Result on $B \to \pi\tau\nu$ at Belle

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Talk by Harrison Schreeck
University of Göttingen

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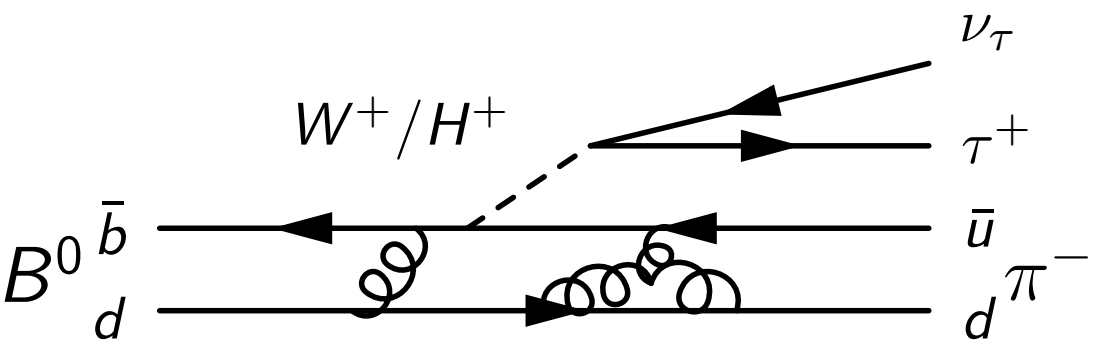
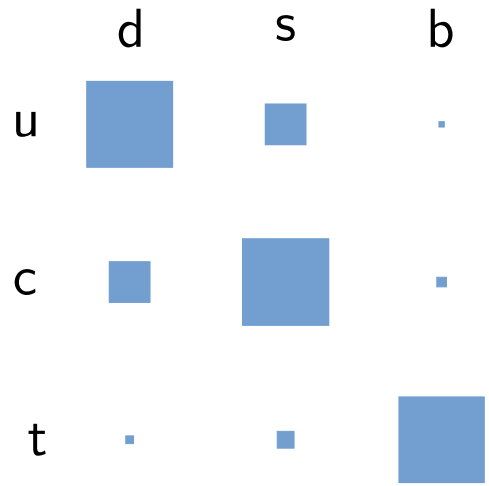
Motivation

- $B^0 \to \pi^- \tau^+ \nu_\tau$ has not been observed yet and no limit has been published
- New physics models like 2HDM predict additional charged Higgs $H^\pm$
- $\mathcal{B}(B \to D^{(*)} \tau \nu)/\mathcal{B}(B \to D^{(*)} \ell \nu)$ shows 3.9σ deviation from SM prediction





$H_\mu = \langle \pi^- | \, u\gamma^\mu(1-\gamma^5)\bar{b} \, | B^0 \rangle = f^+(q^2) \times (\ldots) + f^0(q^2) \times (\ldots)$

$\mathcal{B}(B \to \pi\tau\nu)$ depends on $|V_{ub}|^2$, f^+, f^0

$R(\pi) = \frac{\mathcal{B}(B \to \pi\tau\nu_\tau)}{\mathcal{B}(B \to \pi\ell\nu_\ell)}$ depends on f^0/f^+

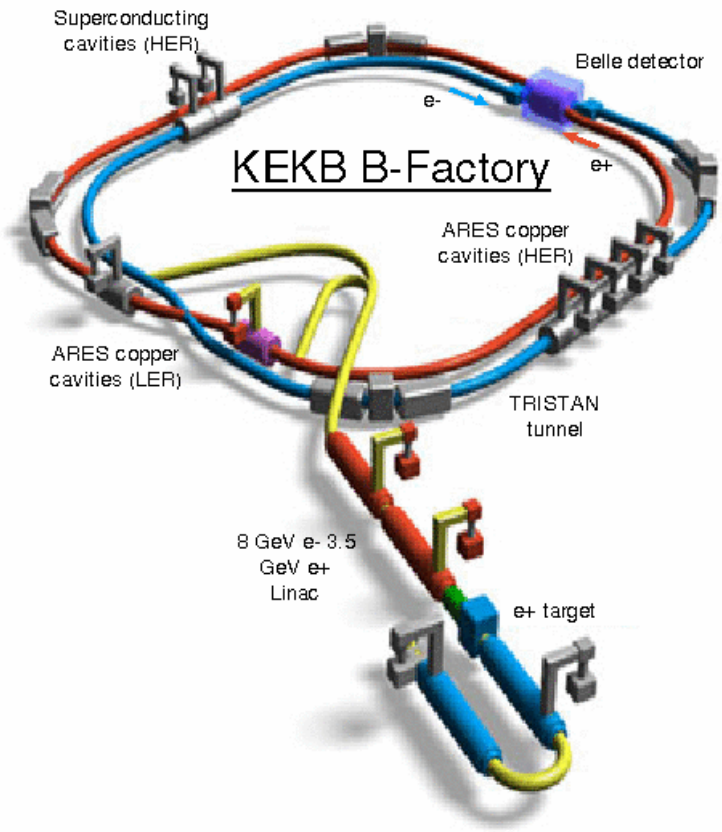
SM Prediction

$$R(\pi) = 0.641(17)$$ (lattice QCD, FNAL/MILC arXiv:1510.02349[hep-ph])

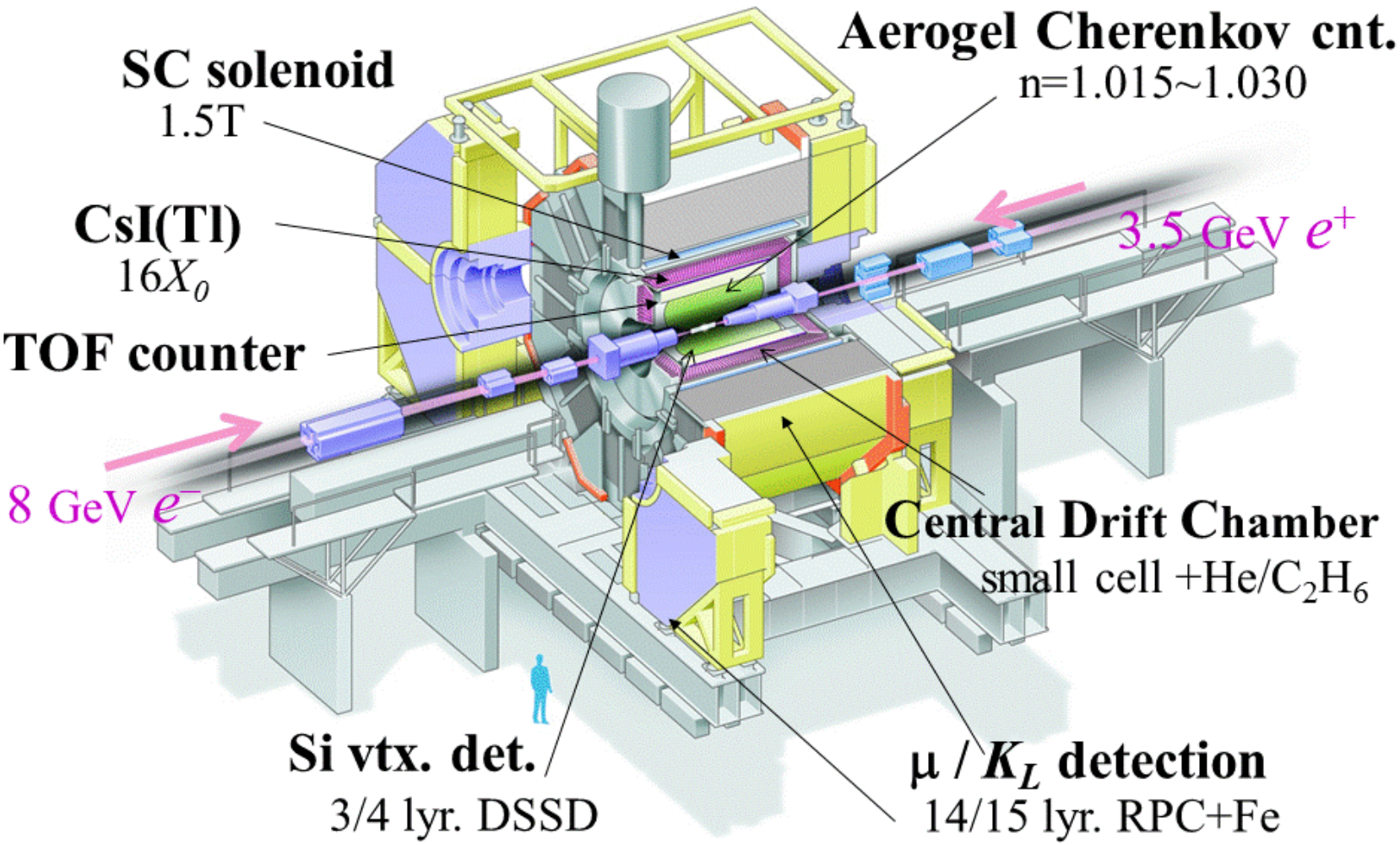
$$\mathcal{B}(B \to \pi\tau\nu) = 9.35(38) \cdot 10^{-5}$$

KEKB

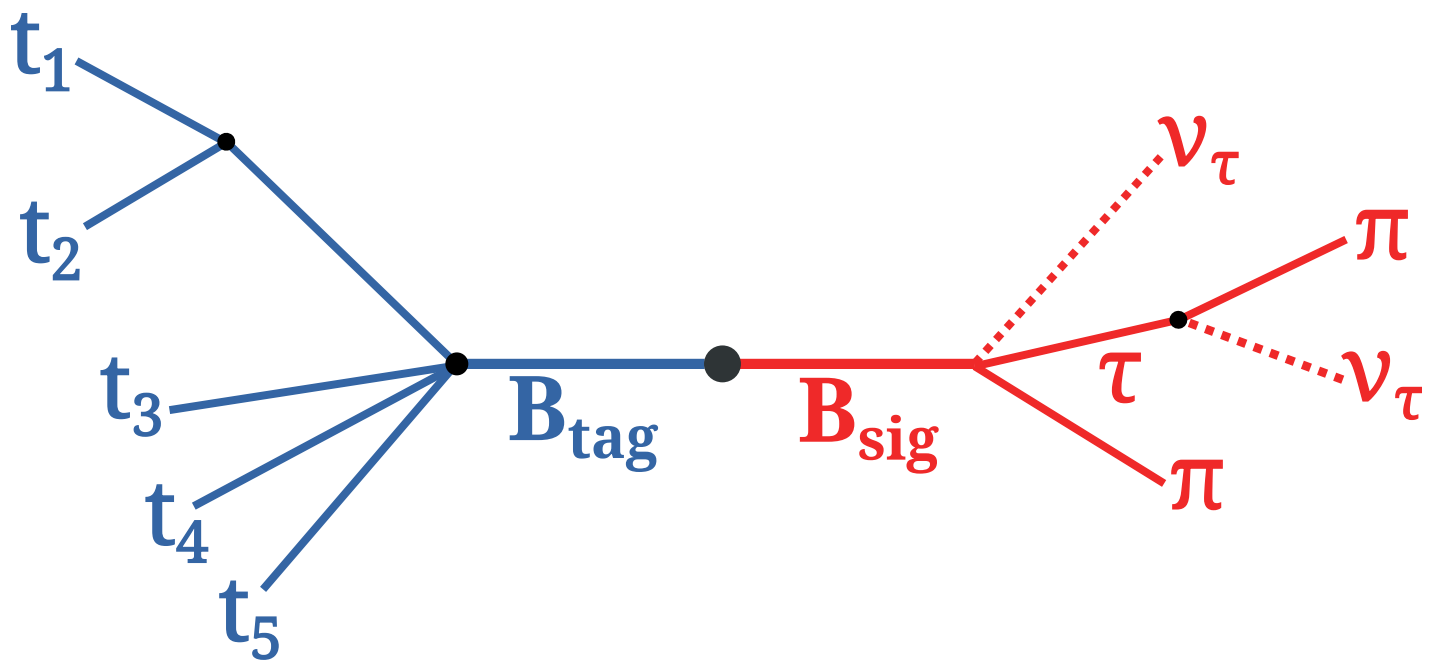
- located at the KEK in Tsukuba, Japan
- asymmetric electron-positron collider (8 GeV electron, 3.5 GeV positron beam)
- center-of-mass energy of 10.58 GeV ($\Upsilon(4S)$ resonance)
- $\Upsilon(4S)$ decays almost exclusively into $B\bar{B}$ pairs
- $B\bar{B}$ boosted into the electron direction to study CP violation



