Measurements of R_D and R_{D^*} by Belle and BABAR

Focus on Hadronically Tagged $B\bar{B}$ Samples

Belle: PRD 92, 072014 (2015)*
BABAR: PRL 100, 101802 (2012), PRD 88, 072012 (2013) **

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$B \to D^{(*)}\tau\nu$ vs $B \to D^{(*)}l\nu$

- Measurements of the ratios to test the SM predictions

$$R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}$$

Focus on purely leptonic τ decays

Several experimental and theoretical uncertainties cancel in the ratio!

- $\Upsilon(4s) \to B\overline{B}$ decays are fully reconstructed:
  - hadronic B decay : tag (tag efficiency 0.2% to 0.3%)
  - D or D* decays to hadrons
  - single $e^{\pm}$ or $\mu^{\pm}$ (BABAR : $p_{\mu}^* > 0.2$, $p_e^* > 0.3$ GeV)
  - conservation of charge and flavor
  - no additional charged particles - Belle vetoes additional π^0
- kinematic selection : $q^2 > 4$ GeV^2 to suppress $D^{(*)}l\nu$
- Background suppression by NN/BDT (combinatorial BG and $D^{**}l\nu$)
- Full Belle and BABAR data sample

BABAR and Belle: Signal and Backgrounds

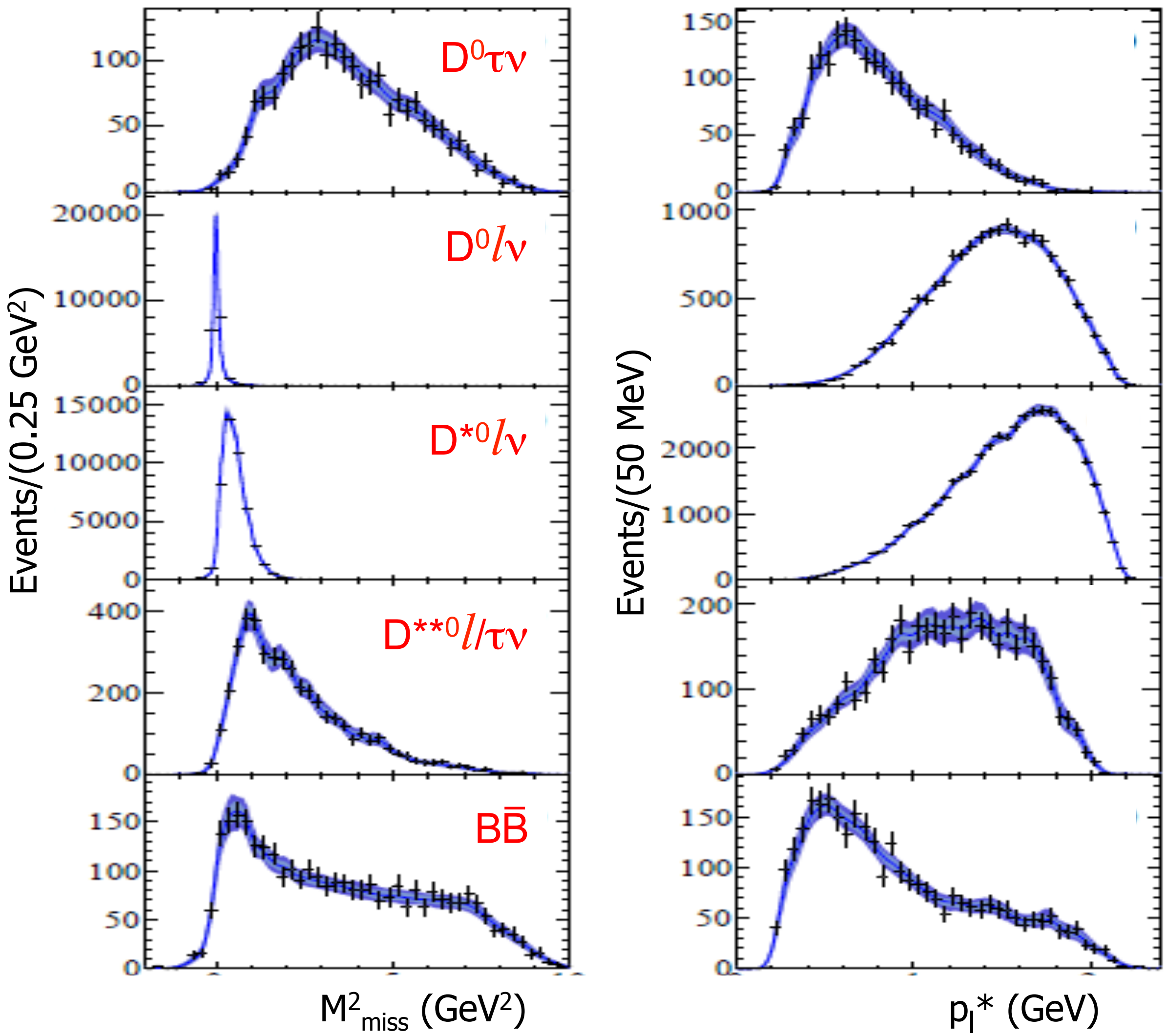
- Signal: $B \to D\tau\nu$, $D^*\tau\nu$, $\tau \to l\,\nu_\tau\nu_l$, $l = e, \mu$ — Signature: $3\,\nu$
- Normalization: $B \to D\,l\,\nu$, $D^*\,l\,\nu$, $l = e, \mu$ — Signature: $1\,\nu$
- Principal BG: $B \to D^{**}l\,\nu$, $l = e, \mu, \tau$; $B \to \bar{D}D_s(\to \tau\,\nu)$
  $B\bar{B}$ combinatorics (B_{tag}, D, D* signal, hadron/lepton mis-ID
  Non-$B\bar{B}$: $e^+e^- \to q\bar{q}(\gamma)$
- Uncertainties: MC simulation
  BF/FF for s.l. B decays: $B \to D/D^*/D^{**}l\,\nu$, , $l = e, \mu, \tau$
  BF/kinematics of other B and D decays
  Detection and reconstruction efficiencies for signal and BG
- Tools: Use latest predictions and measurements
  Data control samples to verify and adjust simulations
  Suppress backgrounds by individual cuts and NN/BDT

