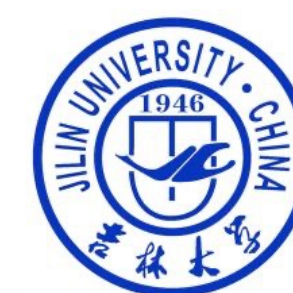


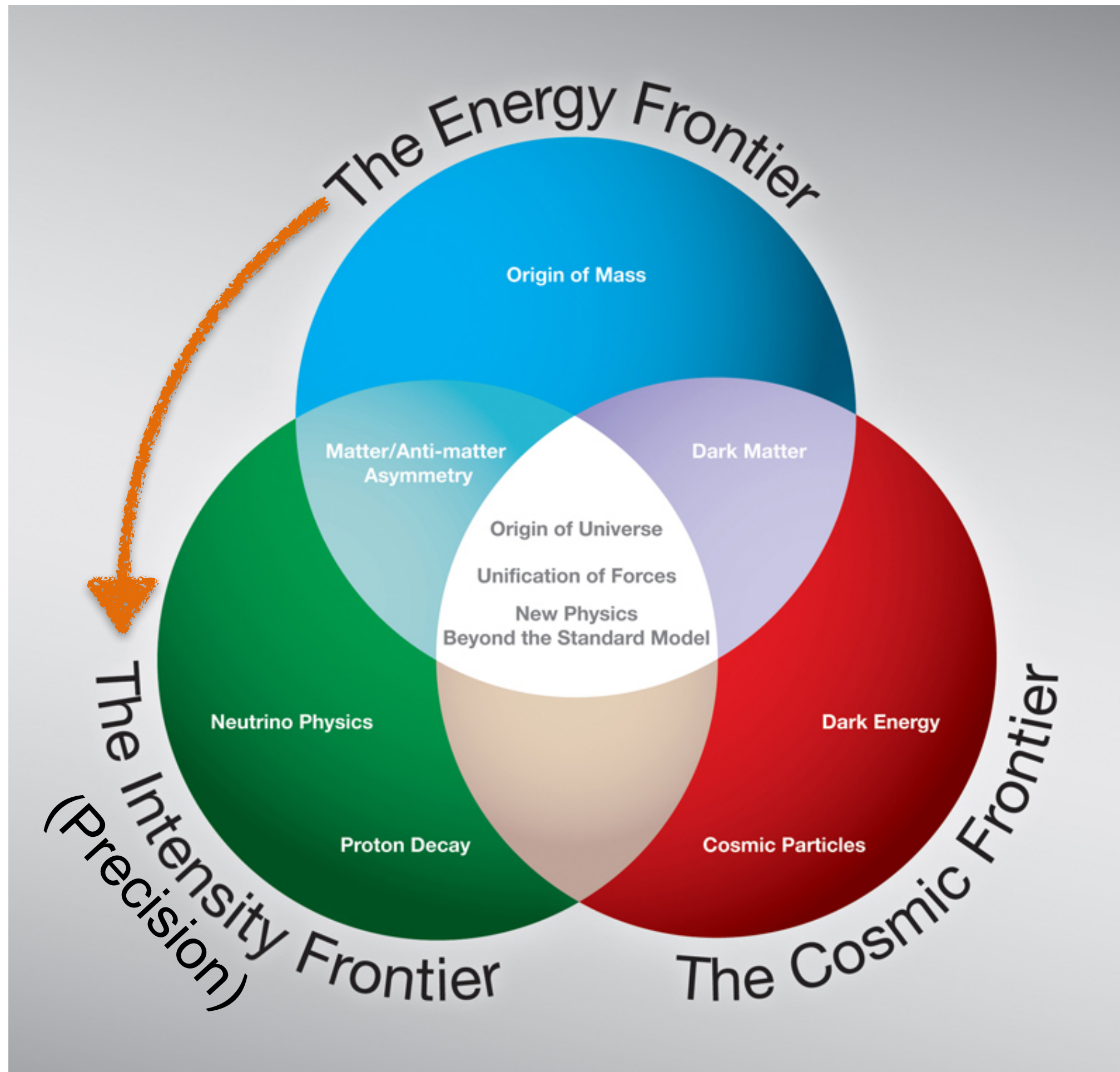
# Precision measurements as a probe of new physics: From Higgs Bosons to $\tau$ -leptons



Fabian Becherer  
Color meets Flavor Symposium, 15.07.2026



# Precision is becoming the discovery tool



The LHC has not yet revealed new heavy particles

Instead,

- Higgs precision
- Flavor precision
- Rare decays
- Complementary searches

For me

- Energy → Precision Frontier
- ATLAS, Higgs → Belle II,  $\tau$



# The Higgs Boson: A window to new physics

## Why the Higgs?

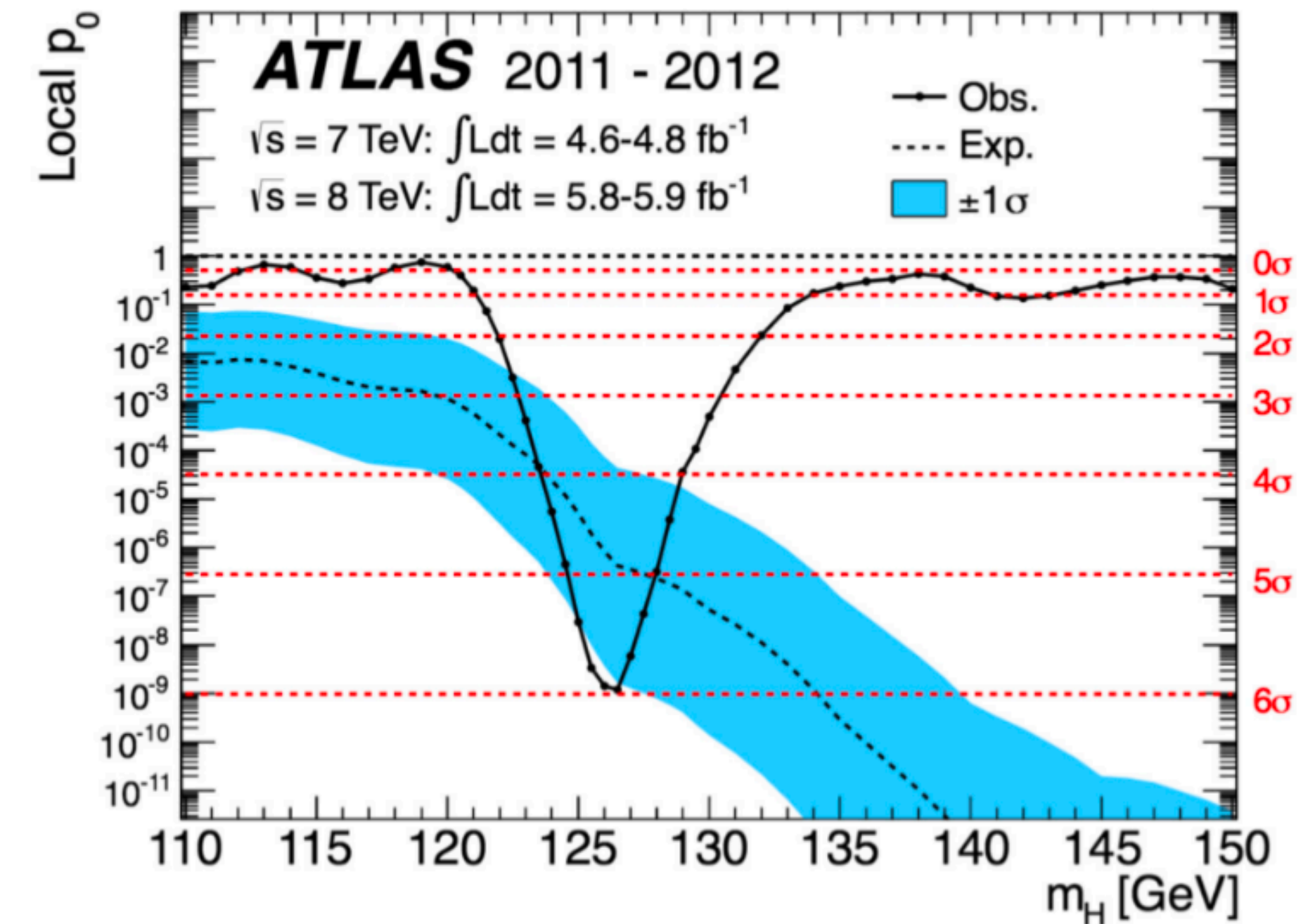
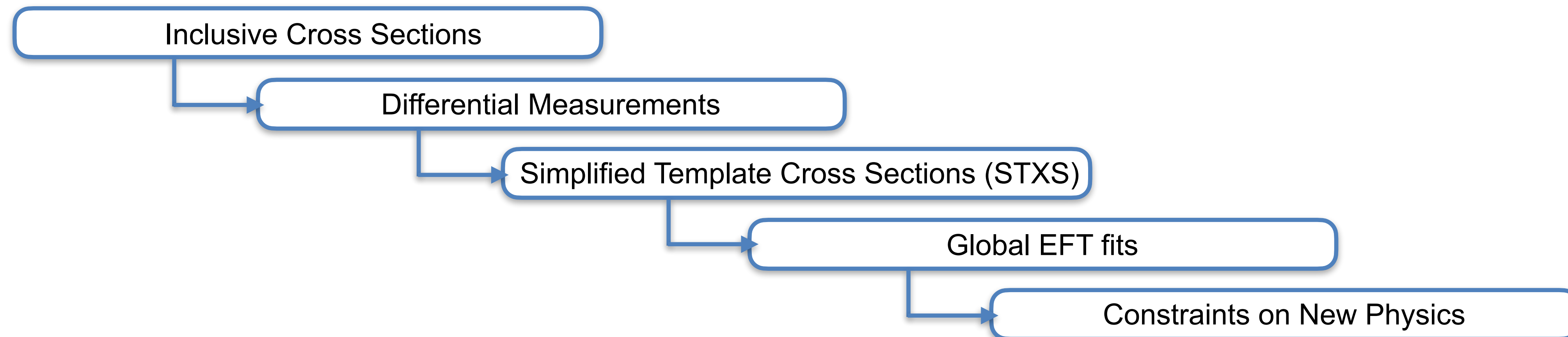
After the 2012 discovery, the central question became:

**Is the observed Higgs boson exactly the SM Higgs?**

The Higgs sector is particularly sensitive to new physics

- Only fundamental scalar particle in the SM
- Its couplings originate from electroweak symmetry breaking
- Many BSM scenarios predict coupling deviations at the percent level
- Indirect effects may appear long before direct production of new particles

## The Precision Program

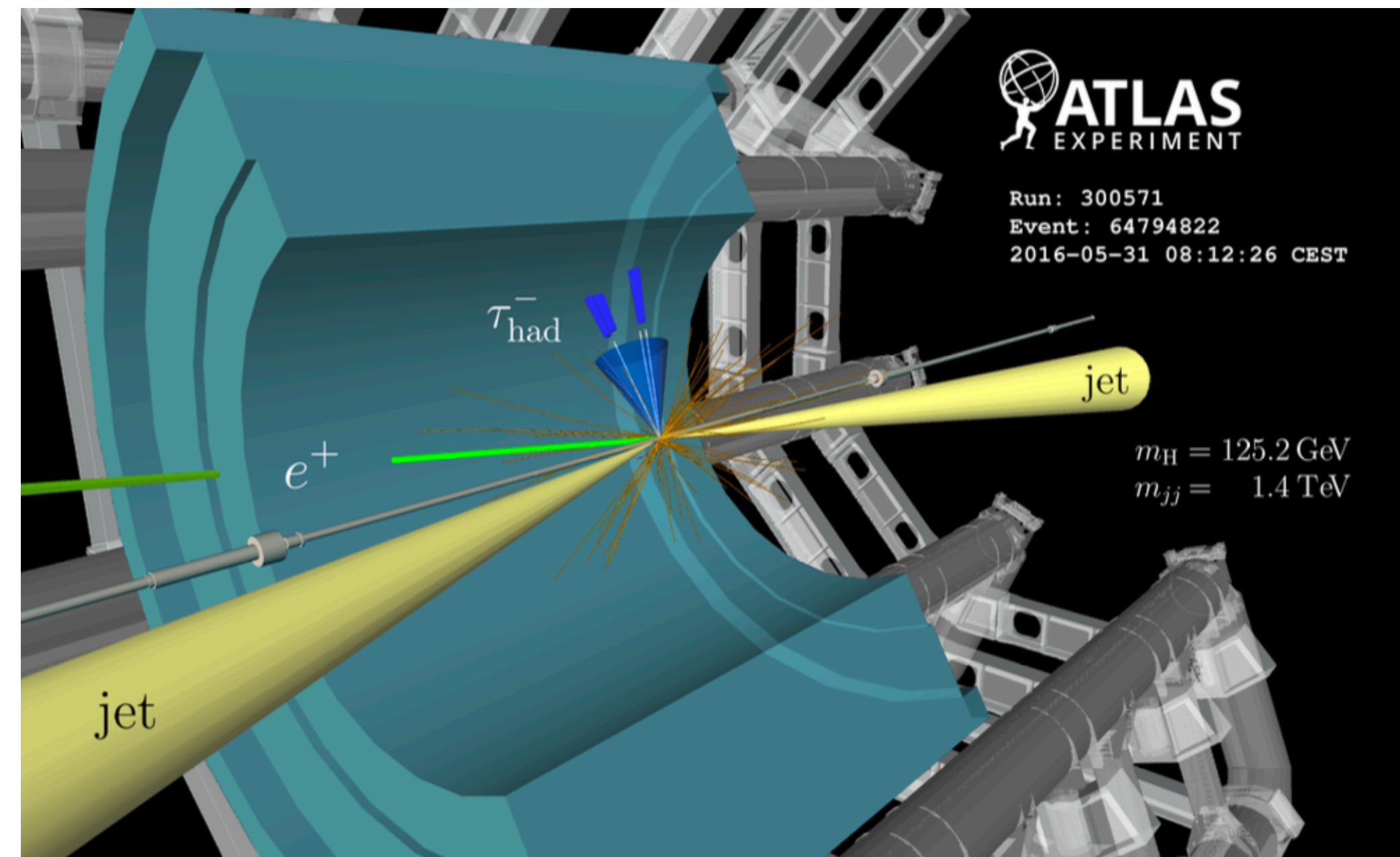
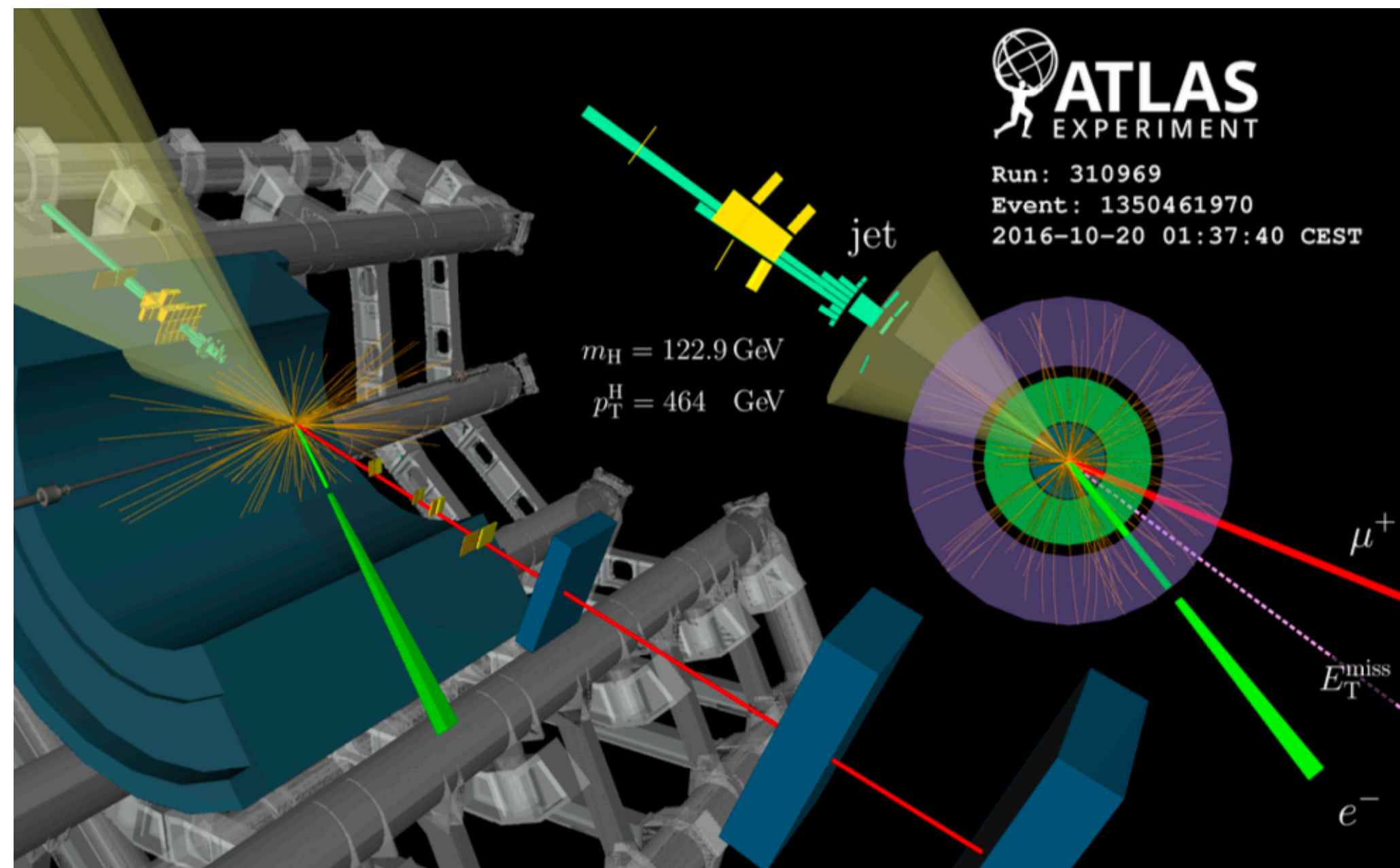




