$b \to c \{e, \mu, \tau\} \nu$ at Belle II

(Workshop style talk)

Phillip Urquijo
B → τ Workshop
Nagoya
March 2017

Belle II

THE UNIVERSITY OF MELBOURNE

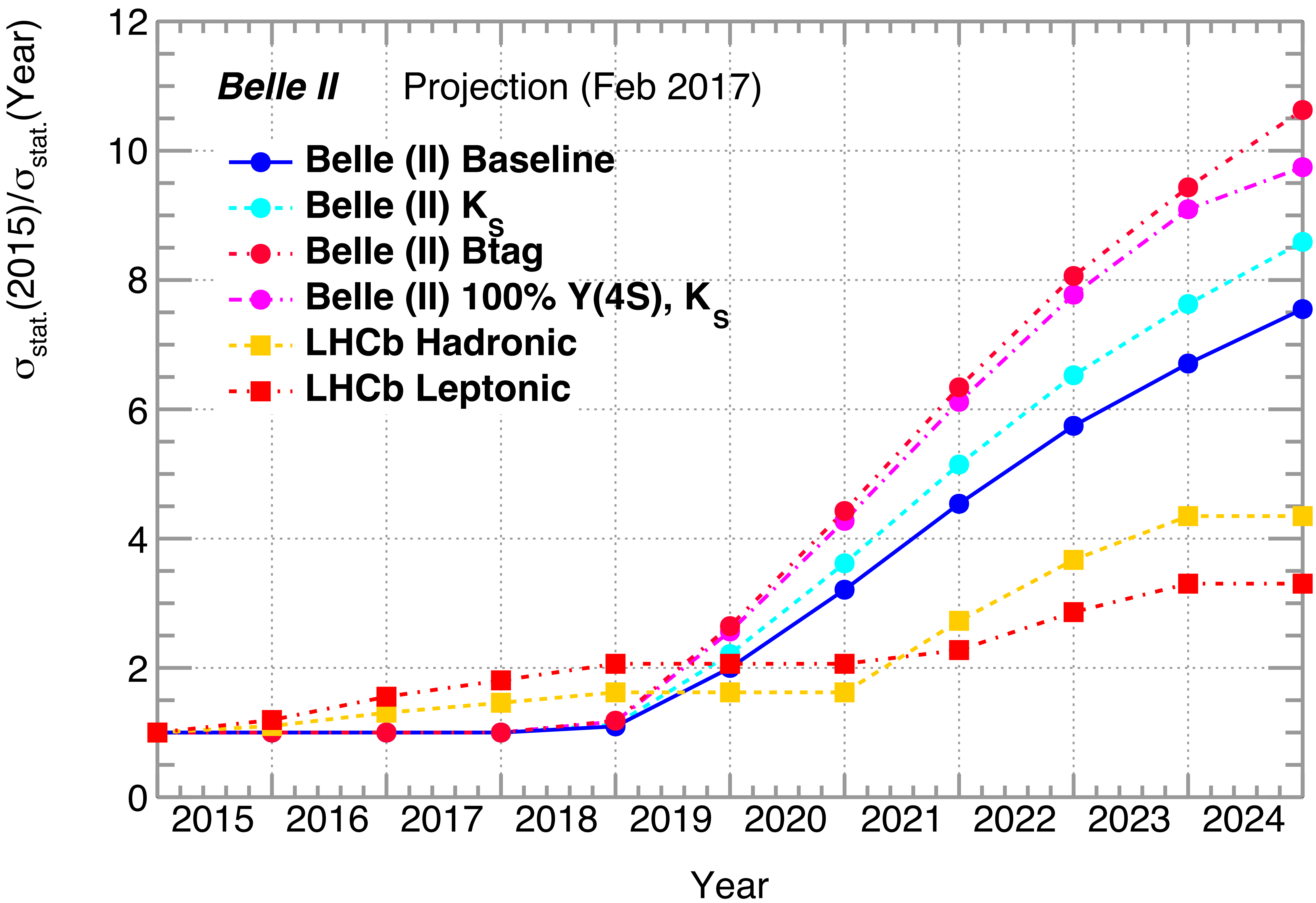
Australian Government
Australian Research Council

Outline

- Main aim: discuss key limiting factors to achieving high precision in $b \to c$ $l\ \nu$ measurements.

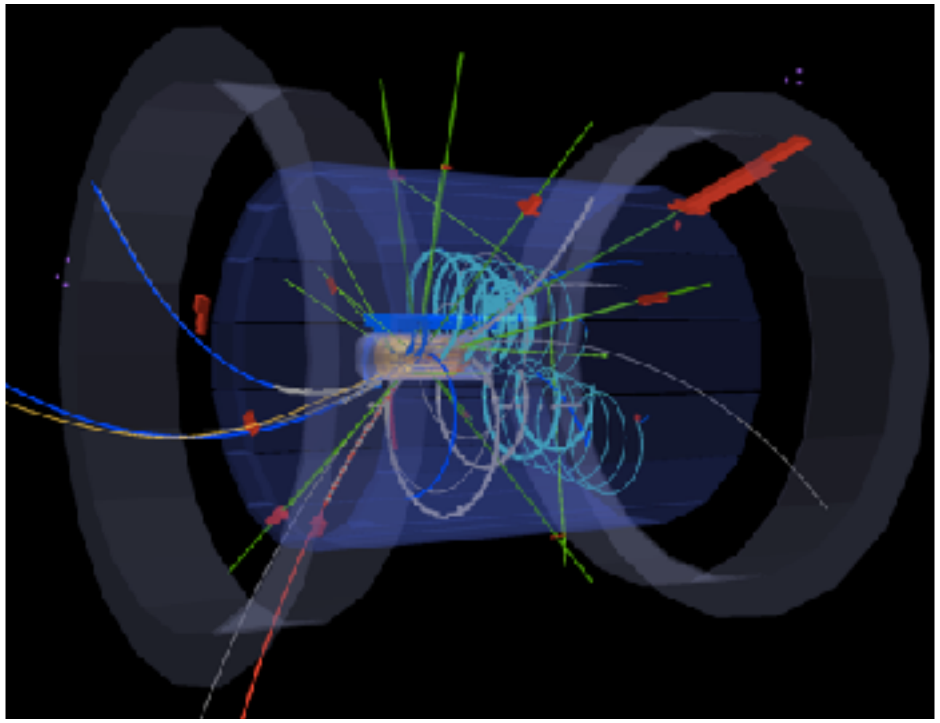
- Key Belle II upgrades.
  - Tracking at low pT
  - Particle ID
  - Neutrals & beam background
- Towards a <u>precise</u> and <u>unbiased</u> $B \to D^{(*)} \tau \nu$
  - Leading uncertainties in $B \to D^{(*)} \tau \nu$ measurements
  - Outlook for $B \to D^{**} l \nu$.
  - $B \to D^{(*)} l \nu$, Bfs, FFs and LFUV.
- Tension with $B \to X \tau \nu$.

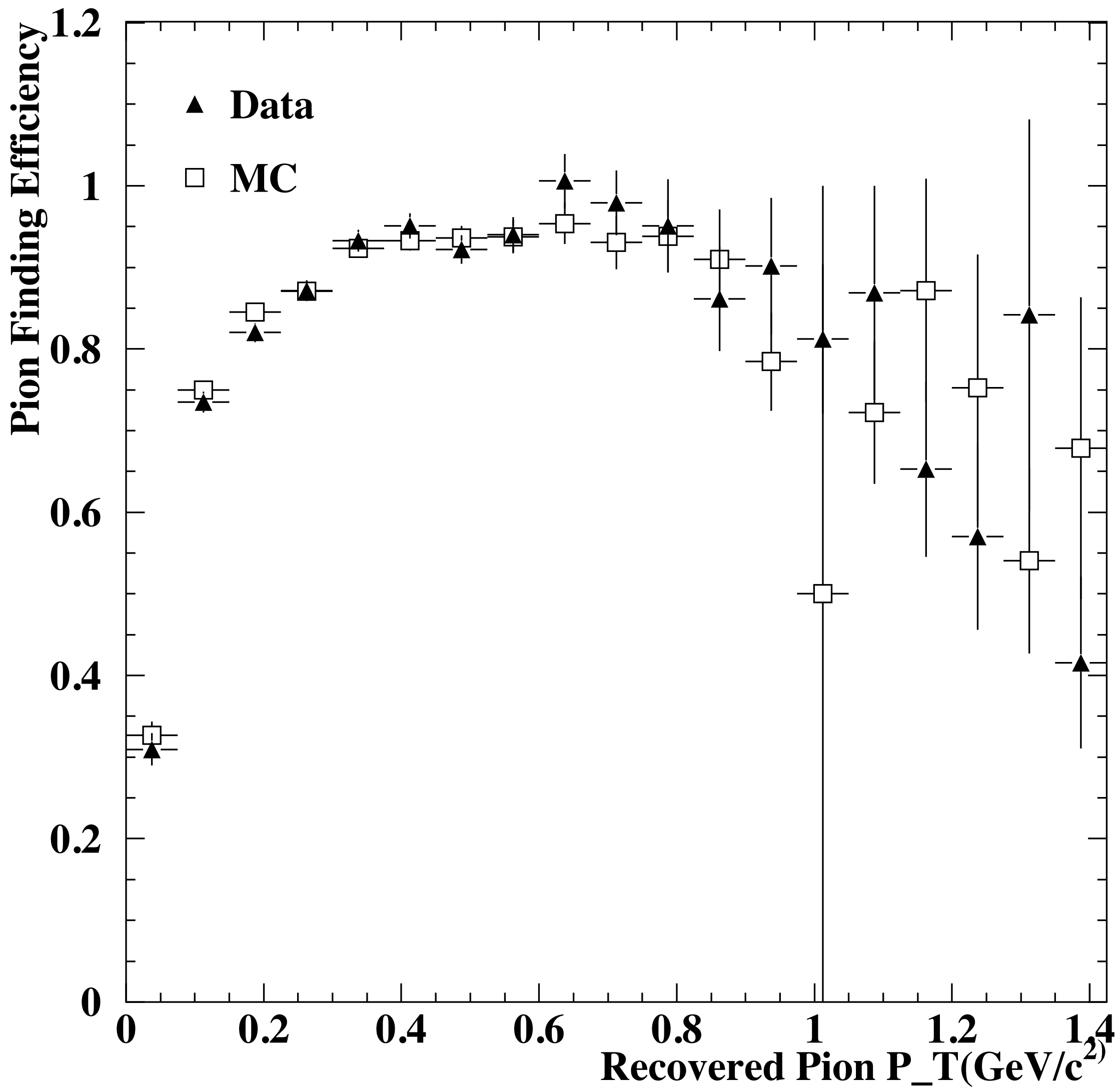
Statistical power projections

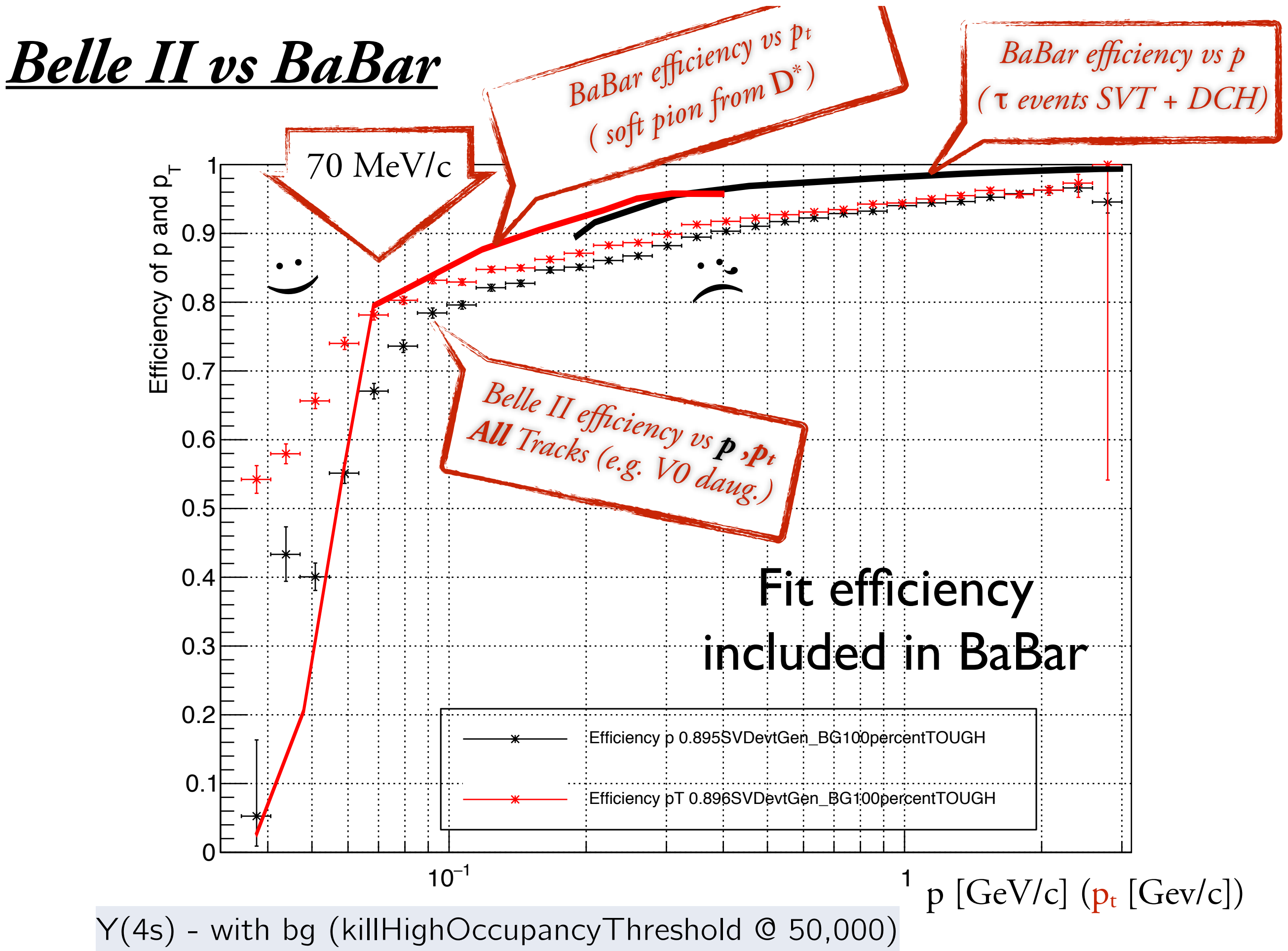


Track efficiencies

- VXD (Pixel + Strip) & CDC
- VXD-dedicated tracking based on cellular automaton model.
- $\langle p_{\pi\text{-slow}} \rangle \sim 100$ MeV

