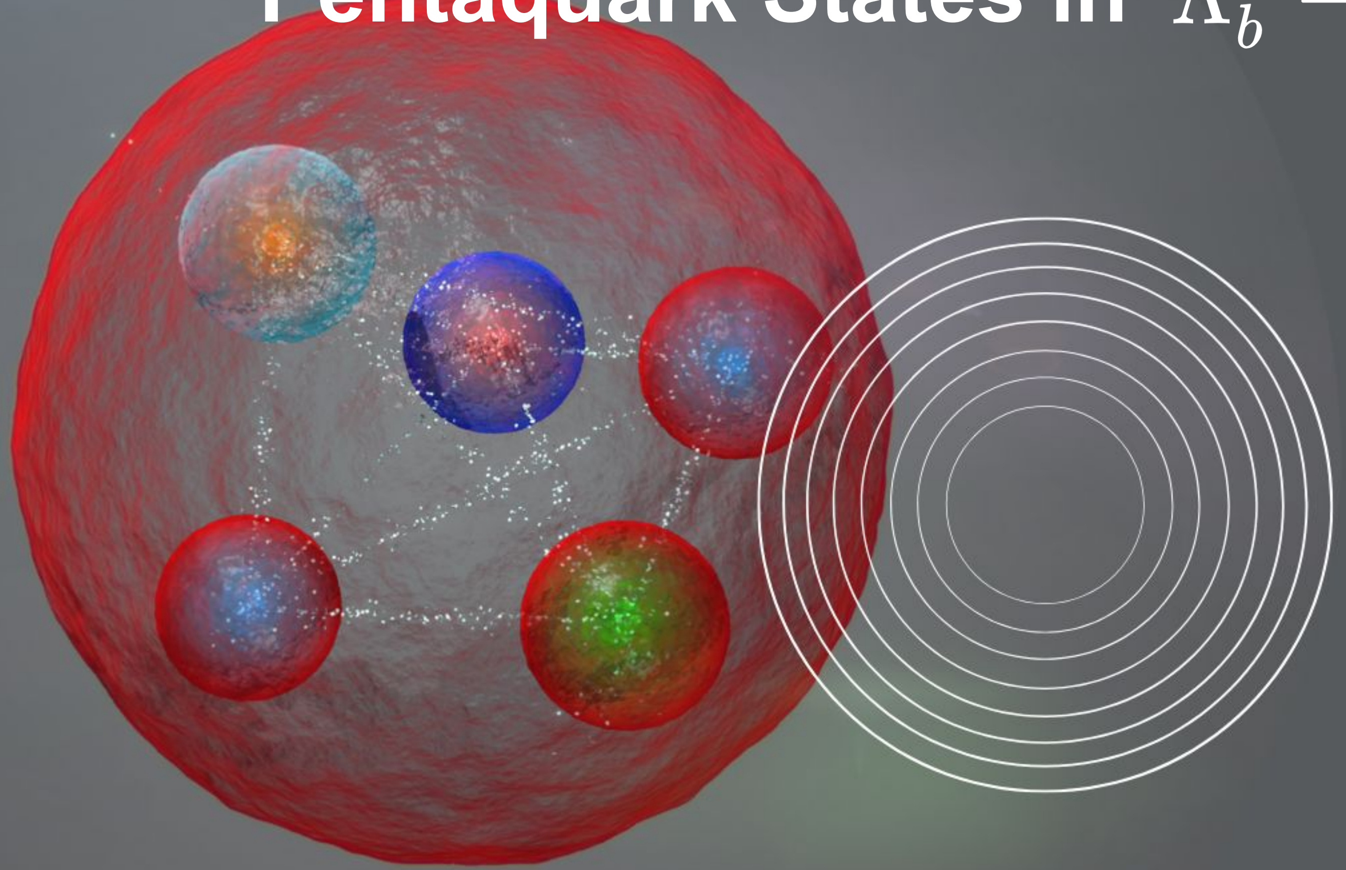
AEPSHEP 2024
June 23rd, 2024

Phys.Rev.Lett. 115 (2015) 072001

Observation of $J/\psi\, p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi\, K^- p$ Decays

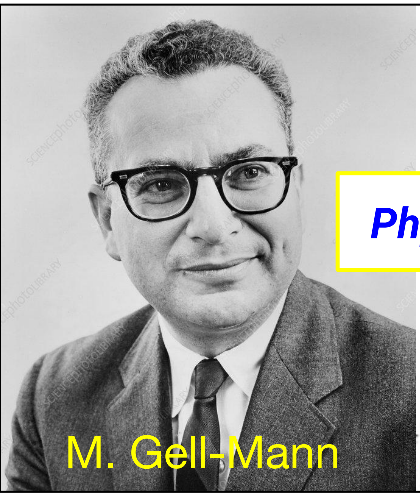


A.Kauniskangas on behalf of

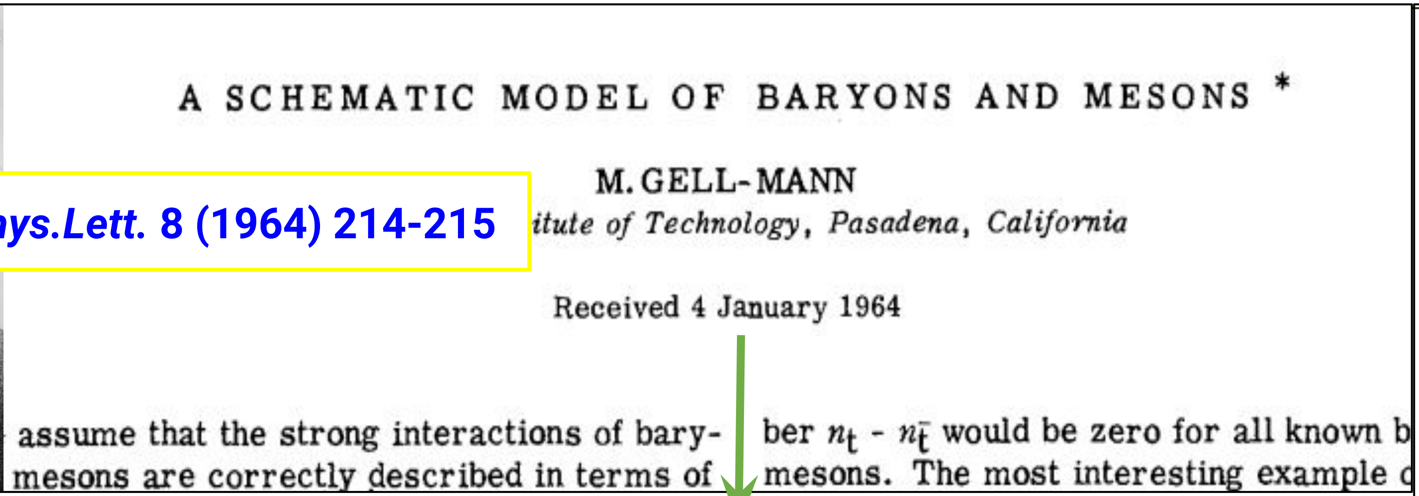
GROUP A

Quark model

Successfully describes all of the observed hadrons!


M. Gell-Mann

Phys.Lett. 8 (1964) 214-215

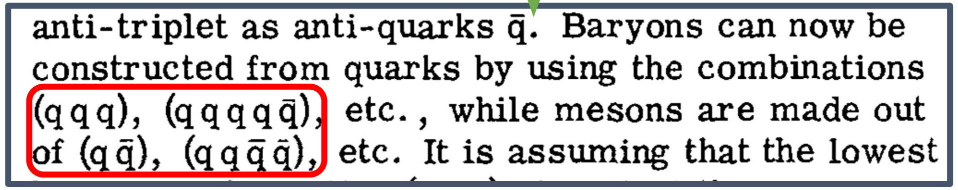

A SCHEMATIC MODEL OF BARYONS AND MESONS *

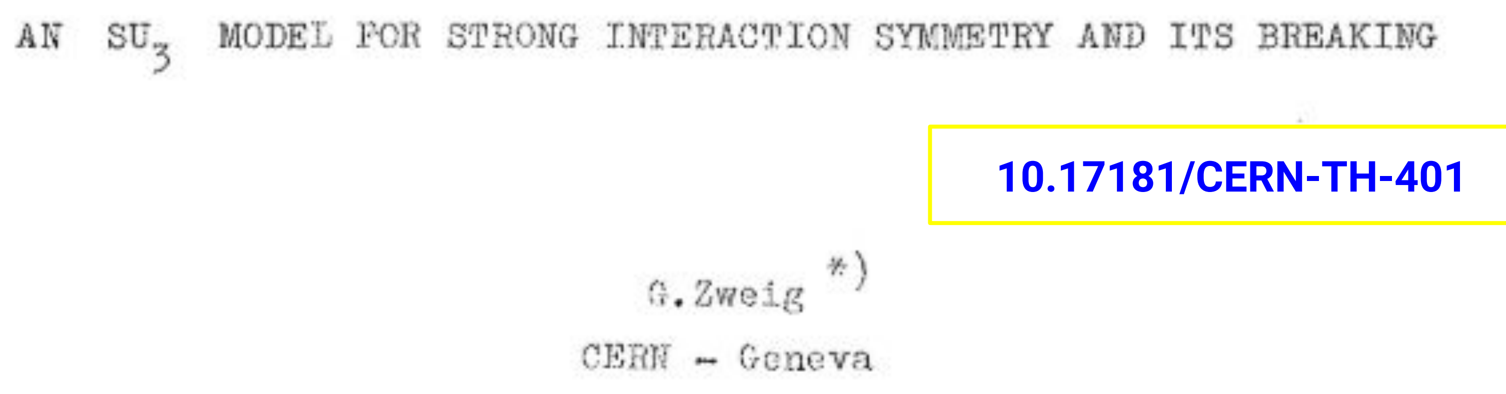
M. GELL-MANN
itute of Technology, Pasadena, California

Received 4 January 1964

assume that the strong interactions of bary-
mesons are correctly described in terms of

ber $n_t - n_{\bar{t}}$ would be zero for all known b
mesons. The most interesting example o

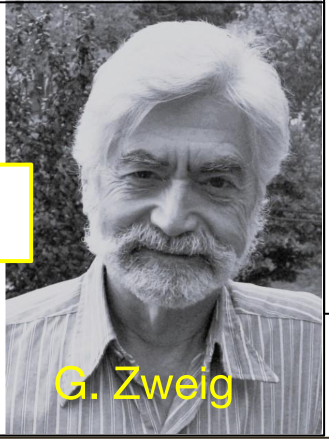

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest


AN SU$_3$ MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)

CERN - Geneva

10.17181/CERN-TH-401


G. Zweig

1964

Classification of **mesons** and **baryons**

$q\bar{q}$ $qqq, \bar{q}\bar{q}\bar{q}$

1977-1978

Model of **diquarks** and **di-antiquarks** (**Jaffe**), with its development (**Strottman**)

1987 $qqqq\bar{q}$

The name of **"pentaquark"** was proposed by **Lipkin.**

Pathway to Pentaquarks

1997
Prediction of Θ^+ pentaquark properties by Diakonov et al.

2003
LEPS reported *strong evidence* for the Θ^+ pentaquark

2006
PDG releases report that pentaquarks probably don’t exist

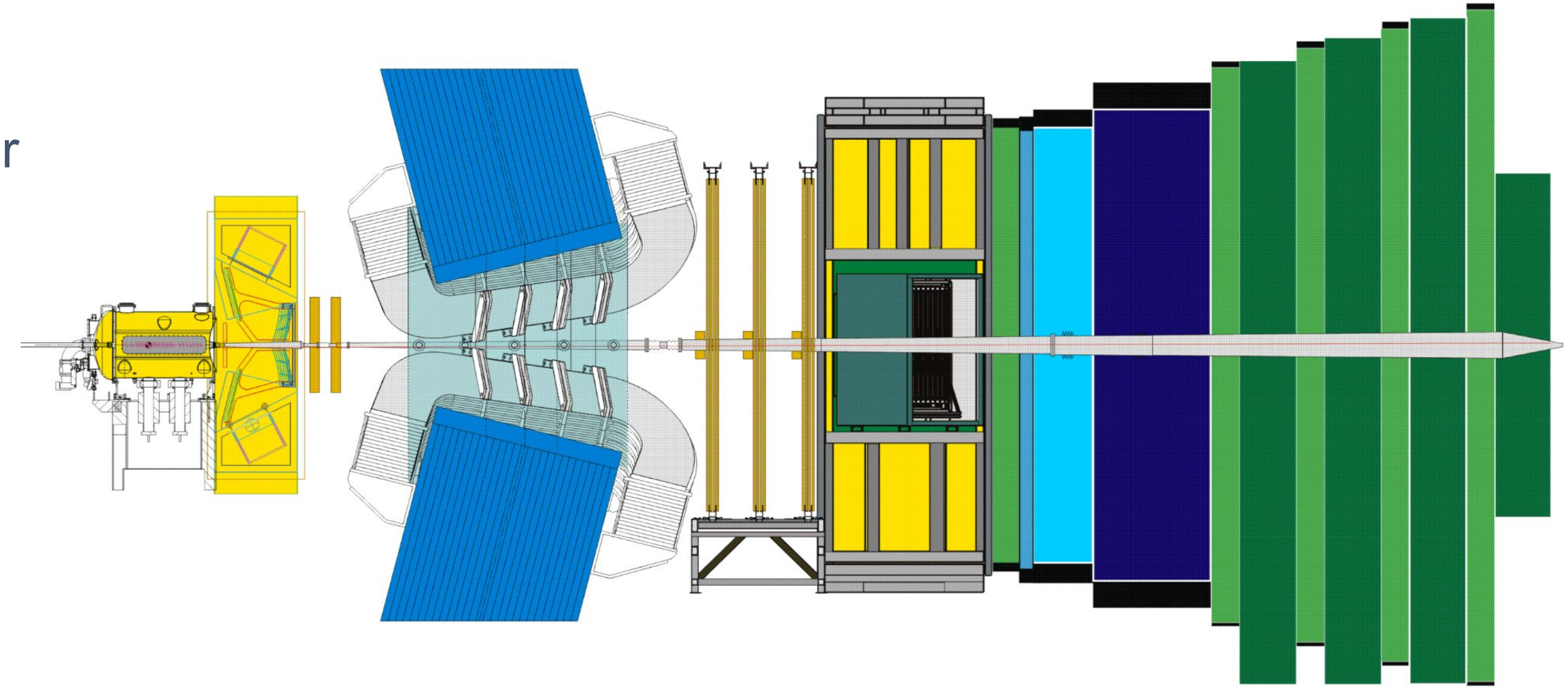
2009
LEPS *again claims* the discovery Θ^+

2015
LHCb releases this paper

For instructive reviews and related experimental reports see: Dzierba et al. (2005), Hicks (2012), and Schumacher (2006).

