Experimental Perspectives on Semileptonic B_s decays

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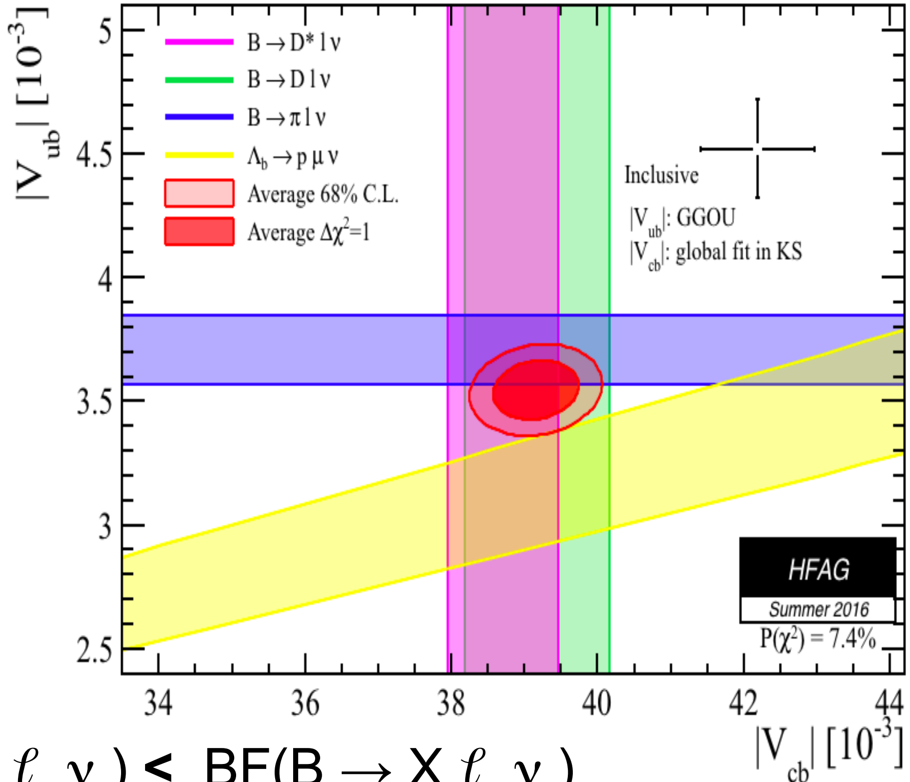
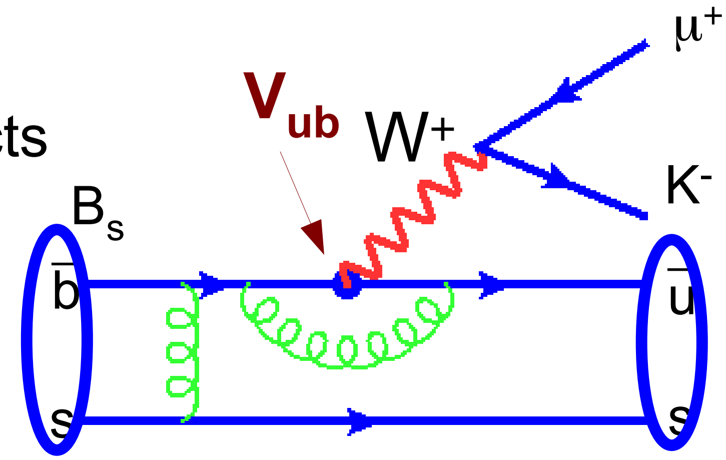
Semileptonic B decays



- Many puzzles still unsolved
  - $|V_{ub}|$ Exclusive – Inclusive discrepancy
    - $\Lambda_b \to p\ \mu\ \nu$ consistent with $B \to \pi\ \ell\ \nu$
  - $|V_{cb}|$ Exclusive – Inclusive discrepancy
    - Dominated by precise $B \to D^*\ \ell\ \nu$
    - $B \to D\ \ell\ \nu$ consistent with both!
  - $BF(B \to (D + D^* + D^{**} + D^{(*)}\pi\pi + D_sK\ X)\ \ell\ \nu) <\ BF(B \to X\ \ell\ \nu)$
    - Other excited D** states not measured? Missing modes with multipions or other mesons (η)?
  - 1 / 2 < 3 / 2: OPE predicts $B \to D(1/2)\ \ell\ \nu \ll B \to D(3/2)\ \ell\ \nu$
    - Direct measurements observe an enhancement of the $B \to D(1/2)\ \ell\ \nu$
      - Inconsistences between BaBar and Belle!
  - R(D)-R(D*) discrepancy with SM prediction at 4σ level
    - Combined measurements from BaBar, Belle and LHCb

Semileptonic B_s decays

- Much less is know on semileptonic B_s decays
  - Only difference with $B^{0/+}$ is the spectator quark
- Expected corrections due to SU(3) breaking effects



- Inclusive decays
  - Bigi et al. JHEP09(2011) 012, solid prediction
    - $\Gamma(B_s) / \Gamma(B_d) \sim 0.99$

- Exclusive Form Factors for $B_s \rightarrow D_s(*)\ell\nu$ expected similar to $B \rightarrow D(*)\ell\nu$
  - P-QCD: differences < 10%, Xiao et al Chin.Sci.Bull (2014)
  - LatticeQCD in $B_s \rightarrow D_s\ell\nu$: very small SU(3) breaking
    - Steeper slope and larger curvature FNAL/MILC PRD85, 114502(2012)
    - Similarly HPQCD, arXiv:1611.09667v2; Atou at al. EPJC (2014) 74:2861
    - Not yet L-QCD calculations for $B_s \rightarrow D_s^*\ell\nu$

Lattice calculation possible only at large recoil, it would be crucial to test experimentally the SU(3) brwaking in the full kinematic range

Why semileptonic B_s decays ?

- Cross-check of the B SL decay: everything done on B semileptonic can be repeated on B_s
  - Important to measure magnitude of the SU(3) breaking
  - Measurements of the FF are crucial for predictions of hadronic B_s decays

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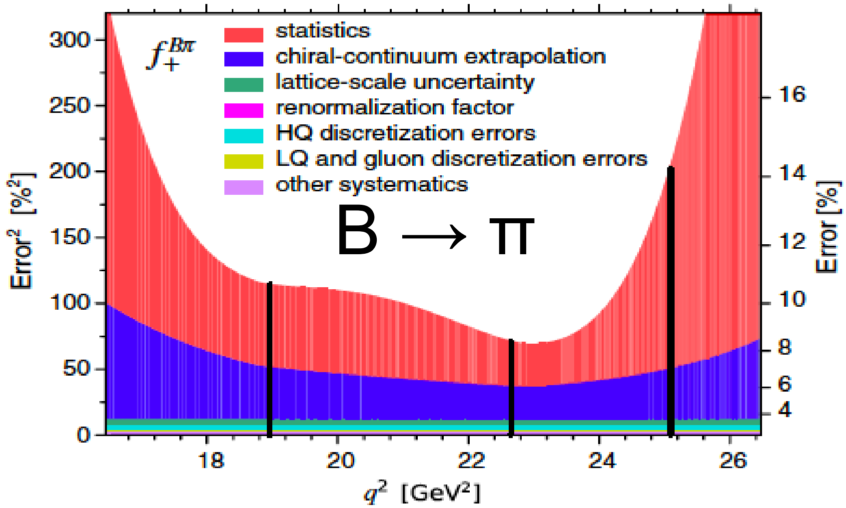
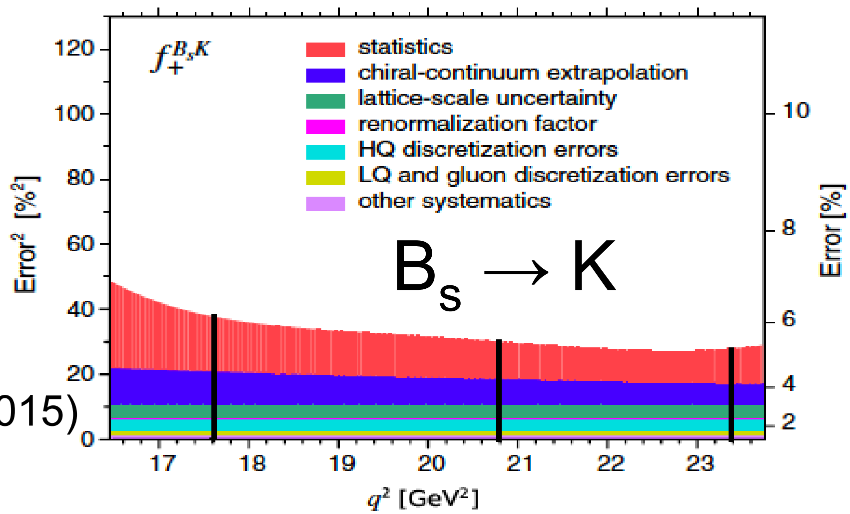
- Lattice more precise: calculations can be done at the s-quark physical mass
- True for both $b \to c$ and $b \to u$

Golden modes for $|V_{cb}|$ and $|V_{ub}|$

$$B_s \to D_s^{(*)} \ell \nu_\ell$$
$$B_s \to K \ell \nu_\ell$$





RBC-UKQCD(2015)

$B_s \to K \mu \nu$ @ LHCb

- Comparison with $\Lambda_b \to p \mu \nu$

S. Stefkova @ ICHEP

Decay	$\Lambda_b^0 \to p\mu^-\overline{\nu}$	$B_s^0 \to K^-\mu^+\nu$
Production fraction	20%	14%
Branching fraction	4×10^{-4}	1×10^{-4}
Source of backgrounds	Λ_c^+	Λ_c^+, D^0, D^+, D_s
$\mathcal{B}(X_c)$ error HFAG16	±3.7%(biggest systematic!)	±3.9%
Theory error FF	5%	< 5%
Normalization channel	$\Lambda_b^0 \to \Lambda_c^+\mu^-\nu$	$B_s^0 \to D_s^-\mu^+\nu$

Backgrounds in the normalization channel for the B_s: more difficult to fight

$$\frac{B(\Lambda_b \to \Lambda_c \mu\nu)}{B(\Lambda_b \to \Lambda_c \mu\nu X)} \approx \frac{6.2\%}{10.2\%}$$

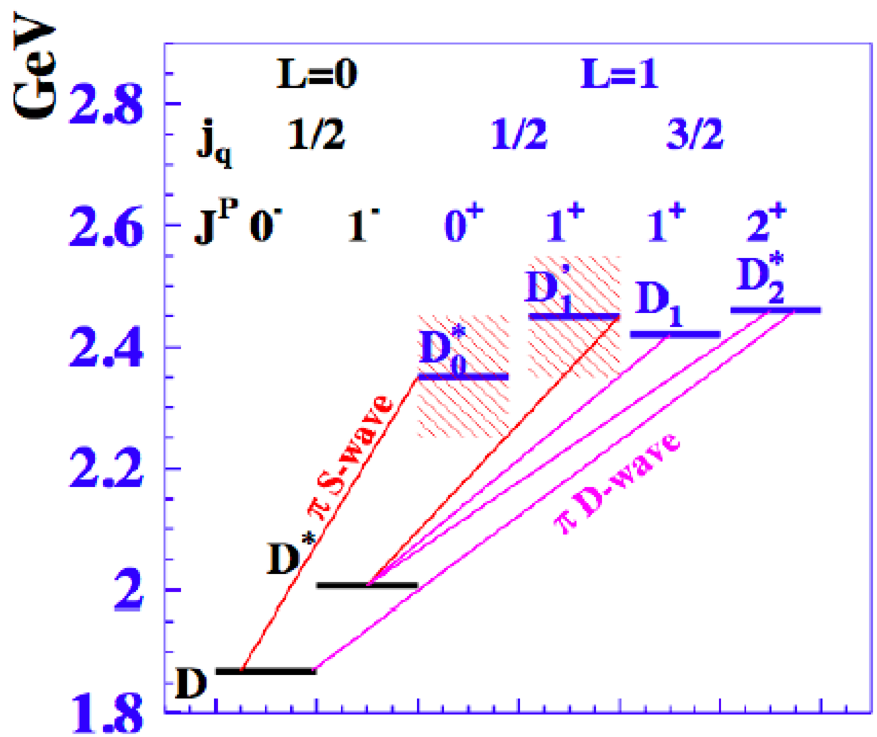
$$\frac{B(B_s \to D_s \mu\nu)}{B(B_s \to D_s \mu\nu X)} \approx \frac{2.4\%}{8.1\%}$$

