9th International Workshop on CKM-UT

CKM 2016

Mumbai, 28 Nov - 2 Dec 2016

Mini-review on $|V_{ub}|$ & $|V_{cb}|$ at LHCb: status and prospects

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On behalf of LHCb Collaboration

Outline

- I'll focus on $|V_{ub}|$
  - I'll cover some technicalities that apply also to $|V_{cb}|$ measurements
- Introduction to LHCb
- Measurement of $|V_{ub}|/|V_{ub}|$ with $\Lambda_b \rightarrow p\,\mu\nu$
  - Isolation, corrected mass and reconstruction of q^2
- Issues with the ongoing measurement of $B_s \rightarrow K\,\mu\nu$
- Improvements on the kinematics reconstruction of semileptonic decays
- Some future measurements
- Outlook

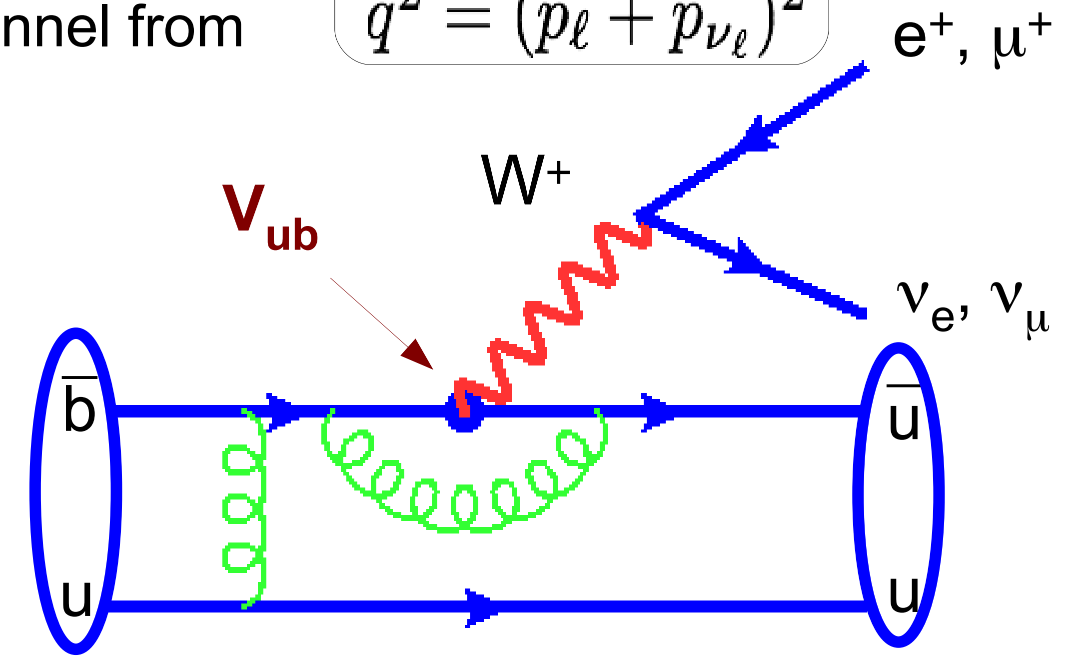
Heavy hadron b →u semileptonic decays

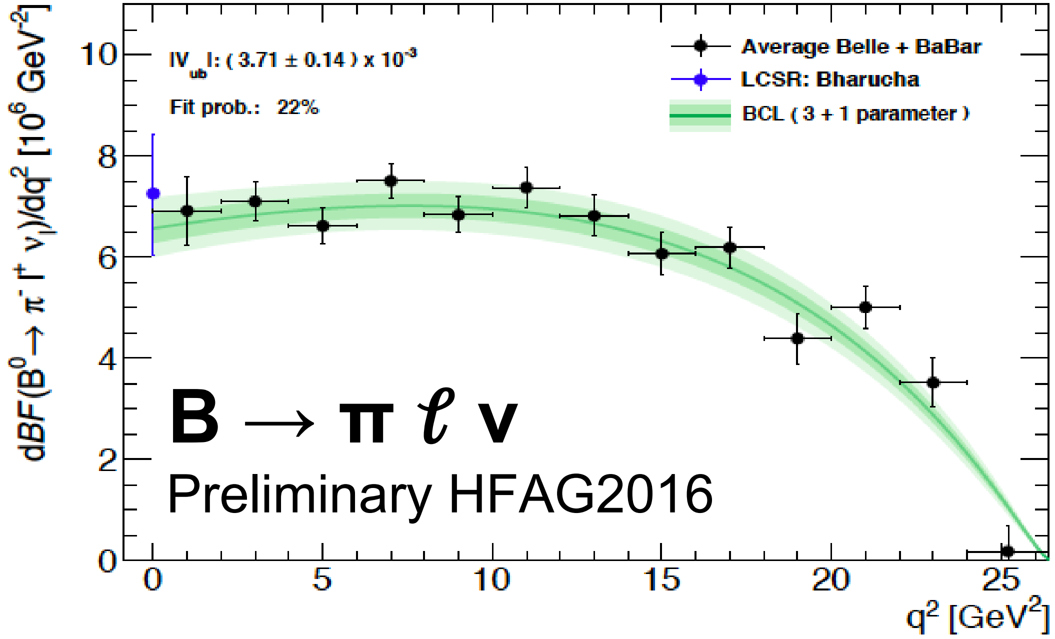
- Semileptonic decays are clean channel from theoretical point of view:
  - Factorization of the hadronic and leptonic current

$$\mathcal{M}(B\to\pi\ell^-\overline{\nu}) = -i\frac{G_F}{\sqrt{2}}\cdot V_{ub}\cdot L^\mu H_\mu$$

  - Beauty hadrons decay allow to extract the CKM parameters $|V_{cb}|$ and $|V_{ub}|$ with good precision

$$q^2 = (p_\ell + p_{\nu_\ell})^2$$





B → π ℓ ν

Preliminary HFAG2016

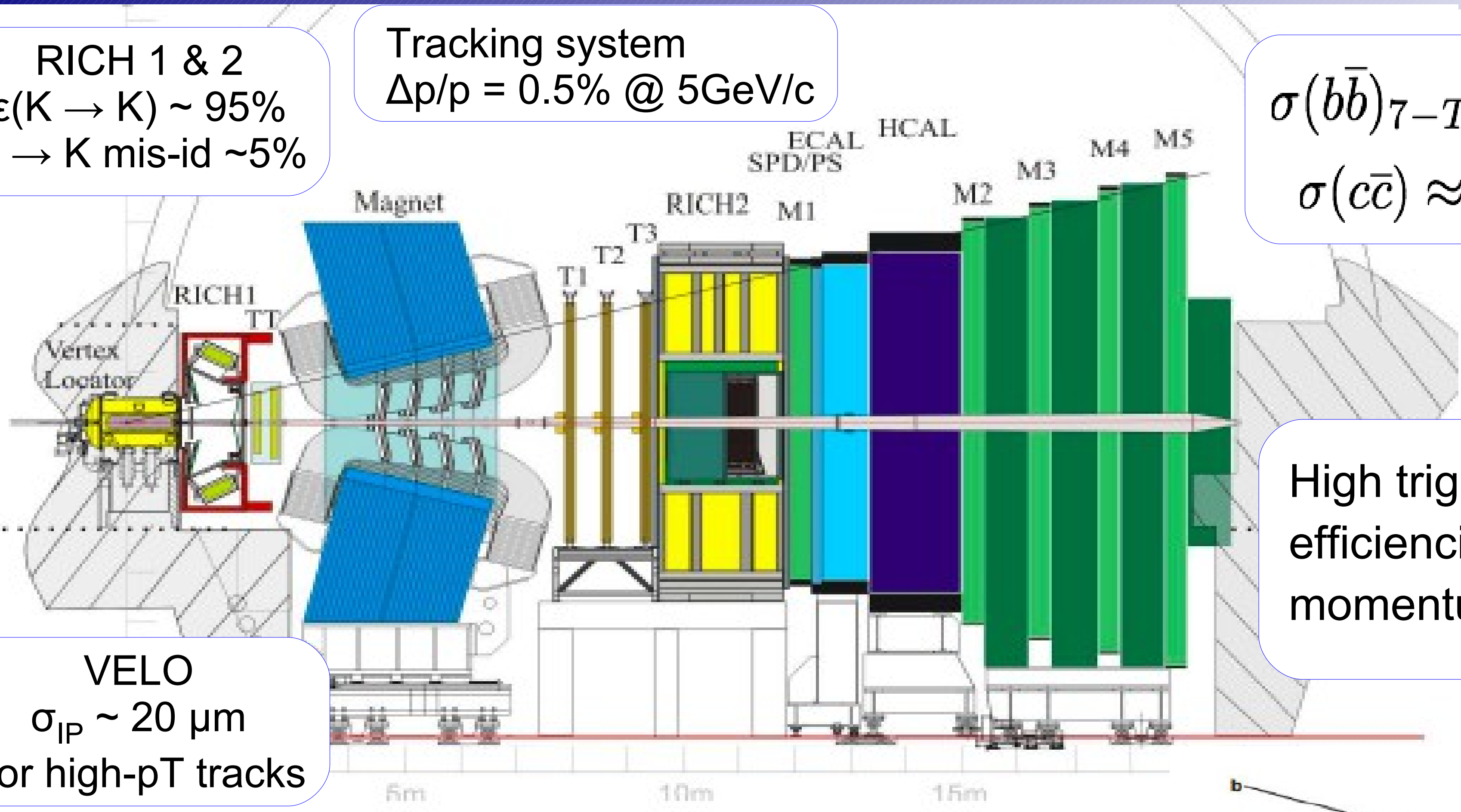
Parameter	Value
$\lvert V_{ub}\rvert$	$(3.71 \pm 0.14)\cdot 10^{-3}$
b_1^+	0.421 ± 0.012
b_2^+	-0.396 ± 0.032
b_3^+	-0.622 ± 0.126

Uncertainty on $|V_{ub}|$ at 3.7% thanks to latest improvements on lattice-QCD

Discrepancy with inclusive $|V_{ub}|$ at 3σ

The LHCb experiment

JINST 3 (2008) S08005



RICH 1 & 2
ε(K → K) ~ 95%
π → K mis-id ~5%

Tracking system
Δp/p = 0.5% @ 5GeV/c

$$\sigma(b\bar{b})_{7-TeV} \approx 290\mu b$$

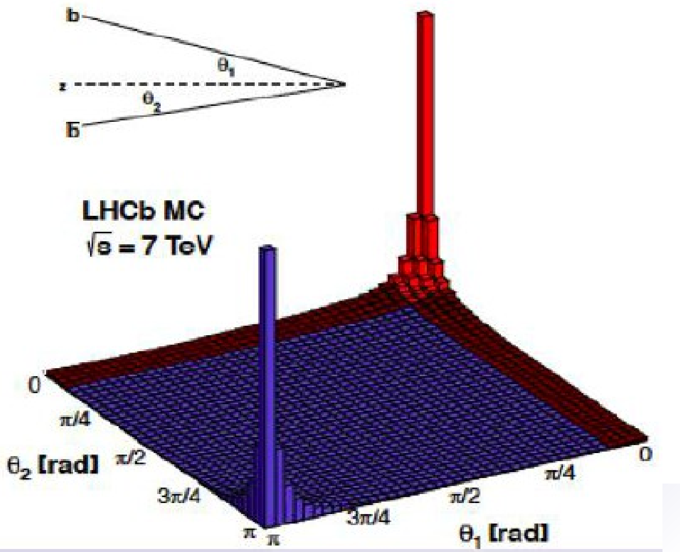
$$\sigma(c\bar{c}) \approx 20 \times \sigma(b\bar{b})$$

High trigger efficiencies, low momentum thresholds

VELO
σ_{IP} ~ 20 μm
For high-pT tracks

LHCb: forward spectrometer for flavor physics
Excellent tracking and vertexing capabilities.
Excellent PID performances
Access to all hadrons with b- and c-quarks

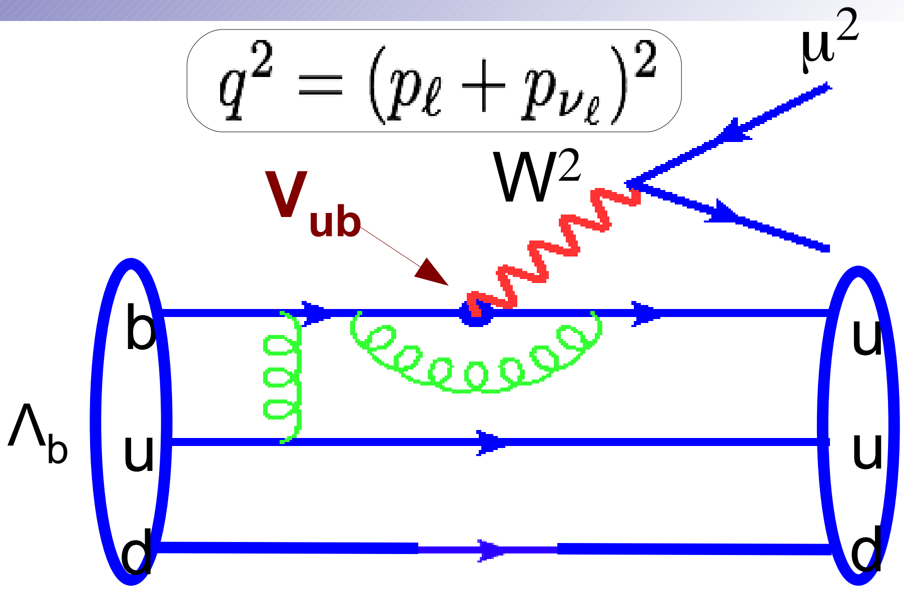
Collected 3.0 fb^{-1} in 2011-2012 @7,8 TeV
2.0 fb^{-1} in 2015+2016 @ 13 TeV



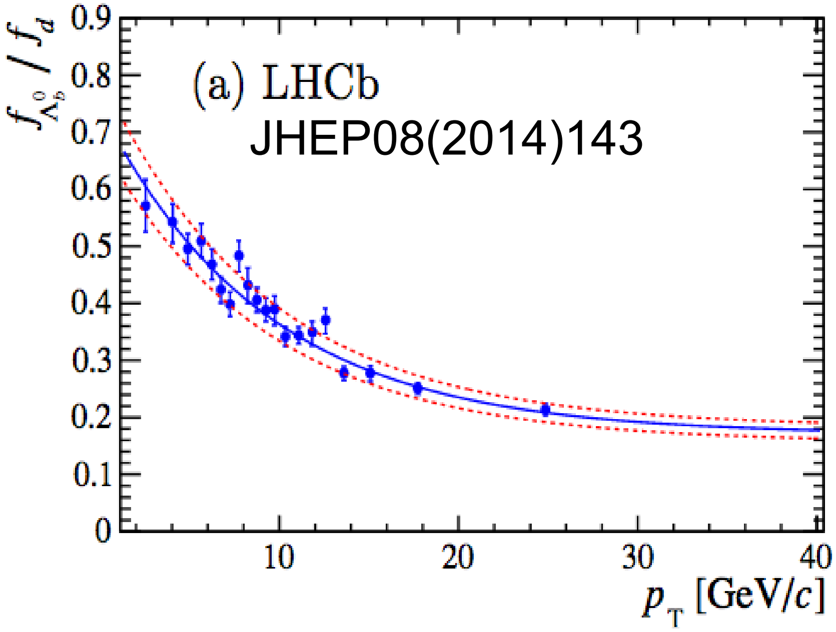
How it was possible $|V_{ub}|$ @ LHCb?

