Universität Zürich[UZH]

Experimental overview and prospects of $|V_{ub}|$ and $|V_{cb}|$ at LHCb

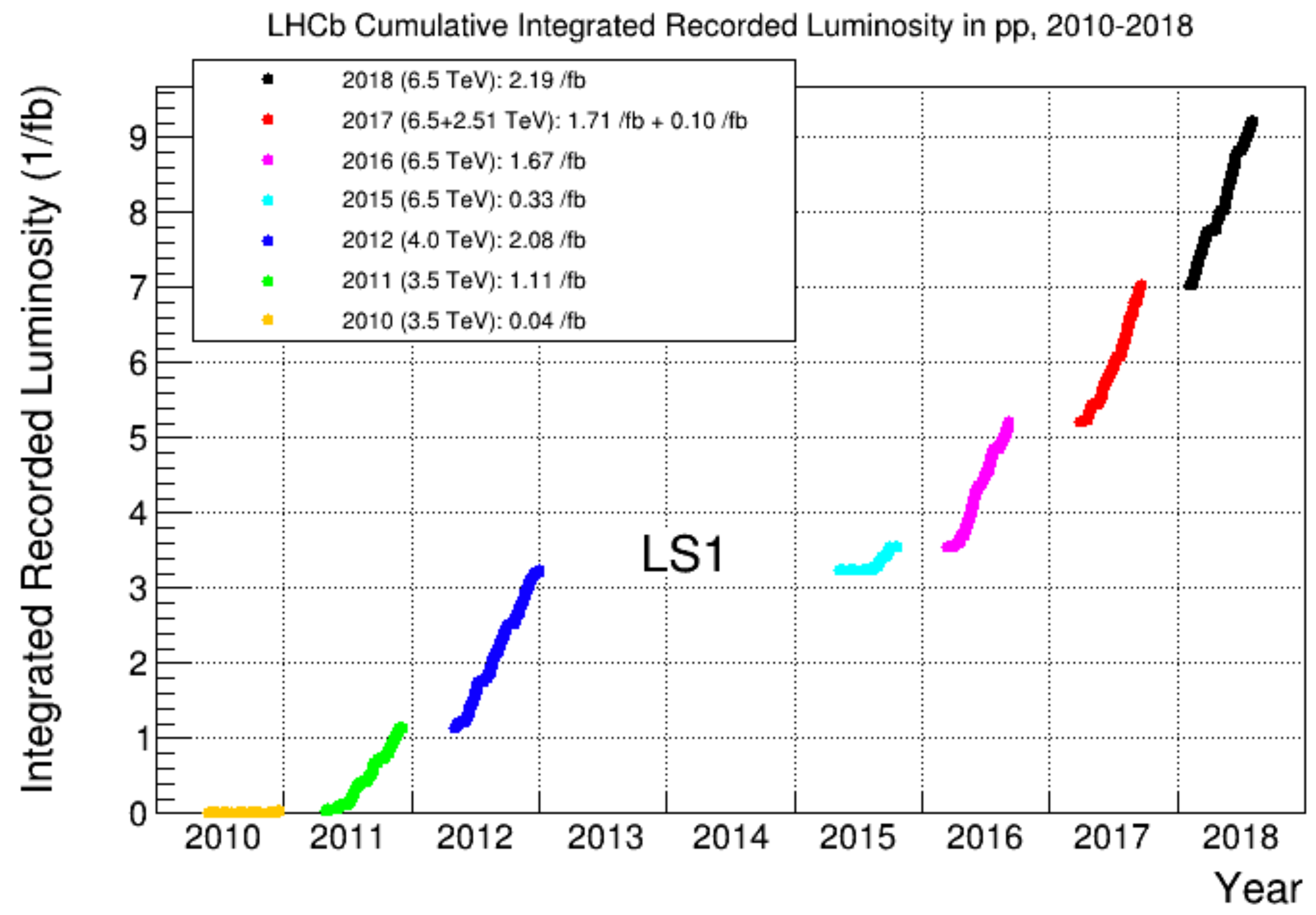
Snowmass mini-workshop on $|V_{ub}|$ and $|V_{cb}|$

Patrick Owen, on behalf of the LHCb collaboration

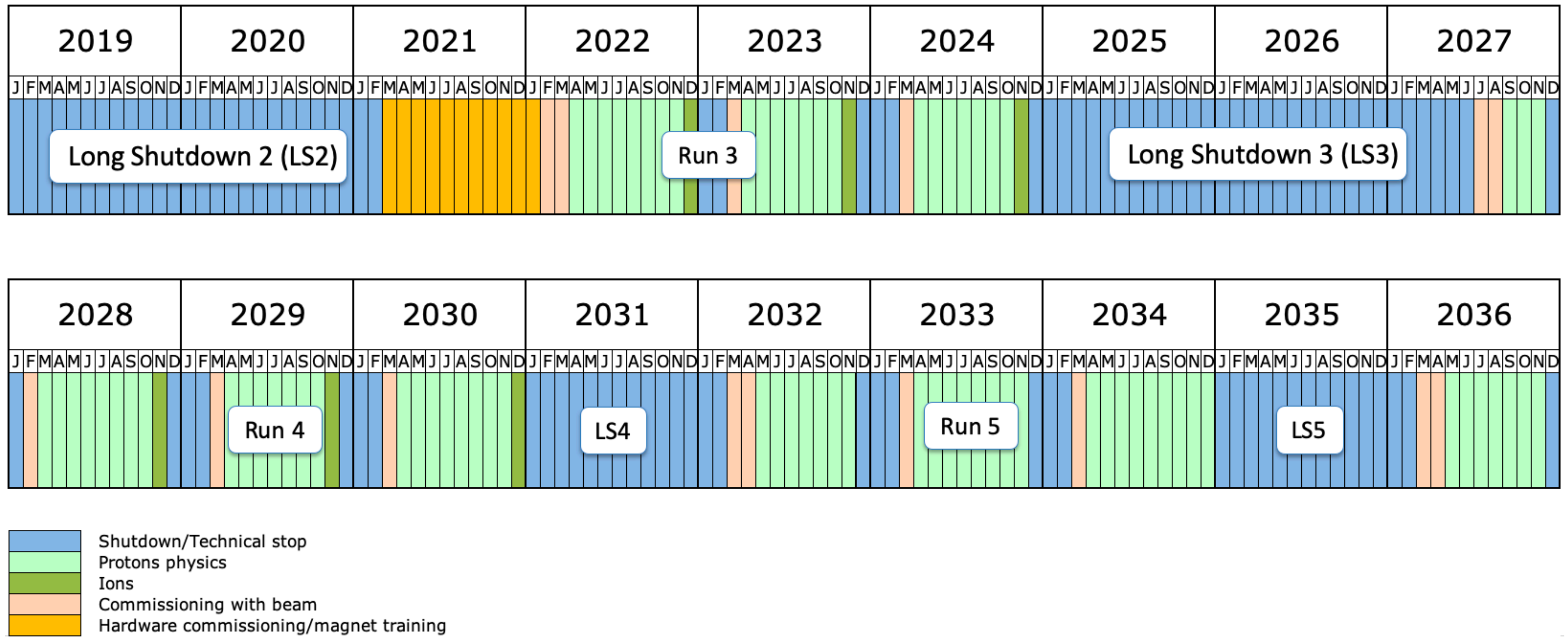
01/11/21

How are we doing

- LHCb has collected 9fb^{-1} of data.



- We are currently commissioning the first upgrade.
  - Hope to take another ~15fb^{-1} in run III without the limitations of a hardware trigger.



- Due to the pandemic, run III was delayed until 2022.

- Plans for upgrade II strongly supported by european strategy for particle physics.

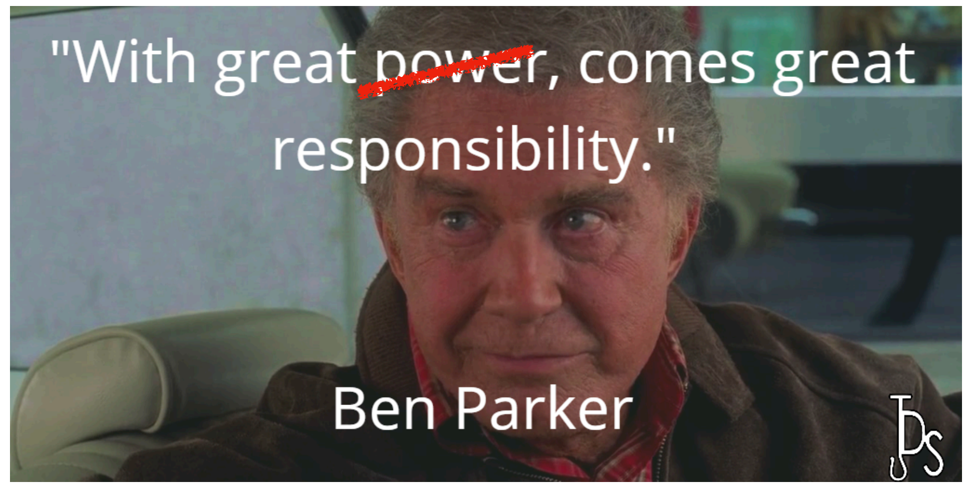
been developed. ***The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.***

ESPP 2020 update

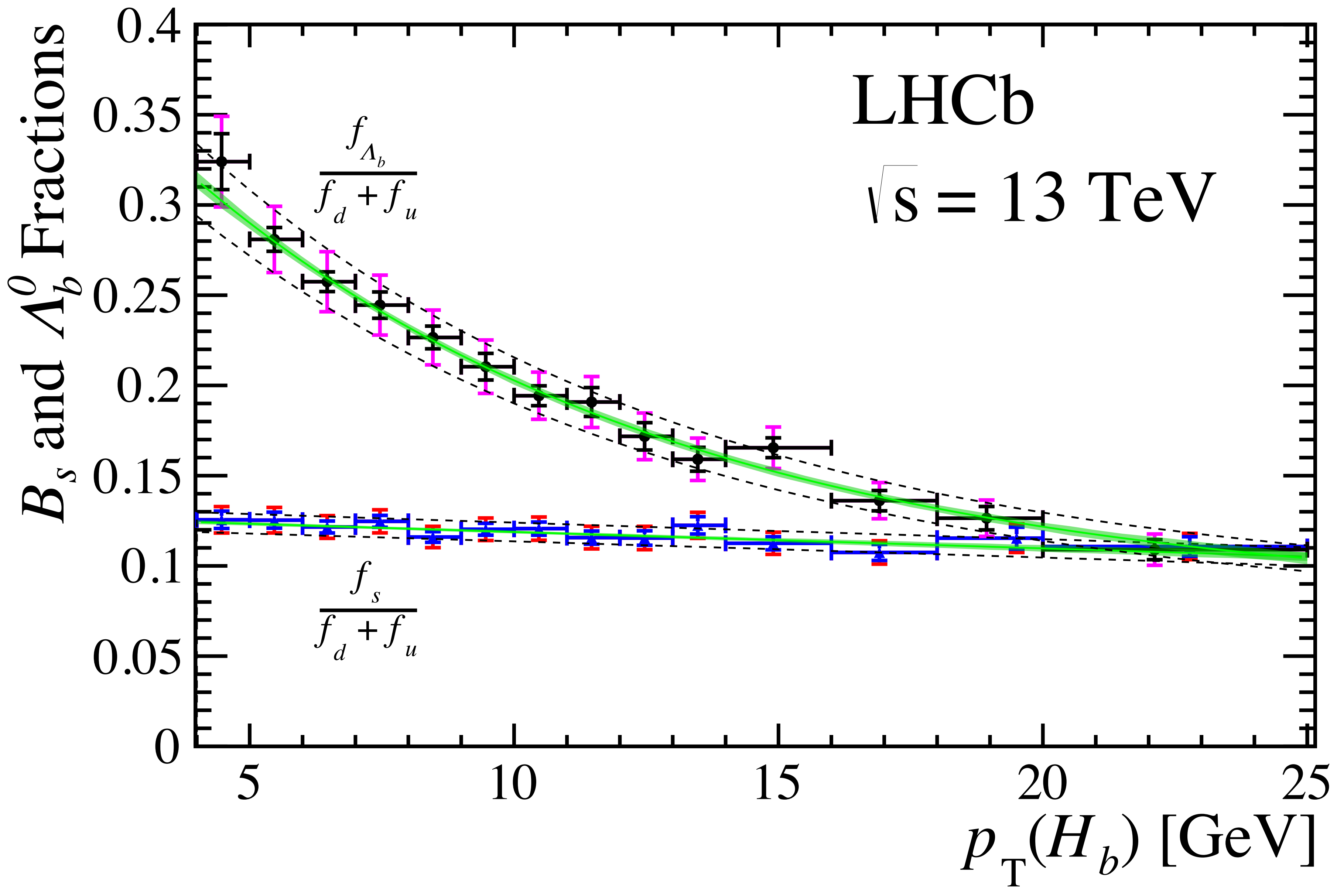
Semileptonic decays at LHCb

- Do not have direct access to absolute branching fractions.
- Do have access to all b-hadron species.
- Have very large signal yields.

