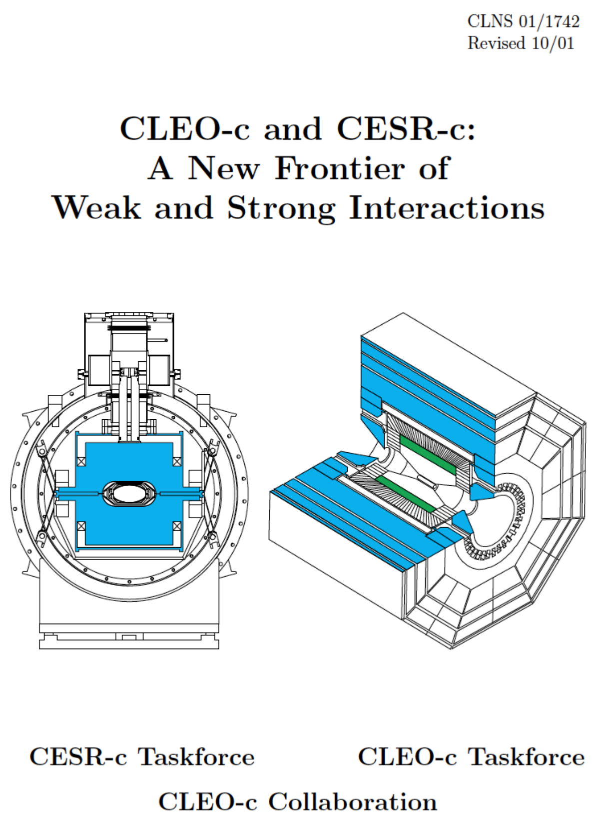
Honoring the career of Peter Lepage

The Lattice Renaissance and beauty and charm: from CLEO-c to LHCb

Marina Artuso
Syracuse University

Preamble: we need to start with CLEO-c



CLNS 01/1742
Revised 10/01

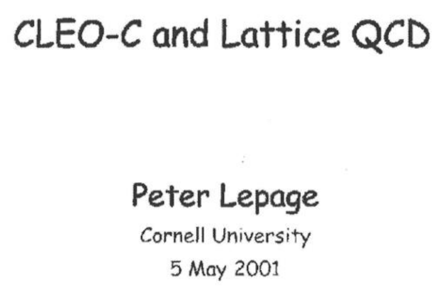
CLEO-c and CESR-c:
A New Frontier of
Weak and Strong Interactions

CESR-c Taskforce **CLEO-c Taskforce**
CLEO-c Collaboration

- This was the time when a lot of the ideas that I will discuss blossomed and a methodology for rigorous experimental verification was developed
- This was my "golden opportunity" to encounter the profound and inspiring ideas that have motivated a large component of my research since
- The CLEO-c task force encompassed an inspiring year of collaboration between theorists and experimentalists to lay the foundations for this last exciting chapter of the CLEO experiment
- One of the strong synergy was with the "Lattice Reinassance" that was explained eloquently to us by Peter, his very inspiring presentations are going to be abundantly quoted in what follows

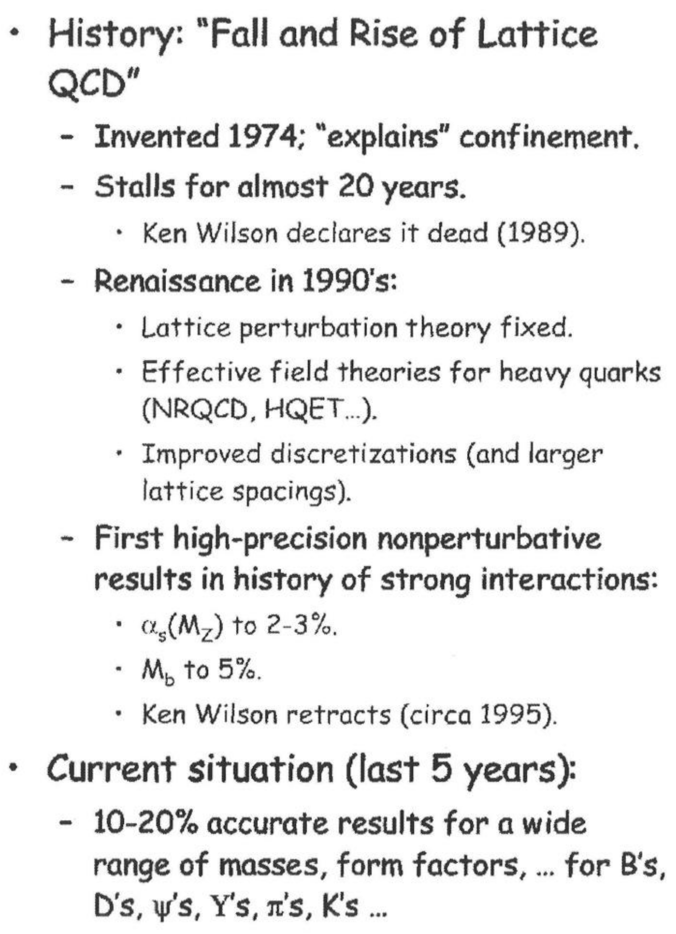
A brief history of lattice QCD

from



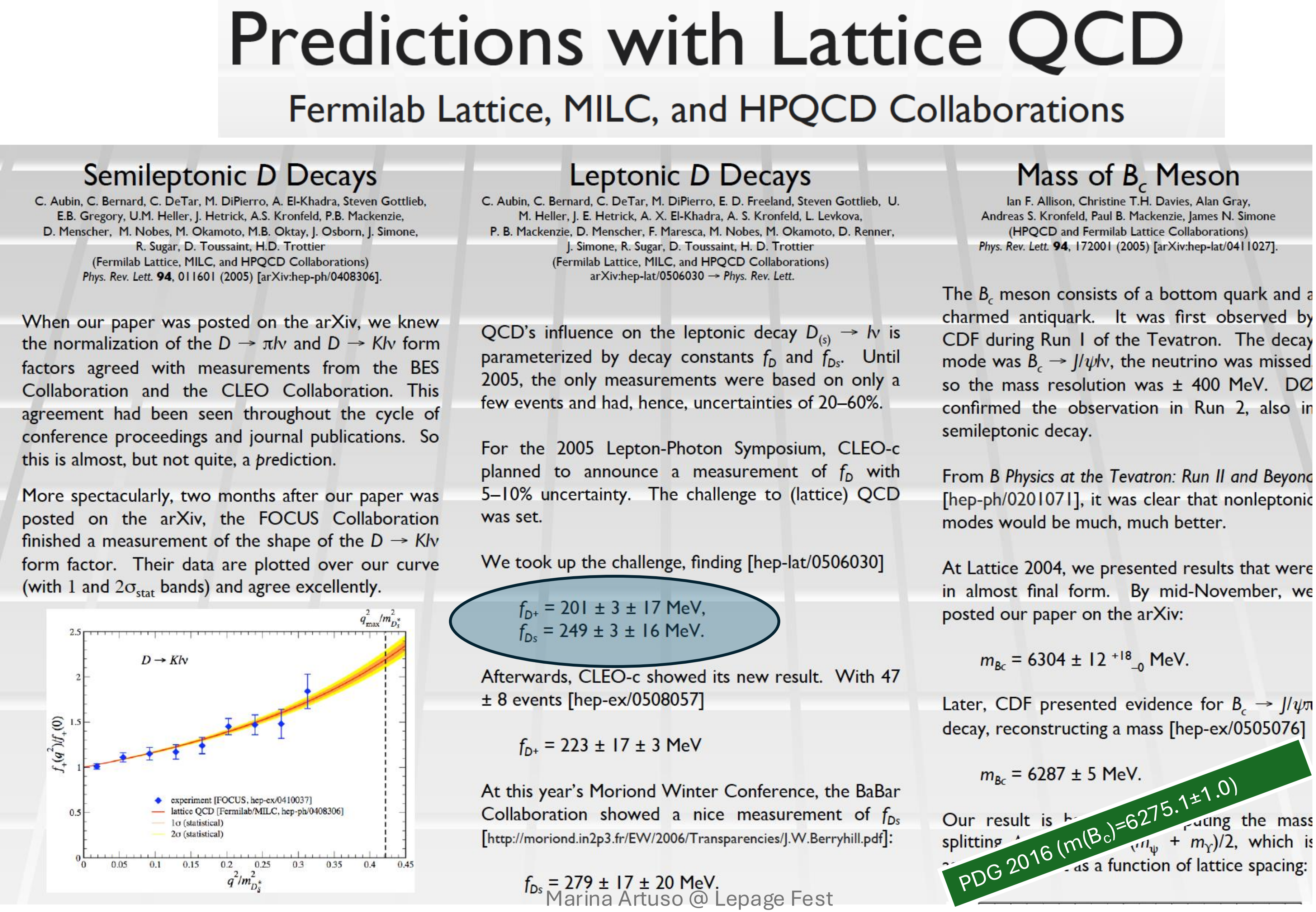
CLEO-C and Lattice QCD

Peter Lepage
Cornell University
5 May 2001



- History: "Fall and Rise of Lattice QCD"
  - Invented 1974; "explains" confinement.
  - Stalls for almost 20 years.
    - Ken Wilson declares it dead (1989).
  - Renaissance in 1990's:
    - Lattice perturbation theory fixed.
    - Effective field theories for heavy quarks (NRQCD, HQET...).
    - Improved discretizations (and larger lattice spacings).
  - First high-precision nonperturbative results in history of strong interactions:
    - $\alpha_s(M_Z)$ to 2-3%.
    - M_b to 5%.
    - Ken Wilson retracts (circa 1995).
- Current situation (last 5 years):
  - 10-20% accurate results for a wide range of masses, form factors, ... for B's, D's, ψ's, Υ's, π's, K's ...

The outcome: a "predictive QCD challenge"



Predictions with Lattice QCD

Fermilab Lattice, MILC, and HPQCD Collaborations

Semileptonic D Decays

C. Aubin, C. Bernard, C. DeTar, M. DiPierro, A. El-Khadra, Steven Gottlieb,
E.B. Gregory, U.M. Heller, J. Hetrick, A.S. Kronfeld, P.B. Mackenzie,
D. Menscher, M. Nobes, M. Okamoto, M.B. Oktay, J. Osborn, J. Simone,
R. Sugar, D. Toussaint, H.D. Trottier
(Fermilab Lattice, MILC, and HPQCD Collaborations)
Phys. Rev. Lett. **94**, 011601 (2005) [arXiv:hep-ph/0408306].

When our paper was posted on the arXiv, we knew the normalization of the $D \to \pi l\nu$ and $D \to Kl\nu$ form factors agreed with measurements from the BES Collaboration and the CLEO Collaboration. This agreement had been seen throughout the cycle of conference proceedings and journal publications. So this is almost, but not quite, a *prediction*.

More spectacularly, two months after our paper was posted on the arXiv, the FOCUS Collaboration finished a measurement of the shape of the $D \to Kl\nu$ form factor. Their data are plotted over our curve (with 1 and $2\sigma_{\text{stat}}$ bands) and agree excellently.

Leptonic D Decays

C. Aubin, C. Bernard, C. DeTar, M. DiPierro, E. D. Freeland, Steven Gottlieb, U.
M. Heller, J. E. Hetrick, A. X. El-Khadra, A. S. Kronfeld, L. Levkova,
P. B. Mackenzie, D. Menscher, F. Maresca, M. Nobes, M. Okamoto, D. Renner,
J. Simone, R. Sugar, D. Toussaint, H. D. Trottier
(Fermilab Lattice, MILC, and HPQCD Collaborations)
arXiv:hep-lat/0506030 → *Phys. Rev. Lett.*

QCD's influence on the leptonic decay $D_{(s)} \to l\nu$ is parameterized by decay constants f_D and f_{D_s}. Until 2005, the only measurements were based on only a few events and had, hence, uncertainties of 20–60%.

For the 2005 Lepton-Photon Symposium, CLEO-c planned to announce a measurement of f_D with 5–10% uncertainty. The challenge to (lattice) QCD was set.

