Charm spectroscopy and rare decays

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on behalf of the LHCb collaboration, including results from BaBar experiment

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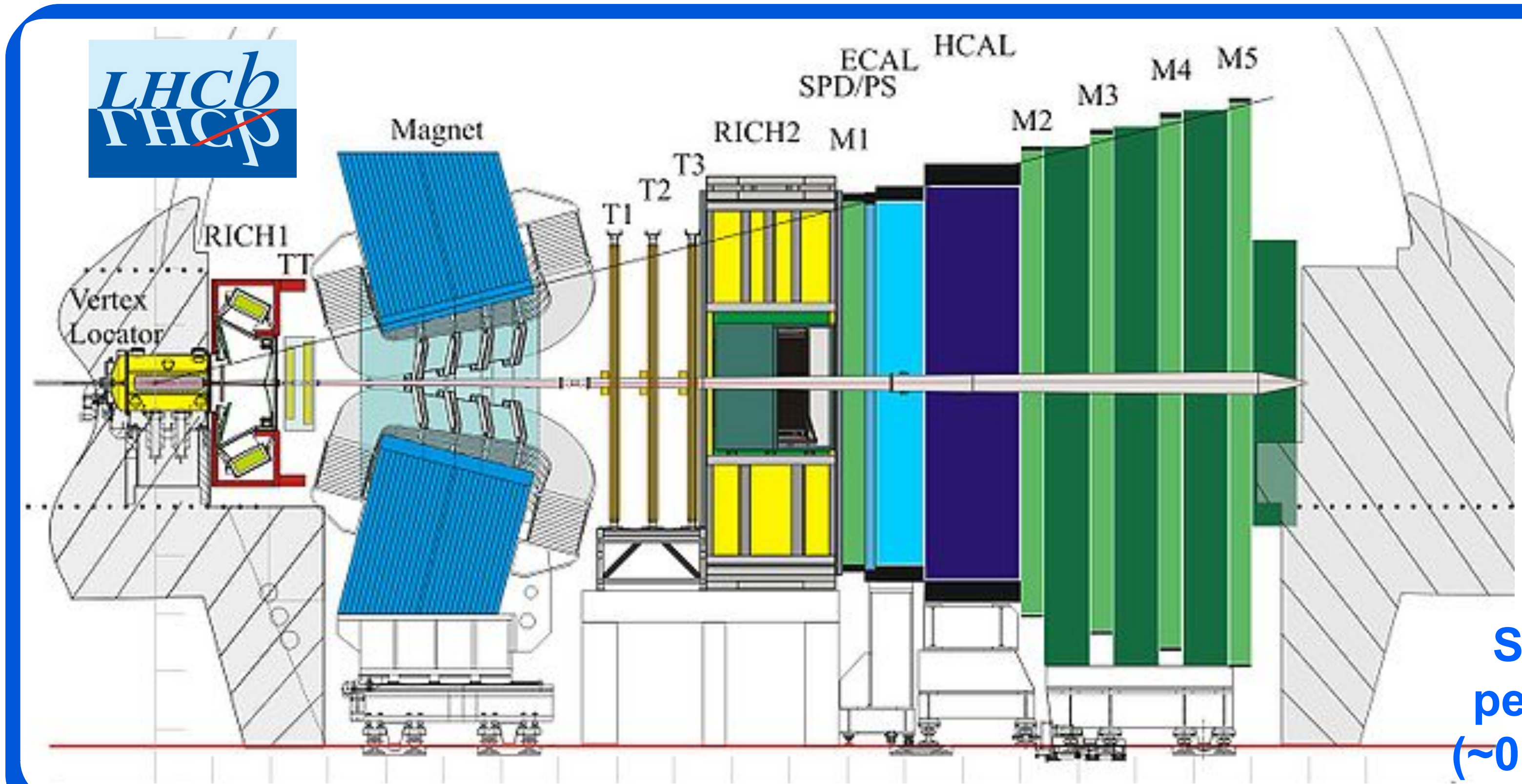
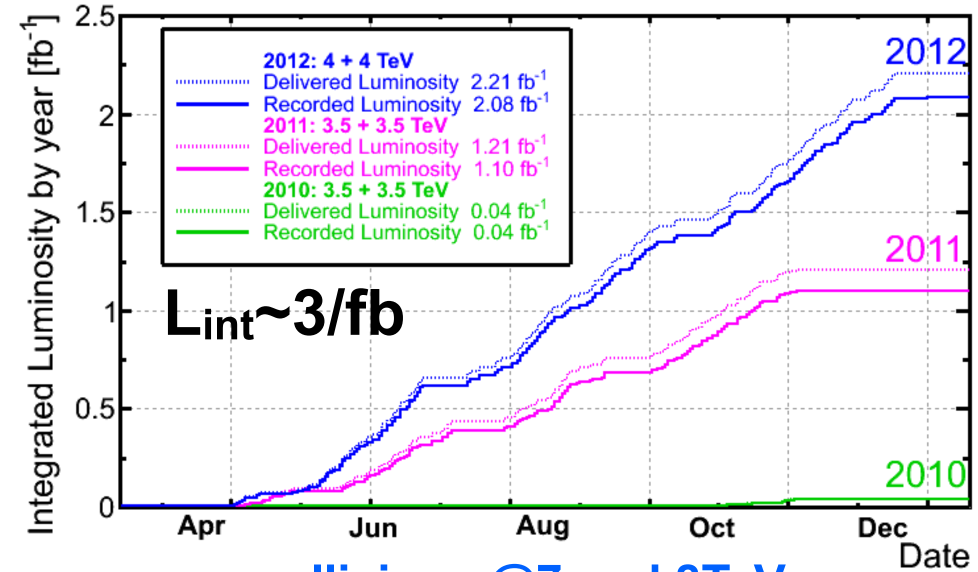
Outline

- Heavy flavors factories
- Charm spectroscopy
  - Excited *D* mesons @LHCb, LHCb-PAPER-2013-026 New
  - Excited D_s mesons @LHCb, JHEP1210(2012)151
- Charm rare decays
  - $D^0 \to \mu^+\mu^-$ @LHCb, LHCb-PAPER-2013-013 New
  - $D^0 \to l^+l'^-$ @BaBar, PRD86(2012)032001
  - $D_{(s)}^+ \to \mu^\mp\mu^+\pi^\pm$ @LHCb, arXiv:1304.6365, Submitted to PRL
  - $D^0 \to \gamma\gamma$ @BaBar, PRD85(2012)091107(R)
- Conclusions

Heavy flavors factories



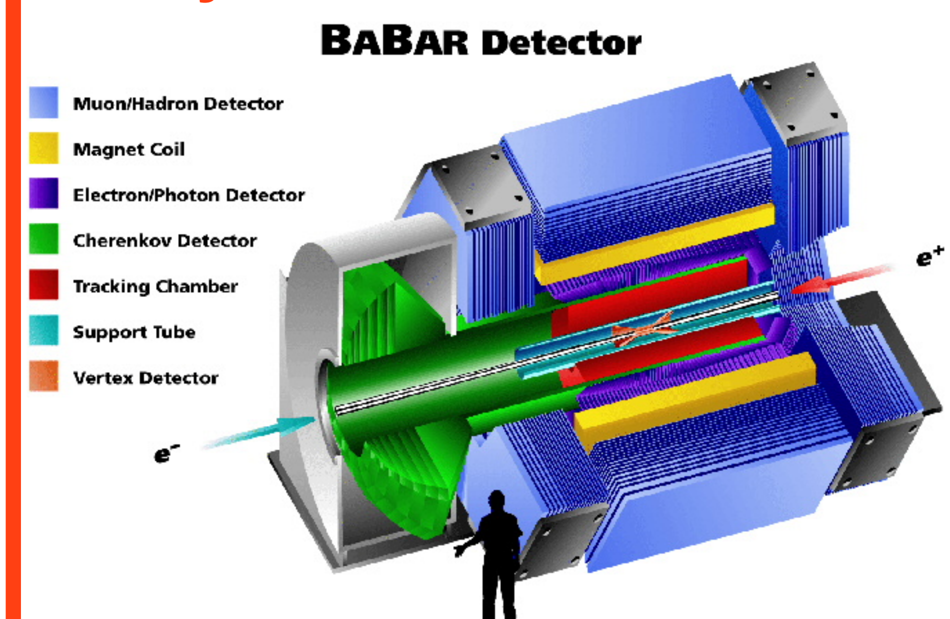


L_{int}~3/fb

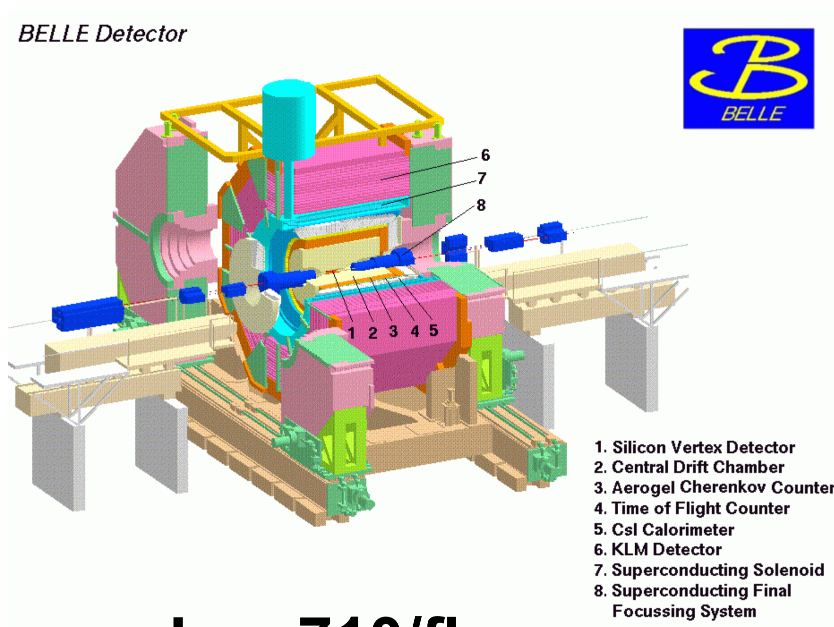
pp collisions @7 and 8TeV

Single arm spectrometer optimized for forward peaked heavy quark production @LHC. Large $b\bar{b}$ (~0.3mb) and $c\bar{c}$ production cross-sections (~1mb)

Asymmetric e^+e^- B-factories @ϒ(4S) + scans in ϒ(nS)



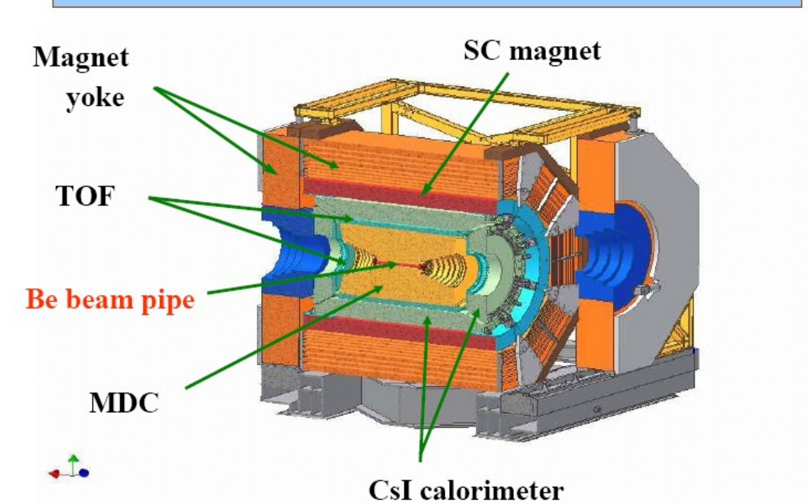
L_{int}~530/fb



L_{int}~710/fb

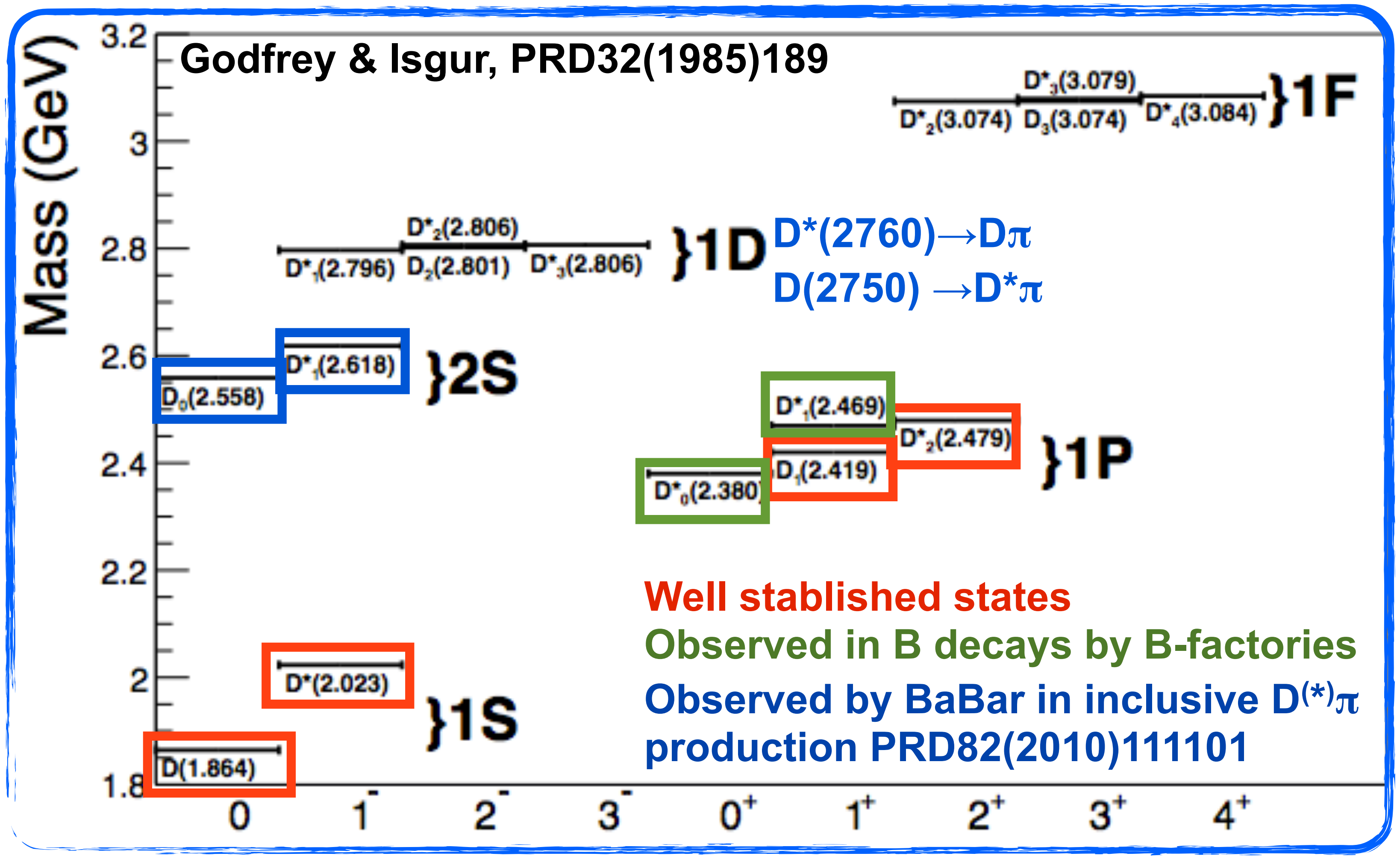
$\sigma(e^+e^- \to c\bar{c})$~1.3nb, >600M of $c\bar{c}$ pairs

The BESIII Detector



e^+e^- @J/ψ, ψ(2S), ψ(3770) c-factory, with the largest database on the charm threshold. L_{int}~3/fb

