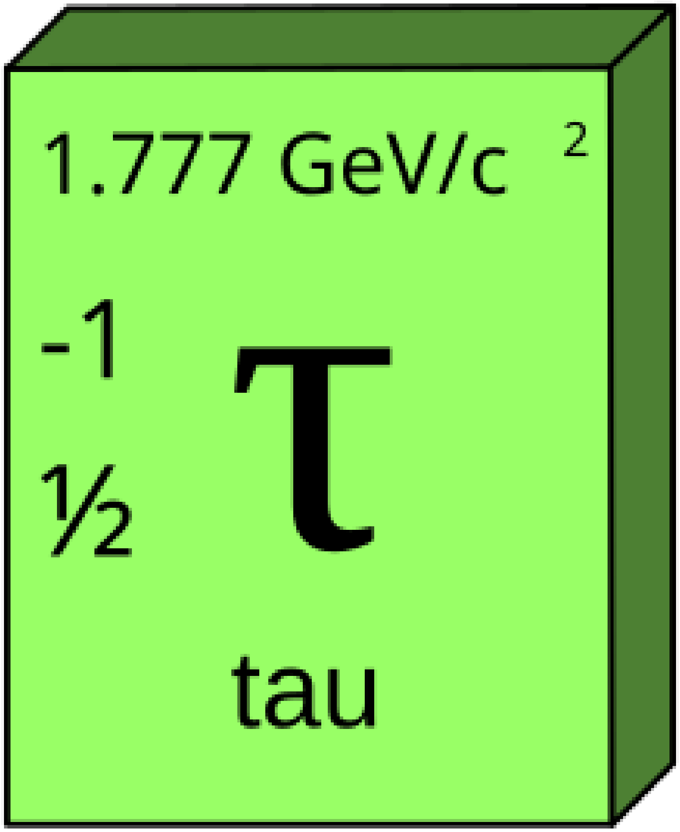
# Tau Analysis 101*



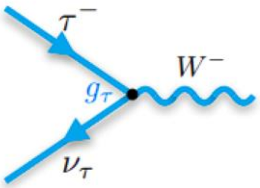
"We use (the name) $\tau$ because it appears to be the third charged lepton to be found and $\tau\rho\iota\tau o\nu$ means third in Greek."
– Martin Perl, Proceedings of the XII Recontre de Moriond (1977)

*Soeren Prell (Iowa State University)*
*Belle II Physics Week*
*October 14-18, 2024 @ KEK*

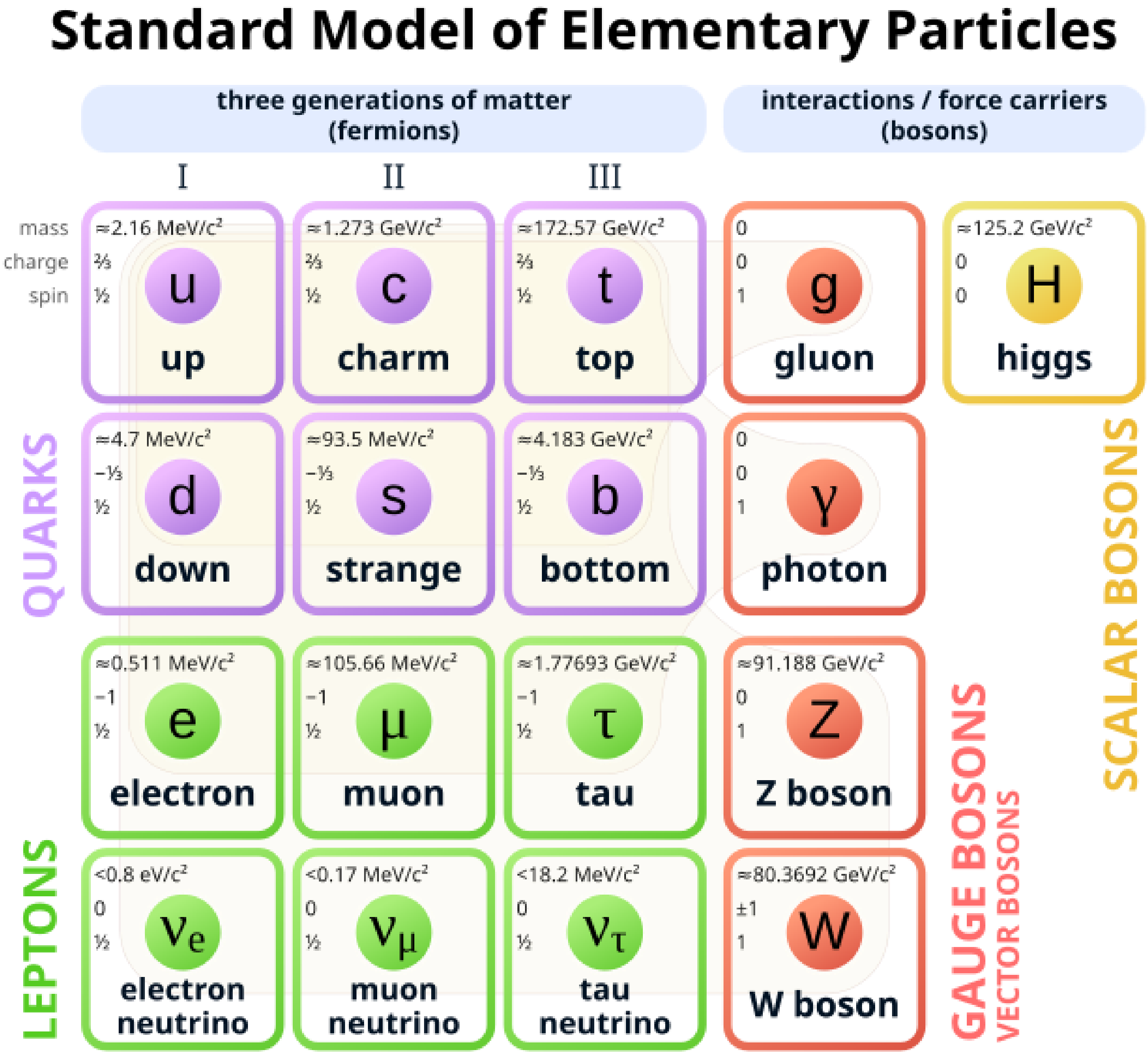
*101 (adjective): showing most basic knowledge about a subject

# *The τ in the Standard Model*

- *τ is a lepton and a member of a left-handed doublet*
  - *τ does not interact strongly*
- *τ lepton number $L_\tau$ is conserved*
  - *τ decays always have a $\nu_\tau$ in the final state*
  - *τ only decays via charged weak current*



- *The τ is heavy*
  - *Only lepton that decays to hadrons (but not to c, b, and t quarks)*

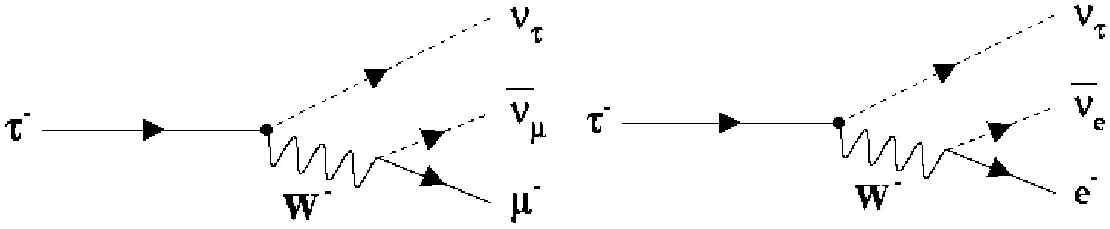


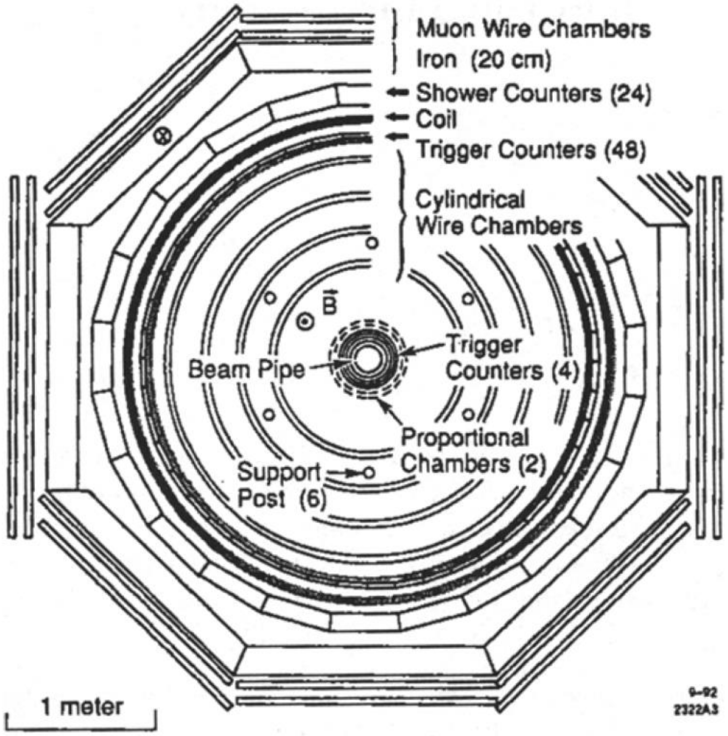
# *Brief history of heavy fermions*

- *1972 Kobayashi & Maskawa predict 3rd generation of quarks to explain CP violation in kaon decays*
- *1974 J/$\psi$ discovered independently at SLAC (Richter et al.) and BNL (Ting et al.) – first strong evidence for the charm quark*
- ***1975 $\tau$ lepton discovered at SLAC –<br>first evidence for 3rd generation fermions (Perl et al.)***
- *1977 $\Upsilon$(1S) discovered at Fermilab (Lederman et al.) – first evidence for the bottom quark and 3rd generation quarks*
- *1995 top quark discovered at Fermilab (D0 & CDF)*

# The $\tau$ discovery (1975)

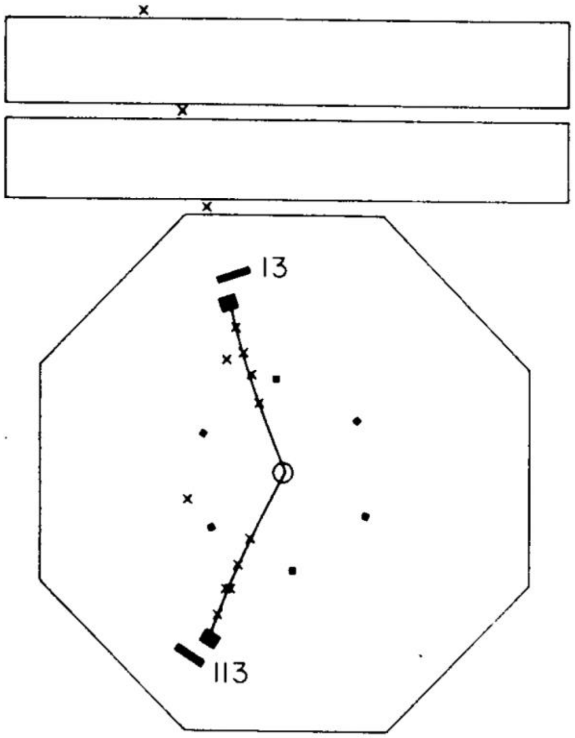
- *If a sequential 3rd charged lepton exists, it will decay to the first two generations*
- *Looking for* $e^+e^- \to \tau^+\tau^- \to e^\pm\mu^\mp E_{miss}$



