SPC: B physics session

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(University of Illinois)

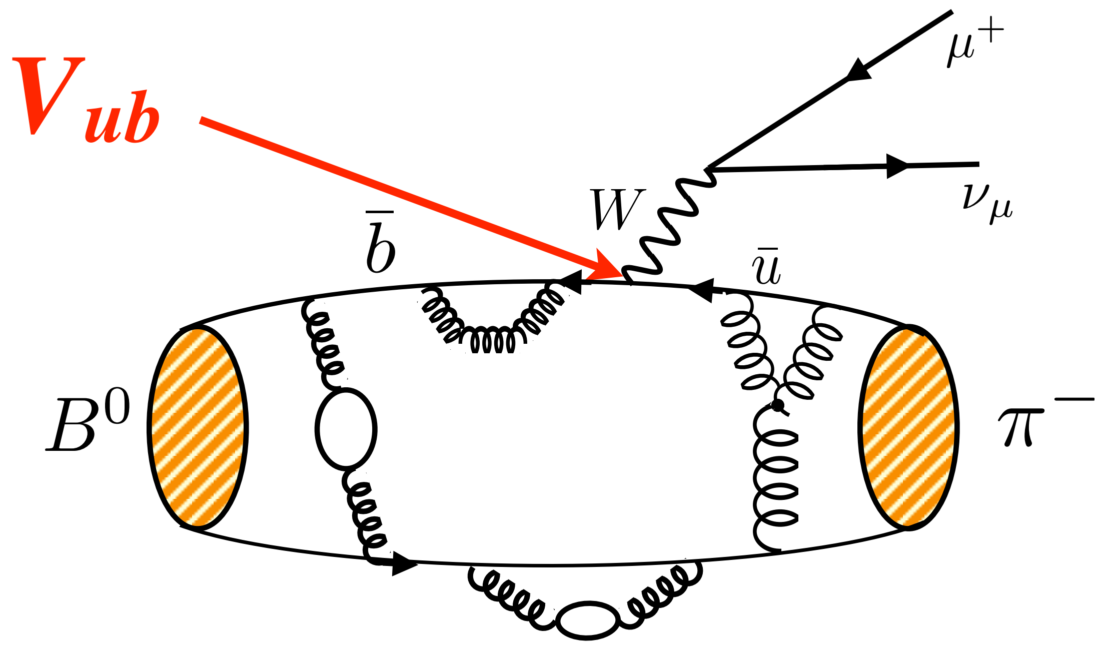
USQCD All Hands meeting, BNL, 29-30 April 2016

Outline

- Motivation
- Proposal overview
- Summary of recent progress in B physics program
  - summary
  - semileptonic decays
  - mixing
  - CKM, BSM phenomenology
- To do list

Motivation

example: $B \to \pi \ell \nu$



generic EW process involving hadrons:

(experiment) = (known) x (**CKM element**) x (had. matrix element)

$\Gamma_{K\ell 3}, \Gamma_{K\ell 2}, \ldots$

$\frac{d\Gamma(B\to\pi\ell\nu)}{dq^2}, \frac{d\Gamma(D\to K\ell\nu)}{dq^2}, \ldots$

$\Delta m_{d(s)}$

$\vdots$

Lattice QCD

parameterize the ME in terms of form factors, decay constants, bag parameters, ...

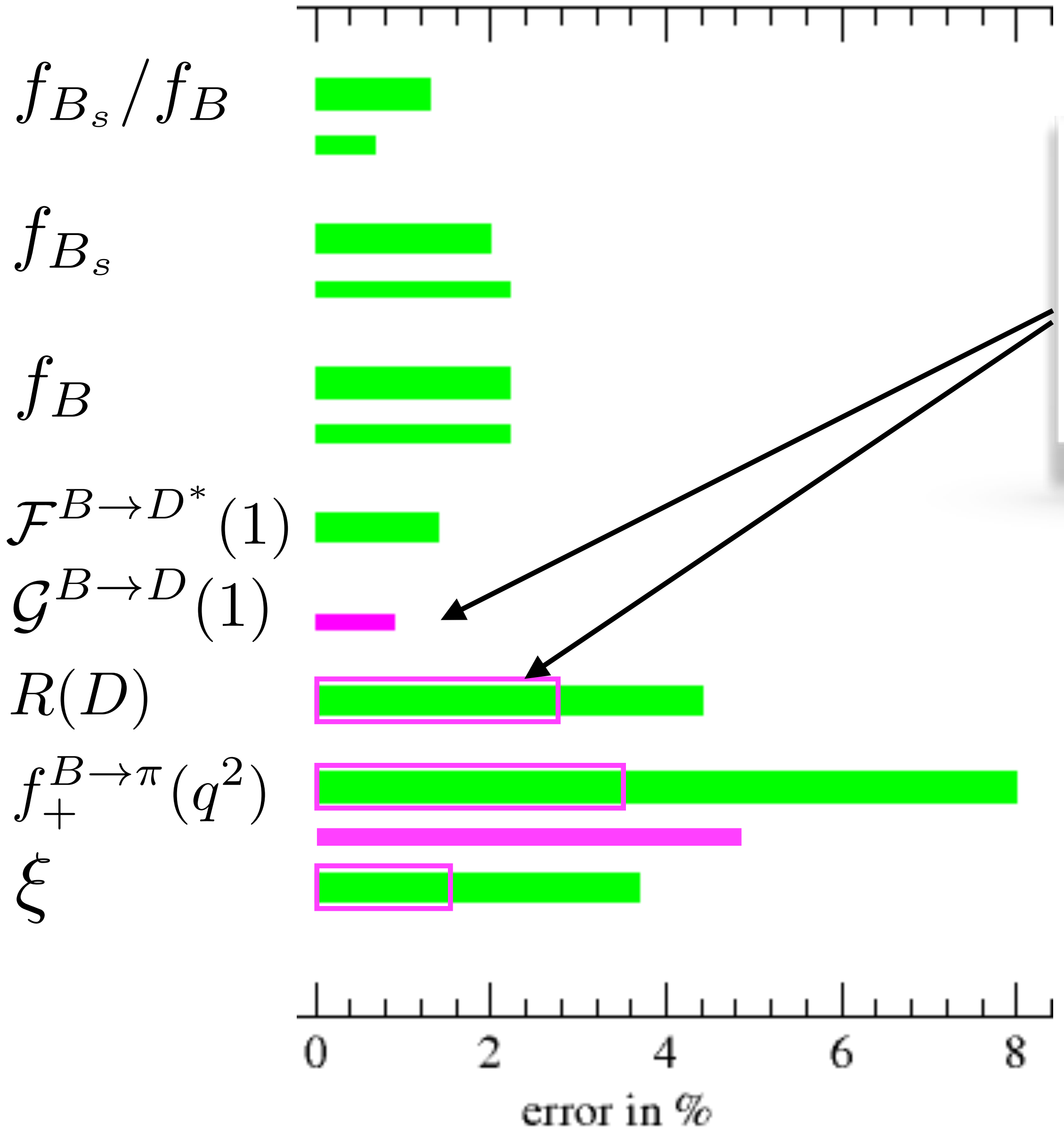
B physics proposal overview

- FNAL/MILC:
  - 5.7M BG/Q + 90.9M Jpsi cluster CPU; storage: 70 TB disk + 78 TB tape
  - broad B and B_s physics program
  - semileptonic D decays
  - quark masses + strong coupling
- RBC/UKQCD:
  - 19.8 M Jpsi CPU; storage: 50.5 TB disk + 300 TB tape
  - $B_{(s)} \to D_{(s)}^{(*)} \ell\nu$, $|V_{cb}|$ and $R(D^{(*)})$
- LANL-SNU:
  - 36 M Jpsi CPU; storage: 25 TB disk + 300 TB tape
  - $B \to D^{(*)}\ell\nu$ and $|V_{cb}|$

+ RBC (Kelly on $K \to \pi\pi$) and Leskovec (on B $\to K\pi\, \ell\ell$)

Summary of recent progress

errors (in %) **(preliminary) FLAG-3 averages** + **new results**



Semileptonic decays

form factors for $B \to D\,\ell\nu$ at nonzero recoil by
FNAL/MILC (Bailey et al,arXiv:1503.07237, PRD 2015)
HPQCD (Na et al,arXiv:1505.03925, PRD 2015)

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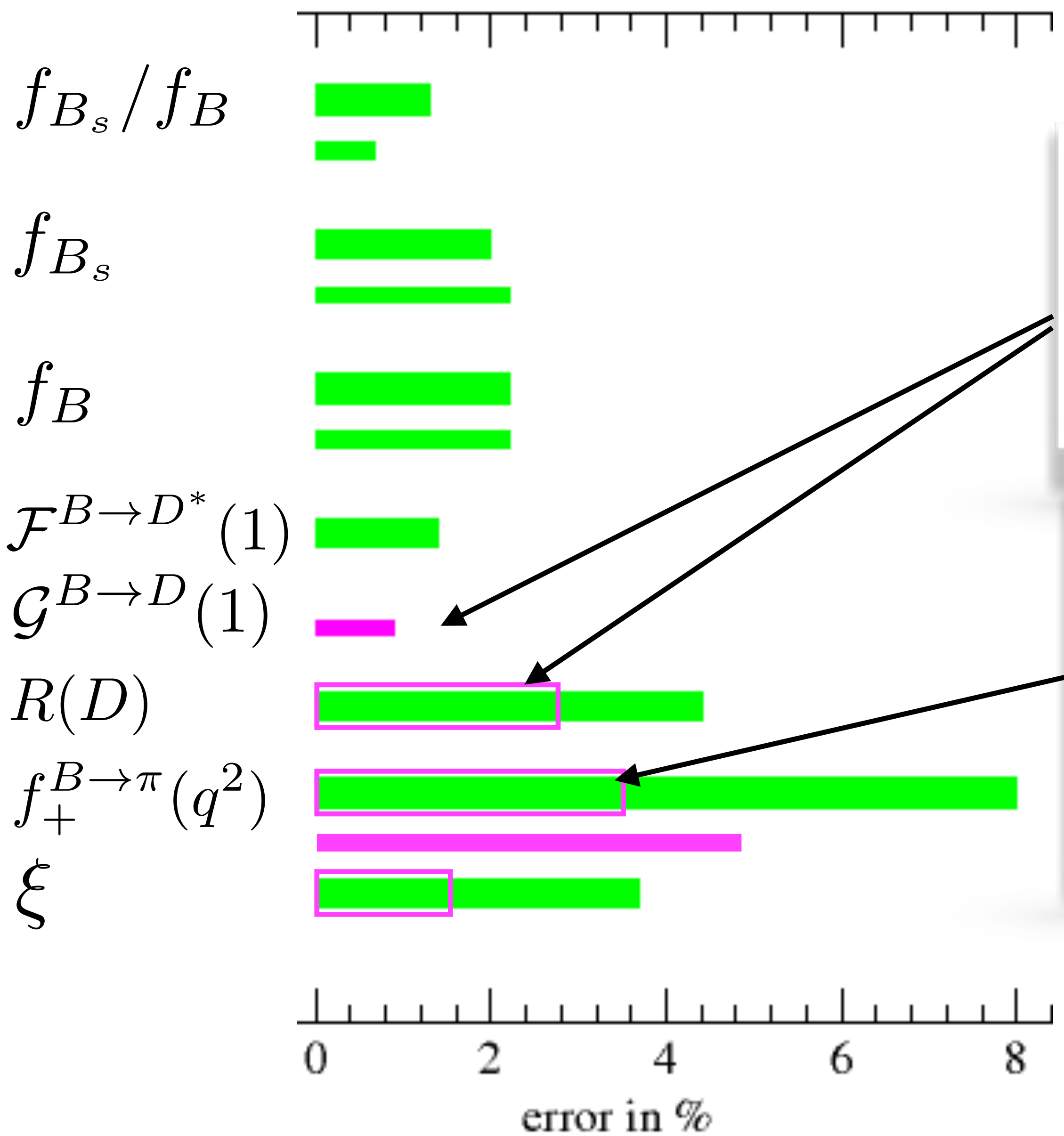

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$B \to \pi\,\ell\nu, B_s \to K\,\ell\nu, B \to \pi\,\ell\ell, B \to K\,\ell\ell,$
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arXiv:1507.01618, 2015 PRL; 1509.06235, PRD 2015;
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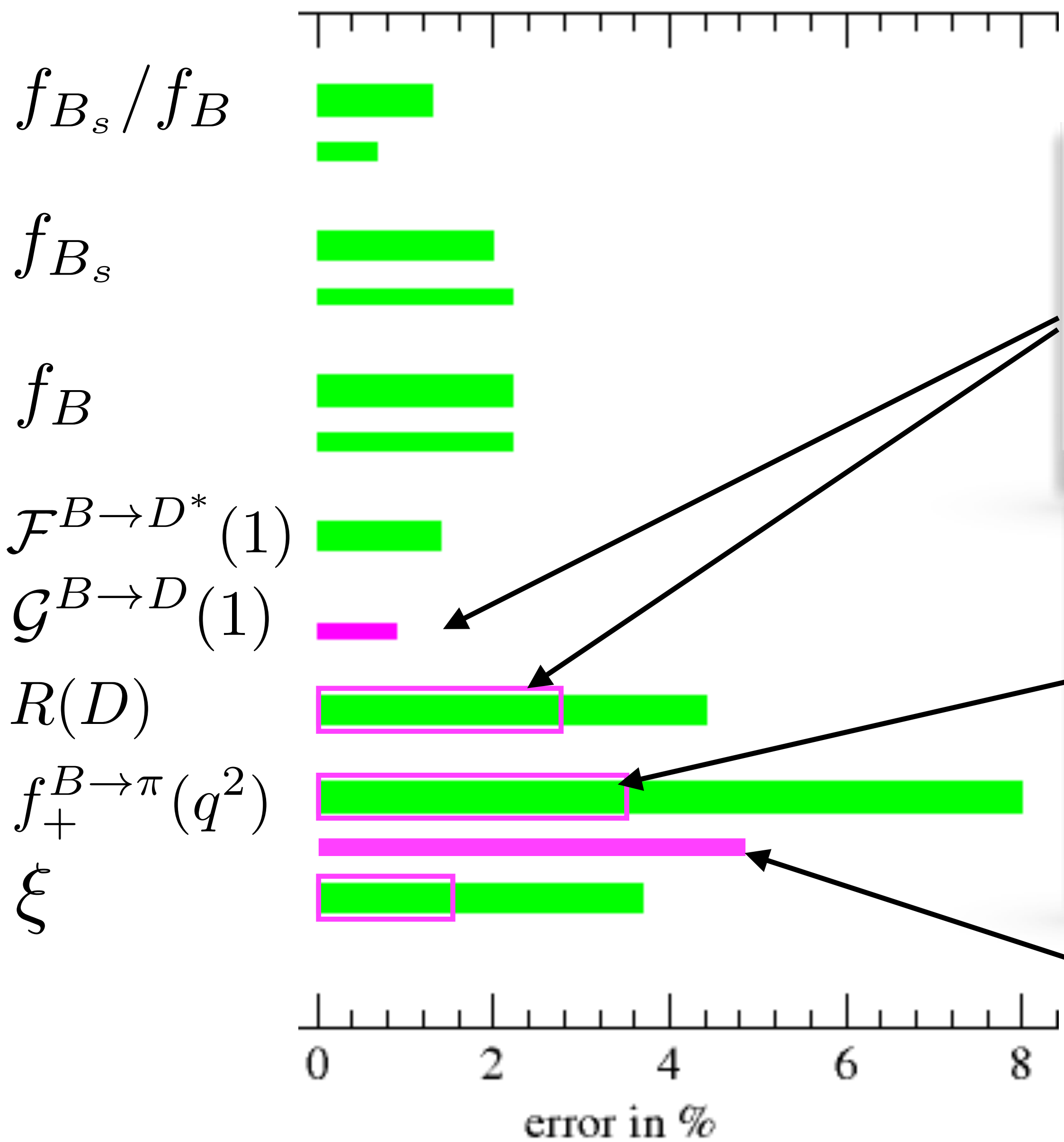

