Heavy Flavors Experiments and LQCD

Vera Lüth

SLAC – Stanford University

A brief – incomplete – overview

Emphasis on
experimental capabilities now and in the future

Potential to Improve Precision Measurements

- CKM Matrix Elements
- Mixing and phases, Δm_d, $\Delta m_{s,}$ Bag Constants B_{Bd} B_{Bs} ξ
- CP asymmetries, angles α β γ,
- Form Factors and Decay Constants, f_D f_{Ds} f_B f_{Bs}
- Rate Decays: Penguin Decays: $b \to s/d\gamma$, $b \to s/d\ \ell^+\ell^-$
- Quark Masses m_b m_c

Not considered: here

- ε_{K} , f_π f_K B_K
- Spectroscopy

Overview of Current and Future Experiments

- e+e-
  - Modest rates, need high integrated luminosity
  - high S/B, open trigger, large solid angle coverage
  - Good track, photon detection and PID
  - “reconstruction of neutrino” possible, inclusive measurements
  - At Y(4S) and (3770), coherent production of BB or DD.
  - For rare decays, detailed understanding of background become important

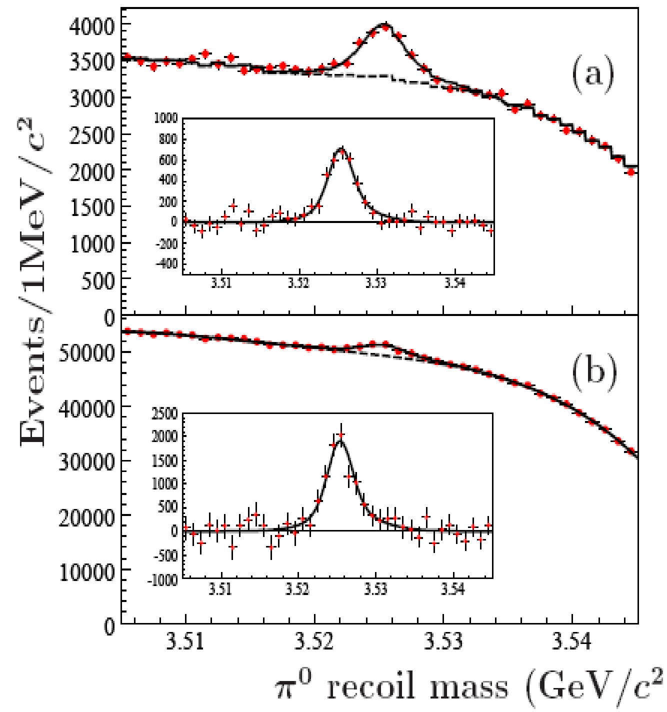
- $\bar{p}p$ and pp
  - Very high production rates of D and B states
  - HF small fraction of x-section: needs selective triggers, high backgrounds
  - Normalization, calibration of acceptance and resolution, challenging
  - Longer decay paths: vertex separation and precision lifetime measurements
  - Focus on Bs and on very rare decays with distinctive signatures.

  Program will develop and new ideas will come up!

BESII @ BEPCII – τ-charm Factory

- Symmetric e^+e^- Collider, 2.0 - 4.6 GeV, $L=10^{33}cm^{-2}s^{-1}$
- Physics program
  - Spectroscopy: Charmonia, light mesons, exotic states (glueballs, etc.)
  - D, Ds: hadronic, leptonic, s.l. decays: Vcs, Vcd, FF, mixing and CP violation
  - Rare decays
- Current sample: 200M Ψ(1S), 100M Ψ(2S)
  - $M(h_c)$= 3525.40±0.40±0.18 MeV,
  - $\Gamma(h_c)$= 0.75±0.45±0.28 MeV

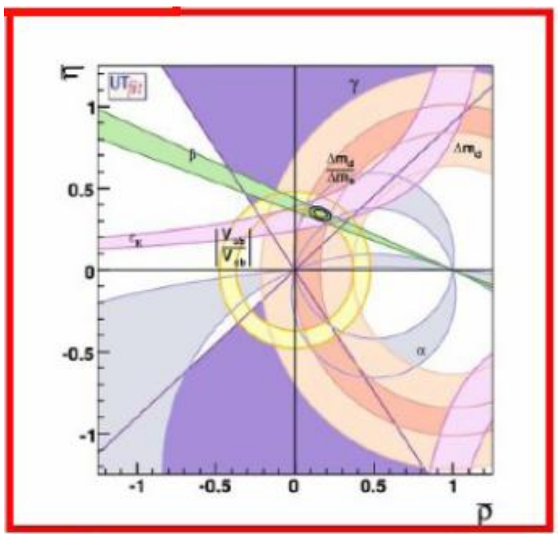
$\psi' \to \pi^0 h_c, h_c \to \gamma\eta_c$

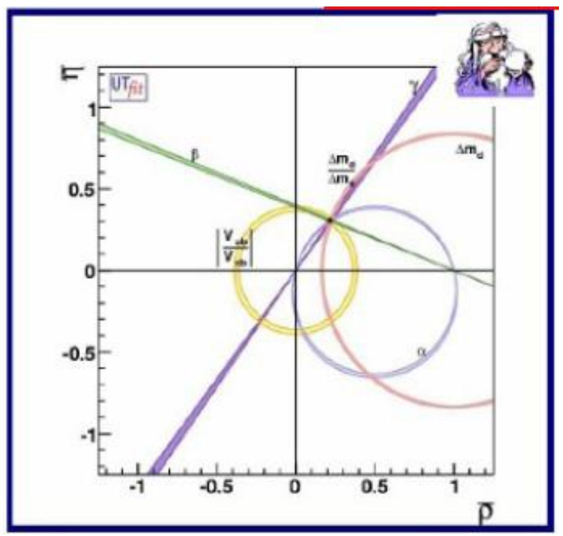


	CMS Mass	Peak Lum.	σ	No. of Events/year
J/ψ	3.097	0.6	3400	10×10^9
$\tau^+\tau^-$	3.670	1.0	2.4	12×10^6
$\psi(2S)$	3.686	1.0	640	3.2×10^9
$D^0\bar{D}^0$	3.770	1.0	3.6	18×10^6
D^+D^-	3.770	1.0	2.8	14×10^6
D_sD_s	4.030	0.6	0.32	1.0×10^6
D_sD_s	4.170	0.6	1.0	2.0×10^6

B Factories – SuperB or KEK_BII When? where?

