

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

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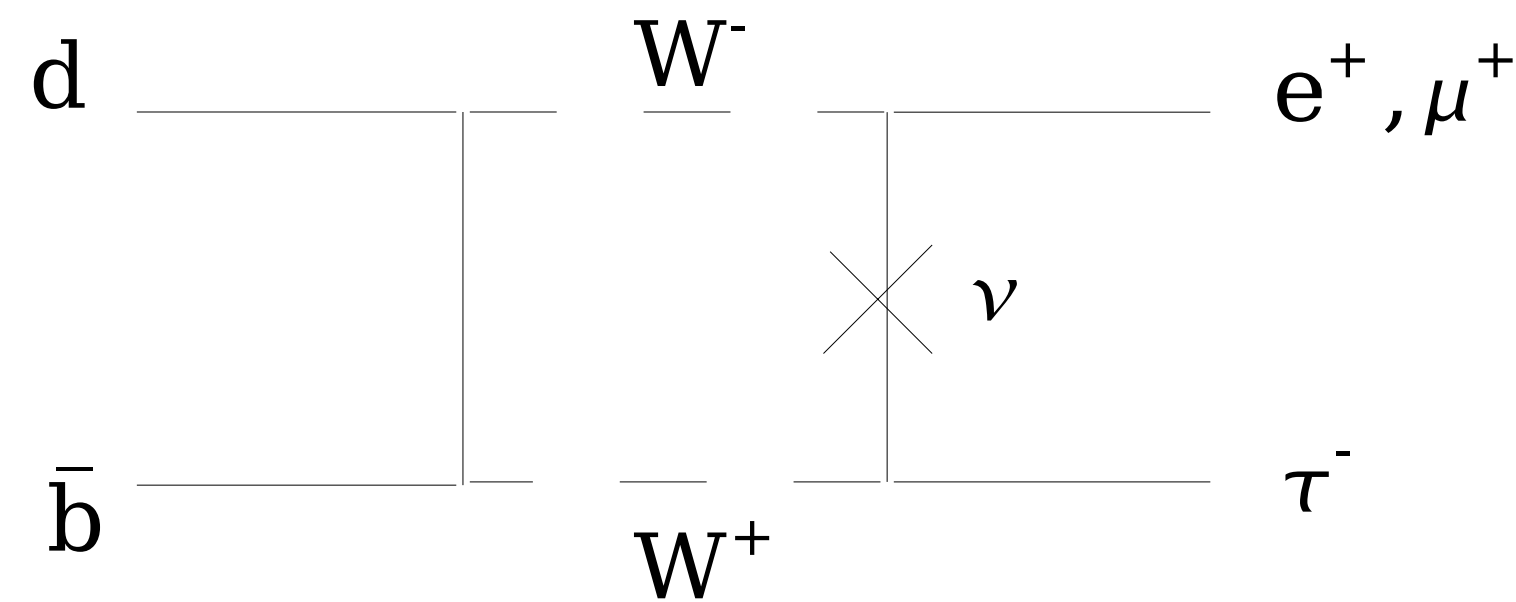
Belle II Summer Workshop 2021

July 13, 2021

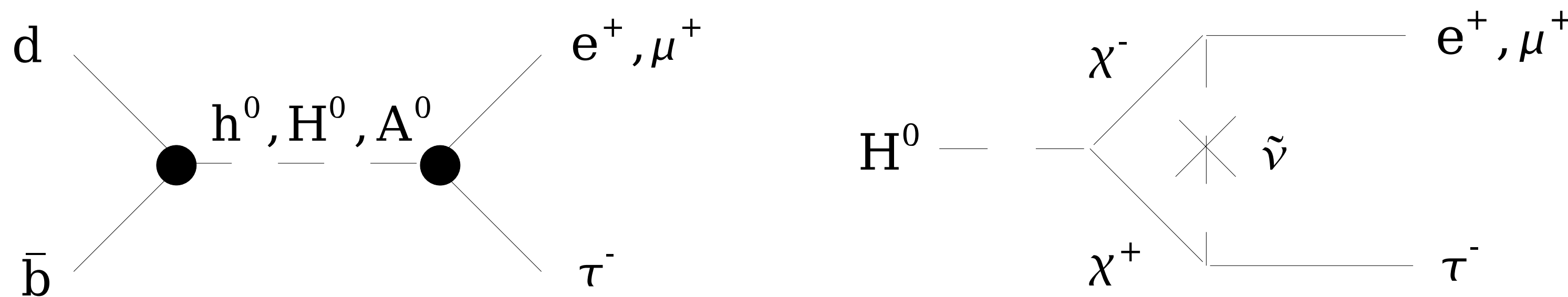
MOTIVATION

Search for Lepton Flavor Violating (LFV) $B^0_{(d)} \rightarrow \tau^\mp l^\pm (l=e,\mu)$ 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 ($\sim 10^{-9} - 10^{-10}$).



Higgs-mediated LFV processes

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

	378 M $B\bar{B}$ (90% CL)	9.6 M $B\bar{B}$ (90% CL)	3fb ⁻¹ of pp collisions (90% CL)
	BABAR <i>Phys. Rev. D 77, 091104(R)</i> (2008)	CLEO <i>PRL 93, 241802 (2004)</i>	LHCb <i>Phys. Rev. Lett. 123, 211801</i> (2019)
$B_{(s)}^0 \rightarrow \tau^\mp e^\pm$	—	—	—
$B_{(s)}^0 \rightarrow \tau^\mp \mu^\pm$	—	—	$< 3.4 \times 10^{-5}$
$B_{(d)}^0 \rightarrow \tau^\mp e^\pm$	$< 2.8 \times 10^{-5}$	$< 1.3 \times 10^{-4}$	—
$B_{(d)}^0 \rightarrow \tau^\mp \mu^\pm$	$< 2.2 \times 10^{-5}$	$< 3.8 \times 10^{-5}$	$< 1.2 \times 10^{-5}$

BABAR

CLEO

LHCb

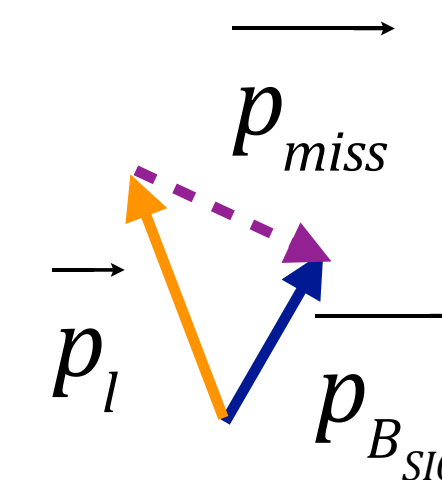
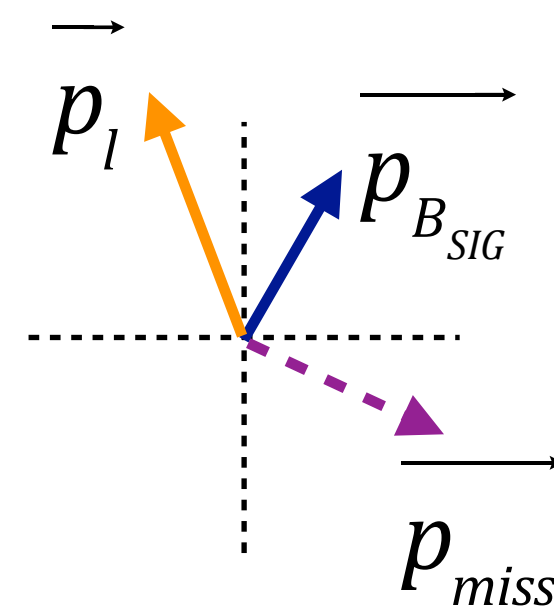
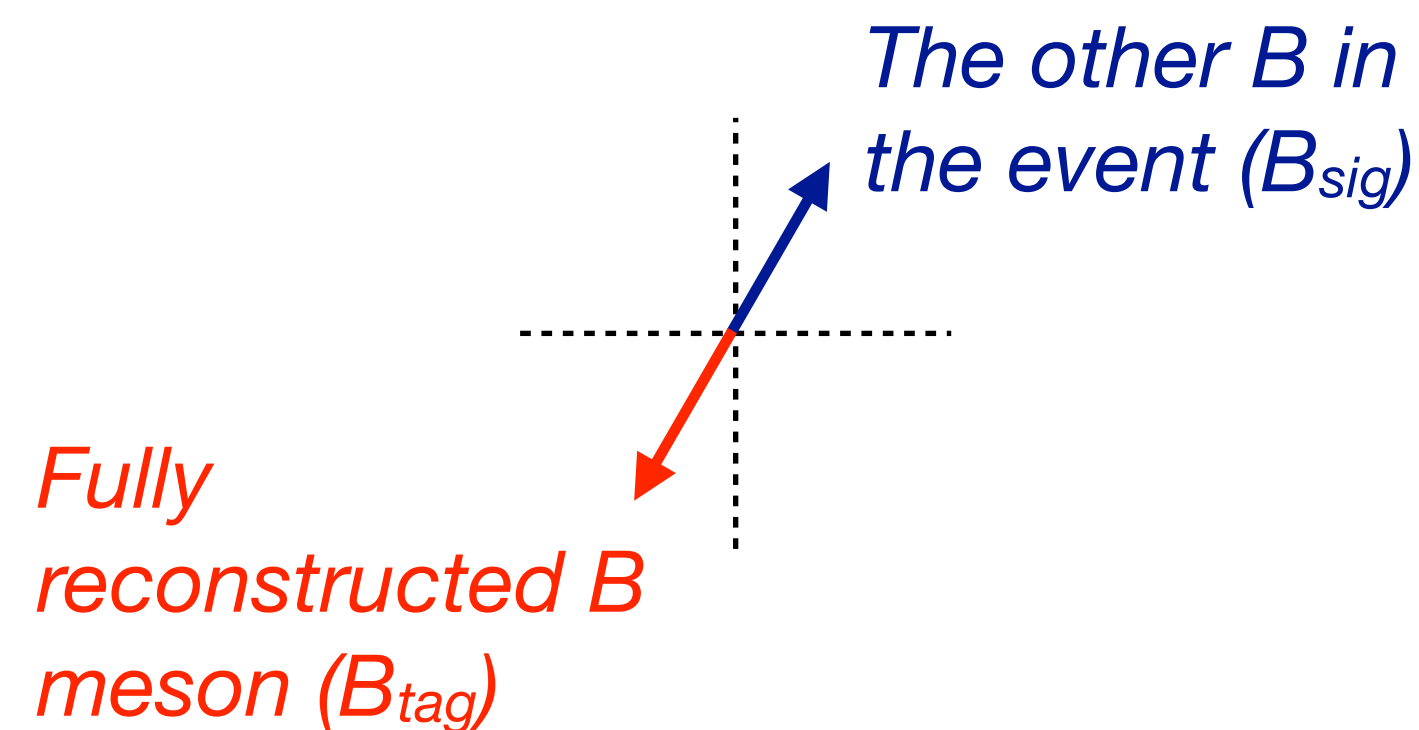
τ decay mode	Branching Fraction
$e^- \bar{\nu}_e \nu_\tau$	17.84 ± 0.05
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.36 ± 0.05
$\pi^- \nu_\tau$	10.90 ± 0.07
$\pi^- \pi^0 \nu_\tau$	25.50 ± 0.10
$\pi^- \pi^0 \pi^0 \nu_\tau$	9.25 ± 0.12
$\pi^- \pi^- \pi^+ \nu_\tau$	9.33 ± 0.08

$\tau \rightarrow e \nu_\tau \bar{\nu}_e$
 $\tau \rightarrow \mu \nu_\tau \bar{\nu}_\mu$

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

ANALYSIS TECHNIQUE

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



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

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

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

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

- 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 M_{miss} for each lepton candidate and
 - obtain the missing mass distribution.

EVENT SELECTION

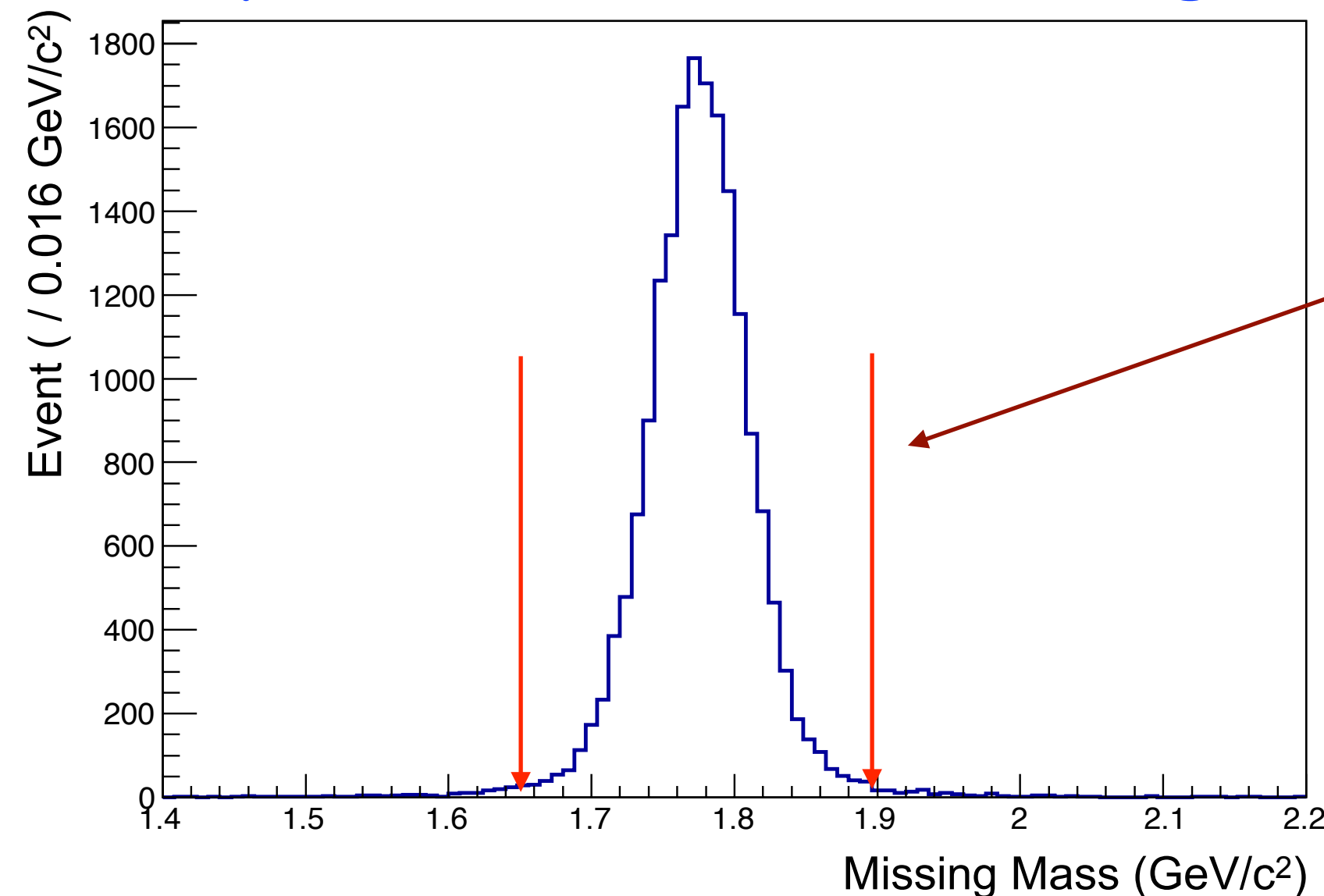
- B_{tag} side is reconstructed in one of 1104 hadronic decay channels using a hierarchical algorithm based on the Neural Network (NN) package in BASF. [M. Feindt, F. Keller, M. Kreps, T. Kuhr, S. Neubauer, D. Zander, A. Zupanc Nucl. Instrum. Methods Phys. Res., Sect. A 654, 432 (2011)]
- $O_{NN} > 0.082 \rightarrow B^0 \rightarrow \tau \mu$, $O_{NN} > 0.095 \rightarrow B^0 \rightarrow \tau e$.
- (B_{tag}) $|\Delta E| < 0.05$ GeV .
- (B_{tag}) $M_{BC} > 5.272$ GeV/c² .
- Exclude tracks coming from B_{tag} side.
- μ ID $> 0.9 \rightarrow B^0 \rightarrow \tau \mu$, e ID $> 0.9 \rightarrow B^0 \rightarrow \tau e$
- $1.4 \text{ GeV}/c^2 < M_{miss} < 2.2 \text{ GeV}/c^2$.
- Every lepton candidate is a B_{sig} candidate.