The LHCb detector

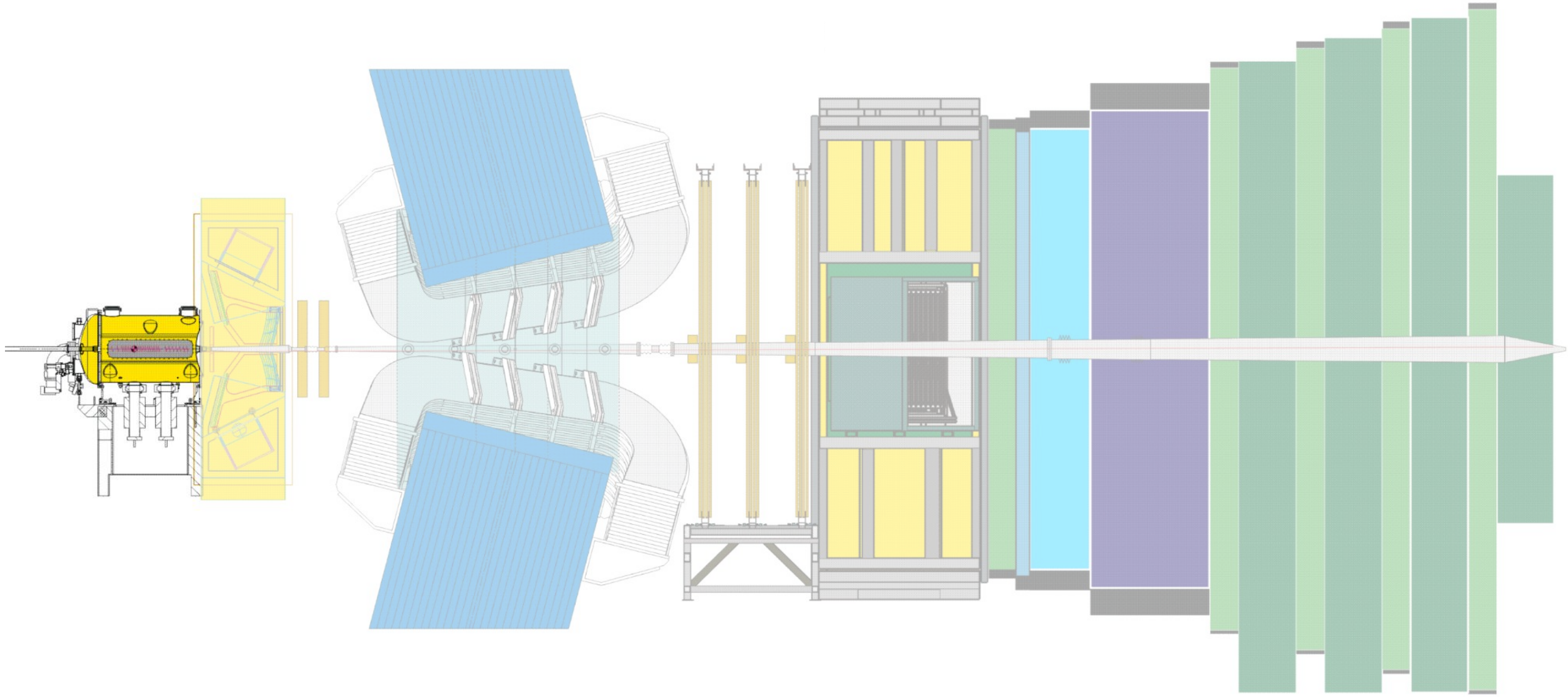
- Single-arm forward spectrometer
- Optimised for the study of particles containing *b* and *c* quarks
- Coverage $2 < \eta < 5$ (0.7 deg $< \theta < 15.4$ deg)



The LHCb detector

VErtex **LO**cator

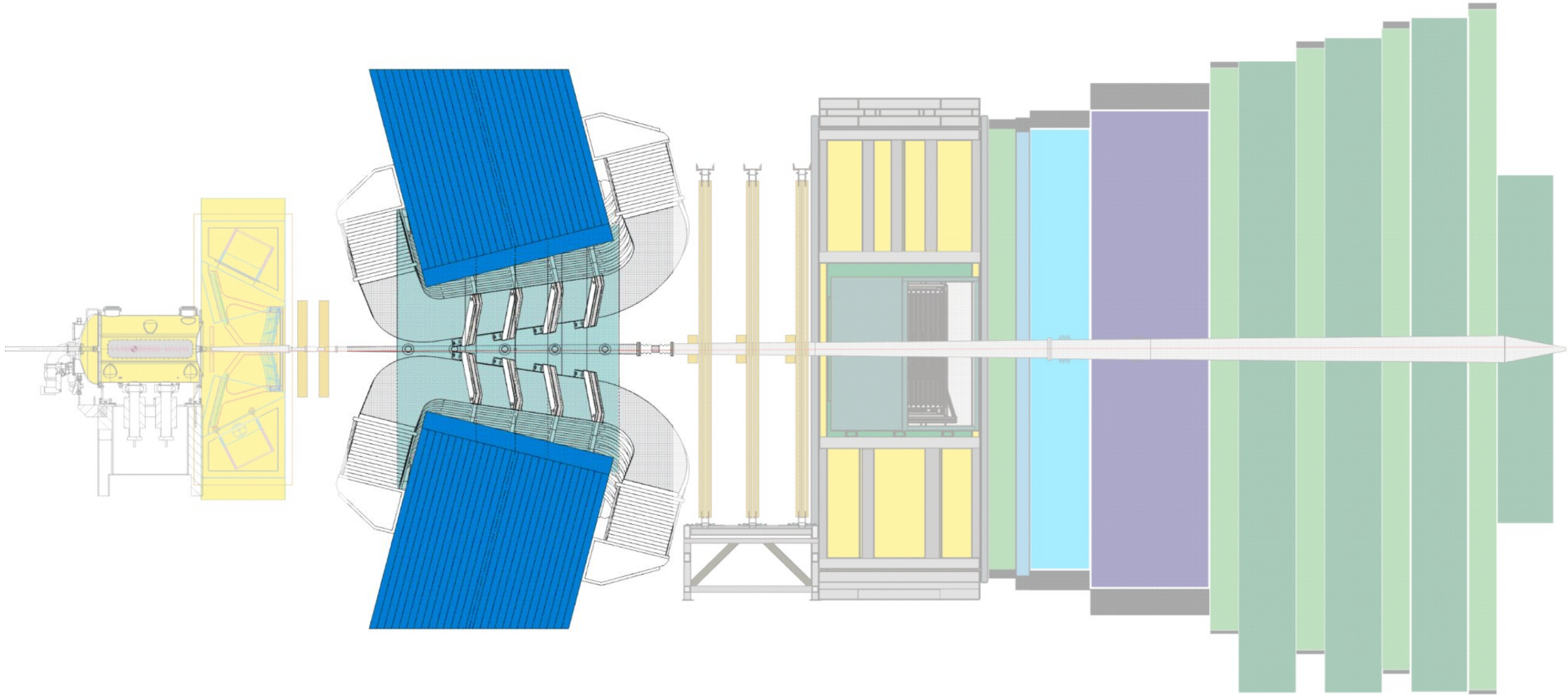
- The closest to the interaction point.
- Silicon detectors
- Measures the tracks of the charged particle that are produced from the p-p collisions with high-resolution



The LHCb detector

Magnet

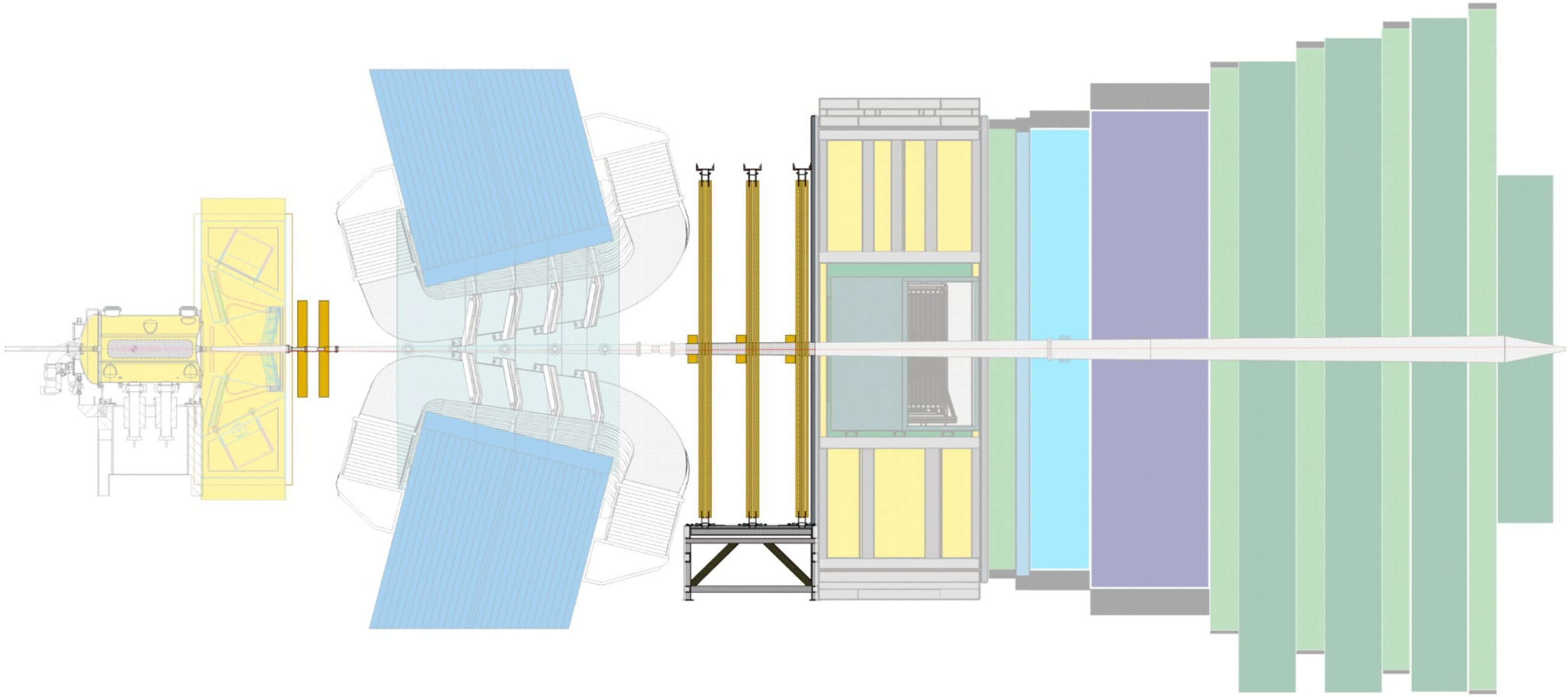
- Bending power: 4 T•m
- Tracker on each side to measure curvature



The LHCb detector

Trackers

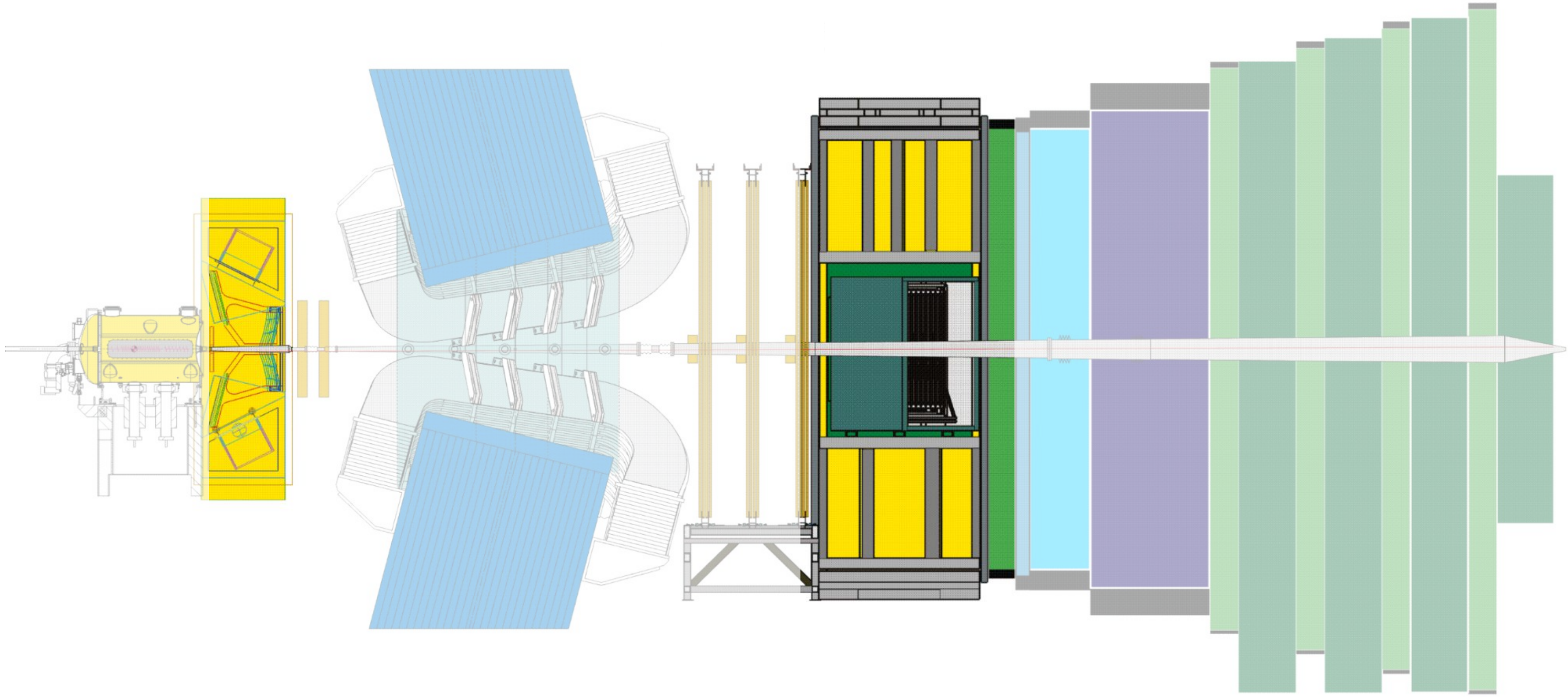
- TT Tracker: Located before the magnet.
- T1-T3 Trackers: Located after the magnet.



