Measuring suppressed semileptonic decays at LHCb: testing the CKM picture at tree level

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Warwick seminar

Outline

- The basic ingredients
  - SU(2)xU(1) in the quark sector and the CKM matrix
  - Unitarity triangle
- Low energy hamiltonians for hadron decays
- Why are SL decays convenient?
  - The role of semileptonic decays in Standard Model testing (and New Physics probing)
- Note:
  - Will not discuss LFUV studies with SL
  - Focus on Cabibbo suppressed SL decays, in particular recent LHCb work

Mass vs Weak eigenstates: CKM matrix

From spontaneous symmetry breaking :

Mass matrices for the quarks : *m = v.G (v = Higgs vev, G EW constants)*

$$\mathscr{L}_{mass} = -\sum_{i,j}^{3} [\tilde{m}_{ij} \overline{U}_{Ri} U_{Lj} + m_{ij} \overline{D}_{Ri} D_{Lj} + h.c.]$$

Diagonalization of the mass matrices to obtain the mass eigenstates, consequence for the charge current kinetic term :

$$\mathscr{L}_{CC} = -[\overline{U}_L \gamma^\mu V D_L W_\mu^+ + \overline{D}_L \gamma^\mu V^\dagger U_L W_\mu^-]$$

$V = P^\dagger_{U_L} P_{D_L}$ **is the famous Cabibbo-Kobayashi-Maskawa (CKM) matrix**

Built with the U and D quarks basis change matrices P (change from weak eigenstates to mass eigenstates)

Discrete symmetries and impact on the CC Lagrangian

Charge conjugation

$$\mathcal{C}\psi(\tilde{x})\mathcal{C}^{-1} = C\bar{\psi}(\tilde{x})^T \quad \mathcal{C}\bar{\psi}(\tilde{x})\mathcal{C}^{-1} = \psi(\tilde{x})^T C \qquad C = i\gamma^2\gamma^0$$

Parity $\tilde{x} = (t, \vec{x}) \rightarrow \tilde{x}_P = (t, -\vec{x})$

$$\mathcal{P}\psi(\tilde{x})\mathcal{P}^{-1} = \gamma^0\psi(\tilde{x}_P) \quad \mathcal{P}\bar{\psi}(\tilde{x})\mathcal{P}^{-1} = \psi(\tilde{x}_P)^\dagger$$

Time inversion $\tilde{x}_T = (-t, \vec{x})$ $\quad \mathcal{T}\psi(\tilde{x})\mathcal{T}^{-1} = i\gamma^1\gamma^3\psi(\tilde{x}_T)$

Charge conjugation + parity = CP (matter to antimatter)

$$\mathcal{CP}\psi(\tilde{x})(\mathcal{CP})^{-1} = C\psi^*(\tilde{x}_P) = C\gamma^0\bar{\psi}^T(\tilde{x}_P)$$

$$\mathcal{CP}W^{\pm\mu}(\tilde{x})(\mathcal{CP})^{-1} = -W^{\mp}_{\mu}(\tilde{x}_P)$$

$$J^{\mu-} = \overline{U}_L\gamma^\mu V D_L \rightarrow -\overline{D}_L\gamma_\mu V^T U_L$$

$$J^{\mu+} = \overline{D}_L\gamma^\mu V^\dagger U_L \rightarrow -\overline{U}_L\gamma_\mu V^* D_L$$

$$\int d^4x\mathcal{L}_{CC} \stackrel{CP}{\rightarrow} \int d^4x - [\overline{D}_L\gamma^\mu V^T U_L W^-_\mu + \overline{U}_L\gamma^\mu V^* D_L W^+_\mu]$$

Important point on V matrix

$$\mathcal{L}_{CC} = -(\overline{U}_L \gamma^\mu V D_L W_\mu^+ + \overline{D}_L \gamma^\mu V^\dagger U_L W_\mu^-)$$

$$\int d^4x \mathcal{L}_{CC} \stackrel{CP}{\rightarrow} \int d^4x - [\overline{D}_L \gamma^\mu V^T U_L W_\mu^- + \overline{U}_L \gamma^\mu V^* D_L W_\mu^+]$$

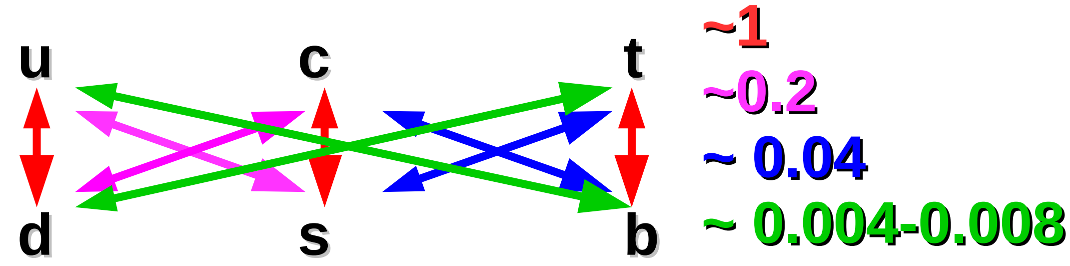
The invariance is ensured if and only if V is real
CP violation means at least one complex phase

V **has N² complex elements**

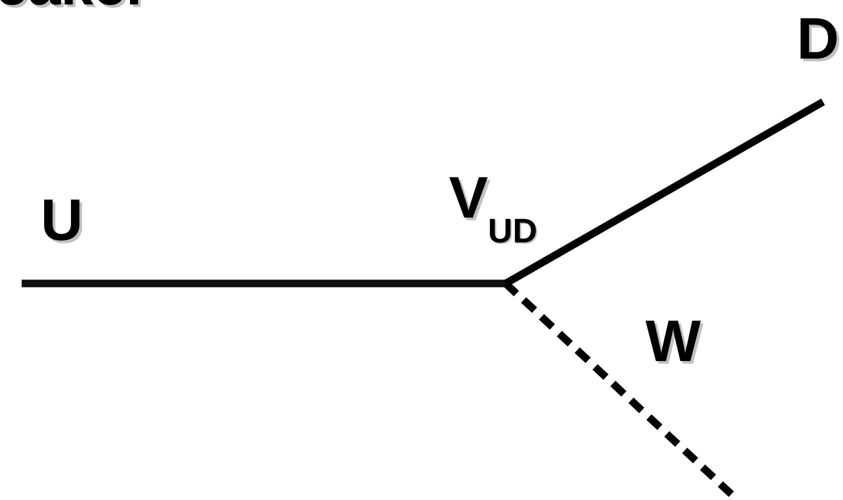
Unitarity $V^\dagger V = 1$ imposes N(N-1)/2 relations for the phases and N(N+1)/2 for the magnitudes
2N-1 phases can be absorbed in the redefinition of the fields
At the end, the number of physical phases is (N-1)(N-2)/2
One needs to have at least N = 3 to have CP violating phases !

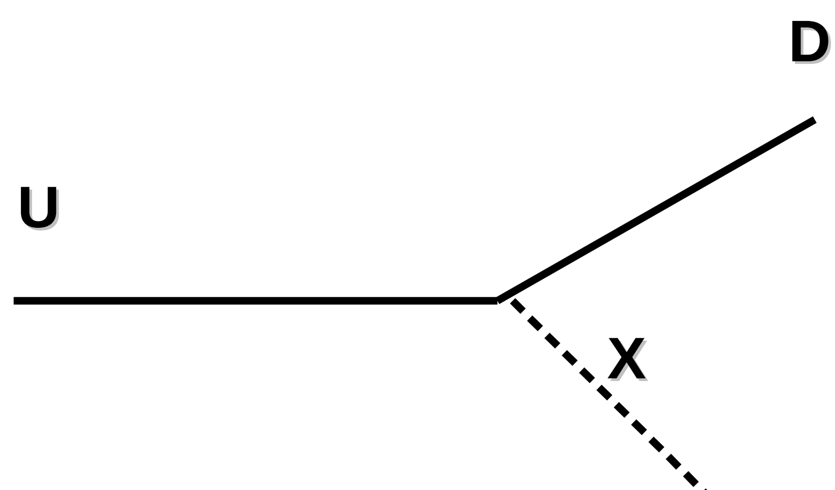
The current CKM picture

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



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





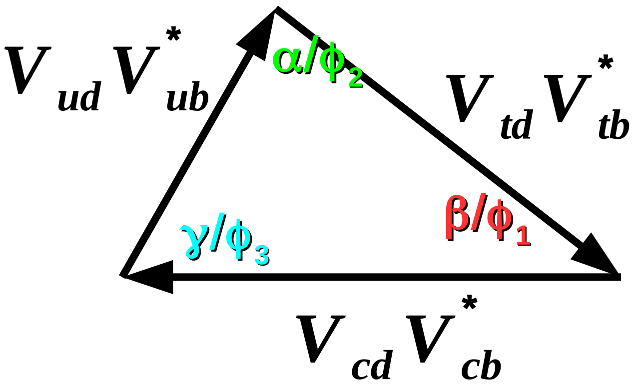
CKM SM picture

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

CKM Unitarity triangle(s)

Unitarity condition implies relations, among which : $\sum_k V_{ik} V^*_{jk} = 0$

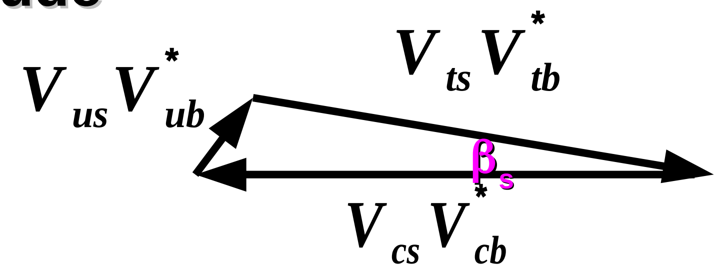
This yields three independent null sums, of which one is particularly interesting :



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

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>

Bottom line

b-hadron decays are the privileged ground for testing the CKM picture

Determine angles and sides of the unitary triangle to test its closure

In principle any b → q transition should give us access to V_{qb}...

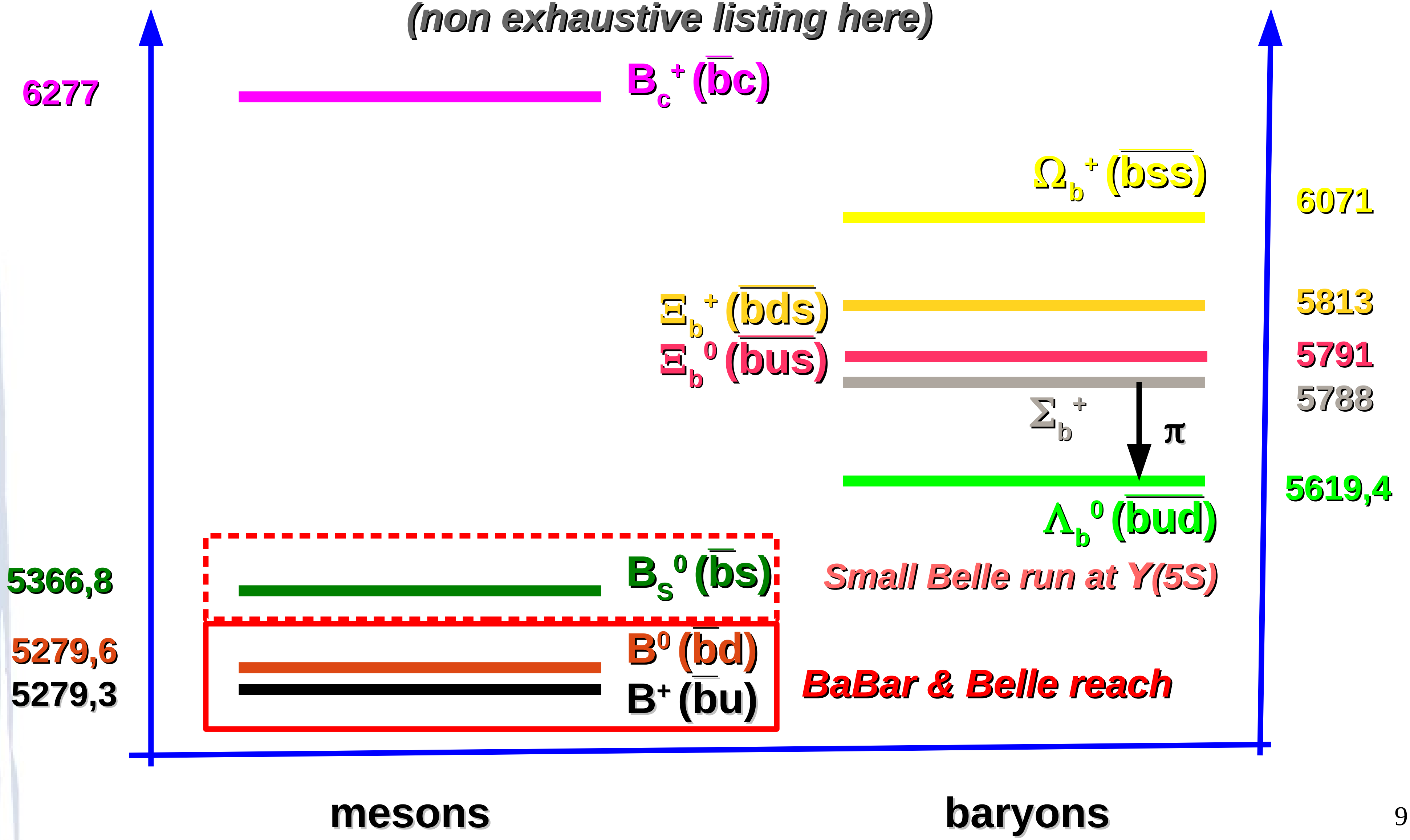
But this is the short range level (EW scale)...

The long range (hadronization) effects make the game more complicated !