Excited *D* states



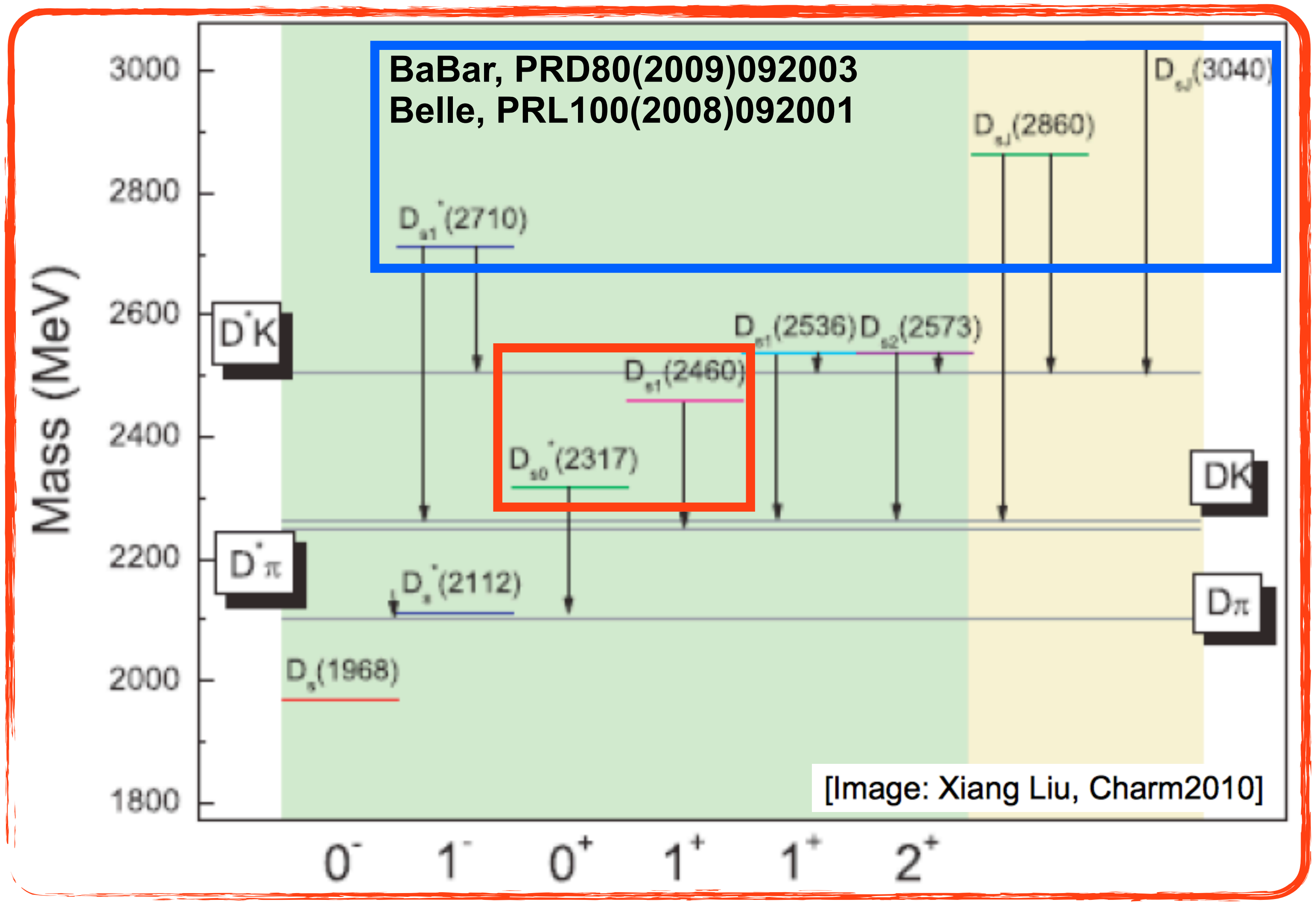
Charm spectroscopy provides a powerful test for quark model predictions in the SM.

Many charmed states predicted in the 80's have not been found experimentally. Often discrepancies between prediction an measurements.

New predictions account for possible bound states or unusual $q\bar{q}'$ mixtures

- ➡ BaBar observed $D(2550)^0$, $D^*(2600)^0$, $D(2750)^0$, $D^*(2760)^0$ and the isospin partners $D^*(2600)^+$ and $D^*(2760)^+$, to be confirmed.
- ➡ Discrepancies between prediction and experiment up to ~50MeV.

Excited D_s states



Charm spectroscopy provides a powerful test for quark model predictions in the SM.

Many charmed states predicted in the 80's have not been found experimentally. Often discrepancies between prediction an measurements.

New predictions account for possible bound states or unusual $q\bar{q}'$ mixtures

- ➟ **Large discrepancy between predictions* and experiment for $D_{s0}^*(2317)$ and $D_{s1}(2460)$**
- ➟ **High mass states observed in $D^{(*)}\pi$ (BaBar) and 3-body B decays (Belle).**
- ➟ **Controversial spin assignment for $D_{sJ}(2860)$. Angular analysis supports $J^P=3^-$, but incompatible with the branching fraction ratio expectation. Overlap of states?**

*Godfrey, Isgur,PRD32(1985)189
Godfrey, Kokosky, PRD43(1991)1679
Isgur,Wise,PRL66(1991)1130

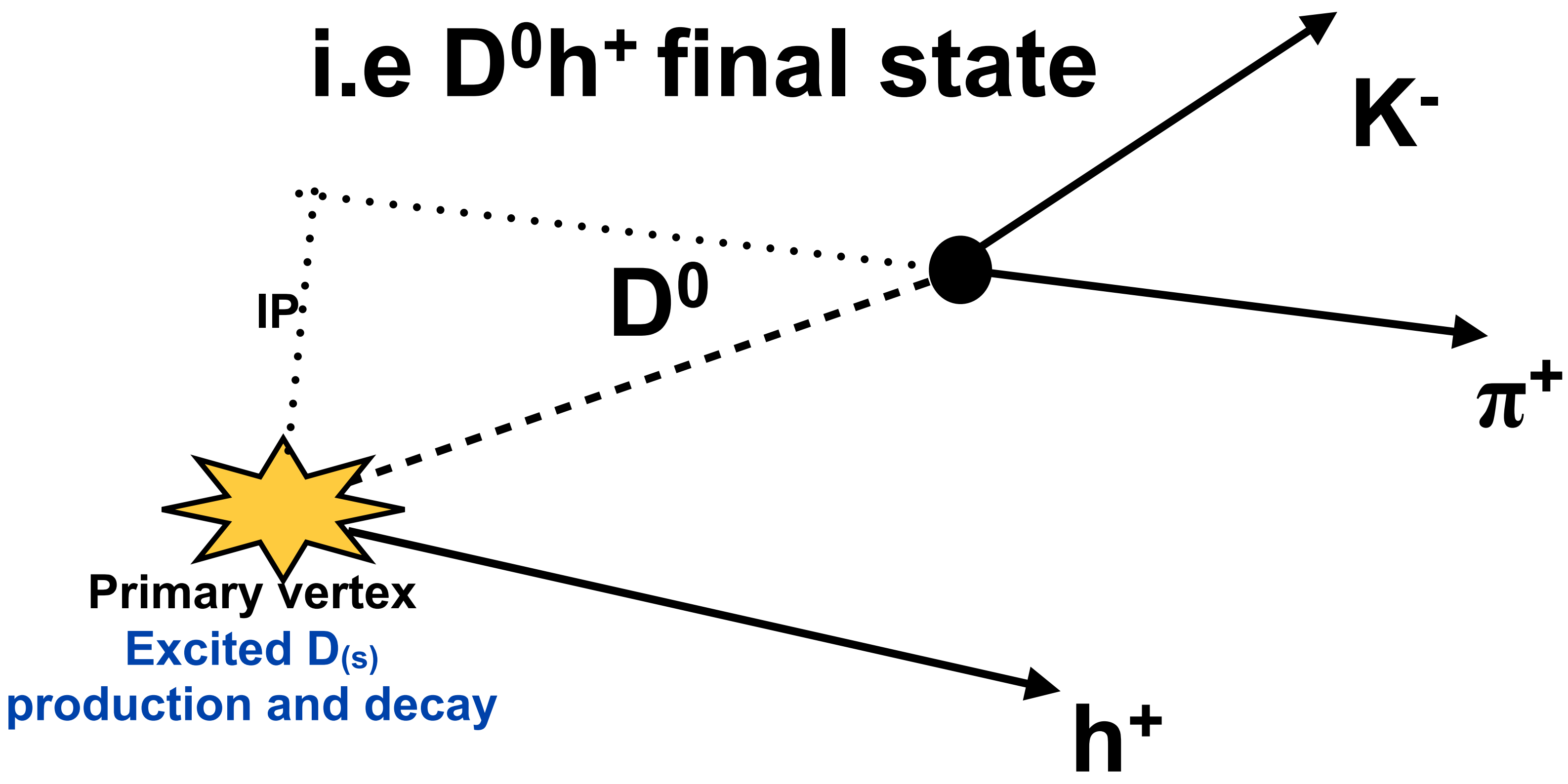
Excited $D_{(s)}$ mesons at LHCb

- Analysis of inclusively prompt produced $D^{(*)}h$ pairs, using 1/fb sample collected during 2011 data taking
- Excited D mesons

New

  - preliminary results, LHCb-PAPER-2013-026
  - $D^0[K^-\pi^+]\,\pi^+$, $D^+[K^-\pi^+\pi^+]\pi^-$, $D^{*+}[D^0\pi^+]\pi^-$
- Excited D_s mesons
  - JHEP1210(2012)151
  - $D^0[K^-\pi^+]K^+$, $D^+[K^-\pi^+\pi^+]K_S[\pi^+\pi^-]$
- D meson candidates reconstructed in CF modes
- Similar strategy used in both analyses

Selection of excited $D_{(s)}$ states



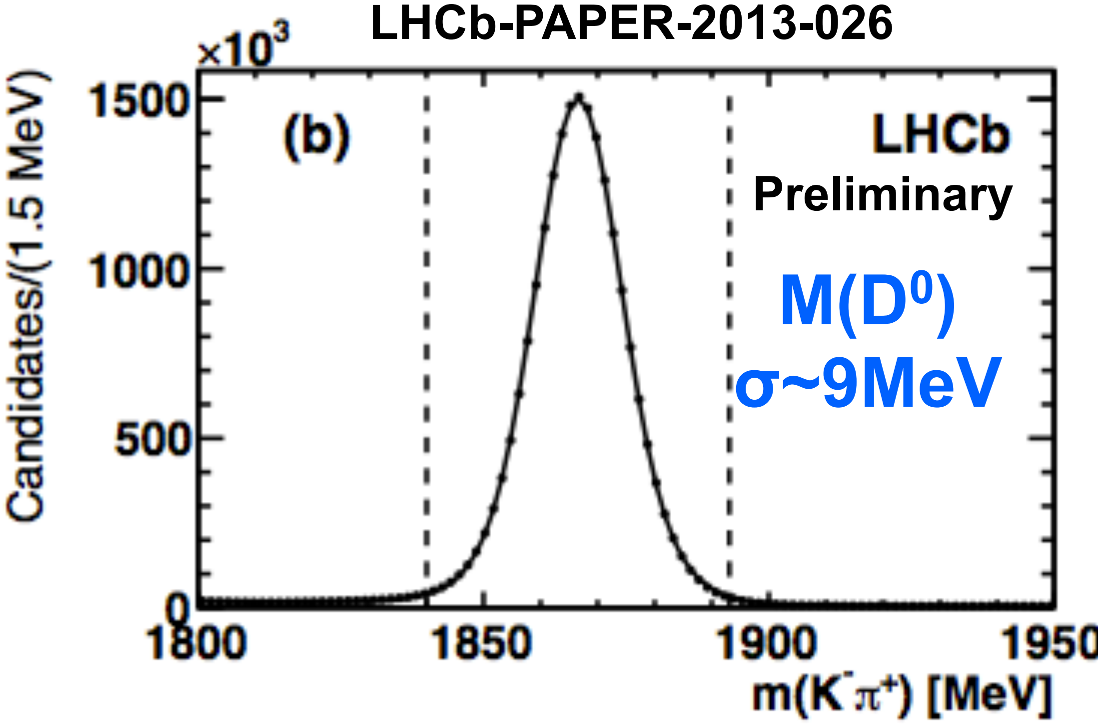
➡ Large combinatorial background from random tracks produced in the primary vertex. Main source of systematic uncertainty

➡ Negligible contribution from fake D, giving their high purity (>95%)

Global selection criteria

- ➟ Tracks and vertices quality
- ➟ Large D flight length
- ➟ Large IP wrt PV for D daughter tracks
- ➟ Small IP wrt PV for the prompt track and D
- ➟ Tight particle ID criteria in the prompt track
- ➟ Large cosθ. Reduction of about 90% of combinatorial background and wrong mass hypothesis tracks.

LHCb-PAPER-2013-026



The *Dh* spectra

$D_1(2420)$ — $D_1(2420)\to D^*[D\pi,D\gamma]\pi$ partially reco

$D_2^*(2460)$ — $D_2^*(2460)\to D^*[D\pi,D\gamma]\pi$ partially reco

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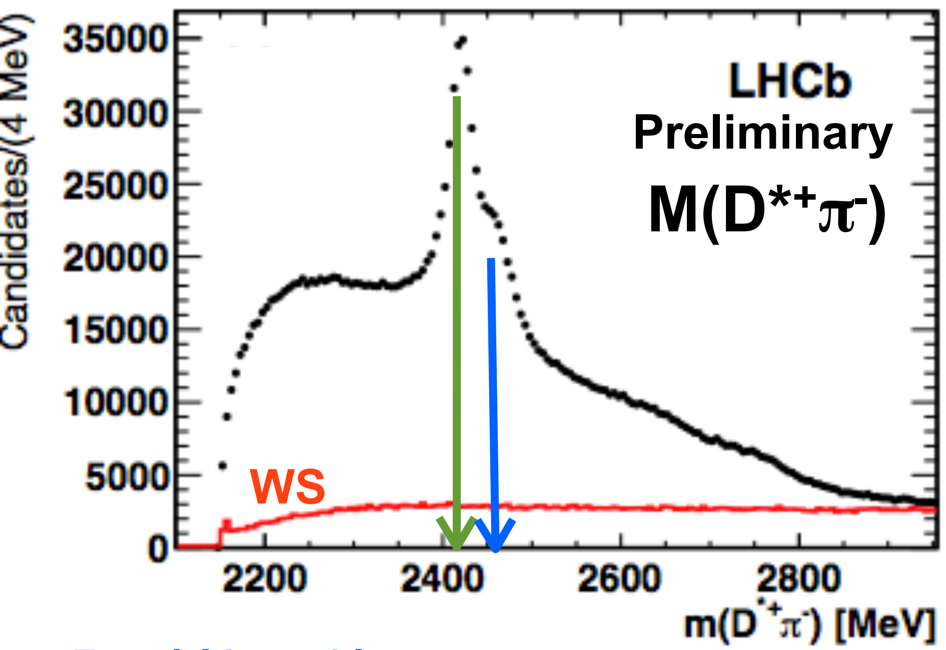
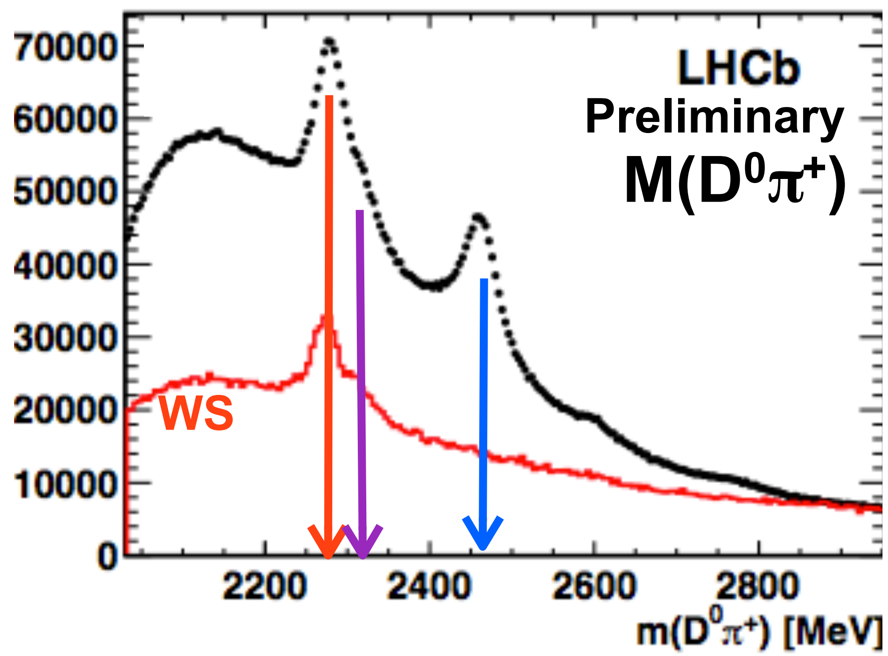
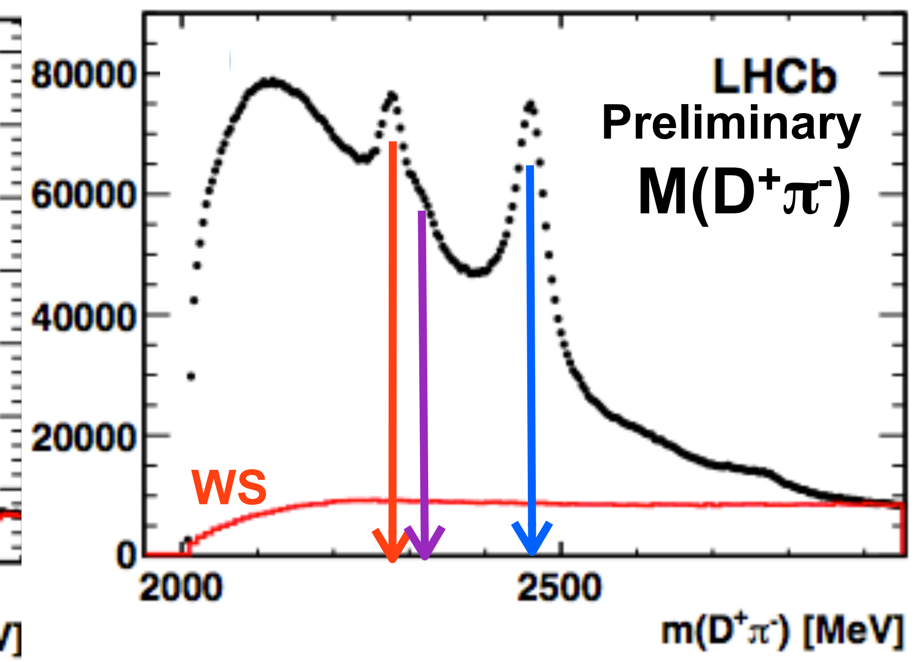
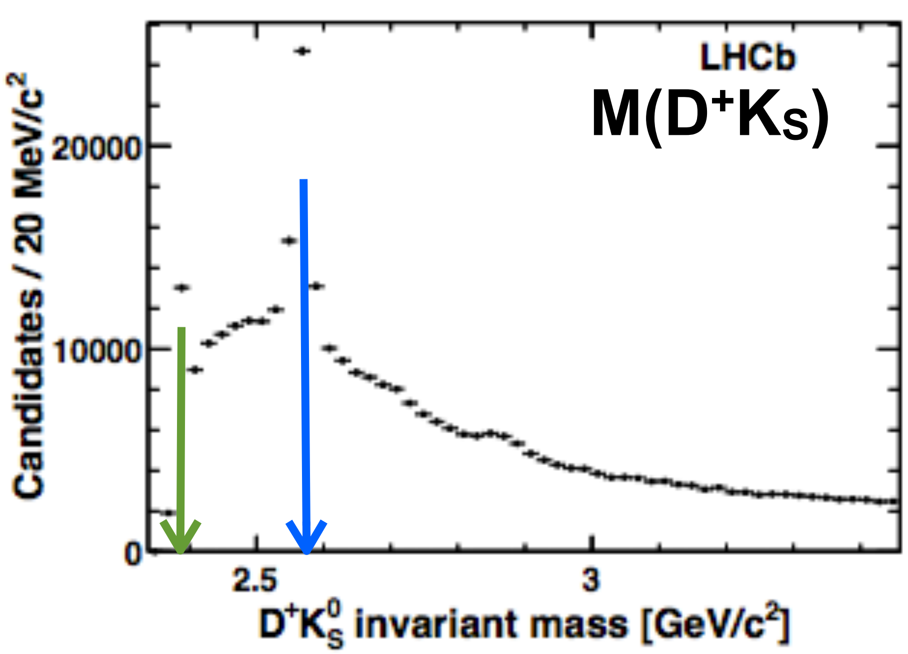