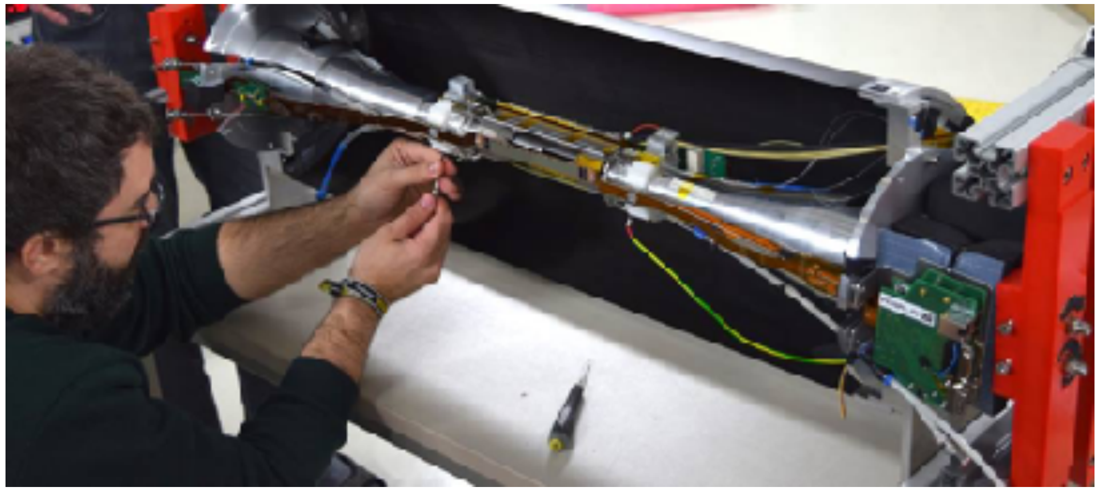


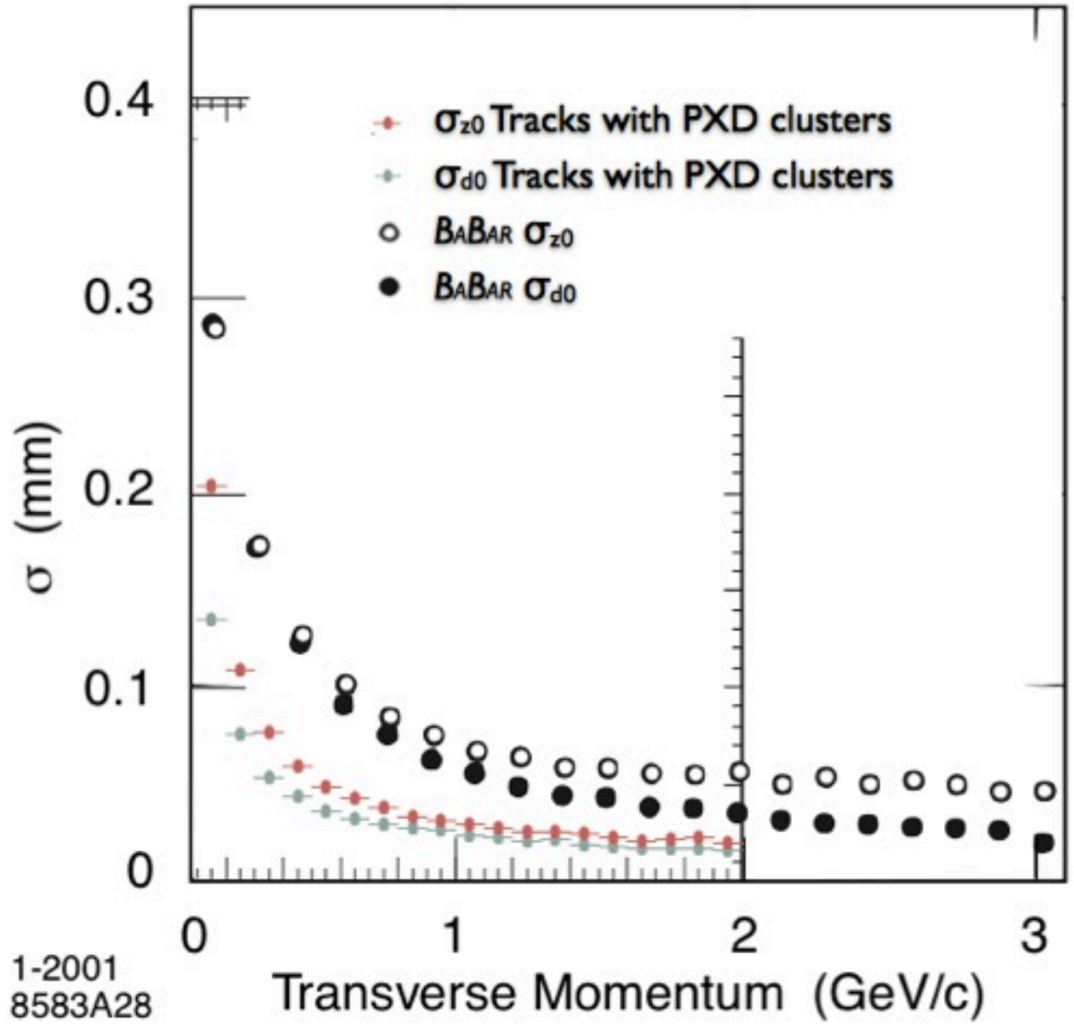


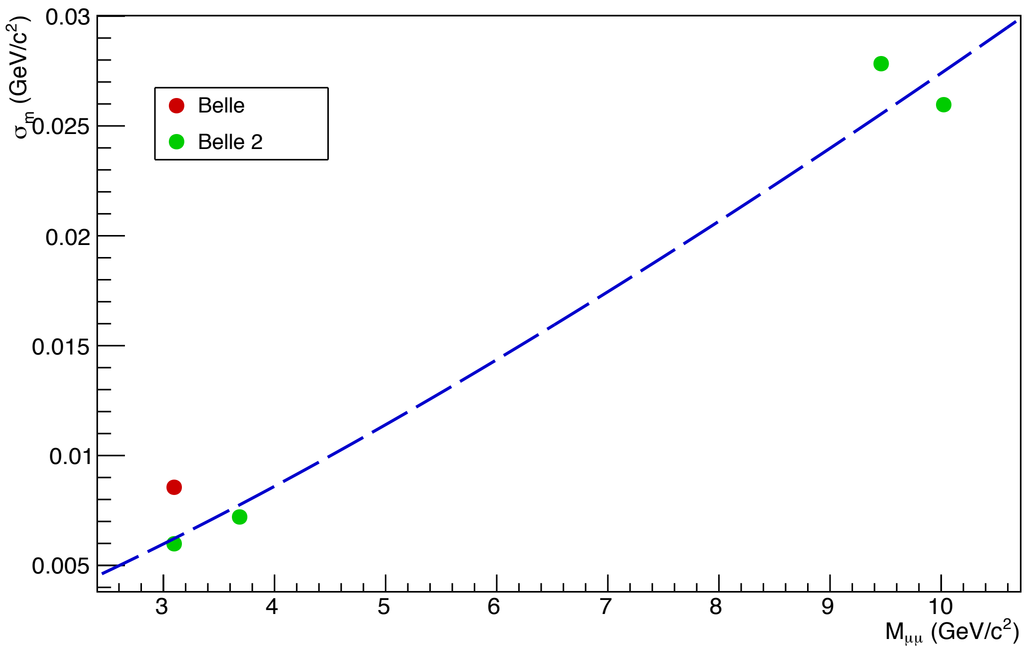


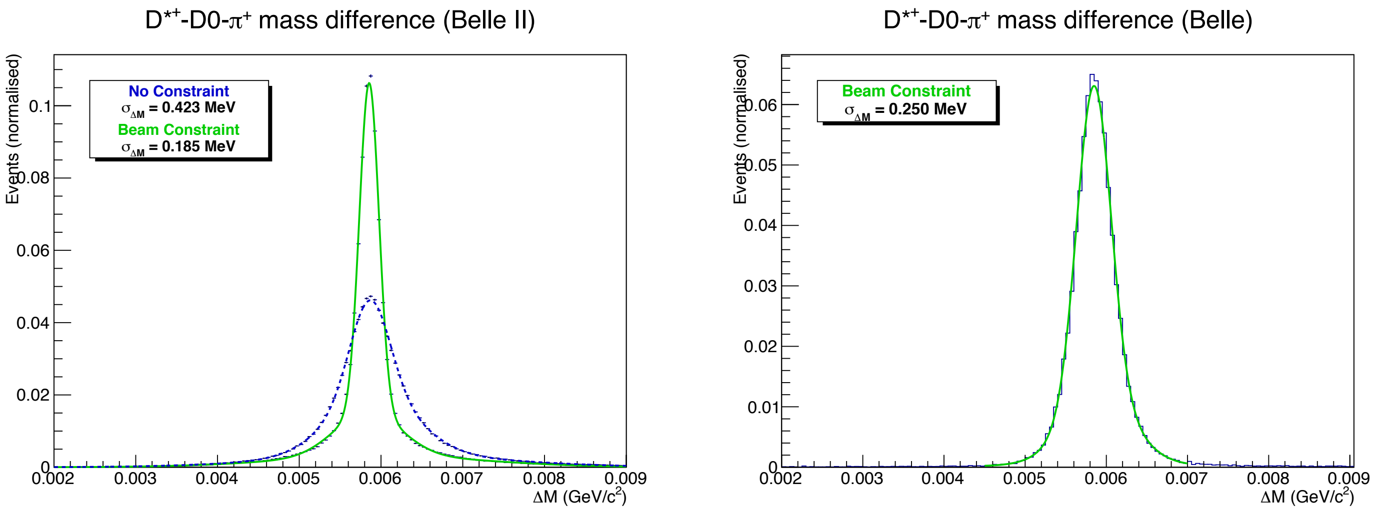
Track Impact parameters & Vertex

- Approx. 2x improvement to IP resolution.
- Mass resolution on J/ψ→*μμ* shows a 27% improvement with respect to Belle. Important for reducing fake D decays.
- ΔM resolution also improves by 30%.



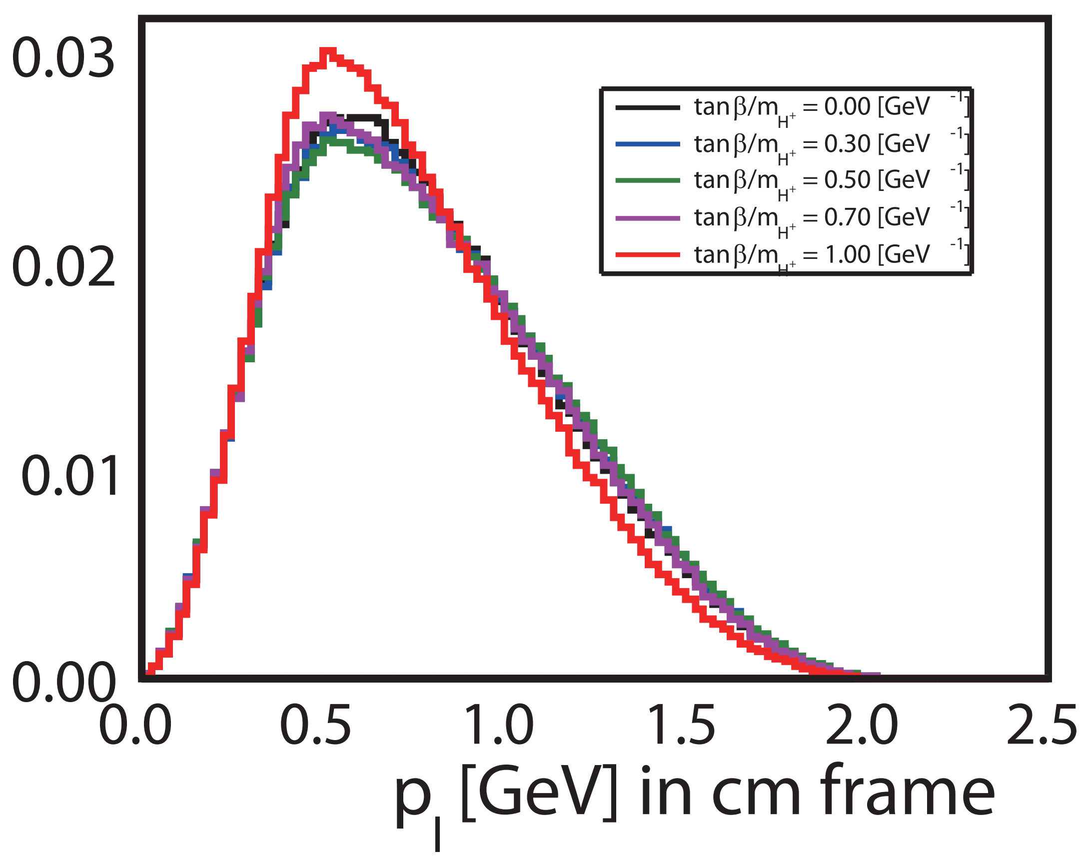


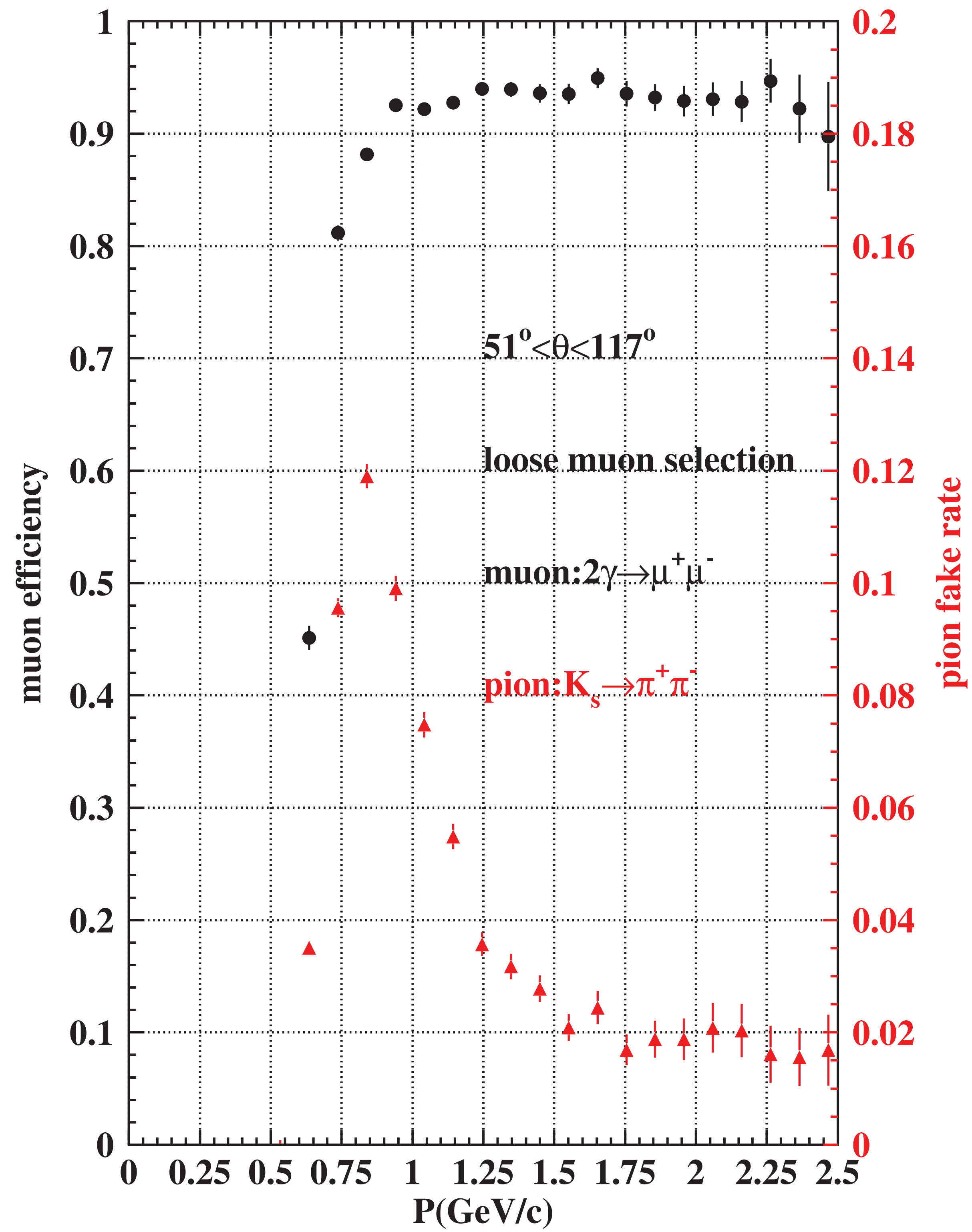




Lepton identification

- e and μ ID.
  - c.f. Belle: track + ECL + ACC + TOF used for e, KLM only for μ.
  - Belle II: TOP, ARICH, dE/dx, ECL-shower depth&Zernike moments → **optimisation for low momentum in progress.**





Beam background

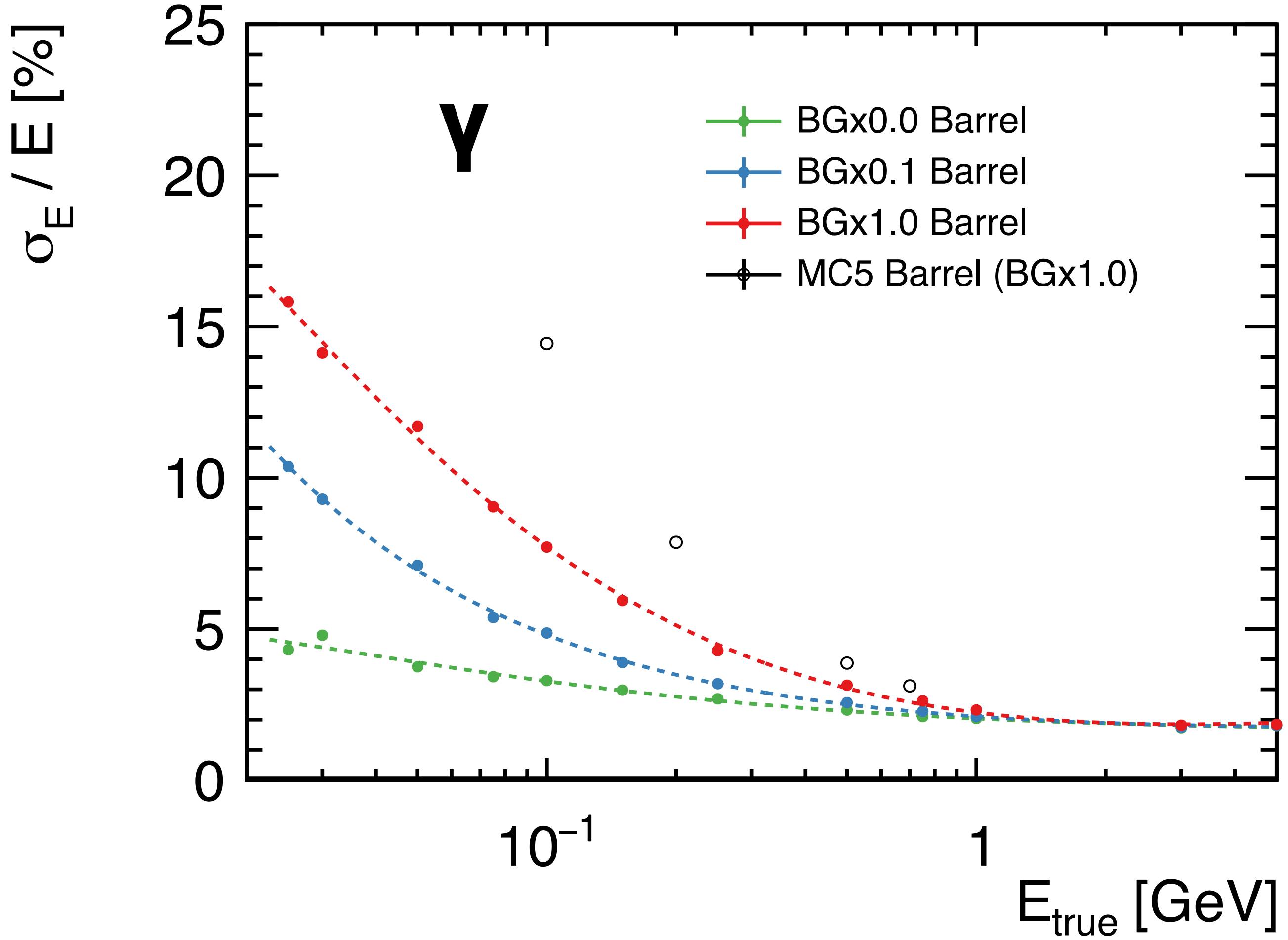
- Increases occupancy in inner Si layers - can degrade tracking.
- Increases off-time energy deposition in the calorimeter.

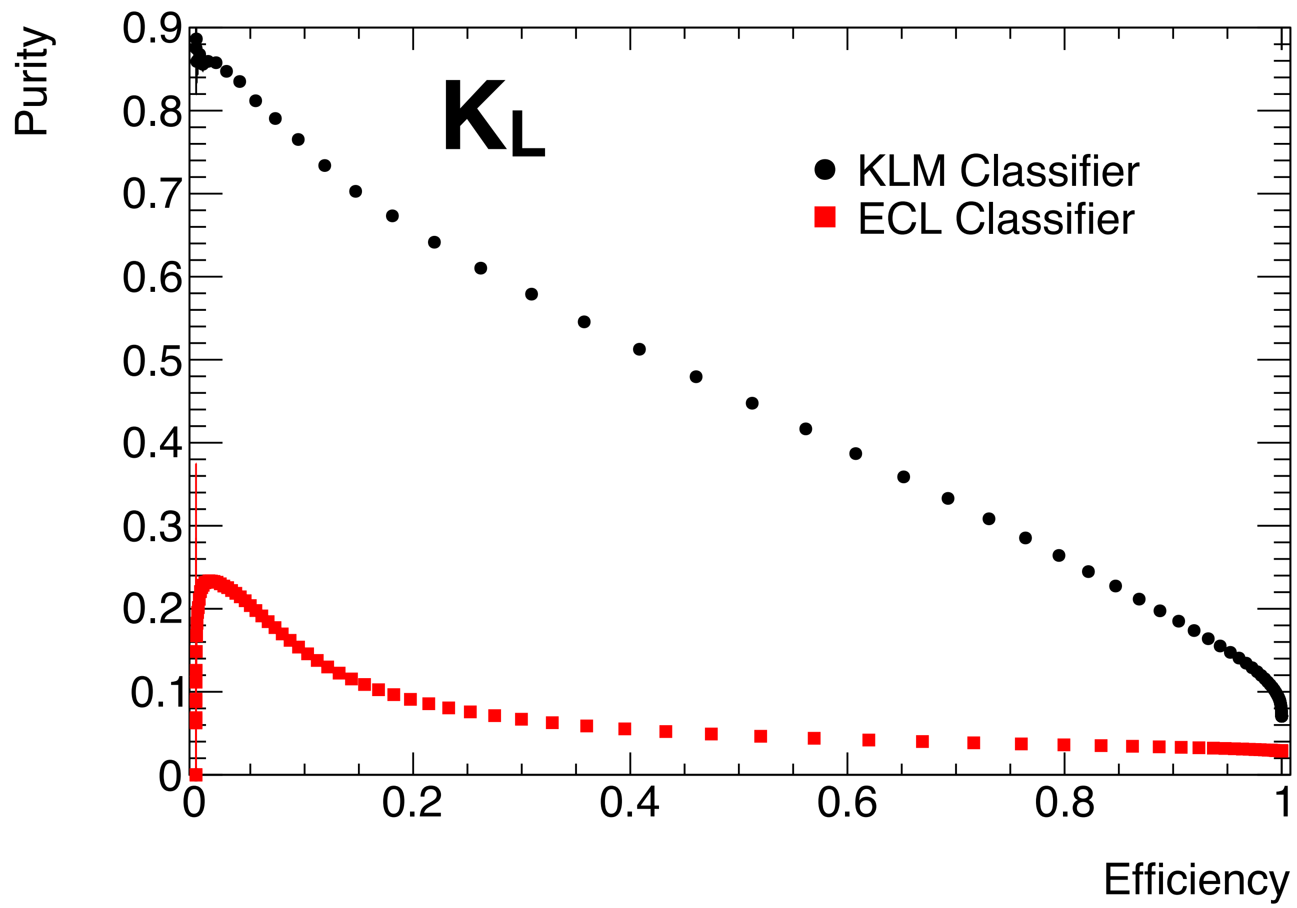
type	source	rate [MHz]
radiative Bhabha	HER	1320
radiative Bhabha	LER	1294
radiative Bhabha (wide angle)	HER	40
radiative Bhabha (wide angle)	LER	85
Touschek scattering	HER	31
Touschek scattering	LER	83
beam-gas interactions	HER	1
beam-gas interactions	LER	156
two-photon QED	-	206

component	background	generic $B\overline{B}$
PXD	10000 (580)	23
SVD	284 (134)	108
CDC	654	810
TOP	150	205
ARICH	191	188
ECL	3470	510
BKLM	484	33
EKLM	142	34

K_L ID & ECL

- ECL highly sensitive to beam background - tackled with use of wave form sampling.
- K_L will be ID'd with KLM and ECL (use of timing in KLM not done at Belle)





$B \rightarrow D^{(*)} \tau \nu$

- Aims
  - R_{D^*}, R_D, $P(\tau)$, $P(D^*)$, $d\Gamma/dq^2$, $d\Gamma/dp_D$, $d\Gamma/dp_l$
- Challenges
  - M_{miss}^2 typically exhibits flat background and flat signal.
  - Beam induced background, scaling with luminosity.

