First Results and Prospects for the LFV decay $\tau \to \ell + \alpha$(invisible) at Belle II

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VIRTUAL CONFERENCE

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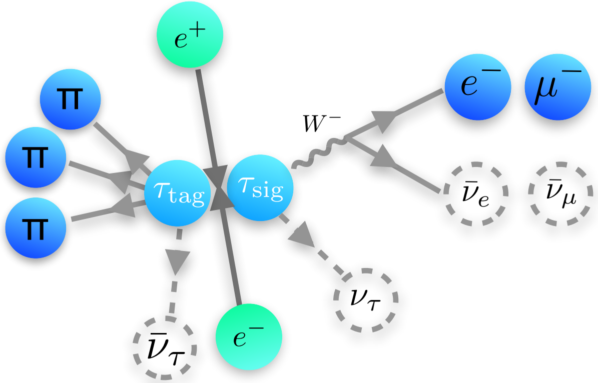
PRAGUE, CZECH REPUBLIC

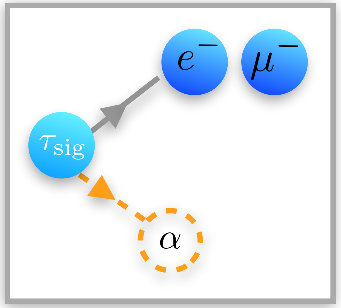
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Belle II

DESY.

Introduction





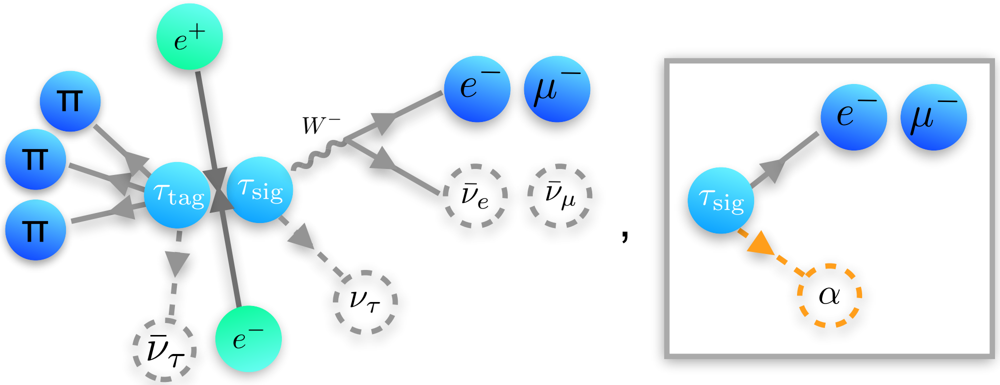
- Search for the two body decay $\boldsymbol{\tau \to e/\mu + \alpha}$ where $\boldsymbol{\alpha}$ is an unobserved particle (missing energy).

- LFV process which is not present in the SM but appears in several NP models e.g. as a Goldstone boson.

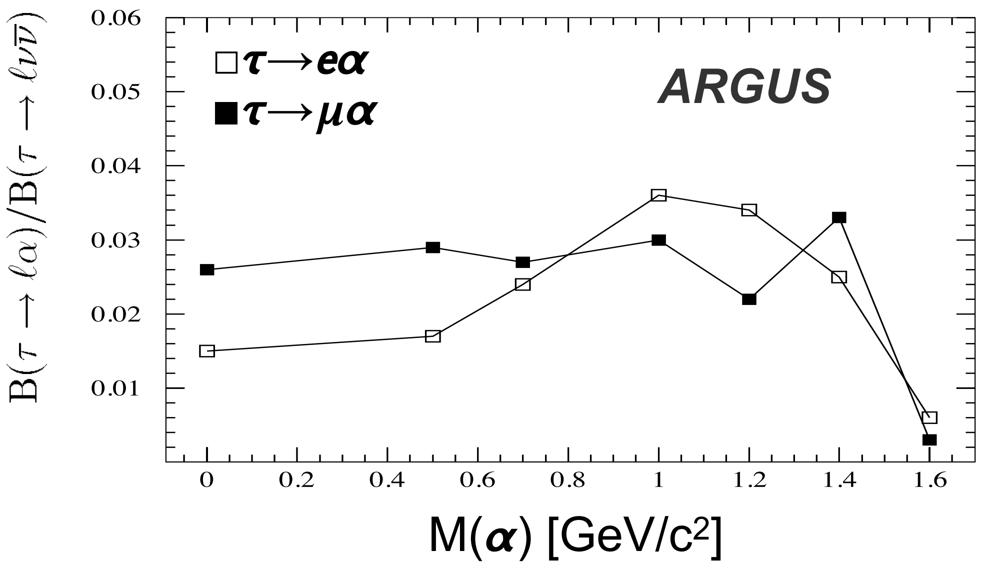
- Model independent search - minimal assumptions are made on the nature of $\boldsymbol{\alpha}$.

