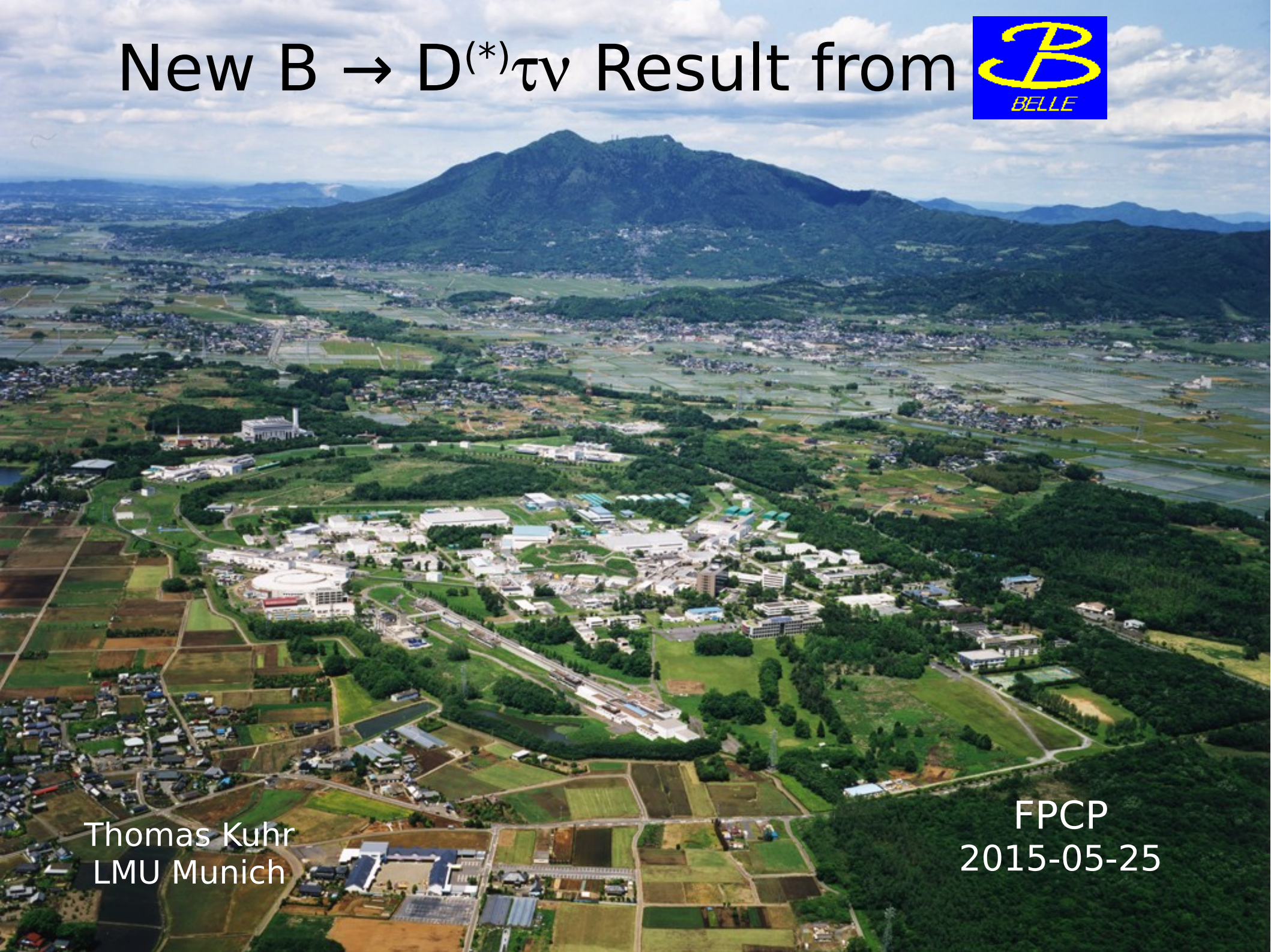
# New B → $D^{(*)}\tau\nu$ Result from

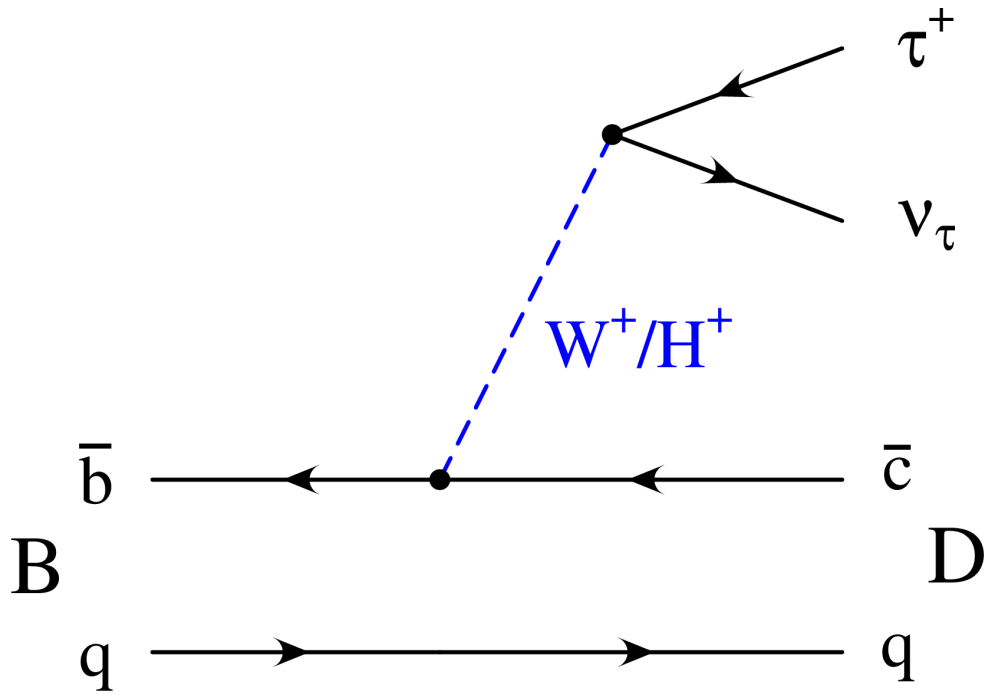


Thomas Kuhr
LMU Munich

FPCP
2015-05-25

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

- Process with third generation quarks and leptons




- New Physics (NP) could change:
  - Branching fraction
  - Tau polarization
- → Effect could be different for D and $D^*$
- *$3.4\sigma$ deviation from SM observed by BaBar, 2HDM type II excluded*

→ Experimental challenge:
2 (hadronic tau decay) or 3 (leptonic tau decay) undetected neutrinos

# Aim

- Measurement of branching ratio relative to corresponding decay to light leptons:

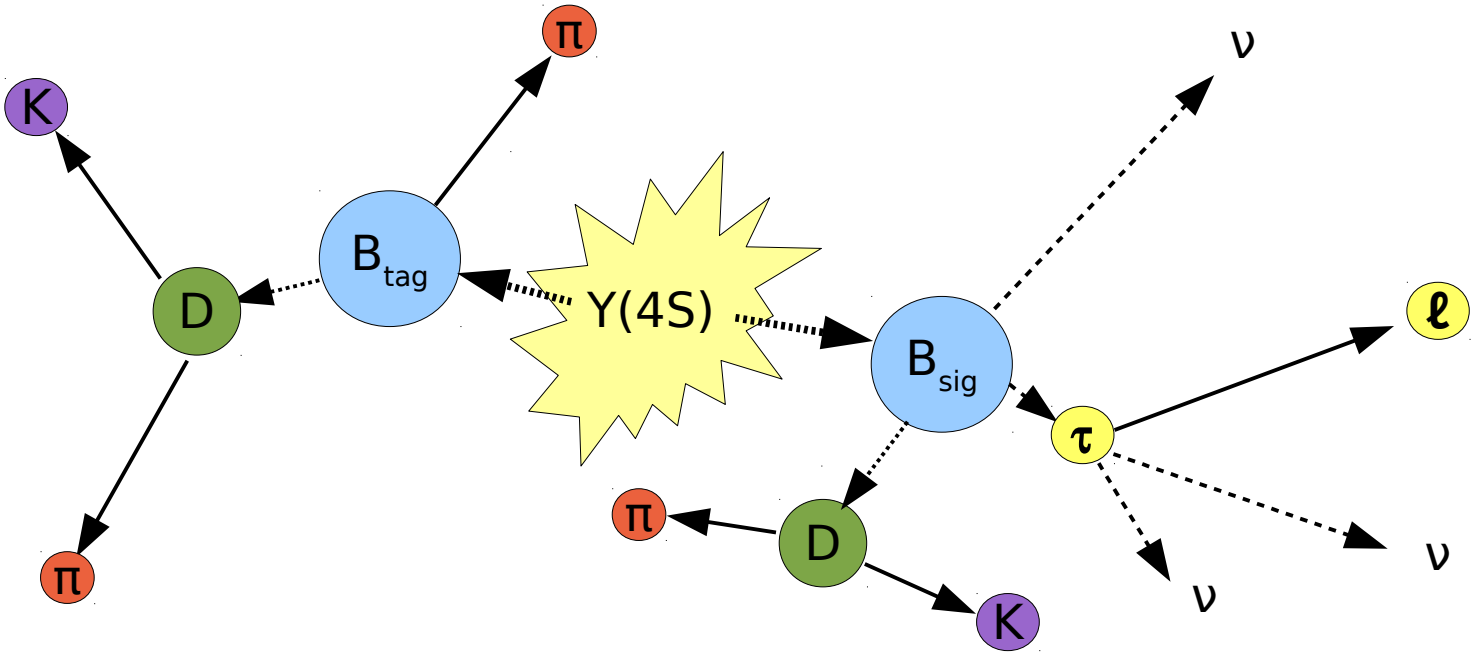
$$R = \frac{\mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D\ell^-\bar{\nu}_\ell)} \qquad R^* = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)}$$

$\ell^-$ = $e^-$ or $\mu^-$

- Reconstruction of leptonic tau decays ($\tau^- \to \ell^-\nu\nu$)
- → Same detectable final state particles of signal and normalization mode
- → Reduction of systematic uncertainties
- → Signal and normalization mode have to be distinguished experimentally

# Tagging

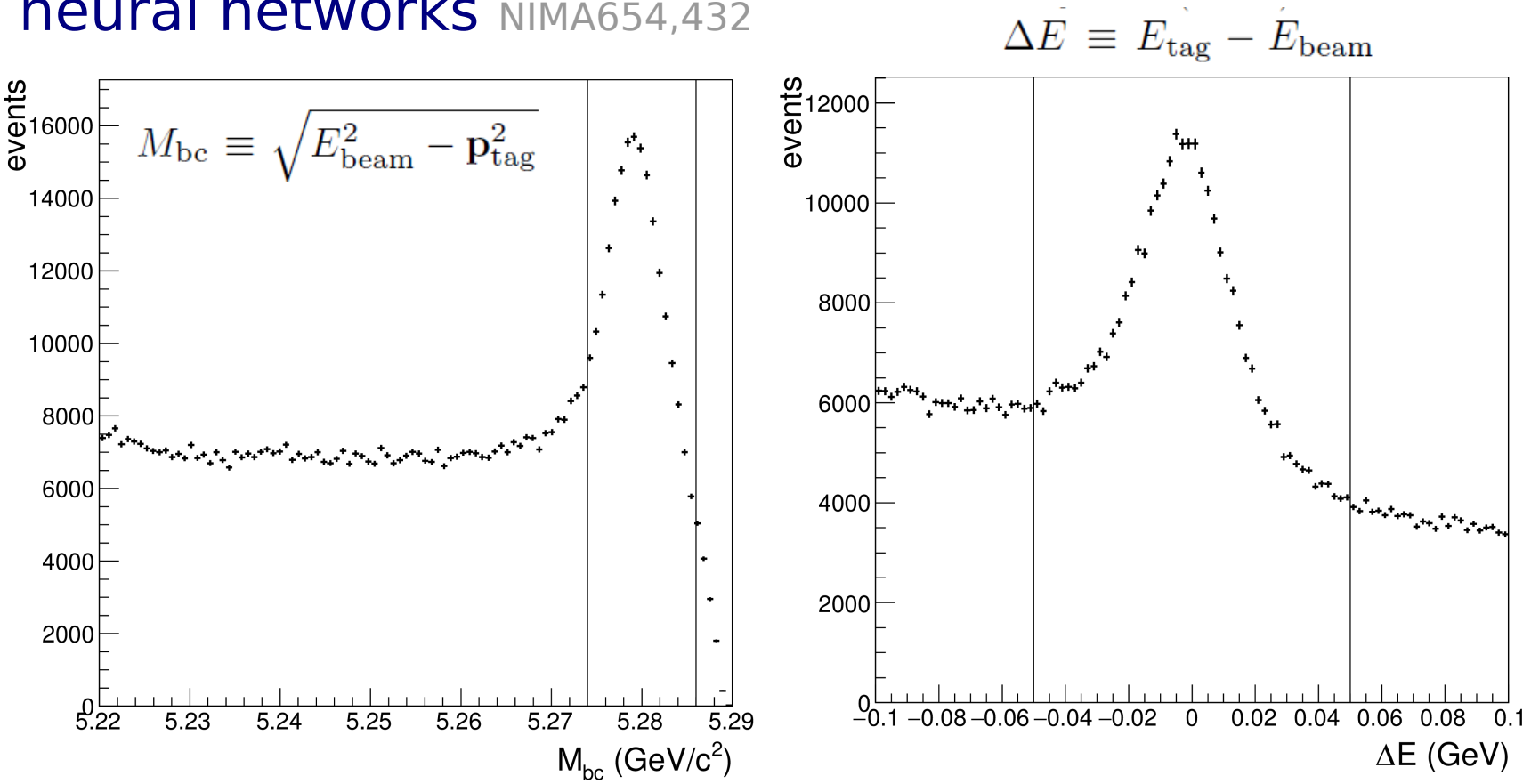
- Exploit fact that a $B\bar{B}$ pair and nothing else is produced in $e^+e^- \rightarrow \Upsilon(4S)$ events at B factories




- ✔ Tag B determines charge and momentum of signal B
- ✔ All remaining particles must come from signal B
- Not possible at hadron colliders

# $B_{tag}$ Reconstruction

- Hierarchical $B_{tag}$ reconstruction of 1149 channels with neural networks NIMA654,432




- Cuts on $B_{tag}$ quality including Fox-Wolfram moments

# Signal Reconstruction

- Four $D^{(*)}\ell^-$ ($\ell^- = e^-$ or $\mu^-$) samples:
  - $D^+ \to K^-\pi^+\pi^+$, $K^0_S\pi^+$, $K^0_S\pi^+\pi^0$, $K^0_S\pi^+\pi^+\pi^-$
  - $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$, $K^-\pi^+\pi^0$, $K^0_S\pi^0$
  - $D^{*+} \to D^0\pi^+$, $D^+\pi^0$
  - $D^{*0} \to D^0\pi^0$, $D^0\gamma$
- Track selection: dr < 2 cm, |dz| < 4 cm
- Lepton ID requirement with 95/92% efficiency for e/μ
- Standard selection of $K^0_S \to \pi^+\pi^-$
- Photon selection: isolated cluster with E > 50 MeV
- $\pi^0 \to \gamma\gamma$ selection: $E_\gamma$ > 80 MeV in endcaps,
  $p^*(\pi^0)$ > 200 MeV (except $\pi^0$ from $D^*$), mass pull $|S_{\gamma\gamma}| < 3.0$

