Semileptonic $B_{(s)}$ Decays

IUPAP Young Scientist Award

Phillip Urquijo

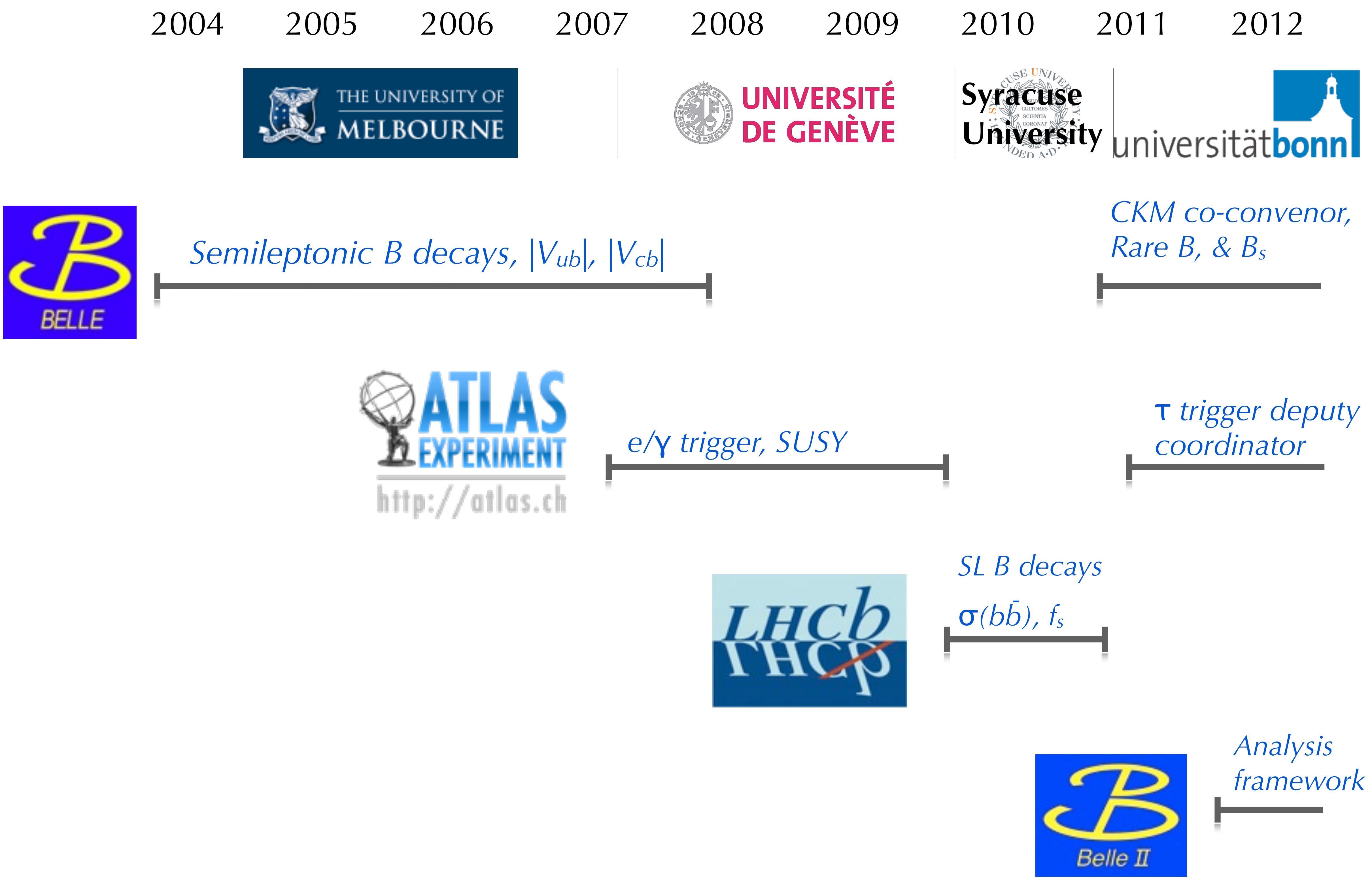
ICHEP
July 10, 2012

Tree Ferns, Healesville

Thank you to my colleagues who worked with me on many of the measurements in this talk, particularly from ***Belle, LHCb, Heavy Flavour Averaging Group***

universität**bonn**

About me



2004 2005 2006 2007 2008 2009 2010 2011 2012

THE UNIVERSITY OF MELBOURNE

UNIVERSITÉ DE GENÈVE

Syracuse University

universitätbonn

BELLE

Semileptonic B decays, $|V_{ub}|$, $|V_{cb}|$

CKM co-convenor,
Rare B, & B_s

ATLAS EXPERIMENT http://atlas.ch

e/γ trigger, SUSY

τ trigger deputy coordinator

LHCb

SL B decays

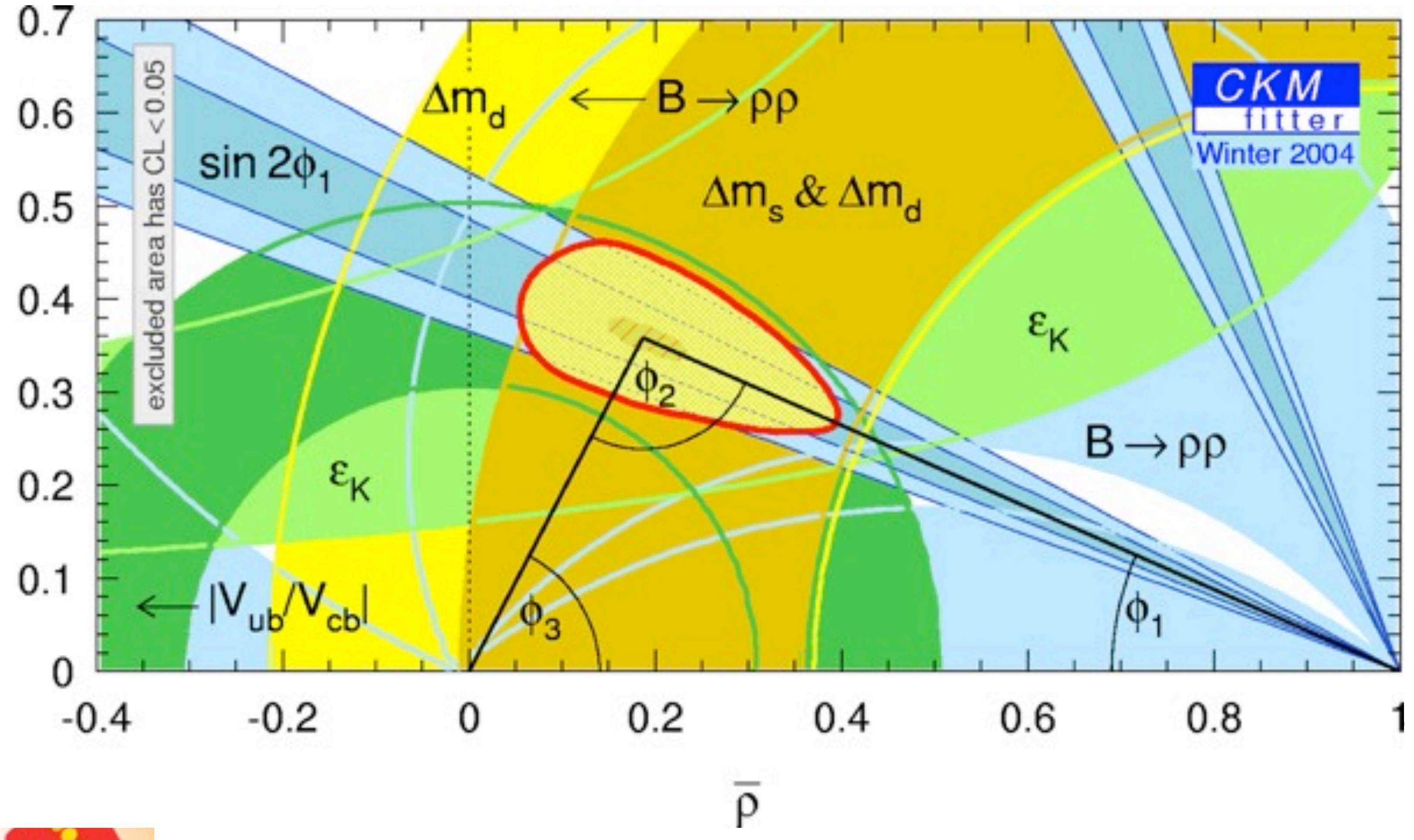
$\sigma(b\bar{b})$, f_s

Belle II

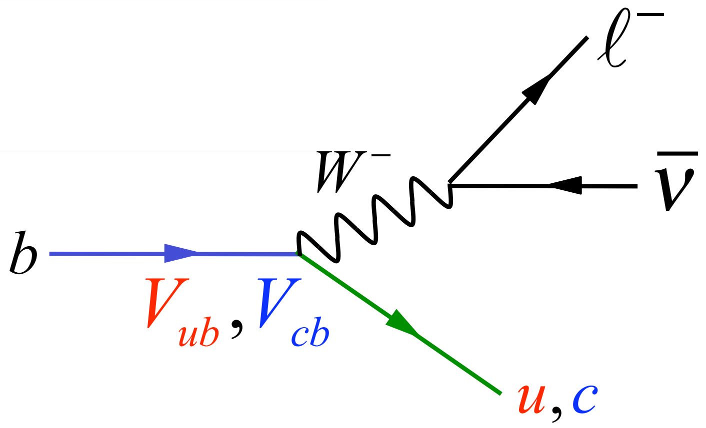
Analysis framework

$|V_{cb}|$, $|V_{ub}|$ and the Unitarity Triangle

- New physics searches in the flavour sector require precise and over-constraining measurements of the sides and angles of the **U**nitarity **T**riangle.
- Must measure CKM matrix elements, fundamental parameters of the Standard Model and cannot be predicted.
- $|V_{cb}|$ and $|V_{ub}|$ have a special role in the UT
  - Accessible from Tree Level processes.
  - Free of **N**ew **P**hysics in loops



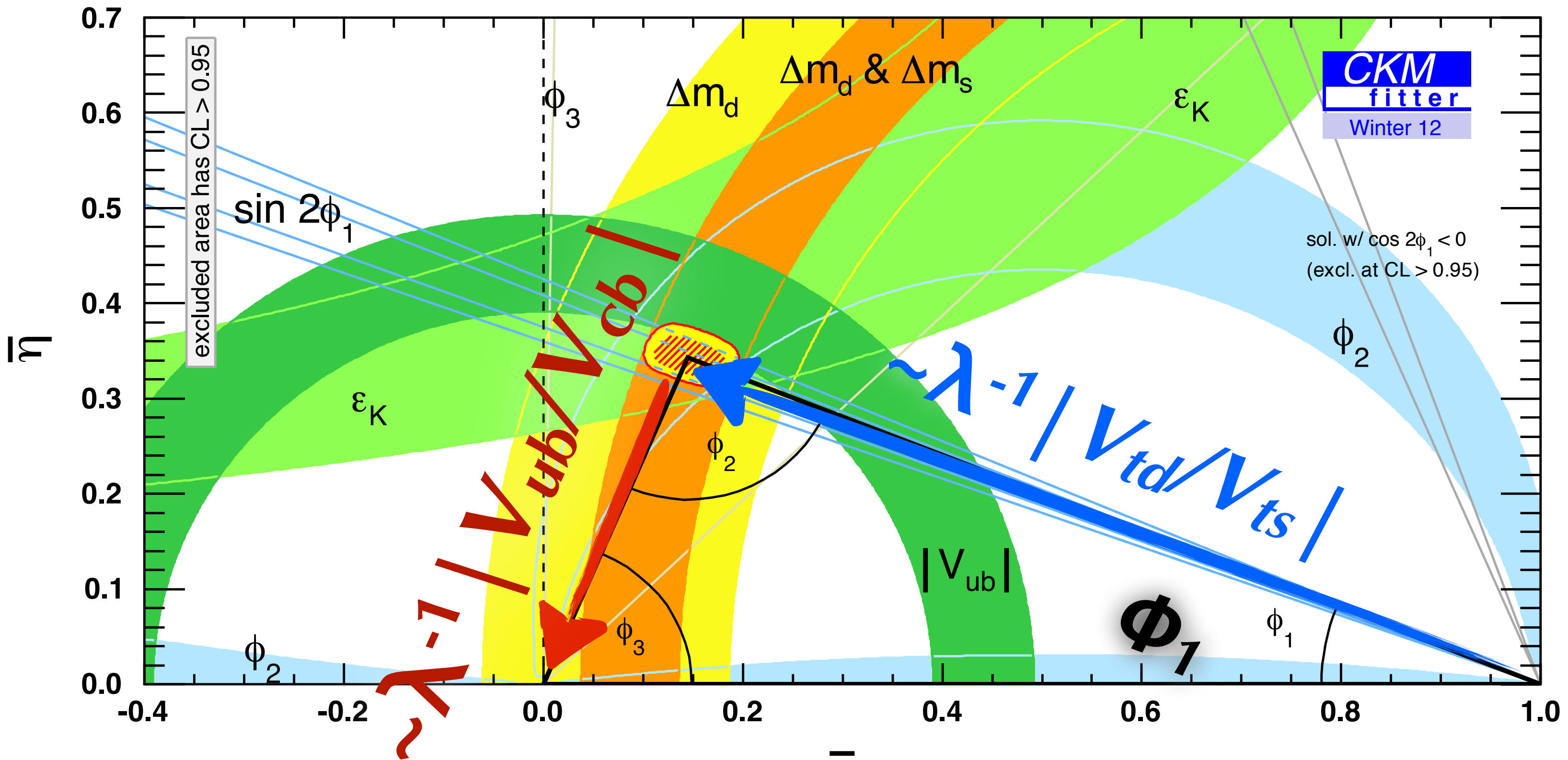
$$\Gamma_x \equiv \Gamma(b \rightarrow x\ell\nu) \propto |V_{xb}|^2$$



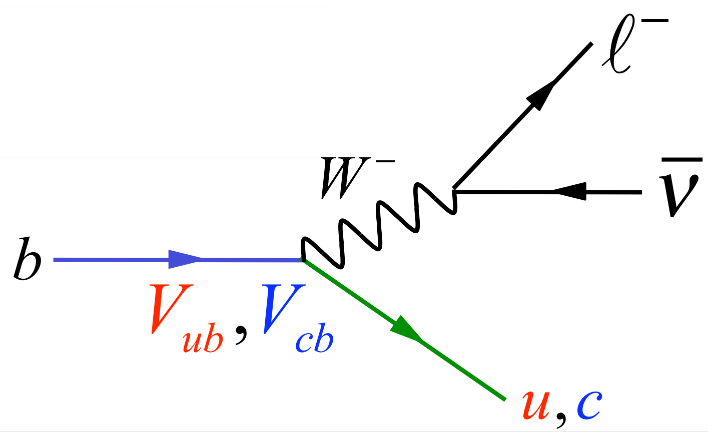
2004	PDG	Prec.
$\lvert V_{td}/V_{ts}\rvert$	<0.25	
Φ_1	(23.5±2.1)	9%
$\lvert V_{ub}/V_{cb}\rvert$ inclusive	0.113 ± 0.21	18%

$|V_{cb}|$, $|V_{ub}|$ and the Unitarity Triangle

- New physics searches in the flavour sector require precise and over-constraining measurements of the sides and angles of the **U**nitarity **T**riangle.
- Must measure CKM matrix elements, fundamental parameters of the Standard Model and cannot be predicted.
- $|V_{cb}|$ and $|V_{ub}|$ have a special role in the UT
  - Accessible from Tree Level processes.
  - Free of **N**ew **P**hysics in loops



$$\Gamma_x \equiv \Gamma(b \to x\ell\nu) \propto |V_{xb}|^2$$

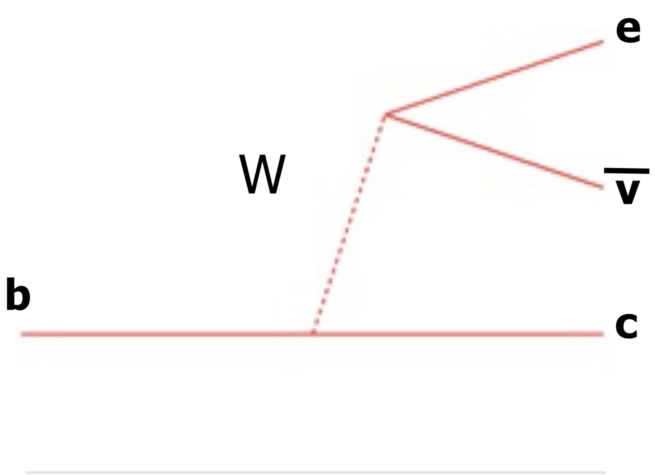


2012	PDG	Prec.
$\lvert V_{td}/V_{ts}\rvert$	0.214±0.006	0.5%
Φ_1	(21.4±0.8)	3.7%
$\lvert V_{ub}/V_{cb}\rvert$ inclusive	0.097±0.007	7.0%

Semileptonic B decays

tree level, short distance:

$b \rightarrow c\, e\, \nu$

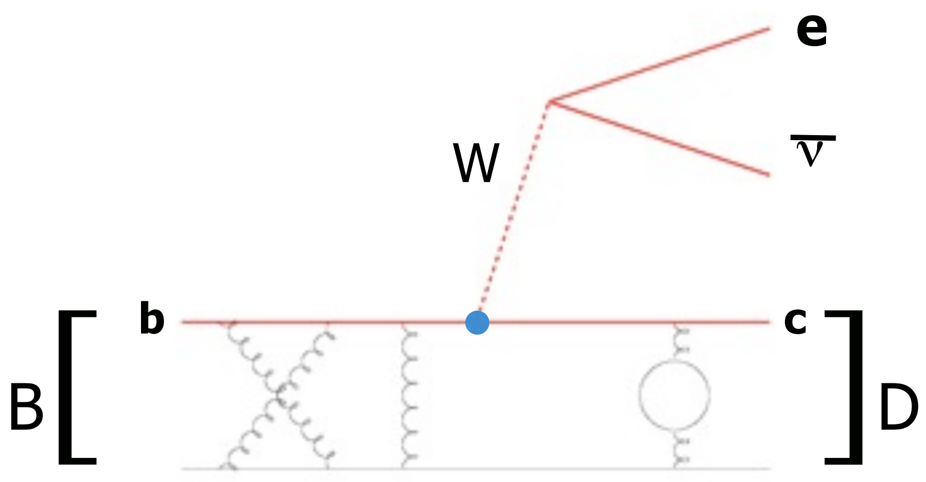


Decay properties depend directly on $|V_{cb}|$ & $|V_{ub}|$ and m_b in the perturbative regime (α_s^n).

Semileptonic B decays

tree level, short distance:

B → D e ν



+ long distance:

Decay properties depend directly on $|V_{cb}|$ & $|V_{ub}|$ and m_b in the perturbative regime (α_s^n).

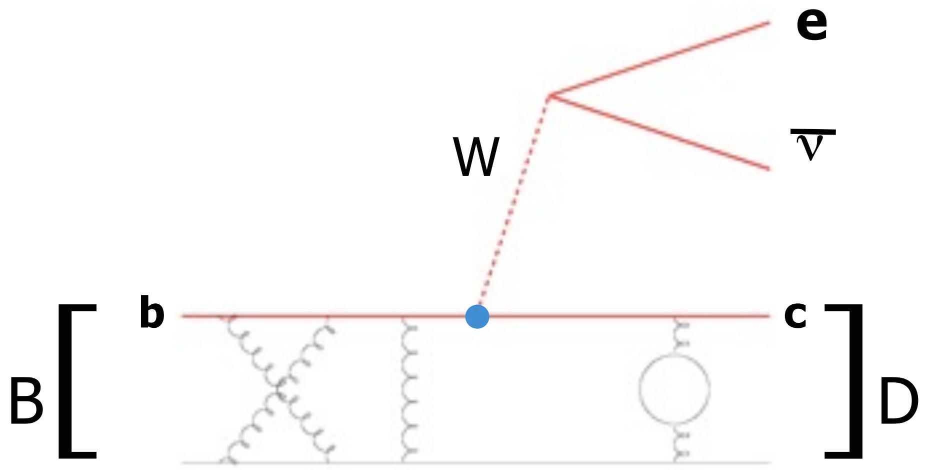
But quarks are bound by soft gluons: non-perturbative

long distance interactions of *b* quark with the light quark in the *B* meson.

Semileptonic B decays

tree level, short distance:

$B \to D e \nu$



+ long distance:

Decay properties depend directly on $|V_{cb}|$ & $|V_{ub}|$ and m_b in the perturbative regime (α_s^n).

But quarks are bound by soft gluons: non-perturbative

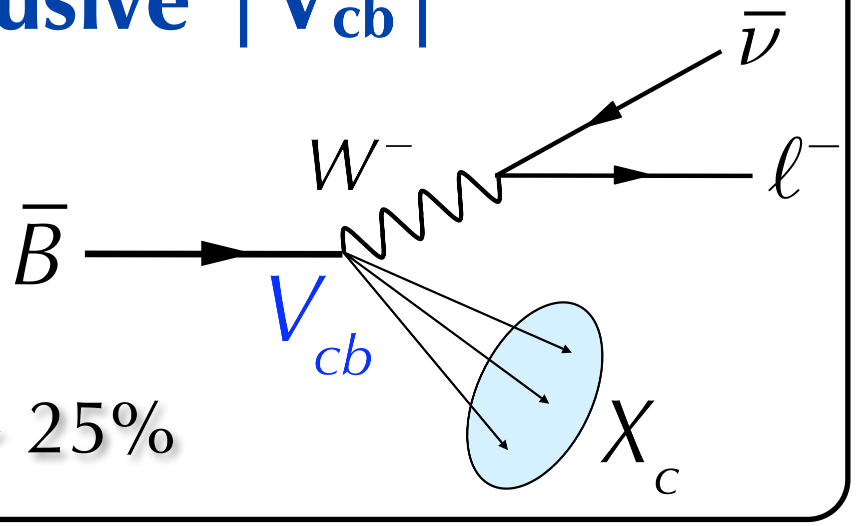
long distance interactions of *b* quark with the light quark in the *B* meson.

Heavy Quark Effective Theory: Precise tools to describe dynamics of the *b* quark

Departure from the heavy quark symmetry can be expressed as $(\Lambda_{QCD}/m_Q)^n$ corrections

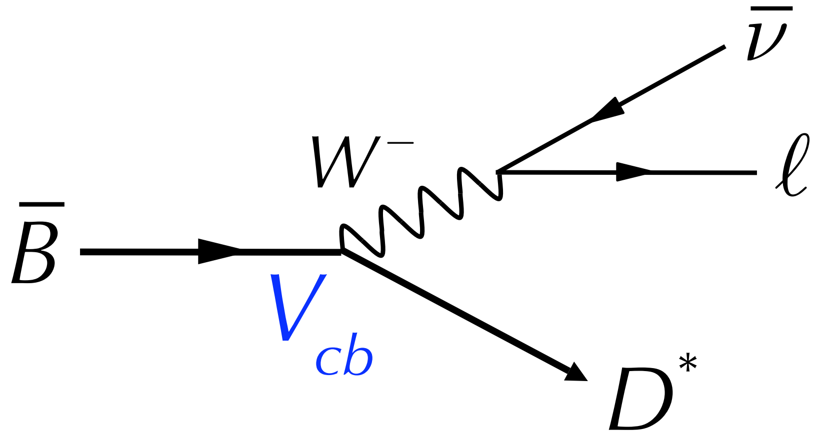
Inclusive versus Exclusive

Inclusive $|V_{cb}|$

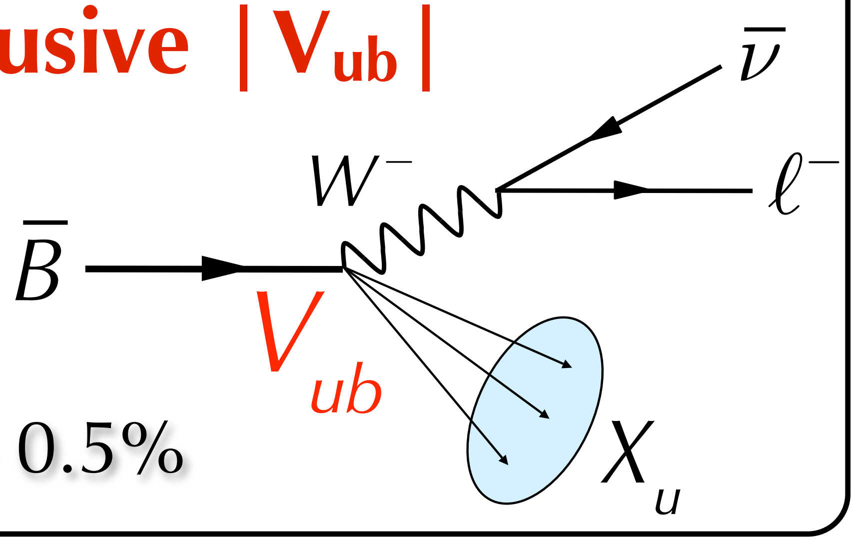


BF~ 25%

Exclusive $|V_{cb}|$

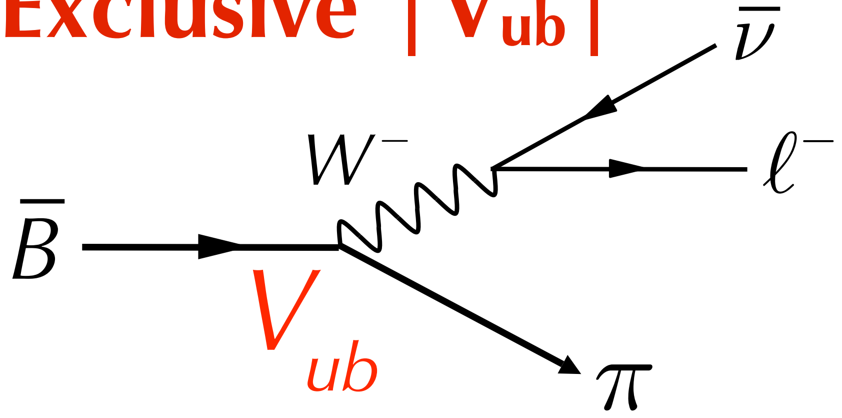


Inclusive $|V_{ub}|$



BF~ 0.5%

Exclusive $|V_{ub}|$



Two **Complementary** approaches using **different** theoretical tools, and **different** experimental signatures.

