QCD@Work - International Workshop on QCD - Theory and Experiment

Spectroscopy of the excited D_s mesons

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On behalf of the LHCb collaboration

Outline

1. The LHCb experiment

2. The spectrum of the excited D_s states
   - LHCb: PRL 126 (2021) 122002
   - LHCb: JHEP 10 (2012) 151
   - LHCb: PRL 113 (2014) 162001

3. Unresolved puzzles

4. LHCb Upgrades and Prospects

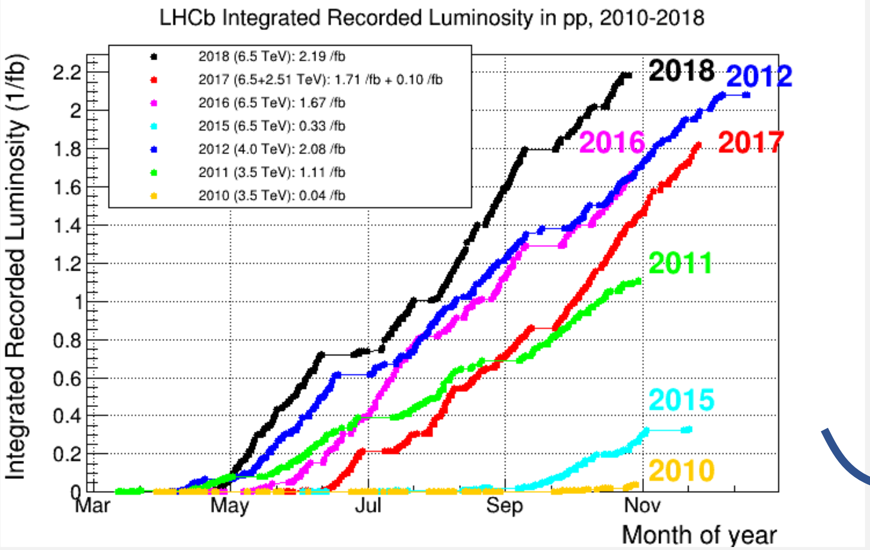
The LHCb experiment

LHCb EXPERIMENT in Run 1 and Run 2

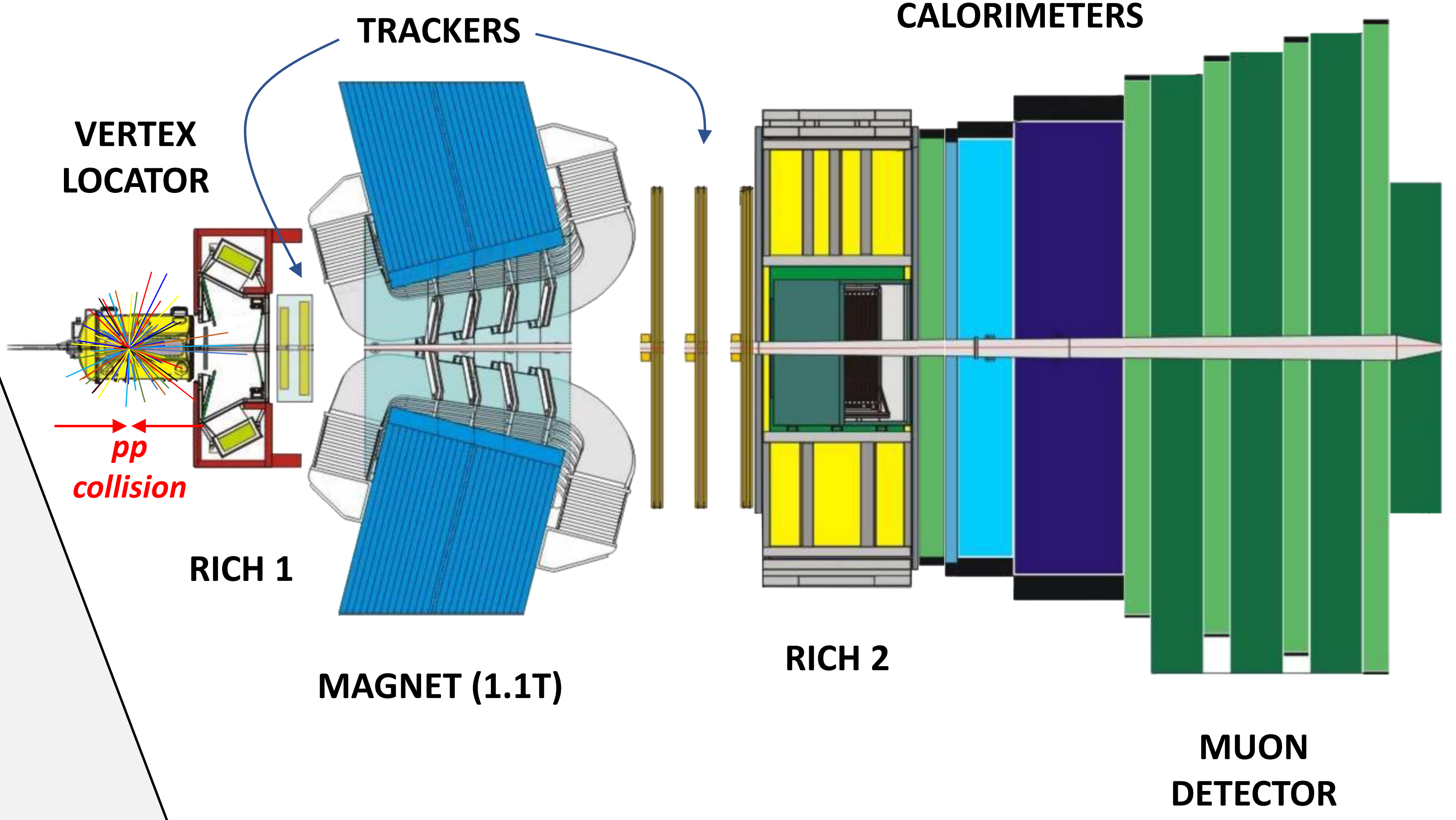
The LHCb experiment has largely contributed to the spectroscopy of the D_s mesons, profiting from a large production cross-section:

$$\sigma(pp \to D_s^+ X) = 353 \pm 9 \pm 76\ \mu b$$

JHEP 05 (2017) 074



EPJ 175, 01004 (2018)

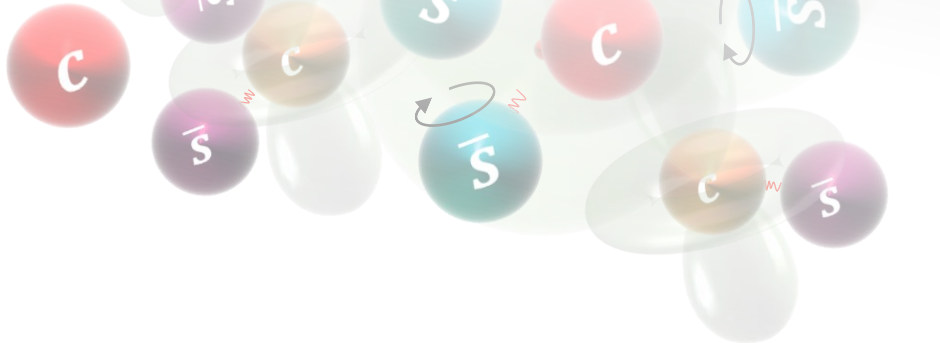


Integrated Luminosity: 9/fb

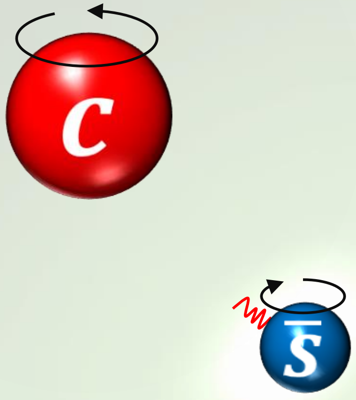
The spectrum of the excited D_s states

LHCb: PRL 126 (2021) 122002
LHCb: JHEP 10 (2012) 151
LHCb: PRL 113 (2014) 162001

D_s SPECTROSCOPY
In the heavy quark limit model



At high energy scale, α_s is small: perturbative interactions and at **short distance scales** $\ll R_{had}$



Strong coupling constant

$$\alpha_s(Q^2) \propto \frac{12\pi}{\ln\left(Q^2/\Lambda_{\mathrm{QCD}}^2\right)}$$

$\Lambda_{\mathrm{QCD}} \approx 0.2$ GeV is the energy scale that separates small from large distance scale.

At small energy scale, α_s is large: interactions with non perturbative confinement phenomena of quarks and gluons at **large length scale**

$R_{had} \sim \frac{1}{\Lambda_{\mathrm{QCD}}} \approx 1\ \mathrm{fm}$

- The **heavy quark** is much smaller than the hadron size and it is surrounded by a strongly interacting cloud of light quarks, antiquarks, and gluons with which the **light quark** interacts.
- The heavy-quark spin effect is not seen by the light quarks, such that the **heavy-quark spin decouples**.