- Asymmetric e+e- Collider, 9.4 – 11.5 GeV   L=(5-10)x 10^{35} cm $^{-2}$ s^{-1}
  3.7 – 4.5 GeV   L= 10^{34} cm $^{-2}$ s^{-1}
- Search for New Physics in B, D, and τ decays: expect: 10-50/ab
  - CKM: angles γ, β, α, Δm_d,
  - Penguin decays: Rad: $B^0 \to K^*\gamma$, $B \to Xs\gamma$, $Xd\gamma$
    EW: $B^0 \to K^*l+l-$, $K^*\nu\nu$ $B \to Xs\ \ell^+\ell^-$, $Xd\ \ell^+\ell^-$
  - Very Rare Decays: $B^0 \to \ell^+\ell^-$, $B+ \to \ell^+\nu$, LF Violations
  - Charm: D^0 mixing, CP Violation, decays constants and FF
  - Spectroscopy   Charmonium, Exotics, charm mesons





$\bar{\rho}$ = 0.163 ± 0.028

$\bar{\eta}$ = 0.344 ± 0.016

Now

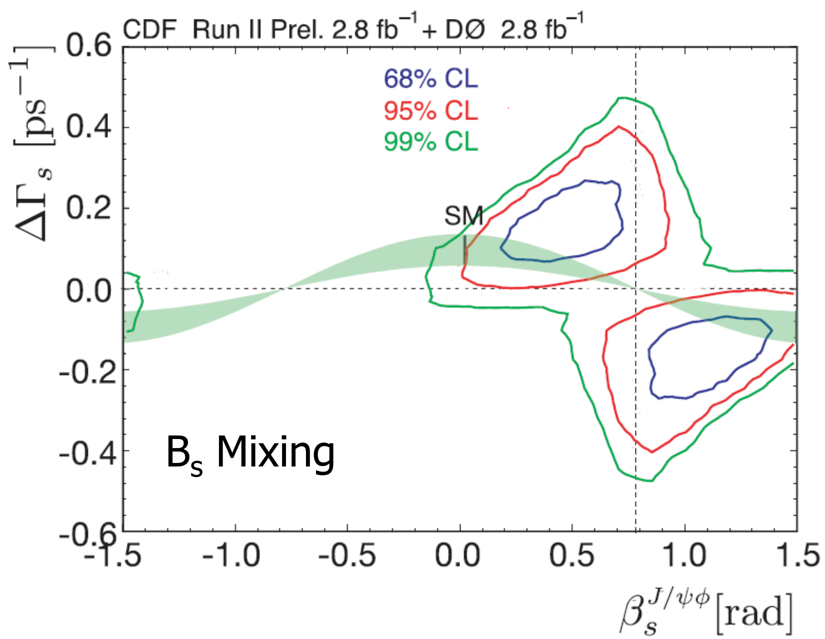
$\bar{\rho}$ = 0.2226 ± 0.0028

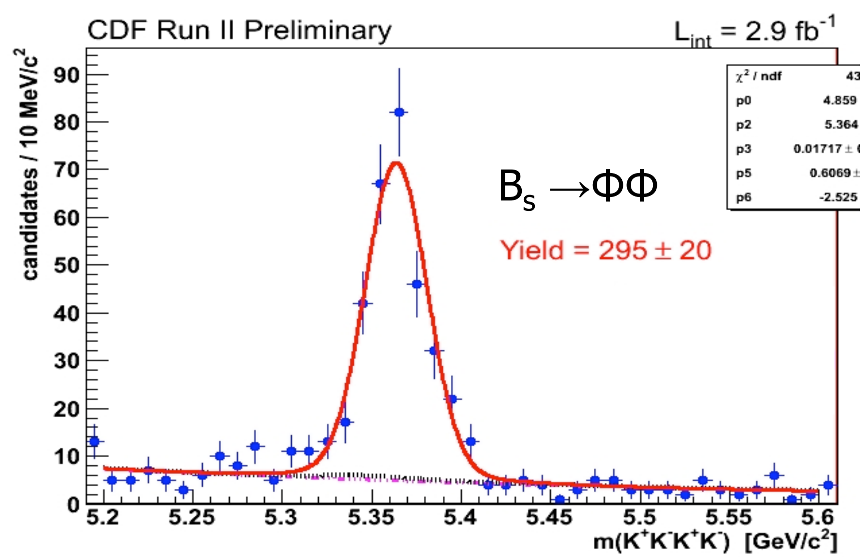
$\bar{\eta}$ = 0.3052 ± 0.0024

50/ab

CDF and D0 @ Tevatron

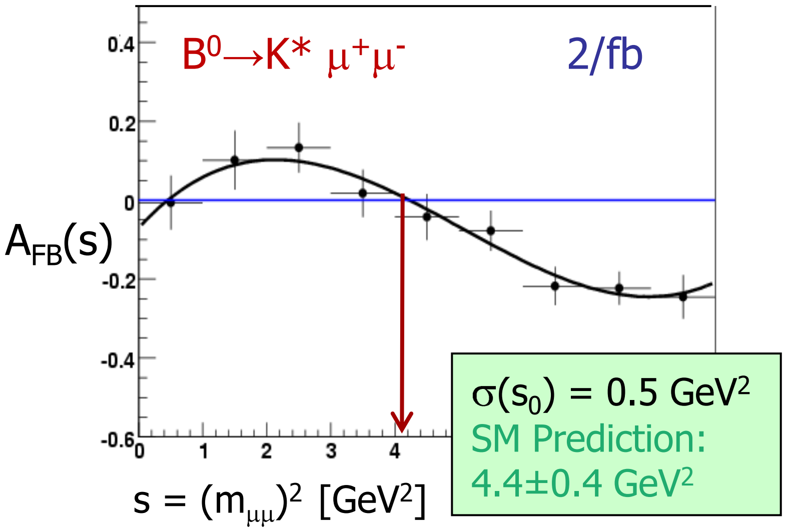
- CDF and D0 were not designed for HF physics, but have a strong HF program! Results available for 4/fb! Expect 10/fb total/experiment.
  - Very large x-section for charm and beauty: B, Bs, Bc, Λb, Σb, ….
  - Sophisticated triggers: high pt tracks/leptons, displaced tracks and vertices
- HF Physics Program
  - B^0 Mixing and CP Violation in Bs system, update for 5.7/fb soon!
  - FCNC - Very rare decays: $B\to K^* \mu+\mu-$, $B_s\to\Phi\ \mu+\mu-$, , $Bs \to\mu+\mu-$,…
  - Lifetimes and spectroscopy: $\Lambda_b\ \Omega_b$, Σ_b, X(3872), Y(4140), …