We took up the challenge, finding [hep-lat/0506030]

$$f_{D^+} = 201 \pm 3 \pm 17 \text{ MeV},$$
$$f_{D_s} = 249 \pm 3 \pm 16 \text{ MeV}.$$

Afterwards, CLEO-c showed its new result. With 47 ± 8 events [hep-ex/0508057]

$$f_{D^+} = 223 \pm 17 \pm 3 \text{ MeV}$$

At this year's Moriond Winter Conference, the BaBar Collaboration showed a nice measurement of f_{D_s} [http://moriond.in2p3.fr/EW/2006/Transparencies/J.W.Berryhill.pdf]:

$$f_{D_s} = 279 \pm 17 \pm 20 \text{ MeV}.$$

Mass of B_c Meson

Ian F. Allison, Christine T.H. Davies, Alan Gray,
Andreas S. Kronfeld, Paul B. Mackenzie, James N. Simone
(HPQCD and Fermilab Lattice Collaborations)
Phys. Rev. Lett. **94**, 172001 (2005) [arXiv:hep-lat/0411027].

The B_c meson consists of a bottom quark and a charmed antiquark. It was first observed by CDF during Run I of the Tevatron. The decay mode was $B_c \to J/\psi l\nu$, the neutrino was missed, so the mass resolution was ± 400 MeV. DØ confirmed the observation in Run 2, also in semileptonic decay.

From *B Physics at the Tevatron: Run II and Beyon* [hep-ph/0201071], it was clear that nonleptonic modes would be much, much better.

At Lattice 2004, we presented results that were in almost final form. By mid-November, we posted our paper on the arXiv:

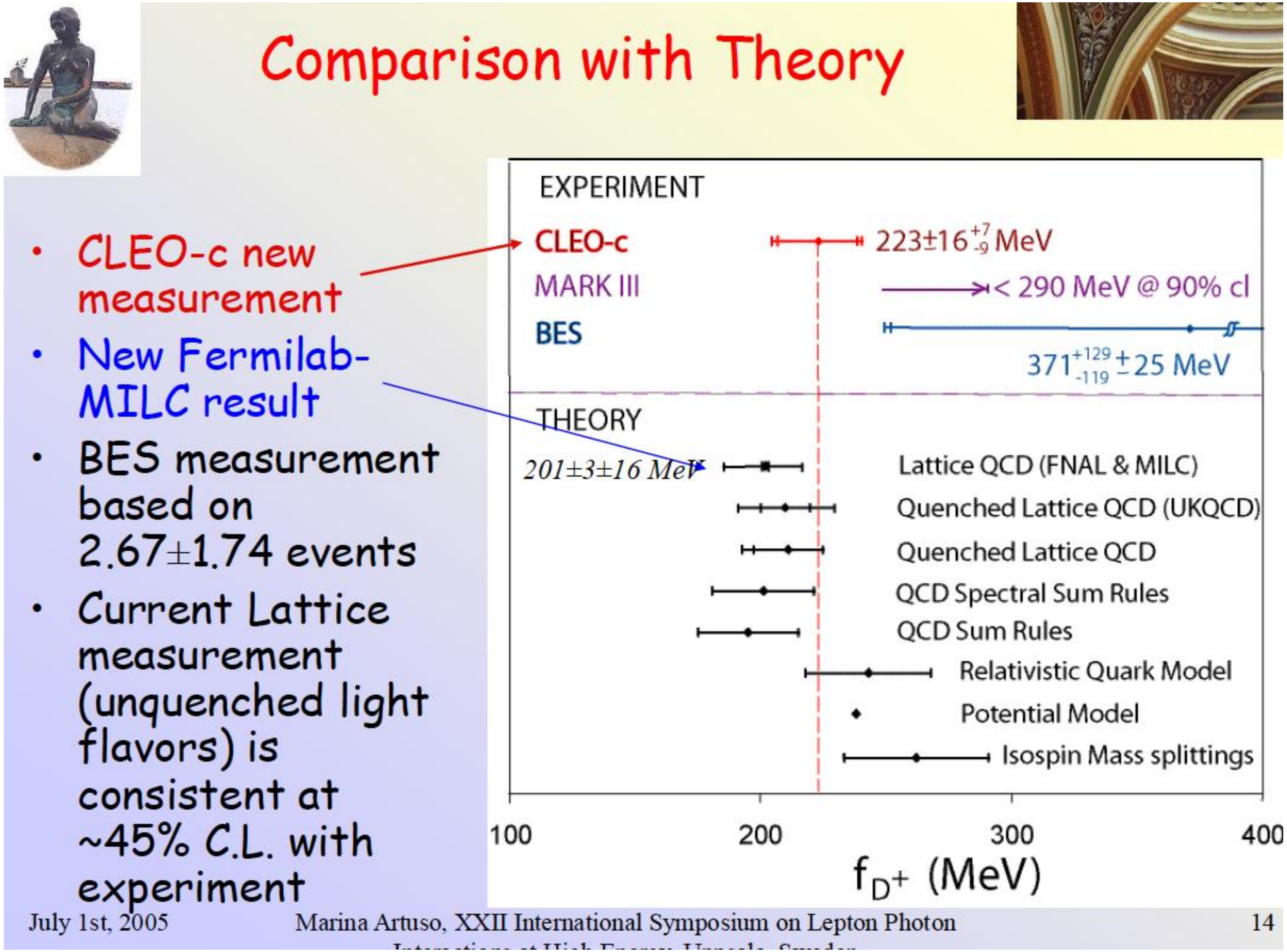
$$m_{B_c} = 6304 \pm 12\,^{+18}_{-0} \text{ MeV}.$$

Later, CDF presented evidence for $B_c \to J/\psi\pi$ decay, reconstructing a mass [hep-ex/0505076]

$$m_{B_c} = 6287 \pm 5 \text{ MeV}.$$

Our result is b puting the mass splitting $(m_\psi + m_\Upsilon)/2$, which is as a function of lattice spacing:

PDG 2016 ($m(B_c)$=6275.1±1.0)

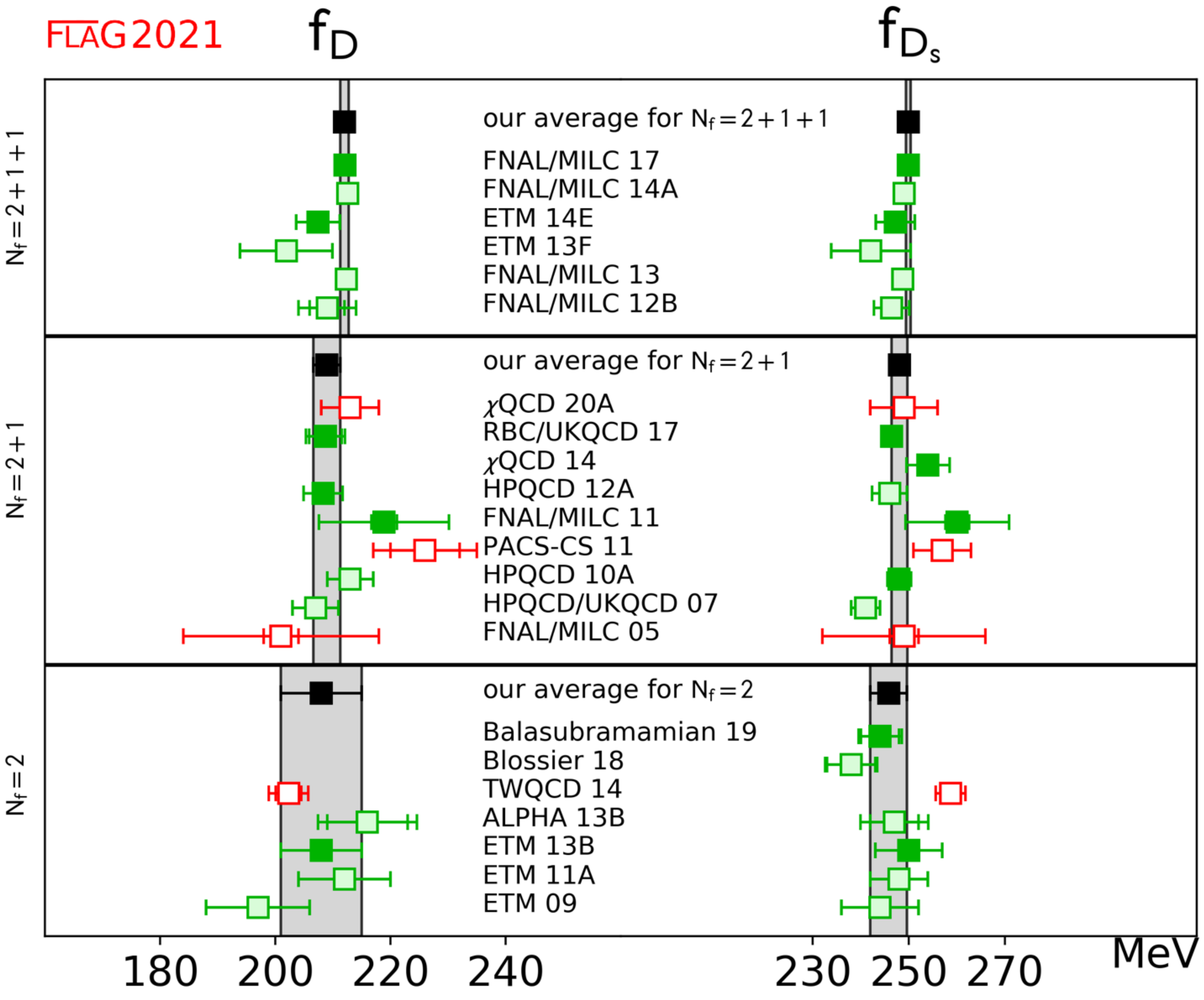


Comparison with Theory

- CLEO-c new measurement
- New Fermilab-MILC result
- BES measurement based on 2.67±1.74 events
- Current Lattice measurement (unquenched light flavors) is consistent at ~45% C.L. with experiment

July 1st, 2005 Marina Artuso, XXII International Symposium on Lepton Photon Interactions at High Energy, Uppsala, Sweden 14

The decay constant now

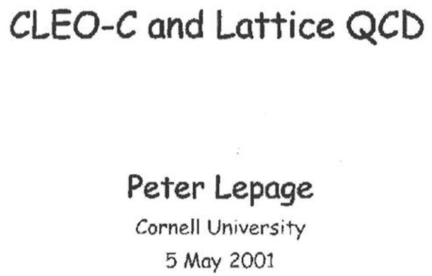


PDG 2024 average

$$|V_{cd}| f_{D^+} = \quad 45.82 \pm 1.05 \pm 0.32 = 45.82 \pm 1.10 \text{ MeV}\,,$$

