Search for $B^0_{(d)} \to \tau^{\mp} l^{\pm}$ (l=e, μ) with Hadronic Tagging Method at Belle

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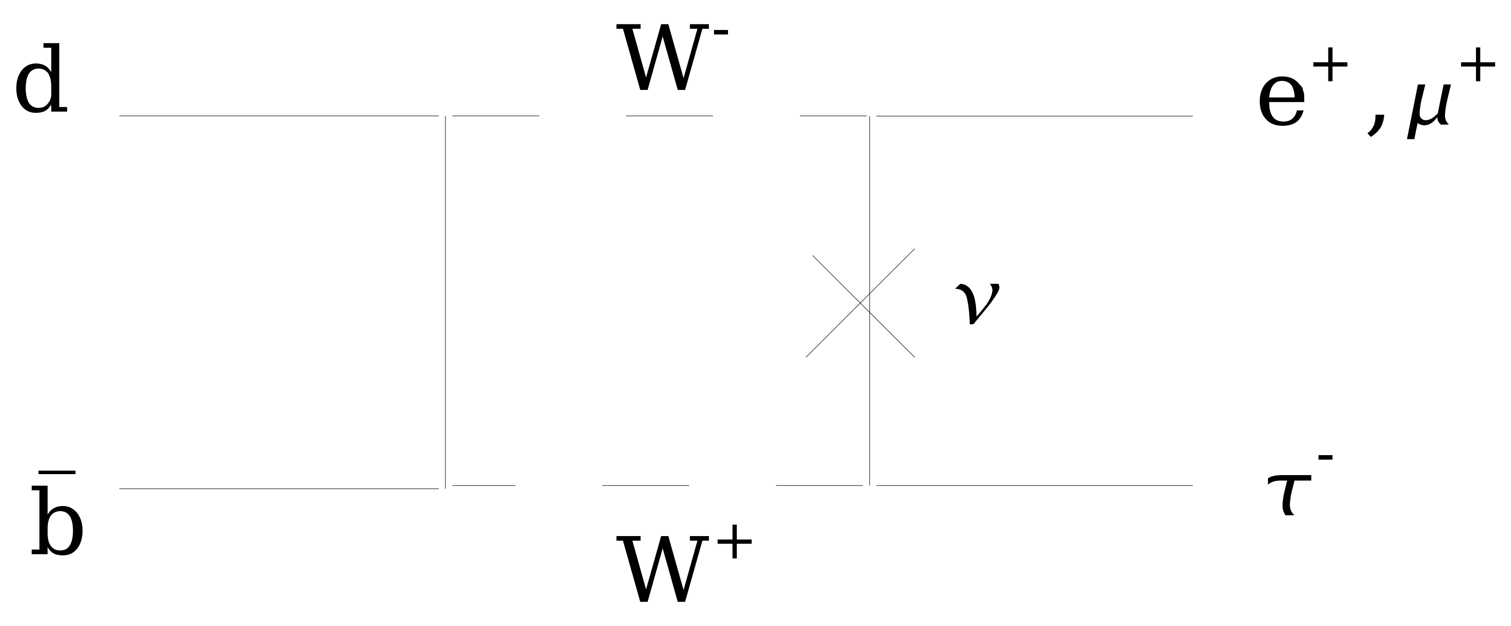
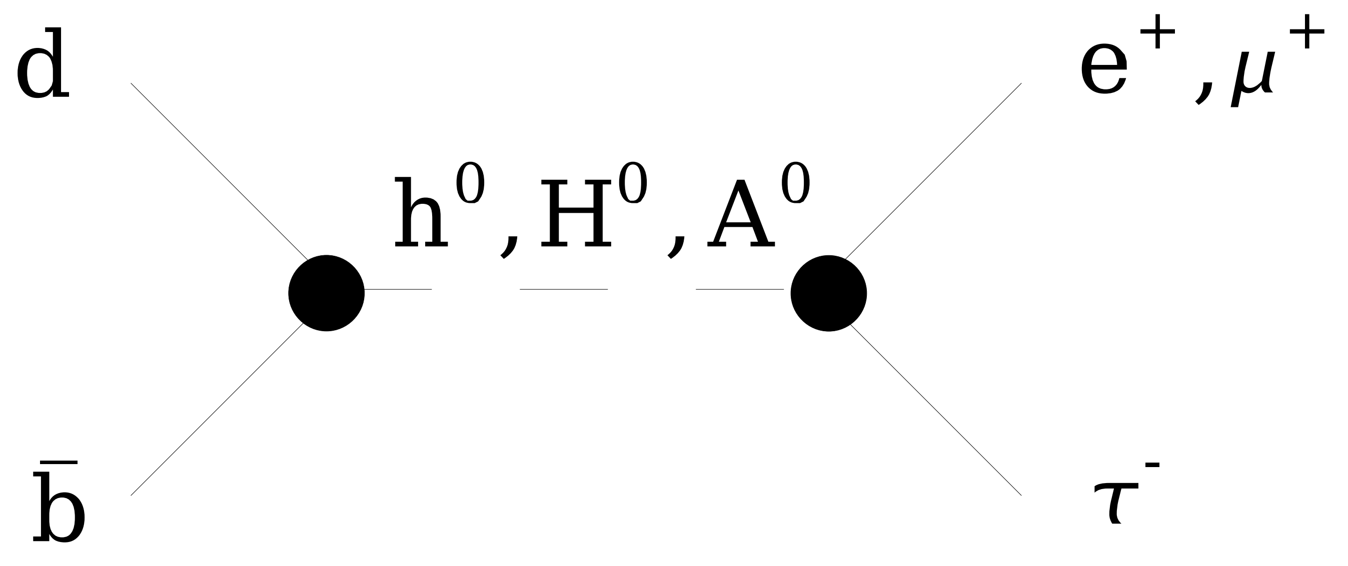
MOTIVATION

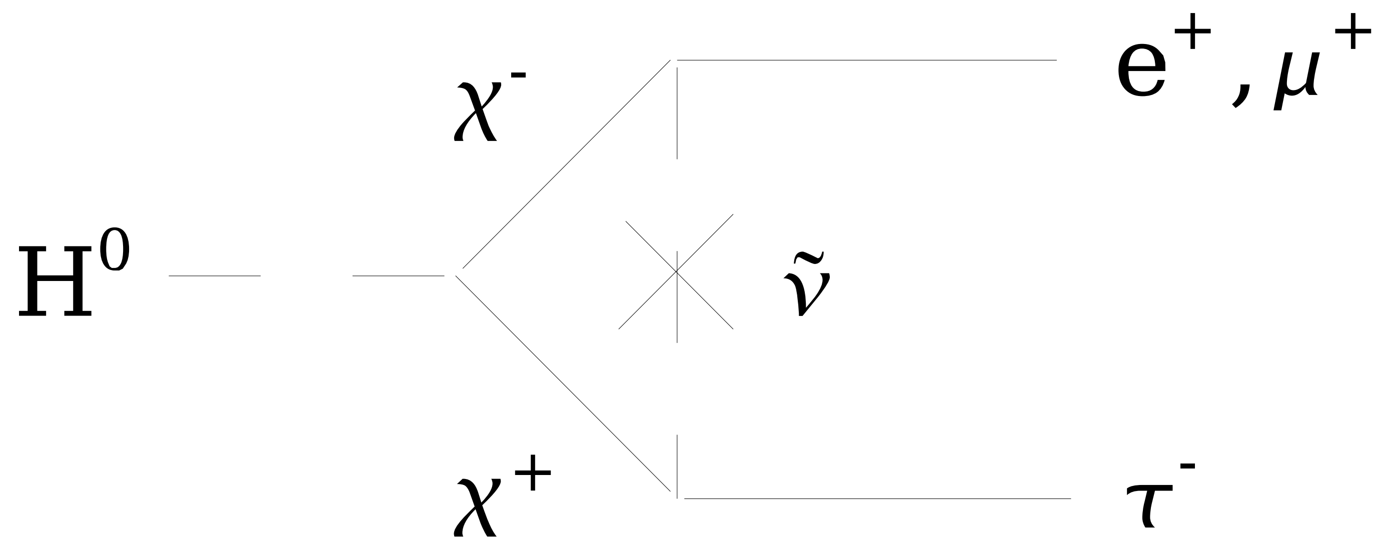
Search for Lepton Flavor Violating (LFV) $B^0_{(d)} \to \tau^\mp l^\pm$ $(l=e,\mu)$ Decays

- Forbidden in the Standard Model (SM) without neutrino oscillations, but in principle it can occur via neutrino mixing. The rate is significantly below current and future experimental sensitivities.



- New physics models such as leptoquarks *[Mod. Phys. Lett. A 33, 1850019 (2018)]* or Higgs-mediation in supersymmetric seesaw models *[Phys. Lett. B 549, 159 (2002)]* predict higher rates (~10^{-9} - 10^{-10}).





Higgs-mediated LFV processes

Current Experimental Limits for $B^0{}_{(d,s)} \to \tau^\mp l^\pm$ Branching Fractions

	BaBar 378 M $B\bar{B}$ (90% CL) *Phys. Rev. D 77, 091104(R) (2008)*	CLEO 9.6 M $B\bar{B}$ (90% CL) *PRL 93, 241802 (2004)*	LHCb 3fb^{-1} of pp collisions (90% CL) *Phys. Rev. Lett. 123, 211801 (2019)*
$B_{(s)}{}^0 \to \tau^\mp e^\pm$	–	–	–
$B_{(s)}{}^0 \to \tau^\mp \mu^\pm$	–	–	$< 3.4\times10^{-5}$
$B_{(d)}{}^0 \to \tau^\mp e^\pm$	$< 2.8\times10^{-5}$	$< 1.3\times10^{-4}$	–
$B_{(d)}{}^0 \to \tau^\mp \mu^\pm$	$< 2.2\times10^{-5}$	$< 3.8\times10^{-5}$	$< 1.2\times10^{-5}$

BaBar

τ decay mode	Branching Fraction
$e^-\bar{\nu}_e\nu_\tau$	17.84 ± 0.05
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.36 ± 0.05
$\pi^-\nu_\tau$	10.90 ± 0.07
$\pi^-\pi^0\nu_\tau$	25.50 ± 0.10
$\pi^-\pi^0\pi^0\nu_\tau$	9.25 ± 0.12
$\pi^-\pi^-\pi^+\nu_\tau$	9.33 ± 0.08

CLEO

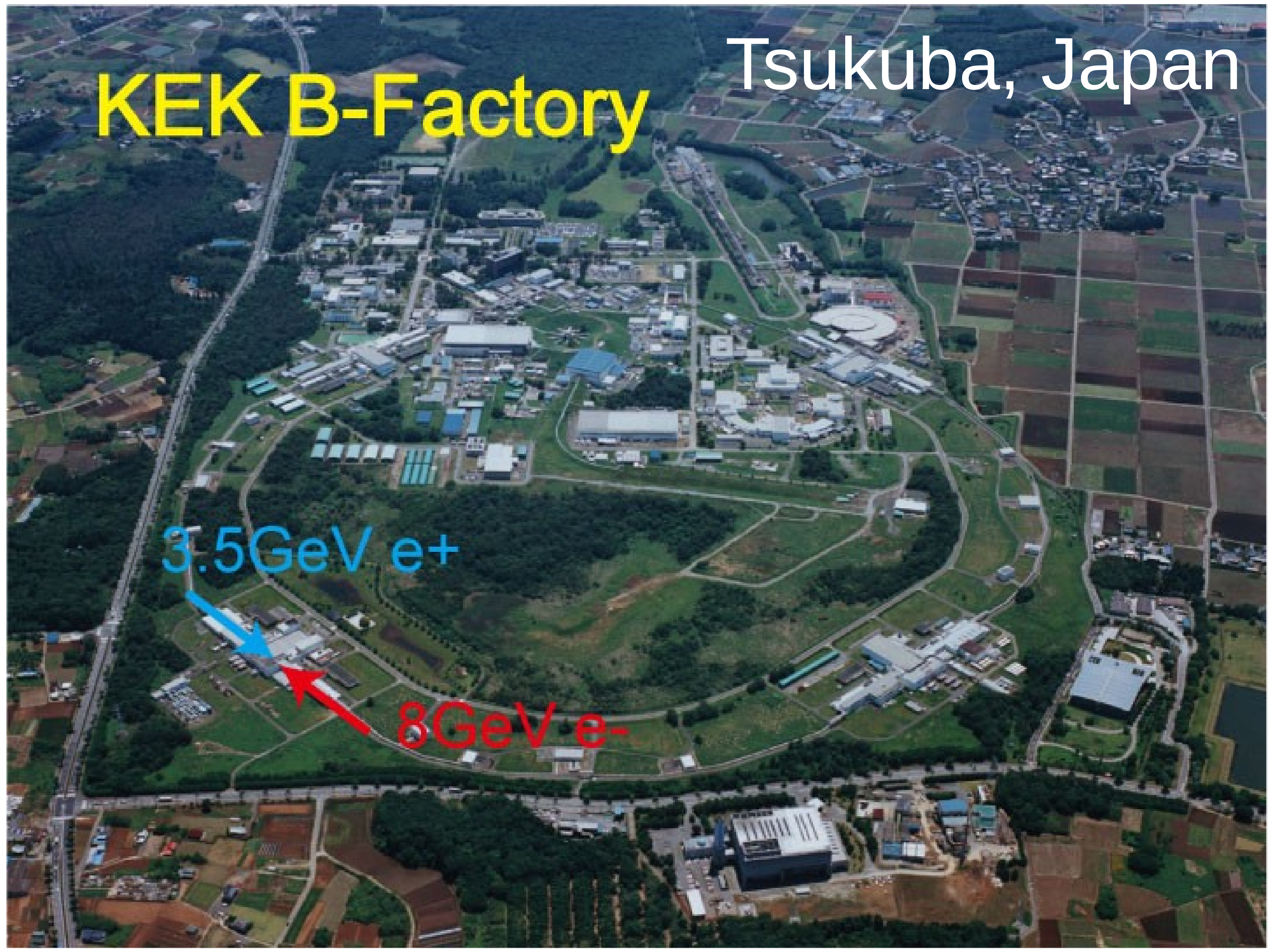
$\tau \to e\nu_\tau \bar{\nu}_e$

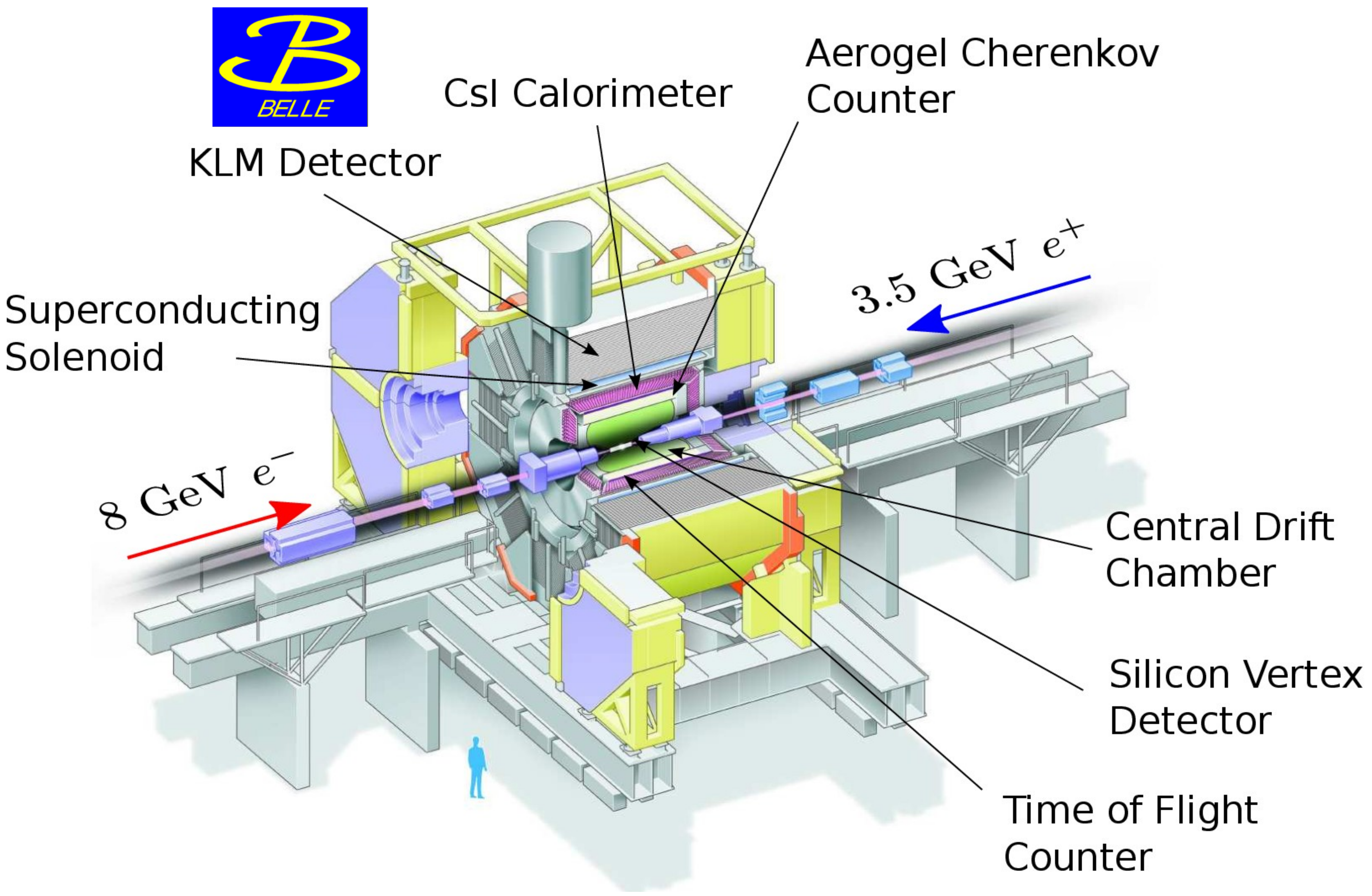
$\tau \to \mu\nu_\tau \bar{\nu}_\mu$

LHCb

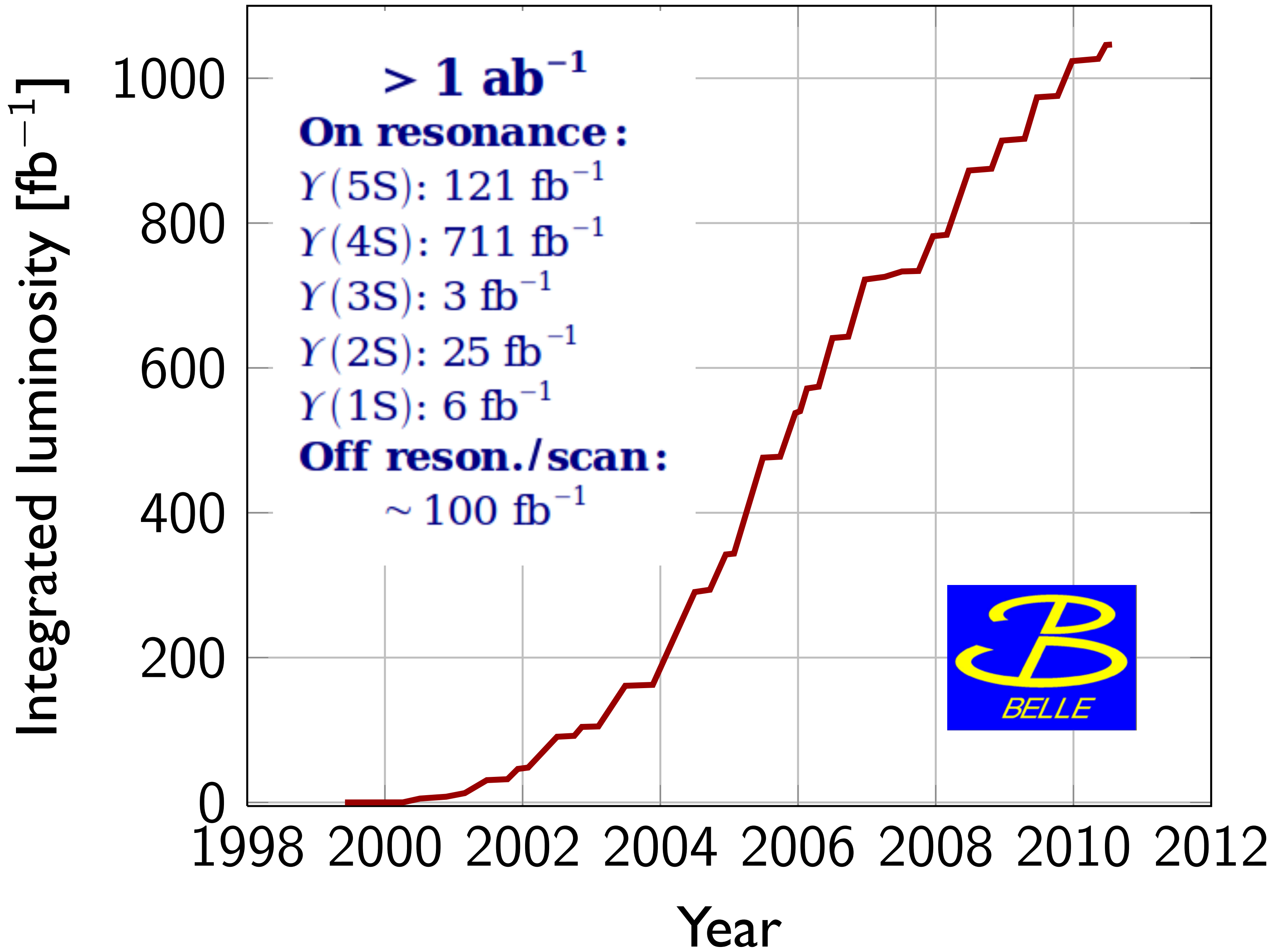
$\tau \to \pi^- \pi^+ \pi^- \nu_\tau$

THE *BELLE* EXPERIMENT (THE FIRST GENERATION B-FACTORY)



