Recent Dark-Sector Results from Belle II

Steven Robertson
Institute of Particle Physics
&
University of Alberta

On behalf of the *Belle II* Collaboration

UCLA Dark Matter 2023
March 30, 2022

INSTITUTE OF
PARTICLE
PHYSICS

Belle II

Dark sectors

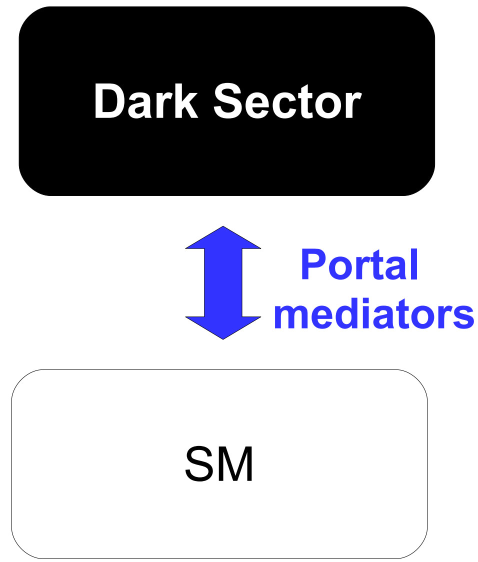
Dark matter may carry charges for non-SM gauge interactions, possibly acquiring mass via dark-sector Higgs etc.

- Effective Field Theory (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 (γ_D , **Z'**) — **Higgs portal** (**S**) — **Neutrino portal**



Electron-positron collider production mechanisms:

- Production of on-shell dark bosons via $e^+e^- \to \gamma Z'$ "**radiative**" and $e^+e^- \to f\,f\,Z'$ "**Z-strahlung**" processes
- Light dark-sector particles can be produced in **decays** of B and D mesons

Outline

Recent results:

- Invisible Z' in $e^+e^- \to \mu^+\mu^- Z'$ arXiv:2212.03066[hep-ex]
- $Z' / S \to \tau^+\tau^-$
- Long-lived spin–0 boson in $b \to s$ decays

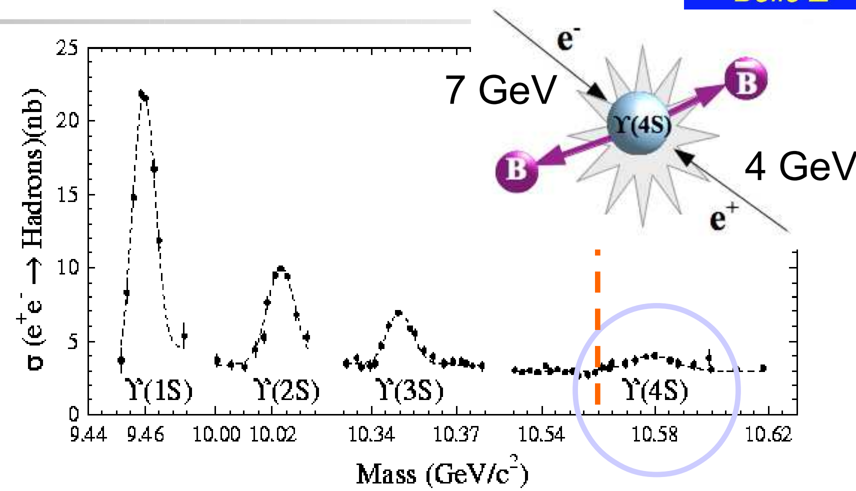
Additional results (not presented):

- $\tau^+ \to l^+\alpha$ (invisible scalar boson) arXiv:2212.03634[hep-ex]
- Dark Higgsstrahlung (invisible $h' + A'$) Phys.Rev.Lett. 130 (2023) 7, 071804

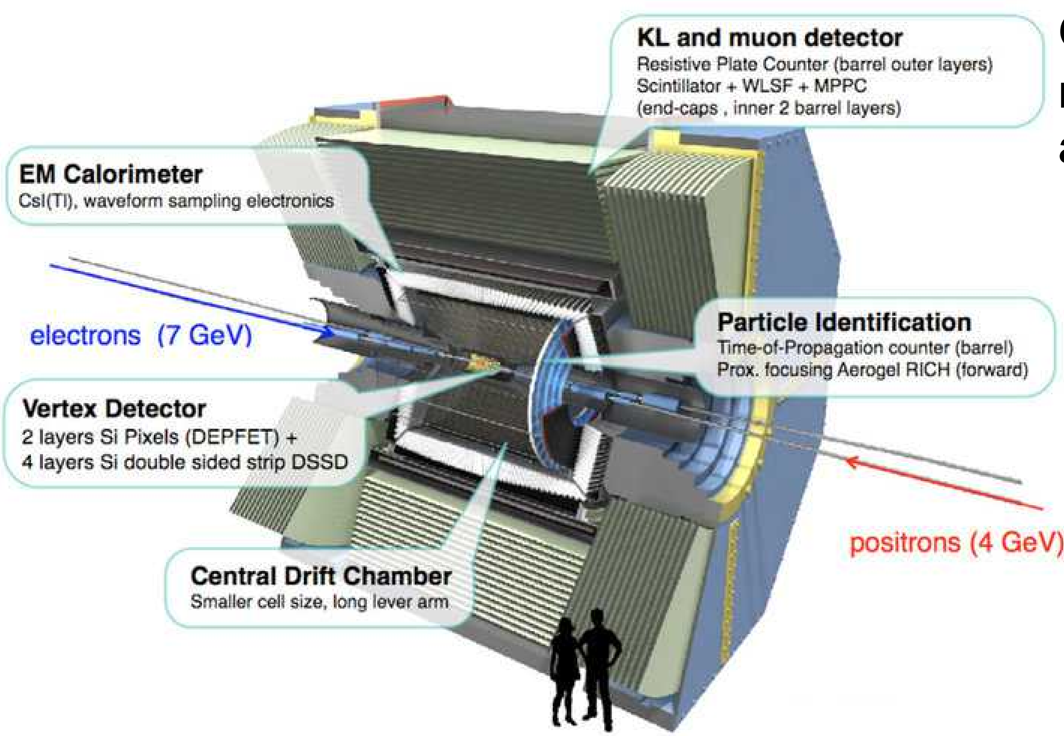
Belle II experiment

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
  - **~100 billion B mesons** in final data set
- Physics data taking began in 2019 – **current results based on < 1% of target data sample**



CUSB (https://inspirehep.net/experiments/1109659)



Optimized for tracking and B vertex reconstruction, K - π particle identification, and precision calorimetry

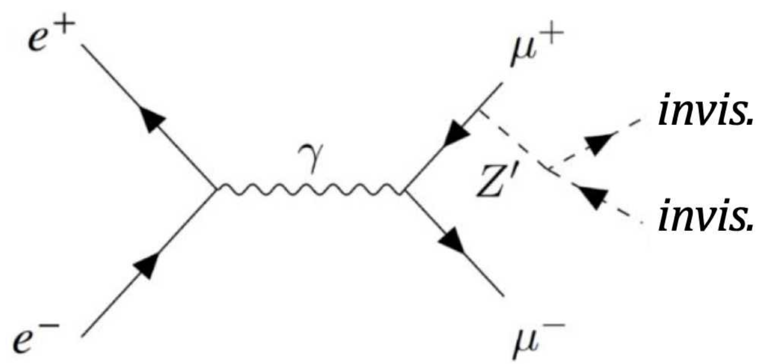
- **Clean** environment with large solid-angle detector coverage and good missing energy reconstruction
- **Inclusive trigger** (N_{tracks}>3) + dedicated low-multiplicity triggers
- Potential to **reconstruct displaced vertices** in $\sim 1\ \mathrm{mm} < c\tau < \sim 10\ \mathrm{cm}\ (\sim 100\ \mathrm{cm})$, with $c\ \ > \sim 3\ \mathrm{m}$ being “missing energy”

