The Belle II experiment, status and prospects for new physics searches

09/12/2020

Gianluca Inguglia

InterLeptons

European Research Council
Established by the European Commission

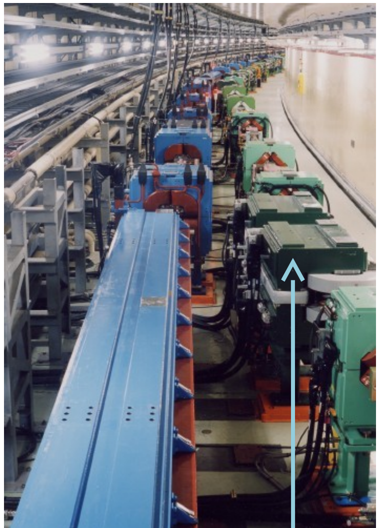
HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

FWF
Der Wissenschaftsfonds.

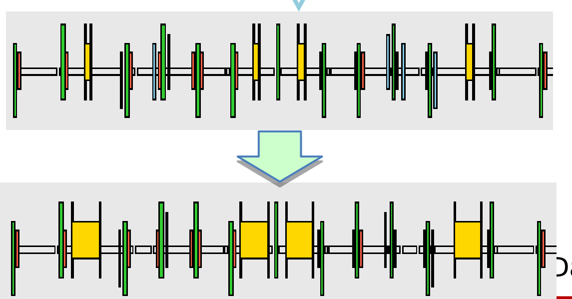
ÖAW
ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

Belle II

KEKB to SuperKEKB

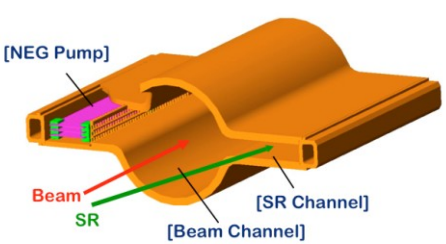


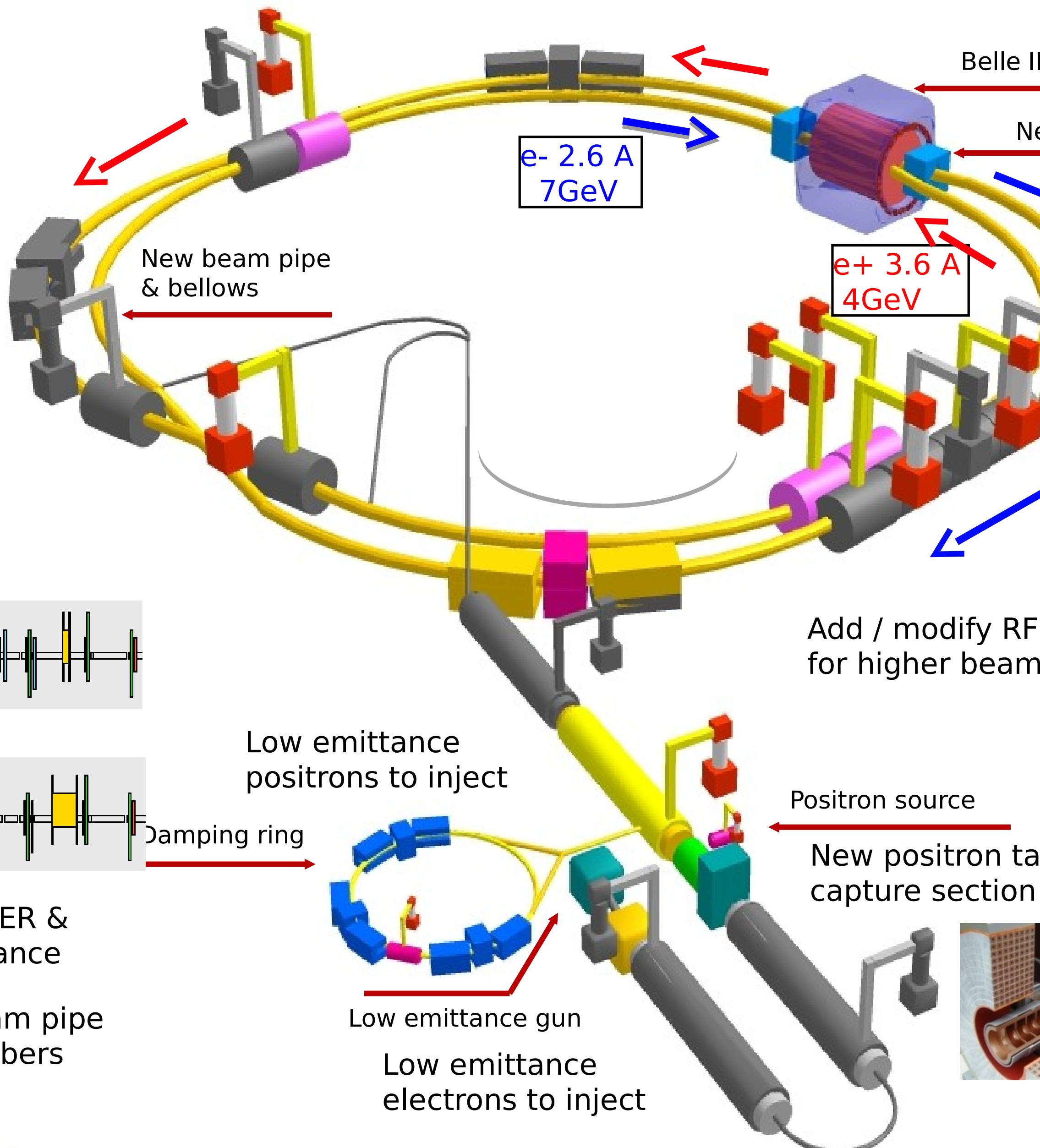
Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers

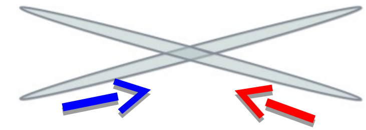




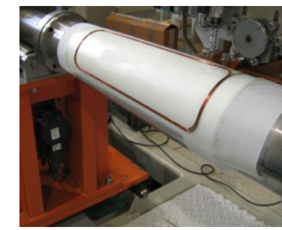
Low emittance positrons to inject

Low emittance electrons to inject

Colliding bunches

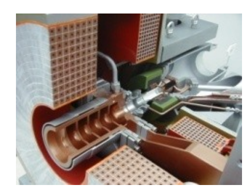


New superconducting /permanent final focusing quads near the IP



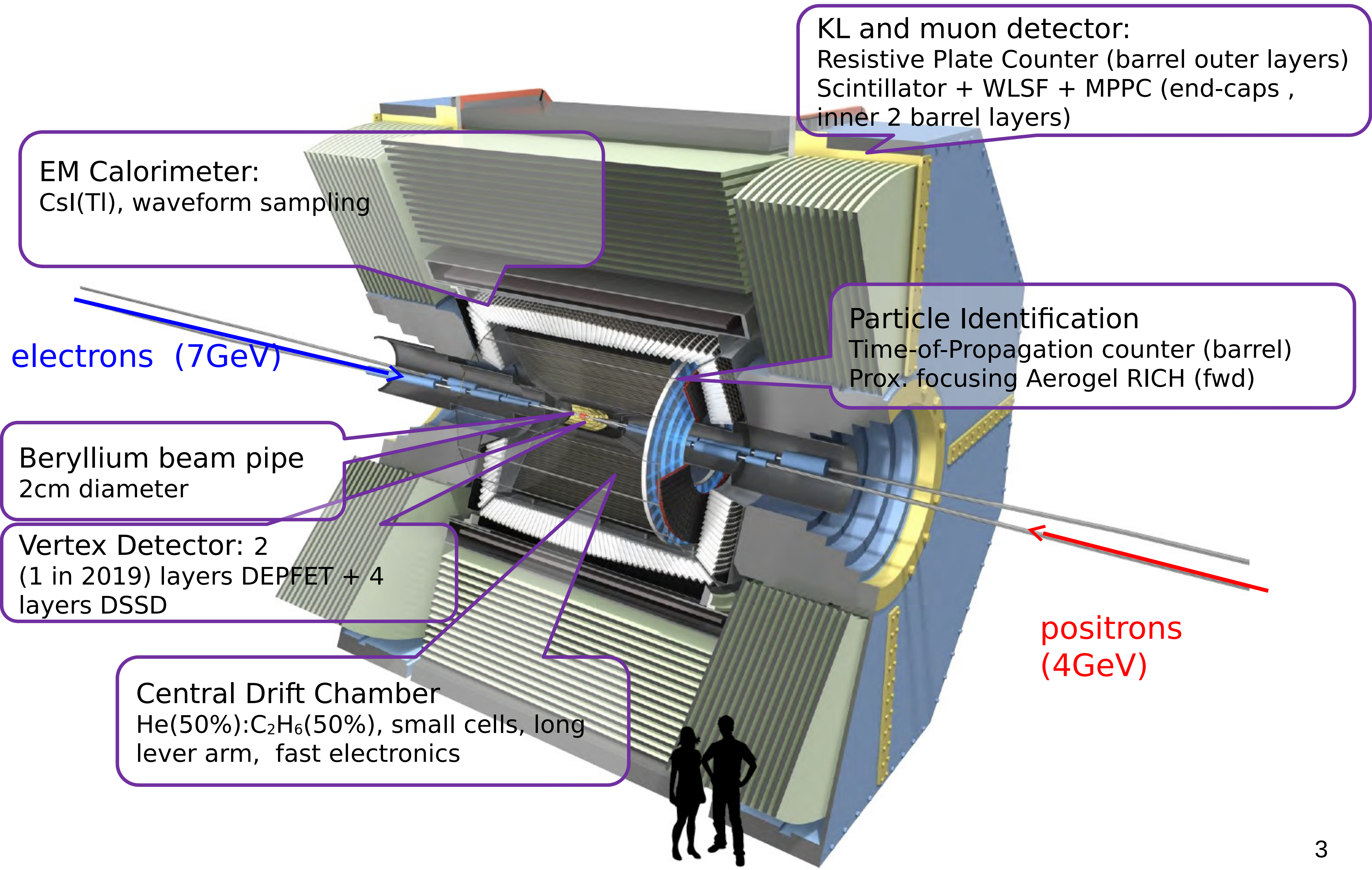
Add / modify RF systems for higher beam current

New positron target / capture section

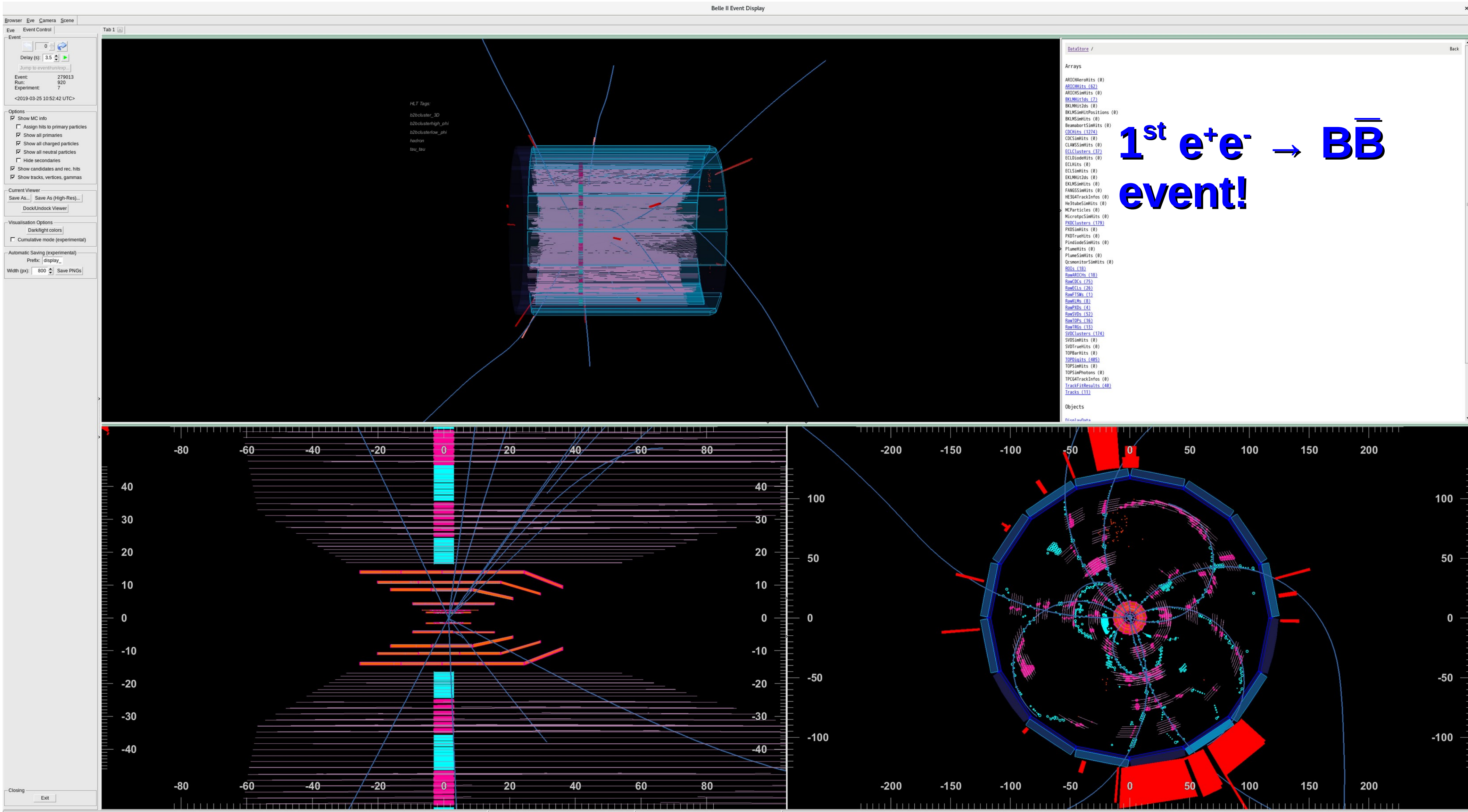


To obtain x40 higher luminosity

Belle II Detector Elements



Belle II first collisions with full detector, 25th March 2019



1st $e^+e^- \rightarrow B\bar{B}$ event!

Belle II first collisions with full detector, 25th March 2019

SuperKEKB, the world's "brightest" particle collider

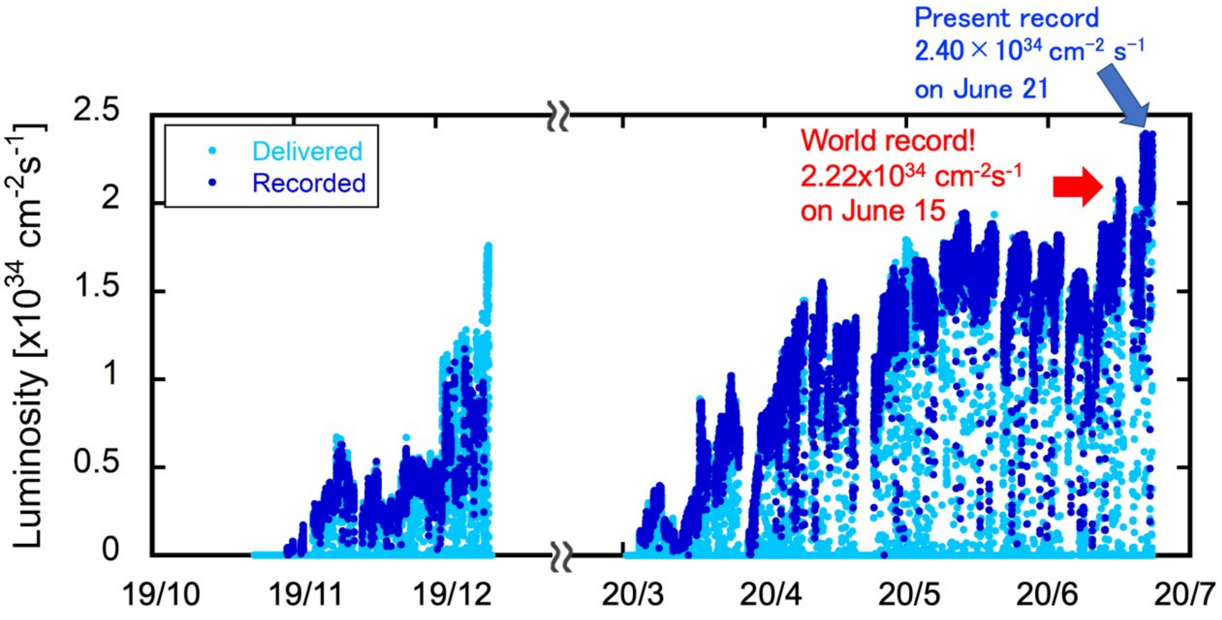
CERNCOURIER | Reporting on international high-energy physics

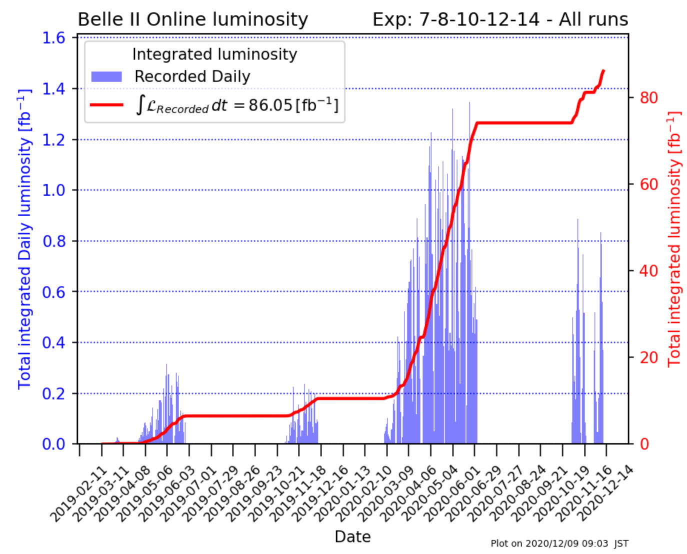
Physics ▾ | Technology ▾ | Community ▾ | In focus | Magazine

ACCELERATORS | NEWS

KEK reclaims luminosity record

30 June 2020





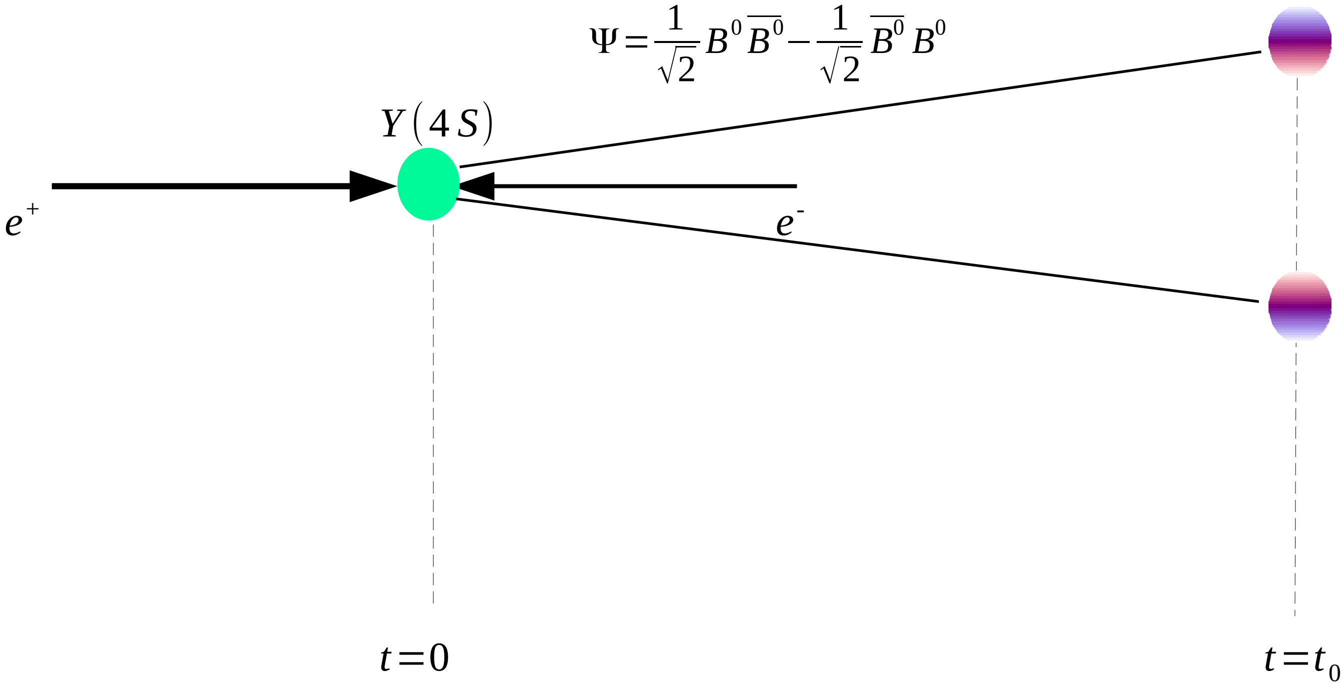
Why a (super) B-factory?

The general aim of a B-factory is to produce and study B mesons via the reaction

$$e^+ e^- \rightarrow Y(4S) \rightarrow B\overline{B}$$

In general one of the two B mesons is tagged and the other is studied.