The LHCb detector

Ring **I**maging **CH**erenkov:

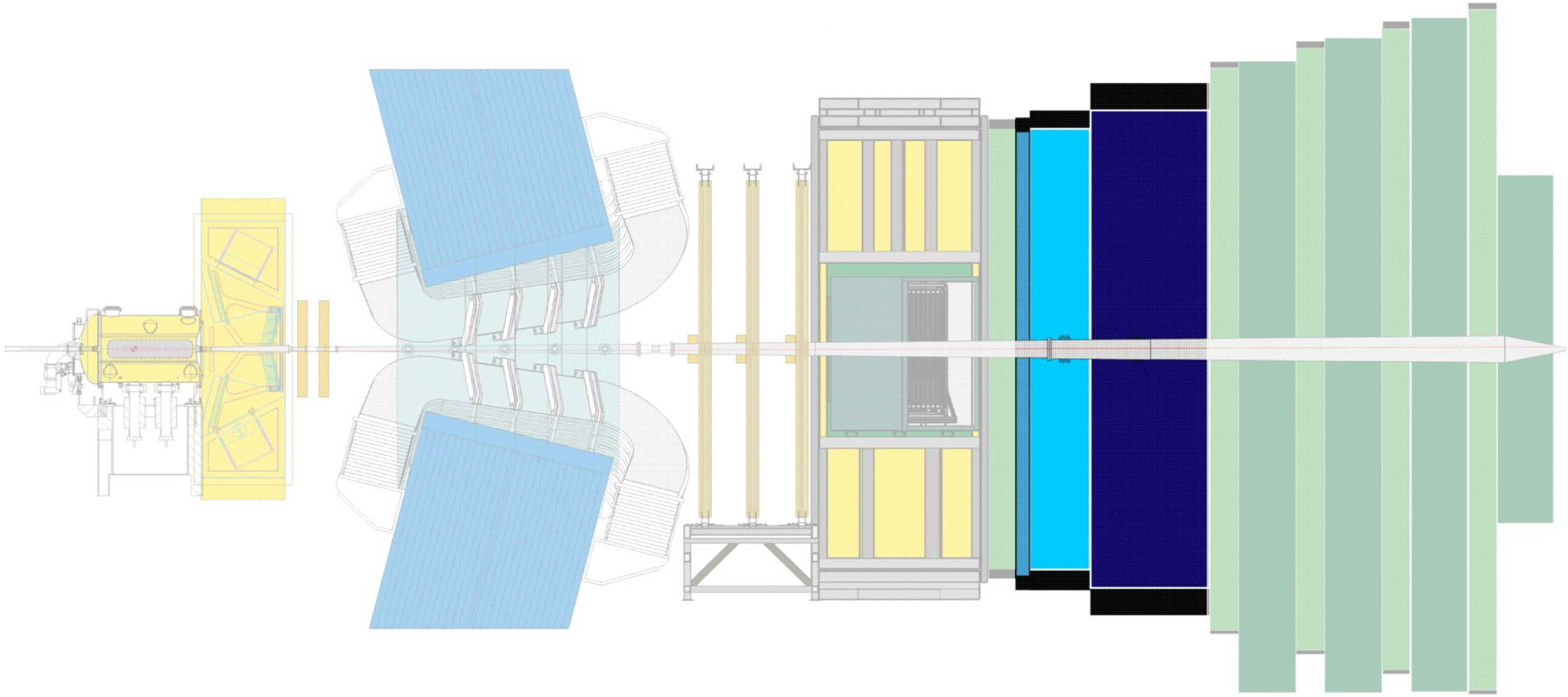
- Measure speed of the particles
- Identify K/π/p over a broad range of momentum **~2-100 GeV**.



The LHCb detector

Calorimeters:

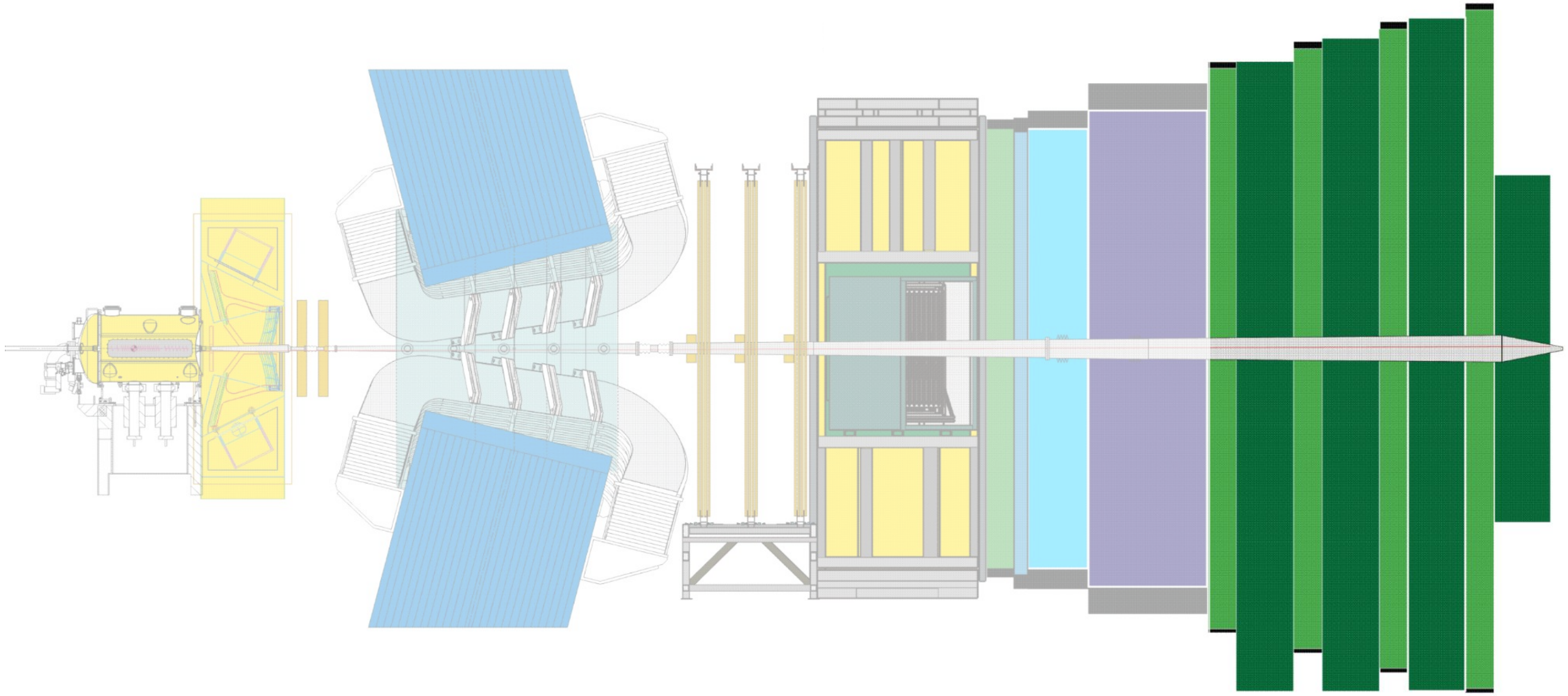
- Electromagnetic Calorimeter (ECAL): Measures energy of photons and electrons
- Hadronic Calorimeter (HCAL): Measures energy of hadrons



The LHCb detector

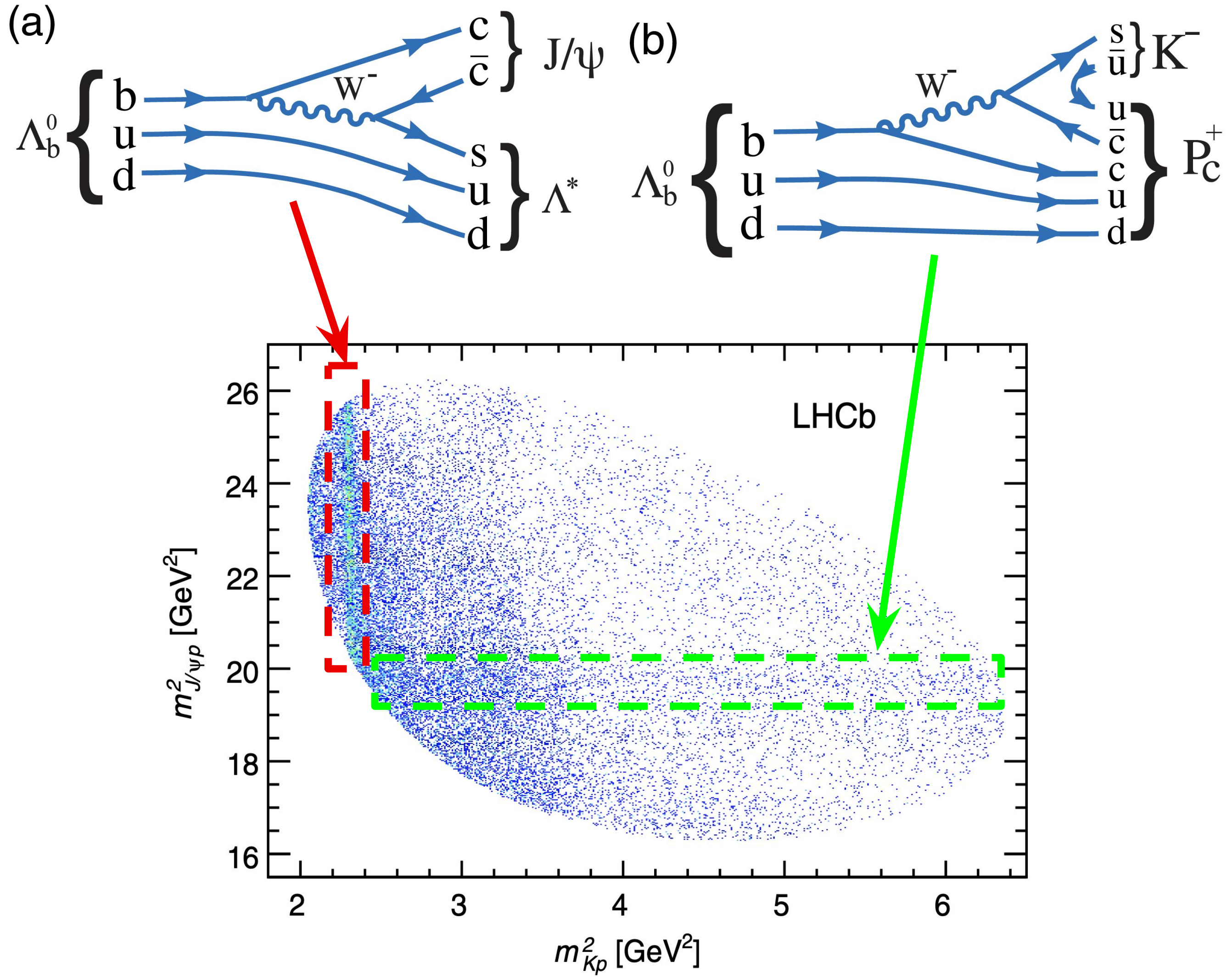
Muon systems:

- Consists of multiple layers of detectors interleaved with shielding material.
- Identify and track muons, which pass through the detector

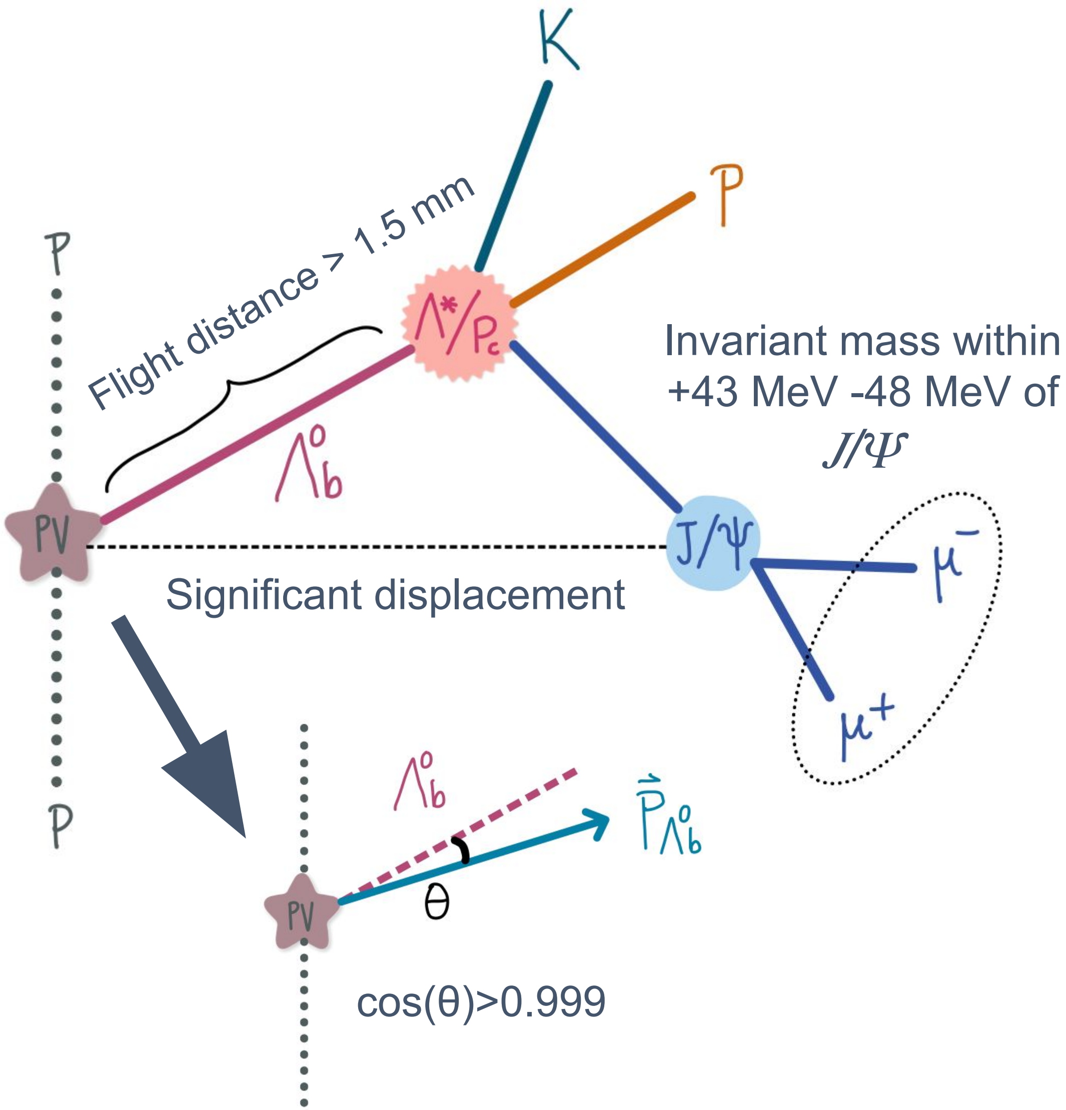


Analysis strategy

- Search for exotic pentaquark contributions to the decay $\Lambda_b^0 \to J/\Psi\, K\, p$
- Dataset: 3 fb^{-1} of p-p collision data collected at c.o.m energies of 7-8 TeV
- Need to
    - Select signal candidates from data
    - Disentangle possible $\mathbf{P}_c$ signal from various Λ^* contributions