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

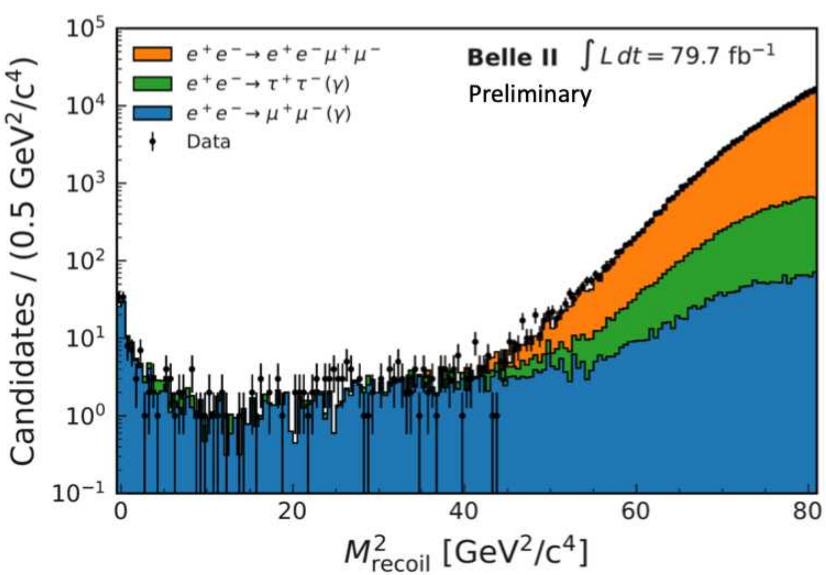
$Z' \to$ invisible

$L_\mu - L_\tau$ 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
- $Z' \to \nu\bar{\nu}$ process (mostly relevant for $m_{Z'} < 2m_\mu$). More generally Z' could be mediator to dark sector, coupling to dark χ via $Z' \to \chi\bar{\chi}$



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



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

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

Z' reconstructed in recoil of di-muon pair

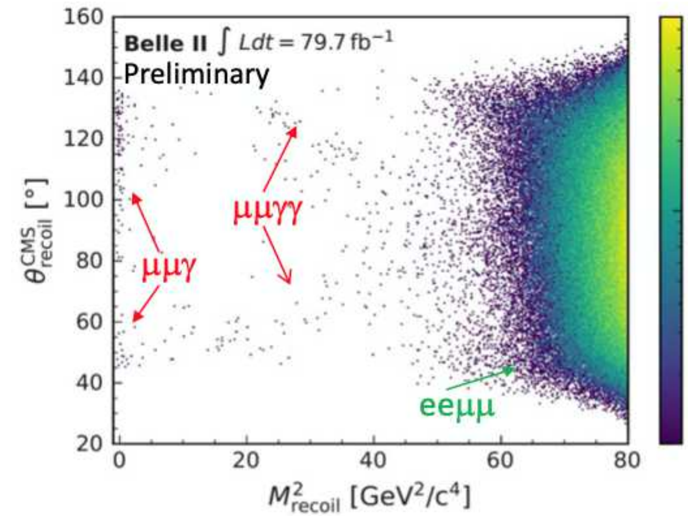
- 2-track trigger w/ muon $p_T^\mu > 0.4$ GeV/c
- No extra energy (γ,π^0) present in the event

$Z' \rightarrow$ invisible

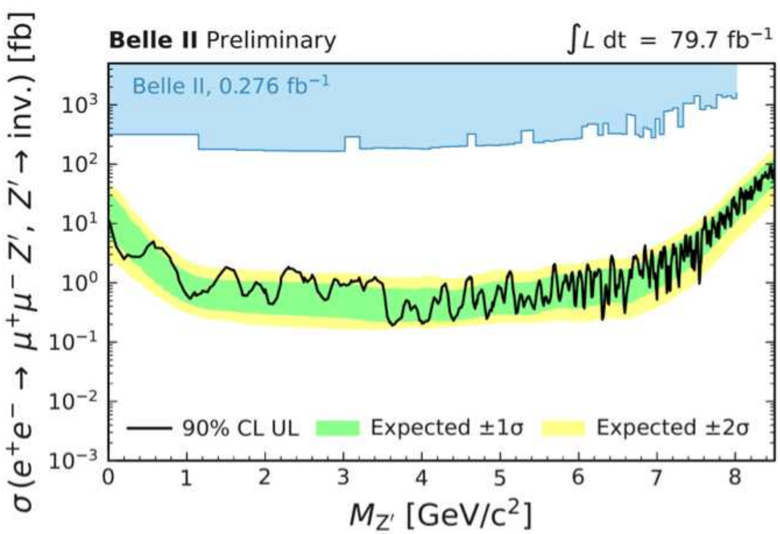
Submitted to PRL
arXiv:2212.03066
Based on 79.7 fb^{-1}

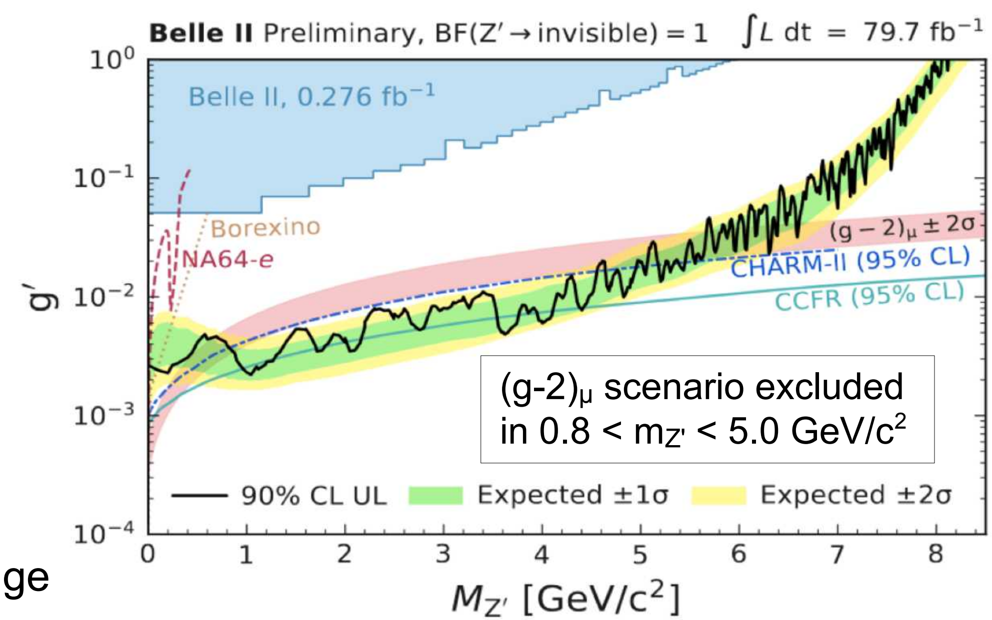
Backgrounds originate from QED processes which mimic the $\mu^+\mu^-$ + missing energy final state, typically due to detector acceptance effects:

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



Neural Net based on kinematic variables optimized for background suppression





$(g\text{-}2)_\mu$ scenario excluded in $0.8 < m_{Z'} < 5.0$ GeV/c^2

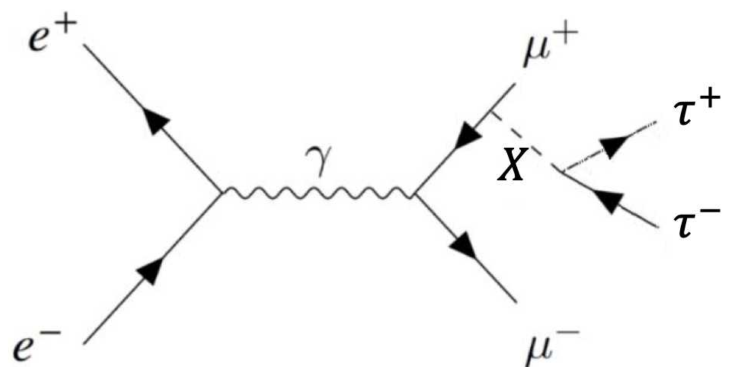
No significant excess seen within signal mass range