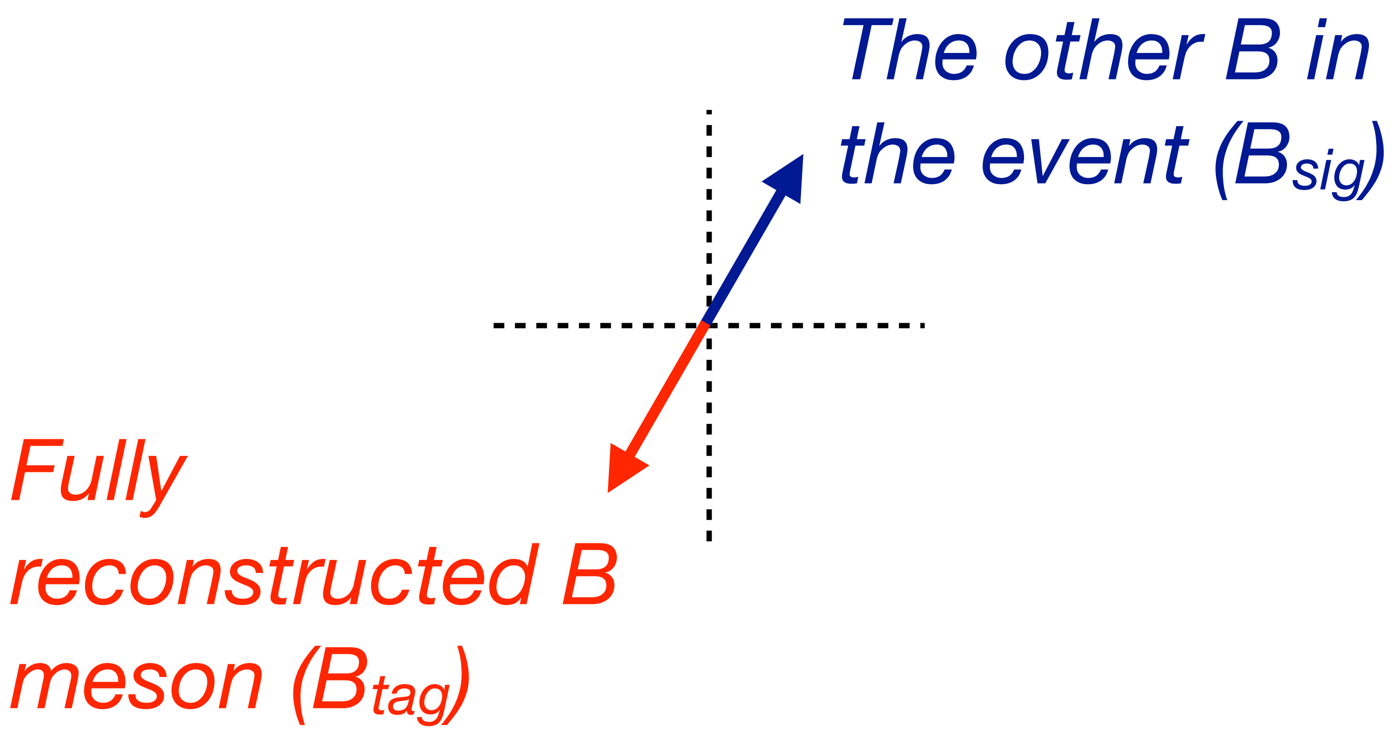


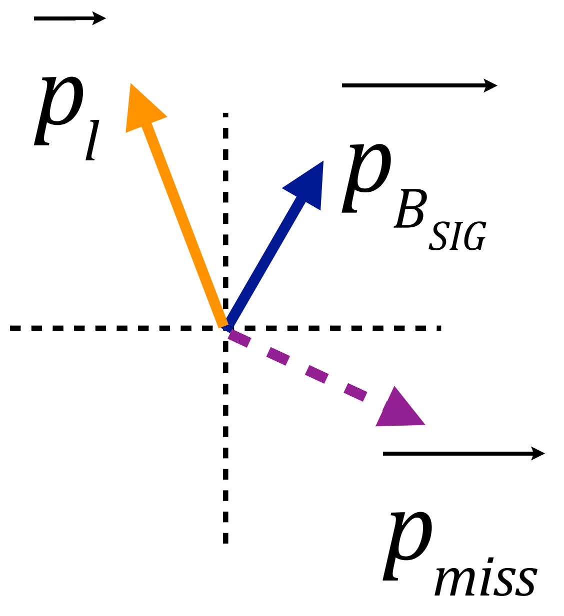
- Operated at the KEKB collider in Tsukuba, Japan (1999-2010).
- Mostly asymmetric beam energy at ϒ(4S) resonance (8 GeV e^- on 3.5 GeV e^+).
- Collected about 772 million $B\bar{B}$ pairs.
- The analyses presented here is based on the full *BELLE* data sample recorded at the ϒ(4S) resonance of 711 fb^{-1}

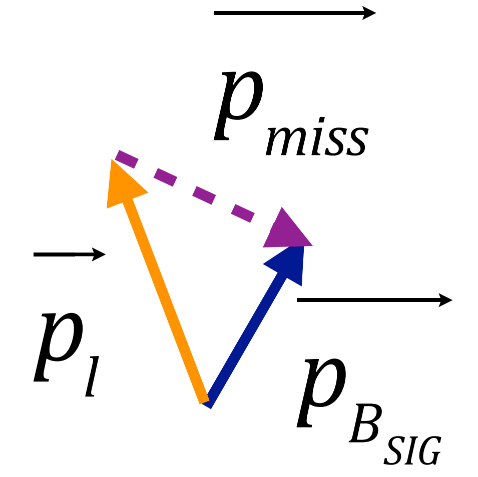


ANALYSIS TECHNIQUE

- **In the ϒ(4S) CM frame** (ϒ(4S)→$B\bar{B}$):
  - energy (E) and Momentum (**p**) of the other B (signal side) is known.
  - Using E and **p** conservation, we can reconstruct τ mass (missing mass) without seeing any τ daughters.







$$\vec{p}_{B_{SIG}} = -\vec{p}_{B_{TAG}}, \qquad E_{B_{SIG}} = E_{BEAM}$$

$$\vec{p}_{miss} = \vec{p}_{B_{SIG}} - \vec{p}_l$$

$$E_{miss} = E_{BEAM} - E_l$$

$$M_{miss} = \sqrt{E_{miss}^{\ 2} - \left(\vec{p}_{miss}\right)^2}$$

- In an event
  - Reconstruct a B meson decaying hadronically (B_{tag}).
  - Exclude tracks coming from B_{tag},
  - In the other B (B_{sig}) side,
    - calculate $\boldsymbol{M_{miss}}$ for each lepton candidate and
    - obtain the missing mass distribution.

EVENT SELECTION

- B_{tag} side is reconstructed in one of 1104 hadronic decay channels using a hierarchical algorithm based on the Neural Network (NN). *[M. Feindt, F. Keller, M. Kreps, T. Kuhr, S. Neubauer, D. Zander, A. Zupanc Nucl. Instrum. Methods Phys. Res., Sect. A 654, 432 (2011)]*

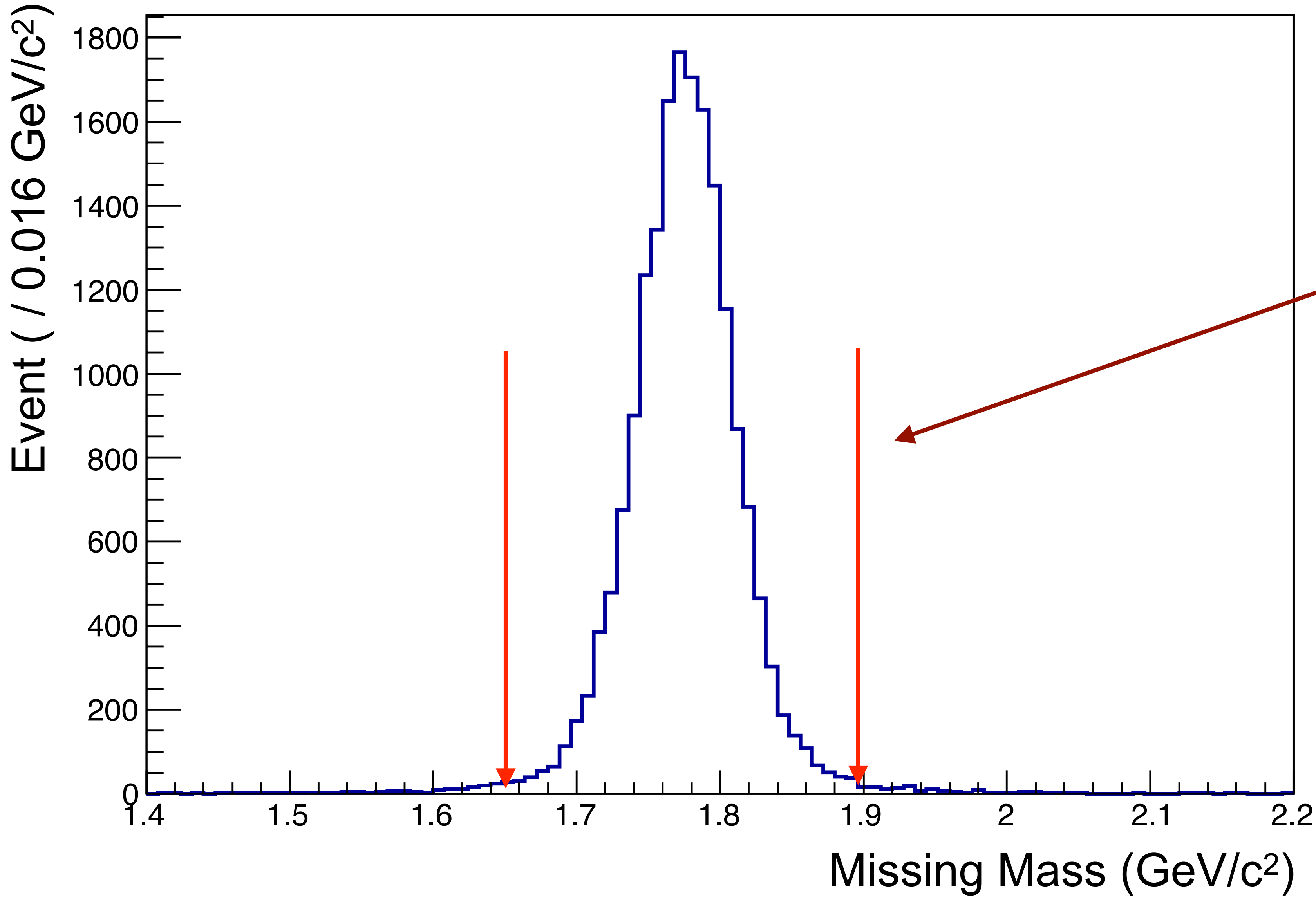
- $O_{NN} > 0.082 \rightarrow B^0 \to \tau\mu$, $O_{NN} > 0.095 \rightarrow B^0 \to \tau e$.
- (B_{tag}) $|\Delta E| < 0.05$ GeV .
- (B_{tag}) $M_{BC} > 5.272$ GeV/c^2 .
- Exclude tracks coming from B_{tag} side.
- 1.4 GeV/c^2 $< M_{miss} <$ 2.2 GeV/c^2 .
- Every lepton candidate is a B_{sig} candidate.

O_{NN}: A single classifier output.
Significantly suppresses $e^+e^- \to q\bar{q}$ continuum events.

Energy difference: $\Delta E = E_B - E_{BEAM}$

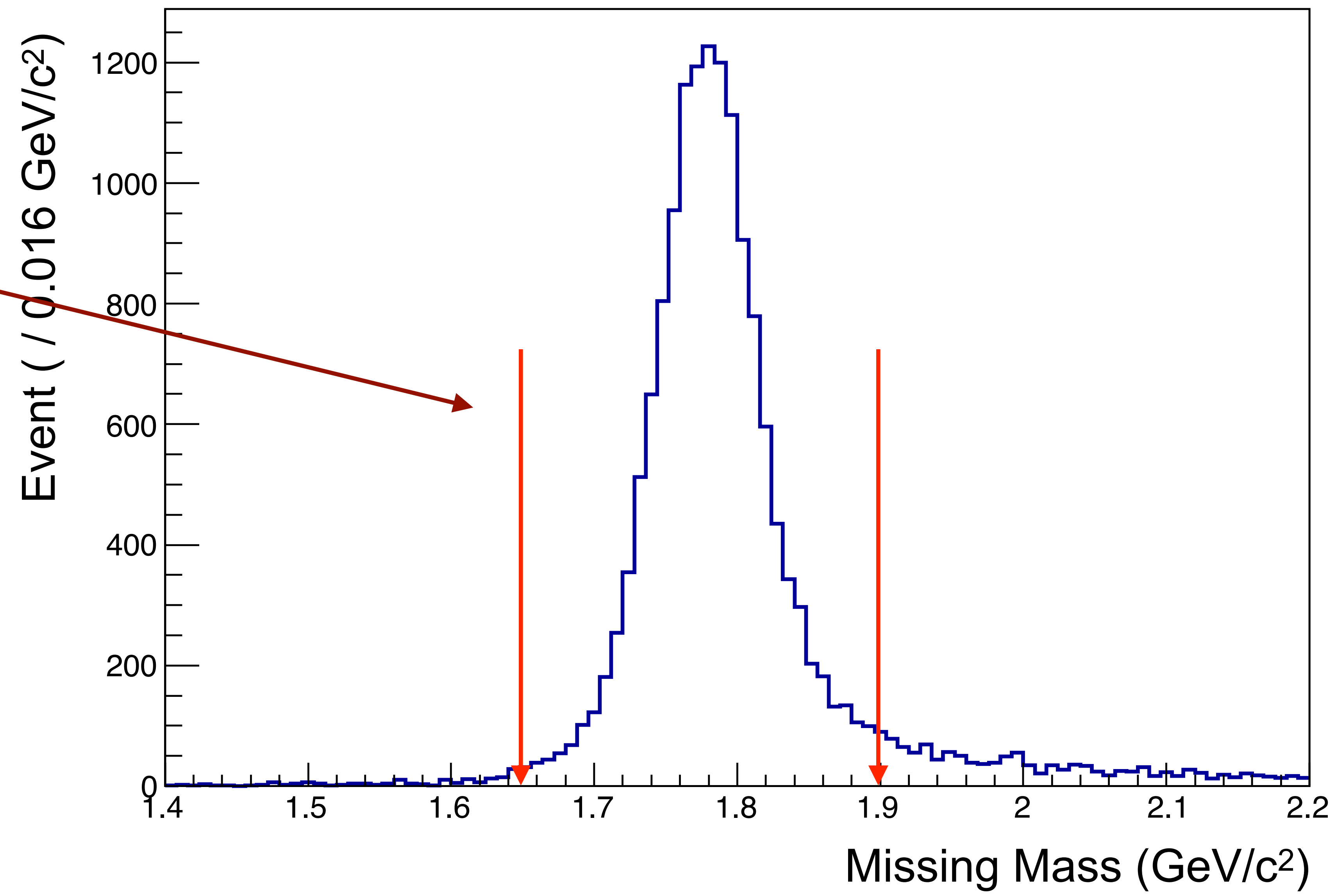
Beam-constrained mass: $M_{BC} = \sqrt{E^2_{BEAM} - \vec{p}^{\,2}_B}$

$B^0 \to \tau\mu$ *(Monte Carlo (MC) using true* μ*)*



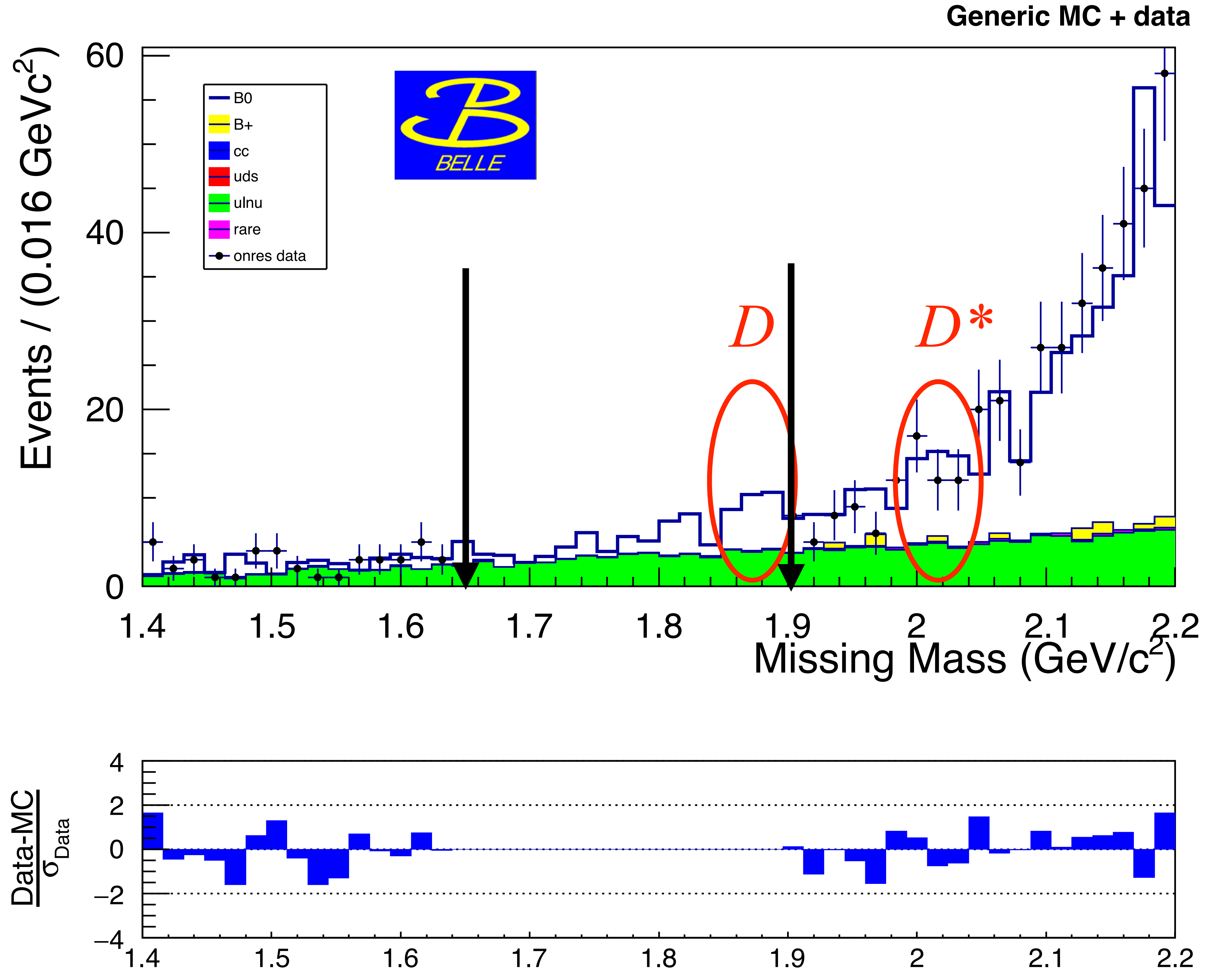
Window **[1.65-1.90]** GeV/c^2 is used to hide the number of events on the data.