# Precision $H \rightarrow \tau\tau$ measurements in ATLAS

## Why $H \rightarrow \tau\tau$ leptons?

- Direct measurement of Yukawa couplings
- Third-generation fermions are particularly sensitive to BSM physics
- Excellent complement to  $H \rightarrow \gamma\gamma$ ,  $ZZ^*$ , and  $WW^*$
- Sensitive to modifications of Higgs couplings in many EFT operators



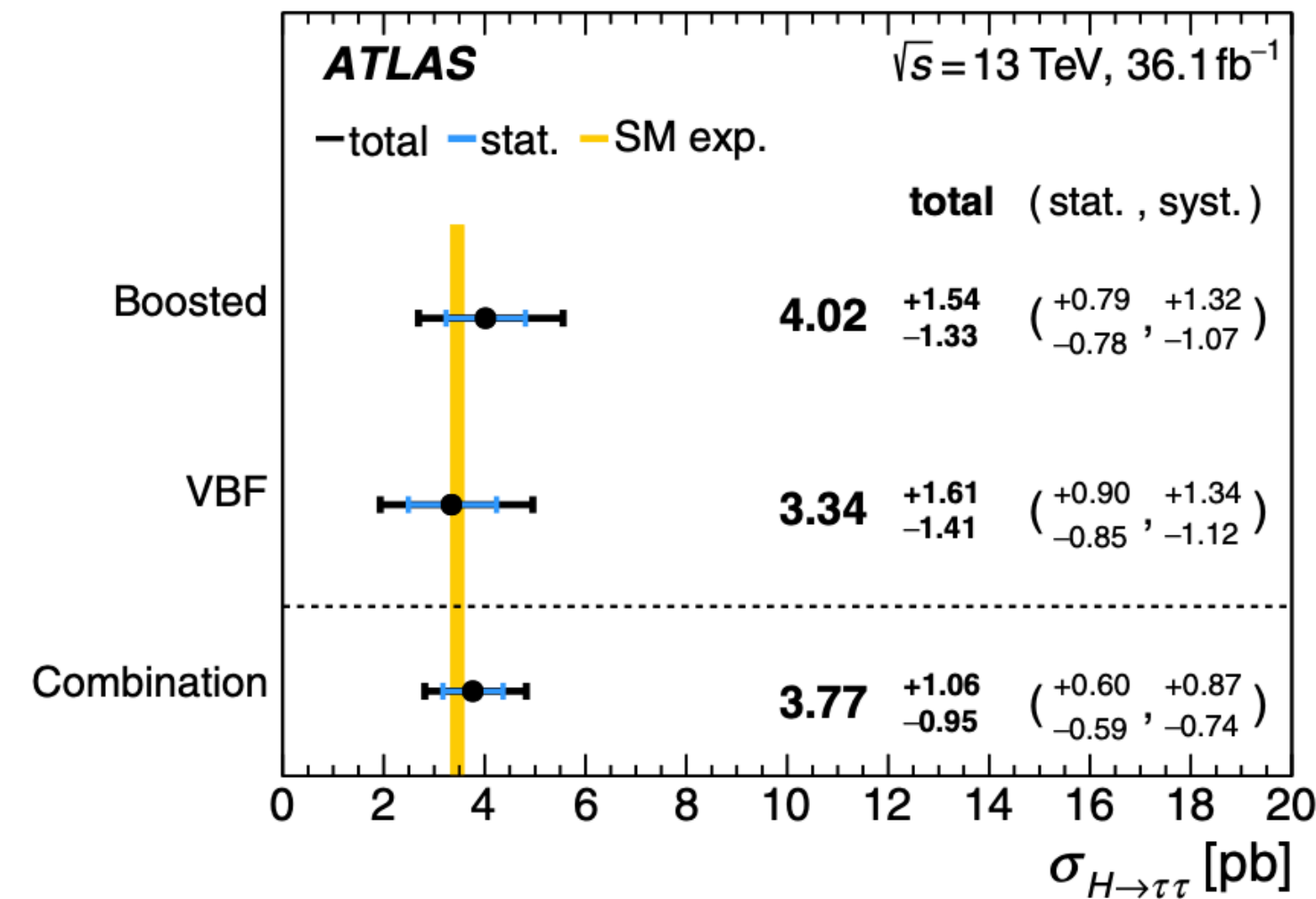


# Measurement in $H \rightarrow \tau\tau$

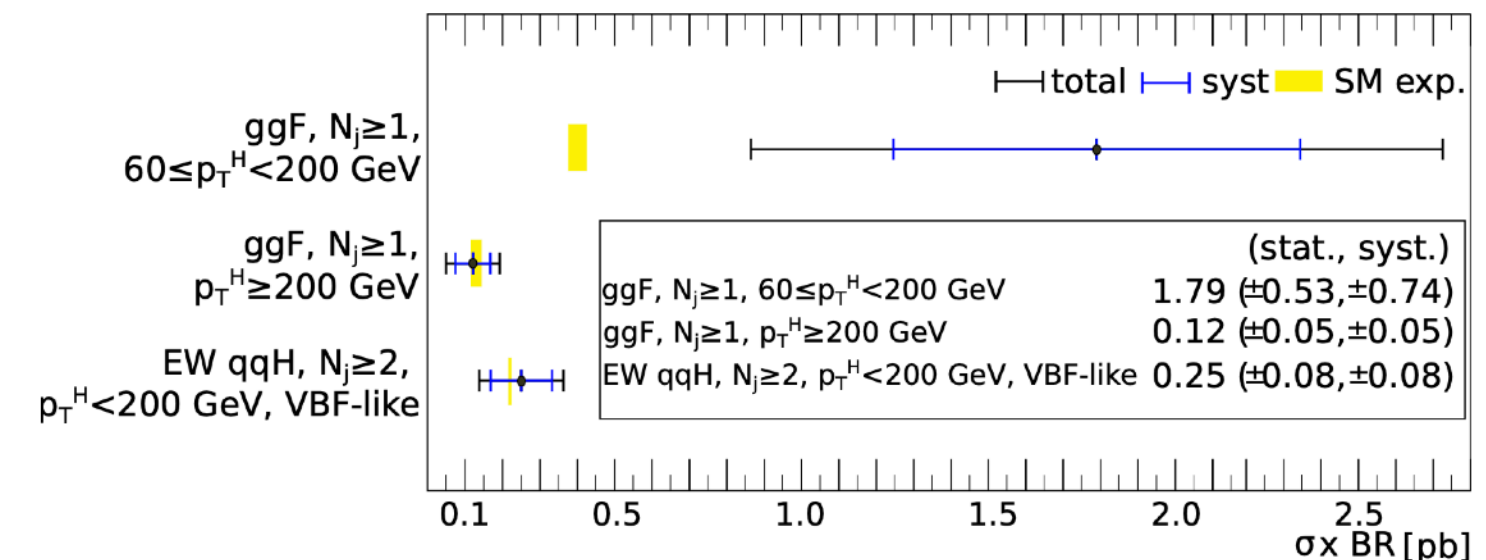
**PRD 99, 072001 (2019)**

- Inclusive cross sections  
→ First observation with ATLAS
- Cut based analysis
- First STXS measurement in  $H \rightarrow \tau\tau$   
→ Prove of principle

## Inclusive cross sections

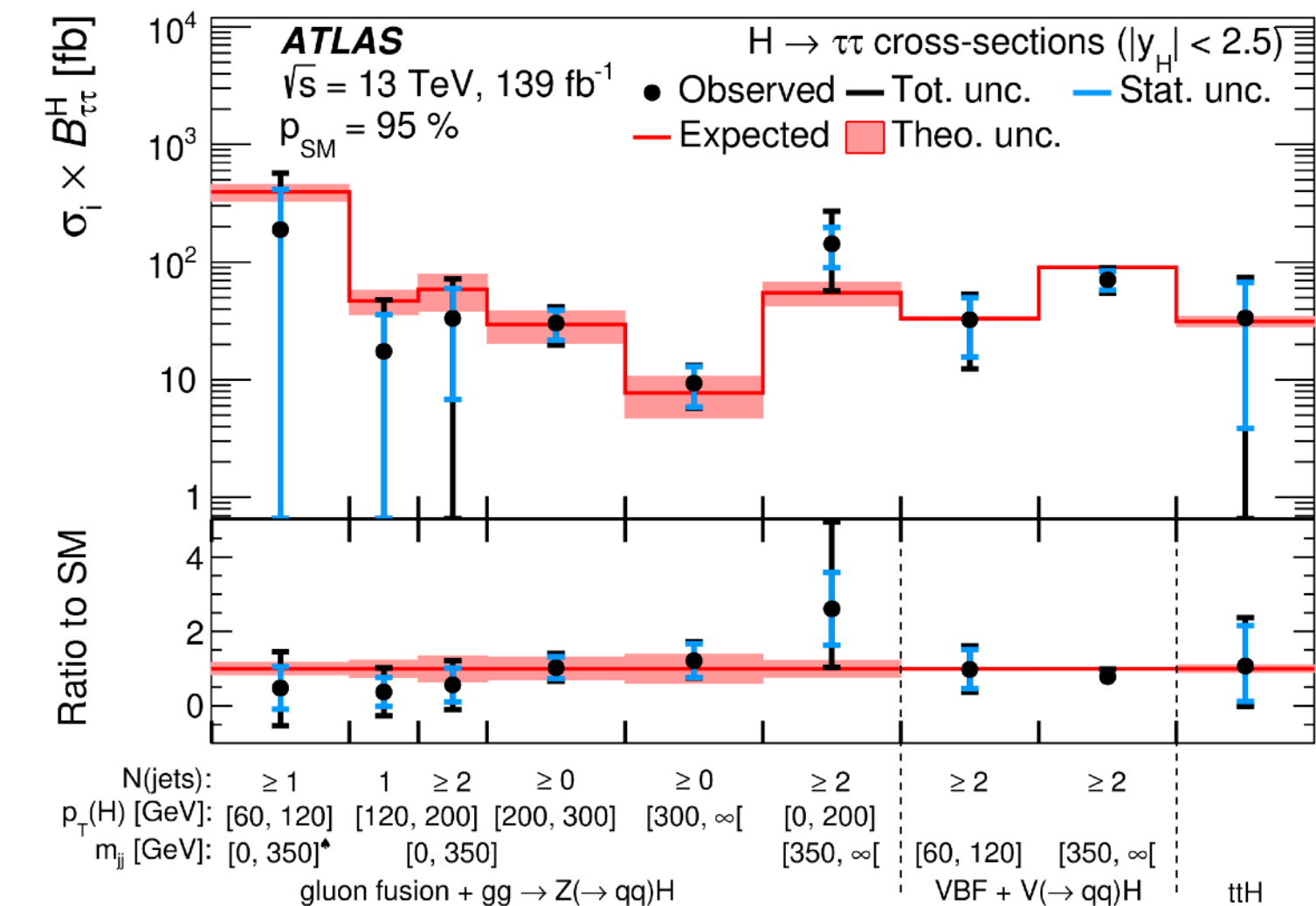
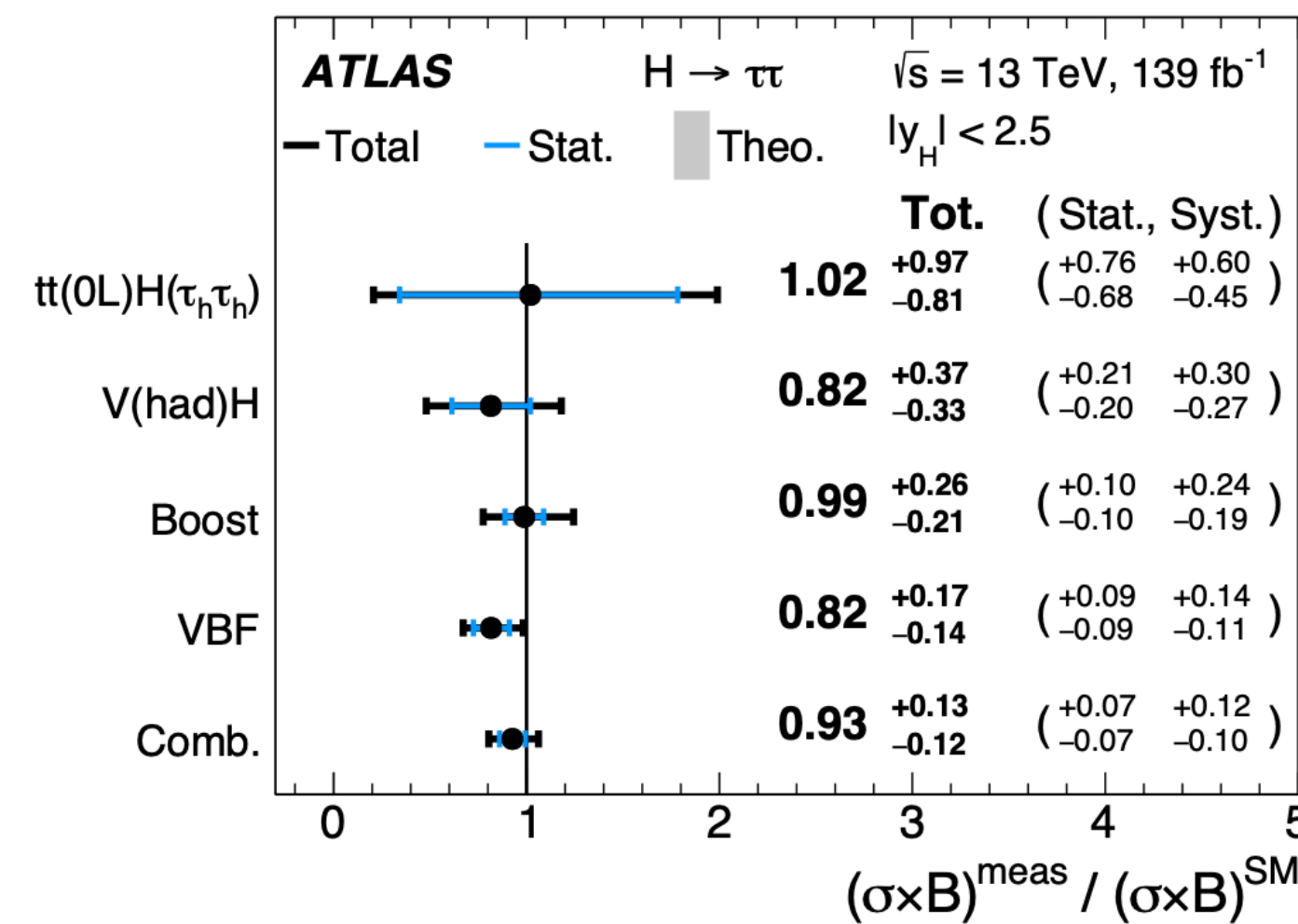


