New pentaquark states in B meson decays at LHCb

End-of-year seminar

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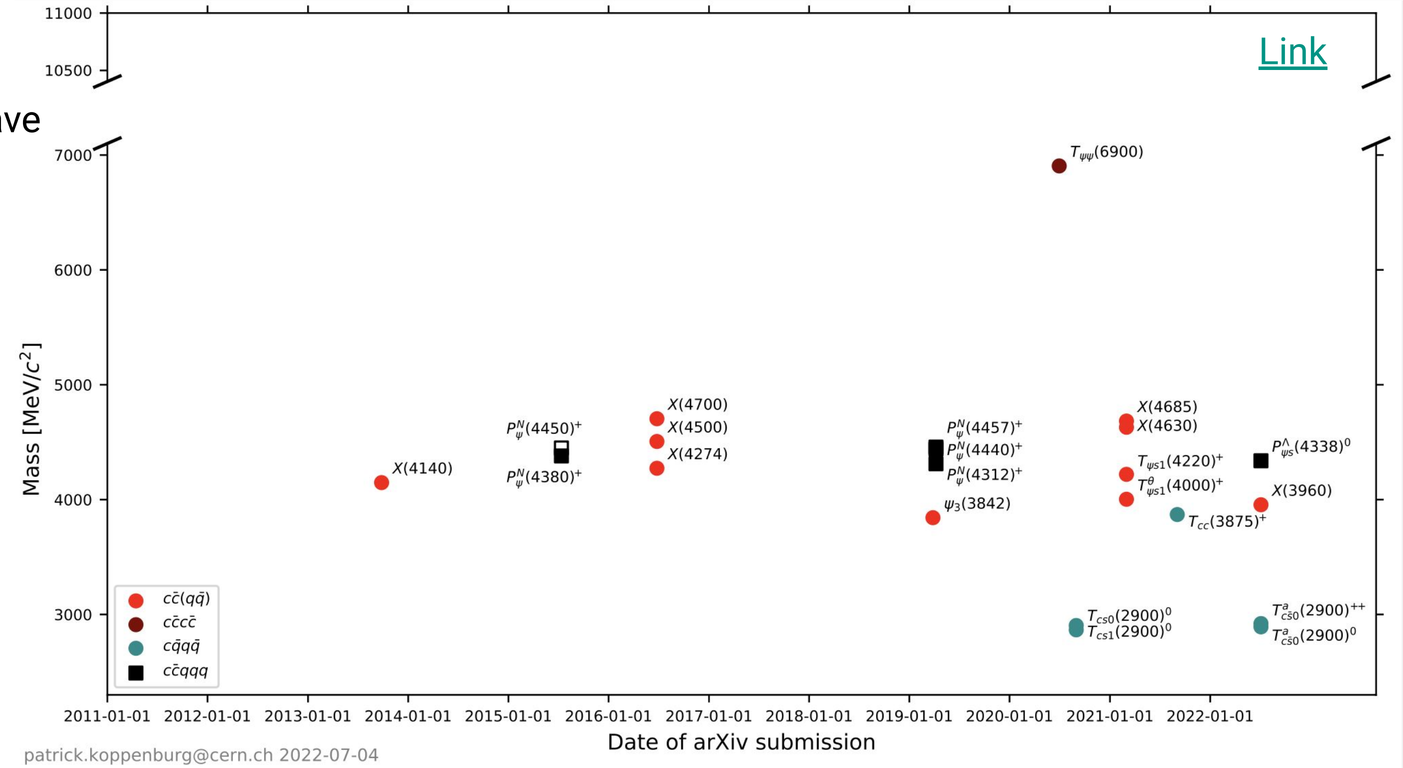
Spectroscopy at LHC

More than 60 hadrons have been observed by LHC

14 manifestly exotic

- minimal quark content different from $q\bar{q}$ and qqq



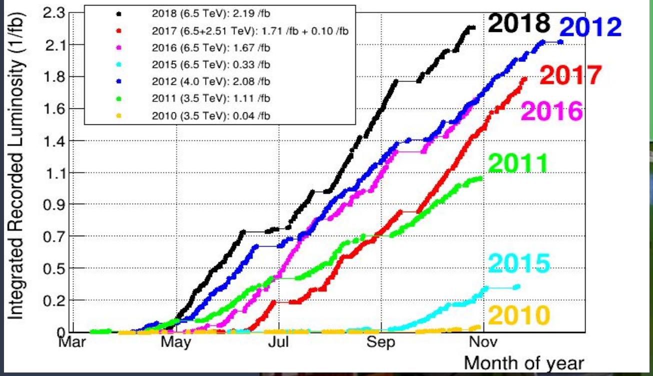
LHCb detector

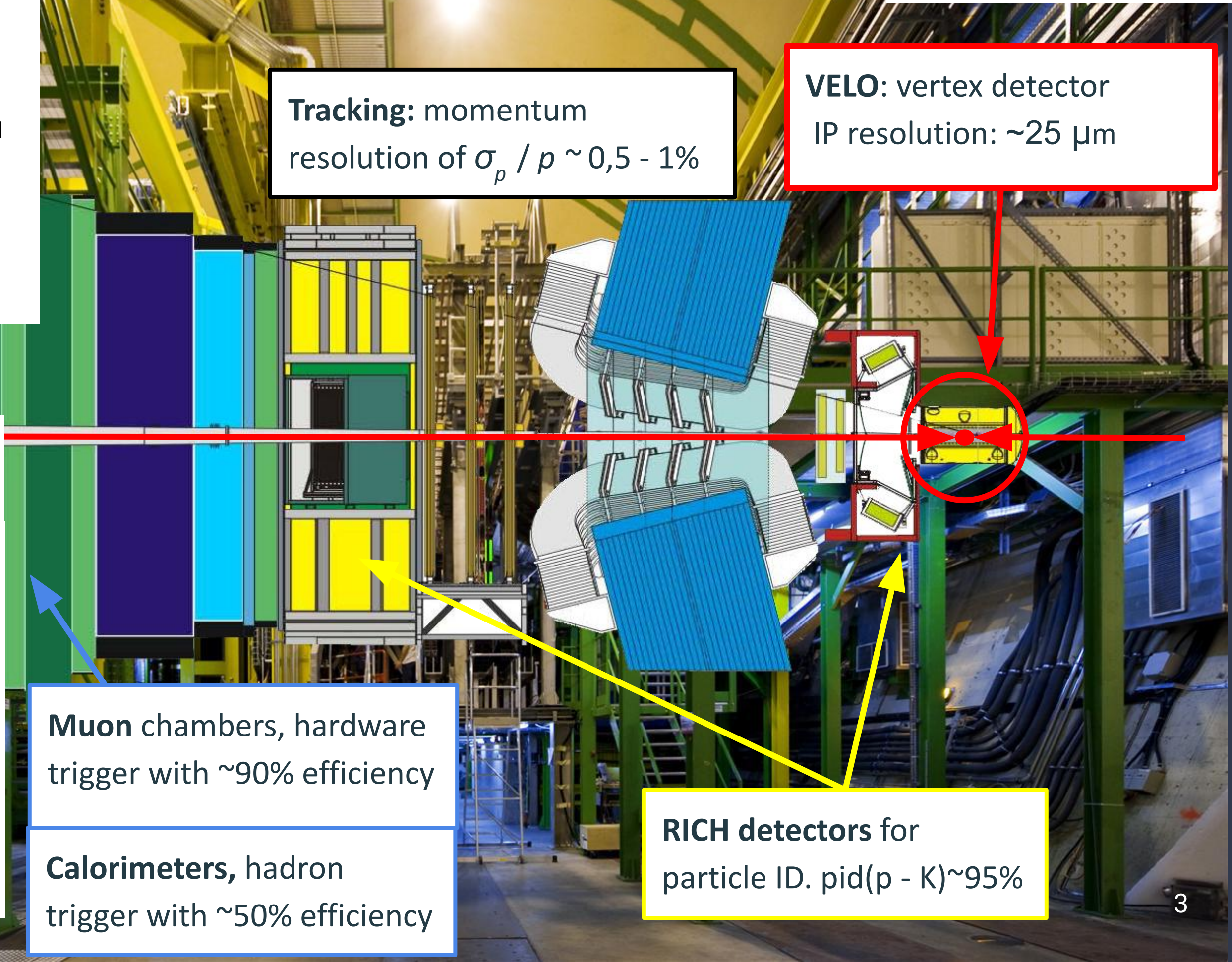
[JINST 3 (2008) S08005](#)
IJMP A 30, 1530022 (2015)

The major player in spectroscopy thanks to its unique dedicated design

- high invariant mass resolution
- PID for separate K, π, p
- highly performant trigger

