Multiplicity-dependent production as observable for hadron nature testing at LHCb

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Outline

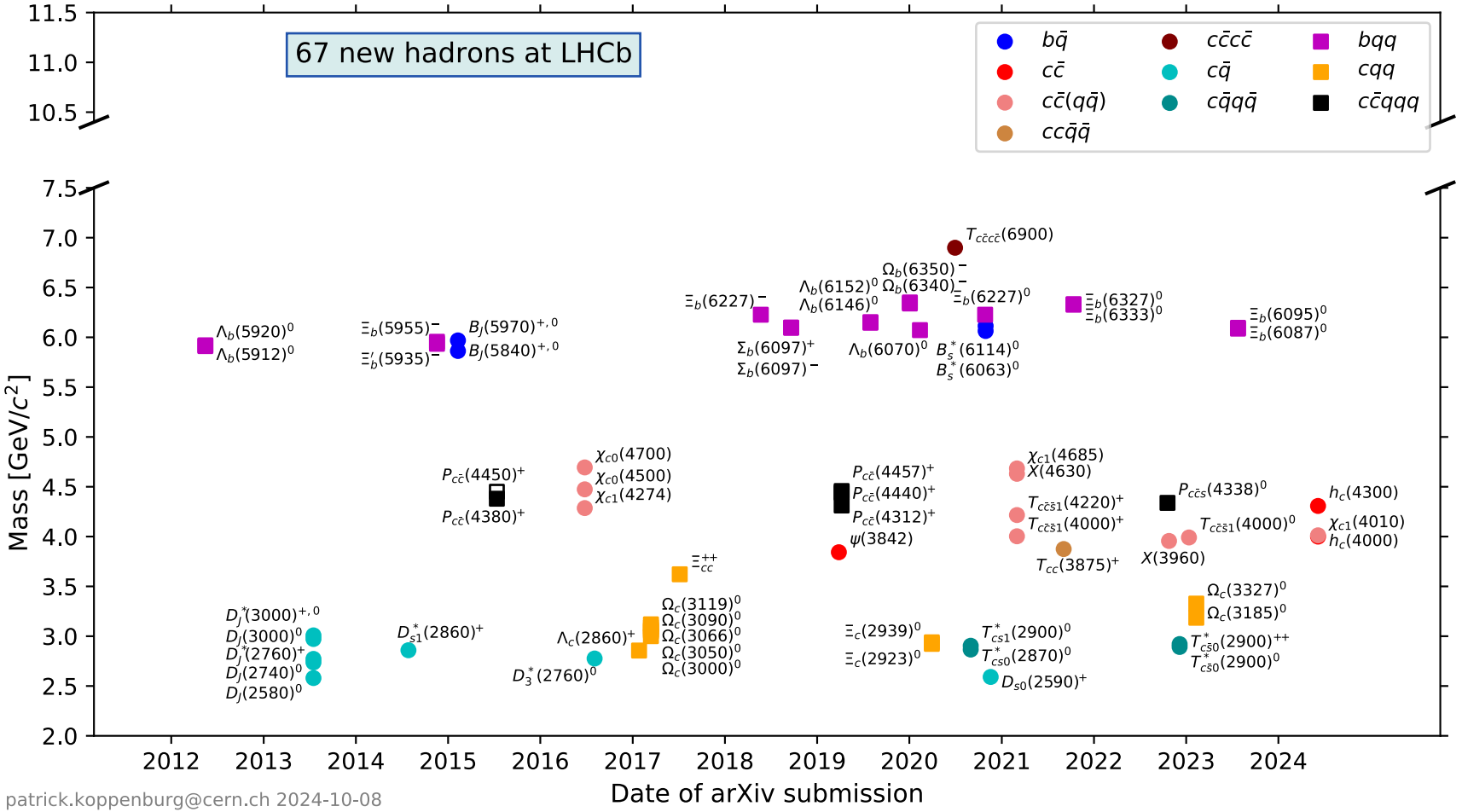
1. Exotic states at LHCb experiment

2. Medium interactions as hadron nature test. The studies over the $\chi_{c1}(3872)$

3. Measurement of exotic D_{sJ} states at LHCb

4. Conclusions and prospects

Exotic states at LHCb experiment



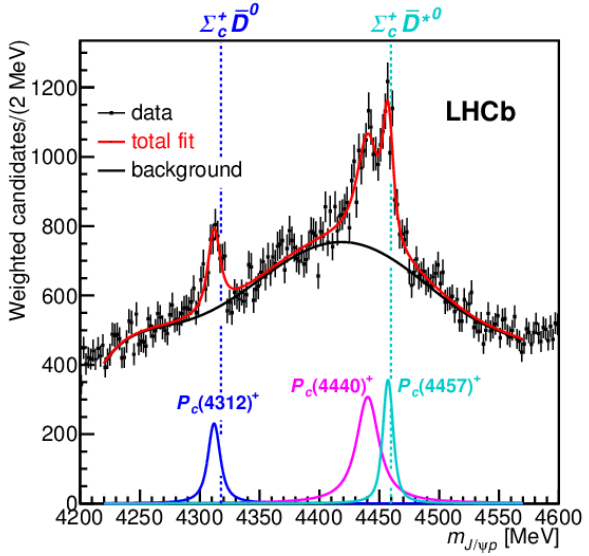
LHCb has proved its huge potential at discovering new exotic states

Strategies for exotic hadron spectroscopy

✓ For discovering new states → Amplitude analysis formalism over B and Λ_b multi body decays

i.e P_c states at $\Lambda_b^0 \to J/\psi p K^-$ decays

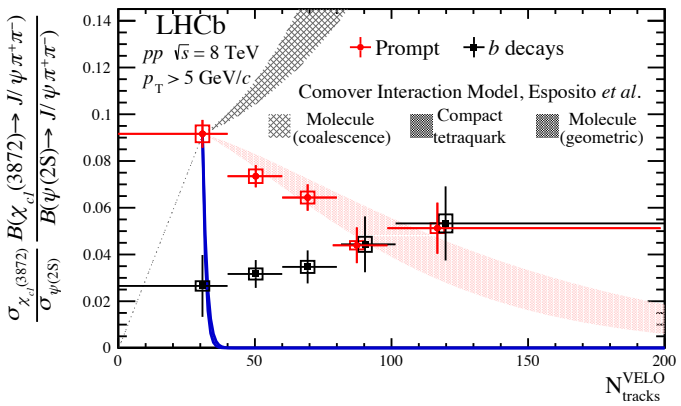
PHY. REV. LETT. 122 (2019) 222001



✓ For testing the nature of exotic candidates:

- Measuring the radiative decays properties → $R_{\psi\gamma} = \dfrac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$ for the $\chi_{c1}(3872)$

PHY. REV. LETT. 126 (2021) 092001



- Measuring direct production of the exotic candidate → **NEW** → $AA \to X_{exotic} + Y$

i.e $\chi_{c1}(3872)$ over $\psi(2S)$ vs multiplicity in pp collisions

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Medium interactions effects as test for the $\chi_{c1}(3872)$ nature

Production vs multiplicity analysis → Interaction with comovers

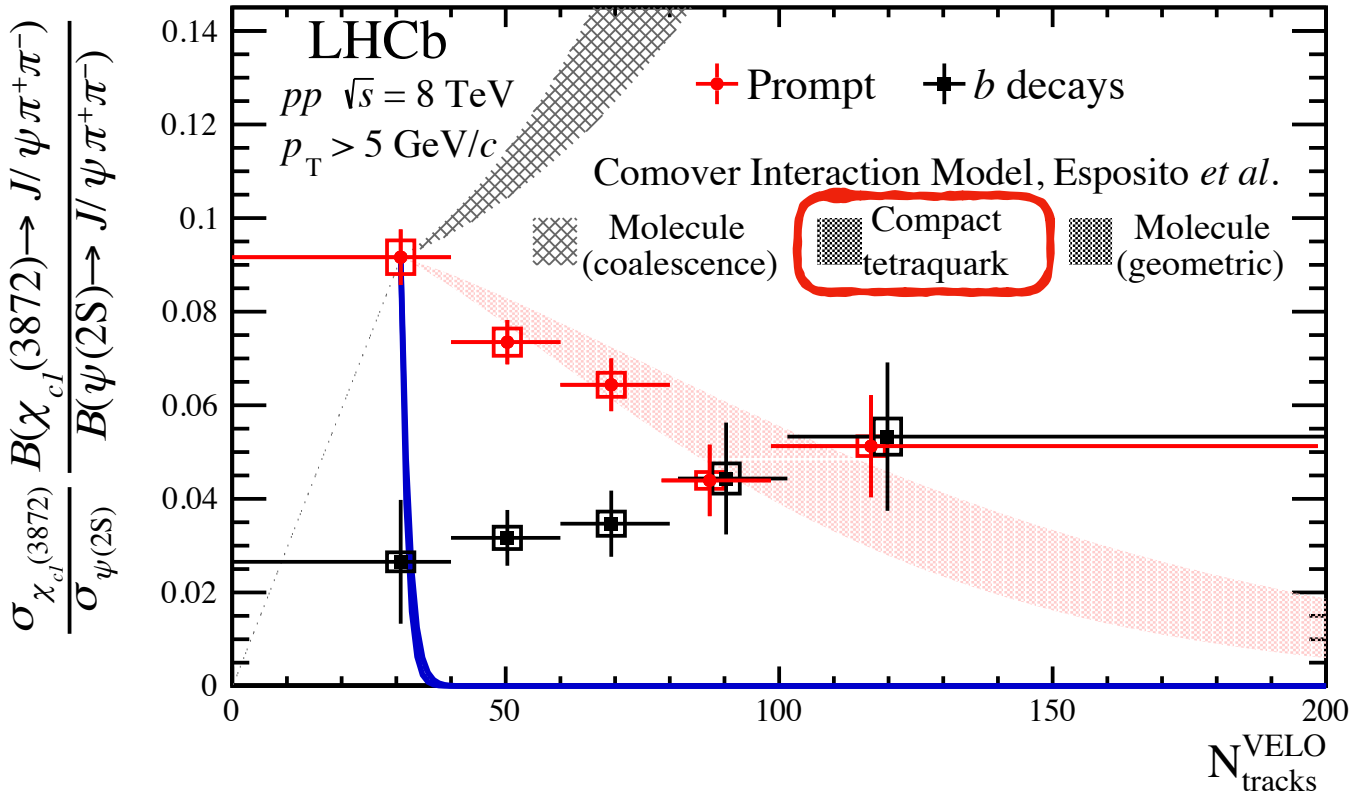
PHY. REV. LETT. 126 (2021) 092001

Production **suppression** is expected due to **break-out** through comover interactions.