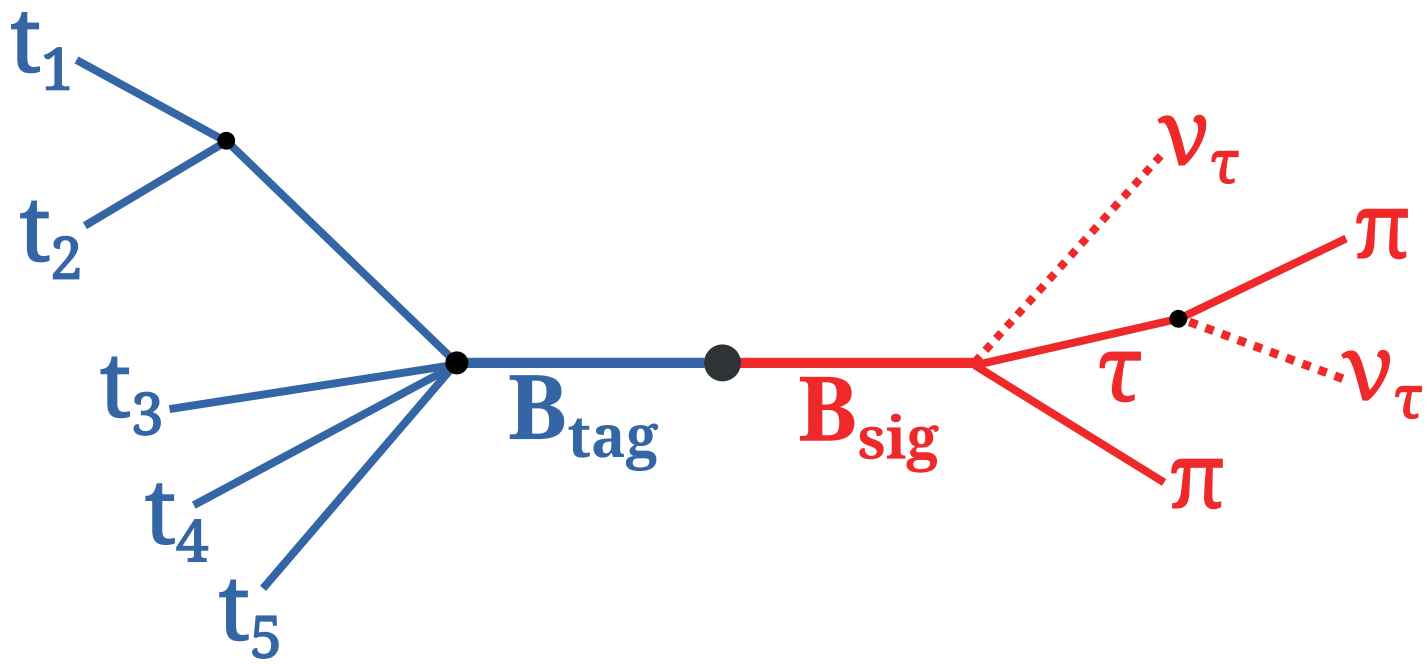
Belle Detector

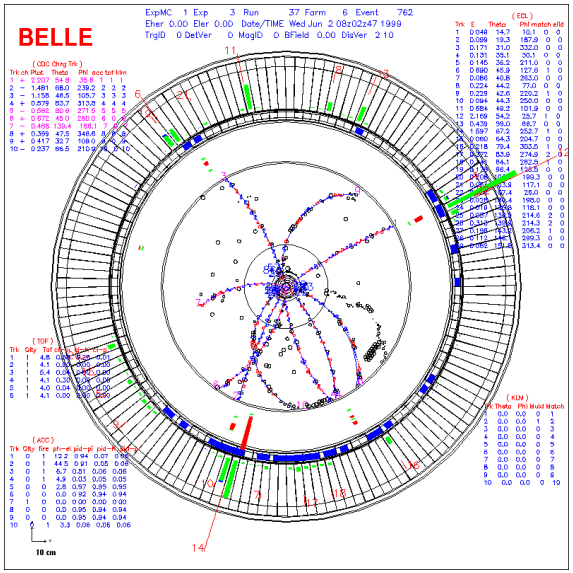


Event Reconstruction

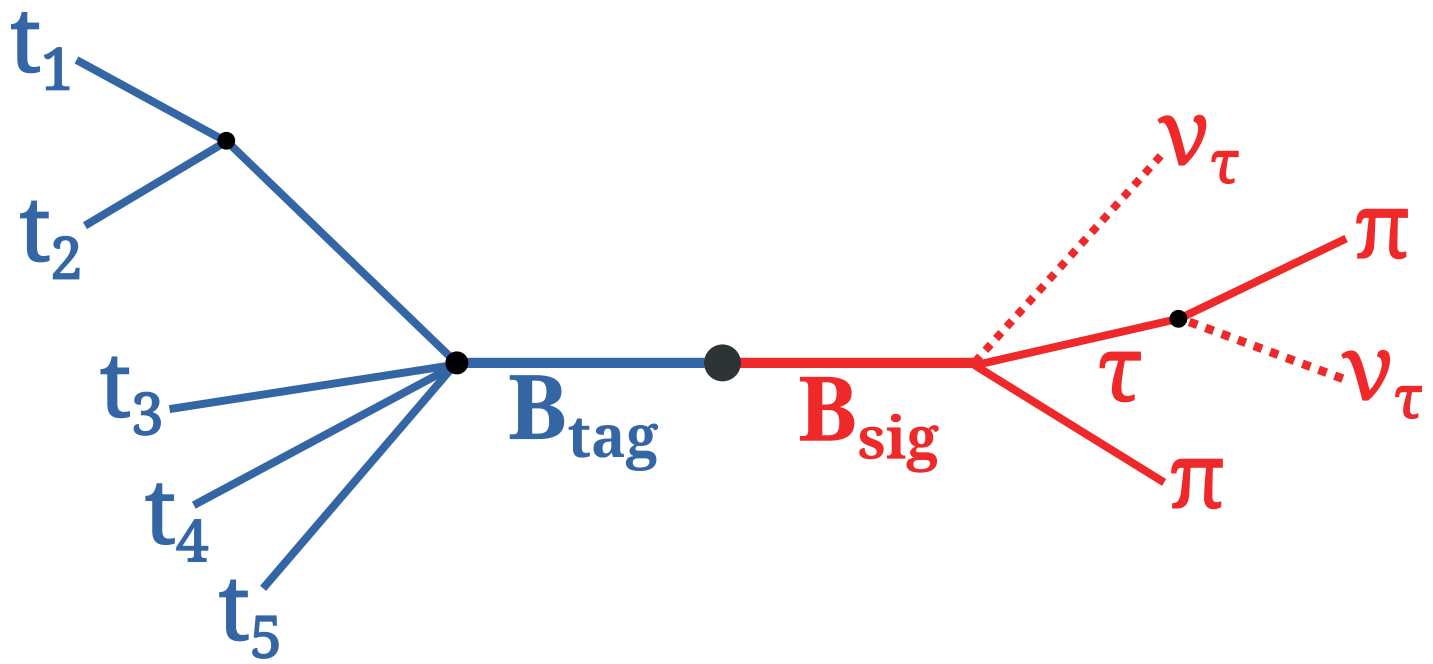


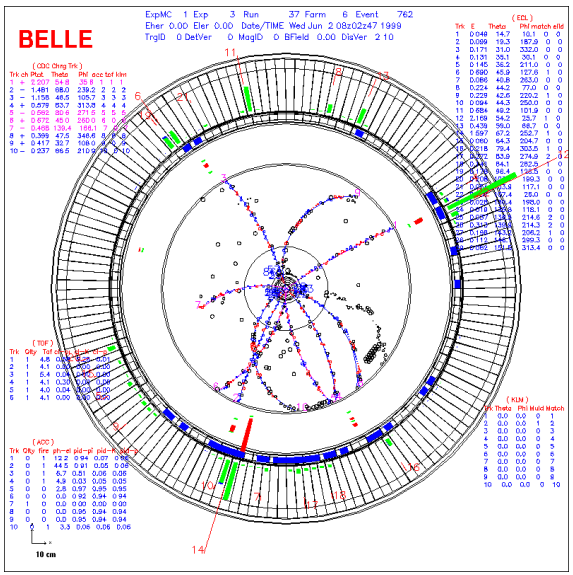
Event Reconstruction

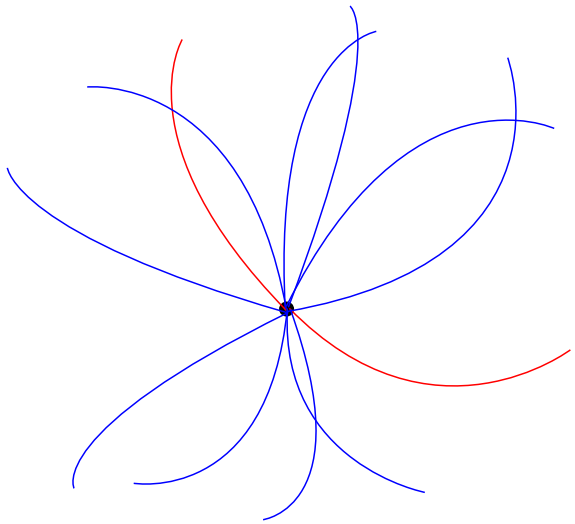




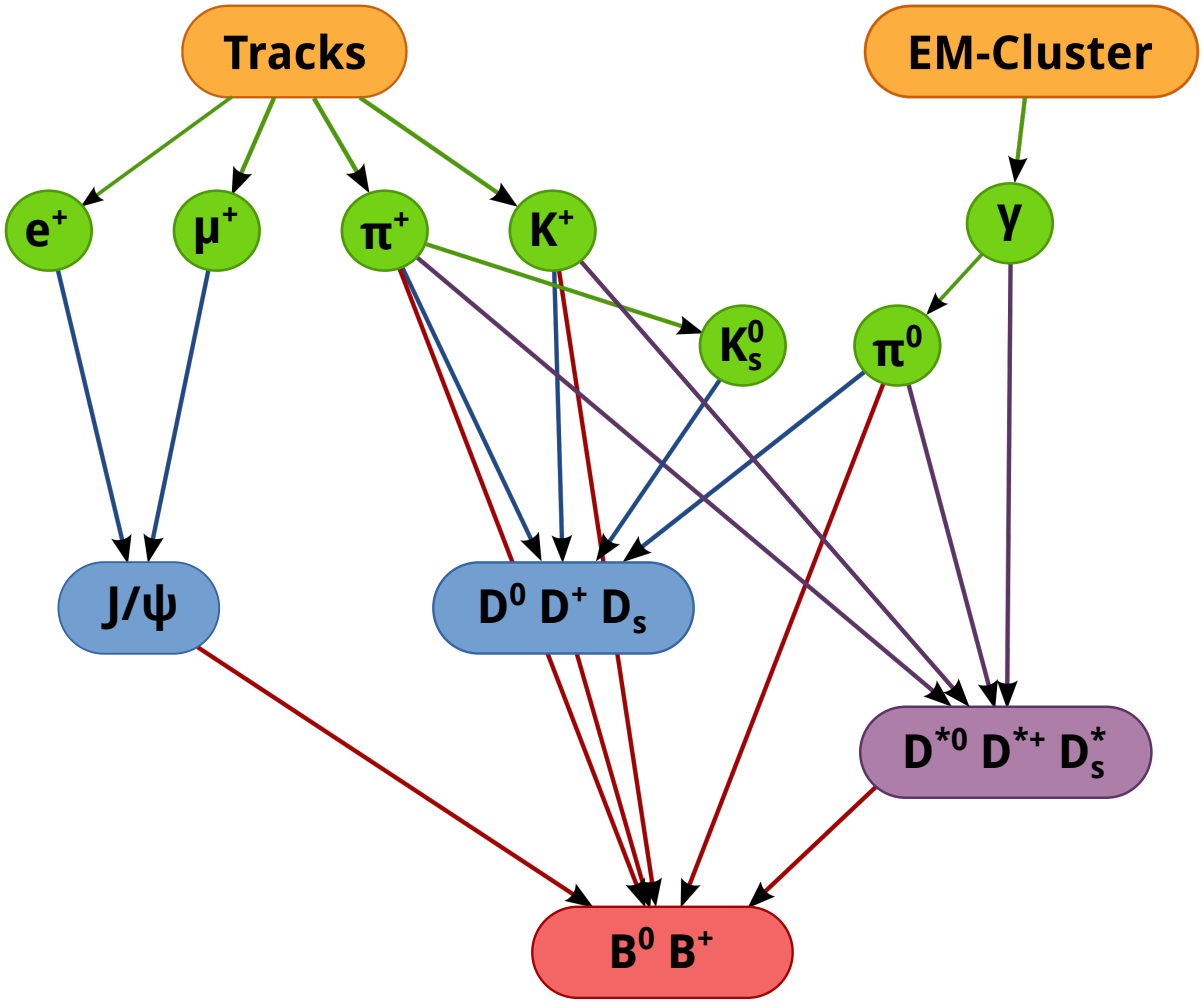
Event Reconstruction





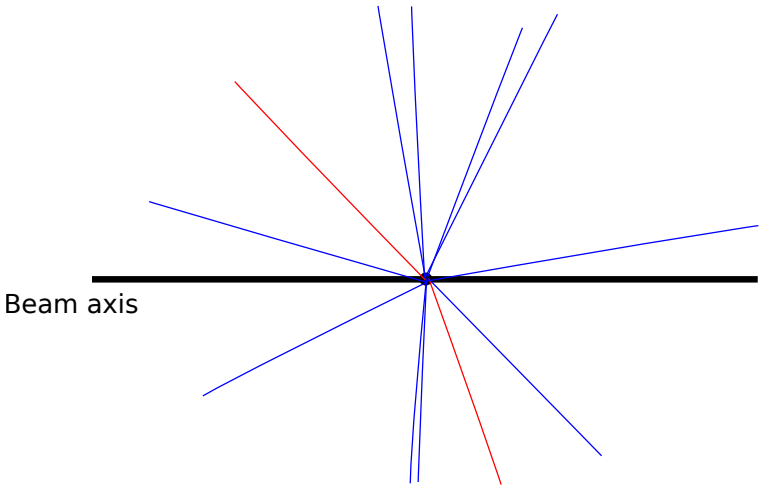


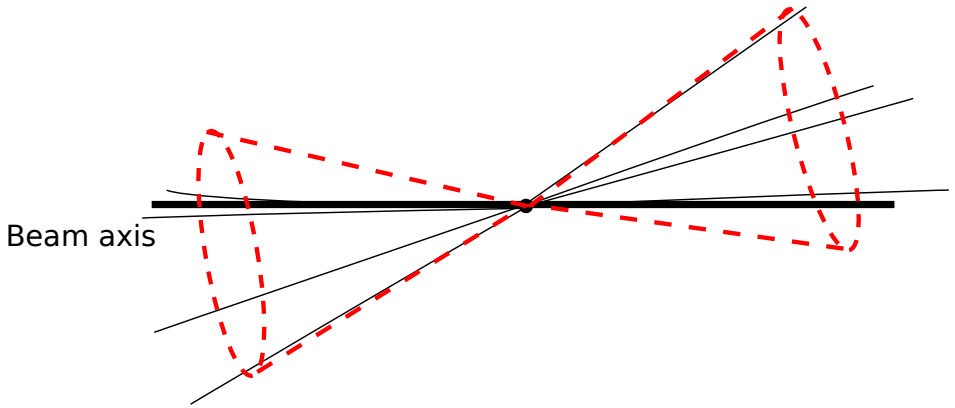
Tagside Full Reconstruction



- hierarchical reconstruction
- based on NeuroBayes (neural network)
- 1104 hadronic decay modes used ($\approx 2\%$ of all B^0 decays)
- efficiency of $\approx$0.18% (for B^0)

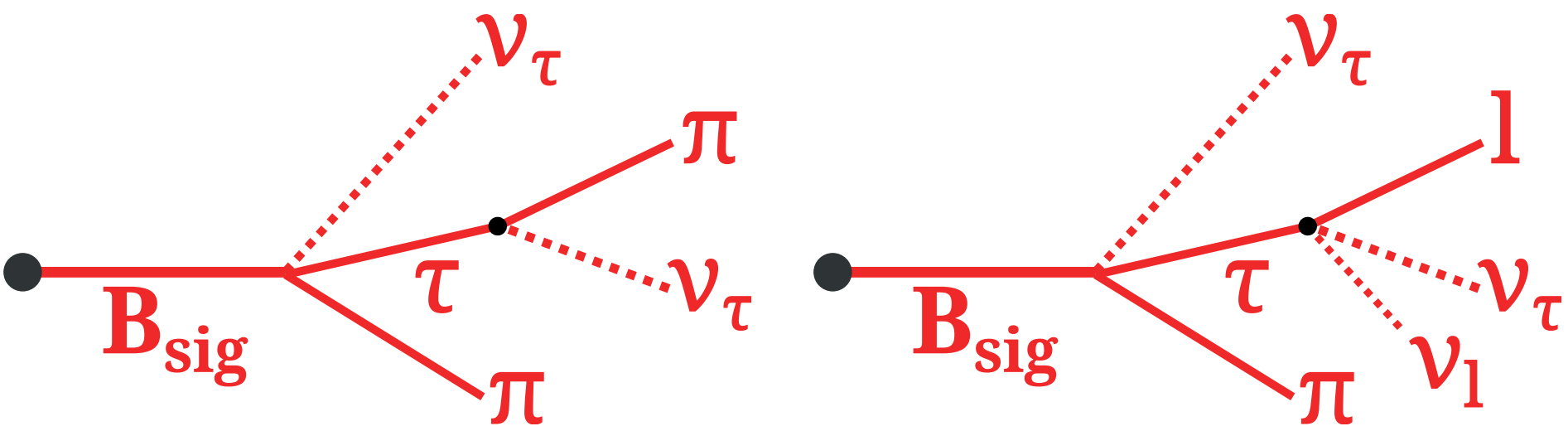
Continuum Suppression





- significant amount of continuum ($e^+e^- \to q\bar{q}$) background (3x larger than $B\bar{B}$)
- can be suppressed because of different event shape compared to $B\bar{B}$ events
- full reconstruction includes continuum suppression
- continuous output variable from 0 to 1, where events closer to 1 are less likely continuum events and have a higher reconstruction quality

Signal Side