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$\Lambda_b\to p/\Lambda_b\to\Lambda_c$ and $\Lambda_b\to\Lambda\,\ell\ell$
(Detmold et al, arXiv:1503.01421, PRD 2015;
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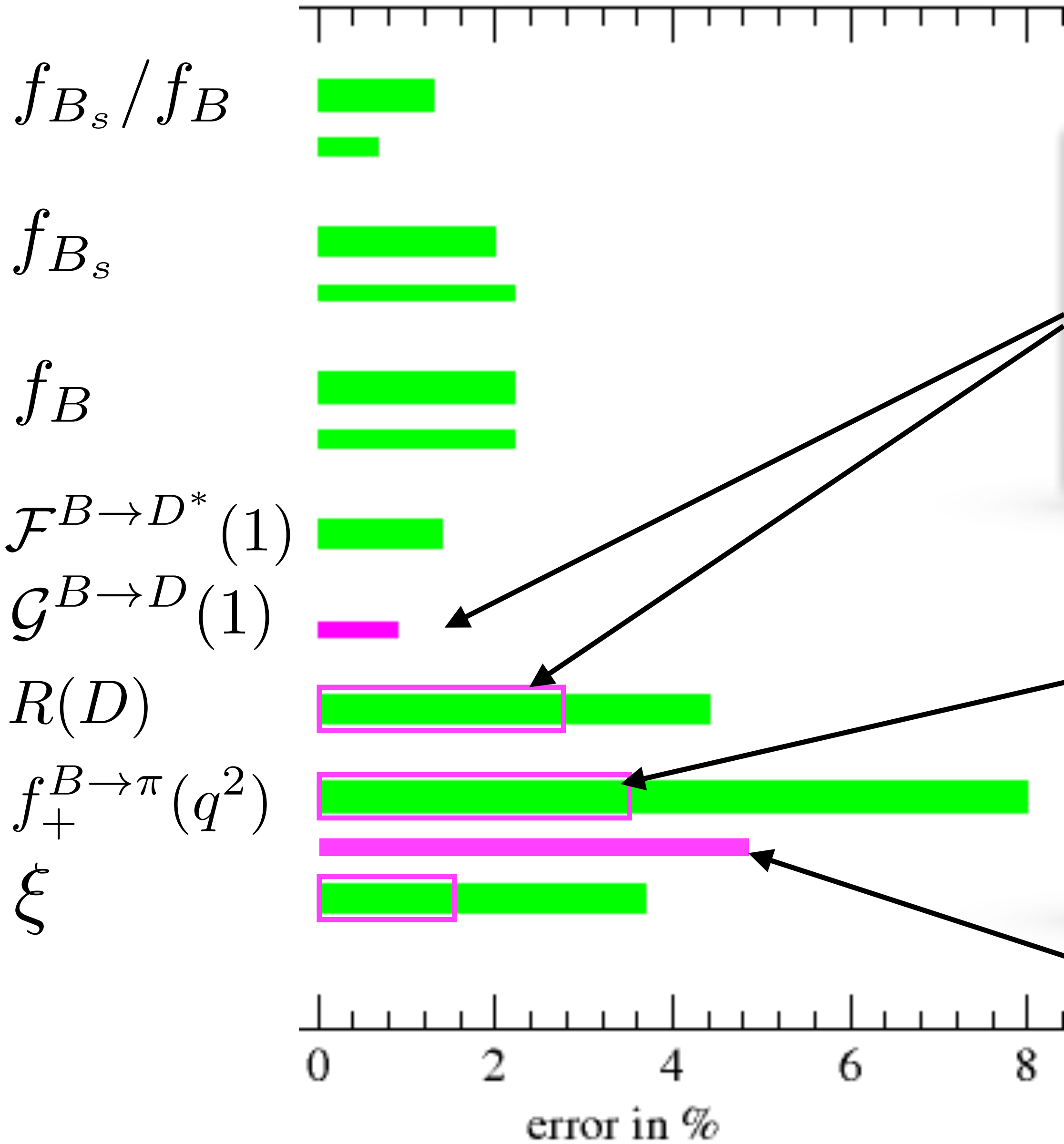

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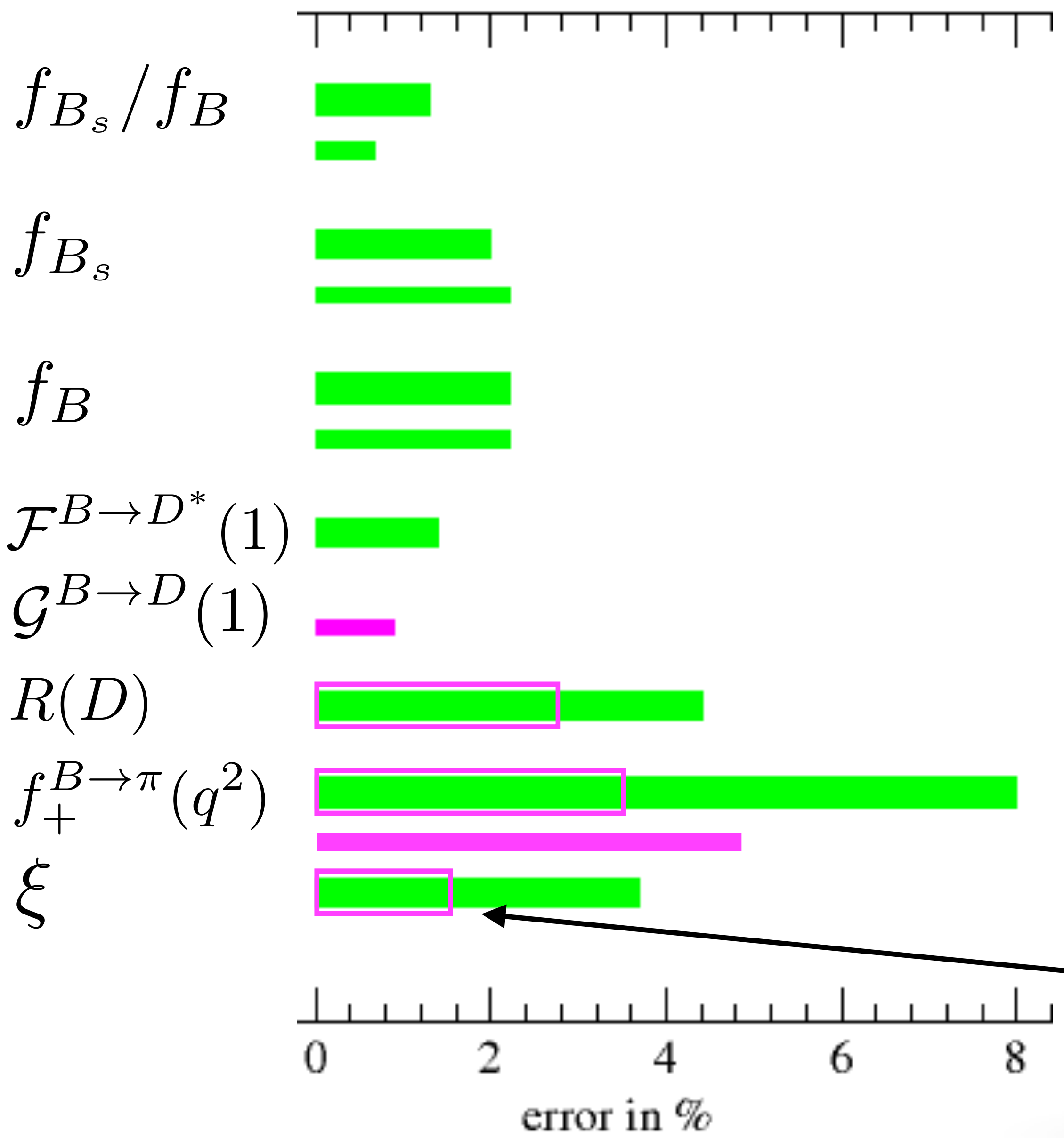
Theory uncertainties are commensurate with experimental errors

Summary of recent progress

errors (in %) **(preliminary) FLAG-3 averages** + **new results**



B meson mixing

First calculation of all five MEs with n_f=3 by FNAL/MILC (Bazavov et al,arXiv:1602.03560)

Quark flavor experiments

⋮

future

Belle II | 50 times the data of Belle

now

NA62, KOTO

LHCb, CMS, ATLAS | run II at 13 TeV is starting, 6 times the data of 2015

BES III

BaBar, Belle,
CDF, D0,
CLEO-c, KLOE, ...

past

ARGUS, CLEO, NA48, KTeV, BNL kaon experiments,...

Quark flavor experiments

⋮

future

Expect significant reductions in experimental errors and measurements of new decay modes

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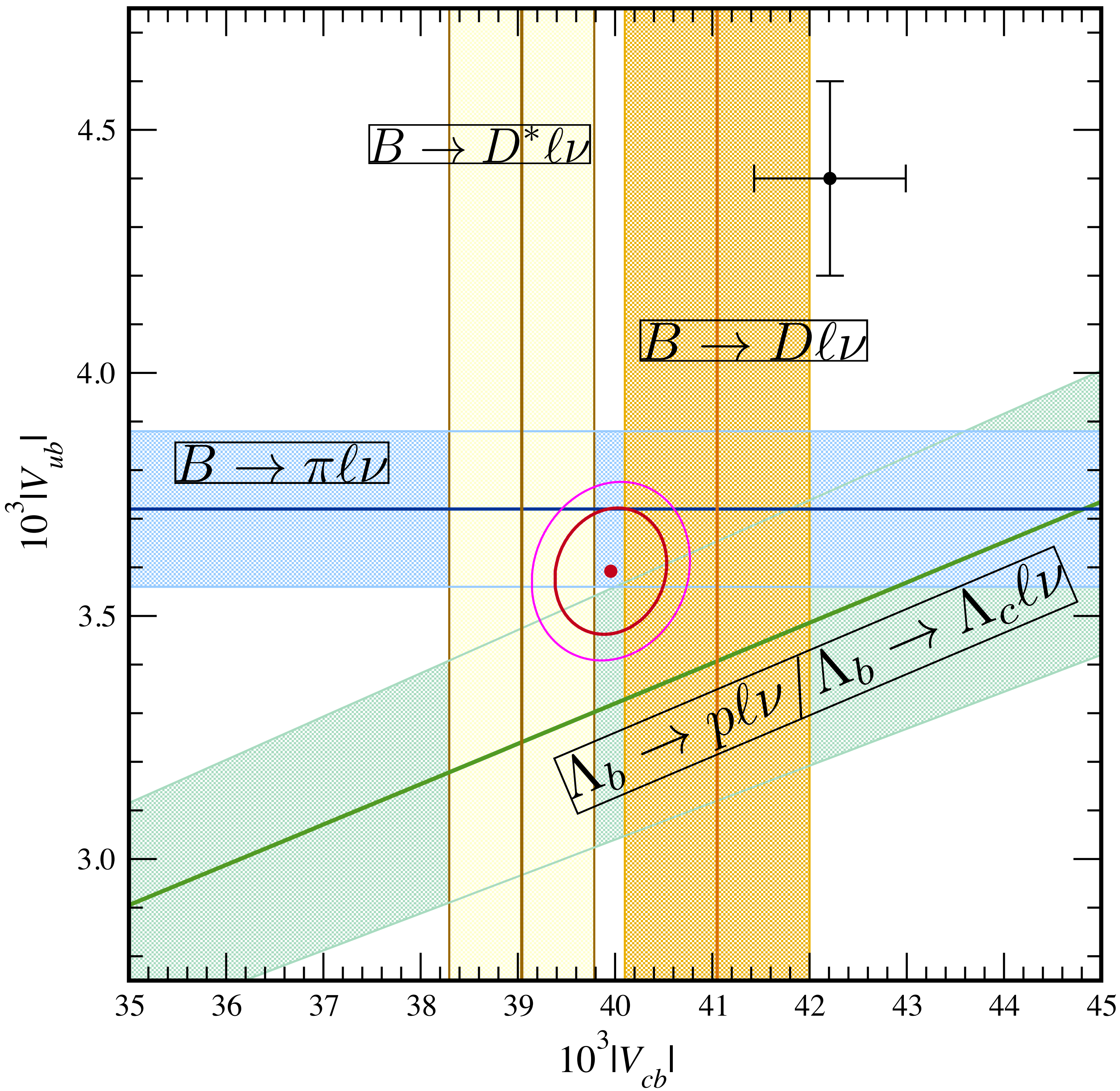
Exclusive vs. inclusive $|V_{cb}|$ and $|V_{ub}|$