Tetraquarks are supposed to have lower binding energy than mesons, so their production is more suppressed (more easy to break)

$$\frac{\sigma_{tetraquark}}{\sigma_{meson}}$$ ↓

$$N_{charged} \sim N^{VELO}_{Tracks}$$ ↑



Medium interactions effects as test for the $\chi_{c1}(3872)$ nature

Production vs multiplicity analysis → Interaction with comovers

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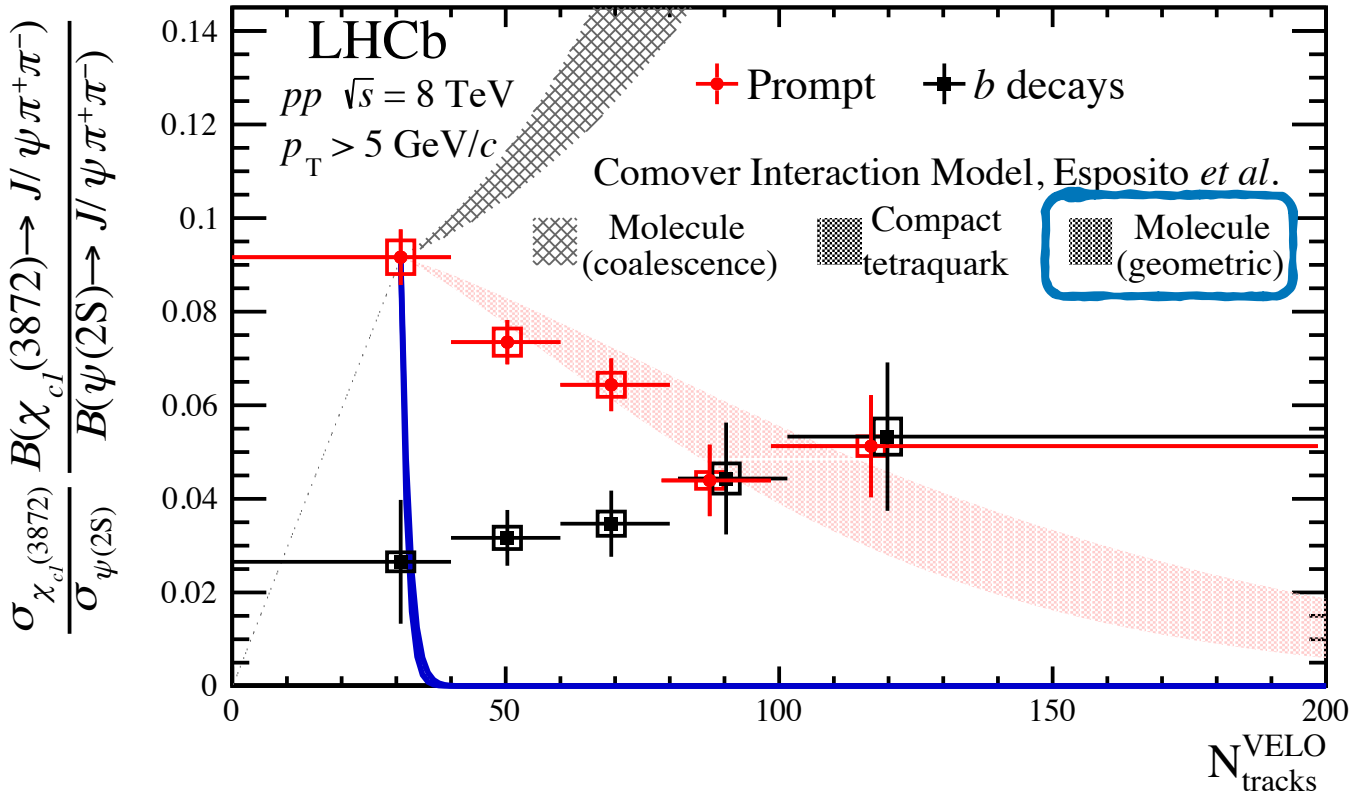
Hadronic molecules are even less bounded than tetraquarks, so suppression is expected to be **higher**

$$\frac{\sigma_{molecule}}{\sigma_{meson}}$$

$$N_{charged} \sim N^{VELO}_{Tracks}$$



Medium interactions effects as test for the $\chi_{c1}(3872)$ nature

Production vs multiplicity analysis → **Interaction with comovers**

However, in high multiplicity media molecules can suffer recombination processes → **coalescence.**

Seeing by ALICE for deuterium (np molecule)

$$\frac{\sigma_{molecule}}{\sigma_{meson}} \uparrow \qquad N_{charged} \sim N^{VELO}_{Tracks} \uparrow$$

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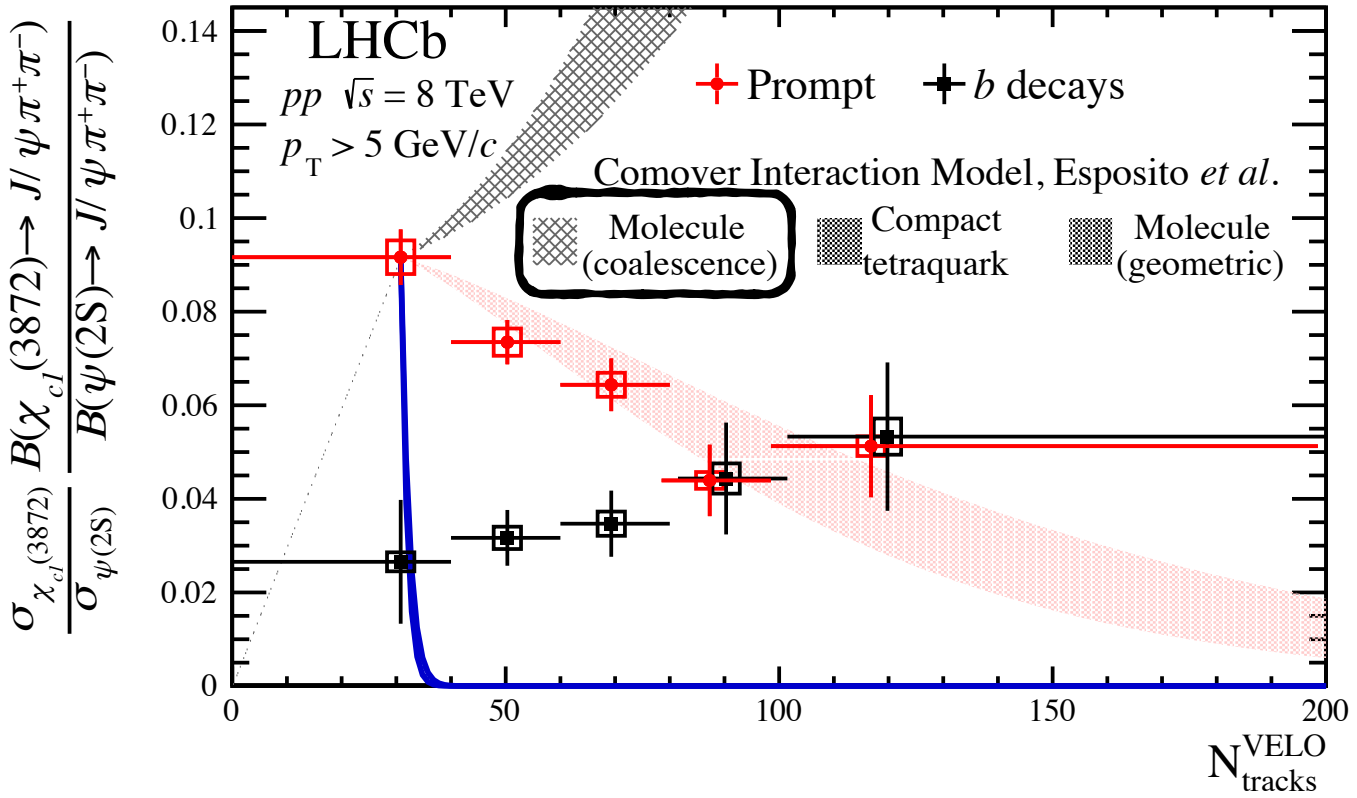

Medium interactions effects as test for the $\chi_{c1}(3872)$ nature

Collective effects can be enhance in more busy colliding systems such as pA or AA collisions

In fact, the production of exotics can be really affected by the formation of the **quark-gluon plasma (QGP)**

In this scenario, an important observable is the **nuclear modification factor**

$$R^X_{pA(AA)} \sim \frac{\sigma^X_{pA(AA)}}{\sigma^X_{pp}}$$

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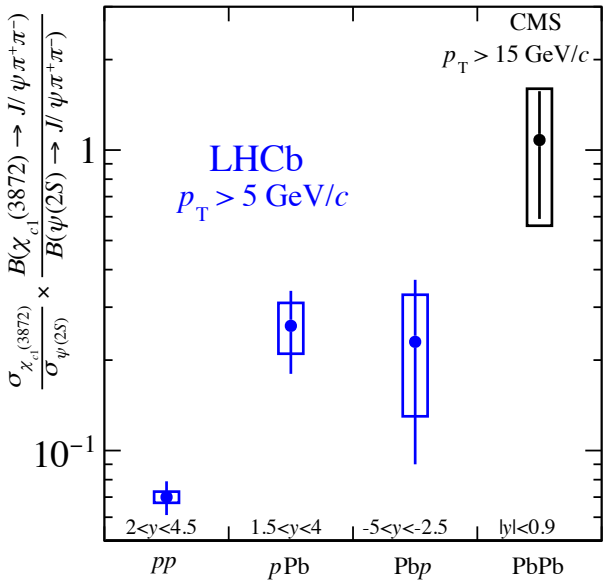