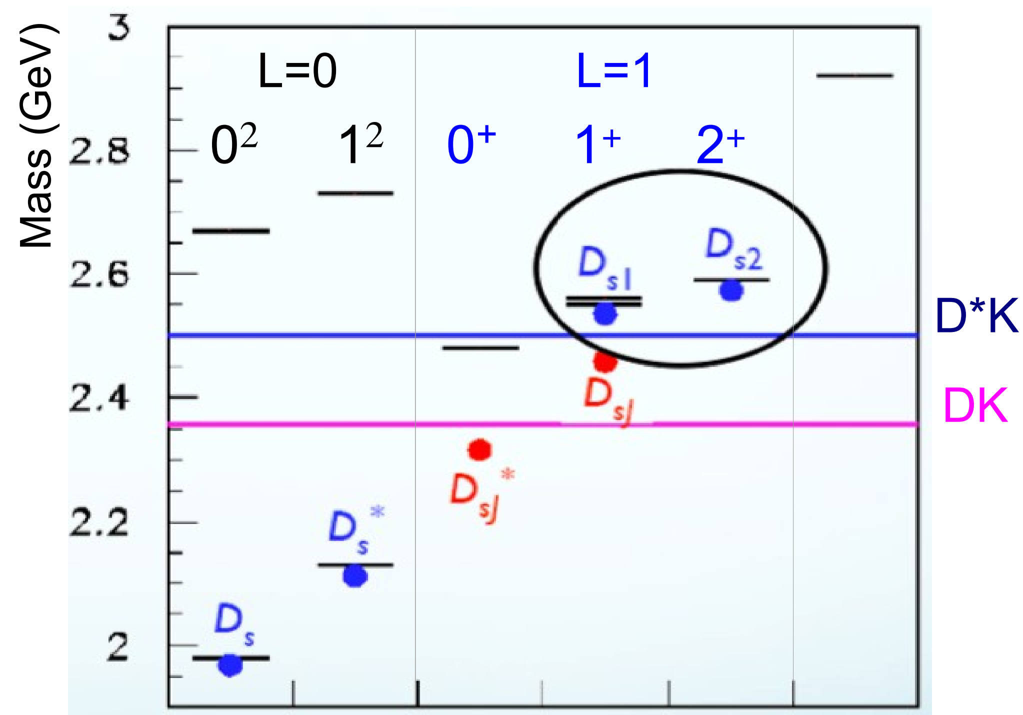
First excited D_s decays mainly in neutrals:
- standard isolation tools does not work
- rely on kinematics and the ECL

- Same trick used for $\Lambda_b \to p \mu \nu$ (both q^2 solutions > 15 GeV^2) or a differential measurement?

Why semileptonic B_s decays ?

- The excited D_s** states have huge differences with corresponding D**





	J^P	Mass (MeV)	Width (MeV)	Observed decays
D_0^*	0^+	2352 ± 50	261 ± 50	$D\pi$
D_1'	1^+	2427 ± 36	384^{+130}_{-105}	$D^*\pi$
D_1	1^+	2421.3 ± 0.6	27.1 ± 2.7	$D^*\pi, D^0\pi^+\pi^-$
D_2^*	2^+	2462.6 ± 0.7	49.0 ± 1.4	$D^*\pi, D\pi$

	J^P	Mass (MeV)	Width (MeV)	Observed decays
D_{s0}^*	0^+	2317.8 ± 0.6	< 3.8	$D_s^+\pi^0$
D_{s1}'	1^+	2459.5 ± 0.6	< 3.5	$D_s^{*+}\pi^0, D_s^+\gamma, D_s^+\pi^+\pi^-$
D_{s1}	1^+	2535.28 ± 0.20	< 2.5	$D^{*+}K^0, D^{*0}K^+$
D_{s2}^*	2^+	2572.6 ± 0.9	20 ± 5	D^0K^+

Why semileptonic B_s decays ?

- The excited D_s^{**} states have huge differences with corresponding D^{**}

- J=1/2 states D_{s0}^* and D_{s1}' are narrow
  - Decay into D_s through neutrals (γ and π^0),
    - Have to rely on kinematics and the ECL (neutral reconstruction/veto)
    - Only D_{s1}' feed-down into D_s^*
- The j=3/2 states D_{s0} and D_{s2}^* decay in DK and D*K
  - Those do not contribute to feed-down into D_s or D_s^*

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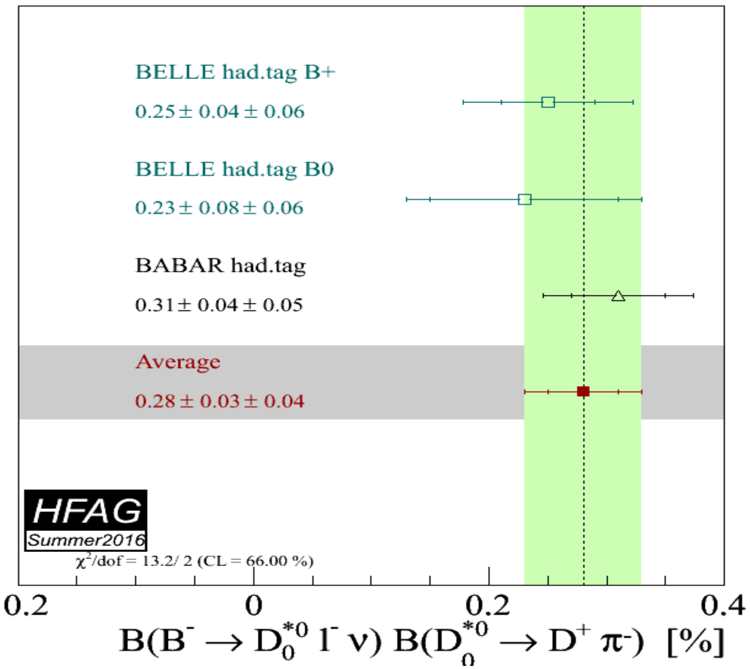
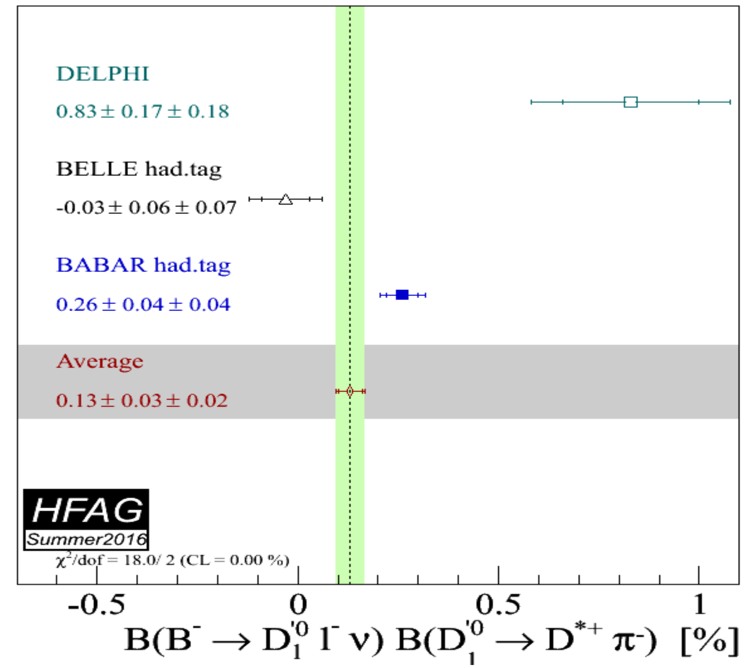
$B \to D^{**}\ell\nu$.ΣΩ $B_s \to D_s^{**}\ell\nu$

- $B \to D^{**}\ell\nu$ Decay into narrow resonances consistent with prediction
  - Decay into wide ½ states not clear





- D_s excited states are all narrow, so they offer a new path to understand these puzzle
  - Moreover SL decays into $D_s(2317)$ and $D_s(2460)$ can shed light on the nature of these states

Becirevich et al. PRD87(2013) 054007

Navarra et. al. PRD92(2015) 014031
Zhao et. al. EPJC51 (20017) 601-606

- SL BF into 3/2 states have been measured by D0 and LHCb
  - Consistent with HQS predictions and B decays

PLB 698 (2011) 14-20

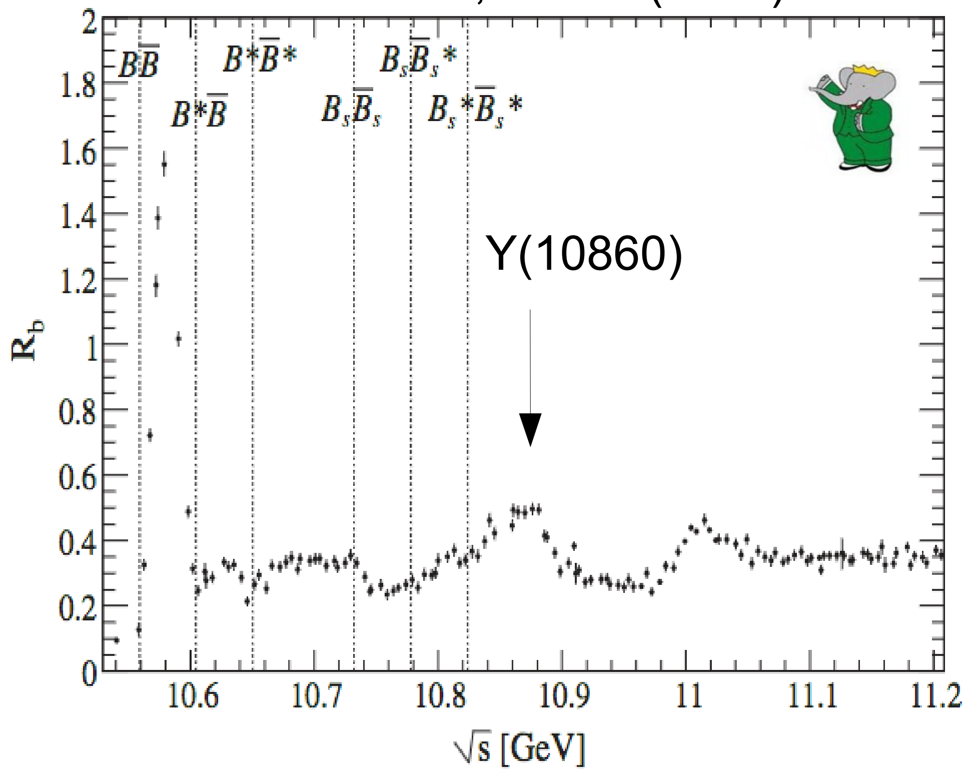
$$\frac{\mathcal{B}(\overline{B}{}_s^0 \to D_{s2}^{*+} X \mu^- \overline{\nu})}{\mathcal{B}(\overline{B}{}_s^0 \to X \mu^- \overline{\nu})} = (3.3 \pm 1.0 \pm 0.4)\%$$

$$\frac{\mathcal{B}(\overline{B}{}_s^0 \to D_{s1}^{+} X \mu^- \overline{\nu})}{\mathcal{B}(\overline{B}{}_s^0 \to X \mu^- \overline{\nu})} = (5.4 \pm 1.2 \pm 0.5)\%,$$

B_s at B-Factories

- At B-Factories B_s production requires special runs at the Υ(5S)

BaBar PRL102,012001(2009)



Υ(4S)
~100% BB

Υ(5S)
~80% BB + B*B + B*B* + BBπ
17.6% $B_s^*B_s^*$
1.35% $B_sB_s^*$
0.5% B_sB_s

~ 1/5 decays into B_s

$m(B_s^*)-m(B_s) \approx 50$ MeV

Belle collected the largest sample at Υ(5S)
L = 121.4 fb^{-1} corresponding to $N(B_s) = 6.53 \times 10^6$
$\sigma(\Upsilon(10860) \rightarrow B_s^{(*)}\bar{B}_s^{(*)}) = (53.8 \pm 1.4 \pm 4.0 \pm 3.4)$ pb
Compared with $\sigma(\Upsilon(4S) \rightarrow B\bar{B}) = 1.06$ nb

Semi-inclusive of Bs decays measurement

$$B_s \rightarrow D_s^{(*)} \ell \nu_\ell X$$

PRD92,072013 (2015)

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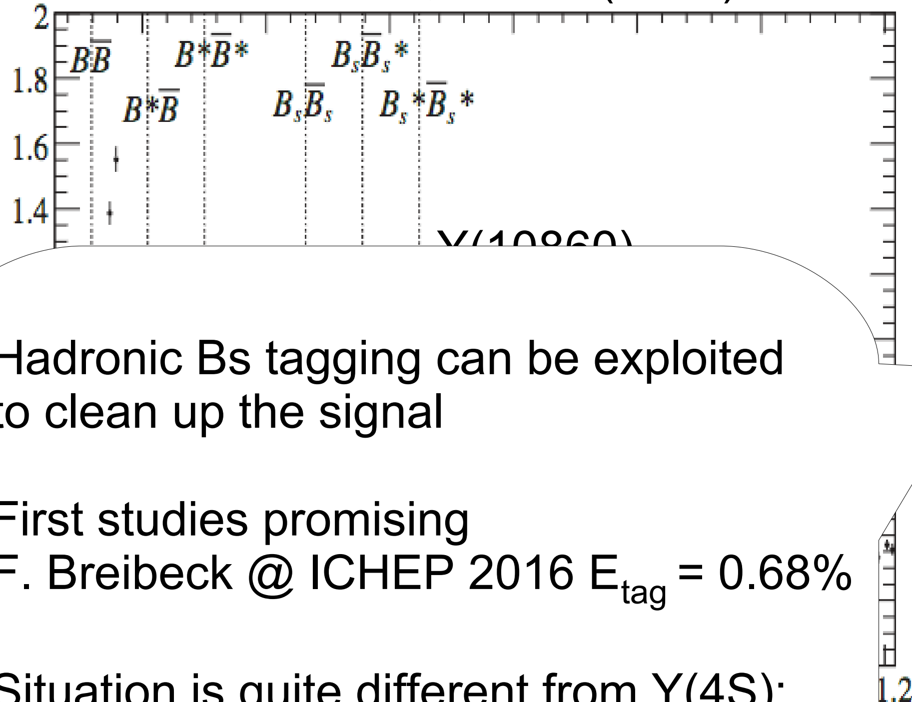

