The University of Manchester

UKRI Science and Technology Facilities Council

LHCb

A NEW PIECE OF THE $|V_{(c,u)b}|$ LONG-STANDING PUZZLE

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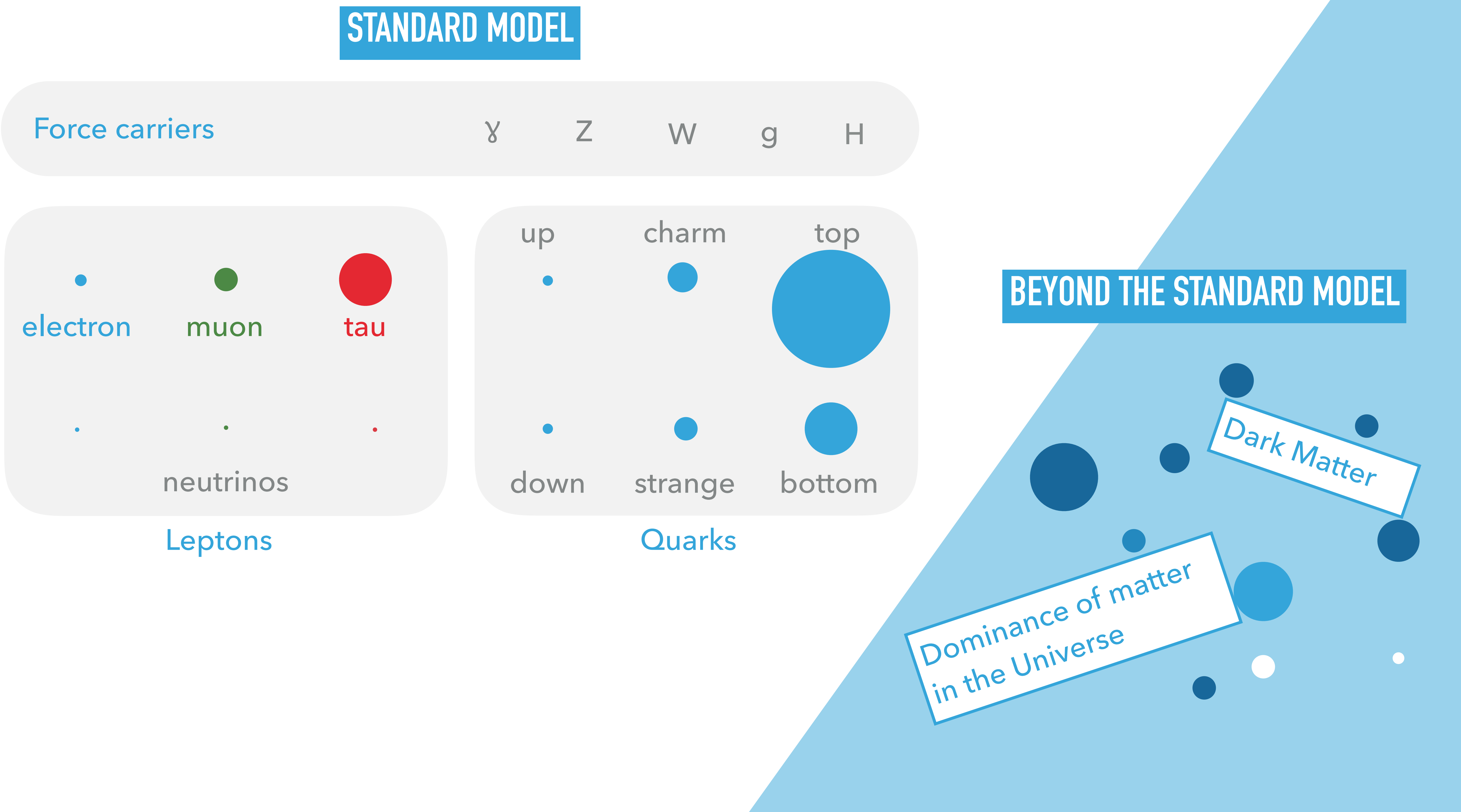
Liverpool Seminar

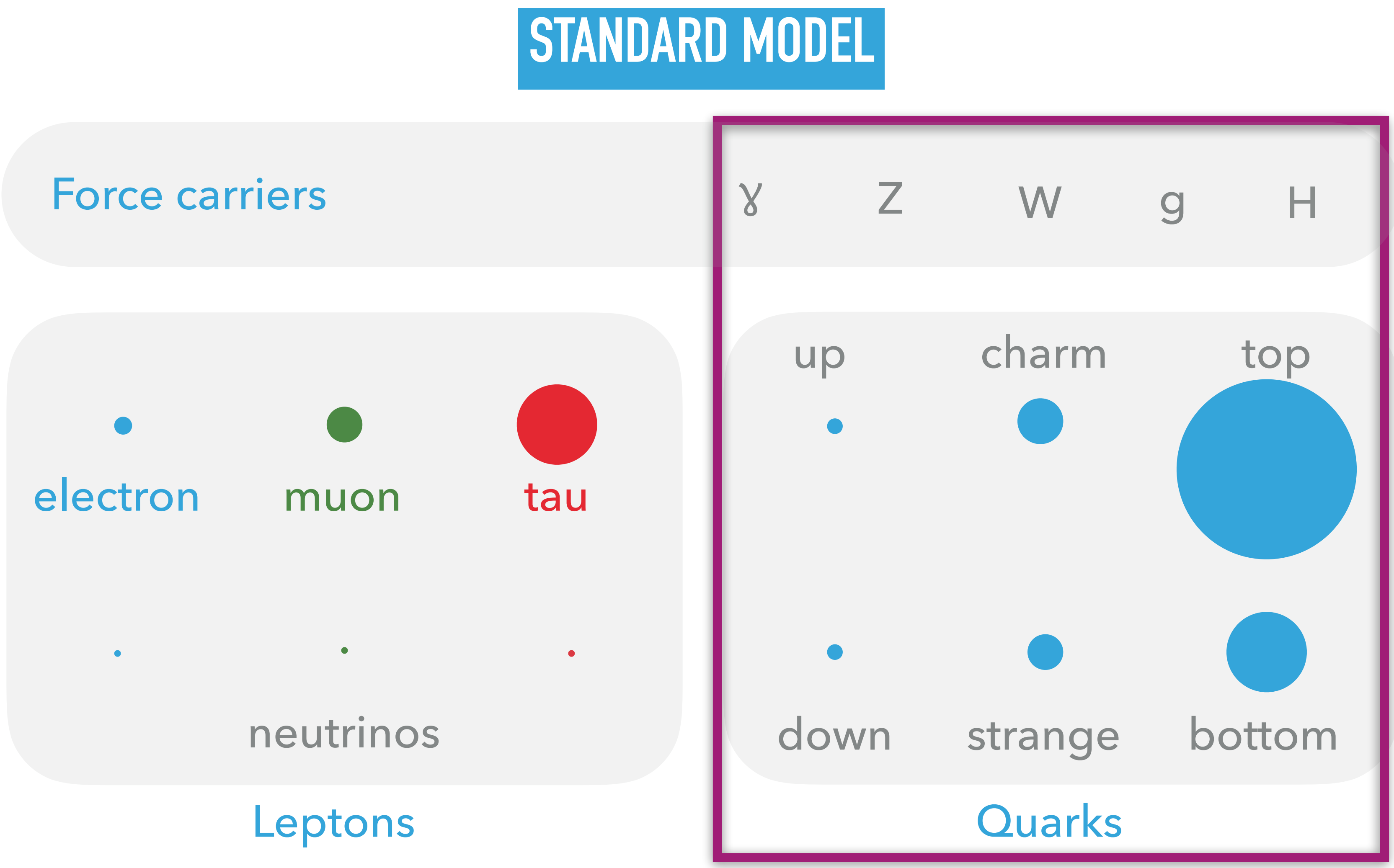
13/01/2021

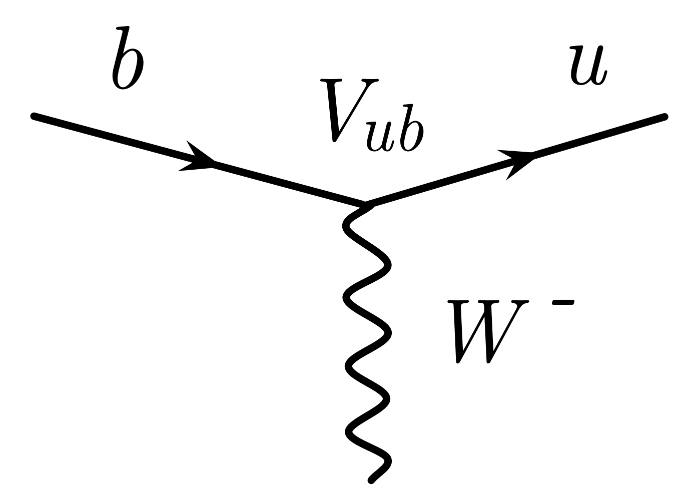
Quark coupling strengths



Quark coupling strengths

- Quark charged weak current couplings are described by the CKM matrix





- The size of the CKM matrix elements determines how much quark transitions are favoured or suppressed

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

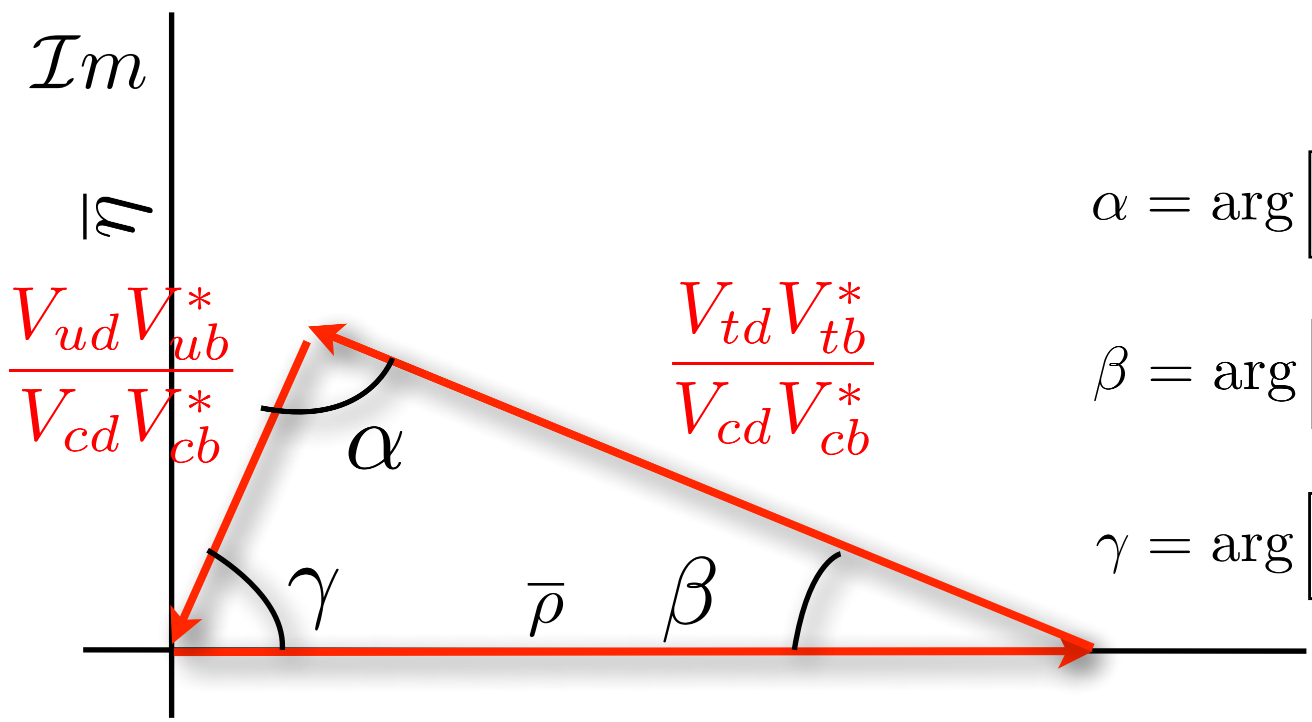
CKM quarks-mixing matrix

- Cabibbo-Kobayashi-Maskawa (CKM) matrix: 3 × 3 unitary matrix, can be parametrised with 3 angles and one CP-violating phase in the Standard Model

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

- From unitarity of the CKM matrix, the unitarity triangles

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



$$\alpha = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

CKM quarks-mixing matrix

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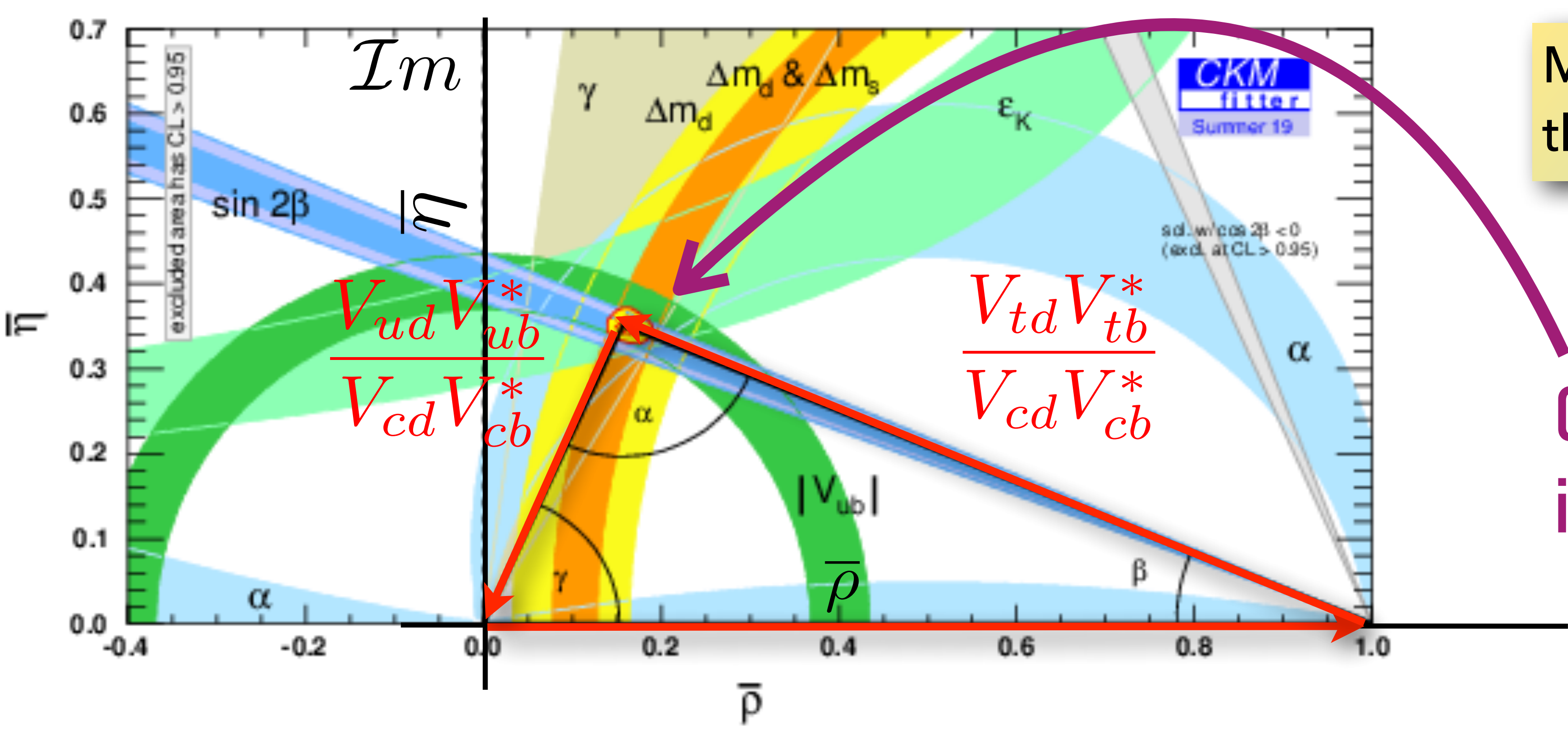
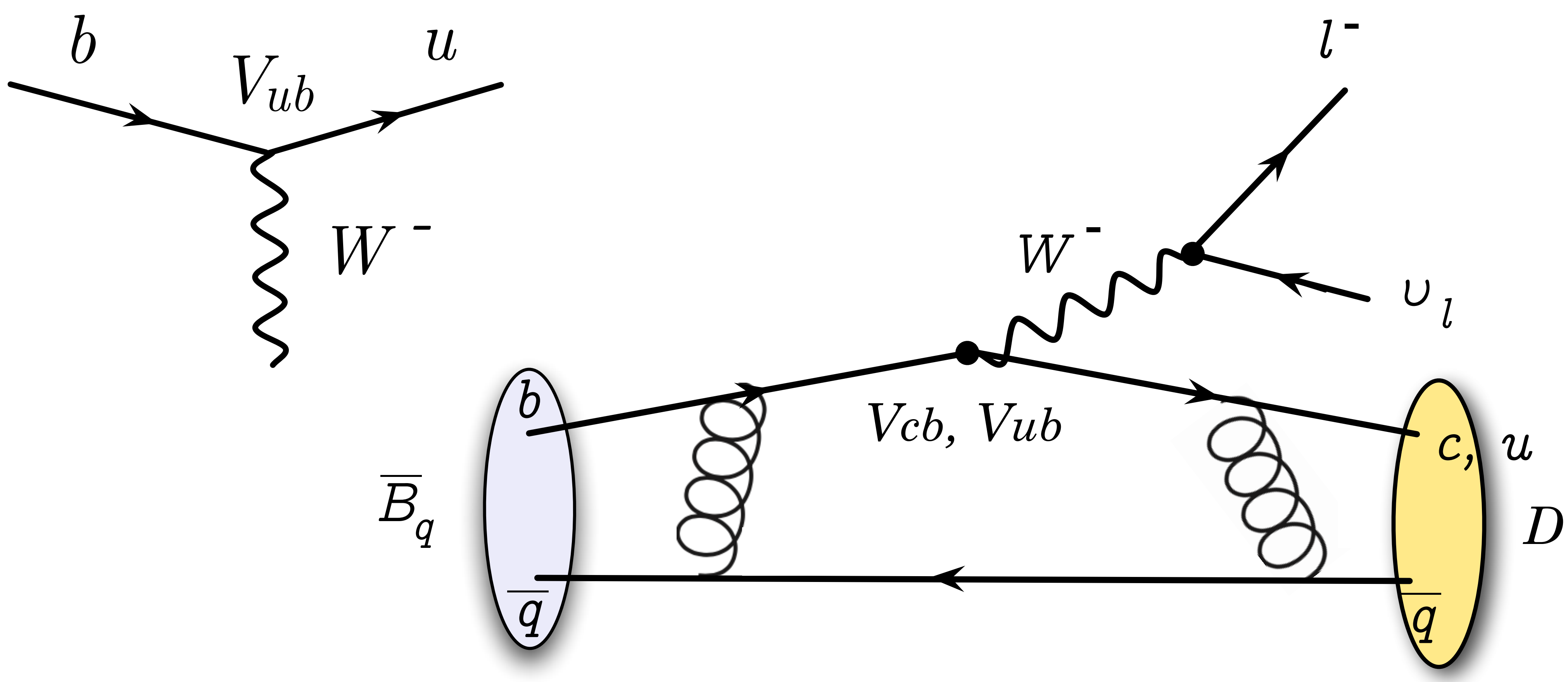


Measurements constraining the CKM elements

Closure of the Unitarity triangle is Standard Model test

Fantastic beasts: Semi-leptonic decays

- Charged current, tree-level (focus on b-hadron) semi-leptonic decays



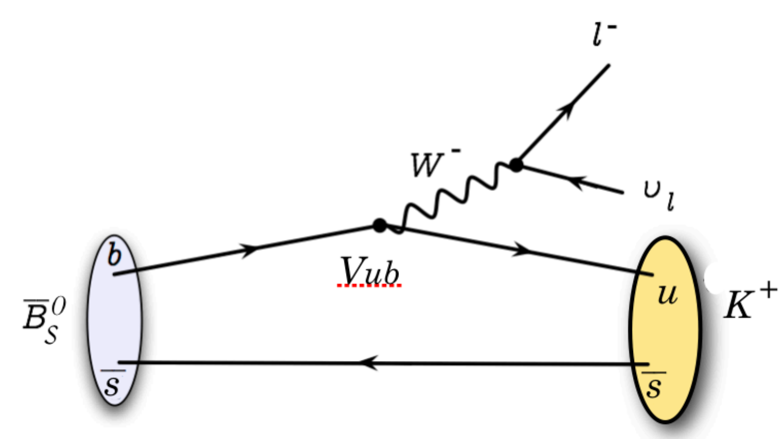
- Large branching fractions, systematics often are the real challenge
- Theoretical uncertainty controllable, depending on Lattice calculation improvements

Useful to measure CKM matrix elements

- Useful for many (direct) measurements of size of the CKM matrix elements

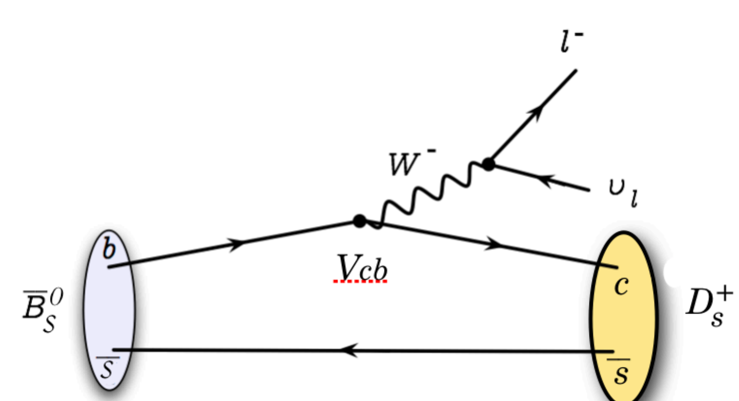
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$|V_{ub}| = (3.82 \pm 0.24) \times 10^{-3}$$



New |Vub|/|Vcb| measurement!

PAPER-2020-038, arXiv:2012.05143 submitted to PRL



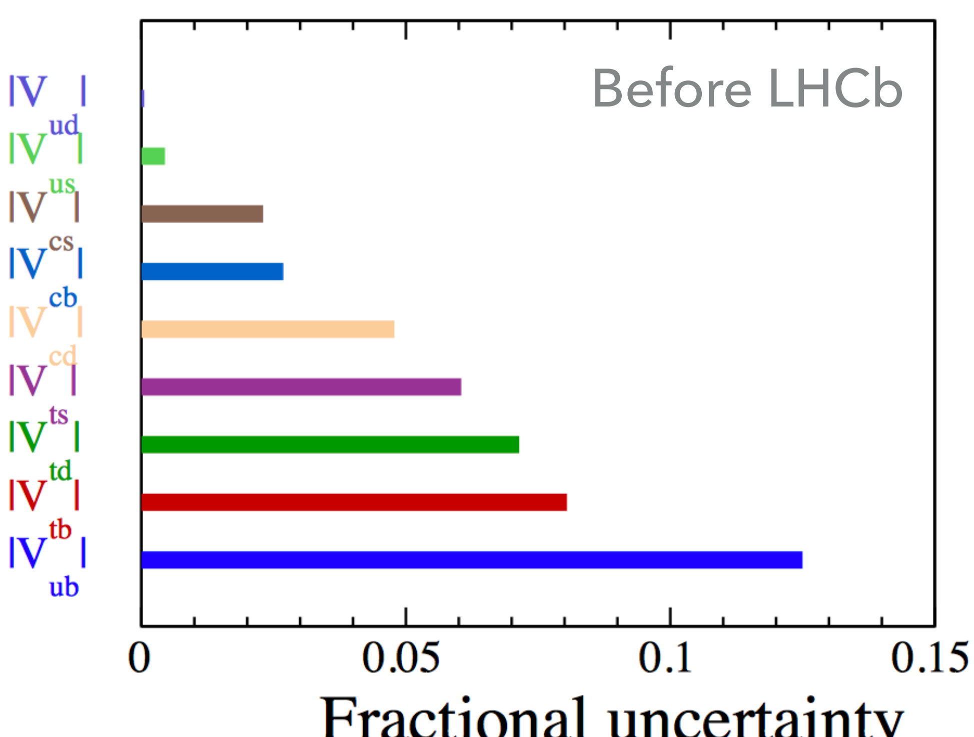
$$|V_{cb}| = (41.0 \pm 1.4) \times 10^{-3}$$

First |Vcb| measurement at a hadron collider!

