Prospects of Belle II on B-meson Semileptonic Decays

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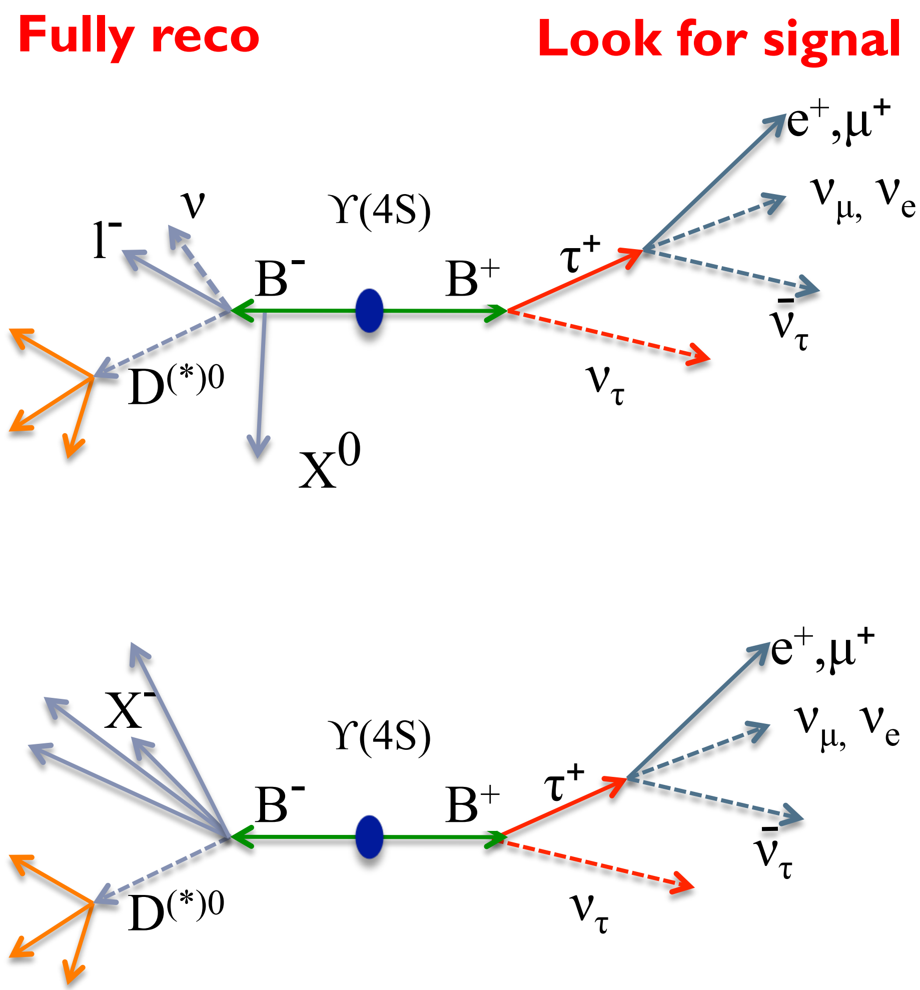
Outline

- Common experimental techniques
- Prospects of Belle II
  - $b \rightarrow c$ with exclusive and inclusive decays
  - $b \rightarrow u$ with exclusive and inclusive decays
  - Semileptonic decays with τ in the final state
  - (Purely leptonic decays in backup slides)

Experimental techniques (tagged analyses)

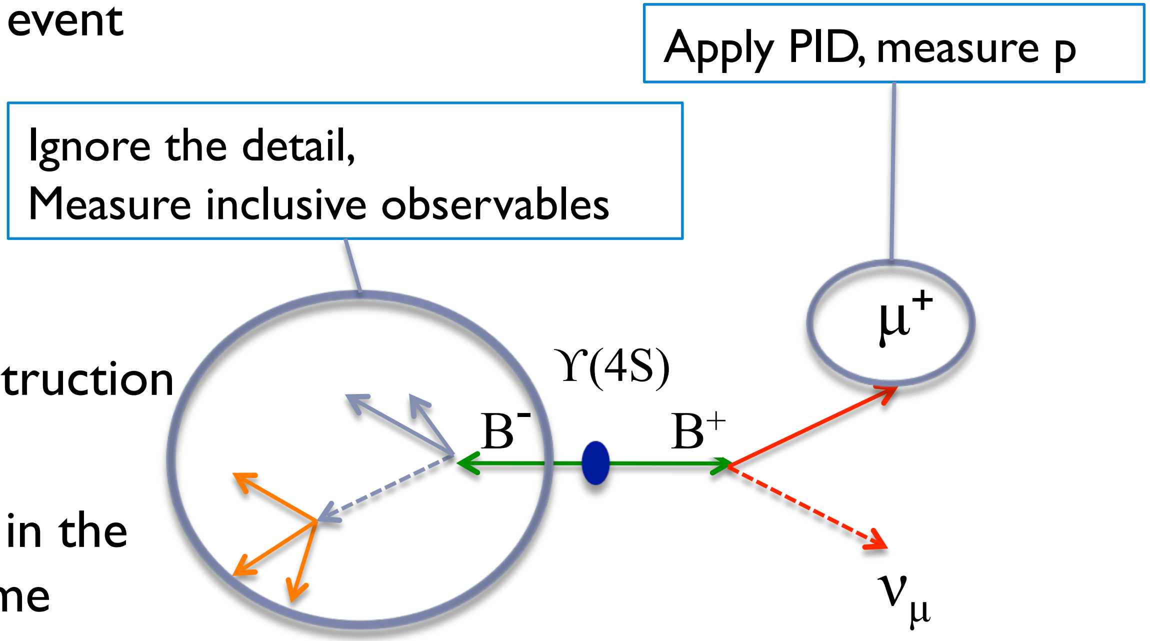
- For signal with weak exp. signature like
  - Decay with missing momentum (many neutrinos in the final state)
  - Inclusive analyses
- background rejection improved fully reconstructing the companion B (tag)

- Tag with semileptonic decays
  - PRO: Higher efficiency ε_{tag} ~ 1.5%
    CON: more backgrounds, B momentum unmeasured
- Tag with hadronic decays
  - PRO: much cleaner events,
    B momentum reconstructed
    CON: smaller efficiency ε_{tag} ~ 0.2%



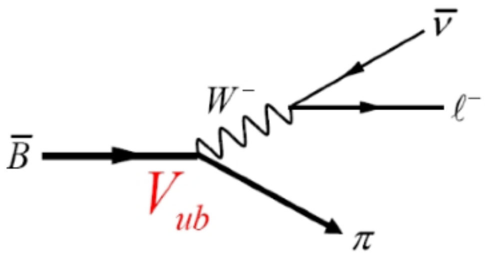
Experimental technique (untagged)