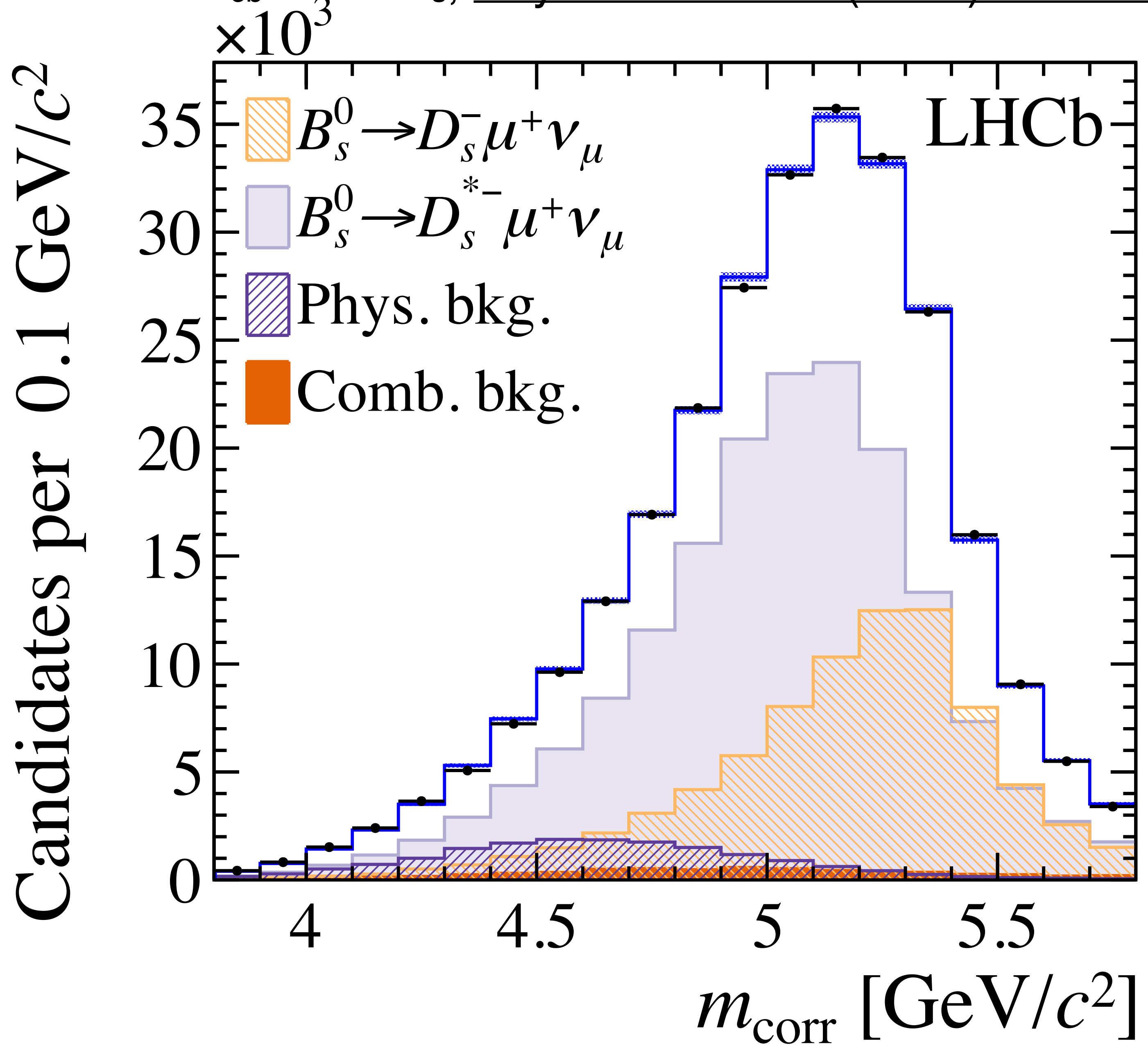
signal yields



B-fractions analysis, Phys.Rev. D100 (2019) no.3, 031102



$|V_{cb}|$ from B_s, Phys. Rev. D101 (2020) 072004



Measurements of $|V_{ub}|/|V_{cb}|$ at LHCb

- Select b—>u decay and fit corrected mass.
- Normalise to convenient b—>c transition
  - same b-hadron
  - well known FF
  - charm hadron BF
- Convert ratio of branching fractions using LQCD and/or LCSR.

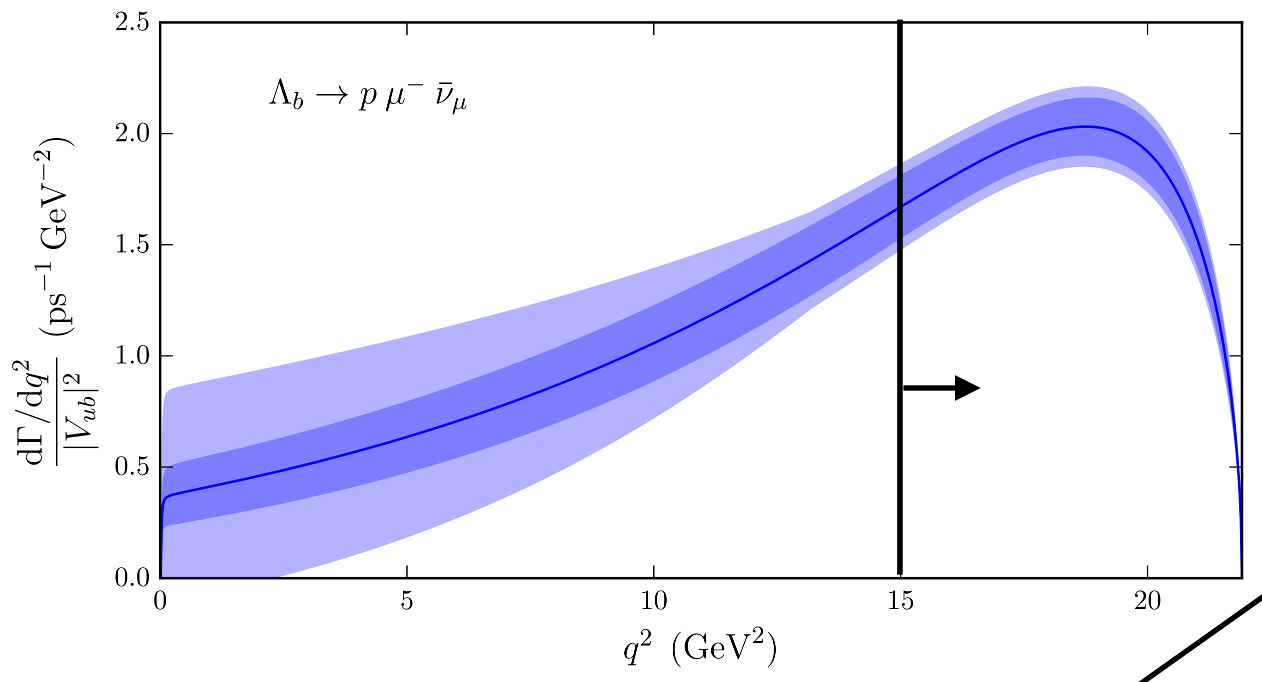
e.g. $$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}}$$

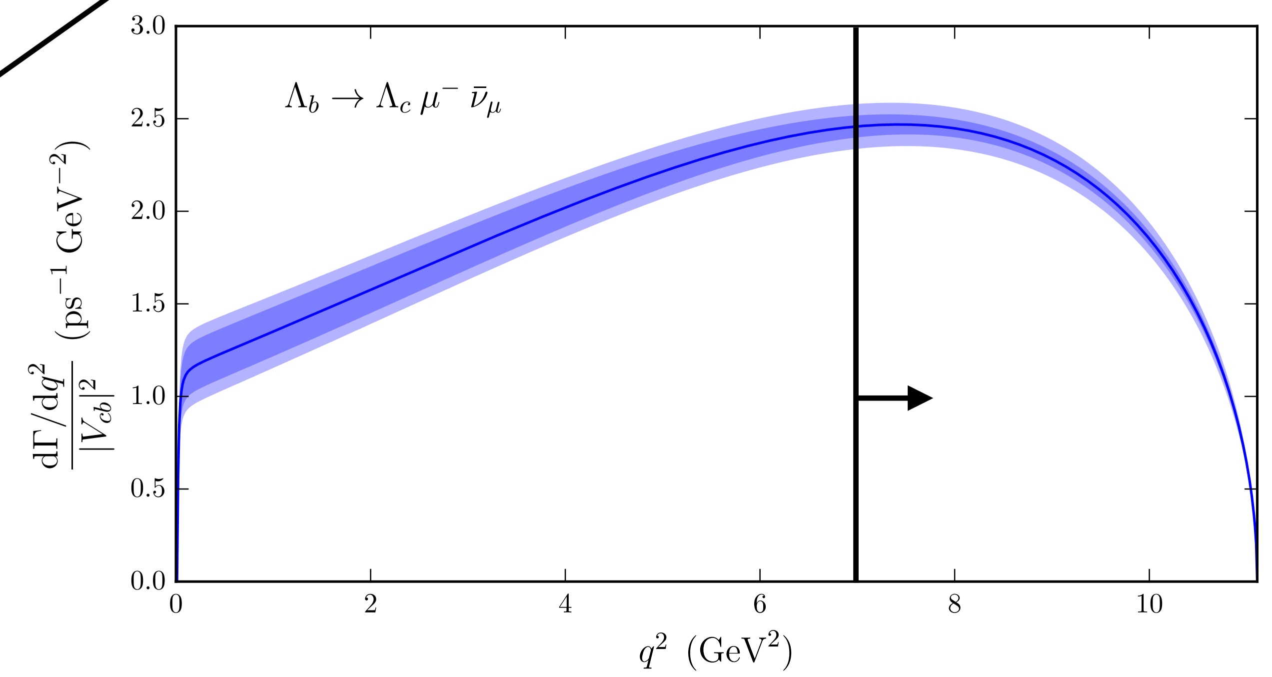
Measurement with $\Lambda_b^0 \to p\mu\nu$ decays

- Measure ratio:

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}}$$

Detmold, Lehner, Meinel, Phys. Rev. D 92, 034503 (2015)