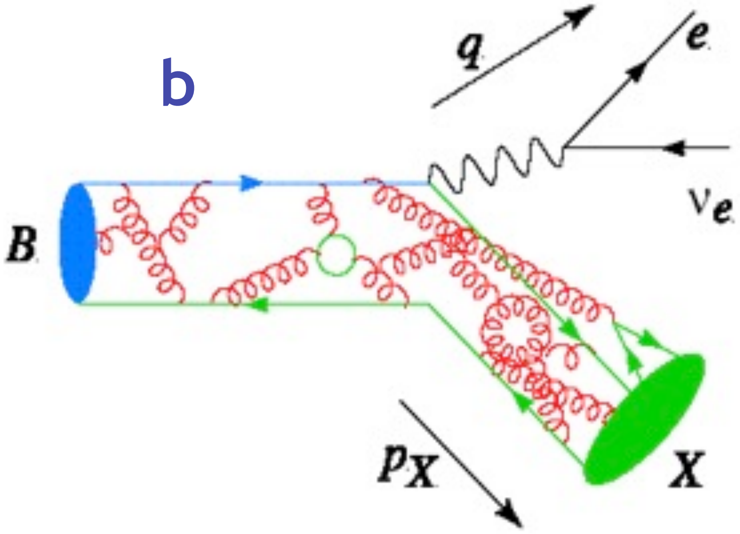
→Crucial independent consistency check.

$$|\mathbf{V}_{\mathbf{cb}}|$$

Theoretical Tools for Inclusive Semileptonic *b* Decays

Operator **P**roduction **E**xpansion predicts the total rate as:

$$\Gamma_{SL} = \underbrace{|V_{cb}|^2 \frac{G_F^2 m_b^5}{192\pi^3}(1+A_{EW})}_{\text{Free quark decay}} \underbrace{A_{pert}}_{\text{QCD Pert.}} \times \underbrace{[c_0(r) + \frac{0}{m_b} + c_2(r, \frac{\mu_\pi^2}{m_b^2}, \frac{\mu_G^2}{m_b^2}) + c_3(r, \frac{\rho_D^3}{m_b^3}, \frac{\rho_{LS}^3}{m_b^3}) + \ldots]}_{\text{Non-perturbative suppressed by } 1/m_b^2}$$



Non perturbative parameters need to be derived from **data.**

m_b ,m_c: renormalisation scheme dependent quantities **Large error from m_b^5**	
Λ_{QCD}^2/m_b^2	**$\mu_\pi^2(-\lambda_1)$ - kinetic energy of b quark,** **$\mu_G^2(\lambda_2)$ - chromomagnetic coupling**
Λ_{QCD}^3/m_b^3	**ρ_D, ρ_{LS} (ρ_1,$\tau_{1\text{-}3}$) (Spin-orbit, Darwin terms)**

Measure ***moments*** integrated over large phase space to allow assumption of ***quark-hadron*** duality

$|V_{cb}|$ from Inclusive $B \rightarrow X_c l^+ \nu$

- **λ_1** and **m_b**, and thus **$|V_{cb}|$** from "moments" in semileptonic decays

$$\langle M_x^n \rangle |_{E\ell > E_0} = \tau_B \int_{E_0} M_x^n d\Gamma = f(E_0, \underbrace{m_b, m_c}_{\text{quark masses}}, \underbrace{\mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3}_{\text{Non-perturbative parameters}})$$

Cut-off

Moments can be calculated for cut-off in E_l

- Need high resolution access to *B* rest frame, unfolded observables:

  Hadronic invariant mass

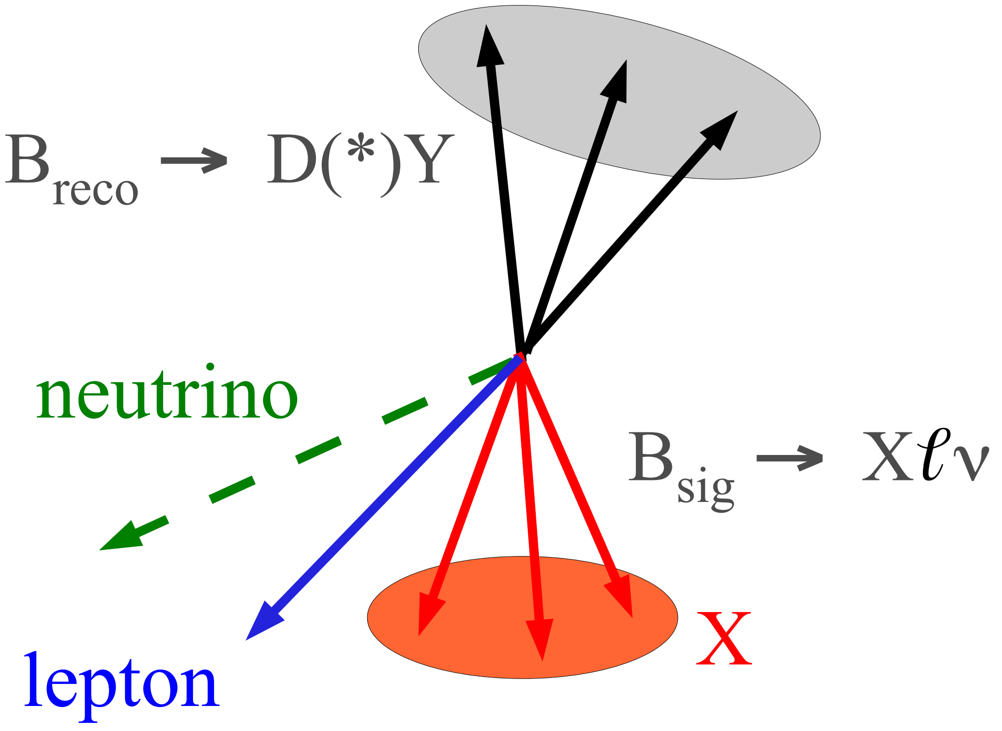
  Lepton momentum

- Use hadronic tag $B_{tag} \rightarrow D^{(*)}Y$ ($Y = n\pi, m\pi^0, pK_s, qK$), to fully constrain the signal side *B* properties:

  →tag - charge - momentum

  New, improved hadronic tag method introduced by Belle in 2012 (see Y. Yook)

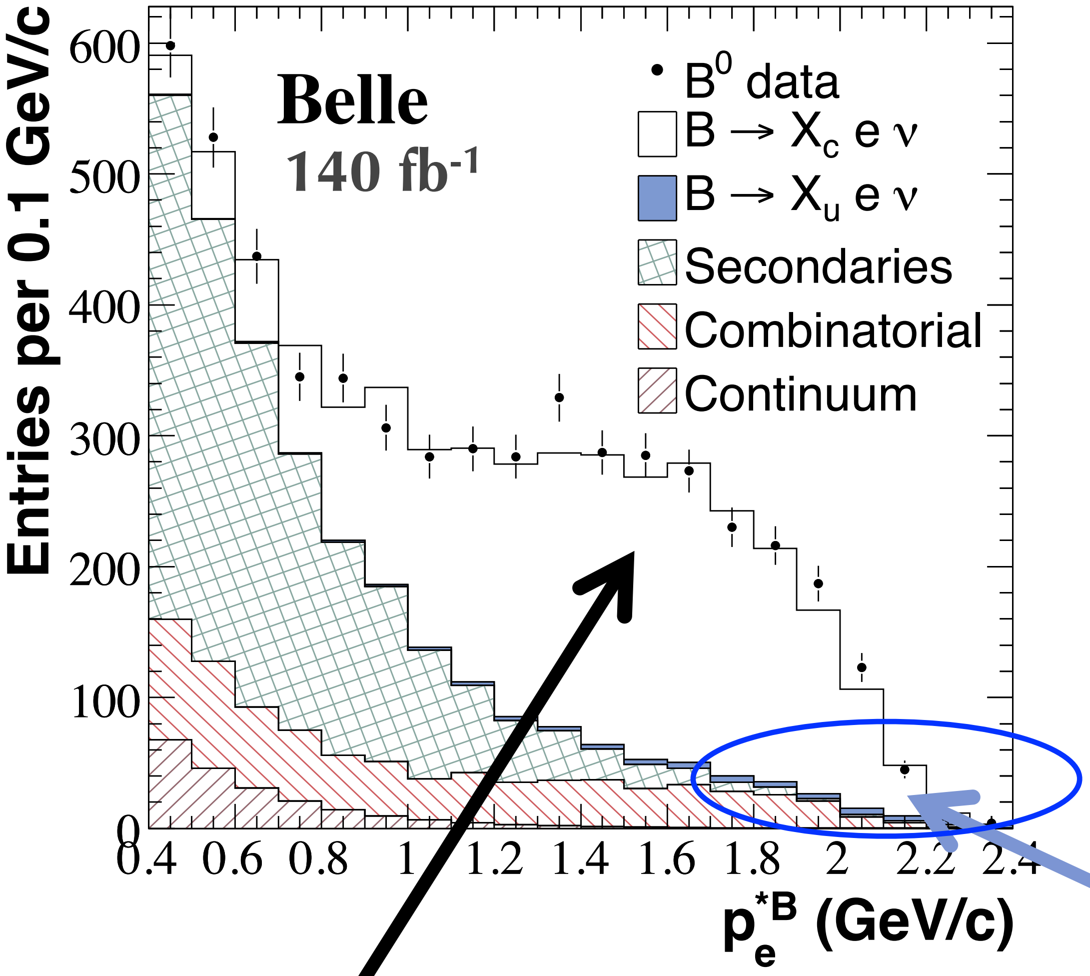
  Used for many neutrino mode analyses, even for **rare $B \rightarrow l^+ \nu$!**



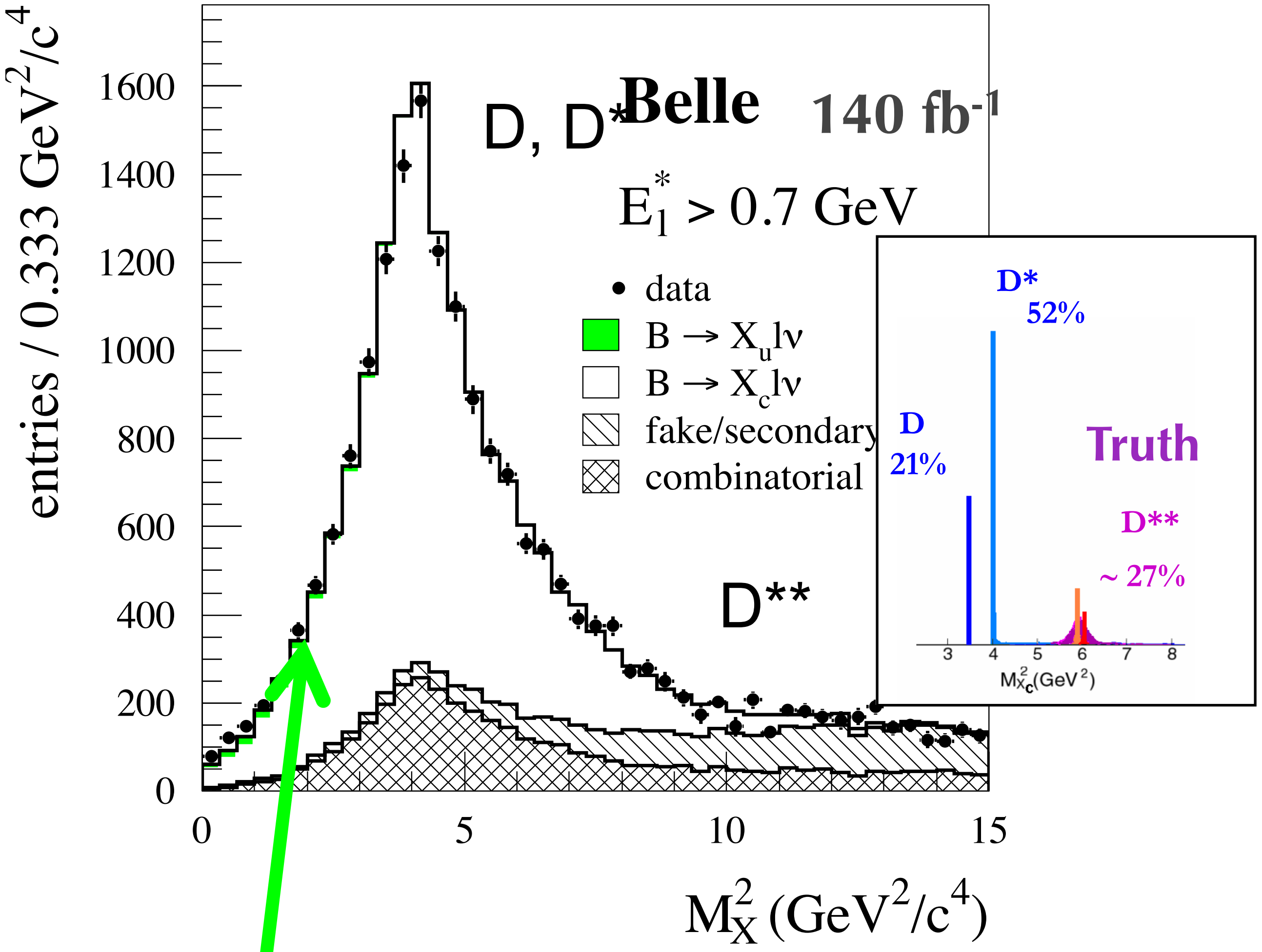
$|V_{cb}|$ Determination

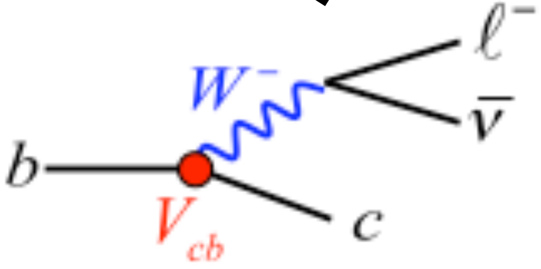
- Inclusive semileptonic decays recoiling against fully reconstructed hadronic tagged ***B***s
- *Unfold* measured spectra & apply *radiative* corrections to obtain true distributions

Lepton momentum

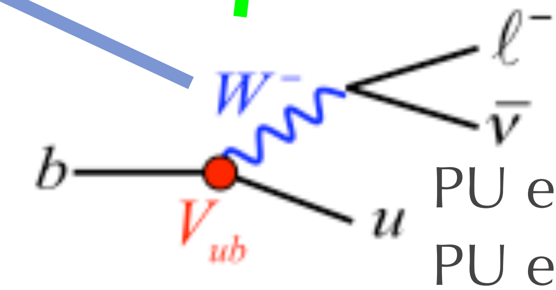


Hadron mass





$$\frac{\Gamma(b \to u\ell\bar{\nu})}{\Gamma(b \to c\ell\bar{\nu})} \approx \frac{|V_{ub}|^2}{|V_{cb}|^2} \approx \frac{1}{50}$$

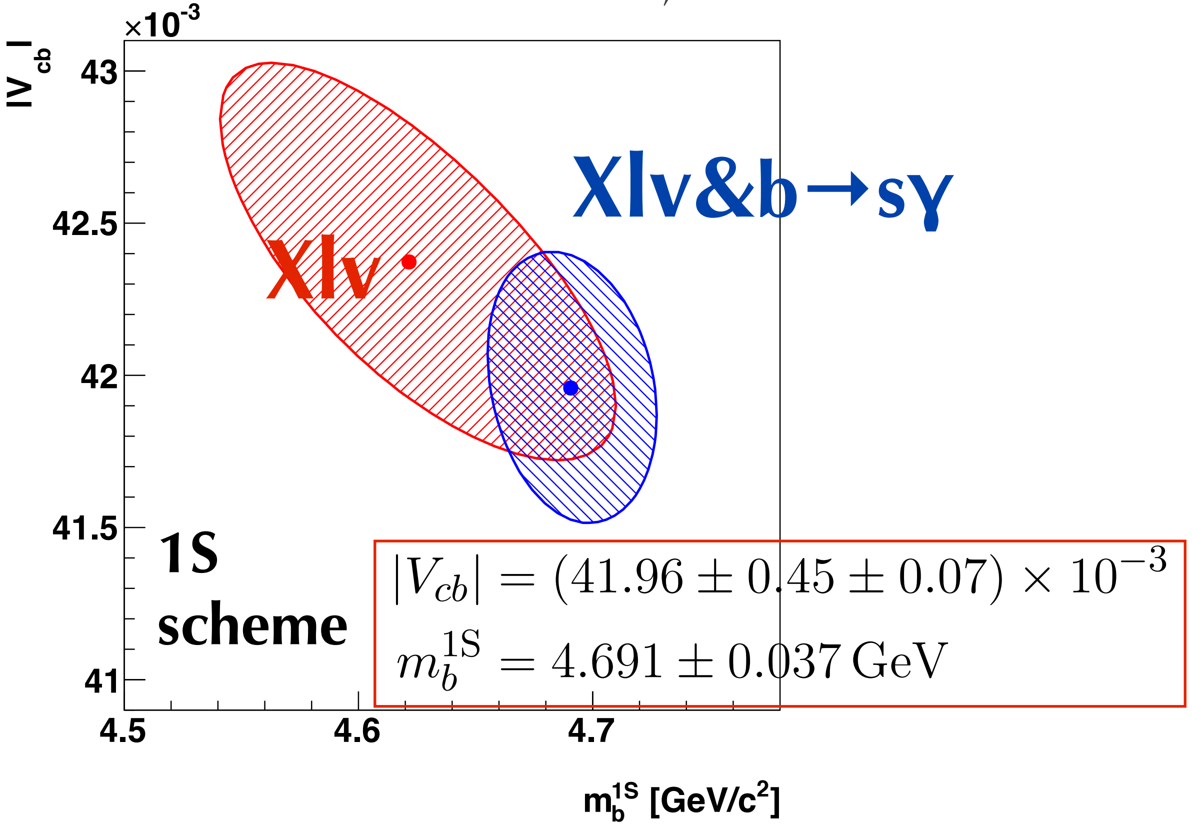


PU et al., PRD.75.032005 (2007)
PU et al., PRD.75.032001 (2007)

$|V_{cb}|$ Global Fit to $B\rightarrow X_c l\nu$ & $B\rightarrow X_s\gamma$

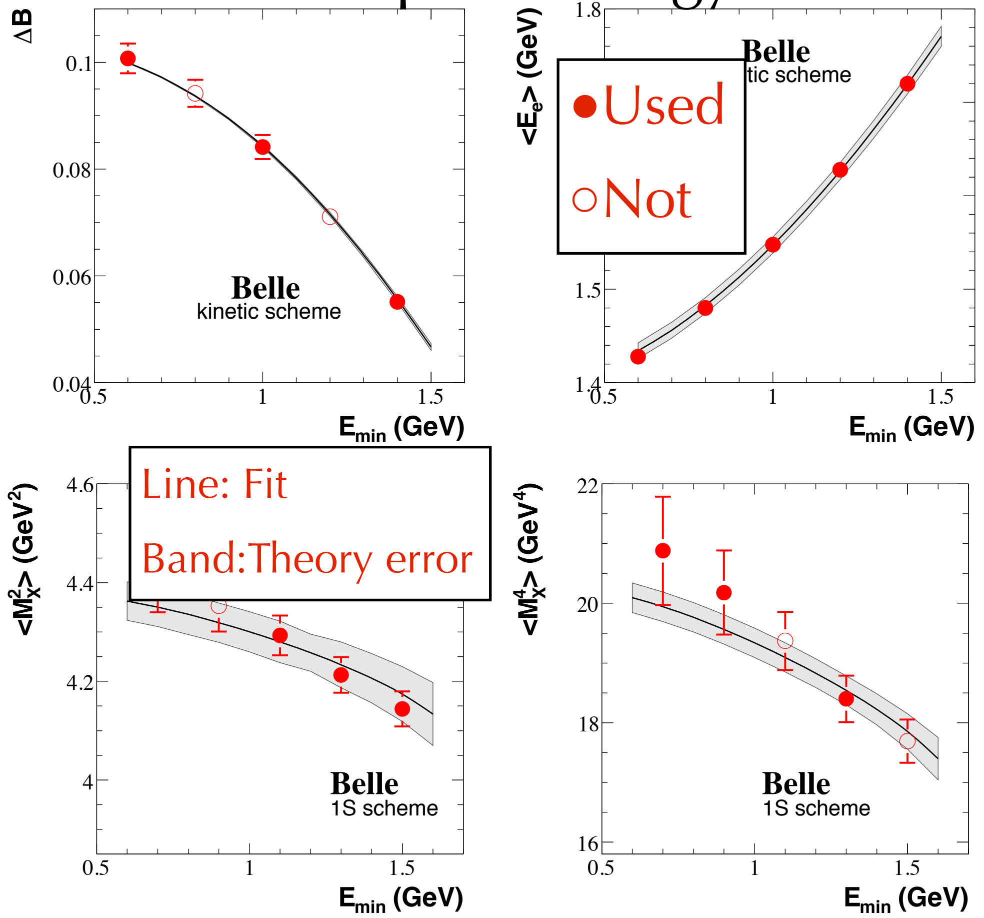
- First fit to **multiple** schemes, with **consistent** results!
- **Tested OPE** parameters used for $|V_{ub}|$
- **Consistency between $X_c l\nu$ and $X_s\gamma$ added confidence to the theory**
  - **$\Delta|V_{cb}|/|V_{cb}|$~1-2%** dominated by theory uncertainties.

HFAG EOF2011/PDG 2012, PU in arXiv:1207:1158

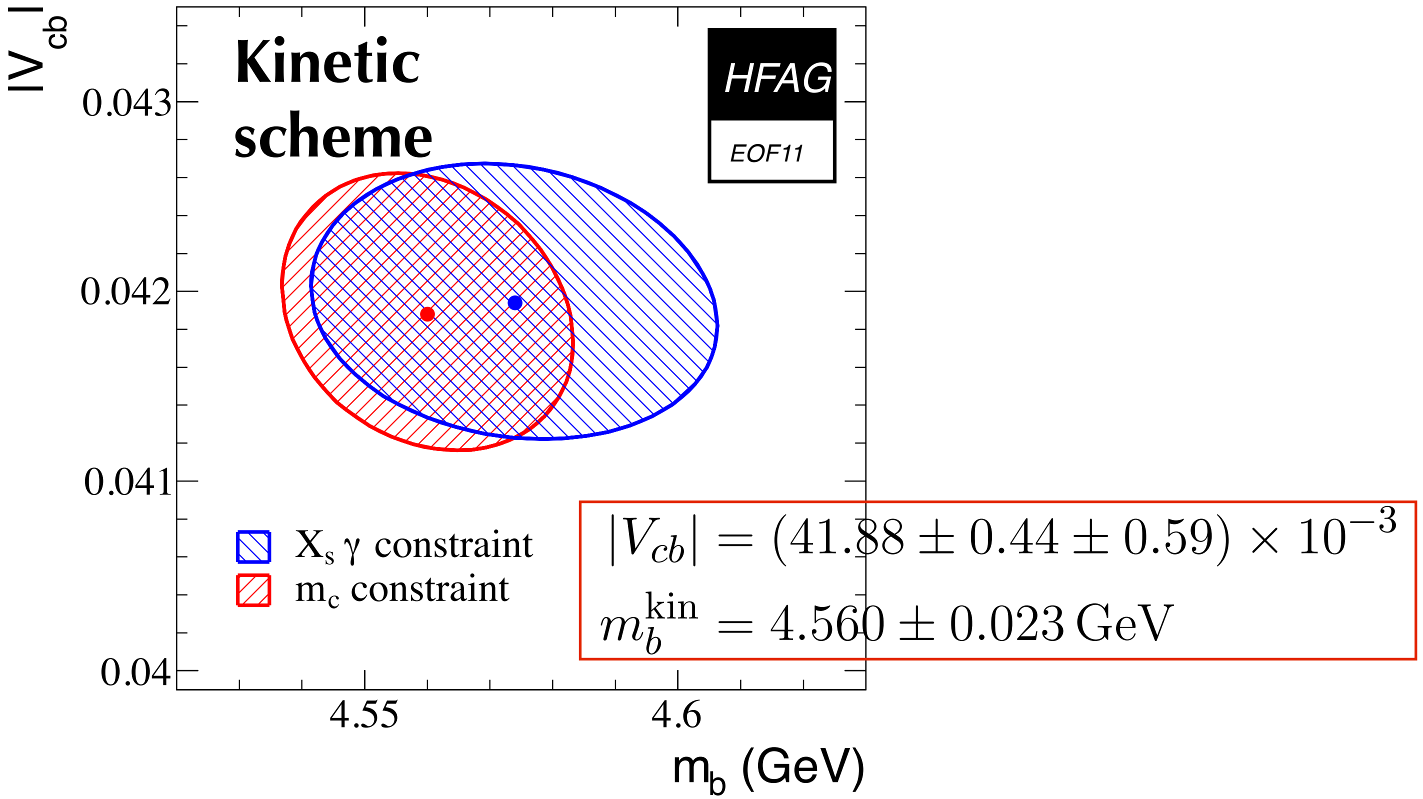


$|V_{cb}| = (41.96 \pm 0.45 \pm 0.07) \times 10^{-3}$
$m_b^{1S} = 4.691 \pm 0.037\,\text{GeV}$

