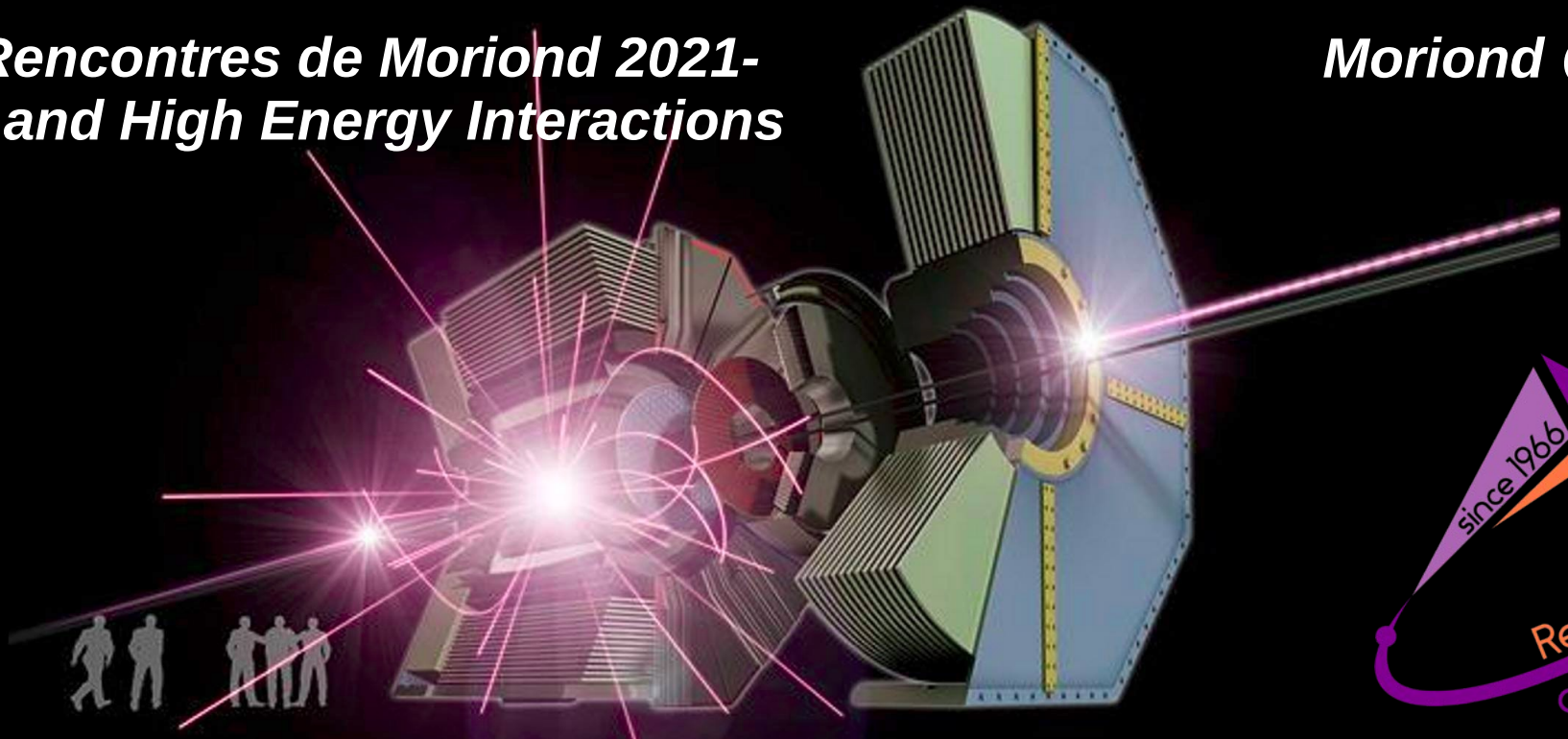
55th Rencontres de Moriond 2021-
QCD and High Energy Interactions

Moriond @ home



New Phenomena Session

Latest results on τ and dark sector physics at Belle II

31/03/2021

Gianluca Inguglia

InterLeptons

HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

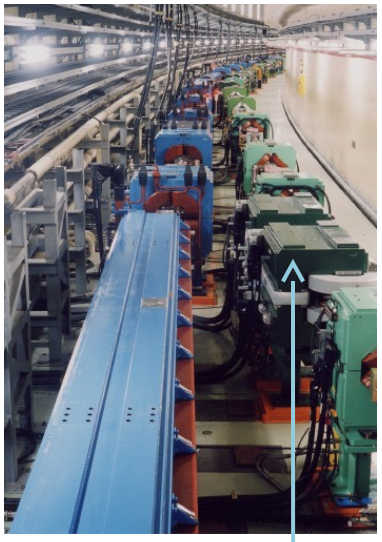
FWF
Der Wissenschaftsfonds.

ÖAW
ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

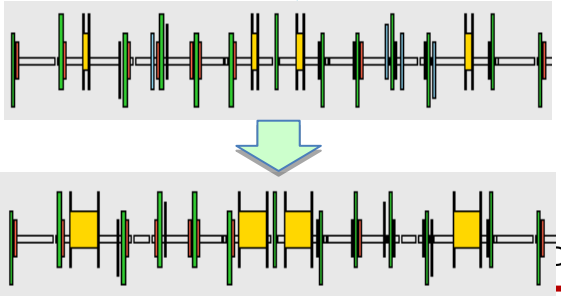
Belle II

erc
European Research Council
Established by the European Commission

KEKB to SuperKEKB

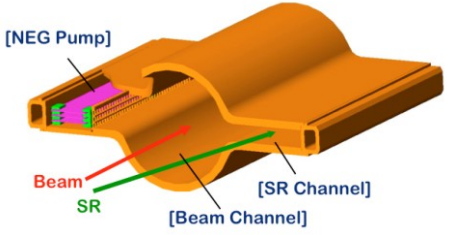


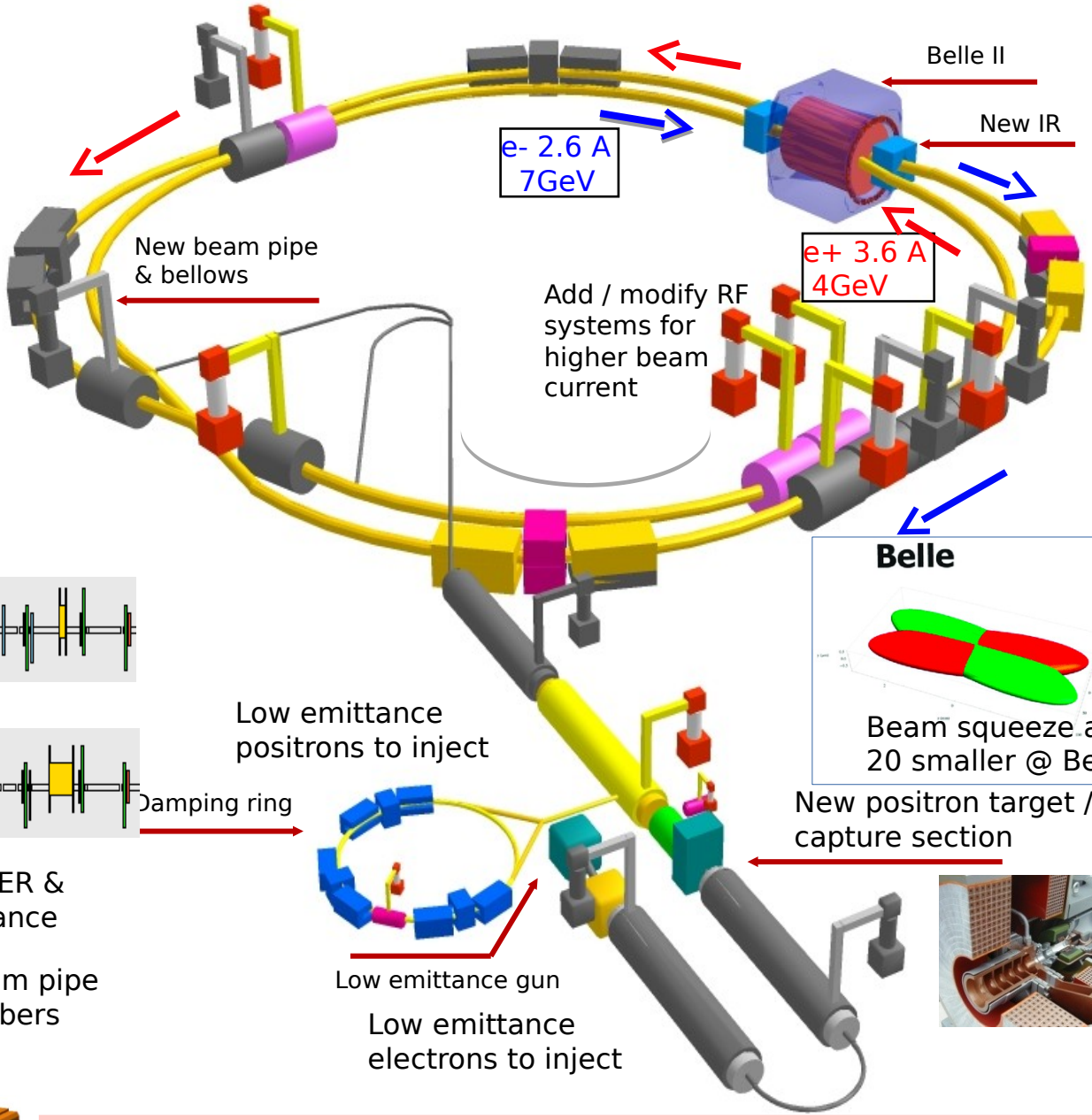
Replace short dipoles with longer ones (LER)



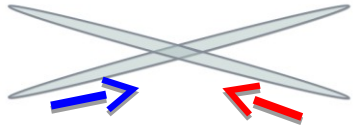
Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers

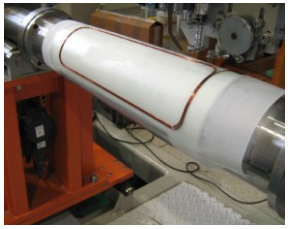


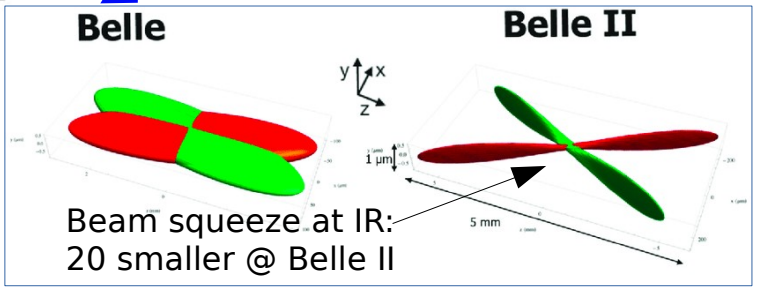


Colliding bunches



New superconducting /permanent final focusing quads near the IP



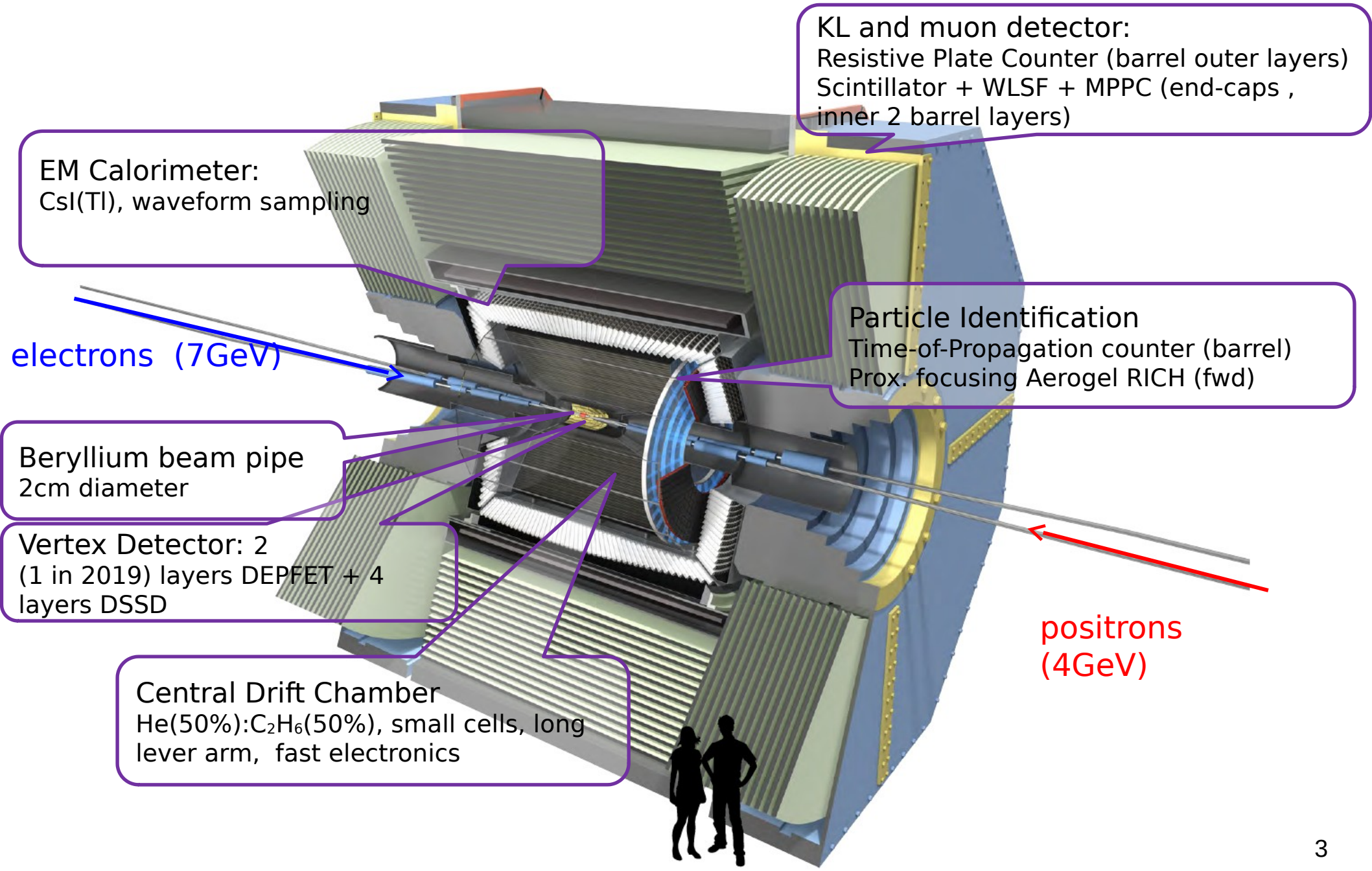


Beam squeeze at IR:
20 smaller @ Belle II

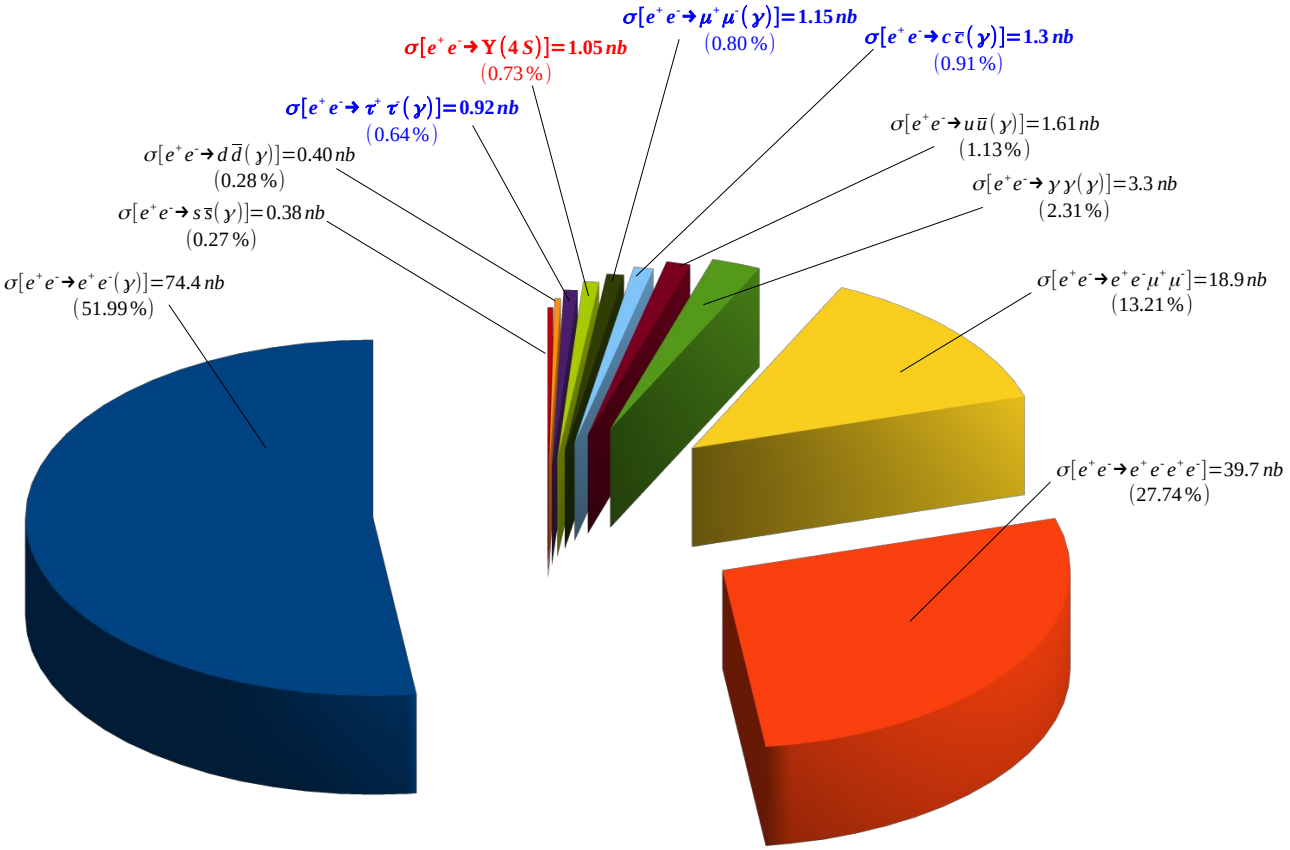
New positron target / capture section

Expect x30 higher luminosity from $2x10^{34} \rightarrow 6x10^{35}$ $cm^{-2}s^{-1}$

Belle II Detector Elements



What happens in e^+e^- collisions at SuperKEKB?



See *The Belle II Physics Book*

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, $\geq 1\ \gamma$ (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

Remember (in an ideal world)!! $N = L \times \sigma$

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

Number of events of a process

Luminosity of an experiment

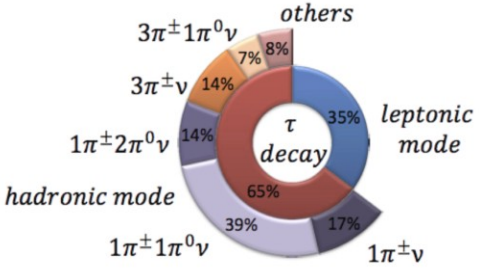
A **SuperB** factory is also a **Super-charm** factory, a **Super-τ** factory, etc..
This is a great feature of this collision scheme that we can take advantage of.

As of today @ Belle II $\int L\,dt = O(100\ fb^{-1})$

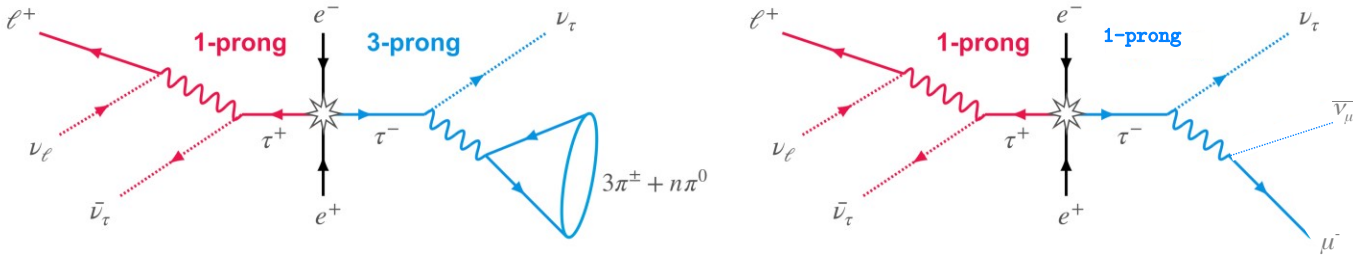
Physics with τ at Belle II

$\sigma[e^+e^- \to \tau^+\tau^-] = 0.92\,nb\,@\,Belle\,II$ — Large production cross-section

Many final states



Different reconstruction techniques



τ as a probe of new physics and of detector performance

Some ongoing physics analyses

- τ mass/lifetime measurements
- LFV $\tau \to l\gamma$
- LFV $\tau \to lll$
- LFV $\tau \to l\pi^0$
- LFV & LNV $\tau \to lhh$
- LFUV $\tau^+ \to l^+\nu_l\bar{\nu}_\tau$, $\tau \to h\nu$
- $|V_{us}|$ from $\tau \to h\nu$
- Absolute BF measurements for $\tau^+ \to l^+\nu_l\bar{\nu}_\tau$
- Dalitz analysis of $\tau \to 3\pi\nu$
- Search for $\tau \to l\alpha$

Some technical studies

- Tracking efficiency
- Trigger efficiency
- Particle (mis-)identification
- π^0 reconstruction
- Vertexing

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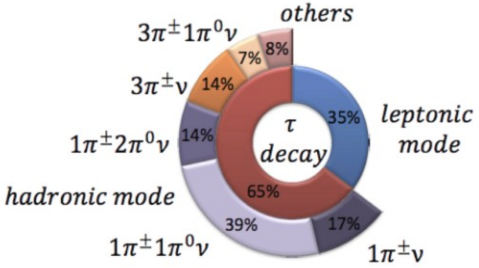

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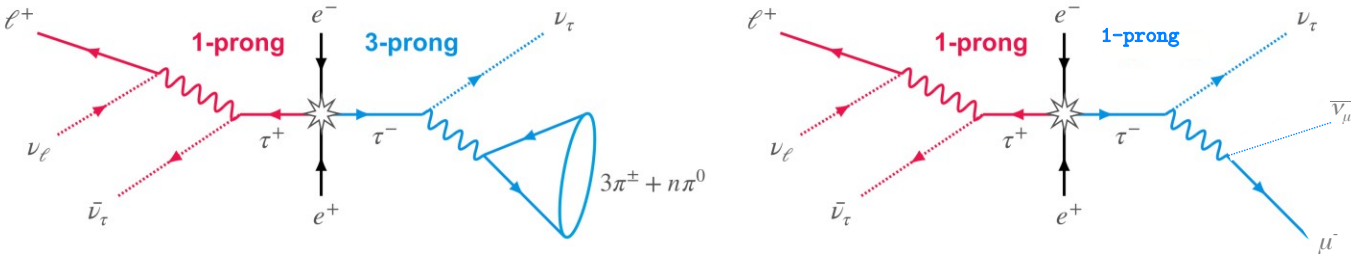