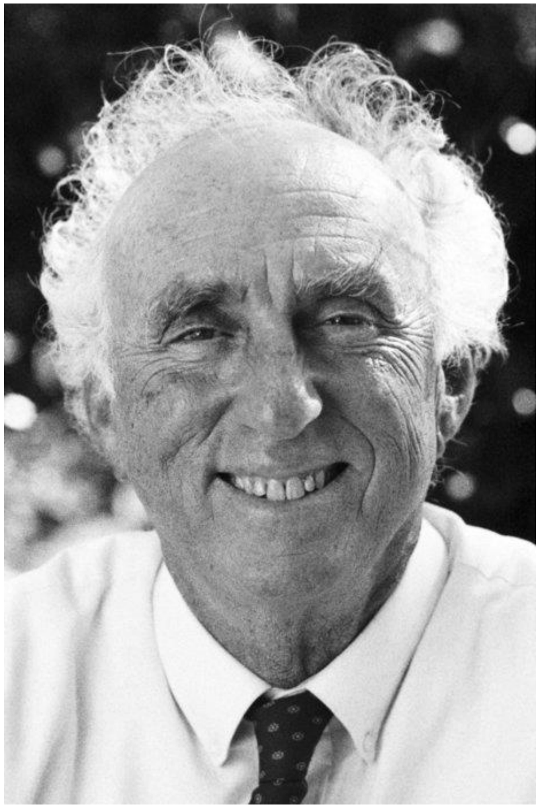


SLAC-LBL detector

Early $e^+e^- \to e^\pm\mu^\mp E_{miss}$ event

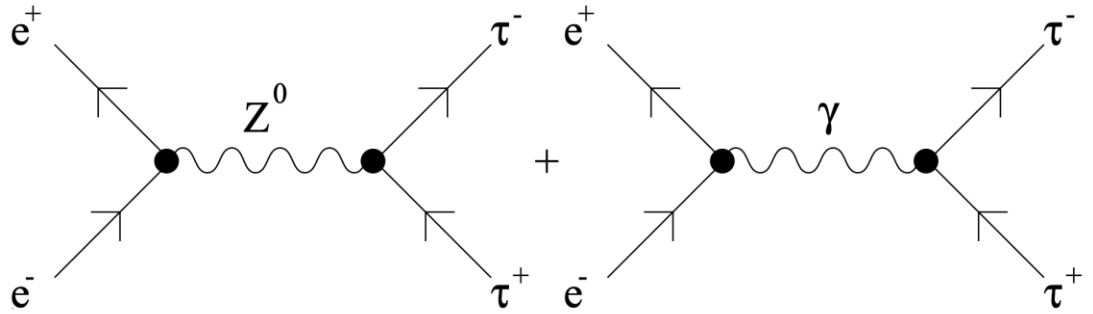


G.J. Feldman at
Lepton Photon 1975

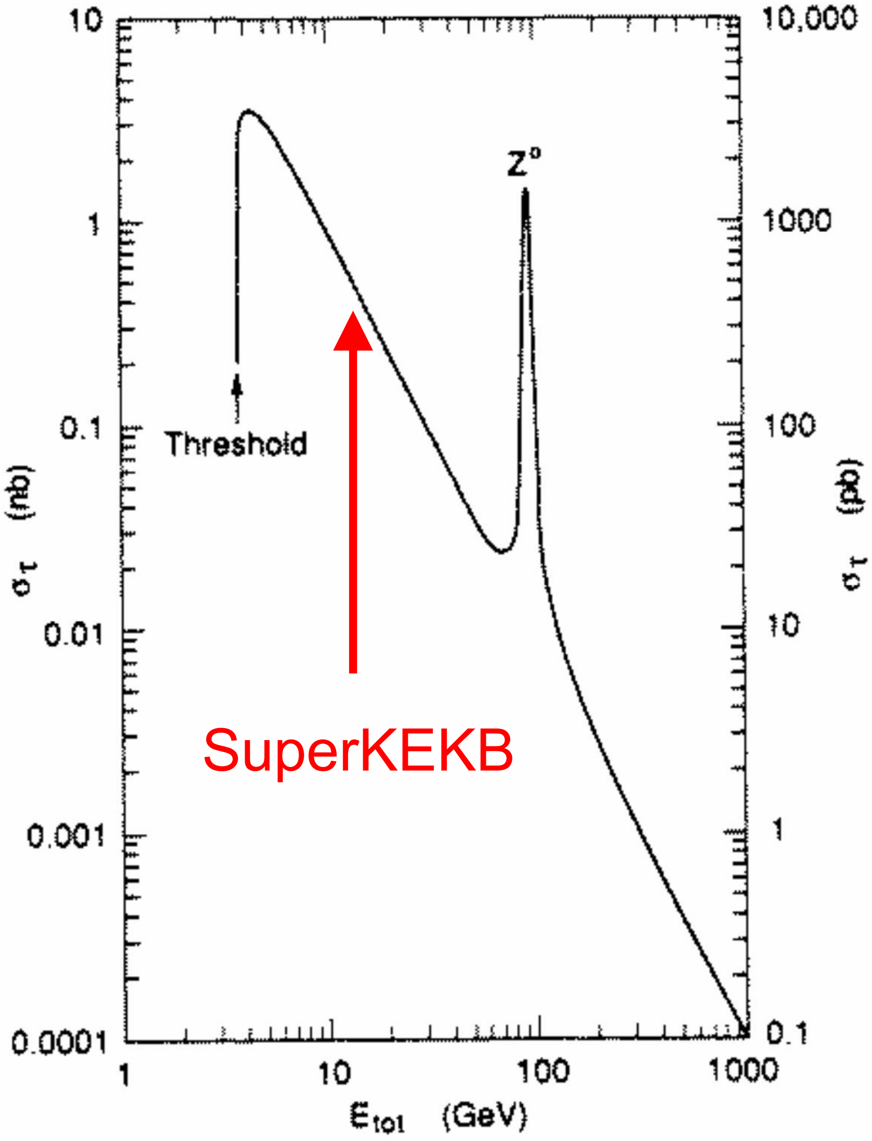


Martin Perl

# $\tau$ pair production in $e^+e^-$ collisions

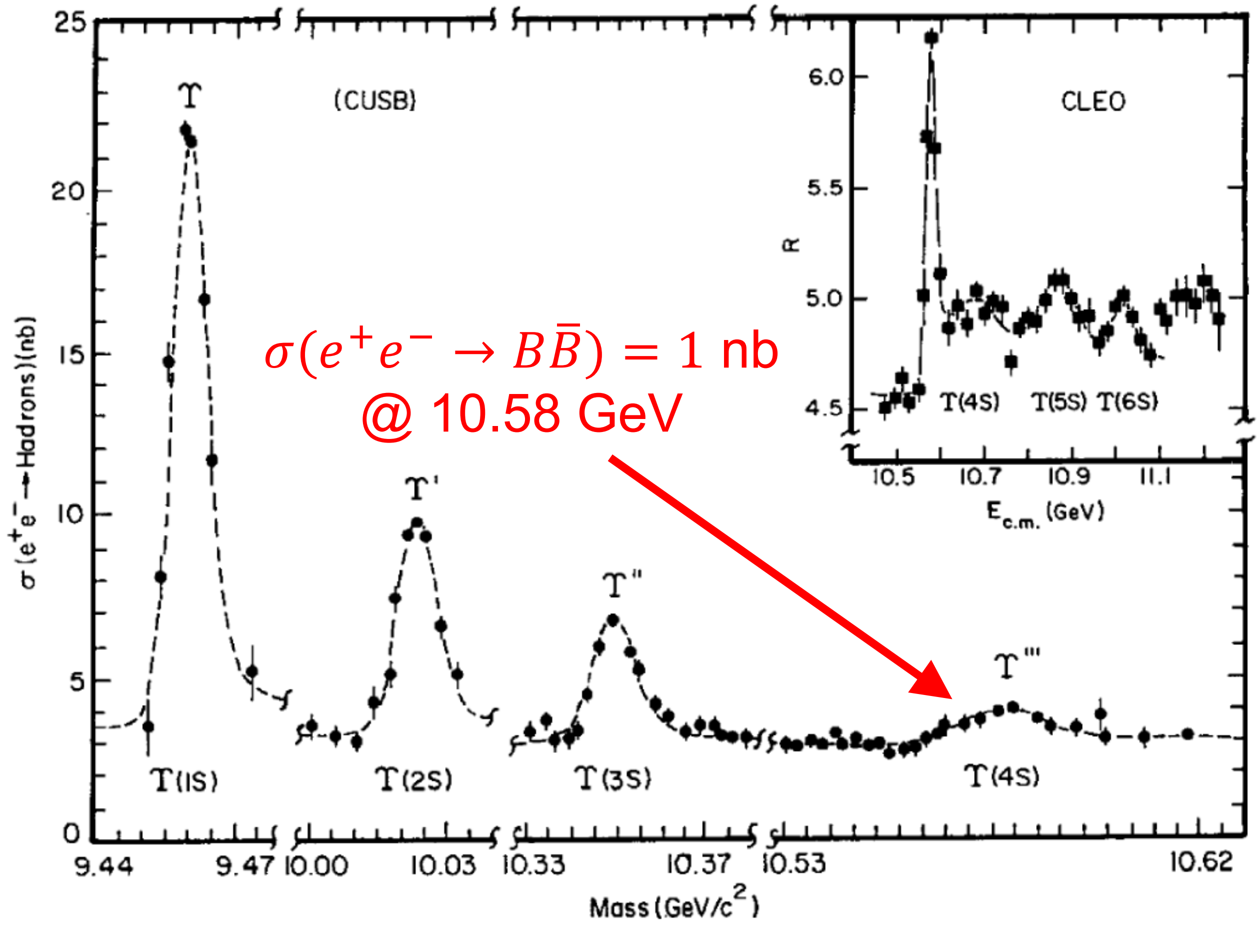


- *1st order diagrams for $\tau$ pair production*
- *$ee \to \tau\tau$ cross-section can be precisely calculated*
  - *Was already calculated before the $\tau$ was discovered (assuming that the $\tau$ is a point-like fermion of a certain mass)*



Cross-section rises sharply at the $2 \times m(\tau)$ threshold

# Belle II is $\tau$ factory !

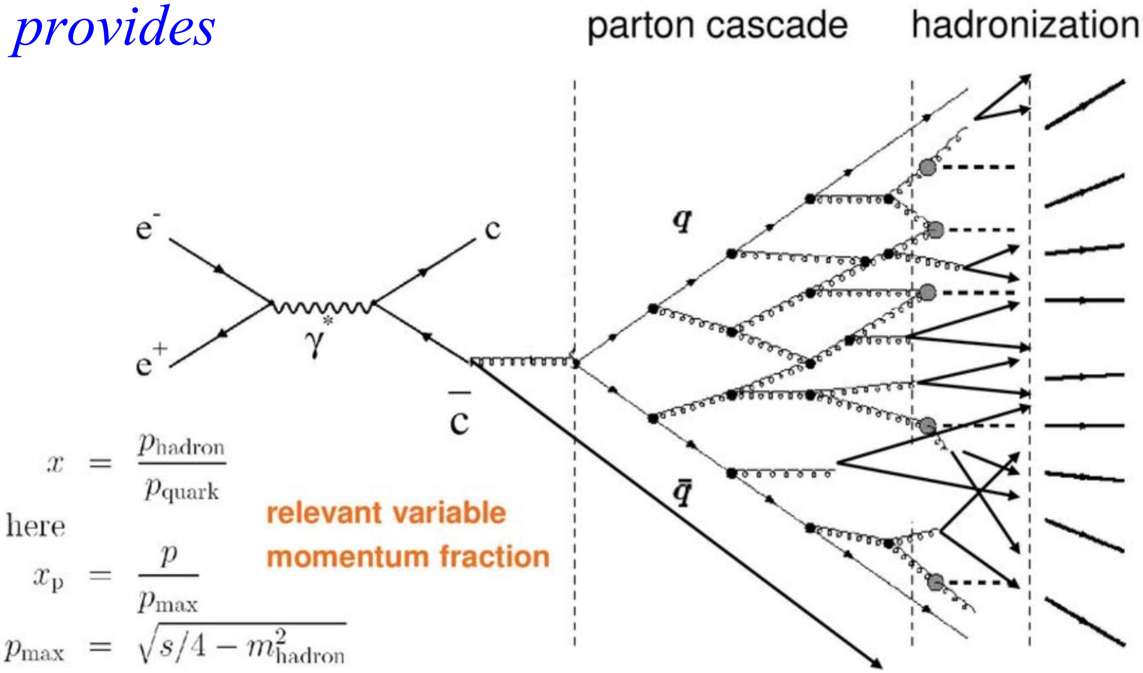


$\sigma(e^+e^- \to B\bar{B}) = 1$ nb
@ 10.58 GeV

- *We call Belle II a B factory because of the large* $e^+e^- \to B\bar{B}$ *cross-section at the* $\Upsilon(4S)$
- *The cross-section* $\sigma(e^+e^- \to \tau^+\tau^-) = 0.919 \pm 0.003$ *nb at 10.58 GeV*
  - *We produce 920,000* $\tau^+\tau^-$ *events per 1* $fb^{-1}$

# $\tau$ pair production is "clean"

- *$B\bar{B}$ production is clean at the $\Upsilon(4S)$*
  - *Only $e^+e^- \to B\bar{B}$ is allowed (no additional particles)*
  - *Not enough energy for $e^+e^- \to B^*\bar{B}$*
  - *Reconstruction on $B$ (tag) provides momentum of the other $B$*
- *Charm (and light) hadron production is not clean*
  - *Additional particles from fragmentation*
  - *Two charm hadrons can be of different types*
- *$\tau$ pair production is clean*
  - *No particles from fragmentation*
  - *$E_\tau^* = E_{beam}^*$ ( = 5.29 GeV at Belle II)*
  - *Reconstructing tag $\tau$ reduces background from non-$\tau$-pair events*



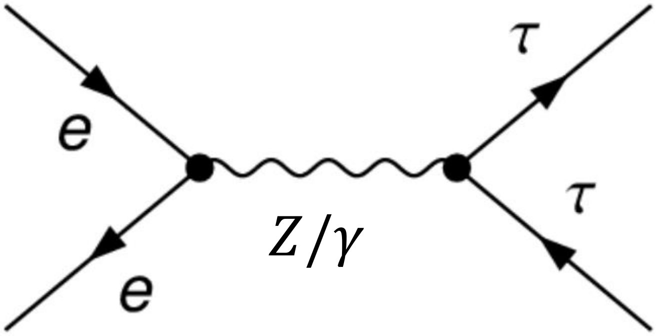
$$x = \frac{p_{\text{hadron}}}{p_{\text{quark}}}$$

here

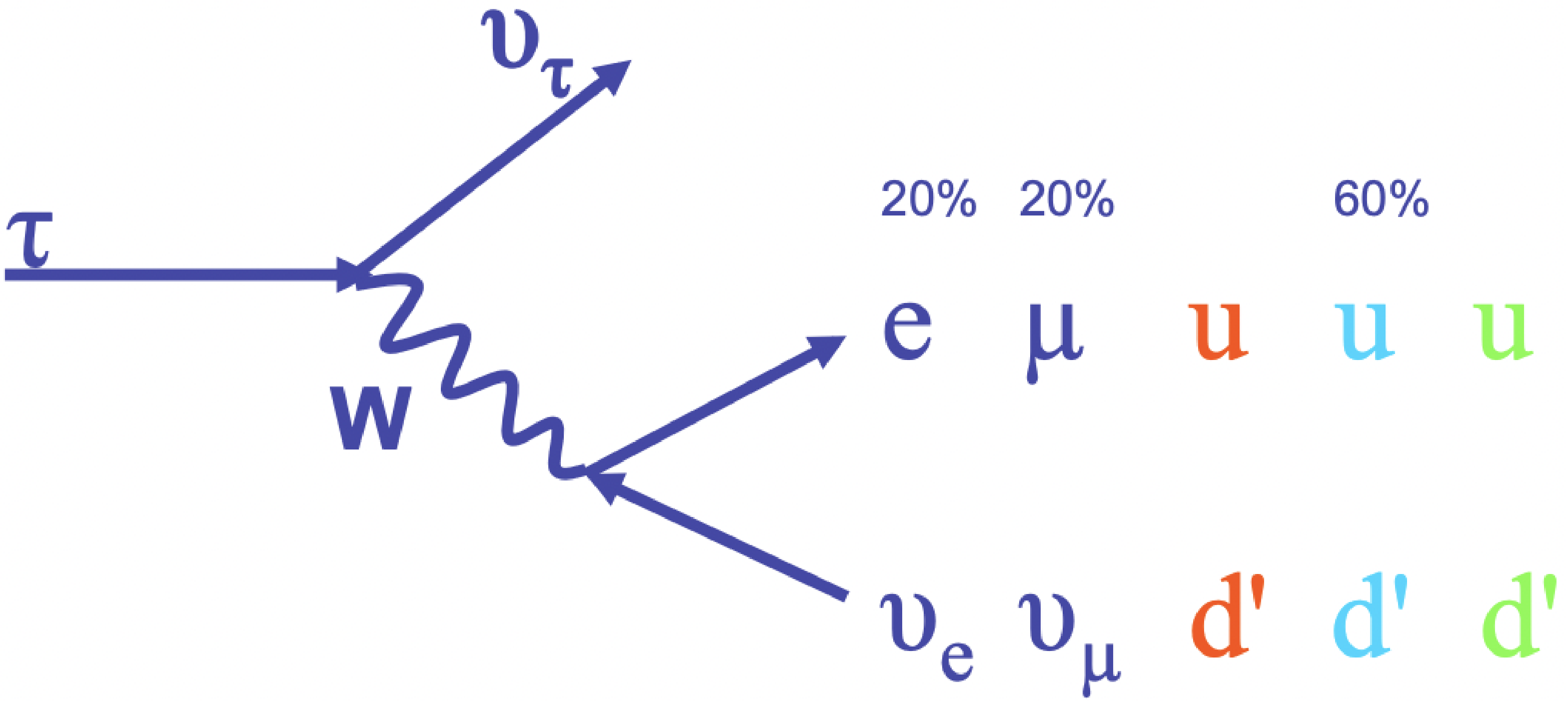
$$x_{\text{p}} = \frac{p}{p_{\max}}$$

$$p_{\max} = \sqrt{s/4 - m_{\text{hadron}}^2}$$

relevant variable momentum fraction



# *τ decay (simplified)*

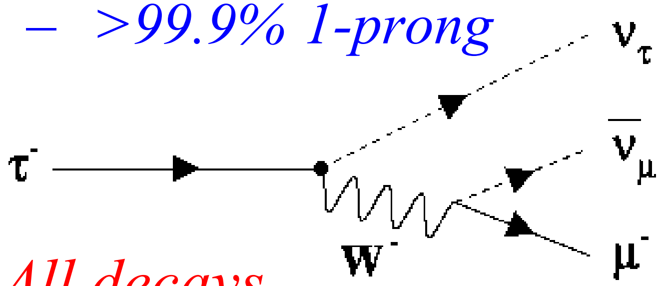


$$|d'\rangle = V_{ud}|d\rangle + V_{us}|s\rangle$$

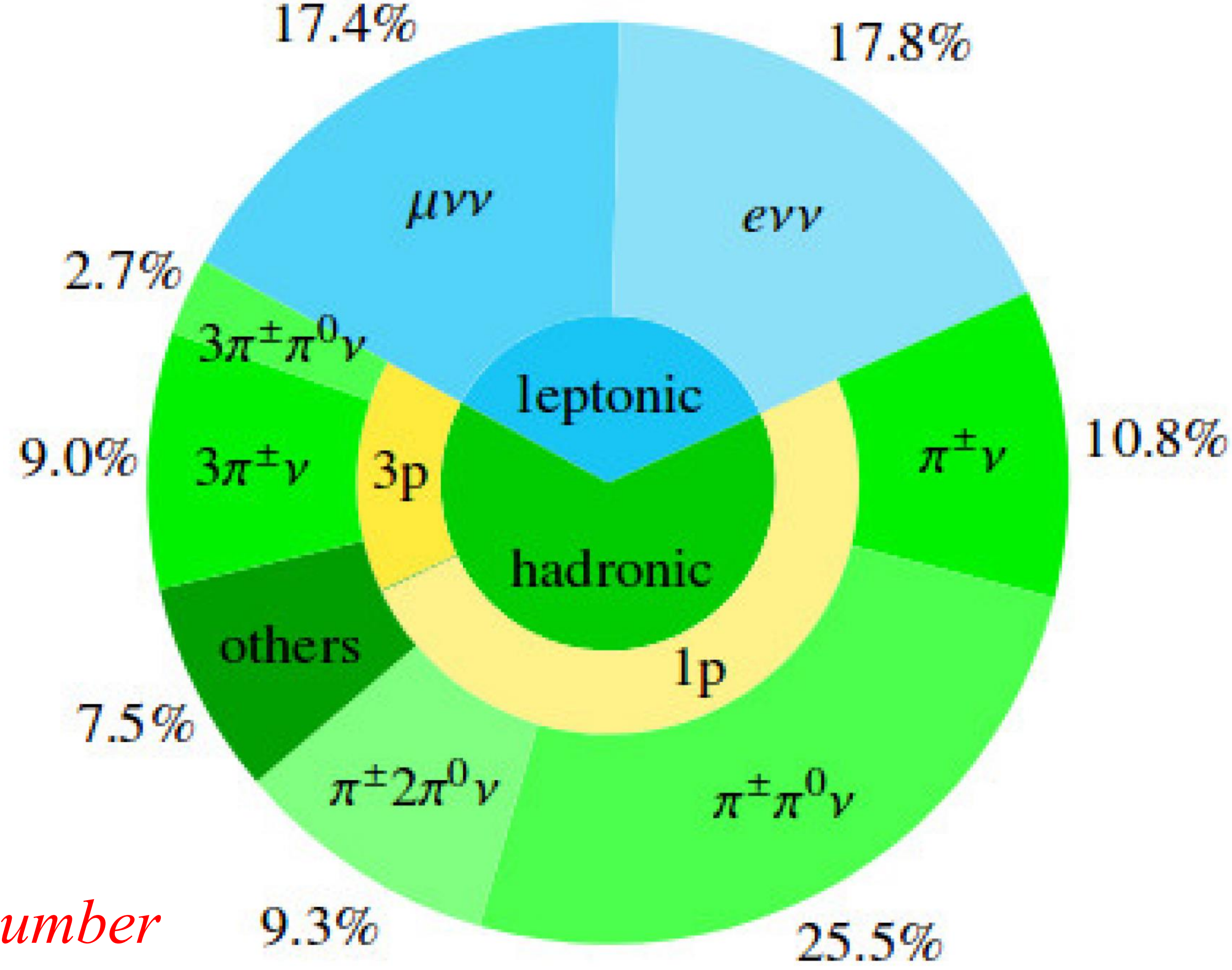
- *Leptonic branching fraction is ~20%*
- *(Semi) hadronic final states are mostly non-strange*
    - $|V_{us}|^2 = \sin^2\theta_C =$ *5% of hadr. decays have net strangeness*

# *$\tau$ branching fractions*

- *35% leptonic*
  - *~ 50:50 electrons and muons*
- *65% hadronic*
- *Leptonic decays*
  - *>99.9% 1-prong*



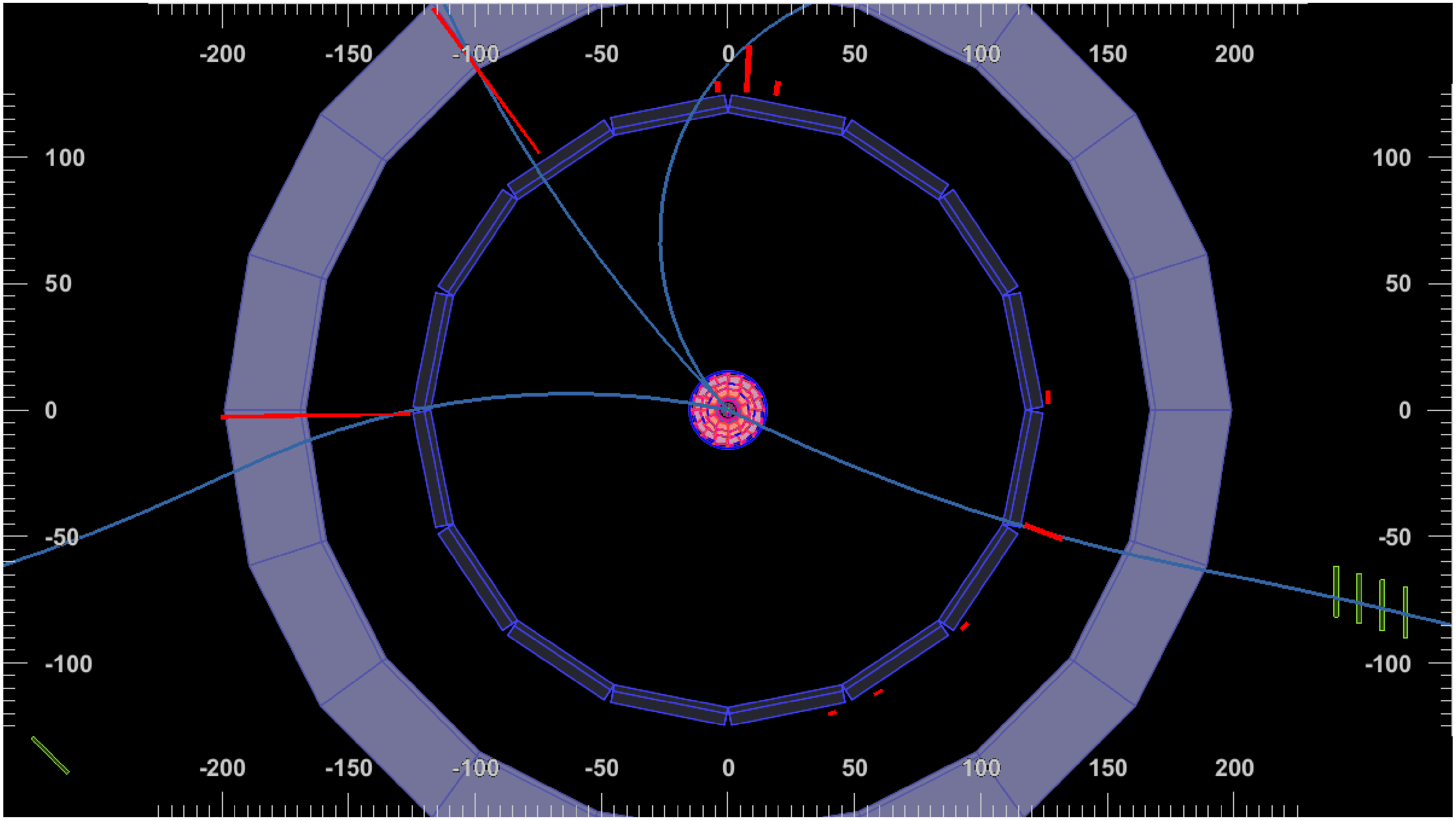
- *All decays*
  - *85 %* *1-prong*
  - *15 %* *3-prong*
  - *0.1 %* *5-prong*
  - *$< 3\times10^{-7}$* *7-prong*
- *All $\tau$ decays have an odd number of charged particles (prongs*) in the final state*



*prong (noun): projecting pointed parts at the end of a fork

# *Tau events are really clean !*

$\tau$ pair events have either 2 tracks (73%), 4 tracks (26%), or 6 tracks (2%)



A typical (3x1) event.