$B^0 \to \tau e$ *(Monte Carlo (MC)using true* e*)*

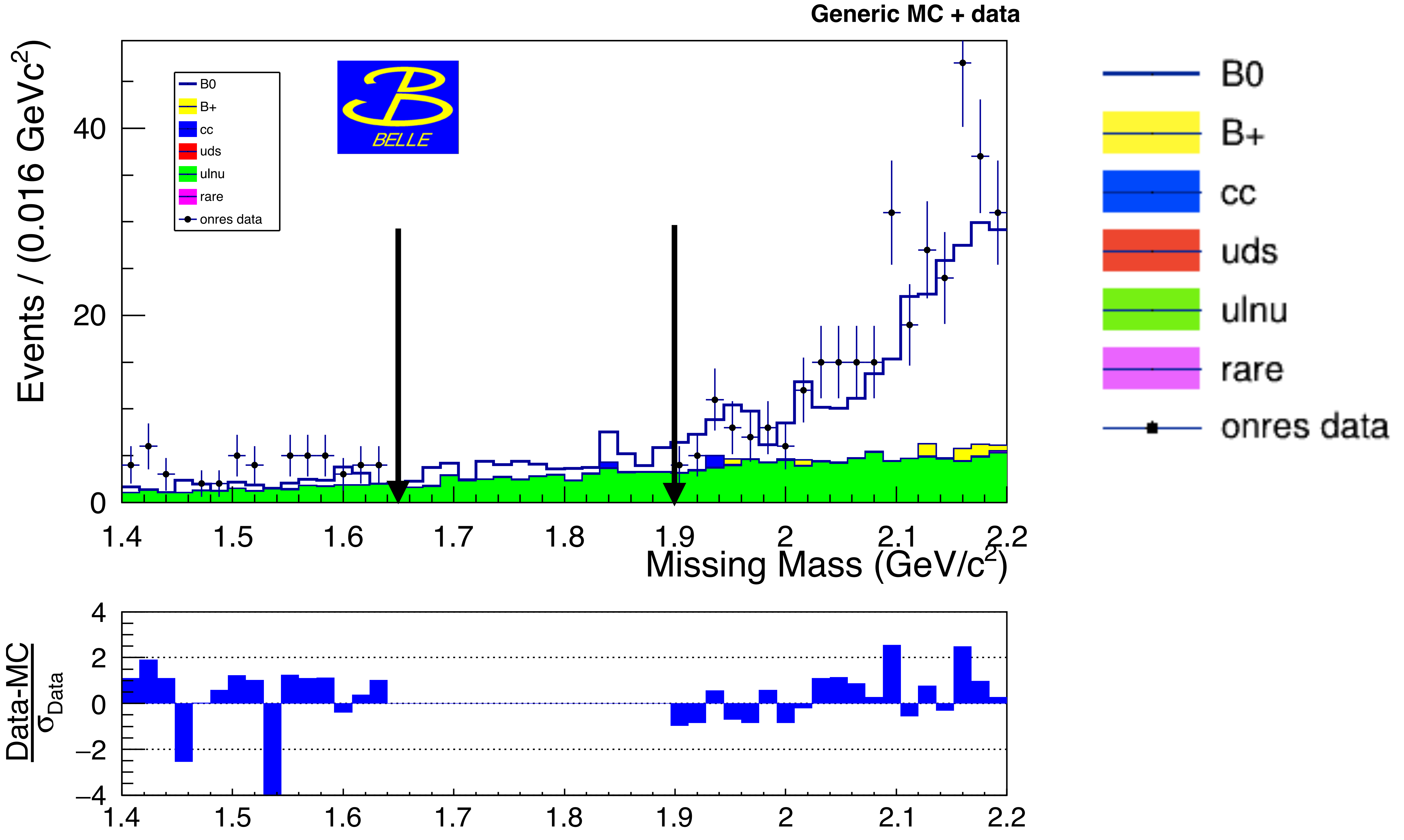


BACKGROUND STUDY

$B^0 \to \tau\, \mu$



$B^0 \to \tau\, e$



- Background originates mainly from $b \to c$ and $b \to ul\nu$ decays smoothly falling in the M_{miss} distributions.
- $B^0 \to \tau\, \mu$: Because π^+ is misidentified as μ^+ , two small peaks are observed: one at M_{miss} ≈1.869 GeV/c² (D meson) and the other M_{miss} ≈ 2.010 GeV/c² (D* meson).

UNBINNED MAXIMUM LIKELIHOOD (ML) FIT DESCRIPTION

Fit Variables

- Missing Mass (M_{miss})

Fit Window

- M_{miss} [1.4 - 2.2] GeV/c^2

Fit Components

$B \to \tau\,\mu$

- Signal $B^0 \to \mu\ \tau$ events that contain correctly identified μ's (true signal) [95%]
- Signal self-cross-feed (SxF) events defined as events containing mis-identified μ's [5%],
- Background (Combinatoric BG ($q\overline{q}$), $b \to ulv$, rare *B* decays)
- Peaking BG-1 ($B^0 \to D\,\pi$)
- Peaking BG-2 ($B^0 \to D^*\,\pi$)

$B \to \tau\, e$

- Signal $B^0 \to e\ \tau$ events that contain correctly identified e's (true signal) [86%]
- Signal self-cross-feed (SxF) events defined as events containing mis-identified e's [14%],
- Background (Combinatoric BG ($q\overline{q}$), $b \to ulv$, rare *B* decays)

Floating Parameters:

$B \to \tau\,\mu$:

- signal, background and $B^0 \to D\,\pi$, $B^0 \to D^*\,\pi$ peaking background yields,
- background shape parameters.

$B \to \tau\, e$:

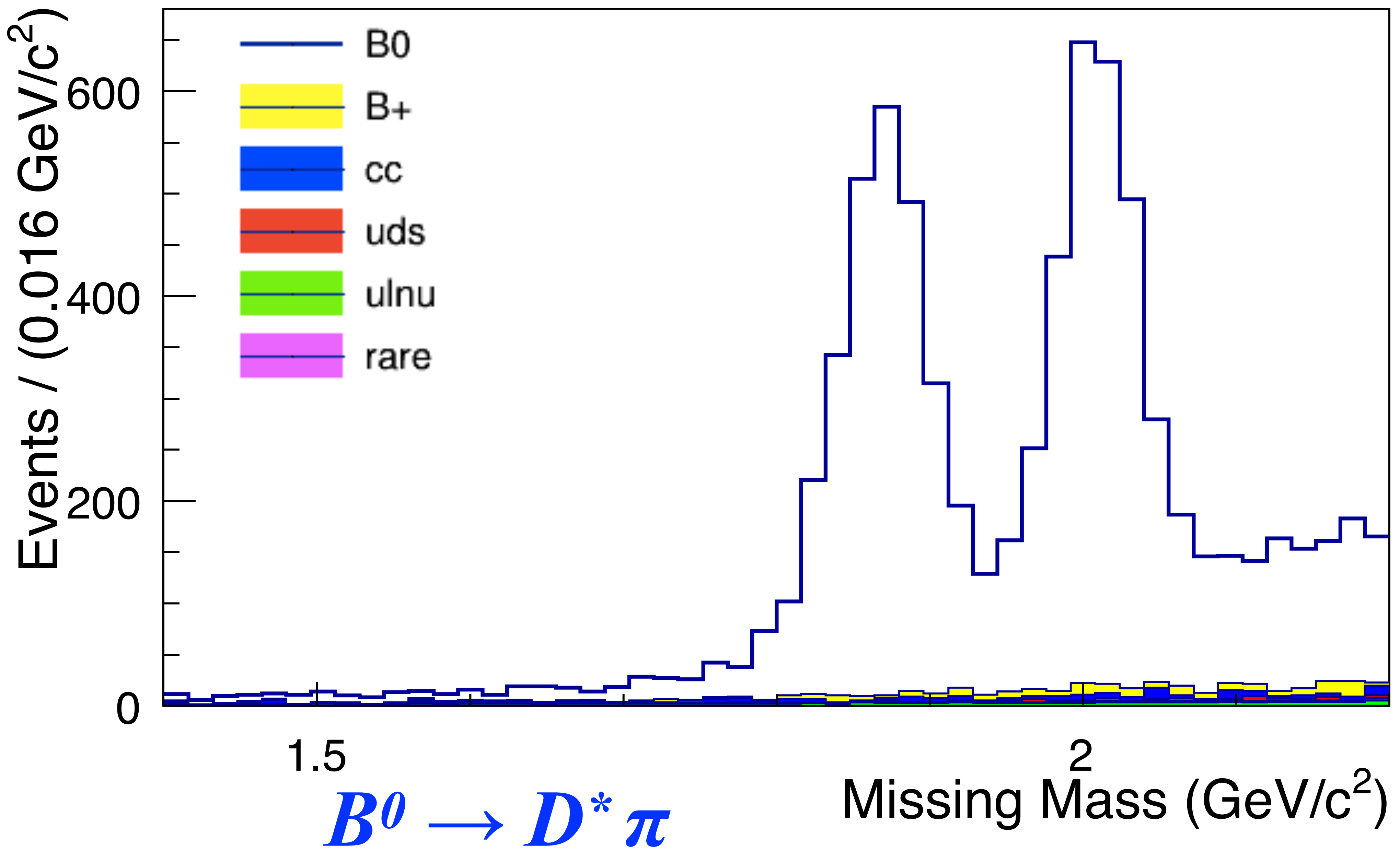
- signal, background yields,
- background shape parameters.

Validation of Analysis Method with Control Sample $B^0 \to D^{(*)}\pi$

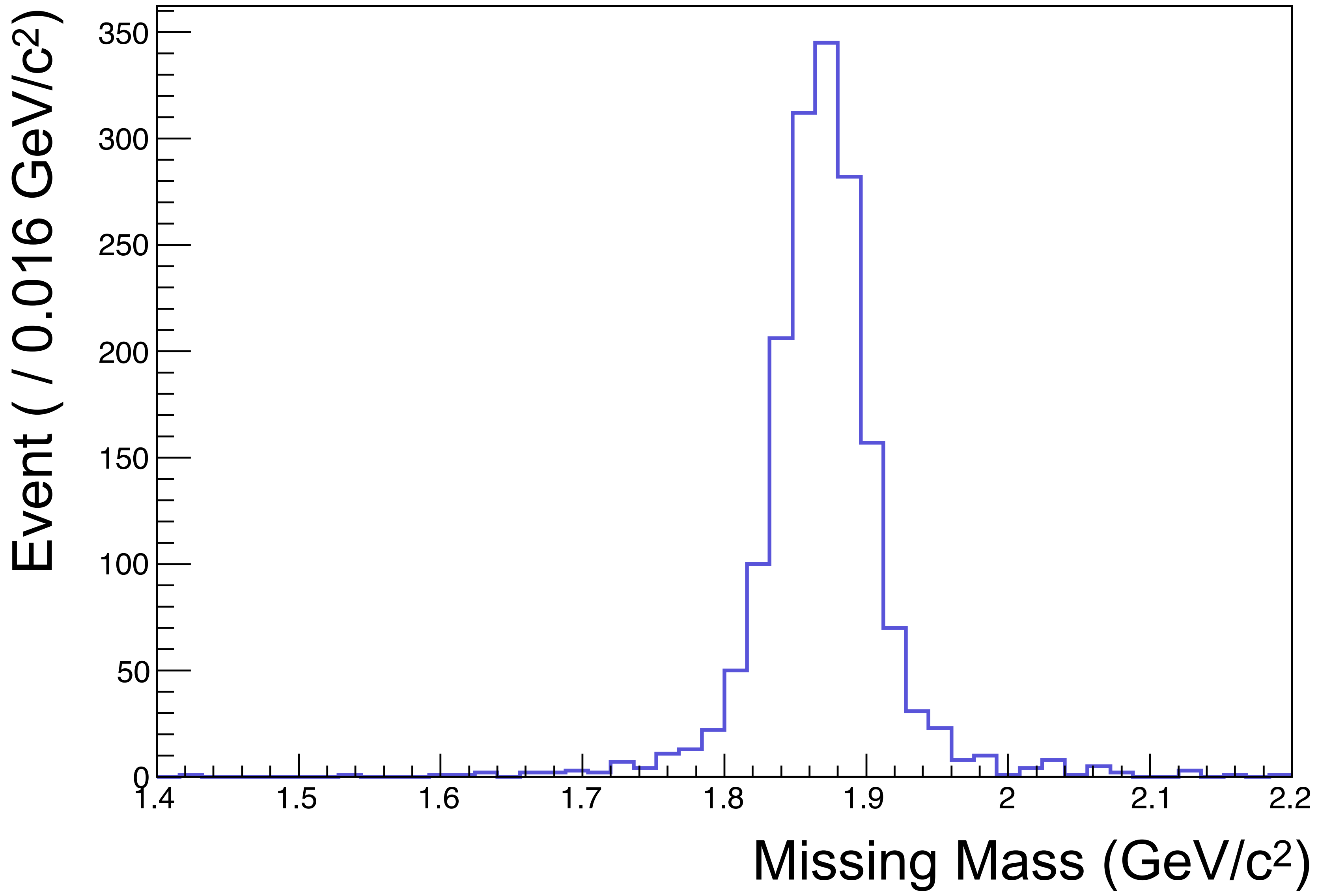
Same $B^0 \to \tau^\mp \mu^\pm$ event selection criteria

- (B_{tag}) $|\Delta E| < 0.05$ GeV .
- (B_{tag}) $M_{BC} > 5.272$ GeV/c^2 .
- $O_{NN} > 0.082$.
- Exclude tracks coming from B_{tag} side.
- 1.4 GeV/$c^2 < M_{miss} <$ 2.2 GeV/c^2.
- Every π candidate is a B_{sig} candidate.

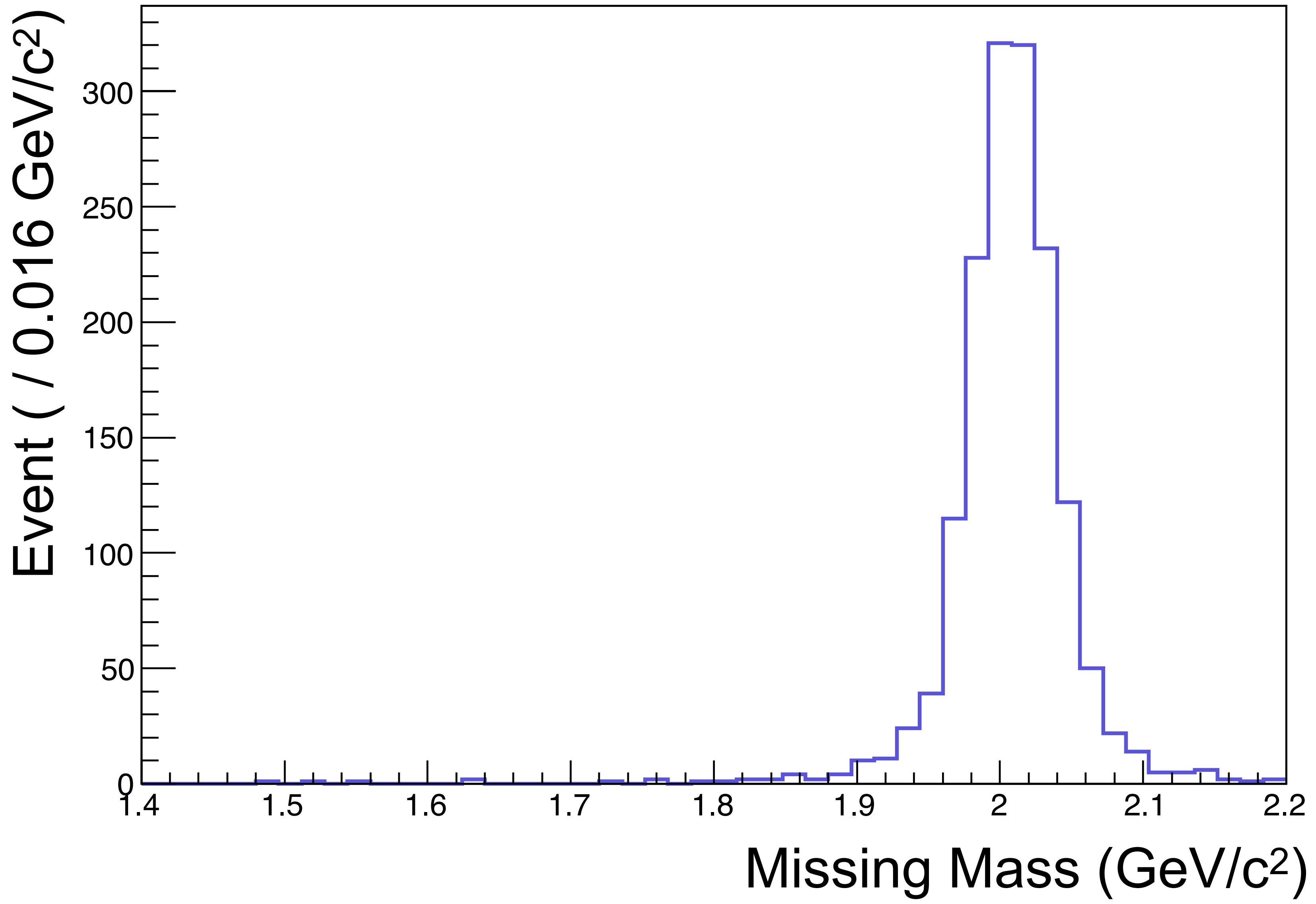
MC (B^0, B^+, $q\bar{q}$, $b \to ul\nu$, rare B decays)



$B^0 \to D\pi$
(MC using true π)



$B^0 \to D^*\pi$
(MC using true π)



$B^0 \to D^{(*)}\pi$ Unbinned ML Fit Description

Fit Variables

- Missing Mass (M_{miss})