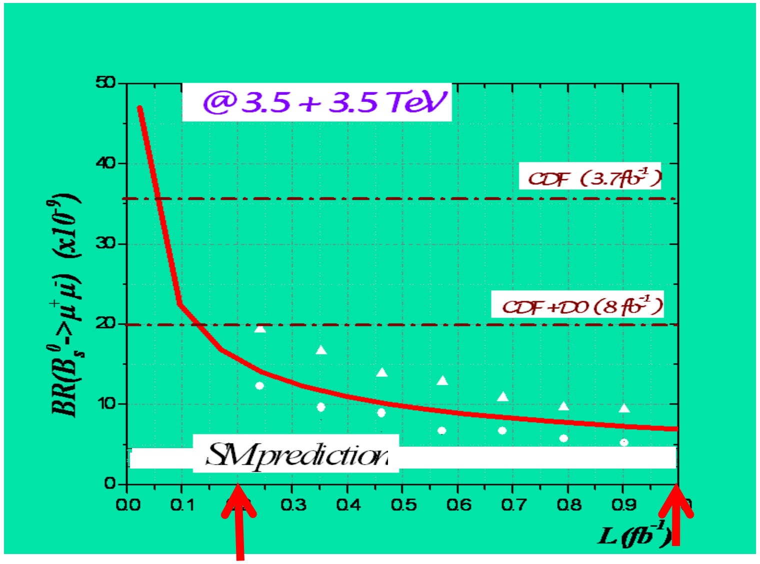




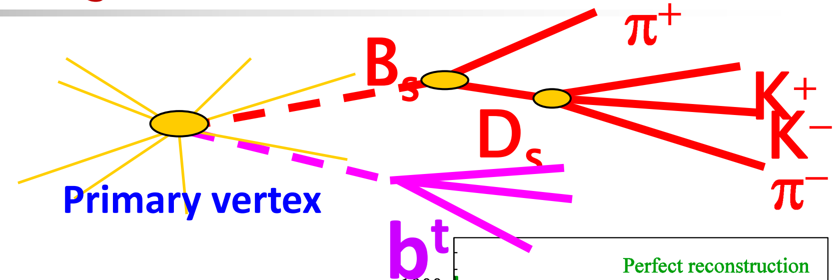
LHCb @ LHC

- pp Collider, 7-14 TeV, $L=10^{31-33} cm^{-2}s^{-1}$: expect: 2010: 0.2/fb 2011: 1/fb
- Physics Program
  - CKM: phase ϕ_s, angles γ, β_s (β, α), Δm_d, Δm_s
  - Penguin decays: Rad: $B^0 \rightarrow K^*\gamma$, $B^0_s \rightarrow \phi\gamma$
    EW: $B^0 \rightarrow K^*\mu^+\mu^-$ $B^0_s \rightarrow \phi\,\mu^+\mu^-$
  - Very Rare Decays: $B^0 \rightarrow \mu^+\mu^-$ $B_s^0 \rightarrow \mu^+\mu^-$
  - Charm: D0 mixing, CP Violation,
  - Spectroscopy, Semileptonic B and D decays??





LHCb: Measurement of B_s Oscillations



<u>Experimental Situation:</u>

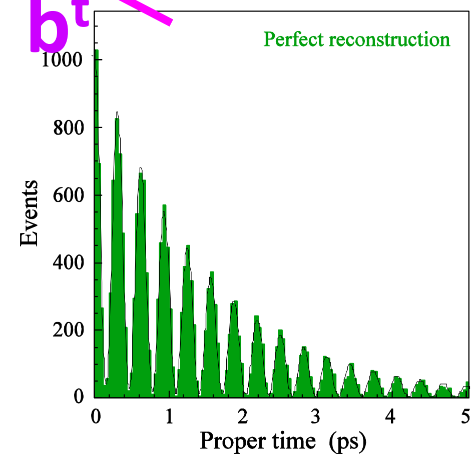
Ideal measurement (no dilutions)

+ flavor tagging dilution, eD^2=8.7%

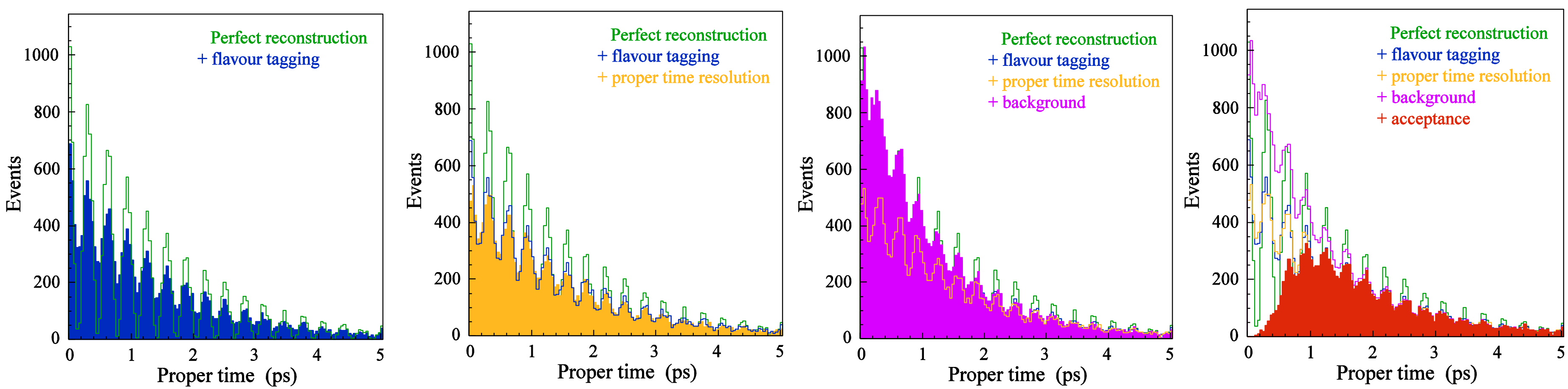
+ decay time resolution σt=40fs

+ Background events

+ Trigger and selection acceptance



Obviously, understanding resolution and dilution will be critical!



Projections for Future Measurements

- Exclusive semileptonic D and B decays
- Leptonic D and B decays
- CP Violation in B_d, B_s and D^0 mesons
- Very rare decays
- Quark Masses

Exclusive D→(K,π) lν: BF and FF

- Primary interest of BF and FF measurements is
  - Measurements of |Vcs| and |Vcd|
  - Validate of QCD calculations, lattice and other,
    - understand relation of D and B decay dynamics, for both, transition to scalar and to vector mesons
    - Important for |Vub| and |Vcb| extraction from B decays

Decay	Exp.	Ecm [GeV]	Lum [1/fb]	$\sigma(M_{pole})$ [MeV]	$\sigma(\alpha_{BK})$	$\sigma(f+(0))$	
D→Kev	**CLEOc**	**3.77**	**0.8**	**20/11**	**0.03/ 0.01**	**1.0%/ 0.7%**	stat/syst
	BABAR	**10.58**	**75**	**12/15**	**0.023/ 0.029**	**1.0%/ 0.7%**	
D→πev	**CLEOc**	**3.77**	**0.8**	**20/10**	**0.07/ 0.02**	**2.9%/ 0.8%**	
	Belle	**10.58**	**282**	**80/40**	**0.21/ 0.10**	**3.2%/ 4.8%**	
	Super_B	3.77	150			0.3%/ 0.1%	

Exclusive $D^+ \to K^- \pi^+ e^+ \nu$, $D_s^+ \to K^+ K^- e^+ \nu$: BF and FF

- With larger samples (250,000 signal events) detailed study of Axial Vector FF becomes possible!
- D^+ and D^+_s decays show similar results, except for r_V ??
- Measurement of P wave contribution, S wave amplitude and phase.
- A very complex analysis – 5-Dim binned likelihood fit !
- Q: Is the pole ansatz adequate?
- Only quenched LQCD calculations available, with stated error of 10%

Decay	Exp.	Ecm [GeV]	Lum [1/ab]	$\sigma(A_1(0))$	$\sigma(r_2)$	$\sigma(r_V)$
Ds→KKev	**BABAR**	**10.58**	**0.214**	**5%**	**13%**	**5%**
D →Kπev	**BABAR**	**10.58**	**0.350**	**1.6%**	**3.8%**	**2.7%**
Ds→KKev	Super_B	10.58	5.0	1%	3%	1.2%
D →Kπev	Super_B	10.58	5.0	0.5	1.0%	1.0%

