$B \to K^* \ell^+ \ell^-$ and $B \to \tau \nu$ at Belle

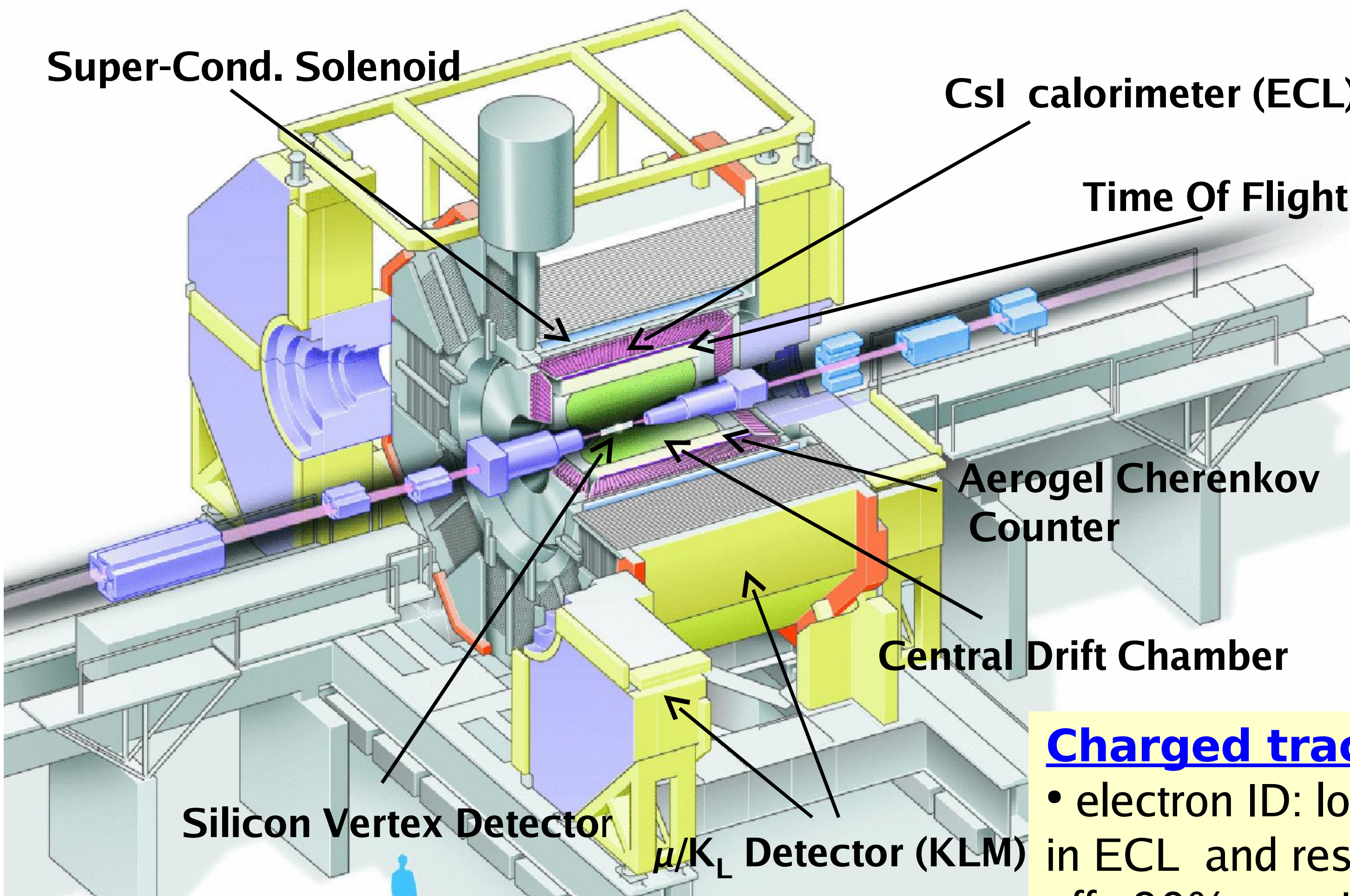
Stefano Villa, EPFL

Flavour in the Era of the LHC - 4th meeting
CERN, October 9-11, 2006

Summary

- *B* physics at Belle
- The $B \to K^{*}\ell^{+}\ell^{-}$ channel
  - forward-backward asymmetry
  - measurement of Wilson coefficients
  - future prospects
- Evidence for $B \to \tau\nu_{\tau}$
  - description of the measurement
  - constraints on charged Higgs
  - future prospects
- Conclusions

B physics at Belle



[*B* production](#)

BB pairs produced at KEKB in e^+e^- (3.5 GeV on 8 GeV) collisions at the $\Upsilon(4S)$ resonance. Collected so far more than 500 fb^{-1}

Charged tracks reconstruction/ID:

- electron ID: loss in CDC, shower shape in ECL and response of ACC; eff≥90%, π-misID rate ≈ 0.1%
- muon ID: based on ECL and KLM; eff≥90%, π-misID rate ≈ 1%
- $K^{\pm}$ selected using ACC, TOF and CDC; eff ≥90% and π-misID rate ≈6%.
- Other charged tracks identified as $\pi^{\pm}$

B signal selection:

typically based on event shape variables with signal window defined using

$$M_{bc} = \sqrt{E_{beam}^2 - p_B^2} \qquad (\approx m_B)$$

and $\Delta E = E_B - E_{beam} \quad (\approx 0)$

$B \rightarrow K^{*} \ell^{+} \ell^{-}$

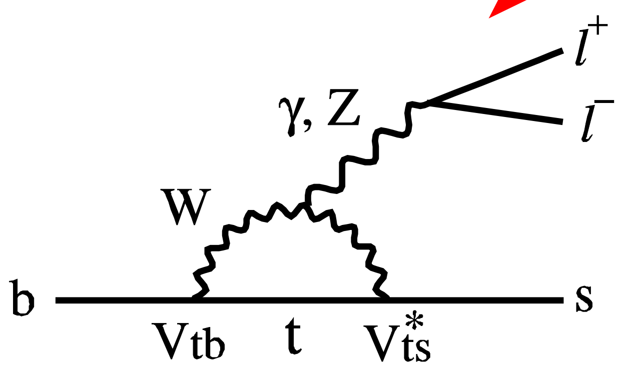
$B \to K^* \ell^+ \ell^-$: a window on BSM physics

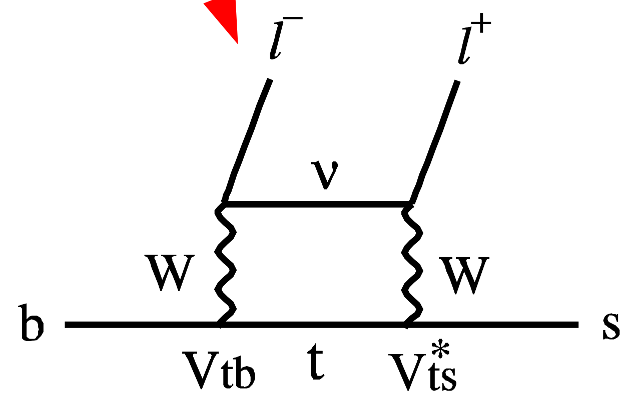
SM:

- $b \to s\ell\ell$: FCNC process, forbidden at tree level
- at lowest order via electromagnetic penguin or box diagrams

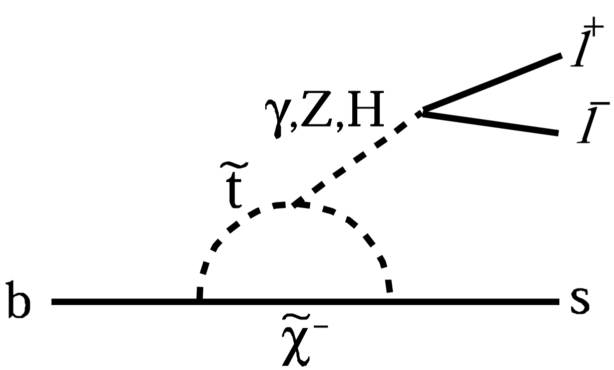
Lepton pair yields useful observables for testing the theory:

- forward-backward asymmetry (A_{FB})
- invariant mass (q^2)





BSM:



Sensitive to new physics via insertion of heavy particles in the internal lines.

$B \to K^* \ell^+ \ell^-$: Wilson coefficients

New Physics at the one loop level can be described in terms of an effective Hamiltonian:

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) \mathcal{O}_i(\mu)$$

Local operators, see next slide

- $C_i(\mu)$ Wilson coefficients: effective strength of short distance interactions
- To leading order, only O_7, O_9 and O_{10} contribute to $b \to s \ell \ell$
- C_i computed perturbatively up to NNLO: $C_i = A_i$ + *higher order terms*
- The $B \to K^* \ell^+ \ell^-$ amplitude depends on A_7, A_9 and A_{10} under the assumption that higher order terms behave like in the SM.

