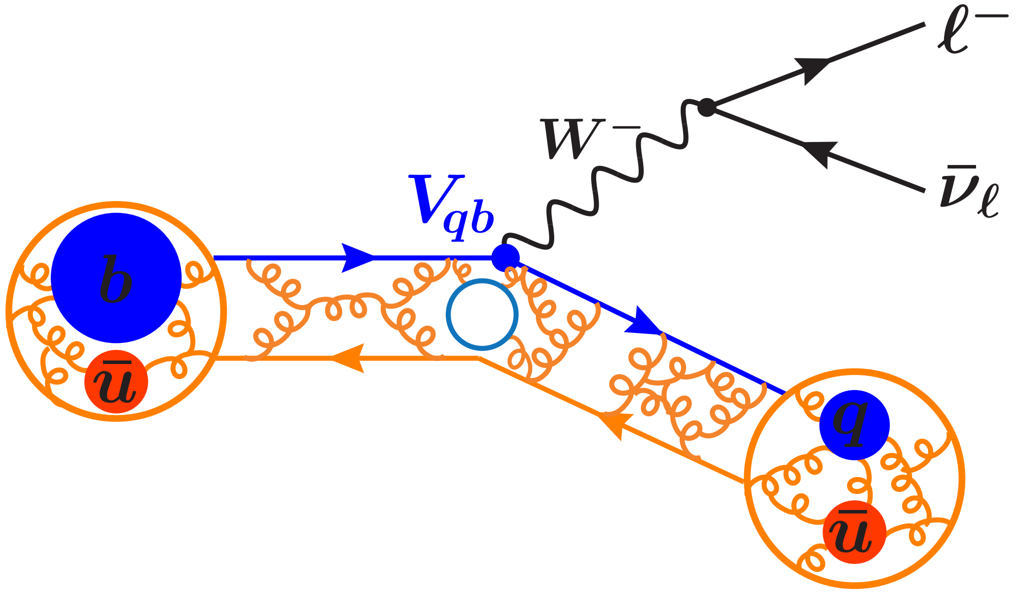


Experimental $|V_{cb}|$ Overview and prospects for Belle II

Florian Bernlochner

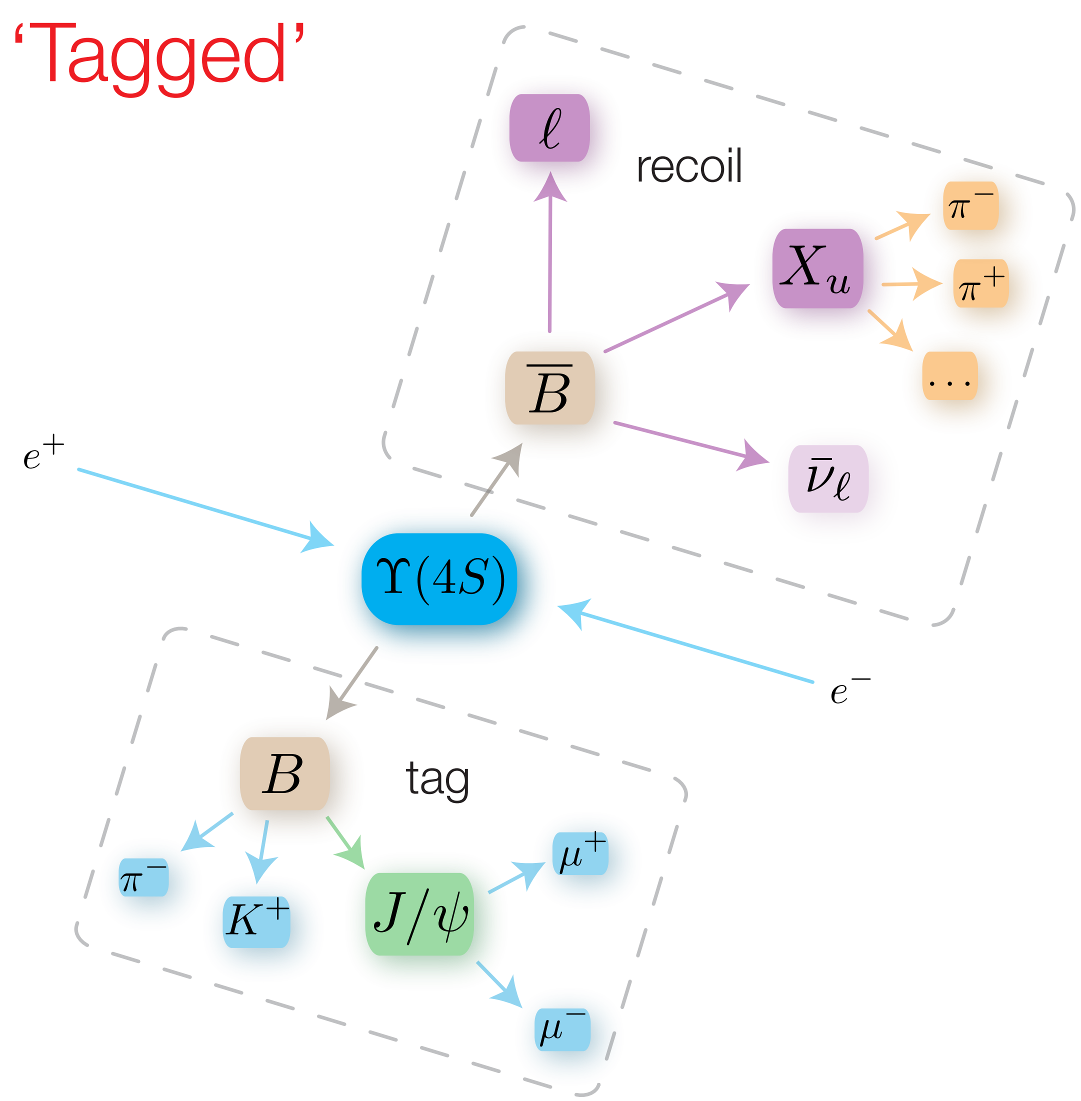
Relevant Decays

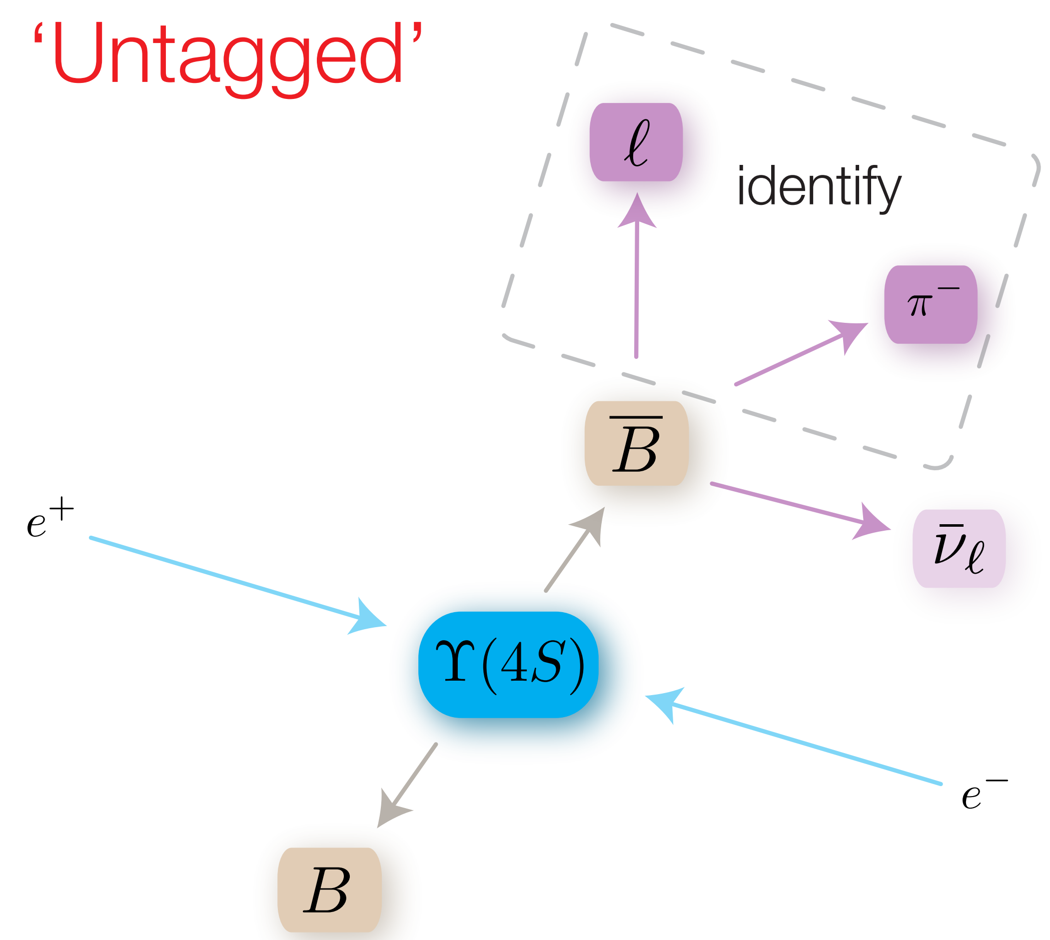
B	B_s	Λ_b
$B \to D\,\ell\,\bar{\nu}_\ell$ $B \to D^*\,\ell\,\bar{\nu}_\ell$	$B_s \to D_s^{(*)}\,\ell\,\bar{\nu}_\ell$	$\Lambda_b \to \Lambda_c\,\mu\,\bar{\nu}_\mu$
Belle II *(LHCb)*	*Belle II* *(LHCb)*	*(LHCb)*
"Golden modes"	*Challenging*	*Talk from Jeroen!*

$$B$$

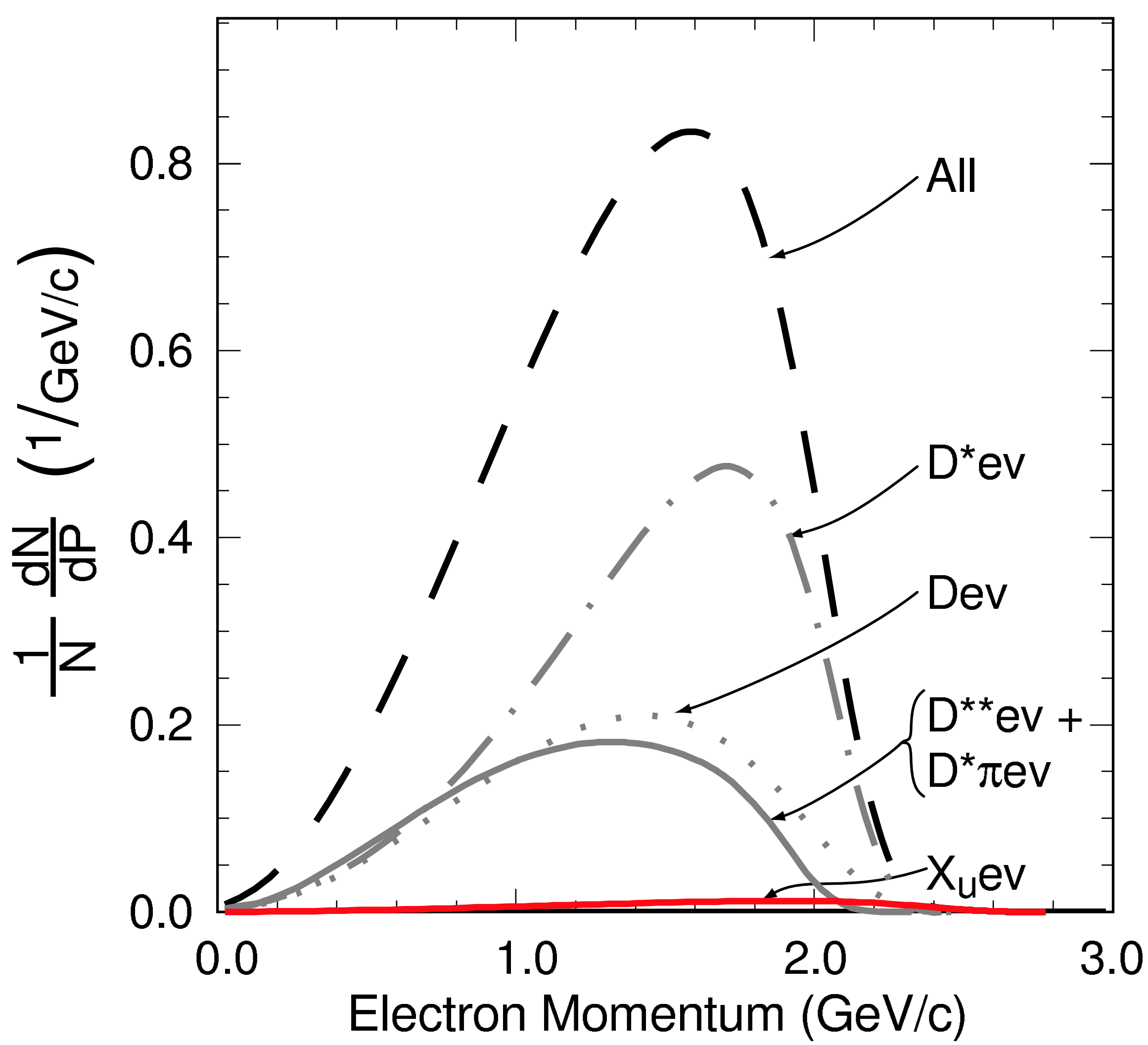
$$B \to D\,\ell\,\bar{\nu}_\ell$$
$$B \to D^*\,\ell\,\bar{\nu}_\ell$$