Phys. Rev. D101 (2020) 072004

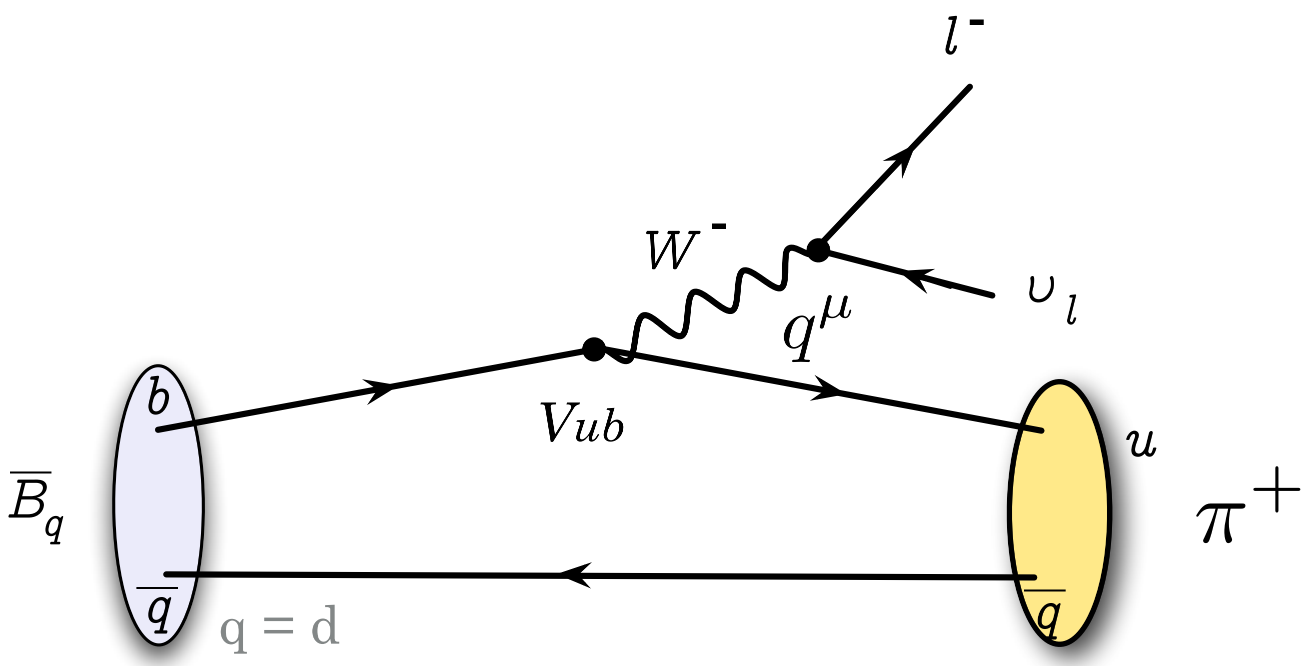
+ differential decay rate shape

JHEP 12 (2020) 144

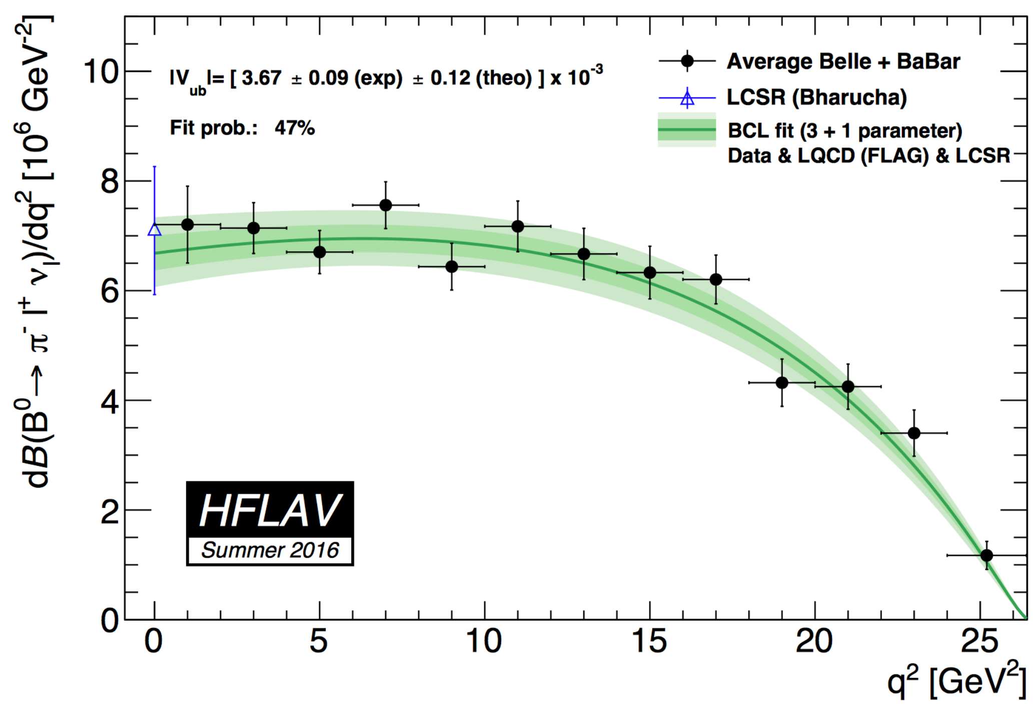


Exclusive $|V_{cb}|$ and $|V_{ub}|$ determinations

- Most frequently used semi-leptonic decay to measure |Vub|:



Ground state such a pion: useful to control theoretical uncertainties



Differential decay rate

Electroweak + phase space

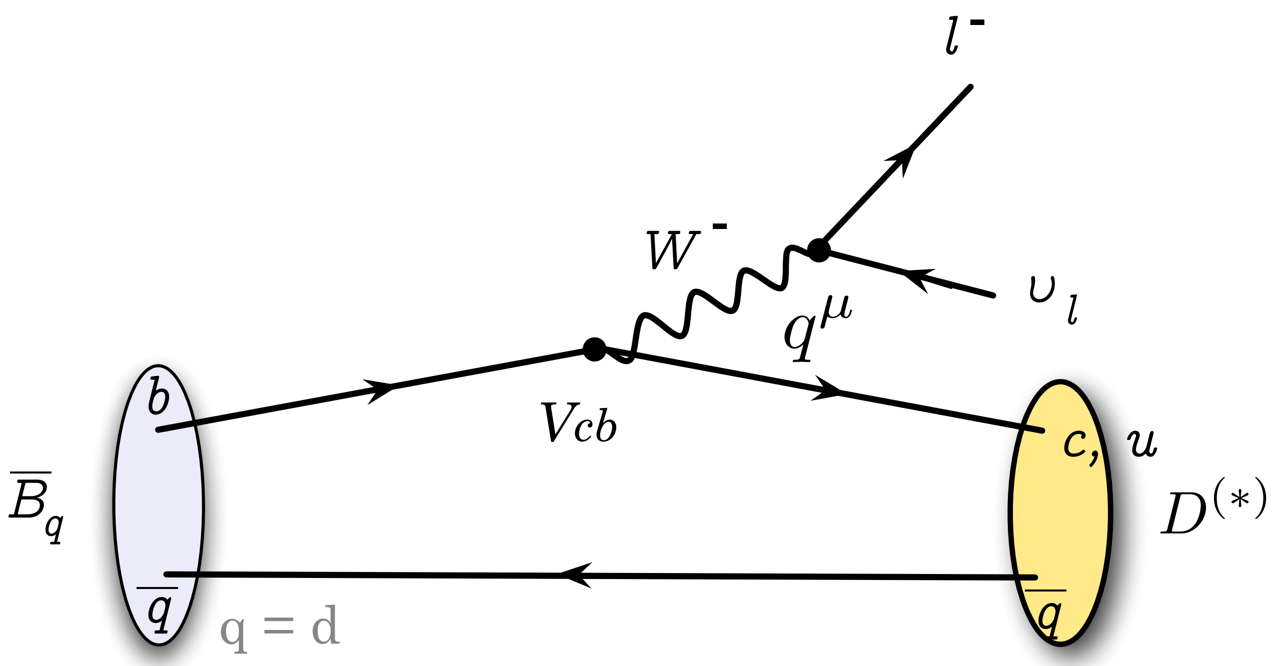
$$\frac{d\Gamma(\overline{B}^0 \to \pi^+ \mu^- \nu_\mu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2 |\vec{p_\pi}|^3}{24\pi^3} |f^+(q^2)|^2$$

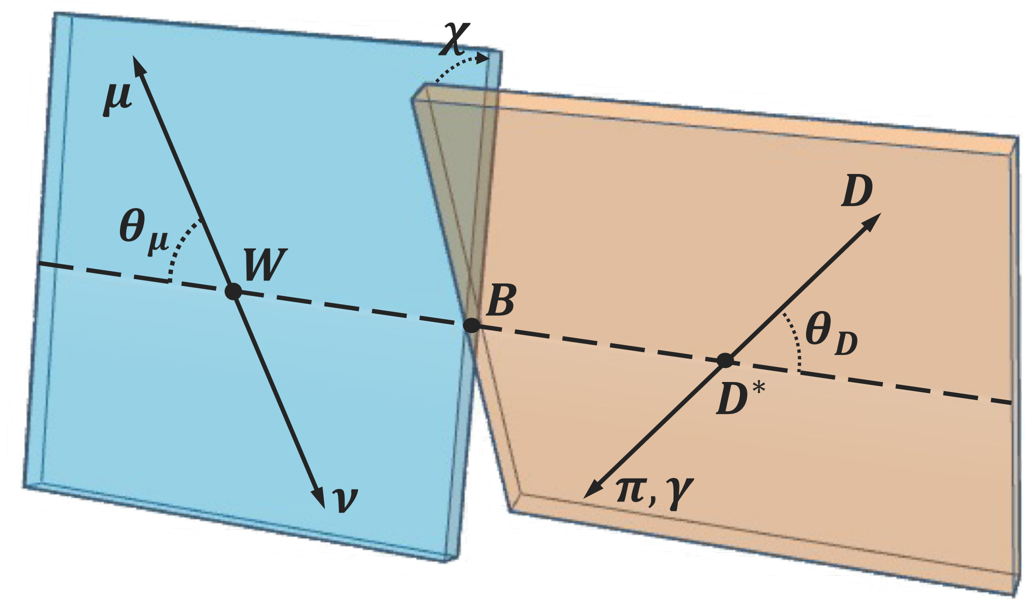
QCD

component encompassed by form factors

Exclusive $|V_{cb}|$ and $|V_{ub}|$ determinations

- Measure differential decay rate of each decay mode





Differential decay rate

Electroweak + phase space

$$\frac{d\Gamma(B^0 \to D^* \mu^+ \nu_\mu)}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |\eta_{EW}|^2 |\vec{p}| q^2}{96\pi^3 m_{B^0}^2} \left(1 - \frac{m_\mu^2}{q^2}\right)$$

$$\times \left[(|H_+|^2 + |H_+|^2 + |H_0|^2) \left(1 - \frac{m_\mu^2}{2q^2}\right) + \frac{3}{2} \frac{m_\mu^2}{q^2} |H_t|^2 \right]$$

*considering lepton mass

Helicity amplitudes

QCD component encompassed by form factors

Inclusive $|V_{cb}|$ and $|V_{ub}|$ determinations

- Forget about the Form Factors, just measure $b \to c\ell\nu$ or $b \to u\ell\nu$

- Measure total semi-leptonic branching ratio, distributions of lepton energy and hadronic invariant mass spectra

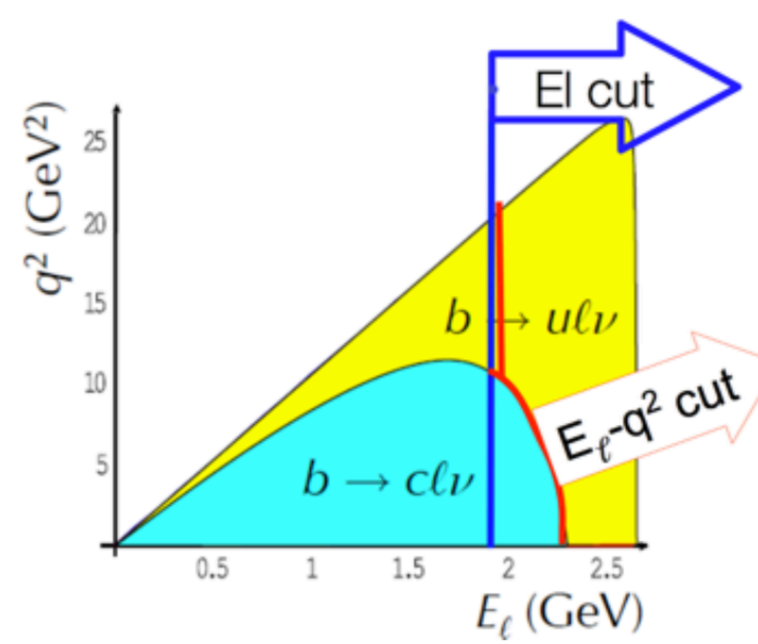
- |Vxb| extraction based on Operator Product Expansion

$$\Gamma(B \to X_c^- \ell^+ \nu) \propto |V_{cb}|^2 \left[\mathcal{O}(\alpha_s) + \mathcal{O}(\alpha_s^2) + \ldots + \mathcal{O}\left(\frac{\Lambda_{QCD}^2}{m_b^2}\right) + \mathcal{O}\left(\frac{\Lambda_{QCD}^3}{m_b^3}\right) + \ldots \right]$$

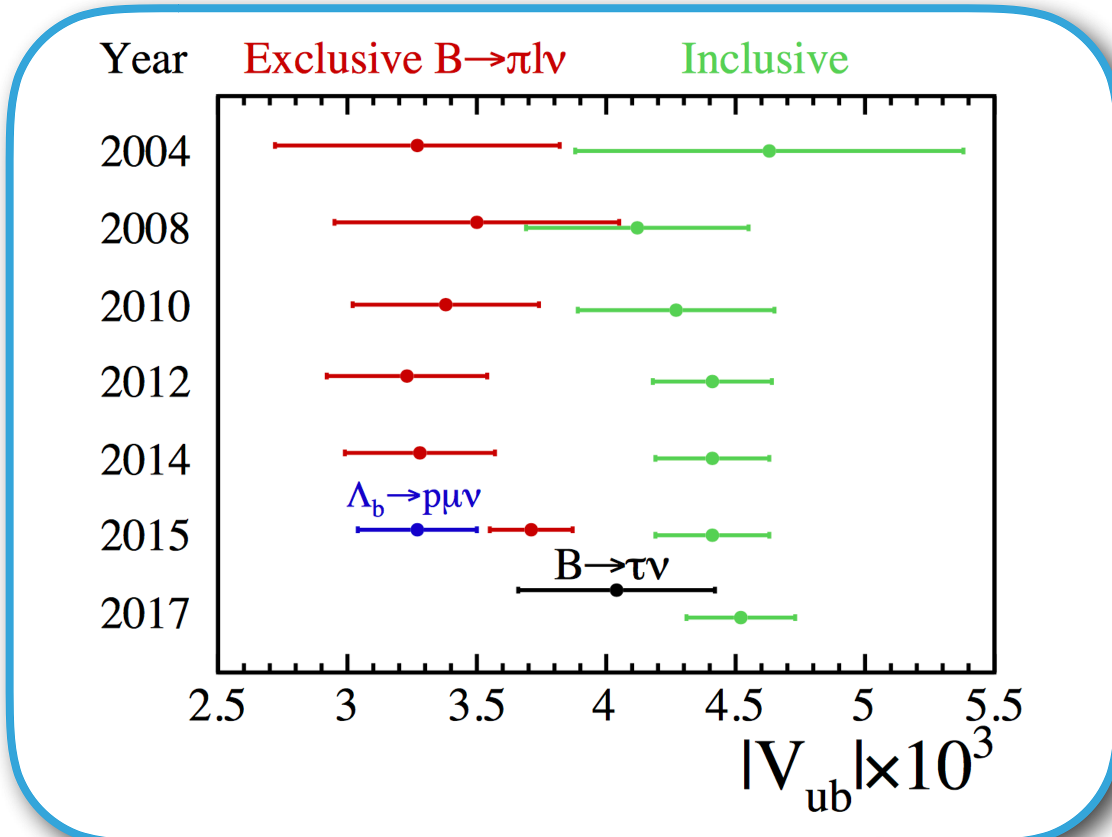
Perturbative expansion

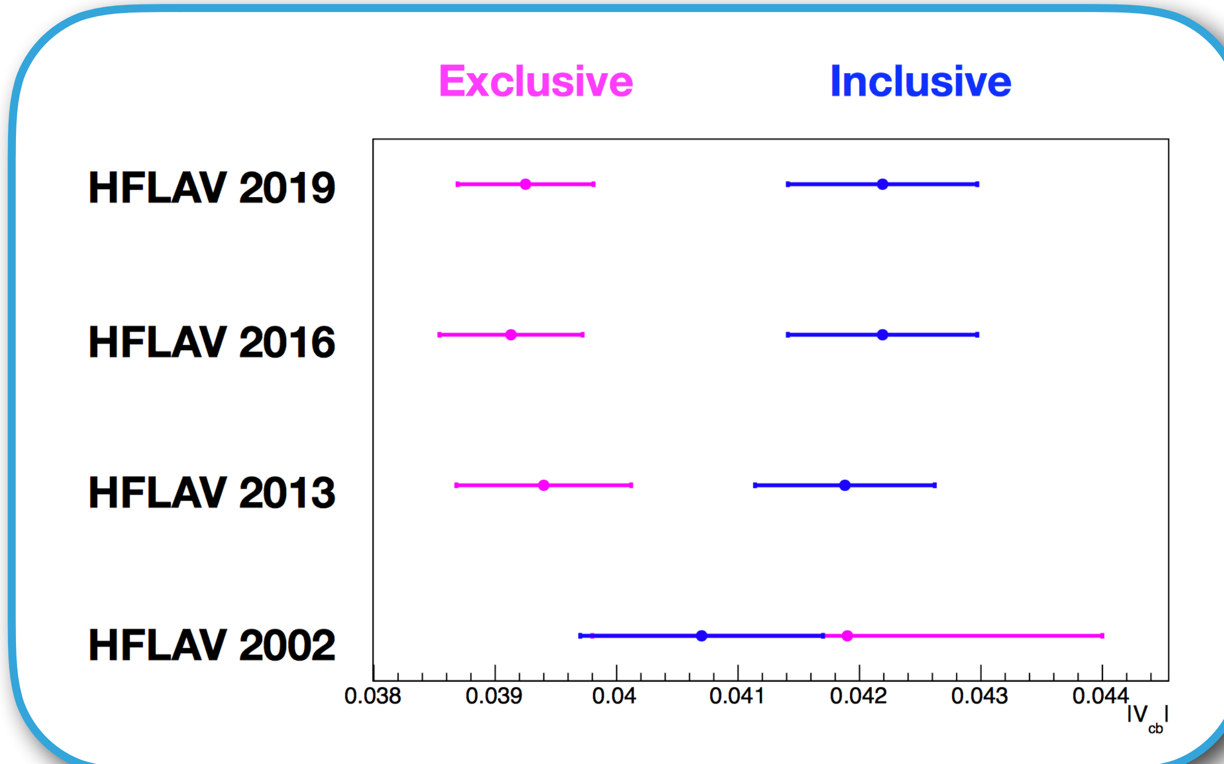
Non perturbative corrections

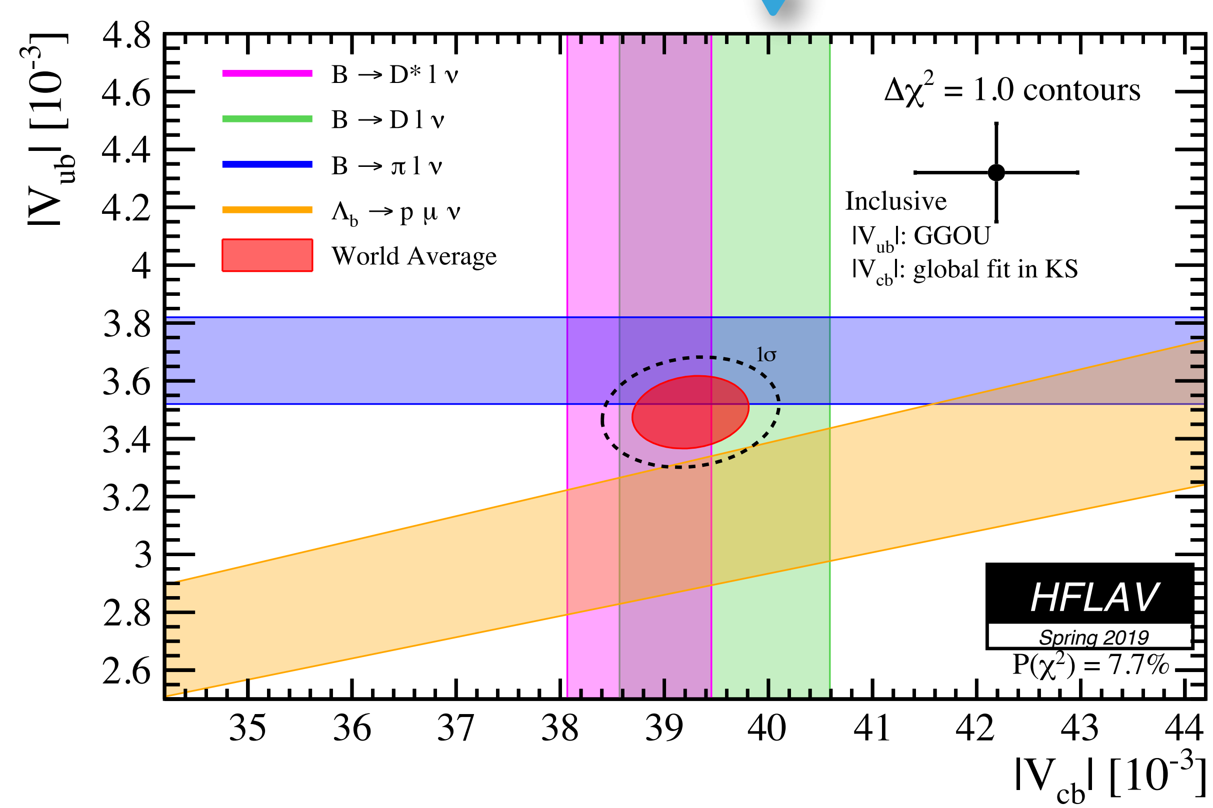
- Experimentally very difficult, especially for Vub transitions: large Vcb background to be excluded



$|V_{cb}|$ and $|V_{ub}|$ status and history



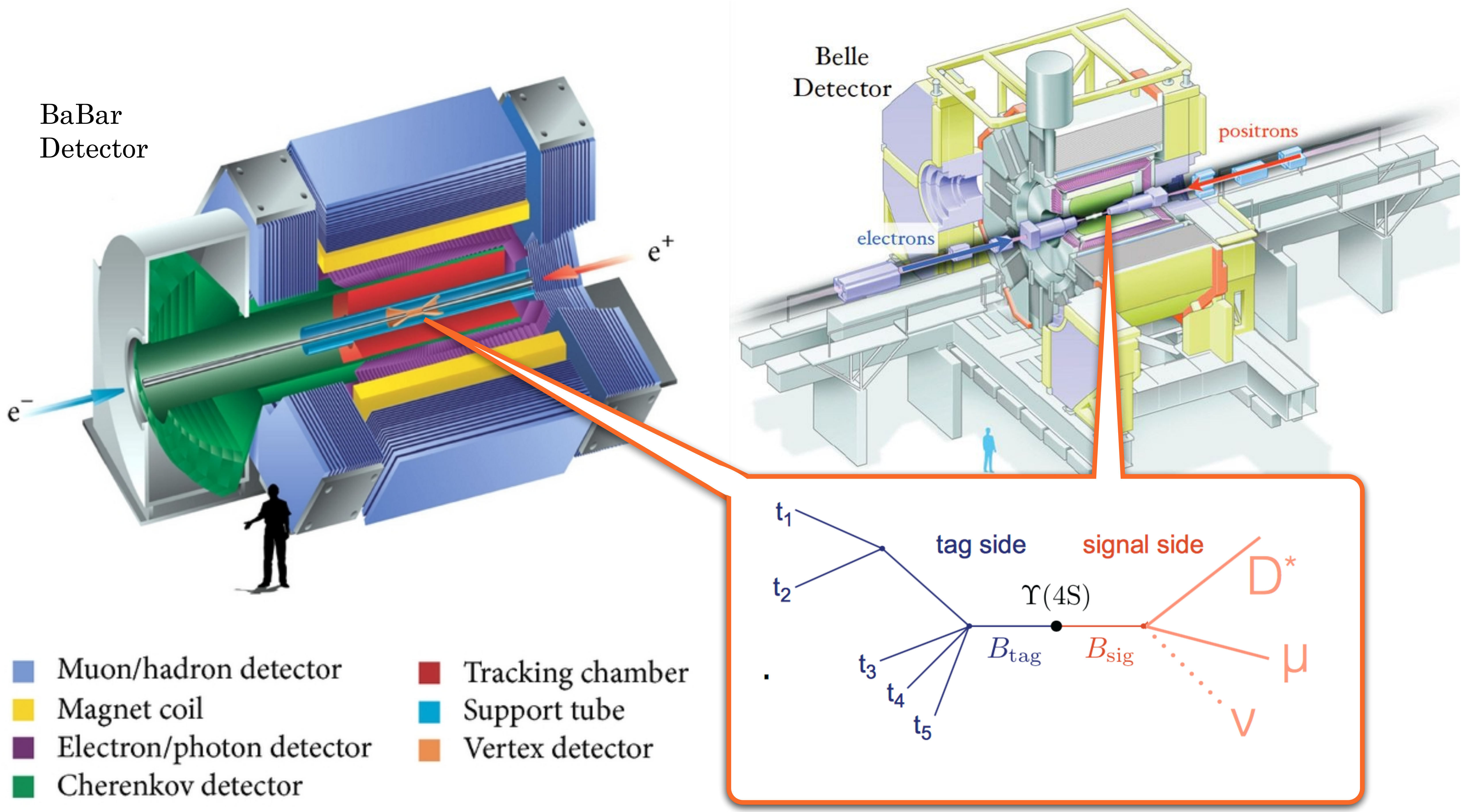




- Not a new discrepancy!
- Vcb: measurements from ALEPH, OPAL (excl. only), CDF (incl. only) DELPHI, CLEO, BaBar, Belle and LHCb (excl. only)
- Vub: measurements from CLEO, BaBar, Belle and LHCb (excl. only)

And where to find them

- B-factories: $B\bar{B}$ produced in pair: clean environment and constrained kinematics