Luminosity:
Run 1 and Run 2: 9 fb^{-1}





Tracking: momentum resolution of $\sigma_p\ /\ p$ ~ 0,5 - 1%

VELO: vertex detector
IP resolution: ~25 μm

Muon chambers, hardware trigger with ~90% efficiency

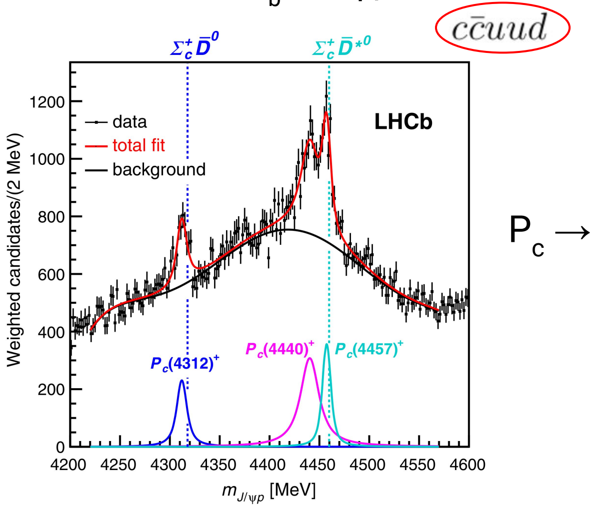
Calorimeters, hadron trigger with ~50% efficiency

RICH detectors for particle ID. pid(p - K)~95%

Pentaquarks

New naming scheme: arxiv2206.15233

First pentaquarks by LHCb in 2015 in $\Lambda_b \to J/\psi p K$

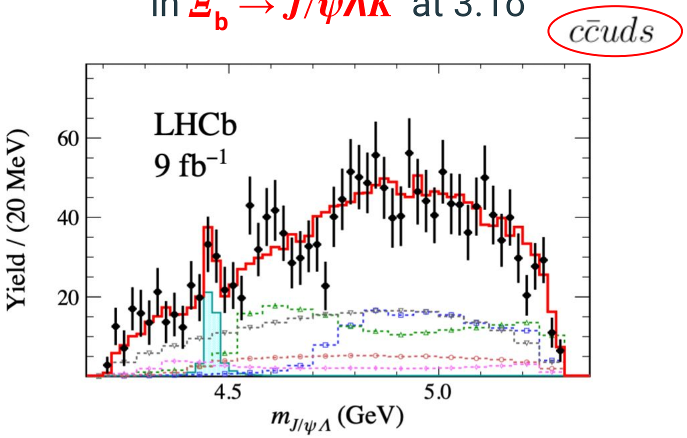


$P_c \to P_\psi^N$

$P_c(4312)^+$ + 2 peaks at 4450 MeV

PRL 122, 222001 (2019)

Evidence for $P_{cs} \to P_{\psi s}^{\Lambda}(4459)$ in $\Xi_b^- \to J/\psi \Lambda K$ at 3.1σ



⇒ pentaquark with strangeness

✓ at $\Xi_c^0 D^{*0}$ threshold

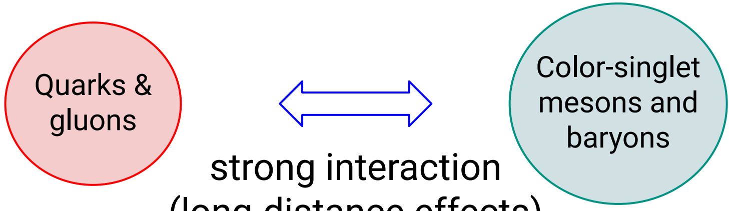
Sci.Bull. 66 (2021) 1278-1287

PLB 772 (2017) 265-273

The unresolved nature

Elementary particles

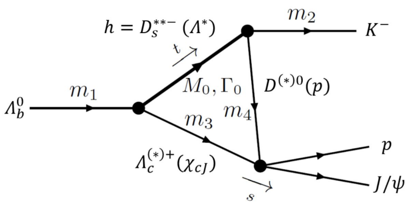
Nature



strong interaction
(long-distance effects)

Rescattering effects

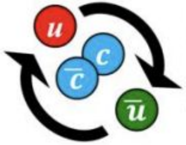
Guo,Meissner,Wang,Yang, PRD 92 (2015) 071502
Liu, Wang, Zhao, PLB 757 (2016) 231
Mikhasenko, arXiv:1507.06552
Szczepaniak, PLB 757 (2016) 61
and others



Compact tetraquark/pentaquark

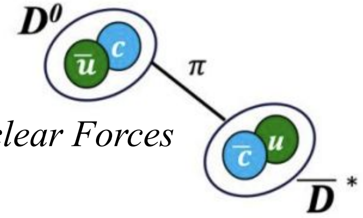
Diquark-antidiquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)

Color Forces



Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

Hadronic Molecules
PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 011502(R) (2019)



Nuclear Forces

How to discriminate?

⇒ Masses & widths

⇒ J^P

⇒ Isospin multiplets

No consensus yet

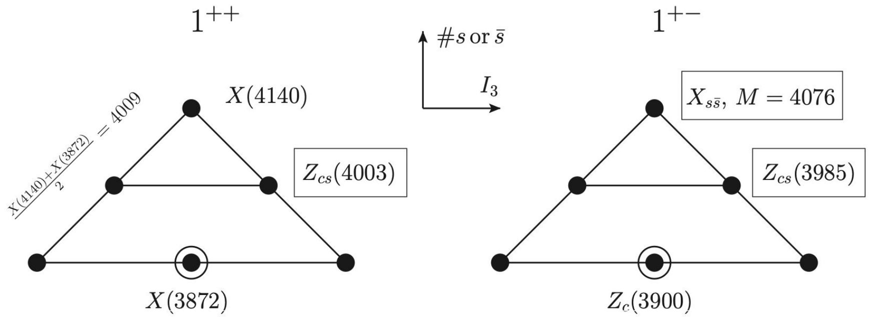
Many peaks close to meson-meson or meson-baryon thresholds and have narrow widths:

		Threshold
$T_{cc}(3875)^+$	$cc\bar{u}\bar{d}$	$D^{*+}D^0$
P_ψ^N	$c\bar{c}uud$	$\Sigma_c\, D^{0(*)}$
$P_{\psi s}^\Lambda(4459)^0$	$c\bar{c}uds$	$\Xi_c{}^0 D^{*0}$

⇒ favor the **molecular** interpretation

In S-wave?
⇒ Need to establish J^P

States belonging to multiplets of $SU(3)_f$ symmetry
ie. $Z_{cs}{}^+(4000)$ and $Z_{cs}{}^+(3985)$



L. Maiani, A. D. Polosa and V. Riquer, Sci. Bull. 66 (2021)

⇒ fit in the **compact model**

Search for states with *s* quark content

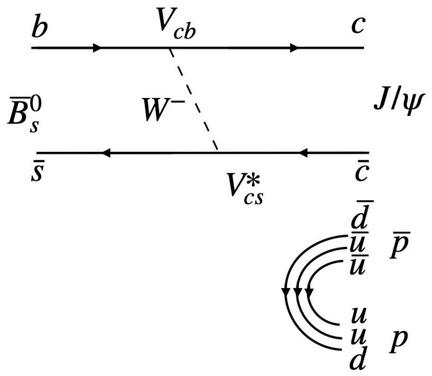
New decays to search for pentaquarks

Multibody decays of *B* meson

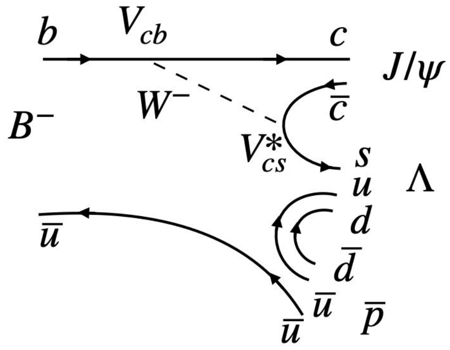
- good invariant mass resolution
- high signal purity

⇒ good place to search for narrow resonances ⇒ Exotic states

$$B_s^0 \to J/\psi p\bar{p}$$



$$B^- \to J/\psi \Lambda \bar{p}$$



Evidence of new structure in $J/\psi p$ and $J/\psi \bar{p}$ systems in $B^0_{(s)} \to J/\psi p \bar{p}$ decays

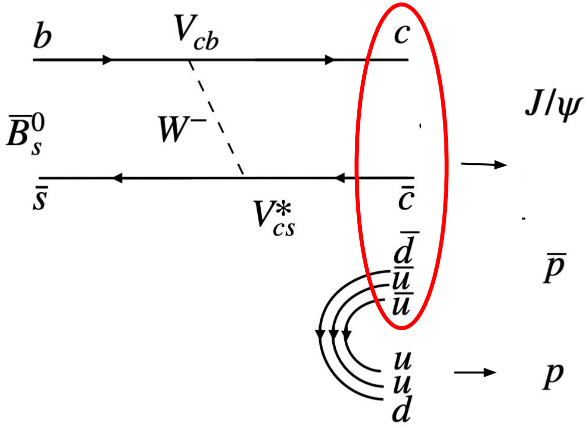
Part of my PhD thesis
& published this year in
PRL 128 (2022) 062001

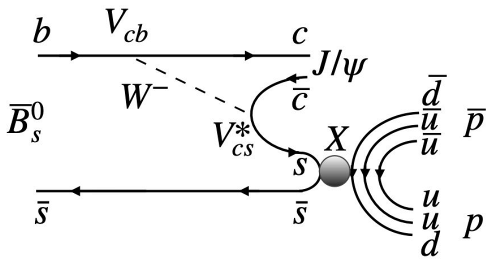
$B_s^0 \to J/\psi p\bar{p}$ decays

PRL 128 (2022) 062001

Search for pentaquark searches in $J/\psi p$ and $J/\psi \bar{p}$ and for glueball[2] in $p\bar{p}$ system

