$B_s \to K\mu\nu$ observation and $|V_{ub}|/|V_{cb}|$: the role of $B_s \to K/D_s$ form factors

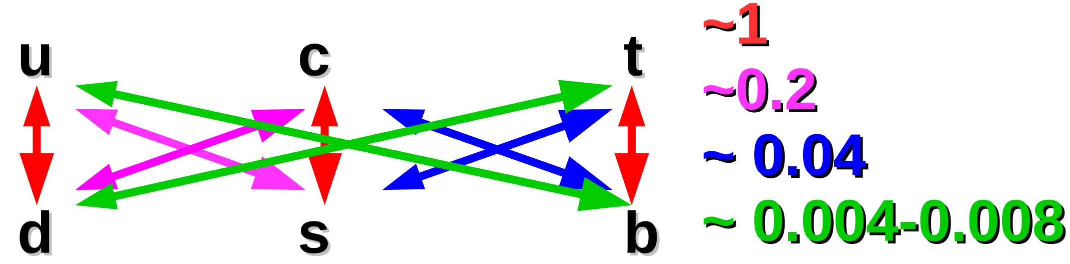
A.Hicheur (LHCb Collaboration)
April 20, 2021
IPPP workshop
« Beyond the flavour anomalies »

Outline

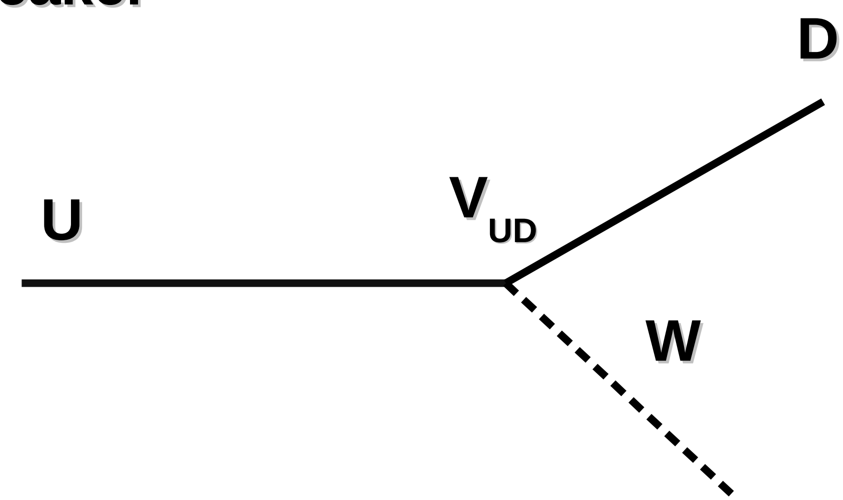
- From EW scale to low energy
  - CKM picture
  - Low energy hamiltonians for hadron decays
- Why are SL decays convenient?
  - The role of semileptonic decays in Standard Model testing in the quark sector
  - Motivation for $|V_{ub}|$
- LHCb searches and input of Form Factors
  - Emphasis on $Bs \to K \mu \nu$

The CKM picture

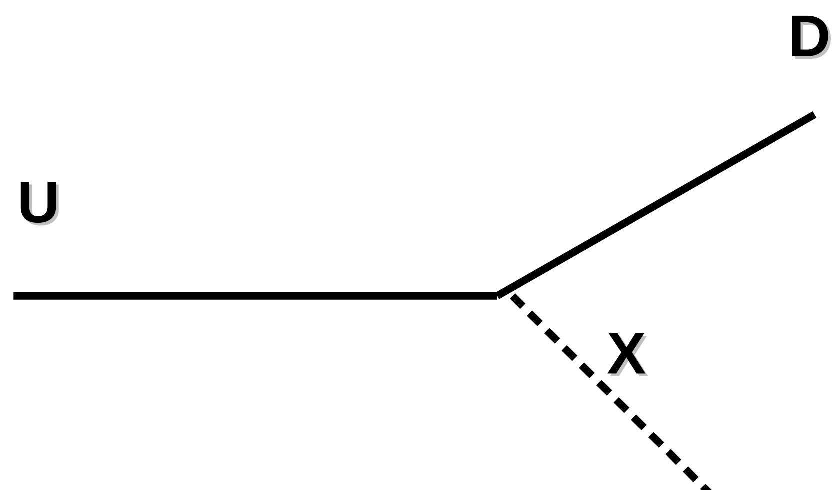
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



Clear hierarchy in the couplings: the further from diagonal, the weaker



CKM SM picture

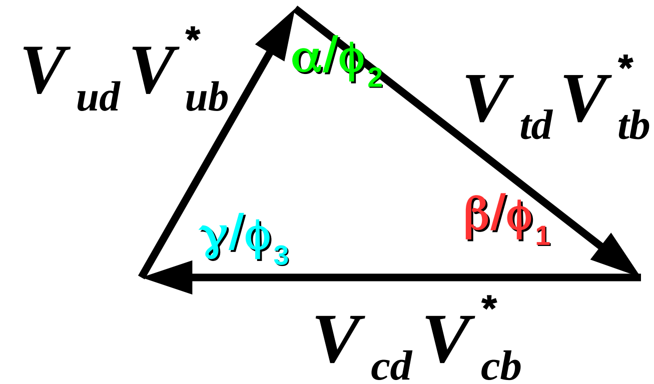


Intervention of beyond SM physics : is the flavour structure maintained ?

CKM Unitarity triangle(s)

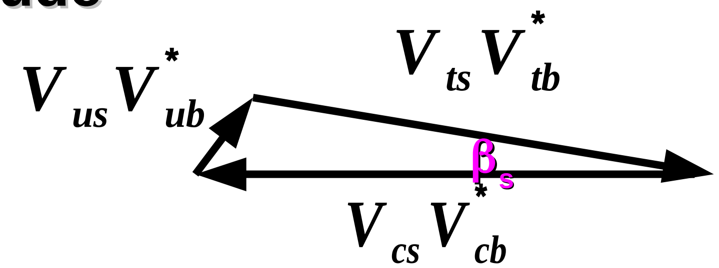
Unitarity condition implies relations, among which $(i \neq j) \sum_k V_{ki} V^*_{kj} = 0$

This yields three independent null sums, of which one is particularly interesting :



$$V_{ud} V^*_{ub} + V_{cd} V^*_{cb} + V_{td} V^*_{tb} = 0$$

This is « the » famous unitarity triangle, well balanced, with three sides of similar magnitude



« B_s triangle » : unbalanced, squeezed

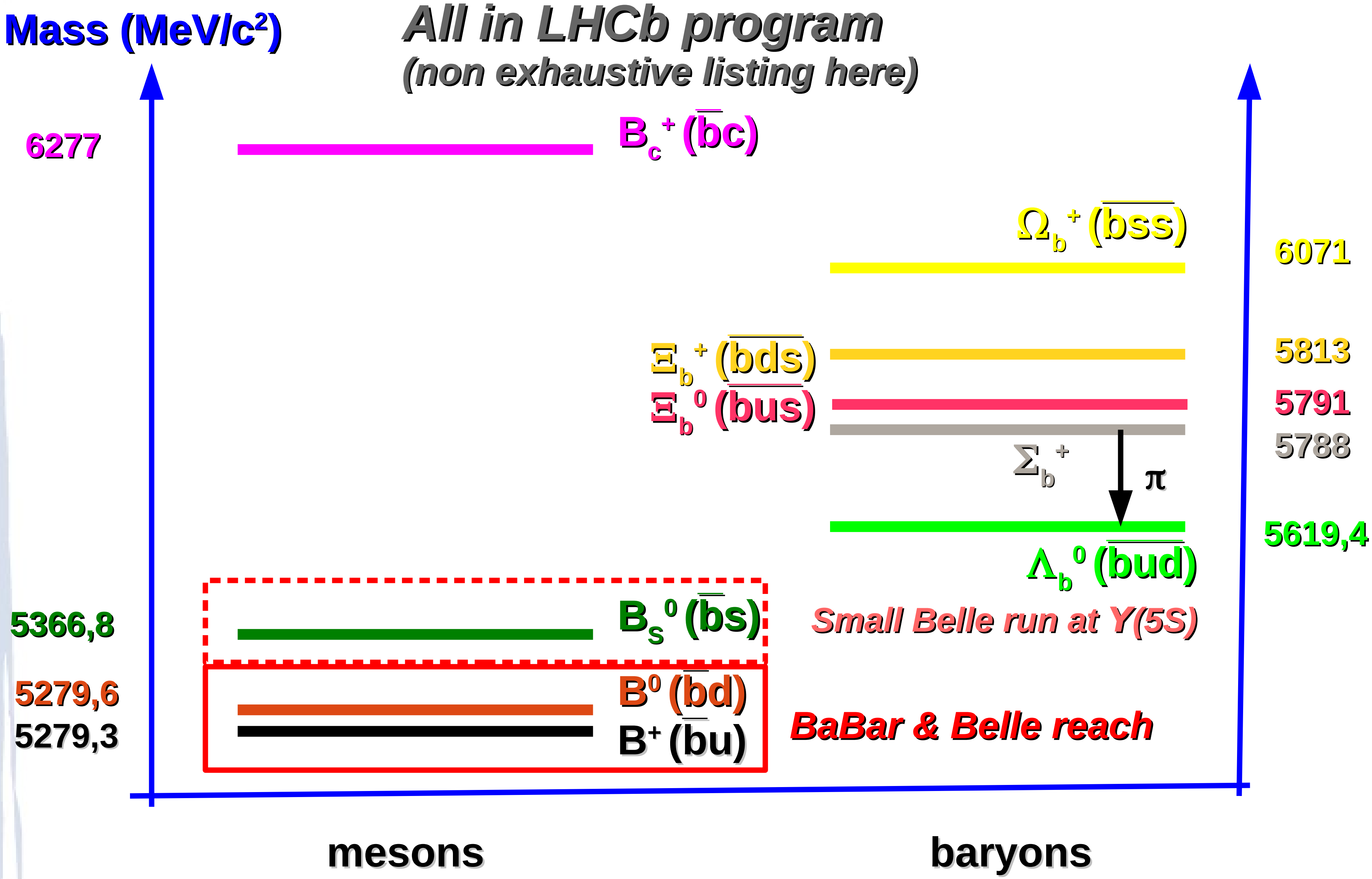
$$V_{us} V^*_{ub} + V_{cs} V^*_{cb} + V_{ts} V^*_{tb} = 0$$

By measuring the sides and angles of the Unitarity triangle, we test the closing relation expected in the Standard Model i<u>n presence of CP violation</u>

b hadrons

All in LHCb program

(non exhaustive listing here)



Not shown here : the excited states of each bound state

Effective Hamiltonians

Derived using Operator Product Expansion + renormalization group to sum up the radiative corrections*

$$H_{eff} = \sum_i V^i_{CKM} \, C_i(\mu) \, O_i(\mu)$$

- i = 1,2 : tree diagrams
- i = 3-6 : gluonic penguin
- i = 7-10 : electroweak penguin
(7γ, 8G : magnetic-penguin)
- leptonic operators (S,P)
- Box operators : to describe oscillations

Quark flavour couplings (CKM for the SM)

Wilson coefficients, integrate physics from EW scale to μ (~ 1 GeV)

6-dim operators (higher orders negligible)

Matrix elements of operators O_i : non perturbative calculations: source of hadronic uncertainties (decay constants, form factors, etc...)

C_i/O_i mix under RG equations: in practice, use effective C_i^{eff}

For right-handed current, use of primed coefficients, C_i' (beyond SM contributions)

** For a exhaustive review, see : G.Buchalla et al, Rev.Mod.Phys.68 (1996) 1125-1144*
https://arxiv.org/abs/hep-ph/9512380

The problem of hadronic uncertainties

The effective Hamiltonians in the OPE come as a product of currents × CKM coupling × Wilson coefficient
But for the observables, one needs to compute matrix elements between hadronic states ! Use of factorization ansatz, e.g for B → XY :

$$\langle X\,Y|O_i|B\rangle=\langle X\,Y|j_1\,j_2|B\rangle\approx\langle X|j_1|B\rangle\langle Y|j_2|0\rangle$$

or $$\langle X\,Y|O_i|B\rangle=\langle X\,Y|j_1\,j_2|B\rangle\approx\langle 0|j_1|B\rangle\langle X\,Y|j_2|0\rangle$$ **(annihilation)**

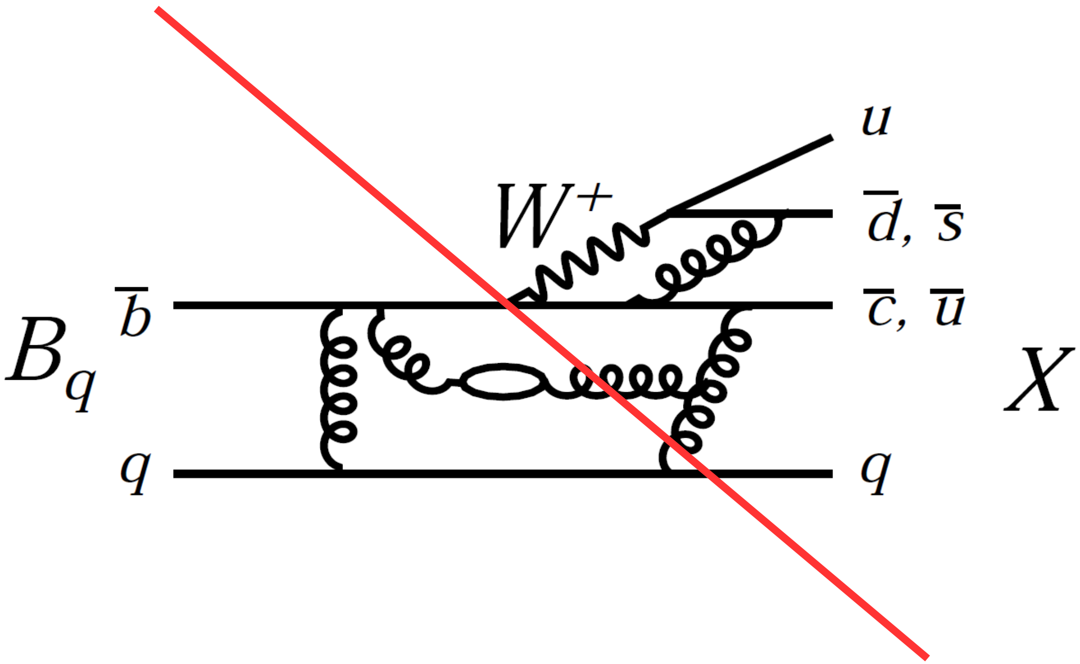
Works very well for modes where two parts of the decay are well decoupled : (semi)leptonic modes

It needs corrections for the hadronic modes since no decoupling is possible (e.g. soft gluon exchange)

After that, the decoupled matrix elements need some non-perturbative QCD techniques to be computed : QCD sum rules, lattice QCD.

For reviews on QCD sum rules, see :
arXiv:hep-ph/9801443, doi:10.1142/9789812812667_0005
arXiv:hep-ph/0010175

Extracting $|V_{ij}|$ with hadronic decays ?



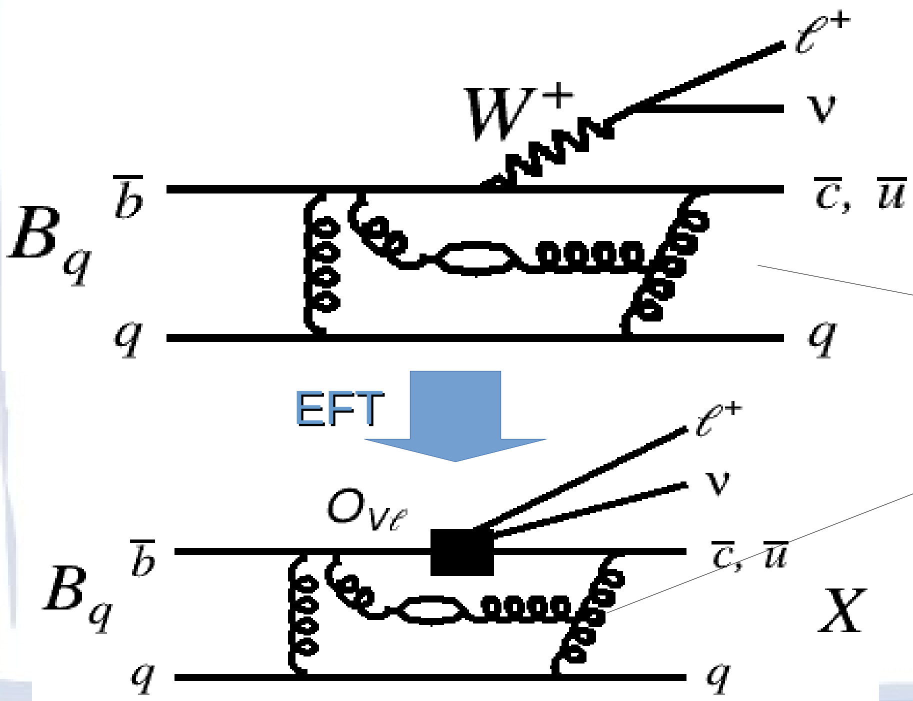
No way with « direct » quantities, or very limited (substantial corrections for non-factorizable effects)

Possible if one uses ratios (asymetries, etc...) for weak angles : example of γ extraction (but still need to deal with strong phases)

Thus....