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

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

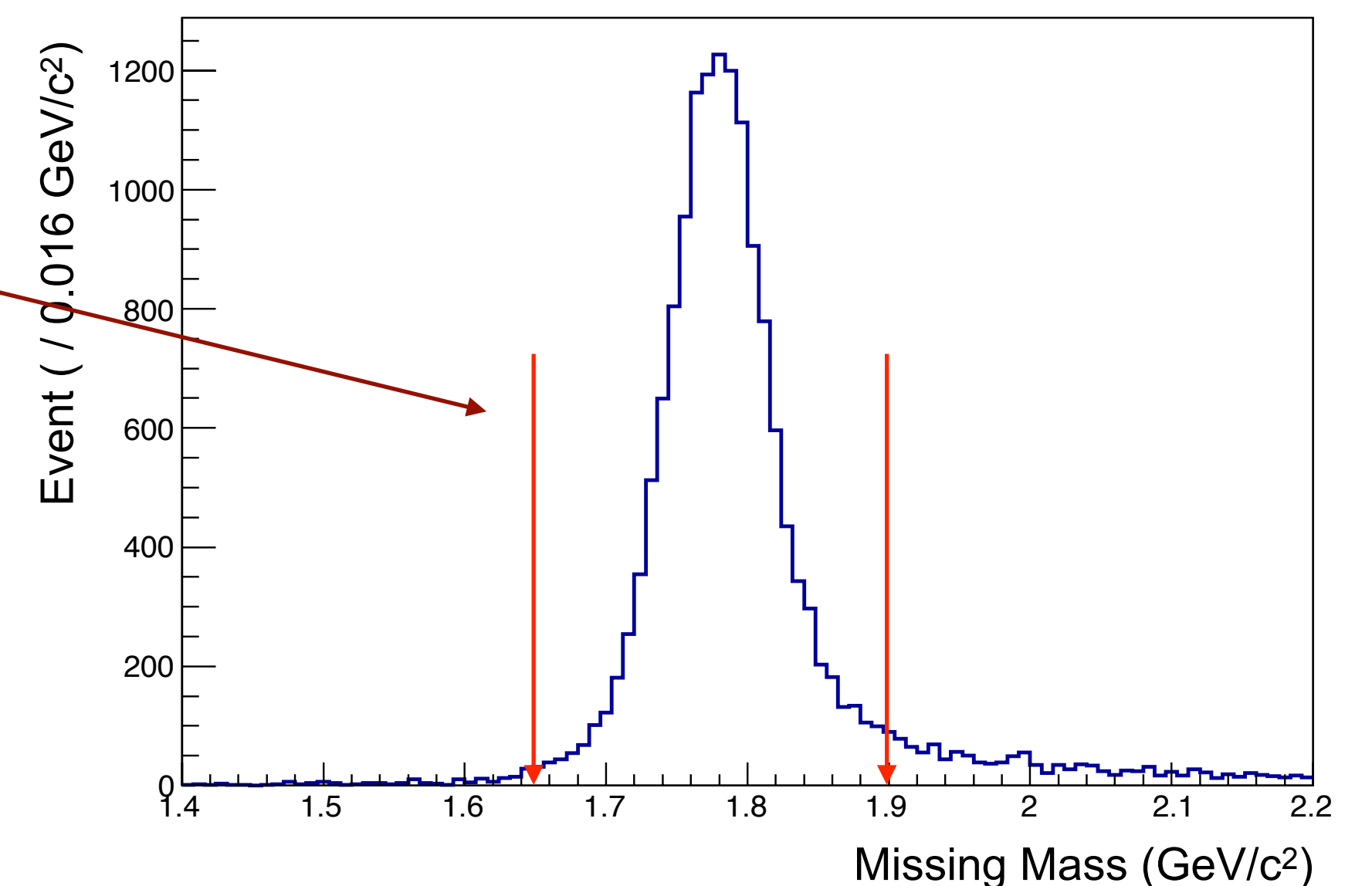
Beam-constrained mass: $M_{BC} = \sqrt{E_{BEAM}^2 - \vec{p}_B^2}$

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



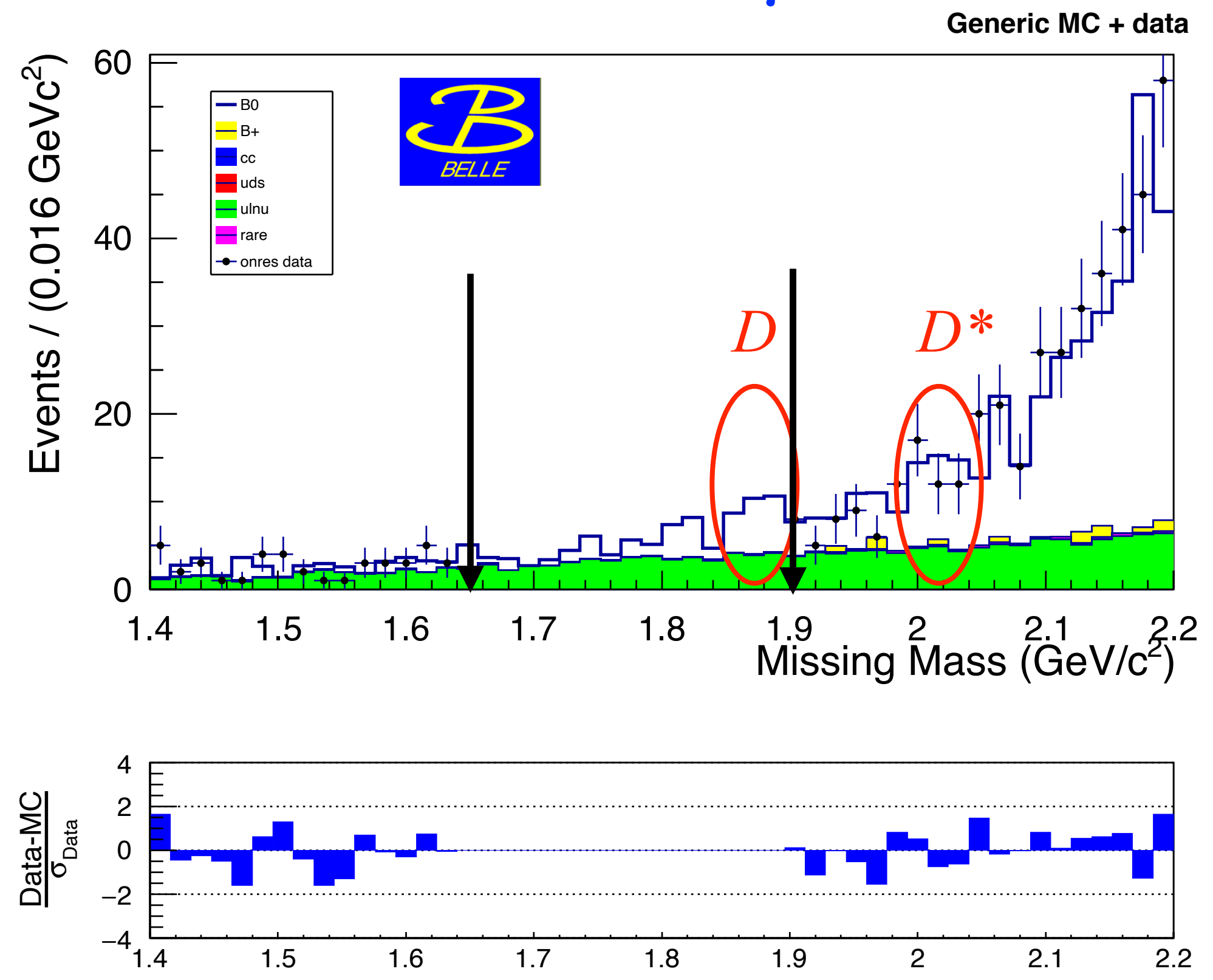
Window [1.65-1.90] GeV/c² is used to hide the number of events on the data.

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

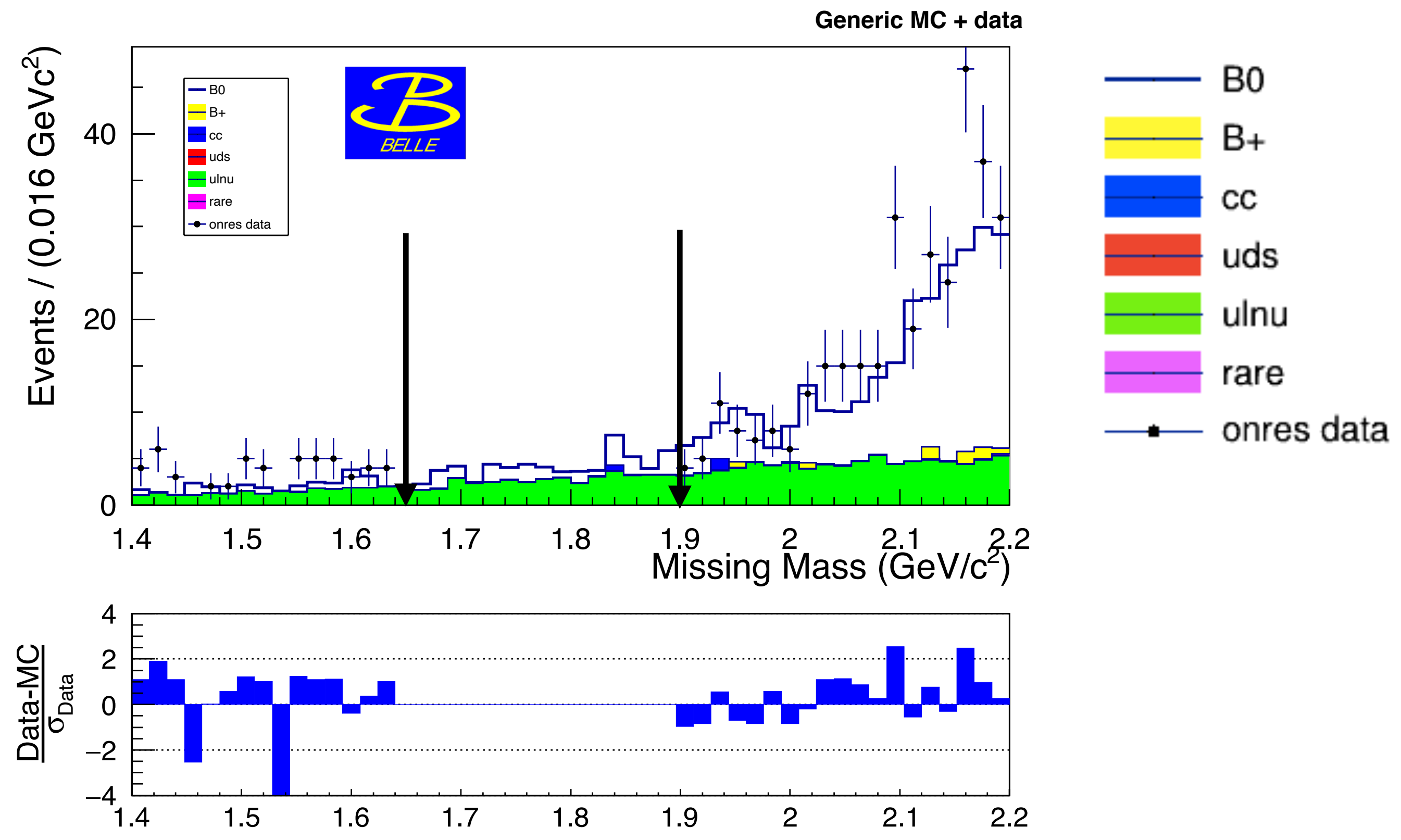


BACKGROUND STUDY

$B^0 \rightarrow \tau \mu$



$B^0 \rightarrow \tau e$



- Background originates mainly from $b \rightarrow c$ and $b \rightarrow ul\nu$ decays smoothly falling in the M_{miss} distributions.
- $B^0 \rightarrow \tau \mu$: Because π^+ is misidentified as μ^+ , two small peaks are observed: one at $M_{\text{miss}} \approx 1.869 \text{ GeV}/c^2$ (D meson) and the other $M_{\text{miss}} \approx 2.010 \text{ GeV}/c^2$ (D^* meson).

UNBINNED MAXIMUM LIKELIHOOD (ML) FIT DESCRIPTION

Fit Variables

- Missing Mass (M_{miss})

$$\underline{B \rightarrow \tau \mu}$$

Fit Window

- M_{miss} [1.4 - 2.2] GeV/c²

$$\underline{B \rightarrow \tau e}$$

Fit Components

- Signal $B^0 \rightarrow \tau \mu$ 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 ($q\bar{q}$), $b \rightarrow ul\nu$, rare B decays)
- Peaking BG-1 ($B^0 \rightarrow D \pi$)
- Peaking BG-2 ($B^0 \rightarrow D^* \pi$)

- Signal $B^0 \rightarrow \tau e$ 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 ($q\bar{q}$), $b \rightarrow ul\nu$, rare B decays)

Floating Parameters:

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

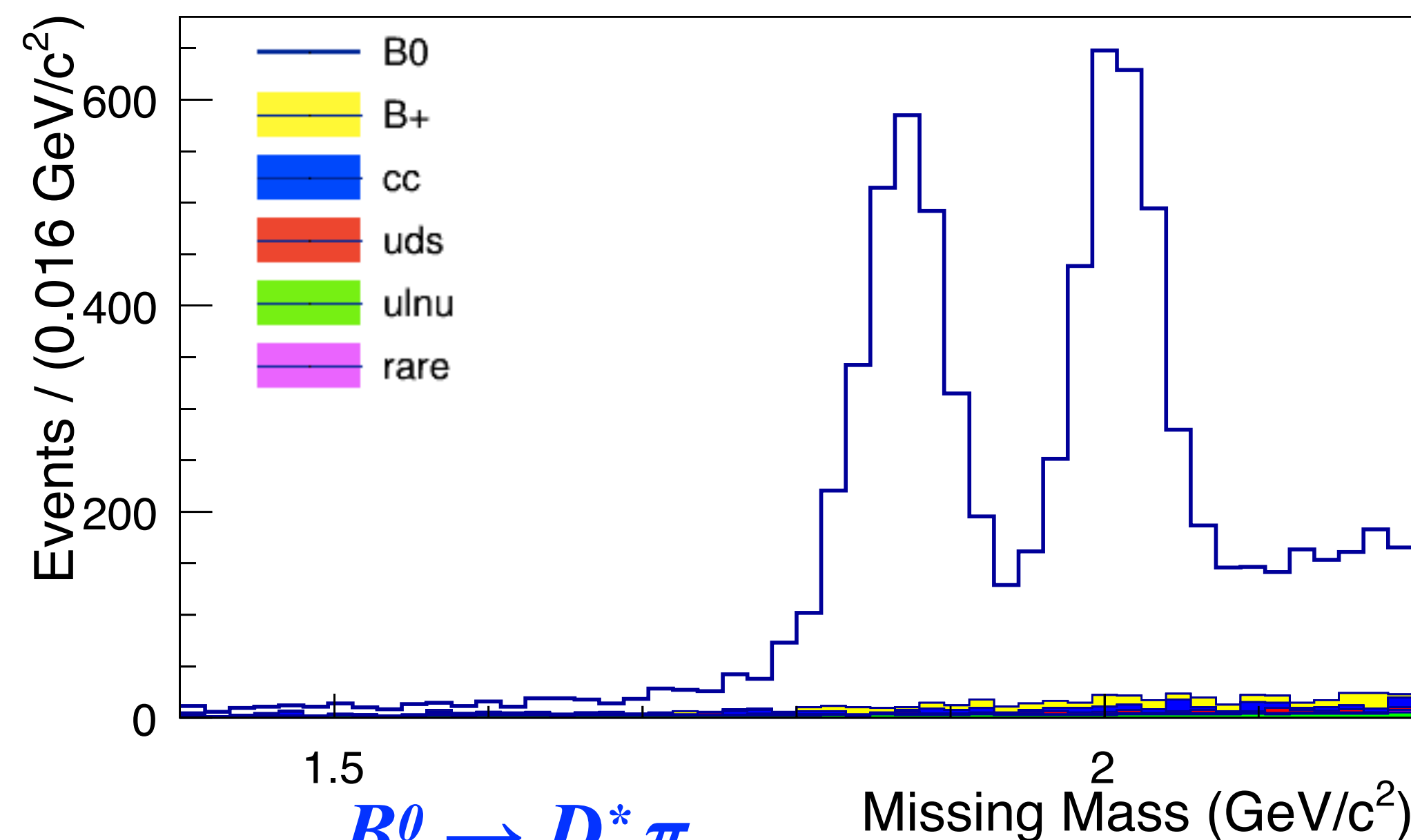
- signal, background yields,
- background shape parameters.