Fit Window

- M_{miss} [1.4 - 2.2] GeV/c^2

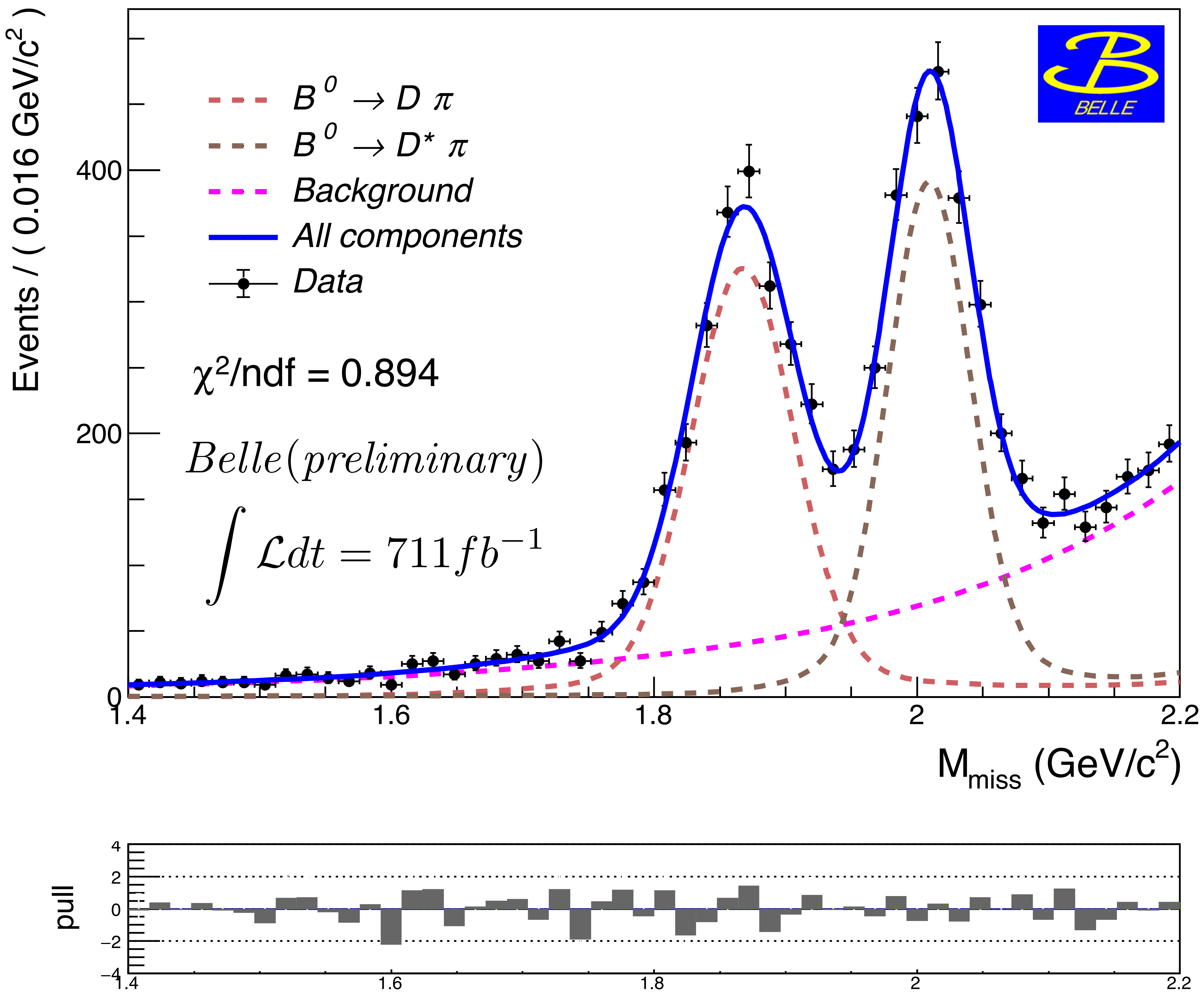
Fit Components

- Signal $B^0 \to D^{(*)}\pi$ events that contain correctly identified π's (true signal) [95%]
- Signal self-cross-feed (SxF) events defined as events containing mis-identified π's [5%],
- Background (Combinatoric BG ($q\overline{q}$), $b \to ulv$, rare B decays)

Floating Parameters:

- signal, background yields,
- means and widths of core Gaussians of $B^0 \to D\pi$ and $B^0 \to D^*\pi$ PDF functions,
- background shape parameters.

$B^0 \to D^{(*)}\pi$ ML Fit Results



$$BR = \frac{N_{sig}}{2 \times N_{B\bar{B}} \times f^{00} \times \varepsilon}$$

$N_{B\bar{B}} = (771 \pm 10.6) \times 10^6$ $f^{00} = BR(\Upsilon(4S) \to B^0 \bar{B}^0) = (48.6 \pm 0.6)\%$

N_{sig}

$B^0 \to D\pi$: **2136 ± 71**

$B^0 \to D^*\pi$: **2071 ± 74**

ε (signal efficiency including tag-side branching fractions and reconstruction efficiencies) :

$B^0 \to D\pi$: **11.2 x 10^{-4}**

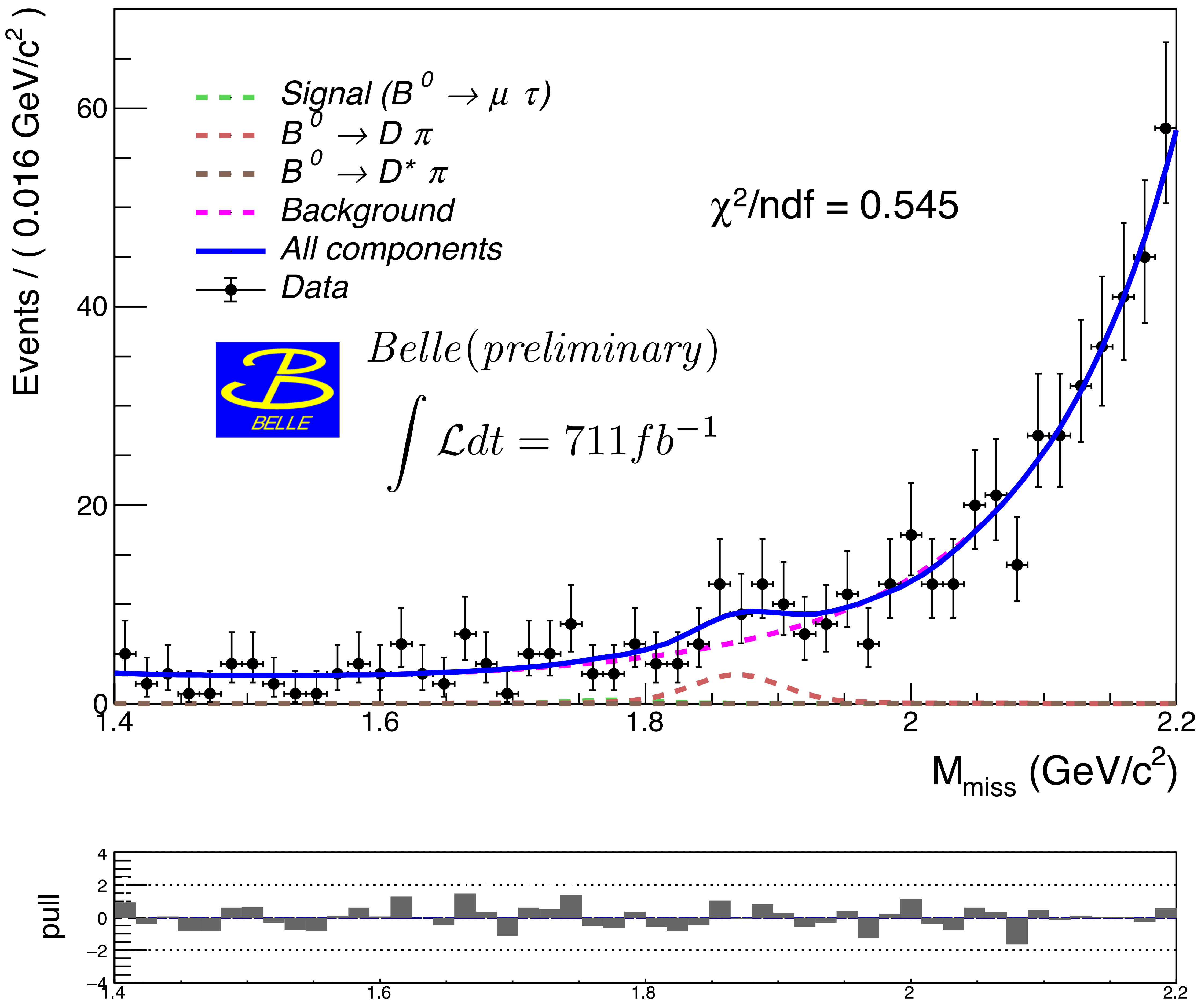
$B^0 \to D^*\pi$: **10.3 x 10^{-4}**

Branching fraction x 10^{-3}

Mode	World average	This measurement	Difference
$B^0 \to D^- \pi^+$	2.52 ± 0.13 (stat+sys)	2.54 ± 0.11 (stat)	0.1σ
$B^0 \to D^{*-} \pi^+$	2.74 ± 0.13 (stat+sys)	2.67 ± 0.12 (stat)	0.4σ

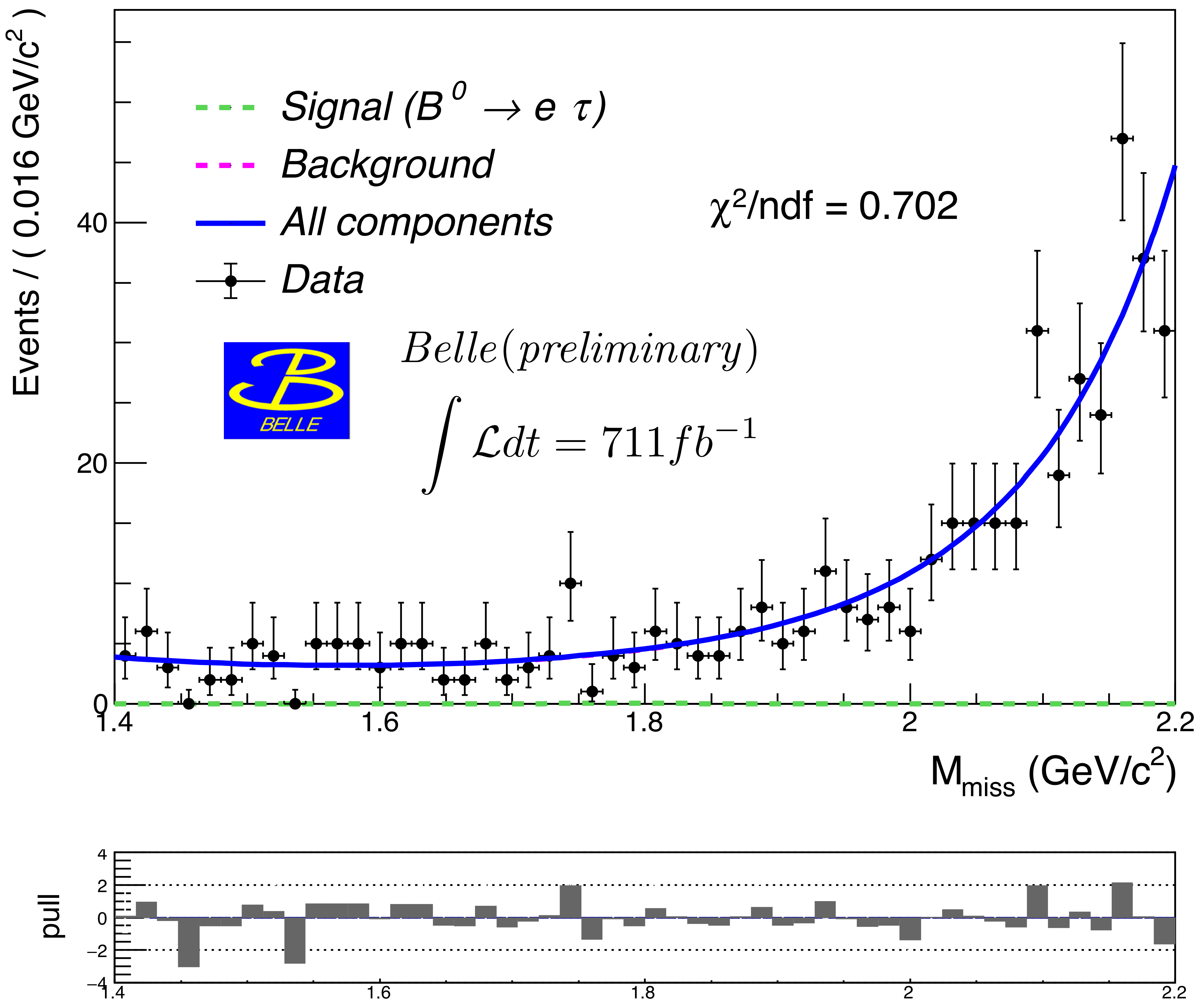
$B \to \tau\, l$ ML FIT RESULTS

$B \to \tau\, \mu$



$$N_{sig} = 1.8^{+8.2}_{-7.6}$$

$B \to \tau\, e$



$$N_{sig} = 0.3^{+8.8}_{-8.2}$$

Conclusion

- We have searched for the lepton-flavor violating $B^0 \to \tau^{\mp} l^{\pm}$ ($l=e, \mu$) decays using the full Belle data set.
- We find no evidence for these decays and set the following upper limits on the branching fractions at 90% C.L. using frequentist method:

Mode	ε (x 10^{-4})	N_{sig}	N_{sig}^{UL}	BR^{UL} (x 10^{-5}) 90% C.L. BELLE preliminary 771 M $B\bar{B}$	BR^{UL} (x 10^{-5}) 90% C.L. BABAR 378 M $B\bar{B}$	BR^{UL} (x 10^{-5}) 90% C.L. LHCb 3 fb^{-1} of pp collisions
$B_{(d)}{}^0 \to \tau^{\mp} e^{\pm}$	9.8	$0.3^{+8.8}_{-8.2}$	11.6	1.6	2.8	-
$B_{(d)}{}^0 \to \tau^{\mp} \mu^{\pm}$	11.0	$1.8^{+8.2}_{-7.6}$	12.4	1.5	2.2	1.2

Extra

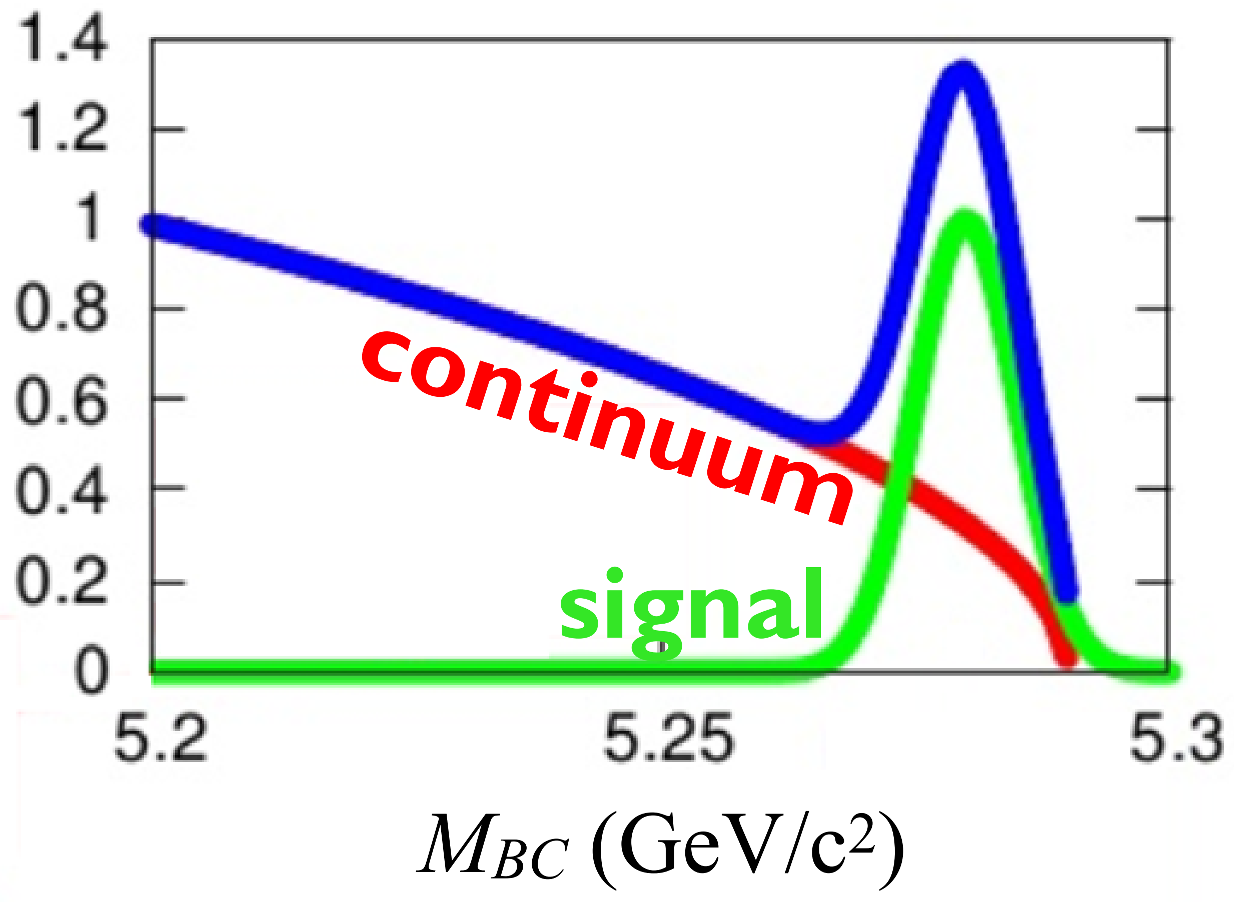
TWO KINEMATIC VARIABLES USED IN B-FACTORIES TO IDENTIFY B MESON

- To identify *B* decays, kinematic variables are used: ***M***$\boldsymbol{M_{BC}}$ and ***ΔE***

