# Studies of excited charm and beauty mesons at LHCb

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On behalf of the LHCb collaboration

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# Overview

**Today I will discuss two topics**

1) **Studies of excited charm mesons, specifically $D_{sJ}$ decays to $D^0K^+$ and $D^+K_S$ final states**

2) **Studies of excited beauty mesons, specifically the properties of orbitally excited $B_S$ mesons**

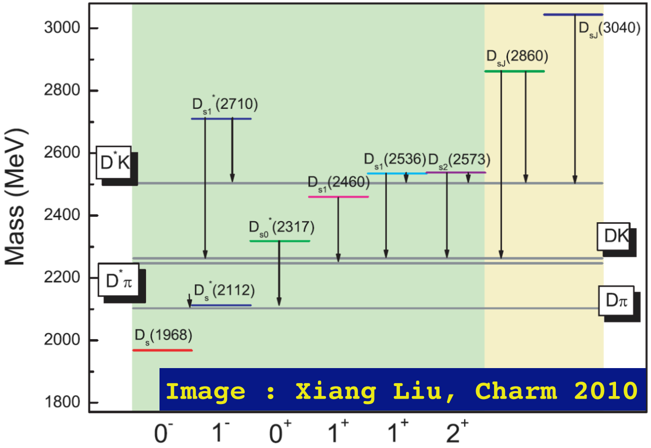
**As we are late in the day, I won't be reviewing the LHCb detector but all the information is in the backup slides so please ask if you have questions on this!**

# Studies of excited charm mesons

# Motivation for studies

System of the heavy and the light quarks: $Q\bar{q}$. $\vec{S} = \vec{s}_Q + \vec{s}_{\bar{q}}$, $\vec{J} = \vec{L} + \vec{S}$.

- $L = 0$. Doublet with $J^P = (0^-, 1^-)$: **($D_s$, $D^*_s$)**
- Orbital excitations with $L = 1$. Two doublets:
  - $\vec{j}_q = \vec{L} + \vec{s}_{\bar{q}} = 1/2$. $J^P = (0^+, 1^+)$: **($D^*_{s0}$, $D'_{s1}$)**
  - $\vec{j}_q = \vec{L} + \vec{s}_{\bar{q}} = 3/2$. $J^P = (1^+, 2^+)$: **($D_{s1}$ , $D^*_{s2}$)**



# Analysis strategy

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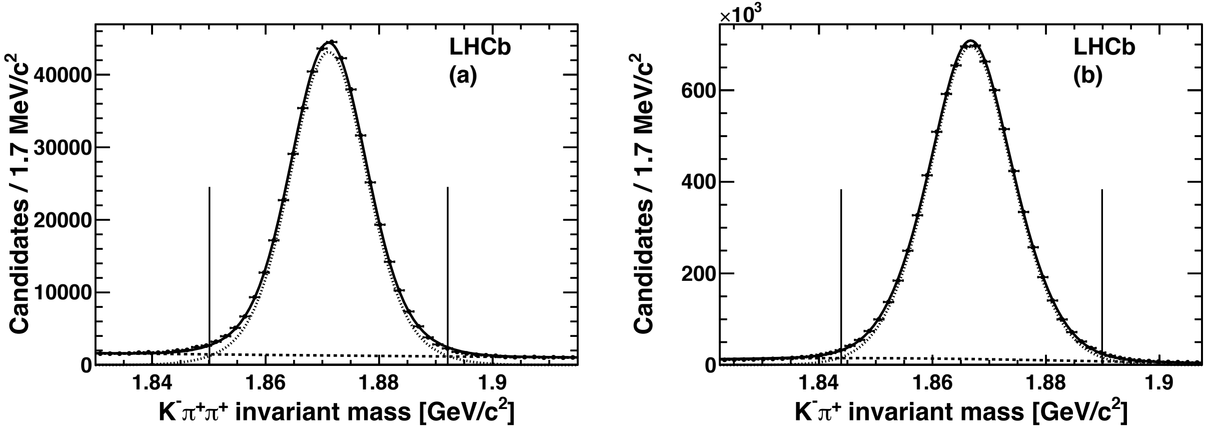
Study $D_{sJ}$ mesons produced directly in the pp interaction at the LHC

=> Takes advantage of the LHC's huge prompt charm production cross-section (see talk by Alex Kozlinskiy earlier today)

Use both $D^0K^+$ and $D^+K_S$ final states to maximize signal yields and reduce the possibility of fake peaks due to background, cross-feed, etc.

$D^{0,+}$ mesons selected cleanly using their transverse momentum and displacement from the primary interaction : most background is from fake DK combinations.

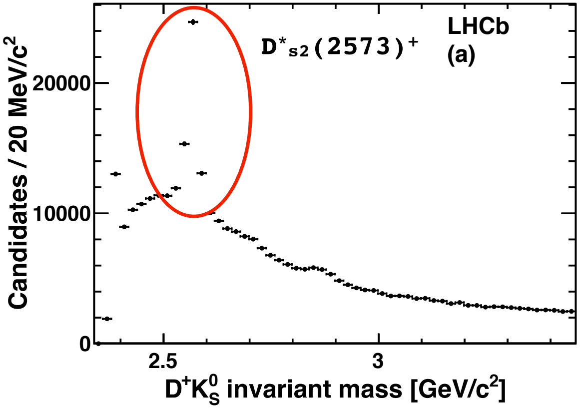


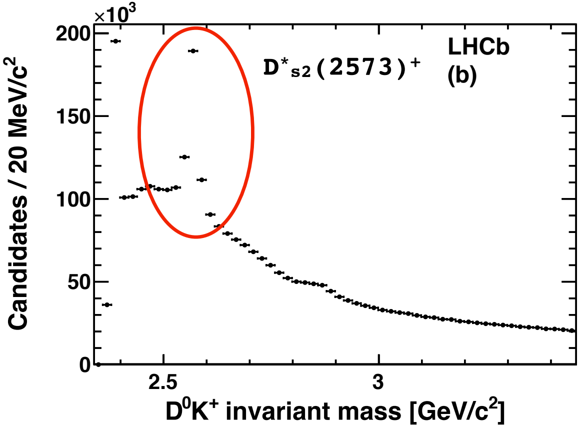
# Event selection



**Remove a lot of combinatorial background by cutting on cosθ > 0, the angle between the kaon momentum (in the $D_{sJ}$ rest frame) and the $D_{sJ}$ momentum in the lab frame**