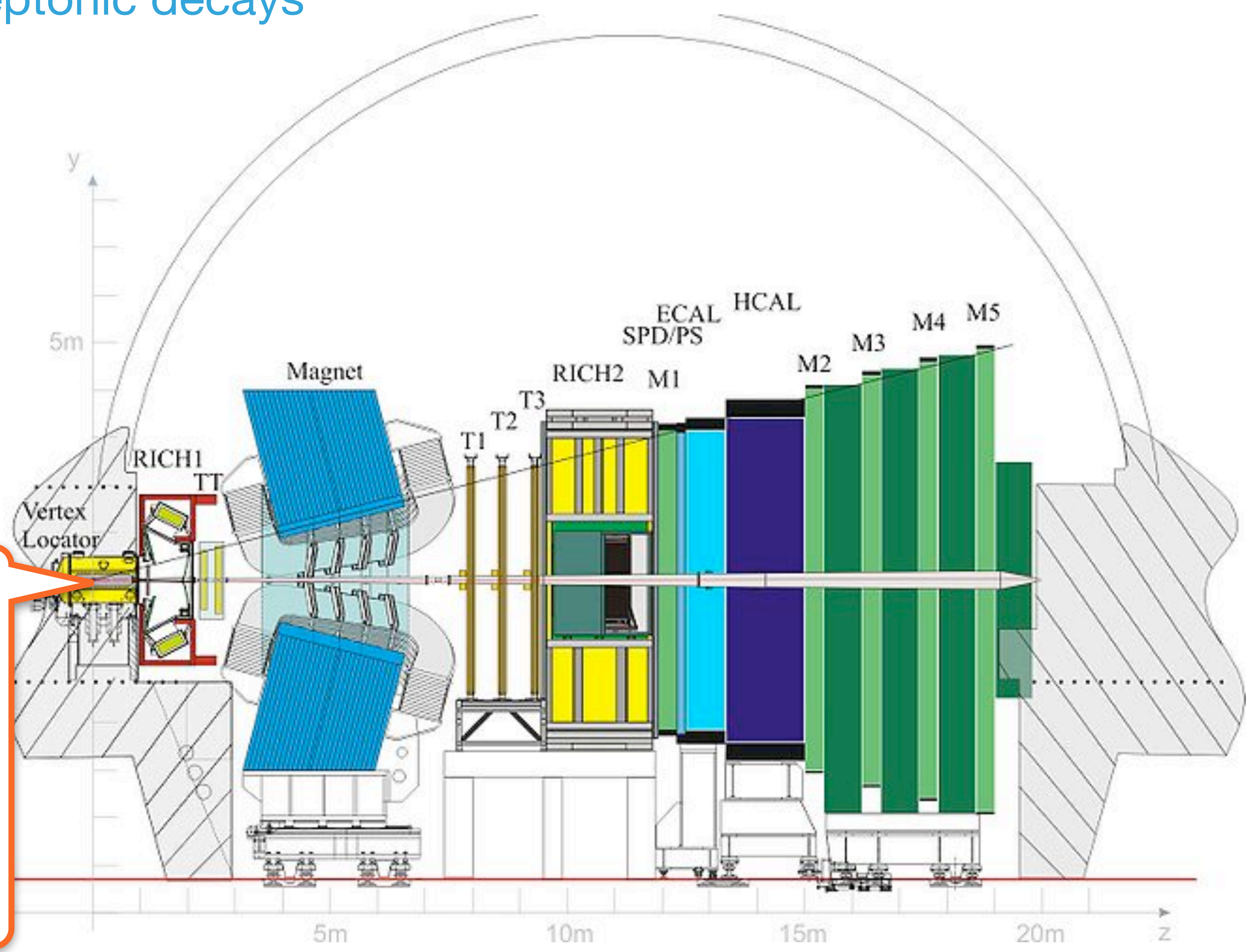


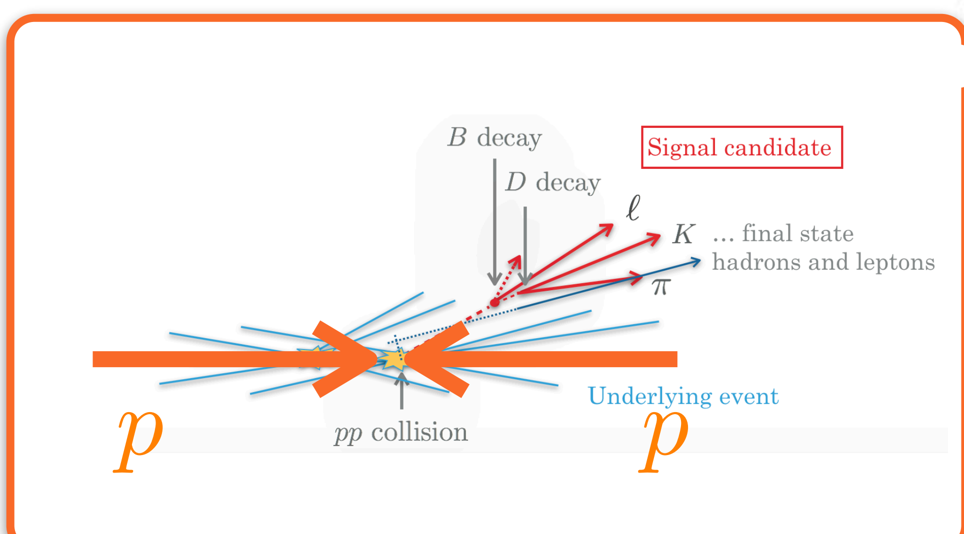
And where to find them

- Single-arm forward spectrometer at LHC collider
    - ~25 kHz bb pairs, ~500 kHz cc pairs produced in the forward region

  Large samples of semi-leptonic decays

- All hadron species are accessible!

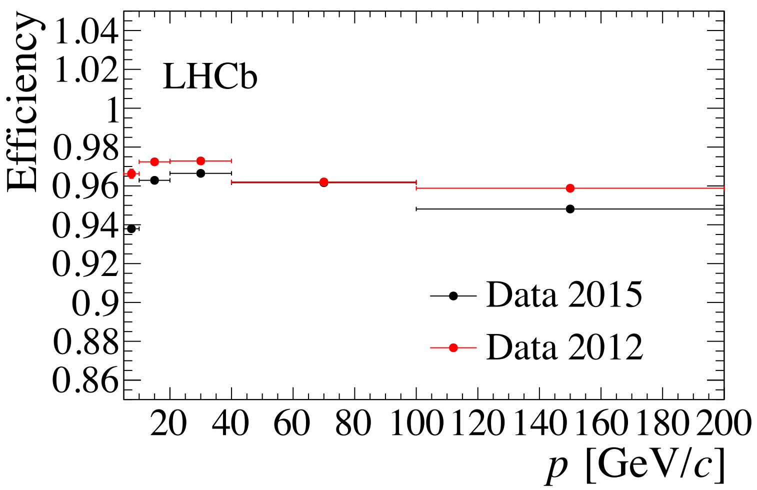




And where to find them

in the forward region

Tracking system: excellent track & vertex reconstruction



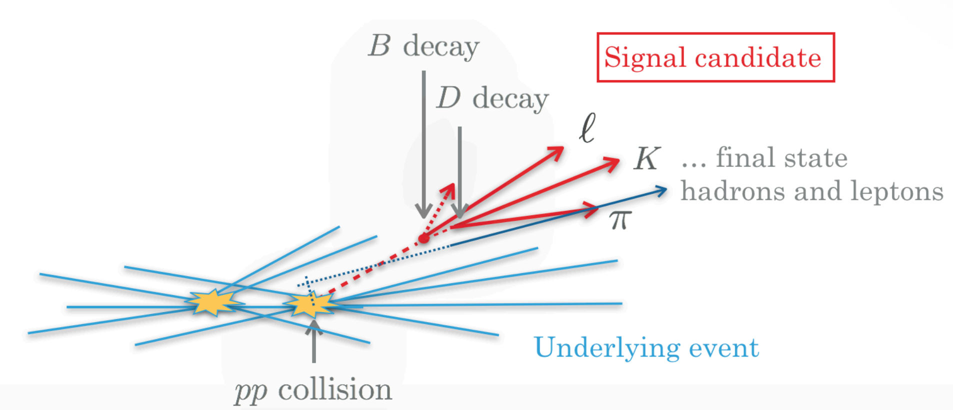
Tracking efficiency > 96%

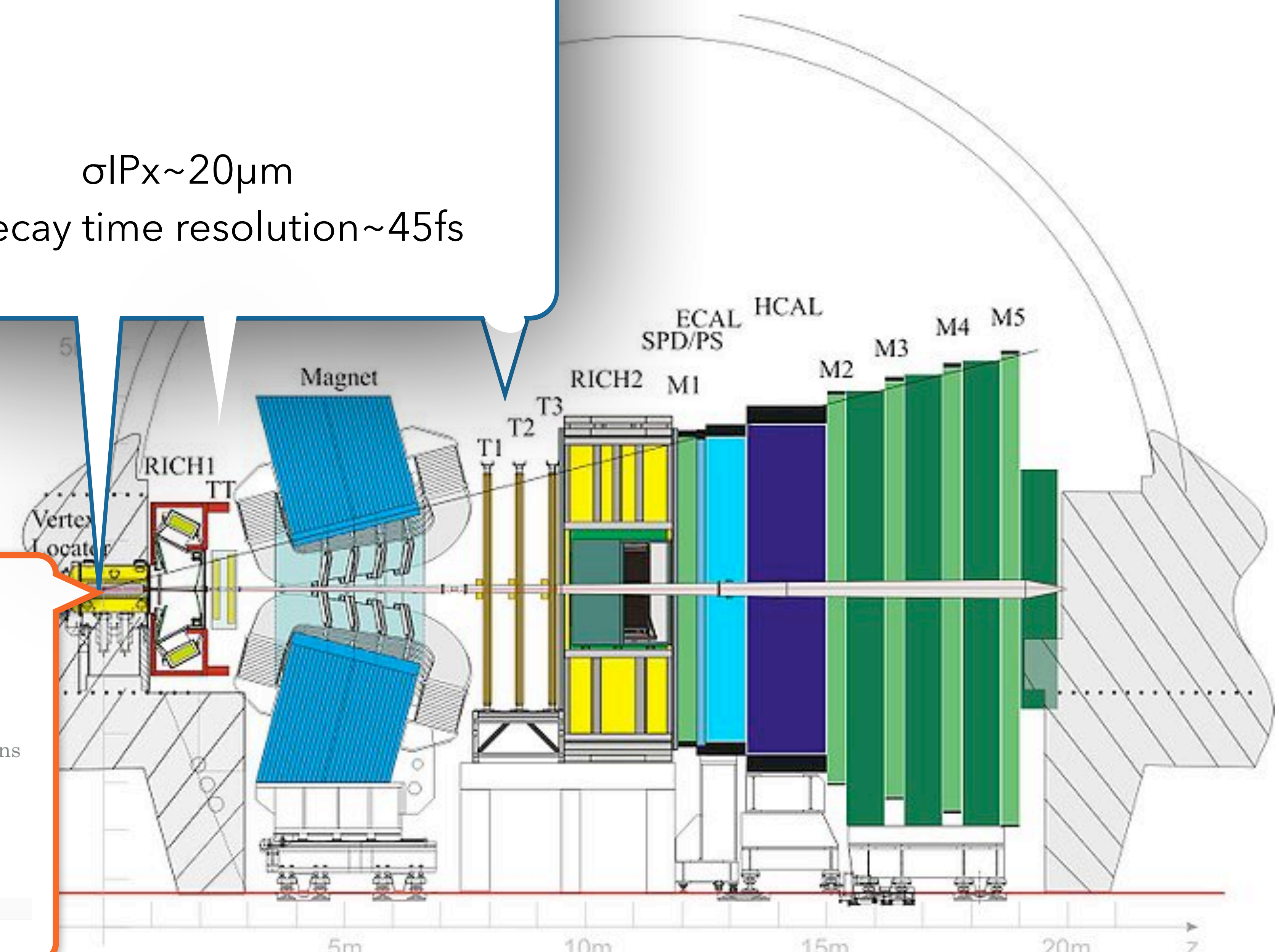
Δp/p = 0.5-1.0%

σIPx~20μm

decay time resolution~45fs

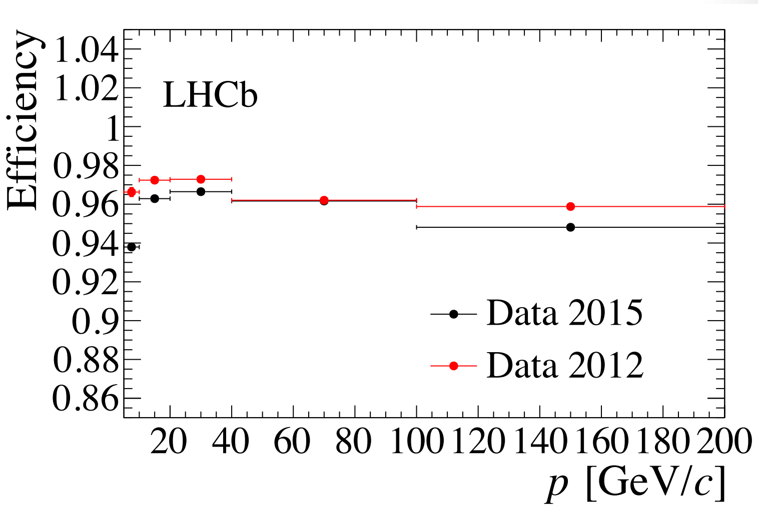
JINST 14 (2019) P04013





And where to find the

Tracking system: excellent track &



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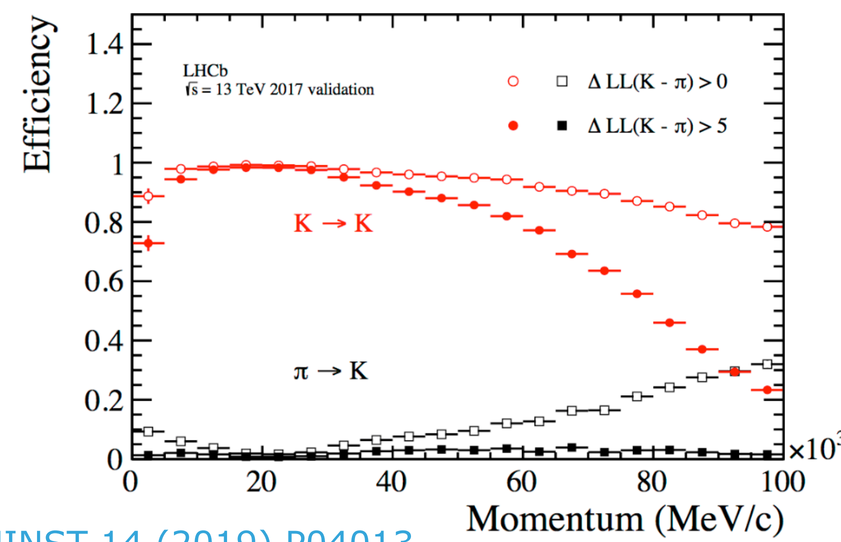
Tr

decay time resolution~45fs

Particle identification



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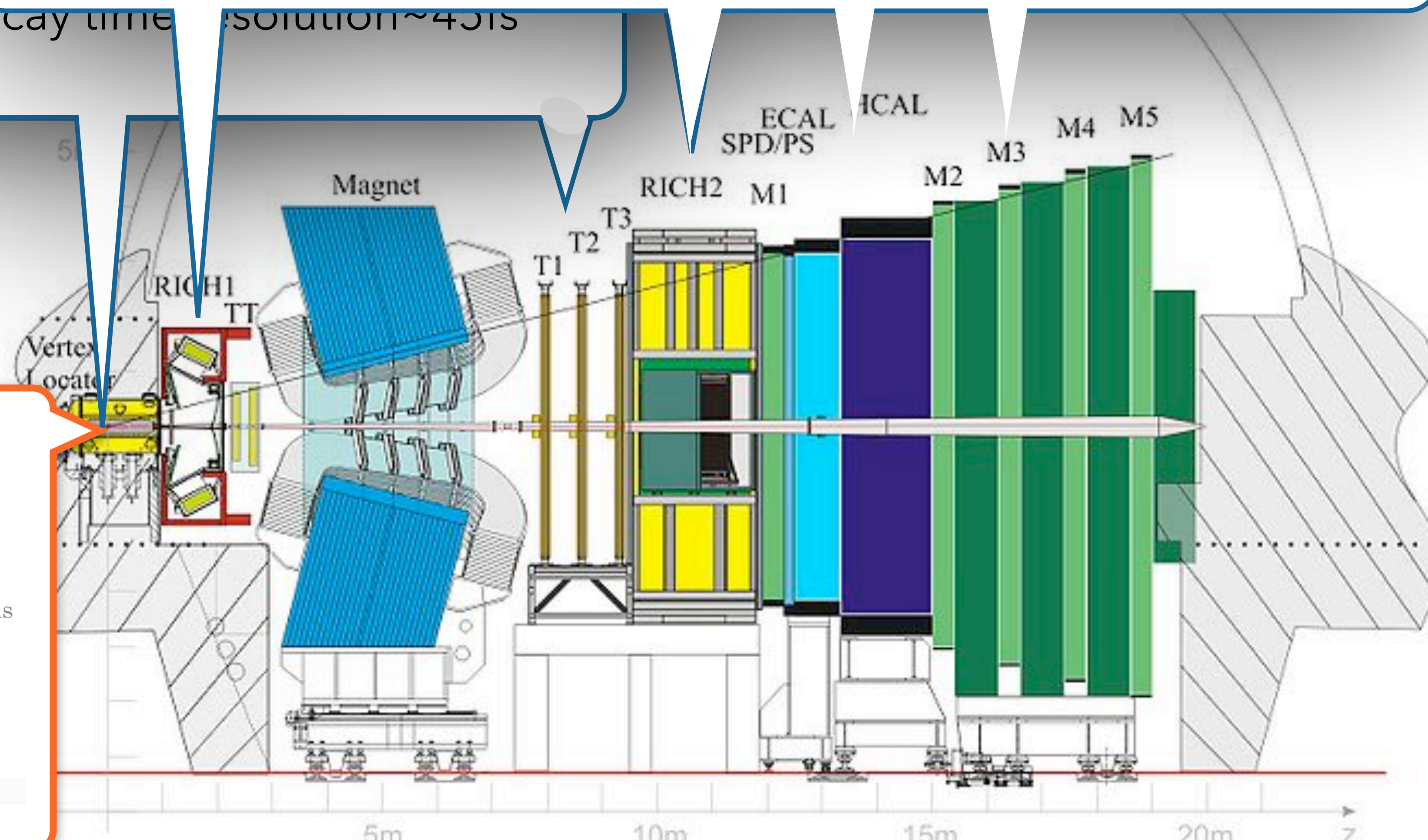
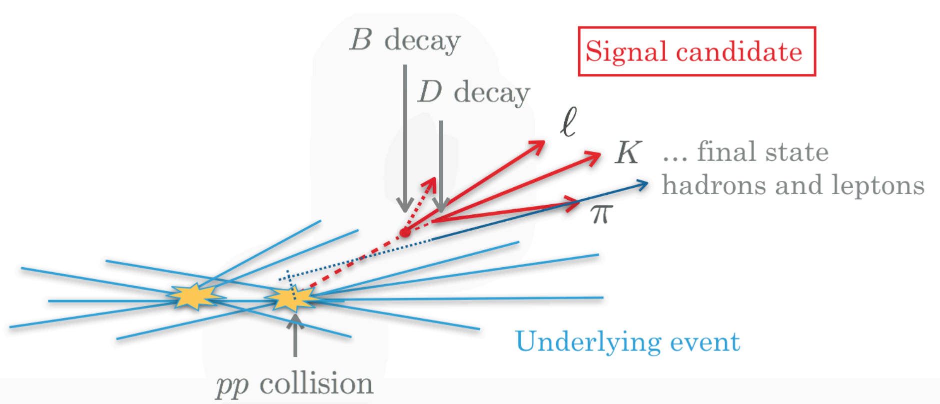
Distinguish between muon, electrons, pions, kaon and protons

Kaon ID efficiency ~95%
Pion mis-ID fraction ~10%
Muon ID efficiency ~97%





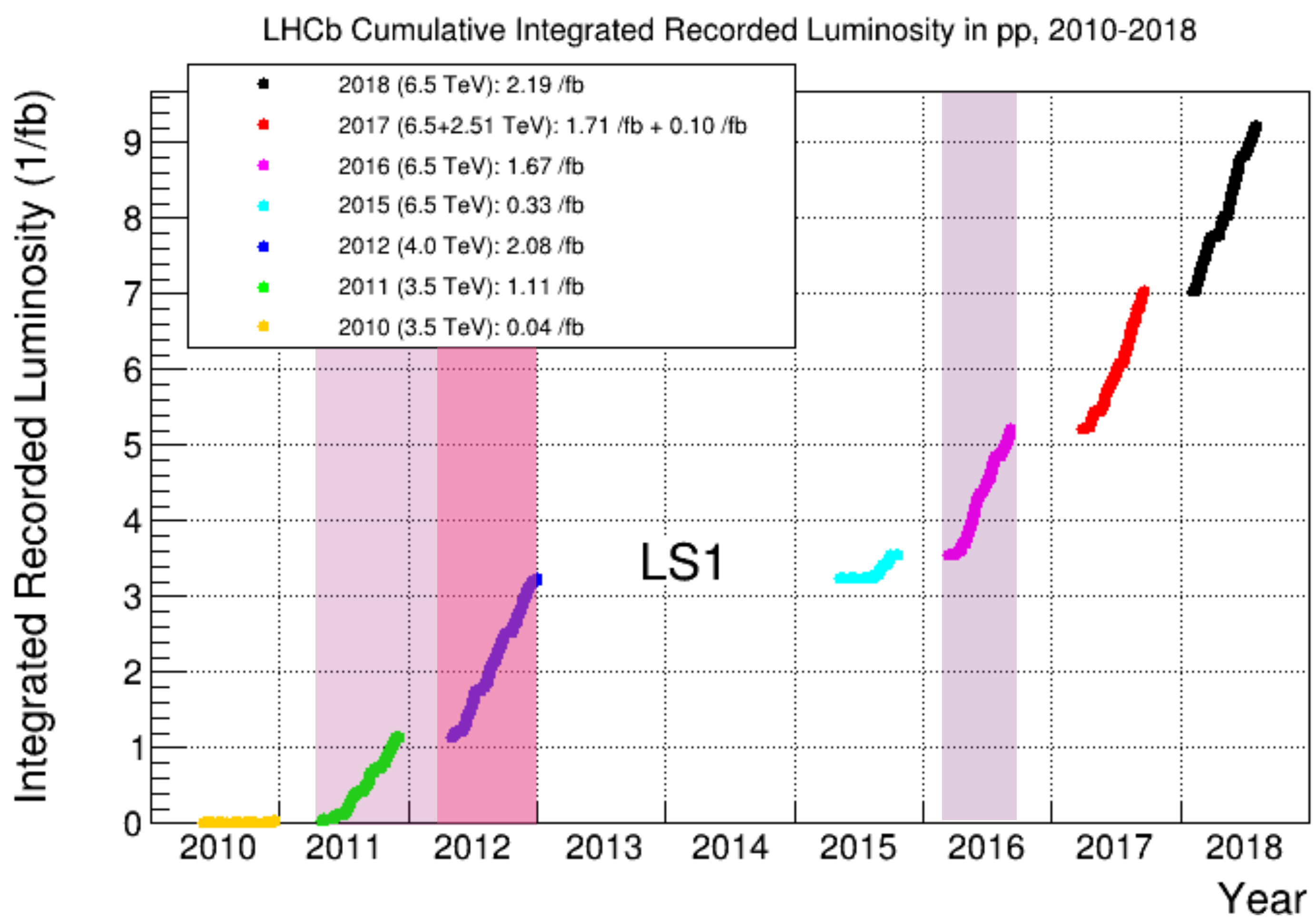
And where to find them

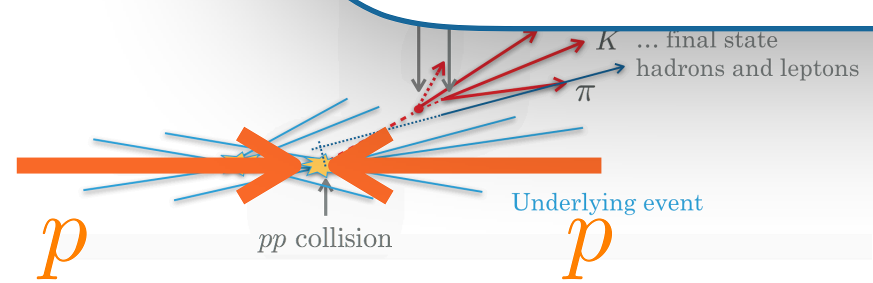
- Single-arm forward spectrometer at LHC collider
  - ~?