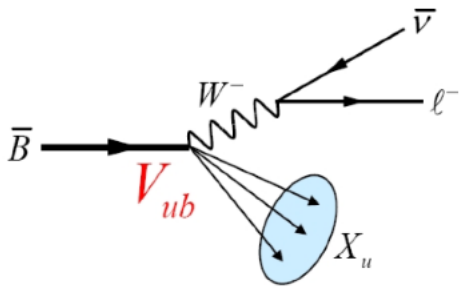
- Inclusive on the rest of the event when the signal signature strong enough
- B → π l ν
  - Loose neutrino reconstruction
- B → μ ν
  - Monochromatic muon in the final state in B rest frame
    - Smeared in the CM frame



High efficiency but large backgrounds, too

|Vub| extraction from b → u





$$\frac{d\Gamma(B\to\pi l\nu)}{dq^2} = \frac{G_F^2}{24\pi^3}p_\pi^3|V_{ub}|^2 \times |f(q^2)|^2$$

$$\Gamma_{SL} = |V_{ub}|^2\frac{G_F^2 m_b^5}{192\pi^3} \times A_{pert} \times A_{non-pert}(1/m_b)$$

Theory input: form factors from Lattice and sum rules

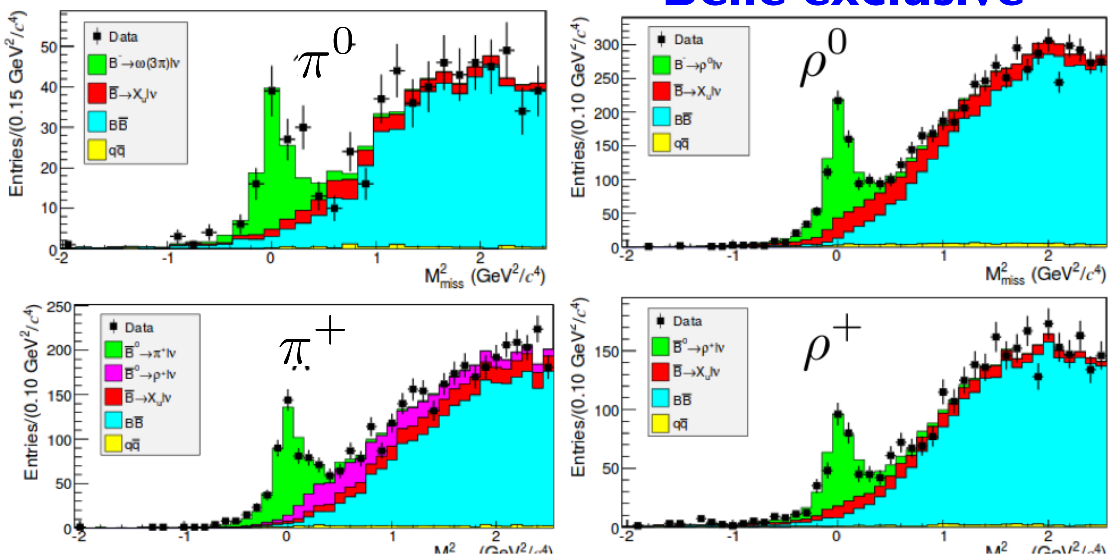
Experimentally more constrained

Both untagged & tagged analyses

Theory input: OPE
Huge b→c l ν background
Must select phase space region (M_x, q^2,p_l) to enhance B→ u signal
Need theory to extrapolate to full rate
Tight selections jeopardize theory extrapolation

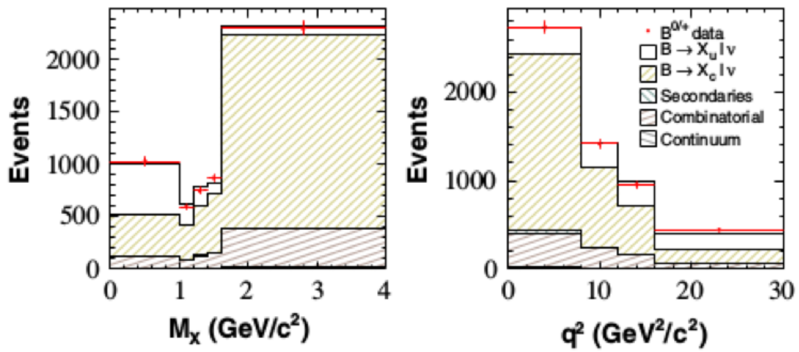
Current Measurements with hadronic tag

Belle exclusive



Clean signal in missing mass for exclusive modes

Belle inclusive



b → u l ν signal enhanced w.r.t. b → c backgrounds in low M_X and high q^2 but

important: control on systematics effects from charm background composition and u quark fragmentation → can be improved with Belle II

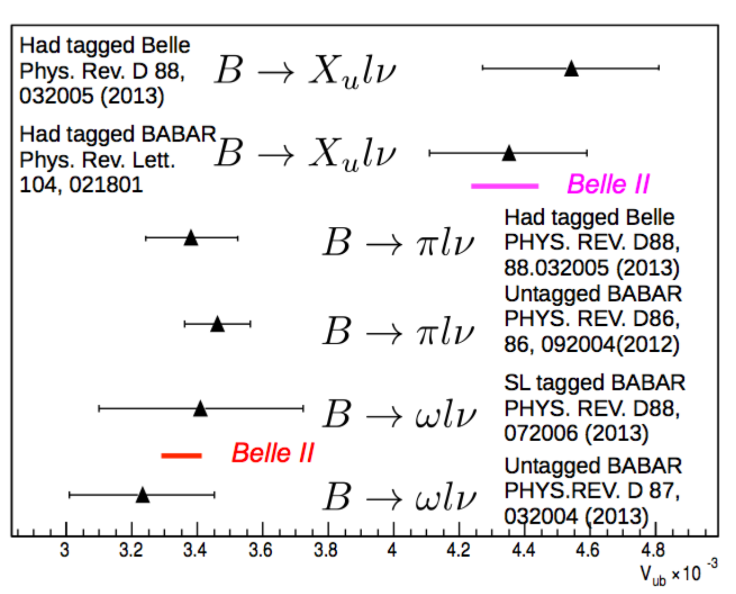
Extrapolation to Belle II (1)

Alexander Ermakov (FPCP14):

$|V_{ub}|_{exc}$ vs $|V_{ub}|_{inc}$ "tension" is still here after years of experimental and theoretical efforts
Just statistics?

A systematic effect in experiment. or theory or both?

