MAX-PLANCK-INSTITUT FÜR PHYSIK

Belle II

Search for the Lepton Flavor Violating Decay $\tau \rightarrow \mu\pi^0$ at Belle II

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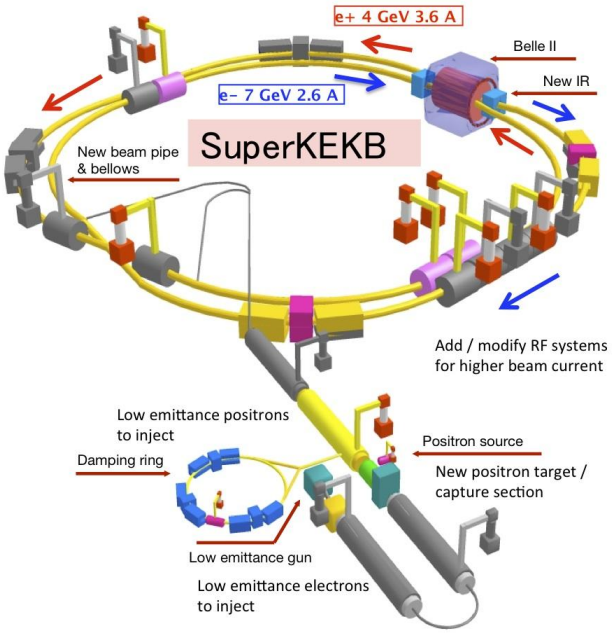
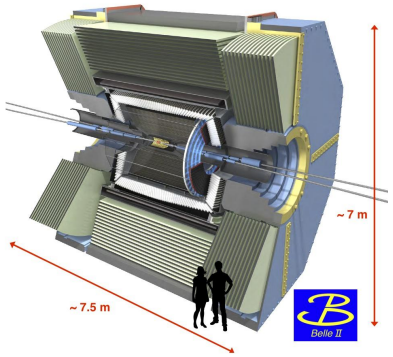
IMPRS Workshop 15/16.11.21

Belle-II-Experiment

Goal: $\int \mathcal{L}\, dt = 50\ \text{ab}^{-1}$



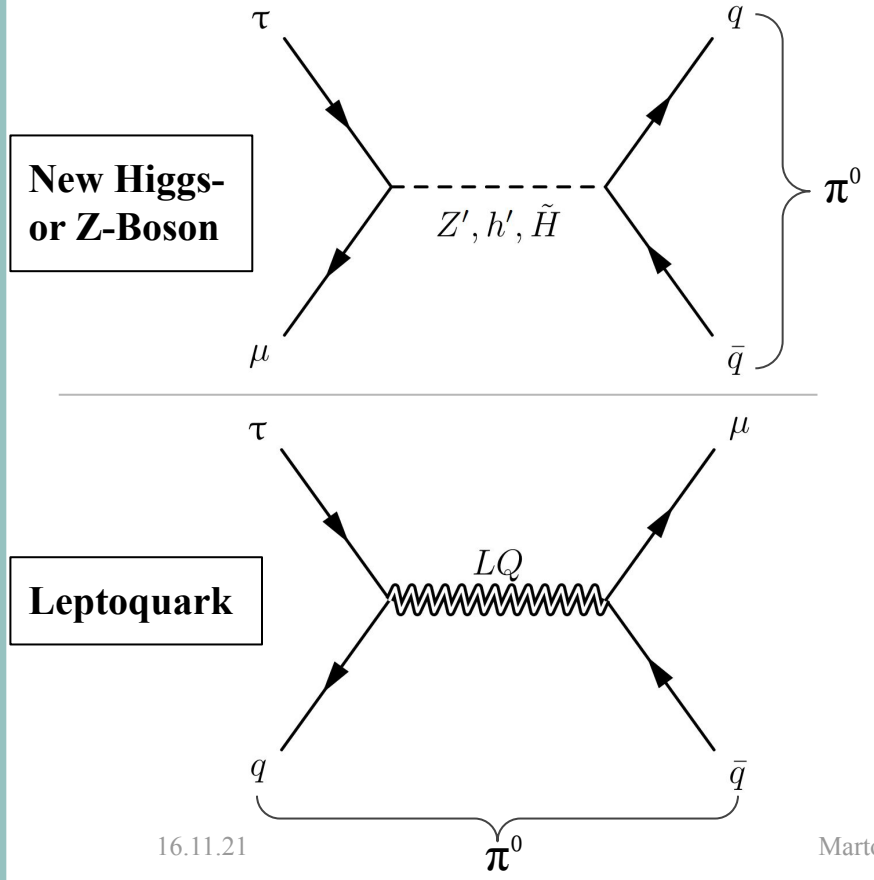


- Asymmetric e^+e^- collider at $\Upsilon(4S)$-resonance (10,6 GeV)
- "B-factory" → $B\bar{B}$-pairs
- Ideal environment for τ-Pair-Production

  → Also τ-factory!

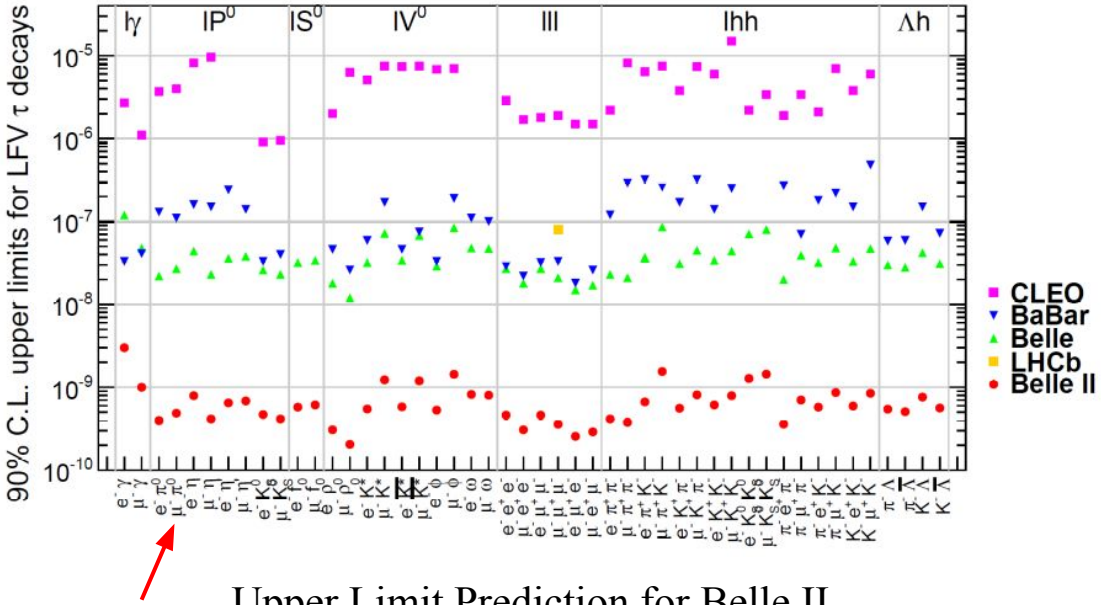
https://belle2.desy.de/
https://www.cityofirvine.org/multicultural-and-international-affairs/tsukuba-japan