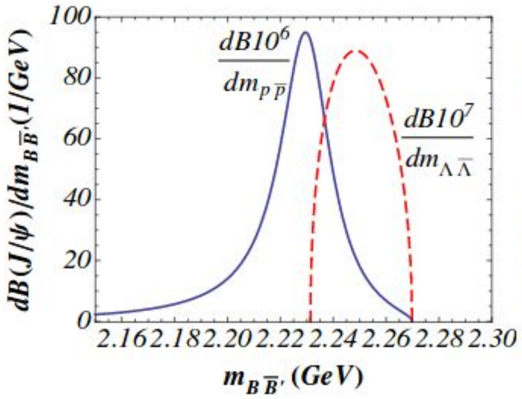
P_c^-





→ Same final state as $\Lambda_b \to J/\psi pK$ [1] but mesonic decay ⇒ clearer channel

Resonant state $f_J(2230) \to p\bar{p}$, peak at 2.2 GeV and $J^P = 2^{++}$ or 4^{++} [2]

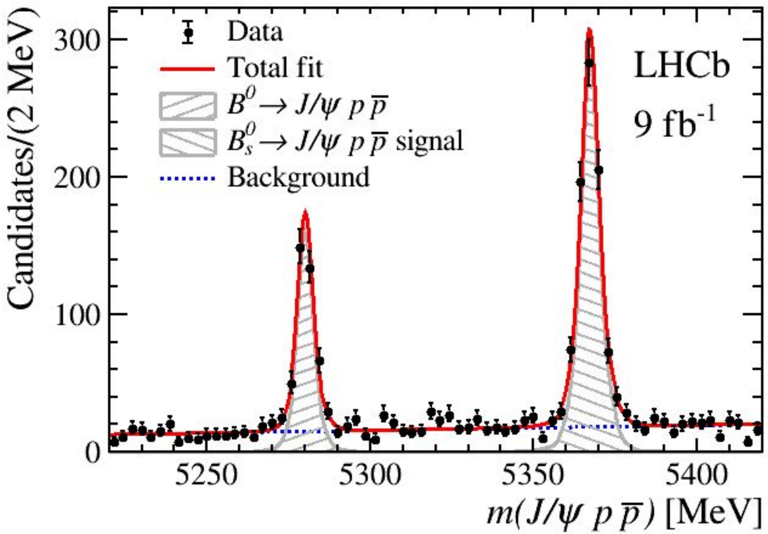


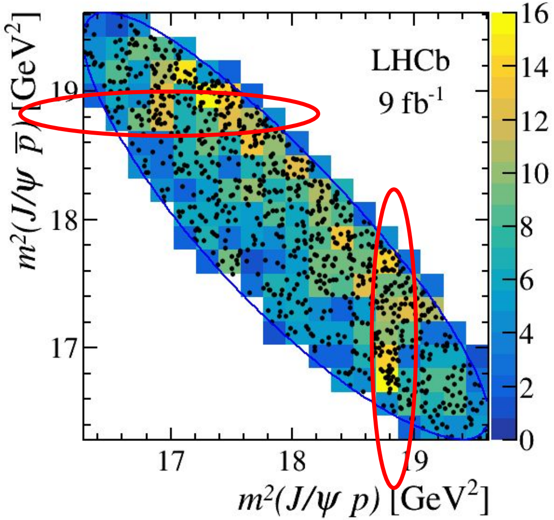
[1] PRL 122, 222001 (2019)
[2] Eur. Phys. J. C75 (2015), no. 3 101

Selection

Dataset: 9 fb^{-1}
~800 B_s events in 3σ window with 15% of background

$N_{sig}(B_s)$ = 776 +/- 30
f_{bkg} = 14.9 +/- 0.6 %
Purity: 85.1%





Structure in J/ψp, but to rule out possible pp reflections

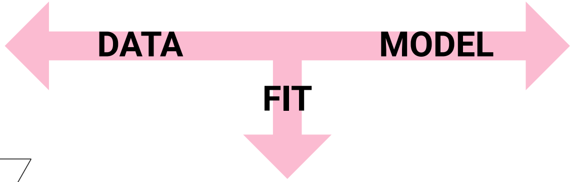
Amplitude analysis in 4D

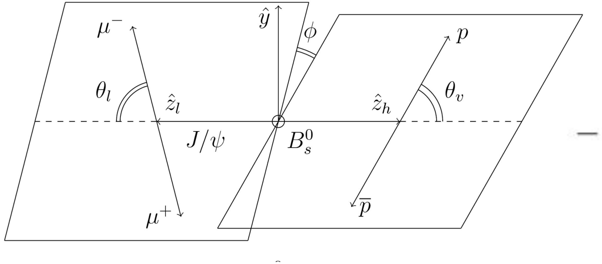
[LHCb-PAPER-2021-018]

The amplitude analysis

4D phsp

$\Phi=(m_{pp}, \cos\theta_l, \cos\theta_v, \varphi)$





$$-2\ln\mathcal{L}(\vec{\omega}) = -2\sum_i \ln\mathcal{P}\left(m_{p\bar{p}i}, \Omega_i|\vec{\omega}\right)$$

Helicity formalism

- flavour untagged B_s decays
- assuming CP symmetry

2-body decay amplitudes:

$$\mathcal{A}^{A->12}_{\lambda_A,\lambda_1,\lambda_2}(\theta_1,\phi_1) = \langle p,\theta_1,\phi_1,\lambda_1,\lambda_2|\hat{T}|J_A,\lambda_A\rangle$$
$$= \mathcal{H}_{\lambda_1,\lambda_2} D^{*J_A}_{\lambda_A,\lambda_1-\lambda_2}(\phi_1,\theta_1,0)\mathcal{R}(m^2_{12}).$$

Helicity couplings — Wigner rotation — lineshape $\Rightarrow$ M, Γ

$\Rightarrow J^P$

Fit models:

- Baseline model: only non resonant (NR) in pp chain
- Baseline + old P_c states: $P_c(4312)$
- Baseline + new P_c state ⇒ Nominal model

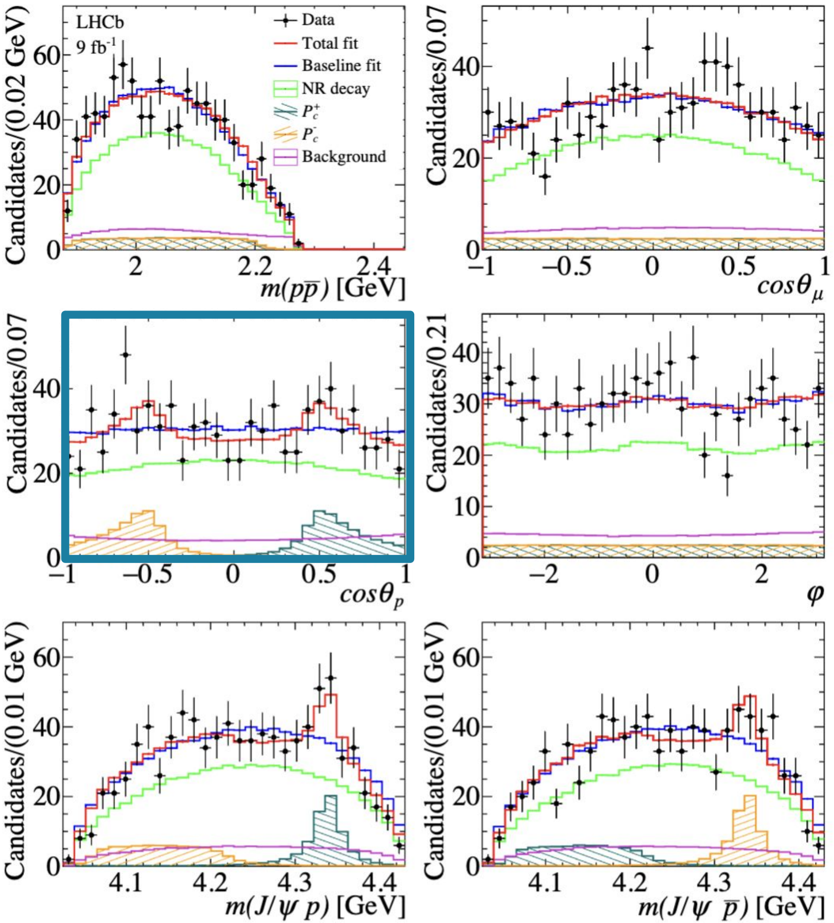
Nominal fit to data

Amplitude contributions:

- NR in S-wave in $p\bar{p}$
- P_c^+ and P_c^- with same M, Γ and coupling

→ Improvement in $cos\theta_p$ (helicity angle of p) w.r.t. baseline model

Goodness of fit test:
$\chi^2/ndf = 0.998 \pm 0.008$



Other models tested:

- **Old P_c states** observed by LHCb in 2019
- **Glueball** at M~2.2GeV and Γ=20 MeV