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

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

Preliminary
Based on 189 fb^{-1}

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



where $\mathrm{X} = Z'$ or S

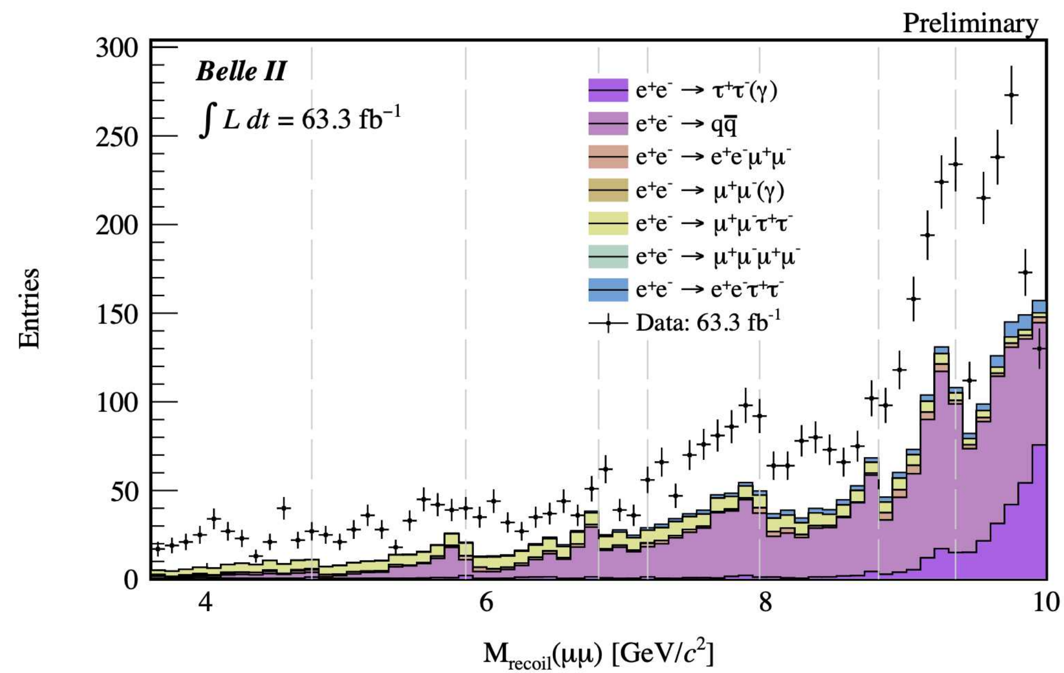
- Z' or (leptophilic) scalar S

4 - track signal topologies:

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

- **Search for a $\tau^+\tau^-$ resonance in $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$**
- Missing mass signature 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



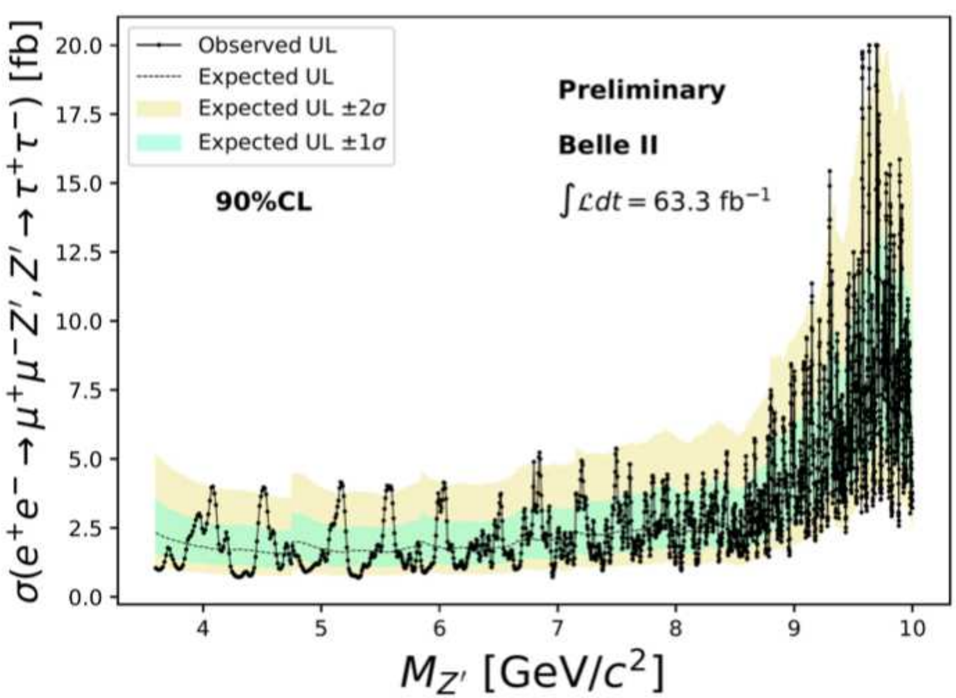
Backgrounds underestimated in simulation due to known missing contributions

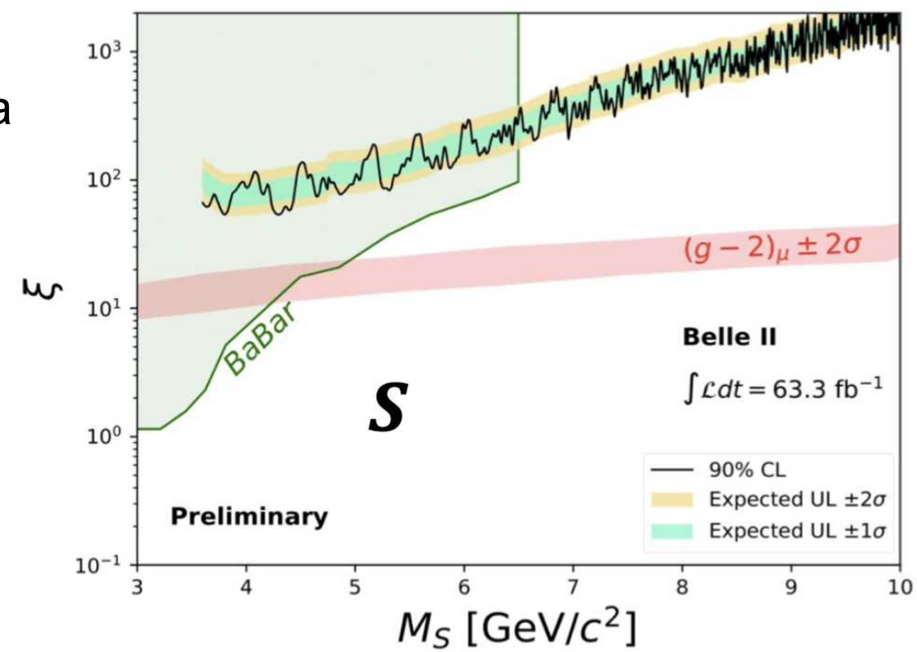
$Z', S \to \tau^+\tau^-$

Preliminary
Based on 189 fb^{-1}

Signal extracted as fits to the $\mu^+\mu^-$ recoil mass spectrum

- "Bump hunt" for a narrow peak above a smoothly varying background
- No significant excess observed





90% CL limits set on the Z' production cross section and scalar couplings

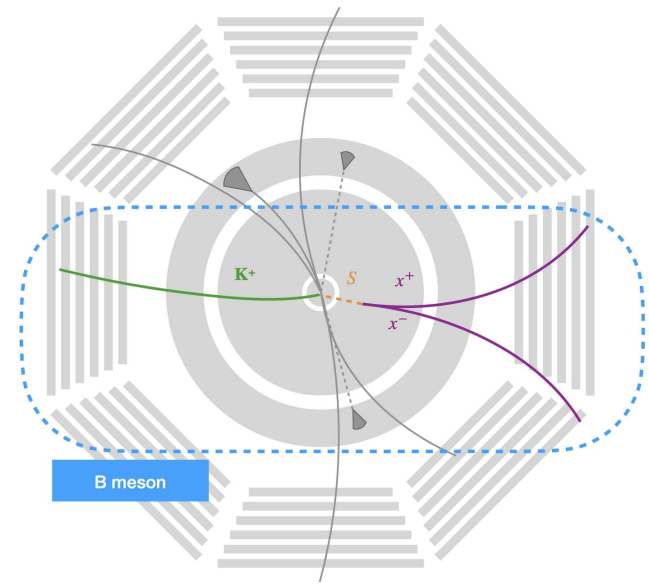
- First constraints on scalar S for $m_S > 6.5$ GeV/c^2

Long-lived spin-0 boson in $b \rightarrow s$ transitions

$B \to KS$

Many "new physics" scenarios include a light scalar (S) that mixes with Standard Model Higgs boson

