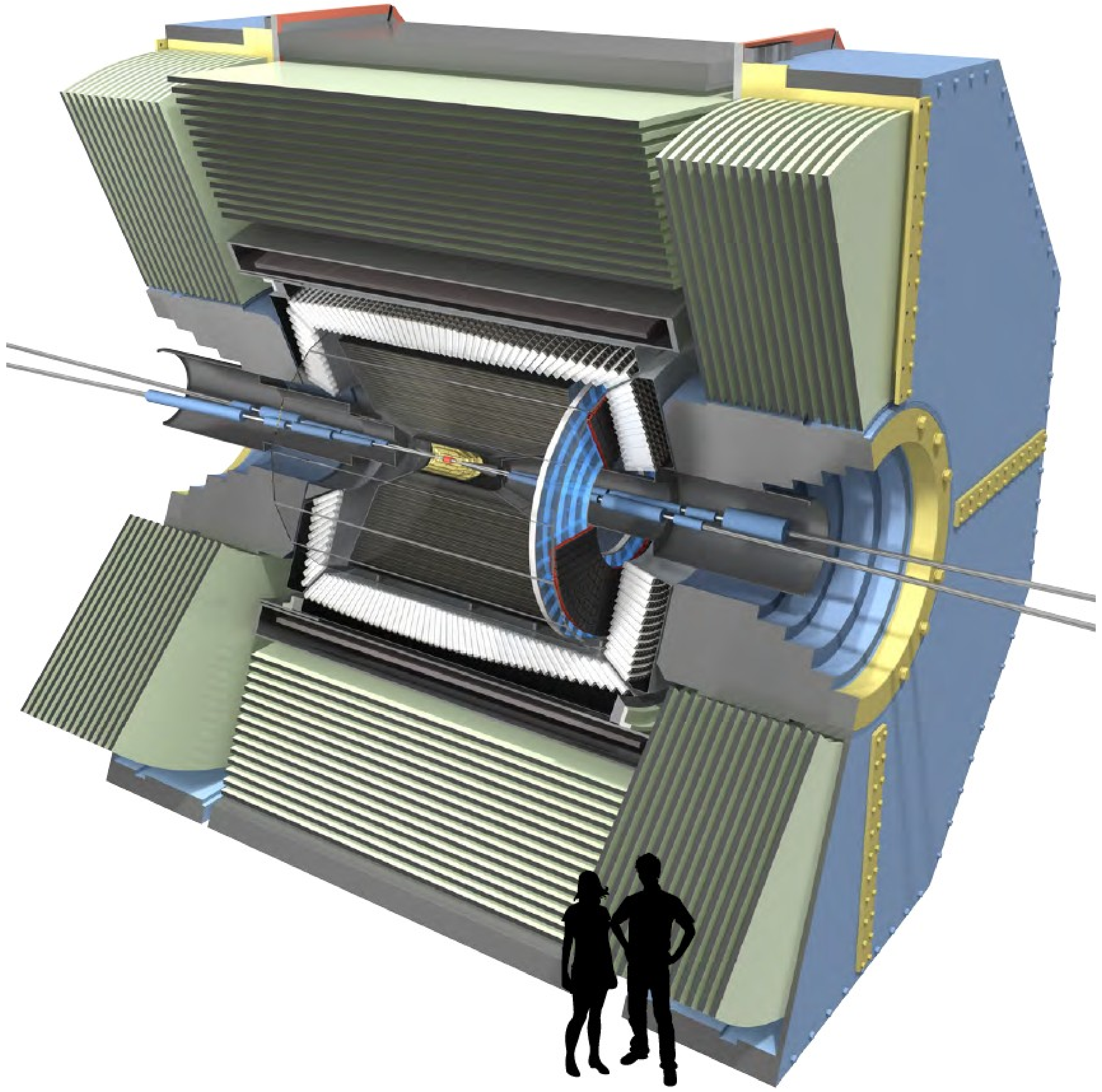
Status of τ Physics



Ami Rostomyan
Belle II Germany Meeting
14.09.2020

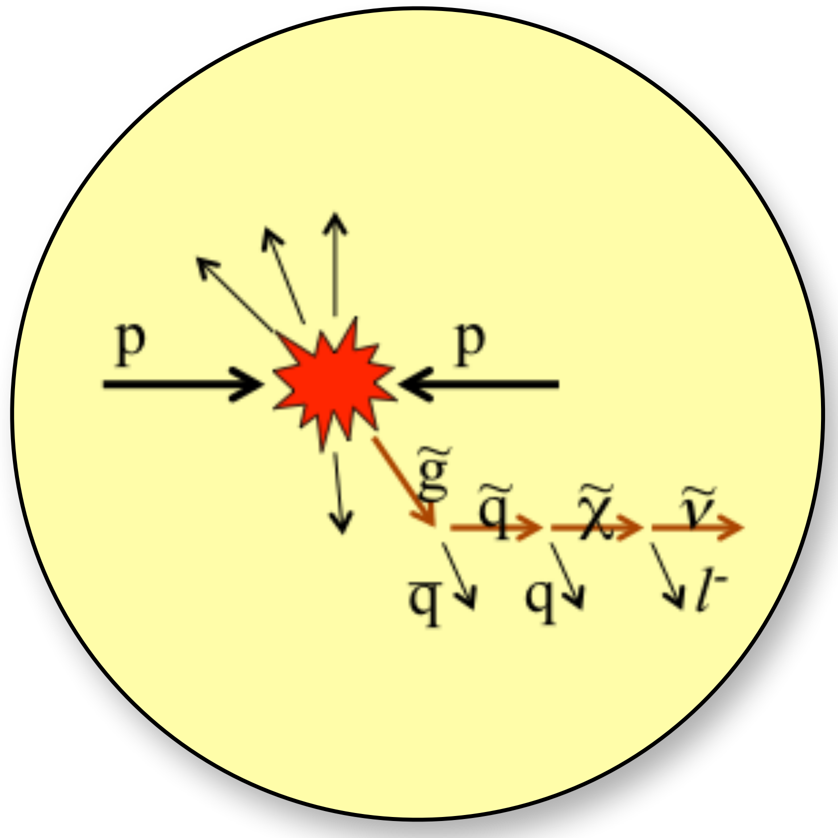
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

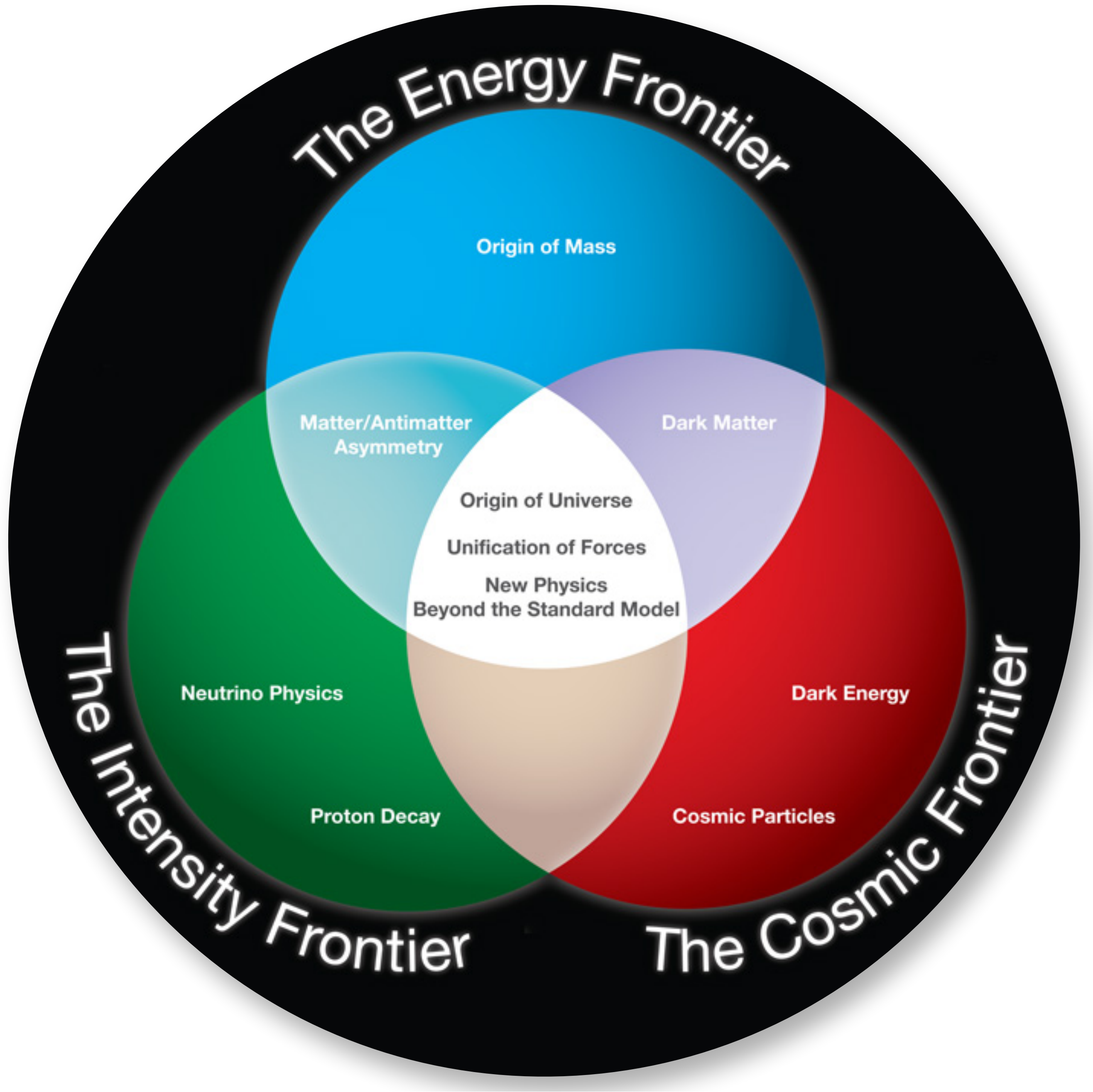
Looking Beyond the Standard Model

Complementary Pathways to New Physics

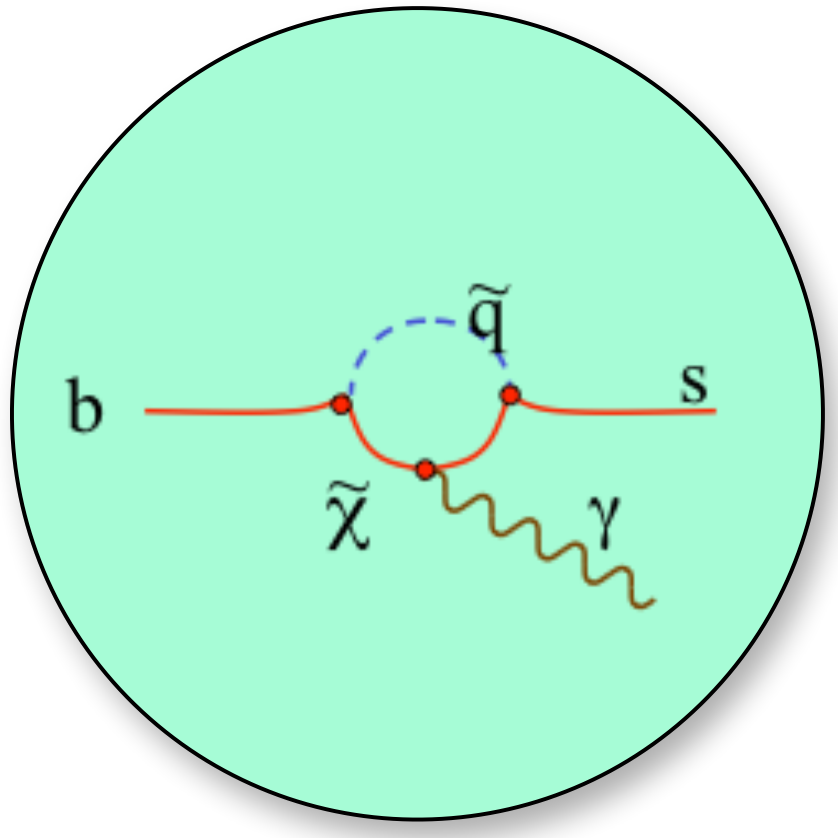
Energy frontier



Direct production of new particles
(limited by the beam energy)



Intensity frontier



Indirect sensitivity through loops
(probe the energy above 10 TeV)

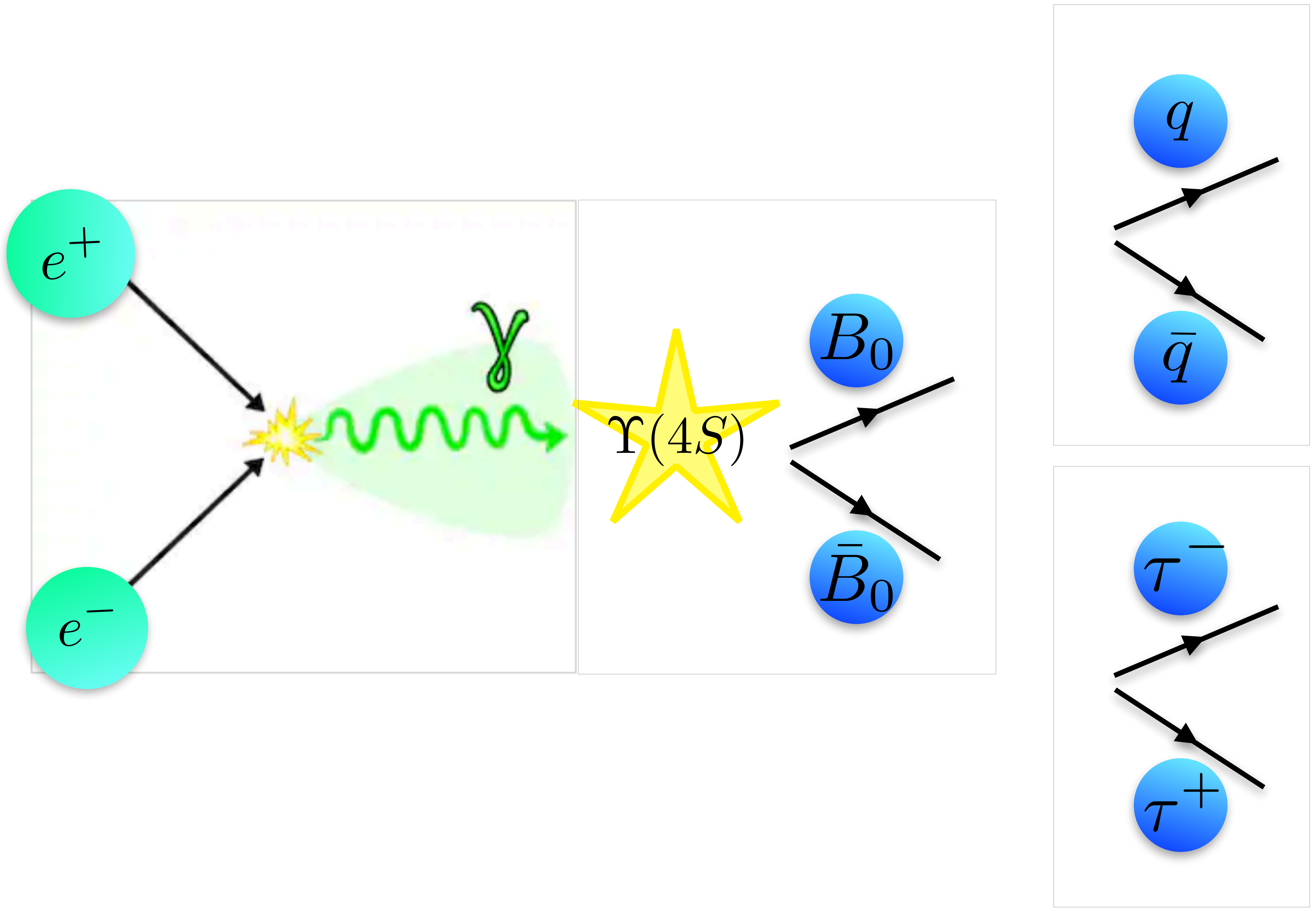
Current experimental situation

- No clear evidence for beyond Standard Model (BSM) physics at high energy frontier
- Intensity frontier offers **indirect** sensitivity to **very high** scales

If NP is seen by one frontier, the confirmation by the other would be important!

B-Factories

Not just B-Factories but also τ factories!



$$\sigma\left(e^+e^- \to \Upsilon(4S)\right) = 1.05\ [\mathrm{nb}]$$
$$\sigma\left(e^+e^- \to q\bar{q}\right) = 3.69\ [\mathrm{nb}]$$
$$\sigma\left(e^+e^- \to \tau^+\tau^-\right) = 0.919\ [\mathrm{nb}]$$

Clean environment

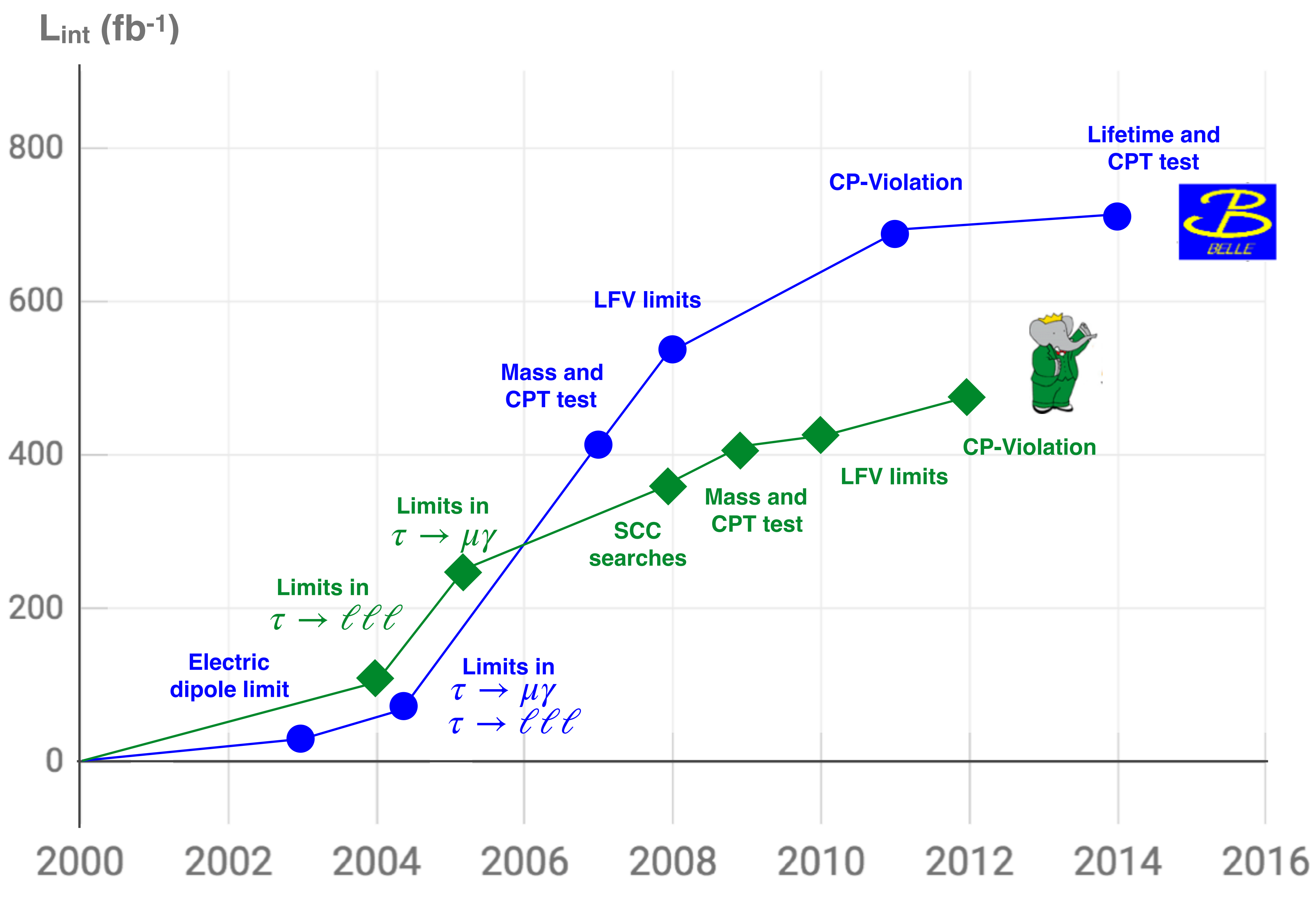
- ➡ Low backgrounds, high trigger efficiencies
- ➡ The kinematics of the initial state is precisely known
- ➡ The neutrino energy can be determined precisely

Hermetic detectors with

- ➡ High reconstruction efficiency → low track multiplicities
- ➡ Good kinematic and vertex resolution
- ➡ Excellent PID capability
- ➡ Excellent γ and π^0 reconstruction

τ physics program

Belle II - The world largest number of $e^+e^- \to \tau^+\tau^-$ events offer data for τ physics with high precision.



