Searches in the B-Physics Sector

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OUTLINE

- Search for Physics BSM
- Hadron Spectroscopy
- Results from CMS and LHCb

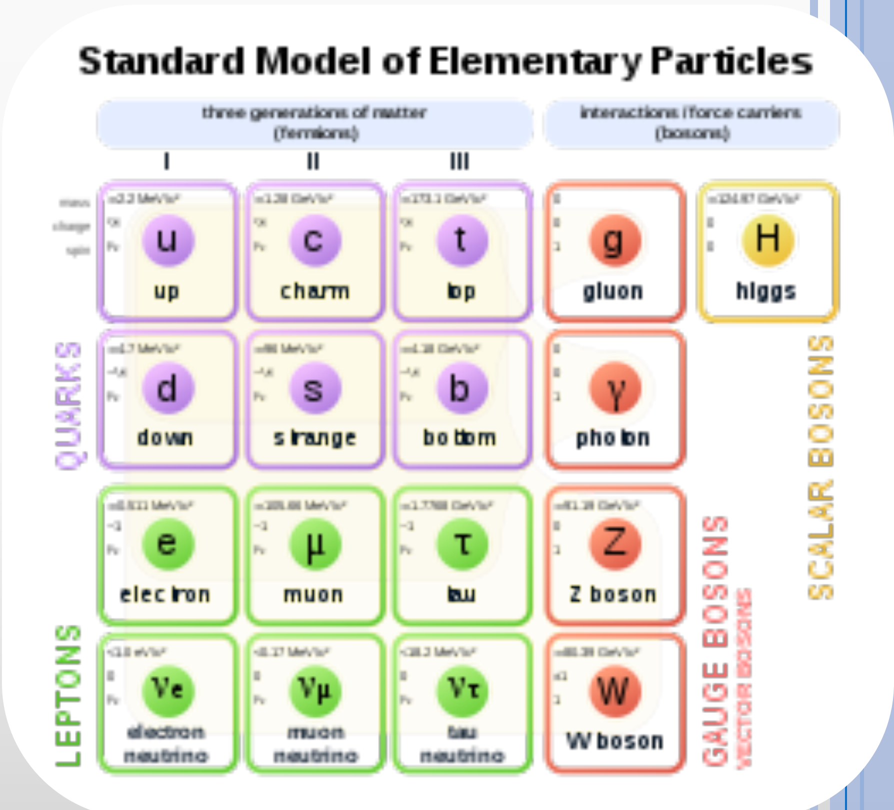
Search for physics BSM

The Standard Model

The Standard Model of particle physics is a successful theory of three (out of four) fundamental interactions that govern the universe: electromagnetism, the strong force, and the weak force.

It explains how all know matter is made of quarks and leptons which interact by force carrying particles: photons, gluons, W and Z.

Fundamental particles acquire mass through their interactions with the Higgs field



Beyond the Standard Model (BSM)

Why are we looking for physics beyond the standard model?

Fundamental questions to be addressed:

- Why there are three families of quarks and leptons?
- Why the masses of fundamental particles span several orders of magnitude?
- How to accommodate gravity into the global quantum picture?

Compelling empirical evidence that the standard model is incomplete!

- Dark matter
- Dark energy
- Non-zero mass of neutrinos
- Baryon asymmetry in the universe

Hunting Physics BSM

Many candidates for BSM particles:

- Supersymmetry particles
- Quantum black holes,
- New boson partners (e.g. Z',…)
- Excited quarks
- Dark matter mediators

How to look for them?

Looking back to the history, often New Physics has showed up first at the intensity frontier rather than at the energy frontier

- ✓ GIM Mechanism used to predict 4th charm quark
- ✓ CP Violation / CKM Matrix used to predict 5th/6th bottom/top quarks
- ✓ Neutral currents found before discovery of Z
- ✓ Top quark mass predicted from electroweak corrections in B physics
- ✓ Higgs mass predicted from electroweak corrections W and Z bosons

Direct and Indirect BSM Searches

Direct Searches (Energy Frontier)

- Use of high-energy colliders (Tevatron, LHC, …) to produce new particles

Indirect Searches (Intensity Frontier) ← **This Talk**

- Production of a huge numbers of particles (B-factories, LHC, …) needed to study very rare processes

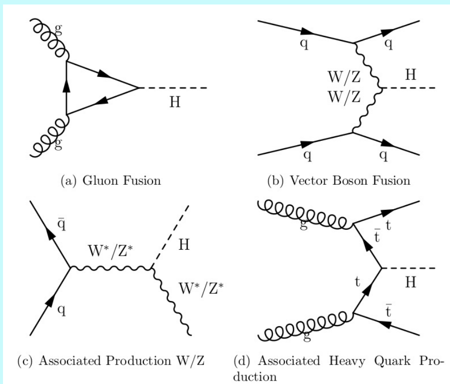
Which rare decays to look at?

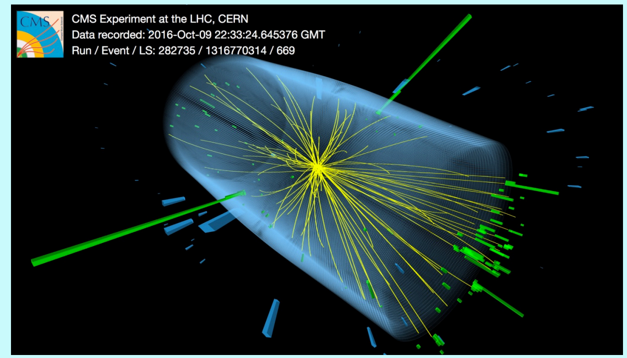
- No SM tree level processes (SM contributions suppressed /absent)
- Small loop or penguin contribution (flavour changing neutral currents) (
- CP Violation
- Lepton flavour / lepton number / lepton universality
- SM prediction should have high precision

EVENT TOPOLOGY AT LHC

Direct Searches (Energy Frontier)

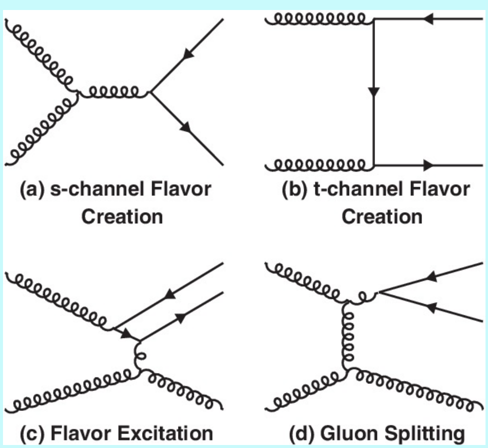
- H→ gg and search for X→ gg

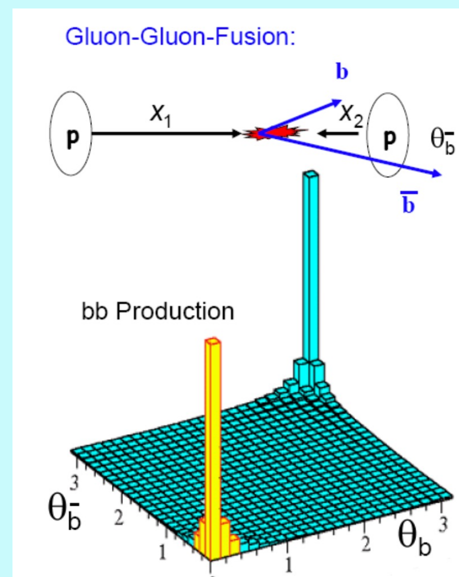




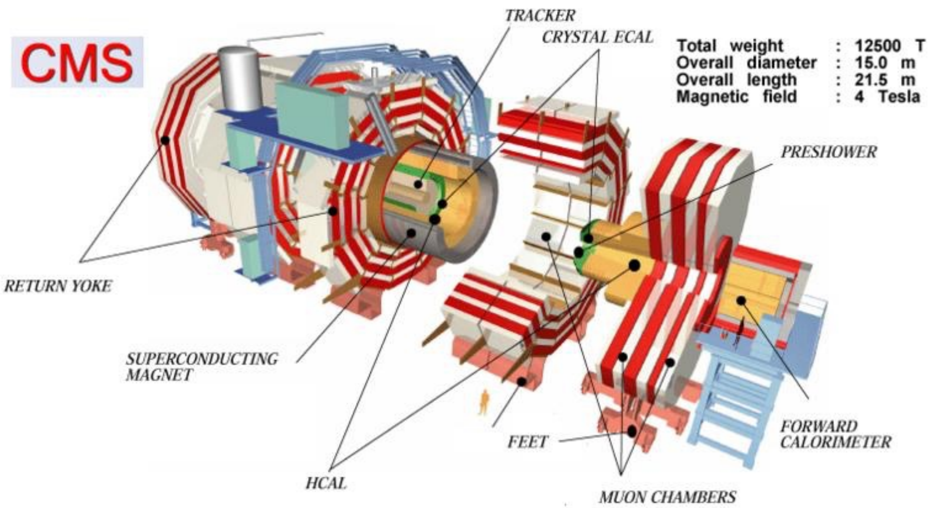
Indirect Searches (Intensity Frontier)

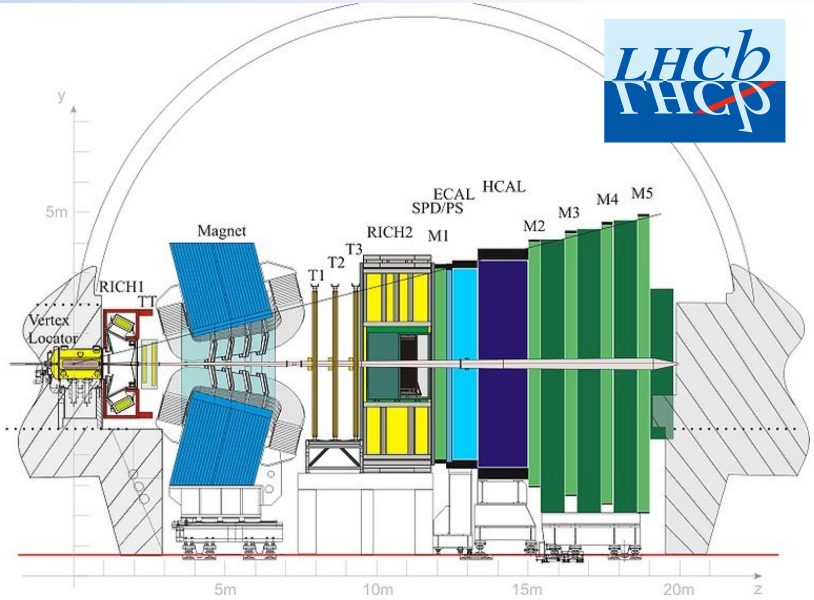
- Search for rare b-hadron decays





CMS and LHCb Detectors





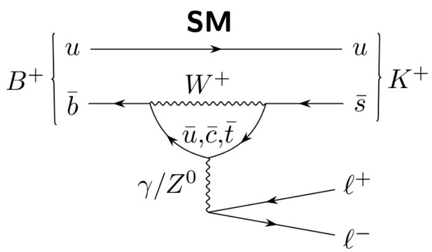
- $|\eta| < 2$
- Mainly high p_T physics (Higgs and Supersymmetry) but large samples of B candidates available
- B-hadrons reconstruction mainly exploits excellent vertex detectors and muon detectors. Excellent vertex and tracking reconstruction capabilities also in high pile-up
- Limited hadron identification, but excellent photon identification

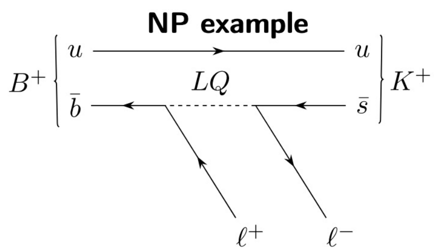
- $2 < \eta < 5$
- b quark production $\sigma \sim 0.3$ mb (7 TeV)
- $\sim 5\ 10^{11}$ b-anti b pairs /year
- Excellent vertex resolution to resolve fast oscillation of B_s (~ 40 fs)
- Good particle ID (π, K, p, γ, μ)
- Precise momentum resolution (~0.5%)

R_K: Test of Lepton Flavour Universality

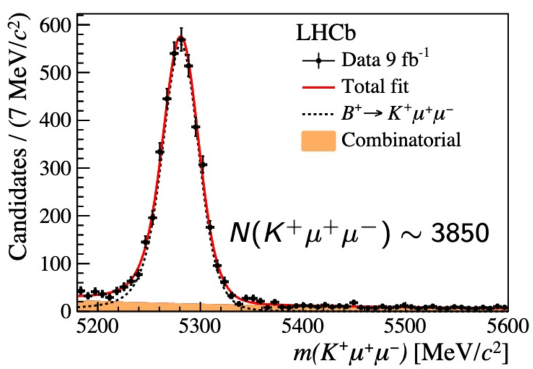
[LHCb-PAPER-2021-004, in preparation]

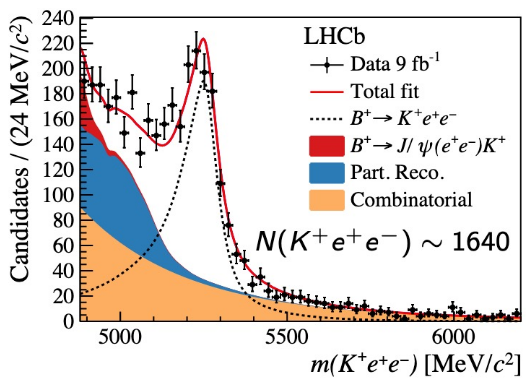
- b→sll decays mediated by flavor changing currents. Sensitive to NP particles
- In the SM couplings of gauge bosons to leptons are independent of lepton flavour→Branching fractions differ only by phase space (~1)
- In SM free from QCD uncertainties affecting other observables

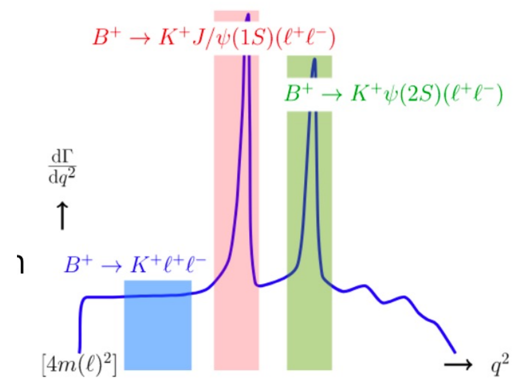




$$R_K = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$







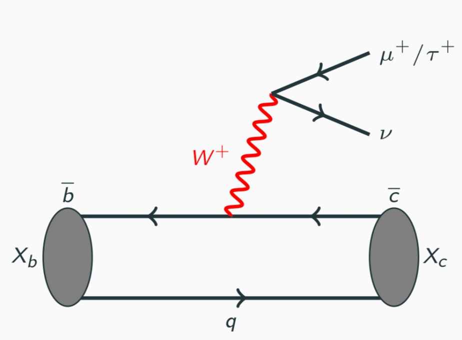
q^2 spectrum, showing selection regions for rare, control, and $\psi(2S)$ channels

$$R_K = 0.846\ ^{+0.042}_{-0.039}\ (\mathrm{stat})\ ^{+0.013}_{-0.012}\ (\mathrm{syst})$$

Evidence of LFU violation at 3.1σ!