**Then optimize further for the significance of the $D^*_{s2}(2573)^+$**



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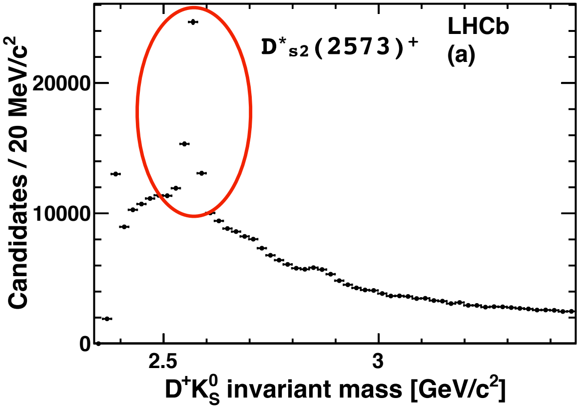
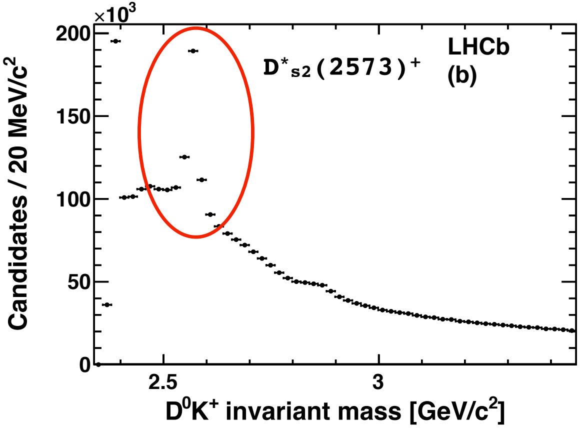
=> Add cuts on the DK $P_T$ and $K^+$ particle identification cuts



# The mass spectrum

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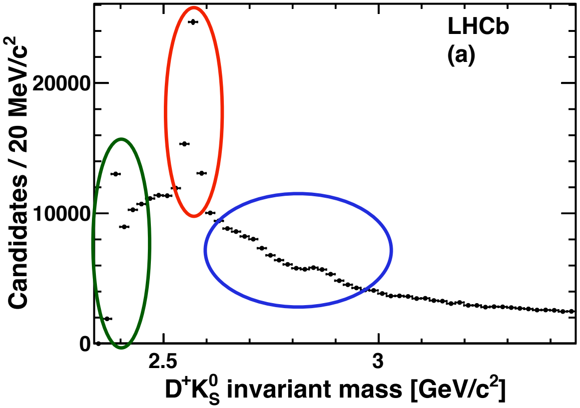
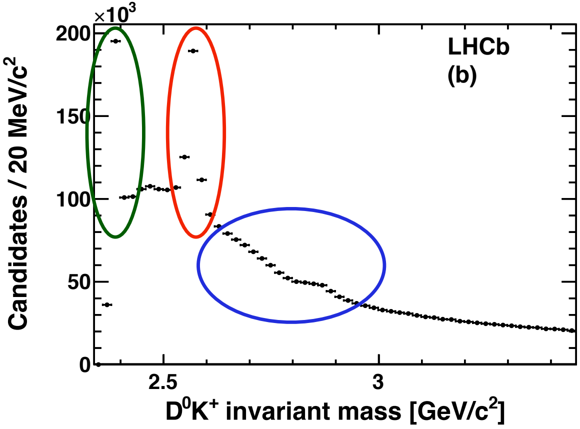
**Similar features in both spectra :**

- $D^*_{s2}(2573)^+$
- $D_{s1}(2536)^+$ feed down via $D^*K$ decays
- $D^*_{s1}(2700)^+$ and $D^*_{sJ}(2860)^+$ states (will be clearer in a slide or two)



# Fit model

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=> Exclude the $D_{s1}(2536)^+$ feed down to avoid modelling the turn-on;

=> Relativistic Breit-Wigners with Blatt-Weisskopf form factors for the signal states (resolution neglected as these are so broad);

=> Chebyshev polynomials for the combinatorial background;

=> Signal parameters shared between the two modes.