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*

- 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

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

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)

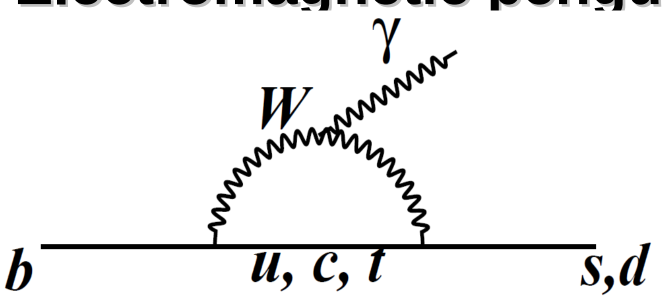
** For a exhaustive review, see : G.Buchalla et al, Rev.Mod.Phys.68 (1996) 1125-1144*
https://arxiv.org/abs/hep-ph/9512380

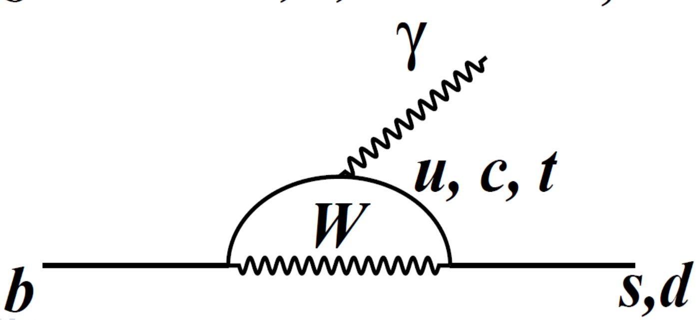
Loop operators and new physics

Loop operators → massive (electroweak) virtual particles : New Physics might intervene. Wilson coefficients affected by NP.

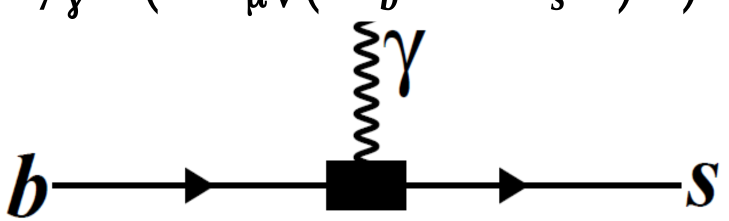
$$C_i(') \rightarrow C_i(')+C_i^{NP}$$

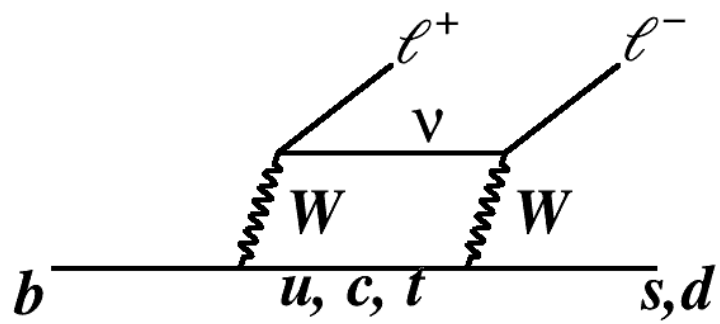
Electromagnetic penguin

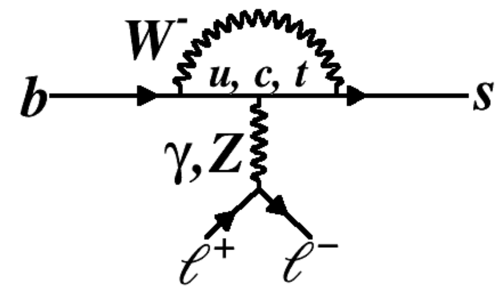




$$O_{7\gamma}=\left(\bar{s}\sigma_{\mu\nu}\left(m_b R+m_s L\right)b\right)F^{\mu\nu}$$

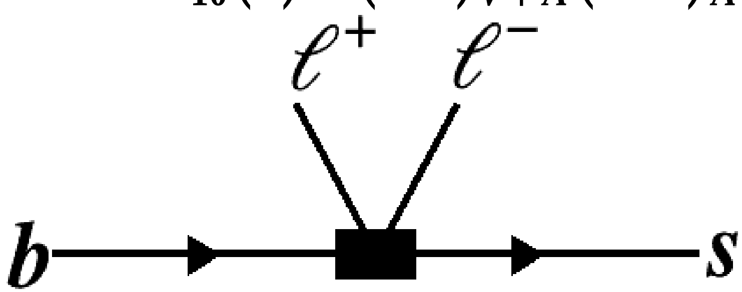






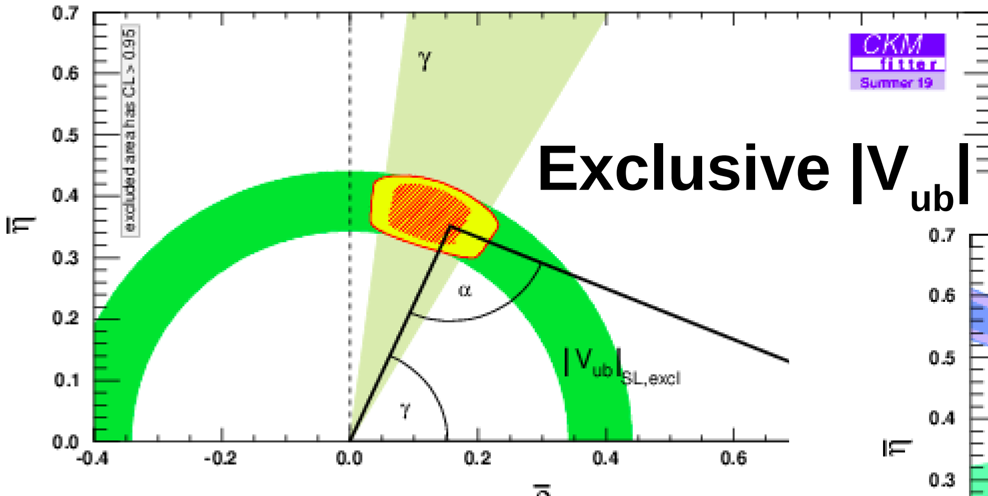
$$O_9(')=\left(\bar{s}b\right)_{V\mp A}\left(\bar{\ell}\ell\right)_V$$

$$O_{10}(')=\left(\bar{s}b\right)_{V\mp A}\left(\bar{\ell}\ell\right)_A$$

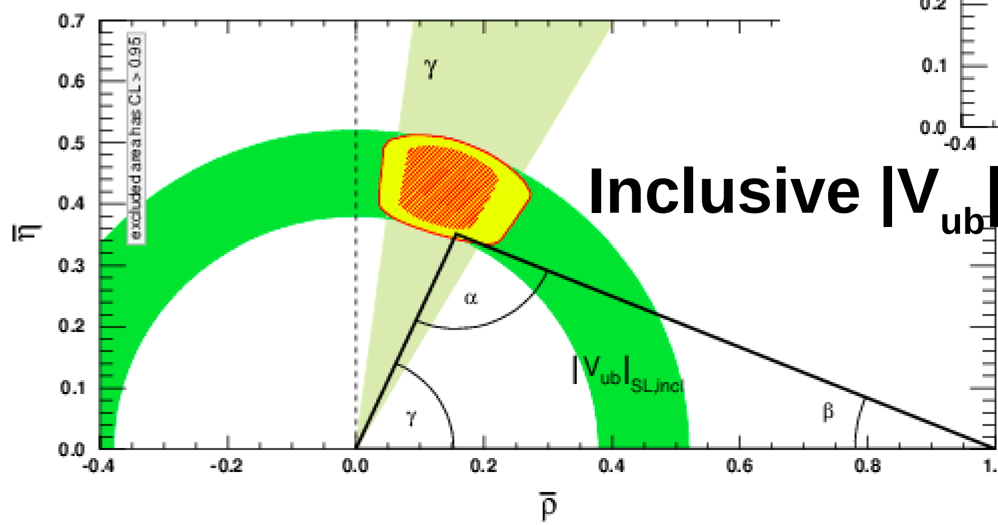


UT contraints from loop vs tree quantities

Tree quantities

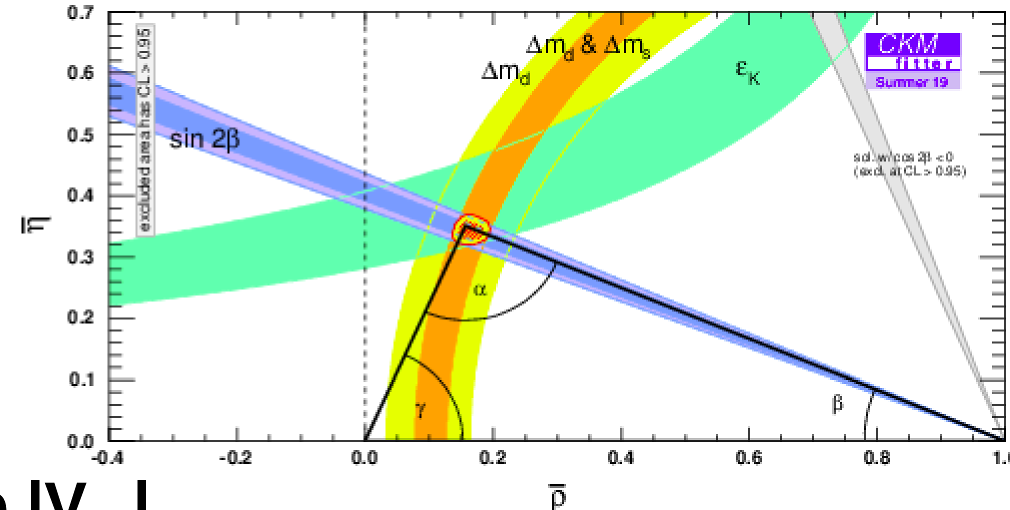


Exclusive $|V_{ub}|$



Inclusive $|V_{ub}|$

Loop quantities



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

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

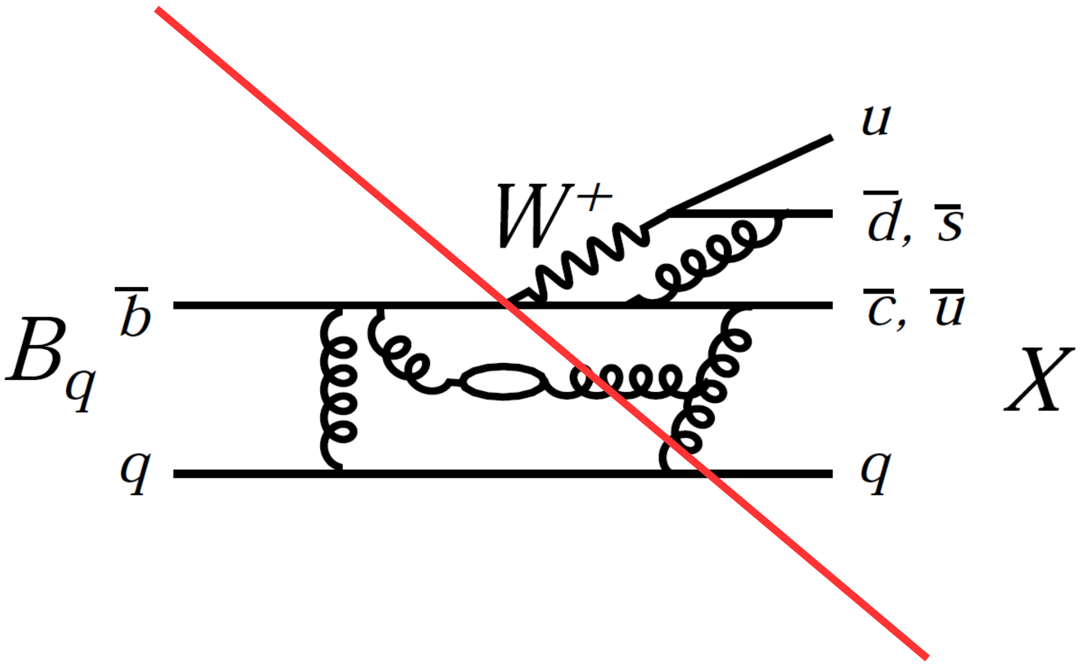
It works exactly or very well for modes where two parts of the decay are well decoupled : (semi)leptonic modes

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 EW scale quantities with hadronic decays ?



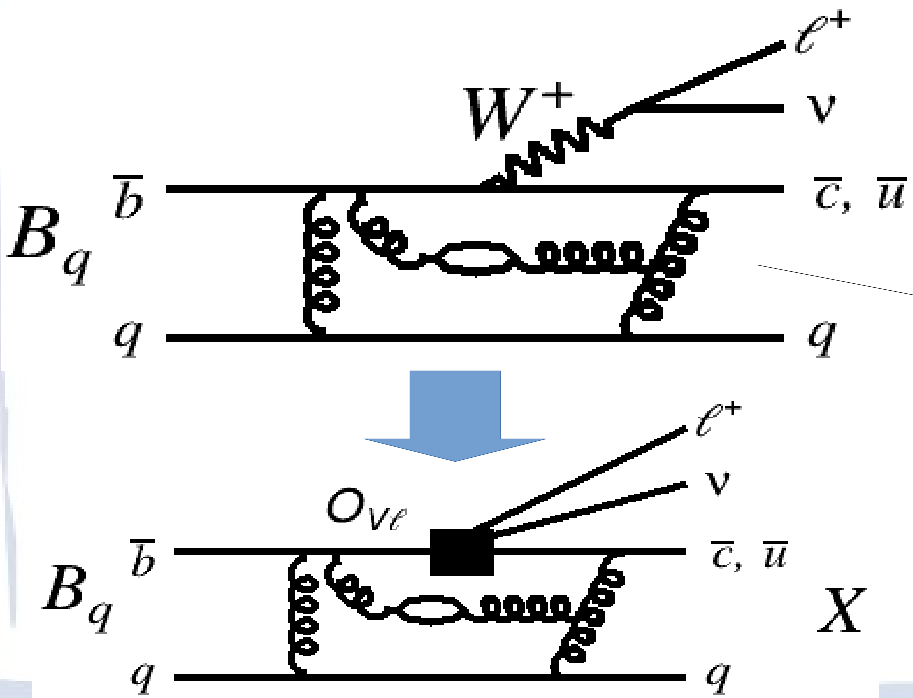
No way with « direct » quantities, or very limited (substantial corrections for non-factorizable effects)

Possible if one uses ratios (asymetries, etc...) : 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