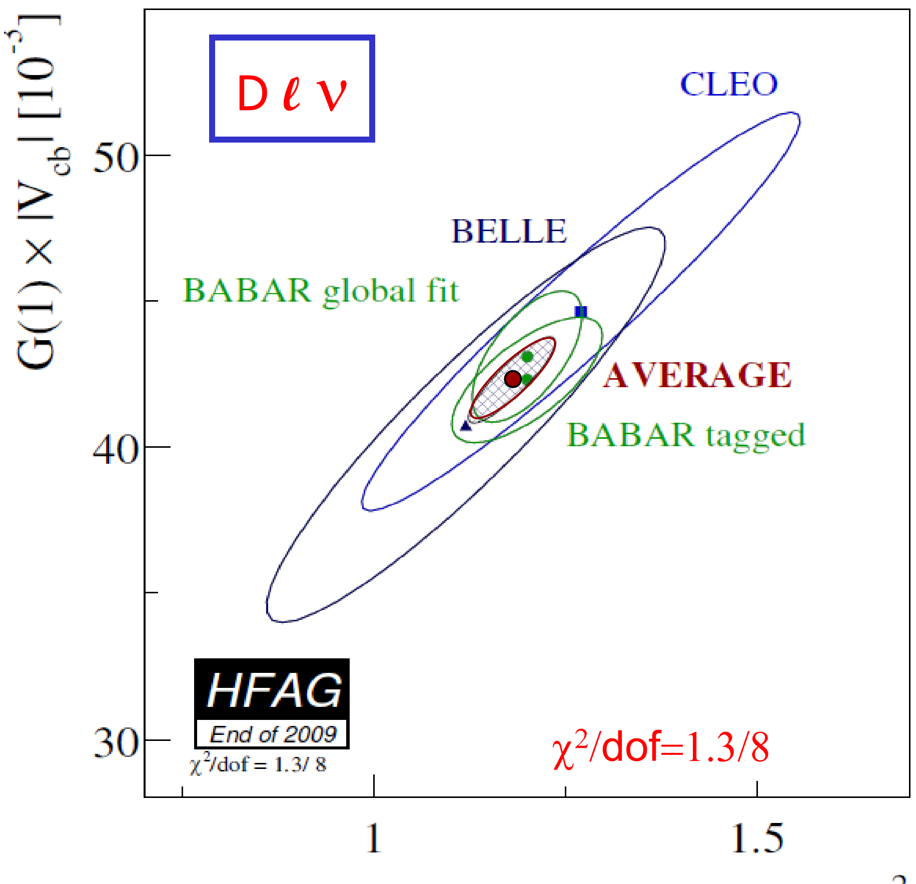
Exclusive B→ D*lν, Dlν: FF and |Vcb|

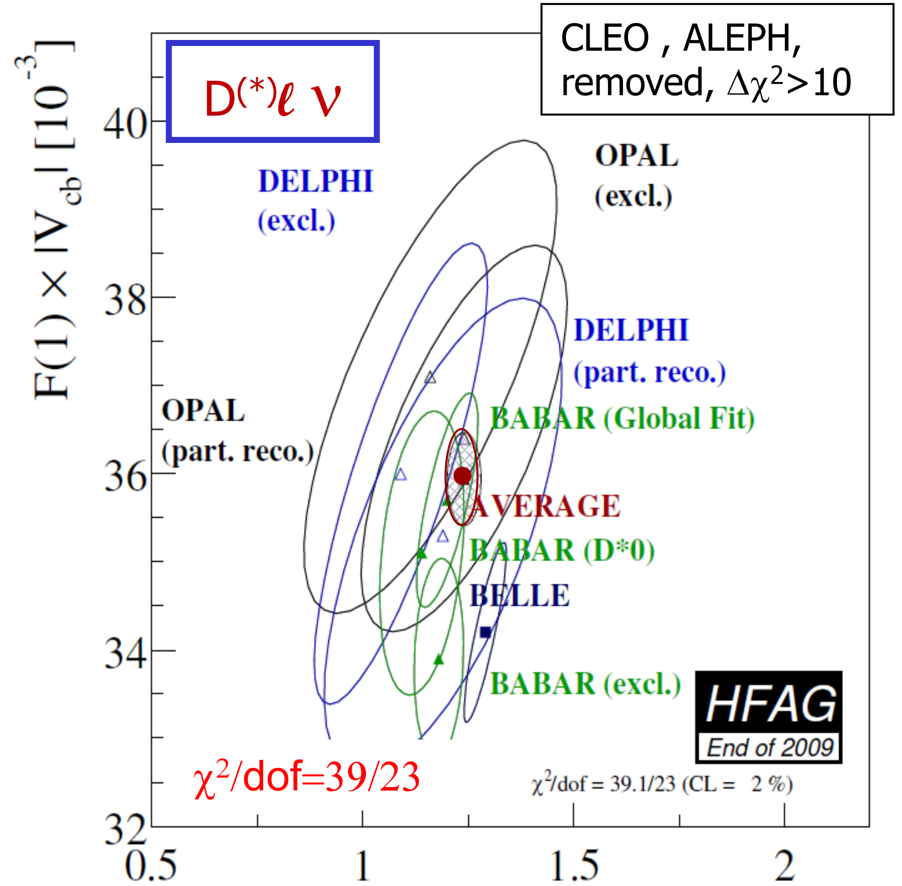
- D*lν – untagged
  - Current FF measurements only with ~100/fb,
  - only CLEO and BABAR have fully 4-Dim measurements of R1, R2, ρ^2
  - Sizable backgrounds, Purity =0.6-0.8, in the future: restrict to cleaner decay channels
  - Puzzling inconsistency of BF Measurements
  - BABAR: F(1)| Vcb|= $(34.4 \quad 0.3_{stat} \quad 1.1_{syst}) \quad 10^{-3}$ 3.3% F(1)*= 0.921 0.024 2.6%

    HFAG F(1) |Vcb|= $(35.94 \quad 0.10_{stat} \quad 0.52_{syst})\ 10^{-3}$ 1.5%
- Dlν – hadronic tags
  - Sizable background reduced by hadronic tag
  - Extrapolation to w=1 impacted by p_D^3, need prediction for w>1
  - BABAR: G(1) |Vcb|=$(42.3 \quad 1.9_{stat} \quad 1.0_{syst})\ 10^{-3}$ 5.1% G(1)*=1.074 0.024 2.2%

    HFAG: G(1) |Vcb|=$(42.3 \quad 0.7_{stat} \quad 1.3_{syst})\ 10^{-3}$ 3.5%
- Future
  - With higher stats. Fully 4-dim analysis should settle FF amd BF issues.
  - Significant improvements possible,
  - Primarily detector and background limited, also BF for B s.l. and D had. decays
  - At SuperB. Syst. Error might be reduced to 1% level, tagged events should help
  - Lattice calculations for w>1 helpful, especially for Dlν
  - Q. Will LHCb contribute??