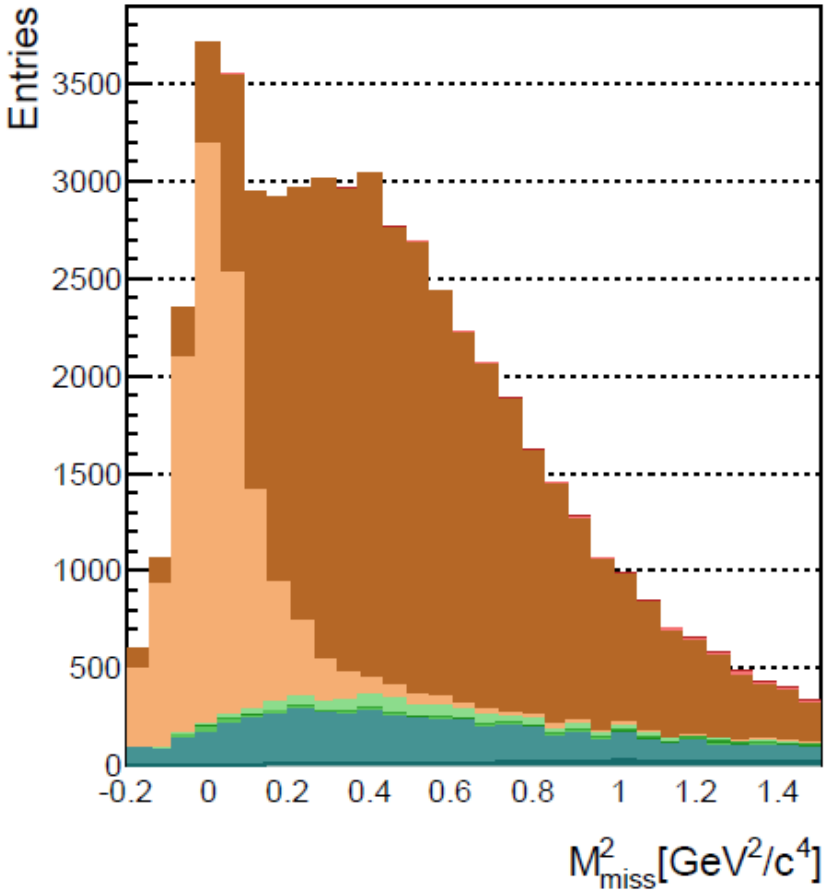
# Signal Selection

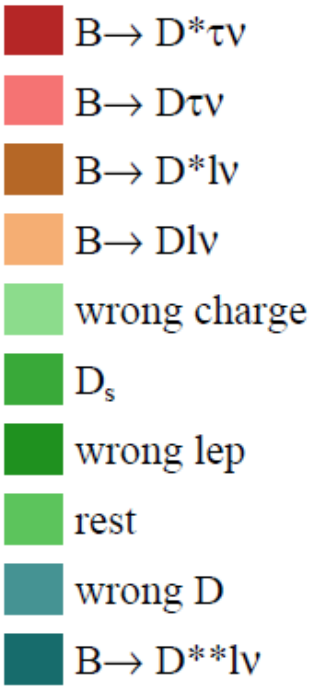
- $p(D^{(*)}) < 3$ GeV/c
- Channel-dependent D mass / $D^*$-D mass difference cut at ±1.5 σ
- No overlap between $B_{tag}$ and $B_{sig}$
- Zero charge of $B_{tag}$ + $B_{sig}$
- No further tracks
- No further $\pi^0$ (with $E_\gamma$ > 50/100/150 MeV in barrel/forward/backward region)

$$M^2_{\text{miss}} = (p_{\text{beam}} - p_{B_{\text{tag}}} - p_{D^{(*)}} - p_\ell)^2 \qquad q^2 \equiv (p_B - p_{D^{(*)}})^2$$

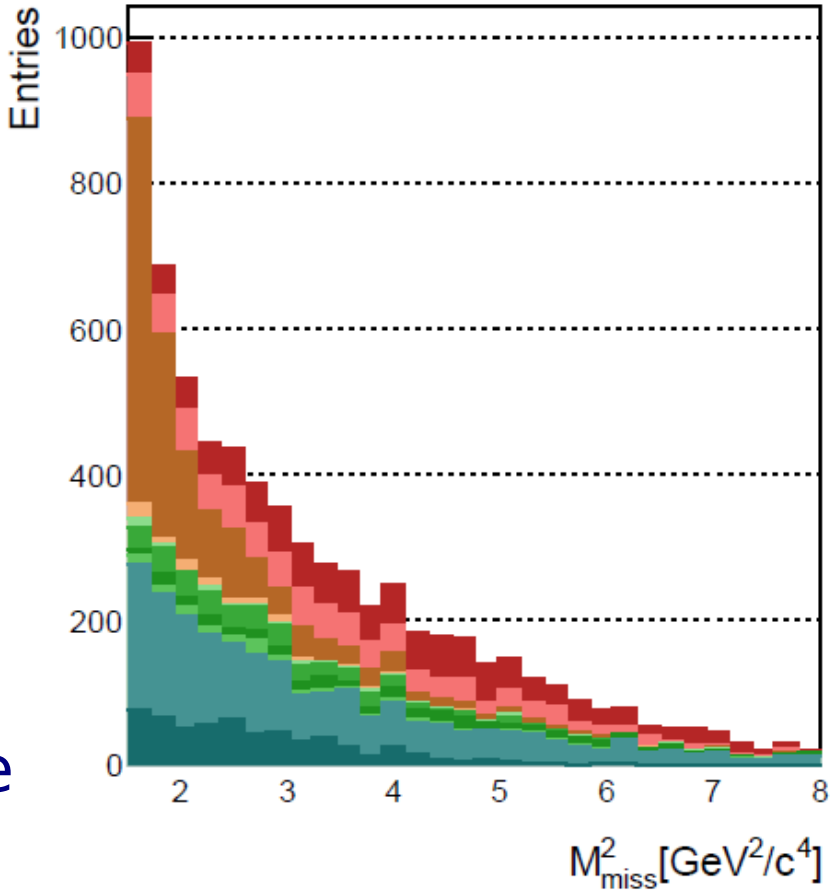
- $-0.2 < M^2_{miss} < 8.0$ GeV$^2$/c$^4$
- $q^2 > 4$ GeV$^2$/c$^2$

# Data Composition

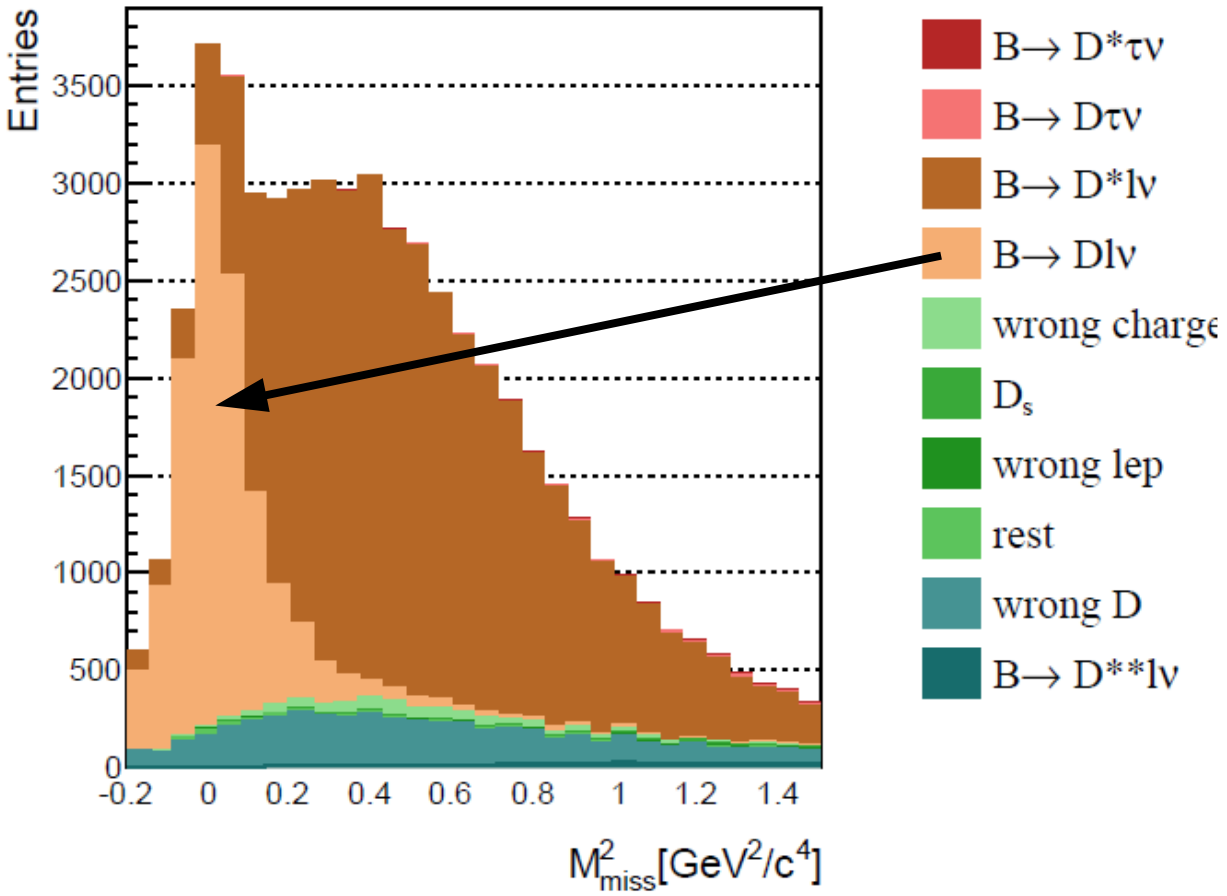



$D^0\ell^-$ sample

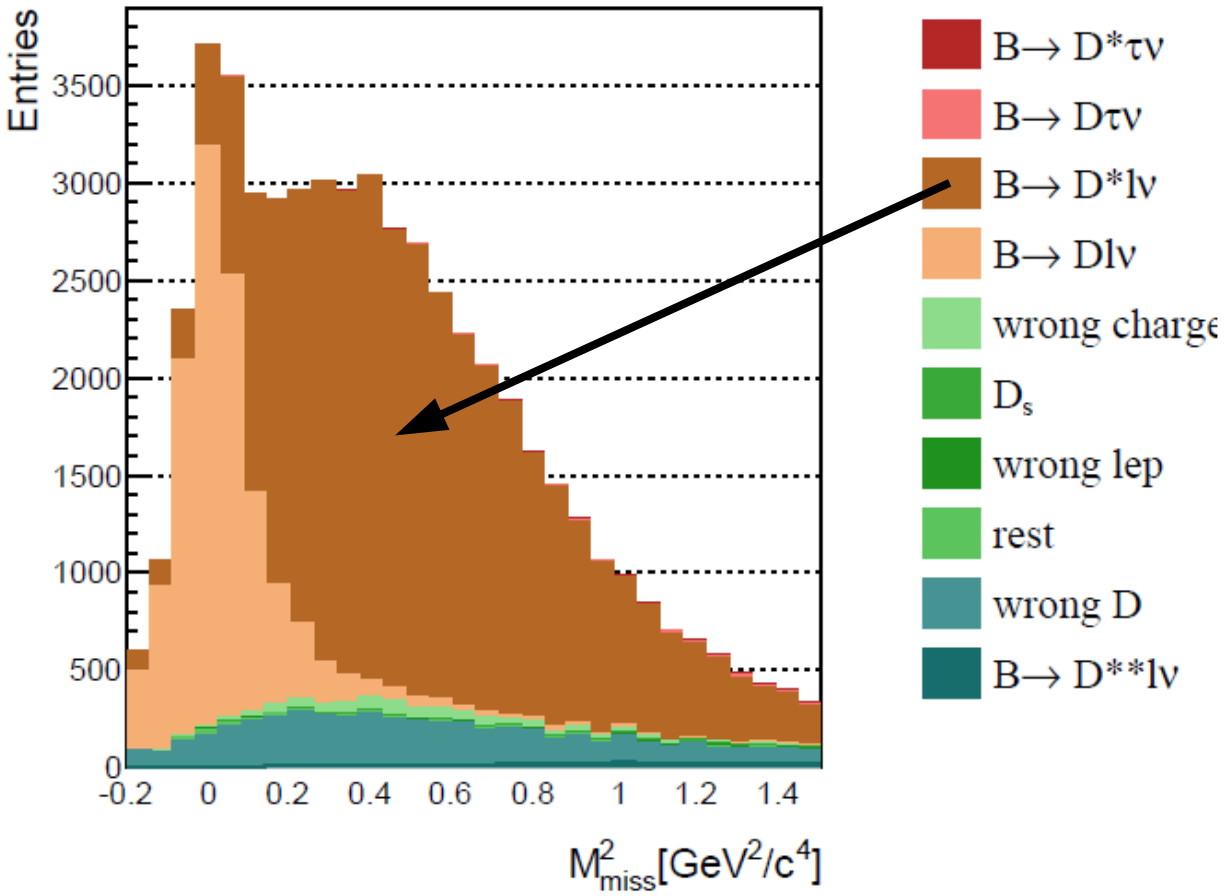


# Lepton Signal




- Correctly reconstructed normalization mode decay $B \to D^{(*)}\ell\nu$
- Only one missing neutrino
- → $M^2_{miss}$ peaks at 0
- Well distinguishable from other components
- → Yield is free parameter in the fit