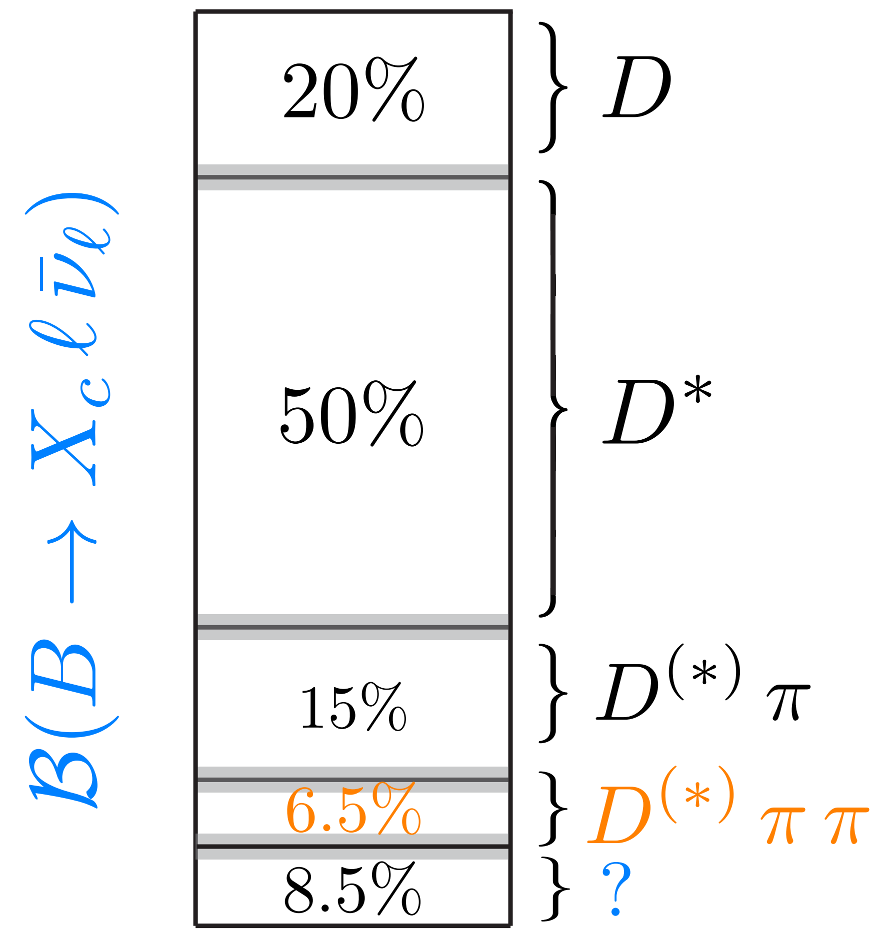
Tagged versus untagged





- Trade off between purity+resolution and efficiency

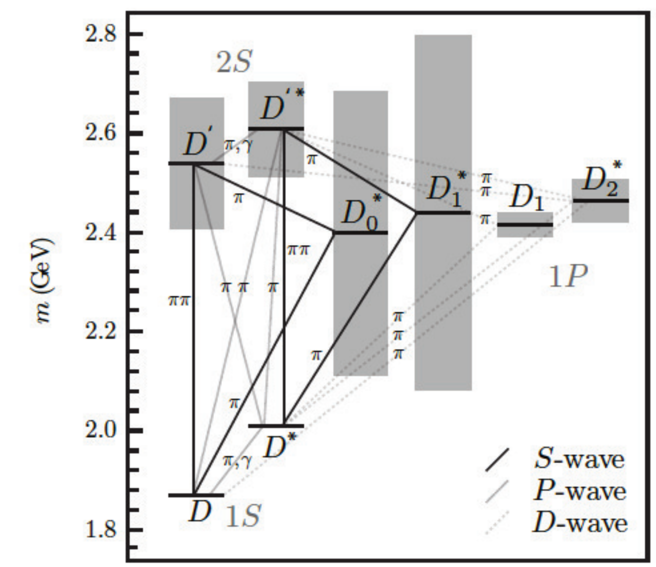




- Typical analysis reconstructs D & D* mesons
  - Problem for lowest mass state: easy mis-categorization due to missing particles which need to be modelled adequately.
- Can reduce background by reconstructing neutrino momentum
  - Makes sure that neutrino is the only missing particle