Historically B-factories provided a variety of very interesting results in the last two decades.

Wide range of observables to confront theory

- Hints on deviations from SM
- CP asymmetries
- Rare decays, forbidden decays, invisible decays
- Angular distributions

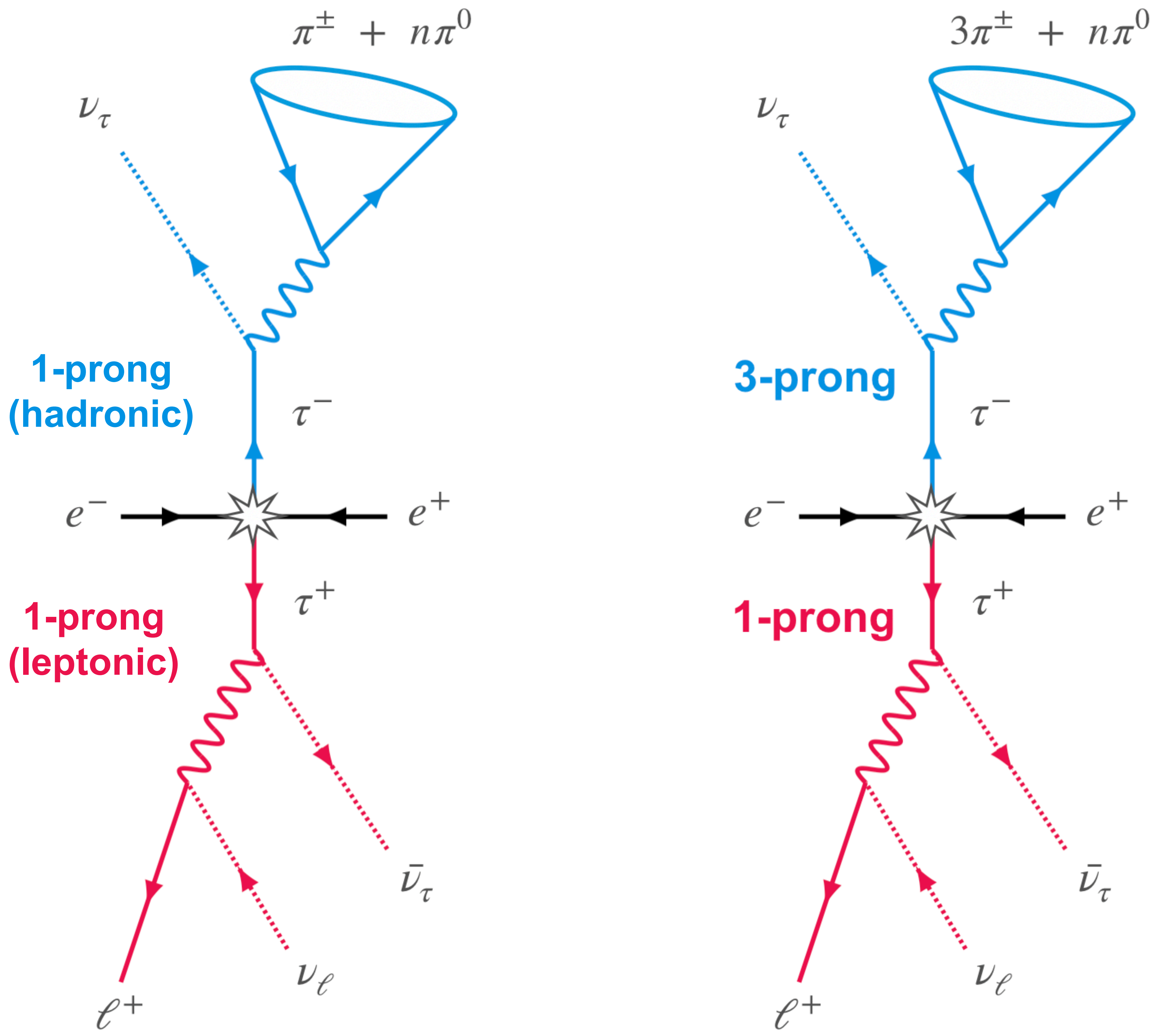
Precise tests of SM, NP searches @German groups

- τ mass measurement
- Lepton universality tests
- V_{us} measurement
- Electric Dipole Moment (CP/T violation)
- CP violation $\tau \to K_S \pi \nu$
- Dalitz analysis
- LFV and LNV decays

Neutrinos on the tag or signal side

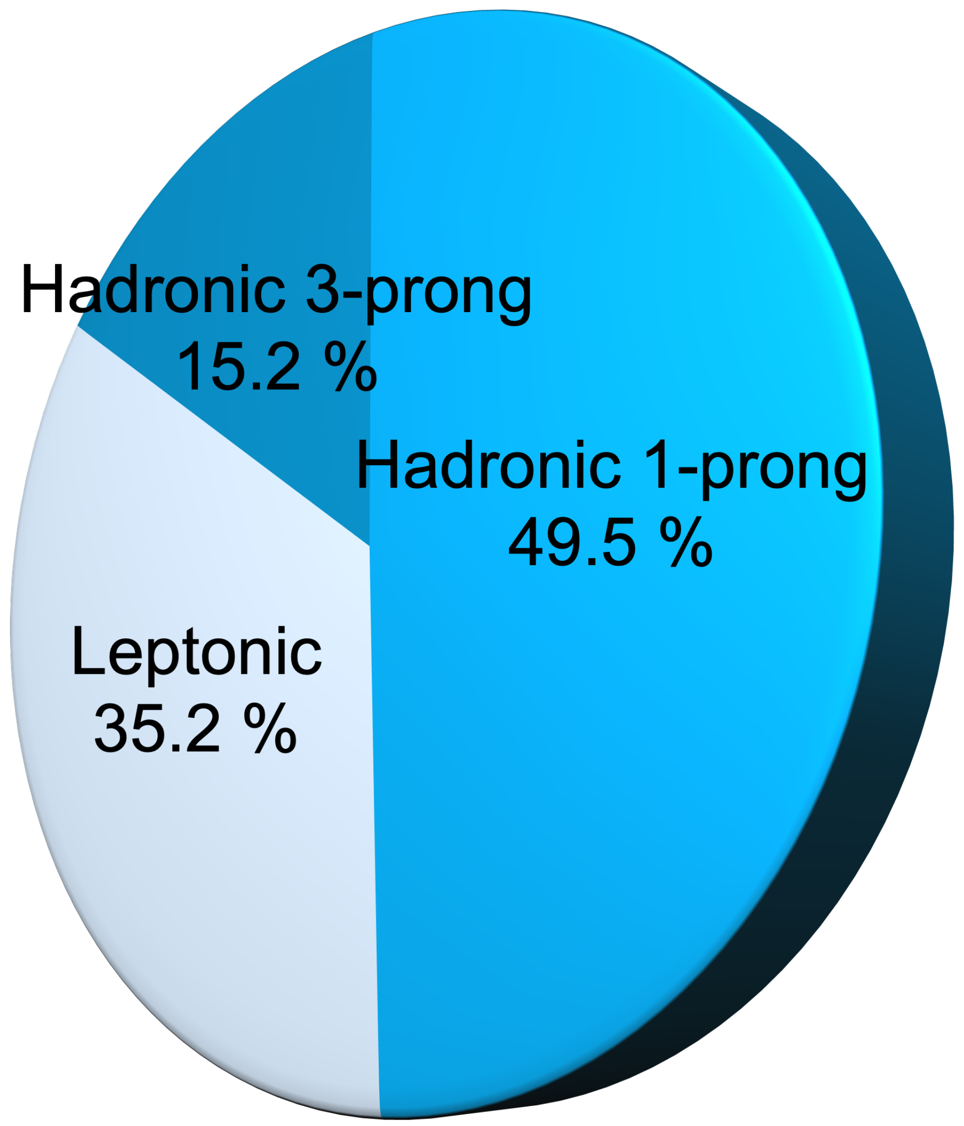
Not possible to reconstruct the full event

- e^+e^- annihilation data is ideal for missing energy channels
- the neutrino energy can be determined precisely



- reconstruct 1-prong, 3-prong τ decays in various channels
  - $e \times \pi$, $e \times \pi\pi^0$, $\mu \times \pi$, $\pi \times \pi\pi^0$, $\mu \times \mu \ldots$
  - $e \times 3\pi$, $e \times 3\pi\pi^0$, $\mu \times 3\pi$, $\pi \times 3\pi\pi^0, \ldots$
  - wide variety of signatures involving tracks (e, μ, π, K) and neutrals (π^0)

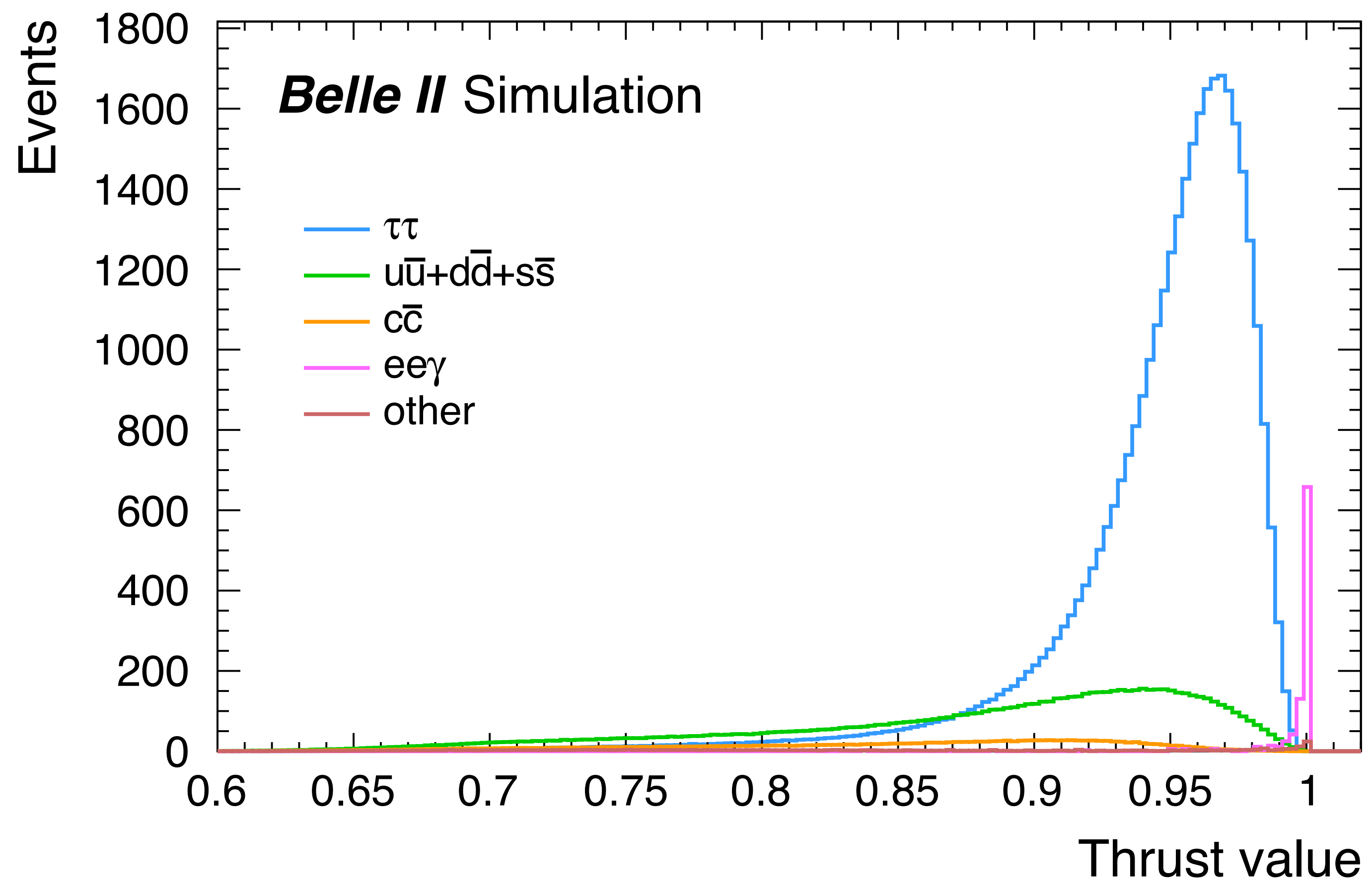
- $e^+e^- \to \tau^+\tau^-$ events are an ideal testbed of performance for low multiplicity physics
  - Level 1 (L1) & high level (HLT) triggers
  - tracking efficiency
  - particle identification
  - π^0 reconstruction efficiency



$e^+e^- \to \tau^+\tau^-$

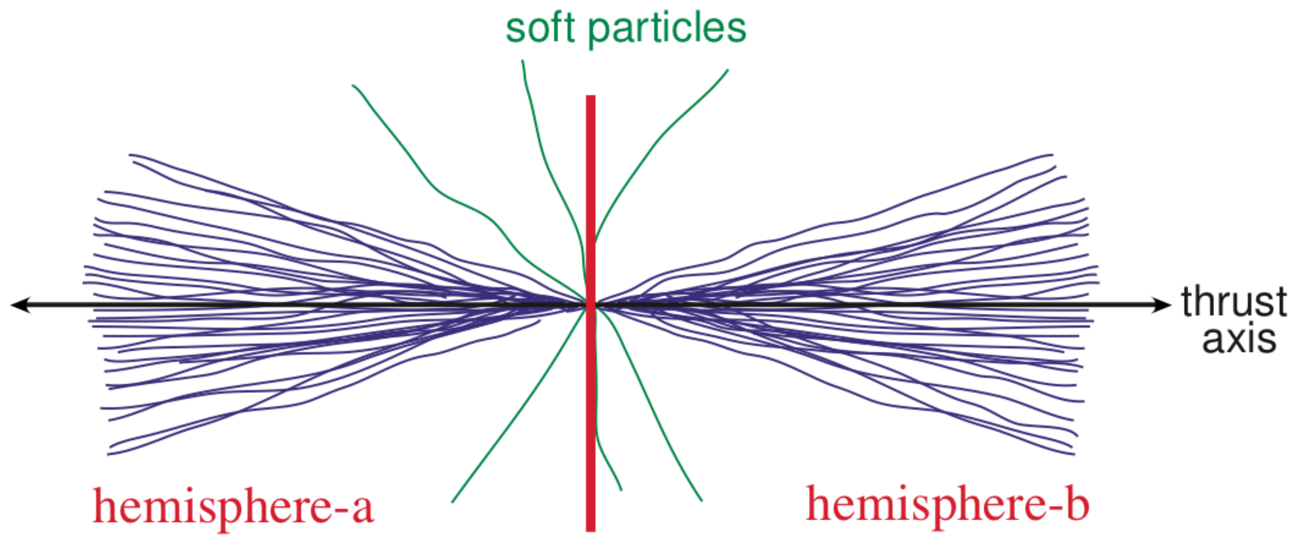
Event topology and kinematics to observe τ leptons