# Lepton Cross-Feed



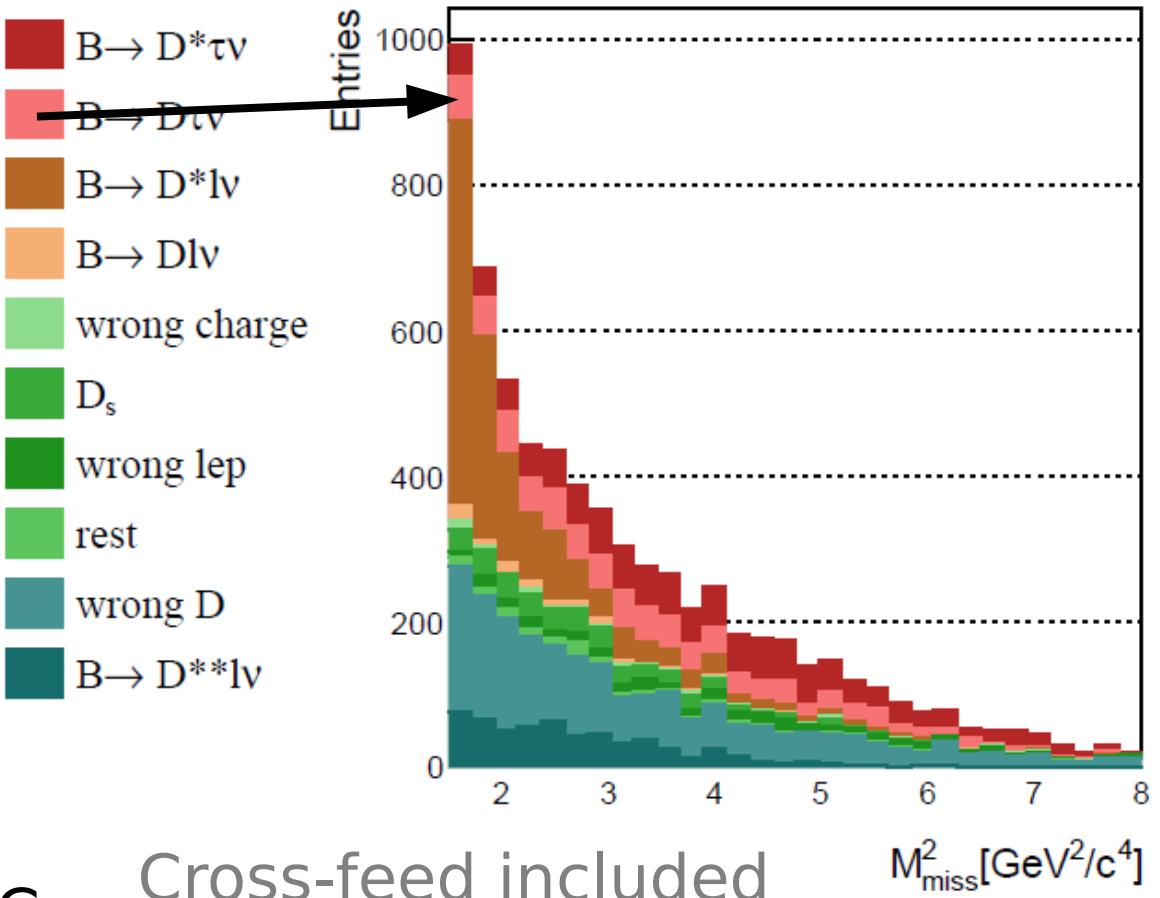

- ➢ $B \to D^* \ell^- \nu$ reconstructed as $B \to D \ell^- \nu$ ($\pi^0$ or $\gamma$ missed)
- Two missing particles
- ➔ $M^2_{miss}$ shifted to higher values and broader
- Still distinguishable from other components
- ➔ Yield is free parameter in the fit

# Tau Signal

- Correctly reconstructed $B \to D\tau^-\nu$, $\tau^- \to \ell^-\nu\nu$
- Three missing neutrinos
- → $M^2_{miss}$ broad
- → Yield given by free parameter R:

$$Y^{D^{+/0}\ell^-}_{\tau\,\mathrm{signal}} = R \cdot Y^{D^{+/0}\ell^-}_{\ell\,\mathrm{signal}} / (2 f_R^{+/0})$$

- Efficiency ratios
  $f_R^+ = 1.69 \pm 0.09$,
  $f_R^0 = 1.91 \pm 0.06$ from MC



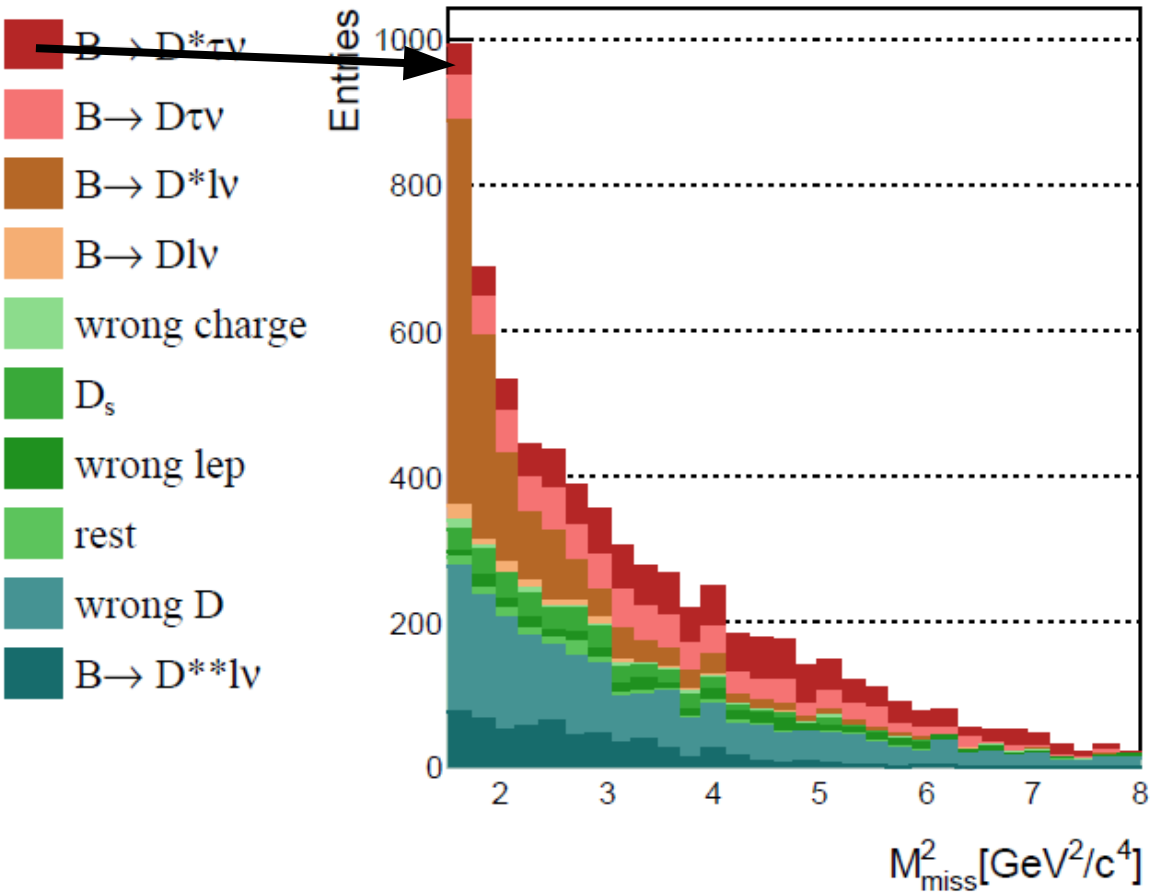

Cross-feed included in tau signal yield for $B \to D^*\tau^-\nu$

# Tau Cross-Feed

- $B \to D^{*}\tau^{-}\nu$ reconstructed as $B \to D\tau^{-}\nu$ ($\pi^0$ or $\gamma$ missed)
- Four missing particles
- → $M^2_{miss}$ similar to tau signal
- → Yield constrained:

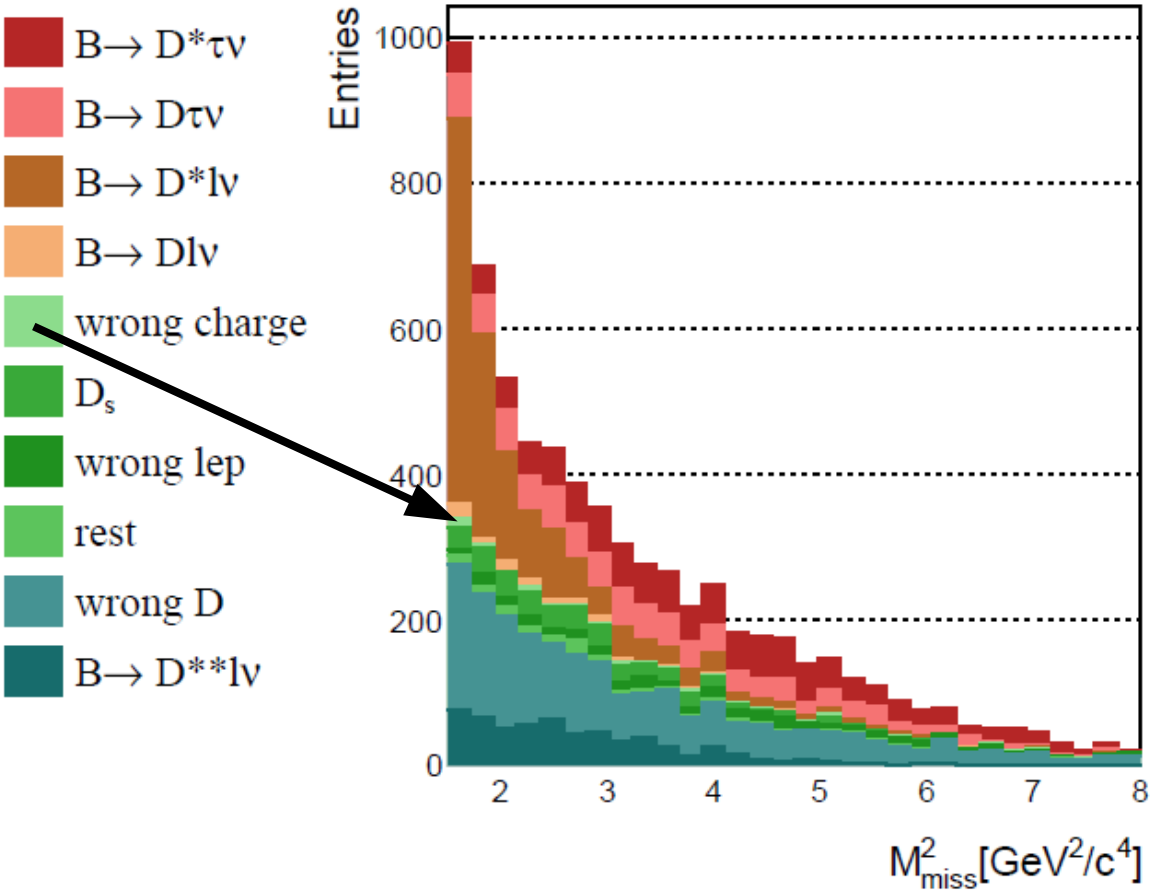
$$Y^{D^{+/0}\ell^-}_{\tau\,\mathrm{CF}} = Y^{D^{*+/0}\ell^-}_{\tau\,\mathrm{signal}} \cdot \frac{Y^{D^{+/0}\ell^-}_{\ell\,\mathrm{CF}}}{Y^{D^{+/0}\ell^-}_{\ell\,\mathrm{signal}}} \cdot \frac{1}{g^{0/+}}$$

- Efficiency ratios $g^{+} = 0.89 \pm 0.08$, $g^{0} = 0.69 \pm 0.04$ from MC



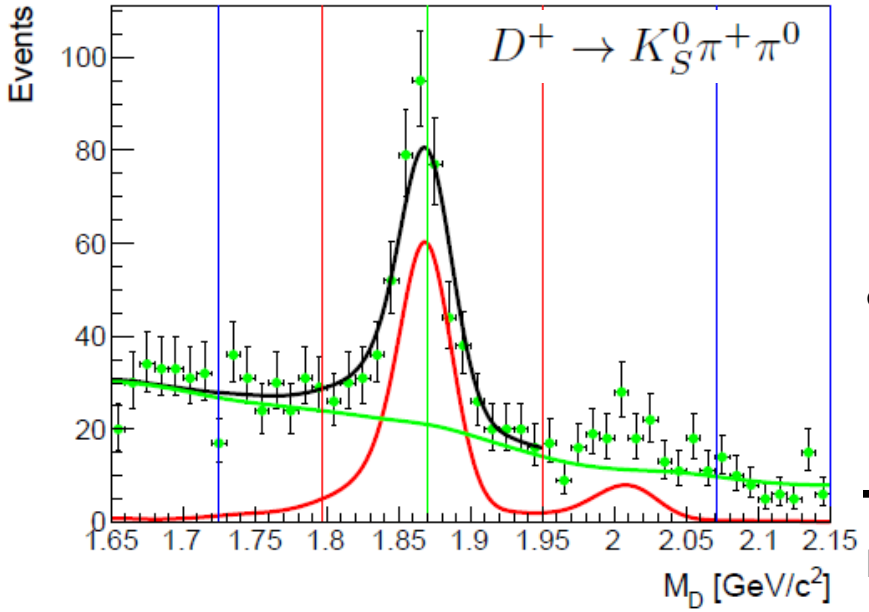
# Wrong-Charge Cross-Feed

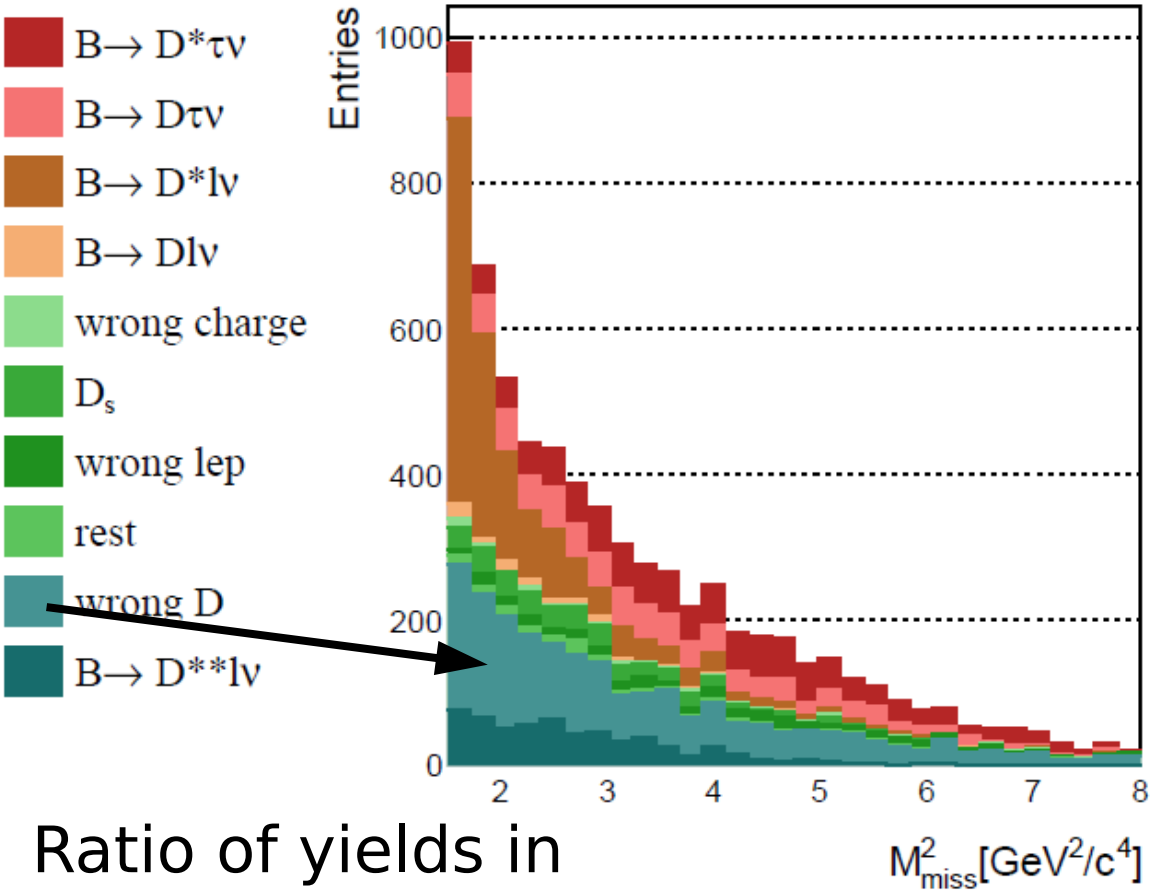
- $B^0 \to D^{*+}\ell^-\nu$ reconstructed as $B^- \to D^0\ell^-\nu$ ($\pi^+$ missed)
- Only in $D^0\ell^-$ sample
- → $M^2_{miss}$ similar to lepton cross-feed
- → Yield constrained relative to $D^{*+}\ell^-$ lepton signal
- Efficiency ratio $f_{wc} = 0.107 \pm 0.004$ from MC