Hadronic Bs tagging can be exploited to clean up the signal

First studies promising
F. Breibeck @ ICHEP 2016 E_{tag} = 0.68%

Situation is quite different from Υ(4S):
Soft gamma's cannot be reconstructed the momentum of the Signal Bs ca be known with multi-fold ambiguties

Υ(4S)
~100% BB

Υ(5S)
~80% BB + B*B + B*B* + BBπ
17.6% $B_s^*B_s^*$
1.35% $B_sB_s^*$
0.5% B_sB_s

~ 1/5 decays into B_s

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... at Υ(5S)
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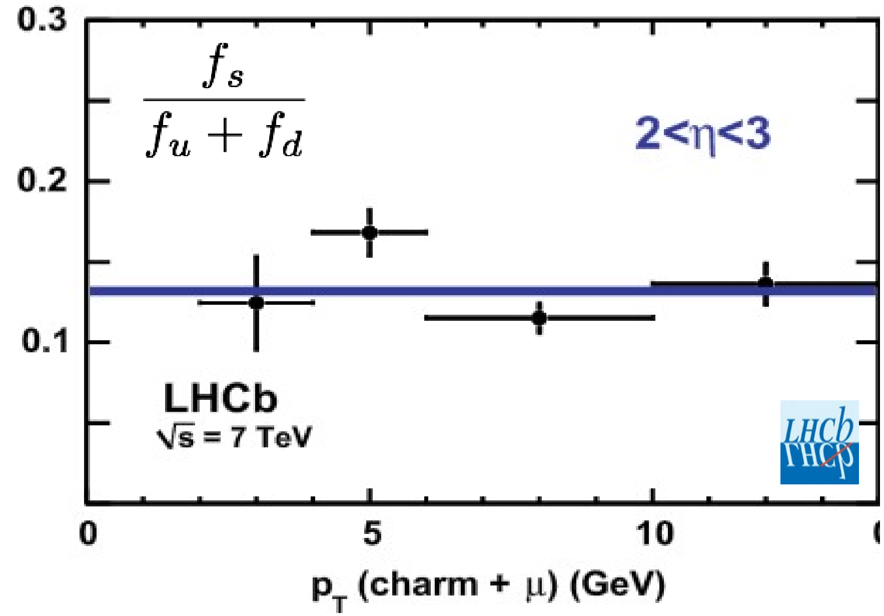
PRD92,072013 (2015)

B_s at LHCb

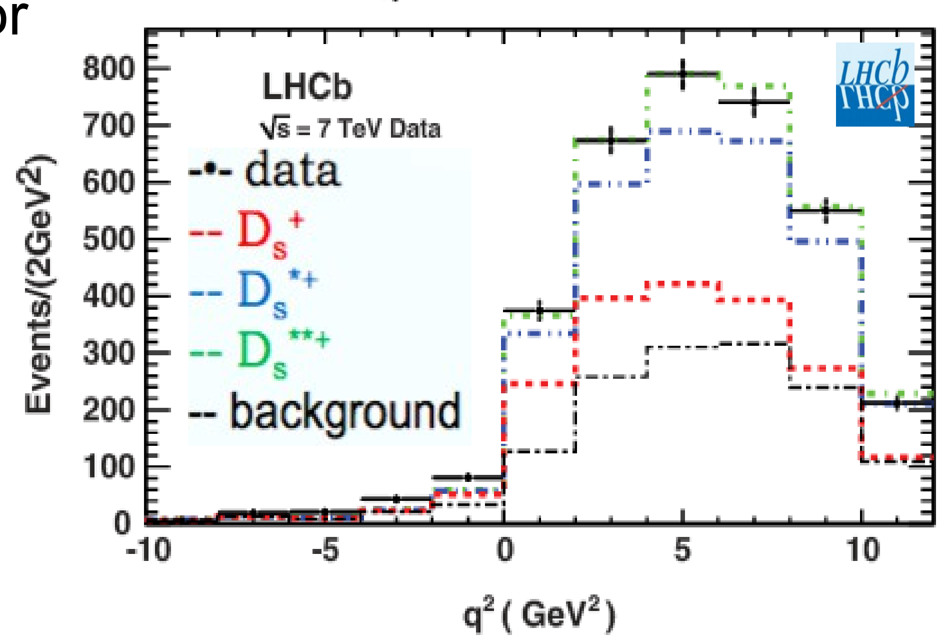
- In the LHCb acceptance
  - $\sigma_{7TeV}(bb) = 72 \pm 0.3 \pm 6.8\ \mu\cap$
  - $\sigma_{13TeV}(bb) = 154 \pm 1 \pm 14\ \mu\cap$
- About 14% of the b-hadrons are B_s

$$f_s/(f_u + f_d) = 0.134 \pm 0.004^{+0.011}_{-0.010}$$

LHCb PRD85(2012) 032008



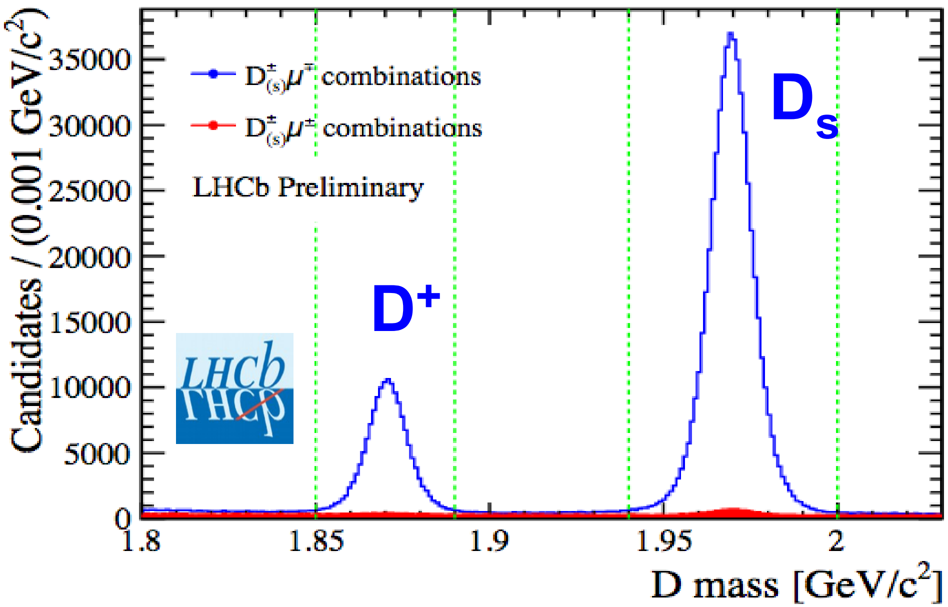
- SL $B_s \to D_s(^*)\ell\nu$ decays largely studied for production, mixing and lifetime studies
- SL decays as a function of the q^2 already studied with only first $3pb^{-1}$ (high efficient trigger)
  - Crude assumptions on D_s^*/D_s
  - Need further studies to translate in measurements of the Form Factors



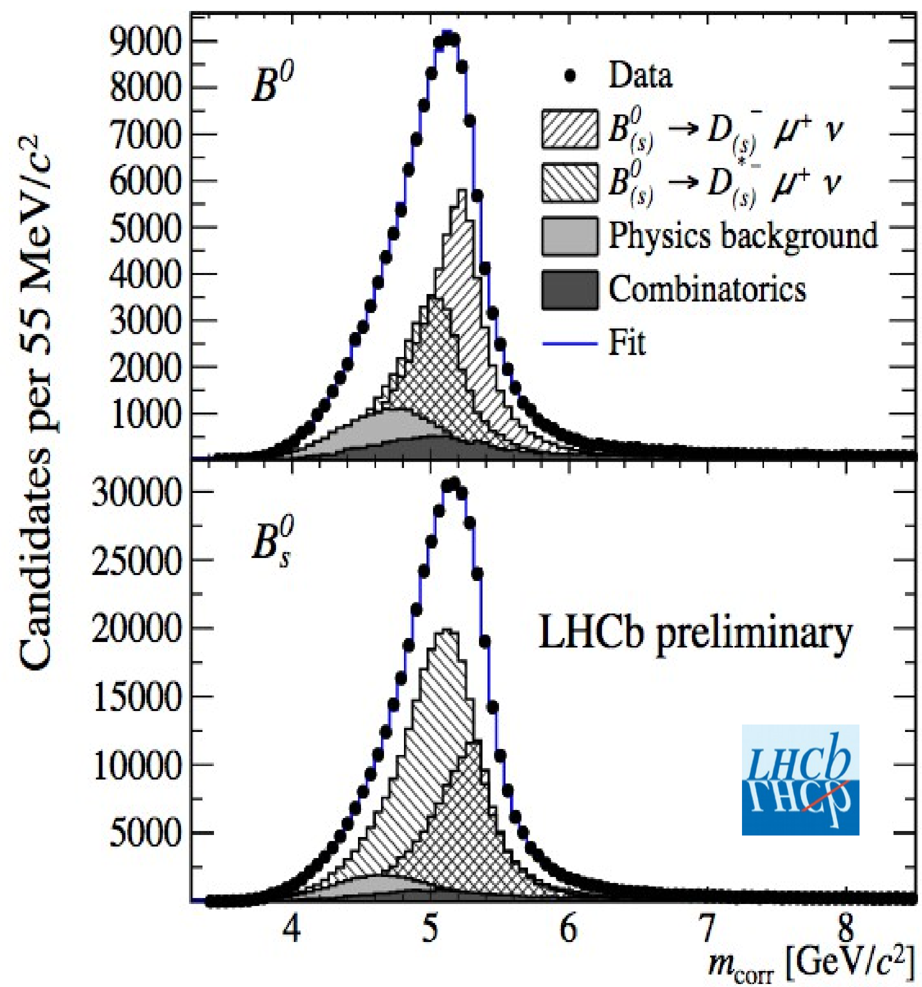
Semileptonic B_s at LHCb: an example

- Preliminary results on flavor-specific lifetime with $B_s \rightarrow D_s(^*)\ell\nu$, $D_s \rightarrow KK\pi$
- Based on $3fb^{-1}$: super-clean sample
  - 100K $D^+\mu$ 400K $D_s\,\mu$

B. Maurin @ Lake Louise 17



Component	Fit fraction [%]
$B_s^0 \rightarrow D_s^- \mu^+ \nu$	29.20 ± 0.52
$B_s^0 \rightarrow D_s^{*-} \mu^+ \nu$	57.77 ± 0.91
$B_s^0 \rightarrow D_{(s)}^{(**)}(D_s)X$	3.21 ± 0.74
$B_s^0 \rightarrow D_s(K\mu\nu)(\tau\nu)$	4.00 ± 0.28
Combinatorial	5.82 ± 0.13