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

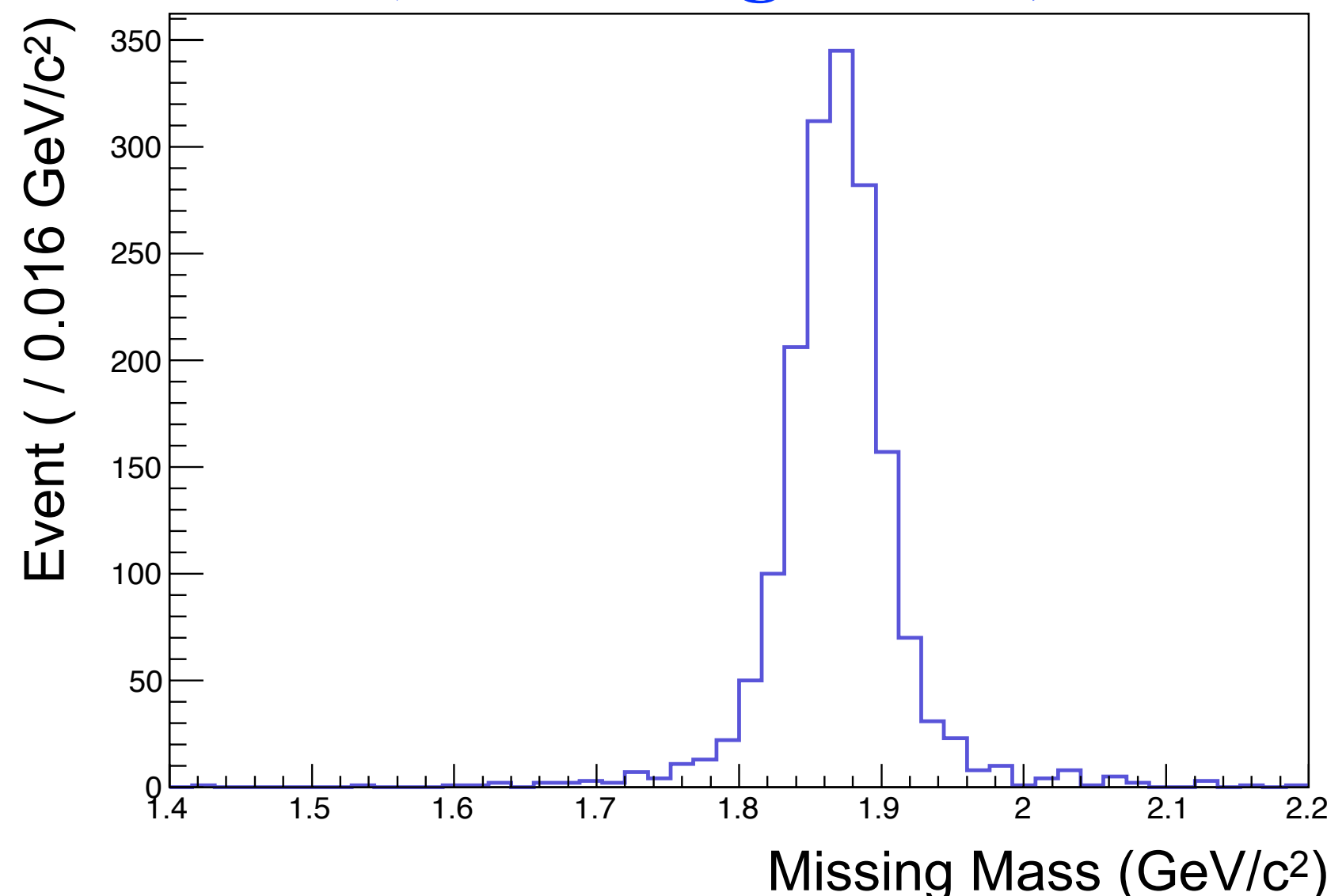
MC ($B^0, B^+, qq, b \rightarrow u\bar{l}\nu, \text{rare } B \text{ decays}$)

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

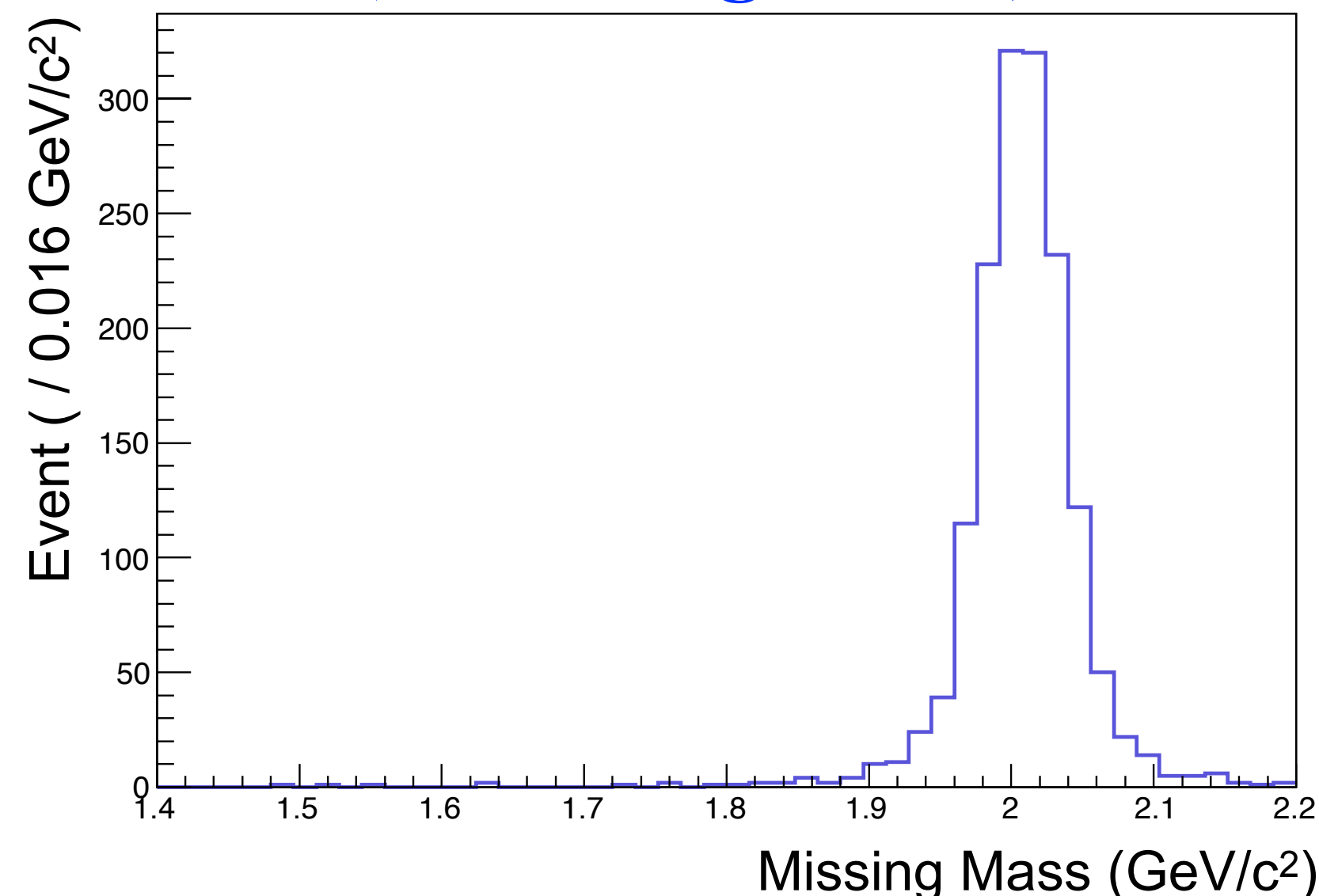
- $(B_{tag}) |\Delta E| < 0.05 \text{ GeV}$.
- $(B_{tag}) M_{BC} > 5.272 \text{ GeV}/c^2$.
- $O_{NN} > 0.082$.
- Exclude tracks coming from B_{tag} side.
- $1.4 \text{ GeV}/c^2 < M_{miss} < 2.2 \text{ GeV}/c^2$.
- $(1 - KID) \geq 0.1, \mu \text{ ID} < 0.9, e \text{ ID} < 0.9$.
- Every π candidate is a B_{sig} candidate.



$B^0 \rightarrow D \pi$
(MC using true π)



$B^0 \rightarrow D^* \pi$
(MC using true π)



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

Fit Variables

- Missing Mass (M_{miss})

Fit Window

- M_{miss} [1.4 - 2.2] GeV/c²

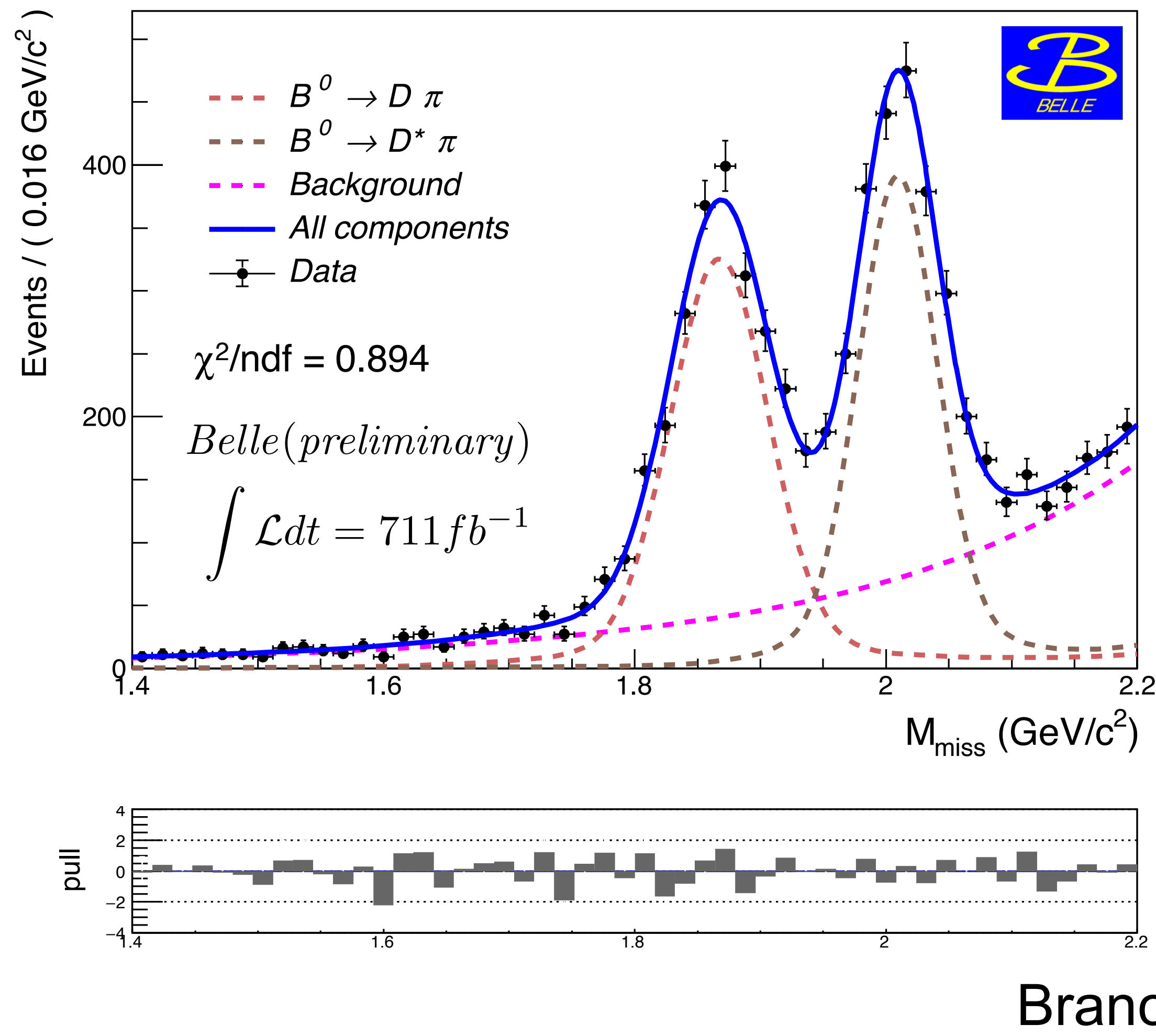
Fit Components

- Signal $B^0 \rightarrow D^{(*)} \pi$ 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 ($q\bar{q}$), $b \rightarrow ul\nu$, rare B decays)

Floating Parameters:

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

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



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

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

N_{sig}

$B^0 \rightarrow D \pi : 2136 \pm 71$

$B^0 \rightarrow D^* \pi : 2071 \pm 74$

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

$B^0 \rightarrow D \pi : 11.2 \times 10^{-4}$

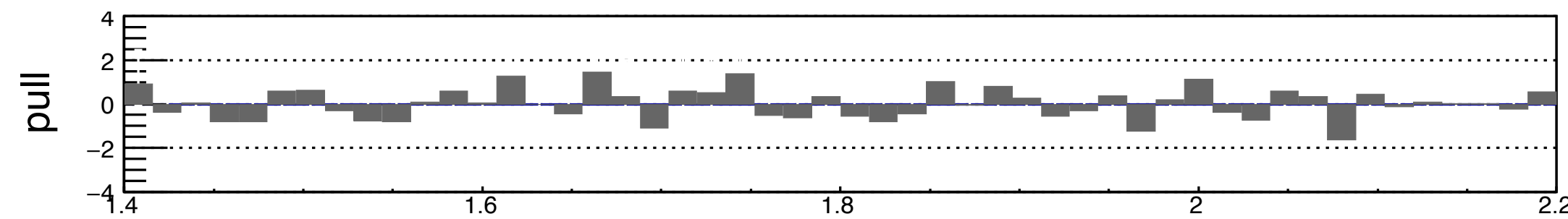
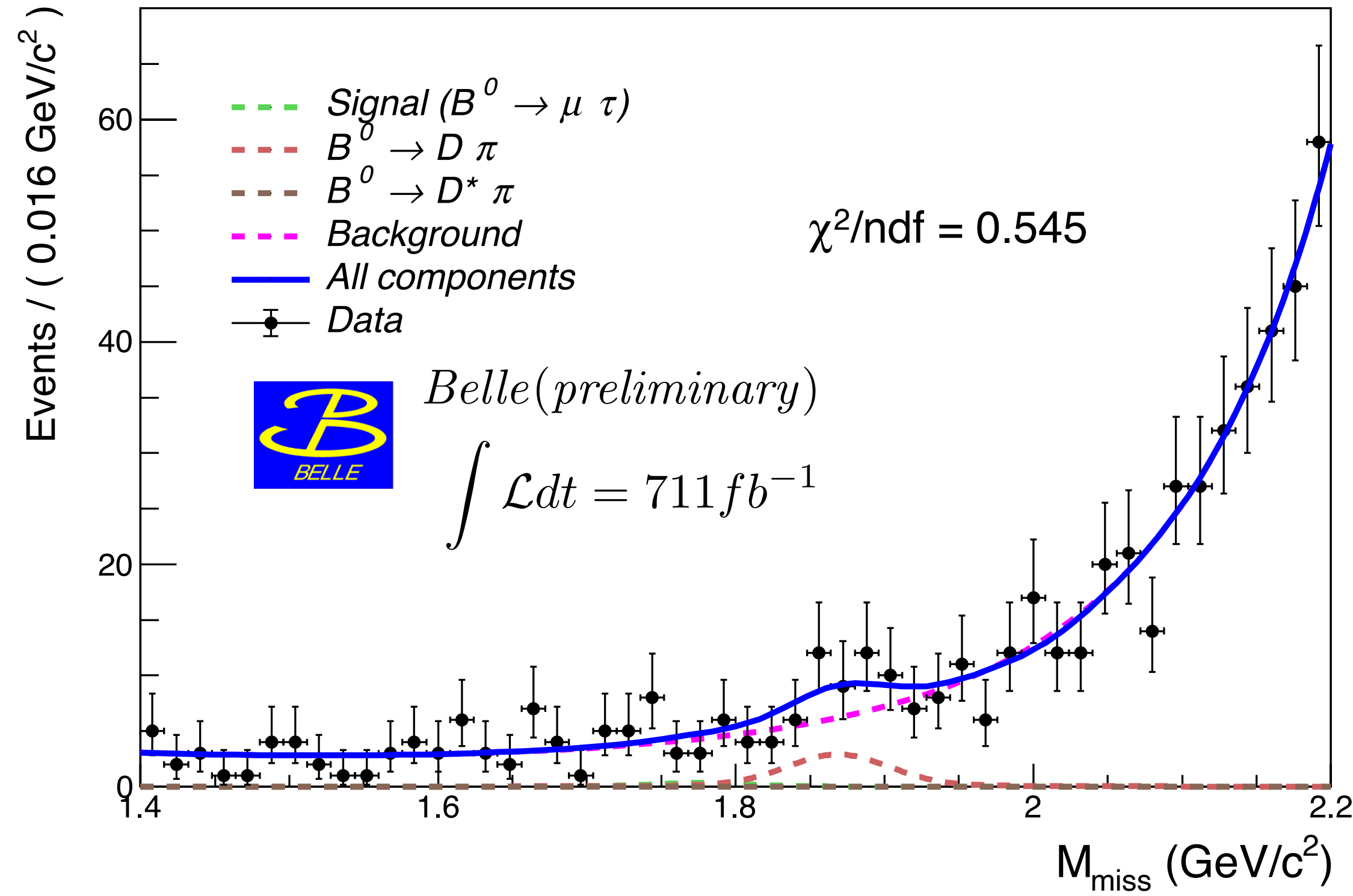
$B^0 \rightarrow D^* \pi : 10.3 \times 10^{-4}$