# Wrong $D^{(*)}$ Mesons

- Combinatorial $D^{(*)}$ background
- $M^2_{miss}$ broad
- → Yield determined from mass (difference) sidebands in data

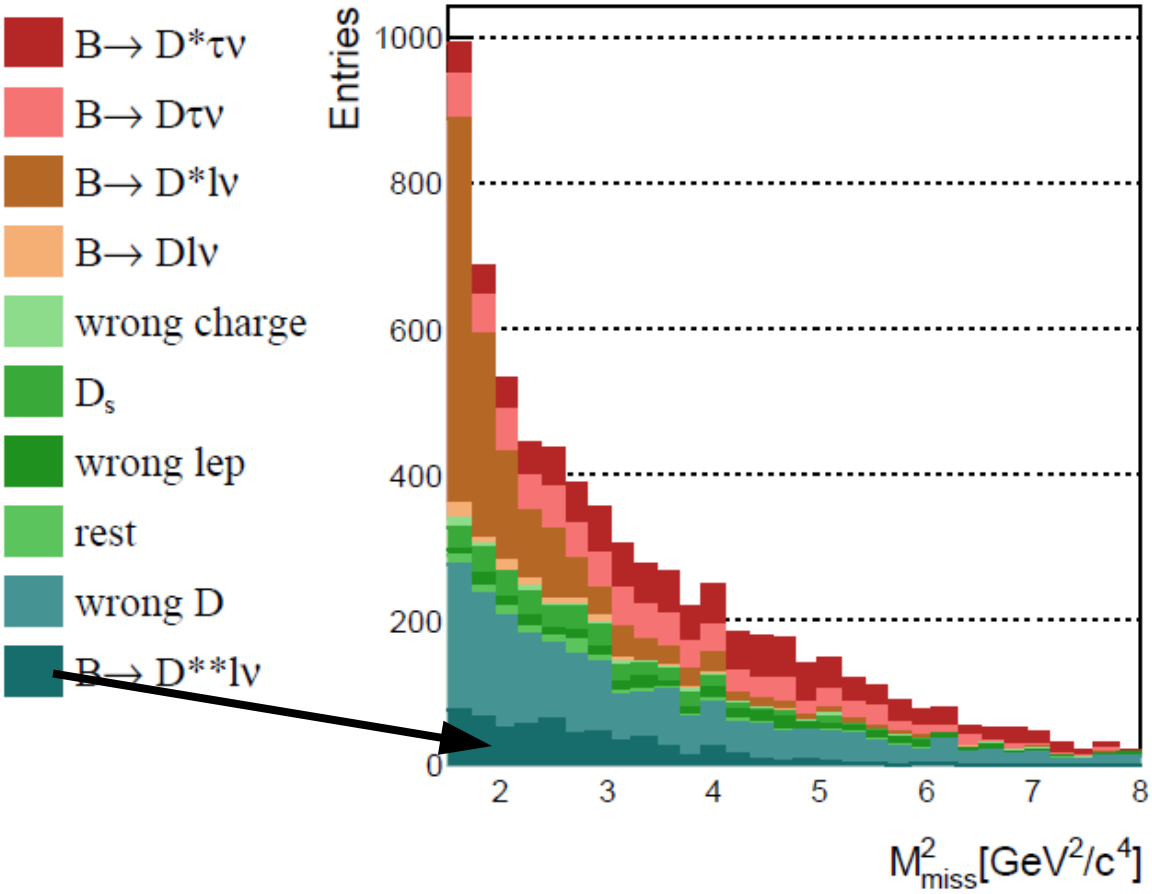



- Ratio of yields in signal and sideband regions from MC

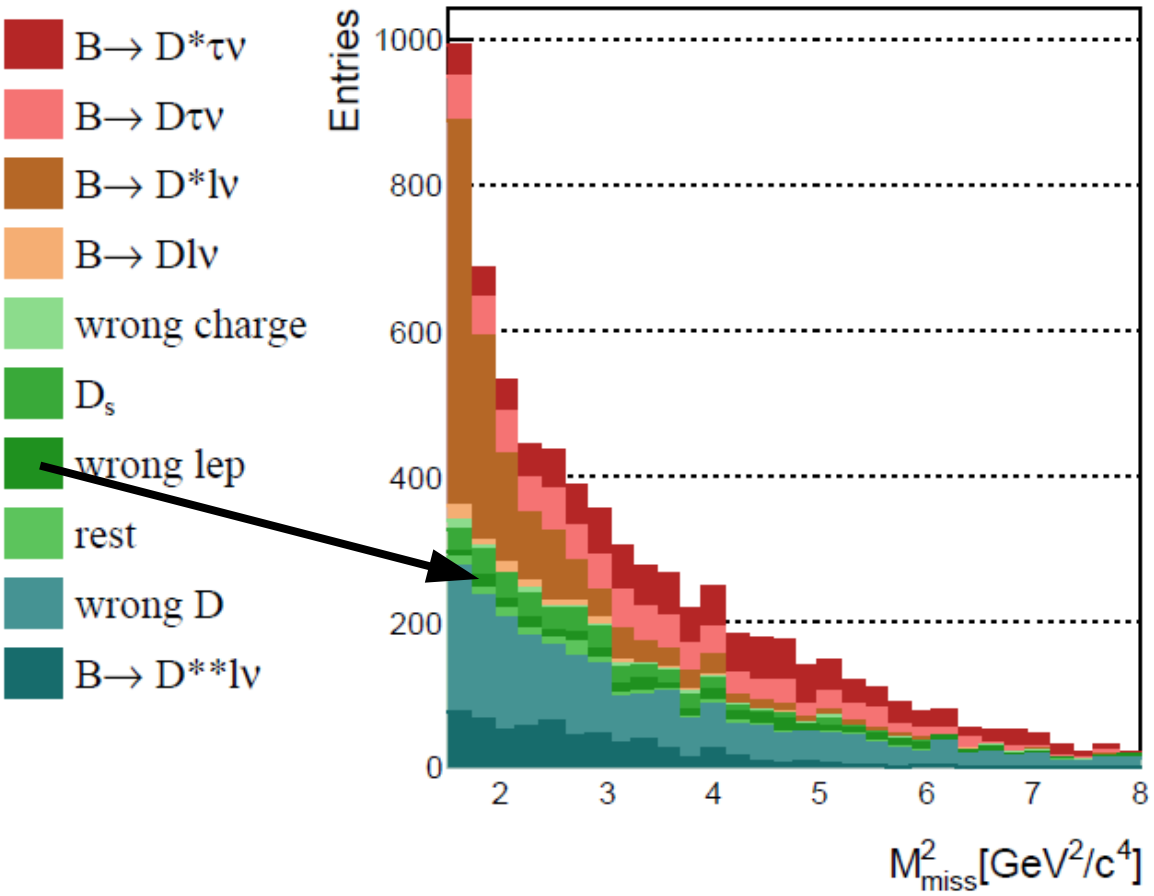
# $D^{**}$ Background

- $B \to D^{**}\ell^{-}\nu$
- One or more pions from $D^{**} \to D^{(*)}(n)\pi$ decay missed
- $M^2_{miss}$ and yield similar to tau signal
- Branching fractions not well known
- Yield is free parameter in the fit



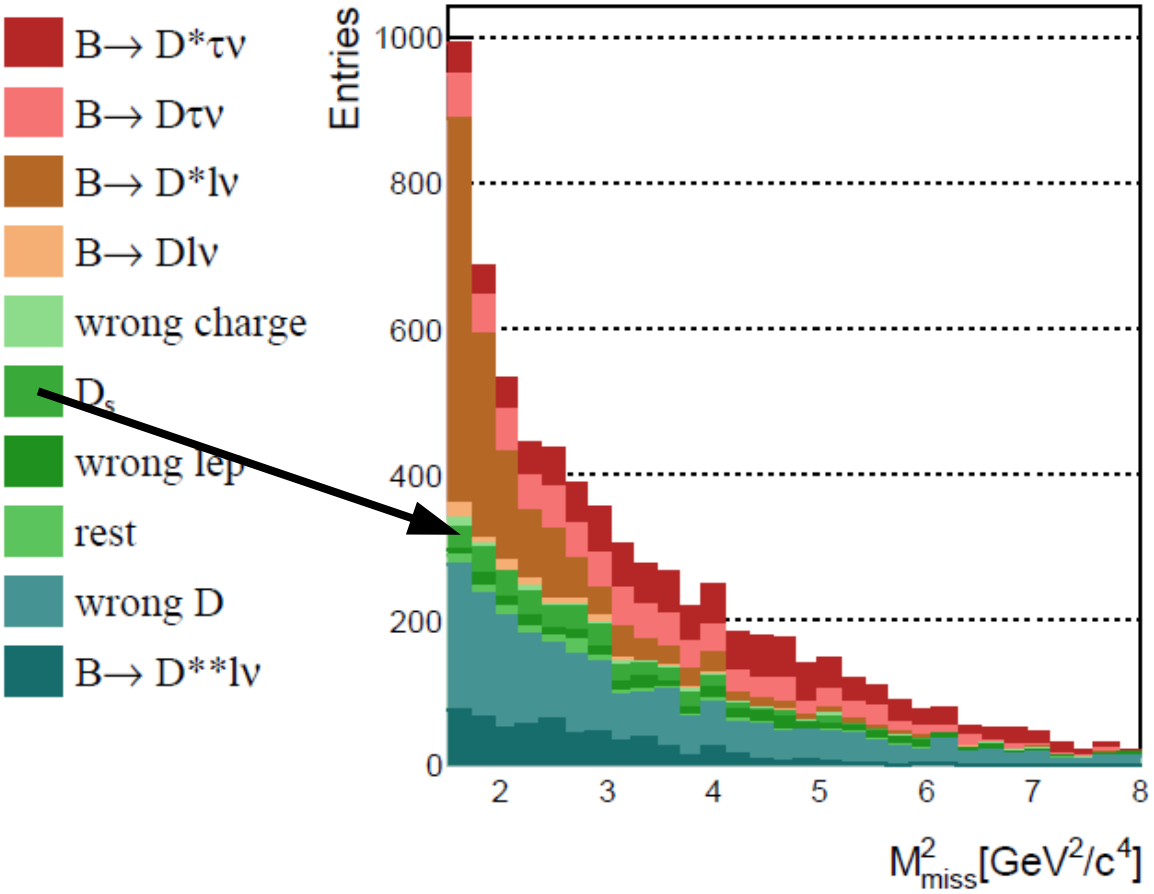
# Wrong Lepton

- B → DK/π with hadron misidentified as lepton
- $M^2_{miss}$ broad, yield small
- Misidentification rate well known
- → Yield determined from MC



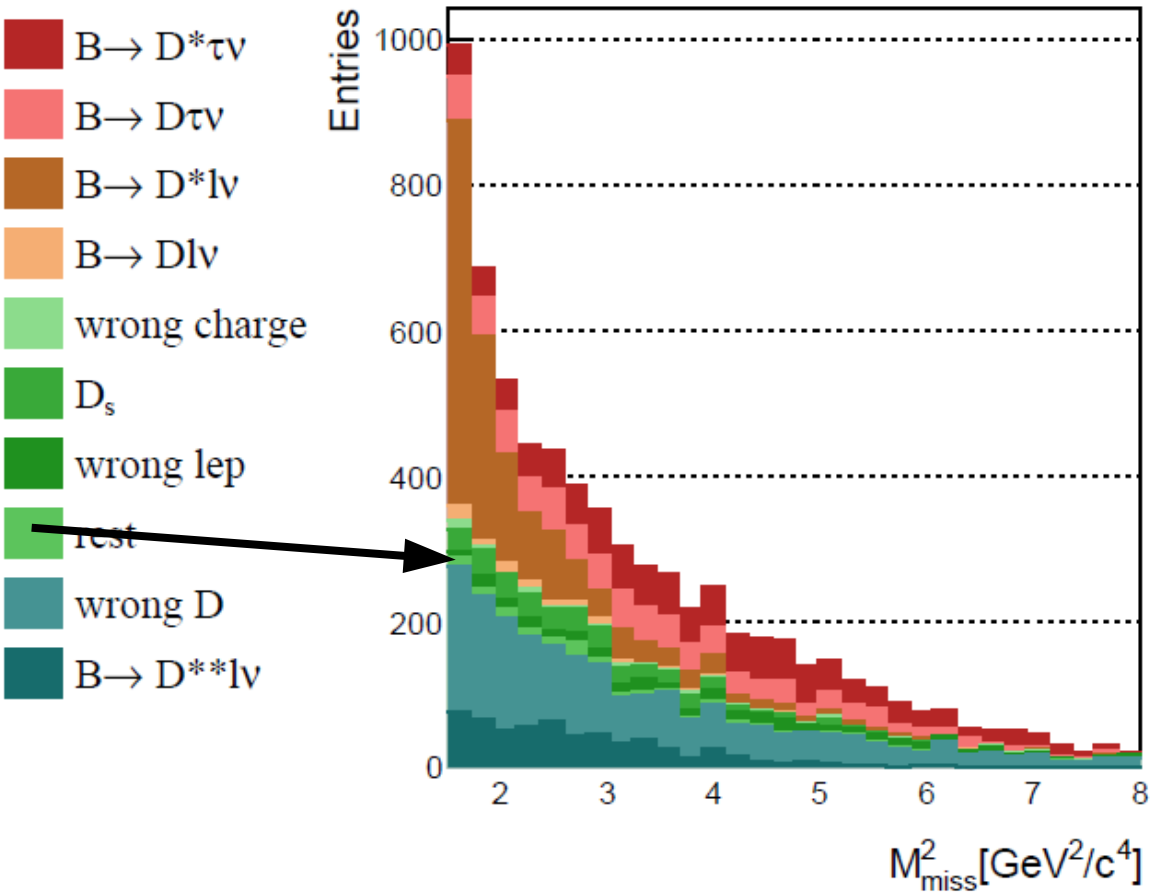
# $D_s$ Decays

- $B \to D_s^- D$ with $D_s^- \to \ell^- \nu(\nu\nu)$
- $M^2_{miss}$ broad, yield small
- Branching ratio well known
- ➔ Yield determined from MC



# Rest

- Anything else
- E.g. events with correctly identified final state particles, but mix up of signal and tag side
- $M^2_{miss}$ broad, yield small
- Yield determined from MC



# Simulation

- Decay chains simulated with EvtGen
- Detector simulation with Geant3

- $10^7$ signal events generated for each reconstruction sample

- Background MC corresponding to 5 times the amount of data
  - ➔ Several corrections to describe data well

