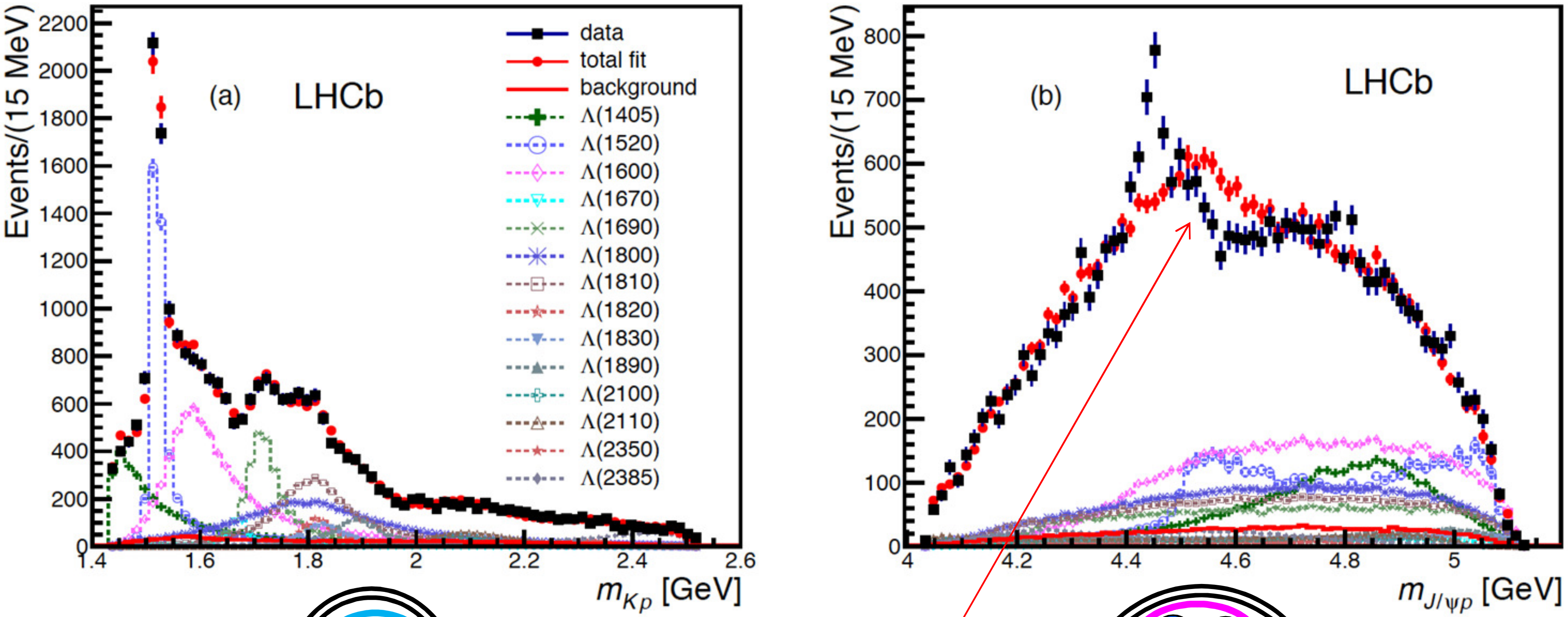
No high-J^P high-mass states limit L

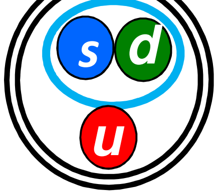
All states, all L

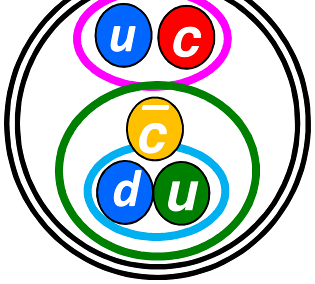
State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	$5/2^-$?	$\approx$2585	200	0	6
			# of fit parameters:	64	146

Fit with $\Lambda^*\to pK^-$ contributions only

of fit parameters: 146







- Include all known Λ excitations:
- m_{Kp} looks fine, but not $m_{J/\psi p}$

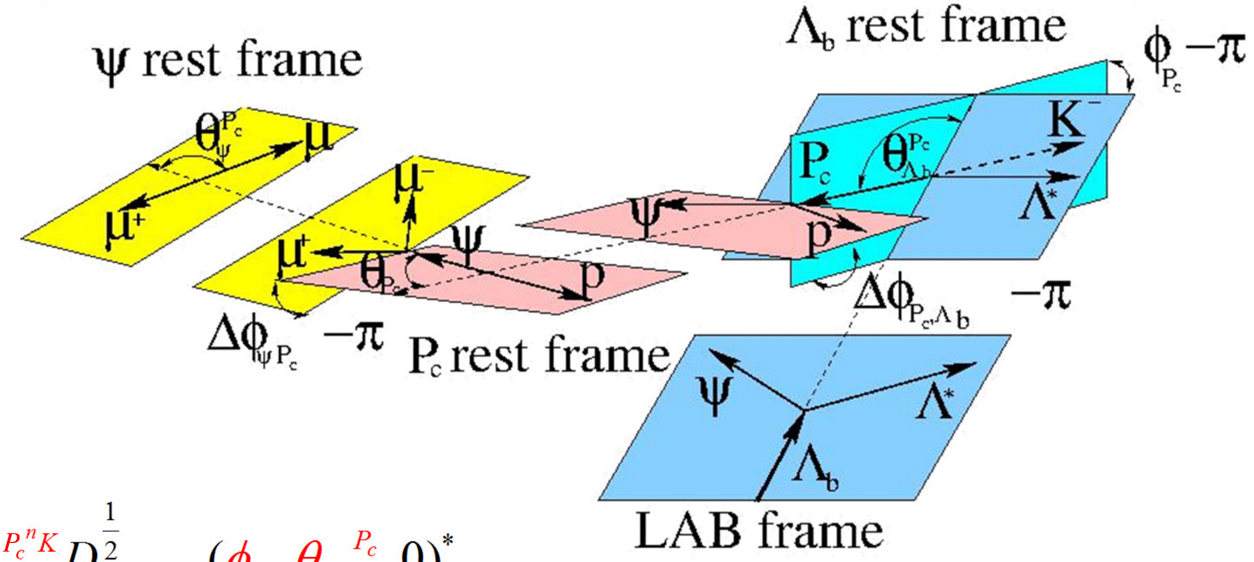
Amplitude Analysis of $\Lambda_b \to J/\psi p K^-$, $J/\psi \to \mu^+\mu^-$

$$\left| M\left(\mathrm{m}_{Kp}, \Omega \,|\, M_{P_c{}^n}, \Gamma_{P_c{}^n}, J_{P_c{}^n}, A_{\lambda_{P_c{}^n}}^{\Lambda_b \to P_c{}^n K}, A_{\lambda_\psi,\lambda_p}^{P_c{}^n \to \psi p}, A_{\lambda_\psi,\lambda_{\Lambda^*}}^{\Lambda_b \to \psi \Lambda_n^*}, A_{\lambda_p}^{\Lambda_n^* \to pK}\right) \right|^2 =$$

$$\sum_{\lambda_{\Lambda_b}=-1/2,+1/2} \; \sum_{\lambda_p=-1/2,+1/2} \; \sum_{\Delta\lambda_\mu=-1,1} \left| M^{\Lambda^*}_{\lambda_{\Lambda_b},\lambda_p,\Delta\lambda_\mu} + e^{i\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p{}^{P_c}=-1/2,+1/2} d^{\frac{1}{2}}_{\lambda_p{}^{P_c},\lambda_p}(\theta_p) M^{P_c}_{\lambda_{\Lambda_b},\lambda_p{}^{P_c},\Delta\lambda_\mu} \right|^2$$

6D analysis

1 mass, 6+2 angles
all derivable from the Λ^* variables



$$M^{P_c}_{\lambda_{\Lambda_b},\lambda_p,\Delta\lambda_\mu} = \sum_n \sum_{\lambda_{P_c}} \sum_{\lambda_\psi=-1,0,1} A_{\lambda_{P_c}}^{\Lambda_b \to P_c{}^n K} D^{\frac{1}{2}}_{\lambda_{\Lambda_b},\lambda_{P_c{}^n}}\left(\phi_{P_c}, \theta_{\Lambda^*}{}^{P_c}, 0\right)^*$$

$$A_{\lambda_\psi,\lambda_p}^{P_c{}^n \to \psi p} D^{J_{P_c{}^n}}_{\lambda_{P_c{}^n},\lambda_\psi-\lambda_p}\left(\Delta\phi_{P_c,\Lambda_b}, \theta_{P_c}, 0\right)^* R\left(m_{\psi p} \,|\, M_{P_c{}^n}, \Gamma_{P_c{}^n}\right) D^1_{\lambda_\psi,\Delta\lambda_\mu}\left(\Delta\phi_{\psi,P_c}, \theta_\psi{}^{P_c}, 0\right)^*$$

