Semileptonic B Decays and Implications for Higgs Searches

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Outline

Semileptonic decays in the B, B_s sector, measurement techniques

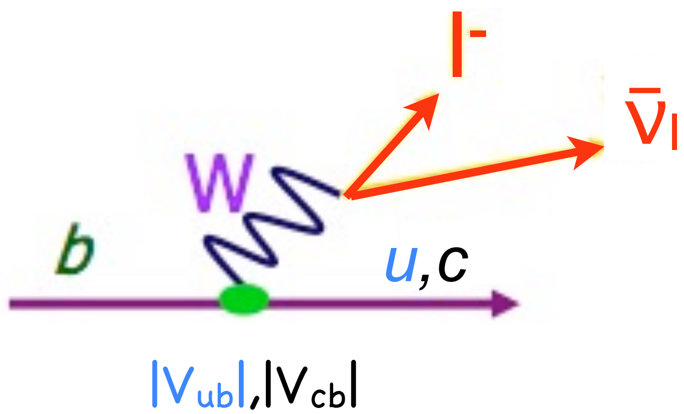
The $|V_{ub}|$, $|V_{cb}|$ puzzle

B_s production rate and semileptonic branching fraction

$B \rightarrow D^{(*)}\tau\nu$ and the two-doublet Higgs model

Semileptonic B Decays

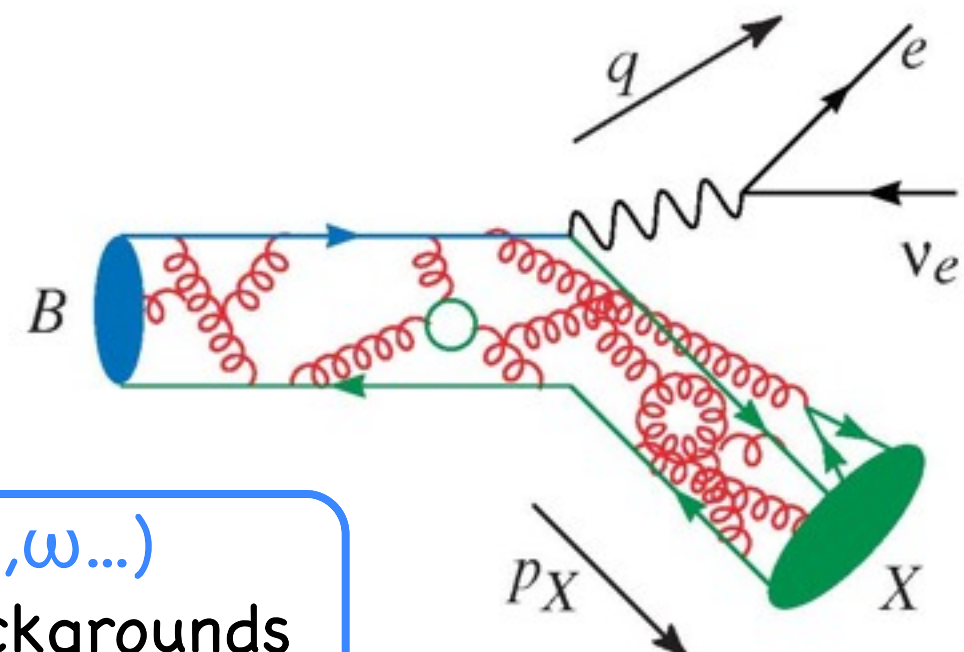
Semileptonic B decays give us a clear view of the b quark inside the B meson



Decay rate depends on $|V_{ub}|$ and $|V_{cb}|$
Leptonic and hadronic currents can be disentangled
Tree-level decays ➟ independent of new physics

Inclusive decays

Large signal rate, high backgrounds
Total rate calculated with HQE
Need to account for non perturbative QCD effects!



Exclusive decays (X=π,ρ,ω...)

Lower signal rate, lower backgrounds
Need Form Factors to describe the decay process

Semileptonic B Decays

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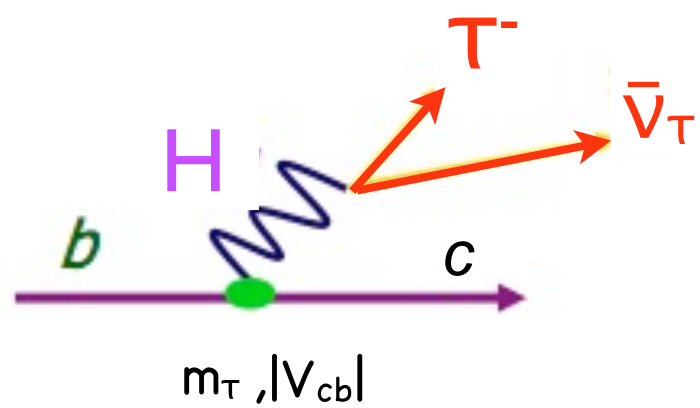

Tree level decays ➠ independent of new physics

but τ final states may be sensitive to charged Higgs exchange

Inclusive decays

Large signal rate, high backgrounds
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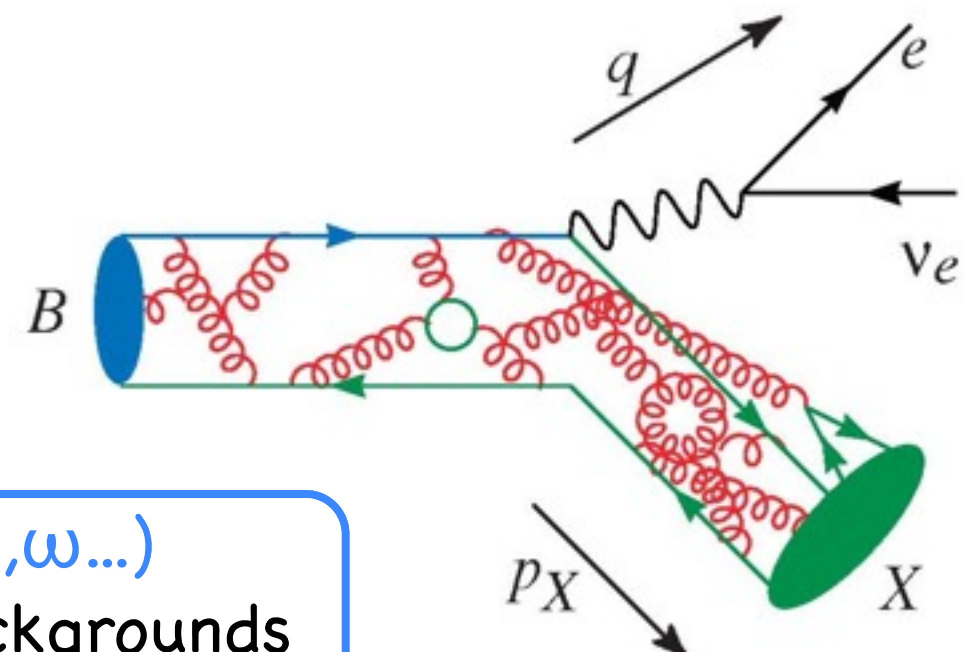

Exclusive decays (X=π,ρ,ω…)

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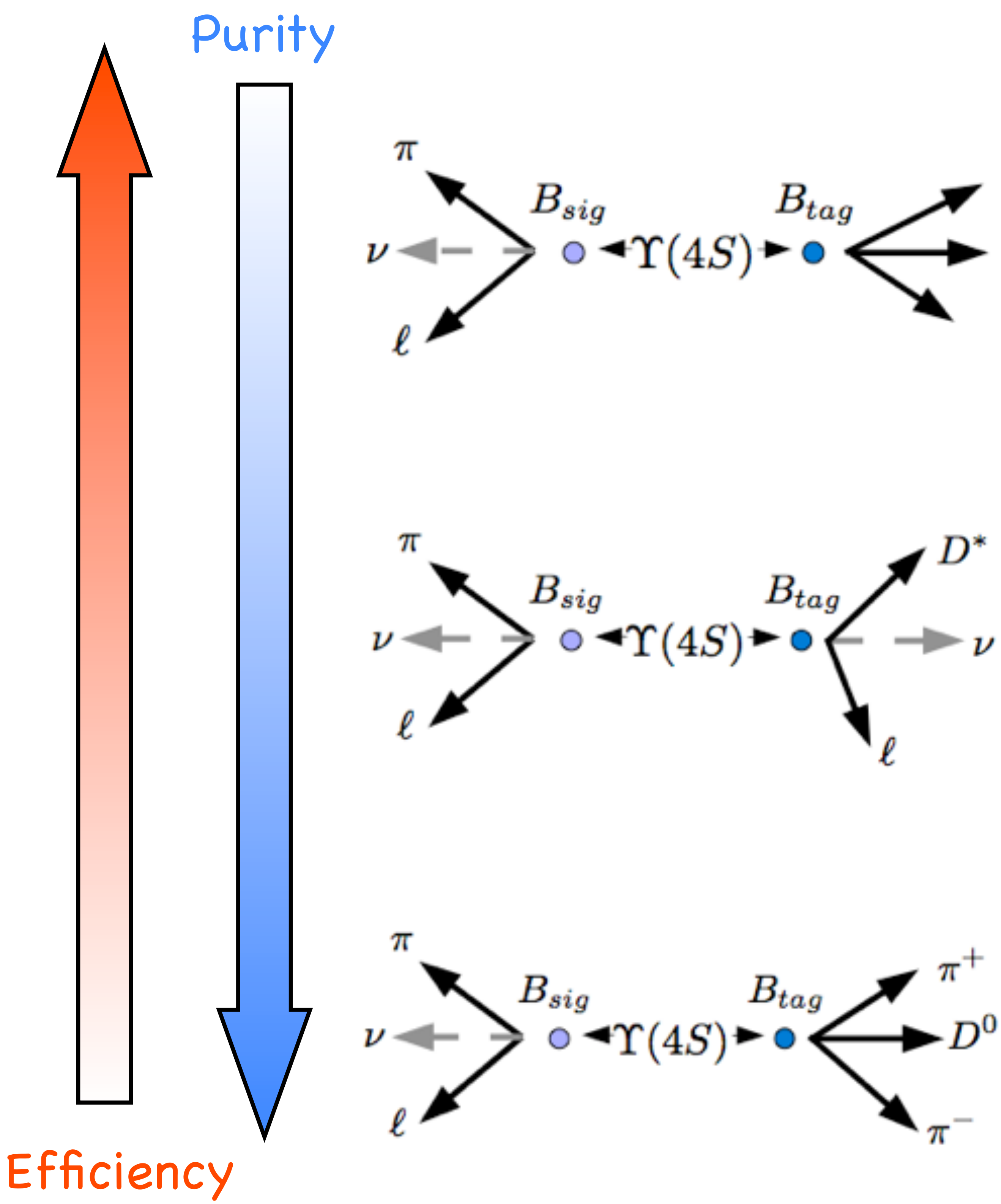
Measurement Techniques - Tagging



Untagged:
Only signal reconstruction
Initial momentum known
High statistics
Sensitive to background simulation

efficiency ≈ 2%

Semileptonic tag:
Reconstruct $B \rightarrow D^{(*)} l \nu$
Full or partial reconstruction of D^*
2ν - incomplete kinematics

efficiency ≈ 0.7%

Hadronic tag:
Reconstruct $B \rightarrow D^{(*)} Y$ ($Y = K, \pi, \ldots$) in ~1000 modes
Closed kinematics, charge and flavour are known

The $|V_{ub}|$, $|V_{cb}|$ puzzle

Using various measurement techniques, we are confronted with a puzzle: $|V_{ub}|$ and $|V_{cb}|$ values from inclusive and exclusive measurements are marginally consistent with each other

$|V_{cb}|$

PRD 81, 032003 (2010)

Inclusive	$(42.1 \pm 0.6 \pm 0.8) \times 10^{-3}$
Combined exclusive	$(37.4 \pm 1.2 \pm 1.4) \times 10^{-3}$