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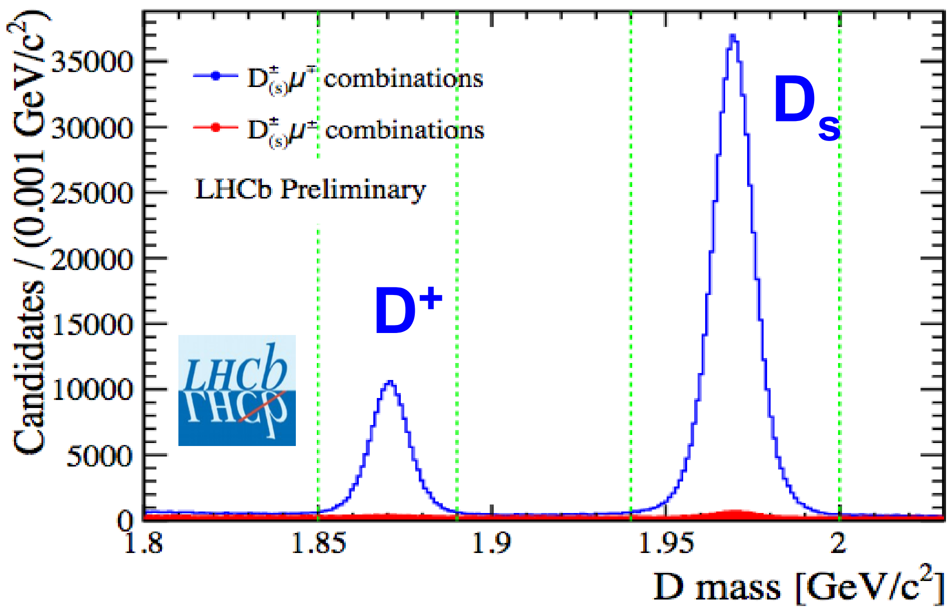
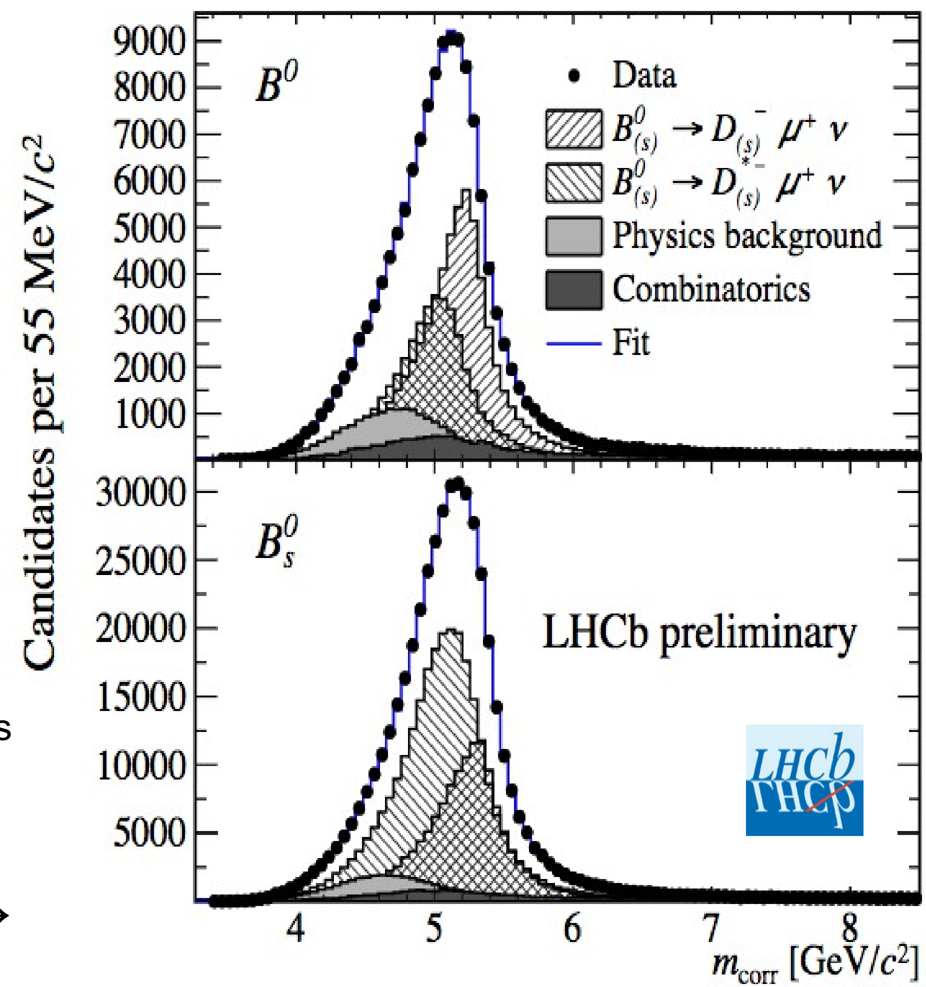
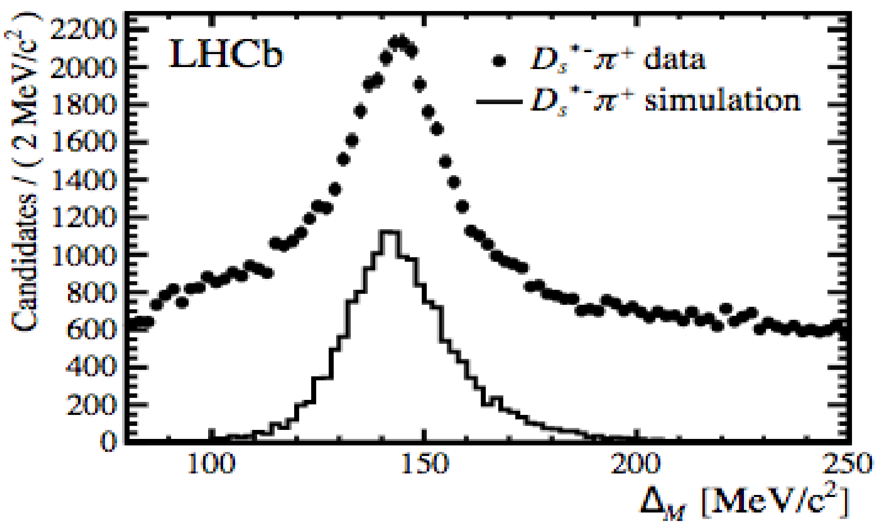


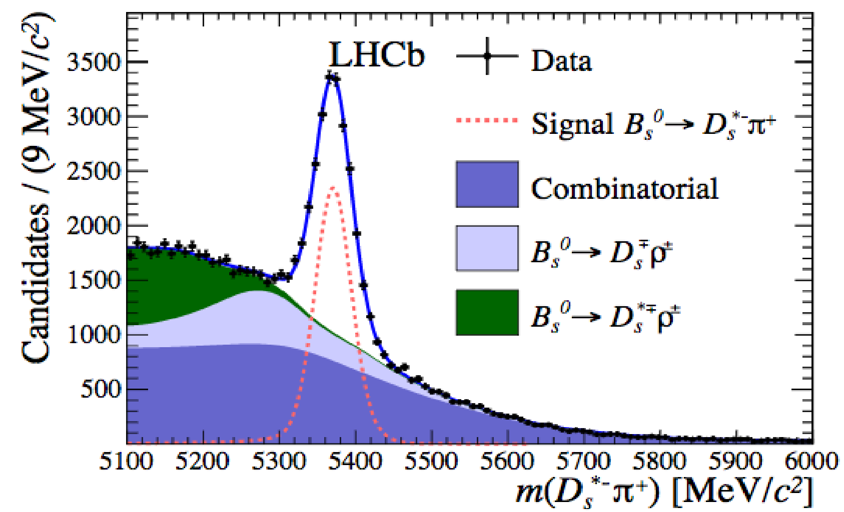


- Good discriminating power between $B_s \rightarrow D_s$ and $B_s \rightarrow D_s^*$
- Study the q^2 distribution is needed for possible measurements of FF shape in $B_s \rightarrow D_s$

Analysis $B_s \rightarrow D_s^* \ell \nu$

- Requires the reconstruction of a soft photon from D_s^*-->$D_s\gamma$ (BF~94%)
  - Already used for $B_s \rightarrow D_s^* \pi$ (JHEP06(2015)130)





- $B_s \rightarrow D_s^* \ell \nu$, expected very clean compared to $B \rightarrow D^* \ell \nu$,
  - only down-feed from $D_{s1}' \rightarrow D_s^* \pi^0$ (BF~50%) decays
- Possible (almost)full angular analysis and extraction of the FFs
  - How to proper normalize the signal and extract $|V_{cb}|$?
    - Most natural channel is $B_s \rightarrow D_s^* \pi$, but uncertainty is ~20%, we have to rely on external measurements from Belle(II)

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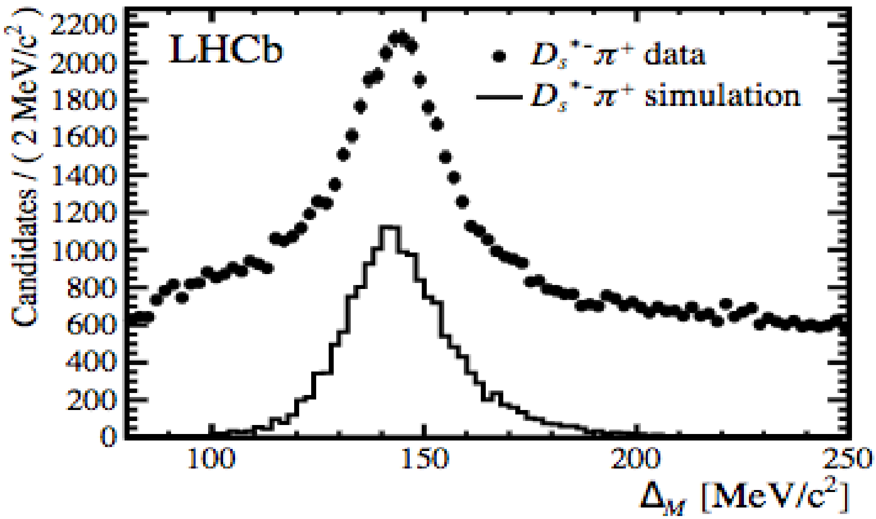

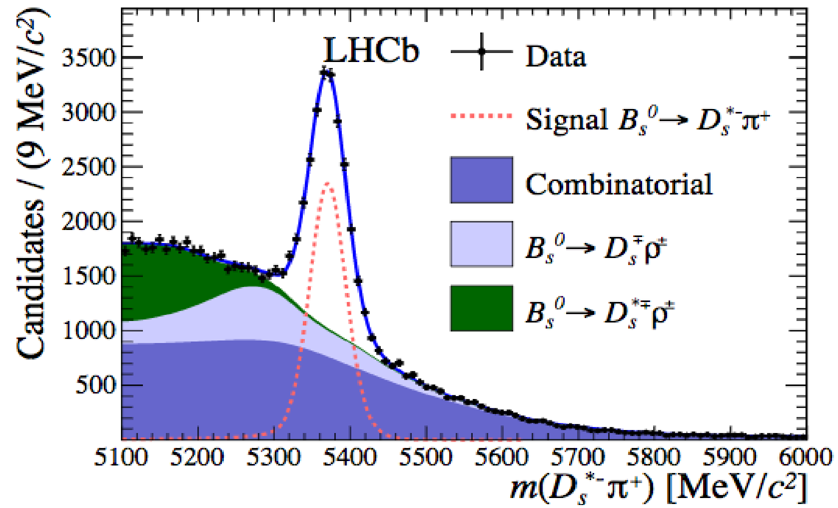

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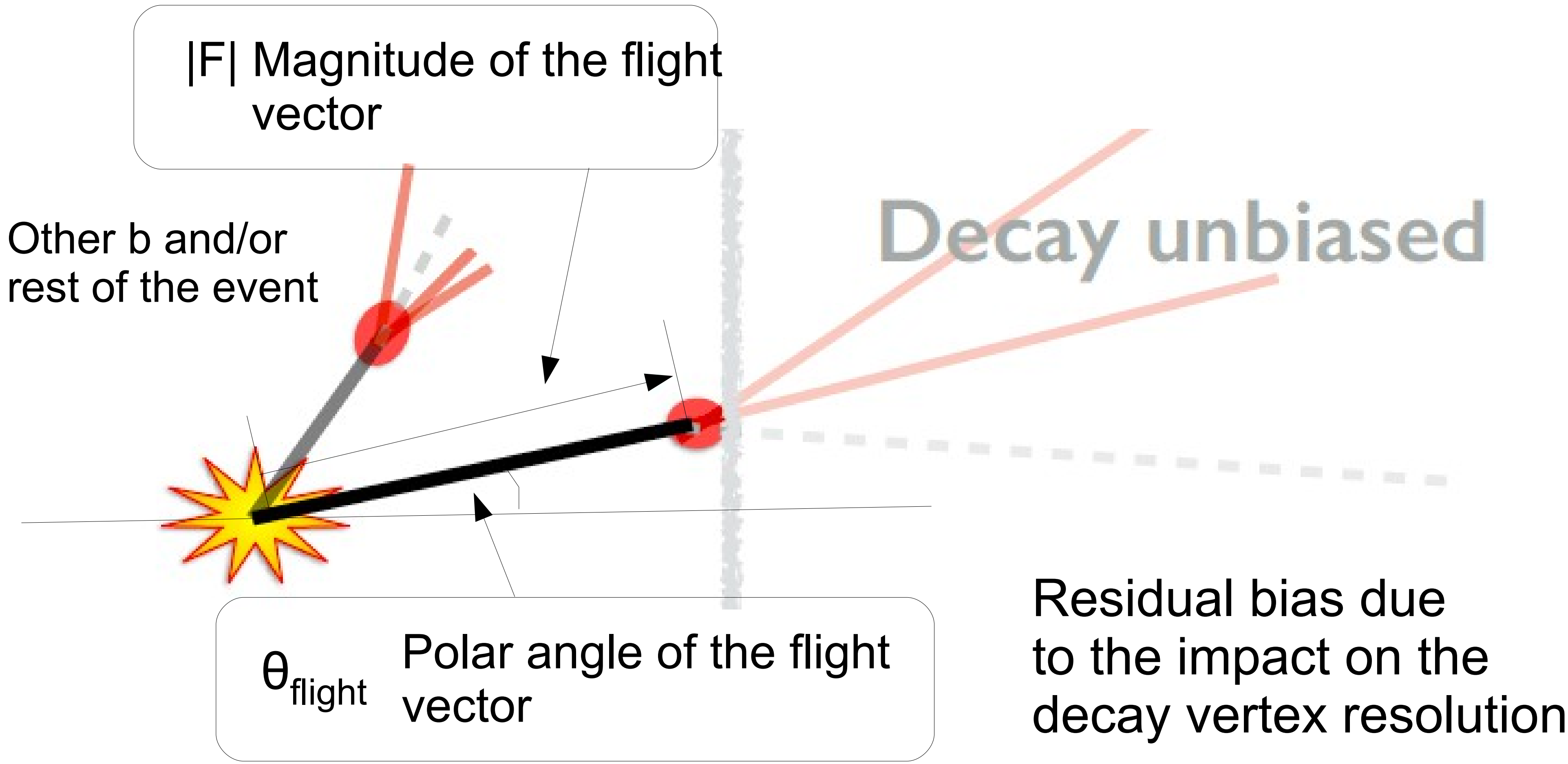
Summary and outlook

- Υ(5S) useful for precise measurement of absolute Bfs
  - SL studied
  - For Belle-II, Good Physics Case for a run at Υ(5S)
- Huge sample of B_s available at LHCb
  - It is going to be fully exploited to measure Form Factors, BF ratios
    - V_{cb} will require a proper normalization channel
  - Decays into D_s^{**} can be studied
  - Access $R(D_s)$ and $R(D_s^*)$
  - $B_s \rightarrow K\mu\nu$: all tools successfully used for $\Lambda_b \rightarrow p\mu\nu$ can be used also in this case

Backup

Improve kinematic resolution

- Can we get useful estimation of the b-momentum without using the momentum of the b-decay products?