Experiment	N_{BB} [10^6]	Tag method	τ mode	Observables	Fit variables
Belle 07	535	Inclusive	$e \nu \nu$, $\pi \nu$	$B(B^0 \rightarrow D^{*+} l \nu)$	M_{bc}^{tag}
Belle 10	657	Inclusive	$l \nu \nu$, $\pi \nu$	$B(B^- \rightarrow D^{(*)0} l \nu)$	M_{bc}^{tag} & p_{D0}
Babar 12	471	Hadronic	$l \nu \nu$	R_D, R_{D^*}, q^2	M_{miss}^2 & p_l
Belle 15	772	Hadronic	$l \nu \nu$	R_D, R_{D^*}, q^2, $\lvert p_l^* \rvert$	M_{miss}^2 & $O_{NB}(E_{ECL})$
Belle 16	772	Semileptonic	$l \nu \nu$	R_{D^*}, $\lvert p_l^* \rvert$, $\lvert p_D^* \rvert$	E_{ECL} & $O_{NB}(\cos\theta_{B\text{-}D^*l})$
Belle 17	772	Hadronic	$\pi \nu$, $\rho \nu$	R_{D^*}, P_τ	E_{ECL} & $\cos\theta_{hel}$

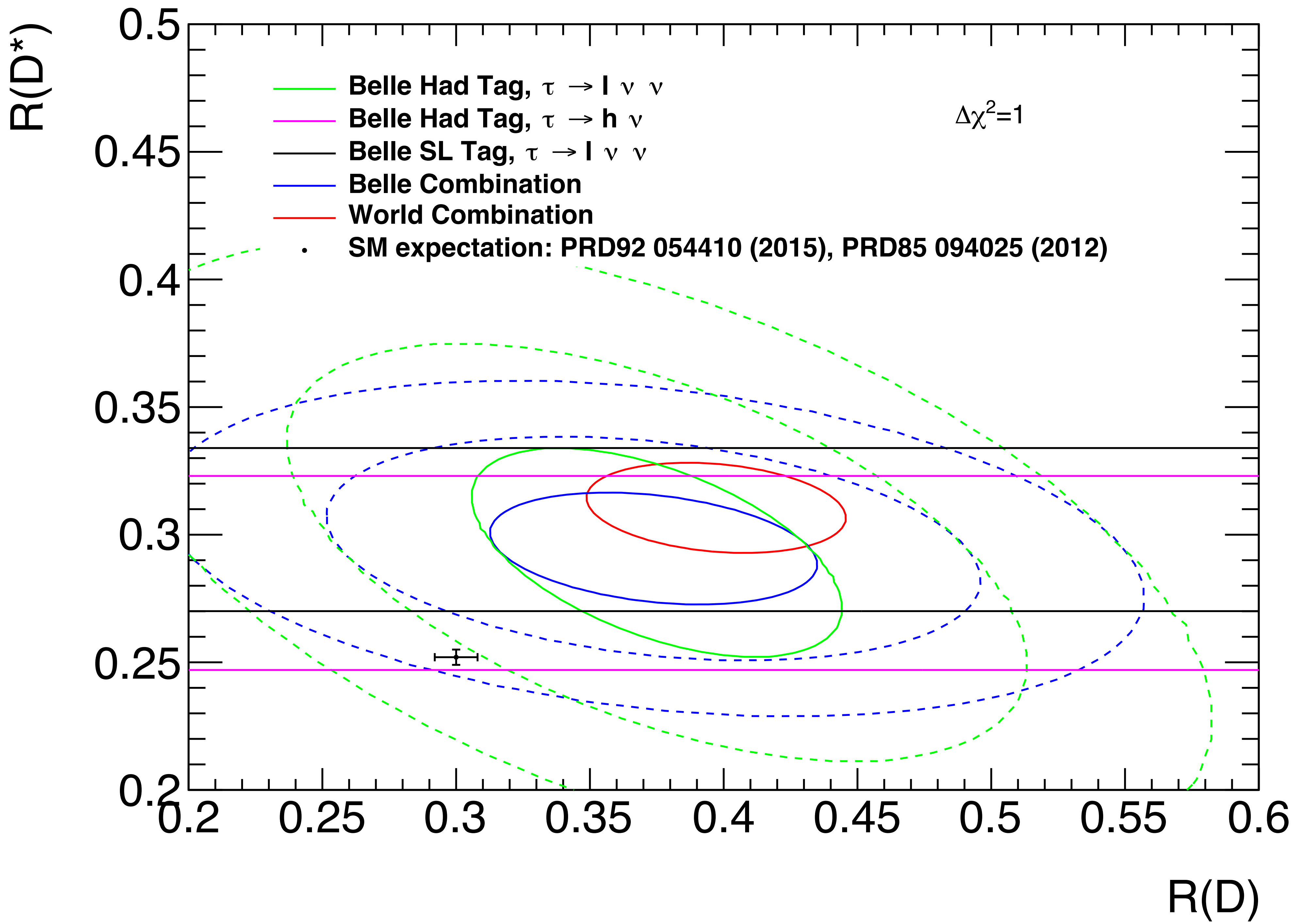
- q^2, p_l and, p_{D^*} are not unfolded

Summary of approaches @ Υ(4S)

Experiment	Tag method	τ mode	R_D	R_{D^*}	ρ
Belle 07*	Inclusive	e ν ν, π ν	0.38±0.11	0.34±0.08	-
Belle 10*	Inclusive	l ν ν, π ν			
Babar 12	Hadronic	l ν ν	0.440±0.058±0.042	0.332±0.024±0.018	-0.27
Belle 15	Hadronic	l ν ν	0.375±0.064±0.026	0.293±0.038±0.015	-0.32
Belle 16	Semileptonic	l ν ν	-	0.302±0.030±0.011	-
Belle 17	Hadronic	π ν, ρ ν	-	0.270±0.035±0.027	-
LHCb 16	-	l ν ν	-	0.336±0.027±0.030	-
Belle ave.	SL+Had	-	0.374±0.061	0.296±0.022	-0.29
HFAG ave.	-	-	0.403±0.040±0.024	0.310±0.015±0.008	-0.23

Belle (private) and HFAG averages take into account correlations.
Belle inclusive not in average (cannot accurately account for correlations).
I symmetrised some errors for this table.

Belle only (i.e. single B-factory)



- Is there a consistent bias in our measurements? How?
- Is it NP? Can we accurately test models?

$B \to D^{(*)} \tau \nu$ systematics @ Belle

Belle PRD 92, 072014 (2015)

- 2017, Hadron tag, $\tau \to h \nu$

Source	Combined $R(D^*)$	Combined P_τ
$D^{**}l^-\bar{\nu}_l$ + had. B composition	5.2%	0.17
MC stat. for PDF construction	3.5%	0.16
Fake D^* yield	2.0%	0.048
Semileptonic decay model	1.9%	0.015
Efficiency corr. for $l^-/\pi^-/\rho^-$	1.8%	0.013
P_τ correction function	0.33%	0.012
Efficiency uncertainty (MC stat.)	0.78%	0.008
$\bar{B} \to D^*l^-\bar{\nu}_l$ yield	0.65%	0.027
$M^2_{\rm miss}$ shape for $\bar{B} \to D^*l^-\bar{\nu}_l$	0.41%	0.001
Fake D^* PDF shape	0.22%	0.001
Total	7.1%	0.24
Expected stat. error	$\sim$ 14%	$\sim$ 0.56

Source	Combined $R(D^*)$	Combined P_τ
$B \to D^{**}l^-\bar{\nu}_l$	0.17%	0.011
$\bar{B} \to D^{**}l^-\bar{\nu}_l$ (100% error)	0.84%	0.054
$\bar{B} \to D^{**}\tau^-\bar{\nu}_l$ (100% error)	2.7%	0.016
Two D	0.77%	0.020
$\bar{B} \to D^*K^-/\pi^-K^0_L$	0.25%	0.014
Other K^0_L mode (100% error)	0.28%	0.021
Other B decays	1.4%	0.058
Other B decays (100% error)	4.1%	0.14
Total	5.2%	0.17

$B \to D^{(*)} \tau \nu$ systematics @ Belle

Belle arXiv:1612.00529
Belle PRD 94, 072007 (2016)

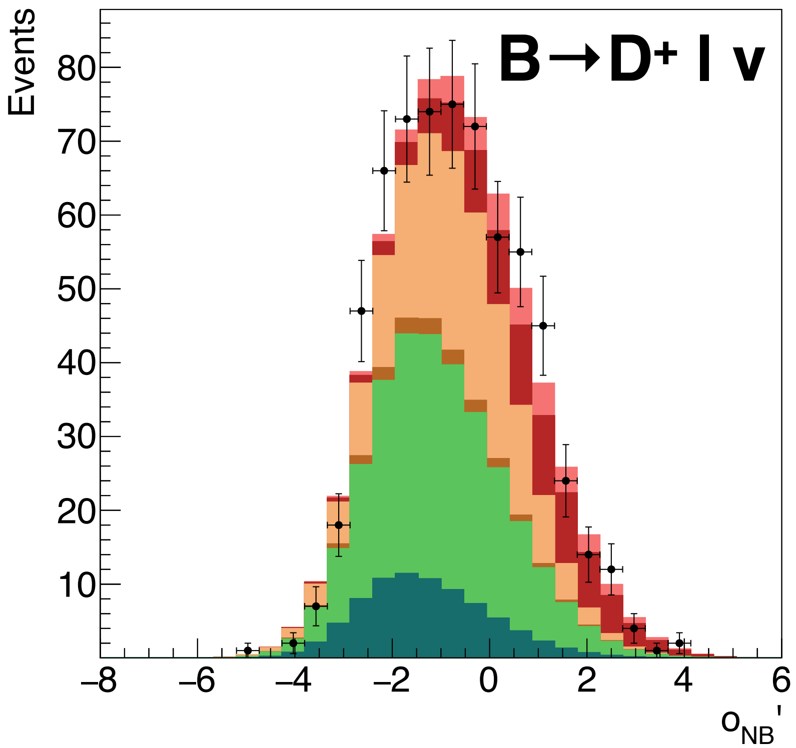
	$R(D)$ [%]	$R(D^*)$ [%]	Correlation
$D^{(*(*))}\ell\nu$ shapes	4.2	1.5	0.04
D^{**} composition	1.3	3.0	-0.63
Fake D yield	0.5	0.3	0.13
Fake ℓ yield	0.5	0.6	-0.66
D_s yield	0.1	0.1	-0.85
Rest yield	0.1	0.0	-0.70
Efficiency ratio f^{D^+}	2.5	0.7	-0.98
Efficiency ratio f^{D^0}	1.8	0.4	0.86
Efficiency ratio $f_{\rm eff}^{D^{*+}}$	1.3	2.5	-0.99
Efficiency ratio $f_{\rm eff}^{D^{*0}}$	0.7	1.1	0.94
CF double ratio g^+	2.2	2.0	-1.00
CF double ratio g^0	1.7	1.0	-1.00
Efficiency ratio $f_{\rm wc}$	0.0	0.0	0.84
$M^2_{\rm miss}$ shape	0.6	1.0	0.00
$o'_{\rm NB}$ shape	3.2	0.8	0.00
Lepton PID efficiency	0.5	0.5	1.00
Total	7.1	5.2	-0.32

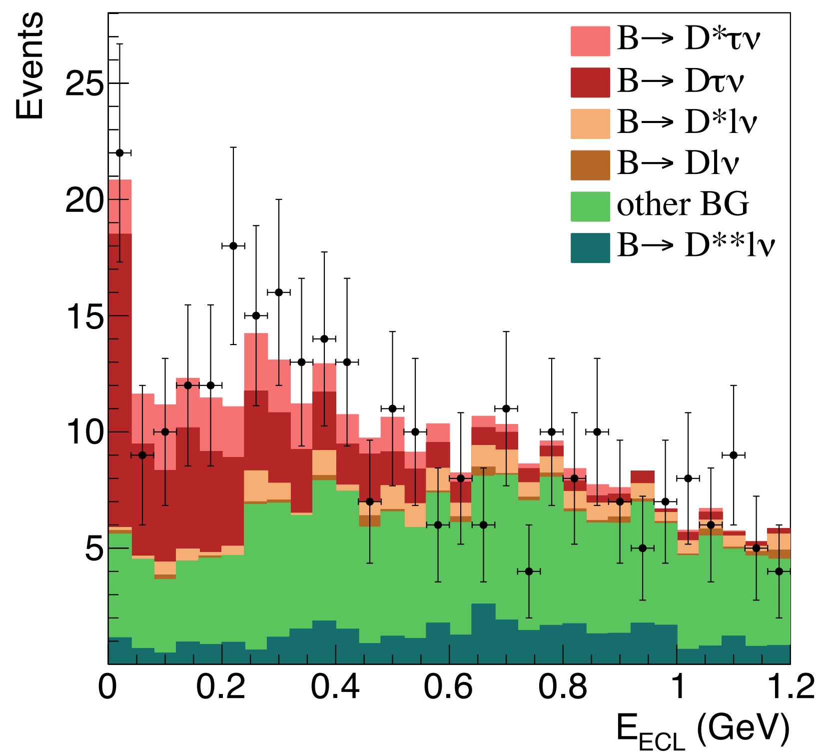
- 2015, Hadron tag, $\tau \to l \nu \nu$
- Combining over systematics we get: ρ=–0.40 B→SL, ρ=–0.22 other
- The sign on the correlation between R_D and R_{D^*} is opposite to Babar!

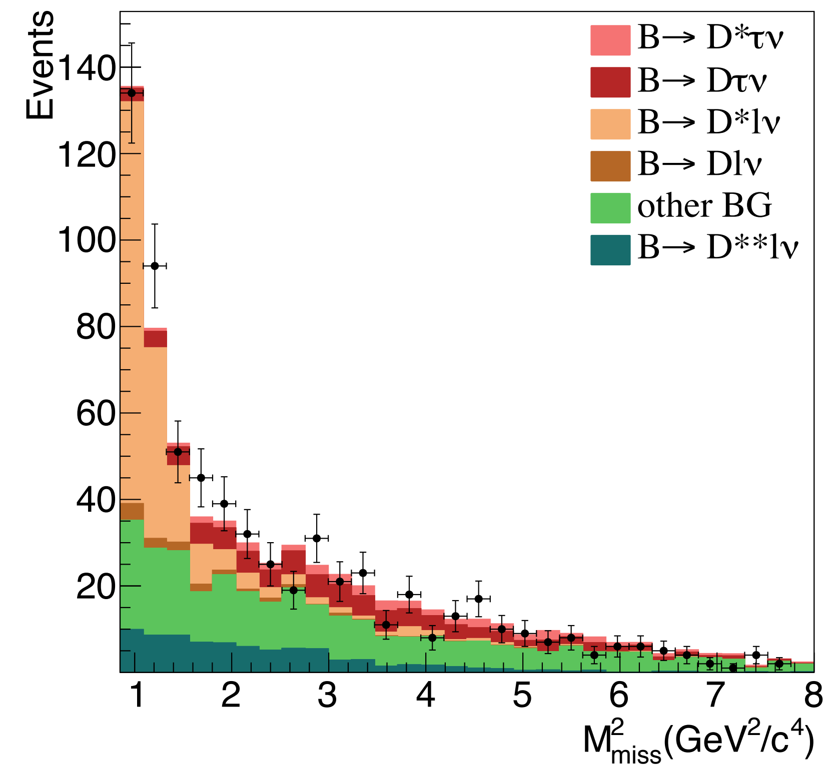
- 2016, Semileptonic tag, $\tau \to l \nu \nu$

Sources	$\mathcal{R}(D^*)$ [%] $\ell^{\rm sig} = e, \mu$	$\ell^{\rm sig} = e$	$\ell^{\rm sig} = \mu$
MC statistics for each PDF shape	2.2%	2.5%	3.9%
PDF shape of the normalization in $\cos\theta_{B\text{-}D^*\ell}$	$^{+1.1}_{-0.0}$%	$^{+2.1}_{-0.0}$%	$^{+2.8}_{-0.0}$%
PDF shape of $B \to D^{**}\ell\nu_\ell$	$^{+1.0}_{-1.7}$%	$^{+0.7}_{-1.3}$%	$^{+2.2}_{-3.3}$%
PDF shape and yields of fake $D^{(*)}$	1.4%	1.6%	1.6%
PDF shape and yields of $B \to X_c D^*$	1.1%	1.2%	1.1%
Reconstruction efficiency ratio $\varepsilon_{\rm norm}/\varepsilon_{\rm sig}$	1.2%	1.5%	1.9%
Modeling of semileptonic decay	0.2%	0.2%	0.3%
$\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)$	0.2%	0.2%	0.2%
Total systematic uncertainties	$^{+3.4}_{-3.5}$%	$^{+4.1}_{-3.7}$%	$^{+5.9}_{-5.8}$%