2.2 σ discrepancy

PRD 74, 092004 (2006)
PRD 77, 032002 (2008)

$|V_{ub}|$

arXiv: 1112.0702 [hep-ex]

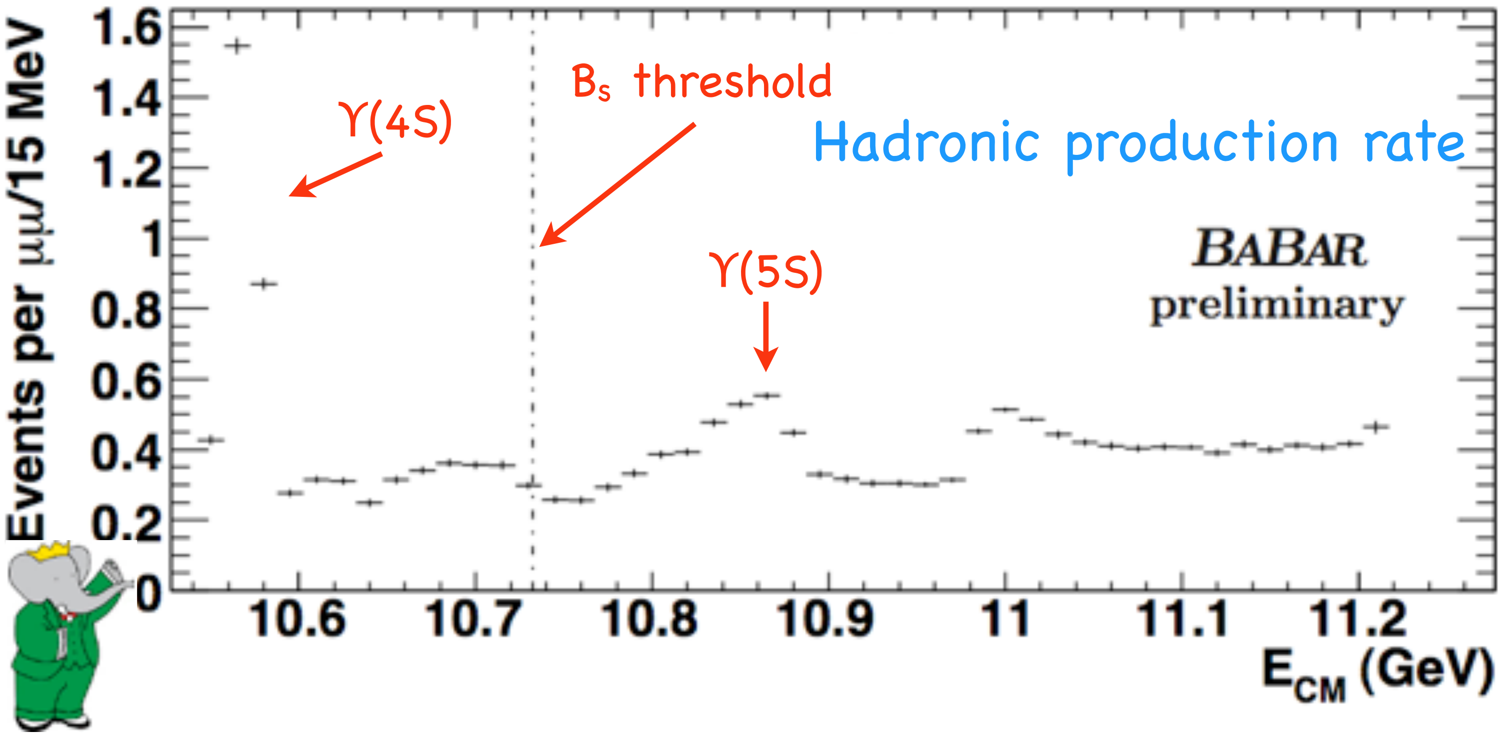
Inclusive	$(4.31 \pm 0.25 \pm 0.16) \times 10^{-3}$
Combined exclusive	$(3.13 \pm 0.14 \pm 0.27) \times 10^{-3}$

2.8 σ discrepancy

PRD 83, 032007 (2011)
PRD 83, 052011 (2011)

What is the source of the discrepancy? Experiment? Theory? Both?

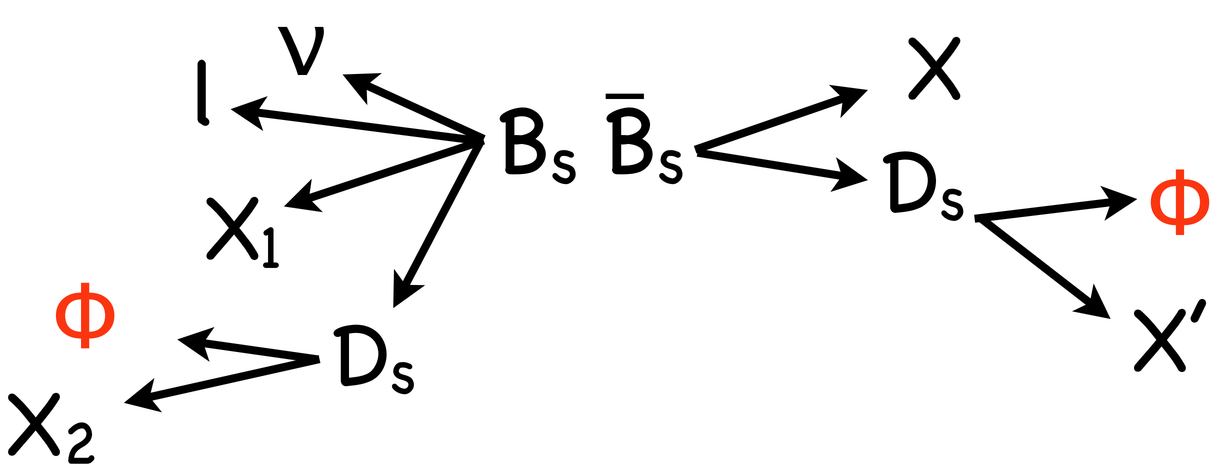
B_s Semileptonic Branching Fraction



PRL 102, 012001 (2009)

Inclusive rate measurement above the ϒ(4S) resonance: 10.56 GeV (open B threshold) to 11.2 GeV (short of Λ_b threshold at 11.24): ≈140 points with a total ≈4.15 fb^{-1}

Φ mesons abundant in B_s decays, compared to $B_{u/d}$:



$B(B_s \to D_s X) \times B(D_s \to \Phi X) \approx 15\%$ (PDG2010)
$B(B \to \Phi X) \approx 3.43\%$ (PDG2010)

$B_s \to D_s l \nu X_1 \to \Phi l \nu X_2 \approx 1.3\%$ (same B_s)
$B \to D l \nu X_1 \to \Phi l \nu X_2 \approx 0.1\%$ (same B)

$B_s \to l \nu X_1$ & $B_s \to \Phi X_2 \approx 1.4\%$ (different B_s)

The inclusive yield of Φ and Φ+lepton in B_s and $B_{u/d}$ decays can be used to measure the $B_s\bar{B}_s/B\bar{B}$ production rate and the B_s semileptonic branching fraction

B_s Semileptonic Branching Fraction

We measure number of events, Φ yield, and Φ yield in correlation with a high-momentum lepton as a function of CM energy

Hadronic event rate

$$R_B[f_s\epsilon_h^s + (1-f_s)\epsilon_h]$$

Inclusive Φ rate

$$R_B[f_s\epsilon_\phi^s P(B_s\overline{B}_s \to \phi X) + (1-f_s)\epsilon_\phi P(B\overline{B} \to \phi X)]$$

Inclusive Φ+lepton rate

$$R_B[f_s\epsilon_{\phi\ell}^s P(B_s\overline{B}_s \to \phi\ell X) + (1-f_s)\epsilon_{\phi\ell} P(B\overline{B} \to \phi\ell X)]$$

$$R_B = \sum_{q=u,d,s} \sigma(e^+e^- \to B_q\bar{B}_q)/\sigma_{\mu^+\mu^-} \qquad f_s \equiv \frac{N_{B_s}}{N_{B_u}+N_{B_d}+N_{B_s}}$$