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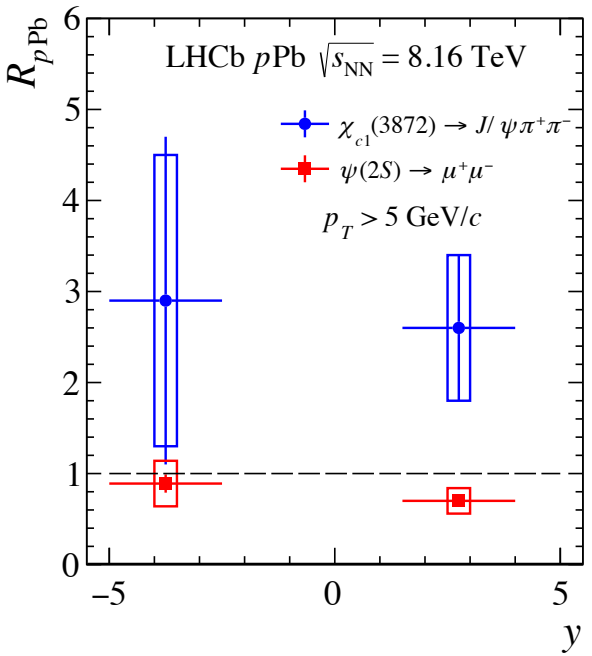

$$R^X_{pA(AA)} = 1$$

$$\downarrow$$

No modification
(Expected common charmonium states)

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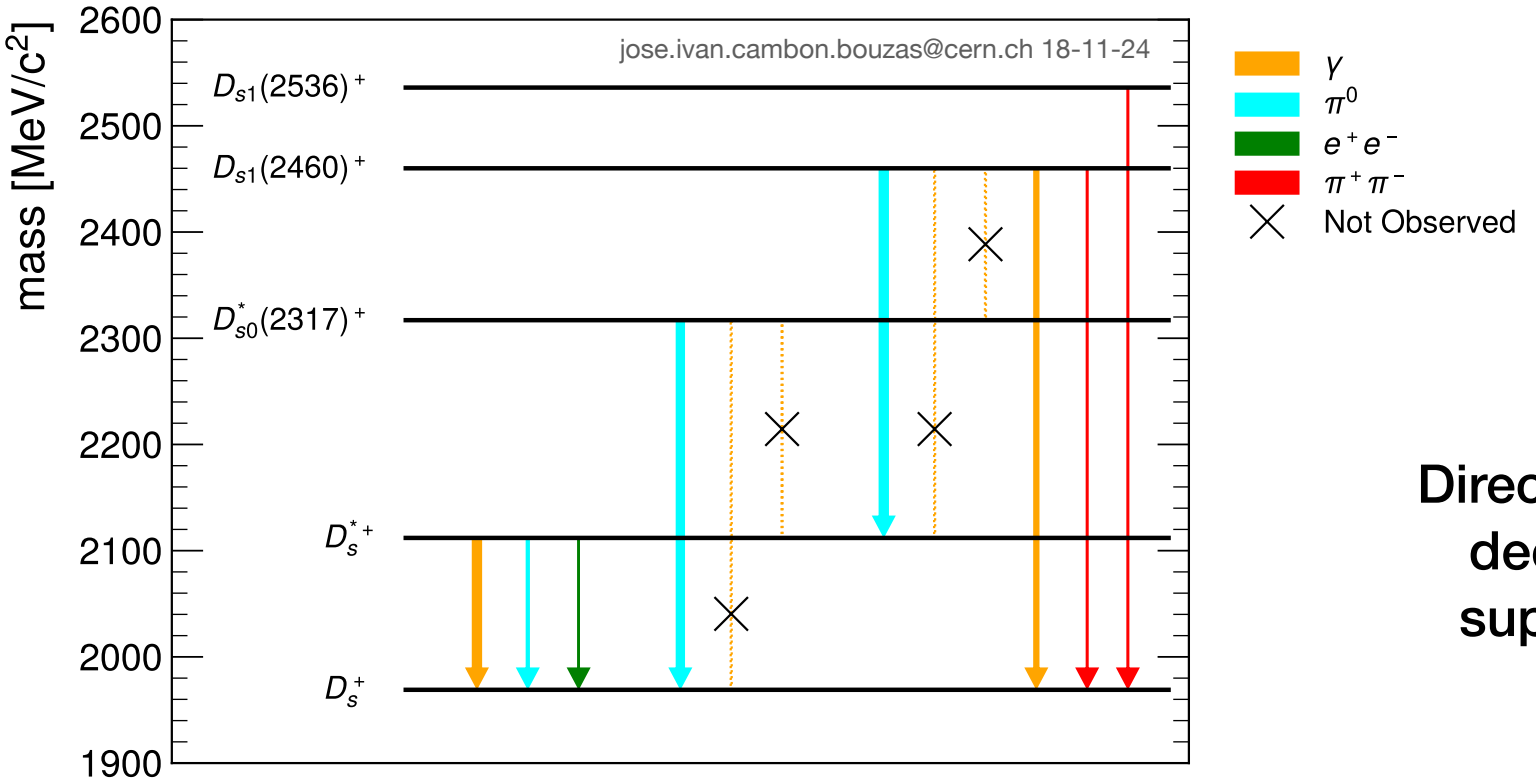
4. Conclusions and prospects

The properties of the first states of the $[c\bar{s}]$ spectrum

1. Their decays



π^0 isospin violating decays are dominant

Direct radiative decays are suppressed

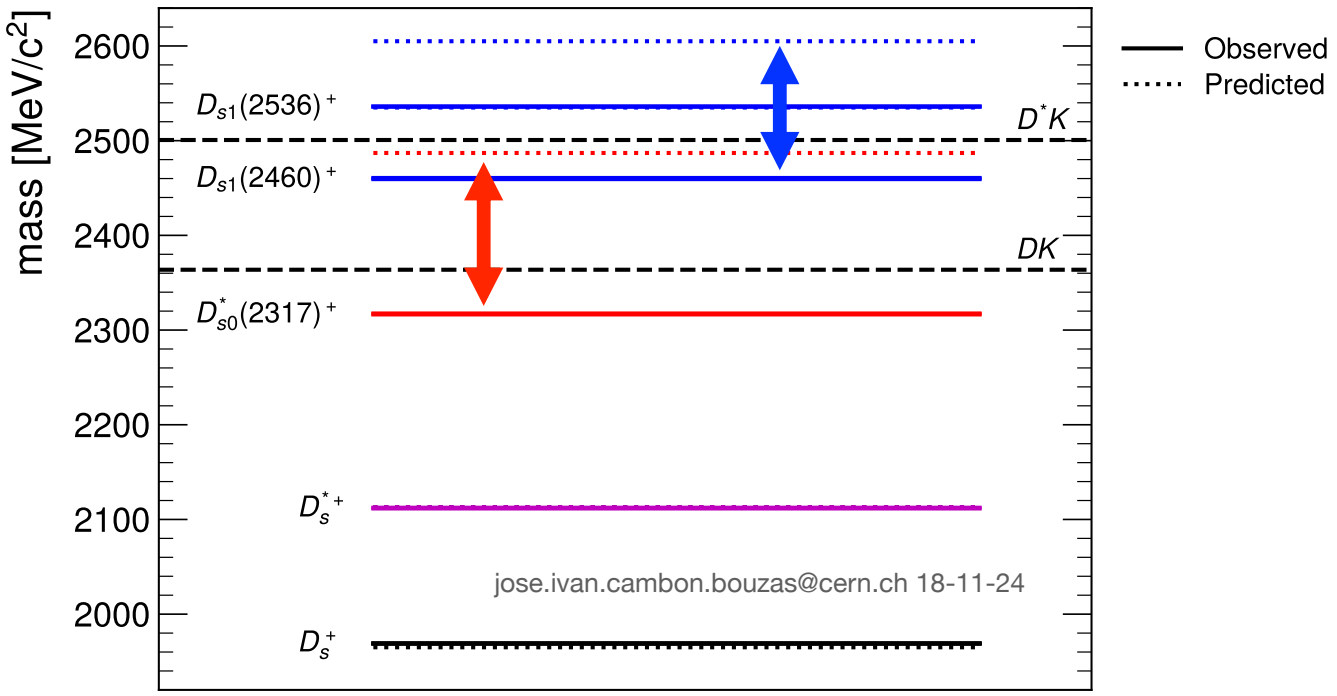
Smaller width than predicted

$$\Gamma(D_{s0}^*(2317)^+) < 3.8 \text{ MeV CL} = 95\%$$

$$\Gamma(D_{s1}(2460)^+) < 3.5 \text{ MeV CL} = 95\%$$

The properties of the first states of the $[c\bar{s}]$ spectrum

2. Their masses



Measured masses are incompatible with predictions for first $J^P = 0^+$ and $J^P = 1^+$ states

The Key

Masses below the DK and D^*K thresholds

$$Q(D^*_{s0}(2317)^+) = m(D^0K) - m(D^*_{s0}(2317)^+) \sim 41\ \mathrm{MeV/c^2}$$
$$Q(D_{s1}(2460)^+) = m(D^*K) - m(D_{s1}(2460)^+) \sim 45\ \mathrm{MeV/c^2}$$

Exotic candidates → **$[cu\bar{s}\bar{u}]$ tetraquarks or DK and D^*K molecules**

Analysis strategy

In few words, emulate the $\chi_{c1}(3872)$ analysis for the D_{sJ} states through radiative decays

Measurement: $\dfrac{\sigma_X \mathcal{B}(X \to abc)}{\sigma_Y \mathcal{B}(Y \to abc)} = \dfrac{N_X}{N_Y} \cdot \dfrac{\varepsilon_Y}{\varepsilon_X}$ **vs** $\mathrm{N}_{\mathrm{Tracks}}^{\mathrm{VELO}}$

For the $D_{s0}^{*}(2317)^{+}$ study: $X\colon D_{s0}^{*}(2317)^{+} \to D_s^{+}\pi^0$ $Y\colon D_s^{*+} \to D_s^{+}\pi^0$

For the $D_{s1}(2460)^{+}$ study: $X\colon D_{s1}(2460)^{+} \to D_s^{+}\gamma$ $Y\colon D_s^{*+} \to D_s^{+}\gamma$