$\uparrow$

3-4 independent **complex** helicity couplings per $P_c{}^n$ resonance

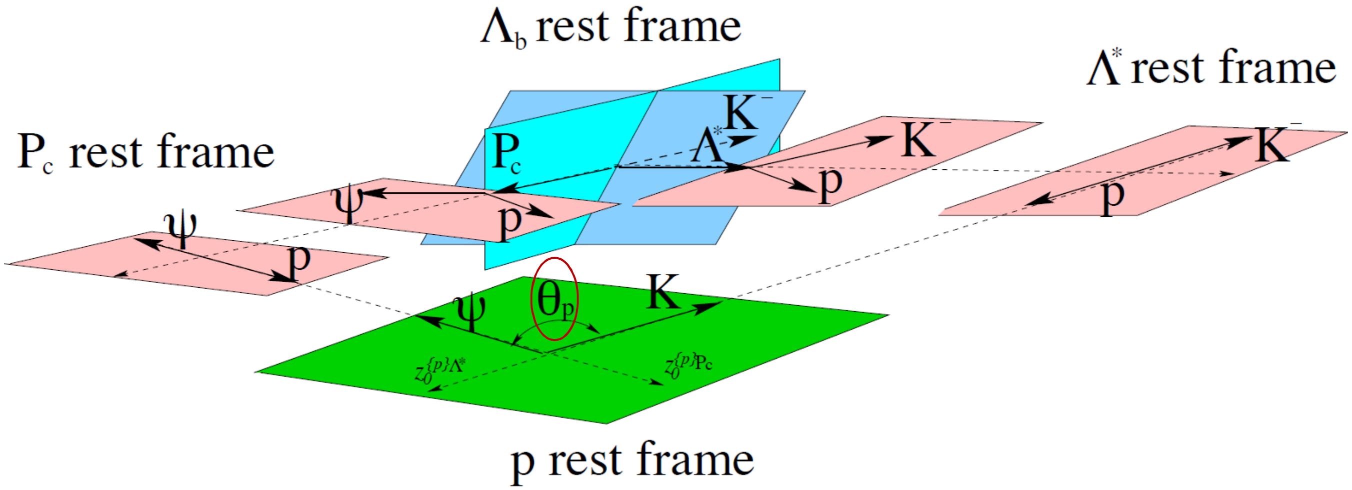
Λ^* Plus P_c^+ Matrix Element

2 additional angles to align the muon and proton helicity frames between the Λ^* and P_c^+ decay chains

also derivable from the Λ^* decay variables

$$\left| M\left(\mathrm{m}_{Kp}, \Omega \,|\, M_{P_c{}^n}, \Gamma_{P_c{}^n}, J_{P_c{}^n}, A_{\lambda_{P_c{}^n}}^{\Lambda_b \to P_c{}^n K}, A_{\lambda_\psi, \lambda_p}^{P_c{}^n \to \psi p}, A_{\lambda_\psi, \lambda_{\Lambda^*}}^{\Lambda_b \to \psi \Lambda_n^*}, A_{\lambda_p}^{\Lambda_n^* \to pK}\right)\right|^2 =$$

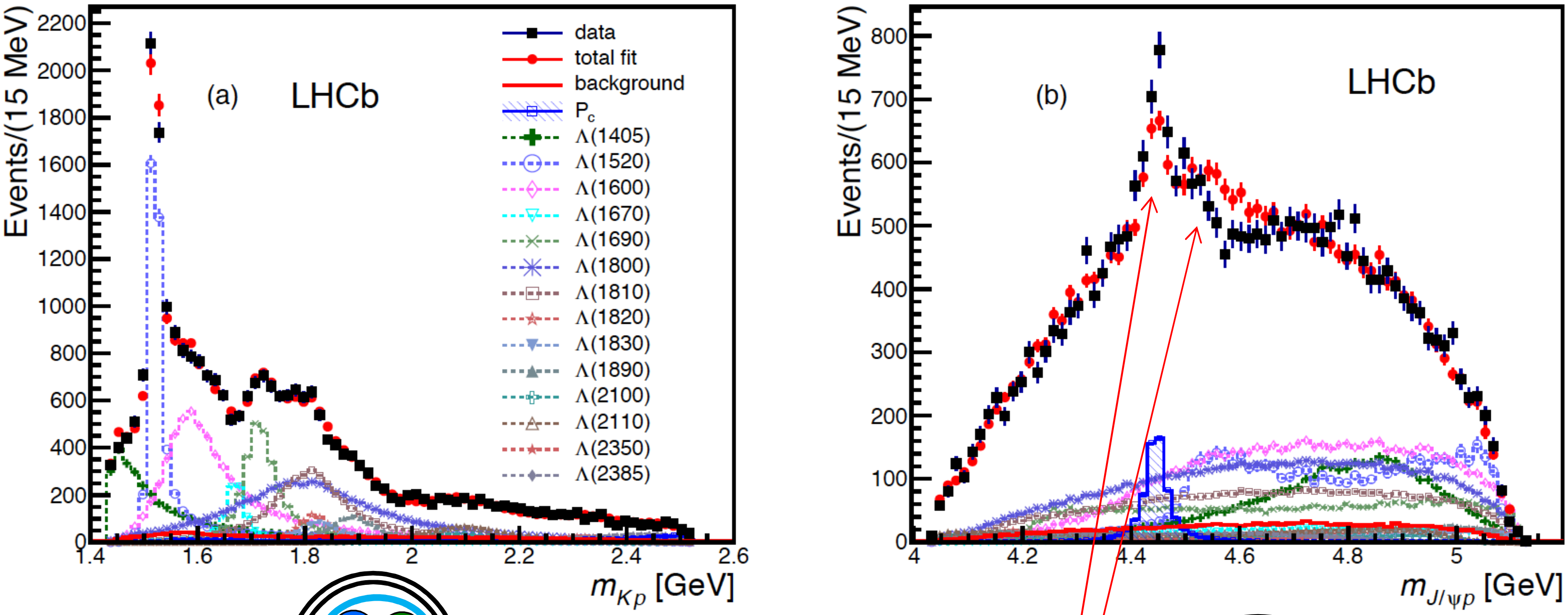
$$\sum_{\lambda_{\Lambda_b}=-1/2,+1/2} \; \sum_{\lambda_p=-1/2,+1/2} \; \sum_{\Delta\lambda_\mu=-1,1} \left| M_{\lambda_{\Lambda_b}, \lambda_p, \Delta\lambda_\mu}^{\Lambda^*} + e^{i \Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p{}^{P_c}=-1/2,+1/2} d_{\lambda_p{}^{P_c}, \lambda_p}^{\frac{1}{2}}(\theta_p) M_{\lambda_{\Lambda_b}, \lambda_p{}^{P_c}, \Delta\lambda_\mu}^{P_c} \right|^2$$

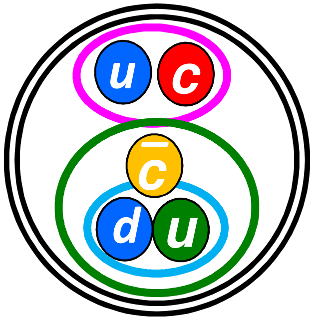


- Without this realignment can't describe Λ^* plus P_c^+ interferences properly
- They integrate out to zero in full phase-space but present in the differential 6D fit-PDF