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# Fit results

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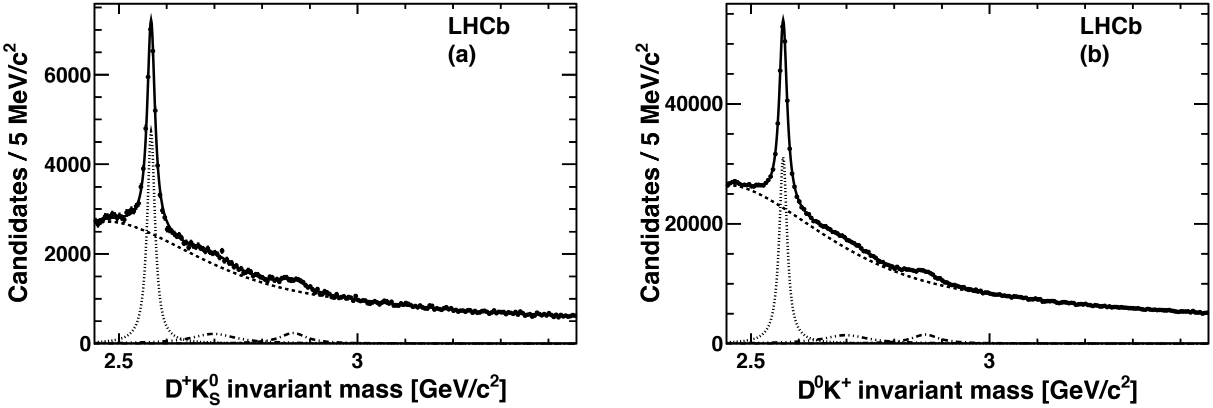

# Fit results, background subtracted

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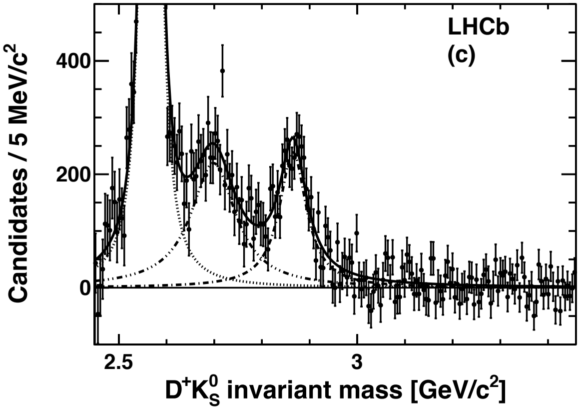
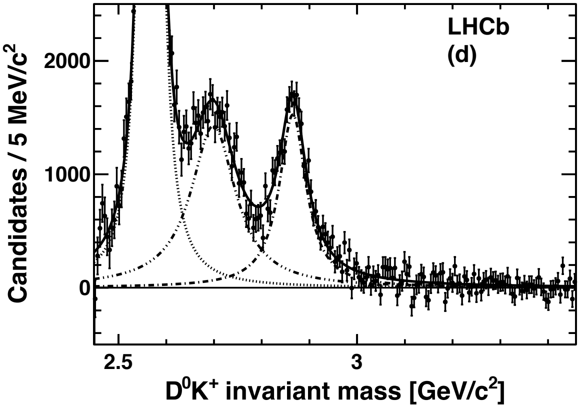
We clearly observe the $D^*_{s1}(2700)^+$ and $D^*_{sJ}(2860)^+$ states

We do not see any significant excess of events above 3 GeV



# Fit results, systematics

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**The systematic uncertainties are dominated by the background and signal models**

**In particular, the background model has to describe not only the combinatorial background from unrelated DK pairs, but also from DK pairs produced in a correlated way in the fragmentation (but not coming from a resonant state)**

**At present all measurements are therefore systematics limited**

| | $D_{s1}^*(2700)^+$ | | $D_{sJ}^*(2860)^+$ | |
|---|---|---|---|---|
| Source | $\delta m$ | $\delta\Gamma$ | $\delta m$ | $\delta\Gamma$ |
| Signal model | 2.2 | 3.0 | 5.5 | 3.4 |
| Background model | 2.1 | 10.2 | 3.8 | 4.2 |
| High mass state | 0.0 | 0.3 | 0.0 | 0.2 |
| Selection criteria | 2.1 | 3.5 | 1.0 | 2.7 |
| Mass resolution | 2.1 | 3.6 | 2.8 | 2.4 |
| Feed-down reflections | 1.2 | 2.9 | 0.1 | 1.4 |
| Bin size | 0.2 | 0.9 | 0.0 | 0.2 |
| Total | 4.5 | 12.1 | 6.3 | 6.6 |

# Mini conclusion

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We clearly observe the $D^{*}_{s1}(2700)^{+}$ and $D^{*}_{sJ}(2860)^{+}$ states

We do not see any significant excess of events above 3 GeV

We have made mass and width measurements which are competitive with the B-factory precisions

Need studies of the $D^{*}K$ spectra in order to shed any further light on the spin-parity assignments of these modes

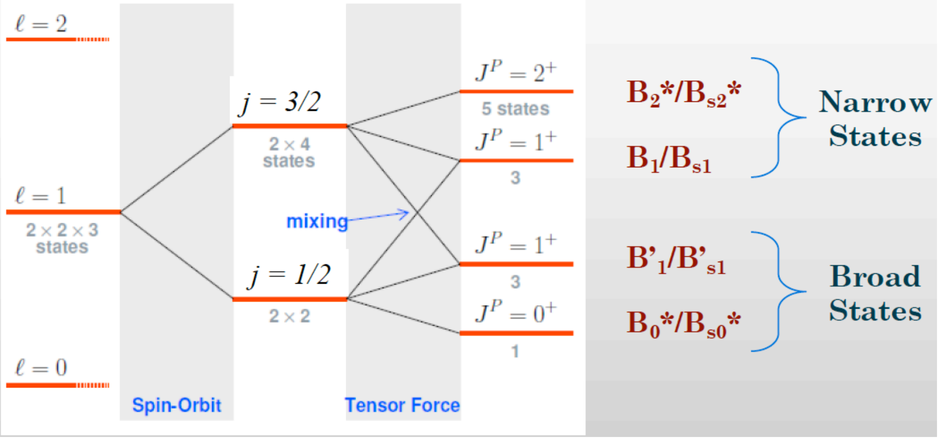
$$\begin{aligned}
m(D^{*}_{s1}(2700)^{+}) &= 2709.2 \pm 1.9(\mathrm{stat}) \pm 4.5(\mathrm{syst})\ \mathrm{MeV}/c^2, \\
\Gamma(D^{*}_{s1}(2700)^{+}) &= 115.8 \pm 7.3(\mathrm{stat}) \pm 12.1(\mathrm{syst})\ \mathrm{MeV}/c^2, \\
m(D^{*}_{sJ}(2860)^{+}) &= 2866.1 \pm 1.0(\mathrm{stat}) \pm 6.3(\mathrm{syst})\ \mathrm{MeV}/c^2, \\
\Gamma(D^{*}_{sJ}(2860)^{+}) &= 69.9 \pm 3.2(\mathrm{stat}) \pm 6.6(\mathrm{syst})\ \mathrm{MeV}/c^2.
\end{aligned}$$