Experimental Recap

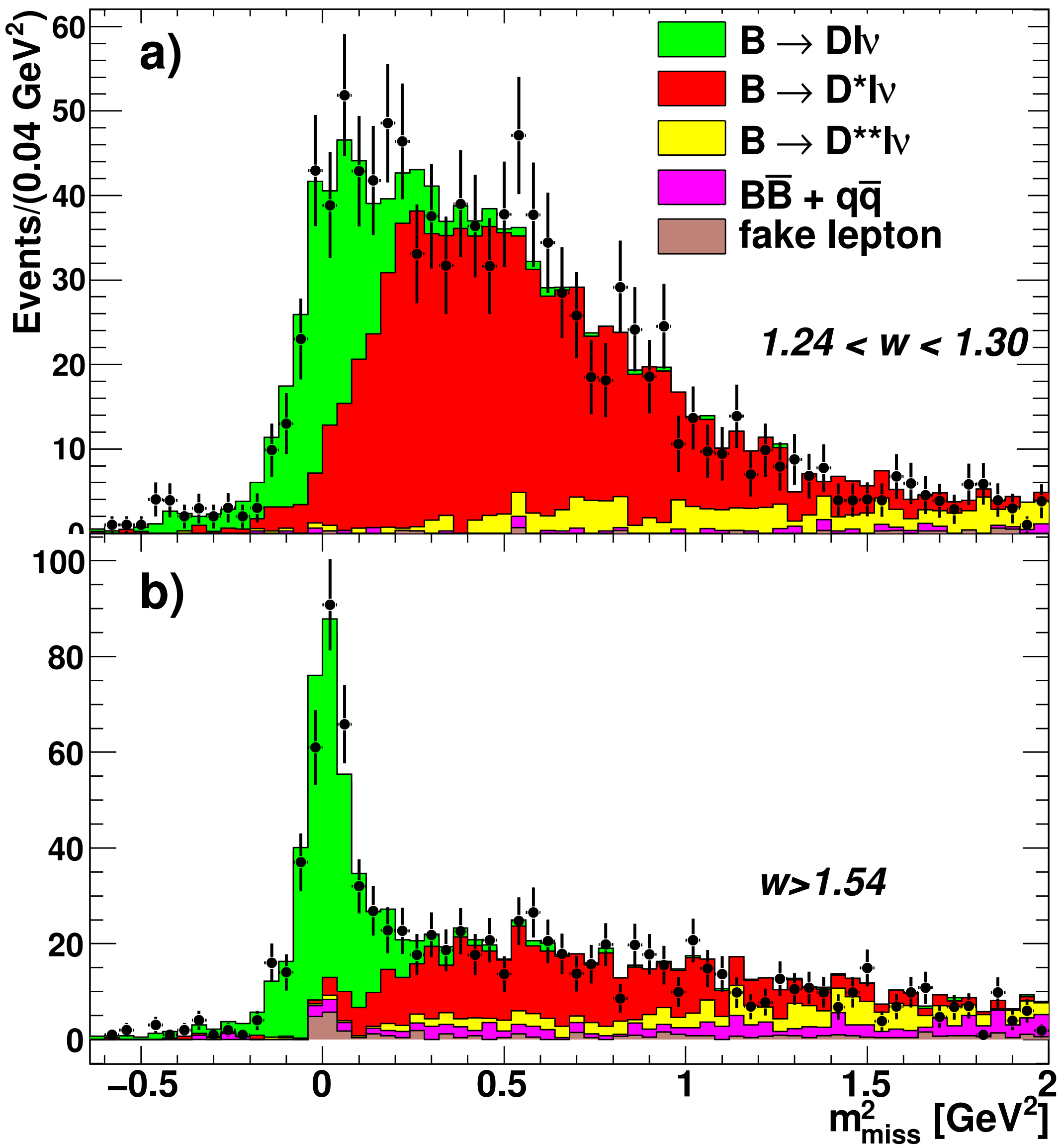
$B \to D\,\ell\,\bar{\nu}_\ell$

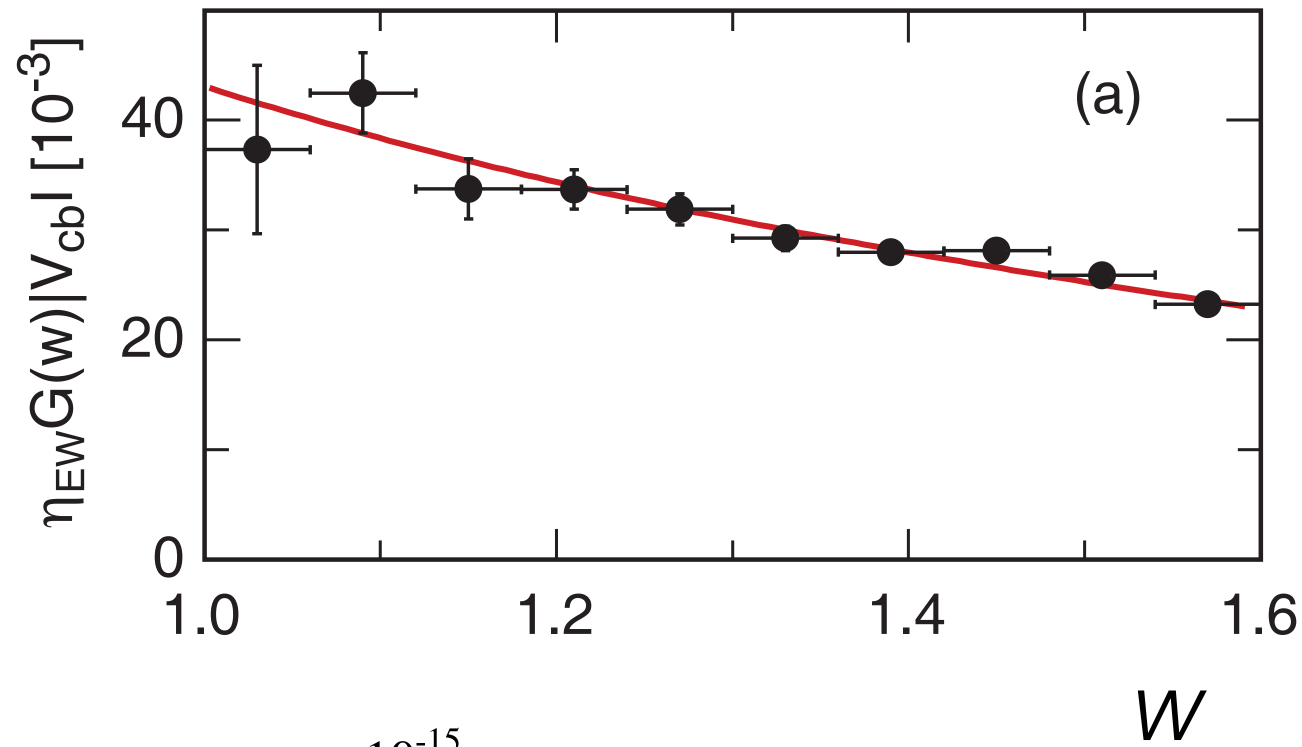


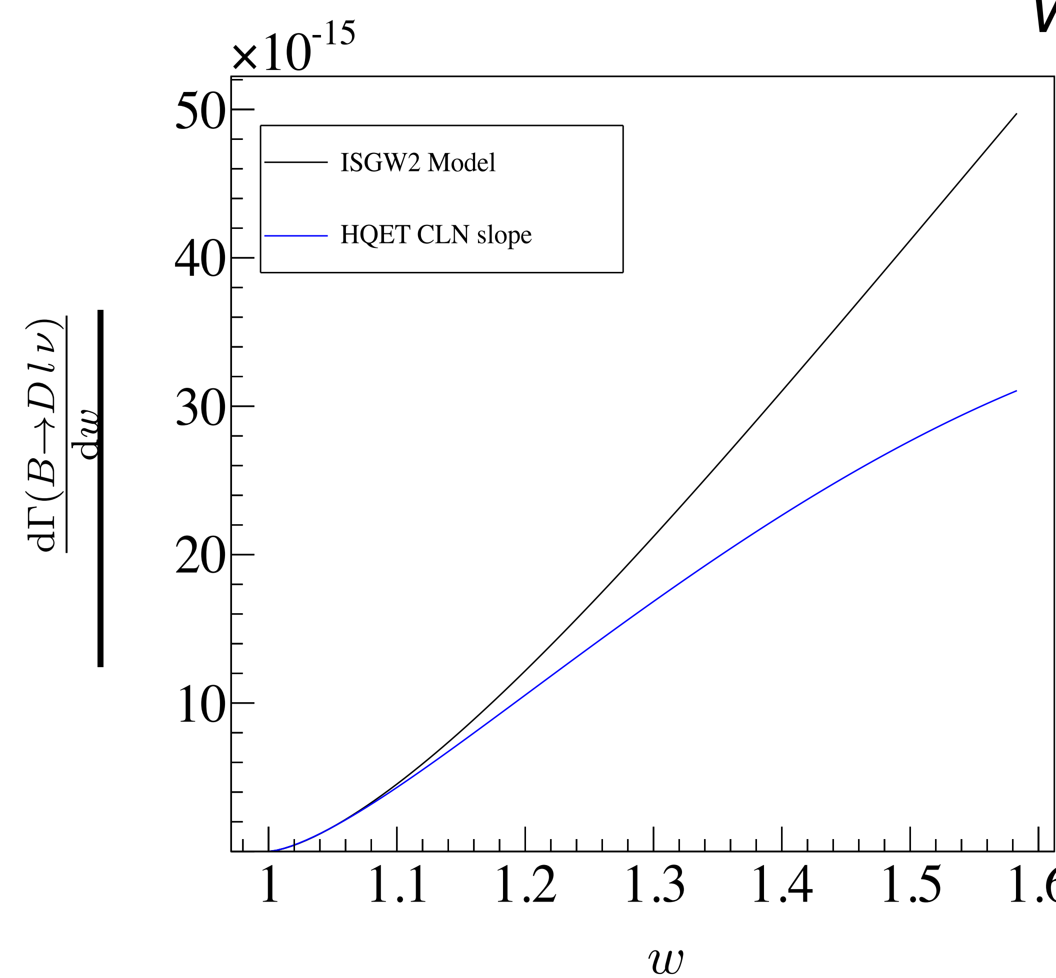
- Challenging due to…
  - large background from 'down-feed' from D*
  - combinatorial background from wrongly reconstructed D-meson candidates
  - Tagged analyses have smaller background
- Measurements from ALEPH (Buskulic et al, 1997), CLEO (Bartelt et al, 1999), Belle (Abe et al, 2002), BaBar (Aubert et al, 2009,2010), …
  - Most precise published measurement is from BaBar
    - hadronic tag
    - branching fraction measured as a function of $w = v_B * v_D$
    - D-mesons reconstructed in a variety of decay modes
    - Signal & Background separation in $m^2_{\mathrm{miss}} = (E_{\mathrm{miss}}, p_{\mathrm{miss}})^2$

Experimental Recap

$B \to D\,\ell\,\bar{\nu}_\ell$







Current world average (HFAG 2014)

$$\rho_D^2 = 1.19 \pm 0.05,$$
$$\eta_{\rm EW}\mathcal{G}(1)|V_{cb}| = (42.65 \pm 1.53) \times 10^{-3}.$$

Experimental Recap $B \to D\,\ell\,\bar{\nu}_\ell$

- Various measurement consistency:
    - Pretty good, the prob. is close to 1 (hinting that some uncertainties spoil the systematic interpretation of this number)

Systematic limited

$B \to D\ell\nu$	$\mathcal{B}$ (%)	$\eta_{\mathrm{EW}}\mathcal{G}(1)\lvert V_{cb}\rvert$ (10^{-3})	ρ_D^2
CLEO untagged (Bartelt *et al.*, 1999)	$2.19 \pm 0.16 \pm 0.35$	$44.88 \pm 5.96 \pm 3.25$	$1.27 \pm 0.22 \pm 0.12$
Belle untagged (Abe *et al.*, 2002)	$2.08 \pm 0.12 \pm 0.52$	$40.96 \pm 4.39 \pm 5.03$	$1.12 \pm 0.19 \pm 0.11$
BABAR hadronic-tag (Aubert *et al.*, 2010c)	$2.14 \pm 0.11 \pm 0.08$	$42.45 \pm 1.88 \pm 1.02$	$1.18 \pm 0.09 \pm 0.06$
BABAR global fit (Aubert *et al.*, 2009d)	$2.16 \pm 0.03 \pm 0.13$	$43.25 \pm 0.80 \pm 2.07$	$1.20 \pm 0.04 \pm 0.06$
HFAG average (Amhis *et al.*, 2014)	$2.13 \pm 0.03 \pm 0.09$	$42.65 \pm 0.72 \pm 1.35$	$1.19 \pm 0.04 \pm 0.04$

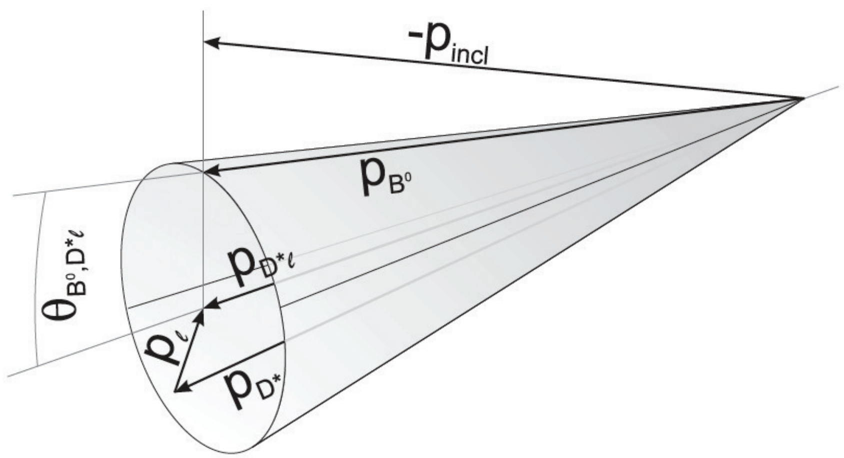
Experimental Recap $B \to D^* \ell \bar{\nu}_\ell$

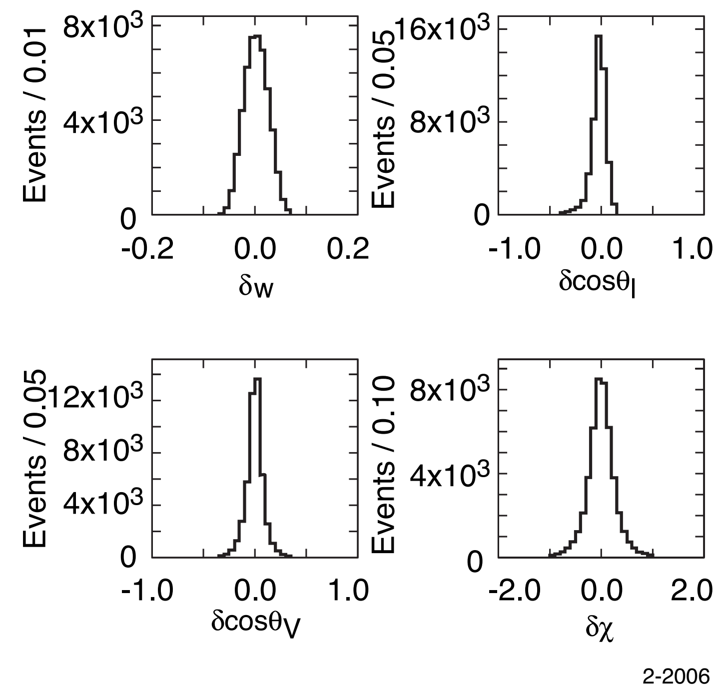
- Challenges
  - ‘down-feed’ from D**
  - slow pion (in)efficiency — problematic particularly at w ~ 1 (small D* momentum)
- Measurements from ALEPH (Buskulic et al, 1997), CLEO (Dubosq et al 1996, Briere et al, 1997), OPAL (Abbiendi et al, 2000), BaBar (Aubert et al, 2008, 2009), Belle (Dungel et al, 2010), …
- First fully differential analysis was from CLEO (Dubosq et al 1996)
  - Determined the parameters $R_1(1)$, $R_2(1)$, ρ_{D^*} in a fit to 1D projections of the four variables defining the differential rate taking into account statistical cross correlations.
    - (q^2, 2 helicity angles & tilting angle between the decay planes)
- BaBar and Belle followed measuring branching fraction and form factor parameters based on the same approach.

Experimental Recap

$B \to D^* \ell \bar{\nu}_\ell$

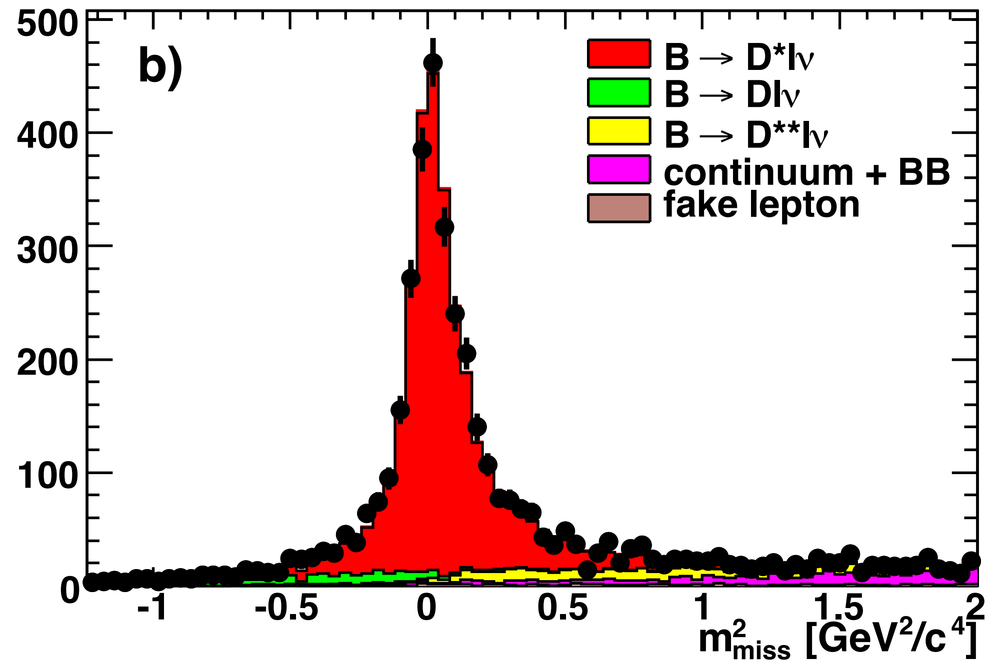
- Untagged results are competitive with tagged ones
- Due to the unknown direction of the neutrino in untagged analyses, the helicity angles and w have to be approximated by averaging over all possible B-meson directions (which are constrained around a cone of the D*l system)





- Eventually full 4D fit analyses appeared (Aubert et al, 2006) that did a fit to the fully differential decay rate.
- In addition a global fit approach, that simultaneously extracted D & D* form factor parameters and normalizations also showed very good sensitivity (and has the smallest experimental uncertainties)

Experimental Recap $B \to D^* \ell \bar{\nu}_\ell$



Tagged analyses have very high purity

- Overall picture of B-Factory results fairly consistent
    - Agreement fair, the probability is 0.15

Current world average (HFAG 2014)