Signal candidate selection



Flight distance > 1.5 mm

Invariant mass within +43 MeV -48 MeV of J/Ψ

Significant displacement

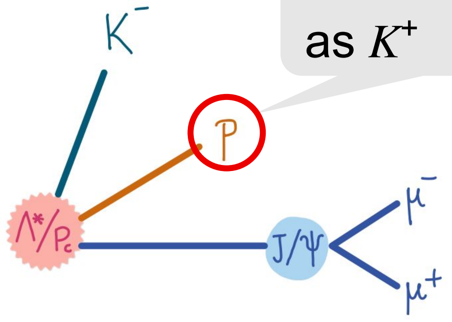
cos(θ)>0.999

- “Messy” hadron collider environment means high levels of background → careful selection of signal candidates necessary
- Trigger & preselection using PID, kinematic and geometrical criteria, including
    - Good fits for each track
    - Positive identification of hadrons
    - p_T > 250 MeV for hadrons
    - p_T > 550 MeV for muons
    - Good vertex fits for the K-p, dimuon, and Λ_b^0

Signal candidate selection

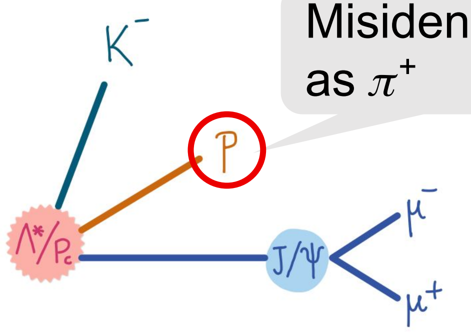
- The combinatorial background is further suppressed with a multivariate selection
    - Boosted decision trees trained on simulated signal and data sideband background samples
  - A cut on the BDT response is chosen such that ~5% background remains within a 2σ window of the Λ_b^0 signal region

- Misidentified backgrounds from B^0 are vetoed using cuts on the $J/\Psi\ K\ p$ invariant mass



Misidentified as K^+

Misidentified as $\bar{B}_S^0$

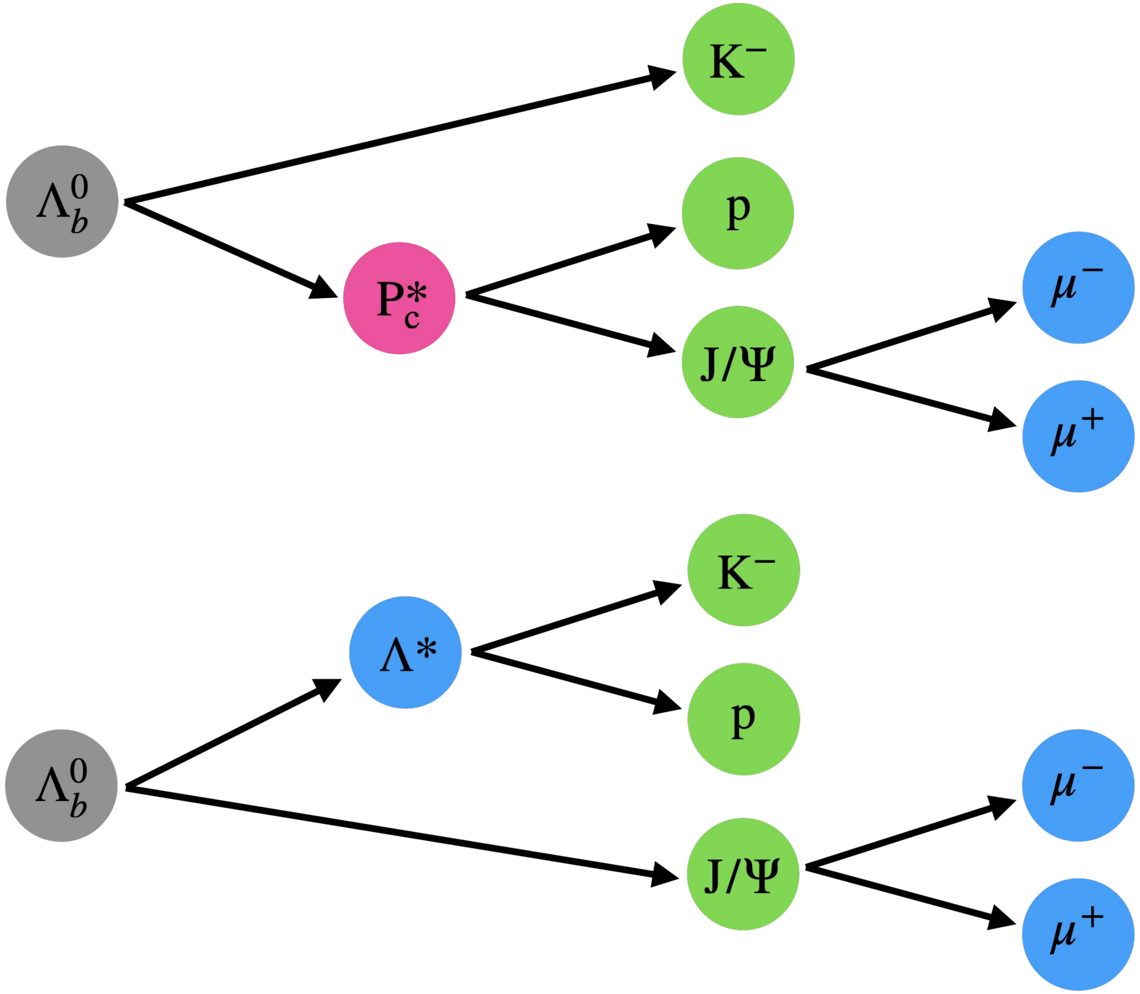


Misidentified as π^+

Misidentified as $\bar{B}^0$

Amplitude analysis

$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}} \sum_{\lambda_p} \sum_{\Delta\lambda_\mu} \left| \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} + e^{i\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{1/2}_{\lambda_p^{P_c},\lambda_p}(\theta_p)\, \mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu} \right|^2$$

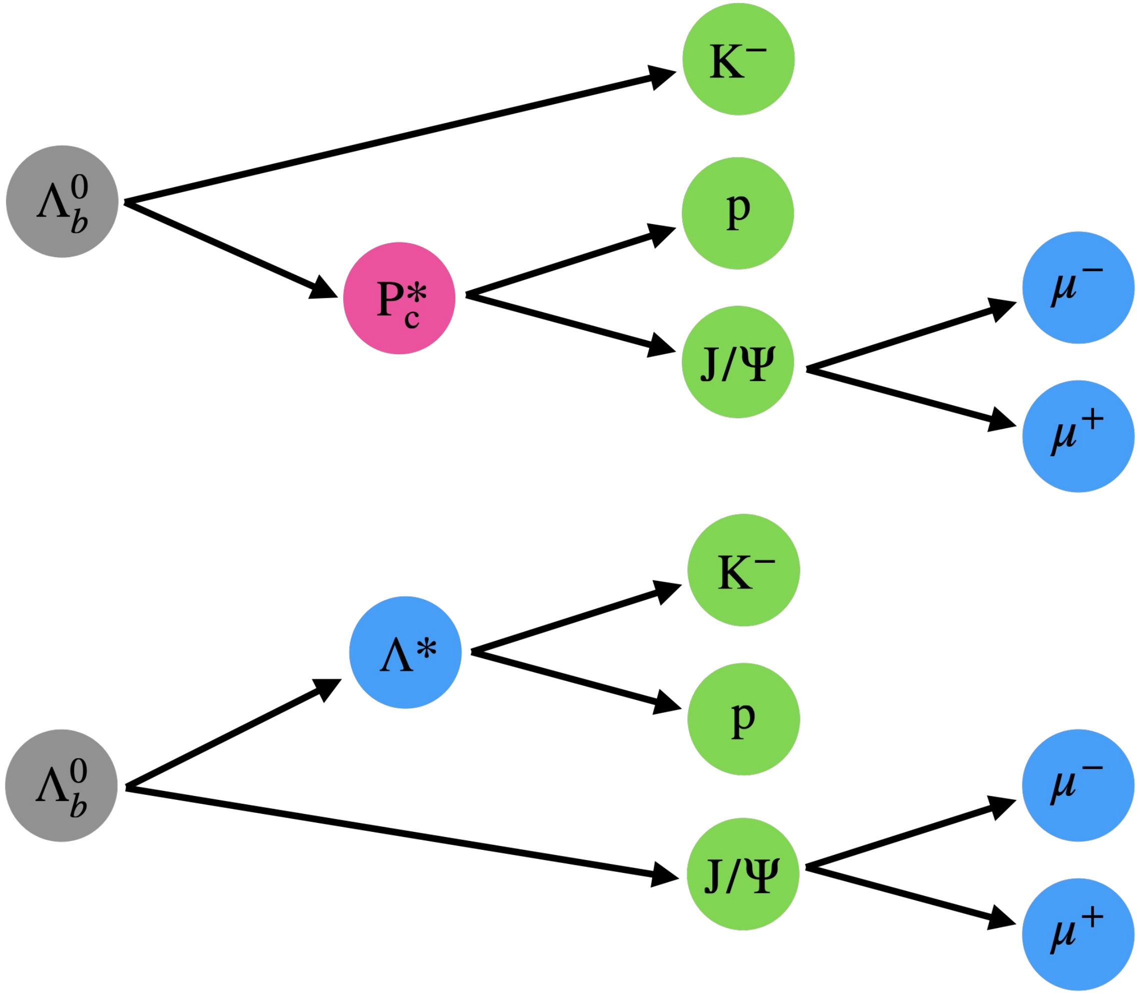


General idea:
Express the total **decay amplitude** in terms of observable d.o.f, and fit to extract parameters and fractions of each component

Amplitude analysis

$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}} \sum_{\lambda_p} \sum_{\Delta\lambda_\mu} \Big| \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} + e^{i\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{1/2}_{\lambda_p^{P_c},\lambda_p}(\theta_p)\, \mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu} \Big|^2$$

Write the amplitude in the **helicity basis**, summing over all initial state and final state helicities



Amplitude analysis

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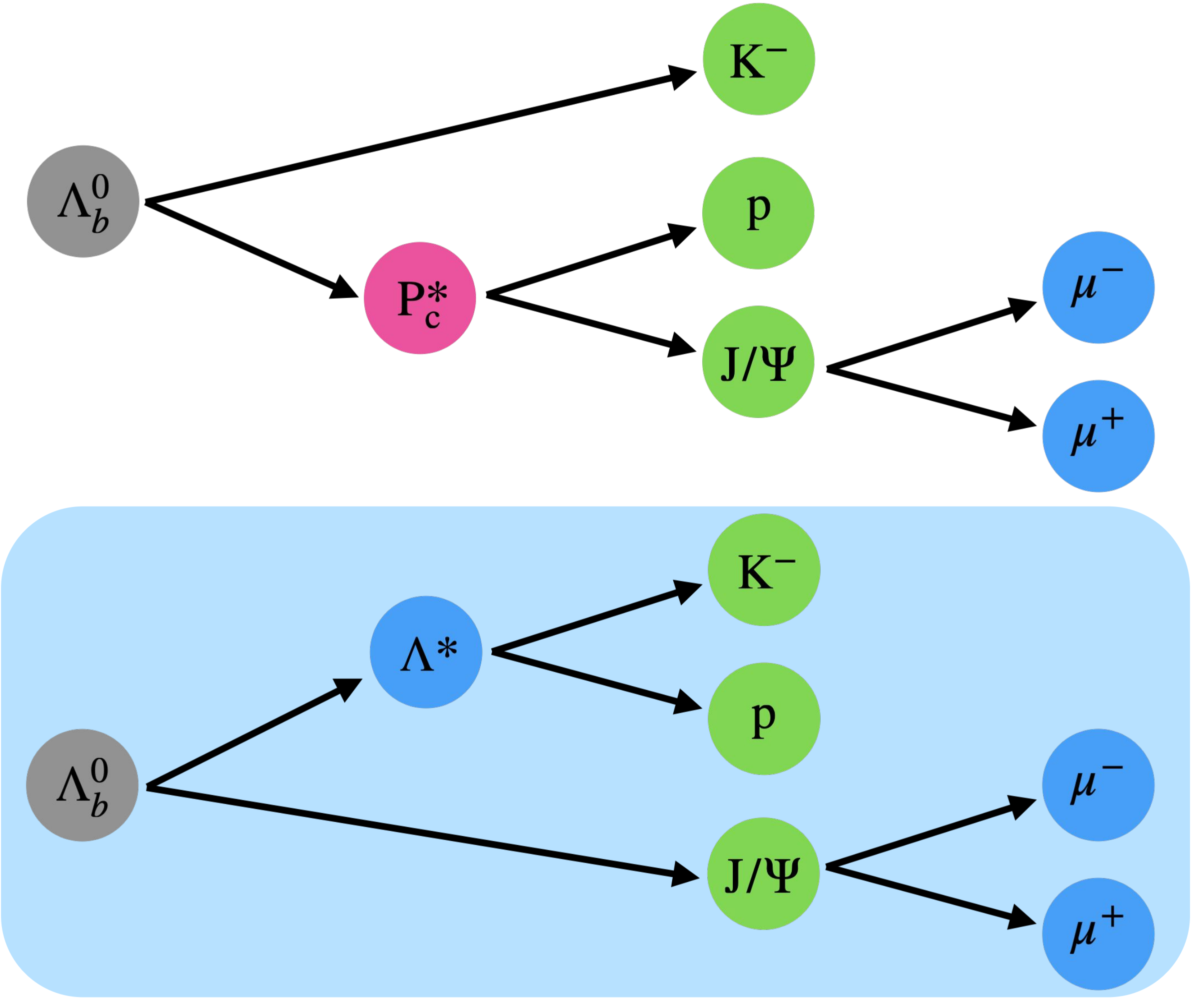