Measure **moments** as functions of Minimum lepton energy threshold, **E_{min}**



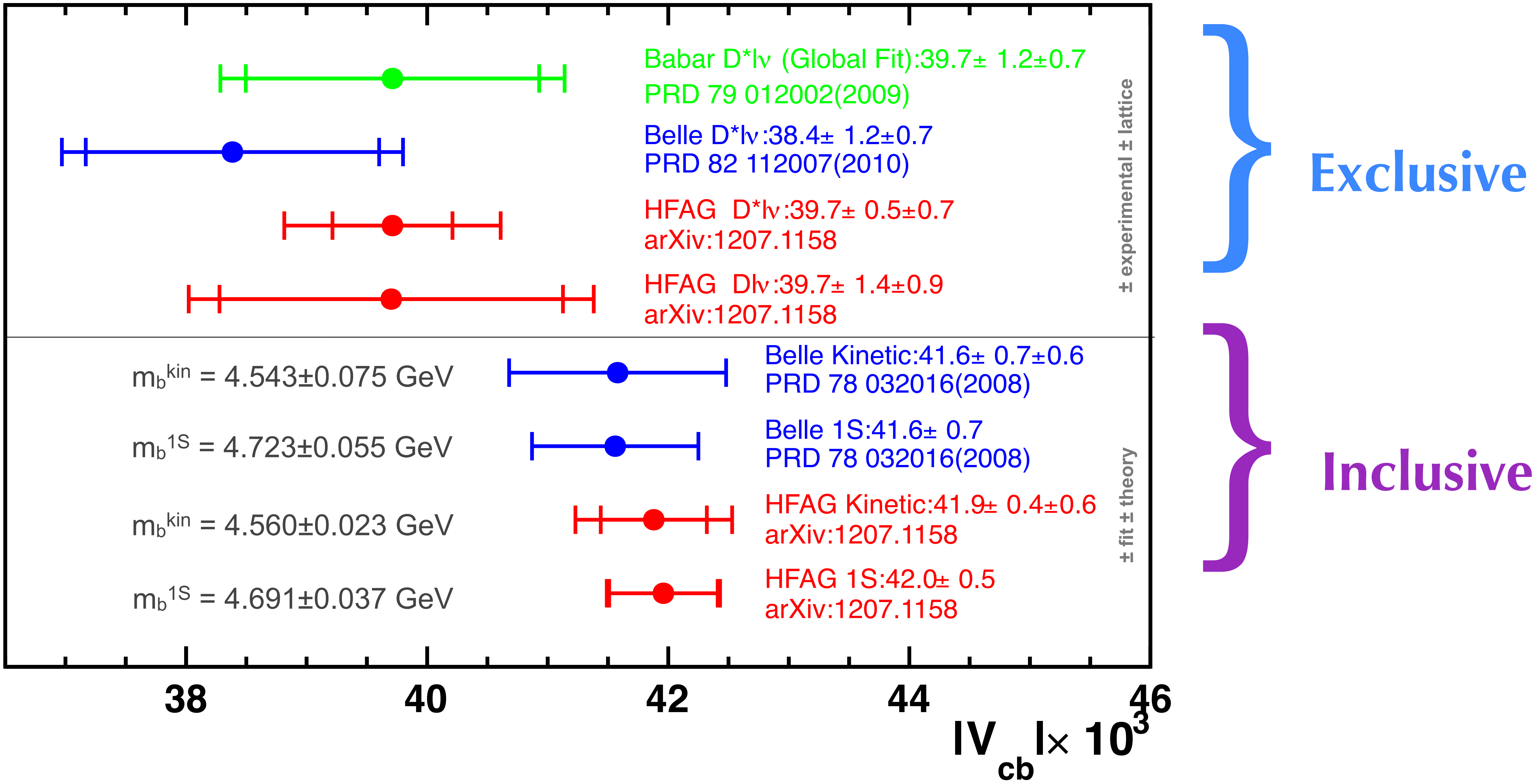
PU et. al. , PRD 78, 032016 (2008)



$|V_{cb}| = (41.88 \pm 0.44 \pm 0.59) \times 10^{-3}$
$m_b^{kin} = 4.560 \pm 0.023\,\text{GeV}$

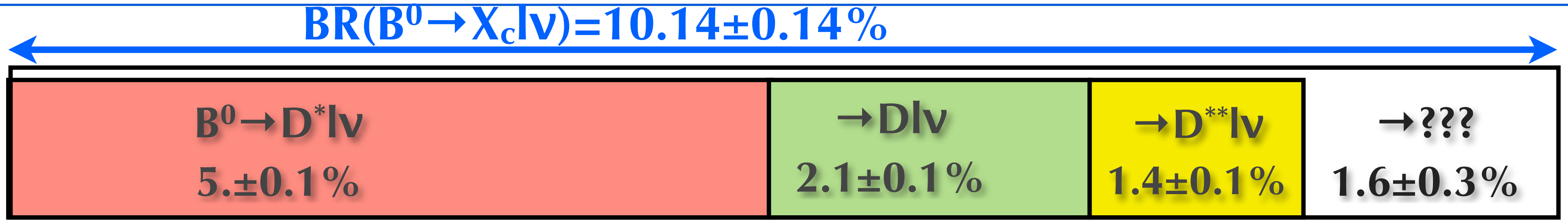
$|V_{cb}|$ Summary

- Small but persistent discrepancy, up to ~2.4σ, between exclusive and inclusive.
  - May not be (only) due to differences in theory/normalisation approaches.
- ΔExclusive~2%, ΔInclusive~1-2% (↓from 4% in 2004)

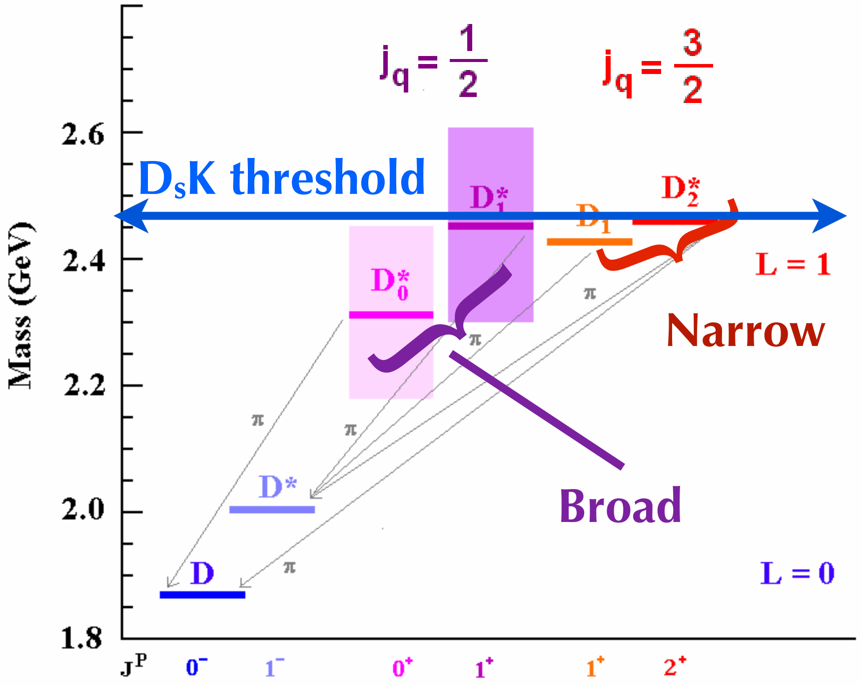


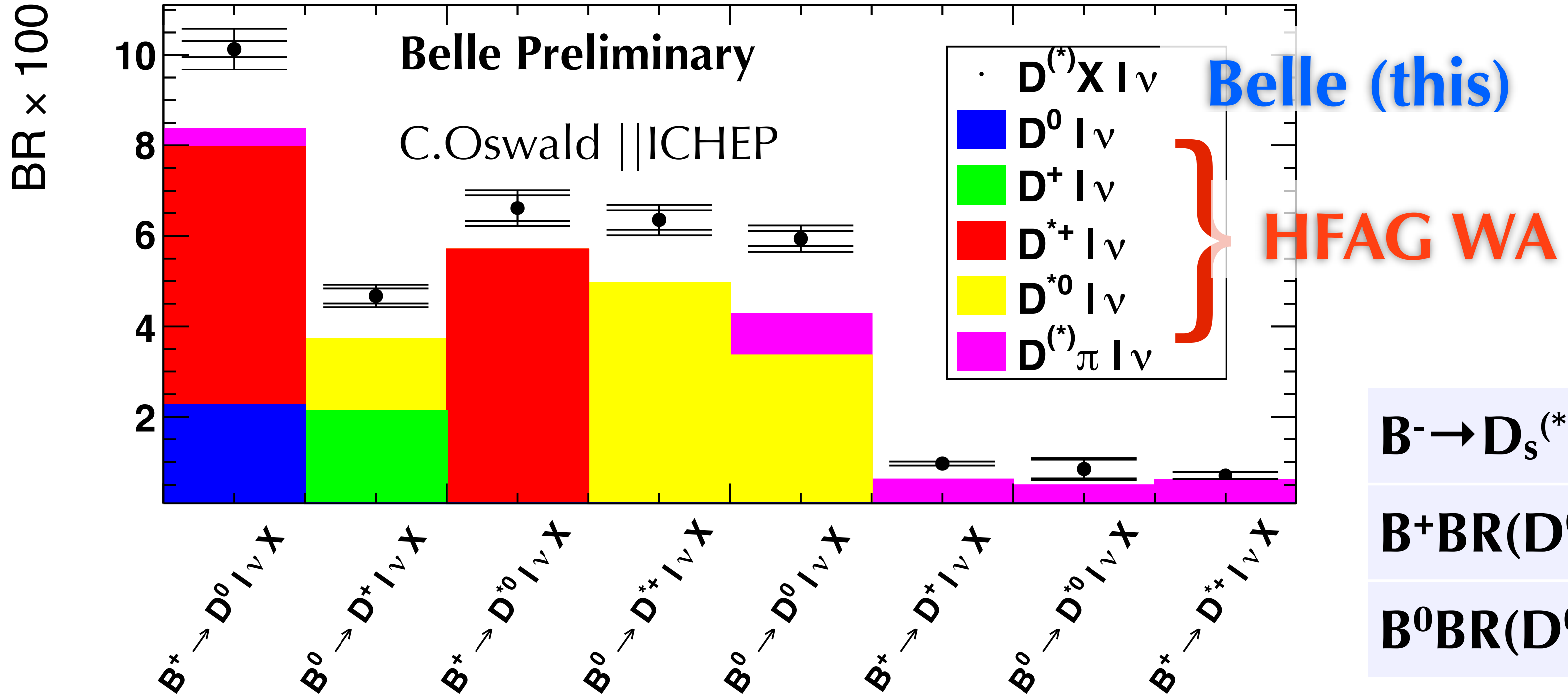
Inclusive-Exclusive Saturation Problem

- ***Puzzle:***



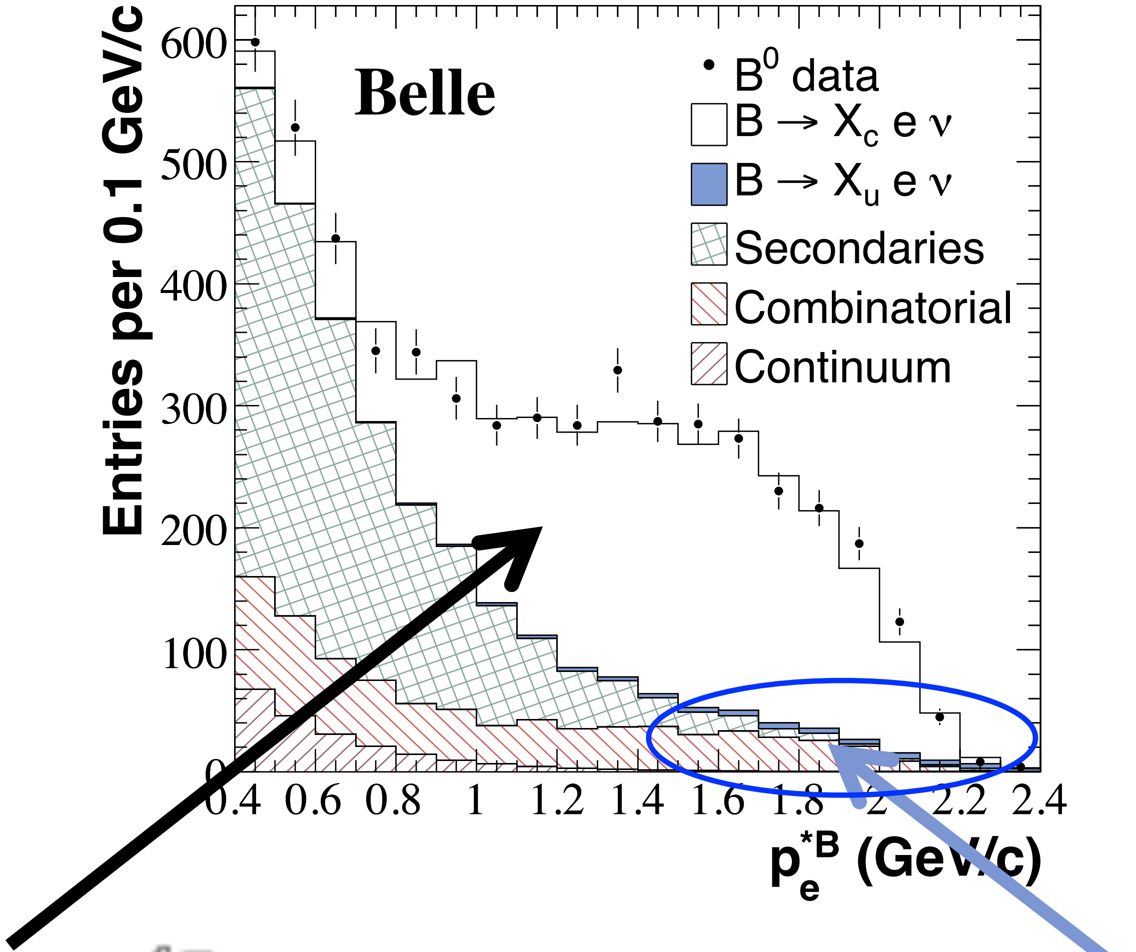
- *Measured* sum of exclusive mode BR's ≠ inclusive
  - ***What is it?*** broad resonances, unmeasured D^{**} decay modes (BR's unknown!) neutral transitions (π^0, η), *Difficult to directly measure!*
    - Affects exclusive $|V_{cb}|$& $D^{(*)}\tau^+\nu$! (S.Stone, Monday)
  - Instead estimate cross feed into $|V_{cb}|$ & $D^{(*)}\tau^+\nu$ measurements using ***$B \to D^{(*)} l\nu X$*** BRs, measured *first* at ICHEP. Should shed some light on the problems.

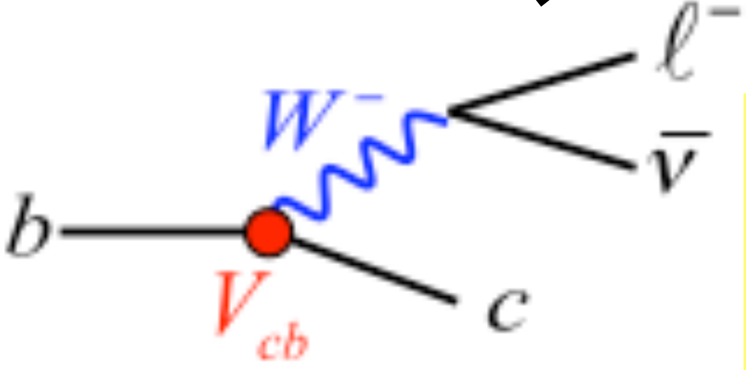




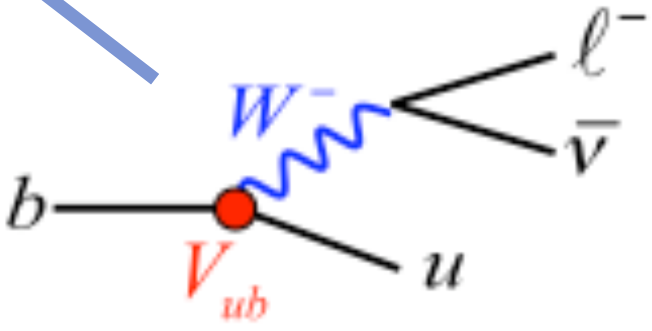
$B^- \to D_s^{(*)} K l\nu$	$(0.59\pm0.12\pm0.15)10^{-3}$
$B^+ BR(D^{0+} l\nu X)/BR(X l\nu)$	$1.027\pm0.018_{stat}\pm0.042_{sys}$
$B^0 BR(D^{0+} l\nu X)/BR(X l\nu)$	$1.010\pm0.015_{stat}\pm0.041_{sys}$

$|V_{ub}|$





$$\frac{\Gamma(b \to u\ell\bar{\nu})}{\Gamma(b \to c\ell\bar{\nu})} \approx \frac{|V_{ub}|^2}{|V_{cb}|^2} \approx \frac{1}{50}$$



$|V_{ub}|$ from Inclusive $B \to X_u l \nu$

- Total rate can't be measured! Too much $\mathbf{B \to X_c l \nu}$ background.
- Remove $\boldsymbol{b \to c l \nu}$: **BUT** lose a part of the $\mathbf{b \to u l \nu}$ signal.

Measure

$$\Gamma(B \to X_u \ell \nu) \times f_C = |V_{ub}|^2 \zeta_C$$

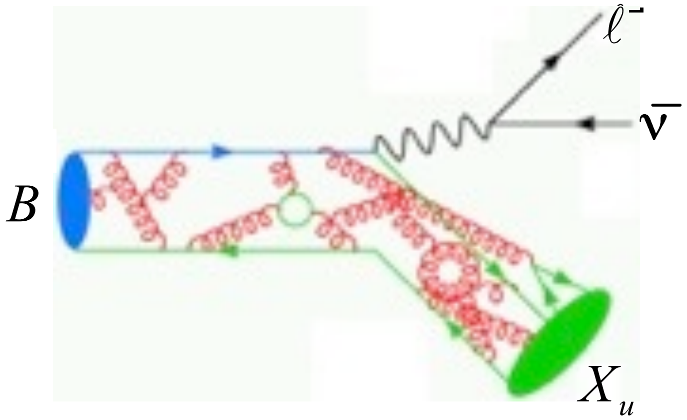
Fraction of the signal that passes the cut
→ corrected for **QCD**, **motion** of ***b***-quark

Cut-dependent constant predicted by theory

Problems:

Restriction of phase space **creates complication, need models, many debates over which to use**

$\Gamma \sim |V_{ub}|^2 m_b^5$, but partial rates $\Delta\Gamma \sim |V_{ub}|^2 m_b^{10}$

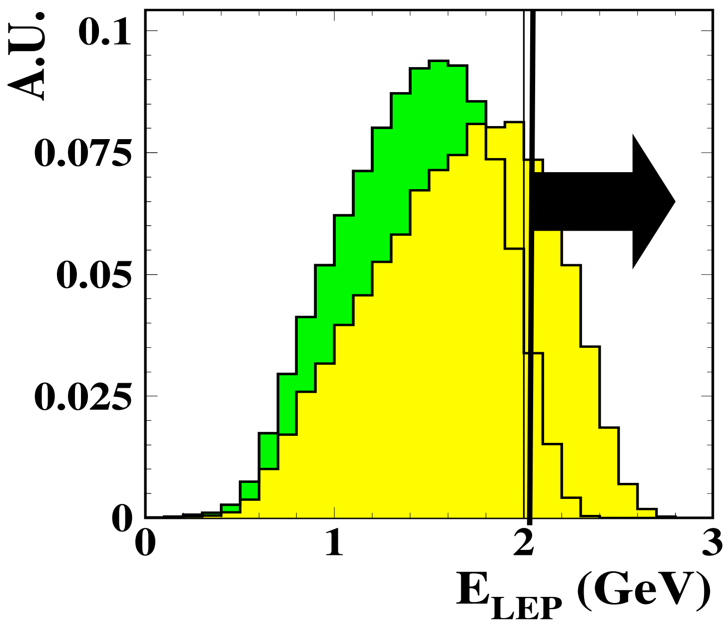


Selecting b→ulν

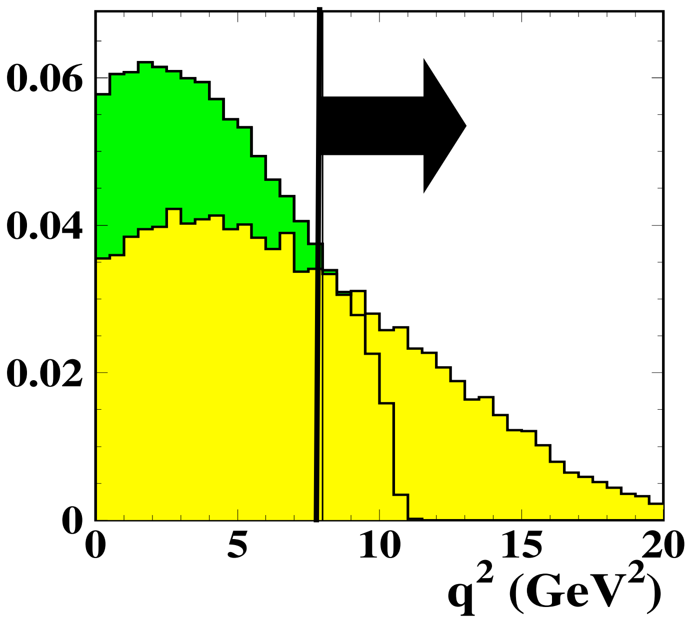
- Need a large fraction of the rate, ***f_c***, to control theory uncertainty.

Use hadronic $B_{tag}\rightarrow D^{(*)}Y$ to reduce combinatorial and precisely reconstruct m_X, q^2.

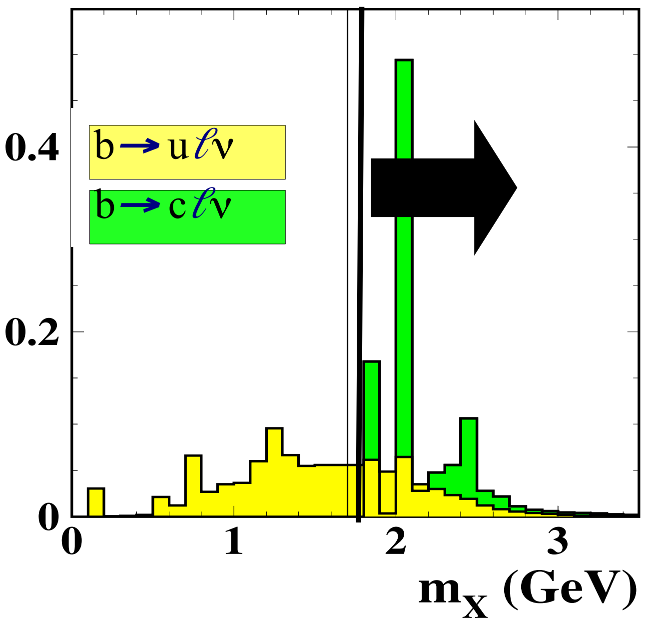
E_l = lepton energy



q^2 = lepton-neutrino mass squared



m_X = hadron system mass



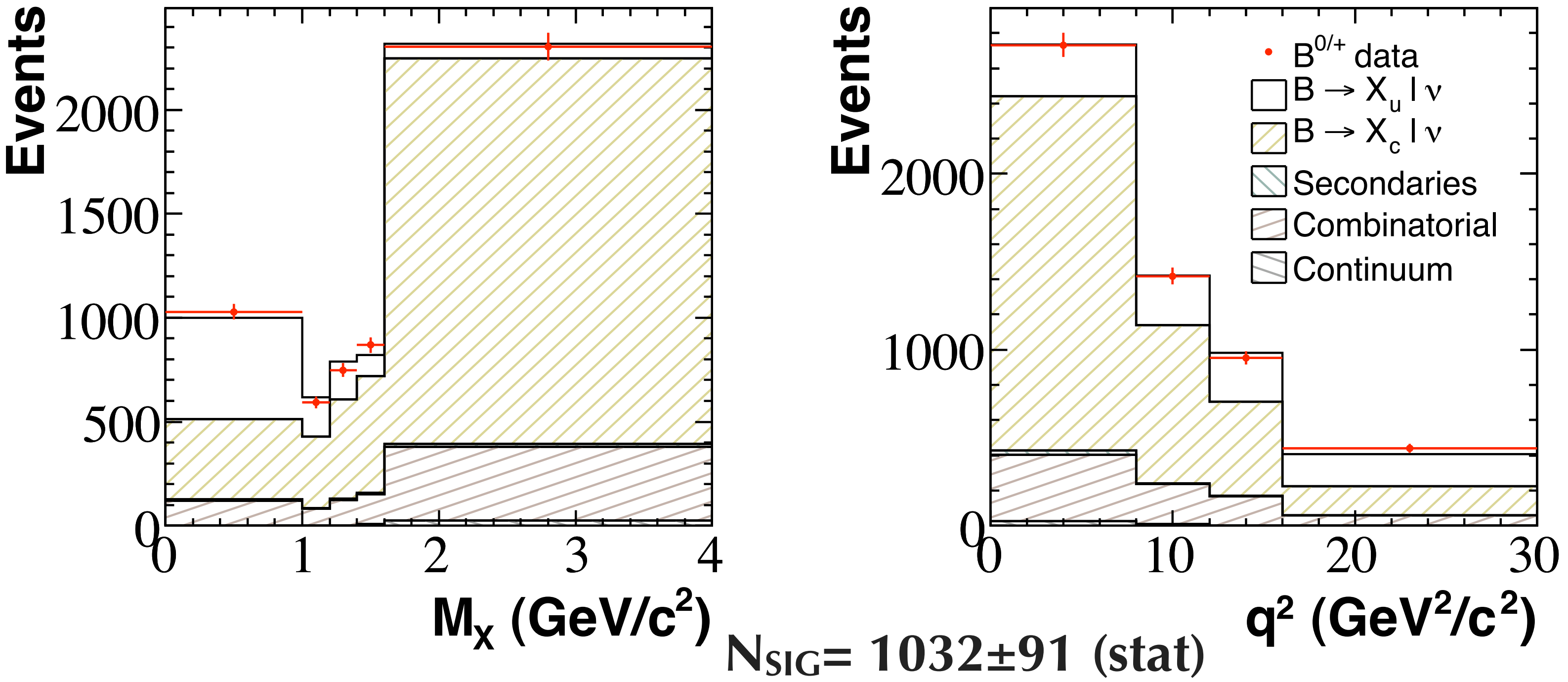
Experimental resolution leads to irreducible clν contamination

	E_{lep}>2 GeV	**q^2>8 GeV^2**	**M_X<1.7 GeV**
f_c	**25%**	**38%**	**65%**

Hadron Mass in Recoil (method)