A. Kronfeld (priv. communication)



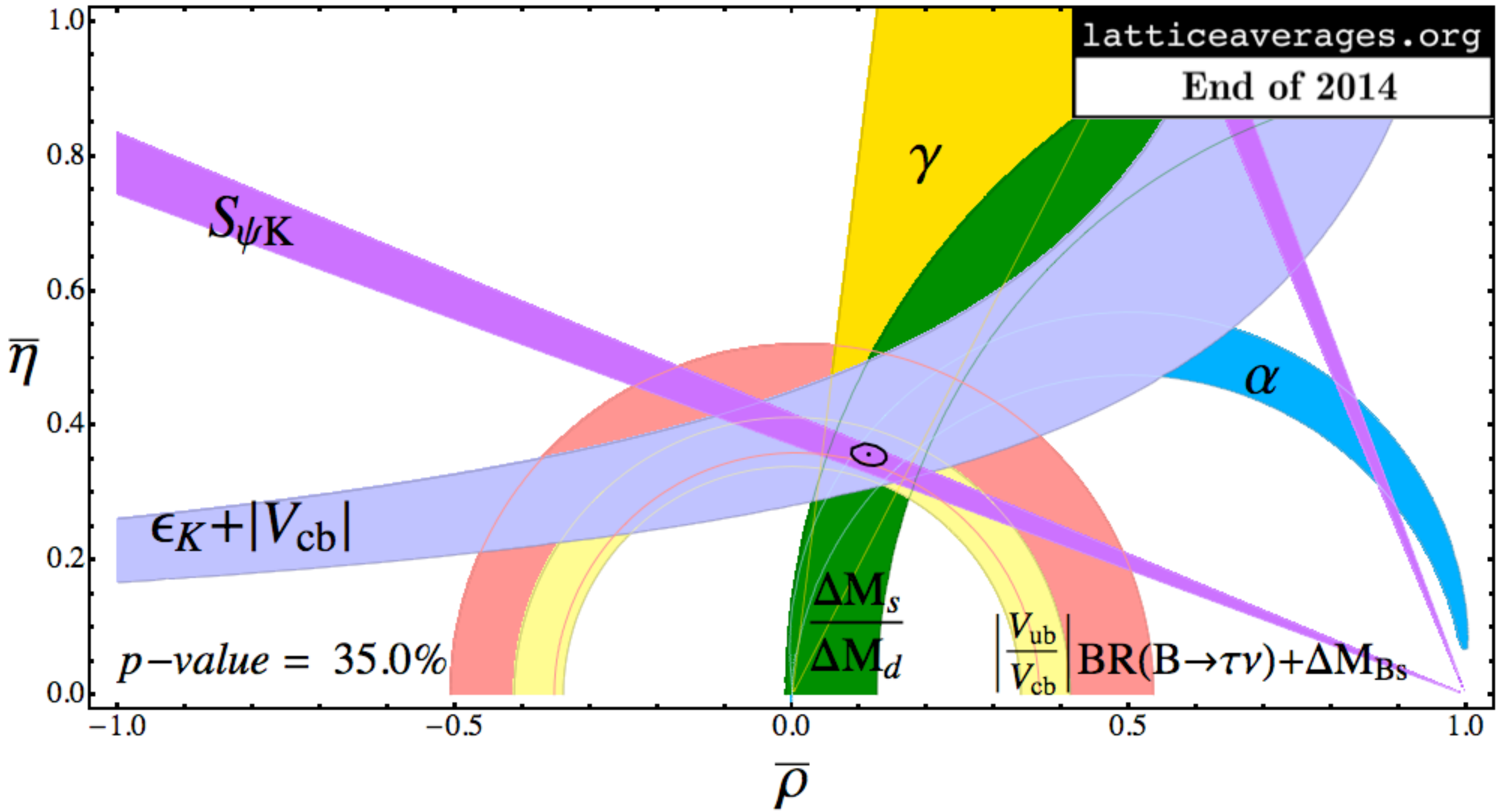
~3σ tension between inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$

New (2015):

- $|V_{cb}|$ from $B \to D\ell\nu$
- $|V_{ub}|$ from $B \to \pi\ell\nu$
- $|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\ell\nu/\Lambda_b \to \Lambda_c\ell\nu$

UT analysis

Laiho, Lunghi & Van de Water (Phys.Rev.D81:034503,2010), E. Lunghi, private comm.



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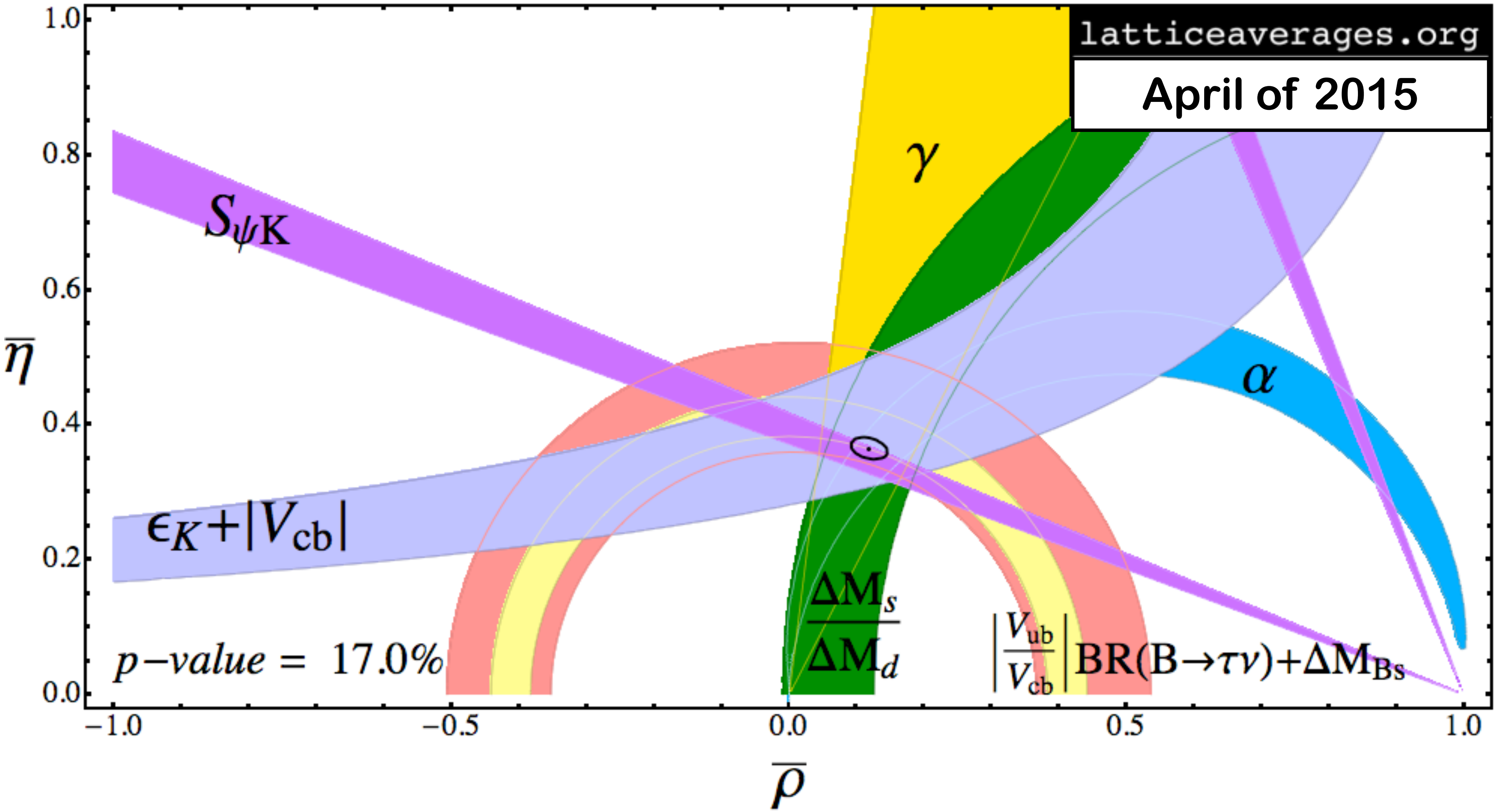

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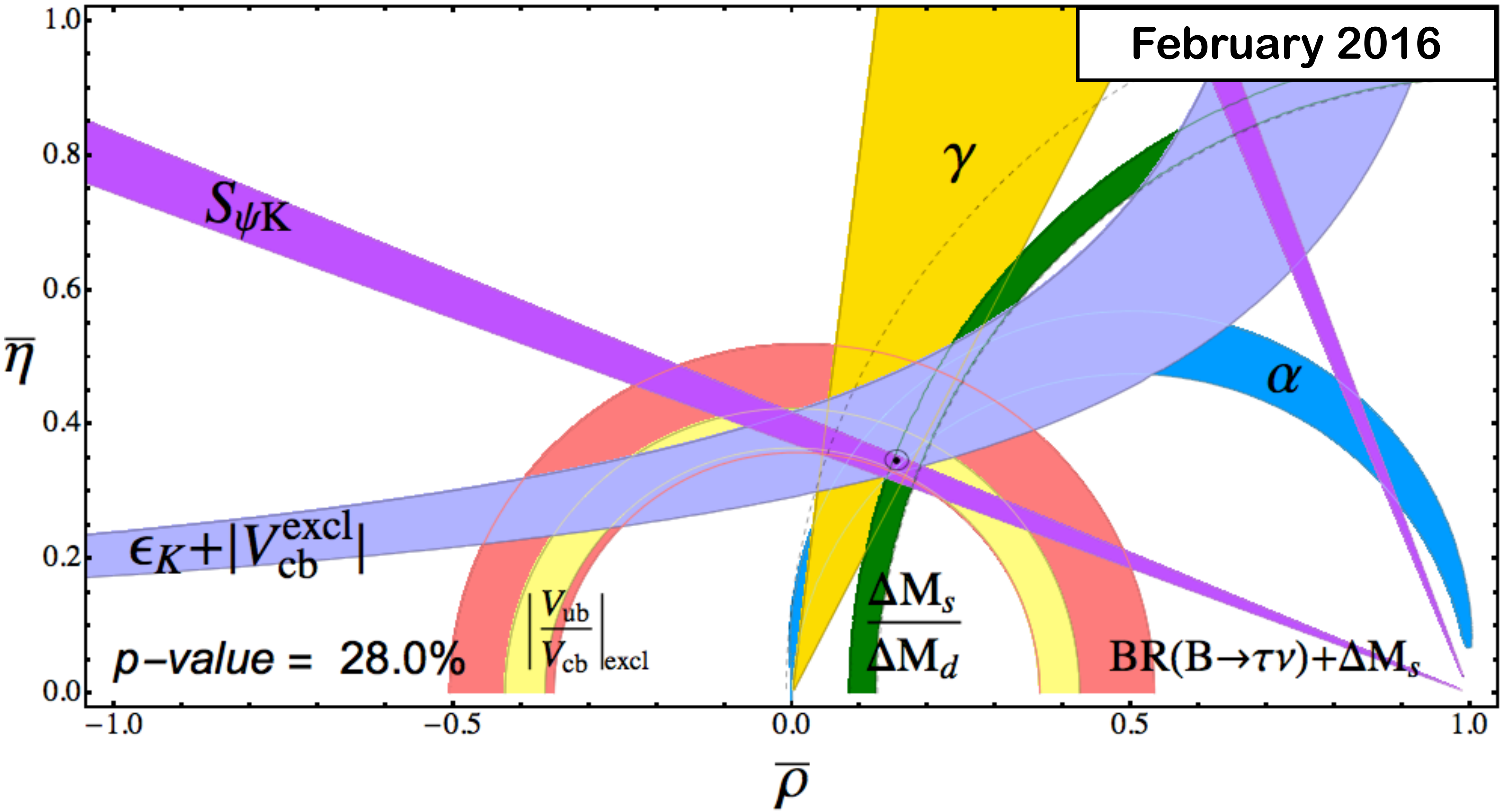
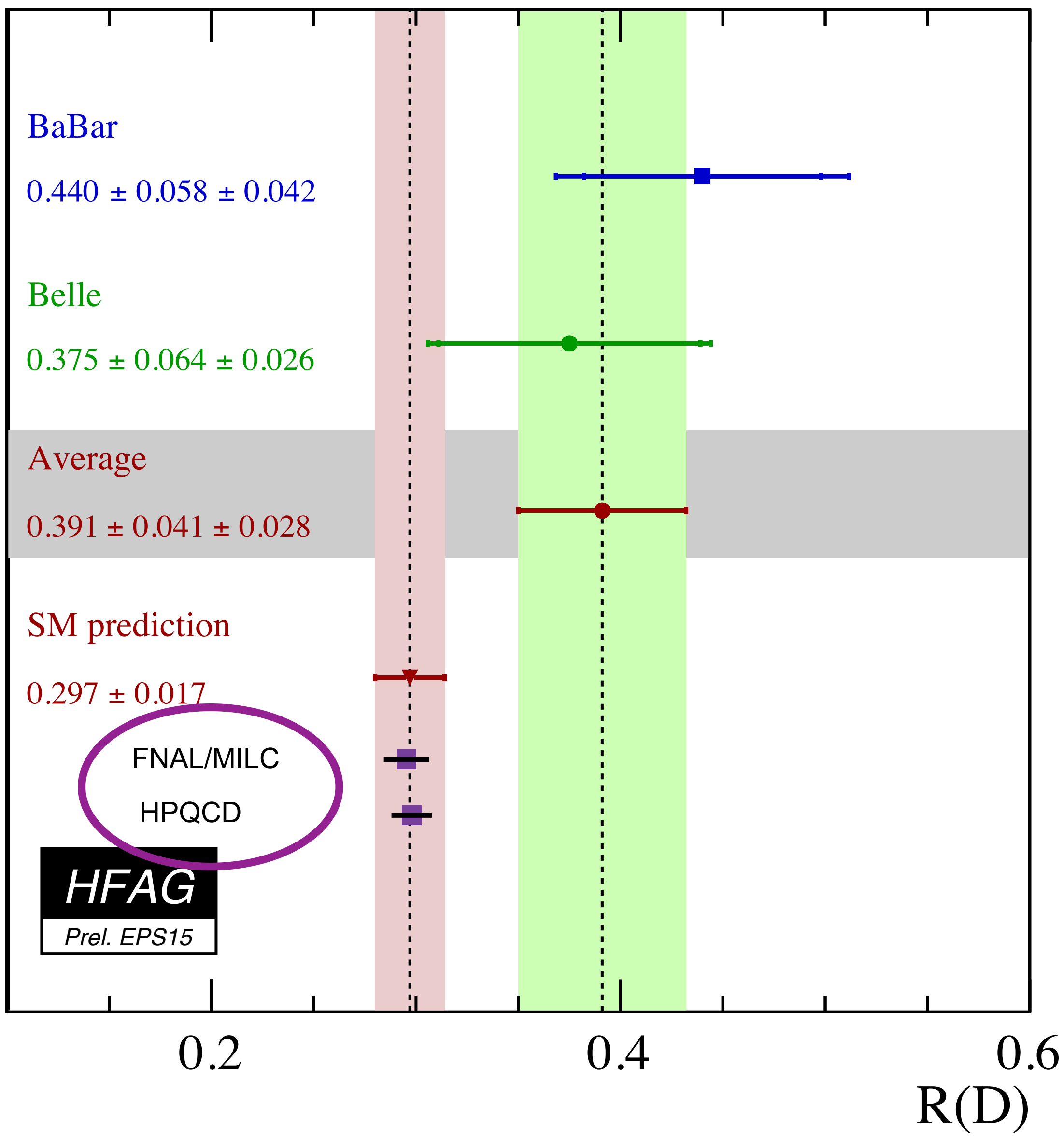