Channels containing leptons in the final state are preferred due to the (quasi)perfect factorization of the matrix elements (second order electromagnetic effects)
Semileptonic B → X ℓ ν

$$\langle X\ell\nu|O_{V\ell}|B\rangle=\langle X\ell\nu|j_\ell\, j_h|B\rangle\simeq\underbrace{\langle X|j_h|B\rangle}_{\text{Non perturbative methods}}\overbrace{\langle \ell\nu|j_\ell|0\rangle}^{\text{trivial}}$$



Non perturbative methods treat what happens inside the hadrons : Form Factors

CKM and (semi)leptonic

	d	s	b
u	$\pi \to \ell \nu$	$K \to \ell \nu$ $K \to \pi \ell \nu$	$B^+ \to \ell \nu$ $H_b \to H_u \ell \nu$
c	$D^+ \to \ell \nu$ $H_c \to H_d \ell \nu$	$D_s \to \ell \nu$ $H_c \to H_s \ell \nu$	$B_c \to \ell \nu$ $H_b \to H_c \ell \nu$
t	$B_d \leftrightarrow \overline{B}_d$	$B_s \leftrightarrow \overline{B}_s$	

All these determinations are limited by the knowledge by decay constants (leptonic) and form factors (semileptonic)

Form Factors and rates

For X pseudo-scalar , only vector part of the current is relevant

$$\langle X|\bar{q}\gamma^{\mu}b|B\rangle = f_{+}(q^2)\left(p_B^{\mu}+p_X^{\mu}-\frac{(m_B^2-m_X^2)}{q^2}\right)+f_0(q^2)\frac{(m_B^2-m_X^2)}{q^2}q^{\mu}$$

$$q=p_B-p_X=p_{\ell}+p_{\nu} \qquad m_{\ell}^2\leq q^2\leq(m_B-m_X)^2$$

Extraction !

experiment

$$\frac{d\Gamma}{dq}(B\rightarrow X\ell\nu)=\frac{G_F^2|V_{xb}|^2}{24\pi^3}\frac{(q^2-m_{\ell}^2)\sqrt{E_X^2-m_X^2}}{q^4 m_B^2}$$

Theoretical calculations

$$\times\left\{\left(1+\frac{m_{\ell}^2}{2q^2}\right)m_B^2(E_X^2-m_X^2)[f_{+}(q^2)]^2+\frac{3m_{\ell}^2}{8q^2}(m_B^2-m_X^2)^2[f_0(q^2)]^2\right\}$$

Since $m_{\ell}^2 << q^2$ in general (for ℓ = e,μ), f_+ « pilots » the decay rate

Form Factors parametrization and calculation

$$z(q^2,t_0)=\frac{\sqrt{1-q^2/t_+}-\sqrt{1-t_0/t_+}}{\sqrt{1-q^2/t_+}+\sqrt{1-t_0/t_+}}$$

$$f_+(q^2)=\frac{1}{1-q^2/m_{B^*}^2}\sum_{k=0}^{K} b_+^{(k)}(t_0)\,z(q^2,t_0)^k \qquad f_0(q^2)=\sum_{k=0}^{K-1} a_0^{(k)}(t_0)\,z(q^2,t_0)^k$$

$$t_+=(m_B+m_X)^2 \qquad t_0=(m_B+m_X)(\sqrt{m_B}-\sqrt{m_X})^2$$

BCL parametrization*

→ Used in the HPQCD and UKQCD papers (inadvertently)

$$t_0=t_+-\sqrt{t_+(t_+-t_-)} \qquad t_-=(m_B-m_X)^2 \qquad t_+=(m_{B^+}+m_\pi)^2$$

→ Used by MILC2019 and FLAG

Usually K=3 *b* parameters are used for the description

FF calculations : either with Lattice QCD (LQCD), which tends to be accurate at high q^2 or Light Cone Sum Rule (LCSR), which is more accurate at low q^2

Bourrely, Caprini, Lellouch, Phys. Rev. D 79 (2009) 013008

Notes on Form Factor parametrization

Asymptotic requirement on f_+ → highest order coeff expressed vs the others.

$$f_+(q^2) = \frac{1}{1-q^2/m_{B^*}^2} \sum_{k=0}^{K-1} a_+^{(k)} \left[z^k - (-1)^{k-K} \frac{k}{K} z^K \right]$$

Kinematic constraint $f_+(0) = f_0(0)$

→ $a_0^{(K-1)}$ **function of** $a_{+,0}^{(k)}$

In the deeds, a parametrization with K = 3 has 3 a_+ and 2 a_0 coefficients

See, e.g., FLAG review 2019, EPJC80 (2020) 113 ; arxiv:1902.08191 Appendix A.5

Inclusive measurements

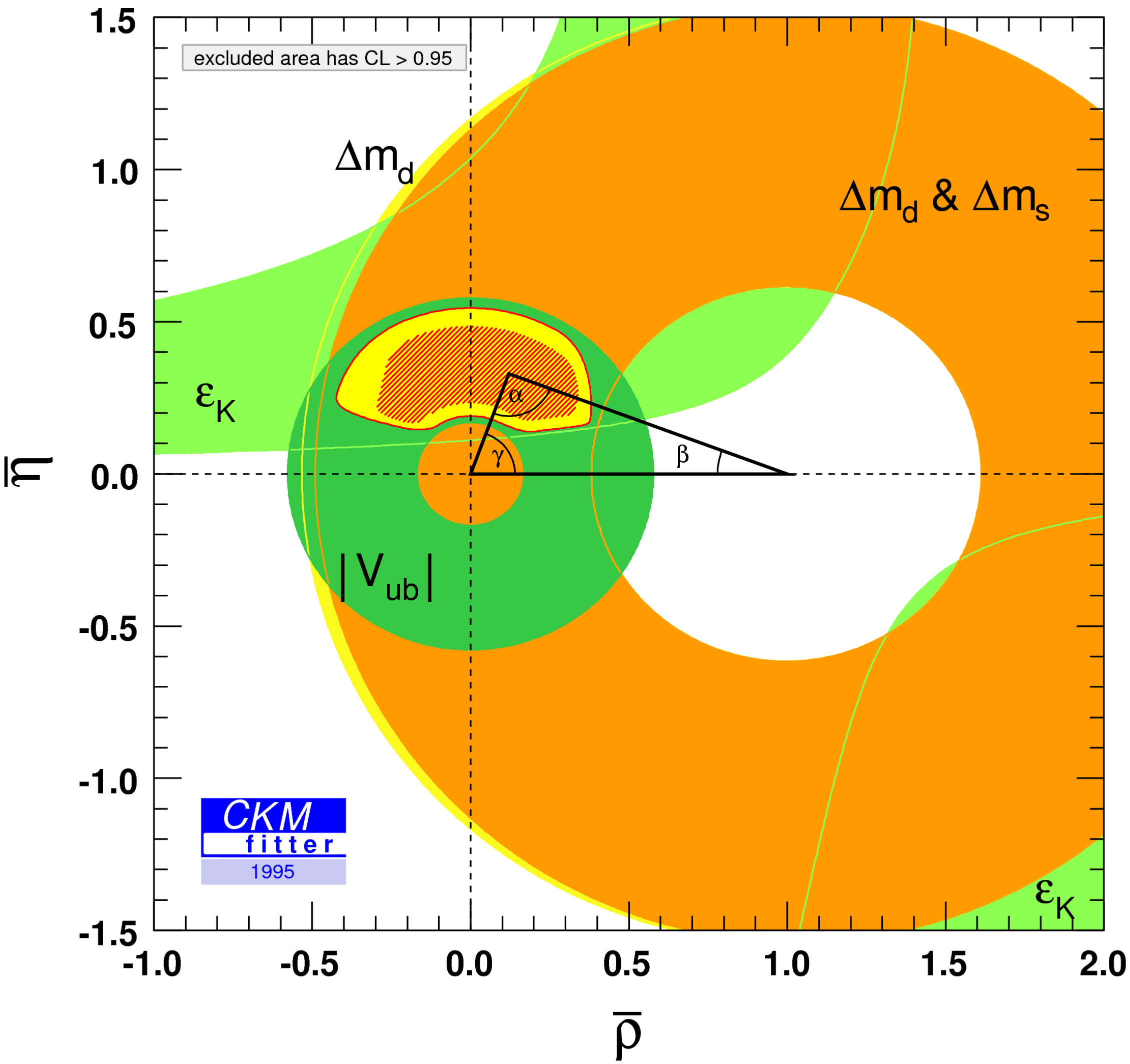
B → (Σ$_X$ X) ℓ ν

Non-perturbative effects from B only

Use of heavy quark expansion (HQE) ~ 1/m_b

(Relevant for B factories)

Unitarity triangle before B factories



Situation in 1995, right after the first top quark observation in Fermilab. The top mass intervenes in the $B - \bar{B}$ mixing : use of mixing frequency Δm possible.

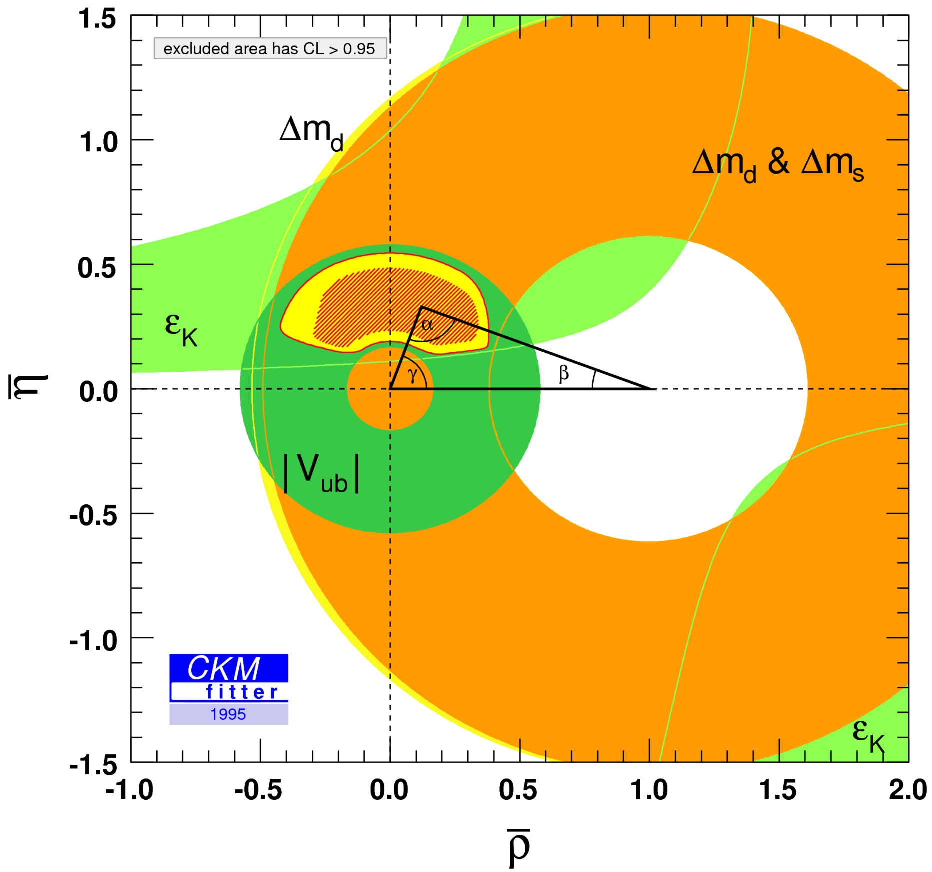
- First $|V_{cb}|$ measurement at LEP

- Evidence for $|V_{ub}|$ (ARGUS, CLEO)

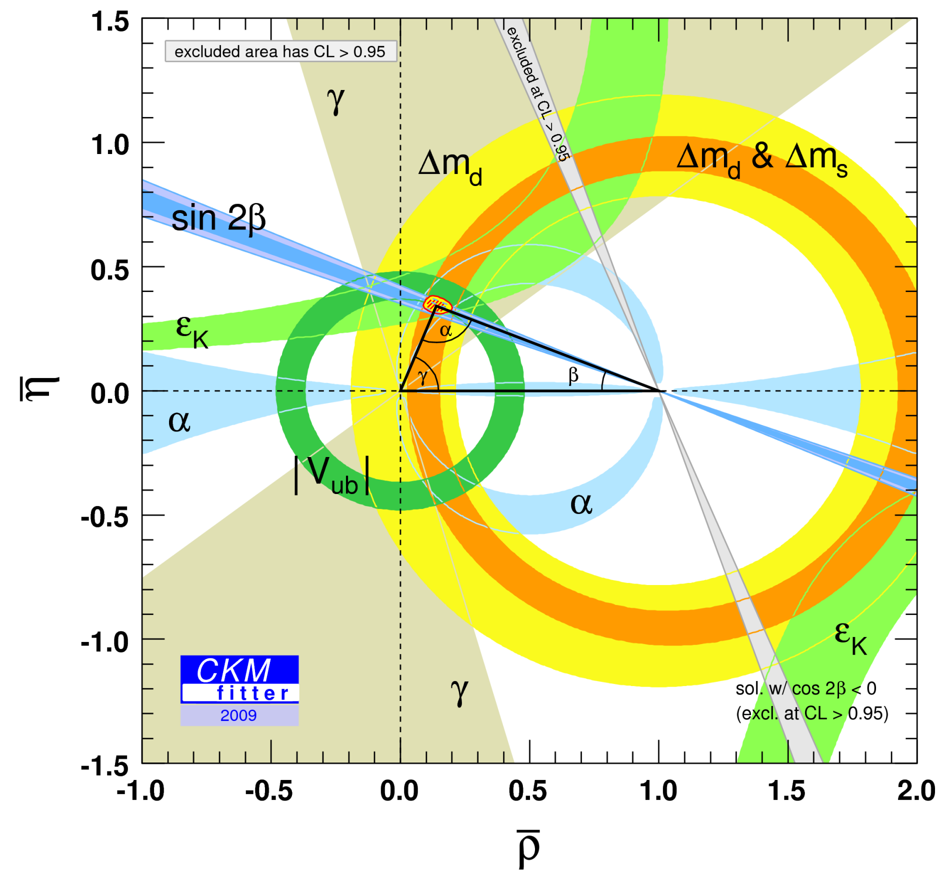
$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} + 1 = 0$$

UT after B factories mandate

1995

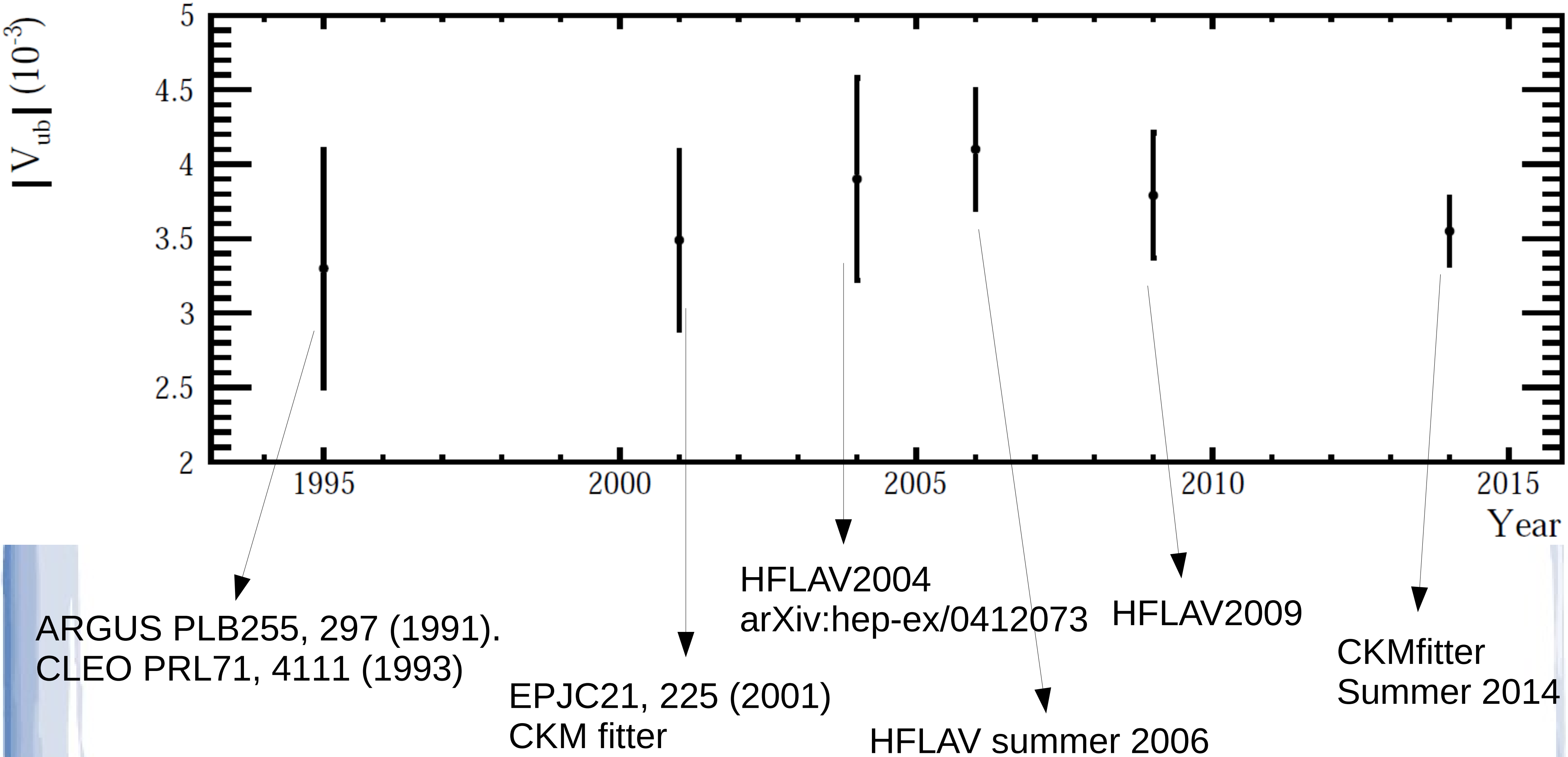


2009



Basically : The B factories established experimentally the CKM picture but a lot of remaining questions (e.g. tree vs loop constraints) and more precision (e.g, $|V_{ub}|$!) is needed.

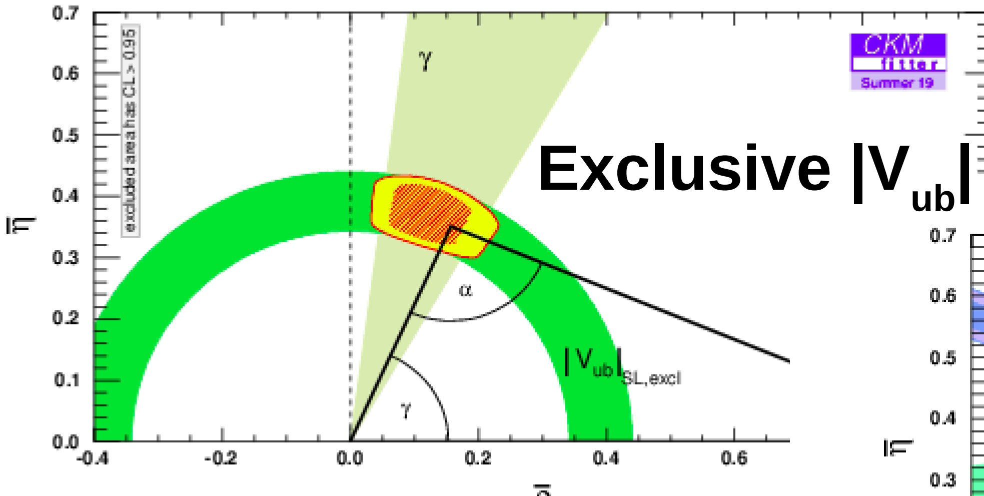
Evolution of $|V_{ub}|$



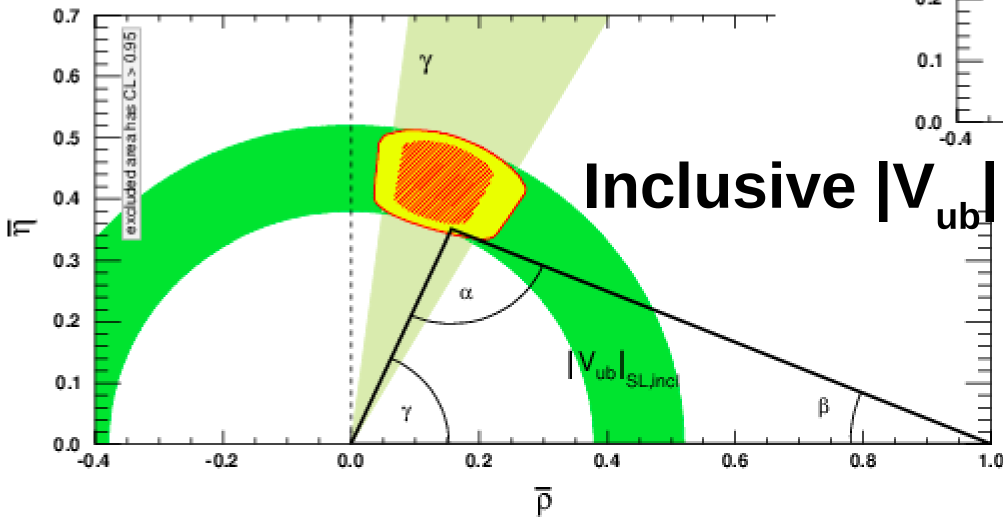
In these averages, inclusive and exclusive modes are not separated (when used)

UT contraints from loop vs tree quantities

Tree quantities

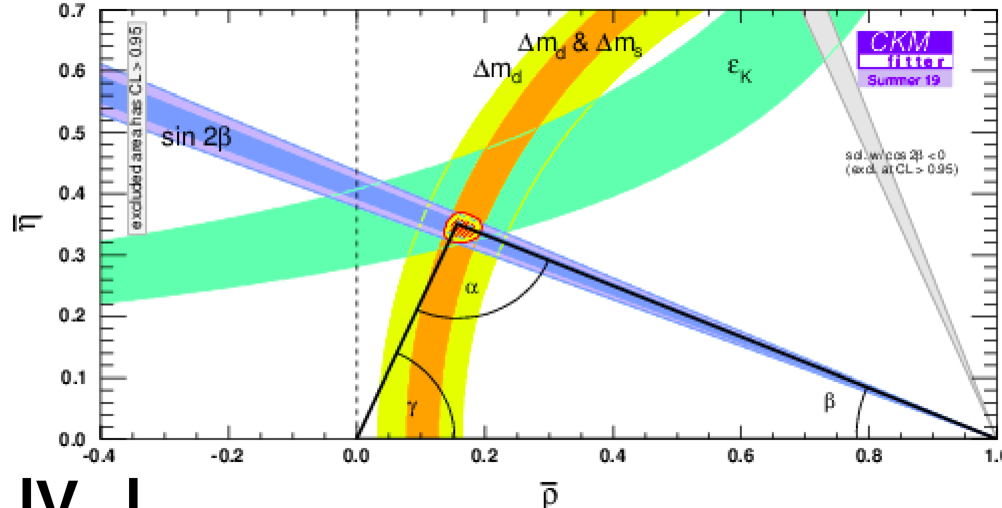


Exclusive $|V_{ub}|$



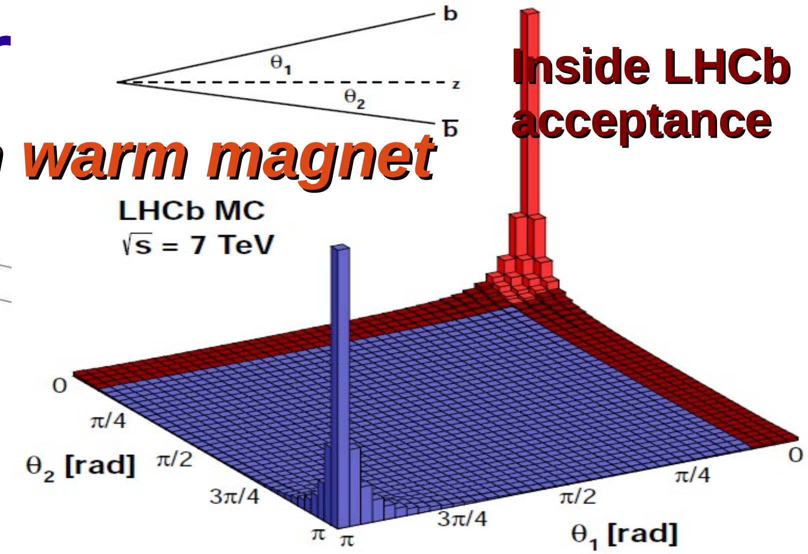
Inclusive $|V_{ub}|$

Loop quantities



$|V_{ub}|$(/$|V_{cb}|$) measurement is crucial in the tree vs loop test !