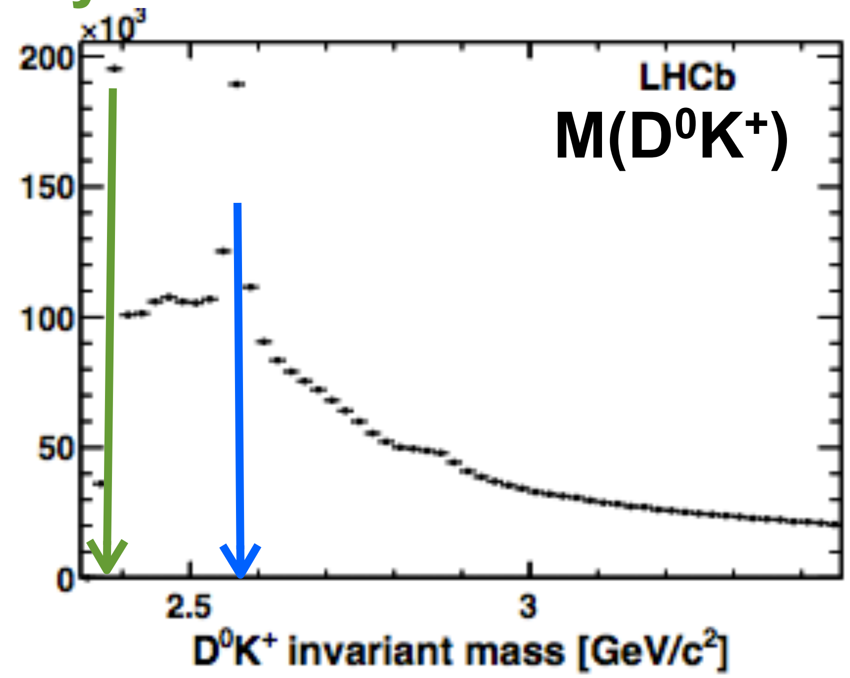




$D_{s2}^*(2573)$

$D_{s1}(2536)\to D^*[D\pi,D\gamma]K$ partially reco





JHEP1210(2012)151

→ Already several contributions in the high mass tails are observed

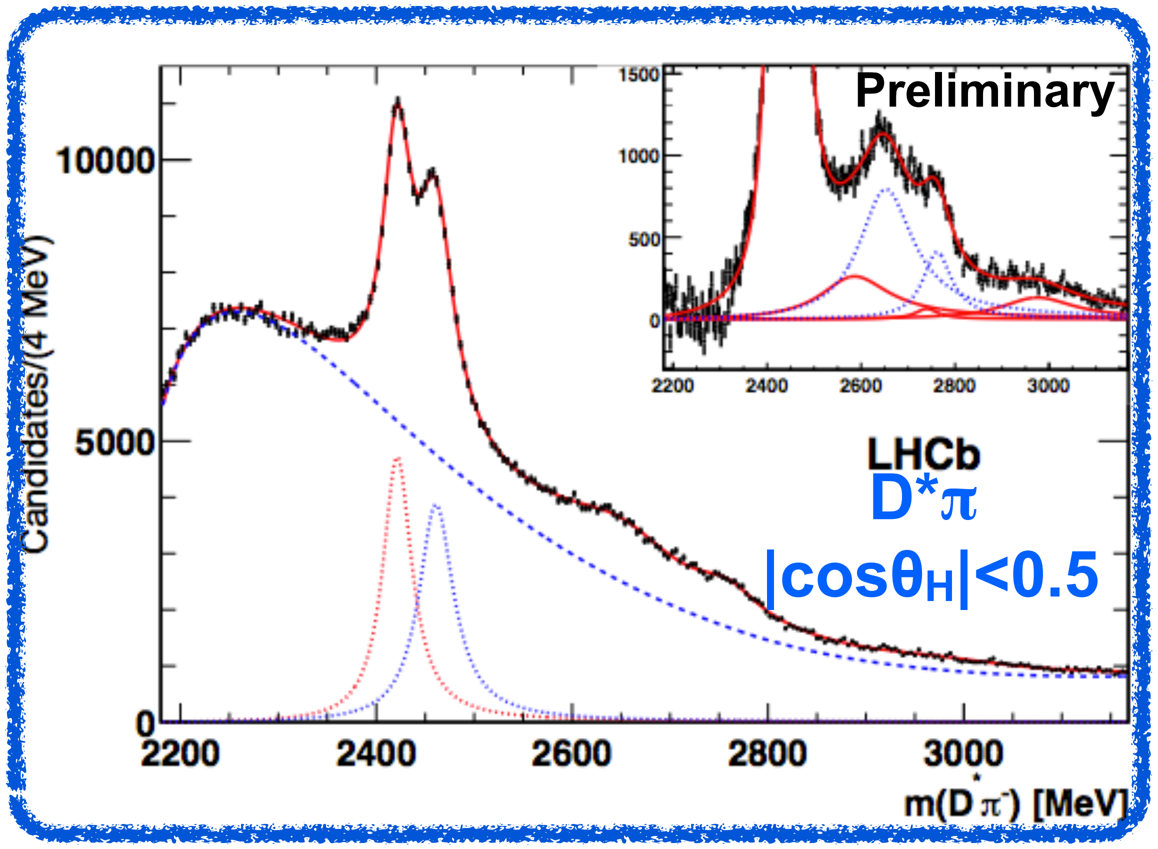
→ Signal described with Breit-Wigner distributions

→ Largest component is bkg (and so systematic). Bkg described with empiric piece-wise function made of exponentials times a threshold function, in Dπ, while for DK a linear combination of Chebyshev polynomials is used

$D^*\pi$ angular analysis

New

LHCb-PAPER-2013-026



Split of the $D^*\pi$ sample in ranges of the helicity angle

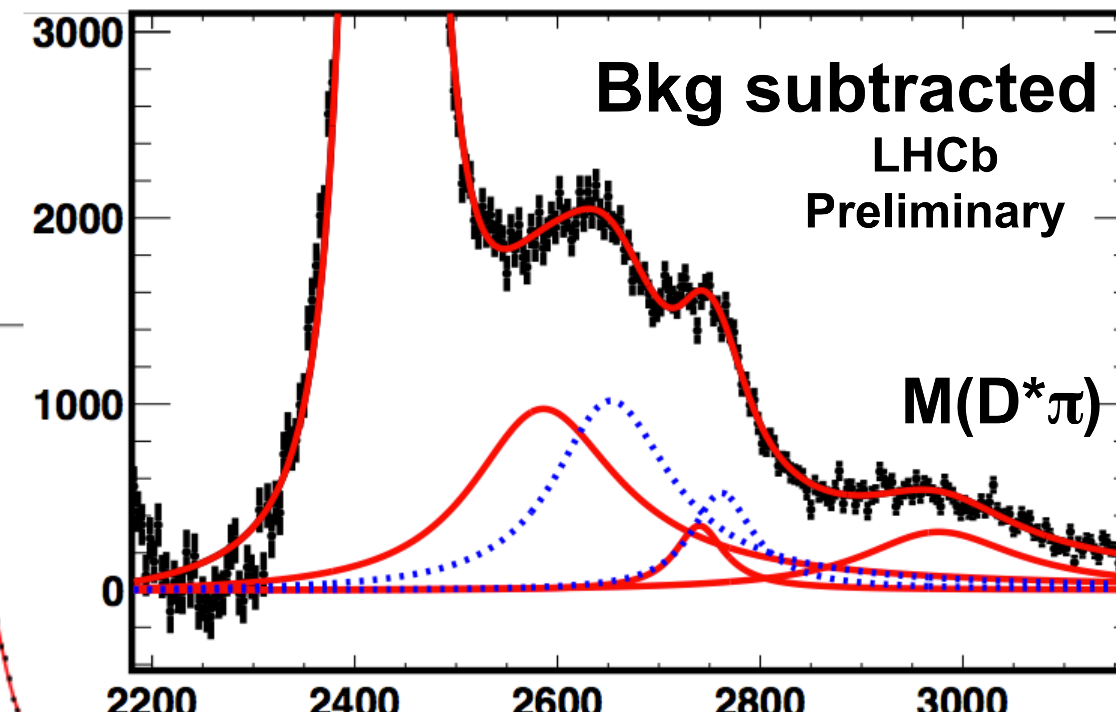
Enhanced natural parity, $|\cos\theta_H|<0.5$, $J^P=0^+,1^-,2^+,...$

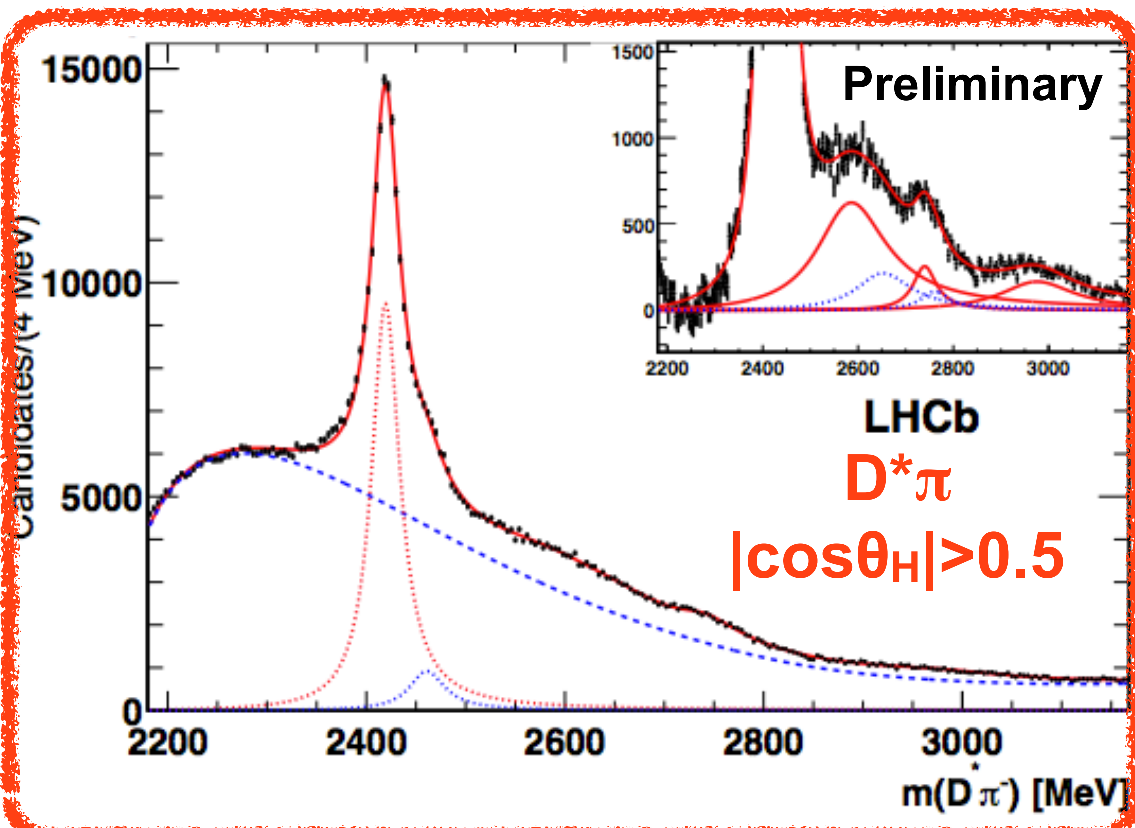
Enhanced unnatural parity, $|\cos\theta_H|>0.5$, $J^P=0^-,1^+,2^-,...$