D_s SPECTROSCOPY

MESON STATE

$$^{2S+1}L_J$$

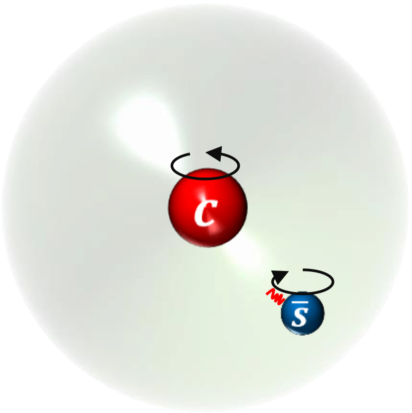
L: orbital angular momentum between constituent quarks (S, P, D correspond to L = 0, 1, 2)

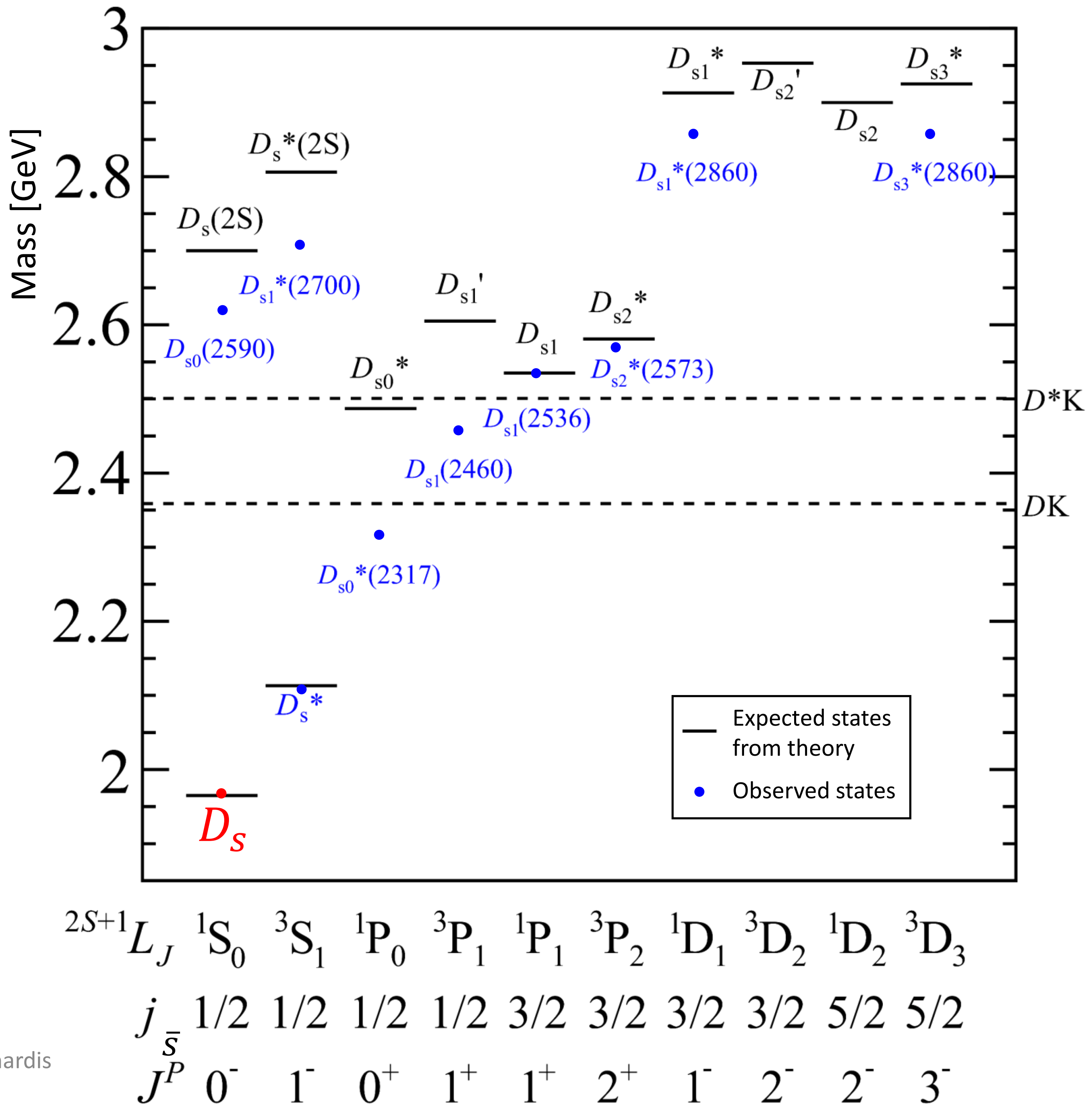
$S = 0, 1$: sum of quark spins

J: total spins of meson state

$j_{\bar{s}}$: sum of L with the spin of light $\bar{s}$ quark

P: parity





The P-wave ($L = 1$) states

Phys. Rev. Lett. 66 (1991) 1130
Phys. Rev. D 12 (1975) 147

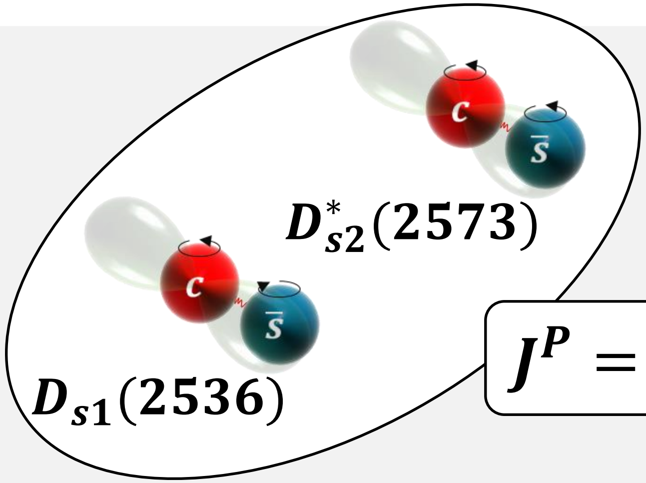
In the heavy quark limit model

Bounding force depends on the spin-orbit coupling only of the light $\bar{s}$ quark

Excited **P-states ($\vec{L} = 1$)**

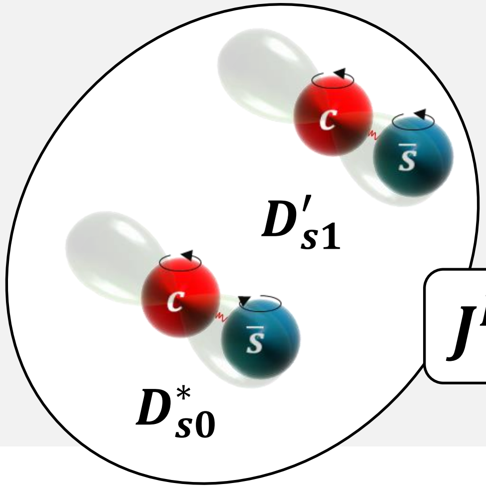
$$L + S_{\bar{s}} \nearrow j_{\bar{s}} = 3/2 \quad \searrow j_{\bar{s}} = 1/2 \quad + \quad S_c = 1/2$$

$\nearrow$



$J^P = 1^+, 2^+$

$\searrow$



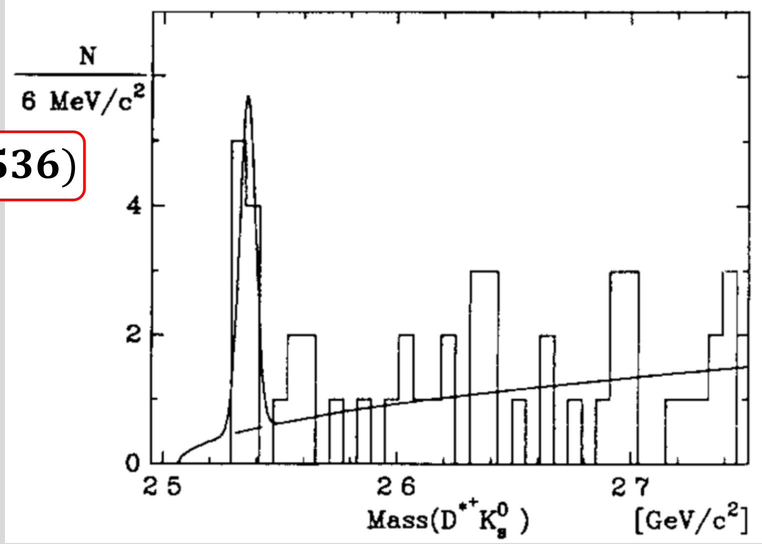
$J^P = 0^+, 1^+$

QCD@Work

Discovery of $D_{s1}(2536)$ and $D^*_{s2}(2573)$

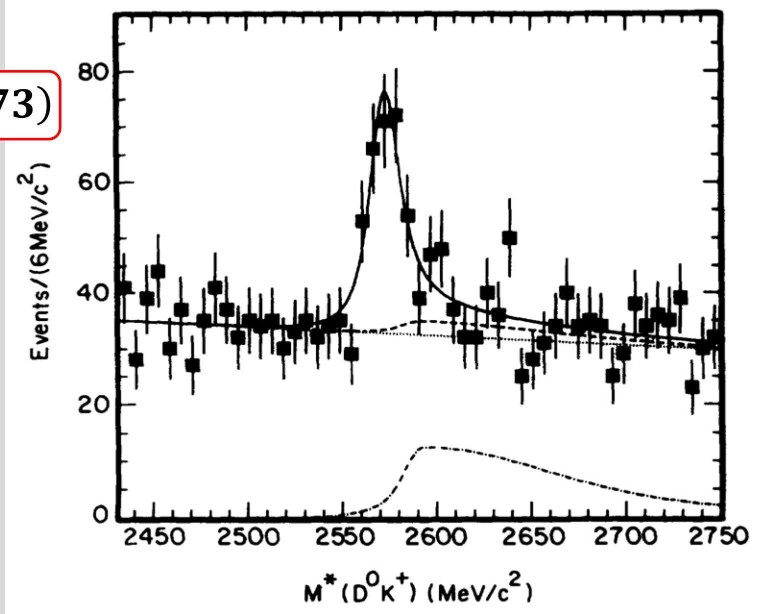
Two narrow states have been observed in the DK and D^*K mass spectra. They are consistent with the expected excited D_s states with $j_{\bar{s}} = 3/2$