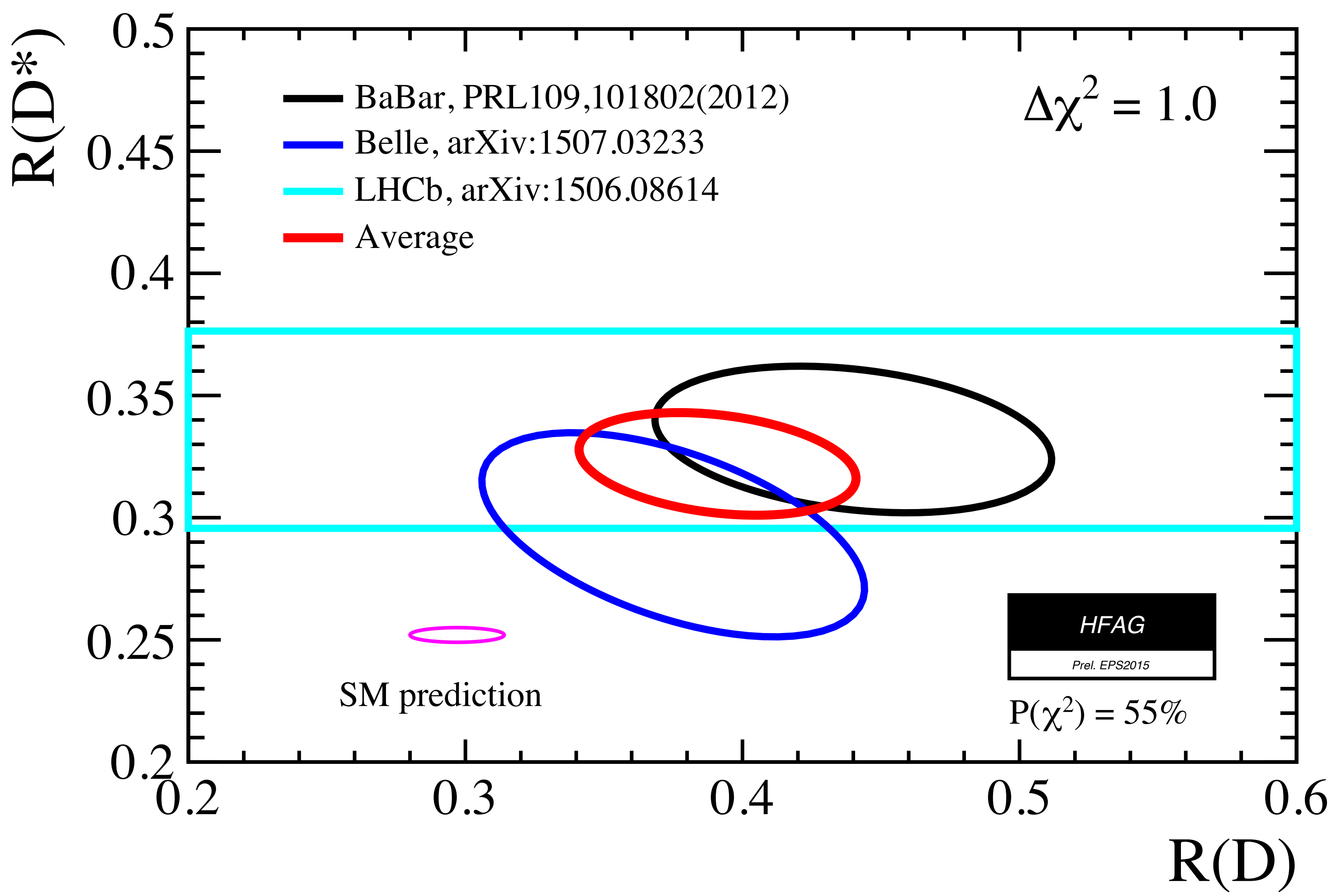
Significant reduction in the allowed region!

The ratio $R(D^{(*)})$

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

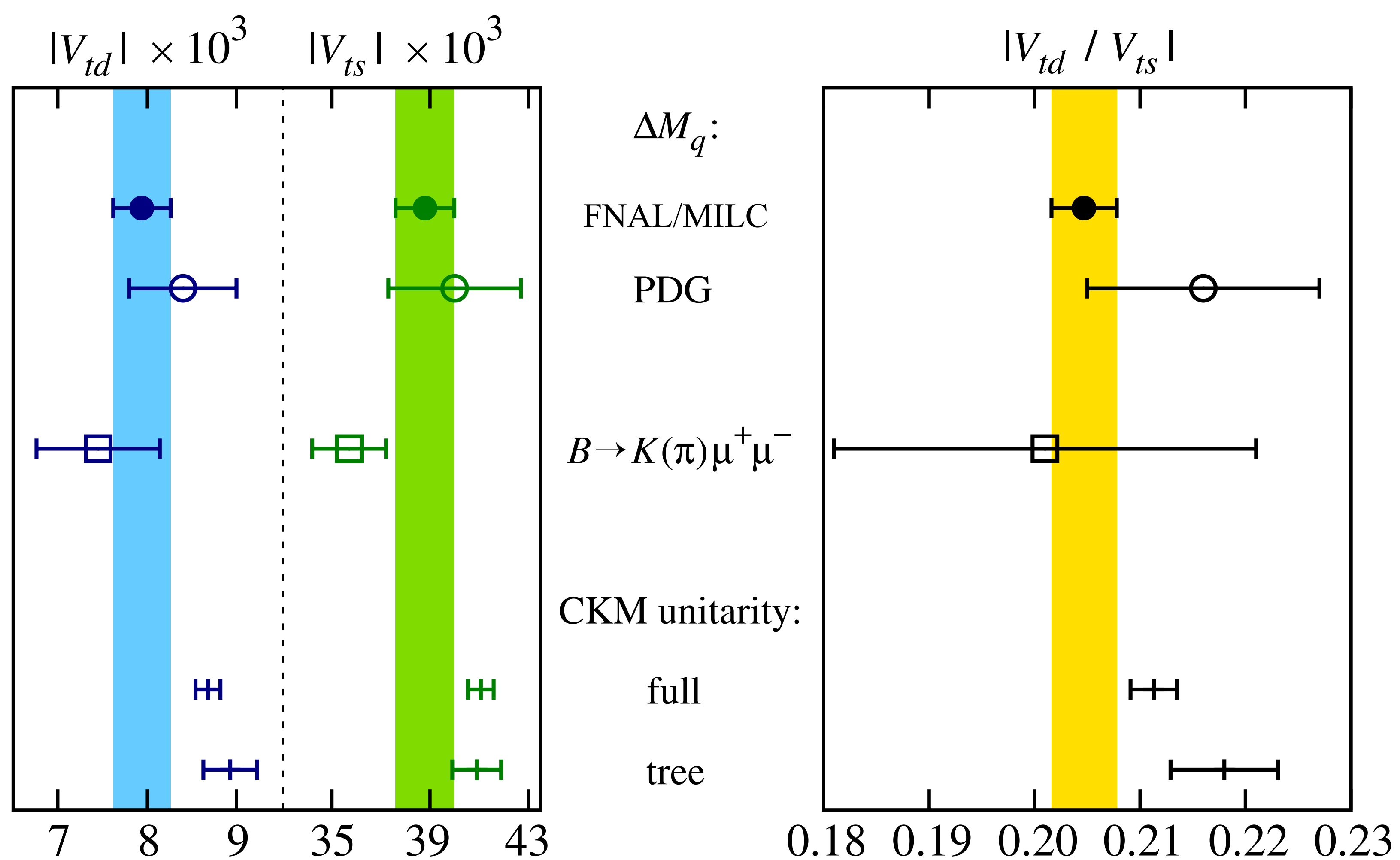
HFAG average for EPS 2015





HFAG average: combined 3.9σ excess

B Mixing and FCNC decays



~2σ tensions between loop processes and CKM unitarity.

To do list

- $B \to D^*$ form factors at nonzero recoil
  - $|V_{cb}|$ determination, check consistency with $B \to D$ det.
  - SM prediction of $R(D^*)$
  - $|V_{cb}|$ also important for ϵ_{K} and rare K decay

- theory errors in $B_{(s)}$ mixing matrix elements still larger than experiment.

- keep up with anticipated experimental improvements
- expand B physics calculations to non-simple quantities
  - ➠ Leskovec talk

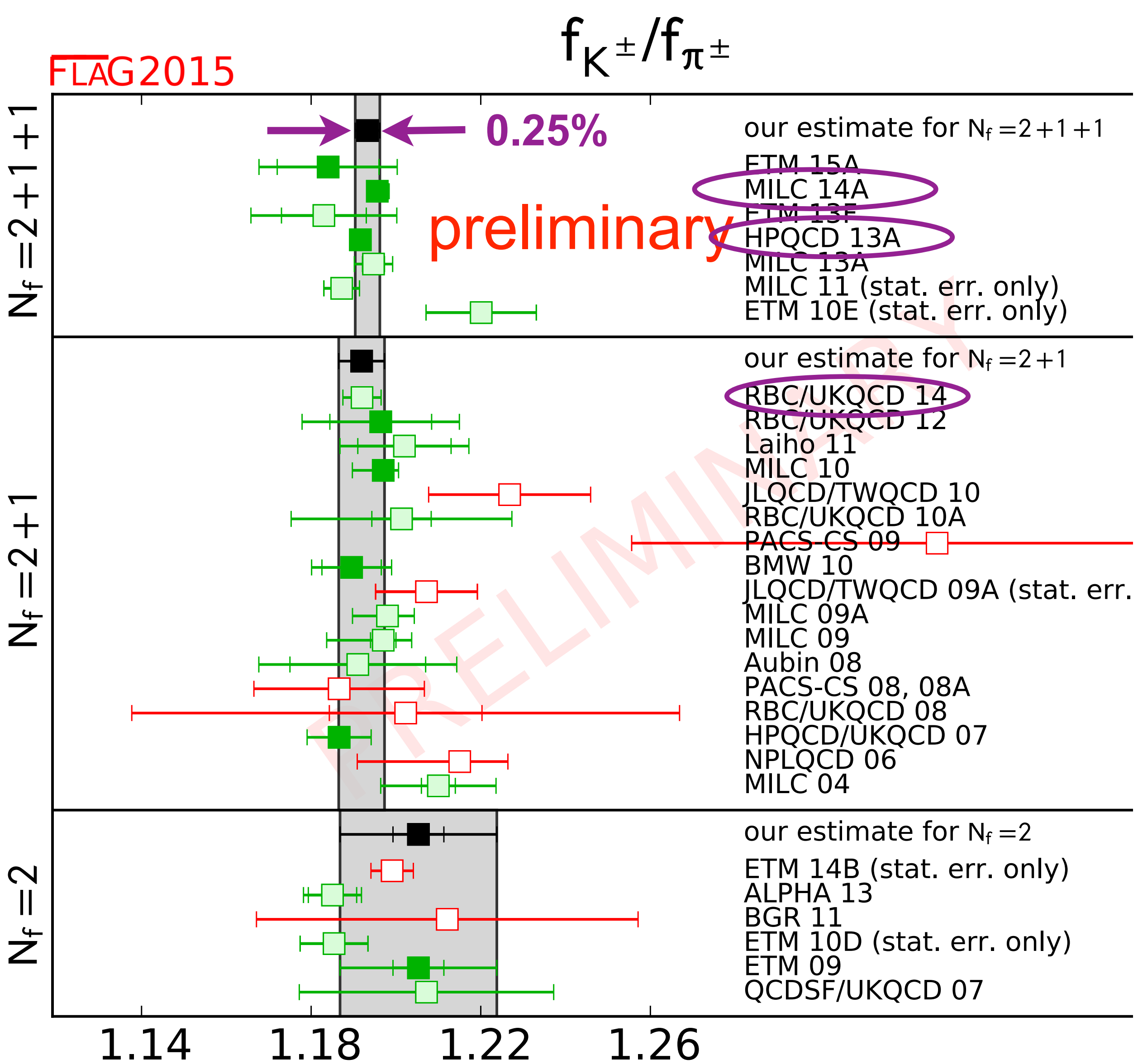
Backup slides

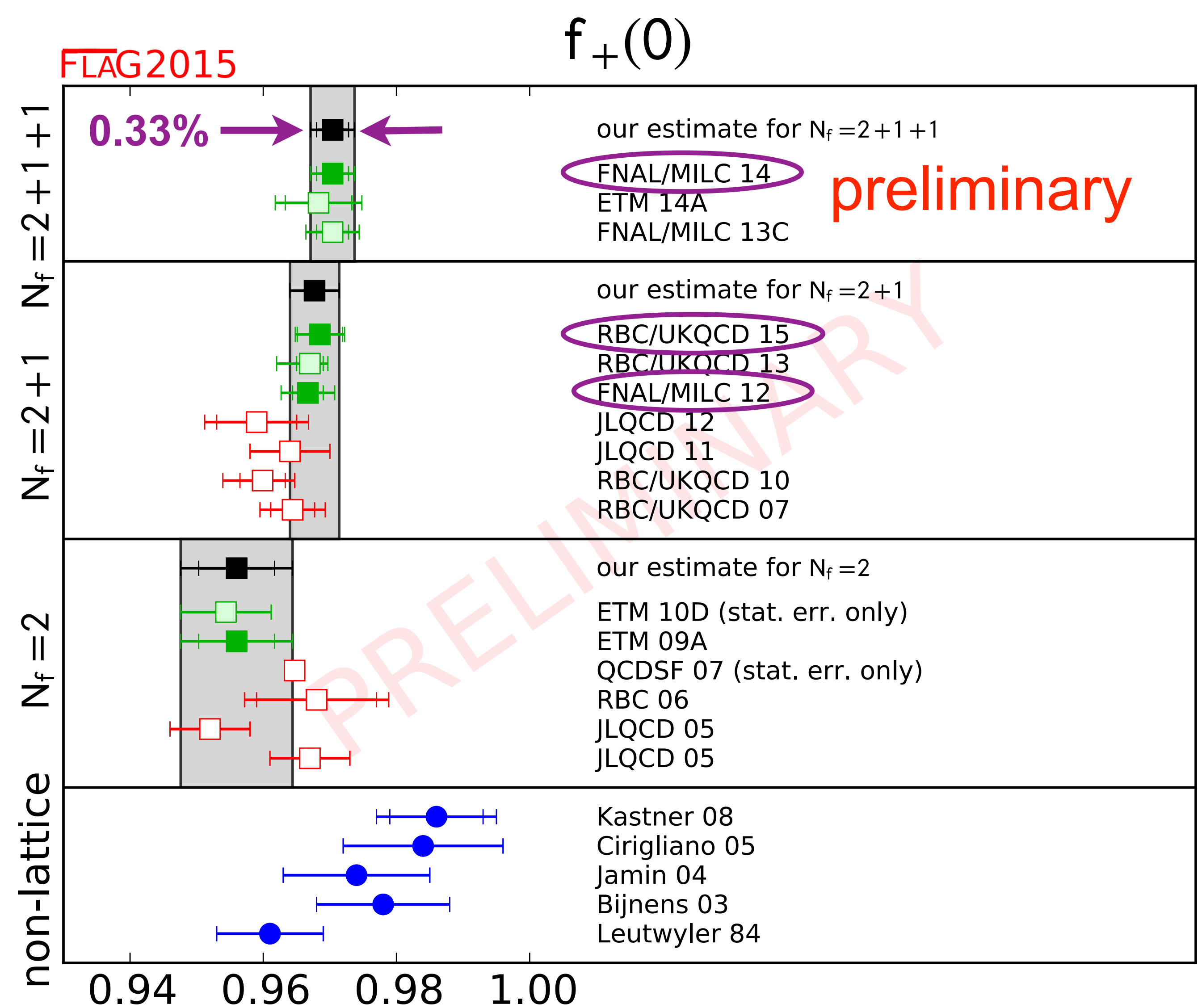
Kaon summary

S. Aoki et al (FLAG-2 review, arXiv:1310.8555, FLAG-3 update)

courtesy of S. Simula (FLAG-3, V_{us} working group)