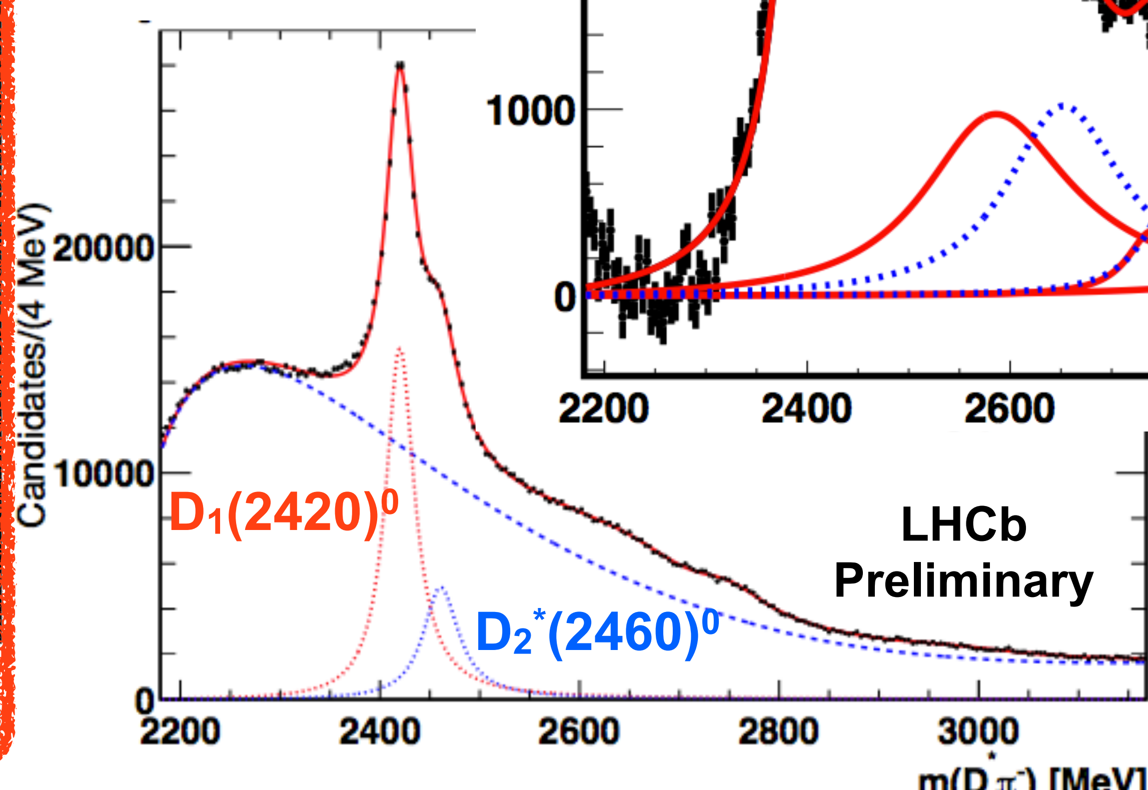
Components found in the high mass tail

$D_J^*(2650)$ $D_J^*(2760)$

$D_J(2580)$ $D_J(2740)$ $D_J(3000)$







$D^*\pi$ angular analysis

New

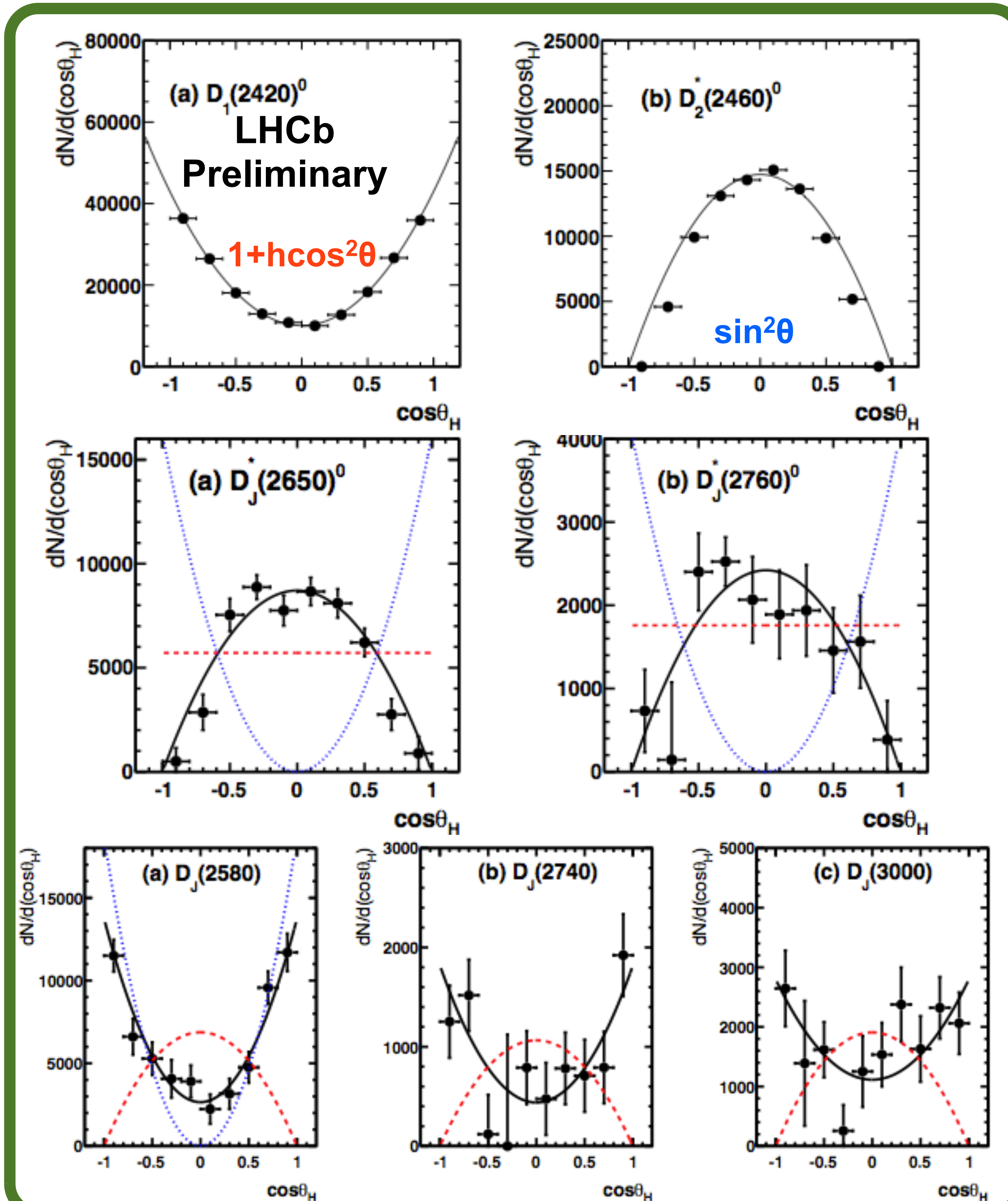
Flat efficiency in cosθ.

Spin-parity analysis in bins of the helicity angle.

For well stablished states, data is well described with the expected hypothesis, $D_1(2420)$ a $J^P=1^+$, and $D_2^*(2460)$ a $J^P=2^+$ state.

Natural parity assignment confirmed for $D_J^*(2650)^0$ and $D_J^*(2760)^0$.

Unnatural parity assignment confirmed for $D_J(2580)^0$, $D_J(2740)^0$ and suggested for $D_J(3000)^0$.



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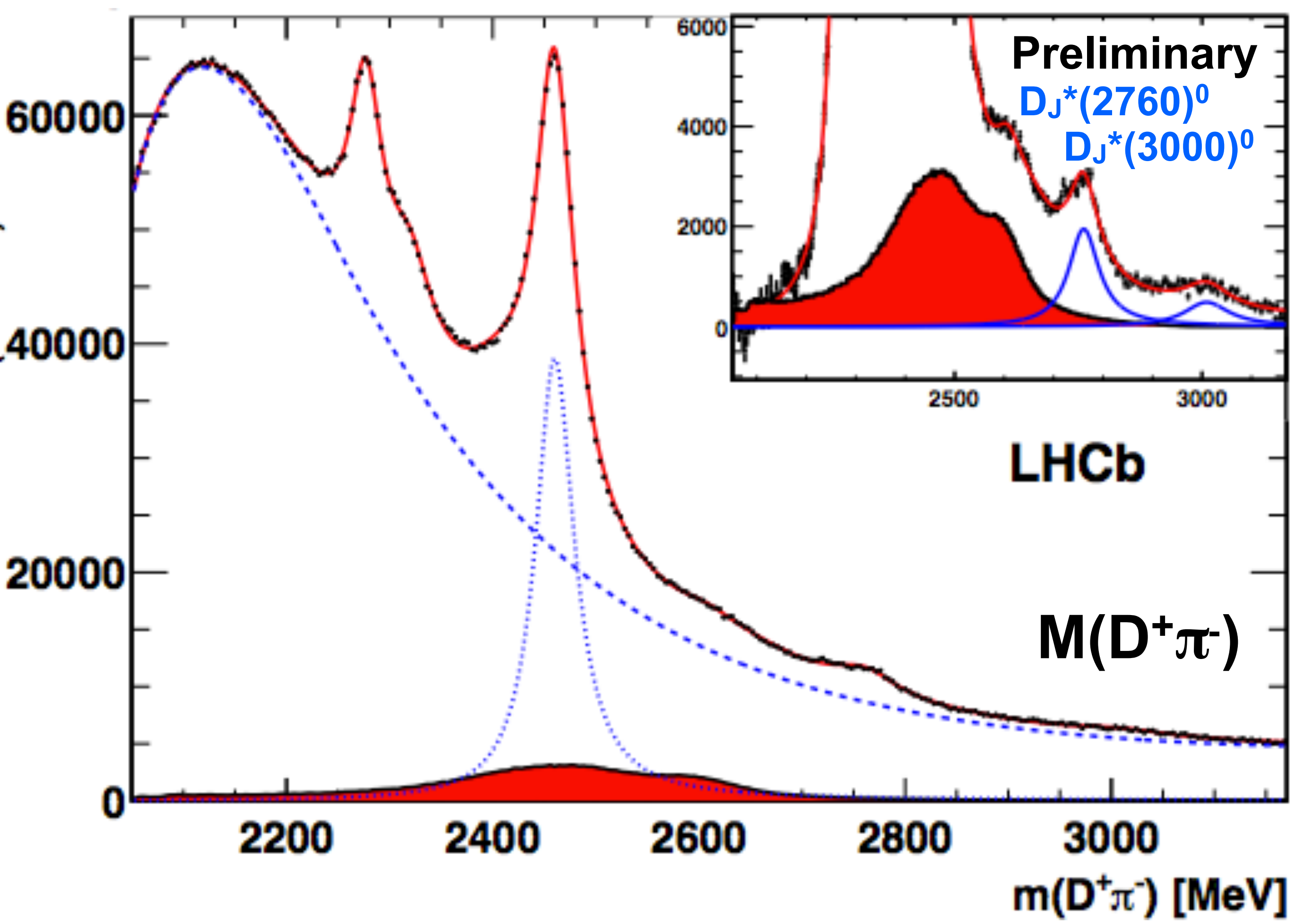
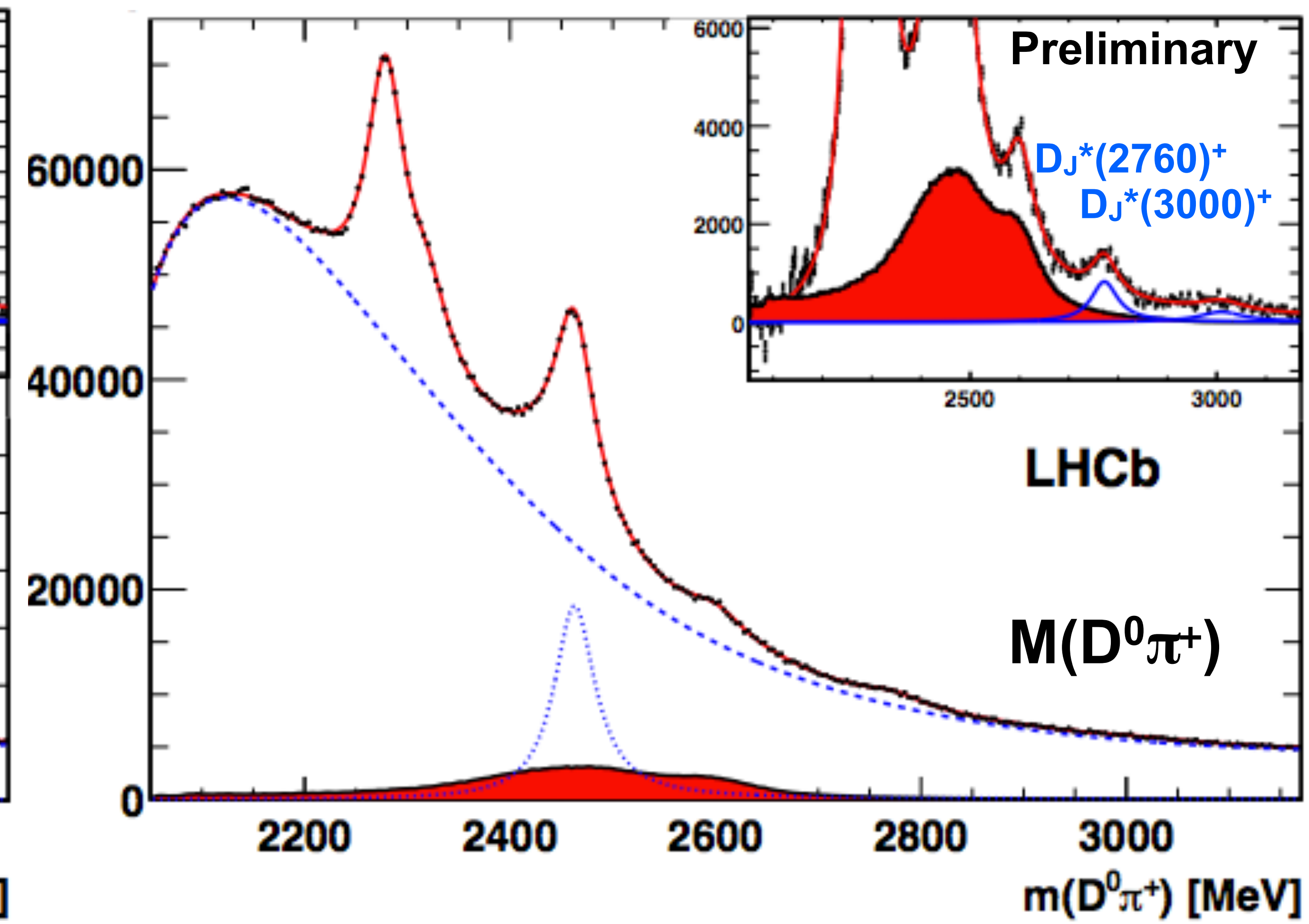
Dπ spectra

New





- Natural parity states

LHCb-PAPER-2013-026

- An iterative separate fit between both spectra, using as input information from $D^*\pi$

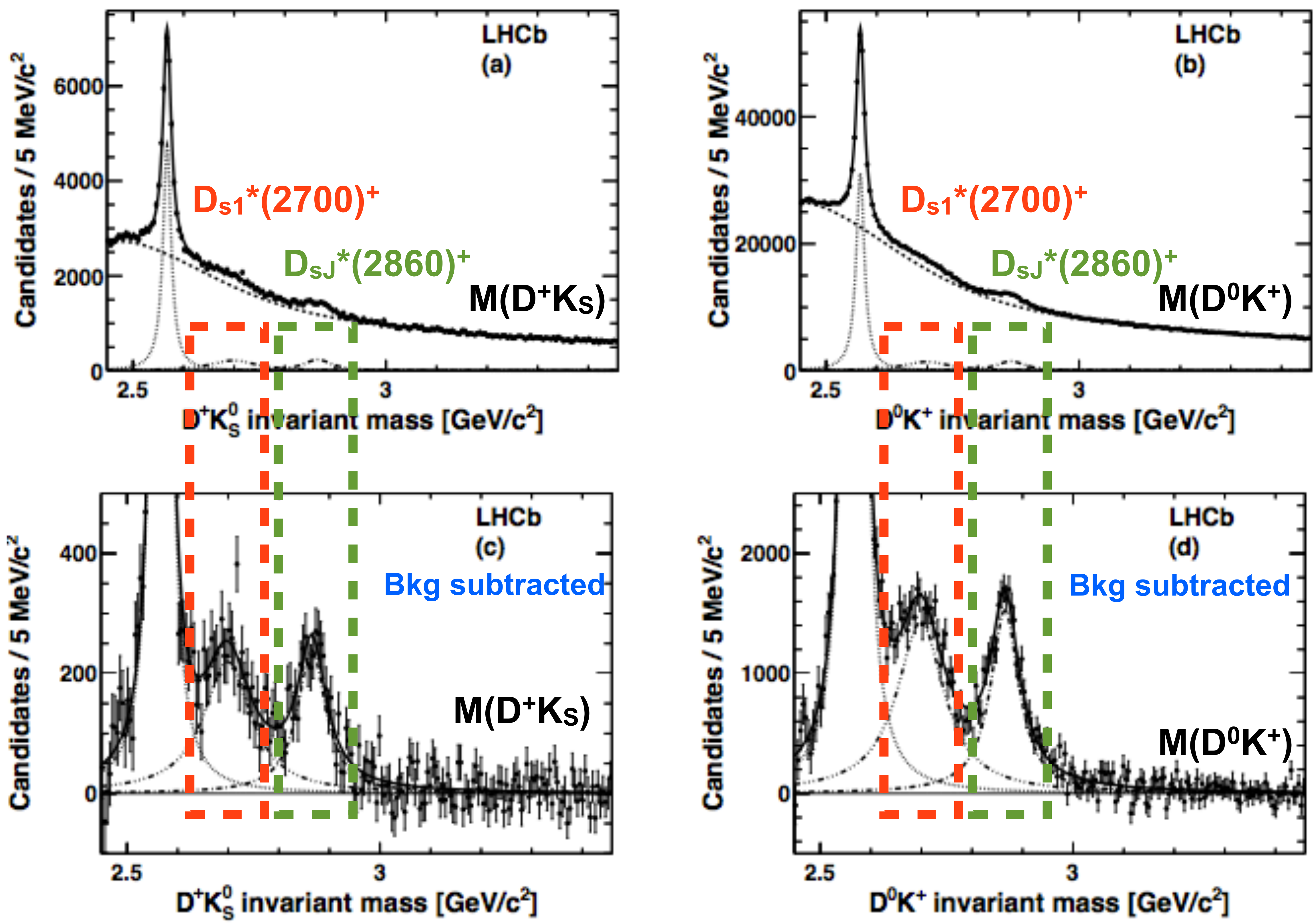
- Feed-down from partially reconstructed structures (Missing π, γ). Yields for high mass feed-downs are scaled from yields extracted for large structures in $D^*\pi$ to the same type of feed-down in $D\pi$, $D_1(2420)$ and $D_2^*(2460)$. Shape extracted from MC simulation.