$$|V_{cs}| f_{D_s^+} = 243.5 \ \pm 2.1 \pm 1.7 = 243.5 \pm 2.7 \text{ MeV}\,,$$

$$f_{D+} = 207.3 \pm 6.6 \text{ MeV}$$



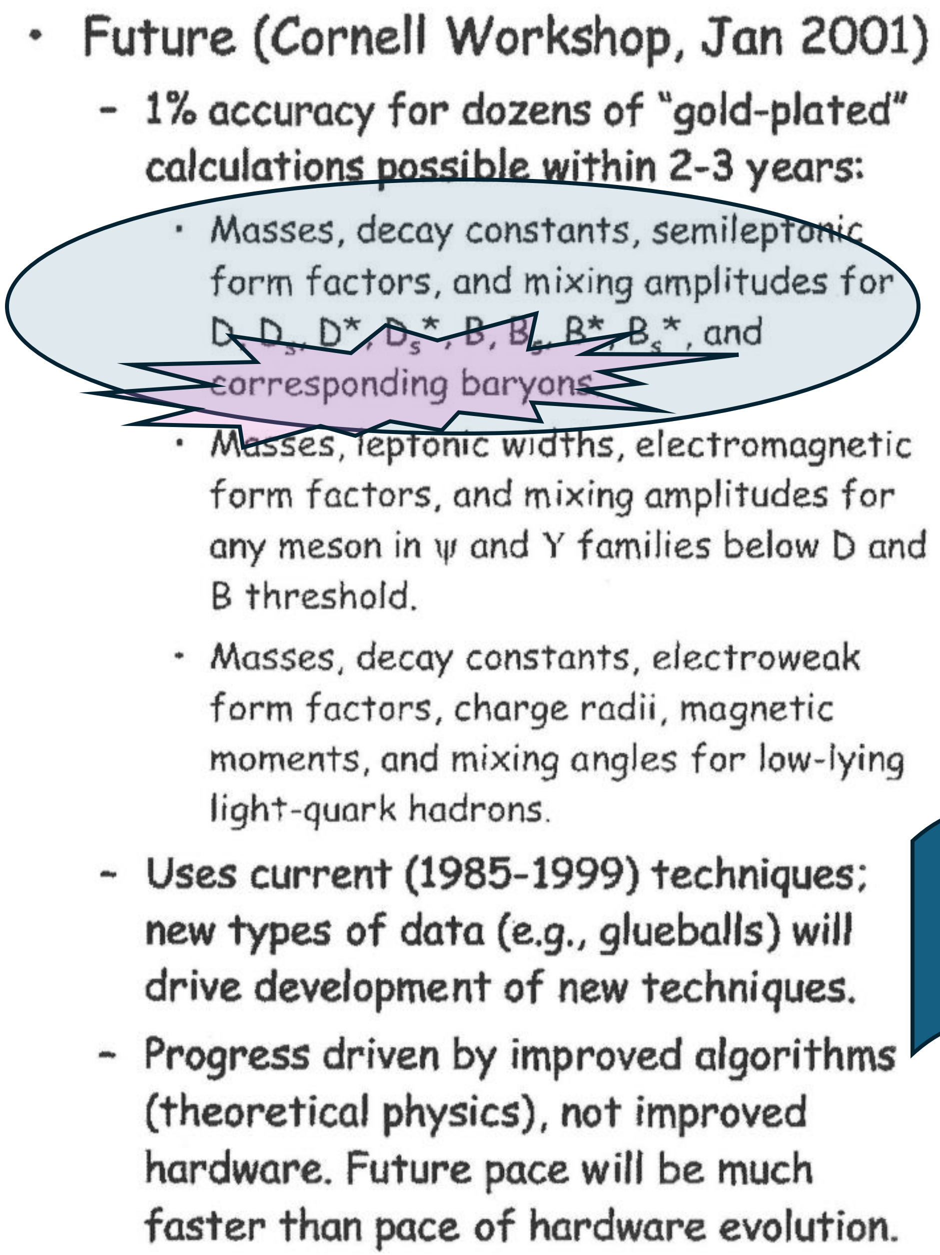
CLEO-C and Lattice QCD

Peter Lepage

Cornell University

5 May 2001

The lattice promise



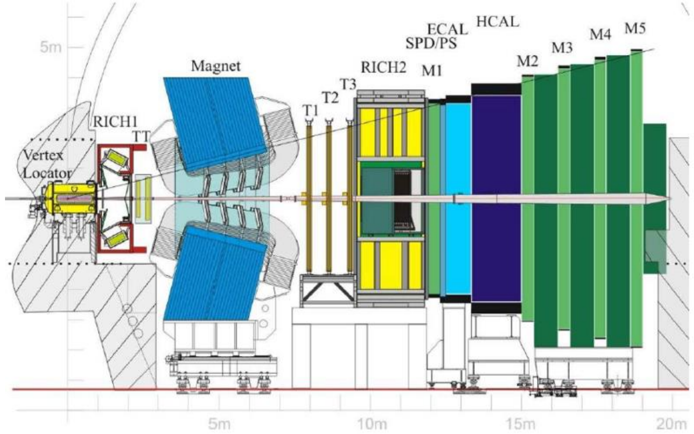
- Future (Cornell Workshop, Jan 2001)
  - 1% accuracy for dozens of "gold-plated" calculations possible within 2-3 years:
    - Masses, decay constants, semileptonic form factors, and mixing amplitudes for D, D_s, D*, D_s*, B, B_s, B*, B_s*, and corresponding baryons.
    - Masses, leptonic widths, electromagnetic form factors, and mixing amplitudes for any meson in ψ and Υ families below D and B threshold.
    - Masses, decay constants, electroweak form factors, charge radii, magnetic moments, and mixing angles for low-lying light-quark hadrons.
  - Uses current (1985-1999) techniques; new types of data (e.g., glueballs) will drive development of new techniques.
  - Progress driven by improved algorithms (theoretical physics), not improved hardware. Future pace will be much faster than pace of hardware evolution.

The exciting promise of exotic hadrons

My next chapter: the LHCb trilogy

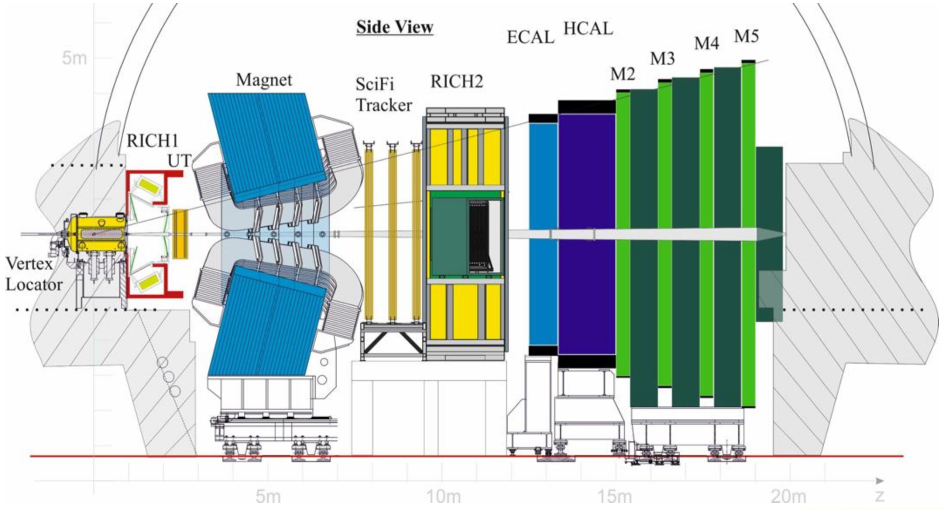
LHCb: Phase I

(an ever-growing physics scope)



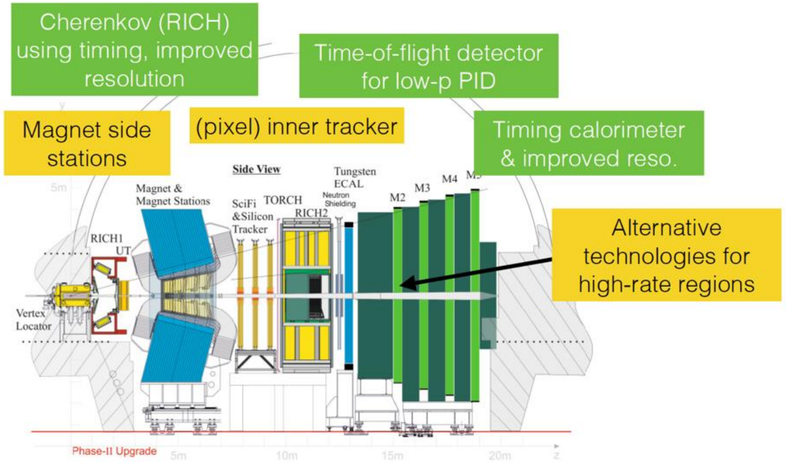
LHCb Upgrade I

(the software trigger edition)



LHCb Upgrade II

(exploiting timing to reach the highest sensitivity)



Cherenkov (RICH) using timing, improved resolution

Time-of-flight detector for low-p PID

Magnet side stations

(pixel) inner tracker

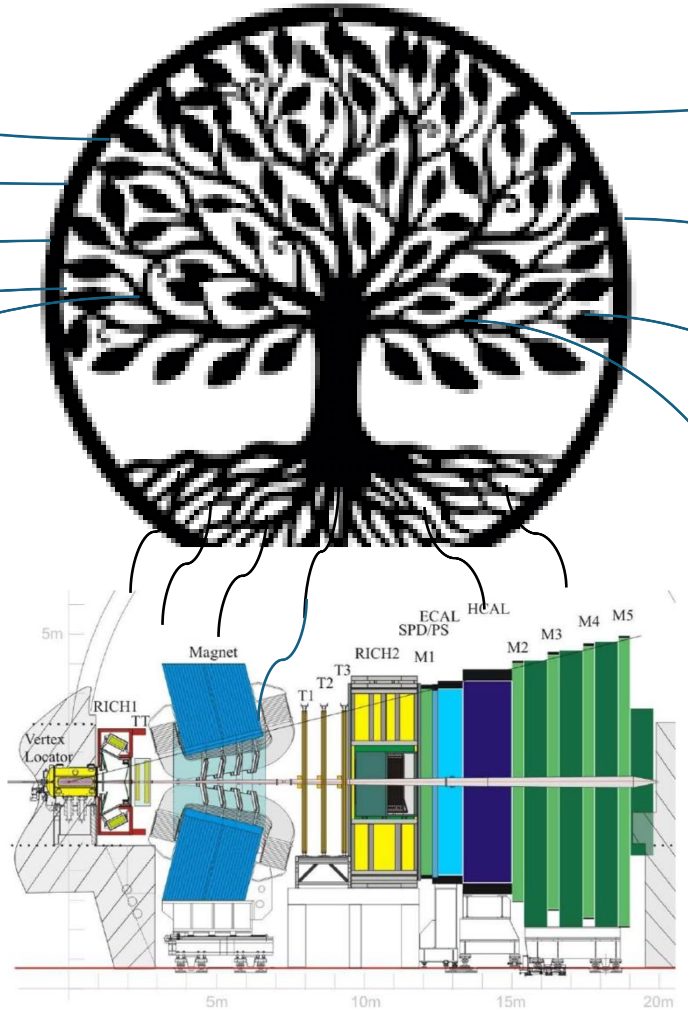
Timing calorimeter & improved reso.

Alternative technologies for high-rate regions

Pixel detector with timing

LHCb physics: beauty, charm and beyond

New leaves are still growing on this rich "tree of knowledge"



CP Violation in charm and beauty decays

Magnitude of quark mixing angles

Rare b and c decays

Neutral meson oscillations

Lepton flavor universality

Conventional and exotic spectroscopy

Search for exotic new particles, axions, dark

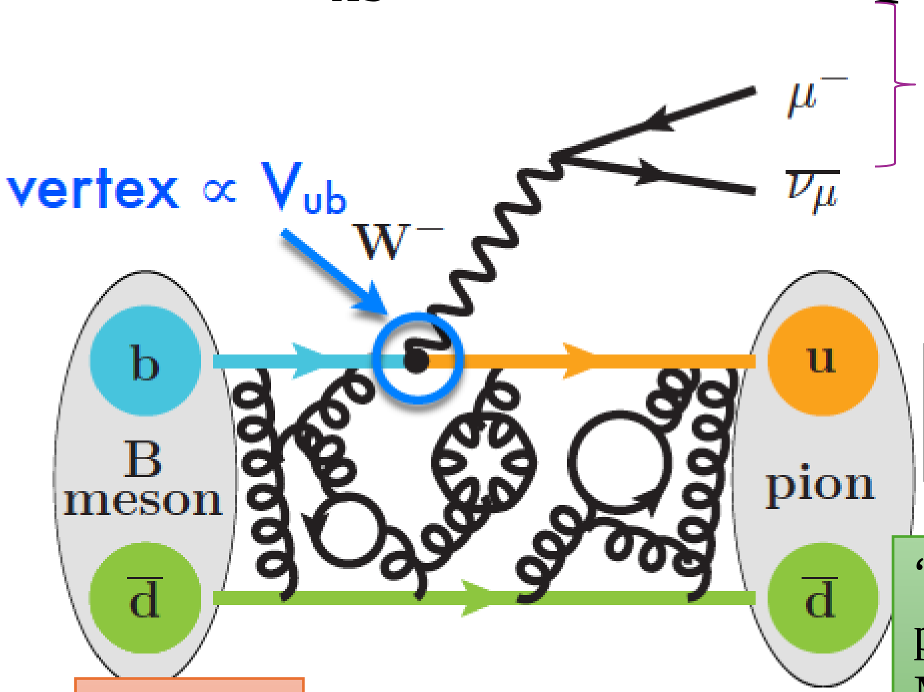
Electroweak physics in the forward

Heavy ion

Precision tests of the Standard Model

The magnitude of V_{xb} and semileptonic b decays

Illustration focused on V_{ub}, change u➛c for V_{cb}.