SM VALUES: $A_7 = -0.330$, $A_9 = 4.069$, $A_{10} = -4.213$

H.H. Asatryan *et al.* Phys. Lett. B 507, 162 (2001); A. Ali *et al.* Phys. Rev. D 66, 034002 (2002)

Operators in $\mathcal{H}_{\rm eff}$

$$\mathcal{O}_1 = (\bar{s}_\alpha \gamma_\mu L c_\beta)(\bar{c}_\beta \gamma^\mu L b_\alpha),$$

$$\mathcal{O}_2 = (\bar{s}_\alpha \gamma_\mu L c_\alpha)(\bar{c}_\beta \gamma^\mu L b_\beta),$$

$$\mathcal{O}_3 = (\bar{s}_\alpha \gamma_\mu L b_\alpha) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu L q_\beta),$$

$$\mathcal{O}_4 = (\bar{s}_\alpha \gamma_\mu L c_\beta) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu L q_\alpha),$$

$$\mathcal{O}_5 = (\bar{s}_\alpha \gamma_\mu L b_\alpha) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu R q_\beta),$$

$$\mathcal{O}_6 = (\bar{s}_\alpha \gamma_\mu L c_\beta) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu R q_\alpha),$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2} \bar{s}_\alpha \sigma_{\mu\nu} (m_s L + m_b R) b_\alpha F^{\mu\nu},$$

→ electromagnetic operator

$$\mathcal{O}_8 = \frac{g}{16\pi^2} \bar{s}_\alpha \sigma_{\mu\nu} (m_s L + m_b R) T^a_{\alpha\beta} b_\beta G^{a\mu\nu},$$

$$\mathcal{O}_9 = \frac{e^2}{16\pi} \bar{s}_\alpha \gamma^\mu L b_\alpha \bar{\ell} \gamma_\mu \ell,$$

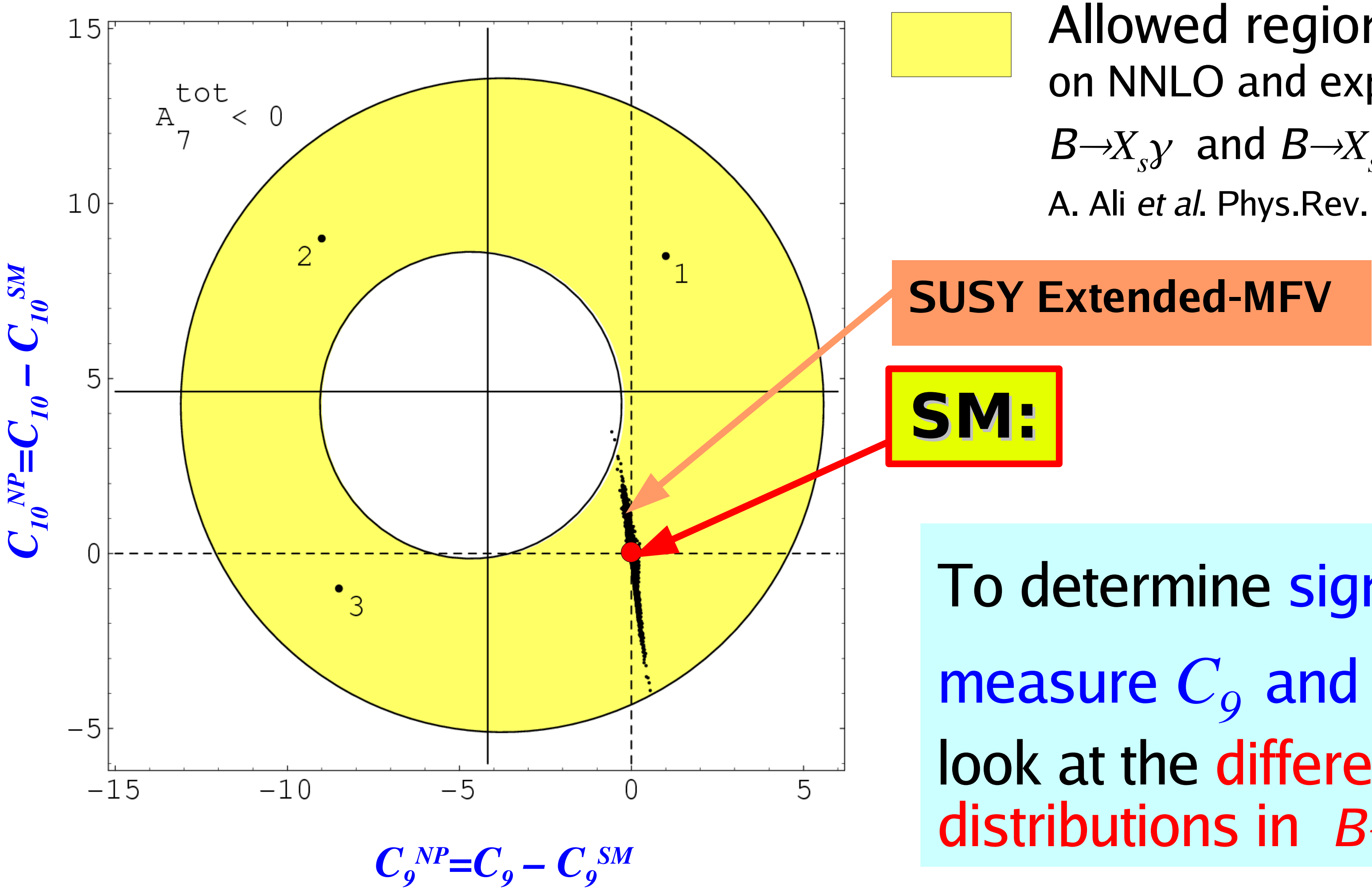
→ semileptonic vector

$$\mathcal{O}_{10} = \frac{e^2}{16\pi} \bar{s}_\alpha \gamma^\mu L b_\alpha \bar{\ell} \gamma_\mu \gamma_5 \ell,$$

→ semileptonic axial-vector

Constraints on Wilson coefficients

The absolute value of C_7 is constrained by $B \to X_s \gamma$; constraints on C_9 and C_{10} (donut-shape) are derived from the $B \to X_s \ell^+ \ell^-$ branching fractions.



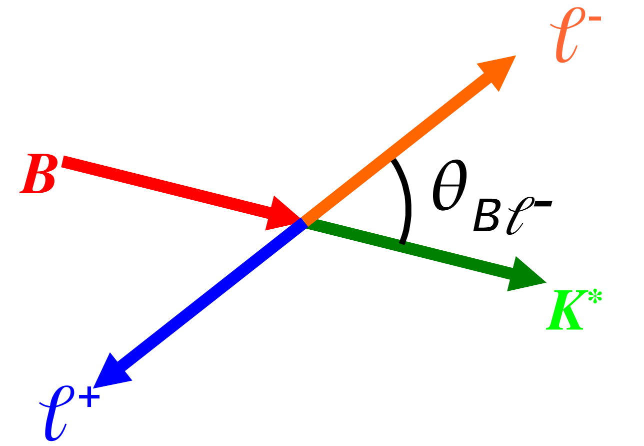
Allowed region at 90% CL, based on NNLO and experimental bounds on $B \to X_s \gamma$ and $B \to X_s \ell^+ \ell^-$ Br's; $A_7 < 0$

A. Ali *et al*. Phys.Rev. D 66, 034002 (2002)

To determine sign of C_7 and to measure C_9 and C_{10} need to look at the differential distributions in $B \to K^* \ell^+ \ell^-$

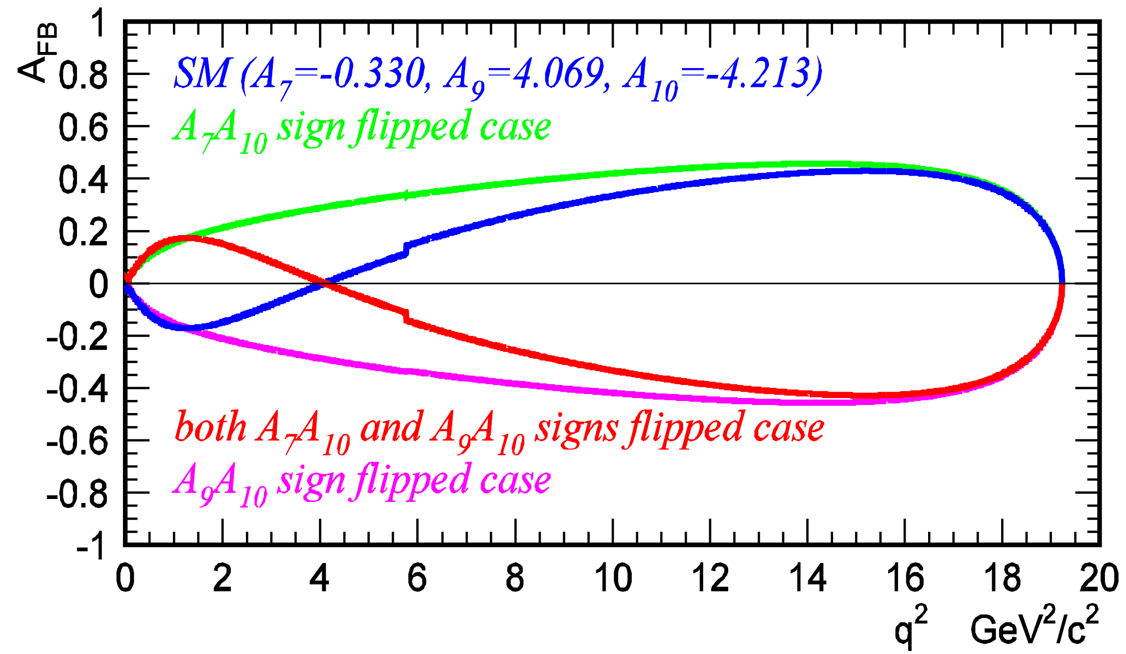
Forward-backward asymmetry in $K^*\ell^+\ell^-$

$$A_{FB}(q^2) = \frac{\Gamma(q^2, \cos\theta_{B\ell^-} > 0) - \Gamma(q^2, \cos\theta_{B\ell^-} < 0)}{\Gamma(q^2, \cos\theta_{B\ell^-} > 0) + \Gamma(q^2, \cos\theta_{B\ell^-} < 0)}$$