- relatively mild deviation of the τ decay particles from the primary trajectory

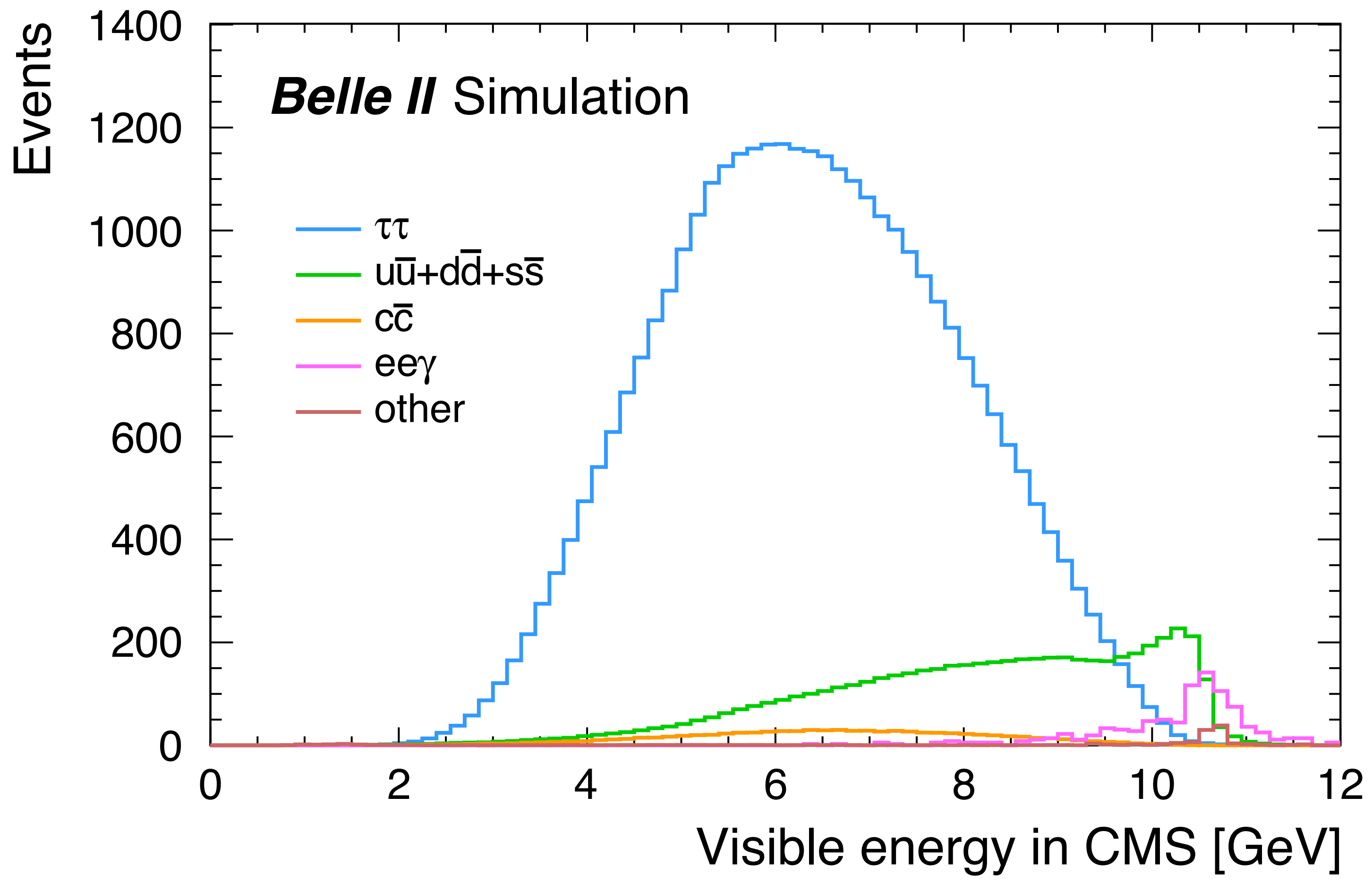


Thrust axis ($\boldsymbol{T}$) is maximising the event shape variable

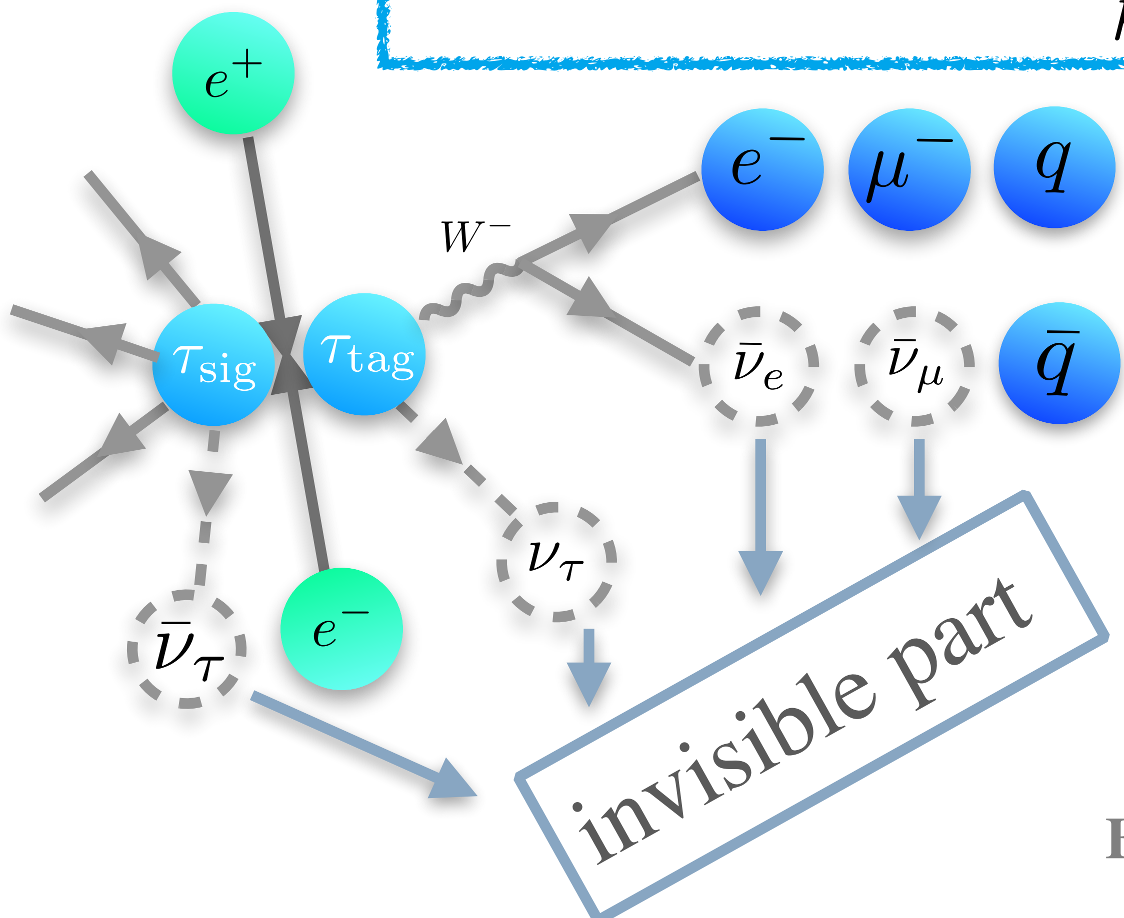
$$\text{thrust value} = \sum_h \frac{\vec{p}_h \cdot \hat{T}}{|p_h|}$$



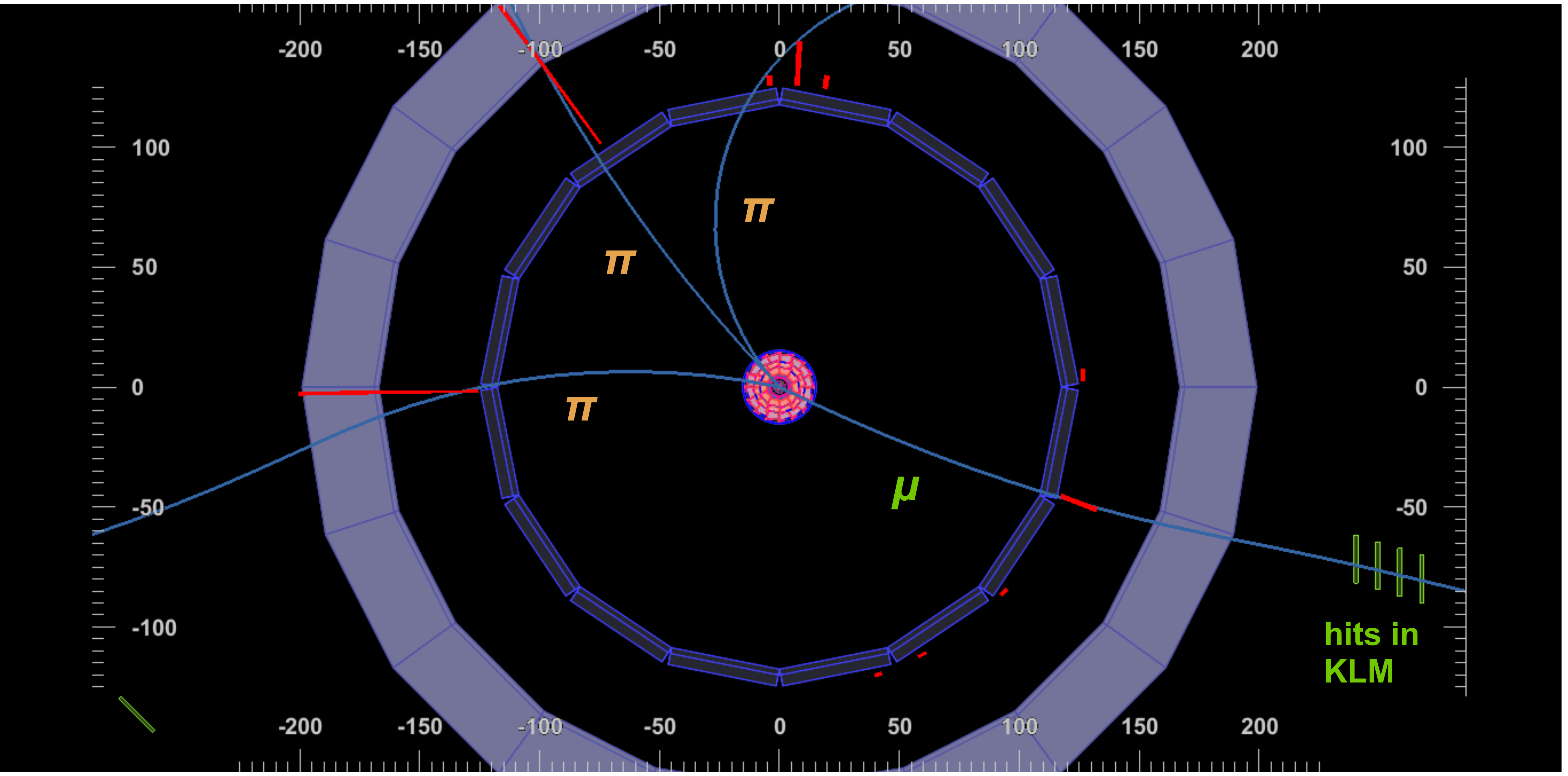
- undetected neutrinos in τ events

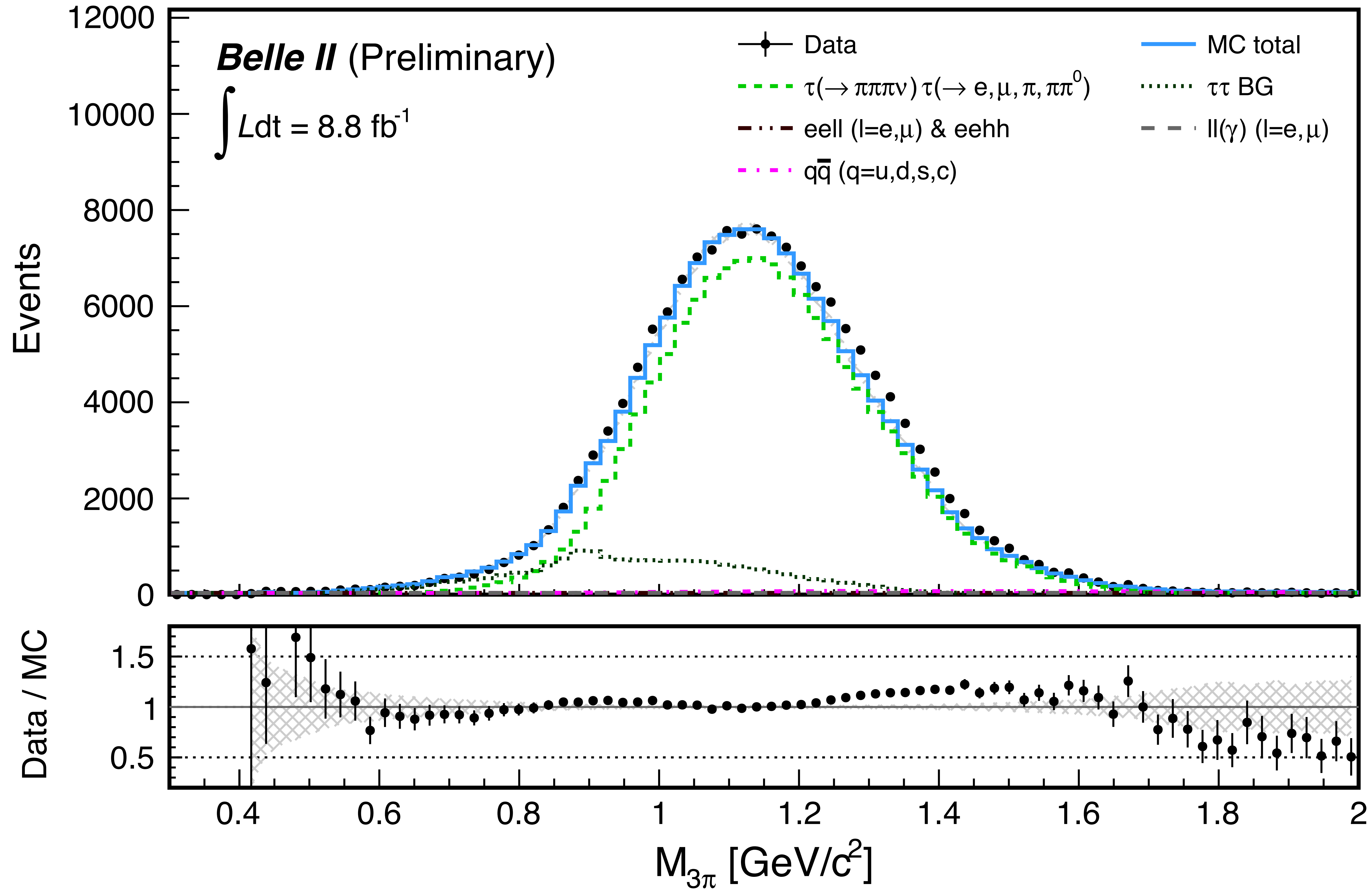


$$\text{visible energy} = \sum_h E_h$$



Clear evidence of τ-pair production in e^+e^- annihilation





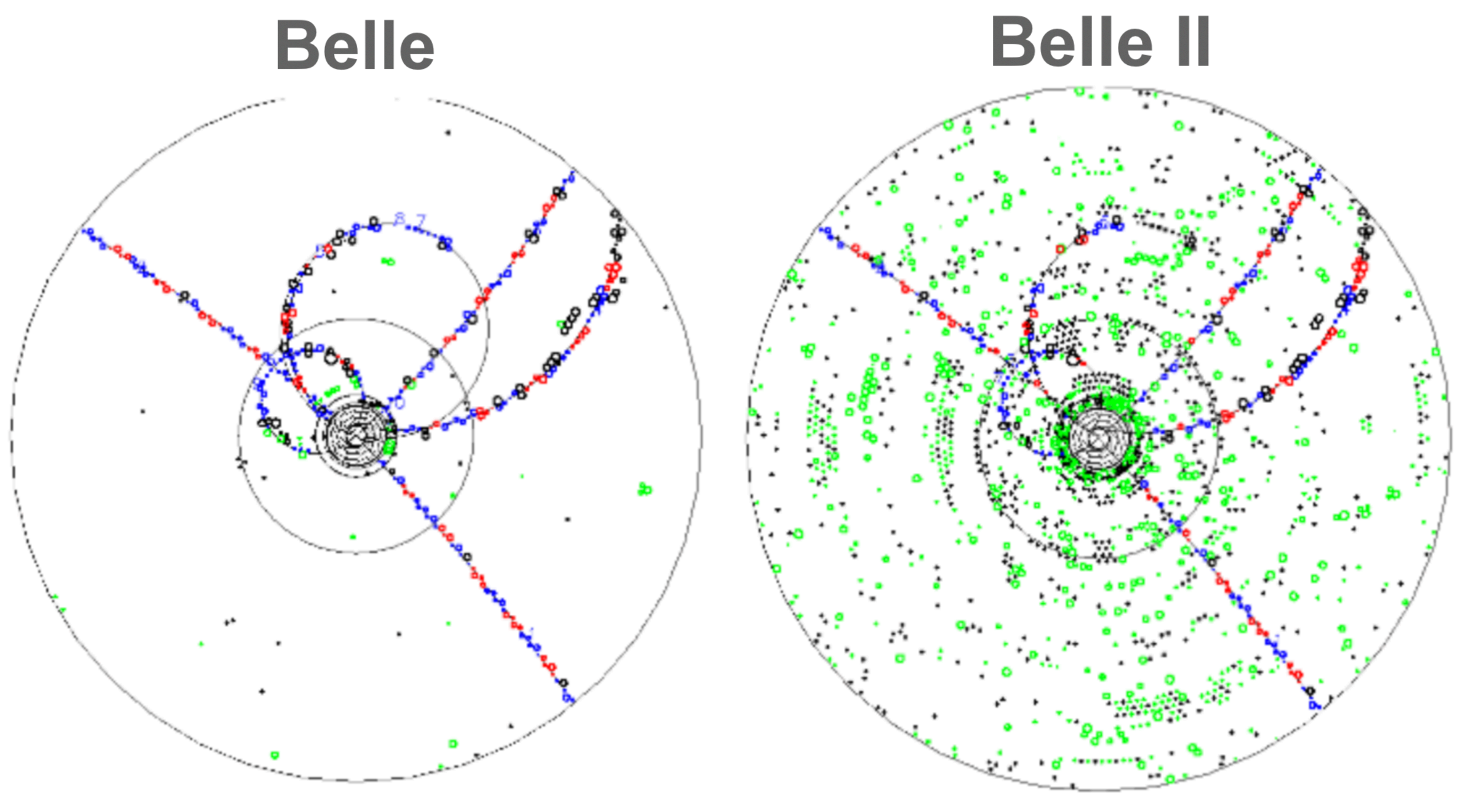
- ➡ after trigger and offline selections, good agreement between data and MC
- ➡ demonstration of the capacity for missing energy analyses with Belle II
- ➡ clean sample

Testbed for L1 CDC and ECL triggers

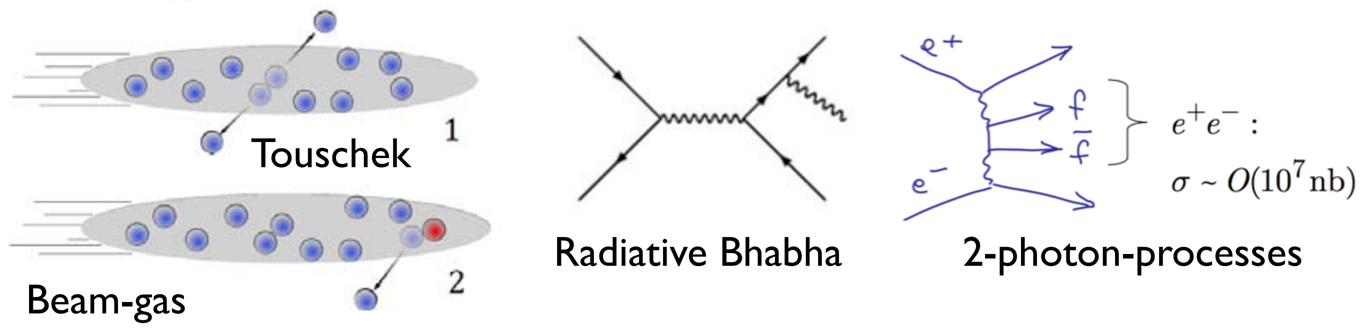
L1 trigger system plays a critical role in enabling τ and other low-multiplicity physics at Belle II.