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Some technical studies

- Tracking efficiency
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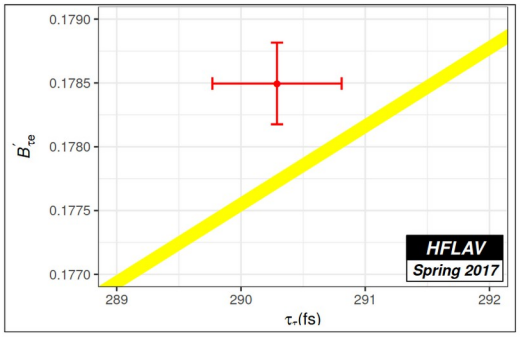
τ mass measurement at Belle II

- τ mass poorly known compared to *e* or μ (a few orders of magnitude less precise)
- Important parameter in lepton unive

$$B^{SM}_{\tau\to l} = B_{\mu\to e}\frac{\tau_\tau}{\tau_\mu}\frac{m_\tau^5}{m_\mu^5}\frac{f_{\tau l}}{f_{\mu e}}\frac{r_W^\tau r_\gamma^\tau}{r_W^\mu r_\gamma^\mu}$$

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

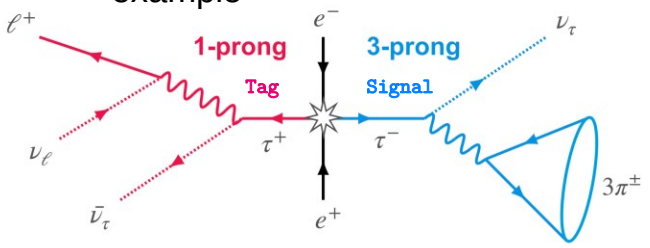


See here

3x1 topology to extract the mass

"Pseudomass" calculated from the 4-momentum of the 3-pion system

example

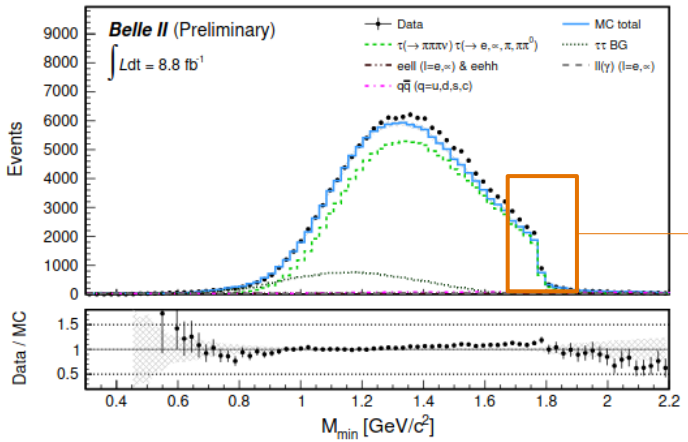


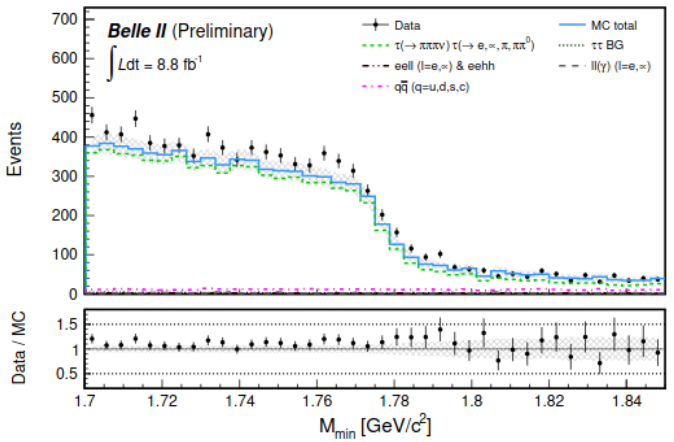
Signal: $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$ $(BF \sim 9.3\,\%)$

Tag: $\tau^- \to l^-\bar{\nu}_l\nu_\tau, \pi^-\nu_\tau, \pi^-\pi^0\nu_\tau$

$(\sum BF \sim 71.52\%)$

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



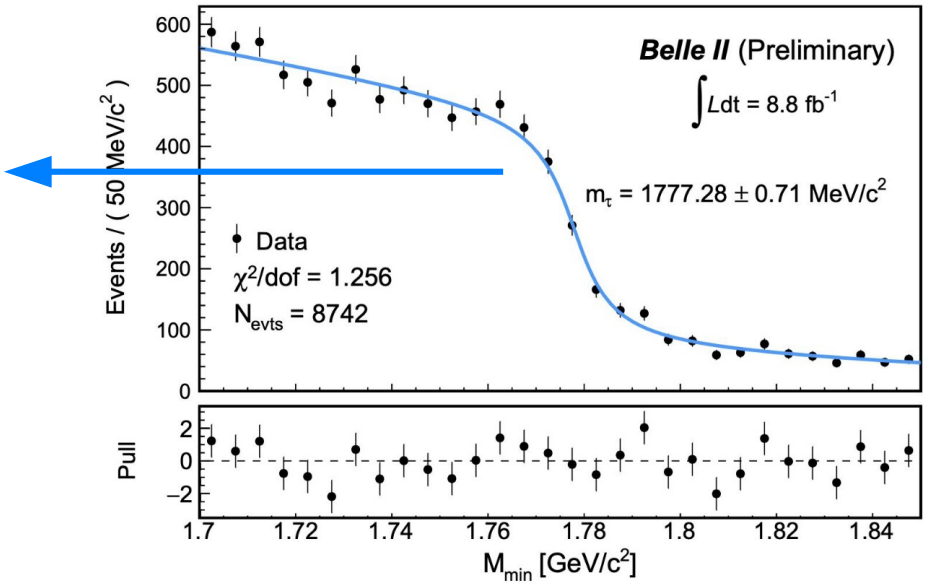


τ mass measurement at Belle II

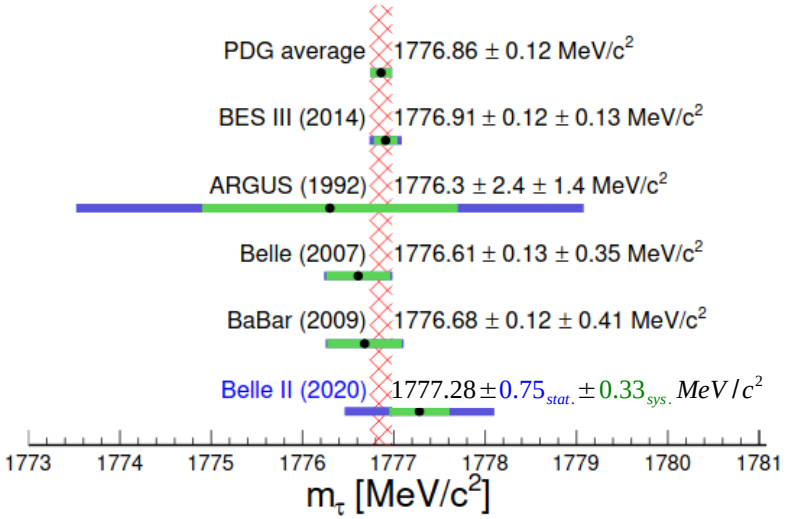
Perform an unbinned maximum likelihood fit to the data using an empirical fit function

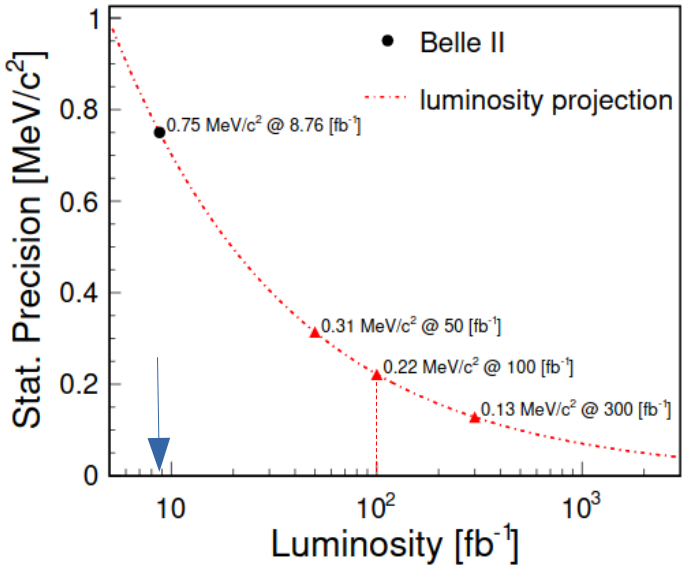
$$F(M_{min}|\overline{P}) = (P_3 + P_4 M_{min}) \tan^{-1}\left(\frac{M_{min} - P_1}{P_2}\right) + P_5 M_{min} + 1$$

$$m_\tau = 1777.28 \pm 0.75_{stat.} \pm 0.33_{sys.}\ MeV/c^2$$



Main source of systematic uncertainties due to tracking corrections → expected to improve as we understand our detector better





Already collected luminosity

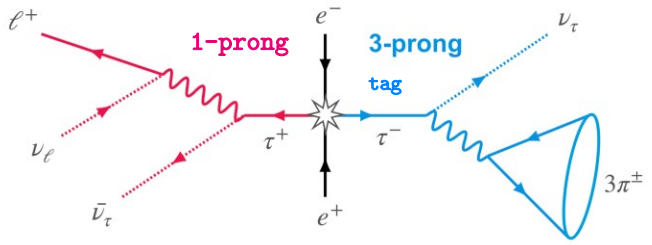
Search for τ → lα at Belle II

- Possible new light boson α in tau decays
- Previous search from ARGUS (1995, 476/pb) and MARK III (1985, 9.4/pb)

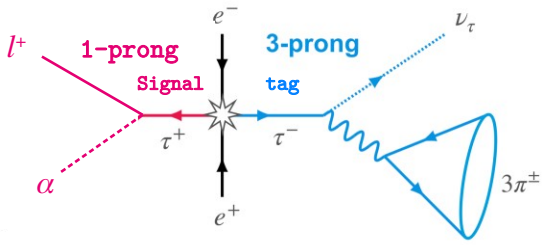
Compare SM rates for leptonic decays of τ to possible signal of new physics by studying the kinematics in the τ rest-frame