Candidate for a $e^+e^- \rightarrow (\tau^+ \rightarrow 3\pi\bar{\nu}_\tau)\left(\tau^- \rightarrow \mu^-\nu_\tau\bar{\nu}_\mu\right)$ event

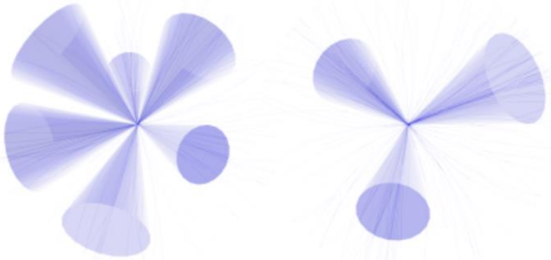
# *$\tau$ pair kinematics*

$$e^+e^- \rightarrow \tau^+\tau^-$$

- *Energy conservation ("jetty" $\tau$ pairs or boosted $\tau$'s)*
  - $E_\tau^* = E_{beam}^* = 5.29\ \text{GeV} \rightarrow p_\tau^* = 5.0\ \text{GeV}$ $(m_\tau = 1.777\ \text{GeV})$
- *Momentum conservation (back-to-back taus)*
  - $\vec{p}^*(\tau^-) = -\vec{p}^*(\tau^+)$ *(* indicates center-of-mass system)*

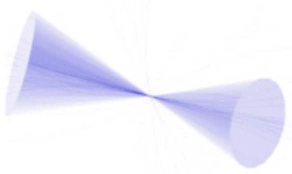
- *Unfortunately, we don't know the direction of the $\tau$'s*
  - *Each $\tau$ decays to one or more neutrinos, taking away momentum*
- *Approximate the directions of the $\tau$'s with the event thrust axis $\hat{n}_T$*
  - *The thrust axis maximizes the thrust magnitude $T$*

isotropic



$T \ll 1$

jetty



$T \sim 1$

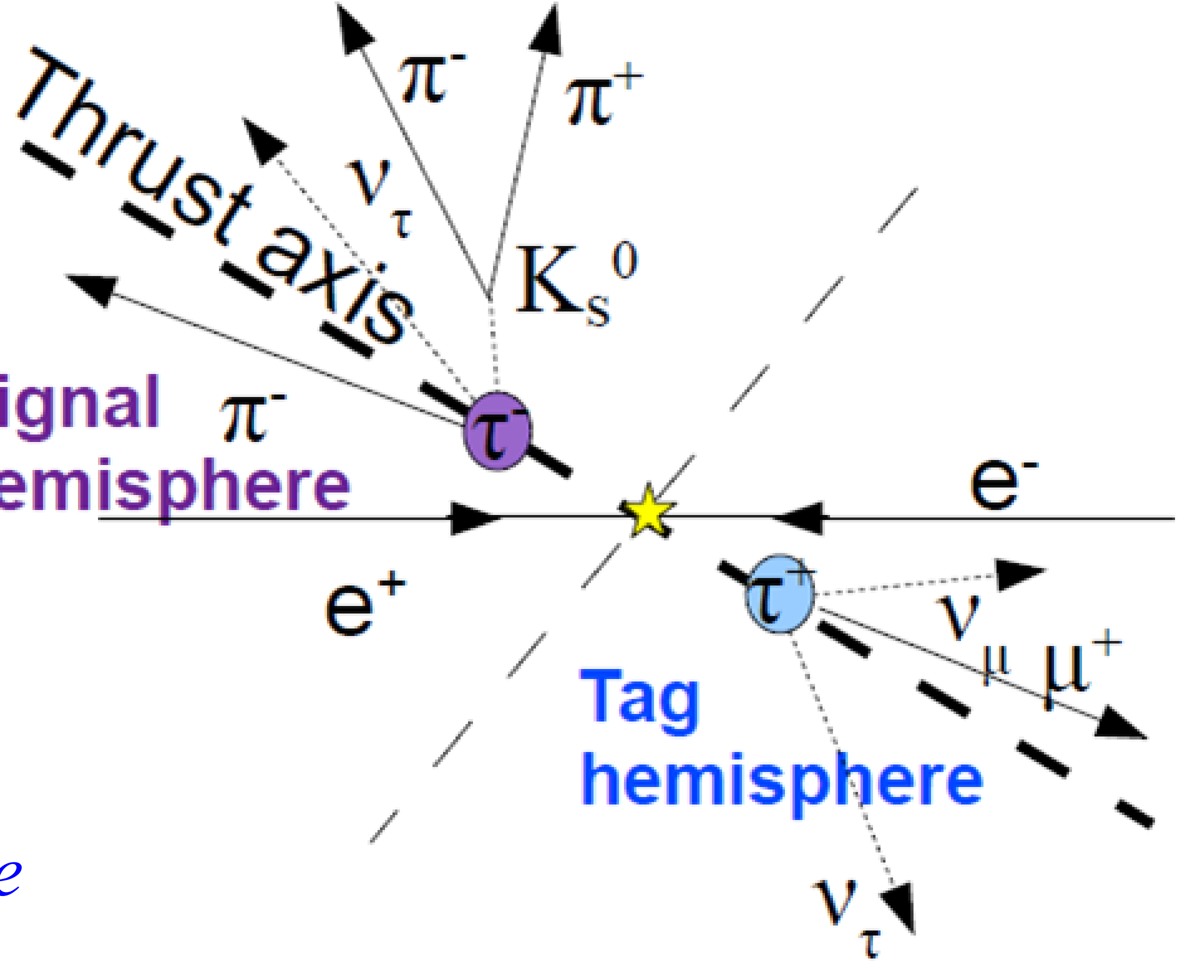
$$T = \frac{\sum |\vec{p}_i^* \cdot \hat{n}_T|}{\sum |\vec{p}_i^*|}$$

*i runs over all tracks and neutral particles in the event*

# *Signal τ and tag τ*

*Use the thrust axis to split event into two hemispheres*

- *Each hemisphere contains decay products of only one τ*



- *The signal hemisphere contains the signal τ, and the tag hemisphere contains the tag τ*

# *Backgrounds*

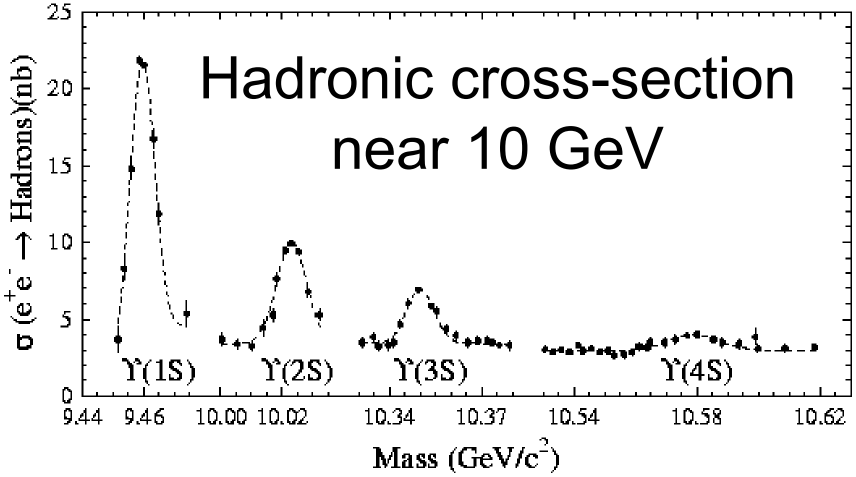
- *The actual background in any analysis strongly depends on the final state under study …*

- *The "usual" backgrounds …*
  - $B\bar{B}$: *many tracks (~10 on average), isotropic topology*
  - $q\bar{q}$ *continuum: many tracks, jetty-ish, few leptons*

*… can be effectively suppressed requiring a **large thrust value**, and either an e or μ in the tag hemisphere **(lepton tag)***

- *The "unusual" backgrounds (low-multiplicity backgrounds)*
  - $e^+e^-(\gamma)$ *or Bhabha events*
  - $\mu^+\mu^-(\gamma)$ *or mu pair events*
  - $e^+e^-$ *X, where X can be a lepton pair, a hadronic resonance or a multi-hadron final state*

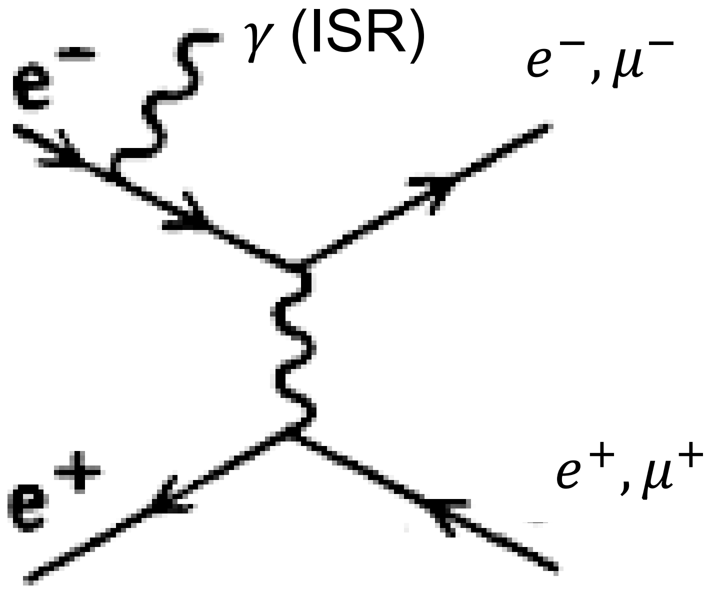
(with or without initial state radiation (ISR) or final state radiation (FSR))

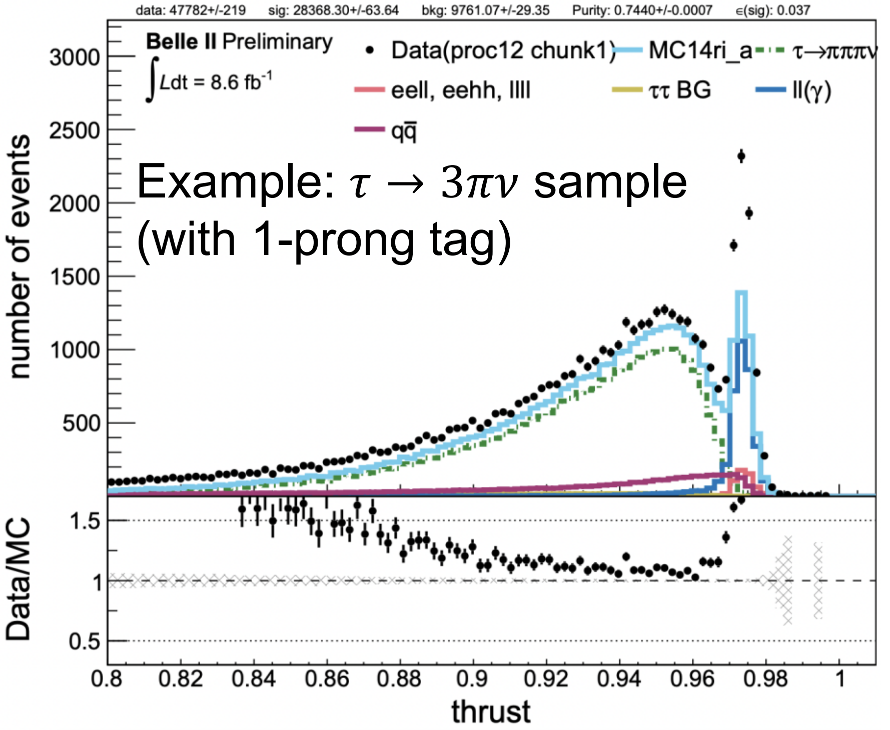


"unusual" backgrounds don't show up here

# *Backgrounds from $ee(\gamma)$ and $\mu\mu(\gamma)$*

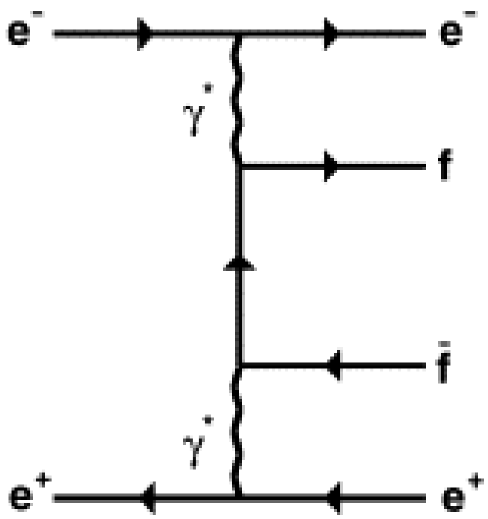
- *$\gamma$ can come from ISR or FSR, or from interaction with detector material (bremsstrahlung)*
- *Relatively easy to identify, but huge cross-section ( $\gg \sigma(ee \to \tau\tau)$ )*
- *Even an issue for (3x1) tau events*
  - *$\gamma$ can convert in detector material to $e^+e^-$ or (if virtual) turn into a vector meson*
- *$\gamma$ is mostly soft, and the leptons have nearly beam energy and remain very collinear*
  - *$\ell\ell(\gamma)$ events have large thrust value*
- *Cut on thrust is effective against $ee(\gamma)$ and $\mu\mu(\gamma)$ backgrounds*





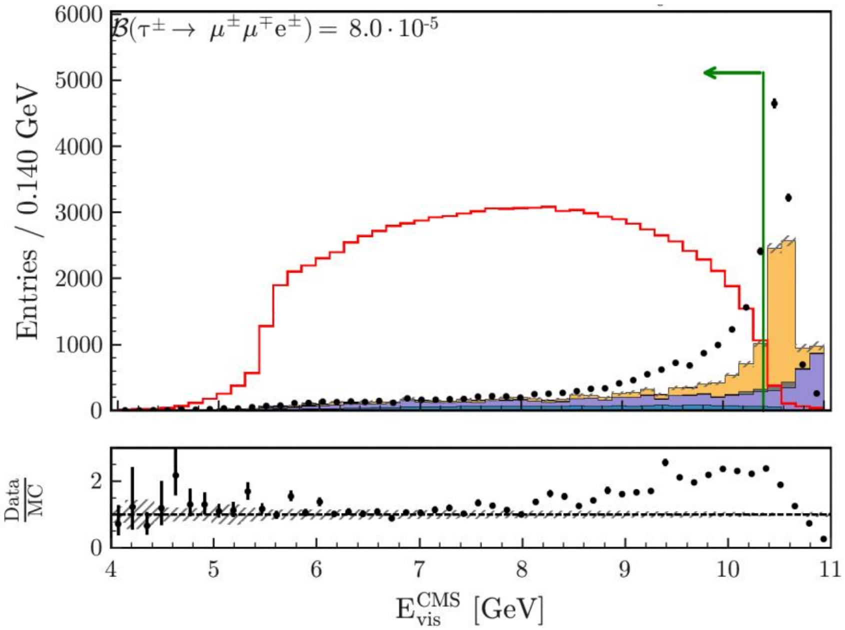
Example: $\tau \to 3\pi\nu$ sample (with 1-prong tag)

# *Four-fermion backgrounds (2-photon events)*



- *Produced fermions $f\bar{f}$ can be leptons or quarks*
  - *quarks can form hadronic resonances* <br>*→ $f\bar{f}$ system can produce 2,3,4, or more hadrons*
- *The $\gamma^*$ are often emitted collinear with the beams and the beam electrons disappear in the beam pipe carrying a lot of energy; but not always*
- *Possible scenarios*
  - *Beam electrons go down the beam pipe → small mass of the $f\bar{f}$ system*
  - *Beam electrons are scattered into the detector → if $f\bar{f}$ system produces 2 tracks, event can mimic (3x1) $\tau$ event* <br>*→ Contrary to $\tau$ events, there are no $\nu$'s and the 4 tracks carry the full CM energy*