$|V_{cb}|$ Measurements from $B \to D^{(*)} \ell^+ \nu$ Decays





$G(1)|V_{cb}| = (42.3 \pm 0.7_{stat} \pm 1.3_{syst})\ 10^{-3}$

$G(1) = 1.074 \pm 0.024$ (Hashimoto, LAT04)

$|V_{cb}| = (37.1\ \pm 4.2_{exp} \pm 0.87_{theo})\ 10^{-3}$

11% 2.2%

$F(1)|V_{cb}| = (35.94 \pm 0.10_{stat} \pm 0.52_{syst})\ 10^{-3}$

$F(1) = 0.921 \pm 0.024$ (PRD 79, 014506, 2009)

$|V_{cb}| = (37.8 \pm 0.66_{exp} \pm 0.85_{theo})\ 10^{-3}$

1.8% 2.3%

B→ D(*) lν: Measurements of BF and $|V_{cb}|$

D lν

Tag	L [1/ab]	Yield Kevts	S/B	stat [%]	syst [%]
No	**0.4**	**100**	**1.0**	**2.6**	**2.8**
No	5.0	720	2.0	1.1	1.4
had	**0.4**	**3**	**1.0**	**4.4**	**3.3**
had	5.0	32	3.0	1.4	1.2
had	50	300	4.0	0.4	0.5

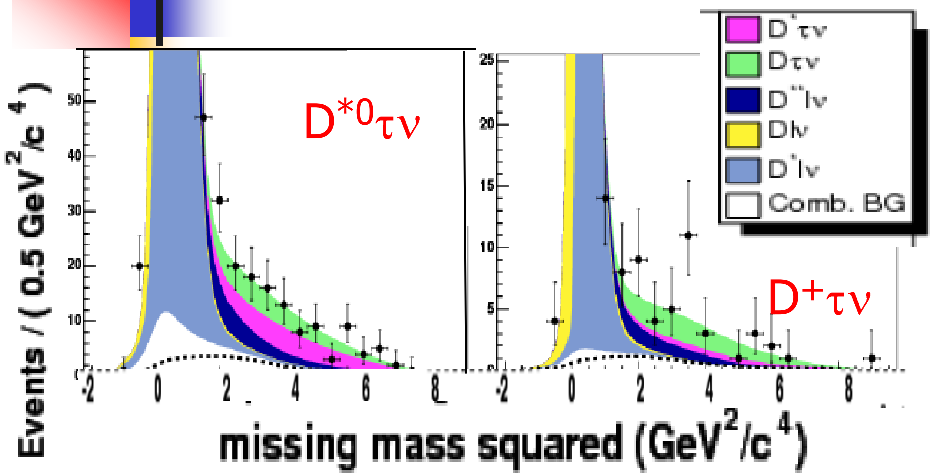
D* lν

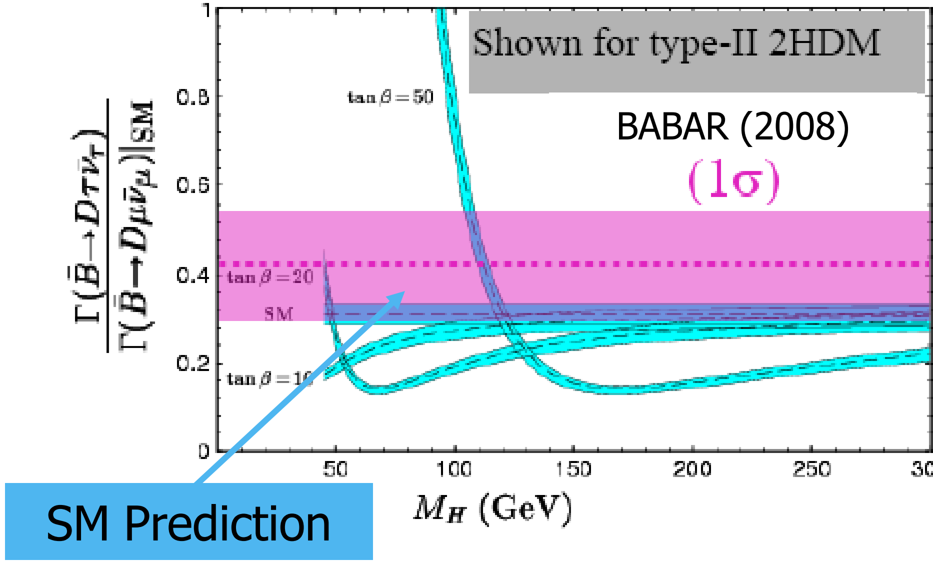
Tag	L [1/ab]	Yield Kevts	S/B	stat [%]	syst [%]
No	**0.08**	**53**	**1.5**	**1.1**	**3.2**
No	1.0	530	2.3	0.5	1.7
s.l.	1.0	30	5	0.9	1.7
s.l.	5.0	150	2	0.5	0.9
had	5.0	25	10	0.8	1.3
had	50	250	10	0.3	0.7

Current measurements limited by systematics Improvements of S/B, background and detector simulations require big effort, but are doable!

FF parameterization by CLN widely adopted. Are there alternatives?

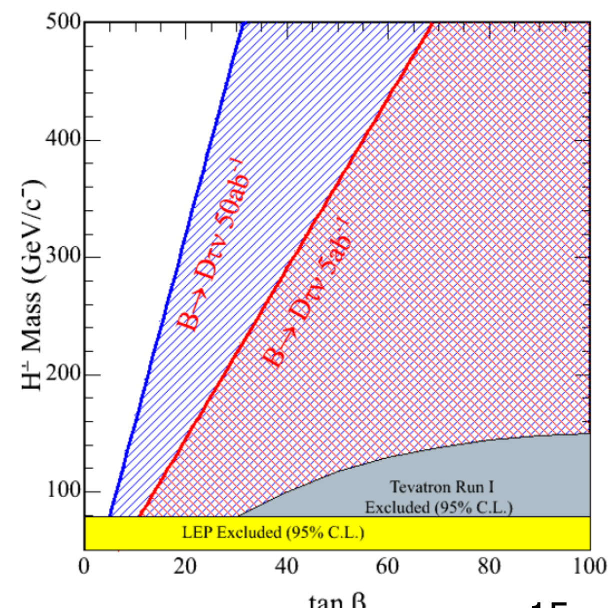
$B \to D^{(*)} \tau^+ \nu$ Decays





BABAR *)	Lum [1/ab]	Stat.	Syst.	Total Error	Est. # events
$B^+ \to D\tau\nu$	**0.2**	**29%**	**13%**	**32%**	**59**
	5	6%	3%	7%	1475
	50	2.5%	1.5%	3%	15000

*) Only for $\tau + \to \ell + \nu\nu$ decays, $\tau \to h + \nu$ add 2x more events!



Exclusive $B \to (\pi,\eta,\rho,\omega)\ell\nu$, FF and $|V_{ub}|$

- $\pi\ell\nu$
  - Current measurements based on 400/fb (No tag), 600/fb (tagged)
  - Challenge for detector and neutrino reconstruction ~4%
    - more restricted solid angle at asymmetric colliders
    - 40% of hadronic B decays unknown, use jetset fragmentation!
  - Very sizable backgrounds – reliance on MC simulation for subtractions
    - non-BB 1-2 % not well studied
    - $X_c\,\ell\nu$, 1-2 % poor BF and FF knowledge
    - other $X_u\,\ell\nu$, not well measured, difficult to separate from signal
- $\eta,\rho,\omega\,\ell\nu$
  - Current measurements based on 400/fb (No tag), 600/fb (tagged)
  - larger combinatorial backgrounds than $\pi l\nu$. q^2 measurements soon!
- Future
  - background reductions with tagged events,
  - FF measurements require much larger luminosity
  - LQCD predictions with higher precision needed

Exclusive $B \to \pi l \nu$, FF and $|V_{ub}|$

Error Assessment for |Vub| :

$B \to \pi l \upsilon$	L [1/ab]	Yield	S/B	stat	syst
No tag	**0.35**	**12,000**	**0.25**	**1.8%**	**5.0%**
No tag	1.0	30,000	0.5	1.0%	2.8
No tag	5.0	150,000	0.6	0.5%	1.8
s.l. tag	**0.25**	**100**	**1.5**	**14%**	**5.0**
s.l. tag	1.0	400	3	7%	2.9
s.l. tag	5.0	2,000	3	3.5%	2.0
Had tag	**0.6**	**80**	**4**	**13%**	**3.3**
Had tag	5.0	600	8	5%	1.5
Had tag	50	6,000	8	1.5%	0.3