- $\theta_{B\ell^-}$ ($\equiv\theta$): angle between B and ℓ^- in the dilepton rest frame
- A_{FB} is a function of q^2 of the dilepton system
- A_{FB} non-zero due to interference of vector (C_7, C_9) and axial vector (C_{10}) couplings

More generally, one can extract the coefficients by fitting the double-differential decay width:
$d^2\Gamma / dq^2\ d\cos\theta$



$B \to K^* \ell^+ \ell^-$ selection

- Dataset: 357 fb^{-1} = 386M *BB* pairs
- Modes: $K^{*+} \to K^+ \pi^0$, $K_S \pi^+$; $K^{*0} \to K^+ \pi^-$
- lepton = e, μ
- Charmonium (J/ψ, $\psi(2S)$) veto
- Dominant background: *BB* with both *B's* decaying semileptonically: suppressed using E_{miss} and $\cos\theta_B^*$
- $B \to K \ell^+ \ell^-$ used as "null test": $A_{FB} \sim 0$ in SM, small BSM

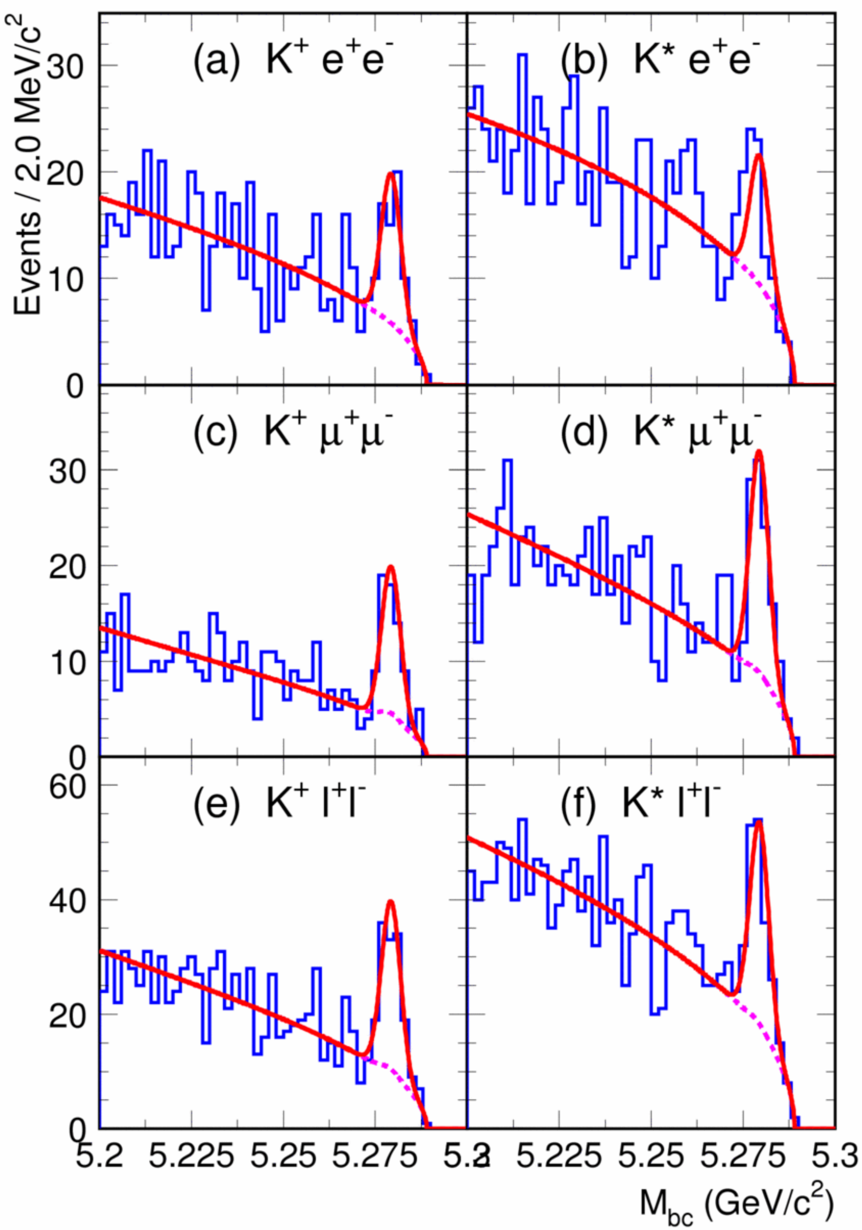
D.A. Demir *et al.* Phys.Rev. D66 (2002) 034015

Signal yield: N_{sig} = 114±13

Consistent with Belle measurement (140fb^{-1}):

$Br(B \to K^* \ell^+ \ell^-) = (11.5^{+2.6}_{-2.4} \pm 0.8 \pm 0.2) \times 10^{-7}$

A. Ishikawa *et al.* Phys.Rev. Lett. 91, 261601 (2003)

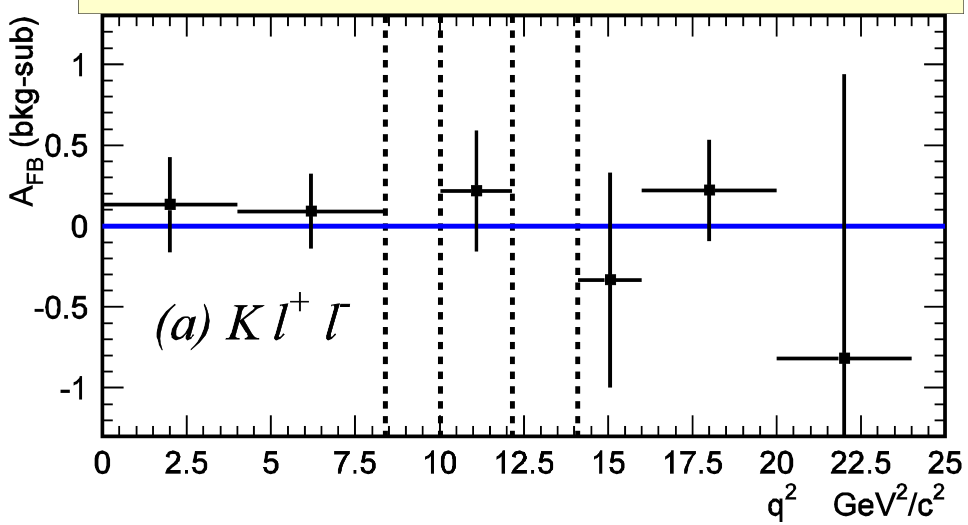


Extraction of A_{FB} and Wilson coeffs.

- Extract the ratio of Wilson coefficients A_9/A_7, A_{10}/A_7 ($A_7 = A_7^{SM} = -0.330$) from an unbinned maximum likelihood fit on events in the signal window with a pdf including $g(q^2,\theta) = d^2\Gamma / dq^2\, d\cos\theta$.
- Several event categories:
  - signal + "cross feeds" from misreconstructed $B \to K^{(*)}\ell^+\ell^-$ or other $b \to s\ell\ell$
  - 4 background sources – dominated by dilepton (80%)

A_{FB} simply obtained by integration: $$\mathcal{A}_{\rm FB}(q^2) = \frac{\int_{-1}^{1} \mathrm{sgn}(\cos\theta) g(q^2,\theta)\, d\cos\theta}{\int_{-1}^{1} g(q^2,\theta)\, d\cos\theta}$$

background subtracted A_{FB} in bins of q^2



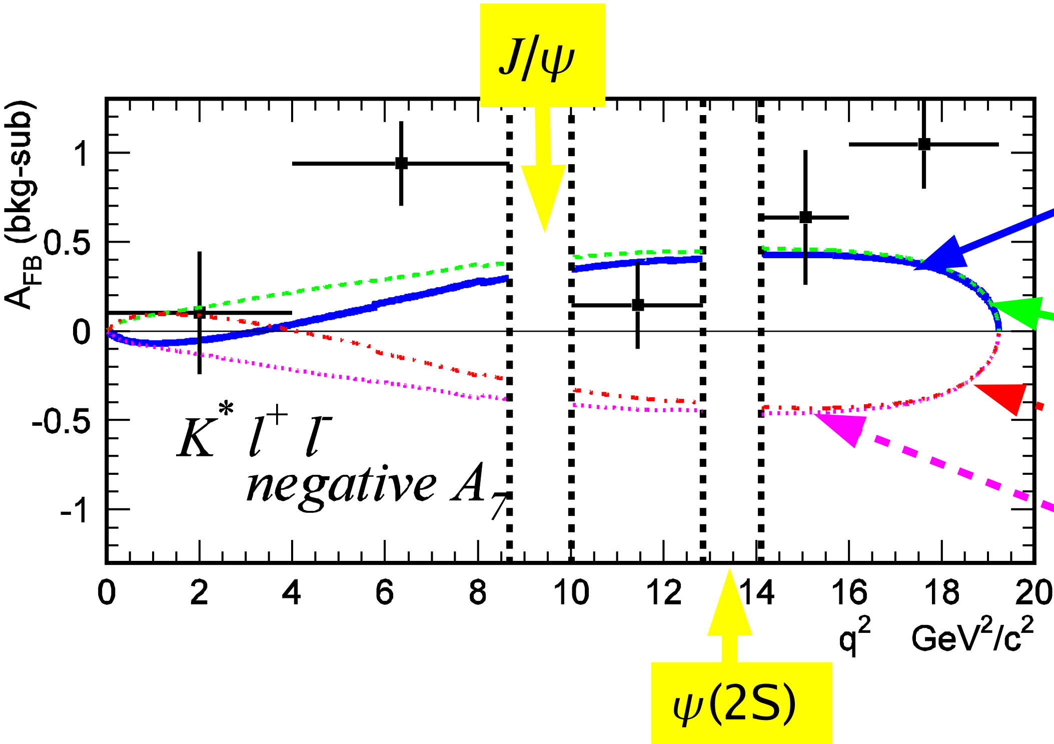
Null test: extract A_{FB} for $B \to K\ell^+\ell^-$