LFV-Decay $\tau \rightarrow \mu\pi^0$



- LFV-decay already at tree-level
- All final state particles are measurable
- 2-body decay
  → in tau rest system Pion and Muon have same total momentum
- tau rest system can be estimated directly from decay products (no neutrino)

Current state of LFV tau-decays



Upper Limit Prediction for Belle II with 50 ab^{-1} integrated luminosity

Integrated Luminosity

Belle	Belle II (9.11.2021)
901 fb^{-1}	216.71 fb^{-1}

Results of Belle:

Mode	Eff. (%)	N_{BG}^{exp}	UL (10^{-8})
$\mu\eta(\to \gamma\gamma)$	8.2	0.63 ± 0.37	3.6
$\mu\eta(\to \pi\pi\pi^0)$	6.9	0.23 ± 0.23	8.6
$\mu\eta$(comb.)			2.3
$\mu\eta'(\to \pi\pi\eta)$	8.1	$0.00^{+0.16}_{-0.00}$	10.0
$\mu\eta'(\to \gamma\rho^0)$	6.2	0.59 ± 0.41	6.6
$\mu\eta'$(comb.)			3.8
$\mu\pi^0$	4.2	0.64 ± 0.32	2.7

Belle2 Physics Book

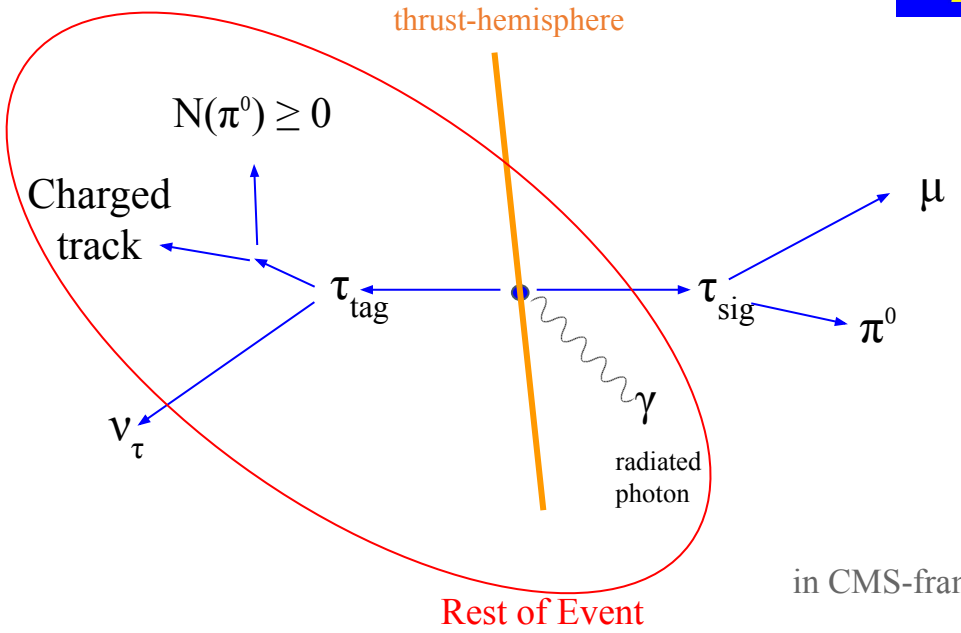
Reconstructing Strategy: MC events

- Blind analysis
- Reconstruct $\tau \rightarrow \mu[\pi^0 \rightarrow \gamma\gamma]$
- 1-1 topology: events with two charged tracks only

→ No direct reconstruction of tau on tag-side

→ Combine all particles not used for signal and build RestOfEvent ("ROE")

→ No losses caused by requiring specific tag-decay channels



in CMS-frame

Tau-decay modes:

$\tau \rightarrow \ell\nu_\ell\nu_\tau$ 40% → 40% } 1-Prong

$\tau \rightarrow q\bar{q}'\nu_\tau$ 60% $(\rho\nu_\tau, \pi\nu_\tau, \ldots)$ → 45% } 1-Prong, 15% } 3-Prong

Monte Carlo Analysis Samples

Signal sample:

- 1 million simulated events
- $\tau_{sig} \rightarrow \mu[\pi^0 \rightarrow \gamma\gamma]$
- $\tau_{tag} \rightarrow$ according to SM

All samples with simulated beam-background and detector effects

Background samples:

Event type	Event name	luminosity equivalent
$e^+e^- \rightarrow q\bar{q}$ (q=udsc)	'qqbar'	100 fb^{-1}
$e^+e^- \rightarrow \tau^+\tau^-$ (SM)	'taupair'	100 fb^{-1}
$e^+e^- \rightarrow B\bar{B}$	'BBbar'	100 fb^{-1}
$e^+e^- \rightarrow e^+e^-\gamma$	'ee'	10 fb^{-1}
$e^+e^- \rightarrow \mu^+\mu^-\gamma$	'mumu'	100 fb^{-1}
$e^+e^- \rightarrow e^+e^-\mu^+\mu^-$	'eemumu'	100 fb^{-1}
$e^+e^- \rightarrow e^+e^-e^+e^-$	'eeee'	10 fb^{-1}