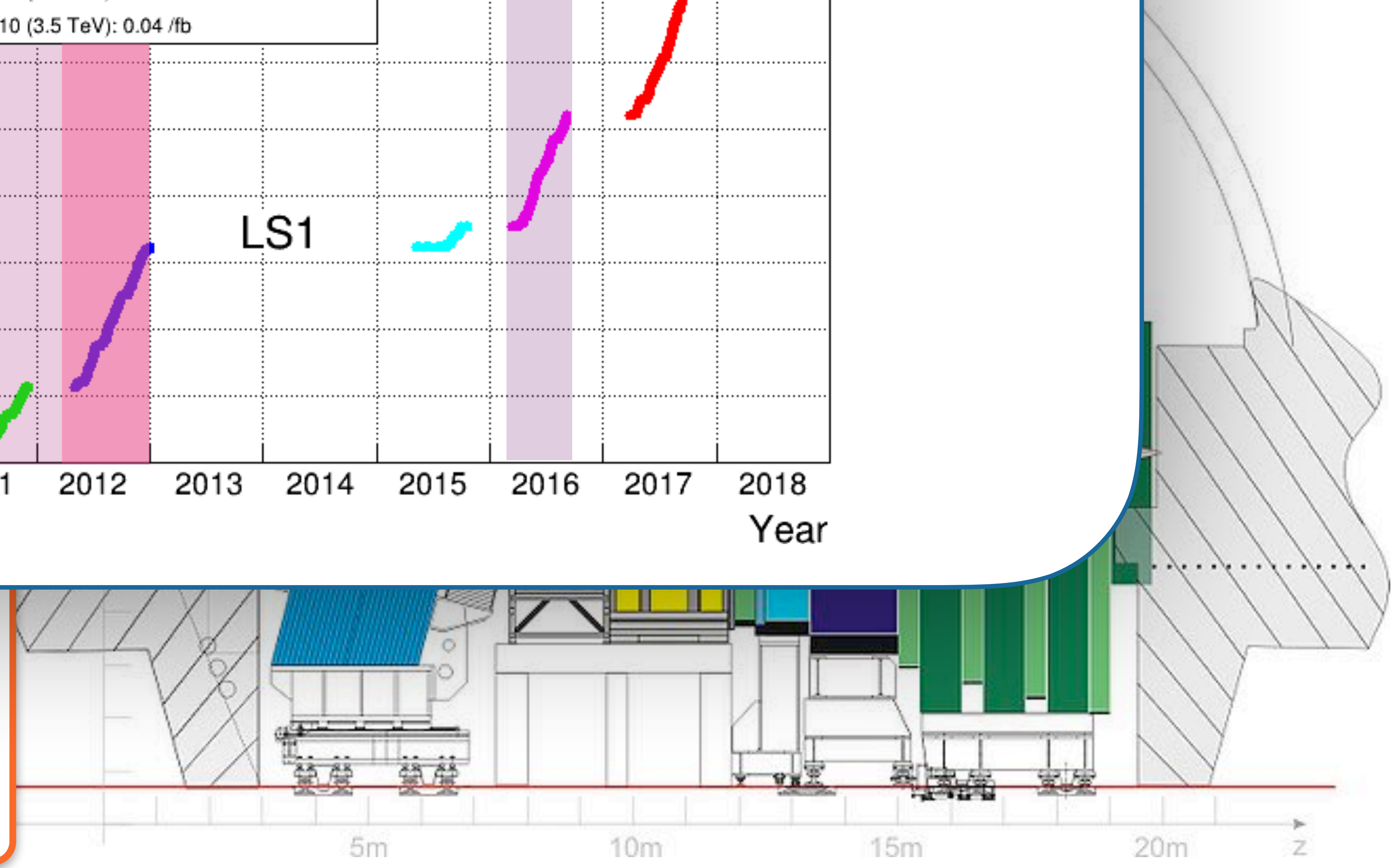
  Larg

- All ha
  are a

Measurements shown here use a subset of the dataset collected!

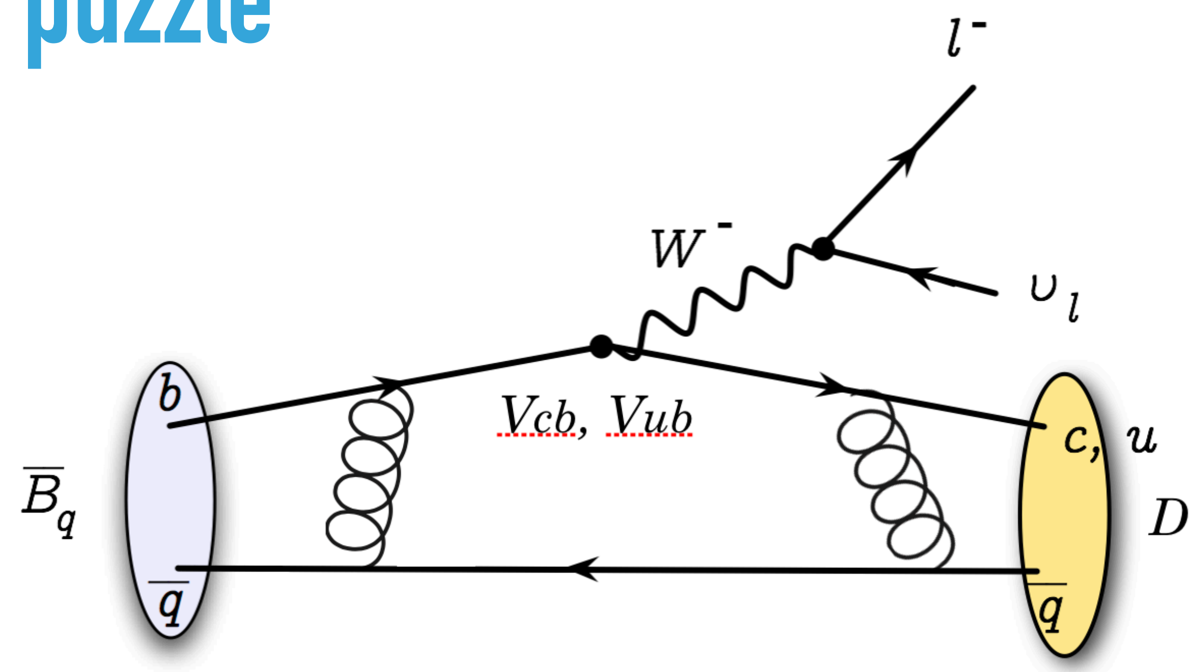




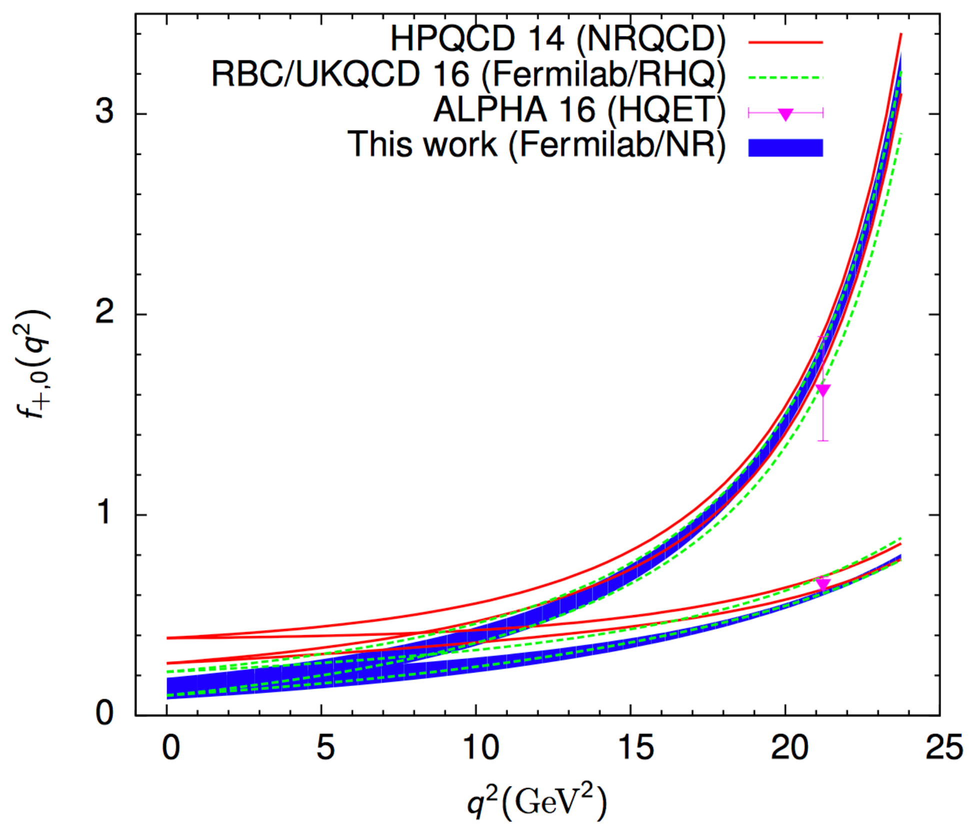


Adding some strangeness to the puzzle

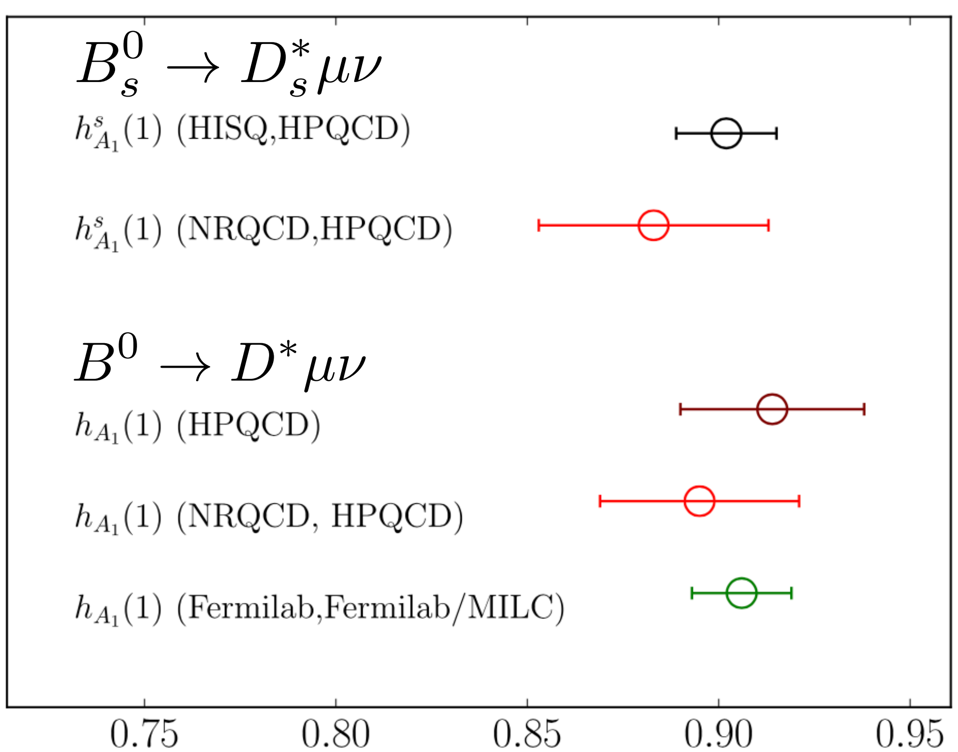
- Experimentally complementary (e.g. different background composition)
- Heavier spectator quark is an advantage for Lattice QCD calculations
- Lots of recent interesting theoretical work



Phys. Rev. D 100, 034501 (2019)

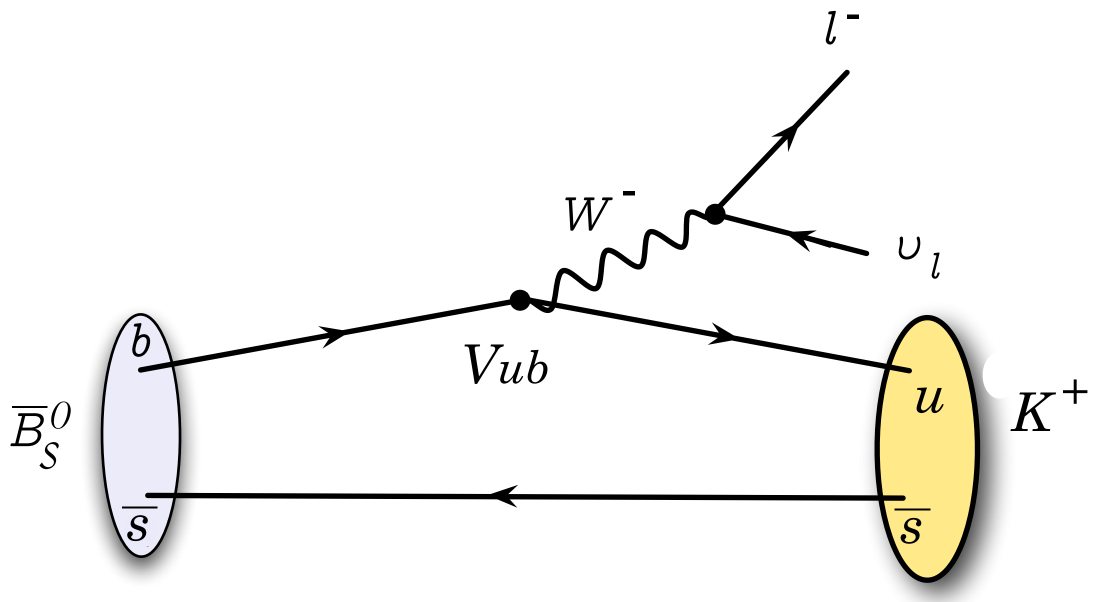


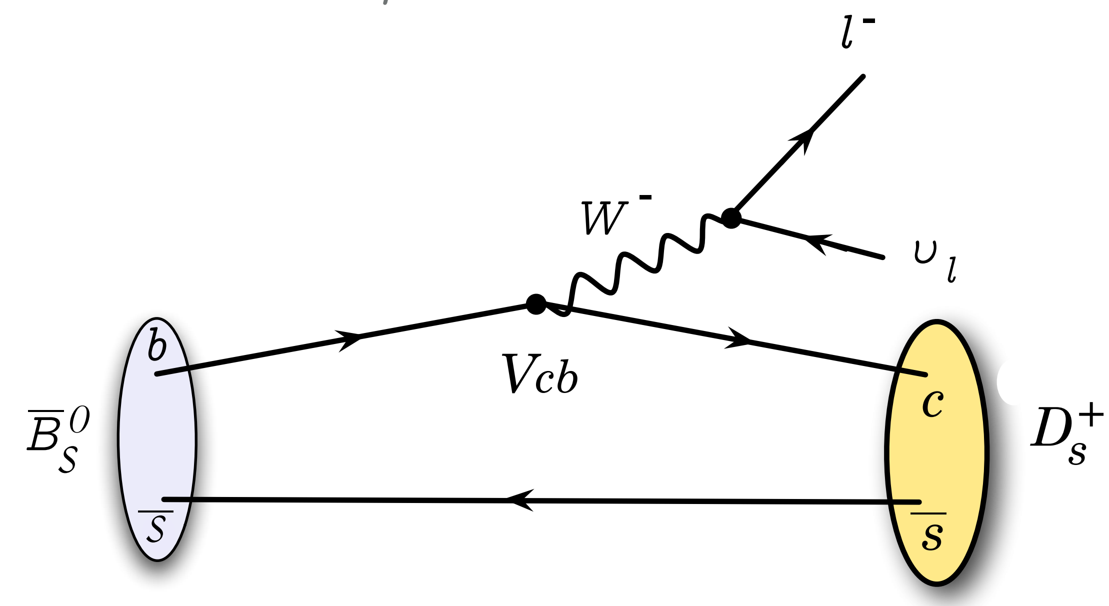
PRD 99 (2019) 114512



Measuring $|V_{ub}|$ using $B_s^0 \to K^- \mu^+ \nu_\mu$ decays

- Different spectator quark with respect to $B^0 \to \pi \mu \nu_\mu$





$$\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \frac{d\Gamma(B_s^0 \to K^- \mu^+ \nu_\mu)/dq^2}{d\Gamma(B_s^0 \to D_s^- \mu^+ \nu_\mu)/dq^2}$$

Experimental measurement: yields & precise efficiency measurement

Theory input

- Theory input: Complementary approaches, decay rates predicted as a function of q^2
  - $B_s^0 \to K^- \mu^+ \nu_\mu$ LCSR(precise at low q^2) & LQCD(precise at high q^2)
  - $B_s^0 \to D_s^- \mu^+ \nu_\mu$ LQCD(precise over full q^2 spectrum)

Hadronic form factors

- Theory input: Complementary approaches, decay rates predicted as a function of q^2
  - $B_s^0 \to K^- \mu^+ \nu_\mu$ LCSR(precise at low q^2) & LQCD(precise at high q^2)
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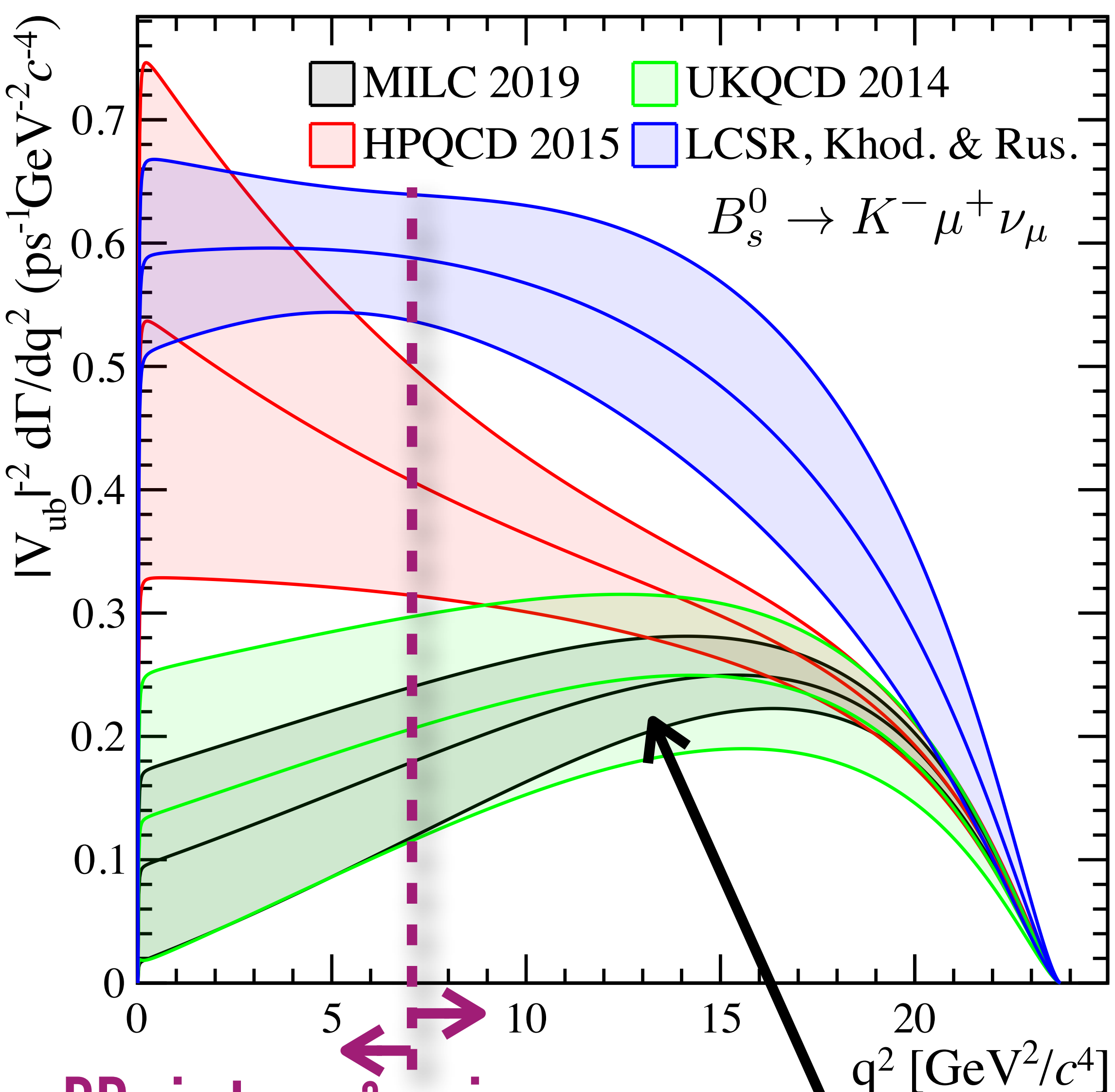
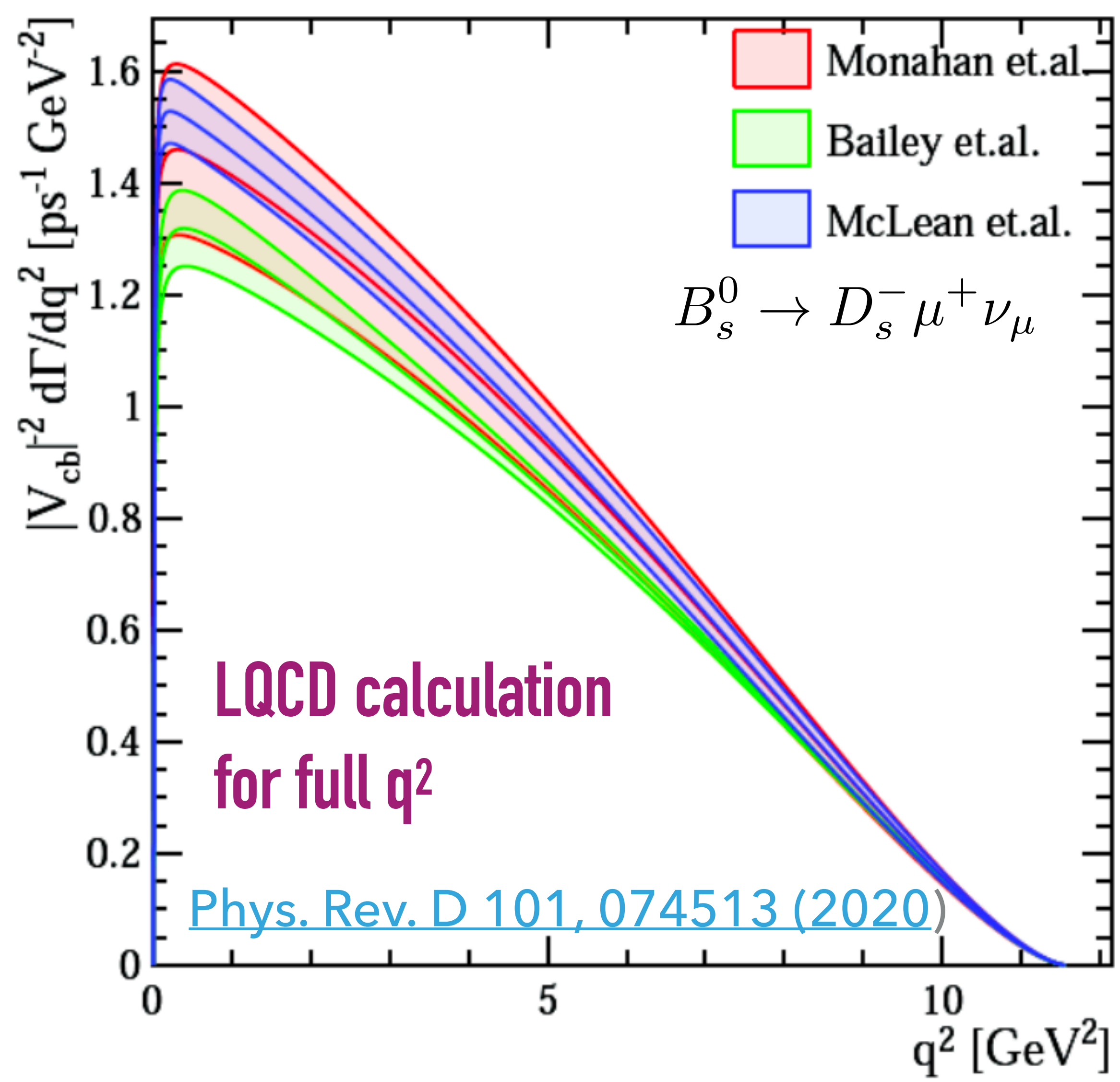
JHEP08(2017)112