Nature Phys. 11(2015)743

- $\Lambda_b \rightarrow p\,\mu\,\nu$ natural baryonic equivalent to $B \rightarrow \pi\,\mu\,\nu$: branching ratio is huge
- Λ_b produced copiously: almost 20% of the b-hadrons in LHCb are Λ_b baryons
- Protons production in other b-hadrons are much smaller than pions: less combinatoric than $B \rightarrow \pi\,\mu\,\nu$



$$q^2 = (p_\ell + p_{\nu_\ell})^2$$



JHEP08(2014)143

- Normalize to $\Lambda_b \rightarrow \Lambda_c (\rightarrow pK\pi)\mu\nu$ to cancel the uncertainties on trigger/selection and on $f_{\Lambda b}$

$$R_{exp} = \frac{\mathcal{B}(\Lambda_b \to p\mu\nu)}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)}$$

Signal

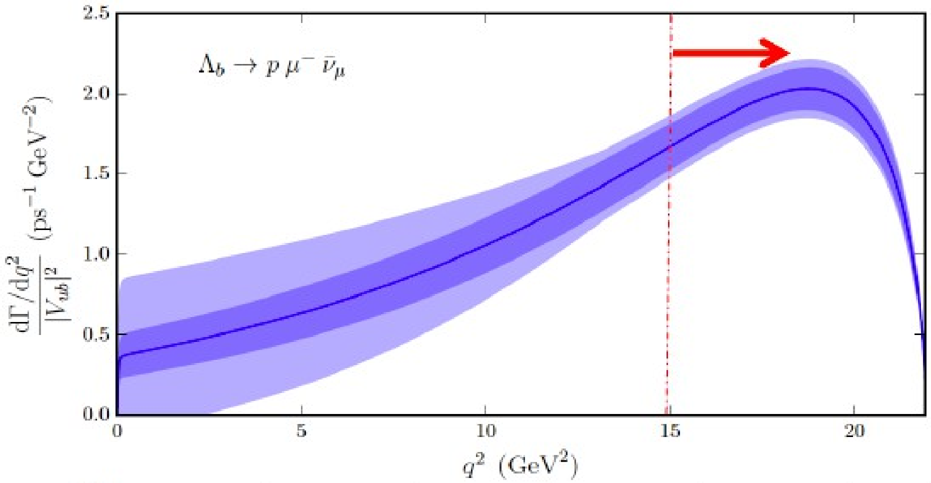
Normalization

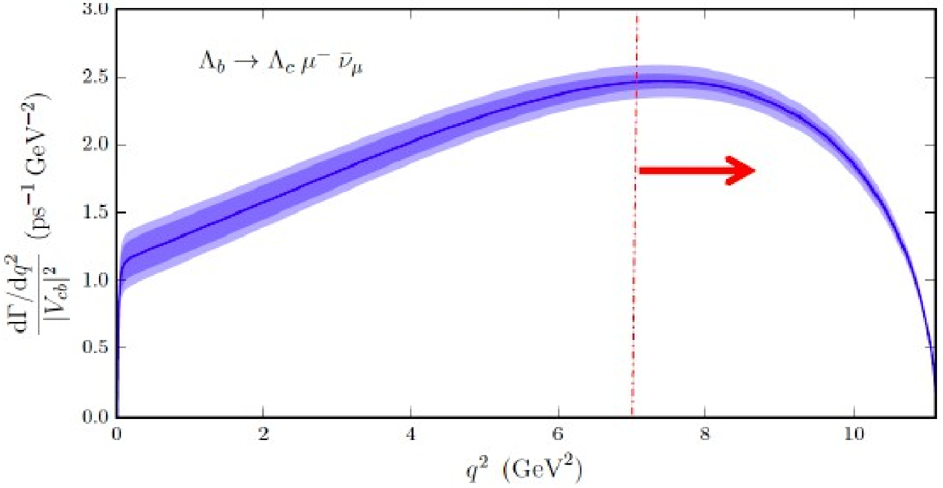
- Convert the ratio to a measurement of

$$|V_{ub}|/|V_{cb}|$$

Theory input

Detmold et al. PRD92(2015)034503





- Most recent calculation based on 2+1 L-QCD calculation using RBC & UKQCD configurations
- The most reliable theory predictions of the ratio of FF are obtained for:
  - $\Lambda_b \to \Lambda_c \mu\nu$ $q^2 > 7$ GeV^2
  - $\Lambda_b \to p \mu\nu$ $q^2 > 15$ GeV^2

$$\frac{|V_{ub}|}{|V_{cb}|} = \sqrt{\frac{R_{exp}}{R_{theory}}}$$

$$R_{theory} = \frac{\int_{15\,\mathrm{GeV}^2/c^4}^{q_{max}} \frac{d\Gamma(\Lambda_b \to p\mu^-\overline{\nu}_\mu)}{dq^2} / |V_{ub}|^2 dq^2}{\int_{7\,\mathrm{GeV}^2/c^4}^{q'_{max}} \frac{d\Gamma(\Lambda_b \to \Lambda_c\mu^-\overline{\nu}_\mu)}{dq^2} / |V_{cb}|^2 dq^2} = 1.471 \pm 0.095(stat) \pm 0.109(syst)$$

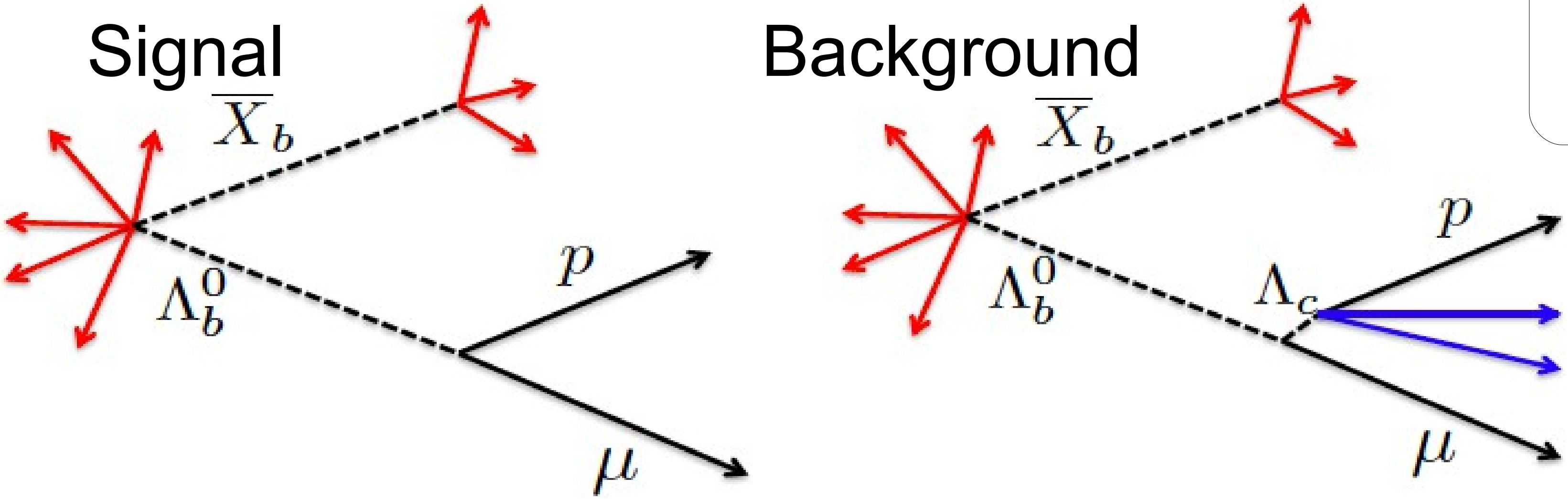
4.9 % of total theoretical uncertainty on |Vub/Vcb|

$\Lambda_b \rightarrow p\mu\nu$: Isolation criteria

Nature Phys.11(2015)743

- $\Lambda_b \rightarrow p\, \mu\, \nu$ has no other tracks sharing secondary vertex
  - Many of the $\Lambda_b \rightarrow \Lambda_c (\rightarrow pX)\mu\nu$ backgrounds do

Excellent PID allows clean p identification



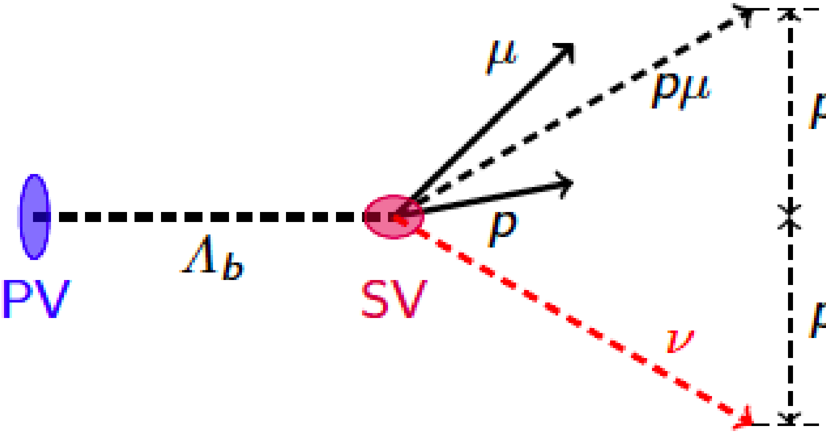
- Required an isolated proton-muon vertex
  - A multivariate classifier to distinguish between these two configurations
- Powerful tool to reduce background from other b-hadrons: 90% rejection & 80% efficiency
  - very difficult to isolate against neutral particles: main backgrounds

$\Lambda_b \to p\mu\nu$: corrected mass

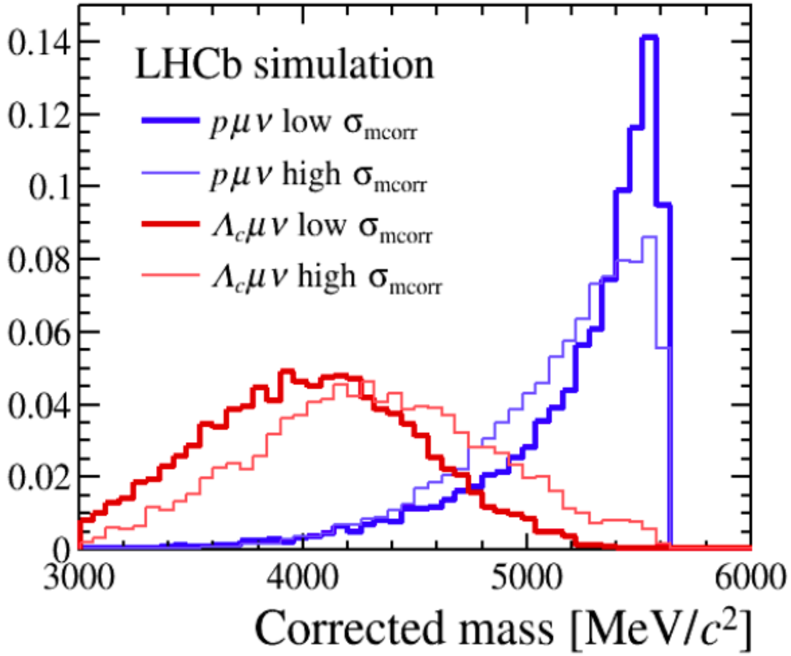
Nature Phys.11(2015)743

- No constraint from beam energy as at B-Factories
- Flight vector between primary collision point and secondary decay point gives a different constraint

$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$

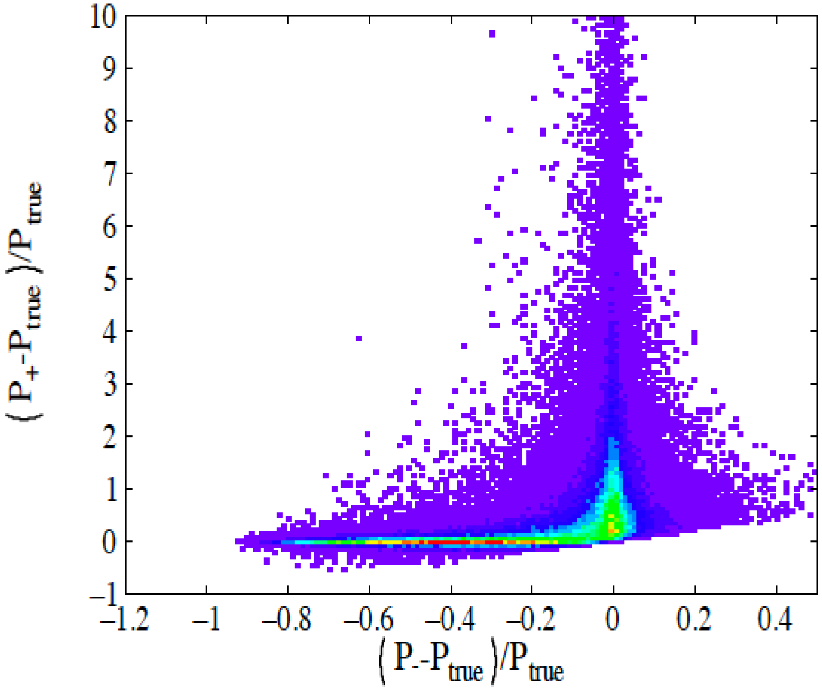


- The corrected mass peak at Λ_b mass when a neutrino is lost but has long tail to lower values
  - Separation between signal and backgrounds improves when requiring low uncertainty corrected mass