Fit with Λ^*'s and one $P_c^+ \rightarrow J/\psi p$ state

of fit parameters: 146 + 10 = 156

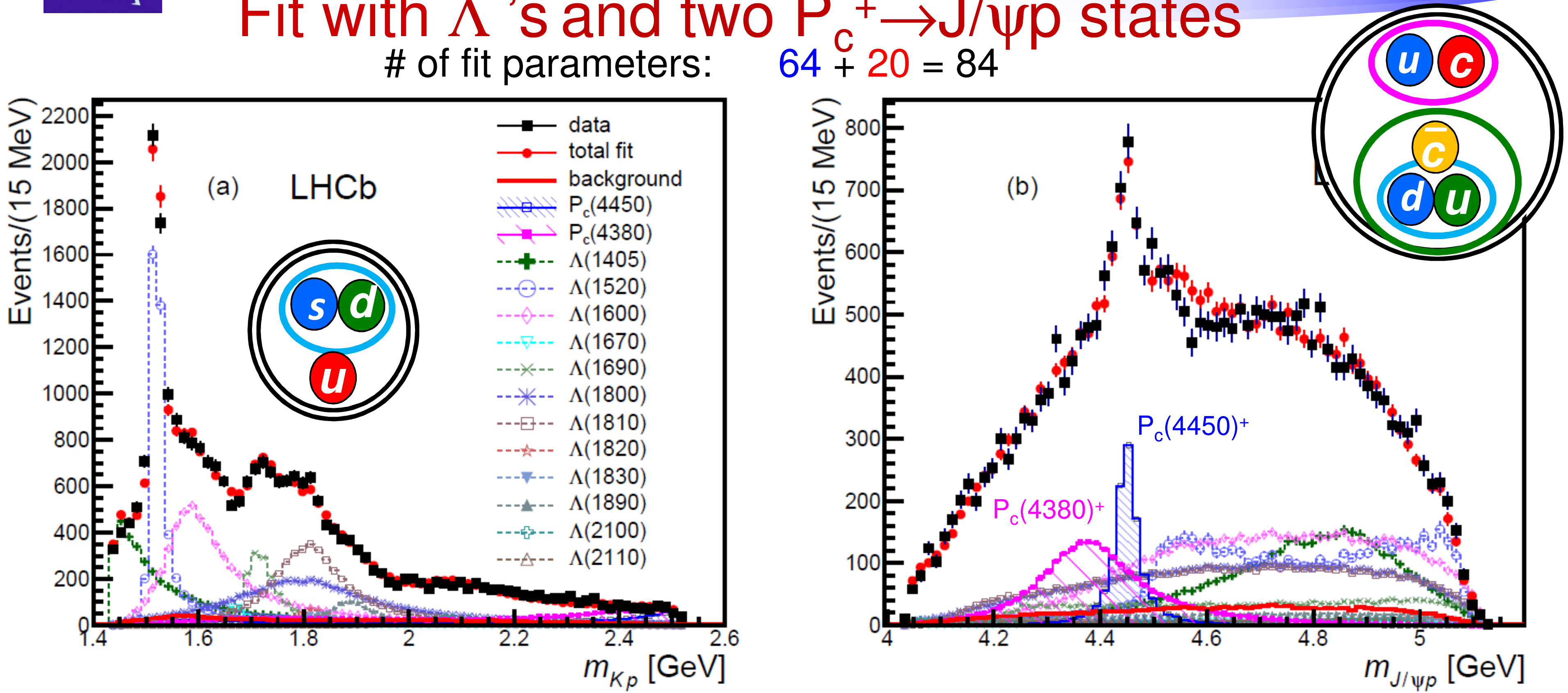




- Try all J^P of P_c^+ up to $7/2^{\pm}$
- Best fit has $J^P = 5/2^{\pm}$. Still not a good fit

Fit with Λ*'s and two $P_c^+ \to J/\psi p$ states

of fit parameters: 64 + 20 = 84



- Obtain good fits even with the reduced Λ* model

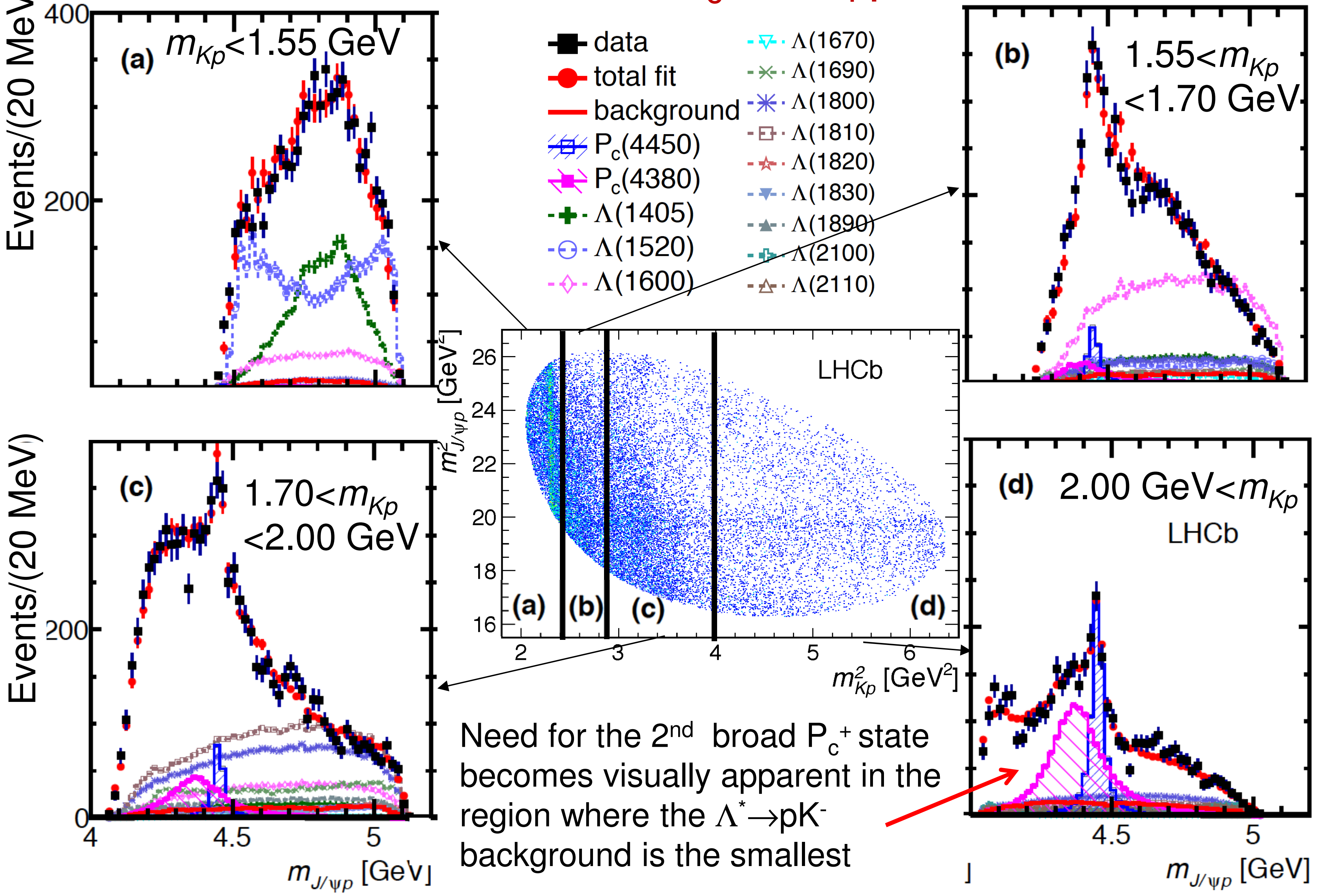
State	Mass (MeV)	Width (MeV)	Fit fraction (%)	Significance
$P_c(4380)^+$	4380 ±8±29	205±18±86	8.4±0.7±4.2	9σ
$P_c(4450)^+$	4449.8±1.7±2.5	39± 5±19	4.1±0.5±1.1	12σ

- Best fit has J^P=(3/2⁻, 5/2⁺), also (3/2⁺, 5/2⁻) & (5/2⁺, 3/2⁻) are preferred

Statistical significances

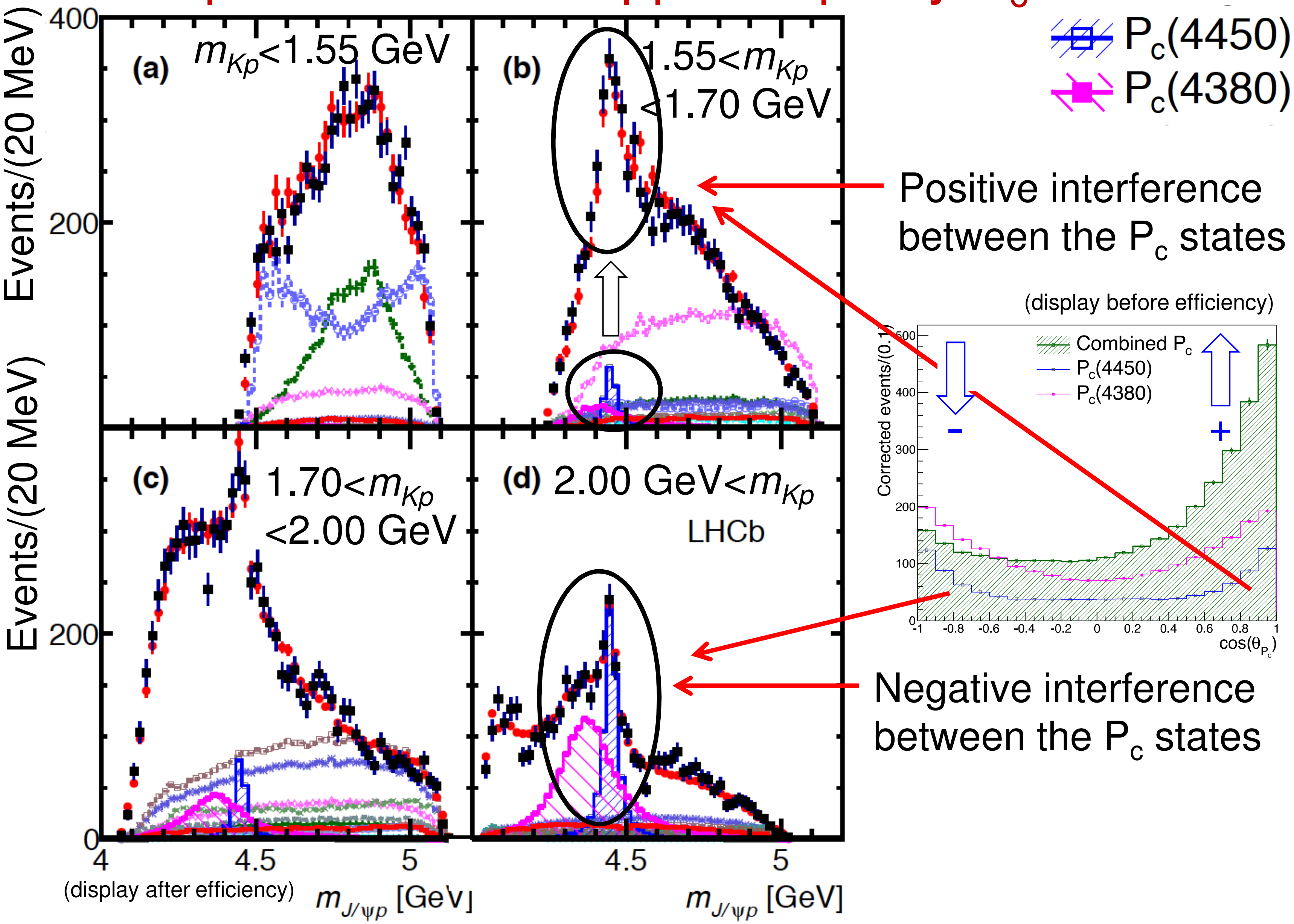
- Fit improves greatly, for 1 P_c $\Delta(-2\ln\mathcal{L})=14.7^2$, adding the 2nd P_c improves by 11.6^2, for adding both together $\Delta(-2\ln\mathcal{L})=18.7^2$
- Simulations of pseudoexperiments are used to turn the $\Delta(-2\ln\mathcal{L})$ values to significances:
  - significance of $P_c(4450)^+$ state is 12σ
  - significance of $P_c(4380)^+$ state is 9σ
  - combined significance of the two P_c^+ states is 15σ
- This includes the dominant systematic uncertainties, coming from difference between extended and reduced Λ^* model results.