Entangled B meson pairs are produced in the decays of Y(4S)

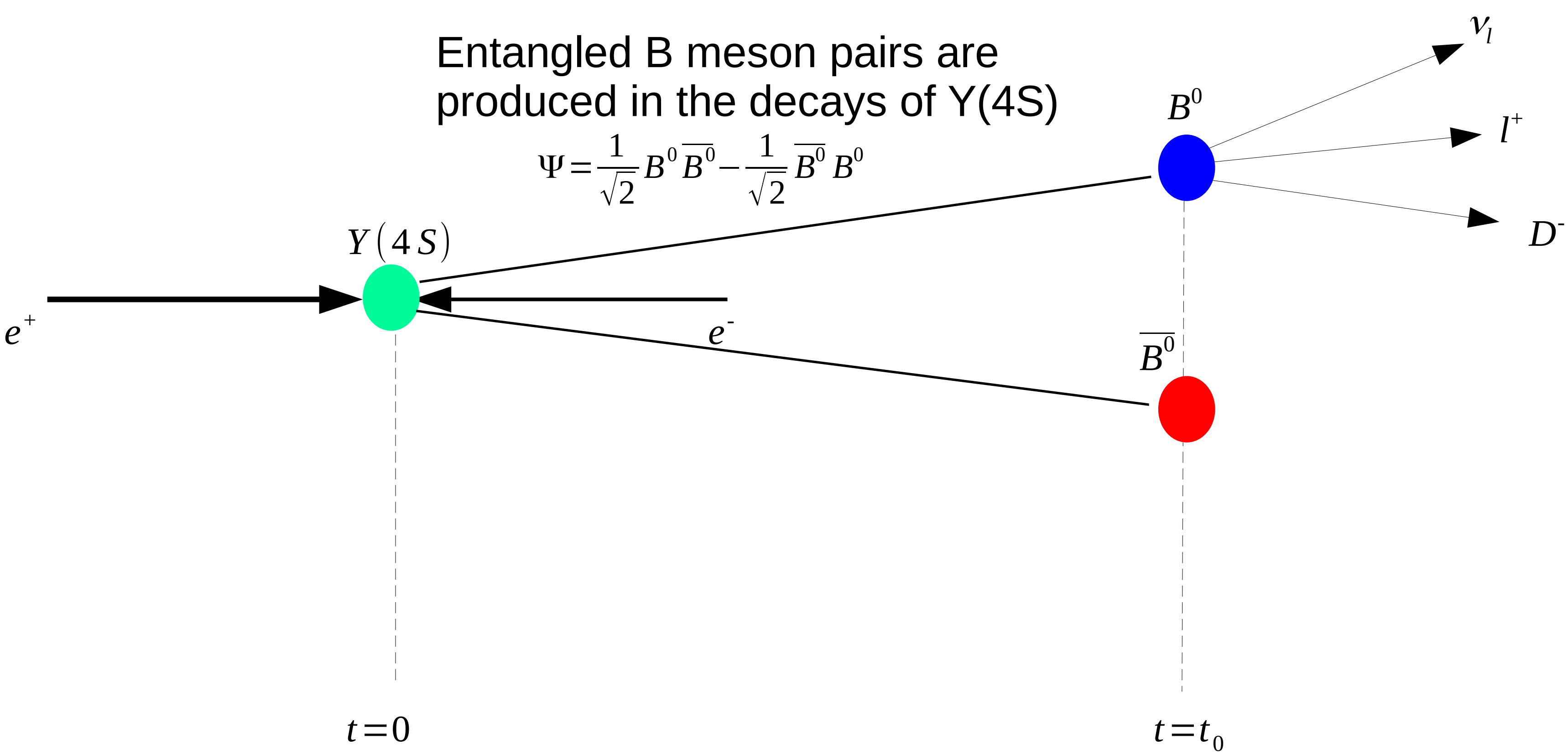


Why a (super) B-factory?

The general aim of a B-factory is to study B mesons via the reaction

$$e^+ e^- \rightarrow Y(4S) \rightarrow B\overline{B}$$

In general one of the two B mesons is tagged and the other is studied

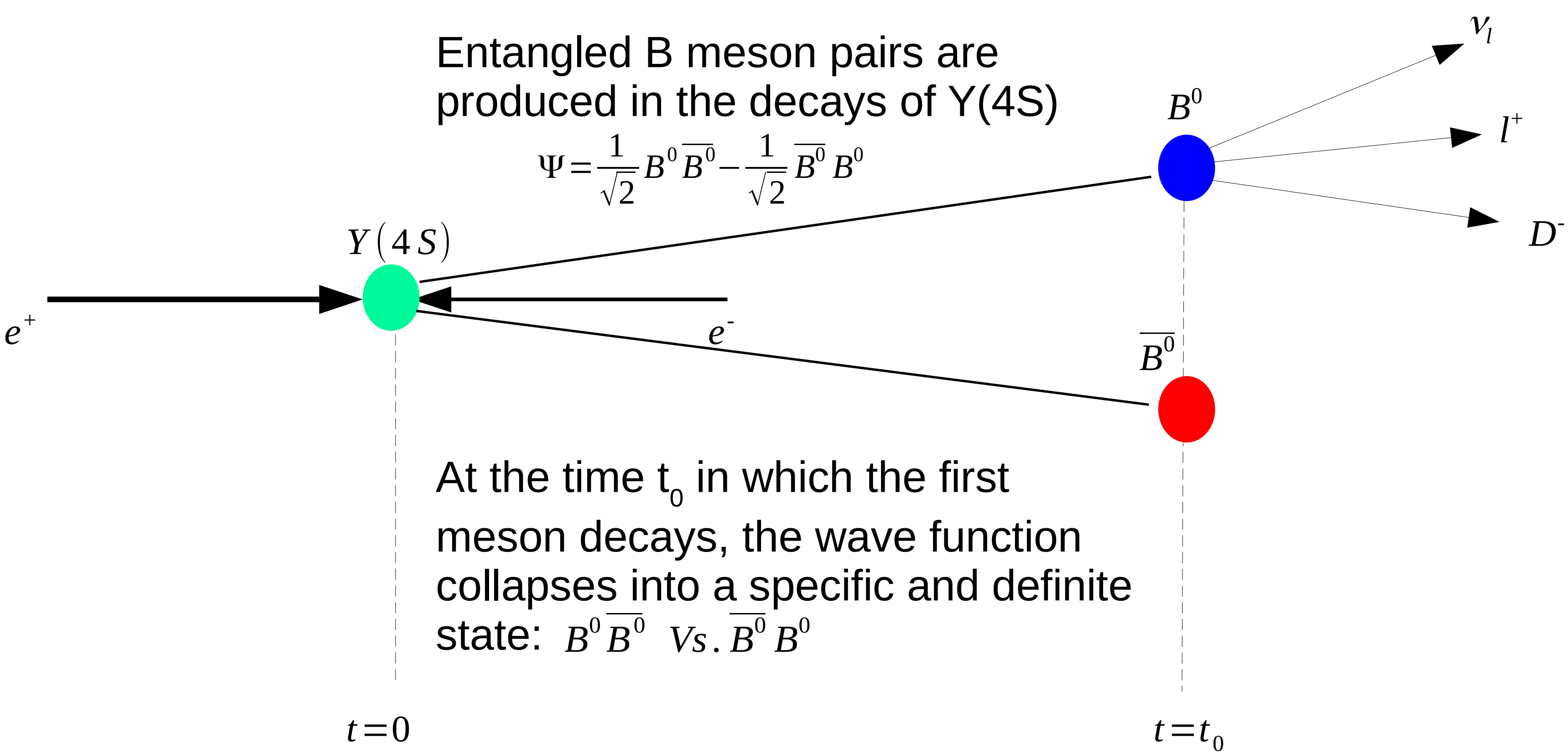


Why a (super) B-factory?

The general aim of a B-factory is to study B mesons via the reaction

$$e^+ e^- \rightarrow Y(4S) \rightarrow B\overline{B}$$

In general one of the two B mesons is tagged and the other is studied

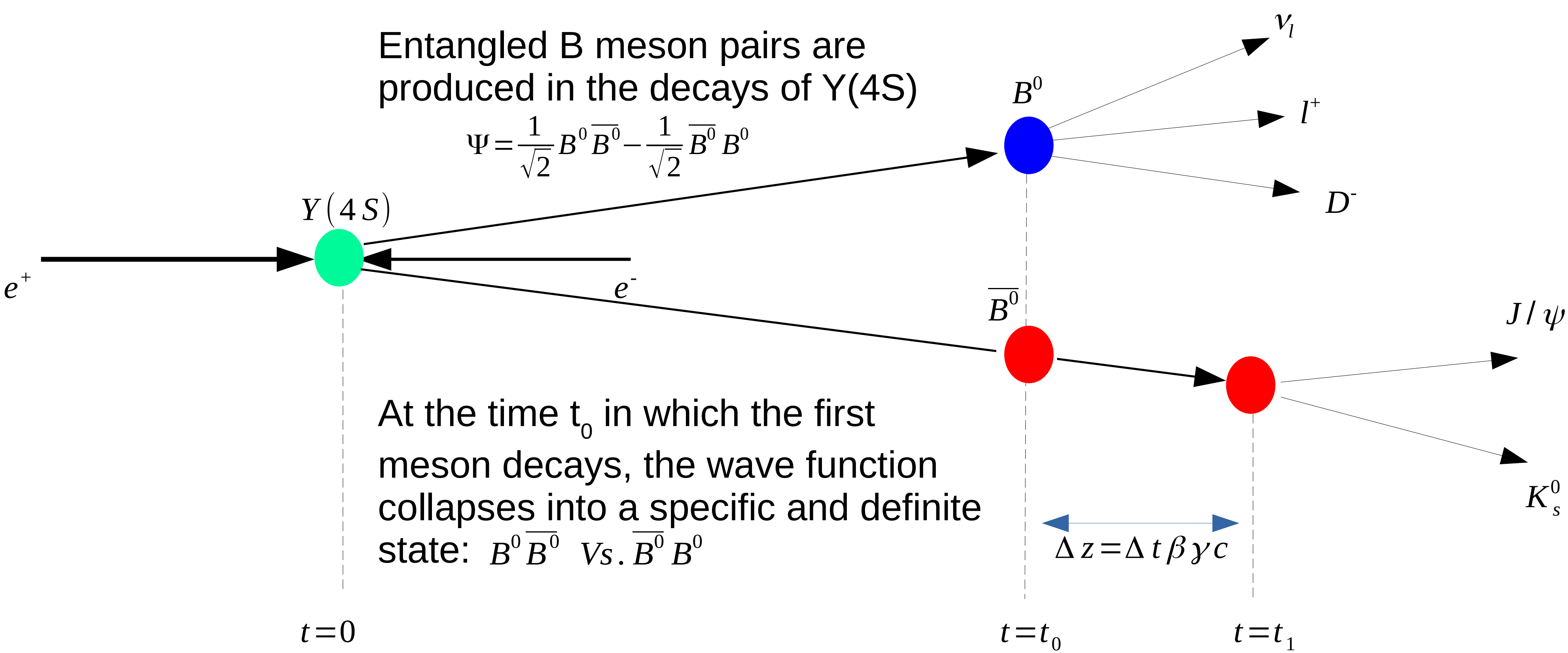


Why a (super) B-factory?

The general aim of a B-factory is to study B mesons via the reaction

$$e^+e^- \to Y(4S) \to B\overline{B}$$

In general one of the two B mesons is tagged and the other is studied



Why a (super) B-factory?

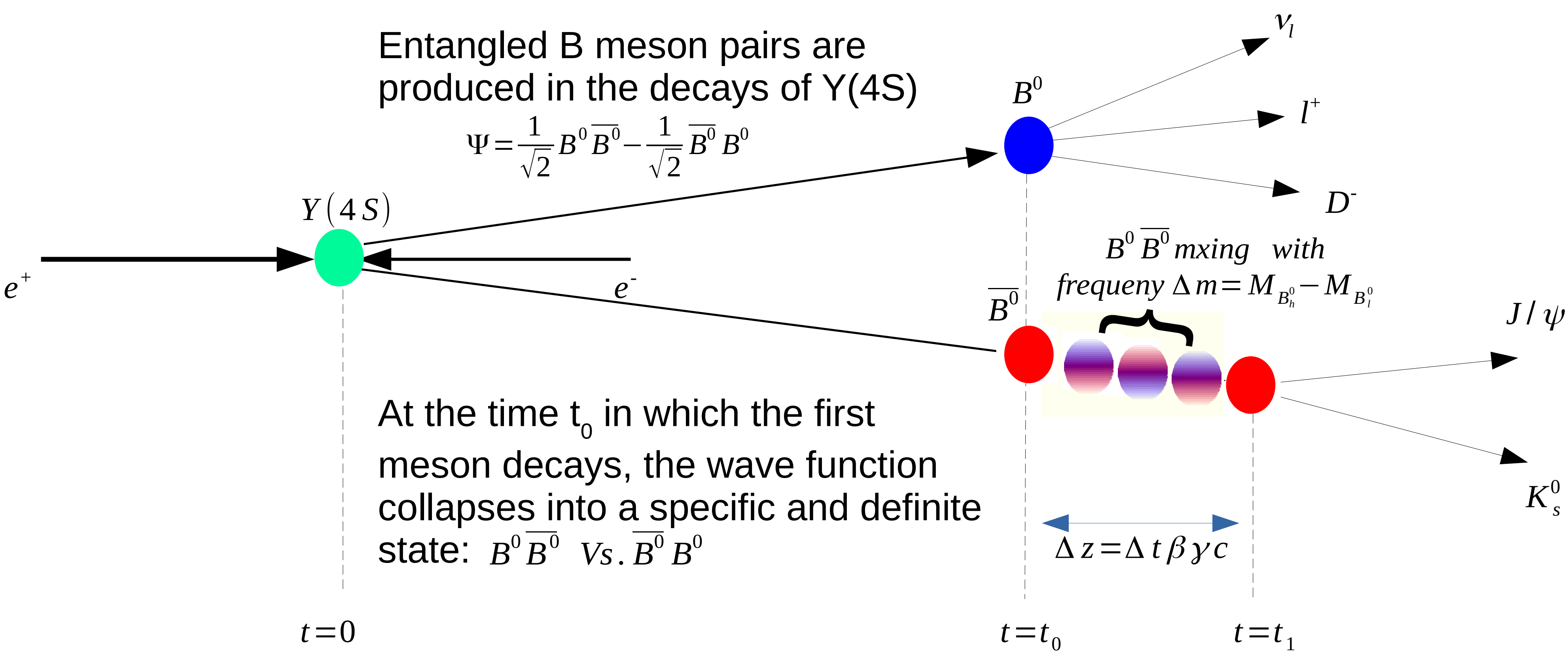
The general aim of a B-factory is to study B mesons via the reaction

$$e^+ e^- \rightarrow Y(4S) \rightarrow B \overline{B}$$

In general one of the two B mesons is tagged and the other is studied

Entangled B meson pairs are produced in the decays of Y(4S)

$$\Psi = \frac{1}{\sqrt{2}} B^0 \overline{B^0} - \frac{1}{\sqrt{2}} \overline{B^0} B^0$$



At the time t_0 in which the first meson decays, the wave function collapses into a specific and definite state: $B^0 \overline{B^0}$ Vs. $\overline{B^0} B^0$

Symmetric vs. asymmetric energy collisions

In order to measure the time at which the decay occurs one has to measure the Traveled distance: $t=L/v$. This requires vertexing with good vertex resolution.

$\tau_B = 1.6\text{x}10^{-12}$ sec

In symmetric energy collisions taking place at the Y(4S) peak

$p_{lab} = 0.3$ GeV, $m_B = 5.28$ GeV

Average flight distance: $<L> = (\beta\gamma)c\tau_B = (p/m)(468\mu m) = (0.3/5.28)(468\mu m) =$ **$(27\mu m)$**

Too small to be measured!!

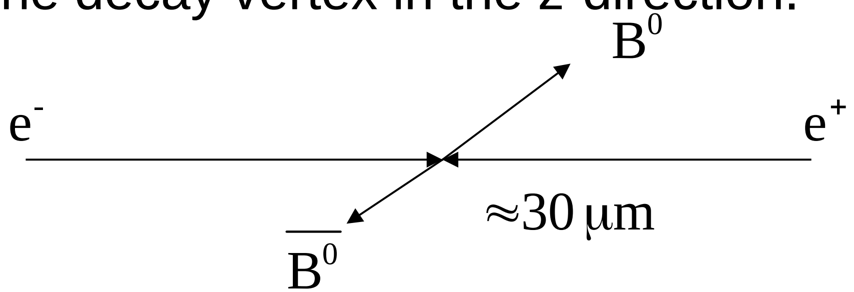
In **a**symmetric energy collisions the entire system is Lorentz Boosted:

$\beta\gamma = p_{lab}/E_{cm} = (p_{high} - p_{low})/E_{cm}$

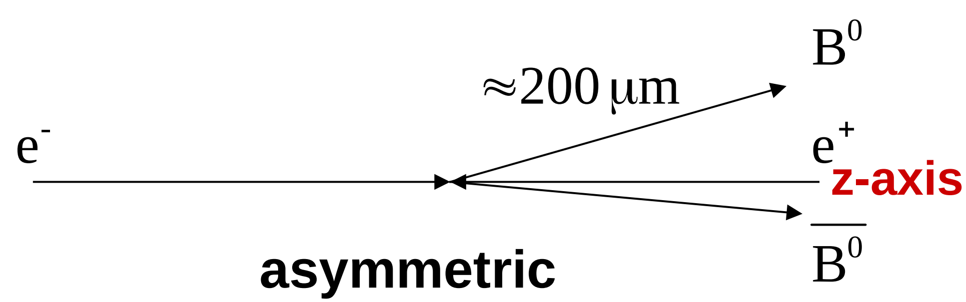
SLAC:	9 GeV+3.1 GeV,	$\beta\gamma = 0.55$	$<L> =$ **$257\mu m$**
KEK:	8 GeV+3.5 GeV,	$\beta\gamma = 0.42$	$<L> =$ **$197\mu m$**
Super-KEKB:	7 GeV+4 GeV ,	$\beta\gamma = 0.28$	$<L> =$ **$131\mu m$**

these distances/lengths can be measured!!

Due to the boost and the small p_{lab} the time measurement is a measurement of the of The decay vertex in the z-direction.