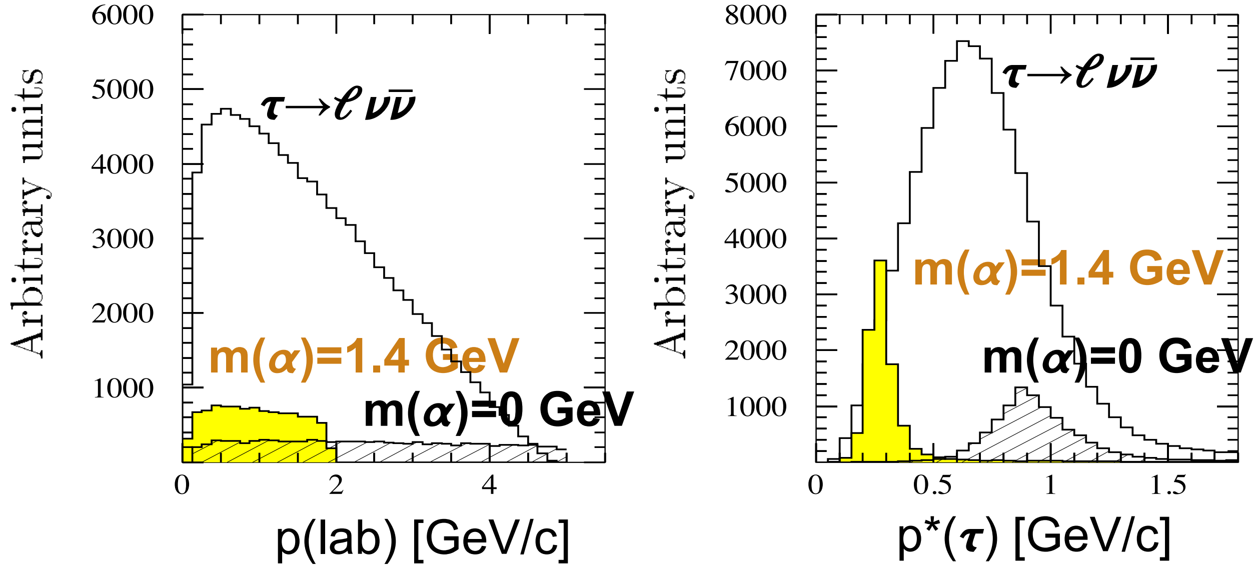
- We present preliminary MC studies and provide UL(95% CL) projections for the $\boldsymbol{\tau \to e\alpha}$ channel measurement at Belle II.

Previous Searches



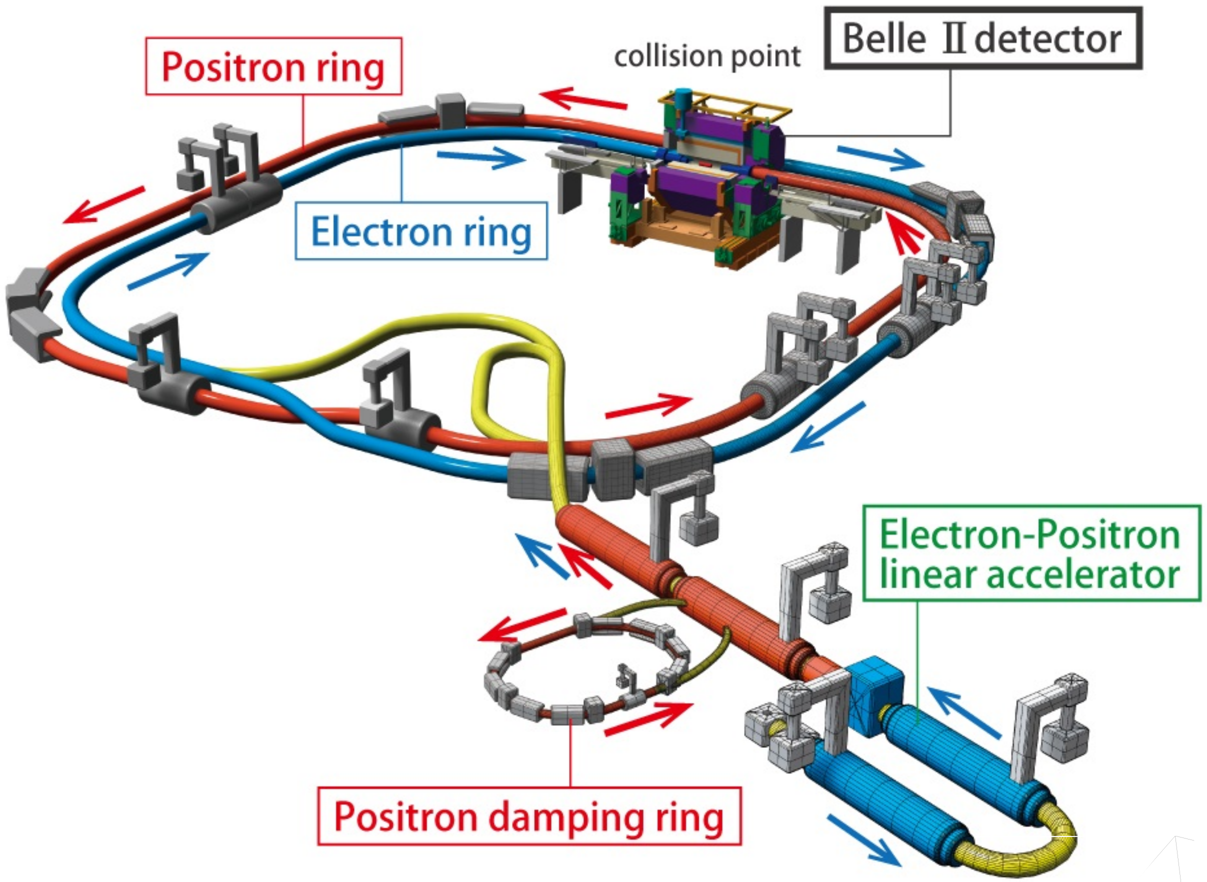
- **Mark III (1985, 9.4 pb⁻¹)**
- **ARGUS (1995, 476 pb⁻¹)**
- Here the lepton momentum is studied in the $\boldsymbol{\tau}$ rest frame, where it manifests as a peak against the SM $\boldsymbol{\tau \to \ell \nu \nu}$ background.