LHCb detector



Forward single-arm spectrometer with warm magnet (possibility to inverse polarity)

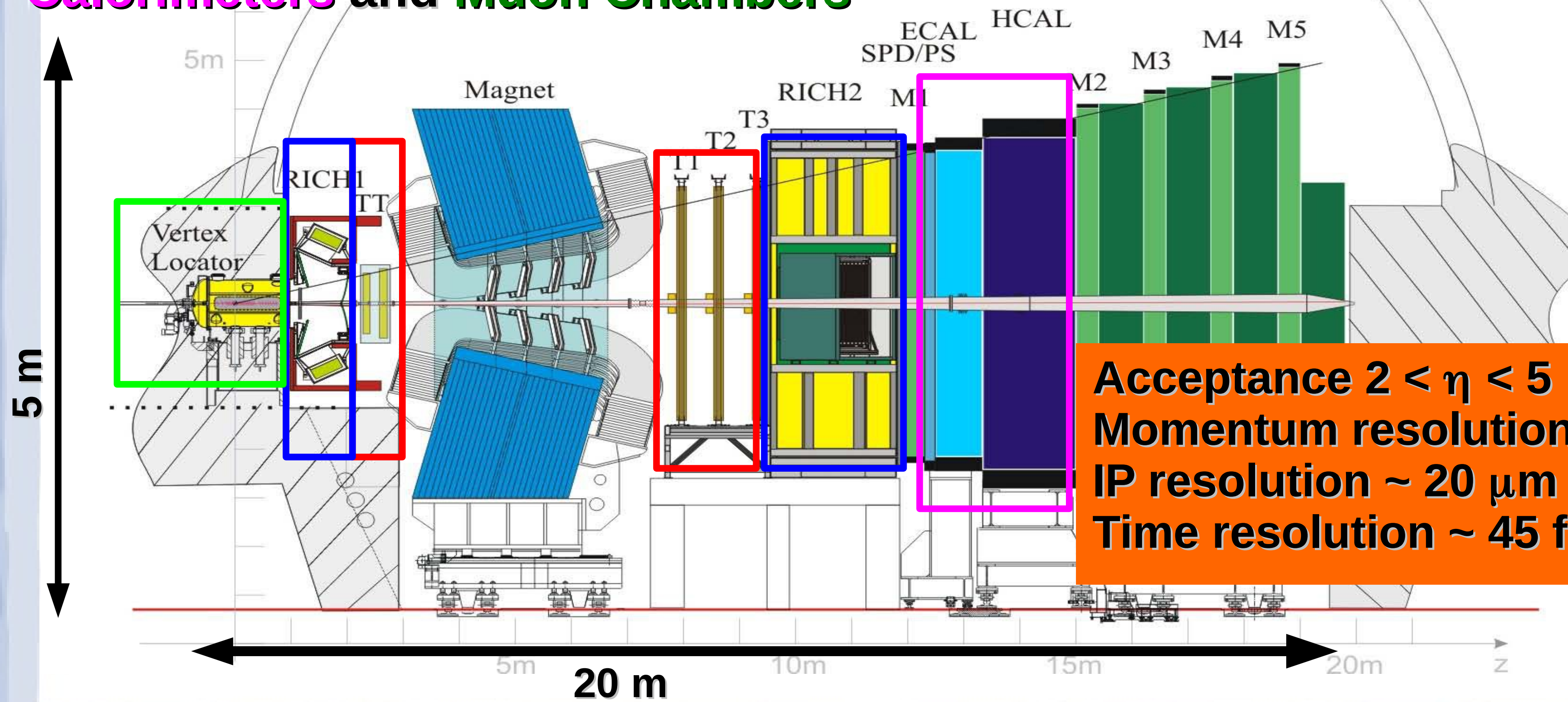
Optimize for b and c hadron studies

Vertexing

Tracking stations

Particle ID Ring Imaging Cherenkov

Calorimeters and Muon Chambers



Acceptance 2 < η < 5
Momentum resolution ~ 0.5%
IP resolution ~ 20 μm
Time resolution ~ 45 fs

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

In the deeds, we normalize b → u decays to corresponding b → c modes to minimize systematics and control efficiency corrections, etc.. Consequence : we measure $|V_{ub}|/|V_{cb}|$

$\Lambda_b \rightarrow p\, \mu\, \nu$, normalized to $\Lambda_b \rightarrow \Lambda_c(\rightarrow pK\pi)\, \mu\, \nu$

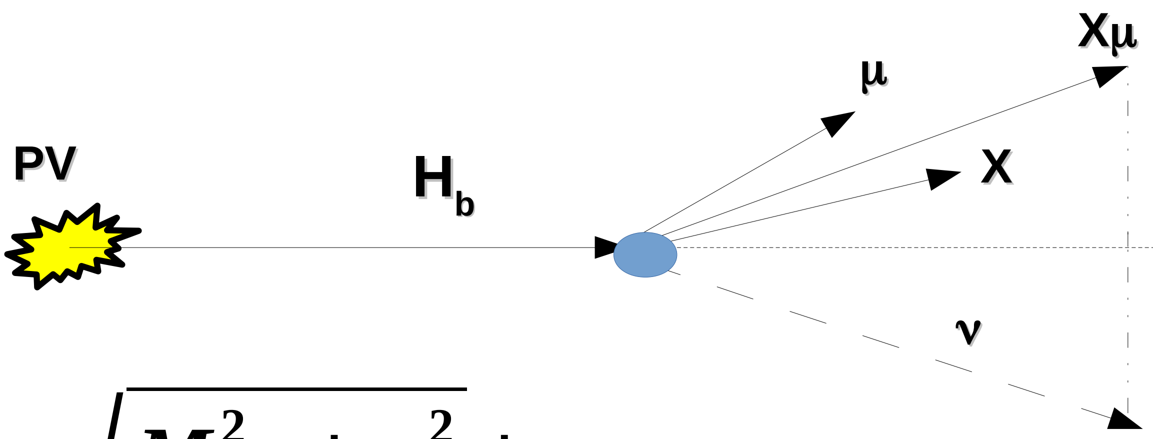
Nature Phys. 11 (2015) 743-747, arXiv:1504.01568

$B_s \rightarrow K\, \mu\, \nu$, normalized to $B_s \rightarrow D_s(\rightarrow KK\pi)\, \mu\, \nu$

arXiv:2012.05143, Phys. Rev. Lett. 126, 081804 (2021)

Will concentrate more on this one

Technique for SL in LHCb



$$p_{\perp}(X\mu)$$

$$p_{\perp}(\nu) = p_{\perp}(X\mu)$$

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

Fit variable : binned template histograms for signal and backgrounds

Use Beeston-Barlow method to account for template uncertainty

$$q^2 = (p_{\mu} + p_{\nu})^2$$

$p_{\parallel}(\nu)$ ***determined from*** $p_{H_b}^2 = m(H_b)^2$ **Two fold ambiguity**

→ **Best solution chosen with regression method**
JHEP 02 (2017) 021

(other methods to approximate q are also used in SL analyses)

Method

Measure :

Experiment

$$R_{BF}=\frac{BF(H_b\to X_u\mu\nu)}{BF(H_b\to X_c\mu\nu)}=\frac{|V_{ub}|^2}{|V_{cb}|^2}\frac{|V_{ub}|^{-2}\int\frac{d\Gamma_K}{dq^2}}{|V_{cb}|^{-2}\int\frac{d\Gamma_{D_s}}{dq^2}}$$

Infer : $\frac{|V_{ub}|}{|V_{cb}|}$ using FF calculations (LQCD, QCD SR)

One q^2 > 15 GeV^2 region for $\Lambda_b \to p\,\mu\,\nu$

Two q^2 bins for $B_s \to K\,\mu\,\nu$; q^2 >< 7 GeV^2

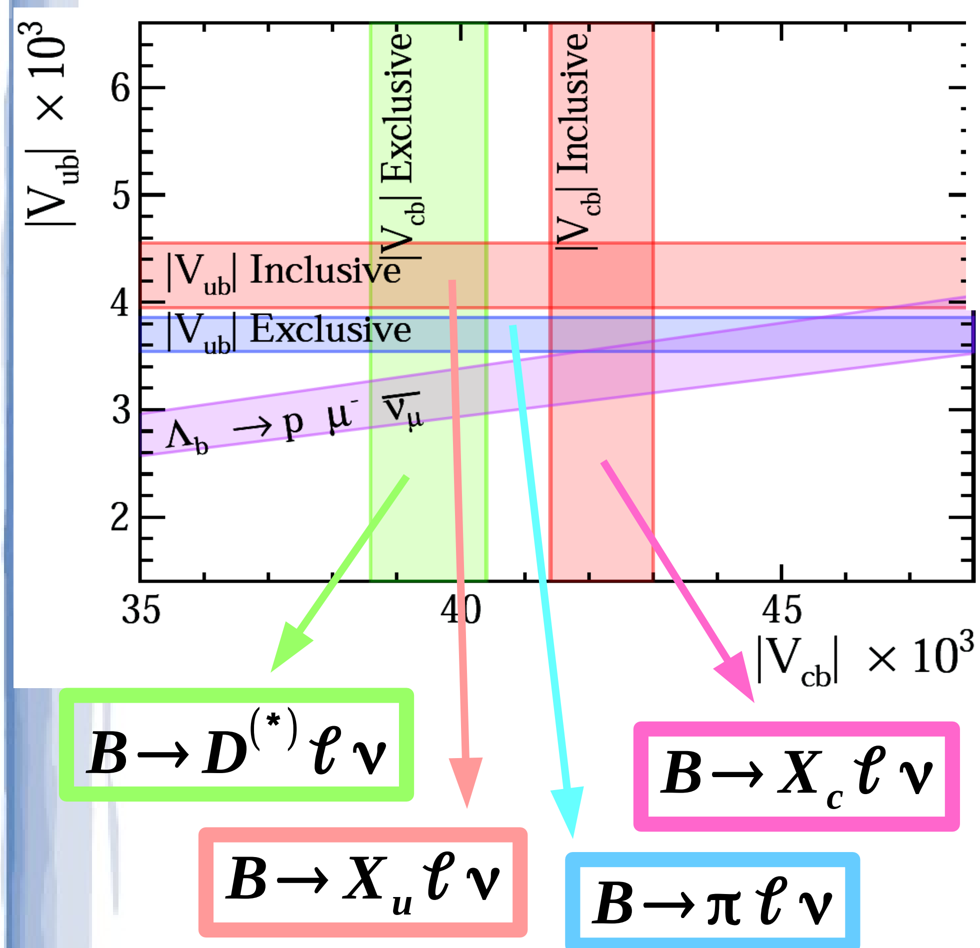
Boundary chosen to get approximately the same expected number of signal events in each bin

*** Measurement of the Branching Fraction for the first time**

*** Provide a $|V_{ub}|/|V_{cb}|_{excl}$ measurement to feed in the excl vs incl puzzle AND the Unitarity triangle side**

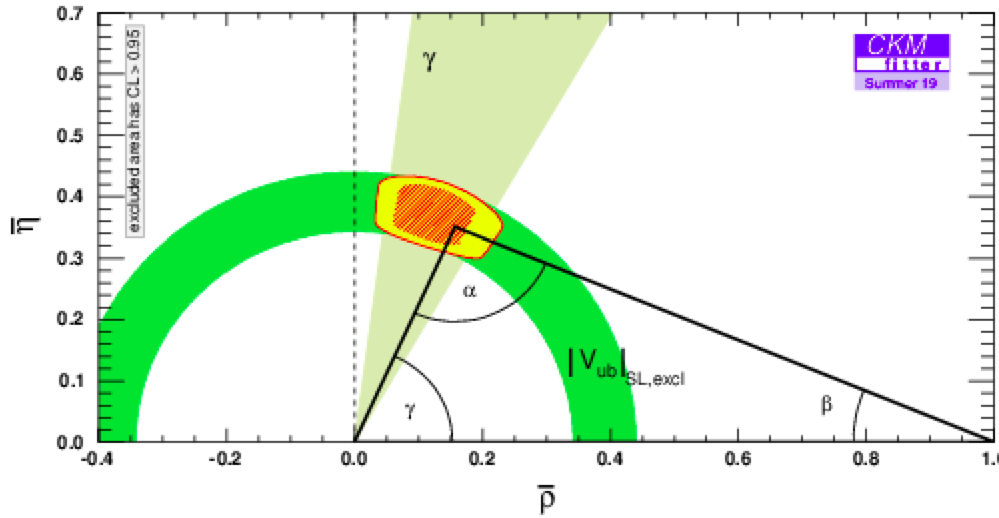
Motivation for $B_s \to K\mu\nu$

Inclusive vs Exclusive puzzle in the plane ($|V_{cb}|$,$V_{ub}|$)

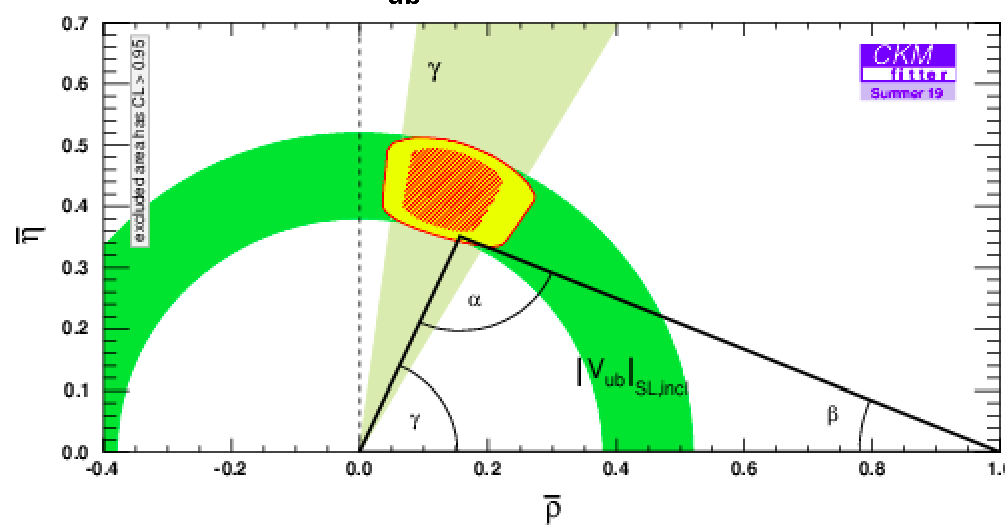


UT apex constraint with γ and $|V_{ub}|$(/$|V_{cb}|$)

Exclusive $|V_{ub}|$(/$|V_{cb}|$)