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



Non perturbative methods treat what happens inside the hadrons, accounting bound states effects : Notion of <u>Form Factor</u>

Form Factors and rates

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

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

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

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 $\ell = e,\mu$), f_+ « pilots » the decay rate

Form Factors parametrization and calculation

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

$$t_+ = \left(m_B + m_X\right)^2$$

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

Ex of BCL* parametrization

$$t_0 = \left(m_B + m_X\right)\left(\sqrt{m_B} - \sqrt{m_X}\right)^2$$

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

Calculations are done 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

Inclusive measurements

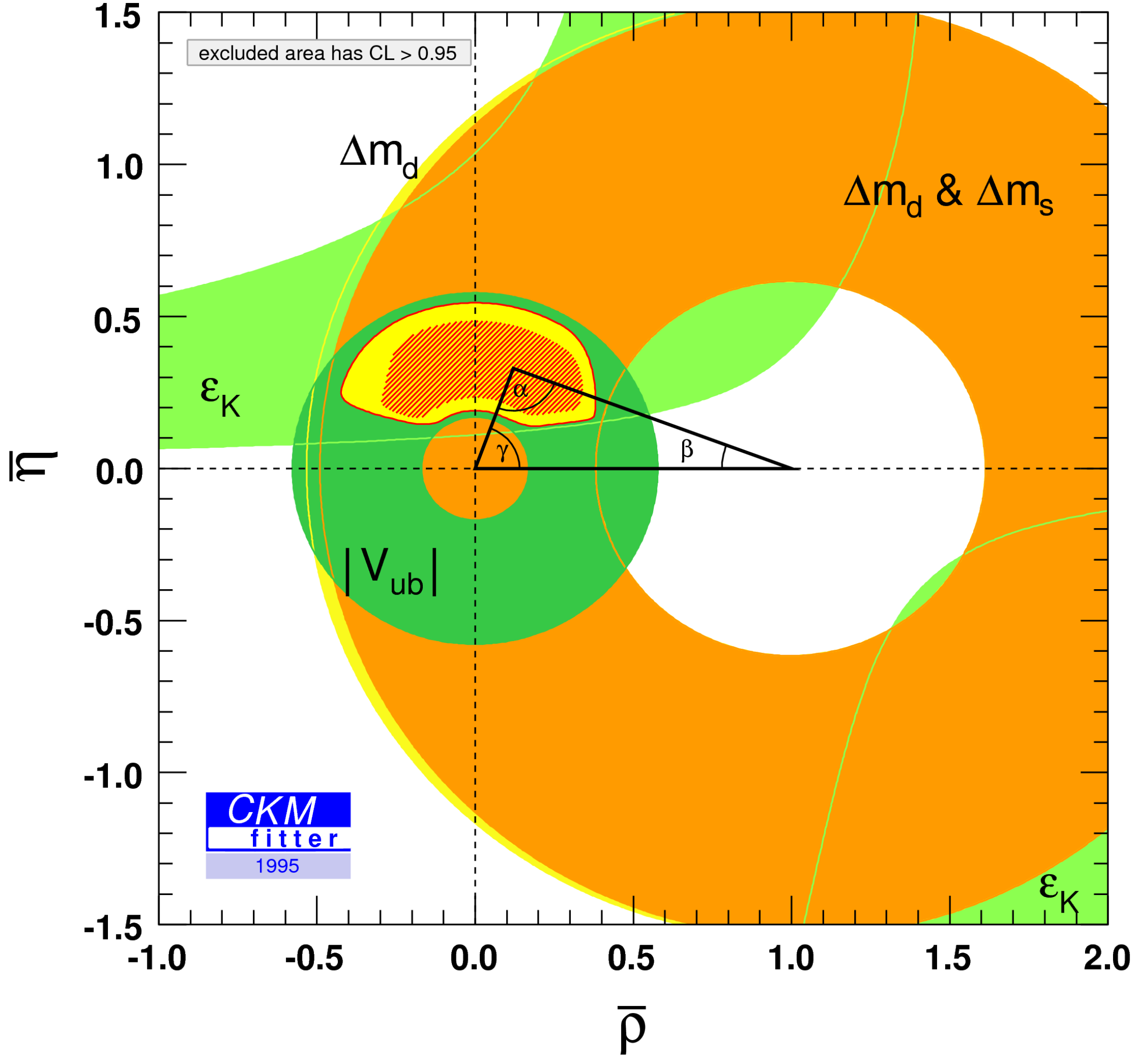
$B \rightarrow (\Sigma_X X) \ell \nu$

Non-perturbative effects from B only

Use of heavy quark expansion (HQE)

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 – $\overline{\mathrm{B}}$ mixing : use of mixing frequency Δm possible.

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

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

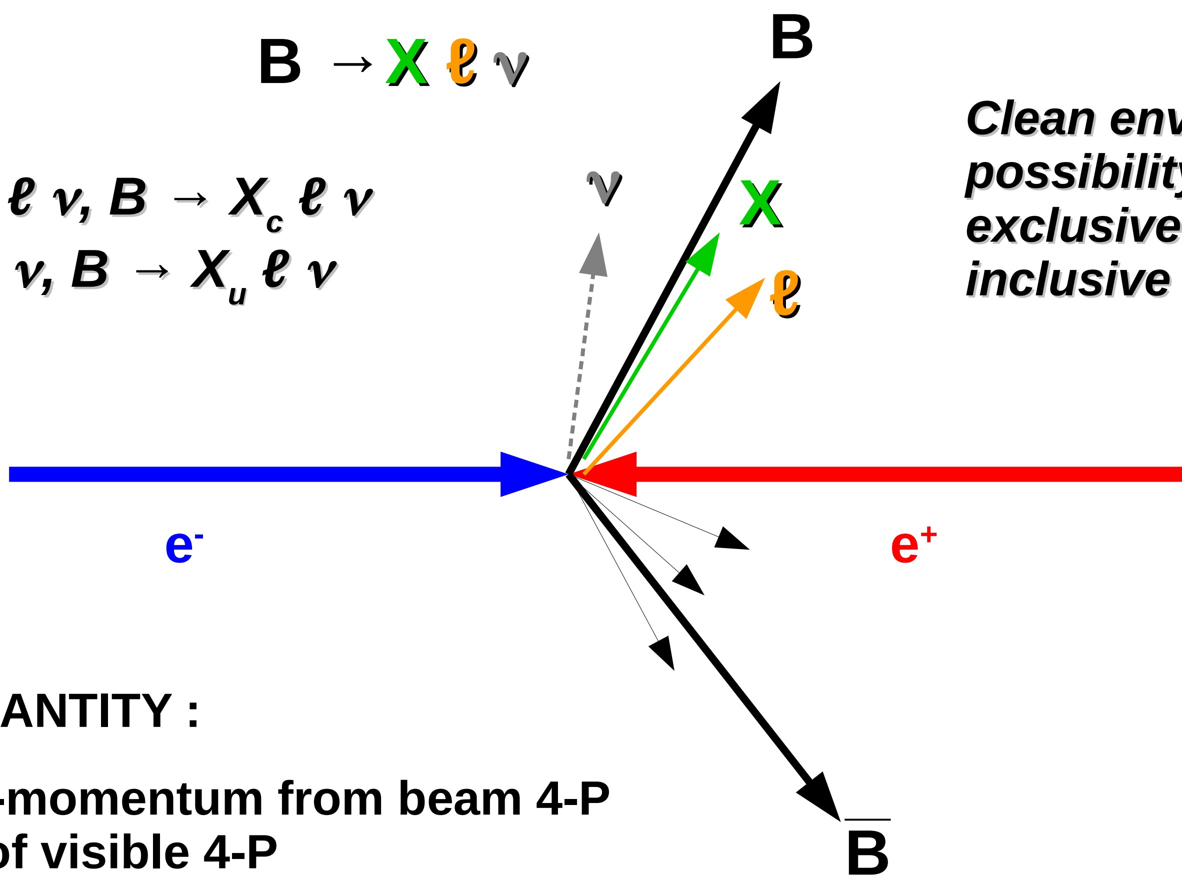
$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} + 1 = 0$$

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

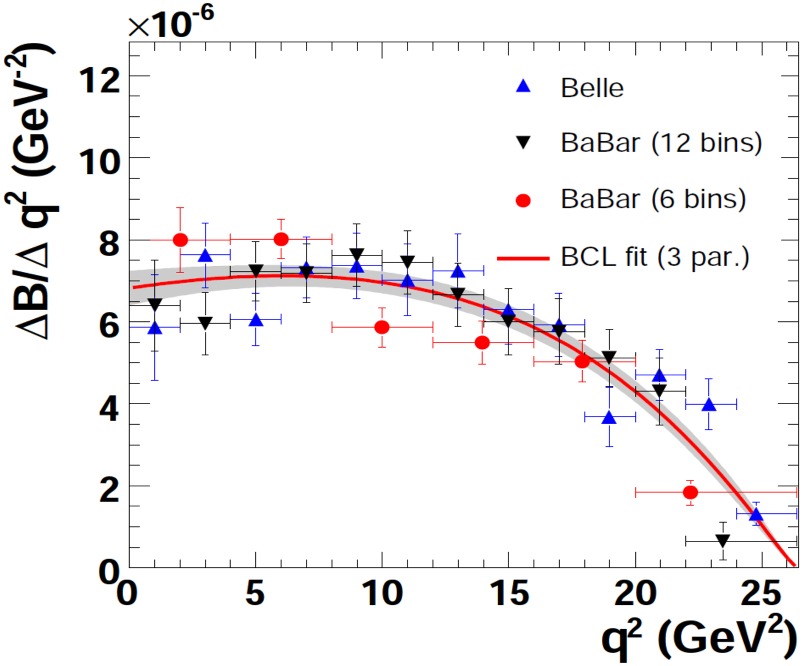
KEY QUANTITY :

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

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

Measurements from B factories

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



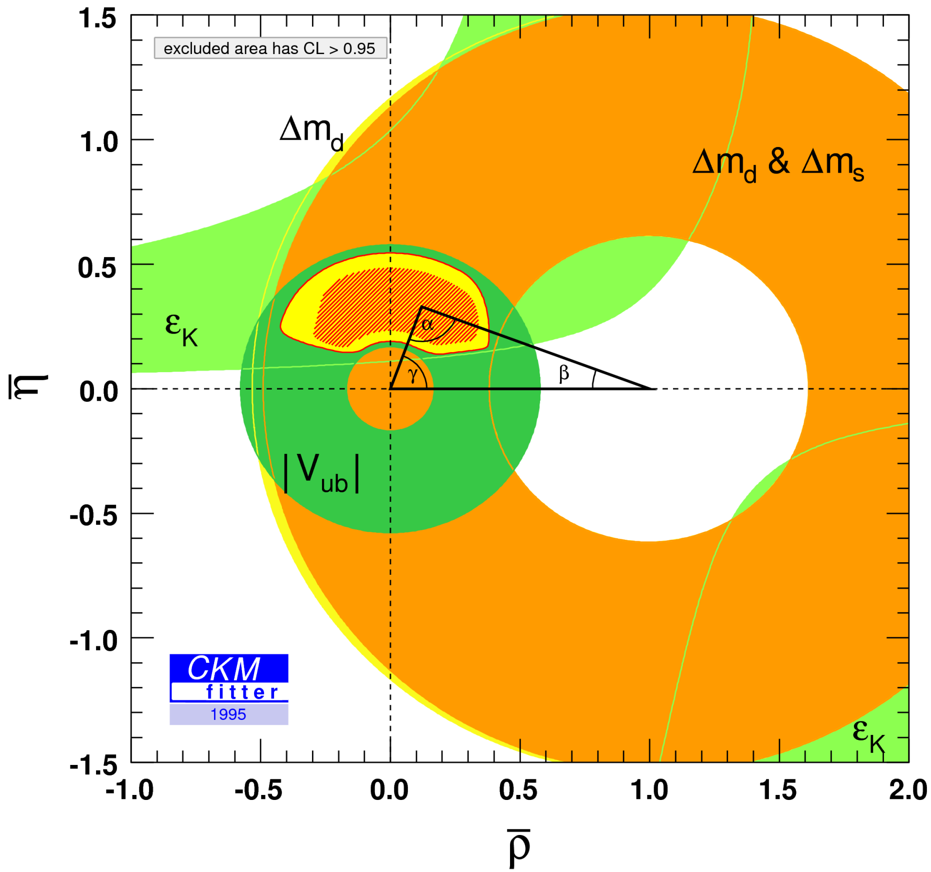
See e.g.,

Eur. Phys. J. C74 (2014) 3026

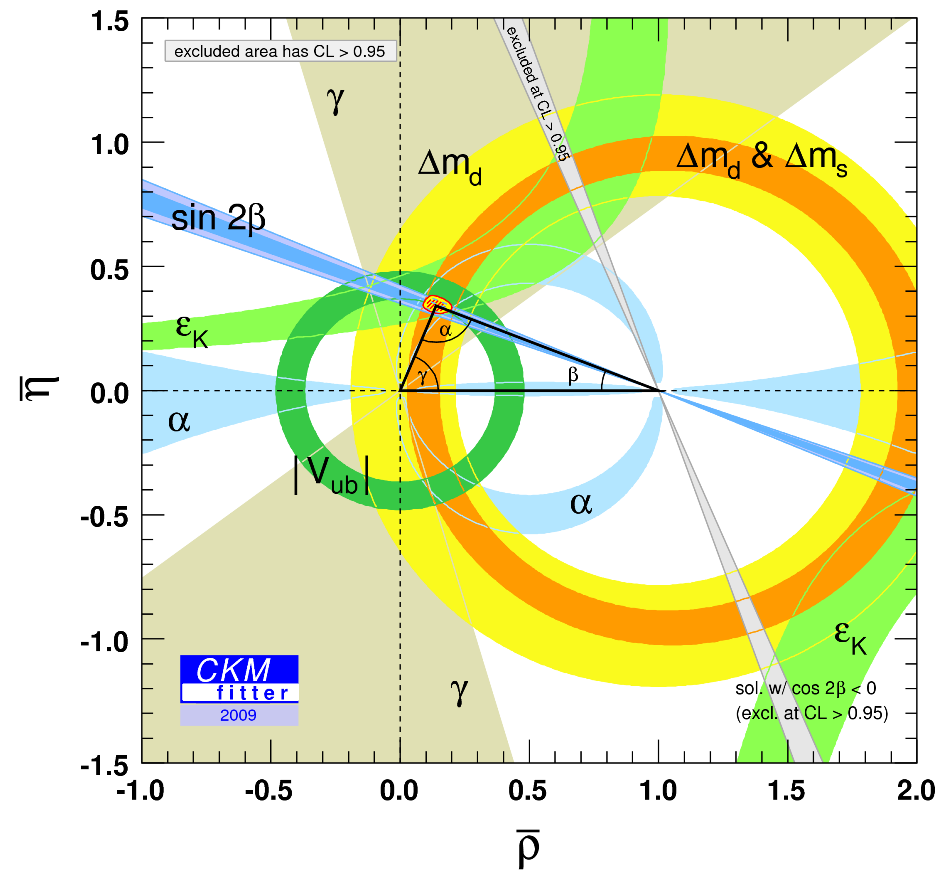
Experiment	$\lvert V_{ub}\rvert\ (10^{-3})$			
BaBar (6 bins)	$3.54 \pm 0.12^{+0.38}_{-0.33}$	$3.22 \pm 0.15^{+0.55}_{-0.37}$	$3.08 \pm 0.14^{+0.34}_{-0.28}$	2.98 ± 0.31
BaBar (12 bins)	$3.46 \pm 0.10^{+0.37}_{-0.32}$	$3.26 \pm 0.19^{+0.56}_{-0.37}$	$3.12 \pm 0.18^{+0.35}_{-0.29}$	3.22 ± 0.31
Belle	$3.44 \pm 0.10^{+0.37}_{-0.32}$	$3.60 \pm 0.13^{+0.61}_{-0.41}$	$3.44 \pm 0.13^{+0.38}_{-0.32}$	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