⇒ No evidence

Evidence of a new exotic state

PRL 128 (2022) 062001

New pentaquark-like state $c\bar{c}uud$
with significance between 3.1-3.7σ

$$M_{P_c} = 4337^{+7}_{-4}(\text{stat}) \pm 2(\text{sys})\text{MeV},$$
$$\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat}) \pm 14(\text{sys})\text{ MeV}$$

⇨ P_c(4337) not consistent with previously observed P_c states

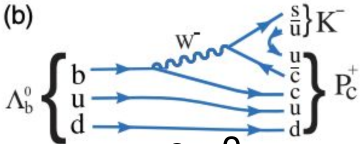
Peculiar that:

- P_c*(4312)* only in Λ_b decays
- P_c*(4337)* only in B_s decays

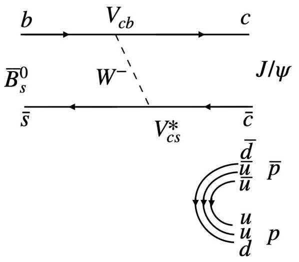
Possible theoretical interpretations

- Tight pentaquark: PRD 104, 114028 (2021)

  Creation processes involving different spin (s_δ) of the di-quark (ud)

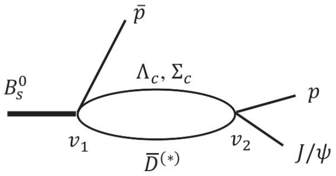


s_δ=0



s_δ=1

- Triangle cusps: Phys. Rev. D **104**, L09150
  Interference effects between
  $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}^*$ threshold cusps
  can explain the oscillation in $\cos\theta_p$



Observation of a $J/\psi\Lambda$ resonance in $B^- \to J/\psi\Lambda\bar{p}$ decays

LHCb-PAPER-2022-031

$B^- \to J/\psi\Lambda\bar{p}$ decays

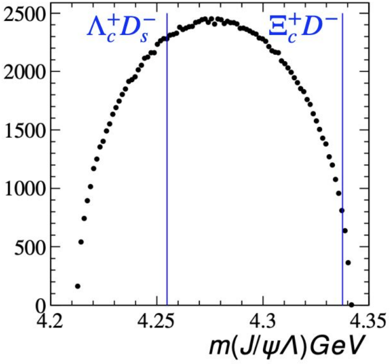
LHCb-PAPER-2022-031

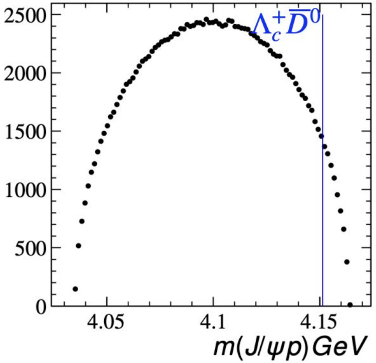
Branching ratio: [1]

$$\mathcal{B}(B^- \to J/\psi\Lambda\bar{p}) = (11.8 \pm 3.1)\cdot 10^{-6}$$

⇒ Candidate for pentaquarks in $J/\psi\Lambda$ and $J/\psi\bar{p}$

Phsp covers thresholds of $\Lambda_c D_s^-$~4251 MeV, $\Xi_c^+ D^-$~4337.6 MeV, and $\Lambda_c^+ D^0$~4151.3 MeV

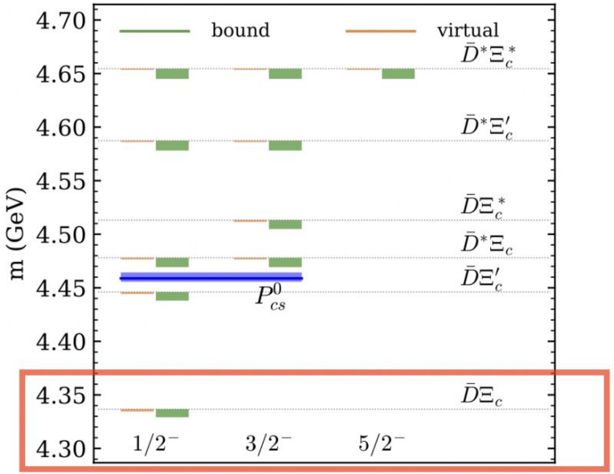




Existing interpretations:

Molecular states: low binding energy = few MeV below threshold

Progr.Phys.41(2021)65-93



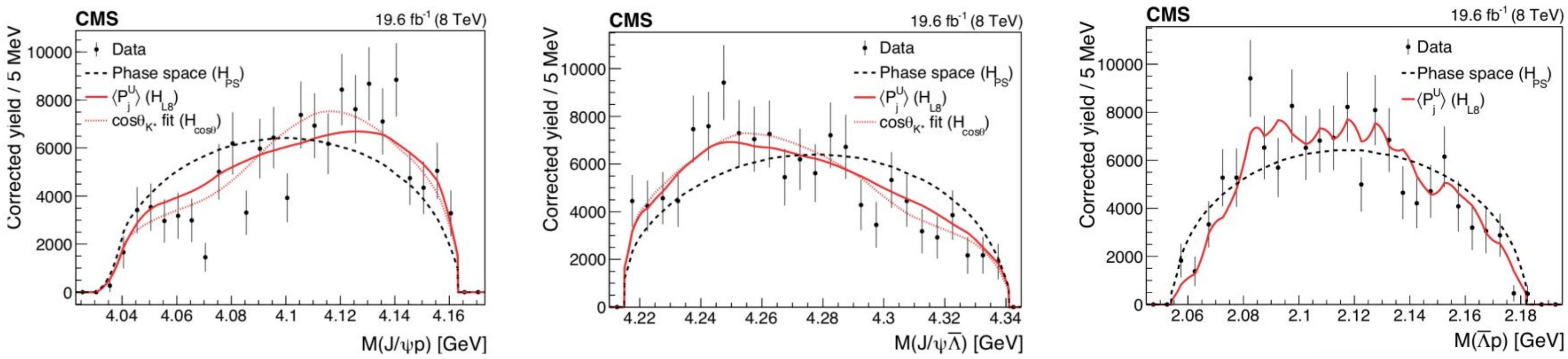
$B^+ \to J/\psi\bar{\Lambda}p$ @CMS: Inconsistency with flat phsp

CMS: JHEP12(2019)100

CMS published results with 19.6 fb^{-1} at 8 TeV

⇒ ~450 signal events

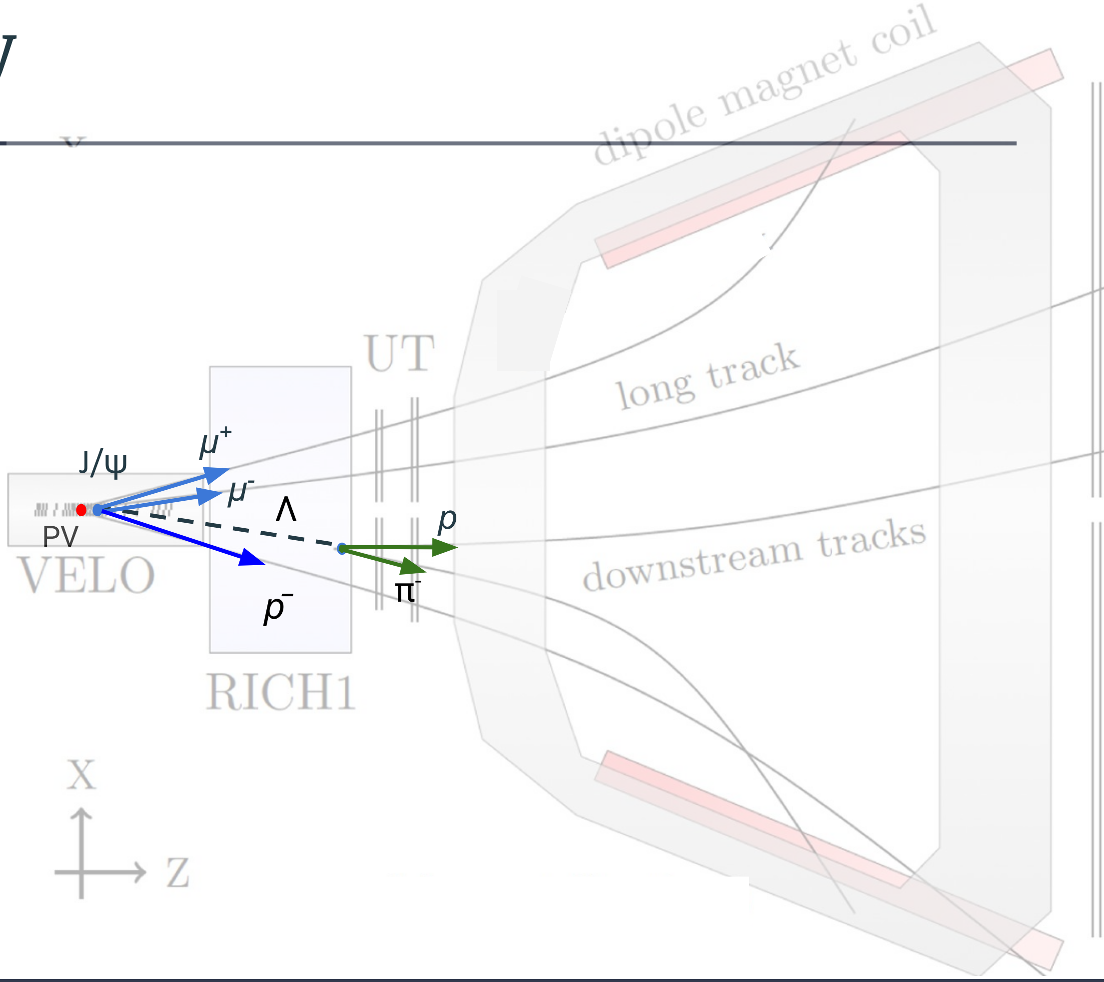
- **Inconsistency** with pure phase space hypothesis
- **K*** can describe the mass projections