NB: Significant differences in tag and signal selection, fitting methods, and assessment of uncertainties

BABAR: $B \to D^{(*)}\tau\nu$: Extraction of Yields from M.L.Fit

- Unbinned M.L. fit - fully 2-dimensional
  Lepton momentum in B rest frame: p_l^*, Missing mass sq: $M^2_{miss} = (P_{ee} - P_{tag} - P_{D(*)} - P_l)^2$
  - 4 signal samples: $D^0 l$, $D^{*0} l$, $D^+ l$, $D^{*+} l$, (l = e or μ)
  - 4 $D^{(*)}\pi^0 l\nu$ control samples
- PDFs from MC (approximated using Keys fct.)
- Fitted Yields (22 free parameters)
  - 4 $D^{(*)}\tau\nu$ Signal
  - 4 $D^{(*)} l\nu$ Normalization + 2 ($D^* l\nu \to D l\nu$ feed-down)
  - 4 Background ($D^{**} l/\tau\nu$) + 4 BG ($D^* l\nu$) +4 $B\bar{B}$ BG
- Fixed Backgrounds
  - B^0–B^+ cross feed
  - $B\bar{B}$ combinatorial BG
  - Continuum $e^+e^- \to q\bar{q}$ (γ)

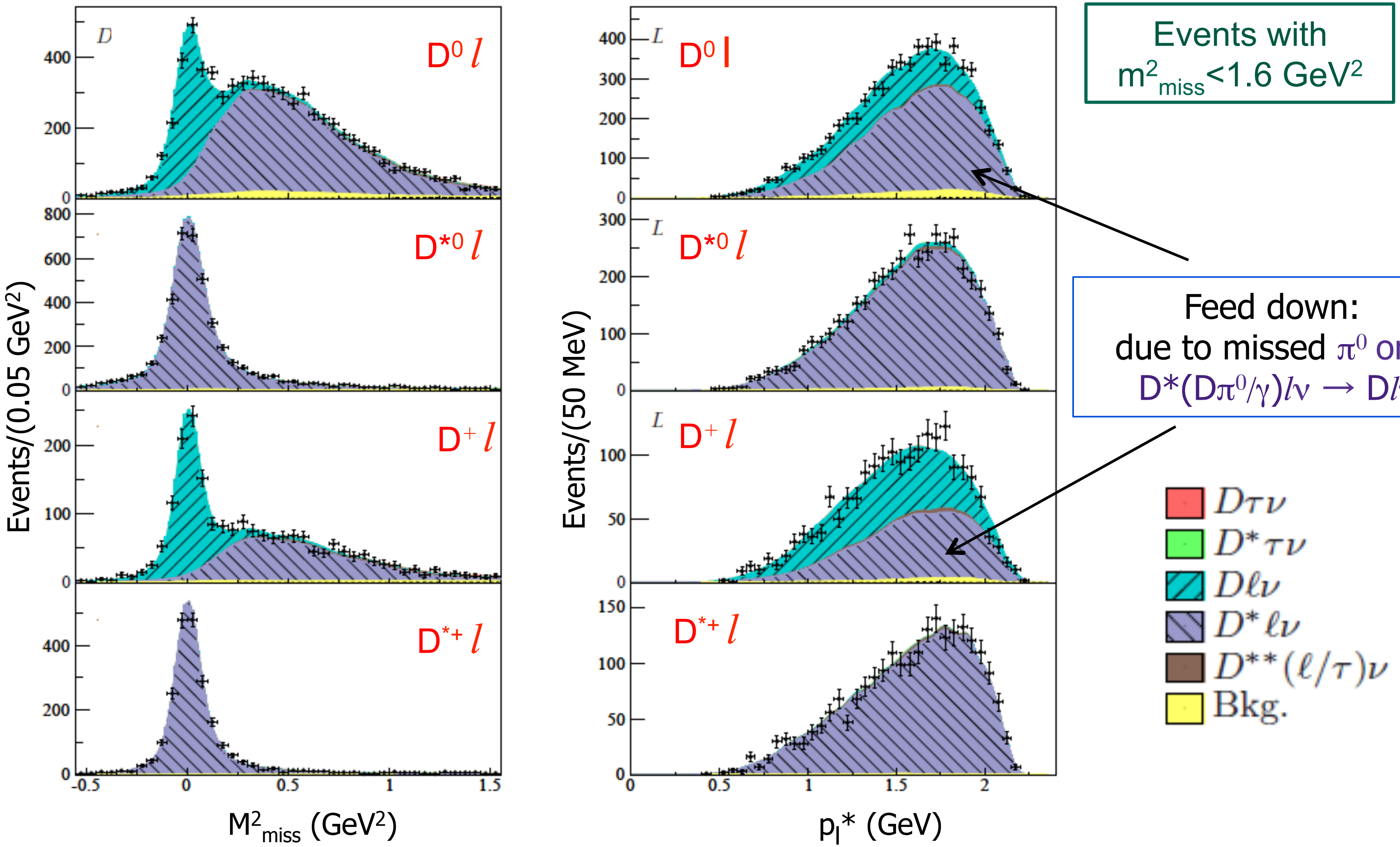
BABAR: 2-D PDFs Based on Keys Functions



- 2-D M^2_{miss} vs p^*_l difficult to describe analytically
  - correlations
  - irregular functions
- Solution
  - non-parametric Kernal Estimators (KEYS)
  - optimize bias vs variance (smoothing)

Blue bands mark 2σ variations due to the stat. uncertainties of MC samples

BABAR: Fit Normalization $B \rightarrow D^{(*)} l \nu$

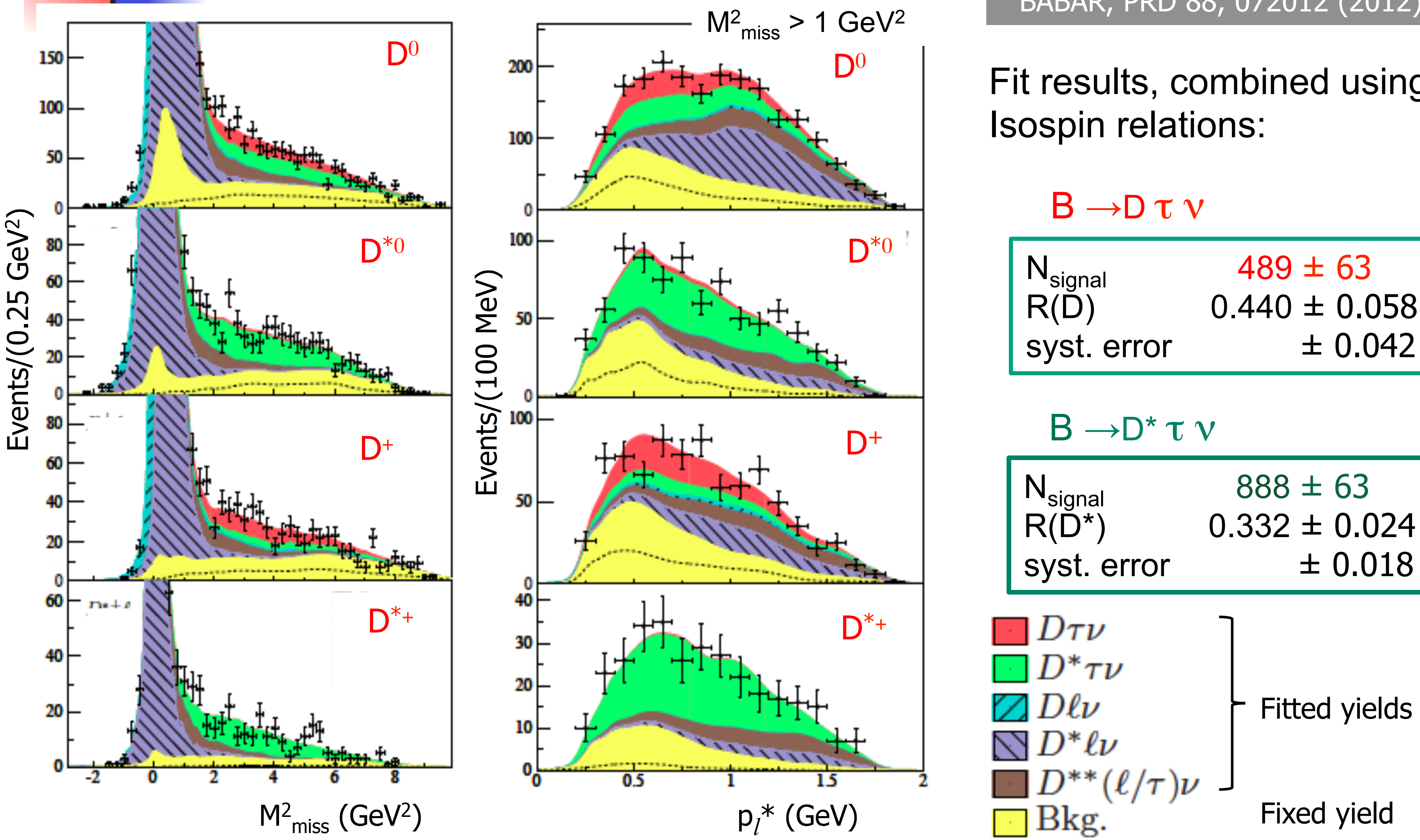


Events with m^2_{miss}<1.6 GeV^2

Feed down:
due to missed π^0 or γ
$D^*(D\pi^0/\gamma) l\nu \rightarrow D l\nu$

BABAR: Fit Results: B→ Dτν and B→ D*τν

BABAR, PRD 88, 072012 (2012)



