Recent Results from Belle II

Steven Robertson
Institute of Particle Physics
&
University of Alberta

On behalf of the
***Belle II* Collaboration**

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Outline

Introduction: the Belle II experiment

Recent results:

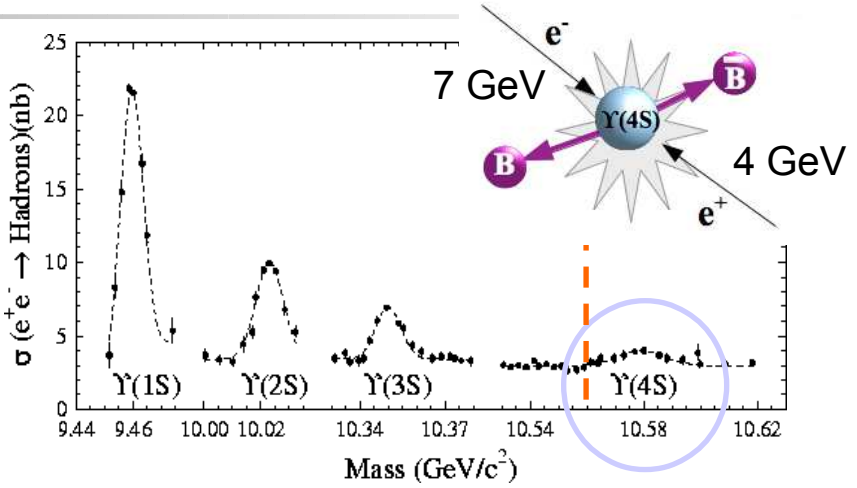
- $B^+ \to K^+ \nu\bar{\nu}$ — Phys. Rev. Lett. 127, 181802 (2021)
- $\tau^+ \to l^+ \alpha \quad (l = e, \mu)$ — Preliminary
- Invisible Z' in $e^+e^- \to \mu^+\mu^- Z'$ — Preliminary (update of Phys. Rev. Lett. 124, 141801 (2020))
- $Z' / S /$ ALP $\to \tau^+\tau^-$ — Preliminary
- Dark Higgsstrahlung: h' and A' — arXiv:2207.00509 (submitted to PRL)

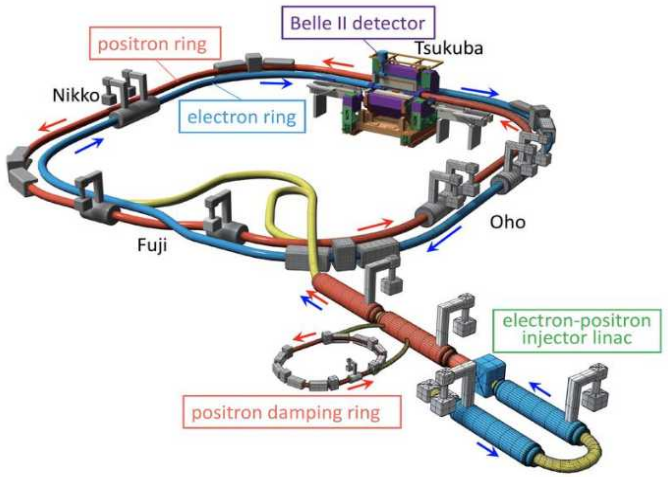
Prospects

Belle II experiment

Belle II experiment at SuperKEKB collider is an e^+e^- asymmetric-energy B factory

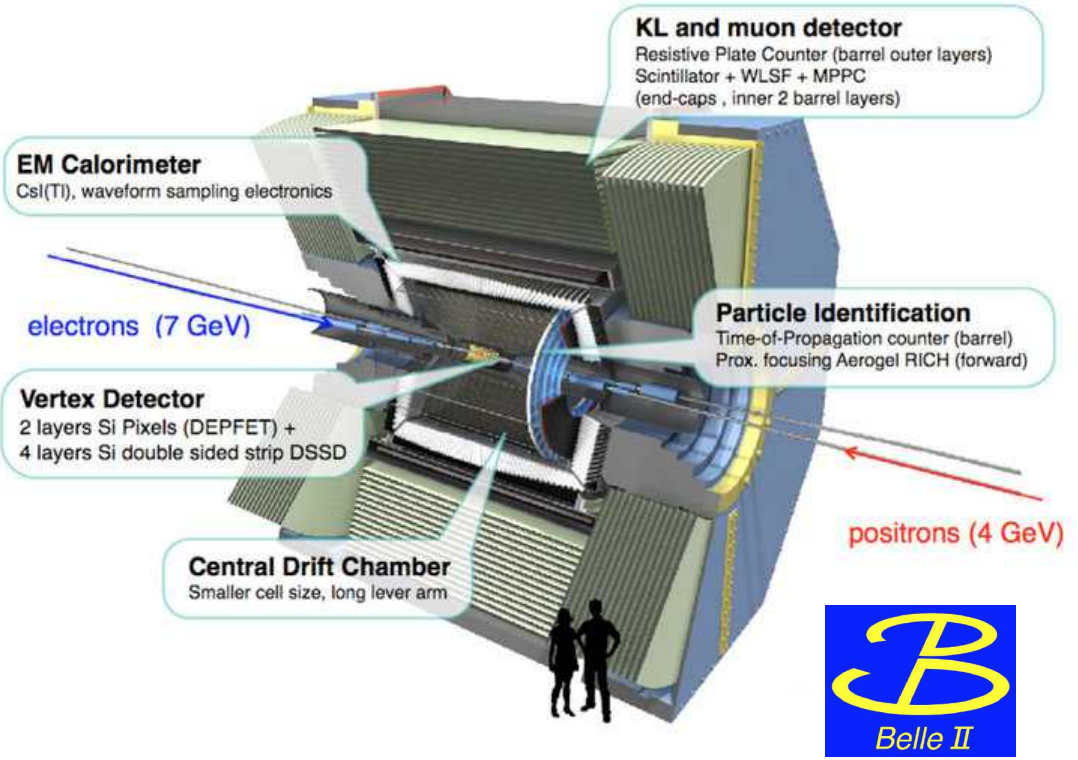
- Target data sample of 50 ab^{-1}, ~30x combined data set of previous experiments
- Detector optimized for B vertex separation and momentum measurement, K - π particle identification and precision calorimetry





SuperKEKB Collider

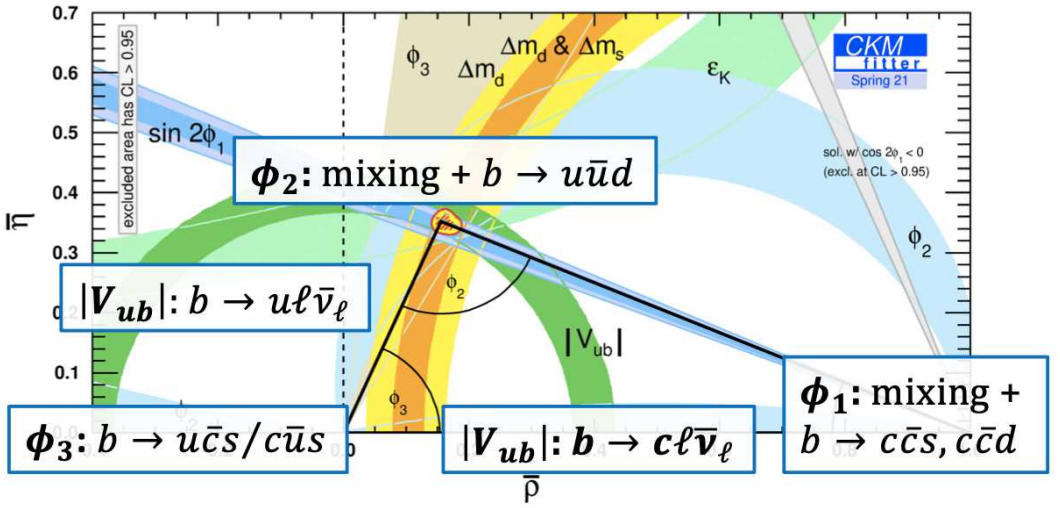
- Record peak luminosity 4.7 × 10^{34} cm^{-2} s^{-1}
- Ultimate goal: 6.5 × 10^{35} cm^{-2} s^{-1}

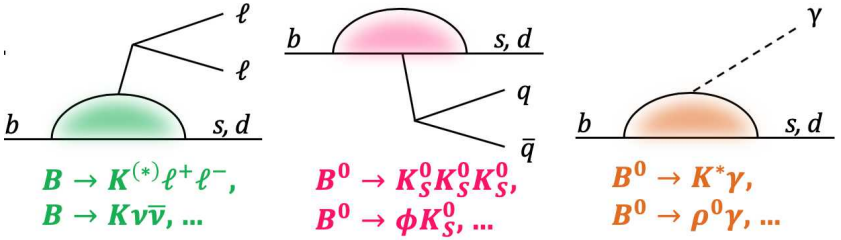


Belle II physics program

Broad physics program for precision characterization of CKM matrix elements and CP-violation in the B meson sector

- Tree and loop-level (e.g. FCNC) processes probed to test for evidence of beyond Standard Model contributions
- High statistics with 50 ab^{-1} target data set





Process	σ (nb)
$b\bar{b}$	1.1
$c\bar{c}$	1.3
Light quark $q\bar{q}$	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40

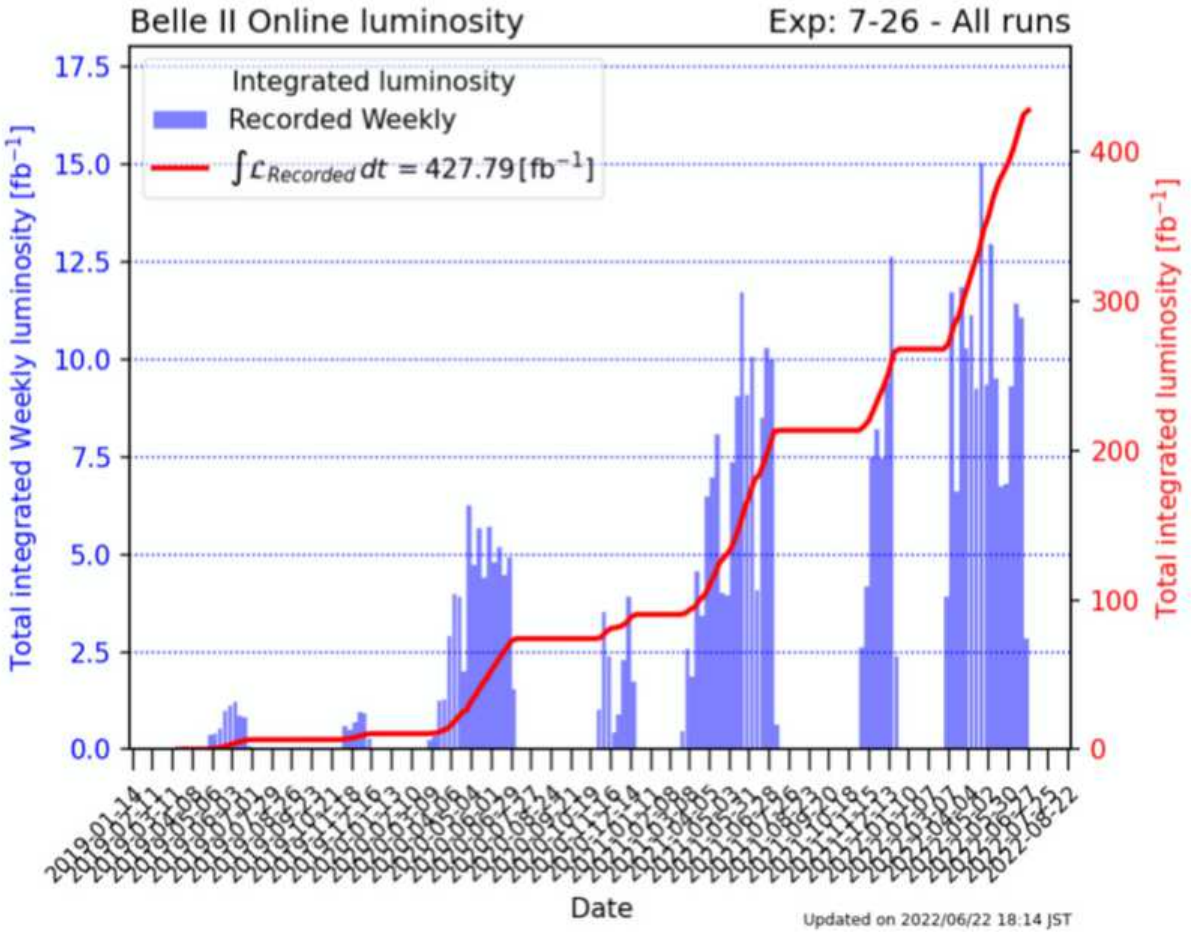
Very extensive program of non-B physics as well:

- Tau, charm precision measurements and rare decay searches
- Quarkonium and “exotic states”
- Light Higgs, Z', dark sector etc.