Data Samples

Data: pp collisions at $\sqrt{s} = 13$ TeV collected in 2016, 2017 and 2018 with $\mathscr{L} \sim 5\ \mathrm{fb}^{-1}$

Simulation: Simulated samples with Pythia8 with LHCb tuning for each year and polarity for all radiative decays of D_s^{*+}, $D_{s0}^{*}(2317)^{+}$ and $D_{s1}(2460)^{+}$

$D_{s0}(2317)^+$ analysis: the $D_s^+\pi^0$ final state

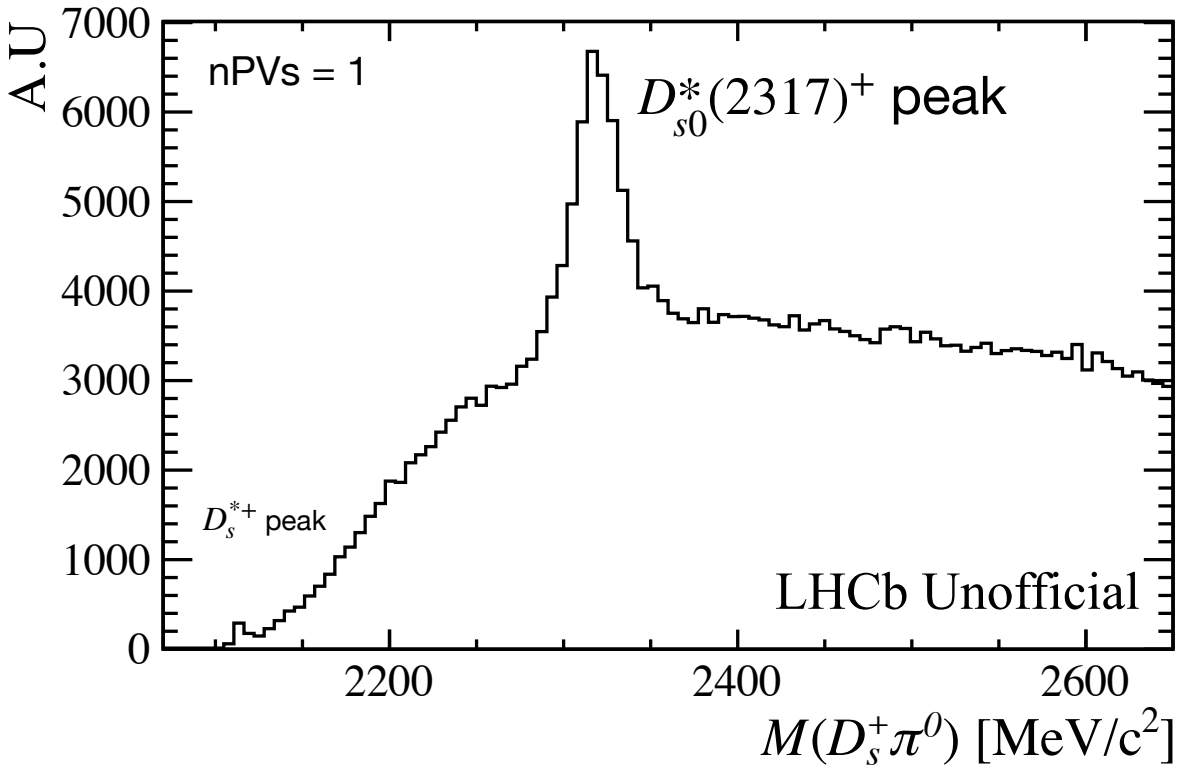
Historically, the $D_{s0}^*(2317)^+$ was studied the most

Contributions:

- $D_{s0}^*(2317)^+ \to D_s^+\pi^0$ signal
- $D_s^{*+} \to D_s^+\pi^0$ signal
- Combinatorial background

Mass constraints are applied in $M(D_s^+\pi^0)$ to improve the resolution

$p_T(\pi^0) > 1100$ MeV/c is applied for reducing background



$D_{s0}(2317)^+$ analysis: the $D_s^+\pi^0$ final state

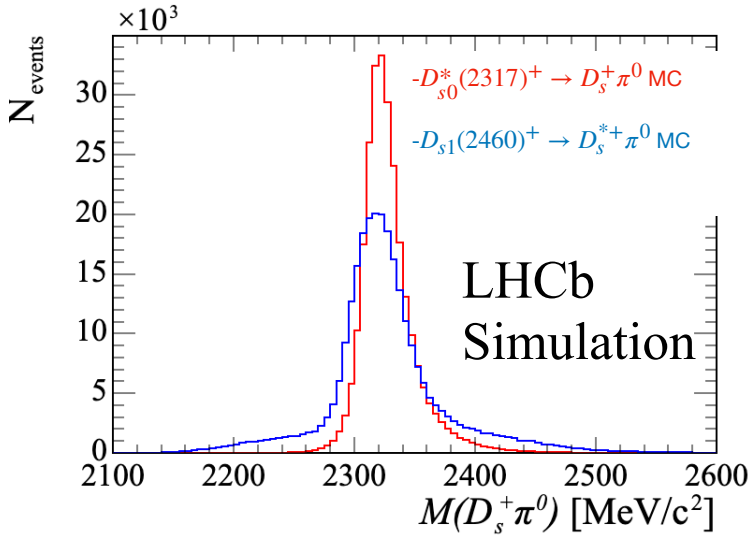
Historically, the $D_{s0}^*(2317)^+$ was studied the most

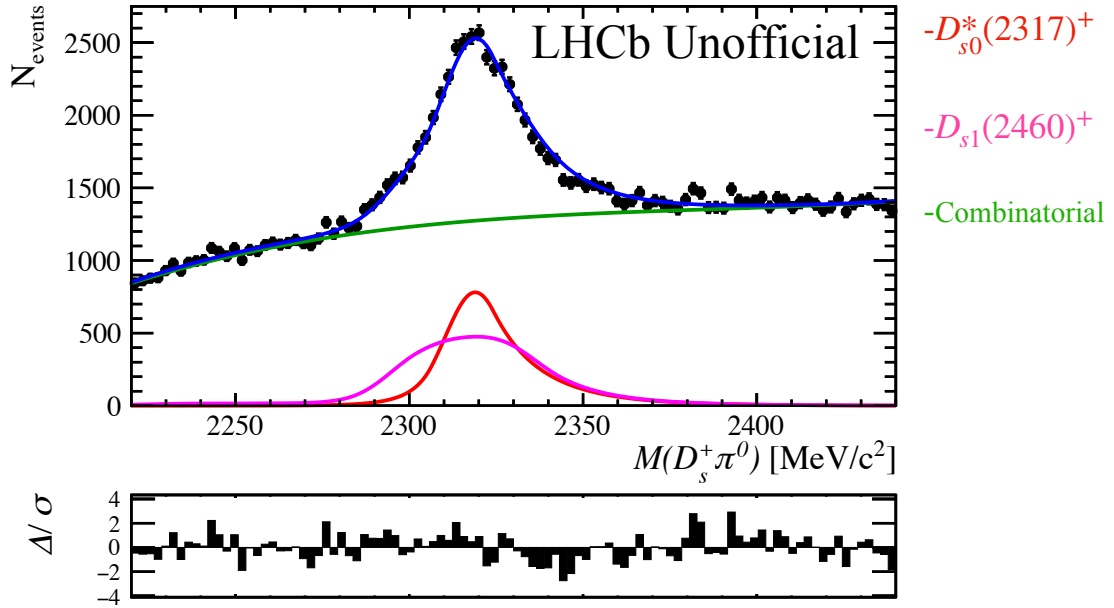
Contributions:

- $D_{s0}^*(2317)^+ \to D_s^+\pi^0$ signal
- $D_s^{*+} \to D_s^+\pi^0$ signal
- Combinatorial background
- $D_{s1}(2460)^+ \to D_s^{*+}\pi^0$ partially reconstructed background

Main challenge of the analysis!

- It peaks in the signal region
- Difficult to separate





$D_{s1}(2460)^+$ analysis: the $D_s^+\gamma$ final state

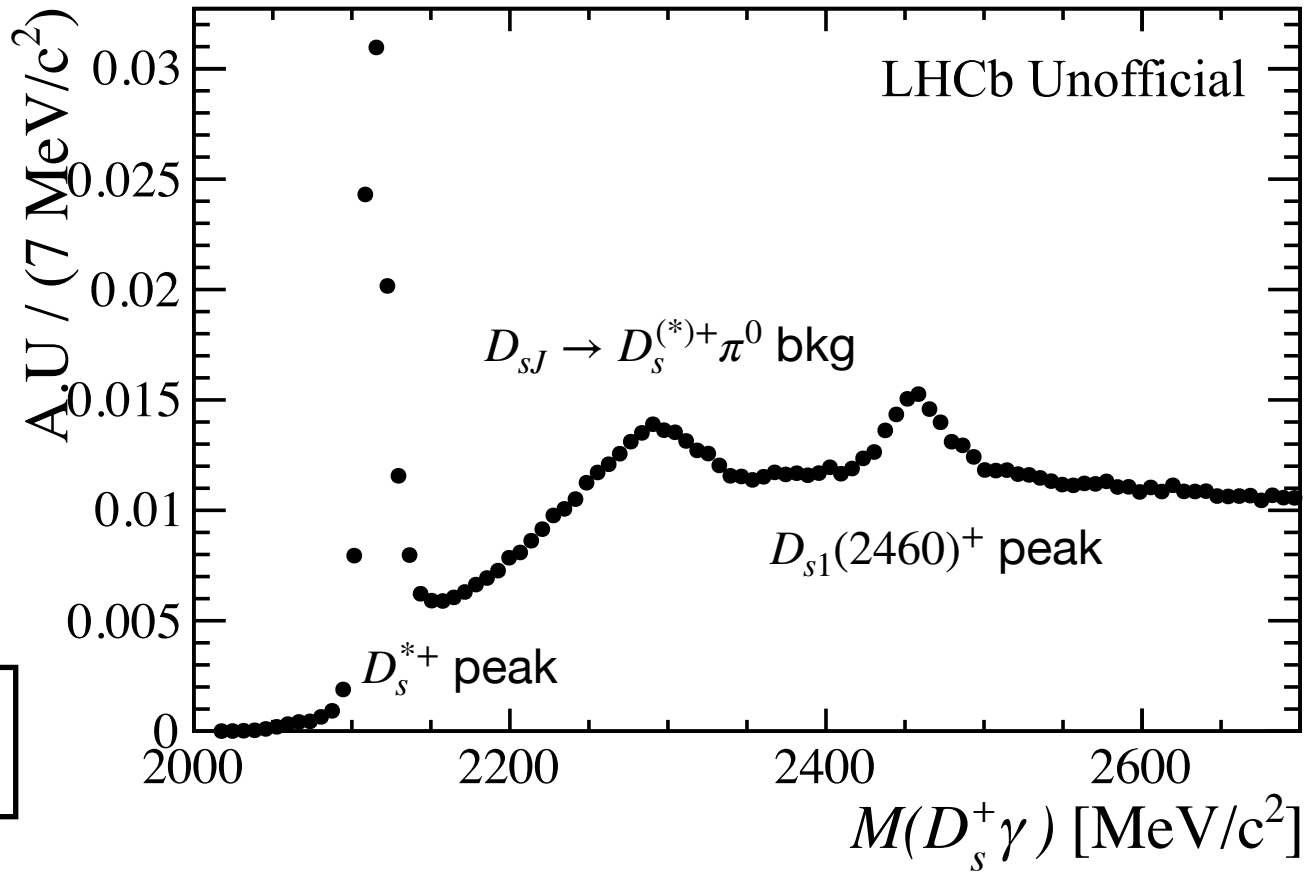
But, the $D_{s1}(2460)^+$ can be easier to analyse