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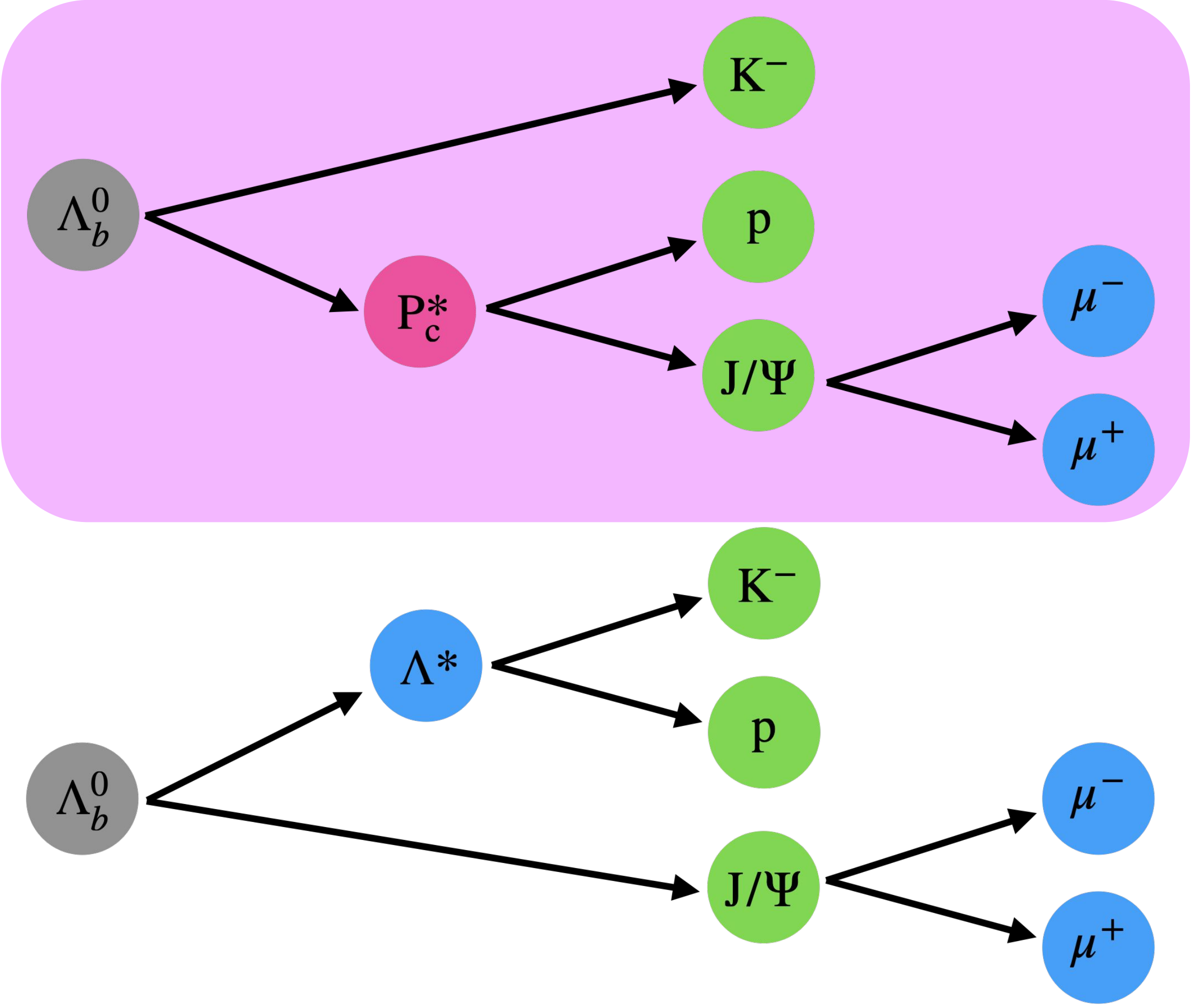


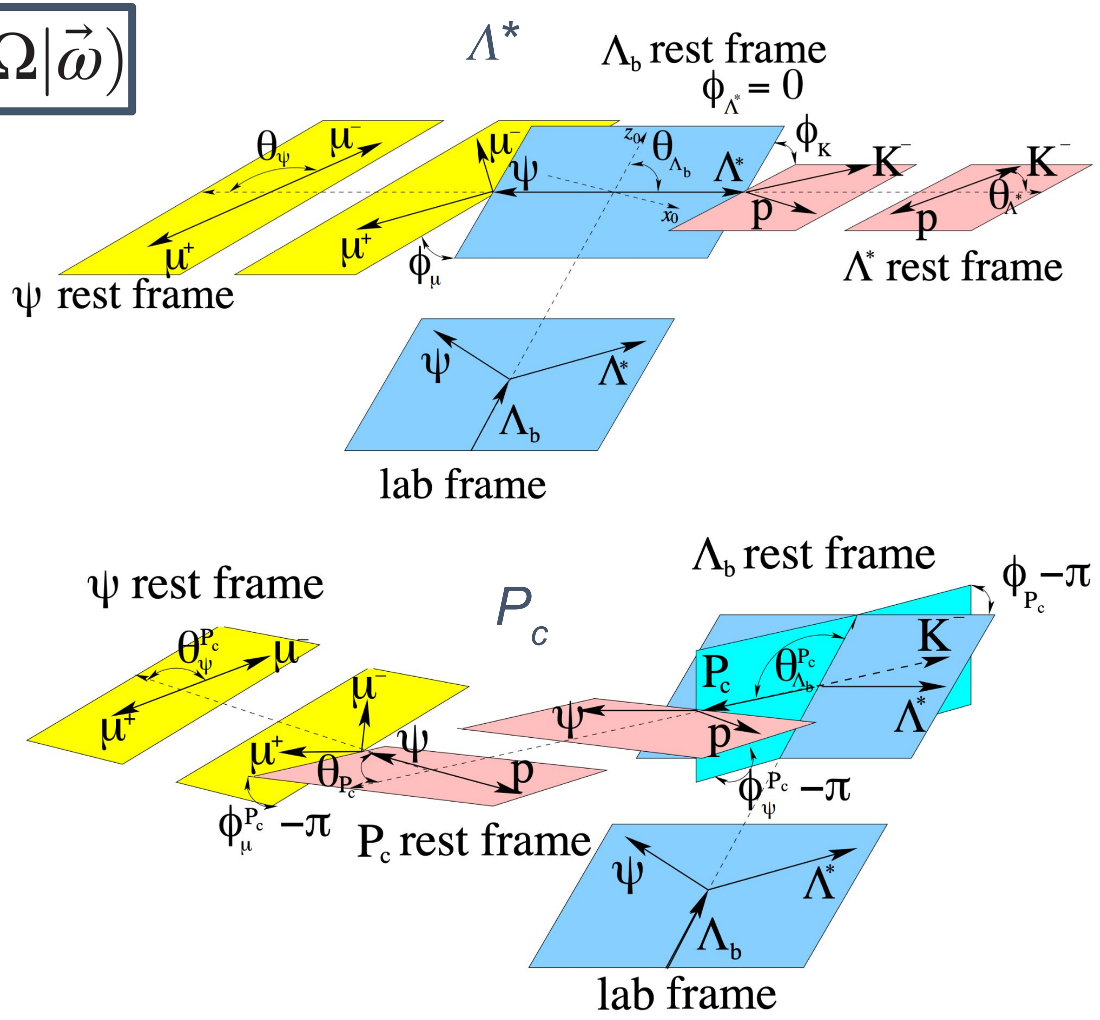
Write the amplitude in the **helicity basis**, summing over all initial state and final state helicities

Amplitude analysis

$$\boxed{\mathcal{M} = \mathcal{M}(m_{Kp}, \Omega|\vec{\omega})}$$

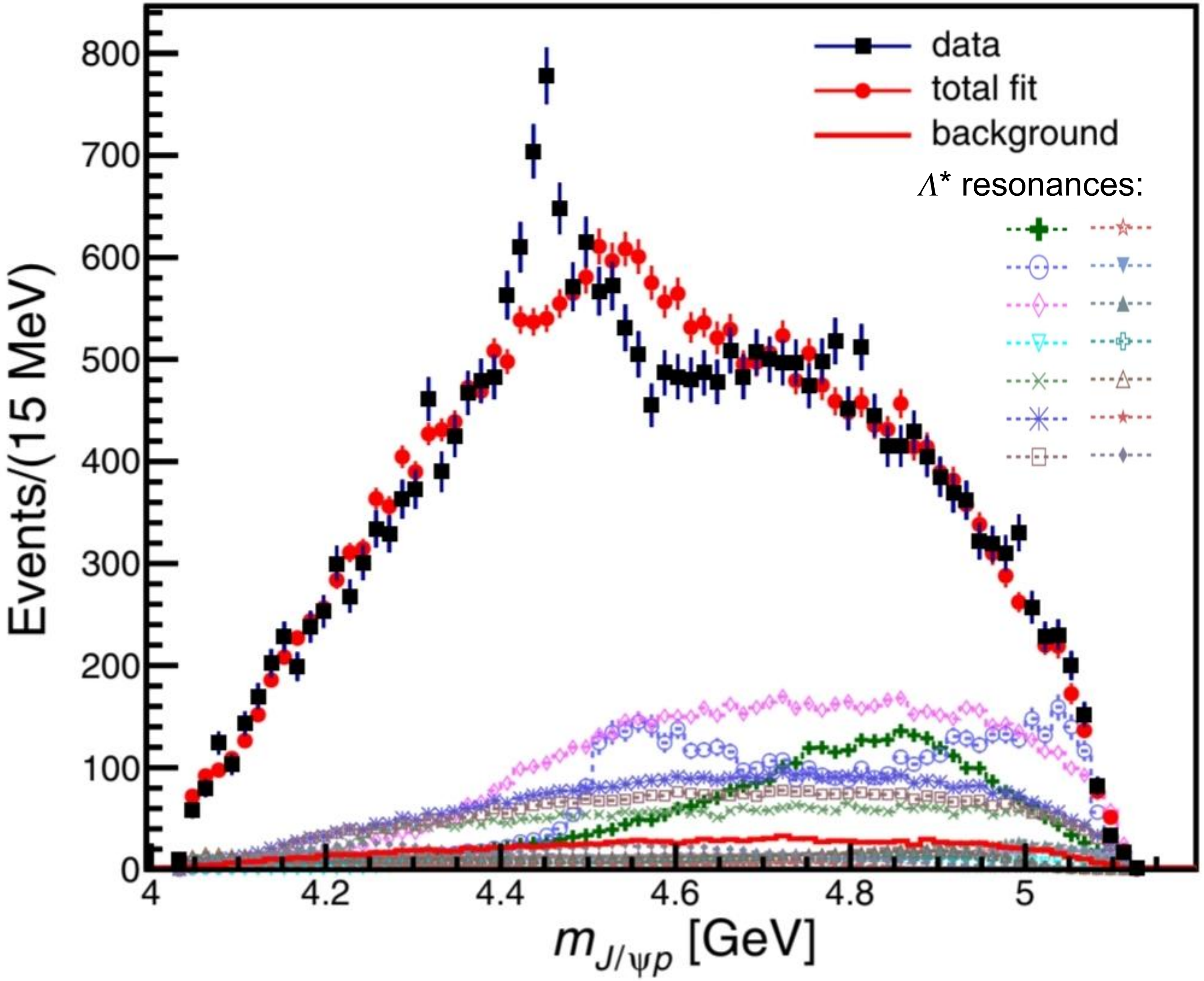
$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}} \sum_{\lambda_p} \sum_{\Delta\lambda_\mu} \left| \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} + e^{i\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{1/2}_{\lambda_p^{P_c},\lambda_p}(\theta_p)\, \mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu} \right|^2$$

Perform an unbinned maximum likelihood **fit** in the 5 independent **decay angles** and the ***K*-*p* invariant mass** (6D)



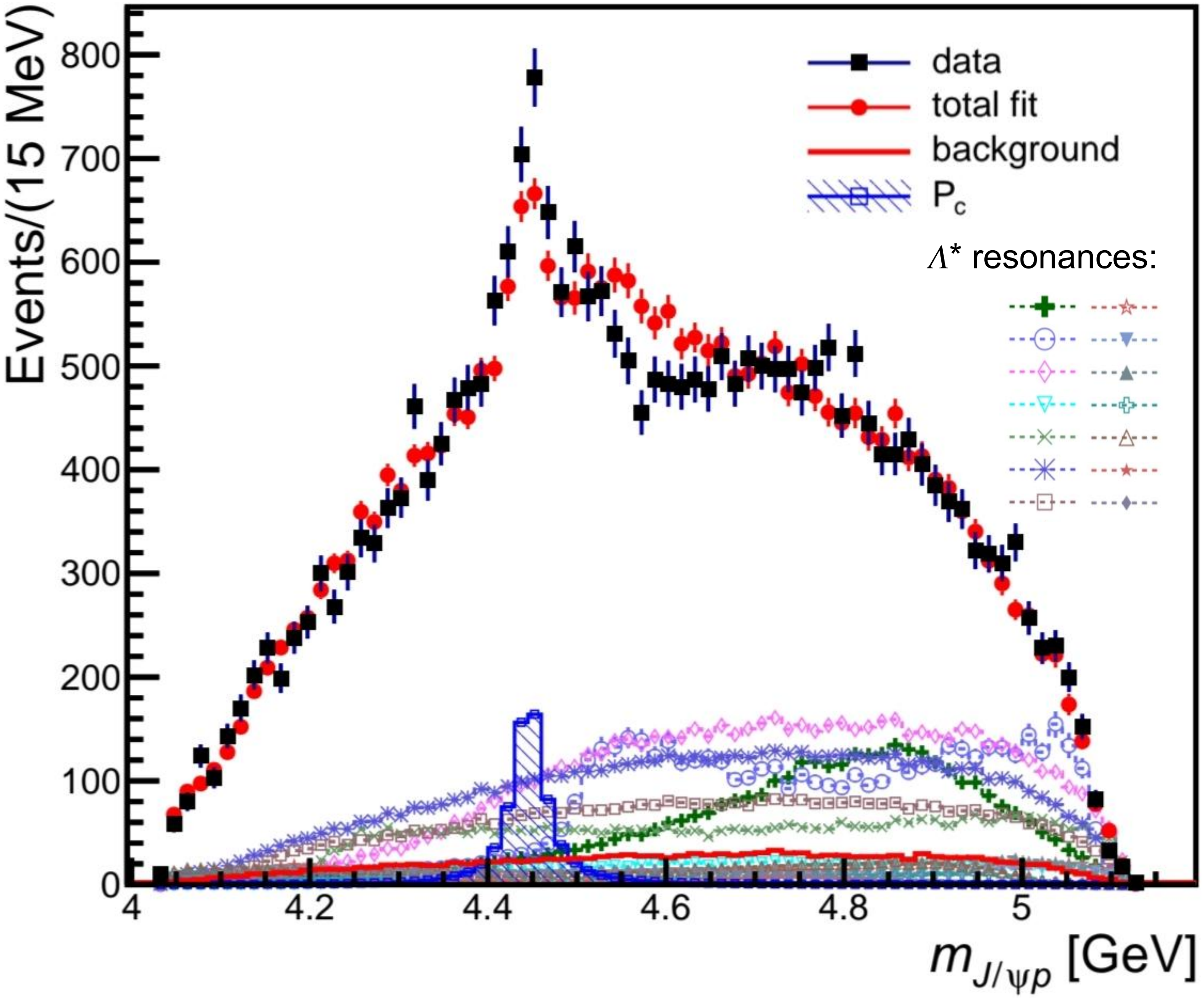
Amplitude fit with Λ^* resonances only

- Extended fit model: all possible known Λ^* states as decay amplitudes → 146 free parameters
- Masses and widths of Λ^* are fixed to PDG values
- Does **not** reproduce $m_{J/\psi\ p}$ spectrum, even if additional resonant and non-resonant components are added