B → D* τ⁻ ν with hadronic tag, τ → l ν ν

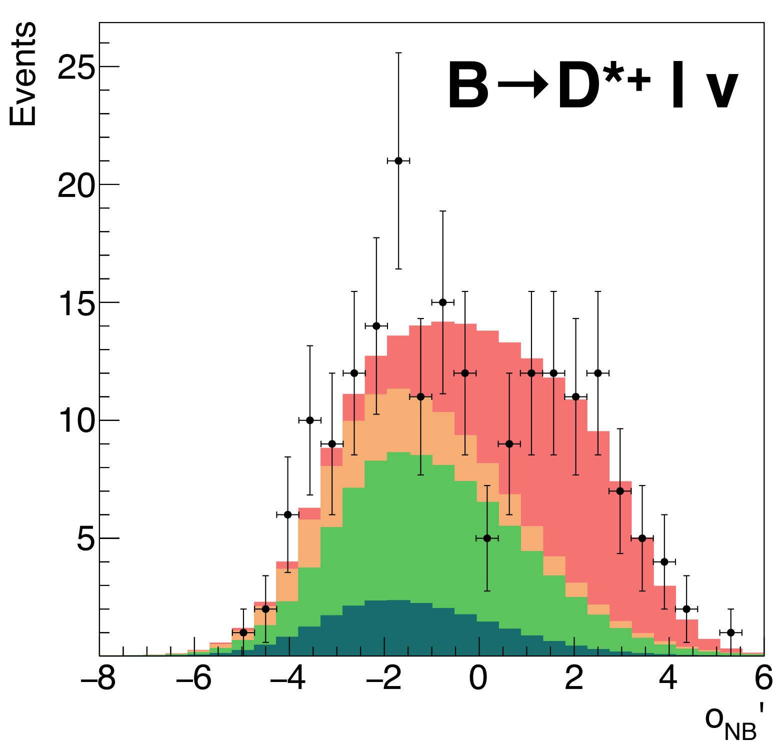


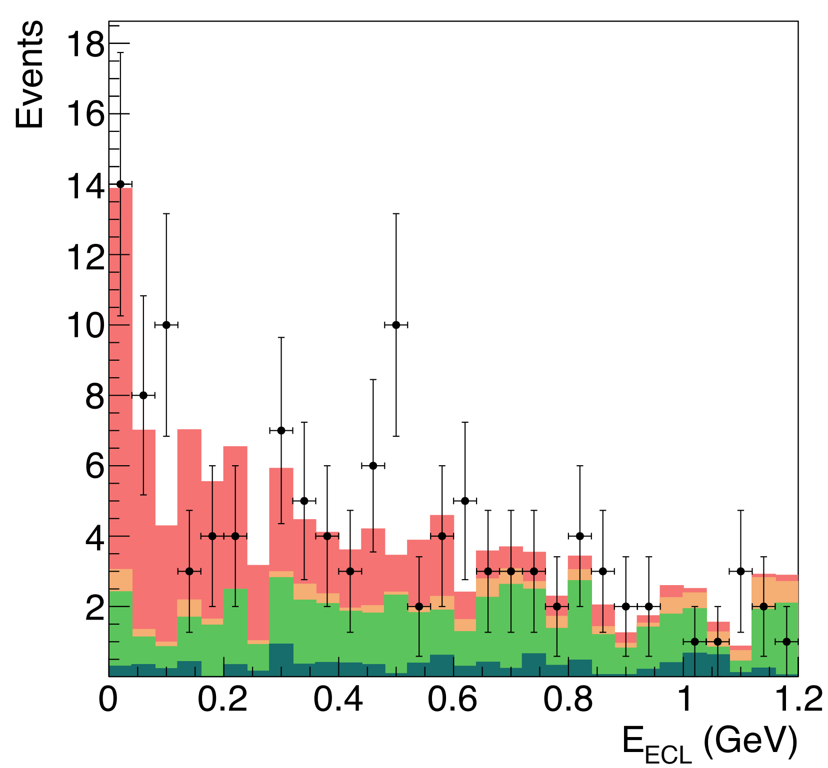


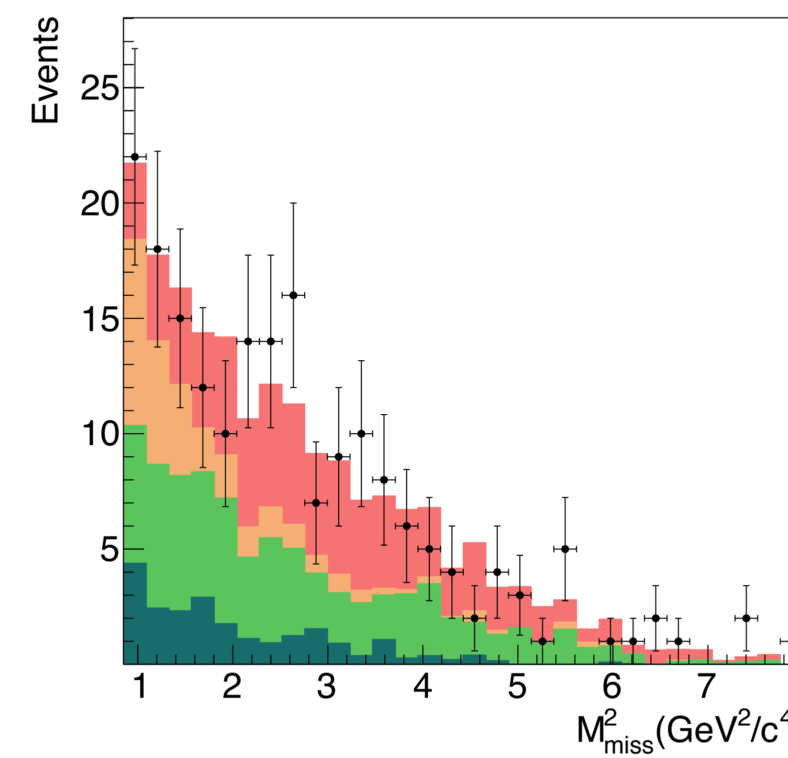


M^2_{miss}> 0.85 GeV

M^2_{miss}> 2 GeV





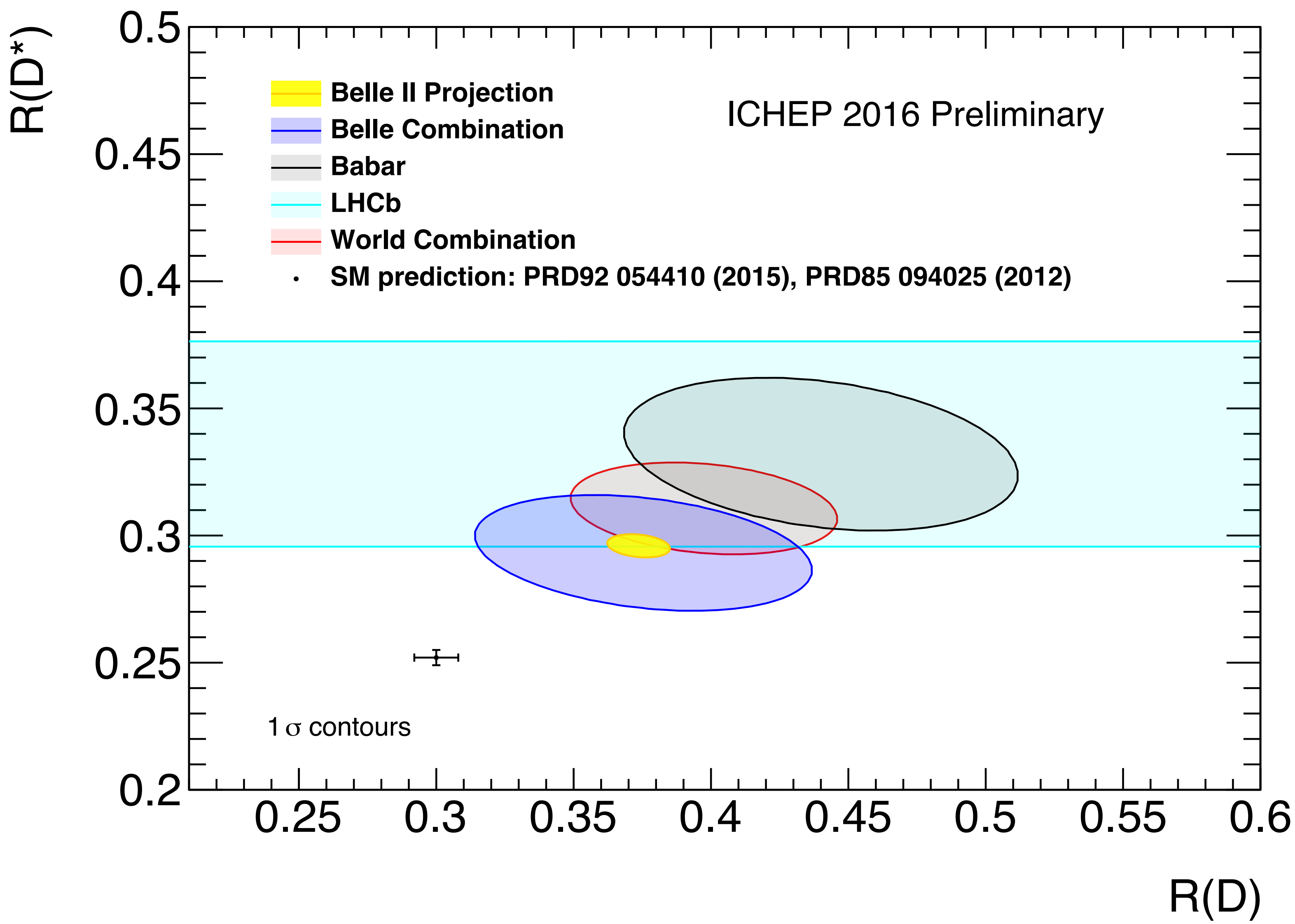


Leading systematic uncertainties (Belle)

	Experiment	Error profile*	SL tag R_{D^*}	Had tag R_{D^*}, $\tau \to h \nu$	Had tag R_{D^*}, $\tau \to l \nu \nu$	Had tag R_D, $\tau \to l \nu \nu$
1	MC statistics	Gauss	2.2	3.5		
2	**$B \to D^{**} l \nu$ modelling**	**Uniform**	**+1, -1.7**	**0.7**	**1.5**	**4.2**
3	$B \to D^* l \nu$	Gauss	+1.3, -0.2	0.8		
4	**D^{**} decay modes**	**Uniform**	**(in 2)**	**(in 2)**	**1.3**	**3.0**
5	**Hadronic B decays**	**Uniform**	**1.1**	**4.4**		
6	**$B \to D^{**} \tau \nu$**	**Uniform**	**(in 2)**	**2.7**		
7	Fake $D^{(*)}$	Gauss	1.4	0.2	0.3	0.5
8	Fake lepton	Gauss		-	0.6	0.5
9	Lepton ID	Gauss	1.2	1.8	0.5	0.5
10	τ Br	Gauss	0.2			
	Total		3.5	7.1	5.2	7.1

* Gauss = data driven, Uniform = nominal central value is arbitrary

Belle II Projections

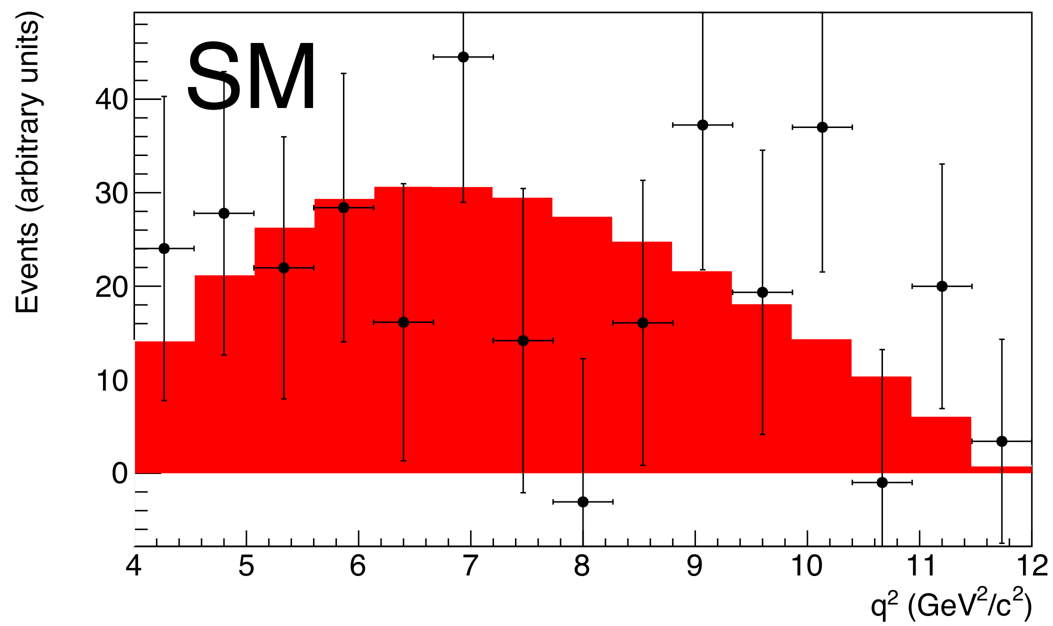


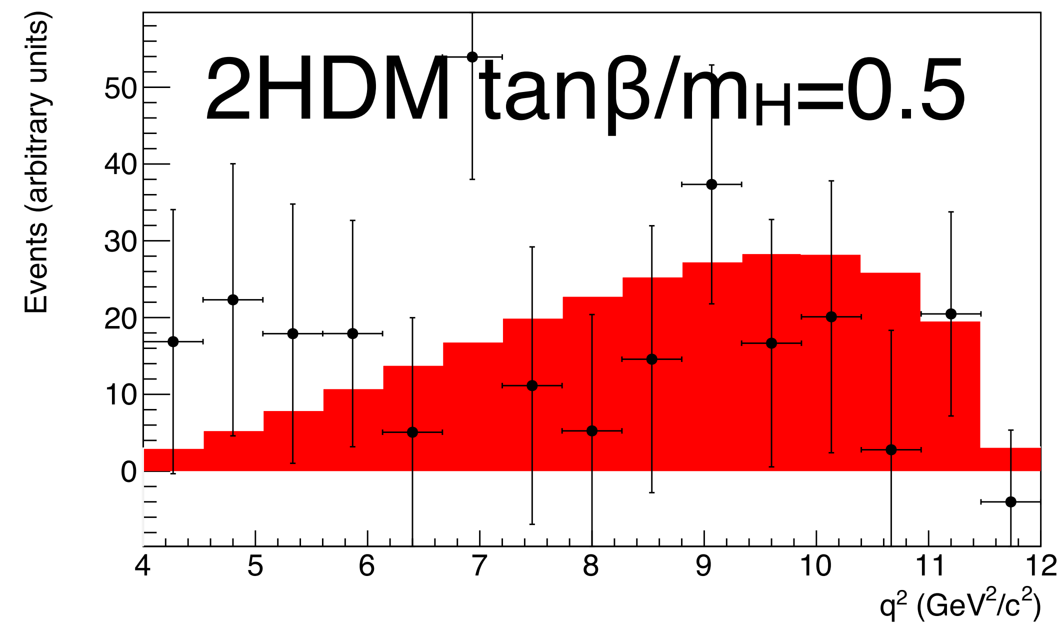
- SL & Had tag full sim sensitivity studies in progress.
- SL background modelling will dominate error @ 50 ab^{-1}.

	ΔR(D) [%]			ΔR(D*) [%]		
	Stat	Sys	Total	Stat	Sys	Total
Belle 0.7 ab^{-1}	14	6	16	6	3	7
Belle II 5 ab^{-1}	5	3	6	2	2	3
Belle II 50 ab^{-1}	2	3	3	1	2	2

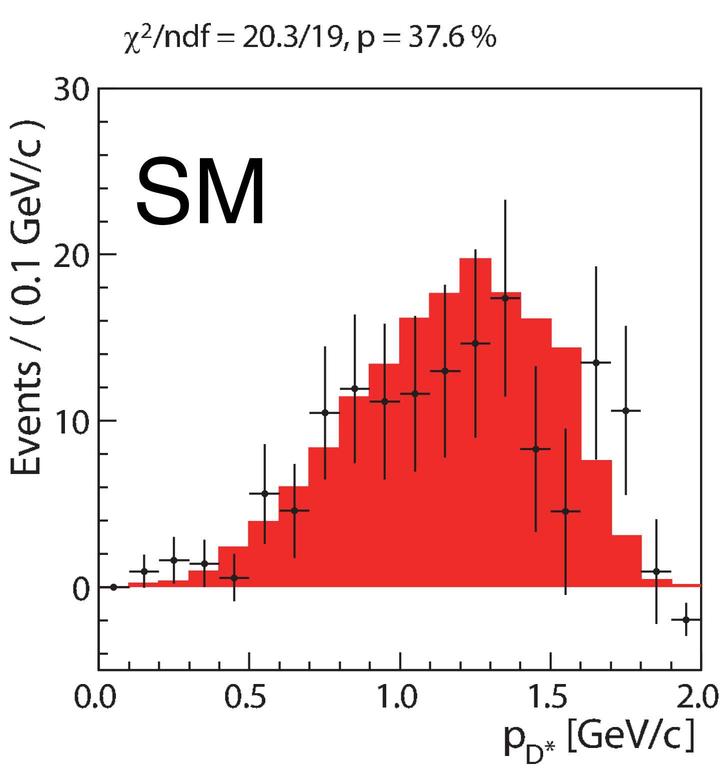
Limits on Type II 2HDM From Belle

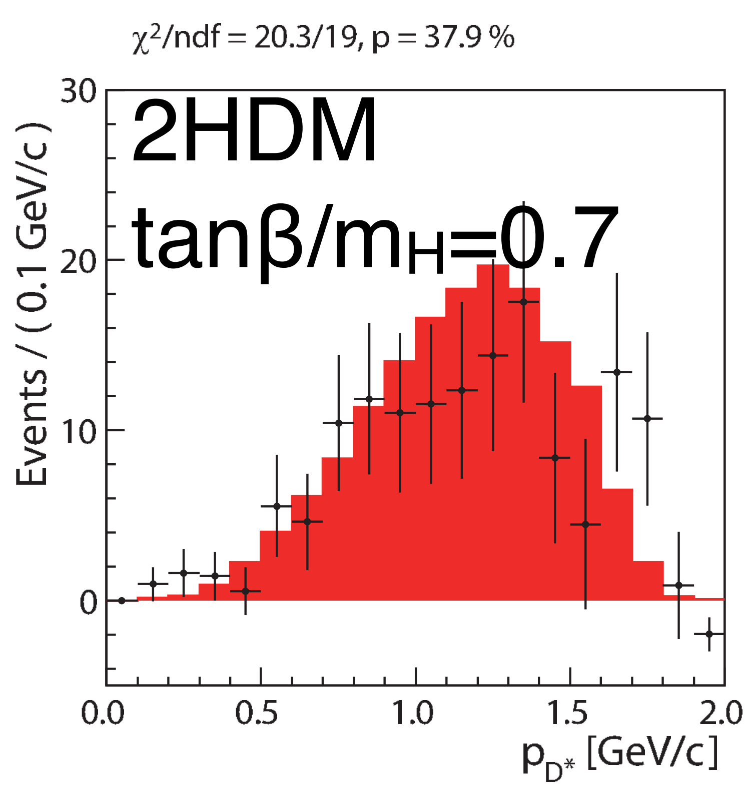
Belle had tag B→ D τ ν, Stat errors only! (same case for Babar)

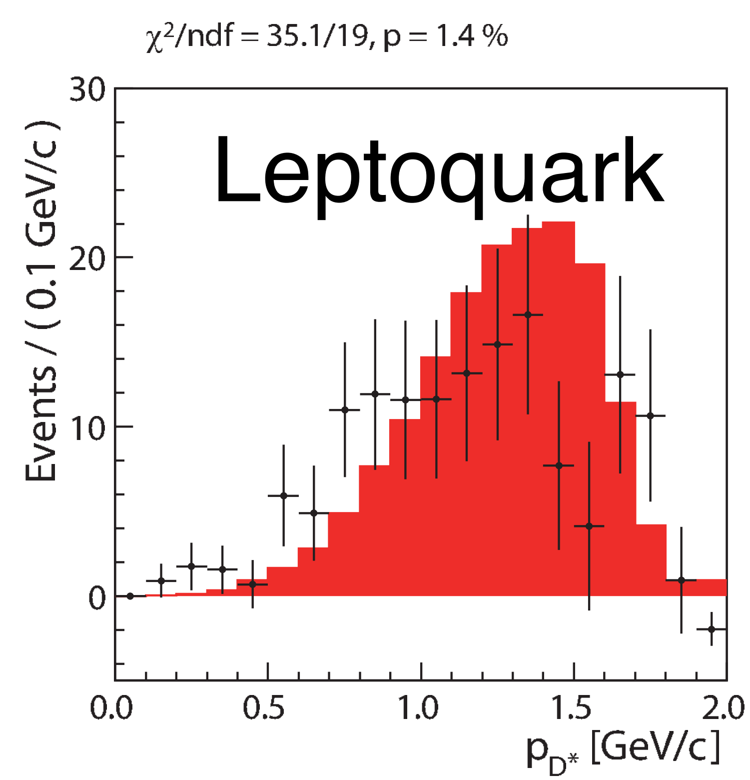




Belle SL tag B → D* τ ν, Stat errors only.