Preselection

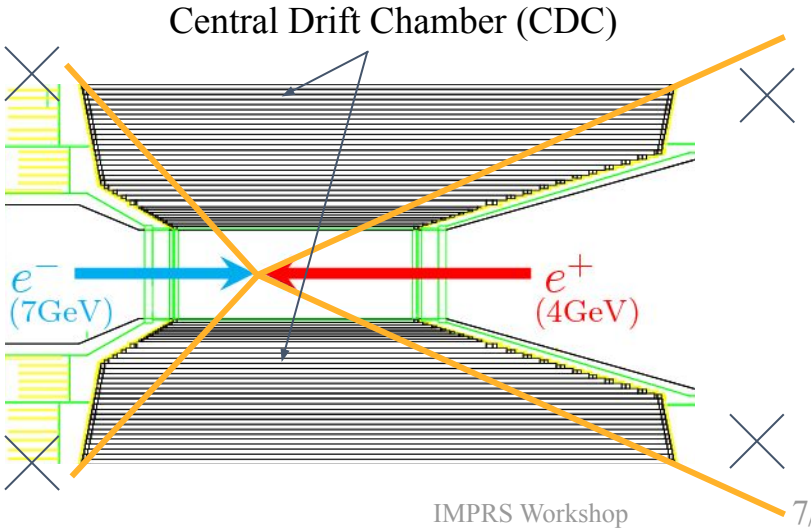
Track-Cuts:	loose Cuts for π^0-photons:	Pi0:	HemisphereCut with thrust-axis:
• N(tracks) = 2 • vertex near interaction point: -1.0 cm < dz < 1.0 cm dr < 1.0 cm	• E > 0.1 GeV • 17° < θ < 150° • N(clusterHits) in calorimeter > 1.5	0.115 GeV < invM < 0.152 GeV	• μ and π^0 from same hemisphere • τ_{sig} and ROE from opposite hemisphere

→ Reduce misreconstruction with beam-background photons

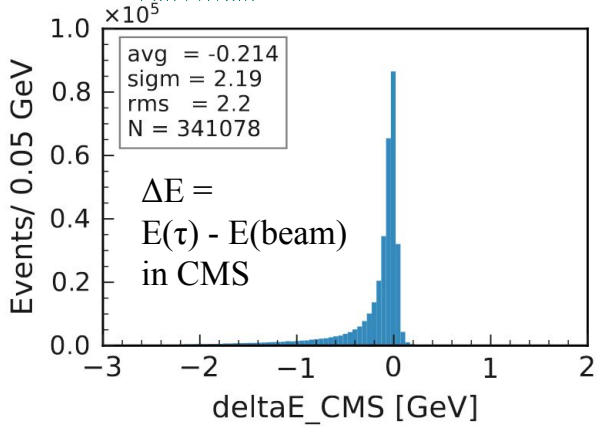
→ 1-1 Topology

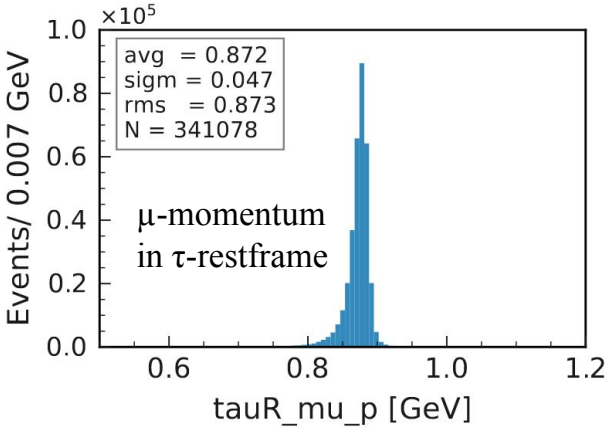
Events generated	Events reconstructed	Events after preselection
1 000 000	631650	341078

- Current trigger: CDC requires 2 full tracks
- polar acceptance only 31°< θ <126°