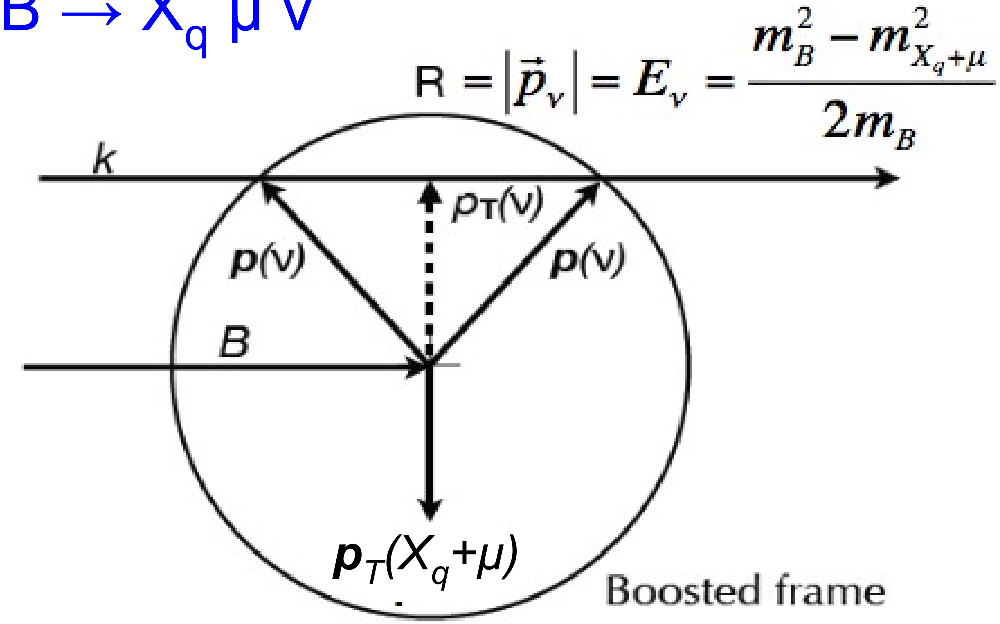


The q^2 dependence

- The knowledge of the Λ_b momentum is needed to measure q^2
    - Hypothesis of just 1-neutrino missing and the well-measured Λ_b flight direction gives the momentum with a 2-fold ambiguity, P_+ and P_-

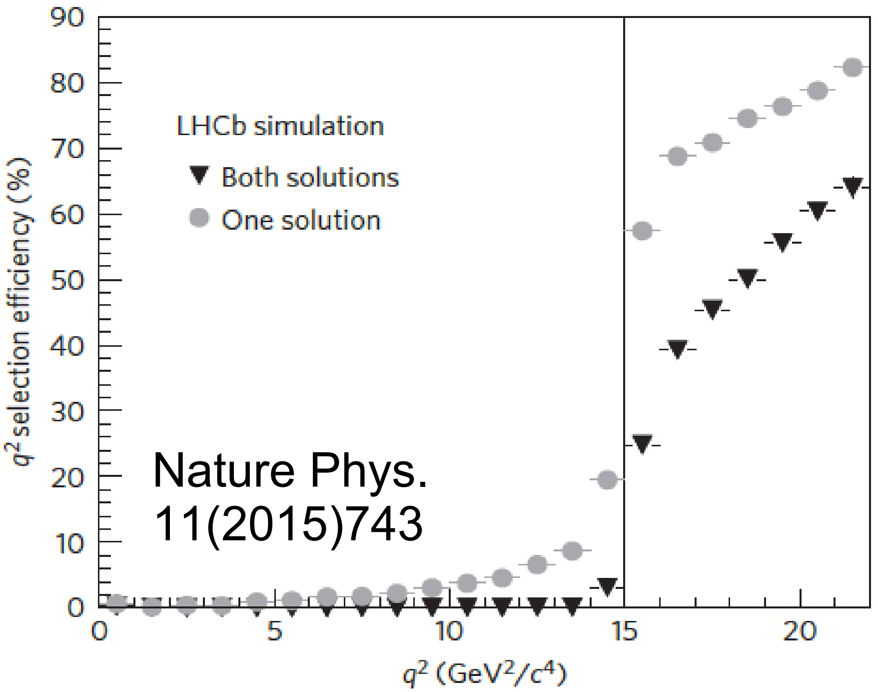


B → X_q μ ν



$$R = |\vec{p}_\nu| = E_\nu = \frac{m_B^2 - m_{X_q+\mu}^2}{2m_B}$$

- Requiring both q^2 from the two solution above 15 GeV^2

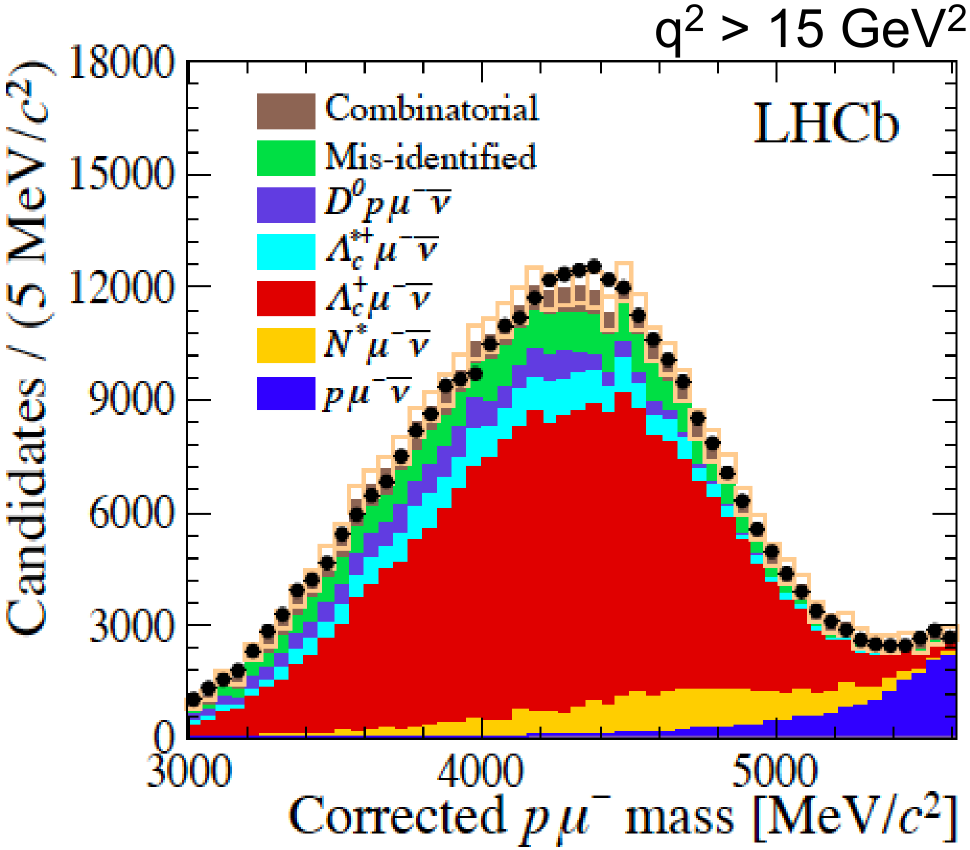


Nature Phys. 11(2015)743

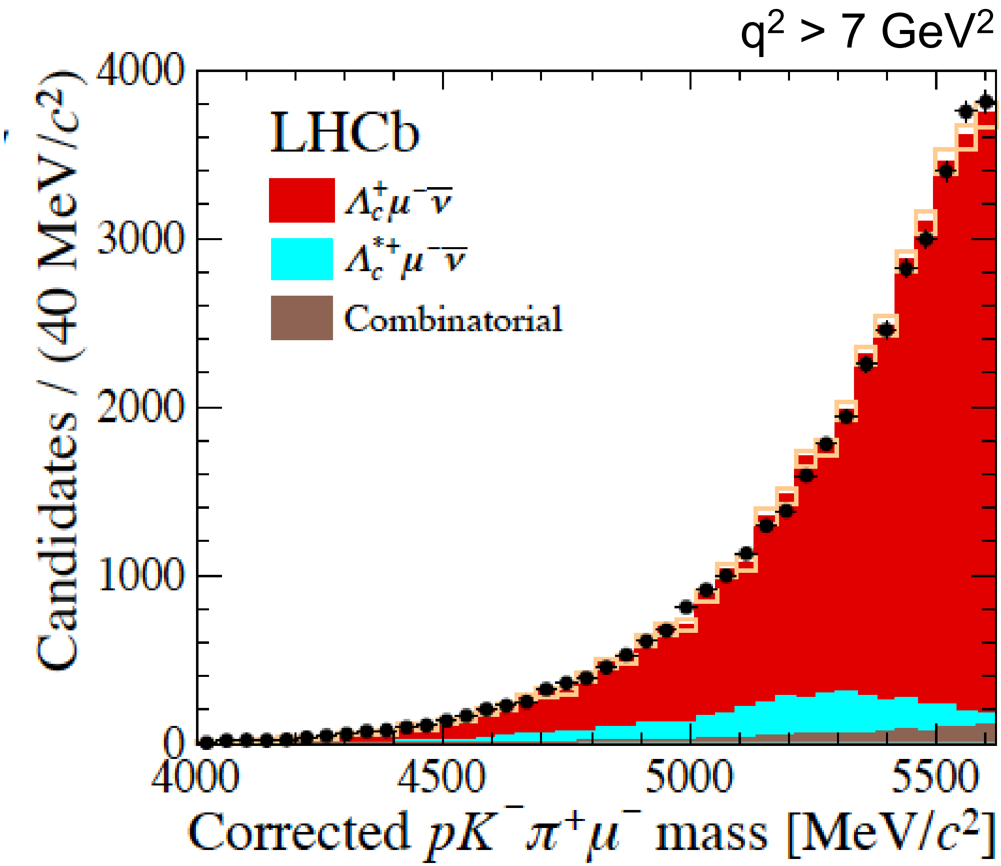
$\Lambda_b \to p\mu\nu$: signal fits

Nature Phys.11(2015)743

Signal N=17687 ± 733



Normalization N=34255 ± 571



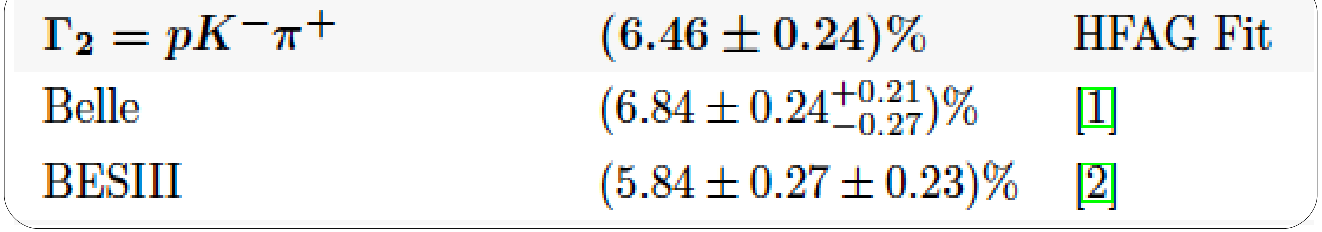
$$R_{exp} = 1.00 \pm 0.04(\text{stat}) \pm 0.08(\text{syst})$$

Systematics dominated by BF($\Lambda_c \to pK\pi$), trigger and tracking efficiency

Updated $|V_{ub}/V_{cb}|$ measurement

Nature Phys.11(2015)743

- LHCb input updated with the new BF($\Lambda_c \to p K \pi$)



$\Gamma_2 = pK^-\pi^+$	$(6.46 \pm 0.24)\%$	HFAG Fit
Belle	$(6.84 \pm 0.24^{+0.21}_{-0.27})\%$	[1]
BESIII	$(5.84 \pm 0.27 \pm 0.23)\%$	[2]

About 2σ difference

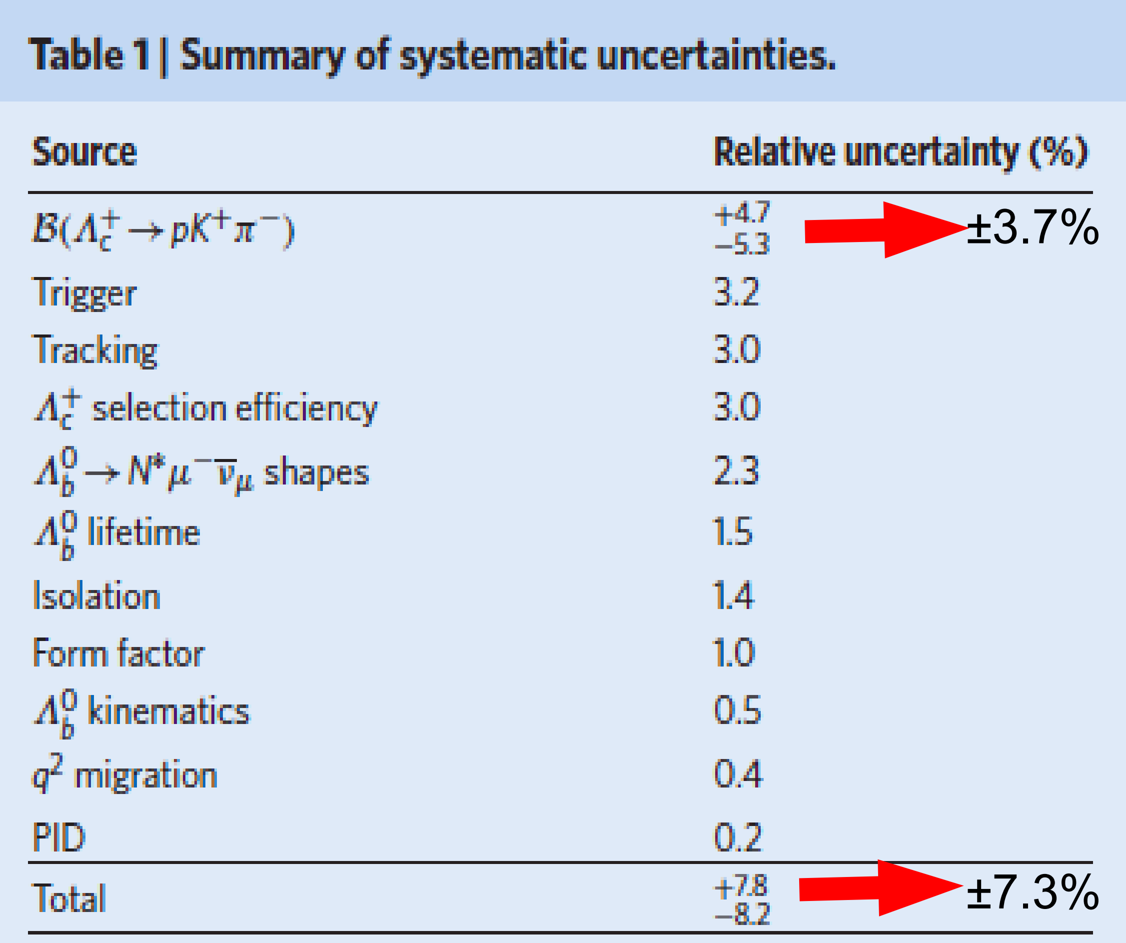


Table 1 | Summary of systematic uncertainties.

Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	3.2
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

±3.7%

±7.3%

Published

R_{exp} =(1.00 ± 0.04 ± 0.07) x 10^{-2}

$|V_{ub} / V_{cb}| = 0.083 \pm 0.004_{exp} \pm 0.004_{FF}$

Rescaled

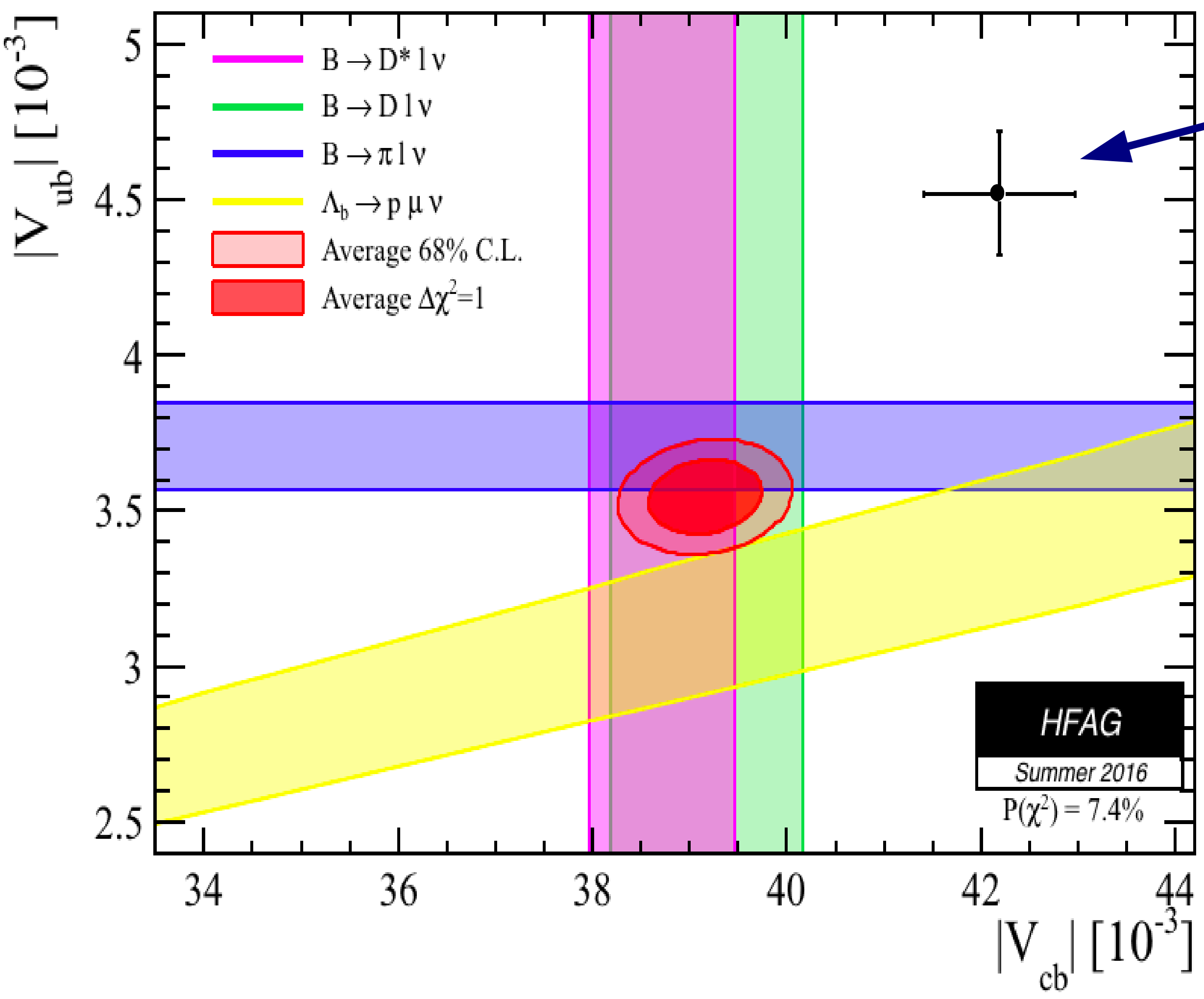
R_{exp} =(0.95 ± 0.04 ± 0.07) x 10^{-2}

$|V_{ub} / V_{cb}| = 0.080 \pm 0.004_{exp} \pm 0.004_{FF}$

- Dominated by systematics and theory uncertainties
  - It will be crucial to have more calculations
  - possible improvements?

Global average including LHCb results

- Including the exclusive determinations in a $|V_{ub}|$-$|V_{cb}|$ (A. Kronfeld's plot)



Inclusive determinations
$|V_{ub}|$: GGOU
$|V_{cb}|$: global fit with kinetic scheme

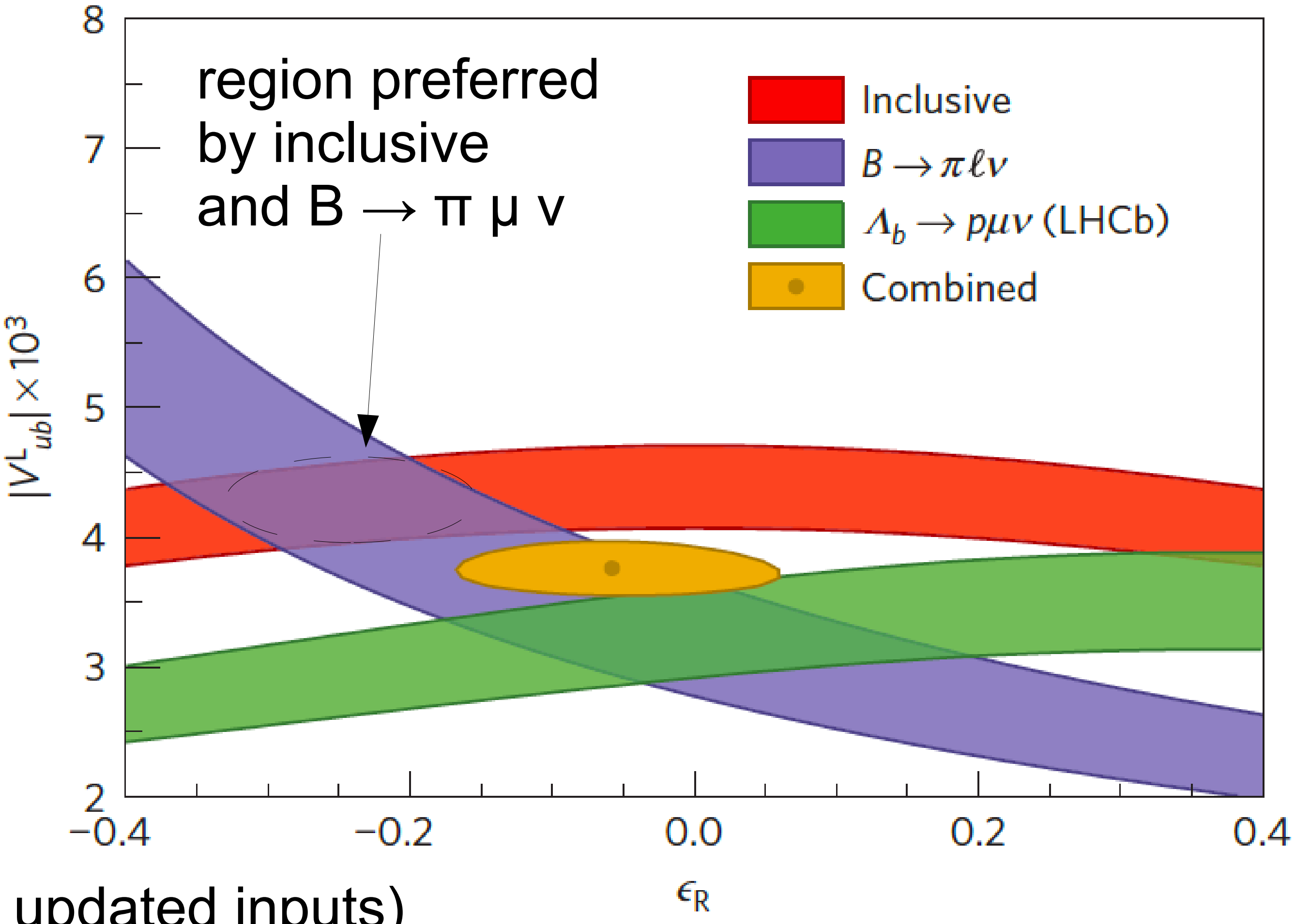
- $\rho(|V_{ub}|,|V_{cb}|)$=+0.14
- $|V_{ub}|$ = (3.55 ± 0.12) x 10^{-2}
- $|V_{cb}|$ = (39.16 ± 0.58) x 10^{-2}

3.4% uncertainty on $|V_{ub}|$
Including LHCb measurement

RH currents

Nature Phys.11(2015)743

- The right-handed current model could explain the historical difference between inclusive and exclusive |Vub|
- The $\Lambda_b \rightarrow p \mu \nu$ has also contribution from axial vector current: different dependence on the RH current

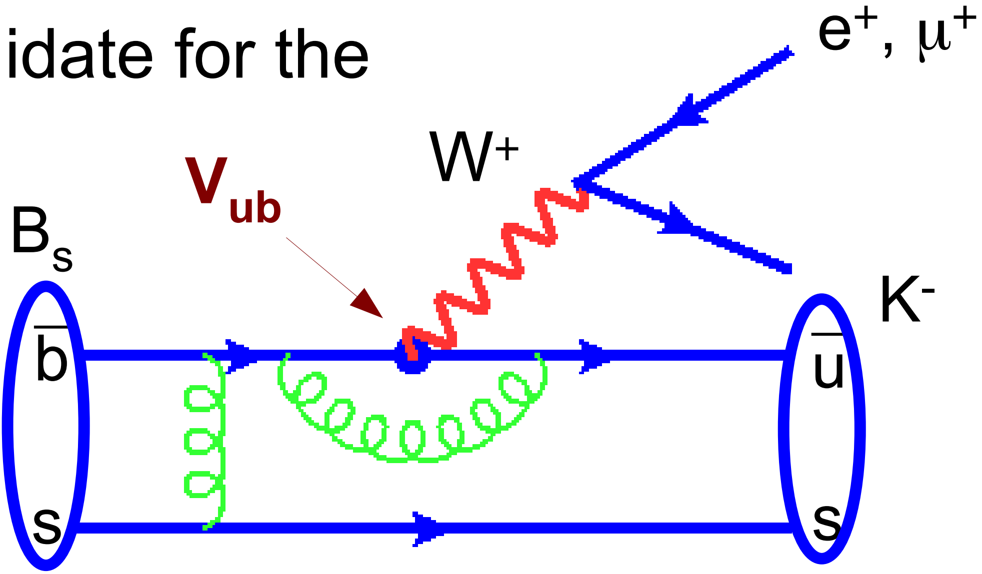


The inclusion of LHCb does not support a significant RH contribution

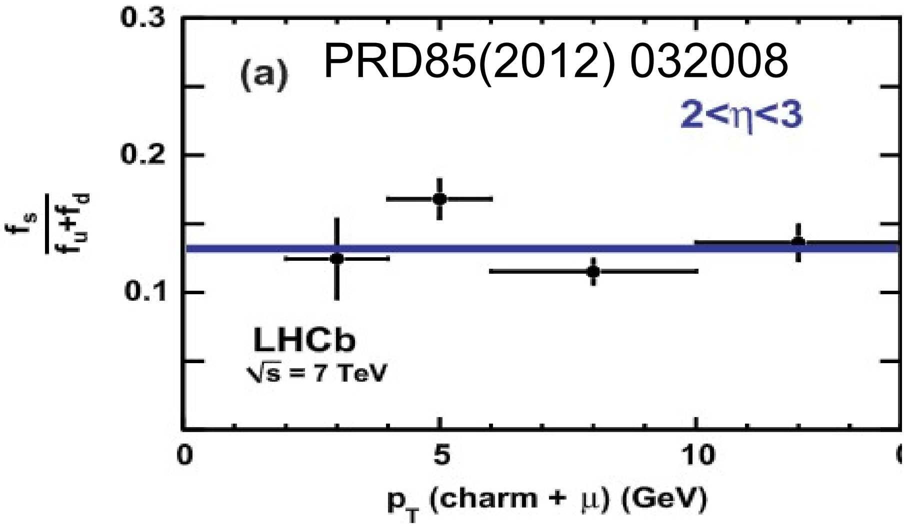
(not updated inputs)

Future measurement: $B_s \to K \mu \nu$

- $B_s \to K \mu \nu$ is the natural candidate for the next measurement



- Huge B_s production: ~14% of the b-hadrons



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

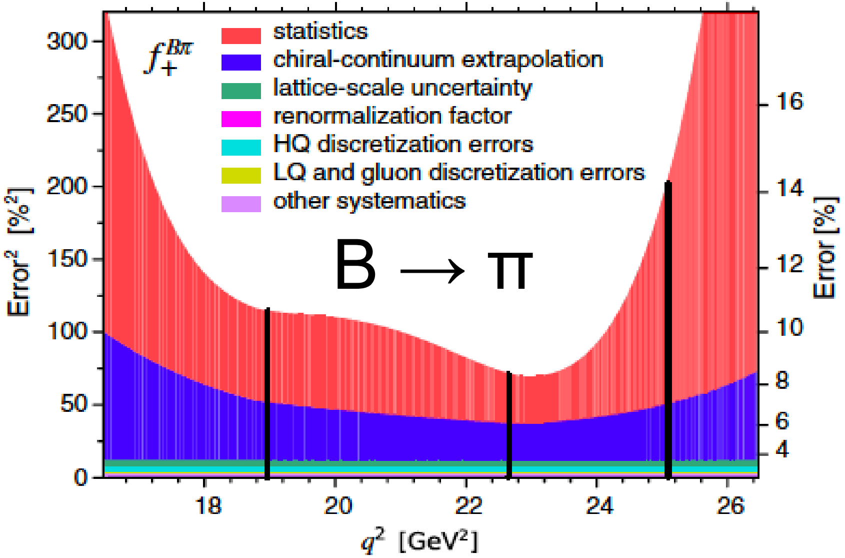
- At Belle-II this channel has to wait for the run at Y(5S)