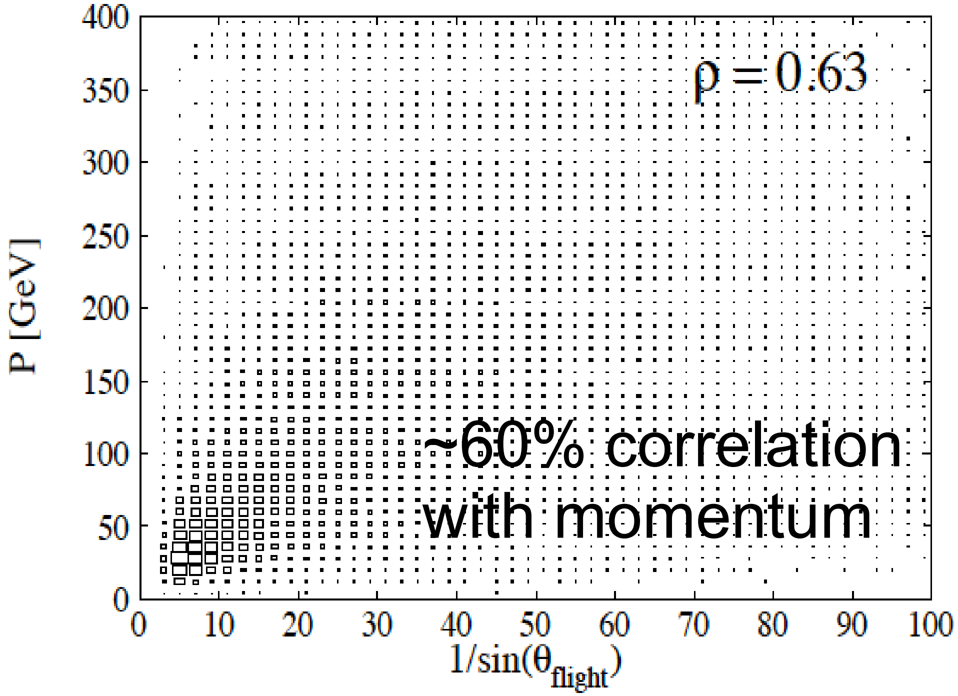
Exploit the flight informations

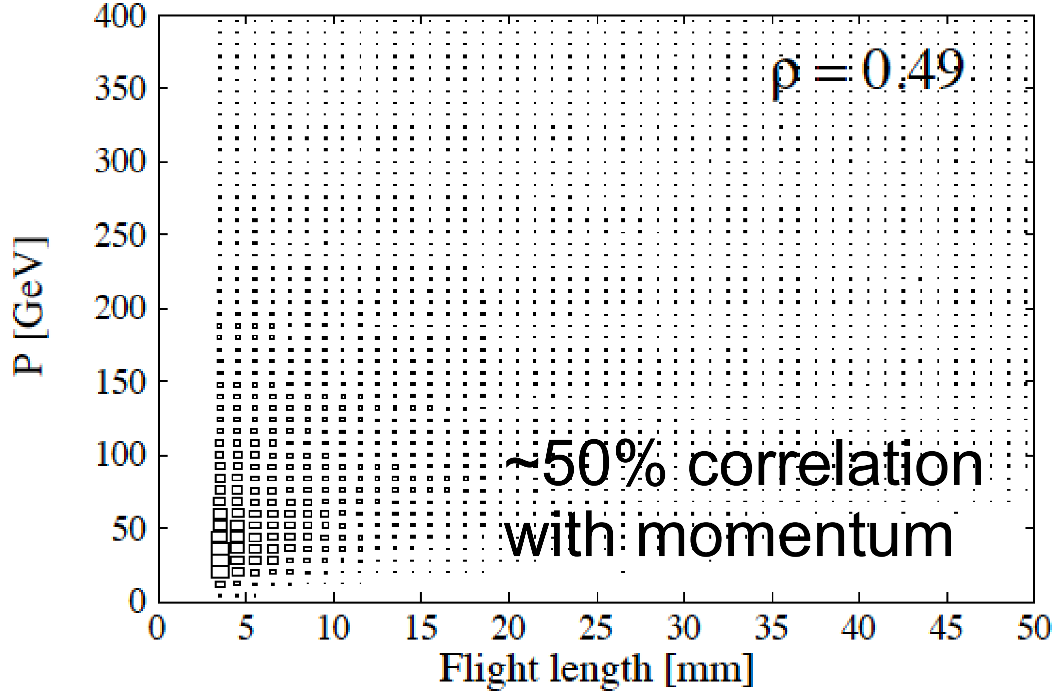
$$P \approx \frac{\overline{P_T}}{\sin\theta_{\text{flight}}}$$

approximation

$$P \approx \frac{M_b|\vec{F}|}{ct}$$

Apply |F|> 3mm





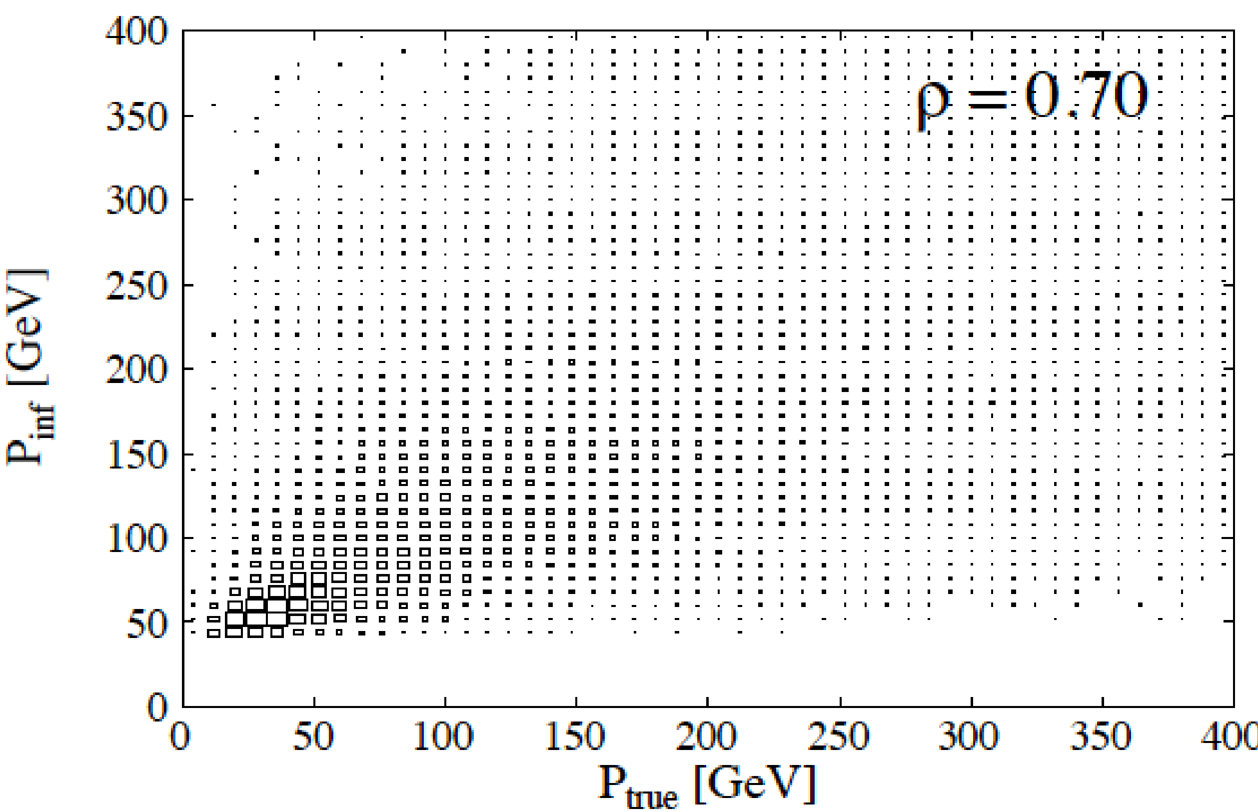
- Study performed with Pythia: pp->beauty at 7, 13 and 100TeV
  - Case study: $B_s \to K^{(*)}\,\mu\,\nu$ / $D^{(*)}\,\mu\,\nu$
    - Vertex quantities smeared with the LHCb VELO resolution

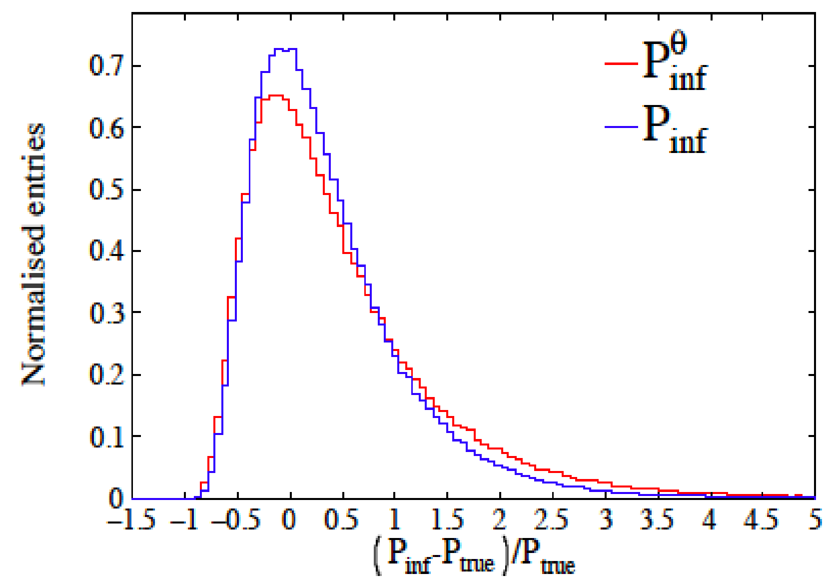
Unbiased momentum reconstruction

- How to exploit these features and some practical applications
  - Arxiv:1611.08522 G.Ciezarek, A.Lupato, MR, M.Vesterinen