- High mass populated with $D_J^*(2760)^{0,+}$ and $D_J^*(3000)^{0,+}$ (natural parity). $D_J^*(2650)^{0,+}$ very hard to extract given feed-downs

DK spectra

JHEP1210(2012)151

Simultaneous fit to D^+K_S and D^0K^+ samples



Summary on spectroscopy

Largest systematic uncertainties from bkg model. Different models used as well as toy MC. Results have been largely cross-checked.

New

LHCb Preliminary
LHCb-PAPER-2013-026

	Resonance	Final state	Mass (MeV)	Width (MeV)	Significance
Unnatural parity	$D_1(2420)^0$	$D^{*+}\pi^-$	$2419.6 \pm 0.1 \pm 0.7$	$35.2 \pm 0.4 \pm 0.9$	
Natural parity	$D_2^*(2460)^0$	$D^{*+}\pi^-$	$2460.4 \pm 0.4 \pm 1.2$	$43.2 \pm 1.2 \pm 3.0$	
Seen only in $D^*\pi$, 1^- 2S $D_1(2618)$	$D_J^*(2650)^0$	$D^{*+}\pi^-$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$	24.5 (15.9)
Natural parity	$D_J^*(2760)^0$	$D^{*+}\pi^-$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 3.4 \pm 37.0$	10.2 (6.0)
Seen by BaBar, unnatural parity 0^-	$D_J(2580)^0$	$D^{*+}\pi^-$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.8 \pm 46.0$	18.8 (13.1)
Unnatural parity, 1^- like 1D $D_1(2796)$	$D_J(2740)^0$	$D^{*+}\pi^-$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$	7.2 (4.7)
NEW compatible with unnatural par.	$D_J(3000)^0$	$D^{*+}\pi^-$	2971.8 ± 8.7	188.1 ± 44.8	9.0 (3.7)
Natural parity	$D_2^*(2460)^0$	$D^+\pi^-$	$2460.4 \pm 0.1 \pm 0.1$	$45.6 \pm 0.4 \pm 1.1$	
Natural parity, 2^- like 1D $D_2(2801)$	$D_J^*(2760)^0$	$D^+\pi^-$	$2760.1 \pm 1.1 \pm 3.7$	$74.4 \pm 3.4 \pm 19.1$	17.3 (5.5)
NEW	$D_J^*(3000)^0$	$D^+\pi^-$	3008.1 ± 4.0	110.5 ± 11.5	21.2 (12.4)
Natural parity	$D_2^*(2460)^+$	$D^0\pi^+$	$2463.1 \pm 0.2 \pm 0.6$	$48.6 \pm 1.3 \pm 1.9$	
Natural parity, 2^- like 1D $D_2(2801)$	$D_J^*(2760)^+$	$D^0\pi^+$	$2771.7 \pm 1.7 \pm 3.8$	$66.7 \pm 6.6 \pm 10.5$	18.8 (8.3)
NEW	$D_J^*(3000)^+$	$D^0\pi^+$	3008.1 (fixed)	110.5 (fixed)	6.6 (5.1)

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

LHCb, JHEP1210(2012)151

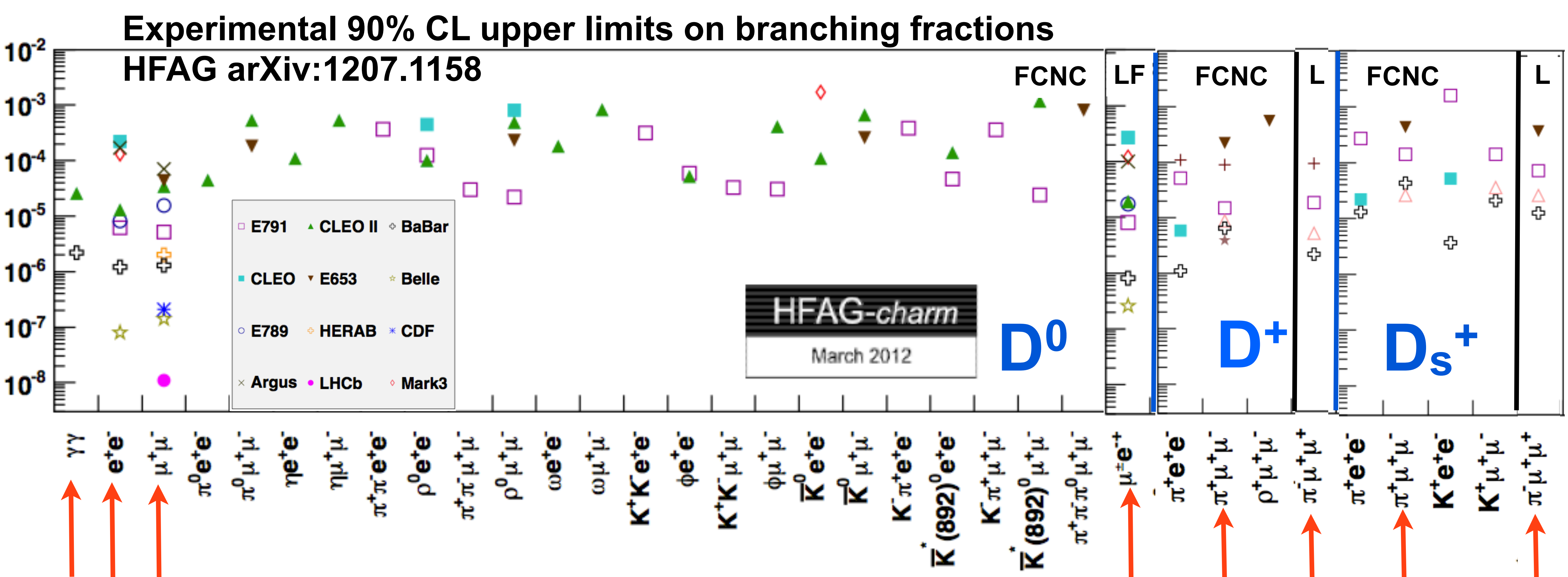
First observation of $D_{s1}^*(2700)^+$ and $D_{sJ}^*(2860)^+$ in hadronic collisions. Resonances observed in BaBar and Belle have been confirmed. All results within agreement. Additional D*K analysis needed to rule out spin parity puzzle on $D_{sJ}^*(2860)^+$ state.

Charm rare decays

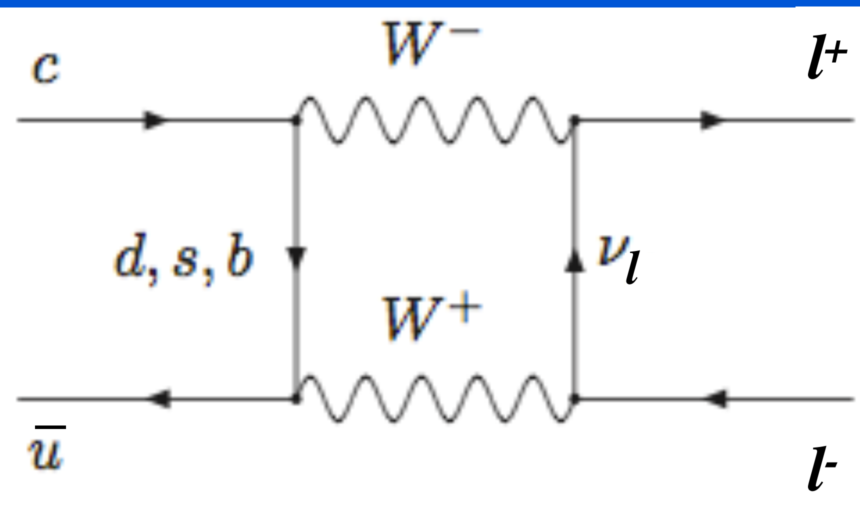
- ➟ Many charm decays are forbidden or highly suppressed in the SM. Usually FCNC, LFV, LV, BV decays.

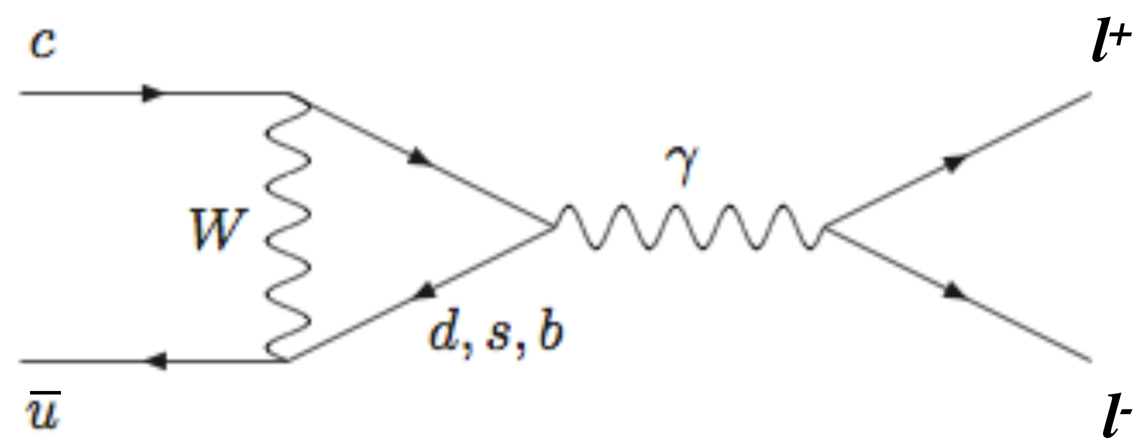
- ➟ Very rare decays help to constrain effects from physics BSM

- ➟ BSM models enhance BF of some of these decays



$D^0 \to l^+ l^-$





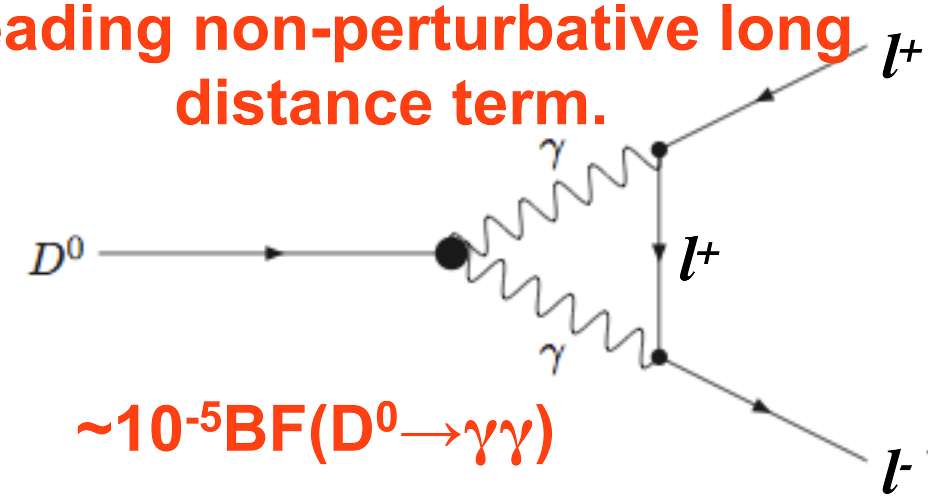
SM prediction*

$BF(D^0 \to e^+e^-) \sim 10^{-23}$

$BF(D^0 \to \mu^+\mu^-) \sim 10^{-13}$

Much smaller BF than current experimental sensitivity ($\sim 10^{-7}$). FCNC process GIM and helicity suppressed in SM

Leading non-perturbative long distance term.



$\sim 10^{-5} BF(D^0 \to \gamma\gamma)$

Some R-parity violating SUSY models enhance $BF(D^0 \to \mu^+\mu^-)$ up to current experimental levels, tree decay diagrams via squark exchange. Window of several orders of for NP. Great scenario for SUSY searches, exploited prior 2010 by many experiments

Argus	H. Albrecht et al., Phys. Lett. B209 (1988) 380
E653	K. Kodama et al., Phys. Lett. B345 (1995) 85-92
CLEO II	A. Freyberger et al., Phys. Rev. Lett. 76 (1996) 3065-3069
E789	D. Pripstein et al., Phys. Rev. D61 (2000) 032005
E791	E.M. Aitala et al., Phys. Lett. B462 (1999) 401-409
HERAb	I. Abt et al., Phys. Lett. B596 (2004) 173
BaBar	B. Aubert et al., Phys. Rev. Lett. 93 (2004) 191801
CDF	T. Aaltonen et al., Phys. Rev. D82 (2010) 091105R
Belle	M. Petric et al., Phys. Rev. D81 (2010) 091102R
LHCb Preliminary	LHCb collaboration, LHCb-CONF-2012-005

http://www.slac.stanford.edu/xorg/hfag/charm/ICHEP12/Rare/rare_d0.html

*Burdman, et.al, Phys. Rev. D 66, 014009 (2002).