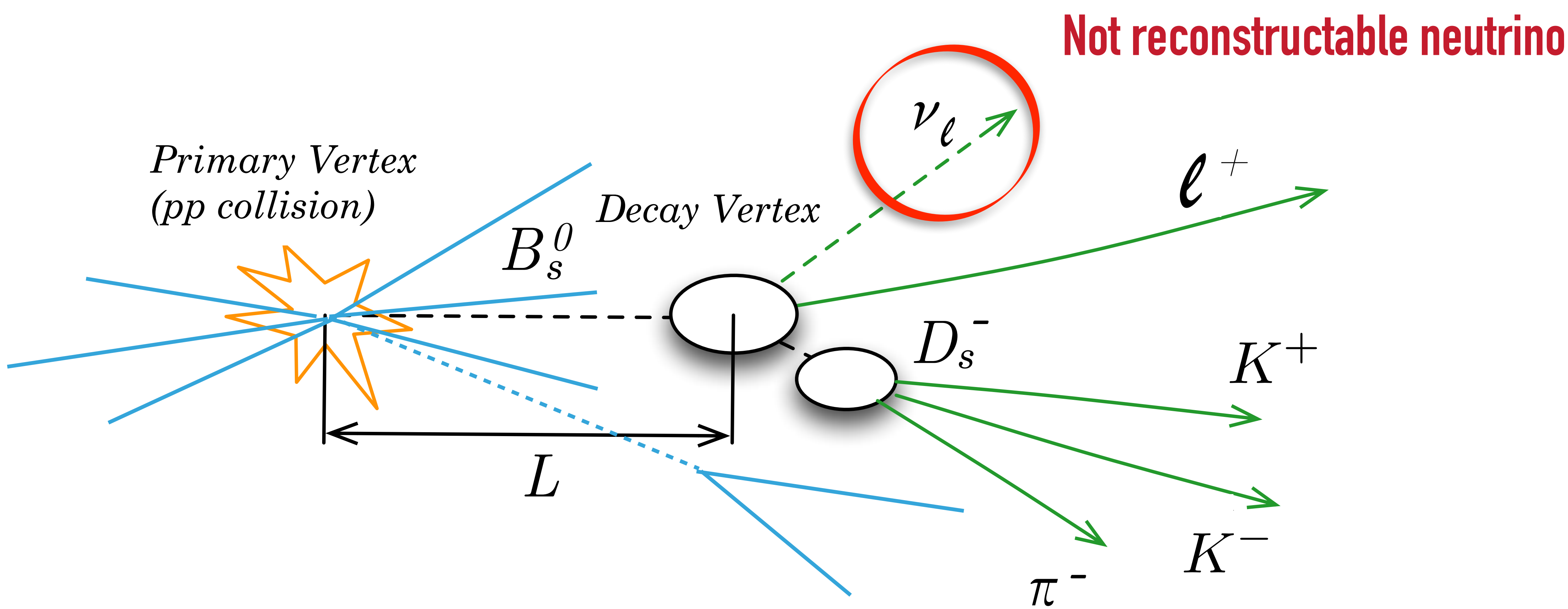


Two BRs in two q^2 regions



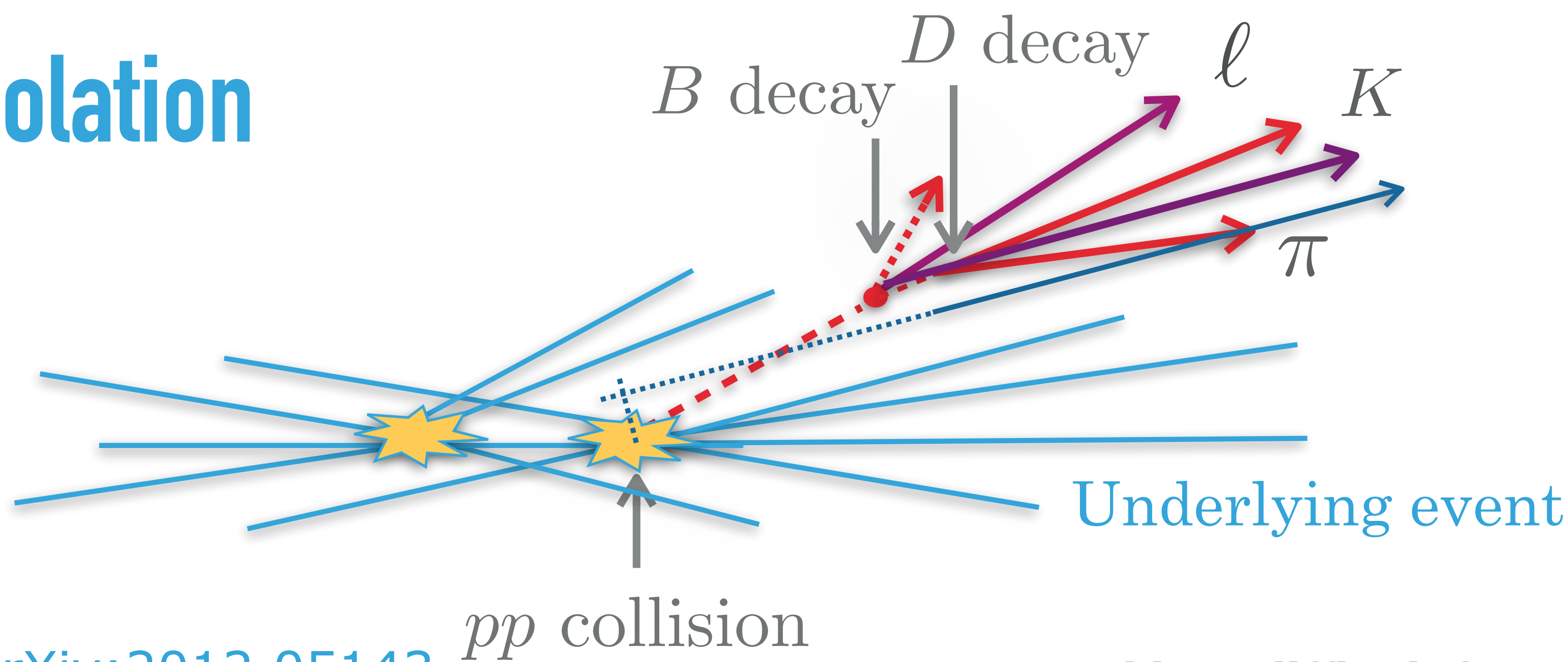
Phys. Rev. D 100, 034501 (2019)

Typical semi-leptonic signatures



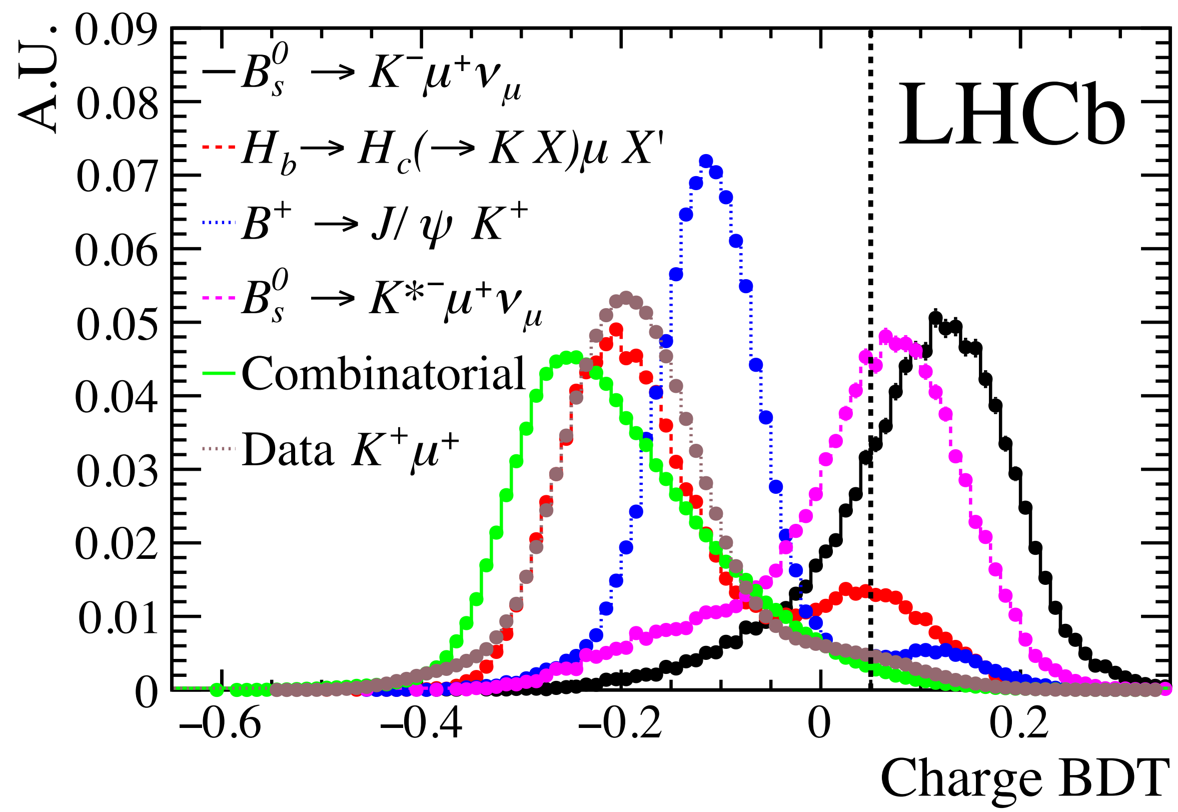
- Partial reconstruction → unconstrained kinematics: (with a single missing particle we can solve for the missing 3-momentum, with a quadratic ambiguity)
- Partial reconstruction → large backgrounds: need to fully exploit vertex topology information, track isolation, available kinematic information

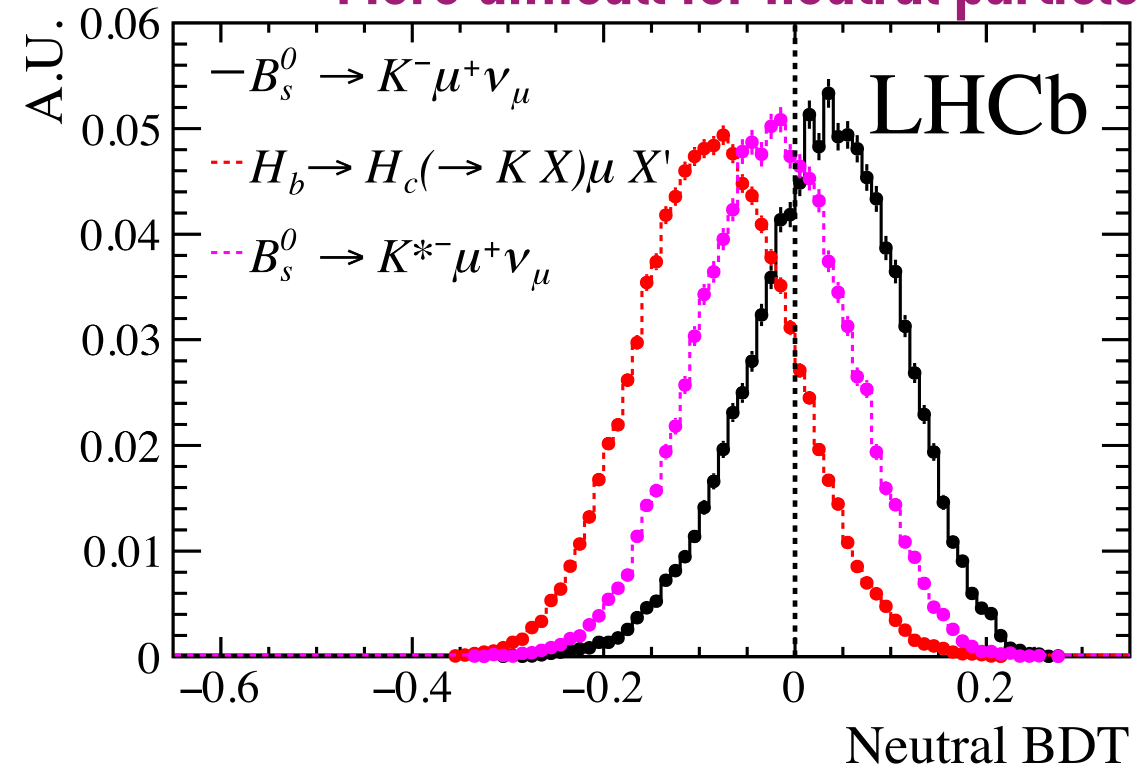
Selection: isolation



[PAPER-2020-038, arXiv:2012.05143]

More difficult for neutral particles

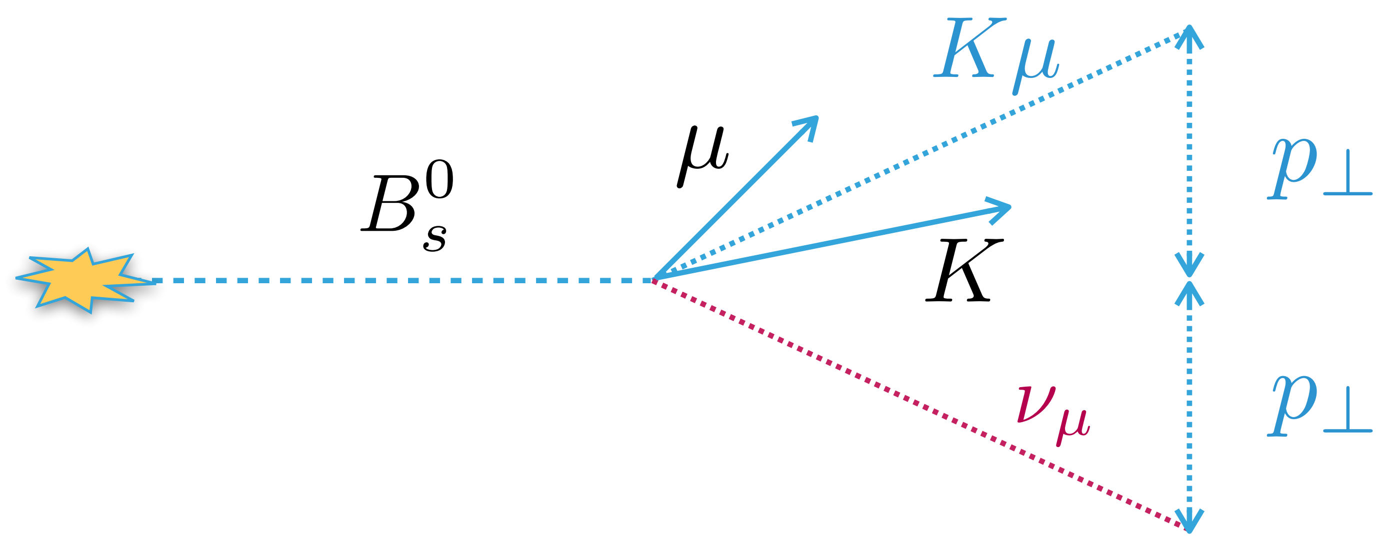




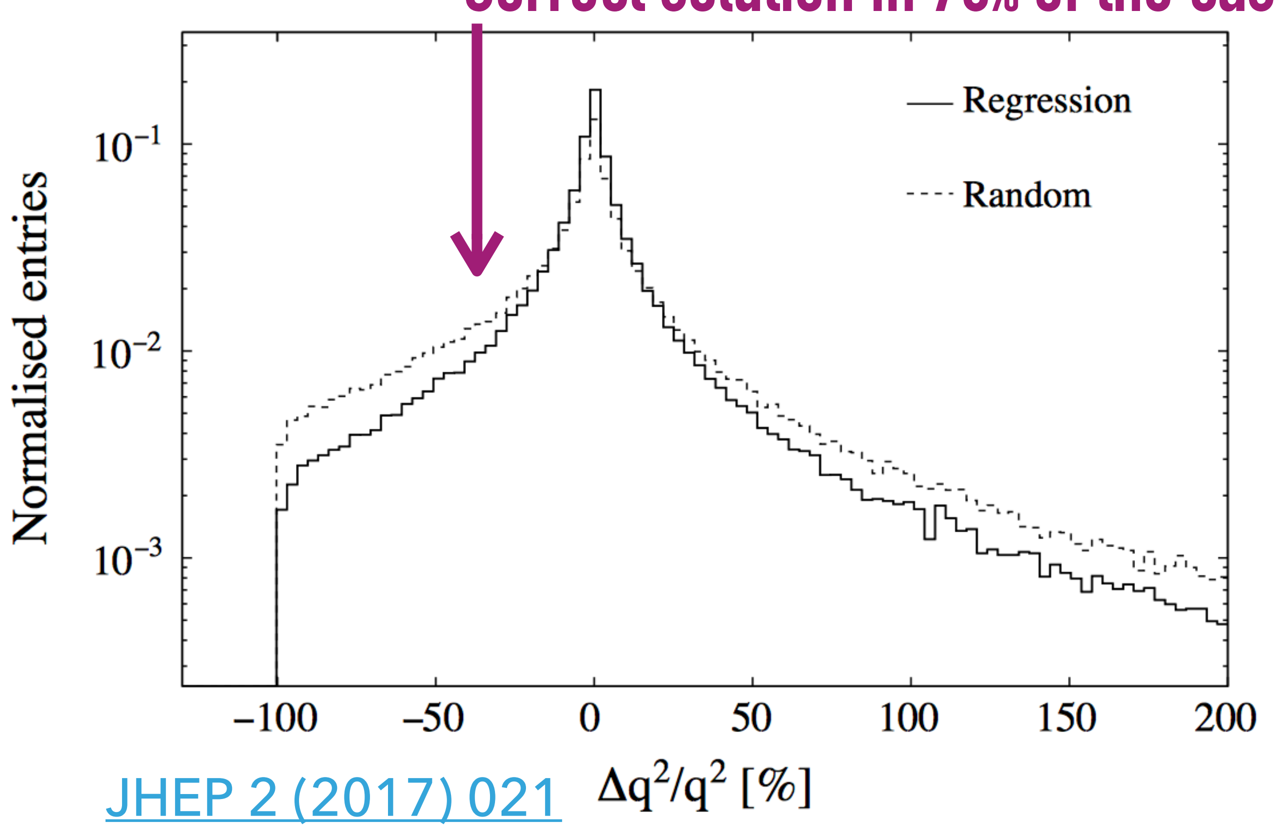
- multivariate algorithm (MVA) is trained to determine if a given track originates from the candidate, or from the rest of the event

Neutrino momentum reconstruction

- Unconstrained kinematics: longitudinal neutrino (or B) momentum component known up to a two-fold ambiguity
- Using linear regression prediction



Correct solution in 70% of the cases



JHEP 2 (2017) 021

$$p_{\parallel} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a},$$

$$a = |2p_{\parallel,X\mu} m_{X\mu}|^2,$$

$$b = 4p_{\parallel,X\mu}(2p_{\perp}p_{\parallel,,X\mu} - m^2_{miss}),$$

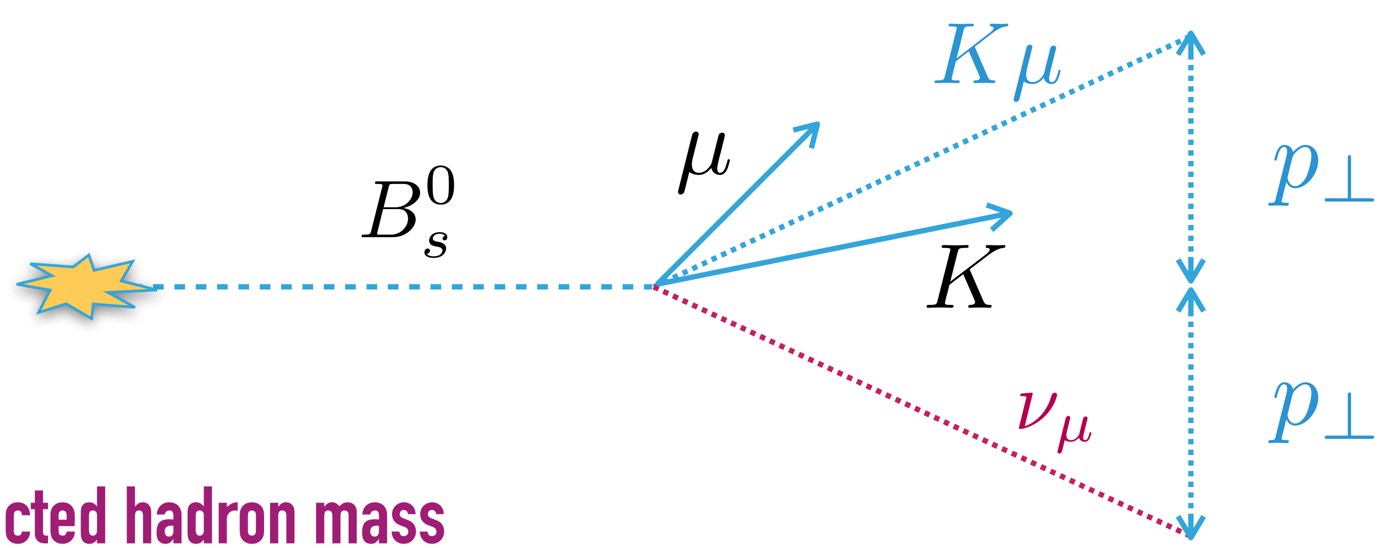
$$c = 4p^2_{\perp}(p^2_{\parallel,X\mu} + m^2_{B^0_s}) - |m^2_{miss}|^2,$$

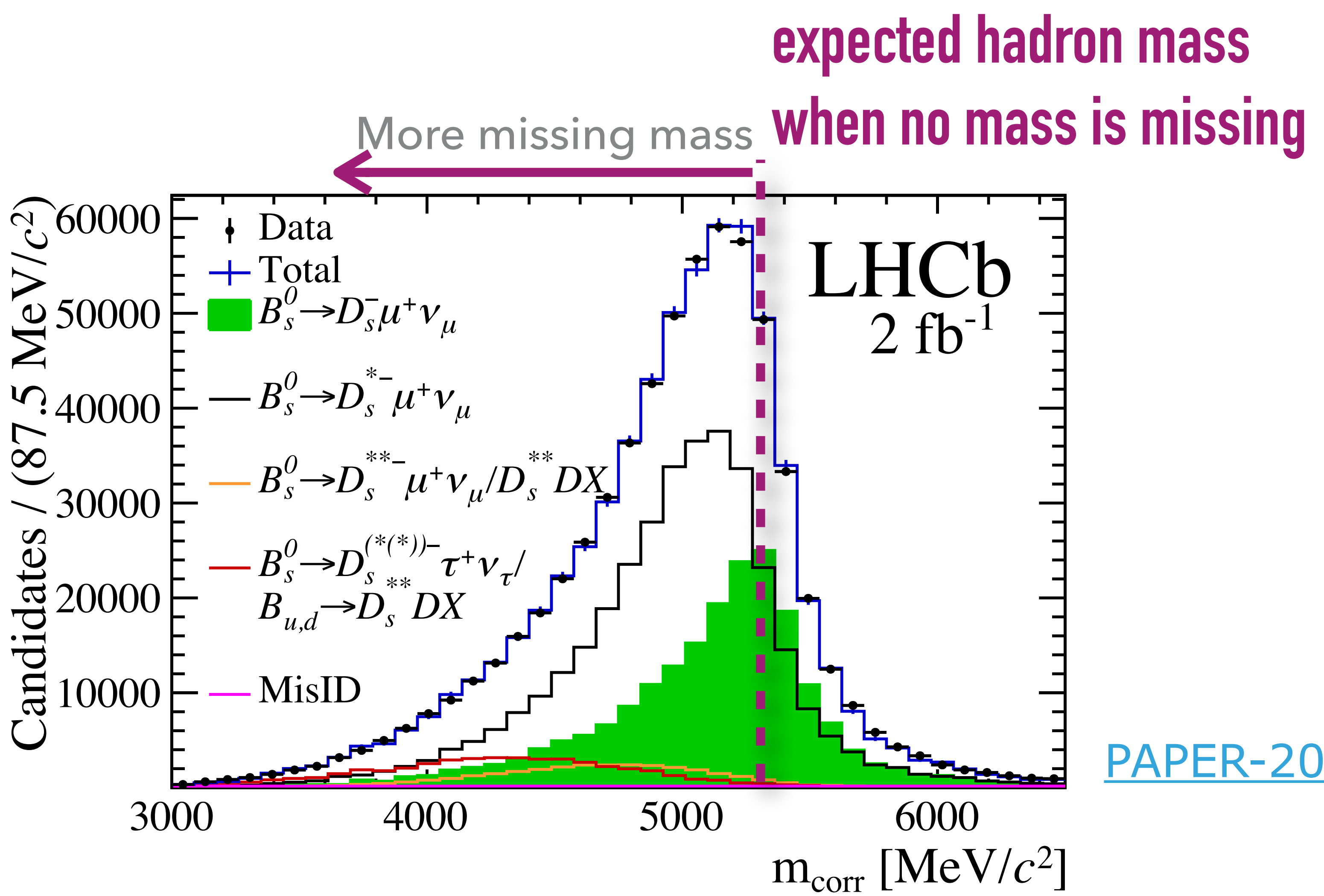
$$m^2_{miss} = m^2_{B^0_s} - m^2_{X\mu}.$$

Signal/background separation

- Use the corrected mass distribution to measure the sample composition

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

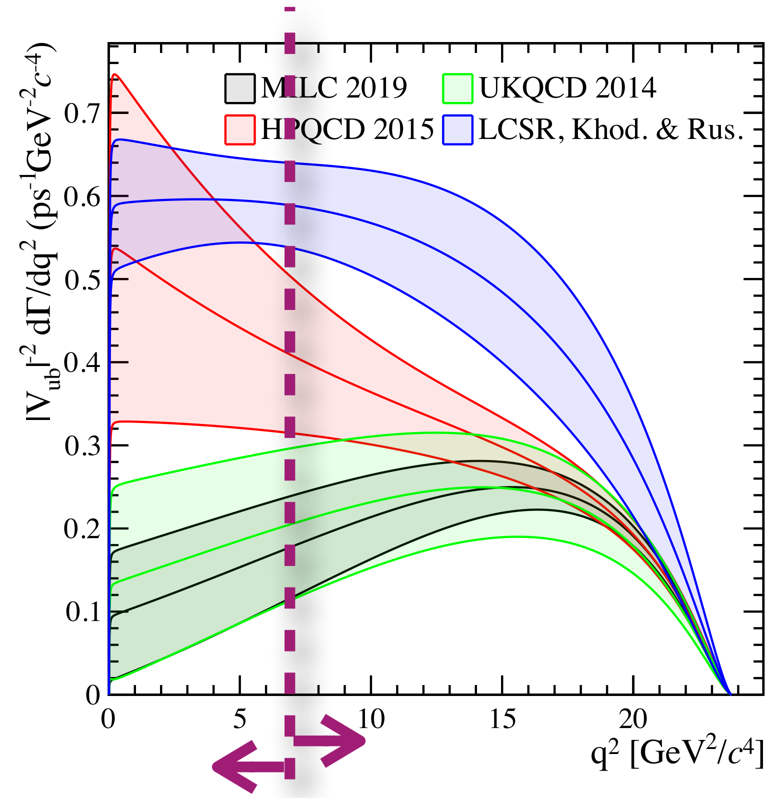




PAPER-2020-038, arXiv:2012.05143

Data Yields

- Vcb dominant background (b->c(->K)μvX), followed by Bs→K*μv and combinatorial



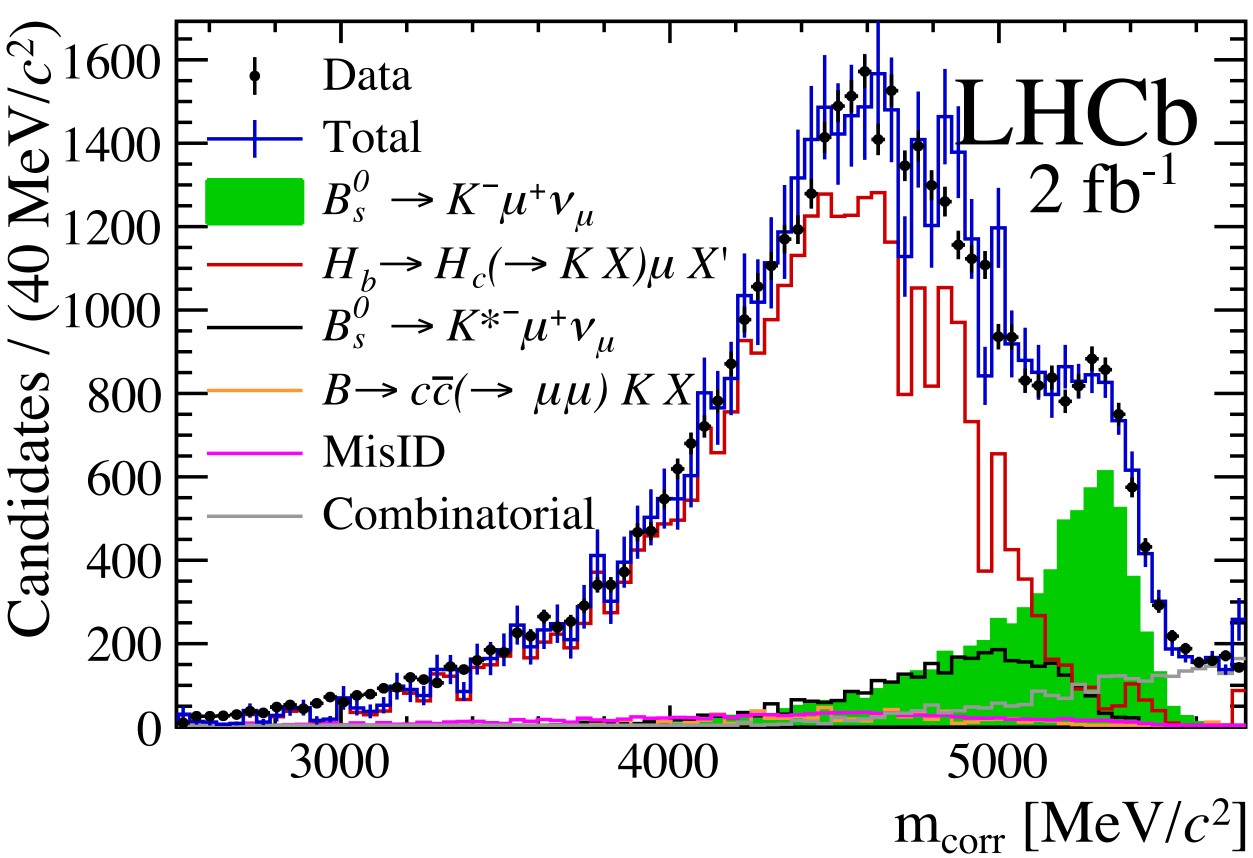
Fit templated from simulated samples corrected to describe the data