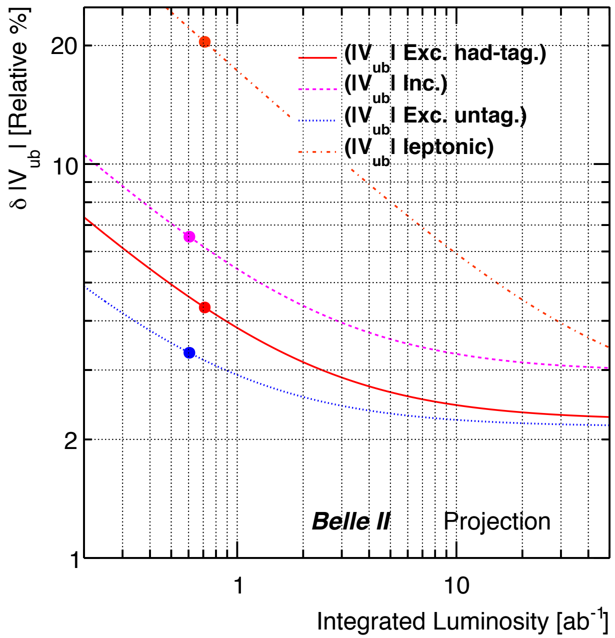
Belle II expected to settle this.



Belle II will reduce the uncertainties on |Vub|

But also provide much more consistency checks for theory and experimental effects

|Vub| extrapolation for Belle II (2)



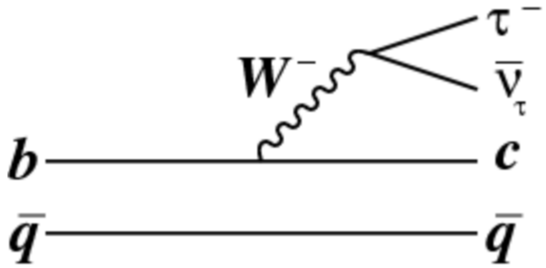
	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\lvert V_{ub}\rvert$ exclusive (had. tagged)					
711 fb^{-1}	3.0	(2.3, 1.0)	3.8	8.7 (2.0)	9.5 (4.3)
5 ab^{-1}	1.1	(0.9, 1.0)	1.7	4.0 (2.0)	4.4 (2.6)
50 ab^{-1}	0.4	(0.3, 1.0)	1.1	2.0	2.3
$\lvert V_{ub}\rvert$ exclusive (untagged)					
605 fb^{-1}	1.4	(2.1, 0.8)	2.9	8.7 (2.0)	9.1 (4.0)
5 ab^{-1}	0.5	(0.8, 0.8)	1.2	4.0 (2.0)	4.2 (2.4)
50 ab^{-1}	0.2	(0.3, 0.8)	0.9	2.0	2.2
$\lvert V_{ub}\rvert$ inclusive					
605 fb^{-1} (old B tag)	4.5	(3.7, 1.6)	6.0	2.5–4.5	6.5–7.5
5 ab^{-1}	1.1	(1.3, 1.6)	2.3	2.5–4.5	3.4–5.1
50 ab^{-1}	0.4	(0.4, 1.6)	1.7	2.5–4.5	3.0–4.8

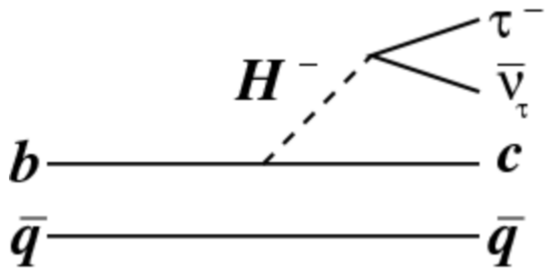
Assumption is theory error down to 2% for exclusive and 2-4 % for inclusive modes

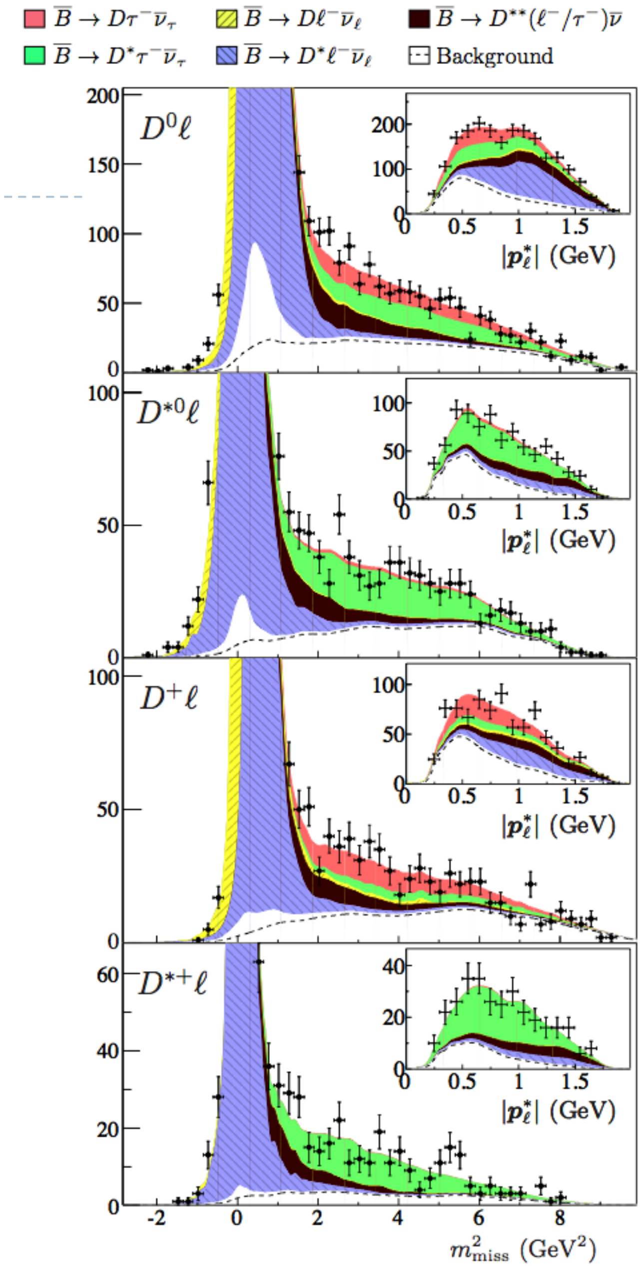
Most promising are exclusive analysis with hadronic tags: to perform clean and detailed exploration of exclusive b→ u modes spectra. Improvements on theory predictions need as well (B → ρ l ν lattice)

Untagged analyses still competitive for |Vub| measurement

$B \to D^* \tau \nu$







Input for SM prediction:

- exp: |Vcb| measurement
- theory: form factor

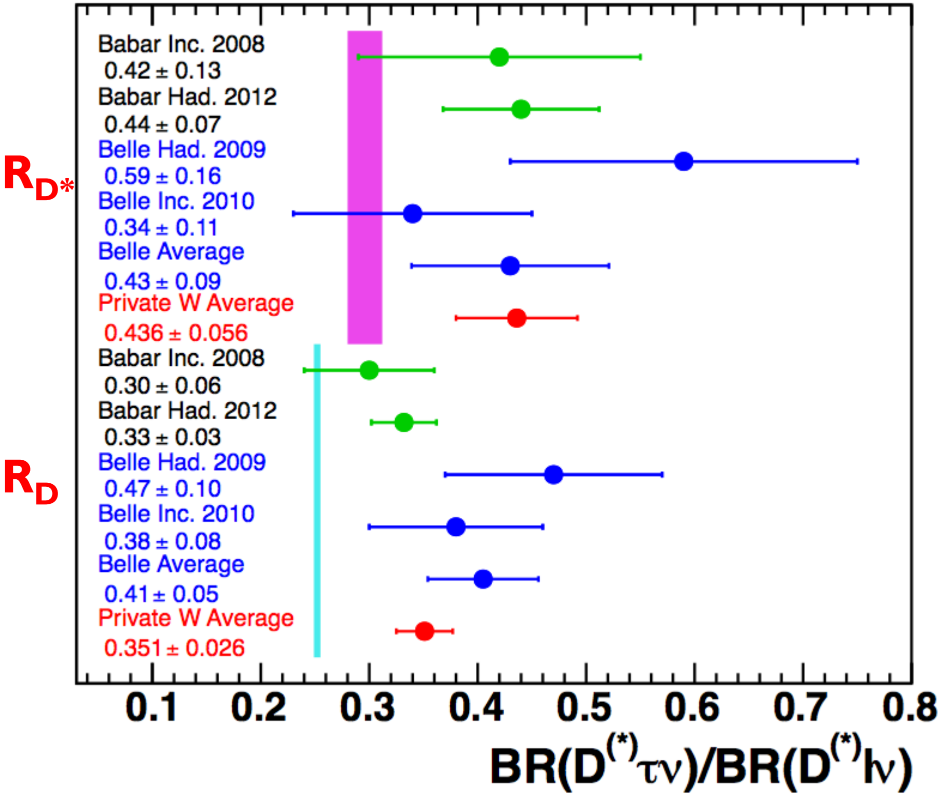
New Physics from Charged Higgs

Measure a ratio R = B($B\to D^{(*)} \tau \nu$)/B($B\to D^{(*)} l\nu$)

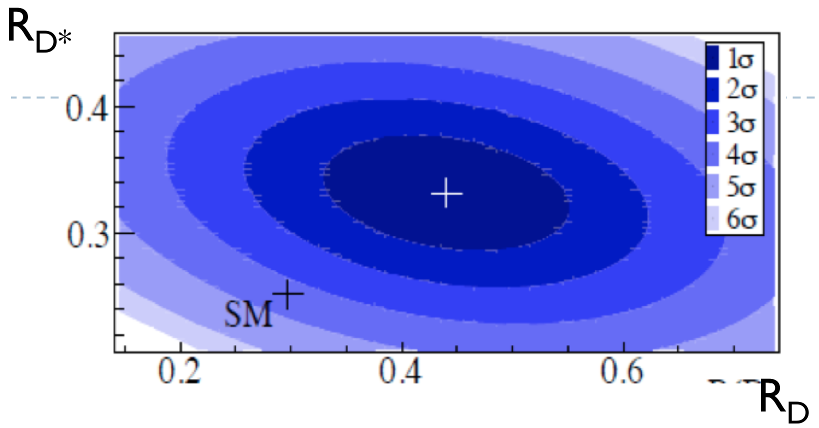
Experimentally hard: signature is not a peak on a smooth background!

Data driven methods to control the backgrounds (combinatorial and D** backgrounds)

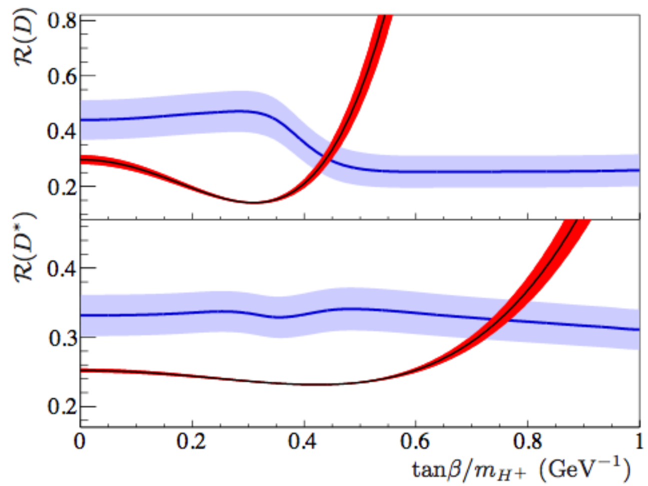
$B \rightarrow D^* \tau \nu$



Surprise: 3σ excess over SM prediction!



Surprise: kills the 2HDM Type II



Belle is working on update

BaBar working on adding more τ decay modes

Belle II improvements

Confirm the excess with few ab^{-1}

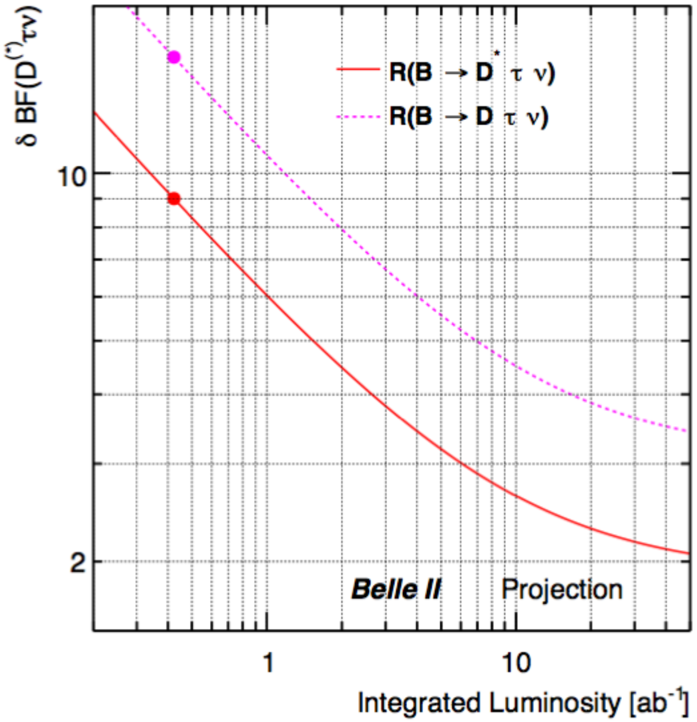
With more data, better understanding of backgrounds tails under the signal.