Belle II luminosity

First Belle II physics data recorded in 2019

- Total integrated luminosity of 362 fb^{-1} at $\Upsilon(4S)$
- 42 fb^{-1} recorded 60 MeV below $\Upsilon(4S)$ ("offpeak")
- 19 fb^{-1} at 10.8 GeV for exotic hadron studies



► Results shown in this talk are all based on much smaller data samples

$B^+ \to K^+ \nu\bar{\nu}$

$B^+ \to K^+ \nu\bar{\nu}$

(Suppressed) flavour-changing neutral current process in the SM proceeding via EW penguin and box diagrams

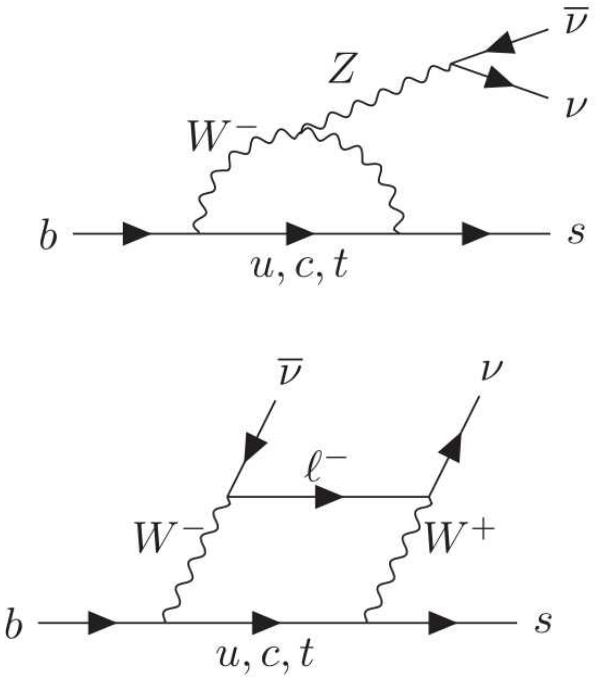
- Analogous to $B \to K l^+ l^-$ but with neutral leptons
- Potentially sensitive to non-SM contributions via additional diagrams with new particles or interactions
- Only a single Wilson coefficient contributes to SM process: $C^{\nu}_{L,\,SM}$ while C^{ν}_{L} and C^{ν}_{R} probe new physics

Standard model expectation:

$$B(B^+ \to K^+ \nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$$

- Experimental challenge arises due to limited kinematic information available as a selection "signature"
- Previous searches from BABAR and Belle based on exclusive (hadronic or semileptonic) reconstruction of second B meson in the event

(see talk by P. Cheema in this session)

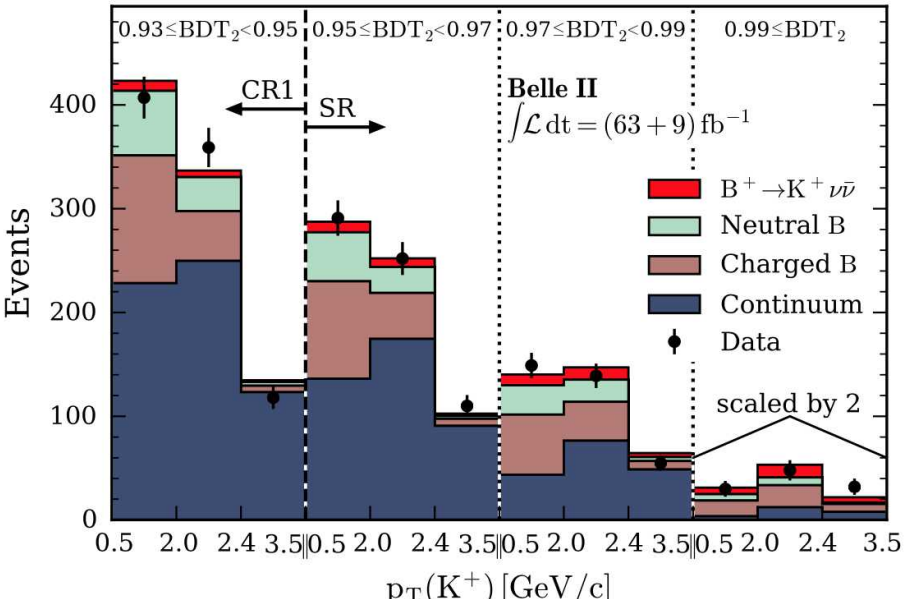


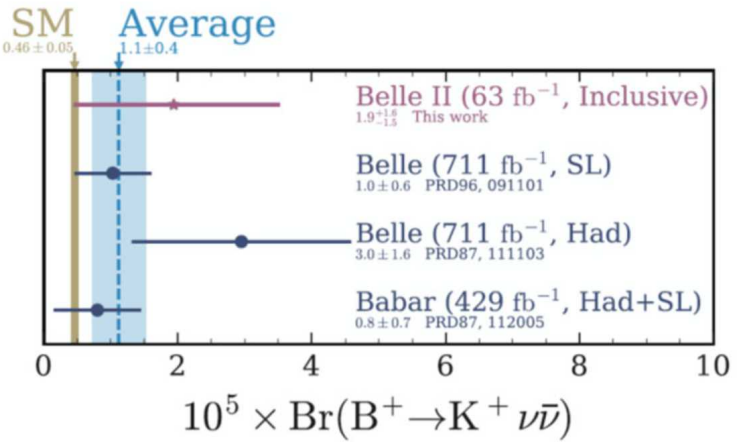
$B^+ \to K^+ \nu\bar{\nu}$

Phys. Rev. Lett. 127, 181802 (2021)

New Belle II approach based on "inclusive" reconstruction of the second B meson in the event

- much higher reconstruction efficiency (~4.3%), hence increased sensitivity in spite of relatively small integrated luminosity
- Use BDT classifiers to identify distinctive characteristics of signal event





$$\mathcal{B}r(B^+ \to K^+\nu\bar{\nu}) = \left(1.9^{+1.3\,+0.8}_{-1.3\,-0.7}\right)\times 10^{-5}$$
$$< 4.1\times 10^{-5}\ @\ 90\%\ \mathrm{CL}$$

Based on 63 fb^{-1}

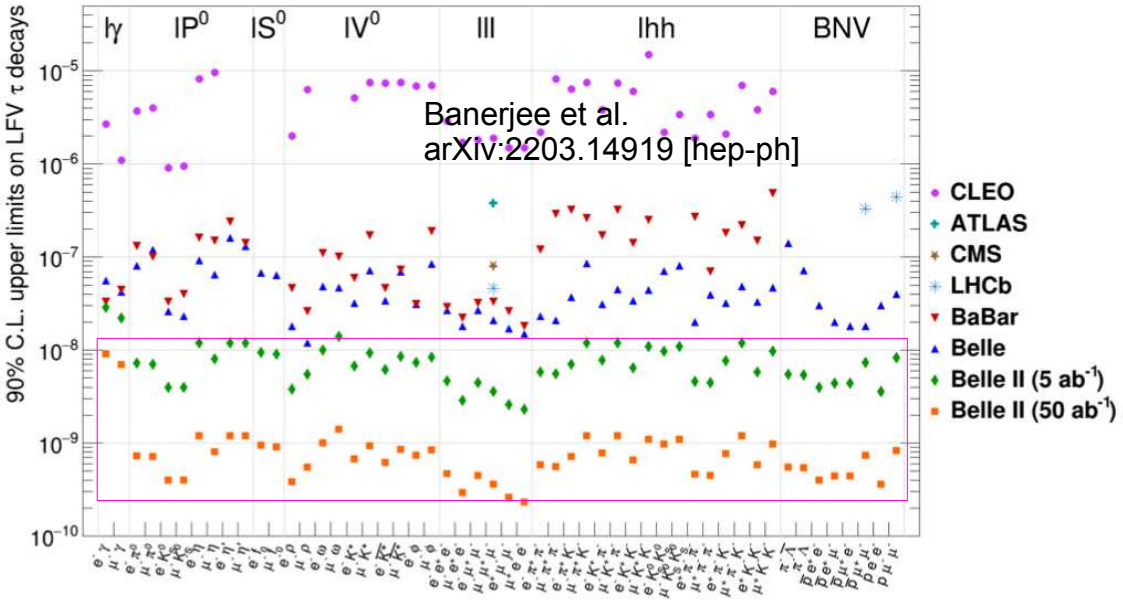
- Sensitivity already approaching that of previous measurements based on much larger data sets from BABAR and Belle.

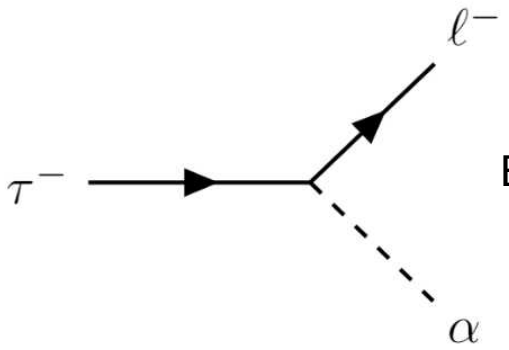
$\tau^+ \to l^+ \alpha$ (invisible boson)

$\tau^+ \to l^+\alpha$ (invisible boson)

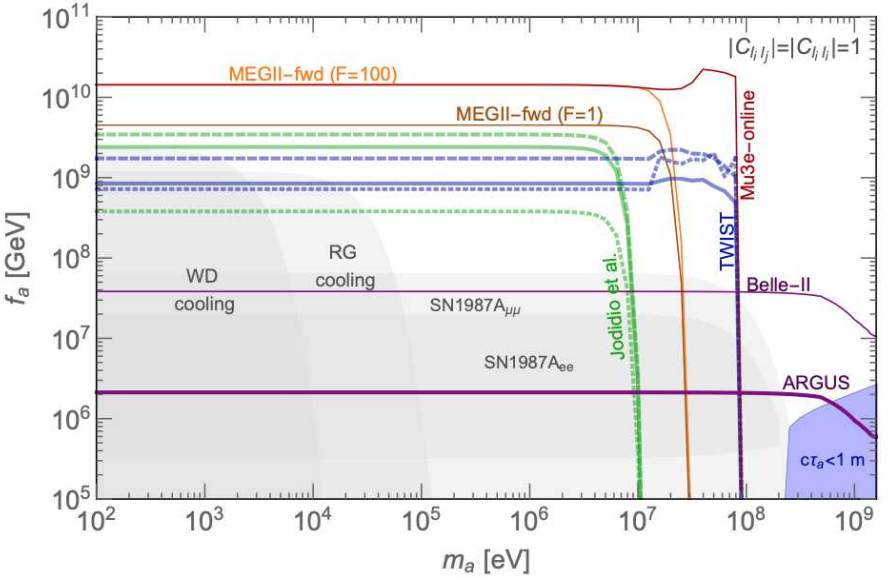
B factories are also tau lepton factories: ~1 million $\tau^+\tau^-$ pairs per fb^{-1}