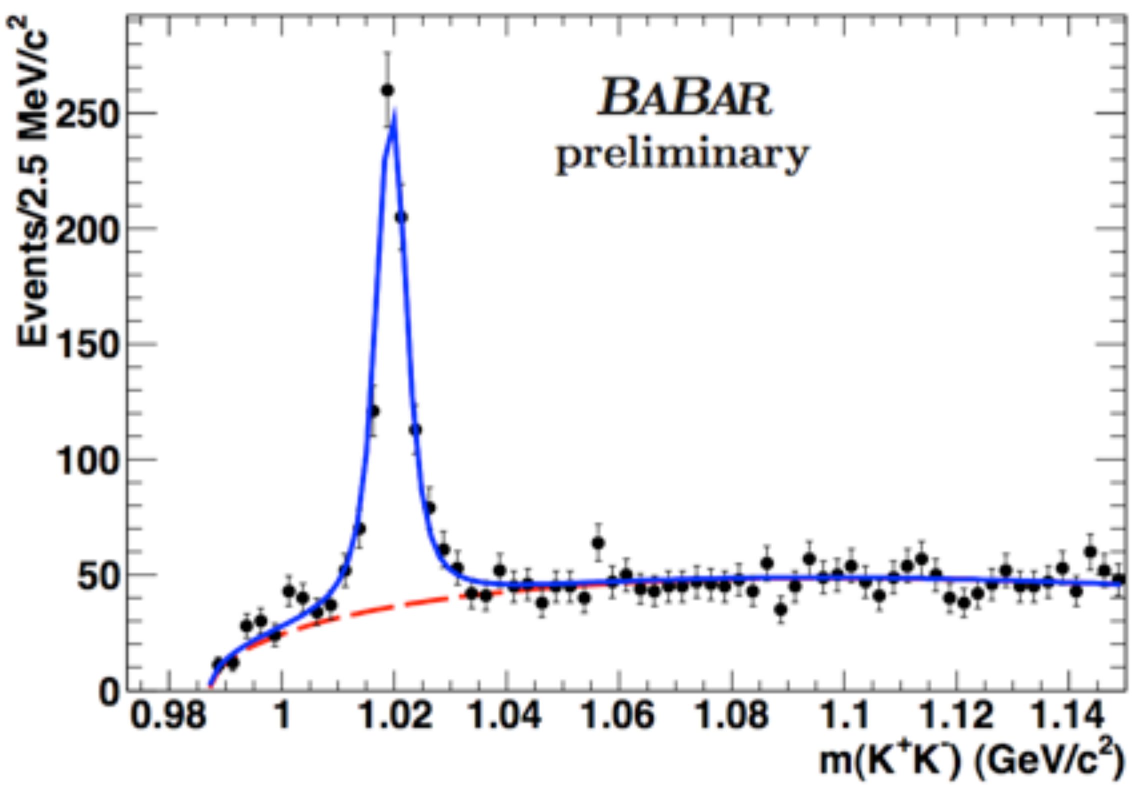
ε_i are efficiencies estimated from MC

P(BB→Φ(l)X) are probabilities that a Φ(l) is produced in a BB event

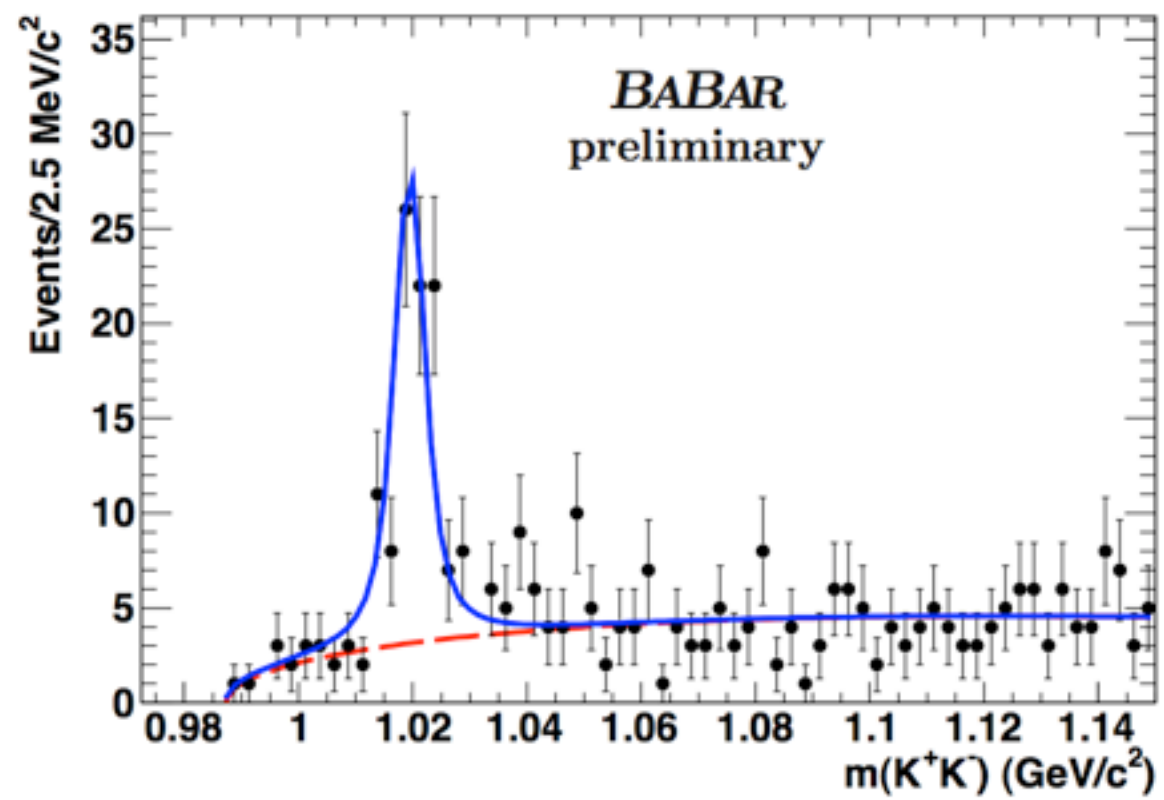
B_s Semileptonic Branching Fraction

For each bin in CM energy, Φ candidates are reconstructed in the Φ→K⁺K⁻ decay mode

$B\bar{B} \to \Phi X$ candidates



$B\bar{B} \to \Phi l X$ candidates

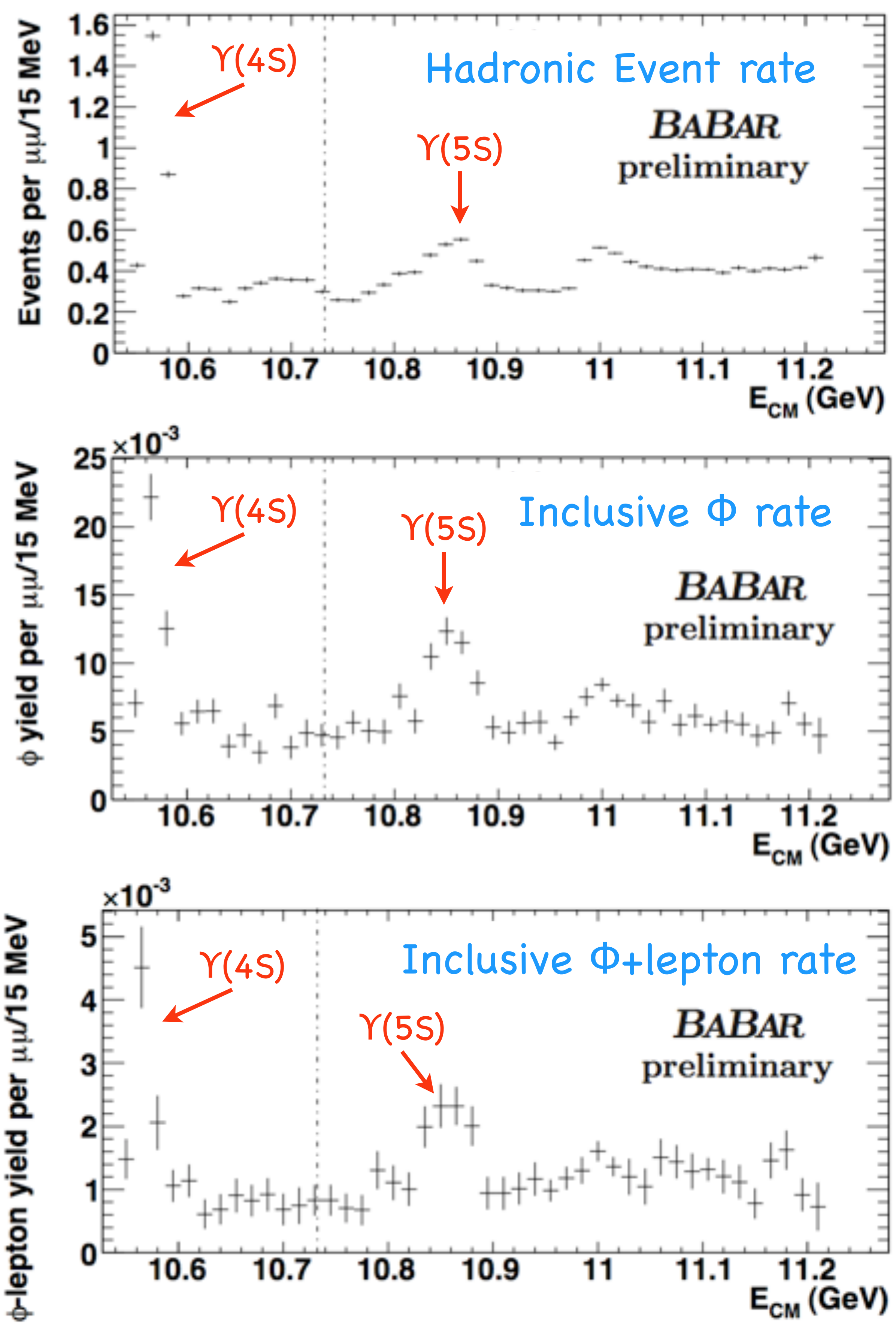


Invariant KK mass in the bin 10.8275 < ECM < 10.8425 GeV

Fit PDF is a Voigt profile for the signal and the product of a linear term and a threshold cutoff function for the combinatorial background

Continuum $e^+e^- \to q\bar{q}$ background is subtracted, bin by bin, using data below Υ(4S) threshold

B_s Semileptonic Branching Fraction



Now we have a measured rate that can be related to the equations showed earlier, noting that unknown quantities can be estimated

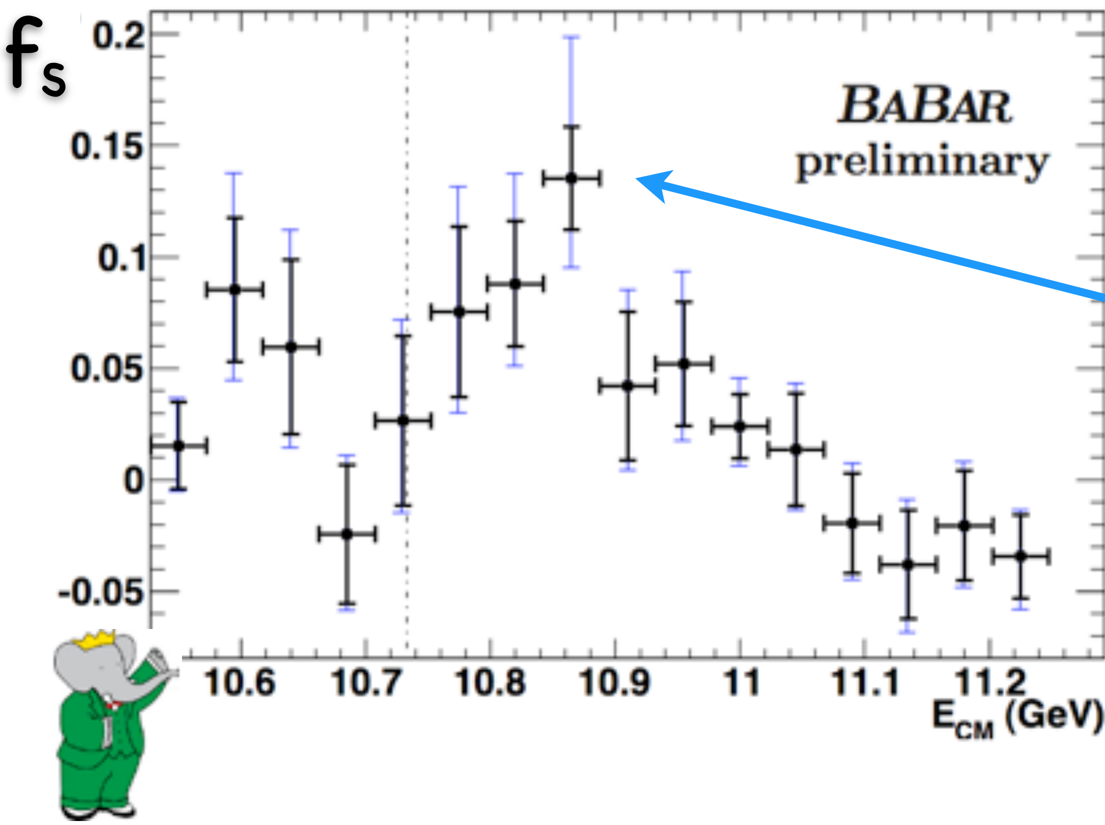
$B_{u/d}$ contributions are measured in data taken at Υ(4S)

f_s is extracted at each energy point from number of events and Φ yield

B_s contributions depend on known quantities, such as:
$BF(B_s \to D_s X)$,
$BF(B_s \to l\nu X)$, $BF(D_s \to l\nu X)$,
$BF(D_s \to \Phi X)$, $B(D_s \to \Phi l\nu Xn)$

Finally, a χ^2 is constructed from measured and expected values of $P(B_s\bar{B}_s \to \Phi l X)$, and minimized with respect to $BF(B_s \to l\nu X)$

B_s Semileptonic Branching Fraction



$$f_s \equiv \frac{N_{B_s}}{N_{B_u} + N_{B_d} + N_{B_s}}$$

B_s production rate compatible with earlier estimates at Υ(5S) peak:

Belle: (19.3 ± 2.9)% PRD 76, 012002 (2007)