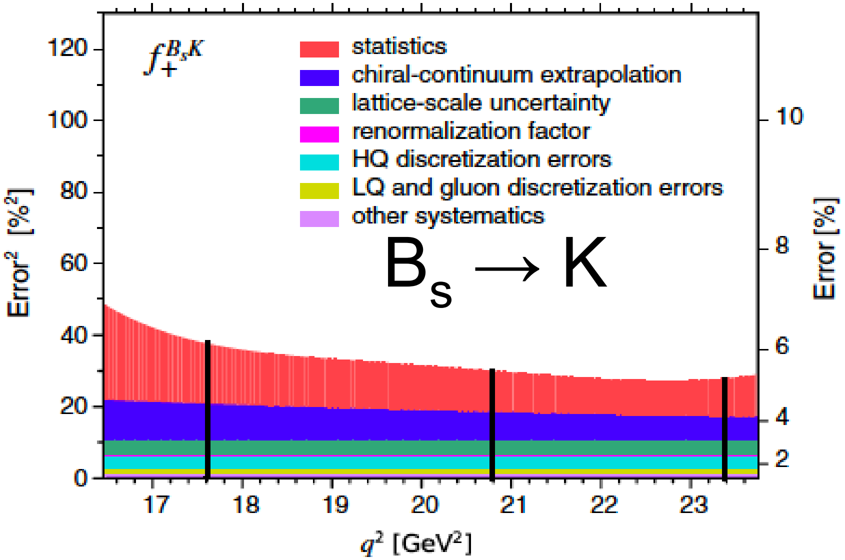
- Form factors can be computed with high accuracy (next slide ⇒)
- Dangerous background from
  - $B_s \to K^* \mu^+ \nu$, with $K^* \to K^- \pi^0$
  - It has to be fitted together with the signal
  - Interesting by itself Phys. Rev. D 92 034013 (2015)

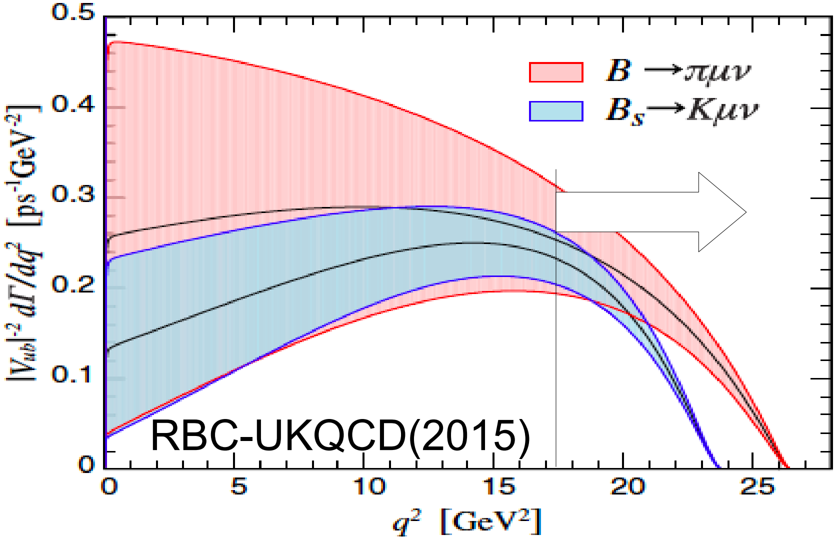
$B_s \rightarrow K \mu \nu$ form factors

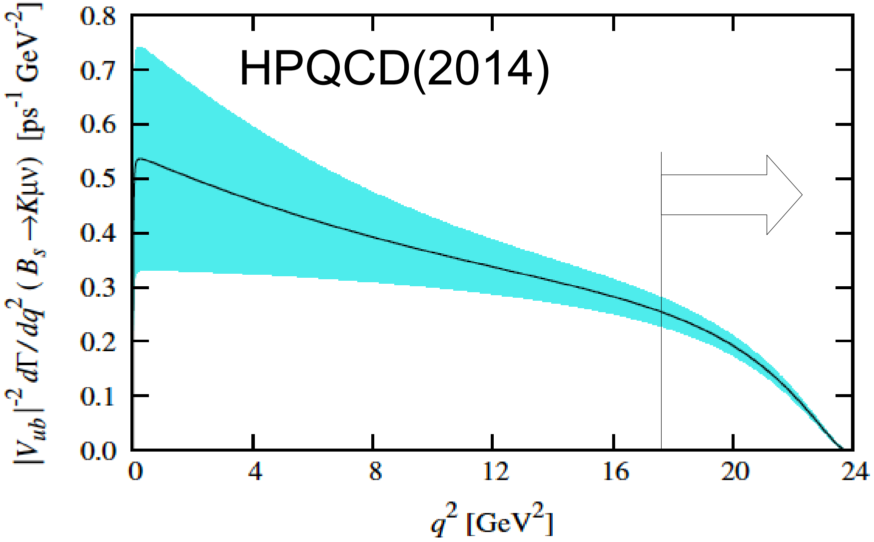
- $B_s \rightarrow K$ golden channel for $|V_{ub}|$: doesn't need extrapolation to spectator-quark physical mass

RBC-UKQCD(2015)









Other calculations ongoing ALPHA, MILC/FNAL

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

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

S. Stefkova @ ICHEP

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

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

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

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

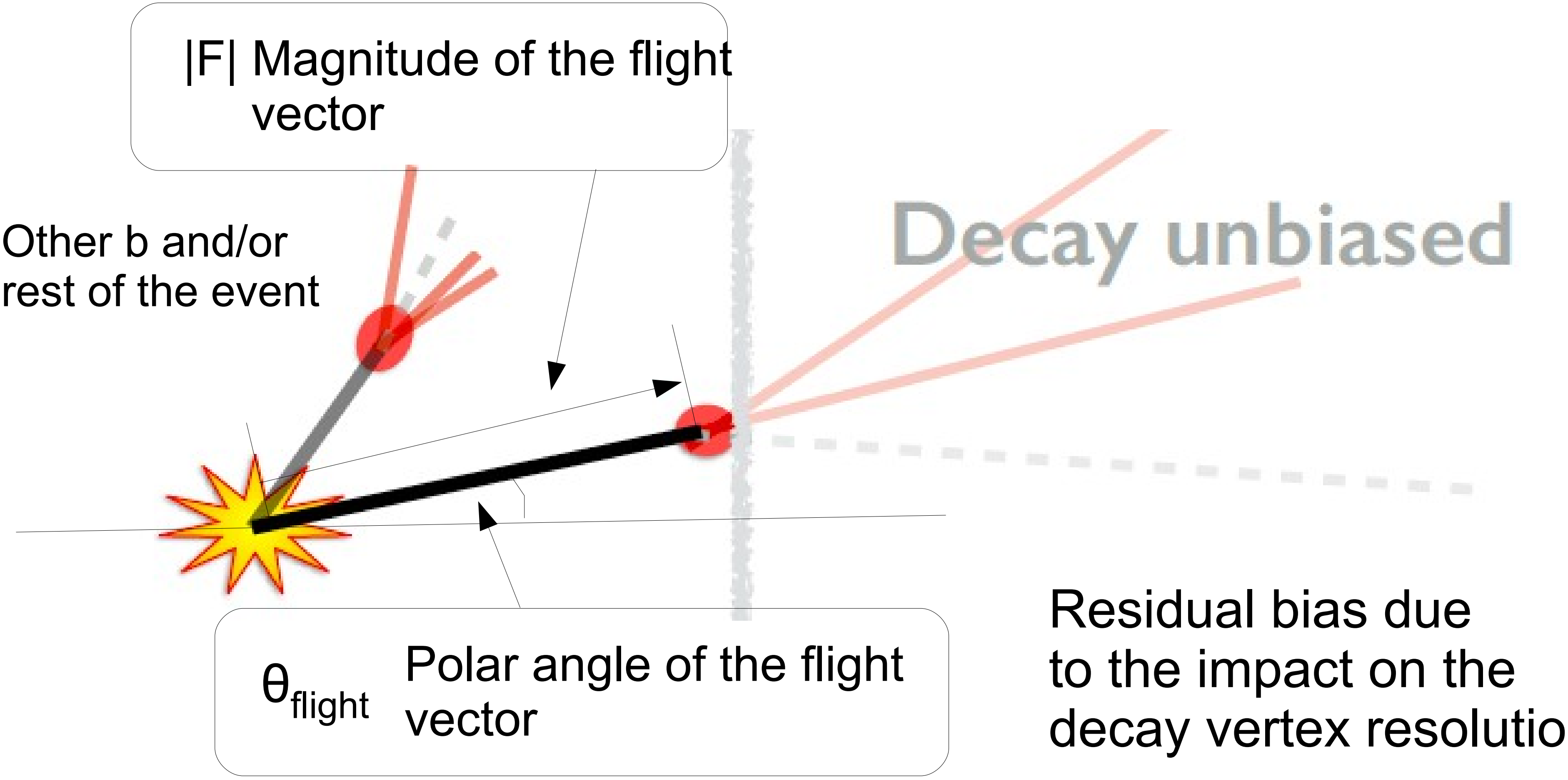
First excited D_s decays mainly in neutrals:

- standard isolation tools does not work
- rely on kinematics and the ECL

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

Improve kinematic resolution

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



|F| Magnitude of the flight vector

Other b and/or rest of the event

θ_{flight} Polar angle of the flight vector

Residual bias due to the impact on the decay vertex resolution

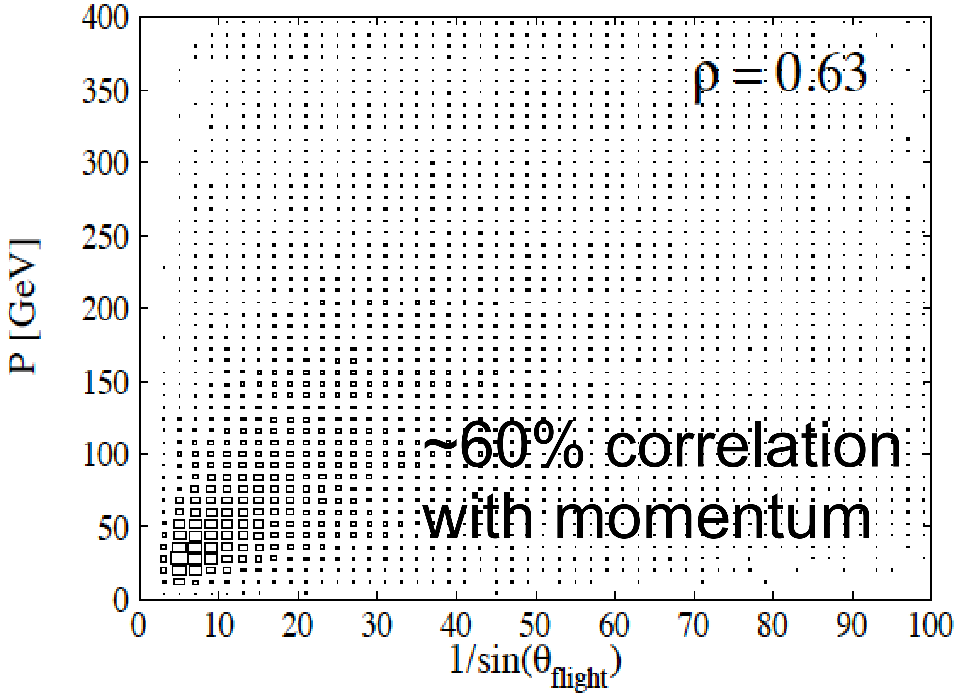
Exploit the flight informations

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

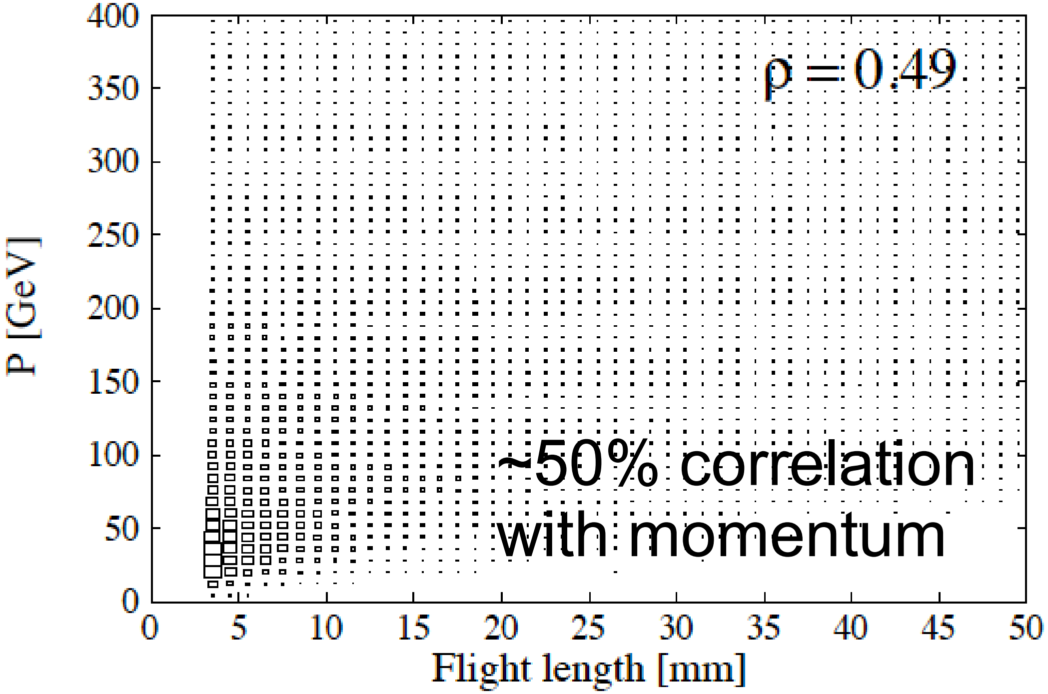
approximation

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

Apply |F|> 3mm



~60% correlation with momentum

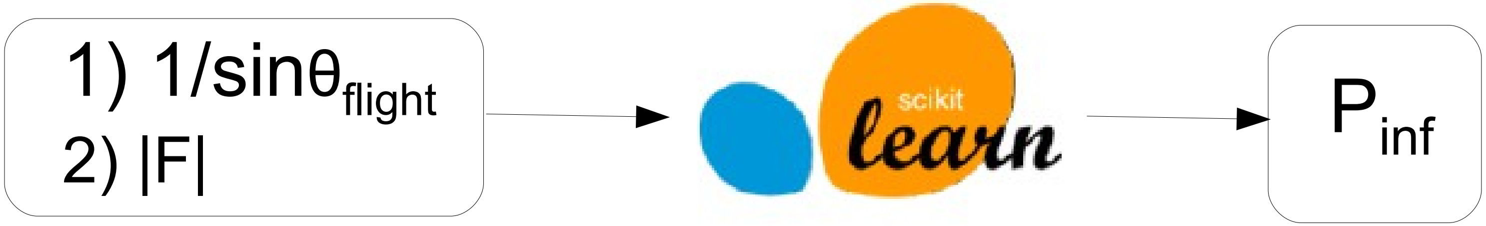


~50% correlation with momentum

- 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

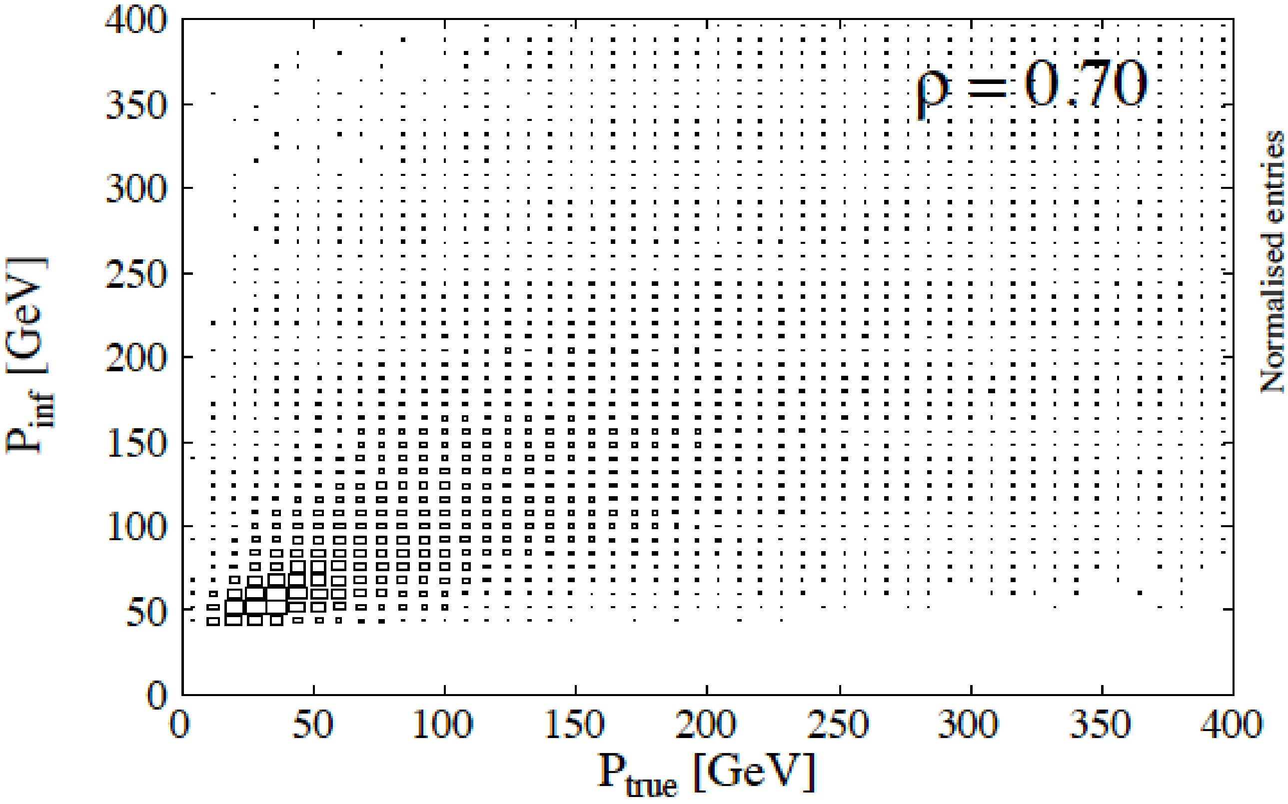
Unbiased momentum reconstruction

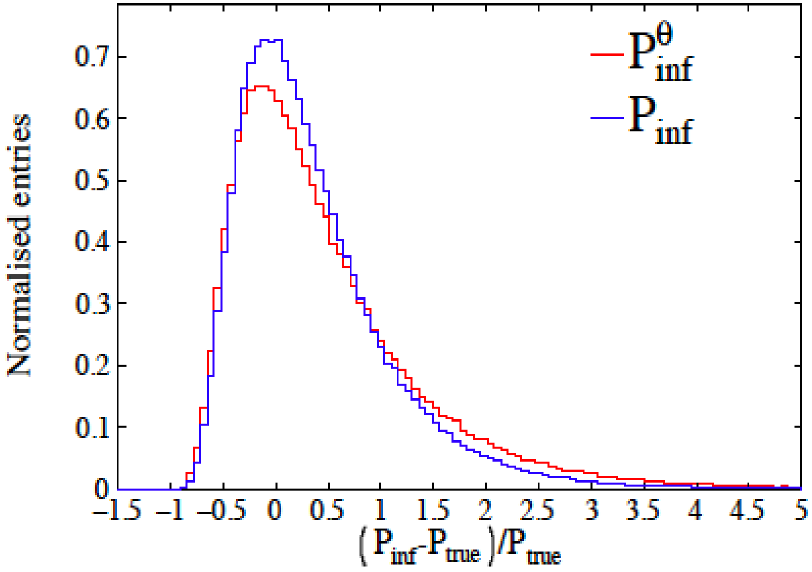
- How to exploit these features and some practical applications
  - Arxiv:1611.08522 G.Ciezarek, A.Lupato, MR, M.Vesterinen



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

P_{inf}



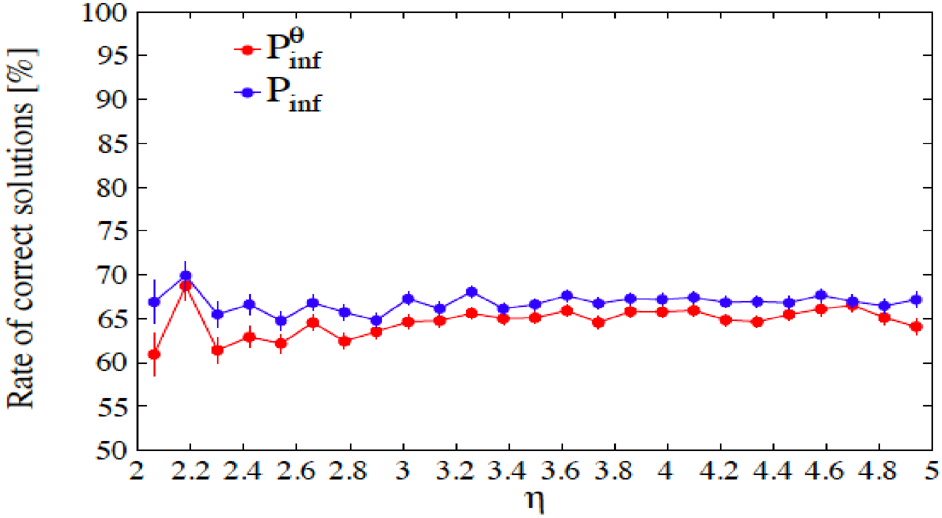


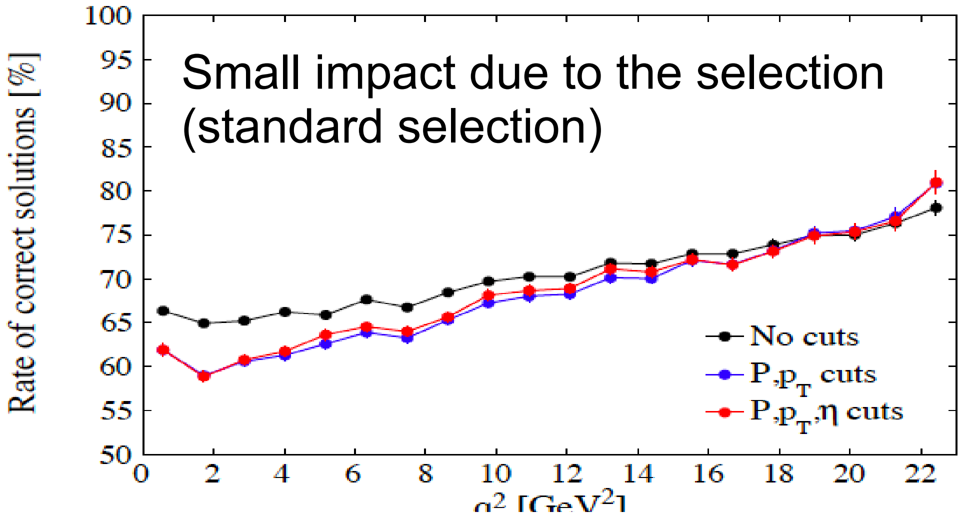
Modest momentum estimate

Application to semileptonic events

ArXiv:1611.08522

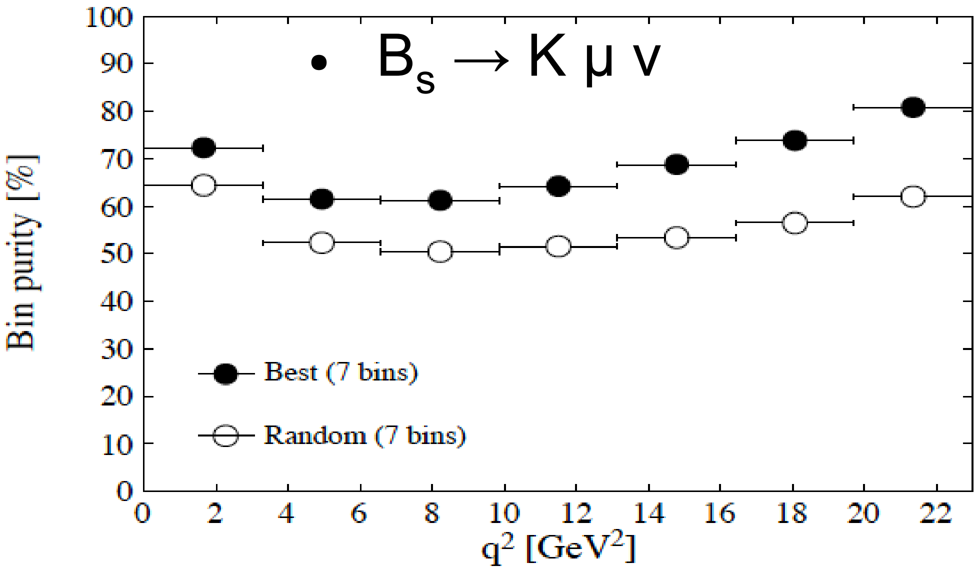
- 2-fold ambiguity in the neutrino momentum reconstruction
- Resolution of P_{inf} is enough to improve the chance to choose the right $P_{+/-}$ solution over random choice $B_s \rightarrow K^{(*)} \mu \nu$





Small impact due to the selection (standard selection)

- 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

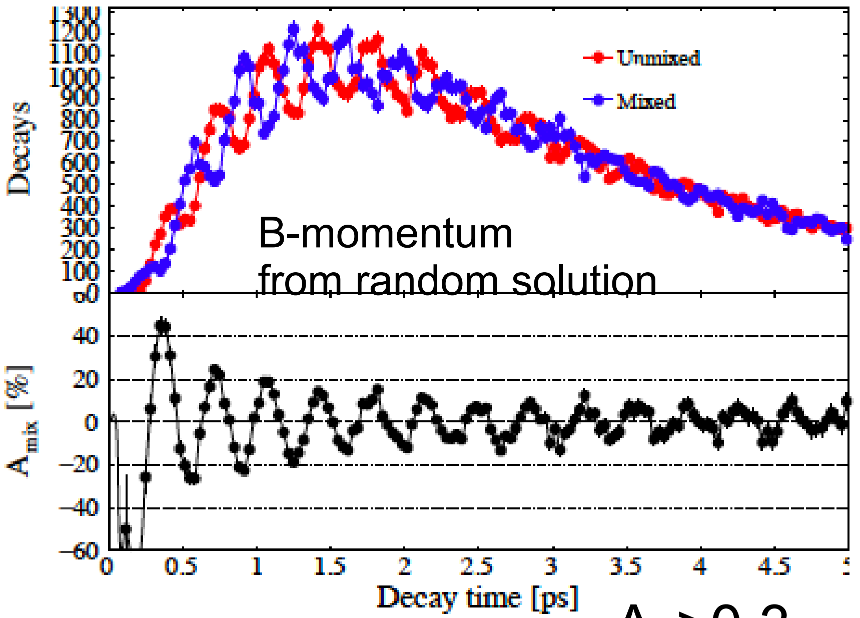


- $B_s \rightarrow K \mu \nu$

Other usage: oscillation measurements

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

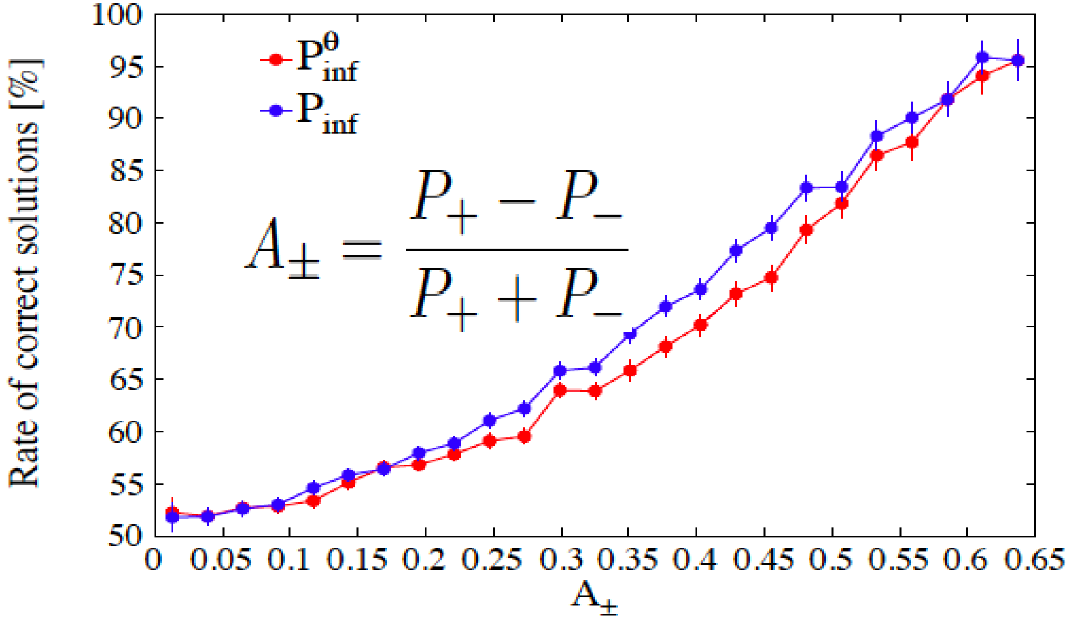
$$\frac{\Gamma[D_s^- \mu^+, t] - \Gamma[D_s^+ \mu^-, t]}{\Gamma[D_s^- \mu^+, t] + \Gamma[D_s^+ \mu^-, t]} = \frac{a_{\rm sl}^s}{2} - \left[\frac{a_{\rm sl}^s + 2A_P}{2}\right]\left[\frac{\cos(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2)}\right]$$