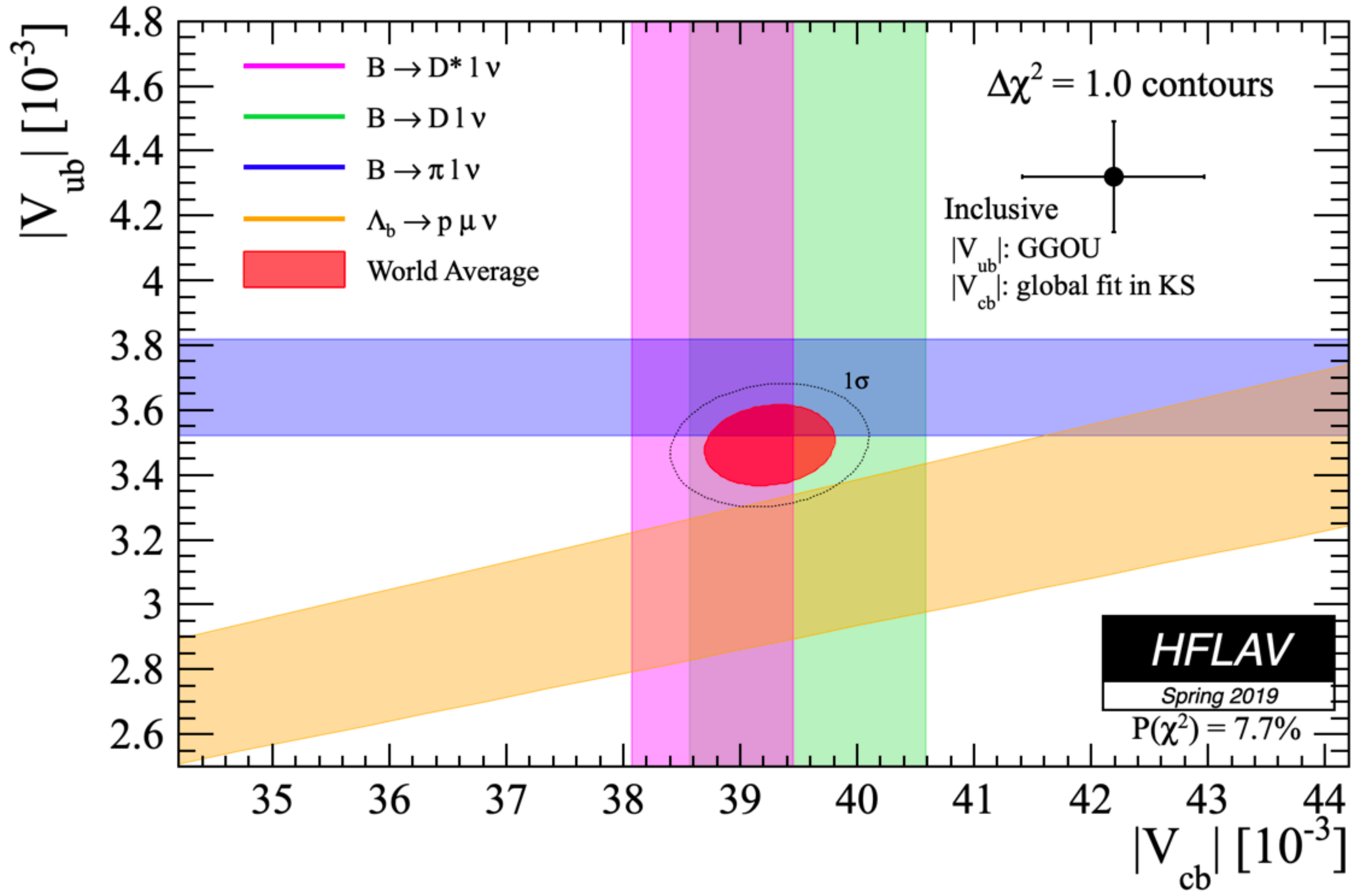




- Uncertainty split equally between experiment and lattice.
  - The former benefits from updates to $\mathcal{B}(\Lambda_c \to pK\pi)$

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004$$

Expt Lattice



LHCb, Nature Physics 10 (2015) 1038

$|V_{ub}|/|V_{cb}|$ from $B_s^0 \to K^+ \mu^- \nu$

LHCb, arXiv:2012.05143

- Measure ratio $\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}$ for new $|V_{ub}|/|V_{cb}|$ measurement with B_s decays.

- Do it to two q^2 regions, to exploit both LCSR and LQCD calculations.

$$\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)_{q^2<7}}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)_{\mathrm{Full}\ q^2}} \qquad \frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)_{q^2>7}}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)_{\mathrm{Full}\ q^2}}$$

- In both cases LQCD is used to determine the denominator, but the uncertainty is sub-dominant.

- D_s mesons reconstructed with the $D_s \to KK\pi$ decay mode.

$B_s^0 \to K^+\mu^-\nu$ vs $\Lambda_b^0 \to p\mu\nu$

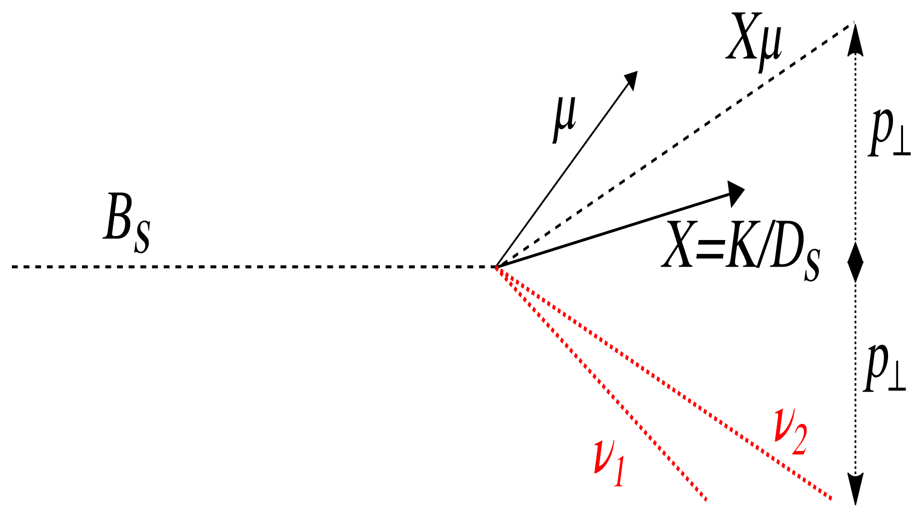
Decay	Λ_b^0	B_s^0
theory error	5%	$\sim 5\%$
prod frac	20%	10%
BF	4×10^{-4}	1×10^{-4}
$\mathcal{B}(X_c)$ error	$\pm 5\%$	$\pm 2.8\%$
background	Λ_c^+	$\Lambda_c^+, D_s, D^+, D^0$

- X_c branching fraction uncertainties scaled up the PDG. Important to get more measurements on these.
    - Both Belle-II and BES-III very important here.

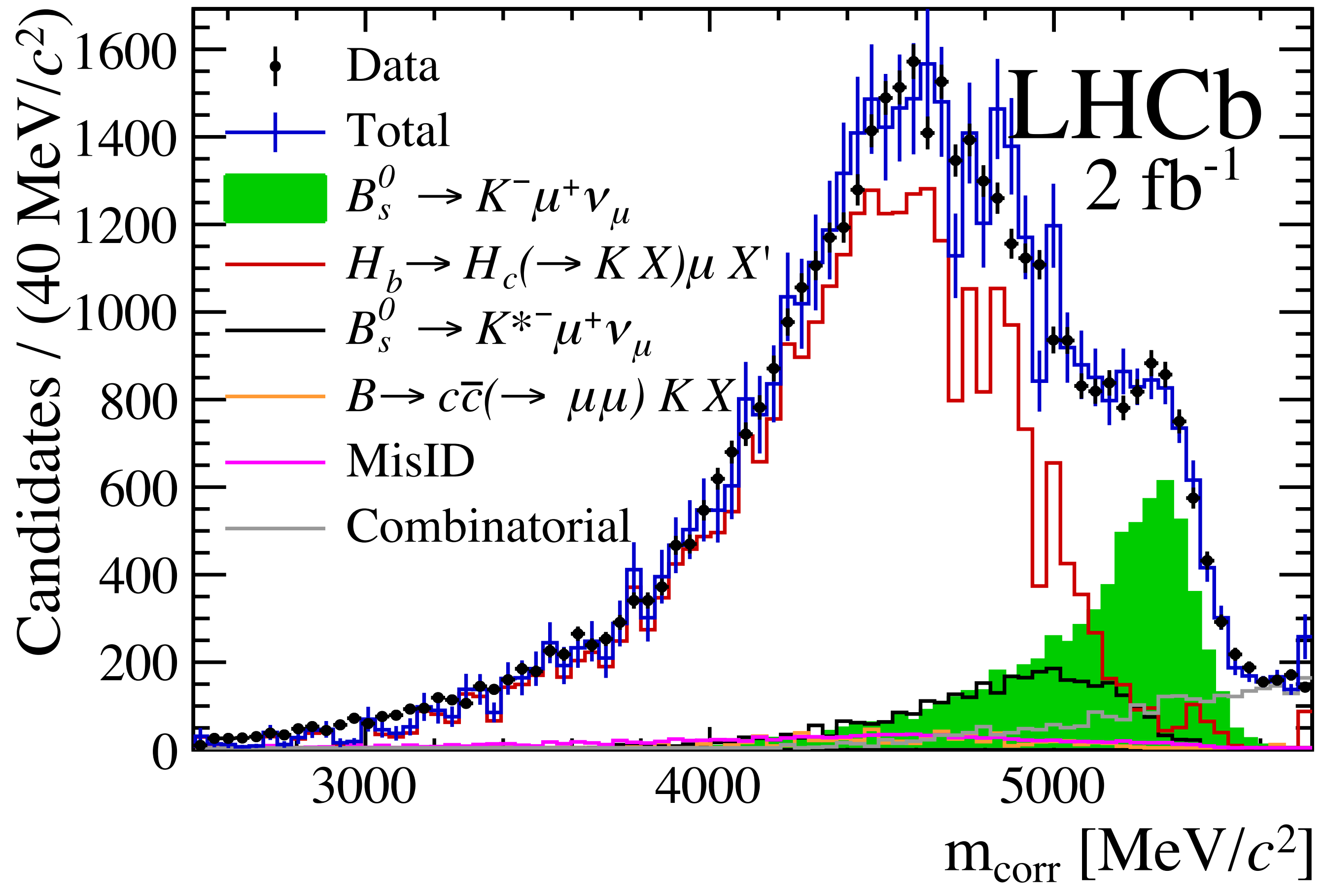
$B_s^0 \to K^+\mu^-\nu$ and $B_s^0 \to D_s^+\mu^-\nu$ fits