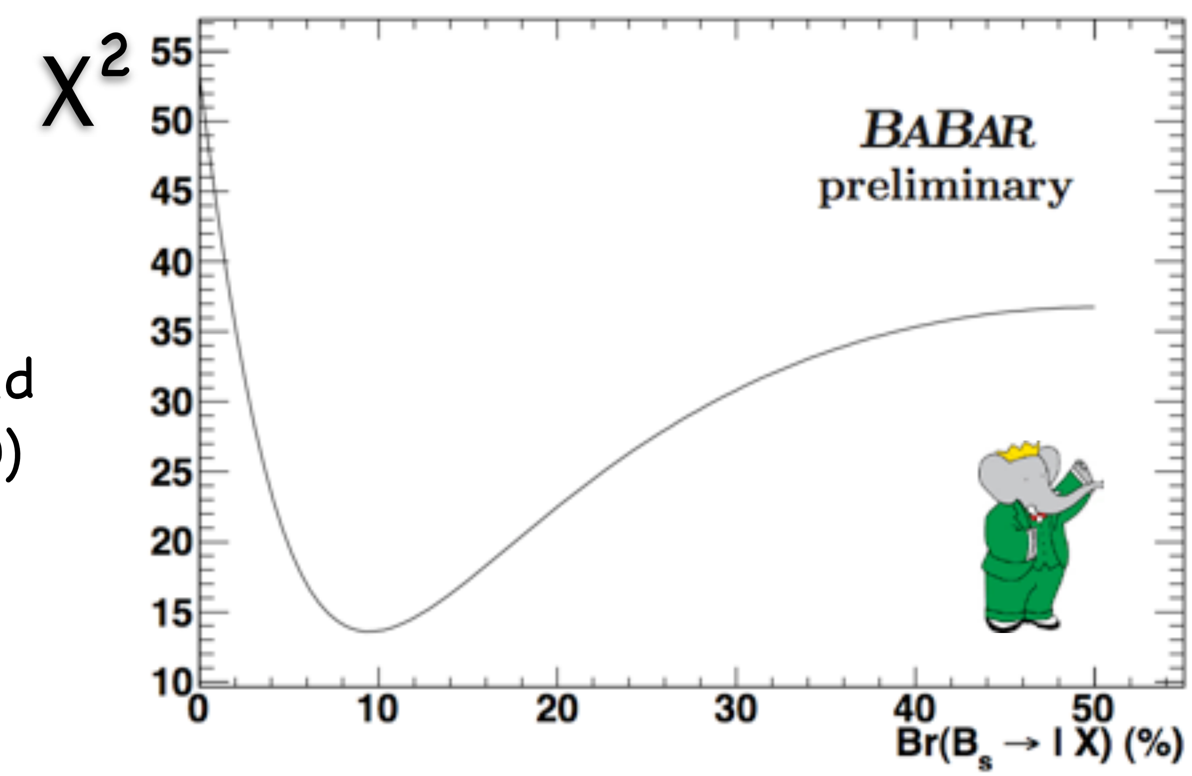
CLEO: $(16.8\pm2.6^{+6.7}_{-3.4})\%$ PRD 75, 012002 (2007)

$$BF(B_s \to l\nu X) = 9.5^{+2.5}_{-2.0}{}^{+1.1}_{-1.9}\ \%$$

Dominant systematic is from inclusive D_s yield per B_s: 0.93 ± 0.25 (Belle and LEP, PDG2010)

arXiv: 1110.5600 [hep-ex]

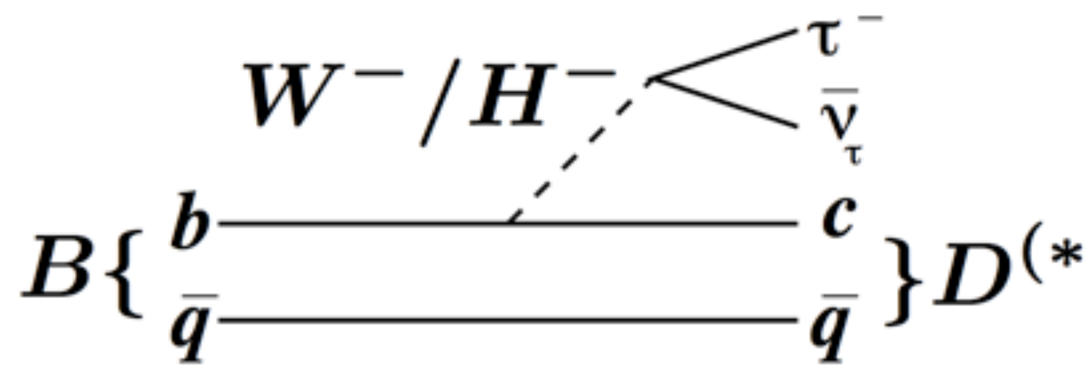
accepted for publication by PRD-RC



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

Semileptonic B decays to τ are not as well known as to e and μ → $D\tau\nu$ measured with 3.8 σ, $D^*\tau\nu$ with 8.1 σ

Their branching fractions can be affected by new physics - the two-doublet model of Higgs sector introduces tree-level interactions with a charged Higgs



A quantity where many theoretical and experimental systematic uncertainties cancel is

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

if $m_b \tan\beta >> m_c$ and $m_H^2 >> q^2$, the rate depends only on:

$$\frac{d\Gamma}{dq^2} = \frac{d\Gamma_{SM}}{dq^2}(1 - m_B^2 \tan^2\beta/m_H^2)^2$$
$$= \frac{d\Gamma_{SM}}{dq^2}(1 - g_s)^2$$

$$g_S = m_B^2 \tan^2\beta/m_H^2$$

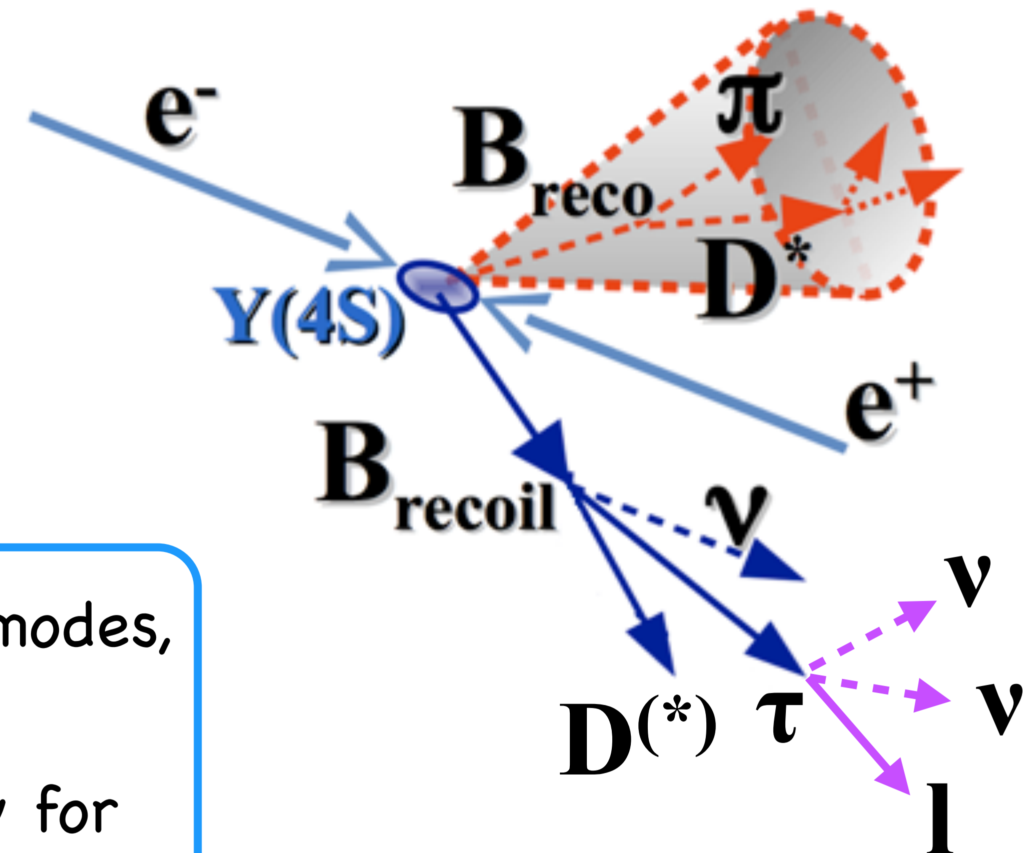
Standard Model predictions:

R(D) = 0.31 ± 0.02 Nierste, Trine, Westhoff (2008)

R(D*) = 0.252 ± 0.013 Chen, Geng (2006)

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

B tagging with full reconstruction of one side in hadronic modes:
$B \to D^{(*)} Y$, $Y = n\pi + m\pi^0 + pK_s + qK$



Requirements on:

$$m_{ES} = \sqrt{E^{*2}_{\rm beam} - p^{*2}_B}$$

$$\Delta E = E^*_B - E_{\rm beam}$$

Signal side: $D^{(*)}$ candidate reconstructed in 11 modes, with $D \to KK$, $D \to K n\pi$ (n=1,2,3)

candidates have e or μ in final state: primary for normalization (1ν), secondary for τ decays (3ν)

no additional particle detected

to discriminate against e, μ from normalization modes:

$$q^2 = (E_{\rm miss} + E_\ell)^2 - (\mathbf{p}_{\rm miss} + \mathbf{p}_\ell)^2$$

Signal region is $q^2 > 4$ GeV^2

$m^2_{\rm miss}$ = invariant mass of missing E and **p**

peaks at 0 for normalization modes, >1 GeV^2 for signal

Boosted Decision Tree (BDT) used to suppress combinatorial, continuum $e^+e^- \to q\bar{q}$ and $B \to D^{**} l \nu$ backgrounds

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

4 main channels: D^0, D^+, D^{*0}, D^{*+}

Unbinned ML fit of m^2_{miss} versus p^*_l distributions

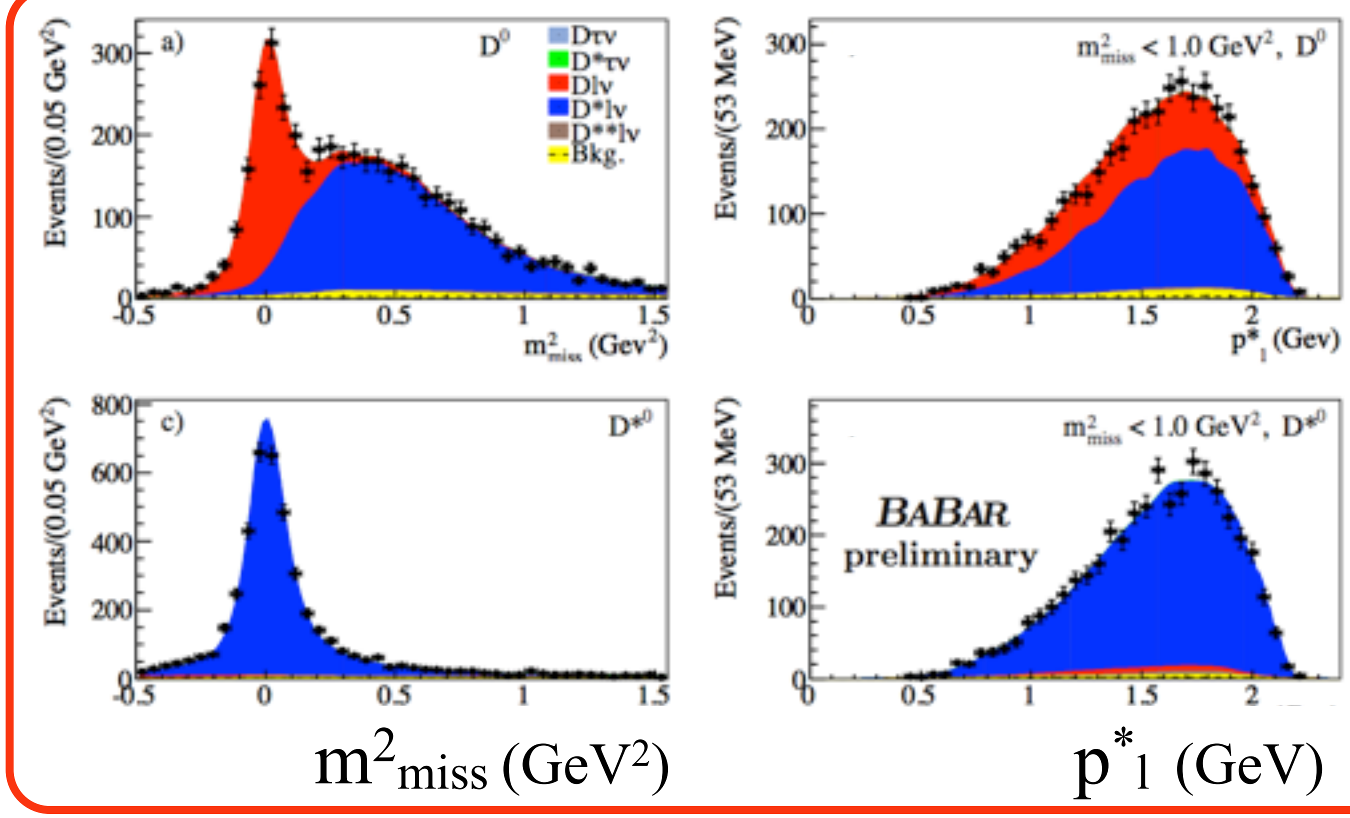
Simultaneous fit to signal and special D^{**}-enriched samples