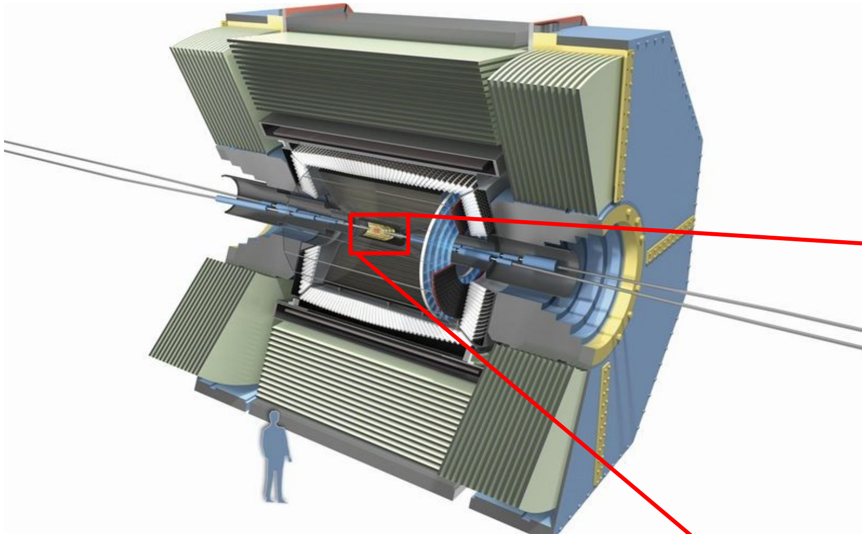
symmetric
CESR



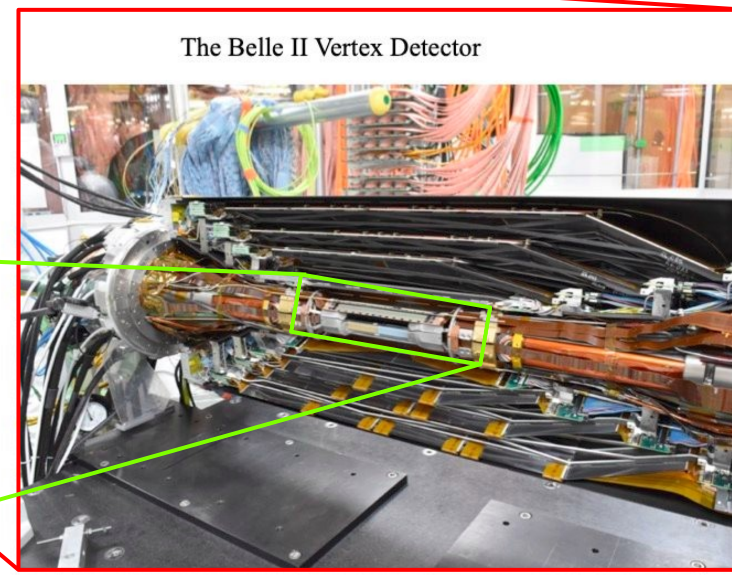
asymmetric
SLAC, KEK

Pixel detector

At the end of Belle running, the inner most layer of the SVD had occupancy ~10% → Have to move to pixelated detectors rather than strips to handle occupancy



Mechanical mockup of pixel detector



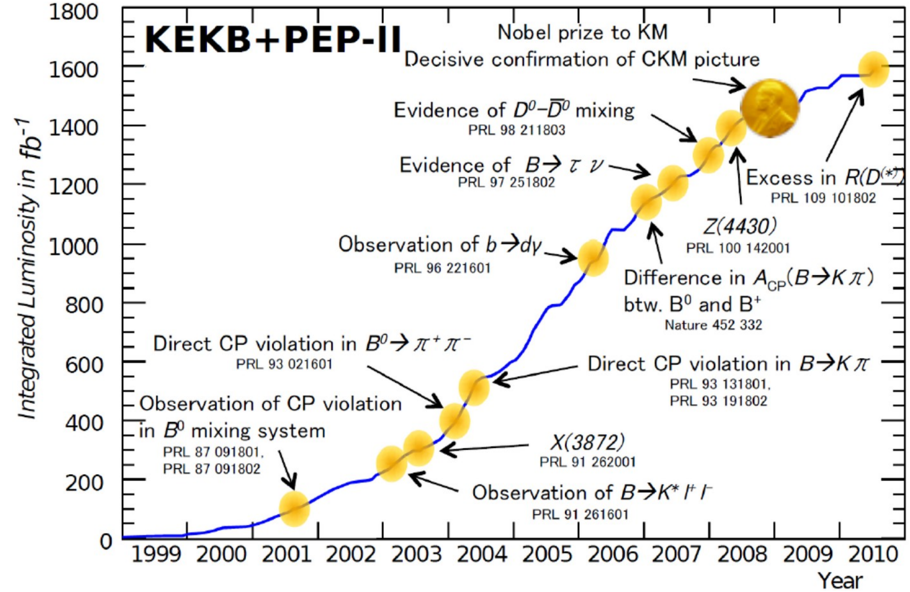
DEPFET pixel sensor

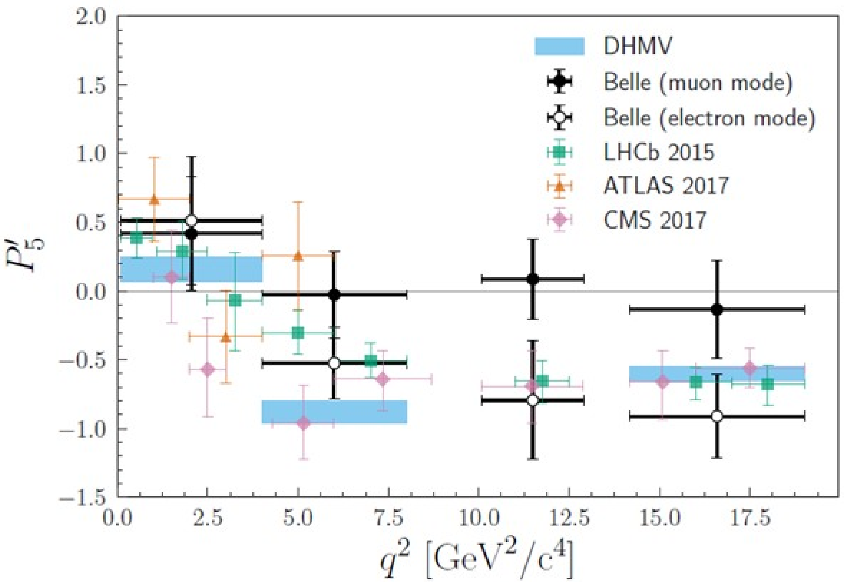
DEPFET sensor: very good S/N but only 75 µm thick. However, complex CO_2 cooling plant needed for high power readout chips.

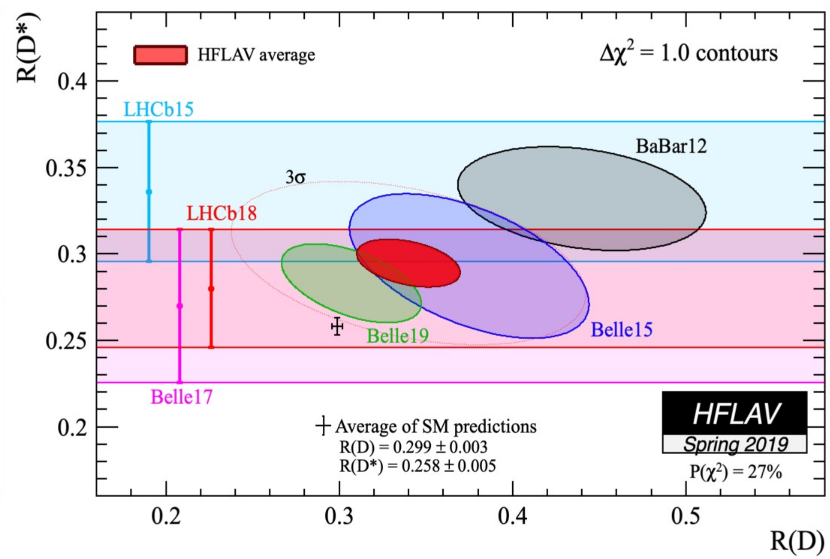
Final vertex resolution ~15 µm

Some physics from Belle to Belle II

- B-factories have been the driving forces in the past decades to establish the CKM mechanism as origin of CP violation and in the search for new physics.
- Few anomalies in the recent years have been observed and large amount of data are required to understand if these are fluctuations or if new physics effects have been observed





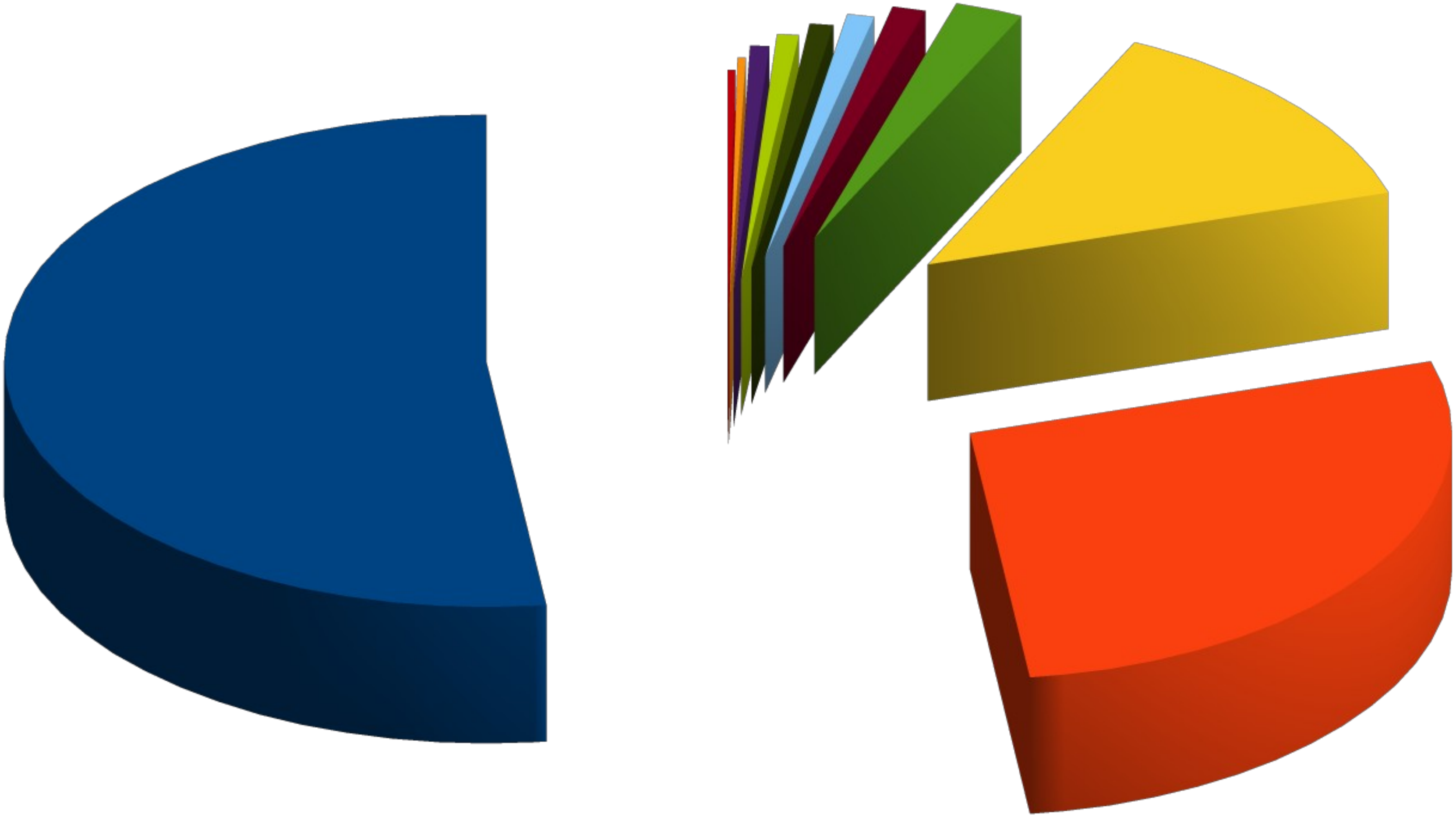


$$R(D)=\frac{BF[\bar{B}^0\to D\tau^-\bar{\nu}_\tau]}{BF[\bar{B}^0\to D l^-\bar{\nu}_l]}$$

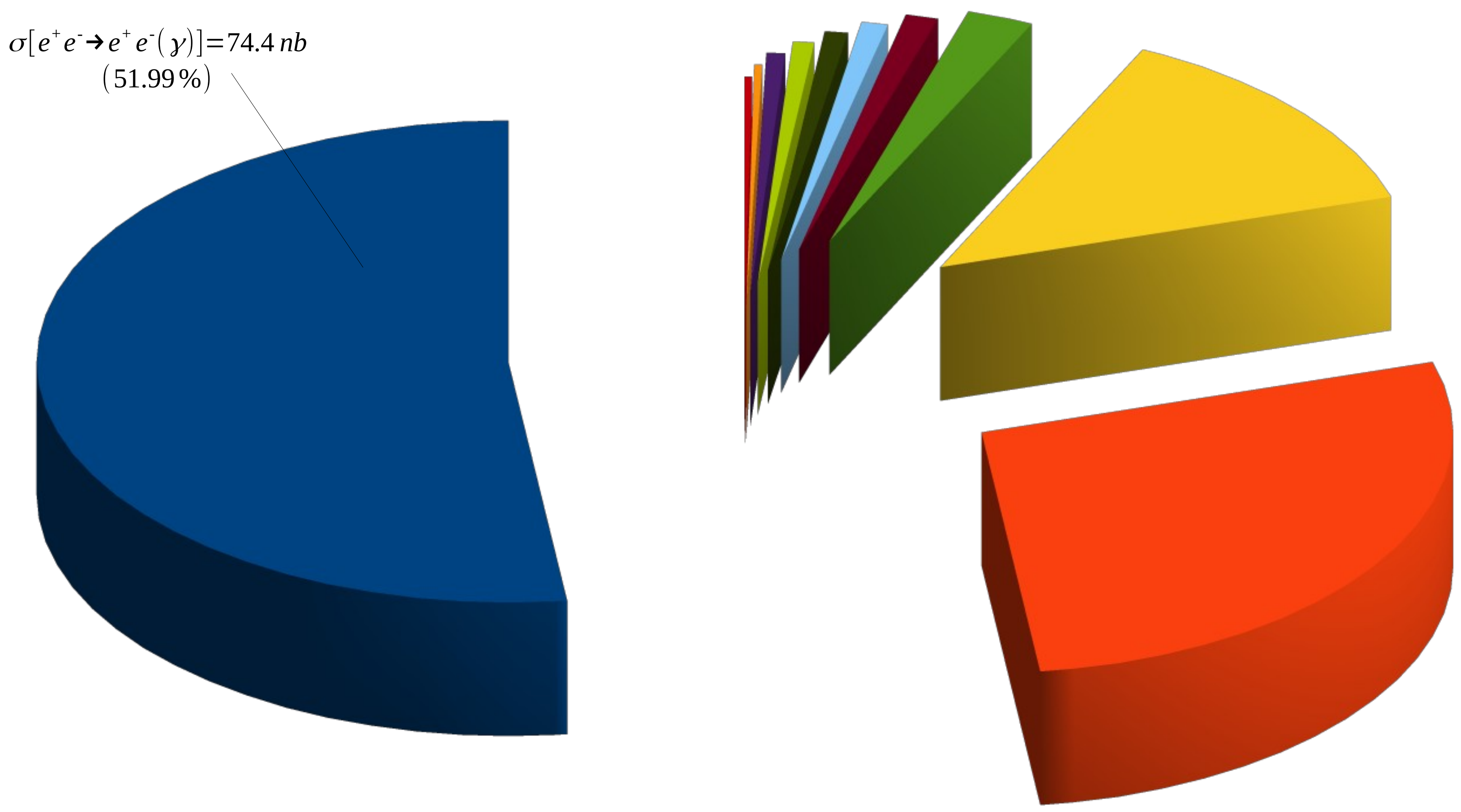
$$R(D^*)=\frac{BF[\bar{B}^0\to D^*\tau^-\bar{\nu}_\tau]}{BF[\bar{B}^0\to D^* l^-\bar{\nu}_l]}$$

- Belle II will provide a complementary approach to new physics searches wrt other experiments
- Rich program of flavor physics studies thanks to the high luminosity
- Physics beyond flavor...

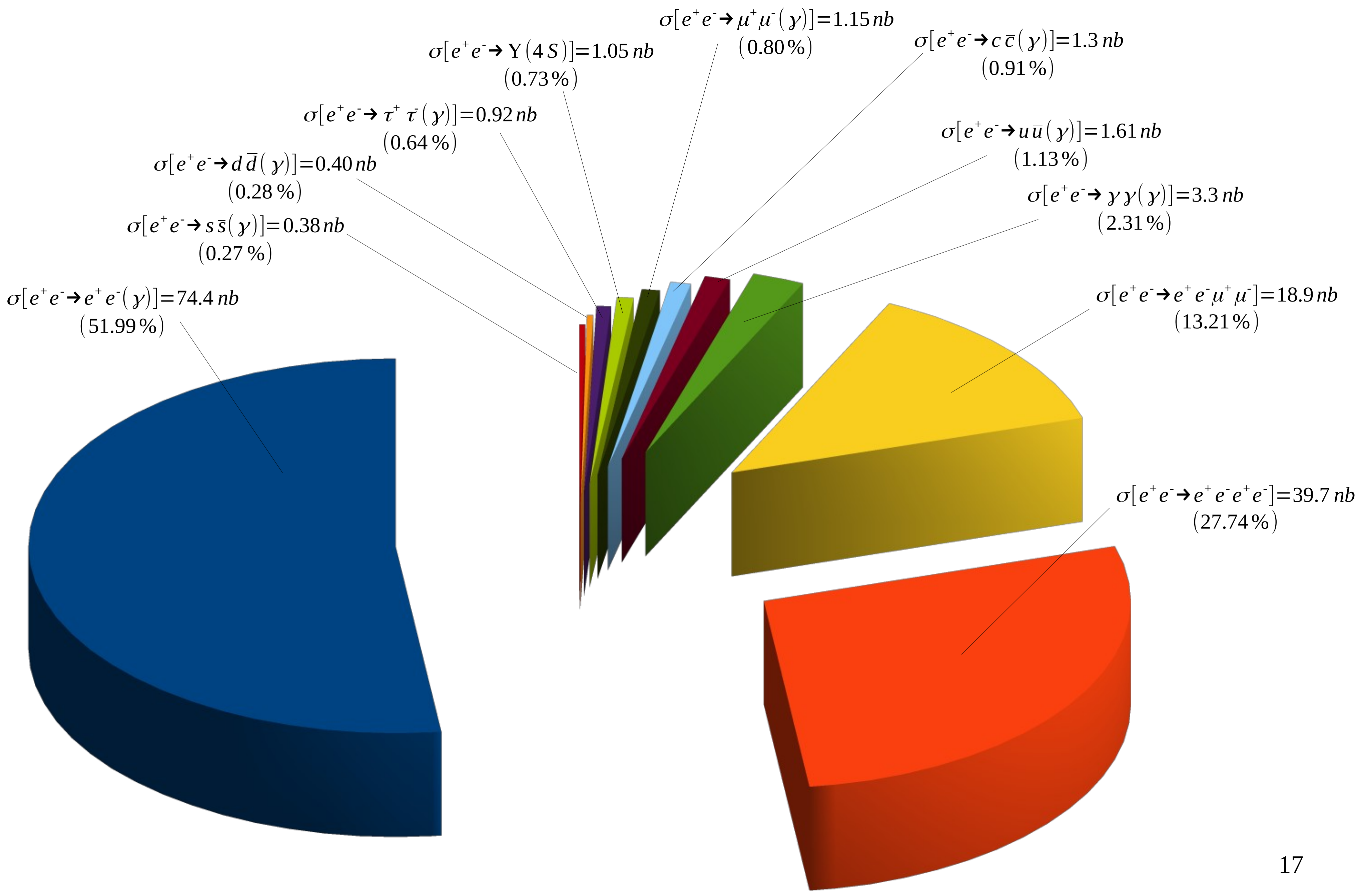
What happens when colliding e^+e^- @Super-KEKB?



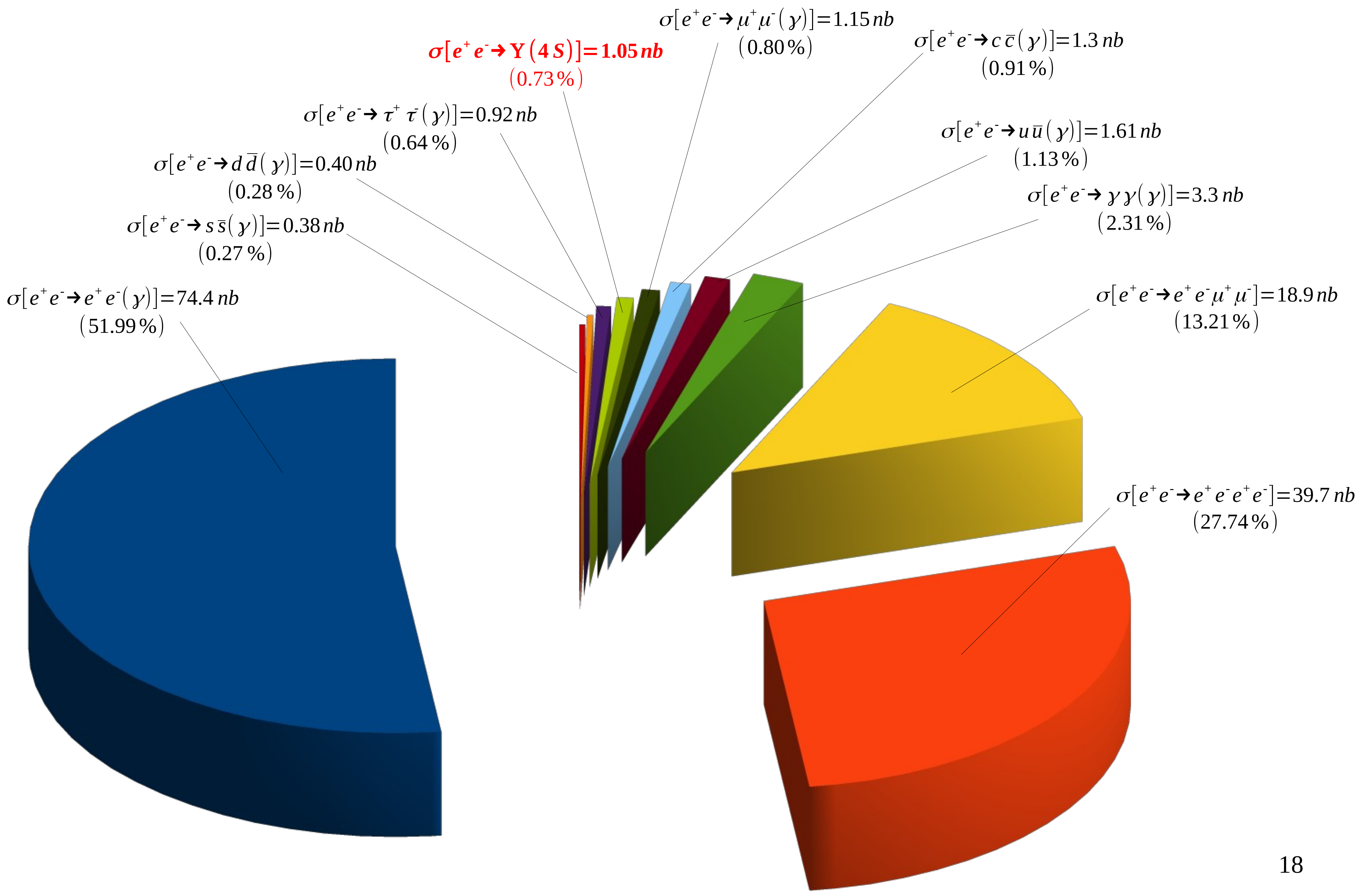
What happens when colliding e^+e^- @Super-KEKB?