Contributions:

- $D_{s1}(2460)^+ \to D_s^+\gamma$ signal
- $D_s^{*+} \to D_s^+\gamma$ signal
- Combinatorial background
- $D_{s0}^*(2317)^+ \to D_s^+\pi^0$ partially reconstructed background
- $D_{s1}(2460)^+ \to D_s^{*+}\pi^0$ partially reconstructed background

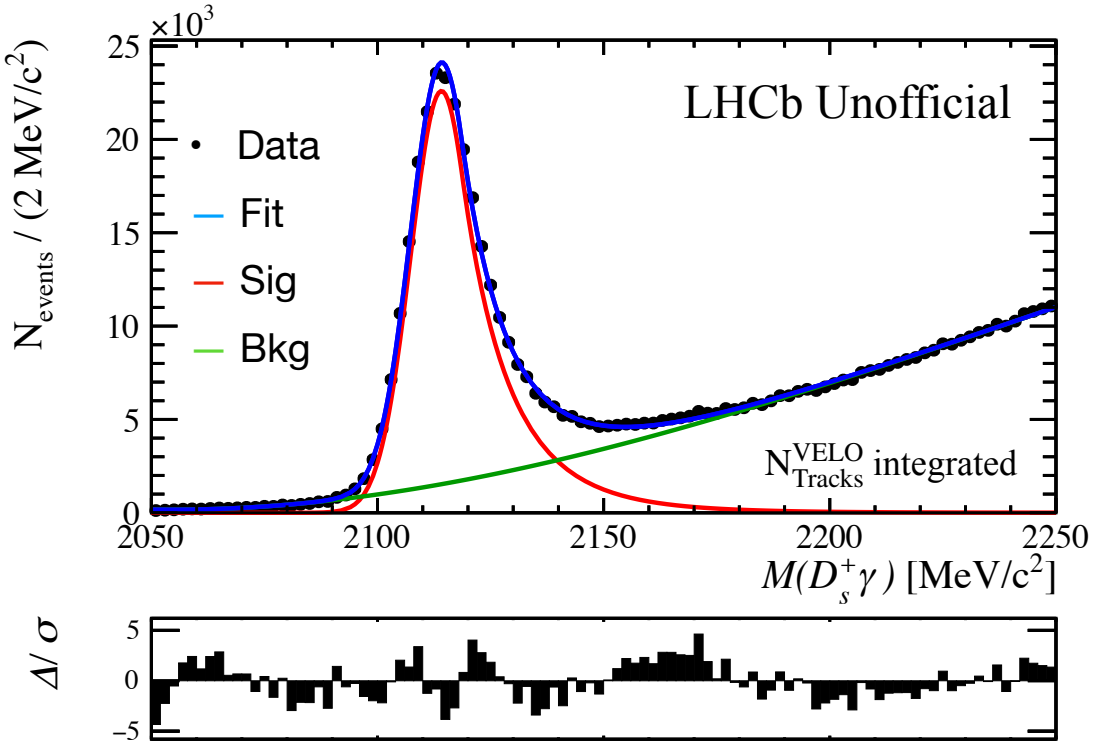
Mass constraints are applied in $M(D_s^+\gamma)$ to improve the resolution

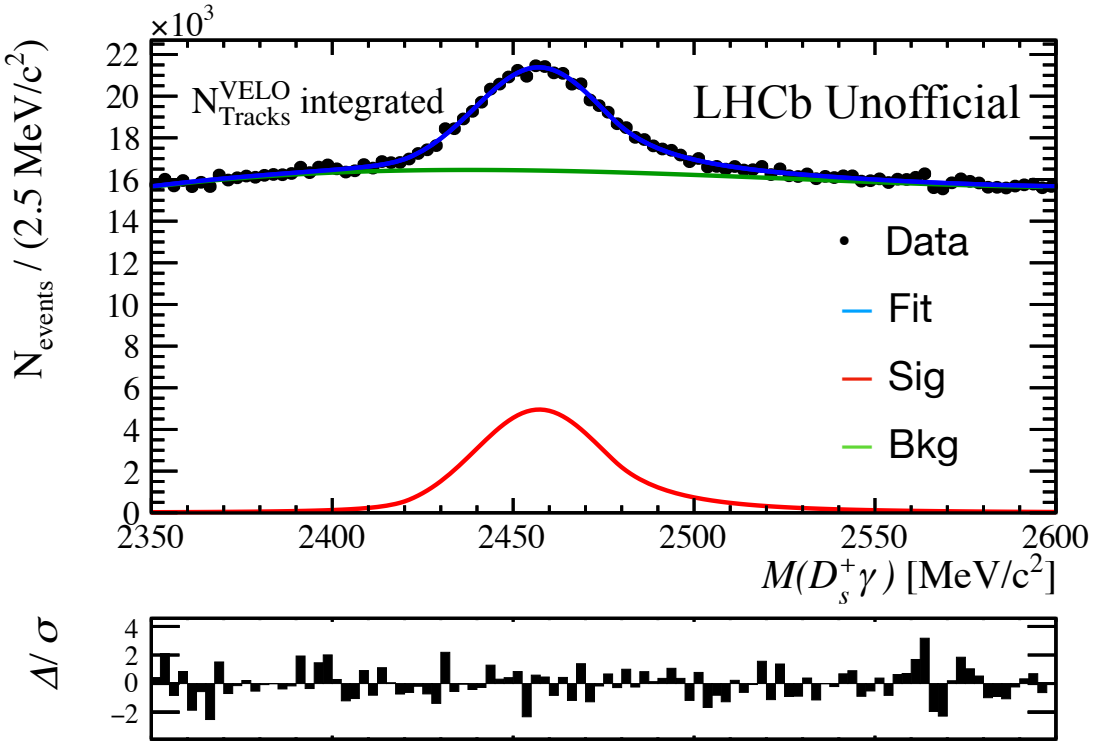
$p_T(\gamma) > 1250$ MeV/c is applied for reducing background



$D_{s1}(2460)^+$ analysis: the $D_s^+\gamma$ final state

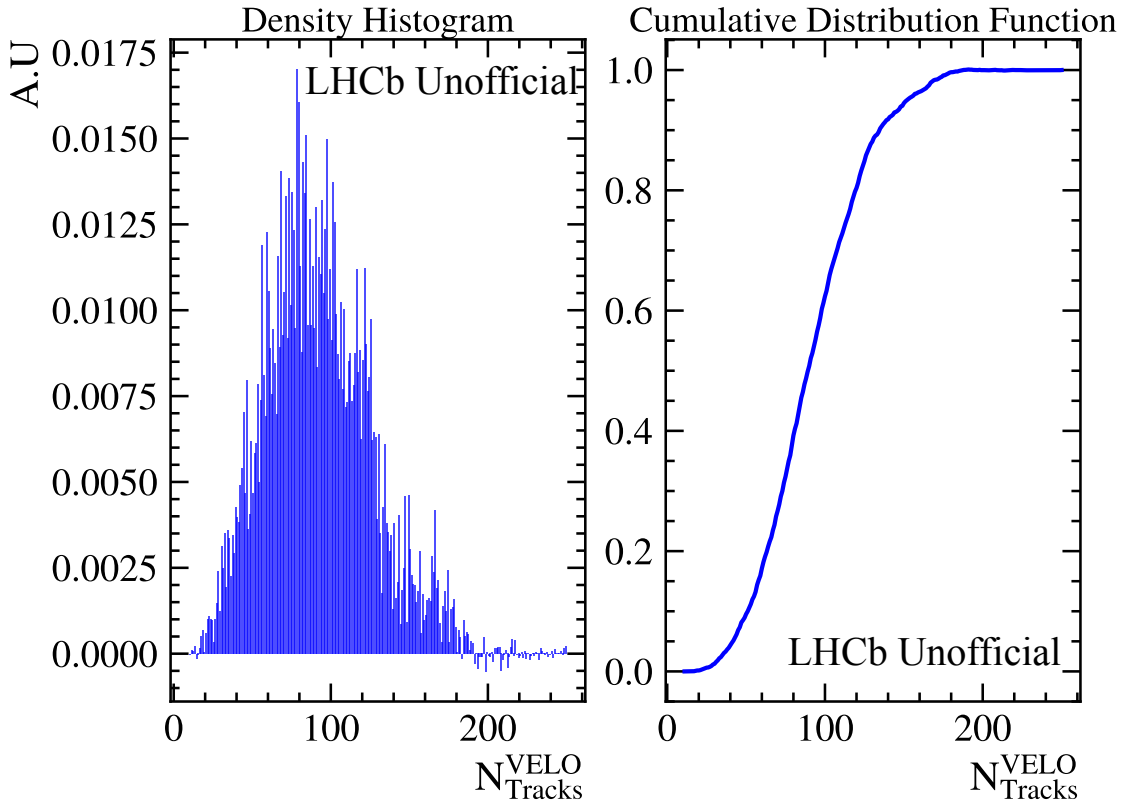
- Signal model: Double Crystal Ball. **For $D_{s1}(2460)^+$, tail parameters are fixed to MC**
- Background model: 3º order Chebyshev polynomial