# Studies of excited beauty mesons

# Motivation for studies

**Precise measurements of excited B meson properties are an important test of Heavy Quark Effective Theory (HQET)**

**HQET is a crucial tool in predicting Standard Model values for CP violation, lifetimes, mixing... and hence setting a benchmark for measurements sensitive to physics beyond the Standard Model**



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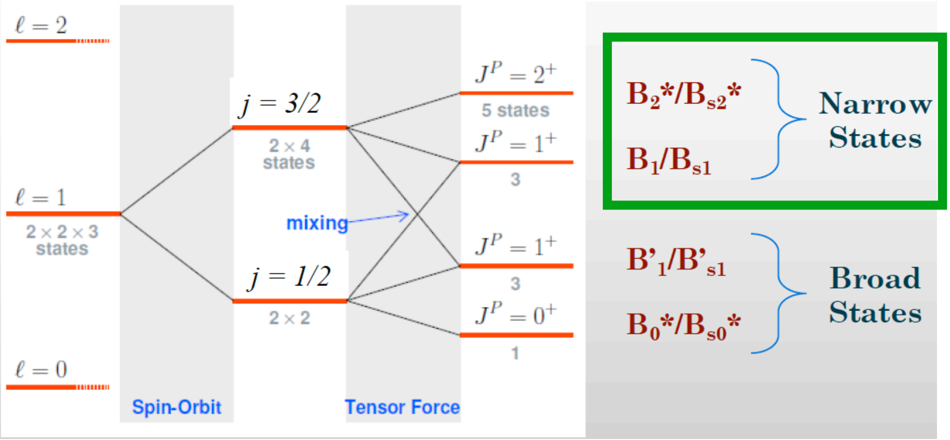
Here we will focus on measurements of the narrow $B^*_s$ states



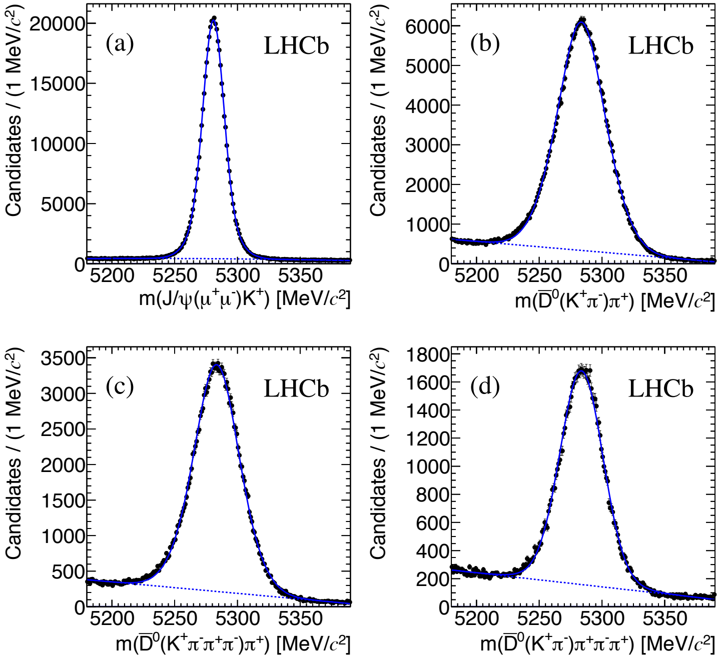
# Analysis strategy and event selection

**Use several B meson final states to maximize signal yields and reduce the possibility of fake peaks due to background, cross-feed, etc.**

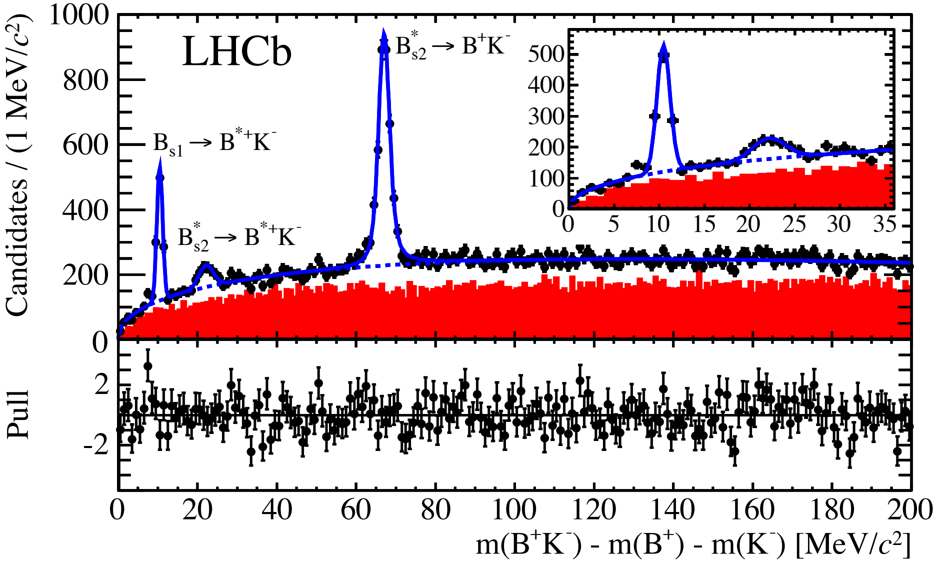
**Almost all background is due to fake BK combinations.**