1) $1/\sin\theta_{flight}$
2) $|F|$

→ scikit learn → P_{inf}



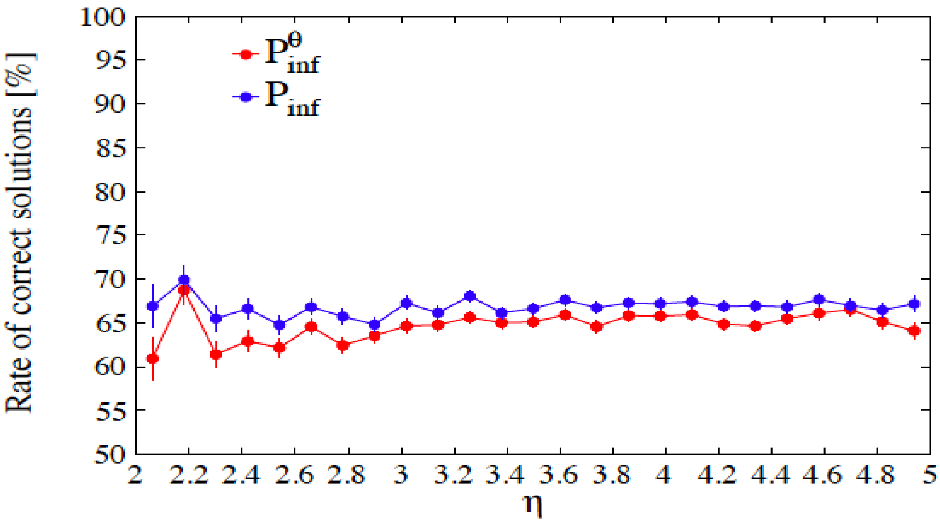


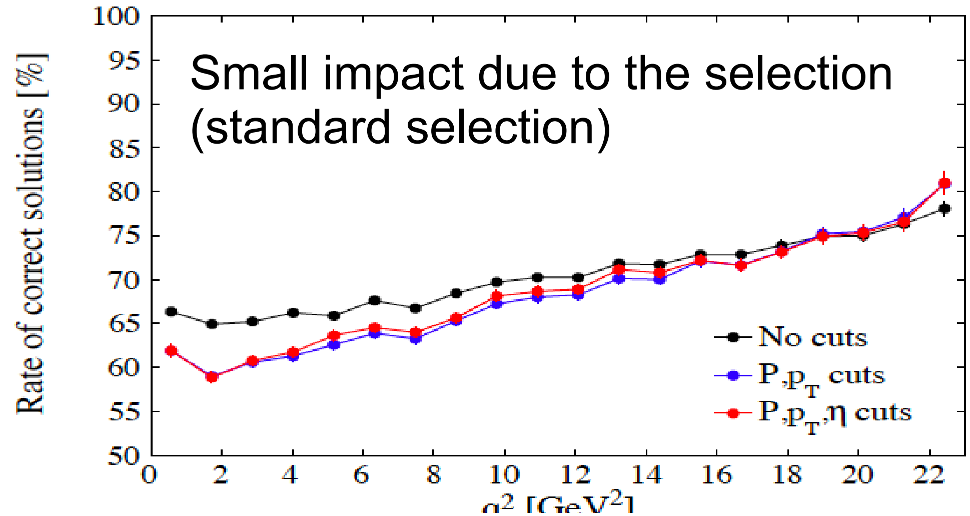
Modest momentum estimate

Application to semileptonic events

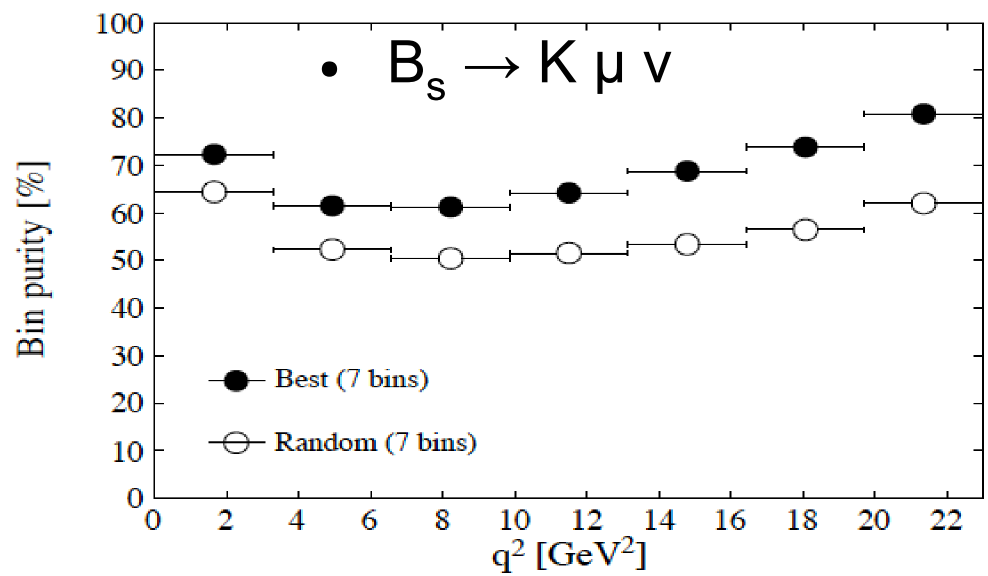
ArXiv:1611.08522

- 2-fold ambiguity in the neutrino momentum reconstruction
- Resolution of P_{inf} is enough to improve the chance to choose the right $P_{+/-}$ solution over random choice $B_s \to K^{(*)} \mu \nu$





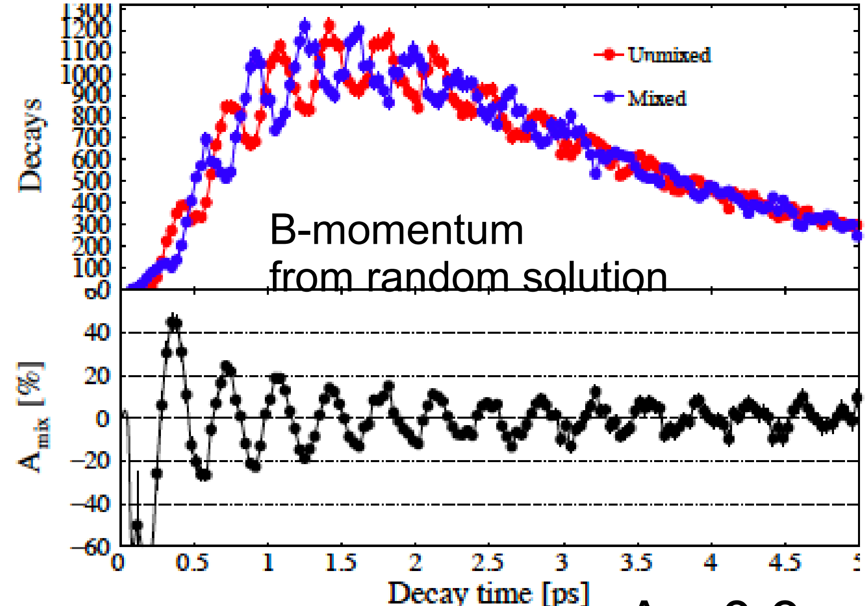
- Application in $d\Gamma/dq^2$ measurements
  - **Bin purity** as figure of merit: fraction of candidates for which the reco-q^2 falls in the same true-q^2 bin



Other usage: oscillation measurements

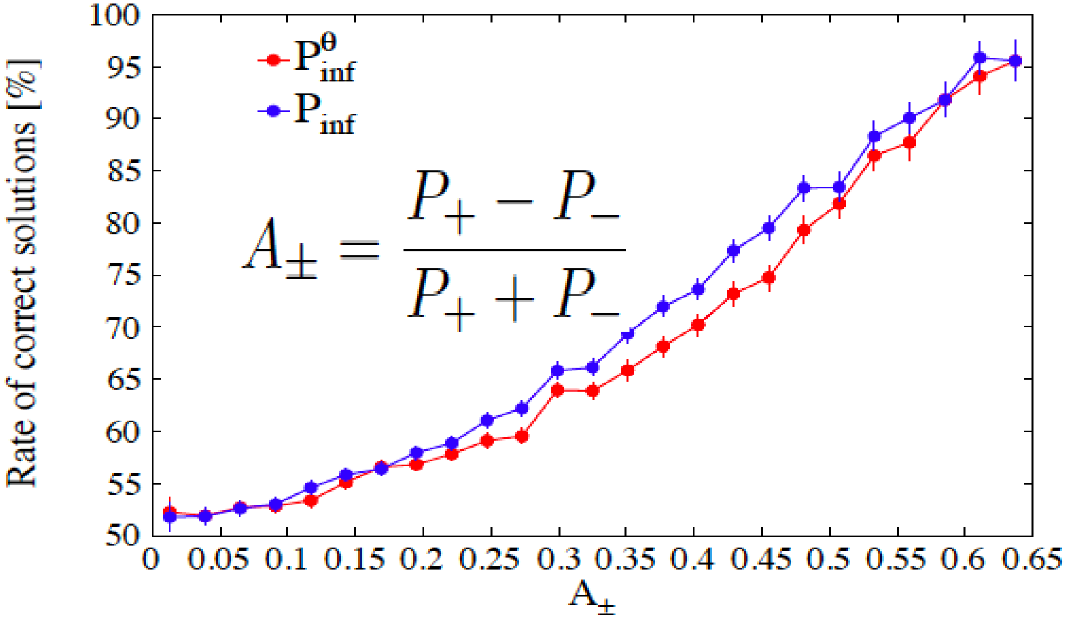
- Large impact on the oscillation measurements with SL decays $B_s \to D_s \mu \nu$

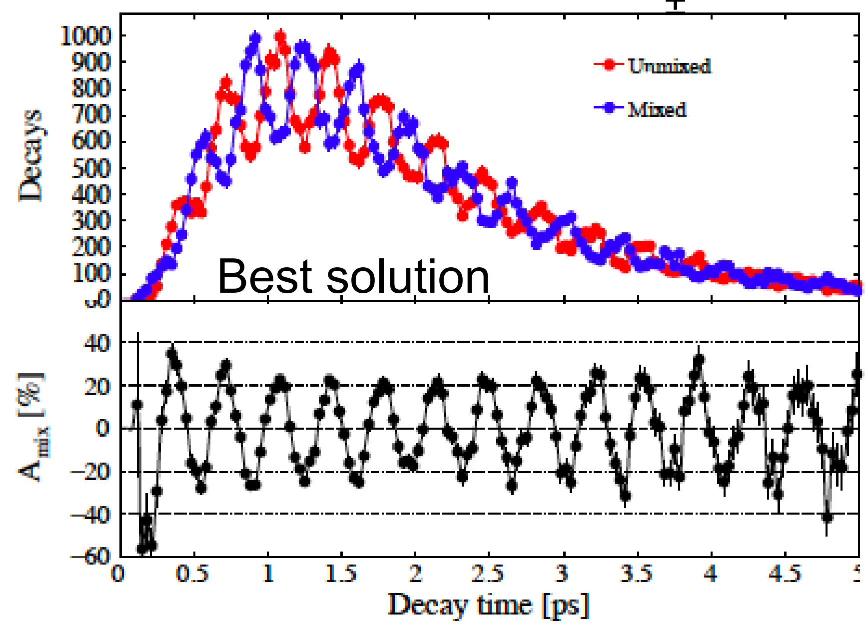
$$\frac{\Gamma[D_s^- \mu^+, t] - \Gamma[D_s^+ \mu^-, t]}{\Gamma[D_s^- \mu^+, t] + \Gamma[D_s^+ \mu^-, t]} = \frac{a_{sl}^s}{2} - \left[\frac{a_{sl}^s + 2A_P}{2}\right]\left[\frac{\cos(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2)}\right]$$