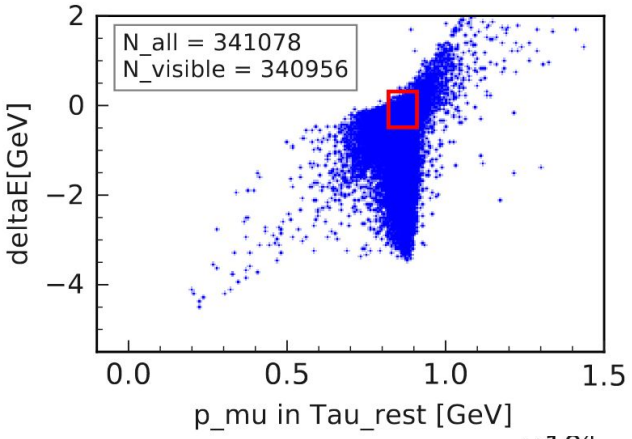
Signal Region - Two Body Decay

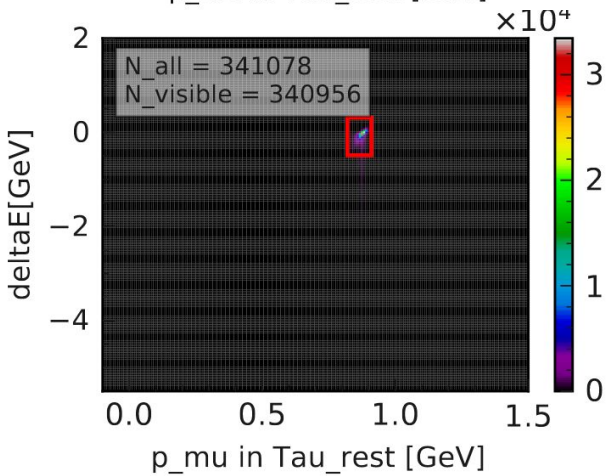




Kinematics:
Fully reconstructable signal with two body decay

2D-Plot

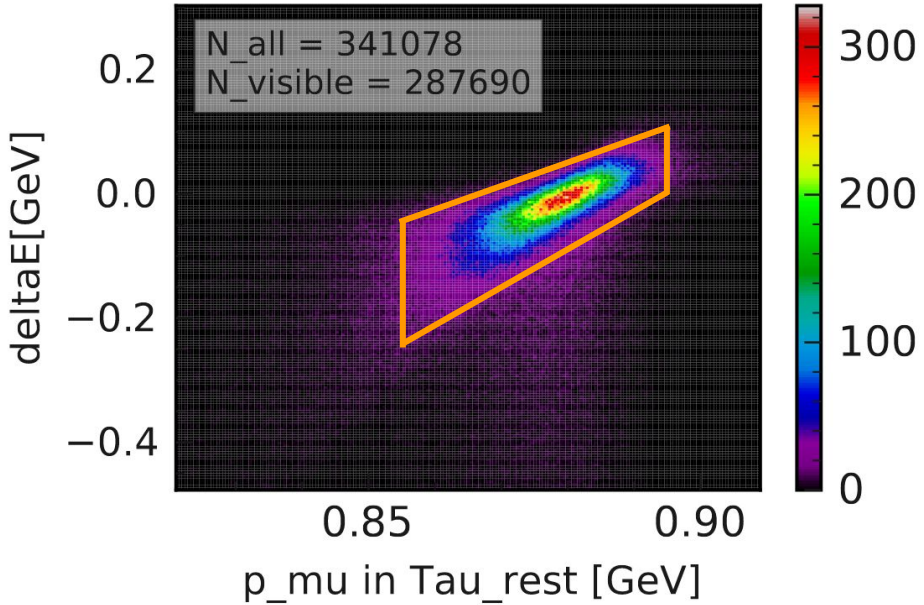




2D-Cut in Signal-Region

- Cut around signal in trapezoid shape

→ 68% of signal inside cut



	signal	$q\bar{q}$	$\tau^+\tau^-$	$B\bar{B}$	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$	$e^+e^-\mu^+\mu^-$	$e^+e^-e^+e^-$
no cuts	341078	20181648	34106885	301277	8034214	659828	11349268	13925376
2D cut	229898	2671	246	1	11328	1660	17	102

Mu-ID Cuts

- Ensures the signal's charged track to be a muon
- muID: Belle II variable combining information from all sub-detectors
- Identity hypothesis for each particle between 0 and 1

	signal	$q\bar{q}$	$\tau^+\tau^-$	$B\bar{B}$	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$	$e^+e^-\mu^+\mu^-$	$e^+e^-e^+e^-$
no cuts	341078	20181648	34106885	301277	8034214	659828	11349268	13925376
2D cut	229898	2671	246	1	11328	1660	17	102
muID >0.50	218758	218	32	0	16	1579	4	2
muID >0.90	208222	119	26	0	2	1547	4	0
muID >0.95	206202	109	25	0	1	1537	4	0
muID >0.99	201679	97	22	0	0	1506	4	0