Our selection strategy

Candidates selected exploiting:

- Trigger on detached $J/\psi \to \mu\mu$
- Λ reconstructed from
  - *tracks* in VELO (= long)
  - *tracks* after VELO (= downstream)
- PID cut on the bachelor antiproton
- good-quality vertex for Λ, J/ψ and B^-



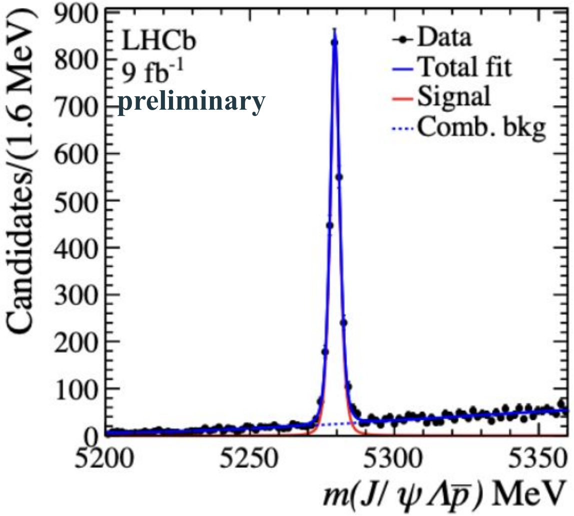
BDT optimization divided in 4 categories:

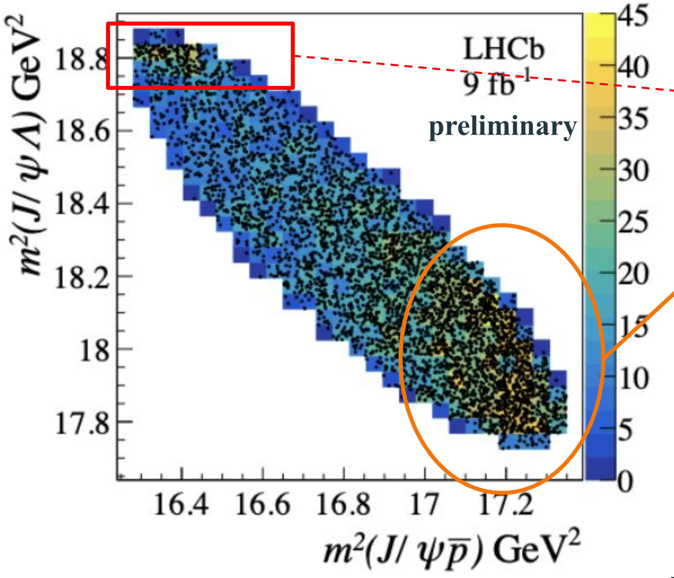
Run 1	long-long
Run 2	down-down

$B^- \to J/\psi \Lambda \bar{p}$ signal candidates

Full LHCb dataset: 9 fb^{-1}

⇒ 4600 candidates in 2.5σ around peak with 93% of purity





Narrow structure in $J/\psi\Lambda$

Activity in $J/\psi\bar{p}$

Possible reflections from $K^*_{2,3,4}$?
⇒ need for a full amplitude analysis

6D phsp

$m(p\bar{\Lambda}), cos\theta_{K^*}, cos\theta_{\psi}, \phi_{\mu}, cos\theta_{\Lambda}, \phi_p$

Model with only K*

Amplitude contributions:

- NR($\bar{p}\Lambda$)
- $K^{*+}_{2,3,4}$ → peaks out of phsp, no obvious contribution in $\bar{p}\Lambda$ distribution

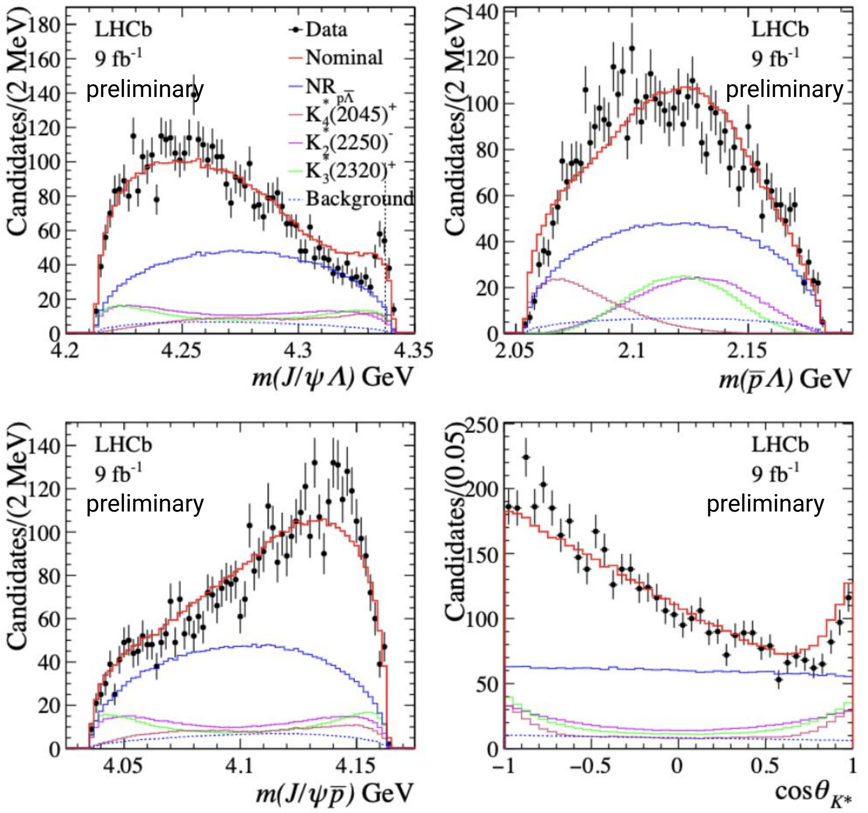
Resonance	Mass (MeV)	Natural width (MeV)	J^P
$K_4^*(2045)^+$	2045 ± 9	198 ± 30	4^+
$K_2^*(2250)^+$	2247 ± 17	180 ± 30	2^-
$K_3^*(2320)^+$	2324 ± 24	150 ± 30	3^+

PDG 2020

Model with K^* cannot describe data

Goodness-of-fit test

$$\chi^2/ndf = 123/33$$



Model with J/ψΛ resonance

Amplitude contributions:

- NR($\bar{p}\Lambda$)
- NR($\bar{p}J/\psi$)
- $P_{\psi s}^{\Lambda}(J/\psi\Lambda)$

} Baseline model

Goodness-of-fit test: = χ^2_{max} of 1D projections

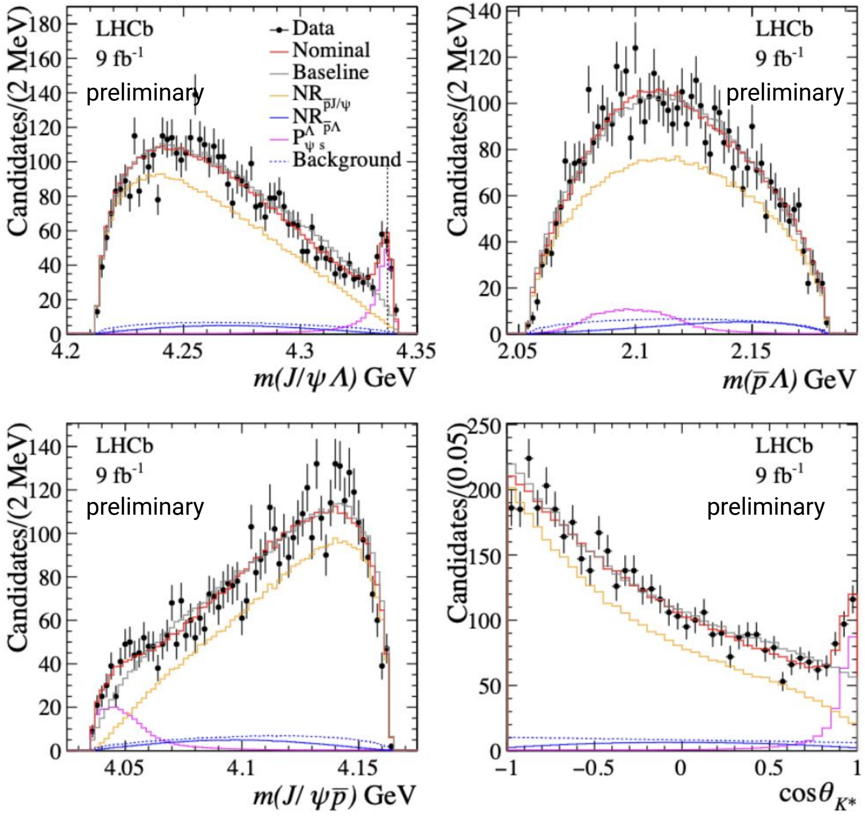
✓ Baseline model

$$\chi^2/ndf = 121/39$$

✓ with $P_{\psi s}^{\Lambda}$

$$\chi^2/ndf = 55.3/39 \qquad p = 4.4\%$$

⇒ Compatible results with m($P_{\psi s}^{\Lambda}$) allowed to go outside of phase space