LHCb, arXiv:2012.05143

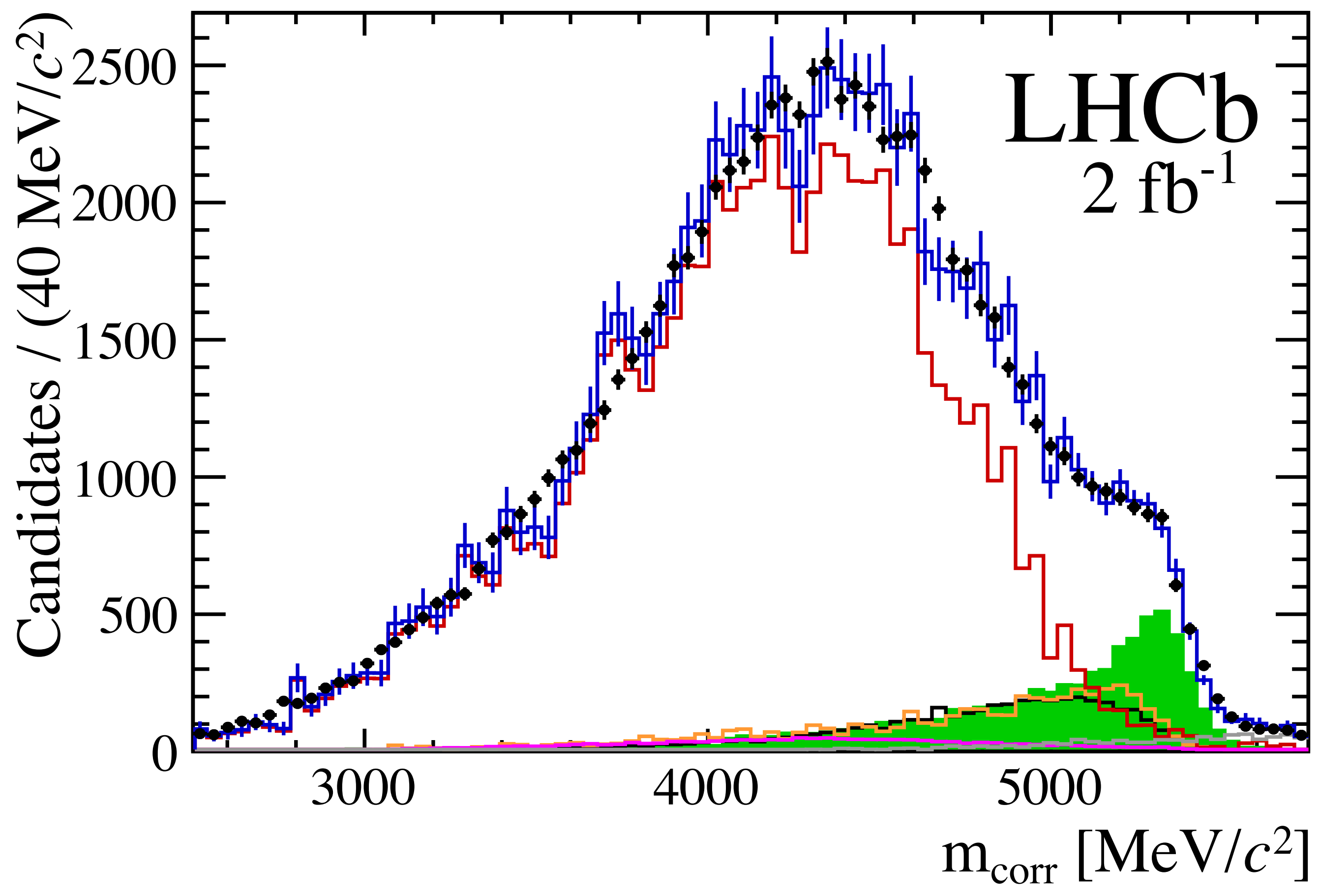
- Fit corrected mass $M_{corr} = \sqrt{M_{X\mu}^2 + p_\perp^2} + p_\perp$



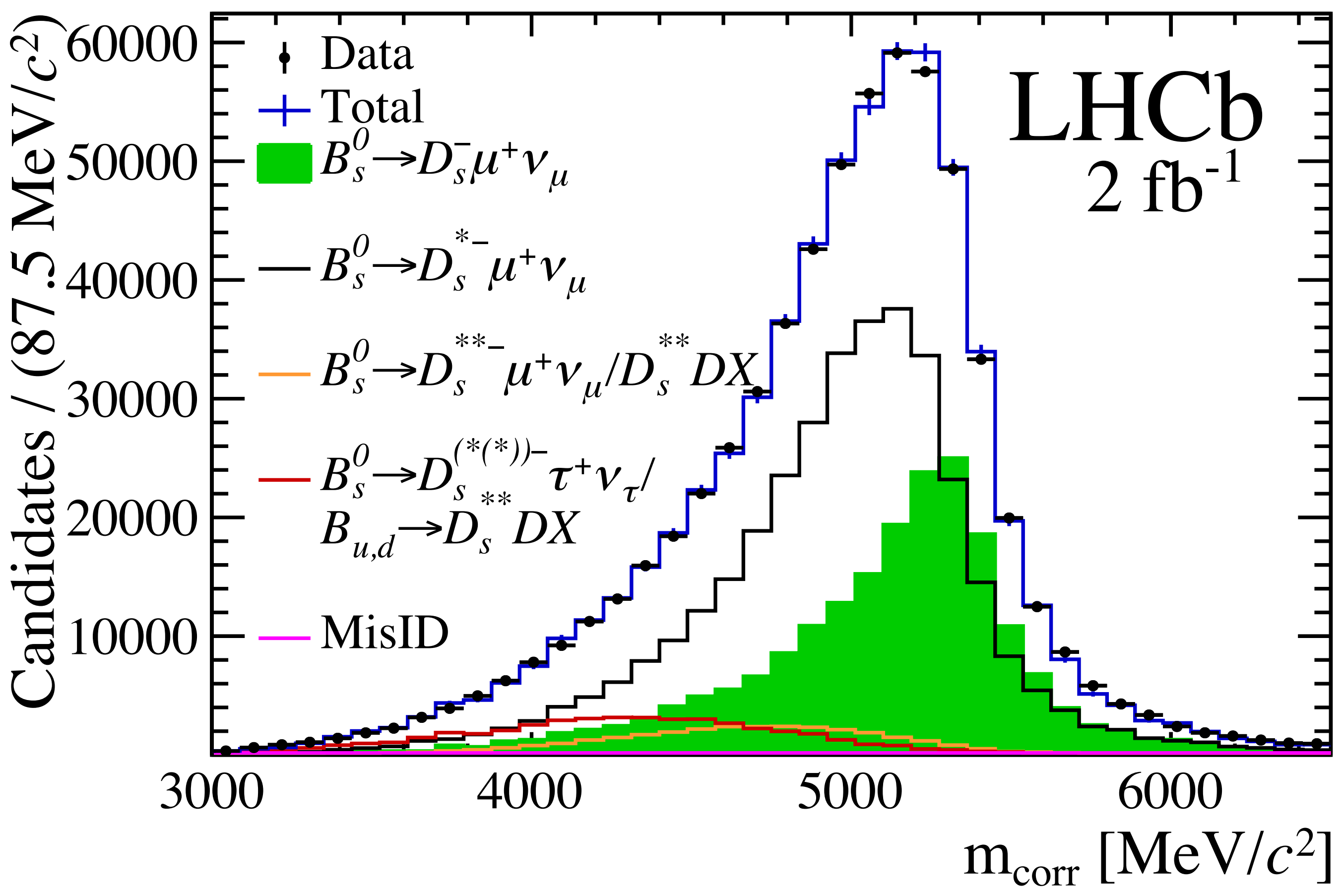
Low q²



High q²



$B_s^0 \to D_s^+\mu^-\nu$



- Shapes for signal reasonably insensitive to form factors.
- Backgrounds more affected. Form factor predictions for e.g. $B_s \to K^{*(*)}$ welcome.

Branching fraction results

LHCb, arXiv:2012.05143

- Relative efficiency is between two-track and four-track final state.
  - Resulting systematic uncertainties due to effects such as tracking and trigger.

- Branching fraction ratios determined to be

$$\frac{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{K^-} \mu^+ \nu_\mu)_{q^2<7}}{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{D_s^-} \mu^+ \nu_\mu)_{\mathrm{Full\ q^2}}} = (1.66 \pm 0.08(\mathrm{stat}) \pm 0.07(\mathrm{syst}) \pm 0.05(\mathrm{D_s})) \times 10^{-3}$$

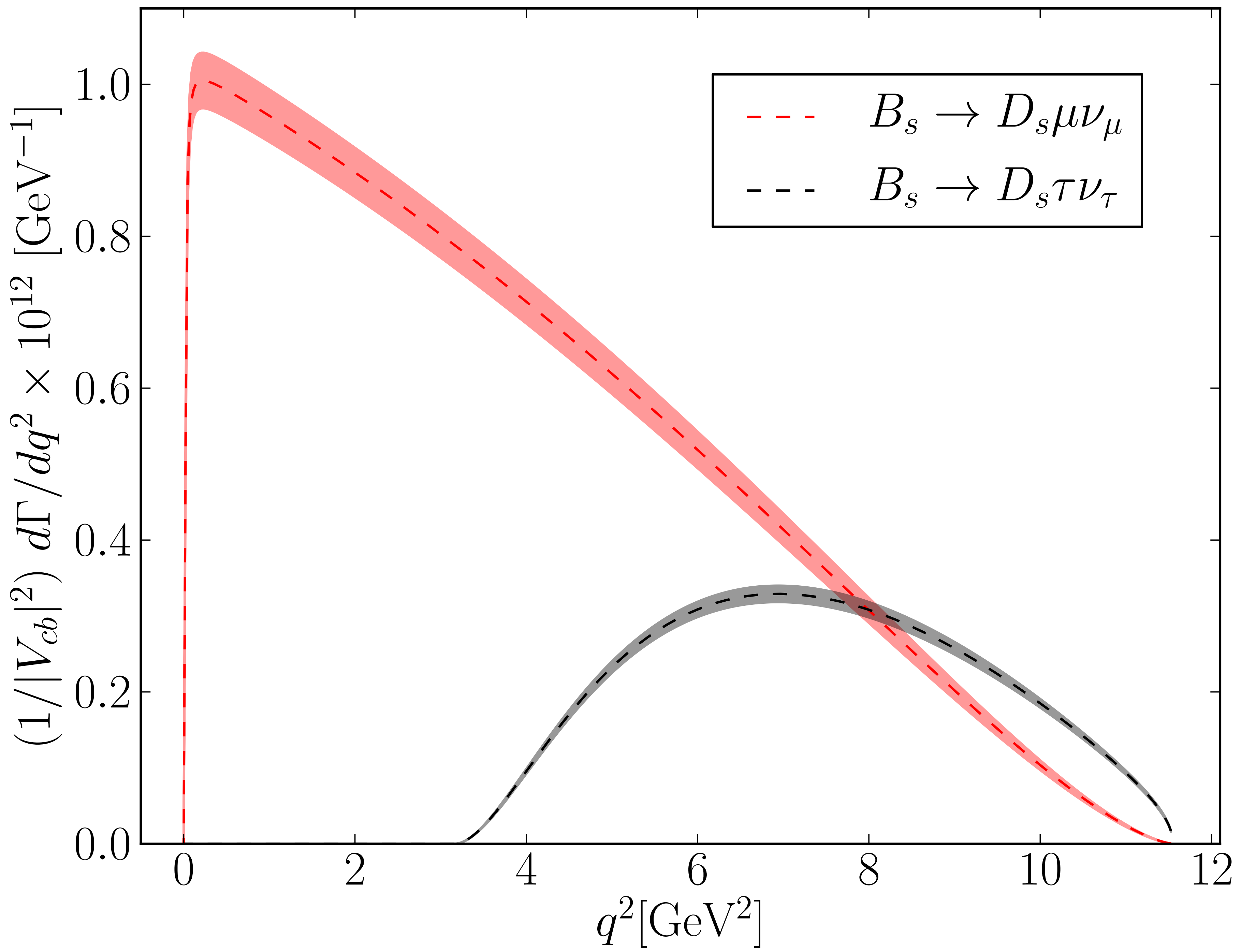
$$\frac{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{K^-} \mu^+ \nu_\mu)_{q^2>7}}{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{D_s^-} \mu^+ \nu_\mu)_{\mathrm{Full\ q^2}}} = (3.25 \pm 0.21(\mathrm{stat}) \,{}^{+\,0.16}_{-\,0.17}(\mathrm{syst}) \pm 0.09(\mathrm{D_s})) \times 10^{-3}$$

- The branching fractions are less limited by the external input c.f. Λ_b^0 case.