We also expect a better understanding of $B \rightarrow D^{**} l \nu$ (most delicate BG)

Measure differential distribution

Expected Uncertainties

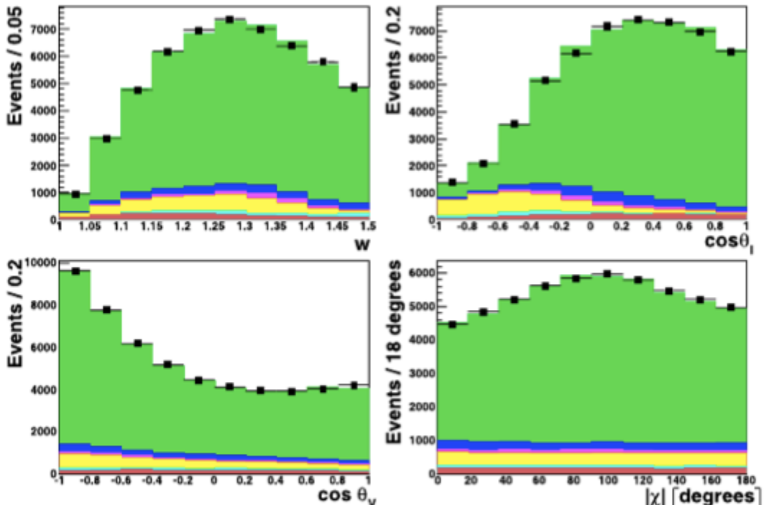
Ratio	5 ab^{-1}	50 ab^{-1}
R_{D*}	3%	2%
R_D	6%	3%

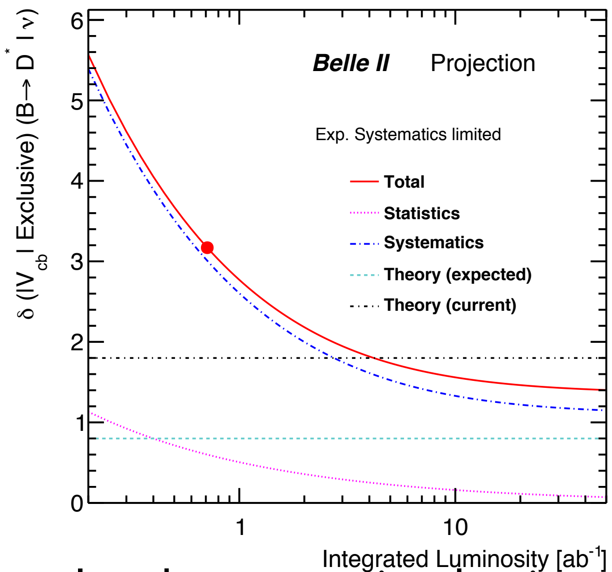


Uncertainty dominated by systematics

|Vcb| exclusive B → D* l ν

•Currently most accurate measurement of |Vcb| from B → D* l ν exclusive decay





Current Belle measurement has 5% total uncertainty, already systematics dominated
Expect theo uncertainty from 2% → below 1% with Belle II taking data
Most of the systematics are detector related and can improve with Belle II apparatus and scale with luminosity.
Experimental irreducible component estimated at 1% level

B→ D* l ν and B→D l ν

	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\lvert V_{cb}\rvert$ exclusive : F(1)					
711 fb^{-1}	0.6	(2.8, 1.1)	3.1	1.8	3.6
5 ab^{-1}	0.2	(1.1, 1.1)	1.5	1.0	1.8
50 ab^{-1}	0.1	(0.3, 1.1)	1.2	0.8*	1.4
$\lvert V_{cb}\rvert$ exclusive : G(1)					
423 fb^{-1}	4.5	(3.1, 1.2)	5.6	2.2	3.6
5 ab^{-1}	1.3	(0.9, 1.2)	2.0	1.5*	2.7
50 ab^{-1}	0.6	(0.4, 1.2)	1.4	1.0*	1.7

Similar level of accuracy from B→ D* l ν and B→ D l ν

B → X_c l ν inclusive at Belle II

(Modest) improvement of experimental uncertainties expected.

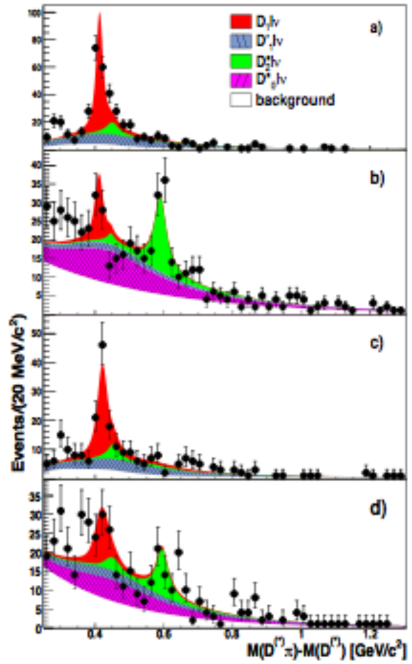
- Better determination of B → D** l ν component
- Improved control on the tag B normalization
- Largest experimental sys effect from PID and tracking

We expect a 0.5% ultimate systematic uncertainty

We assume theory uncertainty at 1% that will saturate the error budget

Detailed exploration of B → D nπ l ν

Hopefully will solve "puzzles" like the gap between inclusive and exclusive rates (and Vcb tensions)



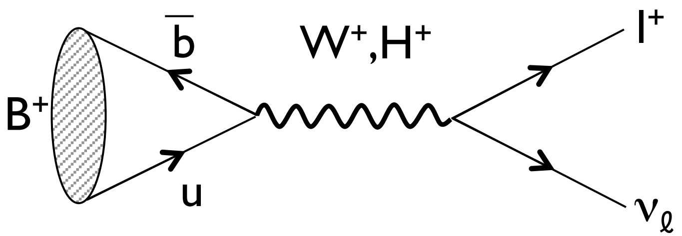
Fitted $D^{(*)}\pi$ mass spectrum of Phys.Rev.Lett. 101 (2008) 261802

Conclusions

- Current measurements provide the following landscape
  - |Vub| measured at 5% but 3σ exclusive-inclusive discrepancy
  - An un-expected excess in B → D(*) τ ν over the SM at slightly more than 3σ
- Also for b → c many things remain to be understood
  - |Vcb| measured at 2% but inclusive vs exclusive tension
  - Exclusive modes do not saturate the inclusive rate
  - Rates to broad and narrow D** resonance not predicted by theory
- Belle II unique place to solve all those puzzles and shed light on new Physics
  - More accurate theory predictions
  - Refinements of experimental techniques to let systematic uncertainties shrink with statistics