$D_{s1}(2536)$

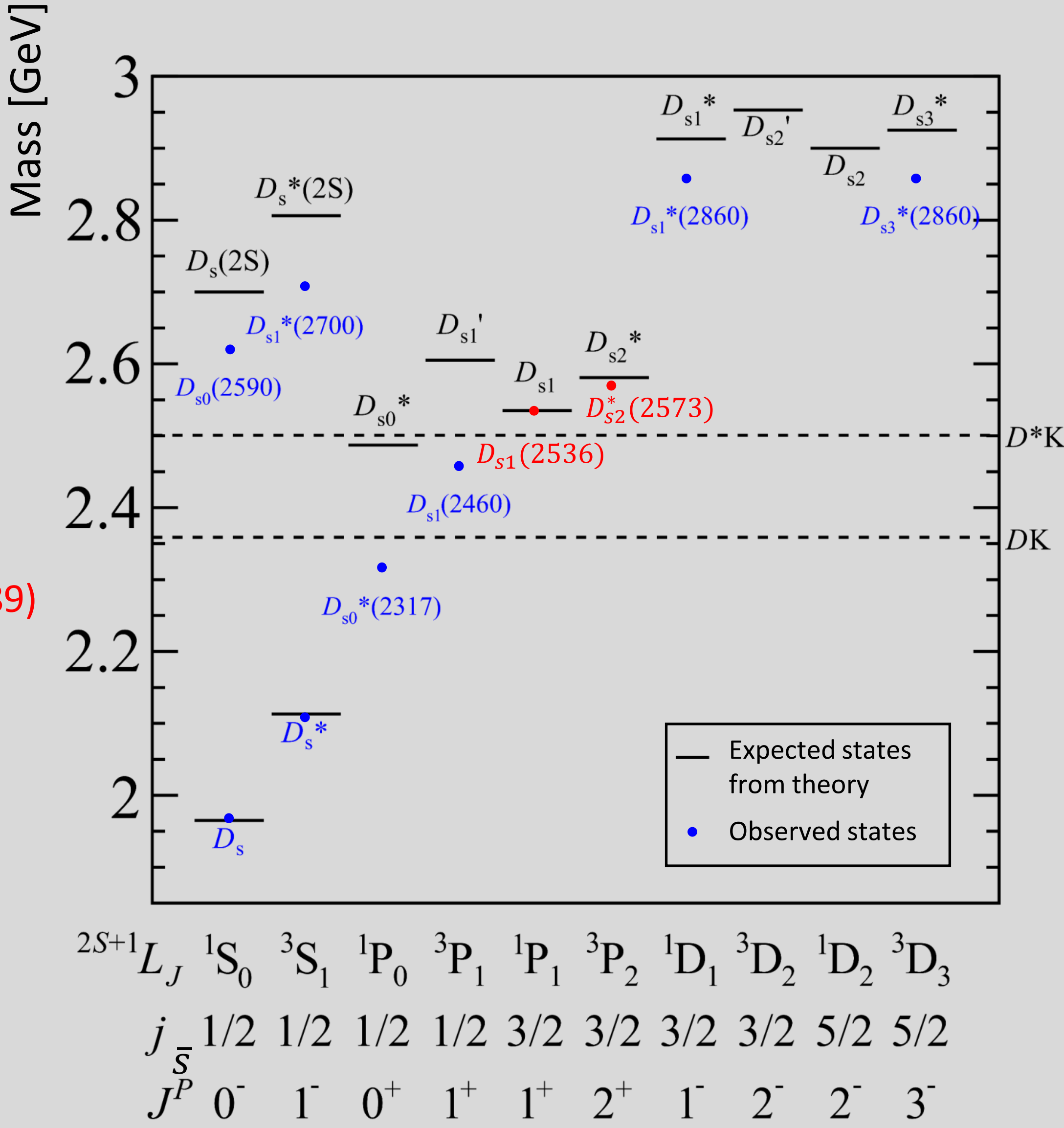


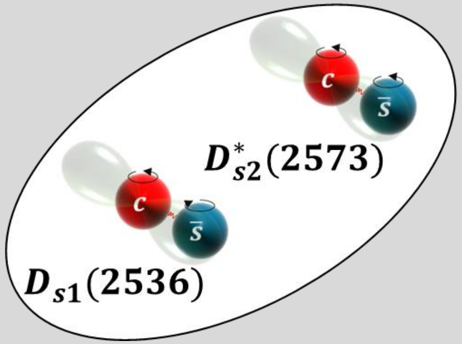
ARGUS: PLB 230, 162 (1989)

$D^*_{s2}(2573)$



CLEO: PRL 72, 1972 (1994)

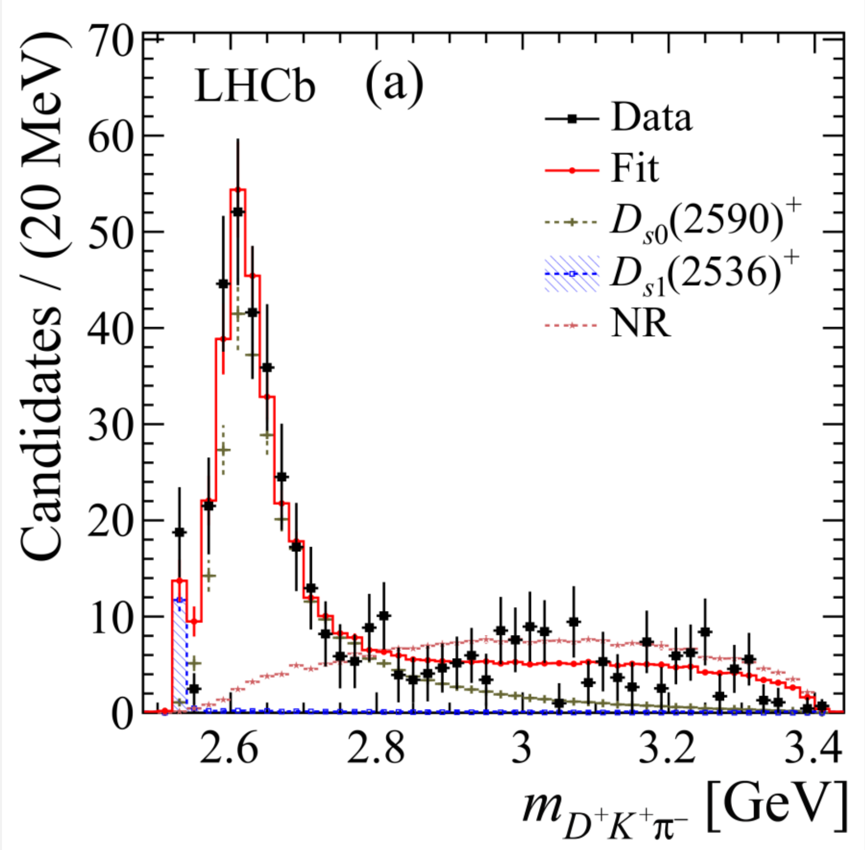




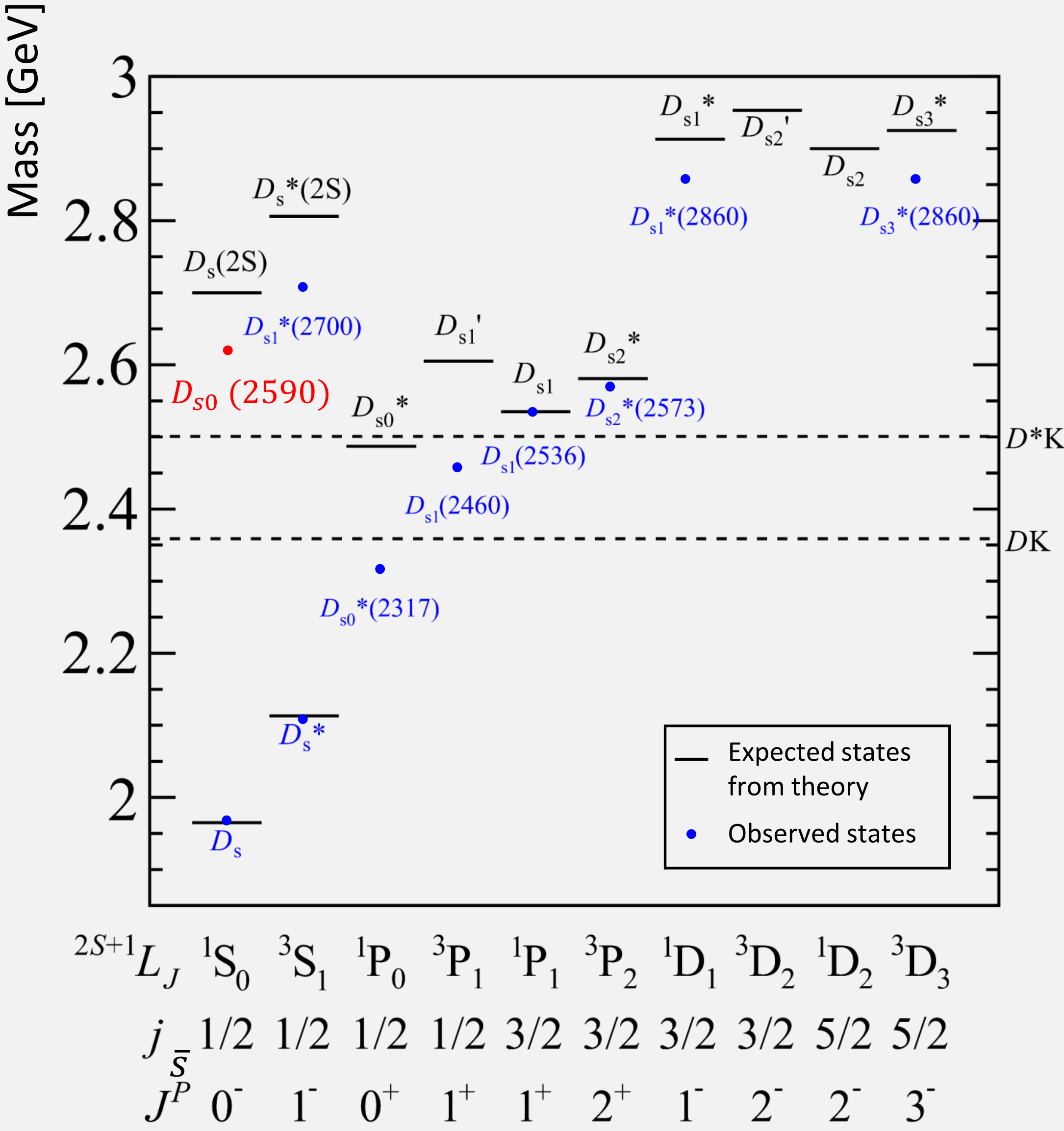
$D_{s0}(2590)$ at LHCb

The $B^0 \to D^- D^+ K^+ \pi^-$ is studied. A new D_s^+ meson, $D_{s0}(2590)^+$, is observed into the $D^+ K^+ \pi^-$ final state and it is interpreted as radial excitation of the ground state.