R(D_s): Lepton Flavour Universality

Test of lepton flavour universality using the transitions $b \to c\tau\nu$ transitions



Study of the semileptonic $B_s^0 \to D_s^- \ell^+ \nu_\ell$ decay ratio

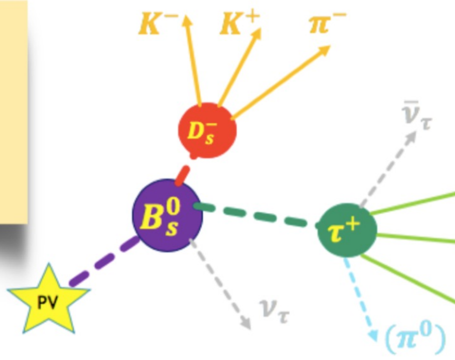
RUN1 and RUN2 data

$$R(D_s) = \frac{\mathcal{B}(B_s^0 \to D_s^- \tau^+ \nu_\tau)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}$$

$D_s^- \to K^+ K^- \pi^-$

HADRONIC

$\tau^+ \to \pi^+ \pi^- \pi^+ (\pi^0) \bar{\nu}_\tau$

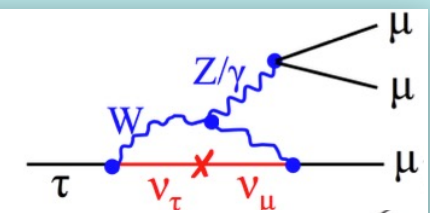


SEARCH FOR THE $\tau\to3\mu$ DECAY

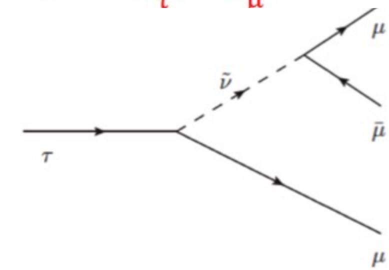
- ❖ $\tau\to3\mu$ transition
  - ✓ doesn't conserve the lepton family number
  - ✓ doesn't involve neutrinos in the final state
    - ➢ Charged Lepton Flavour Violation (CLFV)

Neutrino flavor violation → CLFV (e.g. $\tau\to3\mu$) also allowed

- ❖ Suppressed in the Standard Model:
  Branching Ratio $\tau\to3\mu$ (SM) ~ $\mathcal{O}(10^{-54})$
  from the most recent calculations, EPJ C79 (2019) 84



- ❖ Enhanced BR in SUSY, 2HDM
  $\tau\to3\mu$ (BSM) ~ $\mathcal{O}(10^{-7} \div 10^{-9})$
  https://doi.org/10.1016/j.physrep.2005.08.006
  https://doi.org/10.1103/PhysRevLett.89.241802

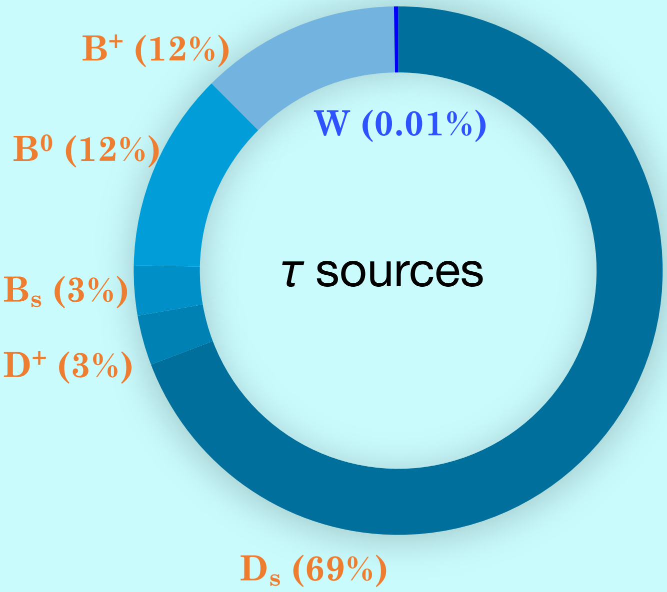


The rates for CLFV processes are expected to provide information regarding the nature of new physics

F. Simone et al.

SEARCH FOR THE $\tau \to 3\mu$ DECAY

Run II, pp @ 13 TeV
2016: 33 fb^{-1}
2017: 38 fb^{-1}
2018: 59.7 fb^{-1}



Heavy Flavour (**HF**) ($D \to \tau\nu$, $B \to \tau\nu$..., $B \to D(\tau\nu)$...)
large cross section; low p_T; high η; high background

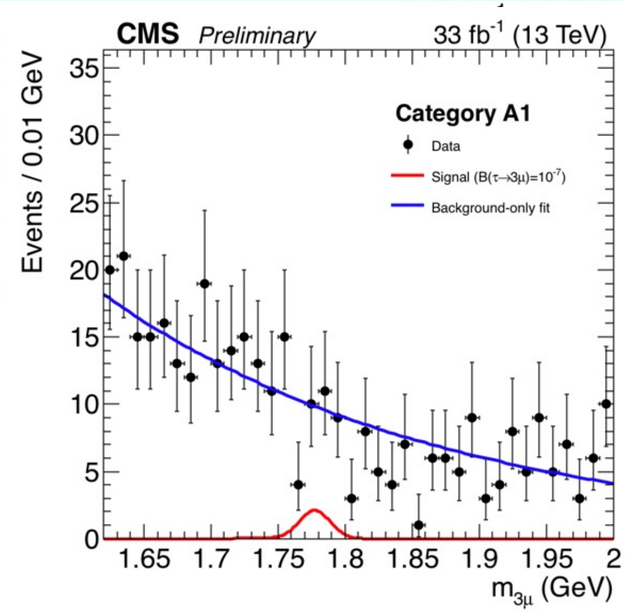
Heavy Flavour (**W**)
relatively small cross section; high p_T; low background

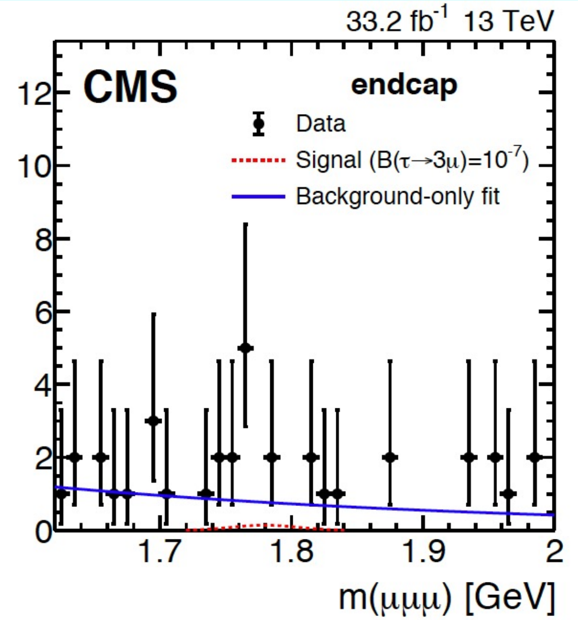
CMS is capable of exploring both (unique!)

F. Simone et al.

Search for the $\tau \to 3\mu$ Decay (2016 data)

HF **W**





$BR(\tau \to 3\mu) < 9.2 \times 10^{-8}$ @90% C.L.

$Br(\tau \to 3\mu) < 19.5 \times 10^{-8}$ @ 90% CL

No signal observed

Run II, pp @ 13 TeV
2016: 33 fb^{-1}
2017: 38 fb^{-1}
2018: 59.7 fb^{-1}

- Analysis of 2017 and 2018 data is ongoing, INFN Bari group works on the Heavy Flavor channel
- INFN Bari group works on $\tau \to 3\mu$ dedicated trigger implementation for Run3

Hadron Spectroscopy

Spectroscopy is a Hot Topic

Discoveries in spectroscopy are between the most cited papers

Observation of CP violation in the B^0 meson system

BaBar Collaboration • Bernard Aubert (Annecy, LAPTH) et al. (Jul, 2001)

Published in: *Phys.Rev.Lett.* 87 (2001) 091801 • e-Print: hep-ex/0107013 [hep-ex]

pdf links DOI cite

Observation of a narrow meson decaying to $D_s^+\pi^0$ at a mass of 2.32-GeV/c^2

BaBar Collaboration • B. Aubert (Annecy, LAPP) et al. (Apr, 2003)

Published in: *Phys.Rev.Lett.* 90 (2003) 242001 • e-Print: hep-ex/0304021 [hep-ex]

pdf links DOI cite 903 citations

#4 Observation of a broad structure in the $\pi^+\pi^- J/\psi$ mass spectrum around 4.26-GeV/c^2

BaBar Collaboration • Bernard Aubert (Annecy, LAPP) et al. (Jun, 2005)

Published in: *Phys.Rev.Lett.* 95 (2005) 142001 • e-Print: hep-ex/0506081 [hep-ex]

pdf links DOI cite 901 citations

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

LHCb Collaboration • Roel Aaij (CERN) et al. (Jul 13, 2015)

Published in: *Phys.Rev.Lett.* 115 (2015) 072001 • e-Print: 1507.03414 [hep-ex]

pdf links DOI cite

Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays

LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) et al. (Jun 25, 2014)

Published in: *Phys.Rev.Lett.* 113 (2014) 151601 • e-Print: 1406.6482 [hep-ex]

pdf DOI cite 1,086 citations

#4 Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$

LHCb Collaboration • Roel Aaij (CERN) et al. (Jun 29, 2015)

Published in: *Phys.Rev.Lett.* 115 (2015) 11, 111803, *Phys.Rev.Lett.* 115 (2015) 15, 159901 (erratum) • e-Print: 1506.08614 [hep-ex]

pdf links DOI cite 868 citations

#2 Observation of a narrow charmonium - like state in exclusive B+- ---> K+- pi+ pi- J / psi decays

Belle Collaboration • S.K. Choi (Gyeongsang Natl. U.) et al. (Sep, 2003)

Published in: *Phys.Rev.Lett.* 91 (2003) 262001 • e-Print: hep-ex/0309032 [hep-ex]

pdf links DOI cite

Observation of large CP violation in the neutral B meson system

Belle Collaboration • Kazuo Abe (KEK, Tsukuba) et al. (Jul, 2001)

Published in: *Phys.Rev.Lett.* 87 (2001) 091802 • e-Print: hep-ex/0107061 [hep-ex]

pdf DOI cite 1,065 citations

#5 Study of $e^+e^- \to \pi^+\pi^- J/\psi$ and Observation of a Charged Charmoniumlike State at Belle

Belle Collaboration • Z.Q. Liu (Beijing, Inst. High Energy Phys.) et al. (Mar 30, 2013)

Published in: *Phys.Rev.Lett.* 110 (2013) 252002, *Phys.Rev.Lett.* 111 (2013) 019901 (erratum) • e-Print: 1304.0121 [hep-ex]

pdf links DOI cite datasets 716 citations

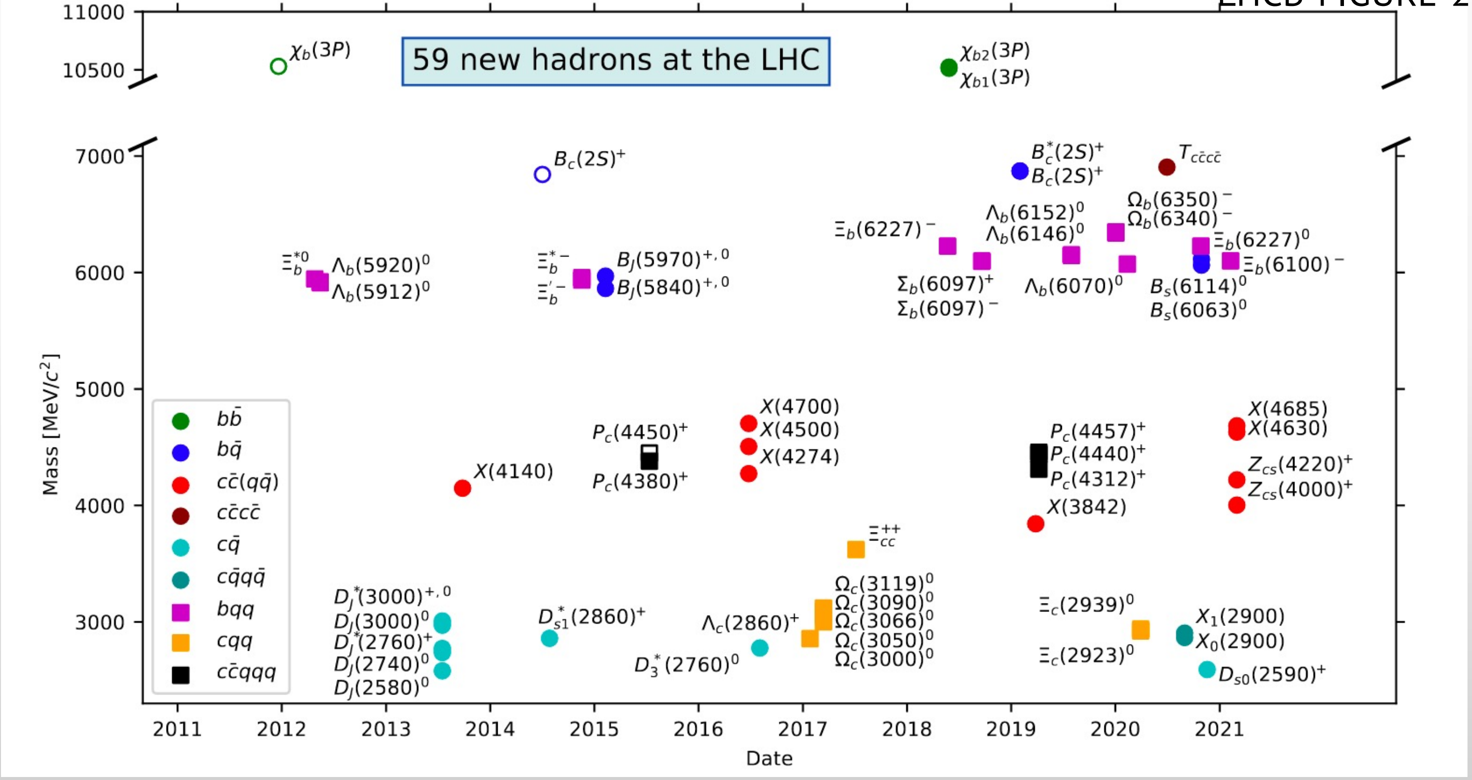
Why spectroscopy draws so much attention?

- The discovery of new particles provides valuable information on probing the limits of the quark model
- New states, bound by QCD, do not test the SM per se
- However they do provide insight into a still-to-be-fully-understood corner of the SM, namely confinement
- Understanding strong interactions could be important for new high energy phenomena
  - ✓ Higgs boson as a composite state
  - ✓ Strong interactions in a dark sector (e.g. arXiv:1602.00714)
  - ✓ Hadronic dark matter?

50+ New Hadrons at LHC!