Example: visible energy of $\tau^- \to \mu^+\mu^-e^-$ candidates in LFV search



# *Missing energy/momentum in $\tau^+\tau^-$ events*

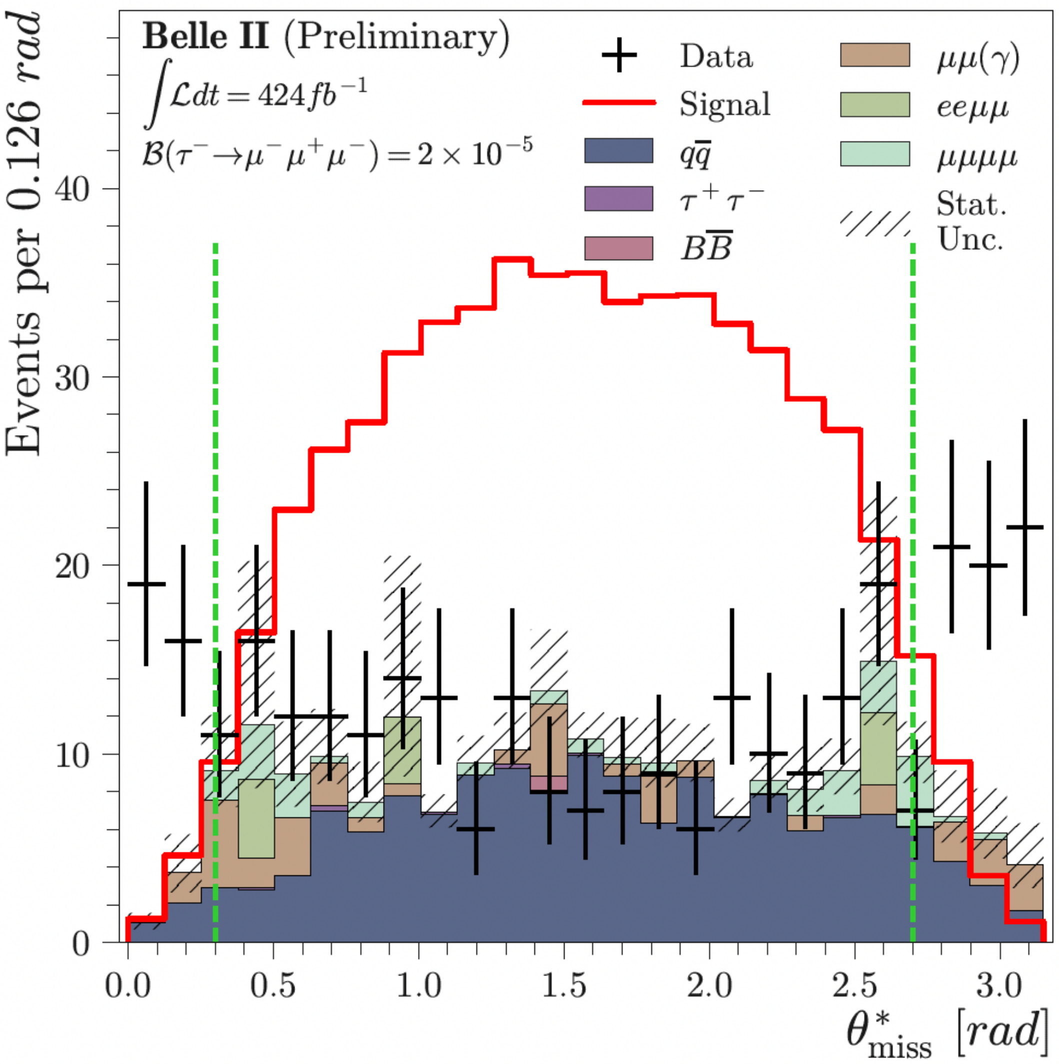
- *$\tau$ pairs have at least 2 $\nu_\tau$ in the SM*
  - *Hadr. $\tau$ decays have 1 neutrino ($\nu_\tau$)*
  - *Leptonic $\tau$ decays also have an $\bar{\nu}_\ell$*

**→ *Large missing energy in $\tau^+\tau^-$ events***

- *Missing energy also arises if particles are not detected (e.g., when they go down the beam pipe)*

- *In reconstructed $\tau^+\tau^-$ events, the missing momentum vector is aligned with visible energy and the thrust axis*

**→ *Missing momentum vector points into fiducial detector volume in $\tau^+\tau^-$ events***



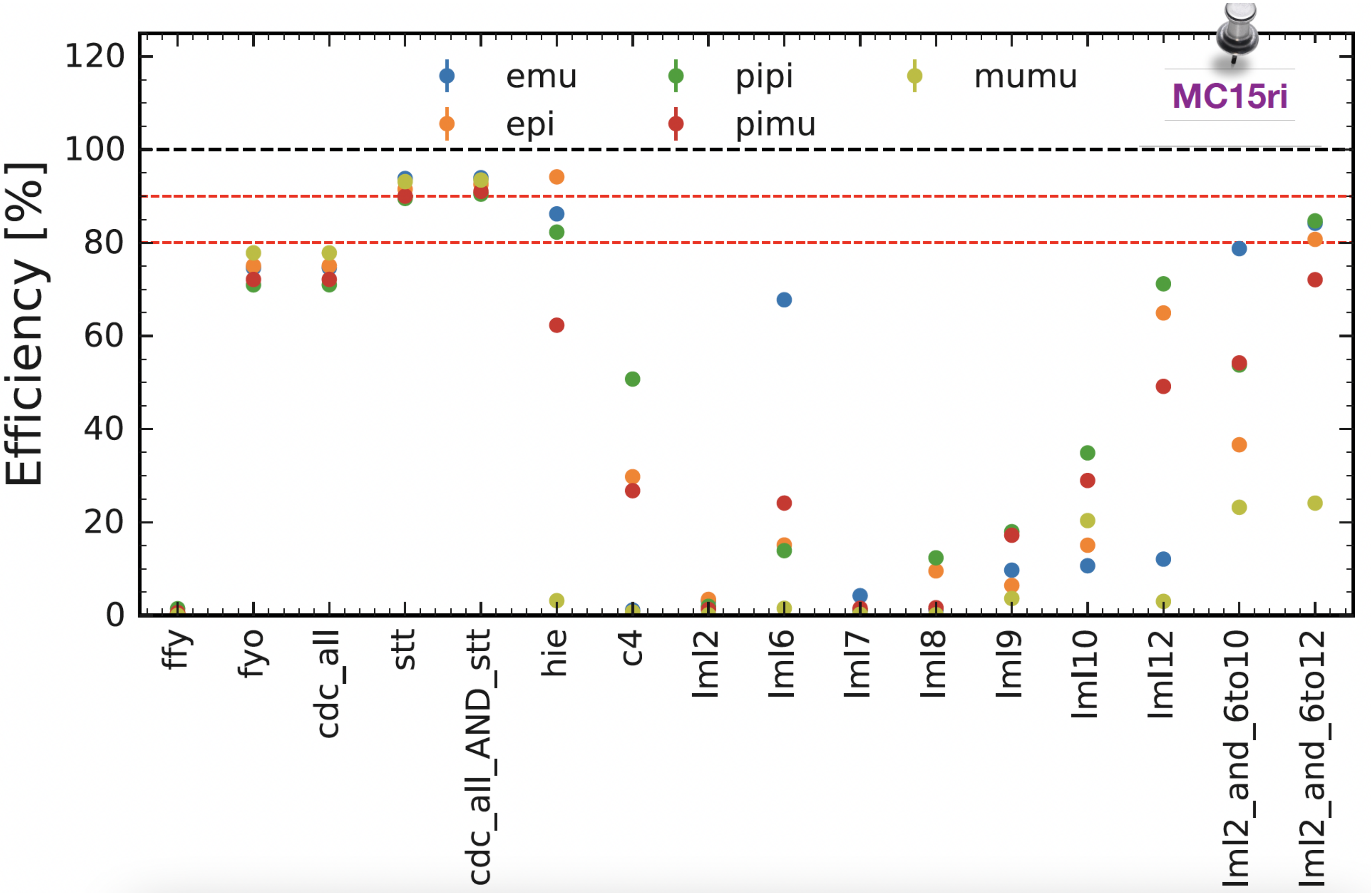
Many low-multiplicity backgrounds are not modeled very well.

# *Typical $\tau$ analysis cuts*

- *Object reconstruction*
  - *Usual criteria for tracks and neutrals (incl. particle ID)*
  - *Resonance masses*
- *Event variables*
  - *Track multiplicity (and neutral multiplicity)*
  - *Thrust magnitude*
  - *Visible energy, missing momentum magnitude, missing mass (squared)*
  - *Missing momentum direction*
- *Tag variables*
  - *3-prong tag (e.g., if signal tau decay is one-prong)*
    - *To reject $\ell\ell(\gamma)$ backgrounds*
  - *1-prong tag (leptonic or hadronic)*
    - *For larger efficiency and to reject $q\bar{q}$ background*
  - *Inclusive tag (combined many ROE variables in a BDT)*

# *Trigger efficiency uncertainty is not negligible!*

- *Trigger efficiency is 100% for $B\bar{B}$ events, but not for $\tau^+\tau^-$ events*
- *$\epsilon_{trig}$ and its uncertainty need to be determined*
- *Worst $\epsilon_{trig}$ for (1x1) topologies*



# *Belle II's τ analyses*

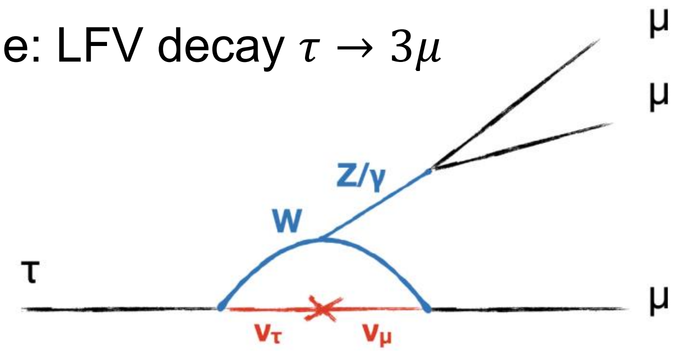
1. ***Lepton flavor violation (LFV) searches***

2. ***(Precision) tests of the SM***

# Lepton number/flavor conservation

- *Lepton flavor is almost conserved in SM*
- *Loop diagrams with ν mixing can give charged lepton flavor violation (cLFV)*

Example: LFV decay $\tau \to 3\mu$



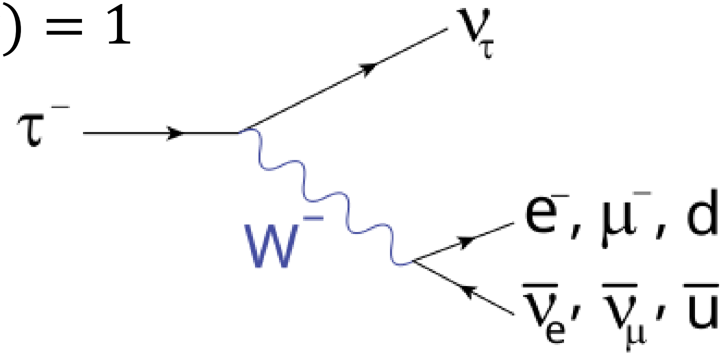
  - *SM cLFV BFs are of order* $10^{-(50\pm2)}$

- *Many beyond SM models predict cLFV:*
  - *E.g., Leptoquarks (LQ), Z'*

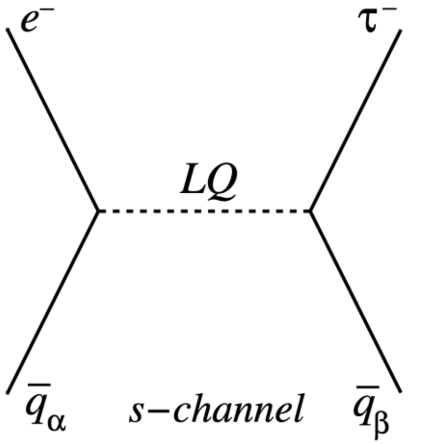
*Any observation of cLFV will make you famous !*

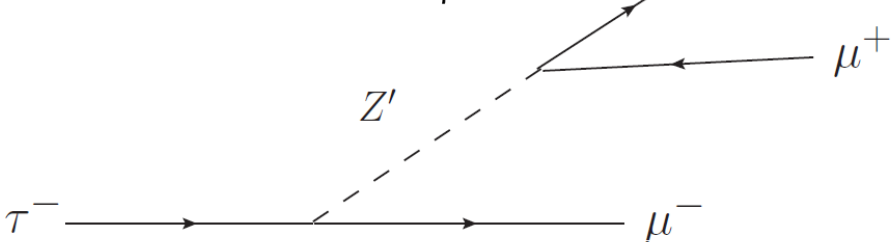
$N_\tau(\nu_\tau) = 1$

$N_\tau(\tau) = 1$

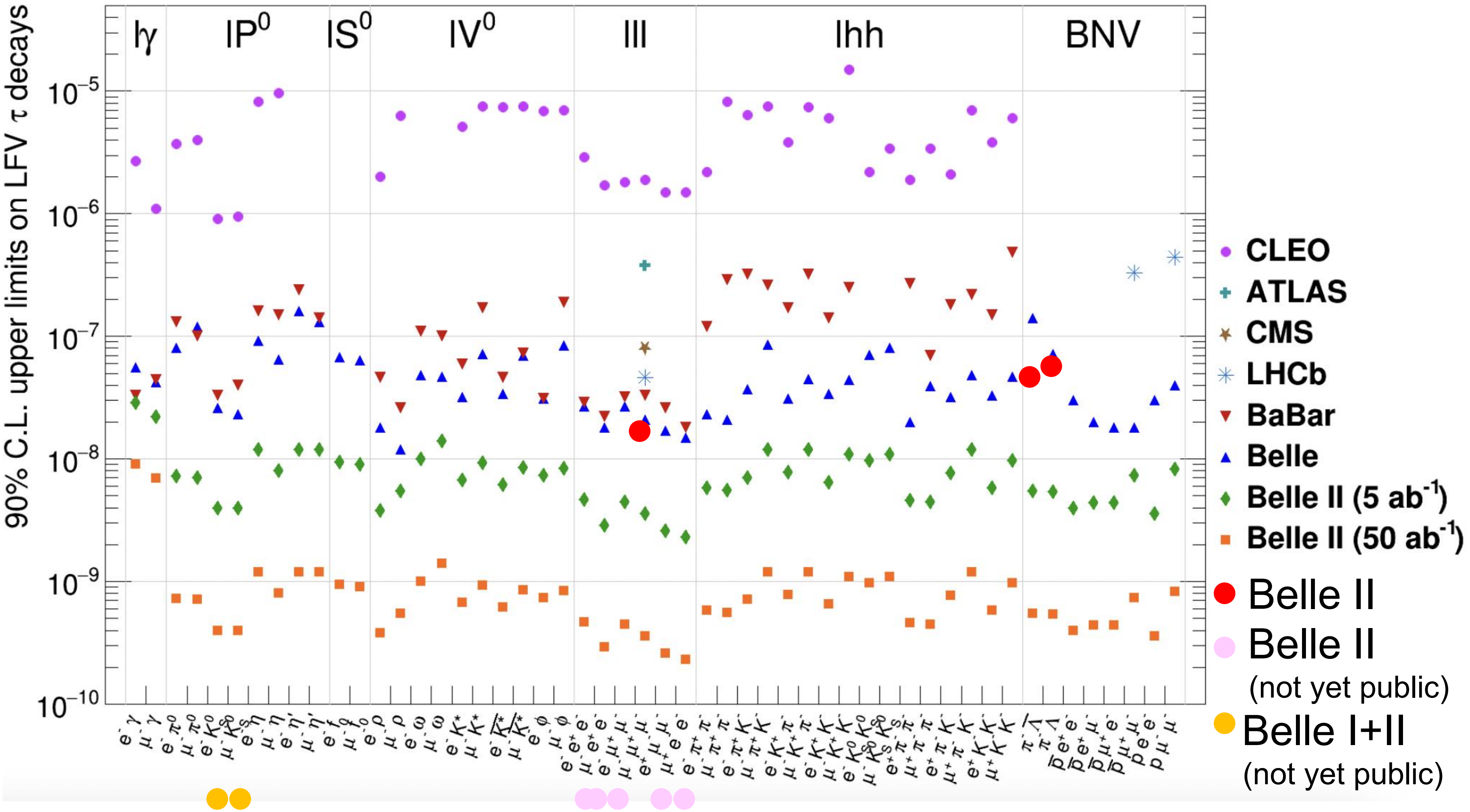


$N_\tau = 0$





# *Limits on LFV $\tau$ decays*

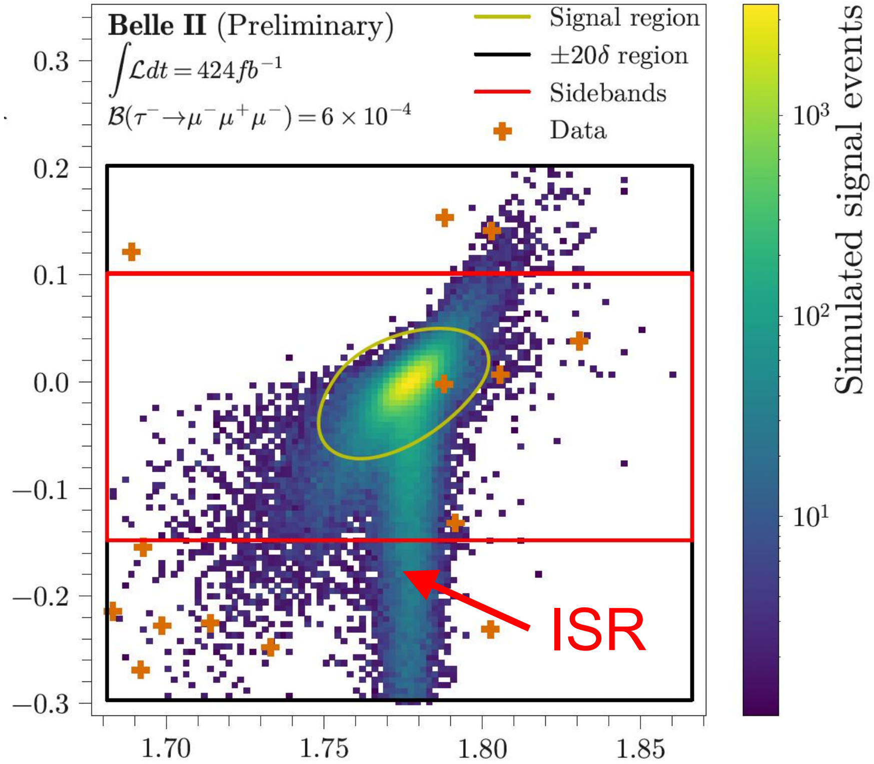


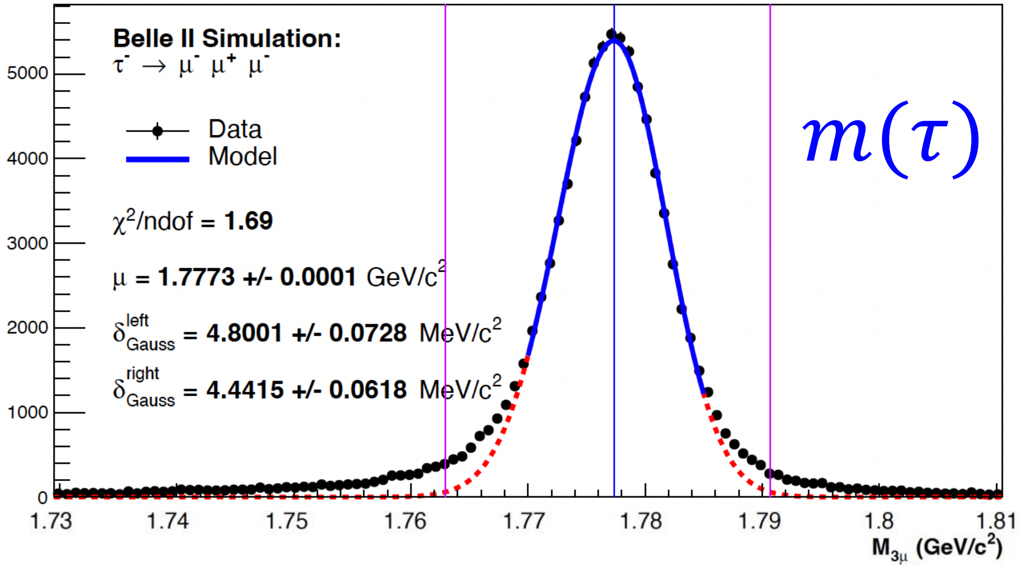
More searches are in progress, but all $\ell S^0, \ell V^0, \ell hh,$ and remaining BNV modes are not covered; should repeat <u>all searches</u> every time our dataset doubles !