Properties

- two opposite charged tracks, 2-3 ν
- τ reconstruction modes: $\tau \to e, \mu, \pi, \rho[\pi^{\pm}\pi^0]$ ($\approx 71\,\%$)
- B^0 not fully reconstructed $\to$ missing momentum/energy

Backgrounds

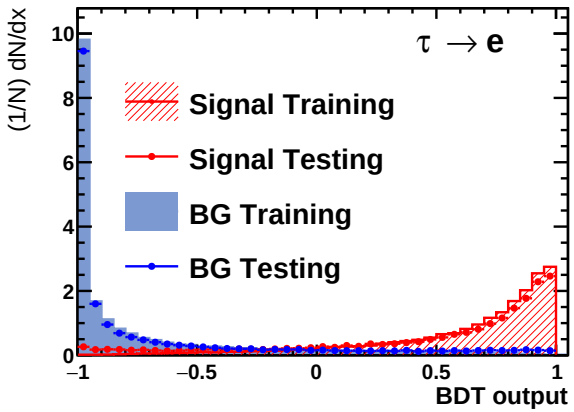
Most important backgrounds:

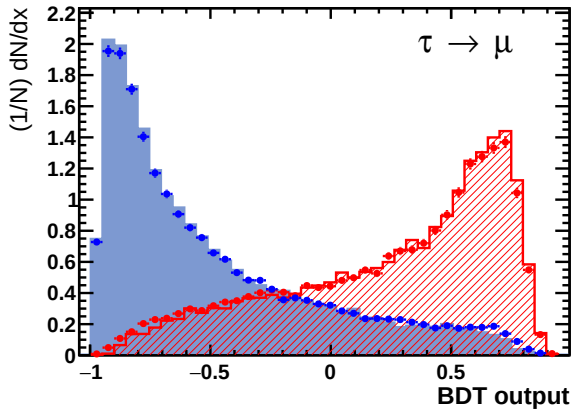
- $B^0 \to \pi^- \ell^+ \nu_\ell$
- $B^0 \to D^{(*)-} \ell^+ \nu_\ell$
- $B^0 \to D^{(*)-} \pi^+$
- $B^0 \to D^{(*)-} \rho^+$
    - $D \to K_L X$
- incorrect B_{tag} reconstruction

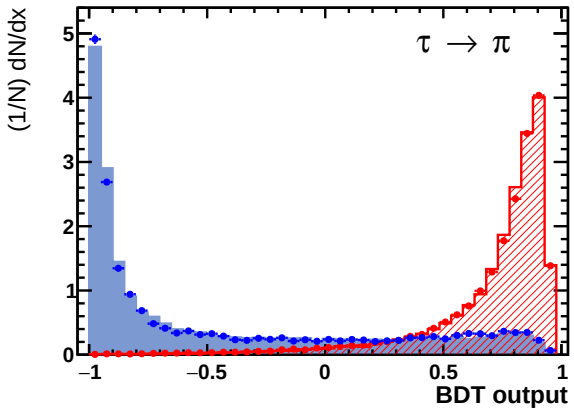
Variables used for suppression:

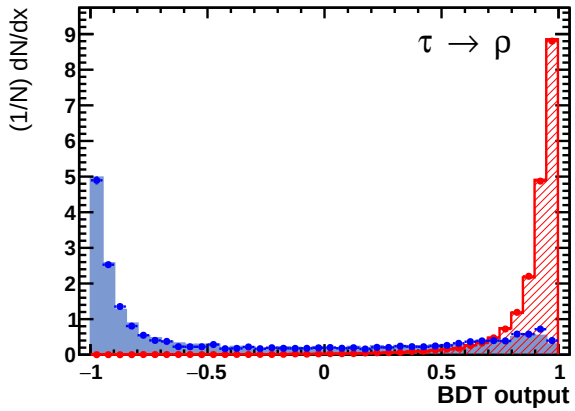
- $p_{\text{miss}} = 2p_{\text{beam}} - p_{B_{\text{tag}}} - p_\pi - p_{\tau\text{-daughter}}$
- $M^2_{\text{miss}} = p^2_{\text{miss}}$
- K_L veto (without energy deposition in the ECL)

Boosted Decision Trees (BDTs)





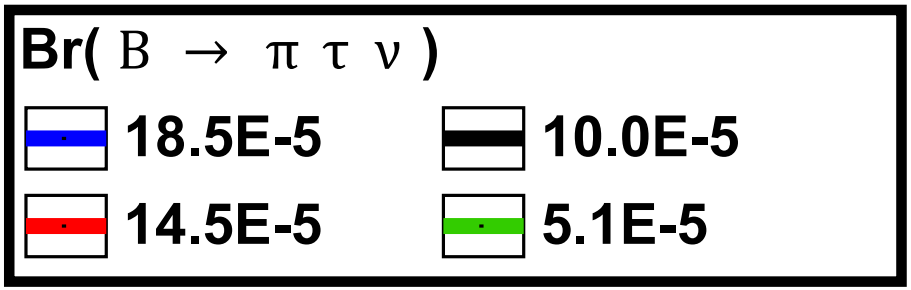


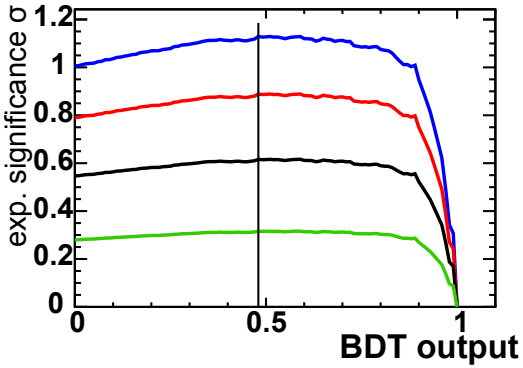


Settings

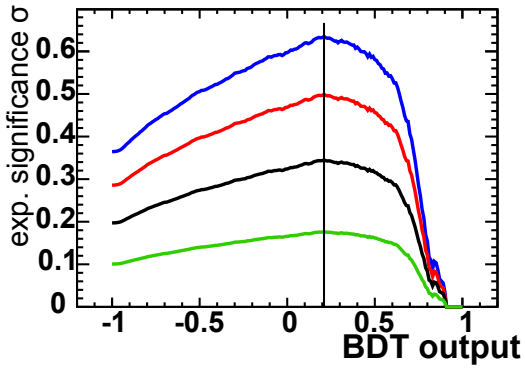
- one BDT for each τ decay mode
- 10-15 kinematic variables
- 200-1000 trees
- $B^0 \to X_c$ as background sample