# Simulation Corrections (1)

- Correct $B_{tag}$ yield
  - Cancels in ratio $R^{(*)}$, but can affect background yields
  - ➔ Correction factors of 0.35 to 1.1 determined per $B_{tag}$ decay mode with semileptonic $B_{sig}$ decays PRD88, 032005
- Wrong $B_{tag}$ yield
  - ➔ Correction factors of 0.99 to 1.14 determined per reconstruction sample from ratio of data/MC yields in $M_{bc}$ sidebands

# Simulation Corrections (2)

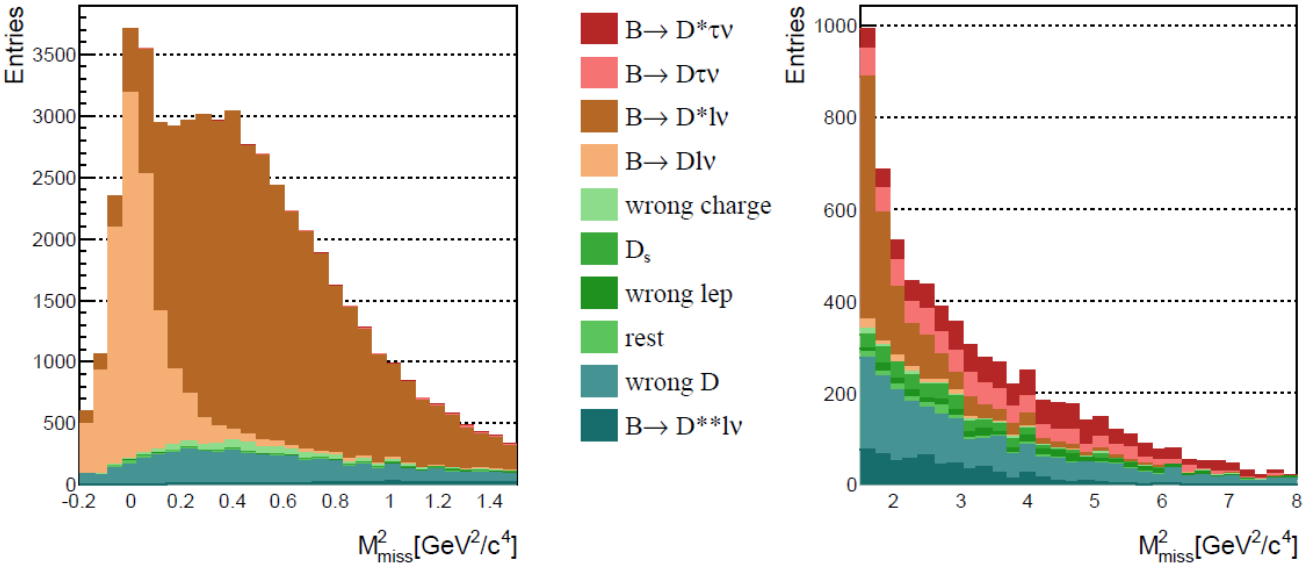
- Lepton fake rate
  - ➔ Correction factors depending on momentum and polar angle
- Lepton efficiency
  - Consistent between MC and data
- Correct D yield
  - ➔ Correction factors of 0.75 to 1.09 determined per $D^{(*)}$ decay mode from ratio of signal yields in data/MC from fit to D mass ($D^*$-D mass difference)
- Wrong D yield: Taken from sideband data

# Simulation Corrections (3)

- $D_s^- \to \ell^- \nu(\nu\nu)$
  - Reweighted to latest branching ratio results
- $B \to D^{**} \ell^- \nu$
  - B decays to $D_2^*$, $D_0^*$, $D_1$, $D_1'$, D(2S), $D^*(2S)$ according to latest branching ratio measurements
  - $D^{**}$ decays to $D^{(*)} + \pi, \pi\pi, \rho, \eta$
  - Reweighting to LLSW model PRD57, 308
- $B \to D^{(*)} \ell^- \nu$
  - Reweighting to latest HQET2 parameters from HFAG

# Fit Strategy

- ✔ $M^2_{miss}$ separates lepton signal, lepton cross feed, and tau signal well
- ✗ But tau signal and $D^{**}$ background very similar in $M^2_{miss}$




- → Split sample at $M^2_{miss} = 0.85$ GeV$^2$/c$^4$
  - Fit $M^2_{miss}$ in low $M^2_{miss}$ sample → Constrain ℓ signal + ℓ CF
- Train NN to distinguish tau signal and (mainly) $D^{**}$ background in high $M^2_{miss}$ sample
  - Fit NN distribution in high $M^2_{miss}$ sample → Constrain $D^{**}$

# Neural Network

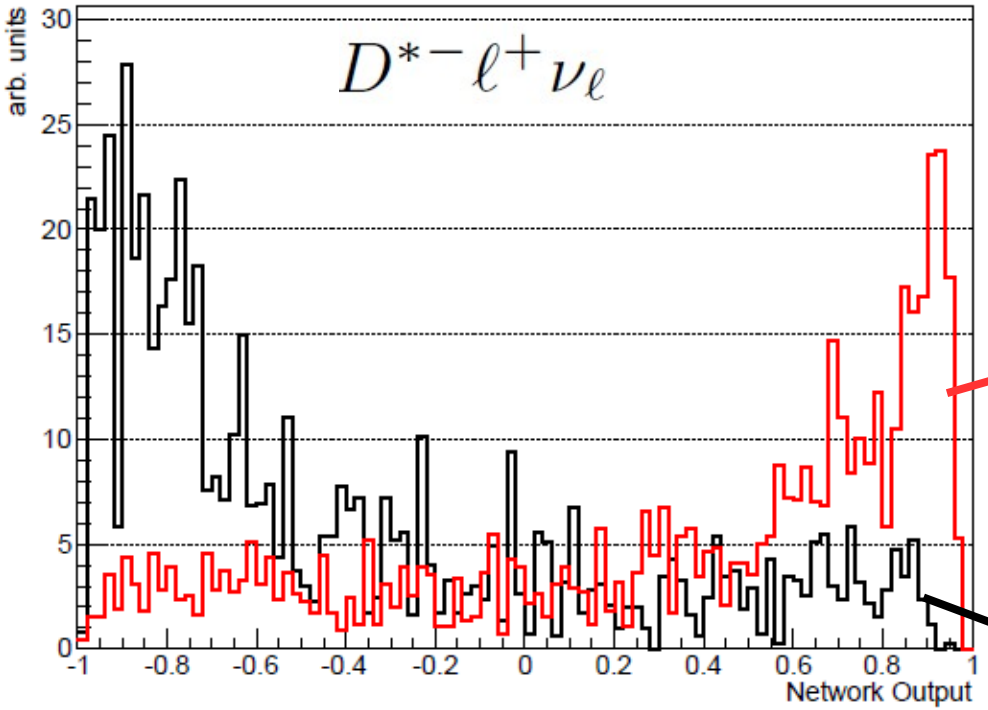
One network per reconstruction sample

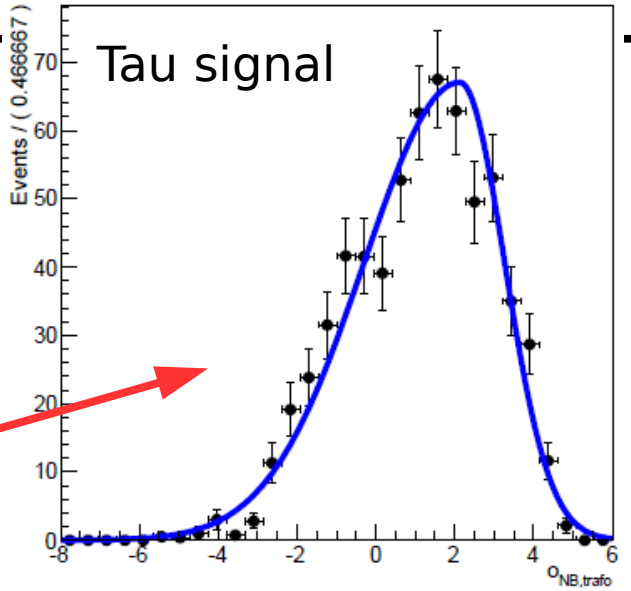
- Signal: tau signal
- Background: $D^{**}$, wrong charge CF, wrong lepton, $D_s$, rest

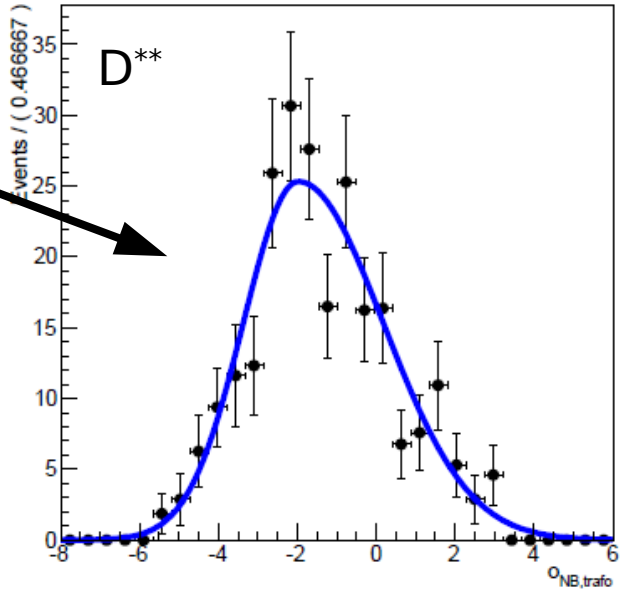
Input variables:

- $M^2_{miss}$
- $E_{ECL}$: sum of energies of clusters not assigned to $B_{sig}$ or $B_{tag}$
  → Most powerful variable
- Momentum transfer $q^2$ and lepton momentum $p_\ell^*$
  → Correlated with $M^2_{miss}$
- Number of unassigned $\pi^0$ with $|S_{\gamma\gamma}| < 5$
- Cos of angle between $D^{(*)}$ momentum and vertex direction
- Decay channel identifiers

# Network Output




- Transformation for easier parametrization:

$$o_{\mathrm{NB,trafo}} \equiv \log \frac{o_{\mathrm{NB}} - o_{\mathrm{min}}}{o_{\mathrm{max}} - o_{\mathrm{NB}}}$$

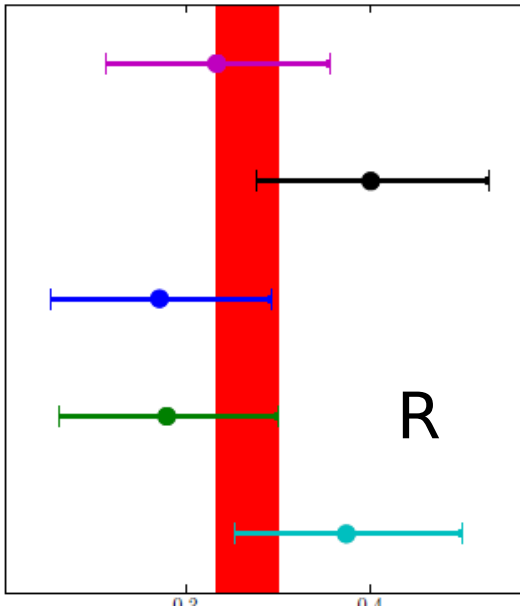
# Fit

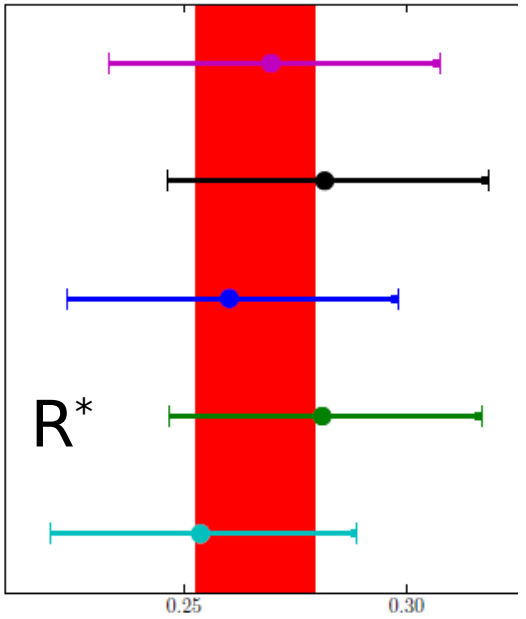
- Smoothed histogram PDFs for $M^2_{miss}$
- Bifurcated Gaussians for $o_{NB,tranfo}$
- ➢ Simultaneous extended maximum likelihood fit of the four reconstruction samples
- ➔ 12 free parameters:
  - Lepton signal yield per sample
  - Lepton cross-feed per $D\ell^-$ sample
  - $D^{**}$ yield per sample
  - R and $R^*$ (assuming isospin symmetry)

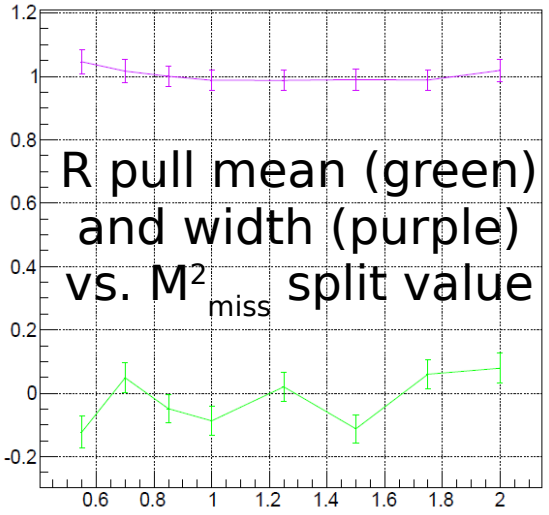
| Component | $D^+\ell^-$ | $D^0\ell^-$ | $D^{*+}\ell^-$ | $D^{*0}\ell^-$ | yield source |
|---|---|---|---|---|---|
| $\ell$ signal | ✓ | ✓ | ✓ | ✓ | fit |
| $\ell$ CF | ✓ | ✓ | - | - | fit |
| $\tau$ signal | ✓ | ✓ | ✓ | ✓ | fit |
| $\tau$ CF | ✓ | ✓ | - | - | constrained |
| wrong charge | - | ✓ | - | - | constrained |
| wrong $D$ | ✓ | ✓ | - | - | $M_D$ SB |
| wrong $D^*$ | - | - | ✓ | ✓ | $\Delta M_{D^*D}$ SB |
| $D^{**}$ | ✓ | ✓ | ✓ | ✓ | fit |
| wrong $\ell$ | ✓ | ✓ | ✓ | ✓ | MC |
| $D_s$ | ✓ | ✓ | ✓ | ✓ | MC |
| rest | ✓ | ✓ | ✓ | ✓ | MC |

# Validation

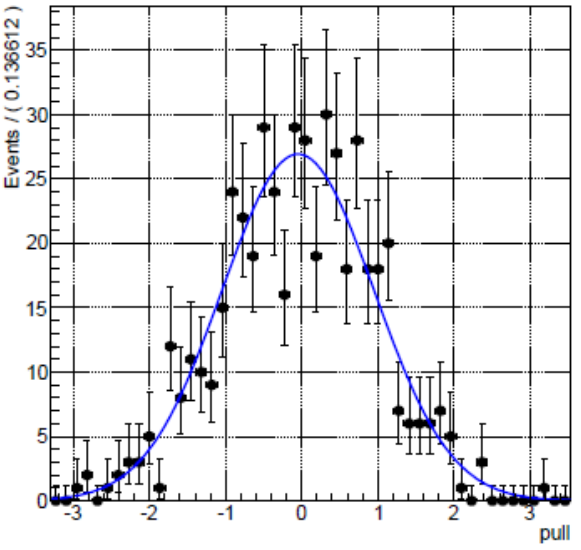
- Cross validation on MC
- 500 pseudo exp.
  → no biases in fit
- $M^2_{miss}$ split value
  → no bias
- Resolution model checked with $D^{(*)}\ell^-\nu$ enriched sample