**We reduce remaining backgrounds with a multivariate selection using the following variables**

**=> B and K transverse momenta**
**=> Kaon particle identification**
**=> BK vertex fit**
**=> Distance of closest approach of the BK system to the primary interaction**



# Mass spectrum and fit model



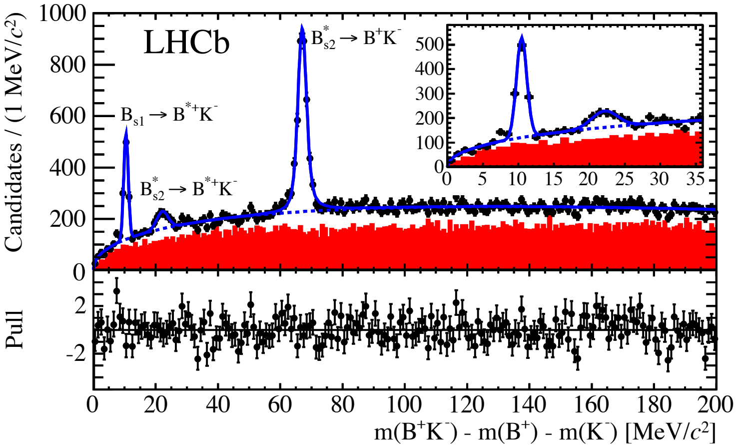
# Mass spectrum and fit model

=> Relativistic Breit-Wigner convolved with simulated Gaussian resolution for the BK signal

=> Gaussians as "effective parametrizations" for the B*K feed-down signals, since these are affected by the missing photon and cannot be fully simulated due to a lack of knowledge of the $B^*_s$ properties.

=> A threshold function for the combinatorial background validated on the wrong-sign sample

$$f(Q) = Q^{\alpha} e^{\beta Q + \delta}$$



# What do we actually measure?

**We fit for**

**=> The yields of all three peaks**

**=> The means of the $B_{s1}$ and $B^*_{s2}$ peaks, and the width of the $B^*_{s2} \to BK$ peak**

**=> The difference in the means of the $B^*_{s2} \to BK$ and $B^*_{s2} \to B^*K$ peaks**

**The branching fraction measurements are corrected for reconstruction efficiencies measured offline**

| Parameter | Fit result |
|---|---|
| $m(B_{s1}) - m(B^+) - m(K^-)$ | $10.46 \pm 0.04 \pm 0.04\,\mathrm{MeV}/c^2$ |
| $m(B^*_{s2}) - m(B^+) - m(K^-)$ | $67.06 \pm 0.05 \pm 0.11\,\mathrm{MeV}/c^2$ |
| $m(B^{*+}) - m(B^+)$ | $45.01 \pm 0.30 \pm 0.23\,\mathrm{MeV}/c^2$ |
| $\Gamma(B^*_{s2})$ | $1.56 \pm 0.13 \pm 0.47\,\mathrm{MeV}/c^2$ |
| $\frac{\mathcal{B}(B^*_{s2} \to B^{*+}K^-)}{\mathcal{B}(B^*_{s2} \to B^+K^-)}$ | $(9.3 \pm 1.3 \pm 1.2)\,\%$ |
| $\frac{\sigma(pp \to B_{s1}X)\mathcal{B}(B_{s1} \to B^{*+}K^-)}{\sigma(pp \to B^*_{s2}X)\mathcal{B}(B^*_{s2} \to B^+K^-)}$ | $(23.2 \pm 1.4 \pm 1.3)\,\%$ |
| $N_{B_{s1} \to B^{*+}K^-}$ | $750 \pm 36$ |
| $N_{B^*_{s2} \to B^{*+}K^-}$ | $307 \pm 46$ |
| $N_{B^*_{s2} \to B^+K^-}$ | $3140 \pm 100$ |

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The world-best $B^*$-$B$ mass difference measurement is a particular highlight

No photon reconstruction so much smaller (and uncorrelated) systematics compared to other measurements

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# Systematic uncertaintites in detail

| Source | $Q(B_{s1})$ ( MeV/$c^2$) | $Q(B^*_{s2})$ ( MeV/$c^2$) | $m(B^{*+}) - m(B^+)$ ( MeV/$c^2$) | $\Gamma(B^*_{s2})$ ( MeV/$c^2$) | $R^{B^*_{s2}}$ (%) | $\sigma^{B_{s1}/B^*_{s2}} R^{B_{s1}/B^*_{s2}}$ (%) |
|---|---|---|---|---|---|---|
| Fit model | 0.00 | 0.02 | 0.03 | 0.01 | 0.2 | 0.5 |
| $B^+$ decay mode | 0.01 | 0.01 | 0.02 | 0.01 | 0.1 | 0.1 |
| Selection | 0.03 | 0.02 | 0.19 | 0.05 | 1.1 | 0.6 |
| $B^+$ signal region | 0.01 | 0.03 | 0.11 | 0.07 | 0.2 | 0.4 |
| Mass resolution | 0.00 | 0.01 | 0.02 | 0.46 | 0.2 | 0.9 |
| Momentum scale | 0.02 | 0.10 | 0.03 | - | - | - |
| Efficiency ratios | - | - | - | - | 0.2 | 0.2 |
| Missing photon | 0.01 | - | 0.01 | - | - | - |
| Total | 0.04 | 0.11 | 0.23 | 0.47 | 1.2 | 1.3 |