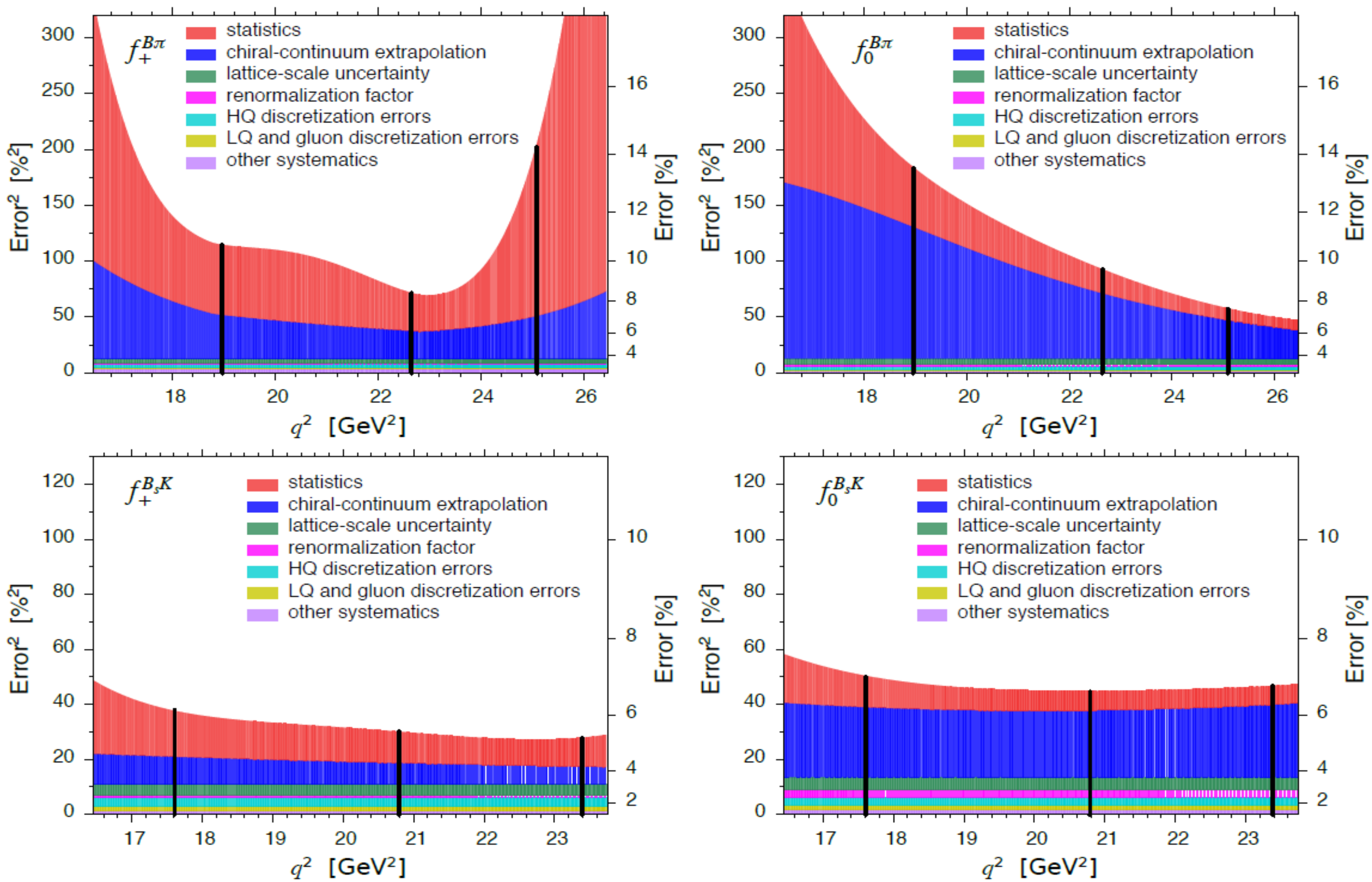


Inclusive $|V_{ub}|$



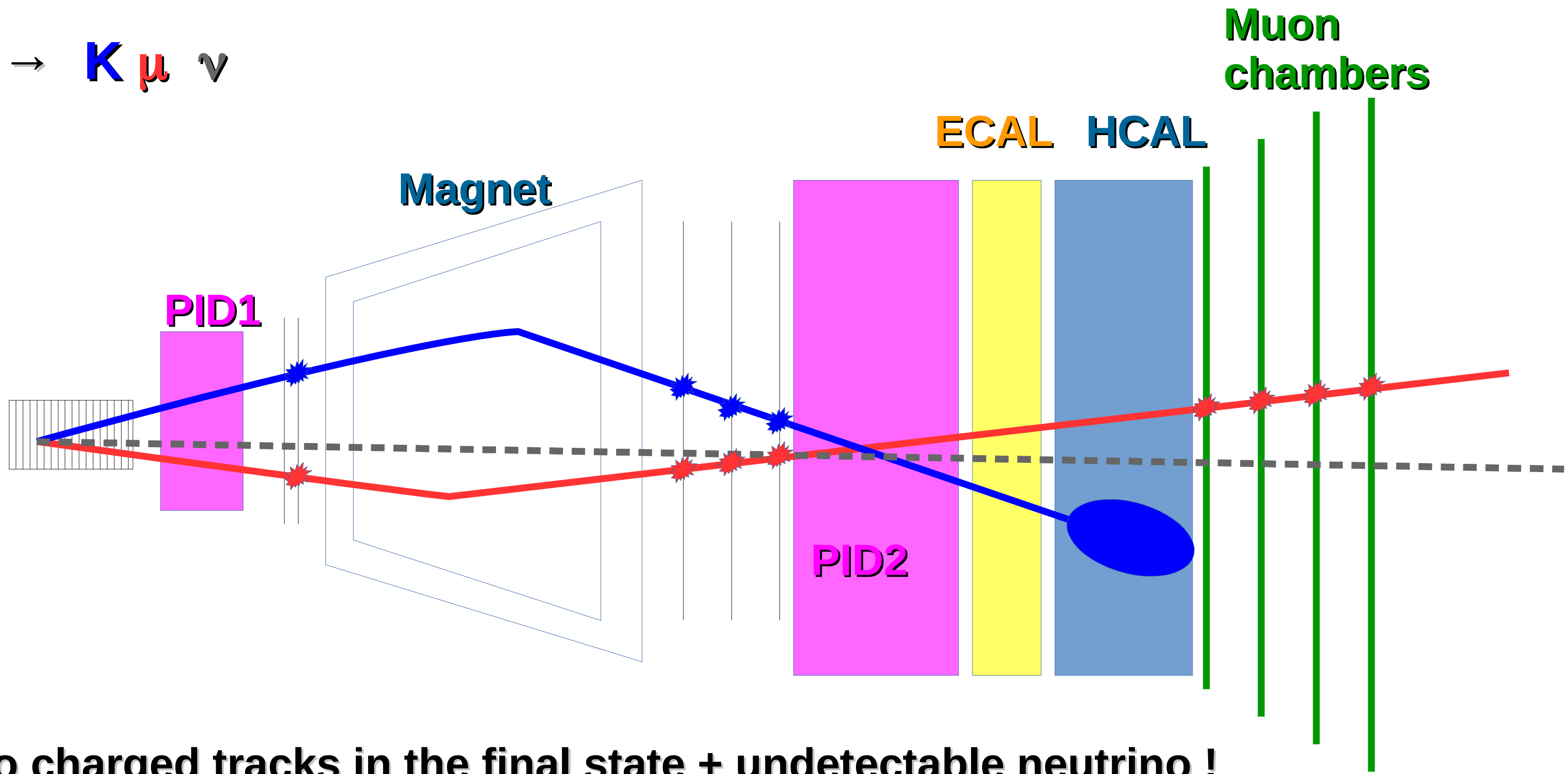
$B \to \pi$ vs $B_s \to K$ FF

FF error budgets in LQCD, as reported in Phys. Rev. D 91, 074510 (2015)



Challenge

$B_s \rightarrow K \mu \nu$



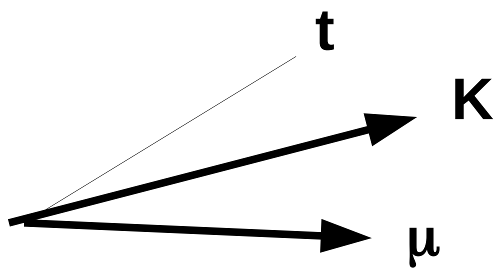
Only two charged tracks in the final state + undetectable neutrino !
Any physics decay with the same tracks + extra tracks or neutral particle is a background !
+ Tracks getting out of acceptance...
Background fighting and characterization involving Machine Learning techniques

Backgrounds for $B_s \to K \mu \nu$

- Dominant V_{cb}: $b \to c(\to KX) \mu \nu$
- $B_s \to K^* \mu \nu$: three resonances ($K^*(892)$, $K_0^*(1430)$, $K_2^*(1430)$) ($\to K^+ \pi^0$)
  - Neutral isolation, model what passes
- $B \to c\bar{c} K (X)$
  - Charged isolation MVA output
- MisID background from e.g., $B \to \pi \mu \nu$
  - Modeled using fake K/μ selection lines
- Combinatorial (reduced with geometrical cut, removing track pairs with transverse momenta in opposite quadrants)

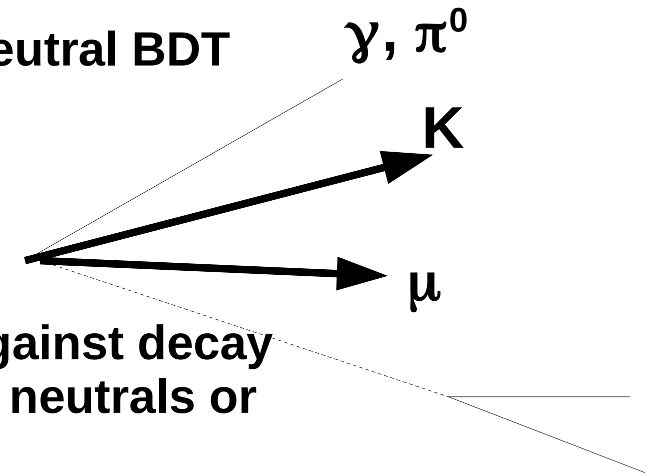
MVA

Charge BDT

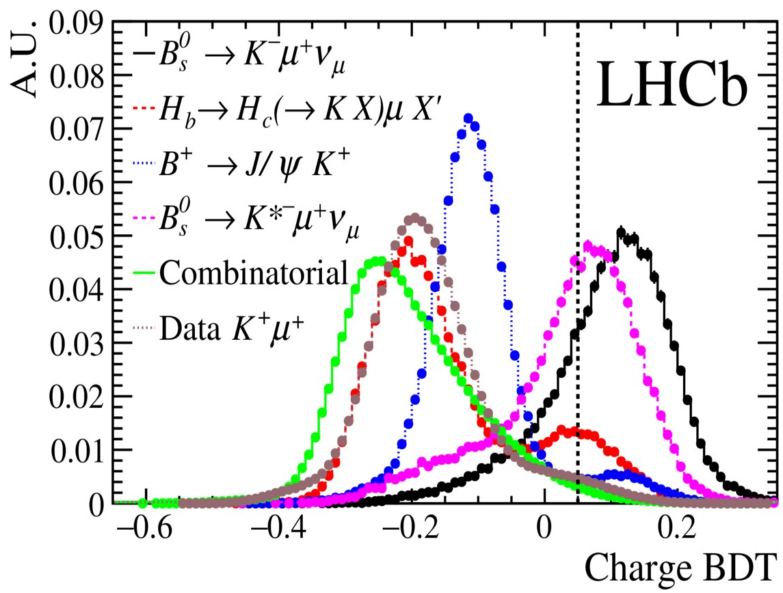


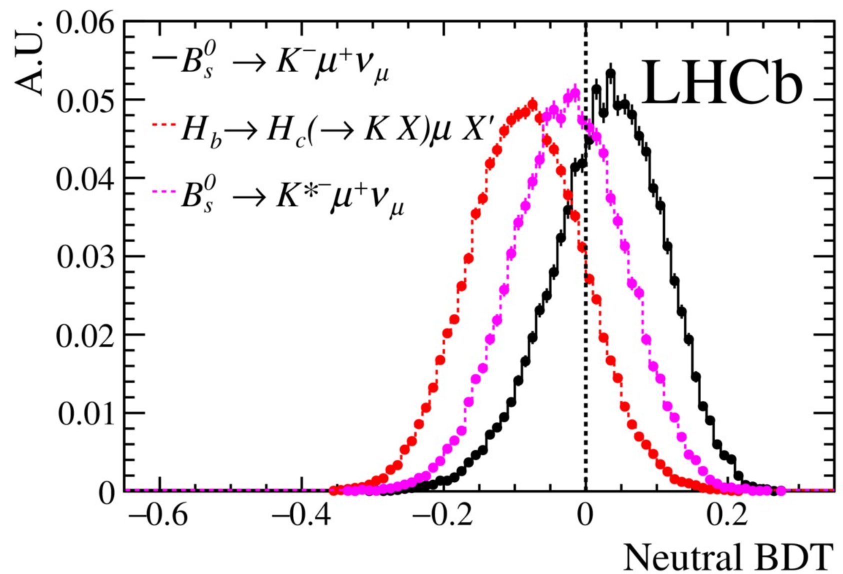
Trained against decay with extra tracks

Neutral BDT



Trained against decay with extra neutrals or long-lived





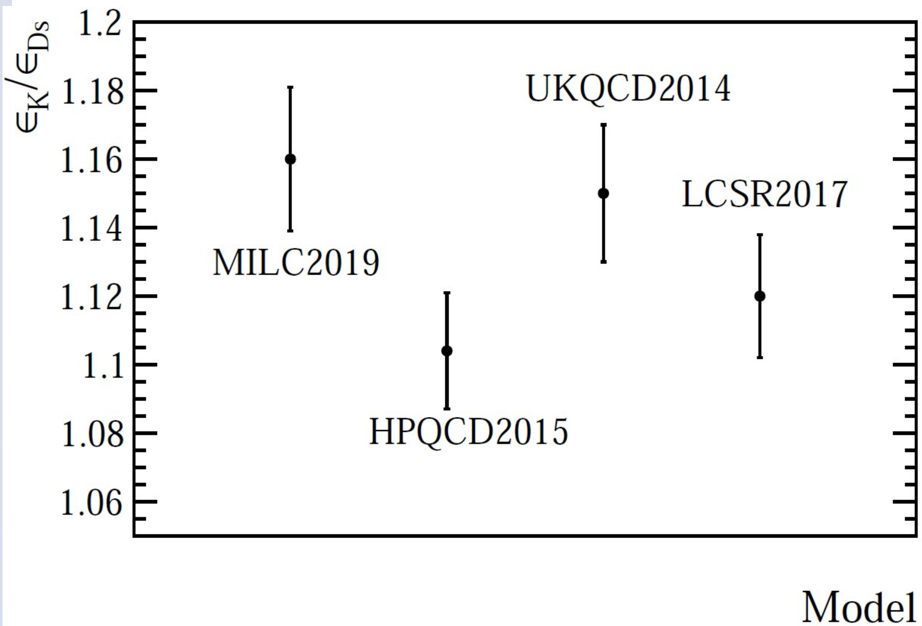
Neutral BDT optimized after charge BDT selection

Backgrounds for $B_s \to D_s \mu \nu$

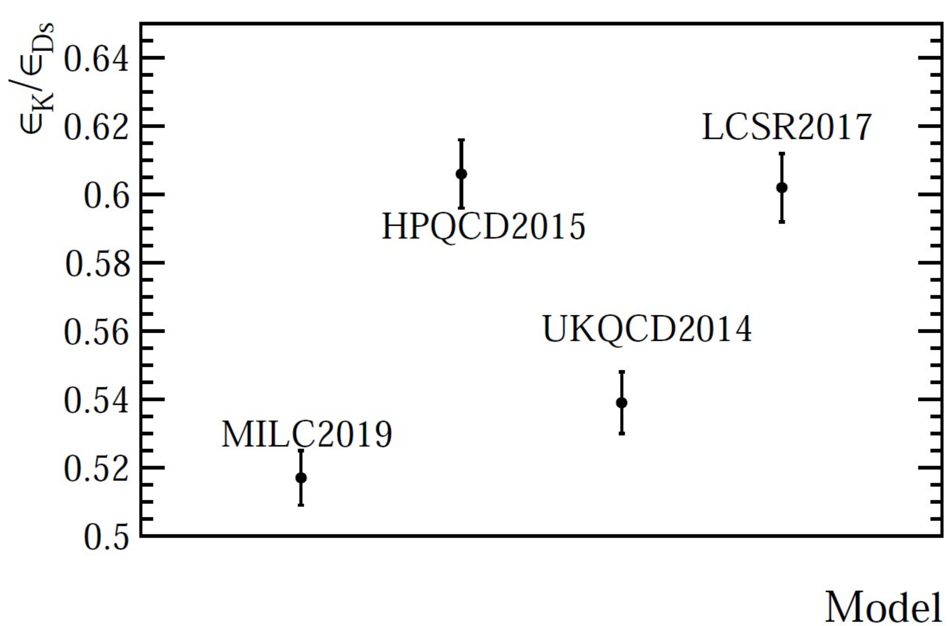
- $B_s \to D_s^* \mu \nu$ ($D_s^* \to D_s \gamma$)
- $B_s \to D_s^{**} \mu \nu$ (higher resonances $\to D_s X$)
- $B_s \to D_s \tau \nu$ ($\tau \to \mu \bar{\nu}_\mu \nu_\tau$)
- $B \to D_s D$ ($D \to \mu \nu X$)
- Note : since the D_s signal is fitted as a function of Mcorr, no combinatorial or reflections emerging from $D_s \to KK\pi$ side

How FF models impact the analysis (practically)

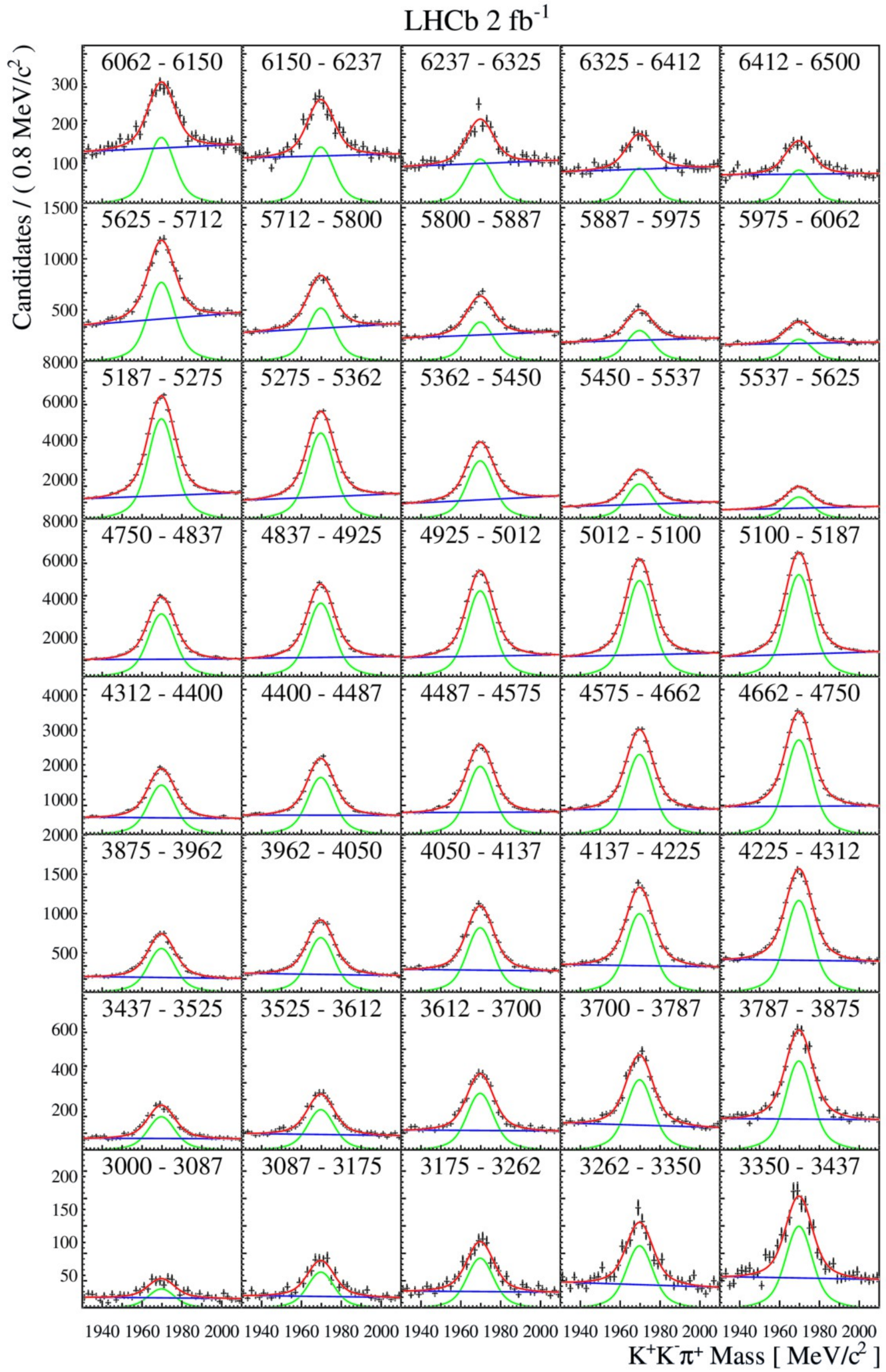
- Variation of the Mcorr shape for the fit(s)
  - Variation of the obtained signal yield
- Variation of the efficiency for each q^2 bin