- Dedicated low-multiplicity trigger lines to ensure high efficiency
- Neutrino-less and Lepton Flavour Violating (LFV) tau decays are a sensitive probe of new physics





$B(\tau^+ \to l^+\alpha) \sim 1 / f_a^2$



Calibbi et al., JHEP09(2021)173

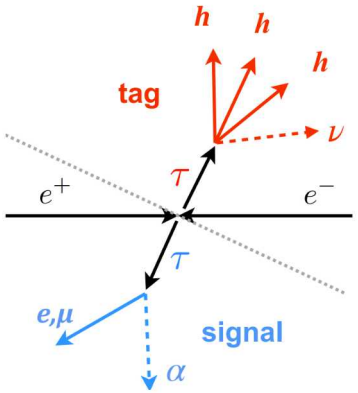
$\tau^+ \to l^+\alpha$ can arise in new physics models such as light long-lived ALPs

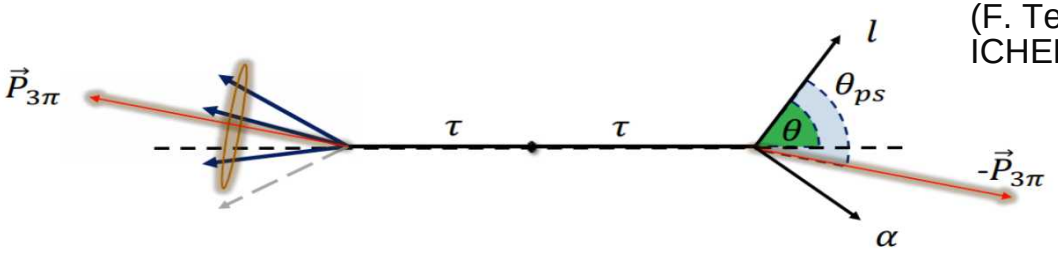
- Long-lived α does not interact in detector
- Previous results from ARGUS, hence accessible to Belle II with early data

$\tau^+ \to l^+ \alpha$ (invisible boson)

Preliminary
(F. Tenchini ICHEP 2022)

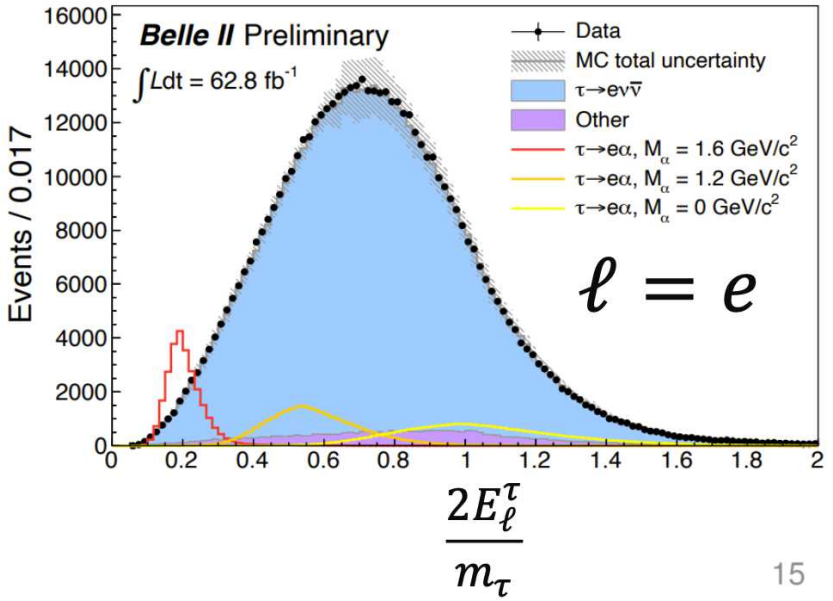
At B factories, $\tau^+\tau^-$ pairs are produced back to back and boosted:





- Signal is similar to $\tau^+ \to l^+ \nu\bar{\nu}$, except that the lepton is mono-energetic in the τ rest frame
- "Bump hunt" in the lepton energy spectrum
- Signal peak smeared by resolution of τ rest frame determination from $\pi^+\pi^-\pi^+$ system:

- Require a 1 - 3 event topology, i.e. 4 tracks with $\tau^+ \to \pi^+\pi^-\pi^+\nu$ in one event "hemisphere"
- Veto events with additional neutrals (γ, π^0)
- Backgrounds from continuum $q\bar{q}$, di-lepton and 4-fermion sources



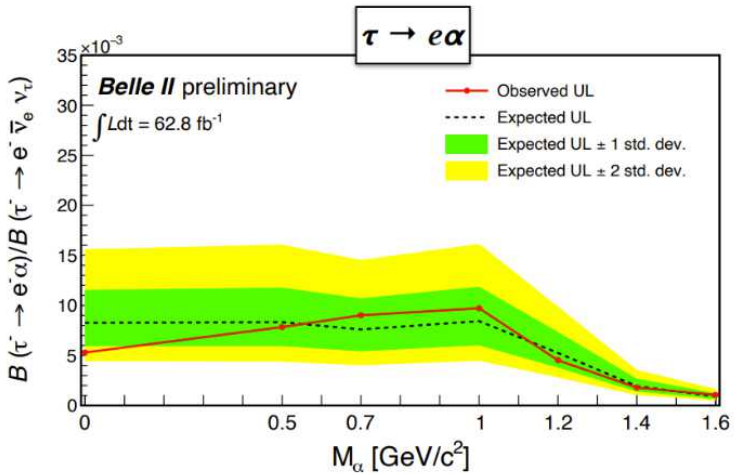
$\tau^+ \to l^+ \alpha$ (invisible boson)

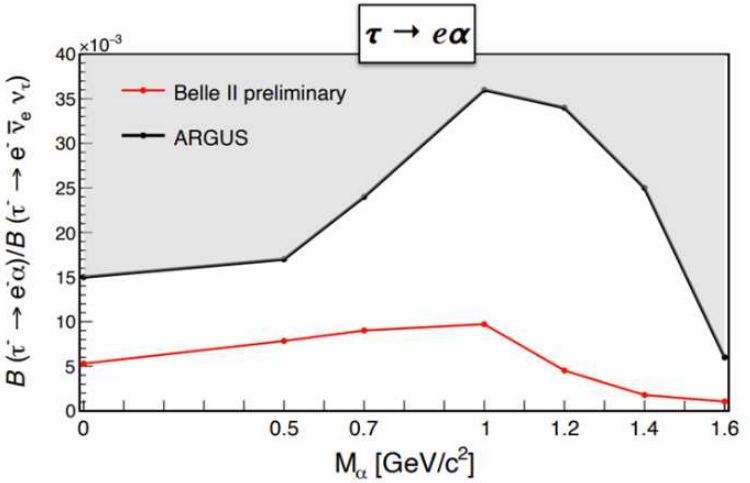
Preliminary
(F. Tenchini
ICHEP 2022)

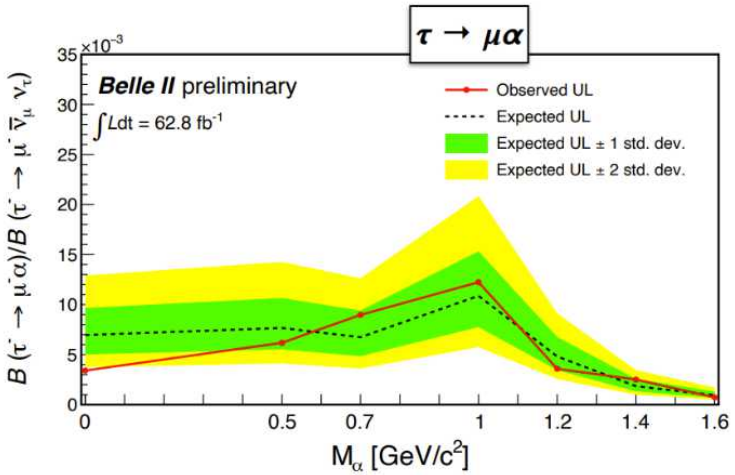
No significant excess seen in either e or μ mode:

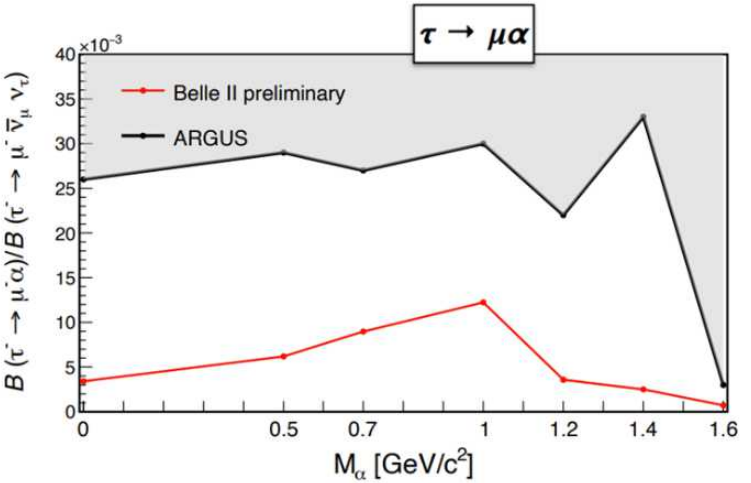
- CLs method to determine 95% C.L. upper limits on branching fraction

Based on 62.8 fb^{-1}







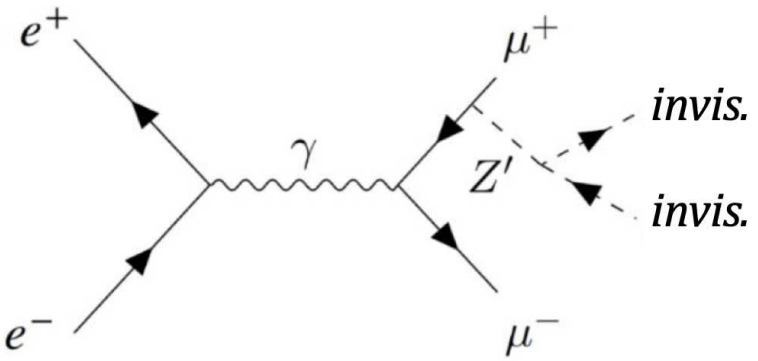


$L_\mu - L_\tau$ gauge boson (Z')

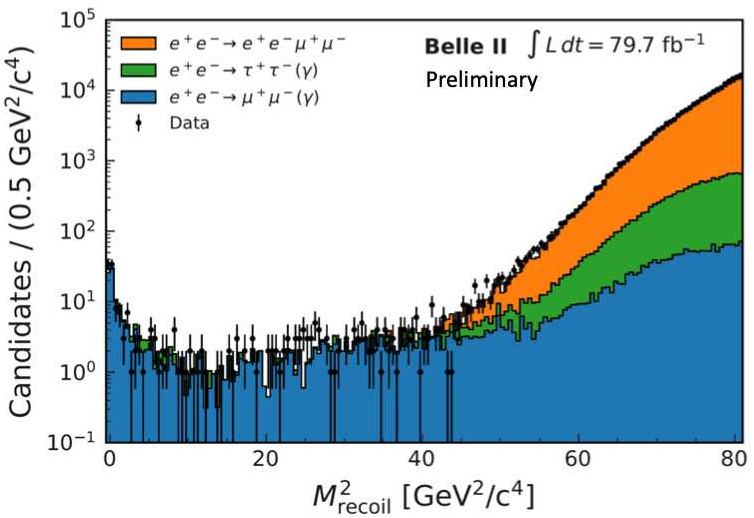
$Z' \rightarrow$ invisible

$L_\mu - L_\tau$ gauge boson Z' couples only to 2nd and 3rd generation leptons

- Avoids stringent existing limits on electron and quark couplings
- Could explain $(g-2)_\mu$ and other flavour anomalies, e.g. $R_{D^{(*)}}$, $R_{K^{(*)}}$
- $Z' \rightarrow \nu\bar{\nu}$ process (mostly relevant for $m_{Z'} < 2m_\mu$). More generally Z' could be mediator to dark sector, coupling to dark χ via $Z' \rightarrow \chi\bar{\chi}$



$$e^+ e^- \rightarrow \mu^+ \mu^- + E_{miss}$$



Z' produced by "Z' -strahlung" process from final-state muon

- Previous limits by BABAR and Belle on $Z' \rightarrow \mu^+ \mu^-$

Z' reconstructed in recoil of di-muon pair

- 2-track trigger w/ muon $p_T^\mu > 0.4$ GeV/c
- No extra energy (γ, π^0) present in the event