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

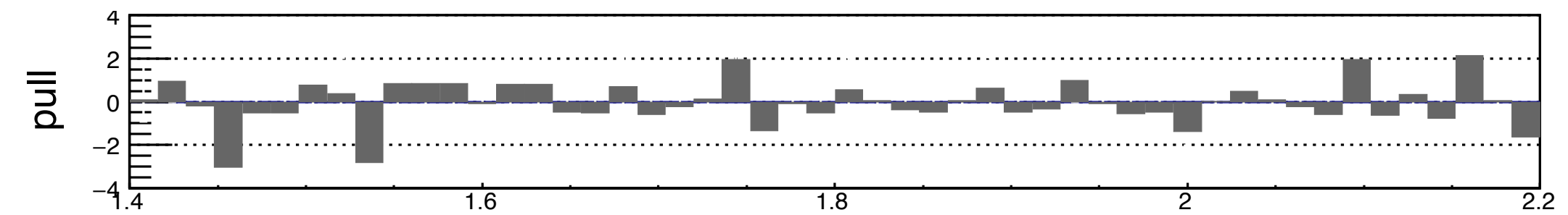
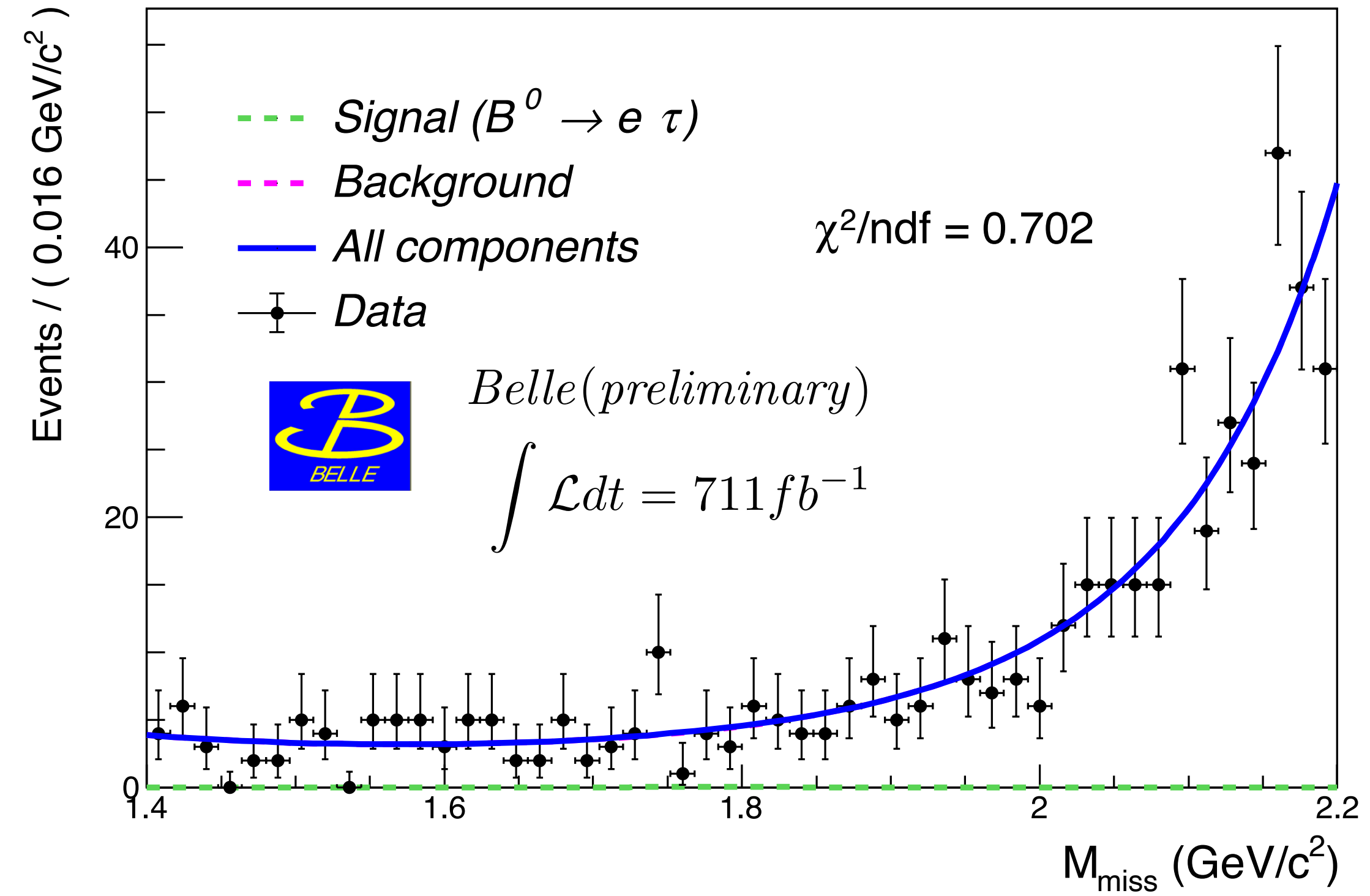
$B \rightarrow \tau l$ ML FIT RESULTS

$B \rightarrow \tau \mu$

$B \rightarrow \tau e$



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



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

Conclusion

- We have searched for the lepton-flavor violating $B^0 \rightarrow \tau^\mp l^\pm$ ($l=e, \mu$) 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 ($\times 10^{-4}$)	N_{sig}	$N_{\text{sig}}^{\text{UL}}$	BR^{UL} ($\times 10^{-5}$) 90% C.L. BELLE preliminary 771 M BB	BR^{UL} ($\times 10^{-5}$) 90% C.L. BABAR 378 M BB	BR^{UL} ($\times 10^{-5}$) 90% C.L. LHCb 3 fb ⁻¹ of pp collisions
$B_{(d)}^0 \rightarrow \tau^\mp e^\pm$	9.8	$0.3^{+8.8}_{-8.2}$	11.6	1.6	2.8	–
$B_{(d)}^0 \rightarrow \tau^\mp \mu^\pm$	11.0	$1.8^{+8.2}_{-7.6}$	12.4	1.5	2.2	1.2

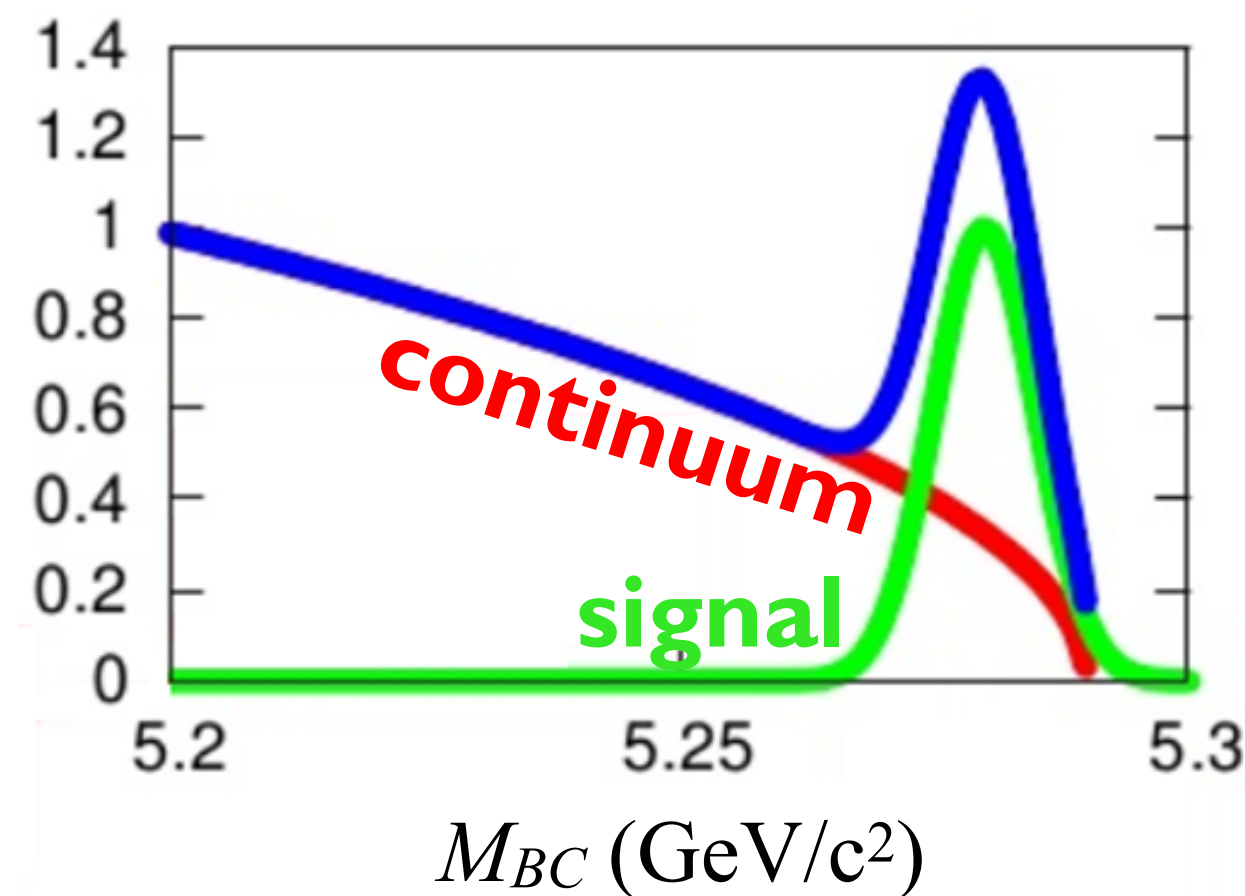
Extra

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

- To identify B decays, kinematic variables are used: M_{BC} and ΔE

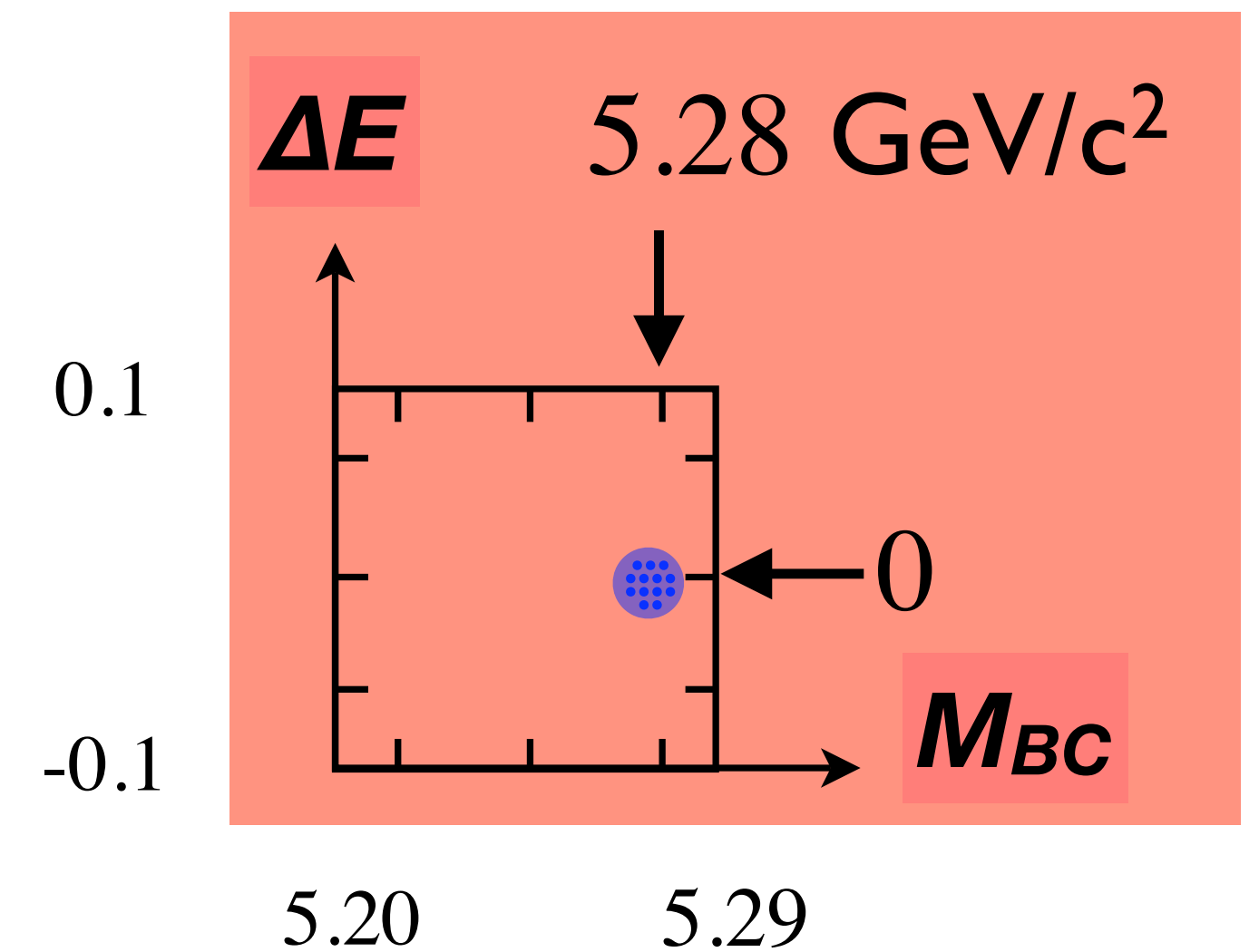
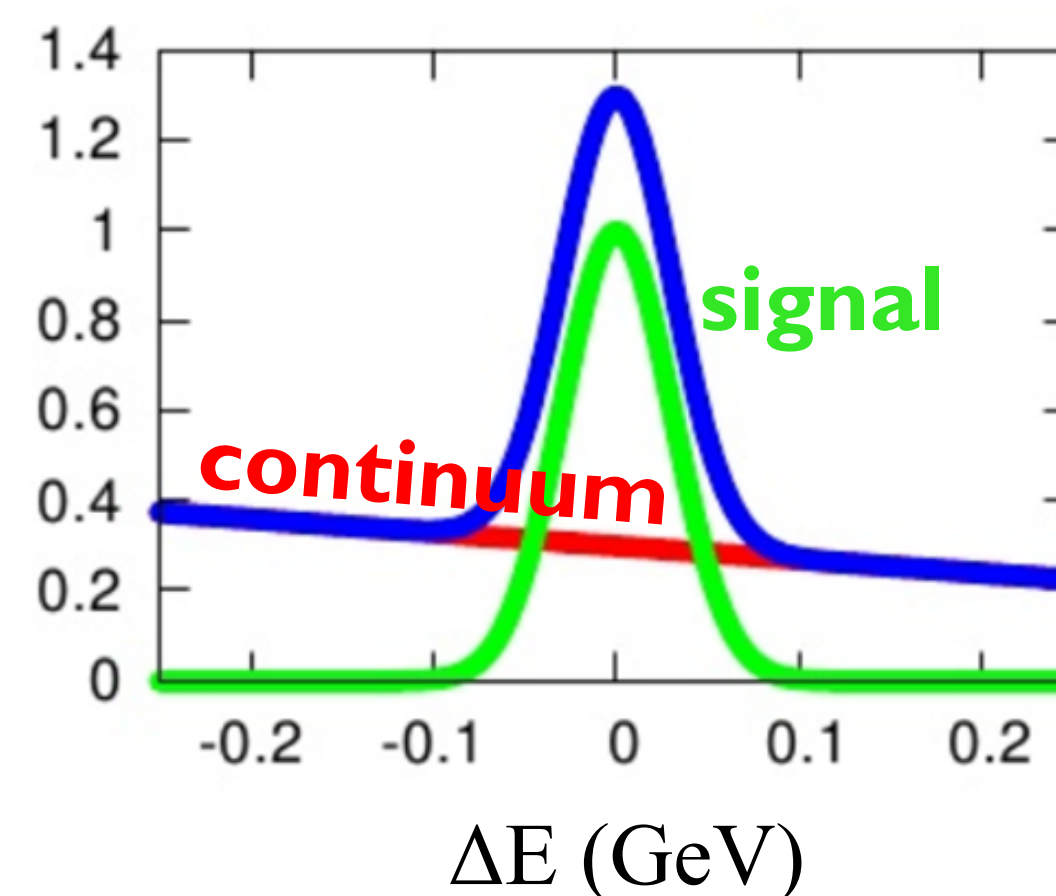
M_{BC} : beam-constrained mass