- Total physics event rate at SuperKEKB design luminosity is **~20 kHz**
- **~3%** of which comes from ee→**ττ**

Higher luminosity comes at the cost of higher machine induced backgrounds



Sizeable beam background



Two primary components: CDC and ECL triggers

- CDC 2D (r-ϕ space) track finding
- ECL total energy and cluster finding, Bhabha veto

Trigger decision is made independently using only CDC or ECL information

- Allows measurement of L1 efficiency in data

Requirements

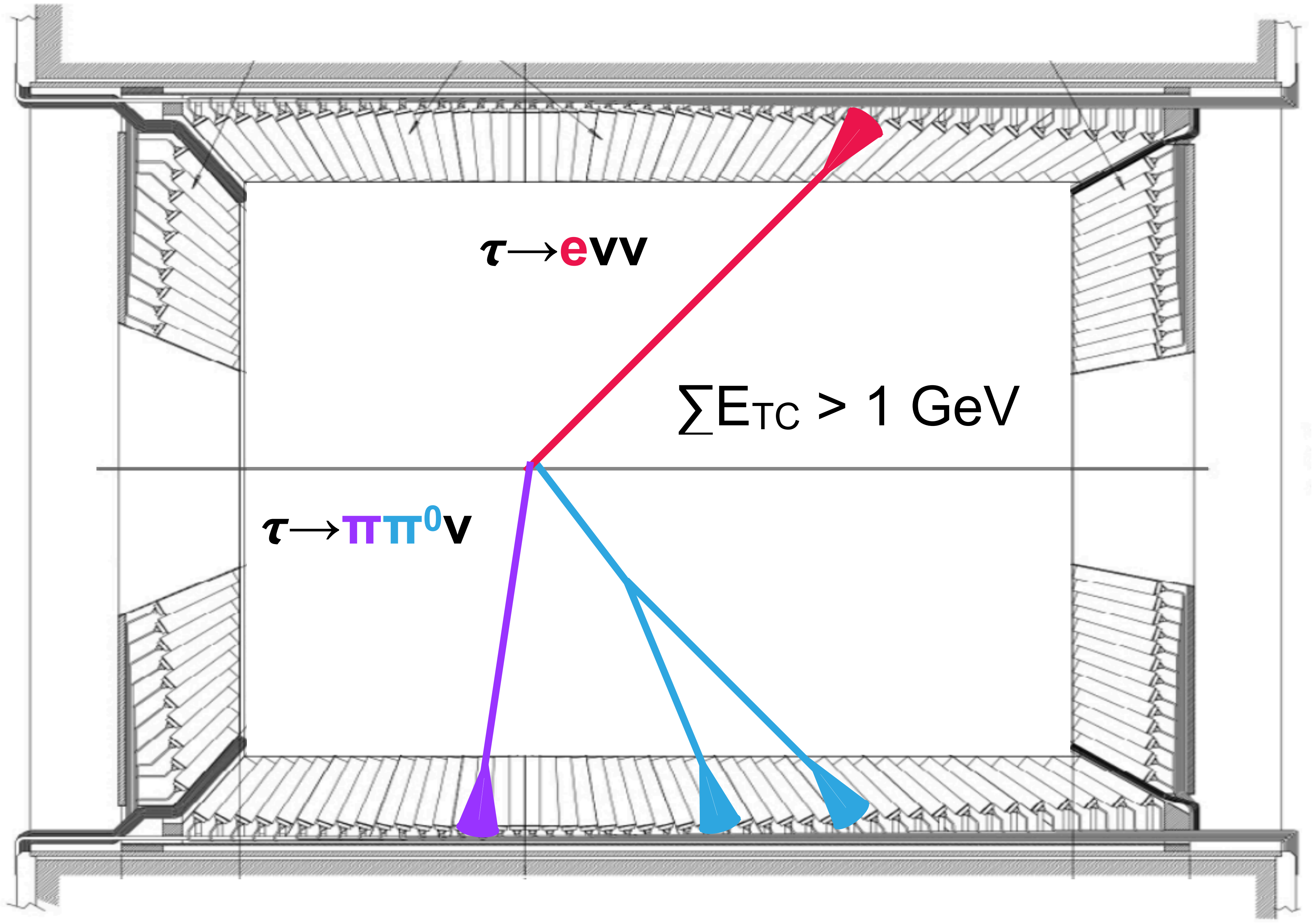
- high efficiency for physics processes
- trigger latency ~5μs, timing precision ≤ 10 ns

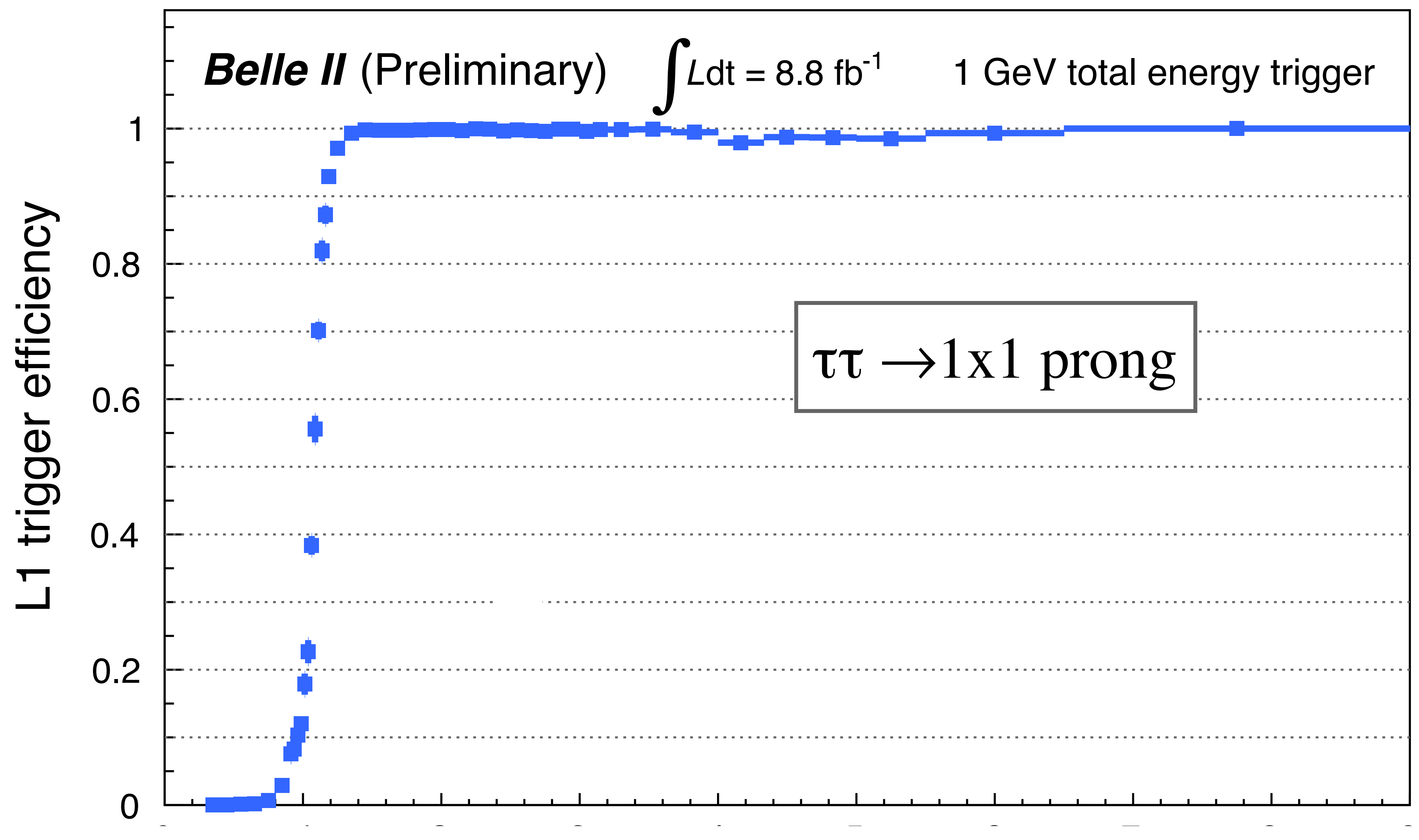
Physics process	Cross section (nb)	Rate (Hz)
$\Upsilon(4S) \to B\bar{B}$	1.2	960
$e^+e^- \to$ continuum	2.8	2200
$\mu^+\mu^-$	0.8	640
$\tau^+\tau^-$	0.8	640
Bhabha ($\theta_{\rm lab} \geq 17°$)	44	350 [a]
$\gamma\gamma$ ($\theta_{\rm lab} \geq 17°$)	2.4	19 [a]
2γ processes [b]	~ 80	~ 15000
Total	~ 130	~ 20000

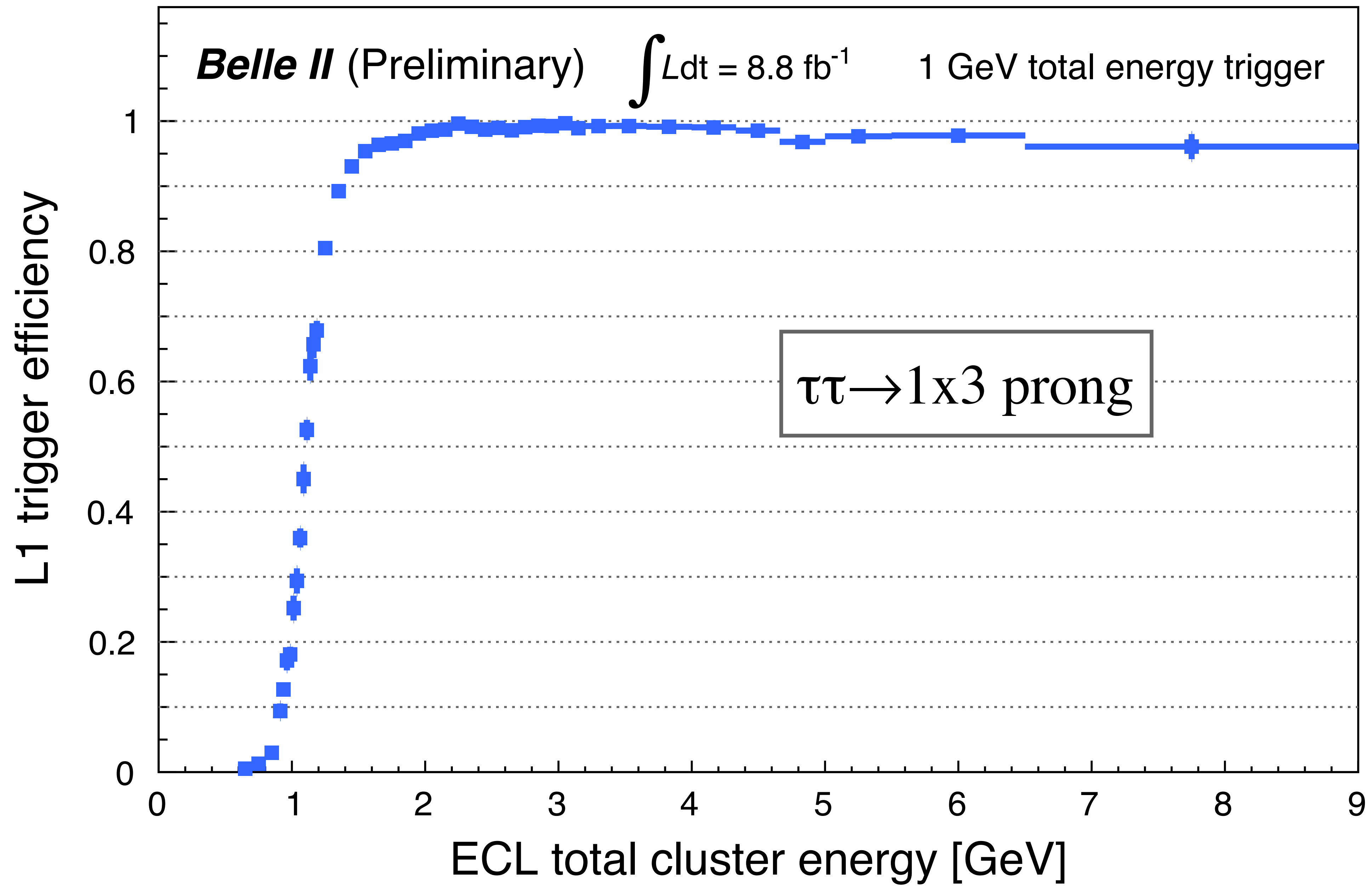
ECL triggers

Main ECL trigger types for τ physics

- Unprescaled **total energy trigger** with 1 GeV threshold
  - Perform well for ee→ττ events that have high energy deposition in ECL (e.g. $\tau \rightarrow e\nu\nu$, $3\pi\pi^0\nu$, $\pi\pi^0\nu$)
- Triggers with **number of isolated clusters**
  - Perform well for ee→ττ events with μ and π in the final state







Full and short track triggers

Main CDC trigger types for τ physics

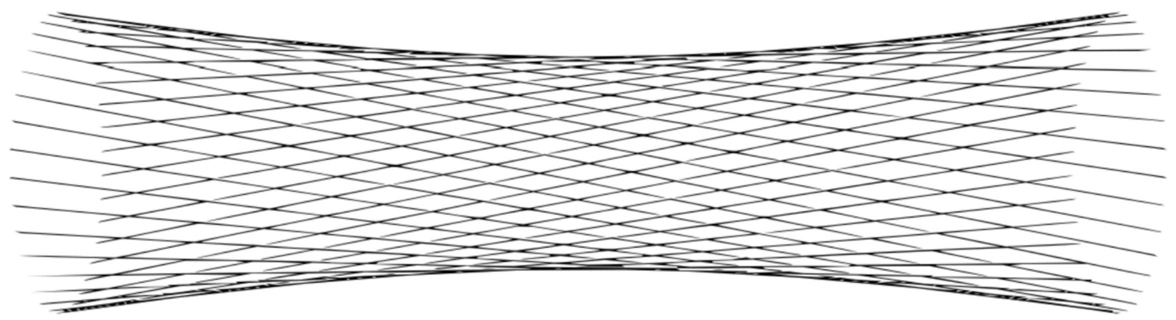
➡ 2D full and/or short tracks

"**full tracks**" pass through all axial CDC superlayers

short tracks" pass through inner most 5 axial + stereo superlayers

axial wires

stereo wires



Full track triggers have low efficiency in endcaps

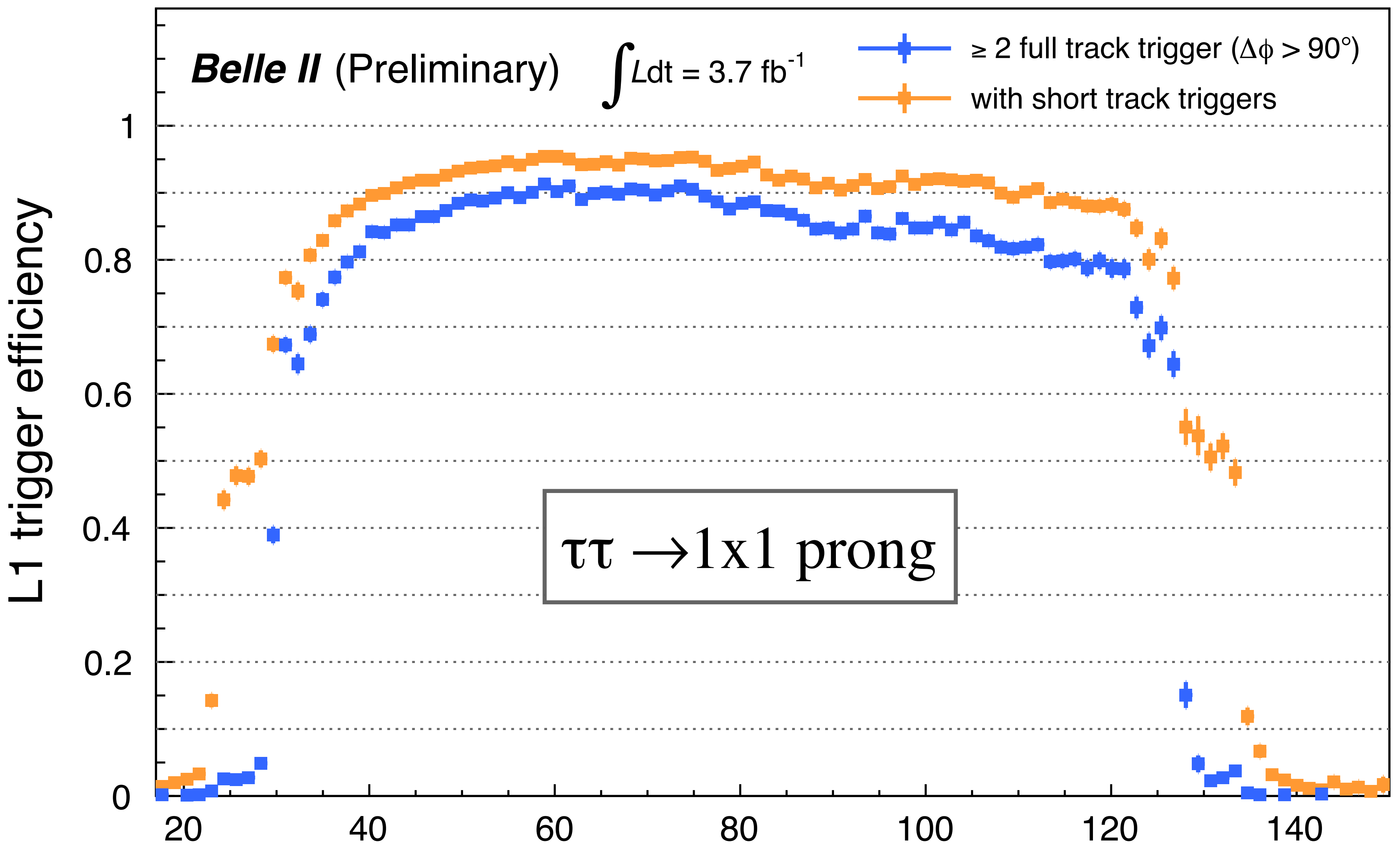
➡ limitations on tau and other low multi physics