$q^2 < 7\ GeV^2$



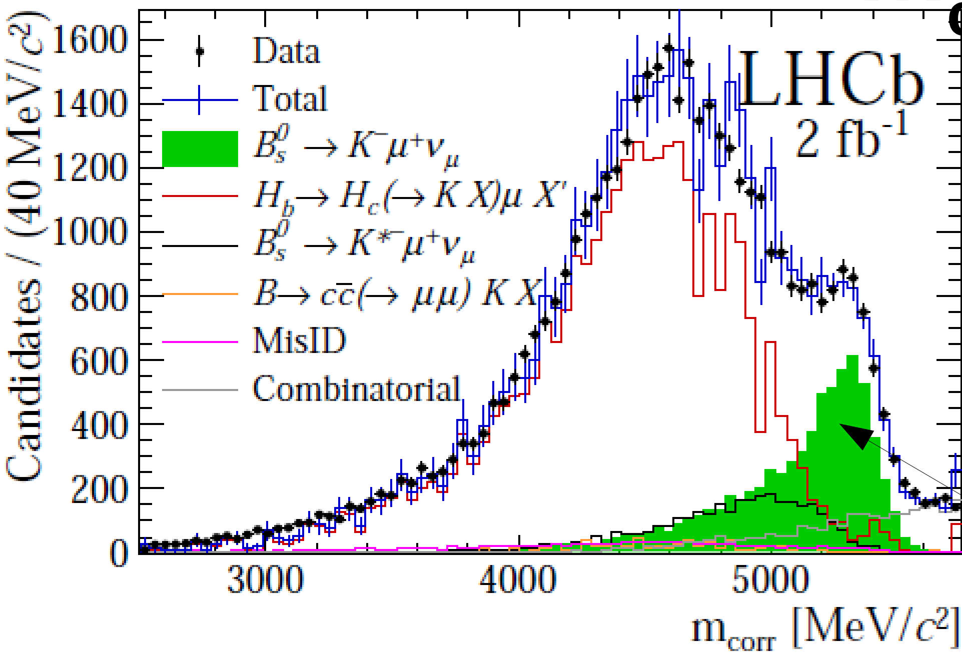
$q^2 > 7\ GeV^2$



Fit of $D_s \rightarrow KK\pi$ in 40 Mcorr bins from 3000 to 6500 MeV/c^2

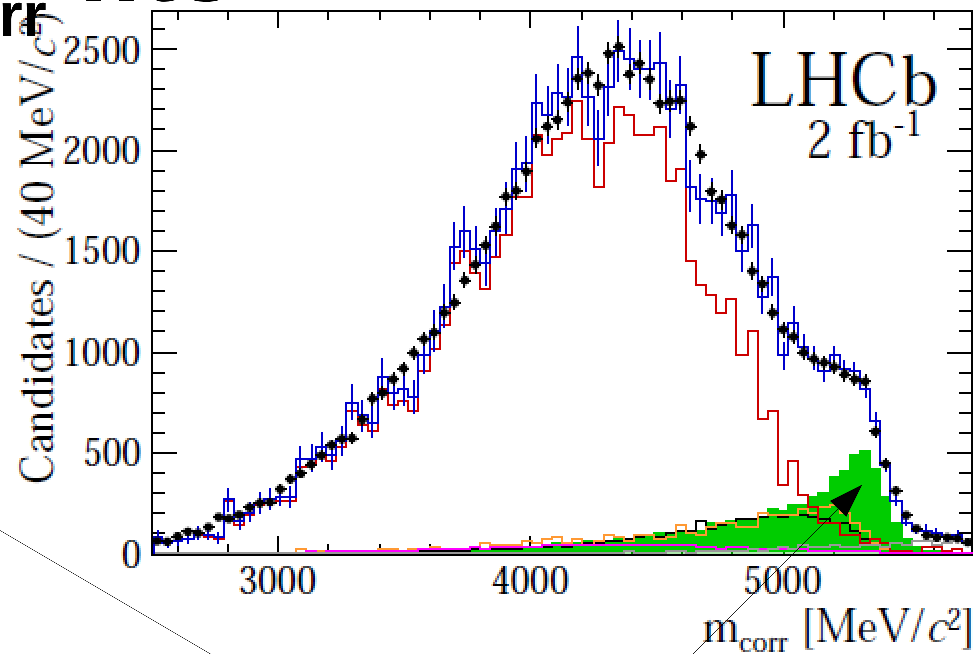
M_{corr} fits

$q^2 < 7$ GeV^2



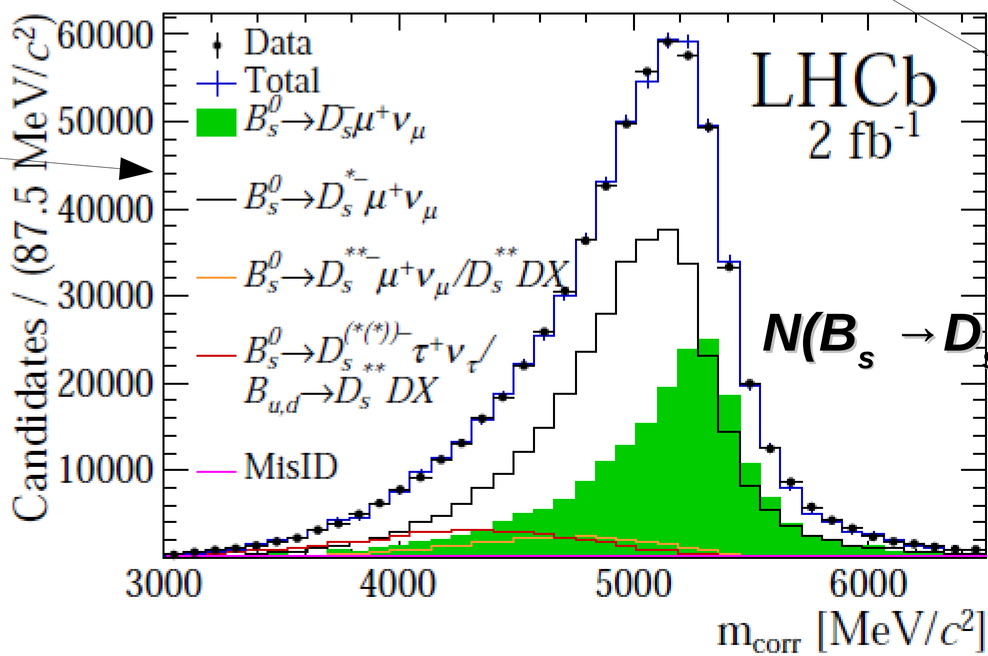
$N(B_s \to K \mu \nu) = 6922$ +/- 285

$q^2 > 7$ GeV^2



$N(B_s \to K \mu \nu) = 6399$ +/- 390

Normalization fit to $B_s \to D_s \mu \nu$



Bumps clearly showing excess of $B_s \to K \mu \nu$

$N(B_s \to D_s \mu \nu) = 201450$ +/- 5200

Uncertainties include fit template limited statistics

BF results

$$R_{BF} = \frac{\mathcal{B}(B_s^0 \to K\mu\nu,\ \text{bin})}{\mathcal{B}(B_s^0 \to D_s\mu\nu)} = \frac{N_K}{N_{D_s}} \times \frac{\epsilon_{D_s}}{\epsilon_K(\text{bin})} \times \mathcal{B}(D_s^+ \to K^+K^-\pi^+)$$

$$R_{\text{BF}}(\text{low}) = (1.66 \pm 0.08\,(\text{stat}) \pm 0.07\,(\text{syst}) \pm 0.05\ (D_s)) \times 10^{-3}$$

$$R_{\text{BF}}(\text{high}) = (3.25 \pm 0.21\,(\text{stat})\,^{+0.16}_{-0.17}\,(\text{syst}) \pm 0.09\ (D_s)) \times 10^{-3}$$

$$R_{\text{BF}}(\text{all}) = (4.89 \pm 0.21\,(\text{stat})\,^{+0.20}_{-0.21}\,(\text{syst}) \pm 0.14\ (D_s)) \times 10^{-3}$$

Low vs High q^2 BF are in the proportions 1:2

Using $\mathcal{B}(B_s^0 \to K\mu\nu,\ \text{bin}) = R_{BF} \times \tau_{B_s} \times |V_{cb}|^2 \times FF_{D_s^+}$

We obtain $\boxed{\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu) = (1.06 \pm 0.05\,(\text{stat}) \pm 0.08\,(\text{syst})) \times 10^{-4}}$

Systematics

$D_s \to KK\pi$ BF brings a 2.8% relative uncertainty

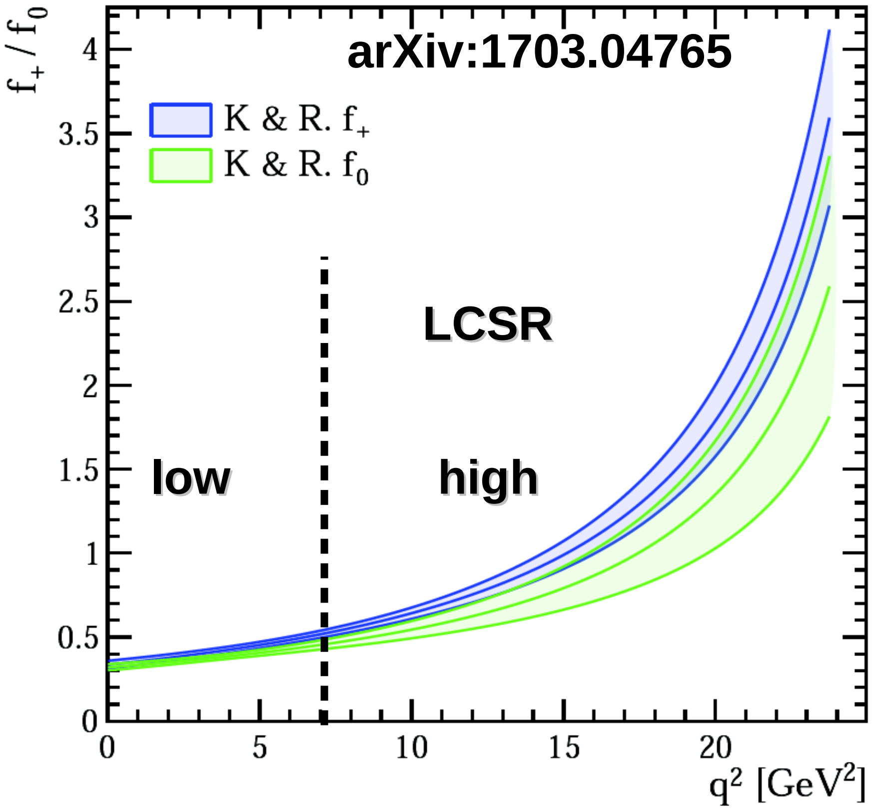
Uncertainty	All q^2	low q^2	high q^2
Tracking	2.0	2.0	2.0
Trigger	1.4	1.2	1.6
Particle identification	1.0	1.0	1.0
$\sigma(m_{\text{corr}})$	0.5	0.5	0.5
Isolation	0.2	0.2	0.2
Charged BDT	0.6	0.6	0.6
Neutral BDT	1.1	1.1	1.1
q^2 migration	–	2.0	2.0
Efficiency	1.2	1.6	1.6
Fit template	$^{+2.3}_{-2.9}$	$^{+1.8}_{-2.4}$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

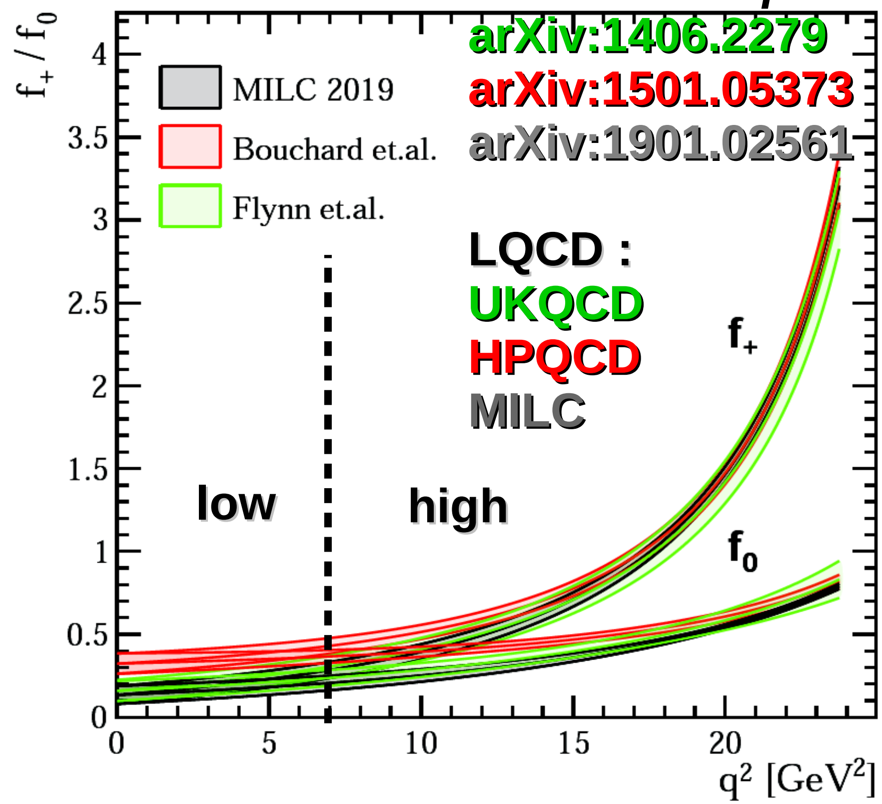
Data/MC corrections with control channel (applies to $\sigma(m_{\text{corr}})$, Isolation, Charged BDT, Neutral BDT)

Vary signal(s) and background shapes due to uncertainty related to statistics or FF model or possibly missing components, etc... (applies to Fit template)

FF calculations $B_s \to K\mu\nu$

Bouchard et al. (HPQCD2014) shows different behaviour at low q^2





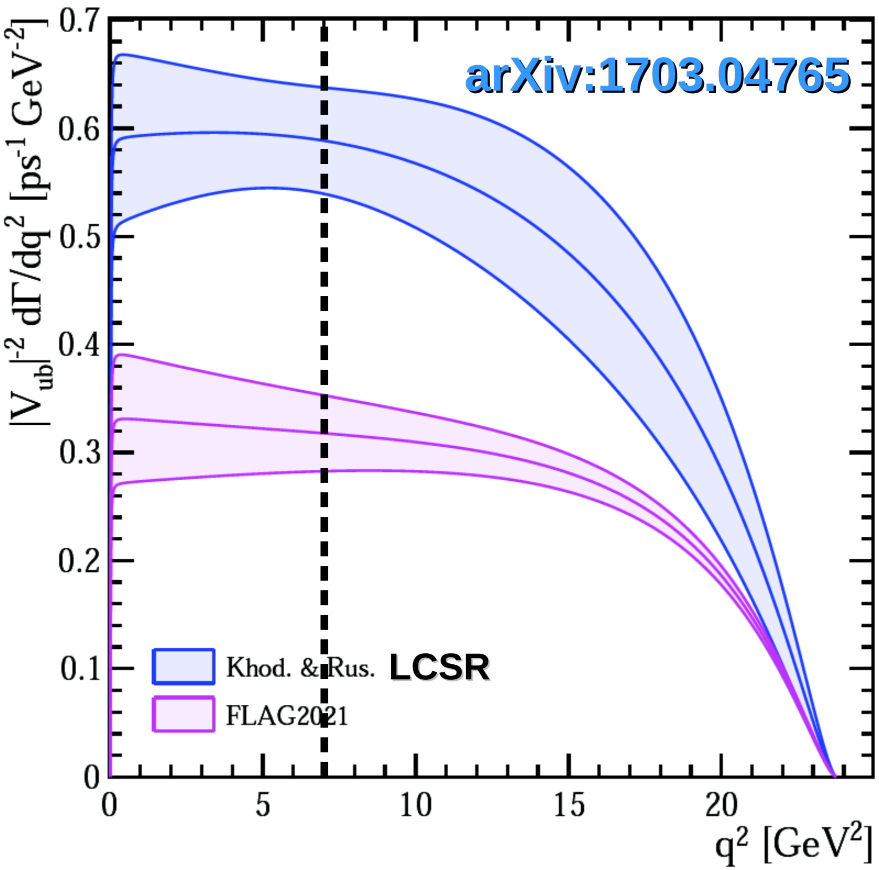
High q^2 : in general better accuracy for LQCD
LCSR not reliable > 12 GeV^2
Low q^2 : LCSR better

The choice was done BEFORE unblinding

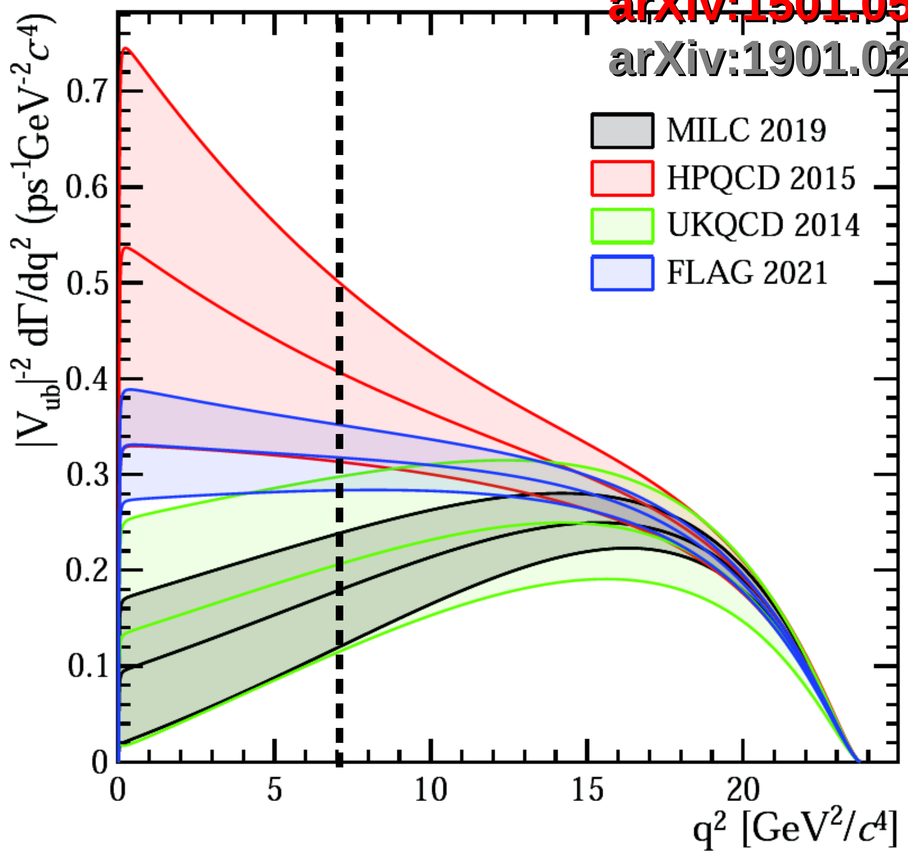
From there, we chose LCSR FF at low q^2 and latest LQCD (MILC 2019) for high q^2

Error bands : produced as the standard deviation of toys using the correlation matrices of the coefficients of the BCL parametrization