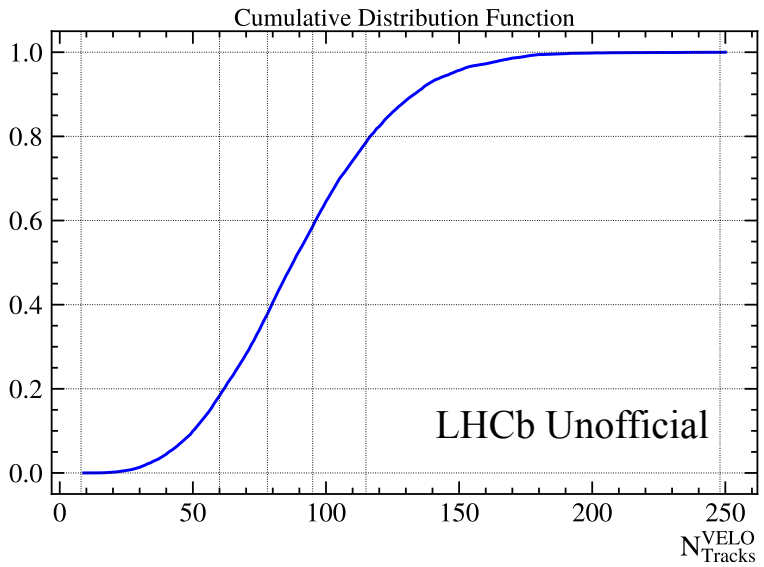




$D_{s1}(2460)^+$ analysis: the $D_s^+\gamma$ final state

The binning choice for the N_{Tracks}^{VELO} is made insuring the same amount of $D_{s1}(2460)^+$ signal for each bin





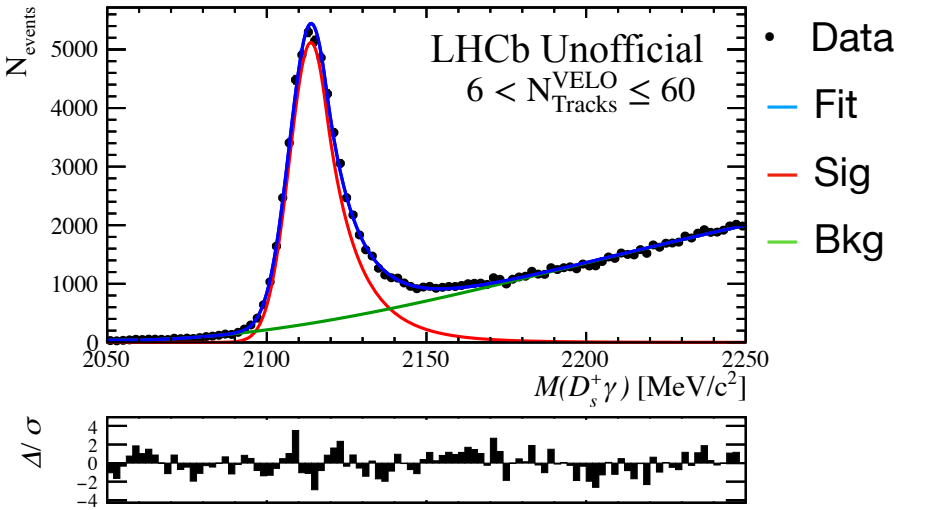
N_{Tracks}^{VELO} bins				
$[6, 60]$	$[60, 78]$	$[78, 95]$	$[95, 115]$	$[115, 250]$

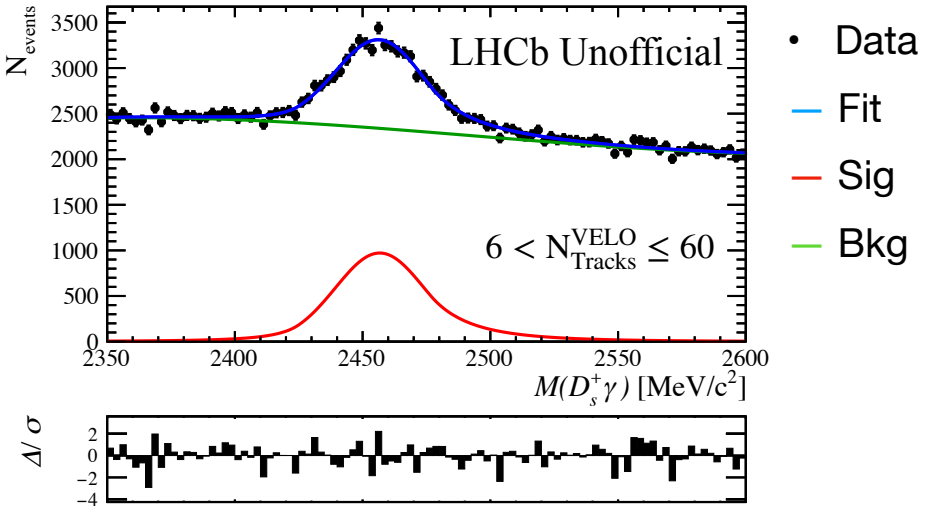
The sPlot technique is used to unfold the $D_{s1}(2460)^+$ signal distribution

$D_{s1}(2460)^+$ analysis: the $D_s^+\gamma$ final state

Next steps

- Performing the fits for both resonances on each N_{Tracks}^{VELO} intervals
- Computing the efficiency corrections using simulation. If needed, the simulation would be corrected using data-driven techniques
- Computing the systematic uncertainties
- Finally, getting the cross section ratio as function of N_{Tracks}^{VELO}





Conclusions

- Exotic spectroscopy is one of the hot topic programs at LHCb
- The study of exotic candidate production as function of multiplicity has been established as a complementary observable for nature testing, specially for the $\chi_{c1}(3872)$
- This new technique is well suited for the study of the D_{sJ} studies, specially for the $D_{s1}(2460)^+$ hadron through radiative decays, whose result is expected to be ready in the mid term

Prospects for the D_{sJ} studies

- The study of the D_{sJ} states can be highly benefited from the new LHCb Run3 data
- Due to the new trigger system, the fully hadronic $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ and $D_{s1}(2536)^+ \to D_s^+\pi^+\pi^-$ decays can be considered for doing the study at pp collisions
- The production vs multiplicity analysis over D_{sJ} can be extended to Run3 PbPb data (and possible pPb) as well as to pA or PbA in **fixed target configuration** thanks to the **SMOG2 system**