D^{**}-enriched samples: $B \to D^{(*)}\pi^0 l\nu$, to determine feed-down

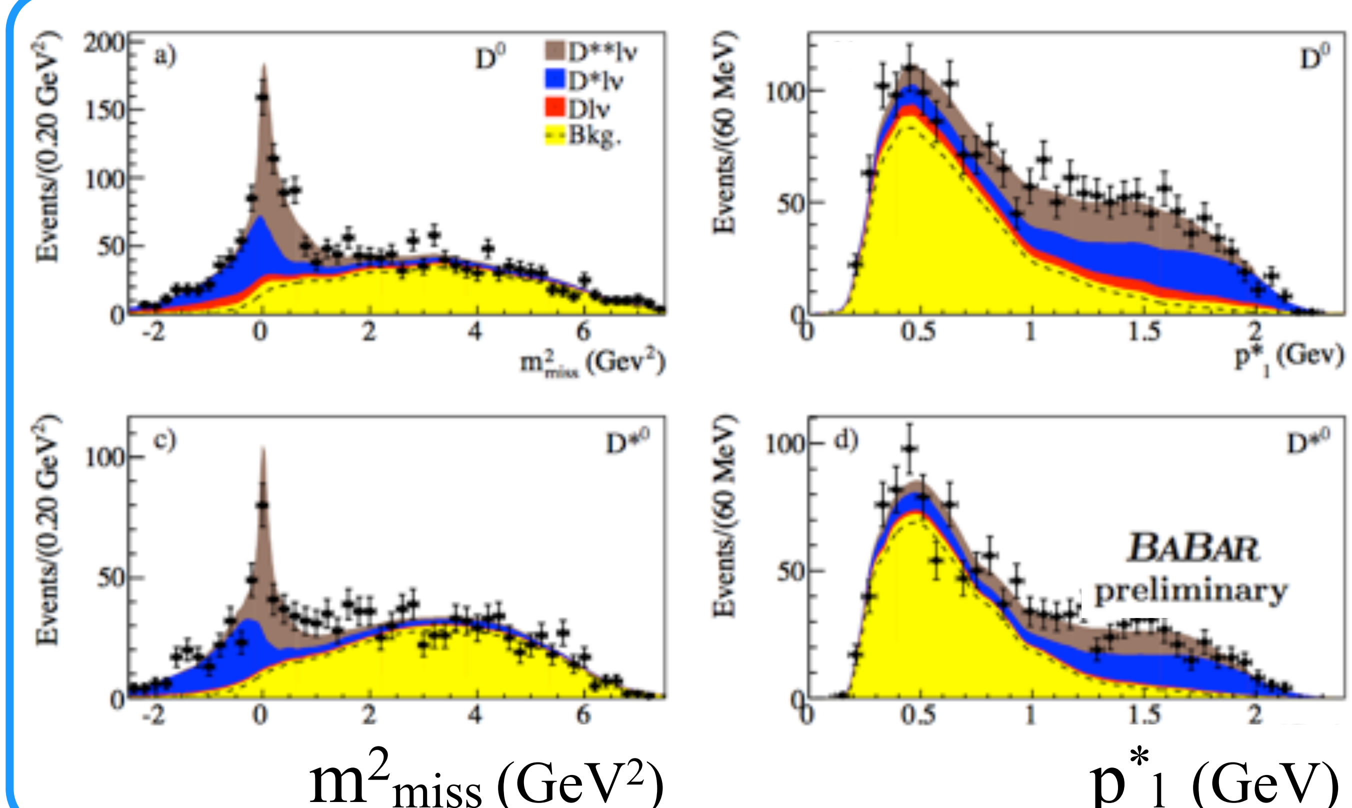
10 parameter fit to 4 signal channels + 12 parameter fit to $D^{(*)}\pi^0$ control channels

Simulation used to fix the relative yields of continuum, B combinatorial and charge cross-feed background

signal samples at low m^2_{miss}

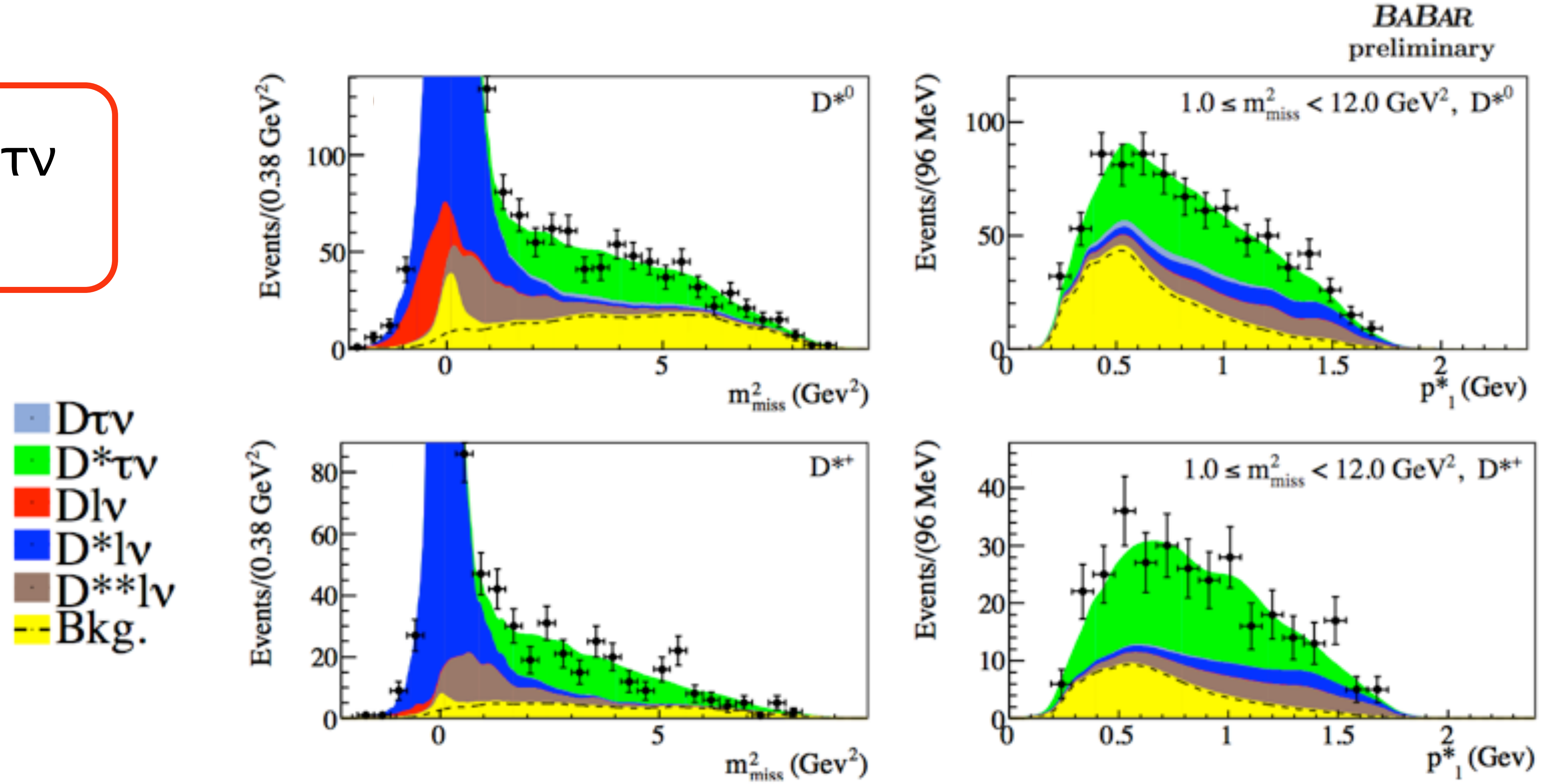


D^{**}-enriched samples



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

Fit to $B \rightarrow D^* \tau \nu$ samples



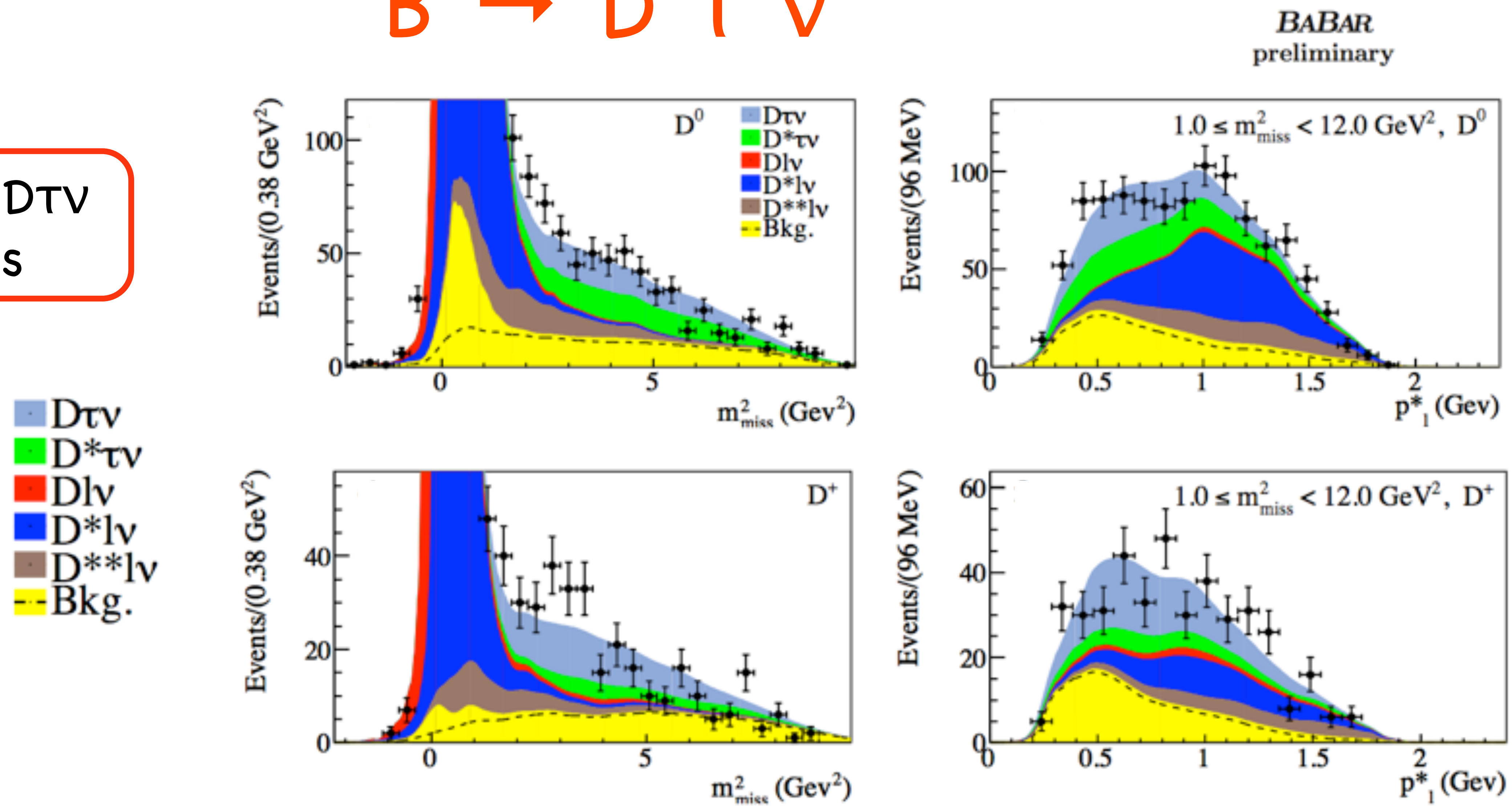
isospin constrained

	D^{*0}	D^{*+}	D^*
N_{sig}	511 ± 48	220 ± 23	730 ± 50
Significance	11.9	12.1	17.1
$R(D^*)$	0.314 ± 0.030	0.356 ± 0.038	0.325 ± 0.023