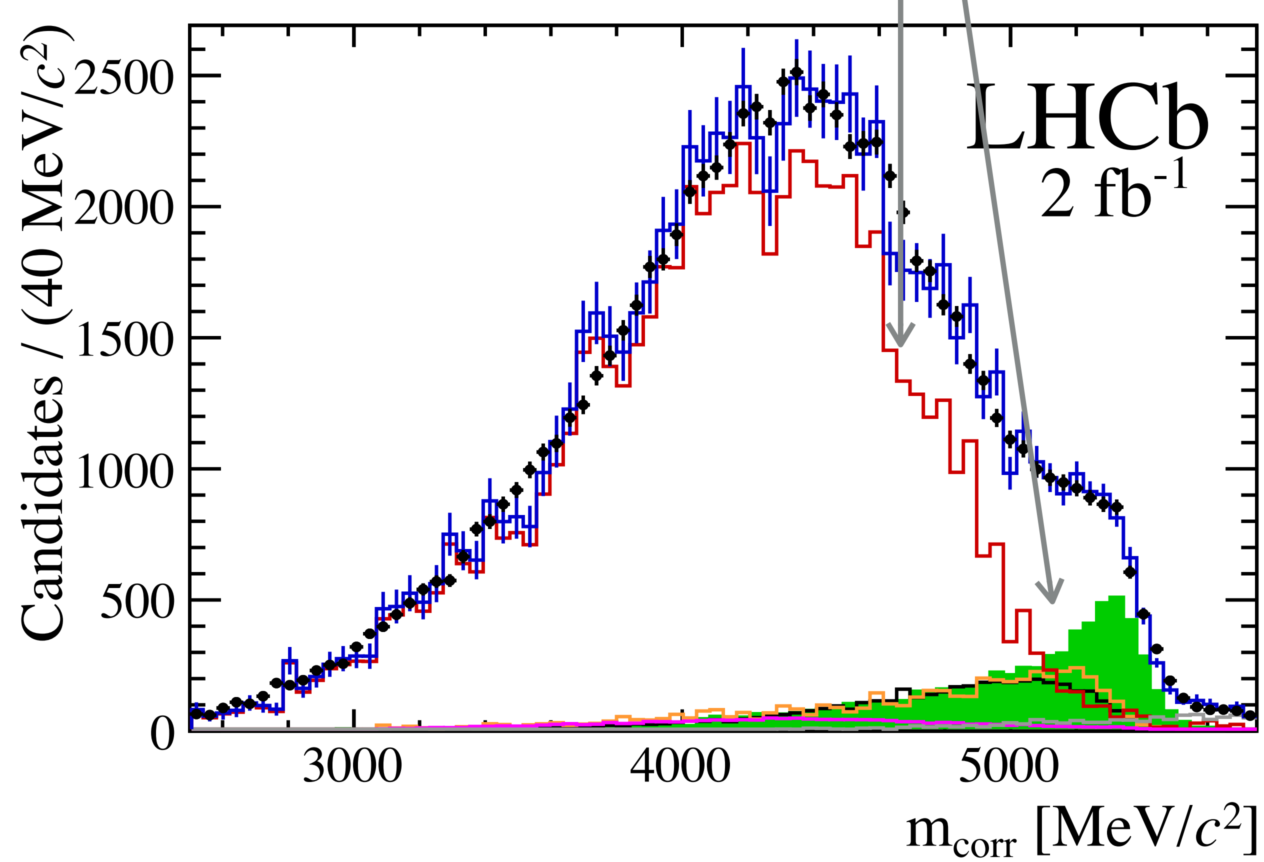
Low q²

$$N_{B^0_s\to K^-\mu^+\nu_\mu}(low) = 6922 \pm 285$$

High q²

$$N_{B^0_s\to K^-\mu^+\nu_\mu}(high) = 6399 \pm 370$$

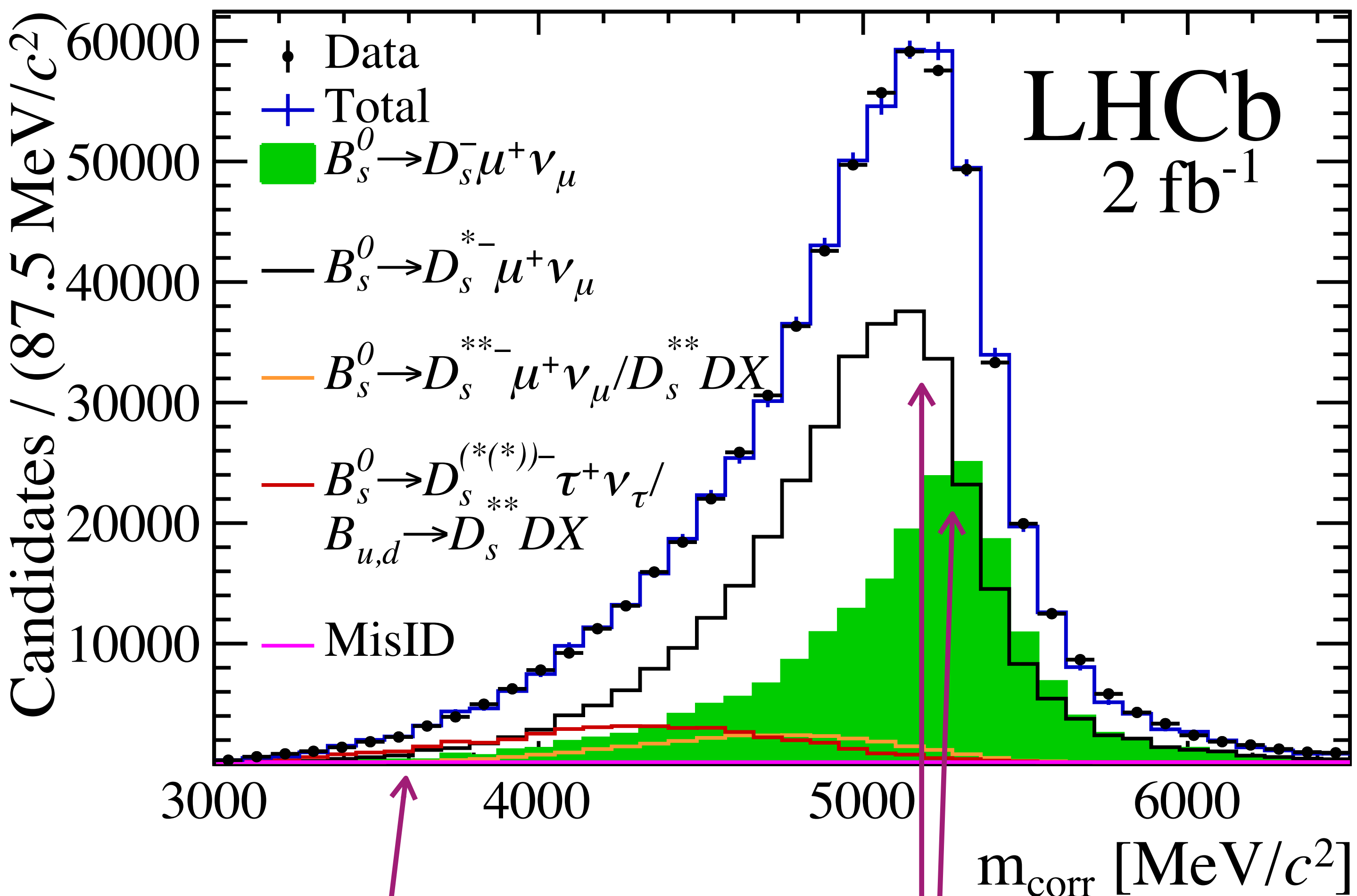




[PAPER-2020-038, arXiv:2012.05143]

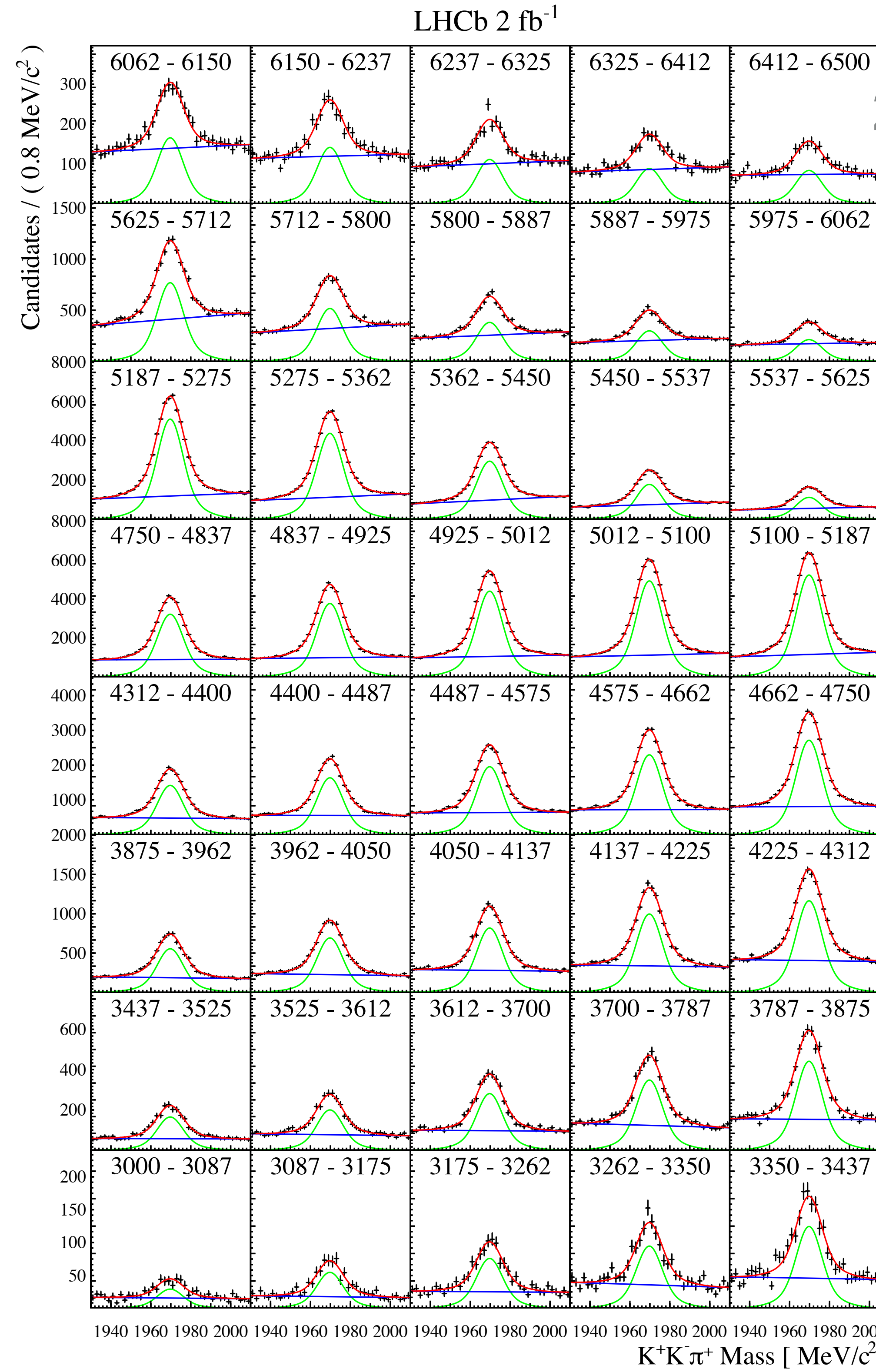
Data Yields

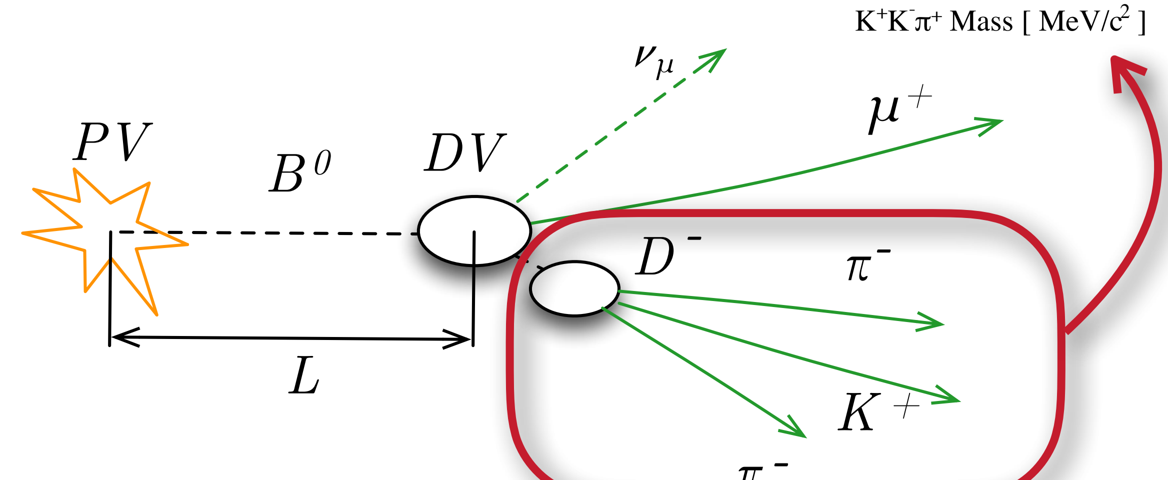
$$N_{B_s^0 \to D_s^- \mu^+ \nu_\mu} = 201450 \pm 5200$$



Ds* and Ds separation

Data driven methods to model (reduced) backgrounds from data





Systematics and Branching Fraction

$\frac{\mathcal{B}(B_s^0 \to K\mu\nu)}{\mathcal{B}(B_s^0 \to D_s\mu\nu)}$ [%]

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	$^{+4.0}_{-4.3}$	$^{+4.3}_{-4.5}$	$^{+5.0}_{-5.3}$
$\mathcal{B}(D_s \to KK\pi)$	2.8	2.8	2.8

$$\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu) = \tau_{B_s^0} \times |V_{cb}|^2 \times FF_{D_s} \times \frac{\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^-\mu^+\nu_\mu)}$$

External inputs

Measured yields and efficiencies from simulation

- Systematic can be reduced with larger data (and MC) samples

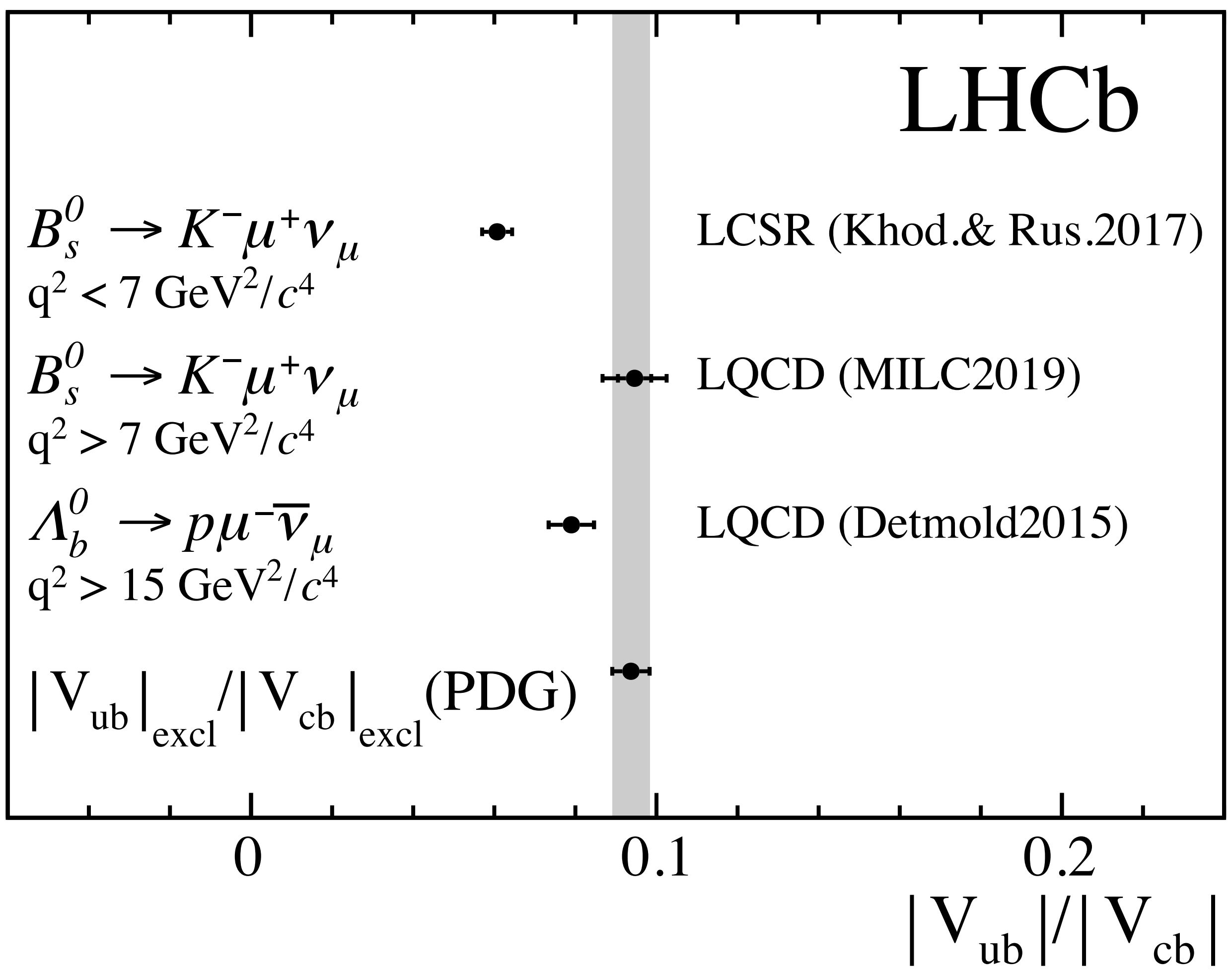
$$\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu) = (1.06 \pm 0.05(\text{stat}) \pm 0.04(\text{syst}) \pm 0.06(\text{ext}) \pm 0.04(\text{FF})) \times 10^{-4}$$

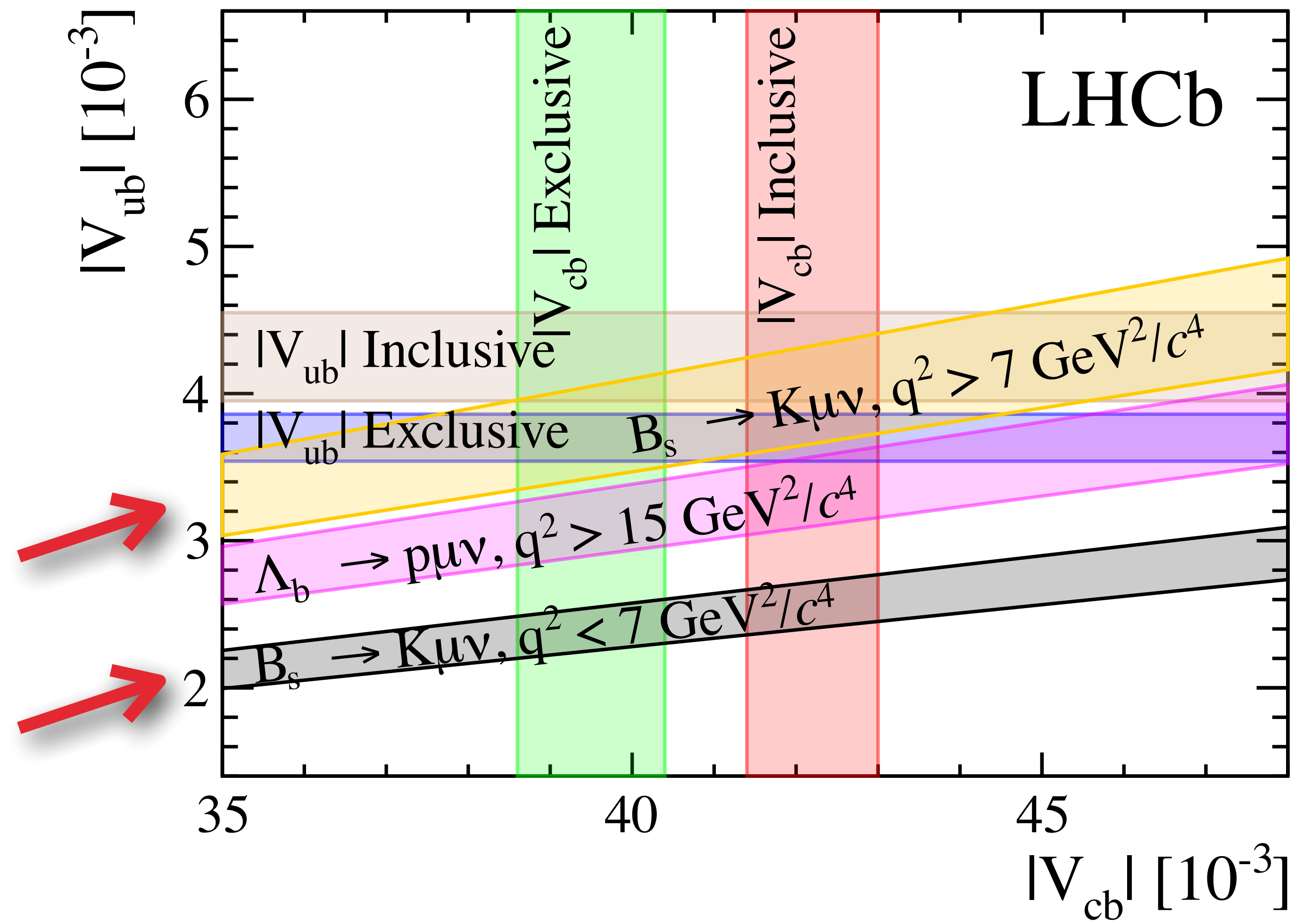
Results

PAPER-2020-038, arXiv:2012.05143

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

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



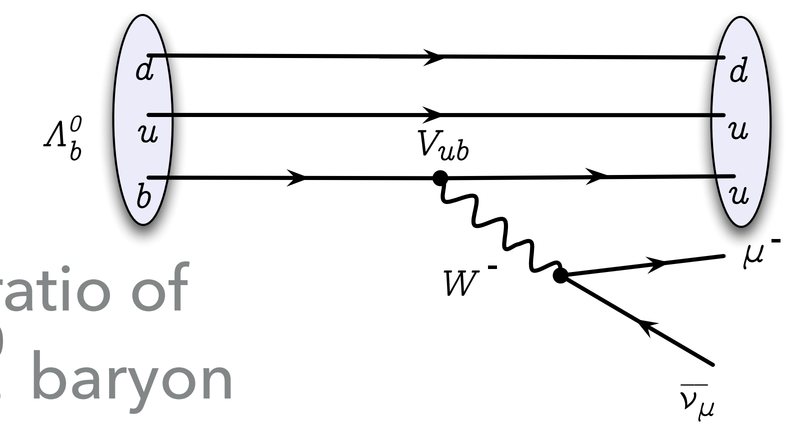


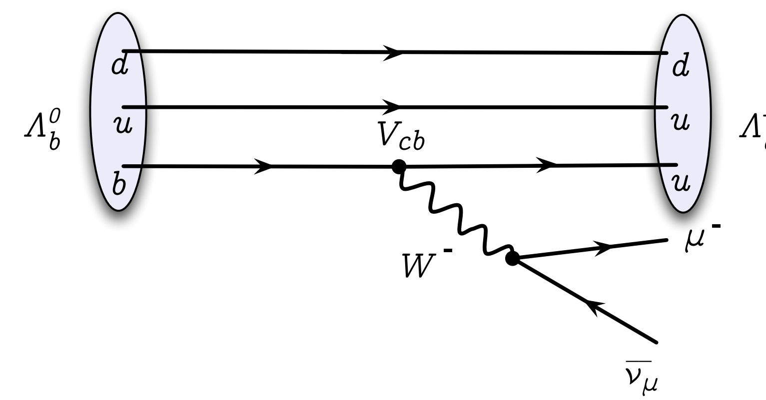
- Discrepancy between measurement at low q^2 and other measurements
- Need to measure the full q^2 shape