UT after B factories mandate

1995



2009



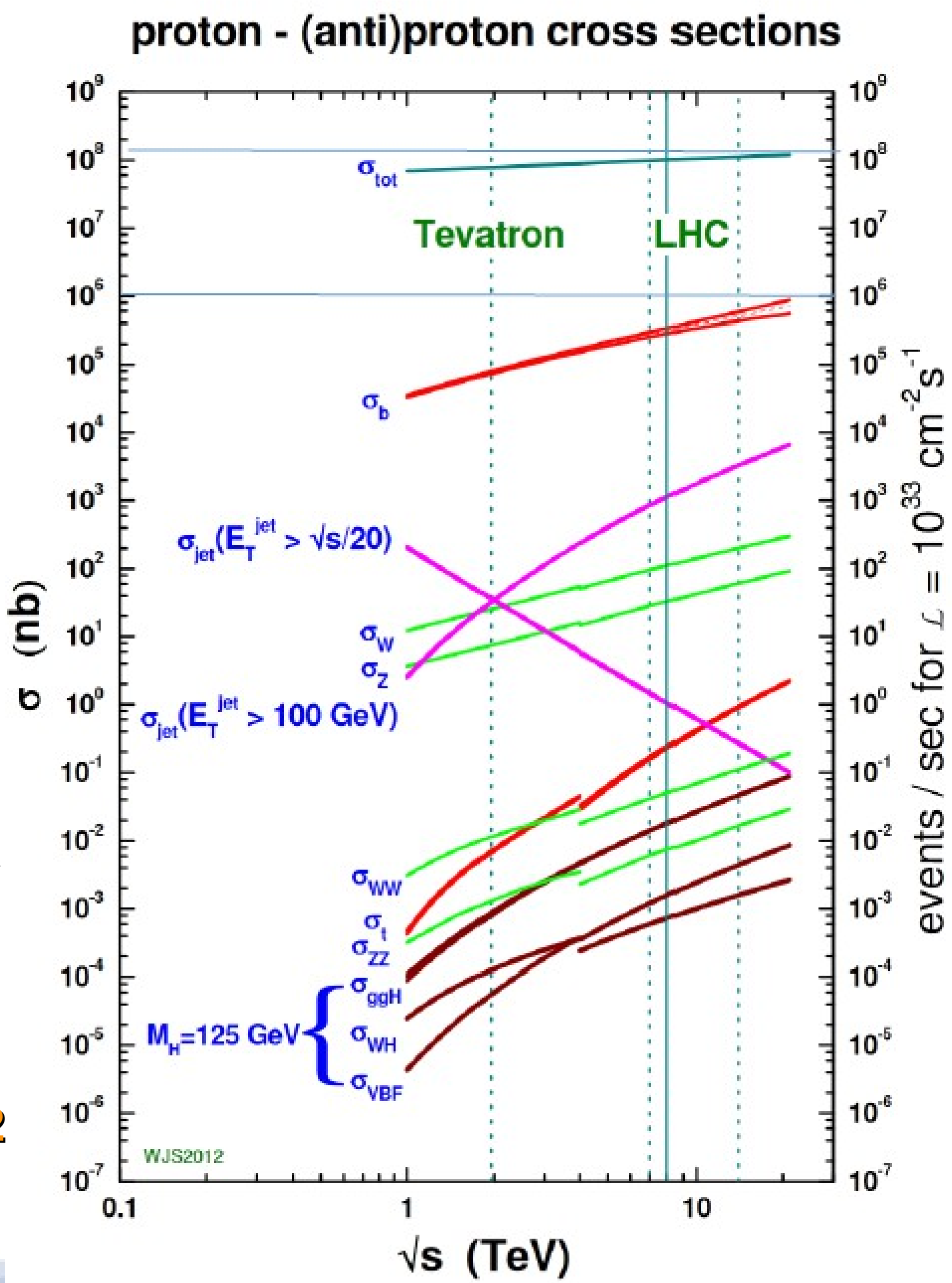
Basically : The B factories established experimentally the CKM picture but a lot of remaining questions (e.g. tree vs loop constraints) and more precision (e.g, $|V_{ub}|$!) is needed.

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*

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

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

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

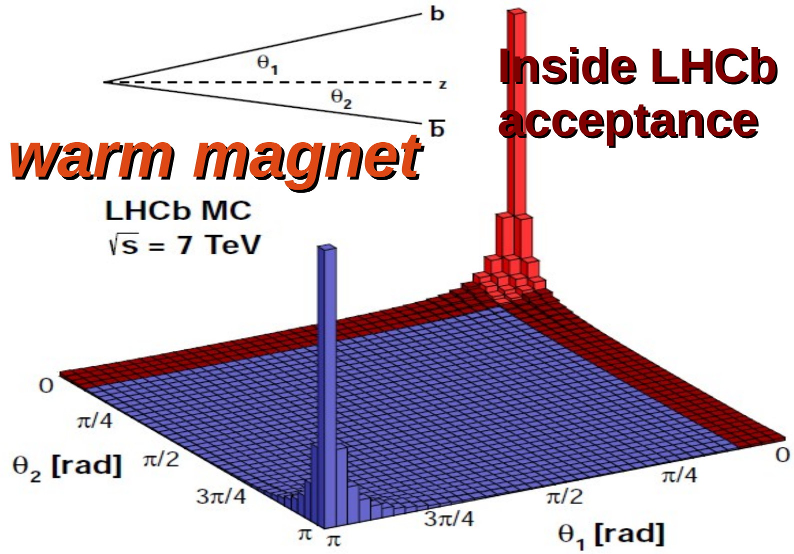
$f_{baryon} = f(b \to \Lambda_b, \Xi_b, \Omega_b)/(f_u+f_d) = 0.240 \pm 0.022$

$f_c = \sigma(B_c) = ?$

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

LHCb detector

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



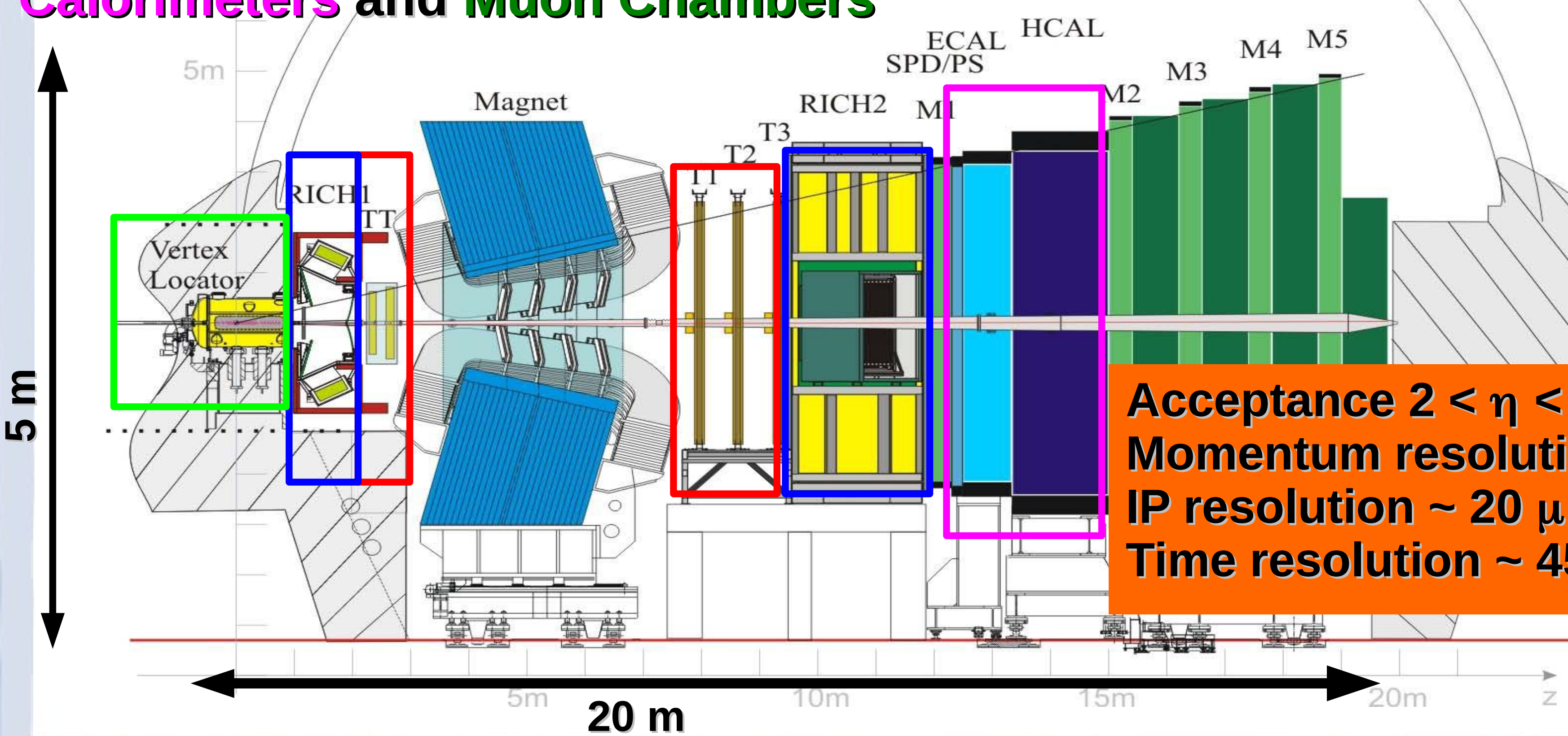
Optimize for b and c hadron studies

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

$|V_{ub}|$ at LHCb

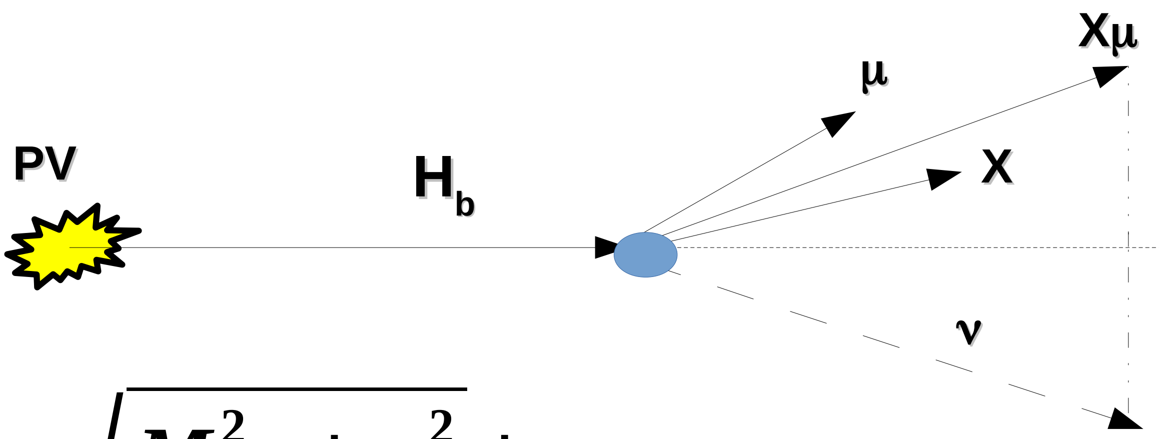
In the deeds, we normalize b → u decays to corresponding b → c modes to minimize systematics and control efficiency corrections, etc..
Consequence : we measure $|V_{ub}|/|V_{cb}|$

$\Lambda_b \rightarrow p\,\mu\,\nu$, 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, accepted by PRL