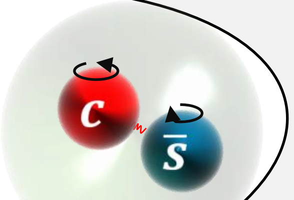
$J^P = 0^-$ is the spin-parity having best fit quality in the amplitude analysis



LHCb: PRL 126 (2021) 122002



$D_{s0}(2590)$



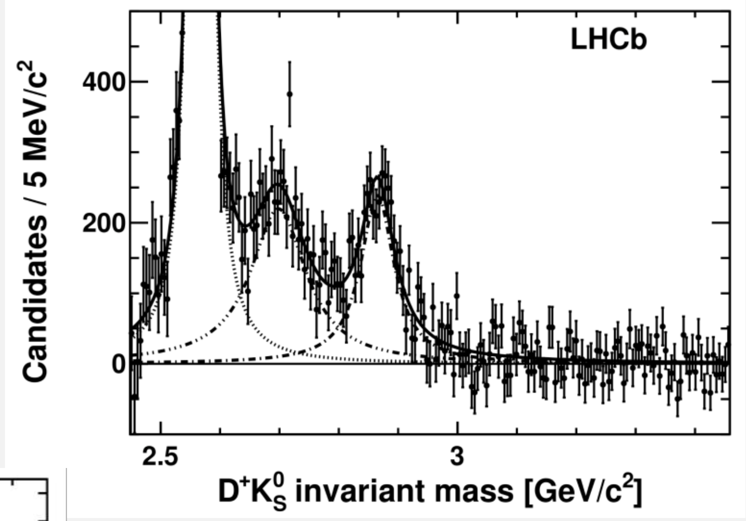
$m_{D_{s0}} = (2591 \pm 13)$ MeV/c^2

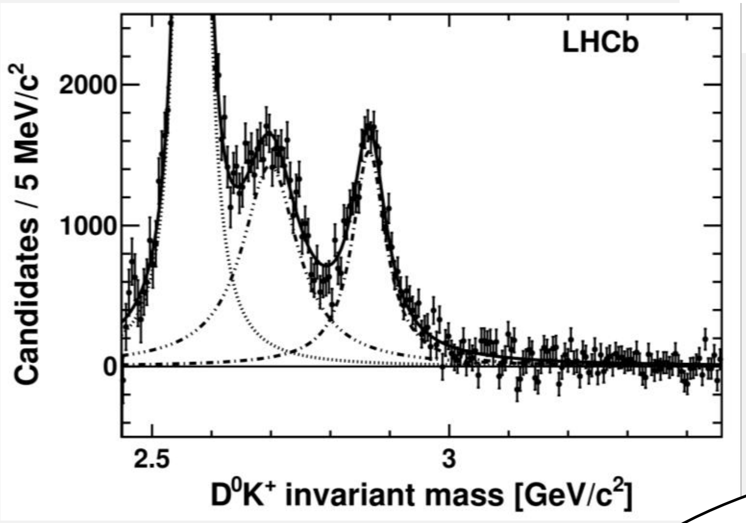
QCD@Work

$D_{sJ}^{*}(2860)$ at LHCb

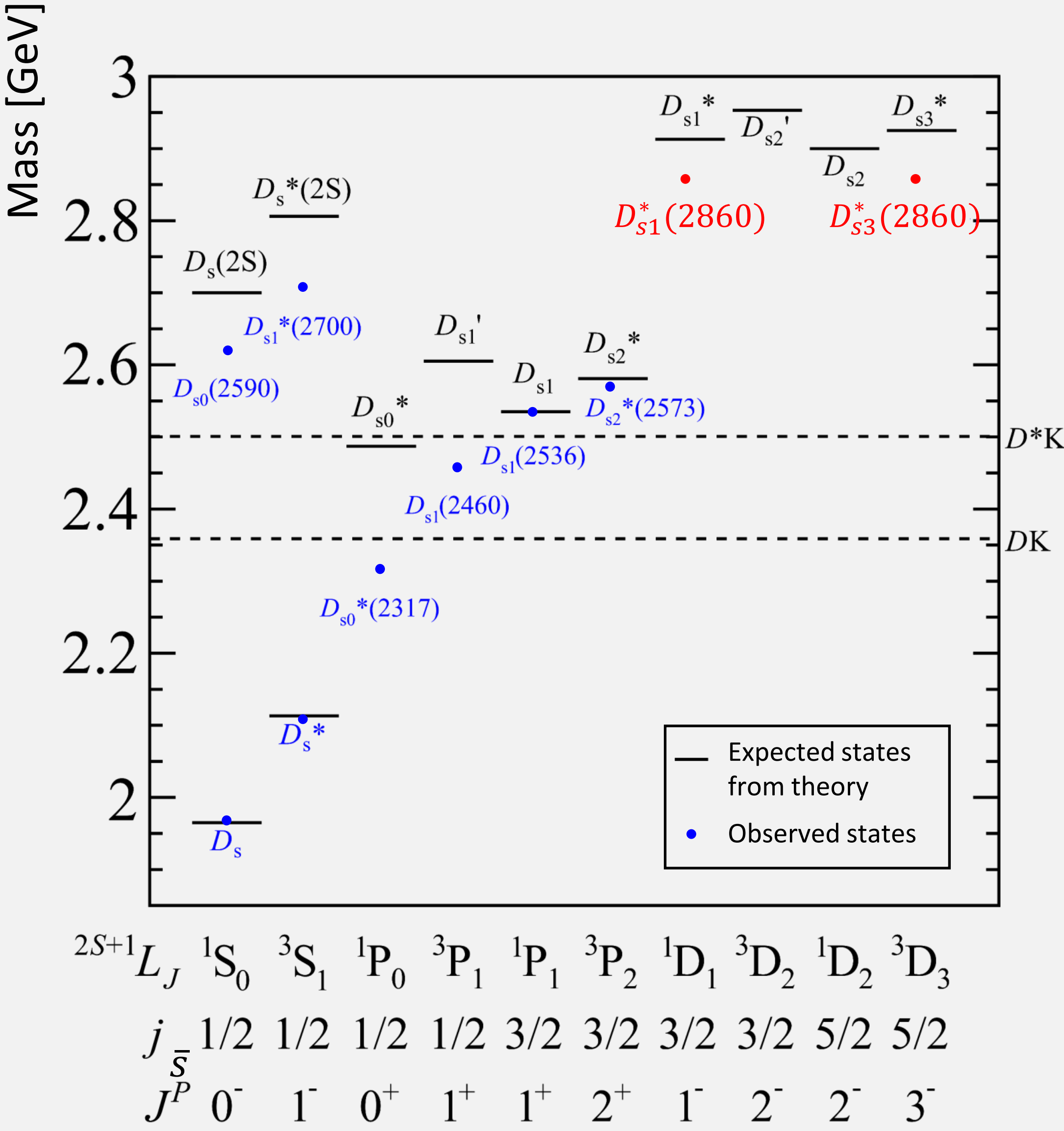
LHCb: JHEP 10 (2012) 151

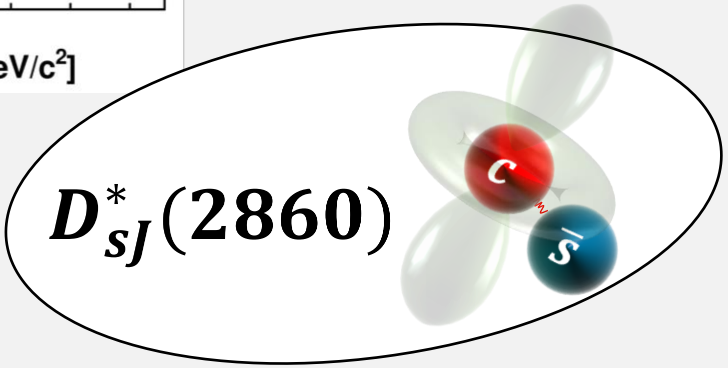
A study of $D^{+}K_{S}^{0}$ and $D^{0}K^{+}$ final states are performed using LHCb data of pp collisions, confirming the existence of the $D_{sJ}^{*}(2860)^{+}$ excited state.