## STXS



**JHEP 08 (2022) 175**

- Four dominant production modes measured
  - First observation of VBF production in  $H \rightarrow \tau\tau$
- First full fledged STXS measurement in  $H \rightarrow \tau\tau$ 
  - ML-based event categorization
- Global profile-likelihood fit
  - 32 signal, 36 sideband region,  $> 500$  parameters



**How can we maximize the sensitivity to new physics?**



# Combination of STXS measurements

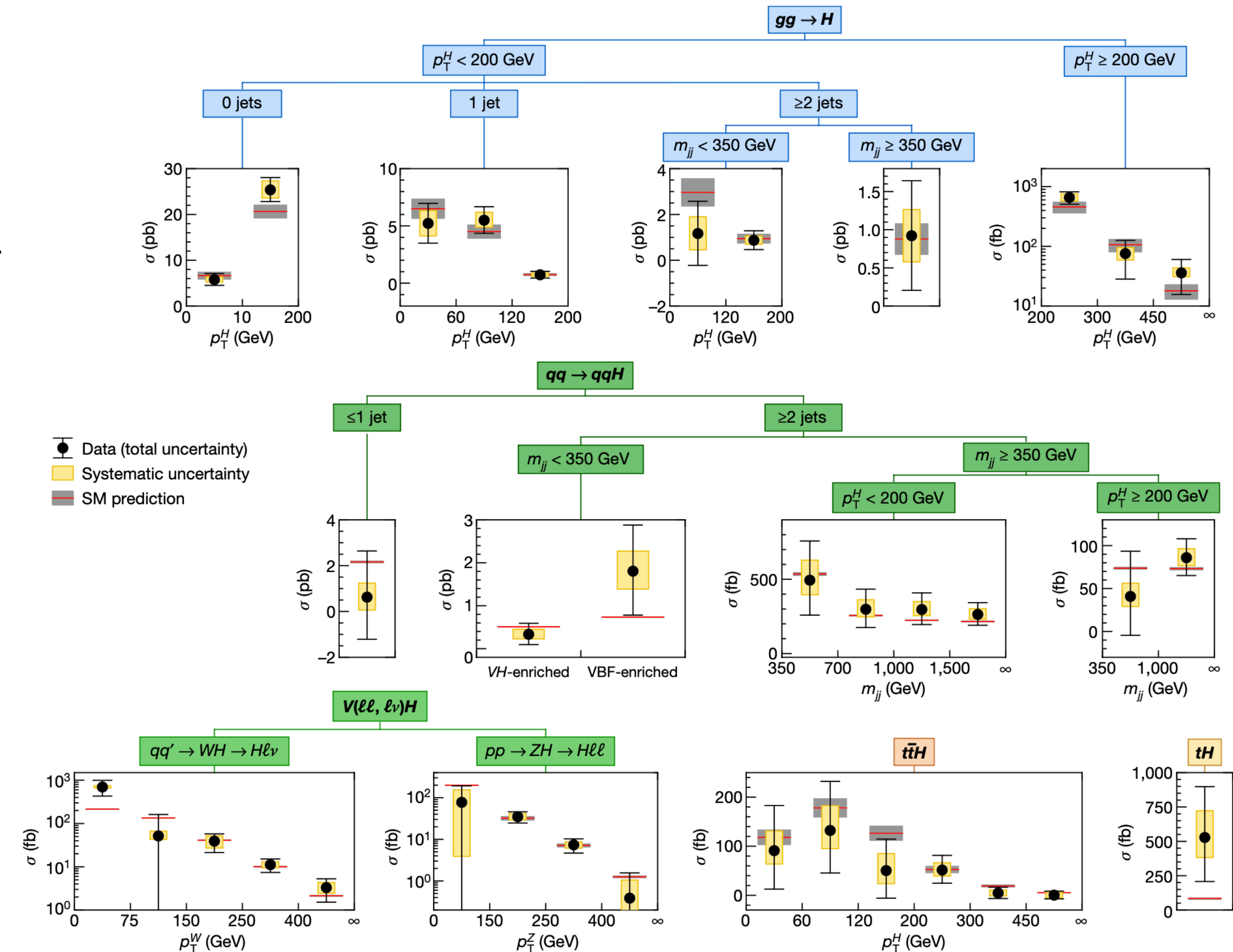
Nature 607, 52-59 (2022)

Combine likelihood models of individual decay channels

$$\mathcal{L}_{\text{comb.}}(n | \vec{r}, \vec{NF}, \vec{\theta}) = \mathcal{L}_{H \rightarrow \tau\tau}(n | \vec{r}, \vec{NF}, \vec{\theta}) \cdot \mathcal{L}_{H \rightarrow \gamma\gamma}(n | \vec{r}, \vec{NF}, \vec{\theta}) \cdot \dots$$

Common definition of parameters needed → STXS framework

- Combination of 12 independent analyses
- Over 23000 parameters → 37 STXS bins measured
- No significant deviation from SM



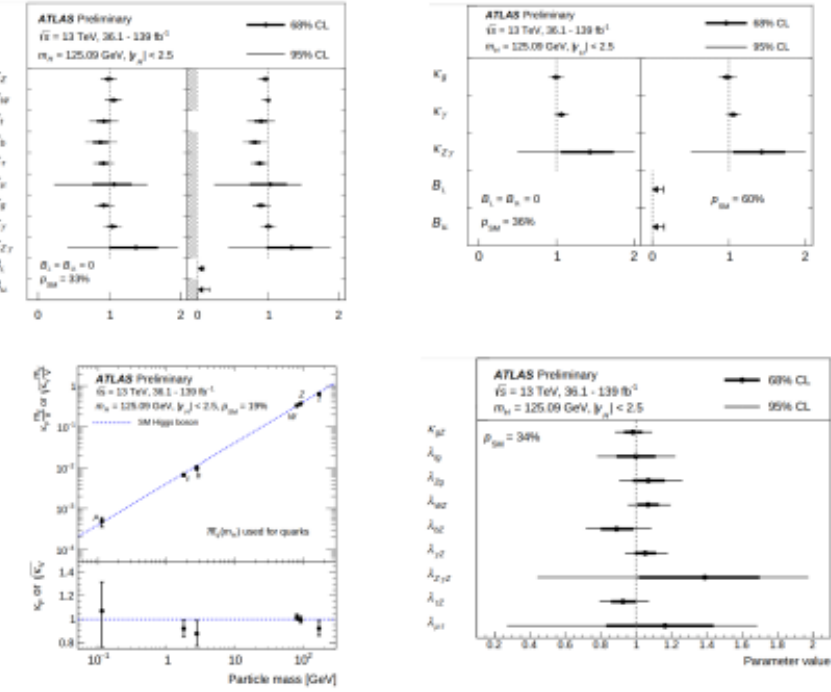
Differential measurements maximize sensitivity to new physics



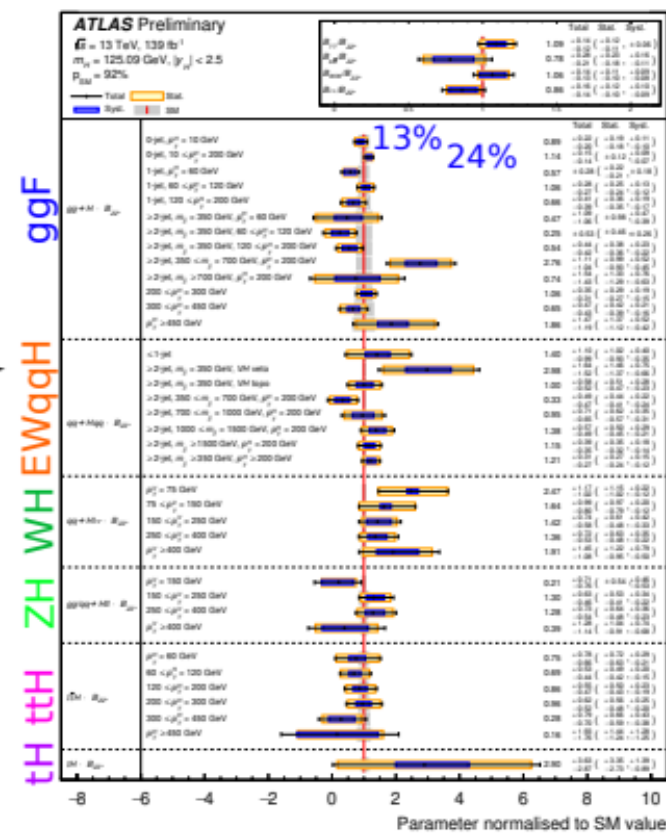
# Interpretations of the results

For global interpretation as e.g. SMEFT a large number of model parameters have to be constrained  
 → Every channel contributes to different parameters

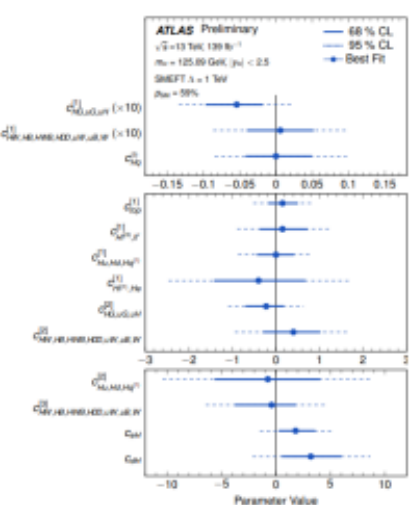
**Higgs boson coupling**



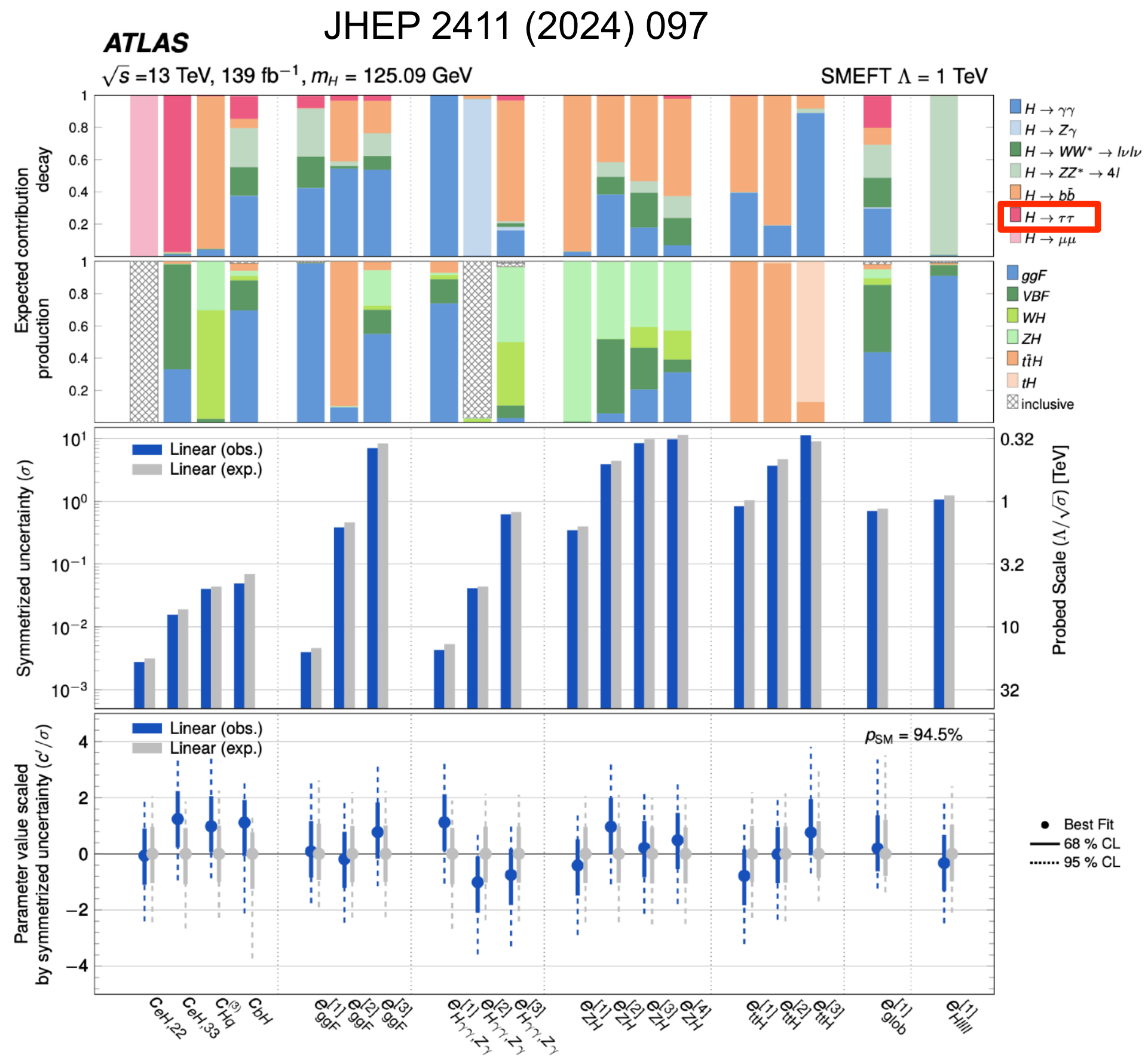
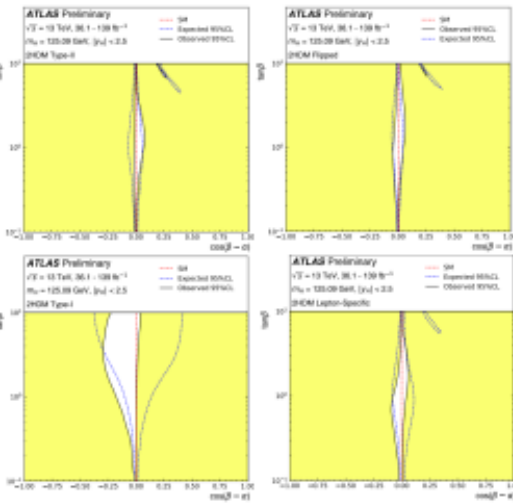
**STXS measurement**