Fit results, combined using Isospin relations:

B →D τ ν

N_{signal}	489 ± 63
R(D)	0.440 ± 0.058
syst. error	± 0.042

B →D* τ ν

N_{signal}	888 ± 63
R(D*)	0.332 ± 0.024
syst. error	± 0.018

BABAR: Systematic Uncertainties

Principal Uncertainties:

- $D^{**}l\nu$: conservative 15%

  constraints and fit to $D^{(*)}\pi^0$ sample,

- PDF Modeling of s.l. decays

  FF, constraints, MC statistics (2D)

- $B\bar{B}$ and non-BB backgrounds

  Corrections and MC statistics

- Event reconstruction and detector effects

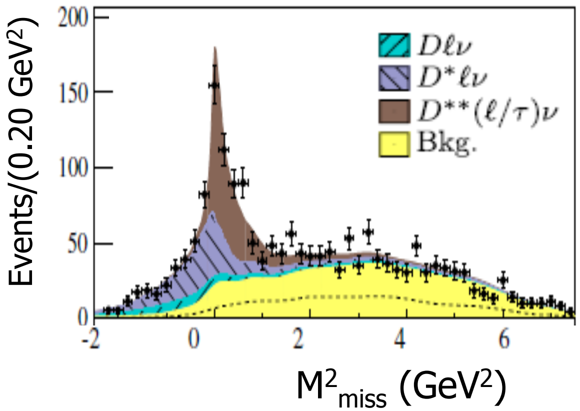
BABAR Source	Uncertainty (%) R(D)	R(D*)
$D^{**}l/\tau\nu$ Background	5.8	3.7
PDF modeling	5.3	2.6
$B\bar{B}$ and non-$B\bar{B}$ BG	5.0	2.7
Efficiencies $\varepsilon_{signal}/\varepsilon_{Norm}$	2.7	1.7
Systematic Uncertainty	9.7	5.6
Statistical Uncertainty	13.1	7.1
Total Uncertainty (%)	16.2	9.0

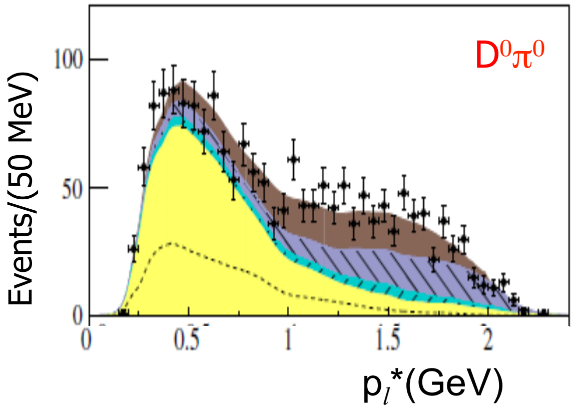
Fit to $D^{(*)}\pi^0 l\nu$ control sample for the sum of the 4 channels:

$D^0\pi^0 l\,\nu$, $D^{*0}\pi^0 l\,\nu$,
$D^+\pi^0 l\,\nu$, $D^{*+}\pi^0 l\,\nu$

Largest errors are Gaussian distributed!

Fit to $D^0\pi^0 l\nu$ Control Samples





Belle: $B \to D^{(*)}\tau\nu$: Extraction of Yields from M.L. Fit

- Simultaneous unbinned M.L. fit to two 1D distributions
  - variables: M^2_{miss} $M^2_{miss} < 0.85$ GeV^2 dominated by $B \to D^{(*)} l \nu$, l=e ,μ
    $\bar{O}_{NB}$ $M^2_{miss} > 0.85$ GeV^2 signal + various BG
  - 4 signal samples: $D^0 l$, $D^{*0} l$, $D^+ l$, $D^{*+} l$, ($e^\pm$ or μ)
- 2 PDFs from MC for signal and backgrounds
  - M^2_{miss} - smoothed histogram
  - $\bar{O}_{NB}$ - biforcated Gaussian (mean and 2 widths)
- Fitted total yields (12 free parameters)
  - 2 ratios R_D and R_{D*} (B^0 and B^+ parameters constrained by isospin)
  - 4 $D^{(*)} l\nu$ Normalization + 2 $D^* l\nu$ feed-down
  - 4 $D^{**} l\nu$ background