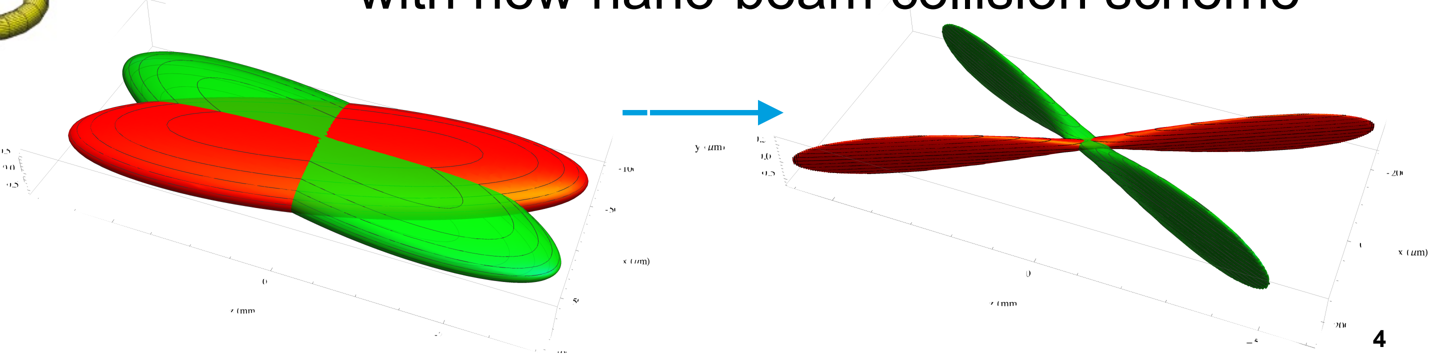
Z.Phys. C68 (1995) 25-28

SuperKEKB @KEK, Tsukuba



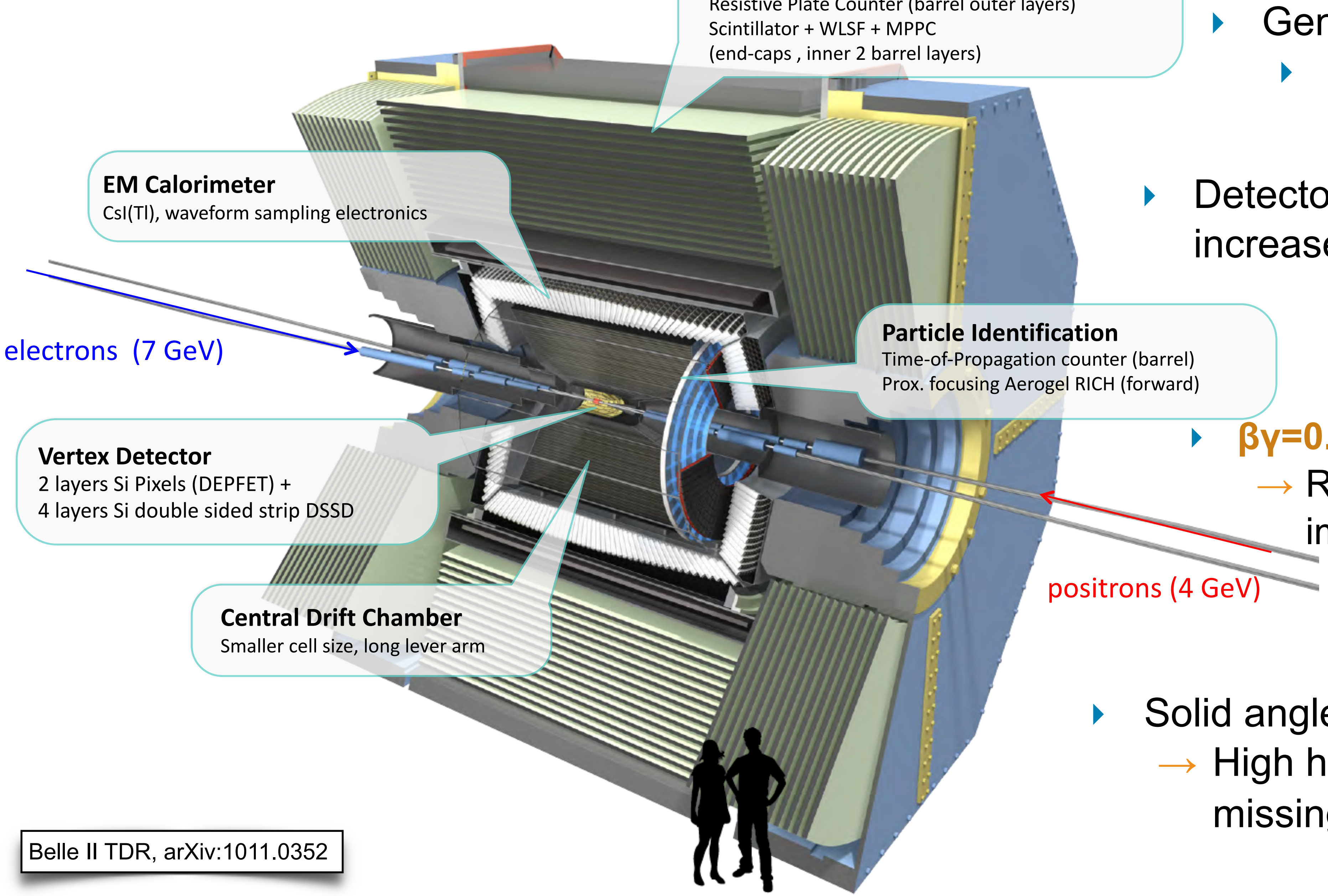
- **New facility** to search for BSM physics by studying B, D and τ decays.
- Asymmetric electron-positron collider:

- Major upgrade to the KEKB accelerator with **x30 the design luminosity ($6x10^{35}$ $cm^{-2}s^{-1}$)**.
  - **x1.5** raw beam current.
  - **x20** smaller beam spot (σ_y*=50 nm) with new nano-beam collision scheme



- **Aim: collect 50 ab^{-1} of collision data** (vs ~1ab^{-1} of Belle)