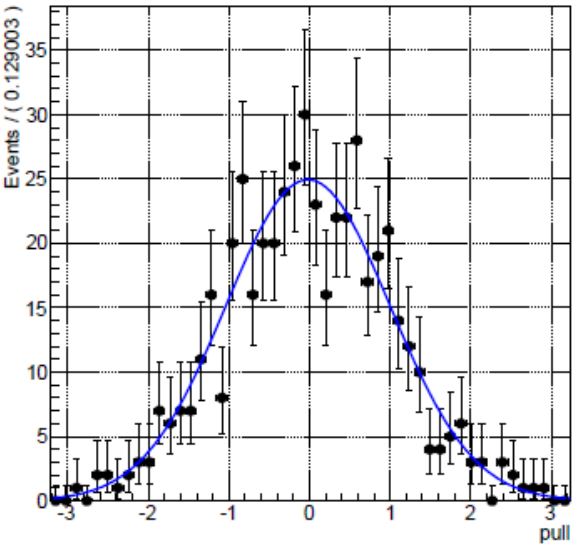




mean: -0.05±0.05 width: 1.00±0.03



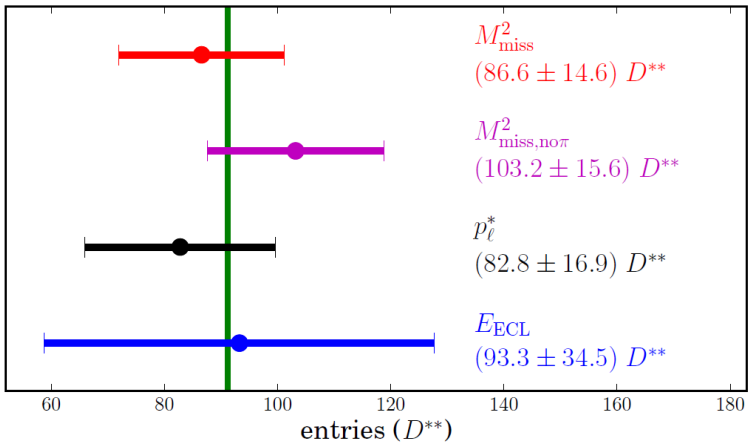

mean: -0.02±0.05 width: 1.02±0.03

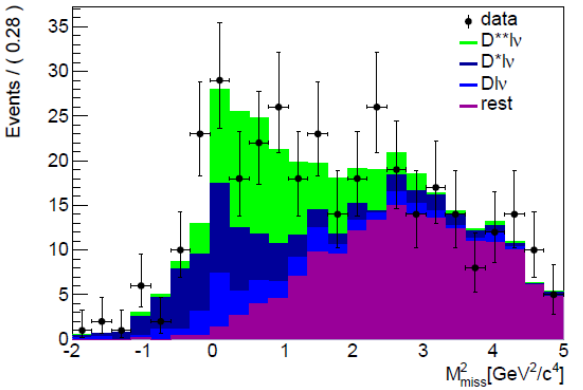


# $D^{**}$ Validation

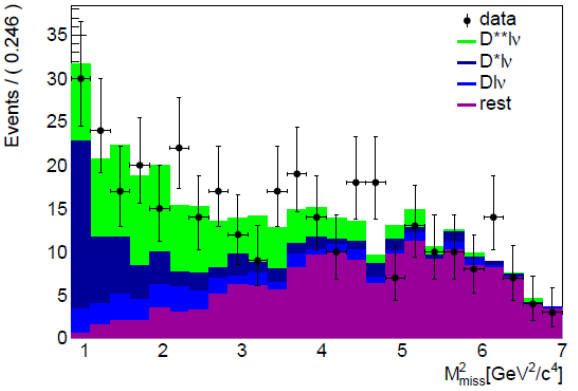
- $D^{**}$ validation sample: additional $\pi^0$ required
- Fit of $M^2_{miss}$, $M^2_{miss,no\text{-}\pi 0}$, $E_{ECL}$, $p_\ell^*$
- Consistent yields
- $D^{**}$ distributions described by MC

$D^+\ell^-\pi^0$

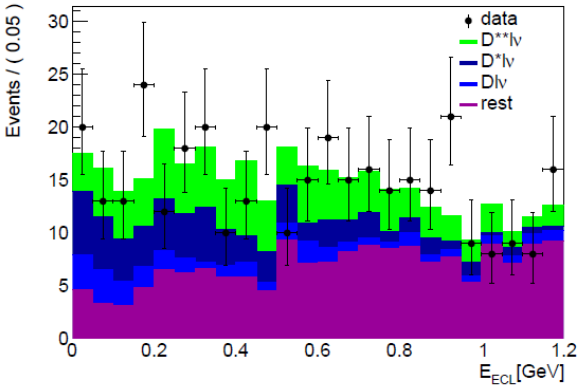


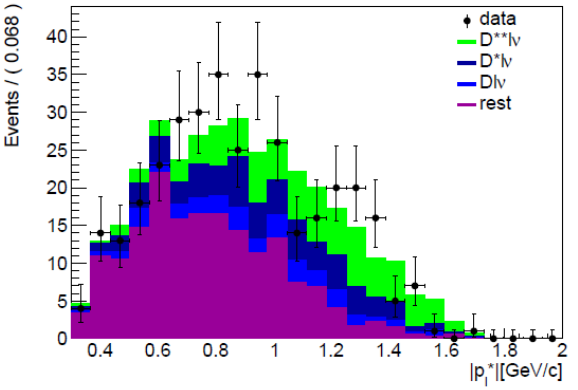

(b) $M^2_{\rm miss}$




(c) $M^2_{\rm miss,no\ \pi^0}$




(d) $E_{\rm ECL}$




(e) $p^*_\ell$

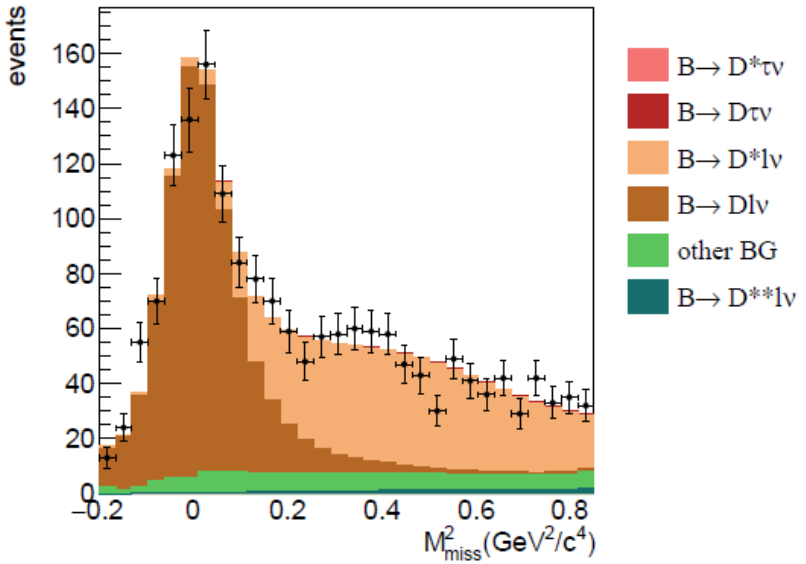
# Systematic Uncertainties

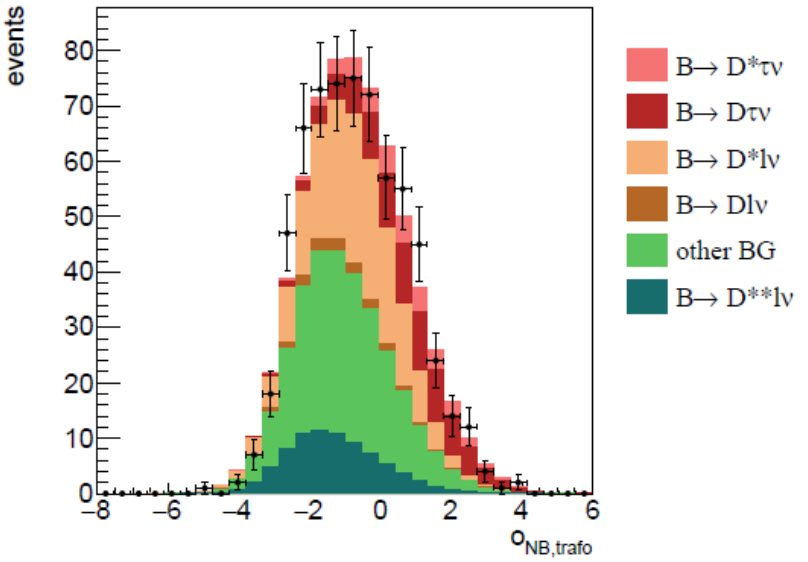
- Decay model uncertainties
- $B \to D^{**} \ell \nu$ branching ratios varied by 42% for $D_2^*$, 35% for $D_0^*$, 15% for $D_1$, 36% for $D_1'$, 100% for $D^{(*)}(2S)$
- MC statistics
- PDF parametrization
- Lepton ID

| | $R$ [%] | $R^*$ [%] | correlation |
|---|---|---|---|
| $D^{(*(*))}\ell\nu$ shapes | 4.2 | 1.5 | 0.04 |
| $D^{**}$ composition | 1.3 | 3.0 | -0.63 |
| wrong $D$ yield | 0.5 | 0.3 | 0.13 |
| wrong $\ell$ yield | 0.5 | 0.6 | -0.66 |
| $D_s$ yield | 0.1 | 0.1 | -0.85 |
| rest yield | 0.1 | 0.0 | -0.70 |
| $f_R^+$ | 2.5 | 0.7 | -0.98 |
| $f_R^0$ | 1.8 | 0.4 | 0.86 |
| $f_{R^*,\mathrm{eff}}^+$ | 1.3 | 2.5 | -0.99 |
| $f_{R^*,\mathrm{eff}}^0$ | 0.7 | 1.1 | 0.94 |
| $g^+$ | 2.2 | 2.0 | -1.00 |
| $g^0$ | 1.7 | 1.0 | -1.00 |
| $f_{\mathrm{wc}}$ | 0.0 | 0.0 | 0.84 |
| $M^2_{\mathrm{miss}}$ shape | 0.6 | 1.0 | 0.00 |
| $o_{\mathrm{NB,trafo}}$ shape | 3.2 | 0.8 | 0.00 |
| lepton PID efficiency | 0.5 | 0.5 | 1.00 |
| $\Sigma$ | 7.1 | 5.2 | -0.32 |