Both charge modes reconstructed with high significance

$B \to D \tau \nu$

Fit to $B \to D\tau\nu$ samples



isospin constrained

	D^0	D^+	D
N_{sig}	226 ± 39	139 ± 21	368 ± 42
Significance	6.2	7.5	9.6
R(D)	0.422 ± 0.074	0.513 ± 0.081	0.456 ± 0.053

first >5σ observation

Background overestimation for m^2_{miss} > 5 GeV^2

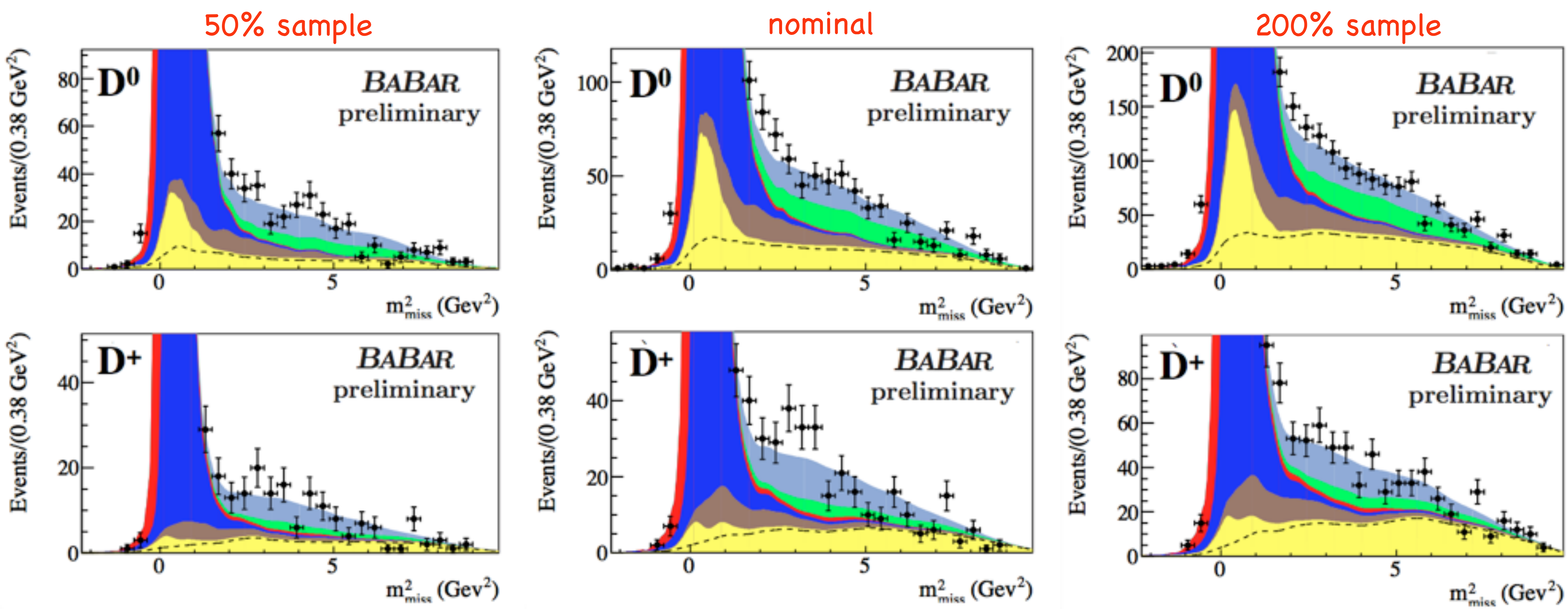
$B \rightarrow D^{(*)} \tau \nu$

Systematic uncertainties:

Currently, the variation of BDT cut dominates

Tight BDT cut: 50% of nominal sample
Loose BDT cut: 200% of nominal sample

→ $R(D^{(*)})$ changes due to statistical and systematic effects

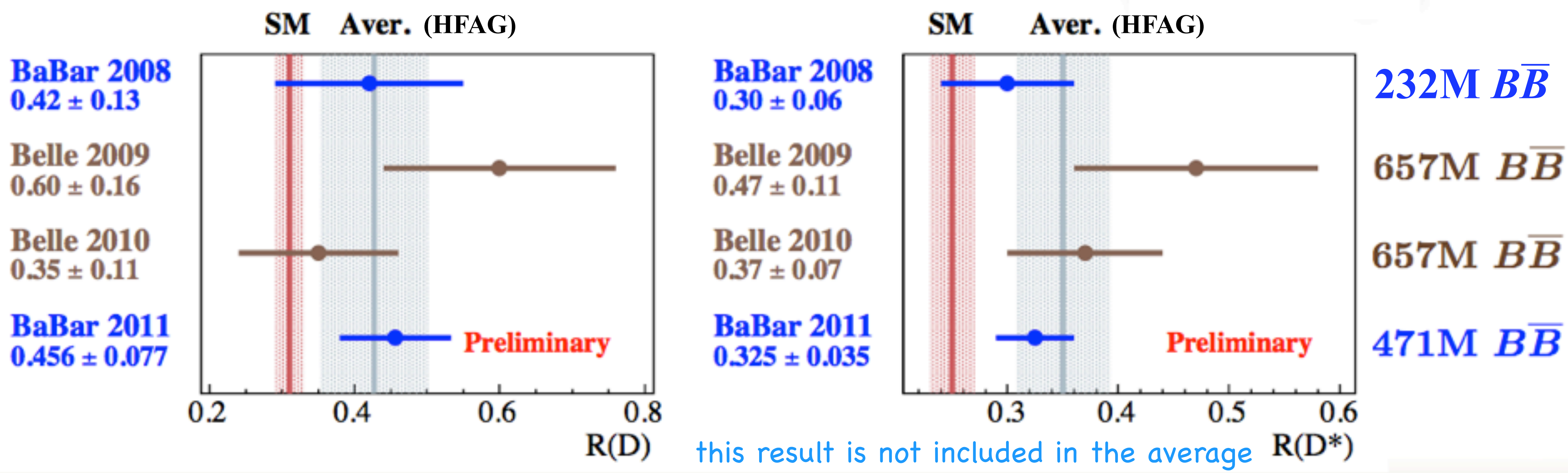


Assign half of the variation as uncertainty:
9.5% for R(D) and 6.5% for R(D*)

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

Mode	N_{sig}	N_{norm}	$\varepsilon_{\text{sig}}/\varepsilon_{\text{norm}}$	$\mathcal{R}(D^{(*)})$	$\mathcal{B}(B \to D^{(*)}\tau\nu)$ (%)	Σ_{tot} (Σ_{stat})
$D^0\tau^-\overline{\nu}_\tau$	226 ± 39	1433 ± 46	2.13 ± 0.06	$0.422 \pm 0.074 \pm 0.059$	$0.96 \pm 0.17 \pm 0.14$	5.0 (6.2)
$D^{*0}\tau^-\overline{\nu}_\tau$	511 ± 48	6839 ± 90	1.36 ± 0.02	$0.314 \pm 0.030 \pm 0.028$	$1.73 \pm 0.17 \pm 0.18$	8.9 (11.9)
$D^+\tau^-\overline{\nu}_\tau$	139 ± 21	704 ± 29	2.19 ± 0.08	$0.513 \pm 0.081 \pm 0.067$	$1.08 \pm 0.19 \pm 0.15$	6.0 (7.5)
$D^{*+}\tau^-\overline{\nu}_\tau$	220 ± 23	2802 ± 56	1.25 ± 0.03	$0.356 \pm 0.038 \pm 0.032$	$1.82 \pm 0.19 \pm 0.17$	9.5 (12.1)
$D\tau^-\overline{\nu}_\tau$	368 ± 42	2140 ± 54	2.15 ± 0.05	$0.456 \pm 0.053 \pm 0.056$	$1.04 \pm 0.12 \pm 0.14$	6.9 (9.6)
$D^*\tau^-\overline{\nu}_\tau$	730 ± 50	9639 ± 107	1.33 ± 0.07	$0.325 \pm 0.023 \pm 0.027$	$1.79 \pm 0.13 \pm 0.17$	11.3 (17.1)