Z' → invisible

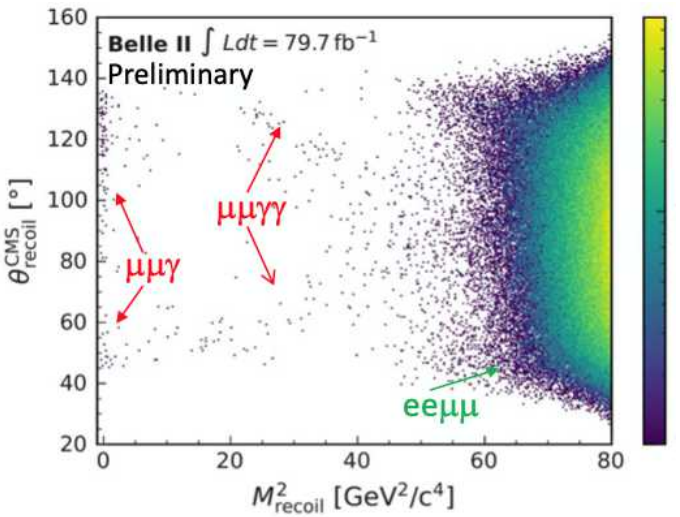
Preliminary

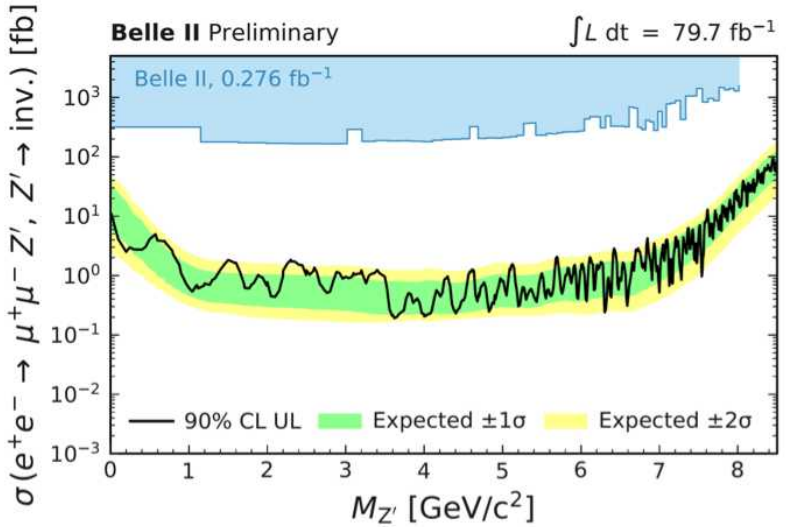
Based on 79.7 fb^{-1}

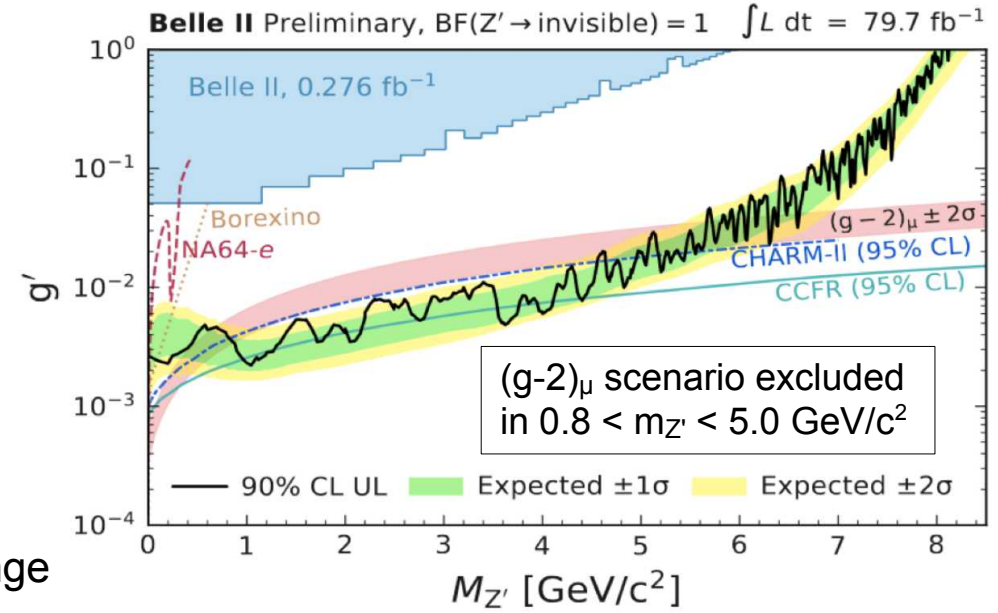
Backgrounds originate from QED processes which mimic the $\mu^+\mu^-$ + E_{miss} final state, typically due to detector acceptance effects:

- $e^+e^- \to \mu^+\mu^-\gamma\,(\gamma)$ undetected photon(s)
- $e^+e^- \to \tau^+\tau^-\,(\gamma)$ muonic τ decays and mis-ID
- $e^+e^- \to e^+e^-\mu^+\mu^-$ missing e^+e^-

Neural Net based on kinematic variables optimized for background suppression







No significant excess seen within signal mass range

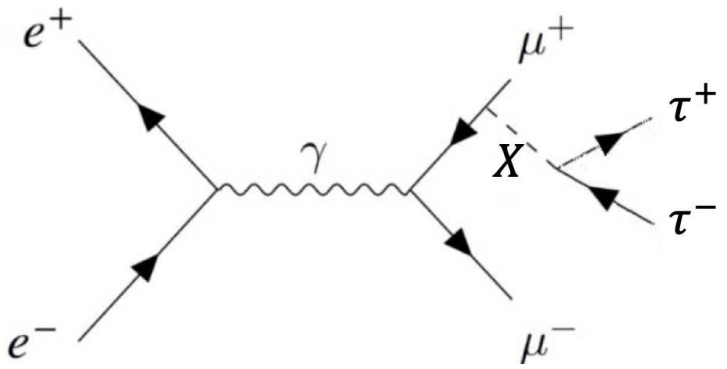
$Z', S, ALP \rightarrow \tau^+\tau^-$

Z', S, ALP $\rightarrow \tau^+\tau^-$

Preliminary

Based on 63.3 fb^{-1}

Extend Z' search to permit additional visible particles in final state:



where X = Z', S or ALP

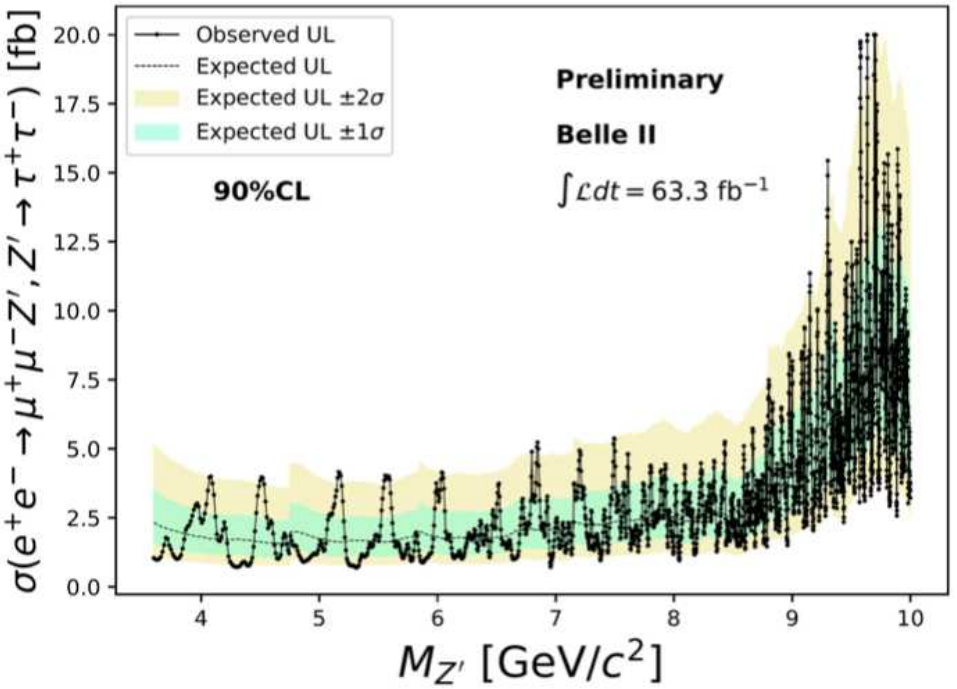
- Z' or (leptophilic) scalar S
- ALP: $C_{ee} = C_{\mu\mu} = C_{\tau\tau}$ $C_{\gamma\gamma} = C_{Z\gamma} = 0$

4 - track signal topologies:

$2\mu + 2(e,\mu,\pi)$

- Missing mass signature ($m_{Z'}$) in recoil of $\mu^+\mu^-$ system

- Substantial backgrounds from continuum di-lepton production (e.g. $\mu^+\mu^-\gamma$, $\tau^+\tau^-$)
- Neural net trained to identify distinctive signal kinematics
- No significant excess observed