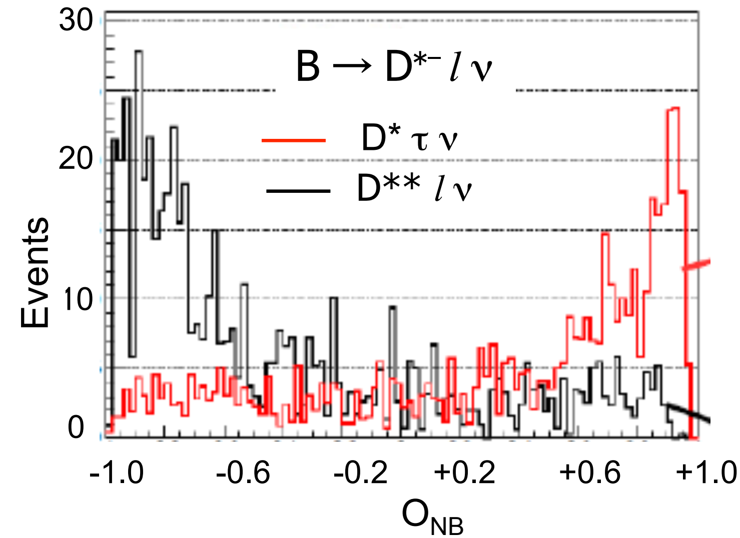
  The relative yields in the two M^2_{miss} regions are fixed to MC predictions!
- Fixed Backgrounds
  - Misidentified leptons (incl. non-leptonic τ decays)
  - $B \to D^{(*)} D_s^- (\to \tau\nu)$ BG
  - Large combinatorial $D^{(*)}$ background, continuum vetoed

Variable based on NN output O_{NB}:

$$\bar{O} \equiv \log \frac{o_{NB} - o_{min}}{o_{max} - o_{NB}}$$

Belle: NN output variable $\bar{O}_{NB}$

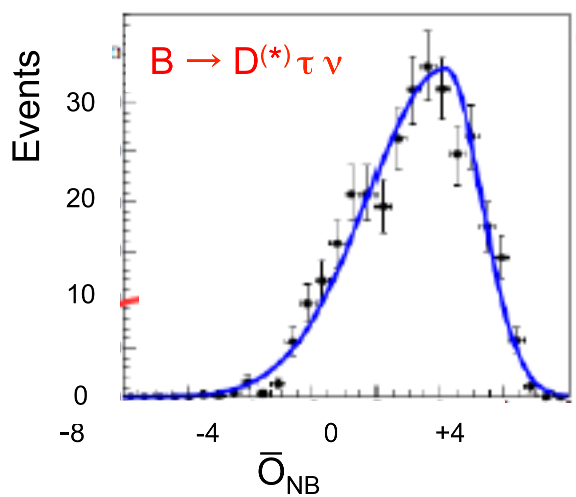
- For each of the 4 data samples, NN are trained to distinguish $B \rightarrow D^{(*)} \tau \nu$ from $B \rightarrow D^{**} \tau \nu$ and other BG sources
- NN uses M^2_{miss} and other variables:
  - E_{ECL} - unassociated energy clusters in ECAL
  - Lepton p^*_l momentum and q^2
  - Extra π^0, direction of B momentum, etc.