2D fit in q2 Mx. (projections shown)

PU et al., PRL 104 2021801 (2010)

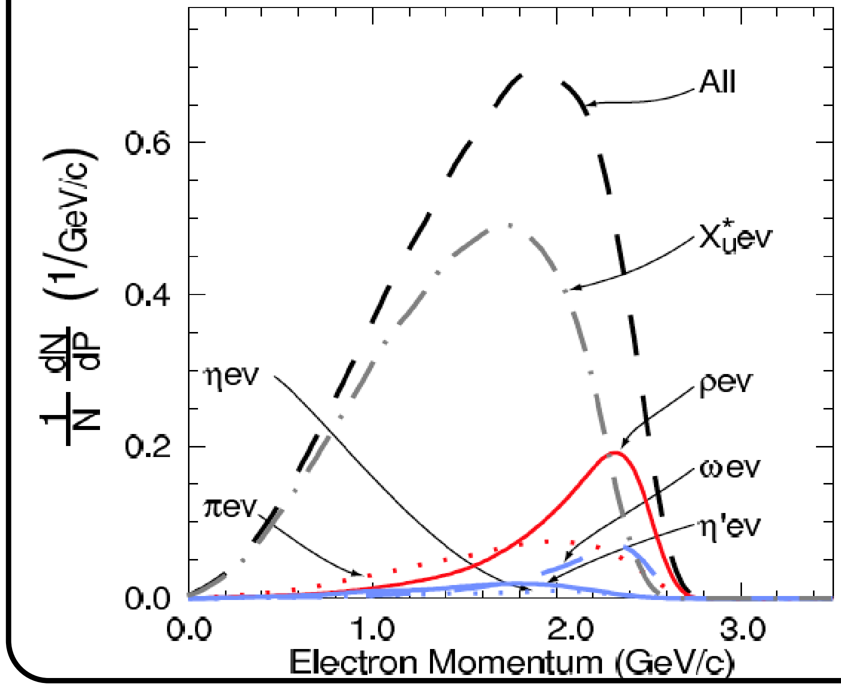


N_{SIG}= **1032±91** (stat)

- My solution: exploit non-linear correlations between kinematic, background & event variables to separate b→u and b→c.
  - Optimise for maximal kinematic phase space coverage:~90%!
  - BDT Efficiency: 22.2%.
    - first BDT in Belle

Errors	%
Det. & Comb.	4.8
B → Xu l v SF	3.6
B → h l v Excl	4.9
B → KK l v	1.5
B → clv backgrd.	1.7

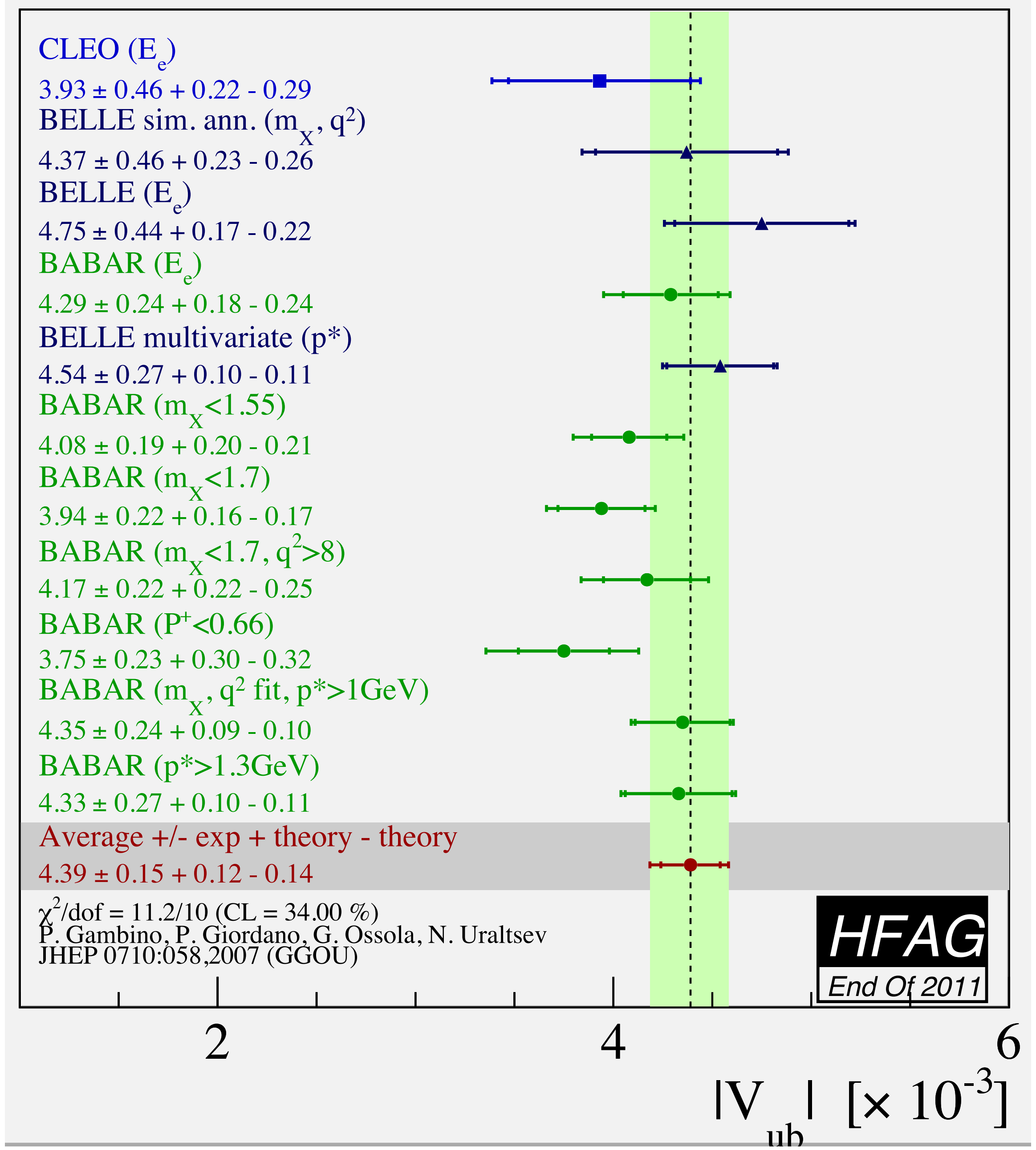
- B → Xu l v: Resonant and non-resonant contribution



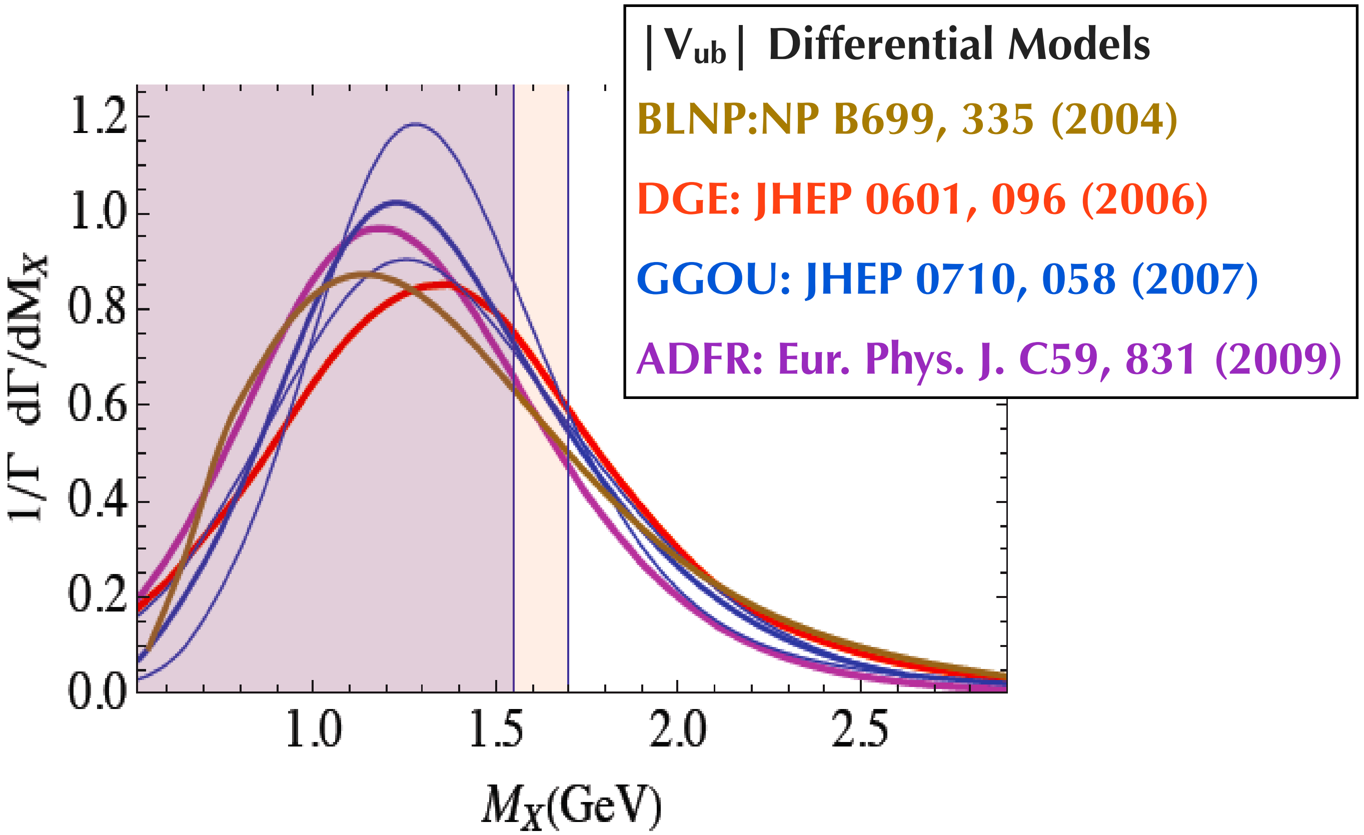
Belle: $\Delta BR(p^*_{lep}>1.0\mathrm{GeV}) = 1.96\ (1 \pm 0.09_{stat} \pm 0.08_{sys})\ 10^{-3}$

Inclusive $|V_{ub}|$

Use m_c, m_b, μ_π^2 from $B\to X_c l\nu$ and $B\to X_s\gamma$



- Agreement between experiments!
- **Theory:** Error **(5-7%)** dominated by m_c, m_b, μ_π^2
- **Experiment**: Error from $B\to\rho/\omega/\eta\, l\nu$, non-resonant. & high X_u mass region (**unmeasured)**



4 approaches:

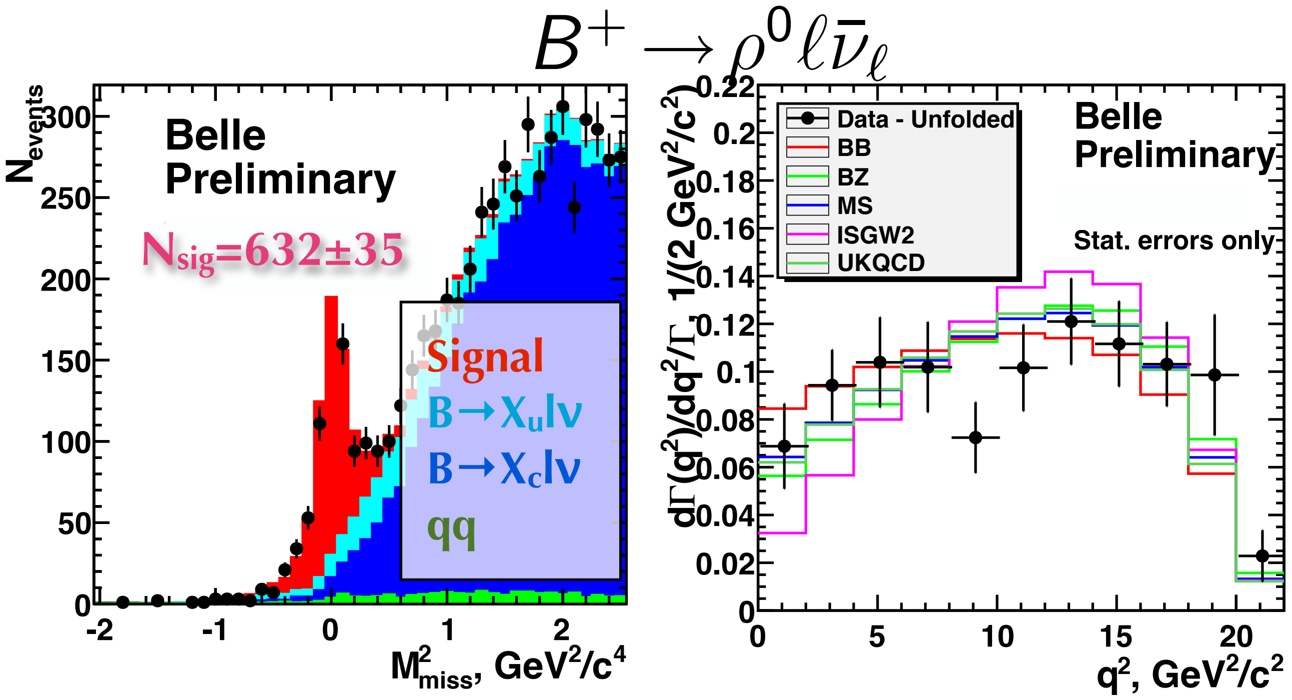
BLNP, DGE, GGOU (above), ADFR

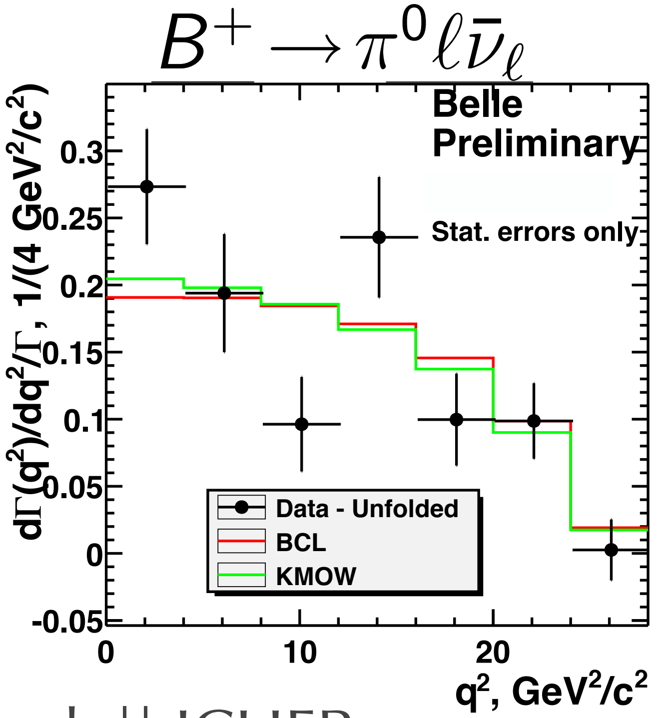
$B\rightarrow(\pi,\rho,\omega,\eta,\eta')l^+\nu$

- Moving towards a complete understanding of $X_u l^+\nu$ semileptonic width, resonant&non-resonant
- In 2012, used new hadronic tag: ~2.1×10^6 B^+ tags, ~1.4×10^6 B^0 tags (2-3 x previous).
  - Best π^0, $\rho^{0/+}$, ω, measurements and best tagged η, η' measurements.
  - $m_{X_u}>1$ GeV still a big challenge.

Approach	Efficiency	Purity
Untagged	**High**	**Low**
Tagged by *B* → *D*$^{(*)}$*lν*	↑	↓
Tagged by *B* → hadrons	**Low**	**High**

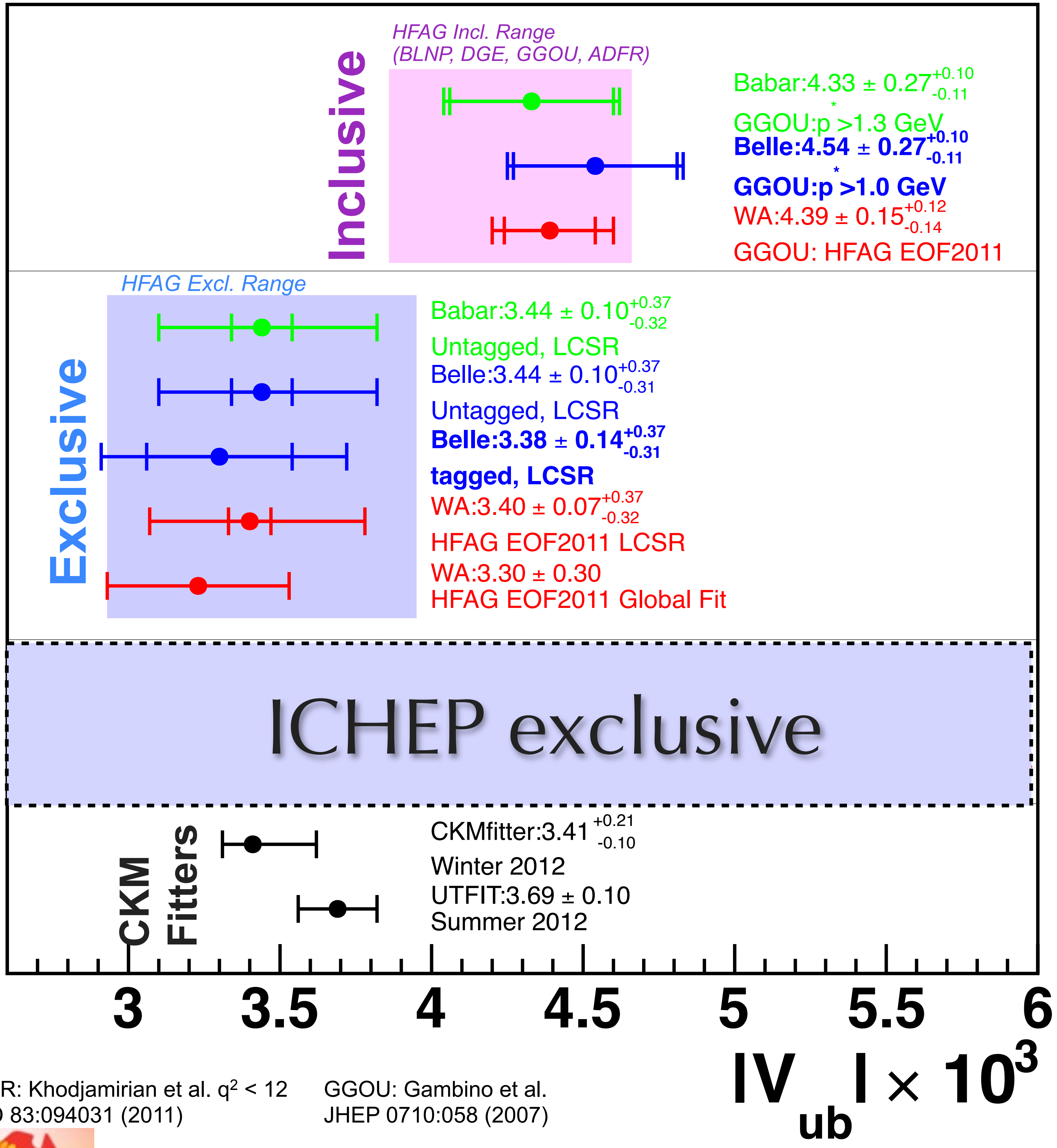
	m(MeV)	**~BR(ave.) x10^{-4}**
$\pi^\pm/\pi^0$	139	1.4
η	547	0.4
$\rho^\pm/\rho^0$	775	2.3
ω	783	1.2
η′	958	0.2
Inc-Σ(Excl)		**14.5**





Y. Yook || ICHEP

$|V_{ub}|$ Summary

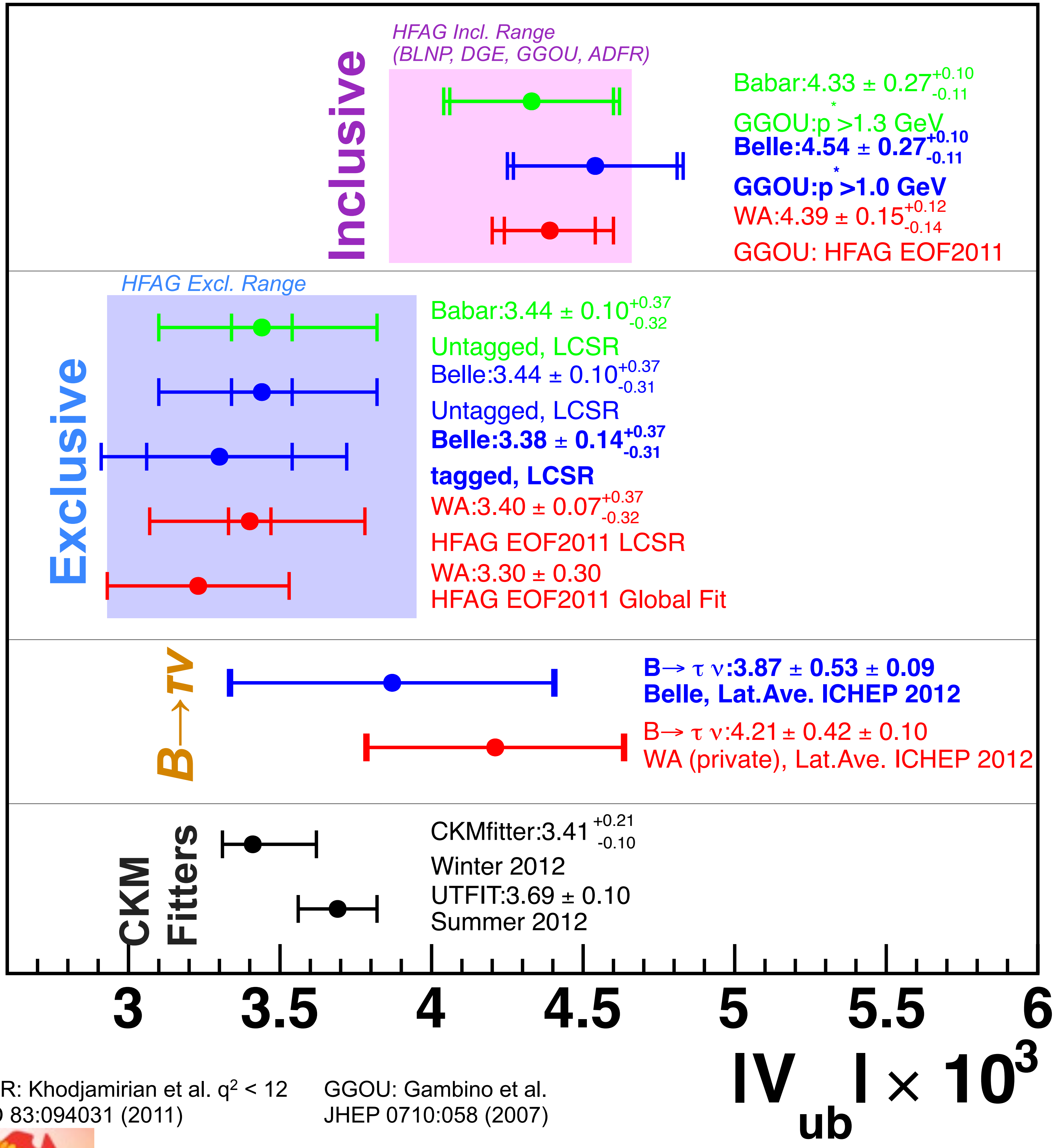


LCSR: Khodjamirian et al. $q^2 < 12$
PRD 83:094031 (2011)

GGOU: Gambino et al.
JHEP 0710:058 (2007)

- ΔIncl.~6% (↓from 18% in 2004)
  ΔExcl.~10%
  Up to 2-3 σ difference between Excl.-Incl.
- Variation on WA in inclusive is substantial, but theory agrees very well for p>1.0 measurements (pure **OPE**)

$|V_{ub}|$ Summary

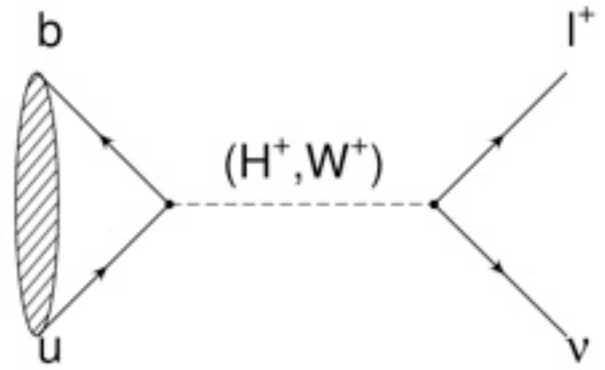


LCSR: Khodjamirian et al. $q^2 < 12$
PRD 83:094031 (2011)

GGOU: Gambino et al.
JHEP 0710:058 (2007)

- ΔIncl.~6% (↓from 18% in 2004)
  ΔExcl.~10%
  Up to 2-3 σ difference between Excl.-Incl.
- Variation on WA in inclusive is substantial, but theory agrees very well for p>1.0 measurements (pure **OPE**)
- **New** Belle results on **B→τν @ICHEP 2012** in agreement with both methods. (See M.Nakao's talk).

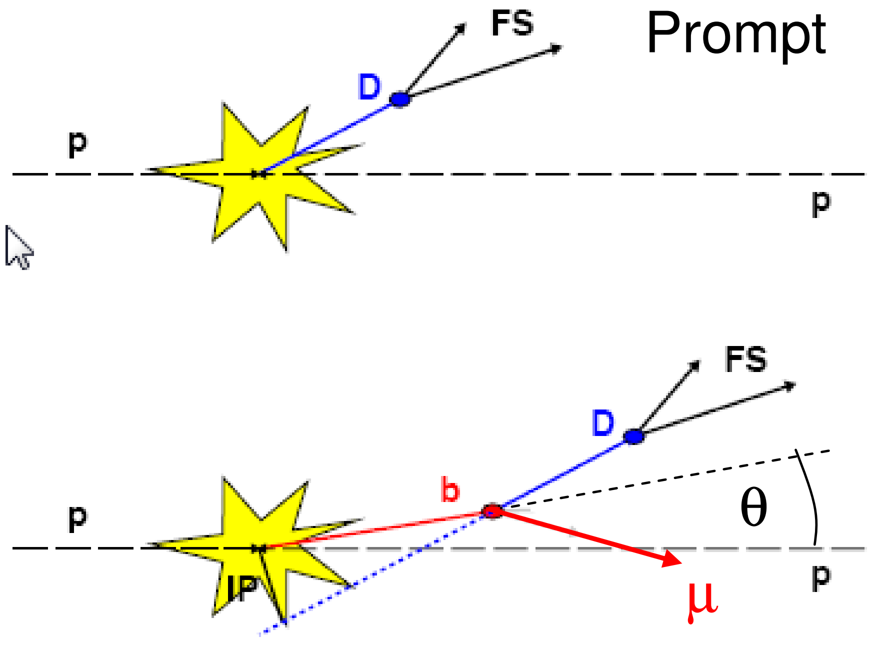
  ΔLeptonic.~10%!!