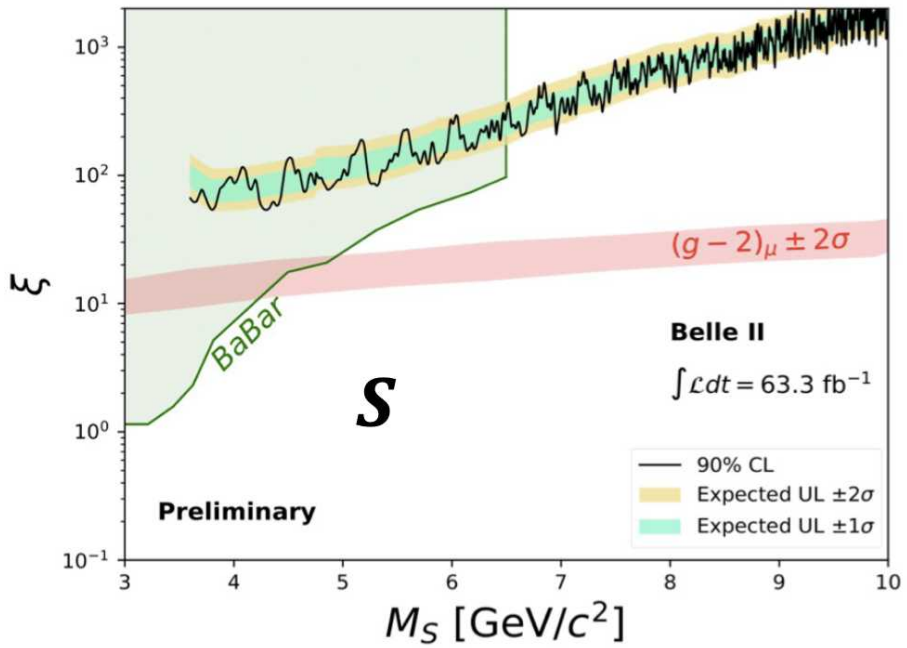


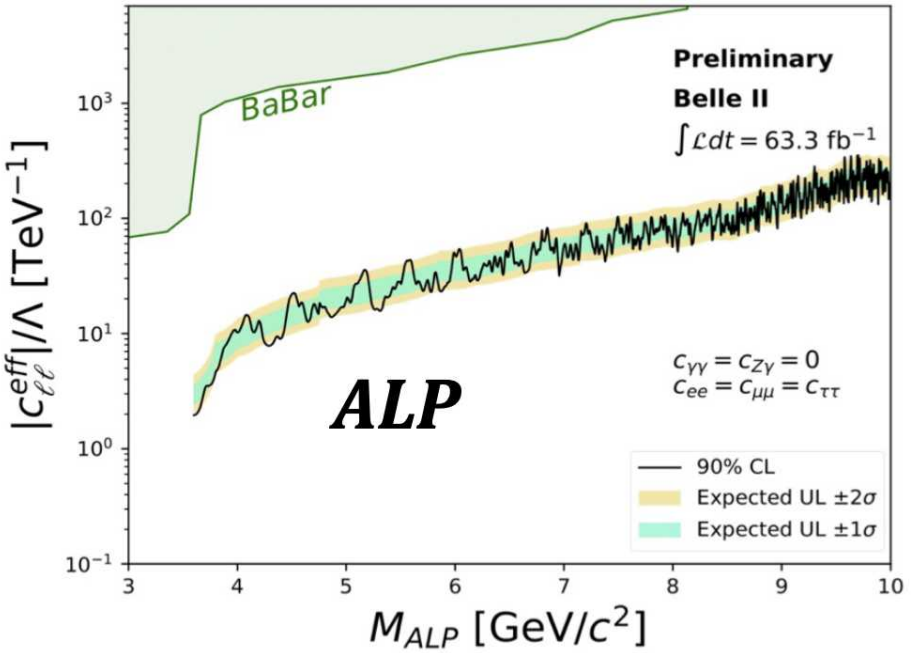
Z', S, ALP $\rightarrow \tau^+\tau^-$

Preliminary

Based on 63.3 fb^{-1}

90% CL limits set on the ALP and scalar couplings:





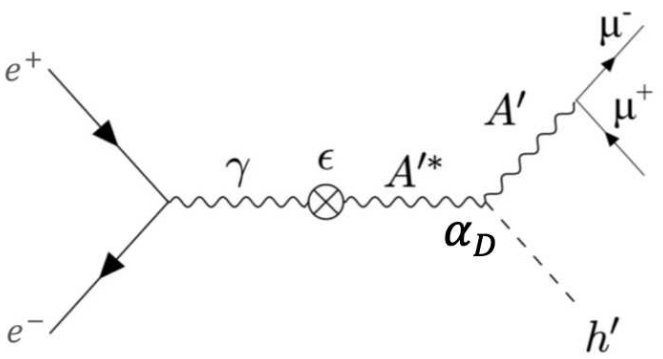
- First constraints on scalar S for $m_S > 6.5$ GeV/c^2
- First experimental constraints on ALP $\rightarrow \tau^+\tau^-$

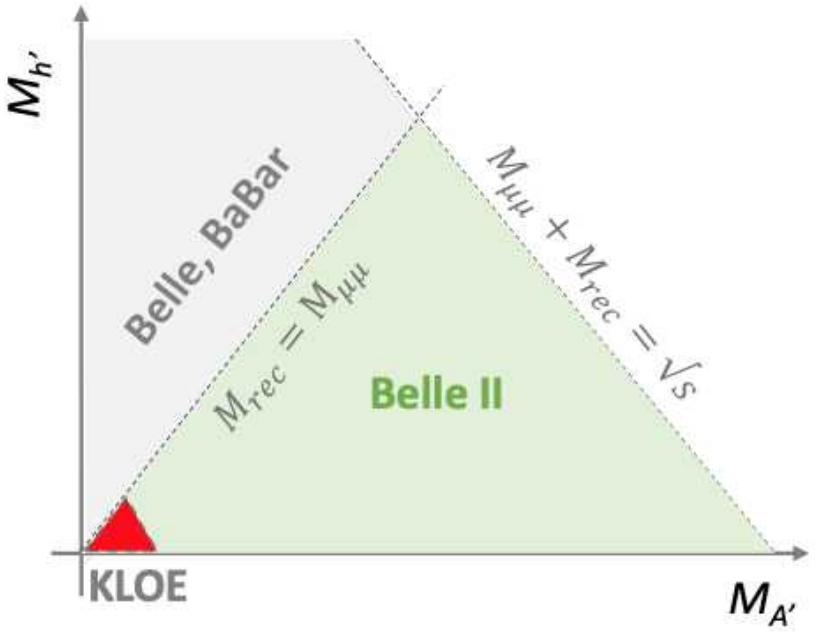
Dark Higgsstrahlung

Dark sector (invisible h' + A')

Dark sector Higgs h' can give mass to dark photon A' through usual SSB mechanism

- No mixing of h' with SM Higgs
- h' coupling to A' is α_D so overall process depends on $\varepsilon^2\alpha_D$





Experimental signature depends on mass hierarchy:

$M_{h'} > M_{A'}$:

- h' → A' A' (6 - track signature)
- Previous BABAR and Belle searches

$M_{h'} < M_{A'}$ **This search**

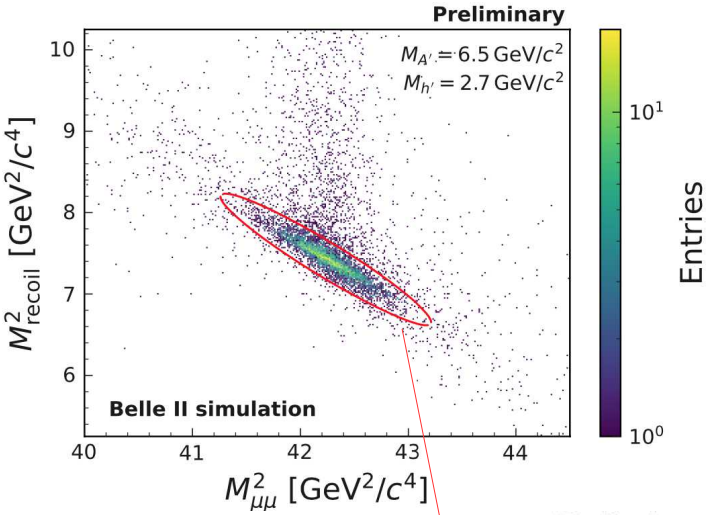
- h' is long-lived (i.e. undetected)
- Experimental signature is 2D peak in $m_{A'} = m_{\mu\mu}$ and $m_{h'} = m_{recoil}$

Dark sector (invisible h' + A')

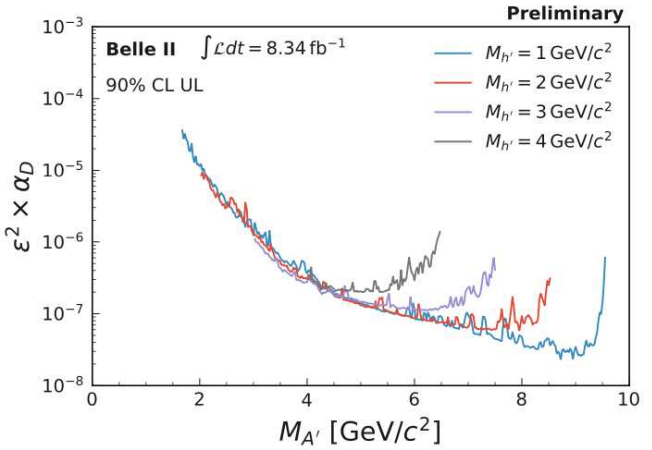
$e^+ e^- \rightarrow \mu^+ \mu^- + E_{miss}$

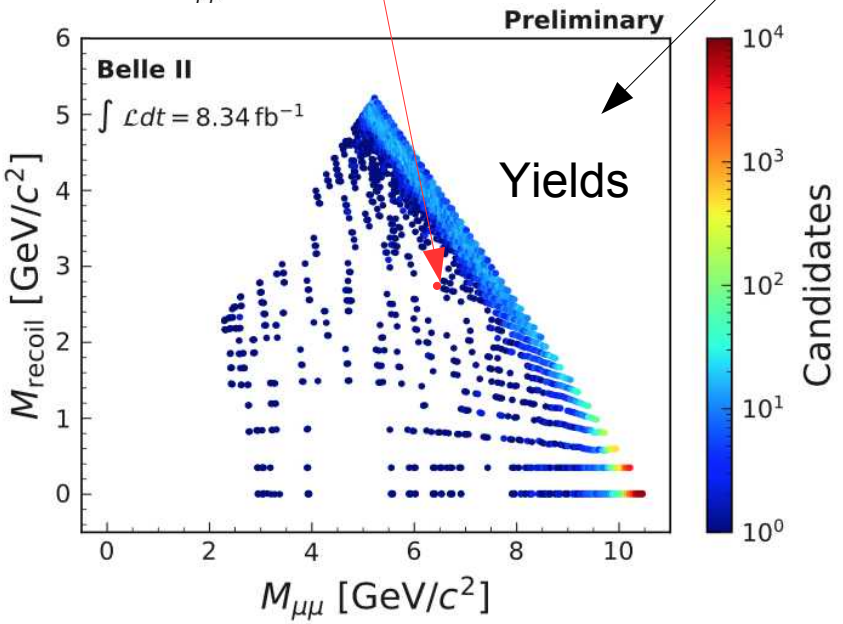
Submitted to PRL
arXiv:2207.00509

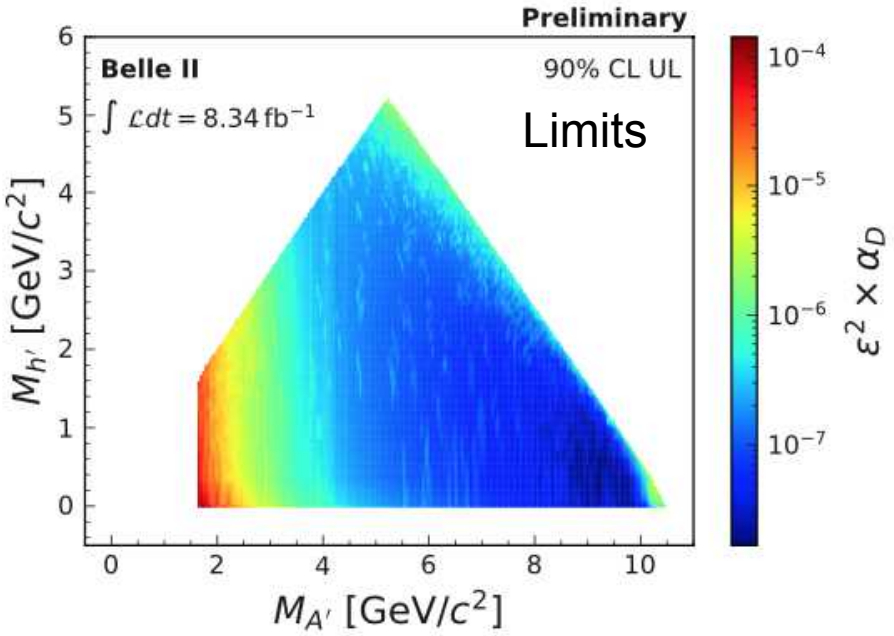
Based on 8.34 fb^{-1}



Scan ~9000 overlapping 2D elliptical mass windows







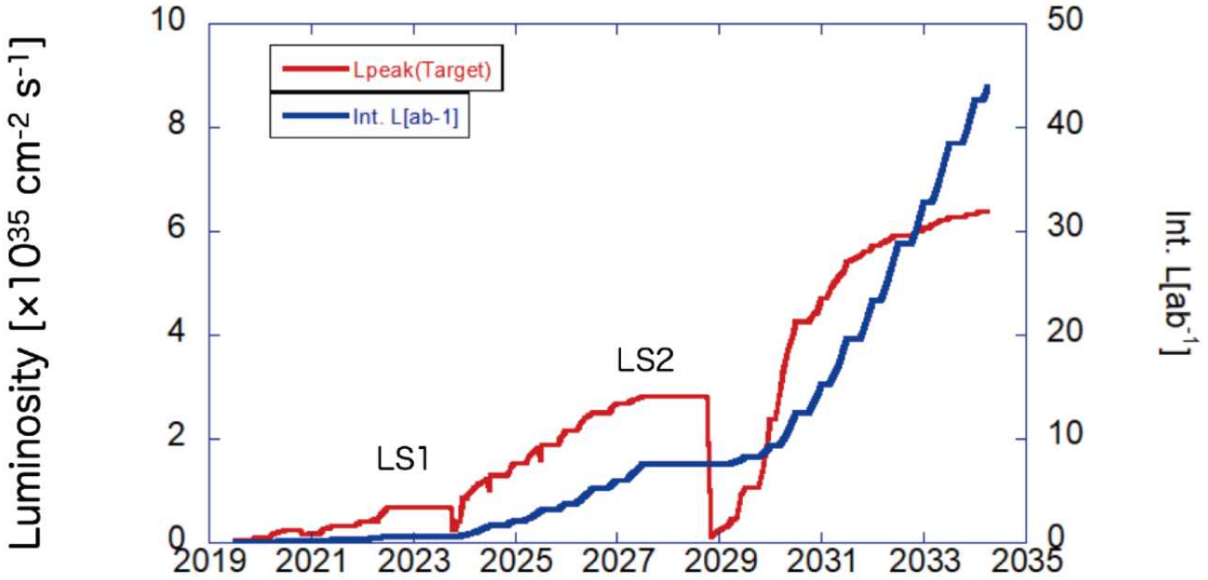
Prospects

Belle II is now approaching an integrated luminosity which is directly competitive with the previous generation of B factories