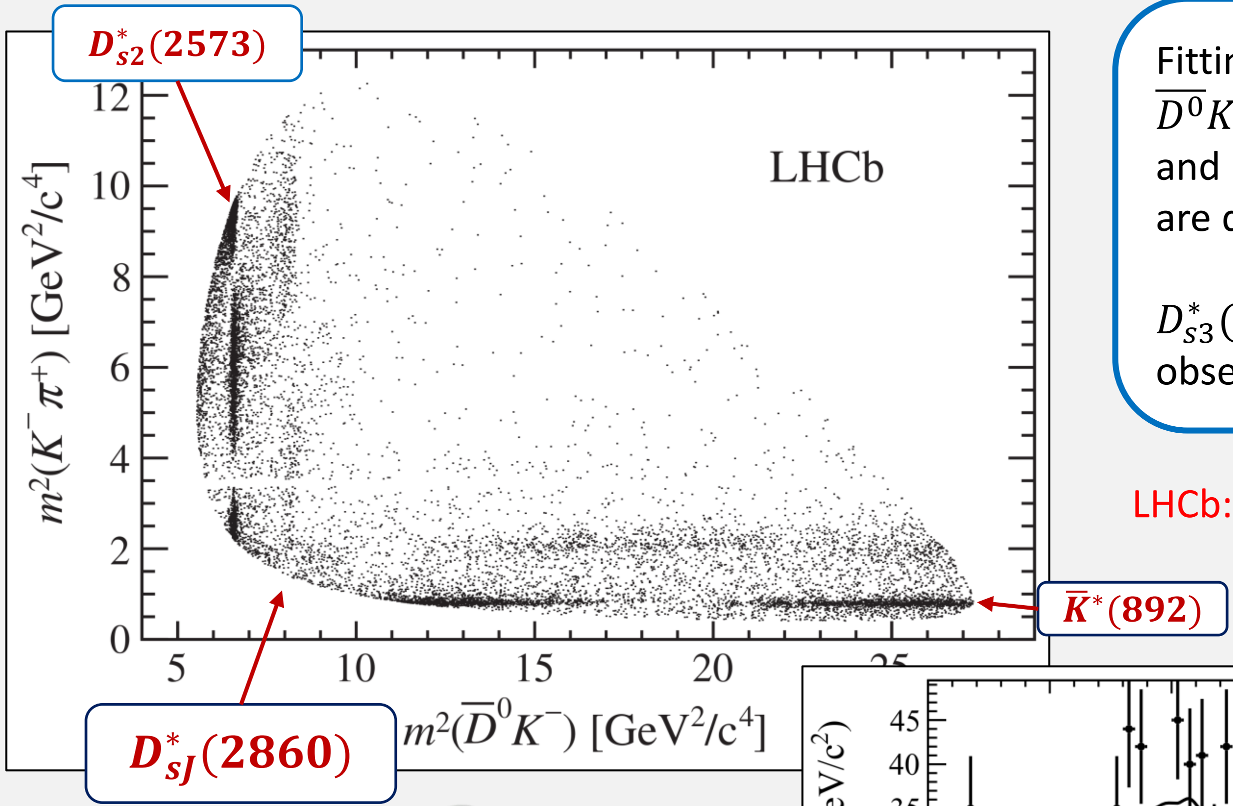


A broad structure at 2.86 GeV/c² is observed, even if the spin-parity J^{P} cannot be measured yet





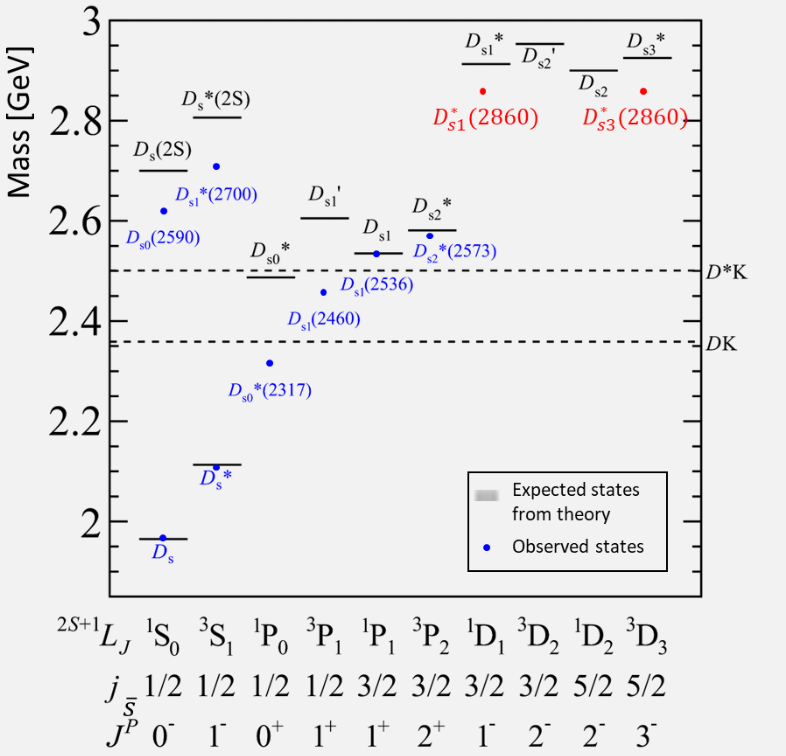
$D^*_{sJ}(2860)$ at LHCb

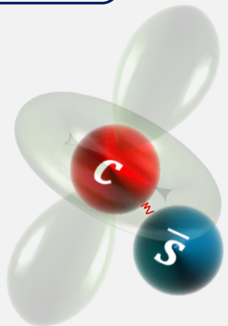


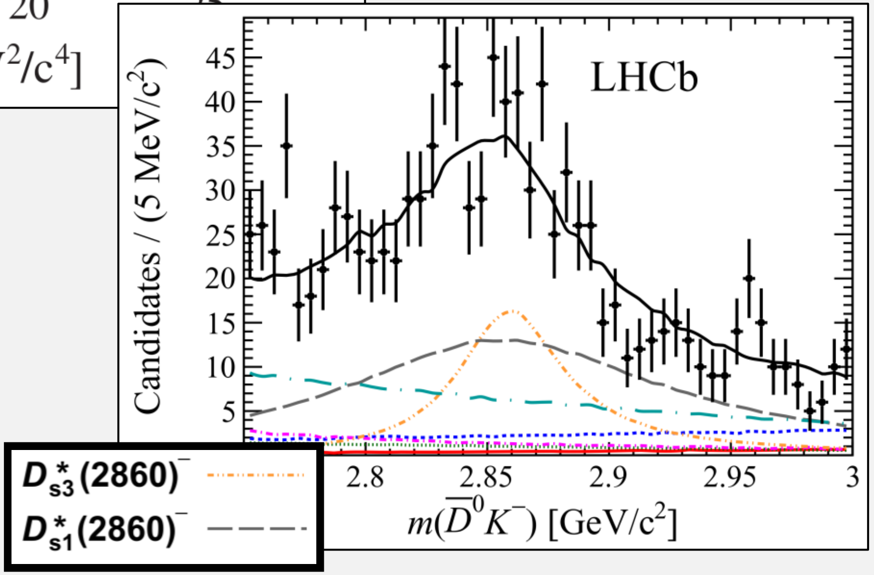
Fitting the Dalitz plot of $B^0_s \to \overline{D^0}K^-\pi^+$ decays, $D^*_{s1}(2860)$ and $D^*_{s3}(2860)$ resonances are distinguished

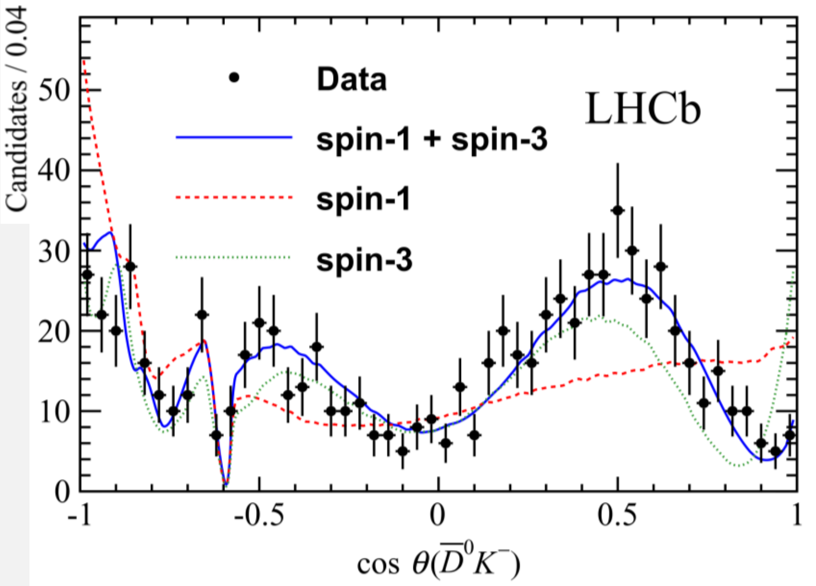
$D^*_{s3}(2860)^-$ is the first spin-3 observed particle in B decays