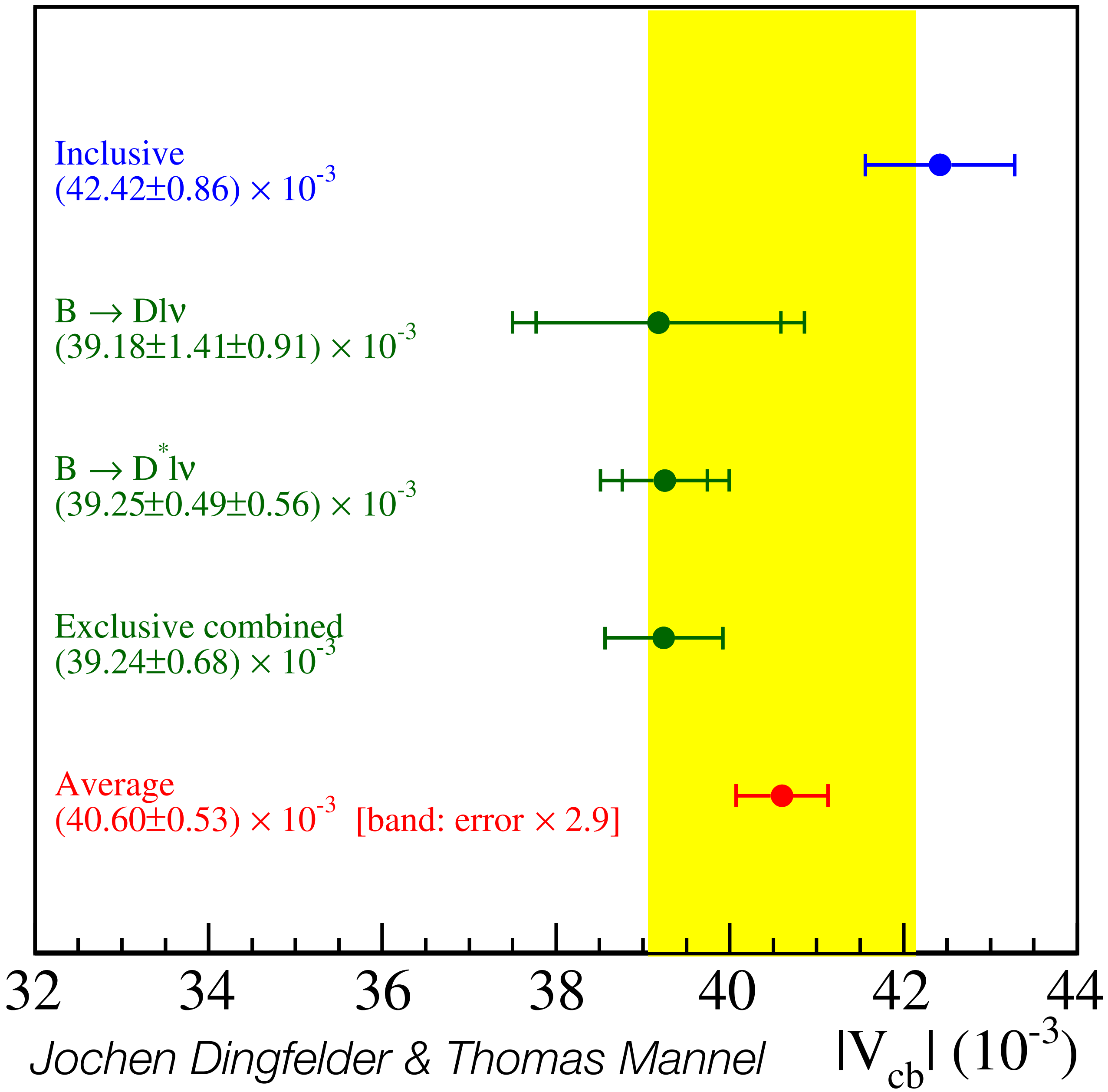
Systematic limited

$B \to D^* \ell \nu$	$\mathcal{B}$ (%)	$\eta_{EW}\mathcal{F}(1)\lvert V_{cb}\rvert$ (10^{-3})	$\rho^2_{D^*}$
CLEO untagged (Briere *et al.*, 2002)	$5.62 \pm 0.18 \pm 0.26$	$39.94 \pm 1.23 \pm 1.63$	$1.37 \pm 0.09 \pm 0.09$
Belle untagged (Dungel *et al.*, 2010)	$4.56 \pm 0.03 \pm 0.26$	$34.60 \pm 0.17 \pm 1.02$	$1.21 \pm 0.03 \pm 0.01$
BABAR untagged $B^0 \to D^{*-}\ell^+\nu$ (Aubert *et al.*, 2008b)	$4.54 \pm 0.04 \pm 0.25$	$33.94 \pm 0.30 \pm 0.99$	$1.19 \pm 0.05 \pm 0.03$
BABAR untagged $B^+ \to \overline{D}^{*0}\ell^+\nu$ (Aubert *et al.*, 2008d)	$4.97 \pm 0.07 \pm 0.34$	$35.22 \pm 0.59 \pm 1.33$	$1.13 \pm 0.06 \pm 0.06$
BABAR global fit (Aubert *et al.*, 2009d)	$4.95 \pm 0.02 \pm 0.20$	$35.76 \pm 0.20 \pm 1.10$	$1.19 \pm 0.02 \pm 0.06$
HFAG average (Amhis *et al.*, 2014)	$4.93 \pm 0.01 \pm 0.11$	$35.81 \pm 0.11 \pm 0.44$	$1.21 \pm 0.02 \pm 0.02$

- Using the latest inputs for the form factor normalization at w = 1:

$$\mathcal{F}(1) = 0.906 \pm 0.013, \qquad \mathcal{G}(1) = 1.081 \pm 0.025\,,$$

Fermilab/MILC: Bailey et al, 2014 *Fermilab/MILC: Qui et al, 2014*



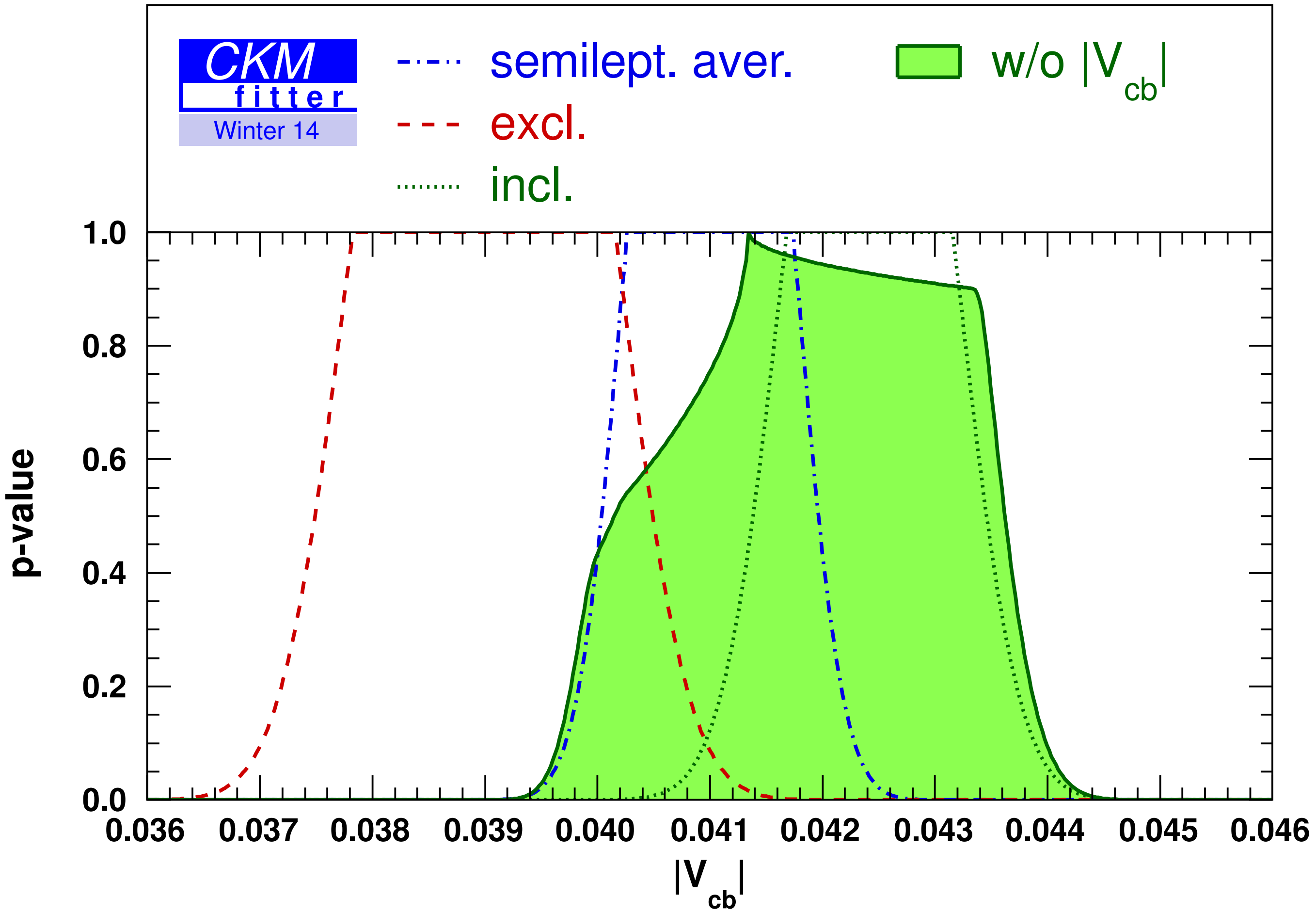
Jochen Dingfelder & Thomas Mannel

- Exclusive only, very consistent picture.
- O(3 sigma) tension between inclusive & exclusive

- Using the latest inputs for the form factor normalization at w = 1:

$$\mathcal{F}(1) = 0.906 \pm 0.013, \qquad \mathcal{G}(1) = 1.081 \pm 0.025\,,$$

Fermilab/MILC: Bailey et al, 2014 *Fermilab/MILC: Qui et al, 2014*



- Exclusive only, very consistent picture.
- O(3 sigma) tension between inclusive & exclusive
- CKM Unitarity finds a value roughly in between

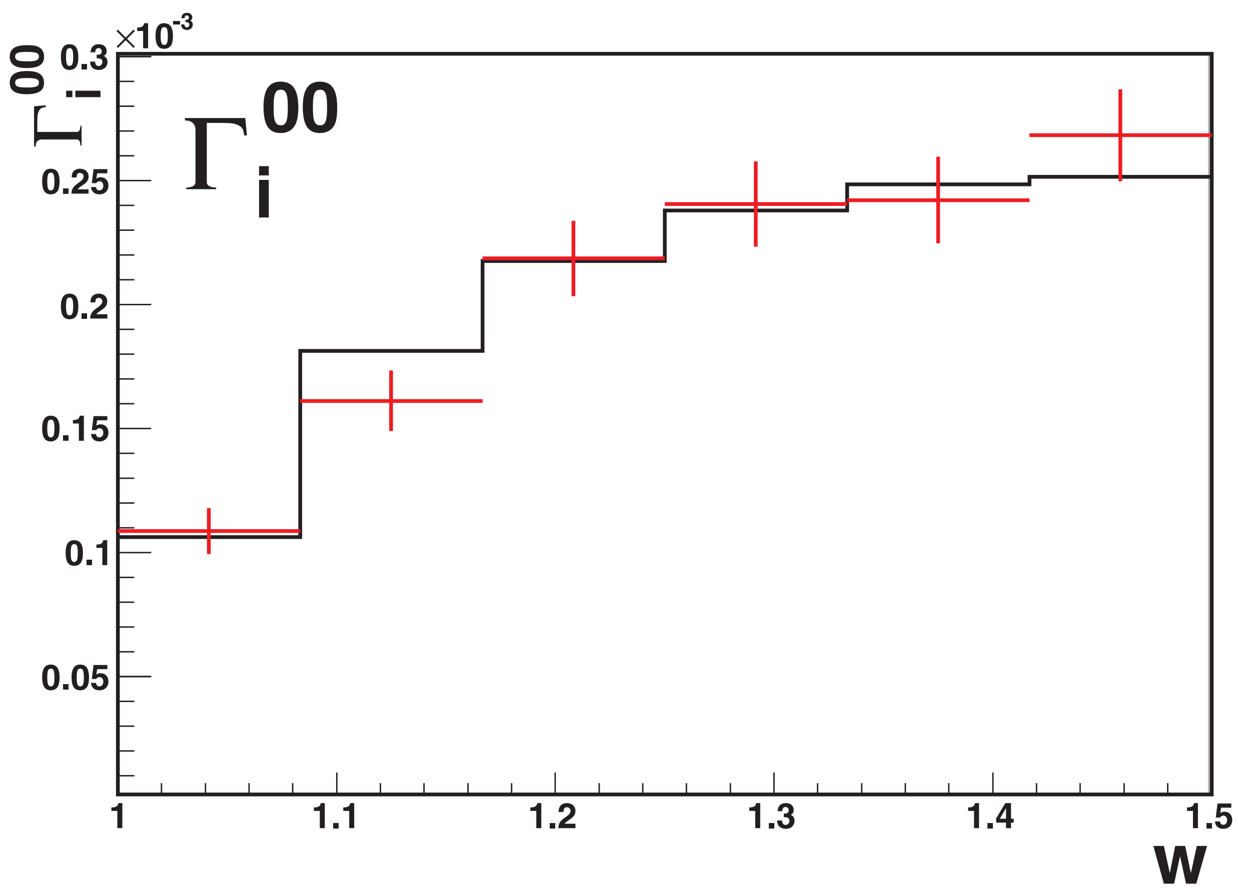
Experimental tests of the CLN parametrization

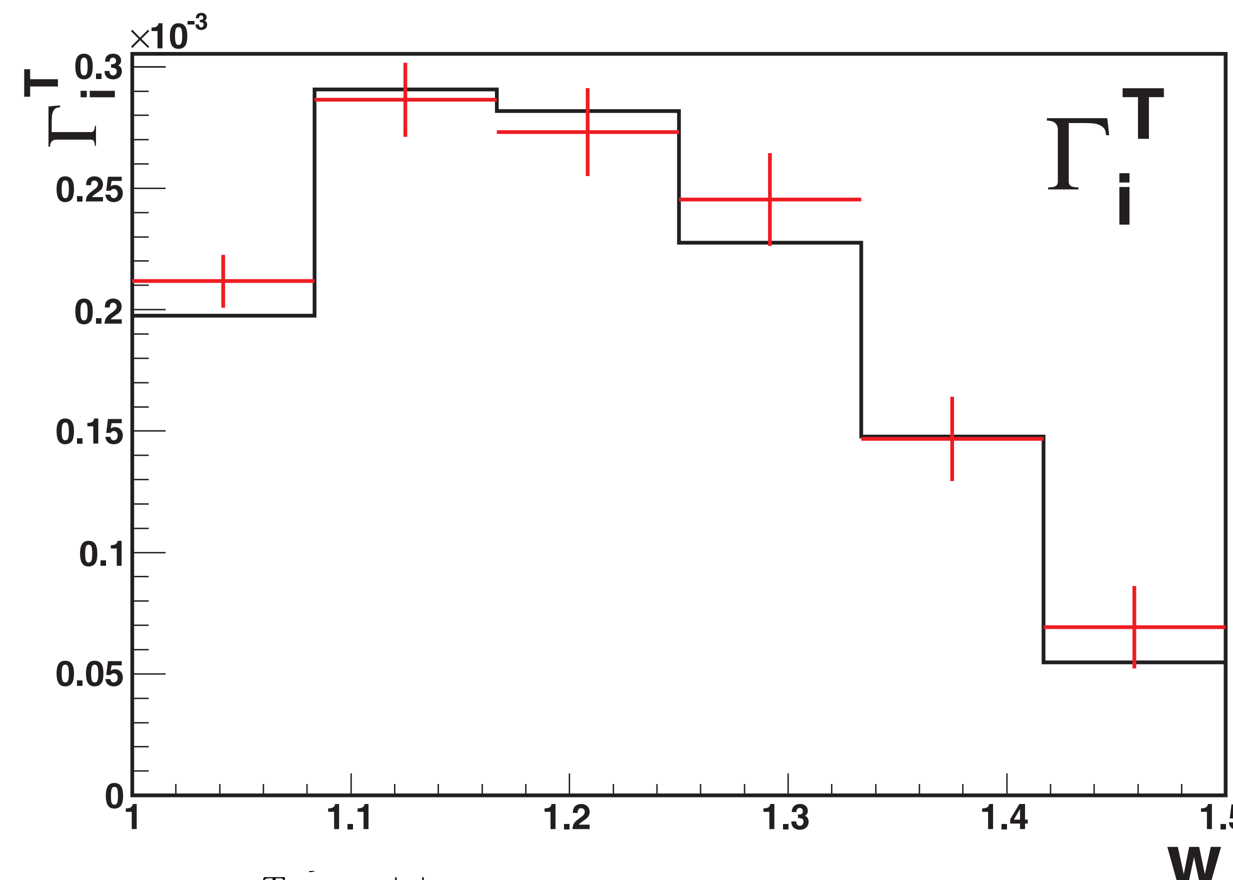
Belle, arXiv:0910.3534v1

- Test of the CLN parametrization by fitting helicity amplitudes and confronting them with fits from the CLN parametrization.