$A_{FB}(B \to K\ell\ell) = 0.10 \pm 0.14 \pm 0.01$

consistent with 0!

Fit results

A. Ishikawa *et al.*, Phys.Rev. Lett. 96, 251801 (2006)



fix $A_7 = -0.330$; $A_{FB} > 0$ at 3.4σ

$A_{FB}(B \to K^* \ell \ell) = 0.50 \pm 0.15 \pm 0.02$

$A_7 A_{10}$ sign flipped — slightly worse fit, but OK

Both $A_7 A_{10}$ and $A_9 A_{10}$ signs flipped

$A_9 A_{10}$ sign flipped

} excluded!

Wilson coefficients:

$A_9/A_7 = -15.3^{+3.4}_{-4.8} \pm 1.1$

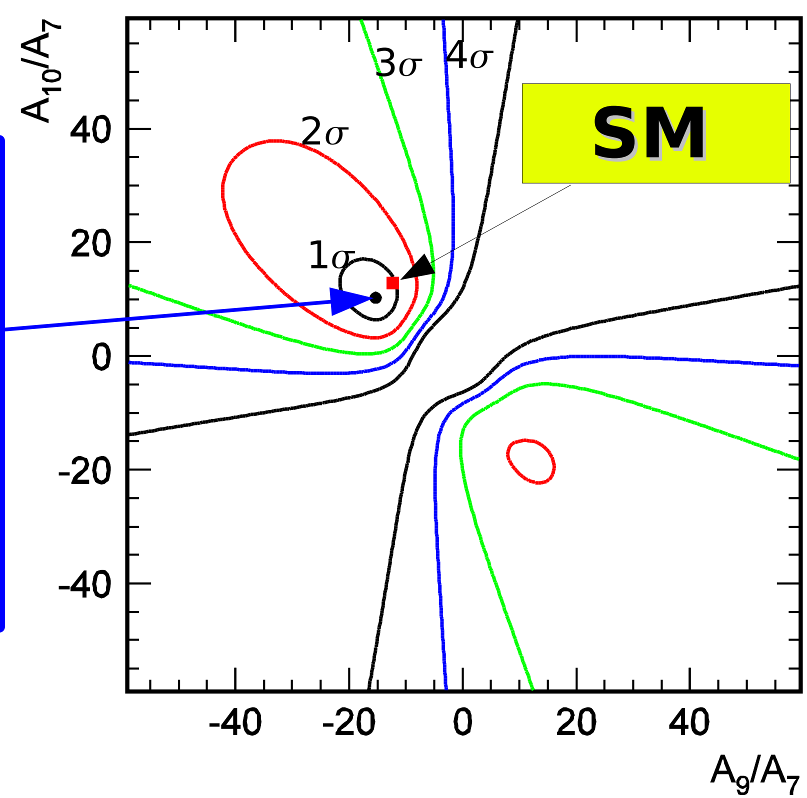
$A_{10}/A_7 = 10.3^{+5.2}_{-3.5} \pm 1.8$

(A_7^{SM})

$-1401 < A_9 A_{10}/A_7^2 < -26.4$ (95% CL, any A_7)

SM:

$$A_9/A_7 = -12.3,$$
$$A_{10}/A_7 = 12.8.$$

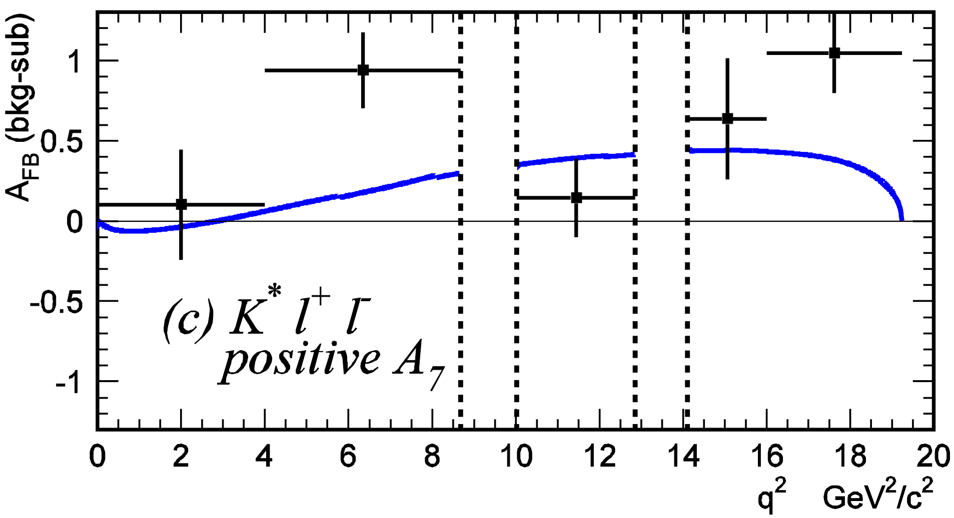


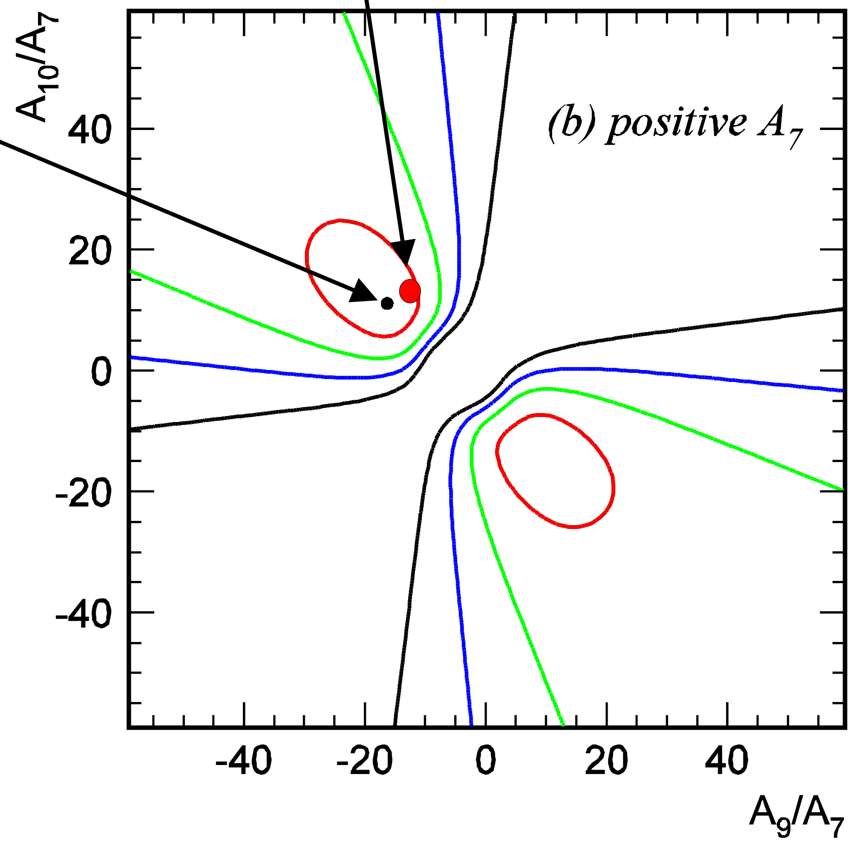
Positive A_7 solution

Best fit for positive A_7 (non-SM like):

$$A_9/A_7 = -16.3^{+3.7}_{-5.7} \pm 1.4,$$
$$A_{10}/A_7 = 11.1^{+6.0}_{-3.9} \pm 2.4,$$