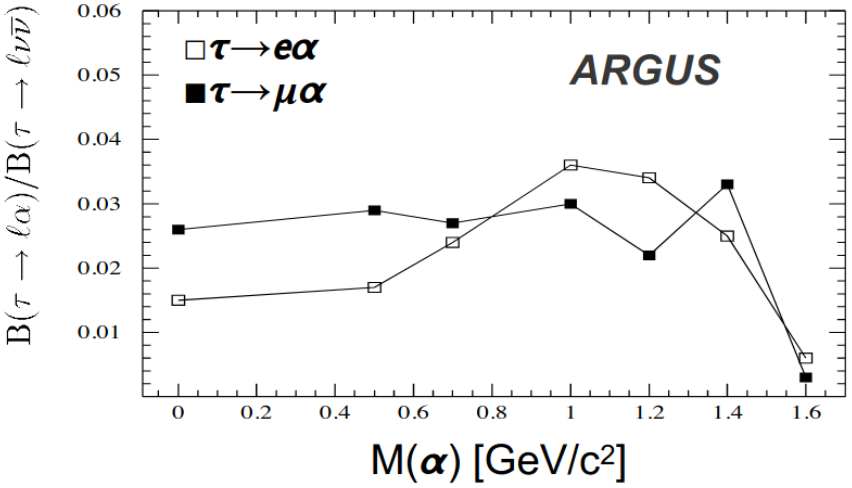
3x1 topology to search for α

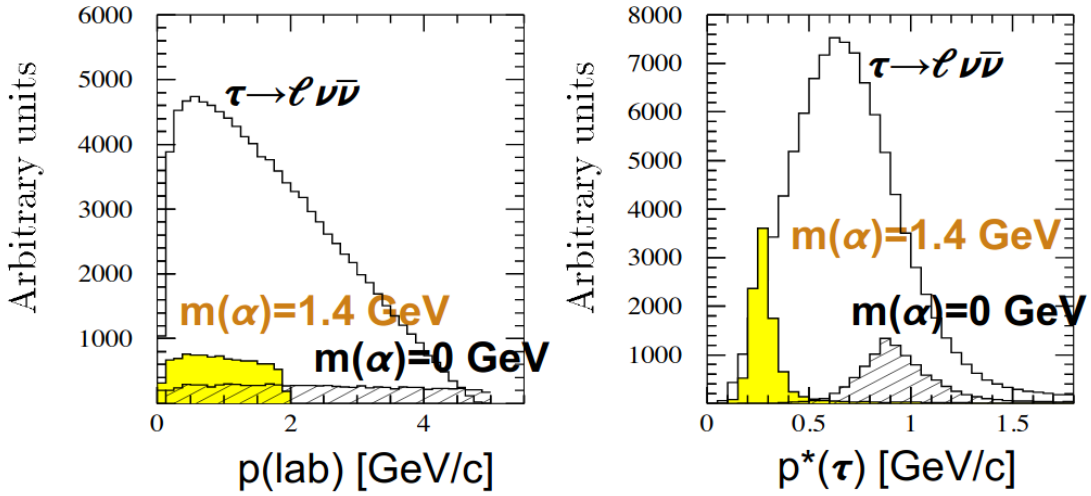
SM background



signal







Z.Phys. C68 (1995) 25-28

We also test an alternative method in tau pseudo rest-frame using the thrust vector:

$$\vec{T} = max\left(\frac{\sum_i \vec{p}_i \hat{T}}{|p_i|}\right)$$

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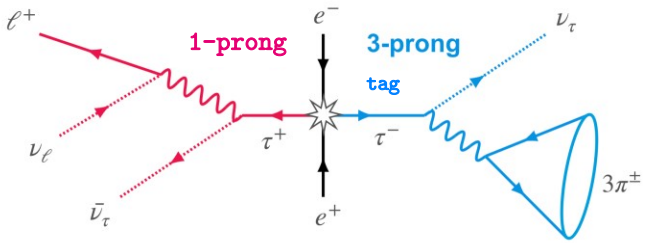
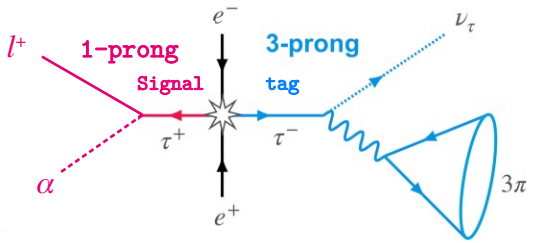
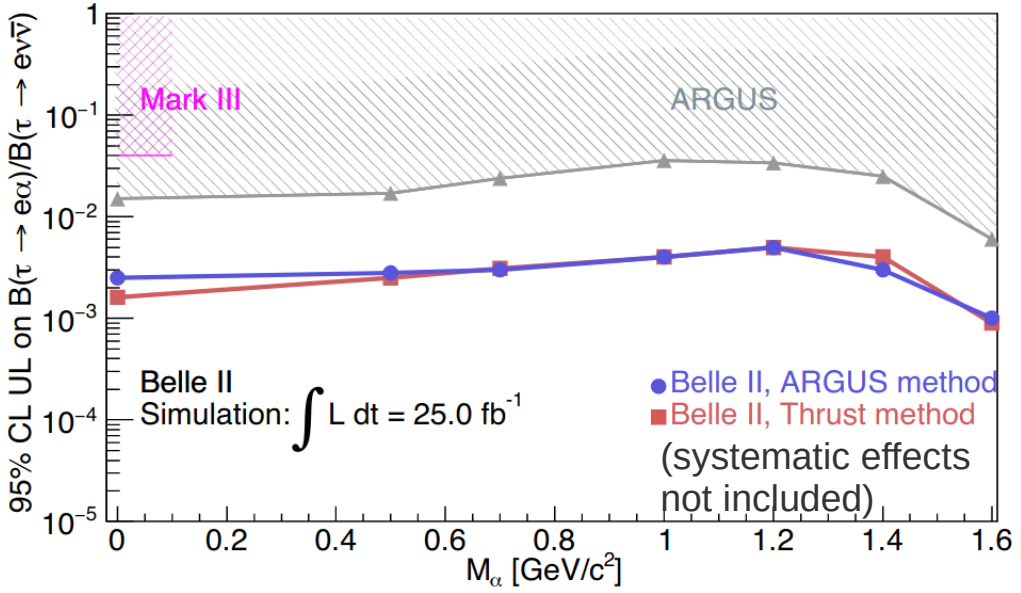


signal



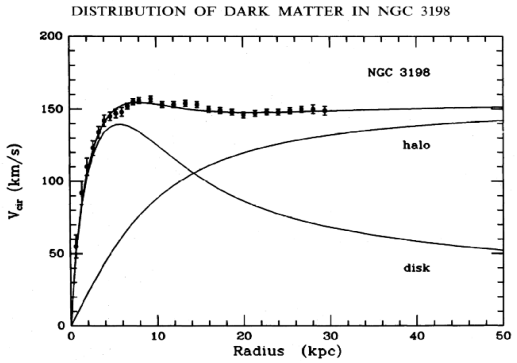
- UL is provided for the ratio $Br(\tau \to e\alpha)/Br(\tau \to e\nu\nu)$

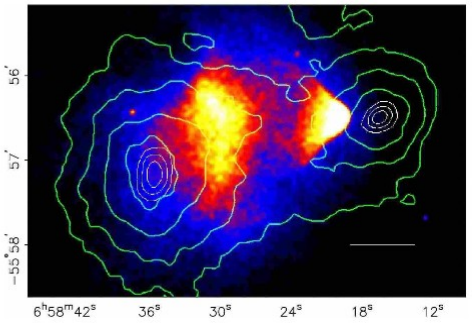


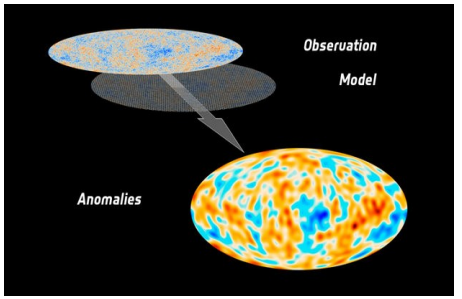
	UL(95% c.l.)		
$M(\alpha)$ [GeV/c^2]	ARGUS (1995)	Argus method	Thrust method
0	0.015	0.0025	0.0016
0.5	0.017	0.0028	0.0025
0.7	0.024	0.003	0.0031
1.0	0.036	0.004	0.004
1.2	0.034	0.005	0.005
1.4	0.025	0.003	0.004
1.6	0.006	0.001	0.0009

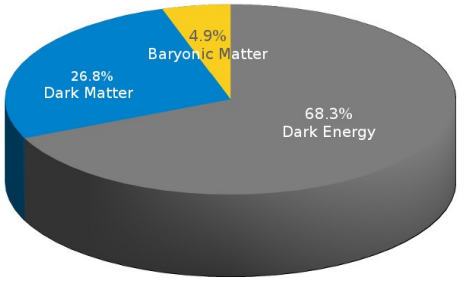
See here

Dark matter?