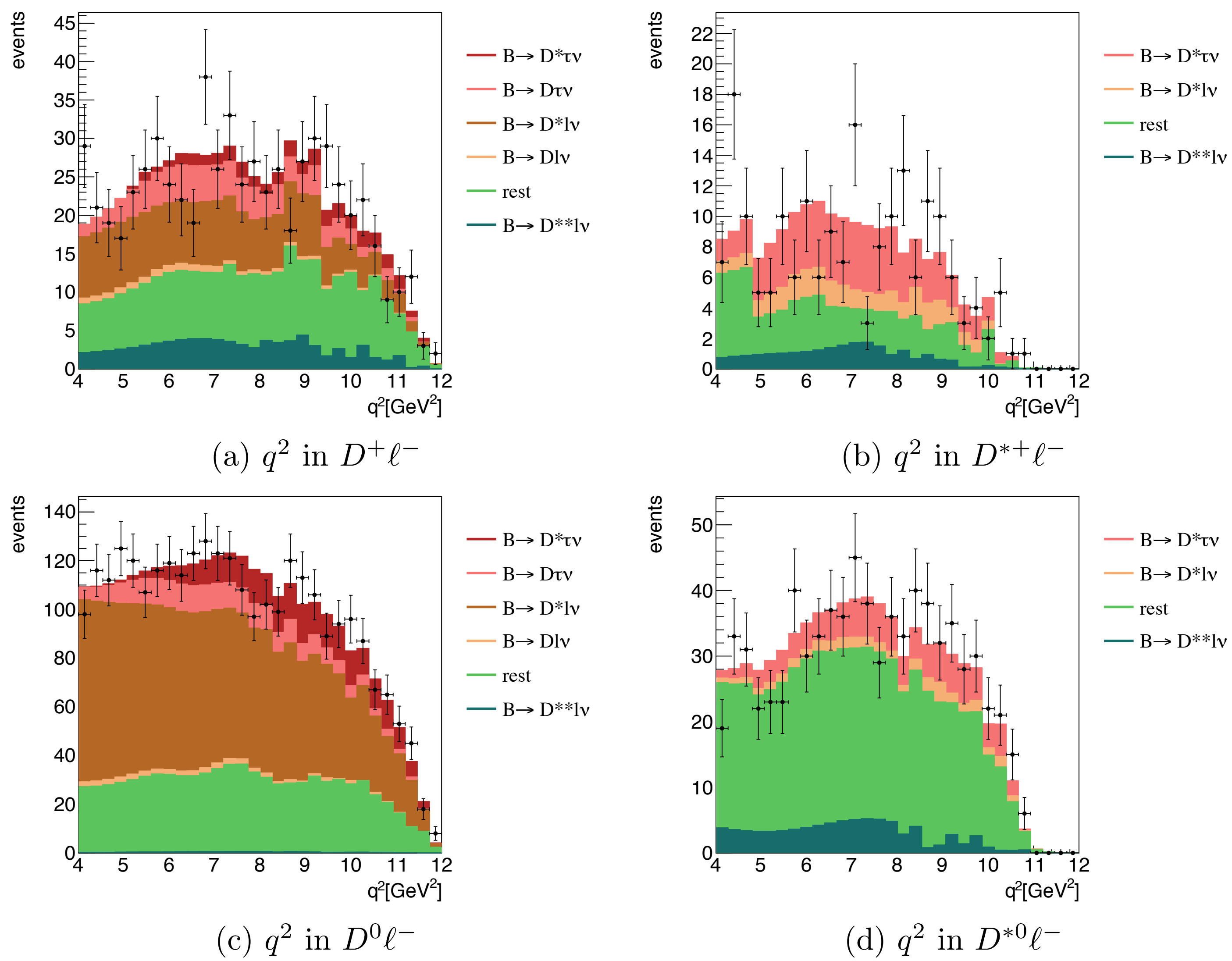




Unsubtracted

- Systematic errors will be large. Belle II must work to improve purity & measure B → $D^{(*,**)}$ l ν background

M. Huschle, PhD Thesis 2015



(a) q^2 in $D^+\ell^-$

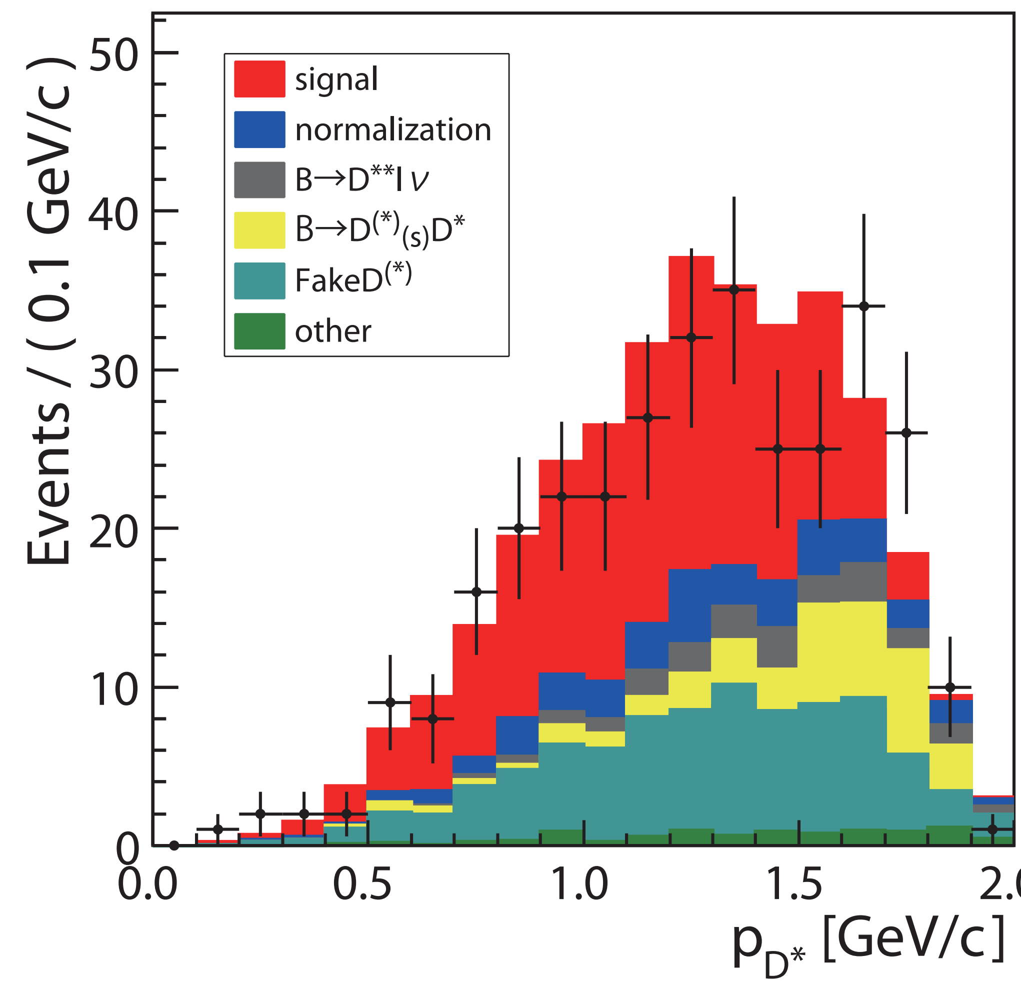
(b) q^2 in $D^{*+}\ell^-$

(c) q^2 in $D^0\ell^-$

(d) q^2 in $D^{*0}\ell^-$

Figure B.13: Fit projections for q^2 in all four reconstruction samples. The region above $M^2_{\rm miss} = 0.85\,{\rm GeV}^2\,{\rm c}^{-4}$ is used.

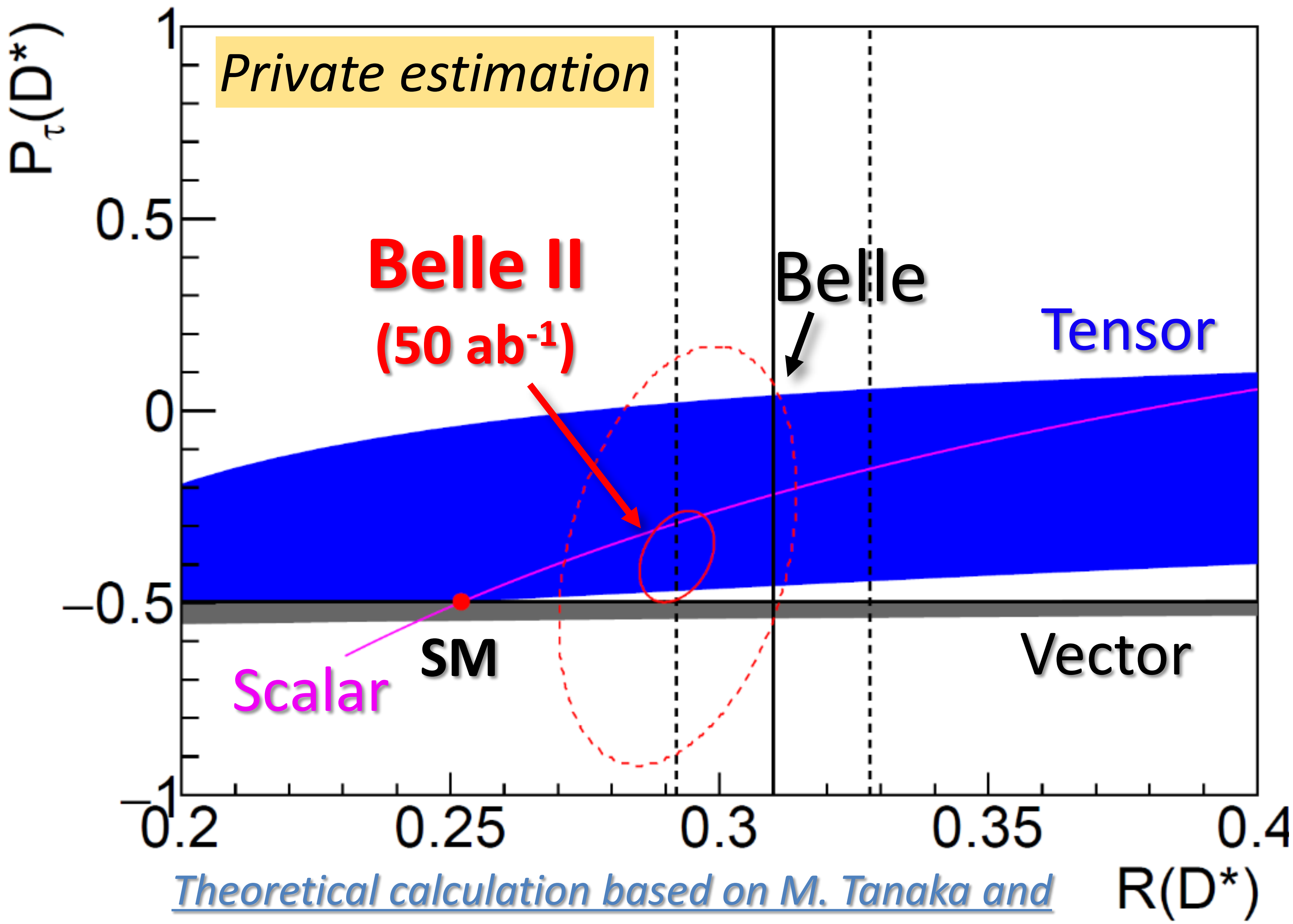
Belle SL tag



Polarisation (see S.Hirose's talk)

- P(τ) measured.
  - Strongly stat. limited. & only done in hadronic tag.
- P(D*) possible too.

$$R(D^*) = 0.270 \pm 0.035(\text{stat.})\,^{+0.028}_{-0.025}(\text{syst.})$$
$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat.})\,^{+0.21}_{-0.16}(\text{syst.})$$

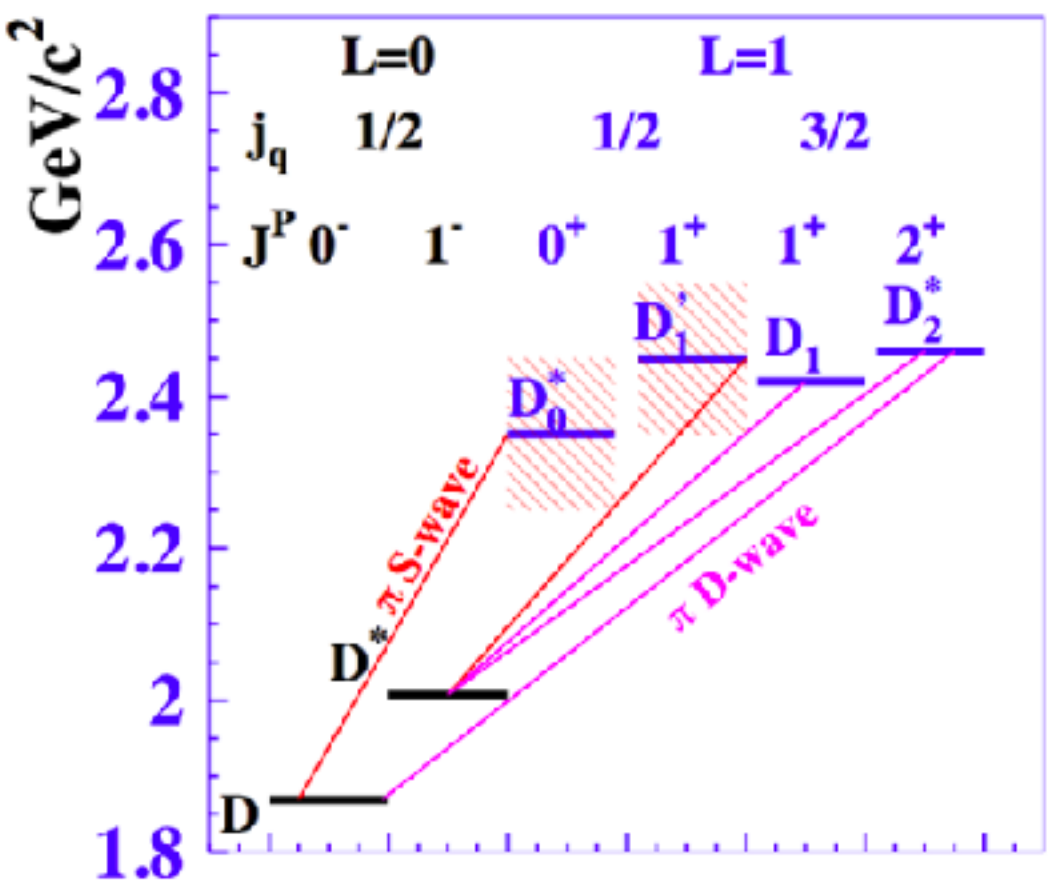


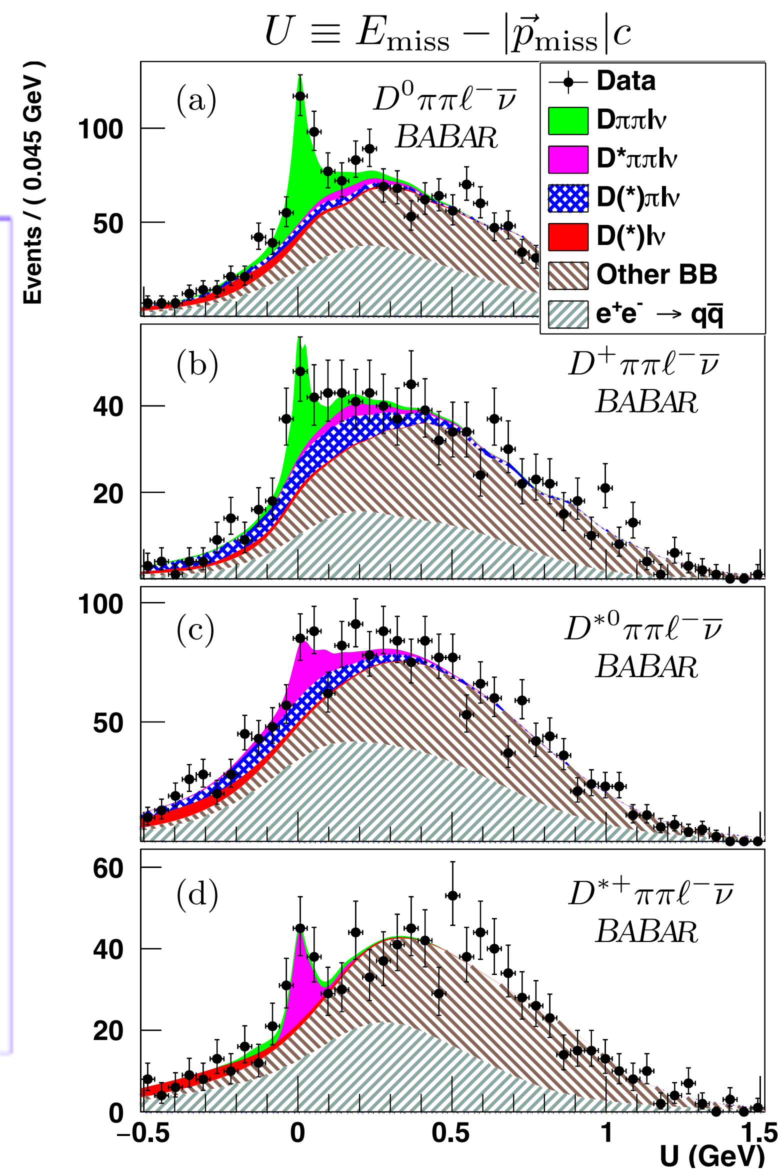
Theoretical calculation based on M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)

B → D** l ν

Babar PRL 116, 041801 (2016)

- 3 problems to cover in Belle II
  - Modelling of B →D** l ν kinematics
  - Normalisation
    - Unmeasured D** → modes, for saturation of B → X l ν
    - B → D(*)nπ l ν + B → D(*)η l ν etc.