$D^0 \rightarrow \mu^+\mu^-$ at LHCb

New

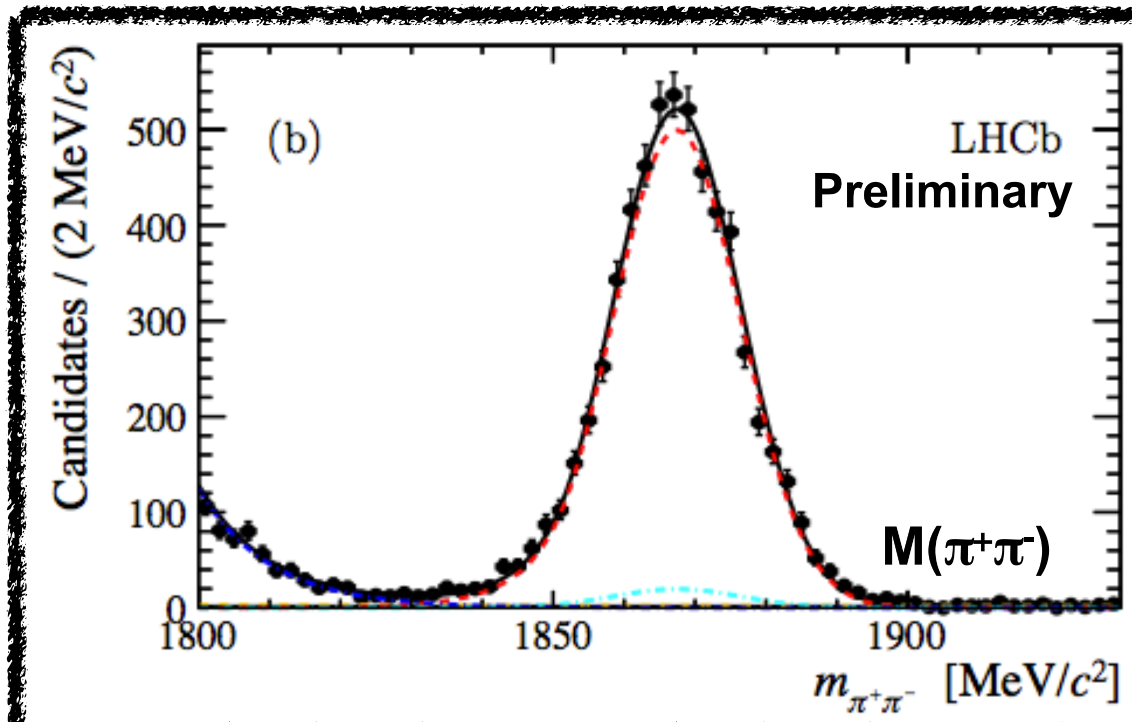
1/fb 2011 data
LHCb-PAPER-2013-013
$D^{*+} \rightarrow D^0(\rightarrow \mu^+\mu^-)\pi^+$

$$\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) = \frac{N_{D^{*+}\rightarrow D^0(\mu^+\mu^-)\pi^+}}{N_{\pi^+\pi^-}} \times \frac{\varepsilon_{\pi\pi}}{\varepsilon_{\mu\mu}} \times \mathcal{B}(D^0 \rightarrow \pi^+\pi^-)$$

PDG

→ Large efficiency from di-muon specific trigger
→ Good track and vertex quality
→ Tracks from D^0 detached from PV
→ D^0 produced in the PV
→ Tight μID and multivariate discrimination for semileptonic D decays and random background reduction, using signal MC and data from the signal sidebands

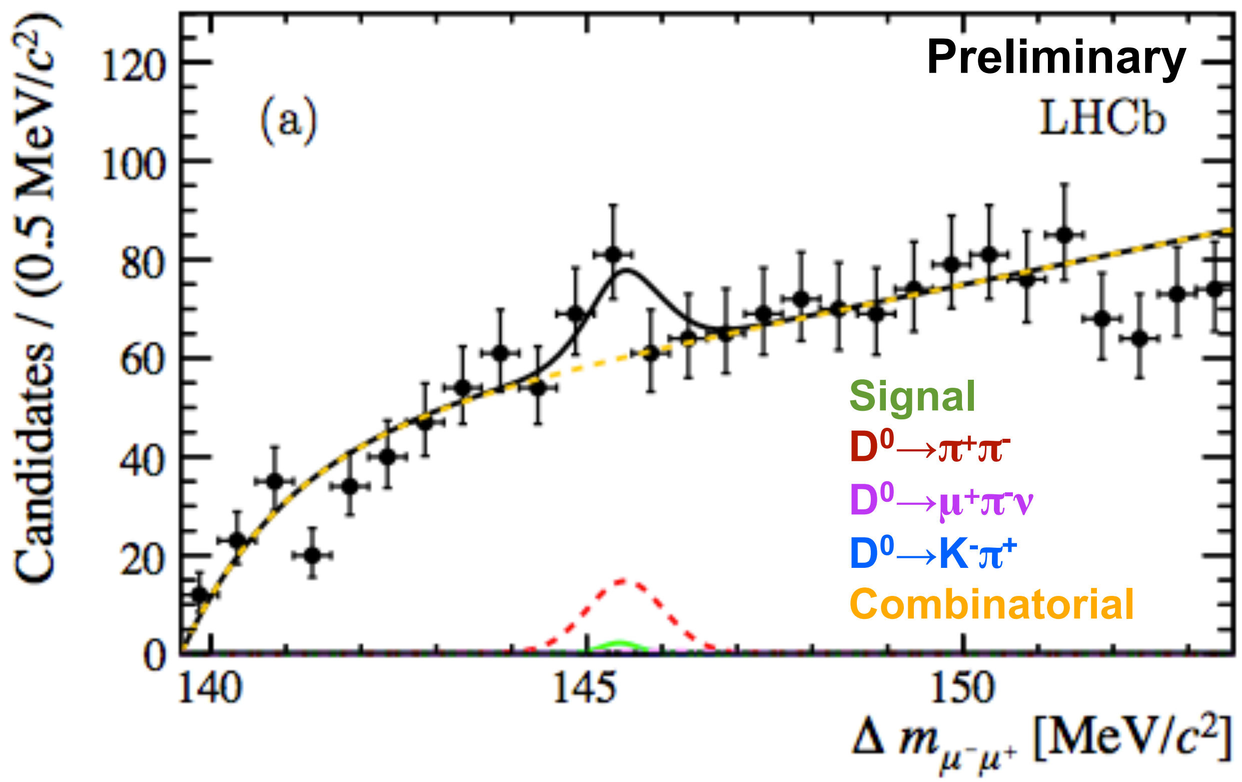
→ Main source of peaking background corresponds to double misID.
→ $D \rightarrow K\pi$ used to control $\pi \rightarrow \mu$ ID rate in data
→ MisID $D^0 \rightarrow \pi^+\pi^-$, contribution yield floated in the fit, with 45±19 as gaussian constraint
→ Stability check using twice looser constraint

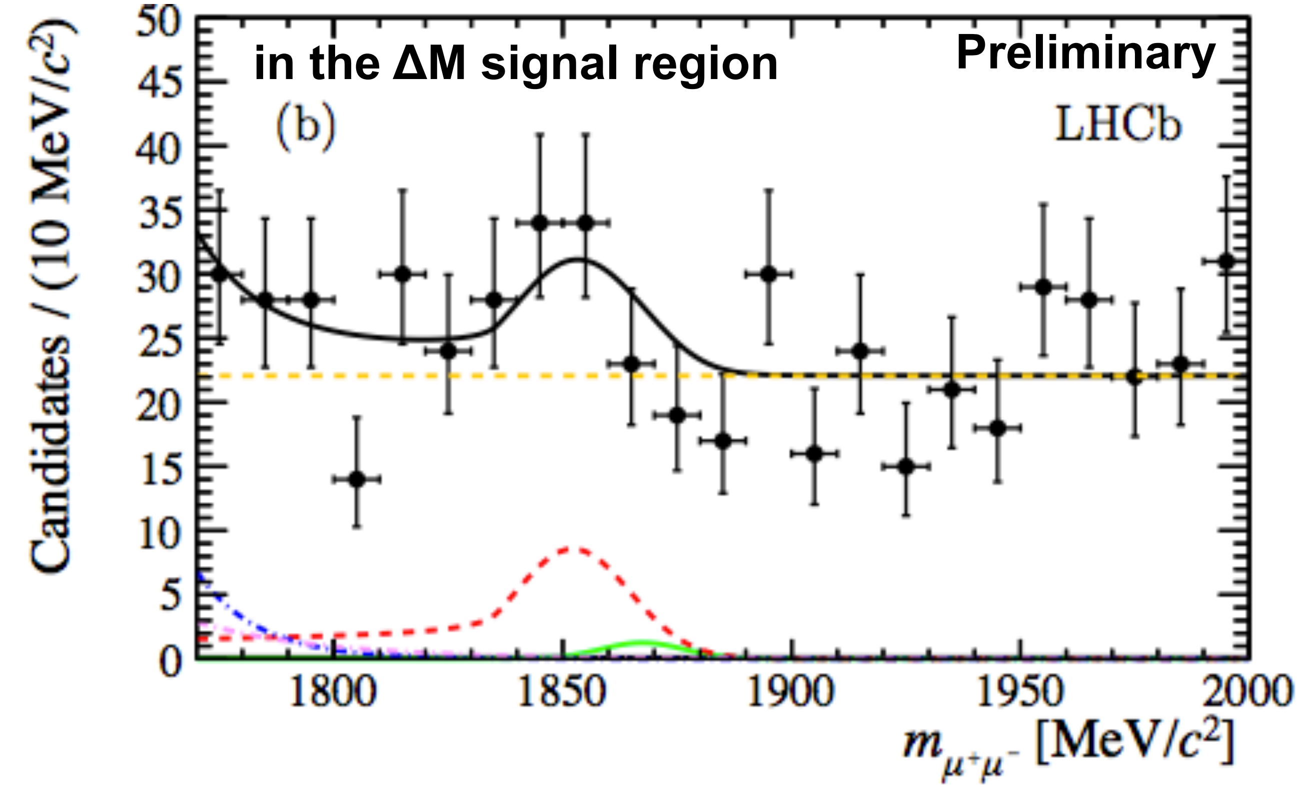


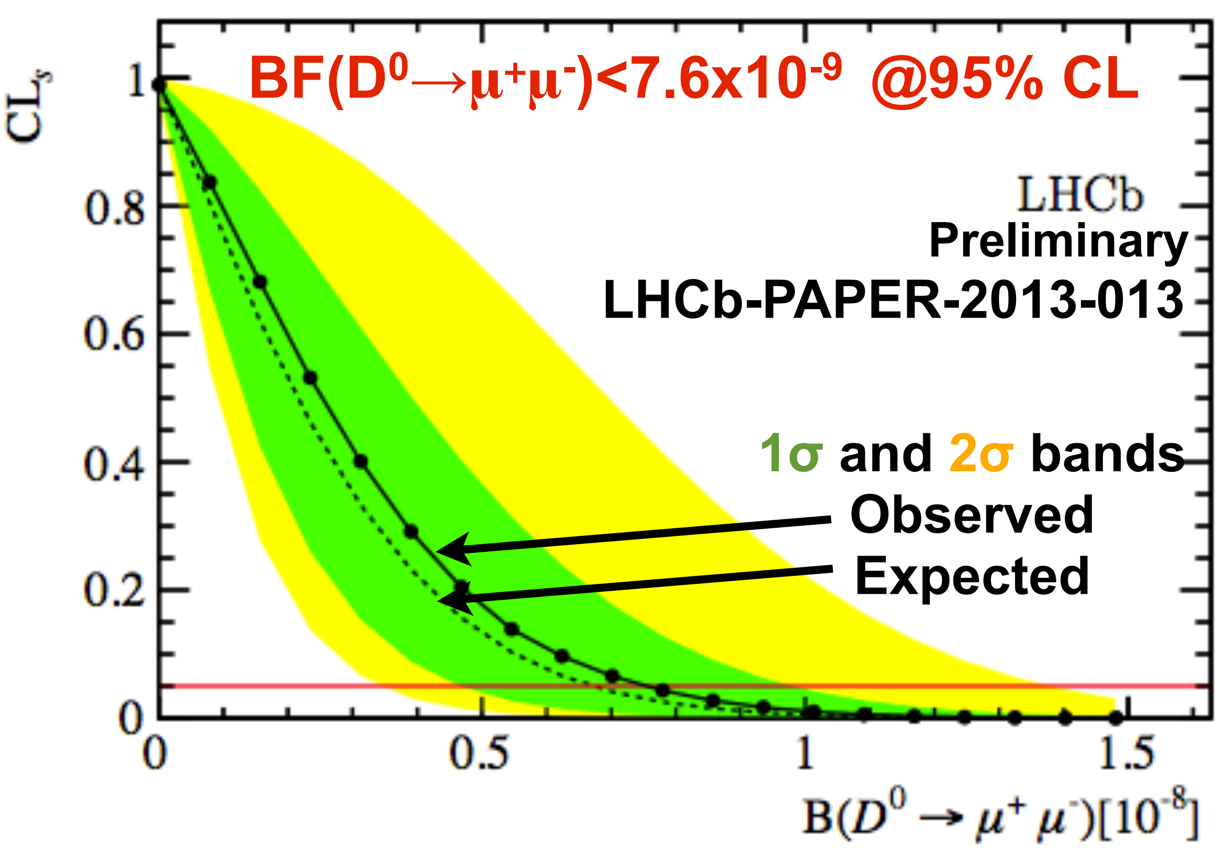
Efficiency ratio
→ Trigger and PID
→ $J/\psi \rightarrow \mu^+\mu^-$ to control trigger and PID efficiency of the signal
→ $D^0 \rightarrow K^-\pi^+$ tagged and untagged as control sample for the normalization mode

$D^0 \to \mu^+\mu^-$ at LHCb

New







Source	relative uncertainty(%)
Material interactions	6.0
Muon identification efficiency	2.6
Hadronic trigger efficiency	4.9
Muon trigger efficiency	2.7
$\mathcal{B}(D^0 \to \pi^+\pi^-)$	1.9
Total systematic uncertainty	8.8

No significant excess of signal wrt the expected background

Most stringent limit up to date

$D^0 \to l^+ l'^-$ at BaBar

468/fb sample, PRD86(2012)0302001

D^0 reconstructed in e^+e^-, $\mu^+\mu^-$ (FCNC) and $e^\mp\mu^\pm$ (LFV)
Normalized to the $\pi^+\pi^-$ decay mode, and the $K^-\pi^+$ final state used to compute particle misID effects

Multivariate methods (Fisher) used to reject large amount of $B\bar{B}$ and $q\bar{q}$ combinatoric events. $\cos\theta_H$ used as well to reject $B\bar{B}$ events

Largest uncertainties from bkg yields determination ~20%

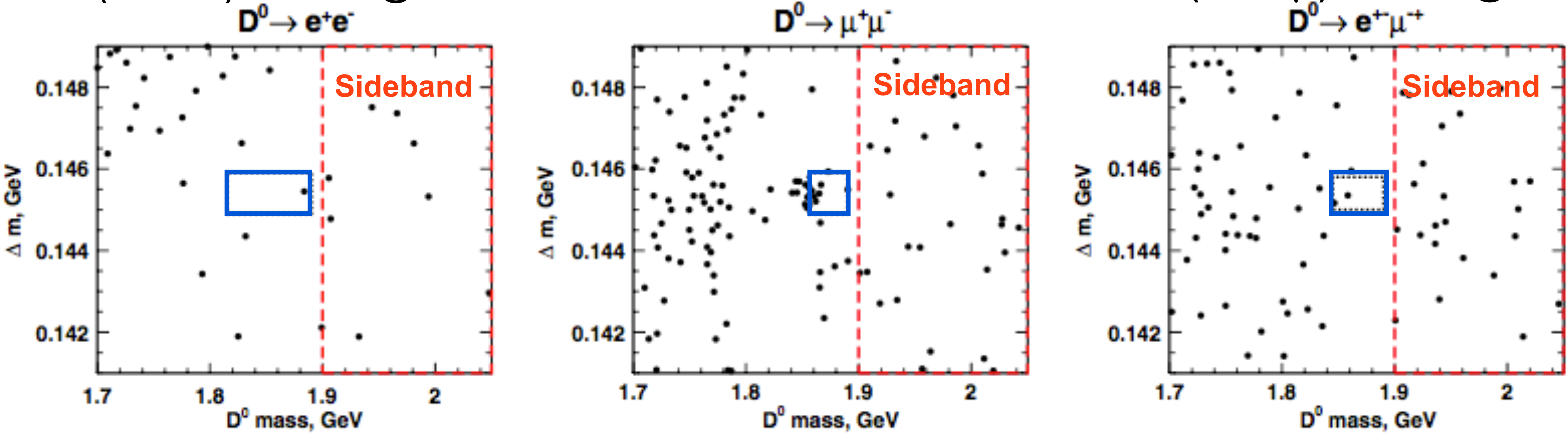
Excess of events in the $\mu^+\mu^-$ signal region, where $\pi^+\pi^-$ events show up. 8 events observed, 3.9±0.6 bkg events expected. Excess is not statistically significant and compatible with upward bkg fluctuation.