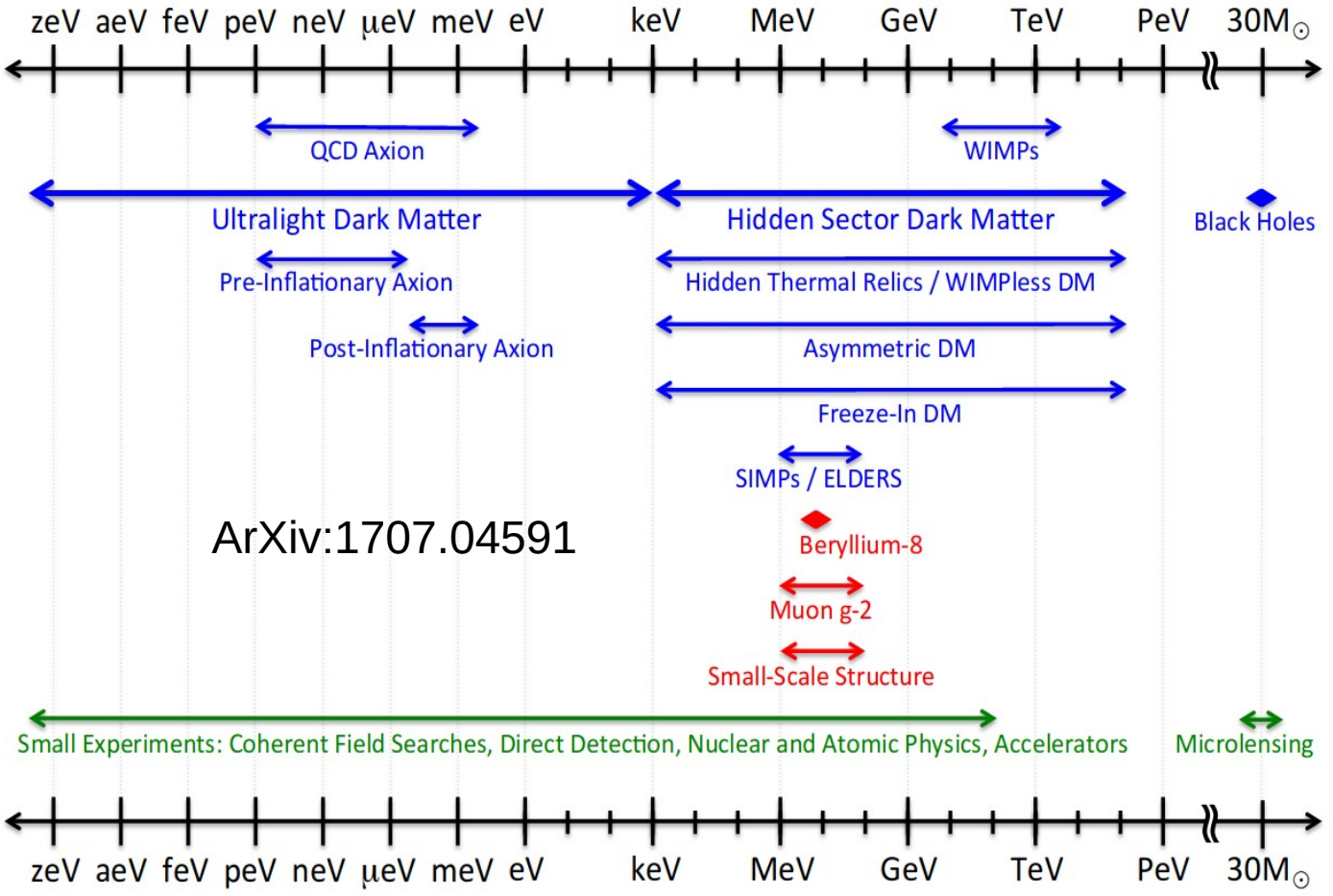






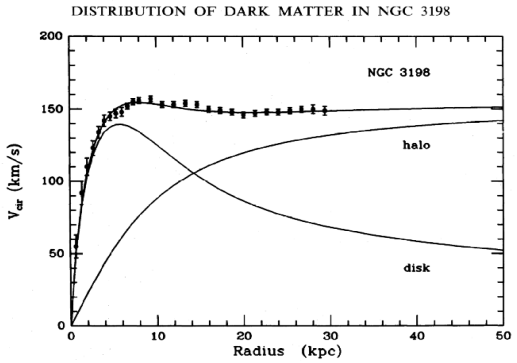


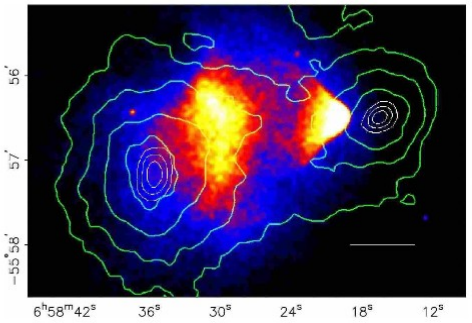
Dark Sector Candidates, Anomalies, and Search Techniques

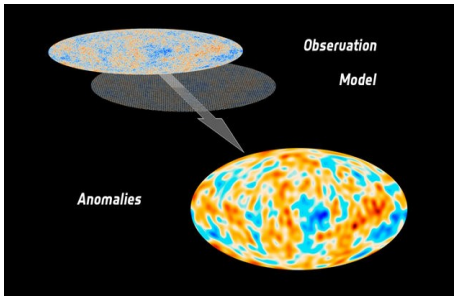


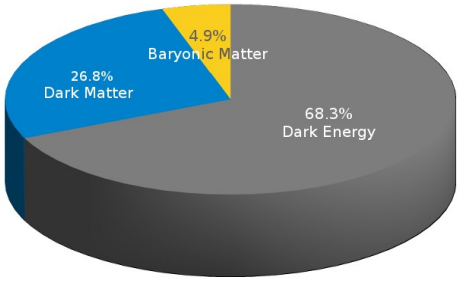
ArXiv:1707.04591

Dark matter?









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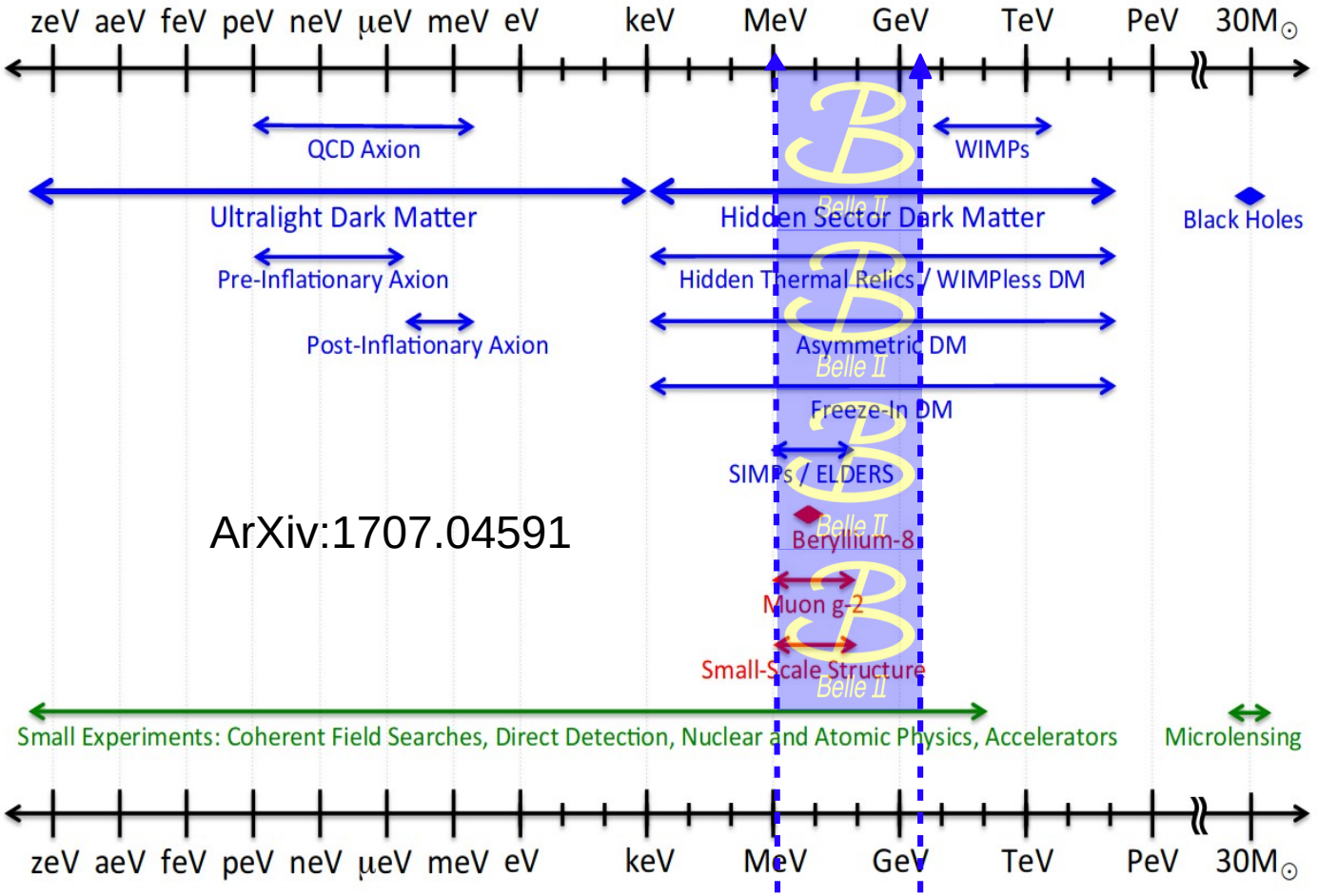

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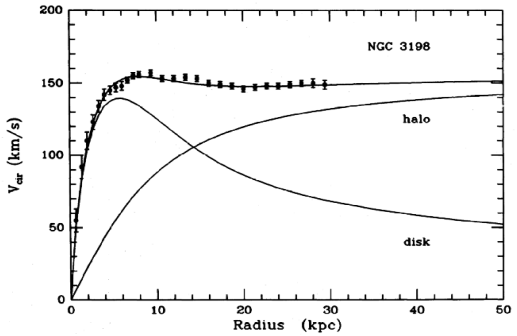
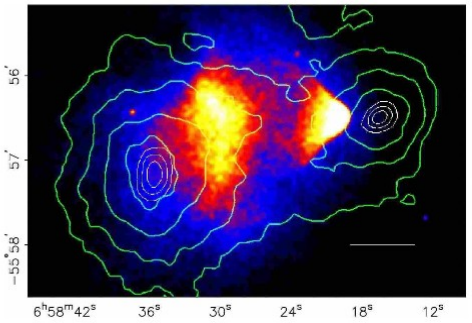
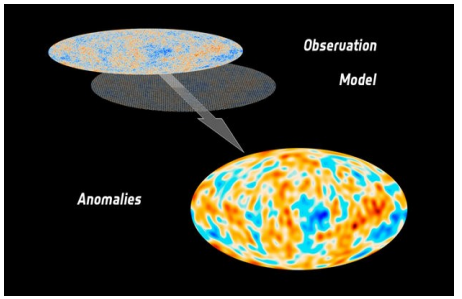
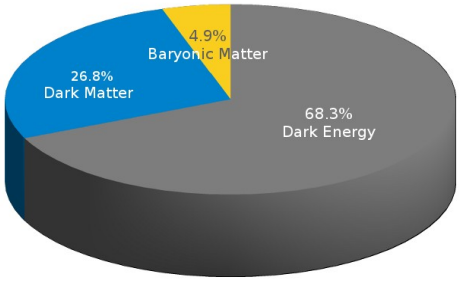
Searching for Dark Matter and Forces @ Belle/Belle II









Belle II

Search for events with missing energy, particle disappearance, dark forces, single/multi-photon final state events, etc.

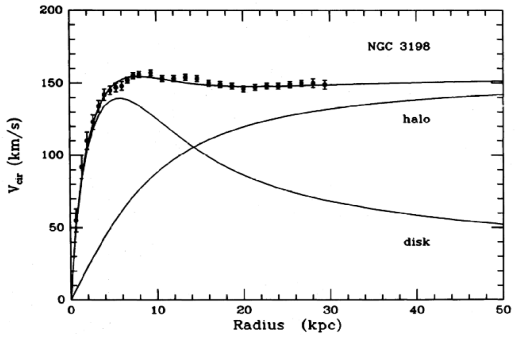
Belle II

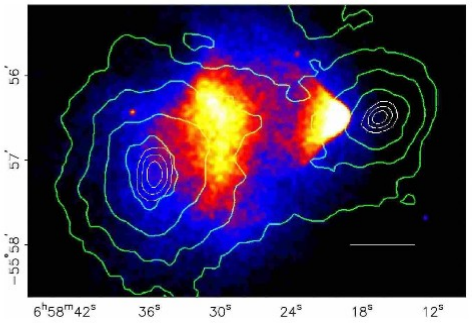
- **Vector portal** $\epsilon F_Y^{\mu\nu} F'_{\mu\nu}\ (dark\ photon\ A'), \sum_l \theta g' \bar{l}\ \gamma^\mu Z'_\mu l\ \ (dark\ Z')$
- **Scalar portal** $\lambda H^2 S^2 + \mu H^2 S\ \ (dark\ Higgs)$
- **Axion portal** $\frac{G_{agg}}{4} a G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{G_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}\ \ (axion, alps)$

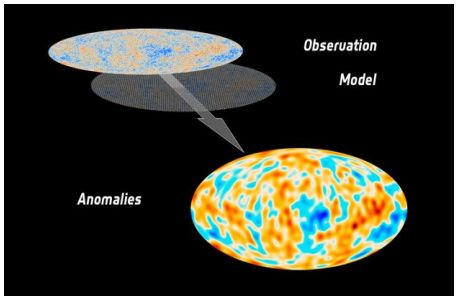
Neutrino portal $k(HL)N\ \ (sterile\ neutrinos)$

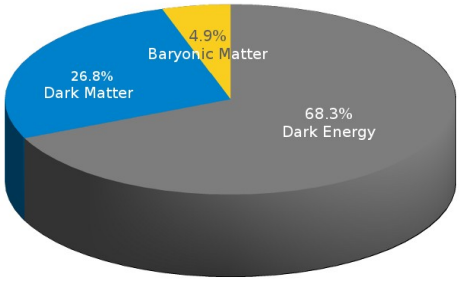
- **More ...**

Searching for Dark Matter and Forces @ Belle/Belle II









Belle II

Search for events with missing energy, particle disappearance, dark forces, single/multi-photon final state events, etc.