Channel	$R^{(*)}_{\pi^+\pi^-} \times 10^3$	$\mathcal{B} \times 10^5$
$D^0\pi^+\pi^-\ell^-\overline{\nu}$	$71 \pm 13 \pm 8$	$161 \pm 30 \pm 18 \pm 8$
$D^+\pi^+\pi^-\ell^-\overline{\nu}$	$58 \pm 18 \pm 12$	$127 \pm 39 \pm 26 \pm 7$
$D^{*0}\pi^+\pi^-\ell^-\overline{\nu}$	$14 \pm 7 \pm 4$	$80 \pm 40 \pm 23 \pm 3$
$D^{*+}\pi^+\pi^-\ell^-\overline{\nu}$	$28 \pm 8 \pm 6$	$138 \pm 39 \pm 30 \pm 3$
$D\pi^+\pi^-\ell^-\overline{\nu}$	$67 \pm 10 \pm 8$	$152 \pm 23 \pm 18 \pm 7$
$D^*\pi^+\pi^-\ell^-\overline{\nu}$	$19 \pm 5 \pm 4$	$108 \pm 28 \pm 23 \pm 4$

D** decays

- **No absolute Br measurements: using a B → D(*) π l ν mode to calibrate all D** l ν channels would be biased.**
- Charm branching ratios need complementary information from hadronic B decays.

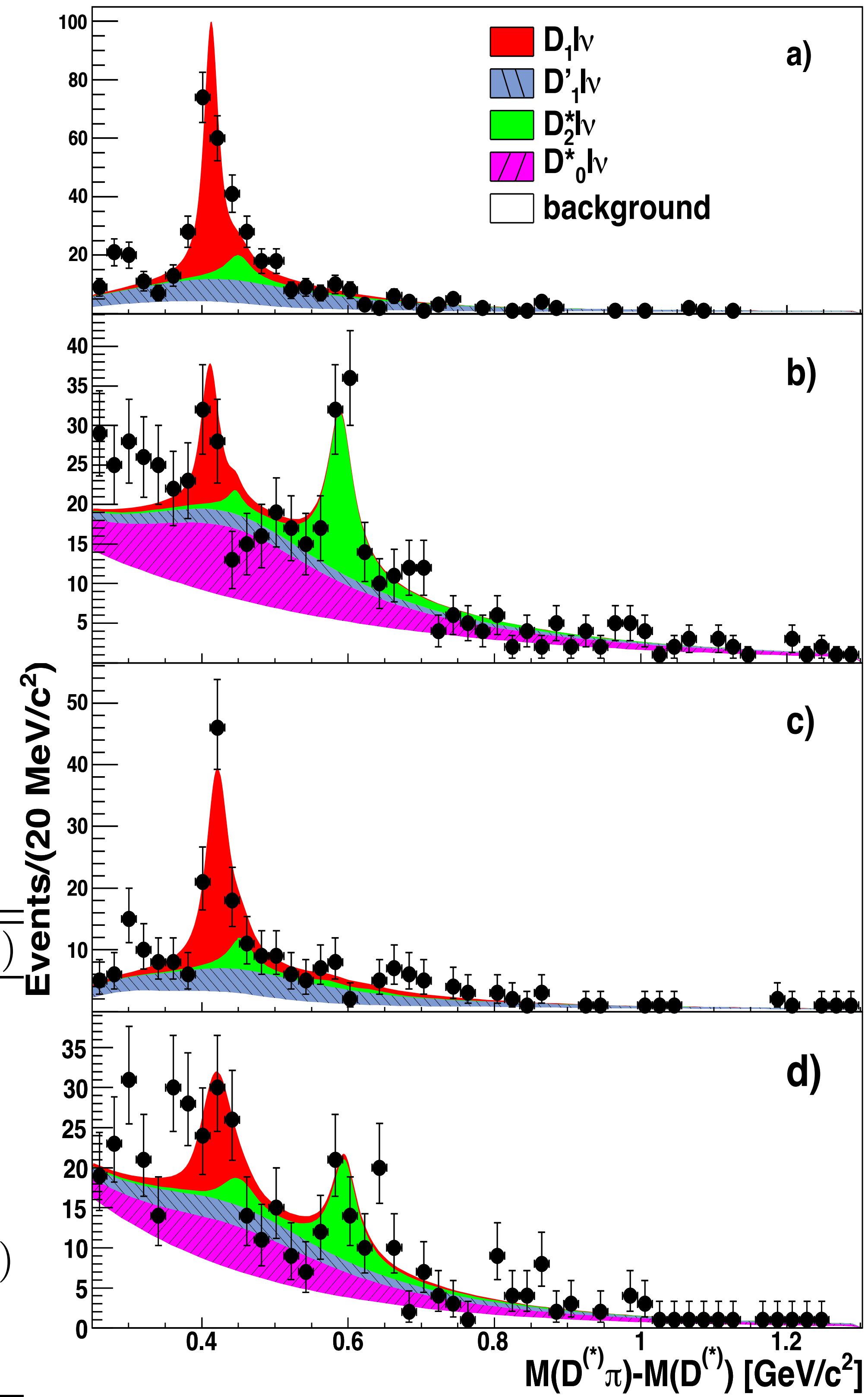
D		J	Observed	Possible
D_0^*	1P	1/2	Dπ	Dη
D_1^*	1P	1/2	D*π	Dππ, Dη
D_1	1P	3/2	D*π, Dππ	$D_0^*\pi$, $D_0^*\rho$, $D_0^*f_0$
D_2^*	1P	3/2	$D^*\pi$, Dπ	Dππ
D'	2S			D(ρ,ππ), D*(η,π)
D'*	2S			D*(ρ,ππ), D(η,π)

- No attempts at neutral modes, or modes with π^0.

B → D** l ν

Babar PRL 101:261802 (2008)

- Narrow modes can be studied as q^2 differentials.
- Broad modes and non-resonant contributions potentially overlap.



Decay Mode	Yield	$\epsilon_{\rm sig}(\times 10^{-4})$	$\mathcal{B}(\overline{B} \to D^{**}\ell^-\bar{\nu}_\ell) \times \mathcal{B}(D^{**} \to D^{(*)}\pi^\pm)$
$B^- \to D_1^0\ell^-\bar{\nu}_\ell$	165 ± 18	1.24	$0.29 \pm 0.03 \pm 0.03$
$B^- \to D_2^{*0}\ell^-\bar{\nu}_\ell$	97 ± 16	1.44	$0.15 \pm 0.02 \pm 0.01$
$B^- \to D_1^{'0}\ell^-\bar{\nu}_\ell$	142 ± 21	1.13	$0.27 \pm 0.04 \pm 0.05$
$B^- \to D_0^{*0}\ell^-\bar{\nu}_\ell$	137 ± 26	1.15	$0.26 \pm 0.05 \pm 0.04$
$\overline{B}^0 \to D_1^+\ell^-\bar{\nu}_\ell$	88 ± 14	0.70	$0.27 \pm 0.04 \pm 0.03$
$\overline{B}^0 \to D_2^{*+}\ell^-\bar{\nu}_\ell$	29 ± 13	0.91	$0.07 \pm 0.03 \pm 0.01$ (< 0.11 @90% CL)
$\overline{B}^0 \to D_1^{'+}\ell^-\bar{\nu}_\ell$	86 ± 18	0.60	$0.31 \pm 0.07 \pm 0.05$
$\overline{B}^0 \to D_0^{*+}\ell^-\bar{\nu}_\ell$	142 ± 26	0.70	$0.44 \pm 0.08 \pm 0.06$

Measurements

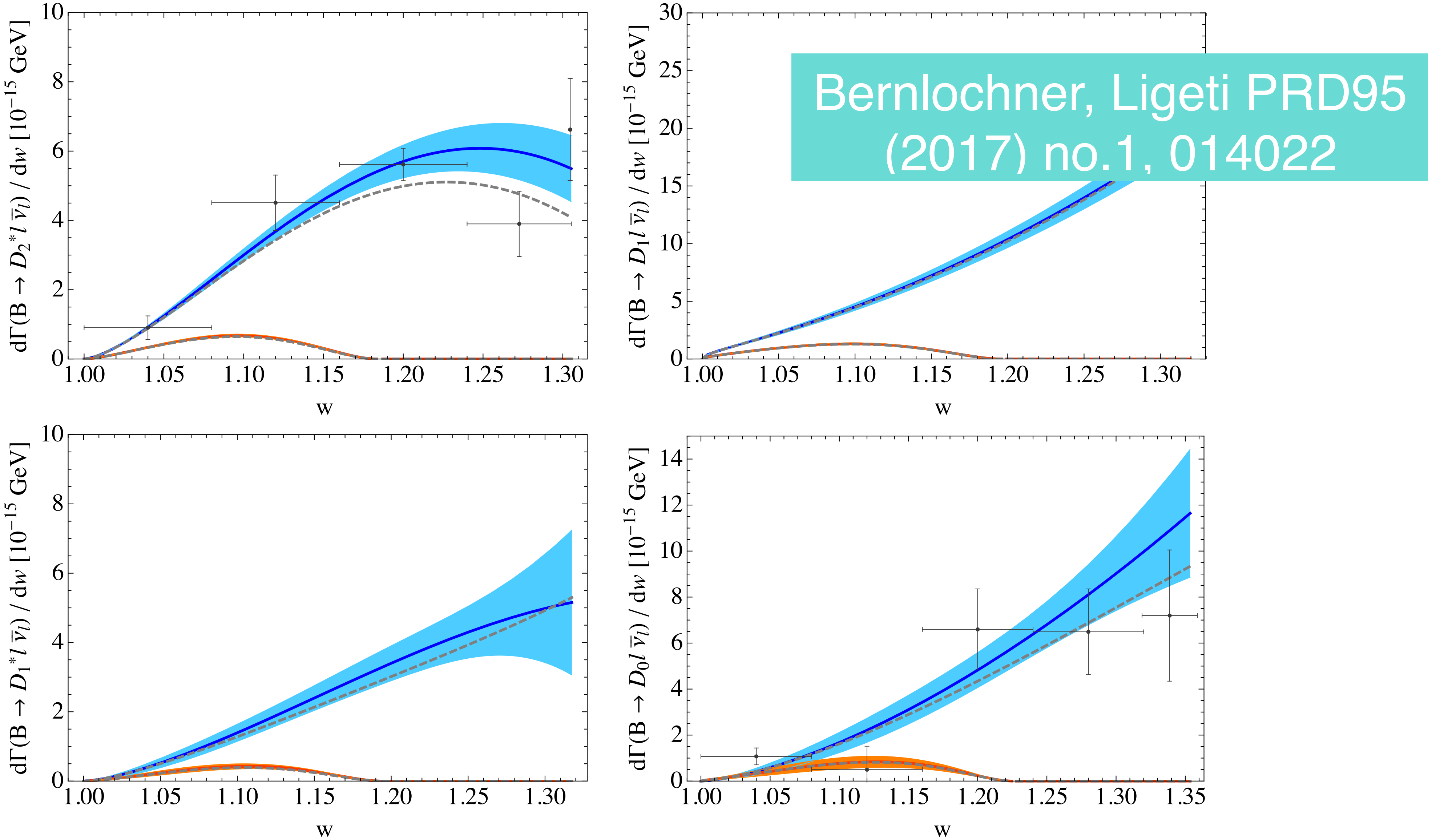
Babar PRL 101:261802 (2008)
Babar PRL 103:051803 (2009)
Belle PRD 77:091503 (2008)

- $B \to D^{(*)} \pi l \nu$
- Normalised with $D l \nu$ or $X l \nu$
- Strong model dependence in systematics - particularly broad J=1/2 modes.

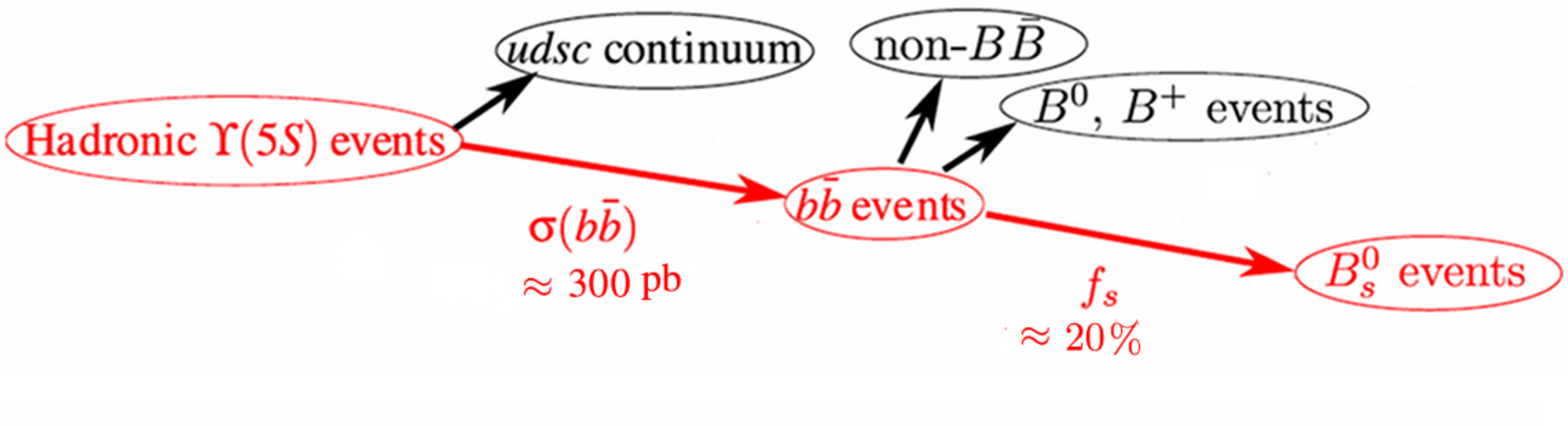
	Belle tagged J=3/2 & 1/2	Babar tagged J=3/2 & 1/2	Babar untagged J=3/2
N_{BB} [10^6]	657	460	208
Error	%	%	%
Tracking		1.8-2.4	1.0-1.8
Particle ID	2	1.2-1.6	1.6-3.0
π^0 & γ Eff.		0.2-4.8	0.3-3.3
MC stats.	in stat.	-	1.8-5.6
Comb.&Cont.	-	0.2-10.4	-
Helicity corr.		**4.5-13.8**	**0.1-0.7**
Signal model	**12-22**		**2.0-4.8**
PDFs		**0.2-8.7**	
N_{BB}	-	-	2.7
D(*) Bfs	10	3-4.5	2.1-5.4
Norm		4-6	-
Bkg	6	-	1.7-3.2
total sys	**14-25**	**5.5-17**	**5.8-9.1**
total stat	**14-40**	**10-20**	**6-17**

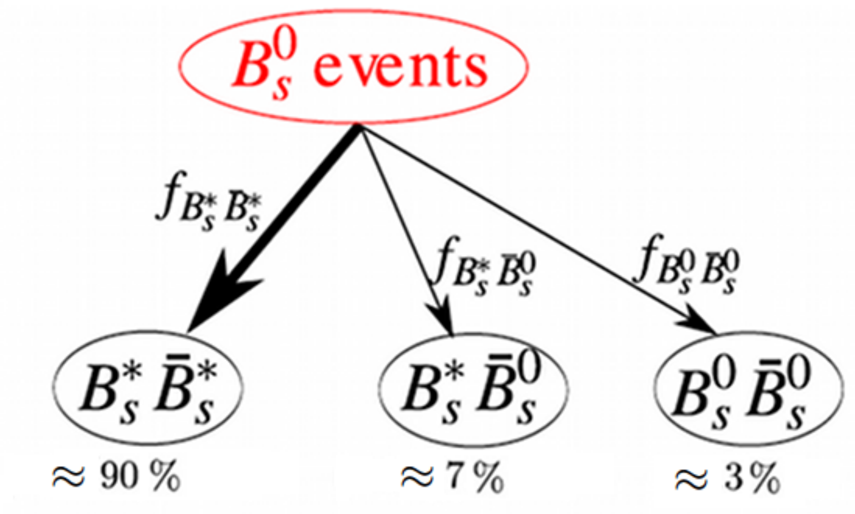
B→D** l ν towards Belle II

- Much more information on differentials of narrow and broad - controls signal modelling errors.
- More complete study of D** decay width with m^2_{miss} studies & hadronic modes.
- Studies in progress using SL and hadronic tags: expect O(10) improvement on seen modes compared to previous Belle study.



B_s decays





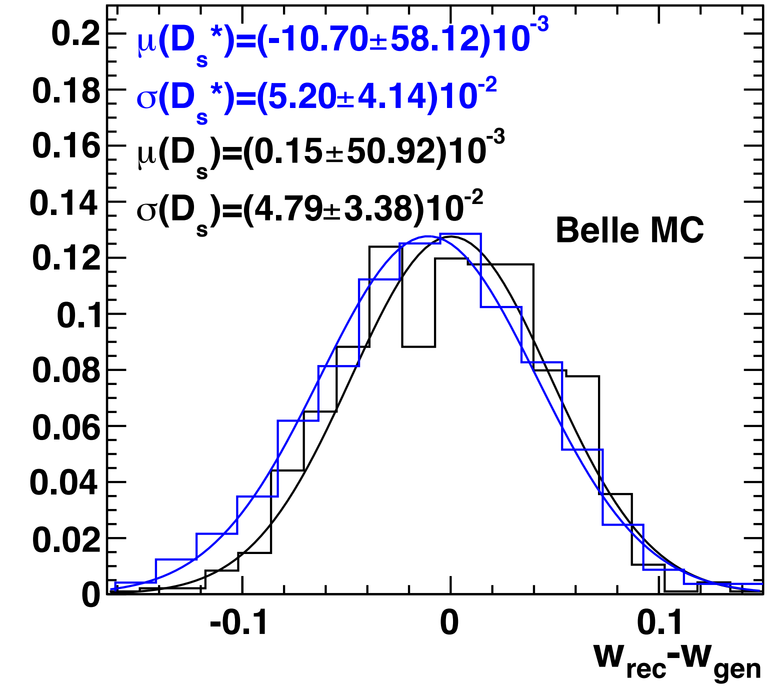
Modes	Width	Dominant decay
D_s	-	$KK\pi$
D_s^*	-	$D_s \gamma$
$D_{s0}^*(2317)$	< 4 MeV	$D_s \pi^0$
$D_{s1}(2460)$	< 4 MeV	$D_s^* \pi^0$
D_{s1}\`(2536)	1 MeV	D^*K
$D_{s2}^*(2573)$	17 MeV	D^0K

- The J=1/2 states are not broad.
- D_{s1} & D_{s1}' have absolute Br.
- 60M B_s^0 pairs / 1 ab^{-1}
- Often have >2 neutrals (π^0 & ν)
- Kinematic smearing
  $B_s^* \rightarrow B_s\gamma$, $\Delta m_{B_s^*}$~49 MeV

$B_s \to D_s^{**}\, l\, \nu$

Belle PRD 92, 072013 (2015)
Belle PRD 87, 072008 (2013)

- Untagged methods can probe D_s^{**} modes.
- Tagging can constrain $B \to D_s^{(*)}\, l\, \nu$
  - Bs full recon. presented at ICHEP 2016 (F. Breibeck)