Over the past 10 years the LHC has discovered 59 new hadrons:
ATLAS (2), CMS (5), LHCb (52)

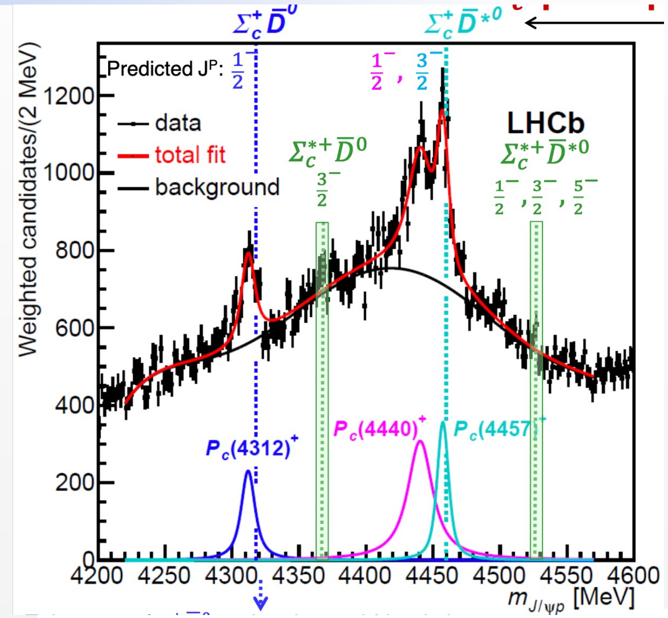
LHCB-FIGURE-2021-001

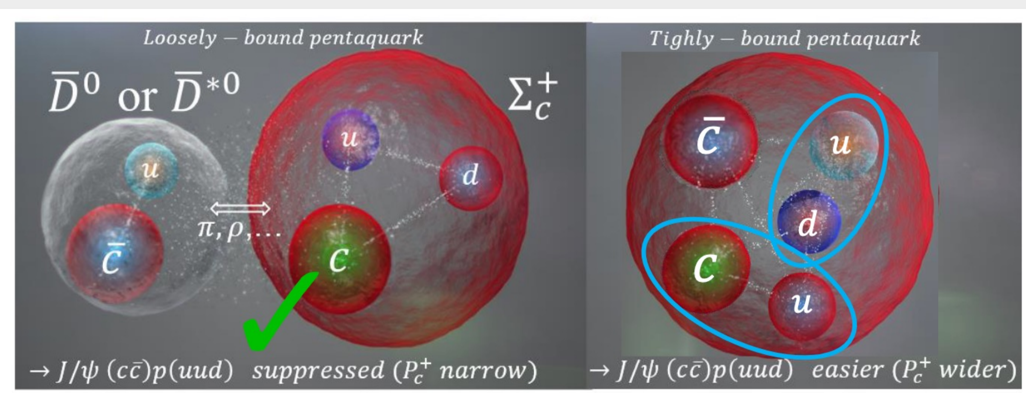


G. Robertons, M. Pappagallo, M. Needham

Search for Pentaquarks in $\Sigma_c D^{(*)}$ States

- The LHCb collaboration announced the discovery of the first pentaquark states, coming from a Λ_b baryon decaying to a $J/\psi pK^-$ final state. Two of the observed structures occurred very close to the $\Sigma_c D^{(*)}$ mass thresholds
- Due to the implications of isospin symmetry, it is expected that there will exist a multiplet corresponding to the pentaquarks shown, with differing total charge.

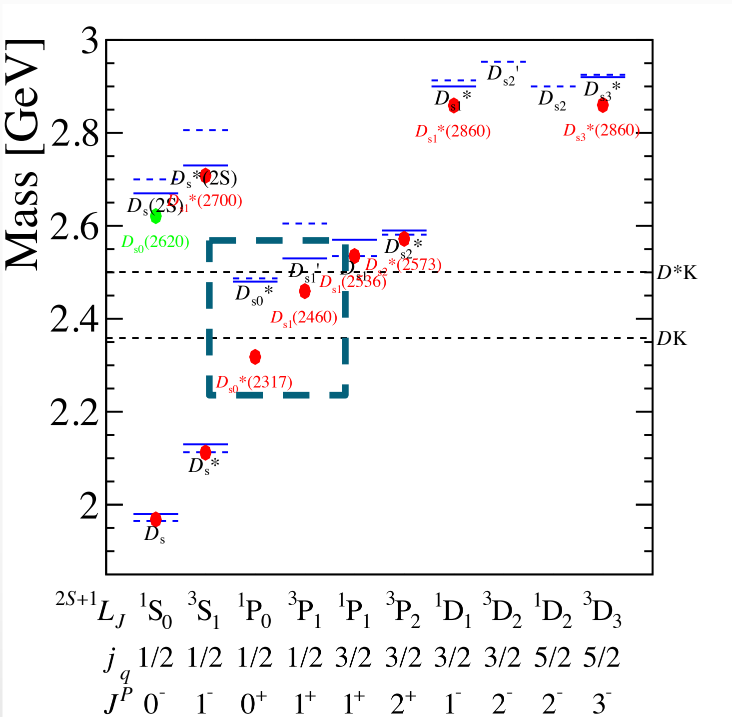




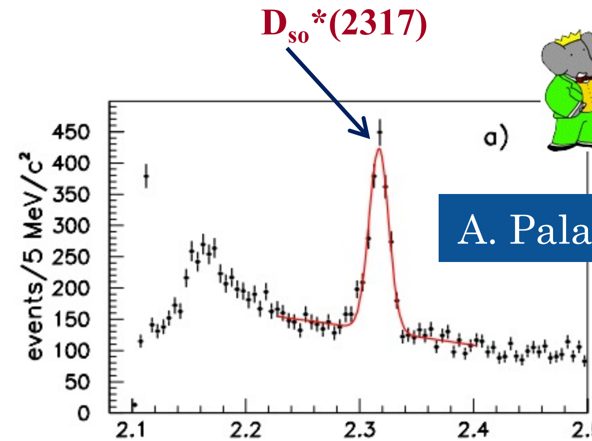
Particle 1	Particle 2	Corresponding Pentaquark
Σ_c^{++}	$\overline{D^0}$	P_c^{++}
Σ_c^{0}	$\overline{D^0}$	P_c^{0}
Σ_c^{++}	D^-	P_c^{+}
Σ_c^{0}	D^-	P_c^{-}
Σ_c^{++}	D^{*-}	P_c^{+}
Σ_c^{0}	D^{*-}	P_c^{-}

Table 1: *Different possible combinations of Σ_c baryons with D mesons to produce the isospin multiplet.*

The Puzzle of the Excited D_s Mesons

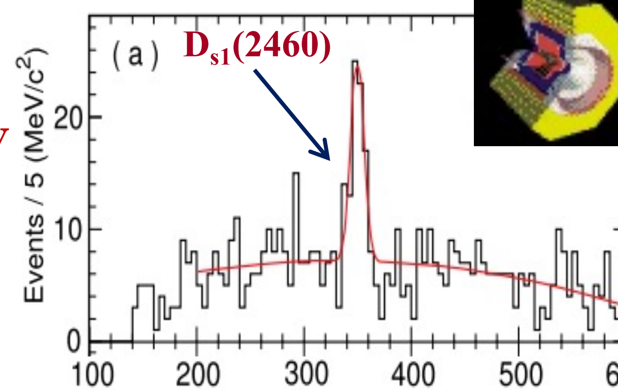


Inclusive studies of $D_s^{(*)}\pi^0$
[BaBar, PRL90, 242001][CLEO, PRD68, 032002]



A. Palano

$M(D_s\pi^0)$



Surprisingly narrow!

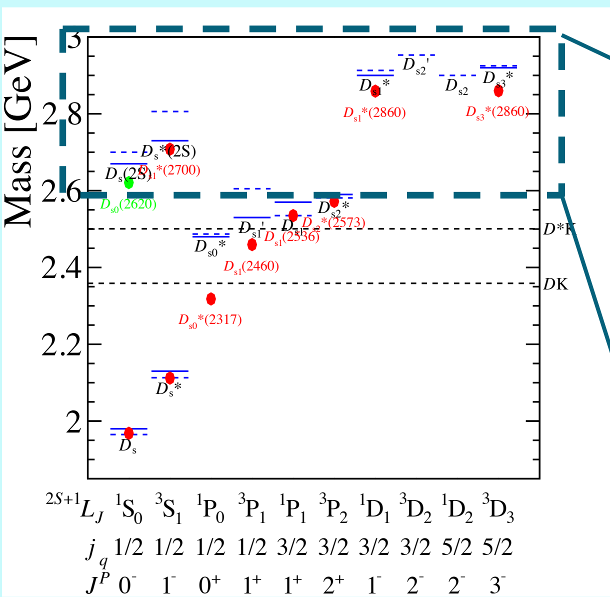
$M(D_s\gamma\pi^0)$-$M(D_s\gamma)$

	Mass (MeV)	Width (MeV)
$D_{s0}^*(2317)^\pm$	2317.7 ± 0.6	< 3.8
$D_{s1}(2460)^\pm$	2459.5 ± 0.6	< 3.5

A. Palano, M. De Serio, A. Pastore, M. Martinelli

Study of $B_{(s)}^0 \to D^*(2010)^- K^0_S \pi^+$ decay channel

- The production of D_s^{**} in $B_{(s)}^0$ decays can help understanding the nature of these states
- Dalitz analyses involving DK final states have been also performed in B_s^0 decays:



Excited charm-strange states above the $D^*_{s2}(2573)$ seen in D(*)K spectra in collisions BaBar e^+e^- and LHCb

State	Mass	Width	Comment
		BaBar	
$D^*_{s1}(2700)^-$	$2710 \pm 2\,^{+12}_{-7}$	$149 \pm 7\,^{+39}_{-52}$	Seen in DK and D^*K
$D^*_{sJ}(2860)^-$	$2862 \pm 2\,^{+5}_{-2}$	$48 \pm 3 \pm 6$	Seen in DK and D^*K
$D_{sJ}(3040)^-$	$3044 \pm 8\,^{+30}_{-5}$	$239 \pm 35\,^{+46}_{-42}$	Seen in D^*K only
		LHCb	
$D^*_{s1}(2700)^-$	$2709.2 \pm 1.9 \pm 4.5$	$115.8 \pm 7.3 \pm 12.1$	Seen in DK and D^*K
$D^*_{sJ}(2860)^-$	$2866.1 \pm 1.0 \pm 6.3$	$69.9 \pm 3.2 \pm 6.6$	Seen in DK and D^*K
$D^*_{s1}(2860)^-$	2859 ± 12	159 ± 23	From $B^0_s \to \overline{D^0} K^- \pi^+$
$D^*_{s3}(2860)^-$	2860.5 ± 2.6	53 ± 7	From $B^0_s \to \overline{D^0} K^- \pi^+$

Now investigating D*K final states in $B_{(s)}^0$ decays …

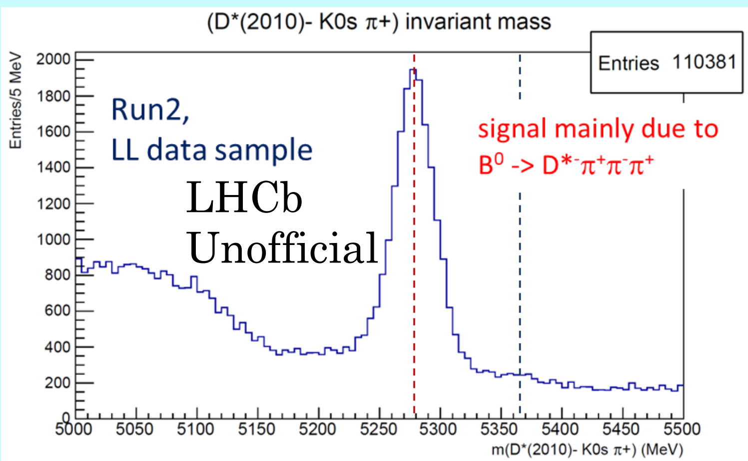
A. Palano, M. De Serio, A. Pastore, M. Martinelli

Study of $B_{(S)}^0 \rightarrow D^*(2010)^- K^0_S \pi^+$ decay channel

- $\mathcal{B}(B^0 \rightarrow D^{*-} K^0_s \pi^+) = (3.0 \pm 0.8) \times 10^{-4}$
- $B^0_s \rightarrow D^{*-} K^0_s \pi^+$ has not been observed
- major background for $B^0 \rightarrow D^{*-} K^0 \pi^+$ with LL K^0_s :

$\mathcal{B}(B^0 \rightarrow D^{*-} \pi^+\pi^-\pi^+) = (7.21 \pm 0.29) \times 10^{-3}$

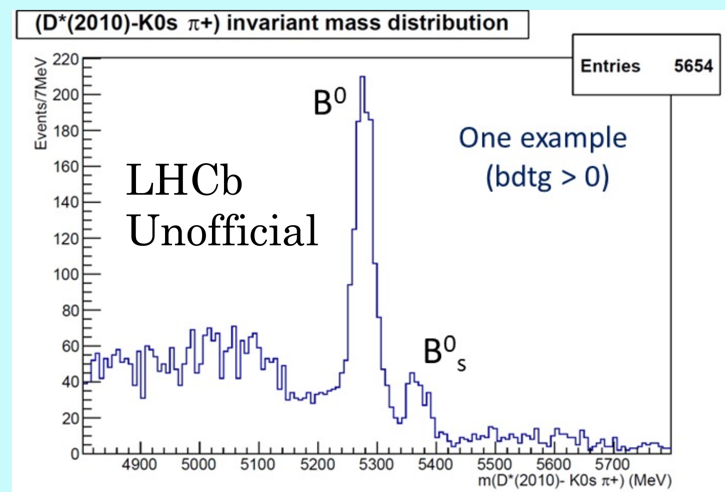
Analysis on-going on Run 1 & Run2 data



PDG B^0 mass = 5279.64 ± 0.13 MeV

PDG B^0_s mass = 5366.88 ± 0.17 MeV

TMVA



WHAT WE KNOW ABOUT $D_{s1}(2460)^+$

- Observed in prompt production and from B decays
- Absolute branching ratios of three decay modes
- $J^P = 1^+$
- $m = 2459.5 \pm 0.6$ MeV
- $\Gamma < 3.5$ MeV at 95% C.L.

$D_{s1}(2460)$

Decay Mode	BR (%)
$D_s^{*+}\pi^0$	48 ± 11
$D_s^+\gamma$	18 ± 4
$D_s^+\pi^+\pi^-$	4.3 ± 1.3
TOT	70 ± 12

Largely dominated by

$m = 2460.2 \pm 0.2 \pm 0.8$ MeV

from $D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$ decays

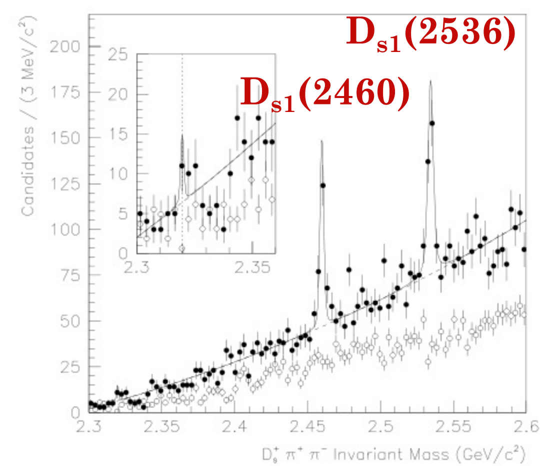
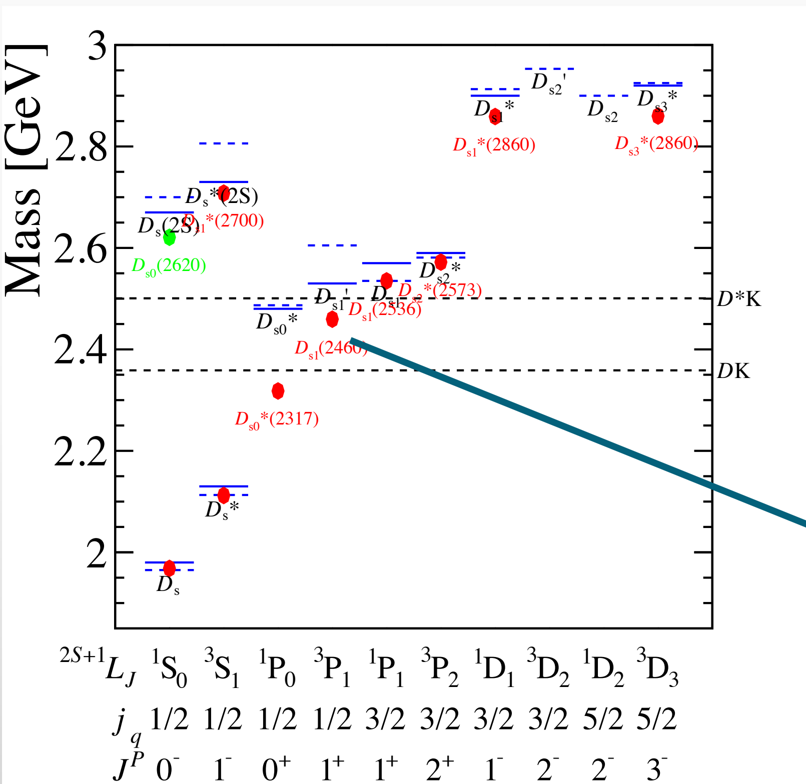


FIG. 33: The invariant mass distribution of (solid points) $D_s^+\pi^+\pi^-$ candidates and (open points) the equivalent using the D_s^+ sidebands. The curve is the fit described in the text. The insert focuses on the low mass region. The dotted line in the insert indicates the $D_{sJ}^*(2317)^+$ mass.