$q^2=m^2(\mu\nu)$

"exclusive" study a specific final state

"inclusive" study an inclusive property of the decay (E_μ, M_{had},q^2)

What we want to know

Experimental observables

Lattice QCD,LC sum rules, HQE..

$(\Gamma, d\Gamma/dq^2 \ldots = |V_{ub}|^2$ x (**Hadronic matrix element**) x (known factors)

Current situation

M. Bona, ICHEP2024

Unitarity Triangle update

V_{cb} and V_{ub}

Latest inputs from arXiv:2310.03680

$|V_{cb}|$ *(excl)* = $(40.13 \pm 0.55)\ 10^{-3}$

$|V_{cb}|$ *(incl)* = $(41.97 \pm 0.48)\ 10^{-3}$

from arXiv:2310.20324

from arXiv:2202.10285

$|V_{ub}|$ *(excl)* = $(3.57 \pm 0.23)\ 10^{-3}$

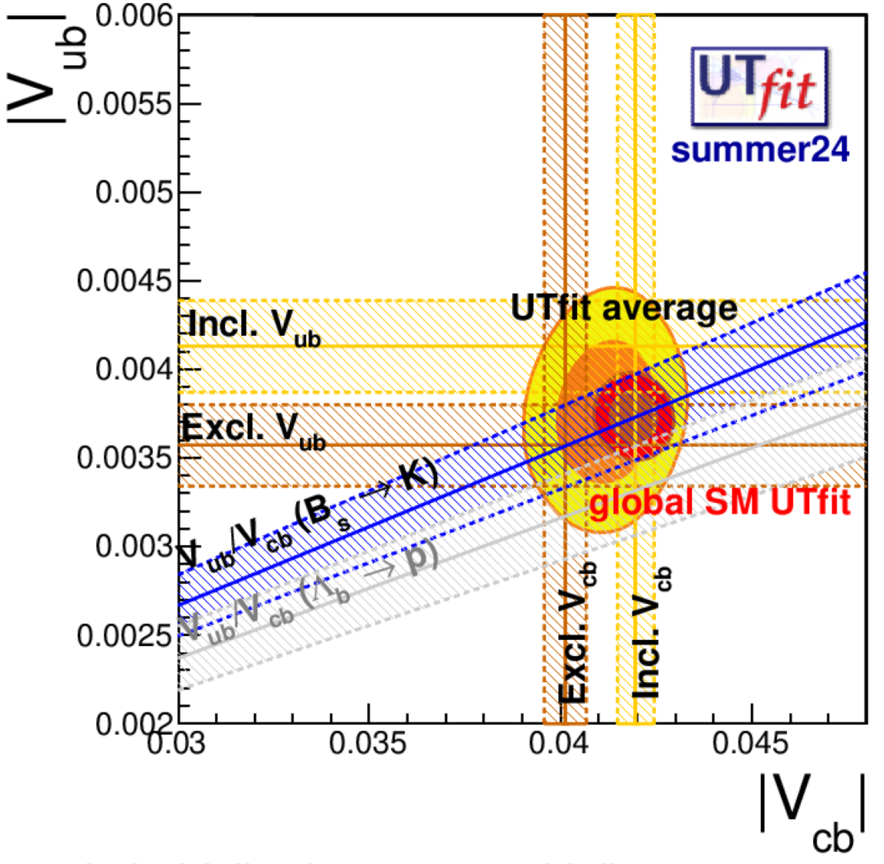
$|V_{ub}|$ *(incl)* = $(4.13 \pm 0.26)\ 10^{-3}$

PDG 2024

from arXiv:2310.03680

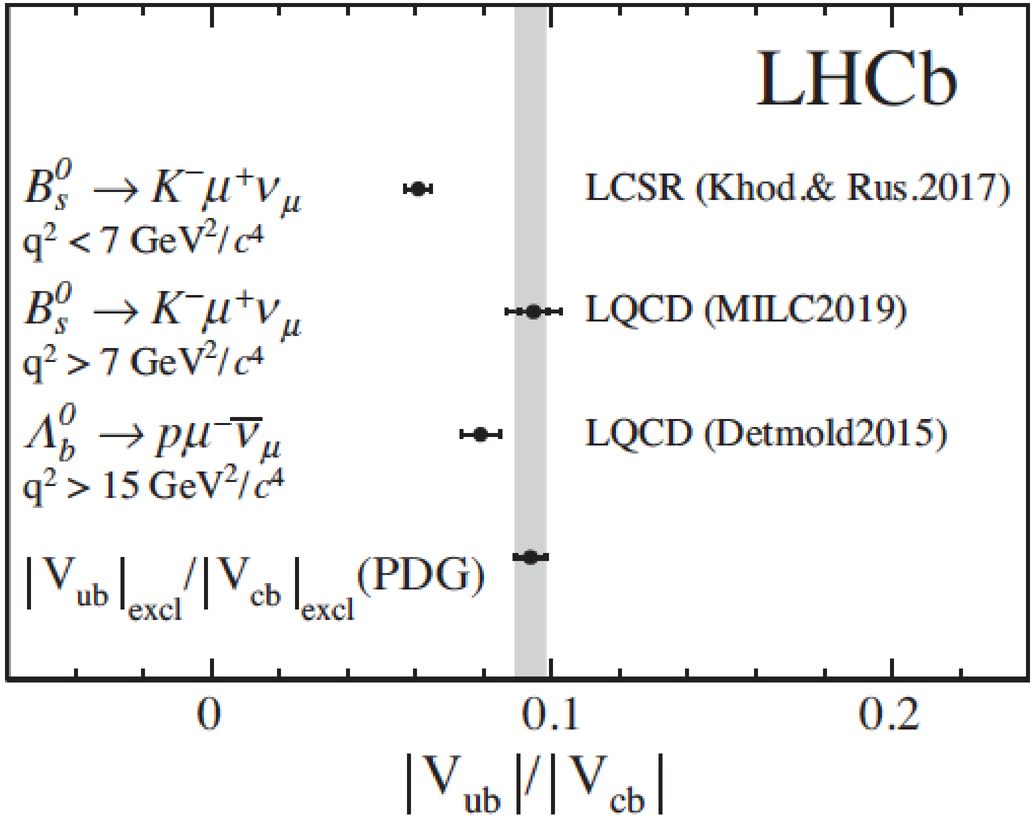
$|V_{ub} / V_{cb}| = (8.7 \pm 0.9)\ 10^{-2}$

$|V_{ub} / V_{cb}|$ *(LHCb)* = $(7.9 \pm 0.6)\ 10^{-2}$ Λ_b, excluded following FLAG guidelines

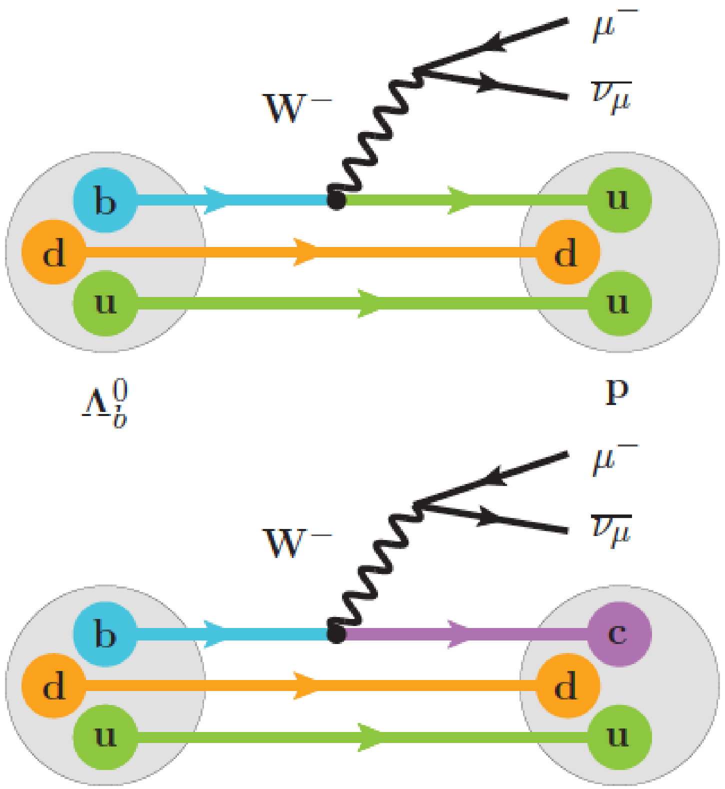


Comments on the LHCb $\frac{|V_{ub}|}{|V_{cb}|}$ from $B_s^0 \rightarrow K^-\mu^+\nu$

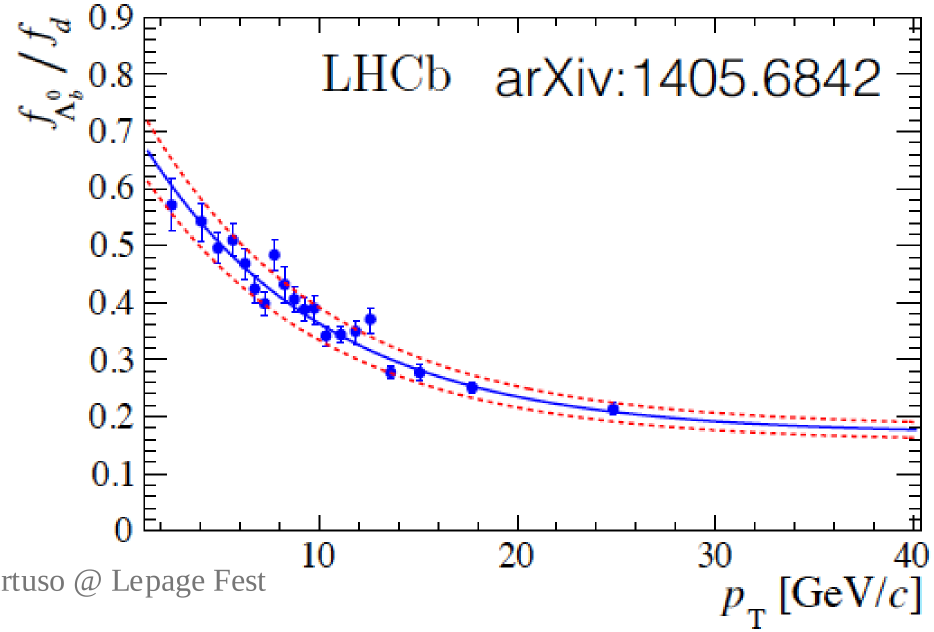
- ❑ LHCb result in 2 q^2 bins, results are not consistent (different theoretical input?)
- ❑ The LHCb measurement is $\frac{|V_{ub}|}{|V_{cb}|}$, any inference on $|V_{ub}|$ needs to express all the inputs and there are several uncertainties that need to be taken into account