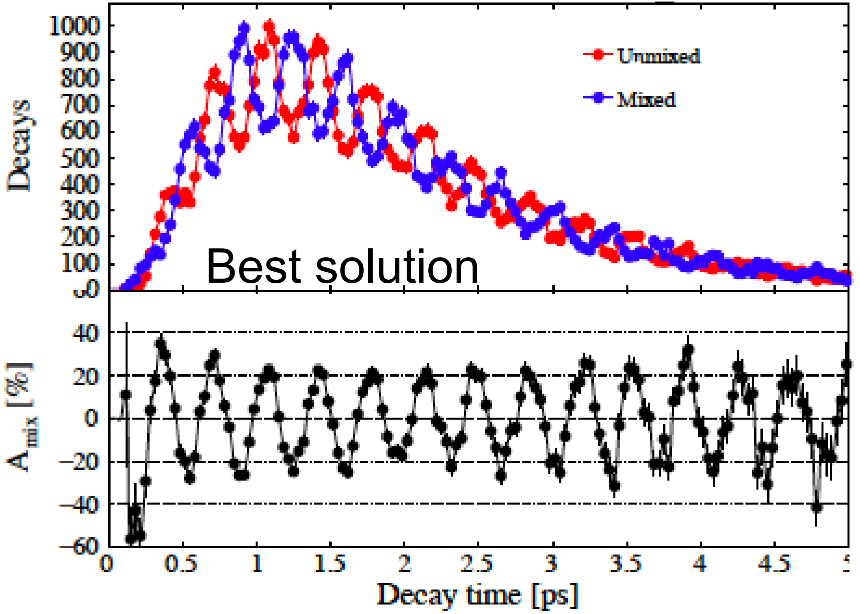
B-momentum from random solution

$A_+ > 0.3$

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



$$A_{\pm} = \frac{P_+ - P_-}{P_+ + P_-}$$

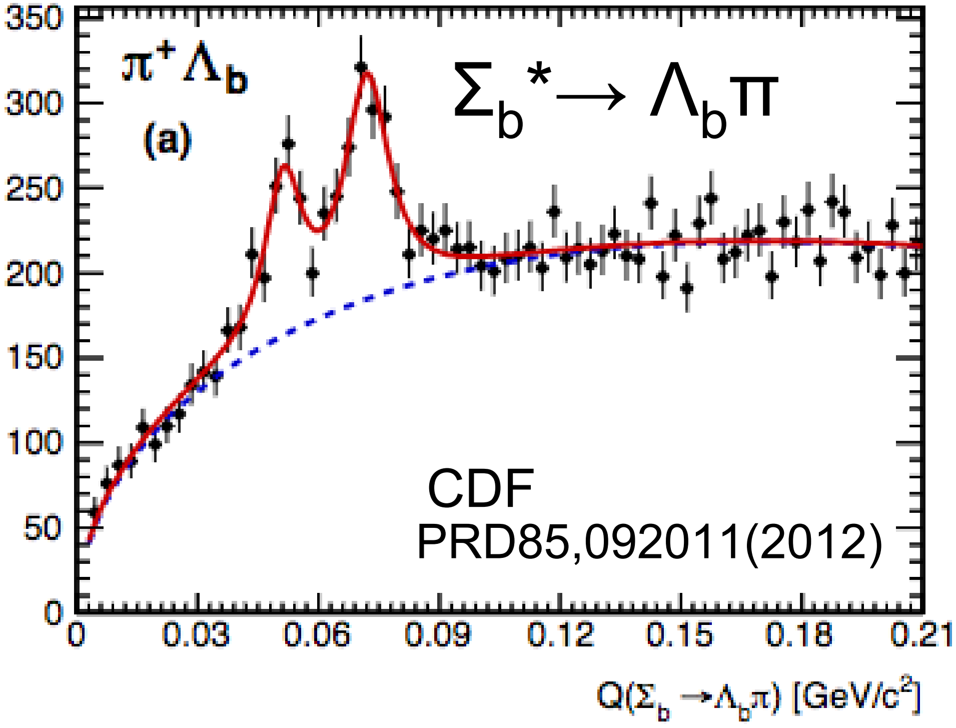


Best solution

ArXiv:1611.08522

Kinematics++ exploiting the resonances

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



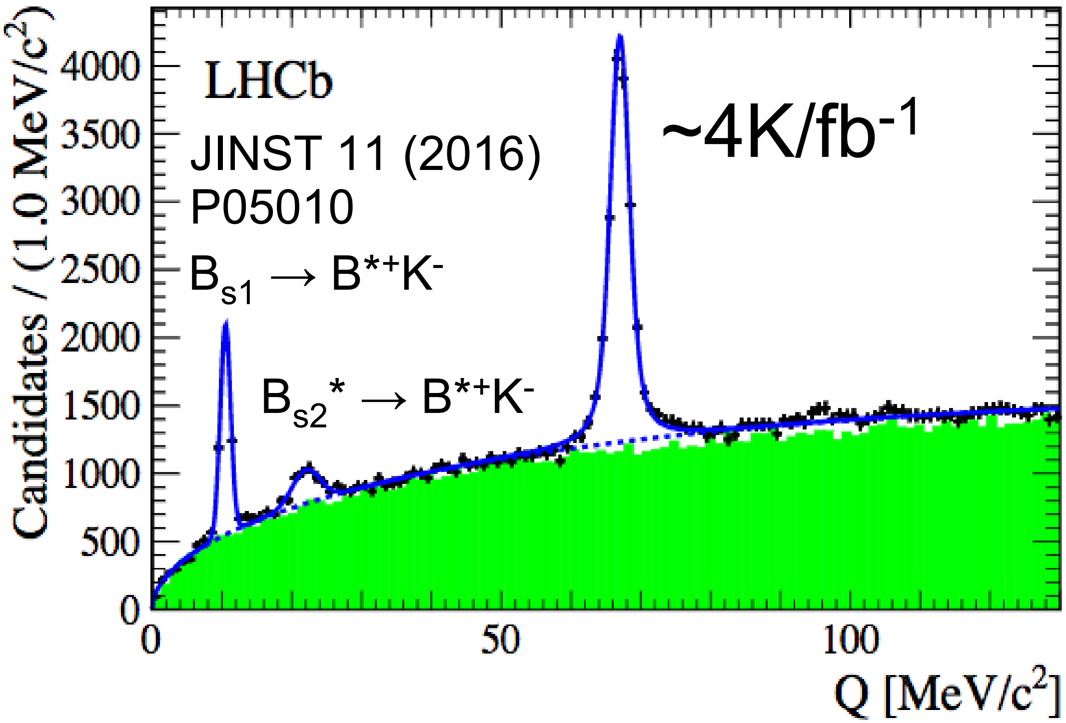
$\Sigma_b^* \to \Lambda_b \pi$

CDF
PRD85,092011(2012)

Λ_b from Σ_b, challenge from the many overlapping states

Promising but we still need to fully exploit these techniques

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



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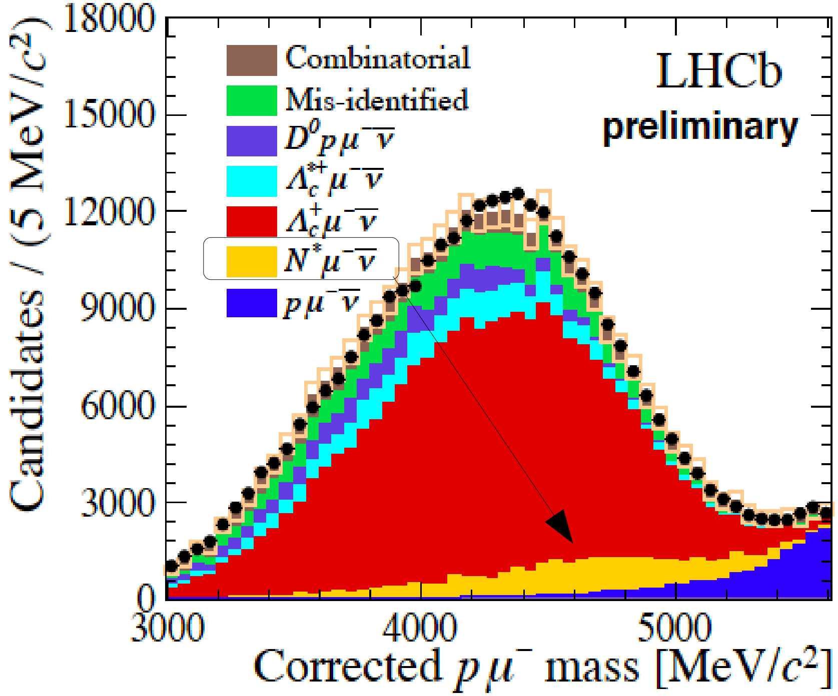
P05010

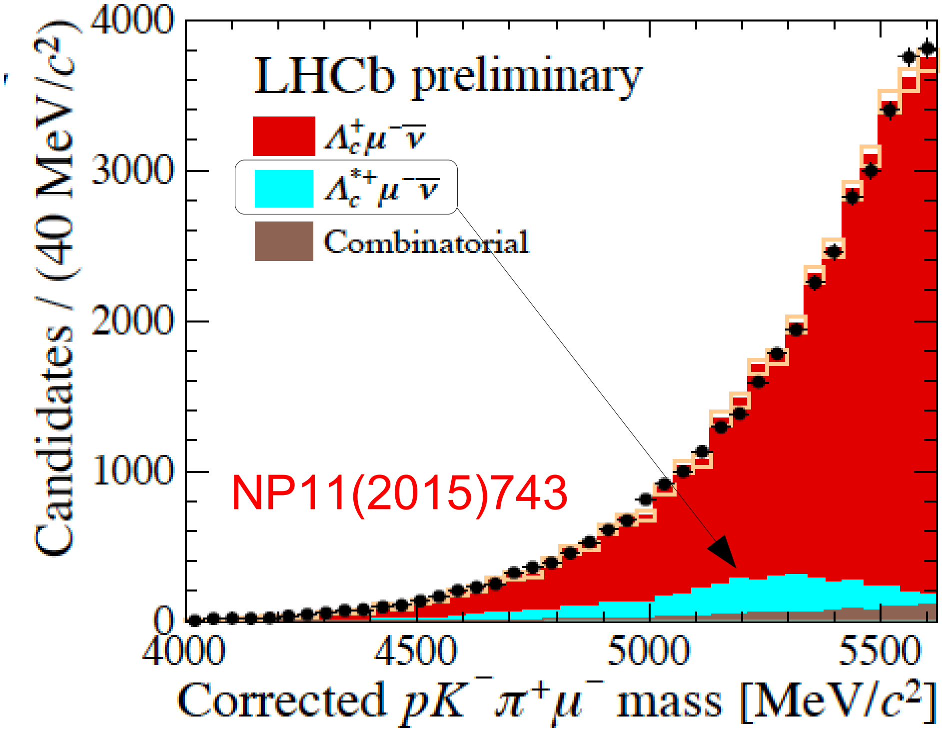
~4K/fb^{-1}

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!





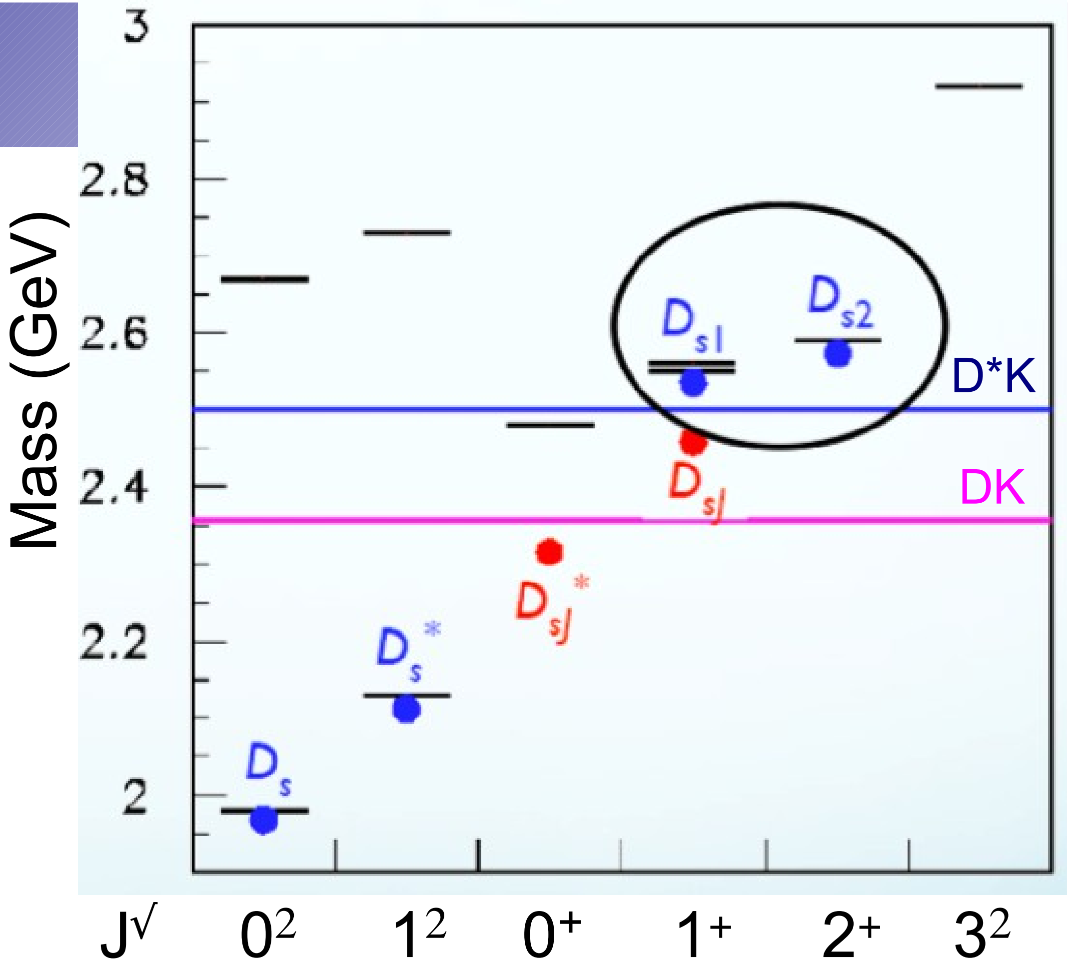
NP11(2015)743

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

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

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

- 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 belowe the DK threshold can be studied explicitly reconstructing the soft π^0 and γ
- To extract $|V_{cb}|$ a proper normalization is required