SM $A_9/A_7 = -12.3,$ $A_{10}/A_7 = 12.8.$

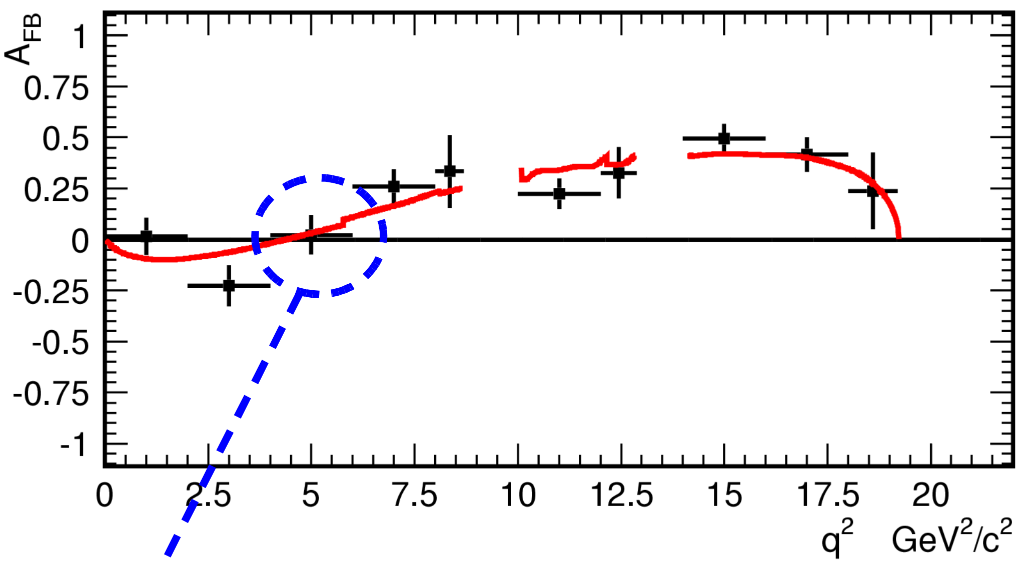




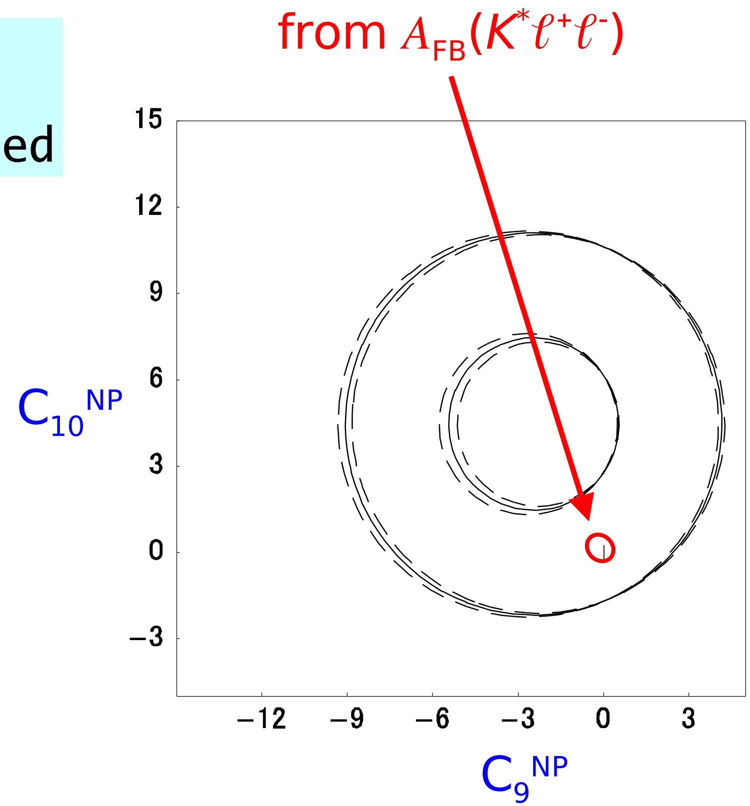
Future prospects for $B \to K^* \ell^+ \ell^-$

Super B-factory goal: $\mathcal{L}=5\text{x}10^{35}\text{cm}^{-2}\,\text{s}^{-1}$; in 1 year $\int\mathcal{L}=5\ \text{ab}^{-1}$

expected performance on $B \to K^* \ell^+ \ell^-$
with 1 year of data taking   no syst. errors included



zero of $A_{FB}(q^2)$ is very sensitive to BSM effects. Will be able to measure it.



$\Delta A_9/A_9 \sim 11\%$

$\Delta A_{10}/A_{10} \sim 13\%$

A. Ishikawa at Lake Louise 2006

$$B^+ \to \tau^+ \nu_\tau$$

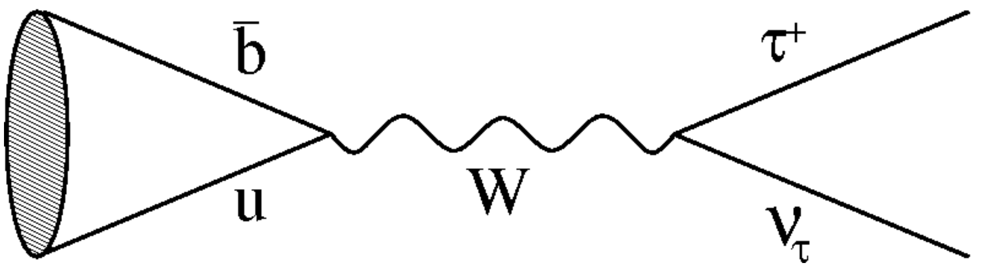
$B^+ \to \tau^+ \nu_\tau$: SM prediction

SM:

B lifetime

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

Direct Measurement of decay constant f_B!



- **Br($B \to \tau\nu_\tau$) ≃ 1.6 x 10^{-4} in SM**
- Other $\ell\nu_\ell$ modes are helicity suppressed ~$(m_\ell)^2$

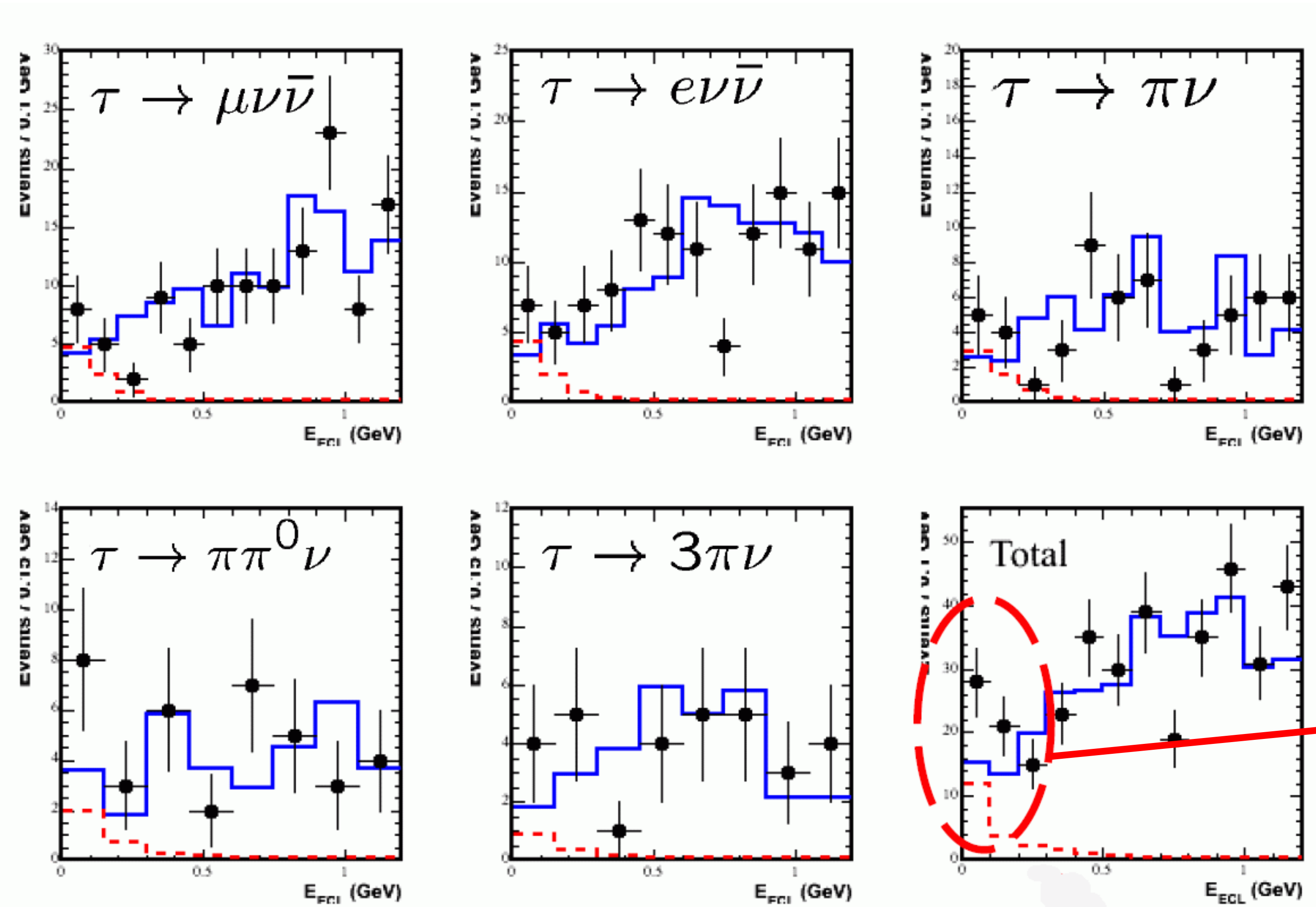
BSM:

Possible enhancements of BF in
- MSSM (charged Higgs): can explore the (M_H, tanβ) plane.
- Pati-Salam models: can set limit on the mass of LQ

Theoretically very clean, experimentally difficult: at least 2 neutrinos...