- Improvements in detector, trigger, and analysis strategies have enabled specific searches for new physics with early Belle II data
- World's best sensitivity in specific LFV τ decays and dark sector searches with current data set

Data collection and physics program is just beginning!

- Look forward to new results with worlds largest B factory data set

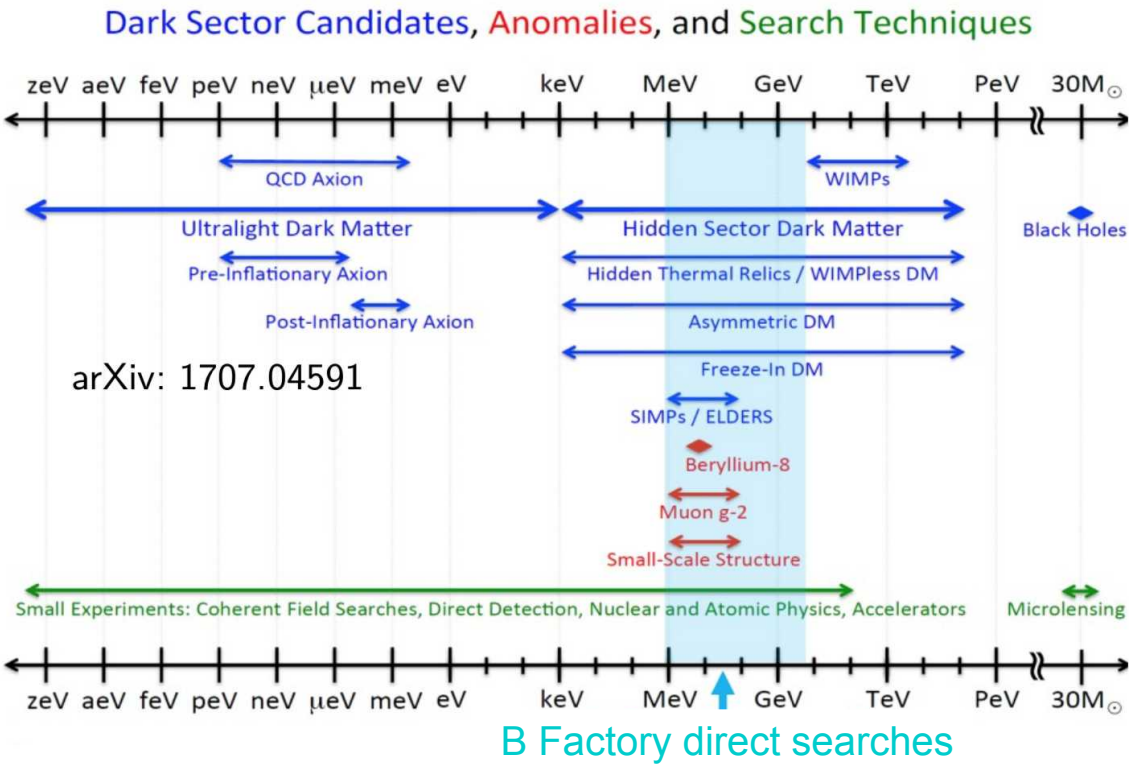


Backup slides

Dark Sector @ B Factories

- Clean e^+e^- environment with hermetic (near 4π) detector coverage; good missing energy reconstruction
- Potential to reconstruct displaced vertices in $\sim 1\text{mm} < c\tau < \sim 10\text{cm}\ (\sim 100\text{cm})$, with $c\tau > \sim 3\text{m}$ being "missing energy"

- Production of on-shell bosons via "radiative" $e^+e^- \to \gamma Z'$ and $e^+e^- \to f\bar{f}Z'$ "-strahlung" processes
- Inclusive trigger for (N_{tracks}>3) hadronic events, but low-multiplicity searches require dedicated triggers



Dark sectors

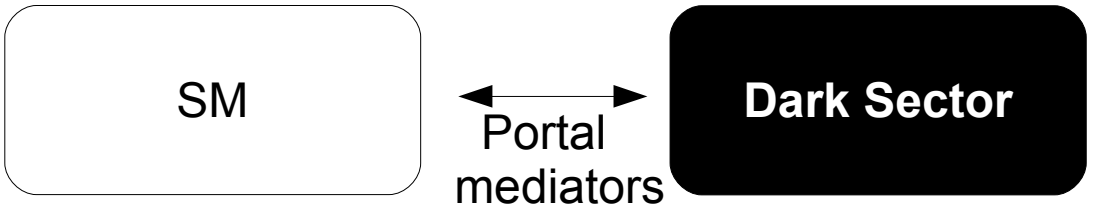
Maybe dark matter is not specifically related to solution to problems of the SM and is, in effect, a distinct “sector”

- Dark sector fermions which carry charges for non-SM gauge interactions, possibly acquiring mass via dark sector Higgs etc.
- EFT provides a number of “portals” to access this dark sector

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Vector portal Higgs portal Neutrino portal



Dark sector can be probed via mixing of the portal mediators with SM bosons

Dark photon

P. Fayet, Phys. Lett. B 95, 285 (1980)
P. Fayet Nucl. Phys. B 187, 184 (1981)
B. Holdom, Phys. Lett. B 166, 196 (1986)

Simplest dark sector scenario: add a new U(1) gauge symmetry, with associated charge carried by dark-sector fermions

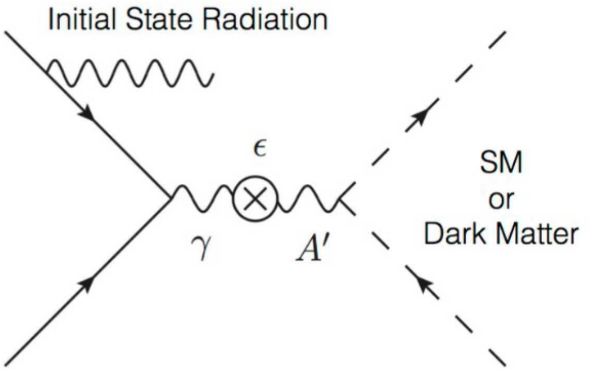
- Spin-1 gauge boson "dark photon" A' (or γ_d, or Z_d in non-minimal models) can mix with SM photon, providing a "portal" to the dark sector.

Kinetic mixing: $\frac{1}{2}\epsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$

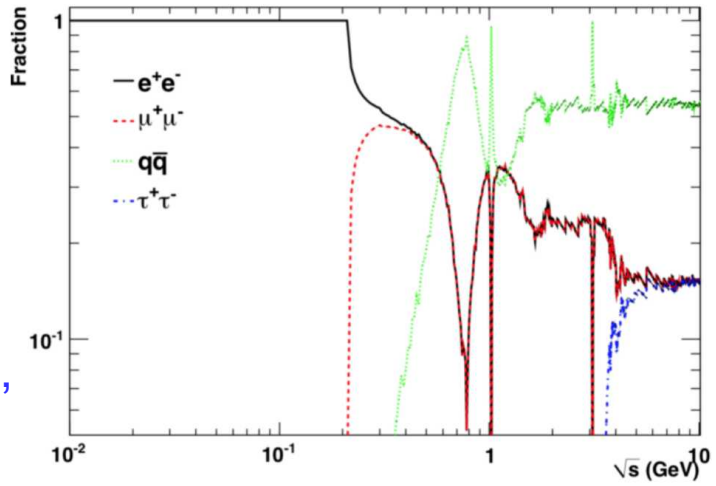
ϵ is the strength of the kinetic mixing

- ϵ could be as large as 10^{-2} for $m_{A'}$ in the GeV range

Lifetime: $\tau_{A'} \sim 1/(\epsilon^2 m_{A'})$



- Decays can either be "prompt" (relative to experimental resolution) or "displaced" (relative to production vertex)
- Decays to SM particles depend on kinematic accessibility, and details of model

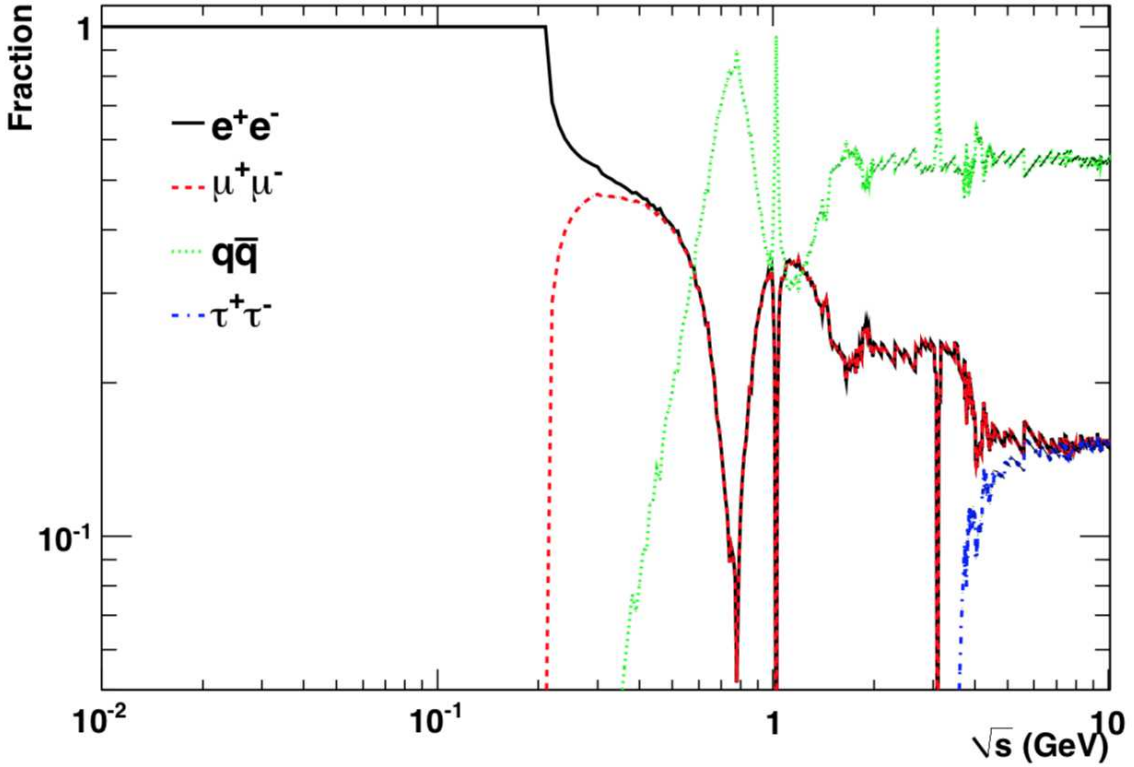


... however, dark sector could be much more extensive, with one or more Abelian or non-Abelian interactions, fermions and Higgs bosons