Fit with Λ^*'s and two $P_c^+ \to J/\psi p$ states



Need for the 2nd broad P_c^+ state becomes visually apparent in the region where the $\Lambda^* \to pK^-$ background is the smallest

Data preferrence for opposite parity P_c^+ states



Positive interference between the P_c states

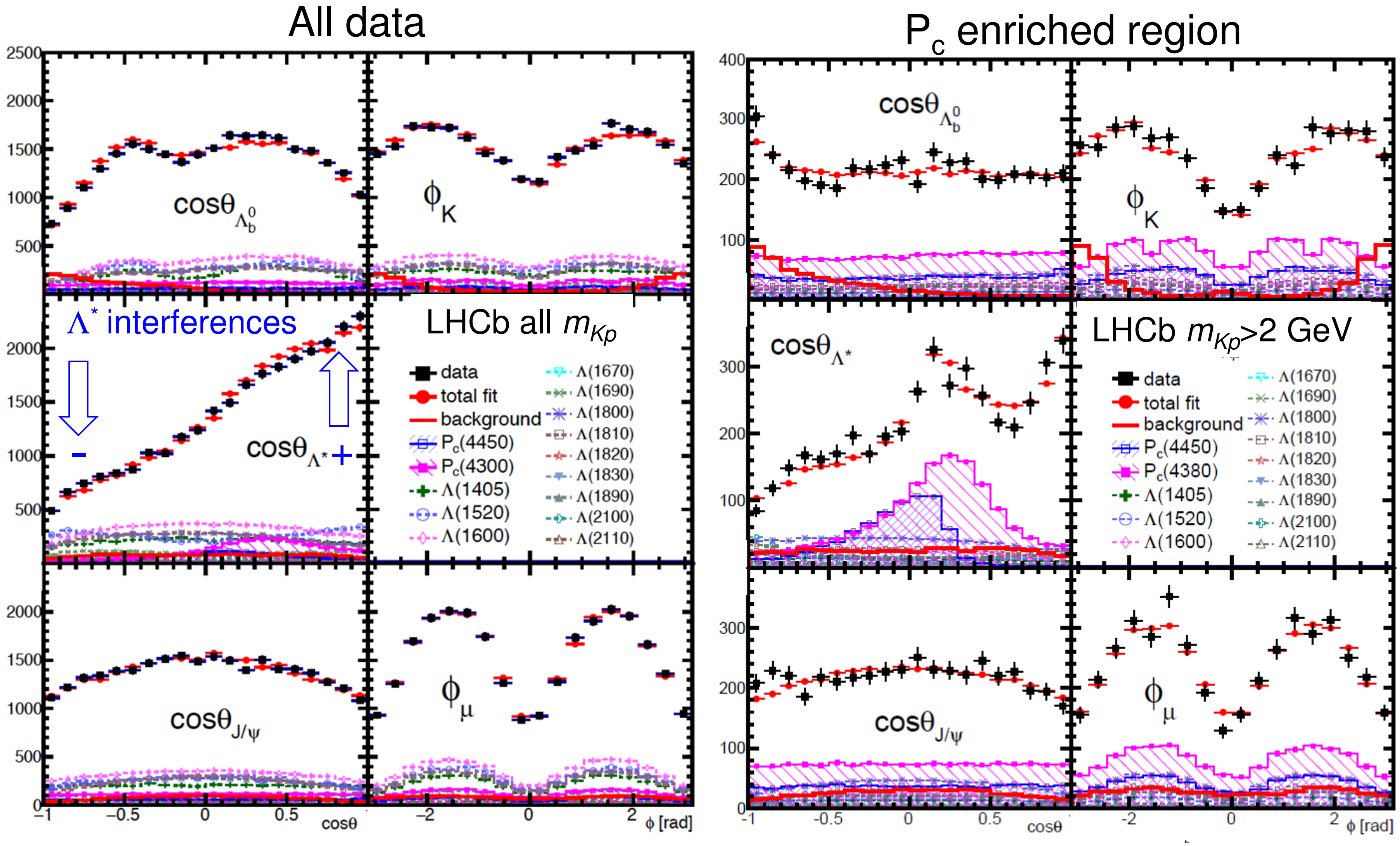
(display before efficiency)

Negative interference between the P_c states

(display after efficiency)