→ moderate muID > 0.90 for further cuts

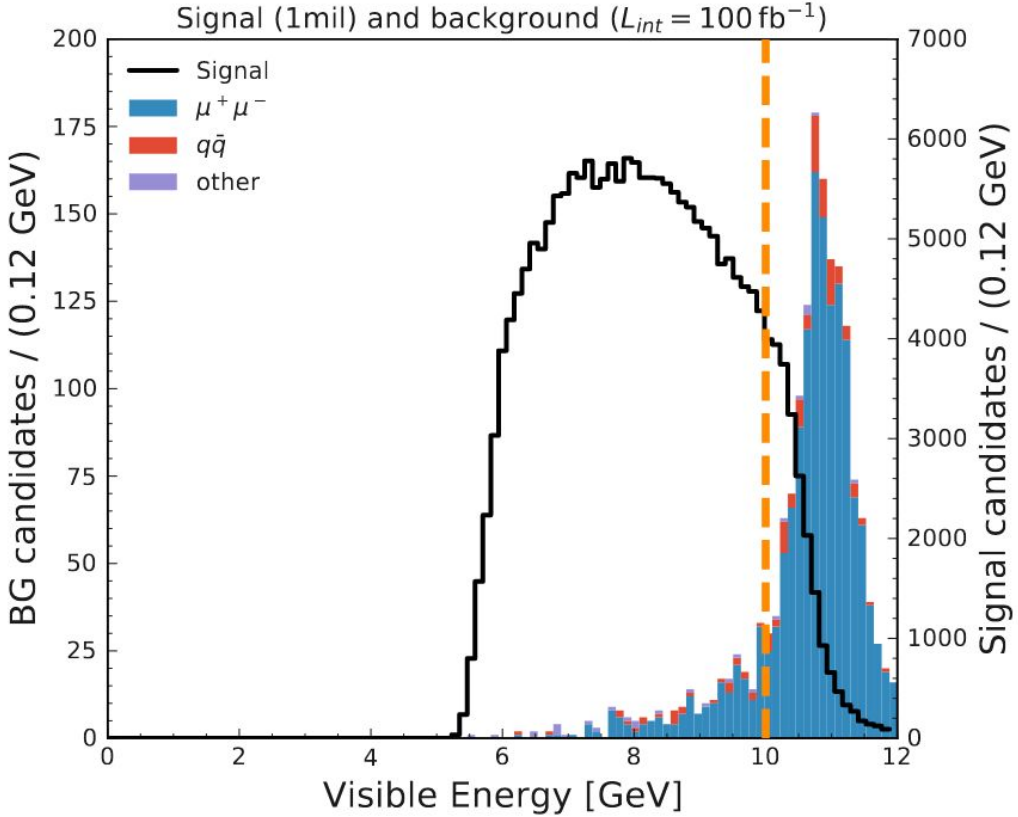
Cut on visible Energy

$$E_{\text{vis}} = \sum E_{\text{reconstructed}} \text{ in CMS-frame}$$

- τ_{tag} creates neutrino
  → missing energy
- μμ-events have no neutrino

$E_{\text{vis}} < 10$ GeV

signal: 208222→ 179867



Cut on polar angle of missing momentum

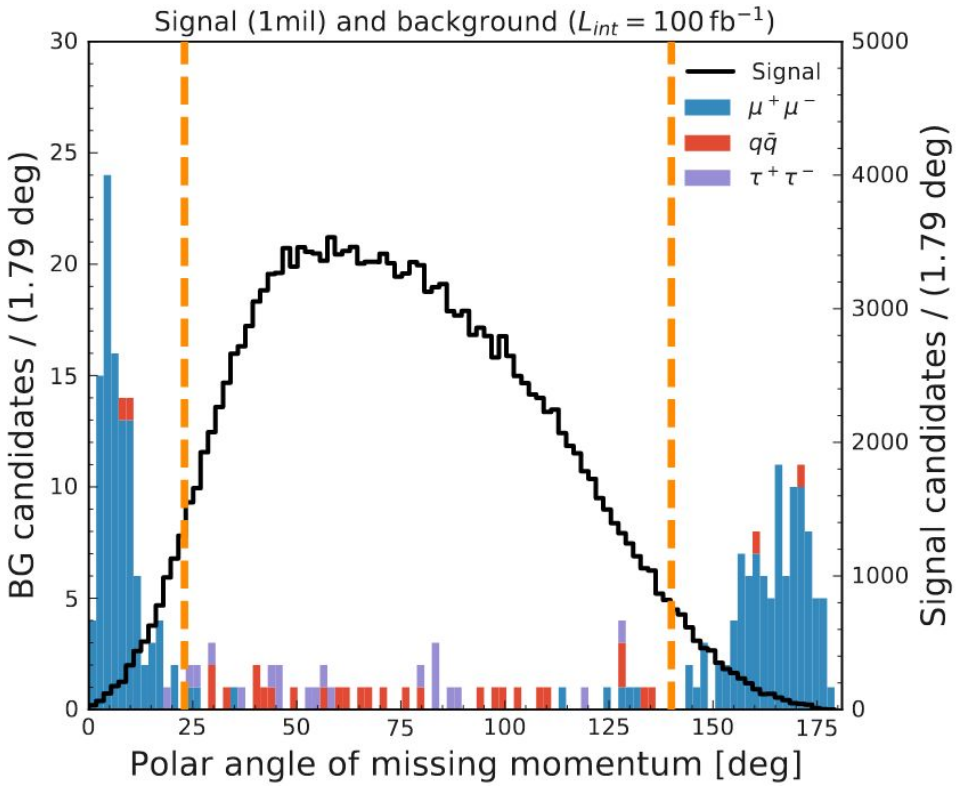
$$\vec{p}_{\text{miss}} = \vec{p}_{e^+e^-} - \sum \vec{p}_{\text{rec}} \text{ in labframe}$$

- Missing neutrino from signal without preferred direction
- Muon events fully reconstructed, undetected initial state radiation in beam-direction

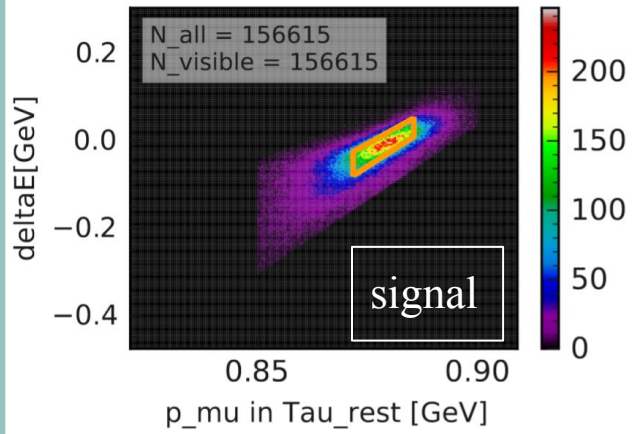
  → missing momentum pointing to shallow polar angles

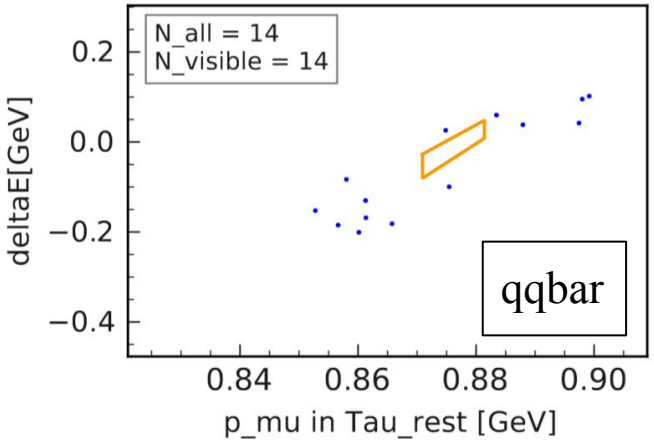
$$23° < \theta(p_{\text{miss}}) < 140°$$