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

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

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

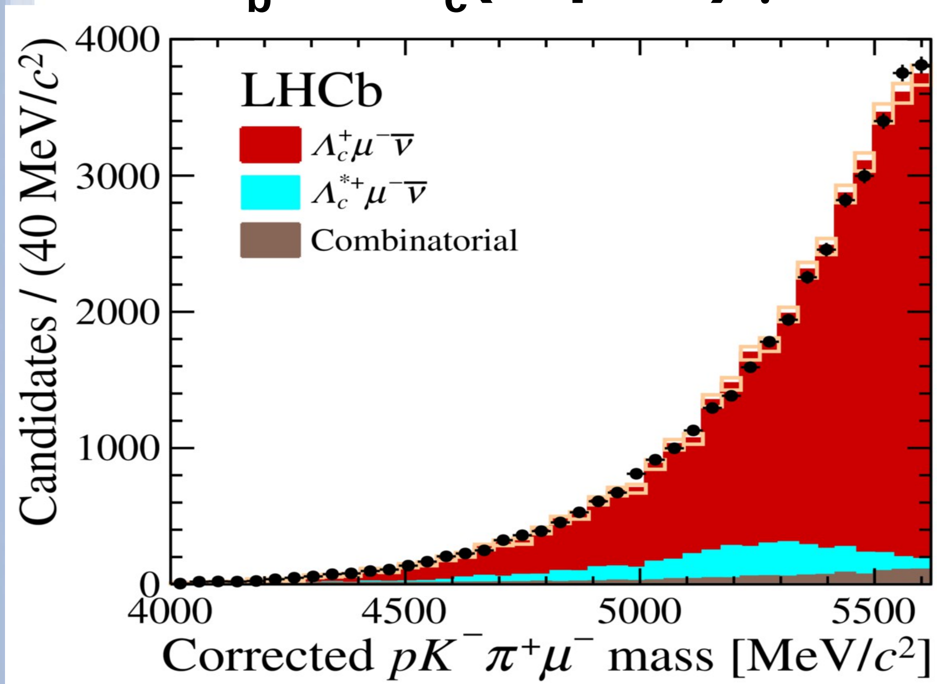
Boundary chosen to get approximately the same expected number of signal events in each bin

*** 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**

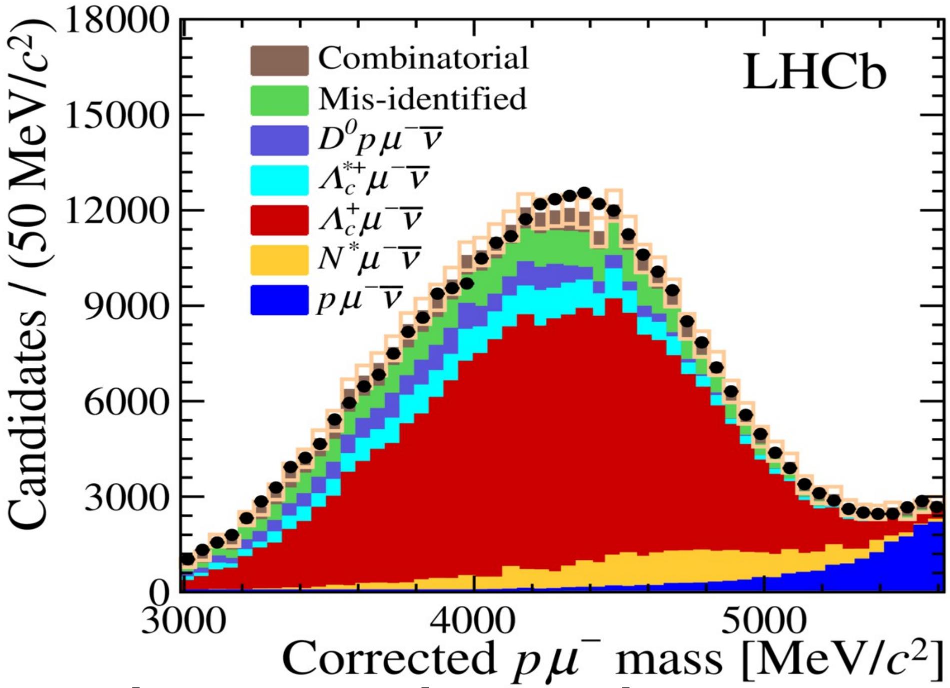
$\Lambda_b \to p\,\mu\,\nu$

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



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

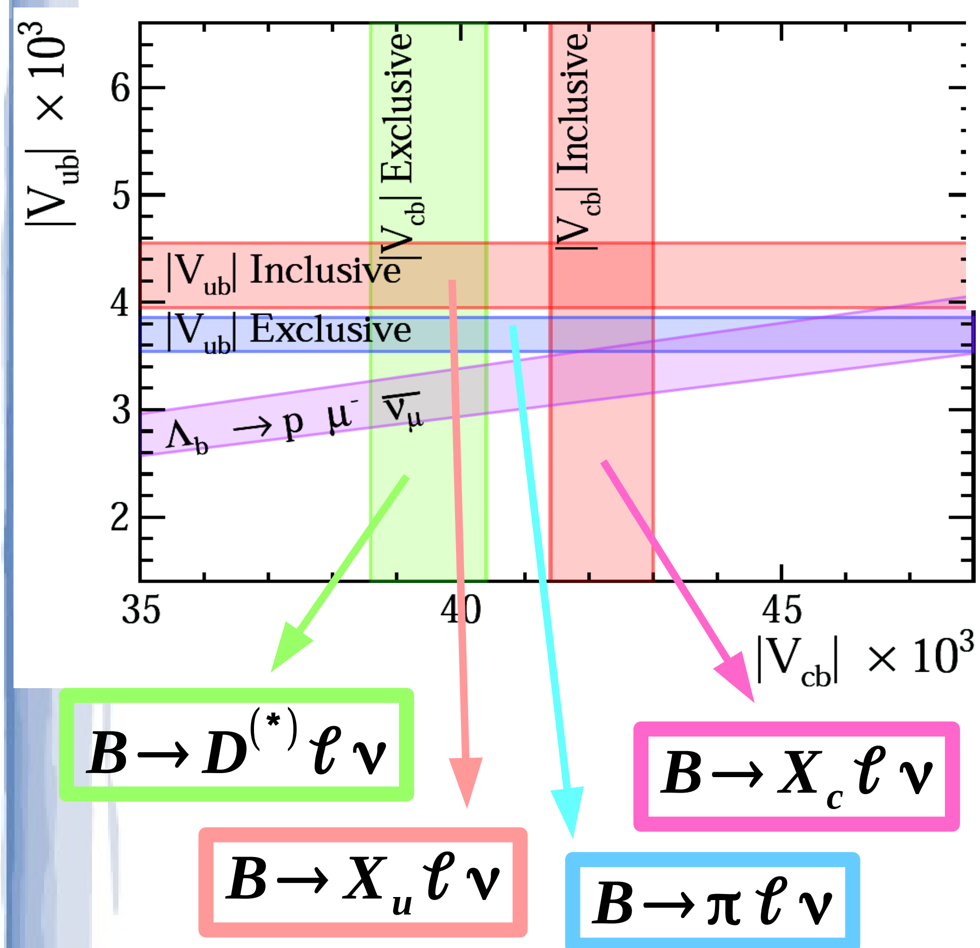
$|V_{ub}|$ / $|V_{cb}|$ = 0.083 +/- 0.004 (exp) +/- 0.004 (FF)
Central value updated to 0.079 after new $\Lambda_c \to pK\pi$ BF

$\Lambda_b \rightarrow p\,\mu\,\nu$ 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	$^{+7.8}_{-8.2}$