- This interference pattern only for states with opposite parity

Angular distributions



All data

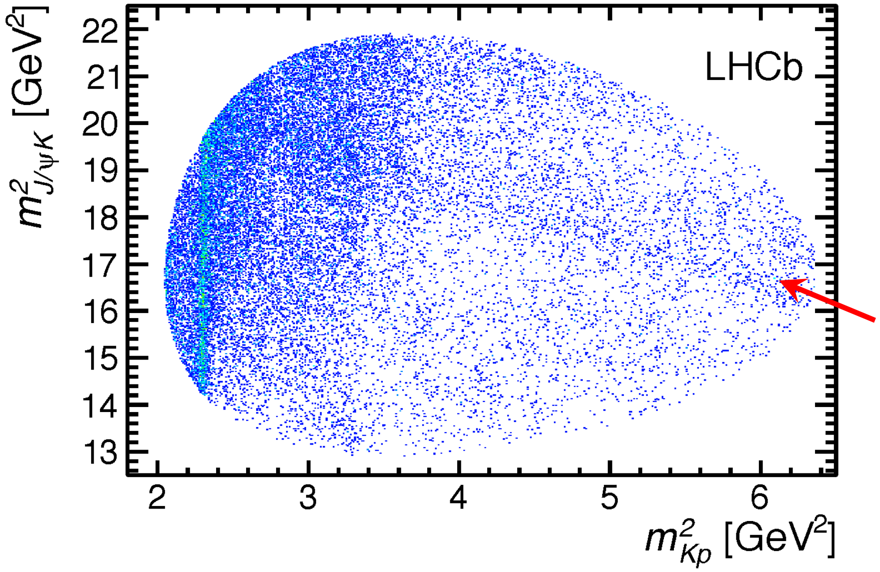
P_c enriched region

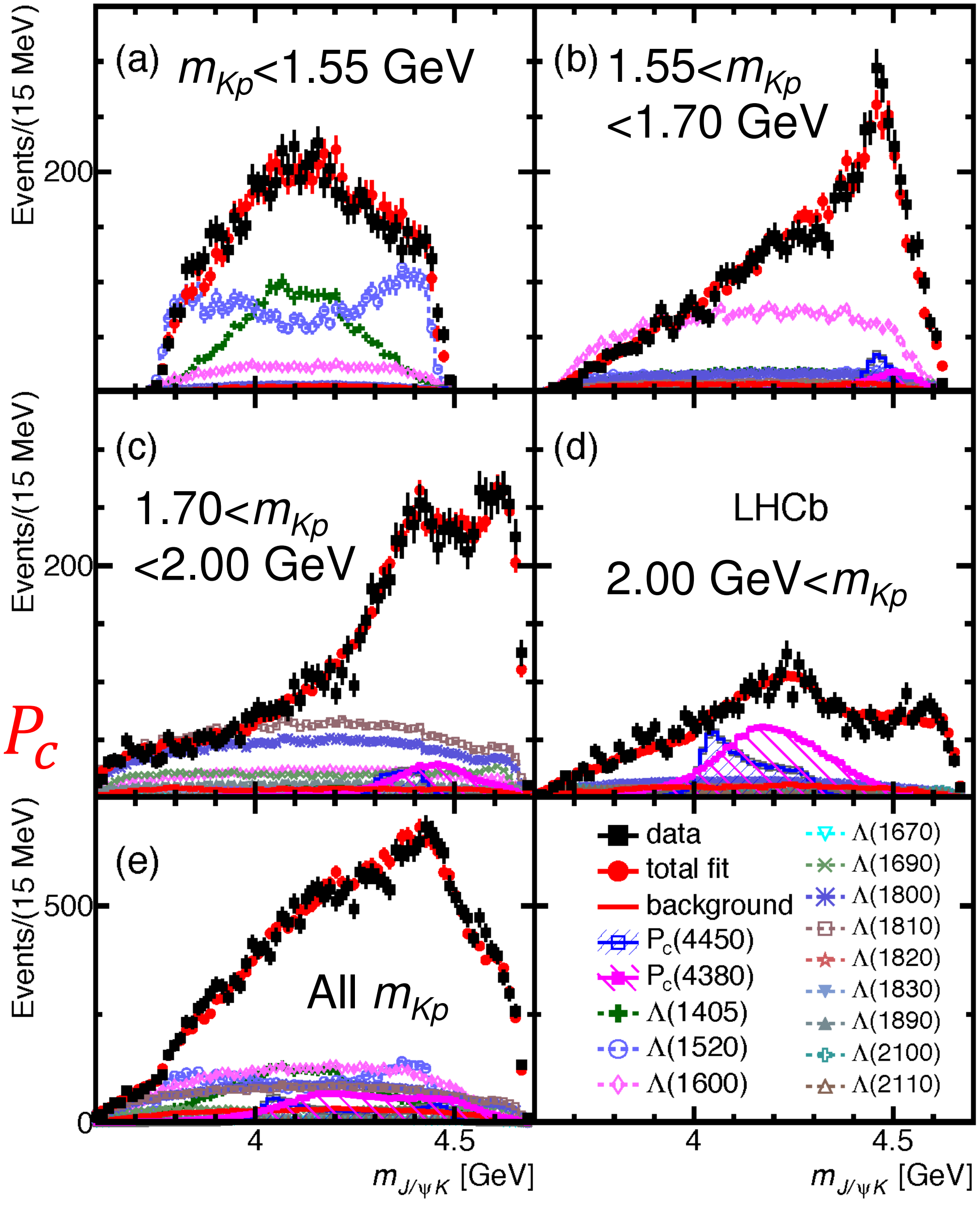
- Good description of the data in all 6 dimensions!

PRL 115, 07201 (2015)

No need for exotic J/ψK$^-$ contributions

- J/ψK$^-$ system is well described by the Λ* and P$_c^+$ reflections.





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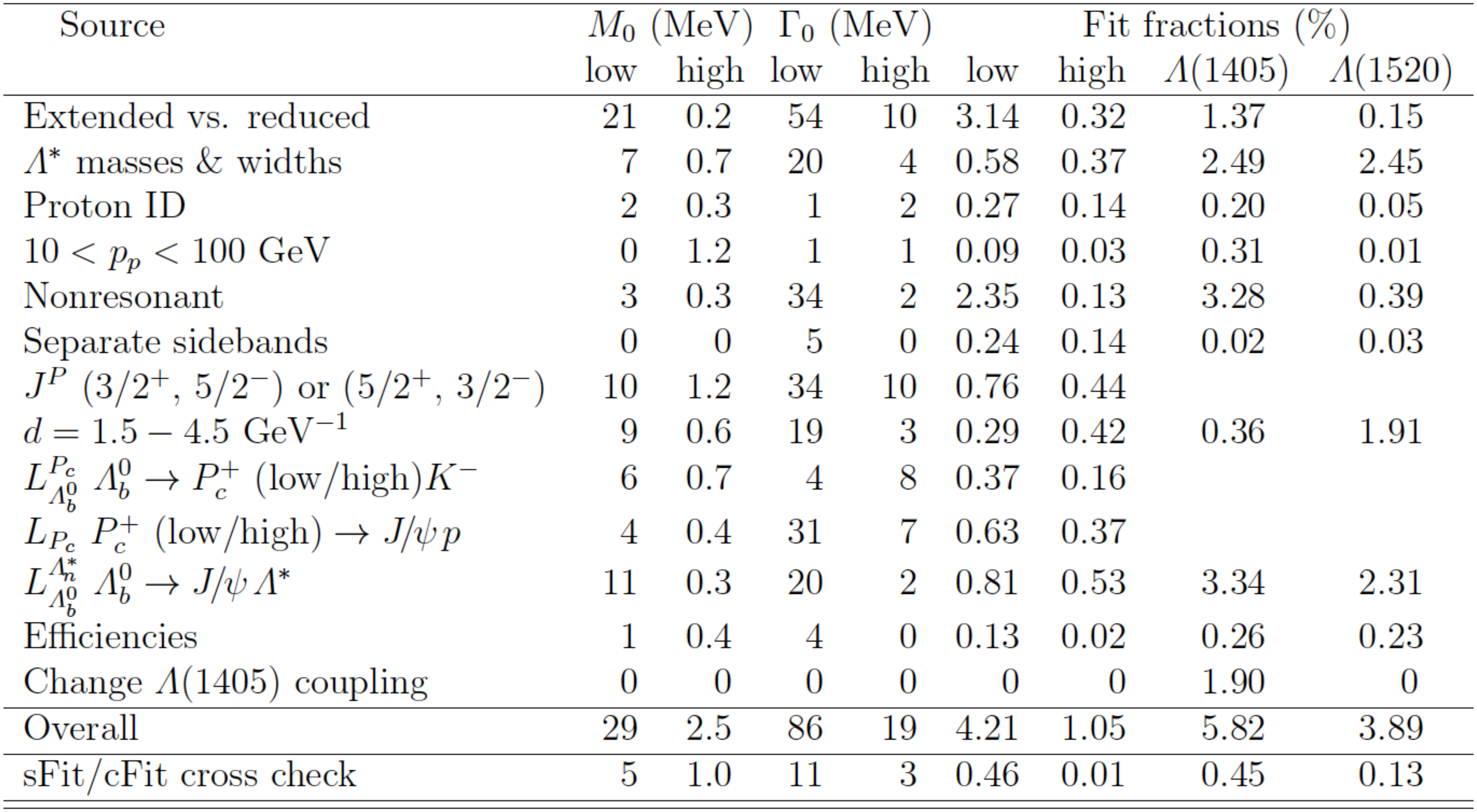
Systematic uncertainties



Source	M_0 (MeV)		Γ_0 (MeV)		Fit fractions (%)			
	low	high	low	high	low	high	$\Lambda(1405)$	$\Lambda(1520)$
Extended vs. reduced	21	0.2	54	10	3.14	0.32	1.37	0.15
Λ^* masses & widths	7	0.7	20	4	0.58	0.37	2.49	2.45
Proton ID	2	0.3	1	2	0.27	0.14	0.20	0.05
$10 < p_p < 100$ GeV	0	1.2	1	1	0.09	0.03	0.31	0.01
Nonresonant	3	0.3	34	2	2.35	0.13	3.28	0.39
Separate sidebands	0	0	5	0	0.24	0.14	0.02	0.03
J^P $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$	10	1.2	34	10	0.76	0.44		
$d = 1.5 - 4.5$ GeV^{-1}	9	0.6	19	3	0.29	0.42	0.36	1.91
$L^{P_c}_{\Lambda_b^0}$ $\Lambda_b^0 \to P_c^+$ (low/high)K^-	6	0.7	4	8	0.37	0.16		
L_{P_c} P_c^+ (low/high) $\to J/\psi p$	4	0.4	31	7	0.63	0.37		
$L^{\Lambda_n^*}_{\Lambda_b^0}$ $\Lambda_b^0 \to J/\psi \Lambda^*$	11	0.3	20	2	0.81	0.53	3.34	2.31
Efficiencies	1	0.4	4	0	0.13	0.02	0.26	0.23
Change $\Lambda(1405)$ coupling	0	0	0	0	0	0	1.90	0
Overall	29	2.5	86	19	4.21	1.05	5.82	3.89
sFit/cFit cross check	5	1.0	11	3	0.46	0.01	0.45	0.13

- Uncertainties in the Λ^* model dominate

Additional cross-checks

- Many additional cross-checks have been done. Some are listed here:
  - The same P_c^+ structure found using very different selections by different LHCb teams
  - Two independently coded fitters using different background subtractions (cFit & sFit)
  - Split data shows consistency: 2011/2012, magnet up/down, $\overline{\Lambda}_b/\Lambda_b$, $\Lambda_b(p_T \text{ low})/\Lambda_b(p_T \text{ high})$
  - Extended model fits tried without P_c states, but with two additional high mass Λ^* resonances allowing masses & widths to vary, or 4 non-resonant terms of J up to 3/2