Feldman-Cousin method used for the CI extraction. Results of same order as 2010 Belle measurement PRD81(2010)091102R

$BF(D^0 \to e^+e^-) < 1.7\times10^{-7}$ @90%

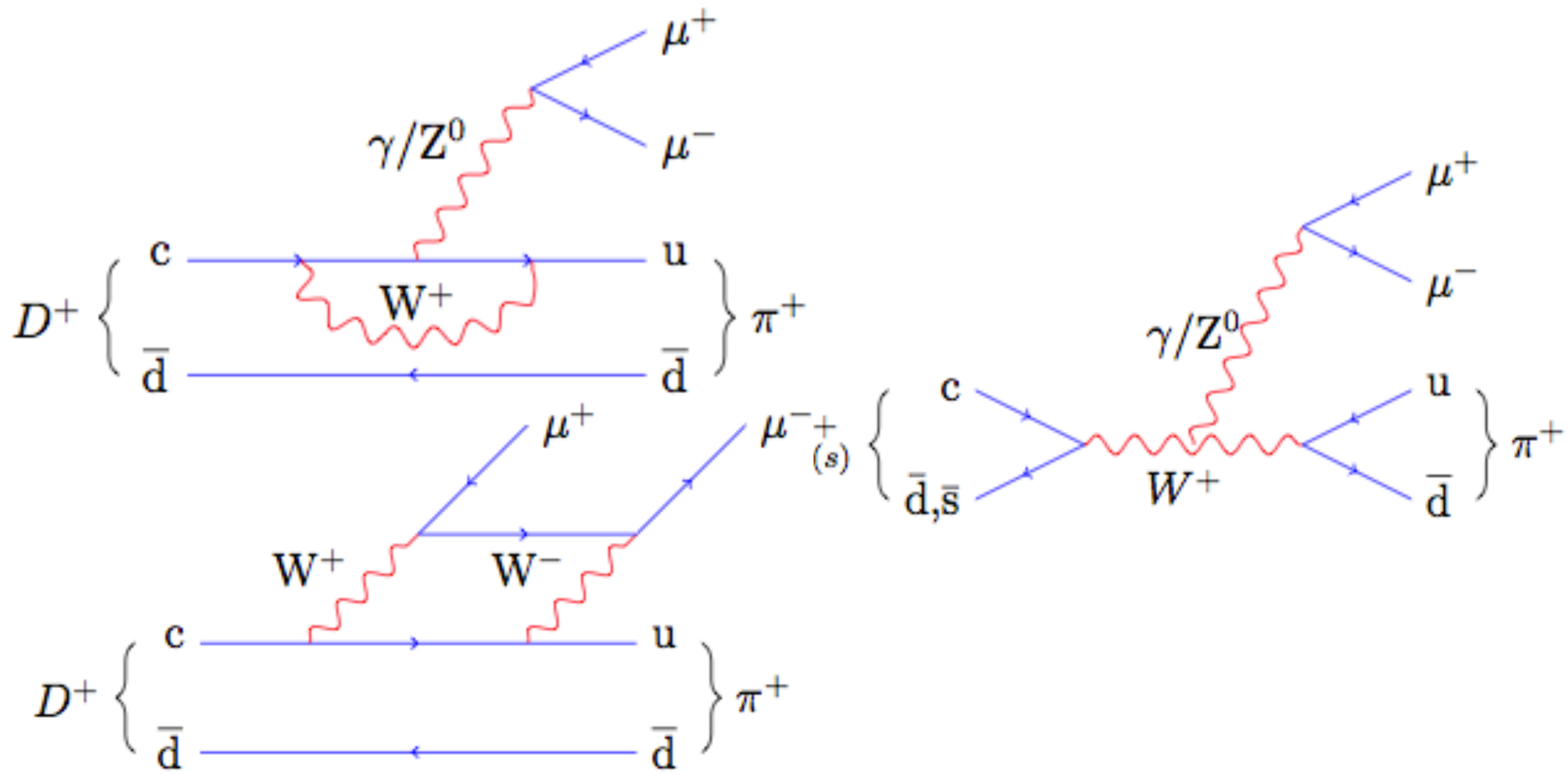
$BF(D^0 \to \mu^+\mu^-)$ in $[0.6, 8.1]\times10^{-7}$ @90%

$BF(D^0 \to e^+\mu^-) < 3.3\times10^{-7}$ @90%

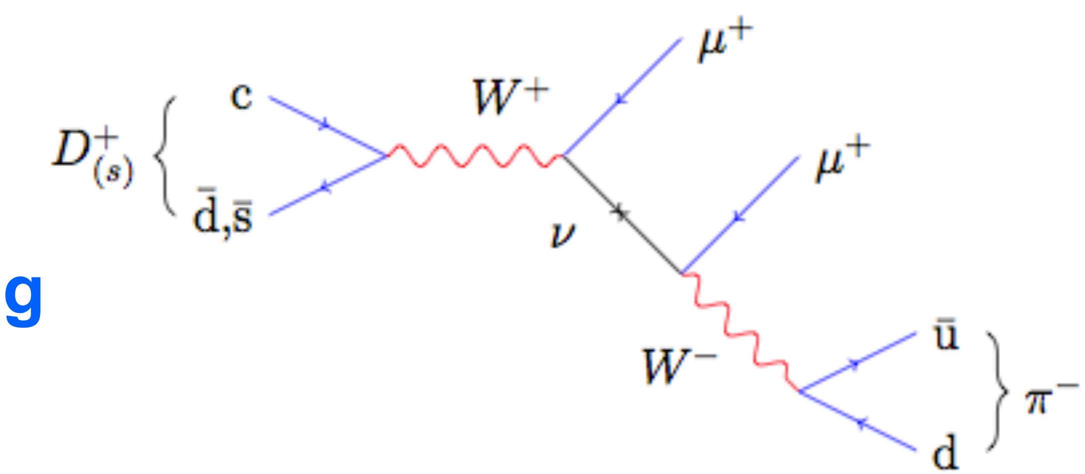


$D_{(s)}^{+} \to \mu^{\mp}\mu^{+}\pi^{\pm}$

FCNC $c \to u\mu^+\mu^-$ transitions in SM heavily suppressed by GIM mechanism
BF_{th}*~10^{-9}
These modes can be enhanced by physics BSM



LNV $c \to u\mu^+\mu^+$ forbidden in SM but allowed in models including Majorana neutrinos



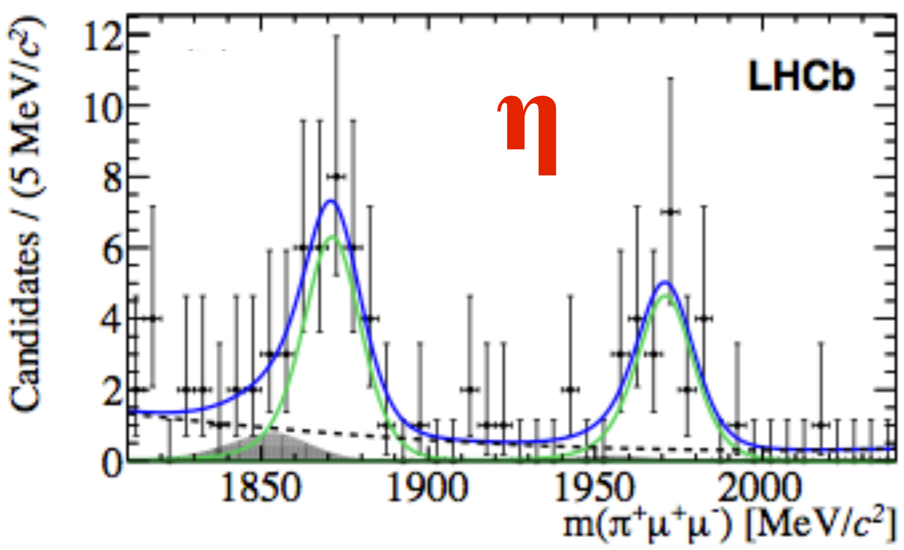
*Fajfer, et.al, PRD64(2001)114009
Fajfer, et.al., PRD76(2007)074010
Paul, et.al, PRD83(2011)114006

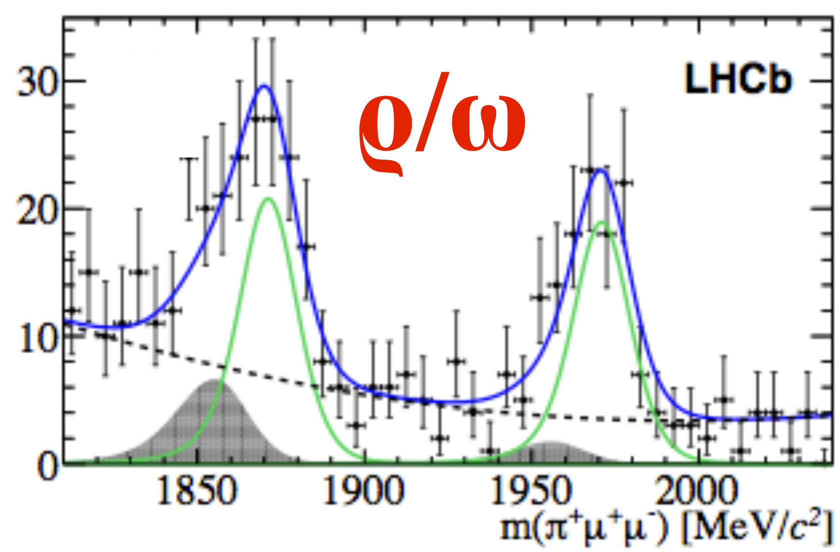
$D_{(s)}^+ \to \mu^+\mu^-\pi^+$ at LHCb

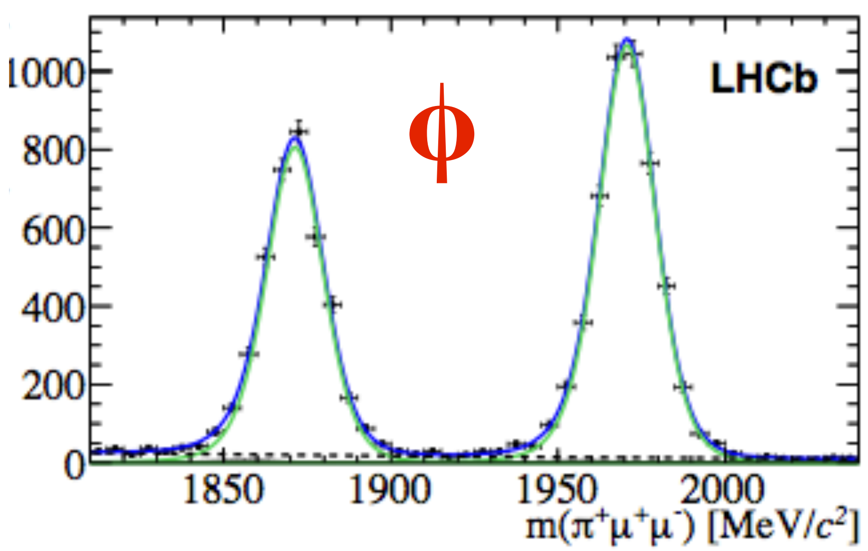
1/fb @√s=7TeV arXiv:1304.6365. Submitted to PLB

→ Selection criteria similar to the one used in $D^0 \to \mu^+\mu^-$ analysis.
→ Additionally, isolation variables exploited at selection
→ Main source of background is the final state with 3 pions
→ $D_{(s)}^+ \to \pi^+\phi(\mu^+\mu^-)$ mode used for normalization and as control sample
→ Analysis performed in regions of $q^2=M^2(\mu^+\mu^-)$
→ Double misID peaking background extracted from the fit. Shape extracted from $D_{(s)}^+ \to \pi^+\pi^+\pi^-$ sample with looser PID requirement and reconstructed with the μ mass hypothesis

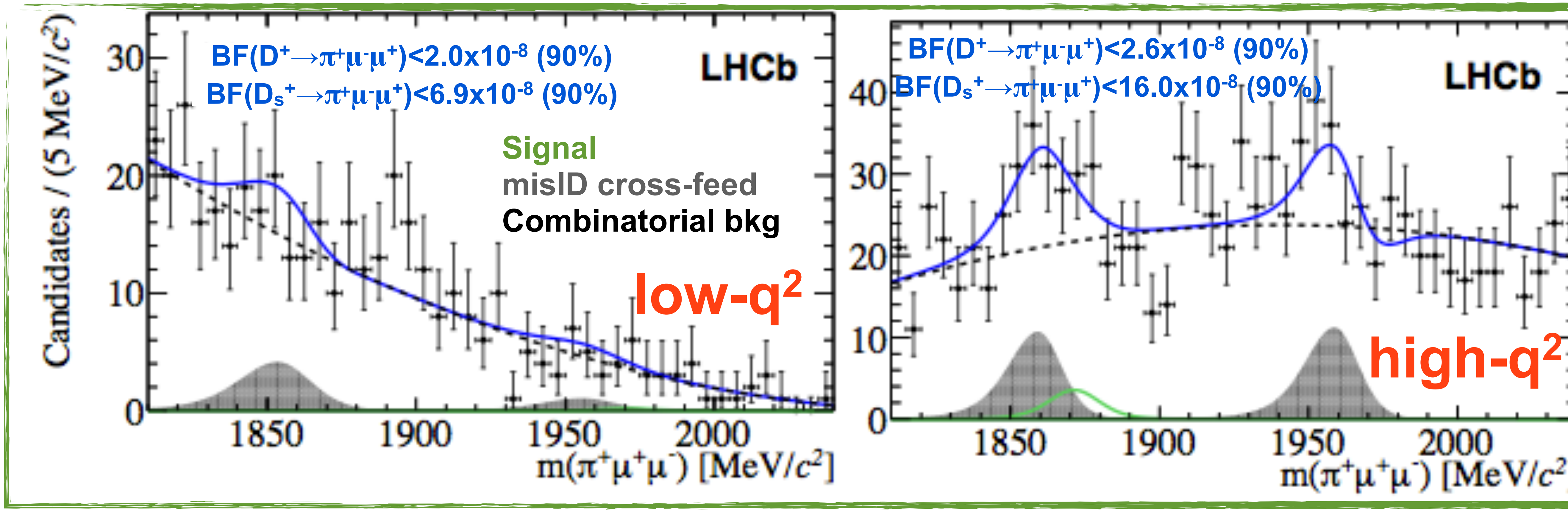
Signal
misID cross-feed
Combinatorial bkg







$D_{(s)}^+ \rightarrow \mu^+\mu^-\pi^+$ at LHCb



FCNC contributions sensitive to NP constrained to regions far from the resonances: low and high q^2 values
Consistent with no signal observation and limit is ~2 orders of magnitude improved wrt previous measurements*

*D0 PRL100(2008)101801
BaBar PRD84(2011)072006

$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3\,(8.3) \times 10^{-8}$$
$$\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) < 4.1\,(4.8) \times 10^{-7}$$

@90(95)% CL

arXiv:1304.6365

$D_{(s)}^{+} \to \mu^{+}\mu^{+}\pi^{-}$ at LHCb

LNV decay forbidden in the SM

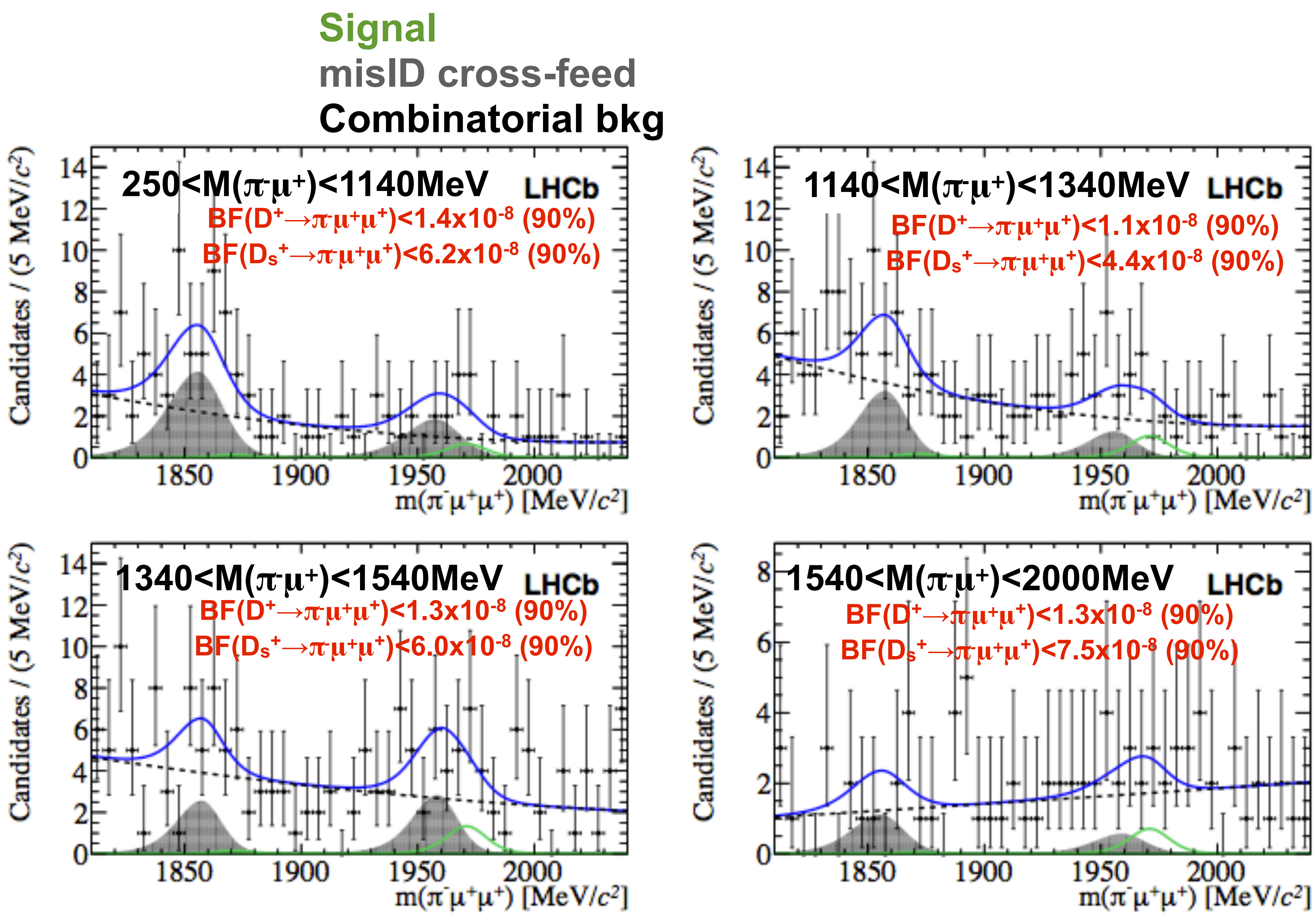
Split in 4 bins in $M(\pi^{-}\mu^{+})$ to improve sensitivity to the signals