Back up and Leptonic decays

$B \to l\,\nu$



Very clean theoretically, hard experimentally

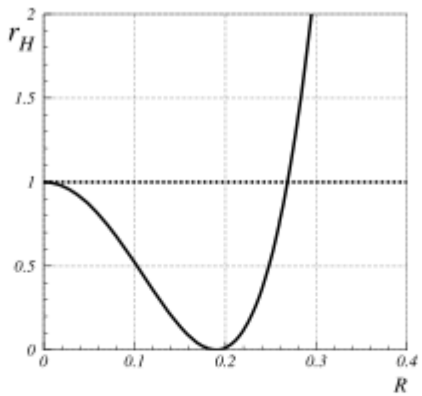
SM contribution suppressed by helicity

Sensitive to NP contribution (charged Higgs)

$$\mathcal{B}(B \to l\nu) = \frac{G_F^2 m_B}{8\pi} m_l^2 (1 - \frac{m_l^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$

$$\mathcal{B}(B \to l\nu) = \mathcal{B}(B \to l\nu)_{SM} \times r_H$$

$$r_H = (1 - \tan^2\beta \frac{m_B^2}{m_H^2})^2$$



Standard Model Predictions

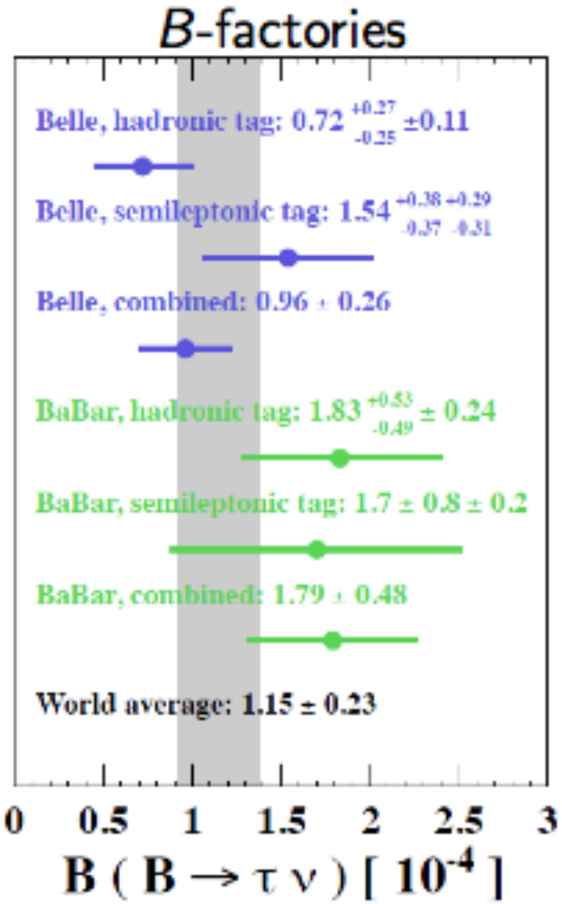
Mode	$\mathcal{B}(B^+ \to \ell^+ \nu_\ell)$	
$\tau\nu_\tau$	$(1.01 \pm 0.29) \times 10^{-4}$	*Accessible with current data sets*
$\mu\nu_\mu$	$\sim 0.45 \times 10^{-6}$	*Need Belle II statistics*
$e\nu_e$	$\sim 0.8 \times 10^{-11}$	*Beyond the reach of experiments*

Belle II can also test lepton flavour universality

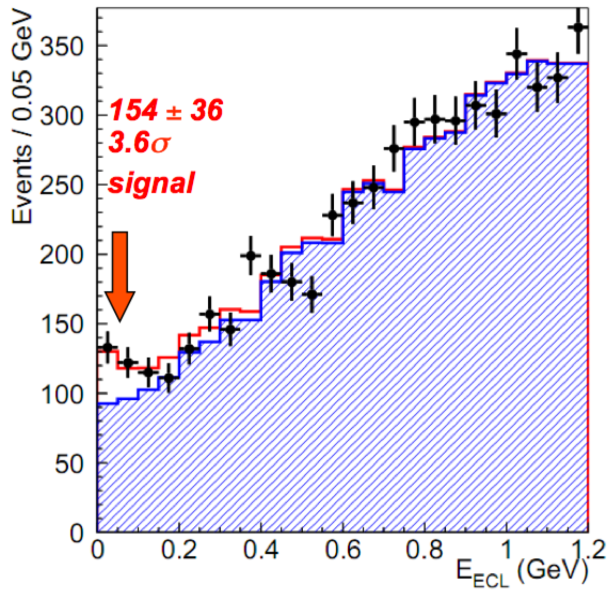
$$R^{\tau e} = \frac{\Gamma(B \to e\nu)}{\Gamma(B \to \tau\nu)}$$