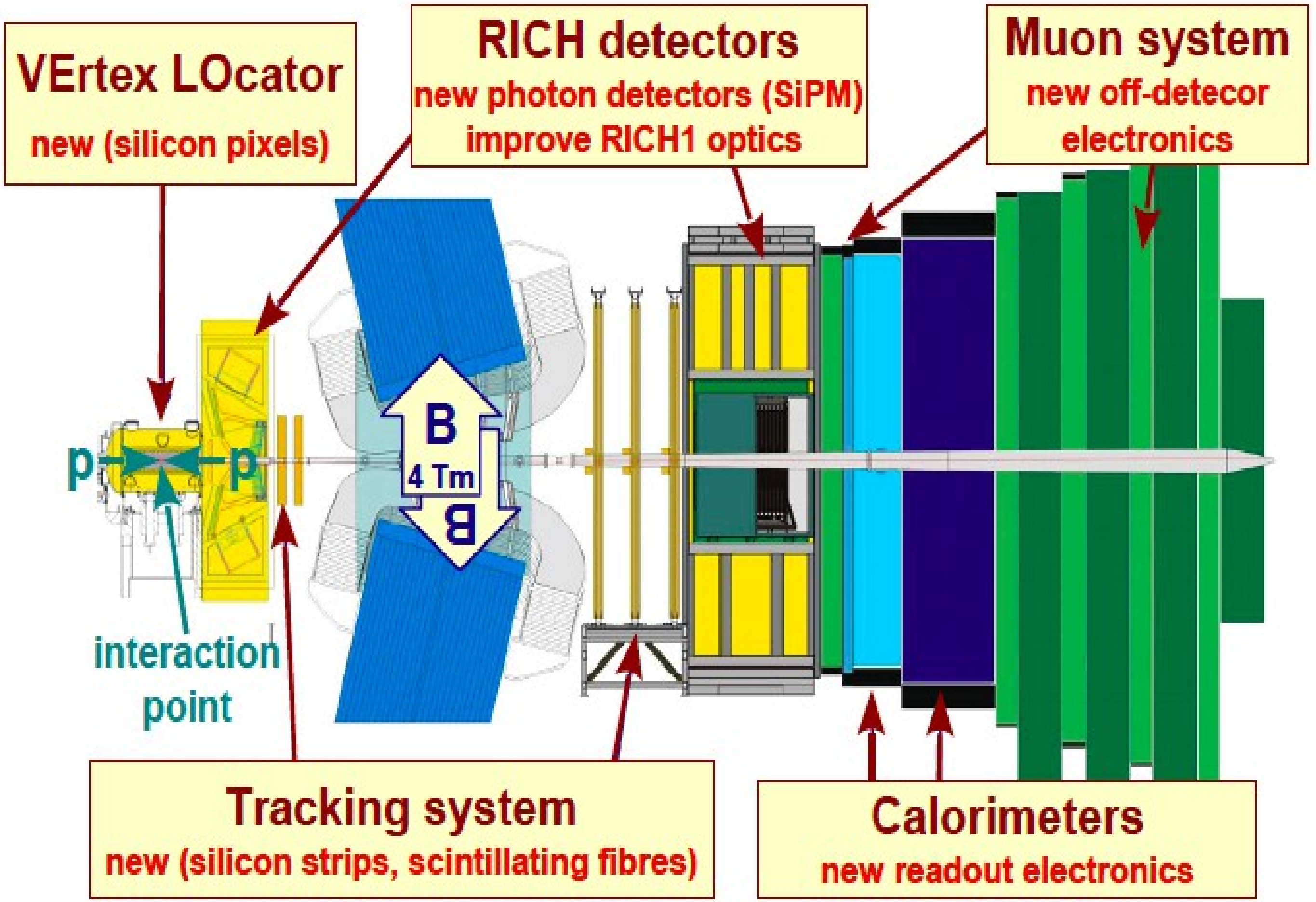
	J^P	Mass (MeV)	Width (MeV)	Observed decays
D_{s0}^*	0^+	2317.8 ± 0.6	< 3.8	$D_s^+\pi^0$
D_{s1}'	1^+	2459.5 ± 0.6	< 3.5	$D_s^{*+}\pi^0, D_s^+\gamma, D_s^+\pi^+\pi^-$
D_{s1}	1^+	2535.28 ± 0.20	< 2.5	$D^{*+}K^0, D^{*0}K^+$
D_{s2}^*	2^+	2572.6 ± 0.9	20 ± 5	D^0K^+

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**



VErtex LOcator
new (silicon pixels)

RICH detectors
new photon detectors (SiPM)
improve RICH1 optics

Muon system
new off-detecor
electronics

Tracking system
new (silicon strips, scintillating fibres)

Calorimeters
new readout electronics

LHCb Upgrade

HL LHC

2021 2024 2027 2030 2031 2034 2035

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

Phase 1

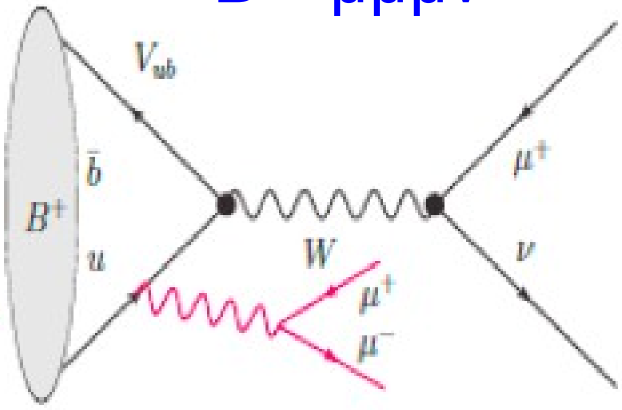
Phase 1b

Phase 2

Outlook

- Better understanding of the SL decays in many b-hadrons are crucial to extract $|V_{ub}|$, $|V_{cb}|$ and study semitauonic B decays
- The present $\Lambda_b \to p \mu \nu$ and the next ongoing analysis will be dominated by the systematic uncertainties. But still the huge statistics available with the upgraded detector will allow to design the cuts to reduce most of the systematics.
  - The systematics due to the normalization channels will continue to require external inputs
- For $|V_{ub}|$ measurements, with much larger statistics, windows for other channels can be exploited

$B \to \mu\mu\mu\nu$



- $B \to \tau \nu$ is not possible at LHCb
- A virtual photon in a couple of muons overcomes the helicity suppression and add a good experimental signature
- BF Is predicted ~ 10^{-8}
- FF calculation are needed JHEP 1609 (2016) 159

Backup

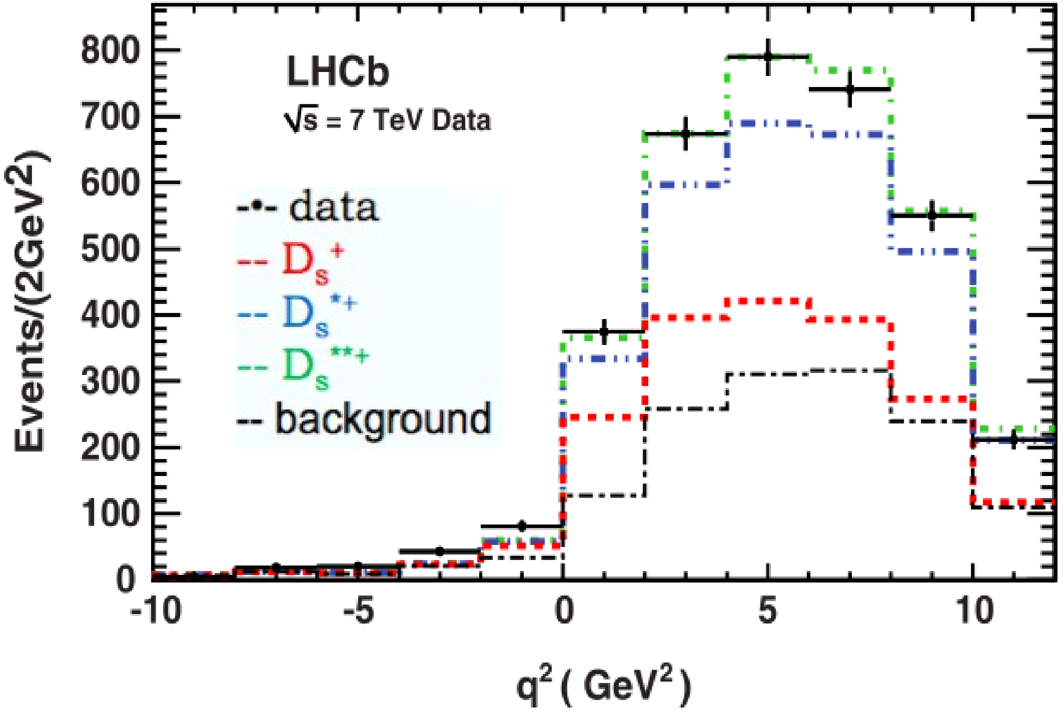
$d\Gamma/dq^2$

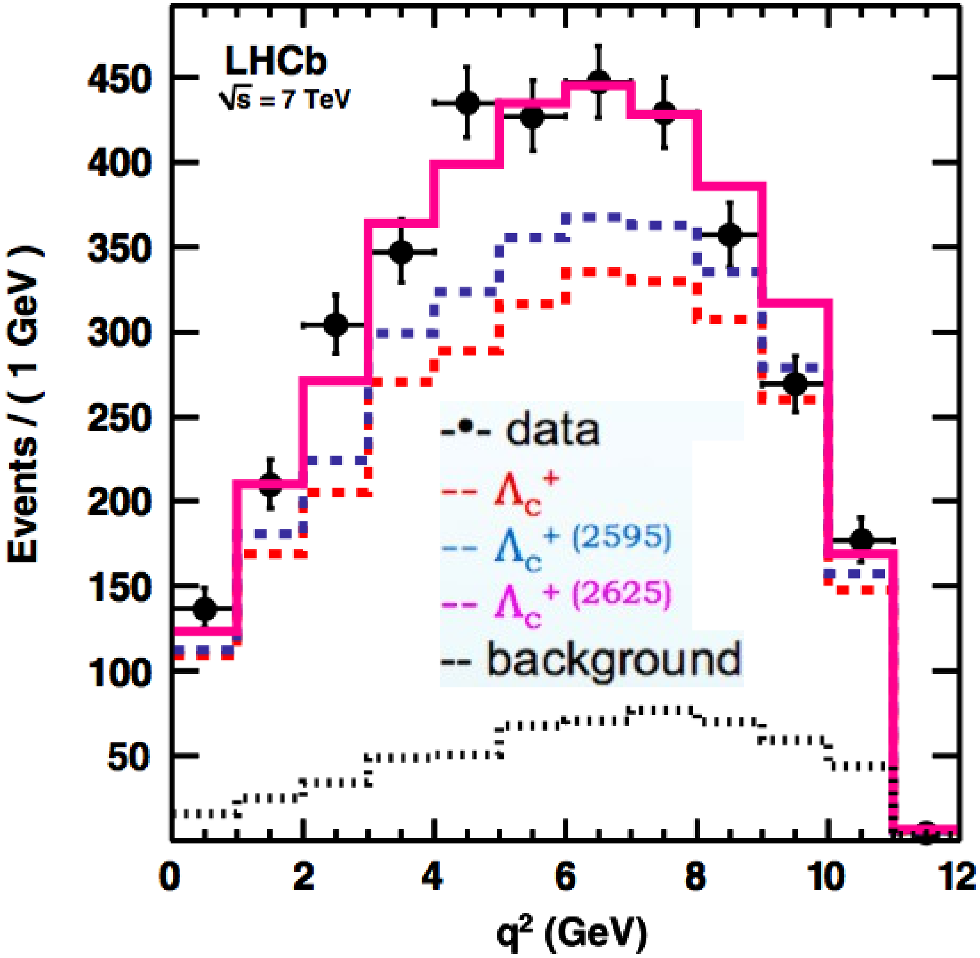
PRD85 (2012) 032008

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

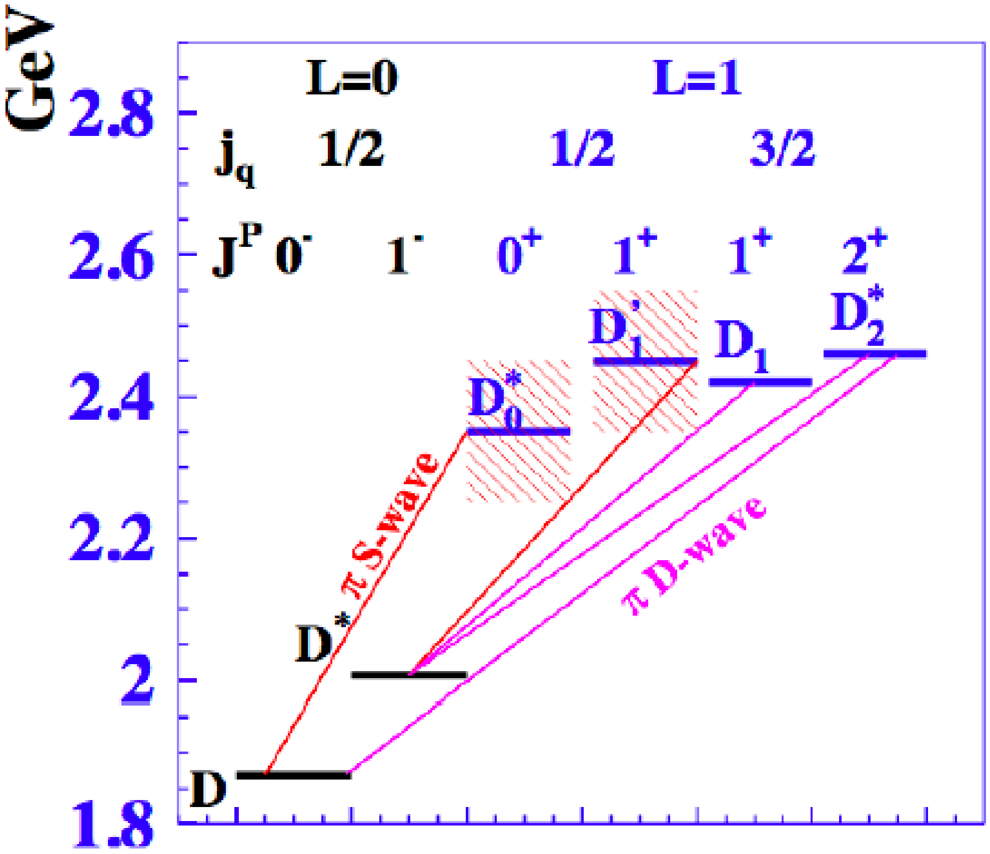
- $B_s \to D_s^{(*)} \mu \nu$
- $\Lambda_b \to \Lambda_c^* \mu \nu$





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