$B_s^0 \to D_s^+ \mu\nu$ inputs

- For both B—>K measurements, we use lattice QCD for the $B_s^0 \to D_s^+ \mu\nu$ form factors in full range.
  - Use most precise calculation from HPQCD.
  - Would be interesting to see a LCSR calculation to be consistent at low q^2.

McLean, Davies, Koponen, Lytle [HPQCD]: Phys. Rev. D 101, 074513 (2020)

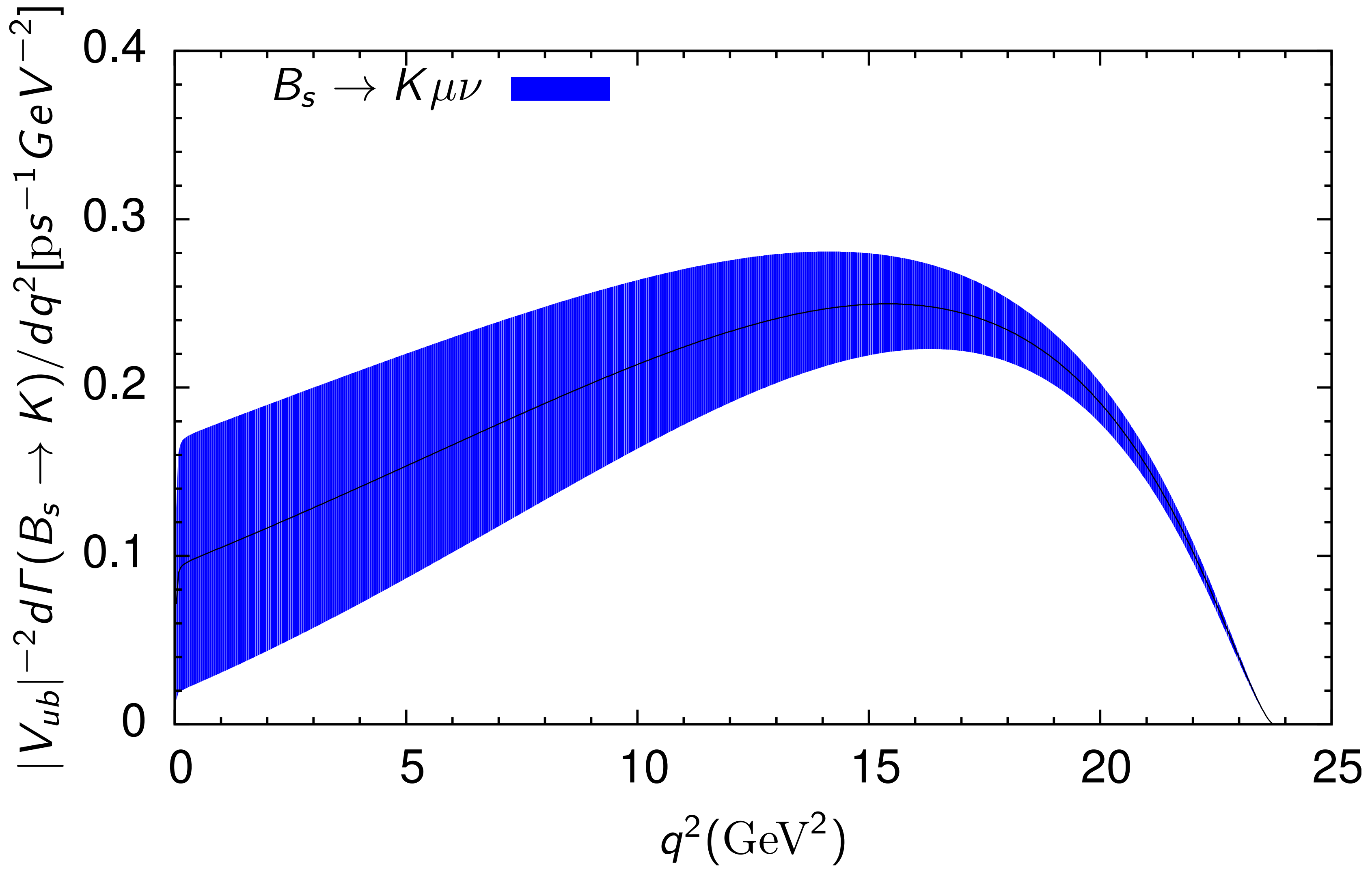


- Uncertainties that affect efficiencies and fit shapes included as small systematics in the measurements.

High q² inputs

- Many precise B_s^0—>K lattice calculations available [1-4].
- In the end, we chose the one which minimised the uncertainty on $|V_{ub}|/|V_{cb}|$.
  - Of course the best now would be to use the recent FLAG average.

We use the MILC/FNAL calculation [4].



and get:

$$|V_{ub}|/|V_{cb}|(\mathrm{high}) = 0.0946 \pm 0.0030\,(\mathrm{stat})^{+\ 0.0024}_{-\ 0.0025}\,(\mathrm{syst}) \pm 0.0013\ (D_s) \pm 0.0068\ (\mathrm{FF})$$

Large contribution to uncertainty from extrapolation.

[1] Bouchard et al [MILC], Phys. Rev. D 90, 054506 (2014)

[2] Flynn et al [RBC-UKQCD], Phys. Rev. D 91, 074510 (2015)

[3] Monahan et al [HPQCD], Phys. Rev. D 98, 114509 (2018)

[4] Bazanov et al [MILC/Fermilab],Phys. Rev. D 100, 034501 (2019)

Correlated form factor uncertainties

- To treat correlated form factor uncertainties fully in the analysis, need full covariance matrix of simultaneous fit to $B \longrightarrow X_u$ and $B \longrightarrow X_c$ form factors.

Detmold, Lehner, Meinel, Phys. Rev. D 92, 034503 (2015)

$\Lambda_b \to p$	a_0^{f+}	a_1^{f+}	a_2^{f+}	a_0^{f0}	a_1^{f0}	a_2^{f0}	$a_0^{f\perp}$	$a_1^{f\perp}$	$a_2^{f\perp}$	$a_0^{g\perp,g+}$	a_1^{g+}	a_2^{g+}	a_0^{g0}	a_1^{g0}	a_2^{g0}	$a_1^{g\perp}$	$a_2^{g\perp}$
a_0^{f+}	1	−0.7671	0.2482	0.5337	−0.2670	−0.0922	0.5121	−0.2469	−0.0180	0.3774	−0.2148	−0.0472	0.4420	−0.2680	0.0018	−0.2284	−0.0231
a_1^{f+}	−0.7671	1	−0.6611	−0.2486	0.1617	0.0653	−0.2526	0.1671	0.0056	−0.2177	0.1480	0.0287	−0.2496	0.1849	−0.0169	0.1534	0.0147
a_2^{f+}	0.2482	−0.6611	1	−0.0792	0.0267	0.2795	−0.0035	−0.0120	0.0425	−0.0562	0.0382	0.0559	−0.0279	−0.0074	0.0870	0.0370	0.0469
a_0^{f0}	0.5337	−0.2486	−0.0792	1	−0.7202	0.2599	0.4581	−0.2052	−0.0146	0.4734	−0.2798	−0.0031	0.3860	−0.2266	−0.0115	−0.2781	0.0048
a_1^{f0}	−0.2670	0.1617	0.0267	−0.7202	1	−0.6947	−0.2404	0.1415	0.0128	−0.2964	0.2603	−0.0377	−0.2410	0.1694	0.0090	0.2610	−0.0279
a_2^{f0}	−0.0922	0.0653	0.2795	0.2599	−0.6947	1	0.0190	−0.0056	0.0297	−0.0019	−0.0529	0.1086	−0.0081	−0.0097	0.0664	−0.0568	0.0874
$a_0^{f\perp}$	0.5121	−0.2526	−0.0035	0.4581	−0.2404	0.0190	1	−0.7672	0.1031	0.3418	−0.1831	−0.0539	0.4313	−0.2713	0.0163	−0.1994	−0.0127
$a_1^{f\perp}$	−0.2469	0.1671	−0.0120	−0.2052	0.1415	−0.0056	−0.7672	1	−0.5040	−0.1983	0.1259	0.0378	−0.2429	0.1907	−0.0274	0.1347	0.0083
$a_2^{f\perp}$	−0.0180	0.0056	0.0425	−0.0146	0.0128	0.0297	0.1031	−0.5040	1	−0.0271	0.0045	0.0524	−0.0286	0.0090	0.0530	0.0120	0.0187
$a_0^{g\perp,g+}$	0.3774	−0.2177	−0.0562	0.4734	−0.2964	−0.0019	0.3418	−0.1983	−0.0271	1	−0.6751	0.2299	0.5903	−0.2849	−0.0084	−0.6325	0.1314
a_1^{g+}	−0.2148	0.1480	0.0382	−0.2798	0.2603	−0.0529	−0.1831	0.1259	0.0045	−0.6751	1	−0.6972	−0.2576	0.1666	−0.0268	0.6832	−0.1976
a_2^{g+}	−0.0472	0.0287	0.0559	−0.0031	−0.0377	0.1086	−0.0539	0.0378	0.0524	0.2299	−0.6972	1	−0.0760	0.0463	0.2693	−0.3207	0.2419
a_0^{g0}	0.4420	−0.2496	−0.0279	0.3860	−0.2410	−0.0081	0.4313	−0.2429	−0.0286	0.5903	−0.2576	−0.0760	1	−0.7868	0.3673	−0.2892	−0.0105
a_1^{g0}	−0.2680	0.1849	−0.0074	−0.2266	0.1694	−0.0097	−0.2713	0.1907	0.0090	−0.2849	0.1666	0.0463	−0.7868	1	−0.7393	0.1798	0.0107
a_2^{g0}	0.0018	−0.0169	0.0870	−0.0115	0.0090	0.0664	0.0163	−0.0274	0.0530	−0.0084	−0.0268	0.2693	0.3673	−0.7393	1	0.0302	0.0637
$a_1^{g\perp}$	−0.2284	0.1534	0.0370	−0.2781	0.2610	−0.0568	−0.1994	0.1347	0.0120	−0.6325	0.6832	−0.3207	−0.2892	0.1798	0.0302	1	−0.6223
$a_2^{g\perp}$	−0.0231	0.0147	0.0469	0.0048	−0.0279	0.0874	−0.0127	0.0083	0.0187	0.1314	−0.1976	0.2419	−0.0105	0.0107	0.0637	−0.6223	1
$\Lambda_b \to \Lambda_c$	a_0^{f+}	a_1^{f+}	a_2^{f+}	a_0^{f0}	a_1^{f0}	a_2^{f0}	$a_0^{f\perp}$	$a_1^{f\perp}$	$a_2^{f\perp}$	$a_0^{g\perp,g+}$	a_1^{g+}	a_2^{g+}	a_0^{g0}	a_1^{g0}	a_2^{g0}	$a_1^{g\perp}$	$a_2^{g\perp}$
a_0^{f+}	1	−0.5220	0.1623	0.7106	−0.2661	−0.0293	0.6259	−0.2683	0.0077	0.1992	−0.1307	−0.0277	0.2833	−0.1838	0.0436	−0.1611	0.0088
a_1^{f+}	−0.5220	1	−0.6595	−0.3199	0.4277	0.0649	−0.2548	0.2618	−0.0102	−0.1403	0.1878	0.0413	−0.1575	0.1932	−0.0364	0.1703	0.0030
a_2^{f+}	0.1623	−0.6595	1	−0.0350	0.1309	0.0939	0.0181	−0.0149	0.0300	−0.0111	0.0190	0.0007	0.0005	−0.0041	0.0186	0.0246	0.0088
a_0^{f0}	0.7106	−0.3199	−0.0350	1	−0.5132	0.1123	0.5190	−0.2037	−0.0014	0.2531	−0.2100	0.0128	0.2012	−0.1481	0.0096	−0.2057	−0.0079
a_1^{f0}	−0.2661	0.4277	0.1309	−0.5132	1	−0.5243	−0.1791	0.2285	0.0094	−0.1770	0.2589	0.0134	−0.1266	0.1854	−0.0086	0.2339	0.0127
a_2^{f0}	−0.0293	0.0649	0.0939	0.1123	−0.5243	1	−0.0222	0.0275	0.0138	0.0044	−0.0148	0.0300	−0.0074	0.0112	−0.0034	−0.0218	0.0075
$a_0^{f\perp}$	0.6259	−0.2548	0.0181	0.5190	−0.1791	−0.0222	1	−0.5829	0.1142	0.1754	−0.1255	−0.0168	0.2874	−0.1811	0.0416	−0.1320	−0.0086
$a_1^{f\perp}$	−0.2683	0.2618	−0.0149	−0.2037	0.2285	0.0275	−0.5829	1	−0.4656	−0.1154	0.1472	0.0360	−0.1487	0.1650	−0.0341	0.1319	0.0096
$a_2^{f\perp}$	0.0077	−0.0102	0.0300	−0.0014	0.0094	0.0138	0.1142	−0.4656	1	−0.0006	−0.0003	0.0057	0.0049	−0.0059	0.0087	−0.0006	0.0033
$a_0^{g\perp,g+}$	0.1992	−0.1403	−0.0111	0.2531	−0.1770	0.0044	0.1754	−0.1154	−0.0006	1	−0.4436	0.0876	0.7054	−0.2594	0.0128	−0.4268	0.0479
a_1^{g+}	−0.1307	0.1878	0.0190	−0.2100	0.2589	−0.0148	−0.1255	0.1472	−0.0003	−0.4436	1	−0.5465	−0.2790	0.3438	0.0541	0.4776	−0.1381
a_2^{g+}	−0.0277	0.0413	0.0007	0.0128	0.0134	0.0300	−0.0168	0.0360	0.0057	0.0876	−0.5465	1	−0.0447	0.1194	0.0577	−0.1482	0.2692
a_0^{g0}	0.2833	−0.1575	0.0005	0.2012	−0.1266	−0.0074	0.2874	−0.1487	0.0049	0.7054	−0.2790	−0.0447	1	−0.5511	0.2196	−0.3015	0.0059
a_1^{g0}	−0.1838	0.1932	−0.0041	−0.1481	0.1854	0.0112	−0.1811	0.1650	−0.0059	−0.2594	0.3438	0.1194	−0.5511	1	−0.7687	0.2440	0.0190
a_2^{g0}	0.0436	−0.0364	0.0186	0.0096	−0.0086	−0.0034	0.0416	−0.0341	0.0087	0.0128	0.0541	0.0577	0.2196	−0.7687	1	0.0004	0.0405
$a_1^{g\perp}$	−0.1611	0.1703	0.0246	−0.2057	0.2339	−0.0218	−0.1320	0.1319	−0.0006	−0.4268	0.4776	−0.1482	−0.3015	0.2440	0.0004	1	−0.5028
$a_2^{g\perp}$	0.0088	0.0030	0.0088	−0.0079	0.0127	0.0075	−0.0086	0.0096	0.0033	0.0479	−0.1381	0.2692	0.0059	0.0190	0.0405	−0.5028	1