$$\frac{\mathrm{d}\Gamma(B^+ \to \bar{D}^{*0}\ell^+\nu_\ell)}{\mathrm{d}w} = \frac{64\pi}{9} F_\Gamma \left(\gamma^{++} + \gamma^{--} + \gamma^{00}\right).$$

$$\Gamma_i^{kk} = \int_{w_i}^{w_{i+1}} \mathrm{d}w\ \gamma^{kk},$$



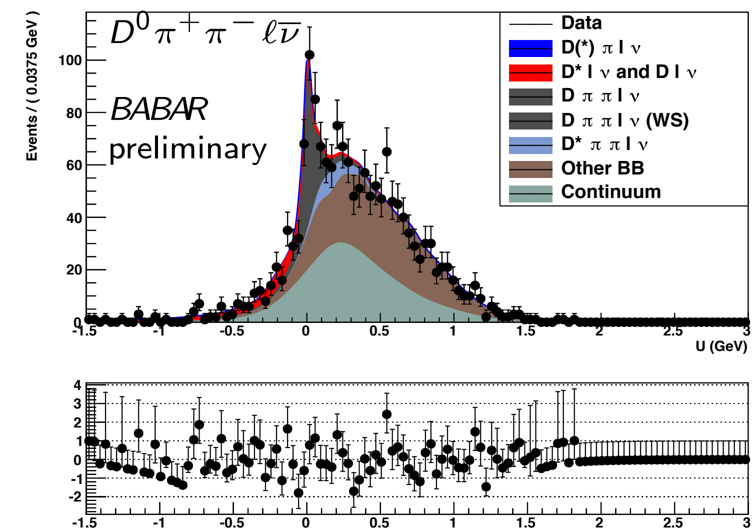


$\Gamma_i^T = \Gamma_i^{++} + \Gamma_i^{--}$

So where can we improve in untagged meas.?

item	Electron sample					
	ρ_D^2	$\rho_{D^*}^2$	$\mathcal{B}(D\ell\overline{\nu})$	$\mathcal{B}(D^*\ell\overline{\nu})$	$\mathcal{G}(1)\|V_{cb}\|$	$\mathcal{F}(1)\|V_{cb}\|$
R_1'	0.44	2.74	0.71	−0.38	0.60	0.71
R_2'	−0.40	1.02	−0.18	0.30	−0.32	0.49
D^{**} slope	−1.42	−2.52	−0.07	−0.09	−0.82	−0.87
D^{**} FF approximation	−0.87	0.33	−0.12	0.19	−0.54	0.20
$\mathcal{B}(B^- \to D^{(*)}\pi\ell\overline{\nu})$	0.28	−0.27	−0.22	−0.80	0.04	−0.49
$f_{D_2^*/D_1}$	−0.39	0.16	−0.38	0.16	−0.41	0.13
$f_{D_0^* D\pi/D_1 D_2^*}$	−2.30	1.12	−1.53	0.97	−2.07	0.85
$f_{D_1' D^*\pi/D_1 D_2^*}$	1.82	−1.14	1.30	−0.65	1.65	−0.70
$f_{D\pi/D_0^*}$	−0.88	−1.28	0.36	0.17	−0.31	−0.34
$f_{D^*\pi/D_1'}$	−0.21	−0.05	−0.13	0.21	−0.18	0.09
NR D^*/D ratio	0.58	−0.16	0.11	−0.09	0.38	−0.04
$\mathcal{B}(B^- \to D^{(*)}\pi\pi\ell\overline{\nu})$	1.19	−1.97	0.25	−1.28	0.78	−1.28
X^*/X and Y^*/Y ratio	0.61	−1.15	0.09	−0.27	0.39	−0.52
X/Y and X^*/Y^* ratio	0.76	−0.83	0.21	−0.65	0.52	−0.60
$D_1 \to D\pi\pi$	2.22	−1.54	0.74	−1.08	1.63	−1.05
$f_{D_2^*}$	−0.14	−0.01	−0.10	0.07	−0.12	0.03
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.73	−0.01	0.43	−0.34	0.62	−0.17
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.69	0.02	−0.21	−1.63	0.29	−0.80
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	−1.46	−0.42	−2.17	0.30	−1.89	0.01
τ_{B^-}/τ_{B^0}	0.26	0.16	0.63	0.27	0.46	0.19
f_{+-}/f_{00}	0.88	0.43	0.66	−0.53	0.82	−0.12
Number of $B\overline{B}$ events	0.00	−0.00	−1.11	−1.11	−0.55	−0.55
Off-peak Luminosity	0.05	0.01	−0.02	−0.00	0.02	0.00
B momentum distrib.	−0.96	0.63	1.29	−0.54	−1.15	0.48
Lepton PID eff	0.52	0.16	1.21	0.82	0.90	0.46
Lepton mis-ID	0.03	0.01	−0.01	−0.01	0.01	−0.00
Kaon PID	0.07	0.80	0.28	0.23	0.18	0.38
Tracking eff	−1.02	−0.43	−3.35	−2.00	−2.25	−1.15
Radiative corrections	−3.13	−1.04	−2.87	−0.74	−3.02	−0.71
Bremsstrahlung	0.07	0.00	−0.13	−0.28	−0.04	−0.14
Vertexing	0.83	−0.64	0.63	0.60	0.78	0.09
Background total	1.39	1.12	0.64	0.34	1.07	0.51
Total	**6.25**	**5.66**	**6.01**	**4.03**	**5.99**	**3.20**

$B \to D^{**}$



D Decays

Detector Performance

QED FSR

So where can we improve in tagged meas.?

	Systematic uncertainty on $\lvert V_{cb}\rvert$, ρ^2 and BF								
	$D^0\ell^-\bar{\nu}_\ell$			$D^+\ell^-\bar{\nu}_\ell$			$D\ell^-\bar{\nu}_\ell$		
	$\lvert V_{cb}\rvert(\%)$	ρ^2	BF (%)	$\lvert V_{cb}\rvert(\%)$	ρ^2	BF (%)	$\lvert V_{cb}\rvert(\%)$	ρ^2	BF (%)
Tracking efficiency	0.5	0.008	0.7	1.1	0.003	1.4	0.7	0.004	1.0
Neutral reconstruction	1.0	0.003	1.2	0.8	0.006	0.9	0.9	0.004	1.2
Lepton ID	1.0	0.009	1.0	0.9	0.009	0.8	0.9	0.009	0.9
Final State Radiation	0.1	0.005	0.2	0.1	0.005	0.2	0.1	0.005	0.2
Cascade $\overline{B} \to X \to \ell^-$ decay background	0.6	-	1.2	1.0	-	2.0	0.8	-	1.5
$B^0 - B^\pm$ cross-feed	0.2	0.003	0.2	0.2	0.003	0.2	0.2	0.003	0.2
$\overline{B} \to D^*\ell^-\bar{\nu}_\ell$ form factors	0.6	0.008	0.5	0.2	0.003	0.2	0.4	0.006	0.3
$\overline{B} \to D^{**}\ell^-\bar{\nu}_\ell$ form factors	0.2	0.007	0.2	0.3	0.006	0.2	0.3	0.007	0.1
D branching fractions	1.0	-	2.0	1.4	-	2.7	1.1	-	2.2
$\mathcal{B}(\overline{B} \to D^{**}\ell^-\bar{\nu}_\ell)$	1.2	0.023	0.6	1.0	0.011	0.9	1.1	0.019	0.6
$\mathcal{B}(\overline{B} \to X\ell^-\bar{\nu}_\ell)$	0.9	-	1.9	0.9	-	1.9	0.8	-	1.7
$B_{\rm tag}$ selection	1.1	0.021	0.6	1.8	0.036	0.8	1.5	0.028	0.8
$\overline{B} \to X\ell^-\bar{\nu}_\ell$ fit	0.7	-	1.4	1.1	-	2.2	0.8	-	1.7
$\overline{B} \to D\ell^-\bar{\nu}_\ell$ fit	1.3	0.018	1.1	1.1	0.027	0.6	1.3	0.020	0.8
B meson lifetime	-	-	0.7	-	-	0.6	-	-	0.6
Total systematic error	3.1	0.04	4.1	3.6	0.05	5.0	3.3	0.04	4.3

Detector Performance

D Decays

QED FSR

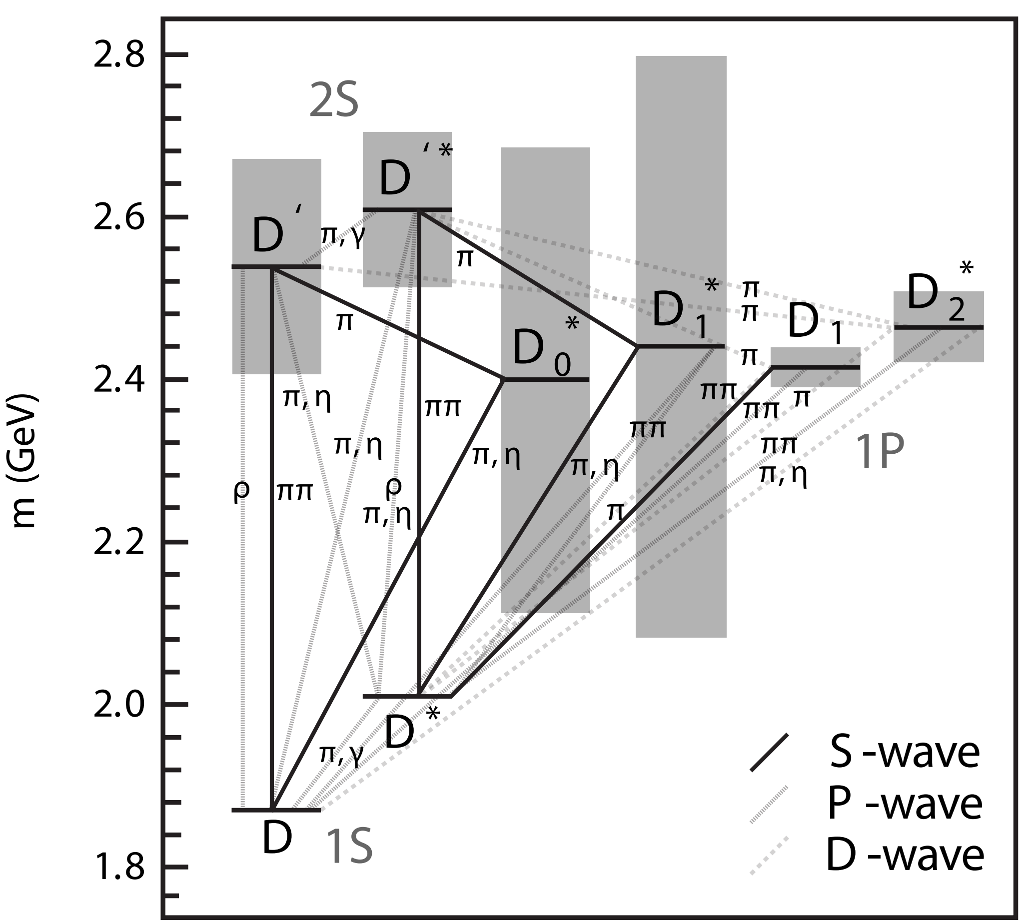
$B \to D^{**}$

Cascades

$B \to X$ SL background

D**

- Further constraining the broad orbital decays will be very challenging.
  - but analyses very statistic limited at this point
  - Very little is known for D** to D n pi for n = 2 and higher.