Belle II Detector

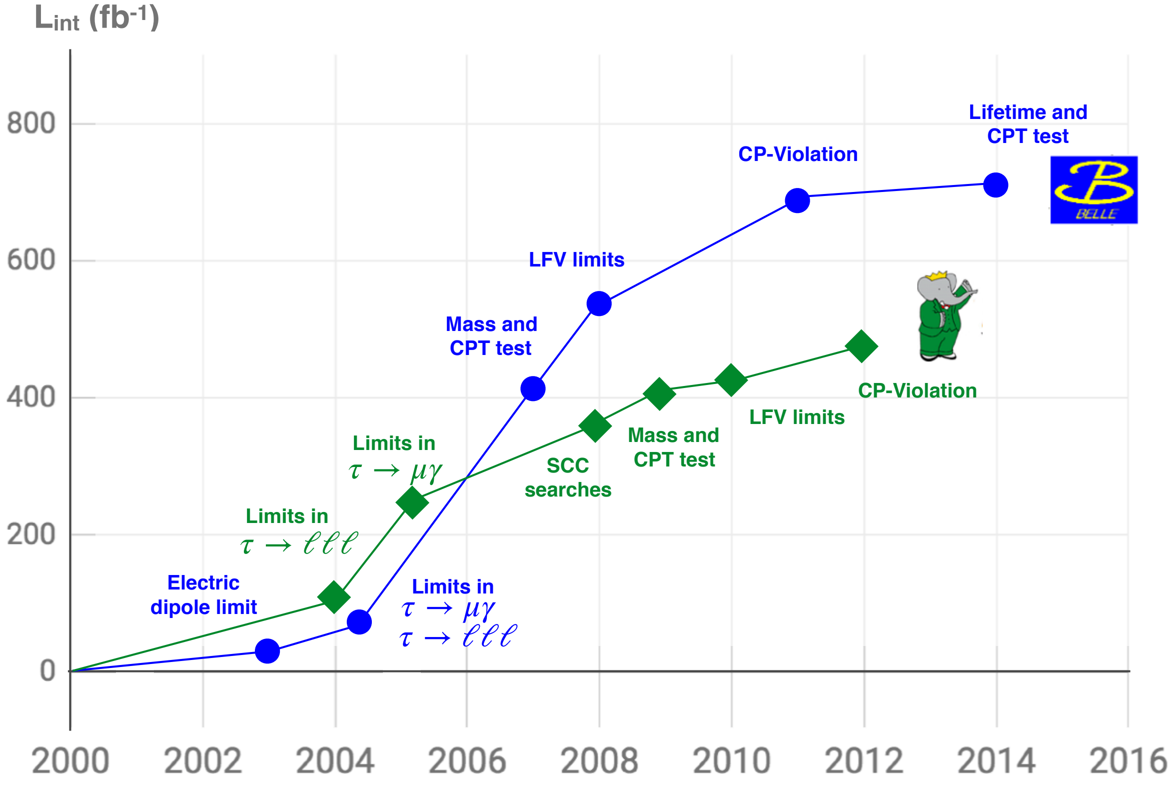


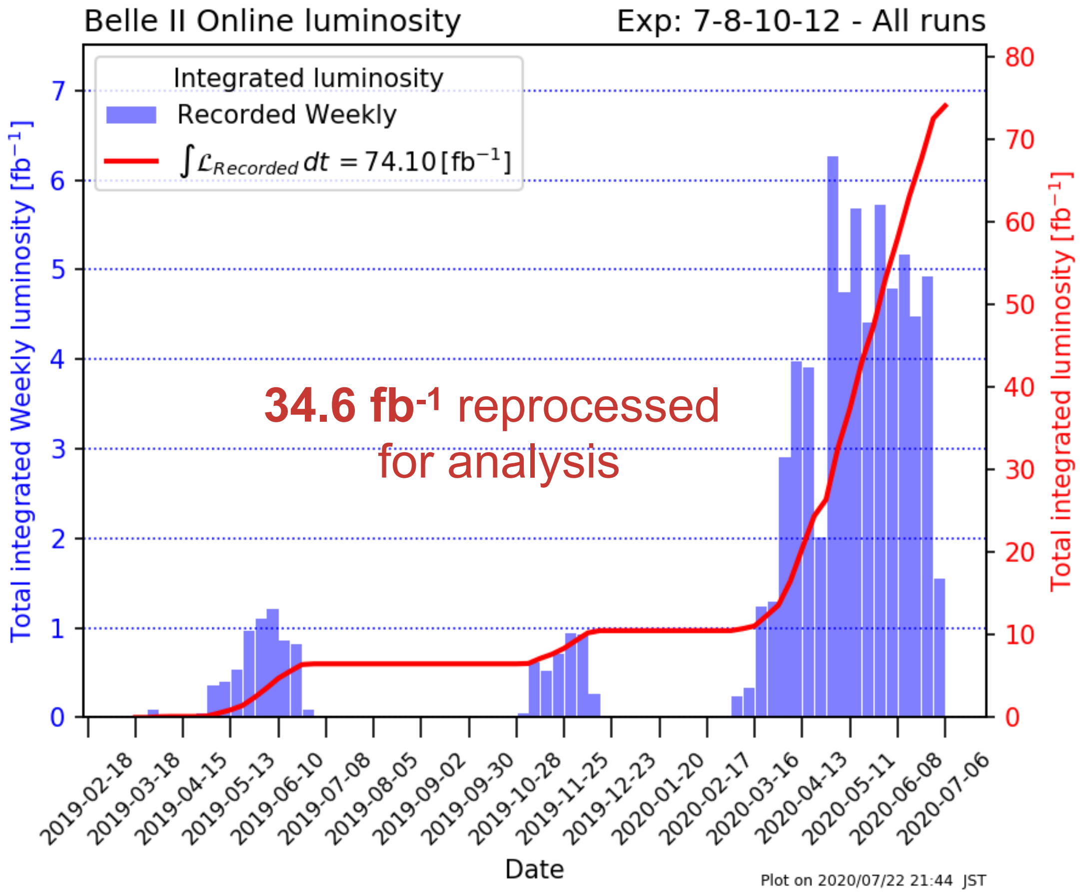
Belle II TDR, arXiv:1011.0352

- General purpose spectrometer
  - **Roll-in: April 2017**
- Detector upgrade to mitigate increased beam background
- **βγ=0.28** (vs **0.42** @KEKB)
  → Reduced boost requiring improved vertex reconstruction
- Solid angle coverage >90%
  → High hermeticity for missing particle decays

Tau Physics at Belle II

- σ($e^+e^-\to\Upsilon(4S)$) = 1.05 nb
- **σ($e^+e^-\to\tau^+\tau^-$) = 0.92 nb**
- Not just a B-factory, but also ***τ* factory**.