Best Cut Selection

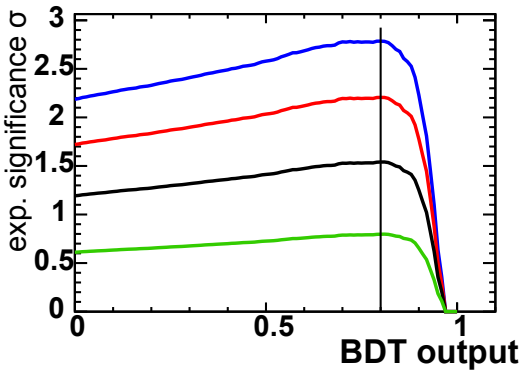




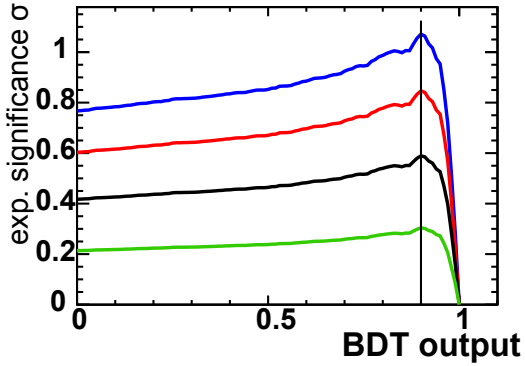
e-mode



μ-mode



π-mode



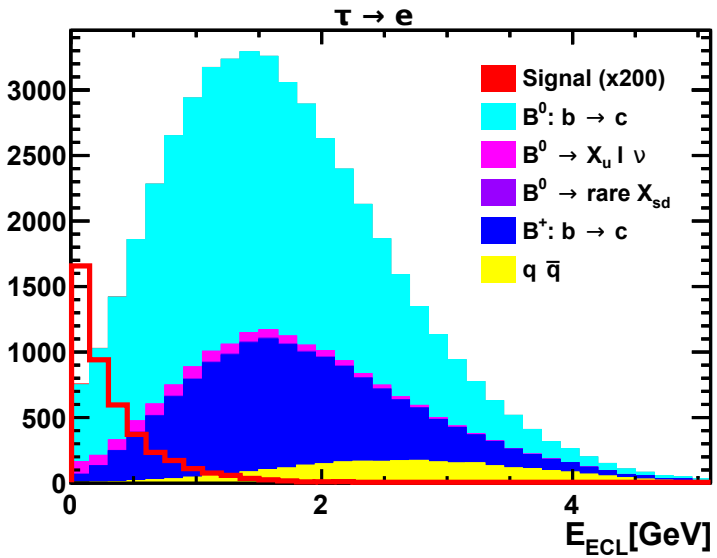
ρ-mode

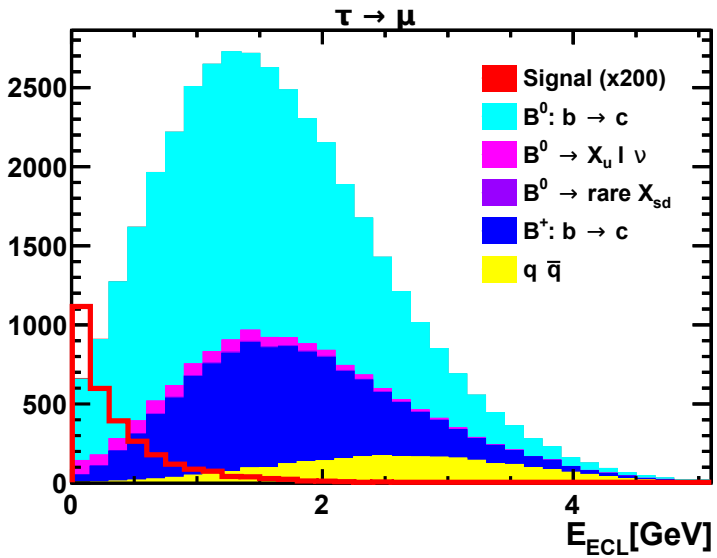
Settings

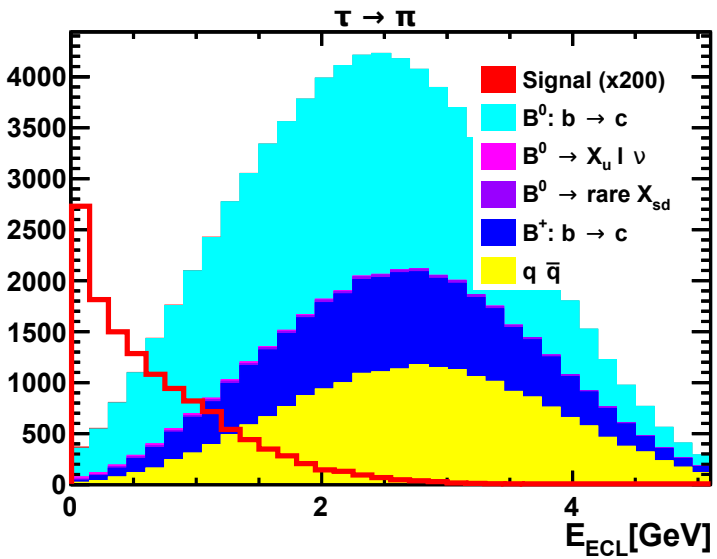
- expected significance used as figure of merit
- scan over 3 variables
  - $\ln\left(o_{\text{Tag}}^{cs}\right)$
  - m_{miss}^2
  - BDT output
- μ mode does not improve result and is not used in the further analysis

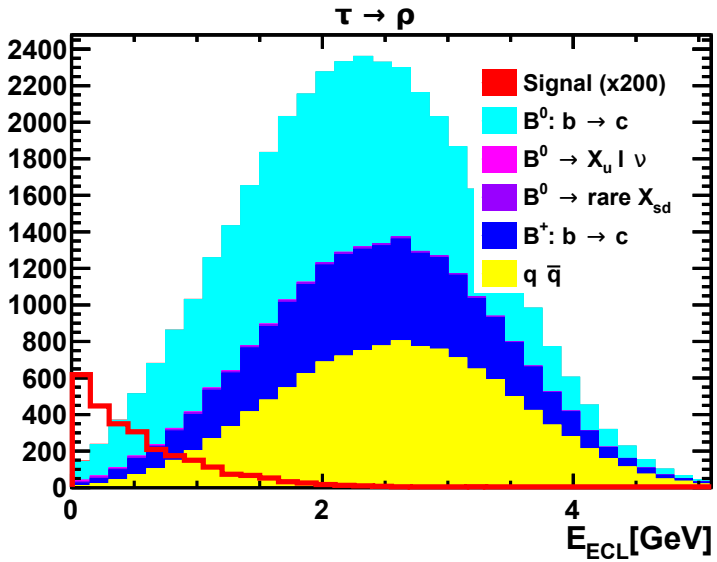
Discriminating Variable:

E_{ECL} : All energy in the ECL that is not associated with B_{tag} or B_{sig}









Fit of scaling factors

Fit

- E_{ECL} distribution used for the fit
- For the fit all background Monte Carlo samples fixed except for $B^0 \to X_c$ and the signal sample

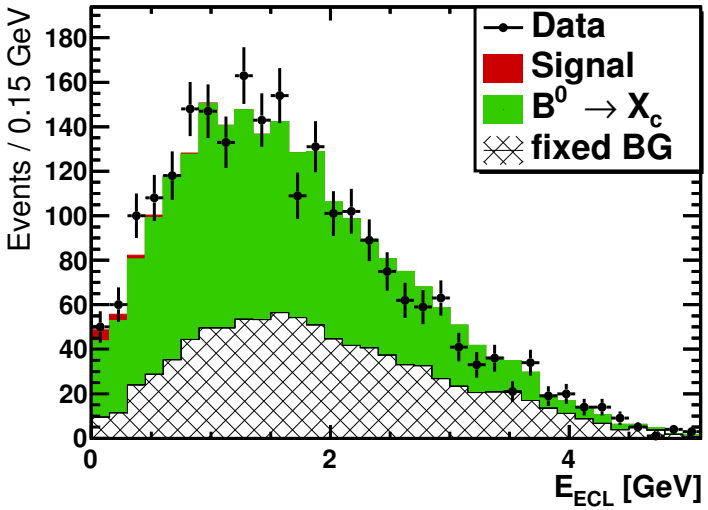
$$\mathcal{L}\left(\mu, \vec{\theta}\right) = \prod_c \prod_b \text{Pois}\left(n_{cb} | \nu_{cb}(\mu, \vec{\theta})\right) \prod_p f_p\left(\hat{\theta}_p | \theta_p\right)$$

μ	Signal strength
θ_p	Nuisance parameter
c	τ channel
b	bin
s	MC sample
n/ν	N observed/predicted
p	Systematic

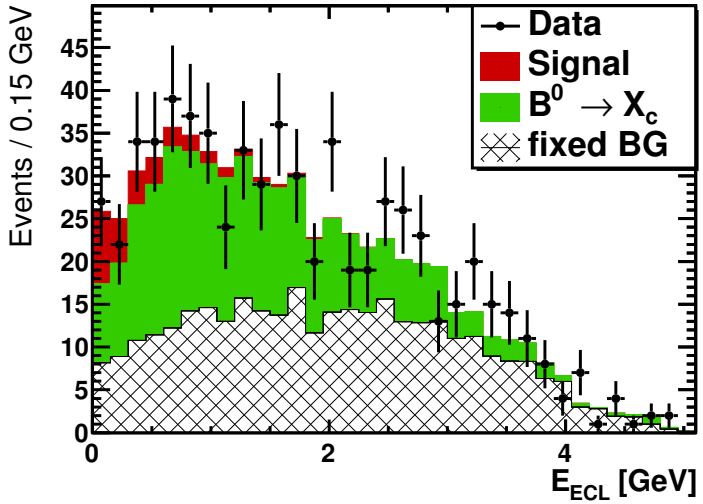
Likelihood

- significance calculated using binned maximum likelihood
- systematics included as nuisance parameters

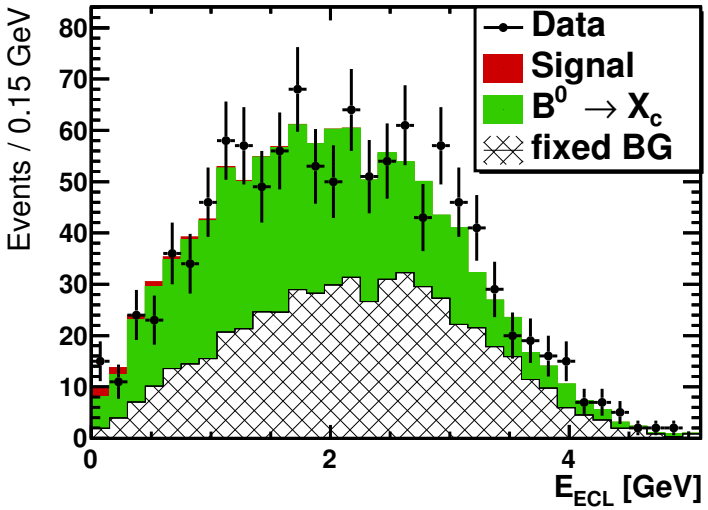
Fit Result



e-mode



π-mode



ρ-mode

Combined Fit Result

Signal events: 52 ± 24

$$\mathcal{B}(B^0 \to \pi^- \tau^+ \nu_\tau) = (1.52 \pm 0.74 \pm 0.13) \cdot 10^{-4}$$

Significance level: 2.4σ

$$\mathcal{B}(B^0 \to \pi^- \tau^+ \nu_\tau) < 2.5 \cdot 10^{-4} \ @\, 90\% CL$$

systematic	relative uncertainty [%]
e ID	1.4
π ID	1.6
π^0 ID	1.0
Track efficiency	0.7
N($B\bar{B}$)	1.4
K_L veto	3.2
BG $\mathcal{B}$	2.8
$D^{(*)}\ell\nu$ model	0.5
Tagside	4.6
$\lvert V_{ub}\rvert$	2.8
Rare MC	2.0
$B \to X_u \tau \nu$	2.2
Background Fit	0.2
Signal model	1.8
total	8.3

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Rare MC	2.0
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Background Fit	0.2
Signal model	1.8
total	8.3

Conclusion and Outlook

Conclusion

- first published search for $B^0 \to \pi^- \tau^+ \nu_\tau$ (arXiv:1509.06521, accepted by PRD)
- $B^0 \to \pi^- \tau^+ \nu_\tau$ is experimentally accessible
- obtained limit $\mathcal{B}(B^0 \to \pi^- \tau^+ \nu_\tau) < 2.5 \cdot 10^{-4}$ compatible with SM prediction $(9.35(38) \cdot 10^{-5})$

Outlook

- analysis with semileptonic tag is being worked on, combination of both analyses possible
- Belle II will improve statistics and the decay will become observable

BACKUP

τ Reconstruction Modes

All tracks are identified using the Belle Particle-ID systems ([0,1]) in the following order:

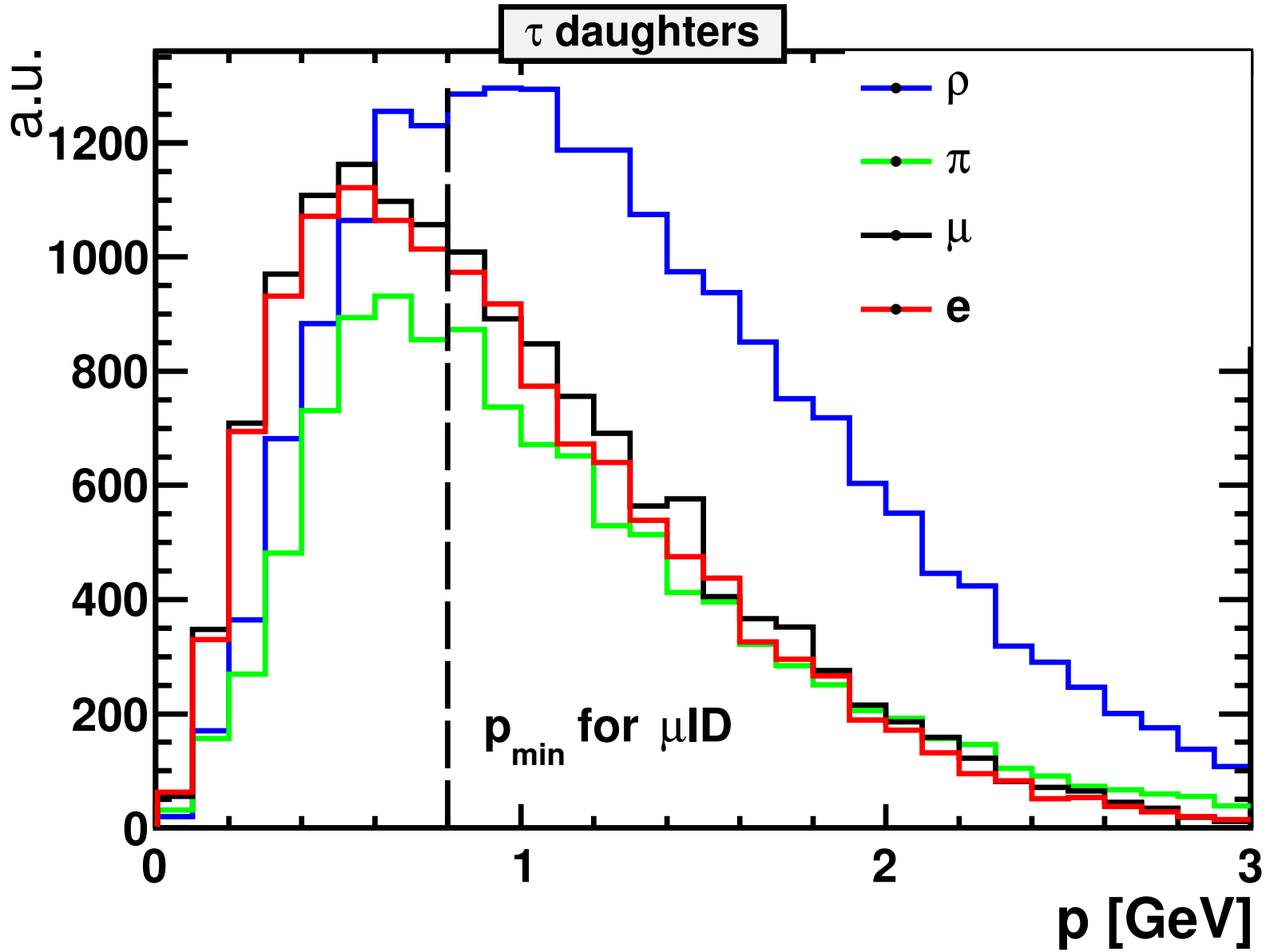
Track identification

1. Electron: $p_{\text{lab}} > 400\,\text{MeV}$ and Electron-ID > 0.9
2. Muon: $p_{\text{lab}} > 800\,\text{MeV}$ and Muon-ID > 0.9
3. Pion: Pion-Kaon-ID > 0.6

τ modes

- $\tau \to e$: 2 tracks identified as electron and pion
- $\tau \to \mu$: 2 tracks identified as electron and muon
- $\tau \to \rho$: 2 Tracks identified as pions and successful mass-vertex-fit with an additional π^0 ($\chi^2 < 20$)
- $\tau \to \pi$: 2 Tracks identified as pions and no successful mass-vertex-fit

Momentum Distribution of τ Daughter Particles



Branching Fraction Calculation

$$\mathcal{M}\left(B^0 \to \pi^- \tau^+ \nu_\tau\right) = -i\frac{G_F}{\sqrt{2}} V_{ub} L^\mu H_\mu$$

$$\begin{aligned} L^\mu &= u_\tau \gamma^\mu (1-\gamma^5) \bar{\nu}_\nu \\ H_\mu &= \langle \pi^- | u \gamma_\mu (1-\gamma_5) \bar{b} | B \rangle \\ &= f^+(q^2)\left[2p_\mu + \left(1 - \frac{m_B^2 - m_\pi^2}{q^2}\right) q_\mu\right] + f^0(q^2)\frac{m_B^2 - m_\pi^2}{q^2} q_\mu \end{aligned}$$

$$\begin{aligned} \frac{d\mathcal{B}(B \to \pi\tau\nu_\tau)/\mathrm{d}q^2}{d\mathcal{B}(B \to \pi\ell\nu_\ell)/\mathrm{d}q^2} &= \frac{(q^2 - m_\tau^2)^2}{(q^2)^2}\left(1 + \frac{m_\tau^2}{2q^2}\right) \\ &\quad \times \left\{1 + \frac{3m_\tau^2 (m_B^2 - m_\pi^2)^2}{4(m_\tau^2 + 2q^2) m_B^2 p_\pi^2} \frac{|f^0(q^2)|^2}{|f^+(q^2)|^2}\right\} \end{aligned}$$

Definition of used Variables

Variable	Definition	Description
$\lvert\vec{p}_l\rvert$		Magnitude of the 3-momentum of the τ daughter particle
$\lvert\vec{p}_m\rvert$		Magnitude of the 3-momentum of the B-meson daughter particle $\pi^{\pm}$
$p_{B_{\text{vis}}}$	$p_{B_{\text{vis}}} = p_l + p_m$	4-momentum sum of both charged tracks of the signal side
$\lvert\vec{p}_{B_{\text{vis}}}\rvert$		Magnitude of the 3-momentum of $p_{B_{\text{vis}}}$
$E_{B_{\text{vis}}}$		Visible energy on the signal side
p_{beam}	$p_{\text{beam}} = \frac{1}{2}(p_{e^-} + p_{e^+})$	Beam momentum
p_{miss}	$p_{\text{miss}} = 2p_{\text{beam}} - p_{B_{\text{tag}}} - p_{B_{\text{vis}}}$	
M^2_{miss}	$\text{M}^2_{\text{miss}} = p^2_{\text{miss}}$	Missing mass squared
E_{miss}		Missing energy, first component of p_{miss}
$p_{(\tau\nu)}$	$p_{(\tau\nu)} = p_\tau + p_{\nu_\tau} = p_{B_{\text{sig}}} - p_m$	4-momentum of the lepton pair
$m^2_{(\tau\nu)}$		Mass squared of the lepton pair
$\lvert\vec{p}_{(\tau\nu)}\rvert$		3-momentum of the lepton pair
N_{π^0}		Number of π^0 candidates on the signal side

4-momentum combinations

$$m_4 = (E_{\text{beam}} - E_m)^2 - (\vec{p}_{\text{beam}} - \vec{p}_m)^2$$

$$m_5 = (p_{\text{beam}} - p_l)^2$$

$$m_{10} = (E_{\text{beam}} - E_m)^2 - (\vec{p}_{\text{beam}} - \vec{p}_m)^2 + (E_{\text{beam}} - E_l)^2 - (\vec{p}_{\text{beam}} - \vec{p}_l)^2$$

$$m_{11} = \frac{(p_{\text{beam}} - p_m)^2}{(p_{\text{beam}} - p_l)^2}$$

$$m_{12} = (E_{\text{miss}} + E_l + E_m)^2 - (|\vec{p}_{\text{miss}}| + |\vec{p}_l| + |\vec{p}_m|)^2$$

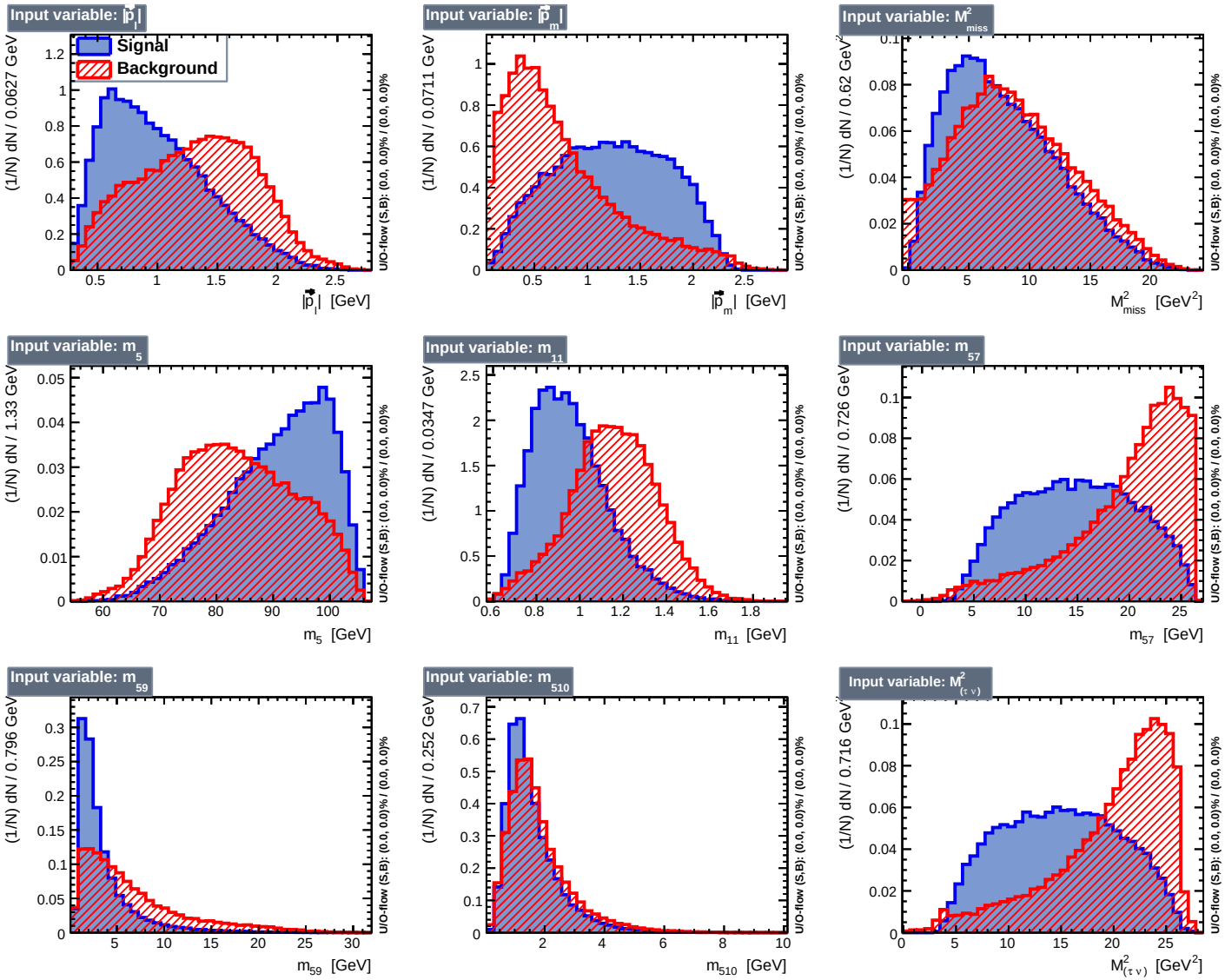
$$m_{15} = \frac{(E_{\text{miss}} - E_m)^2 - (\vec{p}_{\text{miss}} - \vec{p}_m)^2}{(E_l + E_m)^2 + (\vec{p}_l - \vec{p}_m)^2}$$

$$m_{57} = (p_{\text{beam}} - p_m)^2$$

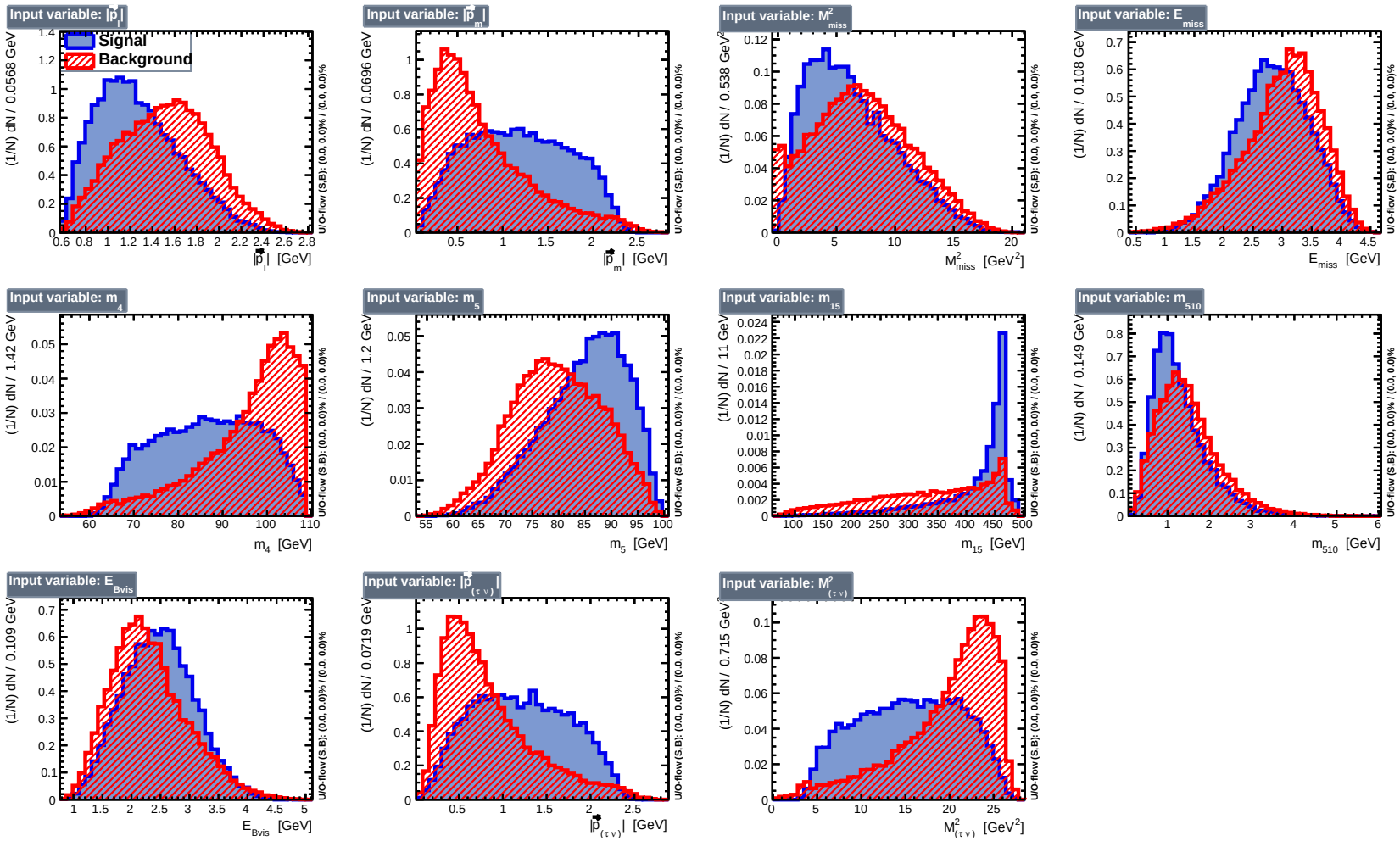
$$m_{59} = \frac{E_{\text{miss}}}{E_m}$$