$A_+ > 0.3$

Rate of correct solution depends on the asymmetry between the two solutions



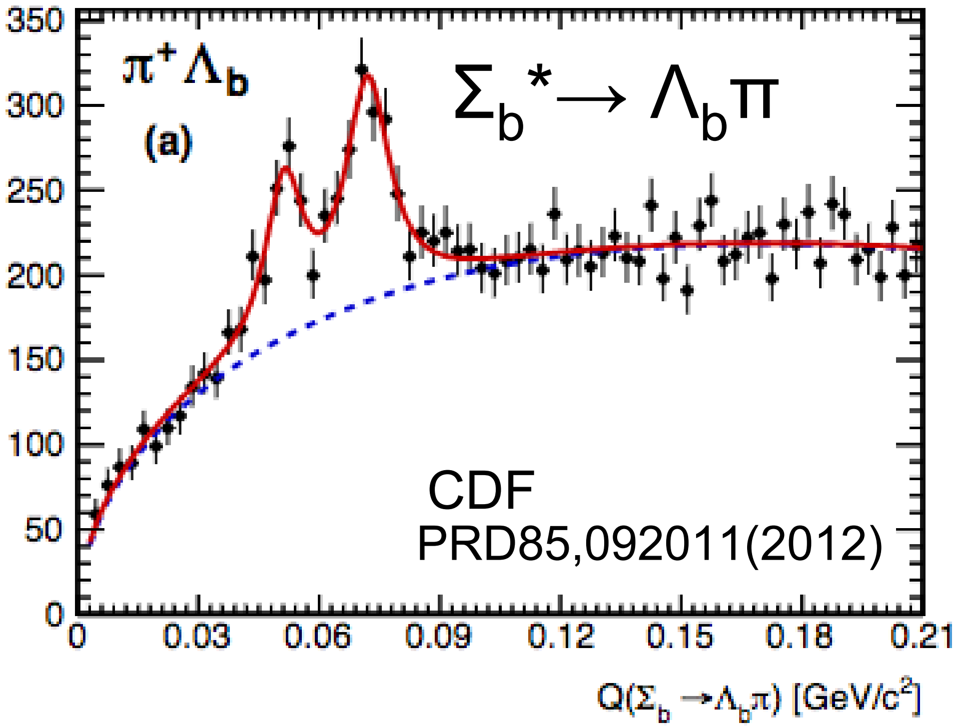


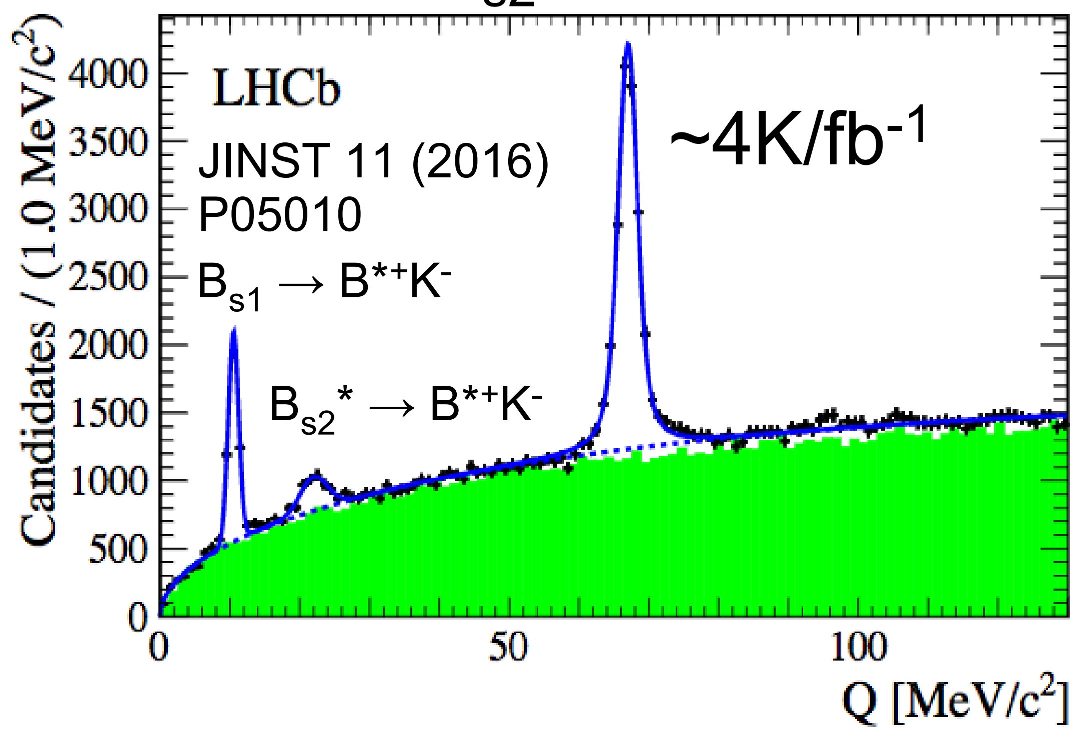
ArXiv:1611.08522

Kinematics++ exploiting the resonances

- Additional constraints if the heavy meson comes from a narrow resonance
  - Sheldon, Zhang Adv.HEP 2014, 9312571

$B_{s2}^* \to B^+K^-$





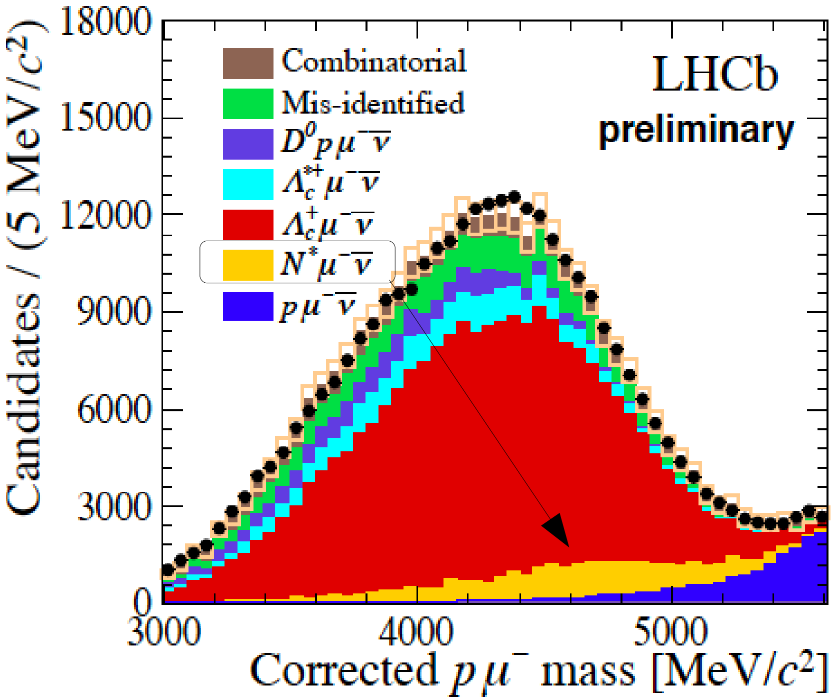
Λ_b from Σ_b, challenge from the many overlapping states

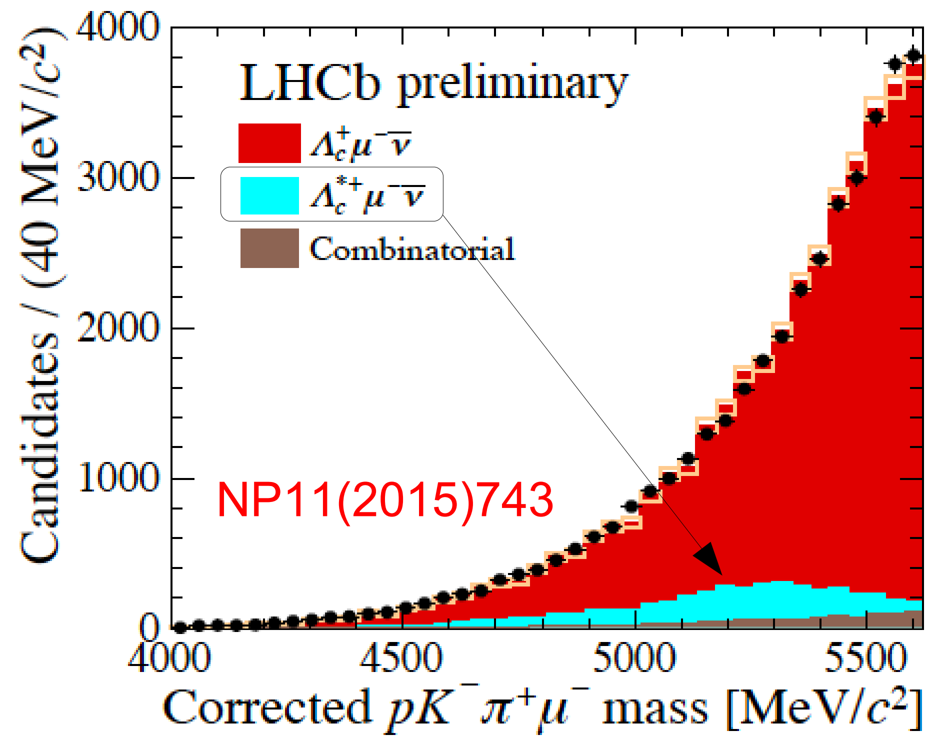
Promising but we still need to fully exploit these techniques

Narrow well separated resonances and clean signature due to the Kaon. It allows to study B_u decays

- $B^+ \to \pi\pi\, \mu\, \nu$
- $B^+ \to KK\, \mu\, \nu$

Other SL decays... in our backgrounds!



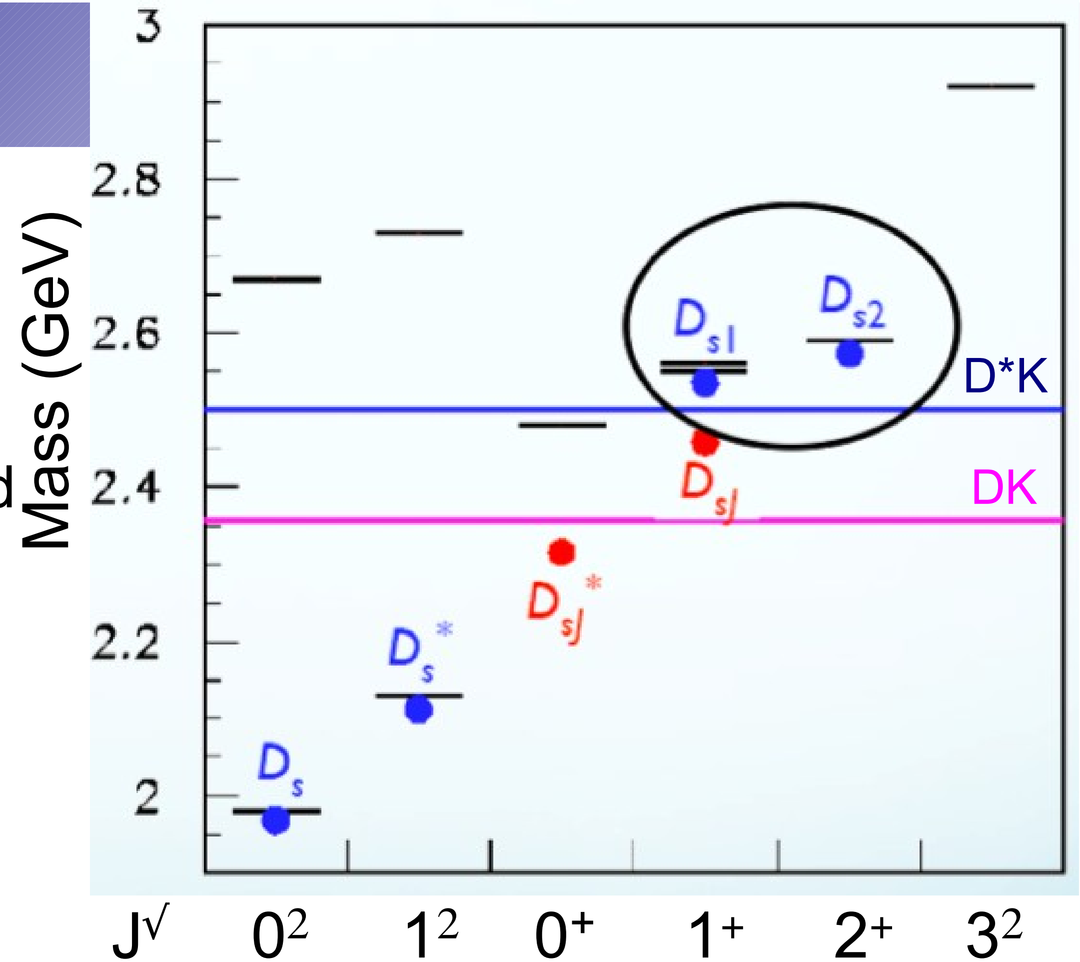


- Large contribution from $\Lambda_b \to N^* \mu \nu$
- Reconstructing $N \to p \pi \pi$
  - Reduce uncertainty due to N* states in $\Lambda_b \to p\mu\nu$ now included with a Gaussian constraints
  - Could be crucial in the study of backgrounds in $\Lambda_b \to p\tau\nu$

- Study explicitly the contributions from $\Lambda_b \to \Lambda_c^* \mu \nu$
  - Adding 2 pions (BF($\Lambda_c^* \to \Lambda_c \pi^+ \pi^-$)=67%)
  - Crucial to understand these background in the study of $\Lambda_b \to \Lambda_c \tau\nu$

$B_s \to D_s^* \mu \nu$

- The D_s^* got down feed only from D_{s1}', higher order resonances decay mainly through DK channels
- Excited D_s^* states are well separated
- The states below the DK threshold can be studied explicitly reconstructing the soft π^0 and γ
- To extract $|V_{cb}|$ a proper normalization is required