LHCb: PRL 113 (2014) 162001









QCD@Work

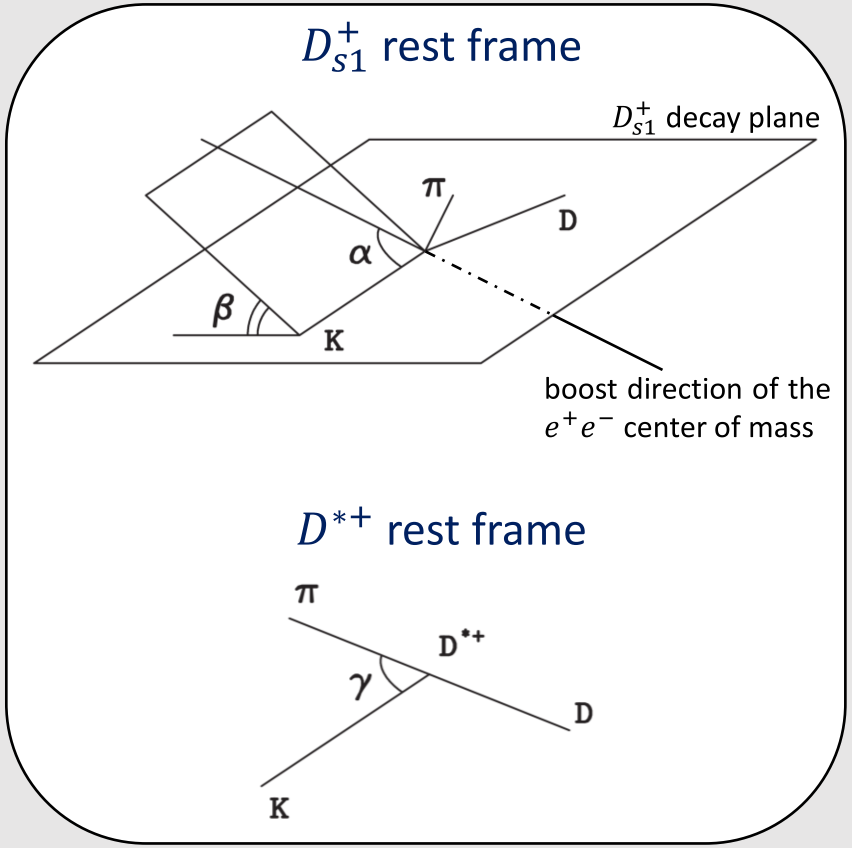
Unresolved puzzles

The puzzle of the $D_{s1}(2536)$

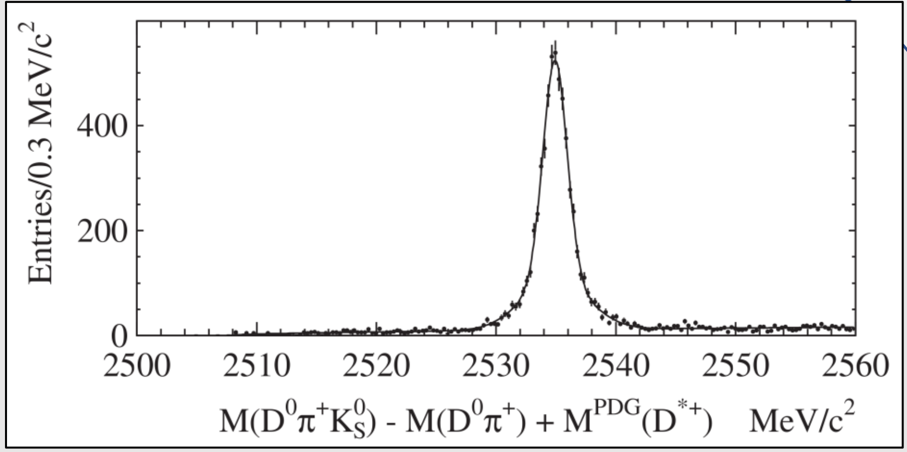
Since the c quark is not infinitely heavy, the $D_{s1}(2536)^+$ can contain an admixture of another state from $j_{\bar{s}} = 1/2$ and can have a small decay fraction in an S-wave.

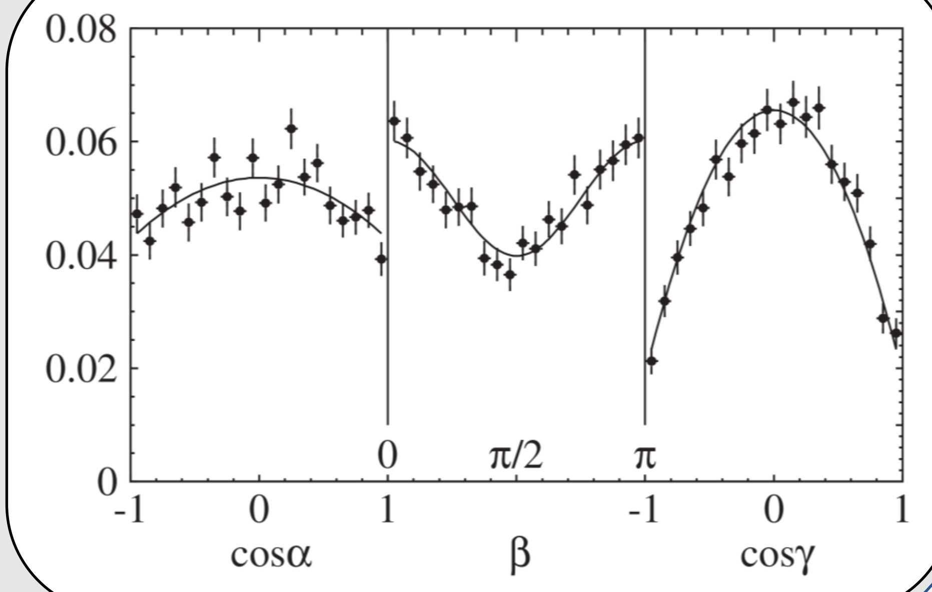
An angular analysis of the $D_{s1}(2536)^+$ decay in $D^{*+}K_S^0$ is performed, showing an unexpected S-wave dominant contribution.

Belle: PRD77 (2008) 032001



$$\frac{\Gamma_S}{\Gamma_{total}} = 0.72 \pm 0.05 \pm 0.01$$



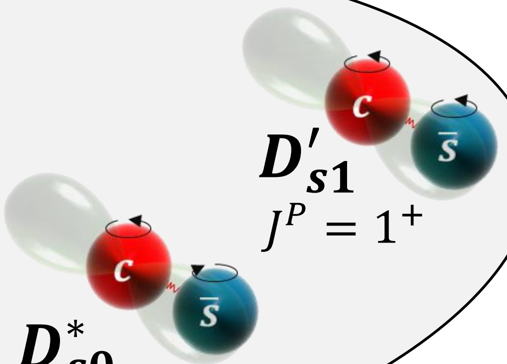


D_s SPECTROSCOPY

$j_{\bar{s}} = 1/2$

Theoretical predictions

Broad states expected to be massive enough that dominant strong decays would have been isospin-conserving in DK and/or D^*K final states.

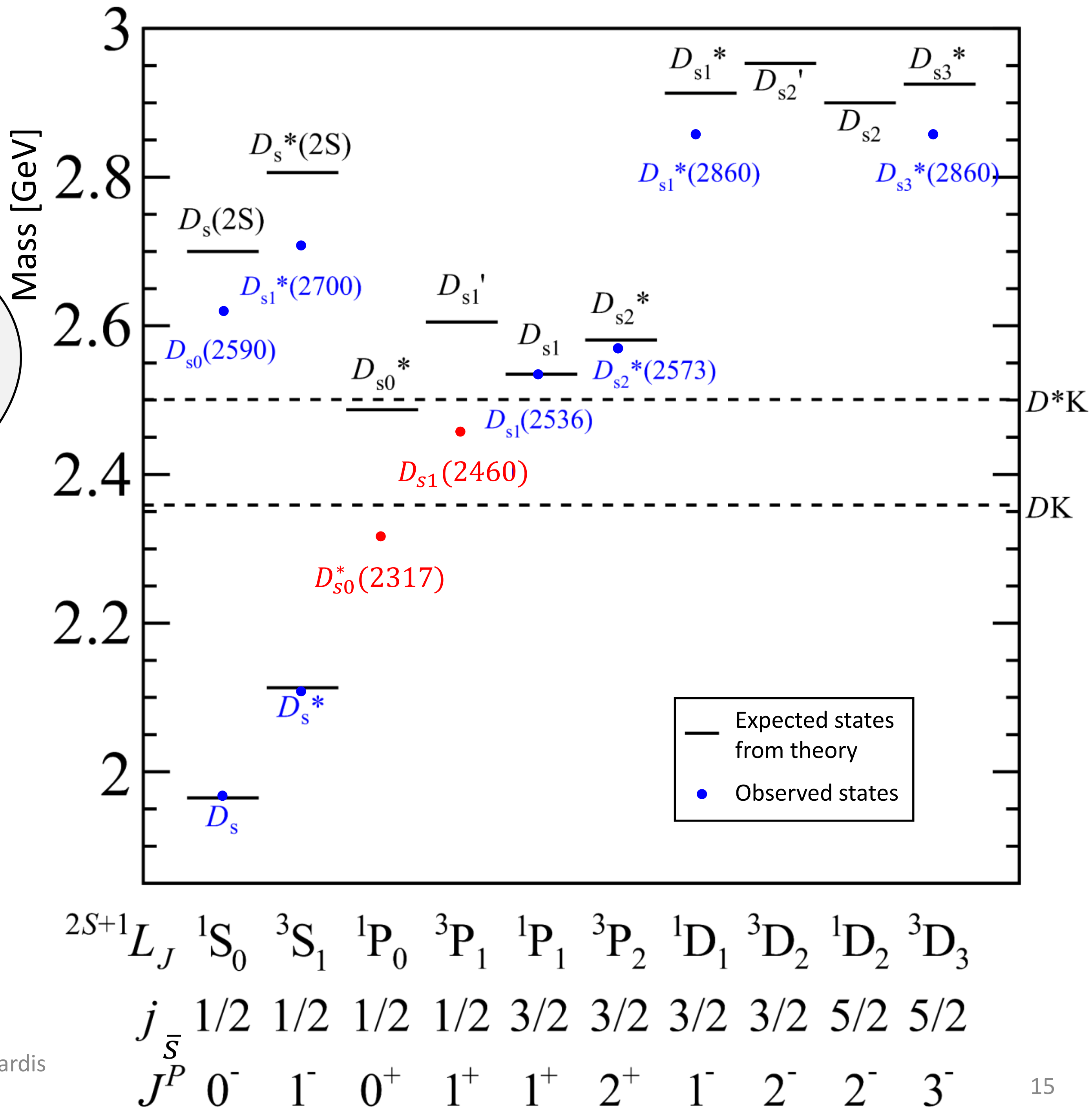


D'_{s1} $J^P = 1^+$

D^*_{s0} $J^P = 0^+$

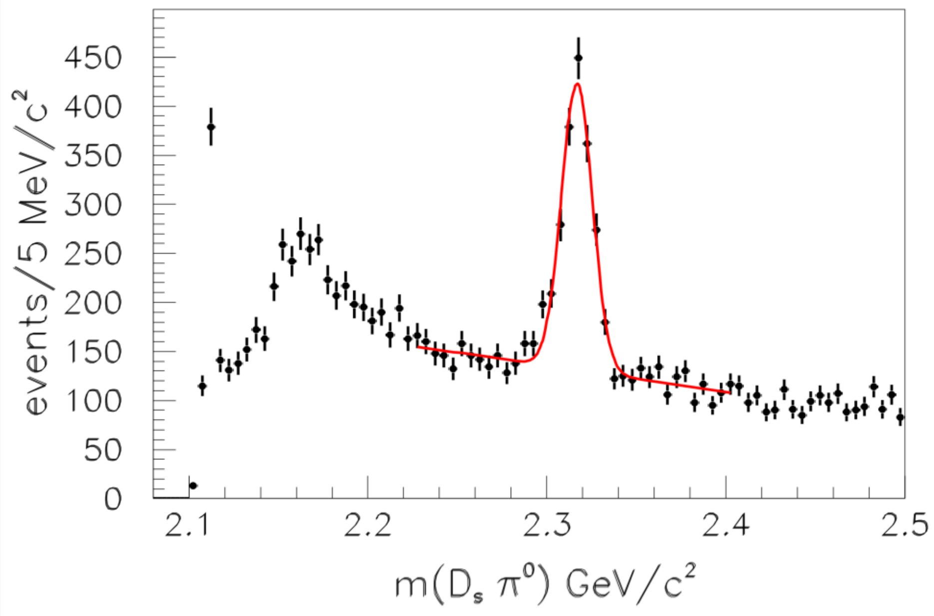
Surprising observations:

- masses smaller than predicted
- observed in the isospin-violating $D_s^{(*)}\pi^0$ channels
- narrow states (width < 4 MeV)



$D_{s0}^*(2317)^+ \to D_s^+\pi^0$
BABAR (2003)

Narrow signal state, labeled as $D_{sJ}^*(2317)^+$, observed in the inclusive $D_s^+\pi^0$ mass distribution by the *BABAR* collaboration.