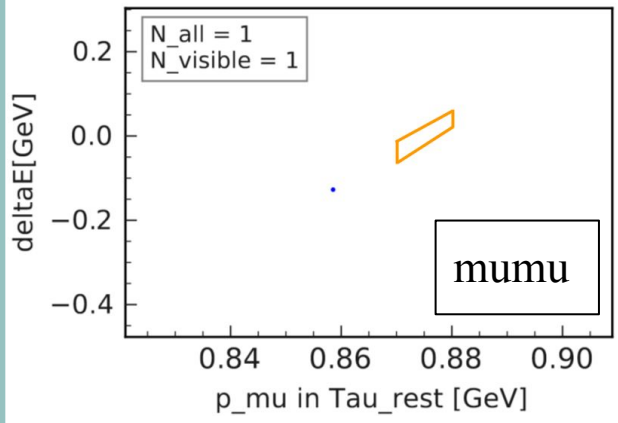
signal: 179867 → 168372

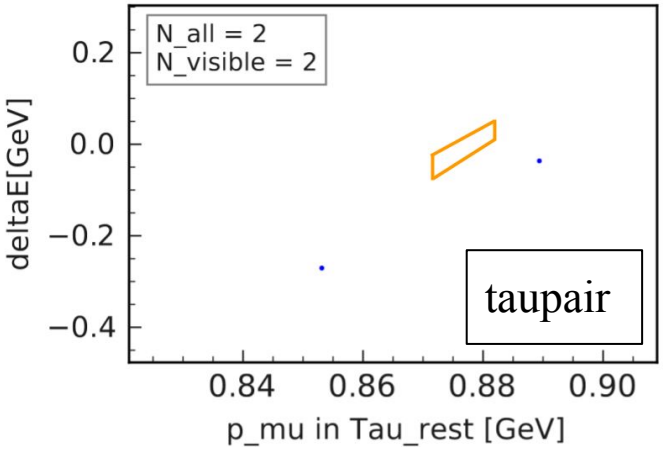


After all cuts - final signal region cut









All BG samples of 100fb^{-1} reduced to zero

156615 → 53489
⟶ 5.3% efficiency

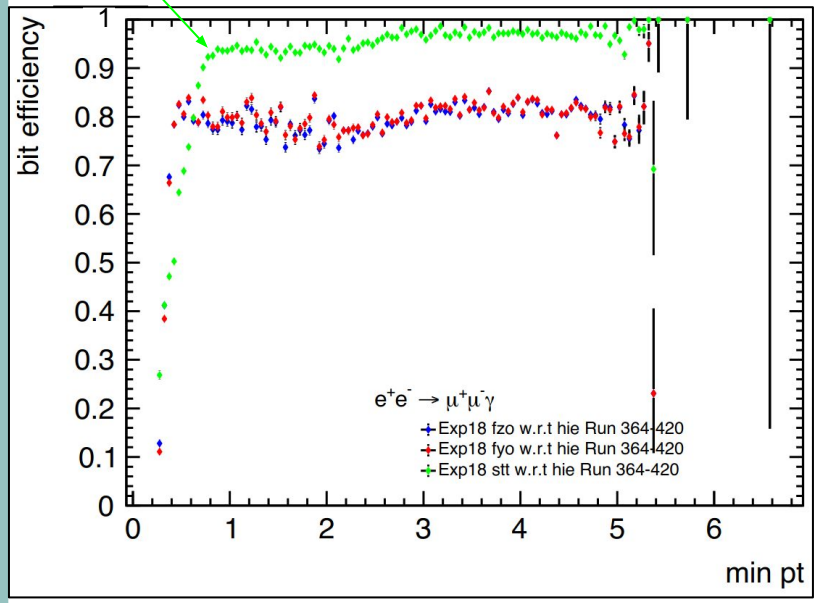
Belle efficiency: 4.2 %

Future Prospects and Steps

Neural trigger at Belle II from 2021:

→ Only requires one charged track

→ Improved reconstruction rate



Next steps:

- Check cut-performance for 500 fb^{-1} MC
- Introduce additional cuts
- Improve cut strategy
- Get analysis approval of τ working group at Belle II

→ Look at real data

→ Extend analysis to $e\pi^0$, $\ell\eta$, $\ell\eta'$

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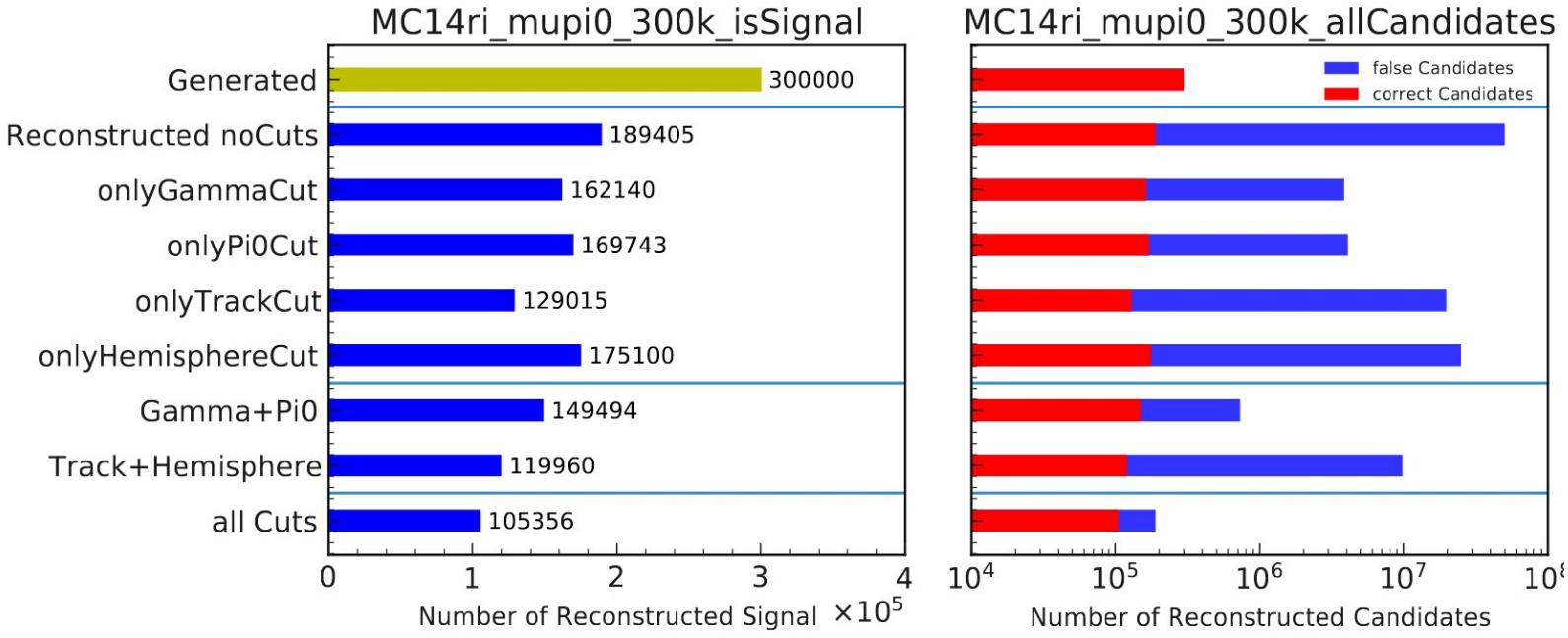
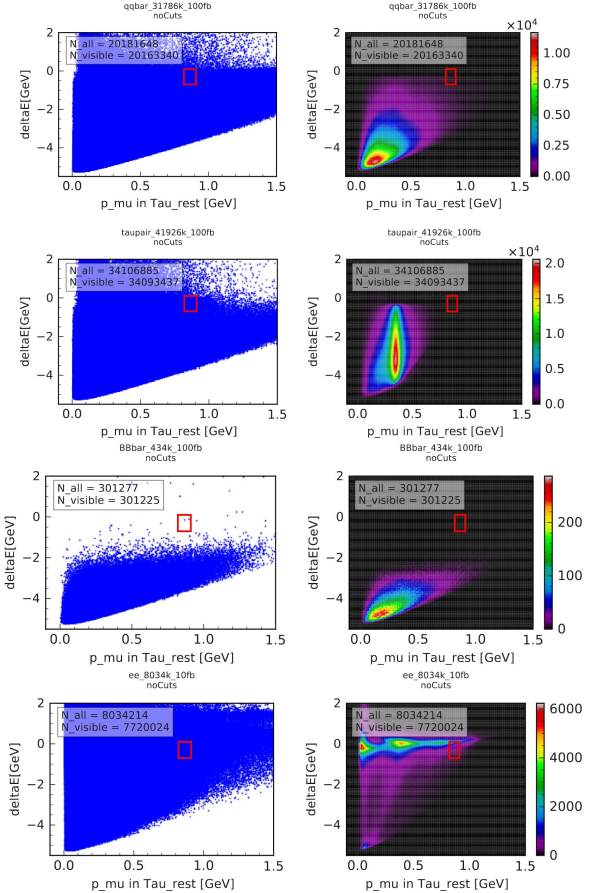
Belle II