$|V_{ub}|^{-2}\int d\Gamma/dq^2\ B_s \to K\mu\nu$



arXiv:1406.2279
arXiv:1501.05373
arXiv:1901.02561

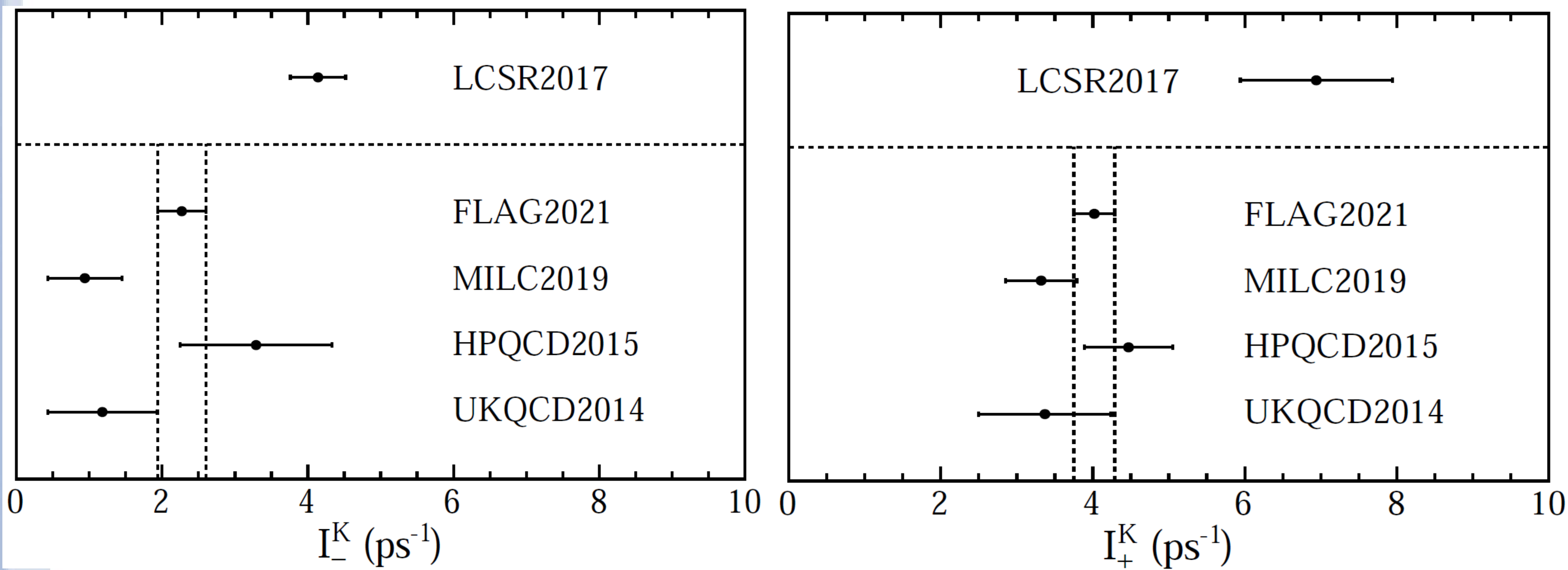


$$I_-^K = |V_{ub}|^{-2}\int_{q^2_{min}}^{7}\frac{d\Gamma_K}{dq^2} \qquad I_+^K = |V_{ub}|^{-2}\int_{7}^{q^2_{max}}\frac{d\Gamma_K}{dq^2}$$

« FLAG2021 » : $q^2_{min}=m^2_\mu \quad q^2_{max}=(m_{B_s}-m_K)^2$

http://flag.unibe.ch/2019/Media?action=AttachFile&do=get&target=FLAG_HQB.pdf

Integral comparisons

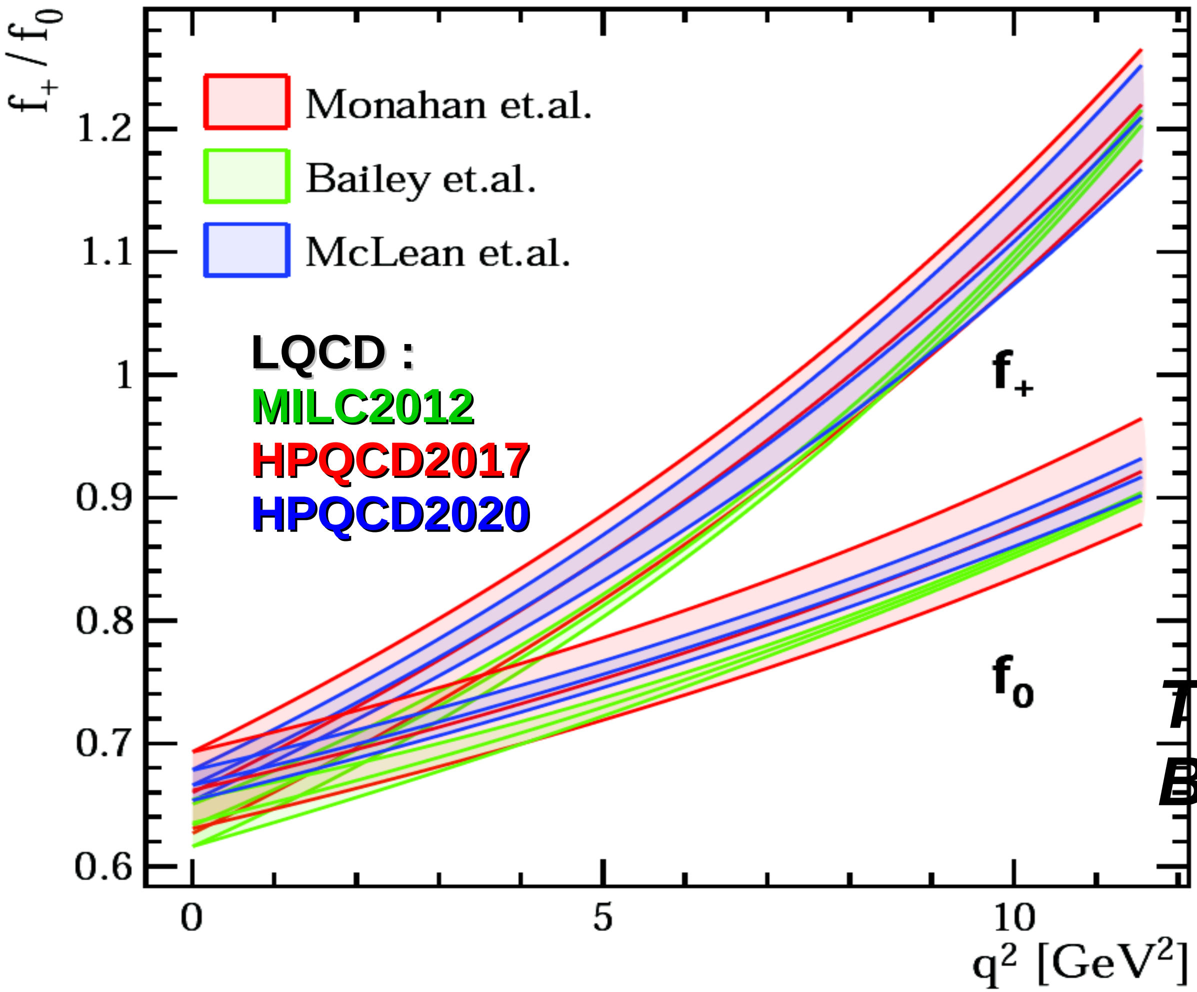


Two remarks :

- LCSR integrals systematically above LQCD

- To which extent the FLAG2021 uncertainty is reliable at low q^2 ?

FF calculations Bs → $D_s\mu\nu$



arXiv:1202.6346
arXiv:1703.09728
arXiv:1906.00701

Chose McLean et al.
Now published at :

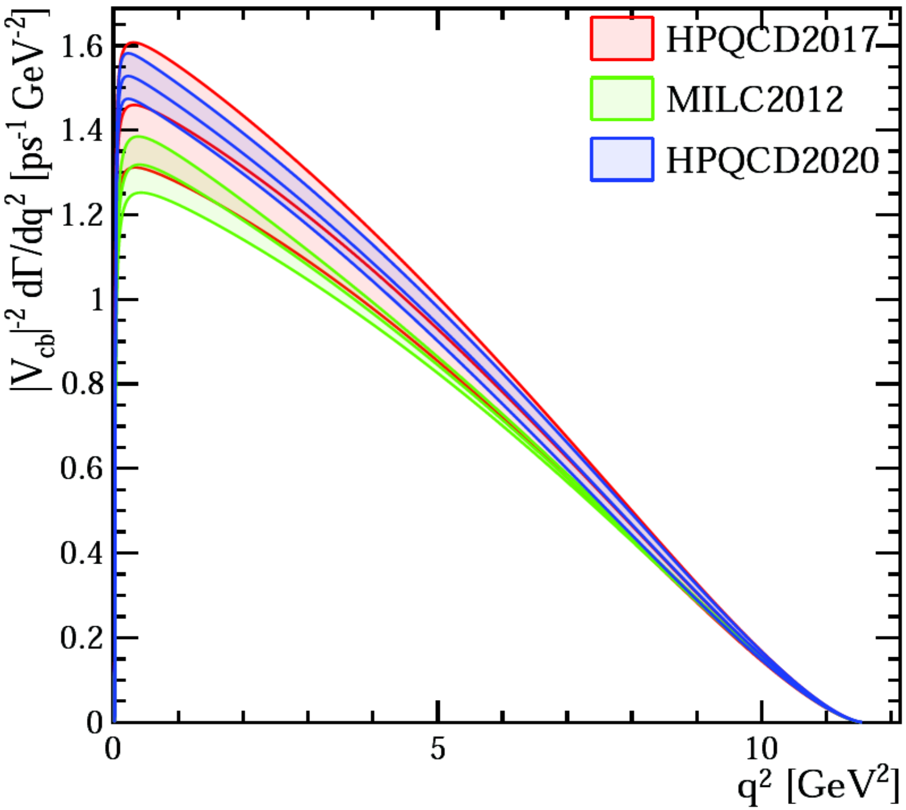
Phys. Rev. D 101, 074513 (2020)

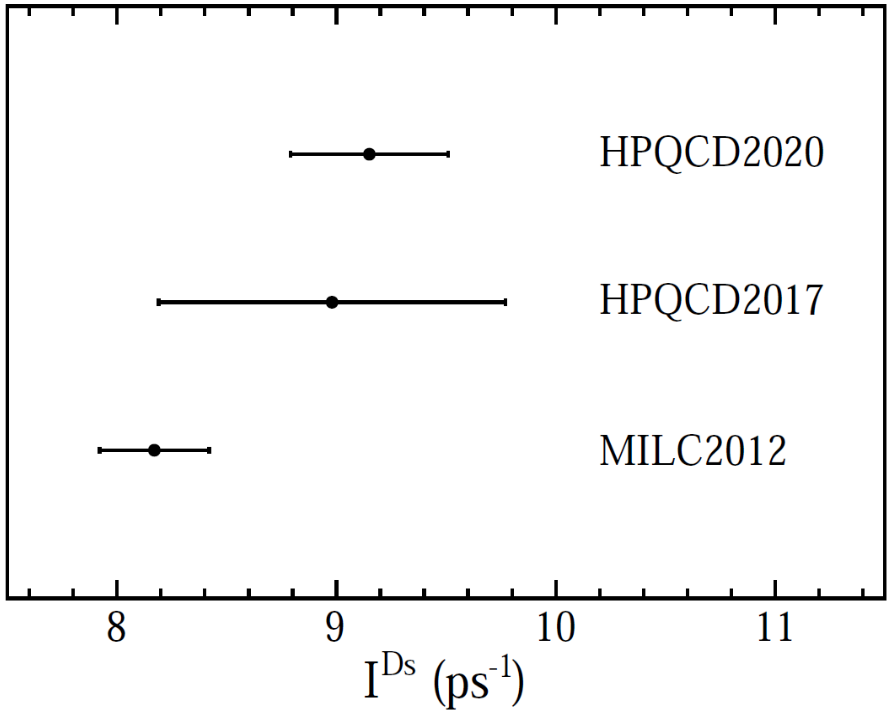
The choice was done BEFORE unblinding

(No LCSR available)

Error bands : produced as the standard deviation of toys using the correlation matrices of the coefficients of the BCL parametrization

$|V_{cb}|^{-2} \int d\Gamma/dq^2 \; B_s \to D_s \mu\nu$





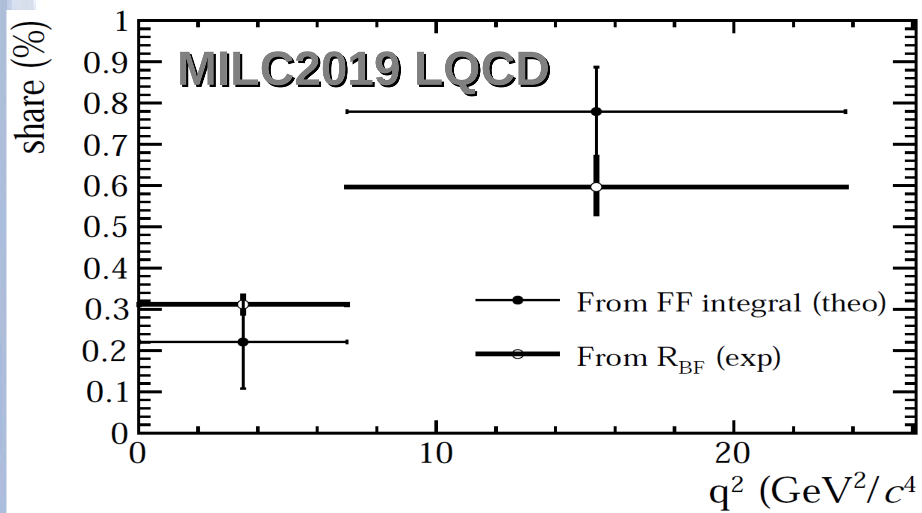
HPQCD2020 used HISQ method

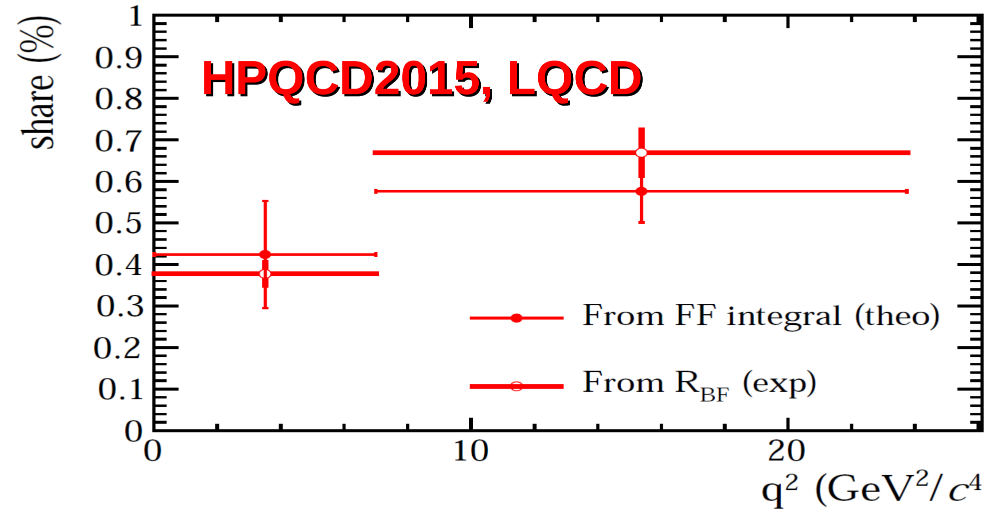
$$I^{D_s} = |V_{cb}|^{-2} \int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma_{D_s}}{dq^2}$$

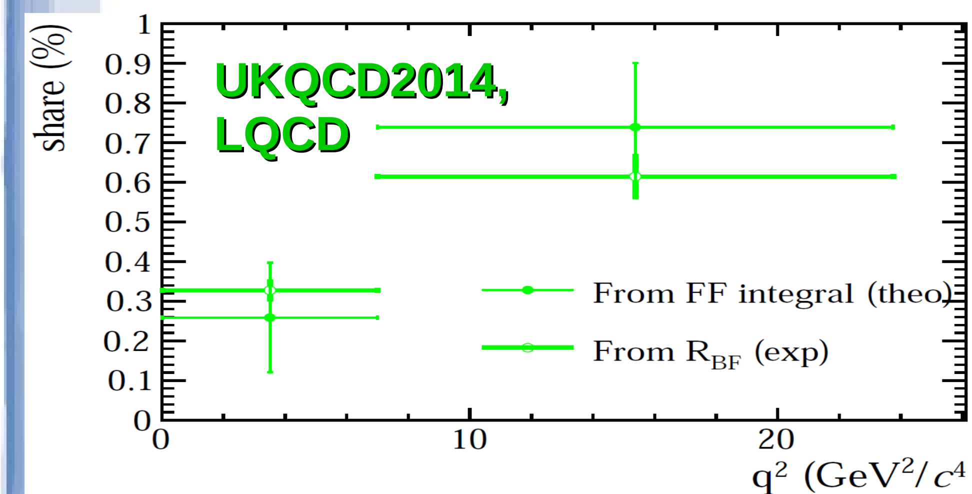
$$q^2_{min} = m^2_{\mu} \qquad q^2_{max} = (m_{B_s} - m_{D_s})^2$$

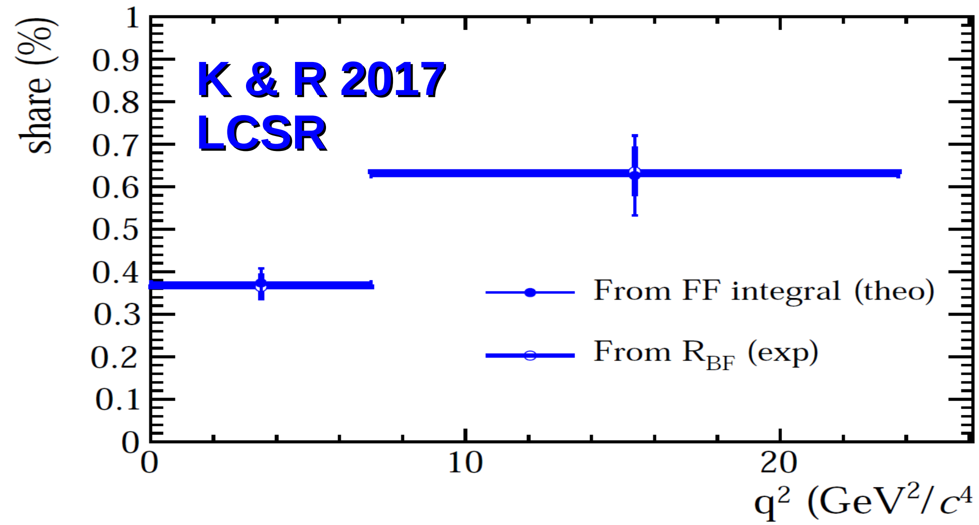
« Shares » in the BF

Both $|V_{ub}|^{-2} \int d\Gamma/dq^2$ and R_{BF} are integrals defined up to a constant. Can we already discriminate between models based on their share in each q^2 bin? => Plot « shares » normalized to unity









Though one might be inclined to discriminate, the uncertainties do not allow to say anything conclusive.