Dark photon

Permitted decays depend on the relative masses of dark fermions and mediator, and of SM fermions

- Models are highly predictive:



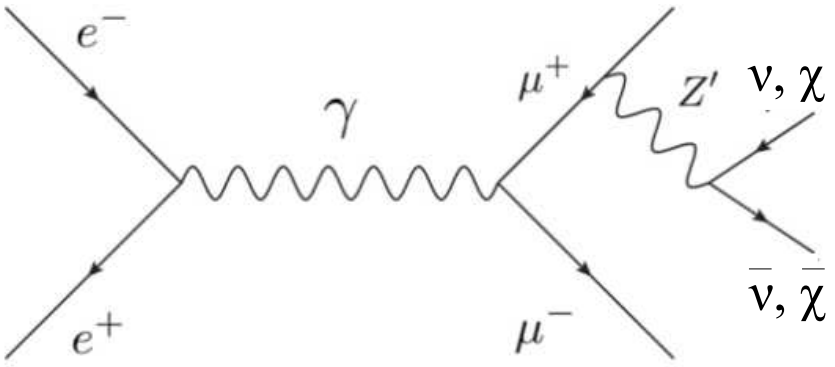
Experimentally, the important feature is a reconstructable narrow A' resonance in a clearly defined topology, i.e a "bump hunt"

- E.g. search for decay of $e^+e^- \to \gamma A'$ via $A' \to \chi\bar{\chi}$ or into SM particles
  - "visible" $A' \to l^+l^-$, decaying promptly or with a displaced vertex
  - "Invisible" A' decays, with A' mass determined from missing energy constraints

Invisible Z'

Search for invisibly decaying Z' in $e^+e^- \to \mu^+\mu^- Z'$

- Z' arises from gauging of difference of leptonic μ and τ number $L_\mu - L_\tau$
- Z' couples to SM only through μ and τ and their associated neutrinos with coupling constant g'



B. Shuve and I. Yavin, Phys. Rev. D 89, 113004 (2014).
W. Altmannshofer, S. Gori, S. Profumo, and F. S. Queiroz, JHEP 12, 106 (2016).

Z' is produced via radiation off of a final state μ

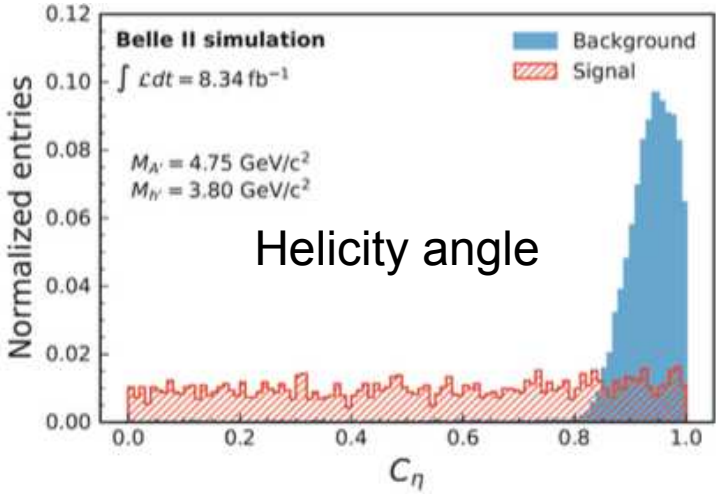
- If $m_{Z'} < 2m_\mu$ then Z' decays to neutrinos
- Alternatively, expect $B(Z' \to \chi\bar{\chi}) \sim 100\%$ if direct decays are possible

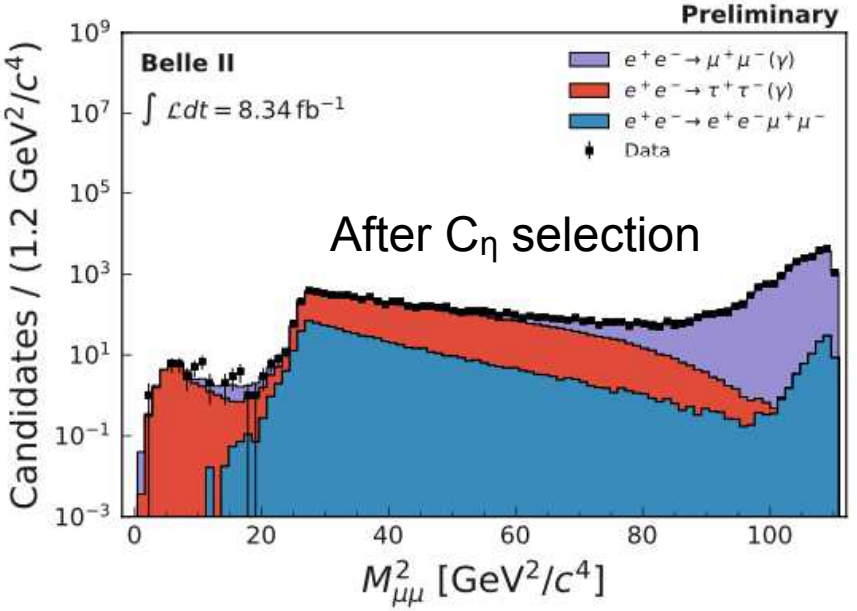
Consider also the LFV scenario of $e^+e^- \to e^+\mu^- Z'$

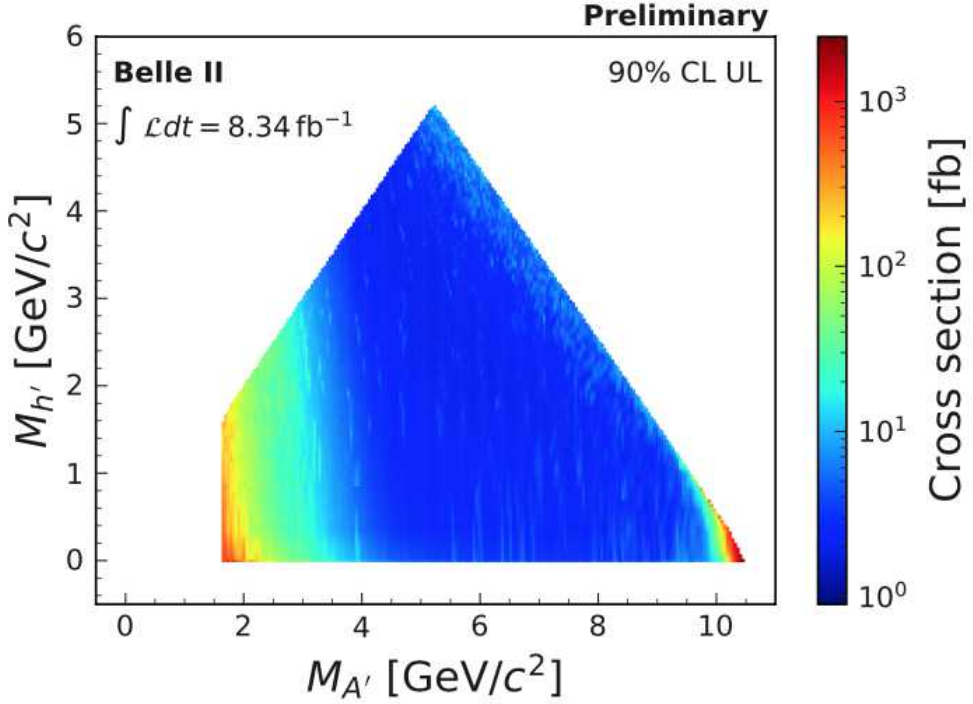
- Identical search methodology, but with PID criteria changed for one of the two leptons

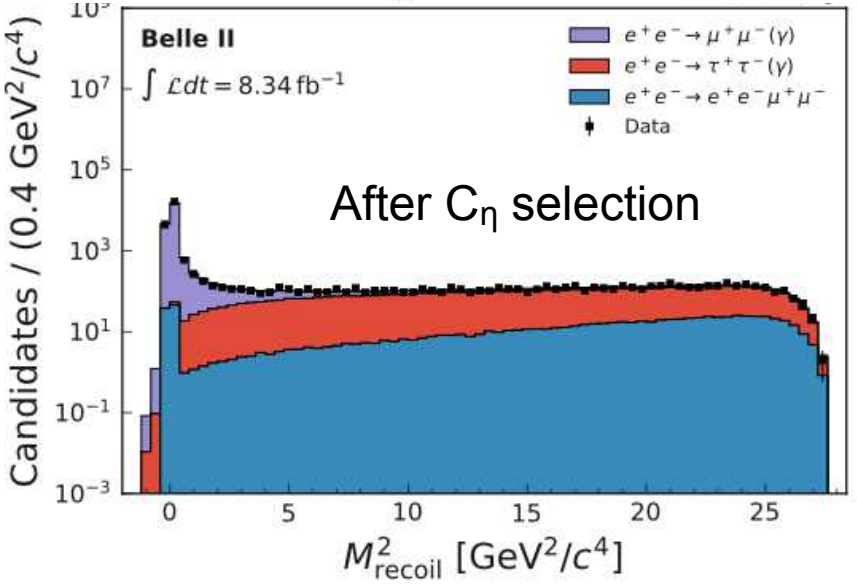
I. Galon and J. Zupan, JHEP 05, 083 (2017).
I. Galon, A. Kwa, and P. Tanedo, JHEP 03, 064 (2017).

Dark sector (invisible h' + A')



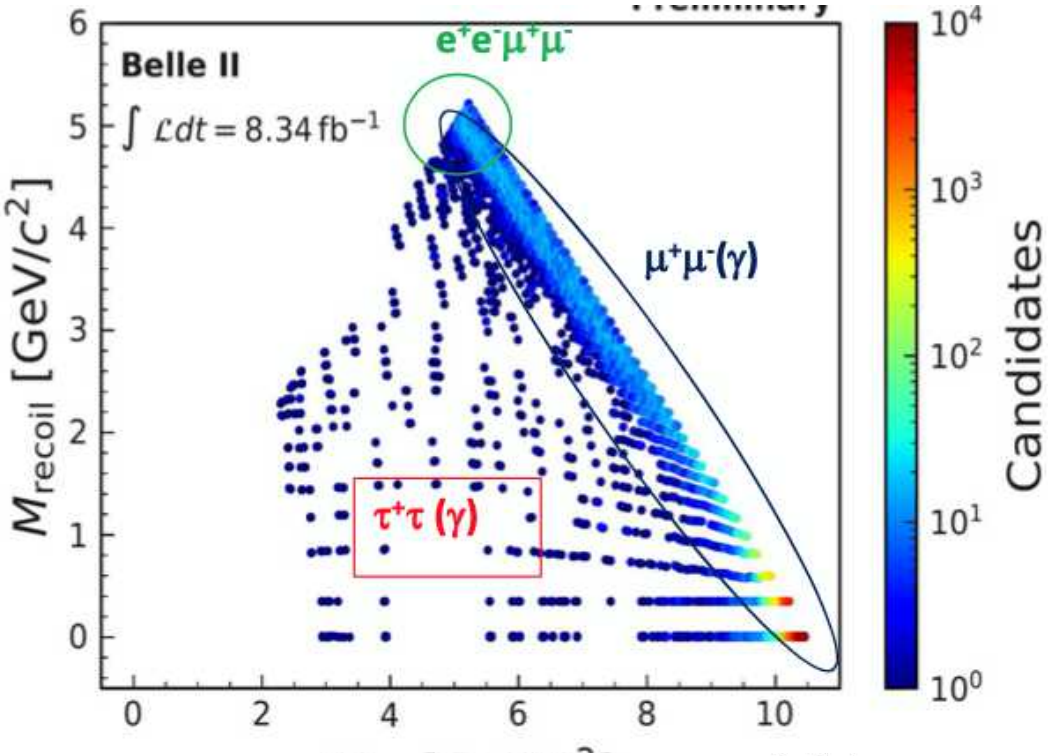






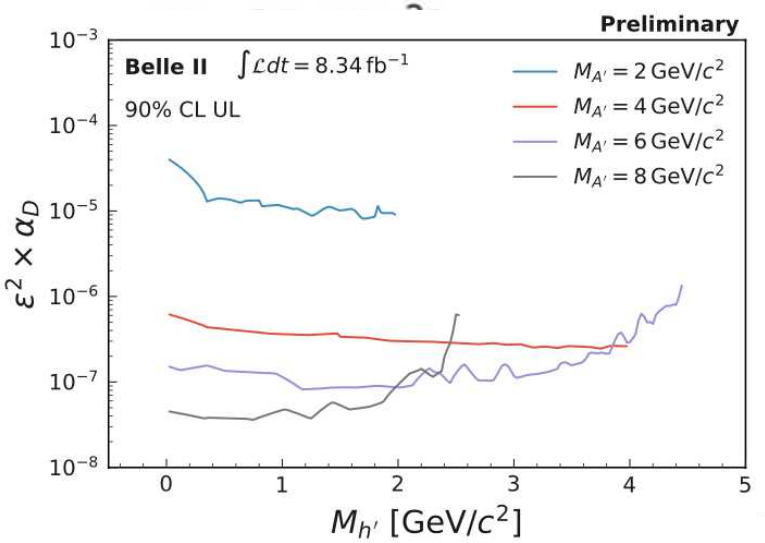
Dark sector (invisible h' + A')