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



ΔE : energy difference

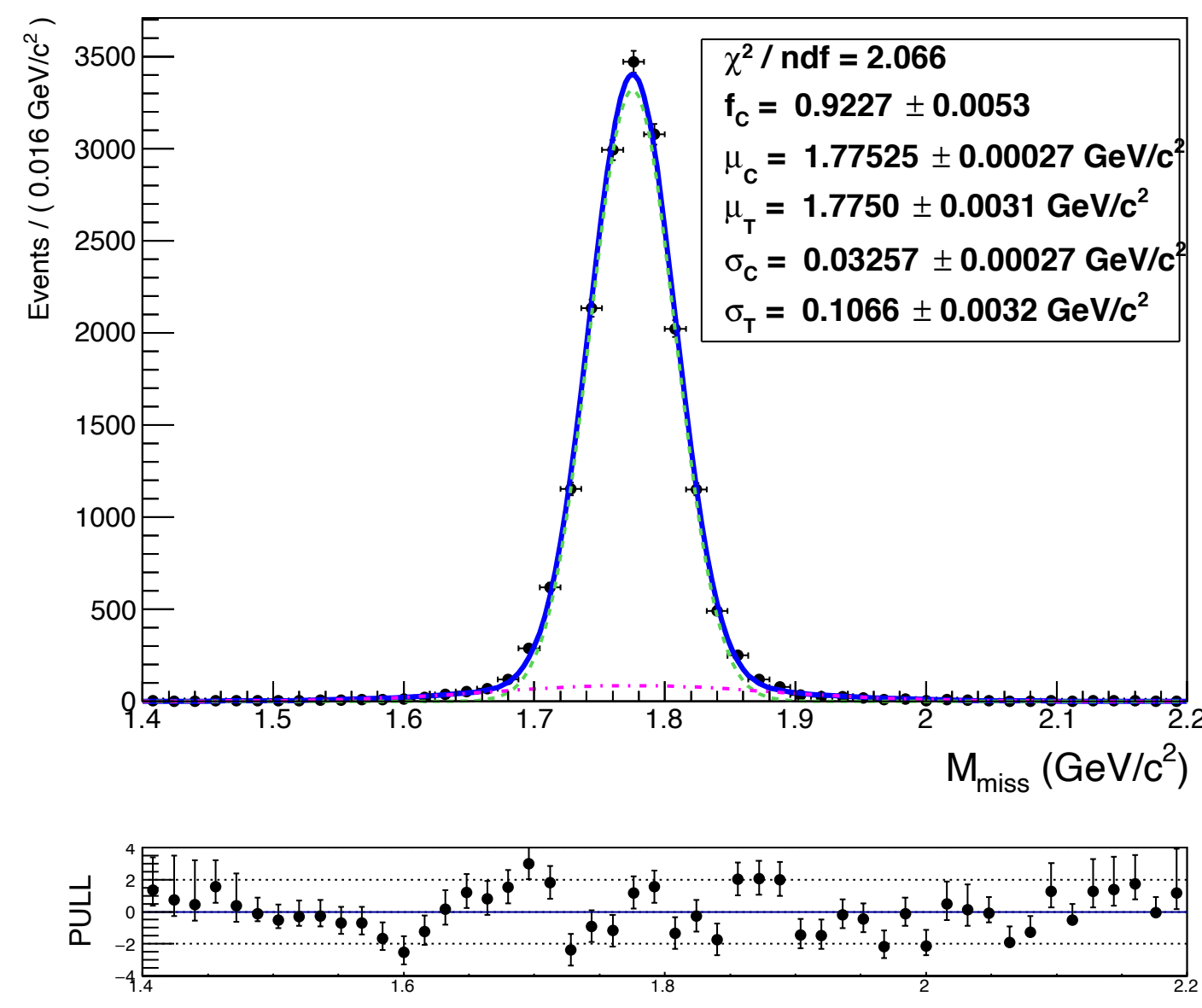
$$\Delta E = E_B - E_{BEAM}$$



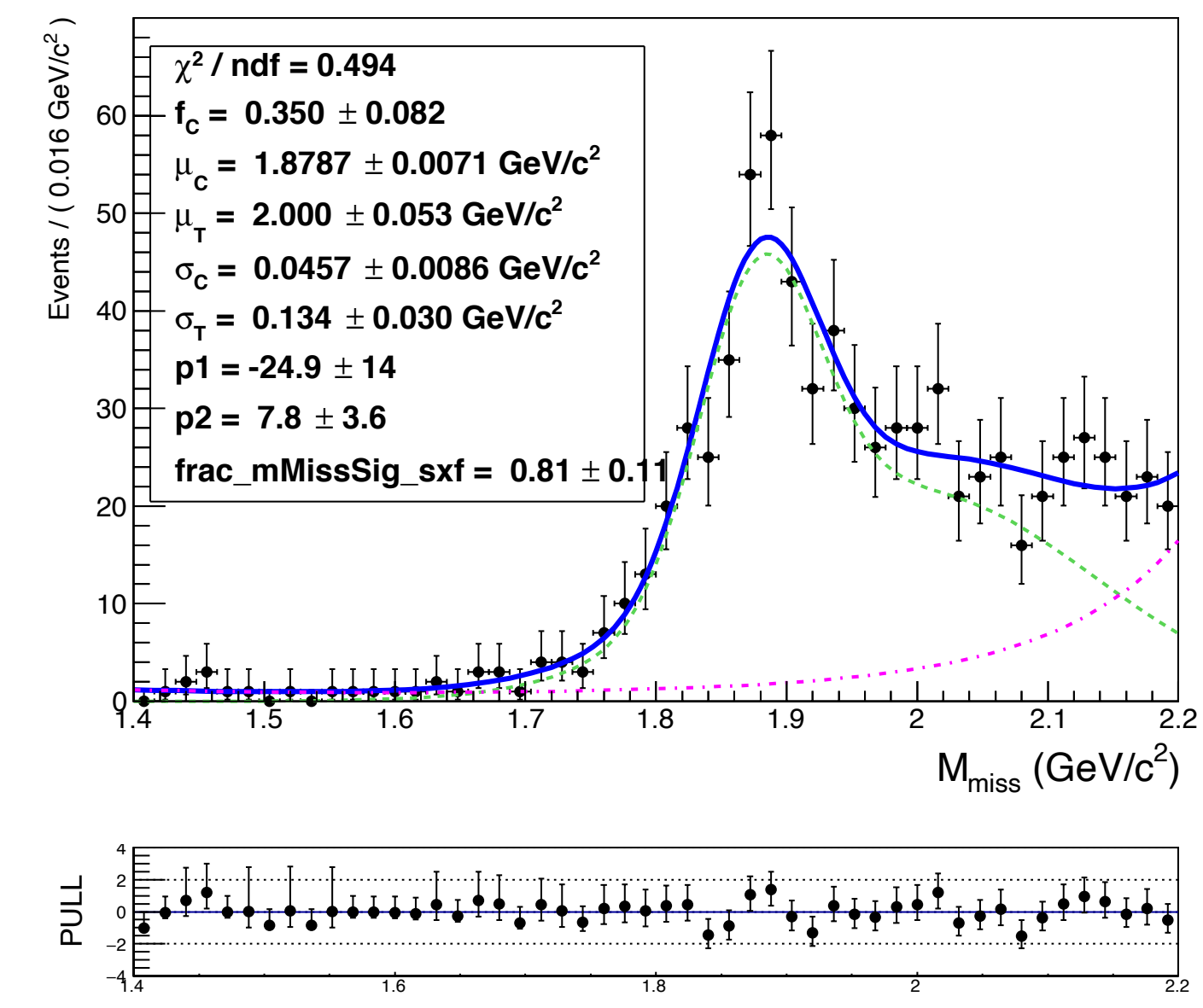
- E_B^* and p_B^* are energy and momentum of B candidate, and E_{BEAM}^* is the beam energy in the $\Upsilon(4S)$ center-of-mass frame.
- continuum events [$e^+ e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$)]

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

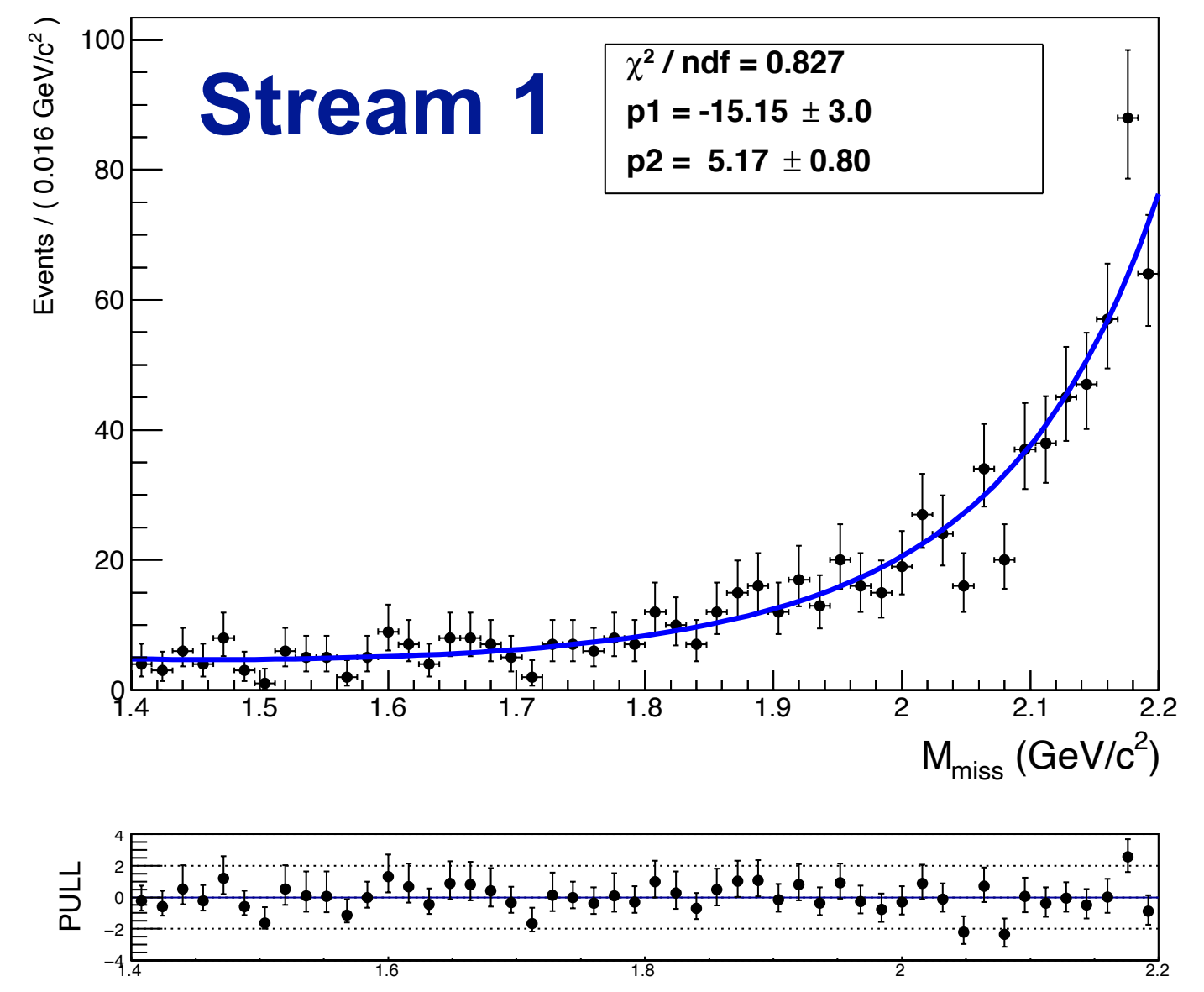
Signal (True) Double Gaussian



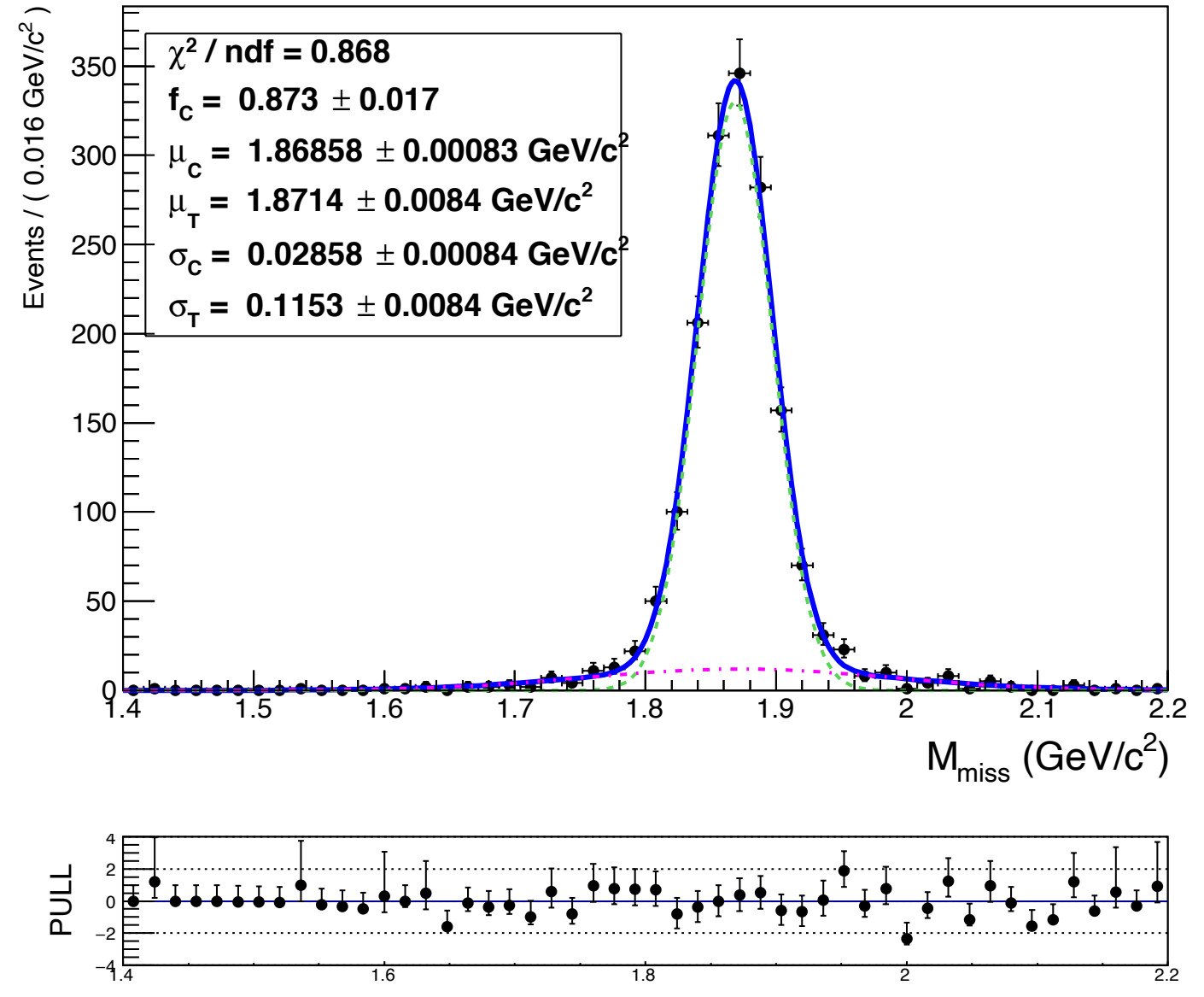
Signal (SxF) Double Gaussian + $e^{(bx+cx^2)}$



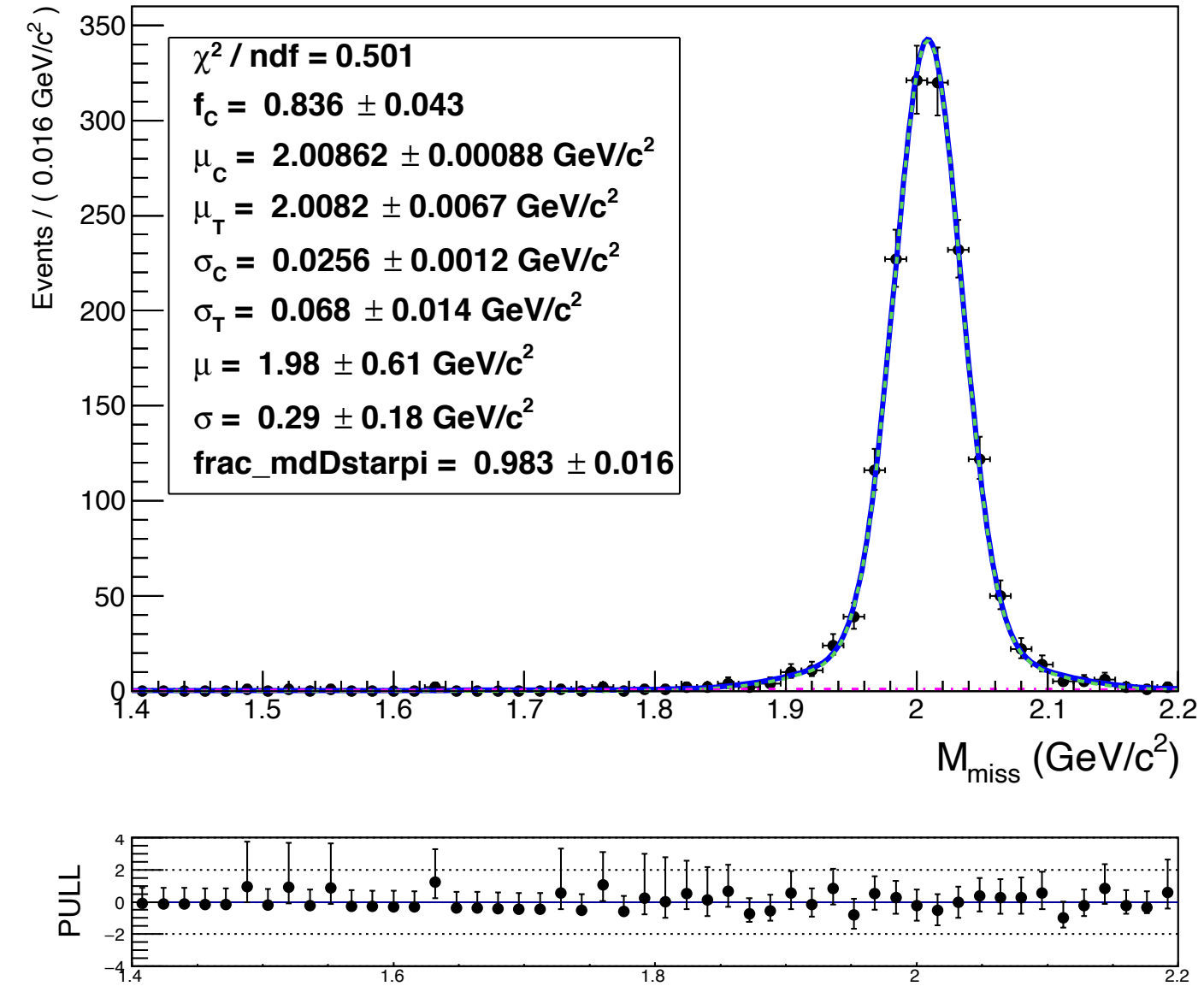
Background (MC Sream 1+ ulnu +rare) $e^{(bx+cx^2)}$