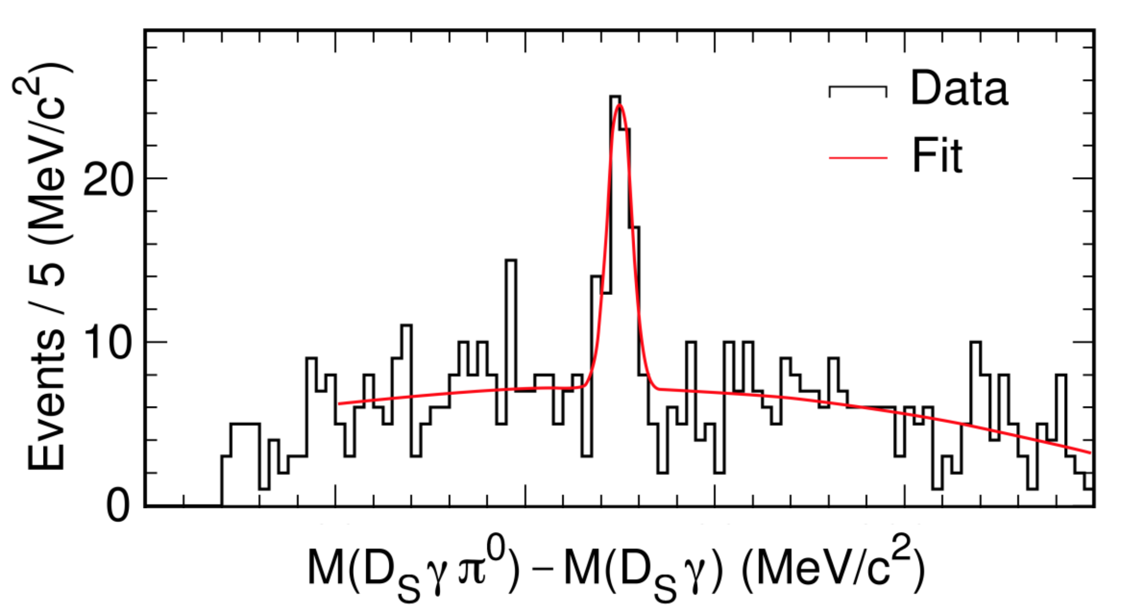


PRL 90 (2003) 242001

"Since a $c\bar{s}$ meson of this mass contradicts current models [...] these models need modification or the observed state is of a different type altogether, such as a four-quark state."

$D_{s1}(2460)^+ \to D_s^{*+}\pi^0$
CLEO (2003)

A narrow peak has been observed by the CLEO collaboration while exploring the $D_s^{*+}\pi^0$ mass distribution.



PRL 68 (2003) 032002

$D_{s1}(2460)^+$ mass is above the kinematic threshold for decay to DK but the narrow width suggests that latter decay does not occur, hinting the state is the missing $J^P = 1^+$ excited state.

The puzzle of the $D_{s1}(2460)$

The coupling with $\vec{S}_c$ of the heavy c quark should equally affect the splittings between $\vec{J} = 1, 2$ states and $\vec{J} = 0, 1$ states. However:

$$m_{D_{s1}(2460)} - m_{D^*_{s0}(2317)} \neq m_{D^*_{s2}(2573)} - m_{D_{s1}(2536)}$$

$\approx 130\ \mathrm{MeV/c^2}$ $\approx 40\ \mathrm{MeV/c^2}$

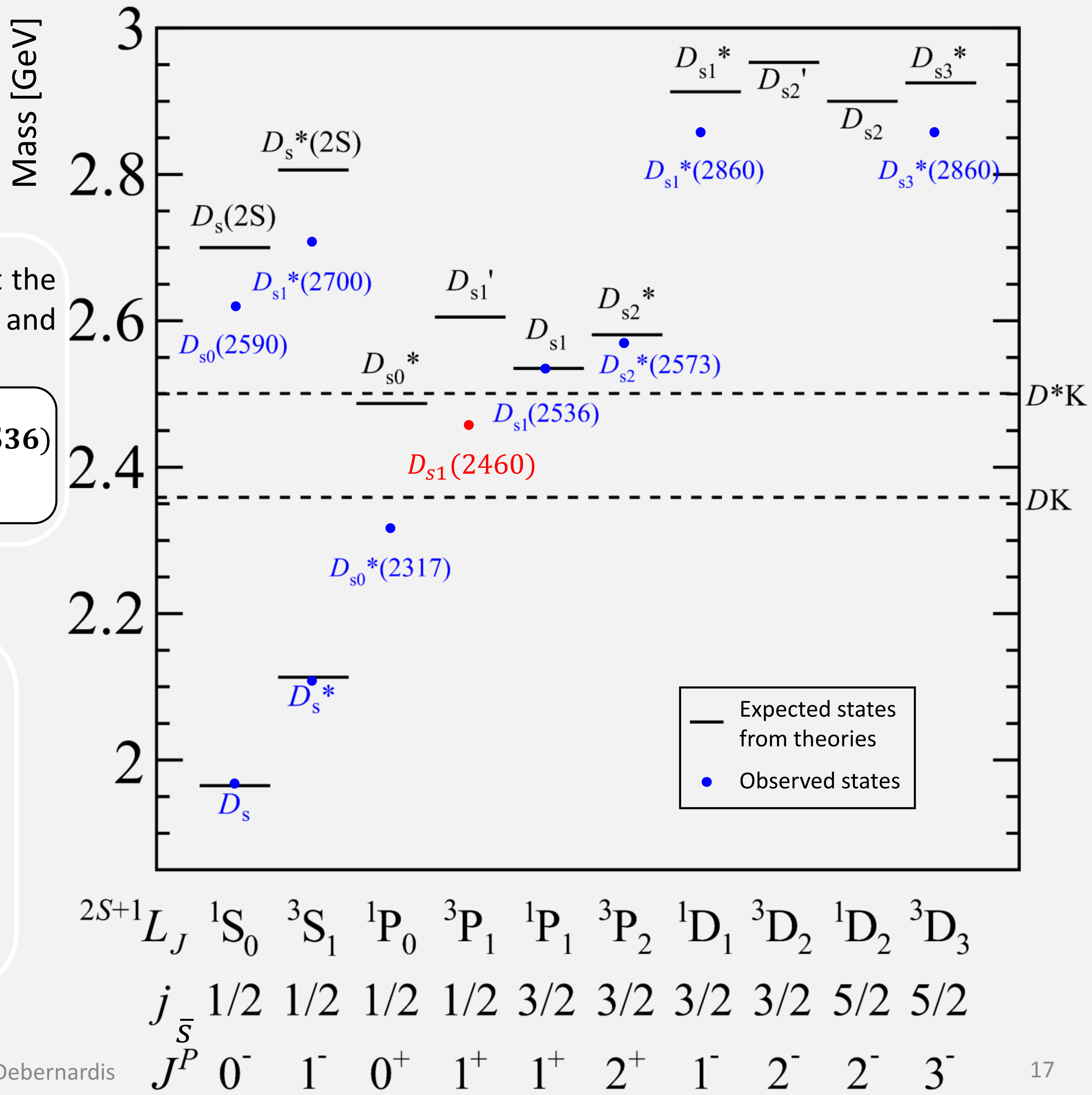
PDG 083C01 (2020-2021)

In the heavy quark limit model the ratio R is ≈ 1. But:

$$R \equiv \frac{BR(B \to D D_{s1}(2460))}{BR(B \to D D^*_s)} \approx \frac{1}{3} \neq 1$$

This anomaly could be explained considering the particle $D_{s1}(2460)$ as a four quark state whose production is suppressed in $B \to D D_{s1}(2460)$ decays.

PLB 572 (2003) 164–170



The puzzle of the $D_{s1}(2460)$

PDG 083C01 (2020-2021)

For the D_s^{*+} meson, radiative decay mode is much more likely because is not isospin-violating, unlike the $D_s\pi^0$ mode.

Same remarks should be also valid for the $D_{s1}(2460)$ in a $c\bar{s}$ scenario.

But isospin-violating $D_s^*\pi^0$ decay mode is much more frequent than $D_s\gamma$ mode, suggesting a 4-quark component ($c\bar{s}u\bar{u}$ or $c\bar{s}d\bar{d}$).