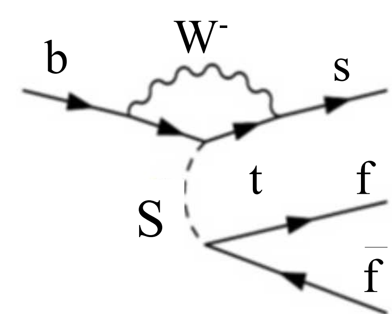
- Singlet field ϕ which mixes with SM Higgs with mixing angle θ
- If this field couples to dark sector χ, then **S can act as a "scalar portal" to dark sector**



For m_S below the B meson mass decays to $2m_\chi > m_S$ to yield correct relic density

- Therefore $S \to$ SM particles
- For small mixing angle, S is long-lived

S can be produced in $b \to s$ flavour changing neutral current processes by coupling to heavy intermediate particles (e.g. t quarks)



- Experimental signature would be a **$B \to KS$** with a reconstructed **displaced S decay vertex**

$B \to KS$

Preliminary
Based on 189 fb^{-1}

Eight exclusive decay B modes:

$$B^+ \to K^+ S$$
$$B^0 \to K^{*0} S \quad (K^{*0} \to K^+\pi^-)$$

where

$$S \to e^+e^-,\ \mu^+\mu^-,\ \pi^+\pi^-,\ K^+K^-$$

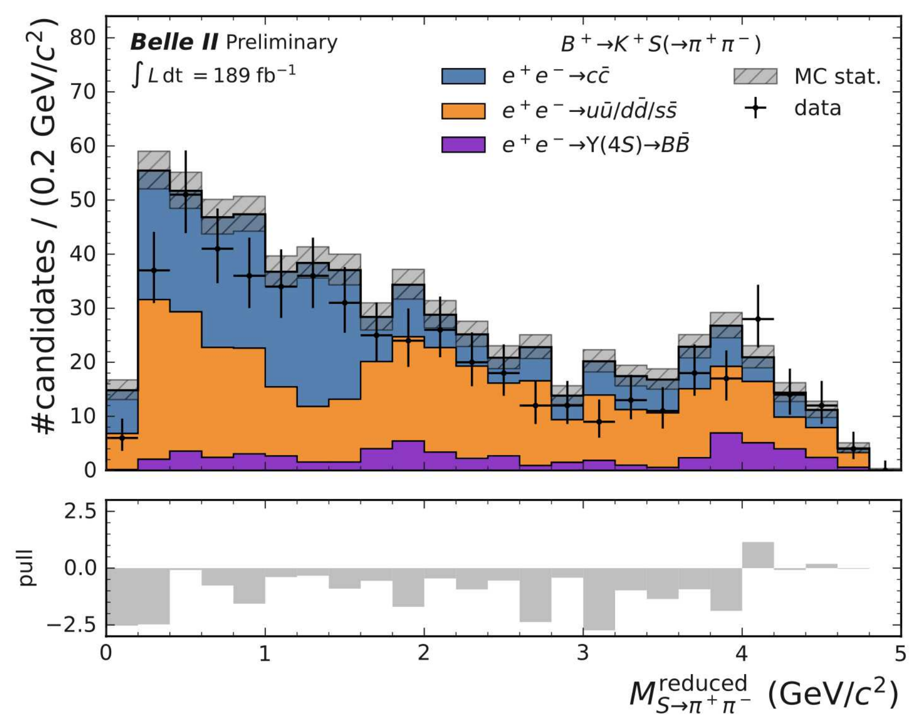
- No missing particles; B meson is fully reconstructed

Require S candidate vertex to be "significantly" displaced from primary interaction vertex

- LLP performance validated using K_S^0 control samples
- K_S^0 mass region vetoed to suppress SM backgrounds

- Exploit B decay kinematics to ensure clear selection of signal candidates
- Background primarily arise from $e^+e^- \to q\bar{q}$ combinatorial sources

Perform a "bump hunt" in the S candidate reduced mass:

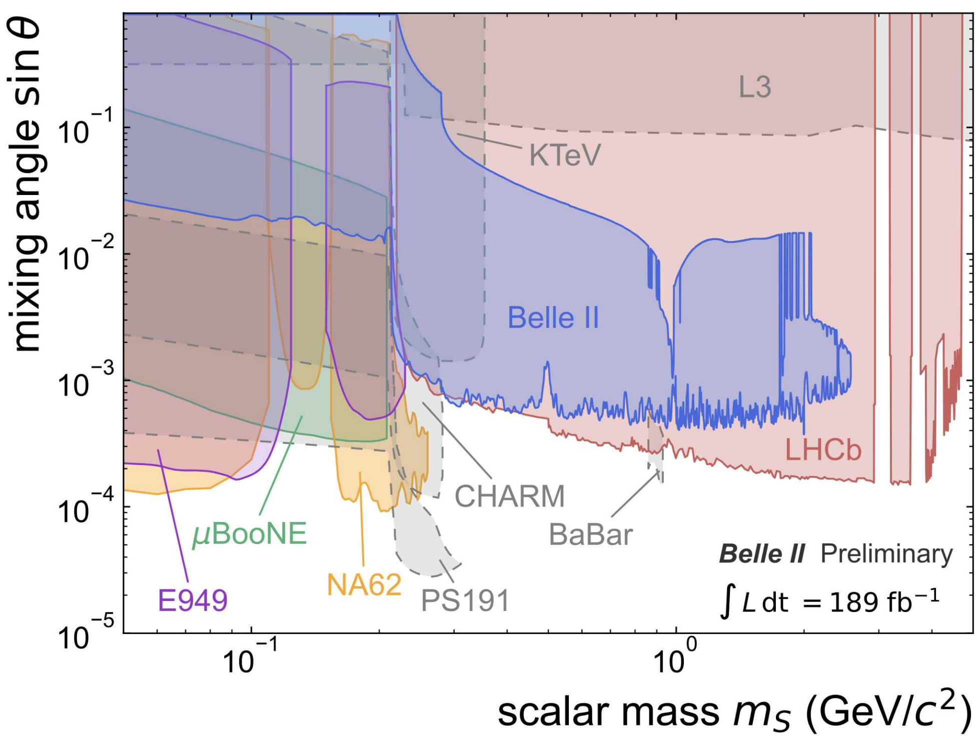


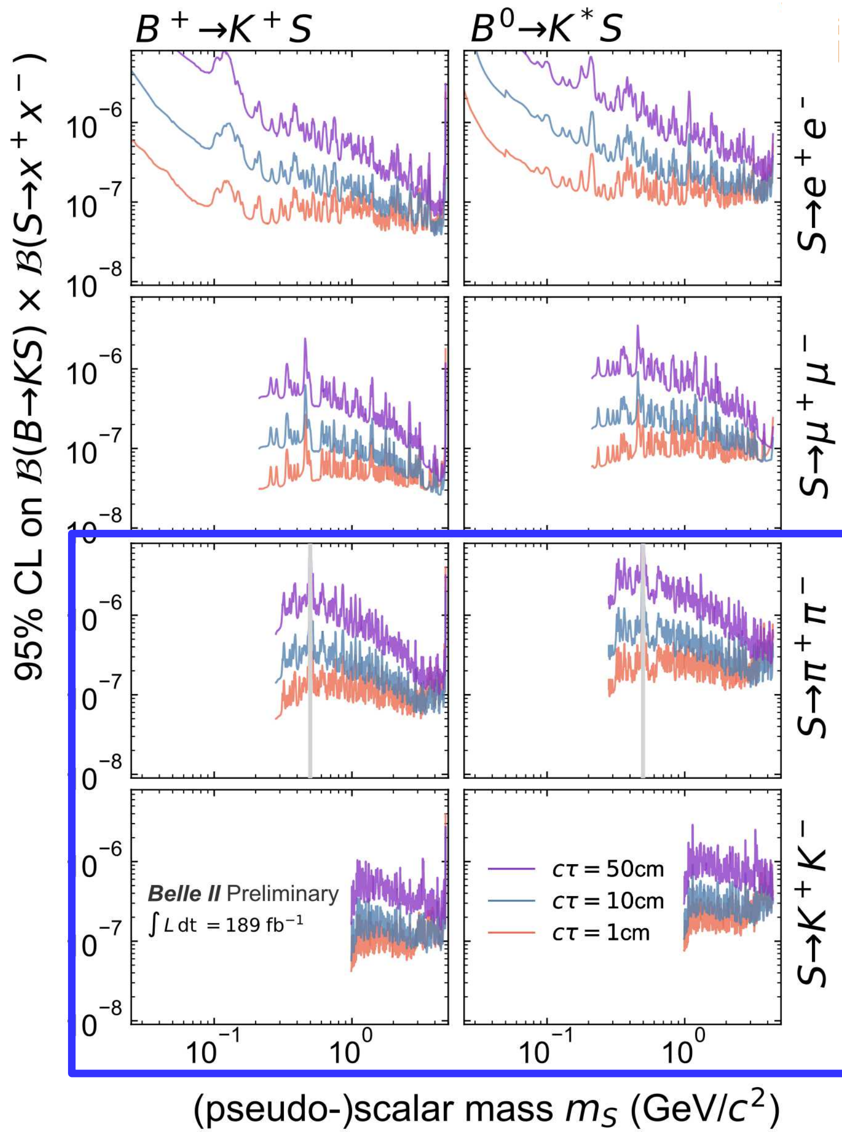
B → KS

Preliminary
Based on 189 fb^{-1}

Probe S lifetimes in range 0.001 < cτ < 400 cm

- Scalar mass sensitivity depends on S decay mode
- Model independent limits on LLP decay branching fractions for each decay mode
- Interpretation as a dark scalar S :
  (PBC BC4) Phys. Rev. D 101, 095006 (2020)
  J. Phys. G: Nucl. Part. Phys. 47 010501