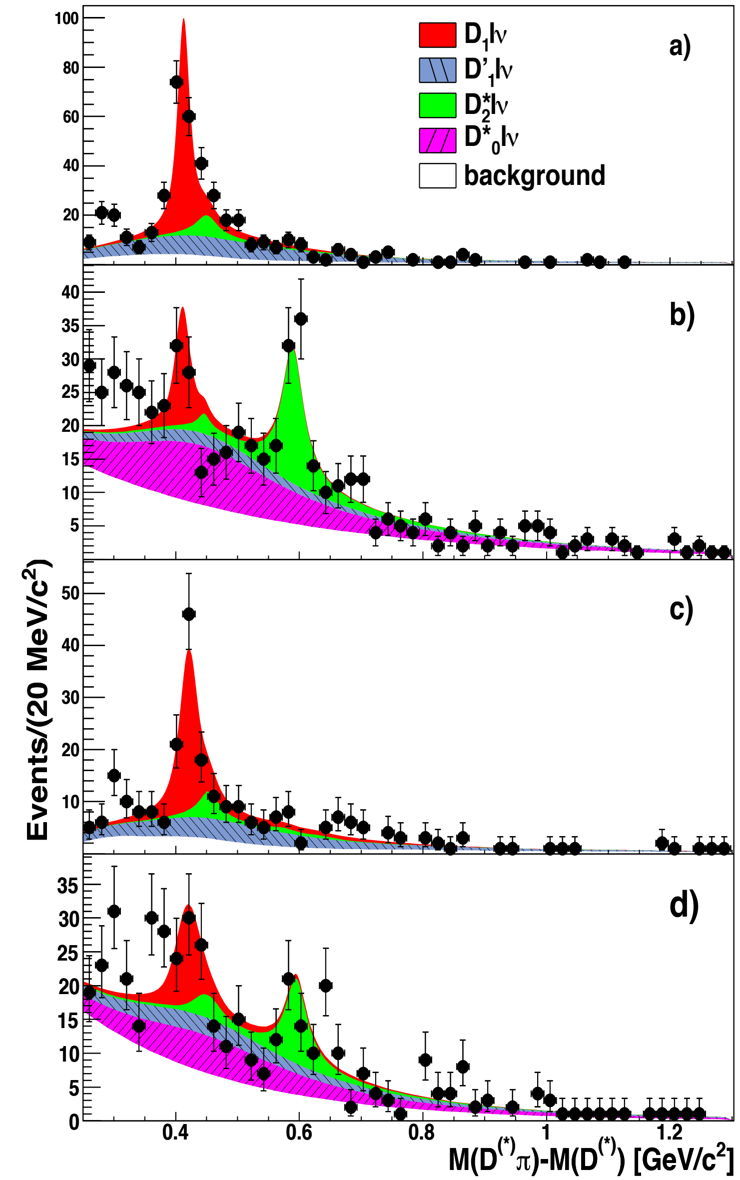


FIG. 1: (Color online) Fit to the $m(D^{(*)}\pi) - m(D^{(*)})$ distribution for a) $B^- \to D^{*+}\pi^-\ell^-\bar{\nu}_\ell$, b) $B^- \to D^+\pi^-\ell^-\bar{\nu}_\ell$, c) $\overline{B}^0 \to D^{*0}\pi^+\ell^-\bar{\nu}_\ell$, and d) $\overline{B}^0 \to D^0\pi^+\ell^-\bar{\nu}_\ell$: the data (points with error bars) are compared to the results of the overall fit (sum of the solid distributions). The PDFs for the different fit components are stacked and shown in different colors.

Can we rule out all new operators?

- No right-handed neutrino; charged lepton current remains left handed.
- $V - A$ structure of the lepton current is well established and we keep it as such:

$$L^\mu = \bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell$$

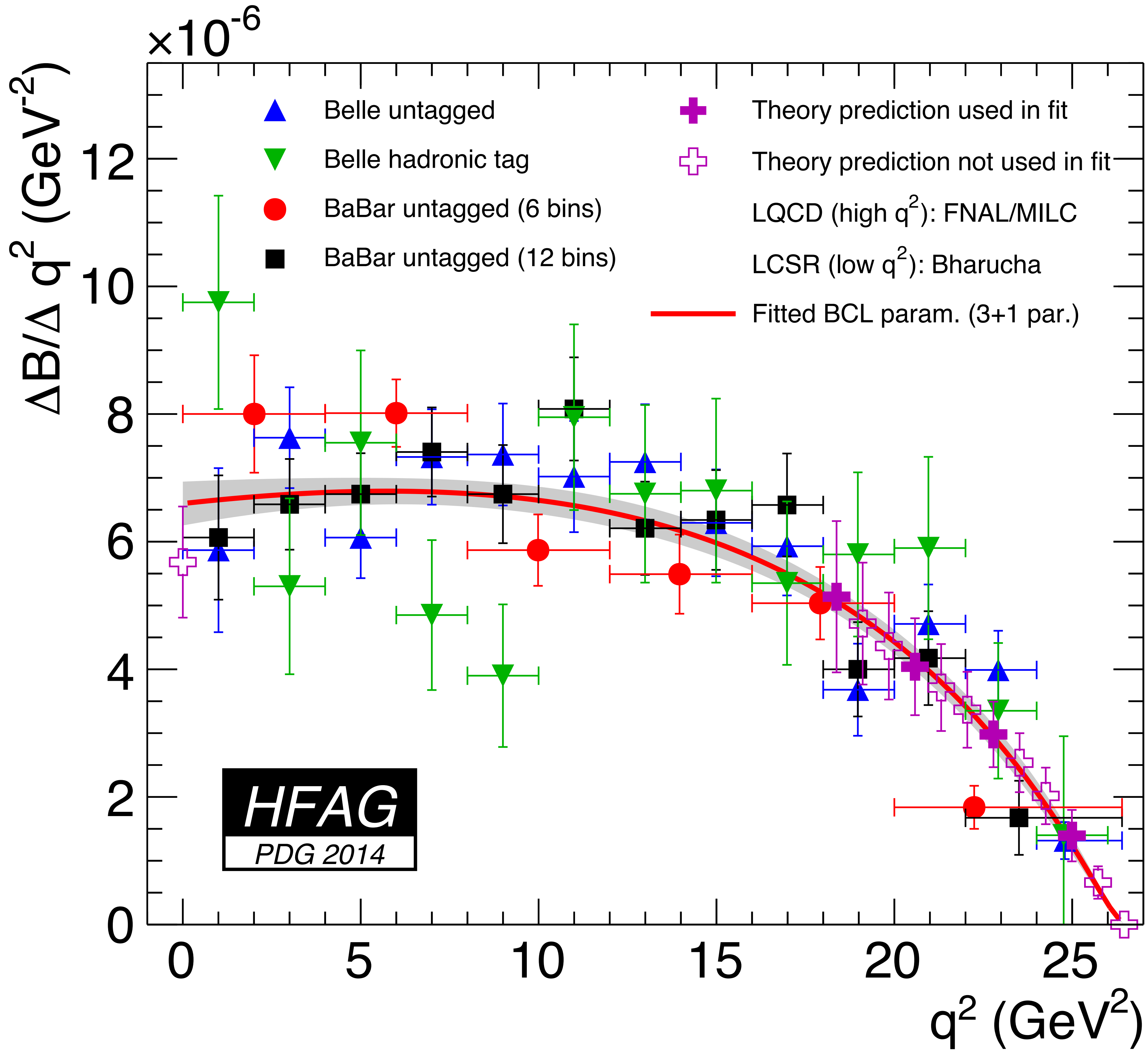
- $b \to c\ell\bar{\nu}_\ell$ can then be described by a general effective Hamiltonian:

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{cb}\big[(1 + g_V)\bar{c}\gamma_\mu b + (-1 + g_A)\bar{c}\gamma_\mu\gamma_5 b + g_S\, i\partial_\mu(\bar{c}b) + g_P\, i\partial_\mu(\bar{c}\gamma_5 b)$$
$$+ g_T\, i\partial_\nu(\bar{c}i\sigma_{\mu\nu}b) + g_{T5}\, i\partial_\nu(\bar{c}i\sigma_{\mu\nu}\gamma_5 b)\big] \times L^\mu = \frac{G_F}{\sqrt{2}} V_{cb}\; H_\mu L^\mu$$

$$g_{V,A} \sim \mathcal{O}\left(\frac{v^2}{\Lambda^2_{\rm NP}}\right), \quad g_{S,P,T,T5} \sim \frac{1}{v}\mathcal{O}\left(\frac{v^2}{\Lambda^2_{\rm NP}}\right)$$

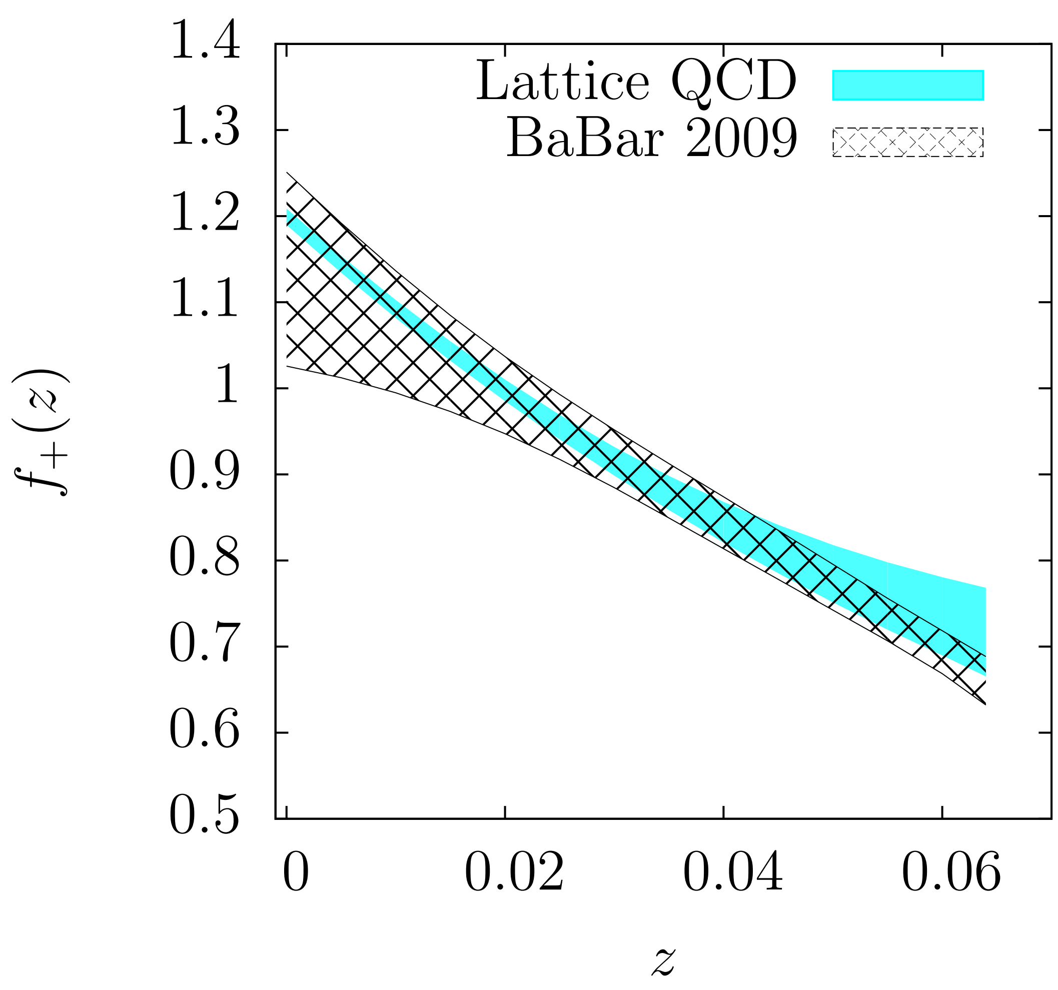
NB: the pseudotensor operator is not independent of the tensor one due to the relation $\bar{c}\sigma_{\mu\nu}\gamma_5 b = -\frac{i}{2}\epsilon_{\mu\nu\alpha\beta}\bar{c}\sigma^{\alpha\beta}b$, but it is convenient to keep this operator.