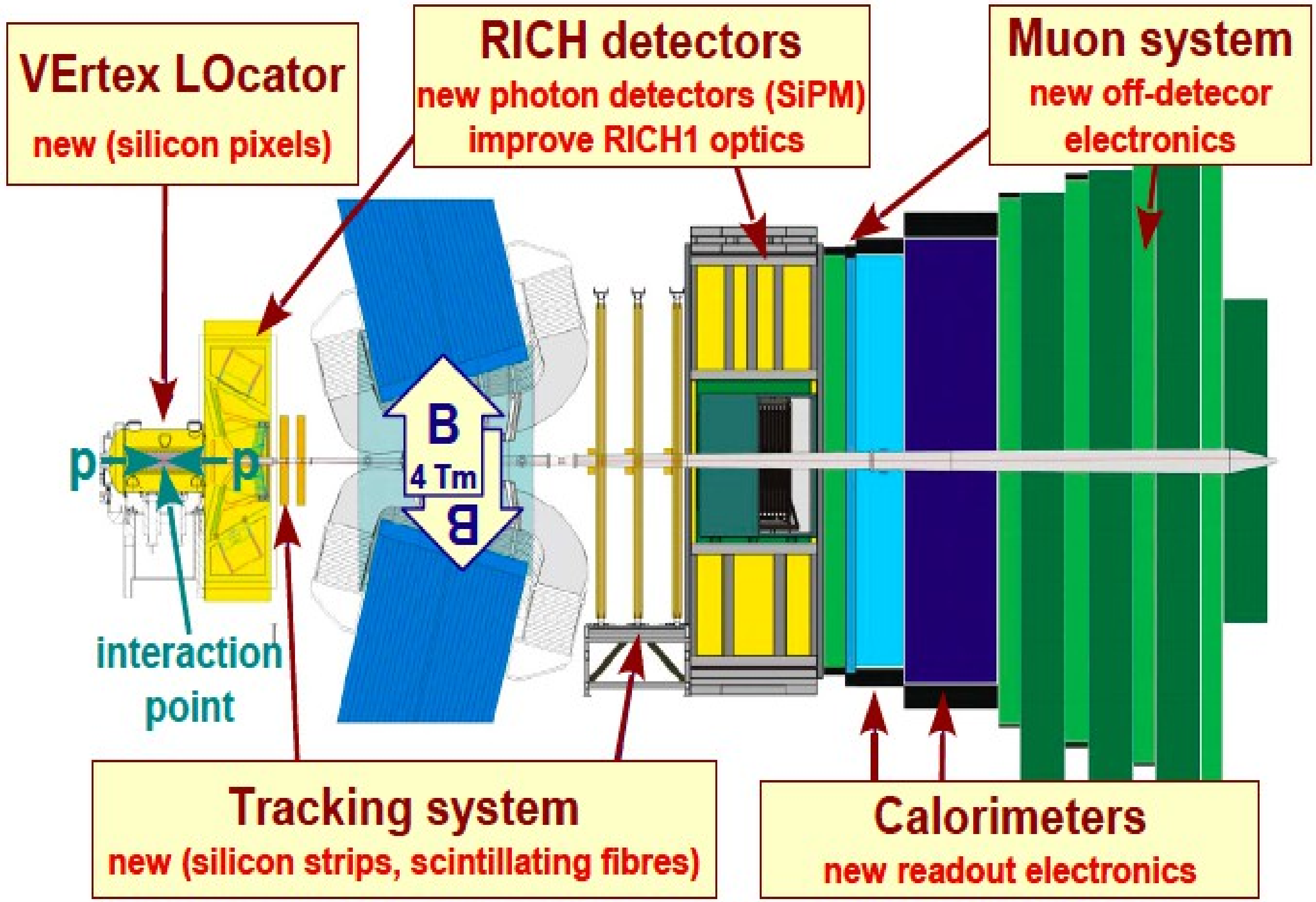
	J^P	Mass (MeV)	Width (MeV)	Observed decays
D_{s0}^*	0^+	2317.8 ± 0.6	< 3.8	$D_s^+ \pi^0$
D_{s1}'	1^+	2459.5 ± 0.6	< 3.5	$D_s^{*+}\pi^0, D_s^+\gamma, D_s^+\pi^+\pi^-$
D_{s1}	1^+	2535.28 ± 0.20	< 2.5	$D^{*+}K^0, D^{*0}K^+$
D_{s2}^*	2^+	2572.6 ± 0.9	20 ± 5	$D^0 K^+$

LS2 Upgrade

LHCC-I-018

40 MHz readout
5 x higher luminosity

	LHCb
Run 1	3
Run 2	10
Run 3	25
Run 4	50
Run 5	**300**



LHCb Upgrade →

HL LHC →

2021 | 2024 | 2027 | 2030 | 2031 | 2034 | 2035

LS2 | Run 3 | LS3 | Run 4 | LS4 | Run 5 | LS5

Phase 1 | Phase 1b | Phase 2

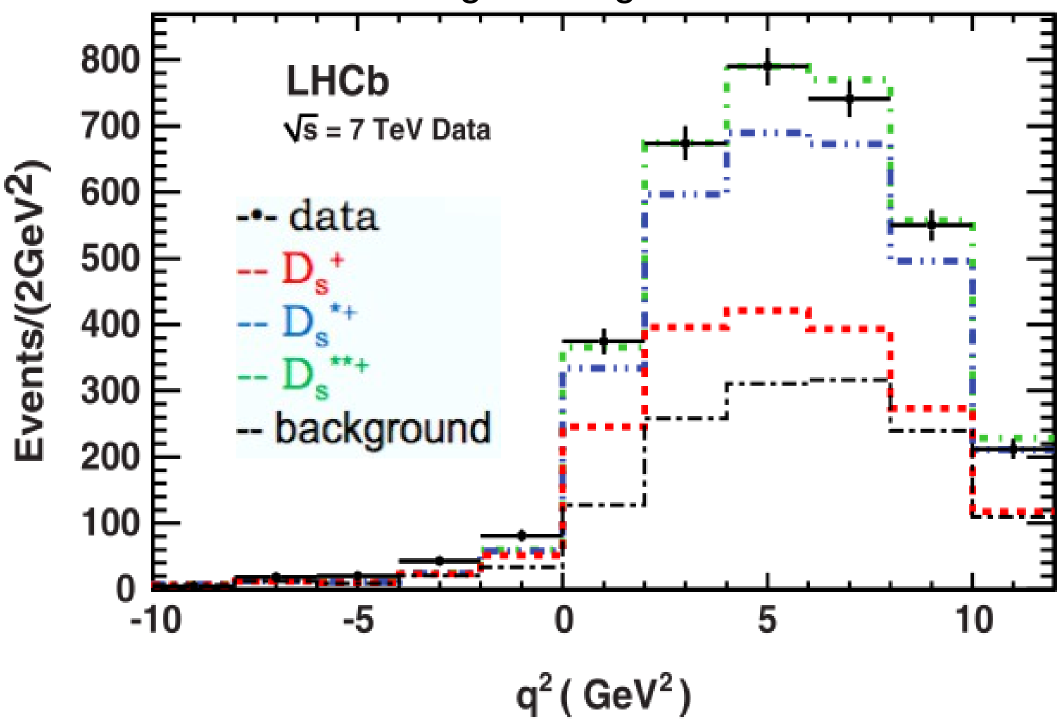
dΓ/dq²

PRD85 (2012) 032008

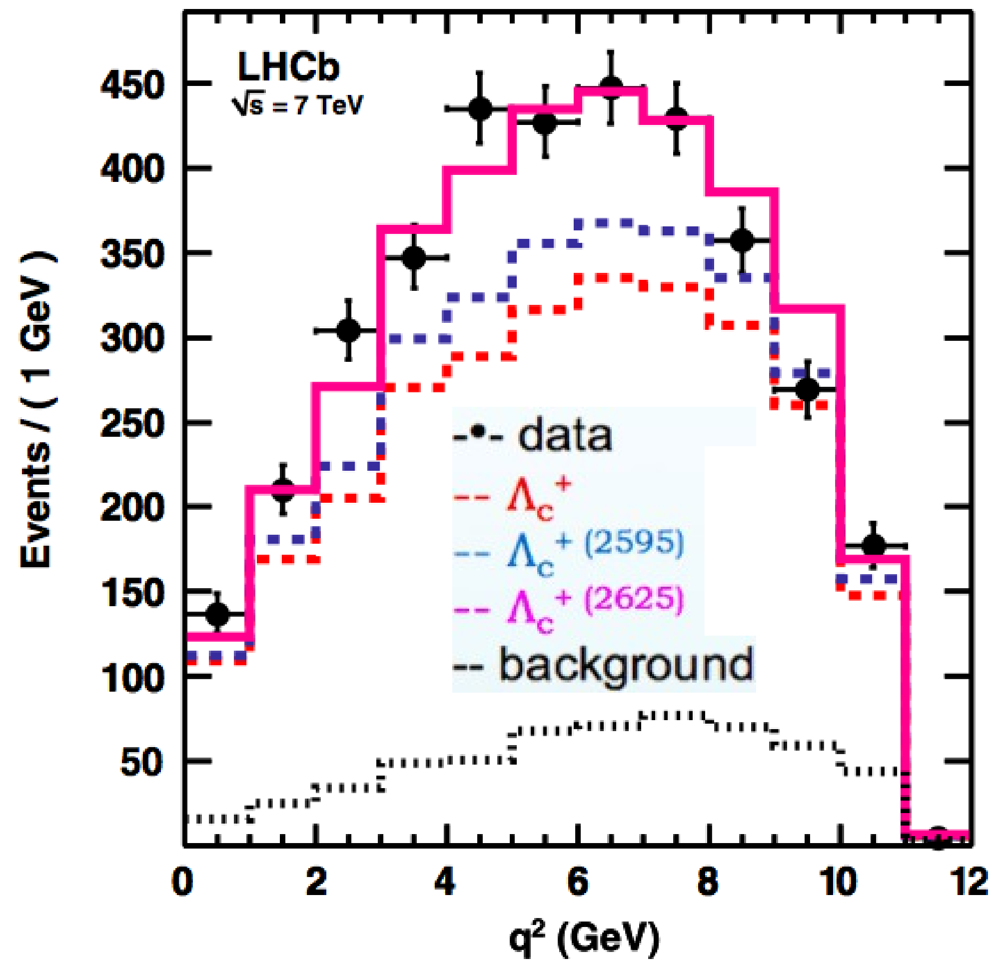
LHCb paper on Bs and Lb production

- Crucial to perform the measurements in bins of q^2
  - SL decays as a function of the q2 already studied with only $3pb^{-1}$ (high efficient trigger)
  - Need further studies to translate in measurements of the Form Factors

- $B_s \to D_s^{(*)} \mu \nu$

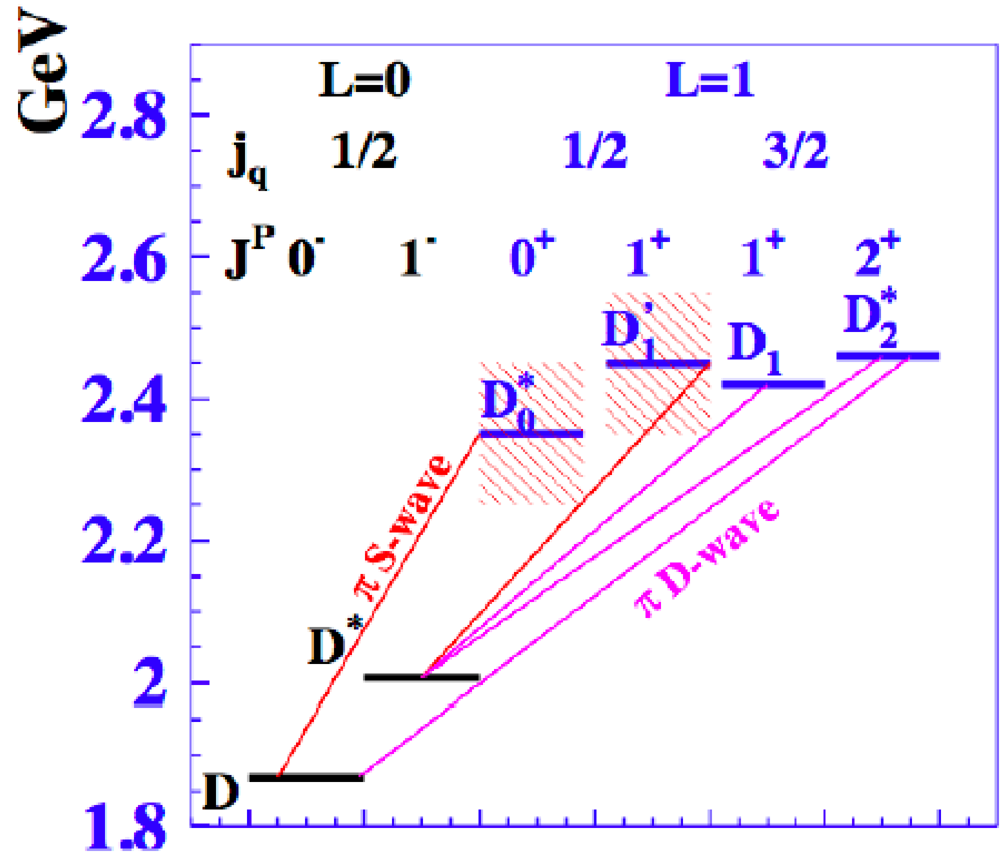


- $\Lambda_b \to \Lambda_c^* \mu \nu$



Crude assumptions on the FFs and on the D_s^*/D_s and Λ_c^*/Λ_c rates

D**



	J^P	Mass (MeV)	Width (MeV)	Observed decays
D_0^*	0^+	2352 ± 50	261 ± 50	$D\pi$
D_1'	1^+	2427 ± 36	384^{+130}_{-105}	$D^*\pi$
D_1	1^+	2421.3 ± 0.6	27.1 ± 2.7	$D^*\pi, D^0\pi^+\pi^-$
D_2^*	2^+	2462.6 ± 0.7	49.0 ± 1.4	$D^*\pi, D\pi$

Composition of SL decays

- Inclusive excited charm production
- Narrow states at higher masses
  - Predicted radial excitations
- He D* helicity angles allow to disentangle the various states