LHC Era: B_s, Λ_b and *b*-production

The LHC Era

- Vast quantity of *b*-mesons: they **can** be precisely reconstructed in modes with one **neutrino**!
  - Clean separation from large IP!
  - Used as a calibration tool (rely on well understood decay properties).
    - $\sigma_{b\bar{b}}$ and f_s/f_d - key to many measurements at the LHC!



$B^+/B^0/\mathbf{B_s}/\Lambda_b$

$\rightarrow D^0 X \mu^- \nu$

$\rightarrow D^+ X \mu^- \nu$

$\rightarrow \mathbf{D_s X \mu^- \nu}$

$\rightarrow \Lambda_c X \mu^- \nu$

- SemileptonicL B_s/Λ_b decays teach us more about $|V_{ub}|/|V_{cb}|$, and for search for NP.

- To achieve this required new, precise measurements of the B_s/Λ_b systems.

Generally charm mesons tag the *b*-hadron species, and the lepton charge tags the *b* flavour, except for cross feed.

↑ ↓ $B_s \rightarrow (D_s^{**} \rightarrow DK) X \mu^- \nu$

$B^{0/+} \rightarrow D_s K X \mu^- \nu$

$\sigma_{b\bar{b}}$ & f_s with Semileptonic $B/B_s/\Lambda_b$ Decays

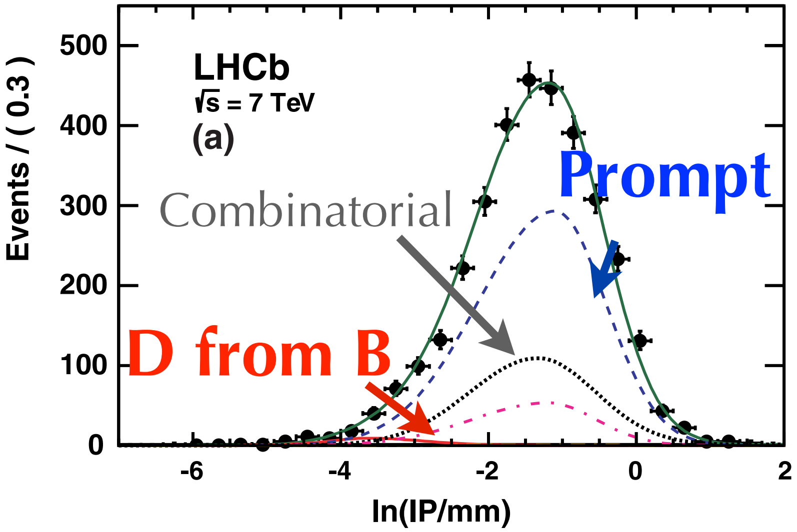
- First Cross section measured with $b \to D^0 X \mu\nu$
  $\sigma_{b\bar{b}}$ (7 TeV:$2>\eta>6$) $=75.3 \pm 5.4 \pm 13.0$ pb
  - As clean as a B-factory
  - First *b* paper at the LHC (3 pb^{-1})

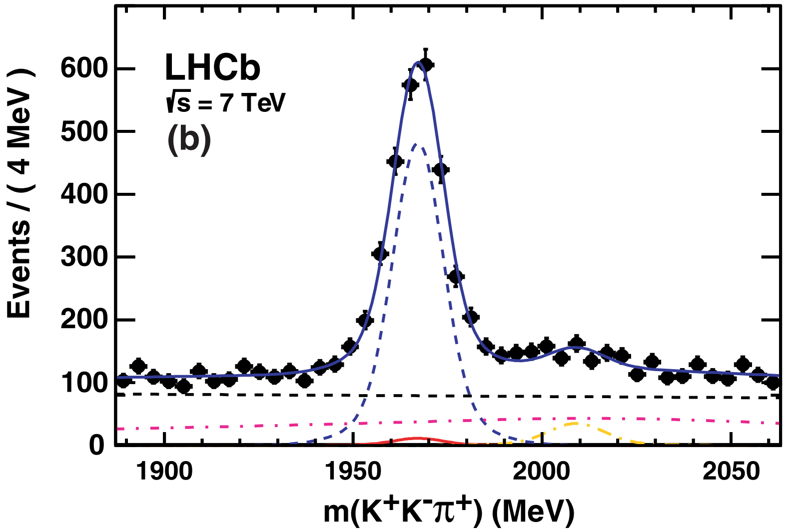
  PU in PLB 694 (2010) 209–216

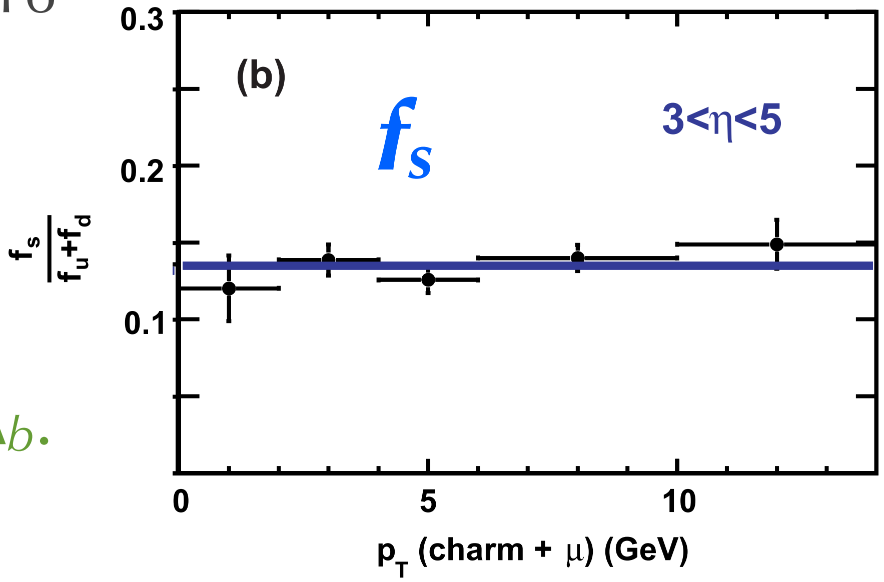
- First Production fraction: $B/B_s/\Lambda_b \to D^0/D^+/D_s/\Lambda_c\ \mu\nu$
  - ***B*$_s$** showed no p_T dependence, **not** flat for Λ_b.
  - Solved a long standing puzzle in ***b*-fragmentation!**

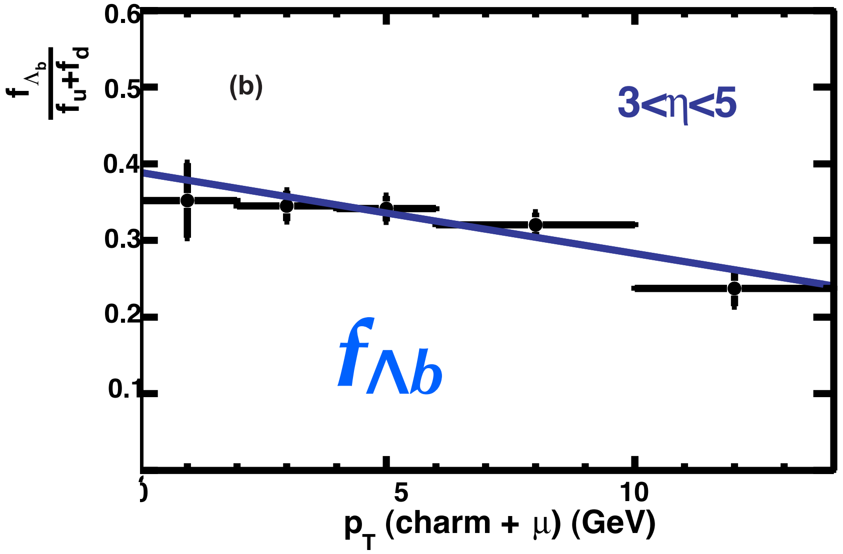
  PU in PRD.85.032008 (2011)

$$\frac{f_s}{f_u + f_d} = \frac{n_{\text{corr}}(\bar{B}^0_s \to D\mu)}{n_{\text{corr}}(B \to D^0\mu) + n_{\text{corr}}(B \to D^+\mu)} \frac{\tau_{B^-} + \tau_{\bar{B}^0}}{2\tau_{\bar{B}^0_s}}$$



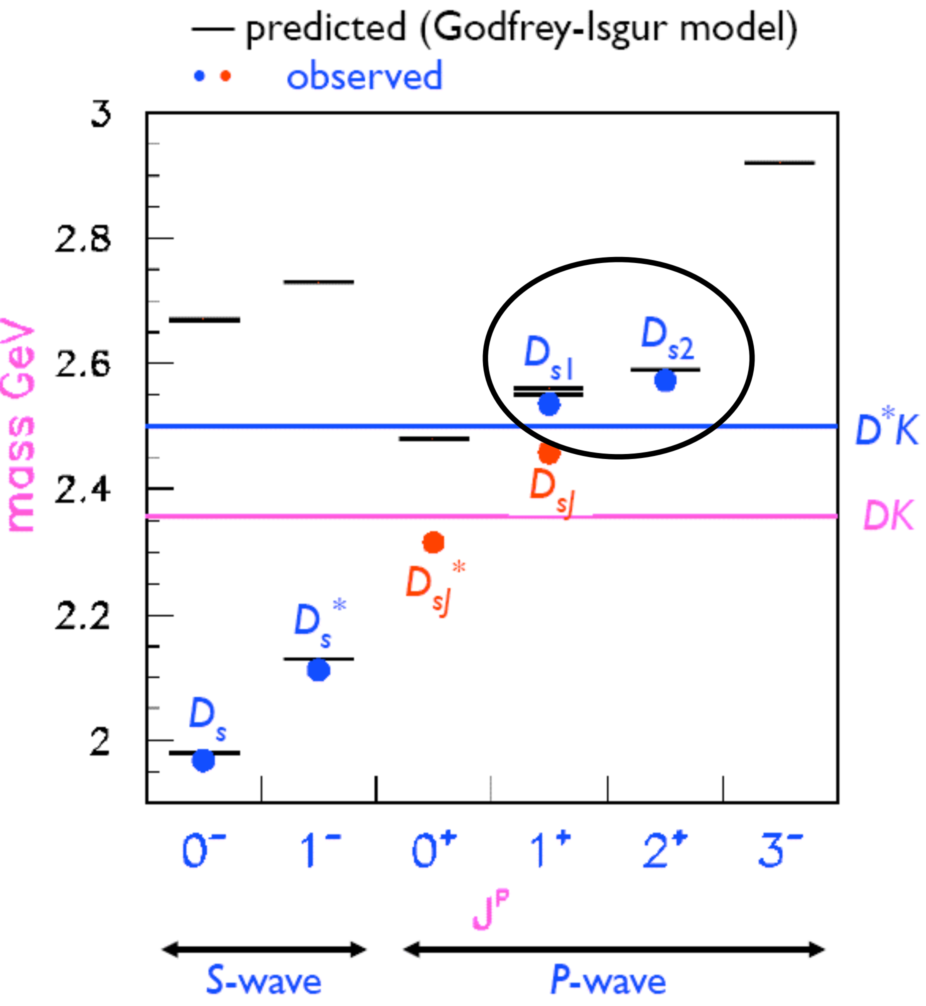






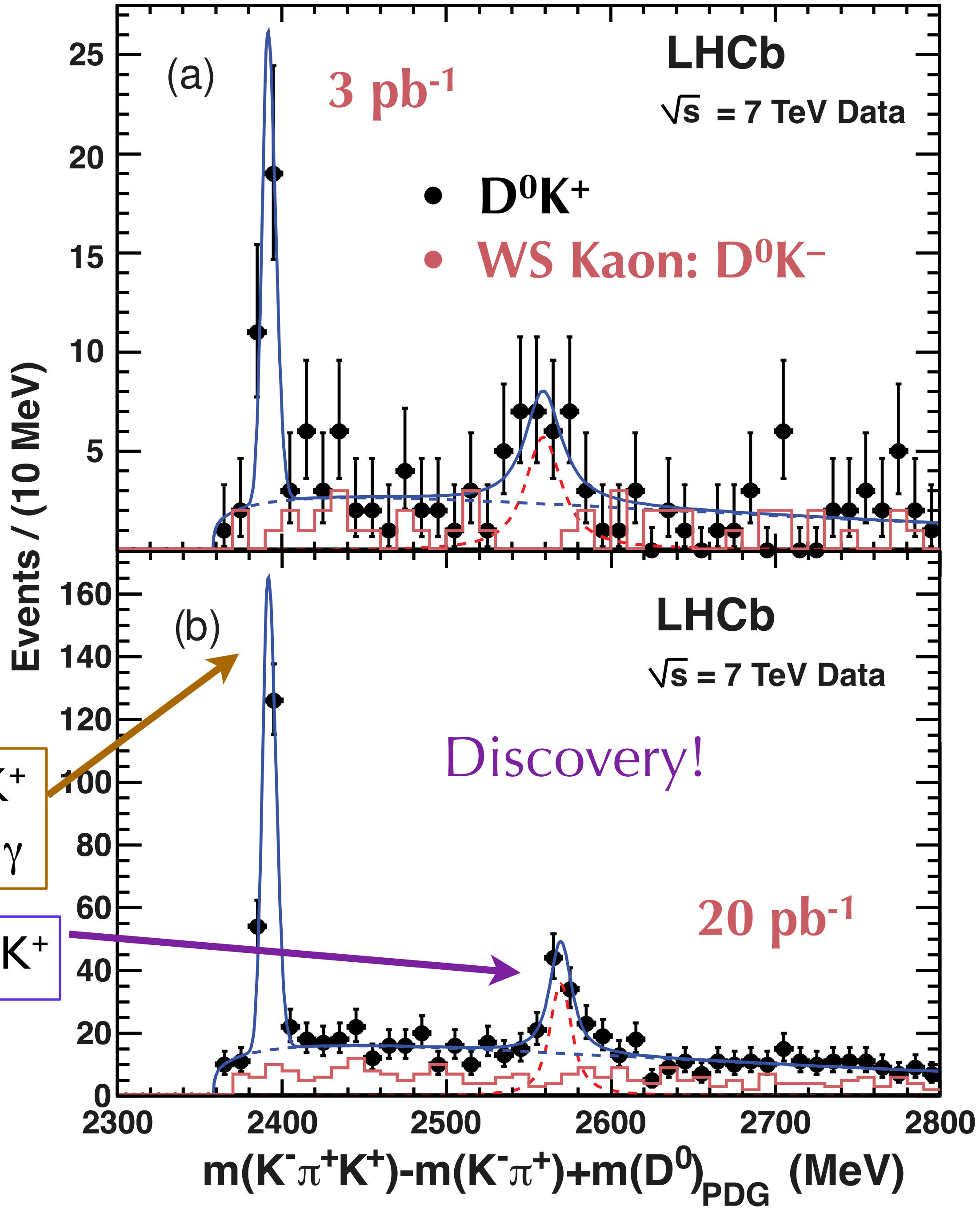
$f_s/(f_u+f_d)$ **= 0.134 ± 0.004 ± 0.011 (LHCb)** 3 pb^{-1}
= 0.128 ± 0.012 (LEP)
= 0.164 ± 0.026 (Tevatron HFAG 2012)

B_s Semileptonic Width Components



- Most precise measurements of $D_s^{**}\mu^-\nu$ modes.
- BR(D_s/D_s^*) modes determined using neutrino reconstruction!
- 8.3σ significance discovery of $B_s \rightarrow D_{s2}\mu^-\nu$.

PU in PLB 698:14-20 (2011)



$D_{s1}(2536) \rightarrow D^*(2007)^0\,K^+$
missed π^0 or γ

$D_{s2}(2573) \rightarrow D^0\,K^+$

$$\frac{\mathcal{B}(\overline{B}{}^0_s \rightarrow D^{*+}_{s2} X\mu^-\overline{\nu})}{\mathcal{B}(\overline{B}{}^0_s \rightarrow X\mu^-\overline{\nu})} = (3.3 \pm 1.0 \pm 0.4)\%$$

$$\frac{\mathcal{B}(\overline{B}{}^0_s \rightarrow D^{+}_{s1} X\mu^-\overline{\nu})}{\mathcal{B}(\overline{B}{}^0_s \rightarrow X\mu^-\overline{\nu})} = (5.4 \pm 1.2 \pm 0.5)\%,$$

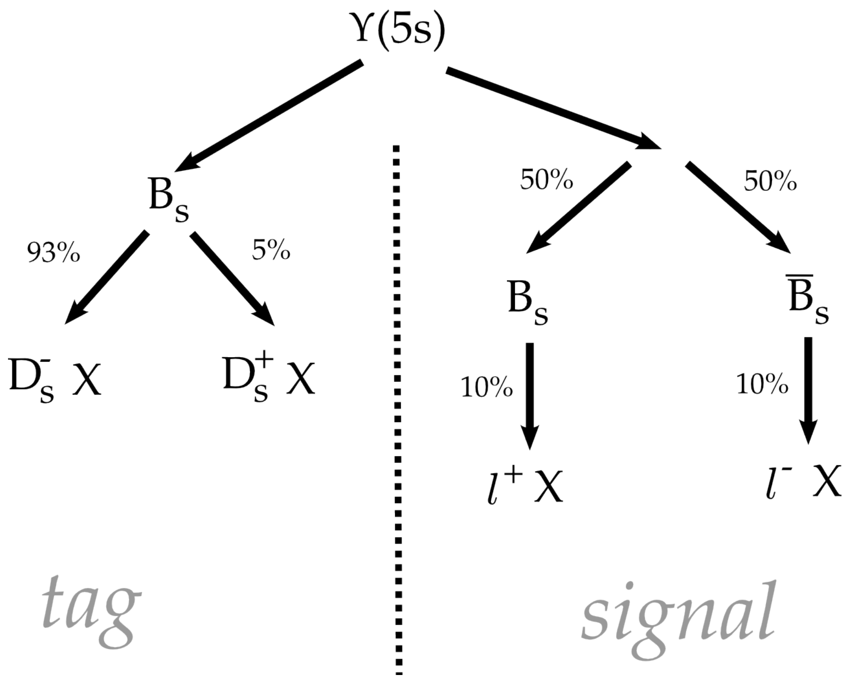
Inclusive Semileptonic B_s Decay Width, Υ(5S)@Belle

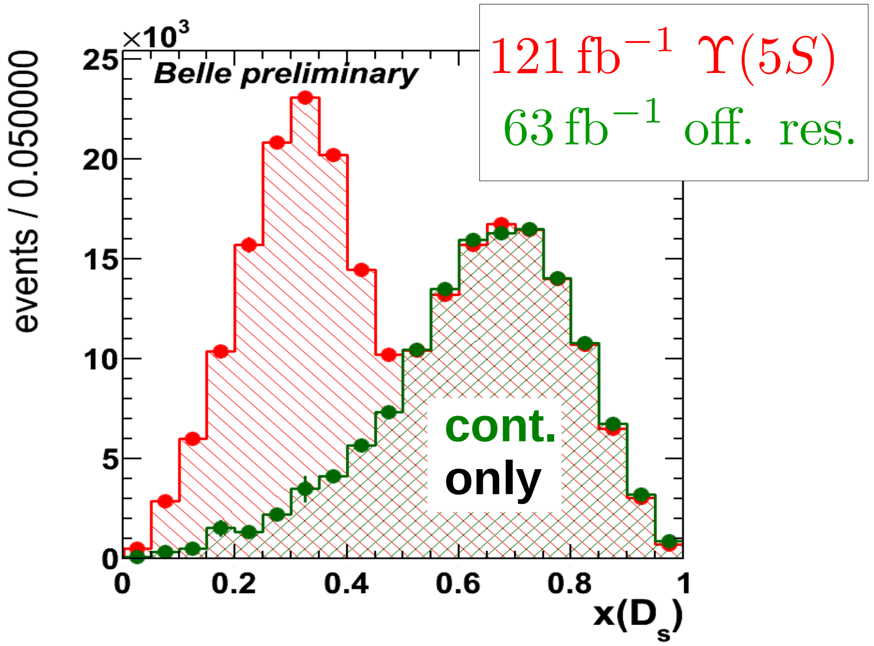
- B_s inclusive width
  - $B_s \rightarrow Xl\nu$
- Assumed from theory (that SU3 symmetry is kept), to measure the production fraction.

$\Gamma_{SL}(B_s)=\Gamma_{SL}(B_d) =\Gamma_{SL}(B_u)$

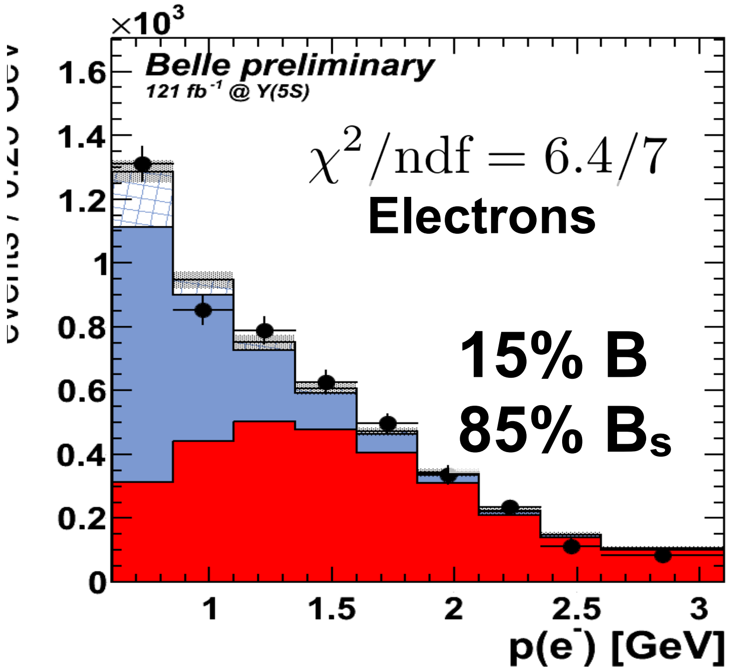
- $\Gamma_{SL}(B_s)$ only precisely measured by Belle at Y(5S) with 121 fb^{-1}.

- Method:
  Inclusive:
  $B_s \rightarrow Xl\nu$ with
  $B_s(\rightarrow D_s)$ tagging
- See C. Oswald@ ICHEP2012





$$x(D_s) = \frac{p(D_s)}{p_{\max}(D_s)} < 0.5$$



$BR(B_s \rightarrow Xl\ \nu)$:l=e,μ $10.61 \pm 0.46_{stat} \pm 0.37_{sys} \pm 0.67_{param}$

Summary

- *Measurements of $|V_{ub}|$ and $|V_{cb}|$ via Semileptonic decays have been a great challenge for both theory and experiment, particularly in controlling hadronic physics.*
- ***"Tension" between inclusive and exclusive analyses persists,** while uncertainties are being reduced.*

$|V_{cb}|$ Exclusive ($D^*l\nu$)

↕ **1-2 σ**

$|V_{cb}|$ Inclusive

$|V_{ub}|$ Exclusive ($\pi l\nu$)

↕ **2-3 σ**

$|V_{ub}|$ Inclusive

$$\left|\frac{V_{ub}}{V_{cb}}\right| = \begin{cases} 0.0846 \pm 0.0035 & \text{fit} \\ 0.089 \pm 0.010 & \text{exclusive} \\ 0.0969 \pm 0.0068 & \text{inclusive} \end{cases} .$$

R. Van der Water

Ratios are compatible

- Will they improve?
  - Next generation B-factories will produce hadronic tagged, high statistics, high purity samples and fully measure the charmless semileptonic spectra.
  - LHCb will provide competitive results in exclusive modes, already starting to dominate in B_s and Λ_b *semileptonic decays*.
  - Still a big challenge for theory
    - Precision data can inspire and validate theory advances.
- Semileptonic decays prove to be important in new physics flavour measurements!