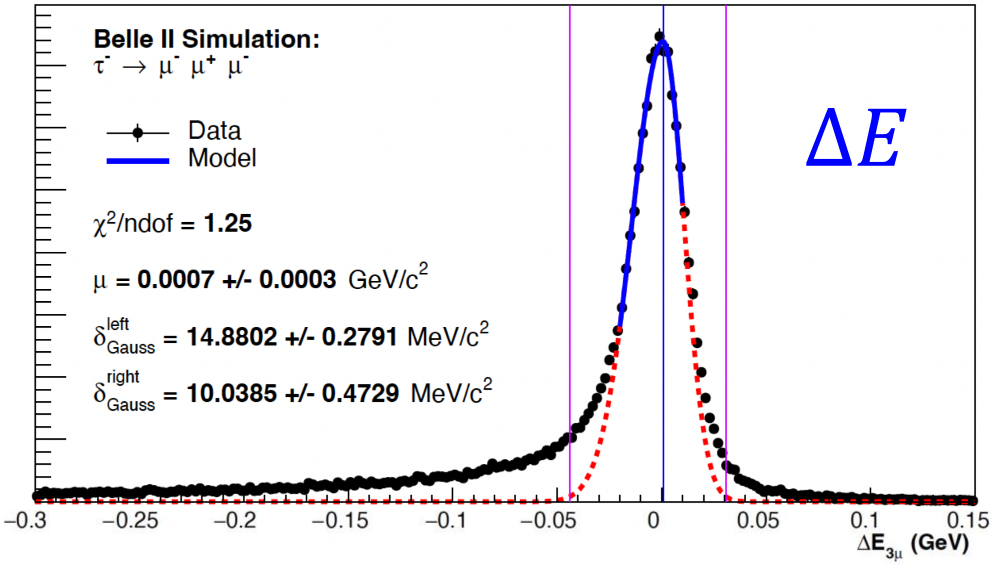
# *Fully-reconstructed $\tau$'s*

- *In (most) LFV $\tau$ searches, final state can be fully reconstructed (no neutrinos)*
- *Important kinematic variables*
  - *mass of $\tau$ candidate $m(\tau)$*
  - *difference between $\tau$ energy and beam energy (in center of mass)* $\Delta E = E^*(\tau) - \sqrt{s}/2$
  - *$\Delta E$ tail towards lower values due to ISR*
- *Signal yield usually estimated in $m(\tau)$-$\Delta E$ signal region*

$m(\tau)$-$\Delta E$ signal region







# *Tests of the SM with $\tau$ measurements*

- *Tau properties*
  - *Lifetime*
  - *Mass*
  - *Electric and magnetic dipole moment (also of $\mu$)*
- *Couplings*
  - *Lepton flavor universality*
  - *Vus*
  - *Michel parameters*
  - *Second class currents*
  - $\alpha_S$
  - *CP violation*
- *Hadronic system*
  - *Spectral functions*
  - *Partial-wave analyses*

Almost all measurements
are systematically limited:
400M $\tau$ pair events !!!

# τ lifetime

- *The τ decays weakly. τ lifetime is the ratio of the leptonic BF and width*

$$\tau_\tau = \frac{1}{\Gamma_{tot}} = \frac{B(\tau \to l\nu_l\nu_\tau)}{\Gamma(\tau \to l\nu_l\nu_\tau))}$$

- *and the leptonic width can be calculated in the SM*

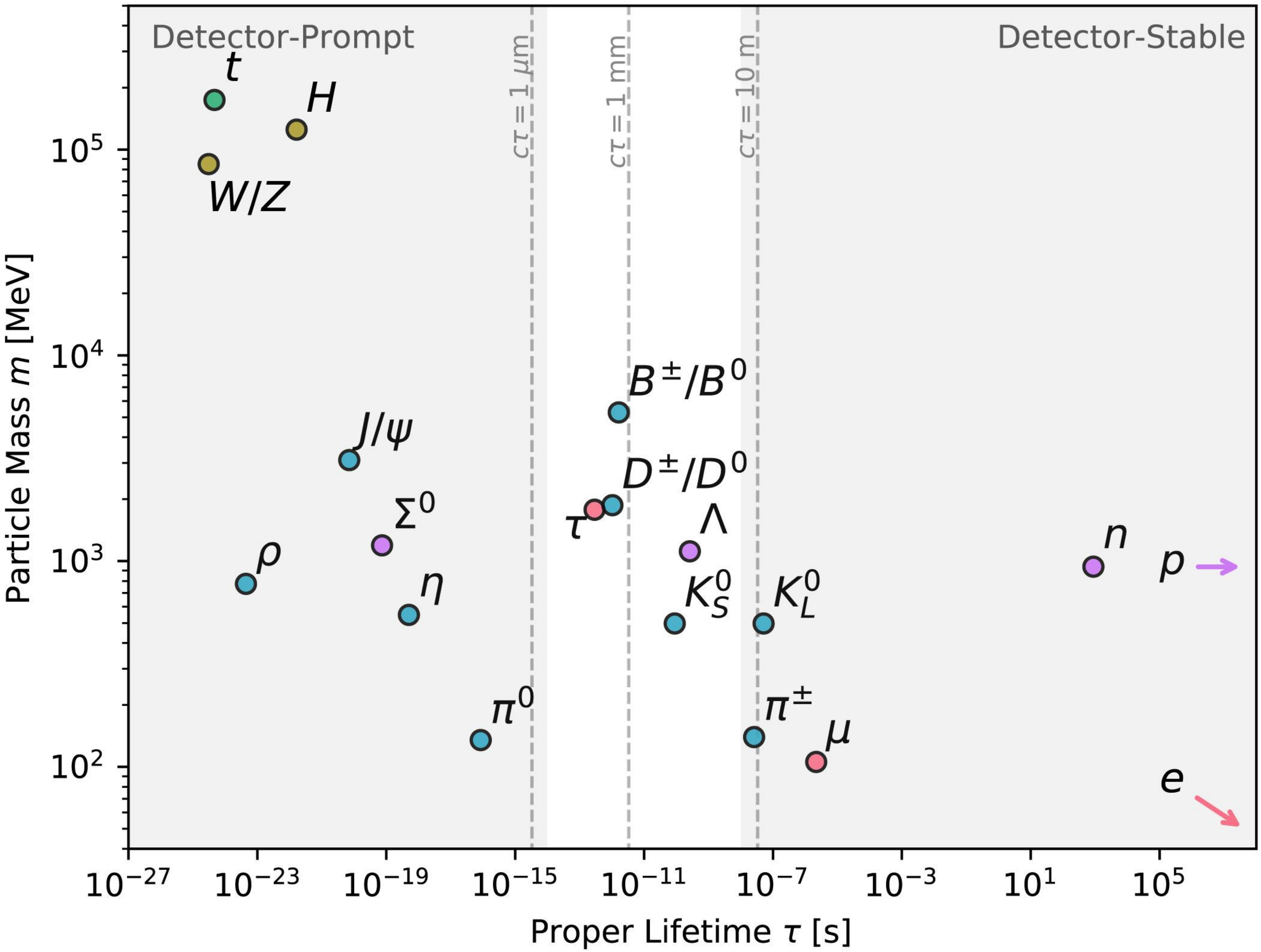
$$\Gamma(\tau^- \to l^-\nu_\tau\bar{\nu}_l) = \frac{G_F^2 m_\tau^5}{192\pi^3} f(\frac{m_l^2}{m_\tau^2}) r_{EW}$$

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$$

$$r_{EW} = \frac{\alpha}{2\pi}\left[\frac{25}{4} - \pi^2 + O\left(\frac{m_\ell^2}{m_\tau^2}\right)\right]$$

$$\boxed{\tau(\tau) \sim 290 \text{ fs}}$$

# *Not quite stable, not quite prompt*



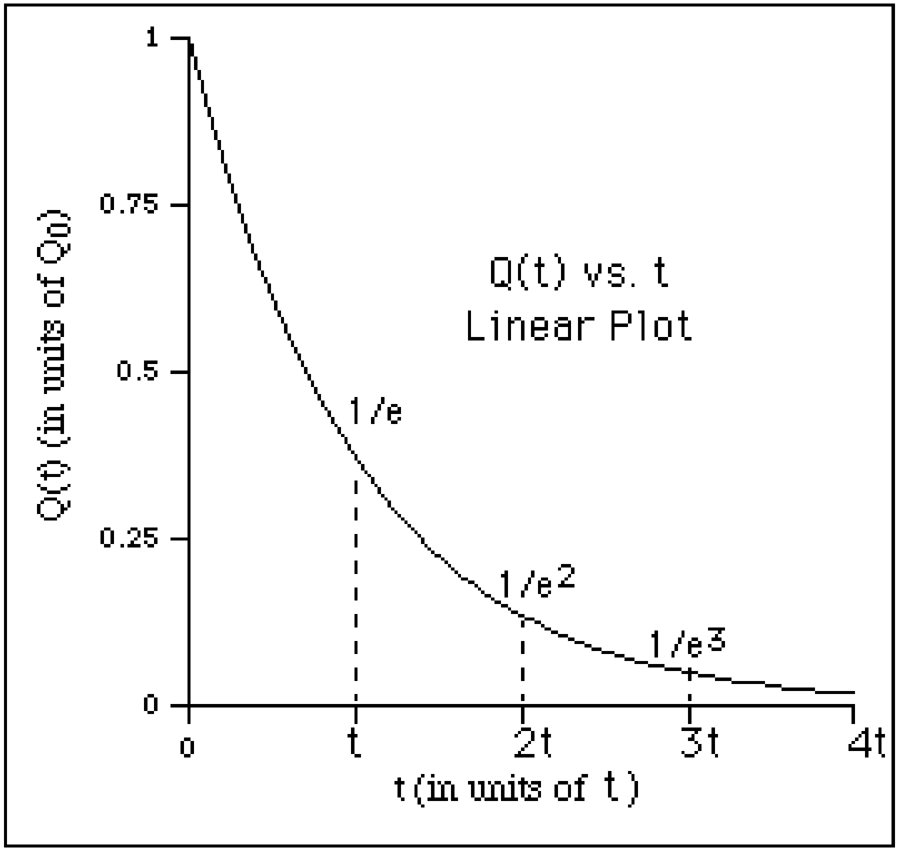
# *Lifetime measurement*

- *Decay time*
  - *distribution is exponential with decay constant* $\lambda = 1/\tau$ *and average of* $\tau$

$$Q(t) = \frac{N(t)}{N_0}\, e^{-\lambda t}$$

$$\langle t \rangle = \tau$$

$N_0$ is number of particles at $t = 0$



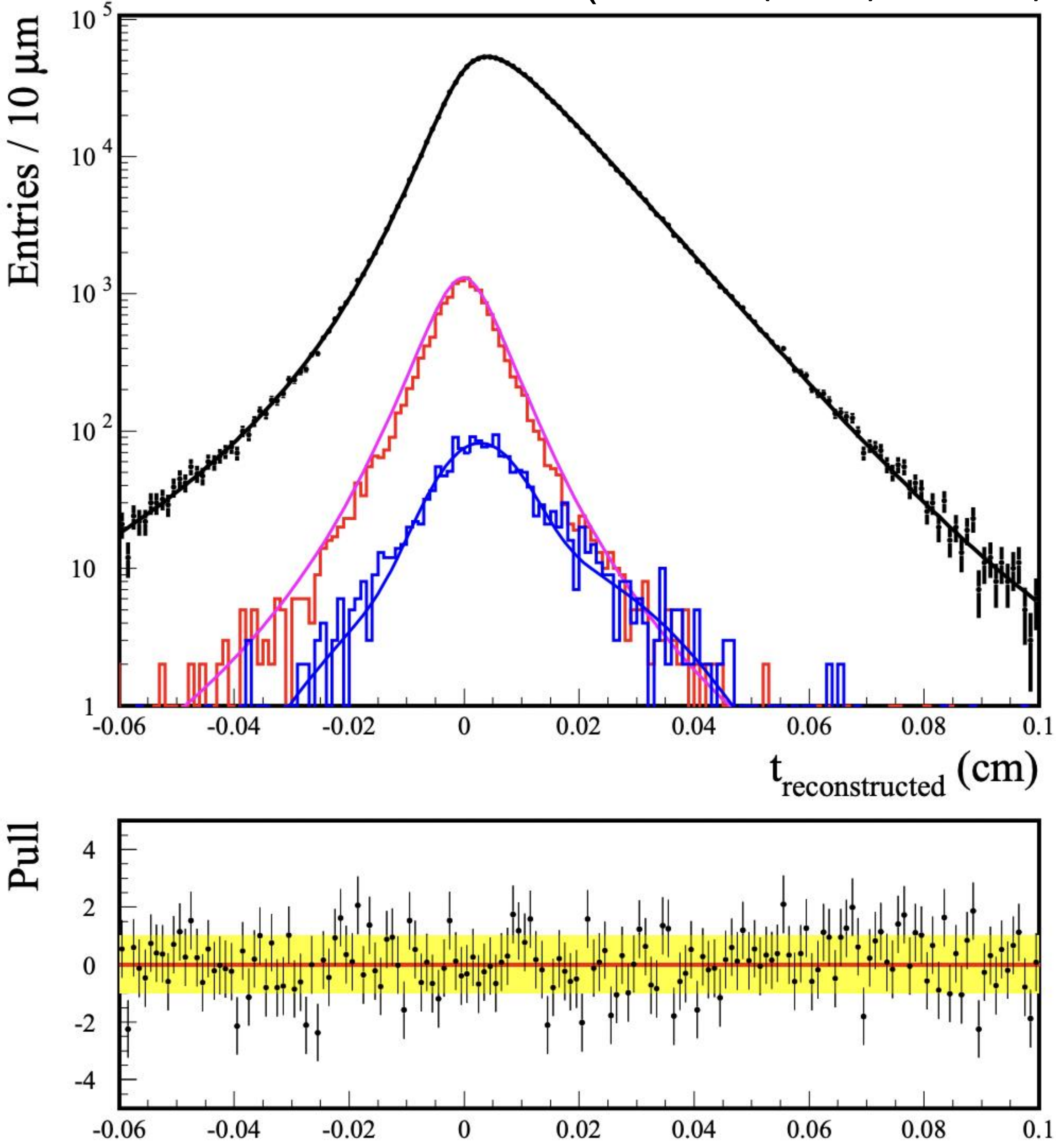
- *Decay times are too short to measure*
  - *Typical timing resolution in Belle II is of order 1 ns (or 3,000 τ lifetimes)*
- *Determine decay time from decay distance ℓ (taking into account time dilation)*

$$t = \frac{\ell}{\beta\gamma c} = \frac{m\ell}{\mathrm{pc}}$$

# $\tau$ lifetime measurement

- *Belle determined $\tau$ lifetime from fit to decay time distribution in (3x3) $\tau$ pair events*
  - *average t is 245 μm (can be measured with good vertex detector)*
- *Negative decay times result from finite detector resolution*

Belle (PRL 112 (2014) 031801)



Best measurement from Belle

(largest syst. error from SVD alignment)

$\tau(\tau) = 290.17 \pm 0.53 \pm 0.33$ fs

# $m_\tau$ measurement at $e^+e^- \to \tau^+\tau^-$ threshold

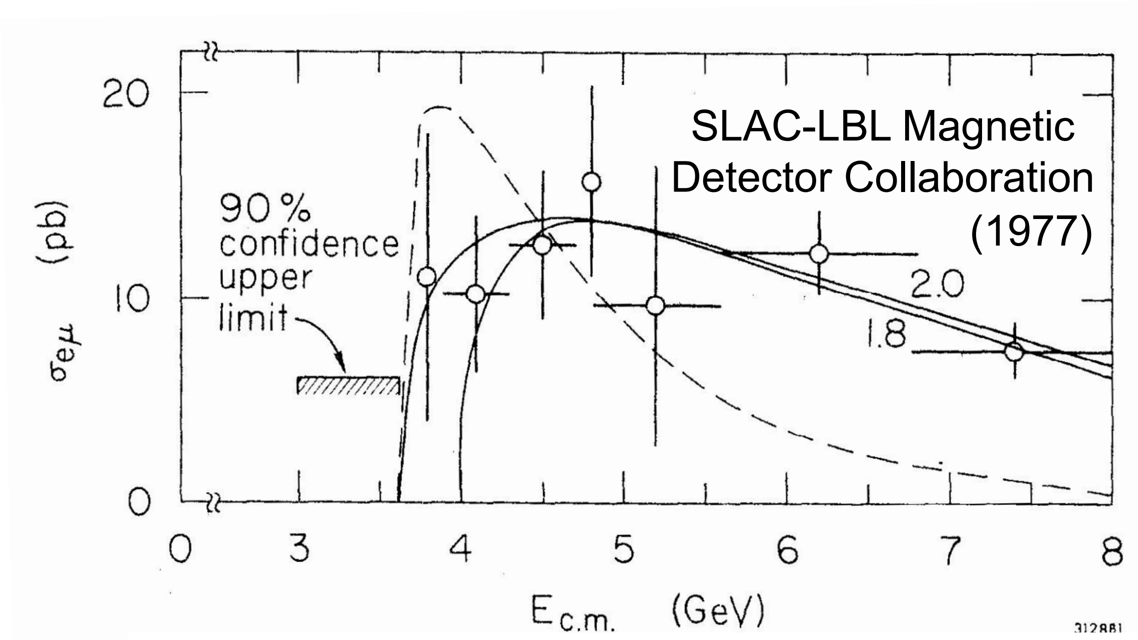
- *$e^+e^- \to \tau^+\tau^-$ cross-section as function of center-of-mass energy at $\tau^+\tau^-$ threshold depends strongly on $m_\tau$*
- *First $m_\tau$ measurements came from the cross-section of $e^+e^- \to e\mu\ X$ events*