**SMEFT**



**BSM models**



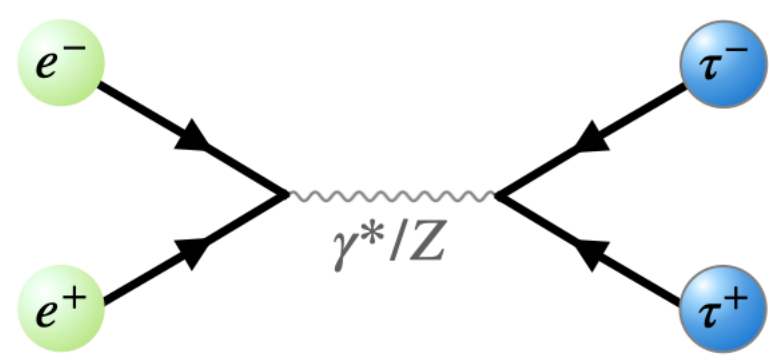
**So far no hints for BSM physics?  
Where else can we search?**



# Why precision $\tau$ physics ?

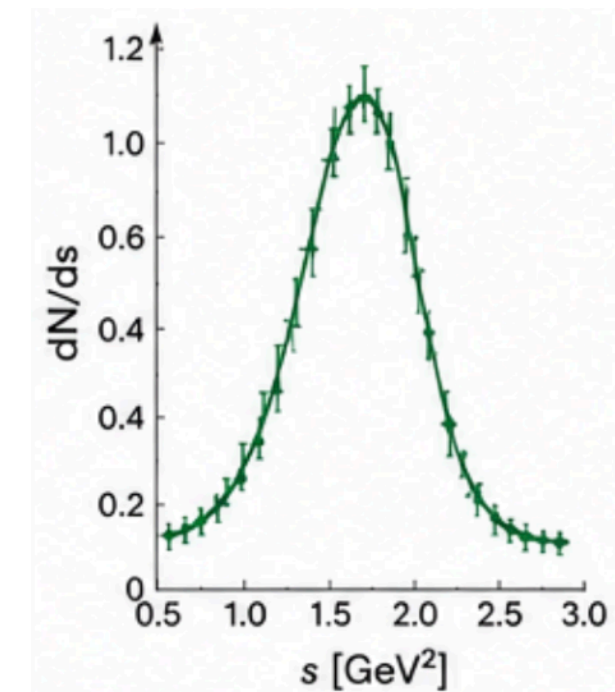
## Its landscape

### 1. Precision SM Tests



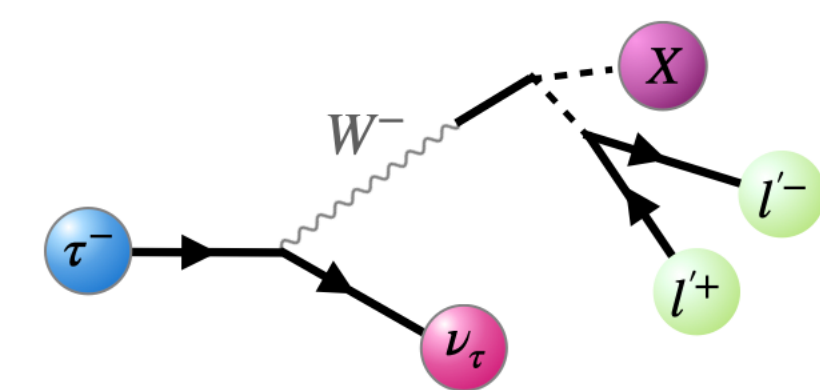
- $\tau$  lifetime
- $\tau$  mass
- LFU
- Michel parameters and polarization
- $g_\tau$
- CPT tests

### 2. Hadron Physics



- Hadronic  $\tau$  decays
- Spectral functions and QCD tests
- Hadronic form factors
- Radiative decays
- Chiral dynamics

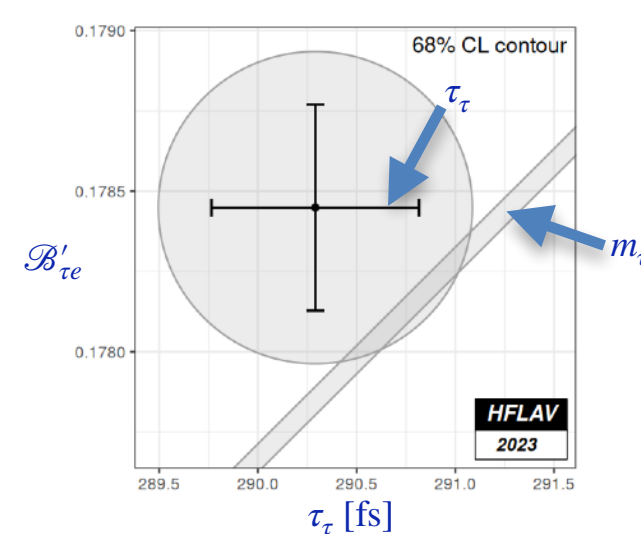
### 3. Searches for New Physics



- LFV
- Light mediators
- EFT interpretations
- Complementary to LHC, B-physics ( $(g-2)_\mu, \dots$ )

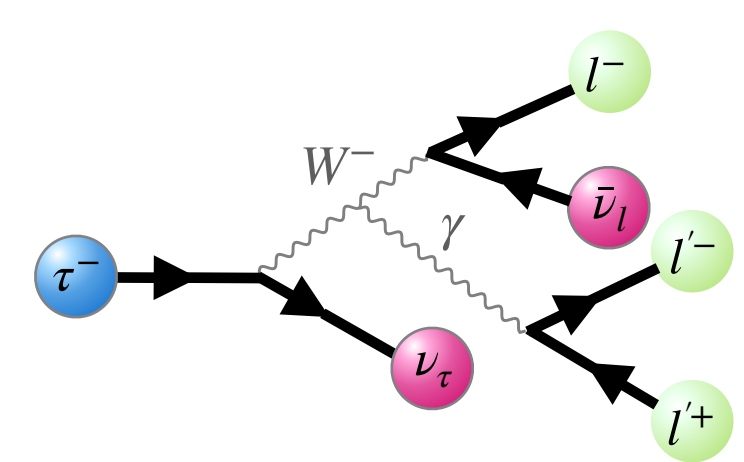
## Belle II Precision Program

### Precision $\tau$ Properties (ongoing)



$\tau$  lifetime,  $\tau$  mass, LFU test

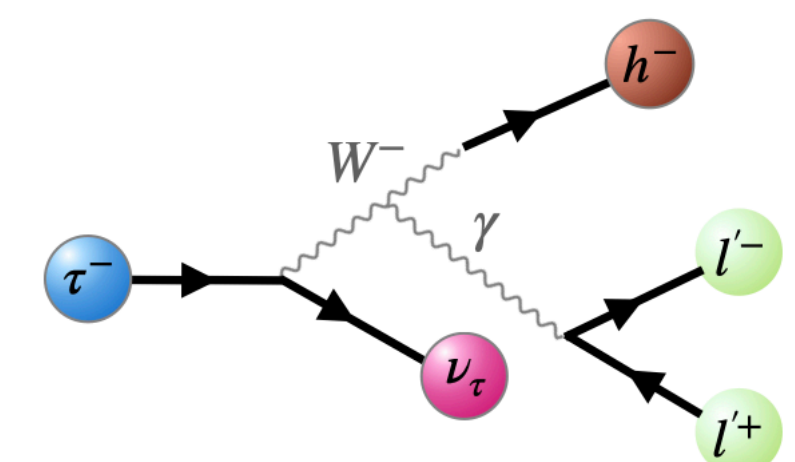
### Leptonic Radiative Decays (ongoing)