Backup

Summary of $|V_{ub}|$ and $|V_{cb}|$

$|V_{cb}|$ Exclusive ($D^*l\nu$)

- Exp. error 1.4%
- LQCD norm. 1.9%

$$|V_{cb}|=(39.04\pm0.55\pm0.73)\cdot10^{-3}$$

2.4 σ

$|V_{cb}|$ Inclusive

- Exp. error 1.1%
- Theory error. 1.4%

$$|V_{cb}|=(41.88\pm0.44\pm0.59)\cdot10^{-3}$$

$|V_{ub}|$ Exclusive ($\pi l\nu$)

- Exp. error 5.5%
- LQCD norm. 7.5%

$$|V_{ub}|=(3.23\pm0.18\pm0.24)\cdot10^{-3}$$

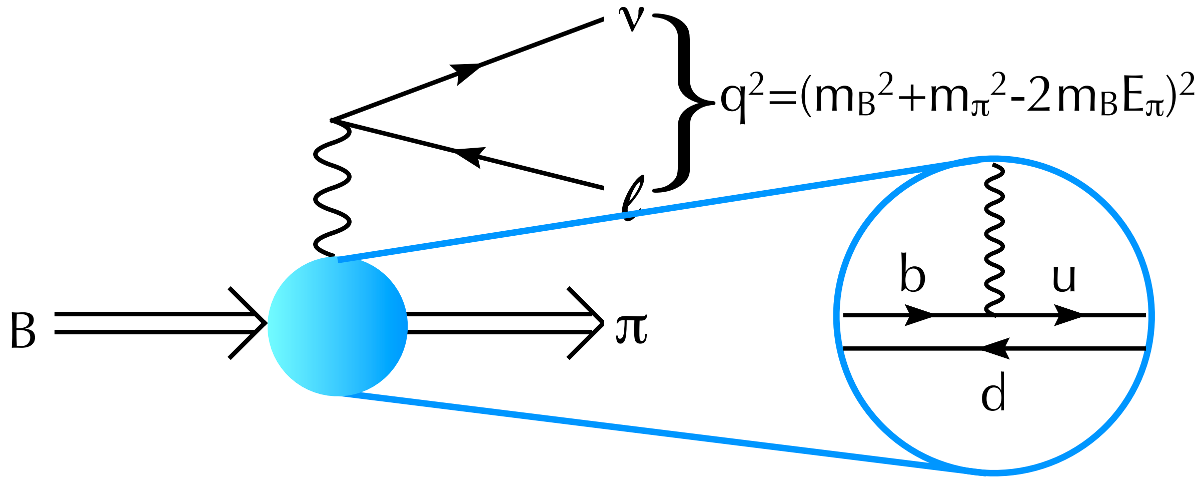
2.7 σ

$|V_{ub}|$ Inclusive

- Exp. error 3.6%
- Theory error 3.9%

$$|V_{ub}|=(4.41\pm0.15\pm0.17)\cdot10^{-3}$$

Exclusive $|V_{ub}|$

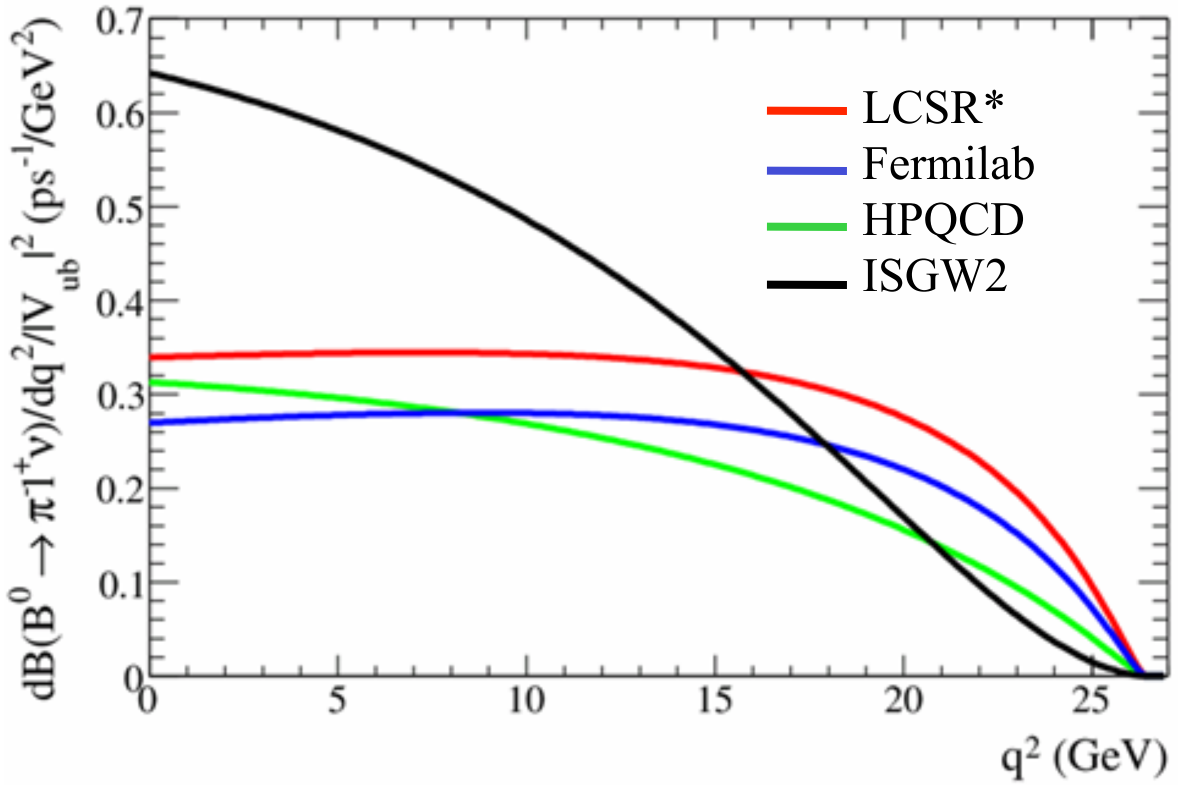


$$\Delta\zeta(0,q^2_{max}) = \frac{G_F^2}{24\pi^3}\int_0^{q^2_{max}} dq^2\, p_\pi^3\,|f_+(q^2)|^2$$

One FF for $B \to \pi l\nu$
with massless lepton

$$= \frac{1}{|V_{ub}|^2\tau_{B_0}}\int_0^{q^2_{max}} dq^2\, \frac{d\mathcal{B}(B\to\pi\ell\nu)}{dq^2}$$

- Exclusive rates determined by $|V_{ub}|$ and Form Factors
  - Calculable at kinematical limits with LightConeSumRules or LatticeQCD
- Empirical extrapolation necessary to extract $|V_{xb}|$ from measurements



Approach	**Efficiency**	**Purity**
Untagged	**High**	**Low**
Tagged by *B* → *D*$^{(*)}$*l*ν	**↑**	**↓**
Tagged by *B* → hadrons	**Low**	**High**

Exclusive $|V_{ub}|$

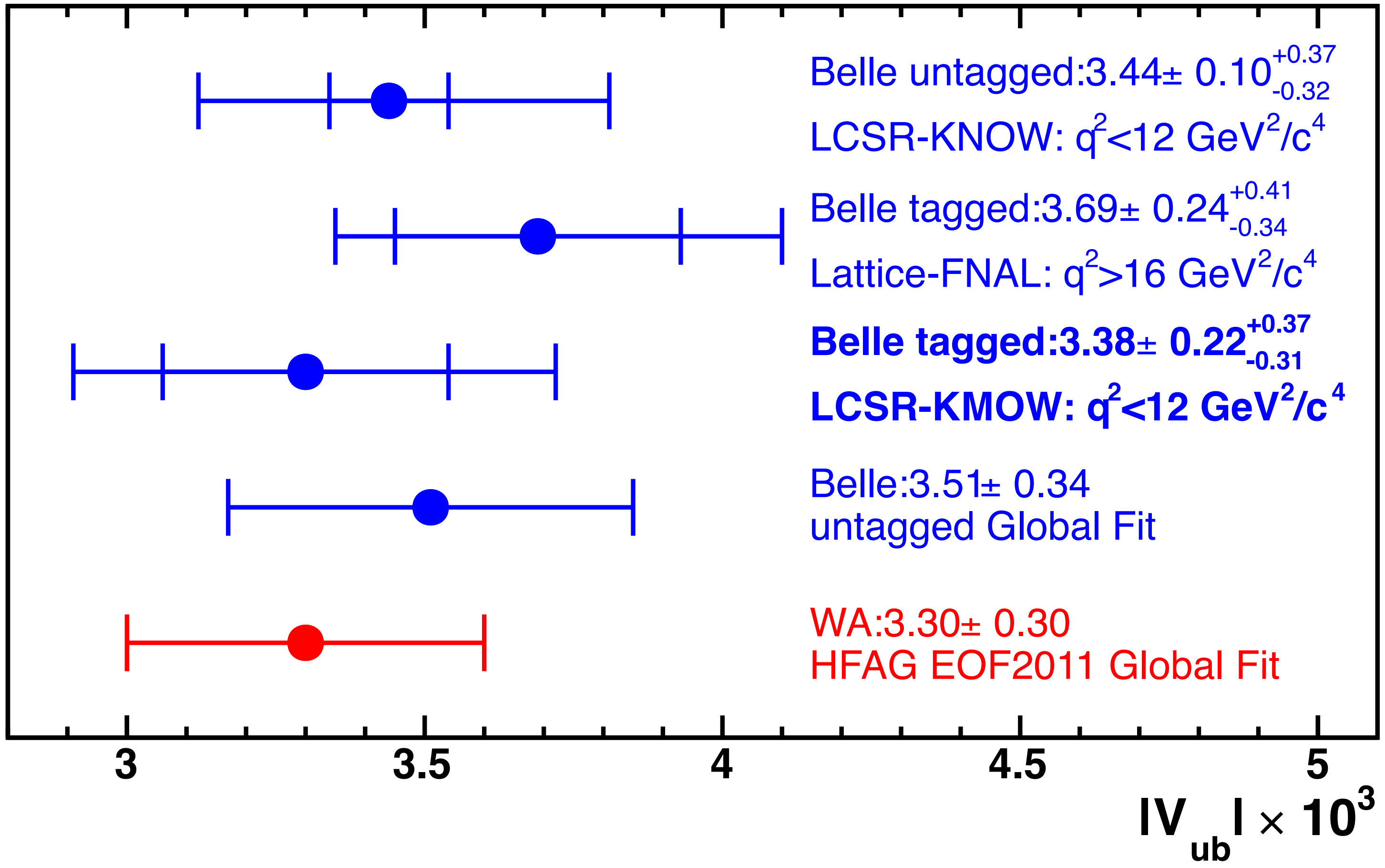
1. $|V_{ub}|$ from partial q^2 integral with **FF** (from theory/lattice).
2. **Fit** data&lattice calculations in q^2(2-3 shape pars + $|V_{ub}|$, data & LQCD correlations)

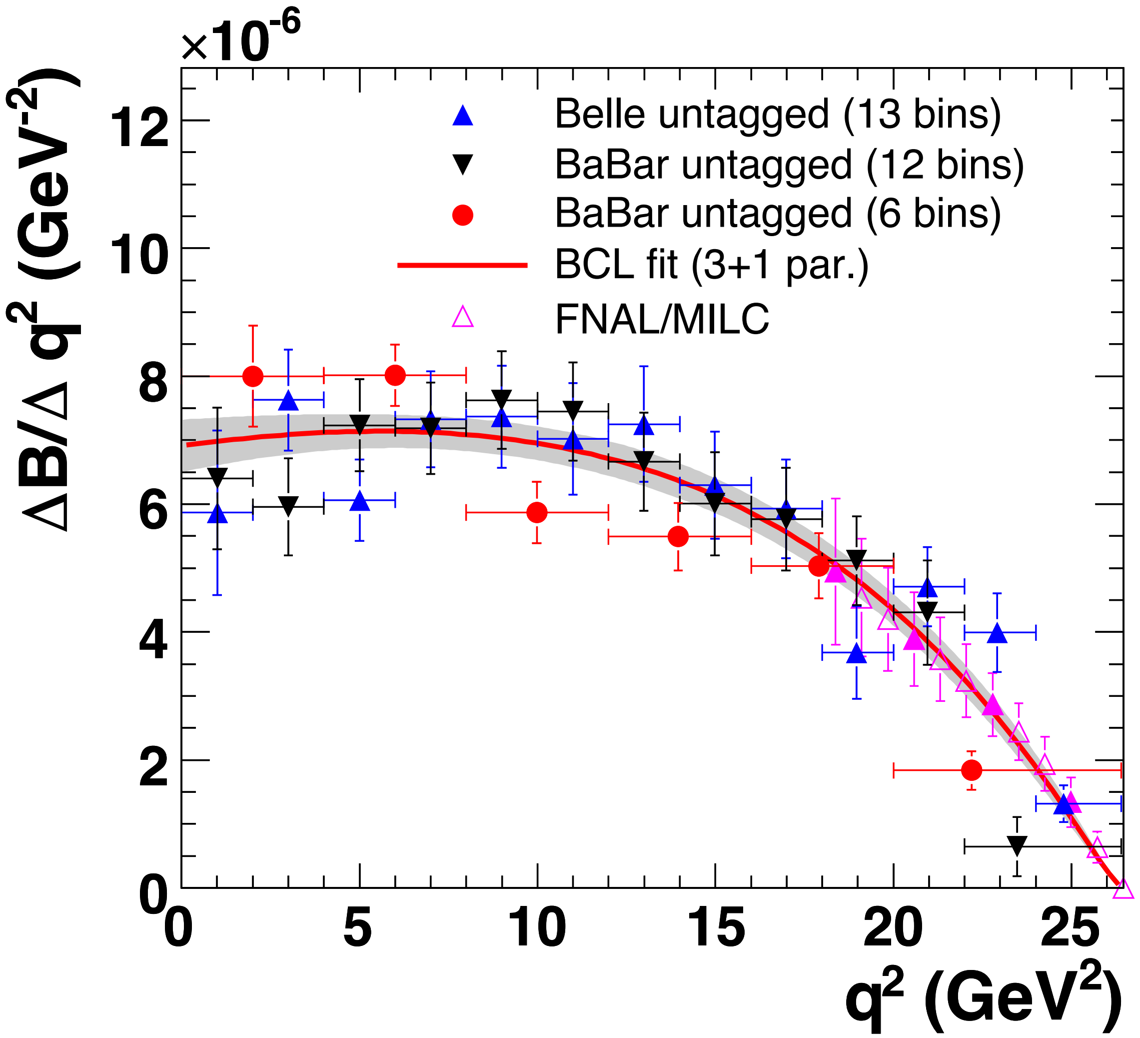
Error budget:

2% from total rate

4% from q^2 shape

8% from FF normalisation





$|V_{ub}|$ Exclusive-Inclusive Puzzle

- Inclusive:
  - $|V_{ub}|$ varies depending upon theoretical framework and is highly sensitive to the input **b-quark** mass.
  - High mass components, and fragmentation will be measured constrained.

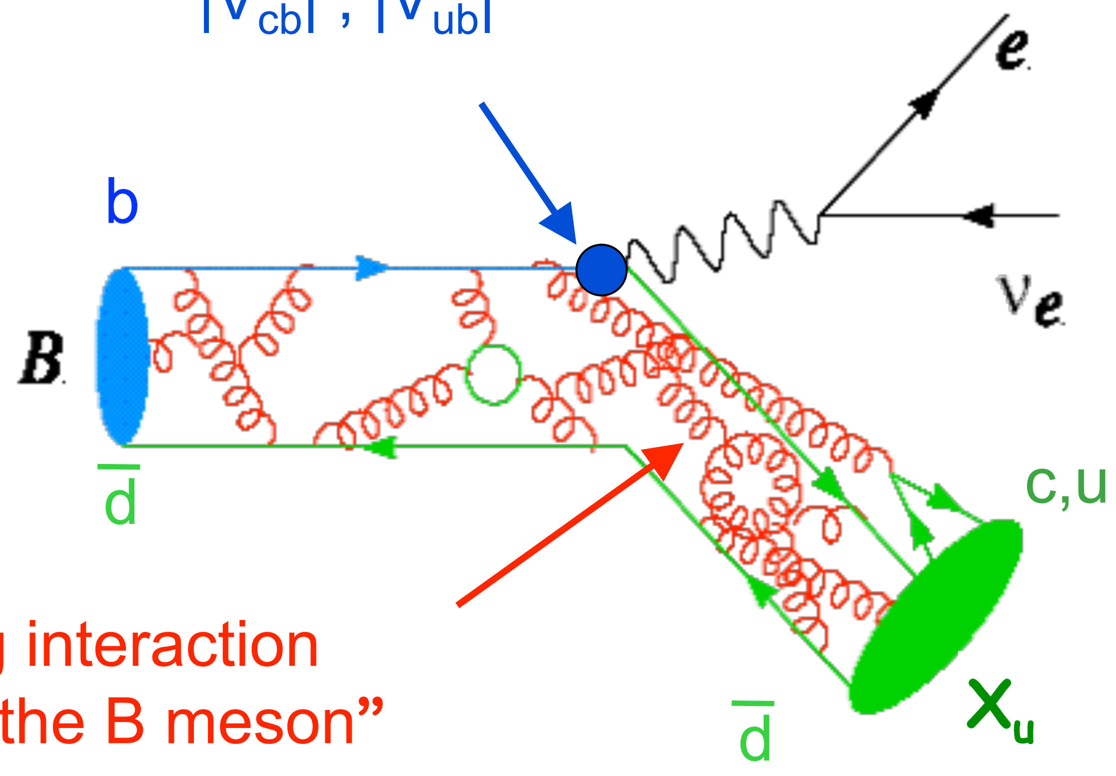
- Exclusive:
  - Rely on normalisation from theory or Lattice, but stat limited tests of those predictions. Rely on precision tests from $D \to \pi/K l \nu$, and q^2 shape comparisons in B decays.
  - $|V_{ub}|$ can be obtained from other exclusive decay channels such as $\mathbf{B_s \to K \mu \nu}$

- **Right handed current?**

How to determine $|V_{qb}|$

2 Complementary approaches using **different** theoretical tools, and **different** experimental signatures.

→Crucial independent consistency check.



Study weak interaction

$|V_{cb}|$, $|V_{ub}|$

Study strong interaction

“Structure of the B meson”

Inclusive:

$$\Gamma(B \to X_c \ell \nu) = \underbrace{\frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2}_{\text{free quark decay}}[[1 + \mathrm{A_{ew}}]\underbrace{\mathrm{A_{nonpert}}\mathrm{A_{pert}}]}_{\text{QCD corrections}}$$

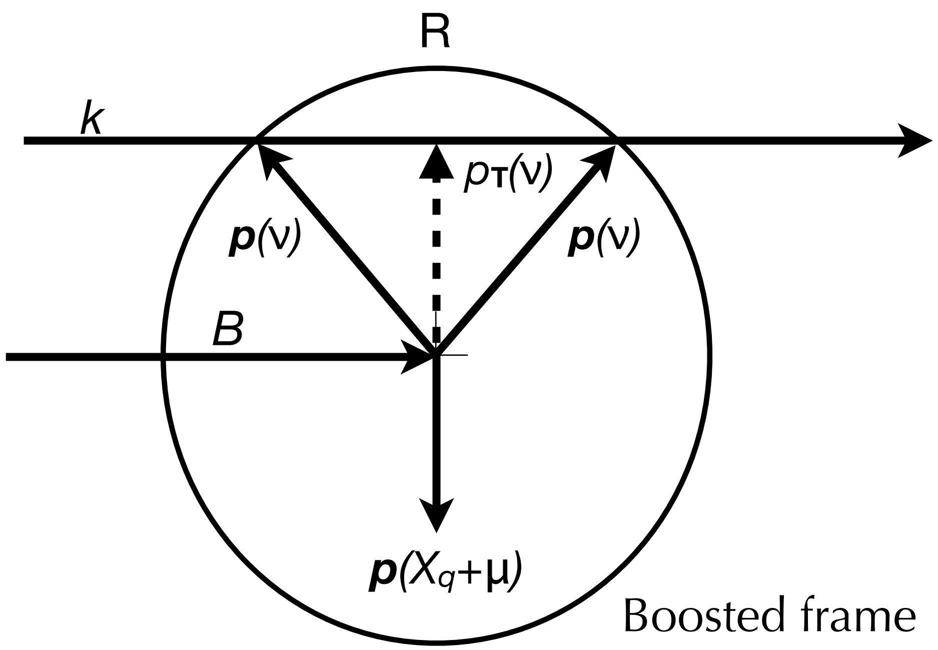
sum over all hadron final states

(heavy quark symmetry)

Exclusive:

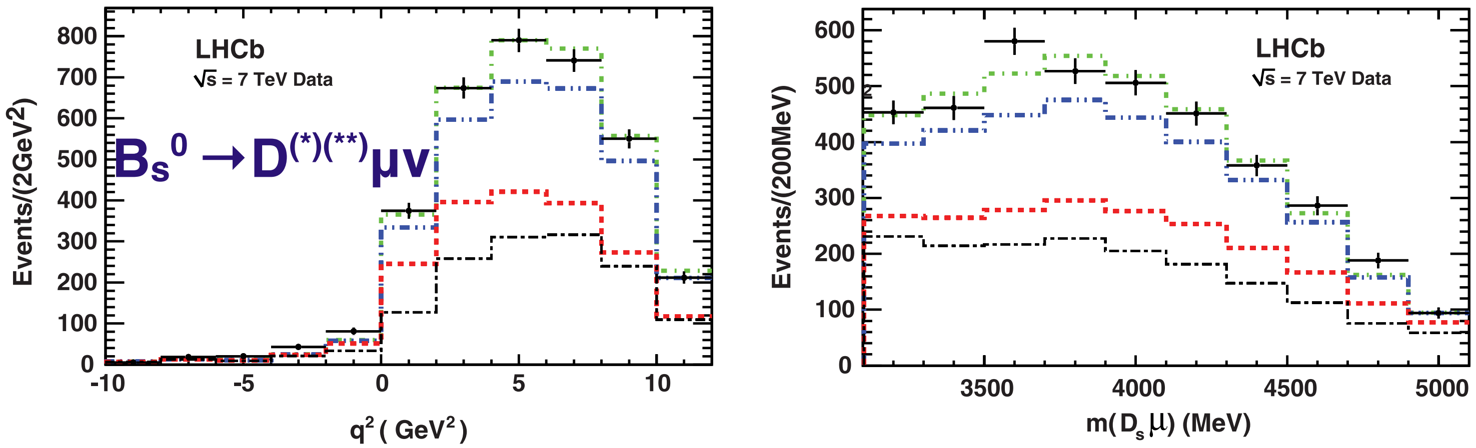
$$\frac{d\Gamma(B \to \pi \ell \nu)}{dq^2} = \frac{G_F^2}{24\pi^2}|V_{ub}|^2 p_\pi^3 \underbrace{|f_+(q^2)|^2}_{B \to \pi \text{ form factor (lattice QCD)}}$$

Outlook for SL B decay measurements

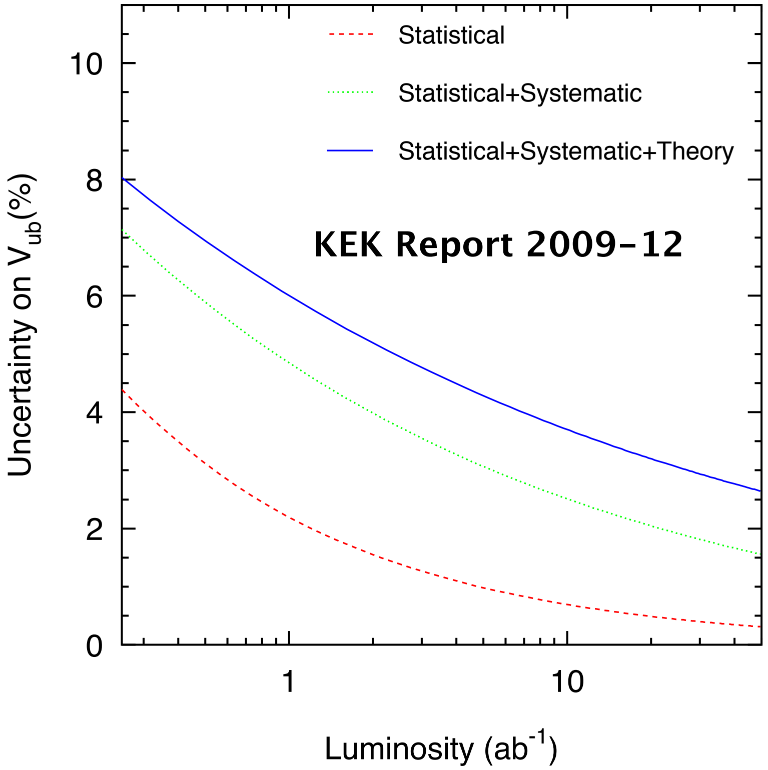


- LHCb: Neutrino/q^2 reconstruction. for exclusive measurements.
  - **$|V_{ub}|$: $B_s \to K^{(*)}\mu\nu$, $B \to \rho\mu\nu$**

PRD.85.032008 (2011)



- **Belle II/SuperB:**
  - High statistics hadronic tag reconstruction.
  - Full exploration of SL charmless (and charmed) mass spectra: up to higher mass.
  - Decay differentials to fully test models
- **Lattice** errors expected to **halve** in the next 2 years



Exclusive $|V_{cb}|$

The $B \to D^{(*)} l\nu$ differential decay rates are proportional to $|V_{cb}|^2$ and form factors.