Λ_b semileptonic decays at LHCb

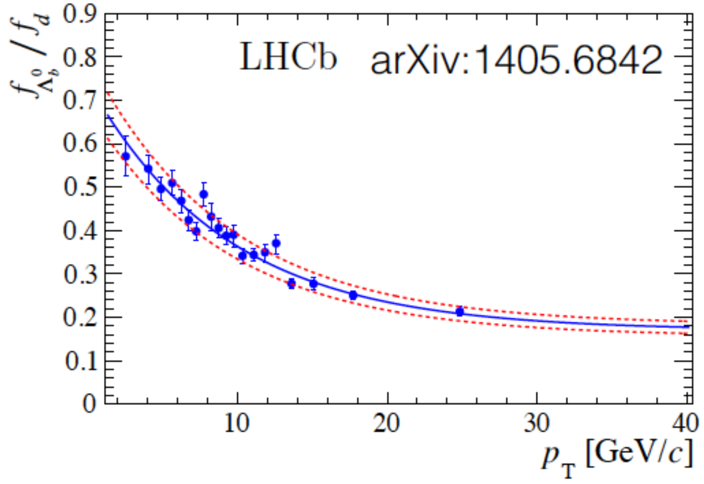


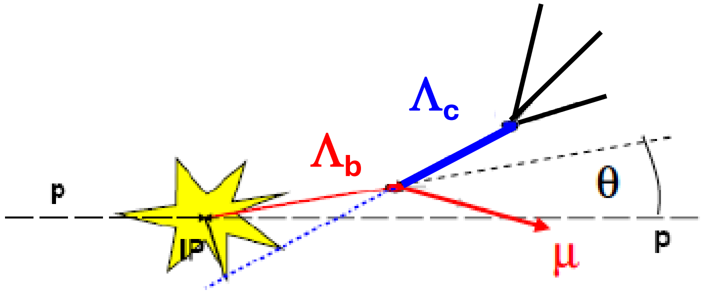
- Use of b-baryon decays provides complementary information to B mesons
- At LHCb Λ_b are produced copiously



$\left|\frac{V_{ub}}{V_{cb}}\right|$ from $\Lambda_b^0 \longrightarrow p\mu^-\bar{\nu}/\Lambda_b^0 \longrightarrow \Lambda_c^+\mu^-\bar{\nu}$

1) Exploit the copious Λ_b production at LCHb
2) Kinematic constraints allow determination of magnitude of Λ_b momentum (modulo 2-fold ambiguity)
3) LHCb determines the ratio in high q^2 region
   - ⇨ Minimize background from Cabibbo favored decays in
   - ⇨ Use region where lattice predictions are expected to be more reliable
3) Use normalization factor derived from Lattice QCD calculation to extract $|V_{ub}/V_{cb}|^2$

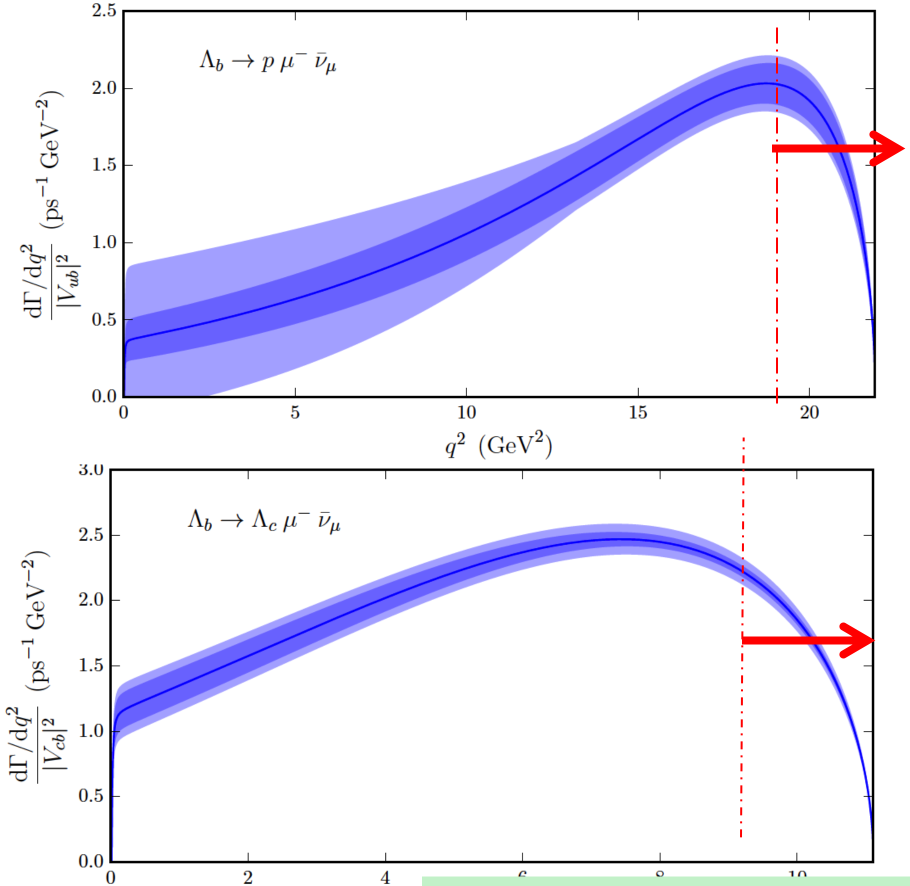




$|V_{ub}/V_{cb}|$

arXiv:1504.01568

arXiv:1503.01421v3 Detmold,Lehner,Meinel



- ❑ Calculation uses 2+1 flavors of dynamical domain-wall fermions, RBC & UKQCD configurations & q^2 dependence parameterized with z-expansion

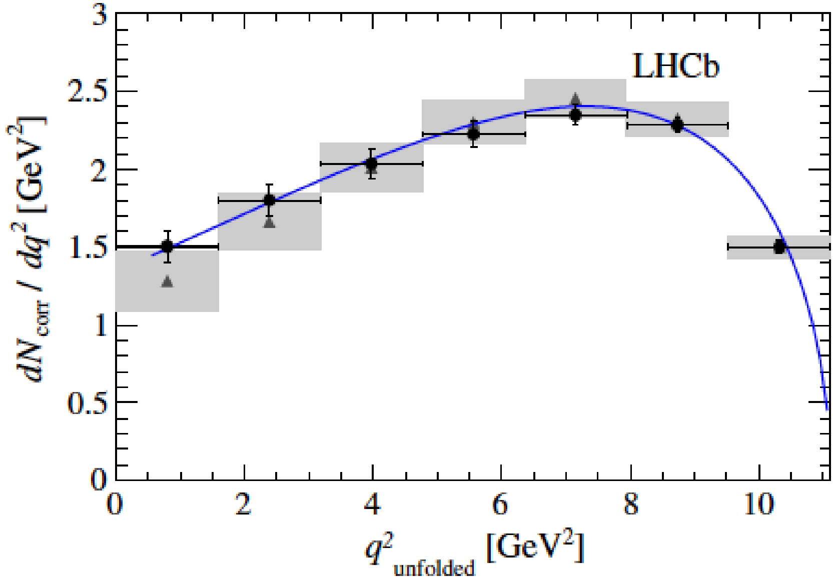
$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \underset{\text{exp}}{\pm 0.004} \underset{\text{th}}{\pm 0.004},$$

$$R_{TH} \equiv \frac{\dfrac{1}{|V_{ub}|^2}\displaystyle\int_{15GeV^2}^{q^2_{\max}} \frac{d\Gamma(\Lambda_b^0 \to p\mu\bar{\nu}_\mu)}{dq^2}dq^2}{\dfrac{1}{|V_{cb}|^2}\displaystyle\int_{7GeV^2}^{q^2_{\max}} \frac{d\Gamma(\Lambda_b^0 \to \Lambda_c^0\mu\bar{\nu}_\mu)}{dq^2}dq^2} = \frac{(12.31 \pm 0.76 \pm 0.77)\,ps^{-1}}{(8.37 \pm 0.16 \pm 0.34)\,ps^{-1}} = 1.471 \pm 0.095 \pm 0.110$$

Comment on $\Lambda_b^0 \longrightarrow \Lambda_c^+ \mu^- \nu$

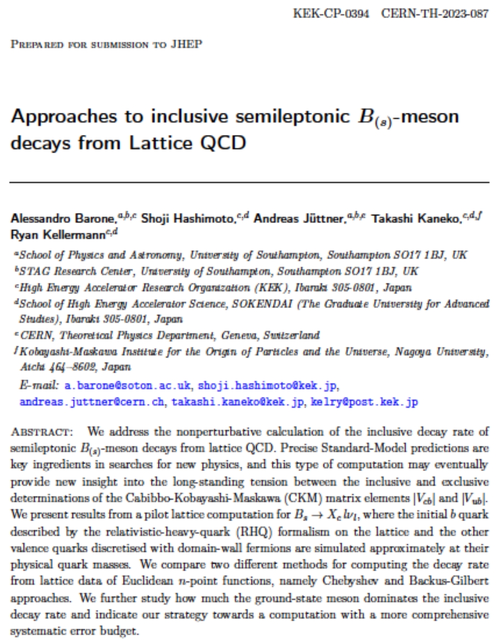
- ❑LHCb studied the q^2 distribution and compared it to the lattice prediction
- ❑Consistent with HQET as noted in q2 spectrum shape LHCb, further pursued in Berlonchner, Ligeti et al
- ❑Analysis with normalization channel is forthcoming so this channel should be taken seriously

q2 spectrum shape LHCb



Final comment on $|V_{cb}|$, $|V_{ub}|$, $\left|\frac{V_{ub}}{V_{cb}}\right|$

- ☐ The inclusive-exclusive comparison chapter cannot be sorted out just by measuring more channels in the same way
- ☐ Important contributions by the lattice to exclusive channels (beyond zero recoil)
- ☐ On the wish list:
  - ☐ Inclusive decays
  - ☐ Beyond the gold-plated modes



KEK-CP-0394 CERN-TH-2023-087

Prepared for submission to JHEP

Approaches to inclusive semileptonic $B_{(s)}$-meson decays from Lattice QCD

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Ryan Kellermann[c,d]

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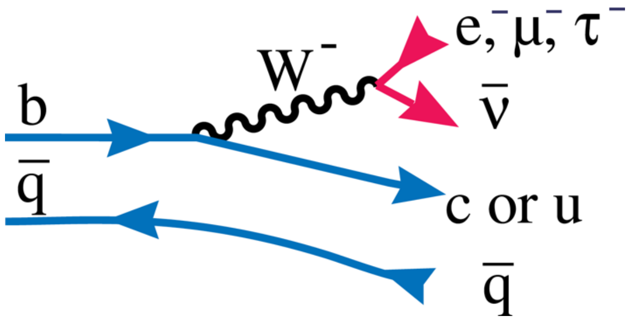
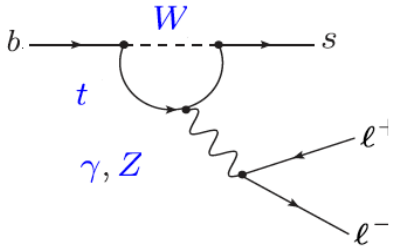
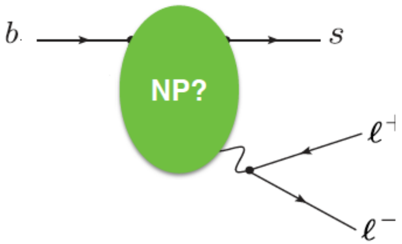
Abstract: We address the nonperturbative calculation of the inclusive decay rate of semileptonic $B_{(s)}$-meson decays from lattice QCD. Precise Standard-Model predictions are key ingredients in searches for new physics, and this type of computation may eventually provide new insight into the long-standing tension between the inclusive and exclusive determinations of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{cb}|$ and $|V_{ub}|$. We present results from a pilot lattice computation for $B_s \to X_c l\nu_l$, where the initial b quark described by the relativistic-heavy-quark (RHQ) formalism on the lattice and the other valence quarks discretised with domain-wall fermions are simulated approximately at their physical quark masses. We compare two different methods for computing the decay rate from lattice data of Euclidean n-point functions, namely Chebyshev and Backus-Gilbert approaches. We further study how much the ground-state meson dominates the inclusive decay rate and indicate our strategy towards a computation with a more comprehensive systematic error budget.