$$\tau^\pm \rightarrow l^\pm \gamma^* (\rightarrow l^+ l^-) \nu_\tau$$

$(l = e, \mu)$

### Hadronic Radiative Decays (new project)



$$\tau^\pm \rightarrow h^\pm \gamma^* (\rightarrow l^+ l^-) \nu_\tau$$

$(h = K, \pi)$

## My projects



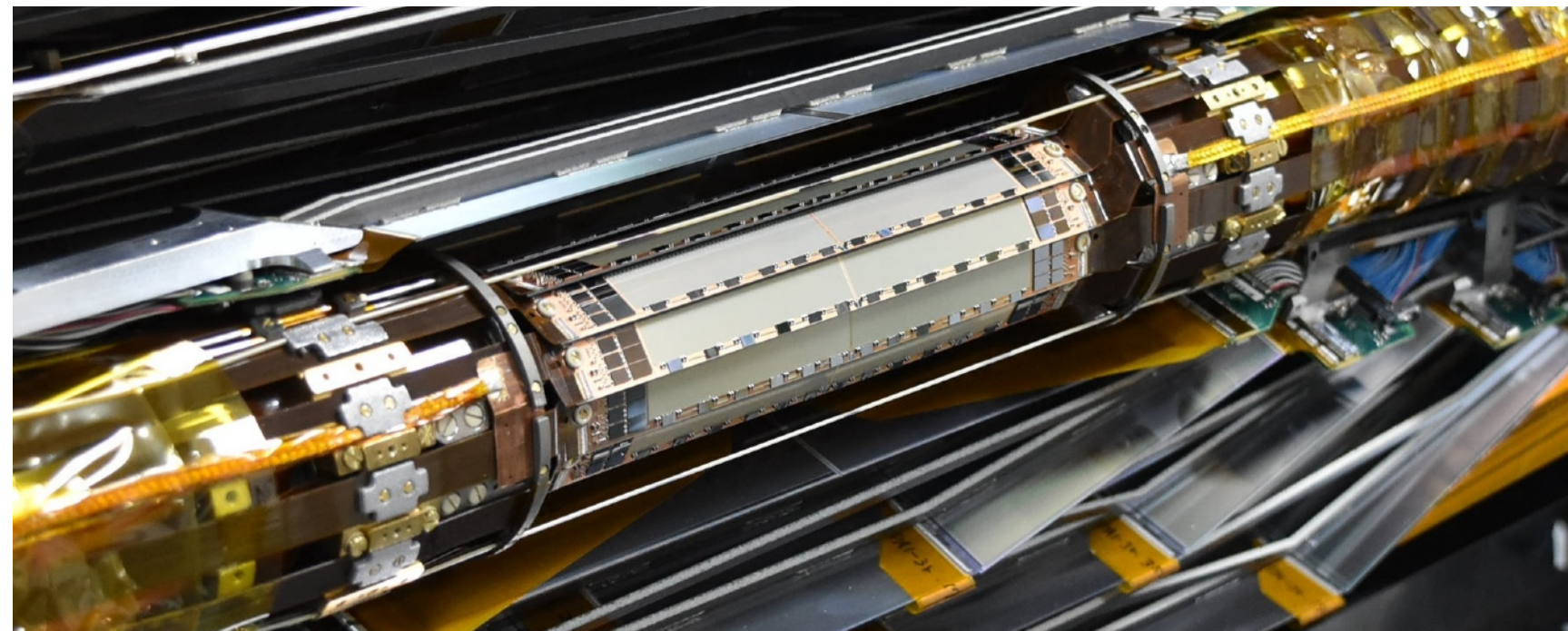
# Belle II

## Overview

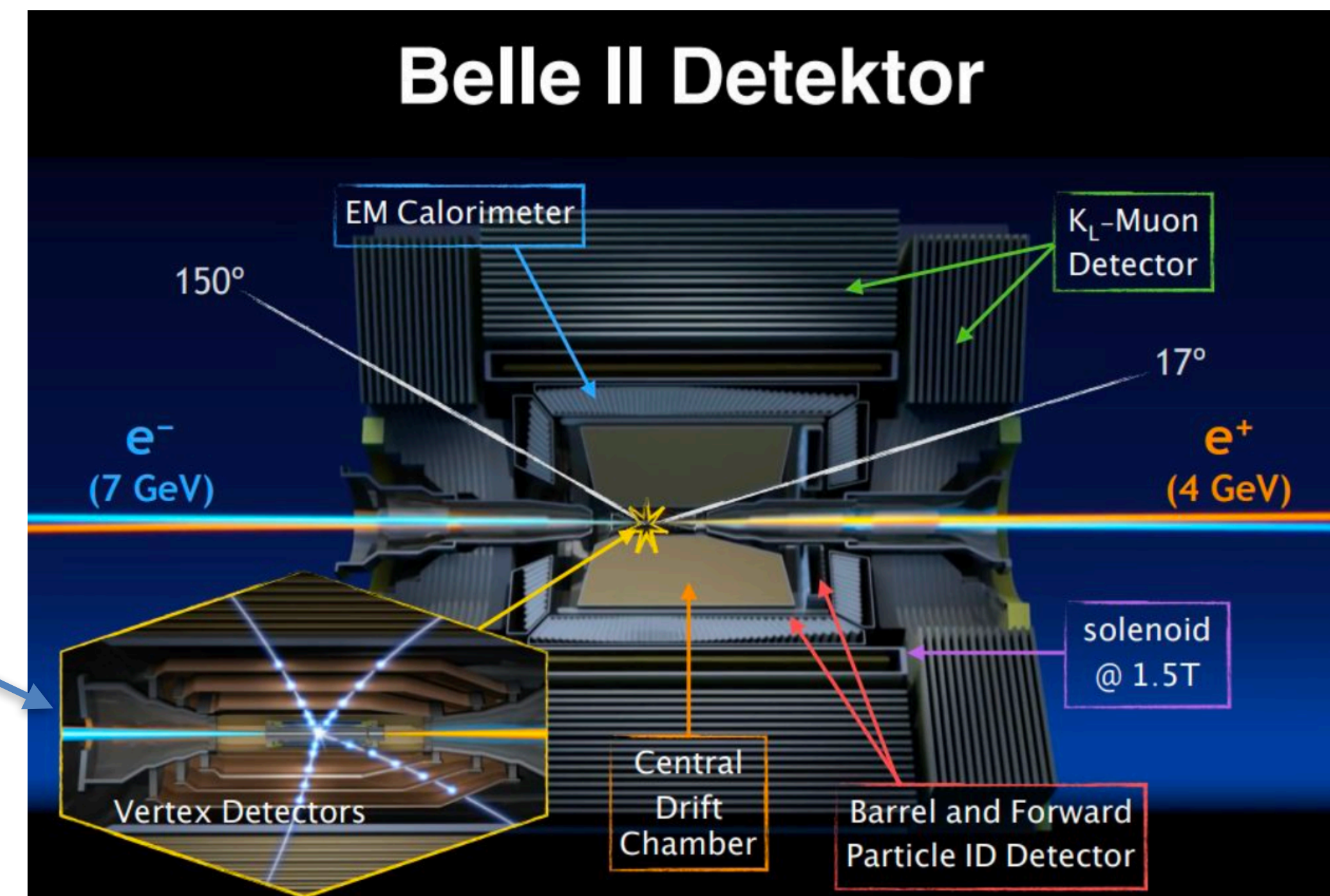
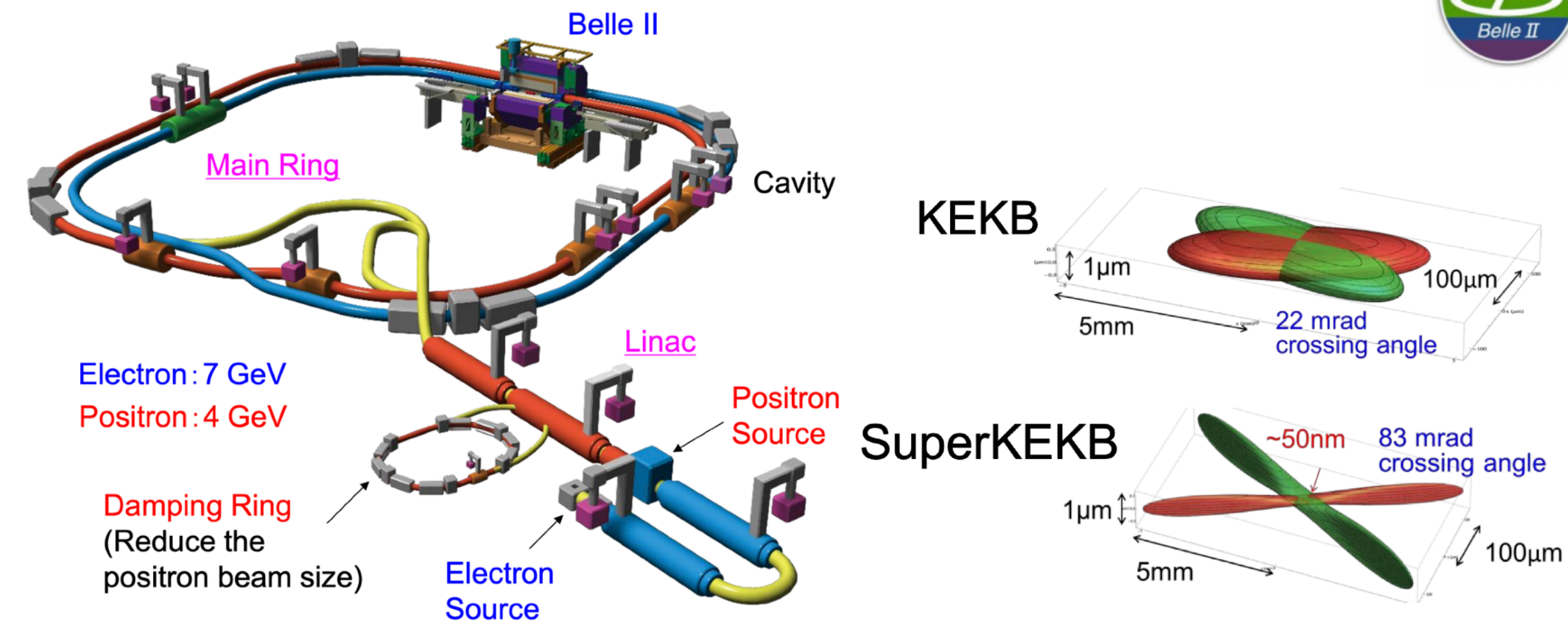
- $e^+e^-$  collider with clean environment
- Known initial states & efficient reconstruction of neutrals
- $\sigma(b\bar{b}) \approx \sigma(\tau\tau) \approx 1 \text{ nb}$
- Peak luminosity world record:  $5.28 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Total dataset (Run 1 + Run 2):  $364 \text{ fb}^{-1} + 550 \text{ fb}^{-1} = 914 \text{ fb}^{-1}$

## Improvements to Belle

- Nano-beam scheme  
→ Precise interaction point (IP) resolution
- Low-multiplicity triggers
- Vertex Detector (PXD)



**Belle II combines a clean  $e^+e^-$  environment, excellent vertex resolution, and the world's largest  $e^+e^- \tau$ -lepton dataset**



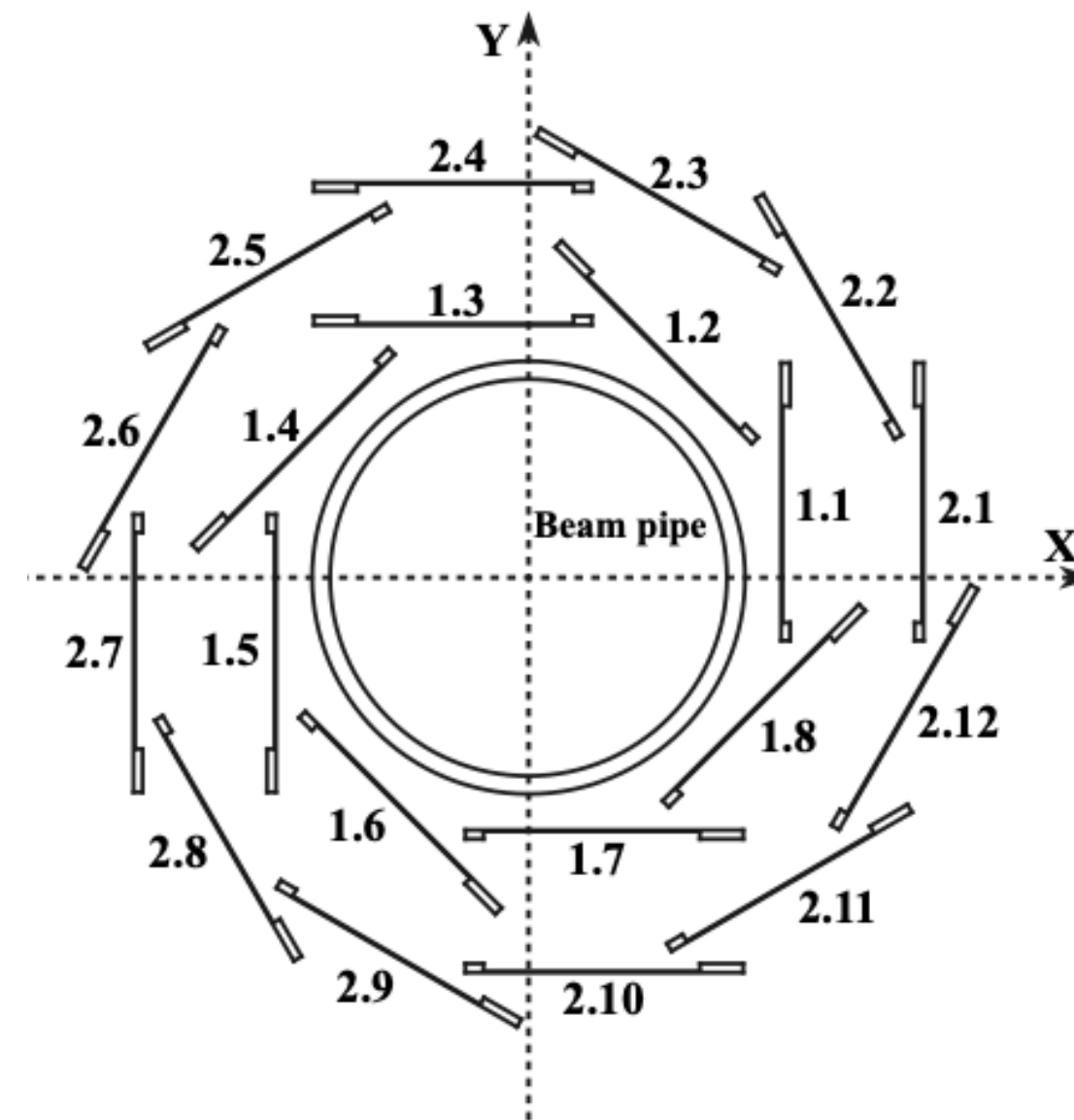
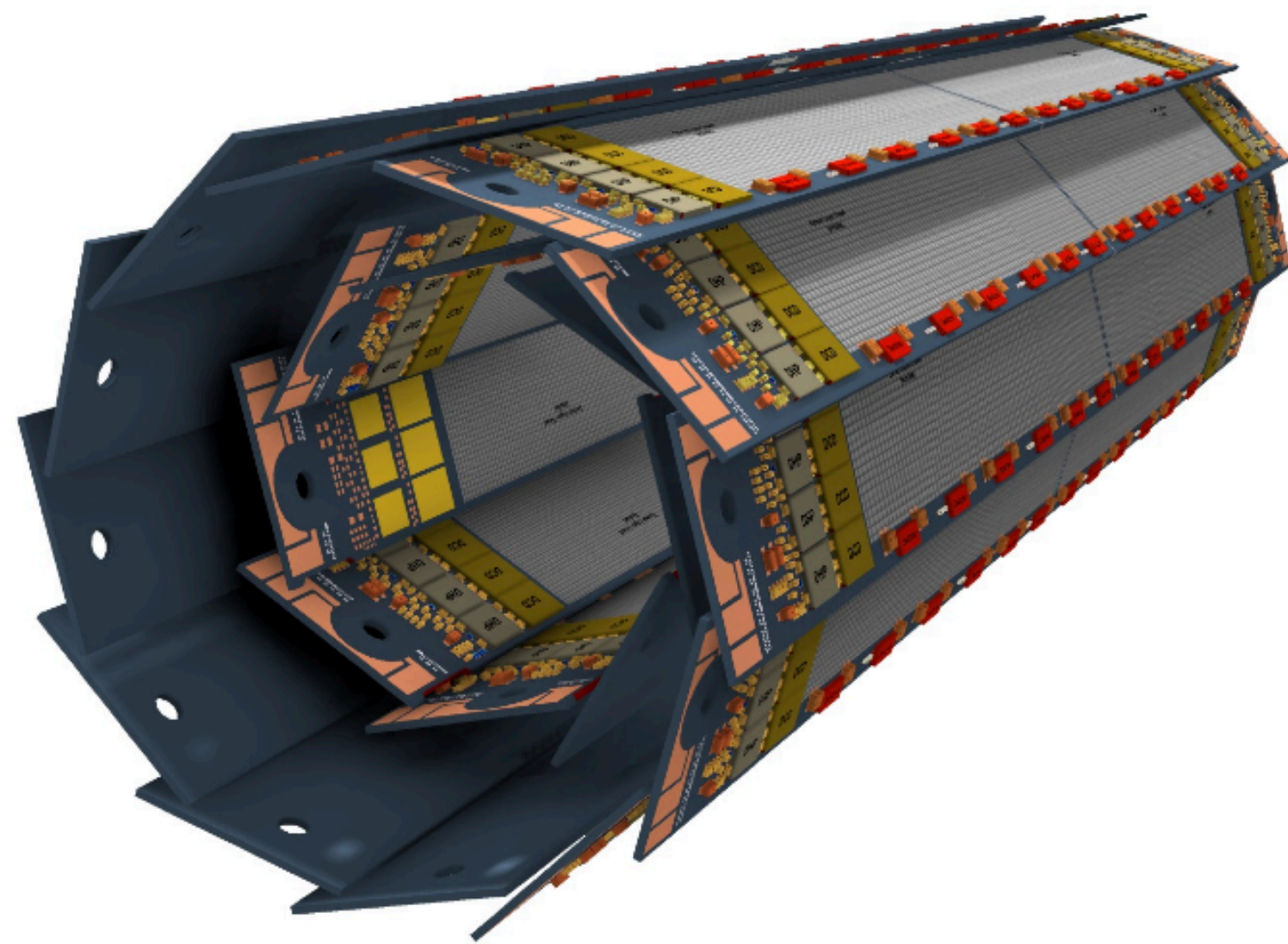


# Precision with the detector

## Why a pixel detector?

### Belle II Vertex Detector (PXD)

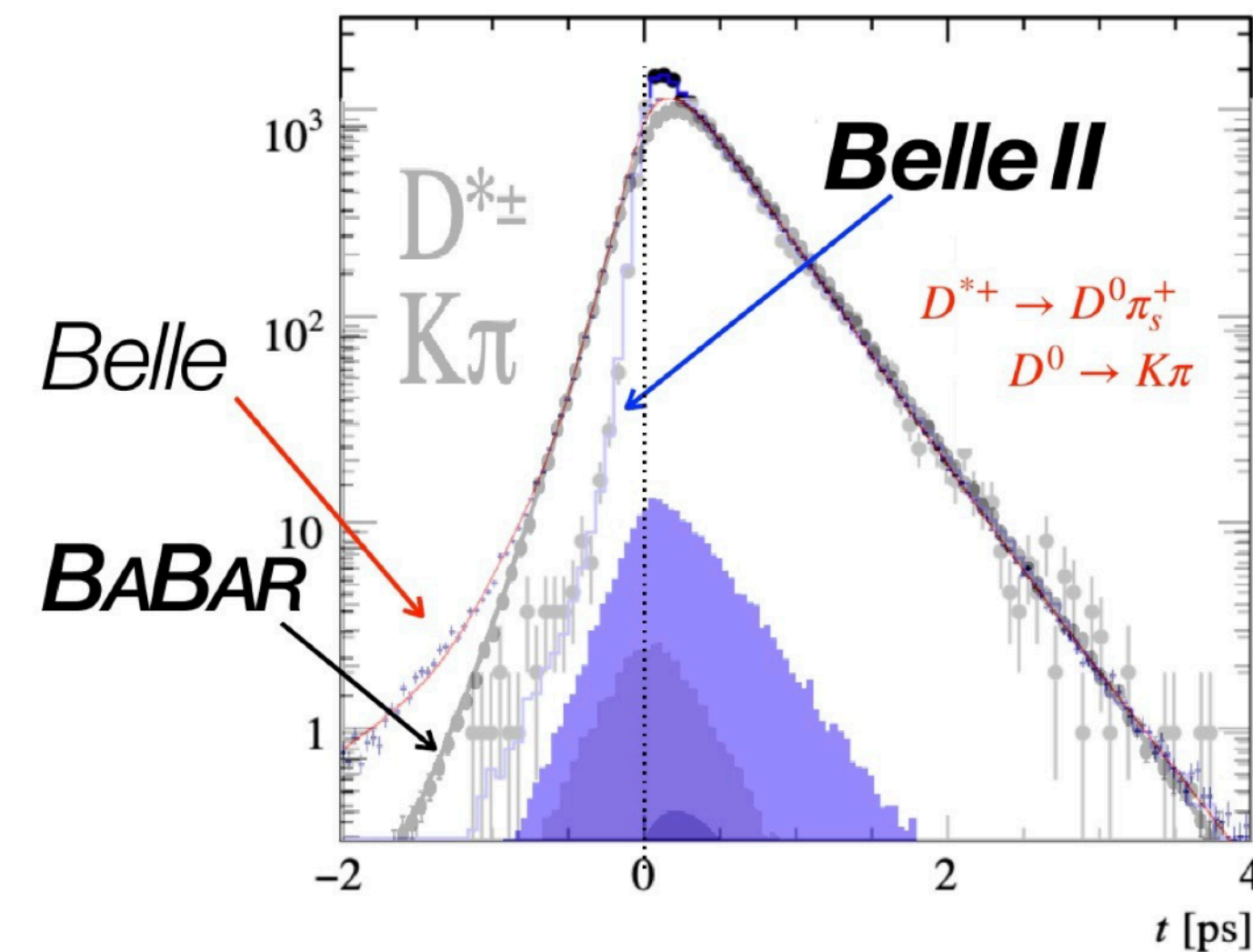
- Two layers of DEPFET pixel sensors
- Excellent impact-parameter resolution
- Precise reconstruction of secondary vertices
- Optimized for heavy-flavor and  $\tau$ -lepton physics