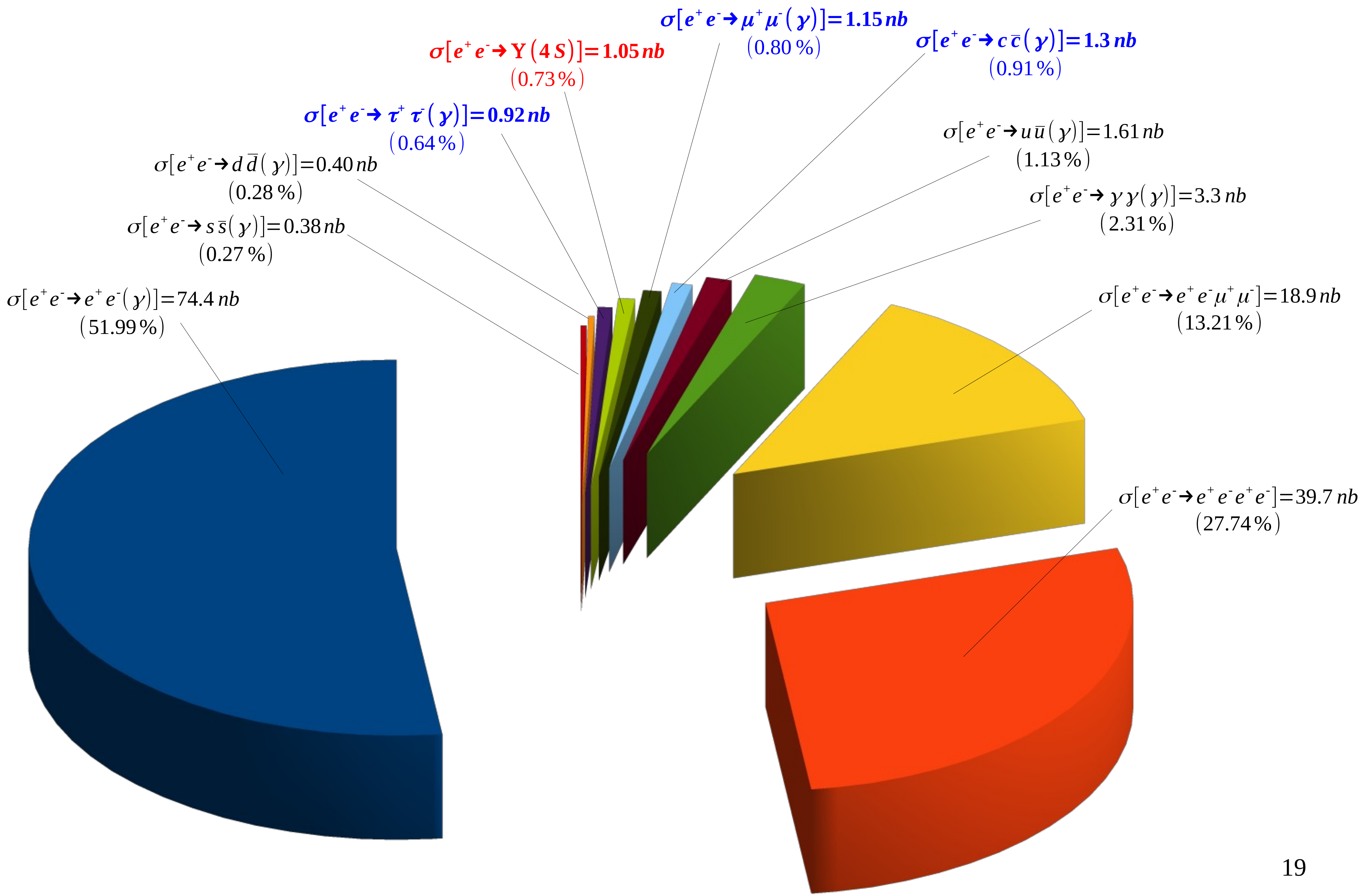
What happens when colliding e^+e^- @Super-KEKB?



What happens when colliding e^+e^- @Super-KEKB?



What happens when colliding e^+e^- @Super-KEKB?



What happens when colliding e^+e^- @Super-KEKB?

Physics process	Cross section [nb]	Cuts
$\Upsilon(4S)$	1.05 ± 0.10	-
$u\bar{u}(\gamma)$	1.61	-
$d\bar{d}(\gamma)$	0.40	-
$s\bar{s}(\gamma)$	0.38	-
$c\bar{c}(\gamma)$	1.30	-
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10° < \theta^*_{e's} < 170°$, $E^*_{e's} > 0.15$ GeV
$e^+e^-(\gamma)$	74.4	e's (p >0.5GeV) in ECL
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta^*_{\gamma's} < 170°$, $E^*_{\gamma's} > 0.15$ GeV
$\gamma\gamma(\gamma)$	3.30	γ's (p >0.5GeV) in ECL
$\mu^+\mu^-(\gamma)$	1.148	-
$\mu^+\mu^-(\gamma)$	0.831	μ's (p >0.5GeV) in CDC
$\mu^+\mu^-\gamma(\gamma)$	0.242	μ's (p >0.5GeV) in CDC, ≥ 1 γ (E_γ >0.5GeV) in ECL
$\tau^+\tau^-(\gamma)$	0.919	-
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5$GeV
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5$GeV

https://en.wikipedia.org/wiki/Barn_(unit)

Unit	Symbol	m²	cm²
megabarn	Mb	10^{-22}	10^{-18}
kilobarn	kb	10^{-25}	10^{-21}
barn	b	10^{-28}	10^{-24}
millibarn	mb	10^{-31}	10^{-27}
microbarn	μb	10^{-34}	10^{-30}
nanobarn	nb	10^{-37}	10^{-33}
picobarn	pb	10^{-40}	10^{-36}
femtobarn	fb	10^{-43}	10^{-39}
attobarn	ab	10^{-46}	10^{-42}
zeptobarn	zb	10^{-49}	10^{-45}
yoctobarn	yb	10^{-52}	10^{-48}

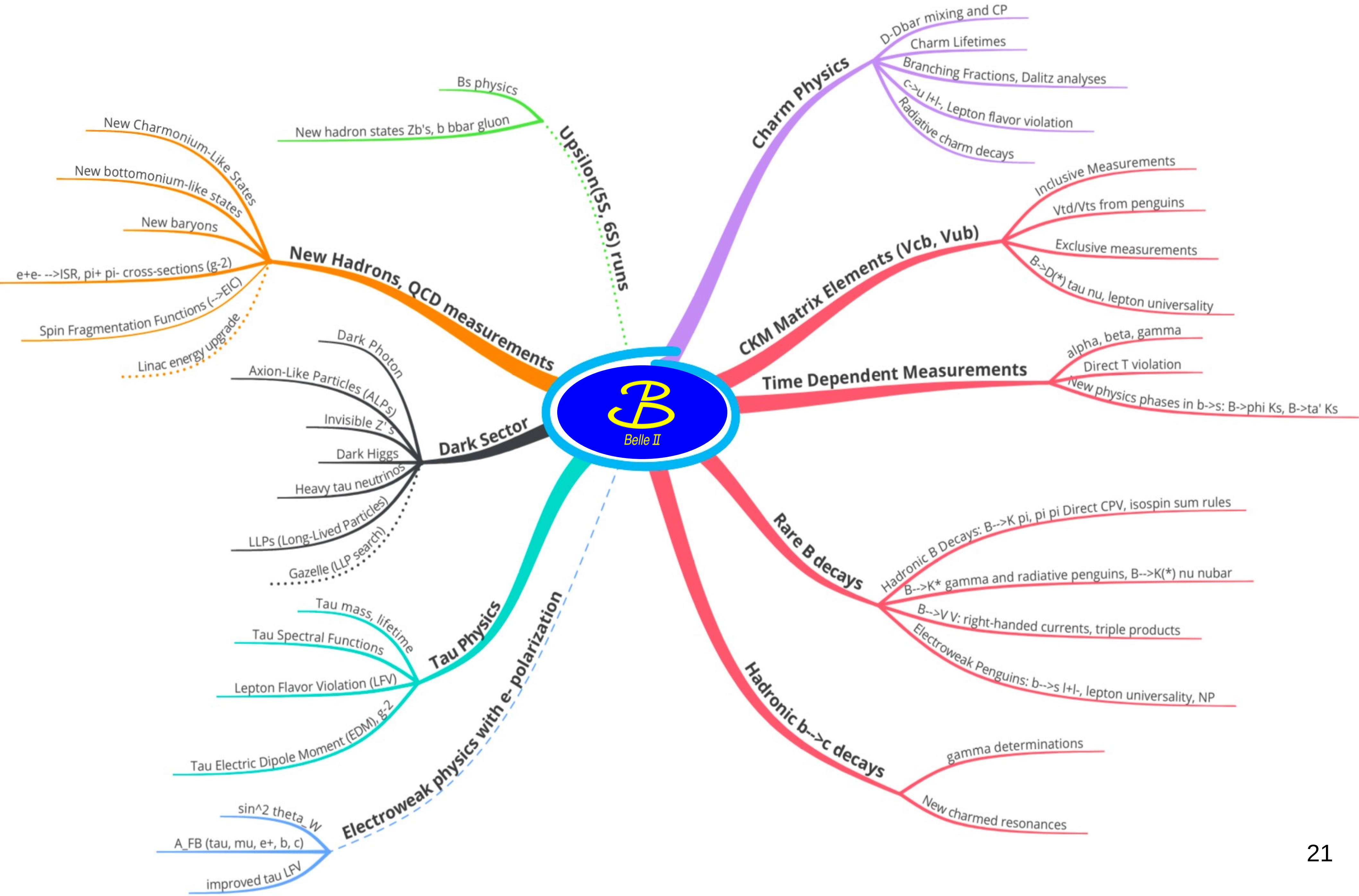
Remember!! $N = L \times \sigma$

Cross-section of the process to be studied in the specific experiment

Number of events of a process

Luminosity of an experiment

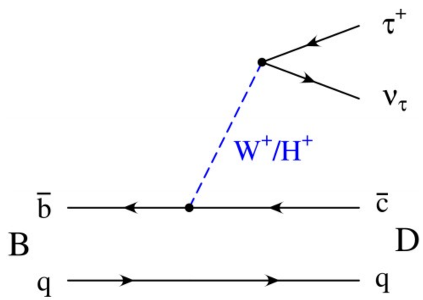
The Belle II physics program



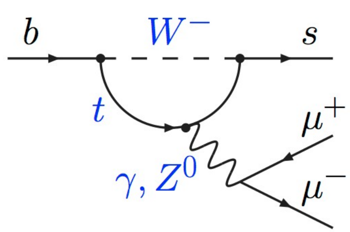
Flavor anomalies

Anomalies have been reported in many processes involving both quarks and leptons

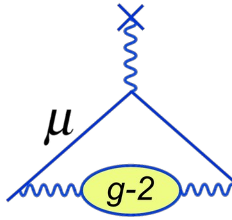
- In the **quark sector** anomalies have been observed for example



  - ***in $b \to c l \nu$***
    - $R(D)=BF[B \to D\tau^+\nu_\tau]/BF[B \to D l^+\nu_l\ (l=e,\mu)]$, ~1.4σ
    - $R(D^*)=BF[B \to D^*\tau^+\nu_\tau]/BF[B \to D^* l^+\nu_l\ (l=e,\mu)]$, ~2.7σ
    - in the $R(D)$-$R(D^*)$ plane ~3.9σ

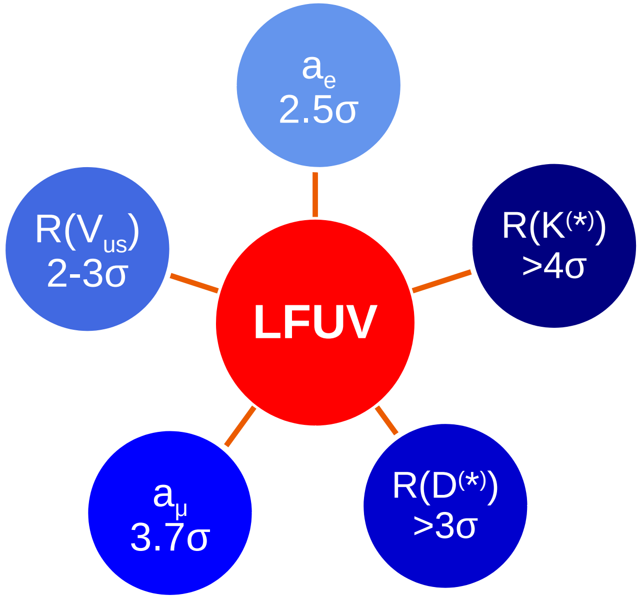


  - ***in $b \to s l l$***
    - $R(K)=BF[B^+ \to K^+\mu^+\mu^-]/BF[B^+ \to K^+e^+e^-]$ ~2.5σ
    - $R(K^{*0})=BF[B^0 \to K^{*0}\mu^+\mu^-]/BF[B^0 \to K^{*0}e^+e^-]$ ~2.2-2.5σ
    - In the angular observables of $B \to K^*\mu^+\mu^-$ ~3.4σ



- In the **lepton sector** anomalies have been observed for example
  - In the anomalous magnetic moment of the muon ***$(g-2)_\mu$*** ~3.8σ
  - In the anomalous magnetic moment of the electron ~2.5σ

Flavor anomalies, tensions in the standard model

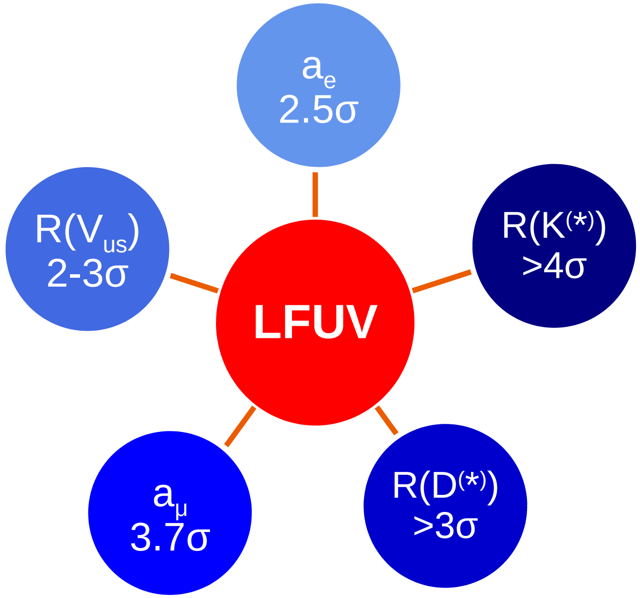


Are these the hints of a new fundamental interaction that violates Lepton Flavour Universality?

“Lepton Flavor Universality refers to an intrinsic accidental property or symmetry of the SM under which the electroweak (gauge) bosons have the same couplings to the three generations of leptons, since the only physical difference between the three generations of leptons derives from Yukawa interactions between the lepton fields and the Higgs field” → The only difference between charged leptons is their mass.

The graphical compilation of anomalies was borrowed with permission from our collaborator Andreas Crivellin, https://arxiv.org/pdf/2002.07184.pdf

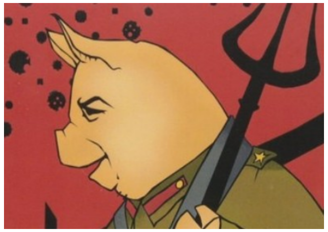
Flavor anomalies, tensions in the standard model



Are these the hints of a new fundamental interaction that violates Lepton Flavour Universality?

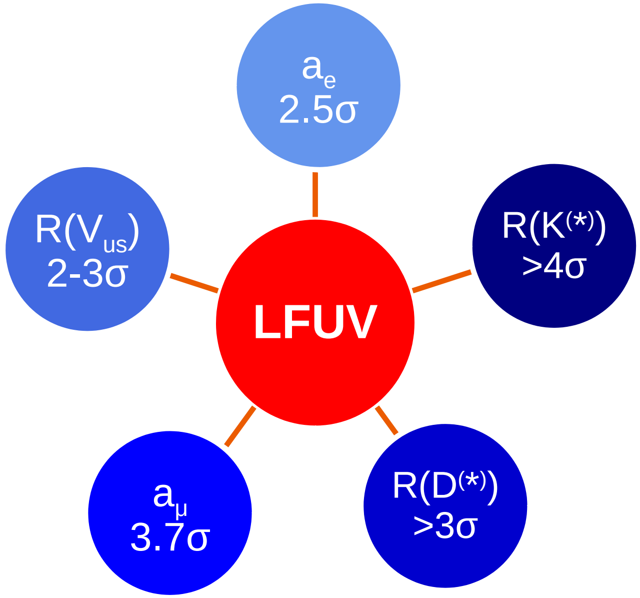
Lepton Flavor Universality from the perspective of a lepton flavor non-universal current:

"All leptons are equals, but some leptons are more equal than others..."



The graphical compilation of anomalies was borrowed with permission from our collaborator Andreas Crivellin, https://arxiv.org/pdf/2002.07184.pdf

Flavor anomalies, tensions in the standard model



Are these the hints of a new fundamental interaction that violates Lepton Flavour Universality?

- Should the observed flavor physics anomalies be due to new physics, are there other independent channels not well experimentally explored that might be affected by the same kind of new physics?
- Can these other channels be used to identify which new physics models are more suitable and which models are instead to be excluded or severely constrained?
- Is it possible to perform these measurements and tests in the clean but energy-limited environment of the Belle II experiment?

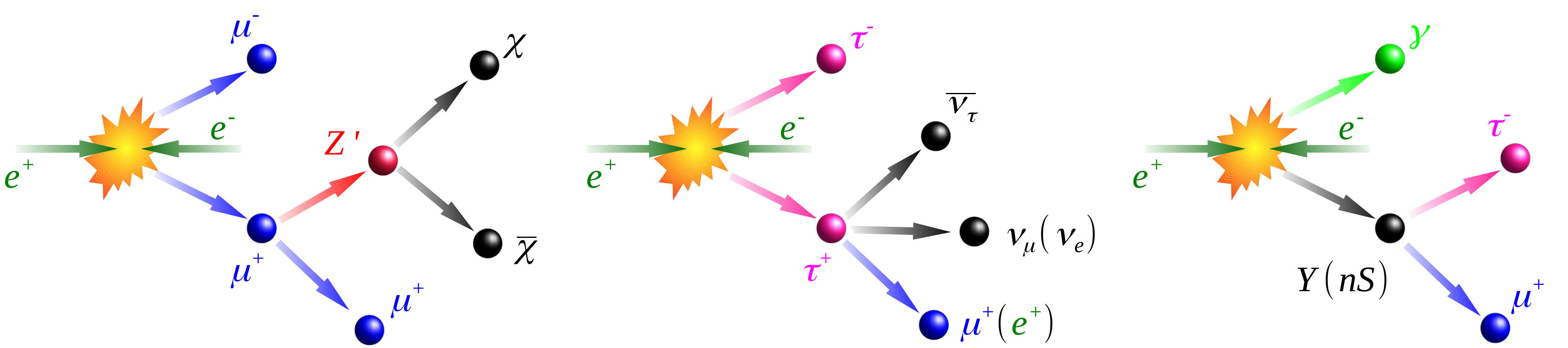
The graphical compilation of anomalies was borrowed with permission from our collaborator Andreas Crivellin, https://arxiv.org/pdf/2002.07184.pdf

Flavor anomalies, tensions in the standard model

- Should the observed flavor physics anomalies be due to new physics, are there other independent channels not well experimentally explored that might be affected by the same kind of new physics?
- Can these other channels be used to identify which new physics models are more suitable and which models are instead to be excluded or severely constrained?
- Is it possible to perform these measurements and tests in the clean but energy-limited environment of the Belle II experiment?