**For the Q values, the momentum scale and selection dominate**

**=> Selection evaluated by varying the cut on the multivariate discriminant**

**For the width of the $B^*_{s2}$, the experimental resolution dominates, because we take it from simulation and can only trust this to ~20%**

**For the branching fractions there are many significant contributions**

# Conversion into absolute masses

**For this we use the PDG values of the $B^+$ mass at the time of the paper**

**The measurements are already systematics dominated**

$$m(B^{*+}) = 5324.26 \pm 0.30 \pm 0.23 \pm 0.17\ \mathrm{MeV}/c^2,$$
$$m(B_{s1}) = 5828.40 \pm 0.04 \pm 0.04 \pm 0.41\ \mathrm{MeV}/c^2,$$
$$m(B^{*}_{s2}) = 5839.99 \pm 0.05 \pm 0.11 \pm 0.17\ \mathrm{MeV}/c^2,$$

# Conclusion

# Summary and prospects

**In the charm studies :**

- => We clearly observe the $D^*_{s1}(2700)^+$ and $D^*_{sJ}(2860)^+$ states
- => We do not see any significant excess of events above 3 GeV
- => Need studies of the $D^*K$ spectra in order to shed any further light on the spin-parity assignments of these modes

**In the beauty studies :**

- => We have made a first observation of the $B^*_{s2} \to B^*K$ decay and used it to make a world best measurement of the B*-B mass difference
- => Most precise measurements of the $B_{s1}$ and $B^*_{s2}$ masses, and a first measurement of the $B^*_{s2}$ width

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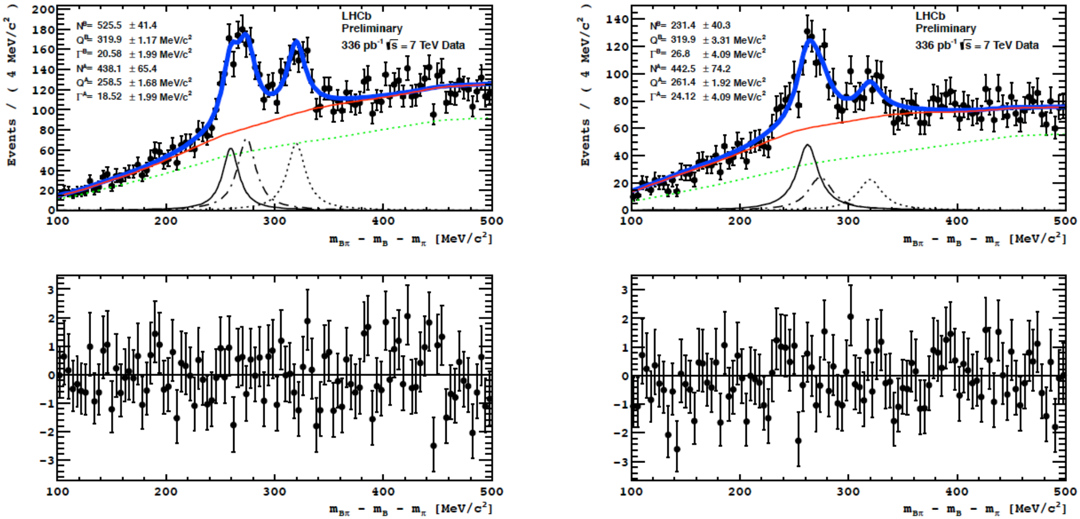
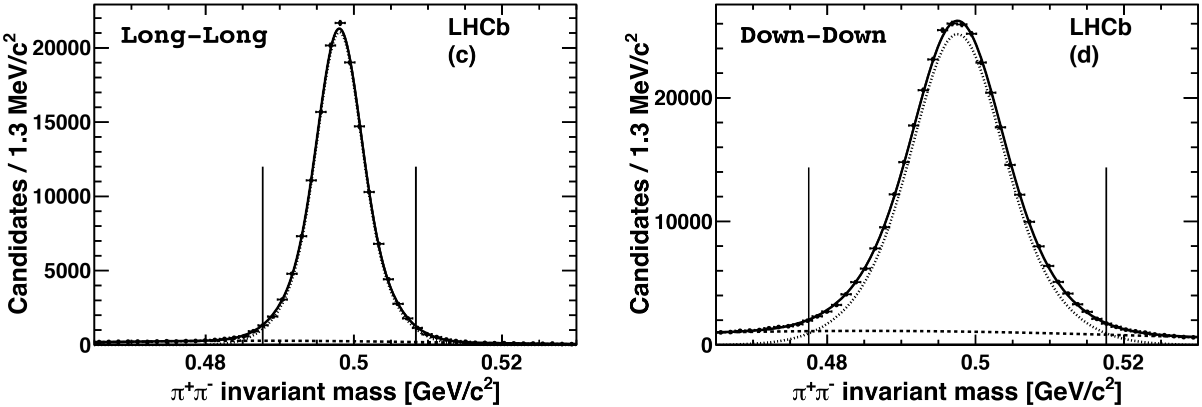
# Summary and prospects

**Stay tuned for more results, in particular an update of our preliminary $B^{*}_{u,d}$ measurements, and $D\pi$ spectroscopy studies should be coming soon!**



# Backups

# $K_S$ signals



Long-Long
LHCb
(c)
Candidates / 1.3 MeV/c2
0
5000
10000
15000
20000
0.48
0.5
0.52
π+π- invariant mass [GeV/c2]
Down-Down
LHCb
(d)
Candidates / 1.3 MeV/c2
0
10000
20000
0.48
0.5
0.52
π+π- invariant mass [GeV/c2]