First results on hadronic modes!

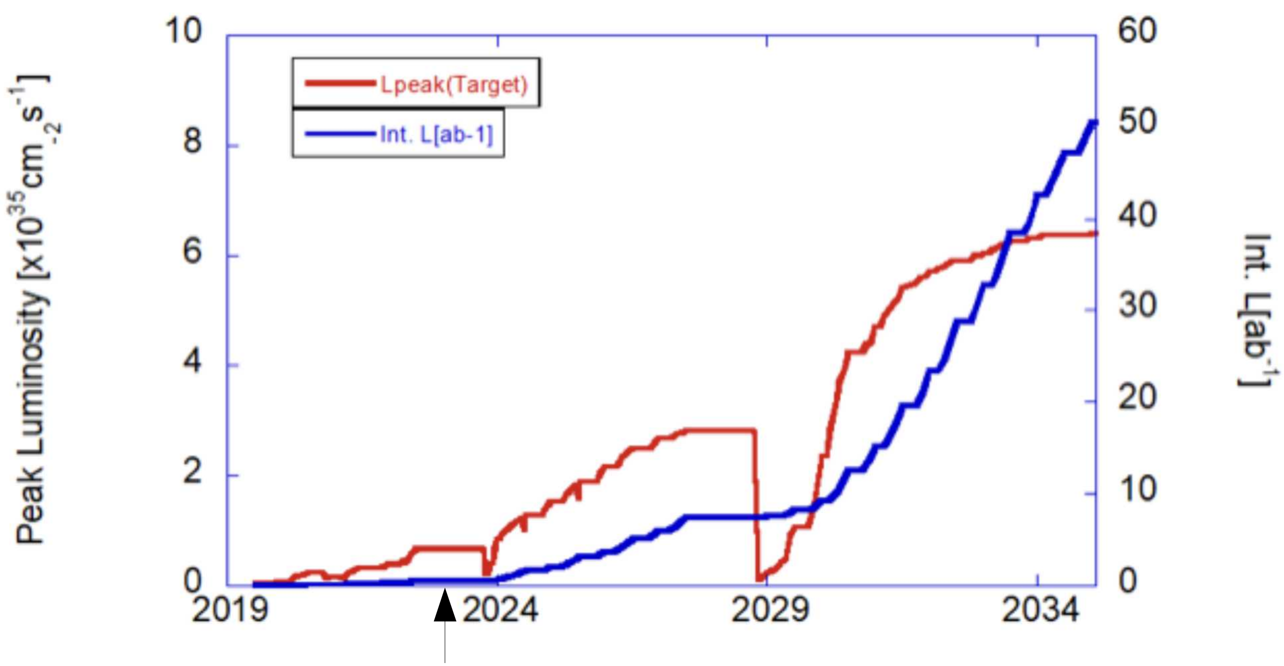
Prospects

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 searches for new physics with early Belle II data
- Interesting and competitive sensitivity in a variety of dark sector searches with current data set; very active ongoing program!

Data collection and physics program is just beginning!