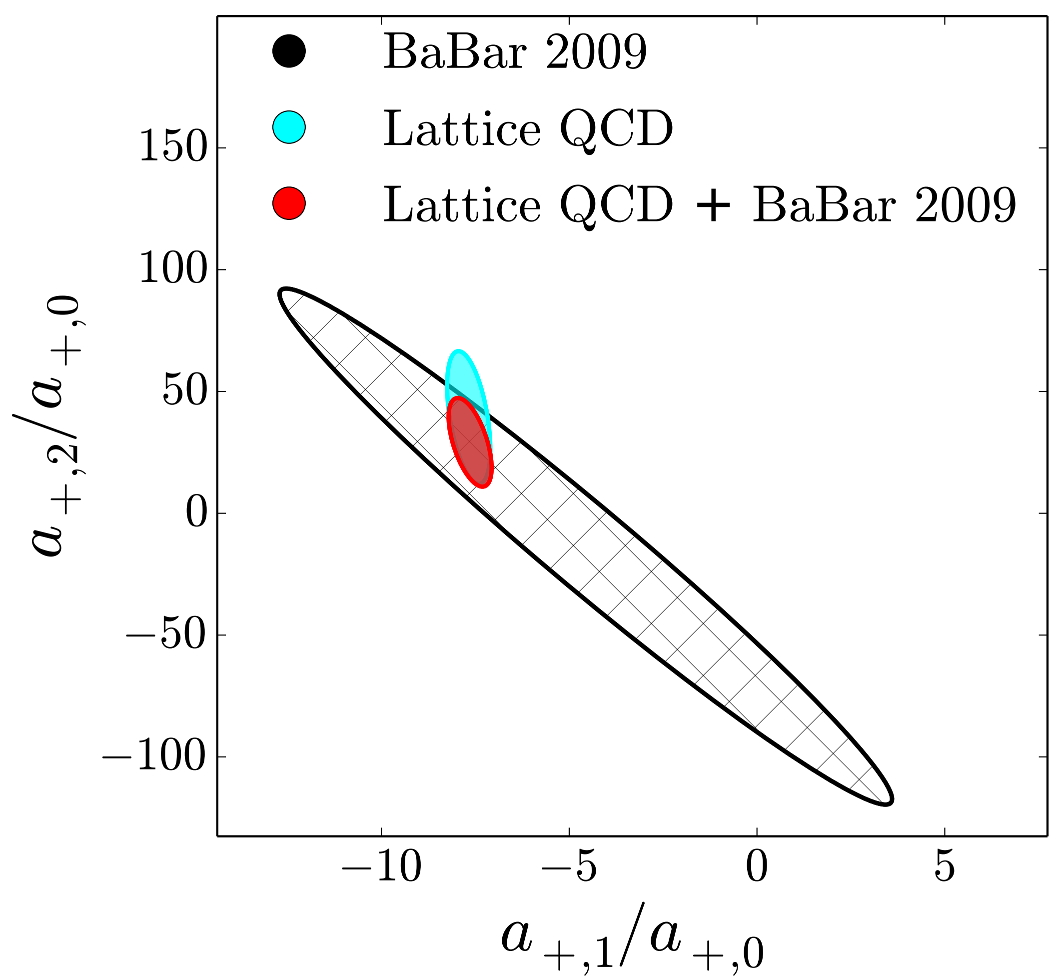
We should aim to have this plot :-)



And we are getting there

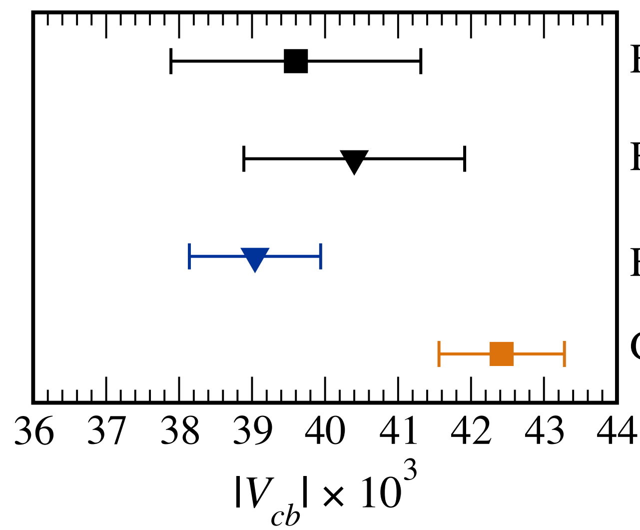
Fermilab/MILC: arXiv:1503.07237





BGL expansion

$$f_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{\infty} a_{i,n} z^n \,,$$



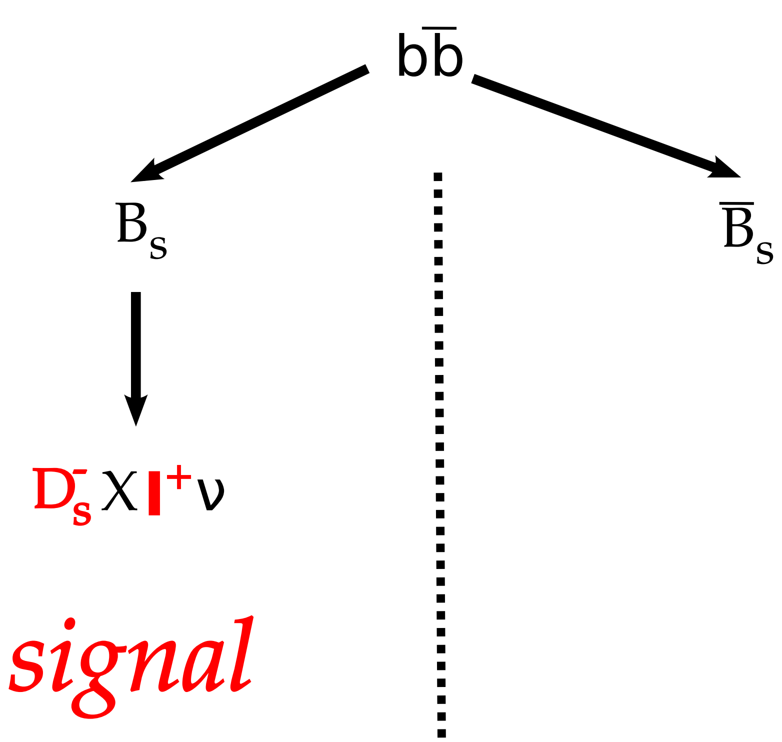
$$B_s$$

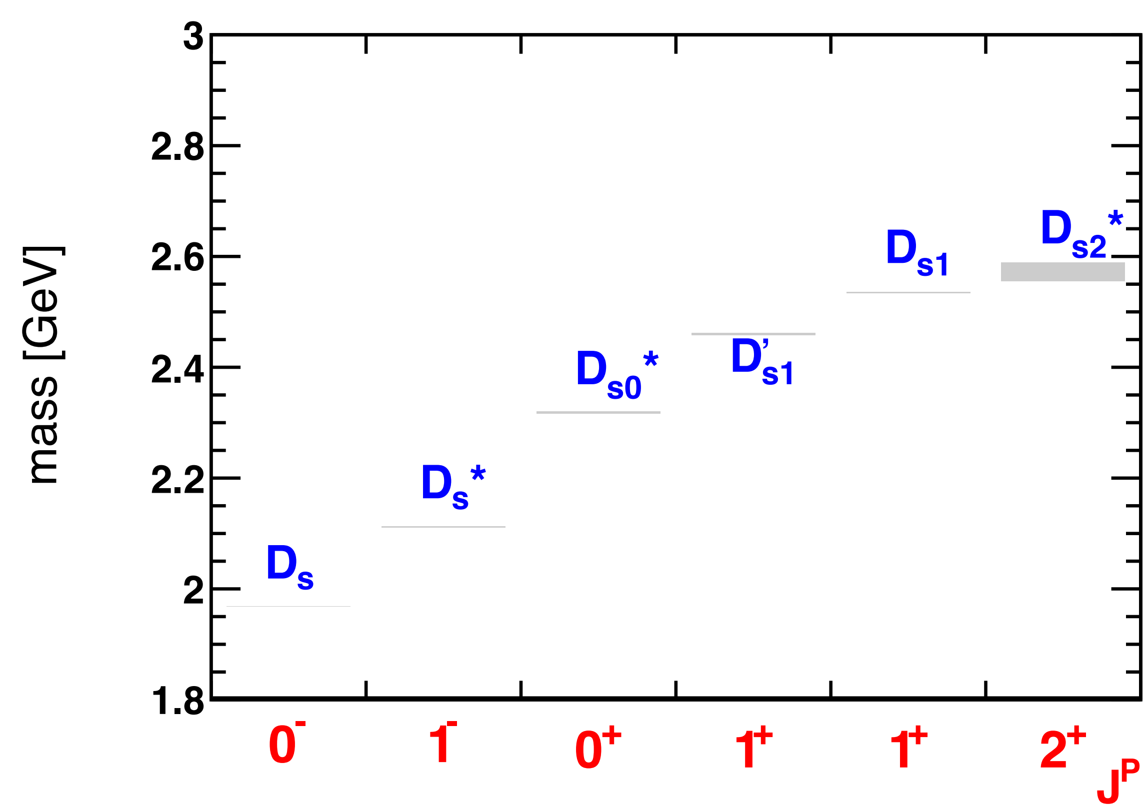
$$B_s \to D_s^{(*)}\, \ell\, \bar{\nu}_\ell$$

Experimental Recap

$B_s \to D_s^{(*)} \, \ell \, \bar{\nu}_\ell$

- Very interesting channel…
  - could be used to test predicted SU(3) flavour symmetry
  - better from a theory point of view due (s versus u,d quark) to calculate form factors
- First measurement of semi-inclusive rates by Belle by Oswald et al
  - Very challenging environment due to Y(5S) decay structure (f_s ~ 0.2)