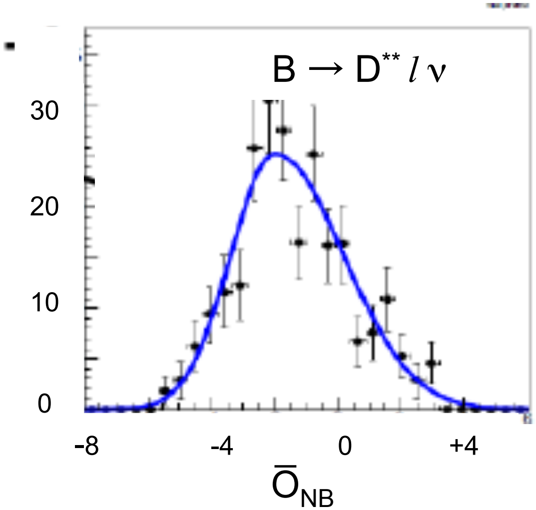


- For the fit, the NN output O_{NB} is transformed into

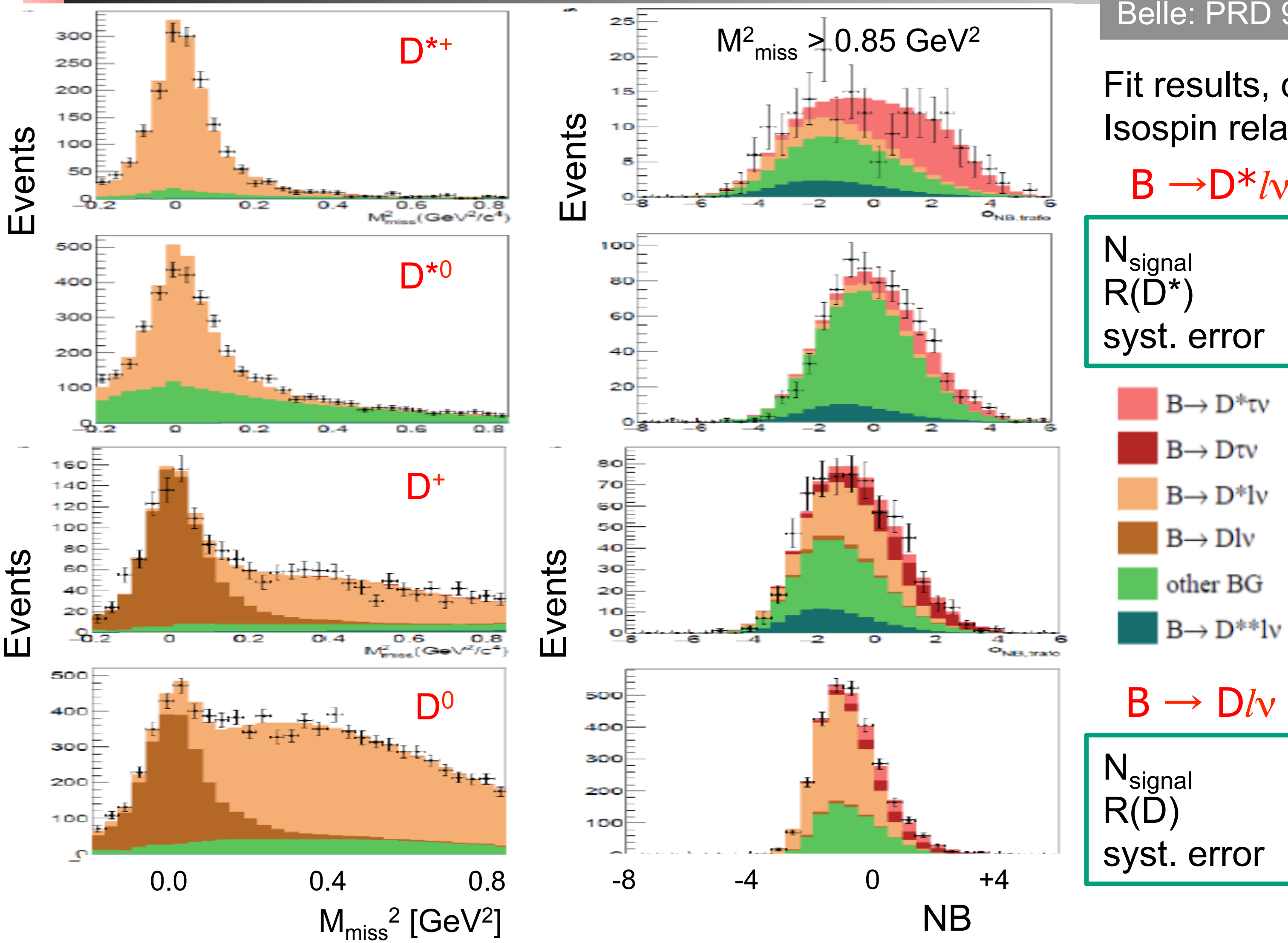
$$\bar{O}_{NB} \equiv \log \frac{o_{NB} - o_{min}}{o_{max} - o_{NB}}$$

a variable with a distribution that can be described by a bifurcated Gaussian function, and is easily fitted by 3 parameters, a mean and lower and upper width.





Belle: Fit Results for B → D*$l\nu$ and B → D$l\nu$



Belle: PRD 92,072014 (2015)

Fit results, combined using Isospin relations:

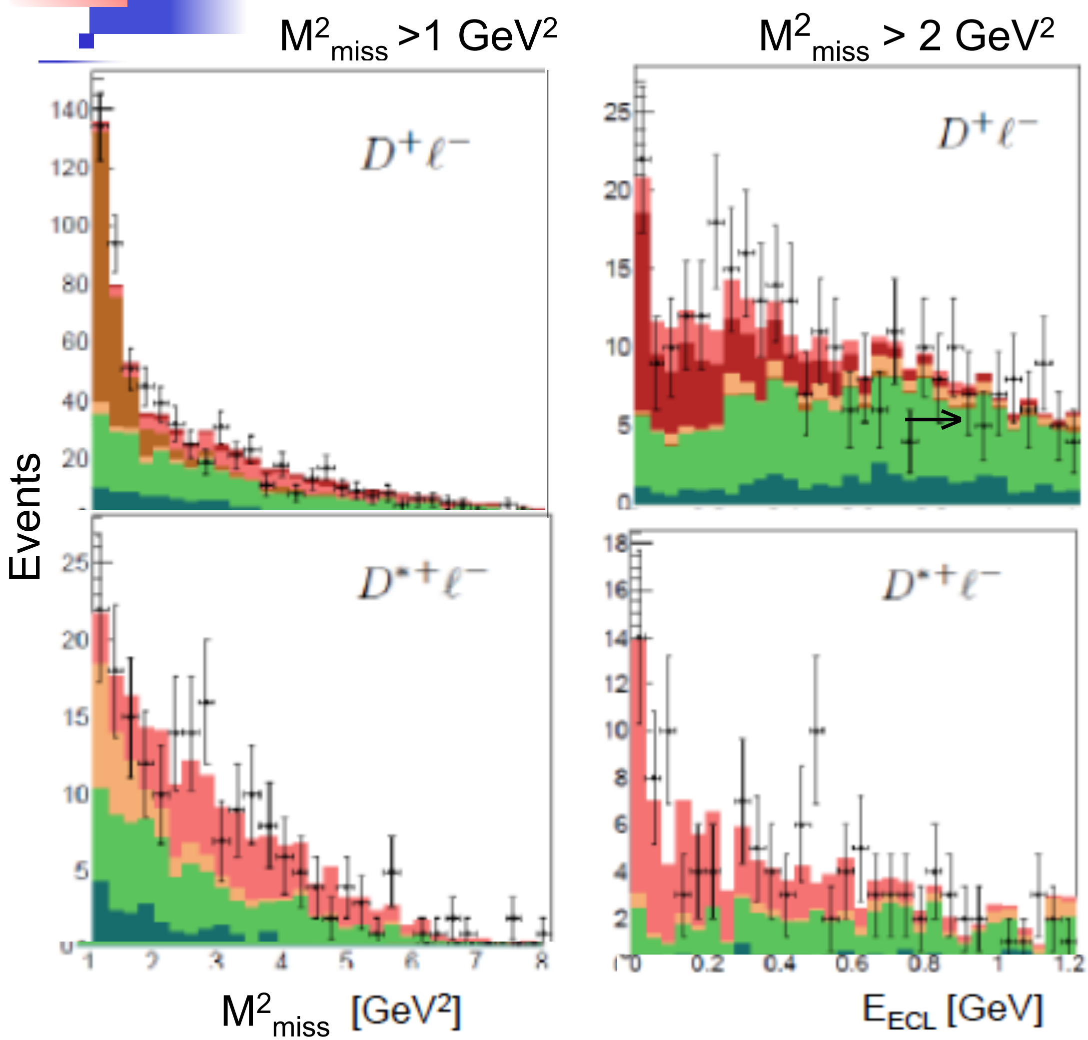
B →D*$l\nu$

N_{signal}	503± 65
R(D*)	0.293 ± 0.038
syst. error	± 0.015

B → D$l\nu$

N_{signal}	320 ± 55
R(D)	0.375 ± 0.064
syst. error	± 0.026

Belle: Cross Checks on Fit Results



Critical variables for NN,
identification of

- signal: 3ν missing
- BG: E_{ECL}
  sensitive to unidentified neutrals: γ, π^0, K_L from incomplete and incorrect reconstruction of B_{tag} and B_{signal} ,

Belle: Systematic Uncertainties

Principal Uncertainties:

- $D^{**} l \nu$ composition and FF
- PDF Modeling and events cross feeds
- $B\bar{B}$ backgrounds and reconstruction
- Efficiency ratios: signal/normalization
  Incl. cross feeds and lepton Mis-ID

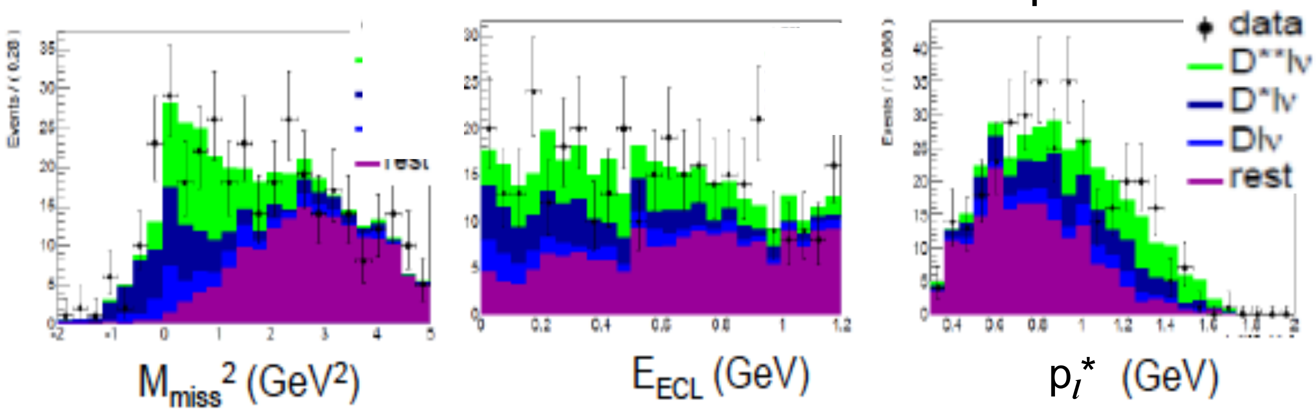
Belle Source	Uncertainty (%) R(D)	R(D*)
$D^{**} l / \tau \nu$ Background	4.4	3.4
PDF modeling	4.3	2.6
$B\bar{B}$ and ~~non-$B\bar{B}$ BG~~	0.7	0.7
Efficiencies $\varepsilon_{signal}/\varepsilon_{Norm}$	3.5	3.3
Systematic Uncertainty	7.1	5.4
Statistical Uncertainty	17.1	13.0
Total Uncertainty (%)	18.4	14.0

NB Non-$B\bar{B}$ background vetoed in tag selection!

Validation of $D^{**} l \nu$ BG with fits to $D^+\pi^0 l \nu$ control sample for three variables used in NN: M^2_{miss}, E_{ECL}, p_l^*

Good agreement with MC simulation!