Indirect search for new physics

The origin story: beauty as a tool for discovery

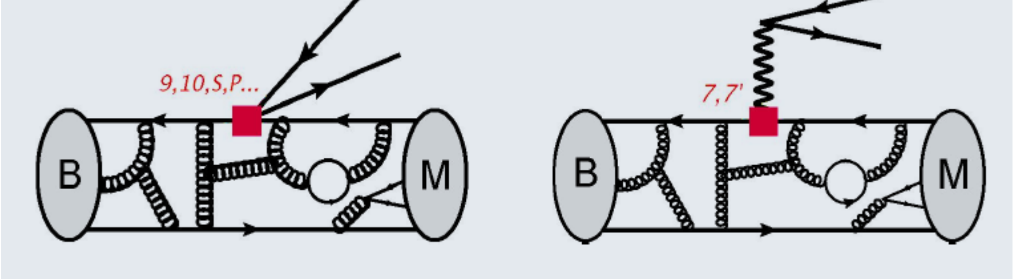






- ❑ Old paradigm: tree diagrams are dominated by Standard Model processes, and loops can unveil new physics manifestations through interference with new particles (maybe not the whole story)
- ❑ Also: things are more complicated: we observe hadron decays → effective Hamiltonian

$$\mathcal{H}(b \to s\ell^+\ell^-) = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_{i=1}^{10} \mathcal{C}_i(\mu)\mathcal{O}_i(\mu)$$

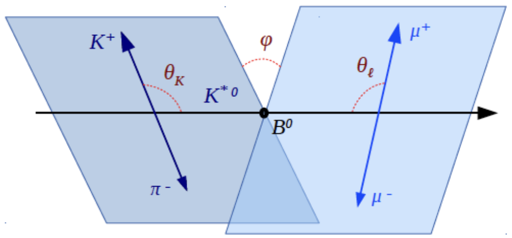


Search for new physics in $b \to s\ell\ell$ decays

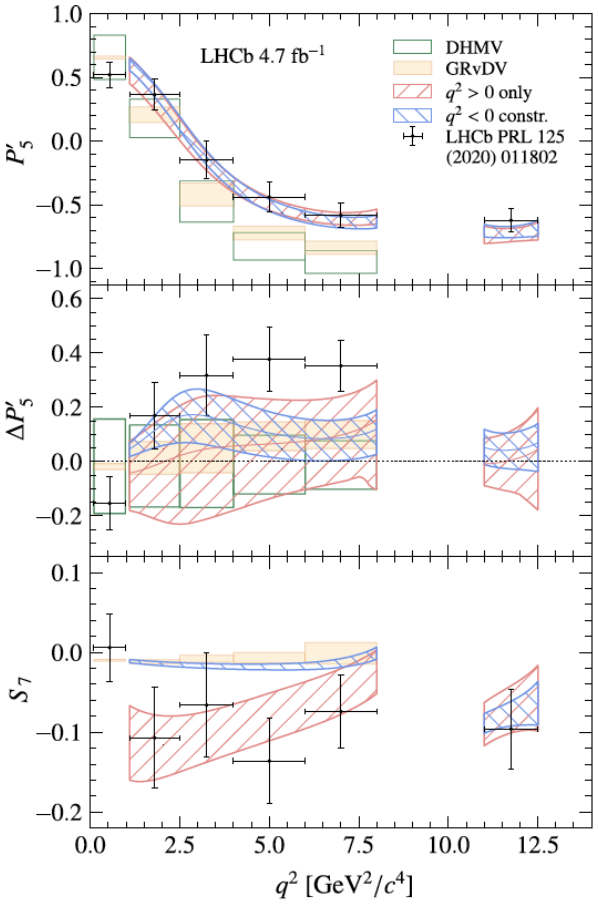
Angular analysis

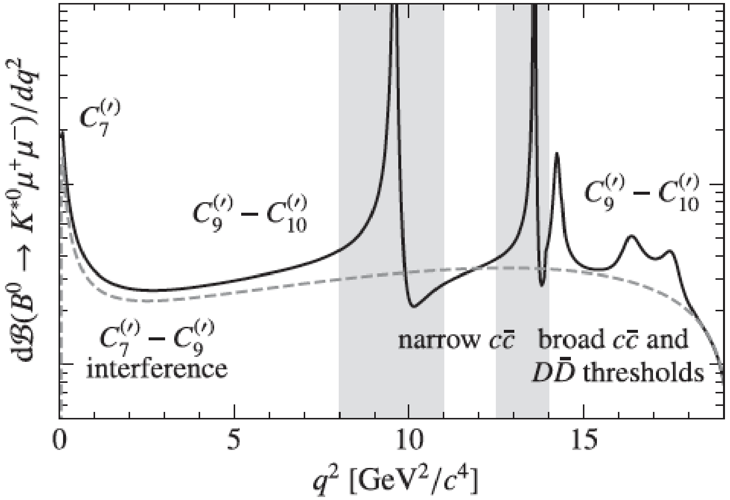
$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_\mathrm{L})A_\mathrm{T}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_\mathrm{L})A_{Re}^\mathrm{T}\sin^2\theta_K\cos\theta_\ell + \sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\ \Big]$$

$q^2 \equiv m^2_{\mu\mu}$



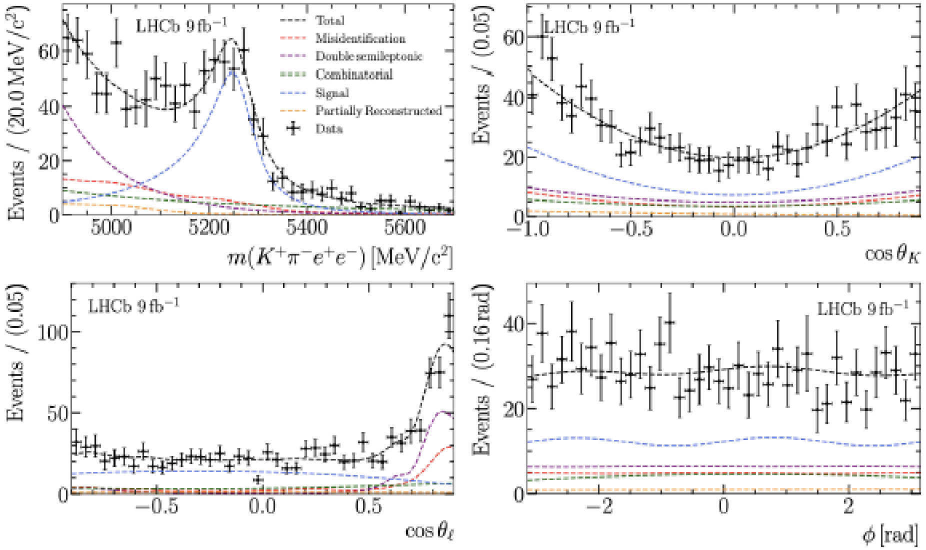
PhysRevLett.132.131801



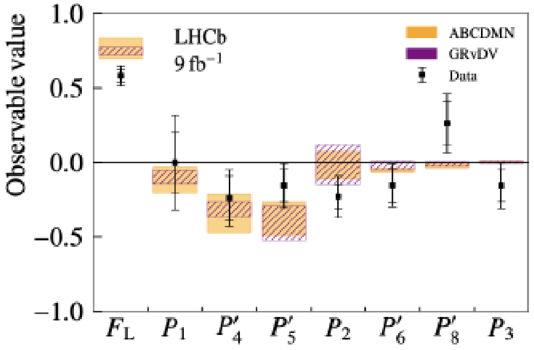


Angular analysis of $B \to K^{*}e^{+}e^{-}$

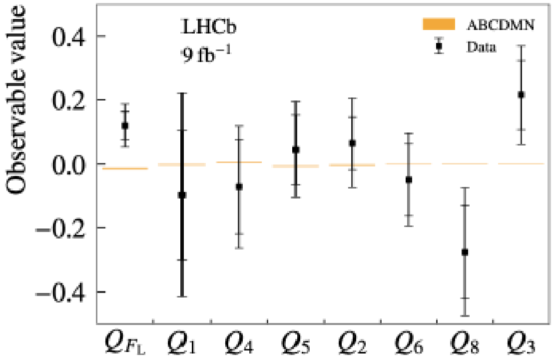
4D unbinned weighted fit to the mass and angular distributions



Allows the extraction of the angular observable in the central q^2 region



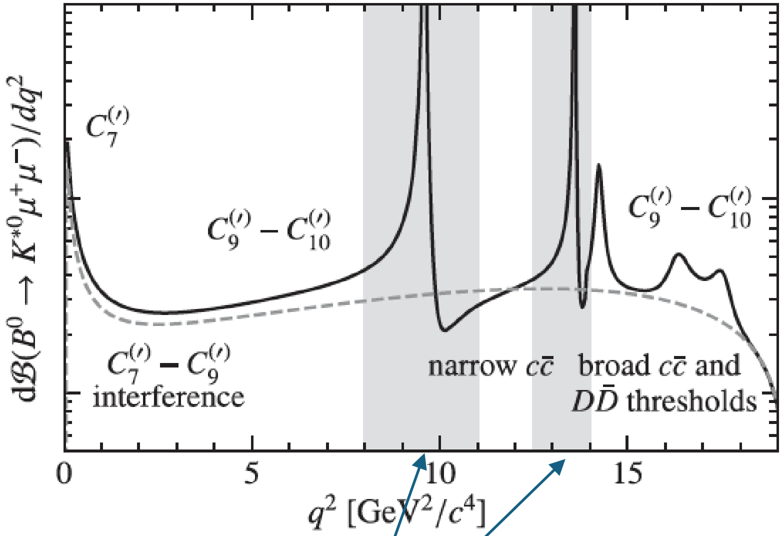
$$Q_i = P_i^{(\mu)} - P_i^{(e)}$$



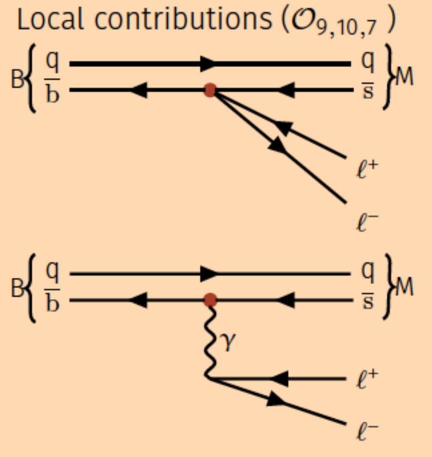
LHCb-PAPER-2024-022 in preparation

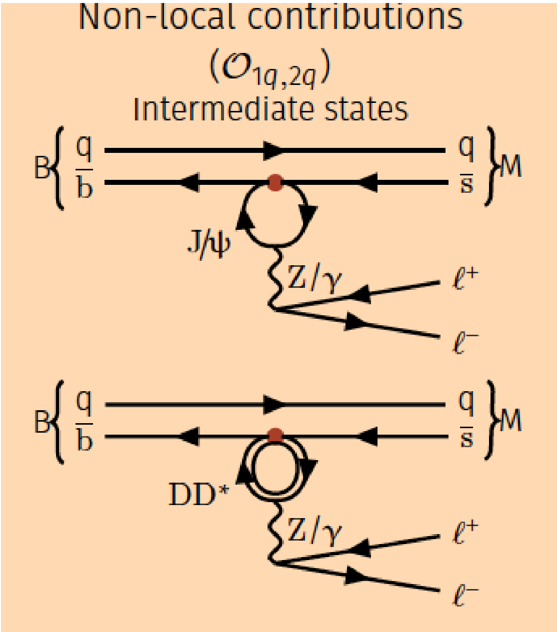
Most precise determination of angular observables and no sign of lepton flavour violating effects are observed

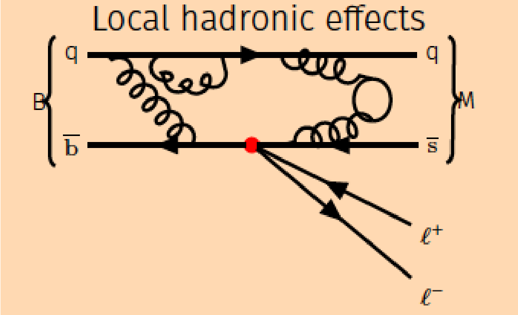
Non-local form factors



Old approach: exclude regions where non-local effects expected to be dominant


Local contributions ($\mathcal{O}_{9,10,7}$)