Uncertainties

Detector simulation

- Particle losses K_L, ν
- Limited solid angle
- Inefficiencies

Backgrounds, BF and FF

- Non-BB processes
- Other $B \to X_u l \nu$ decays
- $B \to X_c l \nu$ decays
- Combinatorial BG

FF parameterization

FF Normalization

Leptonic D decays: $D^+ \to \mu^+ \nu$, $D_s^+ \to (\tau,\mu)^+ \nu$: f_{Ds}/f_D

- Measurements of BF and Decay Constants f_{Ds}/f_D
  - Best results for tagged samples recorded near threshold, 3.77GeV or 4.17GeV
  - Currently statistics limited
  - Systematic error dominated by backgrounds ($D^+ \to K_L e^+ \upsilon$) and tag rate
  - At Y(4S), restricted solid angle results in need for extensive difficult background rejection, and limited resolution.

    BABAR and Belle have published results, but systematic errors are 2x compared to CLEOc, plus normalization problem.
  - Super_B and KEK_B could use enormous statistics at Y(4S),

    plans to take data near 4 GeV!
  - LHCb is unlikely to contribute here!

Leptonic D decays: $D^+ \to \mu^+\nu$, $D_s^+ \to (\tau,\mu)^+\nu$: f_{Ds}/f_D

Experiment	Ecm [GeV] 3.77	Ecm [GeV] 4.17	$\sigma(f_{DS}/f_D)$	
CLEO$_c$	**0.75/fb**	**0.75/fb**	**5%**	
BESIII	20/fb	12/fb	1-2%	
Super-B	150/fb	200/fb	< 1%	Also Y(4S)

- f_{Ds}/f_D is key ingredient to |Vts|/|Vtd| extracted from B_d and B_s mixing;
- LQCD predicts double ratio $$\xi = \frac{f_{Bs}\sqrt{B_{Bs}}}{f_{Bd}\sqrt{B_{Bd}}} = 1.210^{+0.047}_{-0.035}$$
- If we assume $f_{Bs}/f_{Bd} \approx f_{Ds}/f_D$ holds to within a few %, we still need from LQCD : $B_{Bs}/B_{Bd} \approx 1$
- Both stat. and syst. errors can be reduced very significantly with larger data sets.
- Important for CKM tests and |Vub| and |Vcb| extraction from B decays !

Leptonic B decays: $B^+ \to (\mu,\tau)^+ \nu$, BF and f_B

- Purely leptonic processes sensitive to SM parameters and NP,

$$BF_{\tau\upsilon} = C\left(1-\frac{m_\ell^2}{m_B^2}\right)\times f_B^2 |V_{ub}|^2 \tau_B \xi_H, \quad \xi_H = \left(1-\frac{m_B^2}{m_H^2}\tan\beta\right)^2$$

- At 50/ab, a m_H=500GeV with $\tan\beta$=30, would give a w very significant deviation from SM.

Belle	Lum [1/ab]	Stat.	Syst.	Total Error	Est. # Events
$B^+ \to \tau^+ \nu$	**40%**	**28%**	**27%**	**40%**	**24±7**
	5	8%	8%	12%	300±40
	50	3%	3%	4%	3,000±120
$B^+ \to \mu^+ \nu$	5			20%	30 ± 6
	50			12%	280 ± 35

Very Rare Decays $B_s \to \mu^+\mu^-$, $K^*\ell^+\ell^-$, $K^*\gamma$

Current samples too small for SM rates, but test NP processes.

	Belle	SuperB	SuperB	Tevatron *)	LHCb	LHCb
Observable	0.5/ab	5/ab	50/ab	3.7/fb	2/fb	10/fb
$B_s \to \mu+\mu-$ ($6\ 10^{-9}$)				**$4.3\ 10^{-8}$**	$>5\sigma$	10%
$A_{CP}(B \to K^* l^+ l^-)$		11%	1.5%			1.5%
$A_{FB}(B \to K^* l^+ l^-) s_0$		15%	9%		0.5 MeV	
$B0 \to K^{*0} \nu\nu$			35%			
$B+ \to K^+ \nu\nu$			30%			
$B \to K^*\gamma/\Phi\gamma$						
$B \to \rho\gamma$	**20%**		5%			

*) CDF: @95% C.
D0: projects sensitivity of $5.3\text{x}10^{-8}$ @ 95% C.L.
SM expectations: $3.3\text{x}10^{-8}$

Mixing and CP Violation in $B_{d/s}$ Decays

Uncertainties of individual experiments

	Belle	SuperB	SuperB	CDF	LHCb	LHCb
Observable	0.5/ab	5/ab	50/ab	1/fb	2/fb	10/fb
ρ	**20%**		3.4%			
η	**16%**		1.7%			
α ($\pi\pi$,$\rho\rho$,$\rho\pi$)		2^o	$<1^o$		10^o	4.5^o
sin2β	**0.026**	0.016	0.012		~0.02	~ 0.01
γ (DK,combined)		6^o	1.5^o		5^o-10^o	2.4^o
Δm_d [1/ps]	**0.013**					
Δm_s [1/ps]				**0.12**	0.003	
Φ_s ($B_s \rightarrow \Psi\Phi$)					0.023	0.01

Δm_s and Φ_s ($B_s \rightarrow \Psi\Phi$) will be the primary goals of LHCb

Mixing and CP Violation in D Decays

Uncertainties of individual experiments

	Belle	SuperB	SuperB	LHCb	LHCb
Observable	0.5/ab	5/ab	50/ab	2/fb	10/fb
x	**0.25%**	0.12%	0.9%		0.25%
y	**0.16%**	0.10%	0.05%		0.05%
$\delta(K\pi)$	**10°**	6°	4°		
|q/p|	**0.16**	0.10	0.05		
Φ [rad]	**0.13**	0.08	0.05		
A_D	**2.4%**	1%	0.3%		

Great potential for precision studies of Charm sector!

No unquenched lattice results yet?!

Conclusions and Outlook

- Current experiments come to a close, having charted the way for future measurements,
  - CLEOc, BESII, KLOE, BABAR, Belle, CDF, D0
- New experiments will have enormous volumina of data
  - BESIII, LHCb, SuperB or KEKB II,
  - Primary Focus: beyond the standard model – often precision tests of SM, search for very rare processes above SM
  - Need excellent understanding of detector/simulation
  - Absolute measurements challenging, except at Υ(4s) and Ψ(3770).
- Understanding of physics of background
  - predicted distributions need to checked with data
  - Calibration of data selection processes
- Thorough assessment of systematic errors beyond MC and PDG!
  - MC is a great tool, but is does not replace thinking and independent assessments!
  - MC only helps with things we know, but less so with unknown effects!

Conclusions and Outlook

- Understanding the physics of the signal and backgrounds
  - Transformation of matrix elements into event generators!
  - Not always trivial – collaboration with theorists and experimenters desirable!
- Theory input to extract fundamental parameters
  - LQCD has very high credentials, but requires substantial resources – slow!
  - Scrutiny of theoretical assumptions and methods, uncertainties and biases!
  - Selection/Comparison of methods by different groups - workshop are critical!
  - Documentation of values for all input parameters important!