TABLE XI. Correlation matrices of the higher-order form factor parameters for $\Lambda_b \to p$ (top) and $\Lambda_b \to \Lambda_c$ (bottom).

Monahan et al, Phys. Rev. D 98, 114509 (2018)

TABLE XI. Covariance matrix for the coefficients of z-expansion and the corresponding Blaschke factors for the simultaneous fit to the $B_s \to K\ell\nu$ and $B_s \to D_s\ell\nu$ decays. The rows correspond to the columns, moving from top to bottom and left to right, respectively.

$a_1^{(0),K}$	$a_2^{(0),K}$	$a_3^{(0),K}$	$P_0^{(K)}$	$a_0^{(+),K}$	$a_1^{(+),K}$
7.81655746×10^{-3}	5.11931999×10^{-2}	1.26040746×10^{-1}	-3.95599616×10^{-7}	6.67729571×10^{-4}	7.88936302×10^{-3}
	4.94505240×10^{-1}	1.62865239	2.22974369×10^{-6}	3.58512534×10^{-3}	6.75709862×10^{-2}
		6.51816994	-4.88348307×10^{-8}	9.03252850×10^{-3}	1.99167048×10^{-1}
			9.99995307×10^{-7}	-1.81816269×10^{-9}	1.55891061×10^{-7}
				3.09228616×10^{-4}	-5.88646696×10^{-5}
					1.46893824×10^{-2}

$a_2^{(+),K}$	$P_+^{(K)}$	$a_0^{(0),D_s}$	$a_1^{(0),D_s}$	$a_2^{(0),D_s}$	$a_3^{(0),D_s}$
5.54055868×10^{-2}	5.22263419×10^{-9}	4.89761879×10^{-5}	1.47978430×10^{-3}	1.61294090×10^{-4}	-1.50864482×10^{-5}
5.20212224×10^{-1}	4.60220124×10^{-8}	4.23550639×10^{-4}	-1.12557927×10^{-3}	-4.15916006×10^{-4}	6.86722615×10^{-6}
1.72576055	1.64613013×10^{-7}	5.32746249×10^{-4}	-8.00096682×10^{-3}	-1.57760368×10^{-3}	6.07028861×10^{-5}
1.27709131×10^{-6}	4.34812507×10^{-15}	-2.93868039×10^{-9}	3.60812633×10^{-8}	3.12552274×10^{-9}	$-2.93053824\times10^{-10}$
5.57789886×10^{-4}	3.44350904×10^{-9}	1.08803466×10^{-4}	7.14515361×10^{-4}	1.46191770×10^{-4}	-9.57576314×10^{-6}
6.49789179×10^{-2}	-1.42002142×10^{-7}	2.37456520×10^{-4}	-7.74705909×10^{-3}	-1.63296714×10^{-3}	9.27876845×10^{-5}
7.40157233×10^{-1}	8.20182628×10^{-7}	9.33127619×10^{-4}	3.38332719×10^{-4}	-1.12948406×10^{-5}	-1.17310027×10^{-5}
	5.28997606×10^{-8}	$-4.00252884\times10^{-11}$	1.55683903×10^{-10}	8.25859041×10^{-11}	4.62131689×10^{-12}
		1.51331616×10^{-3}	-1.32946477×10^{-3}	-2.95921529×10^{-3}	-1.18940865×10^{-4}
			1.14391084×10^{-1}	3.77594136×10^{-1}	-1.47064962×10^{-2}
				8.04802477	6.00685427×10^{-2}
					8.99580234

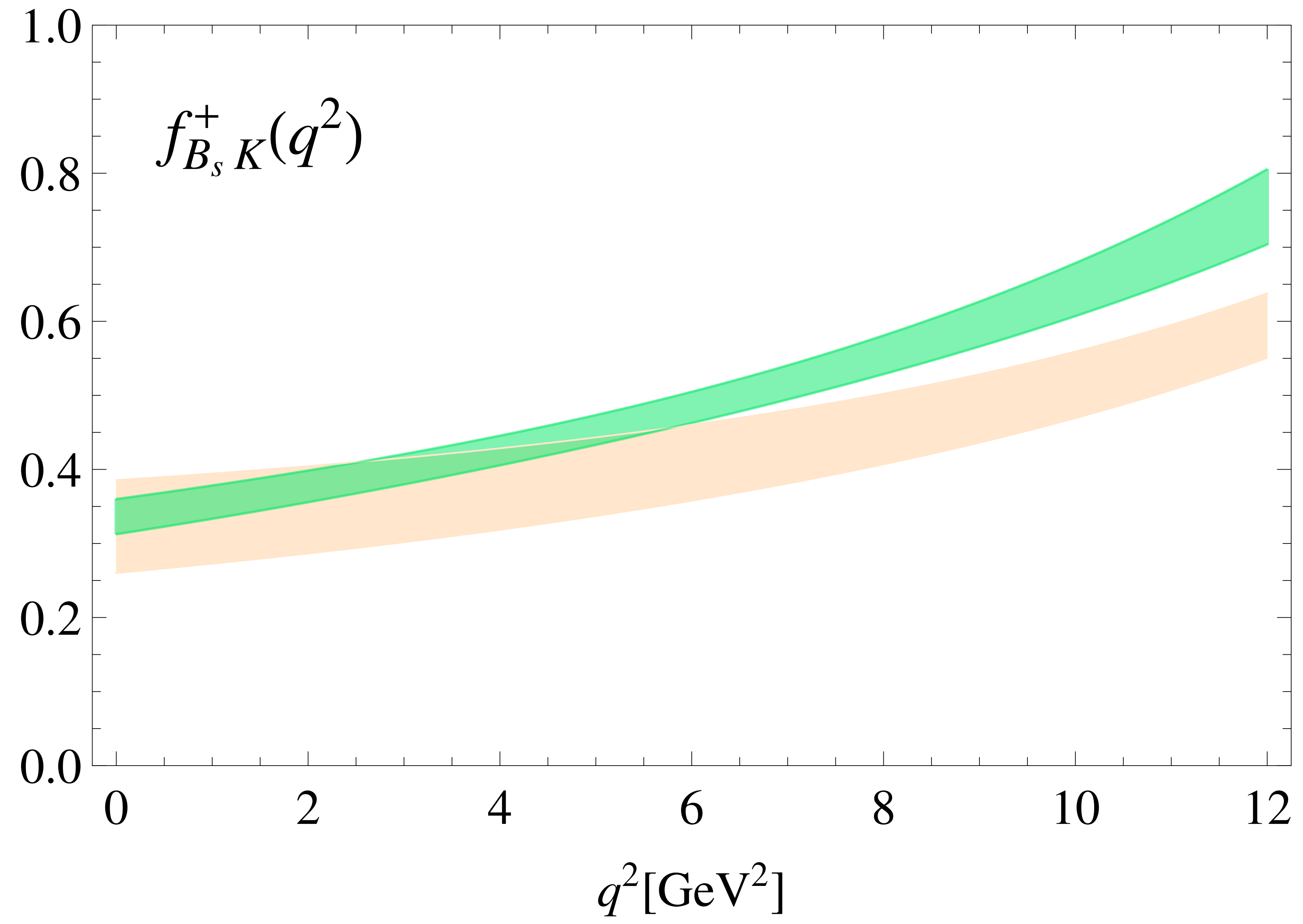
- This should give the ultimate precision.
    - Important if uncertainty from $B \longrightarrow X_c$ form factors is significant.