$$R^{\tau\mu} = \frac{\Gamma(B \to \mu\nu)}{\Gamma(B \to \tau\nu)}$$

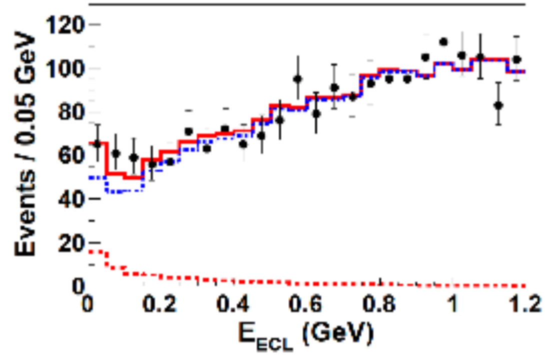
Belle and BaBar measurements



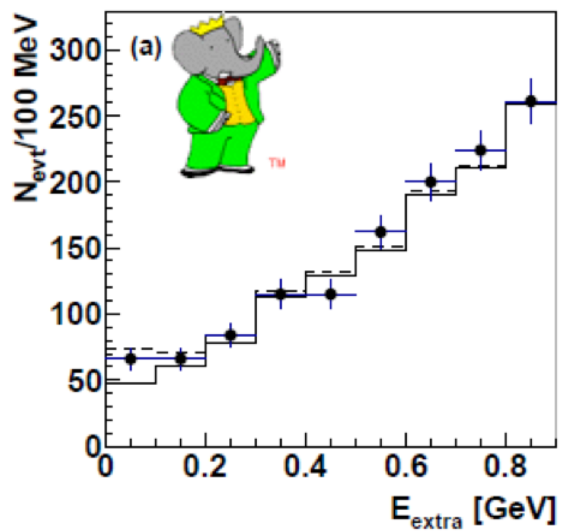
Belle semileptonic tag



Belle Hadronic tag

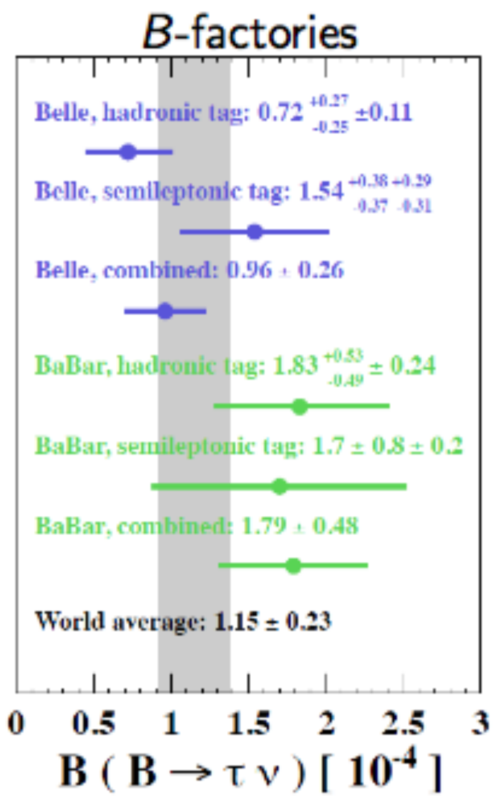


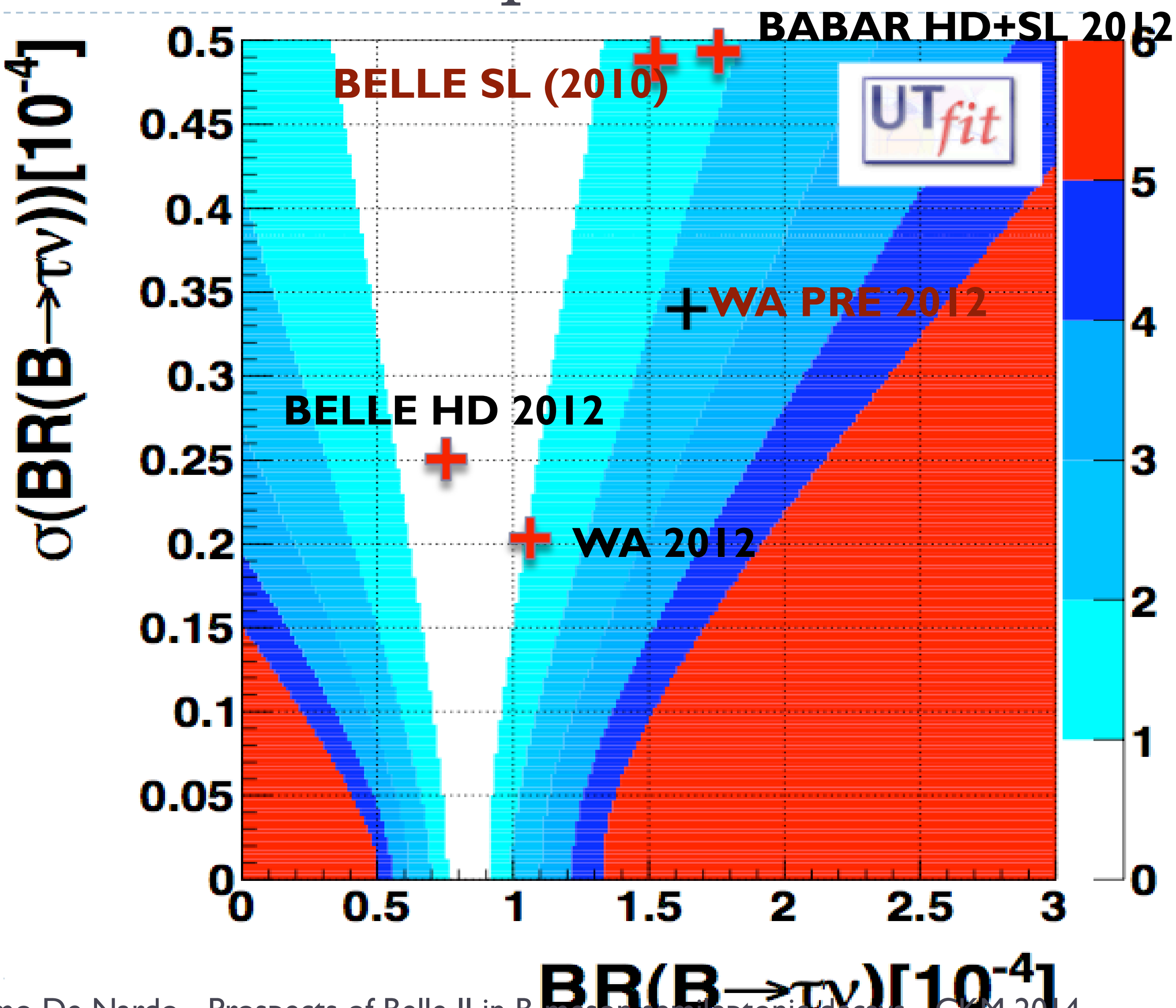
BaBar Hadronic tag



$\mathcal{B}(B \to \tau\nu) = (1.14 \pm 0.22) \times 10^{-4}$(HFAG2013)

Measurements vs UT-fit prediction





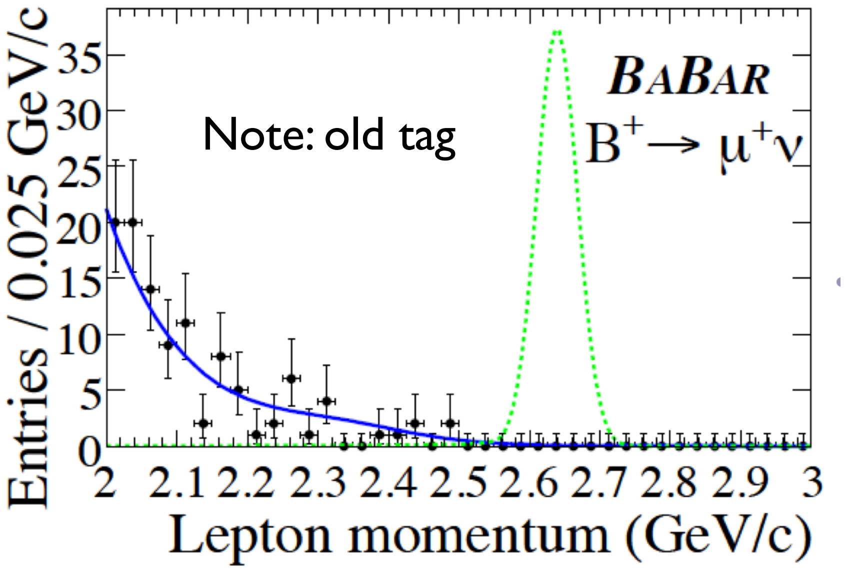
$B \rightarrow \mu\,\nu$ and $B \rightarrow e\,\nu$