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

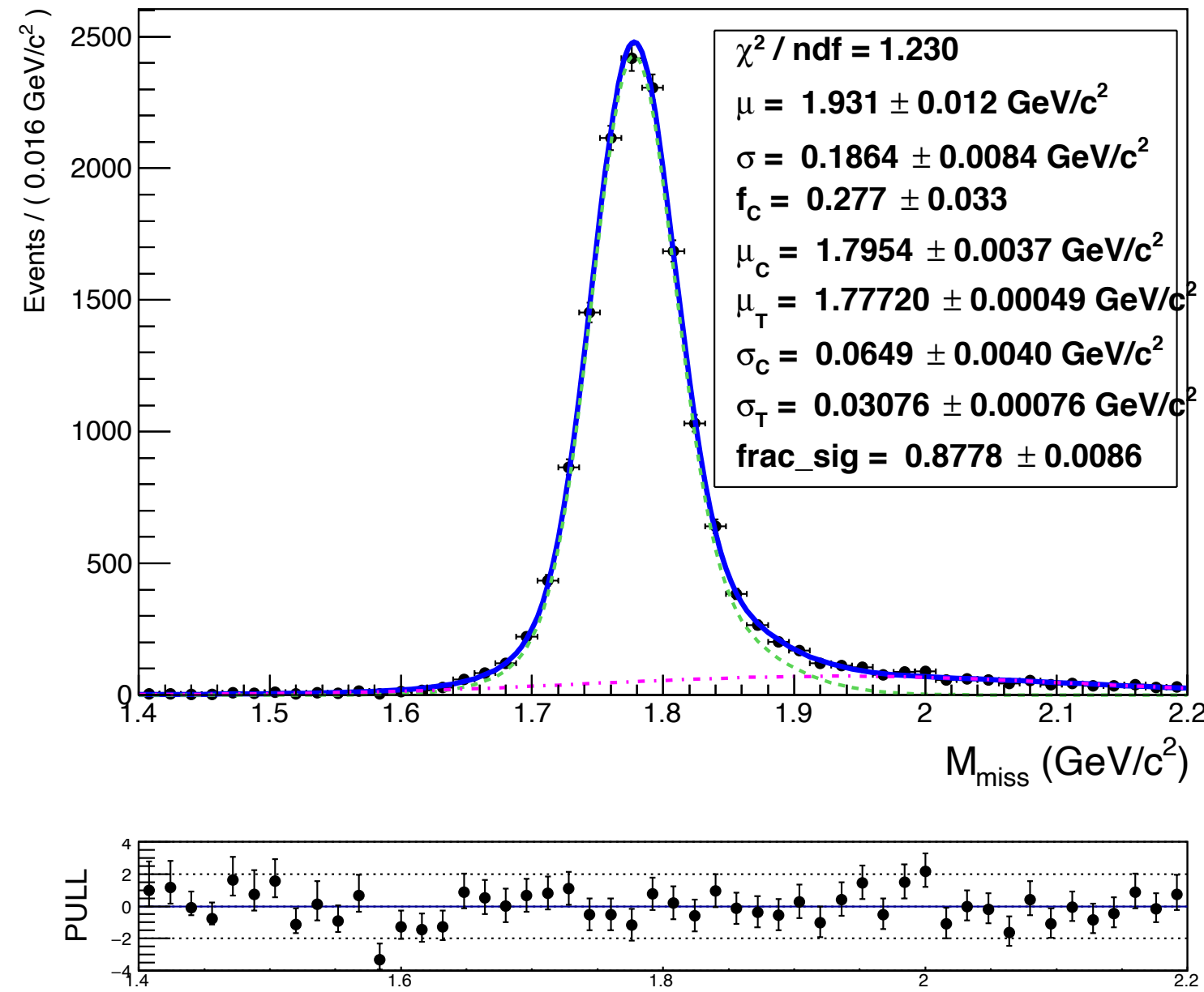


Peaking Bkg ($B^0 \rightarrow D^* \pi$) Double + Single Gaussian

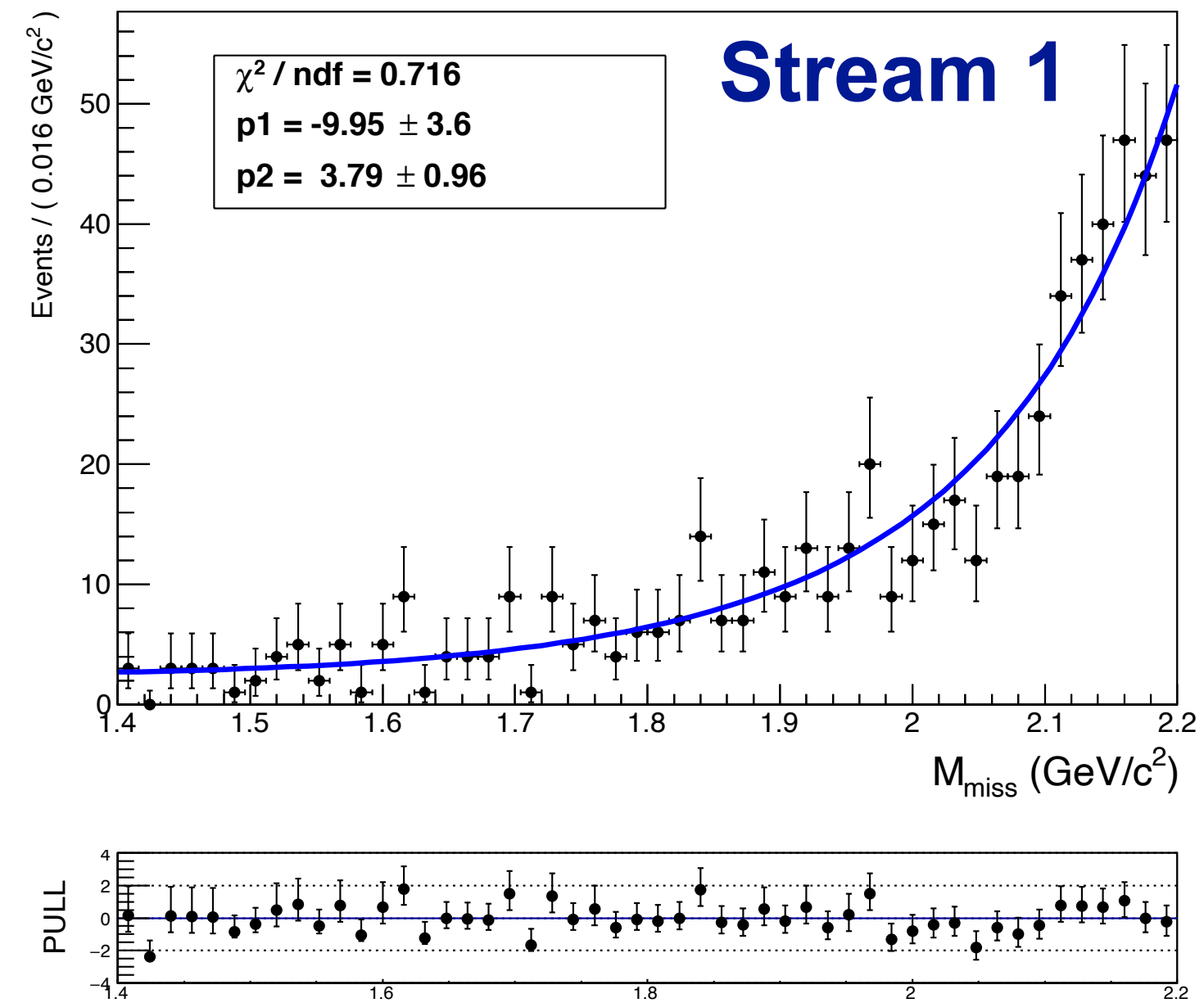
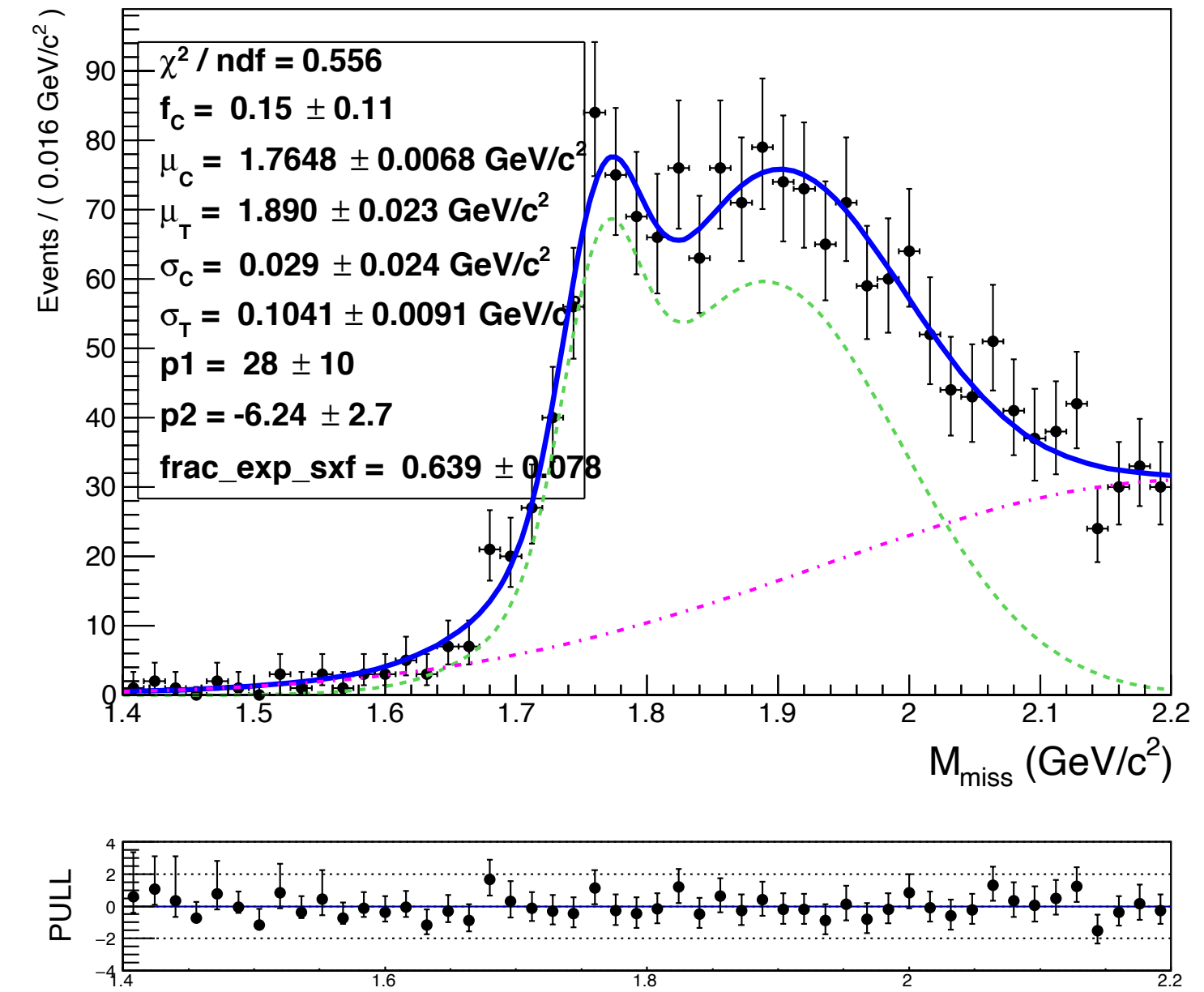


$B^0 \rightarrow \tau e$ Pdf Fit Using MC

Signal (True) Single + Double Gaussian



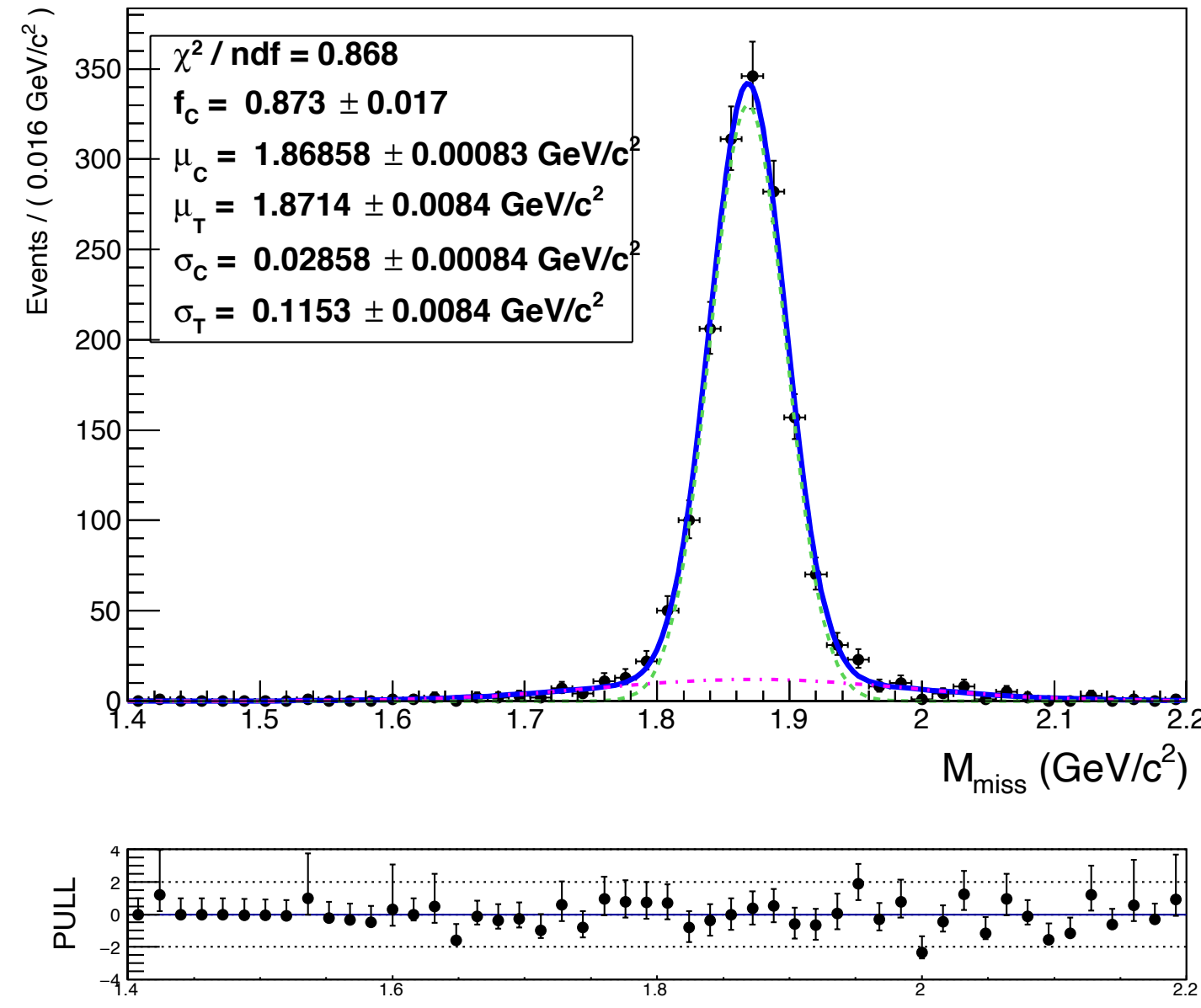
Signal (SxF) Double Gaussian + $e^{(bx+cx^2)}$



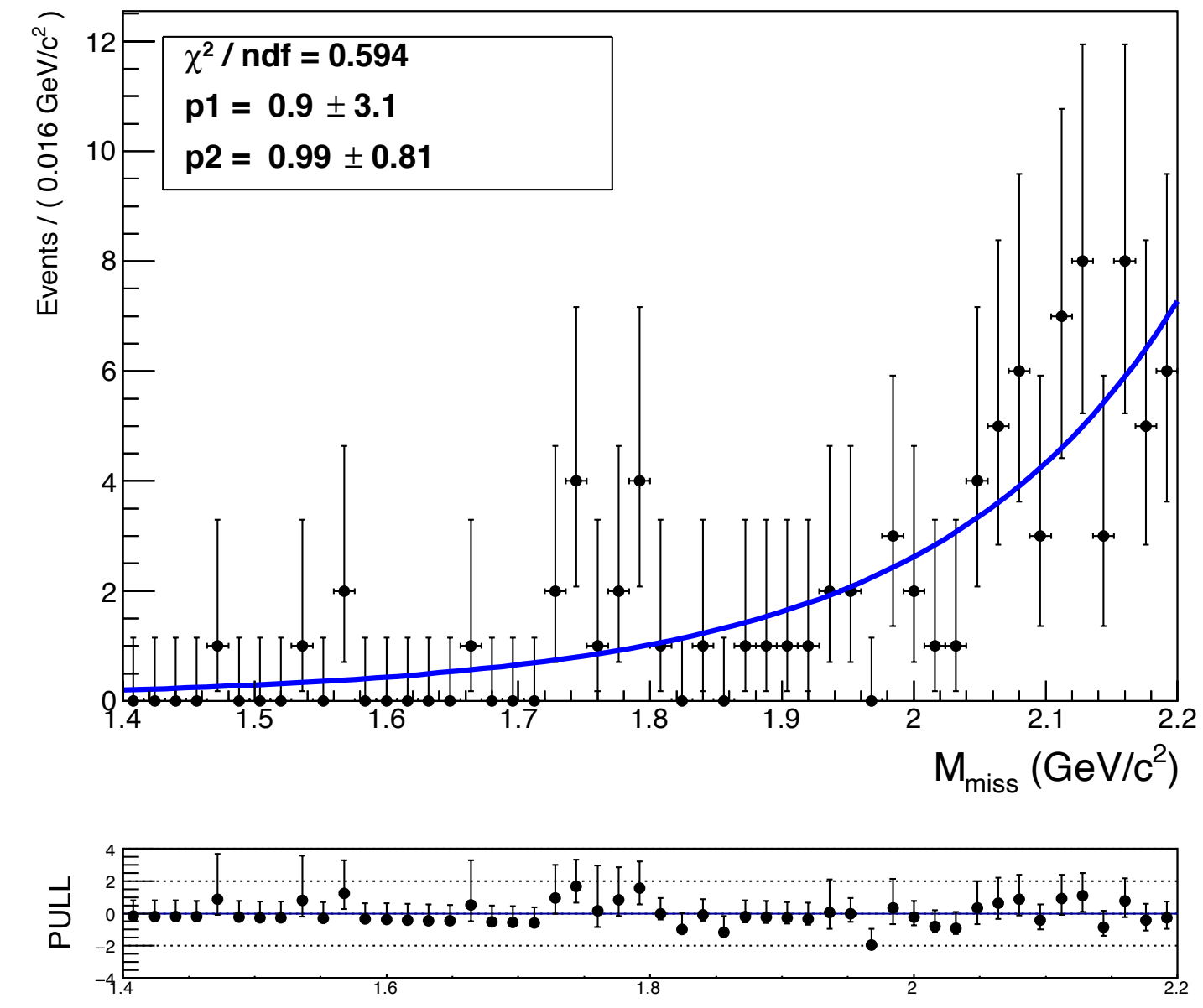
Background (MC Stream 1+ ulnu +rare) $e^{(bx+cx^2)}$