D_s^{*+}	decay modes
$D_s^+\gamma$	$(93.5 \pm 0.7)\%$
$D_s^+\pi^0$	$(5.8 \pm 0.7)\%$
$D_s^+e^+e^-$	$(6.7 \pm 1.6) \times 10^{-1}\%$

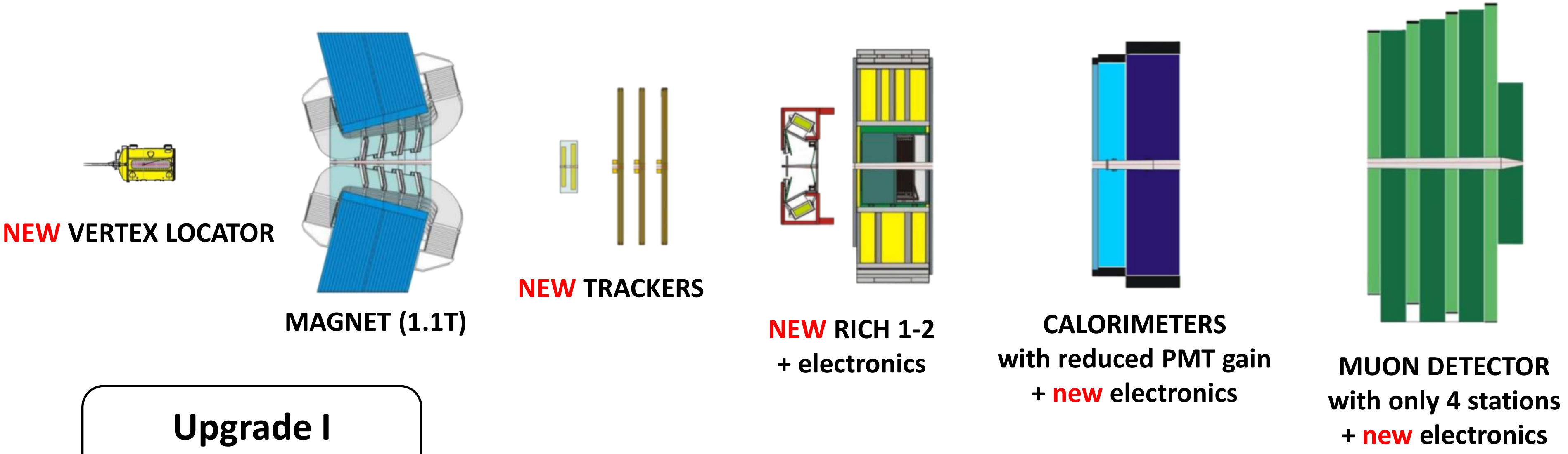
Dalitz decay

$D_{s1}(2460)^+$	decay modes
$D_s^{*+}\pi^0$	$(48 \pm 11)\%$
$D_s^+\gamma$	$(18 \pm 4)\%$
$D_s^+\pi^+\pi^-$	$(4.3 \pm 1.3)\%$
TOT	$(\mathbf{70} \pm \mathbf{16})\%$

LHCb Upgrades and Prospects

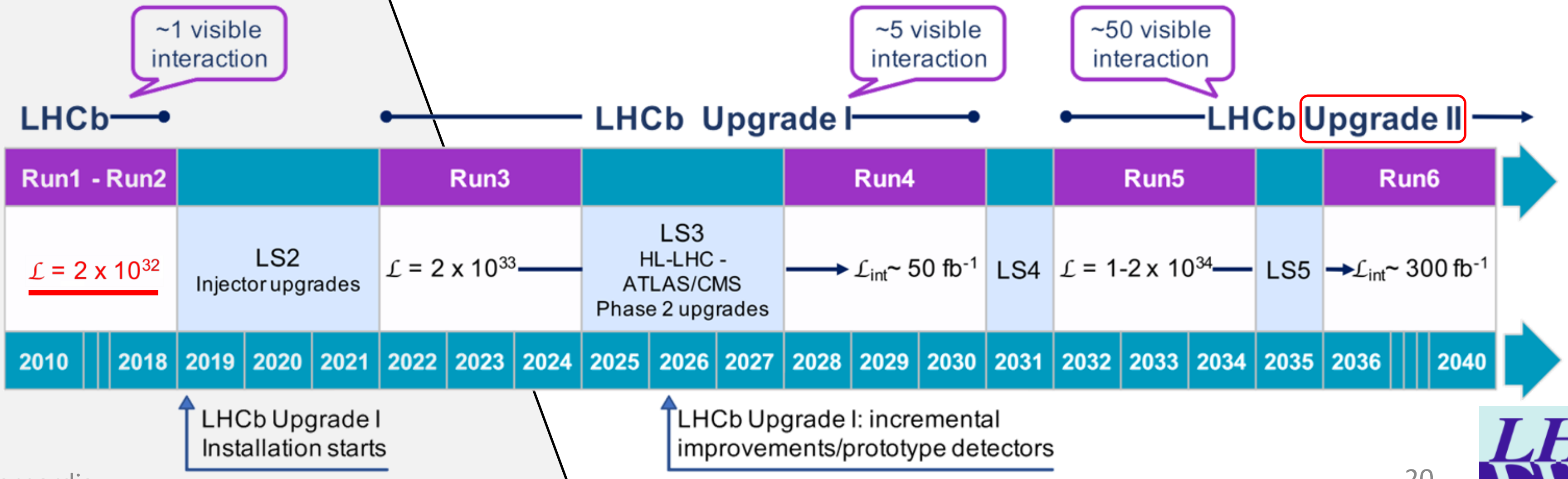
LHCb Upgrades

The LHC luminosity increase up to 1.5×10^{34} $cm^{-2}sec^{-1}$ planned for Run 5 is a great opportunity to improve the precision of the LHCb physics reach, **contributing to disentangle puzzles in the excited D_s states**



Upgrade I for Run 3

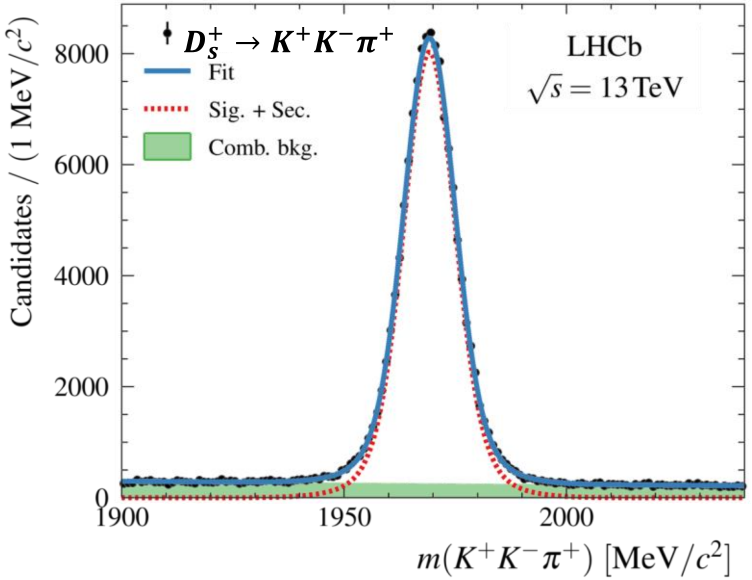
CERN-LHCC-2012-007
CERN-LHCC-2017-003



Summary:

LHCb has made a large contribution to the spectroscopy of the D_s mesons, profiting from the large production cross-section.

New D_s excited state observed: $D_{s0}(2590)$, $D_{s1}^*(2860)$, $D_{s3}^*(2860)$



LHCb: JHEP 05 (2017) 074

Analysis Prospects:

- Search for new decay modes,
  e.g., muonic Dalitz decay $\boldsymbol{D_{s1}(2460) \to D_s + \gamma^* \to D_s\ \mu^+\ \mu^-}$
  inspired by the observed $\chi_{c1}, \chi_{c2} \to J/\psi\ \mu^+\mu^-$ decays
  (PRL 119 (2017) 221801)

- Production measurement of,
  e.g., $\boldsymbol{D_{s1}(2460)}$ via $\boldsymbol{D_s\gamma}$ decays

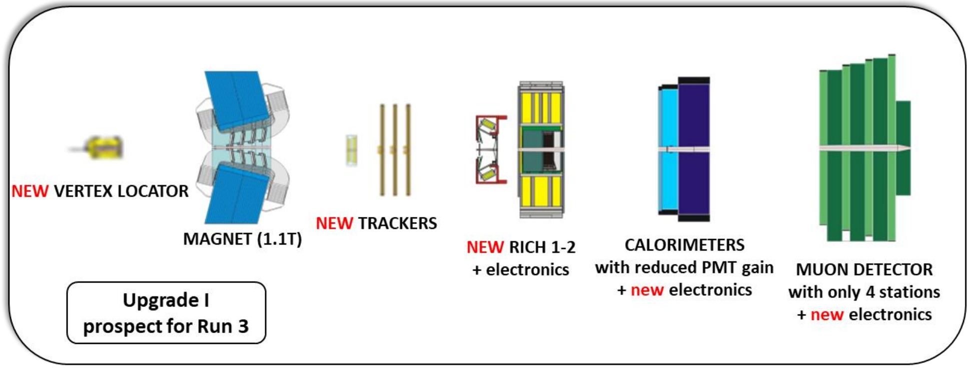
- Quantum numbers measurement
  e.g., $\boldsymbol{D_{s0}^*(2317)^+}$ spin-parity,
  by studying the decay $\boldsymbol{B_s^0 \to D_{s0}^*(2317)^-\pi^+ \to D_s^-\pi^0\pi^+}$

Thank you for your attention

Francesco Debernardis
INFN and University of Bari
On behalf of the LHCb collaboration

D_s

LHCb Upgrade I outline



CERN-LHCC-2012-007
CERN-LHCC-2014-001
CERN-LHCC-2013-022

VELO:

- Si-strips measuring *r* and *phi*. -> Hybrid Pixel Silicon detector
- Two movable halves: get closer to beam [50mm to 5mm] -> [5mm to 3.5mm]
- New ASIC VeloPix

TRACKERS:

- Upstream Tracker (UT):
  Silicon micro-strip planes with finer granularity and closer to beam
  New readout ASIC
- T1-T3:
  Silicon microstrips near beam pipe (Inner Tracker) + straw tubes outer (Outer Tracker) -> (Too high occupancy in central region) -> New detector based on Schintillating Thin Fibers

RICH:

- RICH 1 change everything but the magnetic shielding:
  Mirrors, gas enclosure, quartz windows
  Photon detectors, electronics, detector mechanics
- RICH 2 change only detectors:
  Photon detectors, electronics, detector mechanics

CALORIMETERS:

- Present Calorimeters (ECAL, HCAL) detectors will be kept
- PMT gain will be reduced by a factor 5 to reduce ageing due to higher luminosities
- New front-end electronics to be compatible with the reduced gain and the trigger-less readout

MUON DETECTOR:

- Present Muon detector (M1 removed) will be kept with MWPCs
- Front-End electronics will be redeveloped to be compatible with trigger-less readout