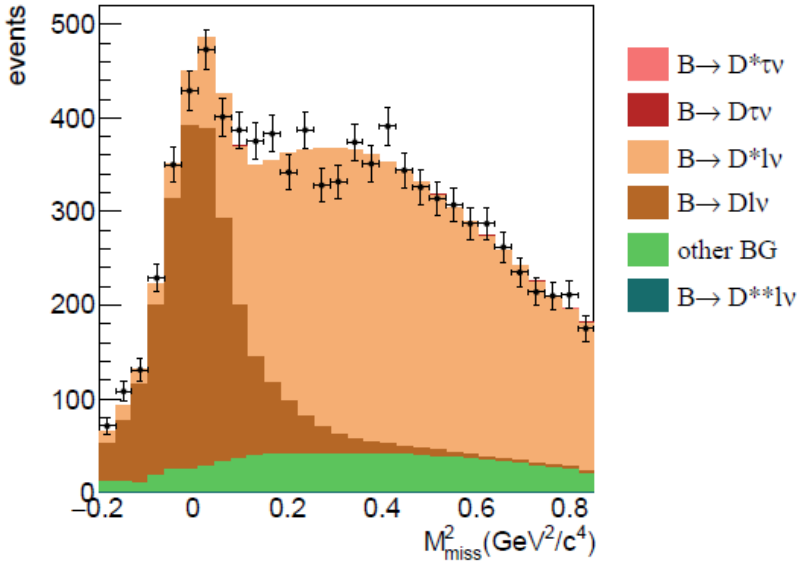
# Fit Result

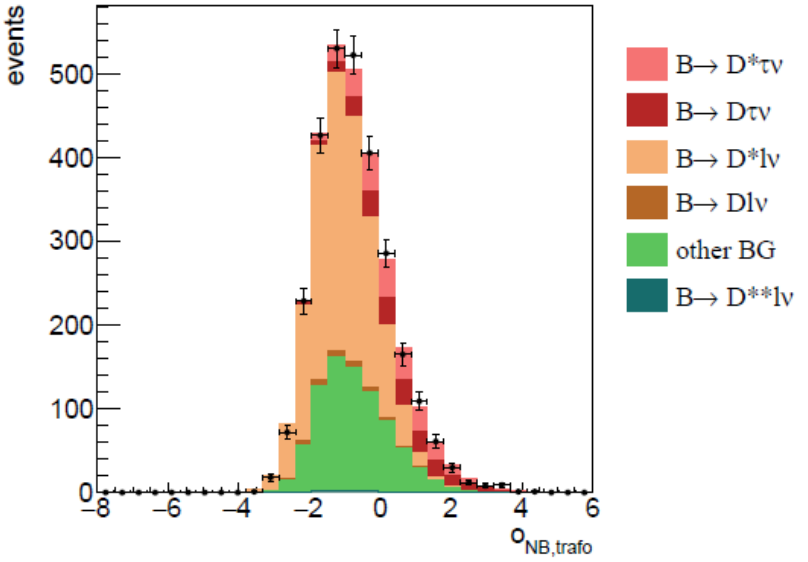
$D^+\ell^-$



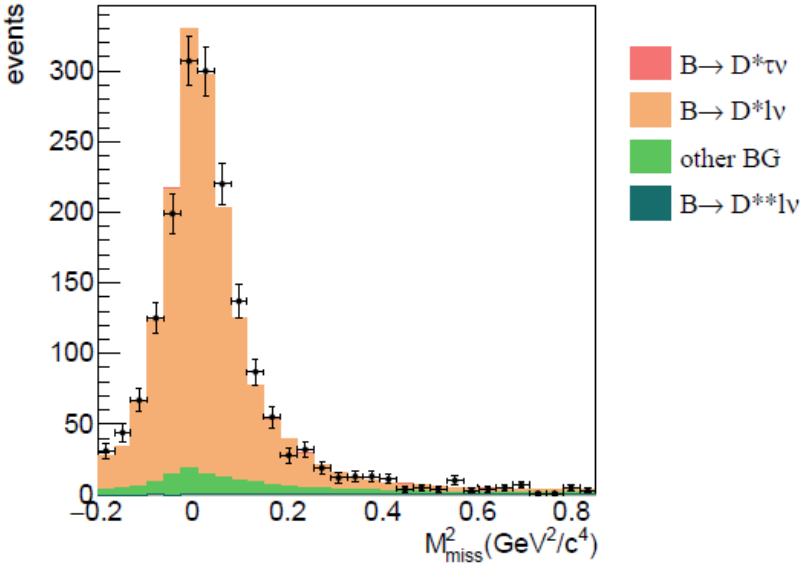

$D^0\ell^-$

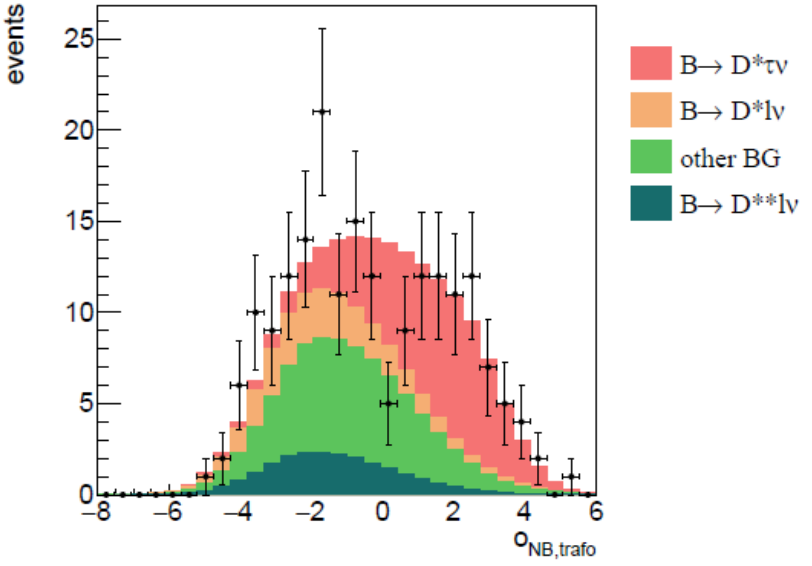


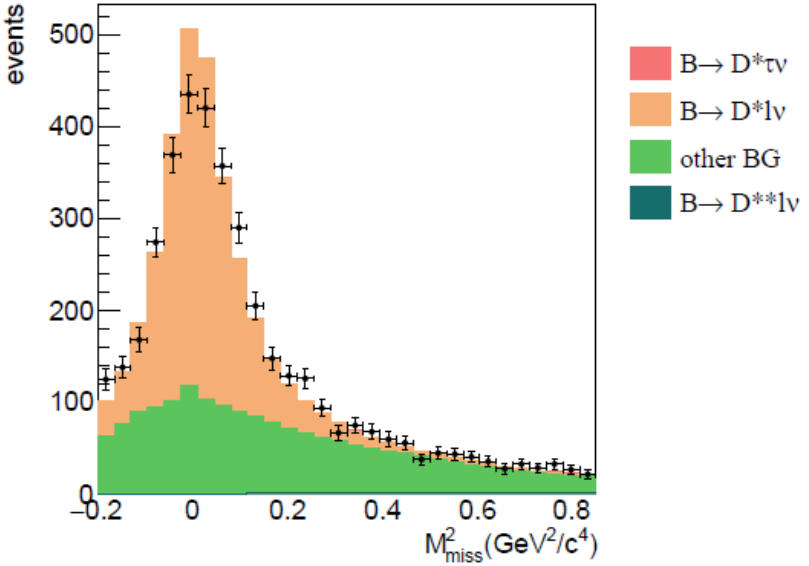
# Fit Result

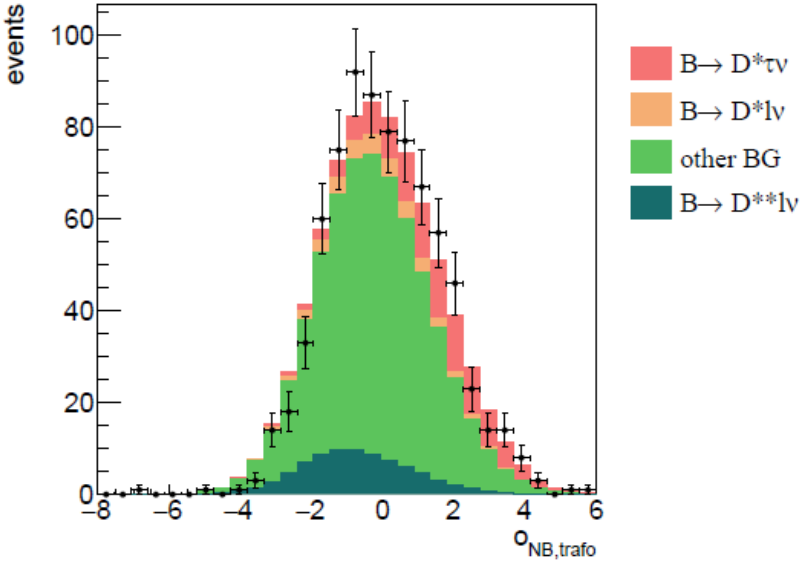
$D^{*+}\ell^-$



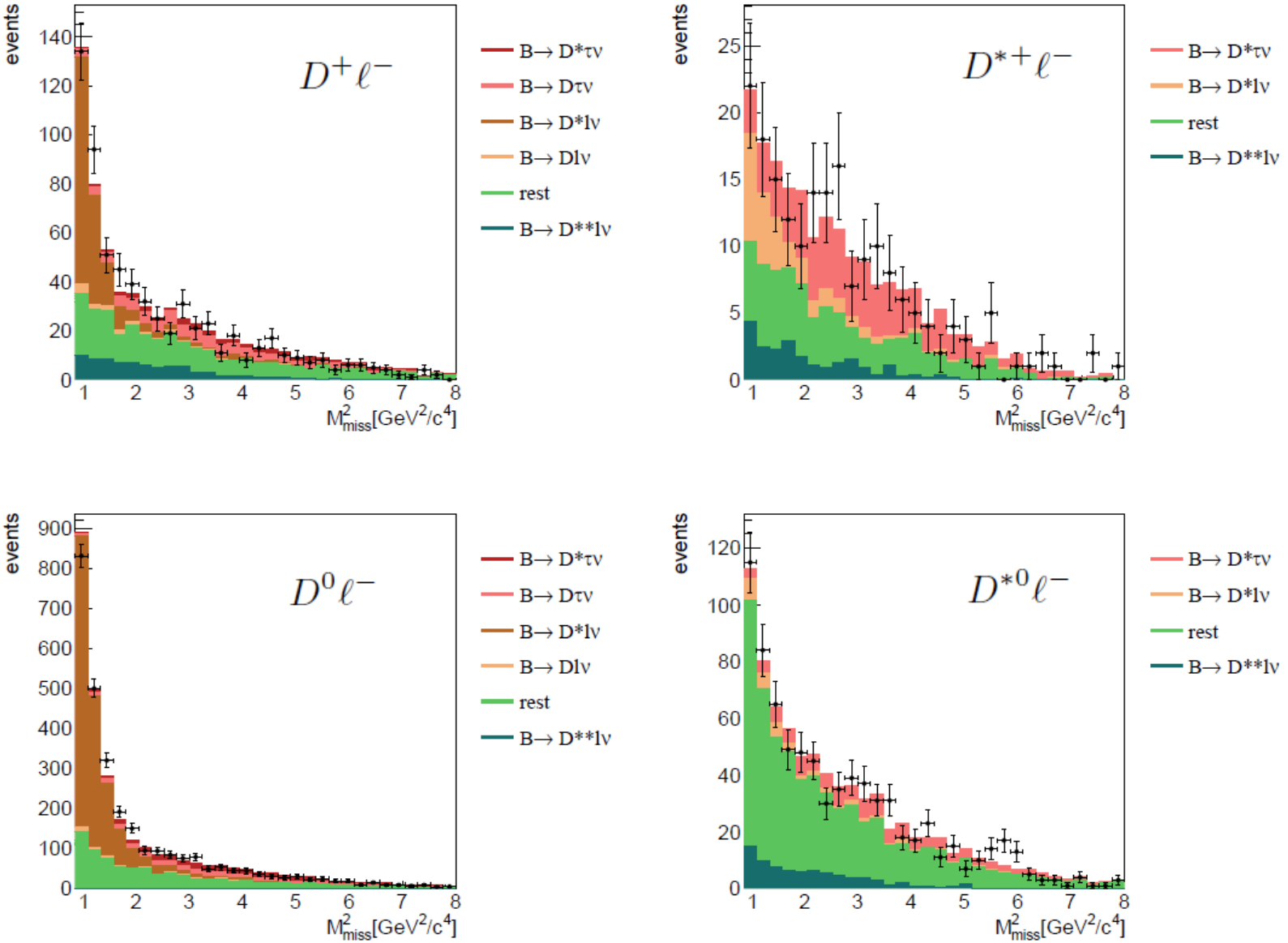




$D^{*0}\ell^-$

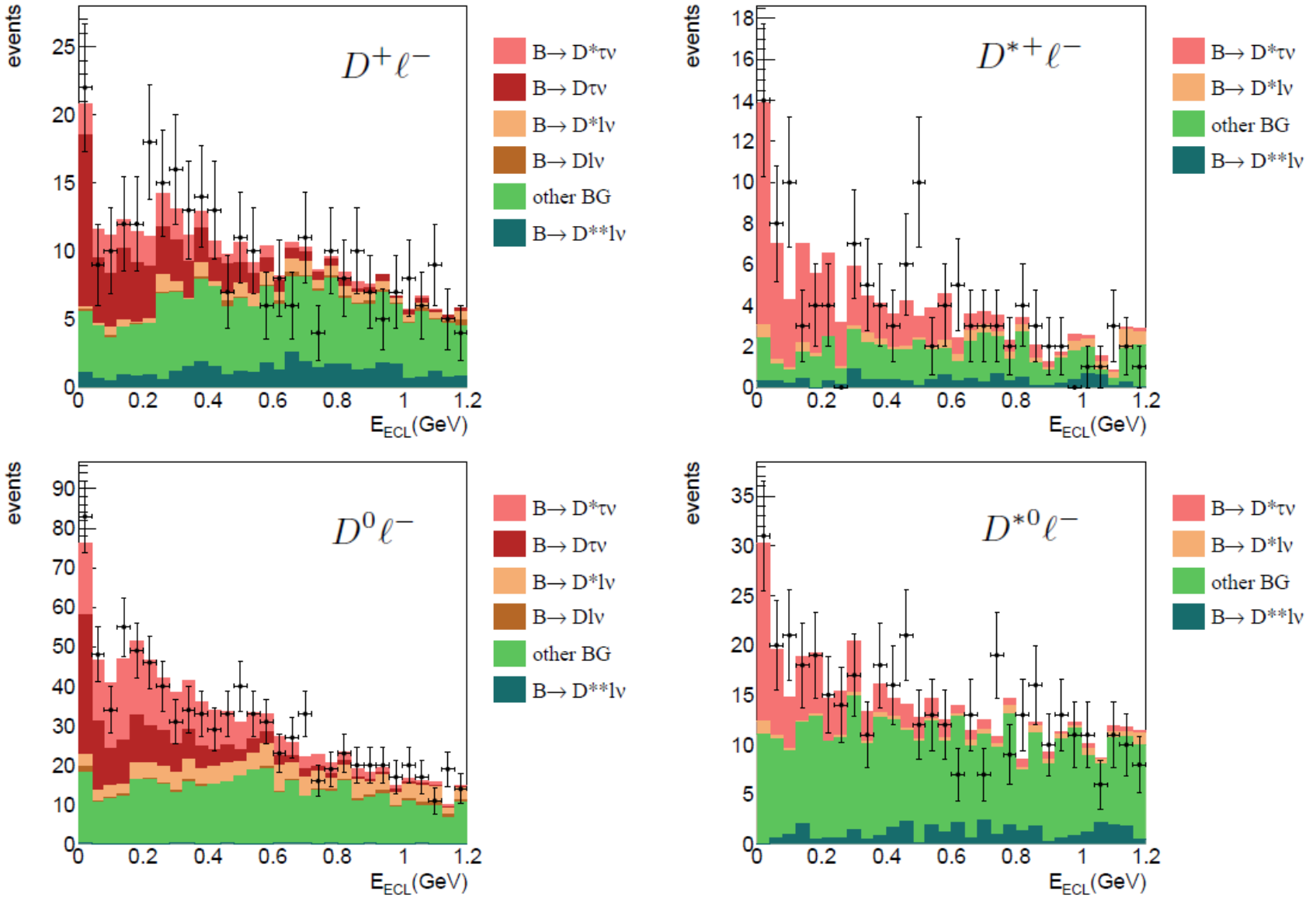


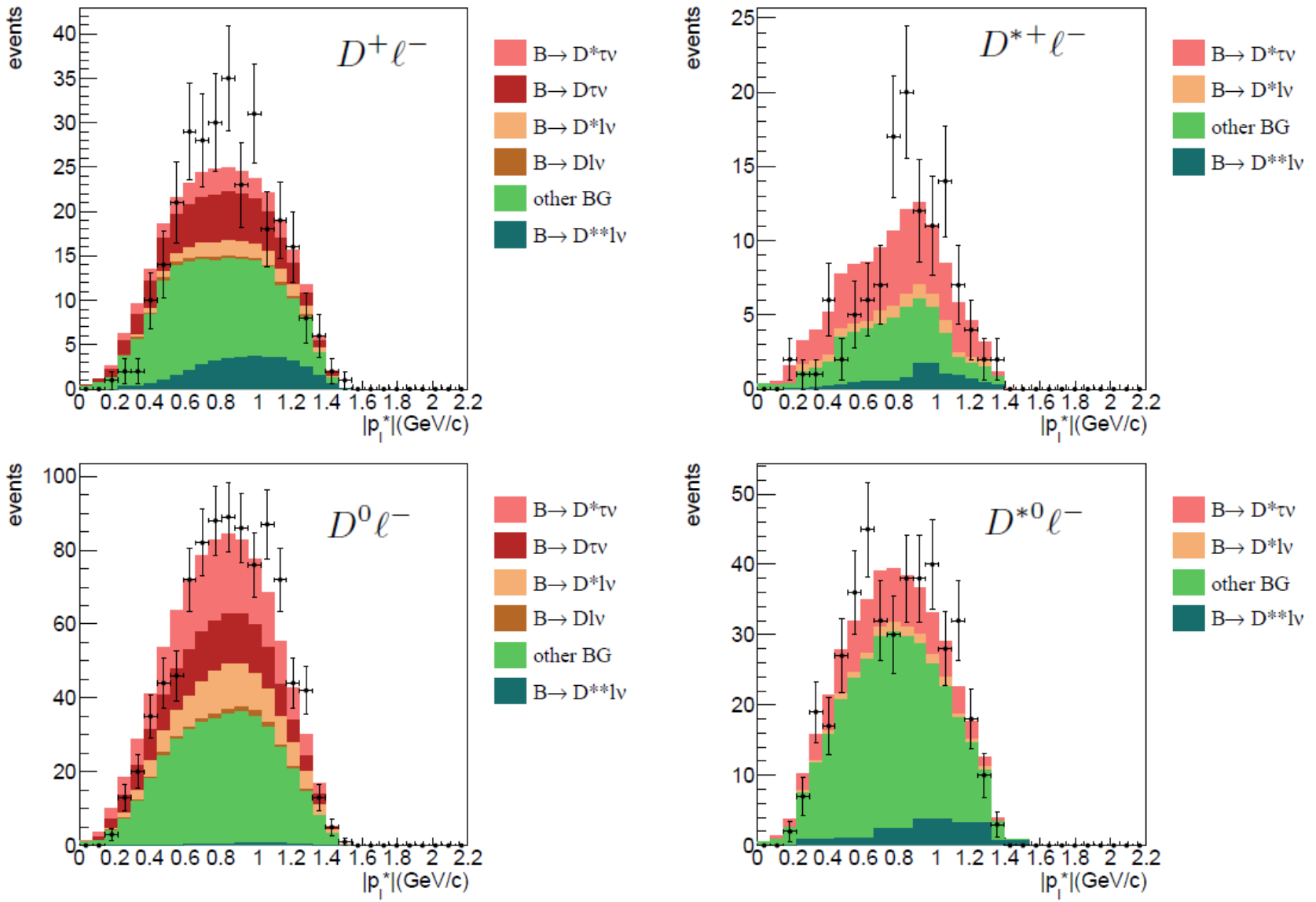
# Fit Projections High $M^2_{miss}$



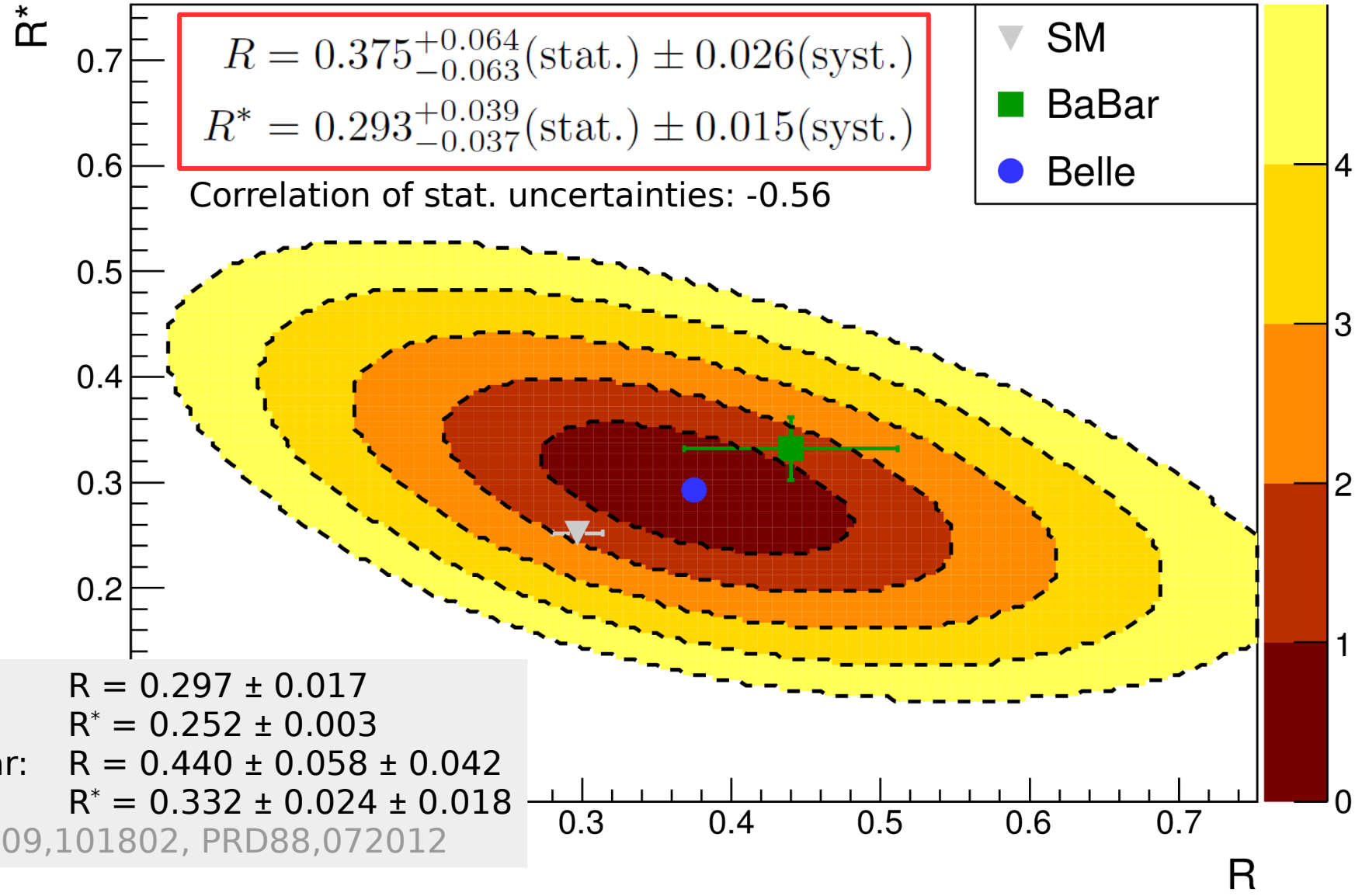
# Fit Projections $E_{ECL}$ for $M^2_{miss} > 2\ GeV^2/c^4$



# Fit Projections $p_\ell^*$ for $M^2_{miss} > 2\ GeV^2/c^4$

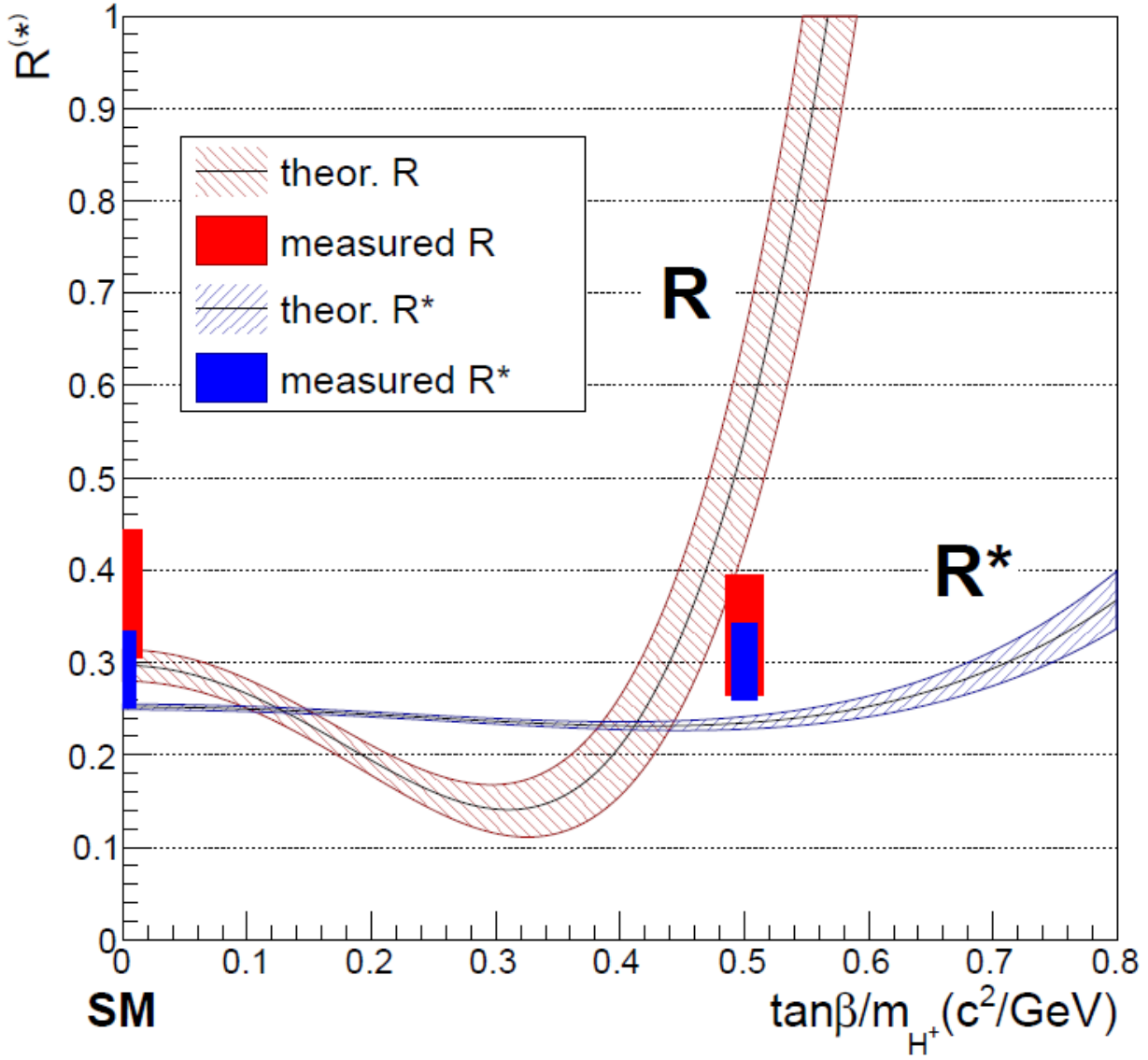


# Result




SM: R = 0.297 ± 0.017
R* = 0.252 ± 0.003
BaBar: R = 0.440 ± 0.058 ± 0.042
R* = 0.332 ± 0.024 ± 0.018
PRL109,101802, PRD88,072012

# What About New Physics?



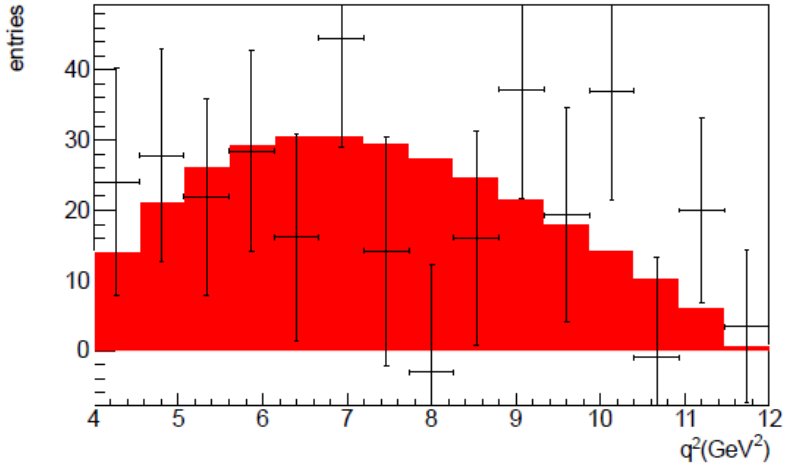