The answer to all above questions is “yes” and we will focus on the following searches:

Three unique experimental searches with leptons and missing energy in the final state

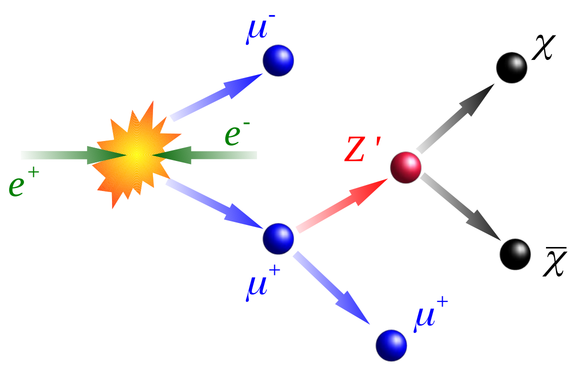


L-flavor preferential coupling: the L_μ-L_τ model and a dark Z'

The model is a new gauge boson, Z', which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

$$\mathcal{L} = -g'\bar{\mu}\gamma^\mu Z'_\mu \mu + g'\bar{\tau}\gamma^\mu Z'_\mu \tau - g'\bar{\nu}_{\mu,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\mu,\mathrm{L}} + g'\bar{\nu}_{\tau,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\tau,\mathrm{L}}.$$

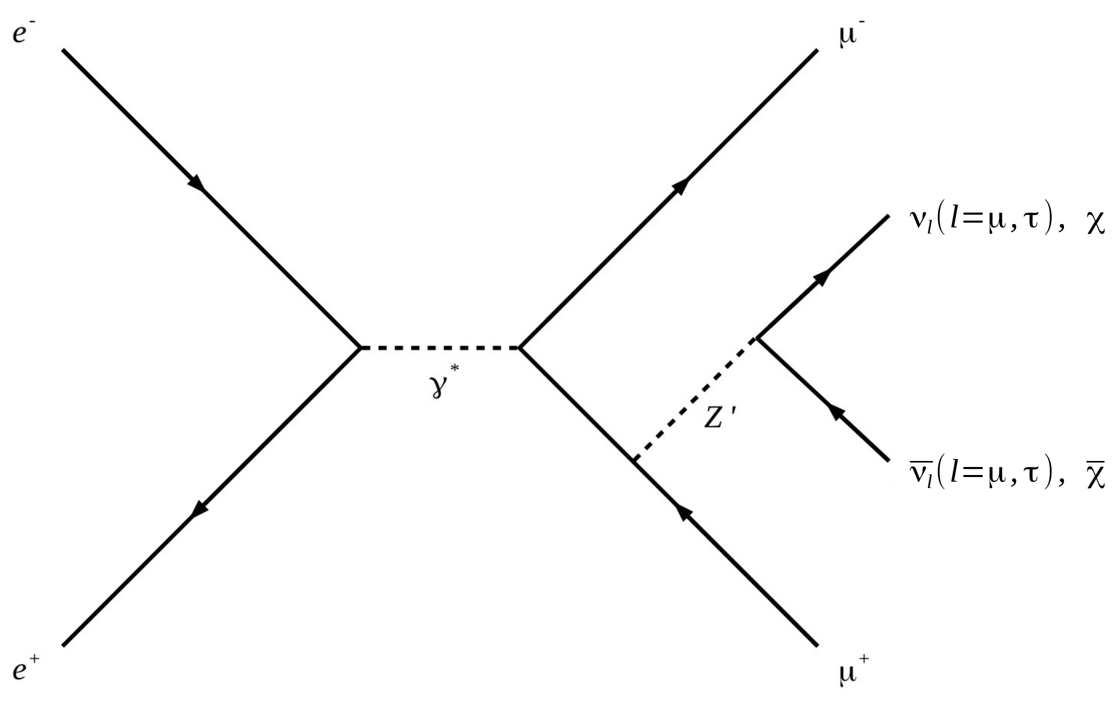
The equations for the partial widths are,



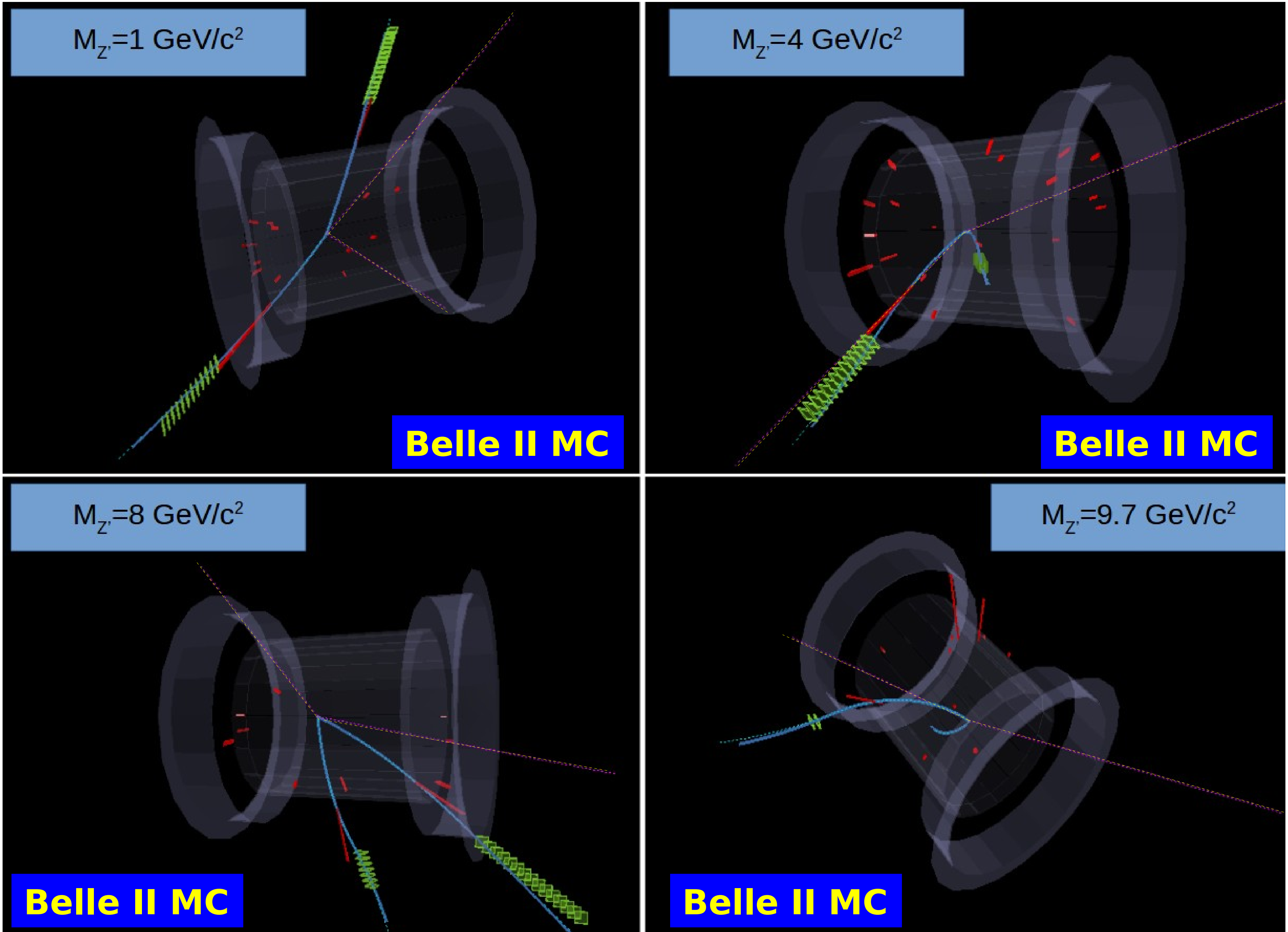
$$\Gamma(Z' \to \ell^+\ell^-) = \frac{(g')^2 M_{Z'}}{12\pi}\left(1 + \frac{2M_\ell^2}{M_{Z'}^2}\right)\sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}}\,\theta(M_{Z'} - 2M_\ell),$$

$$\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) = \frac{(g')^2 M_{Z'}}{24\pi}.$$

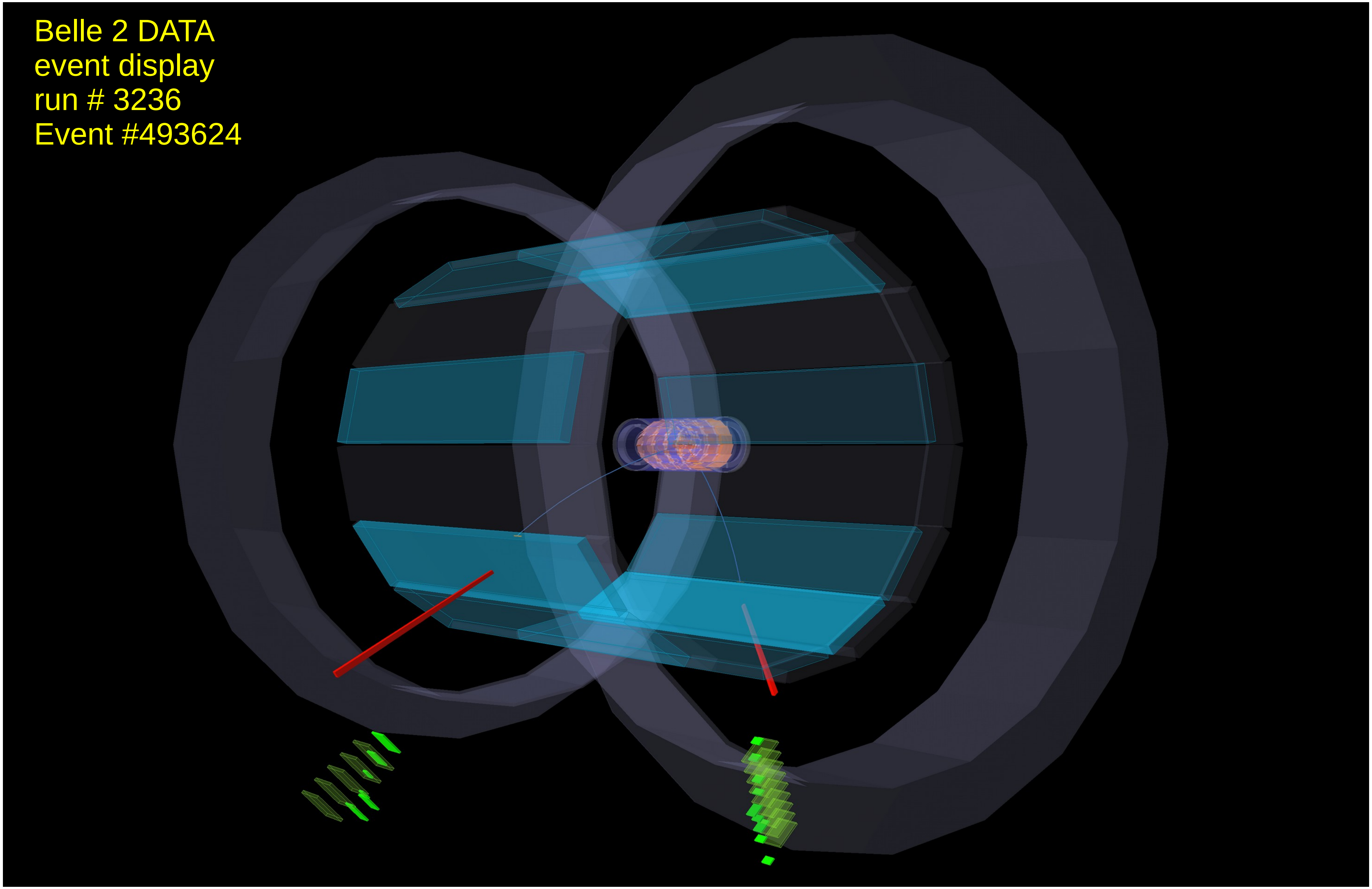
$$BR(Z' \to invisible) = \frac{2\Gamma(Z' \to \nu_l \bar{\nu}_l)}{2\Gamma(Z' \to \nu_l \bar{\nu}_l) + \Gamma(Z' \to \mu\bar{\mu}) + \Gamma(Z' \to \tau\bar{\tau})}$$



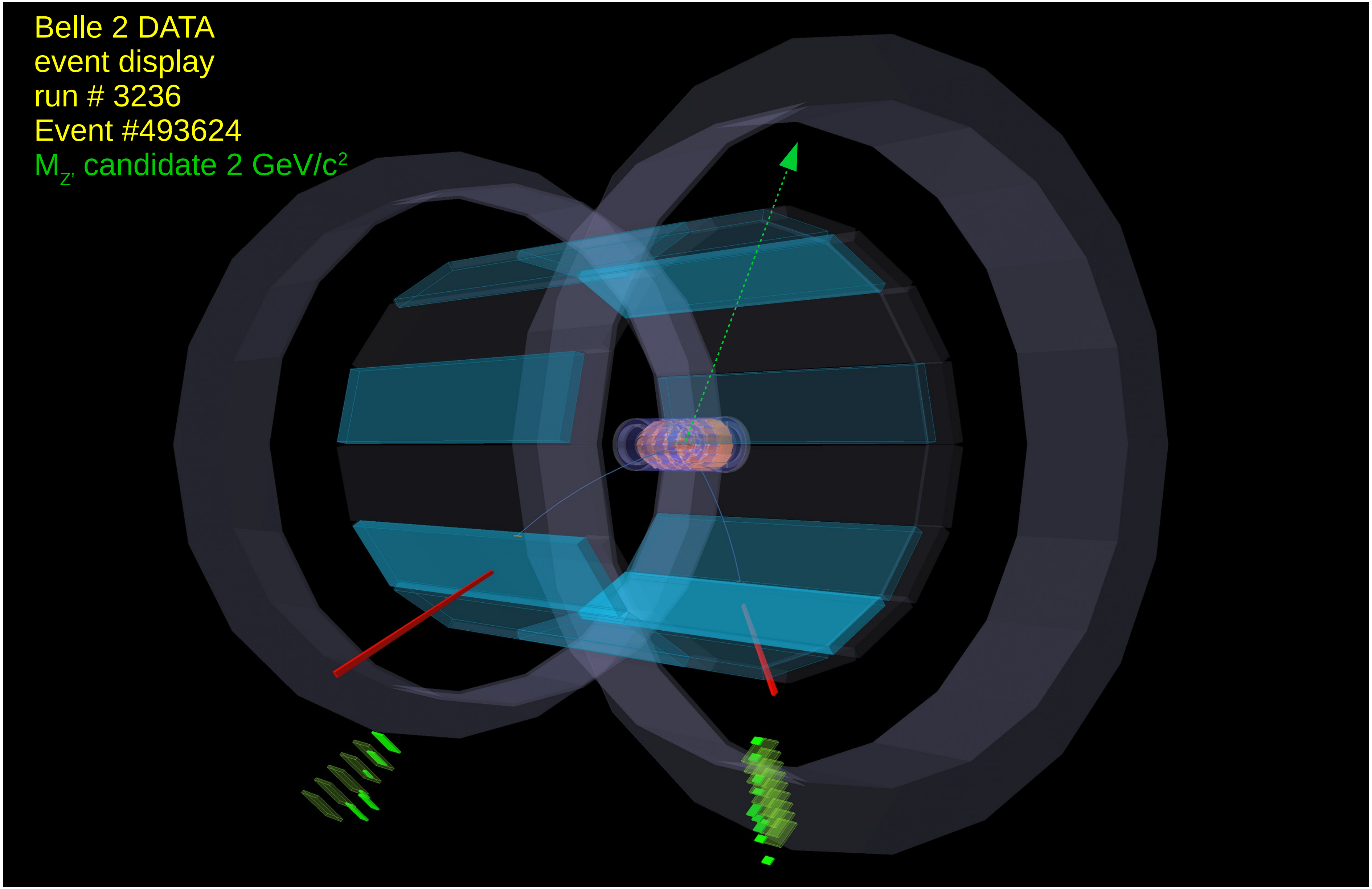
Z’→ invisible, Belle II Event Display



Belle II Event Display



Belle II Event Display

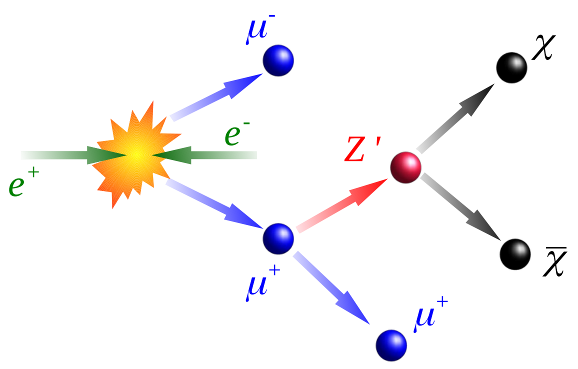


L-flavor preferential coupling: the L_μ-L_τ model and a dark Z'

The model is a new gauge boson, Z', which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

$$\mathcal{L} \;=\; -g'\bar{\mu}\gamma^\mu Z'_\mu \mu + g'\bar{\tau}\gamma^\mu Z'_\mu \tau - g'\bar{\nu}_{\mu,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\mu,\mathrm{L}} + g'\bar{\nu}_{\tau,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\tau,\mathrm{L}}.$$

The equations for the partial widths are,

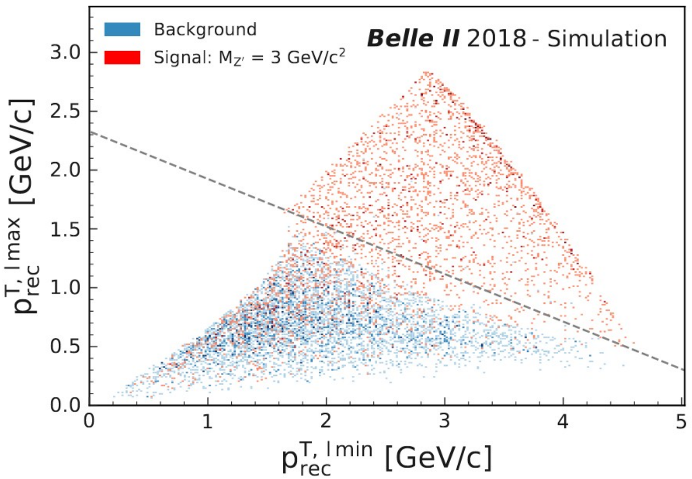


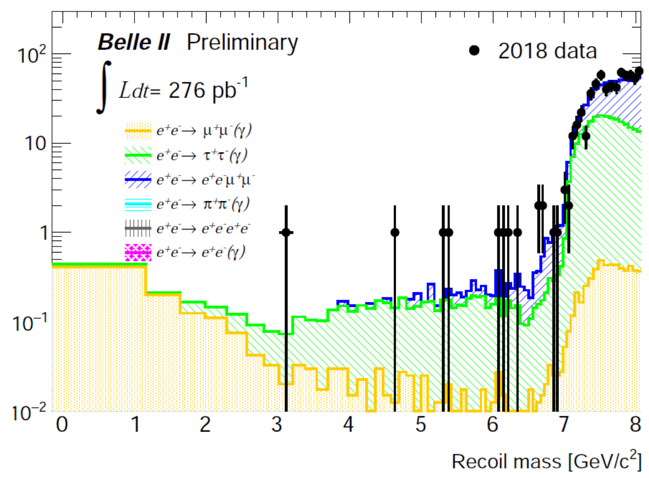
$$\Gamma(Z' \to \ell^+\ell^-) \;=\; \frac{(g')^2 M_{Z'}}{12\pi}\left(1 + \frac{2M_\ell^2}{M_{Z'}^2}\right)\sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}}\,\theta(M_{Z'} - 2M_\ell),$$

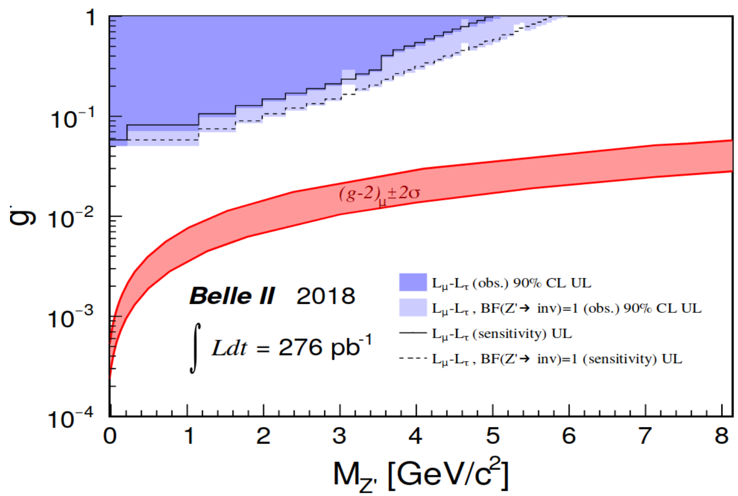
$$\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) \;=\; \frac{(g')^2 M_{Z'}}{24\pi}.$$

$$BR(Z'\to invisible) = \frac{2\Gamma(Z'\to\nu_l\overline{\nu_l})}{2\Gamma(Z'\to\nu_l\overline{\nu_l}) + \Gamma(Z'\to\mu\overline{\mu}) + \Gamma(Z'\to\tau\overline{\tau})}$$

We already pioneered this search, PRL **124**, 141801 (2020), arXiv:1912.11276





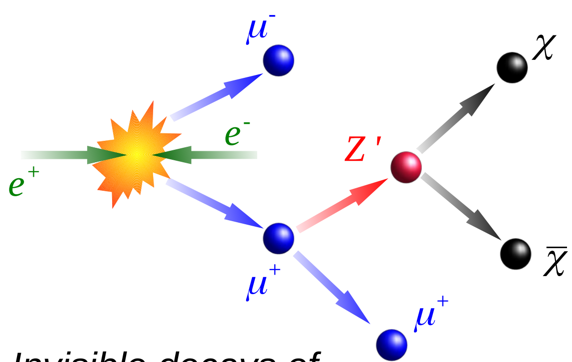


L-flavor preferential coupling: the L_μ-L_τ model and a dark Z'

The model is a new gauge boson, Z', which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

$$\mathcal{L} \;=\; -g'\bar{\mu}\gamma^\mu Z'_\mu \mu + g'\bar{\tau}\gamma^\mu Z'_\mu \tau - g'\bar{\nu}_{\mu,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\mu,\mathrm{L}} + g'\bar{\nu}_{\tau,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\tau,\mathrm{L}}.$$

The equations for the partial widths are,



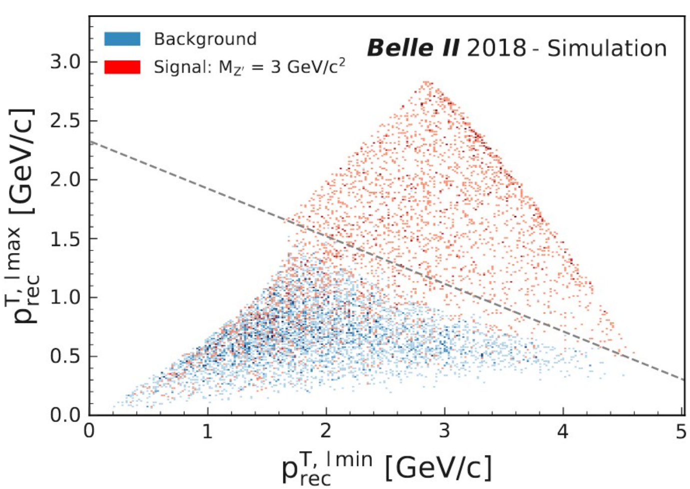
Invisible decays of Z' within the L_μ-L_τ model

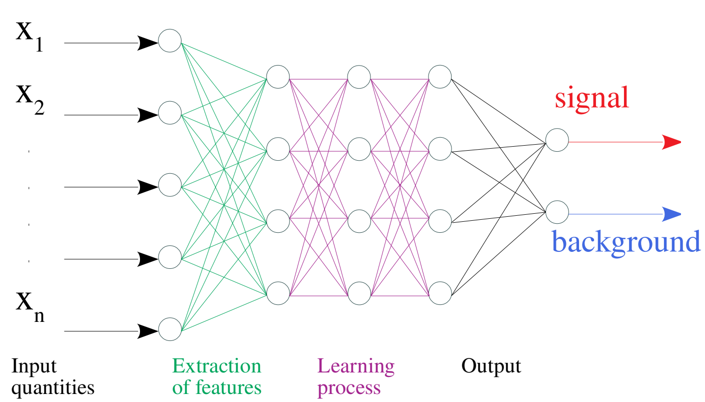
$$\Gamma(Z' \to \ell^+\ell^-) \;=\; \frac{(g')^2 M_{Z'}}{12\pi}\left(1 + \frac{2M_\ell^2}{M_{Z'}^2}\right)\sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}}\,\theta(M_{Z'} - 2M_\ell),$$

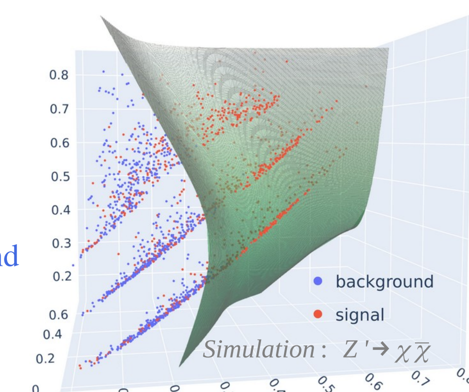
$$\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) \;=\; \frac{(g')^2 M_{Z'}}{24\pi}.$$

$$BR(Z' \to invisible) = \frac{2\Gamma(Z' \to \nu_l \bar{\nu}_l)}{2\Gamma(Z' \to \nu_l\bar{\nu}_l) + \Gamma(Z' \to \mu\bar{\mu}) + \Gamma(Z' \to \tau\bar{\tau})}$$

New machine learning analysis techniques based on ANNs already developed at HEPHY, plan to go deeper...with more data..