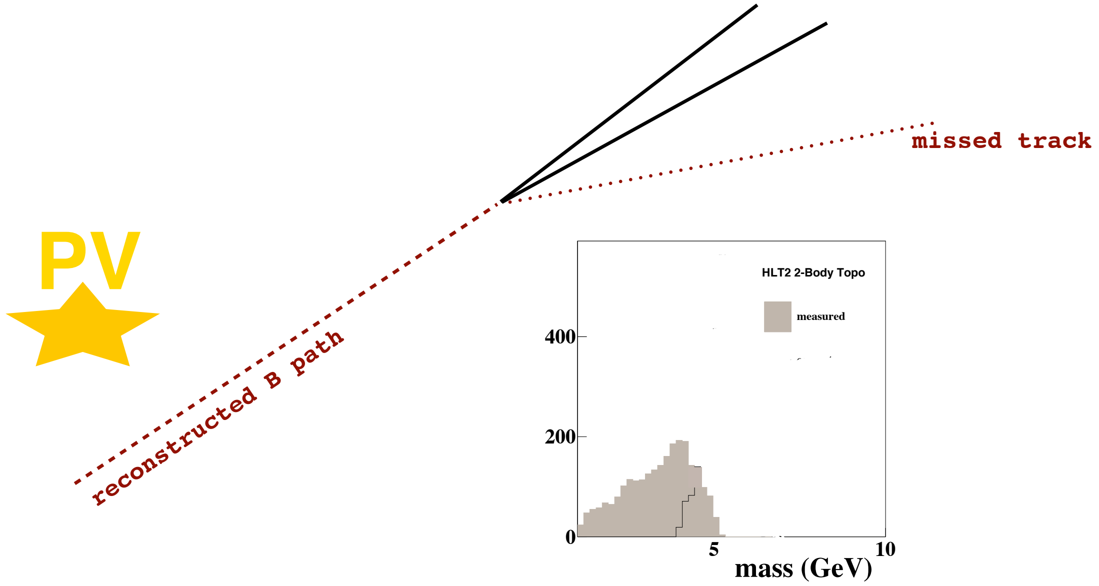
# Multivariate selections from the start

**Question : How is LHCb achieving clean signals in a much dirtier environment than either the B-factories or CDF?**

**Answer 1 : A state of the art detector with ~0.5% momentum resolution and powerful particle identification.**

**Answer 2 : An aggressive use of multivariate selections from the very first stage of the datataking process, the trigger.**

# A topological decision tree trigger



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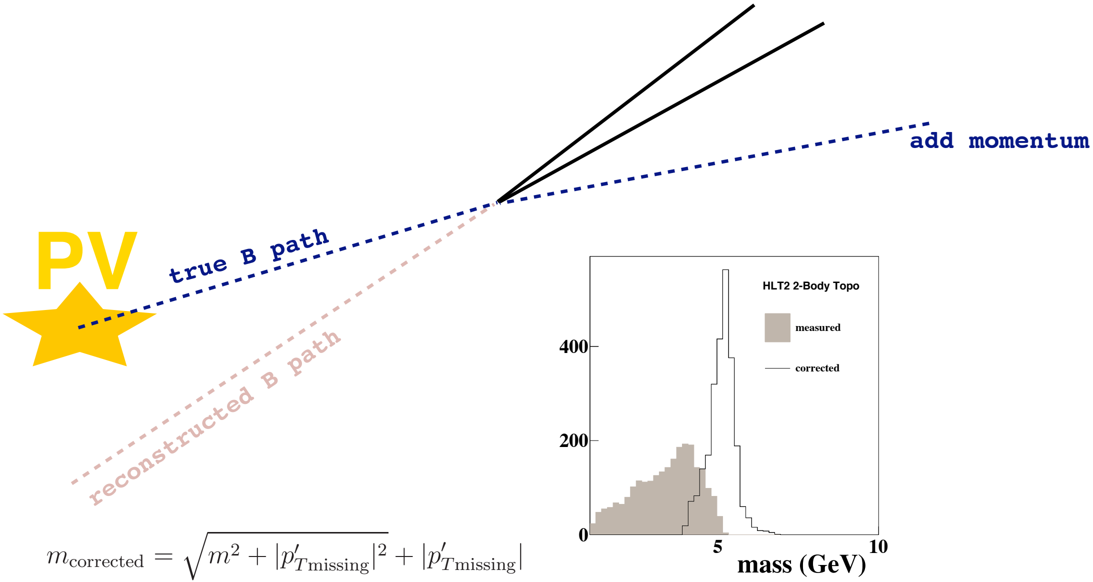
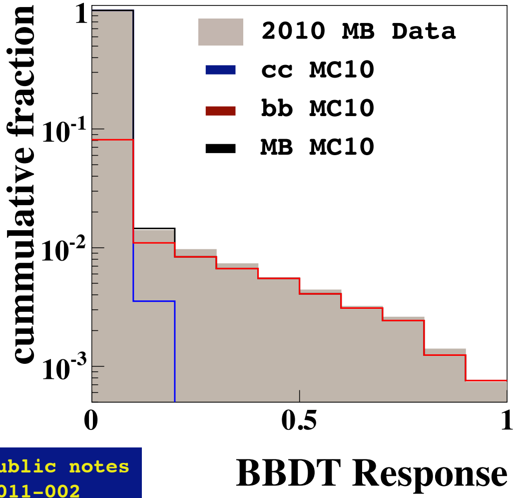
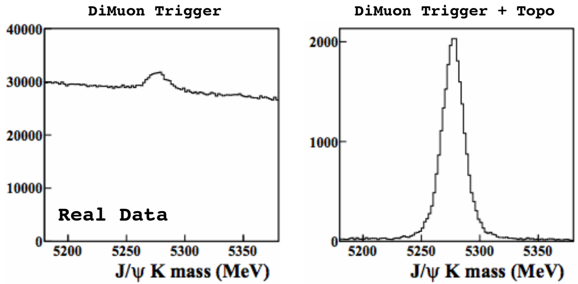



$$m_{\text{corrected}} = \sqrt{m^2 + |p'_{T\text{missing}}|^2} + |p'_{T\text{missing}}|$$

# A topological decision tree trigger

The corrected mass is a good variable, but not good enough to deal with pileup on its own : deploy a boosted decision tree to discriminate between signal and background displaced vertices.