[PRD74 (2006) 032007]

SEARCH FOR $D_{S1} \rightarrow D_S \mu\mu$ DECAYS

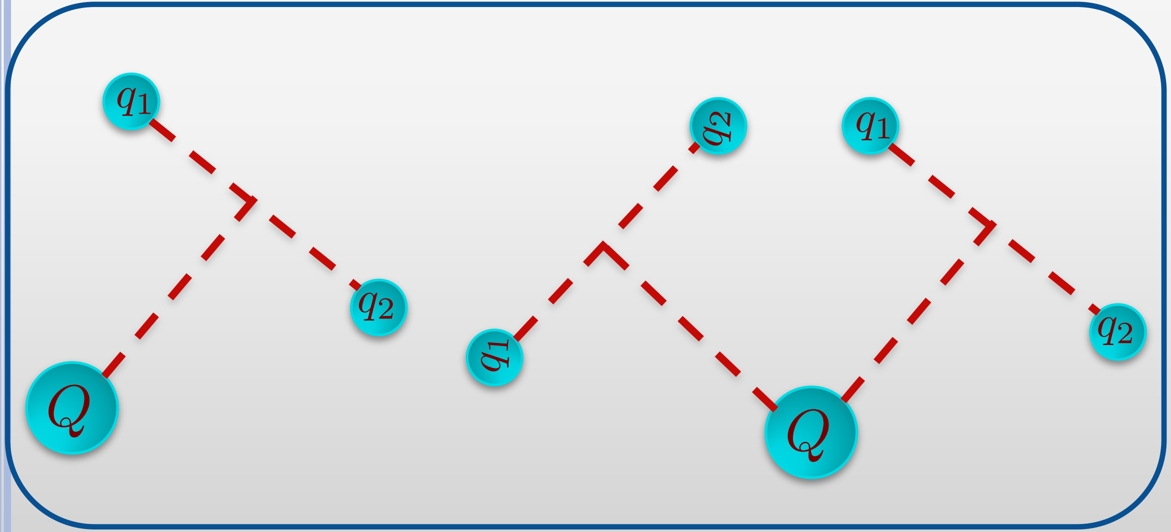
Search for Dalitz decays of $D_{s1}(2460)$ by using the CF decay mode:
$D_s^+ \rightarrow K^+K^-\pi^+$ $(5.45 \pm 0.17)\%$

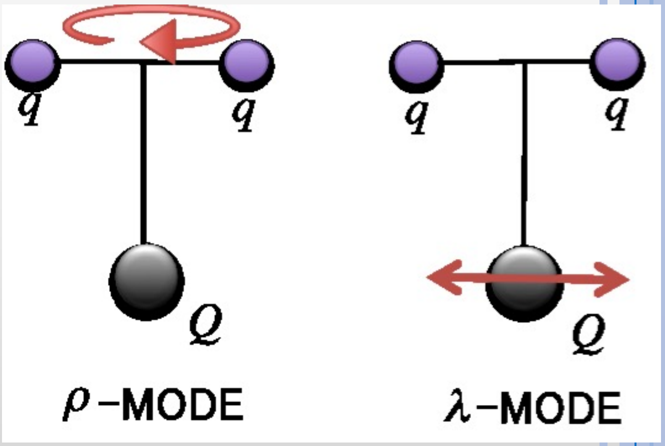


$$\underbrace{D_{s1}(2460)^+}_{J^P = 1^+} \rightarrow \underbrace{D_s^+}_{J^P = 0^-} \underbrace{\mu^-\mu^+}_{J^P = 1^-}$$

Diquark: a Building Block of Hadrons?

- The heavy quark effective theories (HQET) predict the masses of the heavy mesons/baryons by a perturbative expansion of $\Lambda_{QCD}/m_Q \sim 0$
- Precise measurements of the excited heavy meson properties are a sensitive test of the validity of HQET
- The observation of new baryons and measurements of their properties provide information about the role played by diquarks in baryons, which can also help to tune tetraquark and pentaquark models.



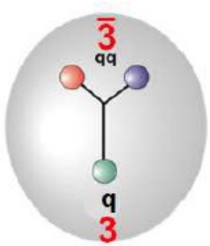


[Phys. Rev. D92 (2015) 114029]

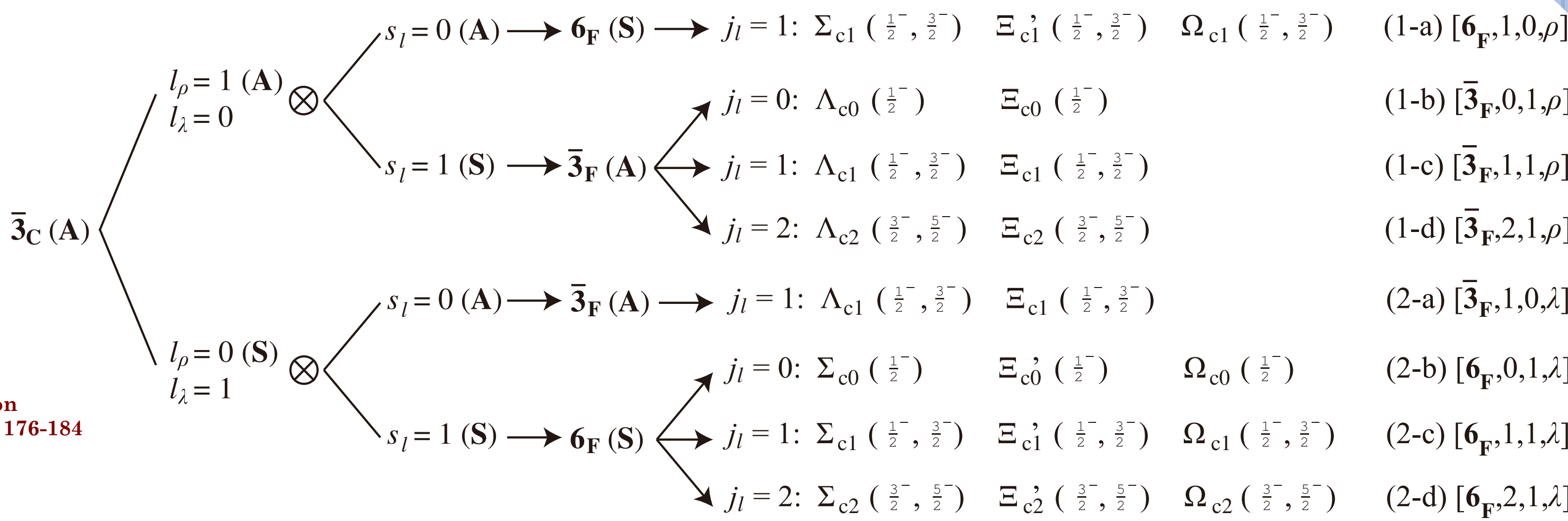
P-wave States

- Baryons made of 3 quarks (fermions)
- Wave function must be antisymmetric under interchange of any two equal-mass quarks

$$|qqq\rangle_A = |\text{color}\rangle_A \times |\text{space, spin, flavor}\rangle_S$$



Credit: M. Pennington
AIP Conf.Proc. 1432 (2012) 176-184



[Phys. Rev. D91 (2015) 054034]

7 excited L = 1 Ω_c → 5 λ-mode excited states

P-WAVE STATES

- Baryons made of 3 quarks (fermions)
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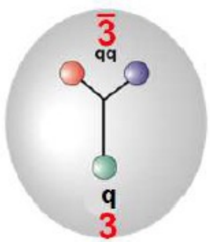
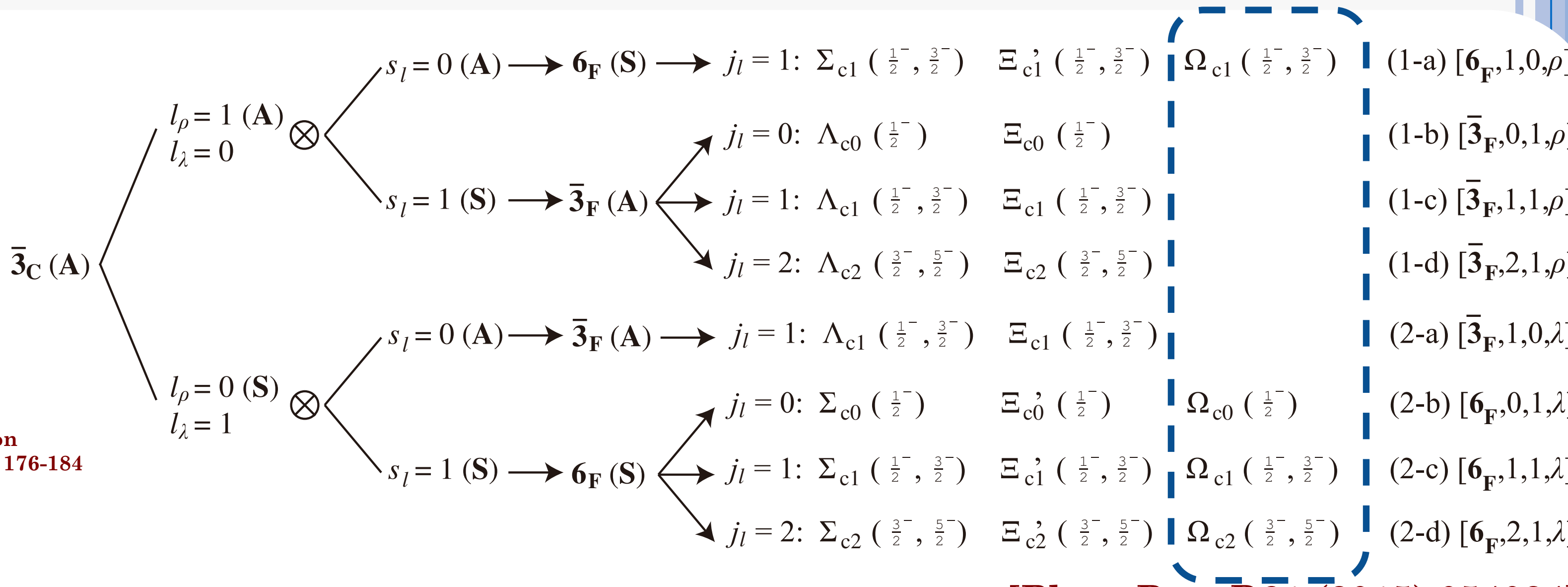


Credit: M. Pennington
AIP Conf.Proc. 1432 (2012) 176-184



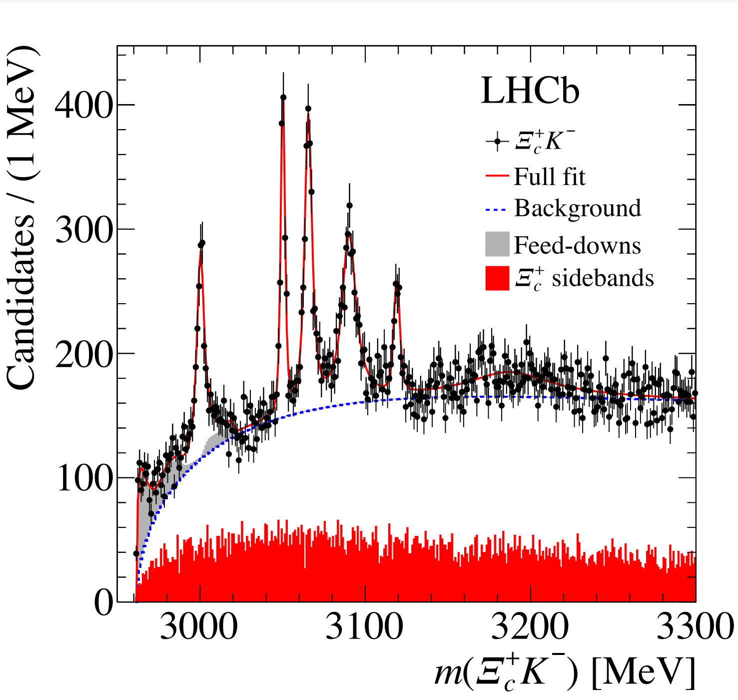
[Phys. Rev. D91 (2015) 054034]

7 excited L = 1 Ω_c ➔ 5 λ-mode excited states

Five New Excited Ω^0_c States!

[LHCb: PRL 118 (2017) 182001]

- Observation of **5** new excited Ω_c states! Two of them extremely narrow
- First time so many states observed in a single mass spectrum
- Comprehensive explanation of all peaks challenges our current knowledge



Are they orbitally excited (L=1) states?
Or radiatally excitations? Or…

TABLE II: Spin-parity (J^P) numbers of the newly observed Ω_c states suggested in various works.