Amplitude fit with 1 P_c state + Λ^* resonances

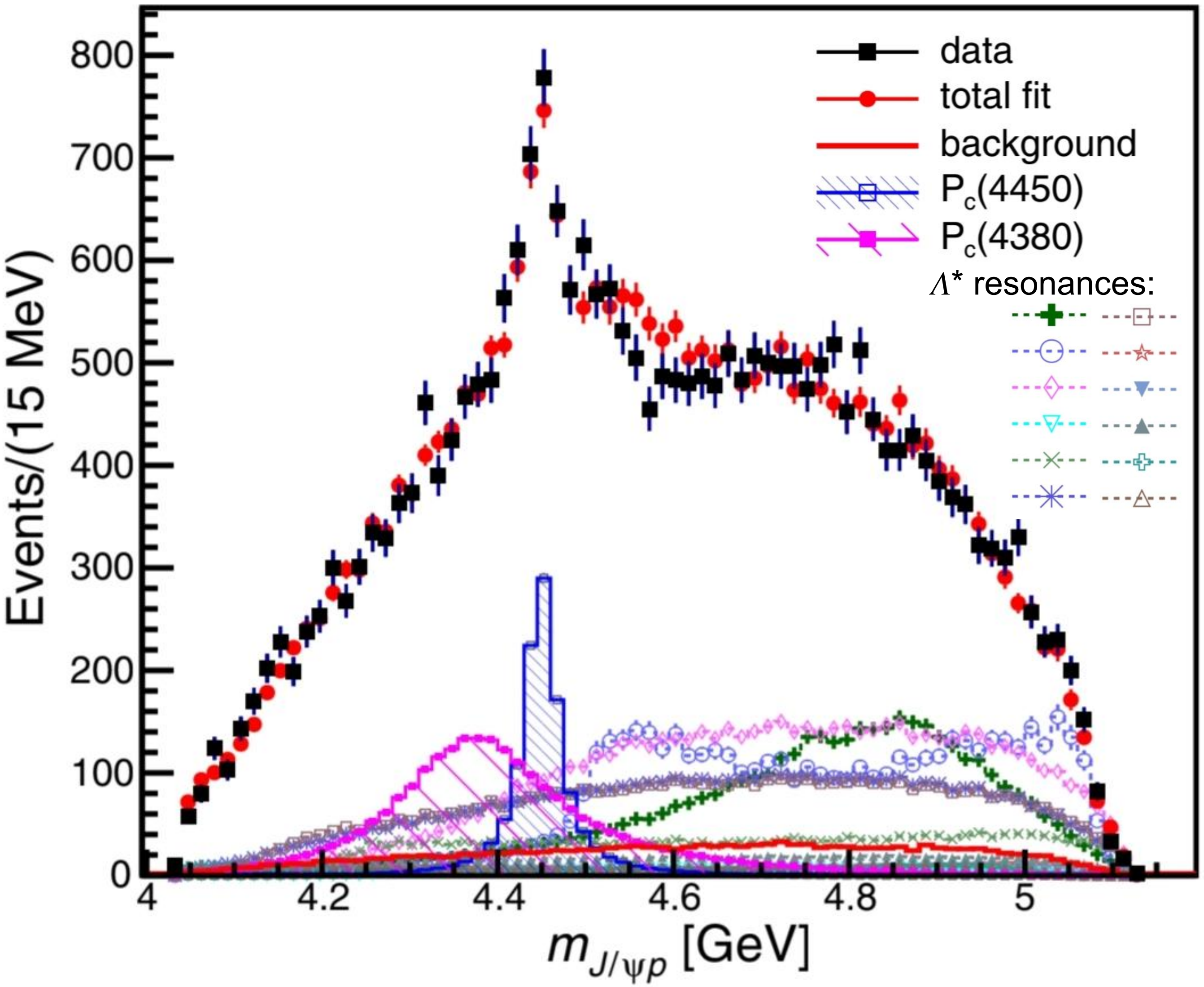
- Reduced fit model: only well-motivated Λ^* resonances → 64 free parameters
- Masses and widths of Λ^* are fixed to PDG values
- Add **one** P_c state with $J = 5/2^+$
- Better reproduction of $m_{J/\psi\ p}$ spectrum, but **fit quality still insufficient**



Amplitude fit with 2 P_c states + Λ^* resonances

- Reduced fit model: only well-motivated Λ^* resonances → 64 free parameters
- Masses and widths of Λ^* are fixed to PDG values
- Add **two** P_c states → **good fit quality**
- Possible spin parity configurations:

	Best fit	**1σ worse**	**2.3σ worse**
P_c(4380)	$J^P = 3/2^-$	$J^P = 3/2^+$	$J^P = 5/2^+$
P_c(4450)	$J^P = 5/2^+$	$J^P = 5/2^-$	$J^P = 3/2^-$



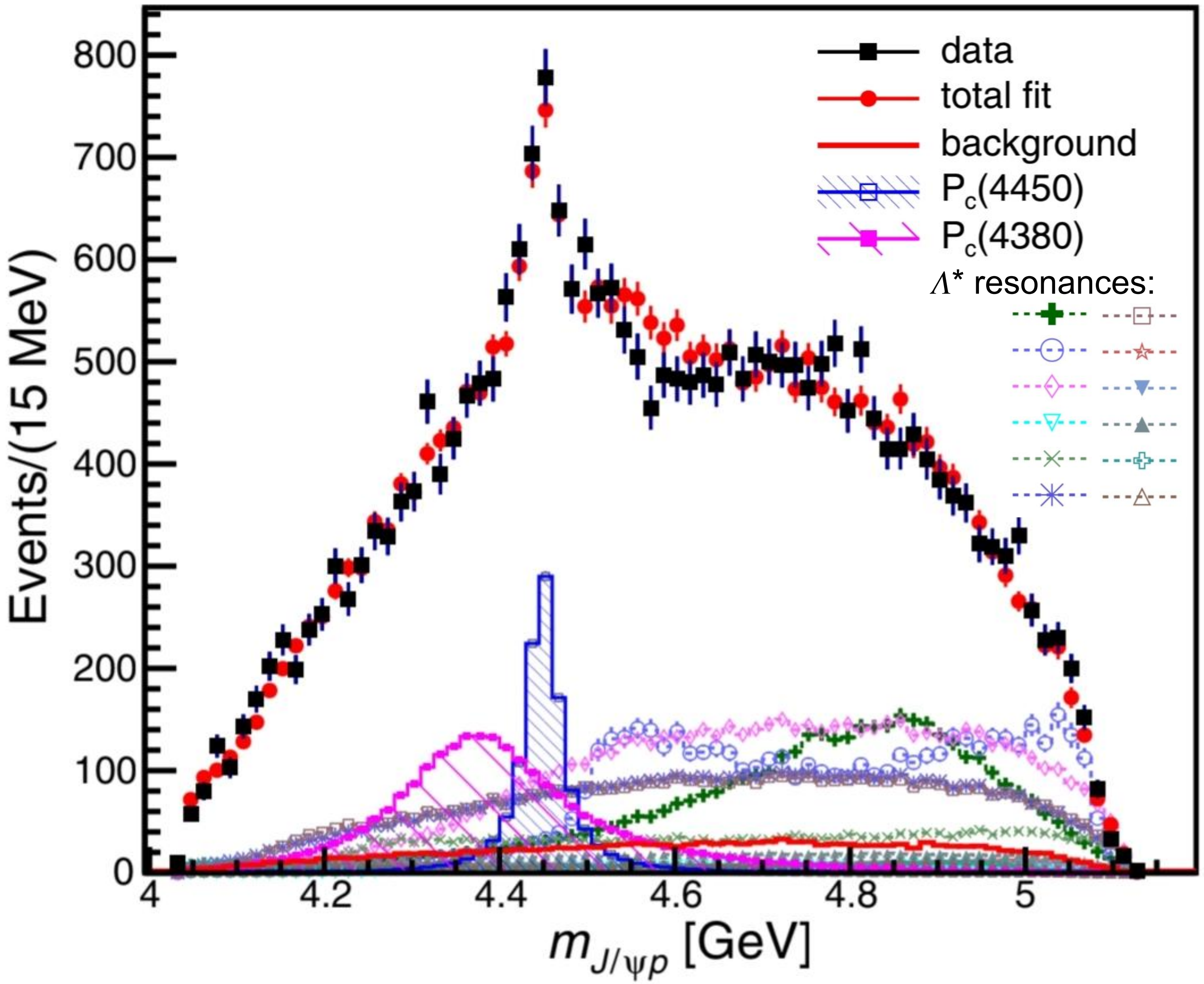
Systematics and Consistency Checks

- **Most important** systematics for mass, width and fit fractions of both P_c resonances:
  - Extended vs. reduced fitting model (i.e. how many Λ^* resonances are included)
  - Different spin parity configurations allowed by fits

- Examples of checks for the **stability of the results:**
  - Two different fit methods, independently developed
  - Fit reproduces other observables: m_{Kp} spectrum, angular parameters
  - Results are stable with LHCb dipole in up and down configurations
  - Removed veto for B^0 and modeled background explicitly → consistent results

Final Result

- Best fit: combined significance of 15σ
- Opposite parity and spins 3/2 and 5/2
- P_c(4380) resonance
  - Fit fraction (4.1 ± 0.5 ± 1.1) %
  - Mass m = (3280 ± 8 ± 29) MeV
  - Width Γ = (205 ± 18 ± 86) MeV
- P_c(4450) resonance
  - Fit fraction (8.4 ± 0.7 ± 4.2) %
  - Mass m = (4449.8 ± 1.7 ± 2.5) MeV
  - Width Γ = (39 ± 5 ± 19) MeV
- Uncertainties: statistical, systematic



After the 2015 LHCb..

Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of the Two-Peak Structure of the $P_c(4450)^+$

R. Aaij *et al.*[*]
HCb Collaboration)

April 2019; published 5 June 2019)

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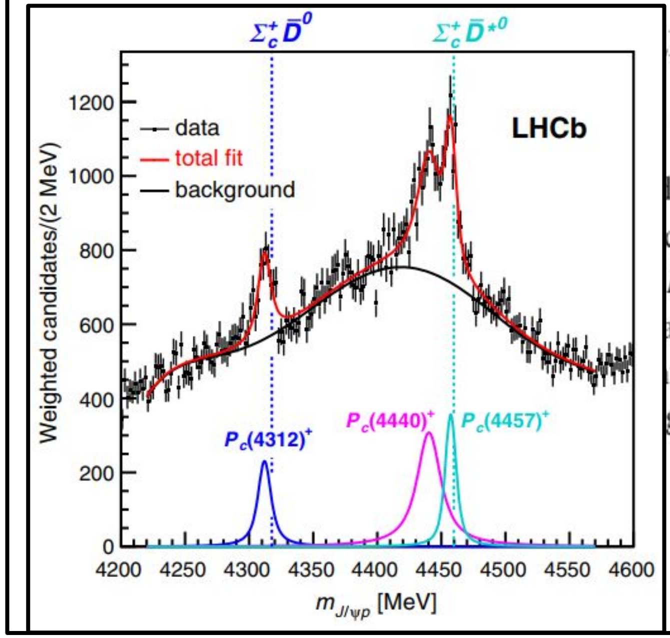

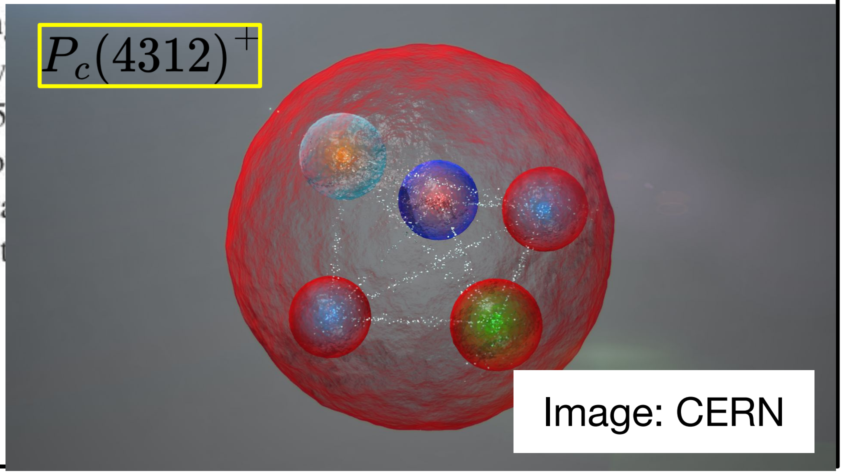

Image: CERN

After the 2015 LHCb..