isospin constrained



Full consistency with earlier BaBar results

all channels observed at >5σ significance

1.8 σ deviation from SM

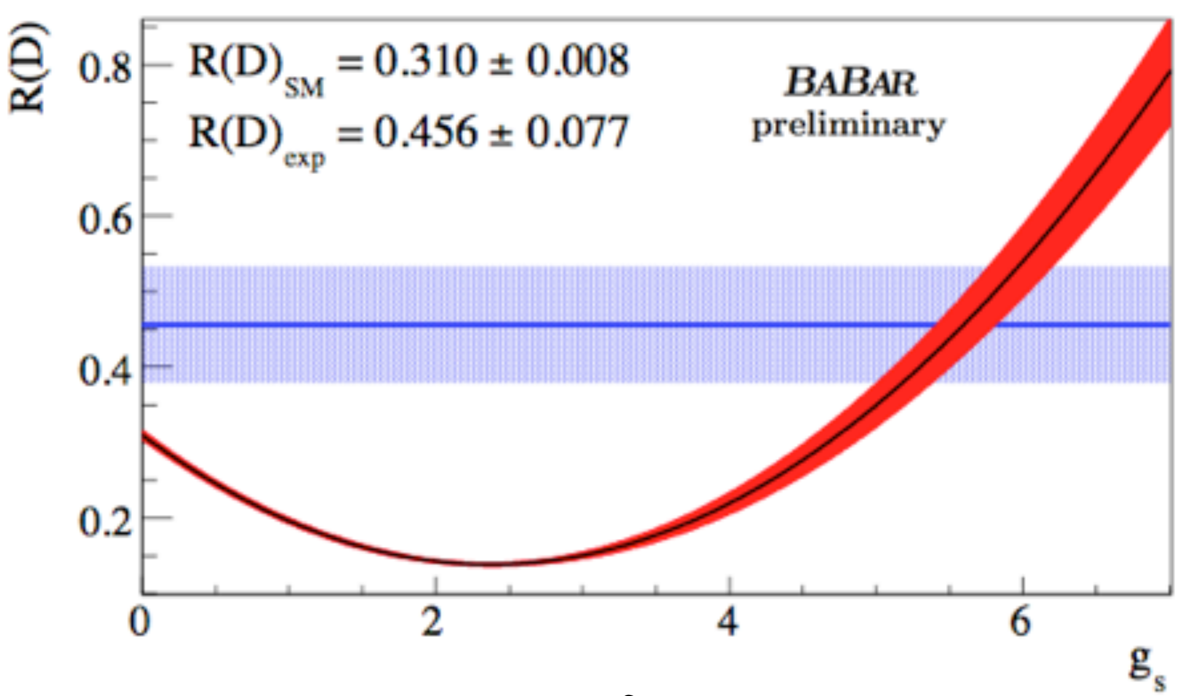
$B \to D^{(*)} \tau \nu$

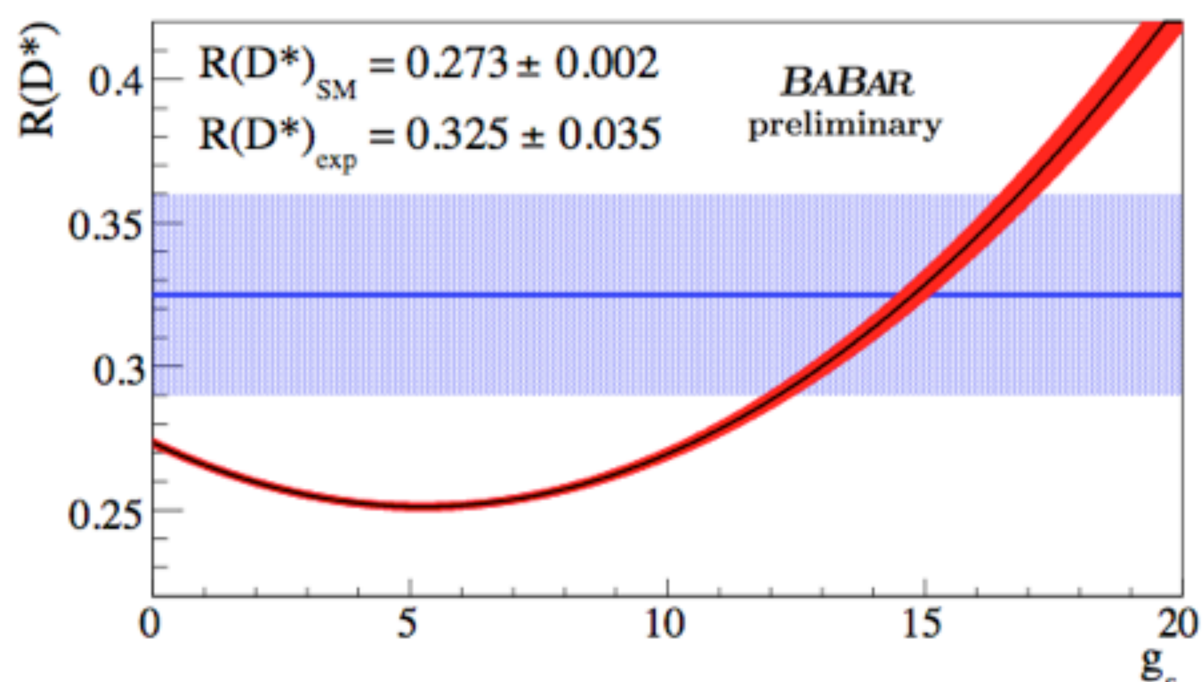
SM prediction obtained with old measurements of Form Factors → Recalculate it using the latest measurements (HFAG, PDG 2010)

ρ^2_D = 1.18 ± 0.06, $\rho^2_{D^*}$ = 1.20 ± 0.05, R_1 = 1.43 ± 0.06, R_2 = 0.82 ± 0.04
m_c/m_b = 0.30 ± 0.02

	$R(D)_{SM}$	$R(D^*)_{SM}$
Hwang, Kim (2000)	0.278 ± 0.042	0.256 ± 0.014
Chen, Geng (2006)	0.301 ± 0.017	0.252 ± 0.013
Nierste, Trine, Westhoff (2008)	0.31 ± 0.02	-
Tanaka, Watanabe (2010)	0.302 ± 0.015	-
Our prediction (after Tanaka, Chen)	**0.310 ± 0.008**	**0.273 ± 0.002**

$$g_S = m_B^2 \tan^2\beta / m_H^2$$





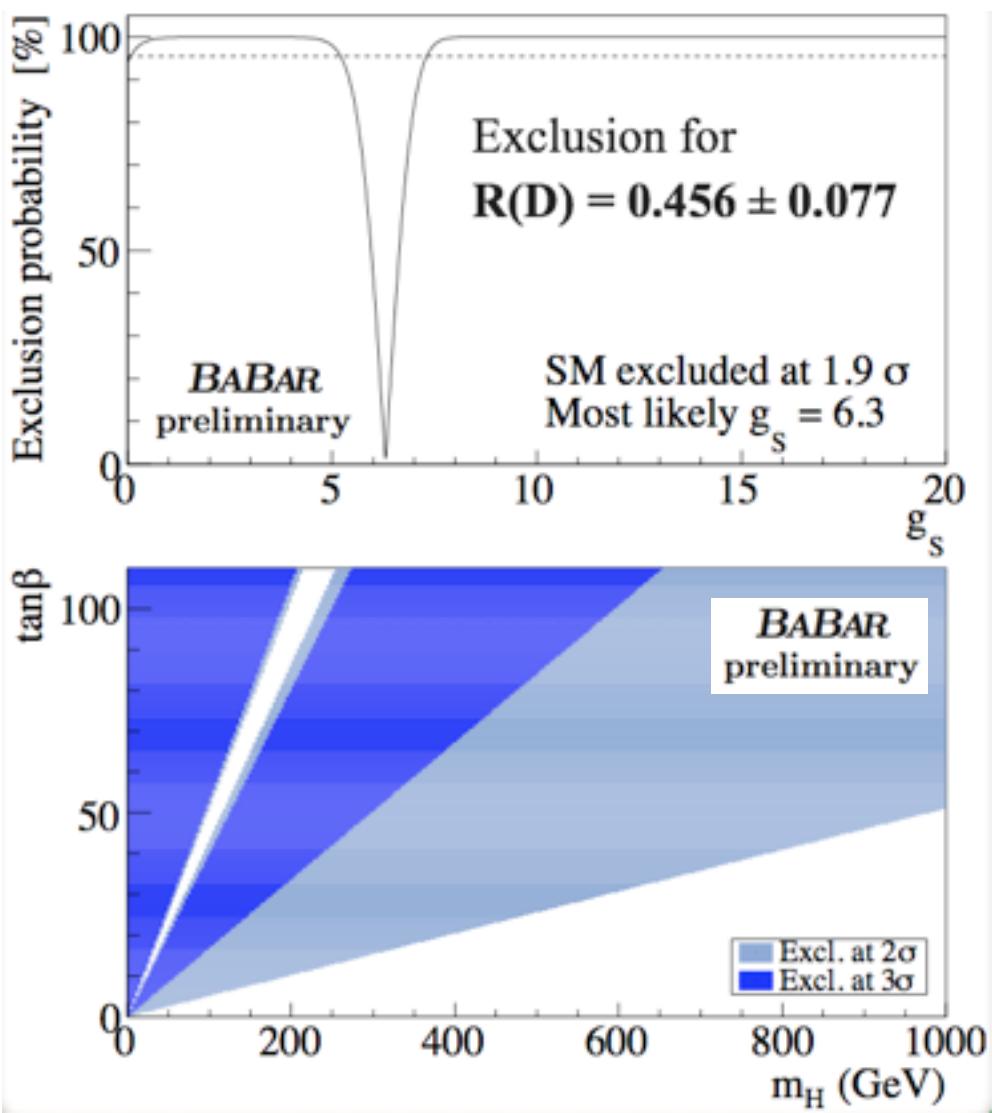
Uncertainties found varying these parameters, and taking RMS of ensemble for each g_s

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

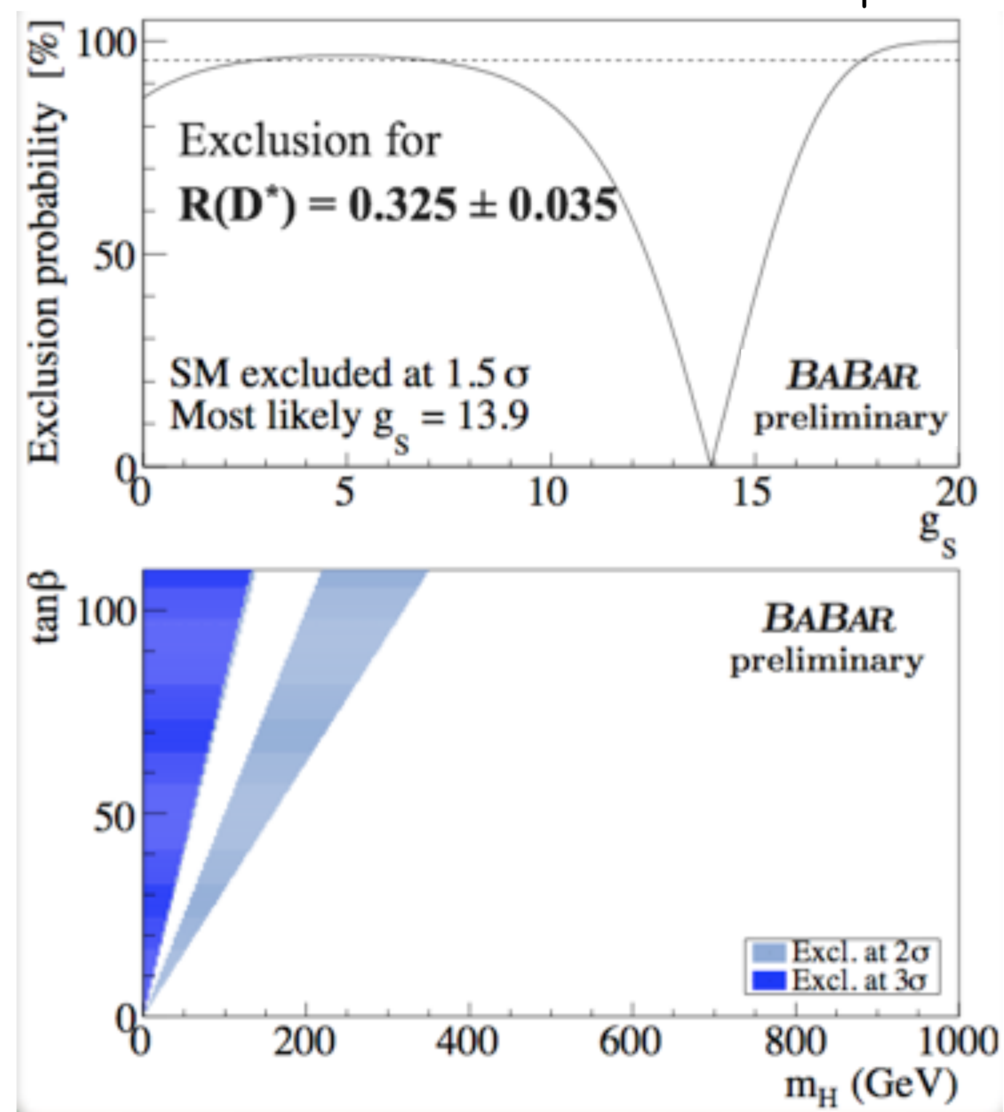
We find the compatibility of our measurements with the charged Higgs model combining the results in a χ^2

R(D), R(D*) compatible with SM at ~2σ

g_s values incompatible between R(D) and R(D*)