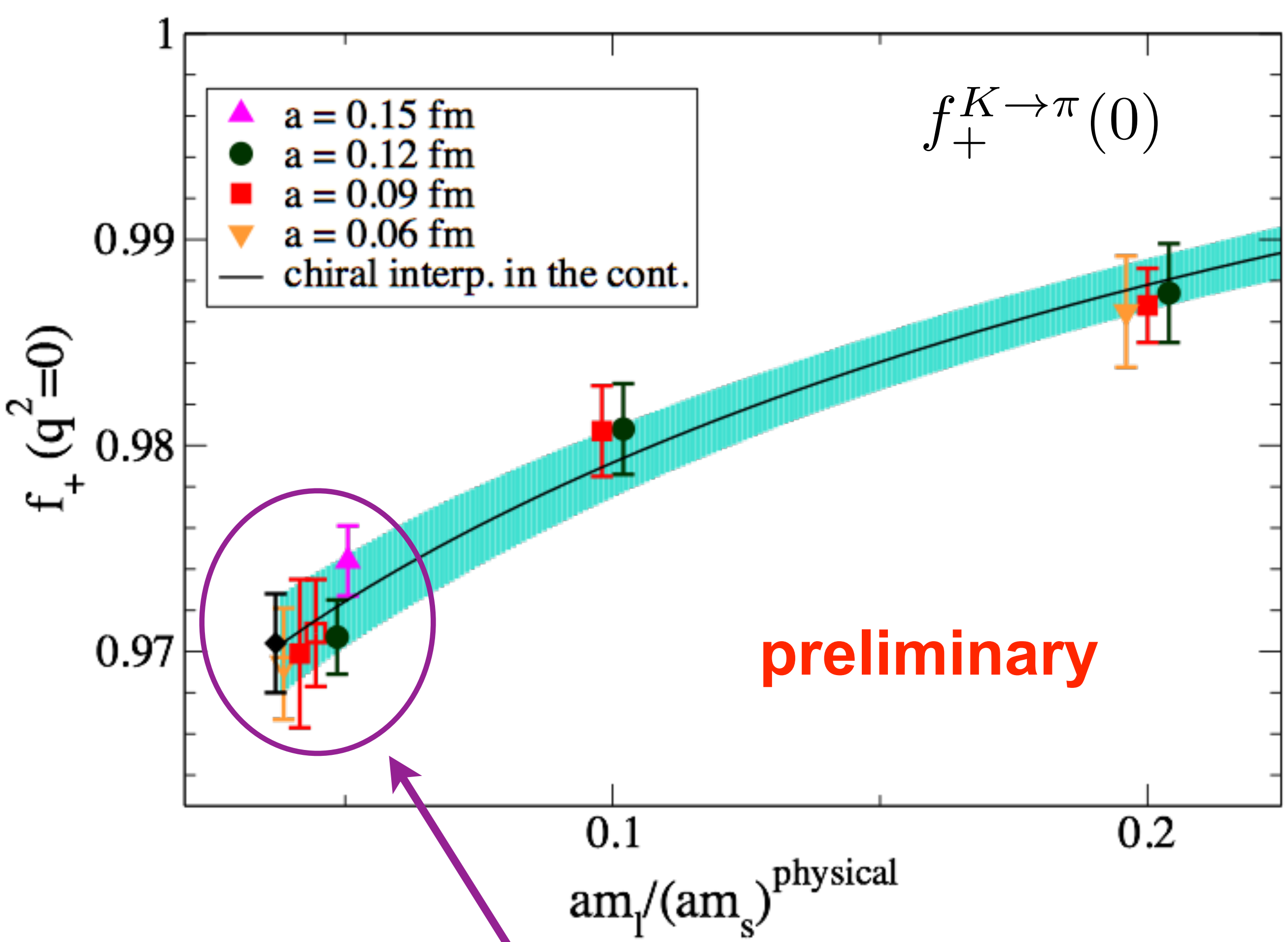
status as of mid 2015



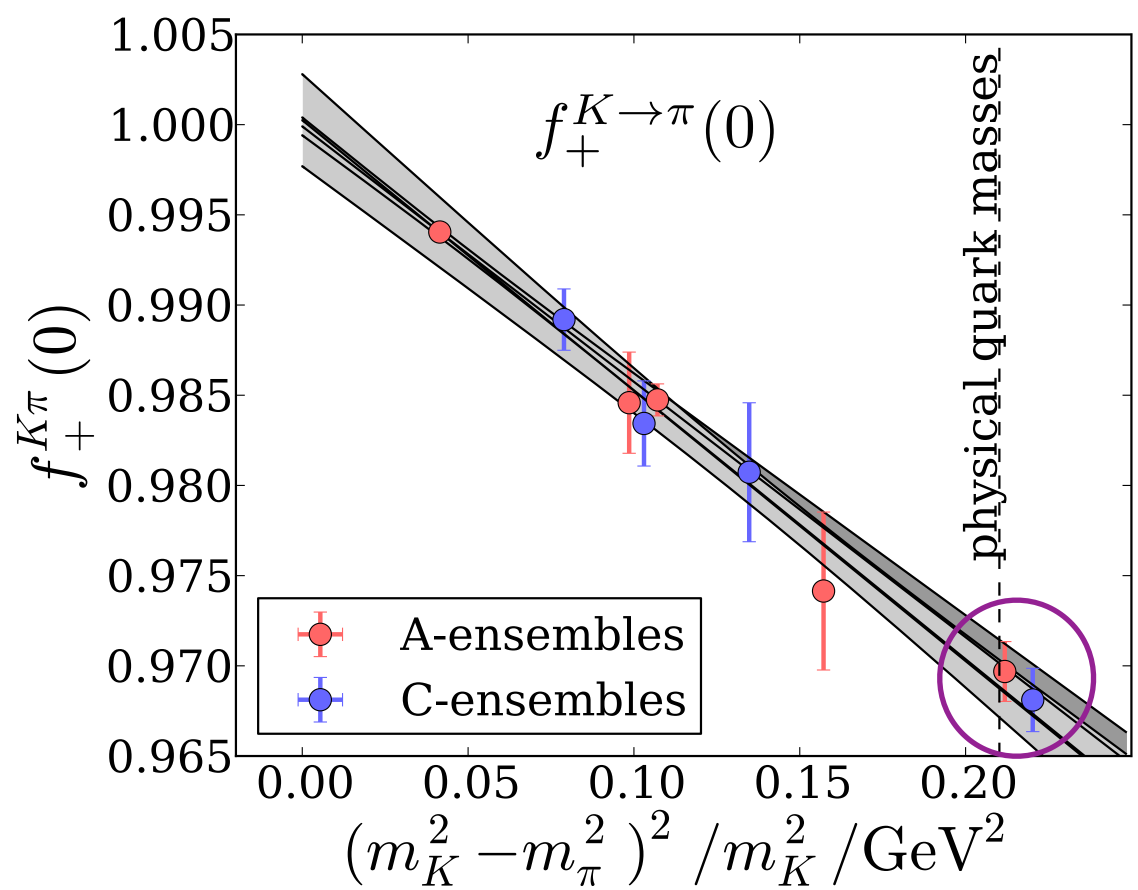


Kaon summary: K_{l3} example

T. Primer (FNAL/MILC) @ Lattice 2014
(update of arXiv:1312.1228)



RBC/UKQCD (1504.01692, JHEP 2015)

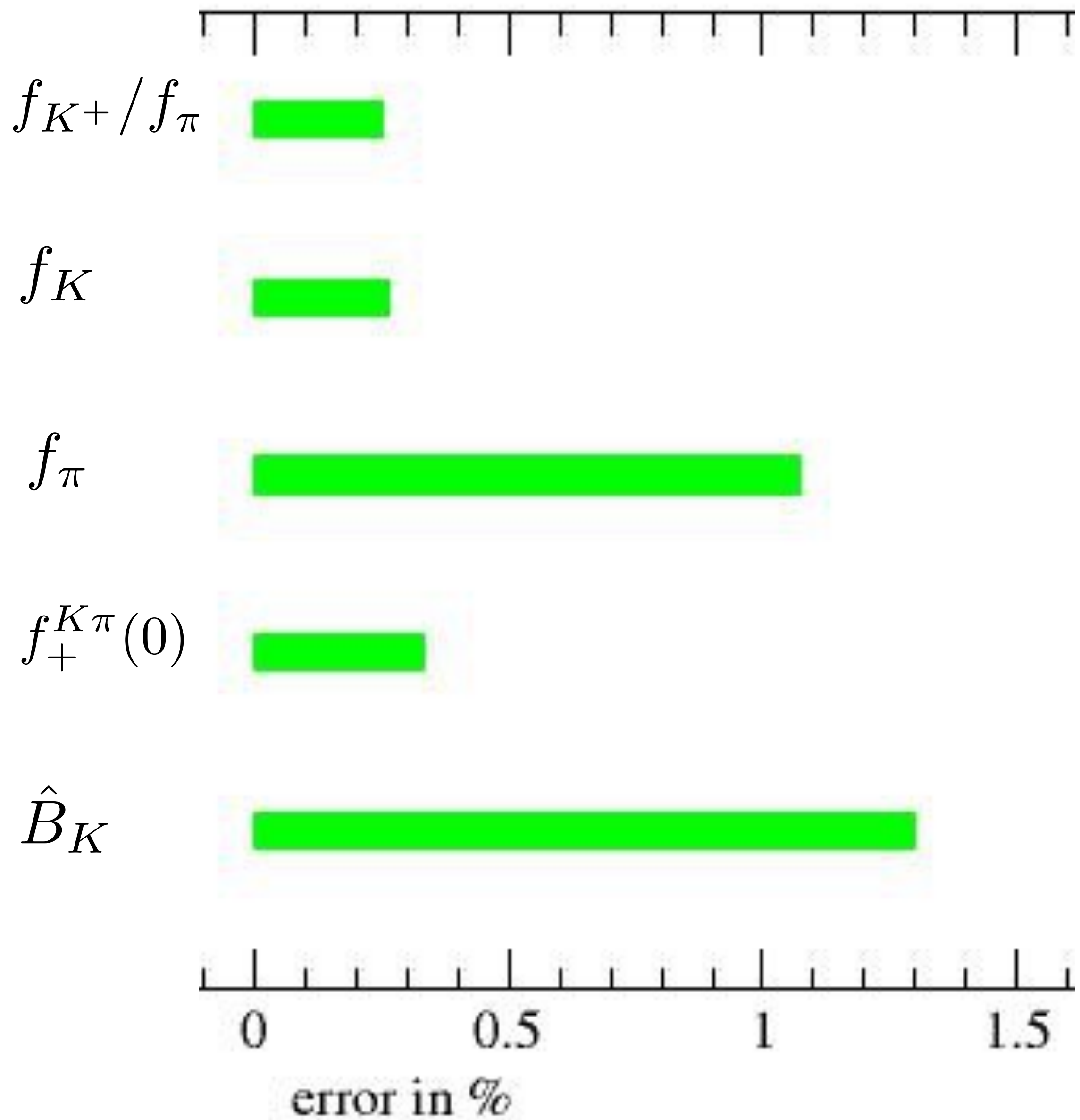


data at the physical point (offset horizontally)

Kaon summary

For all quantities there are results that use **physical mass** ensembles

errors (in %) preliminary **FLAG-3 averages**



independent results (different methods)

small errors due to

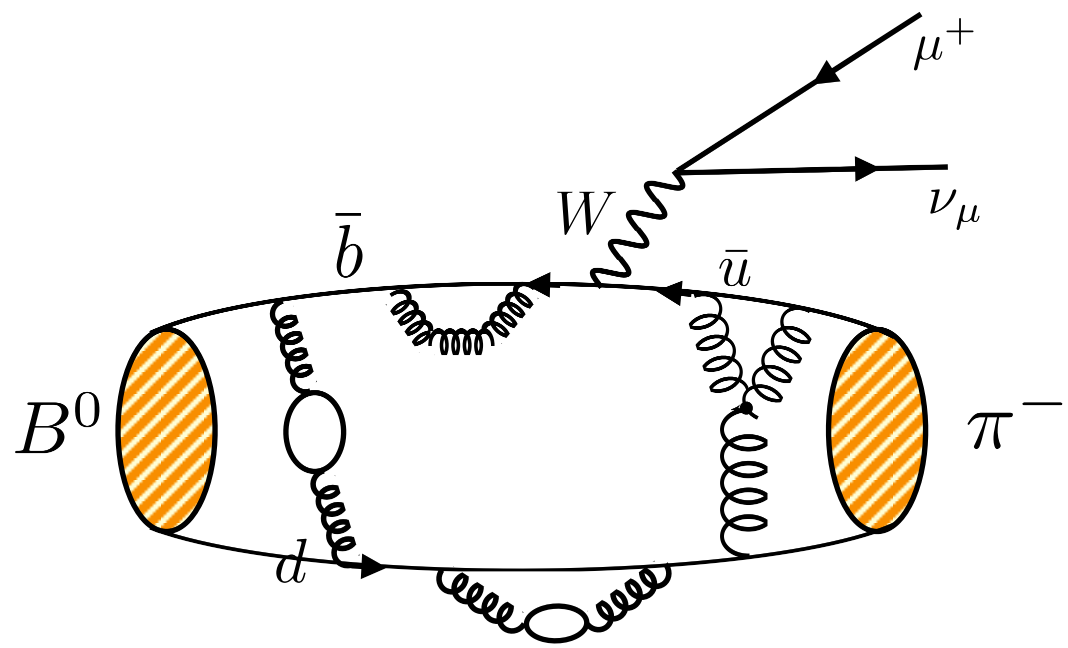
- ✦ **physical light quark masses**
- ✦ improved light-quark actions
- ✦ ensembles with small lattice spacings
- ✦ NPR or no renormalization

Pure QCD
EM affects included phenomenologically (ChPT)

⇒ Lehner talk in g-2 session

Semileptonic B-meson decay at nonzero recoil

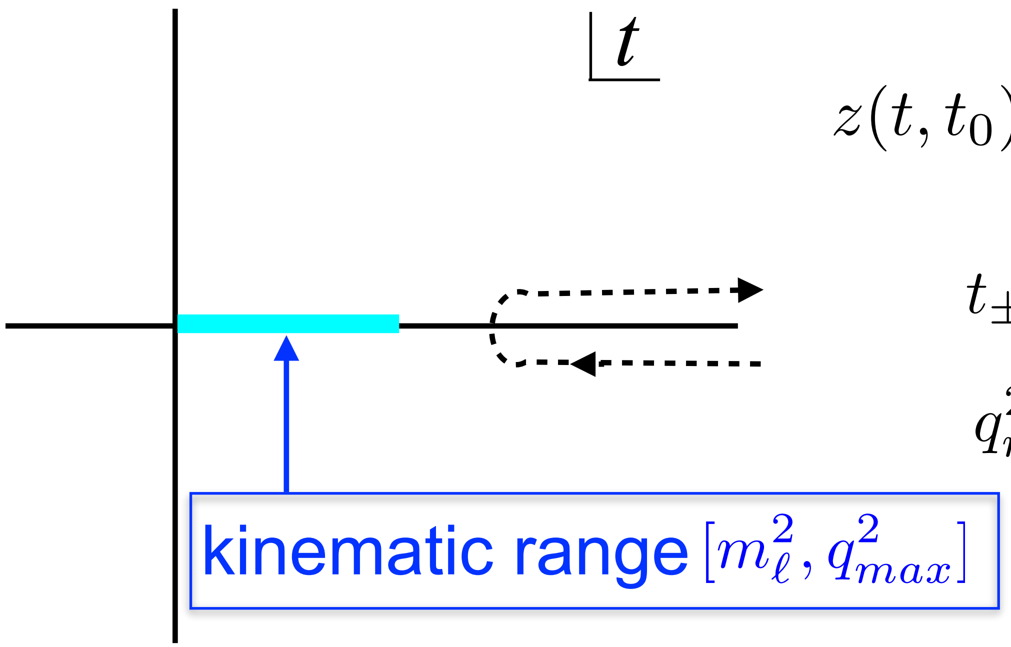
Example: $B \to \pi \ell \nu$



$$\frac{d\Gamma(B\to\pi\ell\nu)}{dq^2} = (\text{known}) \times |V_{ub}|^2 \times |f_+(q^2)|^2$$