Digression about baryons

[Nature Physics 10 (2015)]

- Baryonic equivalent of $B^0 \to \pi\mu\nu_\mu$





- LHCb strategy: measure the ratio of branching fractions of the Λ_b^0 baryon into $p\mu^-\overline{\nu_\mu}$ and $\Lambda_c^+\mu^-\overline{\nu_\mu}$

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu_\mu})} R_{FF}$$

$R_{FF} = 1.470 \pm 0.115(\mathrm{stat}) \pm 0.104(\mathrm{syst})$
W. Detmold, C. Lehner and S. Meinel
[arXiv:1503.01421]

Belle measurement [arXiv:1312.7826]

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})_{q^2>15GeV^2/c^4}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu_\mu})_{q^2>7GeV^2/c^4}} = \frac{N(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})}{N(\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\overline{\nu_\mu})} \times \frac{\epsilon(\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\overline{\nu_\mu})}{\epsilon(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})} \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$$

world average

$|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3}$

- Similar tools: BDT to remove additional tracks that could vertex with a signal candidate, Efficiency from simulation with data-driven corrections

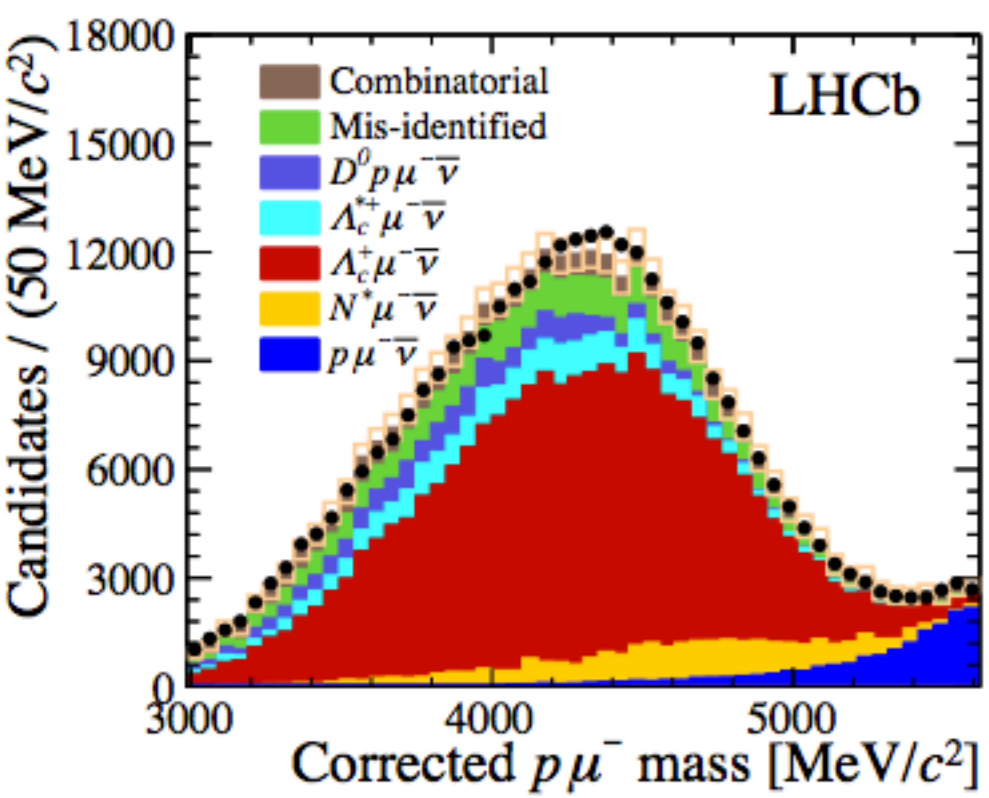
Digression about baryons

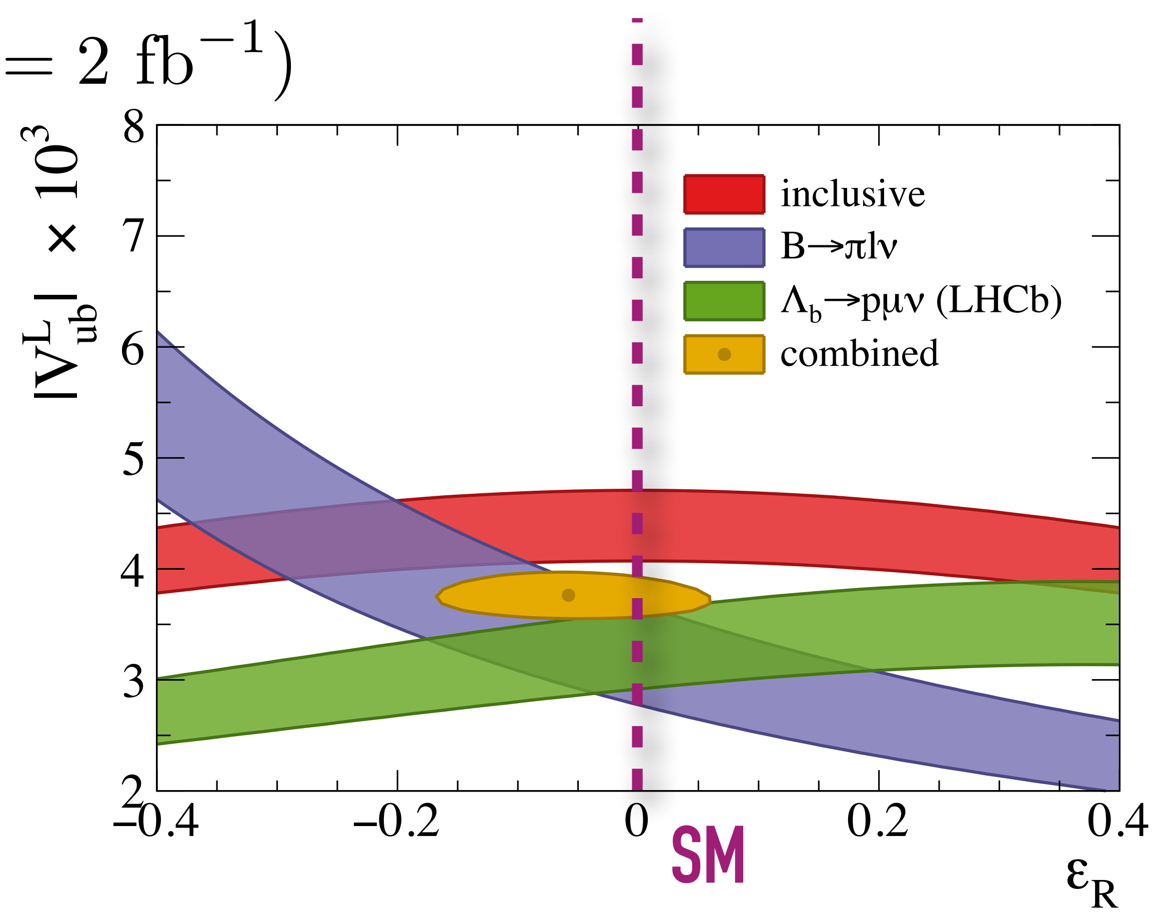
Nature Physics 10 (2015)

- Baryonic equivalent of $B^0 \to \pi\mu\nu_\mu$

New physics right-handed current (V+A)? Need to use something different than purely vector current ($B^0 \to \pi\mu\nu_\mu$)

$N(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu}) = 17687 \pm 733 \ (\mathcal{L} = 2 \text{ fb}^{-1})$





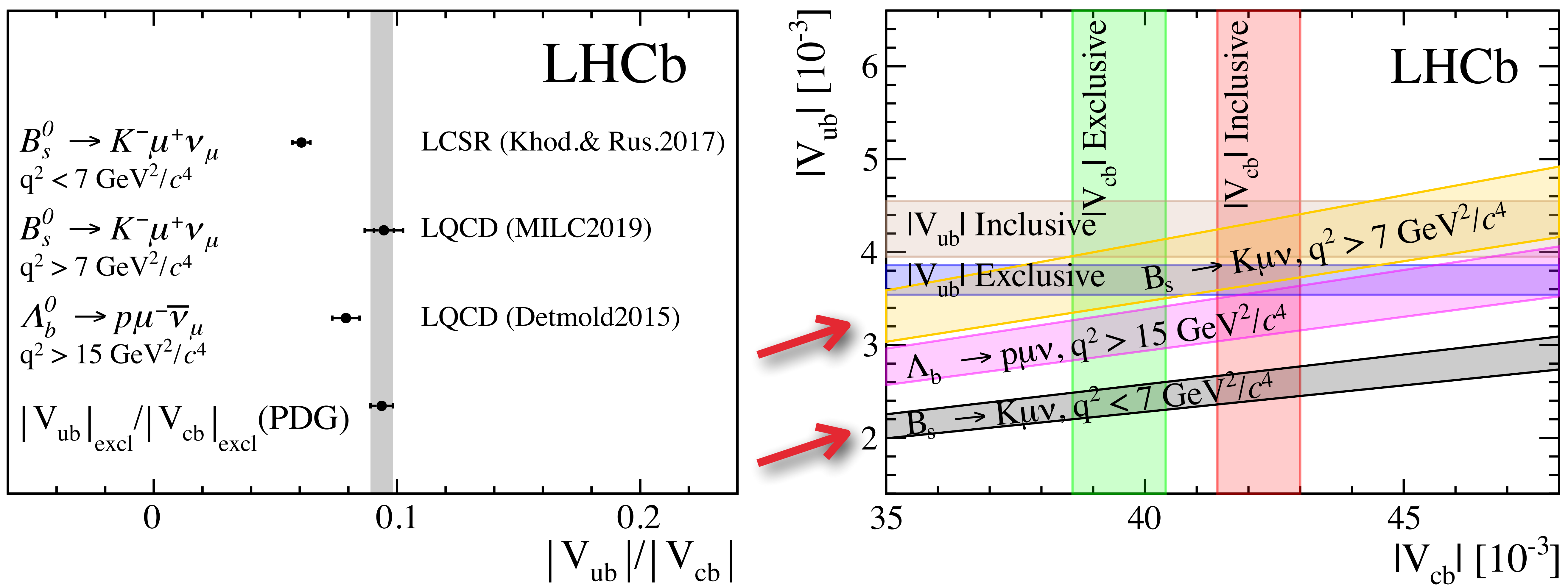
$$|V_{ub}| = (3.27 \pm 0.15(\text{exp}) \pm 0.16(\text{theo}) \pm 0.06(|\text{V}_{\text{cb}}|)) \times 10^{-3}$$

- Does not support a right-handed coupling of significant magnitude

Results

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

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



- Discrepancy between measurement at low q^2 and other measurements
- Need to measure the full q^2 shape

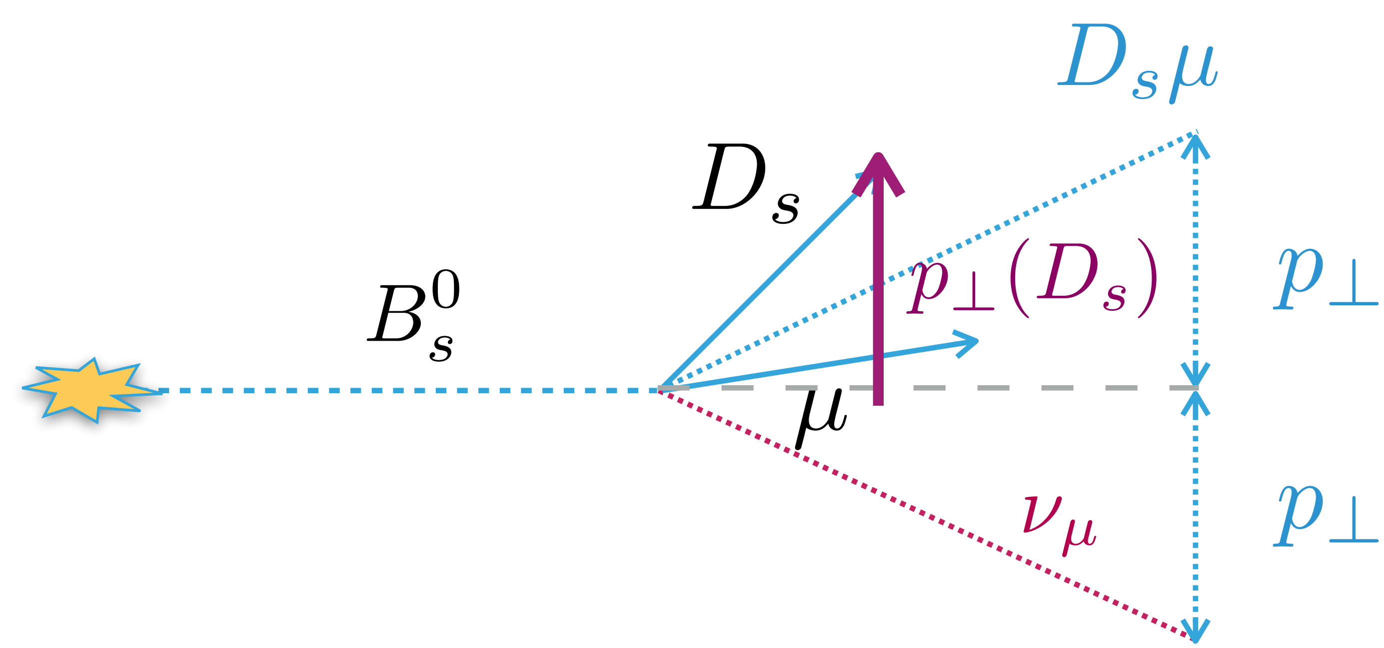
Differential decay rates

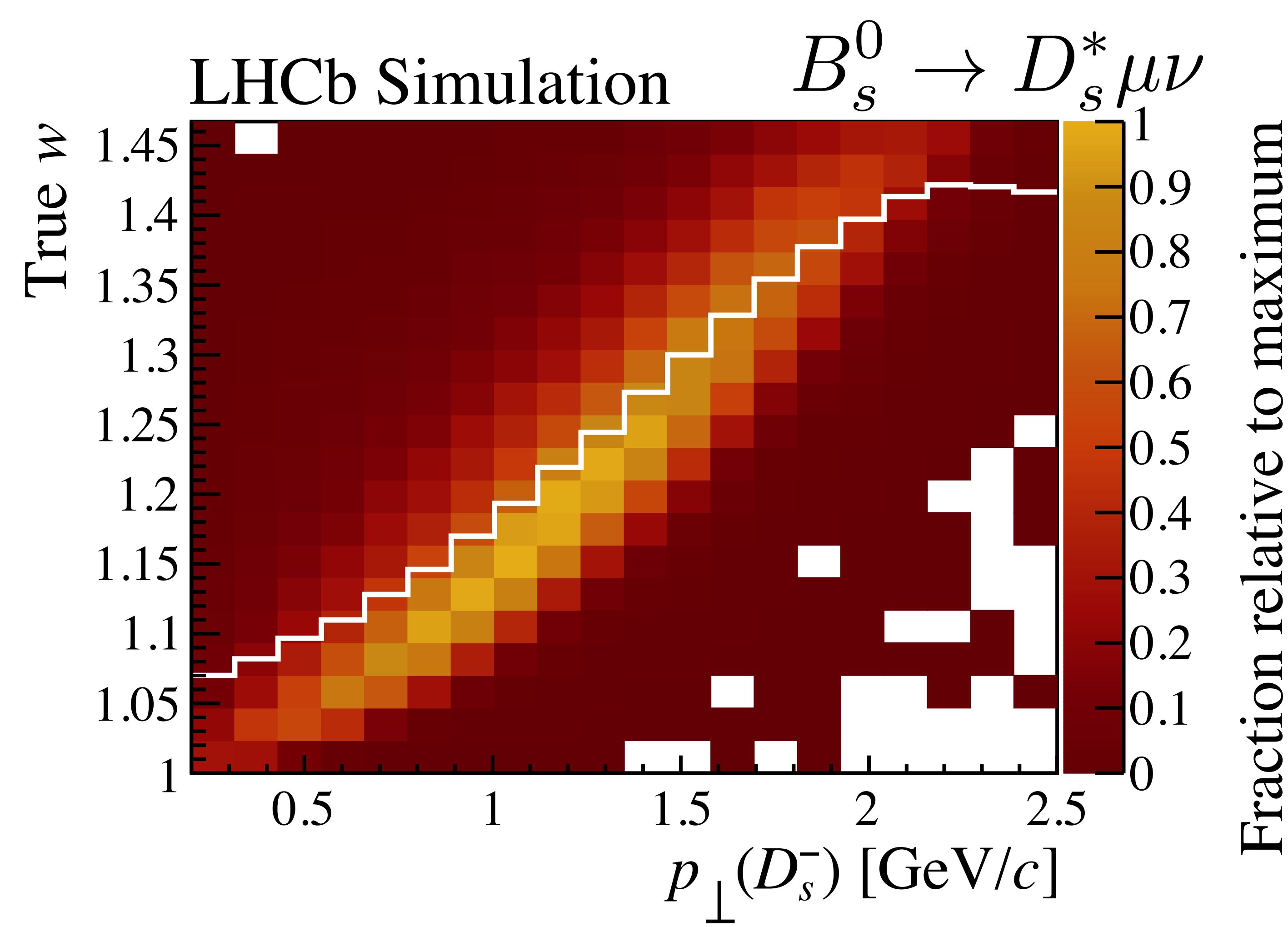
- Very good first results with semi-leptonic b-decays at LHCb

- Extract |Vcb| from measurement of decay rate as a function of q^2 or recoil w ($D_s^{(*)}$ energy in the Bs rest frame)

- Use $p_\perp(D_s)$: fully reconstructed and highly correlated with w

- Very good sensitivity to the form factors, depending on w





$|V_{cb}|$ and hadronic form factors measurement using Bs decays

- Fit to M_{corr} and $p_\perp$ distributions to extract |Vcb| and form factors.
  2D template to model the data, including efficiency

$$\frac{dN_{\rm obs}}{dp_\perp dM_{corr}} = \mathcal{N}\frac{d\Gamma(|V_{cb}|, h_{A_1}, \ldots)}{dp_\perp dM_{corr}} \times \epsilon(p_\perp, M_{corr})$$

- Constrain form factors from lattice QCD [PRD 101 (2020) 074513, PRD 99 (2019) 114512].

- Normalisation $\mathcal{N}$ contains measured B^0 reference yields, input branching fractions, relative b-hadron production probabilities fs/fd and Bs lifetime

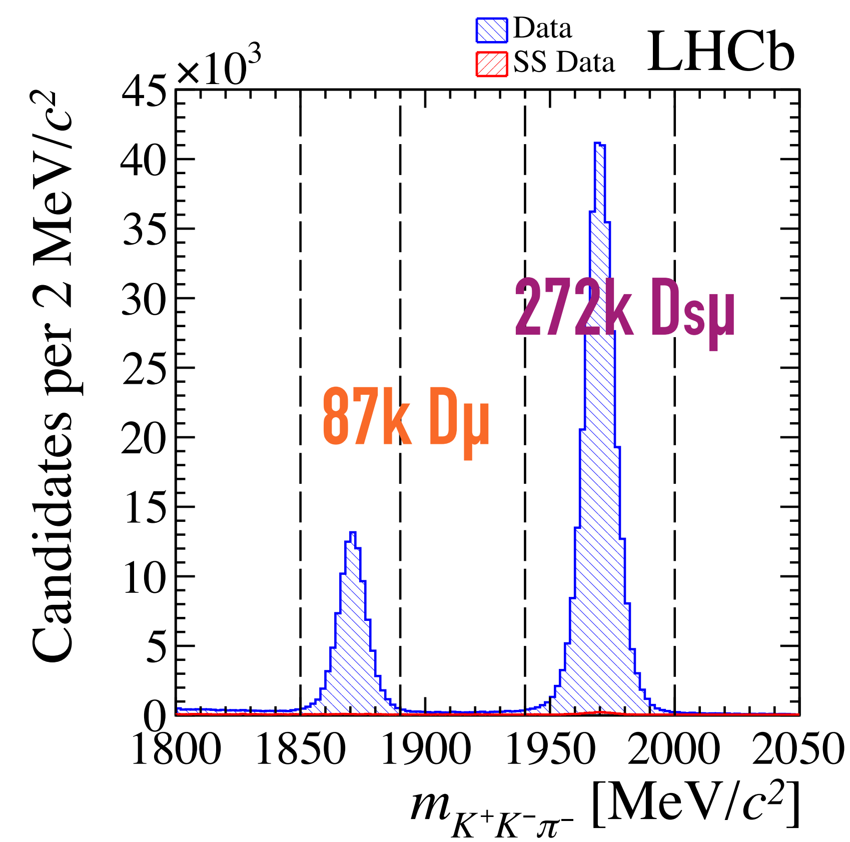
$|V_{cb}|$ and hadronic form factors measurement using Bs decays

- Fit to M_{corr} and $p_\perp$ distributions to extract |Vcb| and form factors.
  2D template to model the data, including efficiency

$$\frac{dN_{\text{obs}}}{dp_\perp dM_{corr}} = \mathcal{N}\frac{d\Gamma(|V_{cb}|, h_{A_1}, \ldots)}{dp_\perp dM_{corr}} \times \epsilon(p_\perp, M_{corr})$$

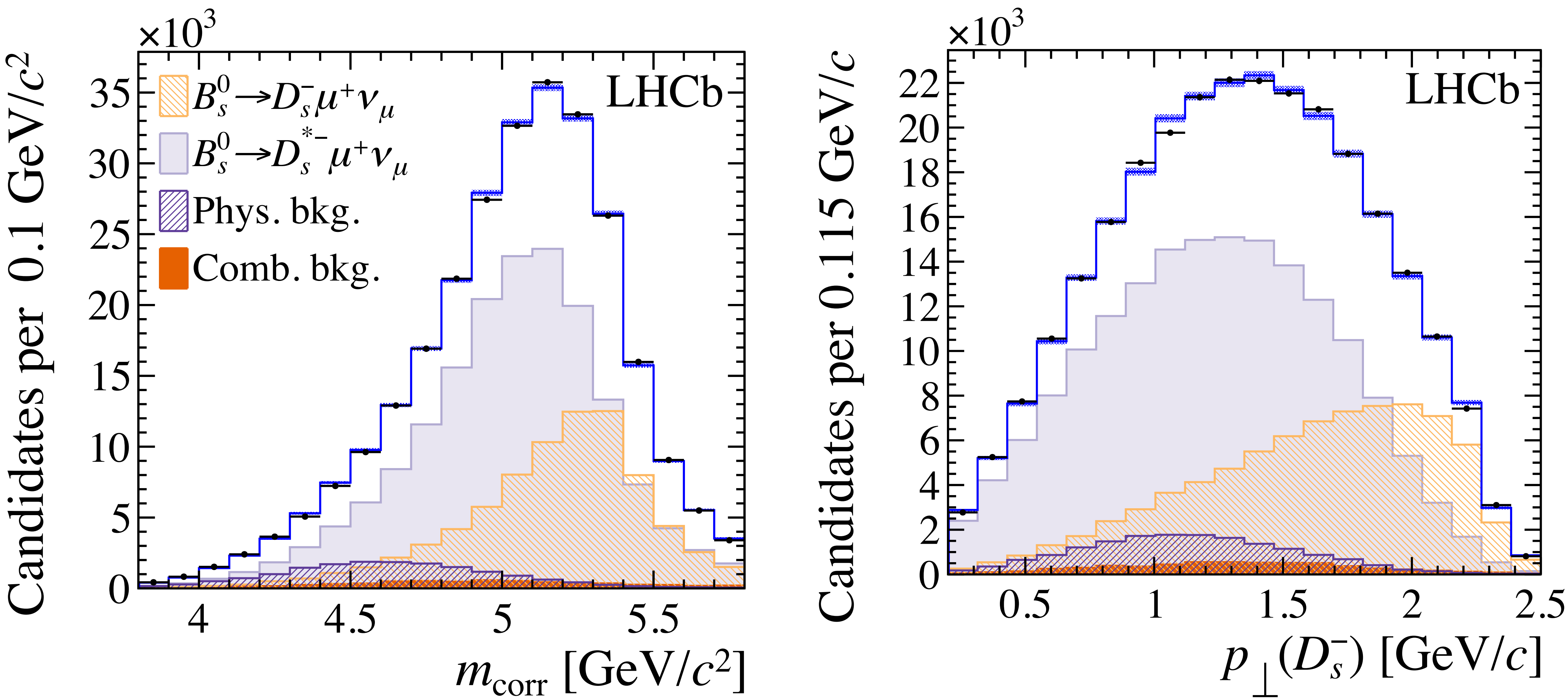
Need to know the number of Bs produced

- pp→bbX cross section measured, but limiting |Vcb| precision (5-8%)
- Reference decays: $B^0 \to D[D\to KK\pi]\mu\nu$
- Input needed: relative production fraction fs/fd (2.5% recision on |Vcb|)



Results

- Analysis uses inclusive sample of Dsμ final state (Ds* partially reconstructed)
- Need form-factor parametrisation to determine |Vcb|. General model from Boyd, Grinstein and Lebed (BGL, PRL 74 (1995) 4603).