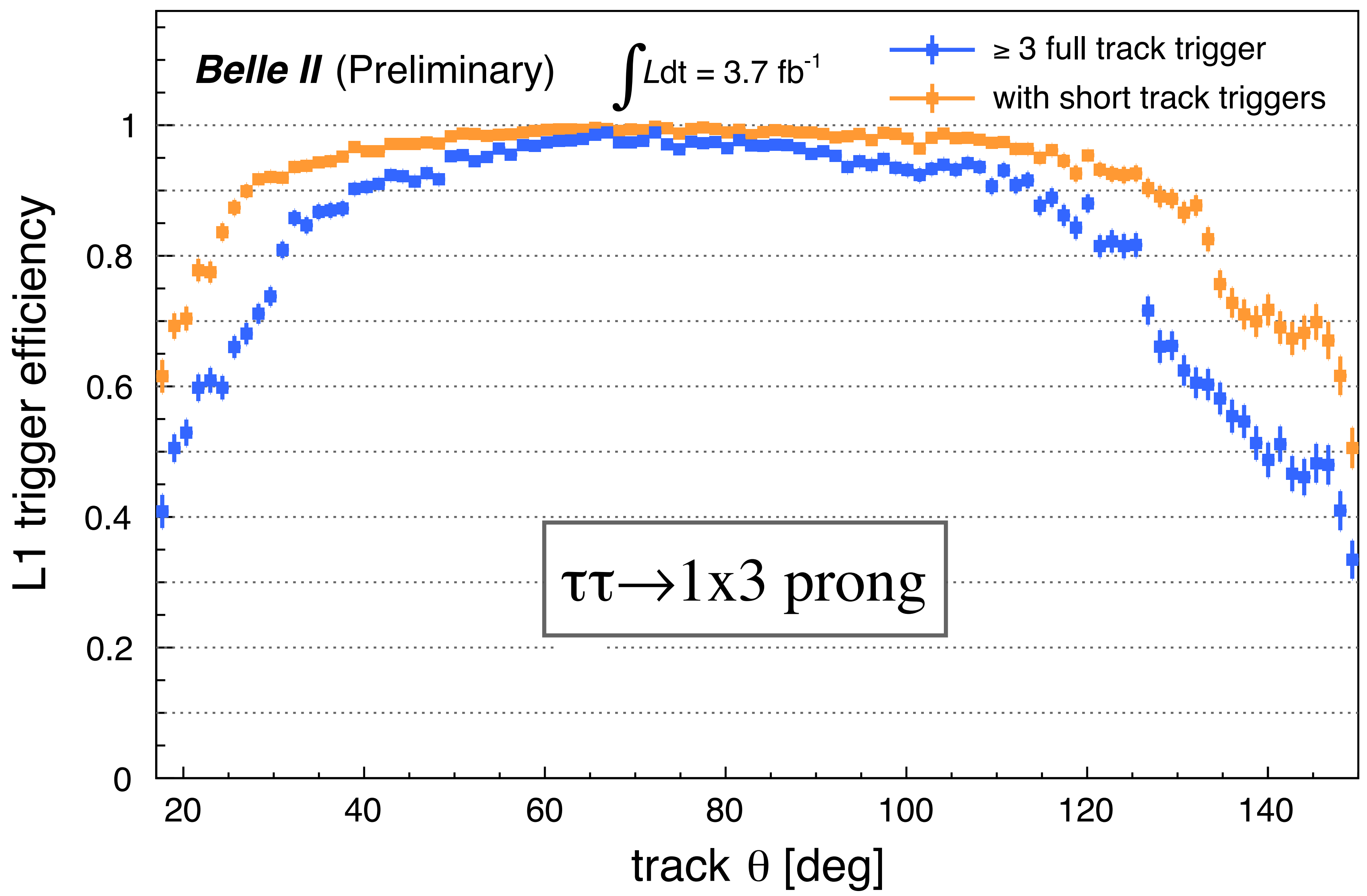
Short track triggers provide a significant gain in efficiency for endcaps / low p_T!

➡ operational since Oct 2019.

z-Vertex Neural Network trigger in preparation

see the talk of Steffen Baehr



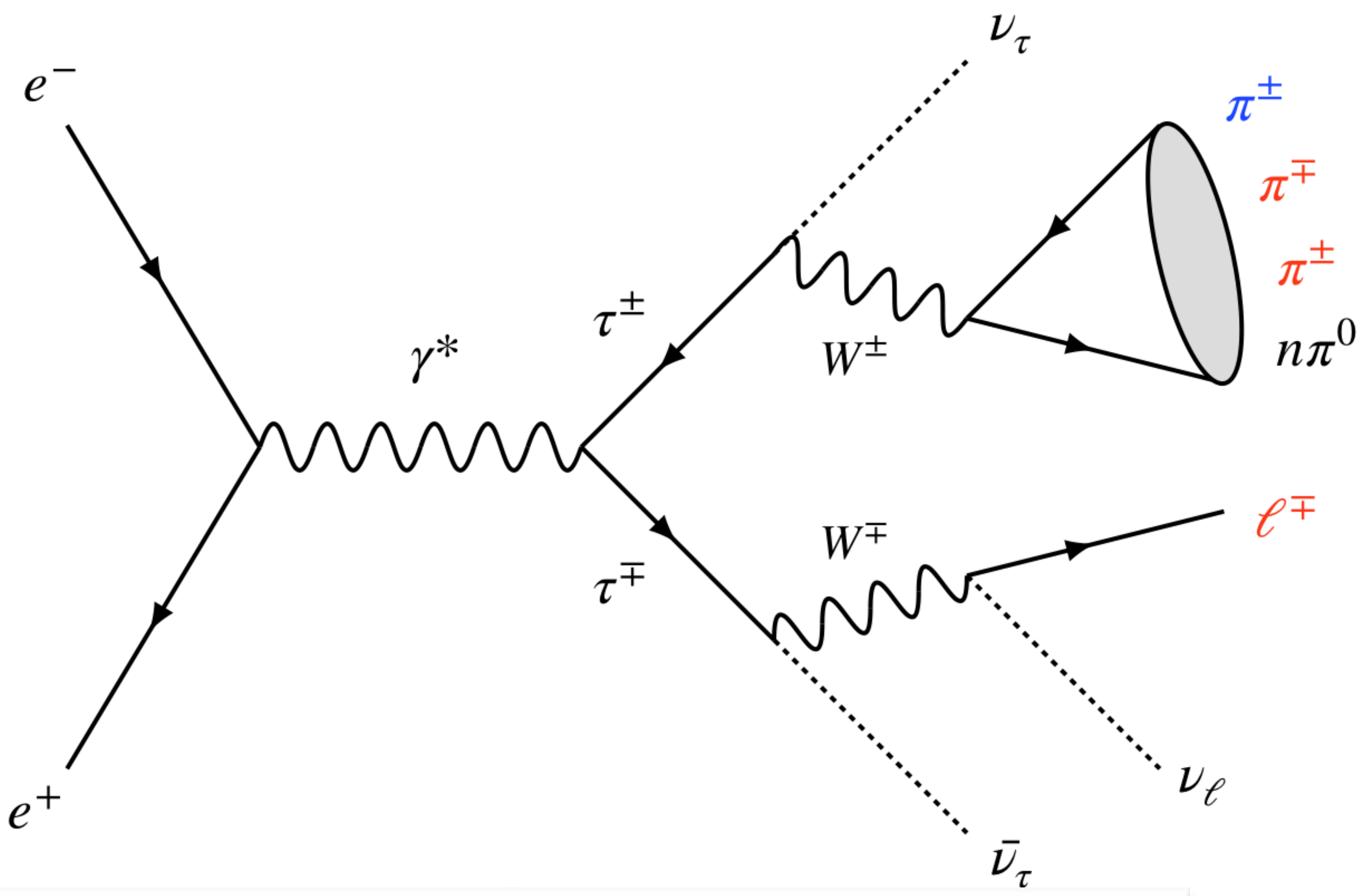


Tracking efficiency

Track reconstruction efficiency is a key performance driver for Belle II physics.

Aim to measure the tracking efficiency using τ-pair events with

- ➡ low multiplicity, but high track density
- ➡ Real detector != simulated detector
- ➡ GOAL: assess the systematic uncertainty due to track finding in physics analyses, based on the measured discrepancy in track reconstruction efficiency between simulation and data



Define according to the charge of the two tracks
- ➡ Opposite Sign (OS) sample
- ➡ Same Sign (SS) sample

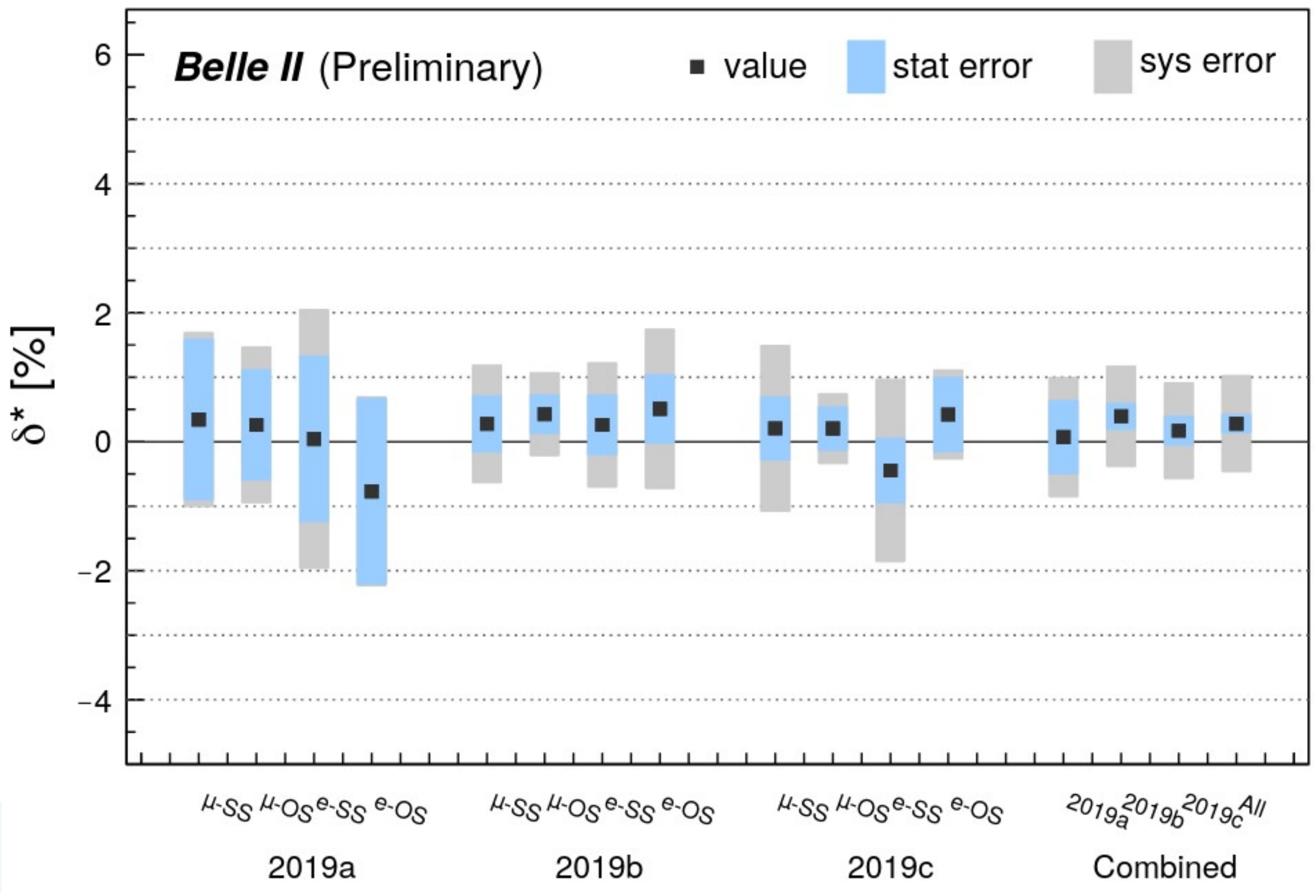
- **tag** = 3 good quality tracks with $\sum q = \pm 1$
- **probe** = look for 4th track from $\pi^\pm$ that passes minimal selections, and conserves charge ($\sum q = 0$)
  $\Rightarrow$ better coverage at low p_T w.r.t Bhabha
- Count the number of events where the probe track is found (N_4) and not found (N_3):

$$\epsilon \times A = \frac{N_4}{N_3 + N_4}$$

where A is the geometric acceptance of the detector

Tracking efficiency using the τ-pair events

Devised strategy to measure $\epsilon \times A$ on data and simulation

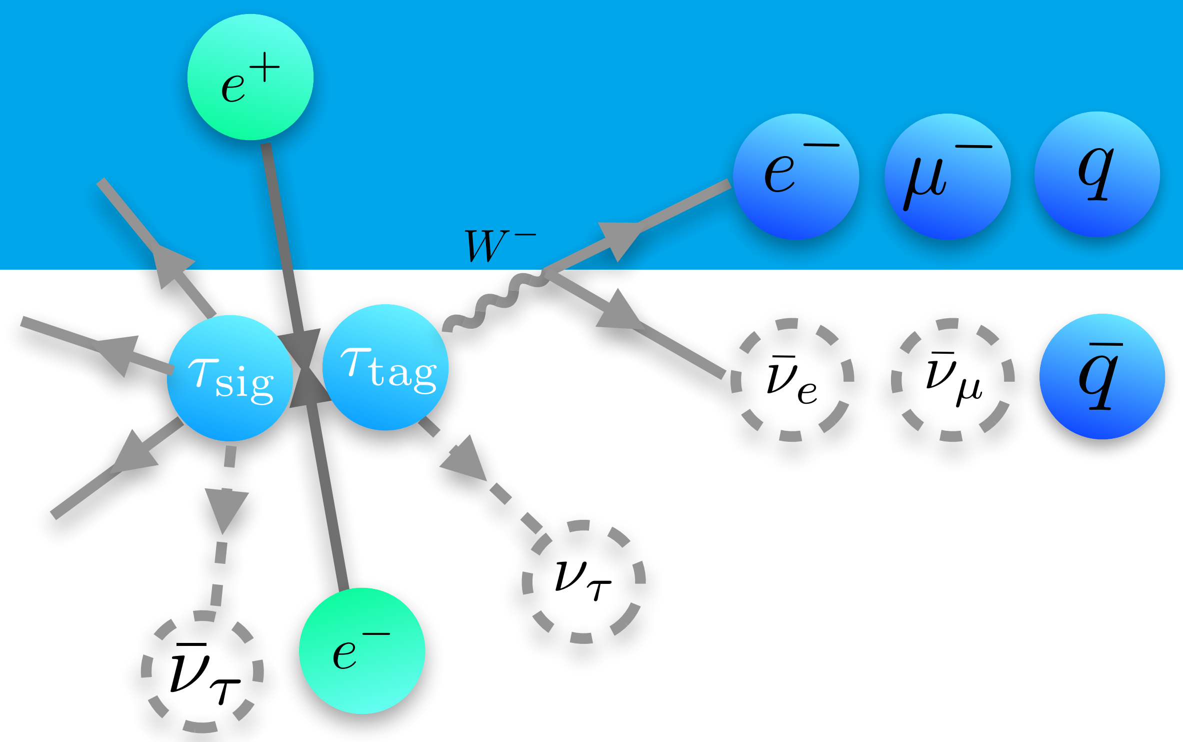


The overall discrepancy δ^* is measured to be:

$$\delta^* = 1 - \epsilon_{data}/\epsilon_{MC} = 0.28 \pm 0.15\ \text{(stat)} \pm 0.73\ \text{(sys)}\ \%$$

- Prescription on how to assign systematic uncertainties for analyses dealing with tracks of transverse momentum $0.2 < p_T < 3.5$ GeV/c, is provided
- Systematic uncertainty dominated by *charge dependence*
  - expected to be improved after a better understanding of *charge asymmetry* effects