$B^+ \to \tau^+ \nu_\tau$: the analysis

- Reconstruct the companion B in exclusive $D^{(*)0}h^+$ and $D^{(*)0}D^{(*)+}_s$ channels to get a pure (55%) B^+B^- sample (6.8×10^5 evts)
- Reconstruct signal from remaining particles in the event
- τ lepton reconstructed in 5 decay modes (81% of all modes)
- Final selection based on remaining energy in ECL: $E_{ECL} \cong 0$ for signal

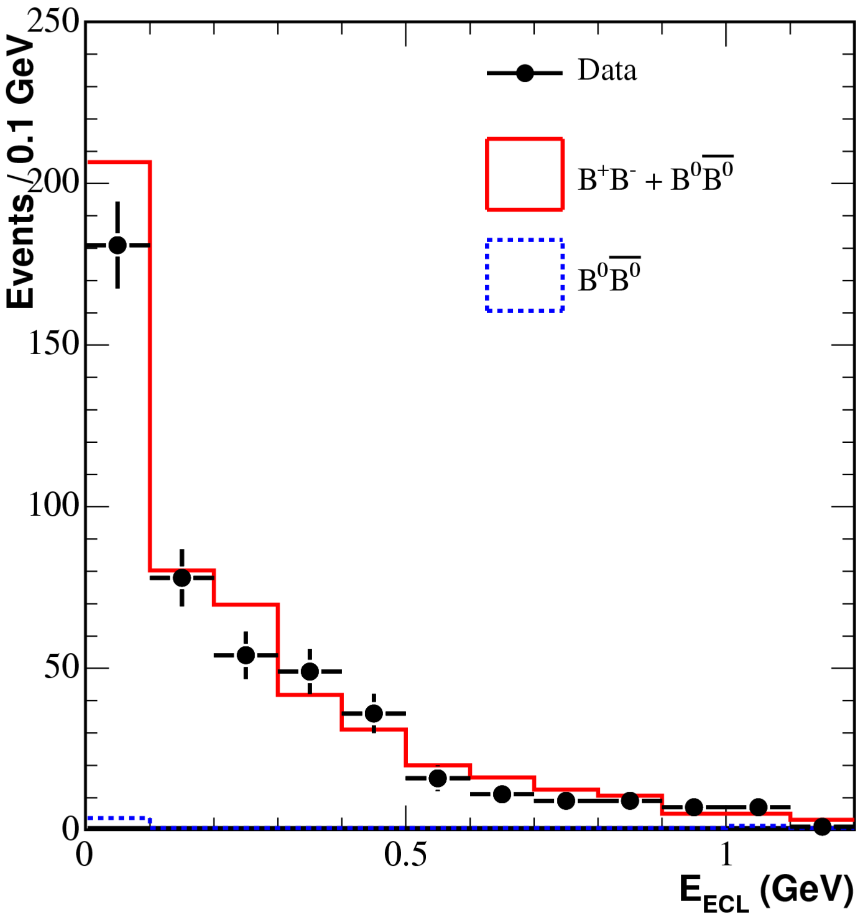


Dataset: 414 fb^{-1}

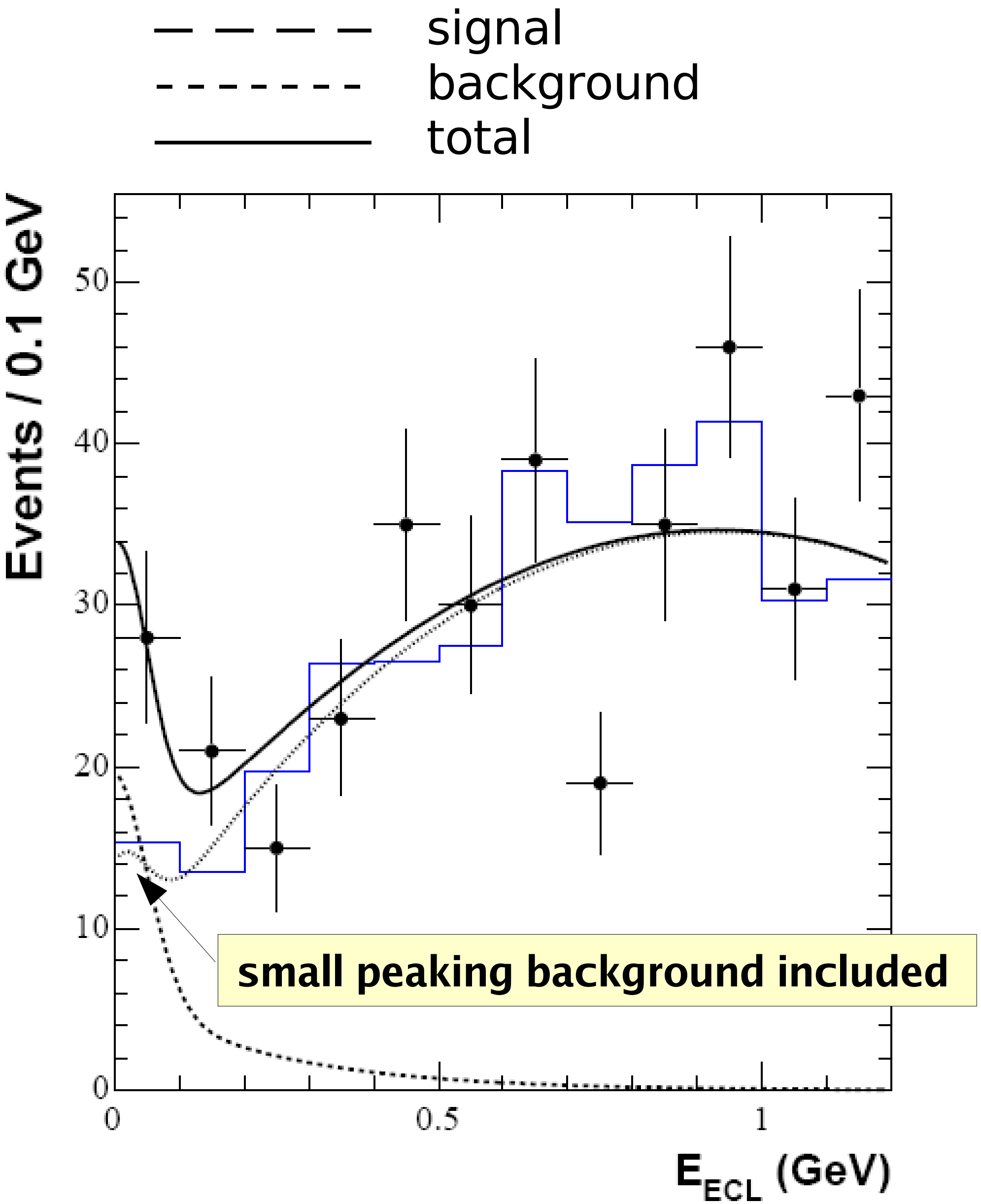
Excess of events visible in the signal region!

$B^+ \to \tau^+ \nu_\tau$: the analysis

To validate the E_{ECL} cut, use a control sample of double tagged events: B_{sig} substituted by $B \to D^{*0} \ell \nu$:



FIT RESULT:



$B^+ \to \tau^+ \nu_\tau$: results

	N_{obs}	N_{s}	N_{b}	Σ
$\mu^- \bar{\nu}_\mu \nu_\tau$	13	$5.6^{+3.1}_{-2.8}$	$8.8^{+0.1}_{-0.1}$	2.2σ
$e^- \bar{\nu}_e \nu_\tau$	12	$4.1^{+3.3}_{-2.6}$	$9.0^{+0.1}_{-0.1}$	1.4σ
$\pi^- \nu_\tau$	9	$3.8^{+2.7}_{-2.1}$	$3.9^{+0.1}_{-0.1}$	2.0σ
$\pi^- \pi^0 \nu_\tau$	11	$5.4^{+3.9}_{-3.3}$	$5.4^{+0.6}_{-0.6}$	1.5σ
$\pi^- \pi^+ \pi^- \nu_\tau$	9	$3.0^{+3.5}_{-2.5}$	$4.8^{+0.4}_{-0.4}$	1.0σ
Combined	54	$17.2^{+5.3}_{-4.7}$	$32.0^{+0.7}_{-0.7}$	3.5σ

First evidence of a purely leptonic B decay

systematics included

BELLE result

$$\text{Br}(B \to \tau \nu_\tau) = (1.79^{+0.56}_{-0.49}(\text{stat})\,^{+0.39}_{-0.46}(\text{syst}))\,\text{x}10^{-4}$$

$$f_B = 0.229^{+0.036}_{-0.031}(\text{stat})\,^{+0.030}_{-0.034}(\text{syst})\ \text{GeV}$$

obtained using
$|V_{ub}| = (4.39 \pm 0.33)\text{x}10^{-3}$ (HFAG)

SM:

$\text{Br}(B \to \tau \nu_\tau) = (1.59 \pm 0.40)\text{x}10^{-4}$

$f_B = 0.216 \pm 0.022$ GeV

from lattice QCD:
HPQCD, Phys. Rev. Lett. 95, 212001 (2005)