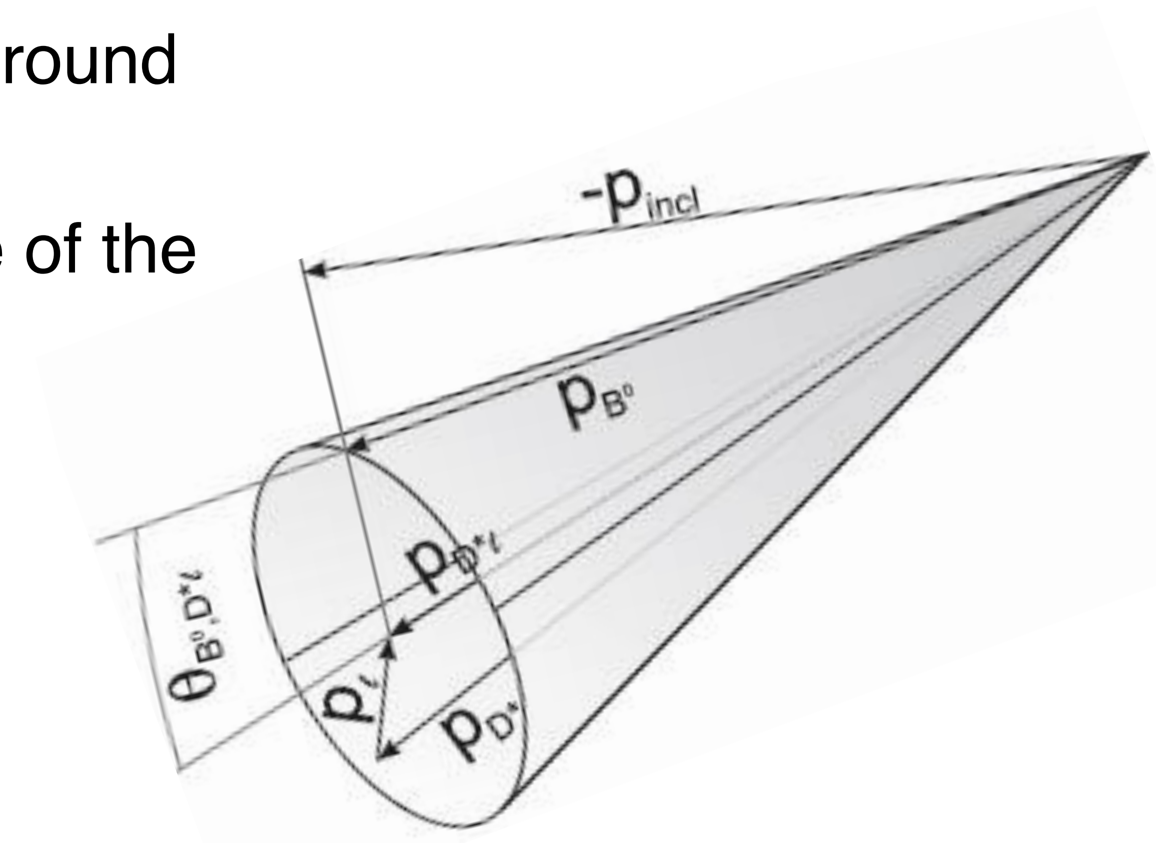
$$w \equiv v_B \cdot v_{D^*} = E_{D^*}/m_{D^*} = \frac{m_B^2 + m_X^2 - q^2}{2 m_B m_{D^*}}$$

Tag Method	Tag eff.	N_{Bs}/N_B	Yields in 121 fb^{-1} /5 ab^{-1}										
			Xlv	Δstat	Δsys	$D_s$lv		D_s^*lv		D_{s0}^*lv		D_{s2}^*lv	
Untagged	2	$f_s/f_{d,u} \simeq 0.25$	2.7M	—	—	7200		10900		800		1300	
Lepton tag	0.1	$f_s/f_{d,u} \simeq 0.25$	135k	—	—	370	/15000	534	/22000	40	1600	70	/2800
D_s: φπ, K_SK,K*K	0.04	$10 \cdot f_s/f_{d,u}$	27k	3%	7%	140	/6000	200	/8500	16	650	26	/1000
B_s full recon.	0.004	≫10	5400	2%	4%	15	/620	20	/880	2	70	3	/110

$B \to D^* l \nu$ & $B \to D l \nu$

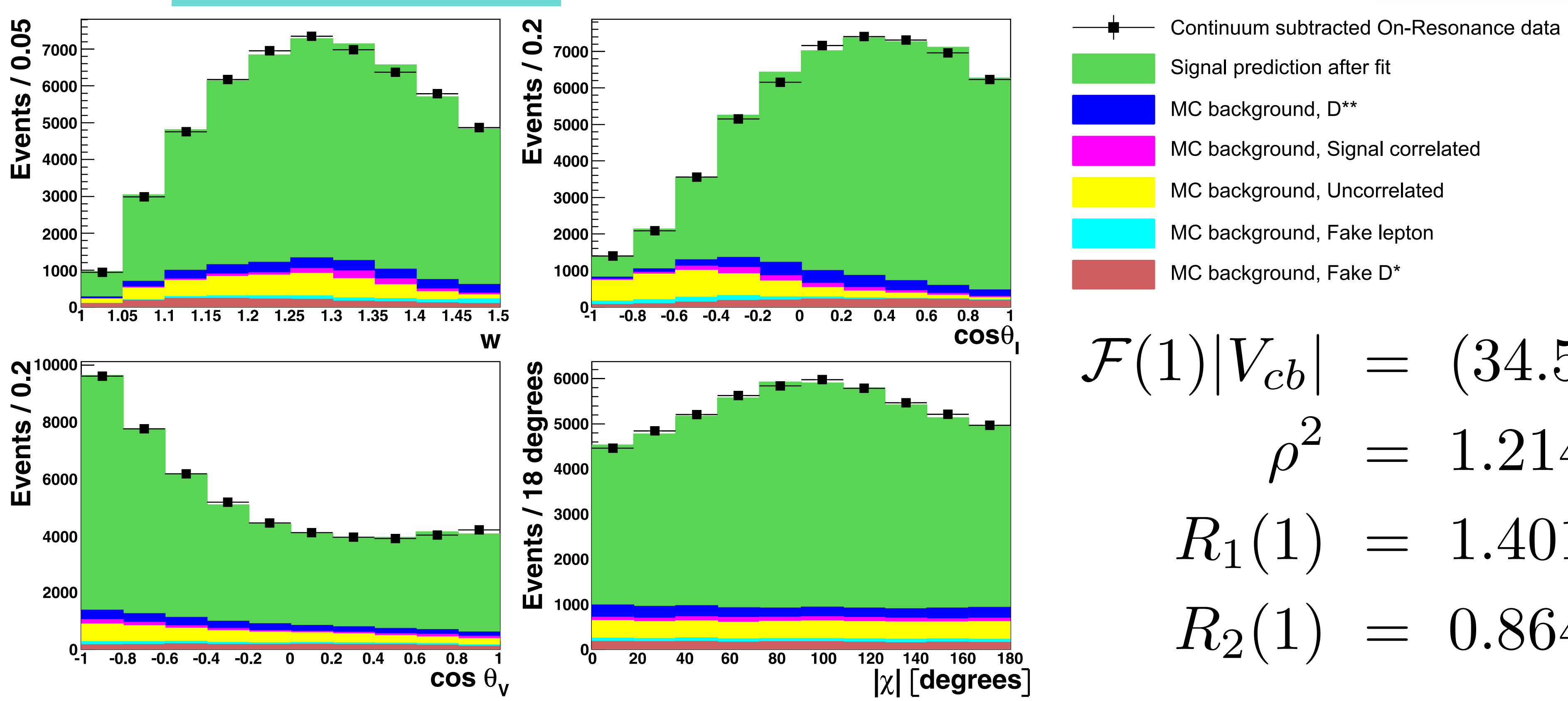
- Aims
  - $|V_{cb}|$
  - LFUV of $B \to D^{(*)} \mu \nu$ / $B \to D^{(*)} e \nu$.
  - NP current, e.g. right handed current via lepton helicity.
  - Normalisation of $B \to D^{(*)} \tau \nu$ (but already precise enough).
- $B \to D^* l \nu$
  - Model independent parameterisation of form factors (as of March 2017)
  - Improved low momentum tracking, and improved tracking efficiencies.
  - Use of tagging methods.
- $B \to D l \nu$
  - Tagging methods will reach normalisation precision limit.

- Conservation of momentum: p_B is on a cone around (D*l) axis making an opening angle $\cos\theta_{B,D^*l}$.
- Taking the sum of momenta of non-signal side of the decay, p_{incl}



$$cos_{B,D^*\ell} = \frac{2E^*_B E^*_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2|\vec{p}^*_B||\vec{p}^*_{D^*\ell}|}$$

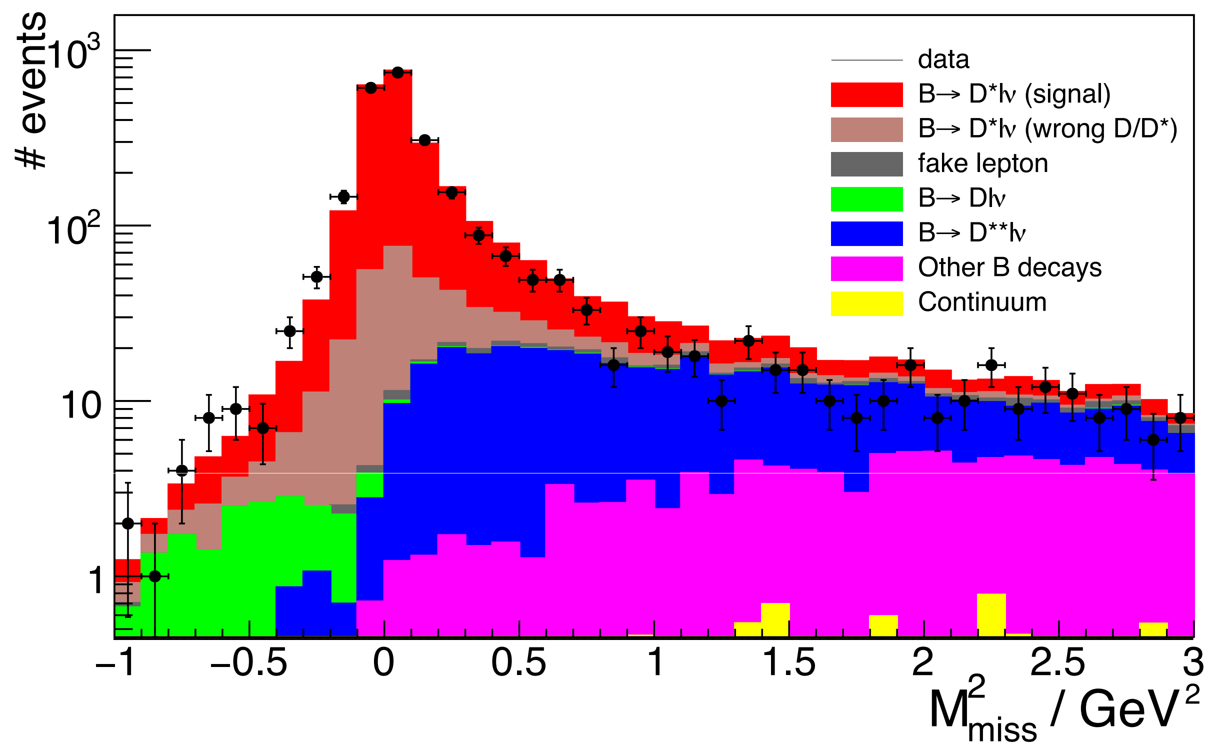
Not unfolded

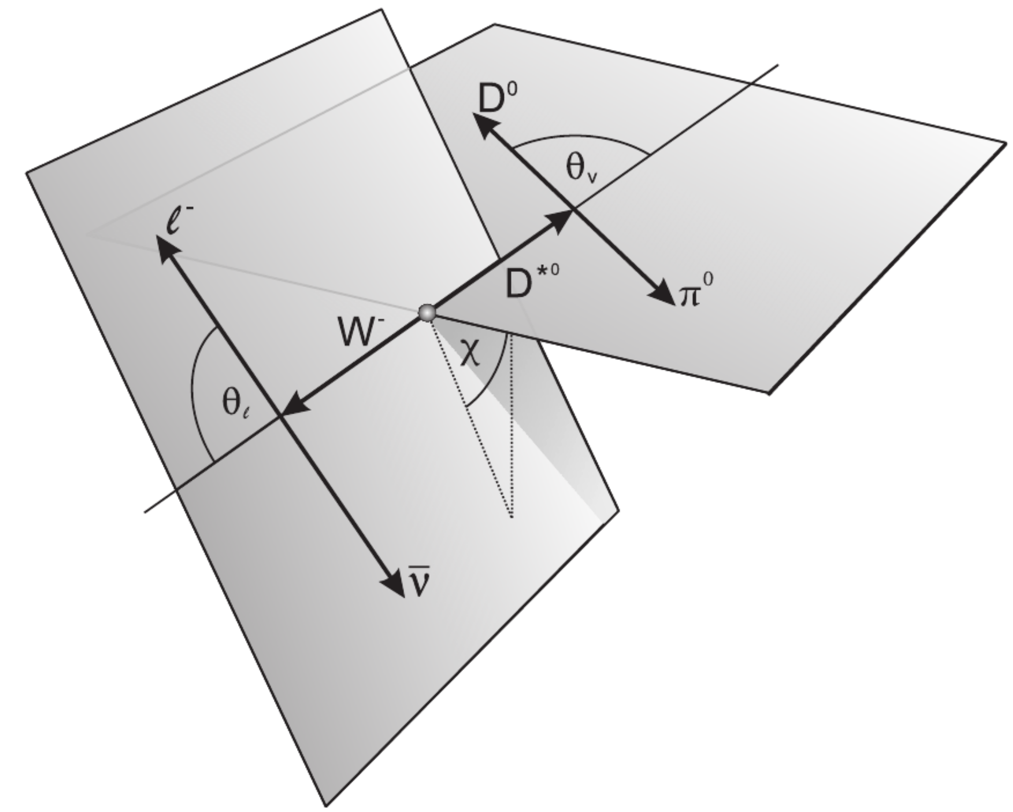


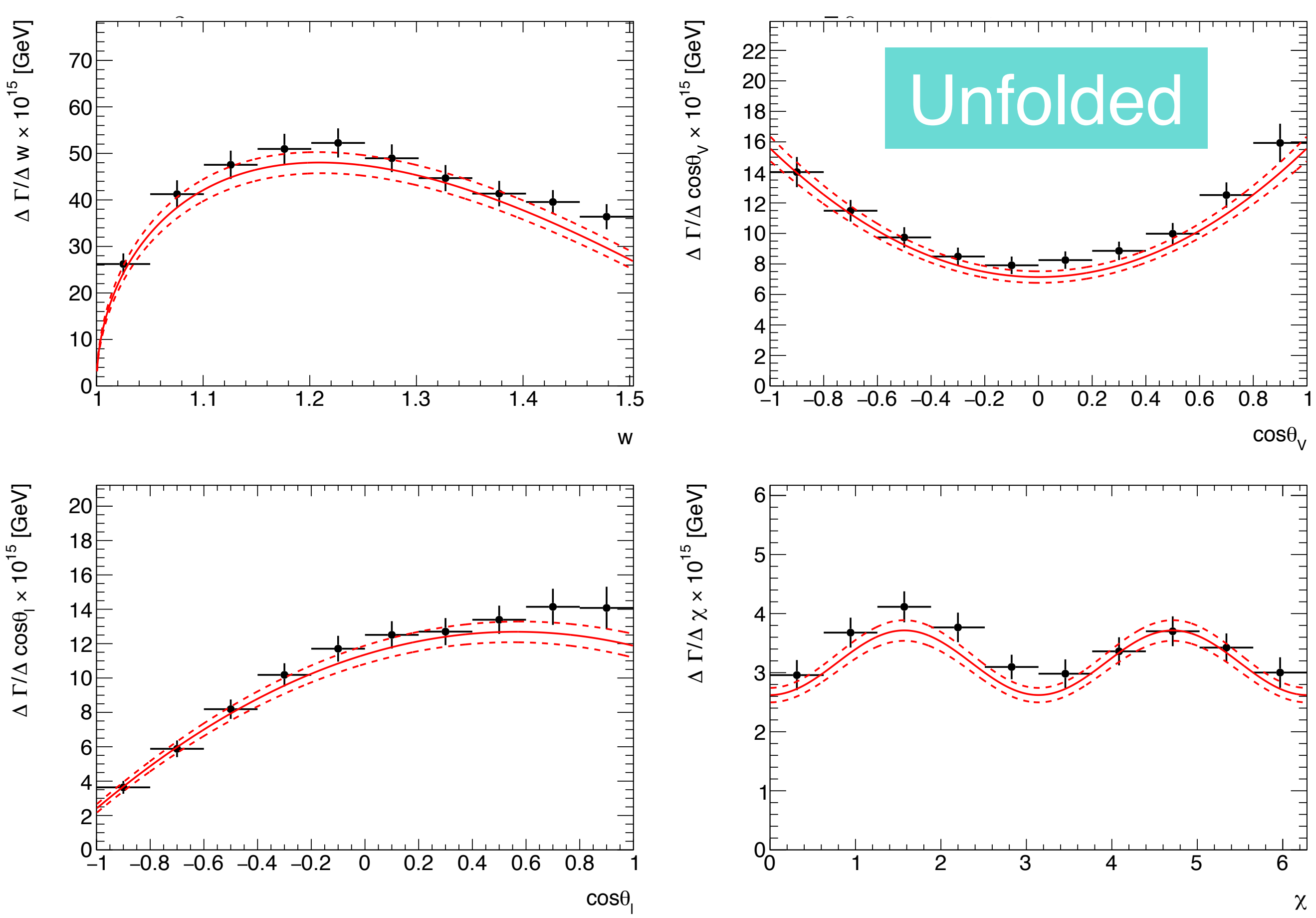
$$\begin{aligned}
\mathcal{F}(1)|V_{cb}| &= (34.5 \pm 0.2 \pm 1.0) \times 10^{-3}, \\
\rho^2 &= 1.214 \pm 0.034 \pm 0.009, \\
R_1(1) &= 1.401 \pm 0.034 \pm 0.018, \\
R_2(1) &= 0.864 \pm 0.024 \pm 0.008,
\end{aligned}$$

B → D* l ν tagged

Belle arXiv:1702.01521







$$\mathcal{B}(\bar{B}^0 \to D^{*+} e^- \bar{\nu}_e) = (5.04 \pm 0.15 \pm 0.23) \times 10^{-2}$$

$$\mathcal{B}(\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu) = (4.84 \pm 0.15 \pm 0.22) \times 10^{-2}$$

$$R_{e\mu} = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+} e^- \bar{\nu}_e)}{\mathcal{B}(\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu)} = 1.04 \pm 0.05 \pm 0.01$$

Model independent measurements

Bigi et al., arXiv:1703.06124

- BGL expansion. More reliable B → D(*) l ν differentials & errors for |Vcb| and for background modelling in B → D(*) τ ν.

$$\frac{d\Gamma(\bar{B}\to D^* l\bar{\nu}_l)}{dw\, d\cos\theta_v\, d\cos\theta_l\, d\chi} = \frac{\eta_{\rm EW}^2 3 m_B m_{D^*}^2}{4(4\pi)^4}\sqrt{w^2-1}\times (1-2wr+r^2) G_F^2 |V_{cb}|^2 \times \{(1-c_l)^2 s_v^2 H_+^2 + (1+c_l)^2 s_v^2 H_-^2 + 4 s_l^2 c_v^2 H_0^2 - 2 s_l^2 s_v^2 \cos 2\chi H_+ H_- - 4 s_l (1-c_l) s_v c_v \cos\chi H_+ H_0 + 4 s_l (1+c_l) s_v c_v \cos\chi H_- H_0\}, \quad (3)$$

$$H_0(w) = \mathcal{F}_1(w)/\sqrt{q^2},$$
$$H_\pm(w) = f(w) \mp m_B m_{D^*}\sqrt{w^2-1}\, g(w).$$
$$f(z) = \frac{1}{P_{1^+}(z)\phi_f(z)}\sum_{n=0}^{N} a_n^f z^n,$$
$$\mathcal{F}_1(z) = \frac{1}{P_{1^+}(z)\phi_{\mathcal{F}_1}(z)}\sum_{n=0}^{N} a_n^{\mathcal{F}_1} z^n,$$
$$g(z) = \frac{1}{P_{1^-}(z)\phi_g(z)}\sum_{n=0}^{N} a_n^g z^n.$$

BGL Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	27.9/32	31.4/35
$\lvert V_{cb}\rvert$	$0.0417\,(^{+20}_{-21})$	$0.0404\,(^{+16}_{-17})$
a_0^f	0.01223(18)	0.01224(18)
a_1^f	$-0.054\,(^{+58}_{-43})$	$-0.052\,(^{+27}_{-15})$
a_2^f	$0.2\,(^{+7}_{-12})$	$1.0\,(^{+0}_{-5})$
$a_1^{\mathcal{F}_1}$	$-0.0100\,(^{+61}_{-56})$	$-0.0070\,(^{+54}_{-52})$
$a_2^{\mathcal{F}_1}$	0.12 (10)	$0.089\,(^{+96}_{-100})$
a_0^g	$0.012\,(^{+11}_{-8})$	$0.0289\,(^{+57}_{-37})$
a_1^g	$0.7\,(^{+3}_{-4})$	$0.08\,(^{+8}_{-22})$
a_2^g	$0.8\,(^{+2}_{-17})$	$-1.0\,(^{+20}_{-0})$

CLN Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	34.3/36	34.8/39
$\lvert V_{cb}\rvert$	0.0382 (15)	0.0382 (14)
$\rho^2_{D^*}$	$1.17\,(^{+15}_{-16})$	1.16 (14)
$R_1(1)$	$1.391\,(^{+92}_{-88})$	1.372 (36)
$R_2(1)$	$0.913\,(^{+73}_{-80})$	$0.916\,(^{+65}_{-70})$
$h_{A_1}(1)$	0.906 (13)	0.906 (13)

- Can we extend this to generic NP couplings?