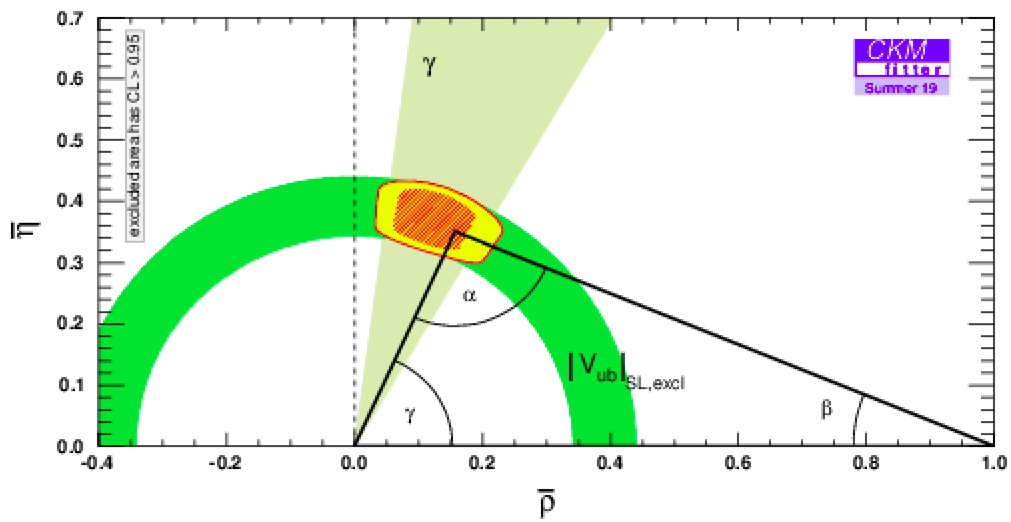
Motivation for $B_s \to K\mu\nu$

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

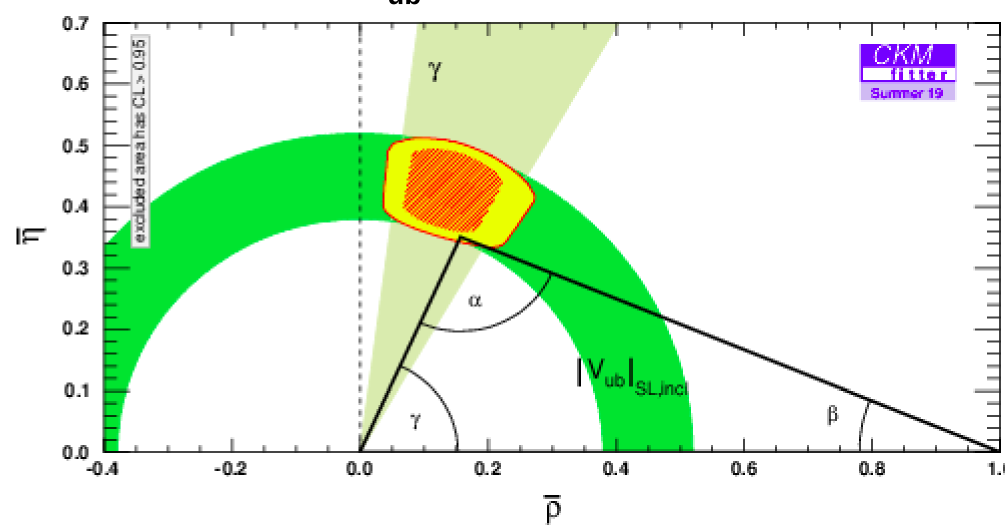


UT apex constraint with γ and $|V_{ub}|(/|V_{cb}|)$

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

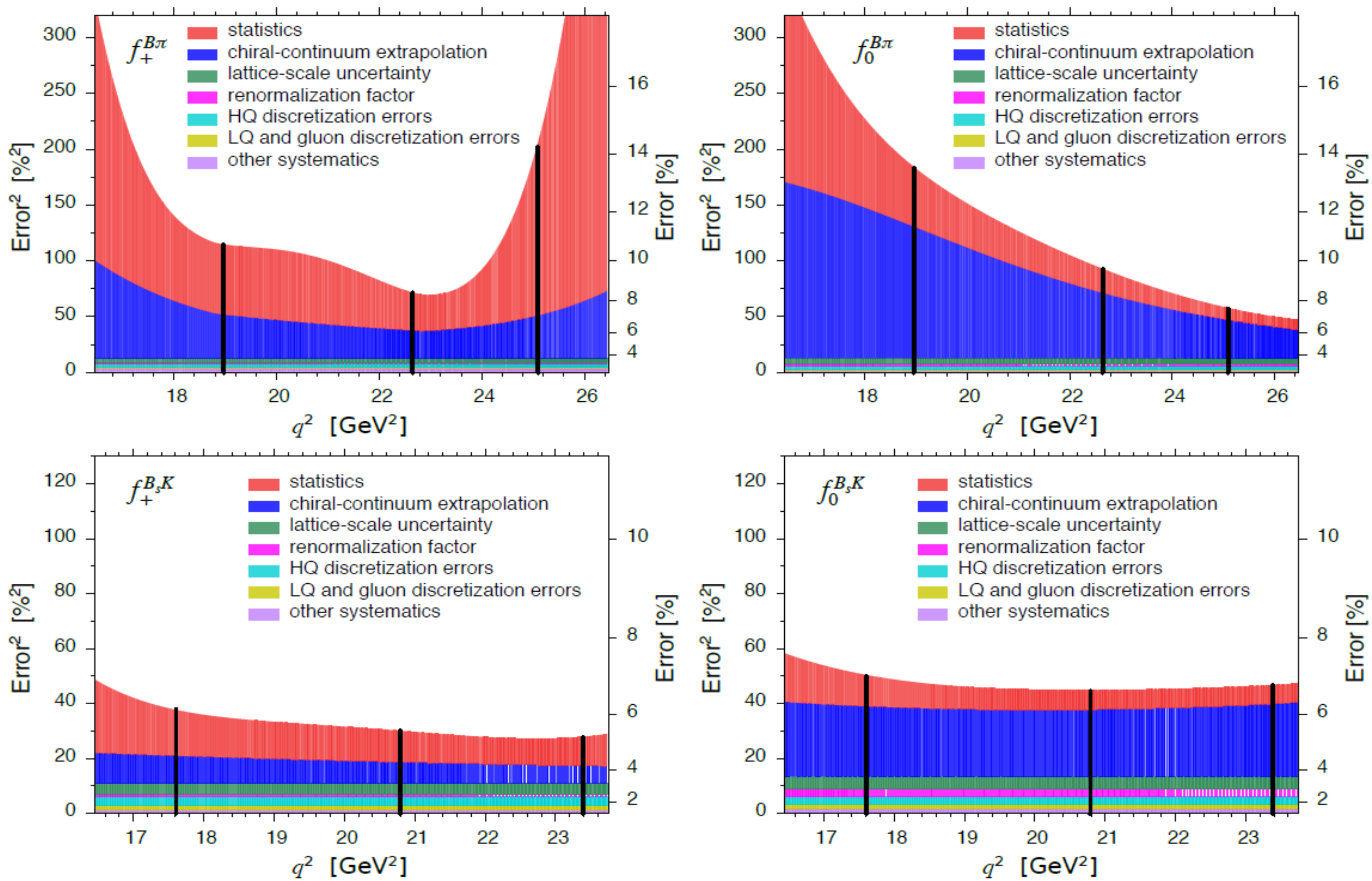


Inclusive $|V_{ub}|$



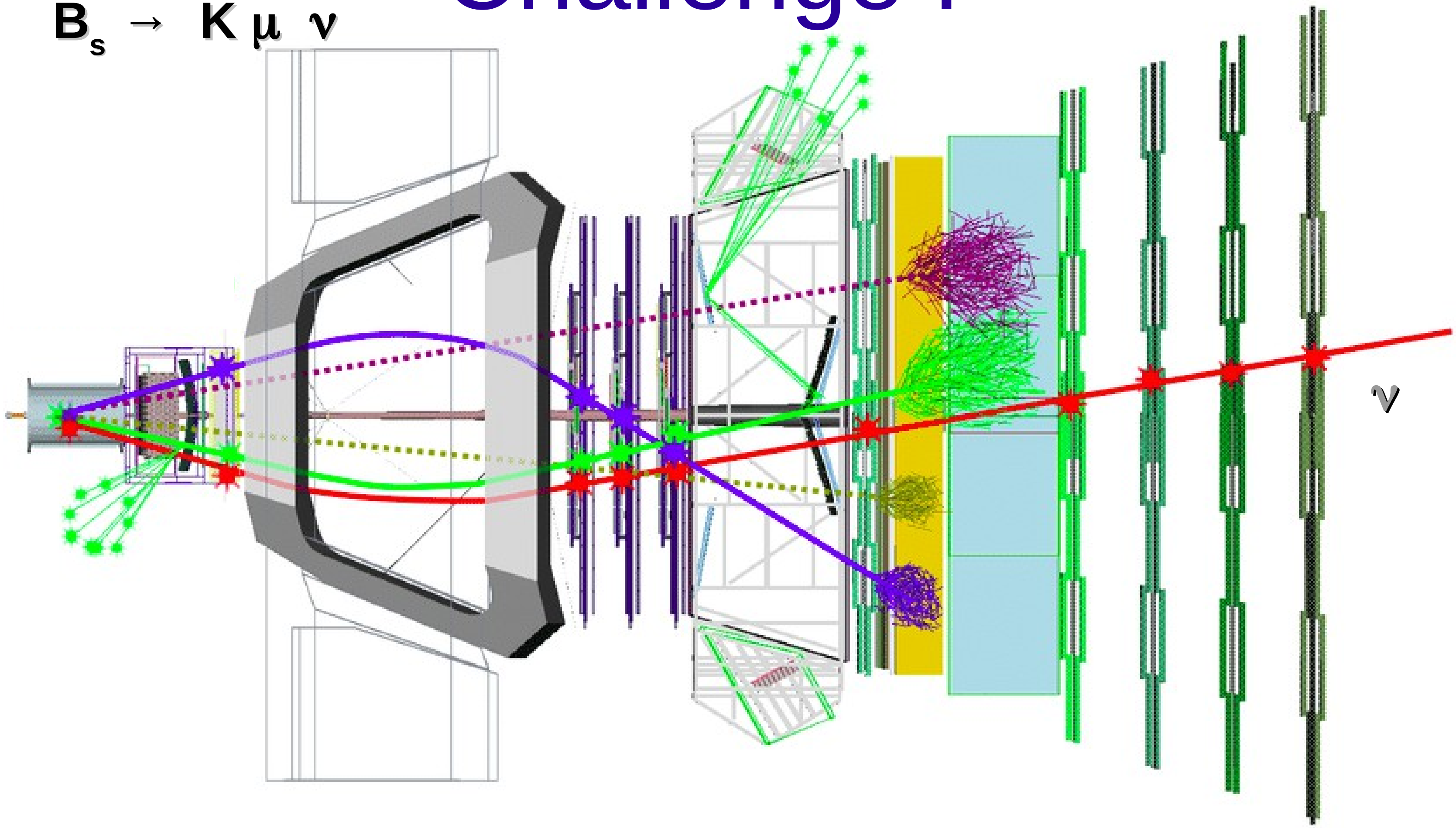
B → π vs B_s → K FF

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



Challenge !

$B_s \rightarrow K \mu \nu$



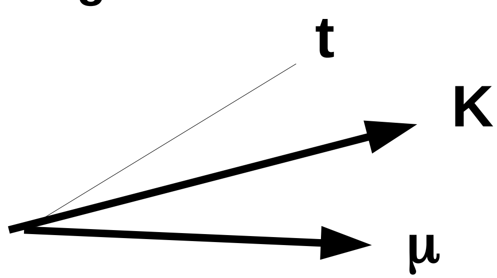
Only two charged tracks in the final state + undetectable neutrino !
Any physics decay with the same tracks + extra tracks or neutral particle is a background !
+ Tracks getting out of acceptance...
Background fighting and characterization involving Machine Learning techniques

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)

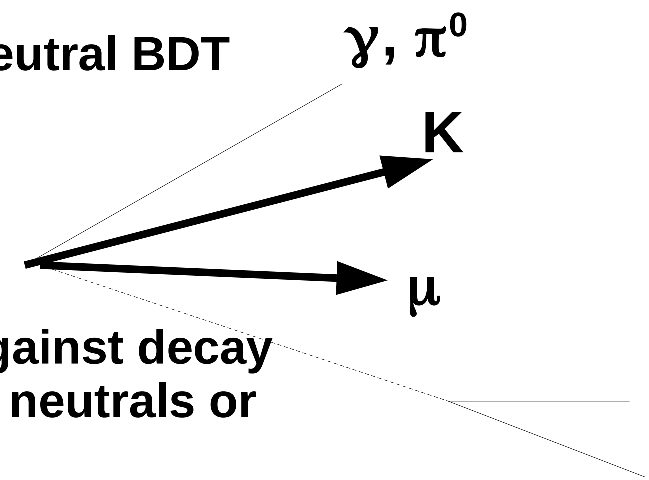
MVA

Charge BDT

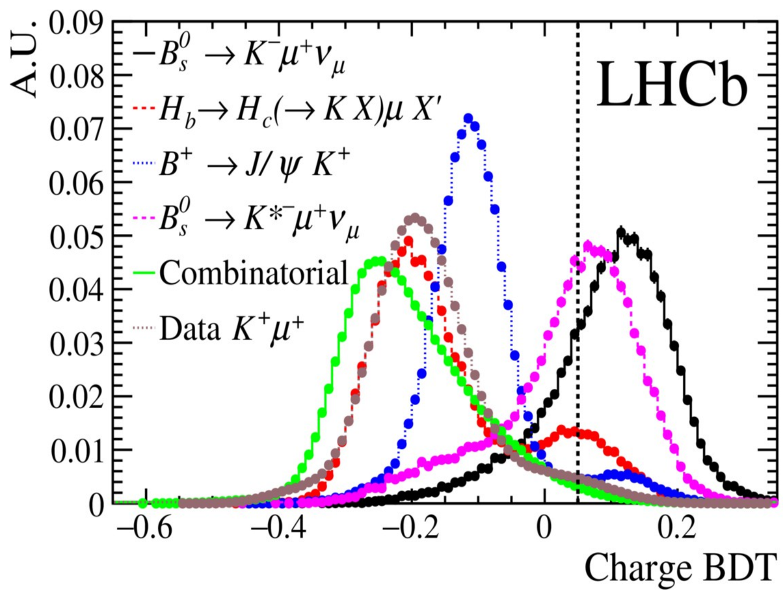


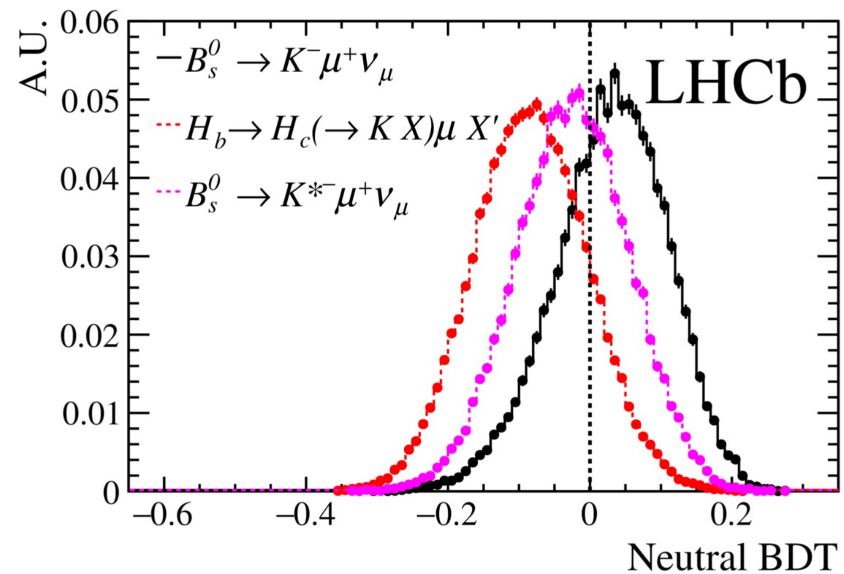
Trained against decay with extra tracks

Neutral BDT



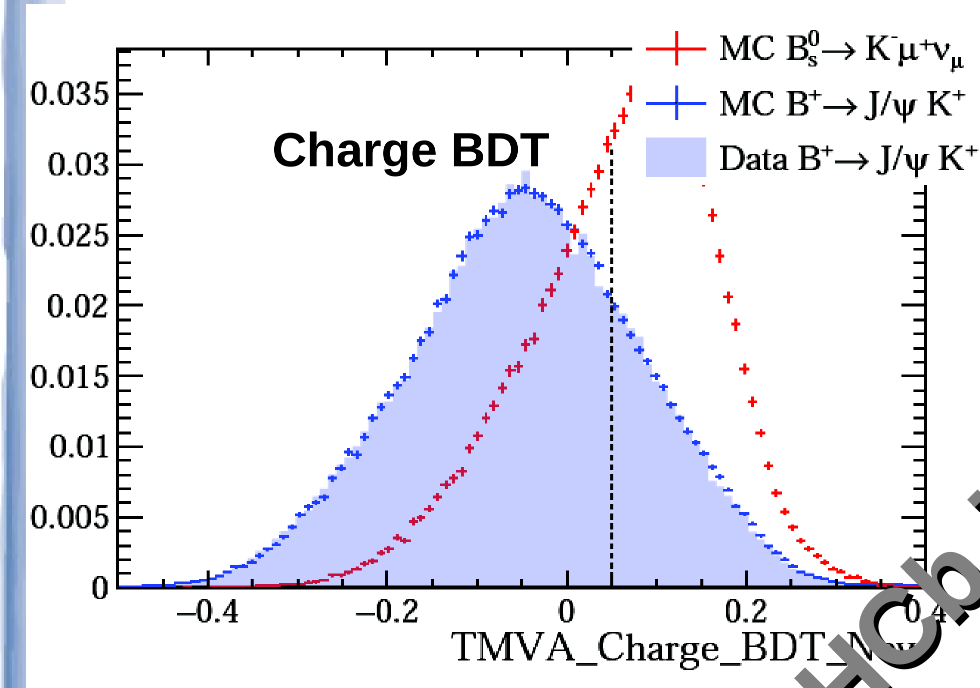
Trained against decay with extra neutrals or long-lived