The τ lepton mass



… cannot be measured directly

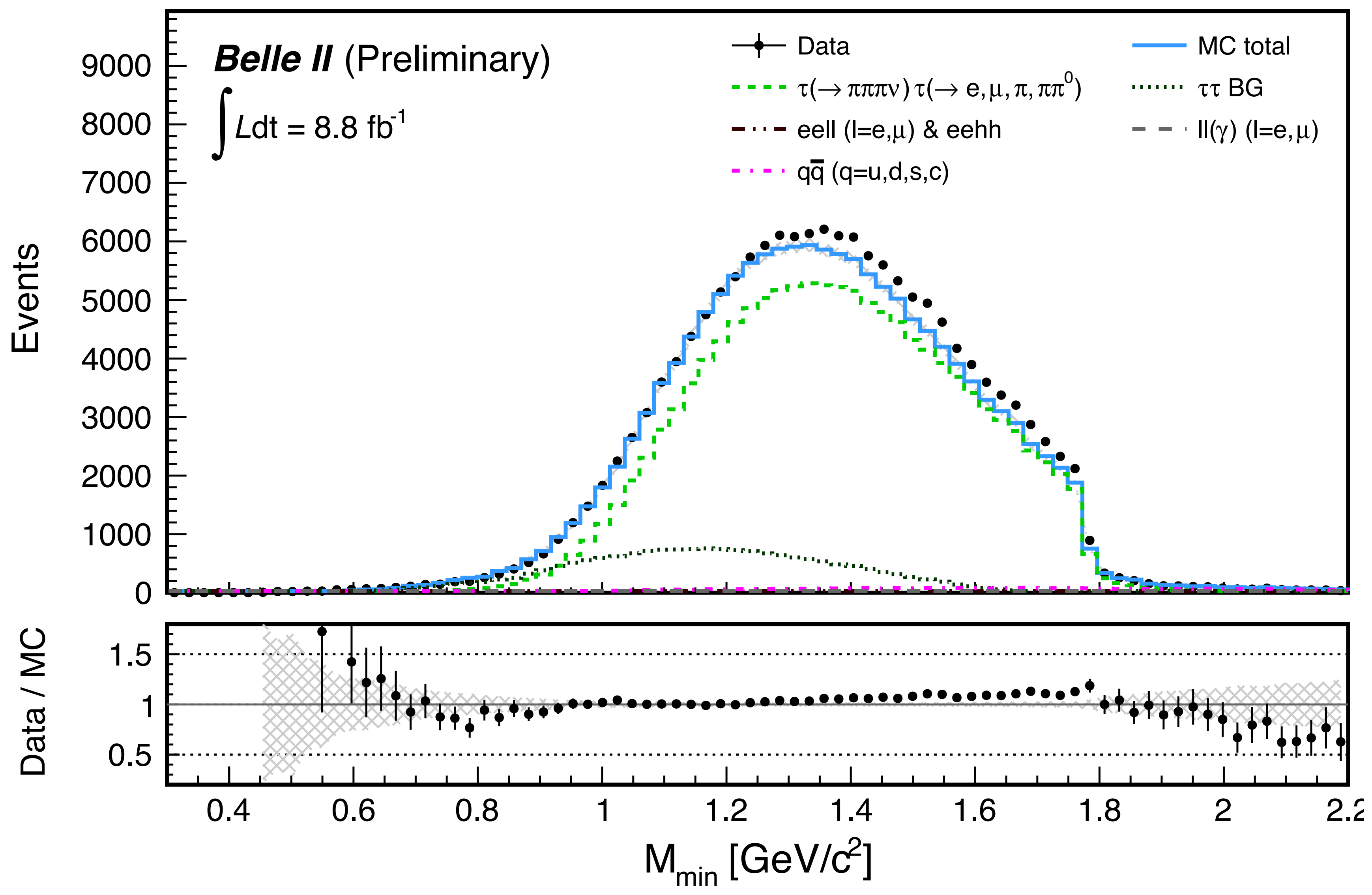
➡ the flight direction is unknown

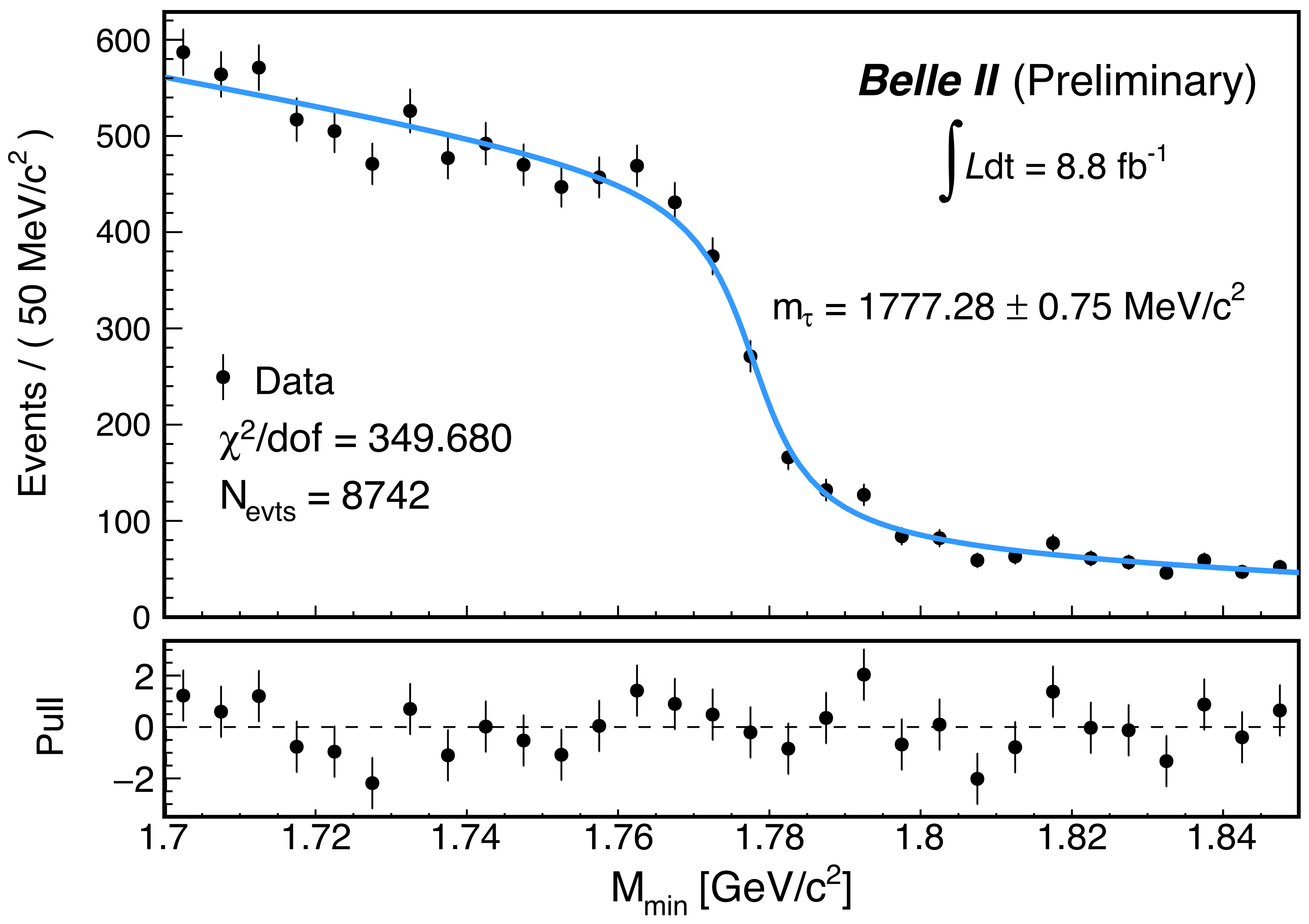
First m_τ measurement at Belle II with a pseudomass technique developed by the ARGUS:

$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \leq m_\tau,$$

➡ approximate the flight direction of the 3π system to be the τ one

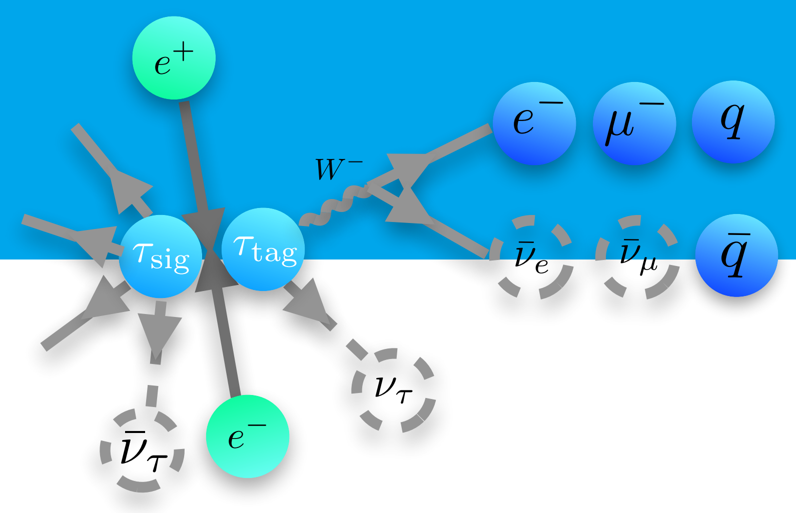
➡ a sharp threshold behaviour in the region close to the nominal value of the τ mass





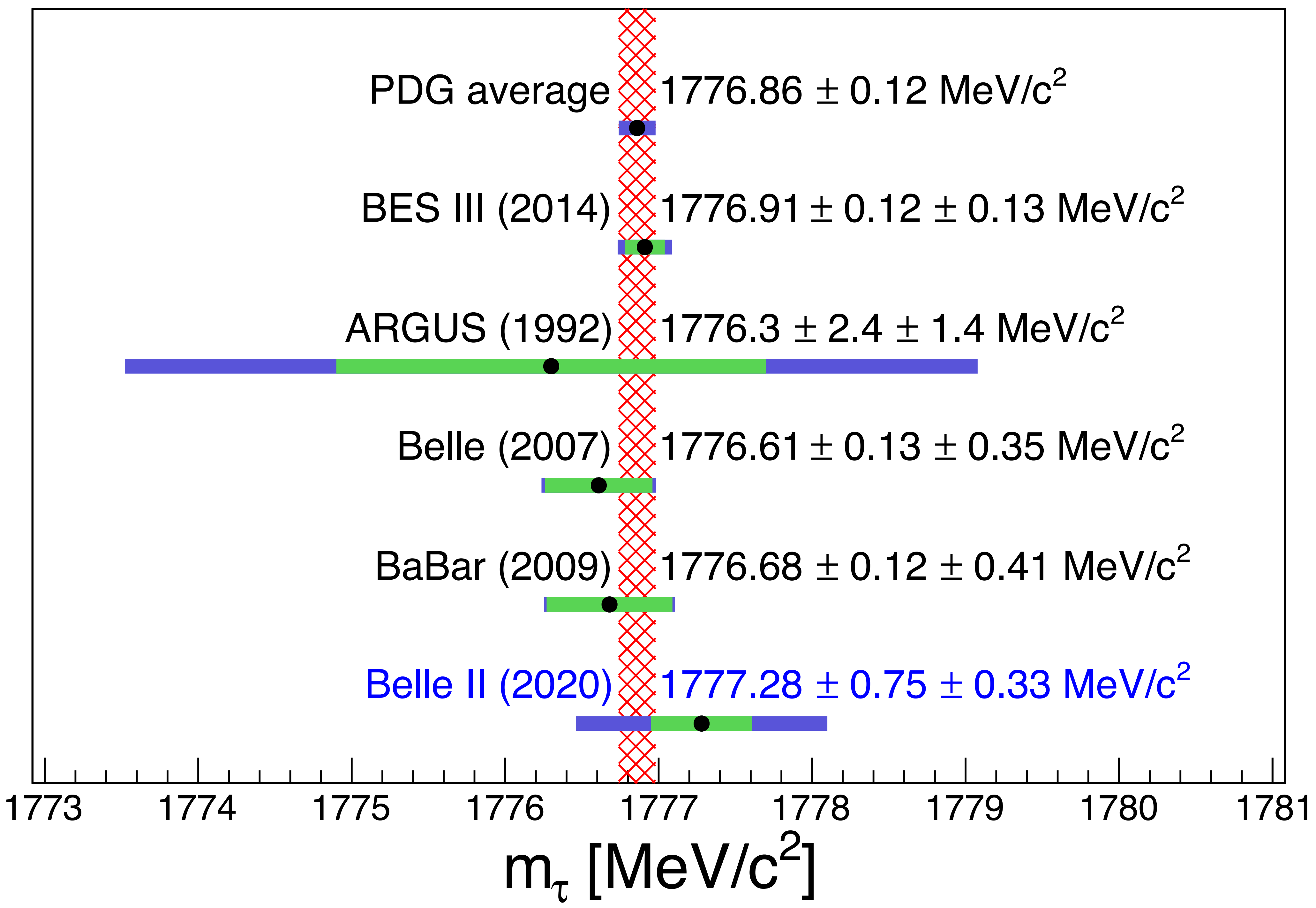
Systematic uncertainty	MeV/c^2
Momentum shift due to the B-field map	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	≤ 0.01
Initial parameters	≤ 0.01
Background processes	≤ 0.01
Tracking efficiency	≤ 0.01

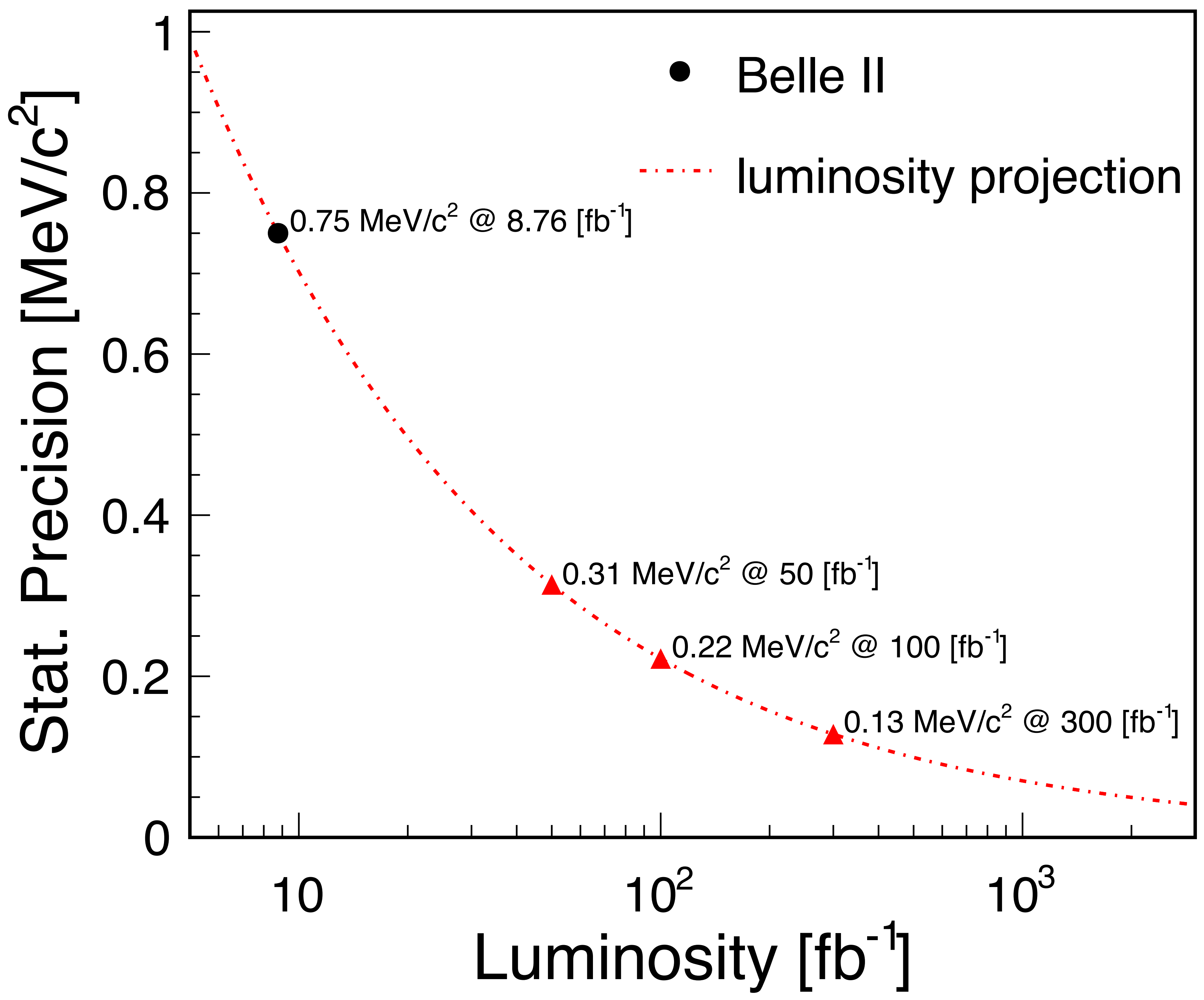
The τ leptons mass



Goal: achieve best precision among pseudomass measurements

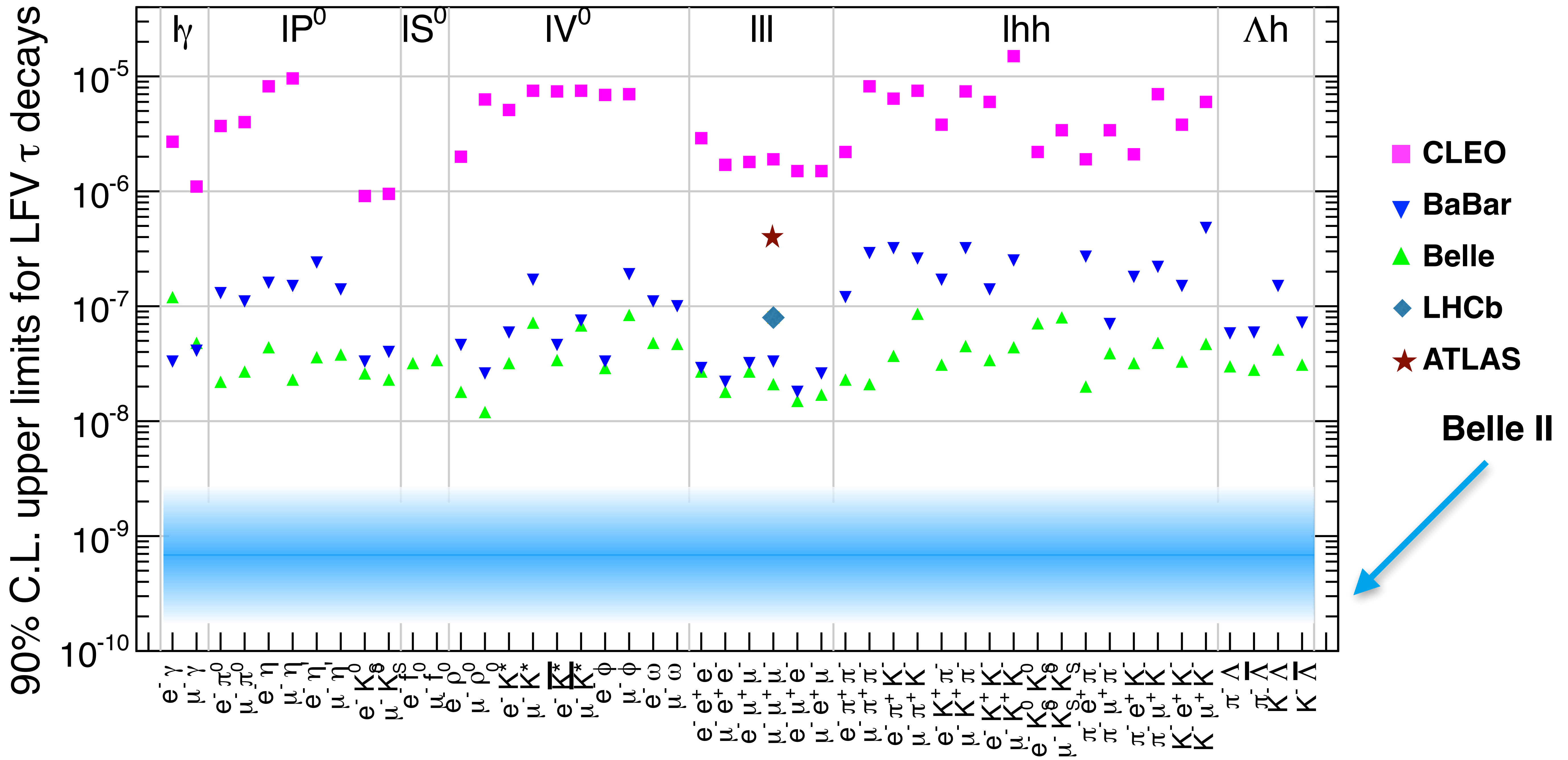
- ➡ best result from BES III from pair production at threshold energy
- ➡ best measurement from pseudomass technique by Belle
- ➡ compatible systematic precision @Belle II with previous B factory results
- ➡ future improvements of systematic uncertainty and statistical precision





Perspectives at Belle II

The upper limits reached for τ decays approached the regions sensitive to NP.



Test the SM in a variety of ways

- ➡ radiative ($\tau \to \ell\gamma$)
- ➡ leptonic decays ($\tau \to \ell\ell\ell$)
- ➡ a large variety of LFV and LNV semi-leptonic decays
- ➡ τ → μ and τ → e: test of the lepton flavour structure

DESY & MPP are involved/have interest in all type of searches!