Backup

Preselection Study



Signal Region - Background Samples

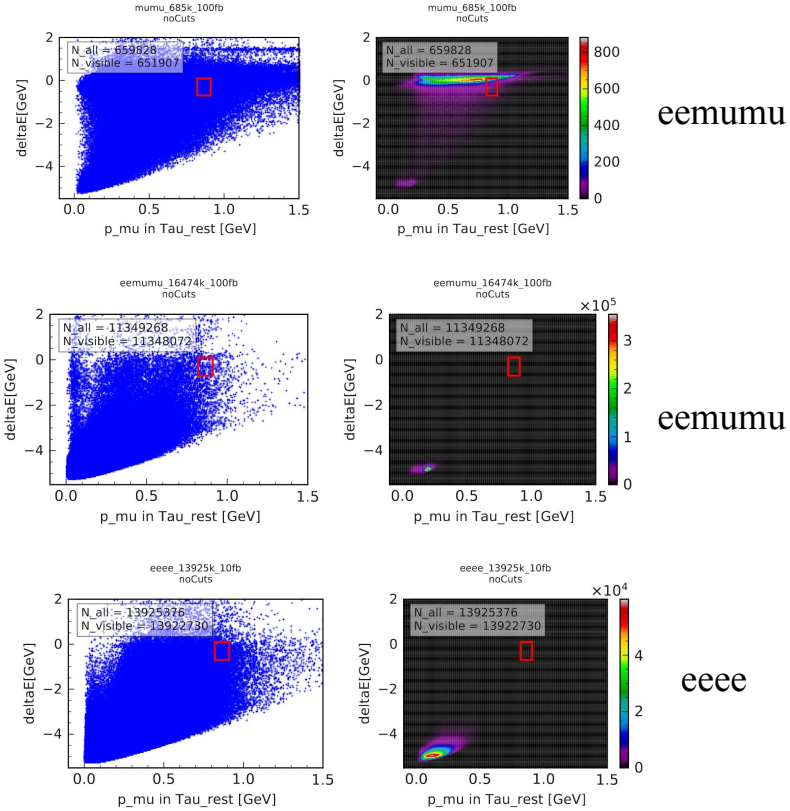


qqbar

taupair

BBbar

ee



eemumu

eemumu

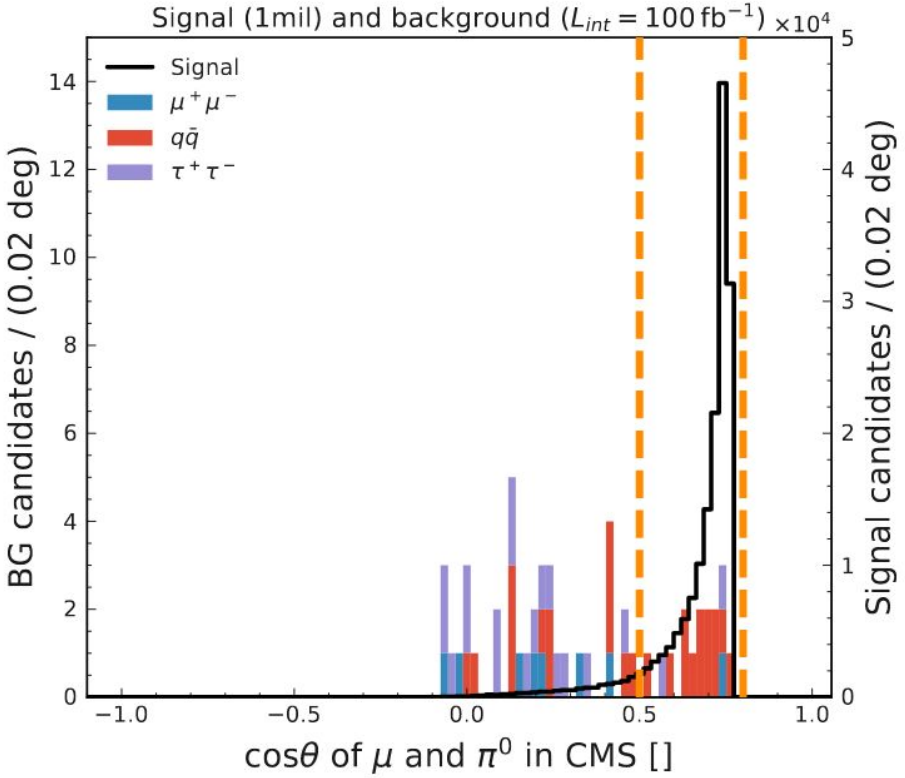
eeee

Cut on CMS angle of mu and pi0

- Opening angle constrained by 2-body kinematics
- BG reduction with small signal loss