- Analysis repeated for 2HDM of type II with $\tan\beta/m_{H^+} = 0.5\ c^2/\mathrm{GeV}$:

$$R = 0.329 \pm 0.060 \pm 0.022$$
$$R^* = 0.301 \pm 0.039 \pm 0.015$$

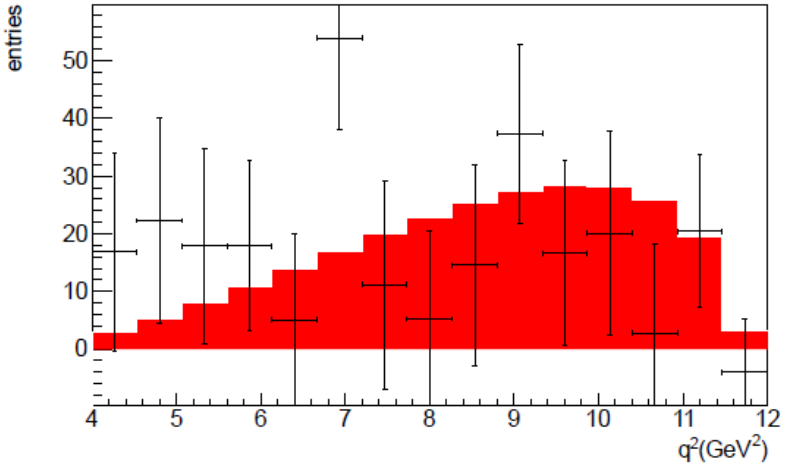
$$R_{2HDM} = 0.590 \pm 0.125$$
$$R^*_{2HDM} = 0.241 \pm 0.007$$

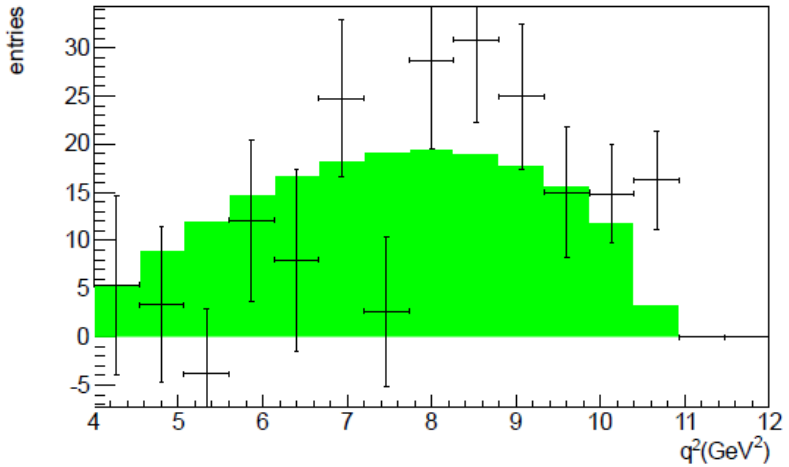
# And the $q^2$ Spectrum?

SM B → Dτν: p=64%

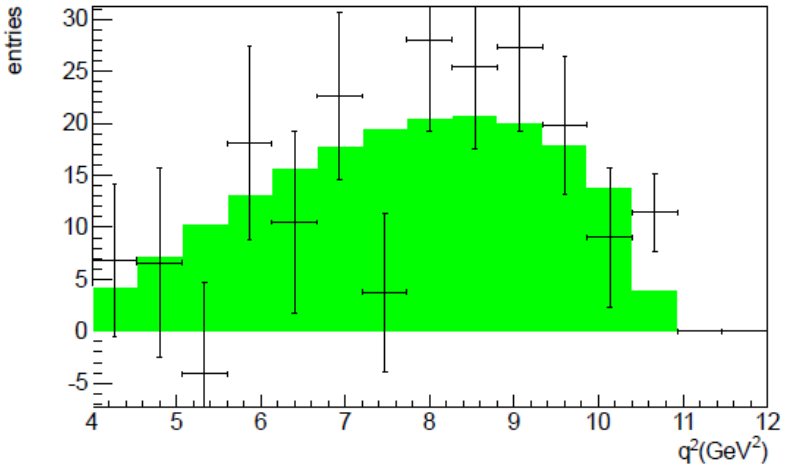



NP B → Dτν: p=53%




SM B → D*τν: p=11%




NP B → D*τν: p=49%

# Summary

- ✔ Measurement with full Belle dataset
- ✔ More sophisticated fit strategy than in previous Belle analysis

$$R = 0.375^{+0.064}_{-0.063}(\text{stat.}) \pm 0.026(\text{syst.})$$
$$R^* = 0.293^{+0.039}_{-0.037}(\text{stat.}) \pm 0.015(\text{syst.})$$

- ➔ Consistent with SM and BaBar result
- ➔ Consistent with 2HDM of type II at $\tan\beta/m_{H+} \approx 0.5\ c^2/\text{GeV}$
- ➢ Have to wait for Belle II (and LHCb)?