- Two track trigger
- Identified muons with pT>0.1GeV/c
- Recoil 4-vector points into barrel calorimeter (ECL)
- No additional energy in the event



Backgrounds predominantly from (radiative) di-lepton events

- $\mu^+\mu^-(\gamma)$ 79%
- $\tau^+\tau^-(\gamma)$ 18%
- $e^+e^-\mu^+\mu^-$ 3%

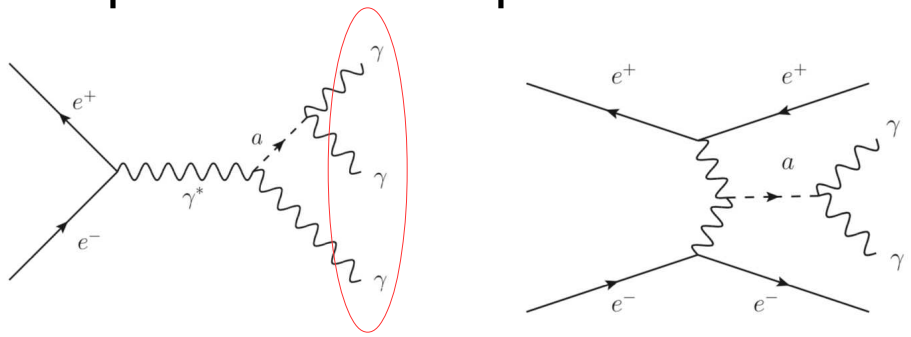


Axion-Like Particles

ALPs are pseudo-scalar particles that couple to bosons

- Unlike QCD axions, there is no specific relationship between coupling and mass

Consider case of coupling to photon. Production via “ALP-strahlung” and “photon fusion” processes

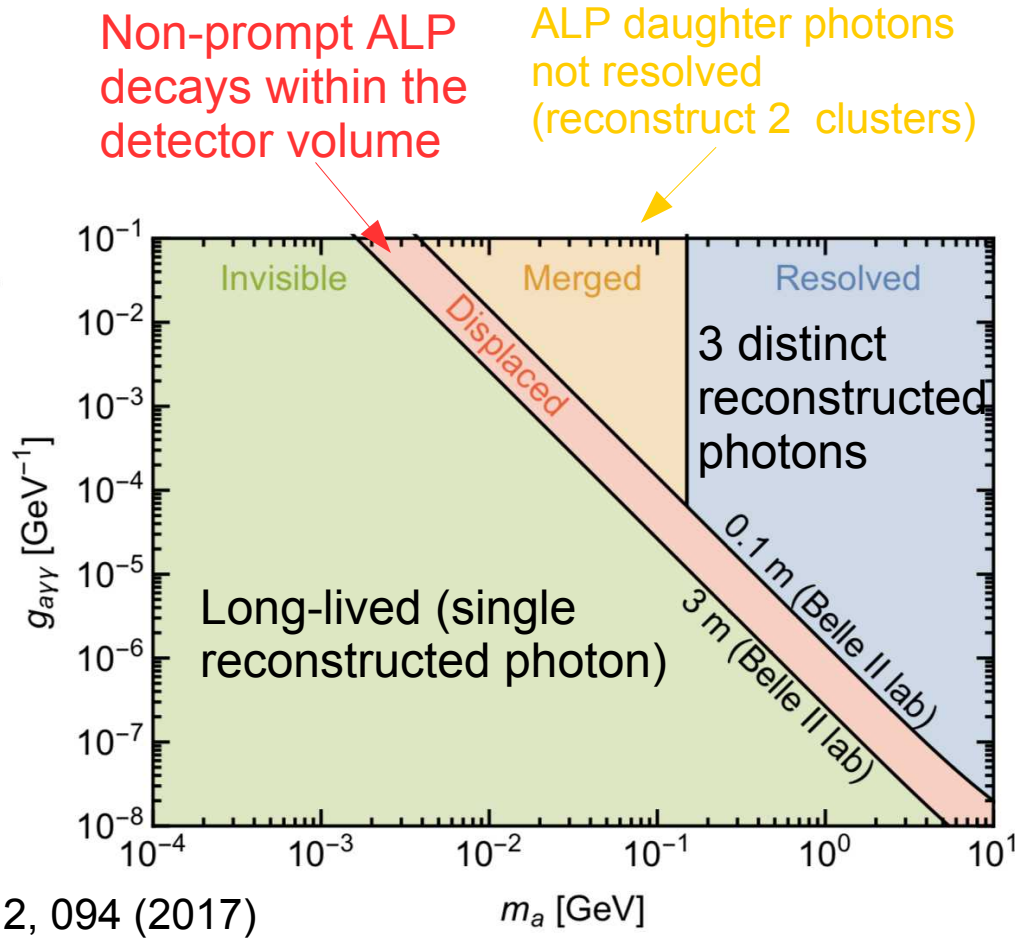


3γ final state

Lifetime depends on mass and coupling:

$$\tau \sim 1/m_a{}^3 g^2{}_{a\gamma\gamma}$$

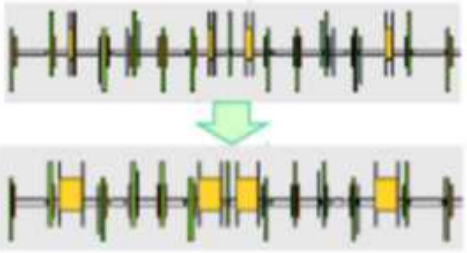
- Several distinct experimental signatures depending on value

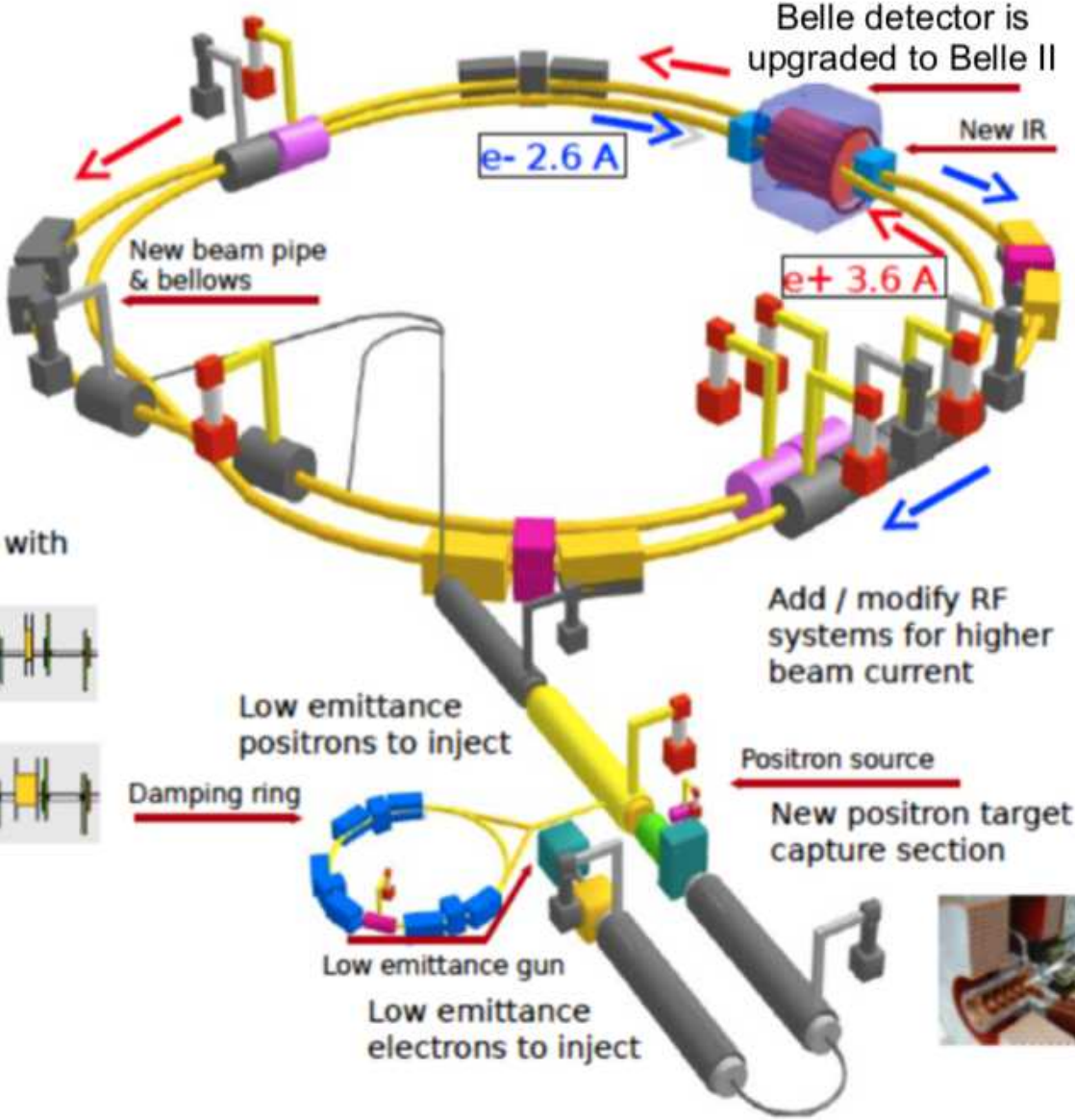


JHEP 1712, 094 (2017)

SuperKEKB

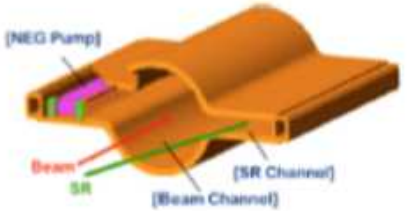
Replace short dipoles with longer ones (LER)





New superconducting /permanent final focusing quads near the IP

TiN-coated beam pipe with antechambers



Redesign the lattices of HER & LER to squeeze the emittance

Belle II Detector

Anticipate ~40x increased instantaneous luminosity, and greatly increased beam background rates

Very substantial "upgrades" to the original Belle detector:

- Replacement of beam pipe and redesign of entire inner detector (including vertex detectors and drift chamber)
- New quartz-bar Time-of-Propagation PID in barrel region
- Retain existing CsI(Tl) calorimeter crystals, but front-end electronics, feature extraction and reconstruction software entirely new
- Entirely new software framework and distributed computing environment