Peaking bkg dominated by 3π final state

No evidence of LNV

Limit ~2 orders of magnitude improved wrt previous measurements*

*BaBar PRD84(2011)072006



$$\mathcal{B}(D^{+} \to \pi^{-}\mu^{+}\mu^{+}) < 2.2\,(2.5) \times 10^{-8},$$
$$\mathcal{B}(D_s^{+} \to \pi^{-}\mu^{+}\mu^{+}) < 1.2\,(1.4) \times 10^{-7}$$

@90(95)% CL

arXiv:1304.6365

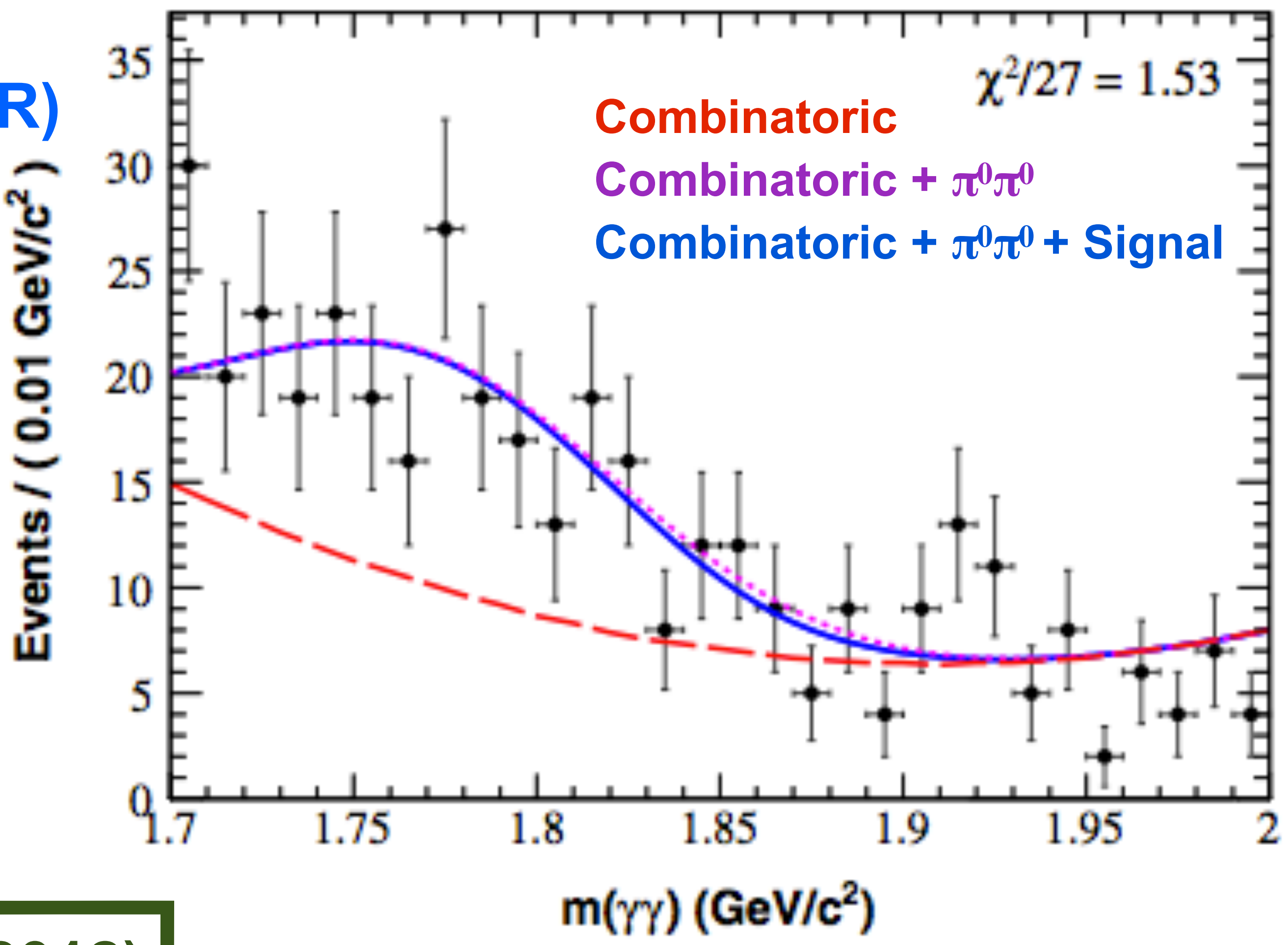
$D^0 \to \gamma\gamma$ @BaBar

→ FCNC mode, forbidden at tree level
- → Observed in K and B meson systems. In charm mesons it is GIM suppressed.
- → Vector meson dominance BF~10^{-8}
- → Short distance BF~10^{-11}
- → MSSM enhancement up to BF~10^{-6}, i.e $c \to u\gamma$ via gluino exchange

BaBar, 470/fb @Υ(4S), PRD85(2012)091107(R)

→ $D^0 \to K_S \pi^0$ used for normalization
→ $D^0 \to \pi^0 \pi^0$ largest background. Largely studied using MC samples
→ Signal yield slightly negative and compatible with no signal observation

→ BF<2.4×10^{-6} @90% CL



BESIII, 2.9/fb @ψ(3770), arXiv:1208.4744 (2012)
→ BF<4.7×10^{-6} @90% CL

Conclusions

- We presented the most recent experimental results on charm spectroscopy and rare decays

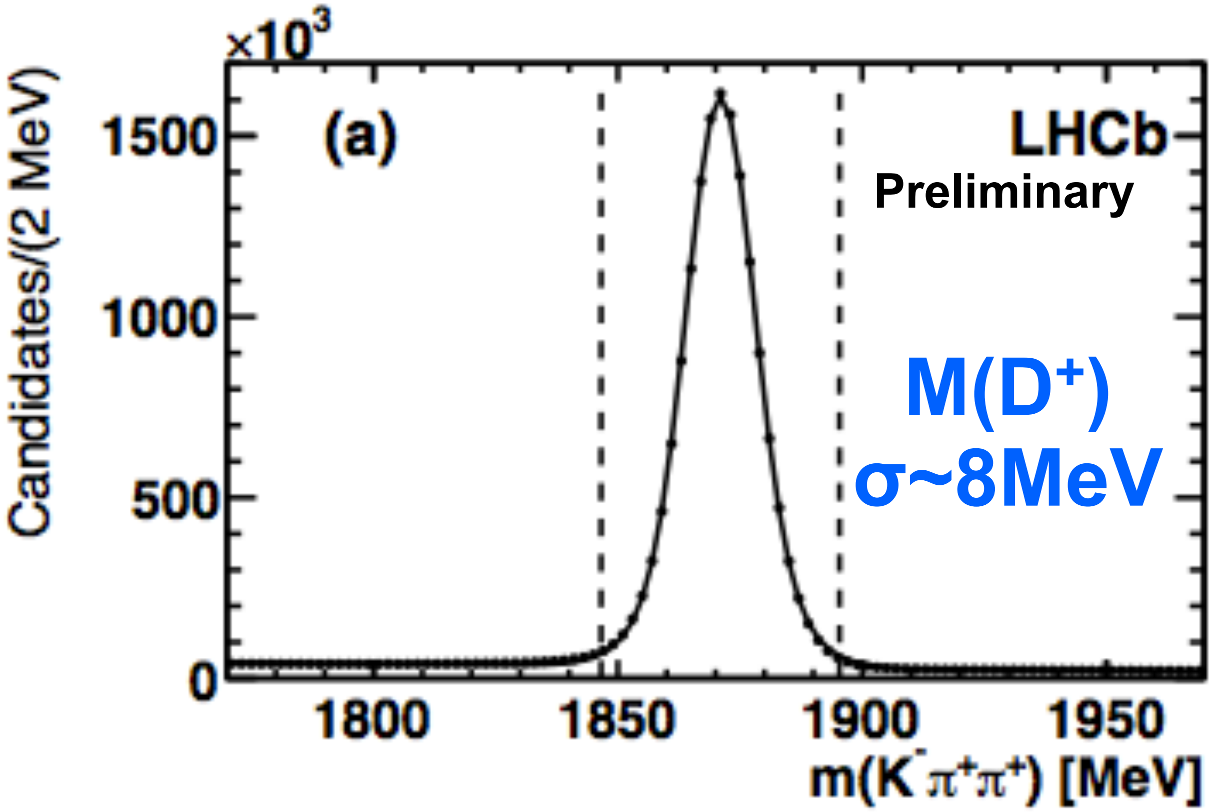
- Heavy flavor facilities have proven the capability to perform world best measurements of the properties of charmed mesons. Collaborations are actively working in the understanding of quark model predictions and searching for physics BSM using charmed meson decays, but also exploring more physics accessible via the study of charm mesons.

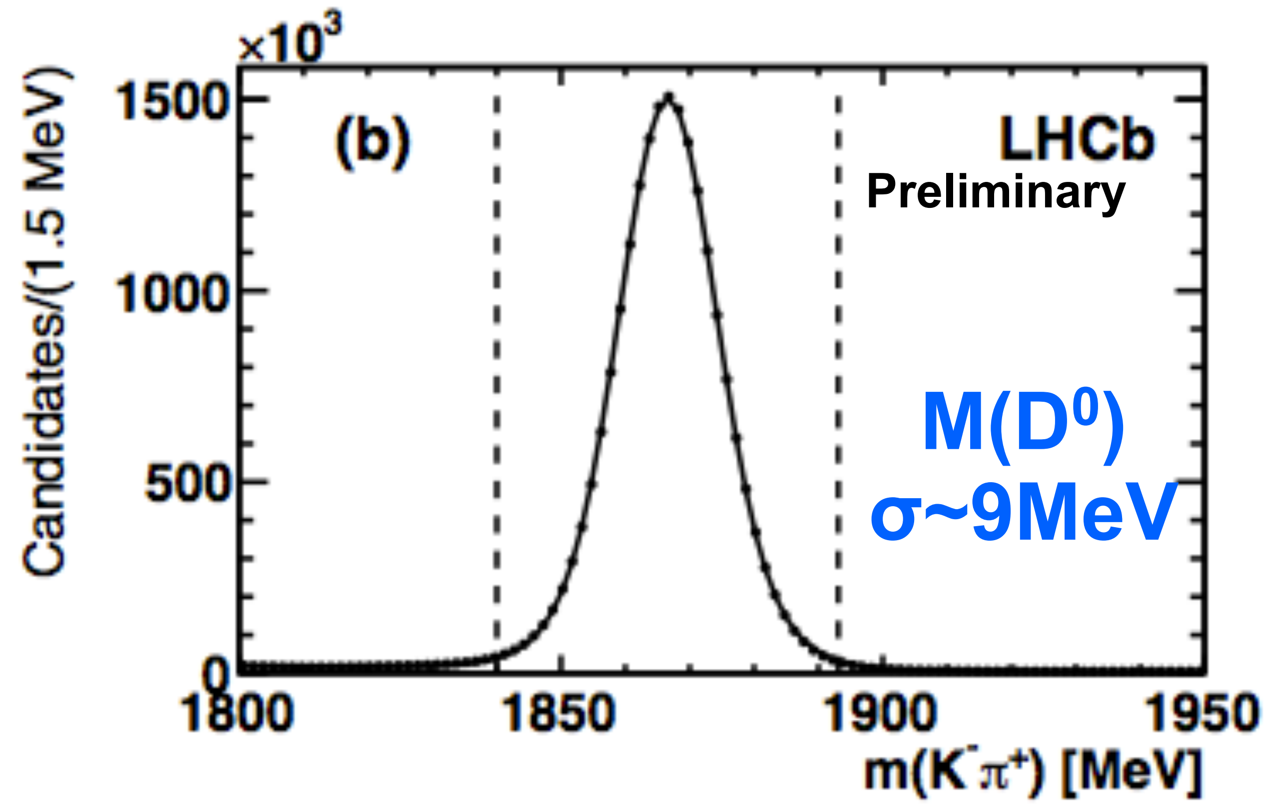
- Many other results still to come. Stay tuned!

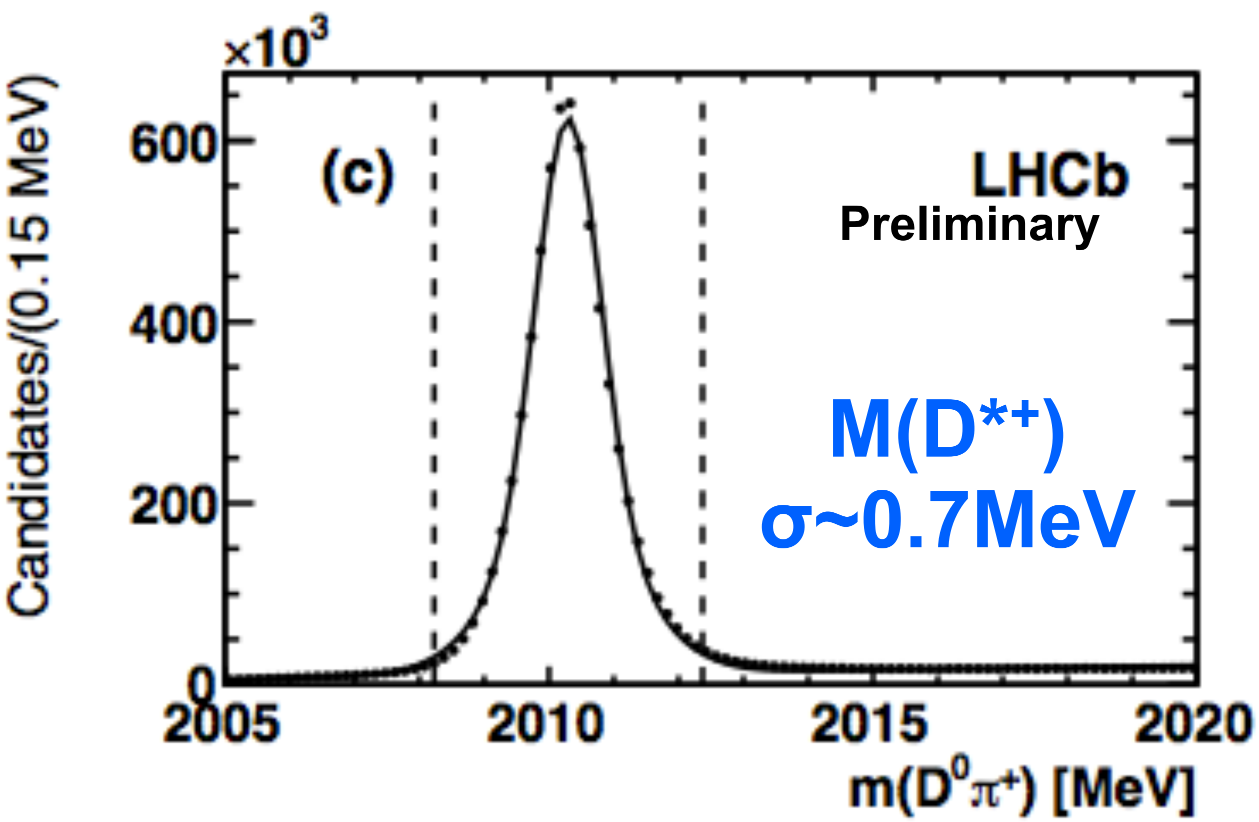
Backup slides

On the *D* signals

New







Purity above 95% in the signal region.
Very large amount of events.
Negligible contribution from fake D mesons.
Selected only events in the ±3σ mass window.

Excellent samples for spectroscopy studies