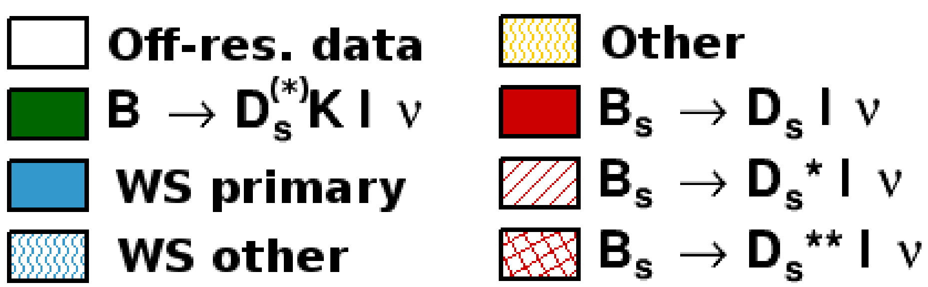


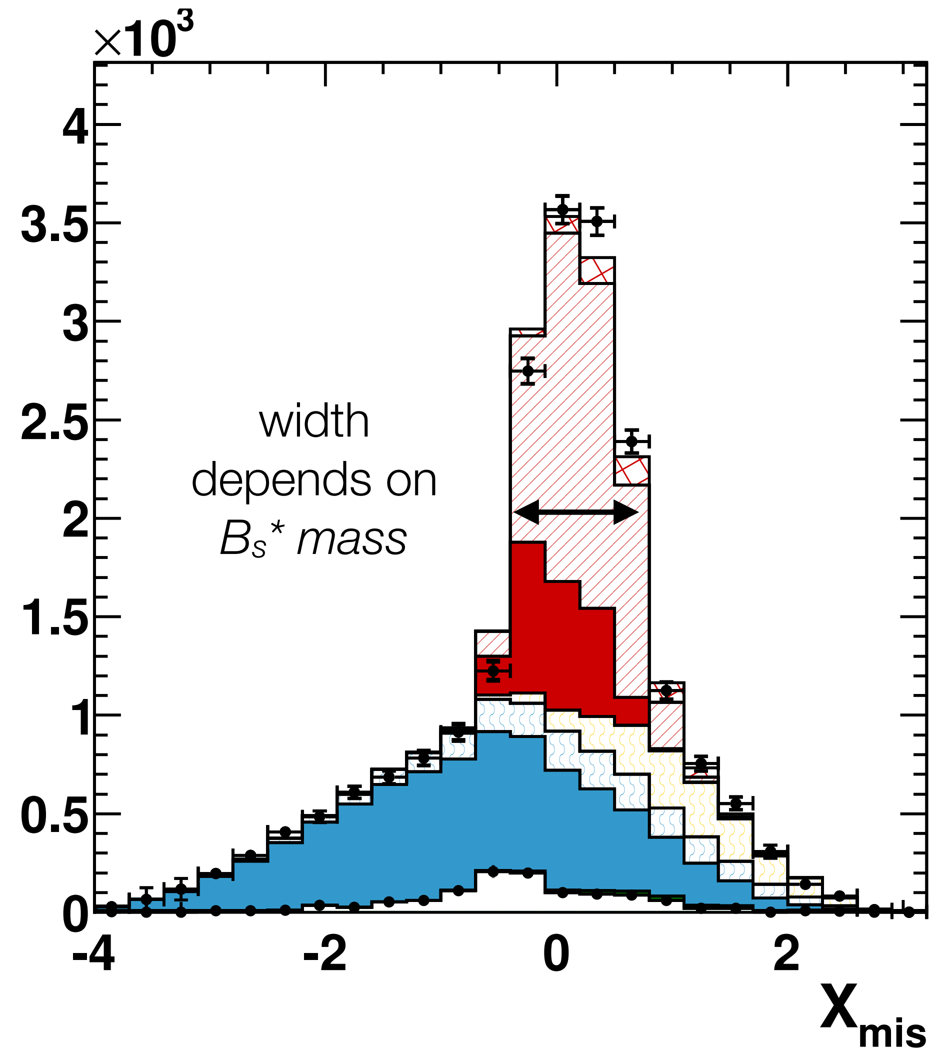
Experimental Recap

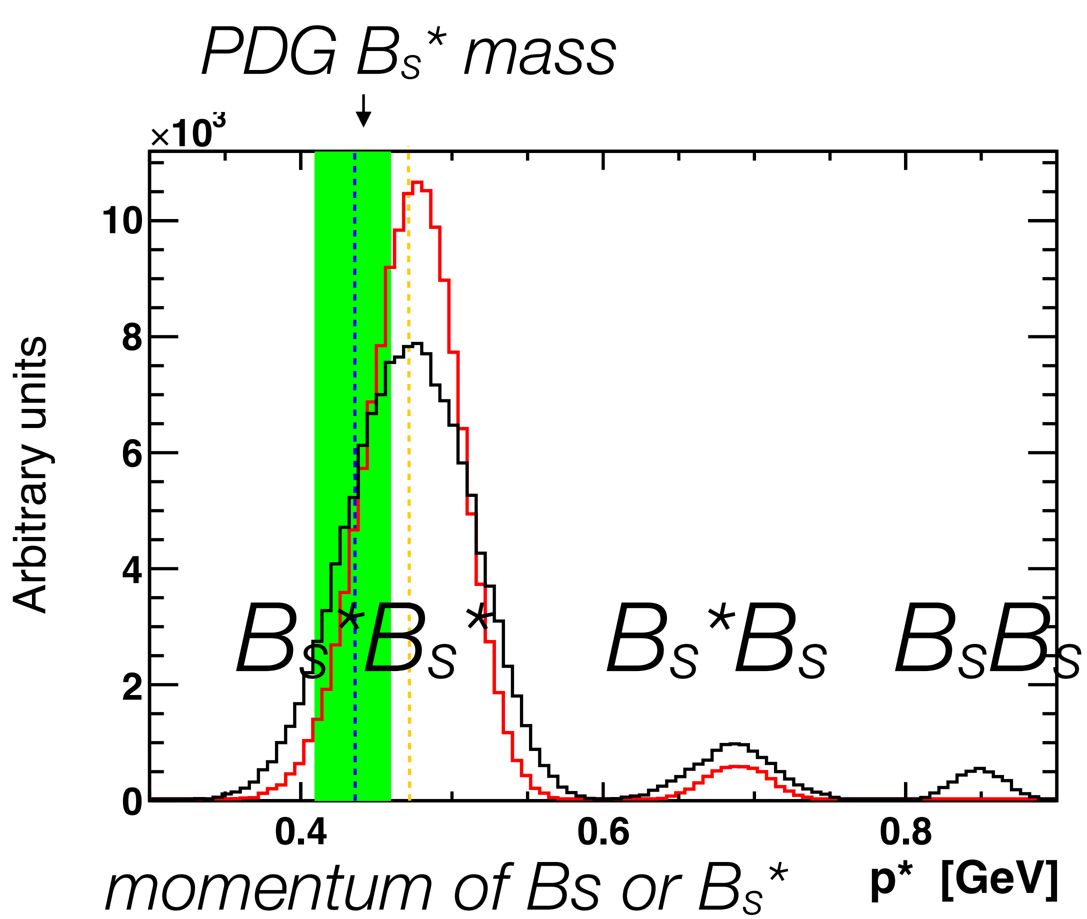
$B_s \to D_s^{(*)}\,\ell\,\bar{\nu}_\ell$

from lepton and Ds

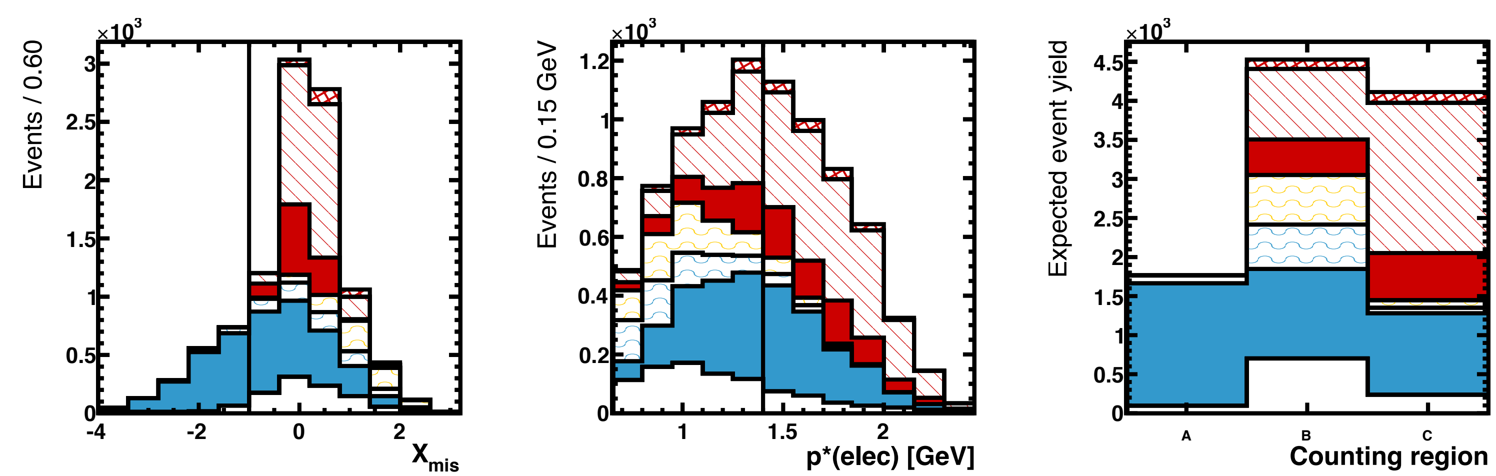
$$X_{\rm mis} = \frac{\sqrt{s/4} - (E^*_{\rm vis} + p^*_{\rm vis})}{\sqrt{s/4 - m^2_{B_s}}},$$







➡ Eventual 3 category analysis



Prospects for Belle II

$$B$$

$$B \to D\,\ell\,\bar{\nu}_\ell$$
$$B \to D^*\,\ell\,\bar{\nu}_\ell$$

- Will be interesting if..
  - we do the legwork and improve on our understanding of the D**
  - get lattice points beyond w = 1 also for D* (I presume in the making)
  - we provide (unfolded) measurements that allow for a later analysis as theory progresses.

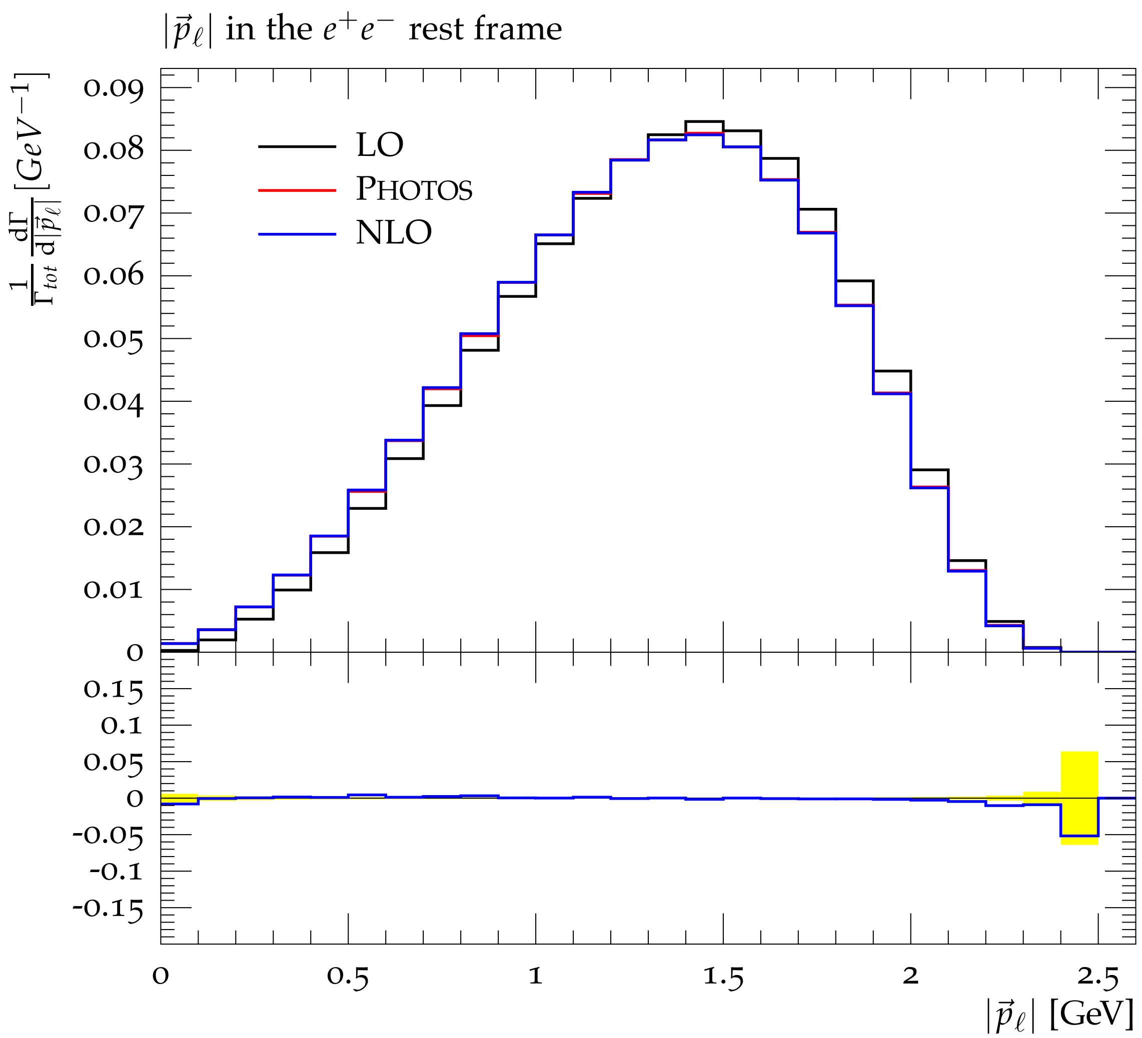
$$B_s$$

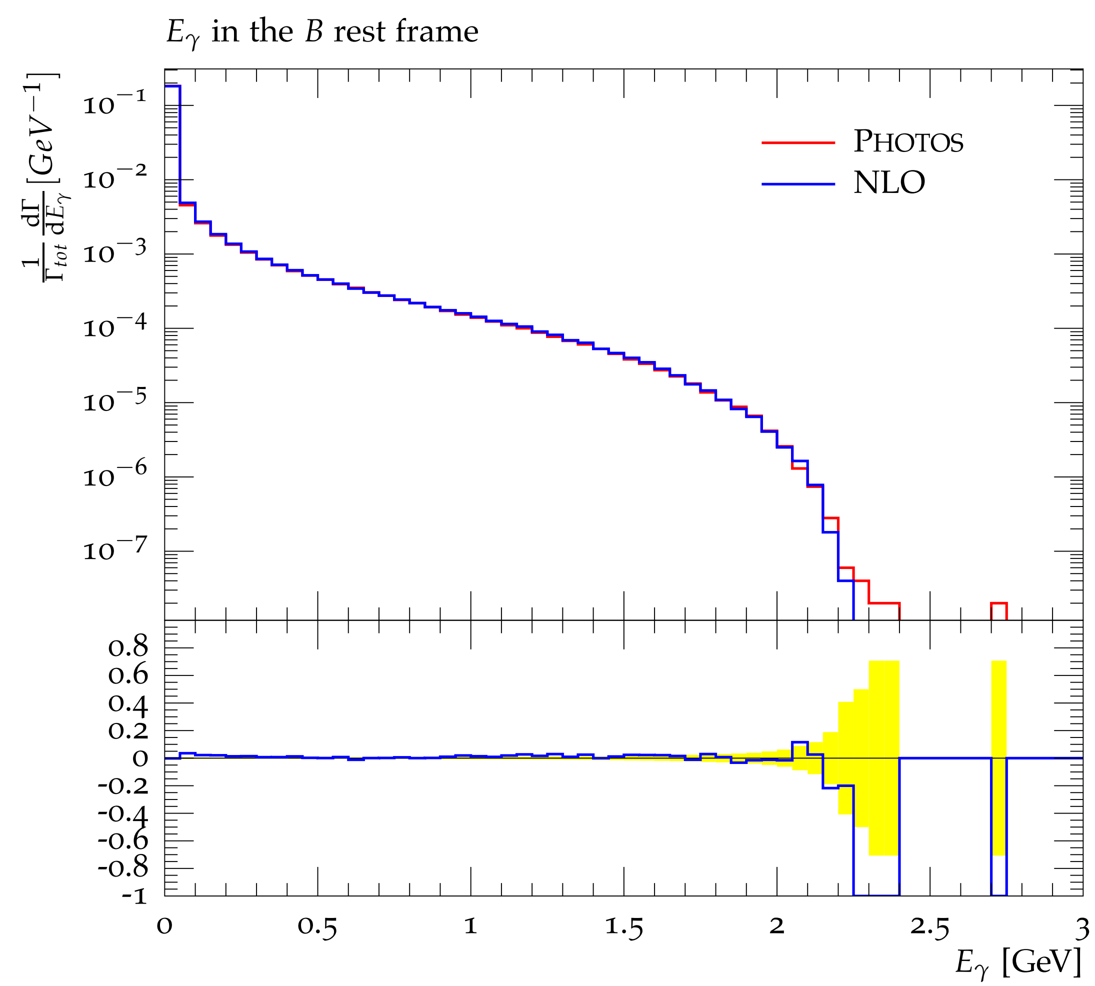
$$B_s \to D_s^{(*)}\,\ell\,\bar{\nu}_\ell$$

- Could be interesting given..
  - A sizeable dataset is available (due to $f_s \sim 0.2$)
  - And the experimental difficulties can be brought under control.

Backup

FSR





$$q^2 = (p_B - p_{D^{(*)}})^2 = (p_\ell + p_\nu + p_\gamma)^2$$