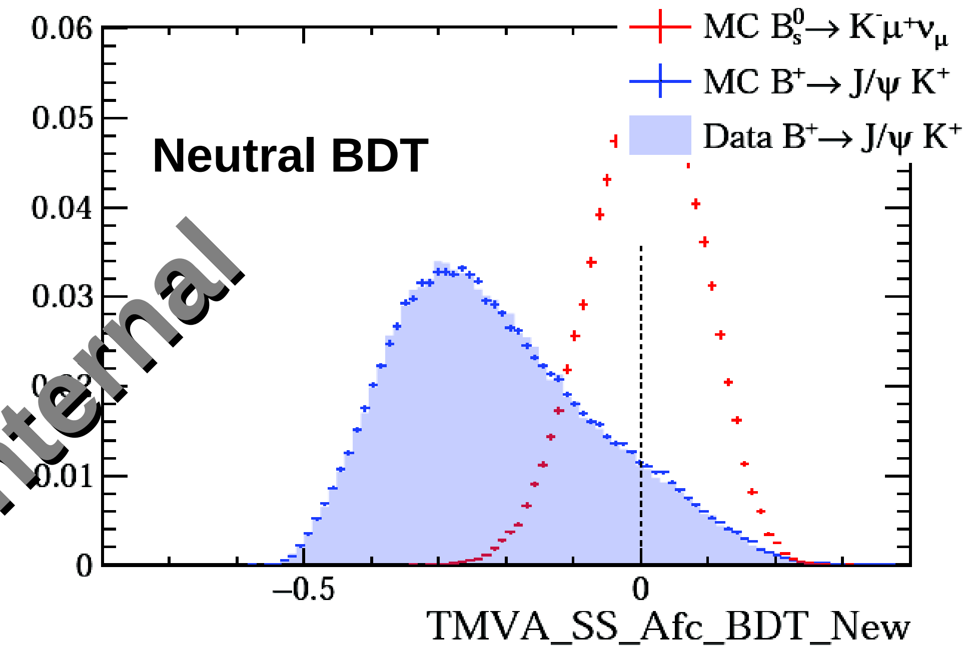


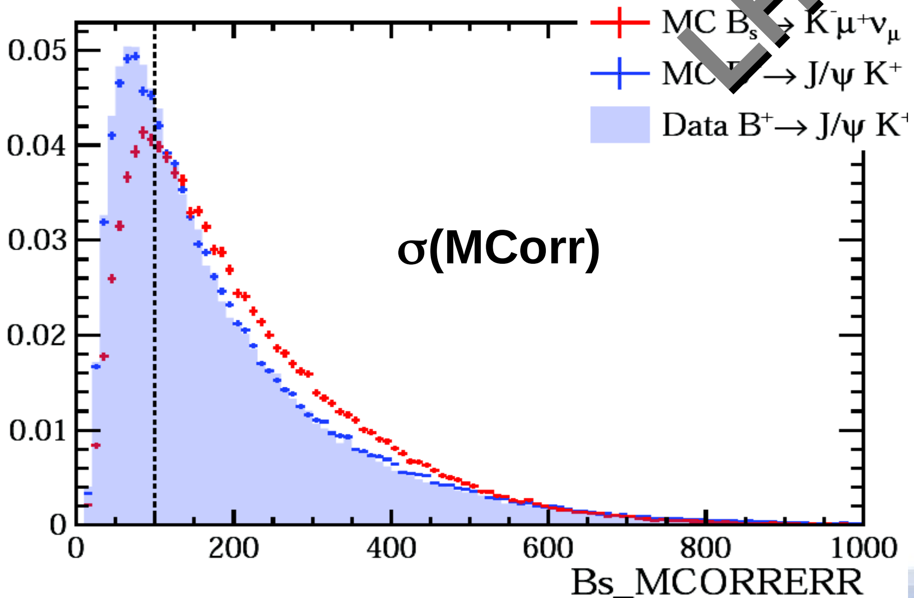


Neutral BDT optimized after charge BDT selection

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







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

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

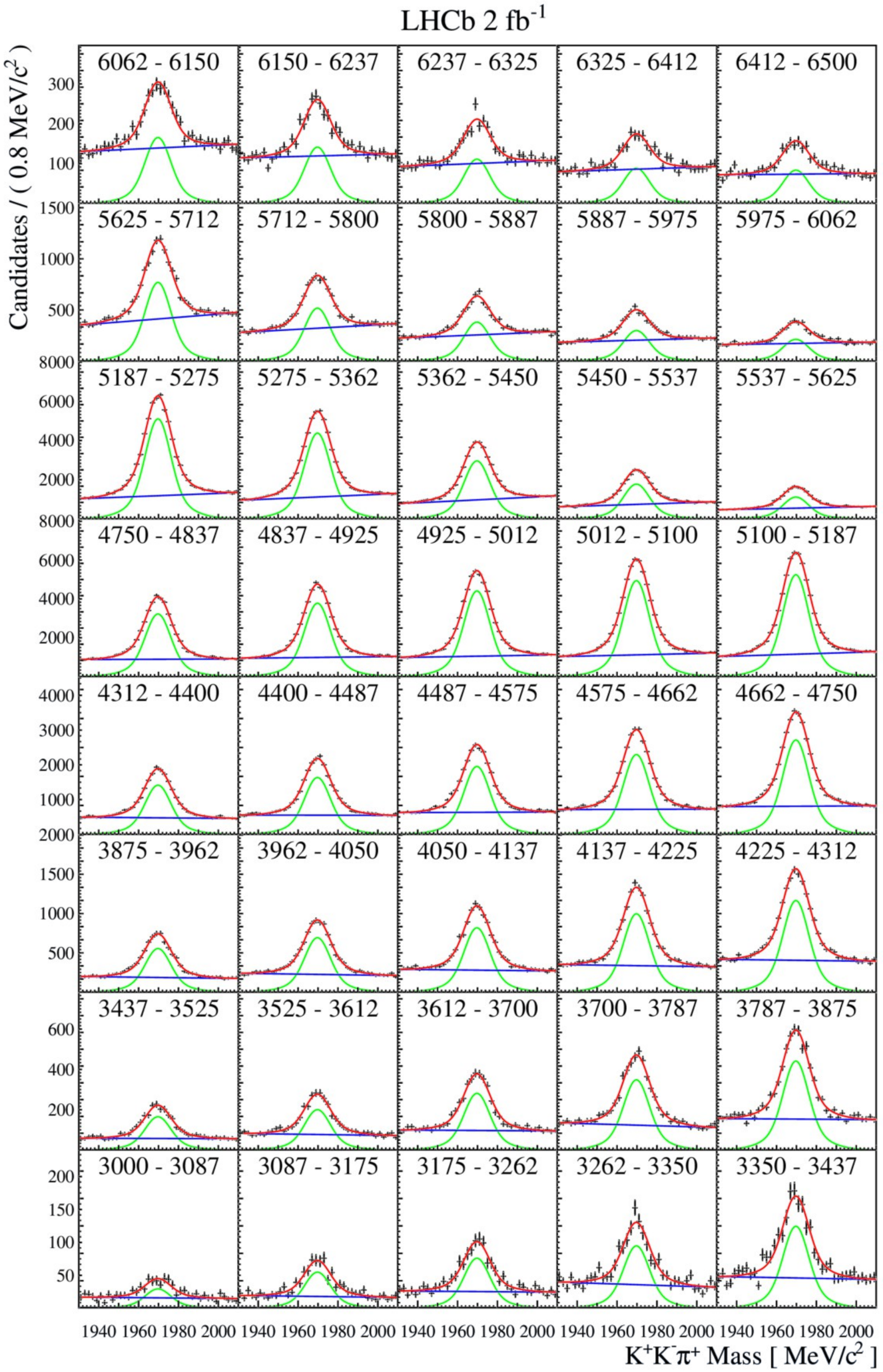
Perform the operation across the Mcorr bins to obtain the MisID yields as a function of Mcorr :

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

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

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

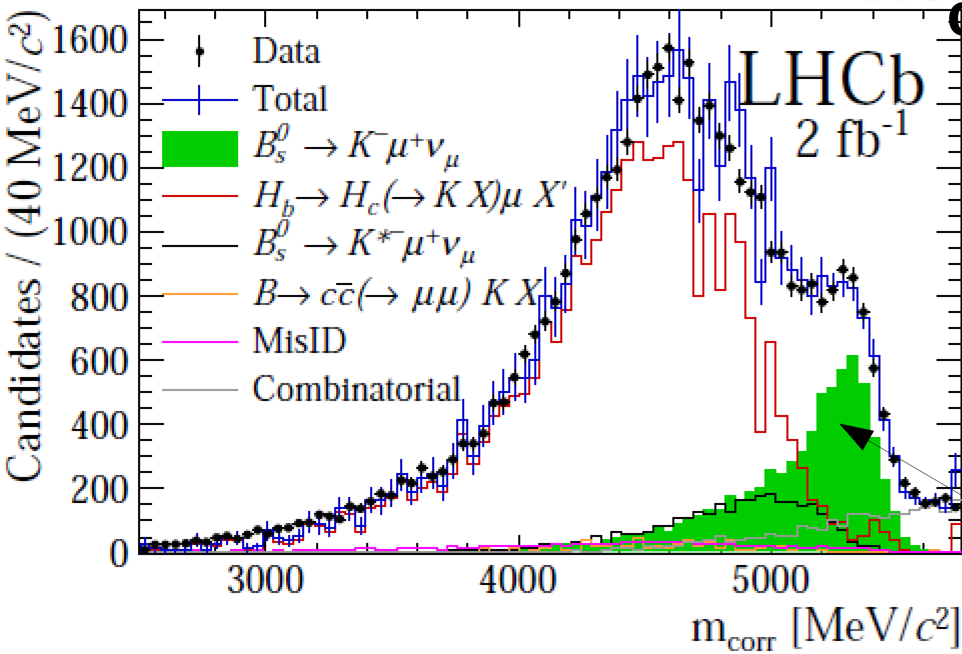
- $B_s \to D_s^* \mu \nu$ ($D_s^* \to D_s \gamma$)
- $B_s \to D_s^{**} \mu \nu$ (higher resonances $\to D_s X$)
- $B_s \to D_s \tau \nu$ ($\tau \to \mu \bar{\nu}_\mu \nu_\tau$)
- $B \to D_s D$ ($D \to \mu \nu X$)
- Note : since the D_s signal is fitted as a function of Mcorr, no combinatorial or reflections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



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

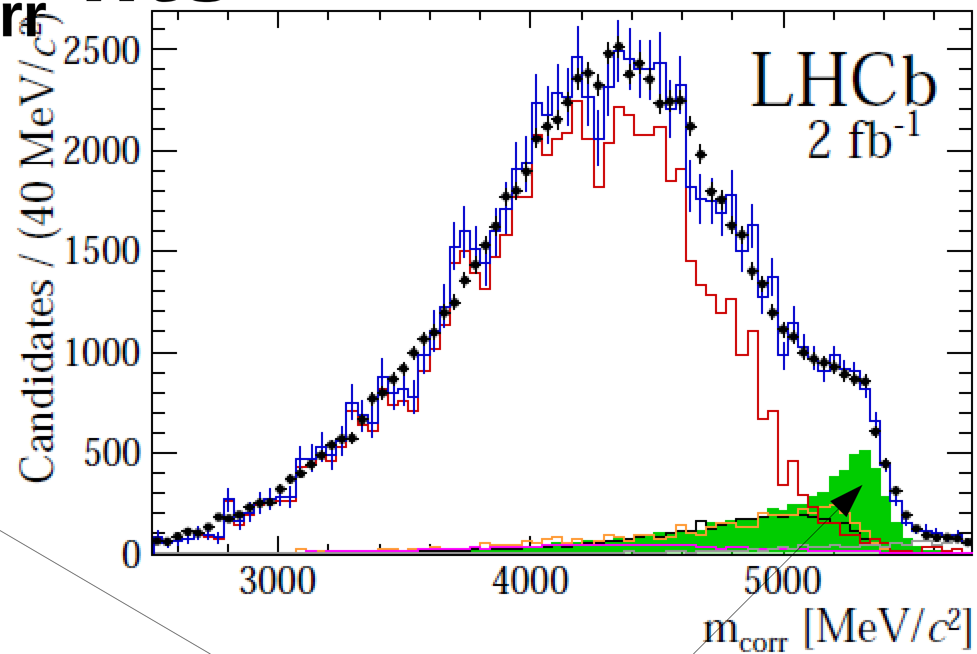
M_{corr} fits

$q^2 < 7\ GeV^2$



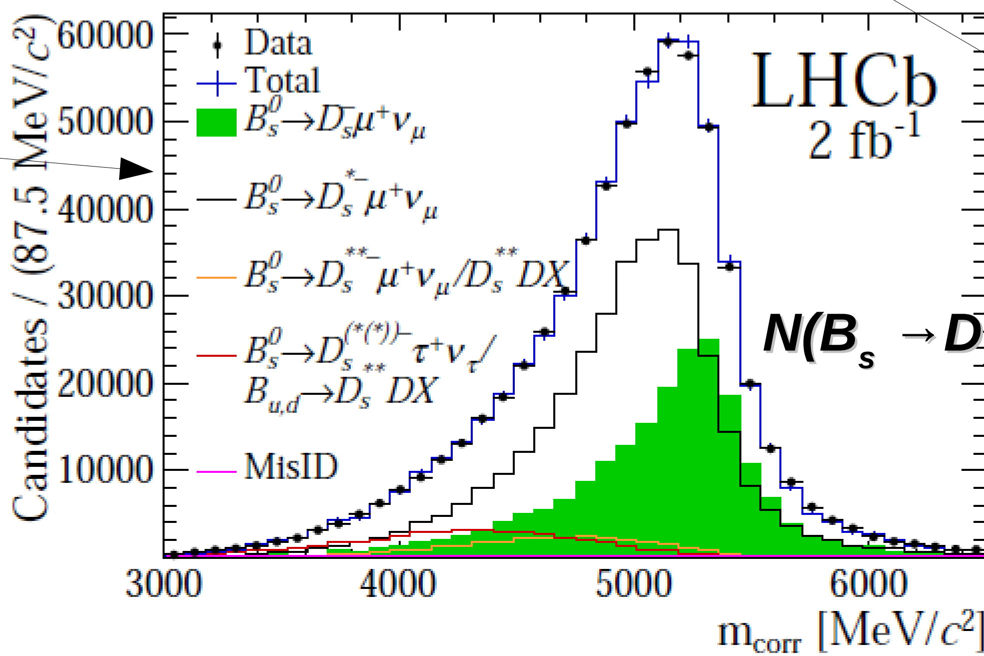
$N(B_s \to K\ \mu\ \nu) = 6922$ +/- 285

$q^2 > 7\ GeV^2$



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

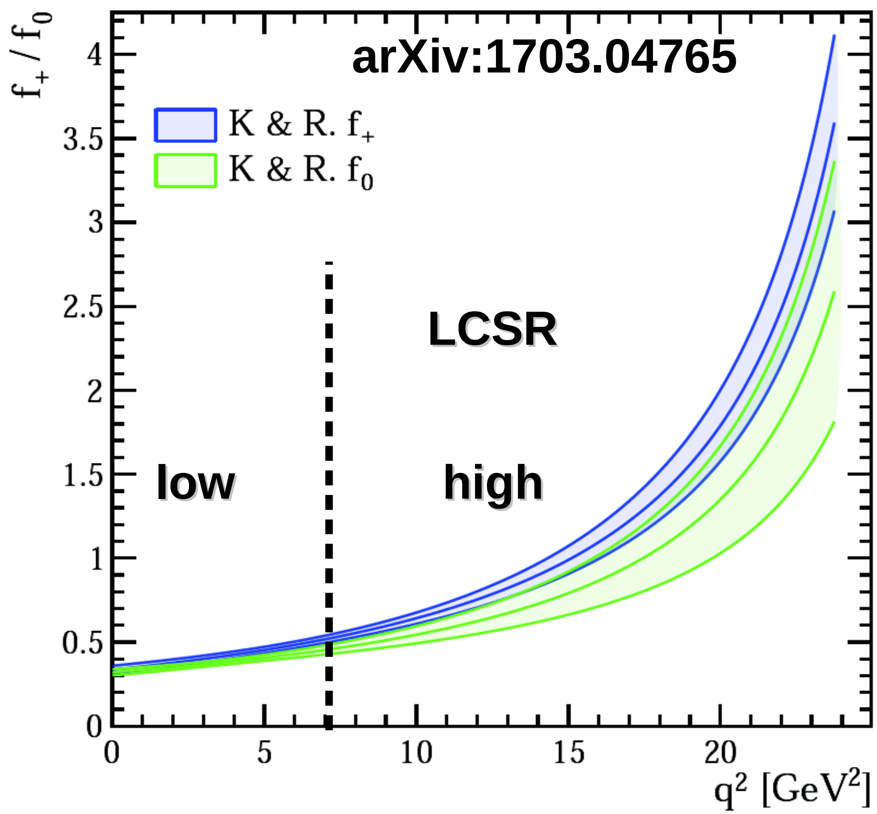
$D_s \to KK\pi$ BF brings a 2.8% relative uncertainty