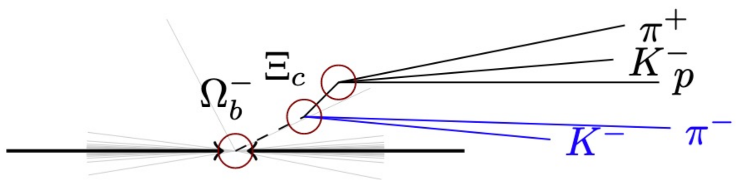
State	[19]	[20]	[21]	[23]	[29]	[25]	[27]	[28]	[32]	[26]	This work
$\Omega_c(3000)$		$1/2^-$	$1/2^-$ $(3/2^-)$	$1/2^-$	$1/2^-$	$1/2^-$	$1/2^-$	$1/2^+$ or $3/2^+$	$1/2^-$		$1/2^-$
$\Omega_c(3050)$		$1/2^-$	$1/2^-$ $(3/2^-)$	$1/2^-$	$5/2^-$	$3/2^-$	$1/2^-$	$5/2^+$ or $7/2^+$	$3/2^-$		$3/2^-$
$\Omega_c(3066)$	$1/2^+$	$1/2^+$ or $1/2^-$	$3/2^-$$(5/2^-)$	$3/2^-$	$3/2^-$	$5/2^-$	$3/2^-$	$3/2^-$	$1/2^+$		$3/2^-$
$\Omega_c(3090)$			$3/2^-$ $(1/2^+)$	$3/2^-$	$1/2^-$	$1/2^+$	$3/2^-$	$5/2^-$	$1/2^+$		$5/2^-$
$\Omega_c(3119)$	$3/2^+$	$3/2^+$	$5/2^-$ $(3/2^+)$	$5/2^-$	$3/2^-$	$3/2^+$	$5/2^-$	$5/2^+$ or $7/2^+$	$3/2^+$	$1/2^-$	$1/2^+$ or $3/2^+$

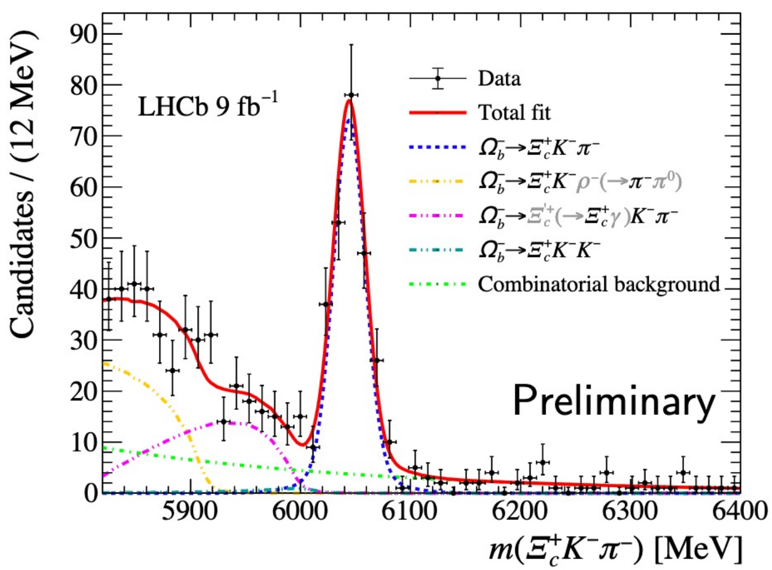
Phys. Rev. D95 (2017) 116010

…are they pentaquarks?

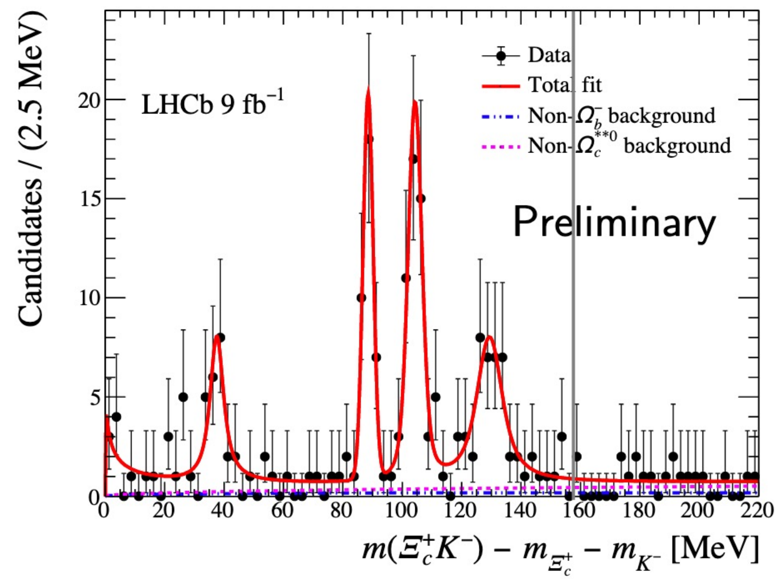
First Exclusive Observation of Ω_c^{**0} in $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ Decays

[LHCb-PAPER-2021-012, in preparation]





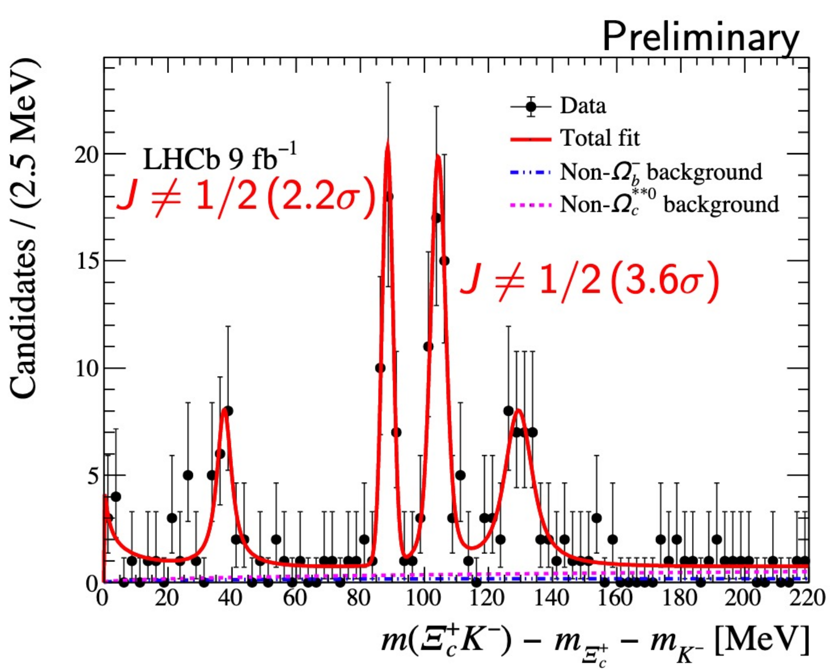
- Strict exclusivity cut ⇒ No feed down!
- Same four peaks (no clear fifth)
- **+ the threshold structure**



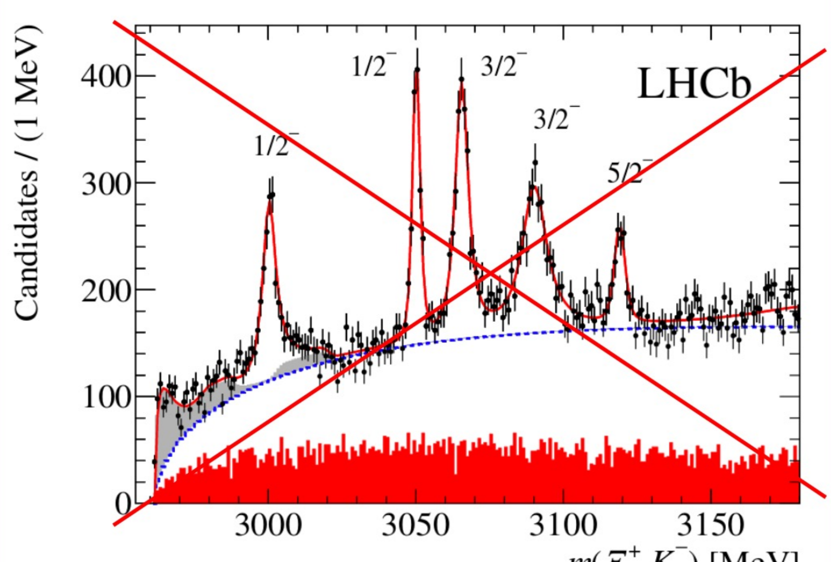
COMBINED SPIN TEST

[LHCb-PAPER-2021-012, in preparation]

A popular J^P assignment: the narrow states are λ-modes in the natural order $1/2^-$, $1/2^-$, $3/2^-$, $3/2^-$, $5/2^-$
[Karliner:2017kfm, Padmanath:2017lng, Wang:2017zjw]



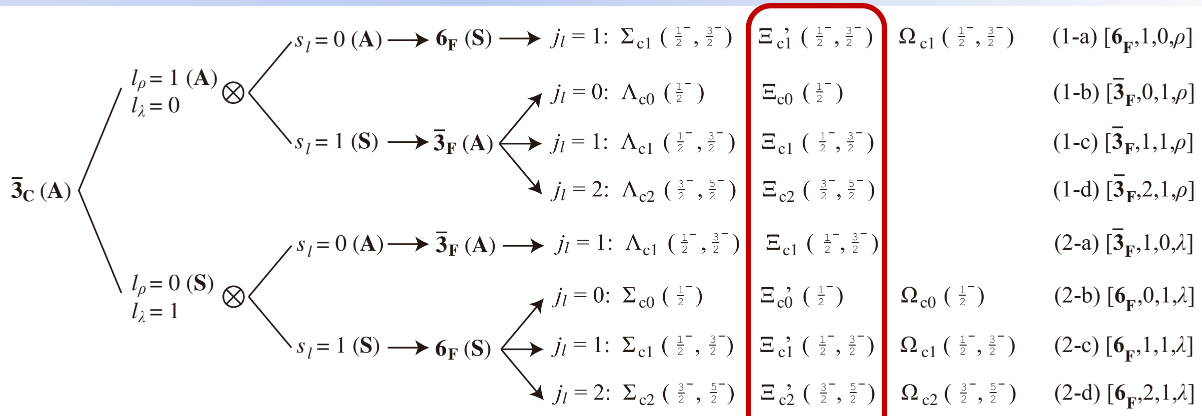
Excluded by 3.6σ

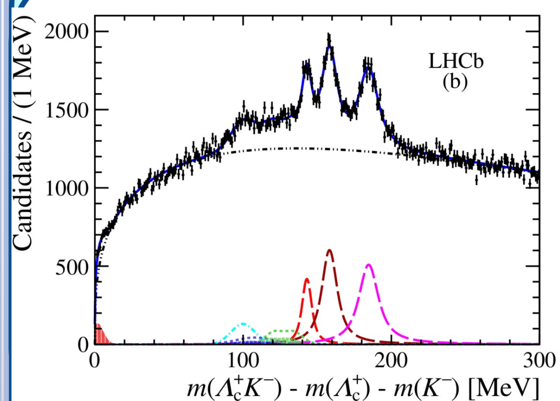


Adapted from Fig. 2 of arXiv:[1703.04639]

to be revisited!

Ξ_c Spectroscopy





$$m(\Omega_c(3050)^0) - m(\Xi_c(2923)^0) \simeq 125\,\text{MeV},$$
$$n(\Omega_c(3065)^0) - m(\Xi_c(2939)^0) \simeq 125\,\text{MeV},$$
$$n(\Omega_c(3090)^0) - m(\Xi_c(2965)^0) \simeq 125\,\text{MeV}.$$

[PRL 124 (2020) 222001]

E. Gabriel, M. Pappagallo, F. Muheim

$\Xi_c^{**0} \rightarrow \Xi_c^0 \pi^+ \pi^-$

L. Lagrange, M. Pappagallo, F. Muheim

$\Xi_c^{**+} \rightarrow \Xi_c^+ \pi^+ \pi^-$

R. O'Neil, M. Pappagallo, M. Williams

$\Xi_c^{**+} \rightarrow \Lambda_c^+ \pi^+ K^-$

F. Oliva, M. Pappagallo, M. Williams

A. Palano, M. Martinelli

Amplitude Analysis of $B^+ \to (K^0_S K\pi)K^+$

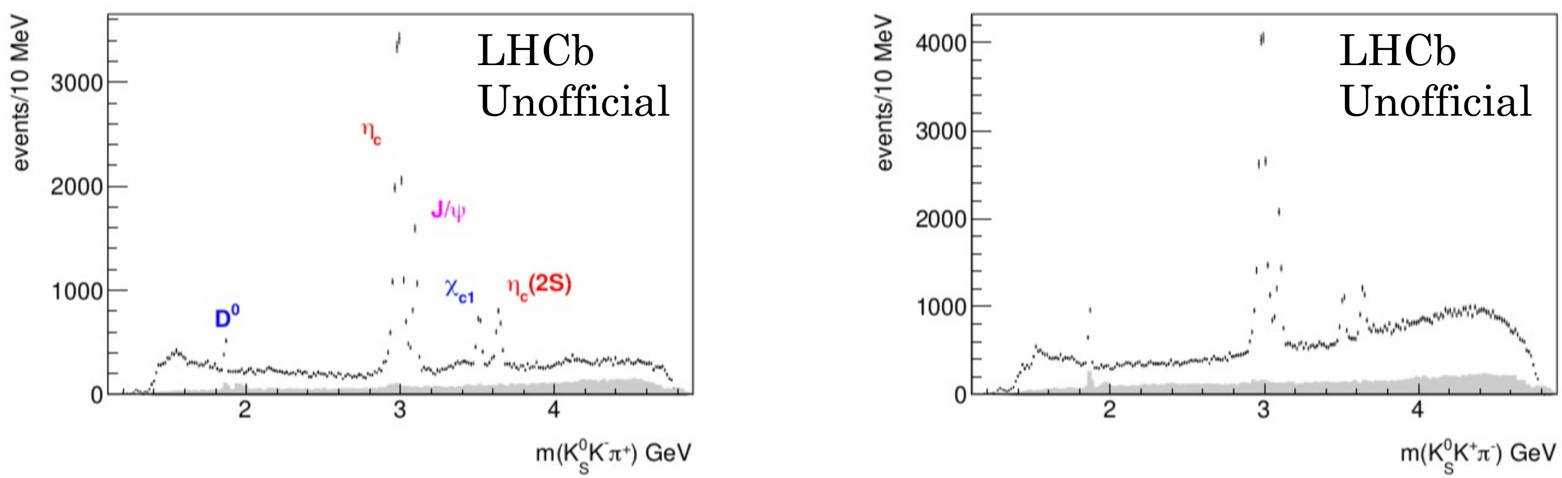
- In this analysis we study the $K^0_S K\pi$ system in the B^+ decay

$$B^+ \to (K^0_S K\pi)K^+$$

- We have two different final states (charge conjugation is implied).

$$B^+ \to K^0_S K^- \pi^+ K^+, \qquad B^+ \to K^0_S K^+ \pi^- K^+$$

- $B^+ \to K^0_S K^- \pi^+ K^+$ (79565 events) and $B^+ \to K^0_S K^+ \pi^- K^+$ (76180 events, two combinations per event).

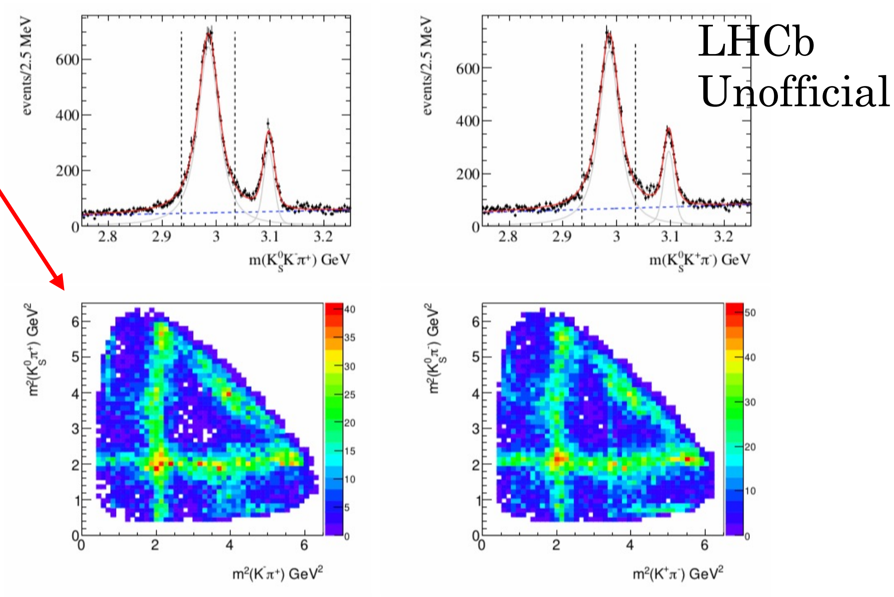


A. Palano, M. Martinelli

Amplitude Analysis of $B^+ \rightarrow (K^0_S K\pi)K^+$

Plan of the work

- Precise measurements of the charmonium resonances parameters.
- Measurement of the partial $B^+ \to (c\bar{c})K^+$ branching fractions.
- Dalitz plot analysis of the $\eta_c \to K^0_S K\pi$ decay.
- Amplitude analysis of the $K^0_S K\pi$ system in the threshold region.