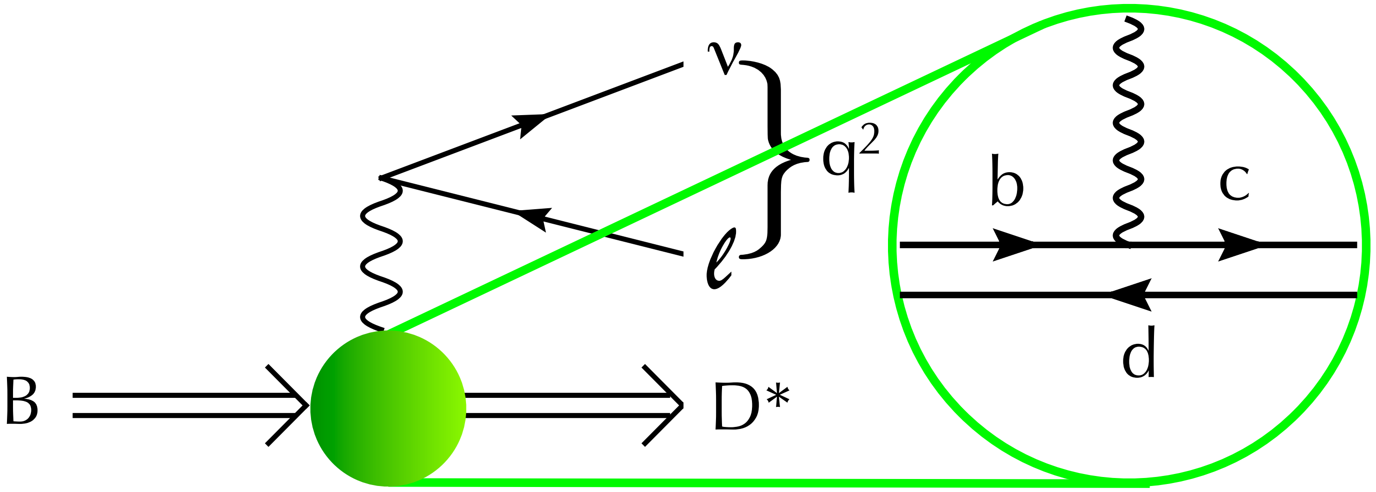
$$d\Gamma(B \to D^{(*)} l\nu)/dw = (G_F^2/48\pi^3)\, m_D^3 (m_B + m_D)^2 (w^2 - 1)^{3/2} |V_{cb}|^2 |F_{B\to D^{(*)}}(w)|^2$$

$$w \equiv v_B \cdot v_{D^{(*)}} = \frac{p_B \cdot p_{D^{(*)}}}{m_B \cdot m_{D^{(*)}}} : D^{(*)} \text{ boost}$$

Take 1 normalisation point

from lattice-QCD at 0-recoil

(w=1) ~2% errors



From experiment

$|V_{cb}|$ x F.F. @w=1

ρ_D, ρ_{D^*} (F.F. slopes)

$F_{B\to D}(1) = 1.074(18)_{stat}(16)_{sys}$

[Fermilab/MILC NPPS 140, 461(2005)]

$F_{B\to D^*}(1) = 0.9077(51)_{stat}(158)_{sys}$

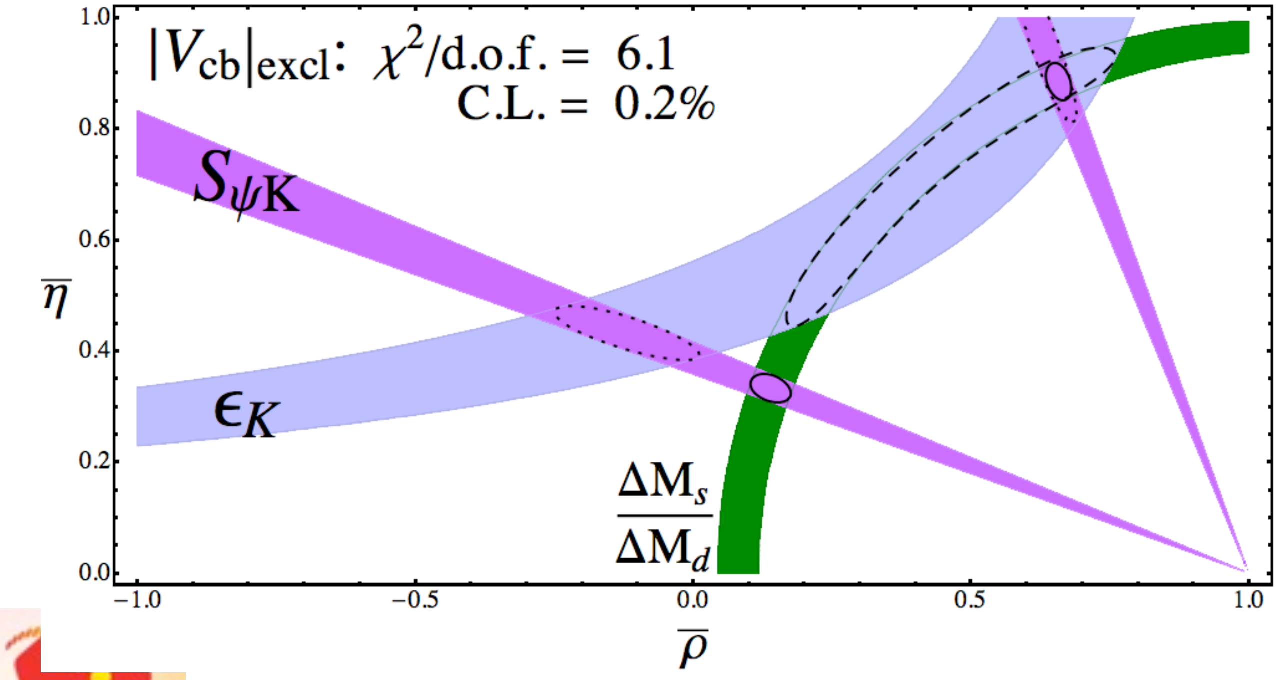
[Fermilab/MILC, arXiv:1011.2166]

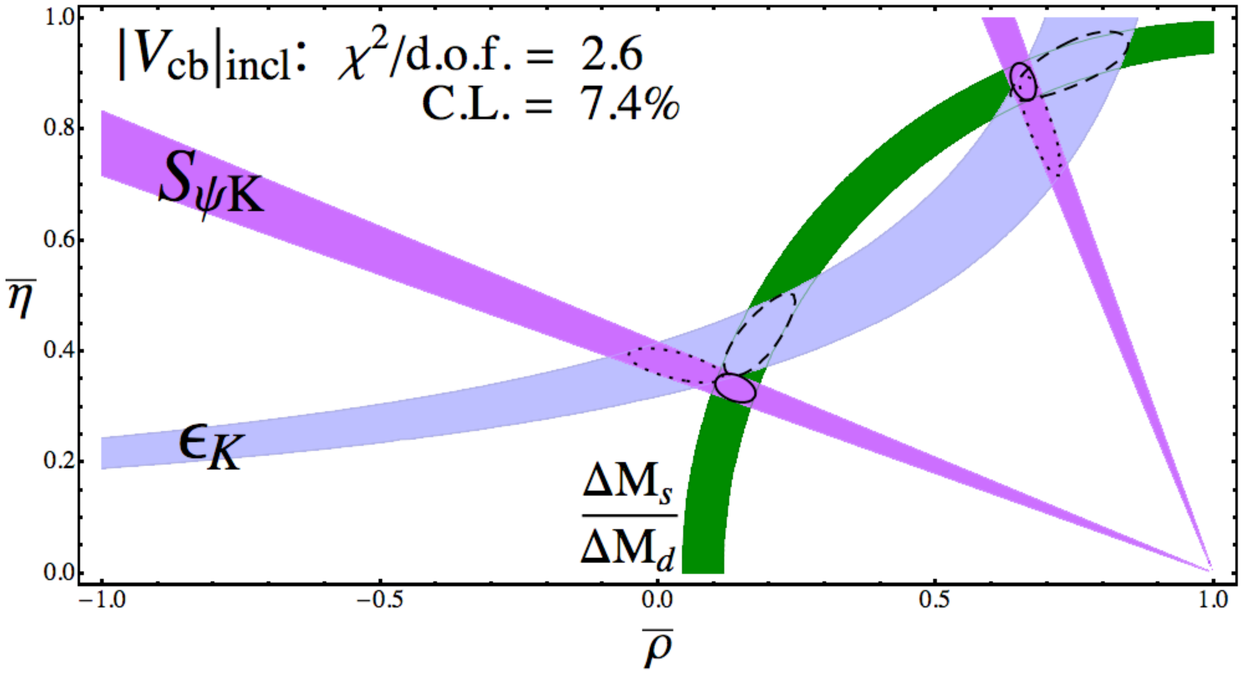
$|V_{cb}|$, $|V_{ub}|$ and New physics

- **Indirect** constraints on NP
- Some UT constraints strongly affected:
  - $\mathcal{B}(B\to\tau\nu)\propto f_B^2\cdot|V_{ub}|^2$
  - ε_K dependent on $|V_{cb}|$
  - $\mathcal{B}(K^+\to\pi^+\nu\nu)\propto|V_{cb}|^4$
  - $\mathcal{B}(K_L\to\pi^0\nu\nu)\propto|V_{cb}|^4$

- **Direct?**
  - LR models could affect the **$b\to ul\nu$** transitions
  - Charged Higgs can affect Cabibbo Favoured decays $B\to D^{(*)}\tau\nu$

$$(\widehat{B}_K)_{\rm fit} = \begin{cases} 1.09 \pm 0.12 & |V_{cb}|_{\rm excl} \\ 0.903 \pm 0.086 & |V_{cb}|_{\rm incl} \\ 0.98 \pm 0.10 & |V_{cb}|_{\rm excl+incl} \end{cases}$$

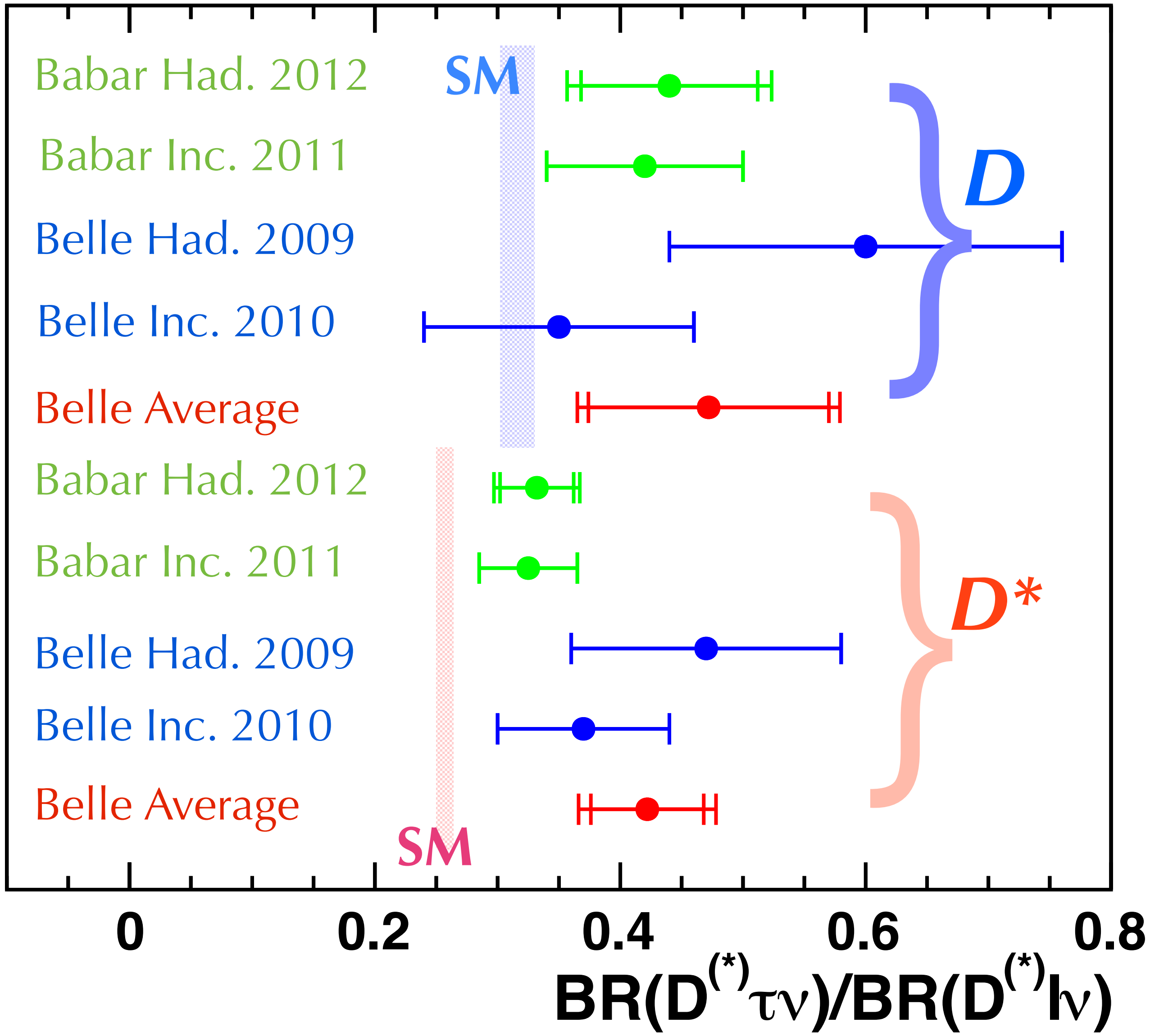




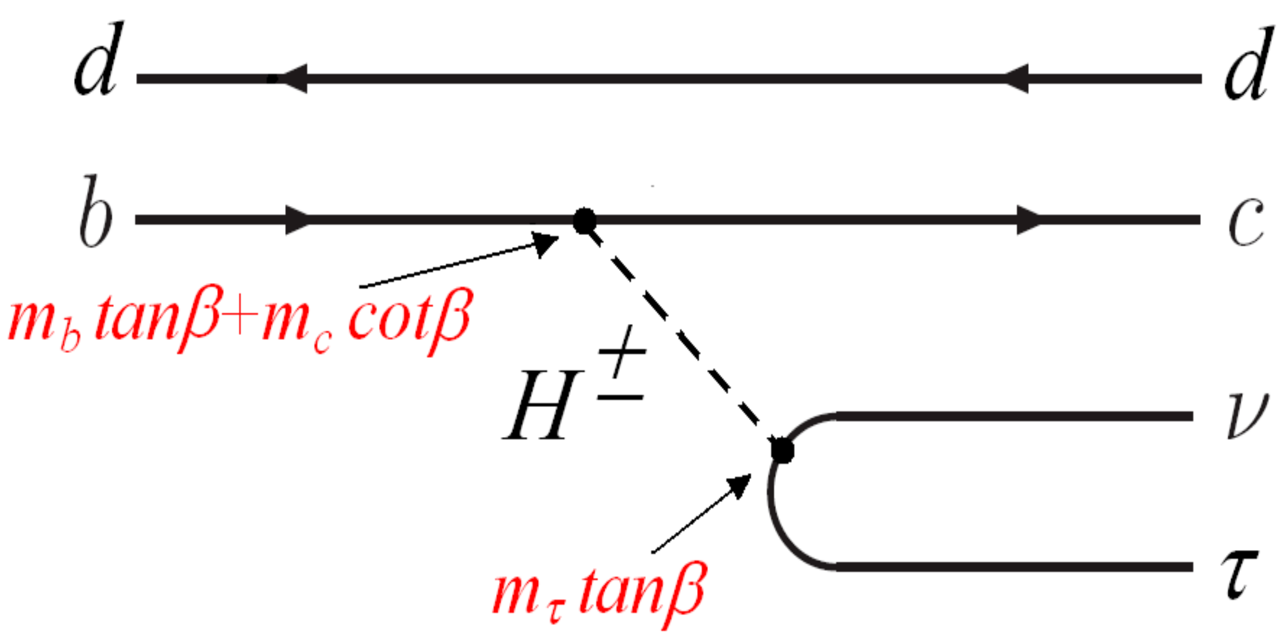
A word on tauonic modes: $B \rightarrow D^{(*)}\tau^{+}\nu_{l}$

- Higher values than expected from the SM

But, no indications in favour of a Type II charged Higgs.



Isospin invariance assumed

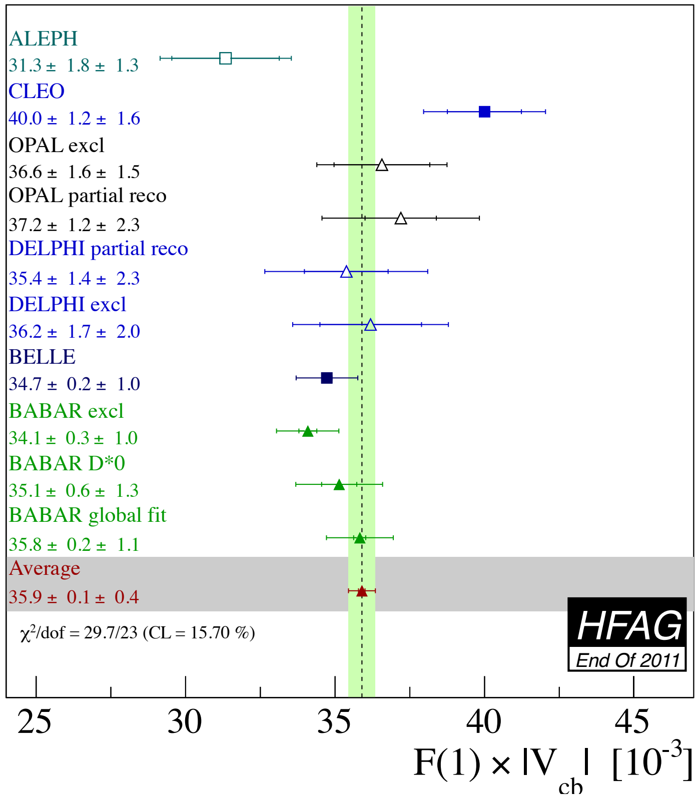


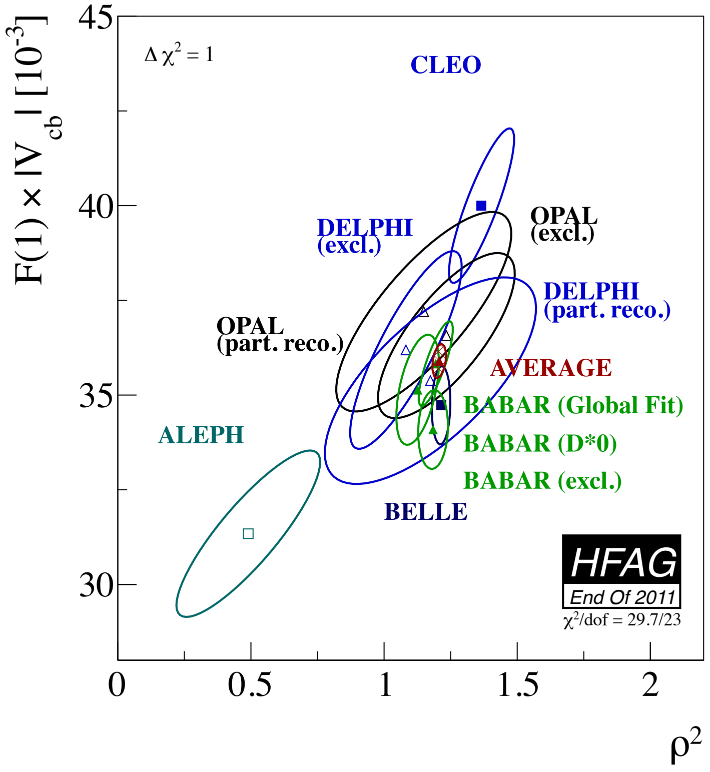
Belle hadronic tag update coming soon!

Exclusive $|V_{cb}|$ Averages

$B \to D^* l\nu$

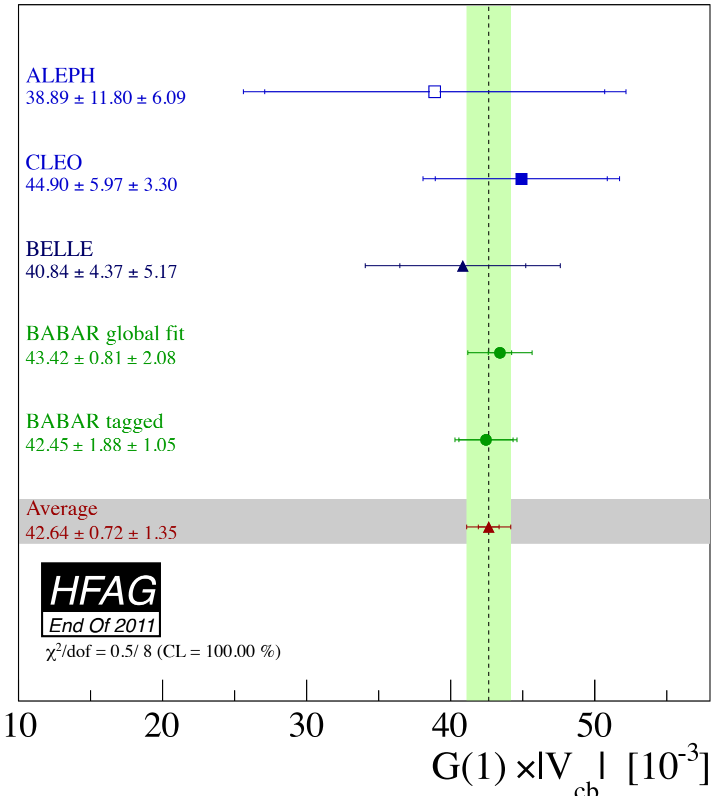
$$|V_{cb}| = (39.54 \pm 0.50_{\rm EXP} \pm 0.74_{\rm LQCD}) \times 10^{-3}$$