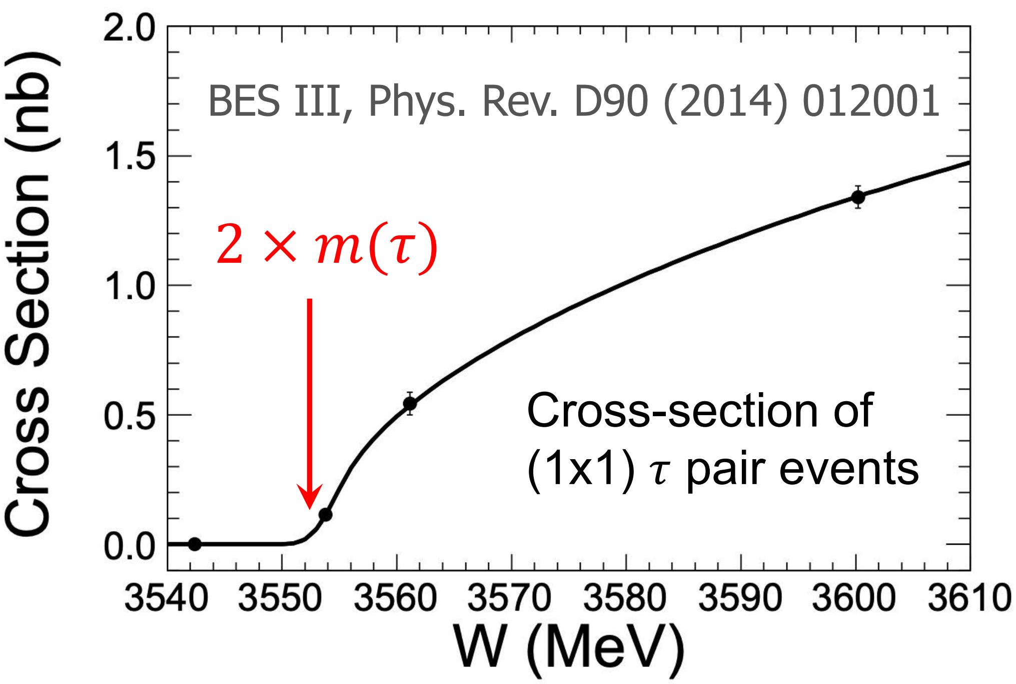
$$m_\tau = (1900 \pm 100)\ \text{MeV}$$

- *This is still one of the most precise techniques*

$$m_\tau = (1776.91 \pm 0.12^{+0.10}_{-0.13})\ \text{MeV}$$

- *… but SuperKEKB operates far away from $\tau^+\tau^-$ threshold*

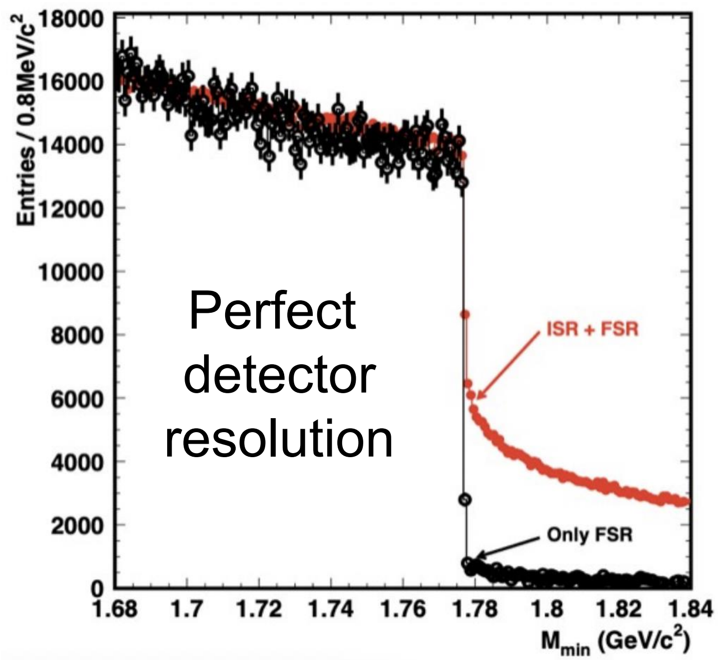




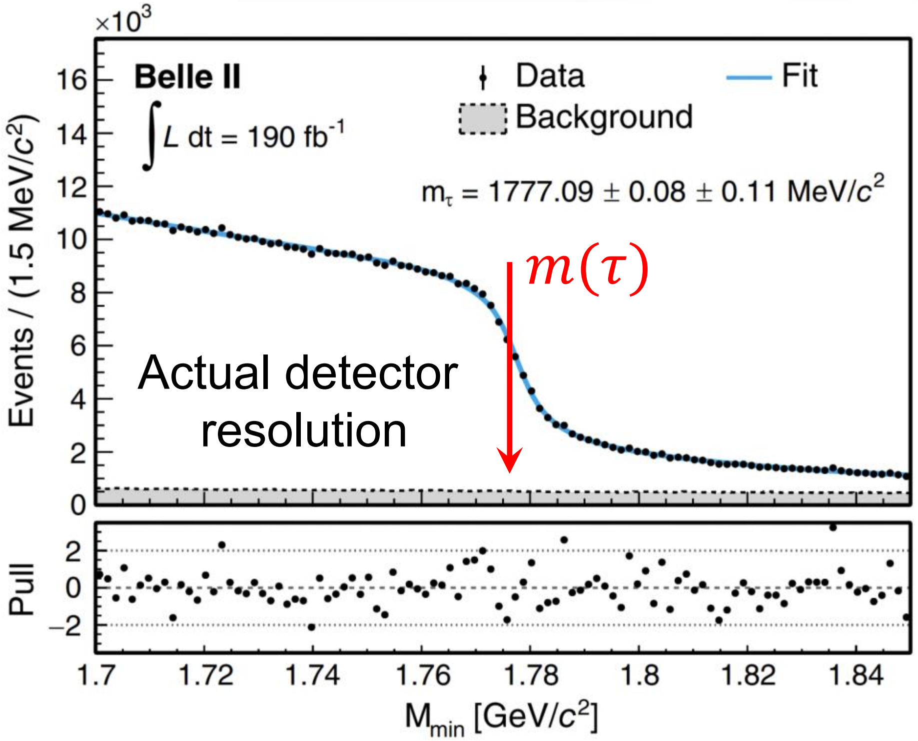
# $m_\tau$ mass measurement at Belle II

- *$\tau$ mass measurement with $\tau \to 3\pi\nu$*
- *$M_{min}$ approximates $m_\tau$ assuming the neutrino direction is the same as the three-pion momentum direction*
  - *If it's not, $M_{min} < m_\tau$*

$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$$



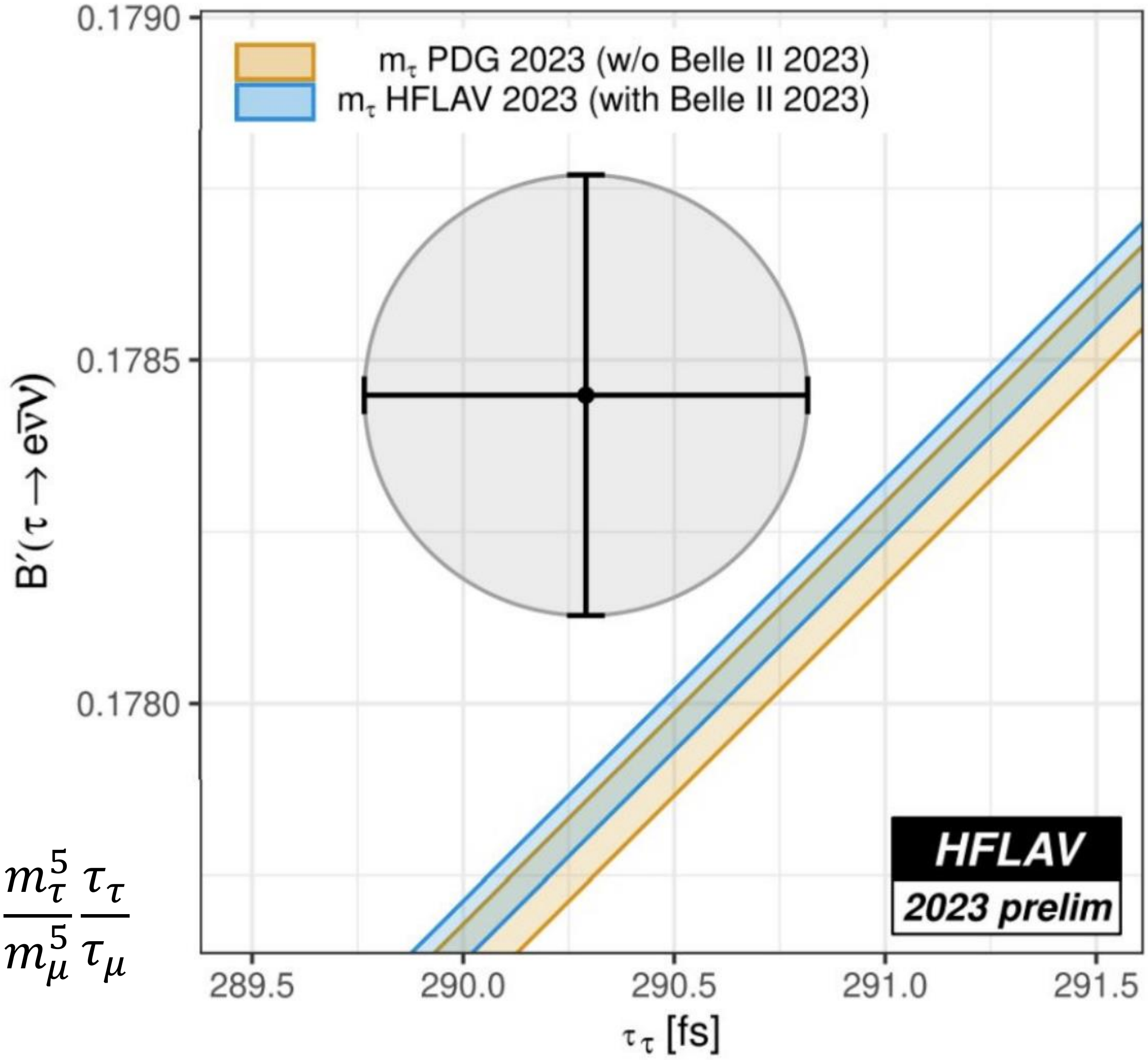
- *Sharp drop of $M_{min}$ distribution at $m_\tau$*
  - *Smeared by detector resolution*
- *Most precise $\tau$ mass measurement*
  - *Largest systematics from knowledge of beam energy and momentum scale*



Belle II, PRD 108 (2023) 032006

# SM test

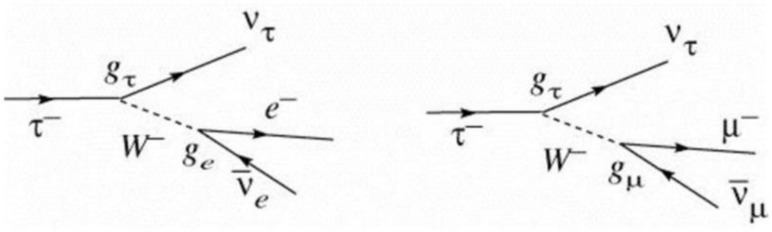
## *Test of SM with τ mass and lifetime*



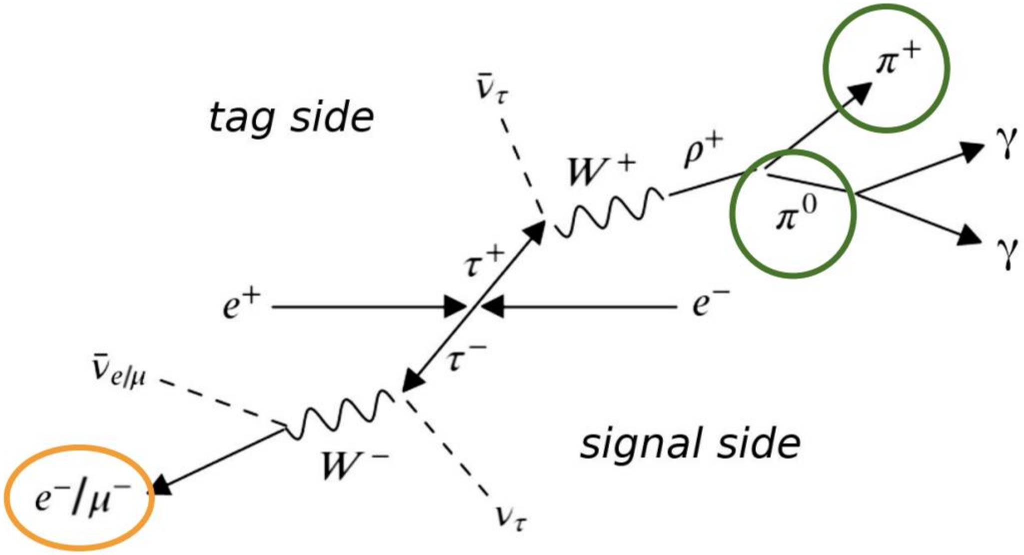
$$B'(\tau \to e\bar{\nu}\nu) \approx B(\mu \to e\bar{\nu}\nu)\,\frac{m_\tau^5}{m_\mu^5}\frac{\tau_\tau}{\tau_\mu}$$

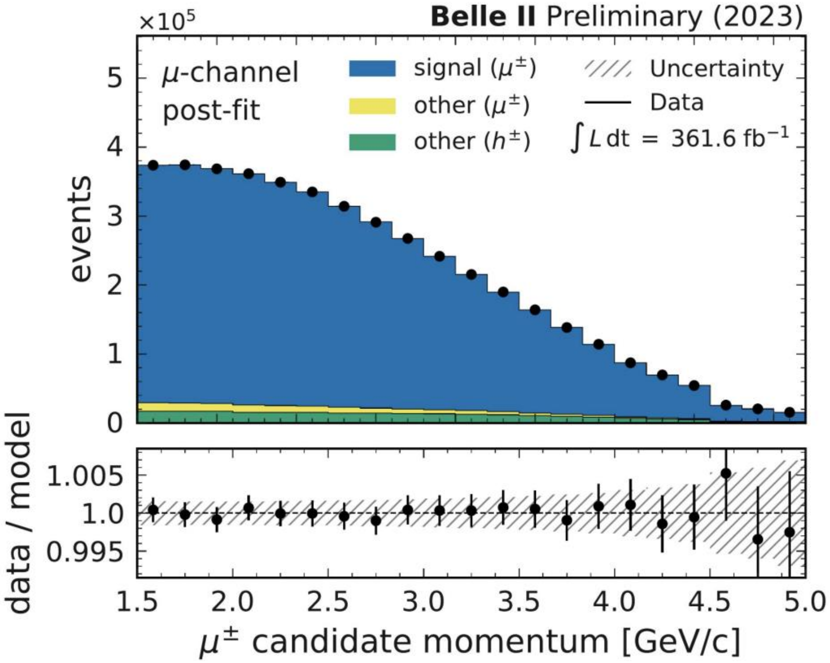
# *Light-lepton universality*

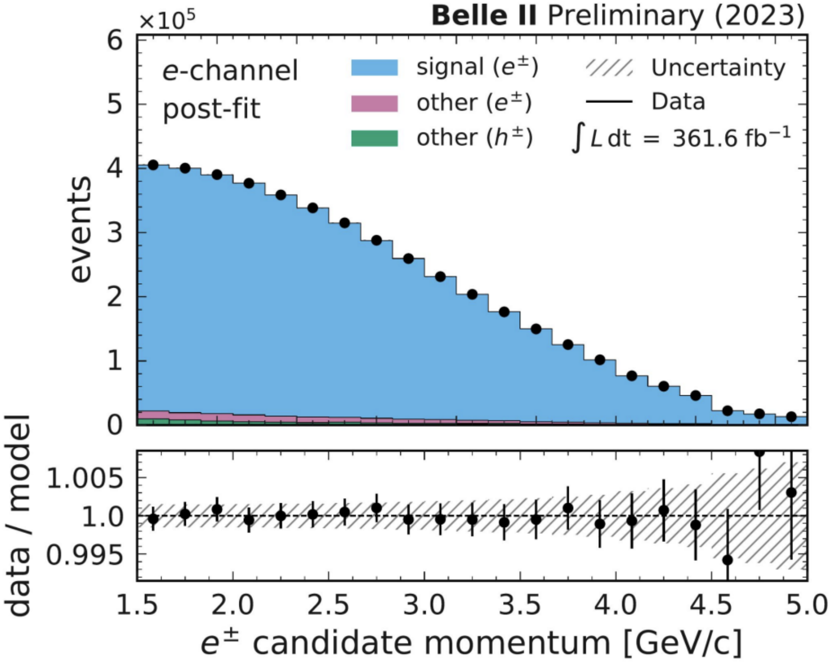
- *In the SM, $g_e = g_\mu$*



$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{\mathcal{B}\left(\tau^- \to \nu_\tau \mu^- \bar{\nu}_\mu(\gamma)\right)}{\mathcal{B}\left(\tau^- \to \nu_\tau e^- \bar{\nu}_e(\gamma)\right)}\,\frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$