Belle II

- **Vector portal** $\epsilon F_Y^{\mu\nu} F'_{\mu\nu}$ $(dark\ photon\ A')$, $\sum_l \theta g' \bar{l} \gamma^\mu Z'_\mu l$ $(dark\ Z')$
- **Scalar portal** $\lambda H^2 S^2 + \mu H^2 S$ $(dark\ Higgs)$
- **Axion portal** $\frac{G_{agg}}{4} a G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{G_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$ $(axion, alps)$

Neutrino portal $k(HL)N$ $(sterile\ neutrinos)$

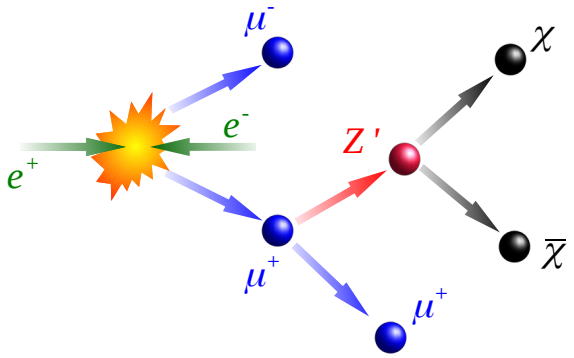
- **More ...**

Lepton non-universal 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,



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

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

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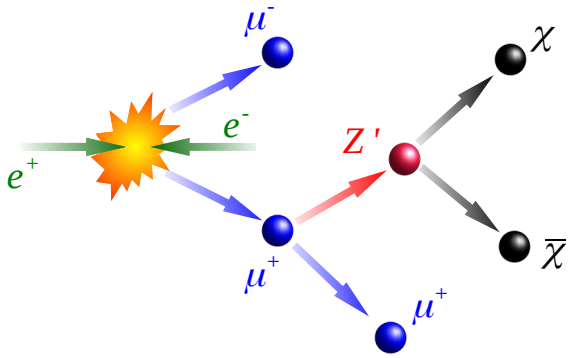

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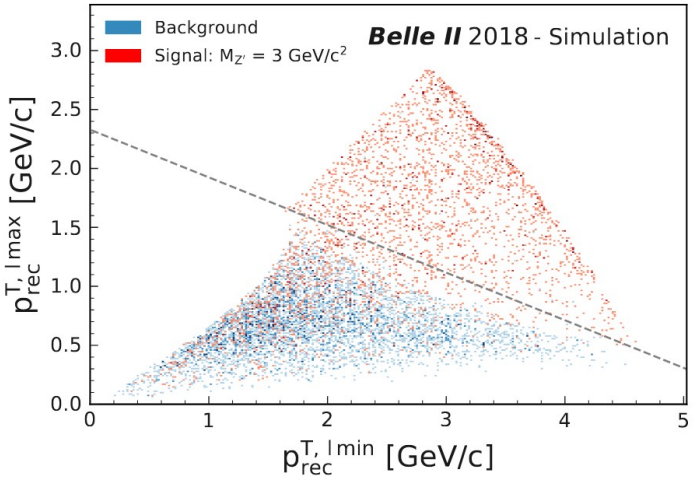
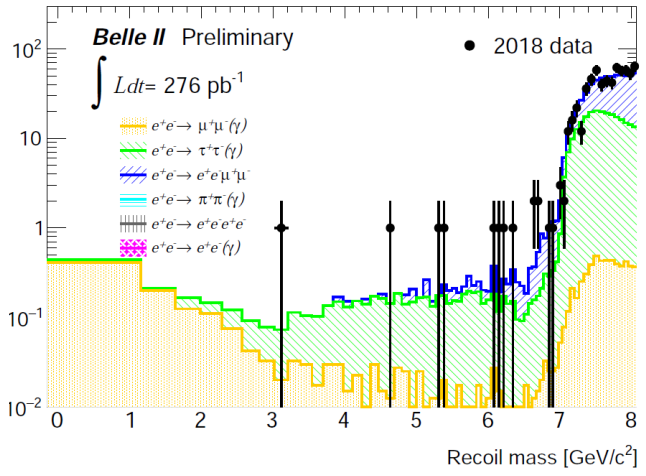
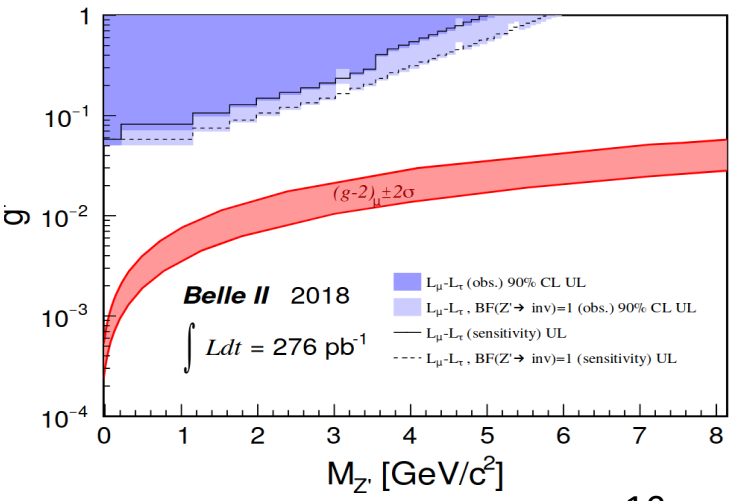
First physics paper @Belle II, PRL **124**, 141801 (2020), arXiv:1912.11276







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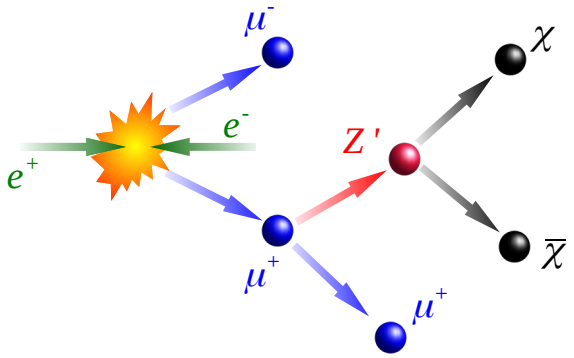

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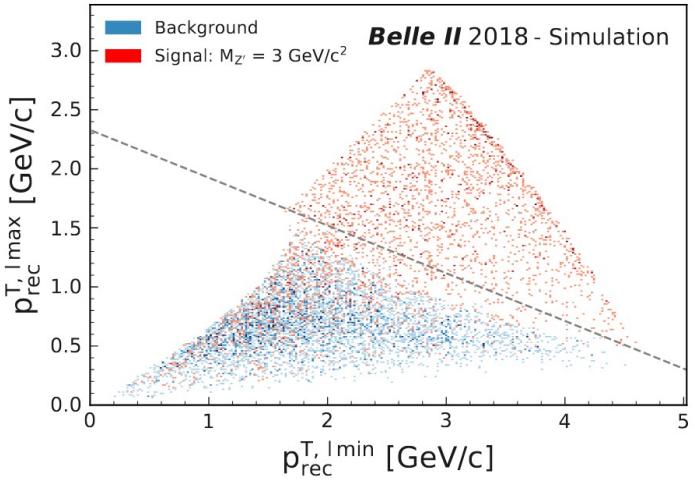
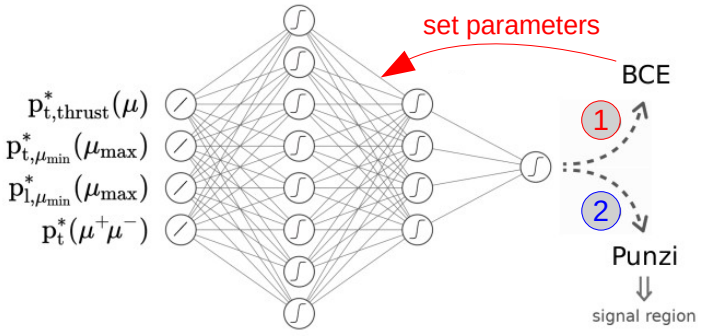
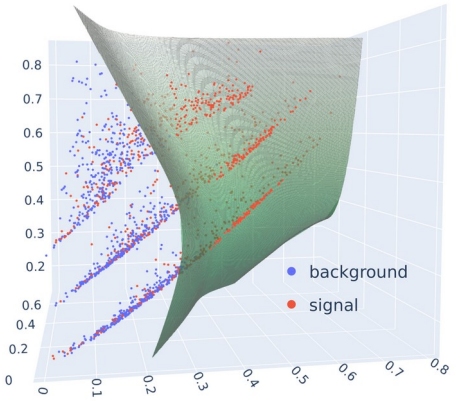
New and improved PID system (KLM) and new machine learning analysis techniques based on artificial neural networksANNs, provide better selection and better sensitivities







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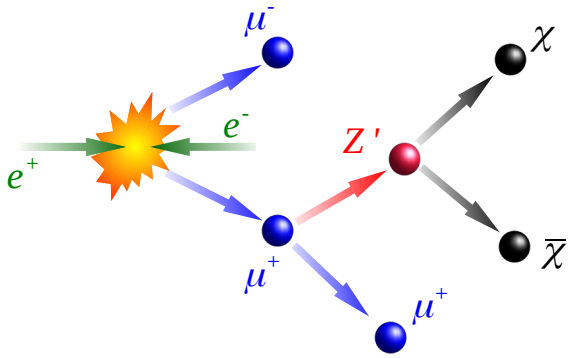

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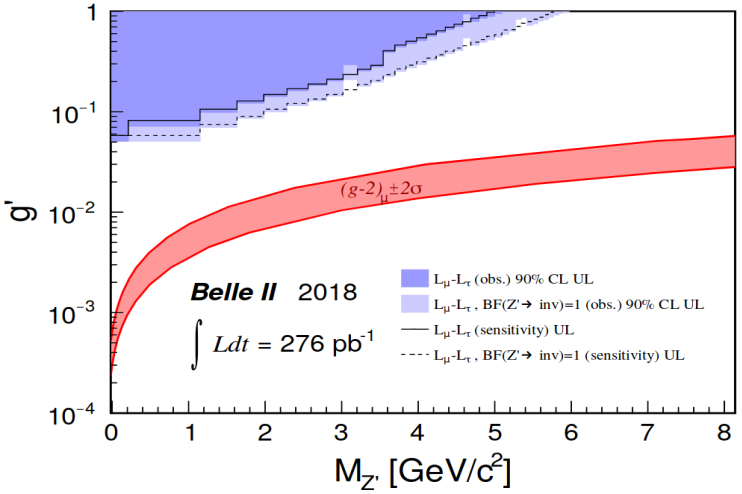
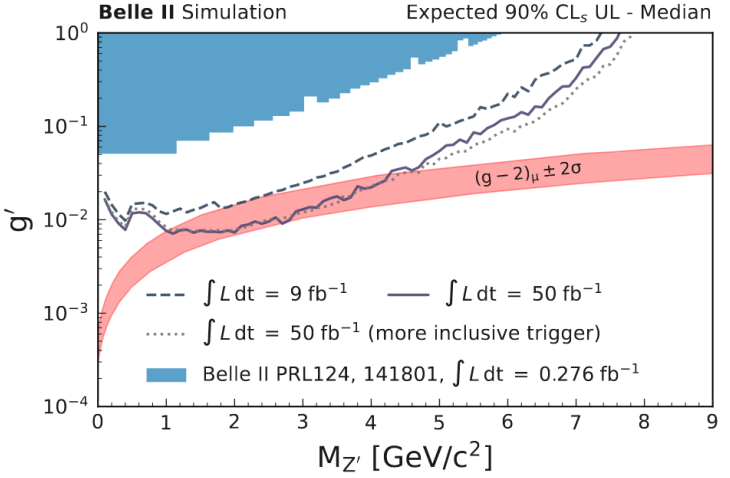
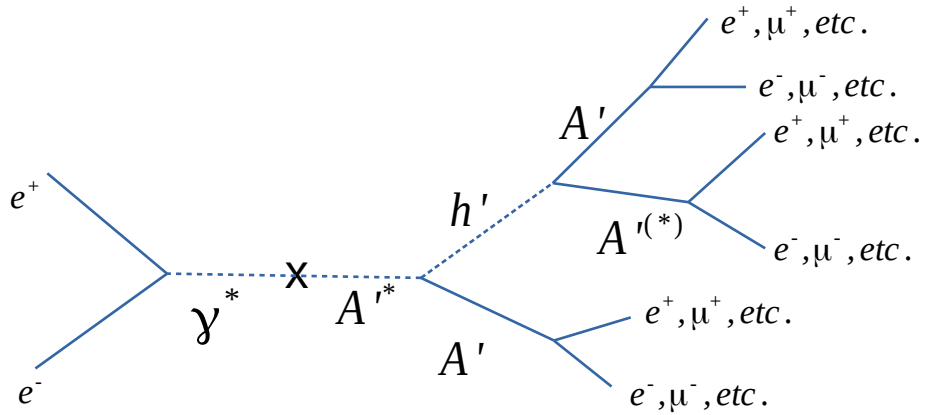