Pdf Fit using MC

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



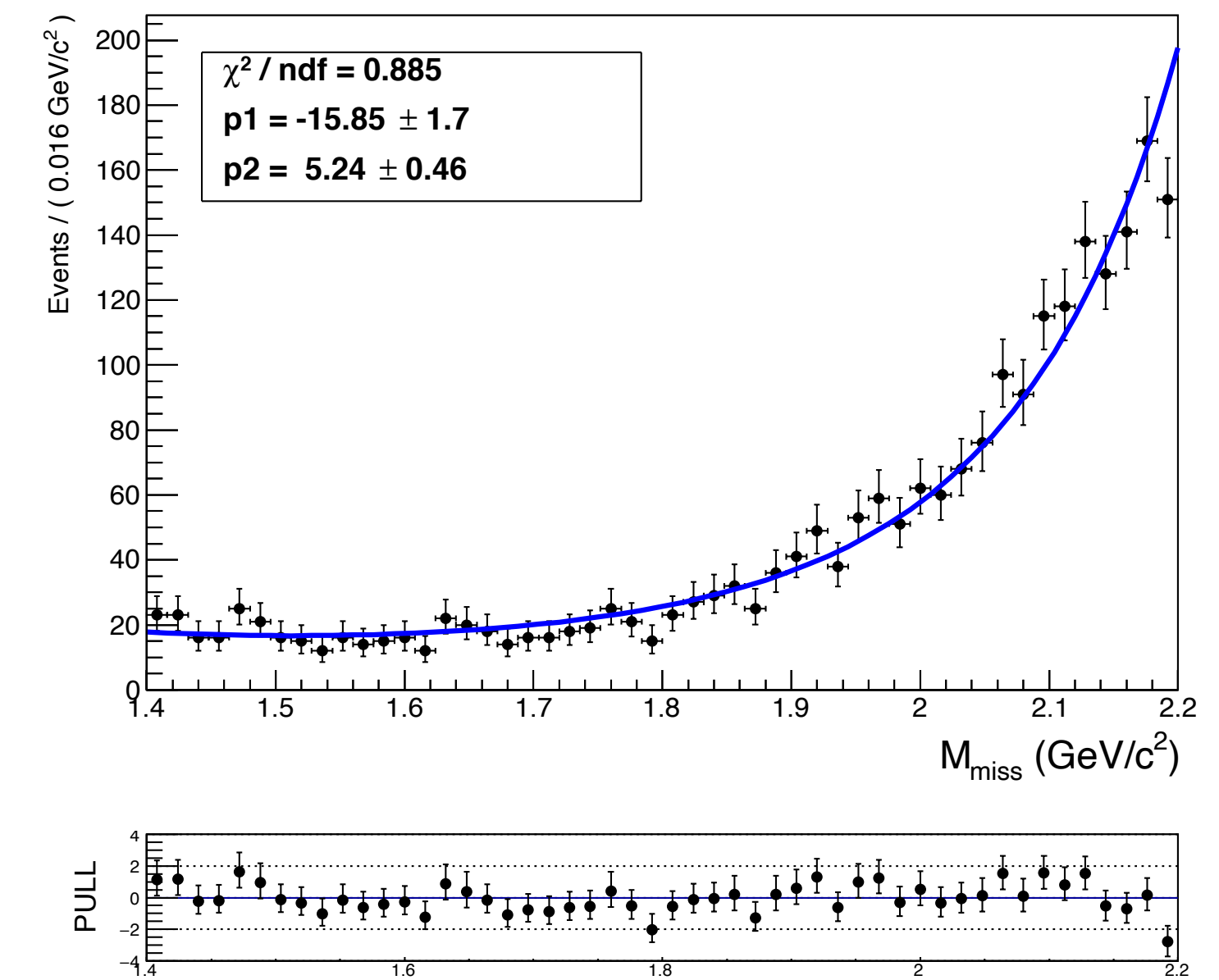
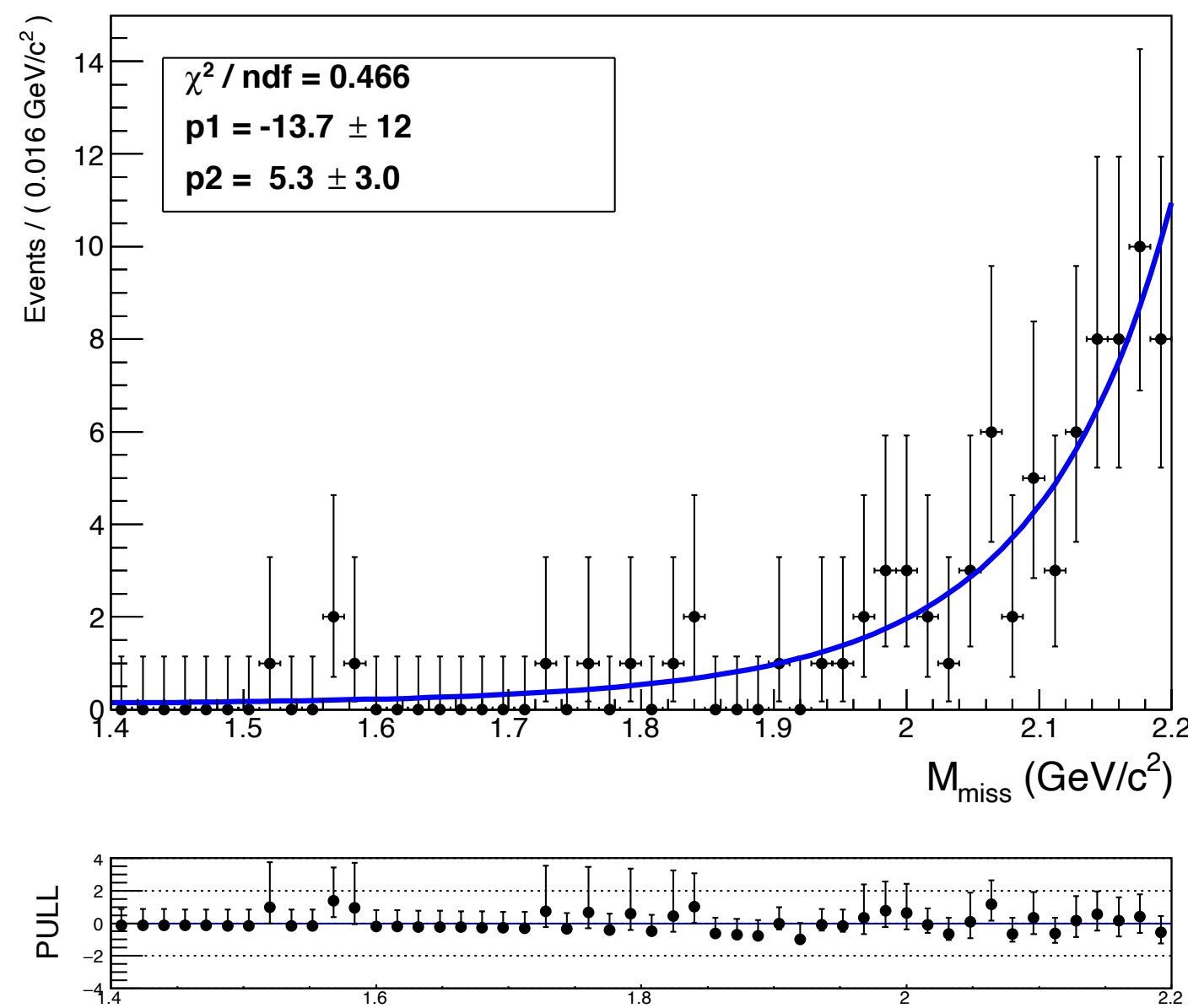
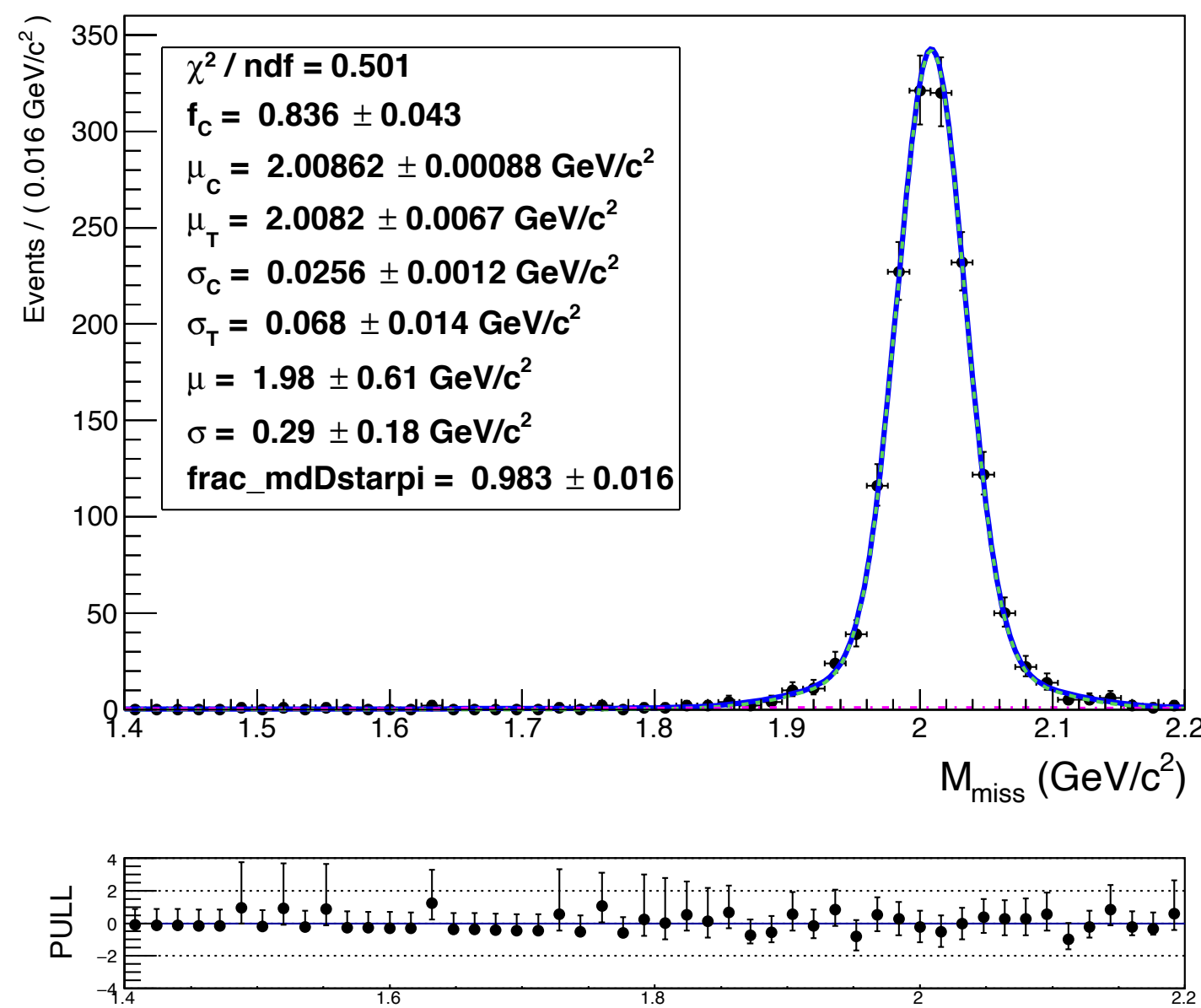
$B^0 \rightarrow D \pi$ SxF signal $e^{(bx+cx^2)}$



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

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

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



UPPER LIMIT ESTIMATION

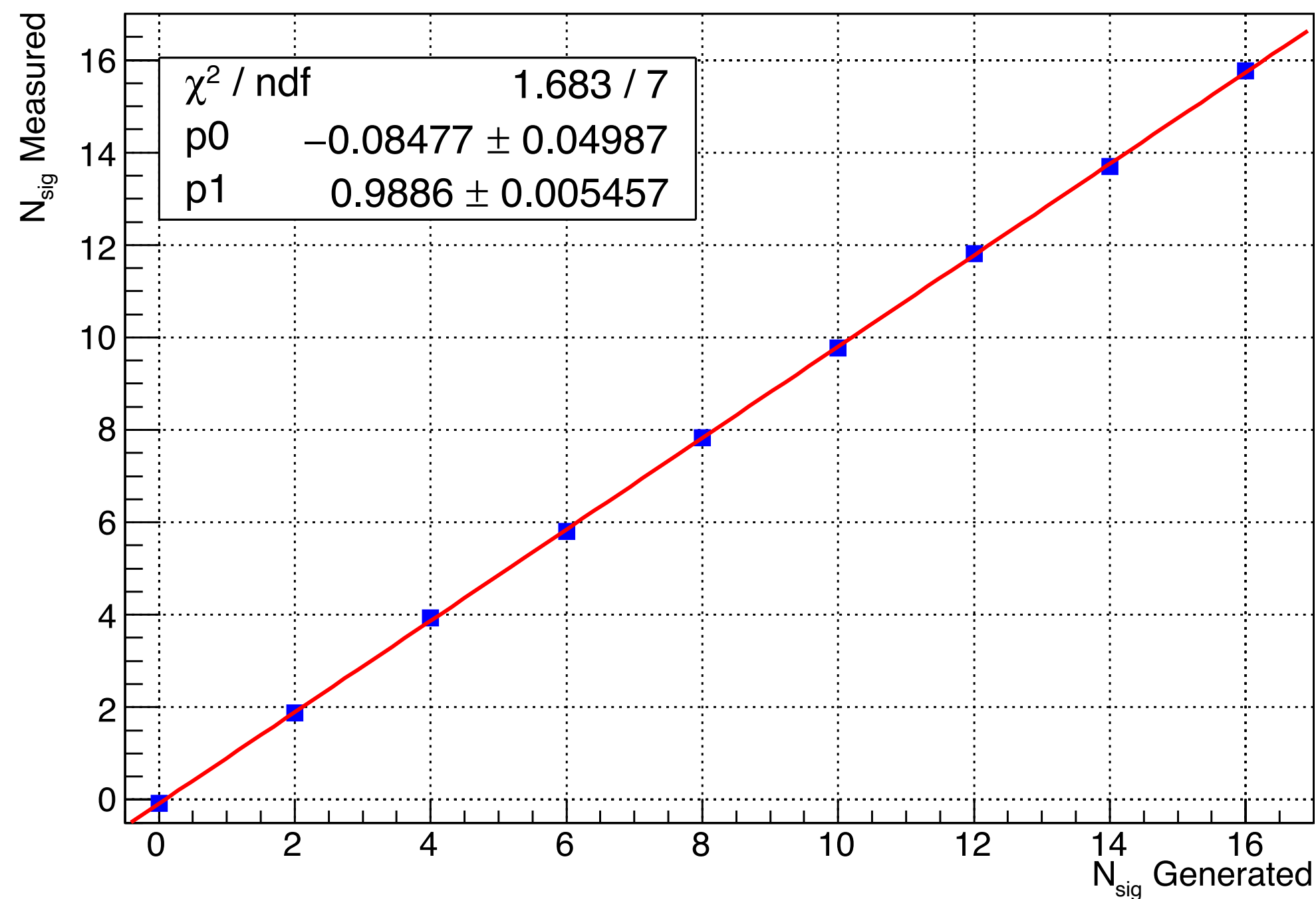
(systematic uncertainties are not included)