Argand diagrams

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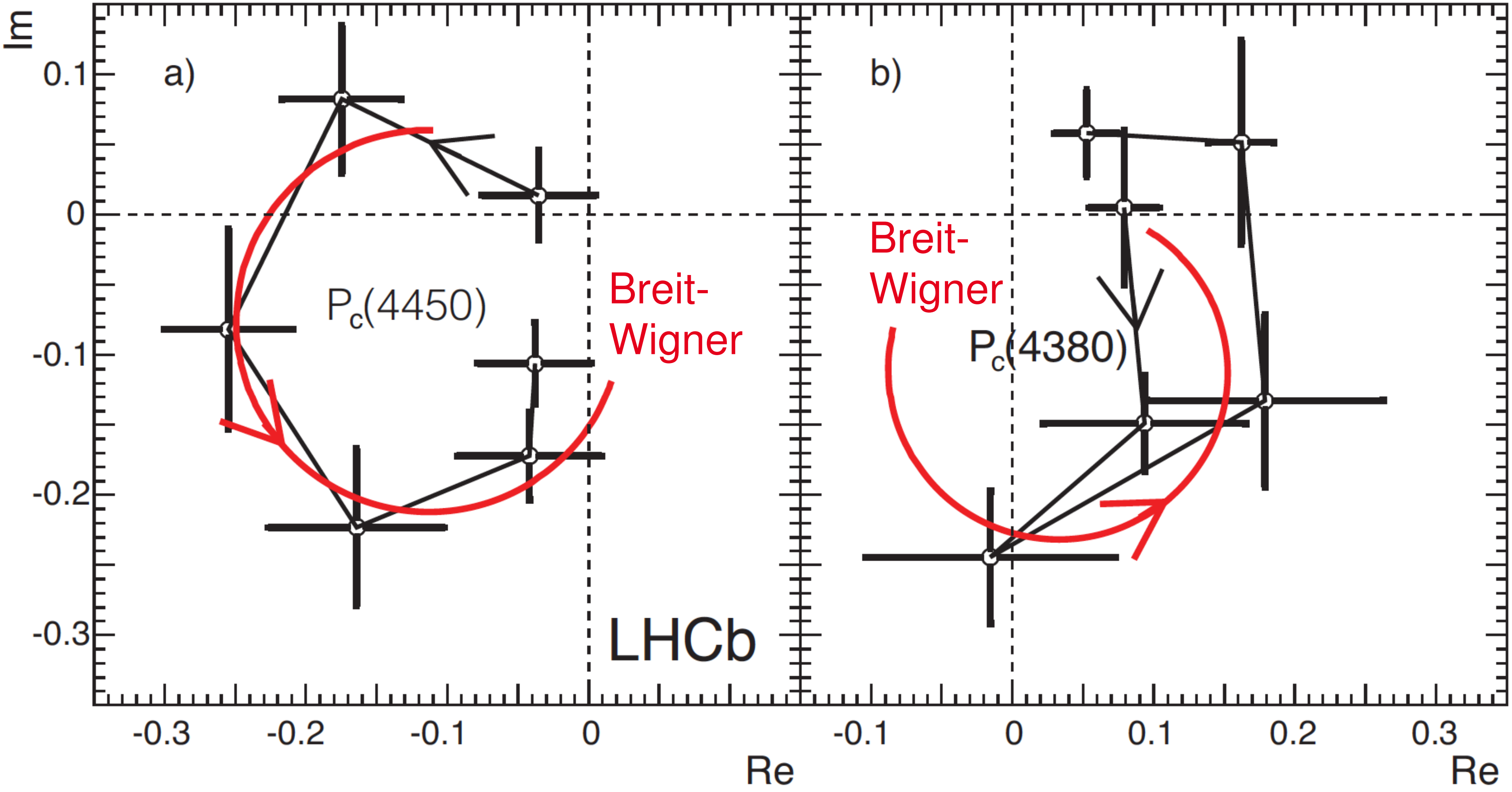
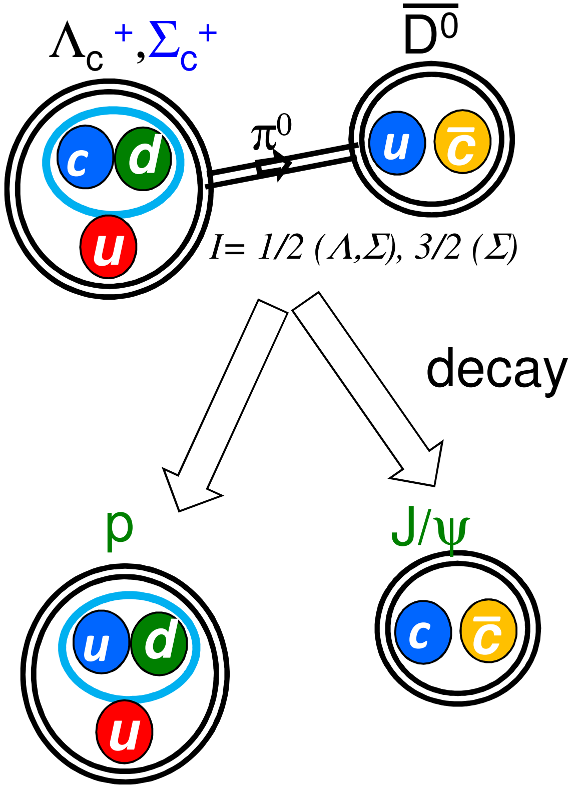
P_c^+ amplitudes for 6 $m_{J/\psi p}$ bins between $+\Gamma$ & $-\Gamma$ around the resonance mass

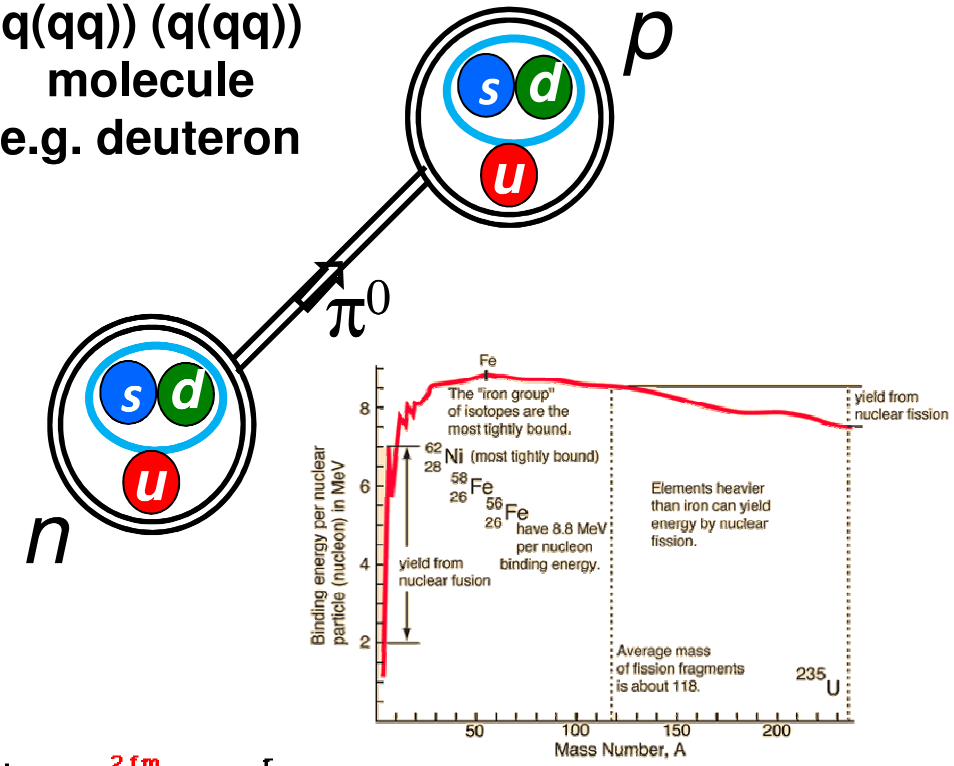


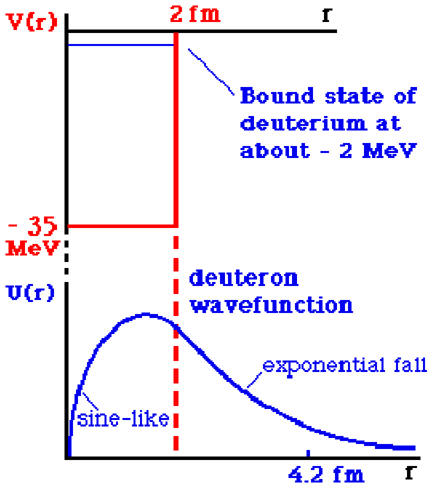
- Good evidence for the resonant character of $P_c(4450)^+$
- The errors for $P_c(4380)^+$ are too large to be conclusive

Molecular states?



(q(qq)) (q(qq)) molecule e.g. deuteron





Difficult to get more than one state ($n=1,l=0$).