In the near term



Dark Higgs-strahlung @ Belle II

See B. Batell, M. Pospelov, and A. Ritz Phys. Rev. D 79, 356 115008 (2009), arXiv:0903.0363



Thanks to (small) kinetic mixing with the standard model photon, the dark photon A' can decay to standard model final states

Higgs-strahlung process

h'= dark Higgs,
A'= dark photon

Higgs-strahlung: h' decays depending on $M_{h'}$ and $M_{A'}$. Measures the coupling constant of the dark photon to the dark Higgs, α_D.

$M_{h'} > 2M_{A'}$: $h' \rightarrow A'A'$, Very low background.

Exclusive: 3 charged tracks pairs with same invariant mass and total energy of the event.

Inclusive: 2 charged tracks pairs, same invariant mass, third A' from 4-mom. of e^+e^- system

$M_{A'} < M_{h'} < 2M_{A'}$: $h' \rightarrow A'A'^*$

$M_{h'} < M_{A'}$: h' (very) **long-lived**.

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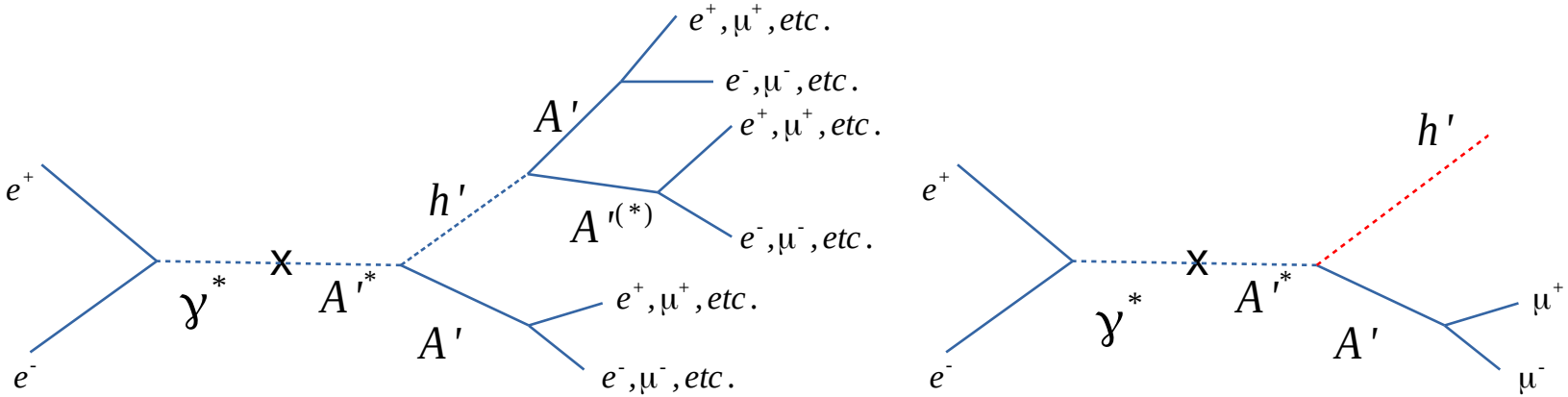

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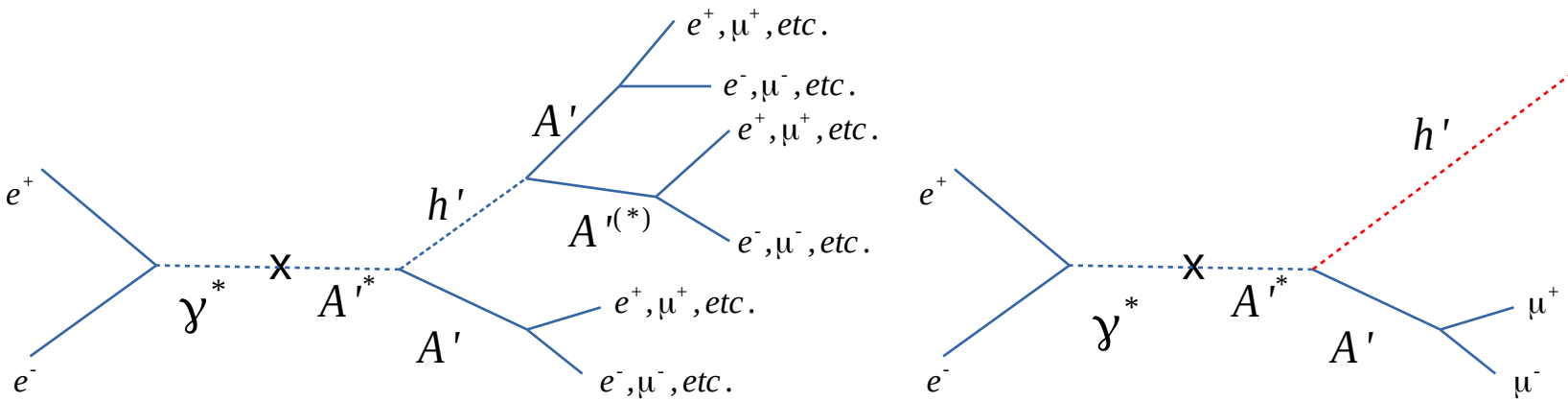

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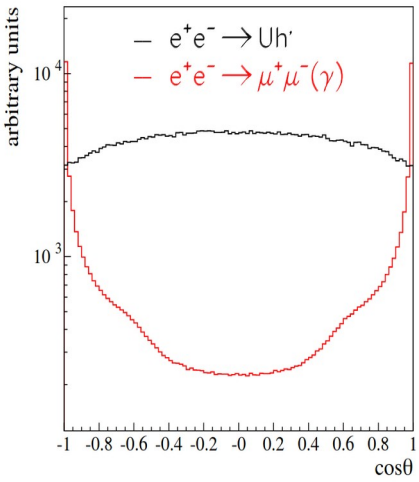
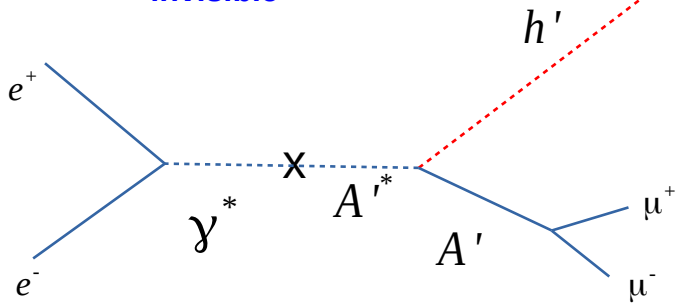
Dark Higgs-strahlung @ Belle II with 10/fb

See B. Batell, M. Pospelov, and A. Ritz Phys. Rev. D 79, 356 115008 (2009), arXiv:0903.0363

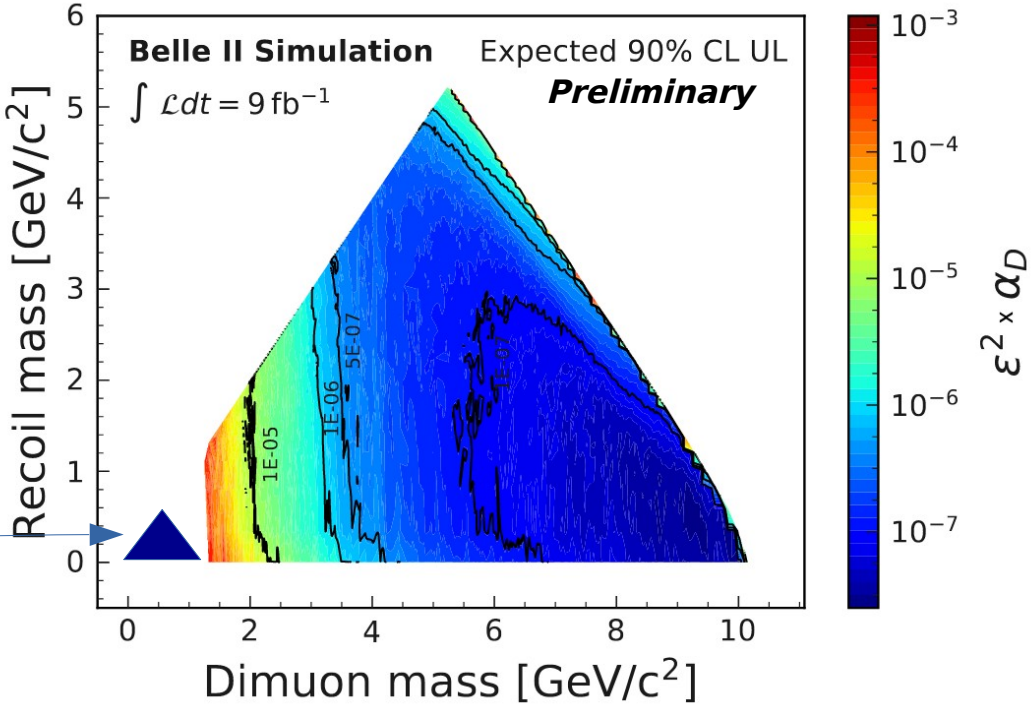


- Identical final state as for the invisible Z' search
- Low SM background
- Allows simultaneous search of a dark Higgs boson and of dark photon
- Existing limits only from KLOE

Current focus on $\mu^+\mu^-$+invisible final state, plans to extend to e^+e^-+invisible