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
$\sigma(m_{\mathrm{corr}})$	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	$^{+4.0}_{-4.3}$	$^{+4.3}_{-4.5}$	$^{+5.0}_{-5.3}$

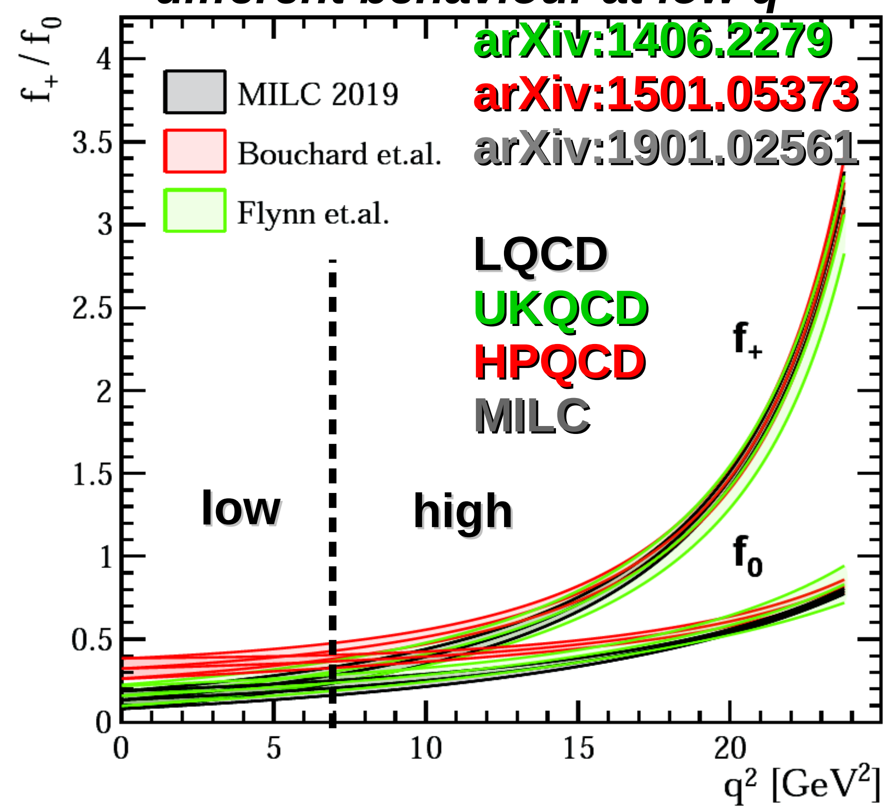
Data/MC corrections with control channel

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

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



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



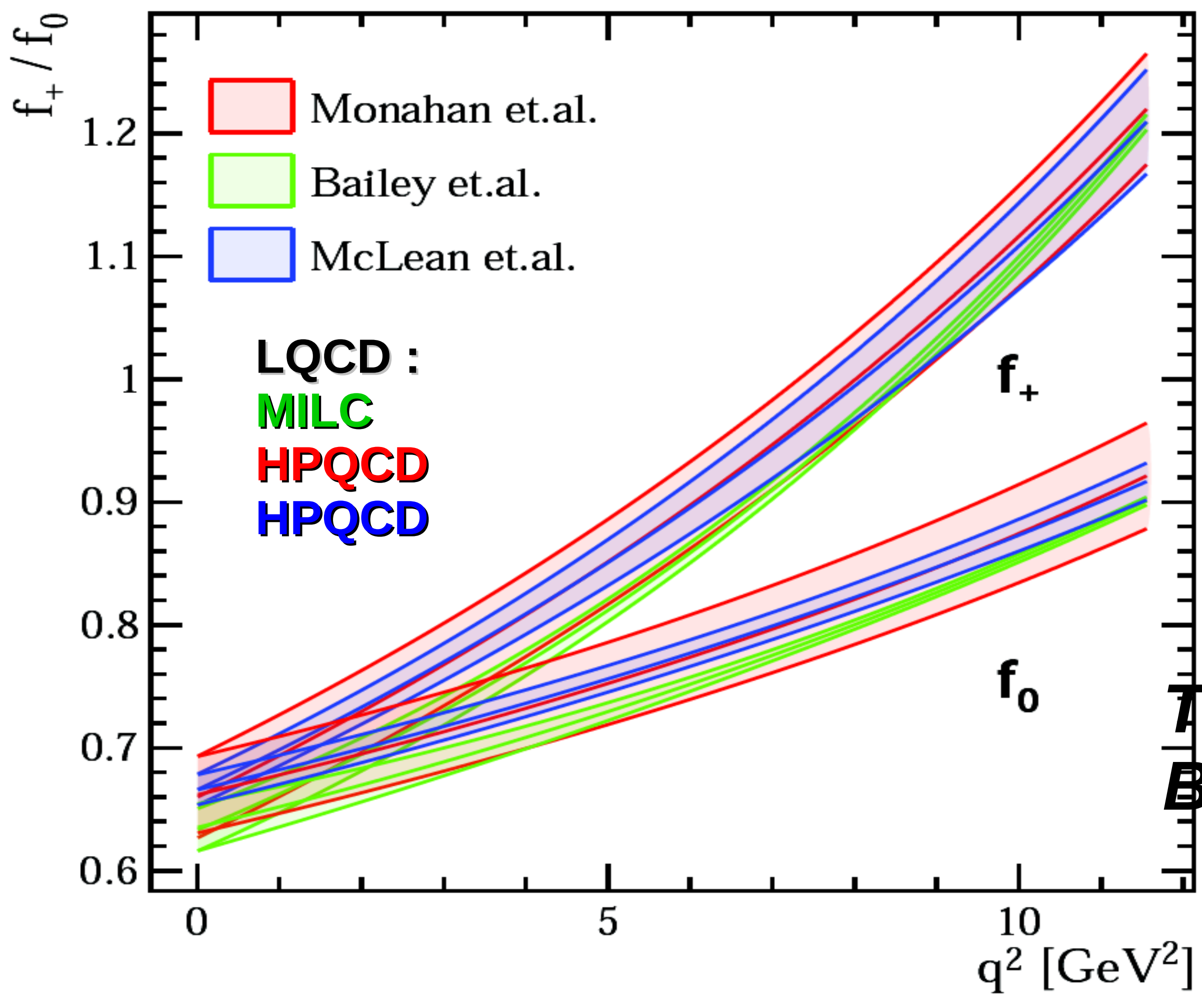
High q^2 : in general better accuracy for LQCD
LCSR not reliable > 12 GeV^2
Low q^2 : LCSR better

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 parametrization

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)

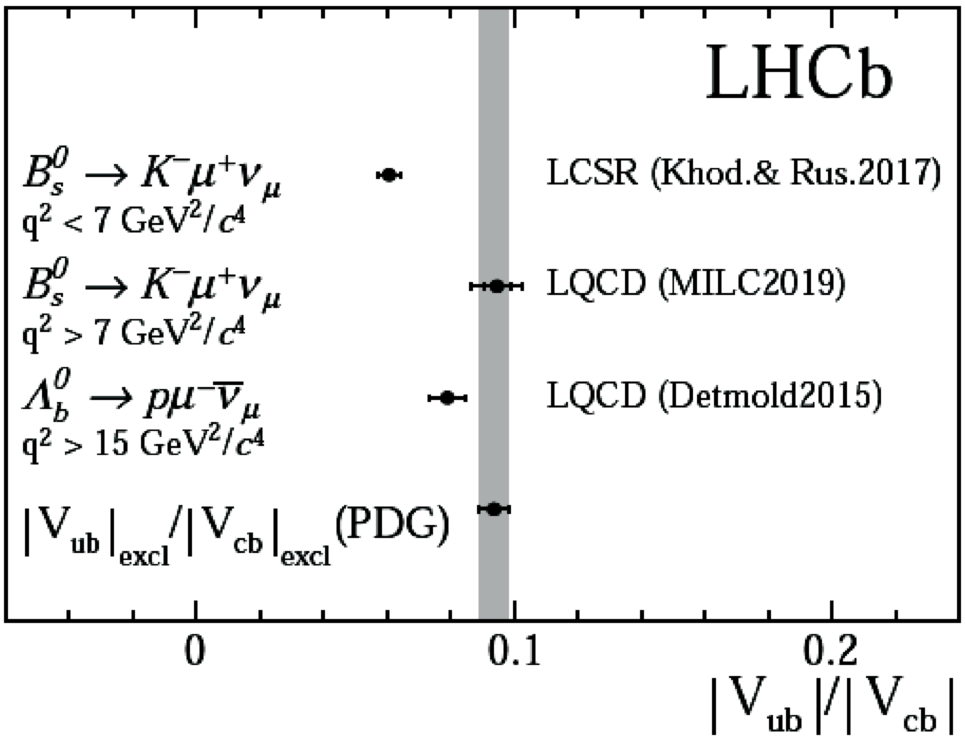
The choice was done BEFORE unblinding

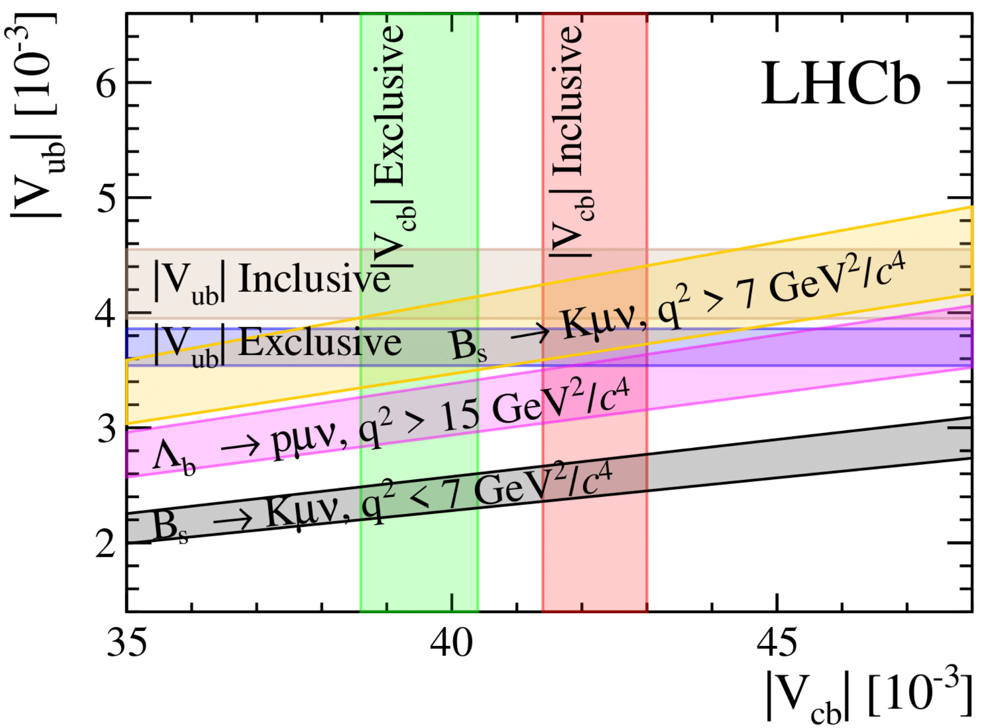
Error bands : produced as the standard deviation of toys using the correlation matrices of the coefficients of the parametrization

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

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

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





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

Summary/conclusion

SL studies have known a veritable « boom » in LHCb

- Besides the LFUV ratios, not mentioned $|V_{cb}|$ from B_s or the FF measurements of $B_s \rightarrow D_s^{(*)}$, $\Lambda_b \rightarrow \Lambda_c$

- $\Lambda_b \rightarrow p\,\mu\,\nu$ / $B_s \rightarrow K\,\mu\,\nu$ and $|V_{ub}|$
  - **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 so that we constrain the FF variation ourselves**
  - **It is expected that a very precise measurement of $|V_{ub}|$ will be provided and thus the (tree-only) closing relation of UT will be tested at high precision**
- **Other modes are investigated in view of $|V_{ub}|$ (e.g $B \rightarrow \rho$)**

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

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

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

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

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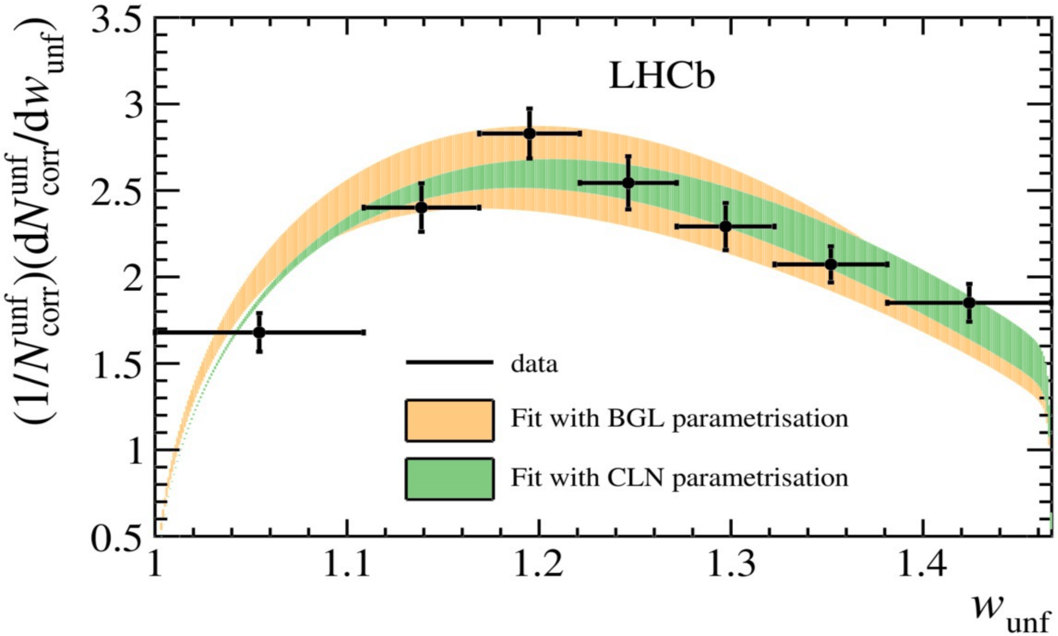

$$\frac{1}{\Gamma}\frac{d\Gamma}{dw}(B_s \to D_s^* \mu \nu)$$

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