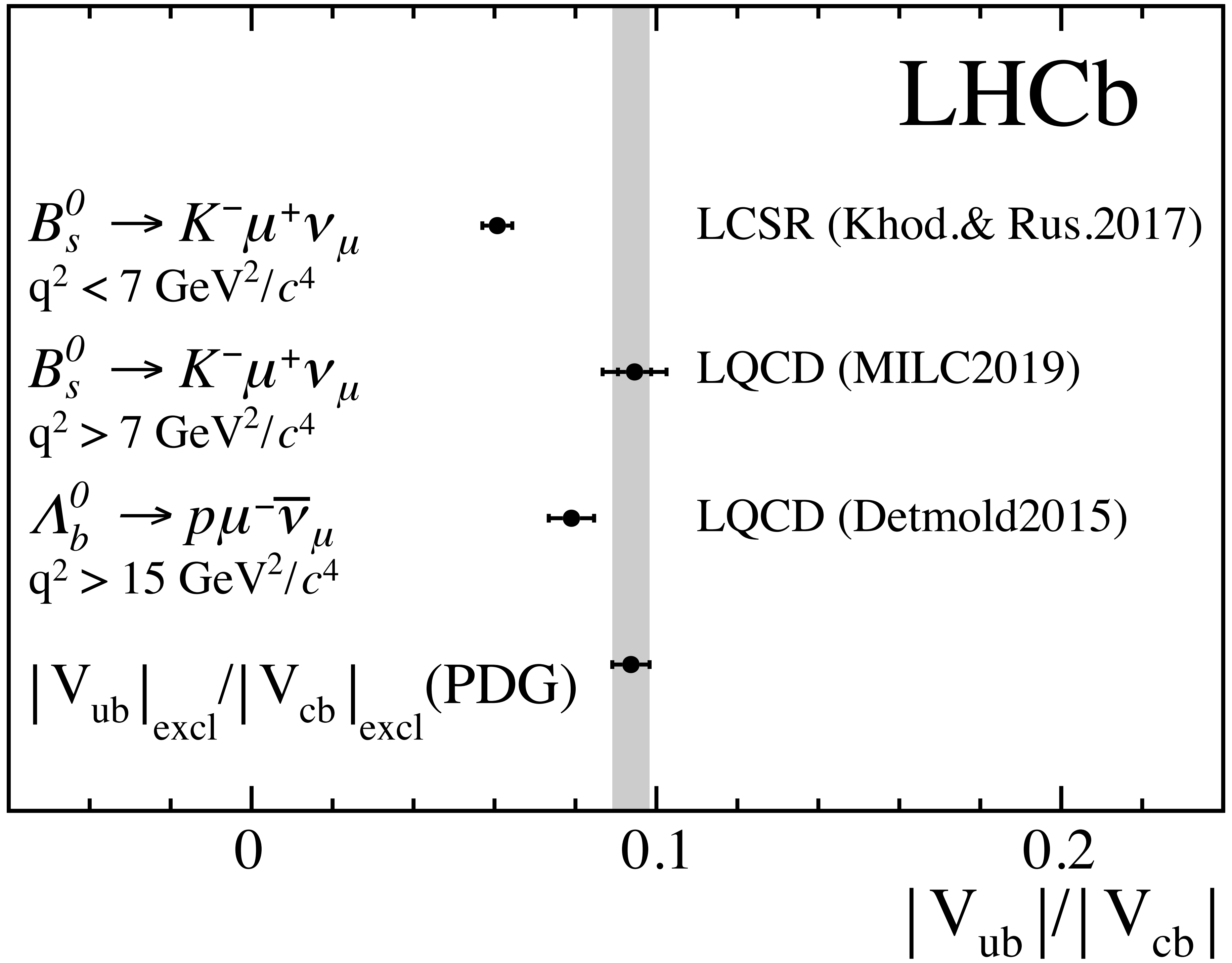
Low q^2 measurement

LHCb, arXiv:2012.05143

- New for $B_s^0 \to K$ measurement was to also provide a measurement at low q^2.

Khodjamirian, Rusov, JHEP08(2017)112



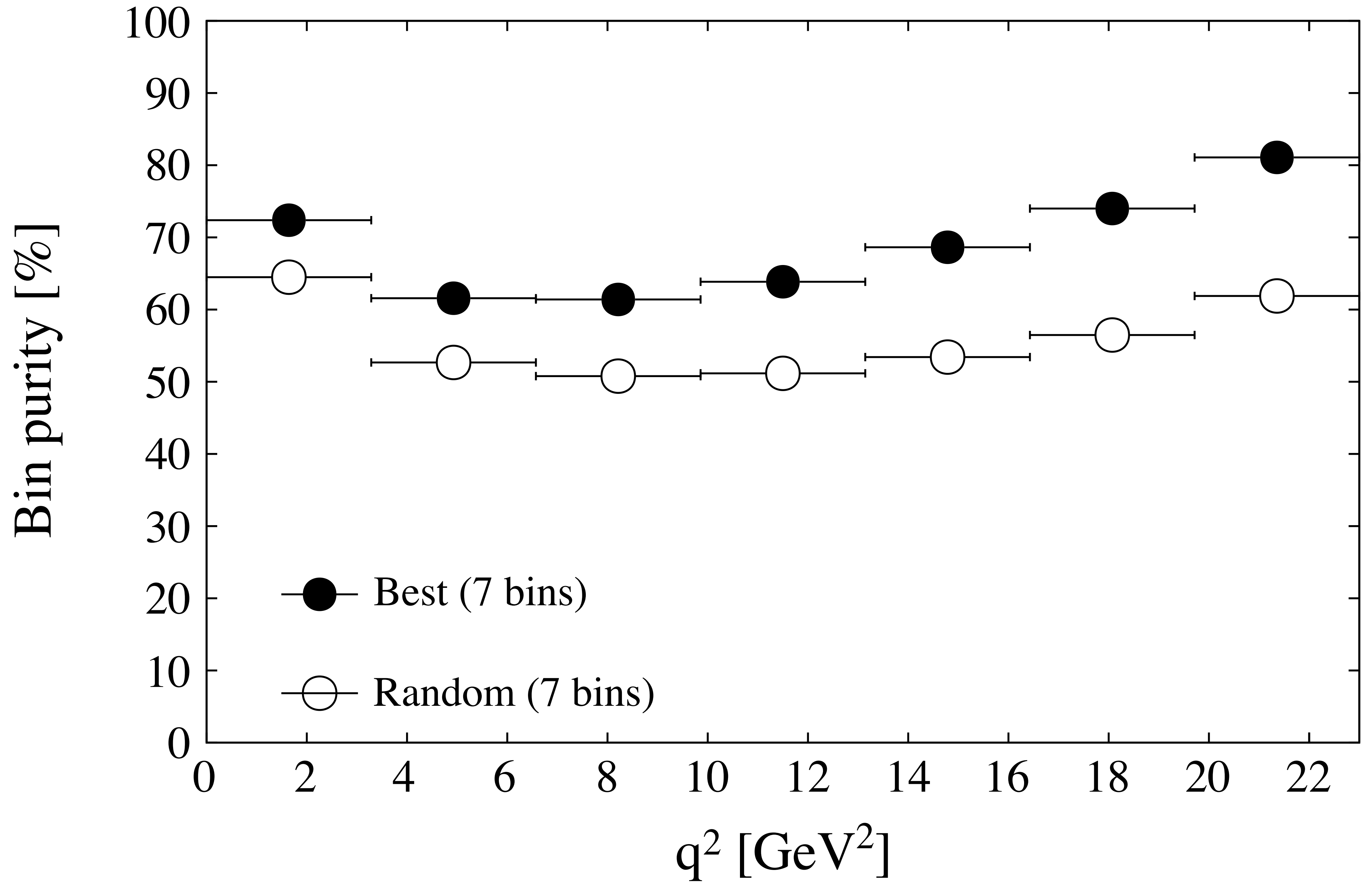


- Measurements do not agree.
  - Would be interesting to see a full LQCD fit including both BF measurements.
  - Also interesting to see a LCSR $B_s^0 \to D_s$ calculation.

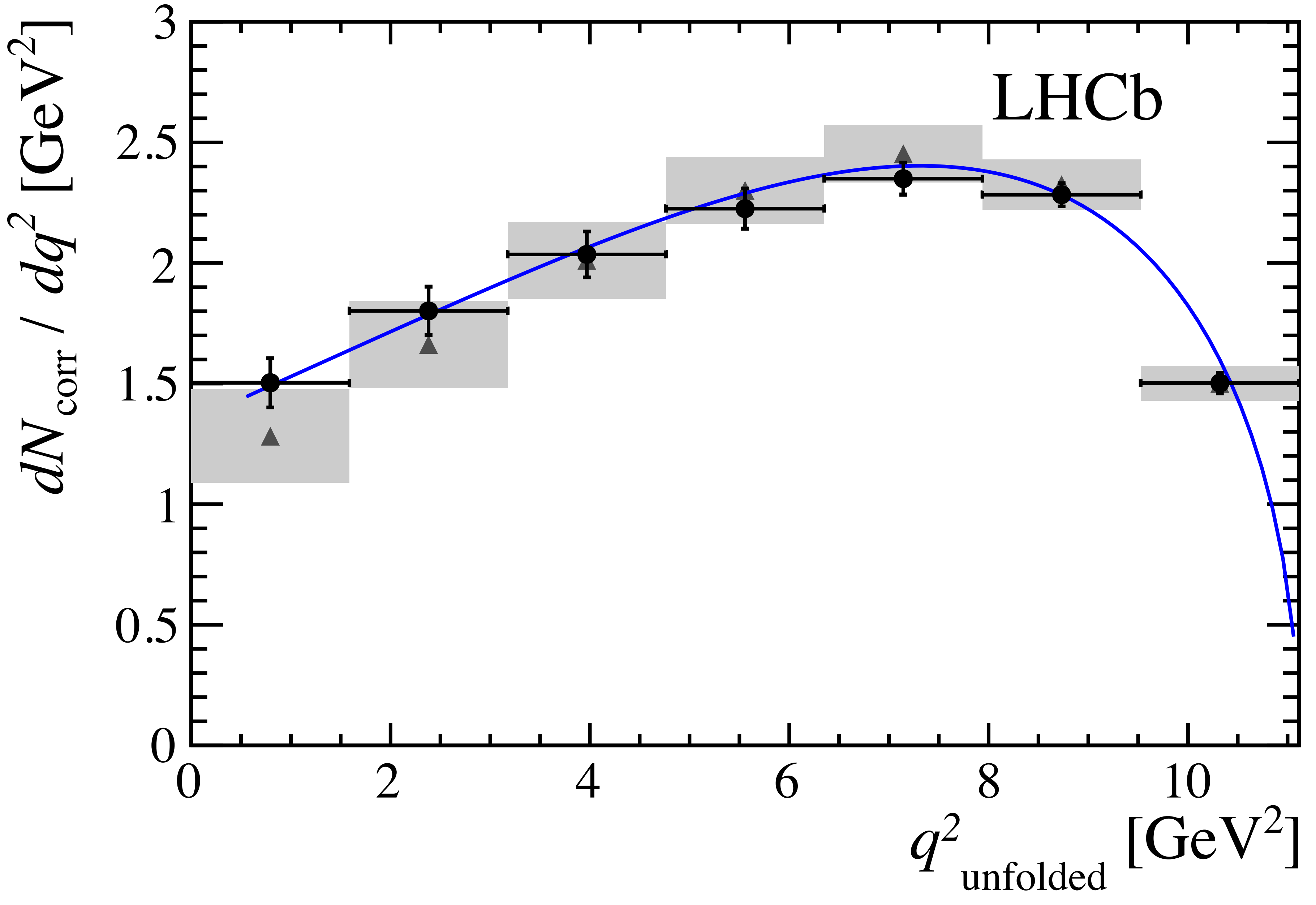
Medium term prospects

- Need to start making differential measurements as fine as possible.
  - In the B_s^0 case this would massively improve the sensitivity.
  - In the Λ_b^0 it would serve as a powerful validation of the lattice calculations ($\Lambda_b^0 \to \Lambda_c$ already shown to be good agreement in our 2017 measurement).

Ciezarek, Lupato, Rotondo, Vesterinen: JHEP02 (2017)021



LHCb-PAPER-2017-016, Phys. Rev. D 96, 112005 (2017)



Long term prospects

- Official goal is to determine $|V_{ub}|/|V_{cb}|$ at 1% level with full upgrade II dataset ($300 fb^{-1}$)
- This requires D_s and/or Λ_c branching fractions to be measured at 1% level.
- Lattice assumed to be at 1% as well, seems doable particularly if we can make very high q^2 bin.