A. Pompili & A. Di Florio et al.

$\Lambda_b{}^0$ Excited States

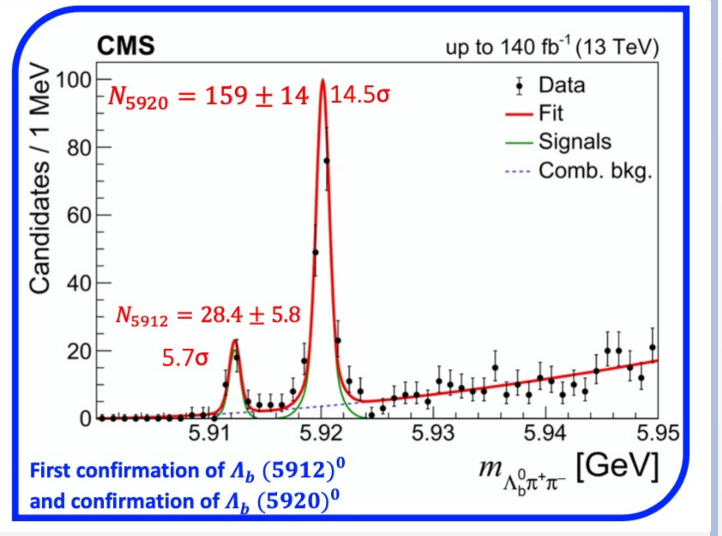
Λ_b^0 excited states in CMS: $\Lambda_b^0 \to J/\psi\Lambda$ and $\Lambda_b^0 \to \psi(2S)\Lambda$

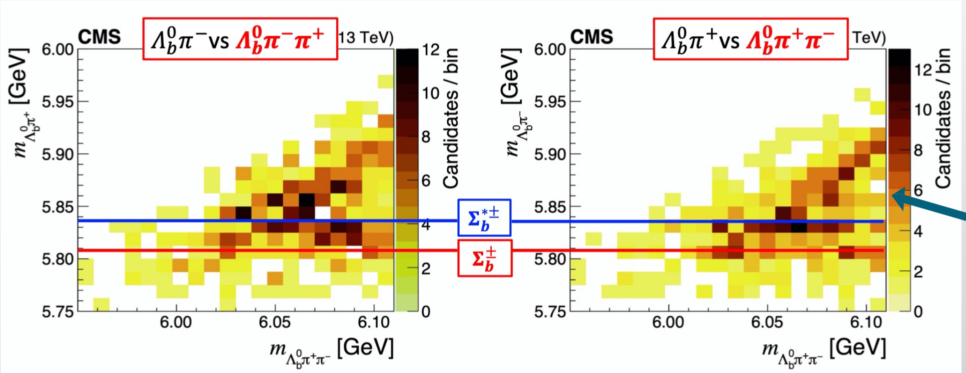
$$M(\Lambda_b(5912)^0) = [5912.32 \pm 0.12(stat) \pm 0.01(syst) \pm 0.17(m_{PDG}(\Lambda_b^0))]\text{MeV}$$

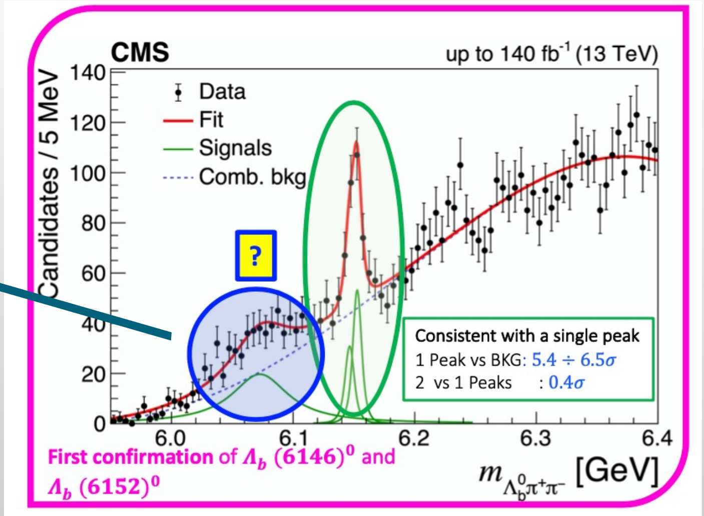
$$M(\Lambda_b(5920)^0) = [5920.16 \pm 0.07(stat) \pm 0.01(syst) \pm 0.17(m_{PDG}(\Lambda_b^0))]\text{MeV}$$

$$M(\Lambda_b(6146)^0) = [6146.5 \pm 1.9(stat) \pm 0.8(syst) \pm 0.2(m_{PDG}(\Lambda_b^0))]\text{MeV}$$

$$M(\Lambda_b(6152)^0) = [6152.7 \pm 1.1(stat) \pm 0.4(syst) \pm 0.2(m_{PDG}(\Lambda_b^0))]\text{MeV}$$



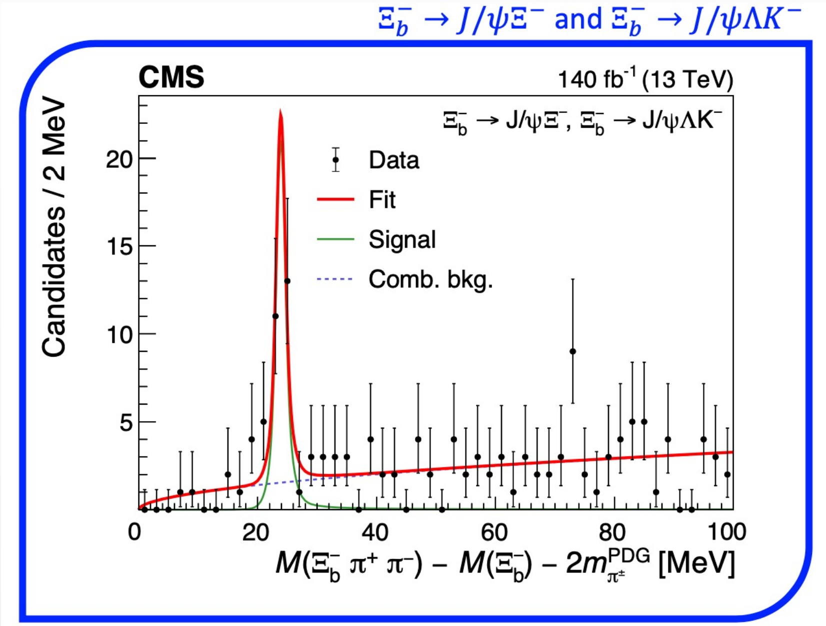


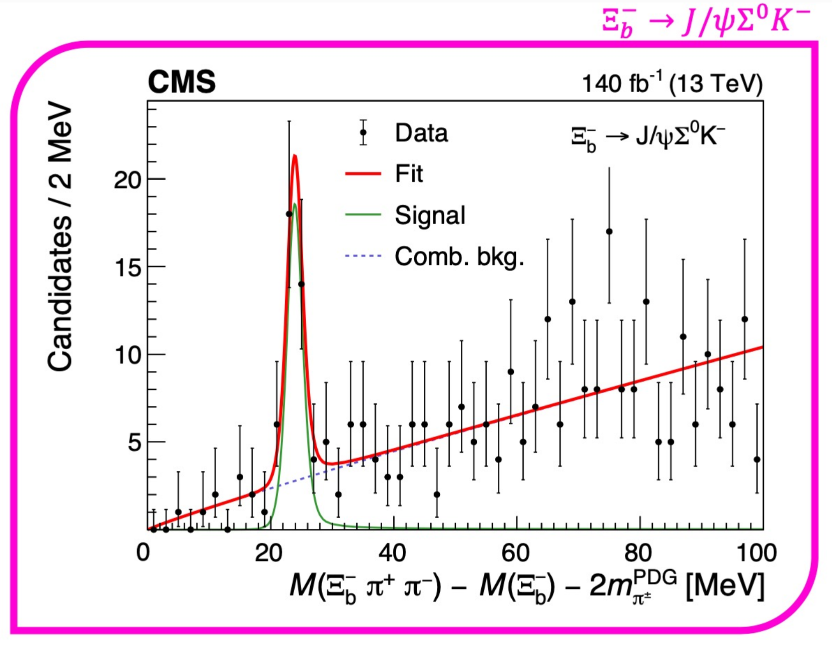


If $\Sigma_b^{(*)\pm} \to \Lambda_b^0\pi^\pm$ vetoed: bump disappears

A. Pompili & A. Di Florio et al.

$\Xi_b(6100)^-$





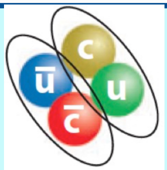
- Significance > **6σ** : **first observation of $\Xi_b(6100)^-$**
- Compatible with the orbitally excited Ξ_b^- with $J^P = \frac{3}{2}^-$ & analogue of $\Xi_c(2815)$

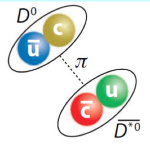
A. Pompili & A. Di Florio et al.

$B_s^0 \rightarrow X(3872)\phi$

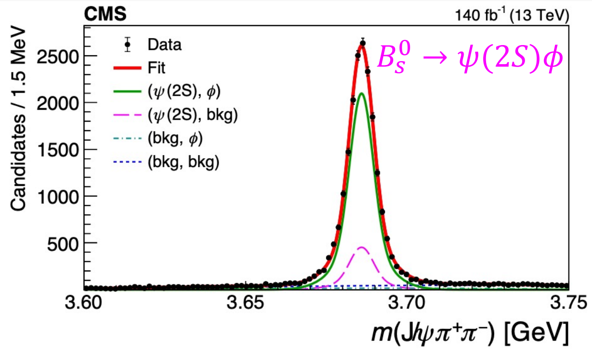
- $X(3872)$ was discovered by Belle in 2003. What we know

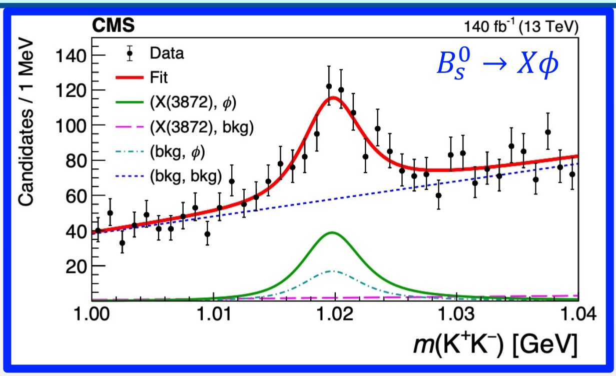
  $m(X)$ very near to $m(D^0D^{*0})$ $J^P = 1^{++}$ $\Gamma < 1.2$ MeV





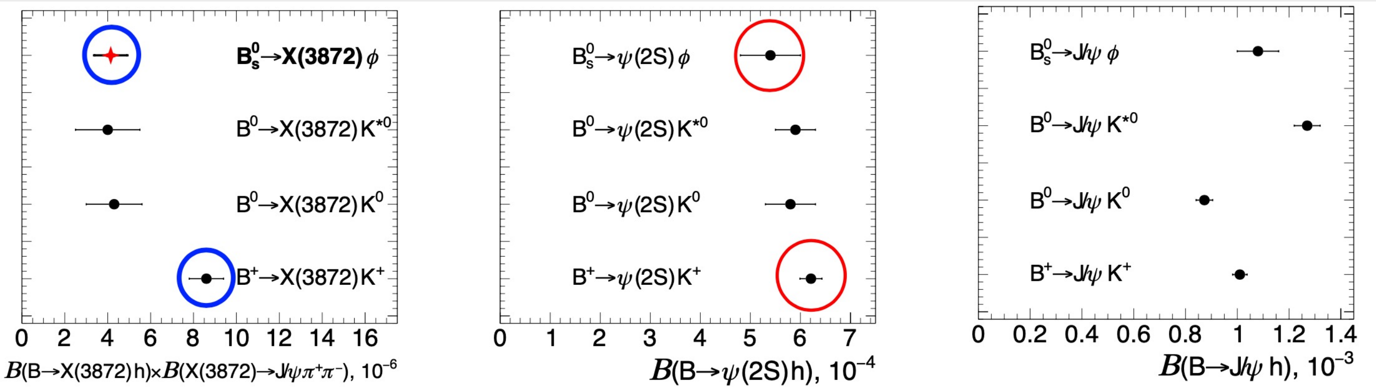
- **What we don't know (yet)**: its nature. A 4quark, a molecule, a mix, $\chi_{c1}(3872)$? Observed in $PbPb$ (prompt & nonprompt), prompt in pp, nonprompt from B^0 , B^+, but not from B_s^0.