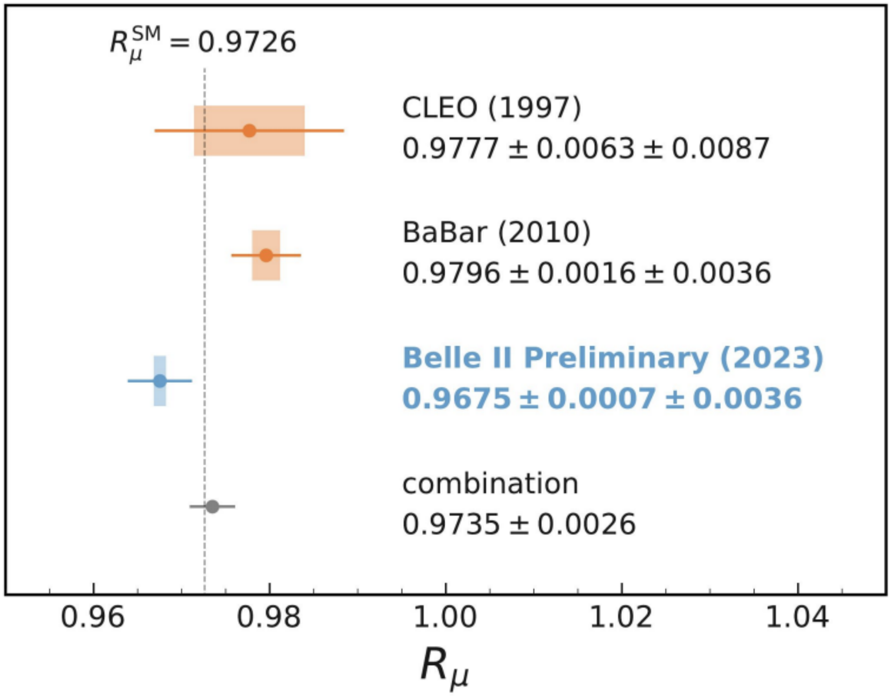


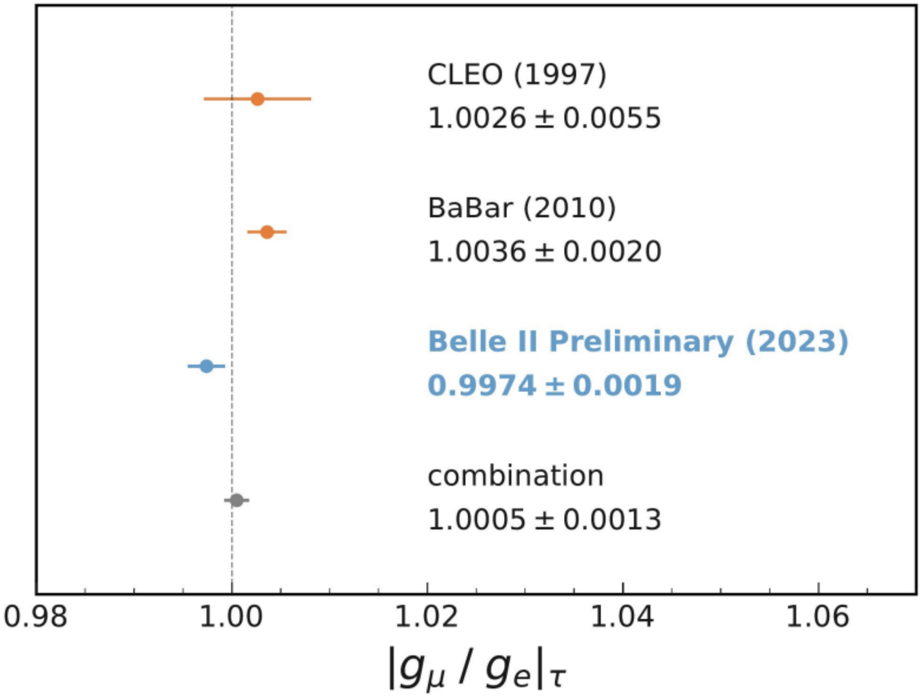


# *Light-lepton universality*

$$R_\mu = \frac{\mathcal{B}(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu(\gamma))}{\mathcal{B}(\tau^- \to \nu_\tau e^- \overline{\nu}_e(\gamma))}$$

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$



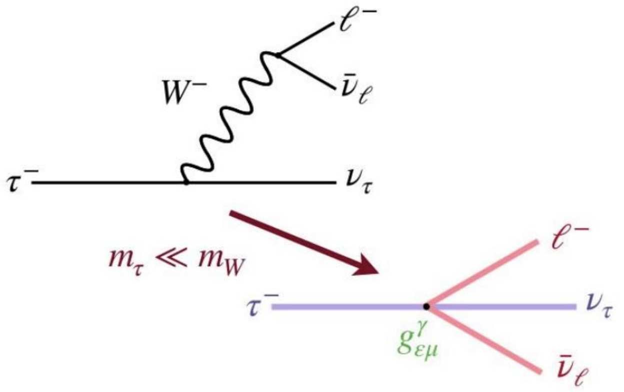


Most precise measurement of $R_\mu$

(largest syst. error from lepton ID)

# Michel parameters

- *Generalized matrix element*



$$= \frac{4G_F}{\sqrt{2}} \sum_{\substack{N=S,V,T\\ i,j=L,R}} g_{ij}^N \left[\bar{u}_i(\ell)\Gamma^N v_n(\nu_\ell)\right] \left[\bar{u}_m(\nu_\tau)\Gamma_N u_j(\tau)\right]$$

$$\Gamma^S = 1, \Gamma^V = \gamma^\mu, \Gamma^T = i\left(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu\right)/2\sqrt{2}$$

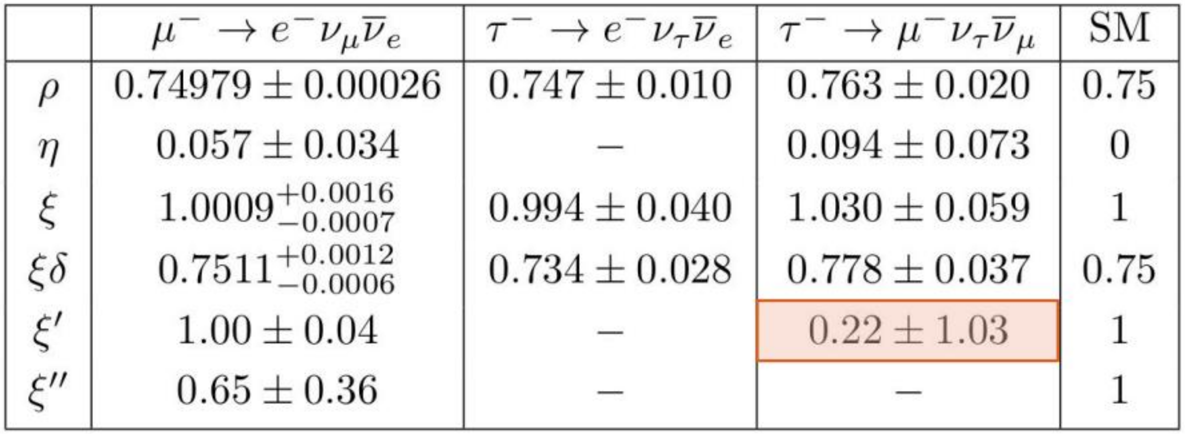
Scalar Vector Tensor

- *Test Lorentz structure of weak current (in SM $g^V_{LL} = 1$, all other $g^N_{ij} = 0$)*

$$\frac{d\Gamma}{dx} = \frac{G^2_{\tau\ell} m^5_\tau}{192\,\pi^3} \left\{ f_0(x) + \rho f_1(x) + \eta \frac{m_\ell}{m_\tau} f_2(x) - P_\tau \left[ \xi g_1(x) + \xi \Delta g_2(x) \right] \right\}$$

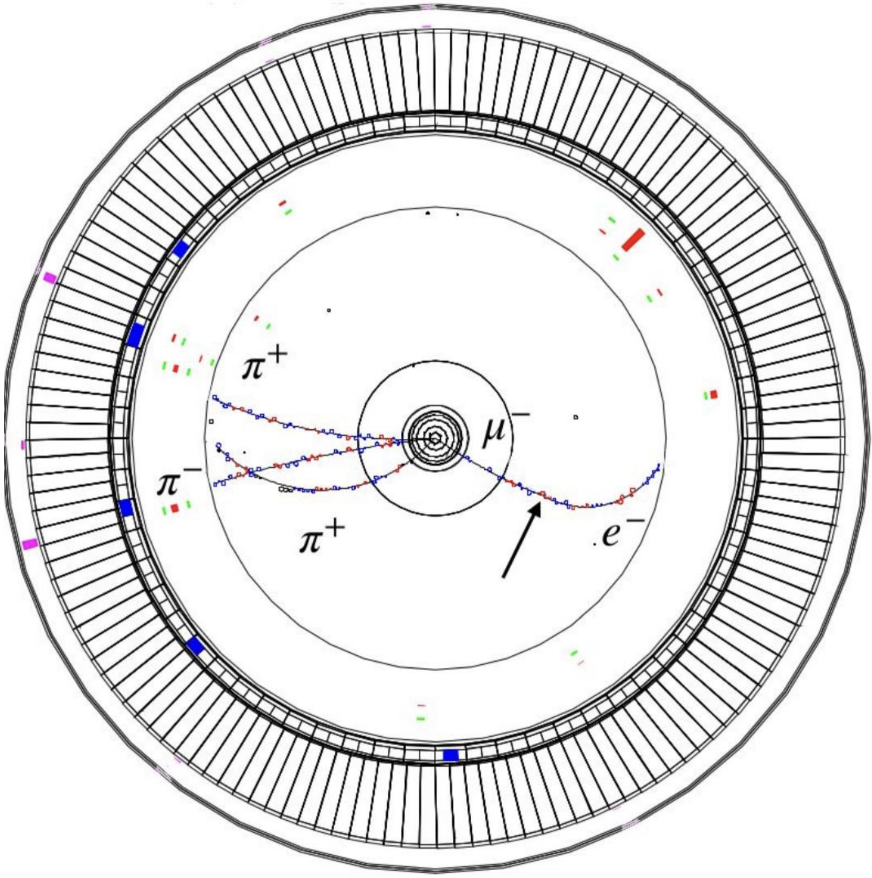
- *Michel parameters $\rho, \eta, \xi$, and $\xi\delta$ are related to $g^N_{ij}$ in SM*

# *Michel parameters (cont'ed)*



| | $\mu^- \to e^- \nu_\mu \overline{\nu}_e$ | $\tau^- \to e^- \nu_\tau \overline{\nu}_e$ | $\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu$ | SM |
|---|---|---|---|---|
| $\rho$ | $0.74979 \pm 0.00026$ | $0.747 \pm 0.010$ | $0.763 \pm 0.020$ | 0.75 |
| $\eta$ | $0.057 \pm 0.034$ | – | $0.094 \pm 0.073$ | 0 |
| $\xi$ | $1.0009^{+0.0016}_{-0.0007}$ | $0.994 \pm 0.040$ | $1.030 \pm 0.059$ | 1 |
| $\xi\delta$ | $0.7511^{+0.0012}_{-0.0006}$ | $0.734 \pm 0.028$ | $0.778 \pm 0.037$ | 0.75 |
| $\xi'$ | $1.00 \pm 0.04$ | – | $0.22 \pm 1.03$ | 1 |
| $\xi''$ | $0.65 \pm 0.36$ | – | – | 1 |

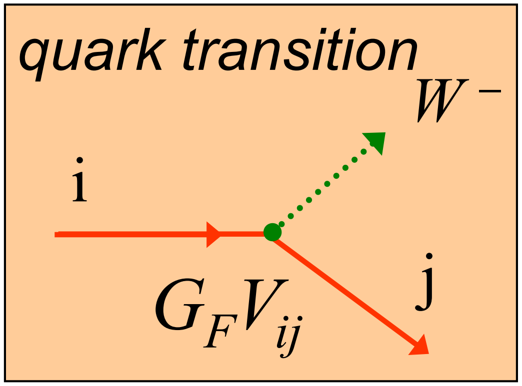
- *All measurements consistent with SM predictions*
- *Most precise measurements are from CLEO and LEP experiments*
- *More Michel parameters can be measured if polarization of outgoing lepton is known*
  - *$\bar{\eta}$ and $\xi\kappa$ in radiative decays*
  - *$\xi'$ with decay in flight muons with $\tau \to \mu\bar{\nu}\nu$ (Belle; PRL **131** (2023) 021801)*



$\xi' = 0.22 \pm 0.94 \pm 0.42$

# *Cabibbo-Kobayashi-Maskawa (CKM) matrix*

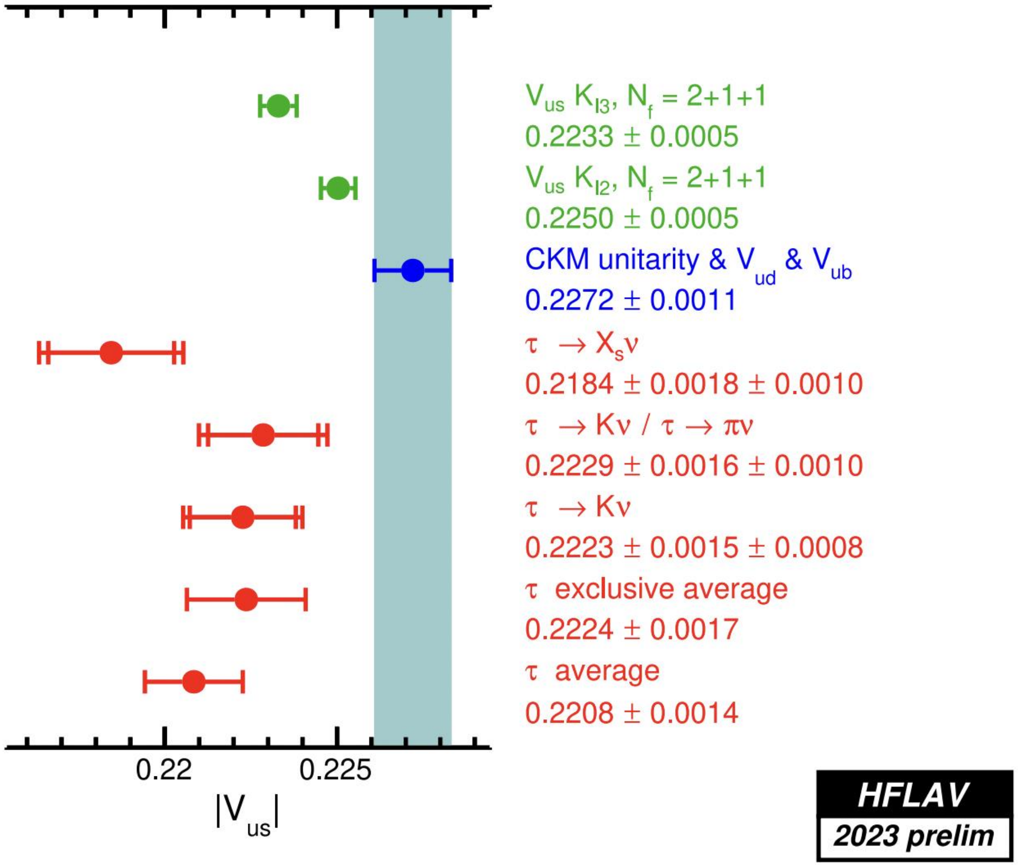
- *Unitary matrix that gives strength of weak quark transitions*
  - *Most relevant for Belle II are $|V_{ub}|$, $|V_{cb}|$, and $\phi_2/\alpha$*



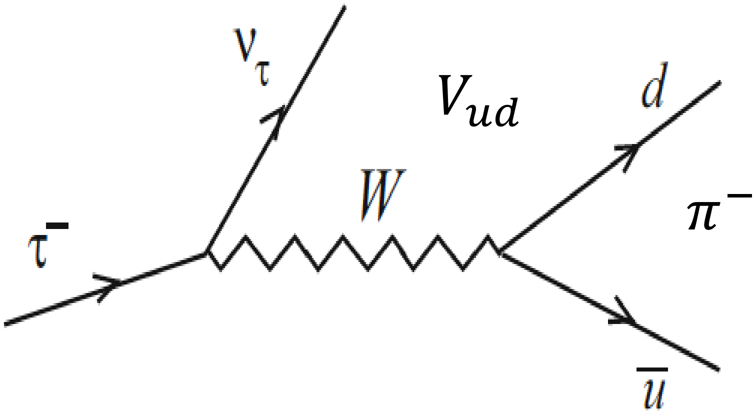
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

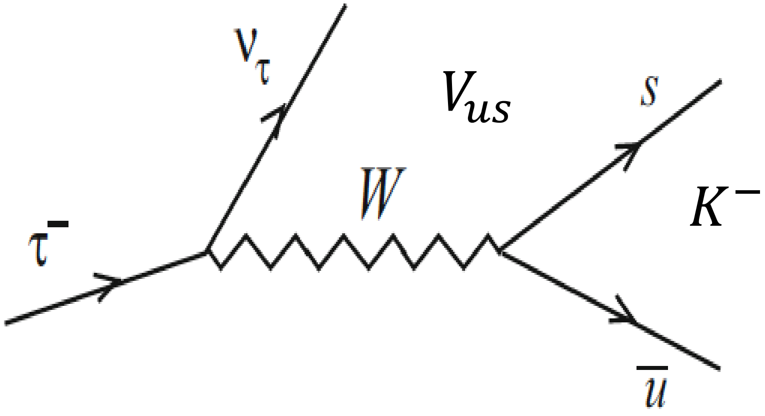
- *Belle II can also measure $|V_{us}|$ with $\tau$ decays*
  - *Current measurements with kaon decays and $\tau$ decays differ from CKM unitarity*

$$|V_{us}|^2 = 1 - |V_{ud}|^2 - |V_{ub}|^2$$



# $|V_{us}|$ from exclusive $\tau$ decays



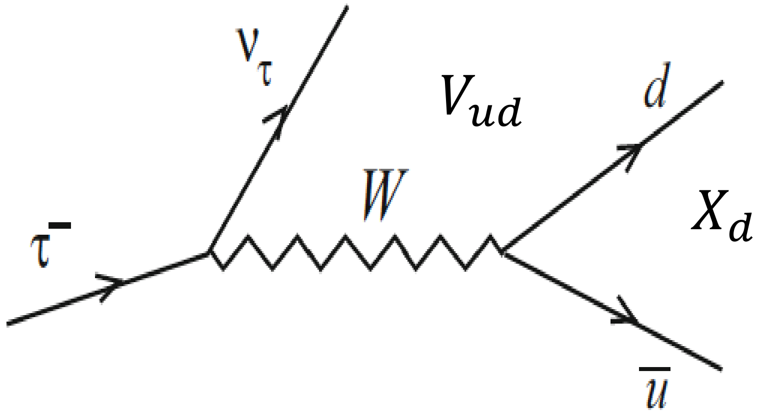


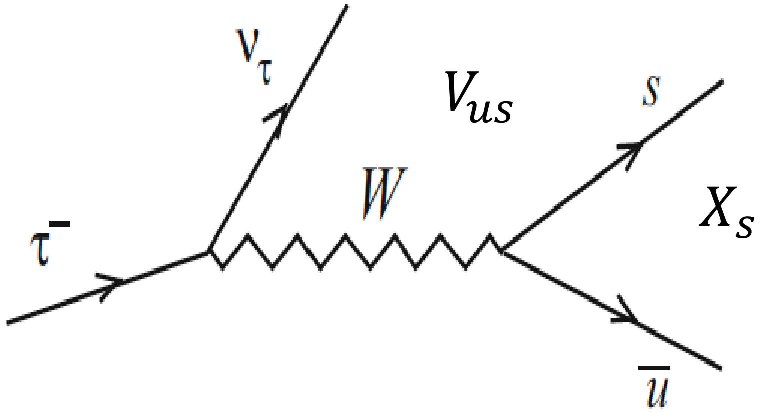
$$\frac{B(\tau \to K^-\nu_\tau)}{B(\tau \to \pi^-\nu_\tau)} = \frac{f_K^2|V_{us}|^2}{f_\pi^2|V_{ud}|^2}\frac{(1-m_K^2/m_\tau^2)^2}{(1-m_\pi^2/m_\tau^2)^2}\delta_{LD}$$