$$m_{510} = \frac{E_{\text{miss}}}{E_{B_{\text{vis}}}}$$

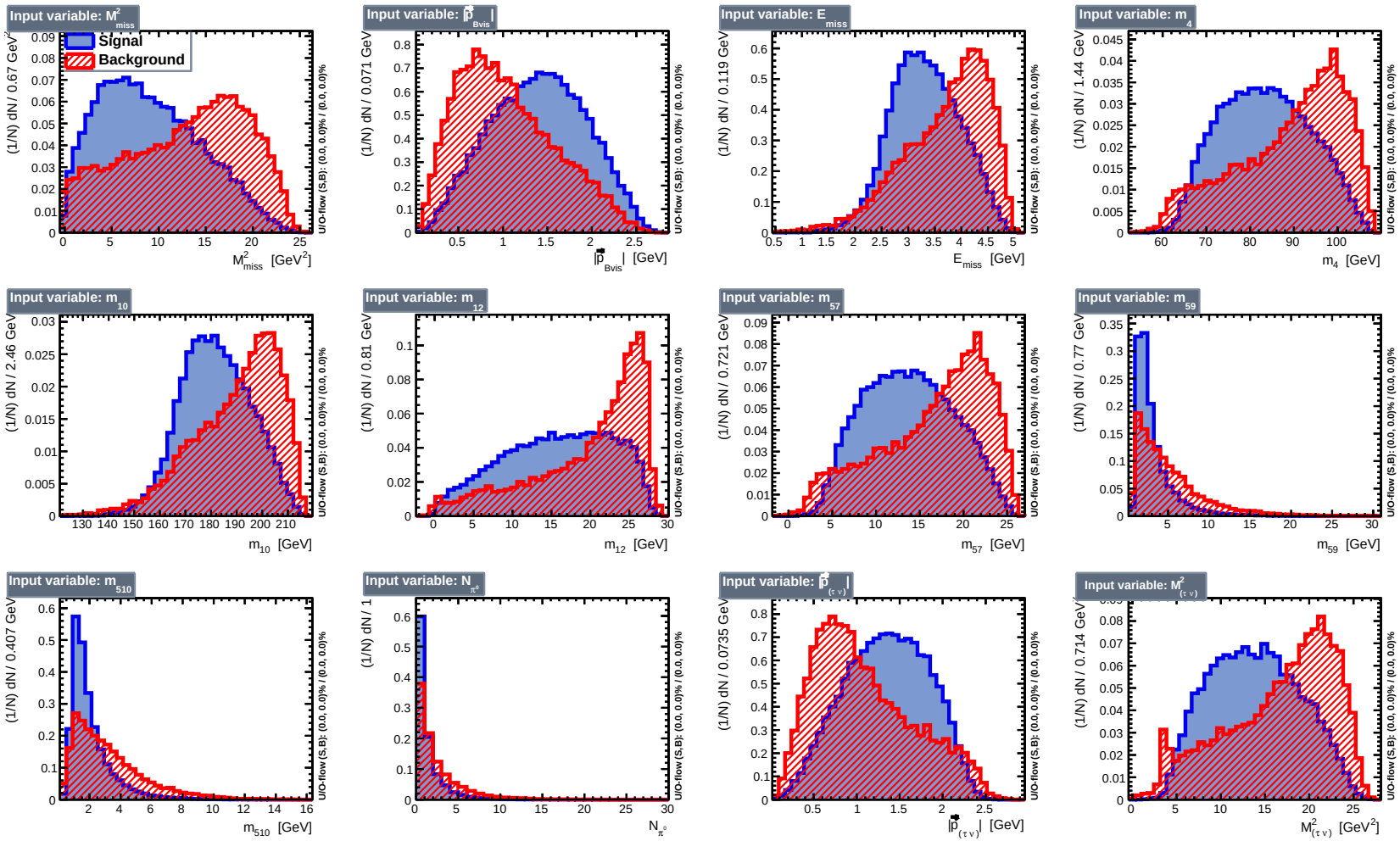
electron mode



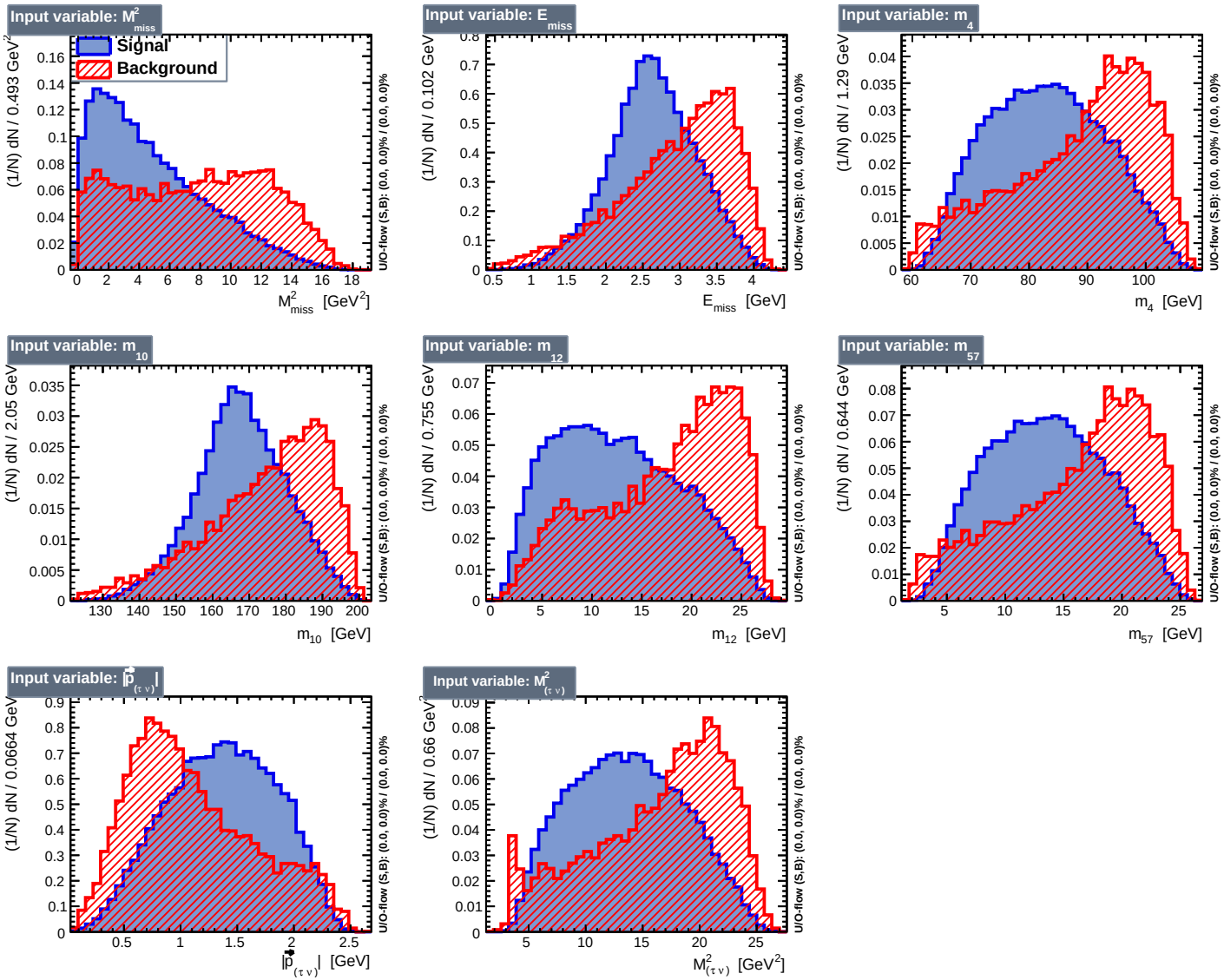
muon mode


Input variable: |p⃗_l|
Signal
Background
(1/N) dN / 0.0568 GeV
|p⃗_l| [GeV]
Input variable: |p⃗_m|
(1/N) dN / 0.0696 GeV
|p⃗_m| [GeV]
Input variable: M²_miss
(1/N) dN / 0.538 GeV²
M²_miss [GeV²]
Input variable: E_miss
(1/N) dN / 0.108 GeV
E_miss [GeV]
Input variable: m_4
(1/N) dN / 1.42 GeV
m_4 [GeV]
Input variable: m_5
(1/N) dN / 1.2 GeV
m_5 [GeV]
Input variable: m_15
(1/N) dN / 11 GeV
m_15 [GeV]
Input variable: m_510
(1/N) dN / 0.149 GeV
m_510 [GeV]
Input variable: E_Bvis
(1/N) dN / 0.109 GeV
E_Bvis [GeV]
Input variable: |p⃗_(τν)|
(1/N) dN / 0.0719 GeV
|p⃗_(τν)| [GeV]
Input variable: M²_(τν)
(1/N) dN / 0.715 GeV²
M²_(τν) [GeV²]
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%

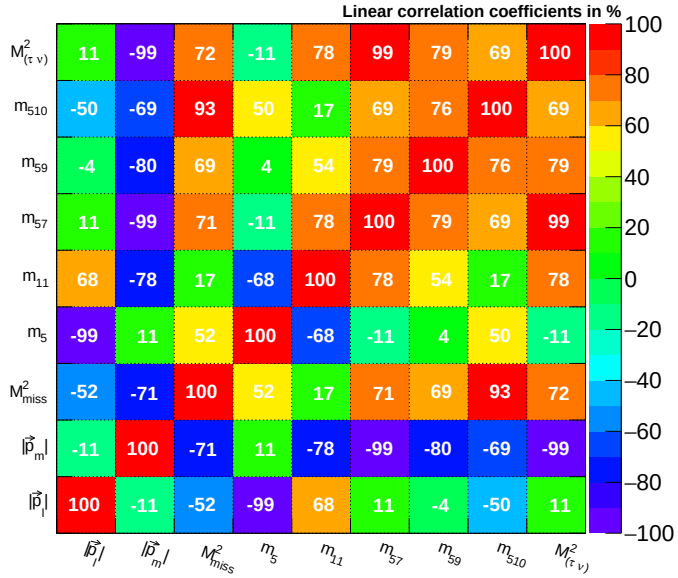
pion mode


Input variable: M²miss
Signal
Background
(1/N) dN / 0.67 GeV²
M²miss [GeV²]
Input variable: |p*Bvis|
(1/N) dN / 0.071 GeV
|p*Bvis| [GeV]
Input variable: Emiss
(1/N) dN / 0.119 GeV
Emiss [GeV]
Input variable: m4
(1/N) dN / 1.44 GeV
m4 [GeV]
Input variable: m10
(1/N) dN / 2.46 GeV
m10 [GeV]
Input variable: m12
(1/N) dN / 0.81 GeV
m12 [GeV]
Input variable: m57
(1/N) dN / 0.721 GeV
m57 [GeV]
Input variable: m59
(1/N) dN / 0.77 GeV
m59 [GeV]
Input variable: m510
(1/N) dN / 0.407 GeV
m510 [GeV]
Input variable: Nπ0
(1/N) dN / 1
Nπ0
Input variable: |p*(τν)|
(1/N) dN / 0.0735 GeV
|p*(τν)| [GeV]
Input variable: M²(τν)
(1/N) dN / 0.714 GeV
M²(τν) [GeV²]
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%