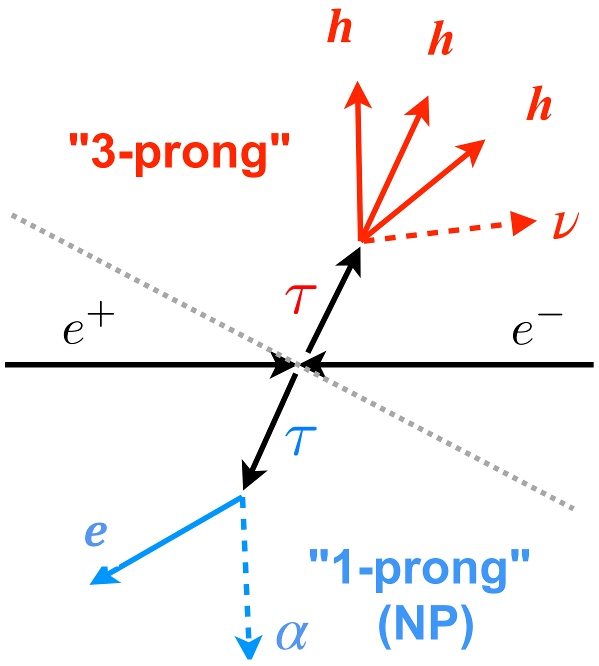


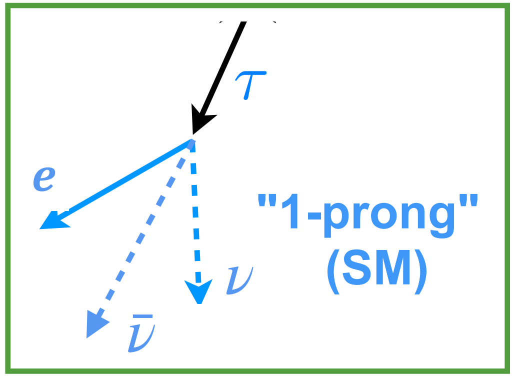


- Historically B-factories provided a variety of very interesting results in the last two decades.
- Luminosity is quickly ramping up to competitive levels for physics discoveries.

Event Reconstruction

- 3x1-prong decay: $\tau \rightarrow$ **eα (signal) , $\tau \rightarrow 3\pi\nu$ (tag)**
  - Exactly 4 good tracks required.
  - Hemisphere separation using thrust vector $\vec{T} = max\left(\sum_i \frac{\vec{p_i}\cdot\hat{T}}{|p_i|}\right)$
- Dominant background: SM $\tau \rightarrow$ **e$\nu\nu$ (irreducible)**
  - Since we don't know **M(α)** we optimise for the SM.
- Other BG: $\tau\tau$ (non-3x1), BBbar, qqbar, ee(γ), μμ(γ), ee$\ell\ell$, beam
- Initially rejected by:
  - **Vertex fit** of the 3-prong tag (reject displaced vertices).
  - **Veto** neutral pions and gamma (qqbar, beam bg).





Tracks
-3< dz<3 cm
dr < 1 cm

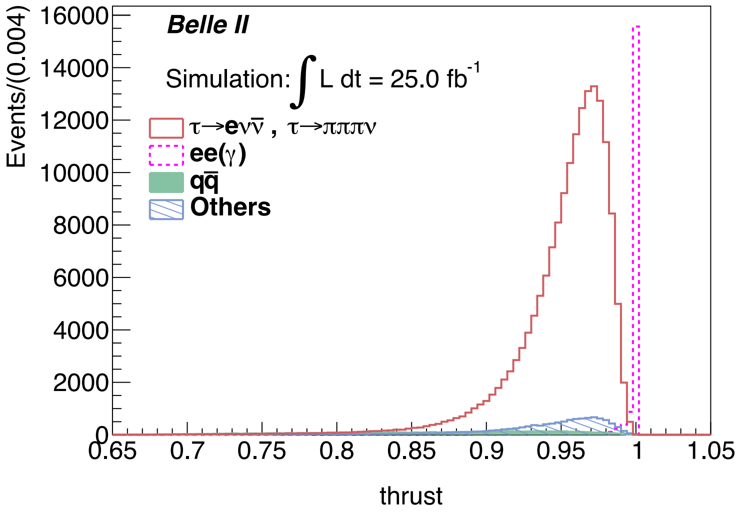
PID
e: E/p > 0.8
π: E/p < 0.8

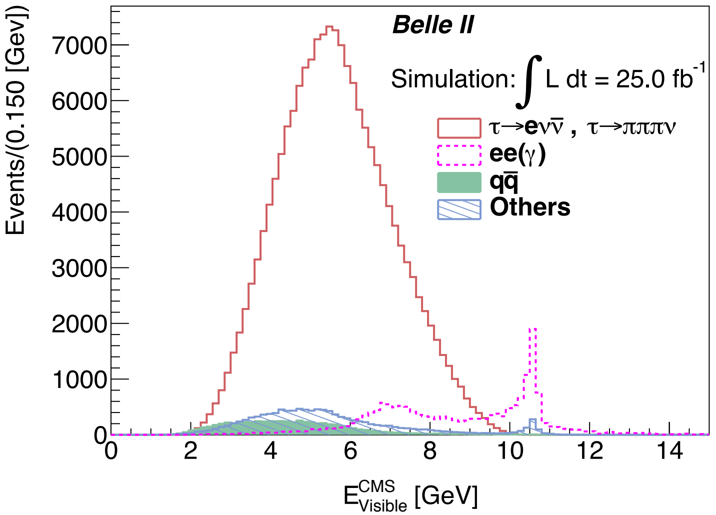
Photons
Within tracking acceptance and
E(γ) > 100 MeV
115<M(γγ)<152 MeV
or
E(γ)>200 MeV