## Why does it matter?

### Physics impact

- Precise  $\tau$  decay vertices
- Improved decay-time resolution
- Better low-momentum tracking
- Reduced systematic uncertainties
- Essential for lifetime and rare-decay measurements



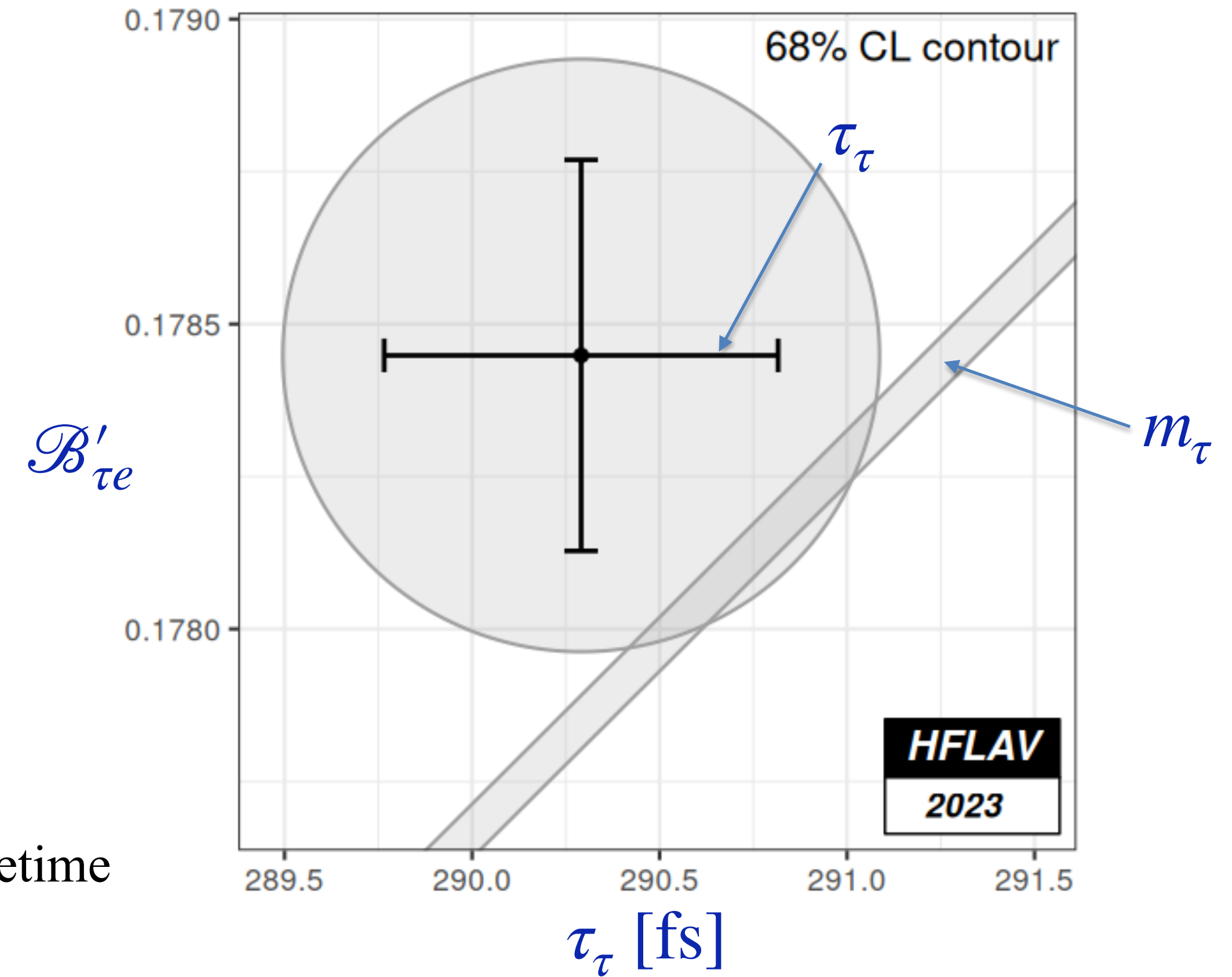
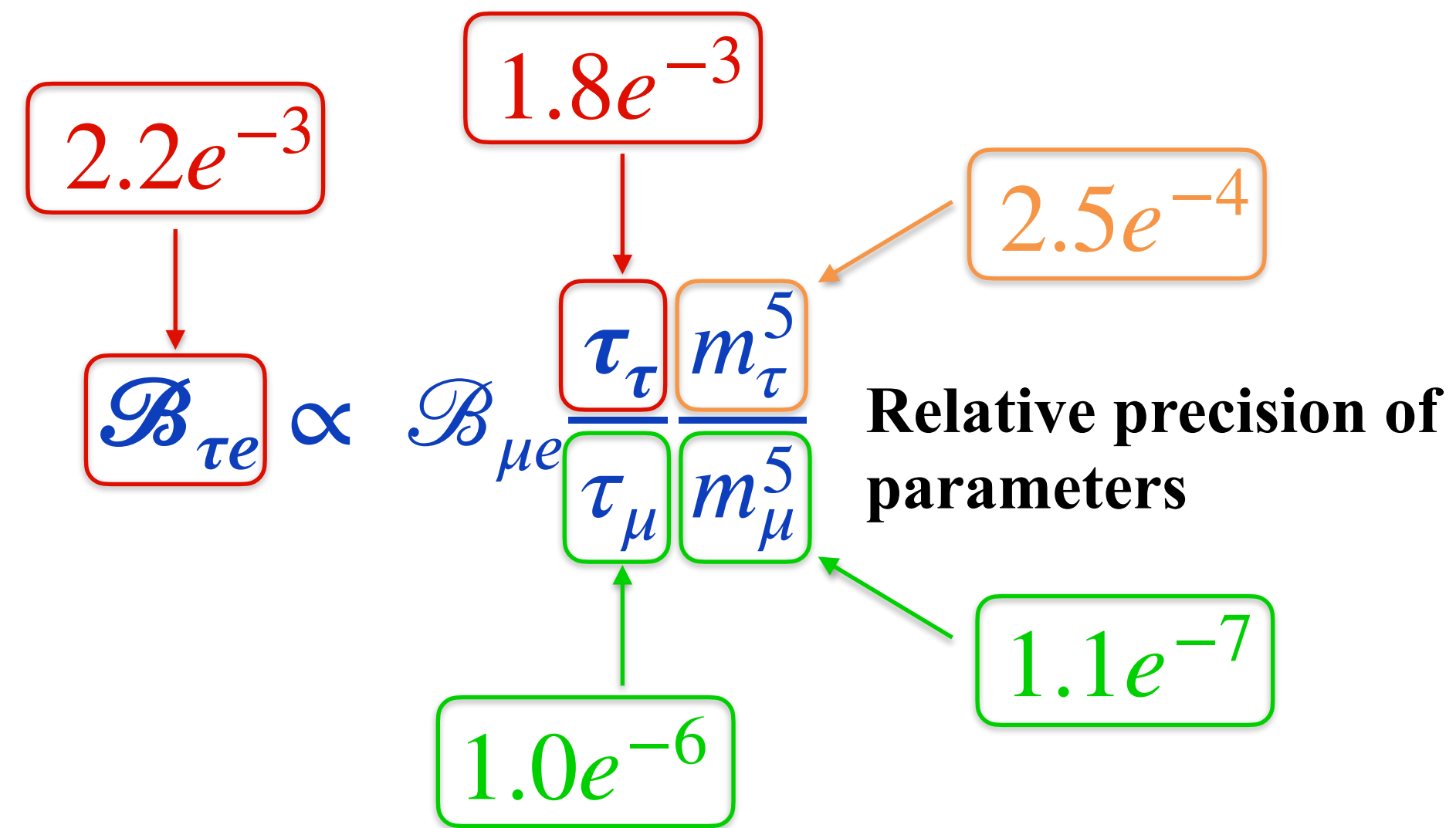
List of Belle II lifetime measurements with high PXD impact:

$D_s^+$ : PRL 131, 171803 (2023)  
 $B^0$ : PRD 107, L091102 (2023)  
 $\Omega_c^+$ : PRD 107, L031103 (2023)  
 $\Lambda_c^+$ : PRL 130, 071802 (2023)  
 $D_0/D^+$ : PRL 127, 211801 (2021)

**The PXD is essential for precision lifetime measurements!**



# Precision $\tau$ measurements and lepton flavor universality



- The limiting factors are the  $\tau$ -branching fraction into electrons and the  $\tau$ -lifetime
- The  $\tau$ -mass precision remains important because of the fifth power
- The uncertainties in the  $\mu$ -parameters are negligible currently

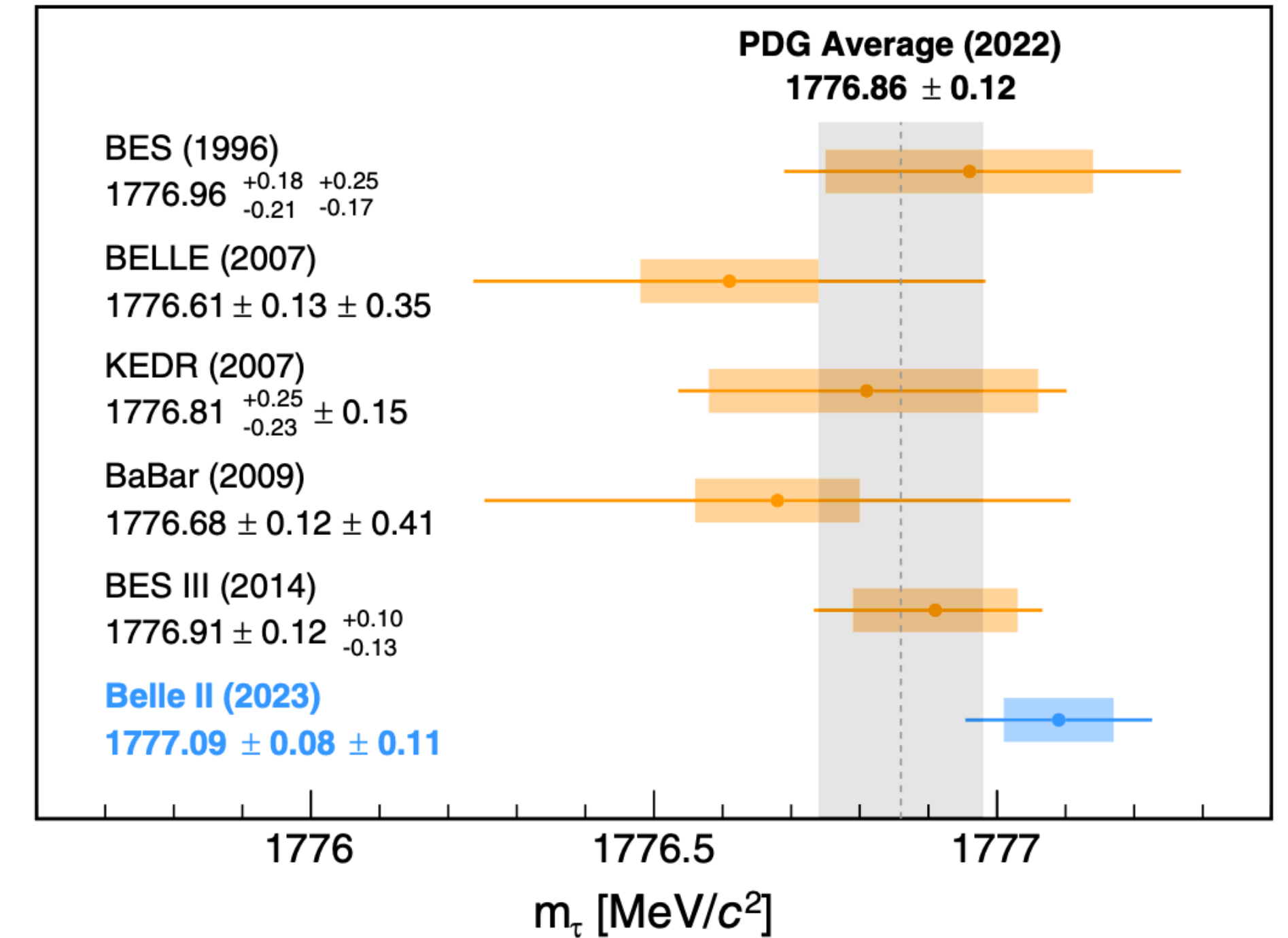
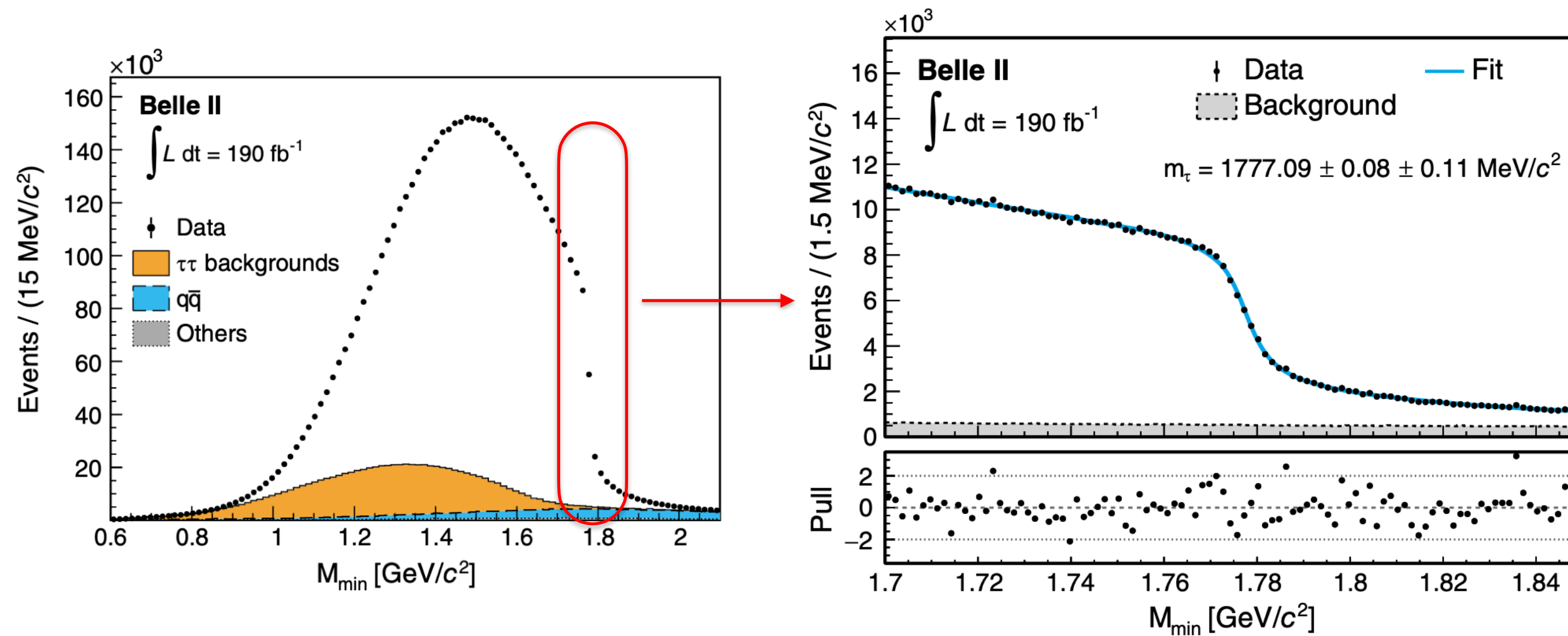
**The  $\tau$ -parameters are an interesting field and still known with limited precision!**  
**The precision of the  $\tau$ -lifetime is one of the limiting factors for the LFU test!**