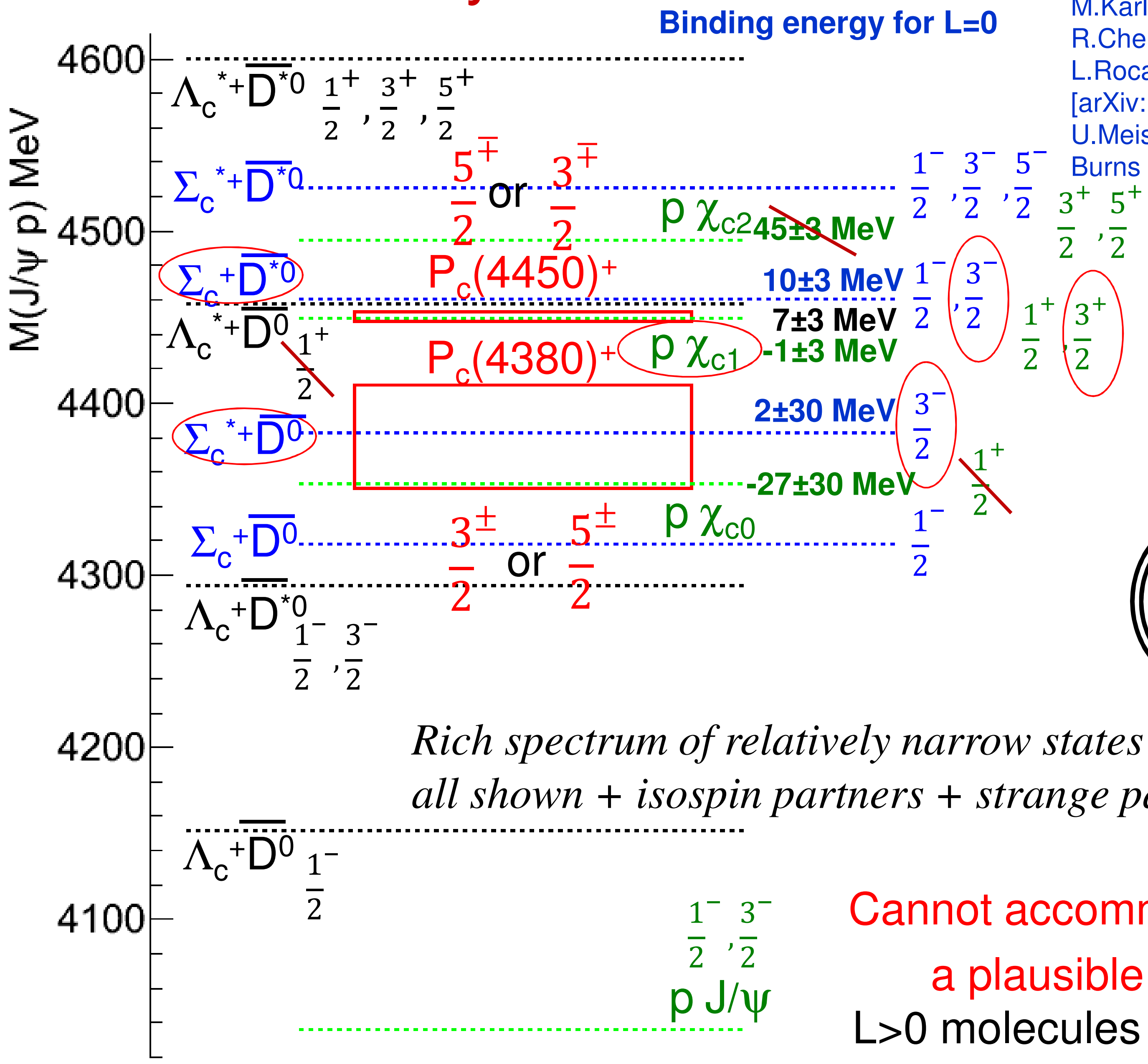
$M = M_1+M_2 -$ (a few MeV)

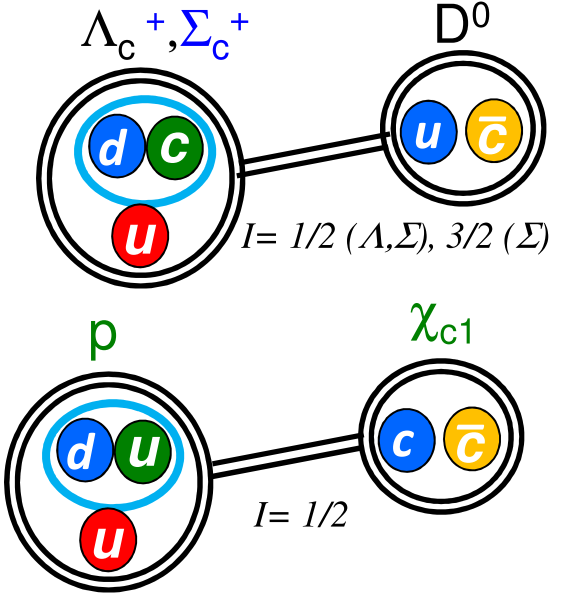
$J^P = (J_1 \otimes J_2)^{P1*P2}$

$\Gamma \sim \max(\Gamma_1,\Gamma_2)$

Baryon-meson molecules?

M.Karliner, J.Rosner [arXiv:1506.06386], R.Chen et al [arXiv:1507.03704 L.Roca,J.Nieves,E.Oset [arXiv:1507.04249].J.He [arXiv:1507.05200] U.Meissner,A.Oller [arXiv:1507.07478],T.J. Burns [arXiv:1509.02460]



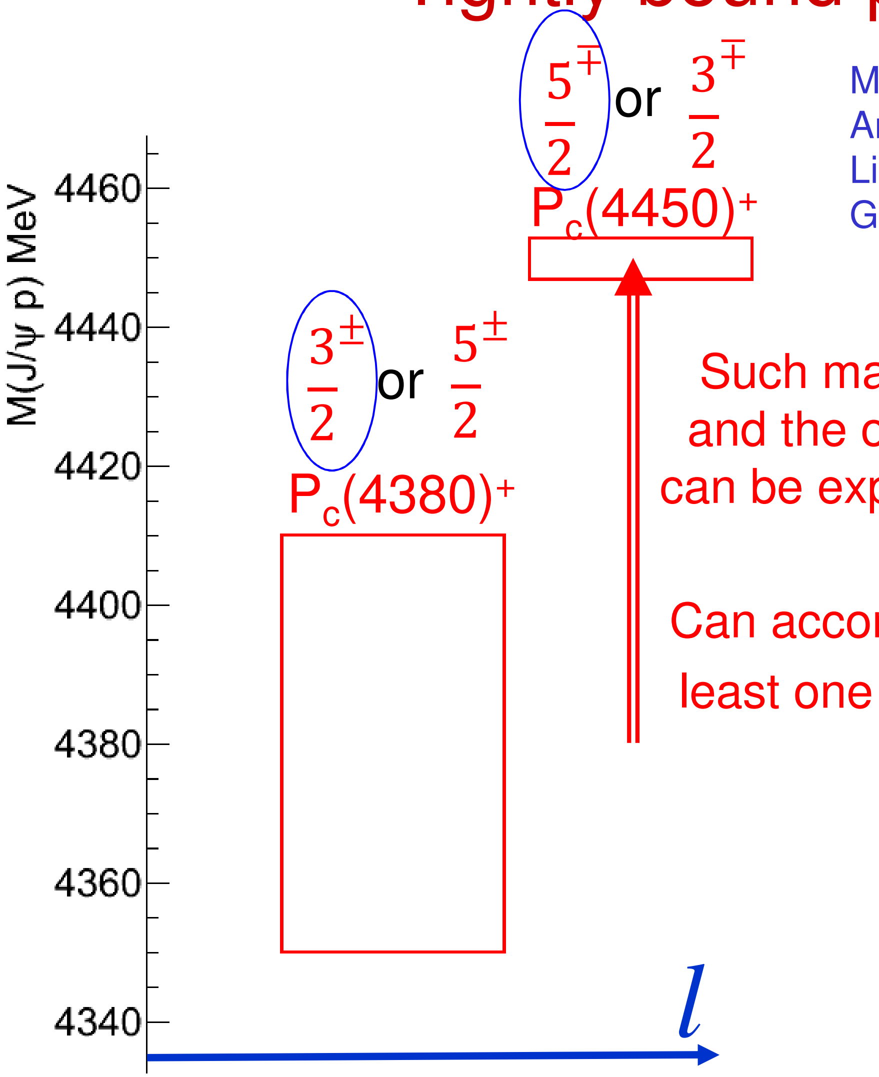


Rich spectrum of relatively narrow states expected:
all shown + isospin partners + strange partners + b quark + …

Cannot accommodate a $\frac{5}{2}^{\pm}$ state with a plausible S-wave molecule

L>0 molecules not likely to be bound

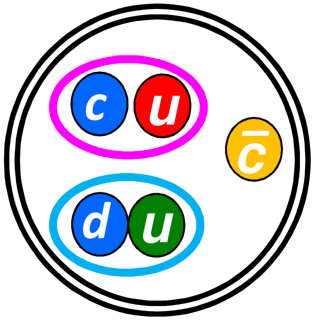
Tightly bound pentaquarks?