★ shape for semileptonic B decays:
use z-expansion for model-independent parameterization of q^2 dependence
(see back-up slide)

The z-expansion

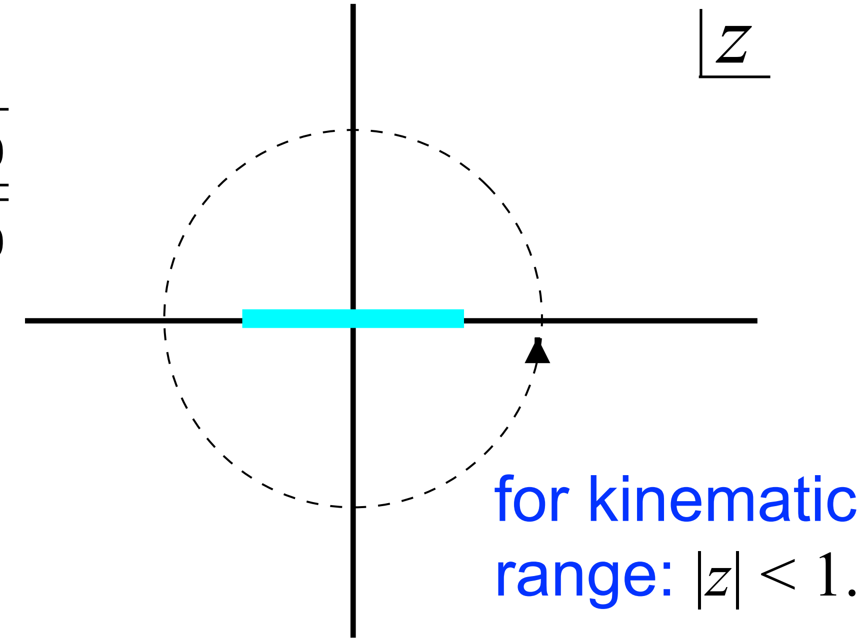


$$t = q^2$$

$$z(t,t_0) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}$$

$$t_\pm = (m_B \pm m_\pi)^2$$

$$q^2_{max} = t_-$$



Bourrely at al (Nucl.Phys. B189 (1981) 157)
Boyd et al (hep-ph/9412324,PRL 95)
Lellouch (arXiv:hep- ph/9509358, NPB 96)
Boyd & Savage (hep-ph/9702300, PRD 97)
Bourrely at al (arXiv:0807.2722, PRD 09)

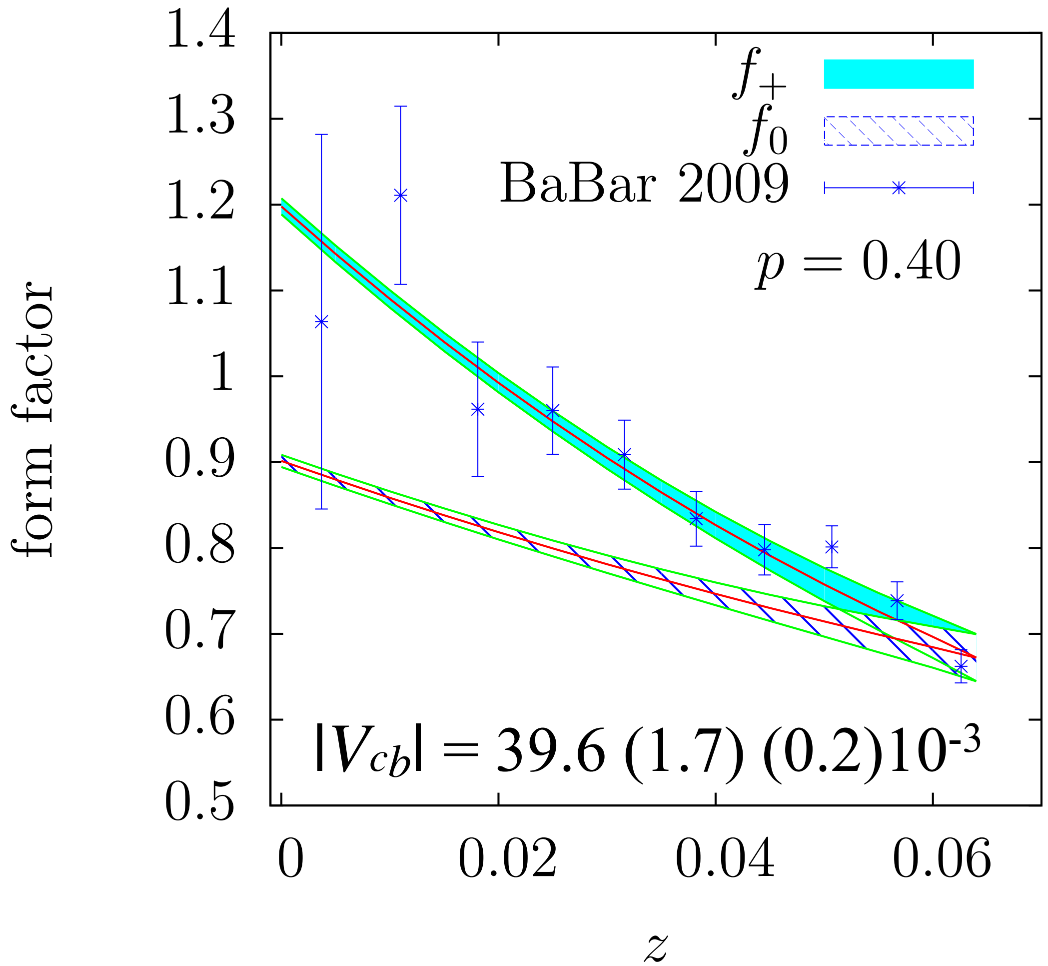
The form factor can be expanded as:

$$f(t) = \frac{1}{P(t)\phi(t,t_0)} \sum_{k=0} a_k(t_0) z(t,t_0)^k$$

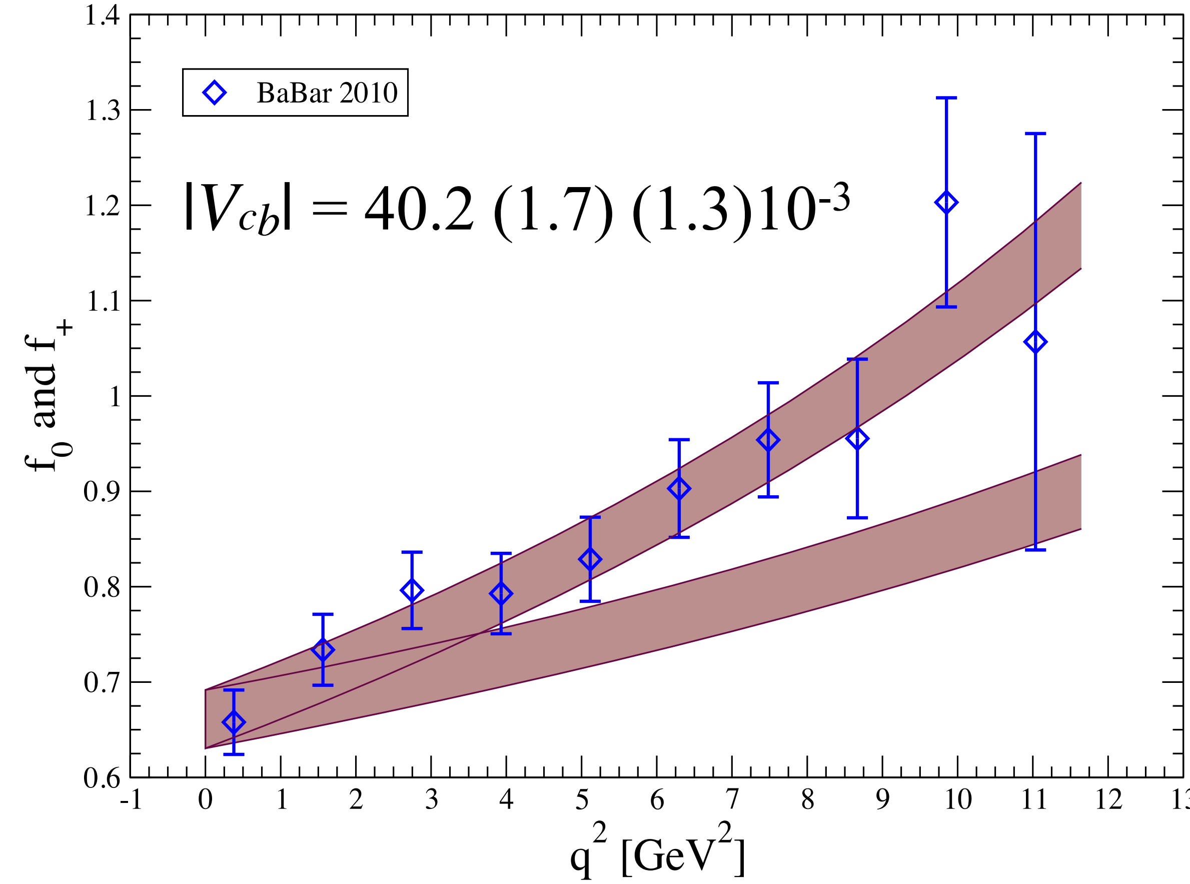
- $P(t)$ removes poles in $[t_-, t_+]$
- The choice of outer function ϕ affects the unitarity bound on the a_k.
- In practice, only first few terms in expansion are needed.

Form factors for $B \to D^{(*)}\ell\nu$ & V_{cb}

FNAL/MILC (arXiv:1503.07237, PRD 2015)



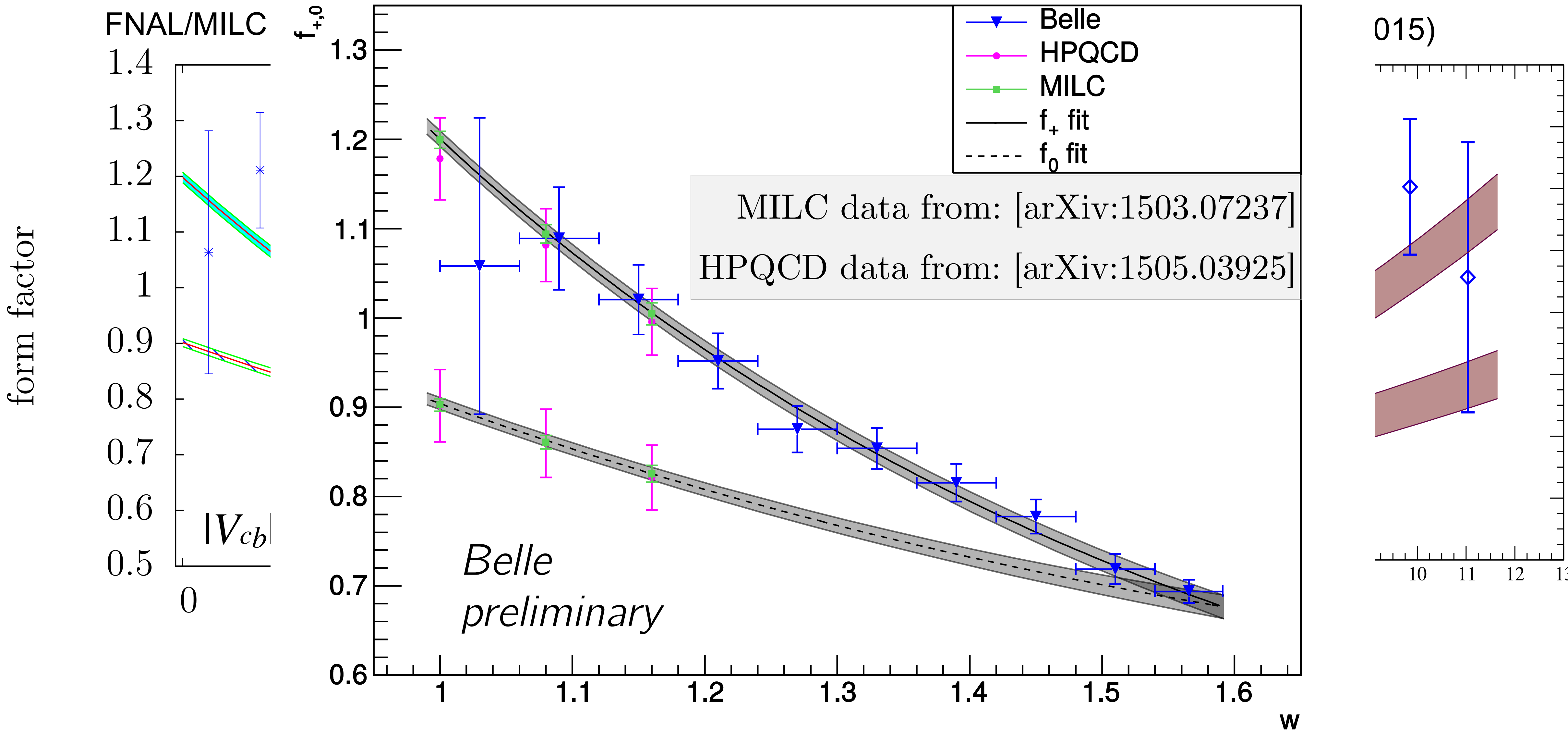
HPQCD (arXiv:1505.03925, PRD 2015)



- combined fit to LQCD form factors + BaBar data.
- LQCD form factor errors (~1.2%) smaller than experiment.