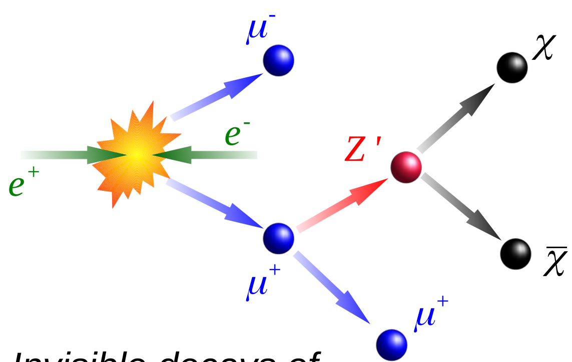


L-flavor preferential coupling: the L_μ-L_τ model and a dark Z'

The model is a new gauge boson, Z', which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

$$\mathcal{L} \;=\; -g'\bar{\mu}\gamma^\mu Z'_\mu \mu + g'\bar{\tau}\gamma^\mu Z'_\mu \tau - g'\bar{\nu}_{\mu,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\mu,\mathrm{L}} + g'\bar{\nu}_{\tau,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\tau,\mathrm{L}}.$$

The equations for the partial widths are,



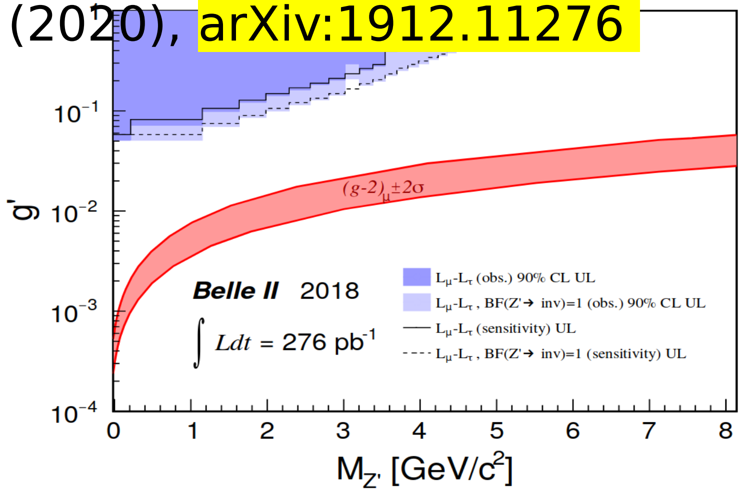
Invisible decays of Z' within the L_μ-L_τ model

$$\Gamma(Z' \to \ell^+\ell^-) \;=\; \frac{(g')^2 M_{Z'}}{12\pi}\left(1 + \frac{2M_\ell^2}{M_{Z'}^2}\right)\sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}}\,\theta(M_{Z'} - 2M_\ell),$$

$$\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) \;=\; \frac{(g')^2 M_{Z'}}{24\pi}.$$

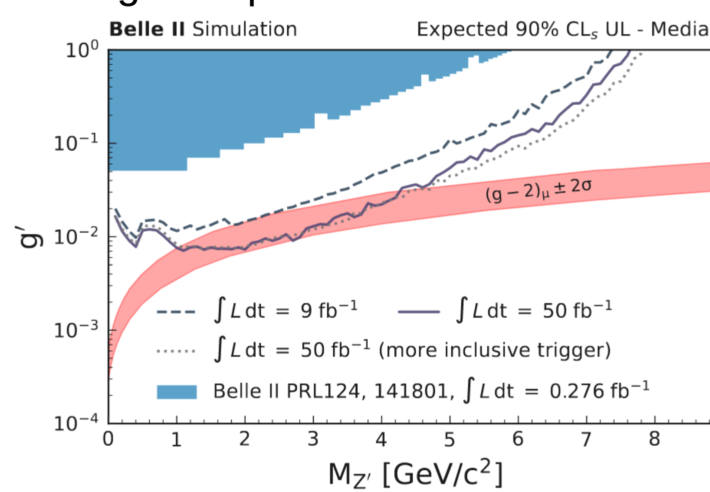
$$BR(Z'\to invisible) = \frac{2\Gamma(Z'\to\nu_l\bar{\nu}_l)}{2\Gamma(Z'\to\nu_l\bar{\nu}_l) + \Gamma(Z'\to\mu\bar{\mu}) + \Gamma(Z'\to\tau\bar{\tau})}$$

We already pioneered this search, PRL **124**, 141801 (2020), arXiv:1912.11276



New machine learning analysis techniques based on ANNs already developed at HEPHY, plan to go deeper...with more data..

In the near term

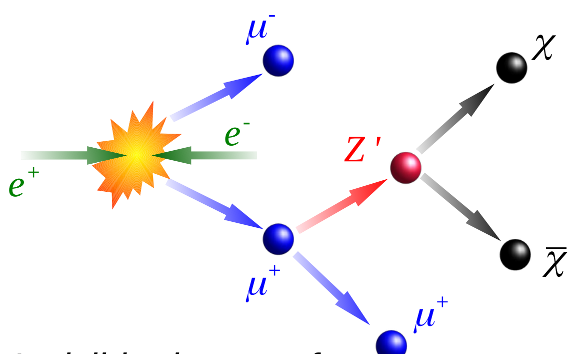


L-flavor preferential coupling: the L_μ-L_τ model and a dark Z'

The model is a new gauge boson, Z', which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

$$\mathcal{L} \;=\; -g'\bar{\mu}\gamma^\mu Z'_\mu \mu + g'\bar{\tau}\gamma^\mu Z'_\mu \tau - g'\bar{\nu}_{\mu,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\mu,\mathrm{L}} + g'\bar{\nu}_{\tau,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\tau,\mathrm{L}}.$$

The equations for the partial widths are,



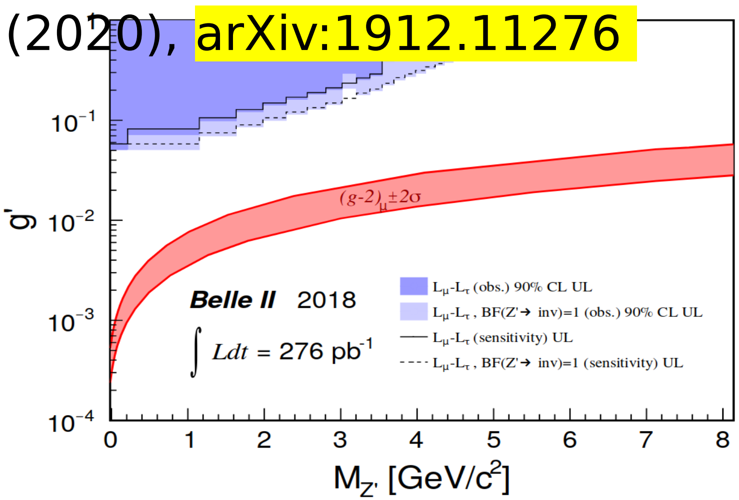
Invisible decays of Z' within the L_μ-L_τ model

$$\Gamma(Z' \to \ell^+\ell^-) \;=\; \frac{(g')^2 M_{Z'}}{12\pi}\left(1 + \frac{2M_\ell^2}{M_{Z'}^2}\right)\sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}}\,\theta(M_{Z'} - 2M_\ell),$$

$$\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) \;=\; \frac{(g')^2 M_{Z'}}{24\pi}.$$

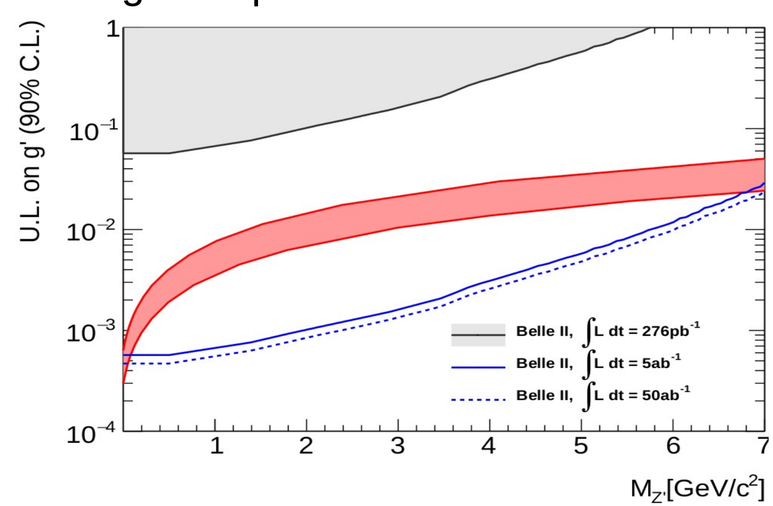
$$BR(Z' \to invisible) = \frac{2\Gamma(Z' \to \nu_l \bar{\nu}_l)}{2\Gamma(Z' \to \nu_l \bar{\nu}_l) + \Gamma(Z' \to \mu\bar{\mu}) + \Gamma(Z' \to \tau\bar{\tau})}$$

We already pioneered this search, PRL **124**, 141801 (2020), arXiv:1912.11276



New machine learning analysis techniques based on ANNs already developed at HEPHY, plan to go deeper...with more data..

With lot of more data



LFU tests in tau decays

https://arxiv.org/pdf/1607.06832.pdf

Lepton flavor violating Z' explanation of the muon anomalous magnetic moment

Wolfgang Altmannshofer[1], Chien-Yi Chen[2,3], P. S. Bhupal Dev[4], Amarjit Soni[5]
[1] *Department of Physics, University of Cincinnati, Cincinnati, OH 45221, USA*
[2] *Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada*
[3] *Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada*
[4] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany and*
[5] *Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*

We discuss a minimal solution to the long-standing $(g-2)_\mu$ anomaly in a simple extension of the Standard Model with an extra Z' vector boson that has only flavor off-diagonal couplings to the second and third generation of leptons, i.e. $\mu, \tau, \nu_\mu, \nu_\tau$ and their antiparticles. A simplified model realization, as well as various collider and low-energy constraints on this model, are discussed. We find that the $(g-2)_\mu$-favored region for a Z' lighter than the tau lepton is totally excluded, while a heavier Z' solution is still allowed. Some testable implications of this scenario in future experiments, such as lepton-flavor universality-violating tau decays at Belle 2, and a new four-lepton signature involving same-sign di-muons and di-taus at HL-LHC and FCC-ee, are pointed out. A characteristic resonant absorption feature in the high-energy neutrino spectrum might also be observed by neutrino telescopes like IceCube and KM3NeT.

This is an Abelian symmetry group L_μ-L_τ where LFV terms are allowed

LFU tests in tau decays

$$\mathcal{L}_{Z'} = g'_L\left(\bar{\mu}\gamma^\alpha P_L\tau + \bar{\nu}_\mu\gamma^\alpha P_L\nu_\tau\right)Z'_\alpha + g'_R\left(\bar{\mu}\gamma^\alpha P_R\tau\right)Z'_\alpha + \text{H.c.}$$

$$P_{L,R} = \left(1 \mp \gamma^5\right)/2$$

Our "standard" Z'

The model is a new gauge boson, Z', which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

$$\mathcal{L} = -g'\bar{\mu}\gamma^\mu Z'_\mu \mu + g'\bar{\tau}\gamma^\mu Z'_\mu \tau - g'\bar{\nu}_{\mu,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\mu,\mathrm{L}} + g'\bar{\nu}_{\tau,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\tau,\mathrm{L}}.$$

The equations for the partial widths are,

$$\Gamma(Z' \to \ell^+\ell^-) = \frac{(g')^2 M_{Z'}}{12\pi}\left(1 + \frac{2M_\ell^2}{M_{Z'}^2}\right)\sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}}\,\theta(M_{Z'} - 2M_\ell),$$

$$\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) = \frac{(g')^2 M_{Z'}}{24\pi}.$$

LFU tests in tau decays

$$\mathcal{L}_{Z'} = g'_L\left(\bar{\mu}\gamma^\alpha P_L\tau + \bar{\nu}_\mu\gamma^\alpha P_L\nu_\tau\right)Z'_\alpha + g'_R\left(\bar{\mu}\gamma^\alpha P_R\tau\right)Z'_\alpha + \text{H.c.}$$

$$P_{L,R} = \left(1 \mp \gamma^5\right)/2$$

$$L_\mu \leftrightarrow L_\tau\,, \qquad \mu_R \leftrightarrow \tau_R\,,$$
$$B^\alpha \leftrightarrow B^\alpha\,, \qquad Z'^\alpha \leftrightarrow -Z'^\alpha$$

Our "standard" Z'

The model is a new gauge boson, Z', which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

$$\mathcal{L} = -g'\bar{\mu}\gamma^\mu Z'_\mu\mu + g'\bar{\tau}\gamma^\mu Z'_\mu\tau - g'\bar{\nu}_{\mu,\mathrm{L}}\gamma^\mu Z'_\mu\nu_{\mu,\mathrm{L}} + g'\bar{\nu}_{\tau,\mathrm{L}}\gamma^\mu Z'_\mu\nu_{\tau,\mathrm{L}}.$$

The equations for the partial widths are,

$$\Gamma(Z' \to \ell^+\ell^-) = \frac{(g')^2 M_{Z'}}{12\pi}\left(1 + \frac{2M_\ell^2}{M_{Z'}^2}\right)\sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}}\,\theta(M_{Z'} - 2M_\ell),$$

$$\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) = \frac{(g')^2 M_{Z'}}{24\pi}.$$

LFU tests in tau decays

$$\mathcal{L}_{Z'} = g'_L\left(\bar{\mu}\gamma^\alpha P_L\tau + \bar{\nu}_\mu\gamma^\alpha P_L\nu_\tau\right)Z'_\alpha + g'_R\left(\bar{\mu}\gamma^\alpha P_R\tau\right)Z'_\alpha + \mathrm{H.c.}$$

$$P_{L,R} = \left(1 \mp \gamma^5\right)/2$$

Lepton doublets → $(\nu_l, l)_L$

$$L_\mu \leftrightarrow L_\tau\,,$$

Lepton singlets → l_R

$$\mu_R \leftrightarrow \tau_R\,,$$

$$B^\alpha \leftrightarrow B^\alpha\,,$$

U(1)^Y gauge field

$$Z'^\alpha \leftrightarrow -Z'^\alpha$$

U(1)' gauge field

Our "standard" Z'

The model is a new gauge boson, Z', which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

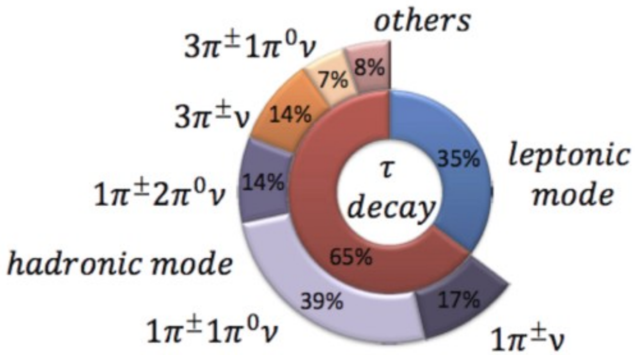
$$\mathcal{L} = -g'\bar{\mu}\gamma^\mu Z'_\mu \mu + g'\bar{\tau}\gamma^\mu Z'_\mu \tau - g'\bar{\nu}_{\mu,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\mu,\mathrm{L}} + g'\bar{\nu}_{\tau,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\tau,\mathrm{L}}.$$

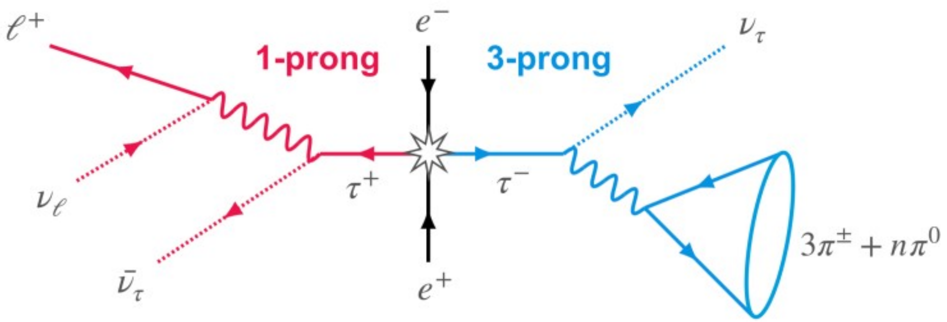
The equations for the partial widths are,

$$\Gamma(Z' \to \ell^+\ell^-) = \frac{(g')^2 M_{Z'}}{12\pi}\left(1 + \frac{2M_\ell^2}{M_{Z'}^2}\right)\sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}}\,\theta(M_{Z'} - 2M_\ell),$$

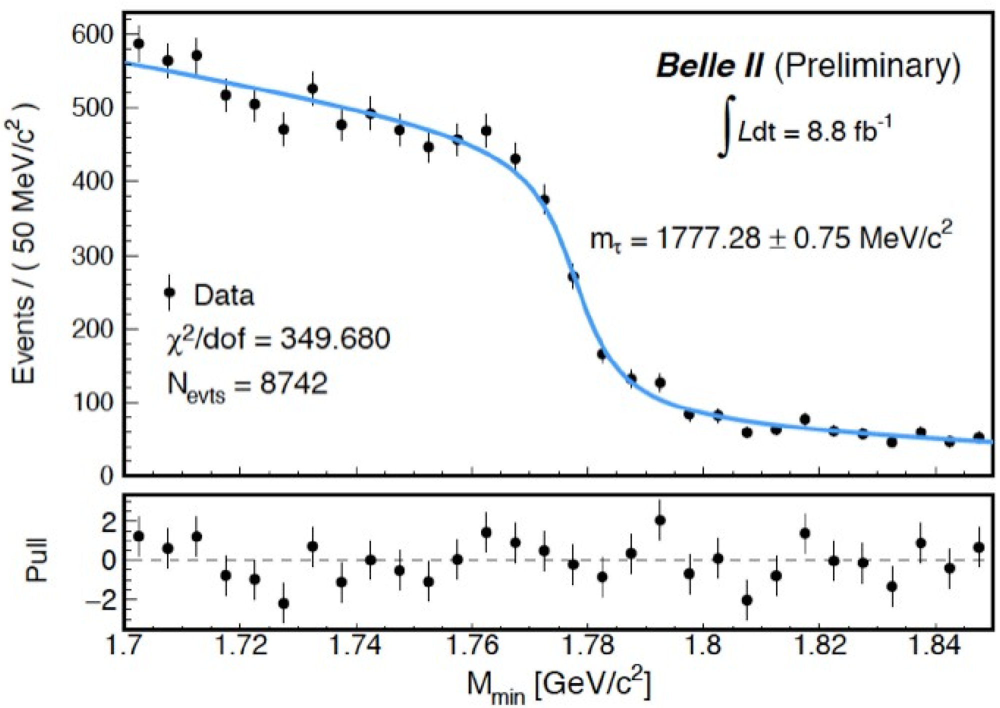
$$\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) = \frac{(g')^2 M_{Z'}}{24\pi}.$$