- Look forward to new results with world's largest B Factory data set

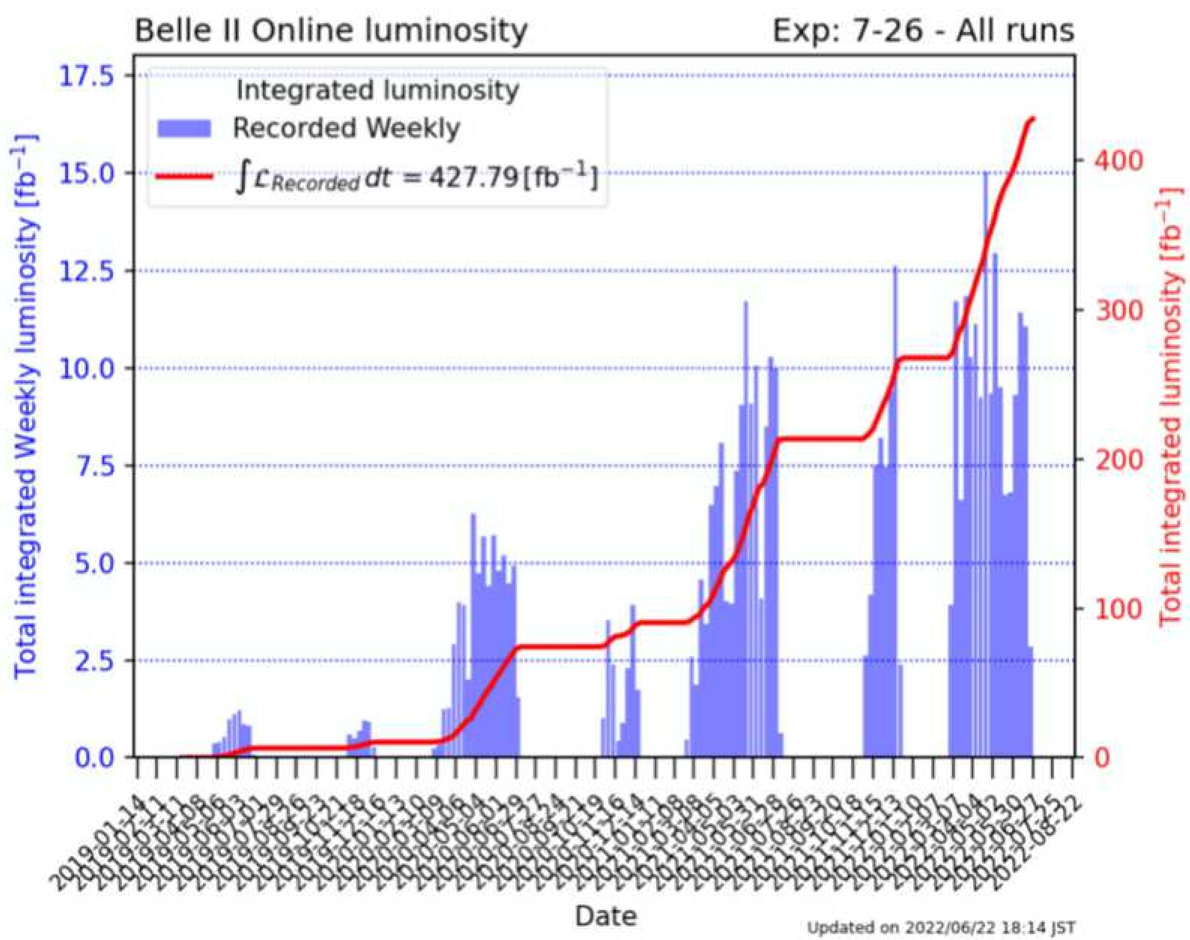


Additional material

Belle II luminosity

First Belle II physics data recorded in 2019

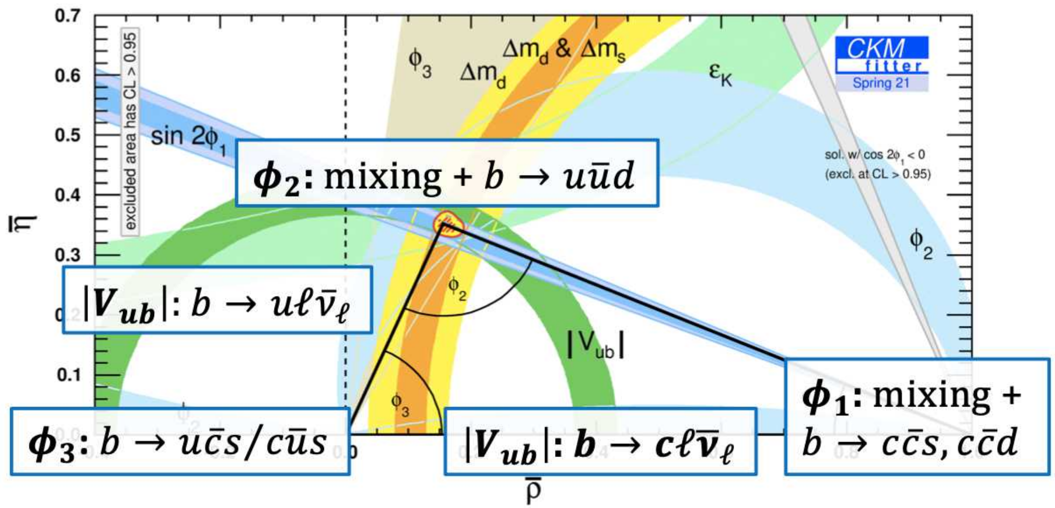
- Total integrated luminosity of 362 fb^{-1} at $\Upsilon(4S)$
- 42 fb^{-1} recorded 60 MeV below $\Upsilon(4S)$ ("offpeak")
- 19 fb^{-1} at 10.8 GeV for exotic hadron studies

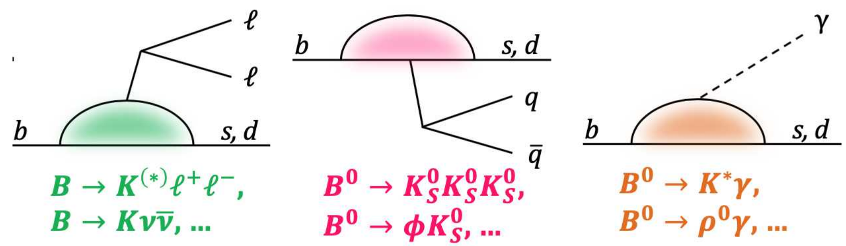


Belle II physics program

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.

Dark photon

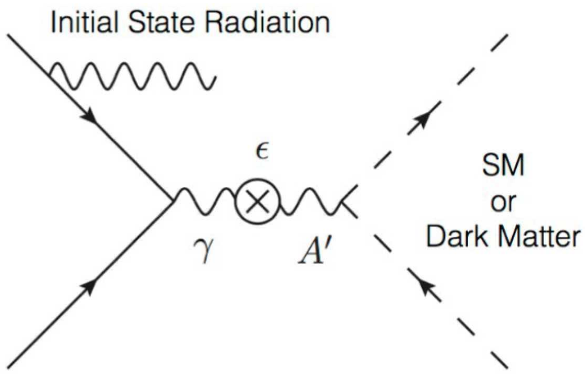
P. Fayet, Phys. Lett. B 95, 285 (1980)
P. Fayet Nucl. Phys. B 187, 184 (1981)
B. Holdom, Phys. Lett. B 166, 196 (1986)

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.

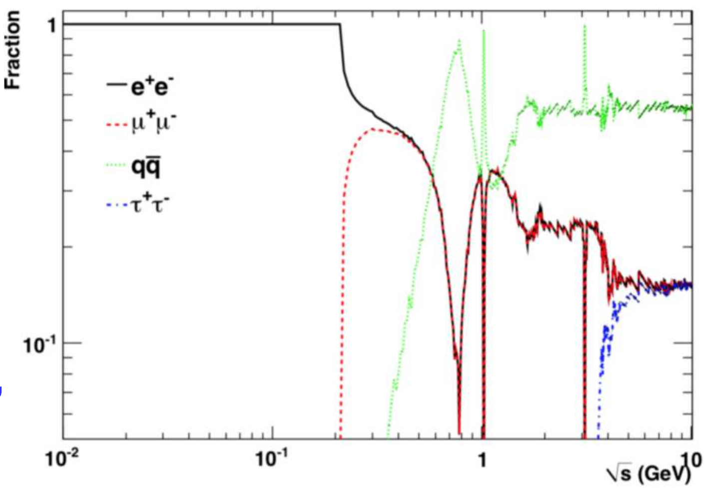
Kinetic mixing: $$\frac{1}{2}\epsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$$

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

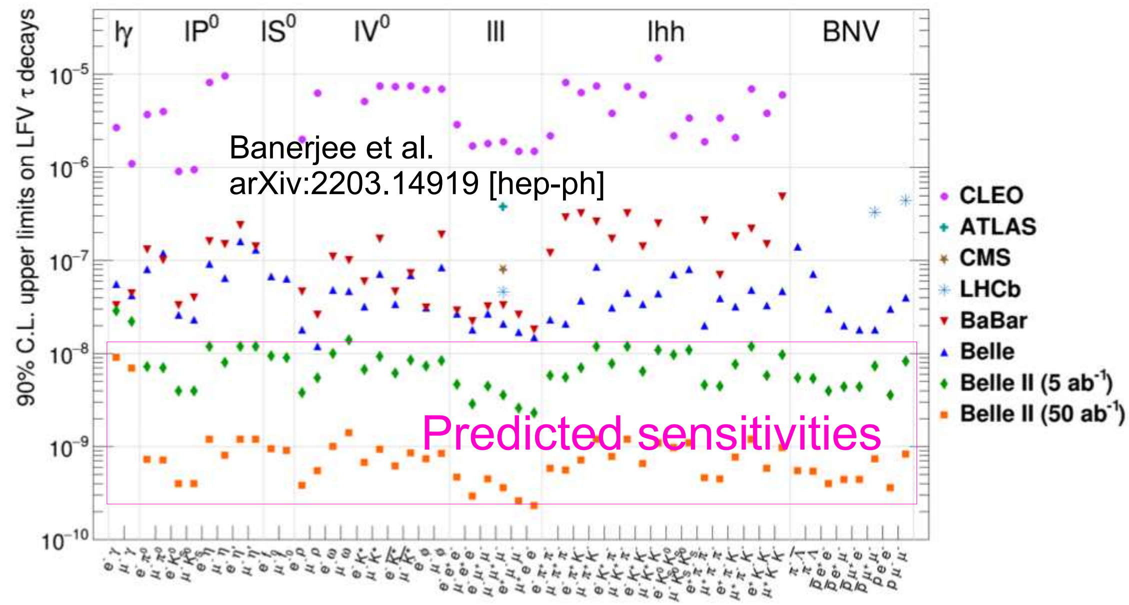
$$\tau^{+} \rightarrow l^{+}\alpha$$

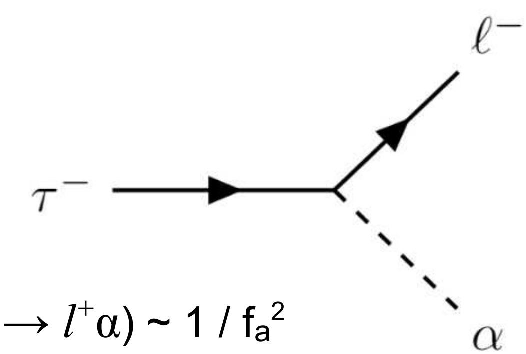
(invisible scalar boson)

$\tau^+ \rightarrow l^+\alpha$ (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