First direct determination of f_B

$B^+ \to \tau^+ \nu_\tau$: constraints on BSM

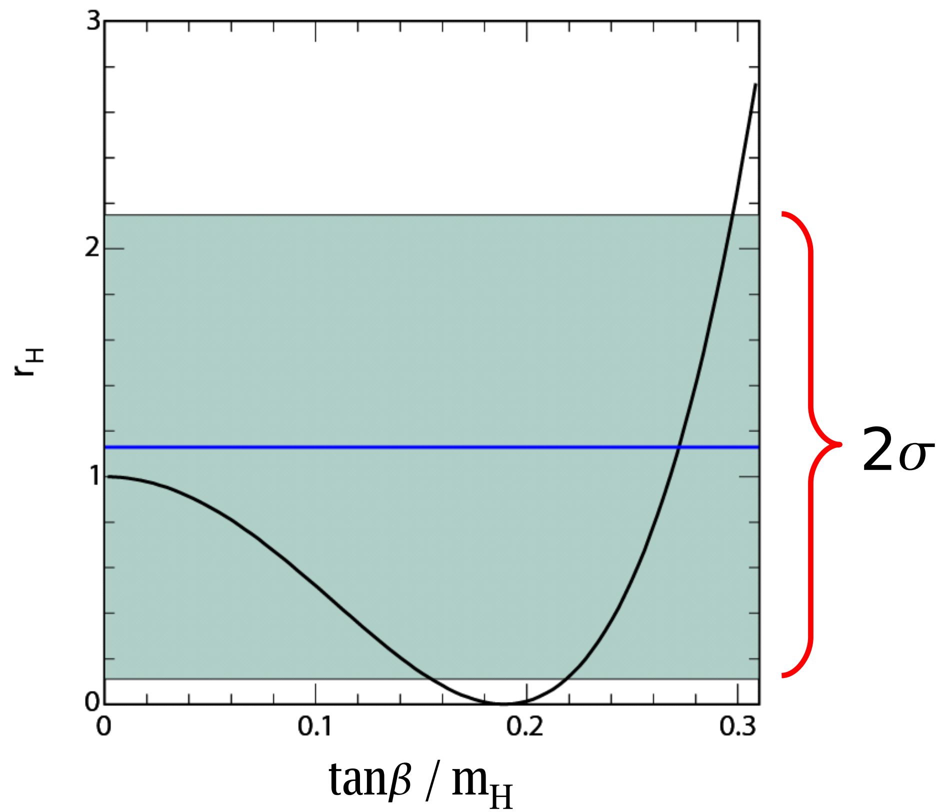
Constraint on Charged Higgs (two Higgs doublet model, type II):

$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\mathrm{SM}} \times r_H \qquad r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

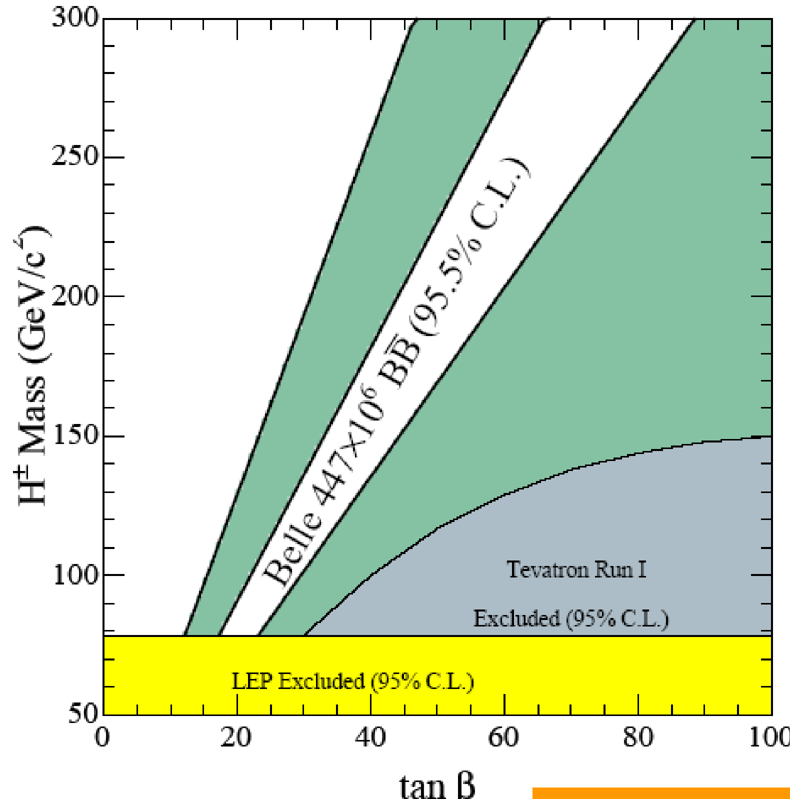
$$\mathcal{B}(B \to \tau\nu) = (1.79^{+0.56}_{-0.49}(\mathrm{stat})^{+0.39}_{-0.46}(\mathrm{syst})) \times 10^{-4}$$

$$\mathcal{B}(B \to \tau\nu)_{\mathrm{SM}} = (1.59 \pm 0.40) \times 10^{-4}$$

$$\Big\} \quad r_H = 1.13 \pm 0.51$$



W.S. Hou, Phys. Rev. D 48, 2342 (1993)



95.5% C.L. exclusion

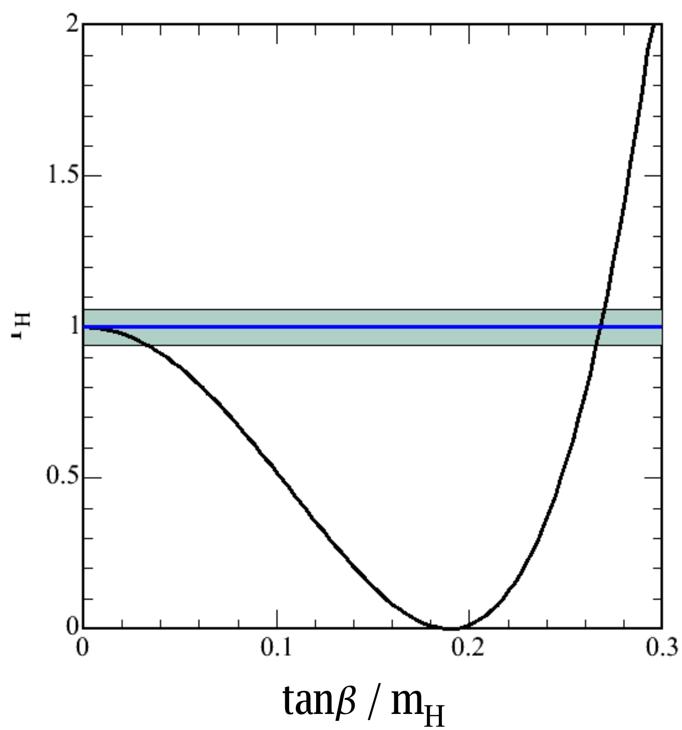
Future prospects for $B^{+}\rightarrow\tau^{+}\nu_{\tau}$

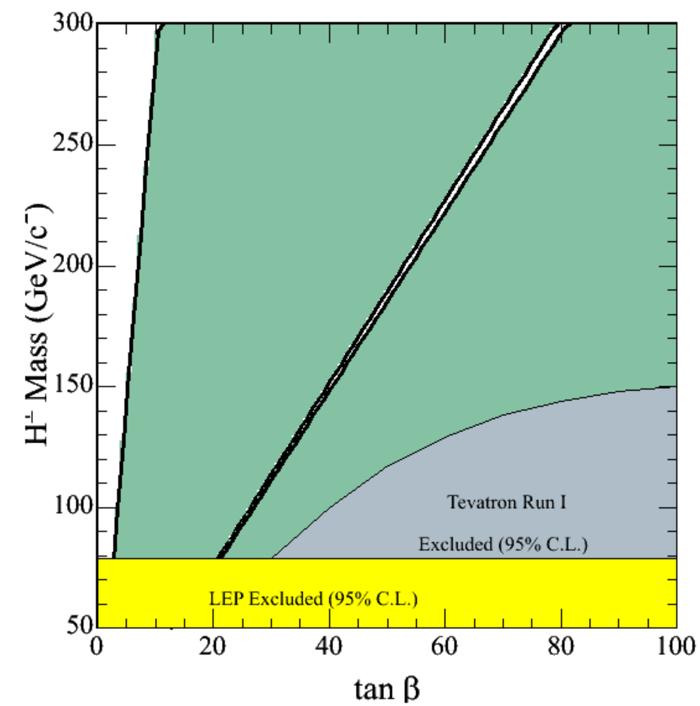
Extrapolating the current results to super-B factory luminosities:
(assuming Δf_B(LQCD) = 5%)

Lum.	$\Delta B(B\rightarrow\tau\nu)_{exp}$	$\Delta\|V_{ub}\|$
414 fb^{-1}	36%	7.5%
5 ab^{-1}	10%	5.8%
50 ab^{-1}	3%	4.4%

With 50 ab^{-1}:

(assuming $\Delta|V_{ub}|$ = 0 and Δf_B = 0)





Conclusions

- Belle performed the first measurement of Wilson Coefficients in $B \to K^* \ell^+ \ell^-$:
  - Integrated forward-backward asymmetry significantly >0
  - First determination of sign of $A_9 A_{10}$
  - Results compatible with SM prediction and ruling out many BSM scenarios
- $B^+ \to \tau^+ \nu_\tau$: first evidence of a purely leptonic *B* decay
  - Measured branching fraction consistent with SM prediction
  - First direct determination of the *B* decay constant
  - Set constraints on M_H–$\tan\beta$ in MSSM
- Still a lot to come from Belle and hopefully Super Belle!