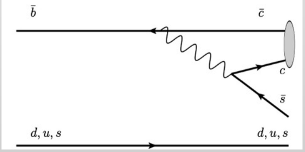


Significance > 6σ : **first observation**

- The measured $\mathcal{B}$ value is consistent with B^0 but two times smaller than the one for B^+ **(not for ψ $2S$ instead)**



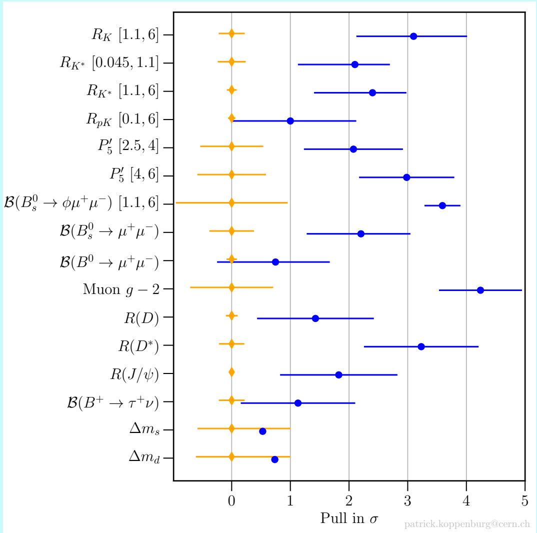
In PhysRevD.102.034017 this results is interpreted as possibly favouring the compact tetraquark hypothesis



Prospects and Future Plans

Short Term

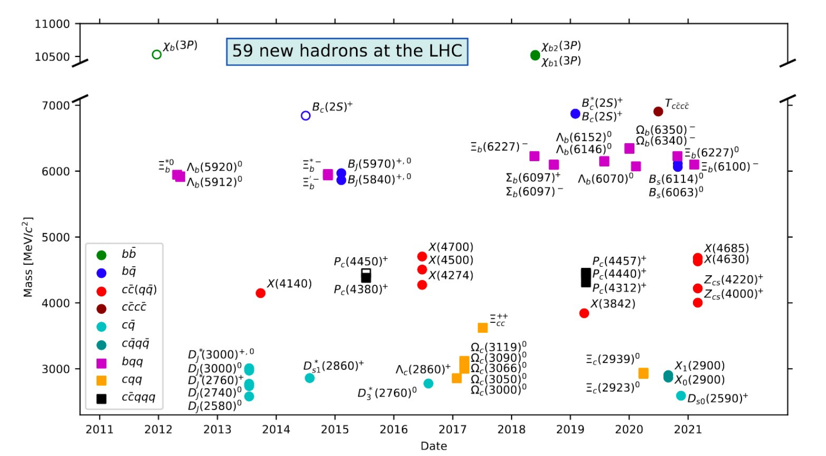
- Though no single measurement deviates more than 5σ from the SM, a global coherent picture starts to emerge
- Many more measurements are in the pipeline: (e.g. R_K vs R_{K^*}, R_ϕ)



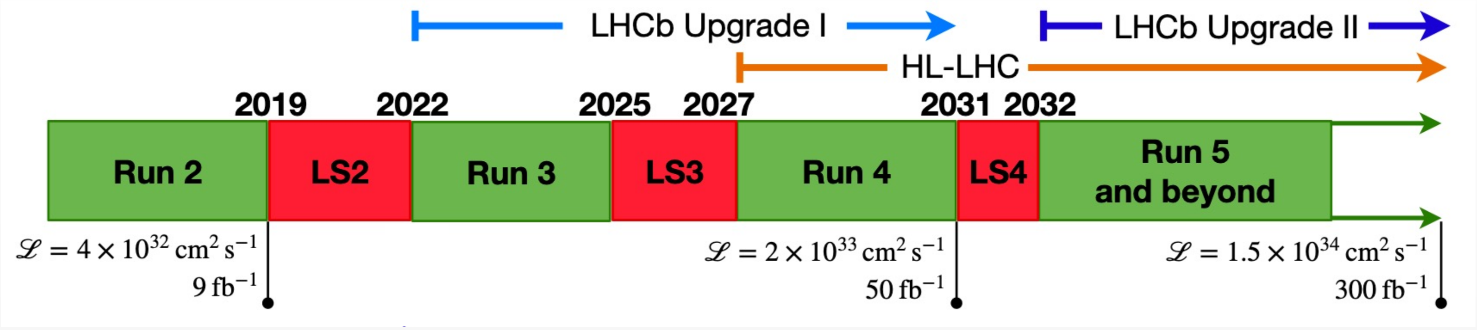
Flavour Anomalies Workshop on 20 Oct 2021
(Organizing Committee: M. Pappagallo, A. Pompili et al.)

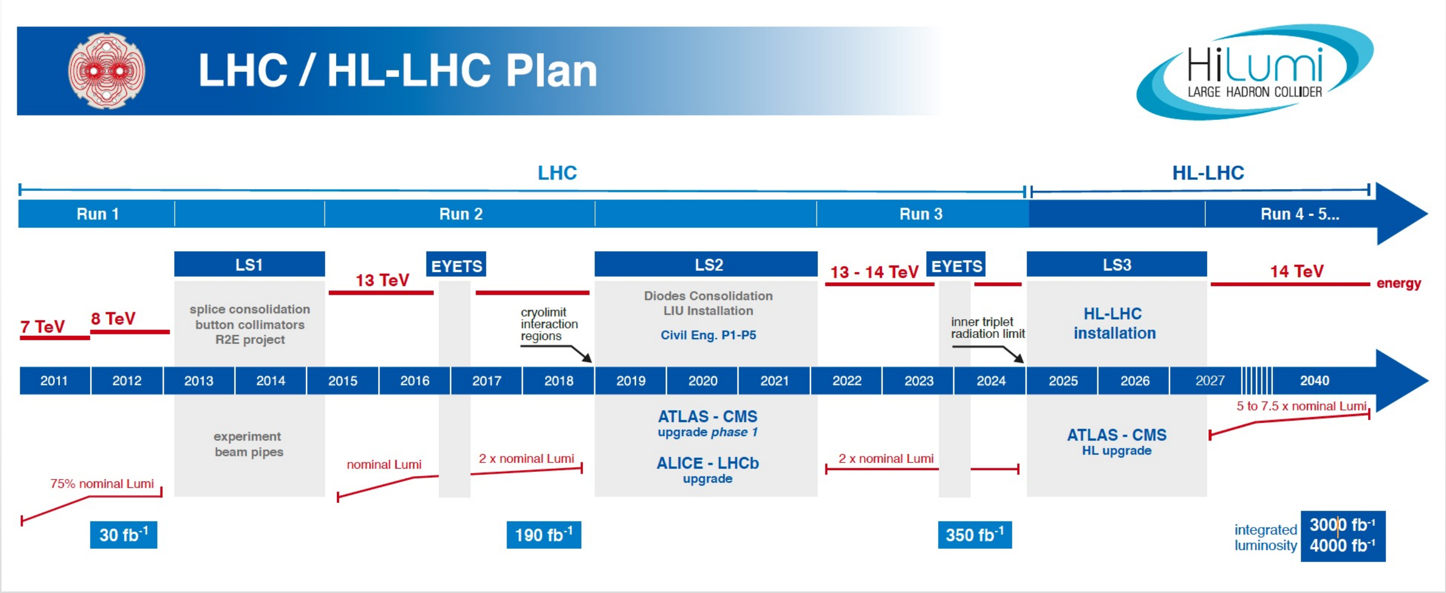
https://www.nikhef.nl/~pkoppenb/anomalies.html

- LHC experiments have contributed largely to the spectroscopy of the heavy hadrons
- Many more on the way! Stay tuned!



LONG TERM:
LHC EXPERIMENTS ARE GOING UNDER UPGRADES





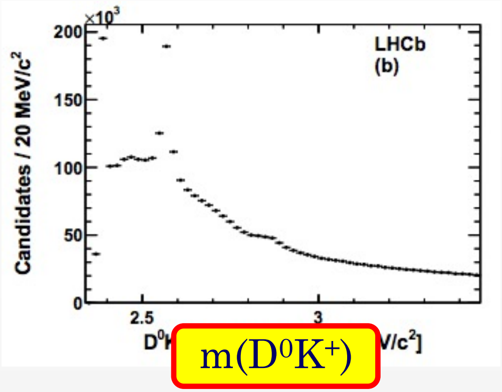
The large data set collected in the HL-LHC era, together with upgraded detectors, will boost sensitivity in searches for physics BSM and heavy hadrons with small production cross sections and/or small decay rates

Back-up slides

How to do spectroscopy?

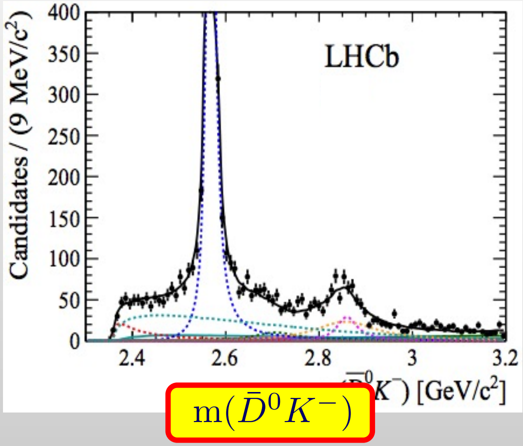
Prompt Production: **(e.g. pp → D_s^{**}(→D^0K) + X)**

- ✓ Large cross sections
- ✗ Large combinatorial background
- ✗ Hard to disentangle broad structures
- ✗ Difficult to assess spin
- ✗ Presence of "reflections"/"feed-downs"



***b*-hadron decays** **(e.g. B_s →D_s^{**}(→D^0K)π)**

- ✓ Small background
- ✓ Access to the phase of the amplitude and spin-parity
- ✗ Limited cross sections
- ✗ High spin resonances suppressed
- ✗ Presence of "shadows"



The puzzle of the scalar mesons

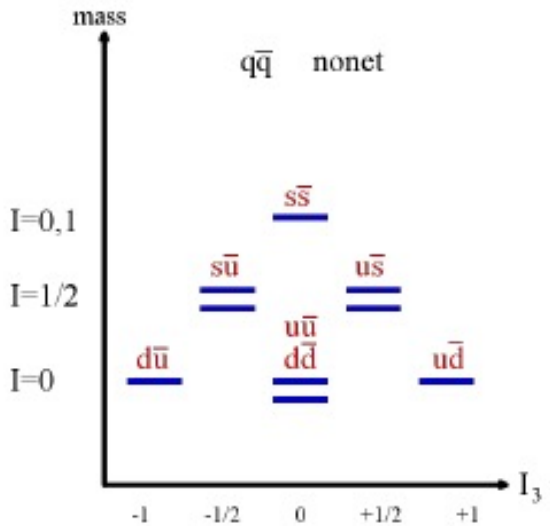
$J^P = 1^-$

$I = 0 : m[\phi(1020)] \approx 1020$ MeV $s\bar{s}$

$I = 1/2 : m[K^*(892)] \approx 892$ MeV $n\bar{s}$

$I = 1 : m[\rho(776)] \approx 776$ MeV $n\bar{n}$

$I = 0 : m[\omega(783)] \approx 783$ MeV $n\bar{n}$

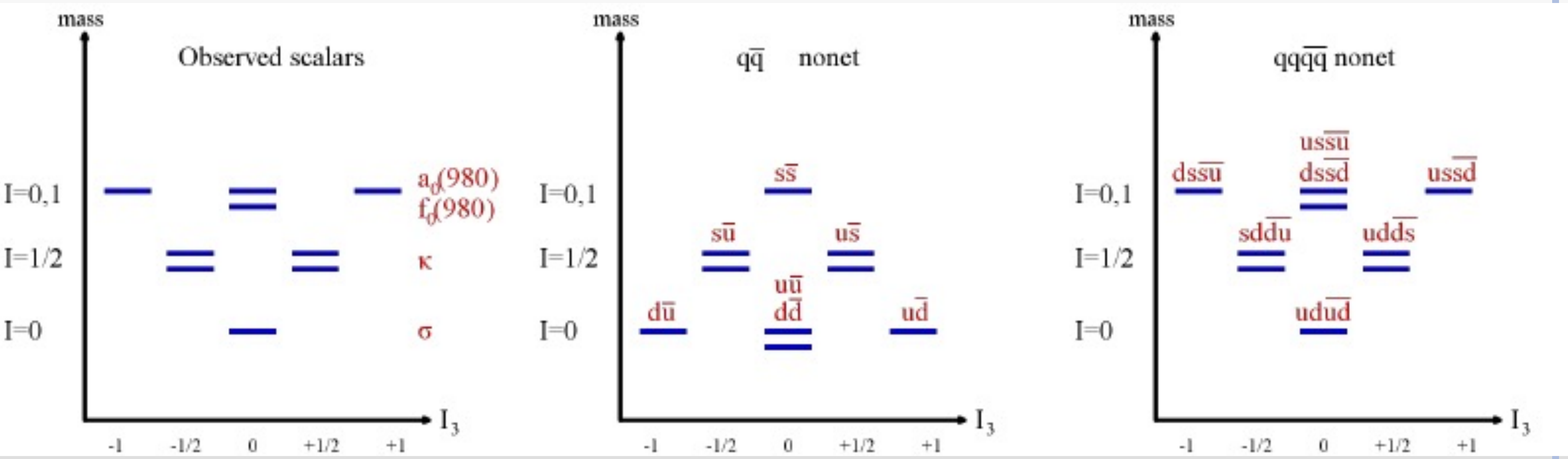


arXiv:1410.8757

The puzzle of the scalar mesons

The inverse mass hierarchy of the scalar mesons

$J^P = 0^+$

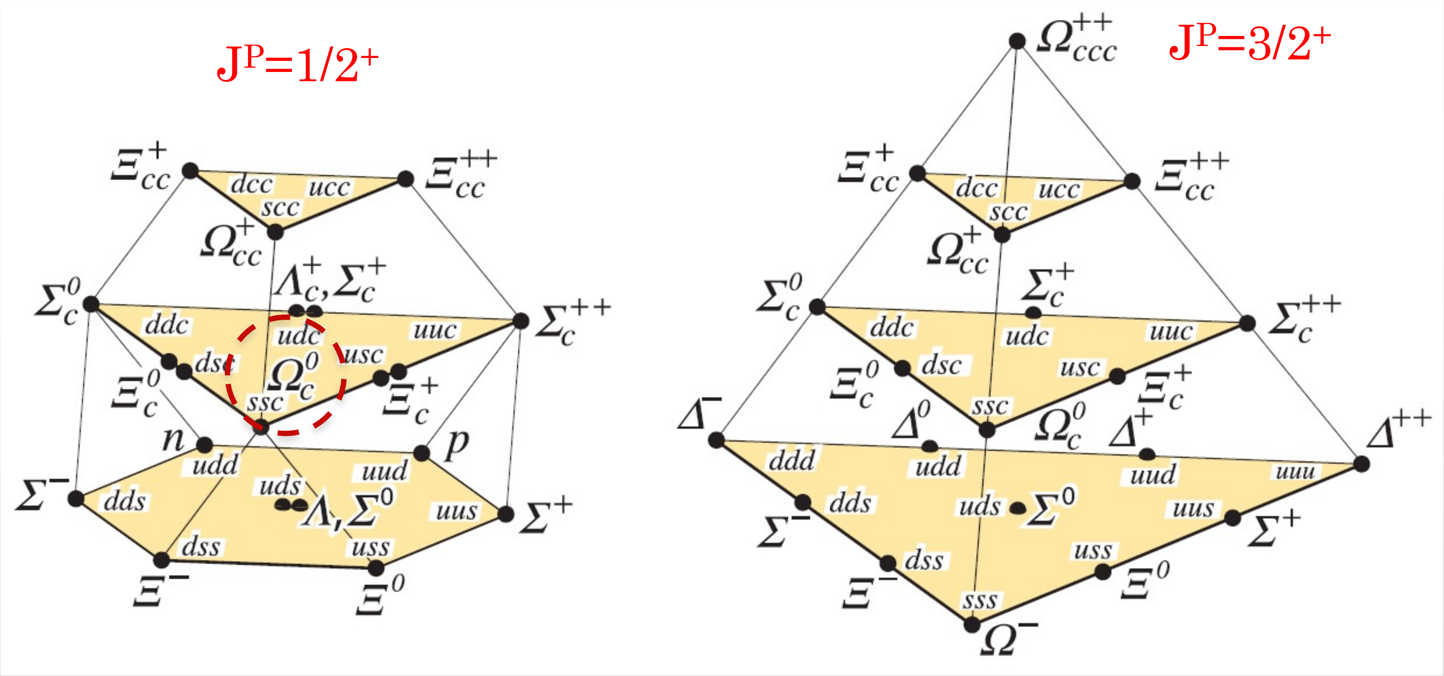


arXiv:1410.8757

GROUND STATES

- Baryons made of 3 quarks (fermions)
- Wave function must be antisymmetric under interchange of any two equal-mass quarks

$$|qqq\rangle_A = |\text{color}\rangle_A \times |\text{space, spin, flavor}\rangle_S$$