Form factors for $B \to D^{(*)}\ell\nu$ & V_{cb}

R. Glattauer (Belle) @ EPS 2015

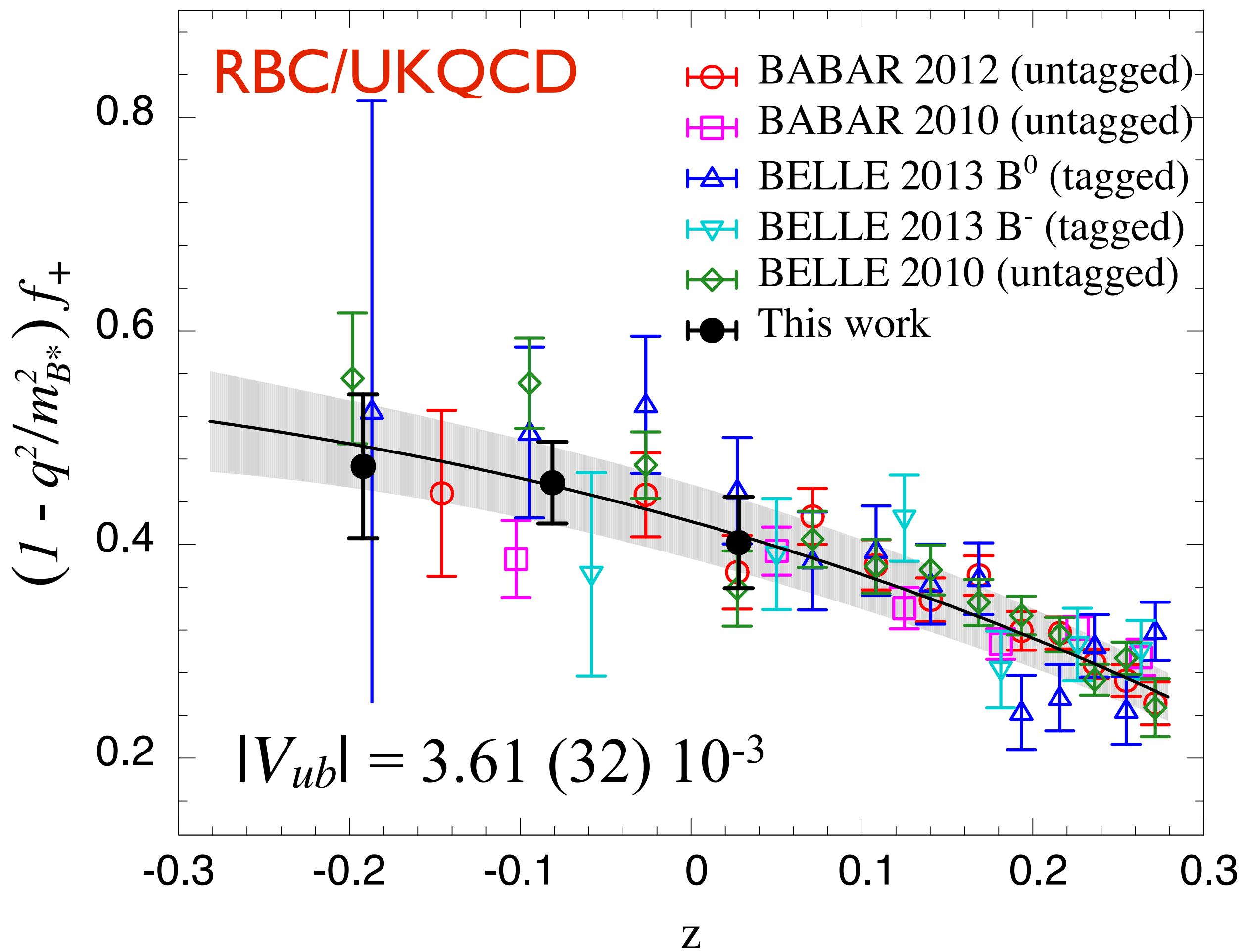


P. Gambino, global fit (Belle + BaBar + HPQCD + FNAL/MILC) @ EPS 2015:

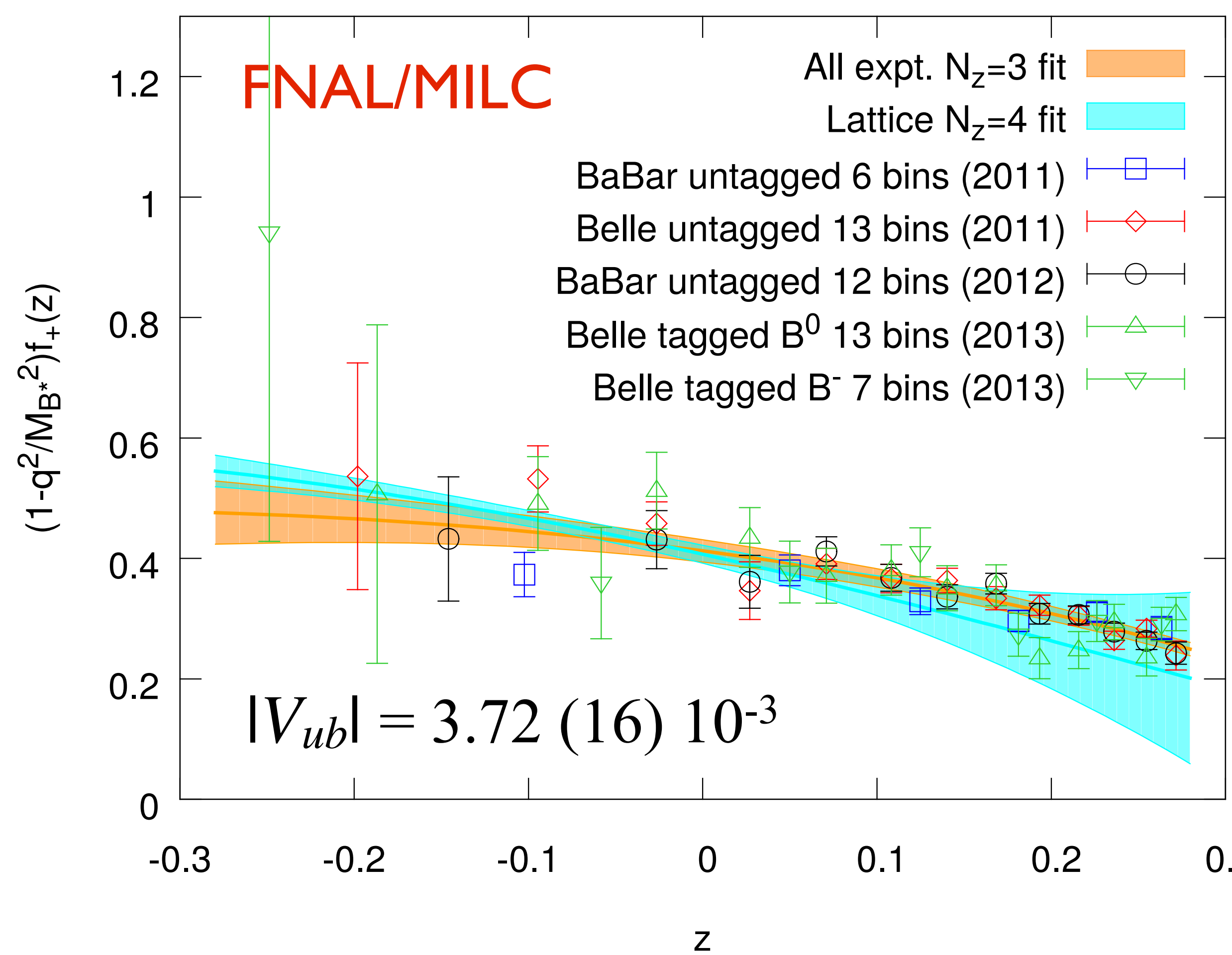
$$|V_{cb}| = 41.09\ (95)\ 10^{-3}$$

Form factor for $B \to \pi \ell \nu$ & V_{ub}

RBC/UKQCD (arXiv:1501.05373, PRD 2015)



FNAL/MILC (arXiv:1503.07839, PRD 2015)

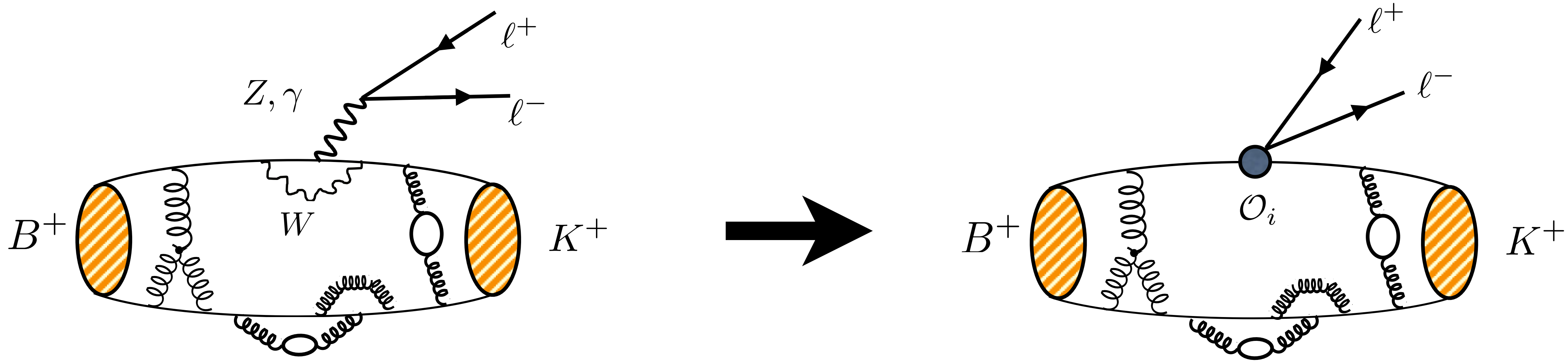


New: First determination of $|V_{ub}/V_{cb}|$ from **baryon** decay!

(Detmold et al, arXiv:1503.01421, PRD 2015) + LHCb (arXiv:1504.01568, Nature 2015)

$$R_{FF} = \frac{|V_{cb}|^2}{|V_{ub}|^2} \frac{\int_{15\mathrm{GeV}^2}^{q^2_{\mathrm{max}}} \frac{d\Gamma(\Lambda_b \to p \mu \nu)}{dq^2} dq^2}{\int_{7\mathrm{GeV}^2}^{q^2_{\mathrm{max}}} \frac{d\Gamma(\Lambda_b \to \Lambda_c \mu \nu)}{dq^2} dq^2} = 1.471 \pm 0.094 \pm 0.109$$

Form factors for $B \to K, \pi\ \ell^+\ell^-$



$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left(C_i O_i + C_i' O_i' \right)$$

Need 3 form factors: $f_{+,0,T}(q^2)$ ⟵

- low recoil (high q^2) OPE
- high recoil (low q^2) SCET
- compare theory with exp.

HPQCD for $B \to K$
(arXiv:1306.0434, 1306.2384, PRL 2013)

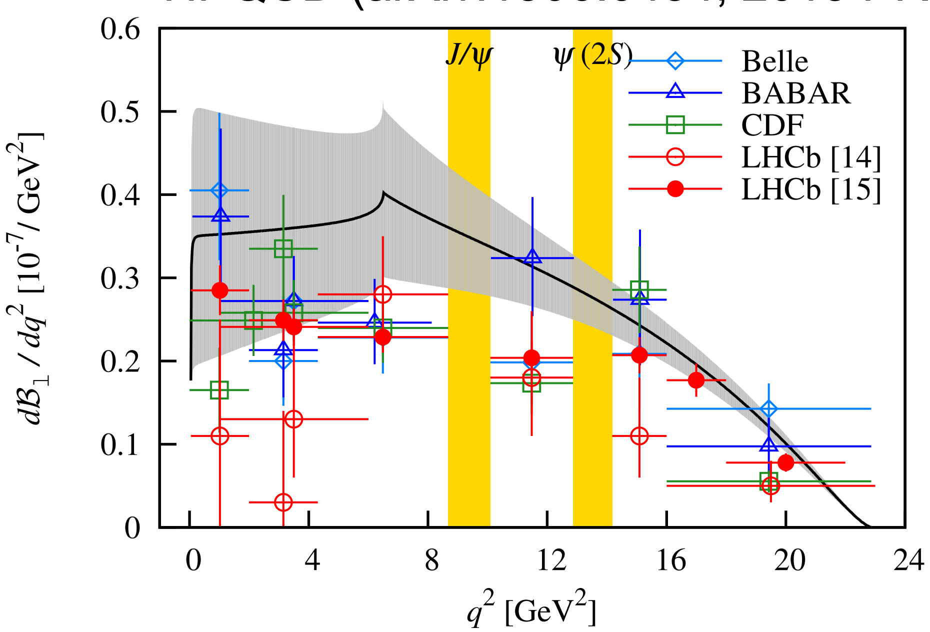
FNAL/MILC for $B \to K, B \to \pi$
(arXiv:1509.06235, 1507.01618, PRL 2015)

also: Detmold & Meinel
(arXiv:1602.01399, PRD 2016)

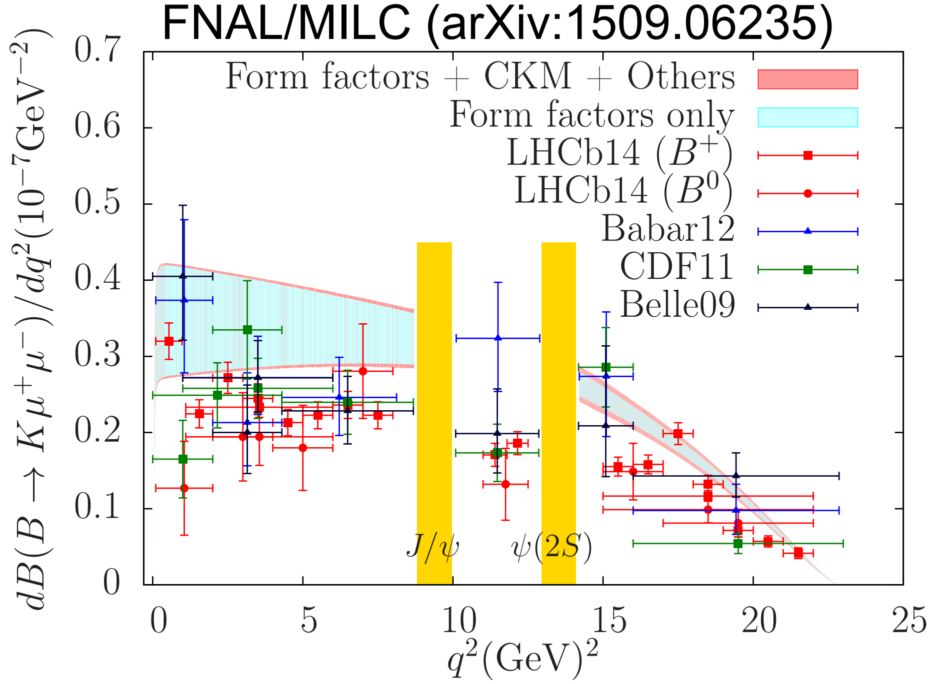
Phenomenology for $B \to K, \pi\, \ell^+\ell^-$

Experiment vs. Theory

HPQCD (arXiv:1306.0434, 2013 PRL)



FNAL/MILC (arXiv:1509.06235)