Model with J/ψΛ resonance

Amplitude contributions:

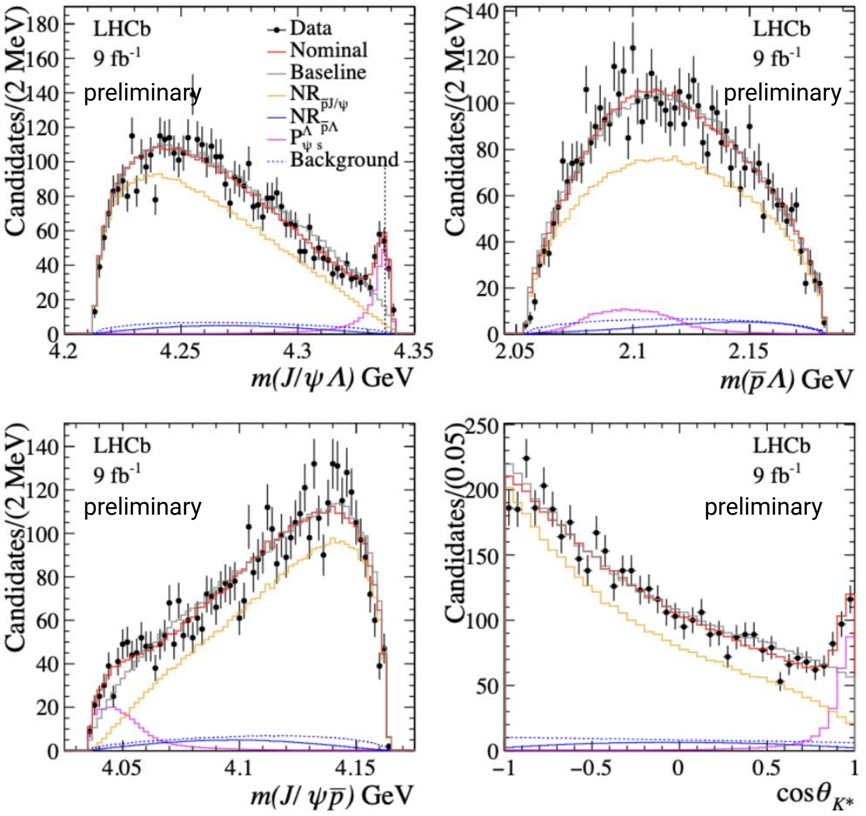
- $NR(\bar{p}\Lambda)$
- $NR(\bar{p}J/\psi)$
- $P_{\psi s}^{\Lambda}(J/\psi\Lambda)$

Fit results:

$m(P_{\psi s}^{\Lambda})$	$4338.2 \pm 0.7\ MeV$
$\Gamma(P_{\psi s}^{\Lambda})$	$7.0 \pm 1.2\ MeV$
$f(P_{\psi s}^{\Lambda})$	$12.5 \pm 0.7\%$

⇒ Spin-parity:
J = ½ determined
P = -1 favored, $\frac{1}{2}^{+}$ rejected @90% CL

From Wilks' theorem:
significance > 10 σ



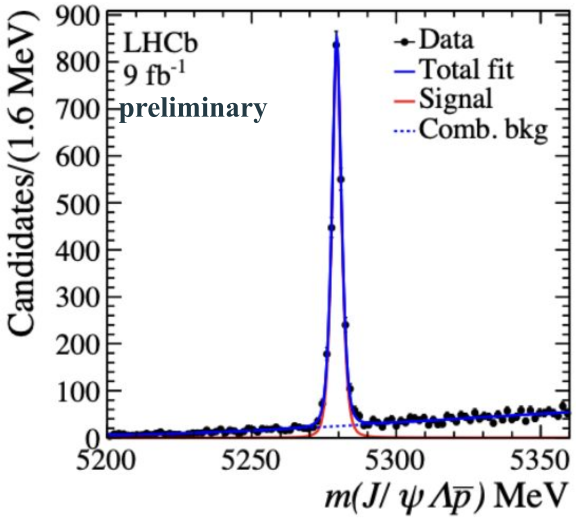
B^- mass measurement

Small Q value, ~128 MeV ⇒ most precise B mass measurement with a resolution of 2 MeV

✓ only with decays of Λ within VELO

$$m(B^-) = 5279.44 \pm 0.05\ (\text{stat}) \pm 0.07\ (\text{syst})\ \text{MeV}$$

From PDG 2020:
$m(B^-) = 5279.34 \pm 0.12$ MeV



Systematic uncertainties

Momentum scale, assigned as α · Q = 0.04 MeV

Energy loss due to uncertainty of the material interaction lengths in the simulation [PLB 708 (2012) 241]

Fit model determined from 1000 toy experiments

	[MeV]
Momentum scale	0.039
Mass fit model	0.050
Energy loss correction	0.030
Total	0.070

Observation of a new J/ψΛ state

First pentaquark candidate $P^{\Lambda}_{\psi s}(4338)$ with strange quark content $c\bar{c}uds$,

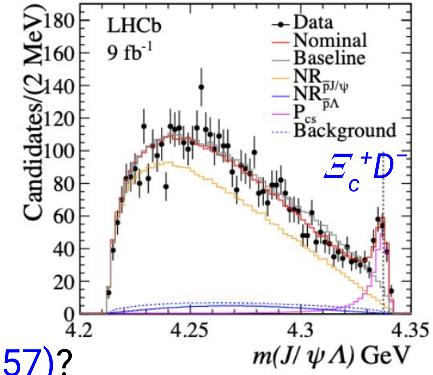
$$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4\,\text{MeV}$$

$$\Gamma_{P_{cs}} = 7.0 \pm 1.2 \pm 1.3\,\text{MeV}$$

⇒ first pentaquark with spin assigned $J^P=½^-$

For theoretical interpretation

- ✓ narrow, close to $\Xi_c^+ D^-$ threshold and in S-wave
- ✓ pentaquark with strangeness, due to SU(3) symmetry
- ✓ at same mass of $P^{N}_{\psi}(4337)$: analogy to $P^{\Lambda}_{\psi s}(4459)$ & $P^{N}_{\psi}(4457)$?



Can be a compact state or are more likely molecular states?

Results & Conclusions

1. New evidence of pentaquark $P_c(4337)$ in $B_s \to J/\psi p\bar{p}$

   ⇒ not clear theoretical interpretation at the moment

   ⇒ extension with Run 3 data

   ⇒ study of $B^0 \to J/\psi p\bar{p}$ to prove the existence of $P_c(4337)$

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

2018		2023	2030
9 fb^{-1}	●	**19 fb^{-1}**	50 fb^{-1}

Reach 5σ within a couple of years of Run3

2. Observation of a new $P^{\Lambda}_{\psi s}(4338)$ with spin 1/2 *in* $B^- \to J/\psi p\Lambda$ ⇒ at threshold of $\Xi_c^+ D^-$ (~4337.6 MeV)

   ⇒ Close to submission to PRL

   ⇒ Update with larger statistics: to study structures in $J/\psi p$

Next-year plan

Other analysis to search for exotics:

→ **Inclusive $J/\psi\Lambda$ production (prompt and detached J/ψ):**
to confirm the new $P_{cs}(4338)$ and $P_{cs}(4459)$ and help discriminate among theoretical models

→ $B_s \rightarrow J/\psi\Lambda\Lambda$ ***decays*** or similar
Small Q-value ~40 MeV ⇒ narrow resonances if present