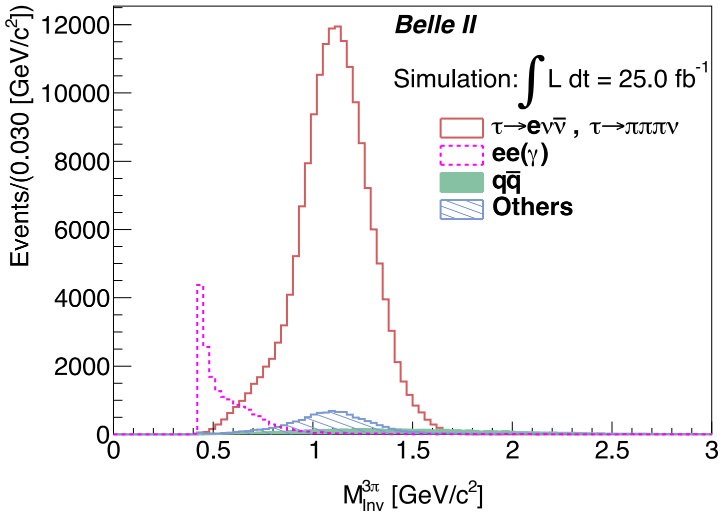
Background Suppression

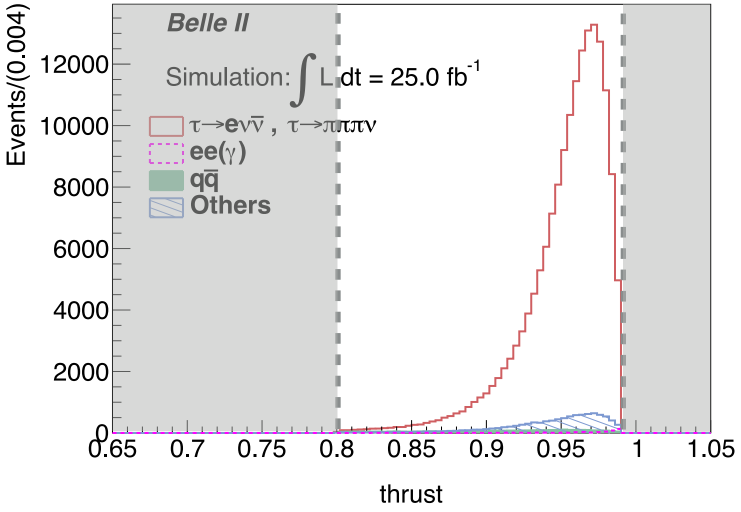
- Cut based selection - Figure of Merit = $\frac{S_{SM}}{\sqrt{S_{SM}+B}}$

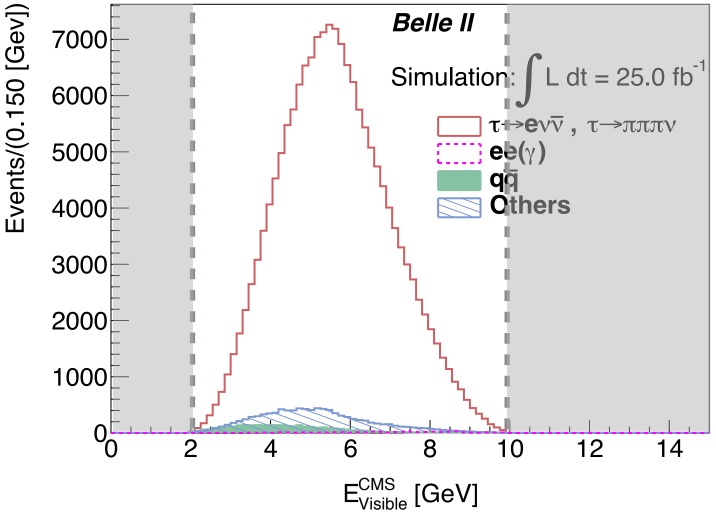
0.8 < thrust < 0.99
2.0 < visible E (CMS) < 9.9
0.48 < Inv M(3-prong) < 1.66