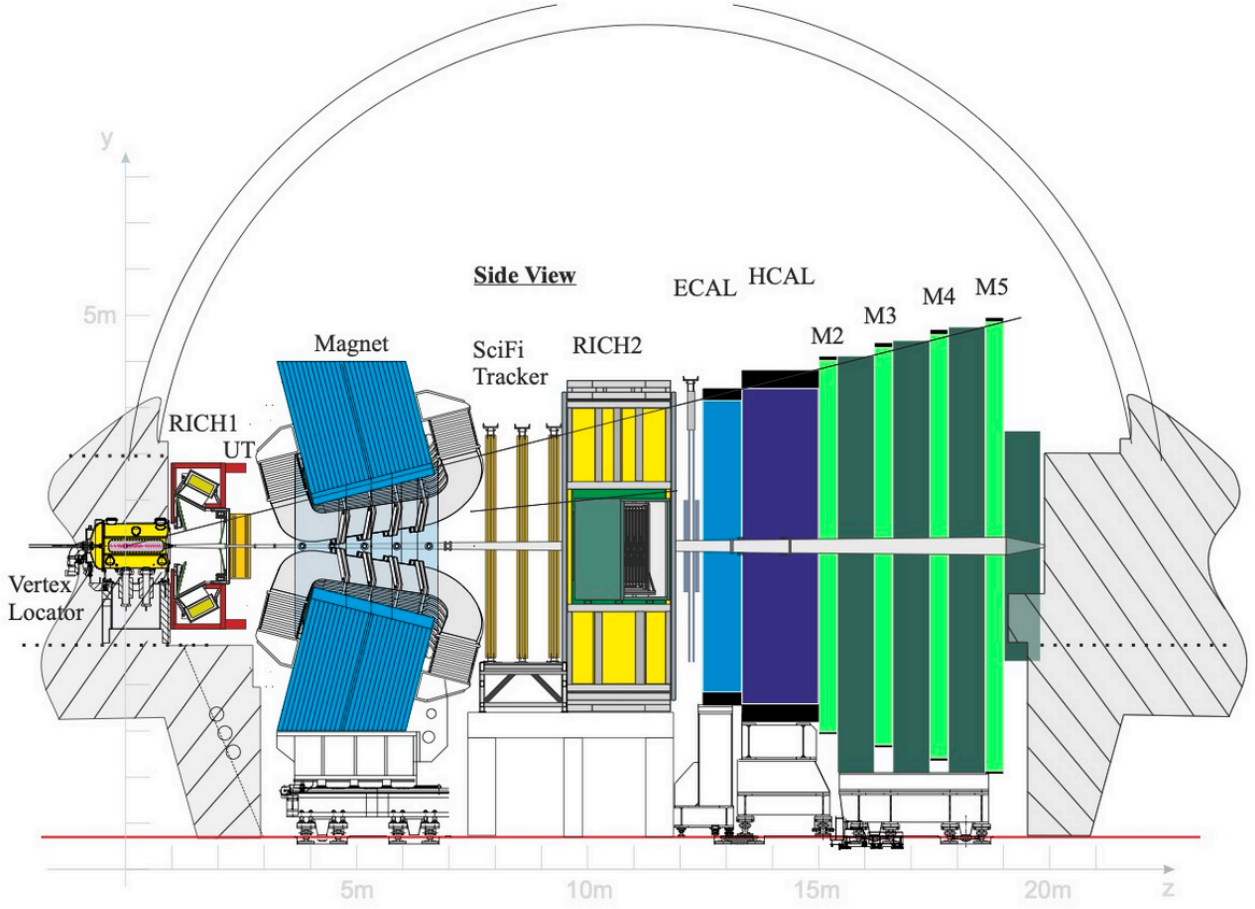
Thank you all for you attention

Backup

LHCb detector

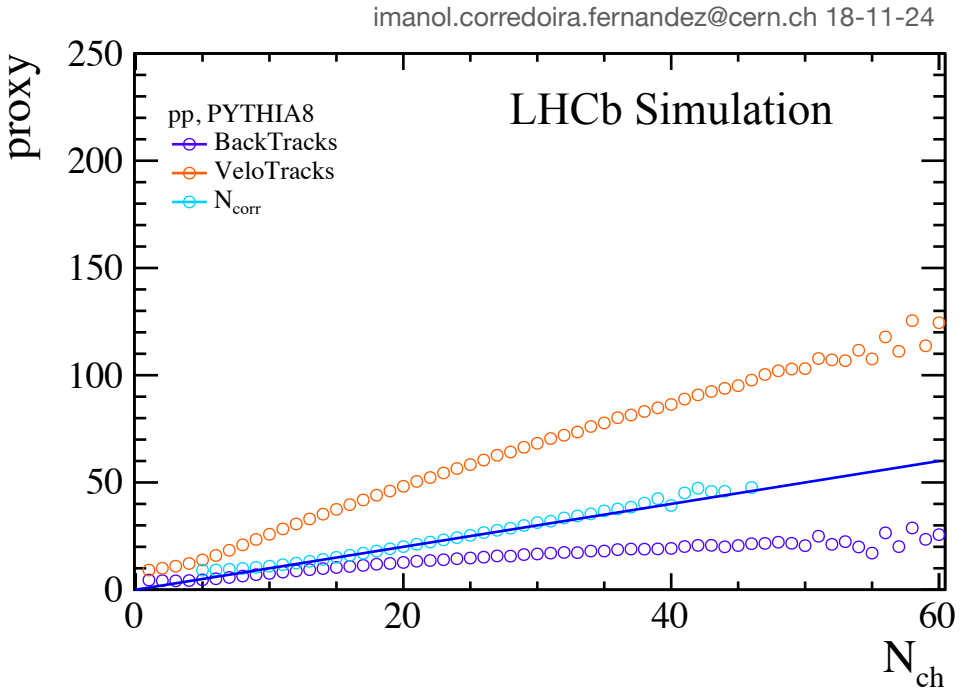
- General-purpose single-arm forward spectrometer
- Pseudorapidity coverage $2 < \eta < 5$
- Optimised for b and c physics. Now it is a general purpose detector
- Three tracking subdetectors:
  - VErtex LOcator (VELO) located around the beamspot
  - Upstream Tracker (UT) located before the magnet
  - 3 Scintillating Fibre tracking stations (SciFi) located after the magnet
- Also includes RICH, ECAL, HCAL and muon stations for PID
- New fully software based trigger
- New SMOG2 system for fixed target configuration

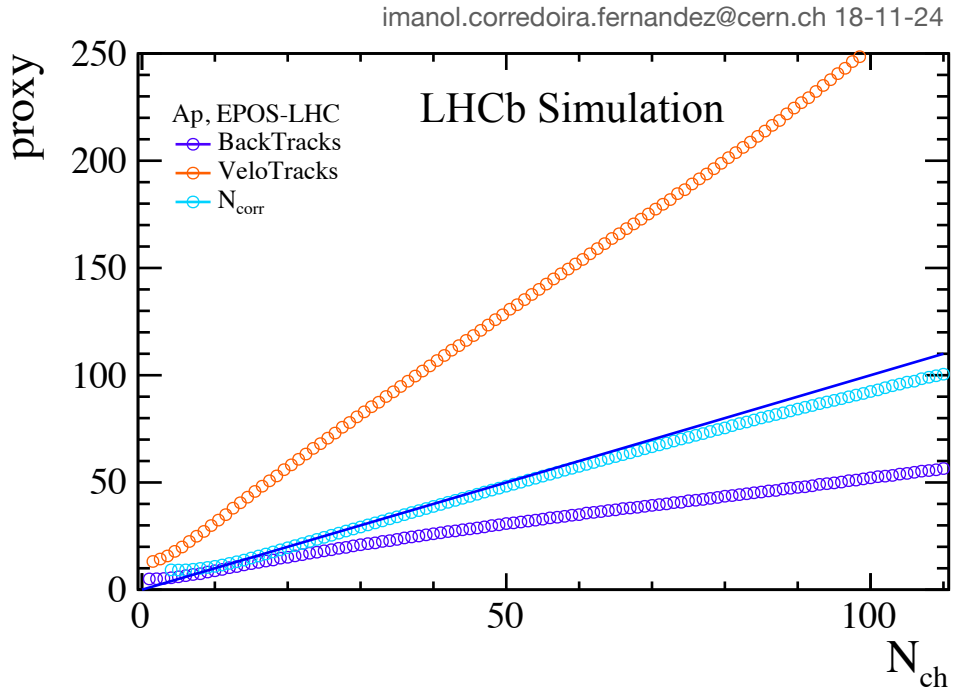
LHCB-TDR-15



Multiplicity proxies at LHCb

- It is a big challenge for the LHC experiments to measure properly the number of charged particles N_{ch} generated in a pp or AA collision
- At LHCb, the most common proxies used are event variables regarding the tracking systems, such as the number of tracks at VELO detector N_{Tracks}^{VELO}, N_{Tracks}^{Back} or the total number of tracks N_{Tracks}
- Those are chosen because are linearly proportional to N_{ch}, but non-linearities appear at low and high multiplicity events



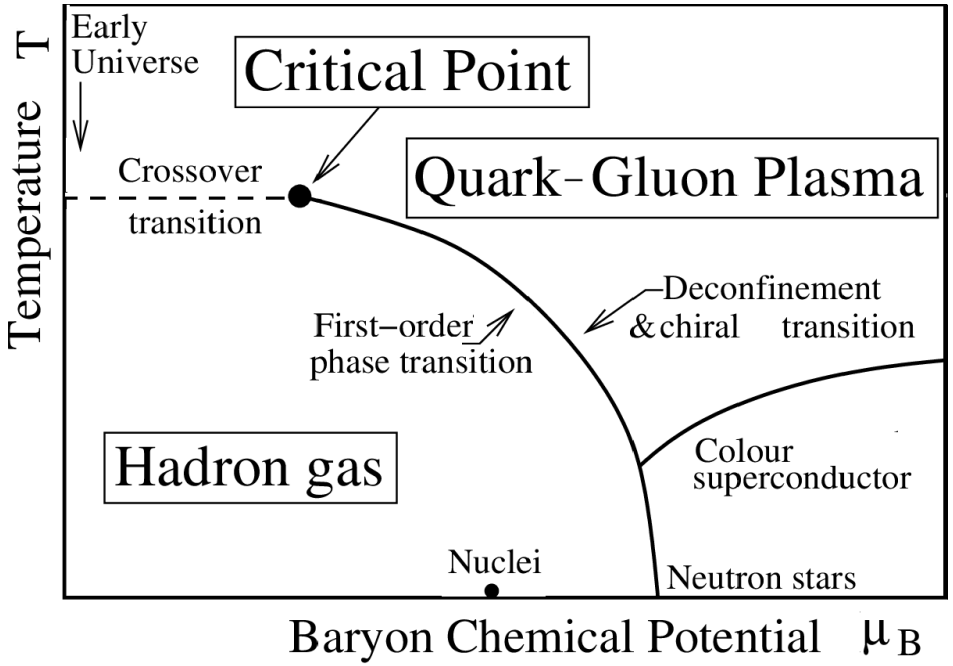


The Quark-Gluon Plasma (QGP)

- The quark-gluon plasma (QGP) is a state where the quark and gluons are decapled and the quarks are de-confined

- According with the QCD phase diagram, it is produced at high temperatures and high densities. Experimentally is produced at heavy ion collisions

AEPSHEP 2012



- The QGP signatures are:

  ✓ Quarkonia production suppression

  ✓ Strangness enhancement

  ✓ Jet quenching

  ✓ Modification of the production of exotics?

The Comover Interaction Model (CIM)

- The Comover Interaction Model is a phenomenological QCD model which simulates how the quarkonia states are produce in a colliding media. The evolution of the production of the states is made through a transport equation

$$\tau \frac{\mathrm{d}\rho_{\mathcal{Q}}}{\mathrm{d}\tau}(\boldsymbol{b}, \boldsymbol{s}, y) = -\langle v\sigma \rangle_{\mathcal{Q}} \rho_c(\boldsymbol{b}, s, y) \rho_{\mathcal{Q}}(\boldsymbol{b}, s, y)$$

- The interaction with the media is condensed in the cross section term $< v\sigma >$

$$\langle v\sigma \rangle_{\mathcal{Q}} = \sigma_{\mathcal{Q}}^{\mathrm{geo}} \int_{E_{\mathcal{Q}}^{\mathrm{thr}}}^{\infty} dp_c p_c^2 \left(1 - \frac{E_{\mathcal{Q}}^{\mathrm{thr}}}{E_c}\right)^n \mathcal{P}\left(E_c\right)$$

- Where E_Q^{th} is proportional to the binding energy, where the possible tetraquark models can be added

The molecular description for $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ states

- Both hadron masses lie below the DK and D^*K thresholds. The difference can correspond to a binding energy of

$$Q(D_{s0}^*(2317)^+) = m(D^0K) - m(D_{s0}^*(2317)^+) \sim 41\ \mathrm{MeV/c^2}$$
$$Q(D_{s1}(2460)^+) = m(D^*K) - m(D_{s1}(2460)^+) \sim 45\ \mathrm{MeV/c^2}$$

- In molecular description, $\Gamma(D_{sJ}) \sim 100\,\mathrm{keV}$, compatible with the measured width bounds

- The following property is fulfilled:

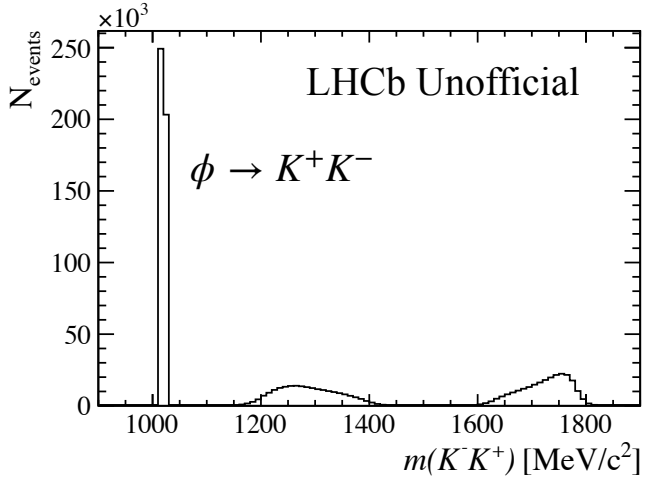
$$M_{D_{s1}(2460)} - M_{D_{s0}^*(2317)} \simeq M_{D^*} - M_D$$

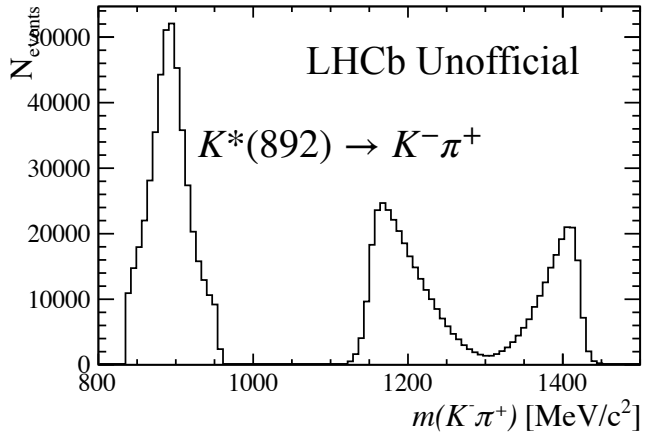
- Which can be understood in several molecular models using the pseudo-Goldstone boson properties of the kaons

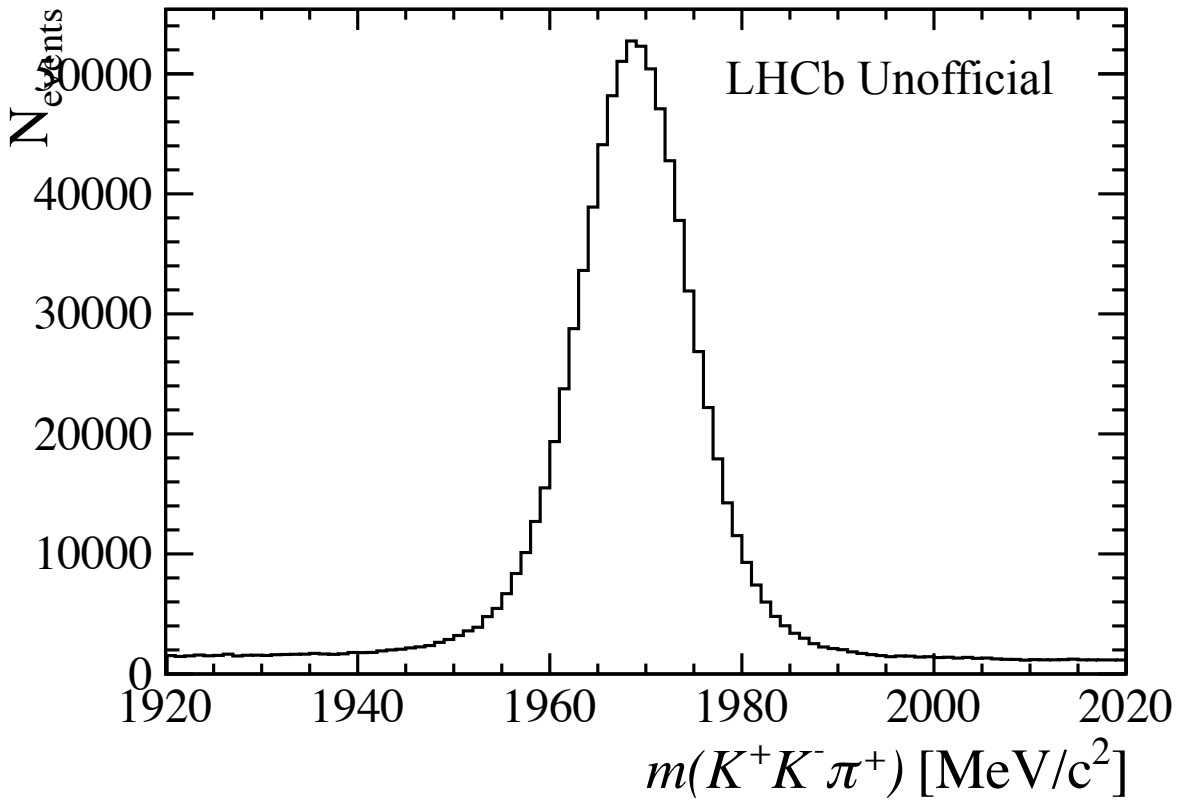
- In fact, B_{s0}^* and B_{s1} molecular partners are expected in this scenarios

The reconstruction of the $D_s^+ \to K^+K^-\pi^+$ decay

- The D_s^+ meson is reconstructed through the well study $D_s^+ \to K^+K^-\pi^+$ electroweak 3-body decay
- Dalitz plot cuts are used to select both $D_s^+ \to \phi(\to K^+K^-)\pi^-$ and $D_s^+ \to K^+K^*(892)(\to K^-\pi^+)$ subdecays







$D_{s1}(2460)^+ \to D_s^{*+}\pi^0$ background in the $D_s^+\pi^0$ final state (in detail)

- 1 of the 3 photons is missed
- Two components:
  - Missing one π^0 photon
  - Missing the D_s^{*+} photon → The most relevant

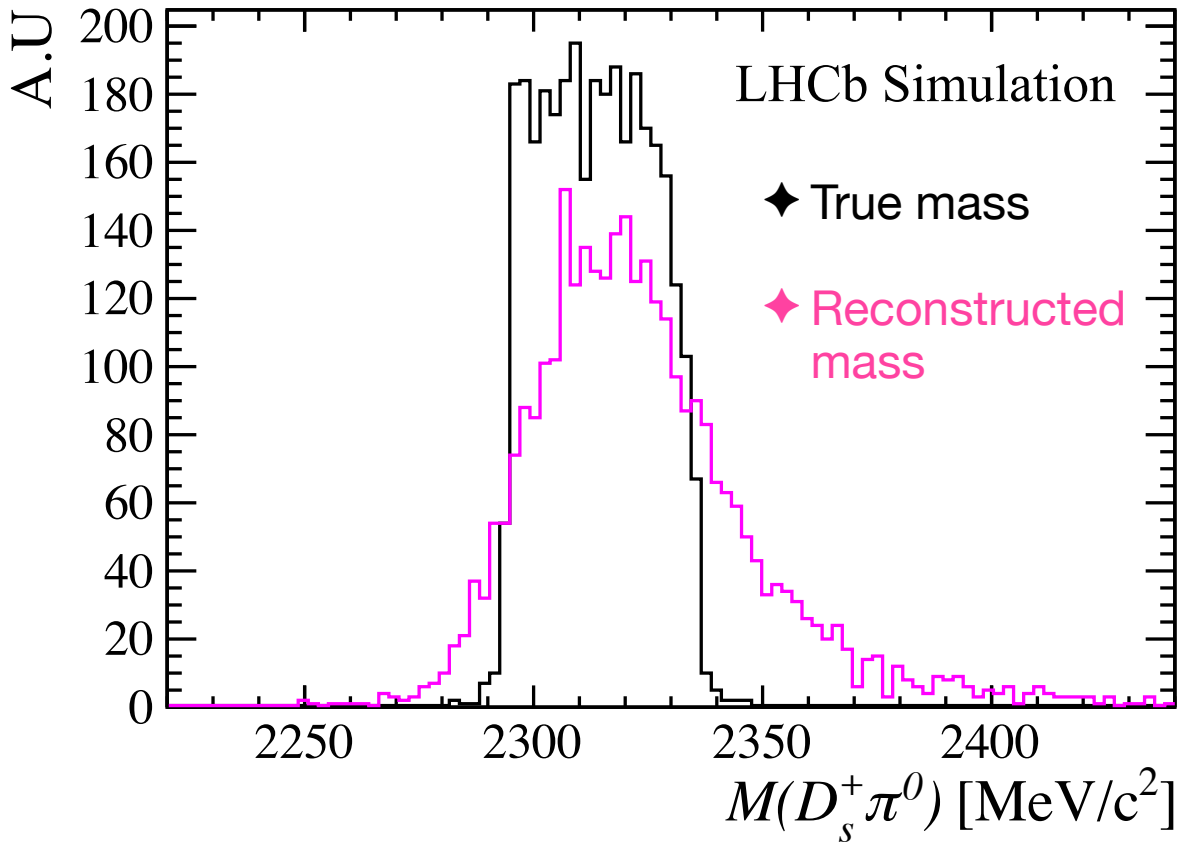
Kinematical property

$$m(D_{s1}(2460)^+) - m(D_{s0}^*(2317)^+) \simeq m(D_s^{*+}) - m(D_s^+)$$

- Consequence ⟶ It peaks in the same region as $D_{s0}^*(2317)^+ \to D_s^+\pi^0$ signal
- Main Difference → True mass distribution

Square distribution → **wider than $D_{s0}^*(2317)^+$ signal**

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



Background studies for the $D_s^+\gamma$ final state (in detail)

Combinatorial background

- Really clean $D_s^+ \to K^+K^-\pi^+$ reconstruction → combinatorial background due to photons
- Difficult to model due to the photon phase space distribution
- Event mixing technique was considered for subtraction

Partially reconstructed backgrounds

- Backgrounds from $D_{sJ} \to D_s^{+(*)}\pi^0$ decays where one photon is missing
- "Shark fin" shape due to the missing momentum of one photon from $\pi^0 \to \gamma\gamma$
- Little feed-up contribution for D_s^{*+} coming from $D_{s1}(2460)^+ \to D_s^{*+}\pi^0$ decay