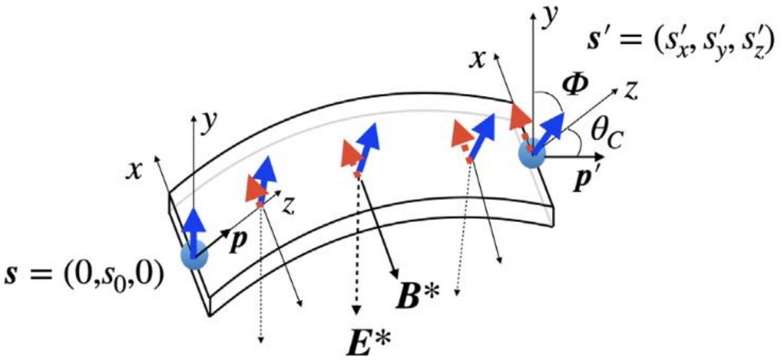
Next-year plan

Simulation of fixed-target experiment at IR3

Eur. Phys. J. C 77, 828

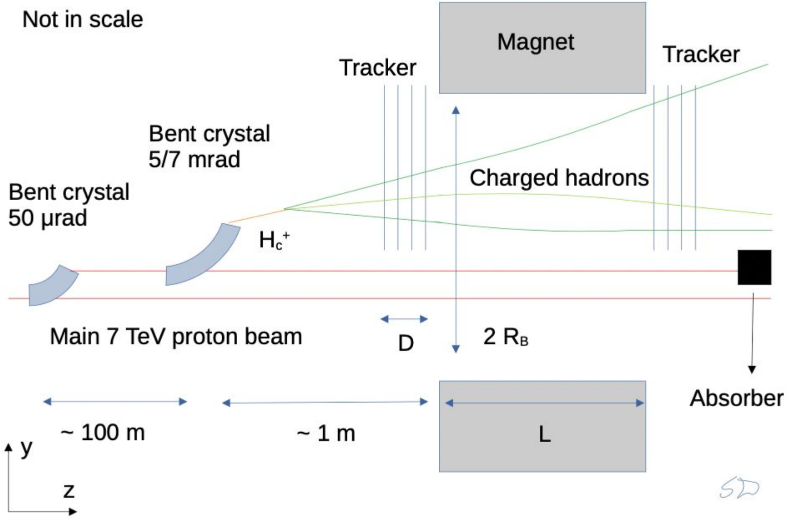
Experiment to measure EDM/MDM of short-lived baryons exploiting channelling in bent crystals

$$\Phi \approx \frac{g-2}{2}\gamma\theta_C, \qquad (1)$$



Setup a full simulation to demonstrate the feasibility of double channeling layout at LHC

- Coordinating a team of people from Valencia, Bonn, UCAS, Milano



Backup slides

New naming scheme

arxiv2206.15233

No PDG rule for
- exotic mesons with s, c, b quantum numbers
- no extension for pentaquark states

Idea of the proposal
- *T* for tetra, *P* for penta
- **Superscript**: based on existing symbols, to indicate isospin, parity and G-parity
- **Subscript**: heavy quark content

Impact on existing states

Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G=0^+$, $J^{PC}=1^{++}$	$\chi_{c1}(3872)$
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\psi 1}(3900)^+$
$c\bar{c}u\bar{d}$	$Z_c(4100)^+$	$I^G=1^-$	$T_\psi(4100)^+$
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\psi 1}(4430)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I=\frac{1}{2}$, $J^P=1^+$	$T^\theta_{\psi s1}(4000)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I=\frac{1}{2}$, $J^P=1^?$	$T_{\psi s1}(4220)^+$
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G=0^+$, $J^{PC}=?^{?+}$	$T_{\psi\psi}(6900)$
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P=0^+$	$T_{cs0}(2900)^0$
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P=1^-$	$T_{cs1}(2900)^0$
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\Upsilon 1}(10610)^+$
$c\bar{c}uud$	$P_c(4312)^+$	$I=\frac{1}{2}$	$P^N_\psi(4312)^+$
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I=0$	$P^\Lambda_{\psi s}(4459)^0$

Model with only NR

Non resonant contribution (J^{PC}=1⁻⁻) + bkg

→ $J^{PC}=1^{--}$ is the only term in S-wave

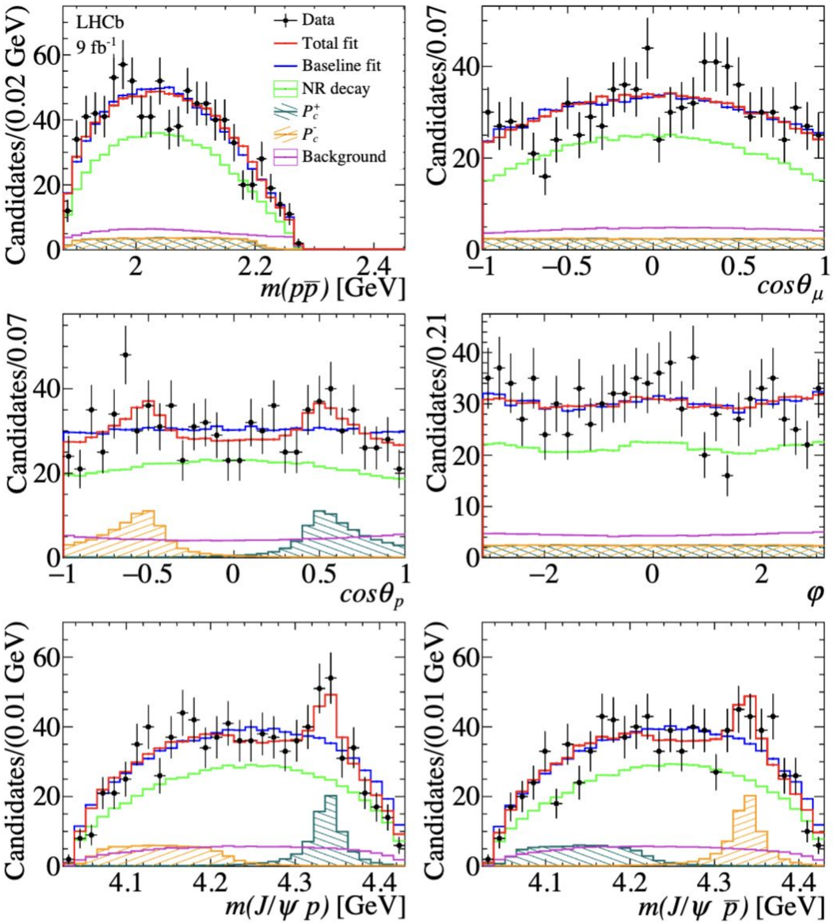
→ Different J^P can be excluded
(2ΔlogL worse by 140 units)

⇨ $m(J/\psi p(\bar{p}))$ still not well described

Goodness-of-fit test:

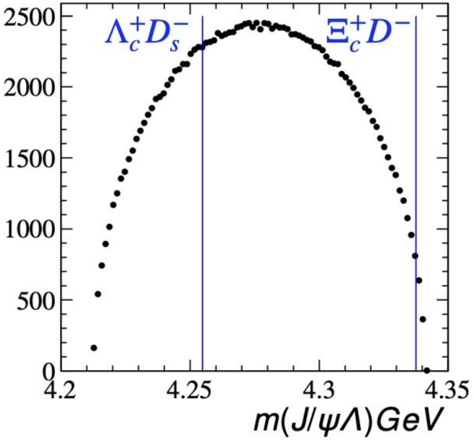
$$\chi^2/ndf = 1.7 \rightarrow p = 4 \cdot 10^{-3}$$

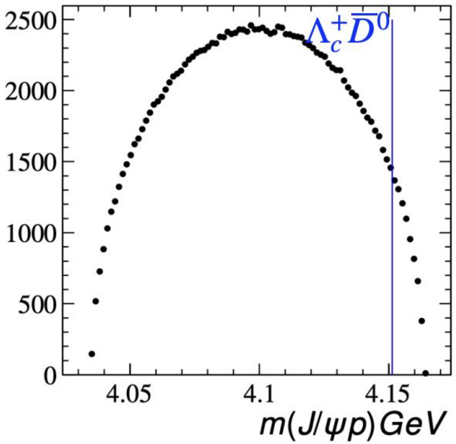
Can we improve upon this model?



Existing predictions: Molecular

Phsp covers thresholds of $\Lambda_c D_s^-$~4251 MeV, $\Xi_c^+ D^-$~4337.6 MeV, and $\Lambda_c^+ D^0$~4151.3 MeV

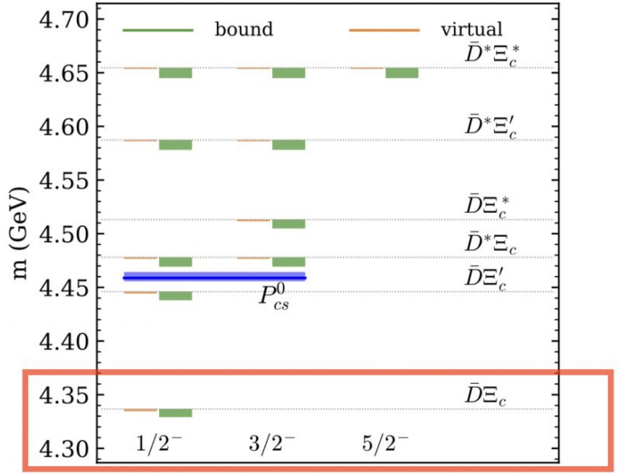




- Previous *P* states not visible because out of the phsp

Attractive Model [Progr.Phys.41(2021)65-93]

~ threshold of any pair of heavy-baryon and anti-heavy meson with attractive interaction

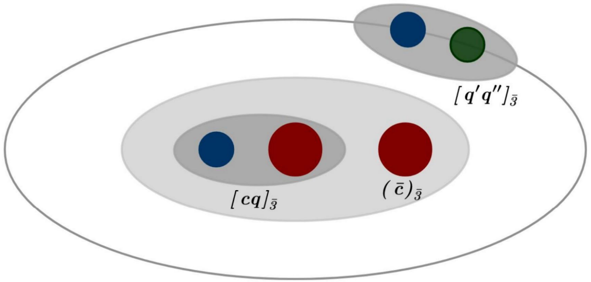


Existing predictions: Tight-pentaquark

JHEP (10) (2019) 256 [arxiv:1907.06507]