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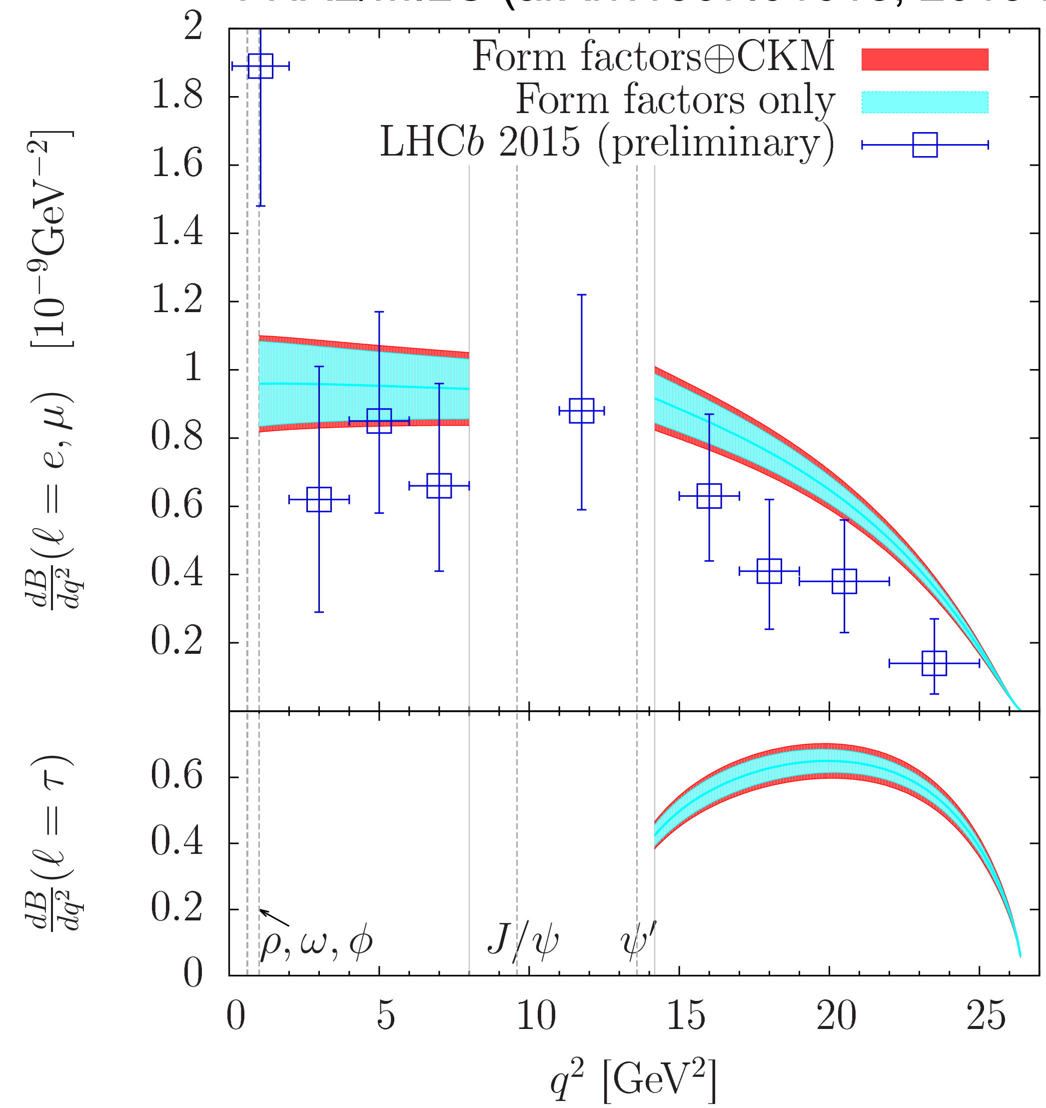

Phenomenology for $B \to K, \pi\, \ell^+\ell^-$

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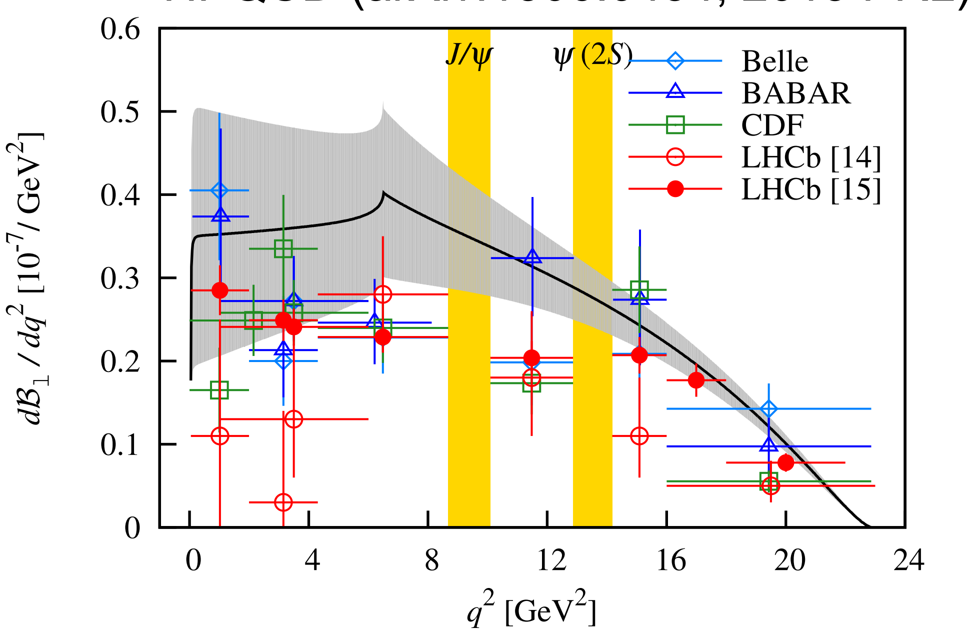
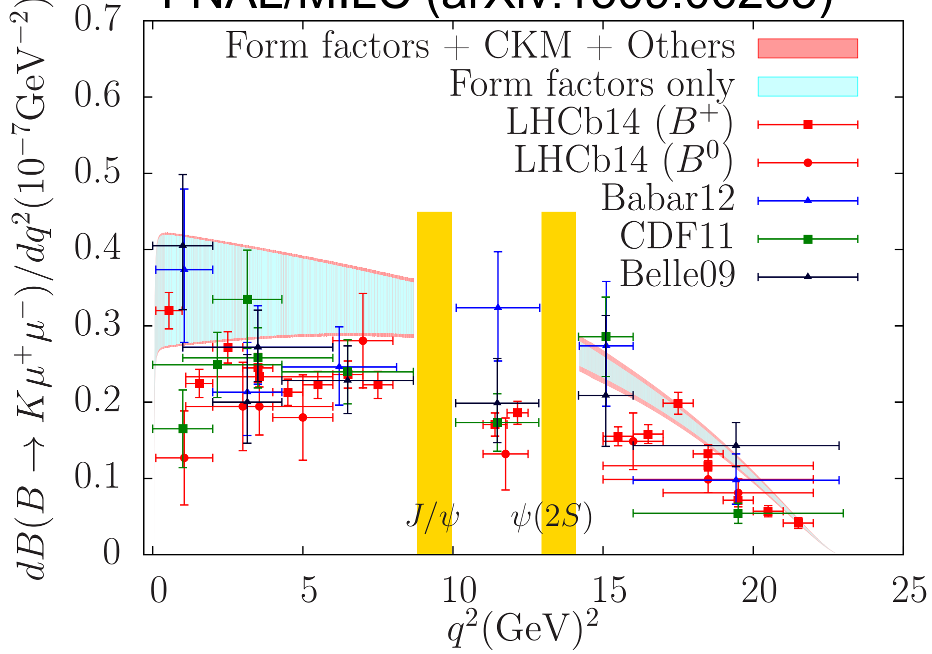


FNAL/MILC (arXiv:1509.06235)



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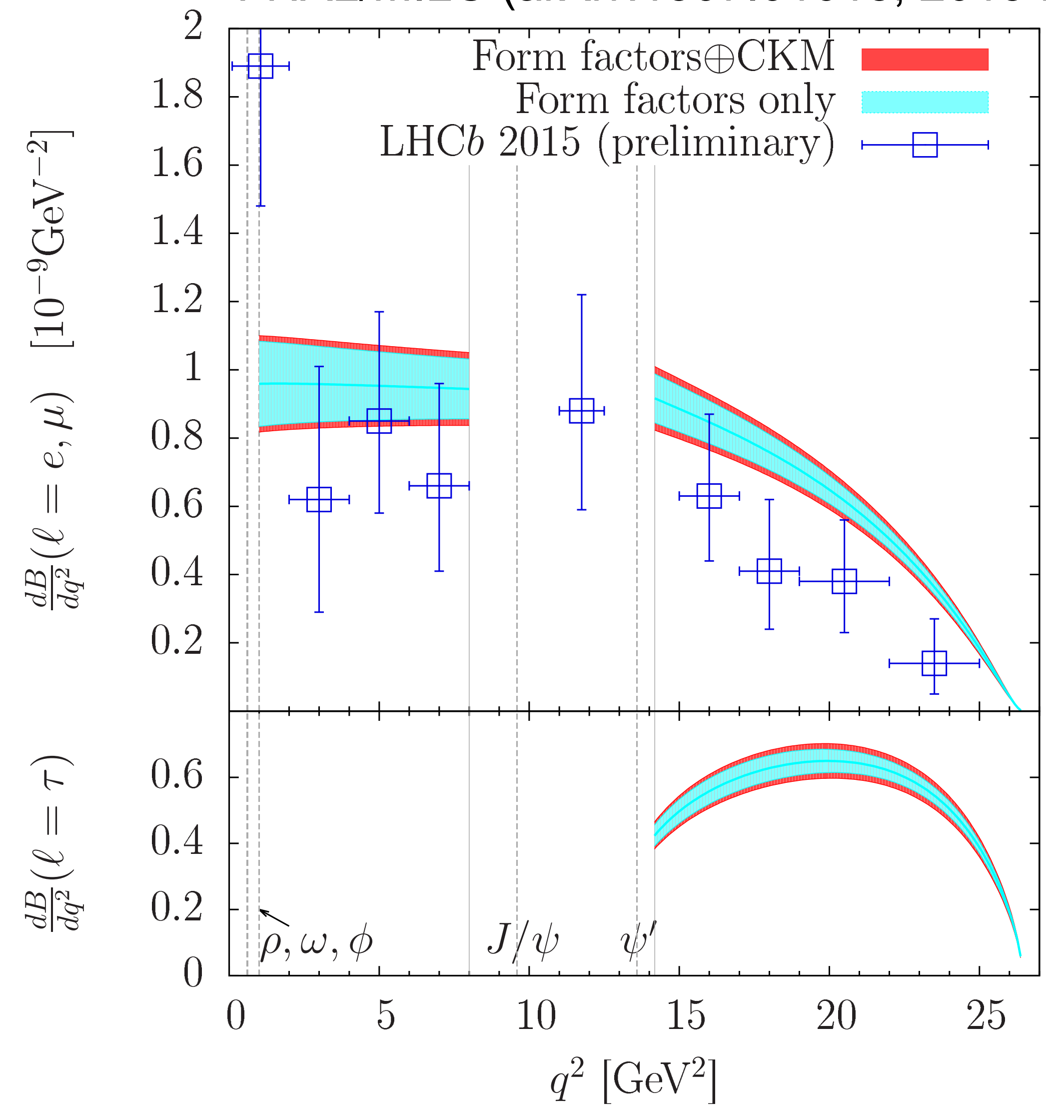


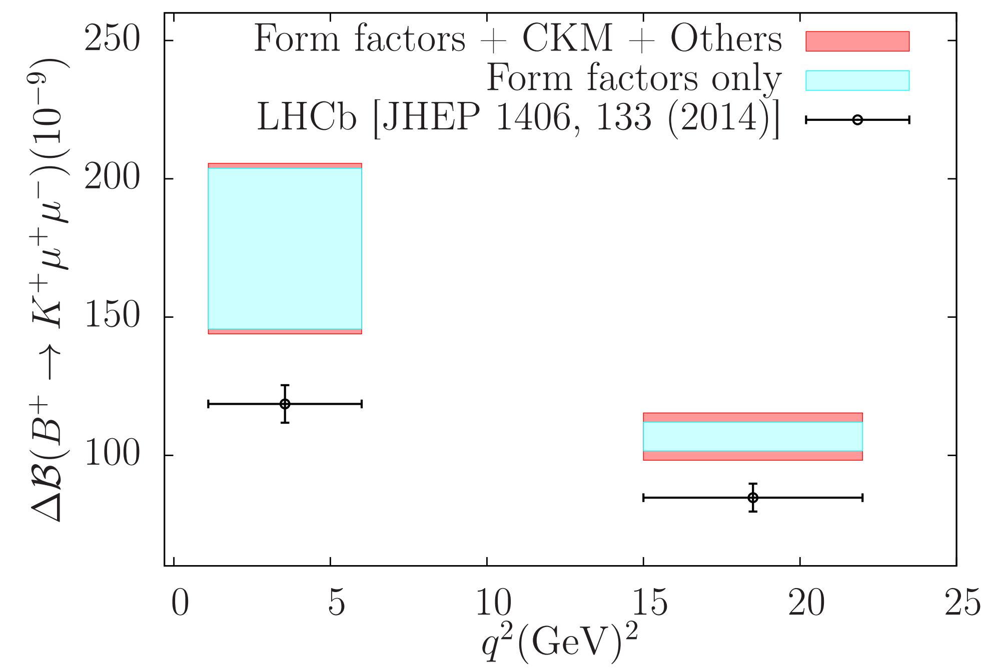
Phenomenology for $B \to K, \pi\, \ell^+ \ell^-$

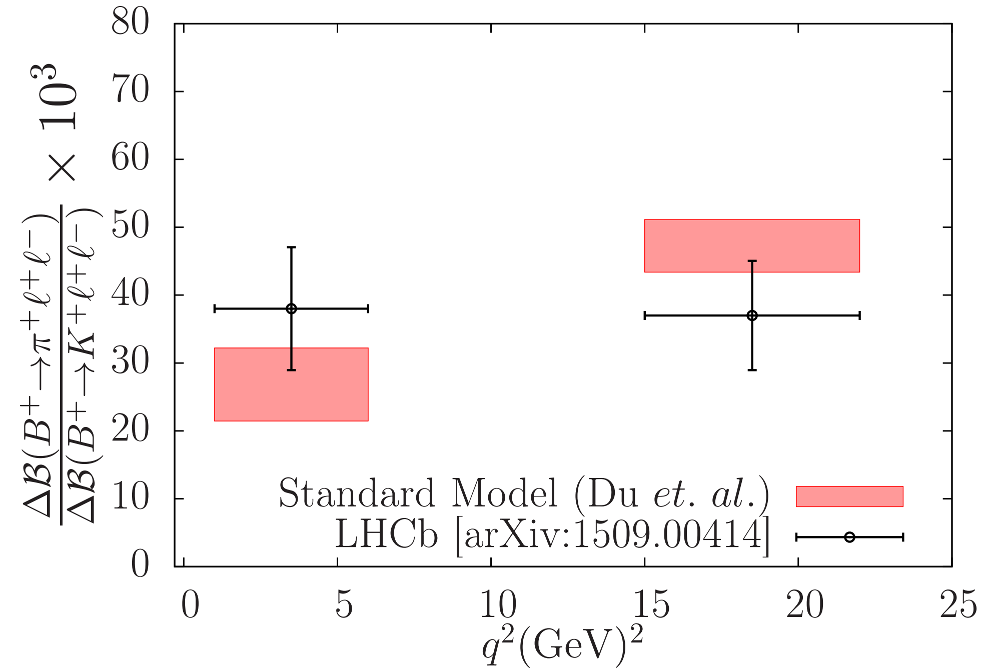
Experiment vs. theory

- LHCb data + FNAL/MILC form factors (arXiv:1509.00414,1403.8044, JHEP 2014)
- focus on large bins above and below charmonium resonances
- theory error commensurate with experiment
- yields $\sim$1-2σ tensions
- $\Rightarrow$ determine $|V_{td}/V_{ts}|$,$|V_{td}|$,$|V_{ts}|$

  or constrain Wilson coefficients

D. Du et al (in preparation)





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