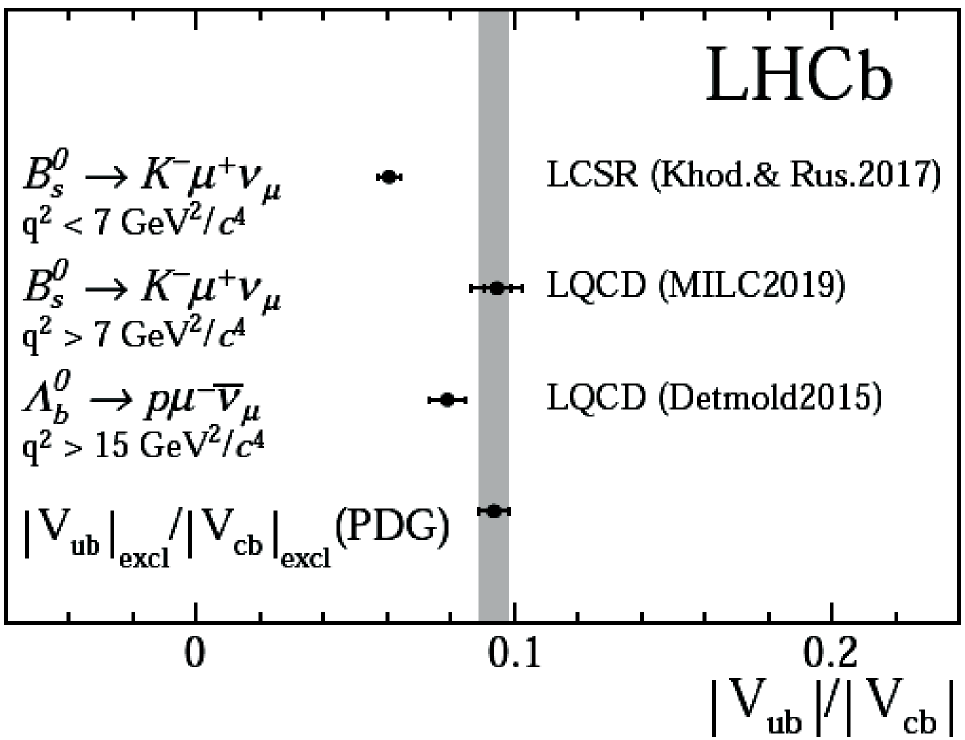
Extracting $|V_{ub}|/|V_{cb}|$

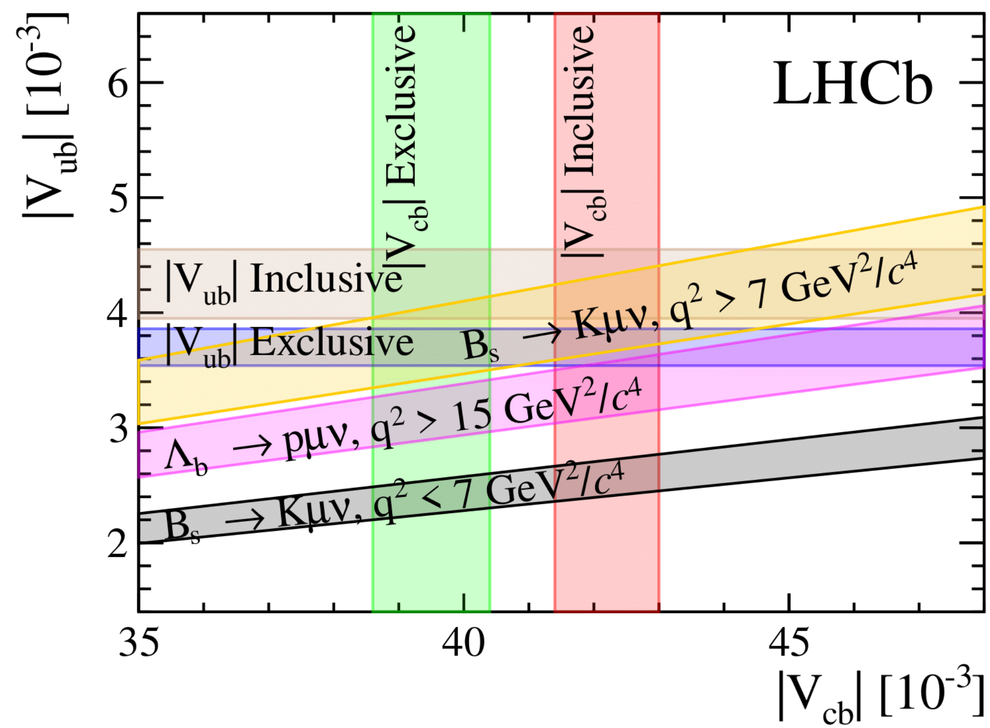
$$\frac{|V_{ub}|}{|V_{cb}|} = \sqrt{R_{BF}^{-(+)} \times \frac{I^{D_s}}{I^{K}_{-(+)}}}$$

Result on $|V_{ub}|/|V_{cb}|$ from $B_s \rightarrow K\mu\nu$

$$|V_{ub}|/|V_{cb}|(\text{low}) = 0.0607 \pm 0.0015\,(\text{stat}) \pm 0.0013\,(\text{syst}) \pm 0.0008\ (D_s) \pm 0.0030\ (\text{FF})$$

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





Hiqh q^2 seems compatible with previous results

Low q^2 departs : problem with LCSR calculation (error budget ? Normalization with LCSR $D_s\mu\nu$ needed?)

Will contribute to the global fit in the ($|V_{cb}|$,$|V_{ub}|$) plane

More FF studies are expected, specially at low q^2

Conclusion/questions

- $\Lambda_b \to p\,\mu\,\nu$ / $B_s \to K\,\mu\,\nu$ and $|V_{ub}|/|V_{cb}|$
  - The unexpected extraction of such a topology will open many doors : the proof of principle is established
  - In the future : multi q^2 bins analysis for more precise extraction ($|V_{ub}|/|V_{cb}|$ and FF parameters)
- Questions : - choice of q^2 binning for future analysis ?
  - HQET/SR for $B_s \to D_s$?
  - Extrapolation from high q^2 : control of error estimate ?
  - FLAG averaging : low q^2 error reduced, can it be taken as « solid » ?
  - Ratio of FF $B_s \to K\,\mu\,\nu$ /$B_s \to D_s\,\mu\,\nu$: correlated ratios have better uncertainties but we would need correlated ratio of the integrals

$$I^X = |V_{xb}|^{-2} \int_{q_i^2}^{q_{i+1}^2} \frac{d\Gamma_X}{dq^2}$$

Backup

Also : CKM « sum to unity »

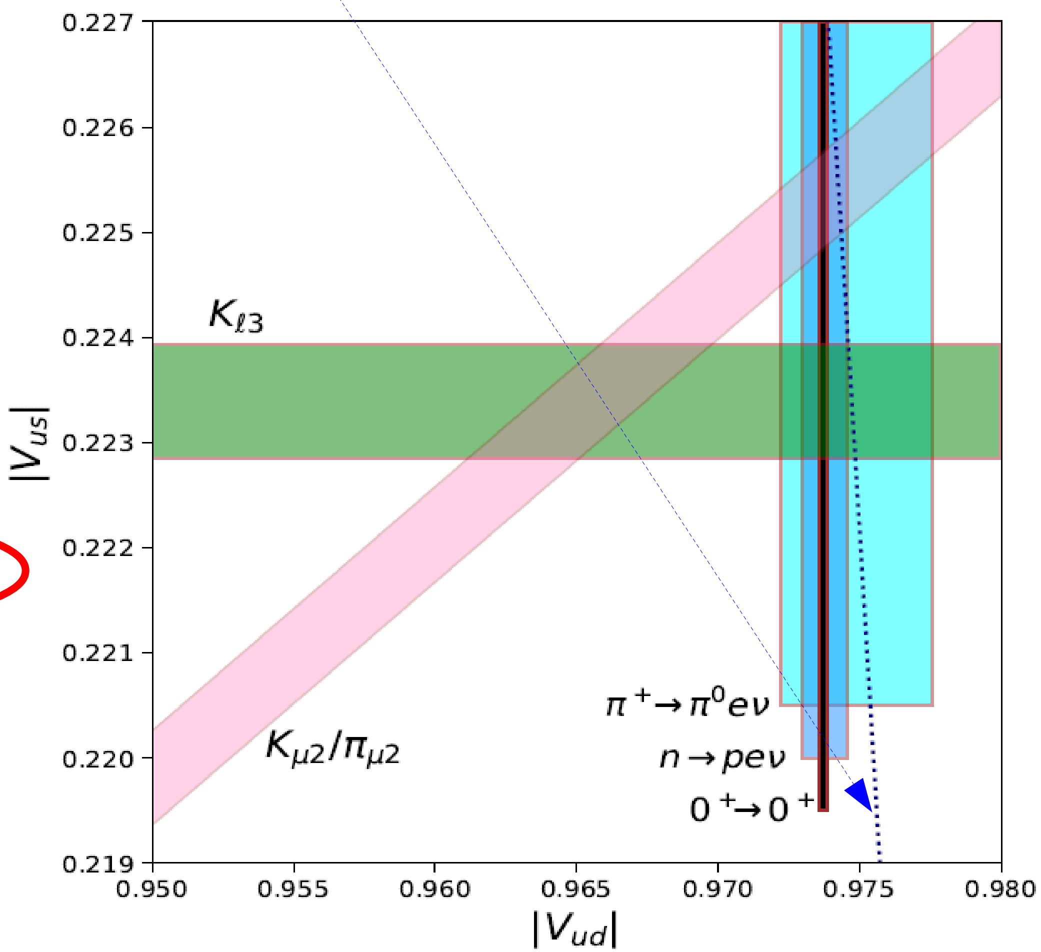
$$\sum |V_{ik}|^2 = 1$$

e.g. $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

The $|V_{us}|$ - $|V_{ud}|$ puzzle !

See M.Wingate arXiv:2103.17224

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

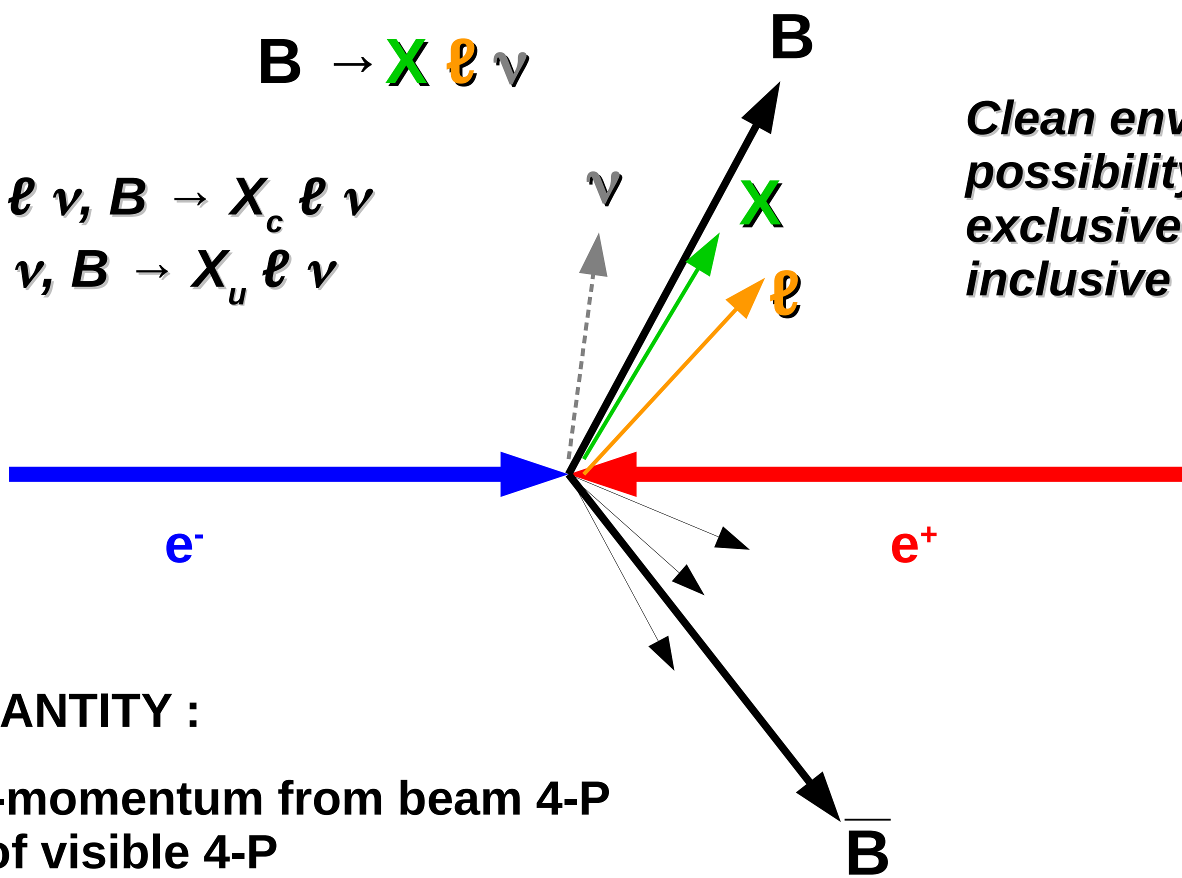


Measurement at B factories

$B \rightarrow X \, \ell \, \nu$

$|V_{cb}|$: $B \rightarrow D^{(*)} \ell \nu$, $B \rightarrow X_c \ell \nu$

$|V_{ub}|$: $B \rightarrow \pi \ell \nu$, $B \rightarrow X_u \ell \nu$



Clean environment, possibility to do exclusive and inclusive studies

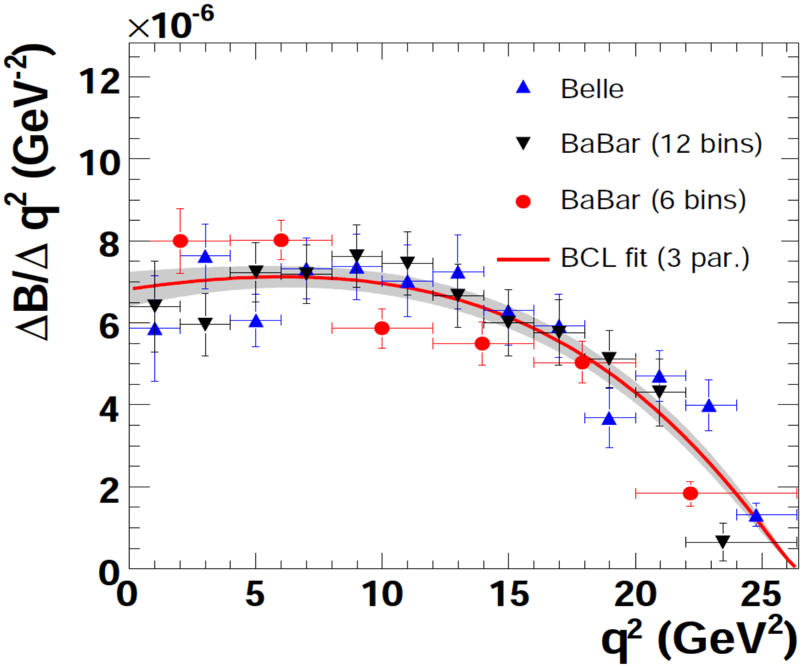
KEY QUANTITY :

Missing 4-momentum from beam 4-P and sum of visible 4-P

$$\tilde{p}_{miss} = \tilde{p}_{beam} - \sum_i \tilde{p}_i \qquad q^2 = \left(\tilde{p}_{miss} + \tilde{p}_\ell\right)^2$$

Measurements from B factories

Example of
$B^0 \rightarrow \pi^- \ell^+ \nu$



See e.g.,

Eur. Phys. J. C74 (2014) 3026

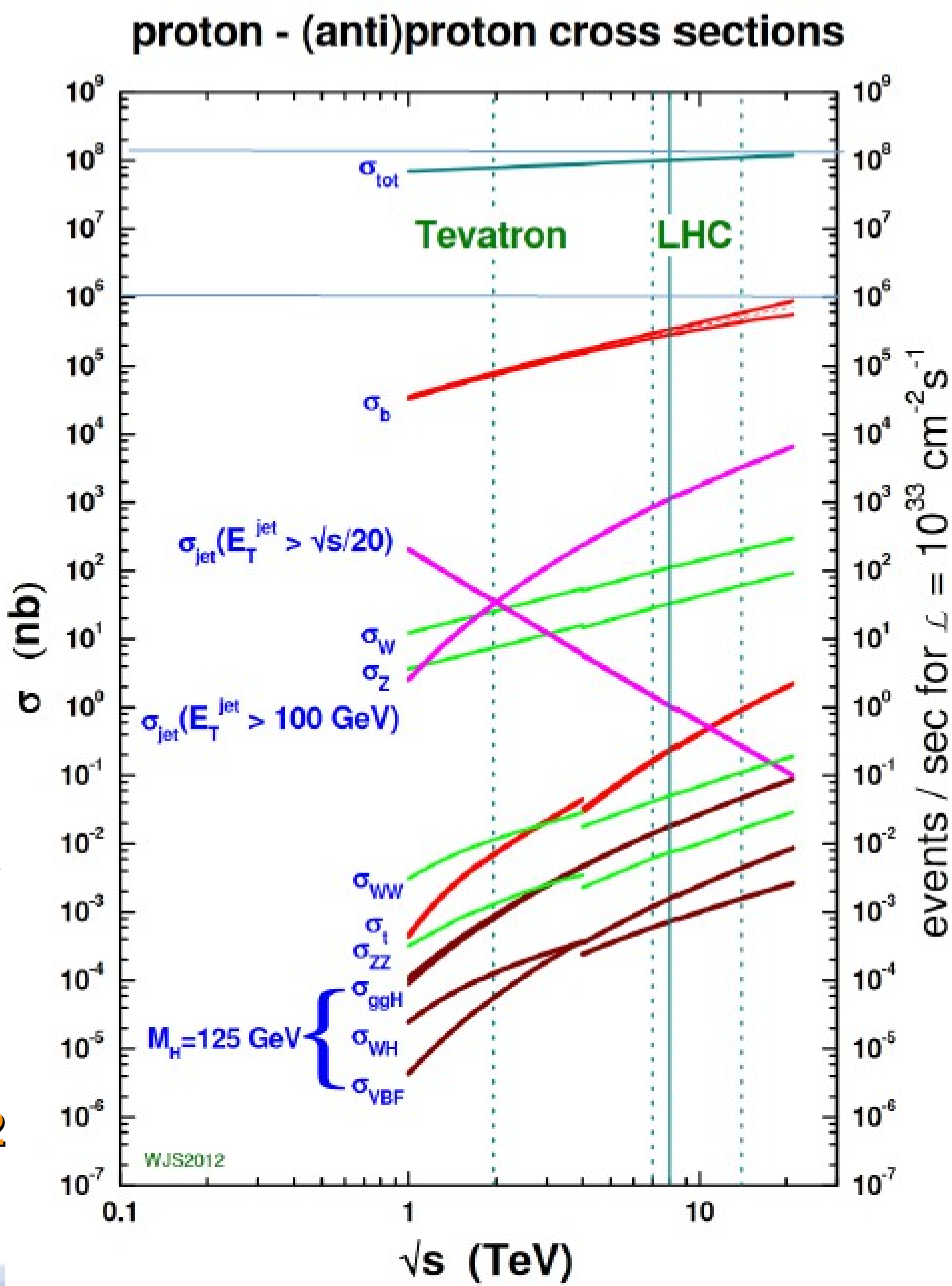
Experiment	$\lvert V_{ub}\rvert$ (10^{-3})			
BABAR (6 bins)	$3.54 \pm 0.12^{+0.38}_{-0.33}$	$3.22 \pm 0.15^{+0.55}_{-0.37}$	$3.08 \pm 0.14^{+0.34}_{-0.28}$	2.98 ± 0.31
BABAR (12 bins)	$3.46 \pm 0.10^{+0.37}_{-0.32}$	$3.26 \pm 0.19^{+0.56}_{-0.37}$	$3.12 \pm 0.18^{+0.35}_{-0.29}$	3.22 ± 0.31
Belle	$3.44 \pm 0.10^{+0.37}_{-0.32}$	$3.60 \pm 0.13^{+0.61}_{-0.41}$	$3.44 \pm 0.13^{+0.38}_{-0.32}$	3.52 ± 0.34
BABAR +Belle	$3.47 \pm 0.06^{+0.37}_{-0.32}$	$3.43 \pm 0.09^{+0.59}_{-0.39}$	$3.27 \pm 0.09^{+0.36}_{-0.30}$	3.23 ± 0.30
Tagged	$3.10 \pm 0.16^{+0.33}_{-0.29}$	$3.47 \pm 0.23^{+0.60}_{-0.39}$	$3.32 \pm 0.22^{+0.37}_{-0.31}$	3.33 ± 0.39
	LCSR	HPQCD	FNAL/MILC	FNAL/MILC fit

LHC pp collisions and $b\bar{b}$

$\sigma(b\bar{b})$ ranging from 200 μb (at 7-8 TeV) to 500 μb (at 13-14 TeV) in the full solid angle, this is 2×10^5 to 5×10^5 times the value of the cross section at the B factories !