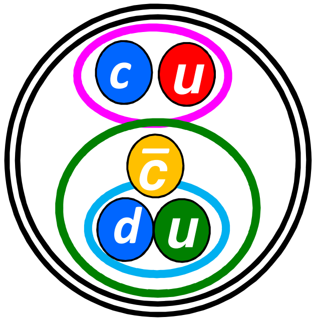
Such mass difference and the opposite parity can be explained by $\Delta l=1$

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

Maiani, Polosa,Riquer [arXiv:1507.04980],
Anisovich et al [arXiv:1507.07652,1509.04898],
Li,He,He [arXiv:1507.08252],
Ghosh et al [arXiv:1508.00356]



R. Lebed [arXiv:1507.05867]



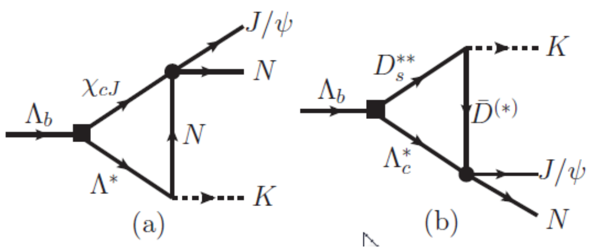
Rich spectrum of states expected:
$S=0$ (lower J)+ l + n + isospin partners
+ strange partners + b quark + …

e.g.

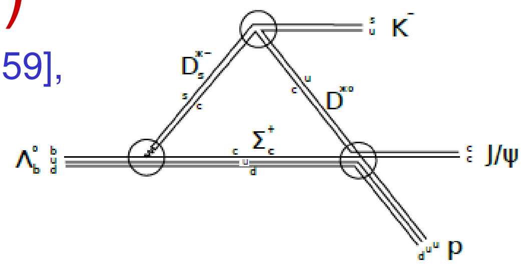
$\bar{c}[cu]_{S=1}\,[ud]_{S=0}$ ***(l=1)***

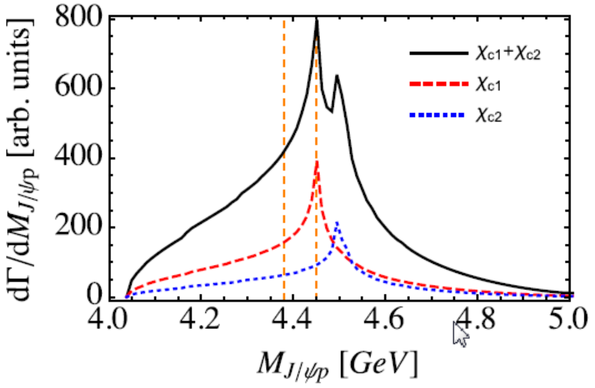
$\bar{c}[cu]_{S=1}\,[ud]_{S=1}$ ***(l=0)***

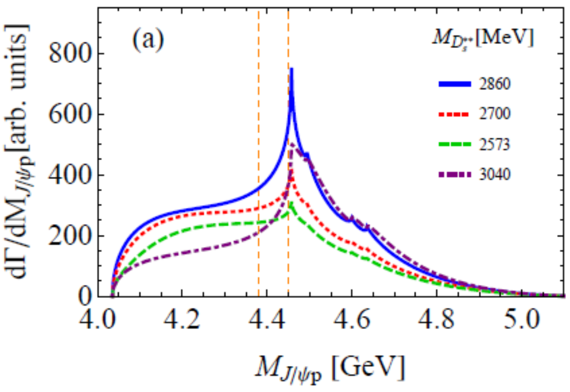
Rescattering (triangular singularity)

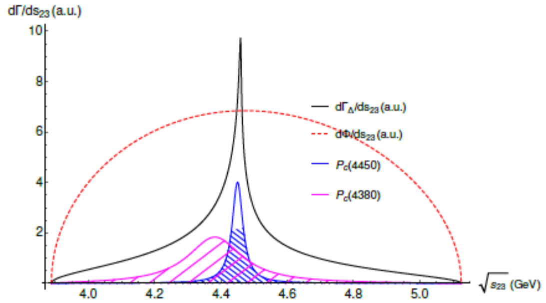


Z.-H.Liu,Q.Wang,Q.Zhao [arXiv:1507.05359],
M. Mikhashenko [arXiv:1507.06552],
A. Szczepaniak [arXiv:1510.01789]

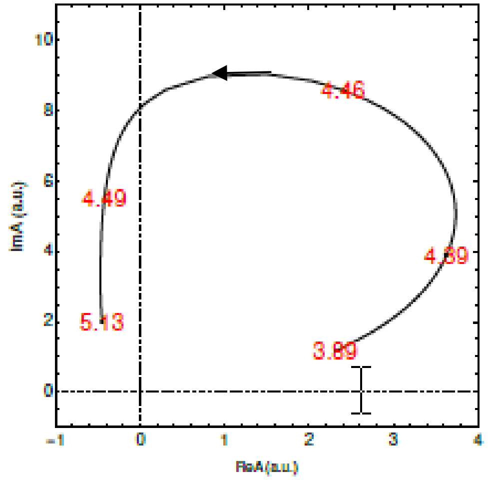








- Conventional hadrons produced and then rescatter (rearrange quarks) to produce a peak in the exotic channel. Peaking structures related to mass thresholds.
- Ad hoc parameter values to generate desired structures.
- Can sometimes arrange for the resonant-like phase running.
- Given proliferation of thresholds, why aren't they everywhere?
- Not clear these models can describe decay angles distributions – predictions and tests on the data are needed.
- In the past, many resonances which are well established by now, were proposed to be rescattering effects (e.g. a_1(1260)).



Future studies of $P_c(4380)^+$,$P_c(4450)^+$

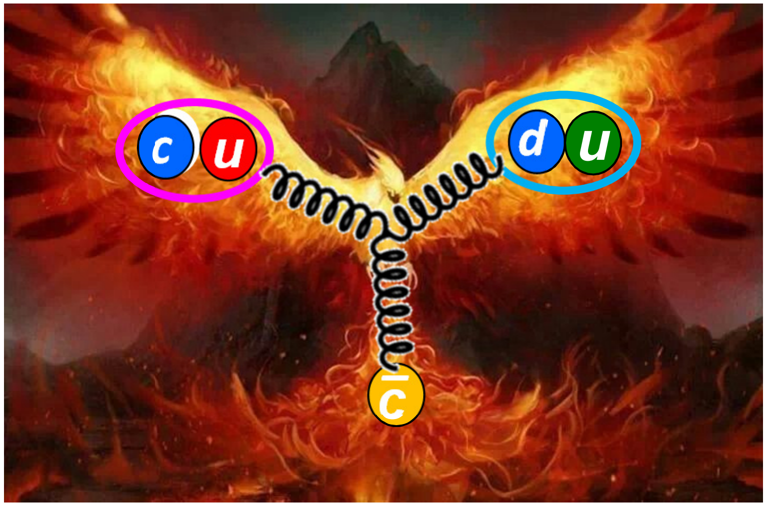
- Nathan has a few months left before he will graduate:
  - We are working on improving Λ^* model in hope that we can improve P_c J^P determinations:
    - In present Isobar model:
      - try new states suggested in C. Fernandez-Ramirez et al paper (arxiv:1510.07065 Oct 23), remove $\Lambda(1800)$
      - more advanced models of non-resonant contributions than what we have tried so far
      - see if our data can contribute to Λ^* spectroscopy
    - Possibly replace the Isobar approach with C. Fernandez-Ramirez et al approach adopted to our data (with their help!)
  - We are interested in testing rescattering models, but need their 6D formulation!
- There is a large effort in LHCb to look for these states in other modes and for other pentaquarks with heavy quarks

Outlook to the future

- At present there are many plausible explanations for the observed P_c^+ states.
- The main competition is between tightly bound models based on diquark substructure, loosely bound molecules and rescattering effects.
- Clarifying J^P values and resonant nature of the discovered P_c^+ states with more statistics will be very important.
- All models predict many other related states to exist. Different models predict different mass spectra. We badly need to discover more elements of future periodic table of such states!
- Interactions forming pentaquark states must also play a role in tetraquark states. It is important to pursue both spectroscopies together!
- Searches for states with even more quarks e.g. sextquarks (i.e. dibaryons) interesting.
- We can do more to test the diquark idea in ordinary baryons! Need experimentalists to do better on identifying all excited baryons.
- So far the most compelling tetraquark and pentaquark candidates have been discovered with hidden charm inside ($c\bar{c}$). The other heavy quark systems should also be creating bound structures ($b\bar{b}$, $b\bar{c}$, $cc\bar{c}$, …)
- We are only at the beginning of hopefully very interesting road ahead…

Conclusion

- Two pentaquark candidates decaying to J/ψp observed by LHCb with overwhelming significance in a state of the art amplitude analysis: they will not go away!



Frank Wilczek's twit on 7/14/15: "Pentaquarks rise from the ashes: a phoenix pair"

Pentaquark candidates rise from the ashes for the 2nd time.

- LHC resurrects them: should not be a surprise given baryon cross-sections.

$c\bar{c}$ pair inside:

- Given the history of Quark Model should not be a surprise either.

Hopefully true July 2015 revolution!

- The simplicity of lower mass excitations of mesons and baryons, which led us to the discovery of quarks via $q\bar{q}$, qqq structures, also misled us to believe that we had already understood hadronic structures. Much experimental and theoretical work remains to be done to achieve this goal.