Non-local contributions ($\mathcal{O}_{1q,2q}$)
Intermediate states


Local hadronic effects

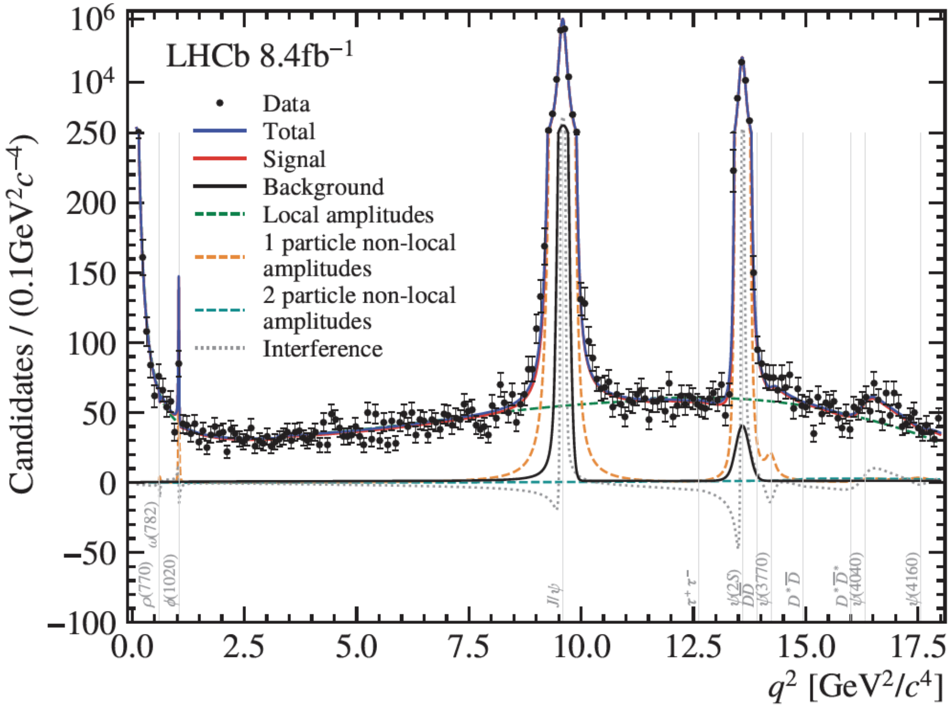
$$\mathcal{A}_\lambda^{L,R}(B \to M_\lambda \ell\ell) = N_\lambda \left\{ (C_9 \mp C_{10})\mathcal{F}_\lambda(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right\}$$

Local form factors

Non-local form factors

Experimental study of local and non-local amplitudes

LHCb-PAPER-2024-011



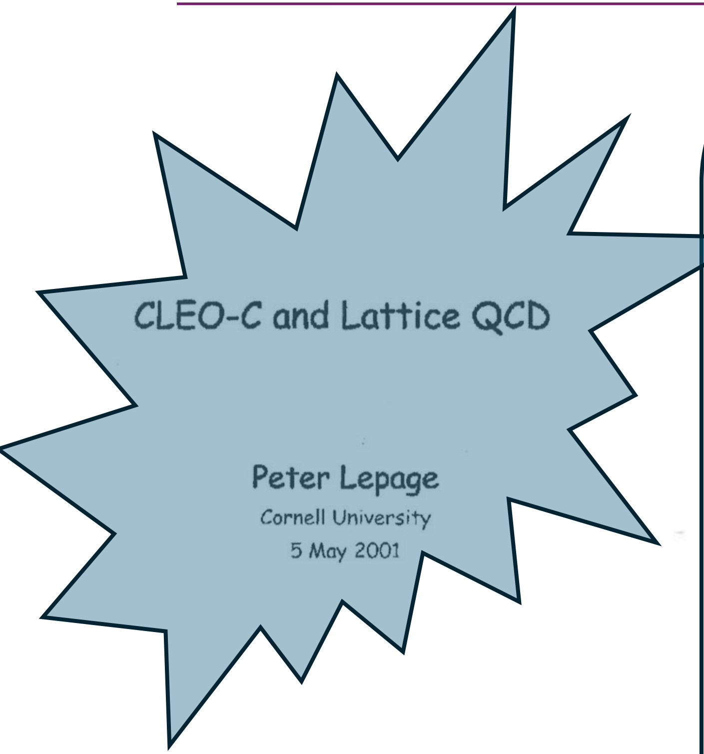
- Full q^2 range of $B^0 \to K^{*0}\mu^+\mu^-$ used in the fit
- Fit model encompasses signal (local, one and two-particle non-local amplitudes & interference terms) & gives:

Wilson Coefficient results	
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$
$\mathcal{C}_9'$	$0.28 \pm 0.41 \pm 0.12$
$\mathcal{C}_{10}'$	$-0.09 \pm 0.21 \pm 0.06$
$\mathcal{C}_{9\tau}$	$(-1.0\pm2.6 \pm 1.0) \times 10^{-2}$

$B^0 \to K^{*0}[\tau^+\tau^- \to \mu^+\mu^-]$ rescattering

QCD in action

The importance of QCD

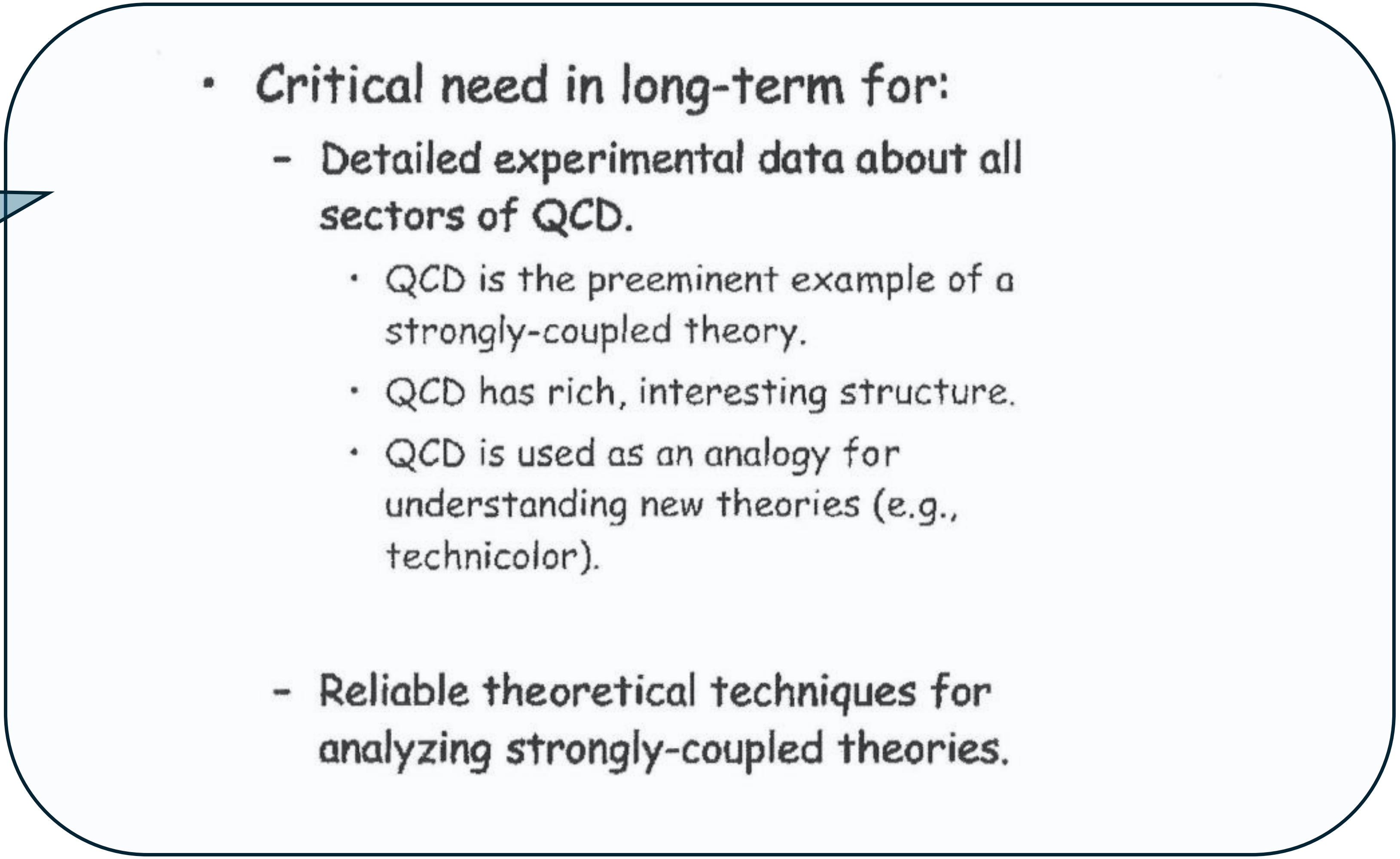


CLEO-C and Lattice QCD

Peter Lepage

Cornell University

5 May 2001



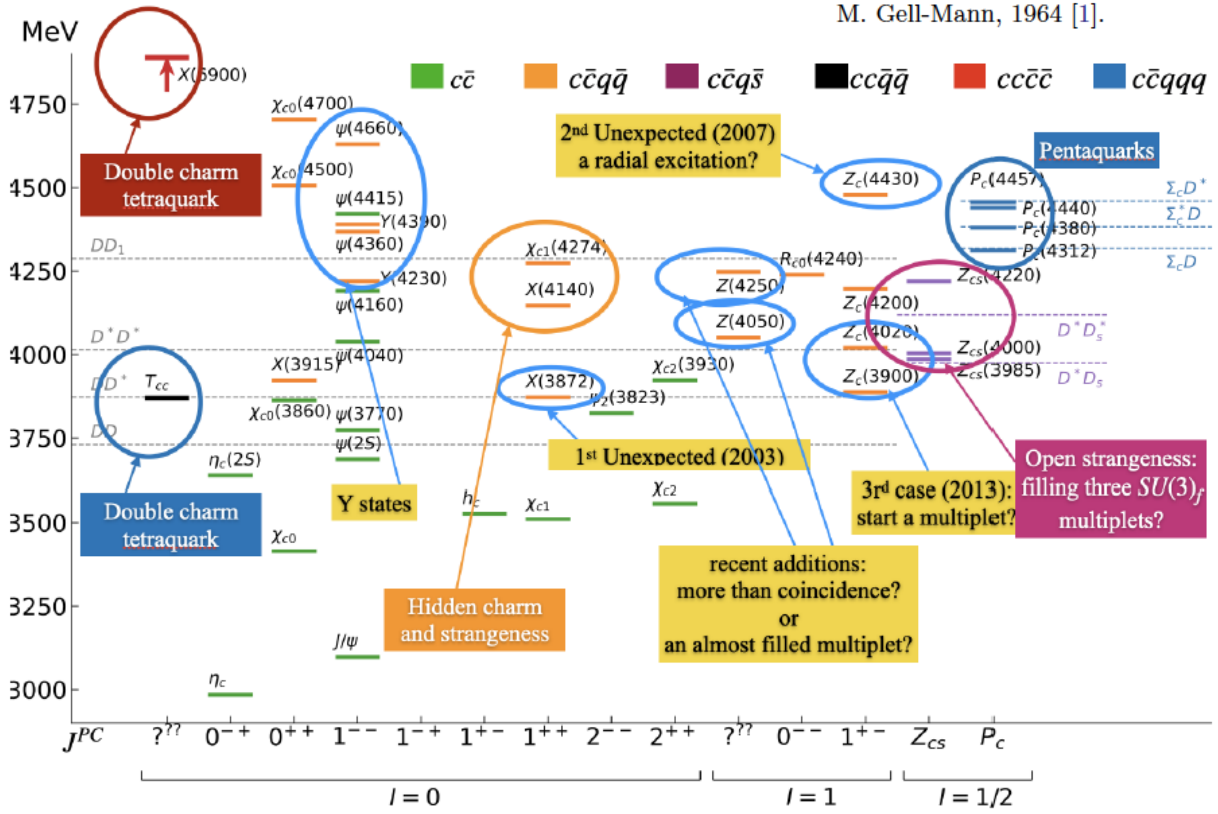
- Critical need in long-term for:
  - Detailed experimental data about all sectors of QCD.
    - QCD is the preeminent example of a strongly-coupled theory.
    - QCD has rich, interesting structure.
    - QCD is used as an analogy for understanding new theories (e.g., technicolor).
  - Reliable theoretical techniques for analyzing strongly-coupled theories.