M

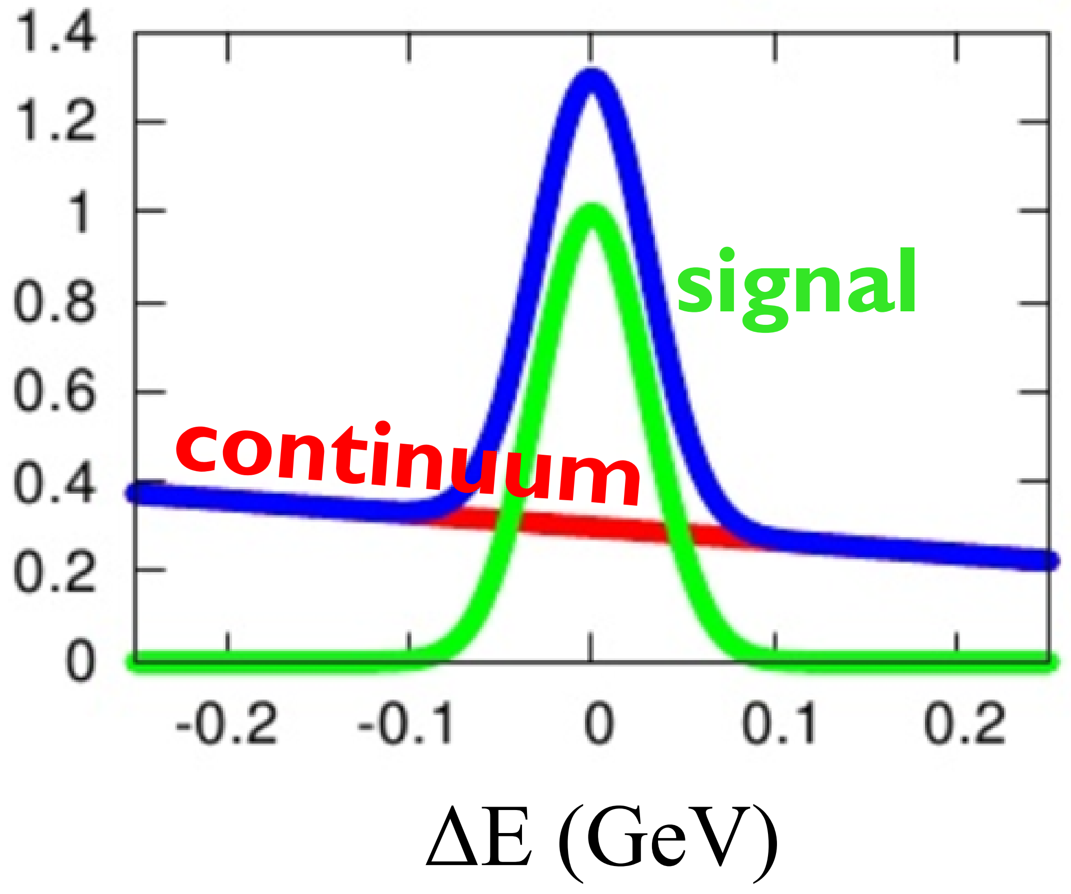
M_{BC} **:** beam-constrained mass

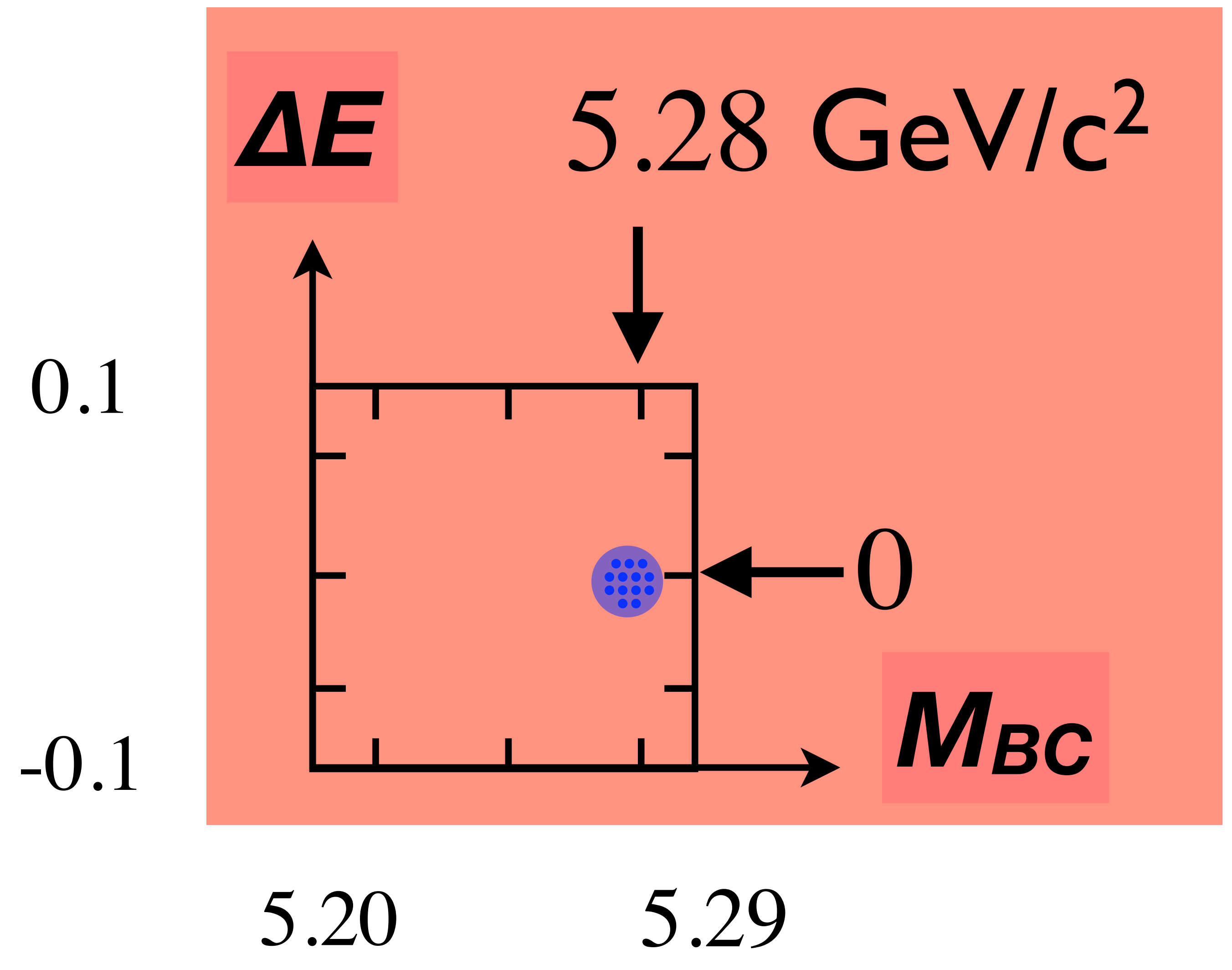
$$M_{BC} = \sqrt{E_{BEAM}^2 - \vec{p}_B^{\,2}}$$



ΔE **:** energy difference

$$\Delta E = E_B - E_{BEAM}$$

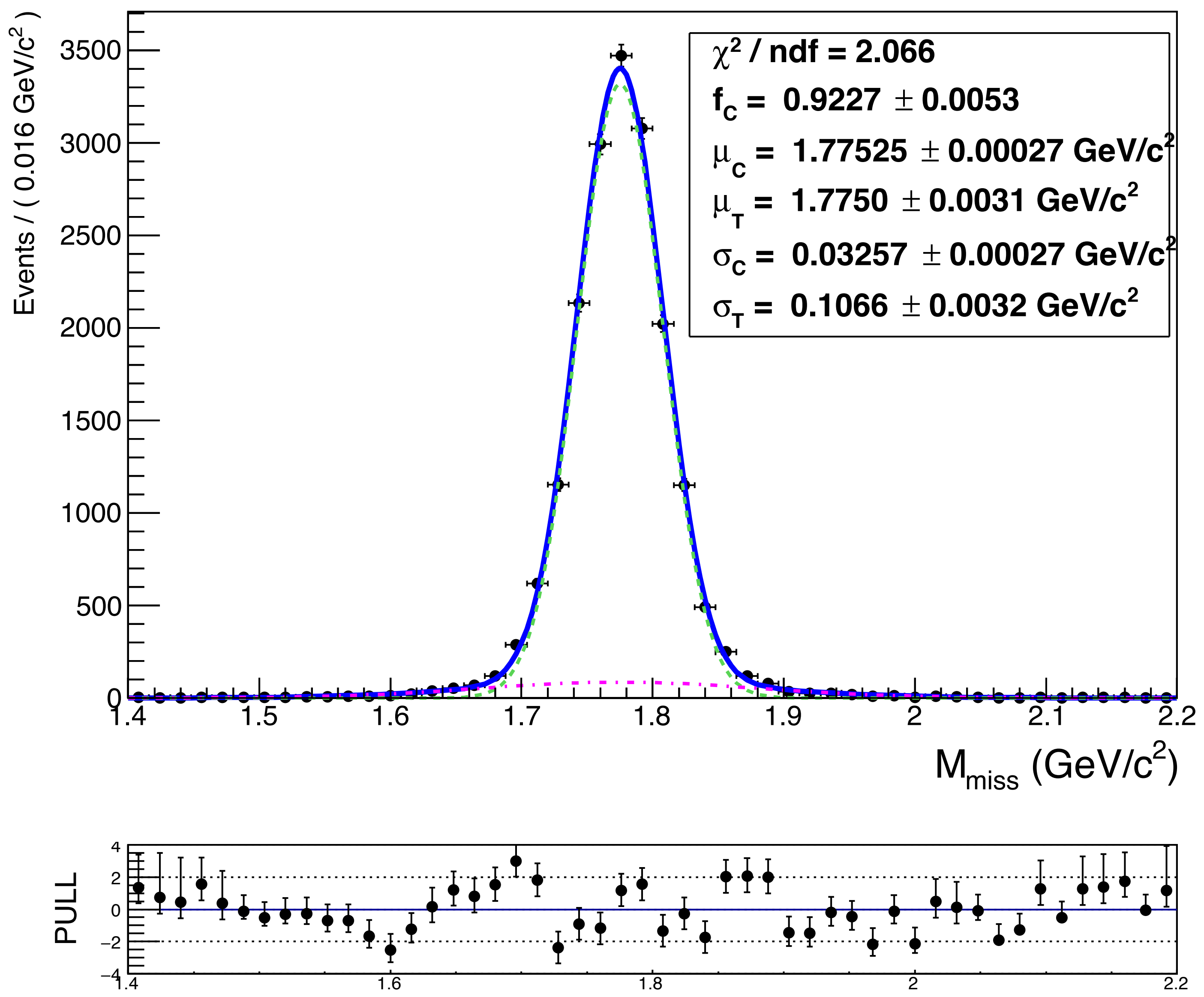




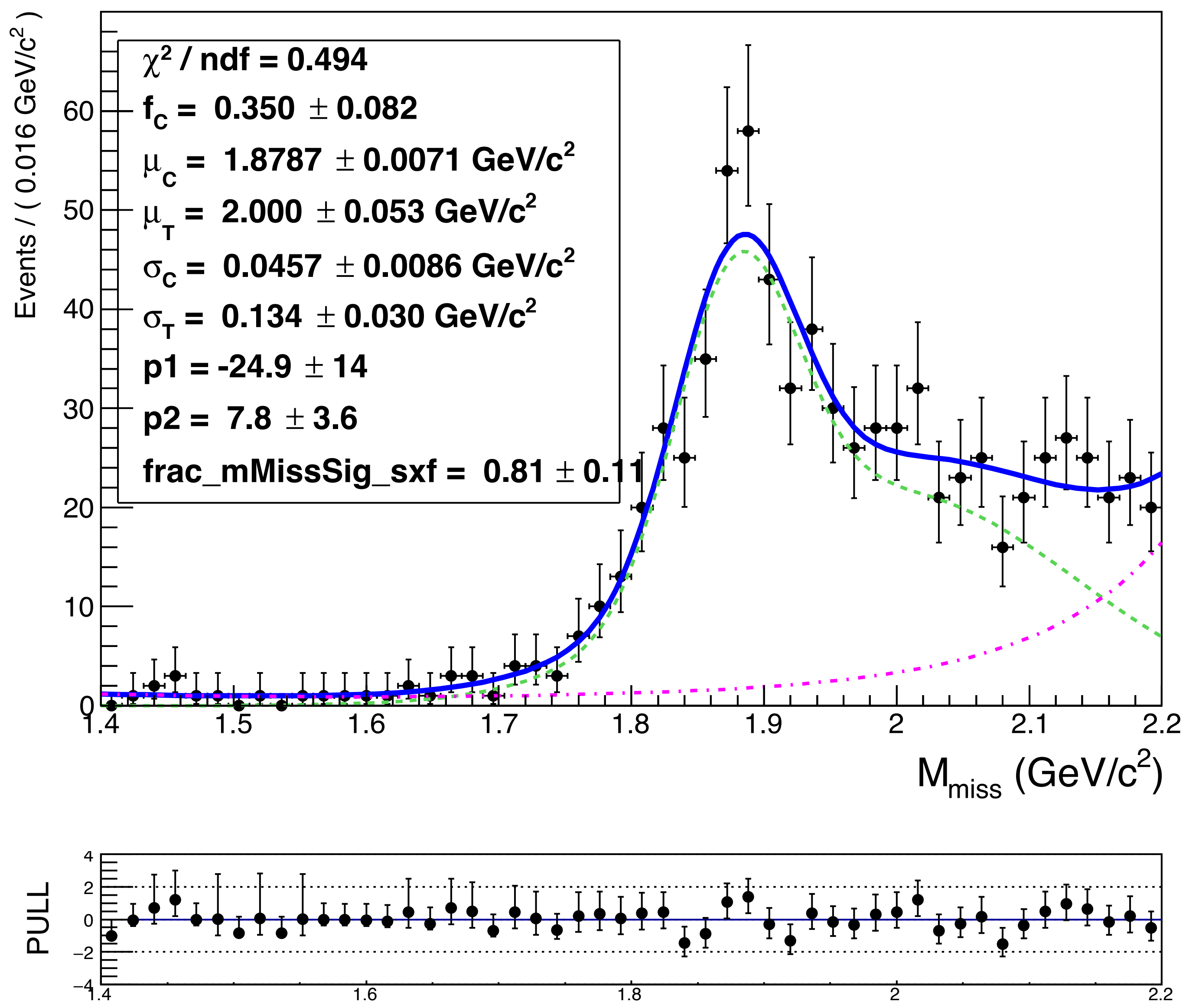
- E_B^* and p_B^* are energy and momentum of *B* candidate, and E_{BEAM}^* is the beam energy in the Υ(4S) center-of-mass frame.
- continuum events [$e^+ e^- \to q\bar{q}$ (q = u,d,s,c)]

$B^0 \to \mu\ \tau$ Pdf Fit Using MC

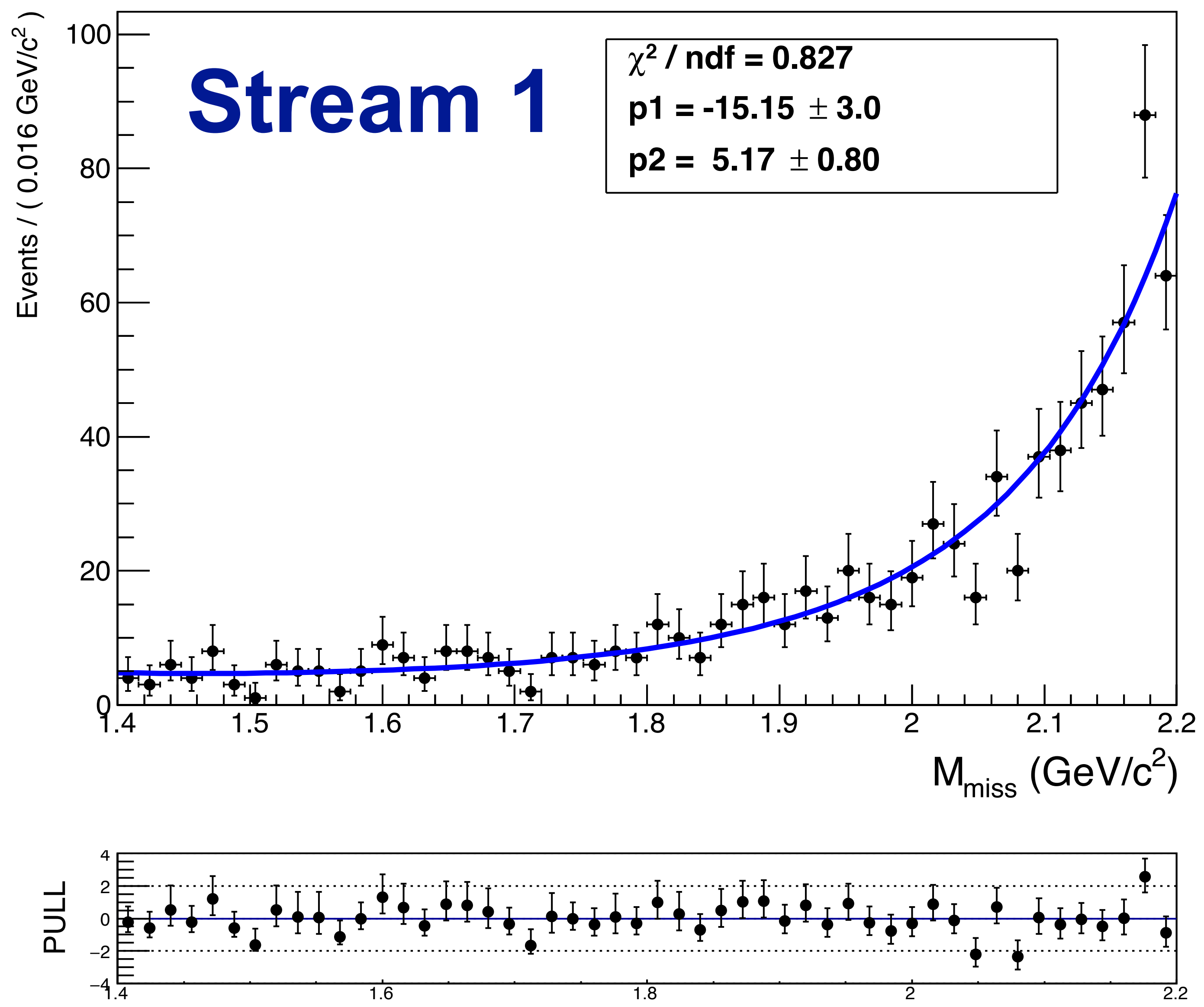
Signal (True) Double Gaussian



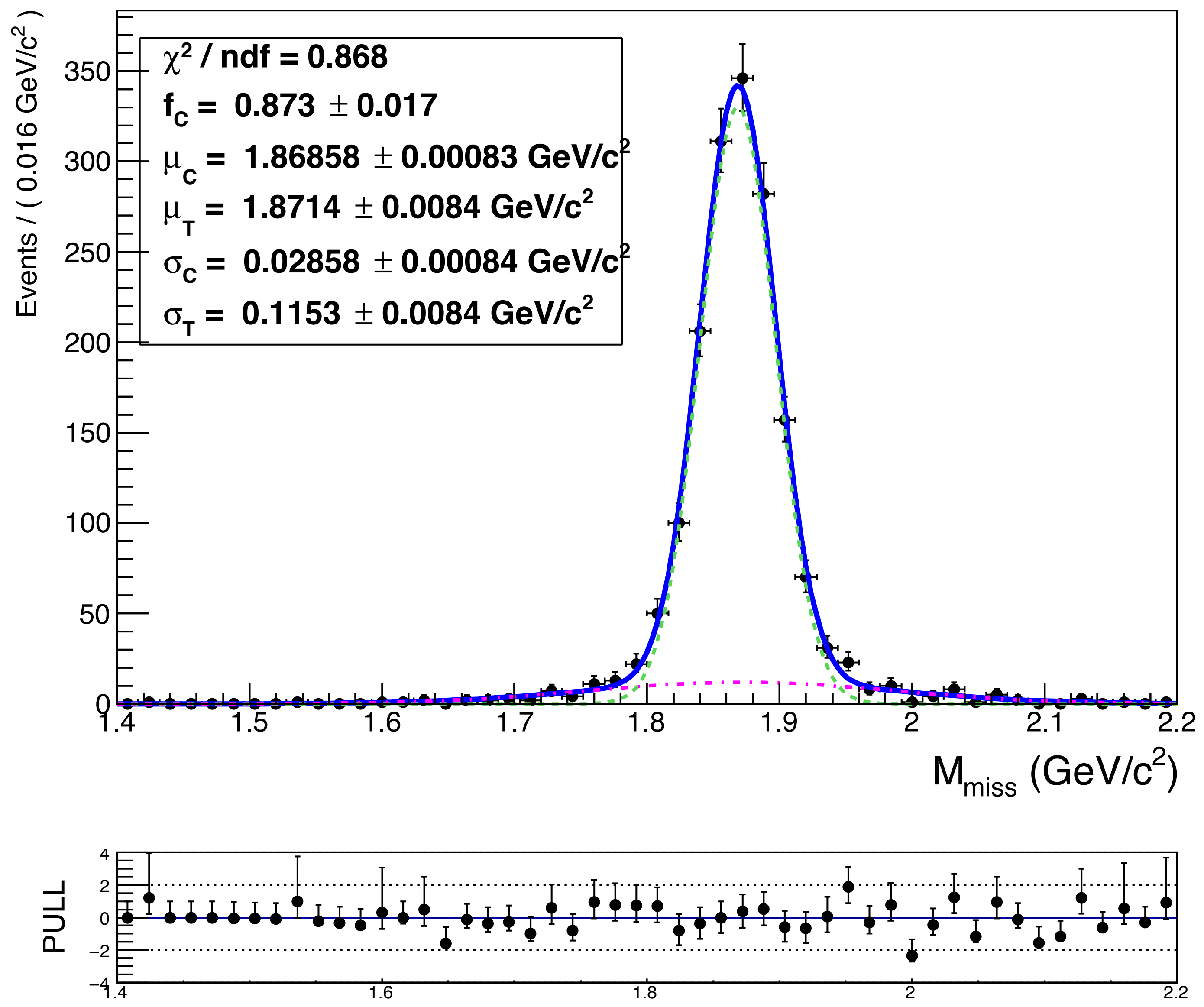
Signal (SxF) Double Gaussian + $e^{(bx+cx^2)}$