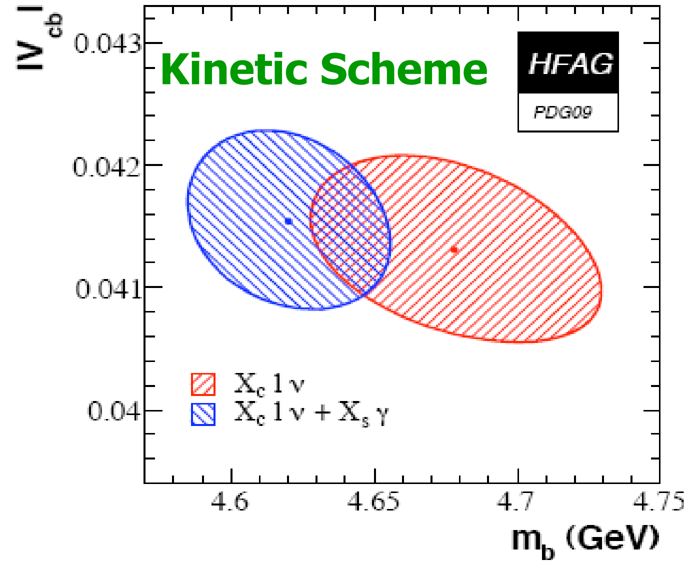
Questions to LQCD Experts

- Leptonic and semileptonic D and B decays
  - Can we extend phase space for FF predictions to full phase space?
    Predictions for decays to Vector and Axial Vector states, as fct. of q^2 ??
  - Predictions for other decay modes? $B \to (\rho,\omega,\eta)\, l\nu$? $D \to K^*\, l\nu$, $D_s \to K\, l\nu$??
  - How do we relate predictions for D to B decays ?
    Which Ratios? Leptonic to semileptonic rates?
- Penguin decays
  - Can we relate $B \to \pi l\nu$ FF to $B \to K^*\gamma$ or $B \to K^* l^+ l^-$? $B \to K^*\gamma$
  - Can LQCD predict BF and asymmetries ACP or AFB?
  - Other rare decays?
- Spectroscopy
  - What are the most critical measurements?
  - Onion or excited D and B meson masses
- Quark Masses
  - There are now very precise predictions of m_c and m_b from sum rules (KA Group)
    Can lattice contribute? How will the lattice masses relate to those needed for comparison with experiments?

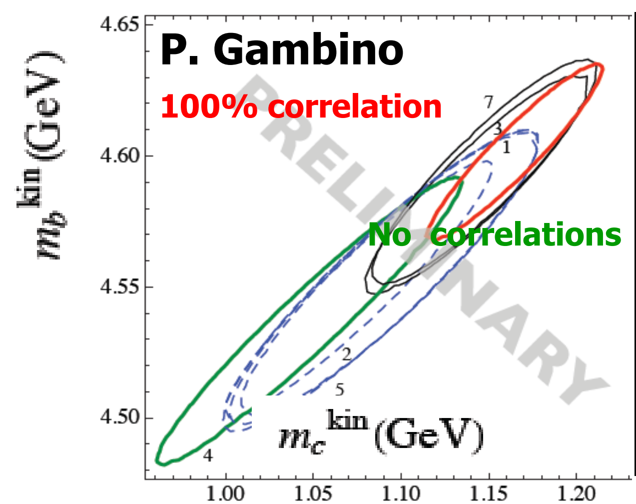
$|V_{cb}|$ Extraction from Global OPE Fits to Moments

- HFAG Result of Global Fit to 64 moments (kinetic scheme)

$$|V_{cb}| = (41.31 \times 10^{-3} (1 \quad 1.2\%_{fit} \quad 1.4\%_{theory})$$
$$m_b = 4.678 \quad 0.051 \text{ GeV}$$
$$m_b - m_c = 3.427 \quad 0.021 \text{ GeV}$$
$$\mu_\pi^2 = 0.428 \quad 0.044 \text{ GeV}^2$$



- Issues
  - Stated theory error now considered generous, overall understanding improved in past 5-10 years
  - Major effort underway to improve higher order QCD terms
    - $\alpha_s^2 \mu_\pi^2$: likely to impact m_b
    - $\alpha_s^2 \beta_0$: mostly impacts total rate and thus $|V_{cb}|$
    - m_b^4 : terms expected to be small
  - Local OPE for $B \to X_s\gamma$ on less solid ground, especially with cut $E_\gamma > 1.8$ GeV
  - unavoidable correlations among moments treatment somewhat ad hoc! impact quark masses
  - Results on m_b are crucial input to $|V_{cb}|$ extraction



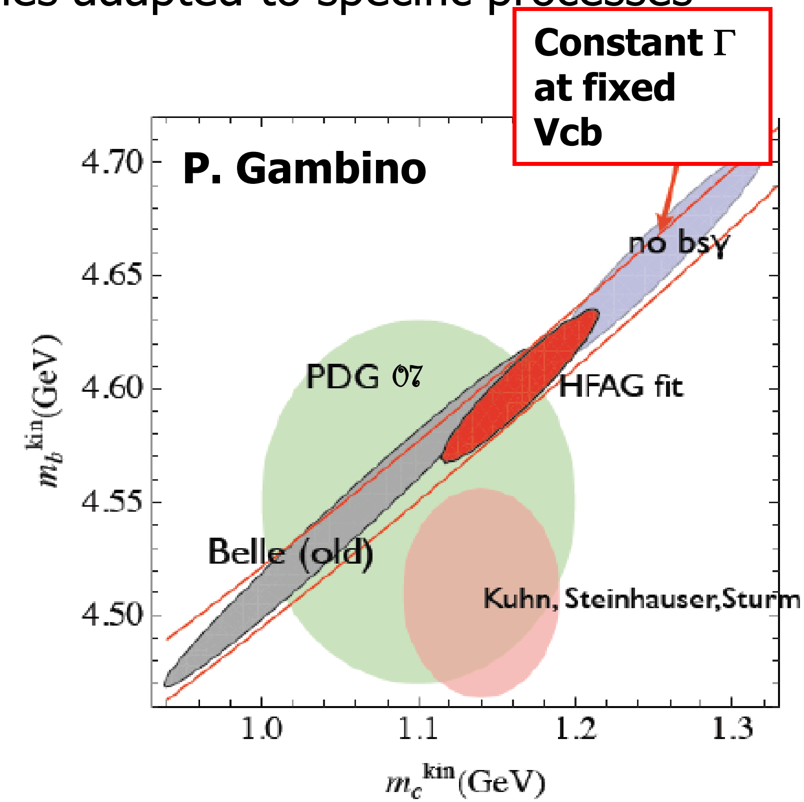
Global Fit to Moments: b-quark mass

- Fits would greatly benefit from additional external input, primarily m_b and m_c
- In kinetic scheme $\Gamma \sim m_b^2(m_b - m_c)^3$,
  fits to moments show linear relation between m_b and m_c!
- Confinement - Quark masses are not physical observables, but defined as formal parameters in QCD action – choice of schemes adapted to specific processes
- Recent update of sum rule calculations at NNNLO result in ($\overline{MS}$ scheme)

  $m_b(m_b) = 4.163 \quad 0.016$ GeV !!

  $m_c(m_c) = 1.279 \quad 0.013$ GeV !!