# Mass measurement

**Pseudo-mass ( $M_{\min}$ ) technique**  $m_{\min} = \sqrt{m_{3\pi}^2 + 2[(E_{\text{beam}}E_{3\pi})(E_{3\pi} - p_{3\pi})]} \leq m_{\tau}$

| Experiment | Reference              |
|------------|------------------------|
| BES        | PRD 53, 20 (1996)      |
| Belle      | PRL 99, 011801 (2007)  |
| KEDR       | PPN 54, 185 (2023)     |
| BaBar      | PRD 80, 092005 (2009)  |
| BES III    | PRD 90, 012001 (2014)  |
| Belle II   | PRD 108, 032006 (2023) |



- The statistical and systematic uncertainty are 0.08 and 0.11 MeV/c<sup>2</sup>, respectively
- Partial Run 1 dataset with 190 fb<sup>-1</sup>
  - Repeat analysis with full Run 1 dataset 364 fb<sup>-1</sup>
  - Improve selection efficiency → Move from cut based to BDT selection: 0.08 → 0.05 MeV/c<sup>2</sup>
- Reduce dominant systematic uncertainties



# Systematic uncertainties

## Beam-energy correction

- Correction derived from  $B\bar{B}$  events
- ☑ More accurate knowledge on B-meson masses and the energy dependence
- ☑ More robust/redefined estimation of the correction

## Charged-particle momentum correction

- Considerable statistical uncertainty from control samples
- Residual dependence of the corrections on other variables
- ☑ Larger data samples → Reduced stat. unc. and 2D corrections
- ☑ More robust fitting method → Reduced method uncertainty

## Uncertainties due to the fit model

- Empirical function to describe the data
  - Limitation in parameters lead to bias and systematic uncertainties
- Complexity of fit function depending on statistical power of the dataset
- ☑ Use more accurate/better empirical function

PRD 108, 032006 (2023)

| Source                                | Uncertainty<br>(MeV/ $c^2$ ) |
|---------------------------------------|------------------------------|
| Knowledge of the colliding beams:     |                              |
| Beam-energy correction                | 0.07 → 0.02                  |
| Boost vector                          | < 0.01                       |
| Reconstruction of charged particles:  |                              |
| Charged-particle momentum correction  | 0.06 → 0.04                  |
| Detector misalignment                 | 0.03                         |
| Fit model:                            |                              |
| Estimator bias                        | 0.03 → 0.02                  |
| Choice of the fit function            | 0.02 → 0.01                  |
| Mass dependence of the bias           | < 0.01                       |
| Imperfections of the simulation:      |                              |
| Detector material density             | 0.03                         |
| Modeling of ISR, FSR and $\tau$ decay | 0.02                         |
| Total                                 | 0.11 → 0.08                  |

**Total uncertainty improved by ~40 % to previous measurement**



# Lifetime measurement

## Production and decay vertex

- Vertex fit of charged pions for decay vertex
- Small SuperKEKB beam spot as production point

## Systematic uncertainties

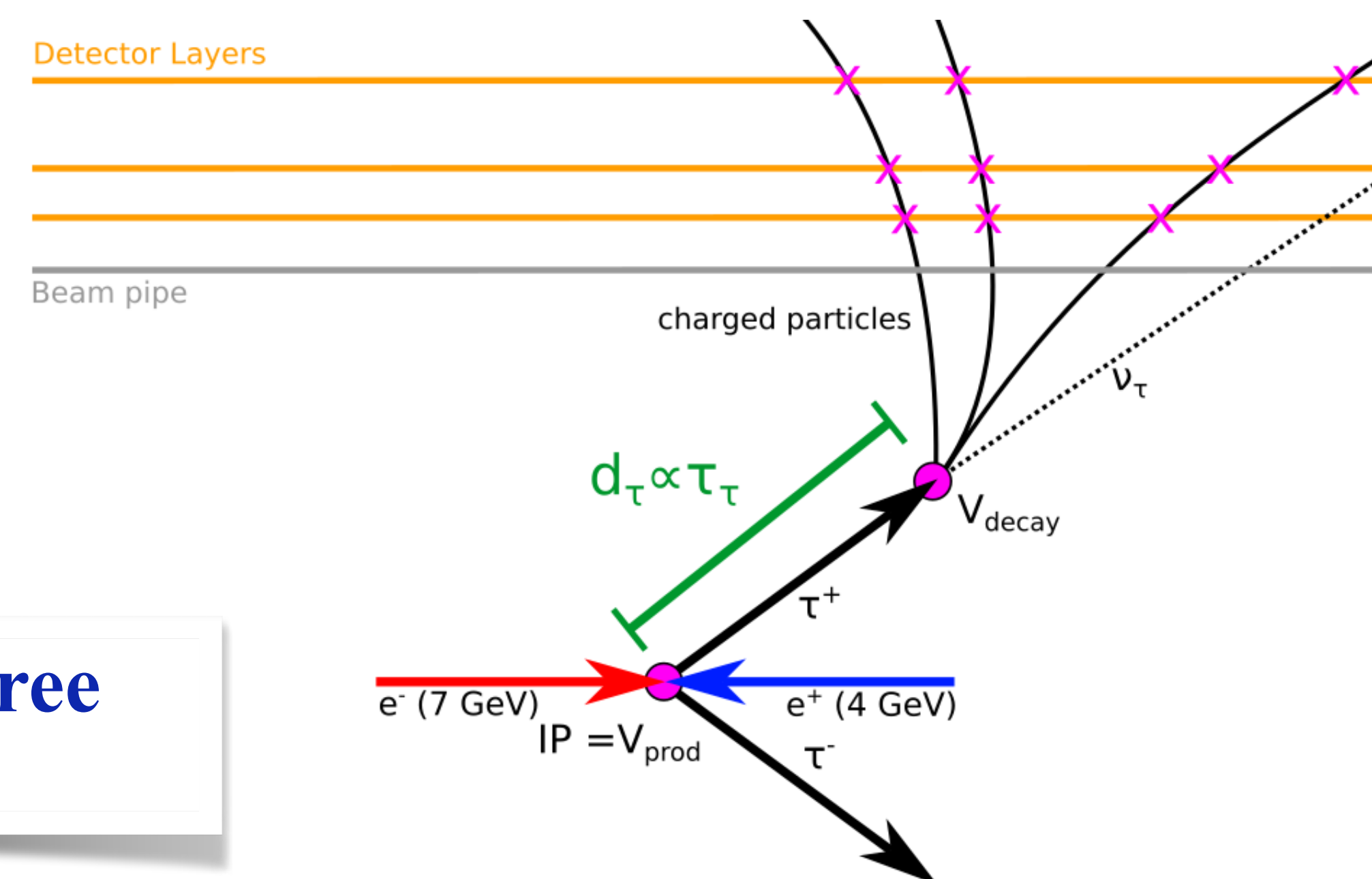
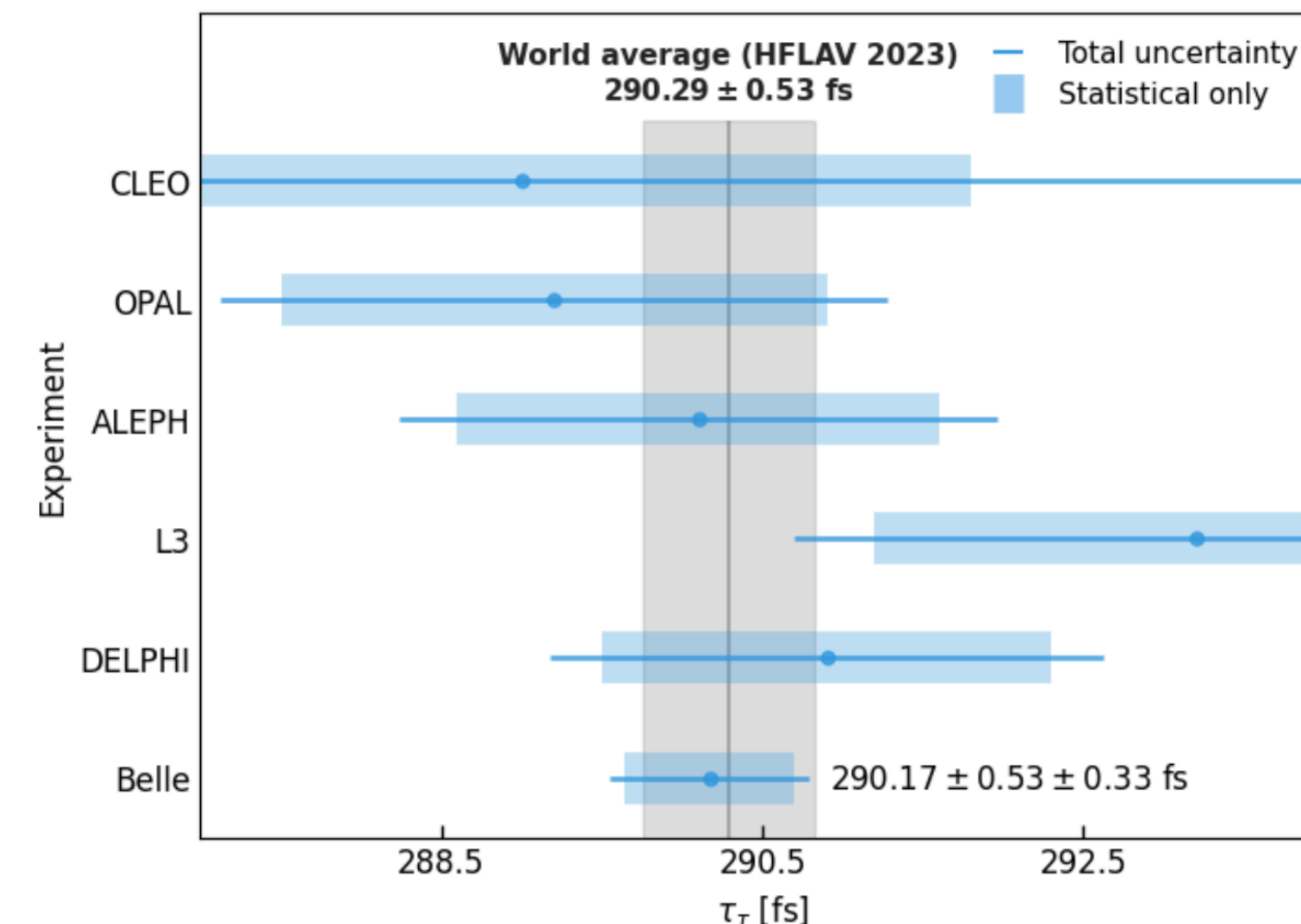
- Superior detector and accelerator reduce systematic uncertainties
- Template fit(s) reduces uncertainties related to the fitting method

## Statistical uncertainty

- Data set size: Belle 711 fb<sup>-1</sup> | Belle II 362 fb<sup>-1</sup>
- Increase signal efficiency
  - Use 3x1 topology (BR 3x3: 0.02 vs. BR 3x1: 0.26)
  - Superior detector: Achieve better event quantities with looser criteria
- > 12 million signal events with a signal purity > 98% | Belle ~ 1 million