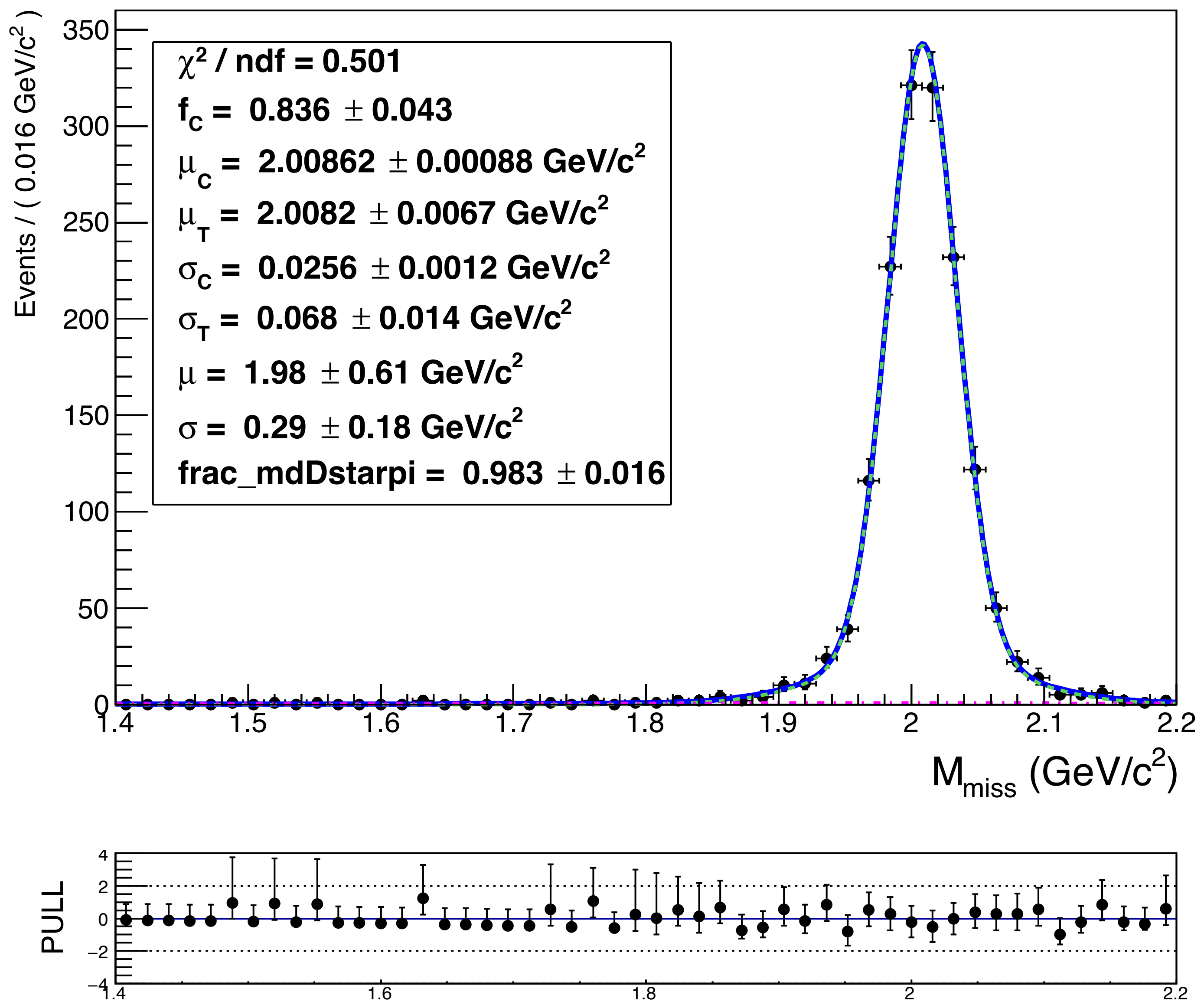
Background (MC qqbar + ulnu +rare) $e^{(bx+cx^2)}$