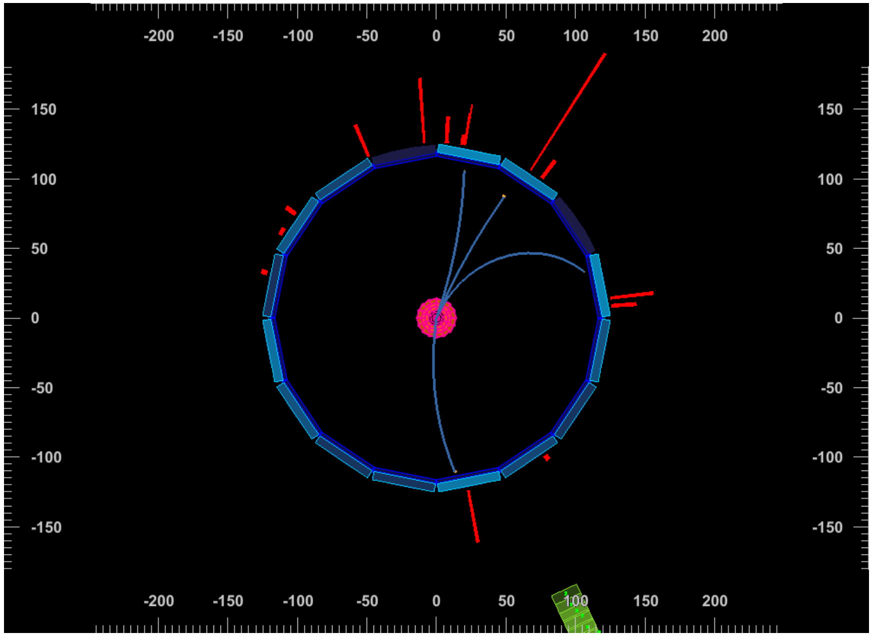
Taus at Belle II





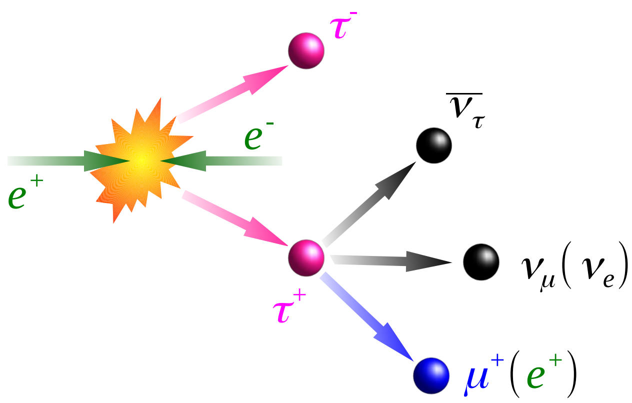
https://arxiv.org/abs/2008.04665





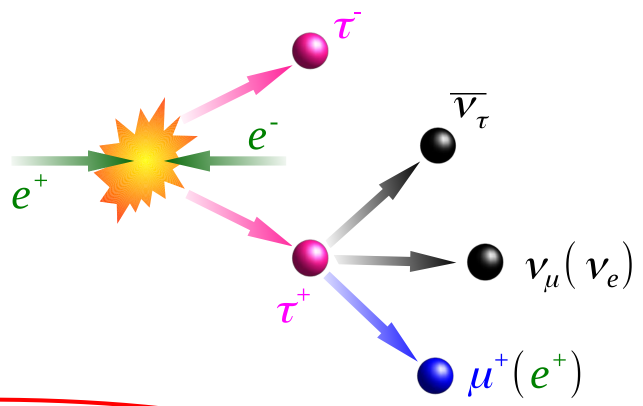
A possible test of LFU in tau decays

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{BF[\tau^- \to \mu^- \bar{\nu_\mu} \nu_\tau]}{BF[\tau^- \to e^- \bar{\nu_e} \nu_\tau]} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$



A possible test of LFU in tau decays

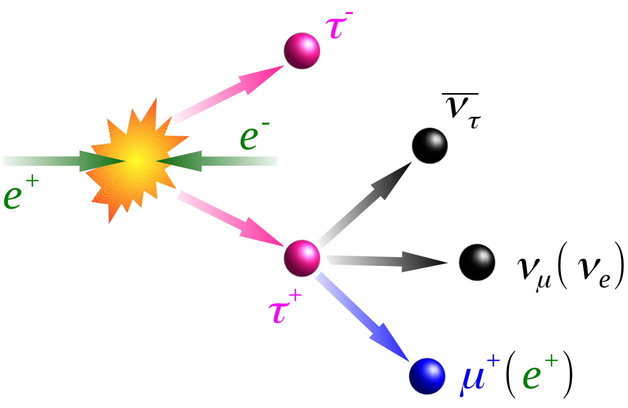
$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{BF[\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau]}{BF[\tau^- \to e^- \bar{\nu}_e \nu_\tau]} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$



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

A possible test of LFU in tau decays

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



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

$$R_\mu = \frac{BF[\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau]}{BF[\tau^- \to e^- \bar{\nu}_e \nu_\tau]}$$

At Babar (Phys. Rev. Lett. **105** 051602, ArXiv: 0912.0242 (2010)), with 500 fb^{-1}, $R_\mu = 0.976 \pm 0.0016_{stat} \pm 0.0036_{sys}$

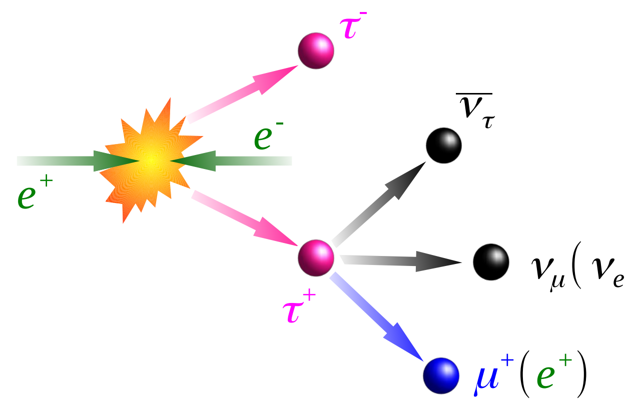
And $(g_\mu/g_e)_\tau = 1.0036 \pm 0.0020$

Can we improve this?

	μ
N^D	731102
Purity	97.3%
Total Efficiency	0.485%
Particle ID Efficiency	74.5%
Systematic uncertainties:	
Particle ID	0.32
Detector response	0.08
Backgrounds	0.08
Trigger	0.10
$\pi^-\pi^-\pi^+$ modelling	0.01
Radiation	0.04
$\mathcal{B}(\tau^- \to \pi^-\pi^-\pi^+\nu_\tau)$	0.05
$\mathcal{L}\sigma_{e^+e^- \to \tau^+\tau^-}$	0.02
Total [%]	0.36

A possible test of LFU in tau decays

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



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

$$R_\mu = \frac{BF[\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau]}{BF[\tau^- \to e^- \bar{\nu}_e \nu_\tau]}$$

At Babar (Phys. Rev. Lett. **105** 051602, ArXiv: 0912.0242 (2010)), with 500 fb^{-1}, R_μ=0.976 ± 0.0016_{stat} ± 0.0036_{sys}

And $(g_\mu/g_e)_\tau$= 1.0036 ± 0.0020

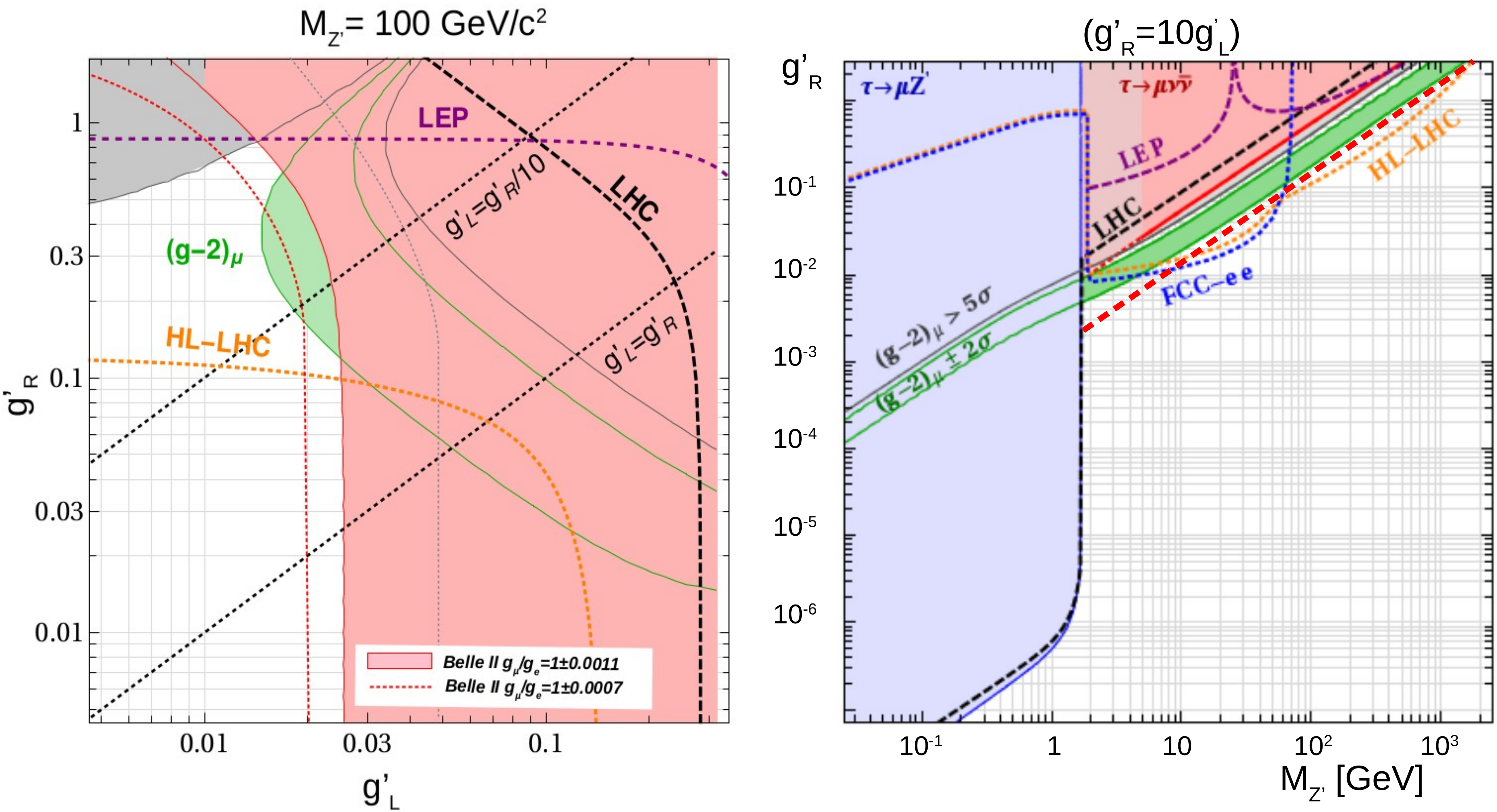
Can we improve this?

Yes, systematics dominated by PID due limited size of data and MC samples → the main sys. component will scale with the luminosity (of both data and MC)

Source of systematic	Belle II	BaBar
Particle ID	0.03-0.05	0.32
Detector	0.02-0.04	0.08
Backgrounds	0.02-0.04	0.08
Trigger	0.03-0.05	0.10
$BF[\tau^- \to \pi^+\pi^-\pi^-\nu_\tau]$	0.03-0.05	0.05
$\pi^+\pi^-\pi^-$ modeling	0.006-0.01	0.01
Radiation	0.01-0.02	0.04
$L_{int.} \times \sigma_{e^+e \to \tau^+\tau^-}$	0.01-0.02	0.02
Total	0.06-0.11	0.36

Achieving *per mille* (or below) precision on R_μ will allow us, should g_μ/g_e=1.0036 as measured by BaBar, to observe lepton flavor non-universal couplings at a precision >5σ

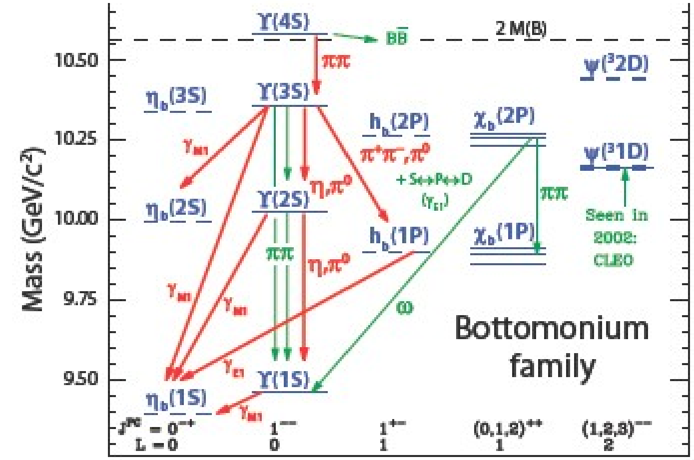
A possible test of LFU in tau decays: yet another Z'?



The sensitivity to a LFV Z' depends on the level of systematics in the test of LFU in tau decays.

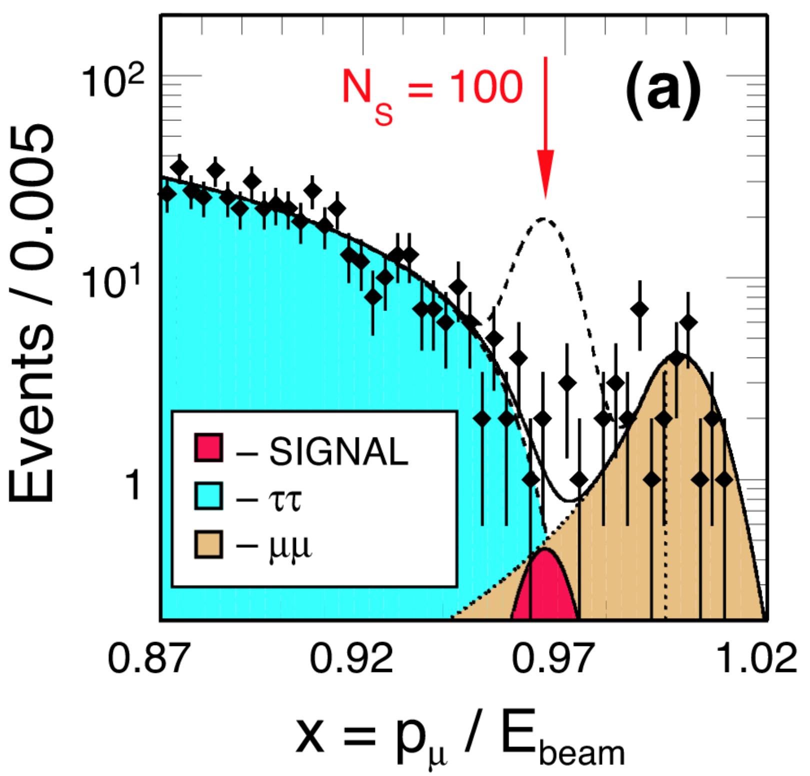
$\Upsilon(nS) \rightarrow \tau\mu$ decays at Belle 2

This is direct search for LFV in the decay of Υ(nS) resonances ($b\bar{b}$ bound state).

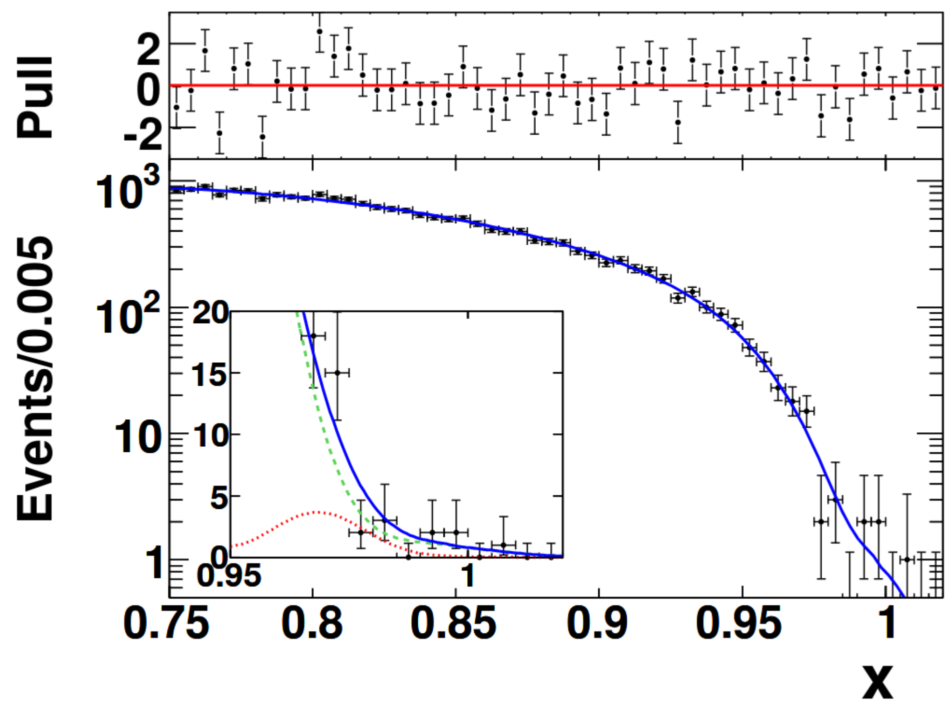


https://arxiv.org/pdf/1001.1883.pdf
BaBar

https://arxiv.org/pdf/0807.2695.pdf
CLEO Υ(1S)



leptonic Υ(3S)→ eτ (χ^2/ndf=52.4/49)



$\Upsilon(1S) \to \tau\mu$ decays at Belle 2

CLEO-III	BaBar
1.1 fb^{-1} @ $\Upsilon(1S) \to$ 2.1 $x10^7$ $\Upsilon(1S)$	
1.3 fb^{-1} @ $\Upsilon(2S) \to$ 9.3 $x10^6$ $\Upsilon(2S)$	13 fb^{-1} @ $\Upsilon(2S) \to$ 98 $x10^6$ $\Upsilon(2S)$
1.4 fb^{-1} @ $\Upsilon(3S) \to$ 5.9 $x10^6$ $\Upsilon(3S)$	26 fb^{-1} @ $\Upsilon(3S) \to$ 116 $x10^6$ $\Upsilon(3S)$

We will look into ISR production, and decays, of Υ(nS) from ISR with data collected at the Υ(4S), unless samples collected at lower energy become available before 2024

Taking into account the cross sections from ArXiv hep-ph/9910523 for ISR bottomonia production at the Υ(4S) (respectively 0.019 nb for Υ(1S), 0.015 nb for Υ(2S) and 0.031 nb for Υ(3S)) and the decay rate for $\Upsilon(2,3S) \to \pi^+\pi^-\Upsilon(1S)$

- 3.1 x 10^7 $\Upsilon(3S)/ab^{-1}$ of data collected at the Υ(4S)
- 1.5 x 10^7 $\Upsilon(2S)/ab^{-1}$ of data collected at the Υ(4S)

  equivalent to
- 2.67 x 10^6 Υ(1S) from $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ $/ab^{-1}$ of data collected at the Υ(4S)
- 1.39 x 10^6 Υ(1S) from $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ $/ab^{-1}$ of data collected at the Υ(4S)

  equivalent to
- **~4 x 10^6 Υ(1S) available per ab^{-1} collected at the Υ(4S) with the ISR technique** (vs. 1.6 x 10^8 di-pion tagged $\Upsilon(1S)/ab^{-1}$ when taking data at the Υ(3S))

$\Upsilon(nS) \to \tau\mu$ decays at Belle 2

CLEO-III

1.1 fb^{-1} @ Y(1S)→ 2.1 x10^{7} Y(1S)

1.3 fb^{-1} @ Y(2S)→ 9.3 x10^{6} Y(2S)

1.4 fb^{-1} @ Y(3S)→ 5.9 x10^{6} Y(3S)