Higgs-strahlung process
h'=dark Higgs, A'= dark Photon

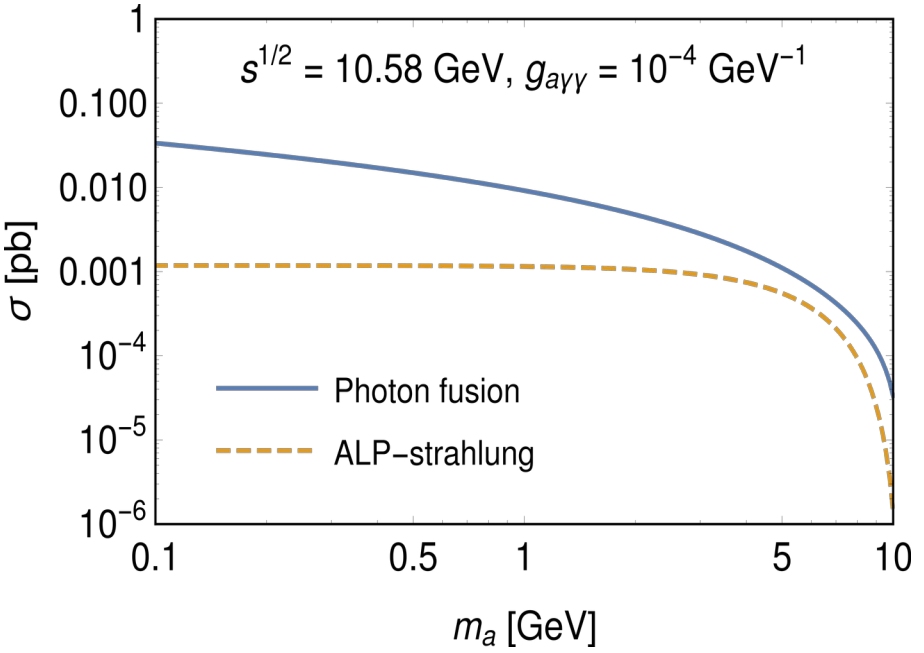


KLOE-2

Approaching data unblinding!

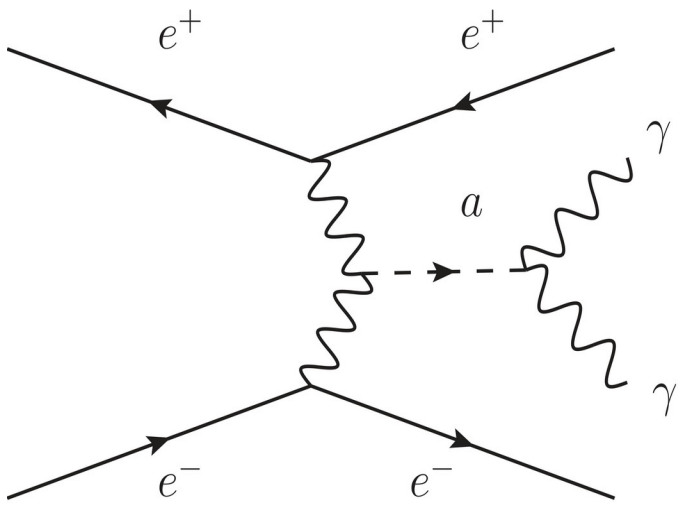
Axion Like Particles (ALPs) at Belle II

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{aZ\gamma}}{4} a F_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4} a Z_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4} a W_{\mu\nu}\tilde{W}^{\mu\nu}$$

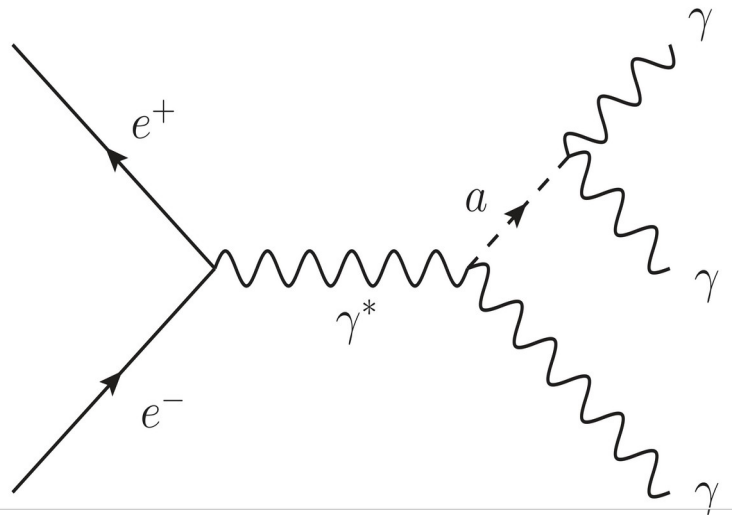


JHEP 1712 (2017) 094

Photon fusion



ALP-strahlung



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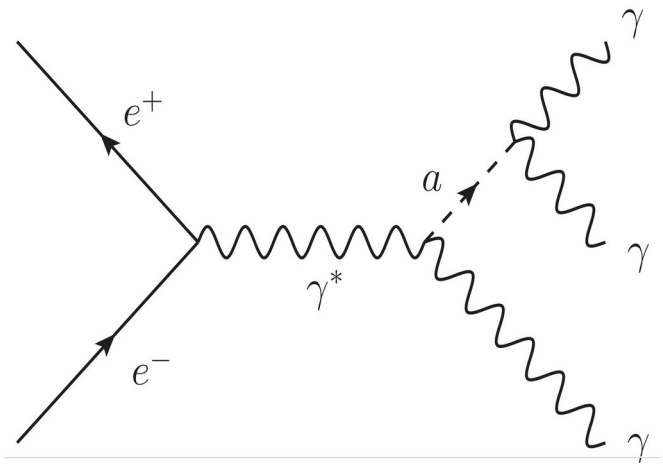
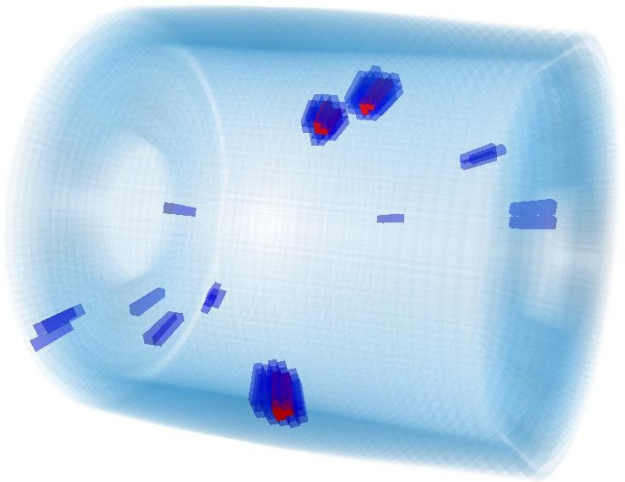
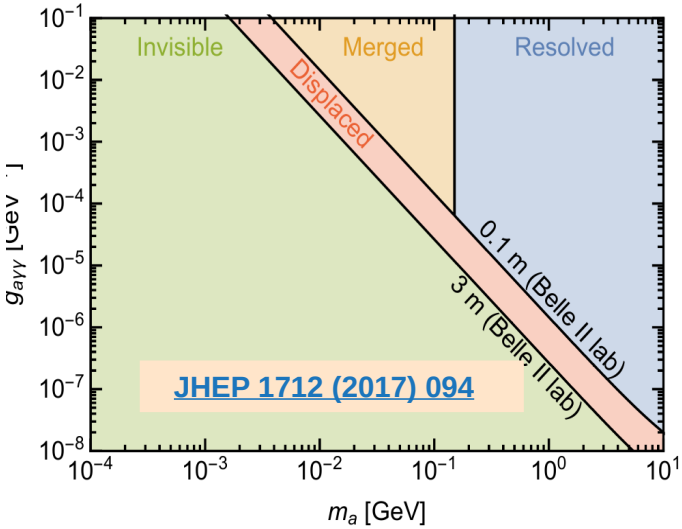
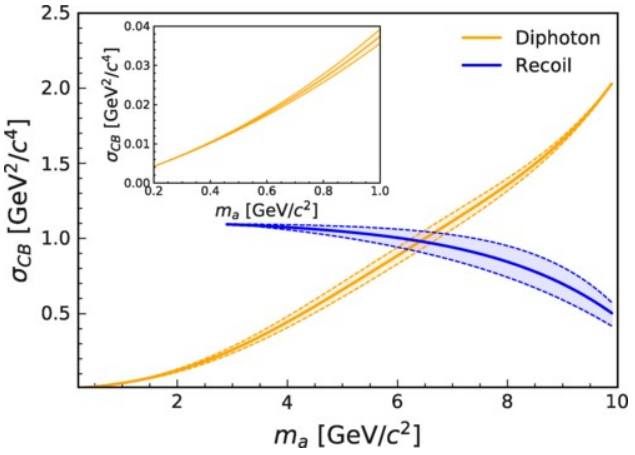
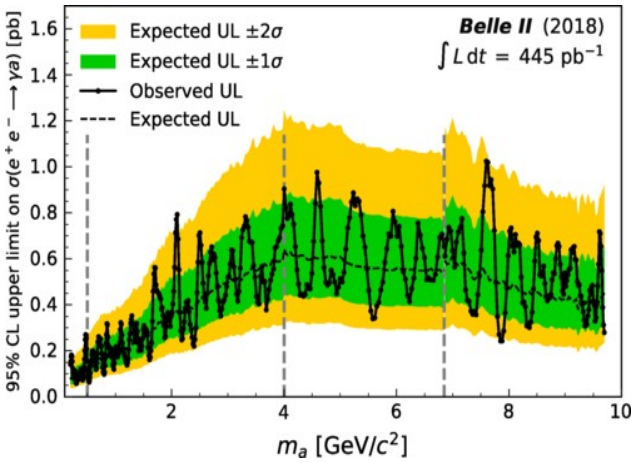


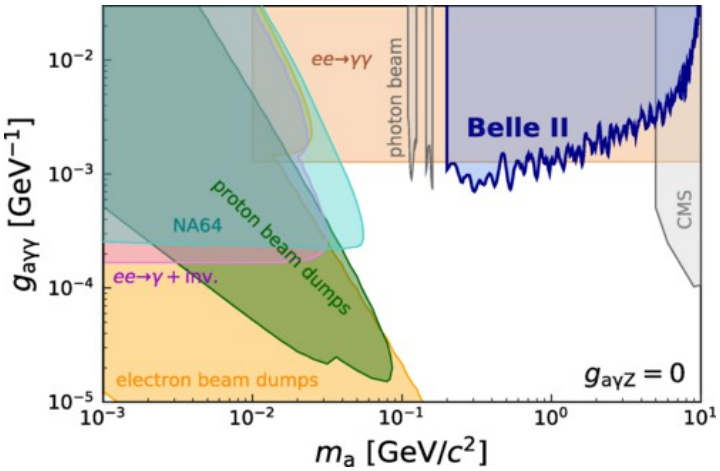




- Three photons that add up to the beam energy + bump on diphoton mass.
- SM background: $e^+e^- \rightarrow \gamma\gamma(\gamma)$, $e^+e^- \rightarrow e^+e^-(\gamma)$, and $e^+e^- \rightarrow$ scalar+$\gamma(\gamma)$







→ ArXiv: 2007.13071

→ Phys. Rev. Lett. 125, 161806

New Phenomena Session

Latest results on τ and dark sector physics at Belle II

Summary

- Presented a selection of recent results and ongoing analyses
- We are accumulating data at unprecedented luminosity
- Many results to be expected in the future

Thank you for your attention!

31/03/2021
Gianluca Inguglia

InterLeptons

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

FWF Der Wissenschaftsfonds.

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

Belle II

erc European Research Council Established by the European Commission