Peaking Bkg ($B^0 \to D\ \pi$) Double Gaussian

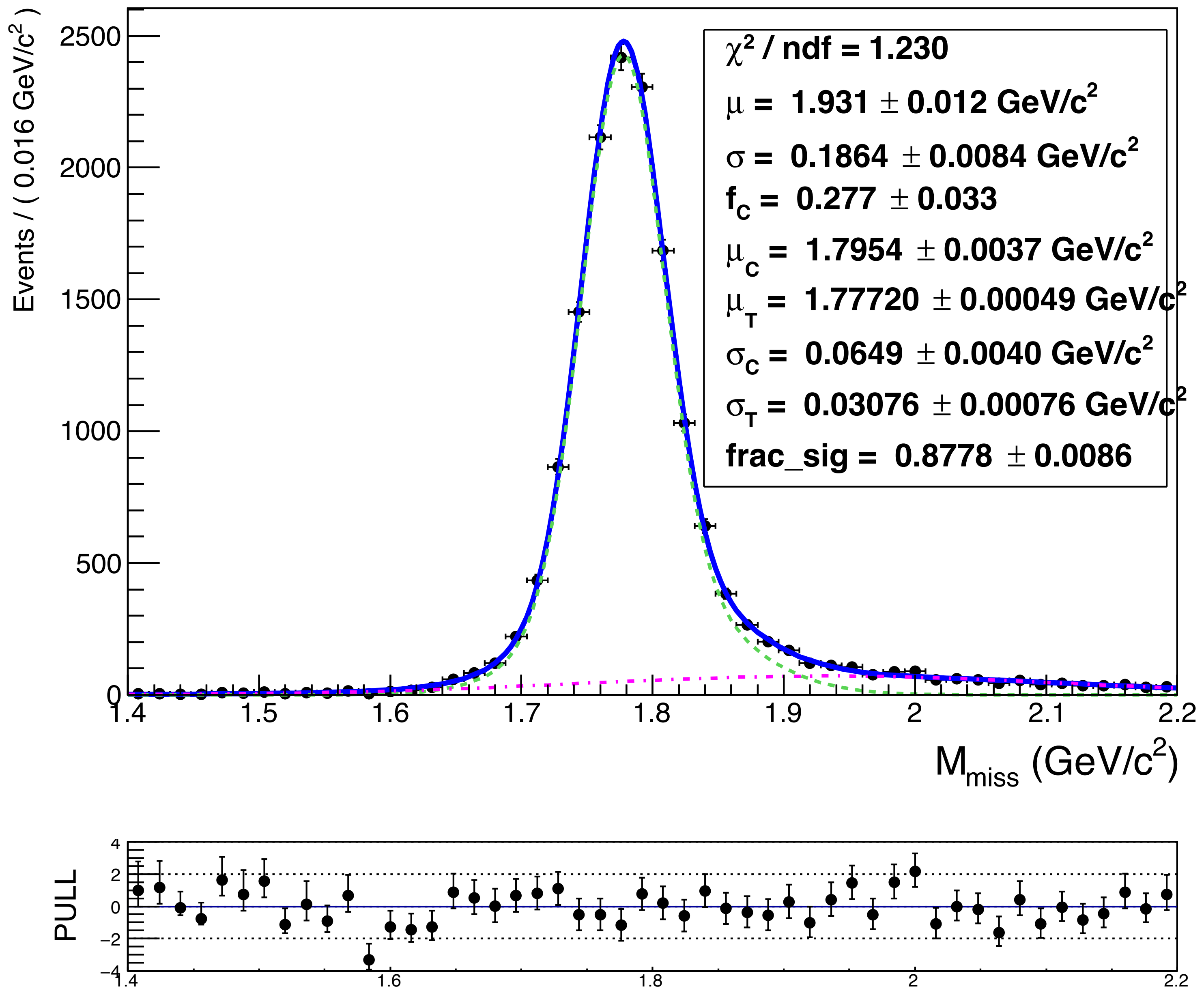


Peaking Bkg ($B^0 \to D^*\ \pi$) Double + Single Gaussian

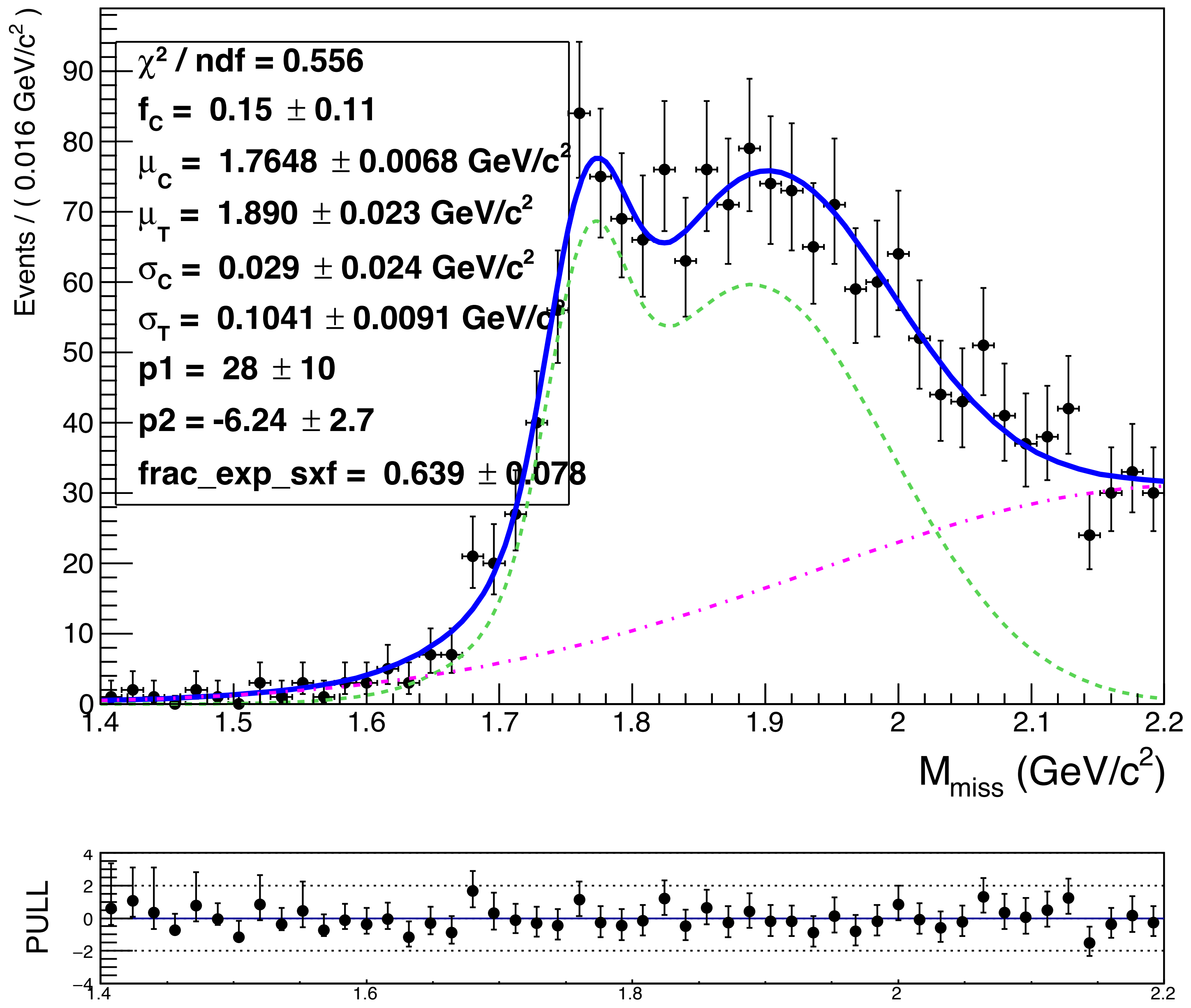


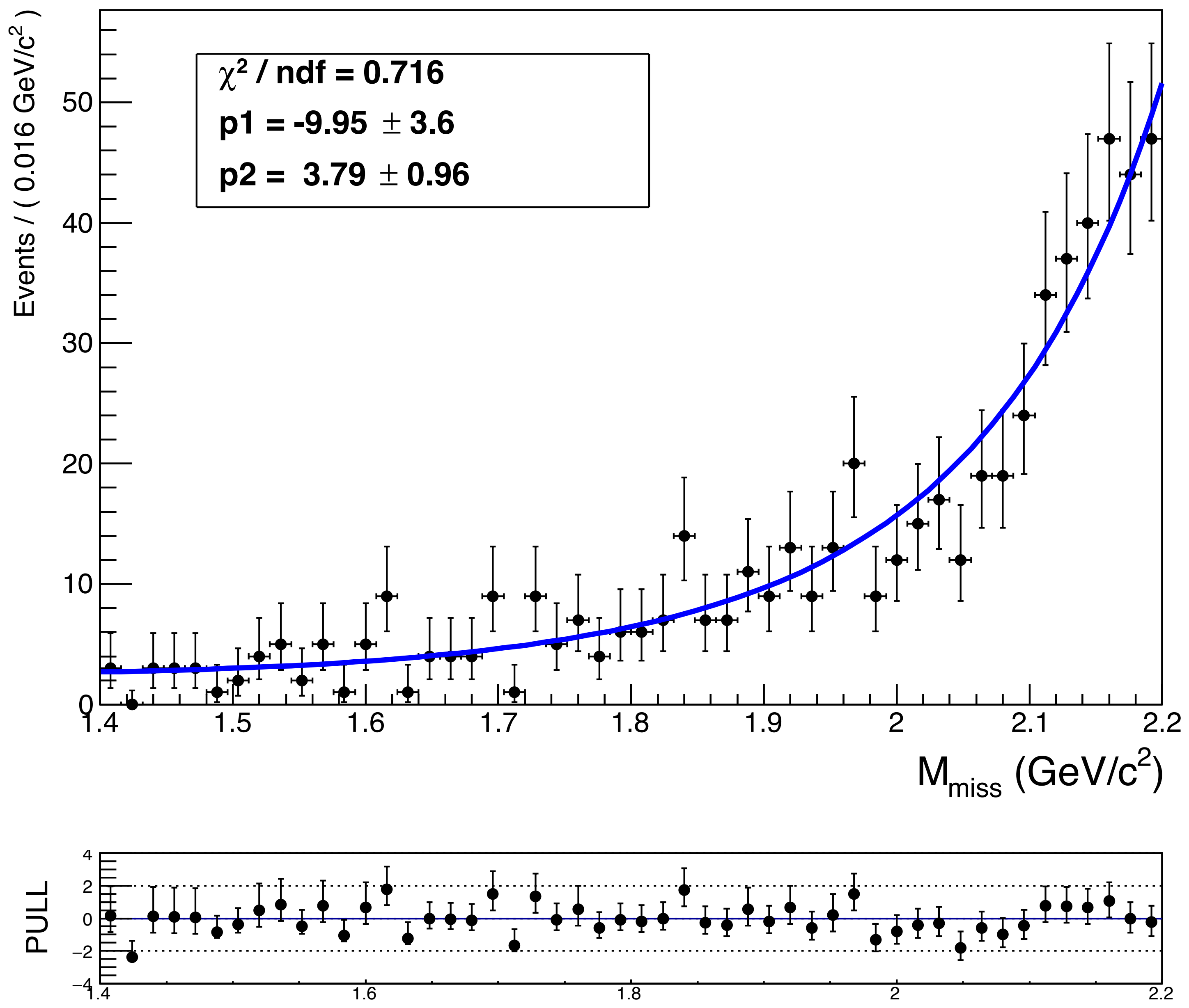
$B^0 \to \tau\, e$ Pdf Fit Using MC

Signal (True) Single +Double Gaussian



Signal (SxF) Double Gaussian + $e^{(bx+cx^2)}$



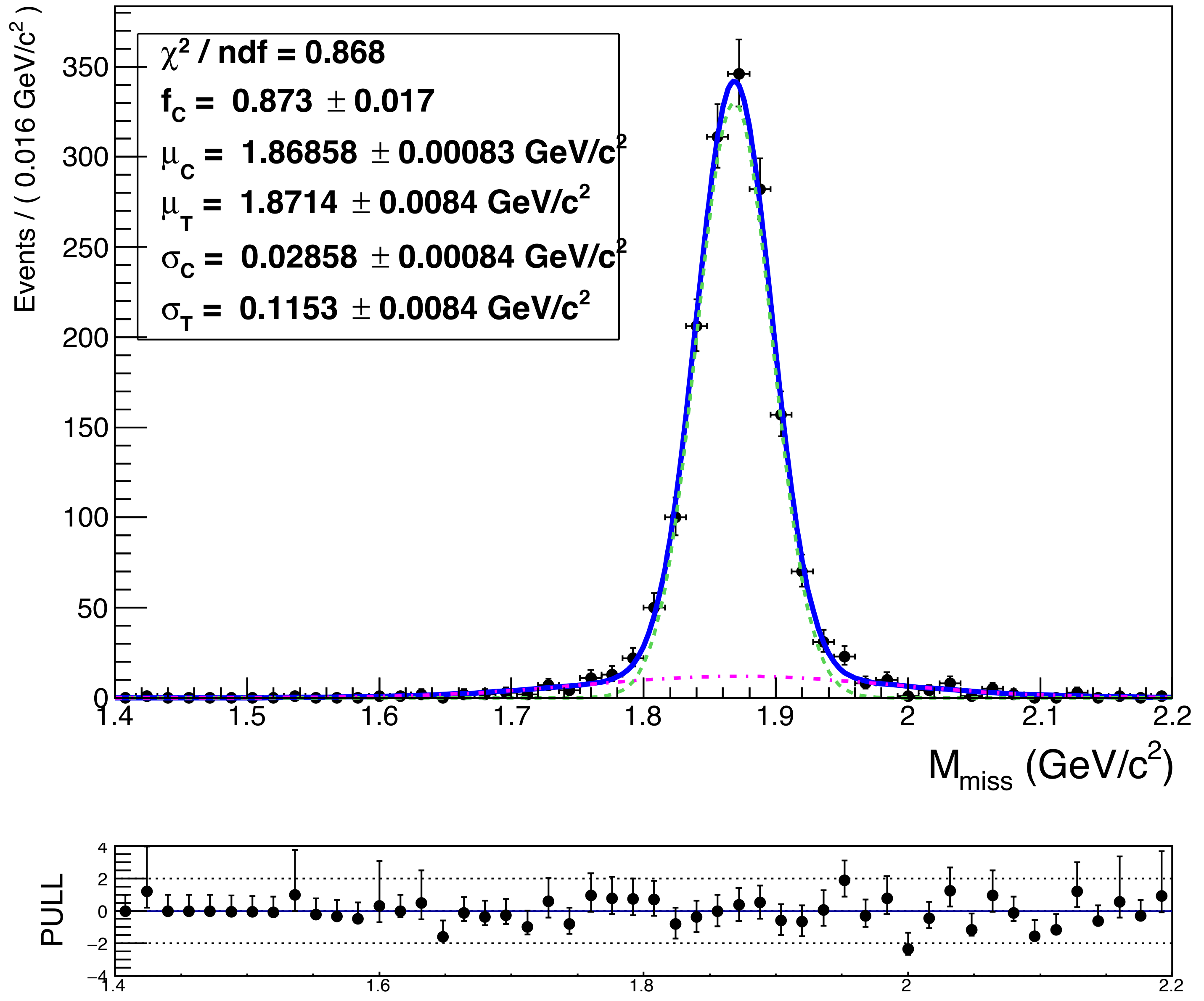


Background $e^{(bx+cx^2)}$

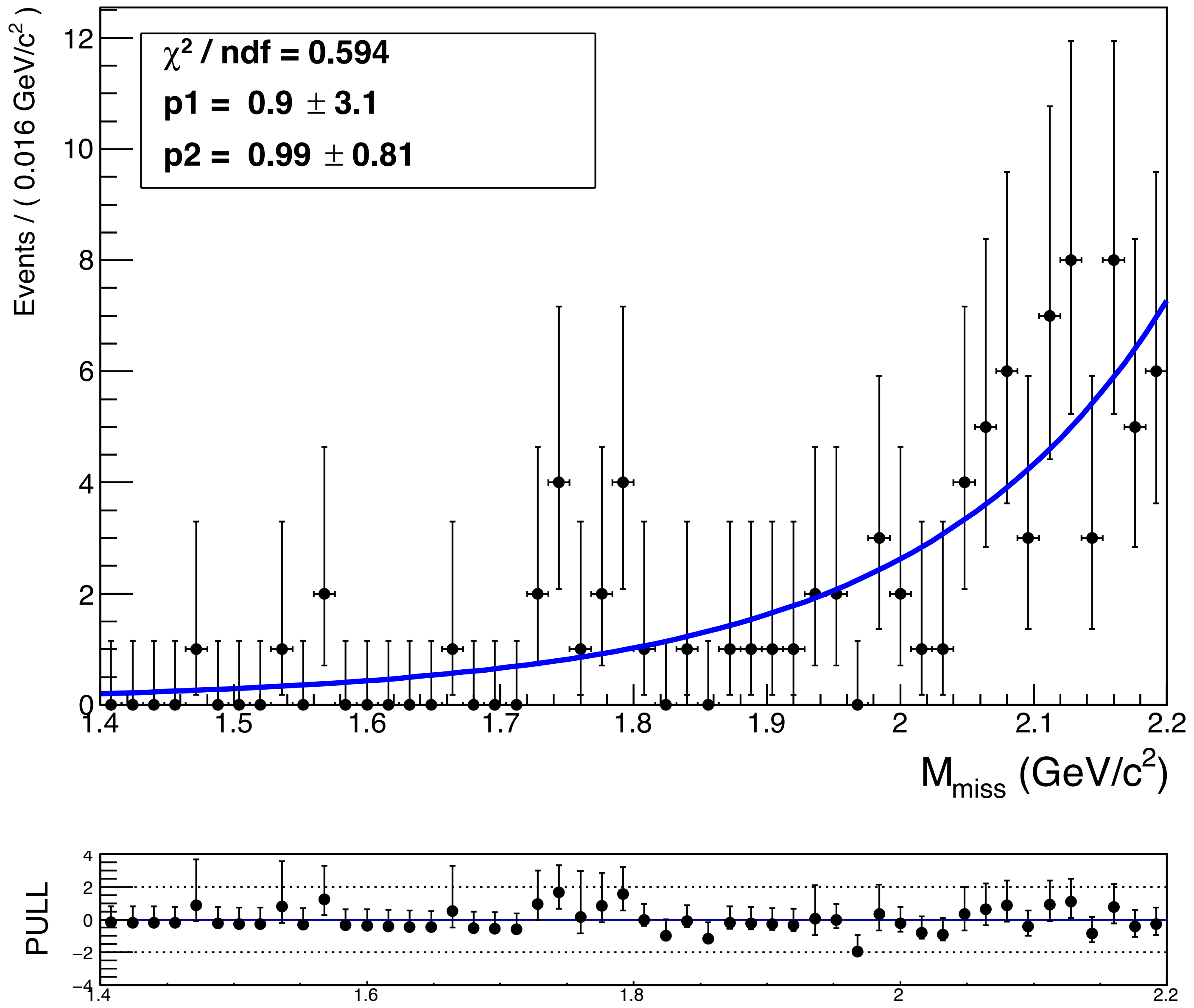
(MC qqbar + ulnu +rare)

Pdf Fit using MC

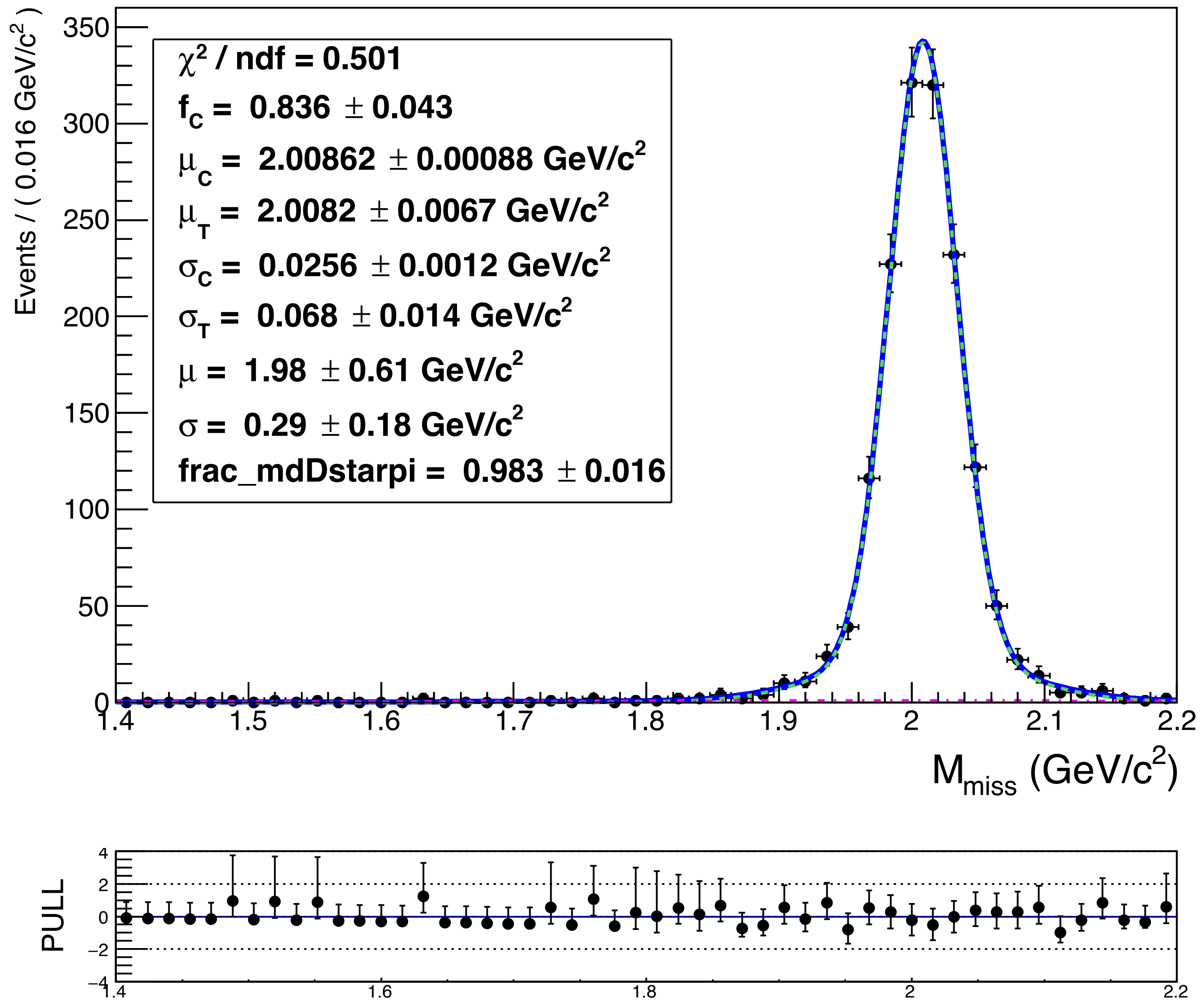
$B^0 \to D\pi$ (true signal) Double Gaussian



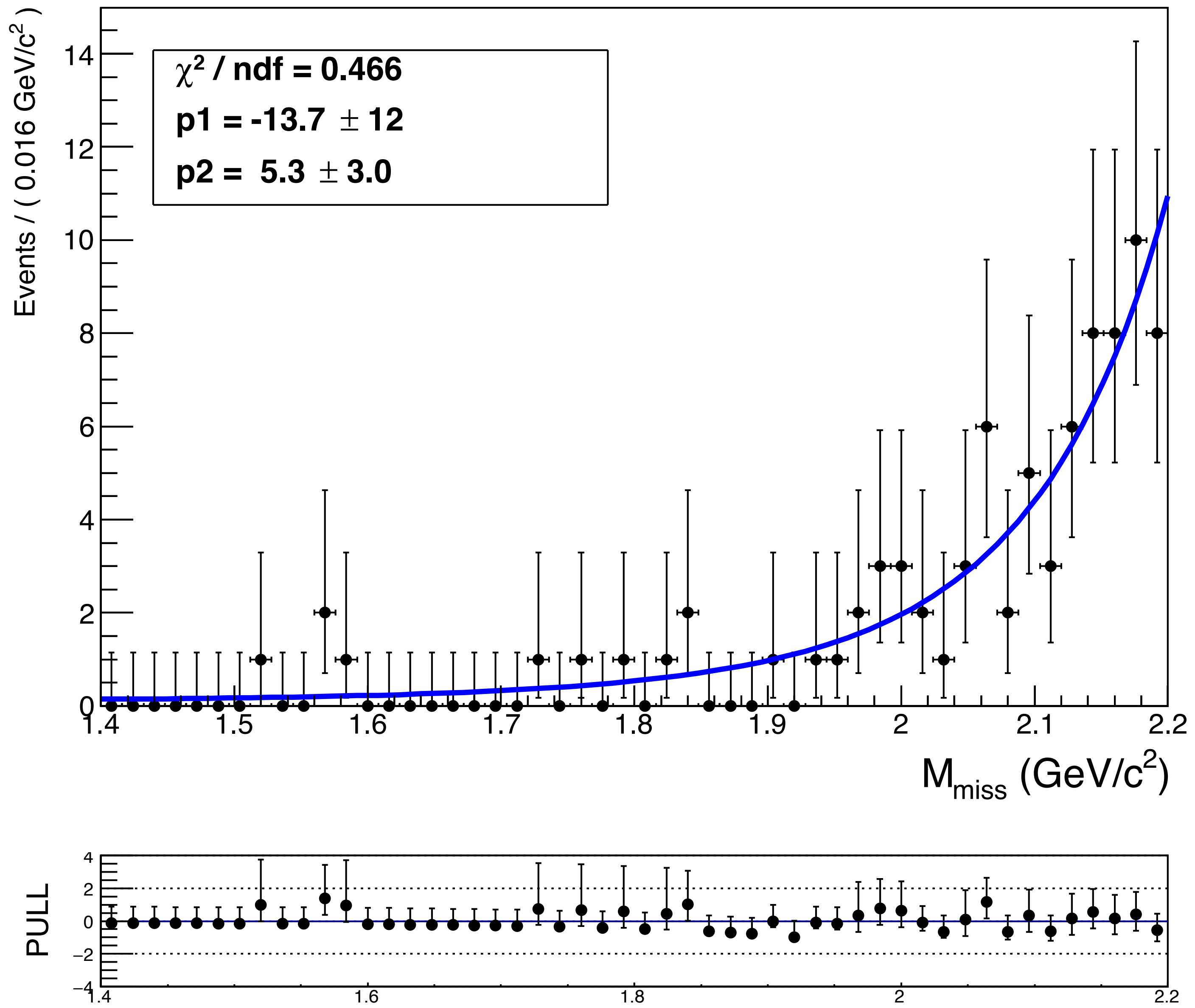
$B^0 \to D\pi$ SxF signal $e^{(bx+cx^2)}$



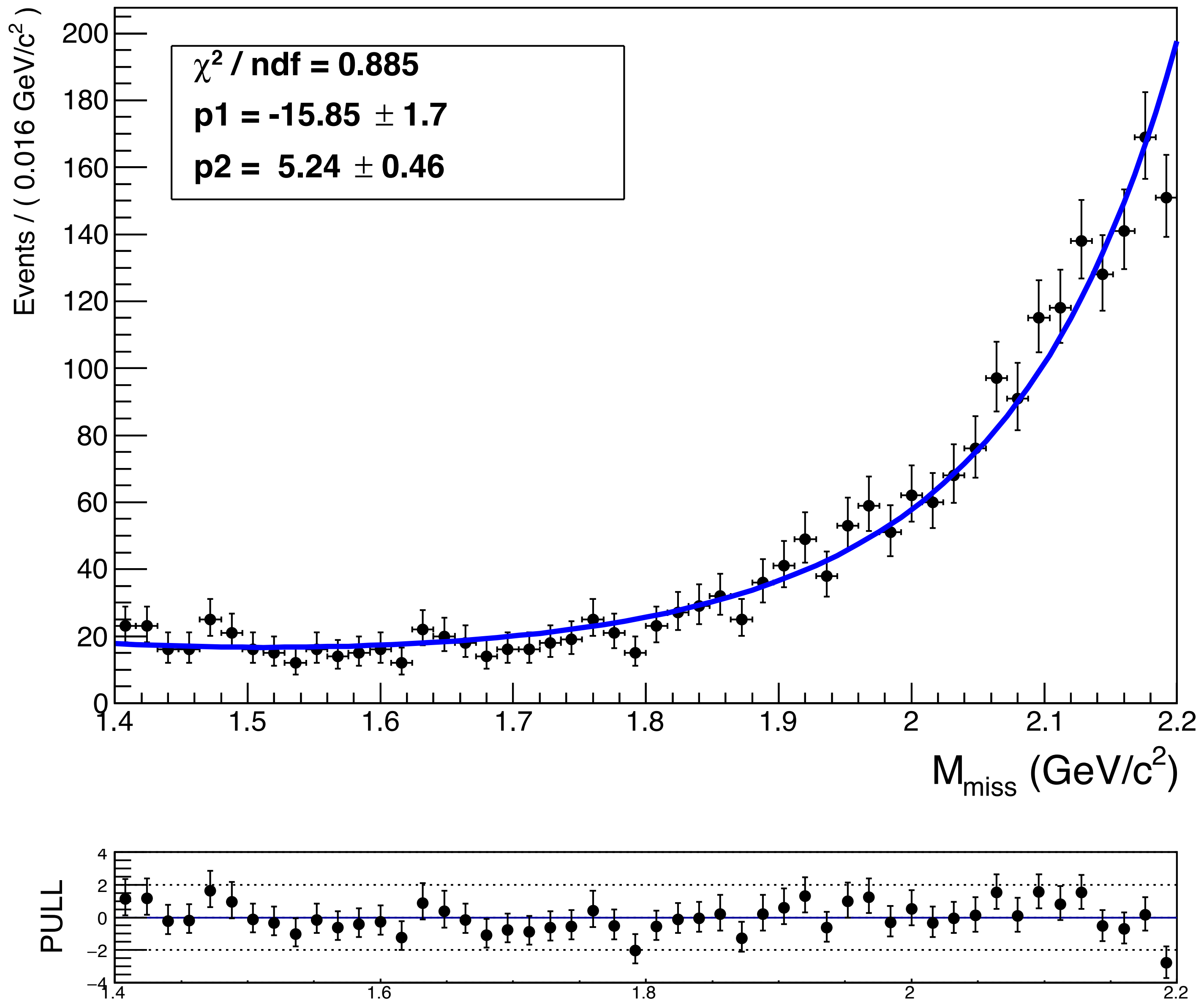
$B^0 \to D^*\pi$ (true signal) Double + Single Gaussian



$B^0 \to D^*\pi$ SxF signal $e^{(bx+cx^2)}$



Background (MC qqbar + ulnu +rare) $e^{(bx+cx^2)}$

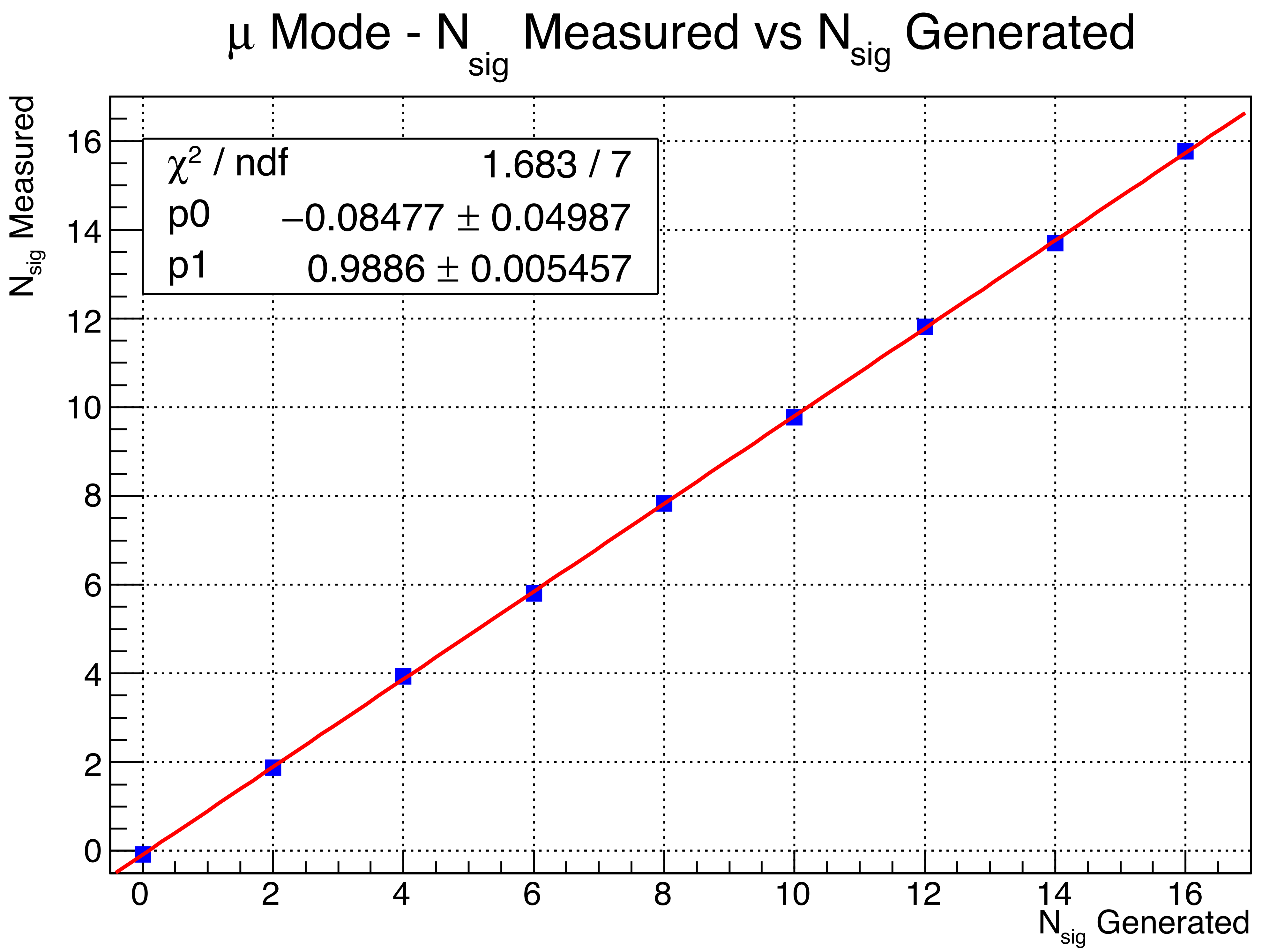


UPPER LIMIT ESTIMATION (systematic uncertainties are not included)