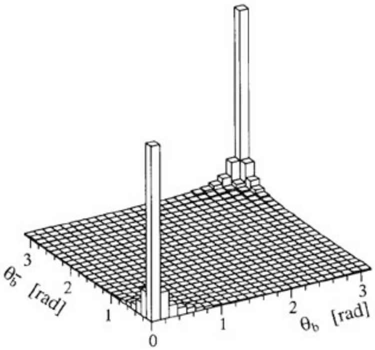

**Left : J/ψK candidates with a dimuon trigger and no detachment required**

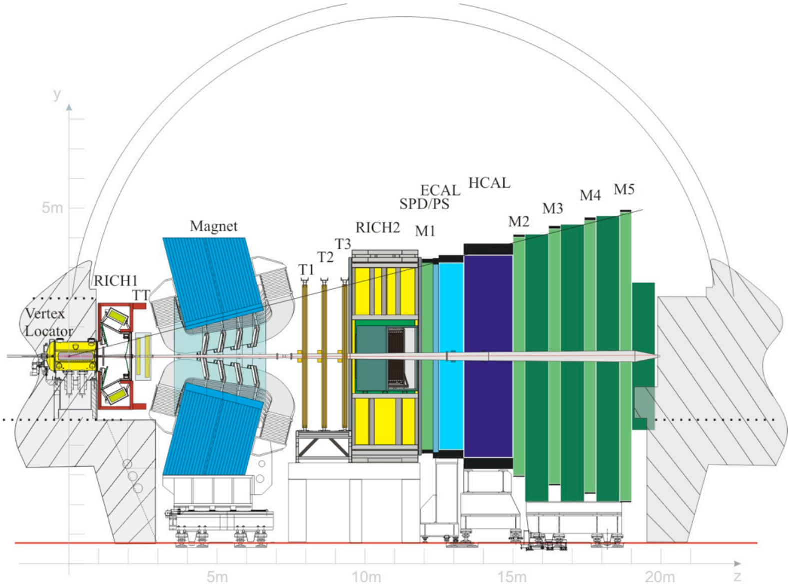
**Right : the subset of these candidates which pass the topological trigger**

**See LHCb public notes**
**LHCb-PUB-2011-002**
**LHCb-PUB-2011-003**
**LHCb-PUB-2011-016**

**Gligorov&Williams** http://arxiv.org/abs/1210.6861

# The LHCb spectrometer



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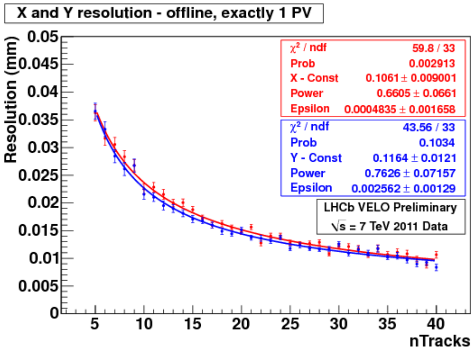


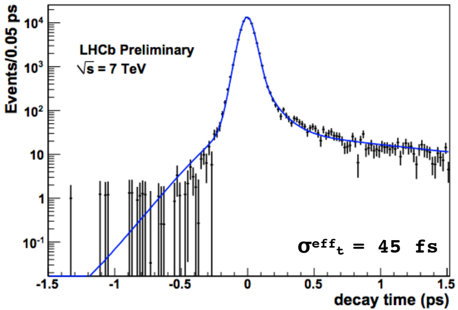


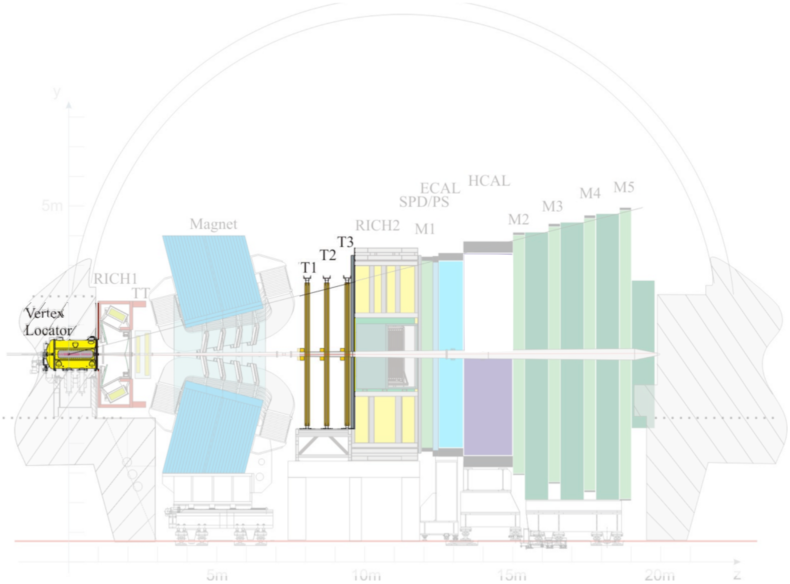

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