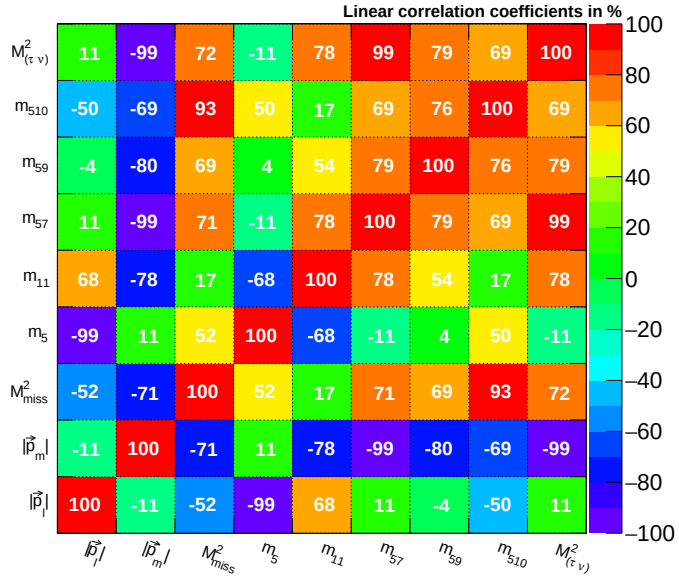
rho mode


Input variable: M²miss
Signal
Background
(1/N) dN / 0.493 GeV²
M²miss [GeV²]
Input variable: Emiss
(1/N) dN / 0.102 GeV
Emiss [GeV]
Input variable: m4
(1/N) dN / 1.29 GeV
m4 [GeV]
Input variable: m10
(1/N) dN / 2.05 GeV
m10 [GeV]
Input variable: m12
(1/N) dN / 0.755 GeV
m12 [GeV]
Input variable: m57
(1/N) dN / 0.644 GeV
m57 [GeV]
Input variable: |p(τν)|
(1/N) dN / 0.0664 GeV
|p(τν)| [GeV]
Input variable: M²(τν)
(1/N) dN / 0.66 GeV
M²(τν) [GeV²]
U/O-flow (S,B): (0.0, 0.0)% / (0.0, 0.0)%

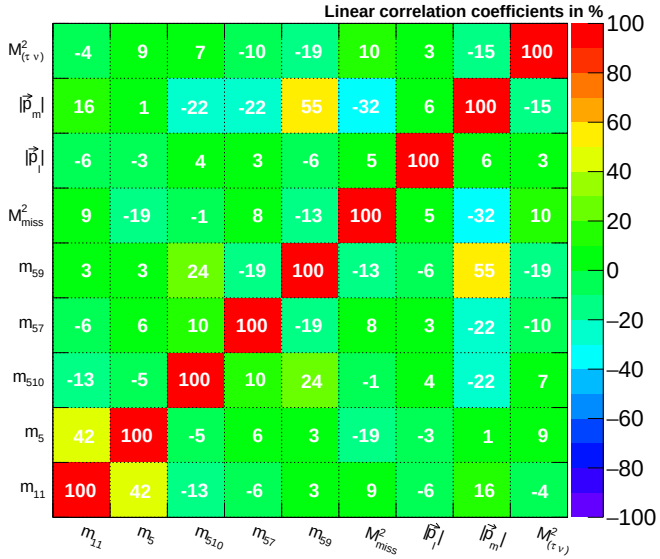
Correlation Matrix (signal)



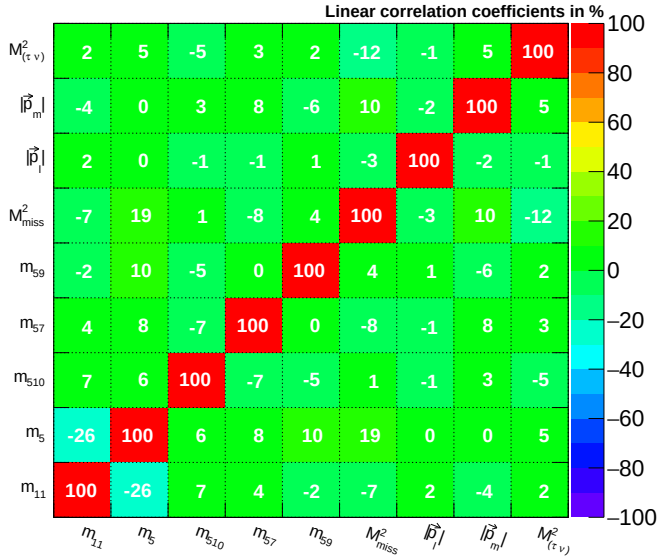
Correlation Matrix (signal)



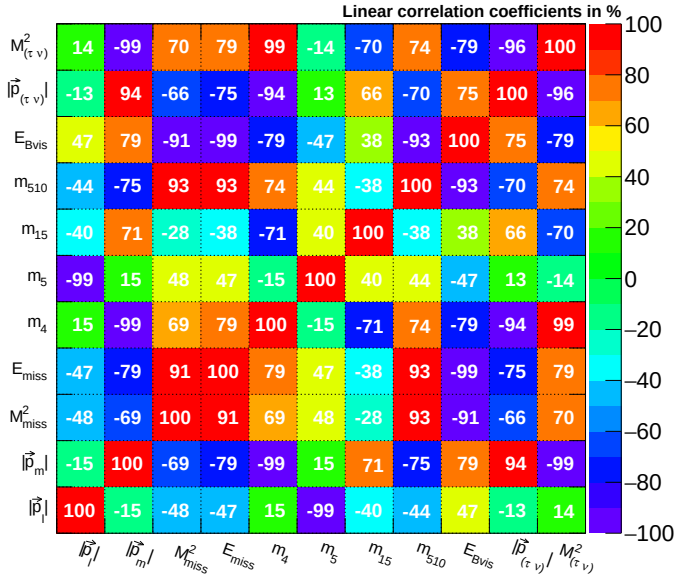
Deco Transformed, Correlation Matrix S



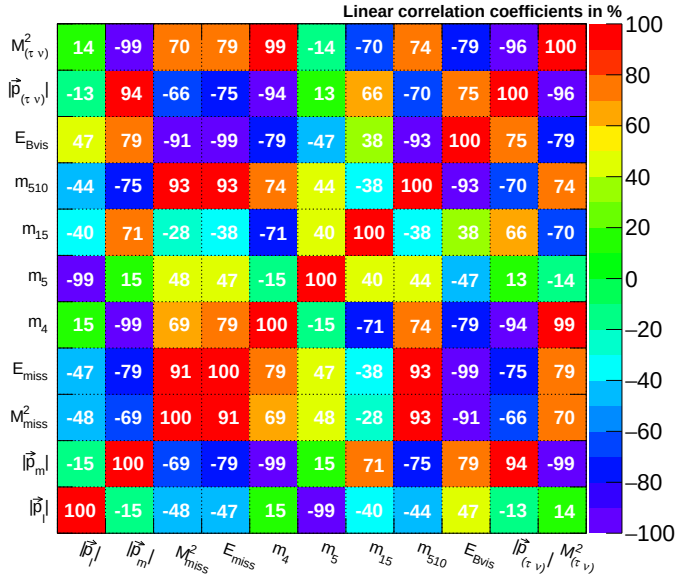
Deco Transformed, Correlation Matrix B



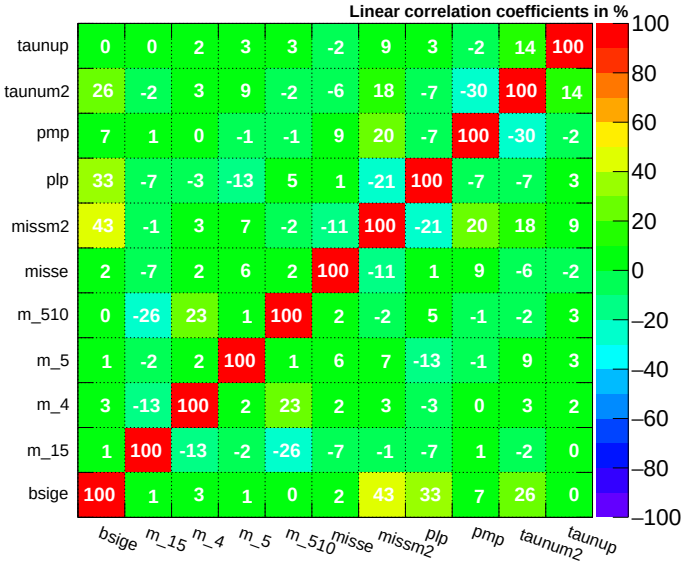
Correlation Matrix (signal)



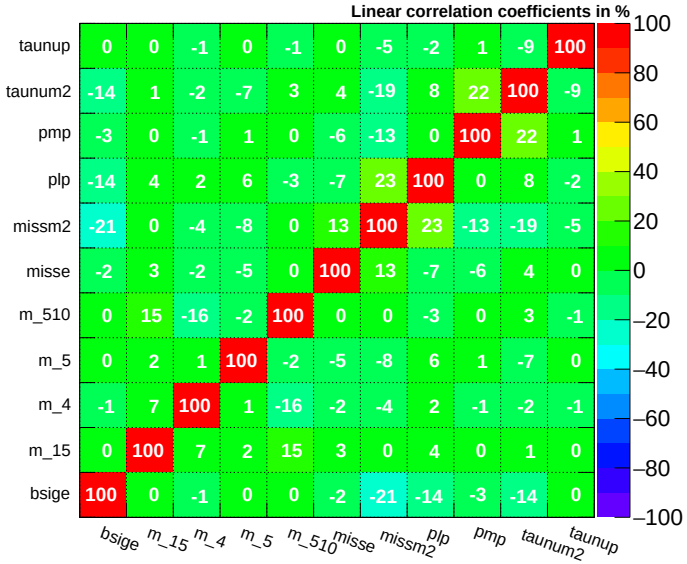
Correlation Matrix (signal)



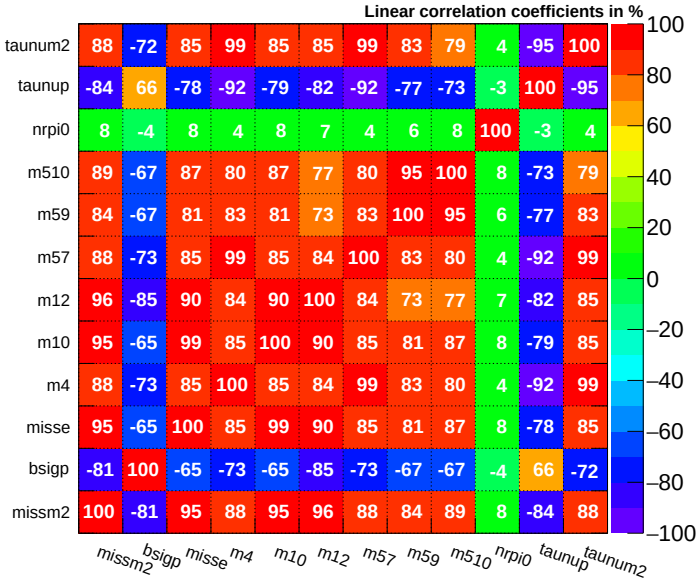
PCA Transformed S



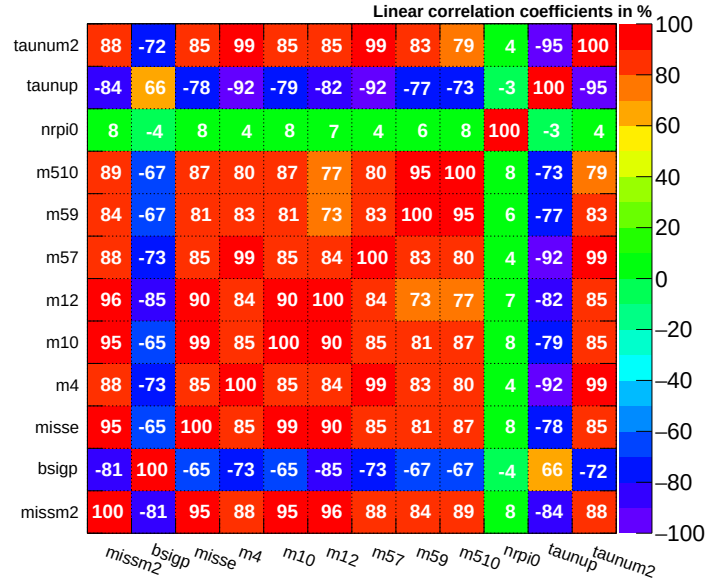
PCA Transformed B



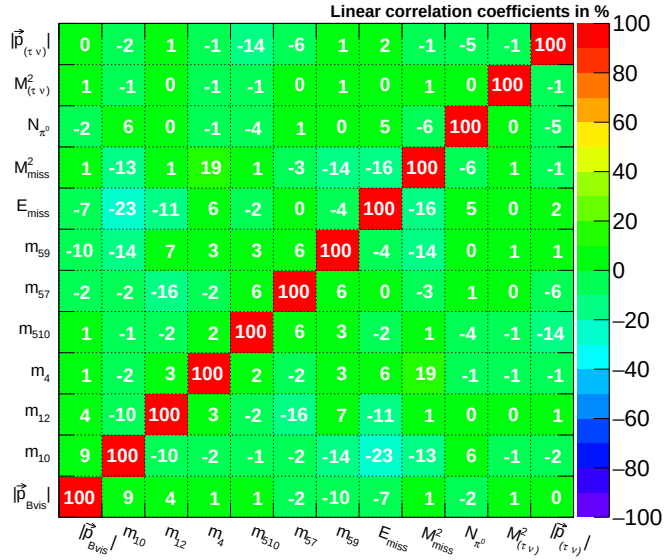
Correlation Matrix (signal)