## Main analysis challenge

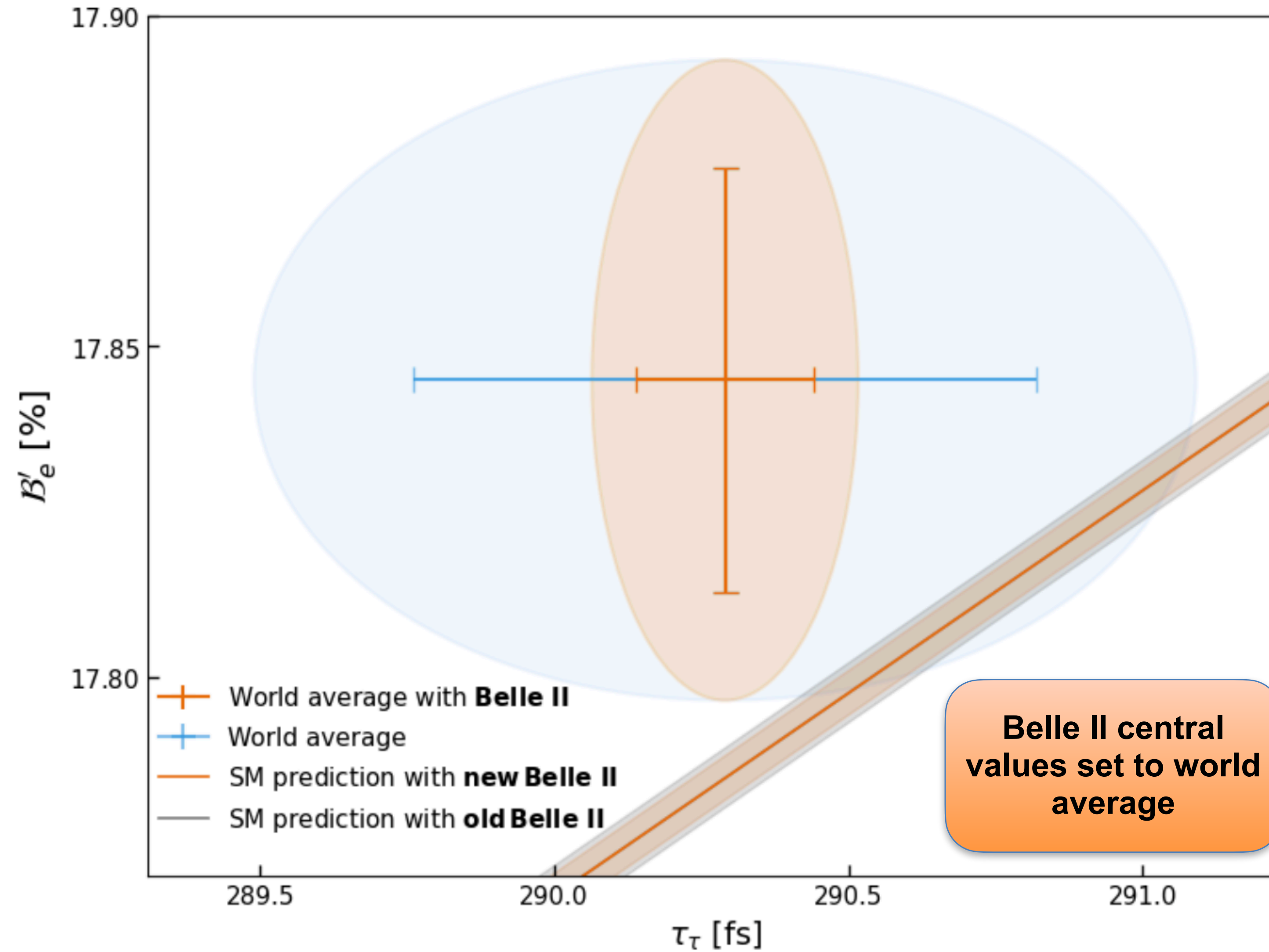
- Precise modelling of the detector response
  - Run-dependent MC + beam-background overlays
  - Multiple data-driven corrections
- Sideband fits to correct background contributions
- Multi-dimensional kinematic correction based on BDTs



**Measurement expected to be more than three times as precise as the world average**



# Impact on the LFU test



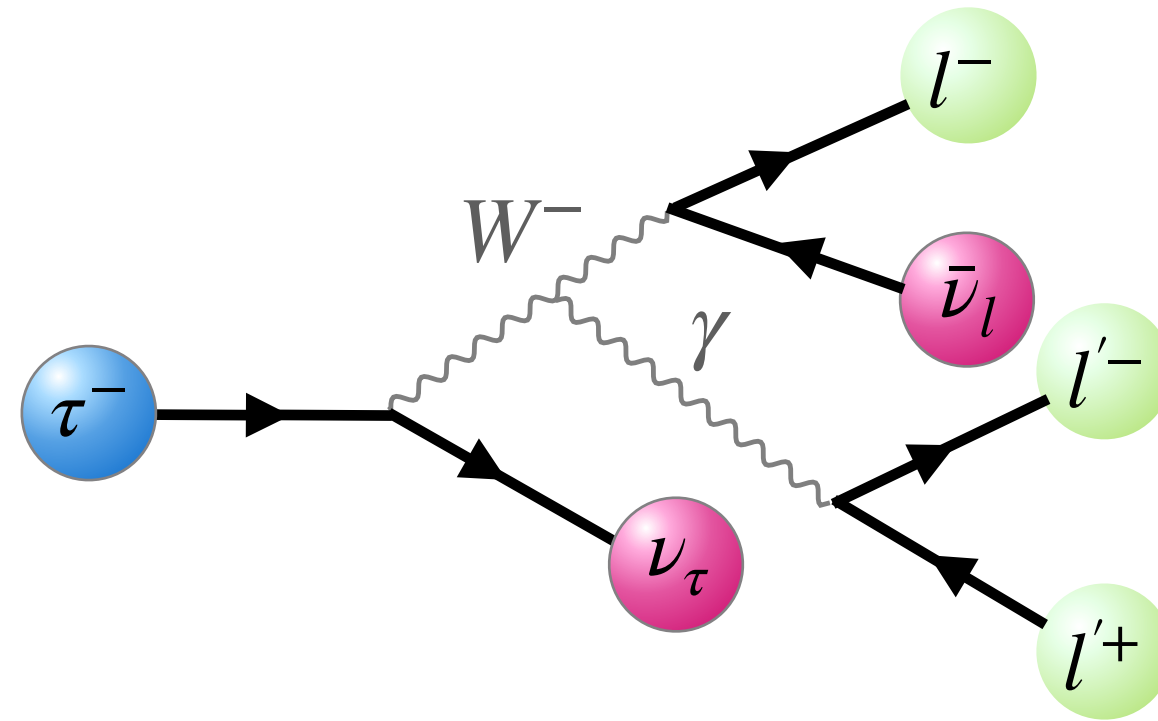
The measurements will significantly strengthen the constraints on the LFU test



# Rare radiative $\tau$ decays

## Leptonic decays

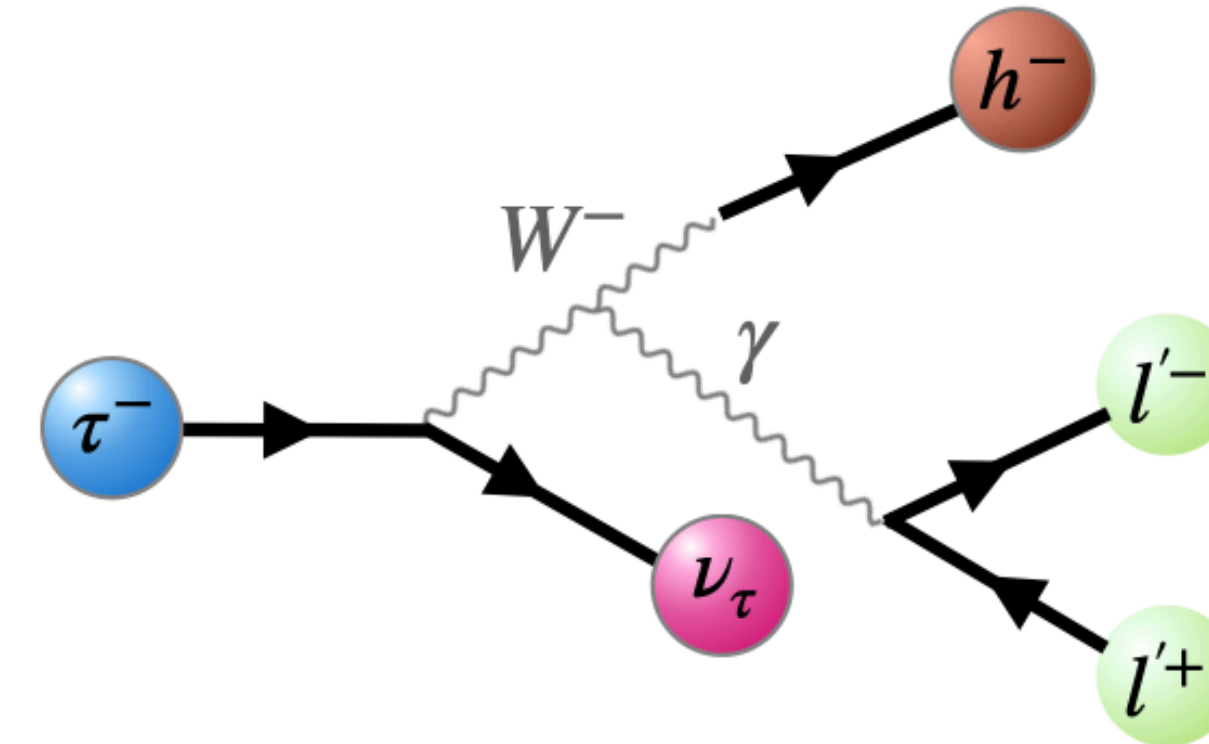
$$\tau^\pm \rightarrow l^\pm \gamma^* (\rightarrow l^+ l^-) \nu_\tau \quad (l = e, \mu)$$



- Precisely known electroweak process
- Precision test of radiative corrections
- Constrain Michel parameters
- Search for CP/T violation
- Clean theoretical interpretation

## Hadronic decays

$$\tau^\pm \rightarrow h^\pm \gamma^* (\rightarrow l^+ l^-) \nu_\tau \quad (h = K, \pi)$$



- Interplay of electroweak and strong interactions
- Sensitive to hadronic structure and form factors
- Test hadronic currents and chiral dynamics
- Sensitive to light mediators coupling to hadrons
- Complementary to leptonic channel

**Together, leptonic and hadronic radiative  $\tau$  decays provide complementary precision probes of the Standard Model and physics beyond it**

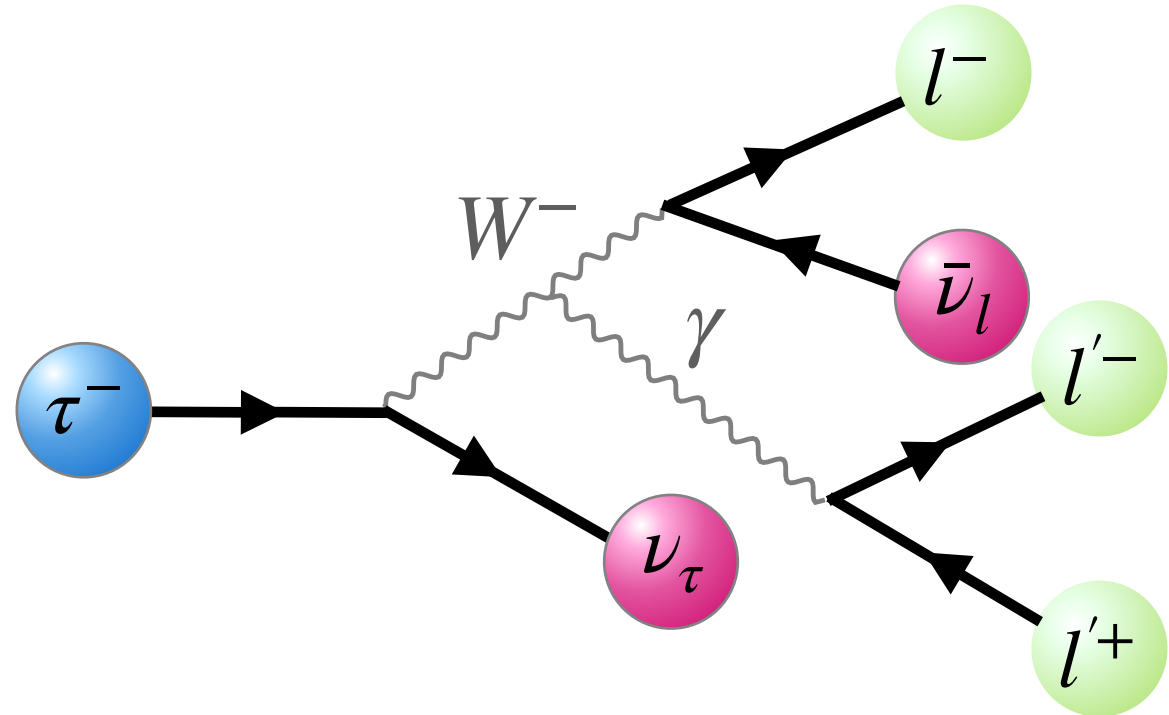


# Leptonic radiative $\tau$ decays

- Measurement by CLEO: PRL 76 (1996) 2637-2641

CLEO

| Channel                                                       | BR from theory                     | BR from PDG                               |
|---------------------------------------------------------------|------------------------------------|-------------------------------------------|
| $\tau^- \rightarrow e^- e^+ e^- \bar{\nu}_e \nu_\tau$         | $(4.21 \pm 0.01) \times 10^{-5}$   | $(2.8 \pm 1.5) \times 10^{-5}$            |
| $\tau^- \rightarrow \mu^- e^+ e^- \bar{\nu}_\mu \nu_\tau$     | $(1.984 \pm 0.004) \times 10^{-5}$ | $< 3.2 \times 10^{-5} (\text{CL} = 90\%)$ |
| $\tau^- \rightarrow e^- \mu^+ \mu^- \bar{\nu}_e \nu_\tau$     | $(1.247 \pm 0.001) \times 10^{-7}$ | —                                         |
| $\tau^- \rightarrow \mu^- \mu^+ \mu^- \bar{\nu}_\mu \nu_\tau$ | $(1.183 \pm 0.001) \times 10^{-7}$ | —                                         |



- Use full available Belle II dataset of  $914 \text{ fb}^{-1}$
- Analyses at a early stage but promising

First estimate of expected events

| Channel                                                       | N <sub>obs</sub> | CLEO |
|---------------------------------------------------------------|------------------|------|
| $\tau^- \rightarrow e^- e^+ e^- \bar{\nu}_e \nu_\tau$         | 603              | 7.8  |
| $\tau^- \rightarrow \mu^- e^+ e^- \bar{\nu}_\mu \nu_\tau$     | 284              | 2.6  |
| $\tau^- \rightarrow e^- \mu^+ \mu^- \bar{\nu}_e \nu_\tau$     | 1.8              | —    |
| $\tau^- \rightarrow \mu^- \mu^+ \mu^- \bar{\nu}_\mu \nu_\tau$ | 1.7              | —    |

Targeting the first observation of  $\mu ee$  and first limits on  $e(\mu)\mu\mu$



# Conclusion

## Connecting the energy and flavor frontiers through precision measurements

### ✓ Precision measurements complement direct searches

The absence of new particles at the LHC makes indirect probes increasingly important for exploring physics beyond the Standard Model.

### ✓ Precision Higgs measurements constrain new physics

Differential Higgs measurements and global EFT interpretations provide stringent tests of the electroweak sector.

### ✓ Detector development enables precision measurements

The Belle II Pixel Vertex Detector provides excellent vertex reconstruction that underpins precision  $\tau$  measurements.

### ✓ Belle II opens a new era of precision $\tau$ -physics

High-statistics data enable world-leading measurements of the  $\tau$  lifetime, mass and lepton flavor universality.

### ✓ Rare radiative $\tau$ decays offer unique discovery opportunities

Processes such as

$$\tau^{\pm} \rightarrow l^{\pm} \gamma^{*} (\rightarrow l^{+} l^{-}) \nu_{\tau} \quad \tau^{\pm} \rightarrow h^{\pm} \gamma^{*} (\rightarrow l^{+} l^{-}) \nu_{\tau}$$

**My research aims to connect precision collider and flavor measurements to explore physics beyond the Standard Model.**



Thank you



CERN



KEK



Freiburg



DESY



Jilin







# Backup