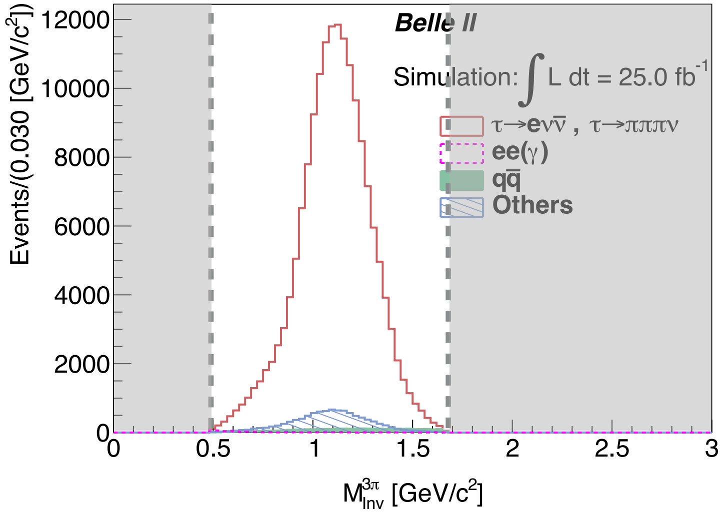






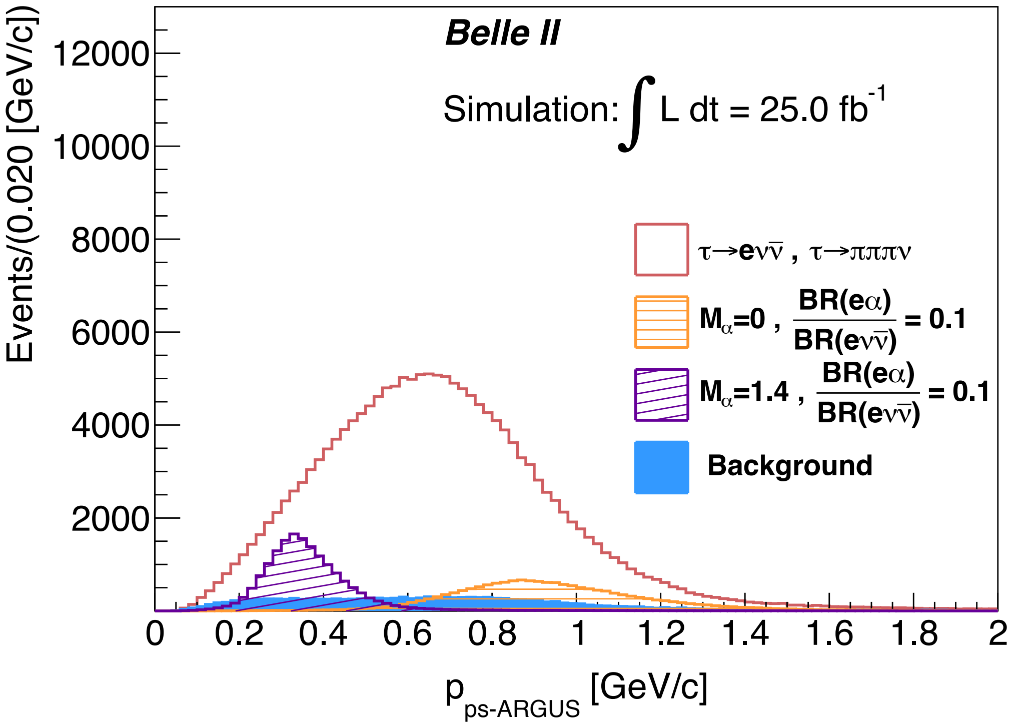


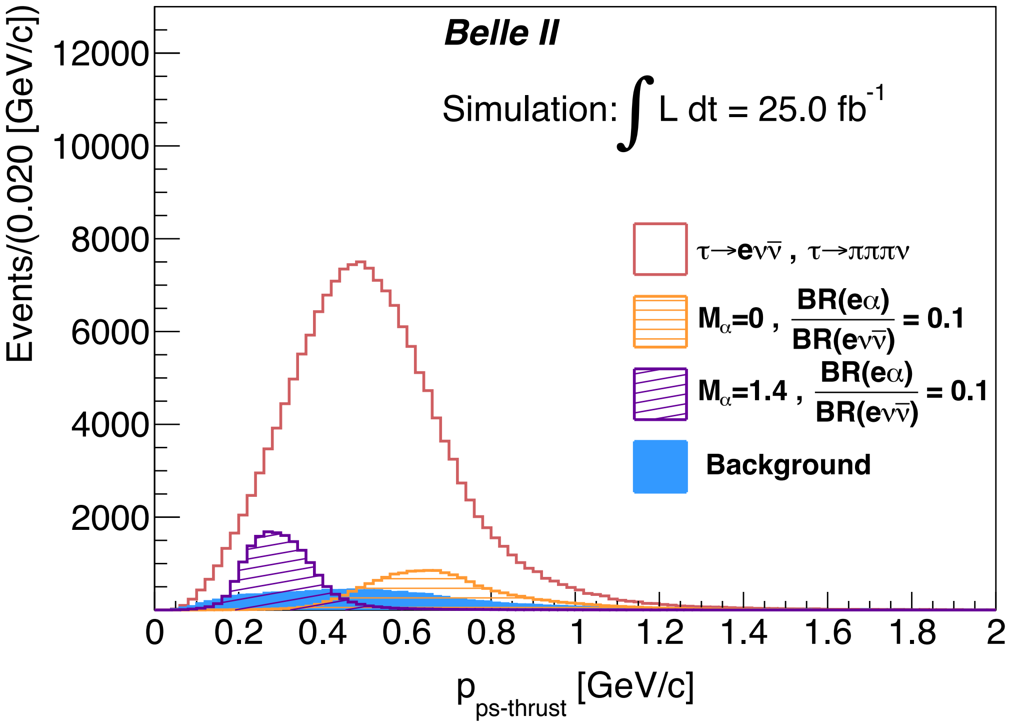




Spectrum in the Pseudo-Rest Frame

- In the signal τ rest frame, the **e** momentum for $\tau \rightarrow e\alpha$ will be a monoenergetic peak; the boost to the τ frame is unknown, so we approximate:
- $E_\tau = \sqrt{s}/2$
- ARGUS method: $\hat{p}_\tau \approx -\hat{p}_{3\pi}$
- Thrust method: $\hat{p}_\tau \approx \hat{T}$





Statistical Model

- We estimate the upper limits through a template-based approach
- The $\tau \to e\alpha$ branching ratio is given by: $Br(sig) = \dfrac{N_{sig}}{2L \cdot \sigma(e^+e^- \to \tau^+\tau^-) \cdot Br(tag) \cdot \epsilon_{sig}}$
- We normalise using the SM channel:

$$poi \equiv \frac{Br(\tau \to e\alpha)}{Br(\tau \to e\nu\nu)} = \frac{\epsilon_{e\nu\nu}}{\epsilon_\alpha}\frac{N_\alpha}{N_{e\nu\nu}}$$

- Data can then be modeled as:

$$F(x) = poi\ \frac{\epsilon_{e\alpha}}{\epsilon_{e\nu\nu}} N_{e\nu\nu} \cdot f_{e\alpha}(x) + N_{e\nu\nu} \cdot f_{e\nu\nu}(x) + N_{bkg} \cdot f_{bkg}(x)$$

where $x = 2E_e/m_\tau$

and f is the template pdf for each contribution.

M(α) $[GeV/c^2]$	$\epsilon_\alpha/\epsilon_{e\nu\nu}$
0	1.09
0.5	1.09
0.7	1.09
1.0	1.07
1.2	1.06
1.4	1.01
1.6	0.74

Upper Limit Estimation Method

- Frequentist profile-likehood method using asymptotic (fast) approach:

$$CL_s \equiv \frac{CL_{s+b}}{CL_b}$$

Eur. 638 Phys. J. C 71, 1554 (2011)

- CL_{s+b}: confidence level for the signal+background hypothesis
- CL_b: confidence level for the background-only hypothesis
- The signal hypothesis is excluded at 95% C.L. if $1 - CL_s \leq 0.95$
  - Provides a conservative estimate of the U.L.