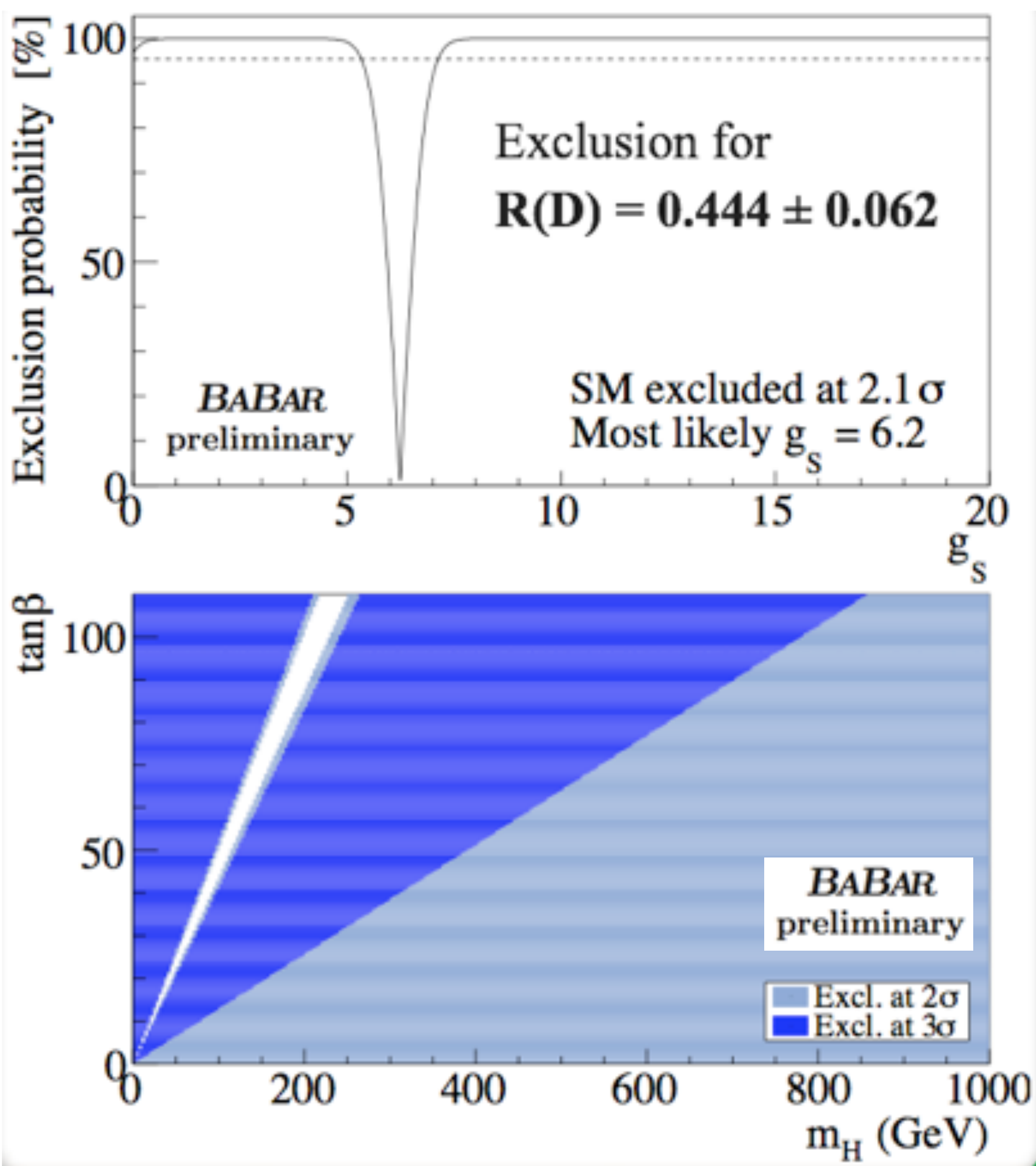
dashed line: 2σ exclusion probability

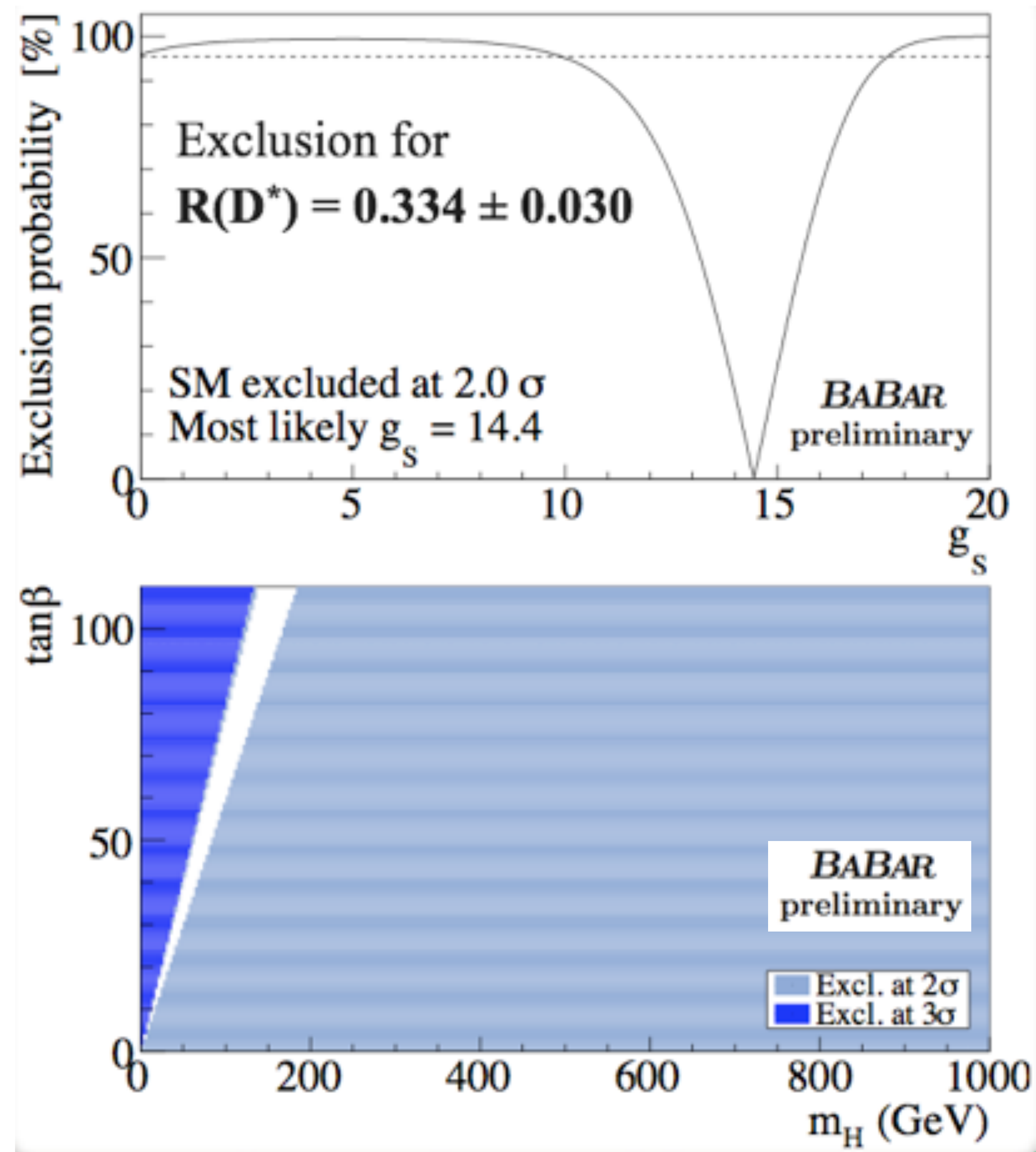


$B \to D^{(*)} \tau \nu$

Very similar results are obtained if we combine measurements from Belle and BaBar

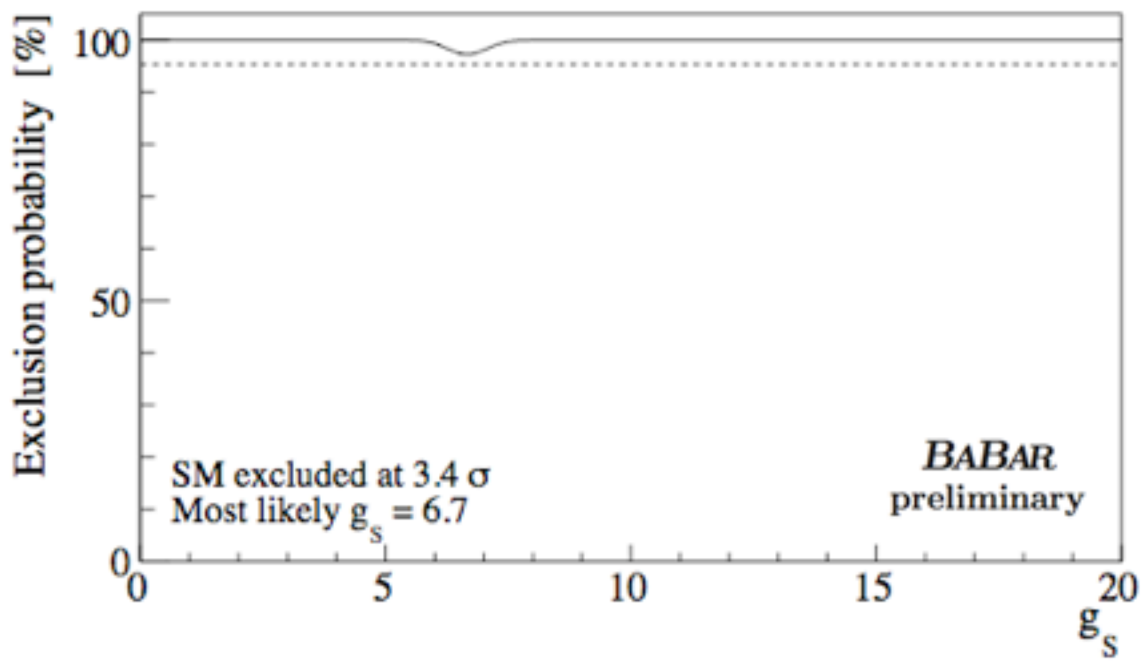
Belle: R(D) = 0.422 ± 0.095, R(D*) = 0.397 ± 0.056

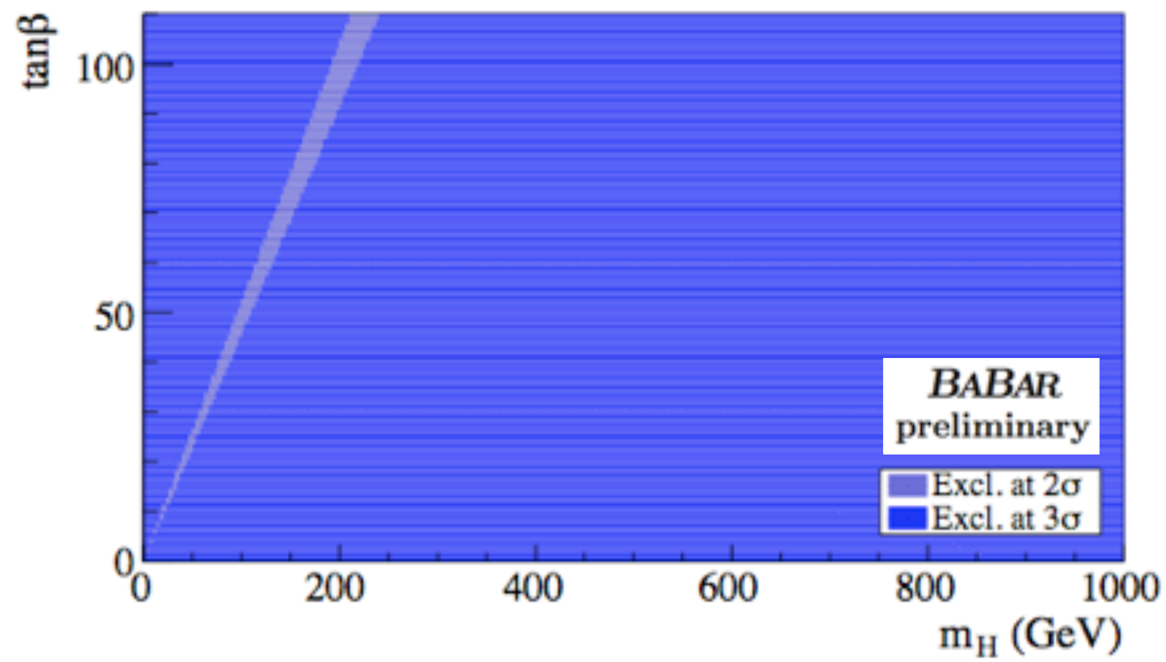




$B \to D^{(*)} \tau \nu$

Check compatibility between R(D) and R(D*), taking correlations into account: the possibility of both results agreeing with SM predictions is excluded at 3.4σ





The two-doublet model of Higgs sector is excluded at 96% level

Conclusions

BaBar continues to probe the SM with the wealth of data available

$|V_{ub}|$ and $|V_{cb}|$ values from inclusive and exclusive measurements are marginally consistent with each other

BaBar has measured the production rate and semileptonic branching fraction of B_s mesons

BaBar has updated its $B \to D^{(*)}\tau\nu$ measurement, with the first observation of $B \to D\tau\nu$ with a significance $>5\sigma$

The results show a 2σ excess over SM, and are not compatible with two-doublet Higgs model