Hidden-charm strange pentaquarks $(\bar{c}_{\bar{3}}[cs]_{\bar{3}}[qq']_{\bar{3}})$

- Doubly-heavy triquark – light diquark model
- very rich spectra with lots of J^P



J^P	This work	refs. [51, 52]	J^P	This work	refs. [51, 52]
	$S_{ld}=0,\ L=0$			$S_{ld}=1,\ L=1$	
$1/2^-$	3961 ± 34	4318 ± 42	$1/2^+$	4275 ± 37	4202 ± 50
	4292 ± 29	4392 ± 38		4341 ± 37	4406 ± 44
$3/2^-$	4362 ± 29	4365 ± 55		4607 ± 32	4430 ± 50
	$S_{ld}=1,\ L=0$			4672 ± 32	4453 ± 40
$1/2^-$	4157 ± 31	4351 ± 42		4685 ± 33	4472 ± 50
	4488 ± 25	4398 ± 38		4784 ± 32	4551 ± 43
	4558 ± 25	4496 ± 41	$3/2^+$	4319 ± 37	
$3/2^-$	4157 ± 31	4304 ± 55		4381 ± 37	
	4488 ± 25	4532 ± 40		4650 ± 32	
	4558 ± 25	4574 ± 40		4712 ± 32	
$5/2^-$	4558 ± 25	4641 ± 40		4633 ± 33	
	$S_{ld}=0,\ L=1$			4687 ± 32	
$1/2^+$	4161 ± 39	4262 ± 63		4778 ± 32	
	4492 ± 35	4373 ± 44	$5/2^+$	4391 ± 37	4682 ± 57
	4552 ± 35	4449 ± 40		4723 ± 32	4756 ± 41
$3/2^+$	4171 ± 39			4723 ± 32	4910 ± 44
	4503 ± 35			4777 ± 32	4952 ± 44
	4562 ± 35		$7/2^+$	4794 ± 32	
$5/2^+$	4579 ± 35	4742 ± 57			

Allowed mass range in $B^- \to J/\psi\Lambda\bar{p}$

$$M(J/\psi\Lambda) \in [4212.58, 4341.07] MeV$$

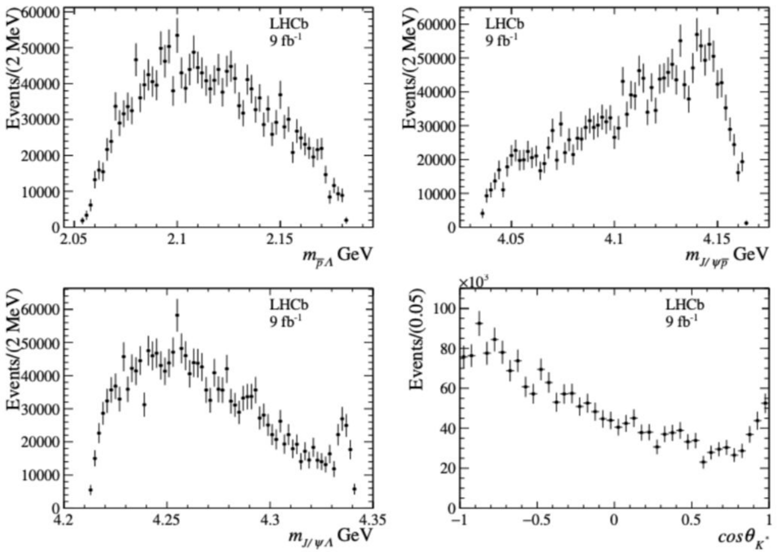
Comparison with CMS results

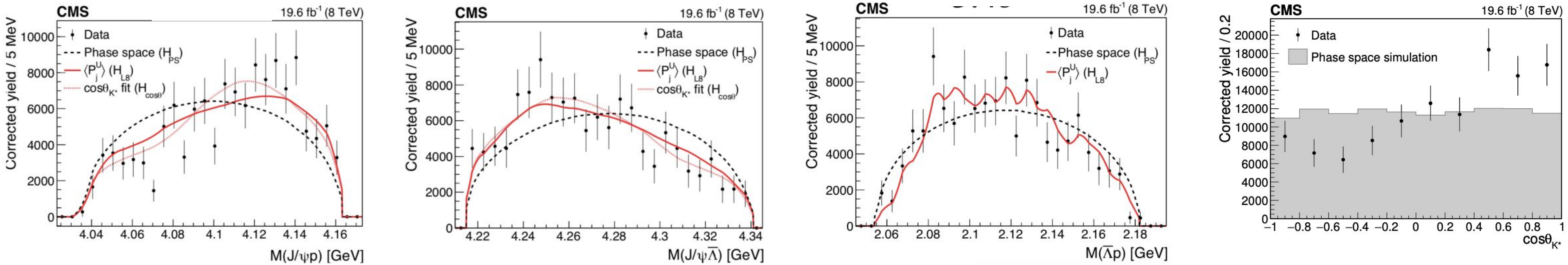
Efficiency corrected and background subtracted plots

Statistics: 10x larger with LHCb dataset
Invariant mass resolution:
- CMS: $m(\Lambda)\sim3.7$ MeV
- LHCb: $m(\Lambda)\sim1$MeV, $m(B)\sim2$ MeV

Trigger and selection cuts, in particular on p_T:
- CMS: Trigger on displaced $J/\psi\rightarrow\mu\mu$, Selection: $p_T(\mu\mu)>6.9$ GeV, $p_T(\Lambda)>1$ GeV and $p_T(p)>1$ GeV
- LHCb: $p_T(\mu)>500$ MeV, no p_T on Λ and p

⇒ Efficiency correction on $m(\Lambda p)$ and $\cos\theta_{K^*}$ instead of 6D





P_{ψ}^{N} contributions in $\bar{p}J/\psi$?

Amplitude contributions:

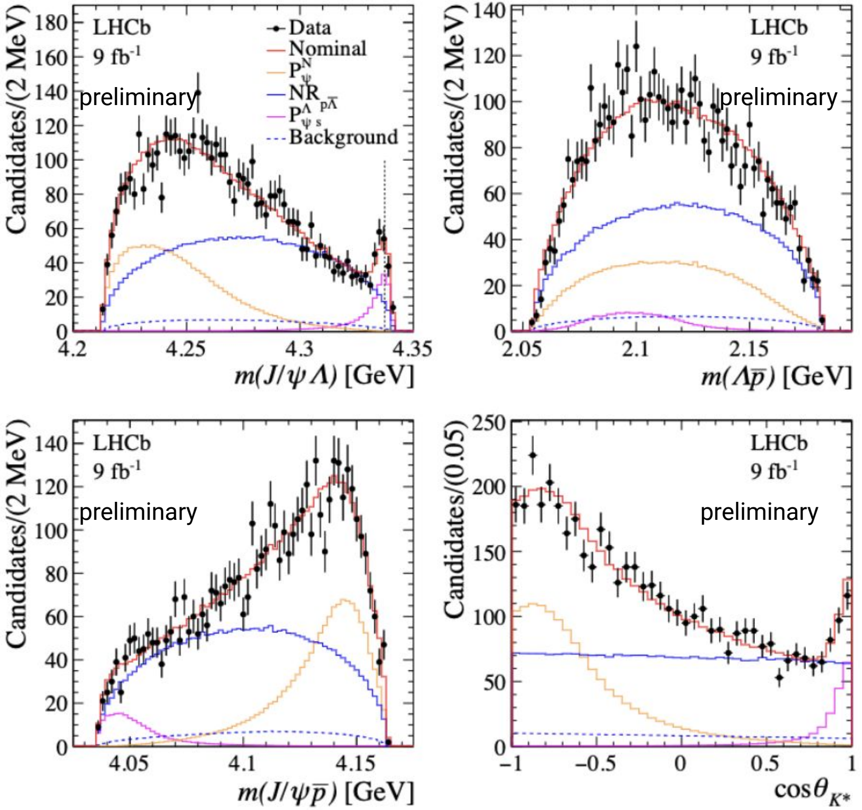
- $NR(\bar{p}\Lambda)$
- ~~$NR(\bar{p}J/\psi)$~~ → $BW(P_{\psi})$ $J^P=½^-$
- $P_{\psi s}^{\Lambda}(J/\psi\Lambda)$

Compatible $P_{\psi s}^{\Lambda}$ results

$m(P_{\psi s}^{\Lambda})$	$4338.8 \pm 1.1\ MeV$
$\Gamma(P_{\psi s}^{\Lambda})$	$8.4 \pm 1.6\ MeV$
$m(P_{\psi}^{N})$	$4152.3 \pm 2.0\ MeV$
$\Gamma(P_{\psi}^{N})$	$41.8 \pm 6.0\ MeV$

-logL decreases by 80 wrt nominal model

⇨ Model with NR polynomial is preferred, not very sensitive to $\bar{p}J/\psi$ structures with current statistics



IR3 detector layout

First bent crystal for secondary beam

Second bent crystal channeling charm hadrons (5/7 mrad of bending)

Spectrometer composed by warm/permanent magnet + tracking stations