- ➡ One of the factors pushing up the sensitivity of probes is the increase of the luminosity
- ➡ Equally important is the increase of the signal detection efficiency
  - ➡ high trigger efficiencies; improvements in the vertex reconstruction, charged track and neutral-meson reconstructions, particle identification, refinements in the analysis techniques…

The searches at Belle II will push the current bounds further by more than one order of magnitude

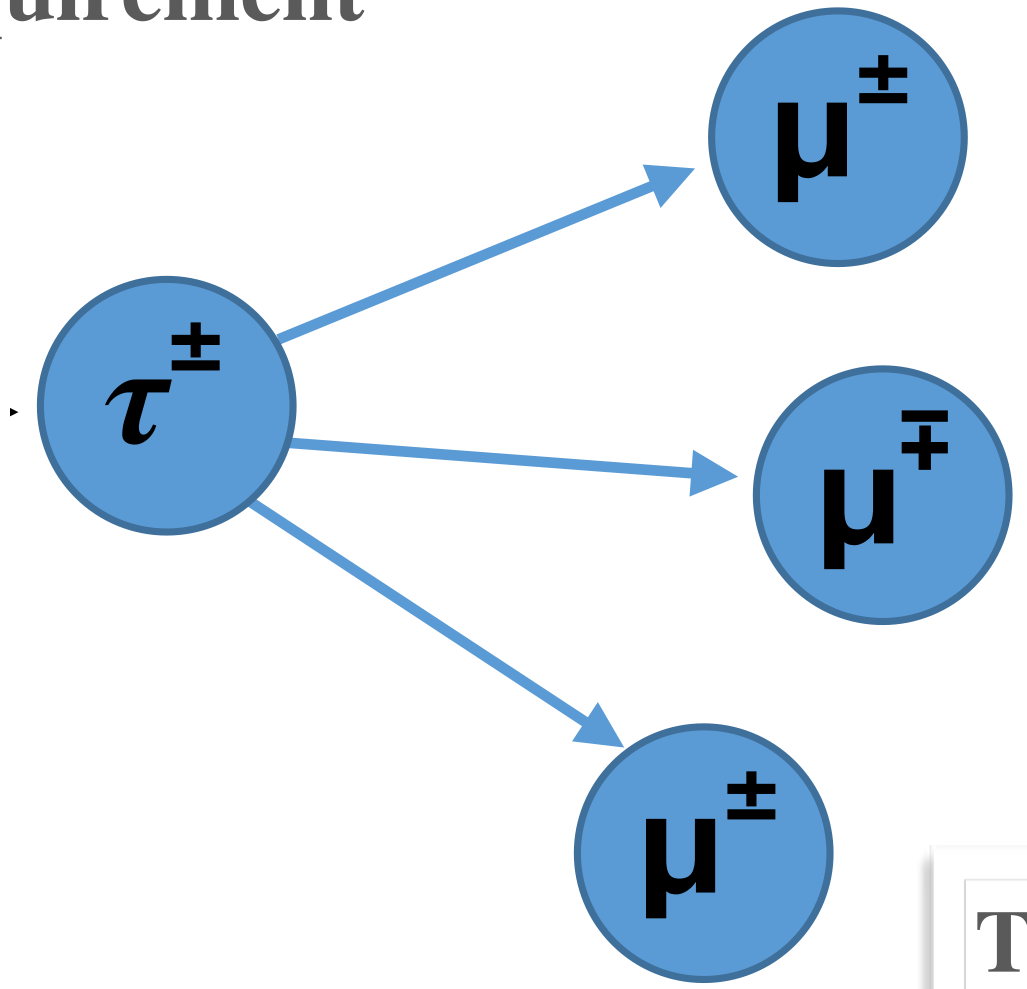
$\tau \to \mu\mu\mu$

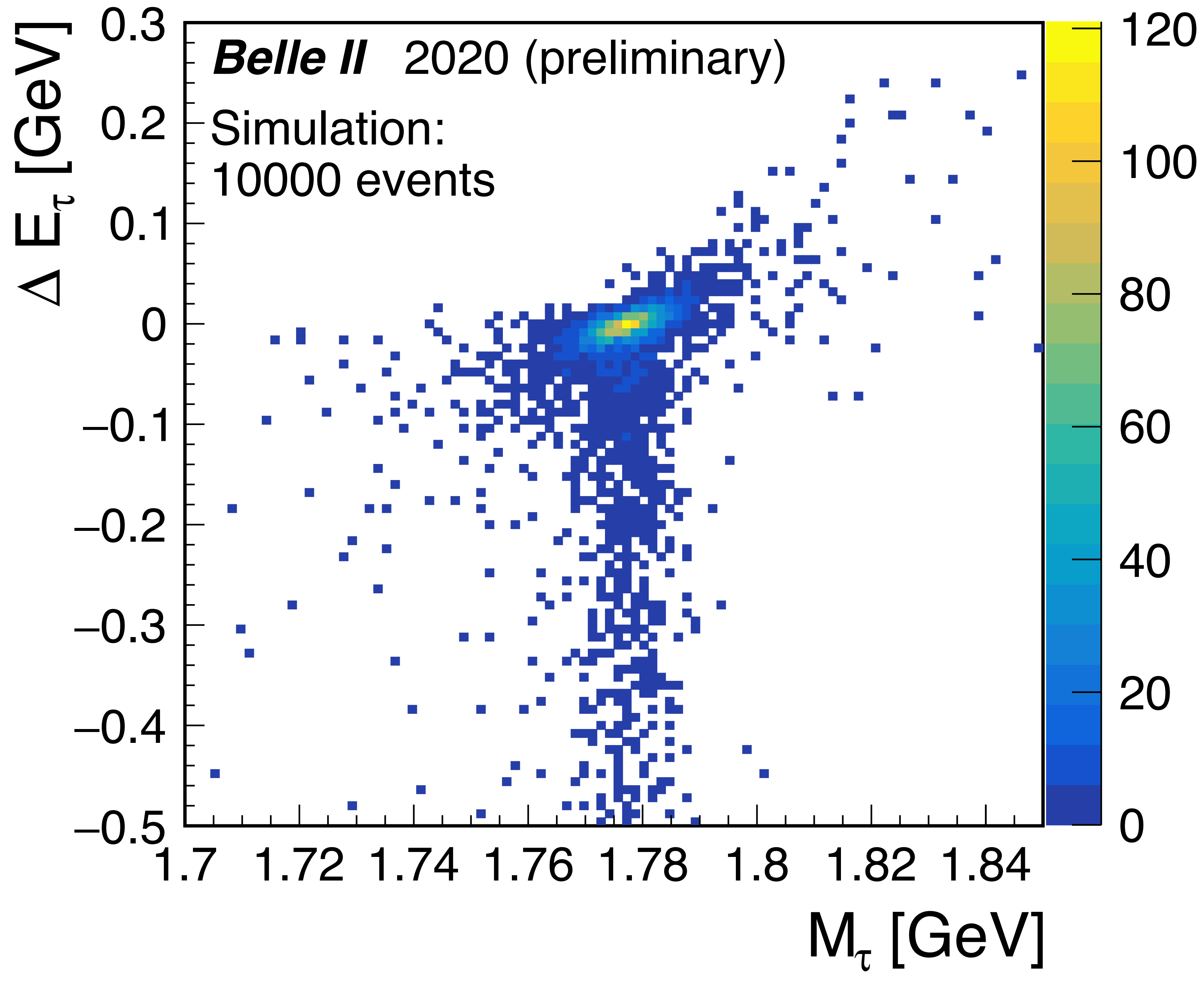
Signal-background discrimination using kinematics of the event

μID - the most powerful discriminating variable

Momentum dependent optimisation of the muID requirement

- $P_\mu < 0.7$ GeV
  - μ do not reach the μ detector (KLM)
- $0.7 < P_\mu < 1$ GeV
  - μ reach KLM but not many layers are crossed
- $P_\mu > 1$ GeV
  - μ reach KLM and many layers are crossed





Other requirement used @Belle and not @Belle II:

- μ veto on tag track
- $P_\mu > 0.6$ GeV

Two independent variables:

$$M_\tau = \sqrt{E^2_{\mu\mu\mu} - P^2_{\mu\mu\mu}}$$

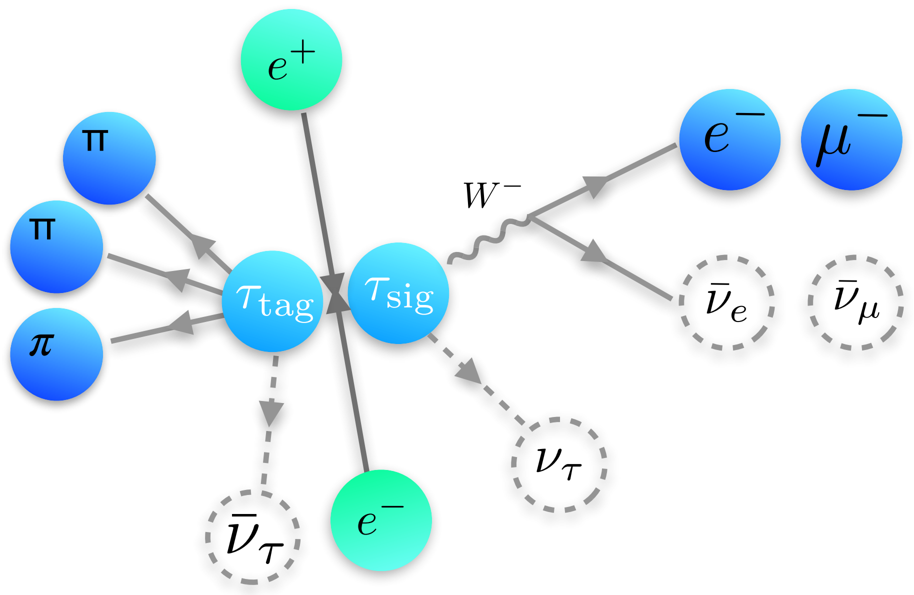
$$\Delta E = E^{CMS}_{\mu\mu\mu} - E^{CMS}_{\text{beam}}$$

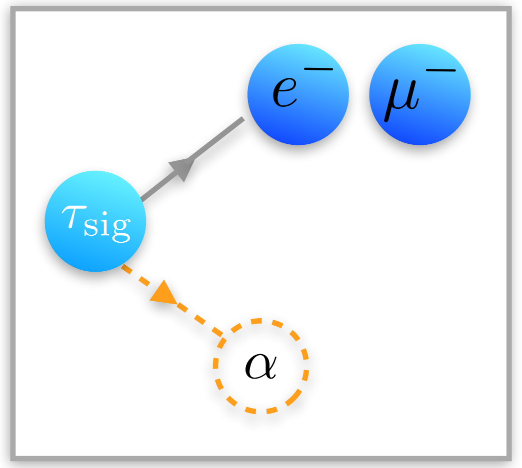
- For signal → ΔE close to 0 and $M_{\mu\gamma}$ close to τ mass

Higher efficiency is foreseen @Belle II than @Belle or @BaBar

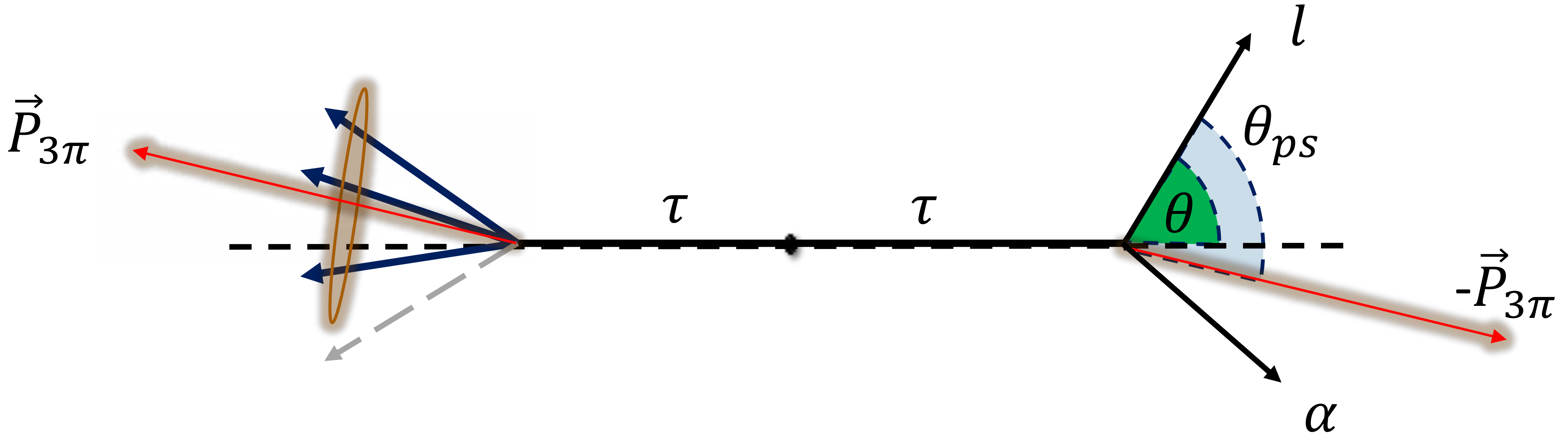
Search for LFV $\tau \rightarrow \ell\alpha$ ($\alpha \rightarrow$ invisible)

Probe the existence of a new boson α





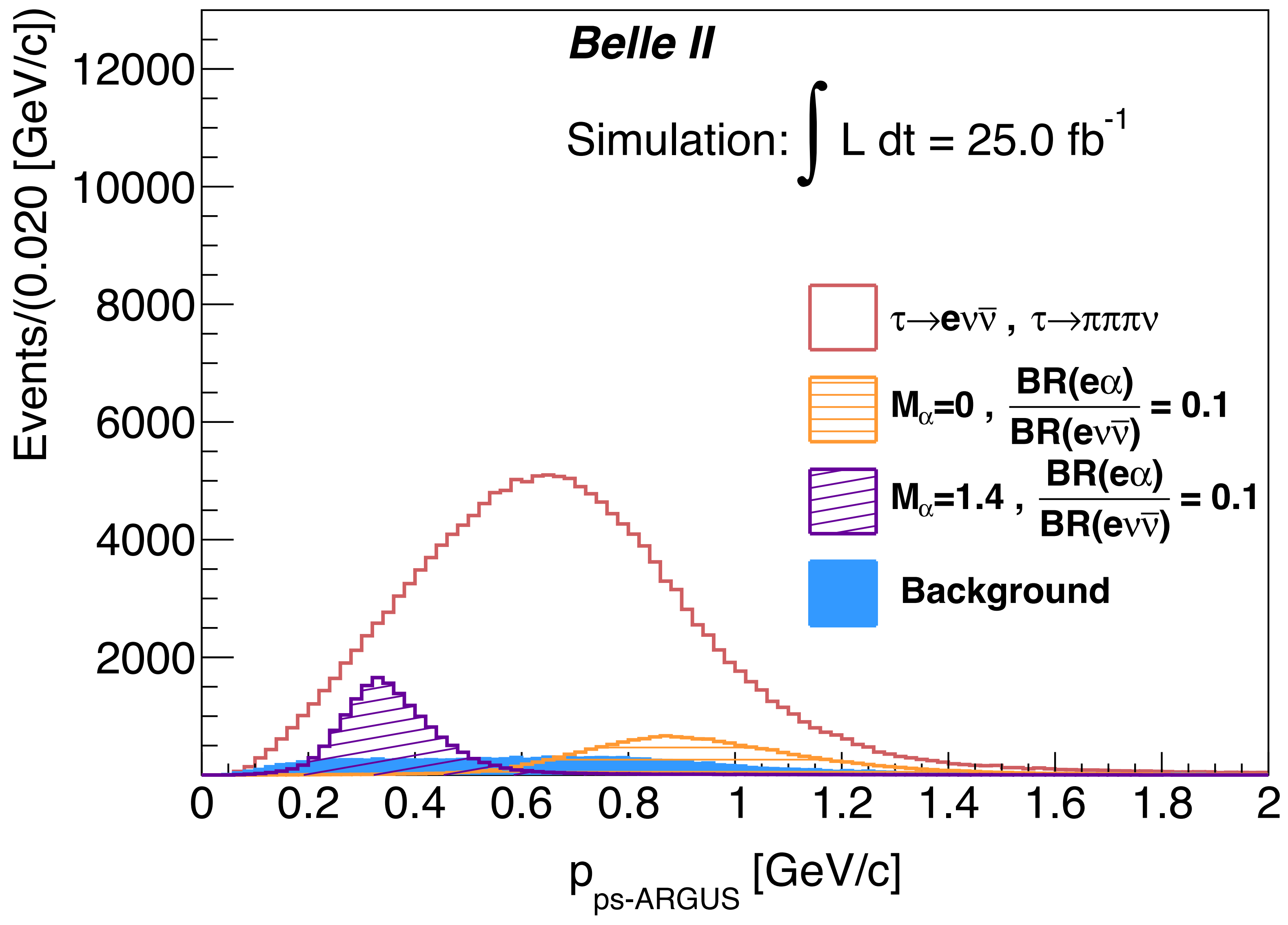
- ➡ previous studied at Mark III (9.4 pb^{-1}) and ARGUS (476 pb^{-1})
- ➡ search for a two body decay spectrum
- ➡ signal will manifest itself as a peak in the τ rest frame