BaBar

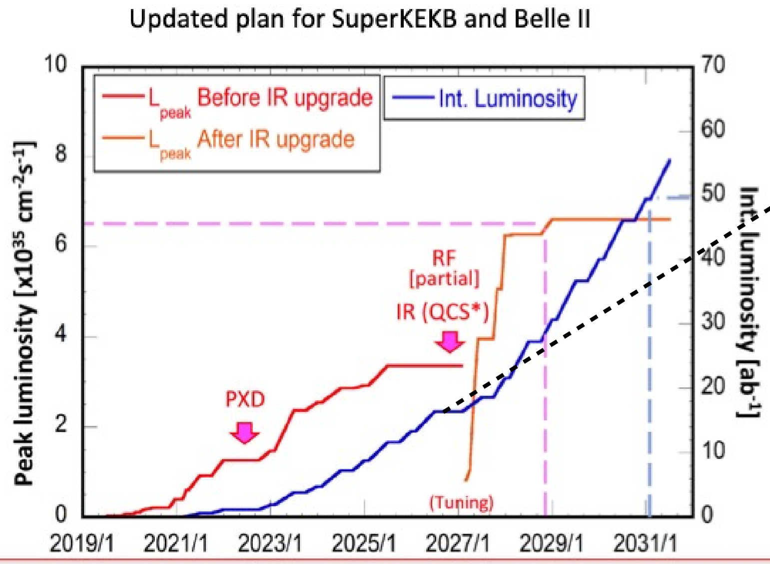
13 fb^{-1} @ Y(2S)→ 98 x10^{6} Y(2S)

26 fb^{-1} @ Y(3S)→ 116 x10^{6} Y(3S)

We will look into ISR production, and decays, of Y(nS) from ISR with data collected at the Y(4S), unless samples collected at lower energy become available before 2024

Resonance	Production mode	Yields in 25 ab^{-1}	Total efficiency	N. of events
$\Upsilon(3S)$	$e^+e^- \to \gamma_{ISR}\Upsilon(3S)$	7.6×10^8	2%	1.5×10^7
$\Upsilon(2S)$	$e^+e^- \to \gamma_{ISR}\Upsilon(2S)$	3.8×10^8	2%	0.8×10^7
	$\Upsilon(3S)^{(ISR)} \to \pi^+\pi^-\Upsilon(1S)$	$2.1\ \times10^7$	4%	0.9×10^6
total $\Upsilon(2S)$				0.9×10^7
$\Upsilon(1S)$	$e^+e^- \to \gamma_{ISR}\Upsilon(1S)$	4.8×10^8	2%	1.0×10^7
	$\Upsilon(3S)^{(ISR)} \to \pi^+\pi^-\Upsilon(1S)$	3.3×10^7	4%	1.3×10^6
	$\Upsilon(2S)^{(ISR)} \to \pi^+\pi^-\Upsilon(1S)$	6.8×10^7	4%	0.3×10^7
total $\Upsilon(1S)$				1.4×10^7

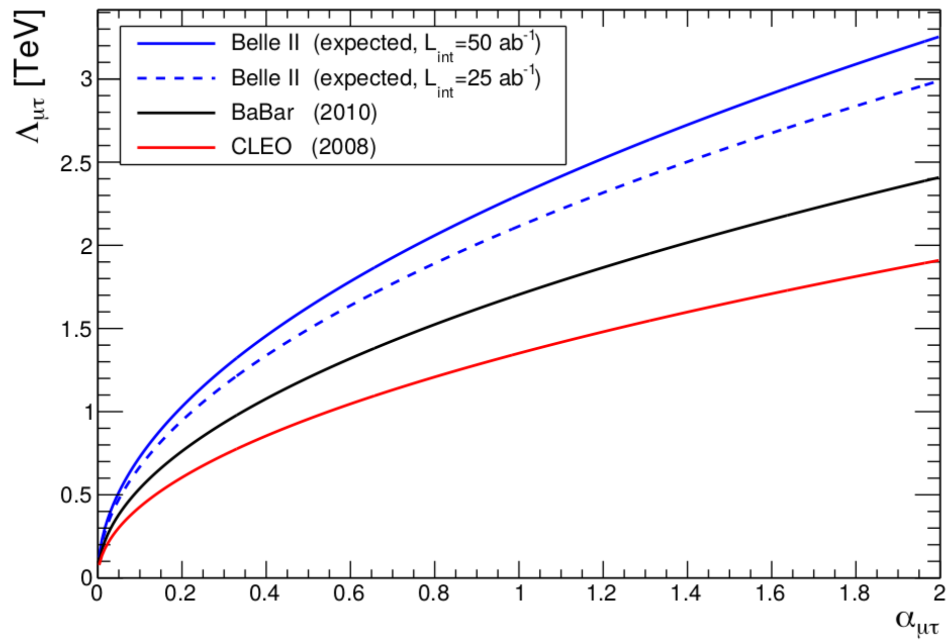
$\Upsilon(1S) \to \tau\mu$ decays at Belle 2



Four steps: *Intermediate luminosity* (1-2 x 10^{35} /cm²/sec, 5ab⁻¹);
High Luminosity (6.5 x 10^{35}/cm²/sec, 50 ab⁻¹) with a detector upgrade
Polarization Upgrade, Advanced R&D
Ultra high luminosity (4 x 10^{36}/cm²/sec, 250 ab⁻¹), R&D Project

We could probe
BF[$\Upsilon(nS) \to \tau\mu$]~5x10^{-7}

$$\frac{BF[\Upsilon(nS) \to \mu^+\tau^-]}{BF[\Upsilon(nS) \to \mu^+\mu^-]} \frac{2q_b^2\alpha^2}{(M_{\Upsilon(nS)})^4} = \frac{\alpha_{\mu\tau}^2}{\Lambda_{\mu\tau}^4}$$



- 3.1 x 10^7 $\Upsilon(3S)$/ab^{-1} of data collected at the Υ
- 1.5 x 10^7 $\Upsilon(2S)$/ab^{-1} of data collected at the Υ
  equivalent to
- 2.67 x 10^6 $\Upsilon(1S)$ from $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ /a
- 1.39 x 10^6 $\Upsilon(1S)$ from $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ /ab
  equivalent to
- **~4 x 10^6 $\Upsilon(1S)$ available per ab^{-1} collected**
  (vs. 1.6 x 10^8 di-pion tagged $\Upsilon(1S)$/ab^{-1} when taking data at the $\Upsilon(3S)$)

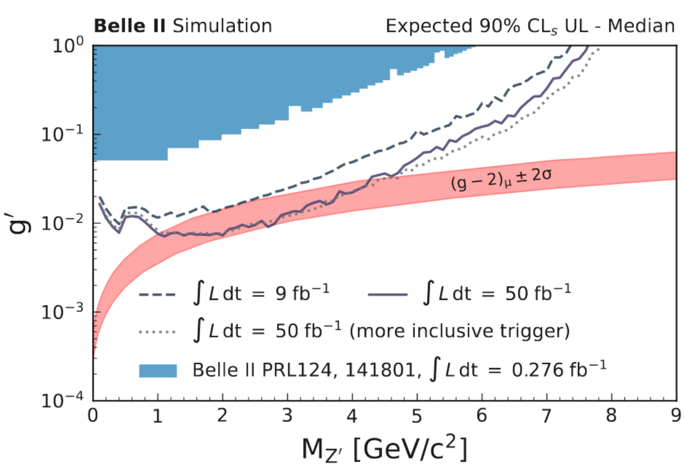
InterLeptons

European Research Council

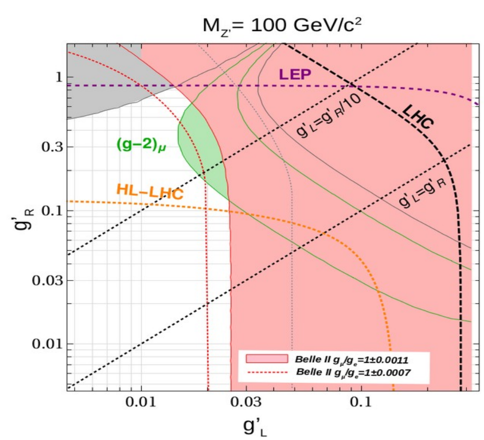
Established by the European Commission

New physics searches at different energy scale

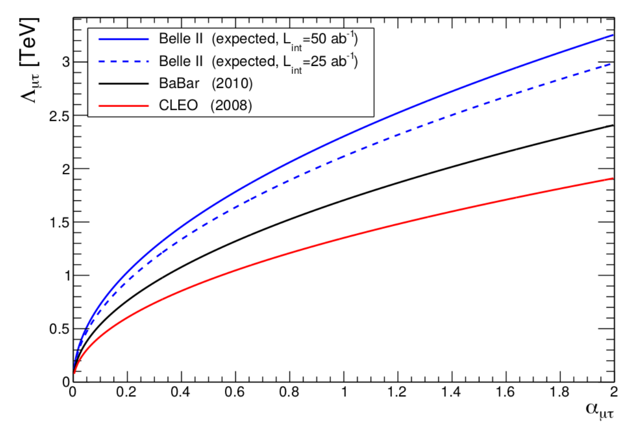
GeV scale



EW scale



TEV scale

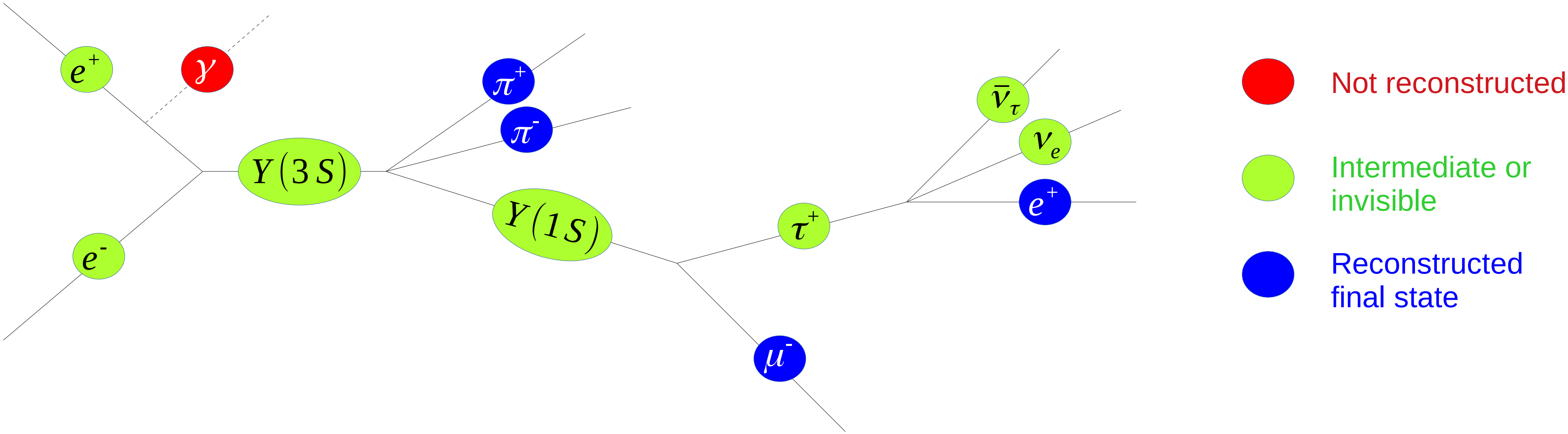


Thank you for your attention!

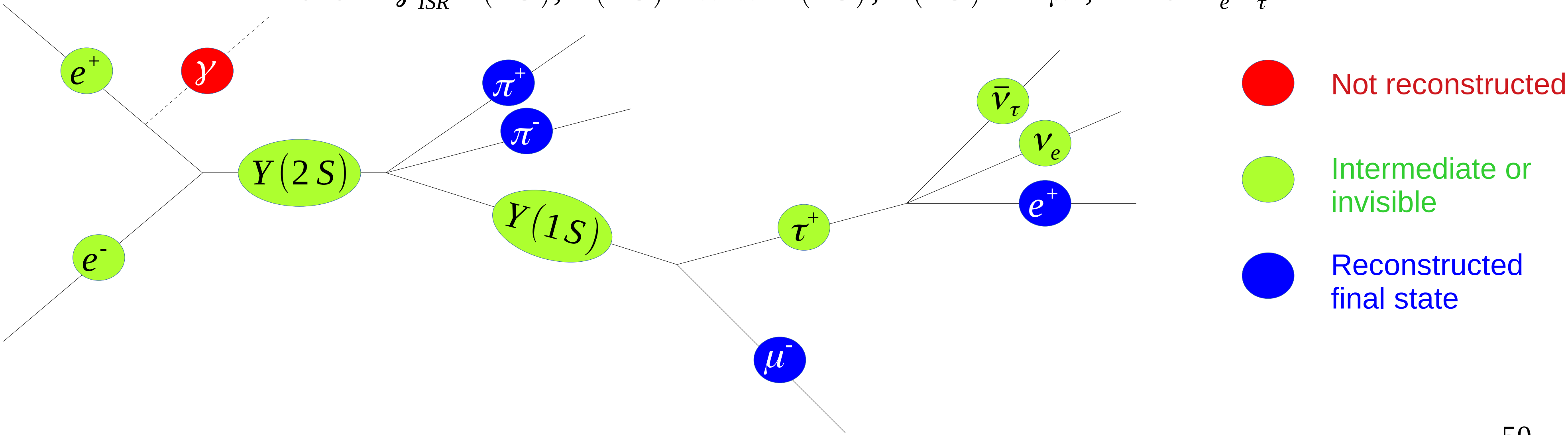
Belle II

Υ(nS) → τμ decays at Belle 2, examples of (untagged) ISR production

$$e^+e^- \rightarrow \gamma_{ISR} \Upsilon(3S), \Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S), \Upsilon(1S) \rightarrow \tau^+\mu^-, \tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$$

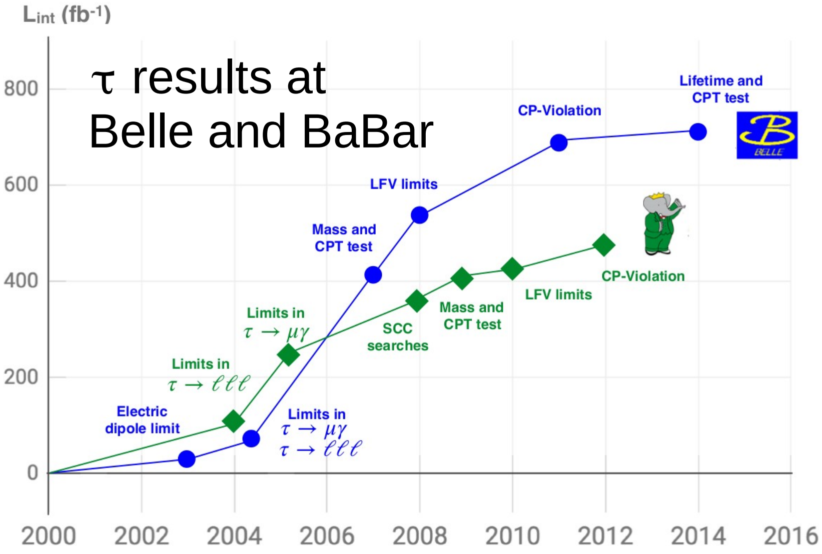


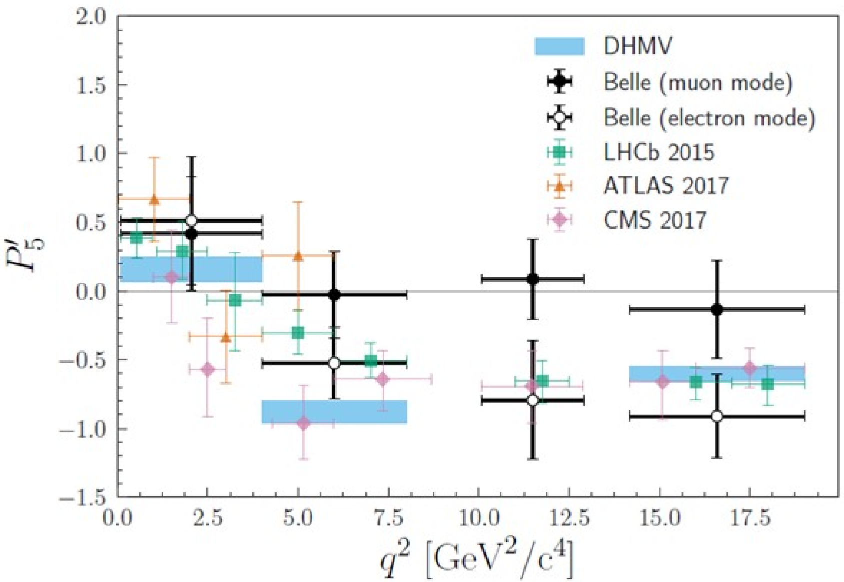
$$e^+e^- \rightarrow \gamma_{ISR} \Upsilon(2S), \Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S), \Upsilon(1S) \rightarrow \tau^+\mu^-, \tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$$

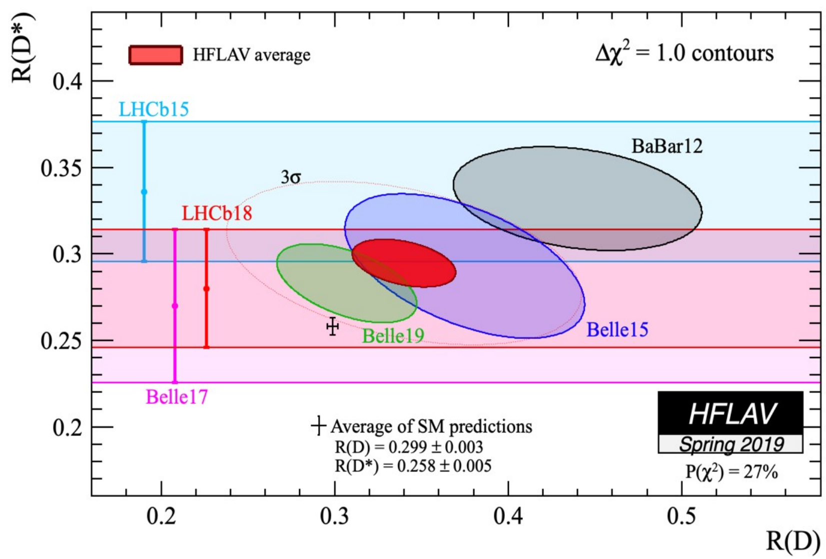


Some physics from Belle to Belle II

- B-factories have been the driving forces in the past decades to establish the CKM mechanism as origin of CP violation and in the search for new physics.
- Few anomalies in the recent years have been observed and large amount of data are required to understand if these are fluctuations or if new physics effects have been observed







$$R(D) = \frac{BF[\overline{B}^0 \to D\tau^- \overline{\nu}_\tau]}{BF[\overline{B}^0 \to D l^- \overline{\nu}_l]}$$

$$R(D^*) = \frac{BF[\overline{B}^0 \to D^* \tau^- \overline{\nu}_\tau]}{BF[\overline{B}^0 \to D^* l^- \overline{\nu}_l]}$$

- Belle II will provide a complementary approach to new physics searches wrt other experiments
- Rich program of flavor physics studies thanks to the high luminosity
- Physics beyond flavor...

$\Upsilon(nS) \rightarrow \tau\mu$ decays at Belle 2

Lepton flavor violating quarkonium decays

Derek E. Hazard and Alexey A. Petrov

https://arxiv.org/pdf/1607.00815.pdf

Phys. Rev. D 94, 074023 – Published 17 October 2016

"Any new physics model that incorporates flavor and involves flavor-violating interactions at high energy scales can be cast in terms of the effective Lagrangian of Eq. (1) at low energies. We argued that Wilson coefficients of this Lagrangian could be effectively probed by studying decays of quarkonium states with different spin-parity quantum numbers, providing complementary constraints to those obtained from tau and mu decays"

	Leptons	Initial state (quark)				
Wilson coefficient (GeV^{-2})	$\ell_1\ell_2$	$\Upsilon(1S)$ (b)	$\Upsilon(2S)$ (b)	$\Upsilon(3S)$ (b)	J/ψ (c)	ϕ (s)
	$\mu\tau$	5.6×10^{-6}	4.1×10^{-6}	3.5×10^{-6}	5.5×10^{-5}	n/a
$\left\|C_{VL}^{q\ell_1\ell_2}/\Lambda^2\right\|$	$e\tau$	–	4.1×10^{-6}	4.1×10^{-6}	1.1×10^{-4}	n/a
	$e\mu$	–	–	–	1.0×10^{-5}	2×10^{-3}
	$\mu\tau$	5.6×10^{-6}	4.1×10^{-6}	3.5×10^{-6}	5.5×10^{-5}	n/a
$\left\|C_{VR}^{q\ell_1\ell_2}/\Lambda^2\right\|$	$e\tau$	–	4.1×10^{-6}	4.1×10^{-6}	1.1×10^{-4}	n/a
	$e\mu$	–	–	–	1.0×10^{-5}	2×10^{-3}
	$\mu\tau$	4.4×10^{-2}	3.2×10^{-2}	2.8×10^{-2}	1.2	n/a
$\left\|C_{TL}^{q\ell_1\ell_2}/\Lambda^2\right\|$	$e\tau$	–	3.3×10^{-2}	3.2×10^{-2}	2.4	n/a
	$e\mu$	–	–	–	4.8	1×10^{4}
	$\mu\tau$	4.4×10^{-2}	3.2×10^{-2}	2.8×10^{-2}	1.2	n/a
$\left\|C_{TR}^{q\ell_1\ell_2}/\Lambda^2\right\|$	$e\tau$	–	3.3×10^{-2}	3.2×10^{-2}	2.4	n/a
	$e\mu$	–	–	–	4.8	1×10^{4}