For a standard luminosity at the LHCb point, ~ 10^5 $b\bar{b}$ events per second !

LHC is a mega b factory ! But with a noisy environment for the b analyses….
This same environment provides the advantage of a per event primary vertex !



One has to account for the b fragmentation*

$f_u = f(b \to B^+) = 0.3 - 0.4$

$f_d = f(b \to B^0) = 0.3 - 0.4$

$f_s = f(b \to B_s^0) / (f_u+f_d) = 0.134 \pm 0.009$

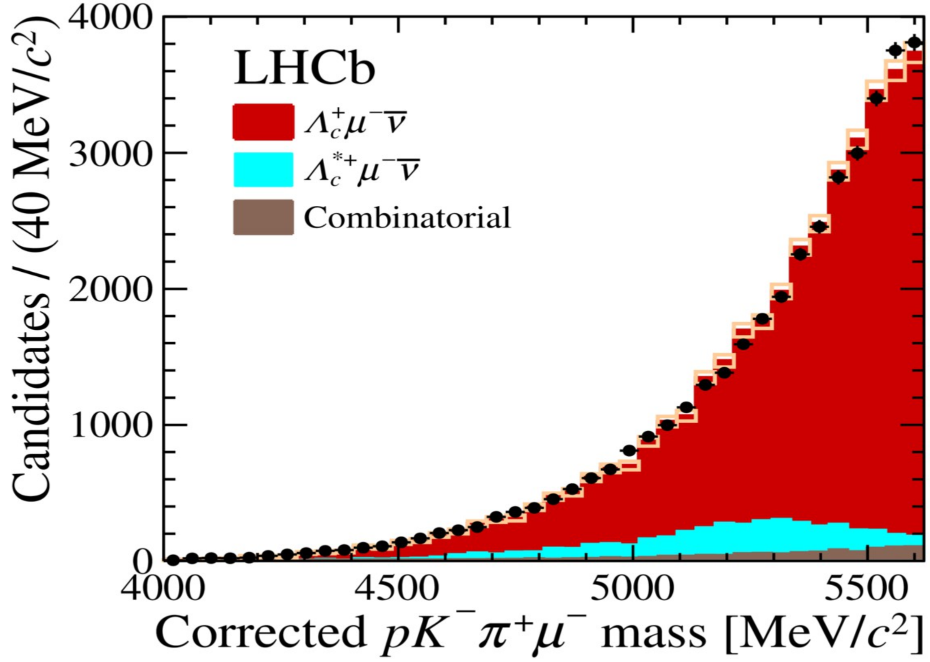
$f_{baryon} = f(b \to \Lambda_b, \Xi_b, \Omega_b)/(f_u+f_d) = 0.240 \pm 0.022$

$f_c = \sigma(B_c) = ?$

(*) Eur. Phys. J. C77 (2017) 895

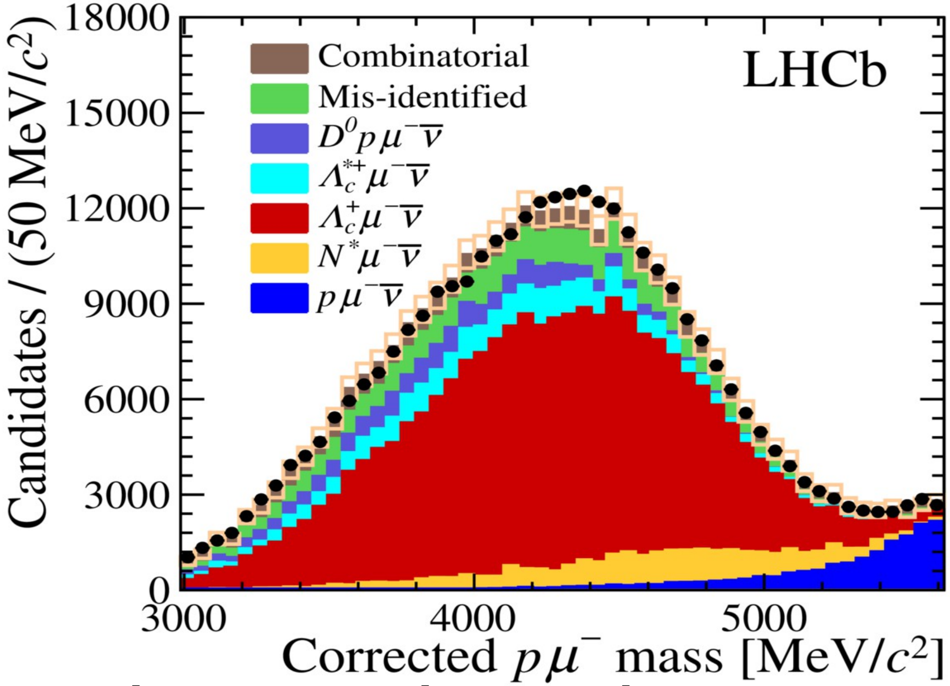
$\Lambda_b \to p \mu \nu$

$\Lambda_b \to \Lambda_c(\to pK\pi) \mu \nu$



$N(\Lambda_b \to \Lambda_c(\to pK\pi) \mu \nu) = 34.2$ k

$\Lambda_b \to p \mu \nu$



$N(\Lambda_b \to p \mu \nu) = 17.7$ k

$q^2 > 15$ GeV^2/c^4 cut to minimize uncertainty from LQCD FF

$|V_{ub}| / |V_{cb}| = 0.083 +/- 0.004$ (exp) $+/- 0.004$ (FF)
Central value updated to 0.079 after new $\Lambda_c \to pK\pi$ BF

$\Lambda_b \rightarrow p\ \mu\ \nu$ systematics

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	$^{+7.8}_{-8.2}$

MisID component(s) estimate

From FakeK (hμ) and FakeMu (Kh) selections

Define μ,π,p,K enriched regions using ID cuts on h

Yields in regions : $N_{\hat{i}}$

Obtain actual misID yields from **Bayes Unfolding**

$$N_{\hat{i}} = \sum_j P(\hat{i}|j) \times N_j$$

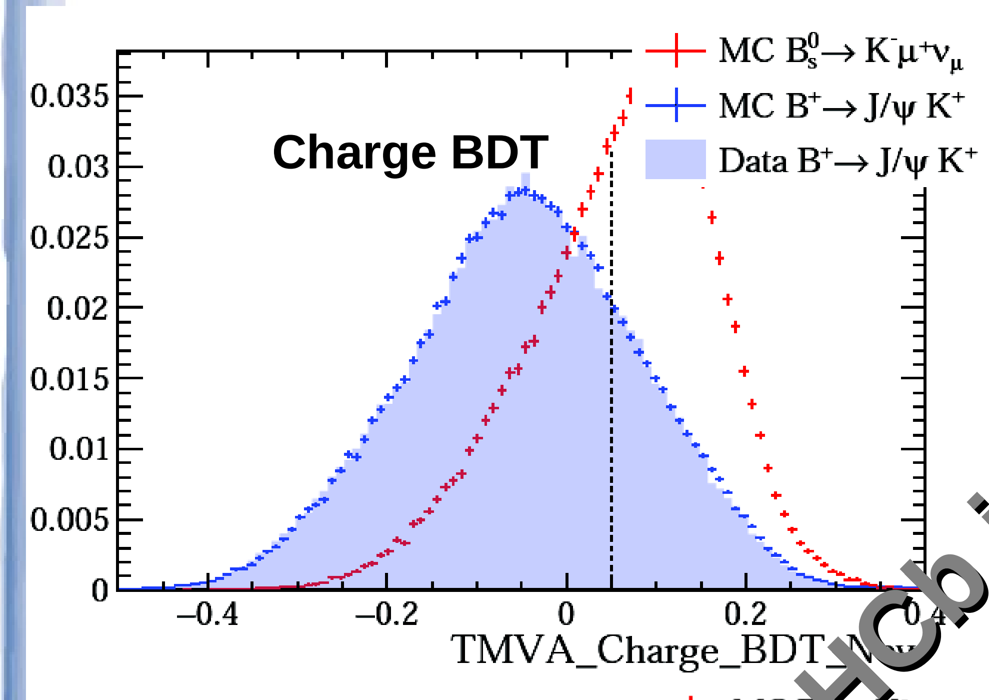
$P(\hat{i}|j)$ obtained from PID calibration samples

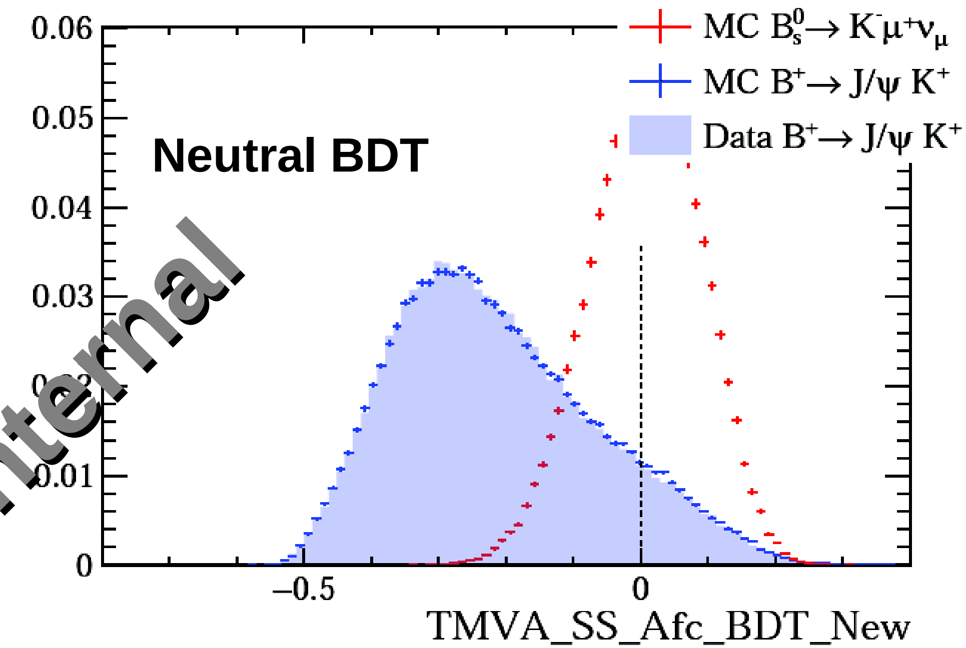
Perform the operation across the Mcorr bins to obtain the MisID yields as a function of Mcorr :

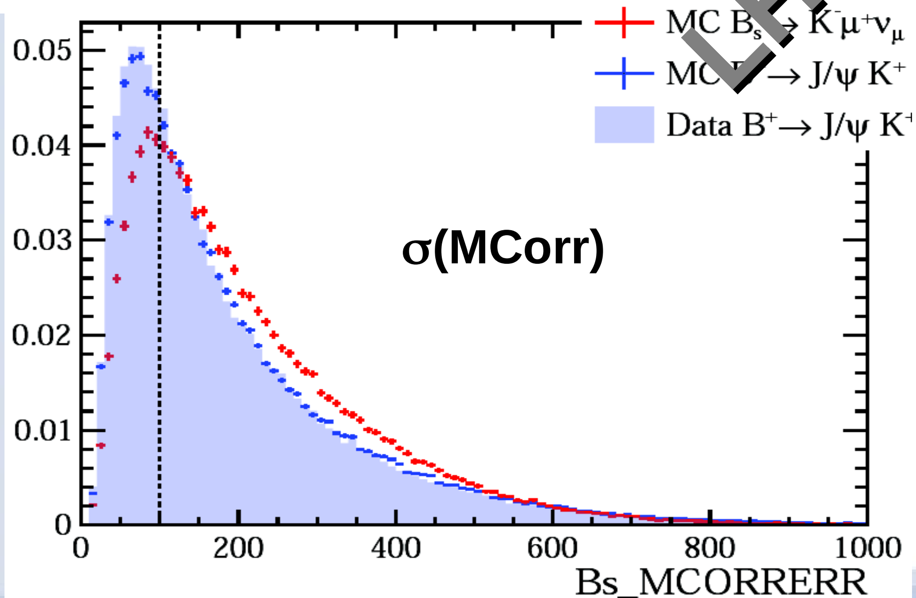
$$Y_i(\zeta) = N_i \times \frac{P(\hat{\zeta}|i)}{P(\hat{i}|i)} \quad N(\zeta) = \sum_i Y_i(\zeta) \quad \zeta = K, \mu$$

This data-driven method enables to infer both the shape and the normalization of the MisID background

Calibration : use of $B^+ \rightarrow J/\Psi(\mu\mu) K^+$







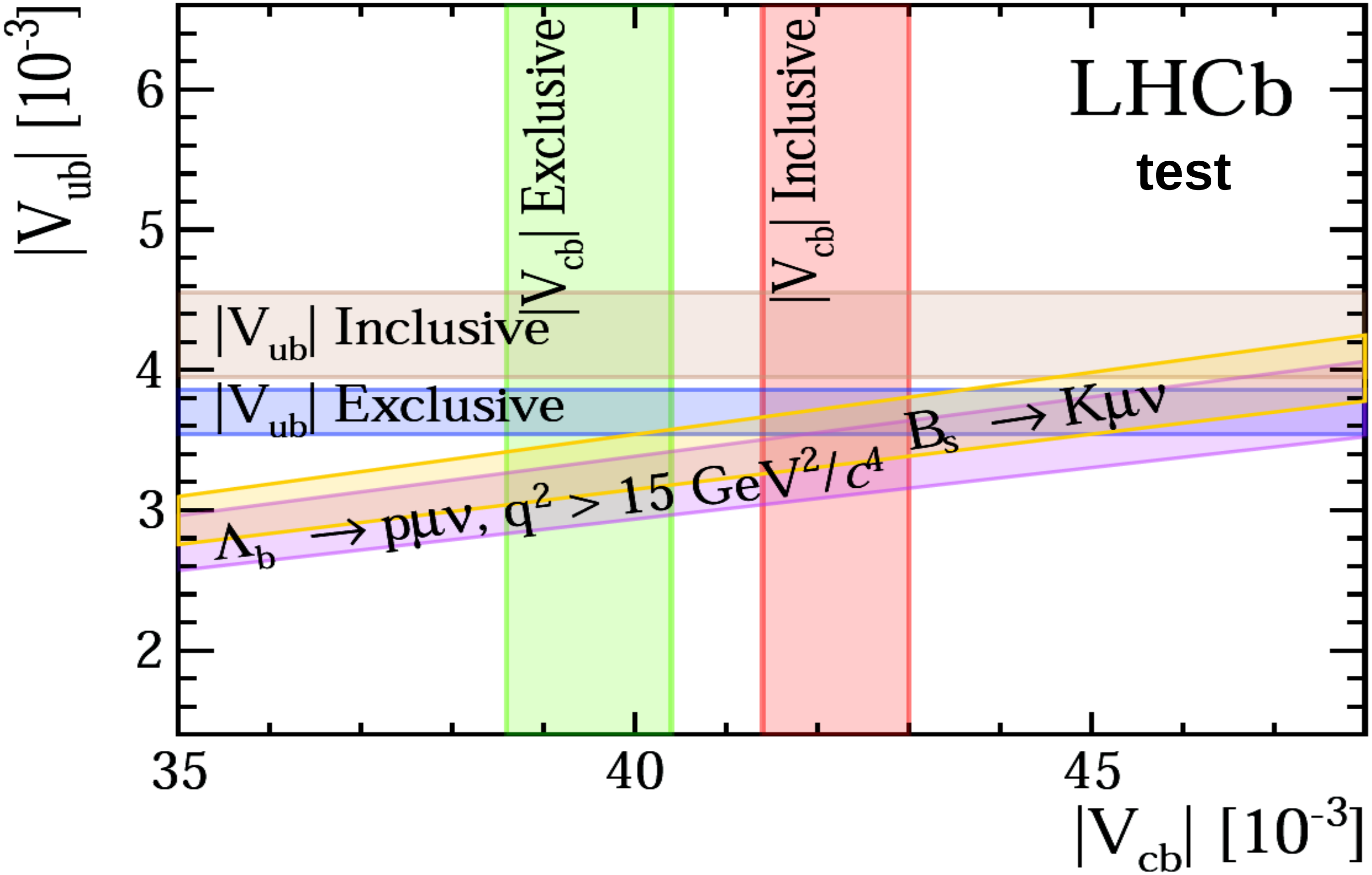
$B \rightarrow J/\Psi K$ used for Data/MC corrections, reconstructed as $K\mu$ or fully

After kinematic reweighing, Data/MC shapes agree well

$K^-\mu^+\mu^-$ decays where μ^- is not detected (out of acceptance) are recovered using « neutrino » method : yield of charmonium background constrained

$|V_{ub}|/|V_{cb}|$ from $B_s \to K \mu \nu$ with FLAG2021 FF

Naive simplified averaging of yields and efficiencies



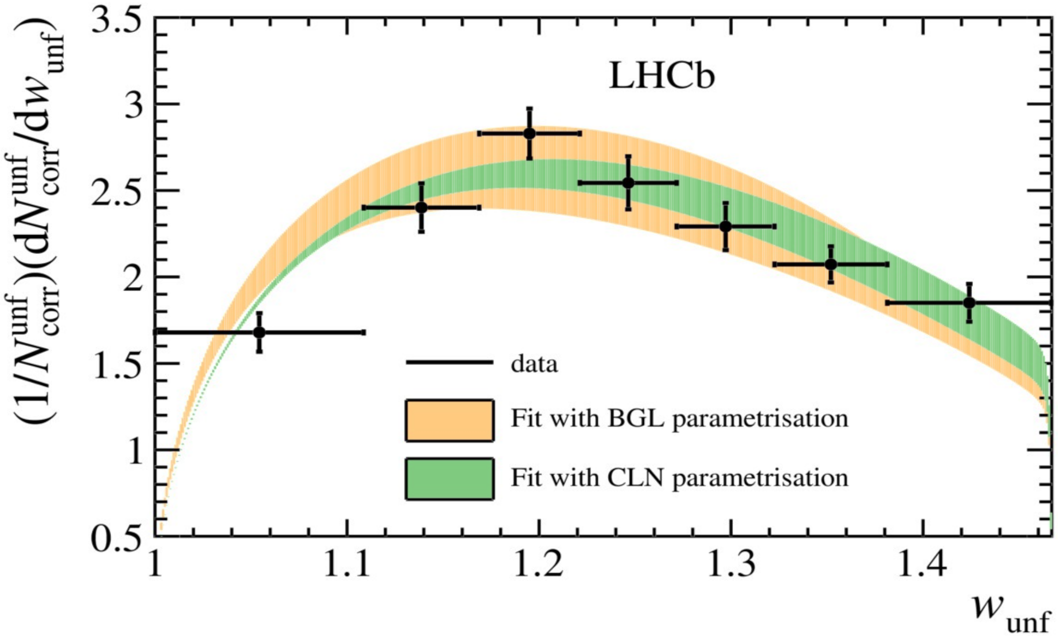
$B_s \rightarrow D_s^{(*)}$ SL

$|V_{cb}|$ from $B_s \rightarrow D_s^{(*)} \mu\ \nu$

$$|V_{cb}|(CLN)=(41.4\pm 0.6(stat)\pm 1.2(ext))\times 10^{-3}$$

$$|V_{cb}|(BGL)=(42.3\pm 0.8(stat)\pm 1.2(ext))\times 10^{-3}$$

Phys. Rev. D101 (2020) 072004



$$\frac{1}{\Gamma}\frac{d\Gamma}{dw}(B_s \rightarrow D_s^* \mu \nu)$$

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$$w=\frac{m_B^2+m_{D^*}^2-q^2}{2\mathrm{m}_B m_{D^*}}$$