  Chertyrkin et al. irXiv: 0907.2120 (2009)
- Currently, translation to kin. Scheme increases error to 40 MeV!
  Still smaller than current PDG error!
- Goal is to fit masses in $\overline{MS}$ scheme directly, so conversion error can be avoided!



Quark Masses from Relativistic Sum Rules: m_b & m_c

Analyses with smallest errors I:

Chetyrkin, Kuhn, Meier, Meierhofer, Marquard Steinhauser (2009)

n	$m_c(3\,\mathrm{GeV})$	exp	α_s	μ	np	total
1	986	9	9	2	1	13
2	976	6	14	5	0	16
3	978	5	15	7	2	17
4	1004	3	9	31	7	33

- $m_c(3\,\mathrm{GeV}) = 986 \pm 13\,\mathrm{MeV}$
- $m_c(m_c) = 1279 \pm 13\,\mathrm{MeV}$

n	$m_b(10\,\mathrm{GeV})$	exp	α_s	μ	total	$m_b(m_b)$
1	3597	14	7	2	16	4151
2	3610	10	12	3	16	4163
3	3619	8	14	6	18	4172
4	3631	6	15	20	26	4183

- $m_b(10\,\mathrm{GeV}) = 3610 \pm 16\,\mathrm{MeV}$
- $m_b(m_b) = 4163 \pm 16\,\mathrm{MeV}$

- theory predictions and errors taken for missing data
- $\alpha_s(\mu)$ and $\overline{m}_Q(\mu)$ taken as theory parameters, $\mu = 2 - 4\ \mathrm{GeV}$, fixed order

Analyses with smallest errors II:

HPQCD, Chetyrkin, Kuhn, Steinhauser, Sturm (2008)

- Lattice data for moments instead of experimental data (lattice error: $\sim 2\ \mathrm{MeV}$)

$$m_c(3\mathrm{GeV}) = 986(10)\ \mathrm{MeV}$$

Thank you for a

very interesting workshop

Relativistic Sum Rules: m_b & m_c

→ Method with the most advanced theoretical computations:

$$\mathcal{M}_n^{\rm th} \equiv \frac{12\pi^2}{n!}\left(\frac{\rm d}{{\rm d}q^2}\right)^n \Pi_c(q^2)\Big|_{q^2=0} = \frac{9}{4}Q_c^2\left(\frac{1}{4m_c^2}\right)^n \bar{C}_n$$

$\mathcal{O}(\alpha_s^2)$ moments — Chetyrkin, Kuhn, Steinhauser (1994-1998)

$\mathcal{O}(\alpha_s^3)$ moments $n=1$ — Boughezal, Czakon, Schutzmeier (2006)

$n=1-4$ — Kuhn, Steinhauser, Sturm (2006)

$\Pi(q^2)$ function at $\mathcal{O}(\alpha_s^3)$ — Mateu, Zebarjad, Hoang (2008)

Kiyo, Meier, Meierhofer, Marquard (2009)

→ Experimental data for R_b, R_c not available in most of the continuum region:

$$\mathcal{M}_n^{\rm exp} = \int \frac{{\rm d}s}{s^{n+1}} R_c(s)$$

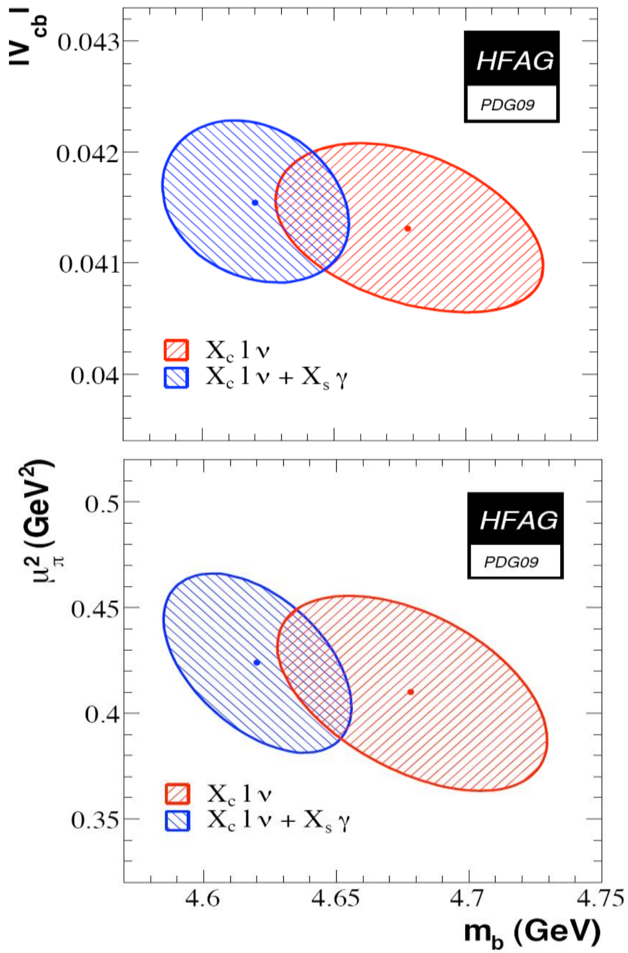
- take continuum theory for missing data

→ Lattice results for moments of scalar and pseudoscalar current correlators:

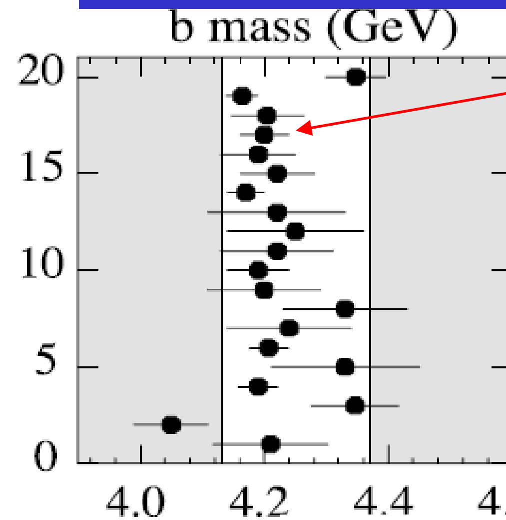
Allison, Lepage, etal, (2008)

Quark Masses and other Parameters

HFAG 2009: Kinetic Scheme

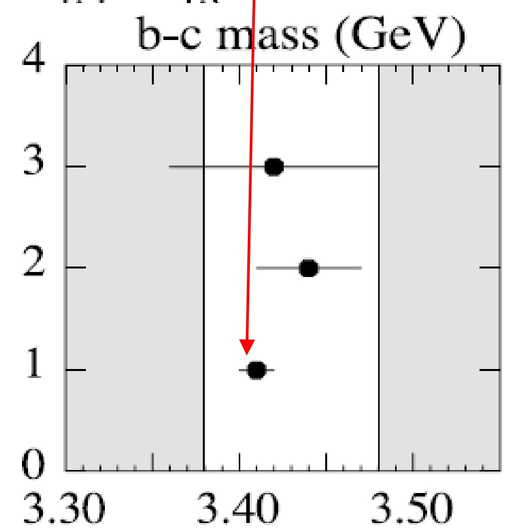


PDG 2009: $\overline{\text{MS}}$ Scheme



Buchmüller, Flächer/BABAR

Some entries rely on same measurements



Calculations of higher order terms in HQE should reduce uncertainties, and probably shift mb and |Vcb| !