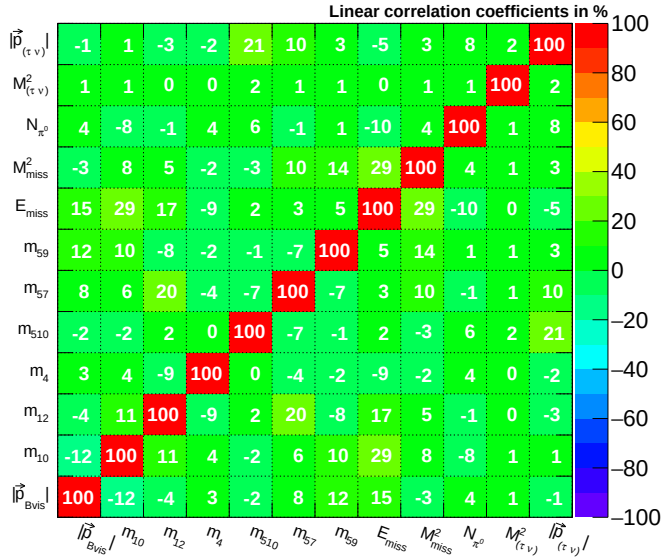
Correlation Matrix (signal)



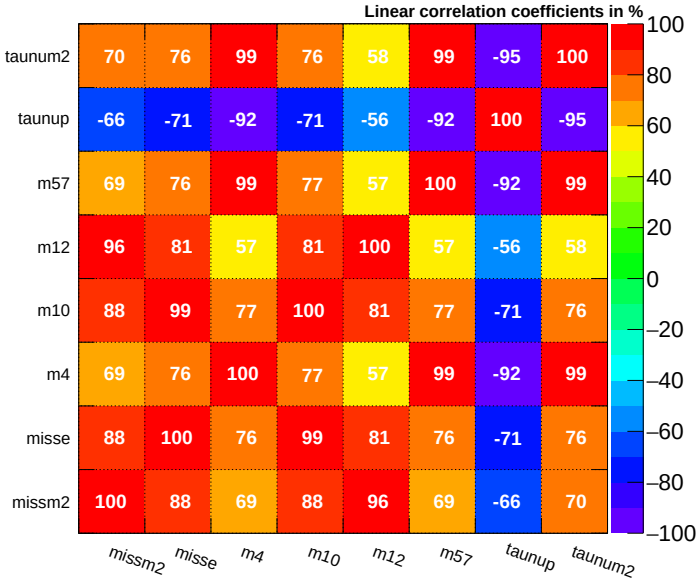
PCA Transformed, Correlation Matrix S



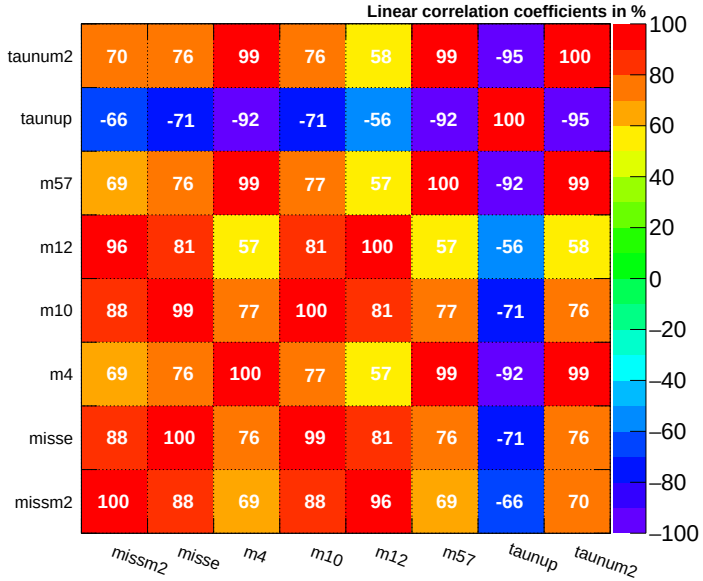
PCA Transformed, Correlation Matrix B



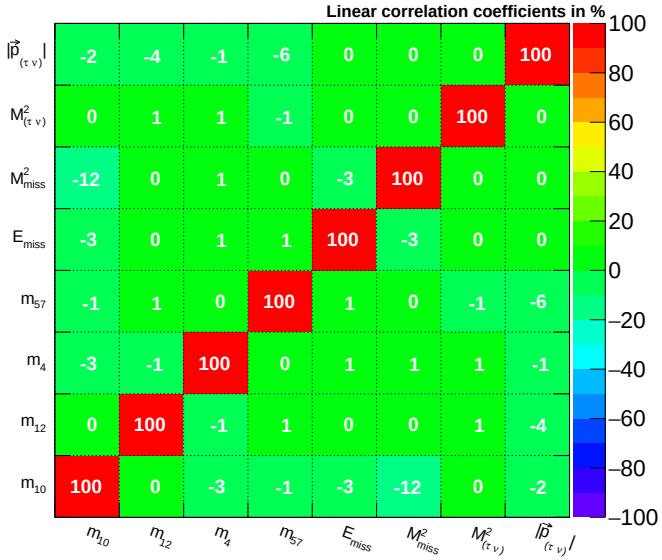
Correlation Matrix (signal)



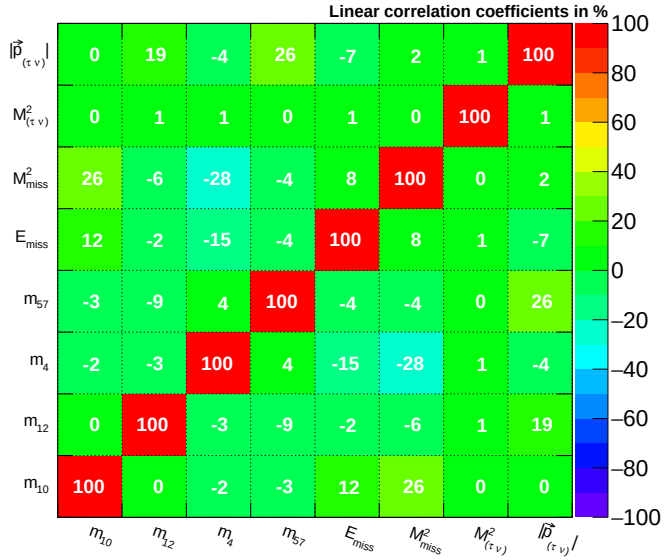
Correlation Matrix (signal)



PCA Transformed, Correlation Matrix S



PCA Transformed, Correlation Matrix B



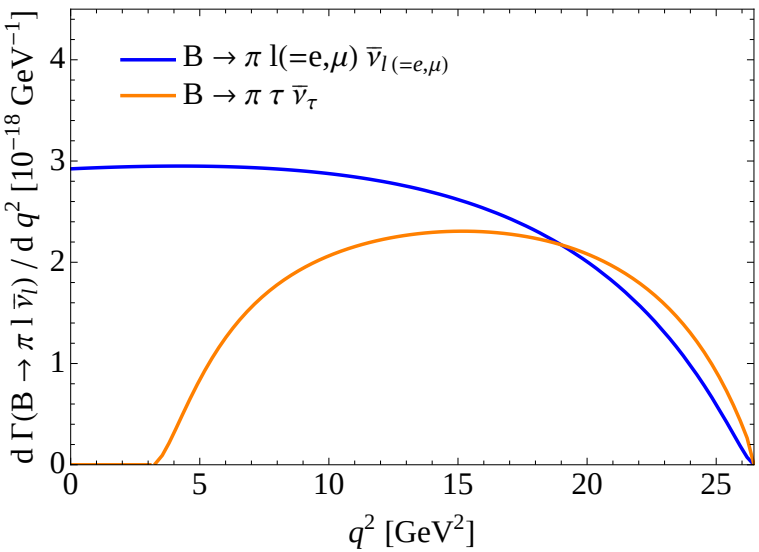
MC Generation

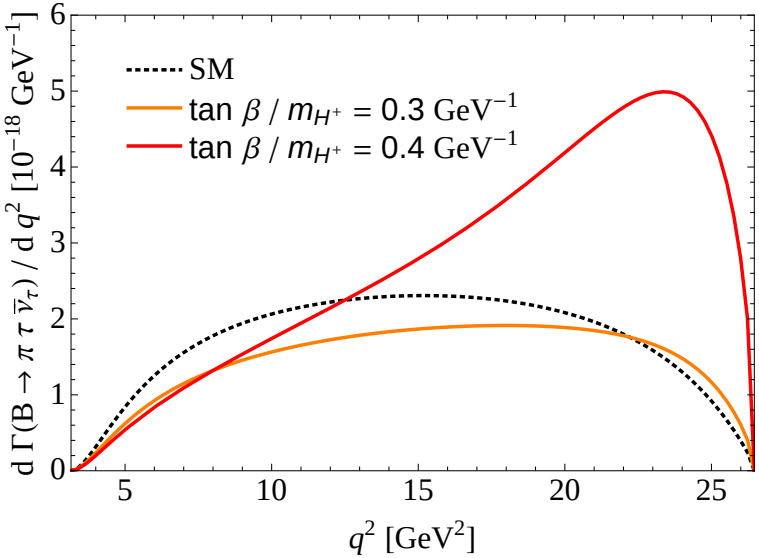
- EvtGen used for $e^+e^- \to \Upsilon(4S)$ and $e^+e^- \to q\bar{q}$
- continuum by PYTHIA
- final state radiation by PHOTOS
- semileptonic $P \to P$ decays with SLPOLE, needs form factors in pole parametrization

- GSIM based on GEANT 3.21
- simulates interaction of generated particles with the detector
- produces data files in real data format

MSSM / 2HDM

- charged Higgs ($H^{\pm}$) modifies the differential branching fraction by an additional factor: $\left(1 + \frac{\tan^2\beta}{m^2_{H^{\pm}}} \frac{q^2}{1 - m_u/m_b}\right)$





Hadronic Full Reconstruction Modes

B^0 modes	B^- modes
$D^{*+}\pi^-$	$D^{*0}\pi^-$
$D^{*+}\pi^-\pi^0$	$D^{*0}\pi^-\pi^0$
$D^{*+}\pi^-\pi^+\pi^-$	$D^{*0}\pi^-\pi^-\pi^+$
$D^+\pi^-$	$D^0\pi^-$
$D^+\pi^-\pi^0$(with D^{*+} veto)	$D^0\pi^-\pi^0$(with D^{*0} veto)
$D^+\pi^-\pi^+\pi^-$	$D^0\pi^-\pi^-\pi^+$
$D^{*+}D_s^{*-}$	$D^{*0}D_s^{*-}$
$D^{*+}D_s^-$	$D^{*0}D_s^-$
$D^+D_s^{*-}$	$D^0D_s^{*-}$
$D^+D_s^-$	$D^0D_s^-$
$J/\psi K_S^0$	$J/\psi K^-$
$J/\psi K^-\pi^+$	$J/\psi K^-\pi^+\pi^-$
$J/\psi K_S^0\pi^+\pi^-$	D^0K^-
$D^0\pi^0$	$D^+\pi^-\pi^-$
$D^{*+}\pi^-\pi^-\pi^+\pi^0$	$D^{*0}\pi^-\pi^-\pi^+\pi^0$
	$J/\psi K^-\pi^0$
	$J/\psi K_S^0\pi^-$

Hadronic Full Reconstruction Modes

D^0 modes	D^+ modes	D_s^+ modes
$K^-\pi^+$	$K^-\pi^+\pi^+$	$K^+K^-\pi^+$
$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$	$K_S^0K^+$
$K^-\pi^+\pi^+\pi^-$	$K_S^0\pi^+$	$\pi^+\pi^+\pi^-$
$K_S^0\pi^0$	$K_S^0\pi^+\pi^0$	$K^+K^-\pi^+\pi^0$
$K_S^0\pi^+\pi^-$	$K_S^0\pi^+\pi^+\pi^-$	$K_S^0K^-\pi^+\pi^+$
$K_S^0K^+K^-$	$K^+K^-\pi^+$	$K_S^0K^+\pi^+\pi^-$
K^+K^-	$K^-K^+\pi^+\pi^0$	$K^+\pi^+\pi^-$
$\pi^+\pi^-$		$K^+K^-\pi^+\pi^+\pi^-$
$\pi^+\pi^-\pi^0$		
$K_S^0\pi^+\pi^-\pi^0$		

D^{*0} modes	D^{*+} modes	D_s^{*+} modes	J/ψ modes
$D^0\pi^0$	$D^0\pi^+$	$D_s^+\gamma$	e^-e^+
$D^0\gamma$	$D^+\pi^0$		$\mu^-\mu^+$

Distribution of τ decays in the final selection

τ^- decay	Relative Occurence (%)
ρ^-	29.54
$e^-\bar{\nu}_e\nu_\tau$	29.43
$\pi^-\nu_\tau$	16.70
$\mu^-\bar{\nu}_e\nu_\tau$	13.21
$a_1^-\nu_\tau$	8.72
other	2.4