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

Linearity Plots

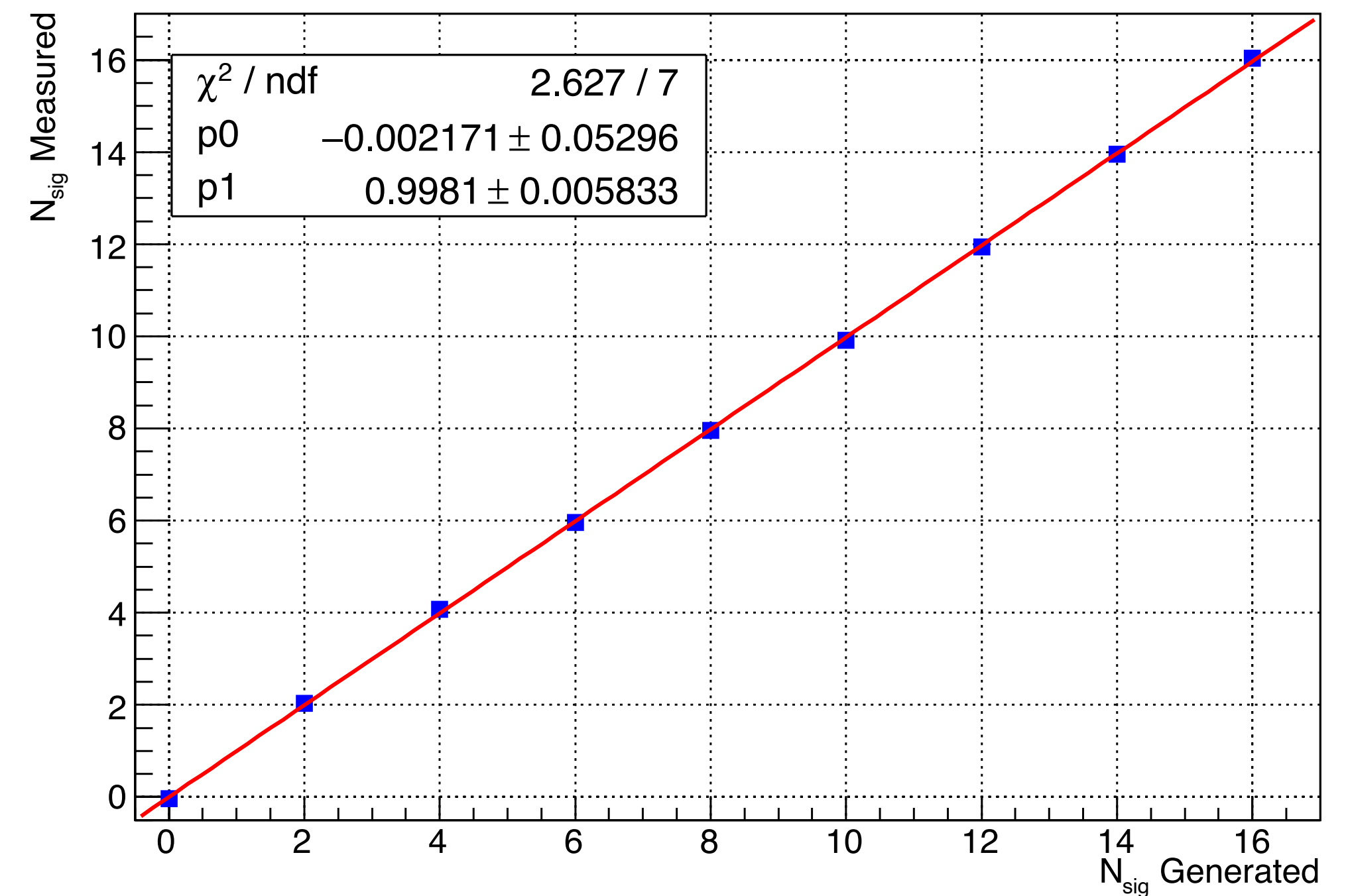
$$B^0 \rightarrow \mu \tau$$

μ Mode - N_{sig} Measured vs N_{sig} Generated



$$B^0 \rightarrow e \tau$$

e Mode - N_{sig} Measured vs N_{sig} Generated

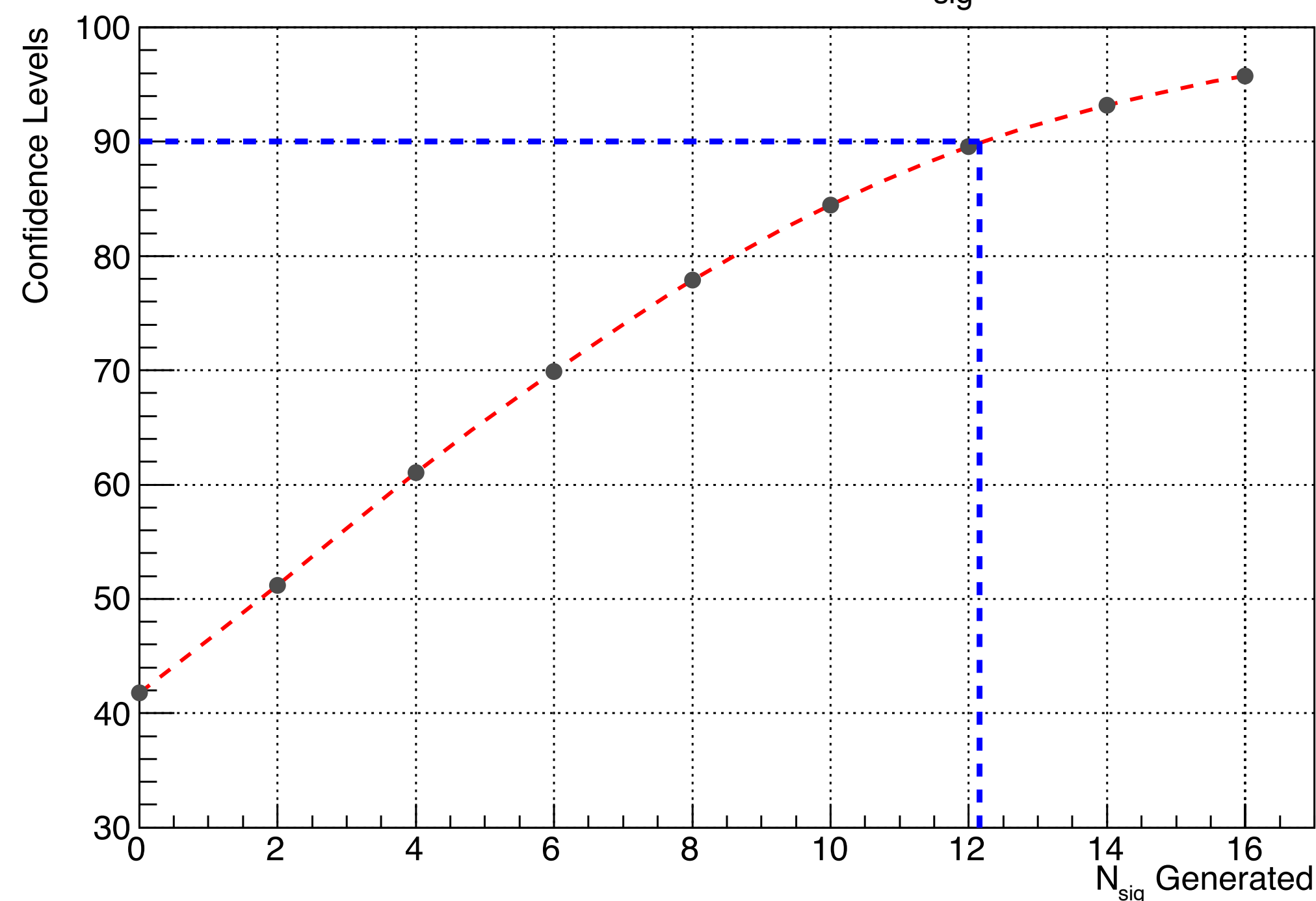


UPPER LIMIT ESTIMATION

(systematic uncertainties are not included)

- Generated 10 K experiments with different number of possible signal yields ($N_{\text{sig}}^{\text{gen}}$) varying from 0 to 16.
- 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.

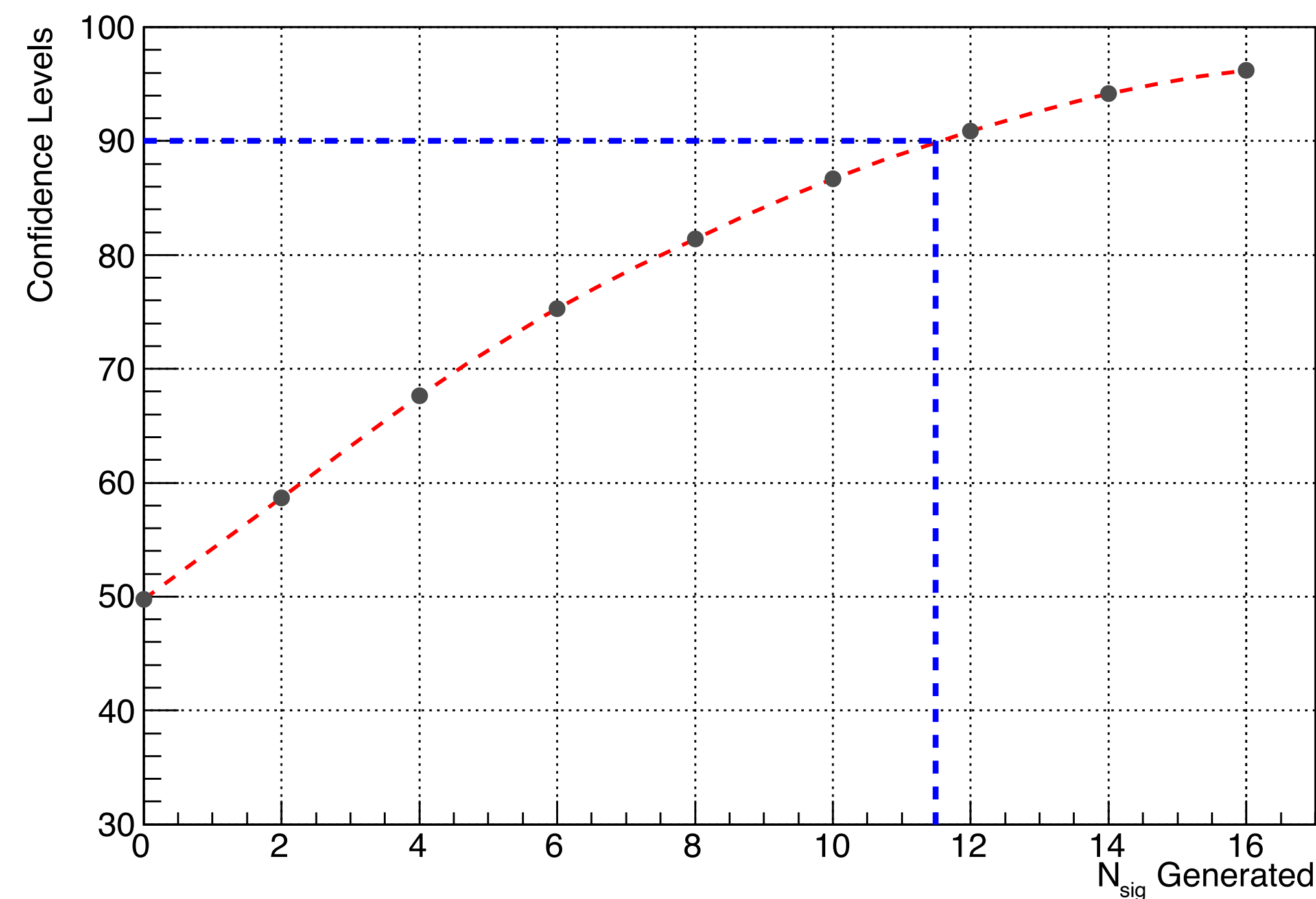
∞ Mode - Confidence Levels vs N_{sig} Generated



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

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

e Mode - Confidence Levels vs N_{sig} Generated



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

SYSTEMATIC UNCERTAINTIES

Source	$B^0 \rightarrow \tau^\pm \mu^\mp$	$B^0 \rightarrow \tau^\pm e^\mp$
PDF shapes	0.7	0.3
Self-cross-feed fraction	< 0.1	0.1
Total (events)	0.7	0.3
<hr/>		
B_{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 $B\bar{B}$ Pairs	1.4	1.4
f^{00} ($B\bar{B} \rightarrow B^0\bar{B}^0$ fraction)	1.2	1.2
Total (%)	5.1	5.2

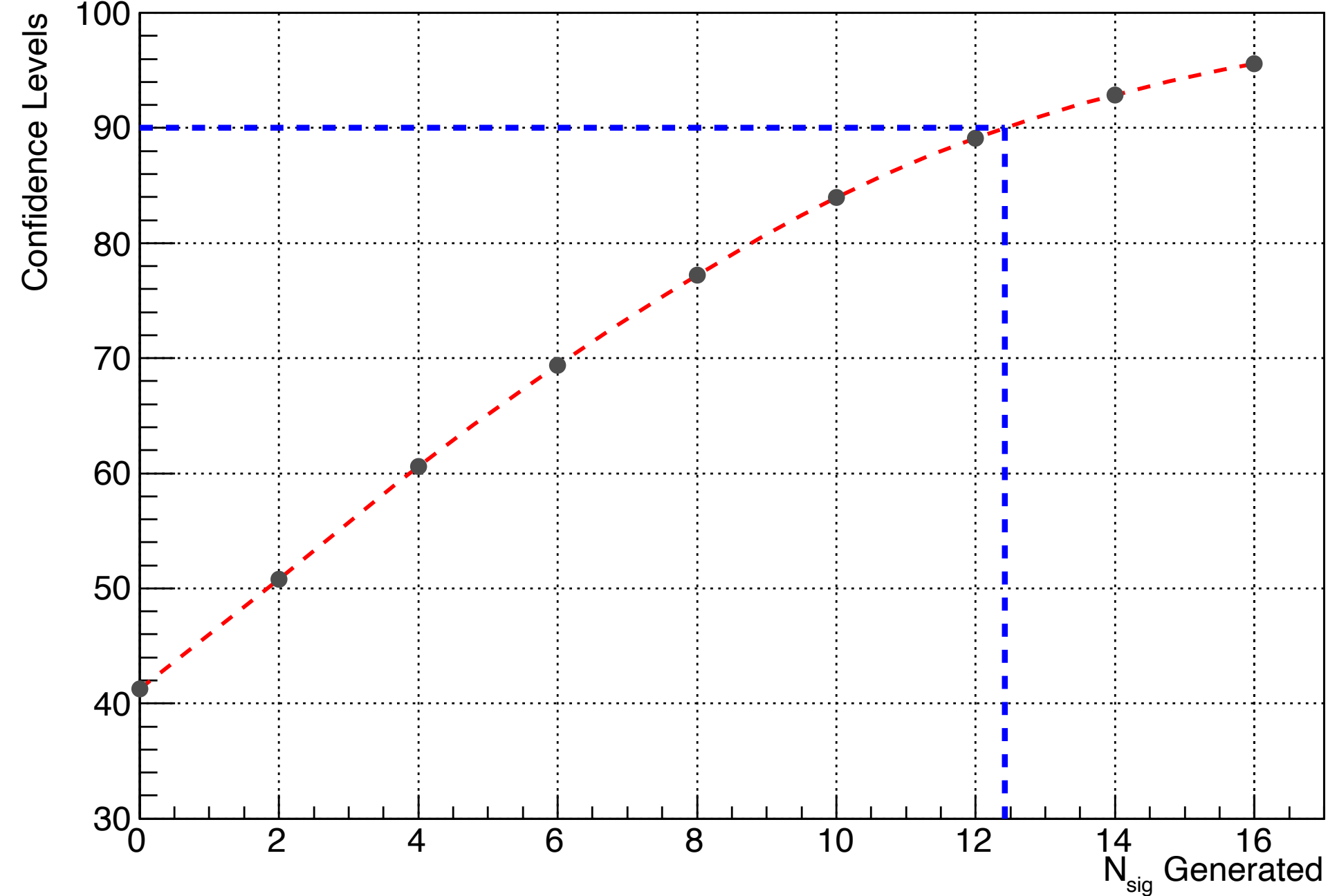
FINAL RESULTS

UPPER LIMIT ESTIMATION

(systematic uncertainties are included)

$$B^0 \rightarrow \mu \tau$$

∞ Mode - Confidence Levels vs N_{sig} Generated

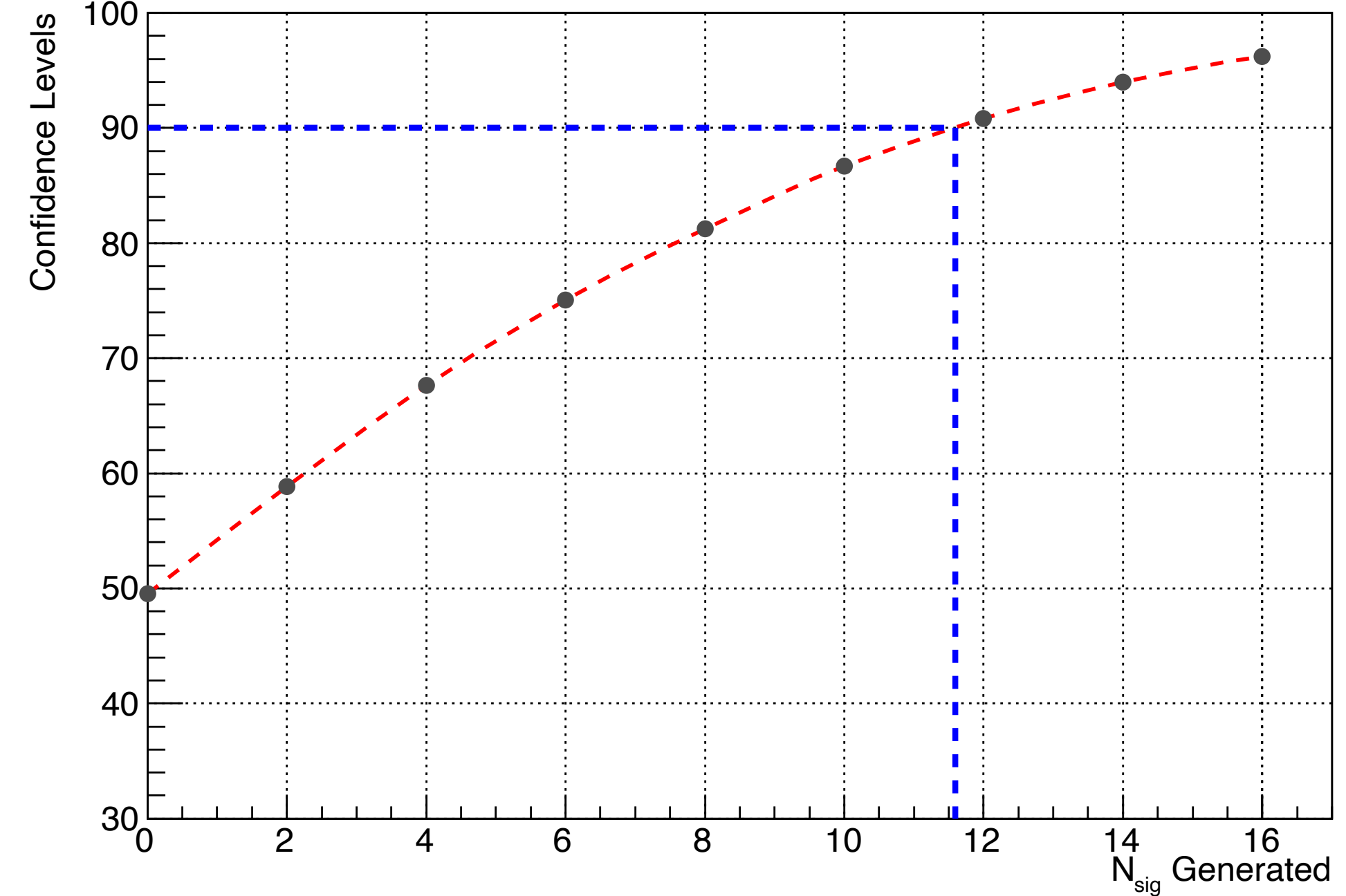


$$N_{sig}^{UL} = 12.4$$

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

$$B^0 \rightarrow e \tau$$

e Mode - Confidence Levels vs N_{sig} Generated



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

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