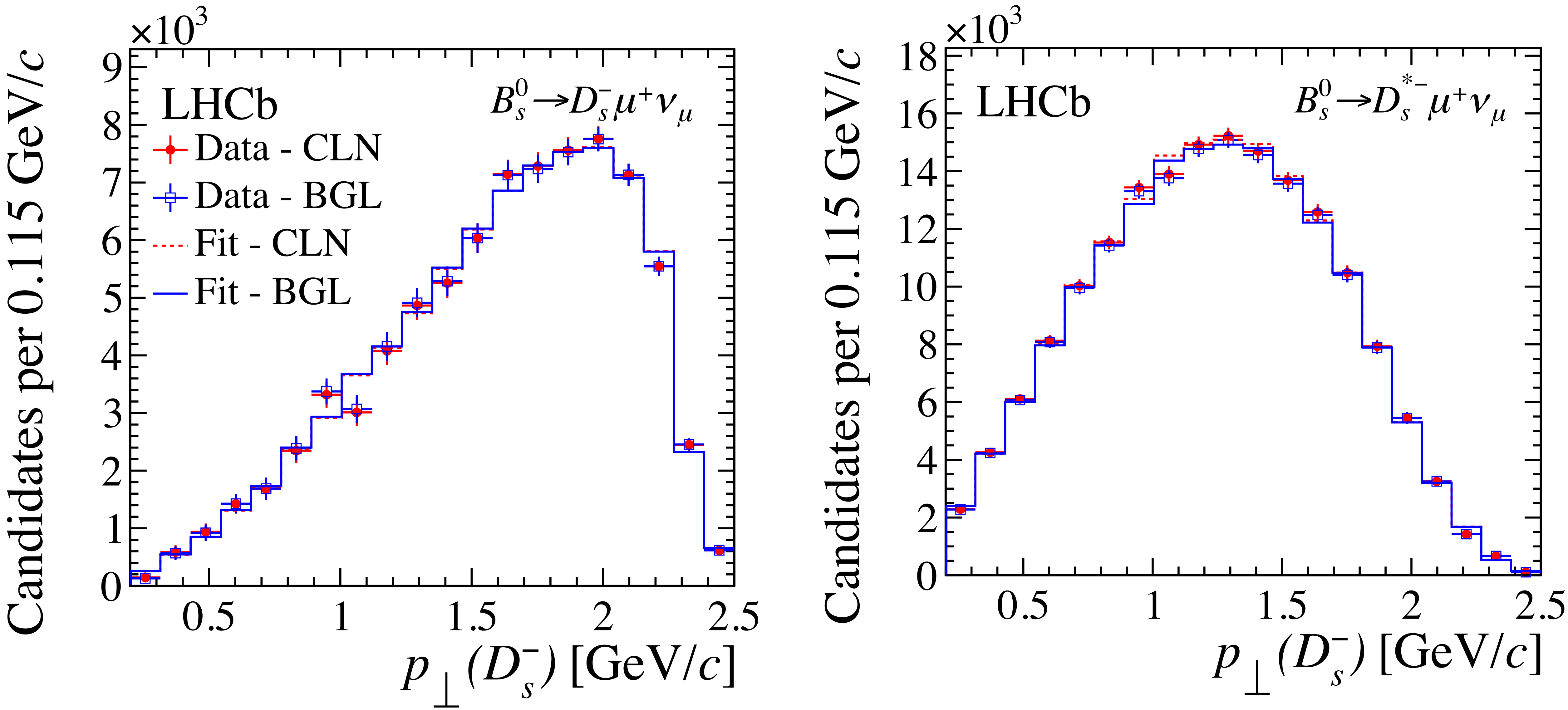
$$|V_{cb}| = (42.3 \pm 0.8(\text{stat}) \pm 0.9(\text{syst}) \pm 1.2(\text{ext})) \times 10^{-3}$$

Different hadronic Form Factor parametrisation

- Compared to the model from Caprini, Lellouch and Neubert (CLN, NPB 530 (1998) 153). No significant difference found

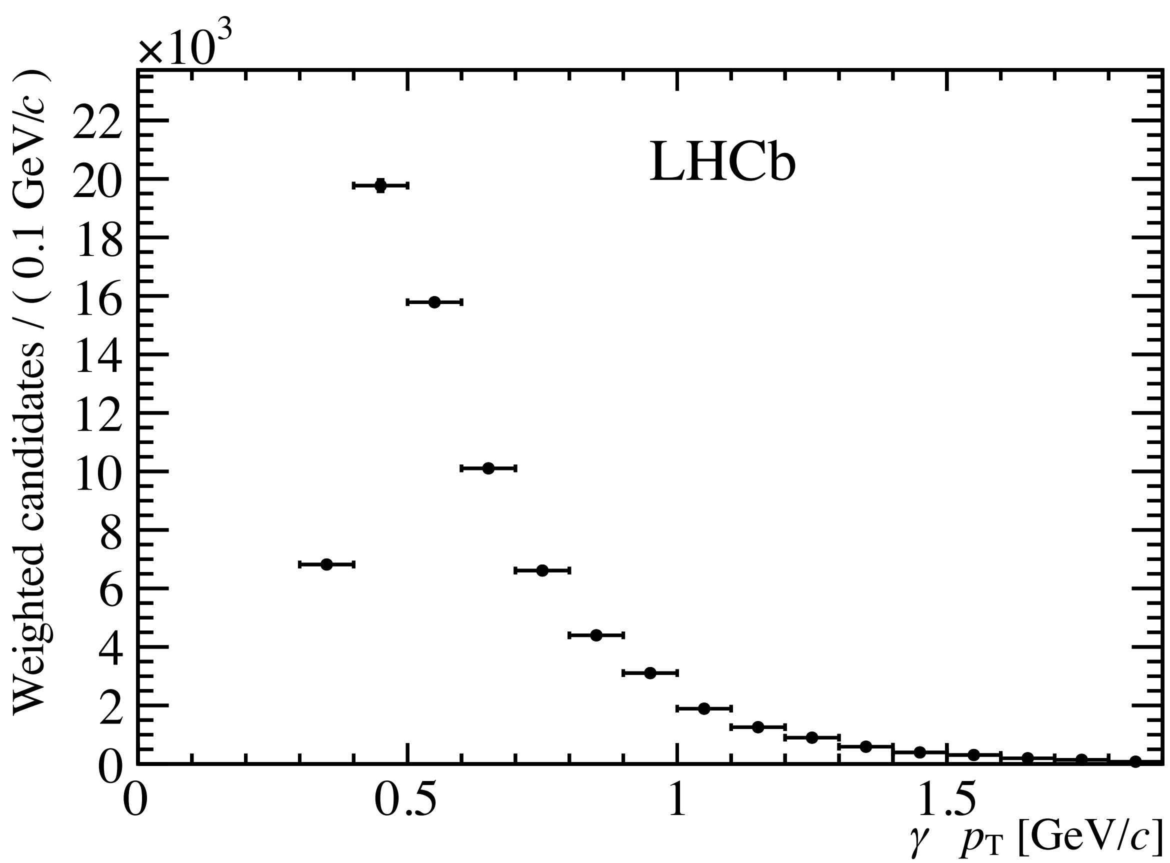
$$|V_{cb}| = (41.4 \pm 0.6(\mathrm{stat}) \pm 0.9(\mathrm{syst}) \pm 1.2(\mathrm{ext})) \times 10^{-3} \quad \text{BGL}$$

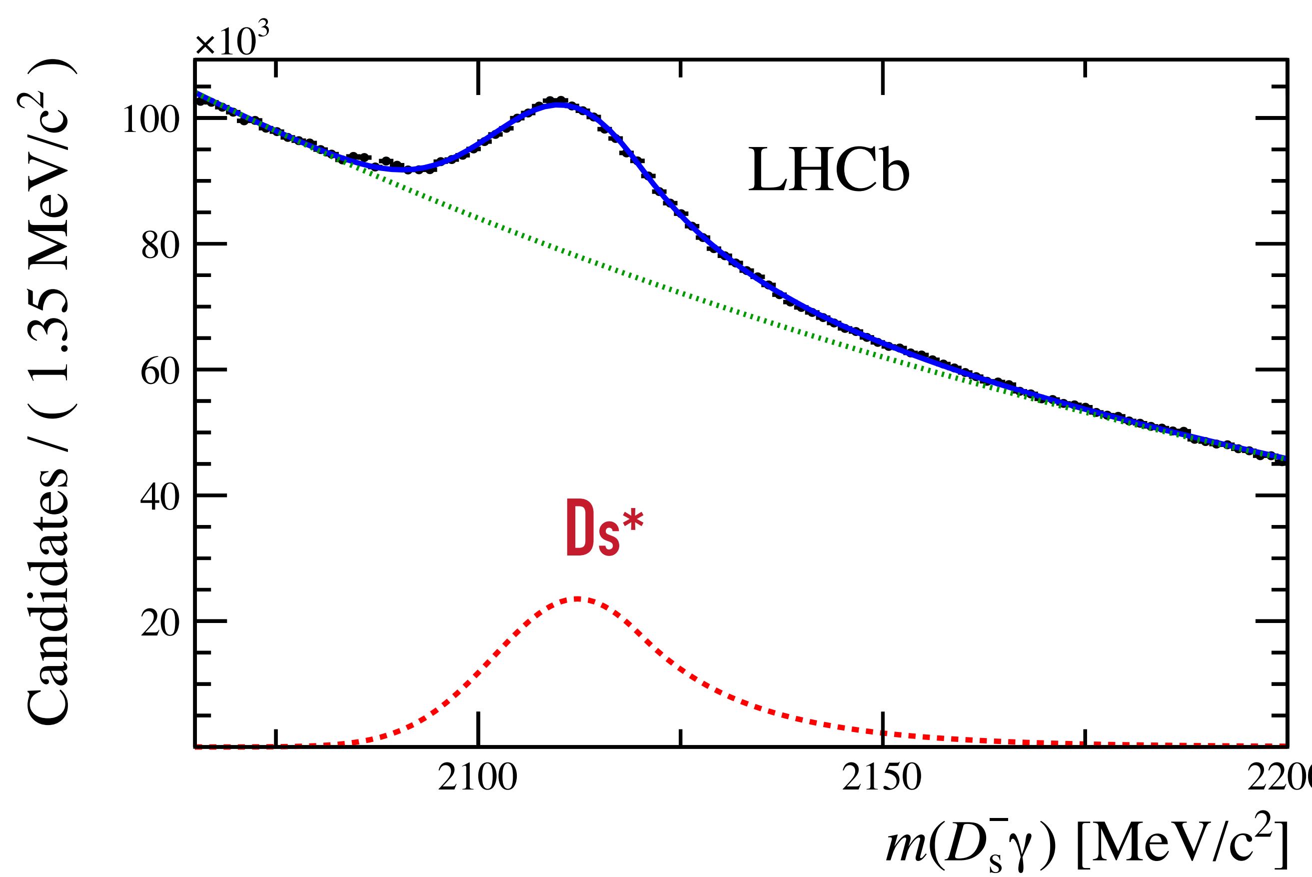
$$|V_{cb}| = (42.3 \pm 0.8(\mathrm{stat}) \pm 0.9(\mathrm{syst}) \pm 1.2(\mathrm{ext})) \times 10^{-3} \quad \text{CLN}$$



Shape of the differential decay rate

- Additional measurements supporting the hadronic form factors
- Measurement of w distribution for Bs→Ds*μν decays
- Independent data set. Fully reconstruct the Ds*→Dsγ by selecting the soft photon in a cone around the Ds flight direction.

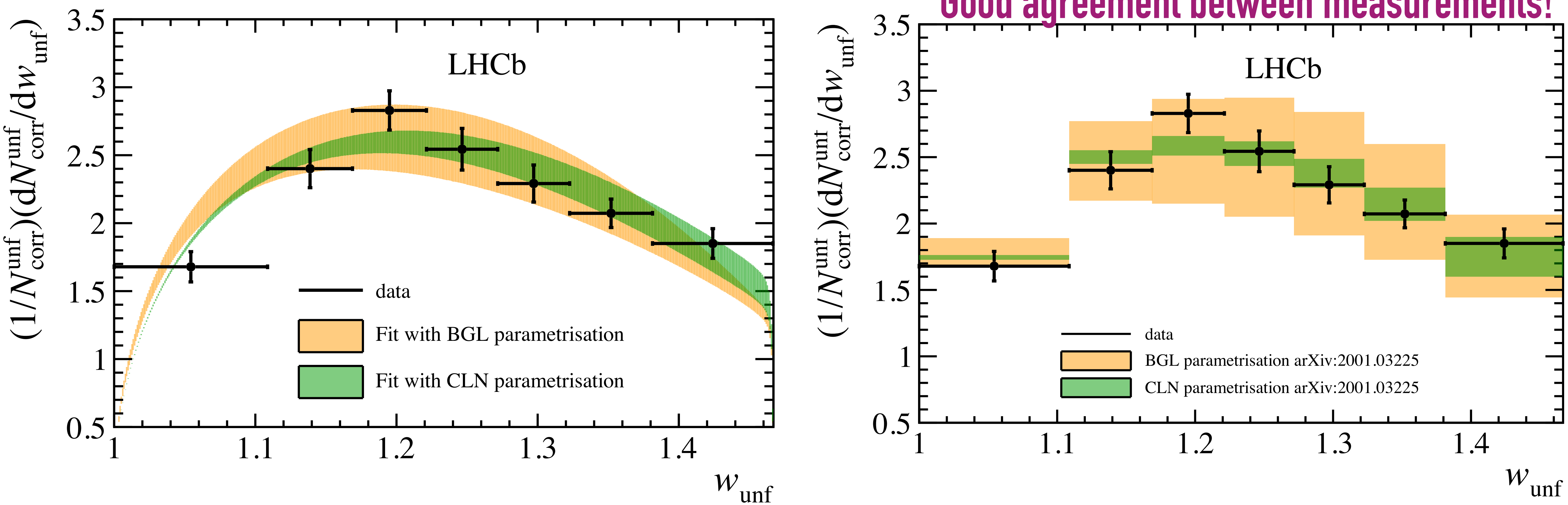




Shape of the differential decay rate

- Approximate w, the energy of the Ds* in the Bs rest frame, with linear regression as for Bs→Kμν [JHEP 02 (2017) 021]
- Fit the corrected mass in bins of the approximate w
- Unfold efficiency and resolution using simulated events

Good agreement between measurements!



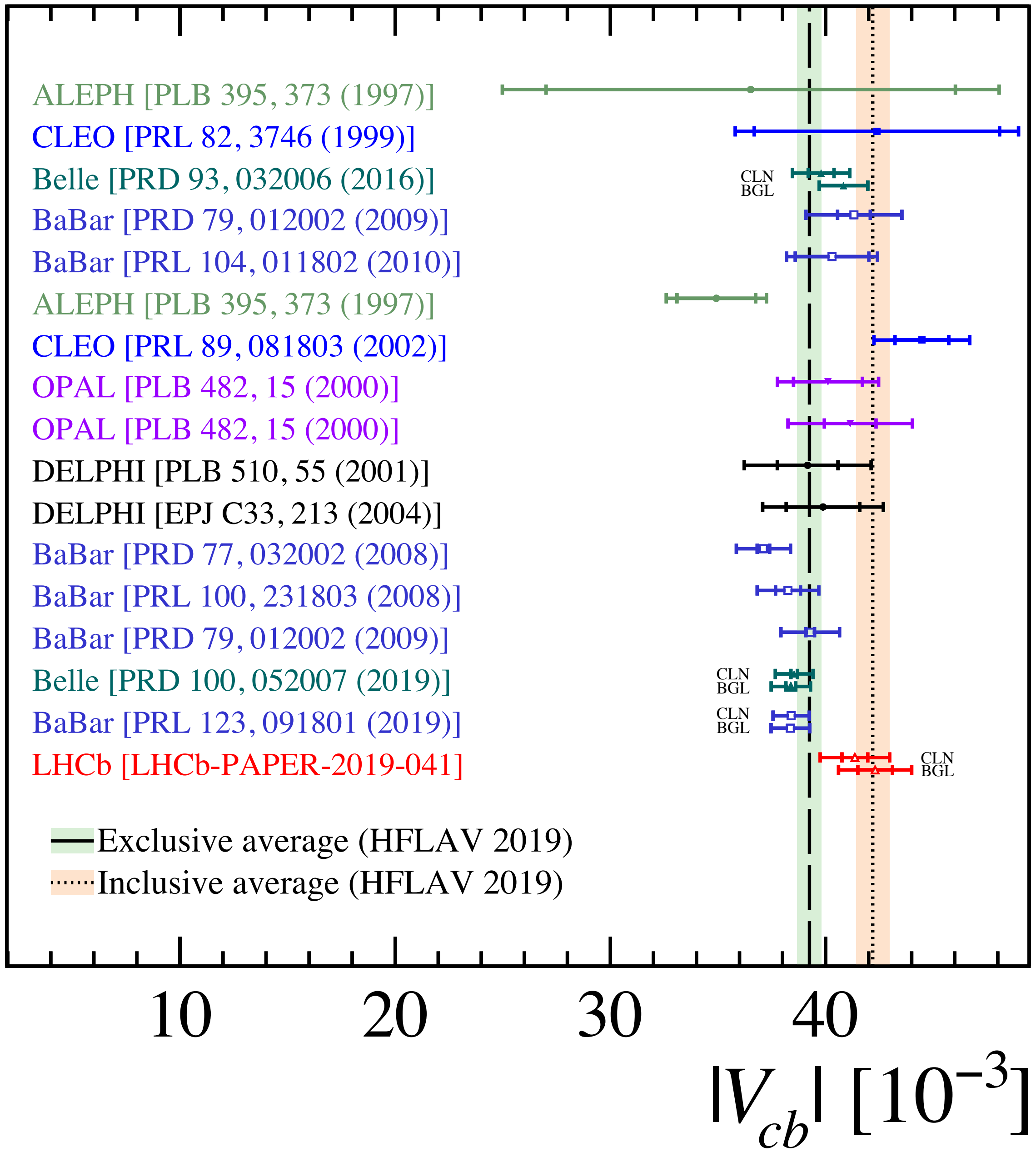
Results

- First measurement of w distribution for Bs→Ds*μν decays
- First measurement of |Vcb| at a hadron collider using both Bs→Dsμν and Bs→Ds*μν decays

$$|V_{cb}| = (41.4 \pm 0.6(\text{stat}) \pm 0.9(\text{syst}) \pm 1.2(\text{ext})) \times 10^{-3}$$

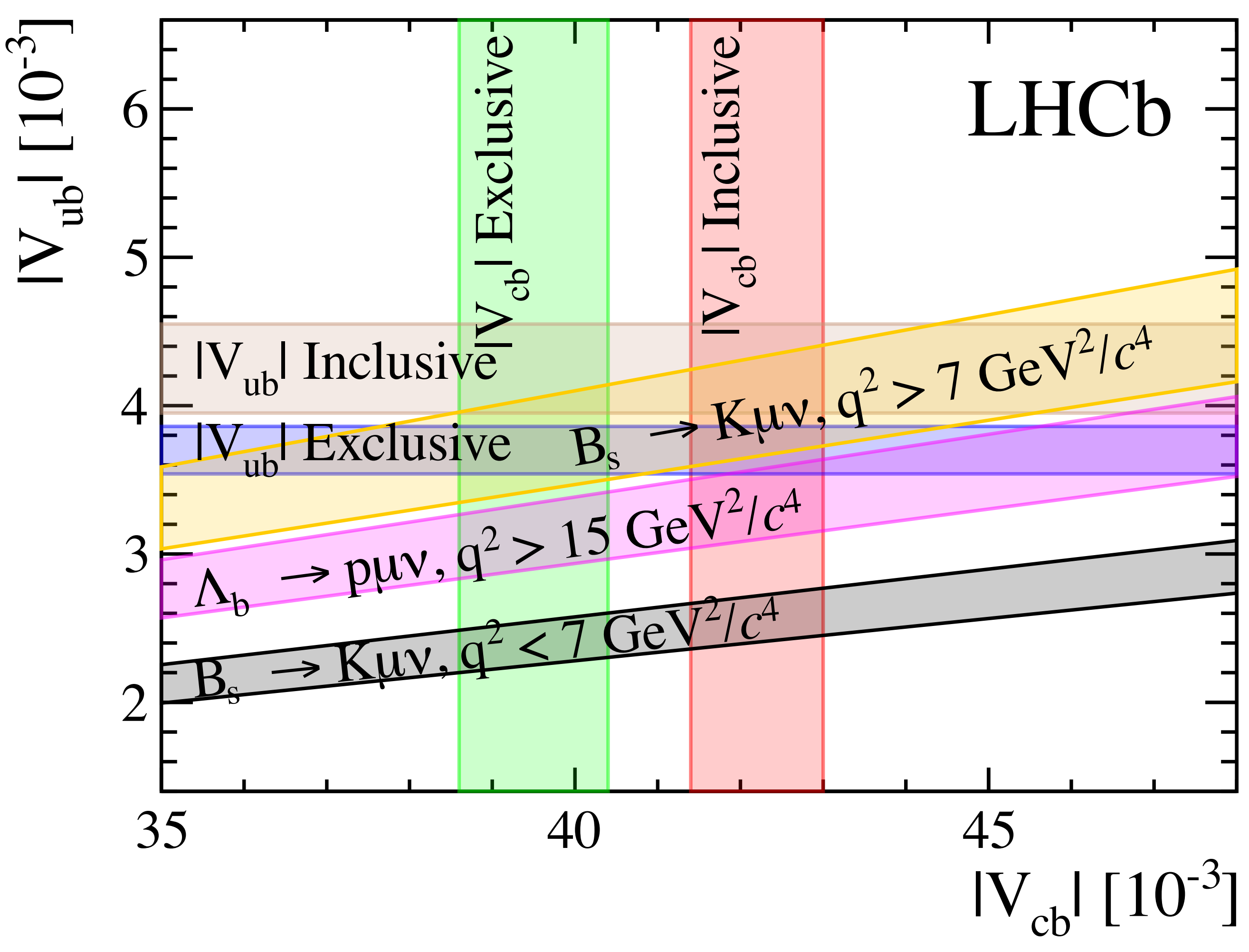
$$|V_{cb}| = (42.3 \pm 0.8(\text{stat}) \pm 0.9(\text{syst}) \pm 1.2(\text{ext})) \times 10^{-3}$$

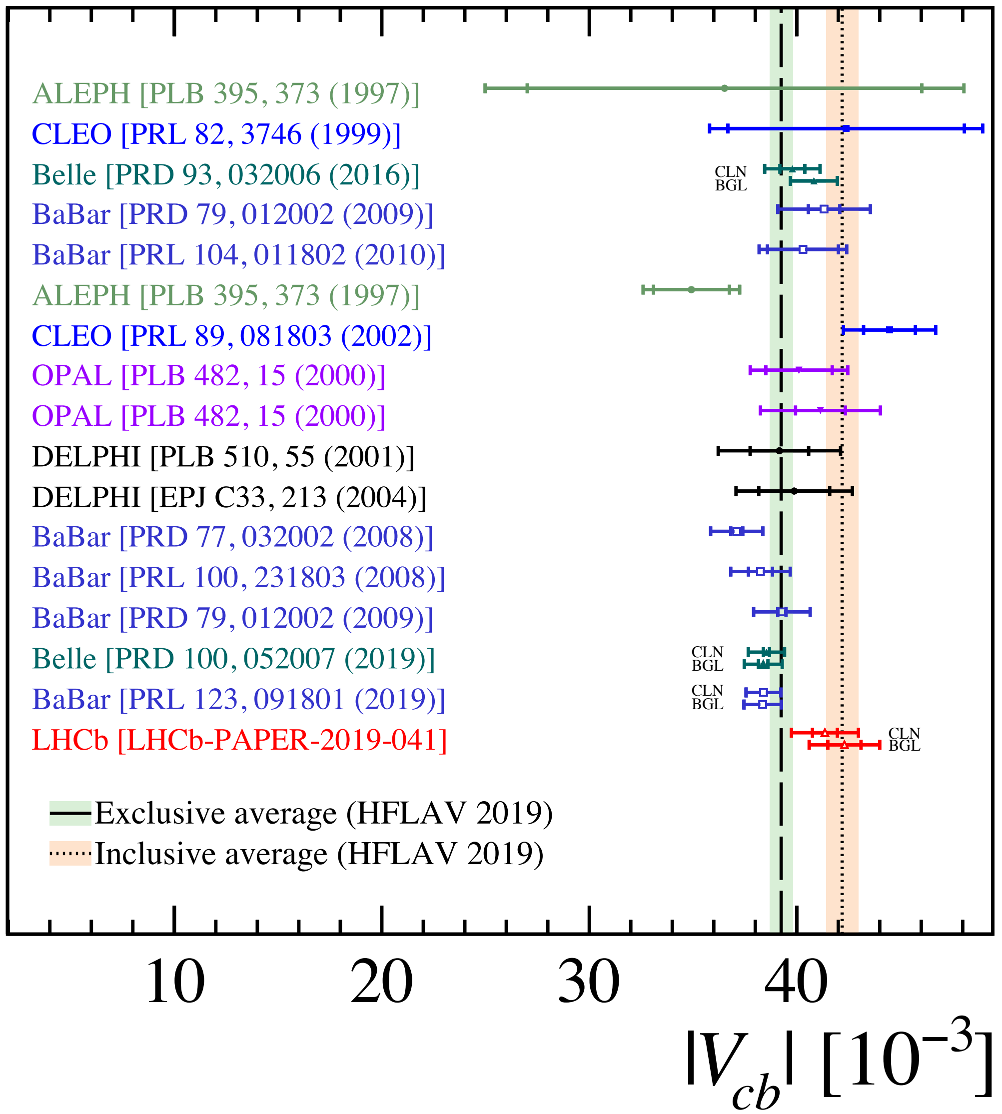
- |Vcb| in agreement with both inclusive and exclusive determination



Conclusions

- LHCb has just started contributing to the |Vub| & |Vcb| picture! Larger samples, additional b-hadron species, additional observables are foreseen
- Progress in experimental techniques and theory go hand-in-hand





THANKS FOR YOUR ATTENTION