$0.5 < \cos\theta\,(\mu\pi^0) < 0.8$

signal: 168372 → 156615



Cutflow

	signal	$q\bar{q}$	$\tau^+\tau^-$	$B\bar{B}$	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$	$e^+e^-\mu^+\mu^-$	$e^+e^-e^+e^-$
no cuts	341078	20181648	34106885	301277	8034214	659828	11349268	13925376
2D cut	229898	2671	246	1	11328	1660	17	102
muID >0.90	208222	119	26	0	2	1547	4	0
E_{visible}	179867	30	20	0	0	231	3	0
$\theta_{\text{missing } \vec{p}}$	168372	26	19	0	0	7	0	0
$\measuredangle(\mu\pi^0)_{\text{CMS}}$	156615	14	2	0	0	3	0	0
tight 2D cut	53489	0	0	0	0	0	0	0

Numbers and Data

- isSignal/Reconstructed:
  53489/53503 = 99,97%

- Belle instantaneous luminosity goal:
  $6*10^{35}$ $cm^{-2}s^{-1}$

Results Belle	
Efficiency	4.2%
Expected BG at 901 fb^{-1}	0.64±0.32

- muID Likelihood for particle hypthesis $\text{muonID} = \frac{\mathcal{L}_\mu}{\mathcal{L}_\text{e} + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_\text{K} + \mathcal{L}_\text{p} + \mathcal{L}_\text{d}}$

- Upper limit prediction: BR < $5.8*10^{-7}$ (90% CL)

Cuts at Belle and BaBar

BaBar	
Cuts general	· 2 or 4 charged tracks, total charge = 0 · Photon conversion tracks rejected · -0.76 < polar angle of missing momentum < 0.92
Cuts signal side	· 1 or 3 tracks and 2 photons · 50 MeV < E_γ < 100 MeV in signal hemisphere · 0.115 GeV/c^2 < m($\pi^0 \to \gamma\gamma$) < 0.150 GeV/c^2 · 1.5 GeV/c < p_{π^0} · track with $p > 0.5$ GeV/c and a identified as a muon by BaBar-PID
Cuts tag side	· total CM momentum on tag side < 4.75 GeV/c · total CM energy $\sum E_\gamma^{CM}$ < 0.2 GeV/c^2 · m_{tag} < 0.4 GeV/c^2
2D-cut parameters	· ΔE, m_{EC} (beam-energy constrained τ-mass), $\pm 2\sigma$ around peak · 1.5 GeV/c^2 < m_{EC} < 2.0 GeV/c^2 , −0.8 GeV/c^2 < ΔE < 0.4 GeV/c^2
Dominant BG	$\tau \to \rho\gamma$, $\tau \to e\nu\bar{\nu}\gamma$, ee, $\mu\mu$, $q\bar{q}$
Luminosity	339 fb^{-1}
Signal efficiency	4.75±0.37 %
Expected BG	1.33 ± 0.15 (2σ-box)
Resolution	$\sigma(m_{EC}) = 9.0$ GeV/c^2, $\sigma(\Delta E) = 46.4$ MeV
Upper limit	$1.1 \cdot 10^{-7}$ (90% C.L.)

Belle	
Cuts general	· all tracks in -0.866 < cos θ < 0.956 · charged tracks $p_t > 0.1$ GeV/c · photon energies $E_\gamma > 0.1$ GeV · zero net charge of candidate tau-pairs · charged lepton momentum 0.115 GeV/c < $\lvert\vec{p_{l\pm}}\rvert$ < 0.152 GeV/c · Visible energy: 5.29 GeV < E_{vis}^{CM} < 10.0 GeV
Cuts signal side	· muon-PID > 0.9 with p > 0.7 GeV/c · reject radiative photons from electrons with cos $\theta_{e\gamma} > 0.99$ · π^0-candidates 1.5 GeV/c^2 < $M_{\gamma\gamma}$ < 4.5 GeV/c^2 · $p_{\pi^0} > 0.1$ GeV/c · π^0-candidate photons: $E_{\gamma 1} > 0.9$ GeV and $E_{\gamma 2} > 0.2$ GeV · extra photon candidates $n_\gamma^{SIG} \leq 1$ · angle between μ and π^0: 0.5 < cos $\theta_{\mu-\pi^0}^{CM}$ < 0.80
Cuts tag side	· missing momentum $\lvert\vec{p}_{miss}\rvert > 0.4$ GeV/c · angle to thrust and $\vec{p}_{miss}$: cos $\theta_{miss-thrust}^{CM}$ < -0.55 · extra photon candidates $n_\gamma^{TAG} \leq 2$ · correlation missing energy and tag momentum: $p_{tag}^{CM} > 1.1 \cdot \log(\cos\theta_{miss-thrust}^{CM} + 0.92) + 5.5$ and $p_{tag}^{CM} < 5\cos\theta_{miss-thrust}^{CM} + 7.8$ · leptonic decay: $p_{miss} > -10m_{miss}^2 + 4$ and $p_{miss} > 1.1m_{miss}^2 - 0.3$ · hadronic decay: $p_{miss} > -5m_{miss}^2 - 0.25$ and $p_{miss} > 2.1m_{miss}^2 - 0.3$
2D-cut param.	· ΔE, M_{inv} (reconstructed invariant mass of τ), 2σ around peak
Dominant BG	$\tau \to \pi^\pm\pi^0\nu_\tau$
Luminosity	· 401 fb^{-1}
Signal efficiency	· 4.53 %
Expected BG	· 0.58±0.34
Resolution	· $\sigma^{high}(M_{inv}) = 14.9$ MeV/c^2, $\sigma^{low}(M_{inv}) = 19.1$ MeV/c^2 · $\sigma^{high}(\Delta E_{inv}) = 33.8$ MeV/c^2, $\sigma^{low}(\Delta E_{inv}) = 63.0$ MeV/c^2
Upper limit	$1.2 \cdot 10^{-7}$ (90% C.L.)