BACKUP SLIDES

$B \to K^* \ell^+ \ell^-$: details of the fit

The Probability Density Function:

$$
\begin{aligned}
& P(M_{\rm bc}, q^2, \cos\theta; A_9/A_7, A_{10}/A_7) \\
= \; & \frac{1}{N_{\rm sig}} f_{\rm sig} \epsilon_{\rm sig}(q^2, \cos\theta) g(q^2, \cos\theta) \\
+ \; & \frac{1}{N_{\rm CF}} f_{\rm CF} \epsilon_{\rm CF}(q^2, \cos\theta) g(q^2, \cos\theta) \\
+ \; & \frac{1}{N_{\rm IF}} f_{\rm IF} \epsilon_{\rm IF}(q^2, \cos\theta) g(q^2, -\cos\theta) \\
+ \; & (1 - f_{\rm sig} - f_{\rm CF} - f_{\rm IF} - f_{K^*hh} - f_{\psi X_s}) \times \\
& \left\{ (f_{K^*\ell h} \mathcal{P}_{K^*\ell h}(q^2, \cos\theta) + (1 - f_{K^*\ell h}) \mathcal{P}_{\rm dl}(q^2, \cos\theta) \right\} \\
+ \; & f_{K^*hh} \mathcal{P}_{K^*hh}(q^2, \cos\theta) + f_{\psi X_s} \mathcal{P}_{\psi X_s}(q^2, \cos\theta).
\end{aligned}
$$

ϵ : efficiency functions, estimated from data and MC

f : event by event signal and background probability, from M_{bc} fit

Wilson coeffs, systematic uncertainties

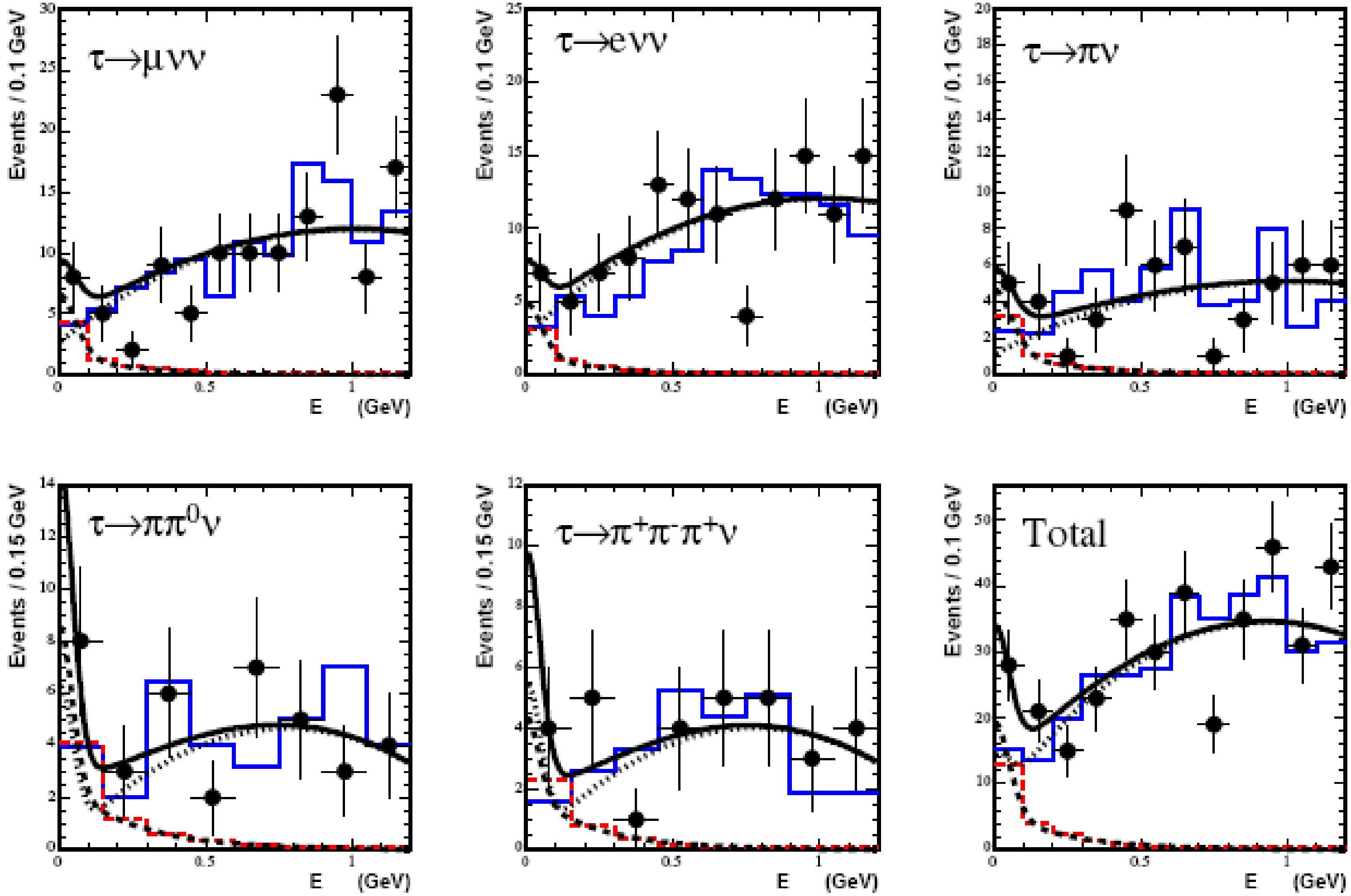
source	negative A_7 solution		positive A_7 solution	
	A_9/A_7	A_{10}/A_7	A_9/A_7	A_{10}/A_7
A_7	+0.2 -0.0	±0.0	+0.1 -0.2	+0.3 -0.1
m_b (4.8±0.2 GeV/c^2)	± 0.7	± 0.5	± 0.6	± 0.4
Form factor model	± 0.7	± 1.7	± 1.0	+2.2
q^2 resolution	± 0.3	± 0.4	± 0.3	± 0.4
efficiency	± 0.1	± 0.0	± 0.1	± 0.1
signal probability	+0.4 -0.5	+0.2 -0.3	+0.4 -0.5	± 0.4
total	**± 1.1**	**± 1.8**	**+1.3 -1.4**	**+2.4 -2.3**

$B^+ \to \tau^+ \nu_\tau$, signal selection criteria

$\tau^- \to \mu^- \nu \bar{\nu}$	$\tau^- \to e^- \nu \bar{\nu}$	$\tau^- \to \pi^- \nu$	$\tau^- \to \pi^- \pi^0 \nu$	$\tau^- \to \pi^- \pi^+ \pi^- \nu$
1 signal-side track				3 signal-side tracks
No signal-side π^0			1 signal-side π^0	No signal-side π^0
$E_{ECL} < 0.2$ GeV			$E_{ECL} < 0.3$ GeV	
$P^*_{\ell^-} > 0.3$ GeV		$P^*_{\pi^-} > 0.8$ GeV	$P^*_{\pi\pi} > 1.2$ GeV	$P^*_{3\pi} > 1.8$ GeV
$P^*_{miss} > 0.2$ GeV		$P^*_{miss} > 1.0$ GeV	$P^*_{miss} > 1.2$ GeV	$P^*_{miss} > 1.8$ GeV
			$\|M_{\rho} - M_{\pi\pi}\| < 0.15$ GeV	$\|M_{\rho} - M_{\pi\ \pi^-}\| < 0.15$ GeV
				$\|M_{a} - M_{3\pi}\| < 0.3$ GeV
$-0.86 < \cos\theta^*_{miss} < 0.95$				

Signal-side efficiency including decay branching fractions: 15.81 ± 0.05%

$B^+ \to \tau^+ \nu_\tau$, fits to individual modes



$B^+ \to \tau^+ \nu_\tau$, systematic uncertainties

- Signal selection efficiencies

Source	$\mu^-\nu\bar{\nu}(\%)$	$e^-\nu\bar{\nu}(\%)$	$\pi^-\nu(\%)$	$\pi^-\pi^0\nu(\%)$	$\pi^+\pi^-\pi^+\nu(\%)$
Tracking	1.0	1.0	1.0	1.0	3.0
τ decay BR	0.3	0.3	1.0	0.6	1.1
MC statistics	0.6	0.6	0.7	1.0	2.0
Lepton ID	2.1	2.1	-	-	-
π^0 reconstruction	-	-	-	3	-
$\pi^\pm$ ID	-	-	2.0	2.0	6.0

- Tag reconstruction efficiency : 10.5%

  Difference of yields between data and MC in the $B \to D^{*0} \ell \nu$ control sample
- Number of BB : 1%
- Signal yield : +22.5% -25.7%

  - signal shape ambiguity estimated by varying the signal PDF parameters

  - BG shape : changing PDF
- **Total systematic uncertainty: +25.5% -28.4%**