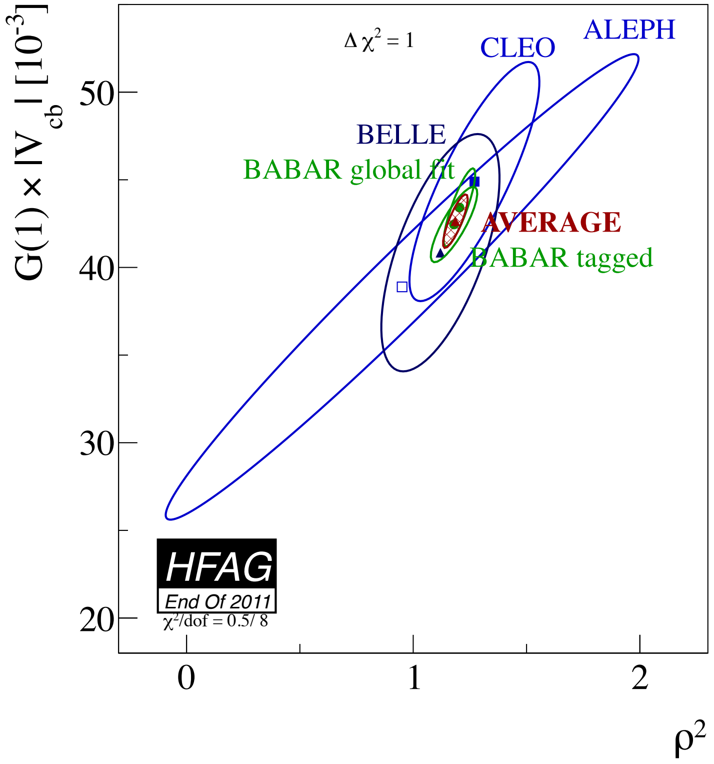




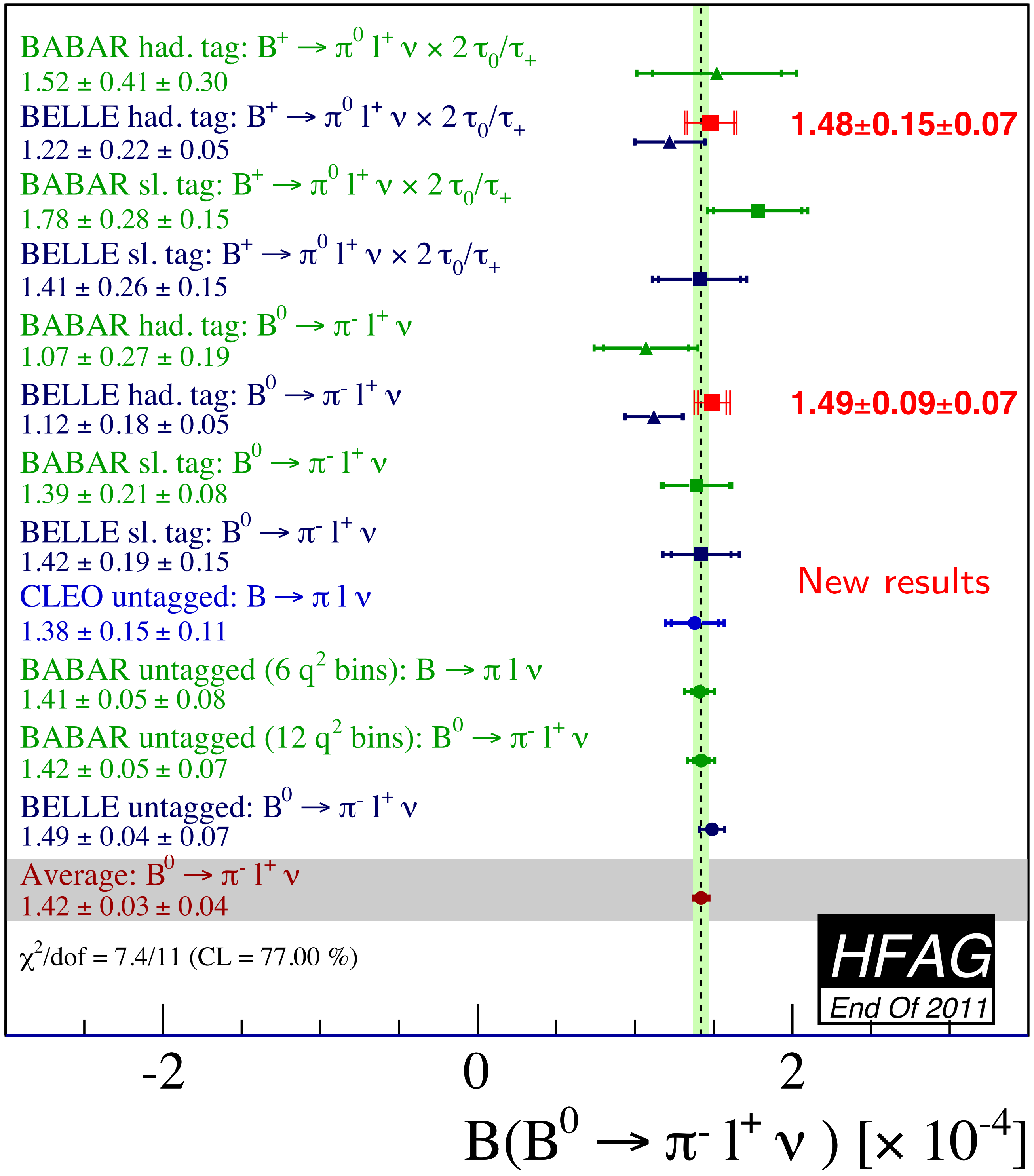
$B \to D l\nu$

$$|V_{cb}| = (39.70 \pm 1.42_{\rm EXP} \pm 0.89_{\rm LQCD}) \times 10^{-3}$$





Exclusive $|V_{ub}|$ Averages

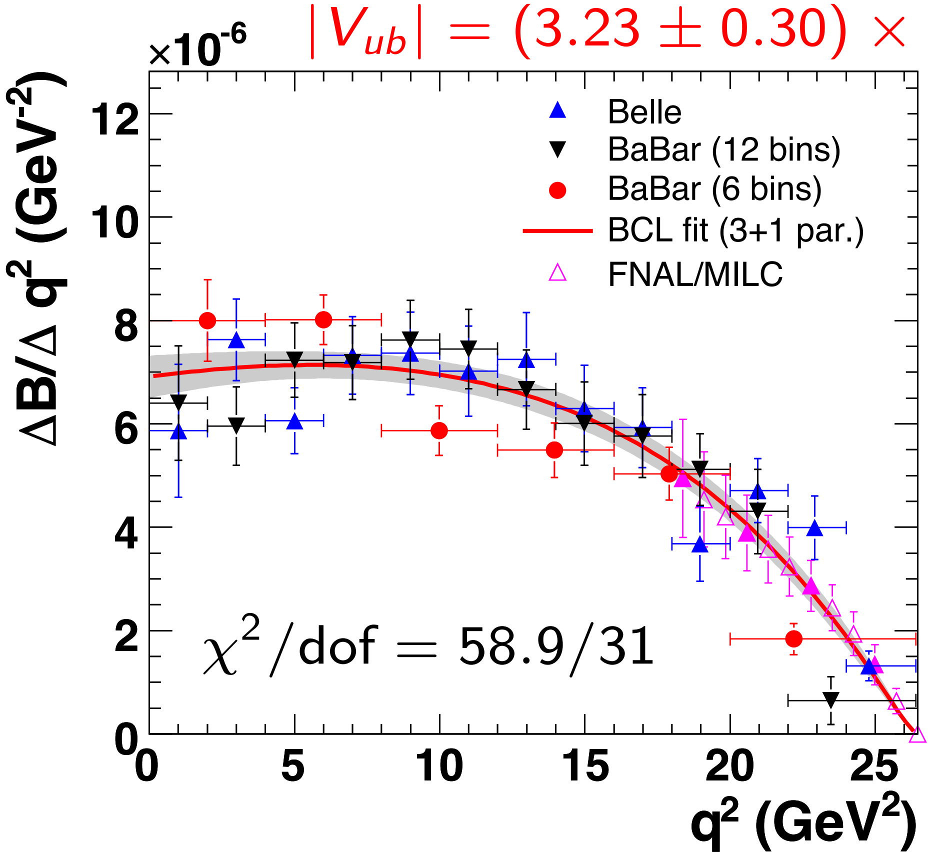


HFAG EOF2011 Average

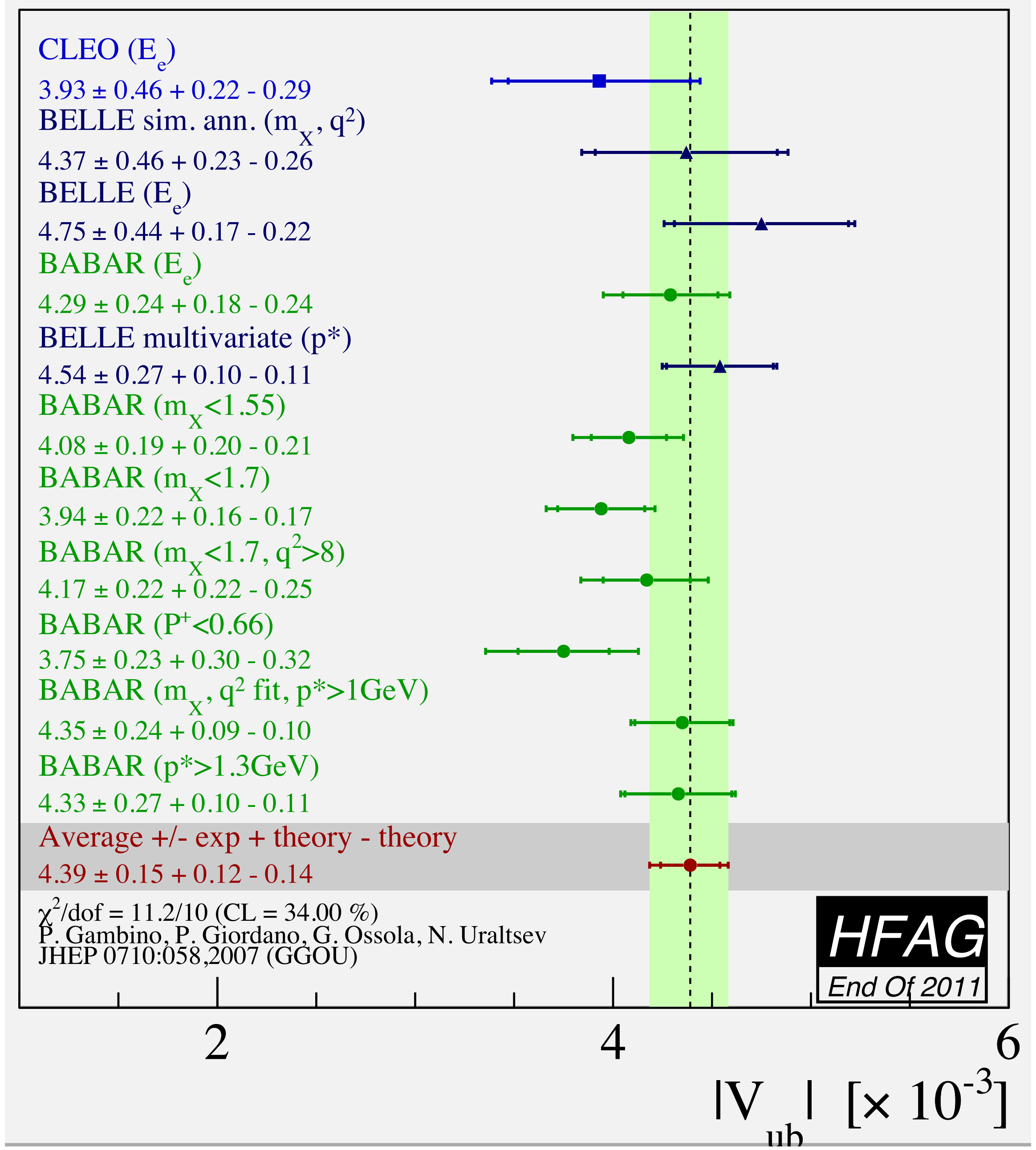
Theory	q^2, GeV$/c^2$	$\lvert V_{ub}\rvert \times 10^3$
LCSR1	< 12	$3.40 \pm 0.07^{+0.37}_{-0.32}$
LCSR2	< 16	$3.57 \pm 0.06^{+0.59}_{-0.39}$
HPQCD	> 16	$3.45 \pm 0.09^{+0.60}_{-0.39}$
FNAL/MILC	> 16	$3.30 \pm 0.09^{+0.37}_{-0.30}$

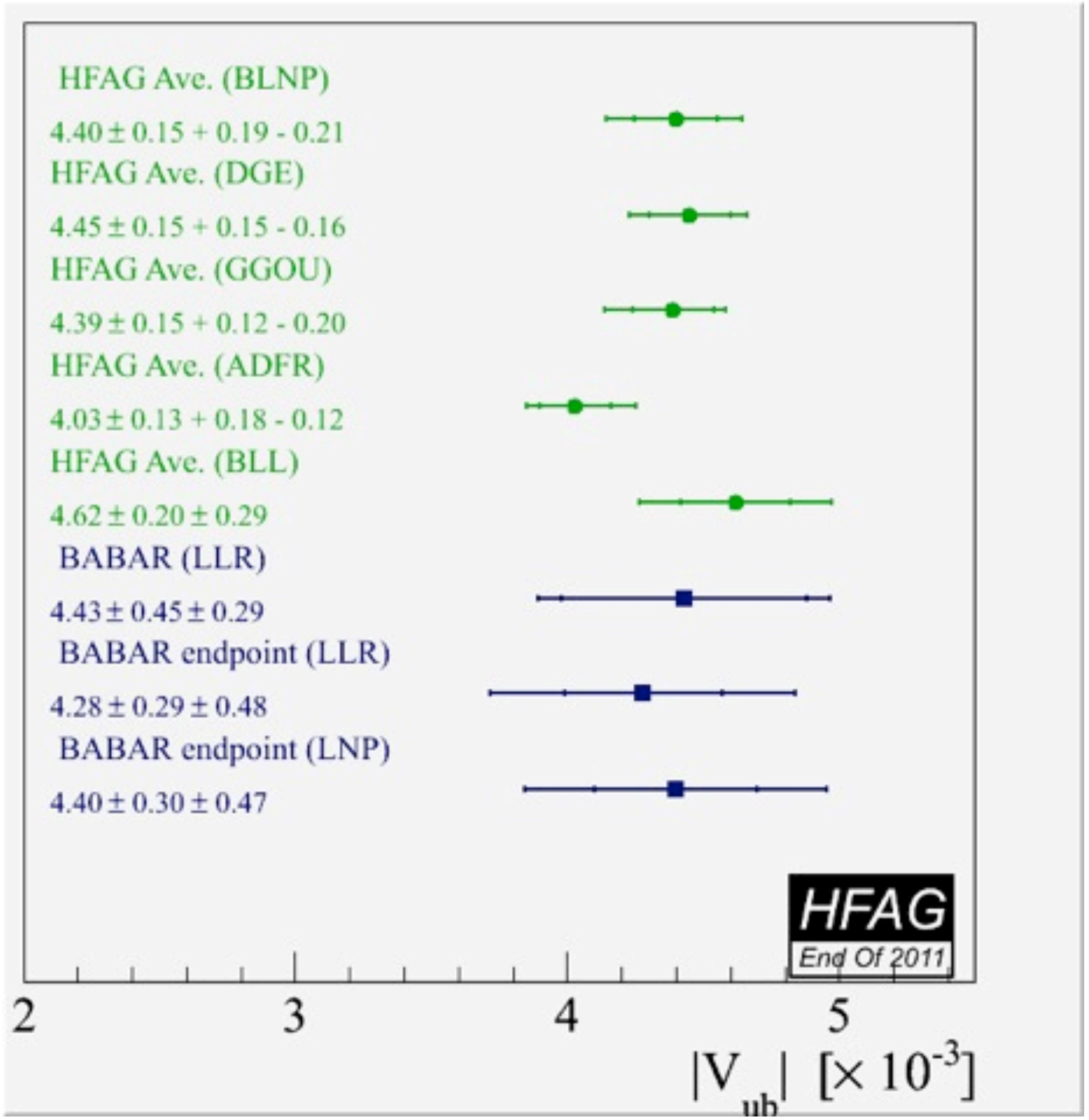
LCSR1 PRD 83 (2011) 094031 HPQCD PRD 73 (2006) 074502
LCSR2 PRD 71 (2005) 014015 FNAL/MILC PRD 79 (2009) 054507

$|V_{ub}| = (3.23 \pm 0.30) \times 10^{-3}$

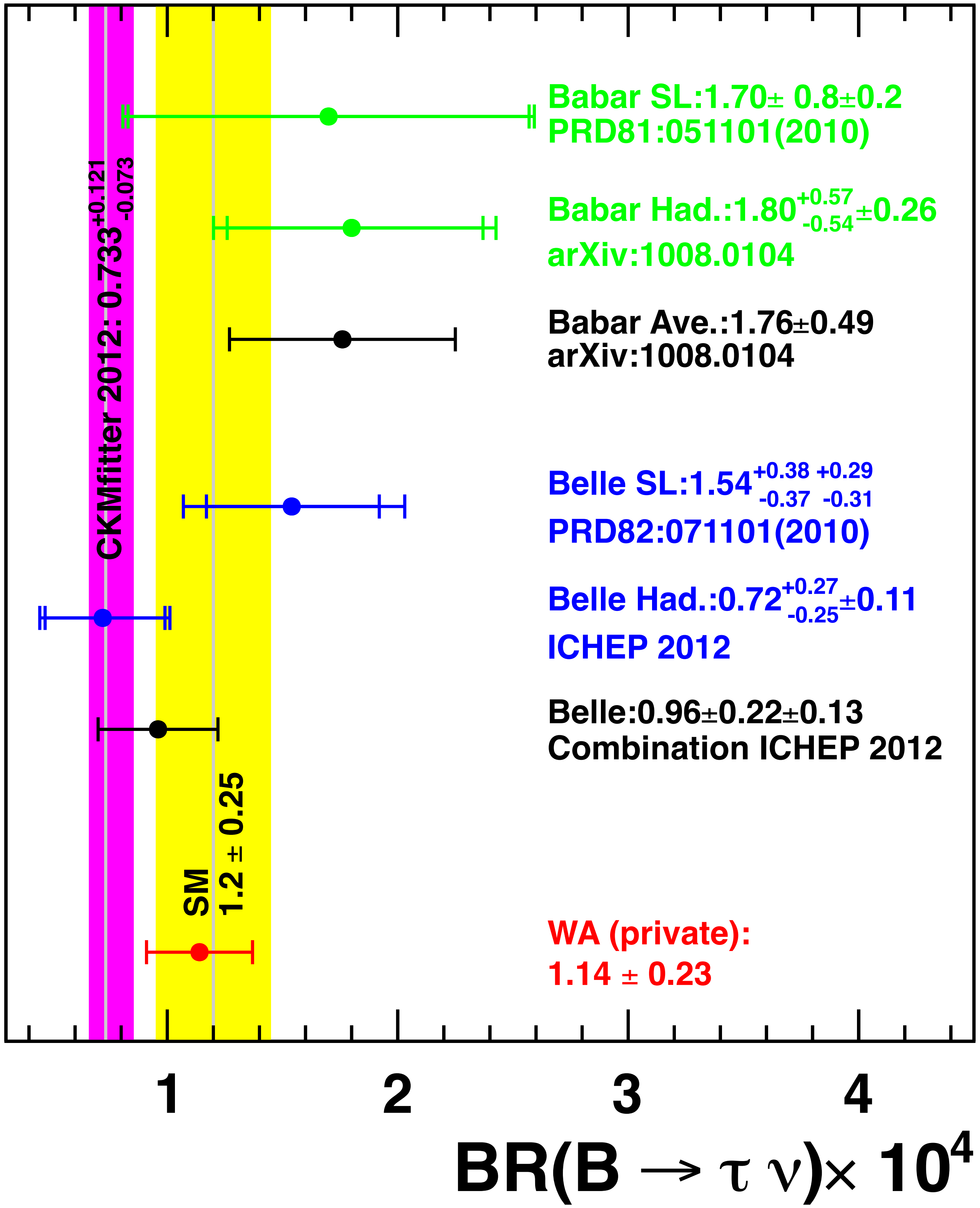


Inclusive $|V_{ub}|$ Averages





B→τν

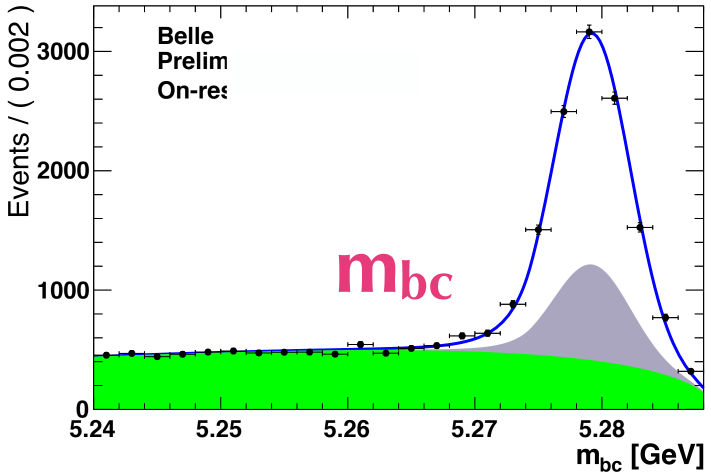


See || talk by Y.Yook

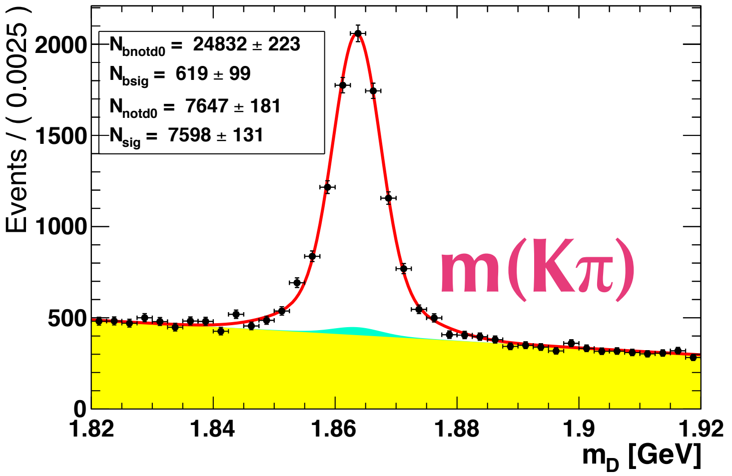
Normalising the production rates

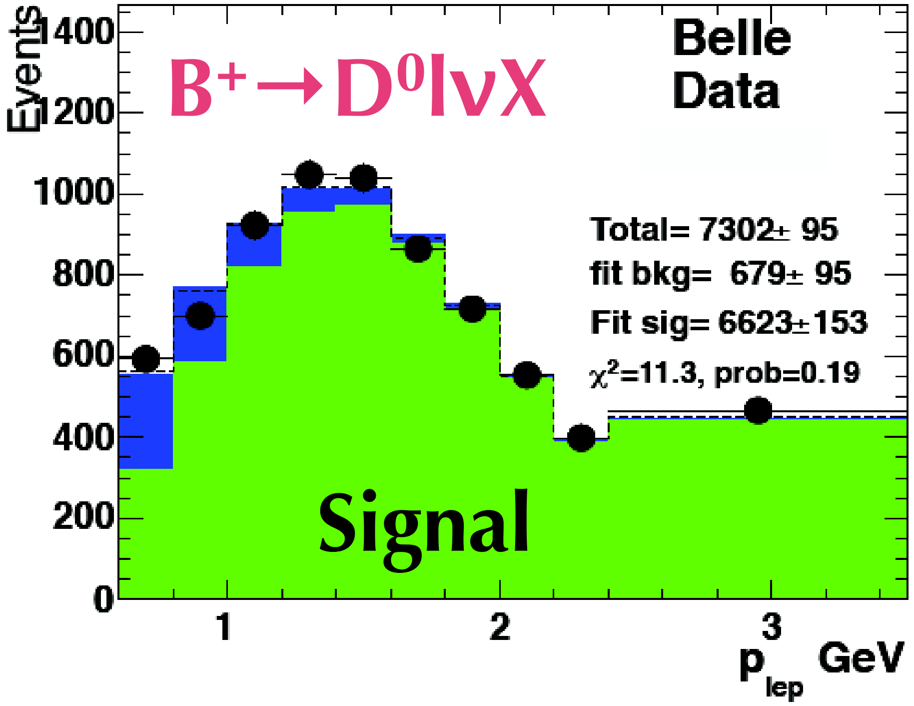
- Key ingredient - the inclusive charm+lepton final states measured for the first time at ICHEP 2012!
  - $B^{+/0}\to D^{(*)}l\nu X/B^{+/0}\to l\nu X$ using Belle's hadronic tagging method.

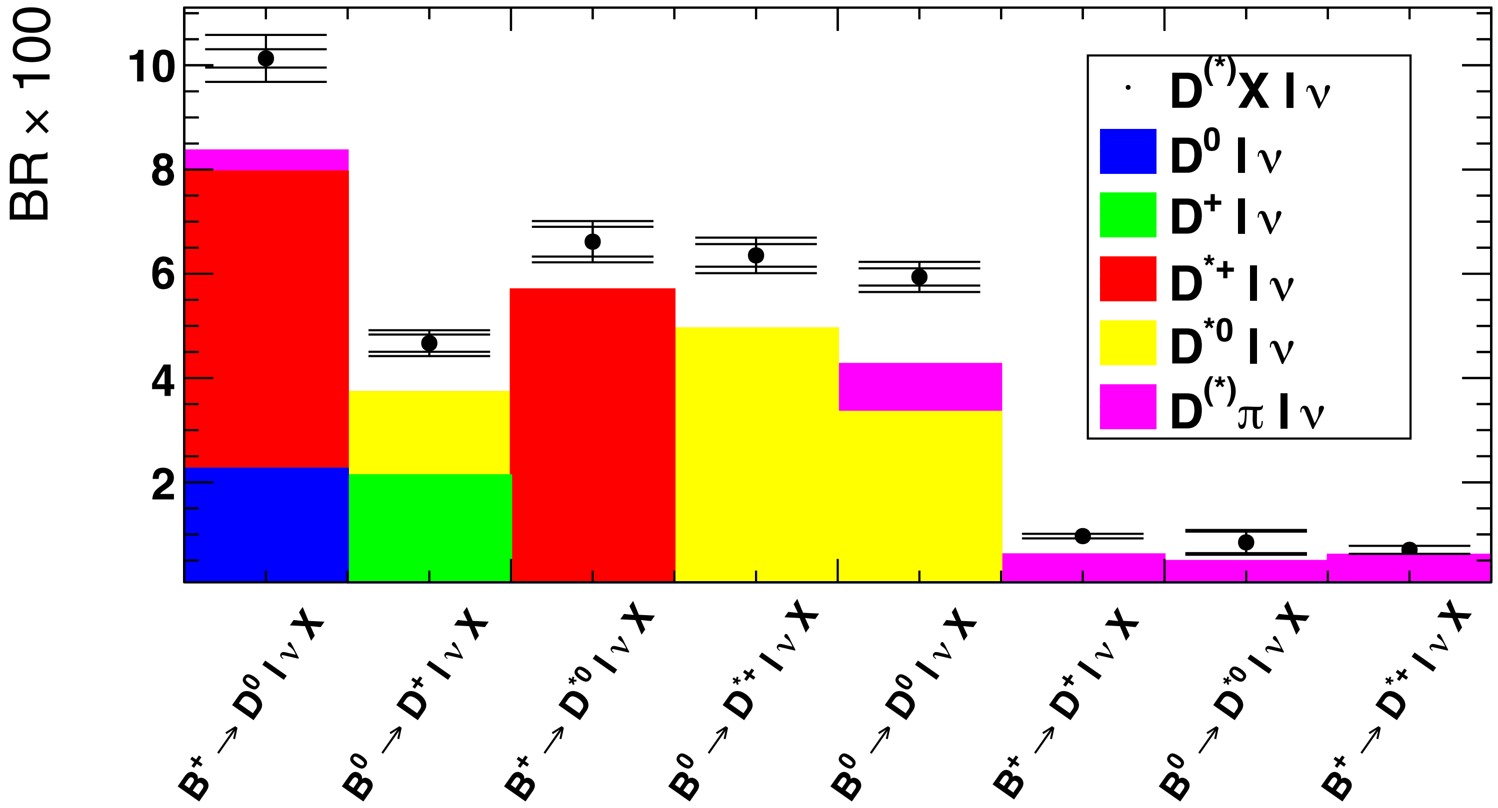
$B^0\to D^0 l\nu X$



$B^0\to D^0 l\nu X$

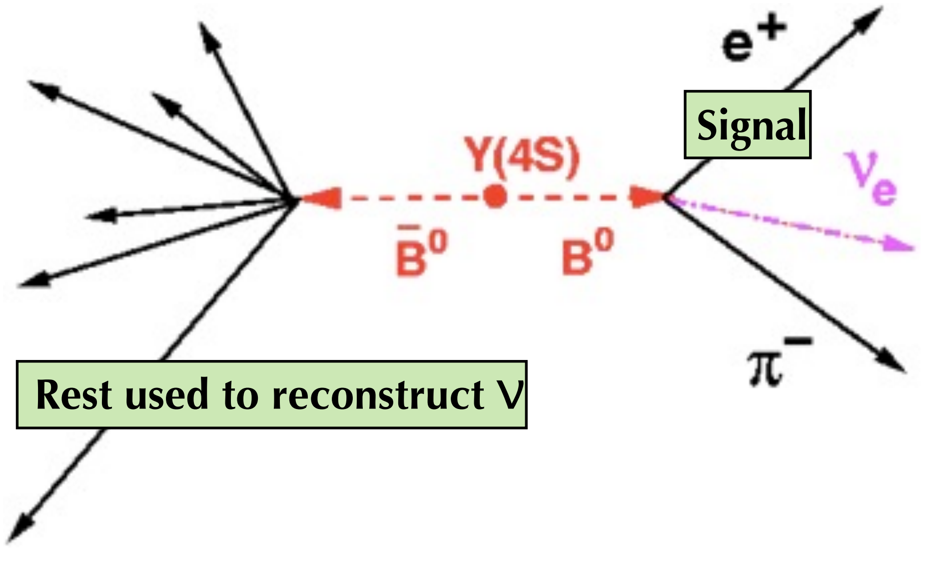
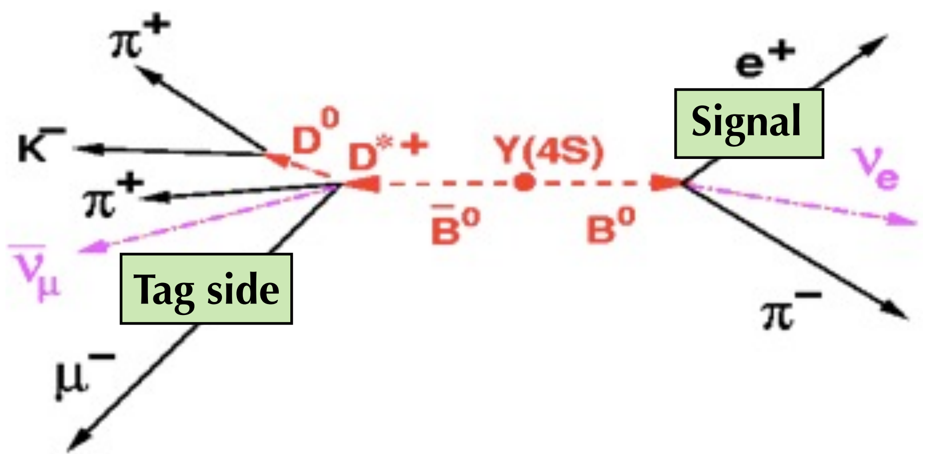






- Also sheds some light on nature of exclusive-inclusive saturation problem.

B-factory Approaches to Measuring $B \rightarrow X_u l \nu$

Untagged Initial 4-momentum known missing 4-momentum = one ν Reconstruct $B \rightarrow X_q\, l\, \nu$ using m_B (beam-constrained) and $\Delta E = E_B - E_{beam}$	
Semileptonic Tag One B reconstructed in $D^{(*)}\, l\, \nu$ modes. **Two missing ν** in event.	
Full Reconstruction Tag One B reconstructed completely in a known $b \rightarrow c$ mode without ν.