Monochromatic lepton in the B rest frame
Almost background free with tagged analyses

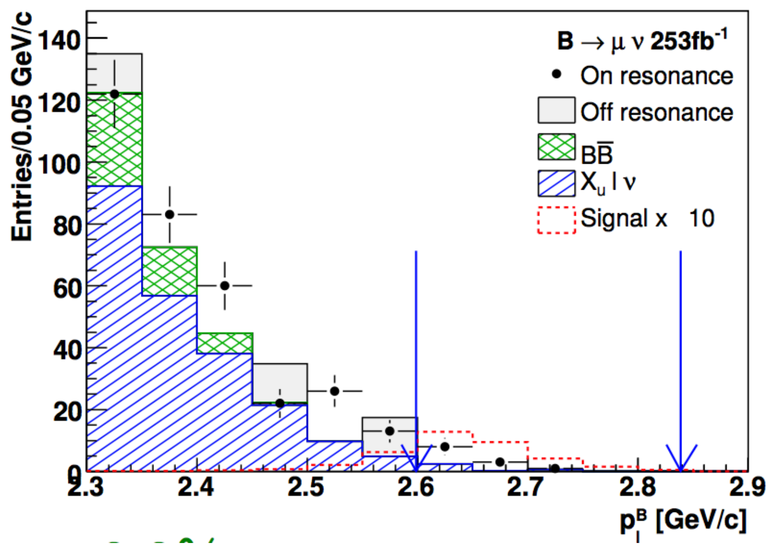
$\mathcal{B}(B \to \mu\nu) < 5.6 \times 10^{-6}$

$\mathcal{B}(B \to \mu\nu) < 1.7 \times 10^{-6}$

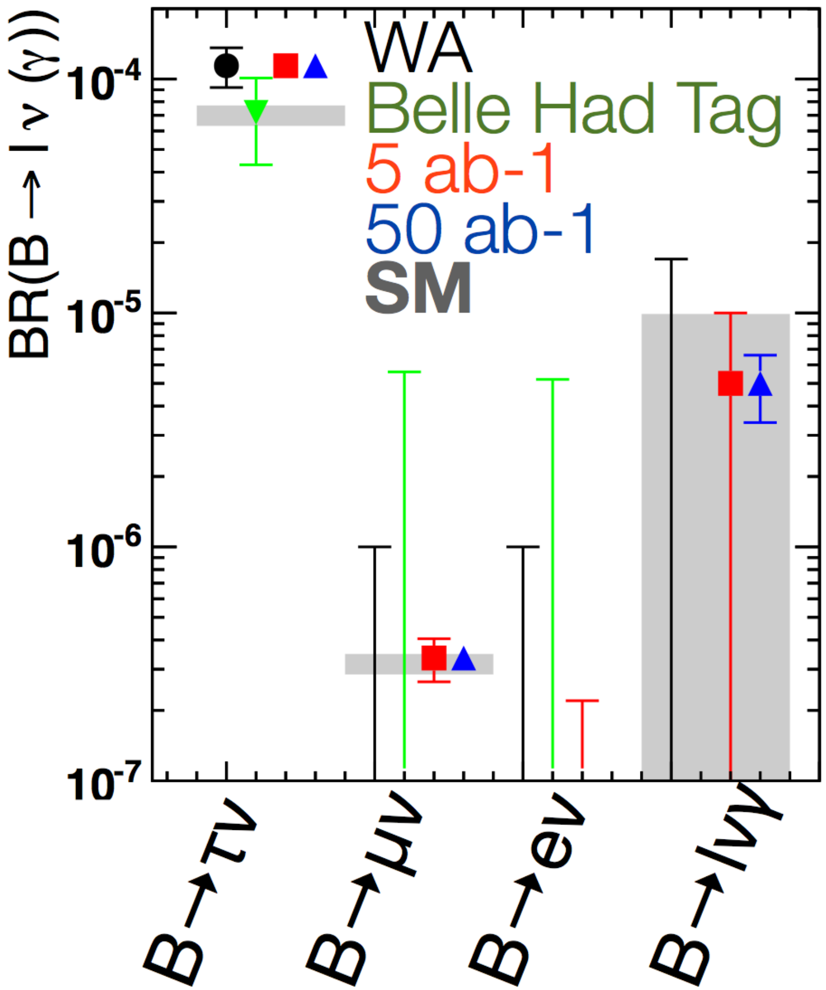
Hadronic tag BaBar



Semileptonic tag Belle



Belle II outlook

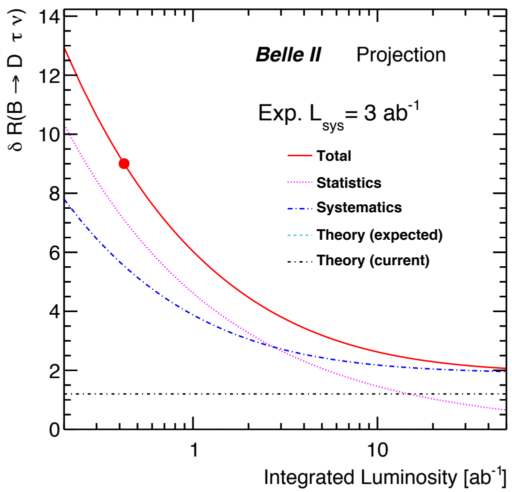


Extrapolated B → τ ν uncertainty
10% after 5 ab^{-1} and 3%-5% after 50 ab^{-1}
Dominated by systematics

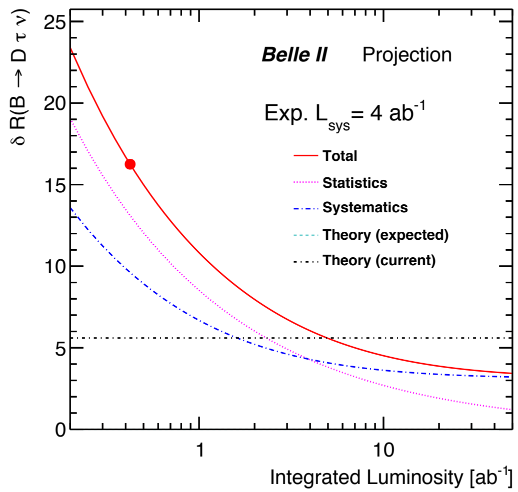
Extrapolated B → μ ν uncertainty
20% after 5 ab^{-1} and 7% after 50 ab^{-1}

B → e ν SM prediction out of reach,
Sensitivity to B.R. of 7 10^{-8} with 50 ab^{-1}

Q:What is the ultimate the ultimate experimental systematic uncertainty?
Naïve guess : 3%



(a)$B \to D^* \tau \nu$



(b)$B \to D \tau \nu$