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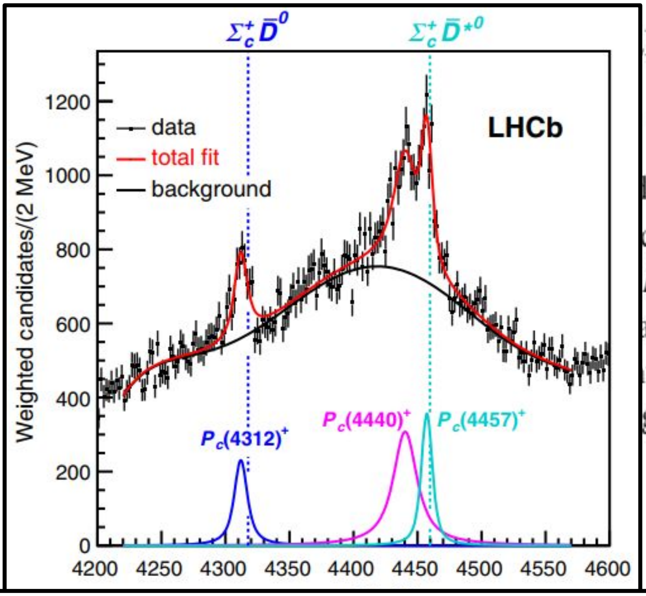

Observation of a $J/\psi\Lambda$ Resonance Consistent with a Strange Pentaquark Candidate in $B^- \to J/\psi\Lambda\bar{p}$ Decays

R. Aaij *et al.**
(LHCb Collaboration)

2022; accepted 12 January 2023; published 17 July 2023)

$\psi\Lambda\bar{p}$ decays is performed using 4400 signal candidates selected on a
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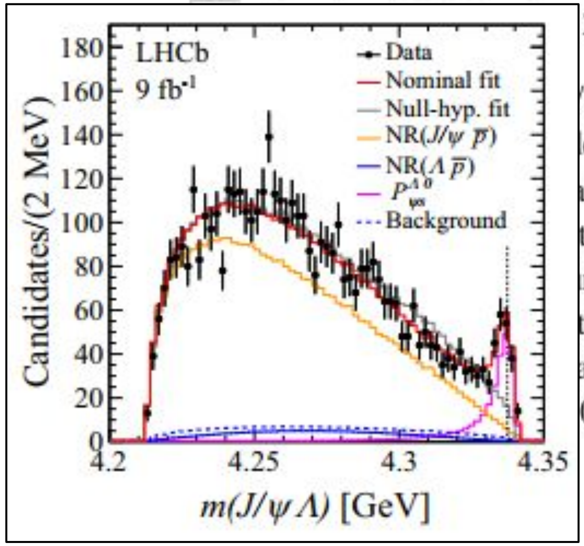

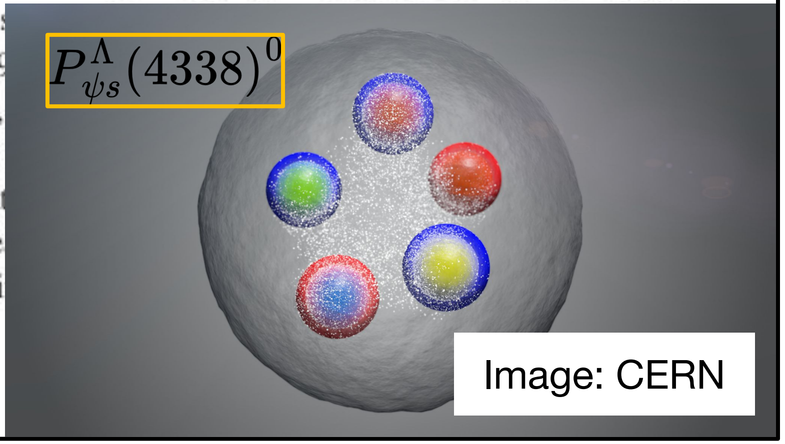

Image: CERN

Image: CERN

Article

Observation of structure in the J/ψ-pair mass spectrum

LHCb collaboration [1]

***Sci.Bull.* 65 (2020) 23, 1983-1993**

After the 2015 LHCb..

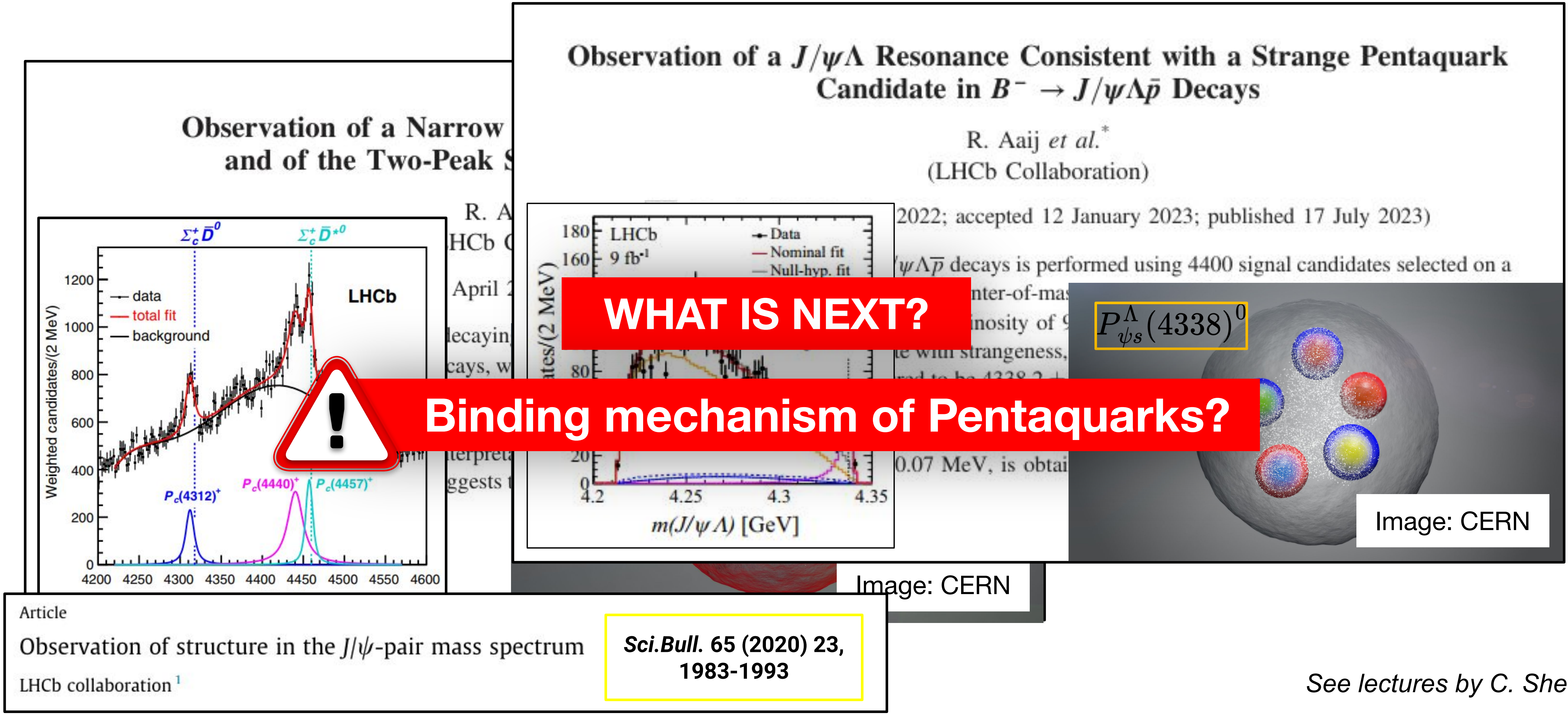

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Image: CERN

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Article

Observation of structure in the J/ψ-pair mass spectrum

LHCb collaboration[1]

***Sci.Bull.* 65 (2020) 23, 1983-1993**

WHAT IS NEXT?

Binding mechanism of Pentaquarks?

See lectures by C. Shen

Épilogue


Pentaquark
Setup & How to Play
ANNIHILATE
MIKE MULLINS
PENTAQUARK
A QUANTUM STATE SOLO GAME
GREEN - CHARM
ANTI-BLUE - ANTI-CHARM

Backup

Definition of θ_p

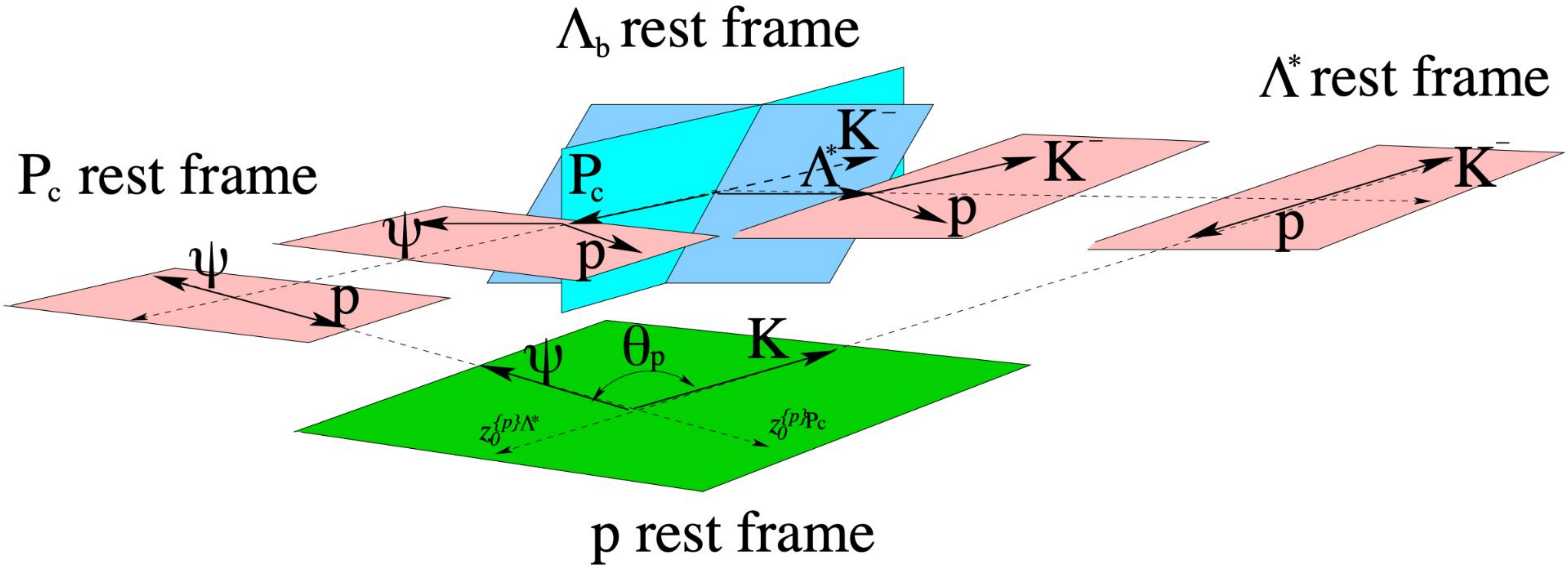
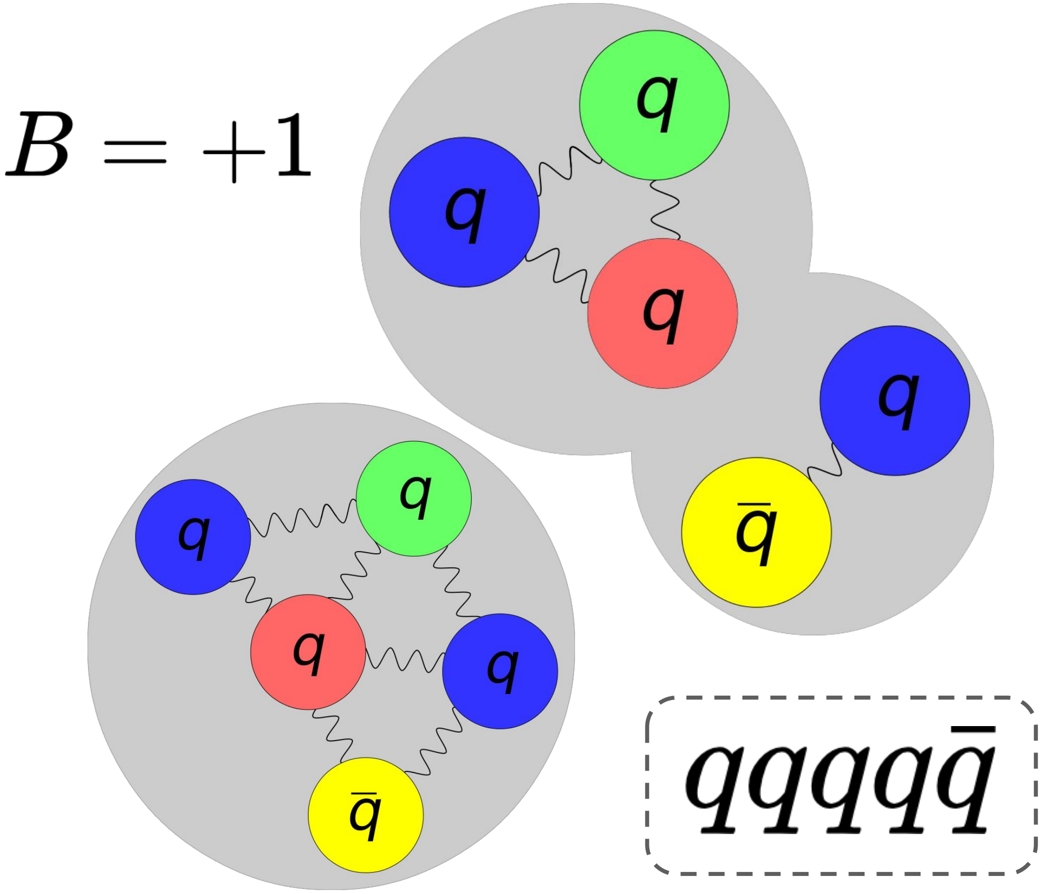


Figure 9: Definition of the θ_p angle.