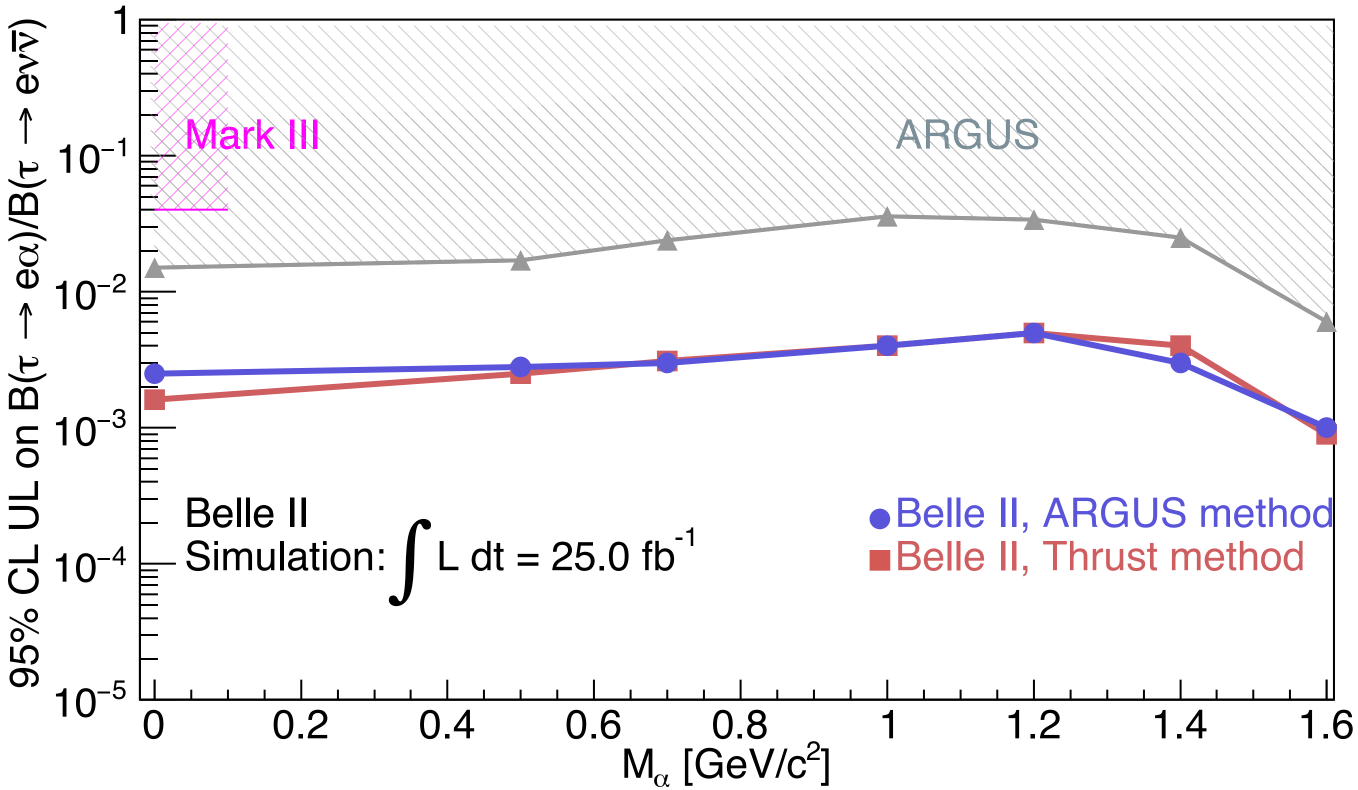
- An **alternative test** is being developed using a Bayesian approach.

MC Study

- We show a preliminary result under the assumption of an integrated luminosity of 25 fb^{-1} under current Belle II data taking conditions.
- SM background: 100 fb^{-1} of simulated $\boldsymbol{\tau\tau}$, BBbar, qqbar, ee(γ), μμ(γ), ee$\ell\ell$
  - Select 25 fb^{-1} at random to treat as background-only pseudodata.
  - Use the remaining 75 fb^{-1} to model templates.
- $\boldsymbol{\tau \rightarrow e\alpha}$: 10^7 events at **M($\boldsymbol{\alpha}$)** = 0, 0.5, 0.7, 1, 1.2, 1.4, 1.6 GeV/c^2
  - BSM decay simulated through phase space model.
  - Tag side decays accordingly to SM.
- Both pseudo-rest frame approximations are tested.

Previous Measurements and MC Estimations

- UL is provided for the ratio $Br(\tau \to e\alpha)/Br(\tau \to e\nu\nu)$



	UL(95% c.l.)		
$M(\alpha)$ [GeV/c^2]	ARGUS (1995)	Argus method	Thrust method
0	0.015	0.0025	0.0016
0.5	0.017	0.0028	0.0025
0.7	0.024	0.003	0.0031
1.0	0.036	0.004	0.004
1.2	0.034	0.005	0.005
1.4	0.025	0.003	0.004
1.6	0.006	0.001	0.0009

BELLE2-NOTE-PL-2020-018

- No systematics effects are taken into account at this stage.

Conclusions and Outlook

- We established a framework for the search of the $\tau \rightarrow e\alpha$ decay at Belle II and showed preliminary estimates for the attainable UL under the assumption of a data set of 25 fb^{-1}.
- Further work is ongoing to identify and incorporate sources of systematic uncertainties.
- Independent cross-checks using a Bayesian approach are being developed as well as new techniques to approximate the tau rest frame.
- Final analysis will incorporate the $\tau \rightarrow \mu\alpha$ channel.

- Belle II has the potential to significantly improve this measurement and provide constraints on NP models.

Thank you for your attention.

Backup

Selection Efficiencies

Sample		Events after all requirements	Efficiency
$\tau \to e\alpha$	$M_\alpha = 0$	221576	14.58%
$\tau \to e\alpha$	$M_\alpha = 0.5$	221713	14.59%
$\tau \to e\alpha$	$M_\alpha = 0.7$	221076	14.54%
$\tau \to e\alpha$	$M_\alpha = 1.0$	218589	14.38%
$\tau \to e\alpha$	$M_\alpha = 1.2$	216014	14.21%
$\tau \to e\alpha$	$M_\alpha = 1.4$	204453	13.45%
$\tau \to e\alpha$	$M_\alpha = 1.6$	150867	9.93%
$\tau \to e\nu\bar{\nu}$		166170	13.36%