B_s^0—>K systematics

Uncertainty	All q^2	low q^2	high q^2
Tracking	2.0	2.0	2.0
Trigger	1.4	1.2	1.6
Particle identification	1.0	1.0	1.0
$\sigma(m_{\text{corr}})$	0.5	0.5	0.5
Isolation	0.2	0.2	0.2
Charged BDT	0.6	0.6	0.6
Neutral BDT	1.1	1.1	1.1
q^2 migration	–	2.0	2.0
Efficiency	1.2	1.6	1.6
Fit template	${}^{+2.3}_{-2.9}$	${}^{+1.8}_{-2.4}$	${}^{+3.0}_{-3.4}$
Total	${}^{+4.0}_{-4.3}$	${}^{+4.3}_{-4.5}$	${}^{+5.0}_{-5.3}$

- The systematics most likely to saturate are those related to the efficiency.
  - Trigger calibration expected to be greatly simplified in run III and beyond.
  - Tracking efficiency is more challenging, need to measure the material in the detector.
  - The rest should go down to small levels.

$|V_{cb}|$ measurement from B_s decays

- Recently measured $|V_{cb}|$ with B_s decays.

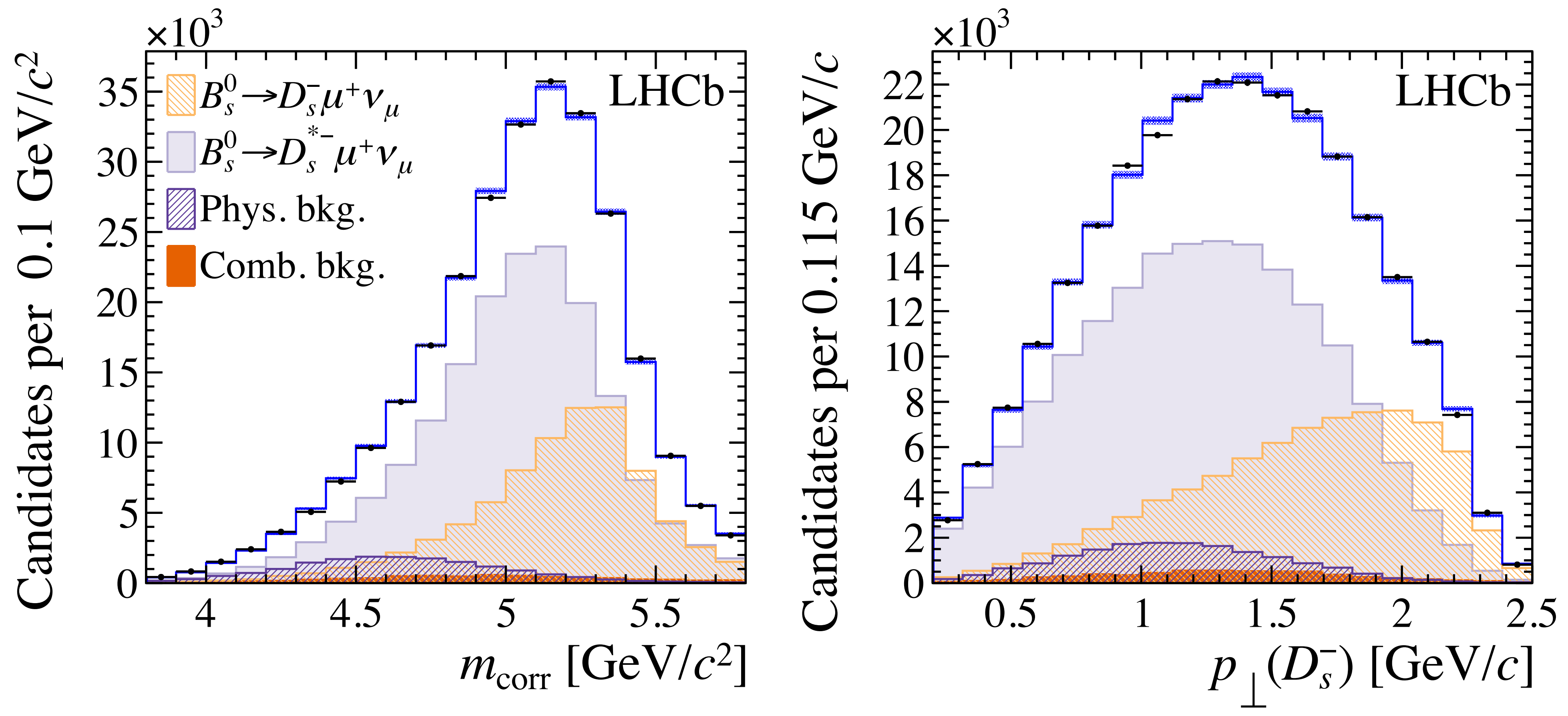
LHCb, Phys. Rev. D101 (2020) 072004

- Normalise B_s^0 signal to corresponding B^0 decays.

$$\mathcal{R} \equiv \frac{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^- \mu^+ \nu_\mu)},$$

$$\mathcal{R}^* \equiv \frac{\mathcal{B}(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu_\mu)}$$

- Fit to determine form factors and signal yield.



- Use $B^0 \to D^{(*)}\mu\nu$ branching fractions to determine normalisation with 4(3)% uncertainty from PDG.
- Measurement of f_s/f_d used to control production fractions.
- Also limited by current knowledge on $D_{(s)}$ branching fractions.

- Also measured $B_s \to D_s^{(*)}$ form factors:

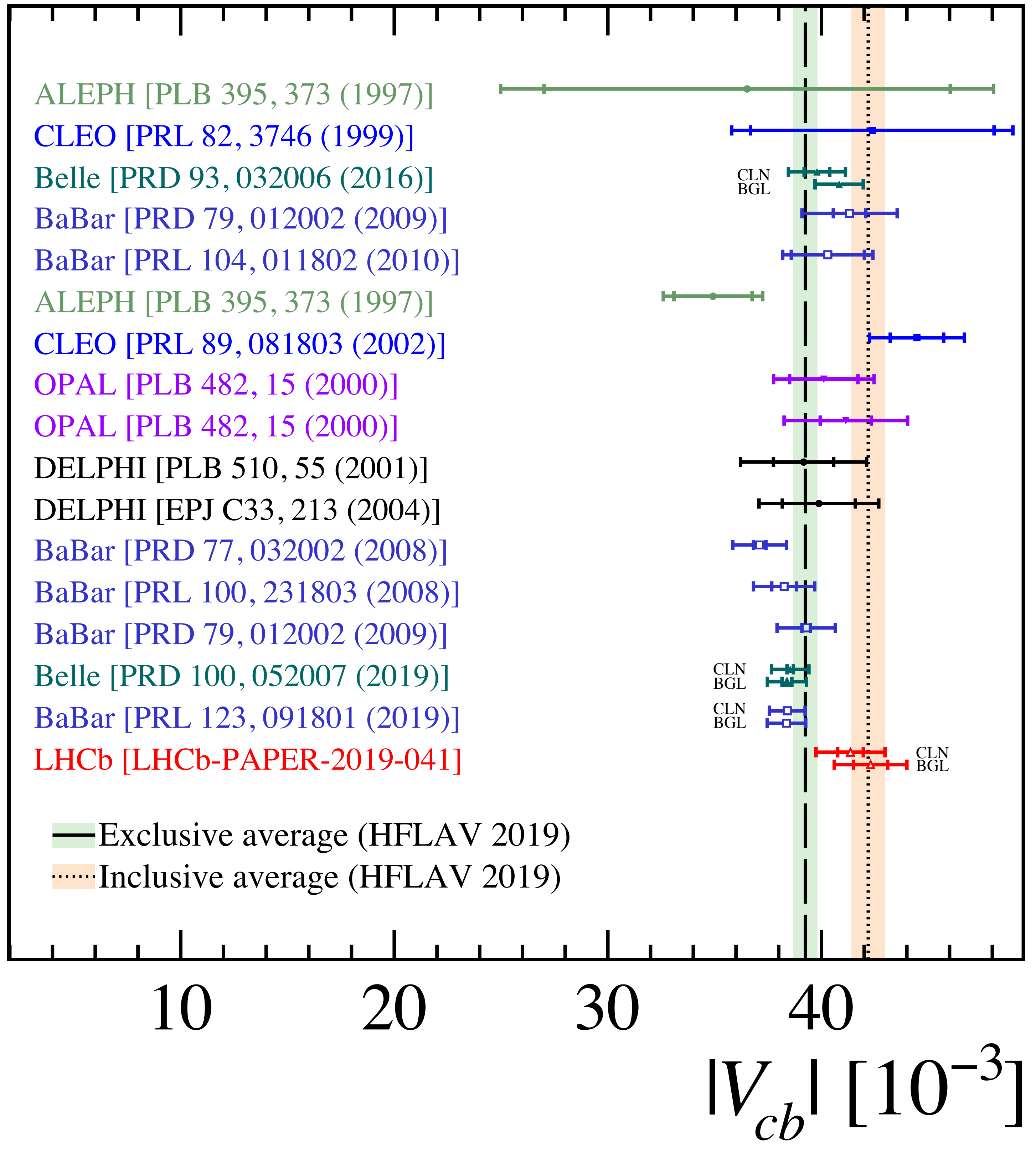
LHCb, arXiv:2003.08453

$|V_{cb}|$ results

- Performed analysis with CLN and BGL parameterisations.
  - Parameters have constraints from e.g. HPQCD [1].

$$|V_{cb}|_{\rm CLN} = (41.4 \pm 0.6\,({\rm stat}) \pm 0.9\,({\rm syst}) \pm 1.2\,({\rm ext})) \times 10^{-3}$$
$$|V_{cb}|_{\rm BGL} = (42.3 \pm 0.8\,({\rm stat}) \pm 0.9\,({\rm syst}) \pm 1.2\,({\rm ext})) \times 10^{-3}$$

- Both results compatible with each other and existing measurements.



[1] McLean, Davies, Koponen, Lytle [HPQCD]: Phys. Rev. D 101, 074513 (2020)

Yes, it really is a $|V_{cb}|$ measurement

- If both numerator and denominator depend on $|V_{cb}|$, how can one be sensitive to $|V_{cb}|$?
- The point is that the denominator is measured, we do not use a prediction which depends on $|V_{cb}|$.
  - The B^0—>$D^{(*)}$ branching fraction measurements could be correlated to the exclusive $|V_{cb}|$ B-factory measurements, but I understand this is a small effect(?).
- We do, however, rely on the equally of semileptonic widths. Bigi, Mannel, Uraltsev, JHEP09(2011)012
  - We are heavily dependent on this in LHCb, so might be useful to provide precise validations in data. More lifetime measurements?

Planned measurements

- Plan to perform a similar measurement with Λ_b^0 decays.
  - Here the normalisation is a bit different, we instead normalise to inclusive Λ_b^0 semileptonic decays and employ equally of partial widths.

$$\Gamma(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu) = \frac{n_{\text{corr}}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)}{n_{\text{corr}}(\Lambda_b^0 \to X_c \mu^-) \times \Gamma(\Lambda_b^0 \to X_c \mu^- \overline{\nu}_\mu)}$$

- Plan is to use the differential measurement as a function of q^2 to control form factor uncertainties a la LHCb-PAPER-2017-016

- Also plan to perform a measurement with $B^0 \to D^* \mu \nu$ decays using a similar method:

$$\frac{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}{\mathcal{B}(B \to \bar{X}_c \mu^+ \nu_\mu X)} = \frac{2n_{corr}(B^0 \to D^{*-}\mu^+\nu_\mu)}{n_{corr}(\overline{D}^0\mu^+X) + n_{corr}(D^-\mu^+X)}$$

Summary and prospects

- LHCb is still relatively new to performing precise $|V_{xb}|$ measurements.
- More dependent on external inputs, but can make precise measurements in the future which are largely uncorrelated to B-factory ones.
- Expect to stay competitive with Belle-II but will take a lot of work.
- Eventually we will perform full angular analyses of these modes, which will also help determinations indirectly.
    - Expect shape information from e.g. $B^0 \rightarrow D^* \mu\nu$ decays to be complimentary to those obtained at e^+e^- machines.