Pentaquarks structure



https://commons.wikimedia.org/w/index.php?curid=41591193

Characteristics:

- classified as **an exotic hadron**
- typically have a higher mass than traditional hadrons
- decay through intermediate states that involve both baryons and mesons

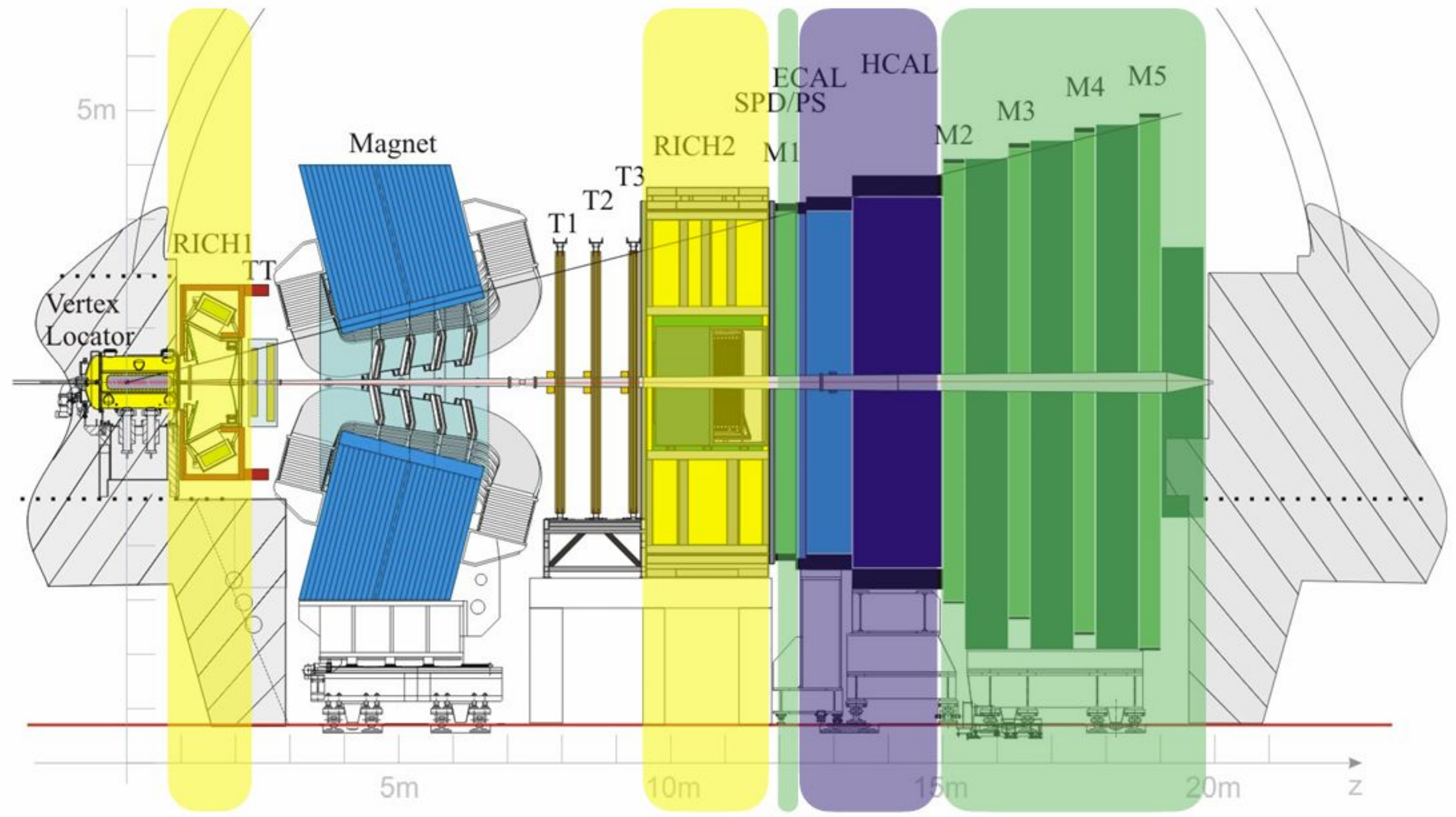
Possible configurations:

1. *Tightly bound state*
2. *Molecular state*
3. *Di-quark and Tri-quark clusters*

What differentiates pentaquark states from any other states?

See lectures by C. Shen

PID(Particle Identification) at LHCb



RICH detectors
RICH 1 and RICH 2 with PID for kaons, pions, protons, and low-momentum leptons

Muon Stations
Five muon stations (M1-M5) with high purity PID for muons

Calorimeters
Scintillating Pad Detector (SPD), Pre-Shower detector (PS), Electromagnetic Calorimeter (ECAL) and Hadronic Calorimeter (HCAL) with PID for electrons, photons and neutral pions

- Information of all sub-detectors is combined to PID variables used in analyses

1) For **charged** PID,
    - DLL_{X_π} : log likelihood difference particle hypotheses of X and π as reference $L = L_{RICH} * L_{calo} * L_{muon}$
    - $ProbNNX$: Neural net output, trained on simulation with input from detector components + tracking information

1) For **neutral** PID,
    - Dedicated neural nets

Trigger & Preselection

Trigger ($\mathrm{J}/\psi \to \mu^+$)

- each muon with $p_T > 500MeV$
- dimuon with opposite charge
- dimuon with vertex fit parameter $\chi^2 < 16$
- dimuon with vertex significantly displaced from the nearest pp interaction vertex
- dimuon invariant mass within $120MeV$ of $\mathrm{J}/\psi(\sim 3.1GeV)$

Preselection

Tracks:

- good track
- remove duplicated reconstruction

Muon:

- each muon with $p_T > 550MeV$
- dimuon constrained to the J/ψ mass

$K^- p$:

- vertex fit parameter $\chi^2 < 16$

Hadrons:

- $p_T > 250MeV$
- impact parameter(respect to primary vertex) $\chi^2 > 9$
- positive PID

Λ_b^0:

- vertex fit parameter $\chi^2 > 50$ for 5 degrees of freedom
- flight distance > 1.5mm
- $cos\left(\overrightarrow{\Lambda_b^0} \leftrightarrow \overrightarrow{p_{\Lambda_b^0}}\right)$

Amplitude Fit

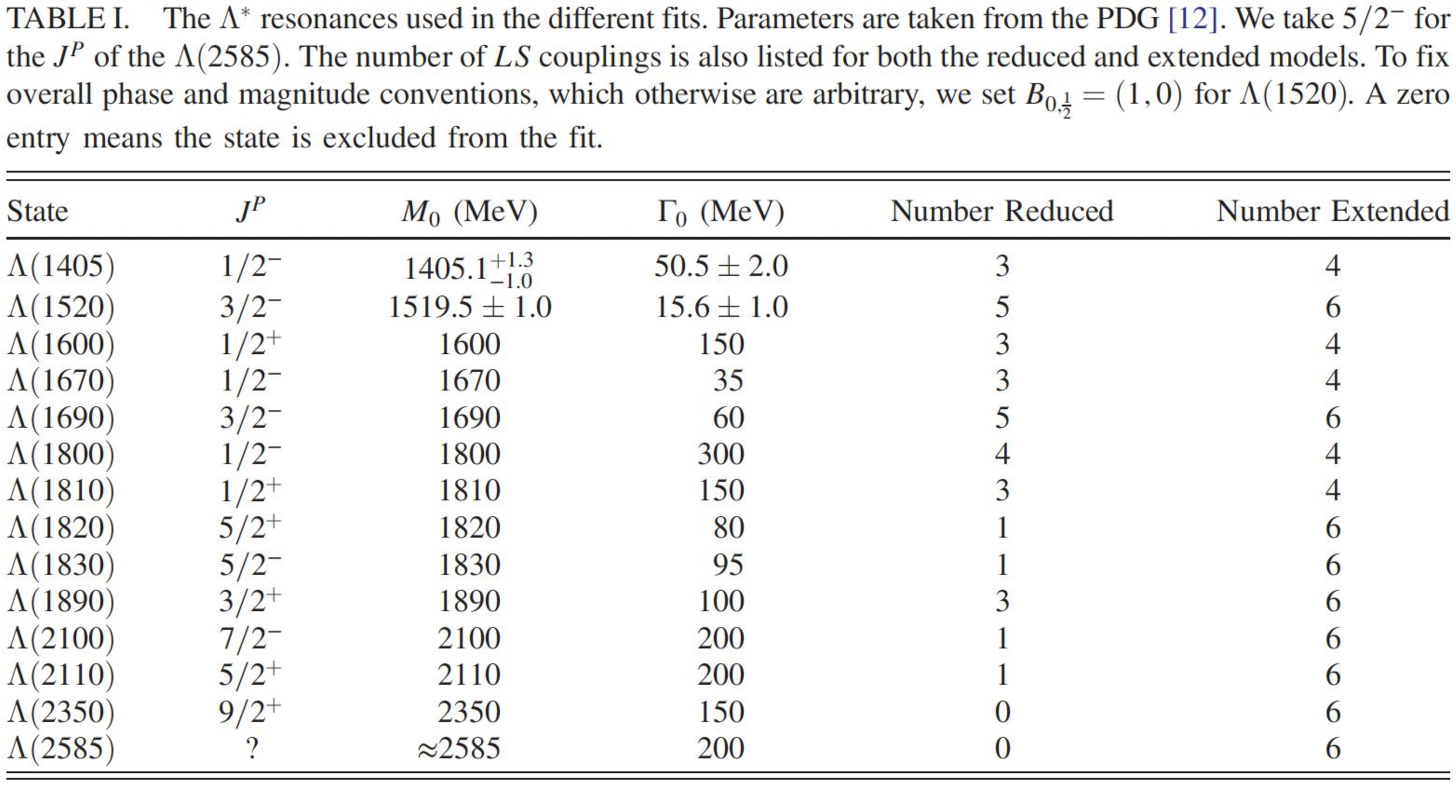
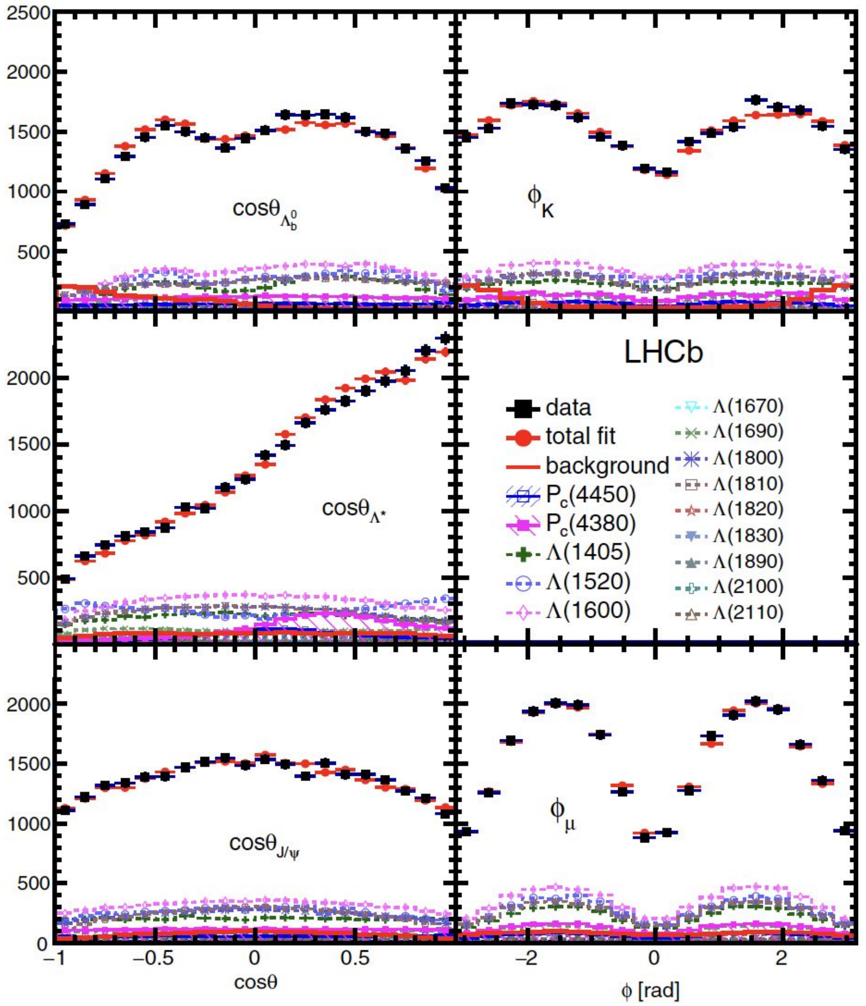


TABLE I. The Λ^* resonances used in the different fits. Parameters are taken from the PDG [12]. We take $5/2^-$ for the J^P of the $\Lambda(2585)$. The number of LS couplings is also listed for both the reduced and extended models. To fix overall phase and magnitude conventions, which otherwise are arbitrary, we set $B_{0,\frac{1}{2}} = (1,0)$ for $\Lambda(1520)$. A zero entry means the state is excluded from the fit.

State	J^P	M_0 (MeV)	Γ_0 (MeV)	Number Reduced	Number 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
$\Lambda(2585)$	?	≈ 2585	200	0	6

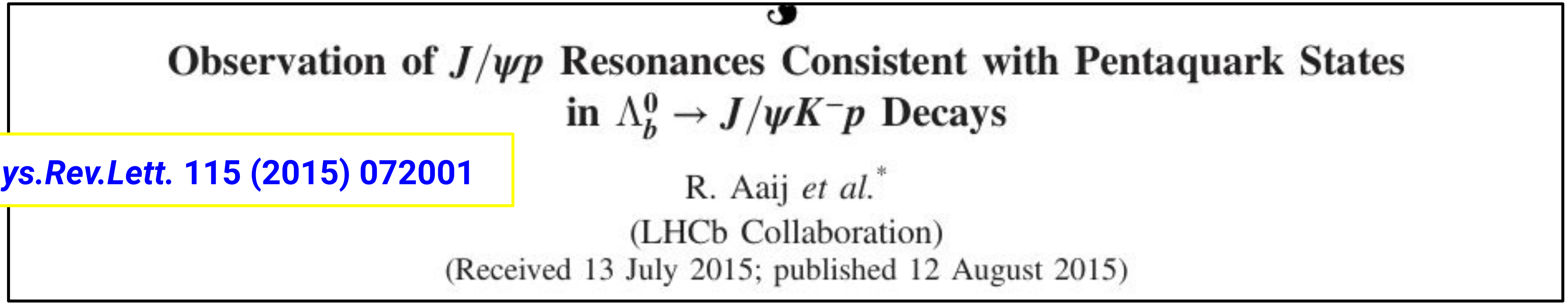


Pathways to pentaquarks

1976 PDG showed the candidates for baryon states with positive strangeness
1994 PDG (+ *subsequent versions*) dismissed the candidates
2003 LEPS *claimed* a discovery of the Θ^+, matched the prediction given by **DPP** (1997), followed by other (10) collaborations
2006 PDG: "*The conclusion that pentaquarks in general, and the* Θ^+*, in particular, do not exist, appears compelling.*"
2009 LEPS *claimed* (once again) the existence of a narrow state: $1524 \pm 4\ \mathrm{MeV}/c^2$

For instructive reviews and related experimental reports see: Dzierba et al. (2005), Hicks (2012), and Schumacher (2006).

Finally.. The 2015 LHCb results



Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

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