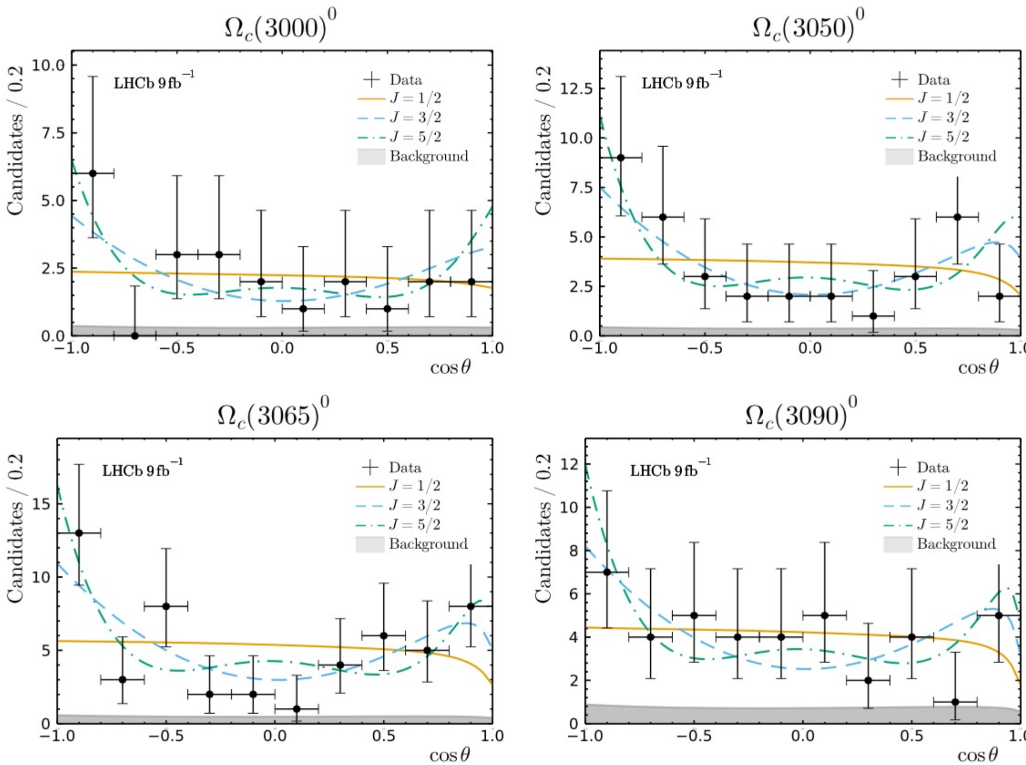
N.B. Ω_c^0 doesn't belong to the same multiplet of the well famous Ω^-

Angular analysis of $\Omega_b^- \to \Omega_c^{**0}(\to \Xi_c^+ K^-)\pi^-$

[LHCb-PAPER-2021-012, in preparation]

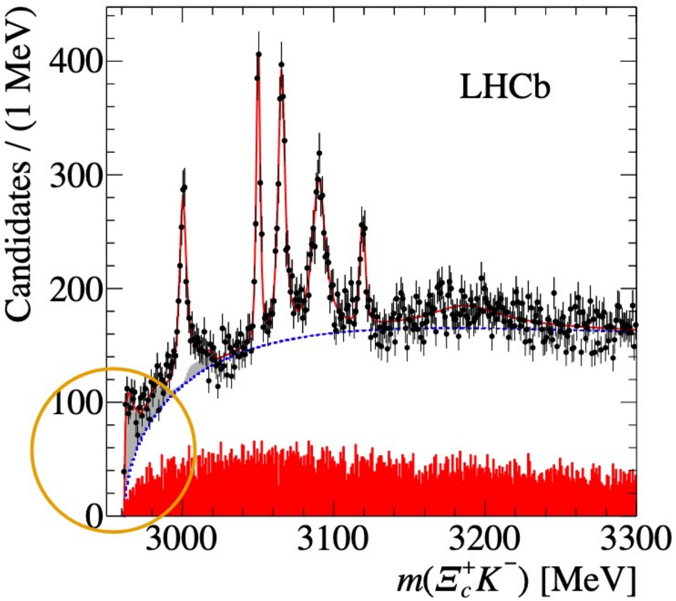
- Spin of Ω_b^- is 1/2
- Ω_c^{**0} cannot have spin projection $> 1/2$
- $\Rightarrow$ non-trivial angular dependence for $J = 3/2$, $J = 5/2$.
- Noticible inefficiency at $\cos\theta = 1$ (soft K^-).

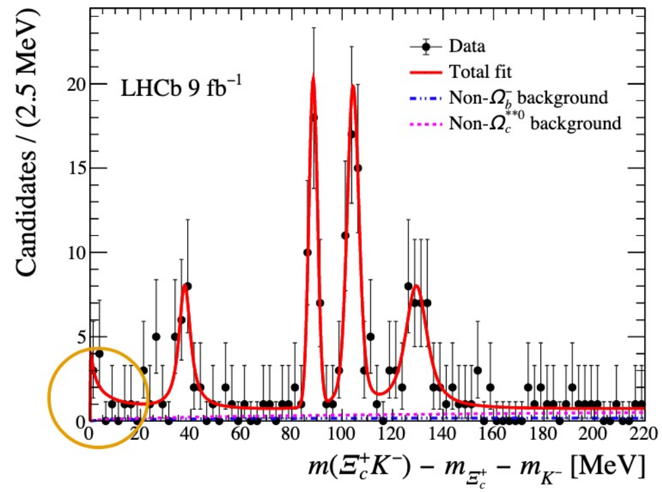
3.6σ: $J(\Omega_c(3065)^0)! = 1/2$
2.2σ: $J(\Omega_c(3050)^0)! = 1/2$



The Threshold Structure

[LHCb-PAPER-2021-012, in preparation]





- Explained in the prompt analysis by the partially reconstructed $\Omega_c(3065)^+ \to \Xi_c'^+ K^-$ with anomalously large coupling.

- Exclusive analysis: no feed down is possible
- Other non-physical sources are excluded
- Singinifance in the nominal fit is 5.3σ, 4.3σ including systematics
- No model sensitivity due to the low statistics

Further investigation in needed!

LHC experiments going to Upgrade

LHCb Going to Upgrade

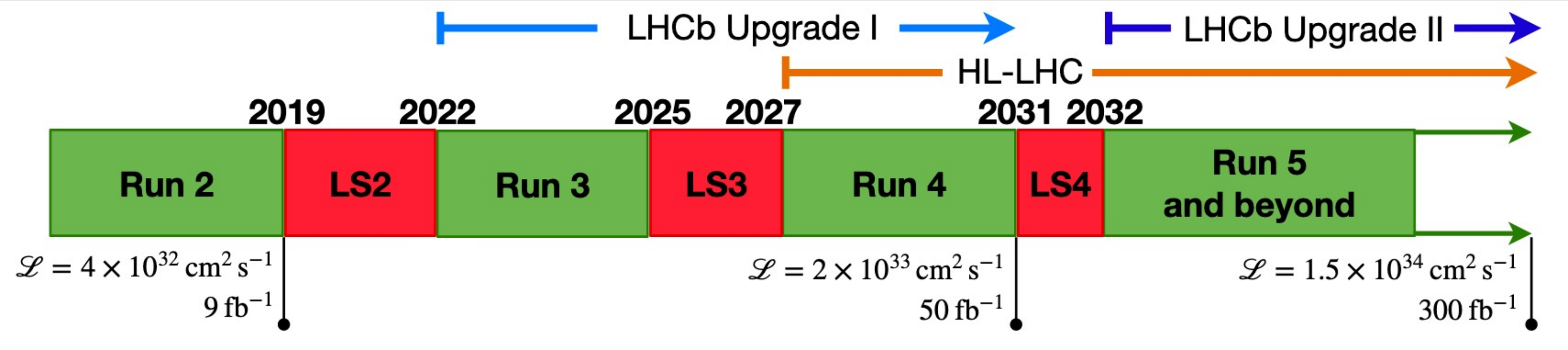
Upgrade I (Approved)

- Main limitation that prevents exploiting higher luminosity with the present detector is the Level-0 (hardware) trigger
  - ✓ Level-0 output rate < 1 MHz (readout rate) requires raising thresholds
- Hadron final states will benefit from removing L0
- Running at $2\text{x}10^{33}$ cm^{-2} s^{-1} with full software trigger, running at 40 MHz

Upgrade II (Under approval)

To be installed in Long Shutdown 4 of the LHC:

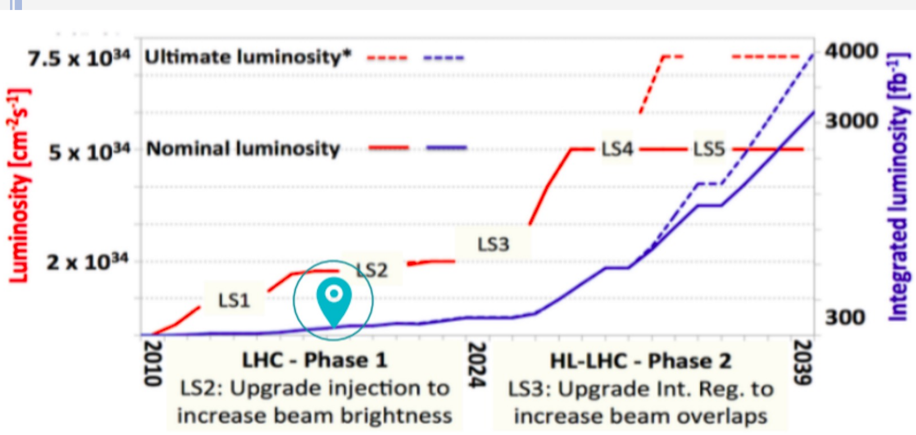
- Subsystems redesigned to operate at a luminosity of 1-2 x 10^{34} cm^{-2} s^{-1}
- Integrated luminosity of > 300 fb^{-1}
- Extension of the experiment's capabilities to select π^0, η and low-momentum tracks

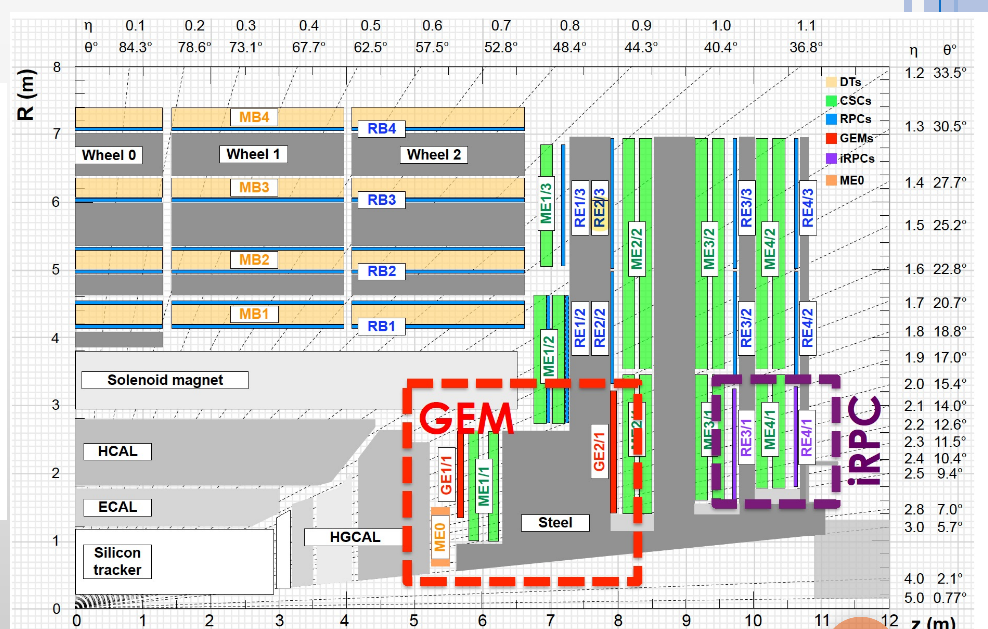


CMS towards Run 3

The $\tau\rightarrow3\mu$ search in Run 3:

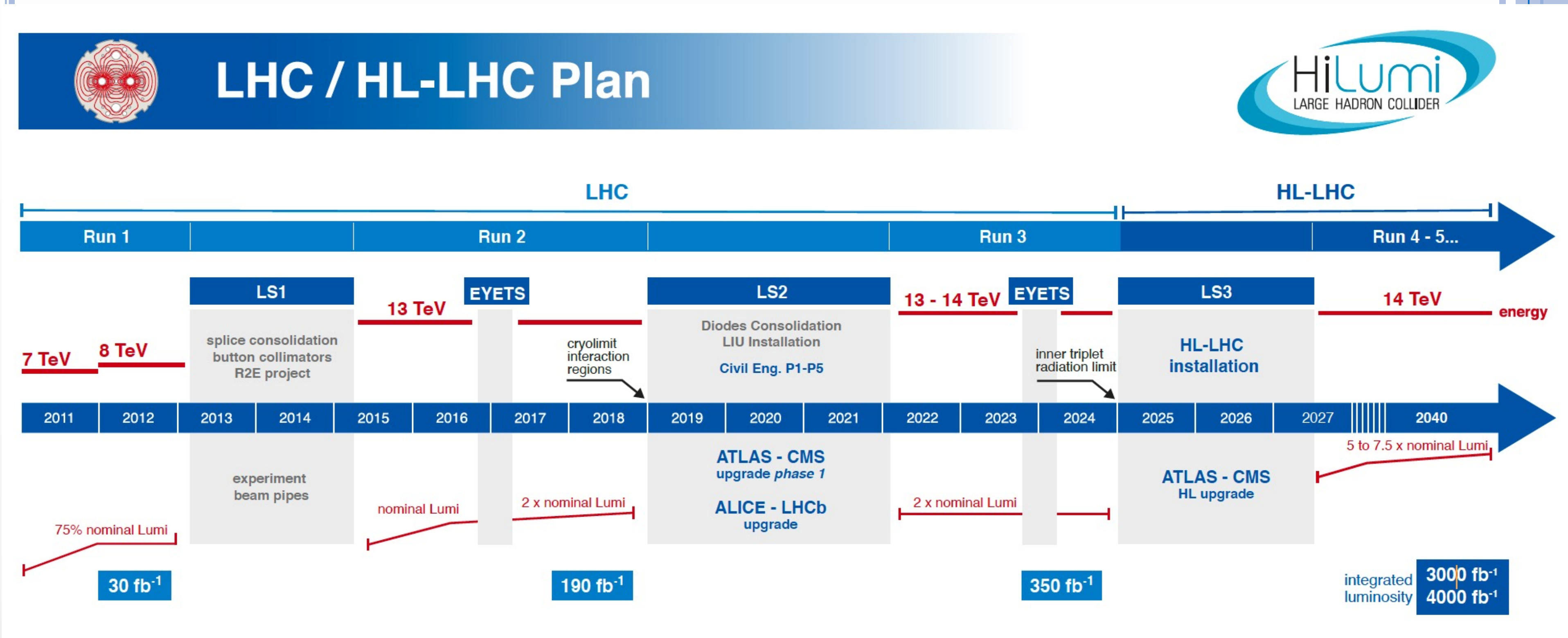
- Study ongoing to optimize the dedicated trigger path
- Goal: lowering the pT threshold to enhance the signal acceptance while keeping similar rates as 2018. Enlarge eta acceptance
- New tools in Run 3:
    - Level-1 trigger: implementation of a 3-μ invariant mass object
    - CSC-GEM segment (1.6 < |eta|< 2.1)
        - improved momentum resolution at L1 trigger
        - Extended eta coverage
- **INFN Bari group works on $\tau\rightarrow3\mu$ dedicated trigger implementation for Run3**





$$\mathcal{L}_{CMS}^{Run3} \sim 200\ fb^{-1}$$

HL-LHC



HL-LHC
– sqrt(s)=14 TeV
– Pile-up = 200
– Lint = 3000 fb-1

To extend the sensitivity for new physics searches, a major upgrade of the LHC has been decided, the **High Luminosity LHC** starting from 2026.