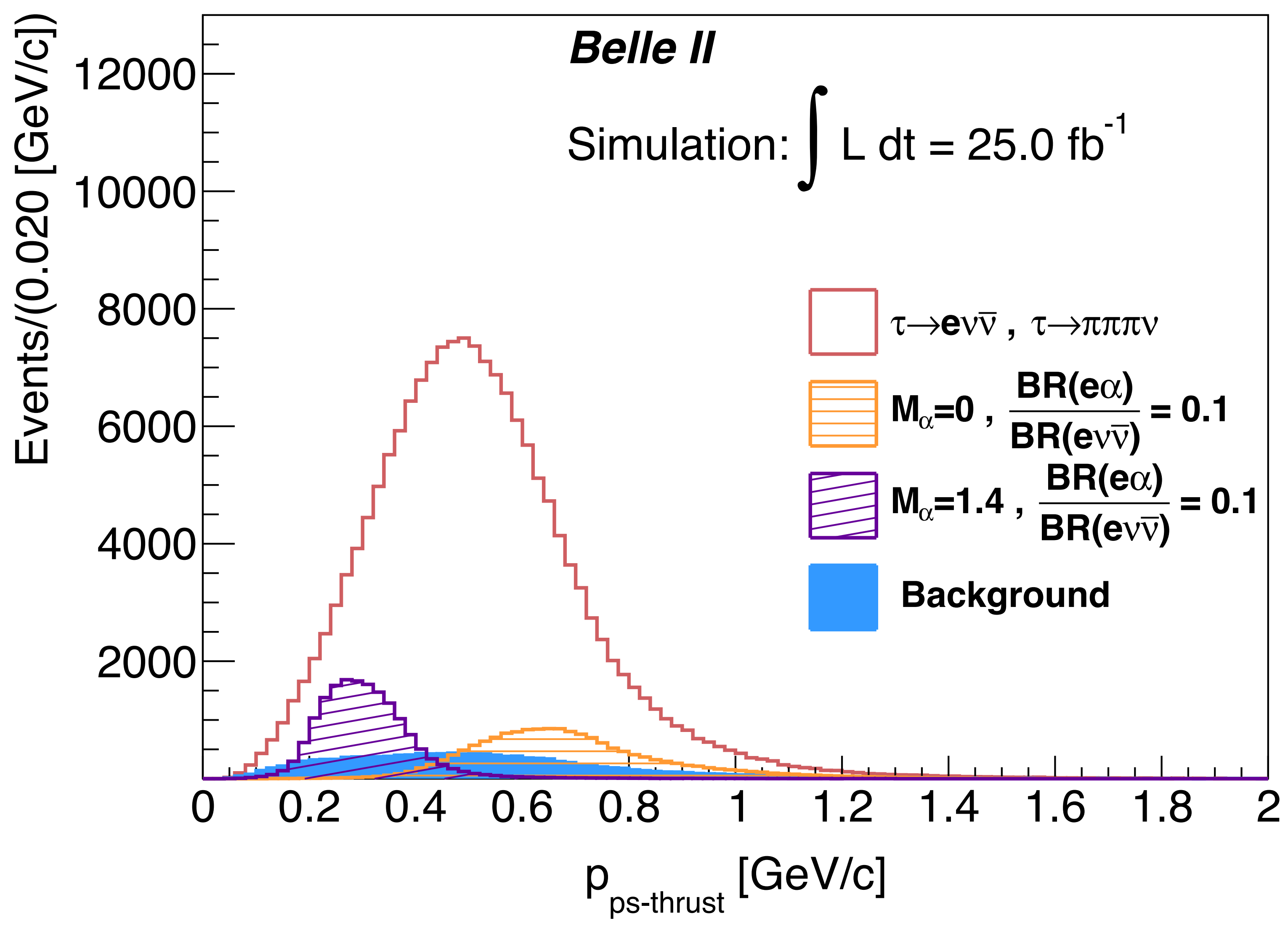


- ➡ cannot access the τ rest frame directly due to the missing neutrino
- ➡ approximate with the following assumptions:

$$E_\tau = \sqrt{s}/2$$

ARGUS method: $\hat{p}_\tau \approx -\hat{p}_{3\pi}$ Thrust method: $\hat{p}_\tau \approx \hat{T}$





Search for LFV $\tau \to \ell\alpha$ ($\alpha \to$ invisible)

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

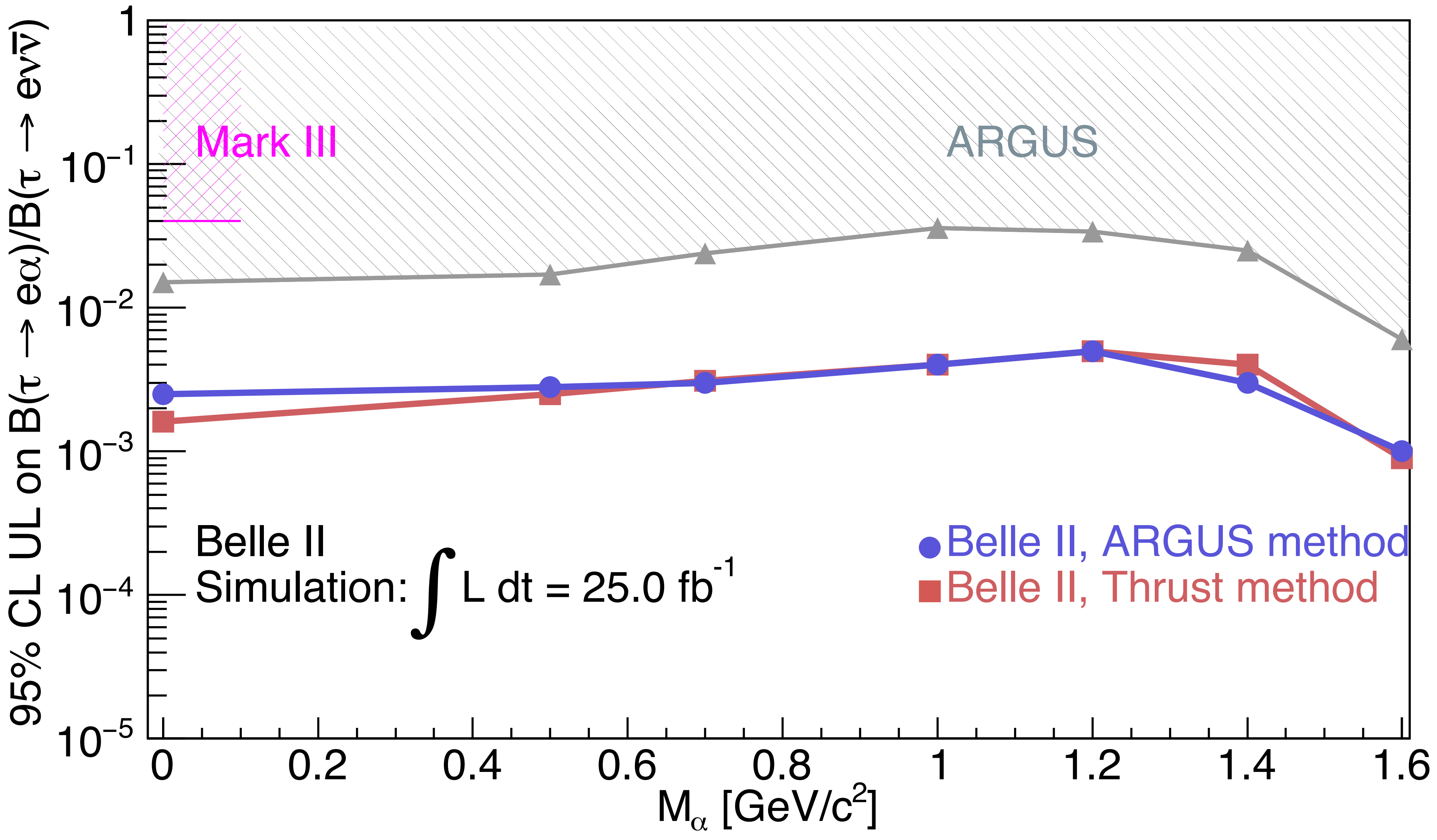
see the talk of Thomas Kraetzschmar

Status of the analysis:

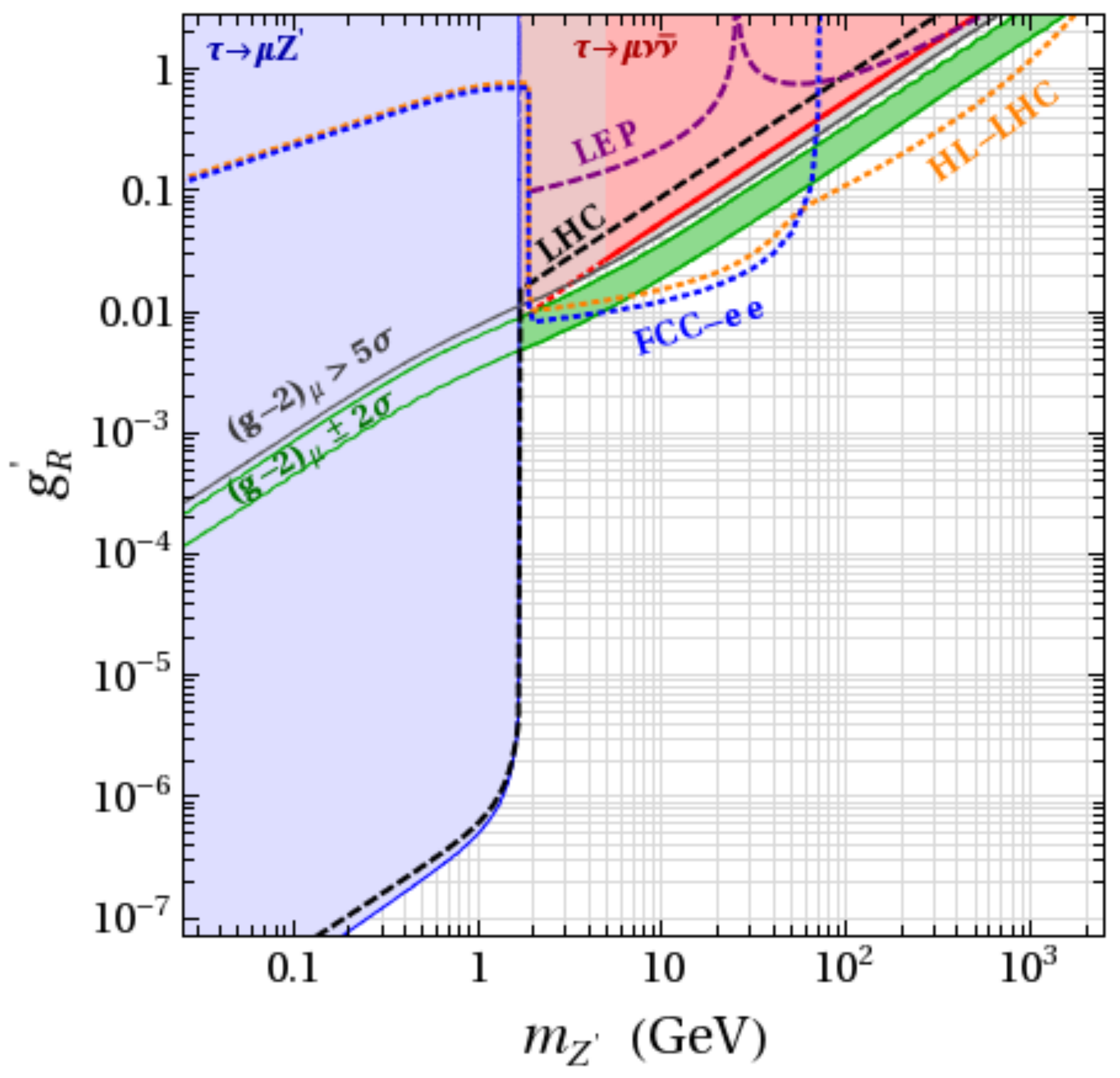
- background suppression already quite effective
- ongoing work to further suppress BG using BDT
- UL estimation using the frequentist profile-likehood method using asymptotic approach
- alternative test using the Bayesian approach

Various NP scenarios:

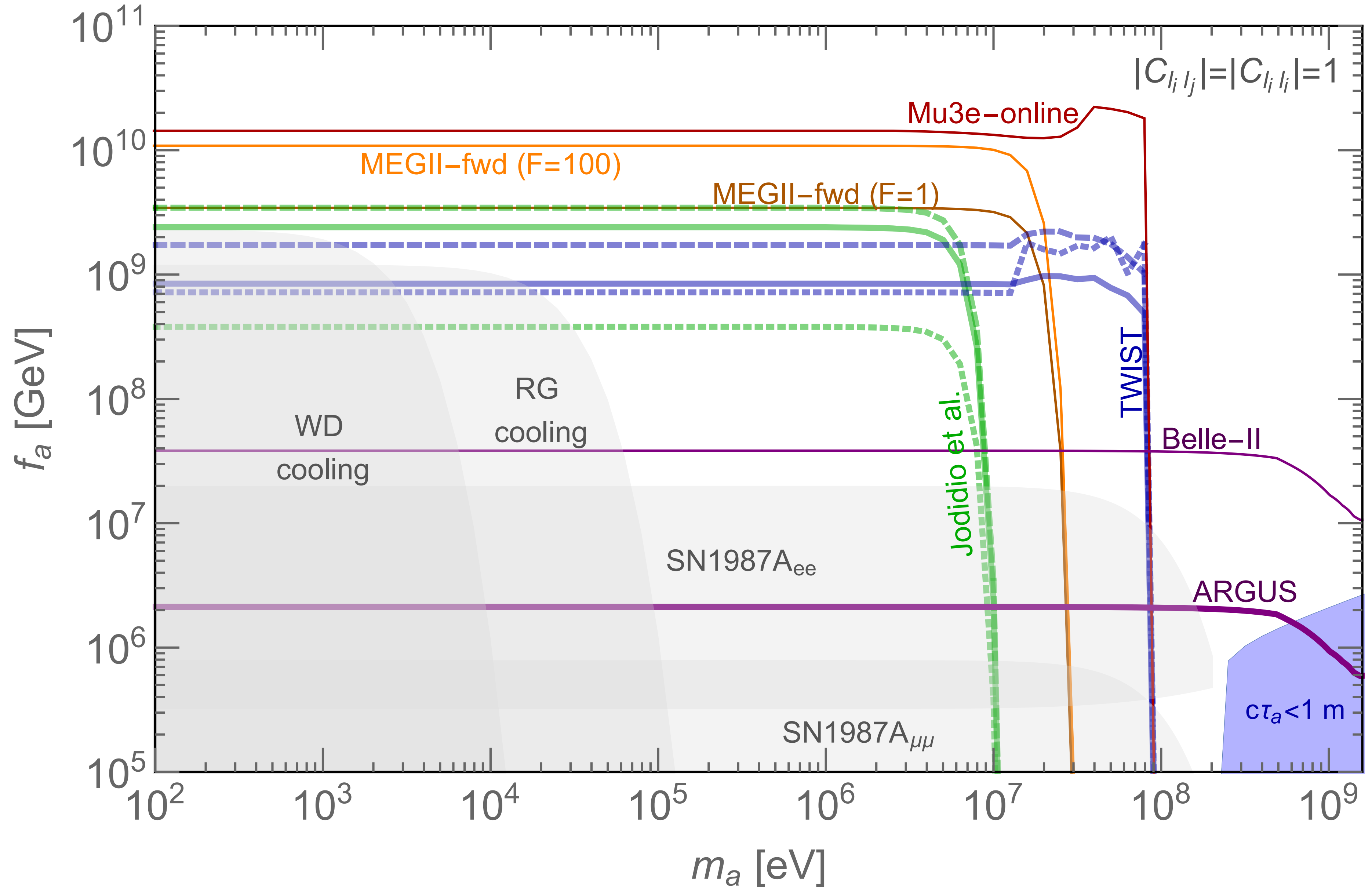
- **LFV Z′**
  - strong bound from ARGUS measurement
- **light ALP *a***
  - exploring regions in parameter space not reachable by other experiments



- W. Altmannshofer, C.Y. Chen, B. Dev, A, Soni -

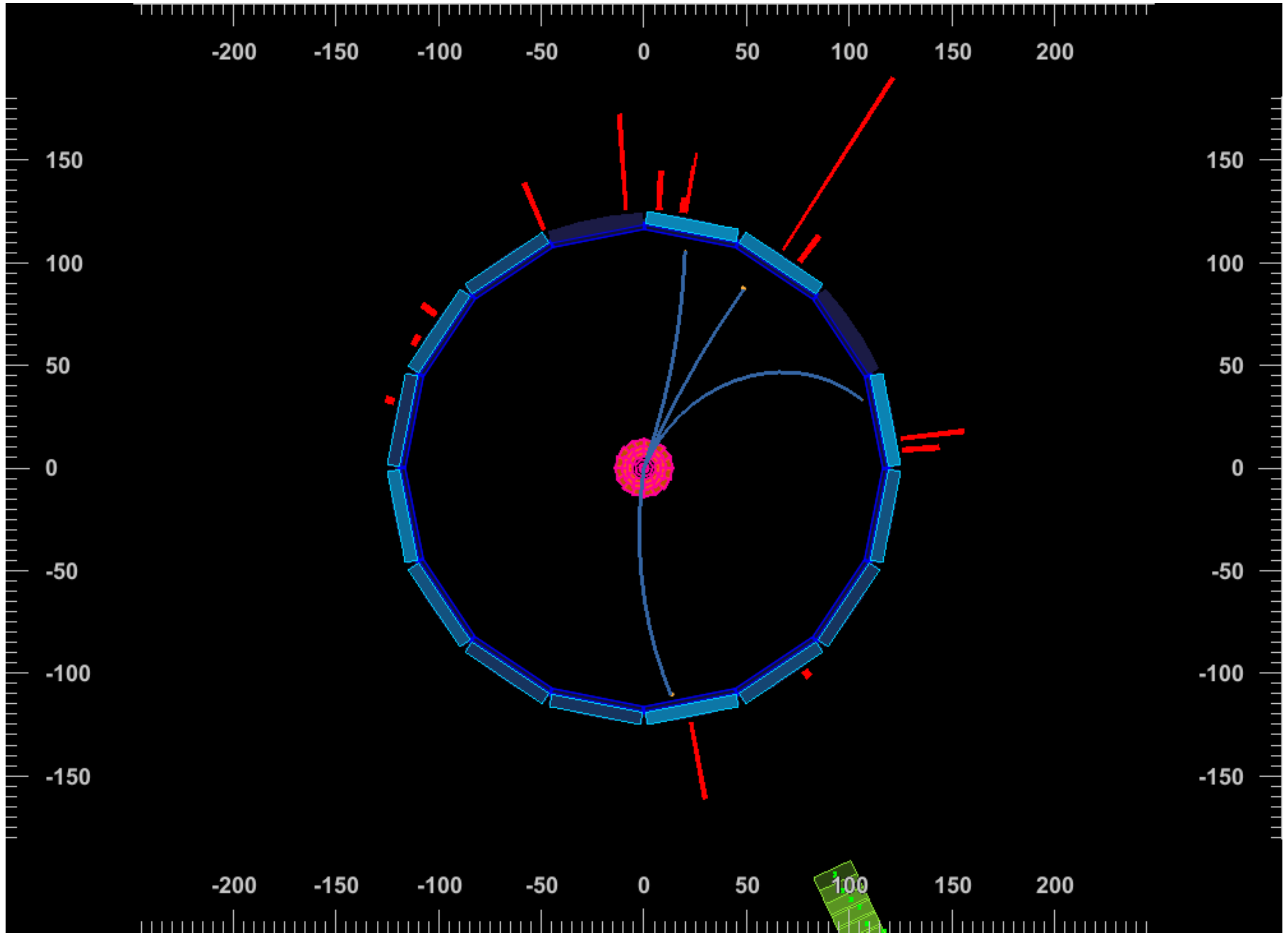


- L. Calibbi, D. Redigolo, R.. Ziegler, J. Zupan -



Outlook

e^+e^- annihilation data is ideal for precision measurements and NP searches!



- Belle II experiment started
  - Achieved world record luminosity $L = 2.4 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Accelerator tuning is ongoing; more data will be recorded soon
- Active physics analyses @German groups
  - τ mass measurement with the early data is very promising and shows the potential of Belle II precision measurements
  - $\tau \to \mu\mu\mu$ indicates the potential of LFV searches
  - Potential LFV $\tau \to \ell\alpha$ publication with early data
- Belle II will provide the world largest number ($5\mathrm{x}10^{10}$) of $e^+e^- \to \tau^+\tau^-$events
  - τ precision measurements and LFV searches will be the goal in the upcoming years and will reach higher sensitivity w.r.t. the previous experiments