Radiative corrections

Dominant systematic error from hadron ID

# $|V_{us}|$ *from inclusive* $\tau$ *decays*



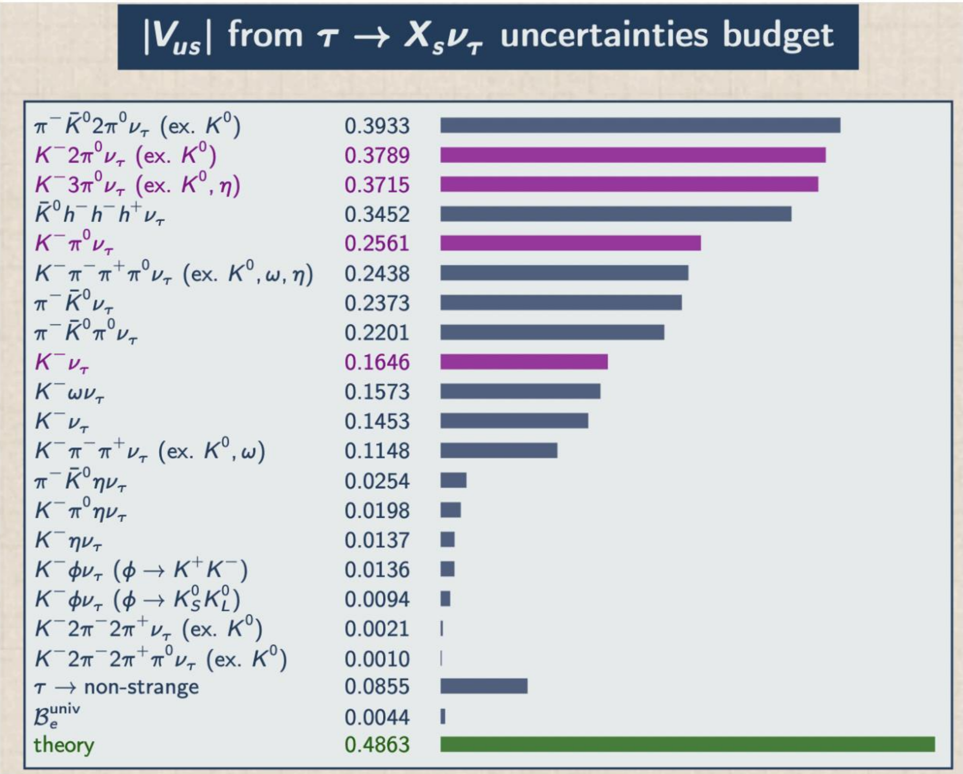


- *Determine* $|V_{us}|$ *from fraction of hadronic* $\tau$ *decays with strangeness*
  - *Inclusive BF as sum of exclusive BFs*
- *Measurements can be extended to higher moments of hadronic mass distributions*

## Spectral Moments:

$$R_\tau^{kl} = \int_0^1 dz(1-z)^k z^l \frac{dR_\tau}{dz}, \;\; z = \frac{q^2}{m_\tau^2}$$

- *Many spectral function measurements are still from the LEP era*



**$|V_{us}|$ from $\tau \to X_s \nu_\tau$ uncertainties budget**

| | |
|---|---|
| $\pi^- \bar{K}^0 2\pi^0 \nu_\tau$ (ex. $K^0$) | 0.3933 |
| $K^- 2\pi^0 \nu_\tau$ (ex. $K^0$) | 0.3789 |
| $K^- 3\pi^0 \nu_\tau$ (ex. $K^0, \eta$) | 0.3715 |
| $\bar{K}^0 h^- h^- h^+ \nu_\tau$ | 0.3452 |
| $K^- \pi^0 \nu_\tau$ | 0.2561 |
| $K^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. $K^0, \omega, \eta$) | 0.2438 |
| $\pi^- \bar{K}^0 \nu_\tau$ | 0.2373 |
| $\pi^- \bar{K}^0 \pi^0 \nu_\tau$ | 0.2201 |
| $K^- \nu_\tau$ | 0.1646 |
| $K^- \omega \nu_\tau$ | 0.1573 |
| $K^- \nu_\tau$ | 0.1453 |
| $K^- \pi^- \pi^+ \nu_\tau$ (ex. $K^0, \omega$) | 0.1148 |
| $\pi^- \bar{K}^0 \eta \nu_\tau$ | 0.0254 |
| $K^- \pi^0 \eta \nu_\tau$ | 0.0198 |
| $K^- \eta \nu_\tau$ | 0.0137 |
| $K^- \phi \nu_\tau$ ($\phi \to K^+ K^-$) | 0.0136 |
| $K^- \phi \nu_\tau$ ($\phi \to K_S^0 K_L^0$) | 0.0094 |
| $K^- 2\pi^- 2\pi^+ \nu_\tau$ (ex. $K^0$) | 0.0021 |
| $K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. $K^0$) | 0.0010 |
| $\tau \to$ non-strange | 0.0855 |
| $\mathcal{B}_e^{\text{univ}}$ | 0.0044 |
| theory | 0.4863 |

Courtesy: A. Lusiani [Tau2023 slides]

# Conclusions

- *$\tau$ pair events at the $\Upsilon(4S)$ are clean and provide many constraints on kinematic variables*
  - *$\tau$ pair events are quite different from B and charm decays*

- *$\tau$ properties and decays provide a wide variety of SM tests and opportunities to search for new physics*

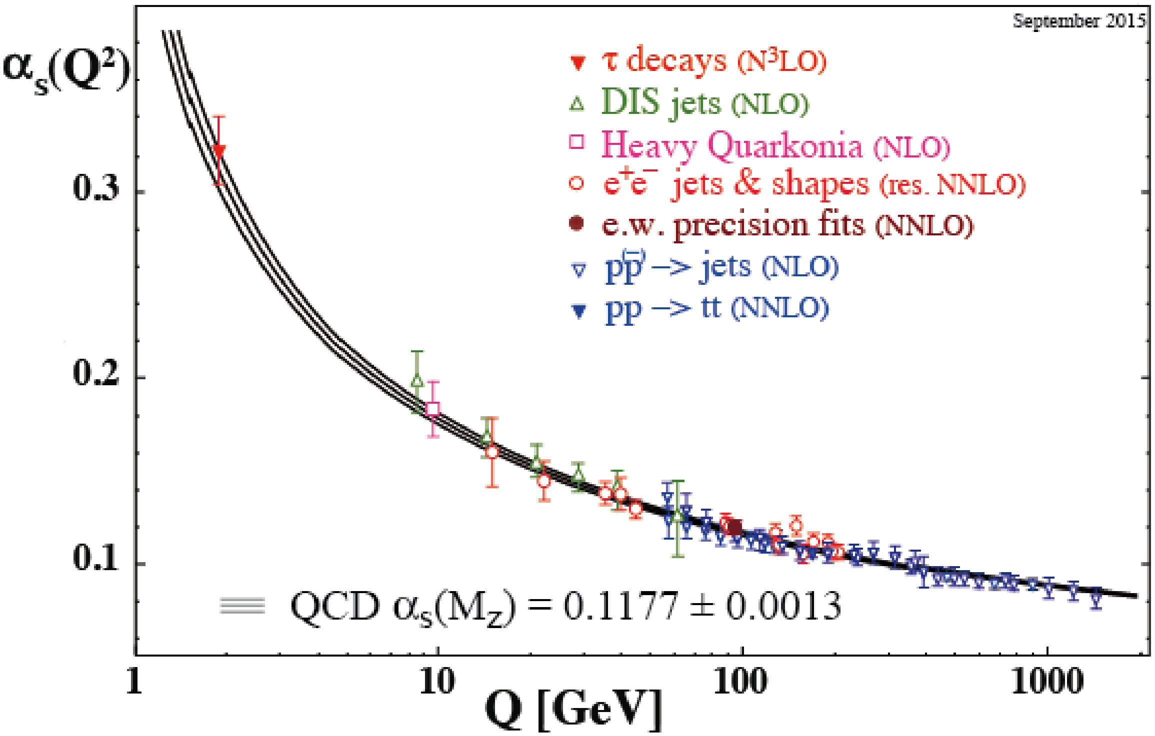
- *Belle II will soon have the largest pile of $\tau$'s in the world*
  - *New physics may be hiding in it …*

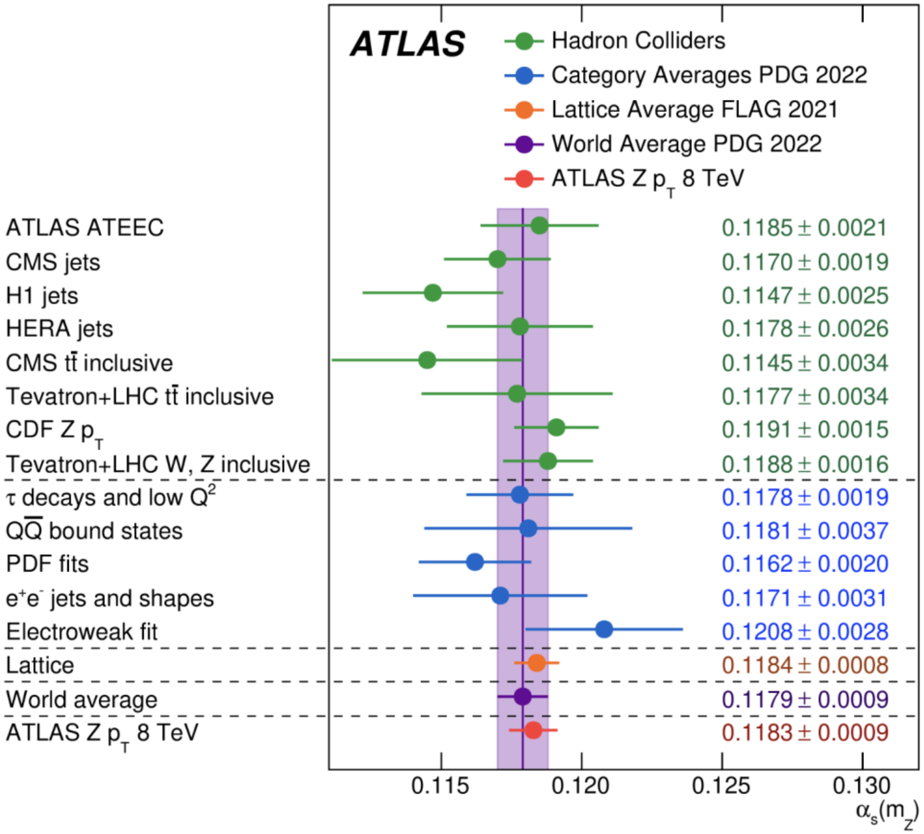
# References

- *“The tau lepton”, Martin Perl, Reports on Progress in Physics, 55 (1992) 653.*
- *“Physics with tau leptons”, Achim Stahl, Springer Tracts in Modern Physics (1999)*
- *“Precision tau physics”, Antonio Pich, Progress in Particle and Nuclear Physics 75 (2014) 41.*
- *“The Physics of the B factories”, A. Bevan, B. Golob, T. Mannel, S. Prell, and B. Yabsley (eds.), Eur. Phys. J. C74 (2014) 3026.*
- *“The Belle II Physics Book”, Belle II Collaboration, E. Kou et al., Prog. Theor. Exp. Phys. (2019)*

# *Back-up slides*

# Strong coupling constant $\alpha_S$



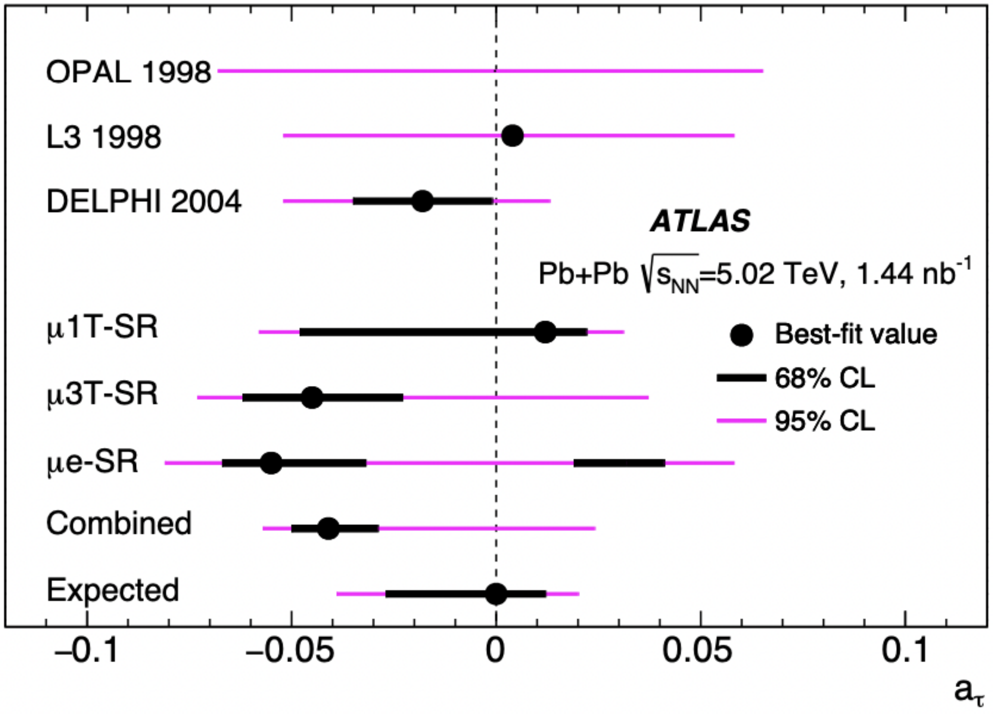


$\alpha_S$ can be determined from $\tau$ hadronic width and spectral moments

Last measurements from LEP & CLEO
→ Very precise measurement from ATLAS at LHC

# *Tau g-2*

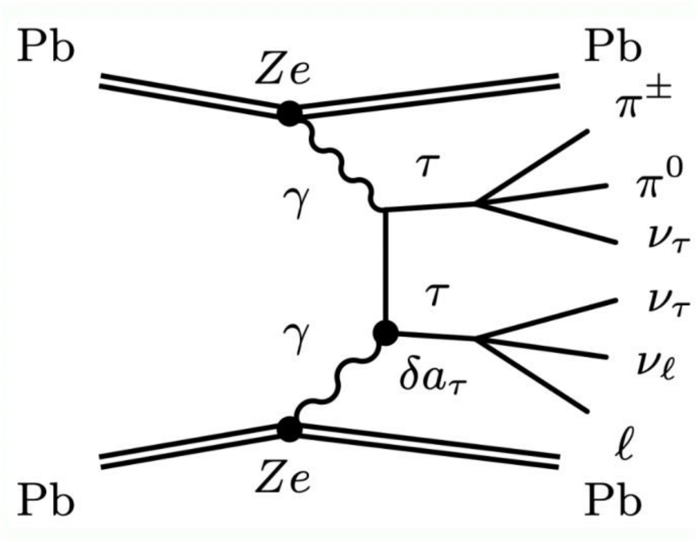
- *Photoproduction cross-section of tau pairs depends on $a_\tau$*
  - *ATLAS result has similar precision to DELPHI result; ALICE analysis is in progress*
- *Also possible at Belle II (pol. beams help)*

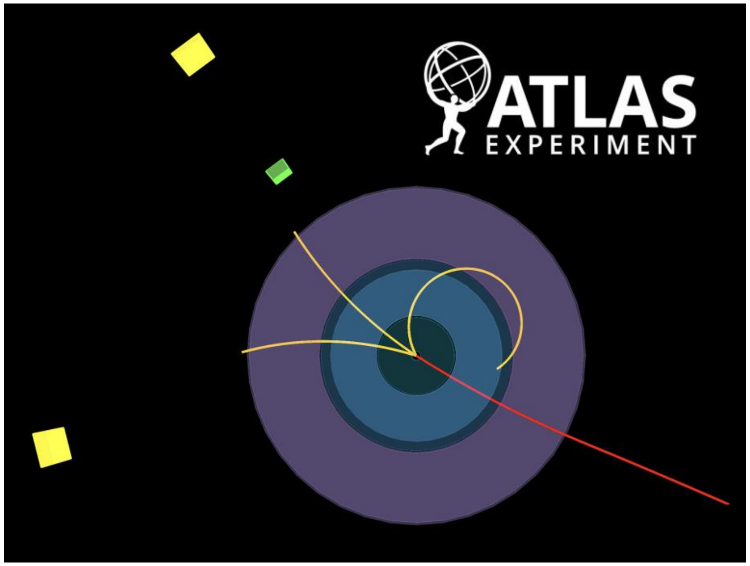


1-loop QED, Schwinger term

$$\alpha/2\pi = 0.0012$$

**Ultra peripheral Pb-Pb collisions**





# *Tau electric dipole moment*

- *New measurement of tau* ***EDM*** *from Belle using spin correlations*
  - *Expect to improve to* $(1-2)\times 10^{-19}$ *ecm with improved technique and Belle II data,*

$$\mathrm{Re}(d_\tau) = (-0.62\pm 0.63)\times 10^{-17}\ \mathrm{ecm},$$
$$\mathrm{Im}(d_\tau) = (-0.40\pm 0.32)\times 10^{-17}\ \mathrm{ecm}.$$