Fits to $D^+\pi^0 l \nu$ Control Sample



BABAR – Belle: Comparison of Signal and BG Yields

Samples	Belle	BABAR	Ratios
$B\bar{B}$ produced [10^6]	722	471	1.6
$D\tau\nu$ signal	320	489	0.65
$Dl\nu$ Normalization	3,147	2,981	1.06
$D^{**}\tau/l\nu$ BG	239	506	0.47
Other BG	2,005	1,033	1.94
Rel. stat. Error [%]	17	13	1.3
$D^*\tau\nu$ signal	503	888	0.57
$D^*l\nu$ Normalization	12,045	11,953	1.01
$D^{**}\tau/l\nu$ BG	153	261	0.59
Other BG	2,477	404	6.13
Rel. stat. Error [%]	13	7	1.8

Event yields and fit sample composition differ significantly.

- Significant difference in Signal yield!
- Belle : smaller $D^{**}l/\tau\nu$ background in signal sample, veto on extra π^0 ?
- BABAR: much smaller $B\bar{B}$ in fit sample, due to cut based on BDT prior to fit!
- Belle: Other BG is dominated by fake π^0 in D^{*0} sample, non-$B\bar{B}$ events are vetoed by B_{tag} quality test due to small FW moments!

Comparison of BABAR and Belle Measurements

In spite of similarity in the composition of the recorded events samples, there are significant differences, resulting in different signal yields:

- the selection of the events in the fit sample,
- the choice of the fit: 2 very different variables and shapes, 1D vs 2D,
- different assessment of uncertainties: MC uncertainties vs data control samples,

NB: The 4 source categories listed below differ to some degree in their definition

Relative Uncertainties (%)	R_D			R_{D^*}		
Source	Belle	BABAR	Ratio	Belle	BABAR	Ratio
$D^{**}l/\tau\nu$ Background	4.4	5.8	0.76	3.4	3.7	0.90
PDF modeling	4.3	5.3	0.80	2.6	2.6	1.01
$B\bar{B}$ and non-$B\bar{B}$ BG	0.7	5.0	0.14	0.7	2.7	0.25
Efficiencies $\varepsilon_{signal}/\varepsilon_{Norm}$	3.5	2.7	1.29	3.3	1.7	1.91
Systematic Uncertainty	7.1	9.7	0.73	5.4	5.6	0.97
Statistical Uncertainty	17.1	13.1	1.31	13.0	7.1	1.93
Total Uncertainty (%)	18.4	16.3	1.14	14.0	9.0	1.55

Additional R_D and R_{D*} Measurements

R_D	$B\bar{B}$ tag	τ decay	# Dτν	# Dlν	R_D	stat. err.	syst. err.
BABAR	had.	eνν, μνν	489 +/- 63	2891 +/- 65	0.440	0.058	0.042
Belle	had.	eνν, μνν	320 +/- 55	3147 +/- 72	0.375	0.064	0.026
HFLAV					0.407	0.039	0.024
Theory					0.300		0.003

R_{D*}	$B\bar{B}$ tag	τ decay	# D*τν	# D*lν	R_{D*}	stat. err.	syst. err.
BABAR	had.	eνν, μνν	888 +/- 63	11,953 +/- 122	0.332	0.024	0.018
Belle	had.	eνν, μνν	503 +/- 65	3797 +/- 74	0.293	0.038	0.015
Belle	s.l.	eνν, μνν	231+/- 23	2,800 +/- 57	0.302	0.030	0.011
Belle	had	πν, ρν	298+/- 29	7,213 +/- 96	0.270	0.035	0.028
LHCb		μνν	16,480	363,000	0.336	0.027	0.030

R_{D*}	$B\bar{B}$ tag	τ decay	# D*τν	# D*π+π−π-	R_{D*}	stat. err.	syst. err.
LHCb		3πν	1,273	17,660	0.285	0.019	0.028
HFLAV					0.304	0.013	0.007
Theory					0.252		0.010

Conclusions

- Experiments at e^+e^- B Factories have played and will continue to play an important role in the study of leptonic and semileptonic B decays, though low production cross sections place a high demand on luminosity - Belle II
- $Y(4s) \to B\bar{B}$ decays, unique advantages to measure R_D and R_{D*}
  - Hadronic tags combined with purely leptonic τ decays offer kinematic constraints for events with 3ν
  - The high degree of cancellation of exp. and theoretical uncertainties lead to reduced uncertainties
  - $D\tau\nu$ have higher sensitivity to spin-0 couplings – Combined $D\tau\nu$ and $D^*\tau\nu$ analyses gain information
  - Kinematic information, i.e. q^2, momenta and angles of $D^{(*)}$ and τ, should provide information about non-SM contribution.
- Still, the analyses are very complex, and further scrutiny is advised!
- 2-body τ decays, $\tau \to \pi\nu$, $\rho\nu$, $a_1\nu$, carry information on the transverse helicity of the τ, as demonstrated by Belle recently, should be further pursued
- s.l. tags are simpler, however, they compromise kinematic event information, challenging separation of signal and BG.
- Hopefully more data and improved understanding of all types of s.l. decays and backgrounds will establish the observed anomaly.

Merci de votre attention

Fits to $D^{(*)}\pi^0$ Samples