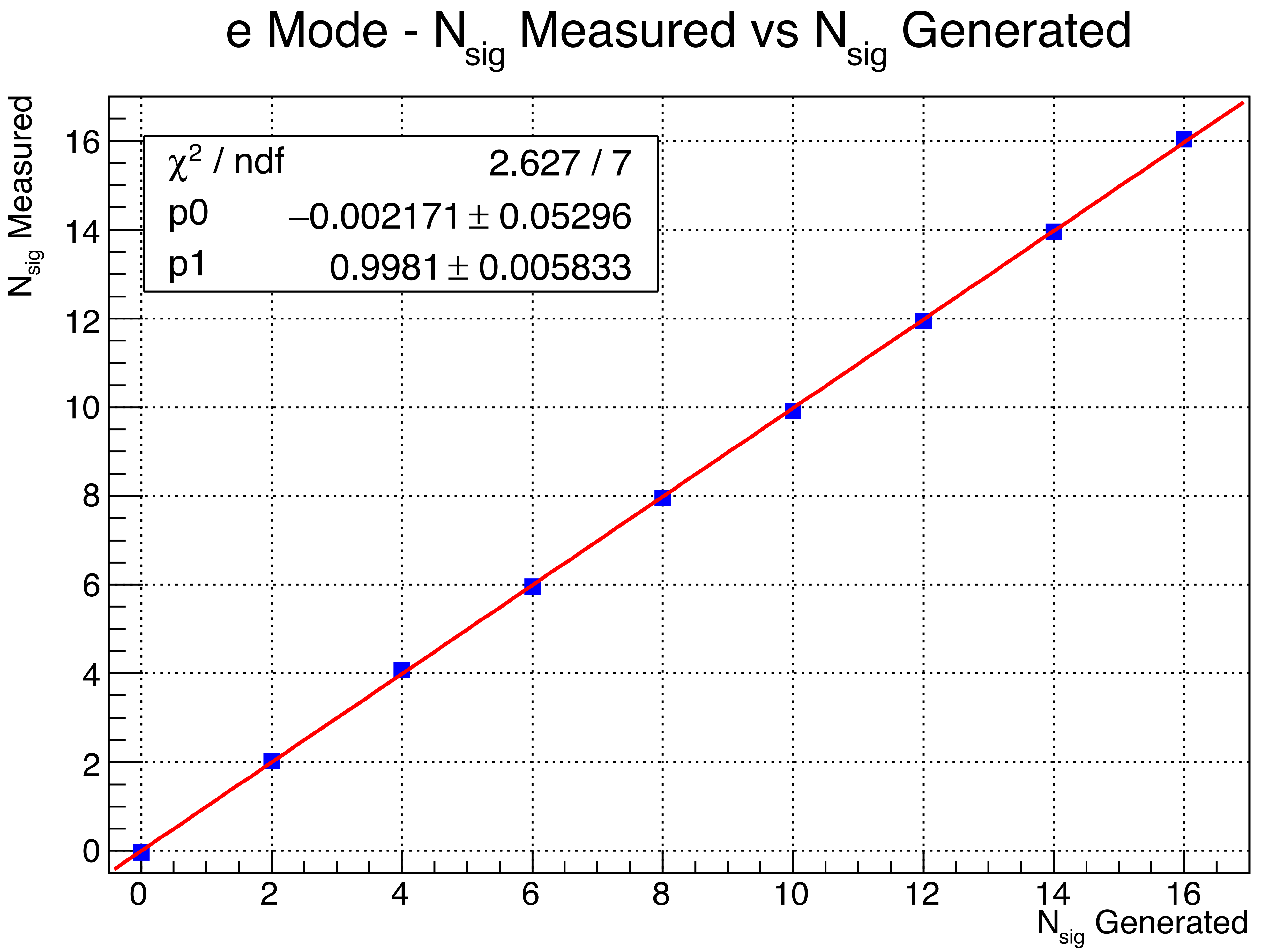
- Using the frequentist method.
- Generated 10000 experiments with different number of possible signal yields (N_{sig}^{gen}) varying from 0 to 16.

Linearity Plots

$B^0 \to \mu\ \tau$

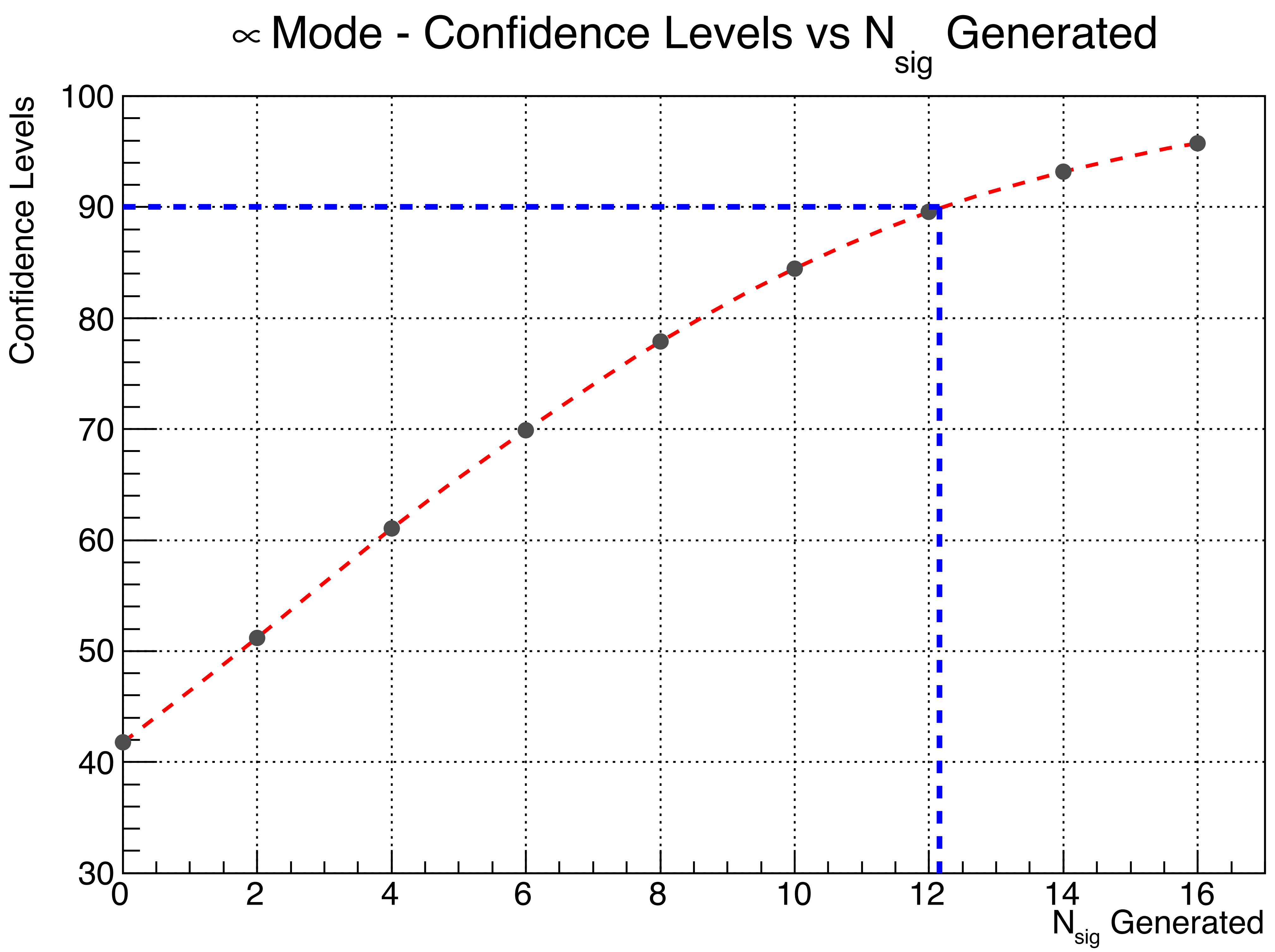


$B^0 \to e\ \tau$

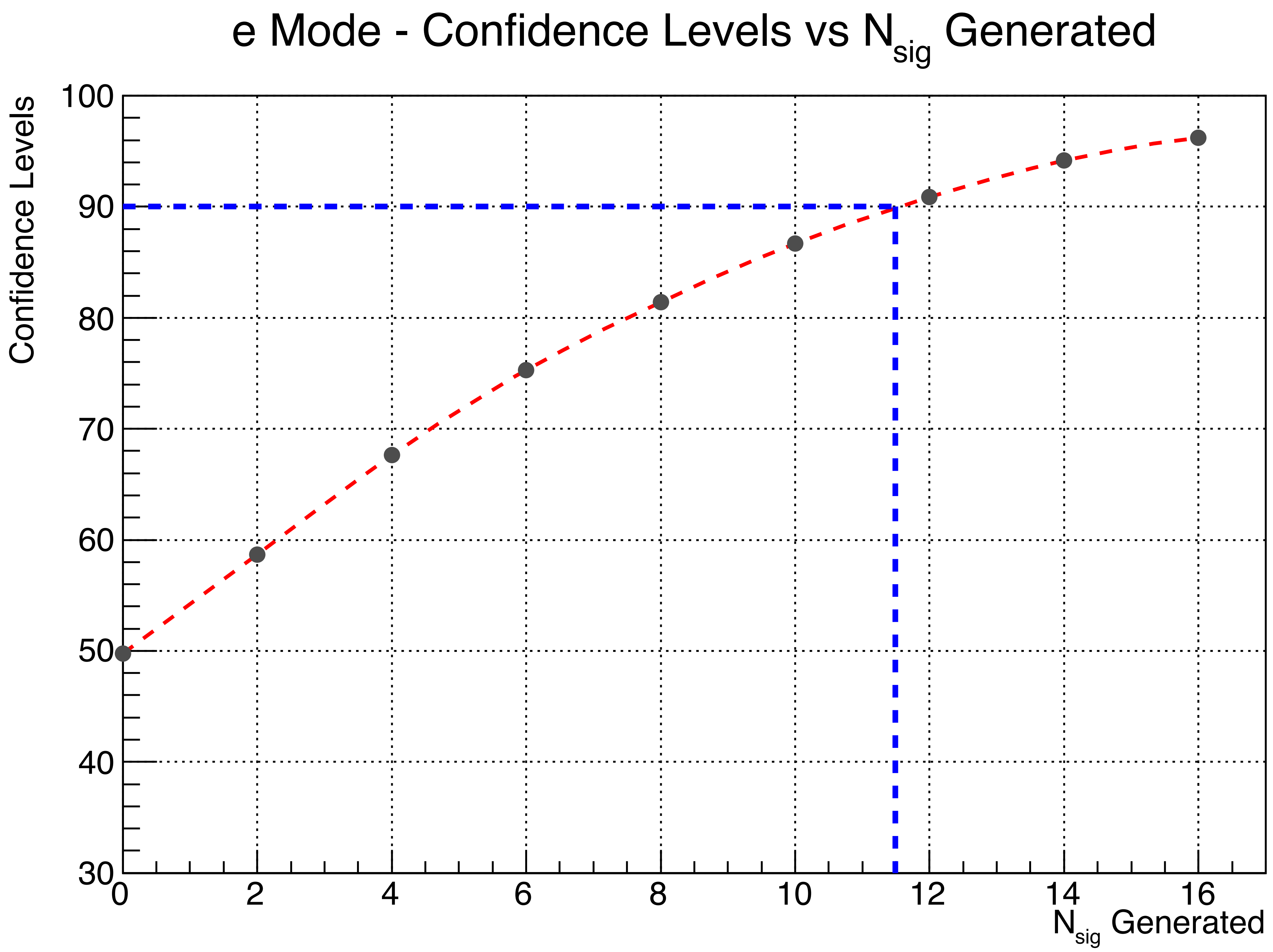


UPPER LIMIT ESTIMATION (systematic uncertainties are not included)

- Fit the generated toy experiments and, for each input signal value, calculate the fraction of the ensemble which gives a fitted signal yield less than what we observe in the Belle data set.



$$N_{sig}^{UL} = 12.2$$



$$N_{sig}^{UL} = 11.5$$

$$BR = \frac{N_{sig}^{UL}}{2 \times N_{B\bar{B}} \times f^{00} \times \varepsilon}$$

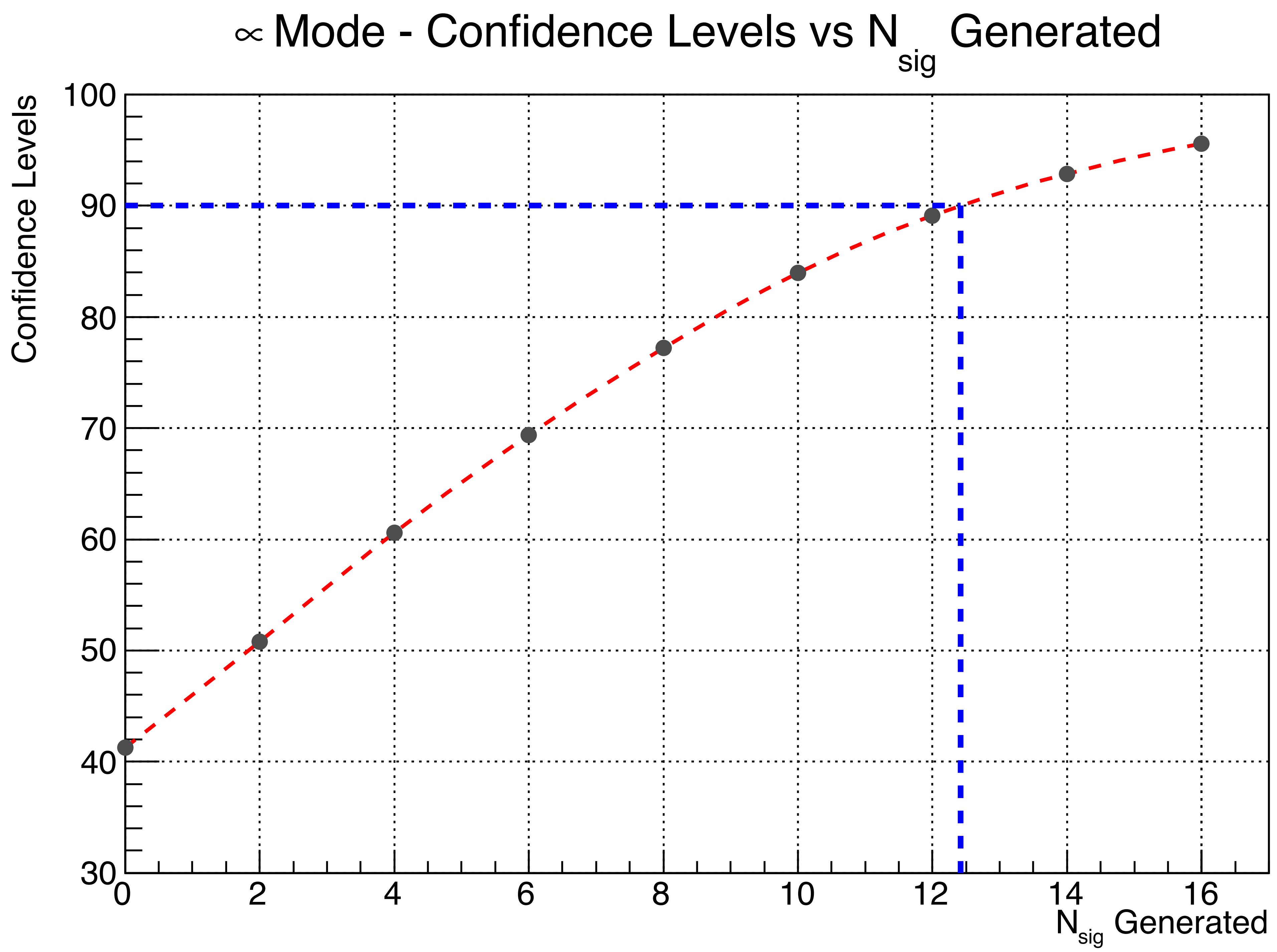
SYSTEMATIC UNCERTAINTIES

Source	$B^0 \to \tau^\pm \mu^\mp$	$B^0 \to \tau^\pm e^\mp$
PDF shapes	0.7	0.3
Self-cross-feed fraction	< 0.1	0.1
Total (events)	0.7	0.3

$B_{\rm tag}$	4.5	4.5
Track reconstruction	0.3	0.3
Lepton identification	1.6	1.8
MC statistics	< 0.1	< 0.1
Number of $B\overline{B}$ Pairs	1.4	1.4
f^{00} ($B\overline{B} \to B^0\overline{B}^0$ fraction)	1.2	1.2
Total (%)	5.1	5.2

FINAL RESULTS UPPER LIMIT ESTIMATION (systematic uncertainties are included)

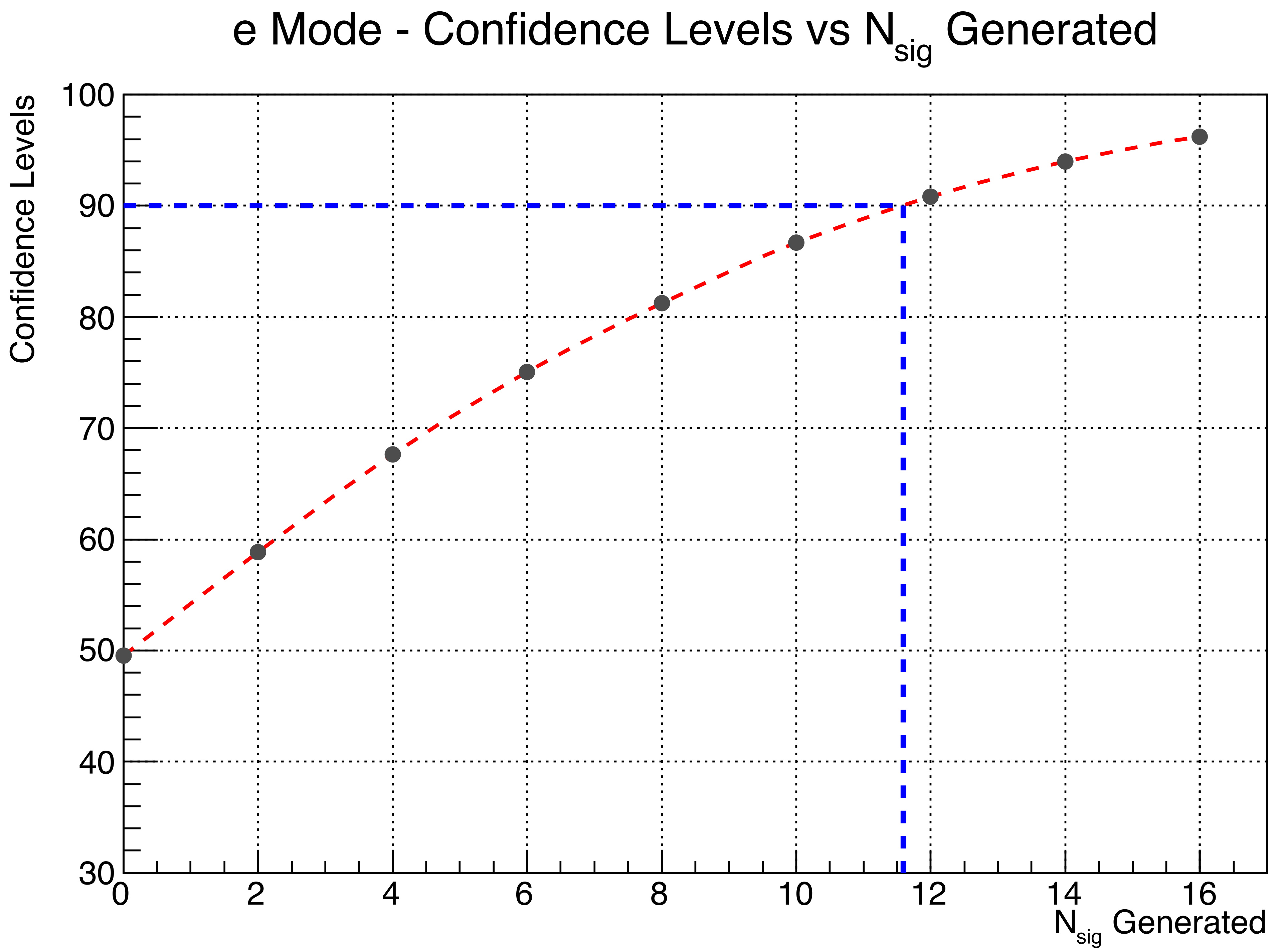
$B^0 \to \mu\ \tau$



$$N_{sig}^{UL} = 12.4$$

$$Br(B^0 \to \mu\tau) < 1.5 \times 10^{-5}$$

$B^0 \to e\ \tau$



$$N_{sig}^{UL} = 11.6$$

$$Br(B^0 \to e\tau) < 1.6 \times 10^{-5}$$