QCD @ work

L. Maiani, A. Pilloni, GGI Lectures on exotic mesons

Baryons can now be constructed from quarks by using the combinations qqq, $qqqq\bar{q}$, etc., while mesons are constructed out of $q\bar{q}$, $qq\bar{q}\bar{q}$, etc.

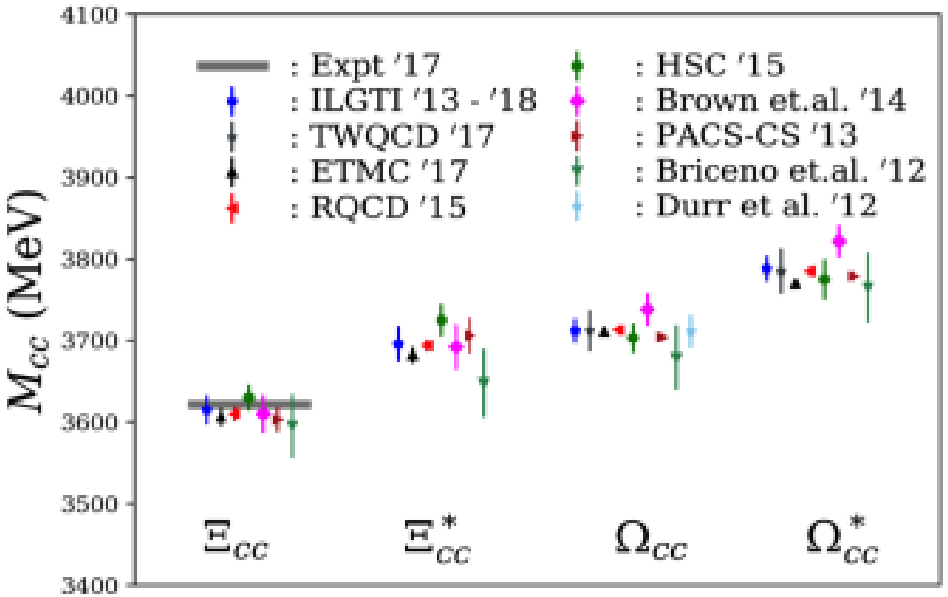
M. Gell-Mann, 1964 [1].

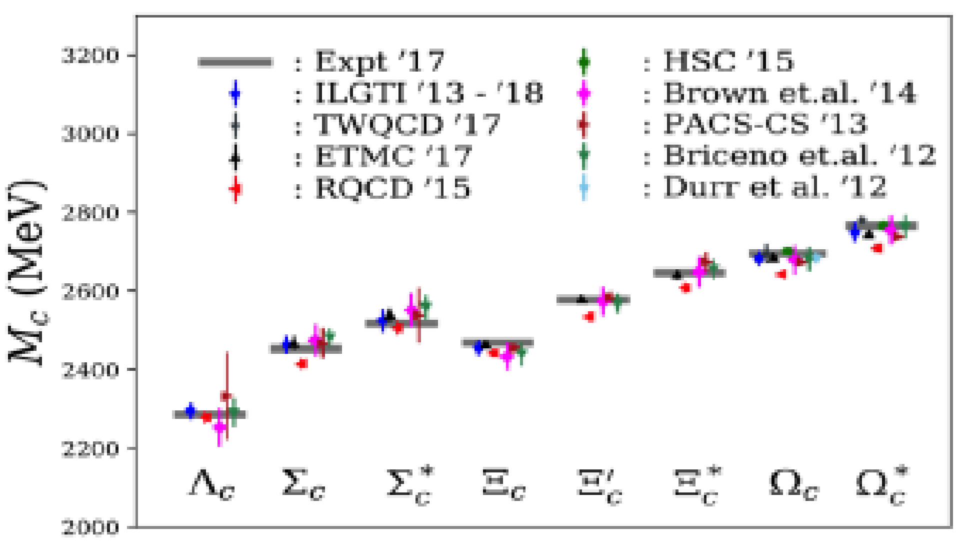


Q1:Can we organize the zoo of known hadrons into a well-motivated structures $(q\bar{q}, qqq, q\bar{q}q\bar{q}, qqqq\bar{q}..)$ with specific quantum numbers and masses consistent with a theoretical model?

Q2: Study manifestations of QCD in collective nuclear phenomena

Lattice QCD spectroscopy



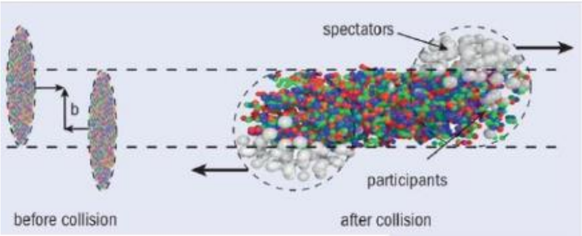


An example of the success in matching recent LHCb discoveries: double-charmed baryons

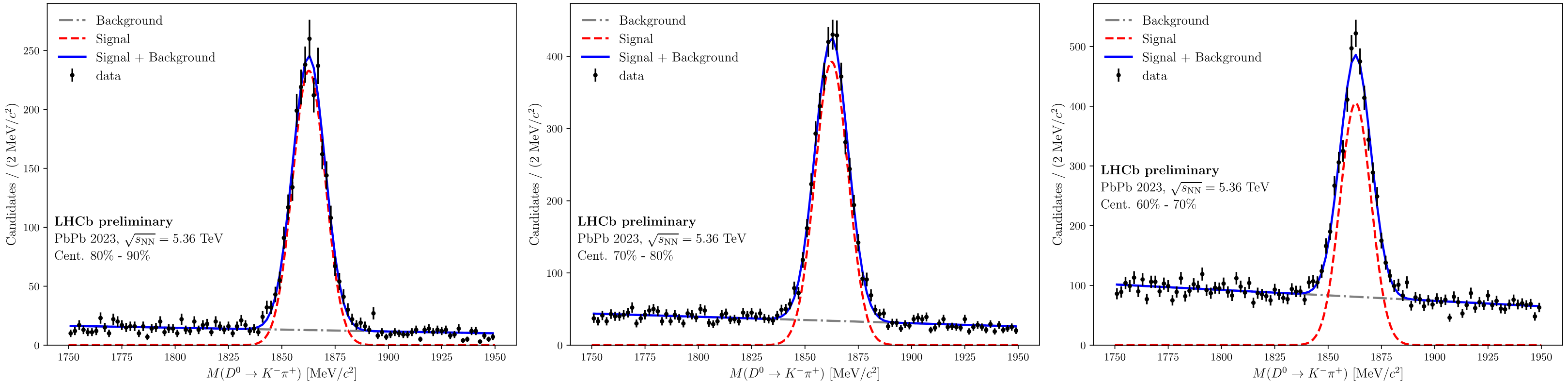
Heavy ion program: 2023 PbPb data

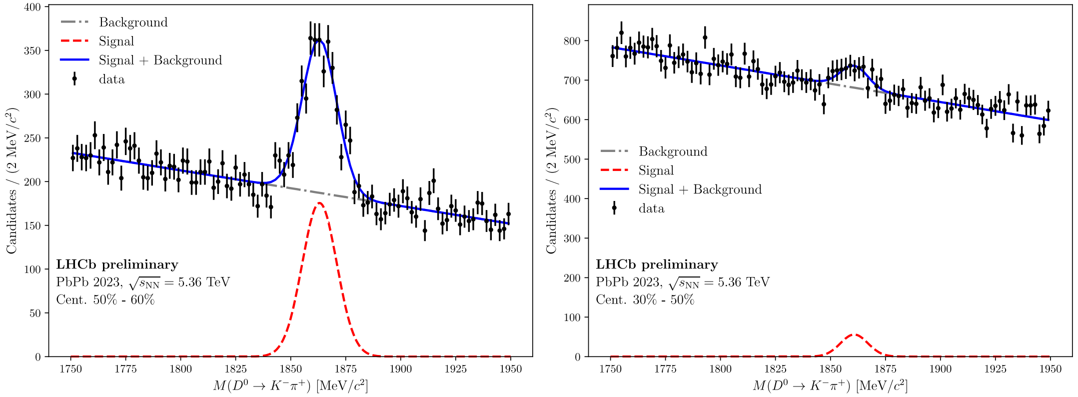
LHCb-Fig-2024-004

- ❑VELO in open position and no UT reached **30% centrality** (70% saturation in Run II)



Nuclear physics connection: interpret collective manifestations of QCD

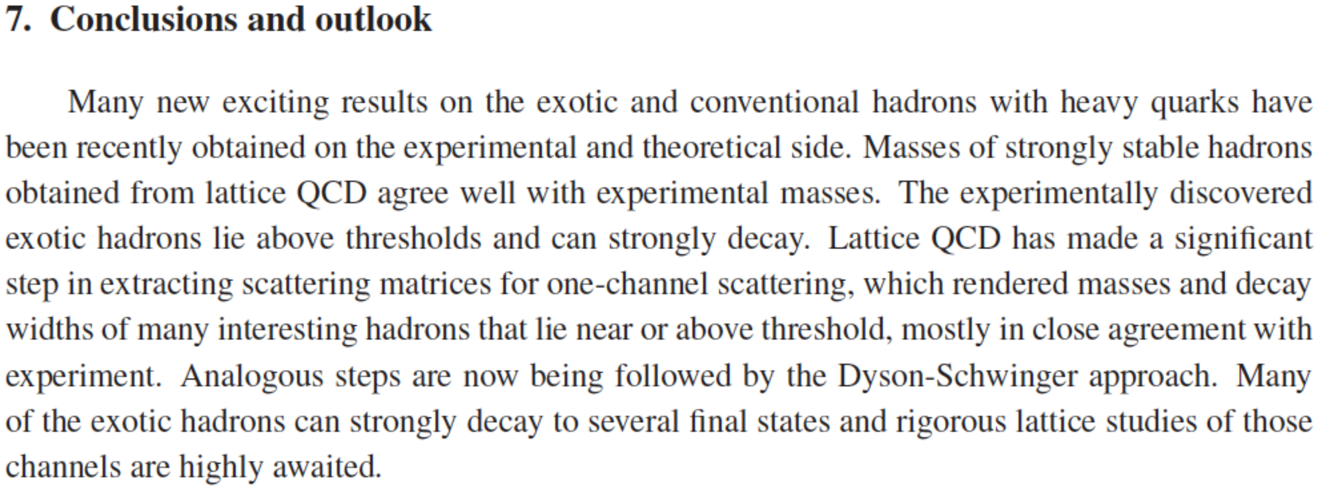




About 20K D^0 decays

High expectations

From S. Prelovsek at Beauty 2019



7. Conclusions and outlook

Many new exciting results on the exotic and conventional hadrons with heavy quarks have been recently obtained on the experimental and theoretical side. Masses of strongly stable hadrons obtained from lattice QCD agree well with experimental masses. The experimentally discovered exotic hadrons lie above thresholds and can strongly decay. Lattice QCD has made a significant step in extracting scattering matrices for one-channel scattering, which rendered masses and decay widths of many interesting hadrons that lie near or above threshold, mostly in close agreement with experiment. Analogous steps are now being followed by the Dyson-Schwinger approach. Many of the exotic hadrons can strongly decay to several final states and rigorous lattice studies of those channels are highly awaited.

Conclusions

- The field of heavy flavor physics remains a vibrant laboratory for discovery, with new perspective opening up with the LHCb upgrade(s) under way and in the planning stage for the HL-LHC era
- The breadth of our program can only be achieved if our progress in developing a quantitative understanding of the hadronic matrix element mediating the decays studied is calculated in a rigorous manner & lattice QCD is crucial to the effort
- **Warm thanks to Peter for his outstanding contribution to the field and for the clarity and inspiration that he brought into our scientific dialogue and for wonderful talks that are still very vivid in my memory after all these years!**

The end