Comparison of approaches @ Υ(4S)

Tag Method	untagged	tagged
Br [10^{-2}]	**4.58**	**4.95**
Errors	%	%
Track	4.50	1.6
Slow track	1.29	0.1
eID	2.18	0.2 (in tag)
μID		0.1 (in tag)
fake leptons	0.07	<0.1
$B \to D^{**} l\nu$, FF	0.24	<0.1
$B \to D^{**} l\nu$, Bfs	0.57	0.2
$D^{(*)}$ Bfs	1.48	0.5
PDFs	0.22	0.9
Tag calibration	0.00	3.6
N_{BB}	1.38	1.4
f_{+0}	1.35	1.1
τ_B	0.59	0
π^0 efficiency	0.00	0.5
Total	**5.8**	**4.5**
Stat	**0.7**	**2.2**

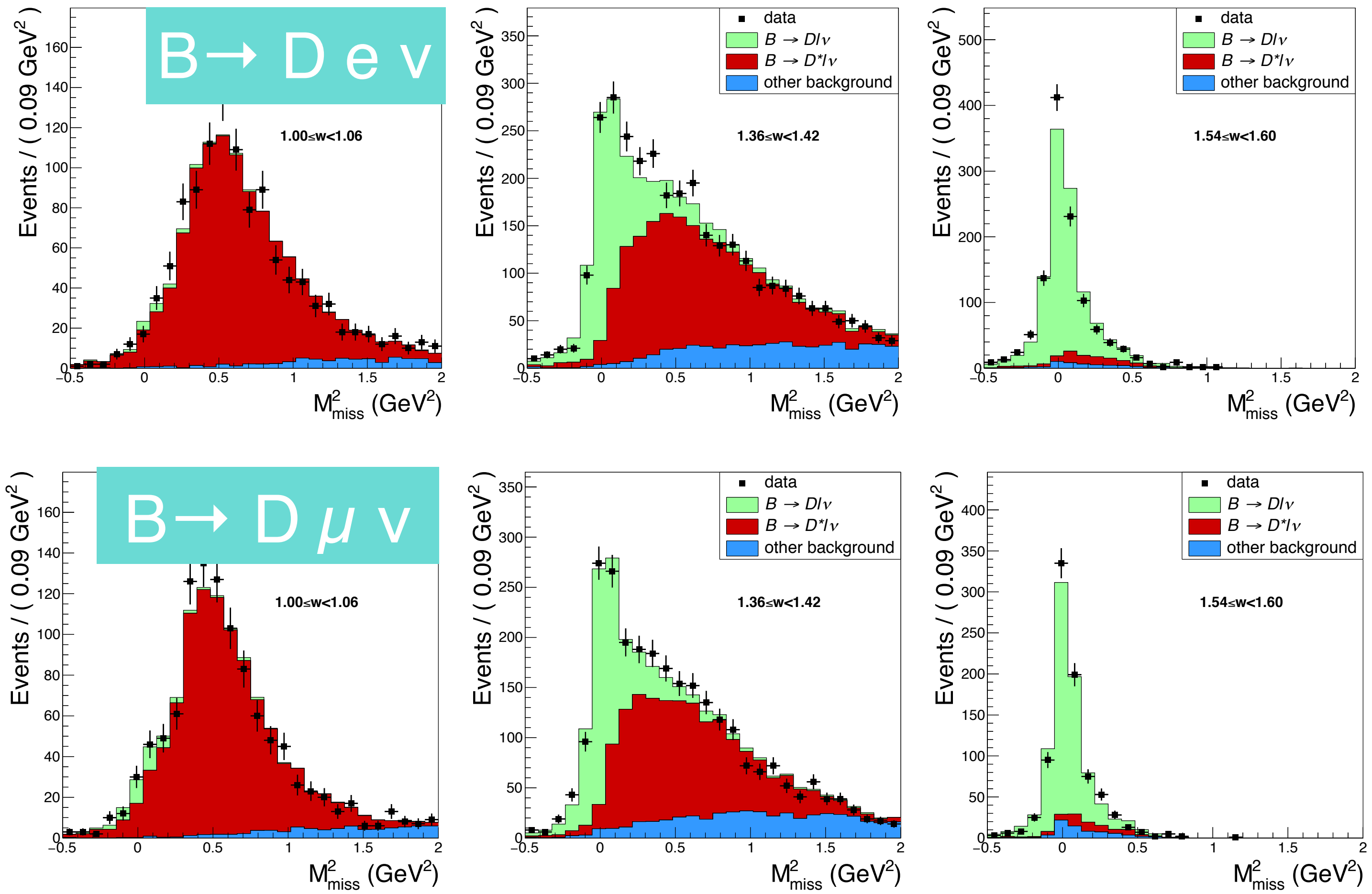
- Only Br compared.
  Untagged measurement predates tracking update in Belle: $\Delta\varepsilon_{track}$ reduced by 3.
- Errors on tracking, PID, π^0 efficiencies are data driven.
  - Slow pion Tracking in Belle II ~2x efficiency < 100 MeV
- Br needs better measure of N_{BB}, f_{+0} — limited by precision of integrated luminosity measurement.
- Tag calibration error can be improved by choosing cleaner tags in larger data sets.
- Most errors cancel in LFUV measurement.
  - Belle tagged: stat±5%, sys±1%
  - Belle untagged (est. - reanalysis in progress): stat±1%, sys±1%
  - Belle II total ±<< 1%.

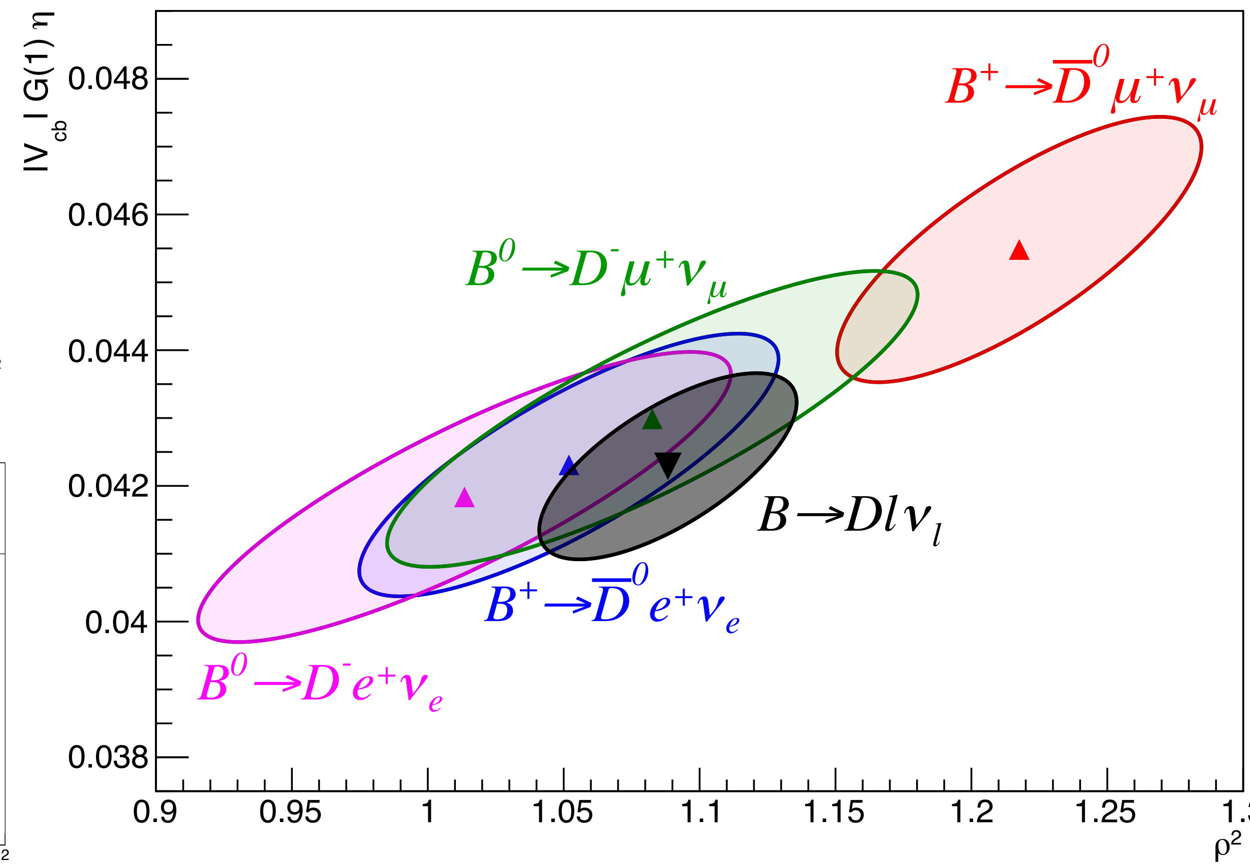
B → D l ν

Belle PRD 93, 032006 (2016)

- Best done with B tagging. Tag calibration with B → X l ν
- First model independent analysis of b → c l ν

	$N=2$	$N=3$	$N=4$
$a_{+,0}$	0.0127 ± 0.0001	0.0126 ± 0.0001	0.0126 ± 0.0001
$a_{+,1}$	-0.091 ± 0.002	-0.094 ± 0.003	-0.094 ± 0.003
$a_{+,2}$	0.34 ± 0.03	0.34 ± 0.04	0.34 ± 0.04
$a_{+,3}$	–	-0.1 ± 0.6	-0.1 ± 0.6
$a_{+,4}$	–	–	0.0 ± 1.0
$a_{0,0}$	0.0115 ± 0.0001	0.0115 ± 0.0001	0.0115 ± 0.0001
$a_{0,1}$	-0.058 ± 0.002	-0.057 ± 0.002	-0.057 ± 0.002
$a_{0,2}$	0.22 ± 0.02	0.12 ± 0.04	0.12 ± 0.04
$a_{0,3}$	–	0.4 ± 0.7	0.4 ± 0.7
$a_{0,4}$	–	–	0.0 ± 1.0
$\eta_{\mathrm{EW}}\|V_{cb}\|$	40.01 ± 1.08	41.10 ± 1.14	41.10 ± 1.14
χ^2/n_{df}	24.7/16	11.4/16	11.3/16
Prob.	0.075	0.787	0.787





$B \to D \, l \, \nu$

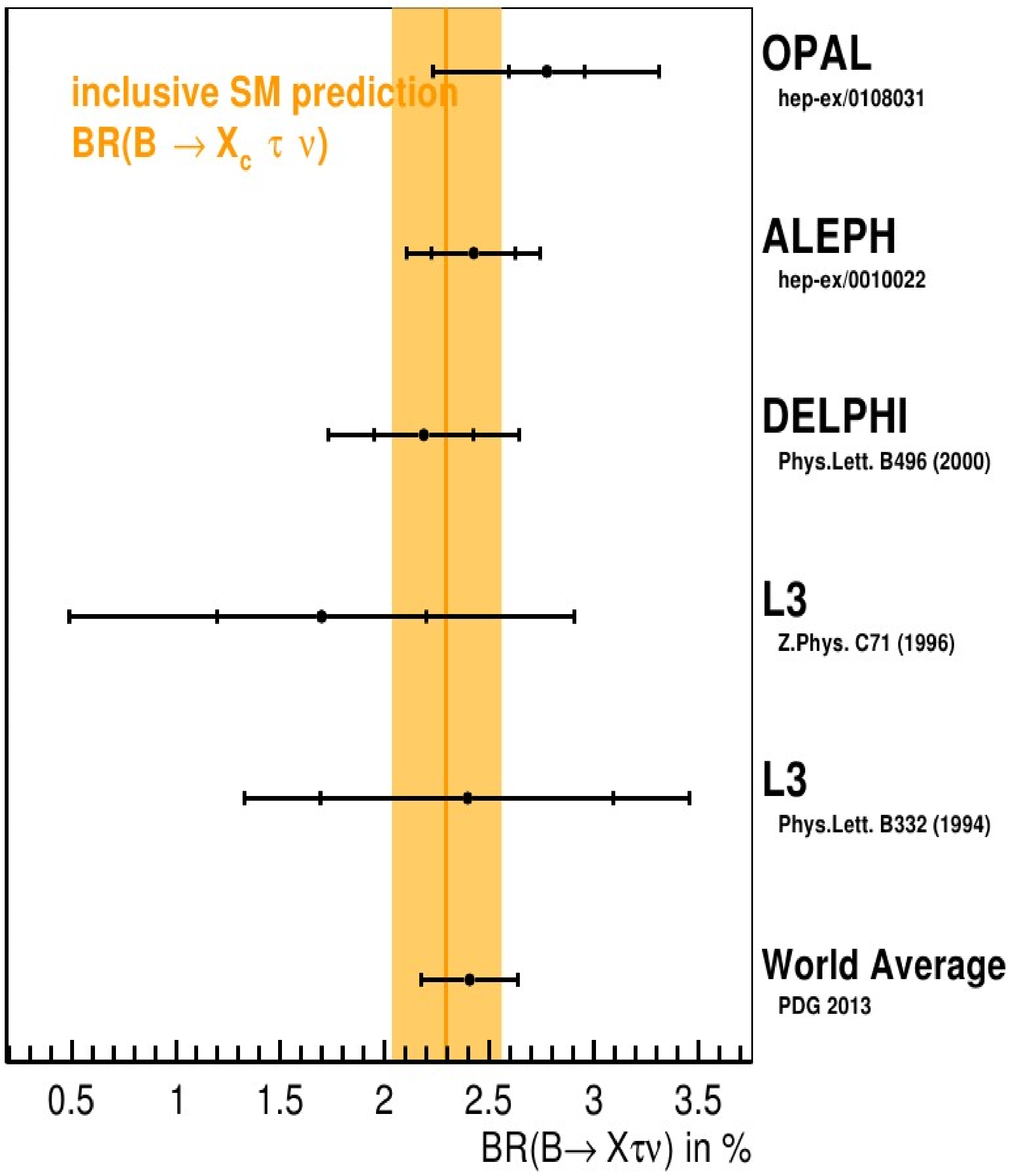
Tag Method	tagged
Br [10^{-2}]	2.31
Errors	%
Track	1.6
$B \to D^{**} l\nu$, FF	0.7
$B \to D^{**} l\nu$, Bfs	0.8
$D^{(*)}$ Bfs	1.8
PDFs	0.5
particle ID	1.0
Tag calibration	**3.3**
Luminosity	1.4
τ_B	0.2
π^0 efficiency	0.6
Total	4.6
Stat	1.3

Sample	Signal yield	$\mathcal{B}$ [%]
$B^0 \to D^- e^+ \nu_e$	$2848 \pm 72 \pm 17$	$2.44 \pm 0.06 \pm 0.12$
$B^0 \to D^- \mu^+ \nu_\mu$	$2302 \pm 63 \pm 13$	$2.39 \pm 0.06 \pm 0.11$
$B^+ \to \bar{D}^0 e^+ \nu_e$	$6456 \pm 126 \pm 66$	$2.57 \pm 0.05 \pm 0.13$
$B^+ \to \bar{D}^0 \mu^+ \nu_\mu$	$5386 \pm 110 \pm 51$	$2.58 \pm 0.05 \pm 0.13$
$B^0 \to D^- \ell^+ \nu_\ell$	$5150 \pm 95 \pm 29$	$2.39 \pm 0.04 \pm 0.11$
$B^+ \to \bar{D}^0 \ell^+ \nu_\ell$	$11843 \pm 167 \pm 120$	$2.54 \pm 0.04 \pm 0.13$
$B \to D \ell \nu_\ell$	$16992 \pm 192 \pm 142$	$2.31 \pm 0.03 \pm 0.11$

- Tag correction dominates - use cleaner modes at Belle II.
- Ratio not explicitly measured in Belle. Errors should cancel.
  $R\mu e$ stat±6%, sys±1% (estimated).
- In Belle II
  $R\mu e$ stat±<1%, sys±<1%. = total±1%

$B \to X \tau \nu$

- Very challenging. Relies on modelling of m^2_{miss} and $B \to X \, l \, \nu$ kinematics.
- Dubious errors quoted by ALEPH (no error on $B \to D^{**} \, l \, \nu$!)
- Work in progress…



Summary

- $B \to D^* \tau \nu$ @ 2%
- $B \to D \tau \nu$ @ 3%
- $B \to D^* l \nu$ LFUV << 1%
- $B \to D l \nu$ LFUV @ 1%
- $B \to D^{**} l \nu$: never done comprehensively at B-factories. A long way to go to eliminate this as bias on $B \to D^{(*)} \tau \nu$.
- $B \to D^{**} \tau \nu$ Florian will discuss this tomorrow