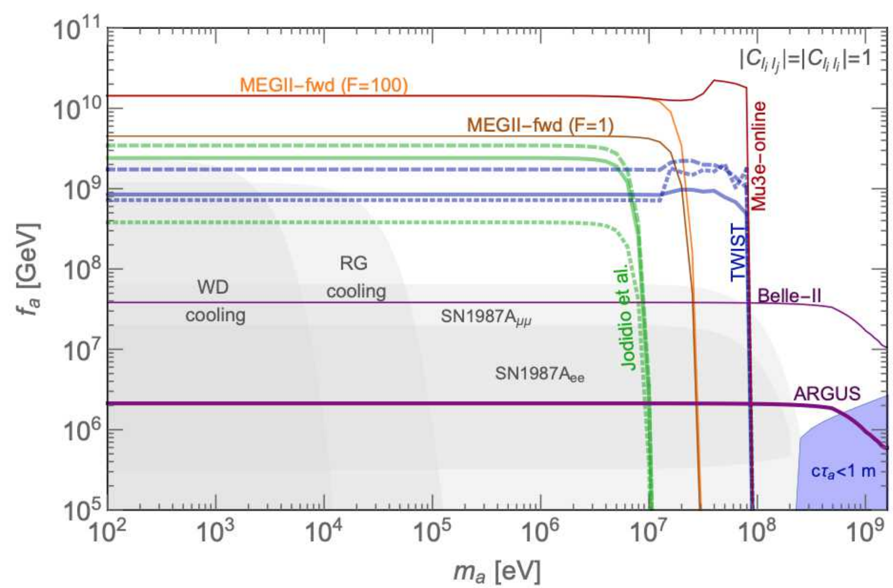




$B(\tau^+ \rightarrow l^+\alpha) \sim 1 / f_a^2$

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

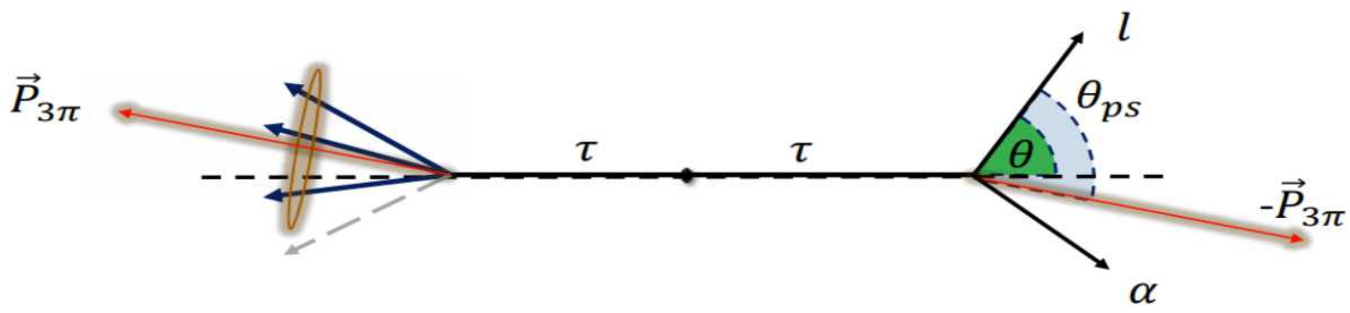
- Long-lived α does not interact in detector



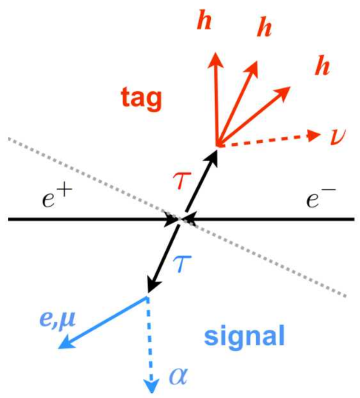
Calibbi et al., JHEP09(2021)173

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

Accepted by PRL
arXiv:2212.03634
Based on 62.8 fb^{-1}

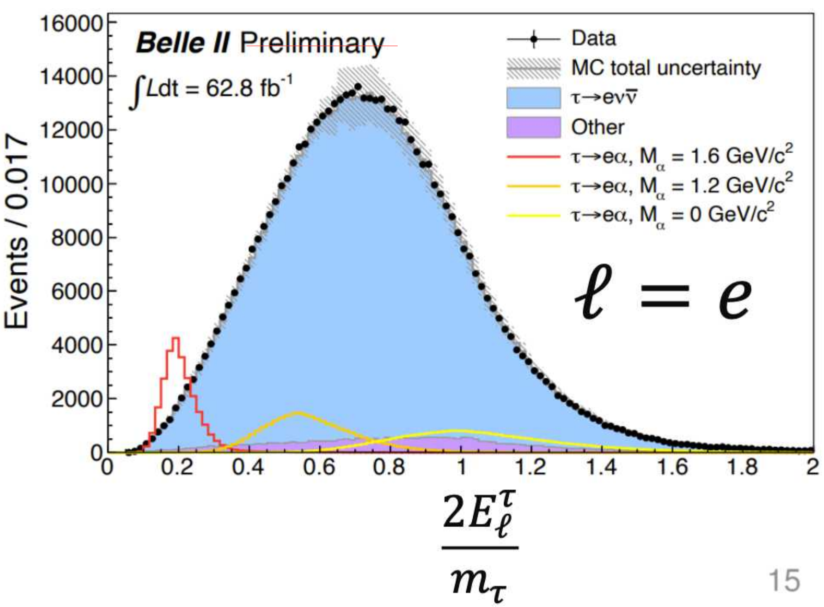


At B factories, $\tau^+\tau^-$ pairs are produced back to back and boosted:



- 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 qq, di-lepton and 4-fermion sources

- Signal is similar to $\tau^+ \to l^+\nu\nu$, 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:

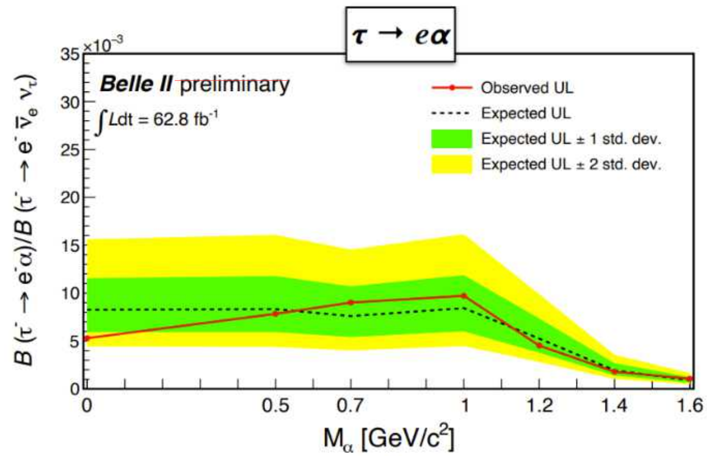


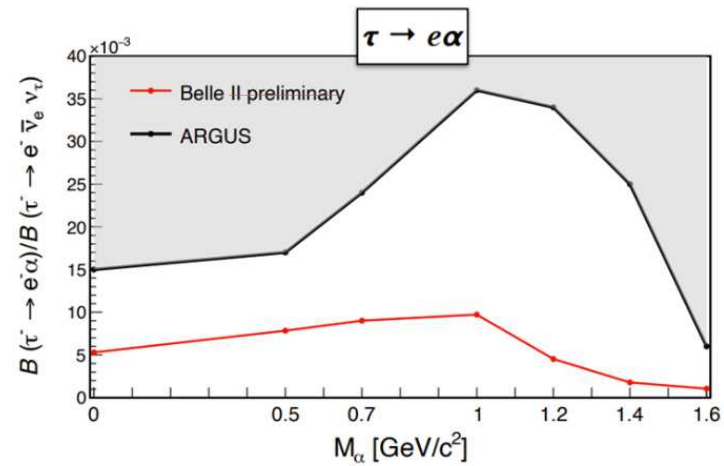
$\tau^+ \to l^+\alpha$ (invisible boson)

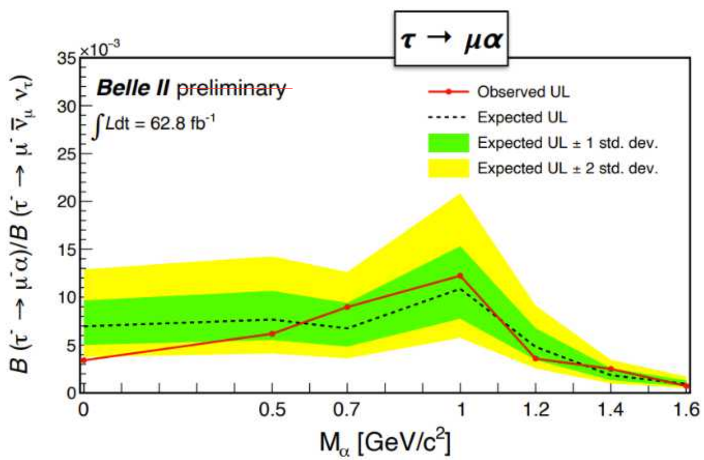
No significant excess seen in either e or μ mode:

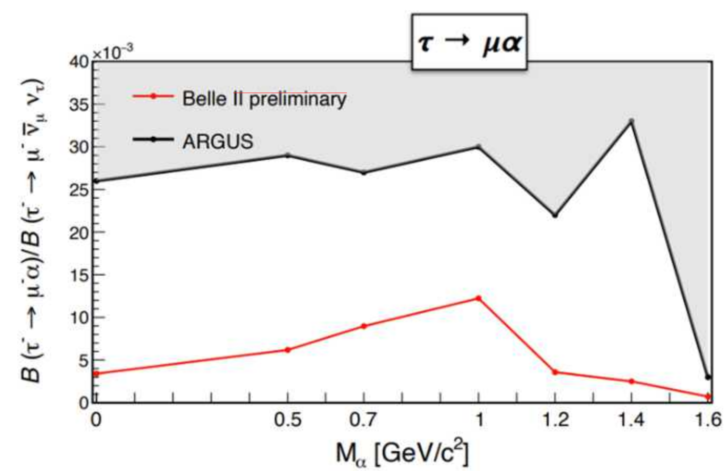
- CLs method to determine 95% C.L. upper limits on branching fraction

Accepted by PRL
arXiv:2212.03634
Based on 62.8 fb^{-1}









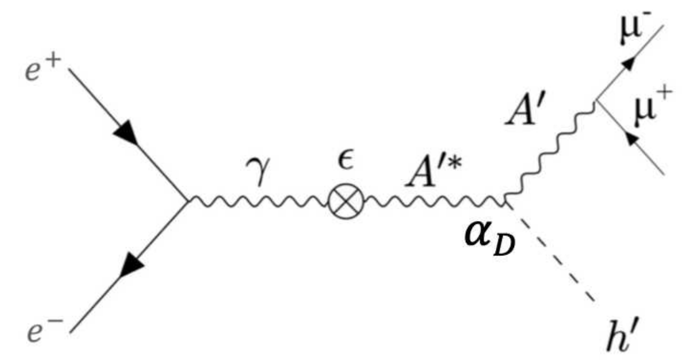
Substantial improvement over previous limits ARGUS Collaboration Z. Phys. C 68, 25 (1995)

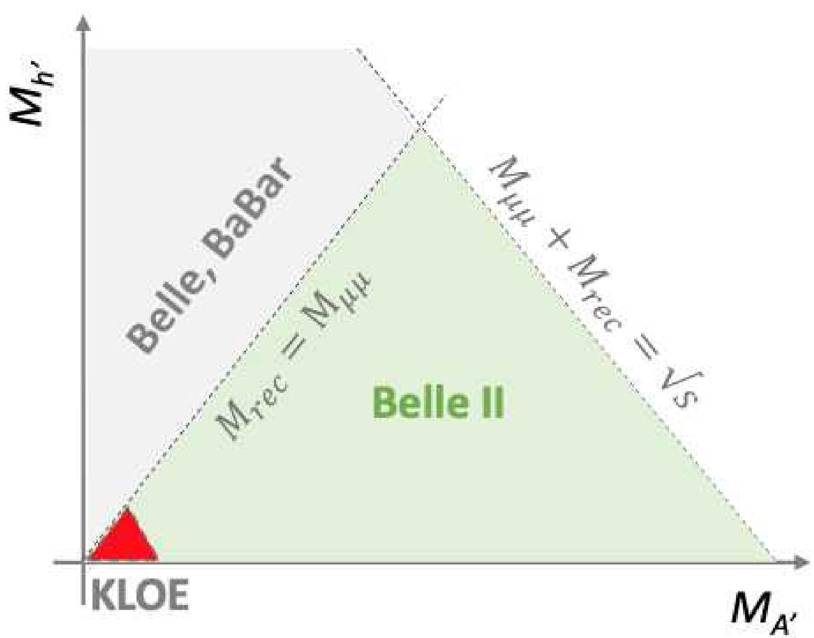
Dark Higgsstrahlung

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

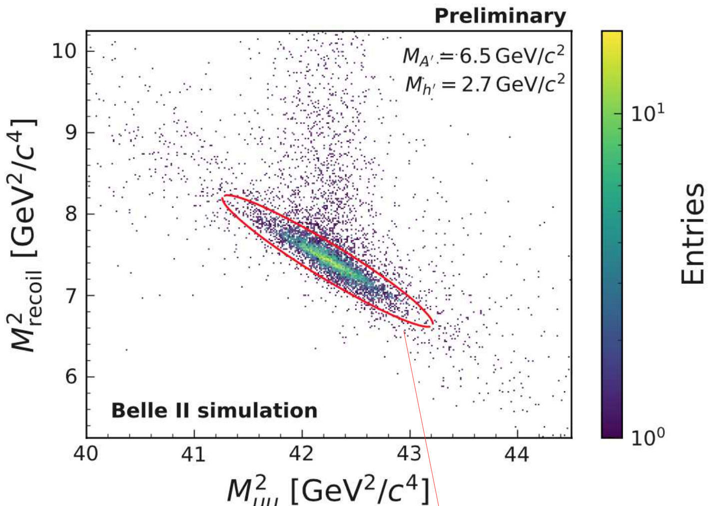
$M_{h'} < M_{A'}$ **This search**

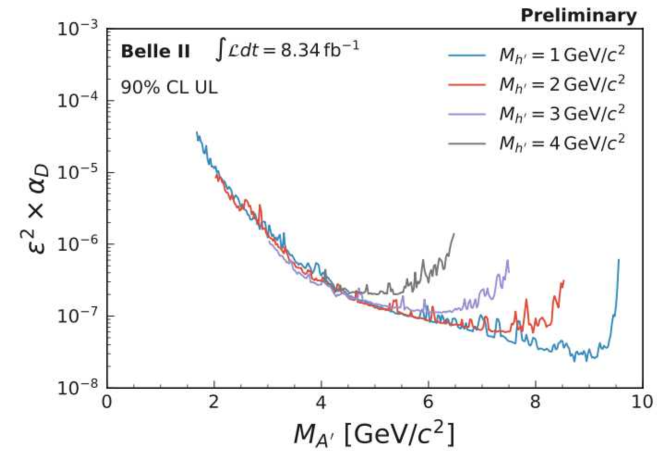
- h' is long-lived (i.e. undetected)
- Experimental signature is 2D peak in $m_{A'} = m_{\mu\mu}$ and $m_{h'} = m_{recoil}$

Dark sector (invisible h' + A')

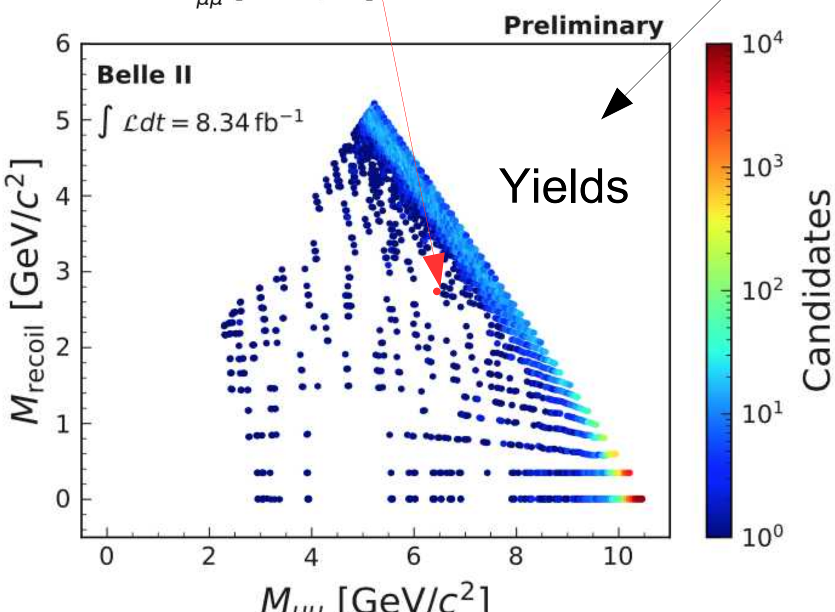
$e^+ e^- \rightarrow \mu^+ \mu^- + E_{miss}$

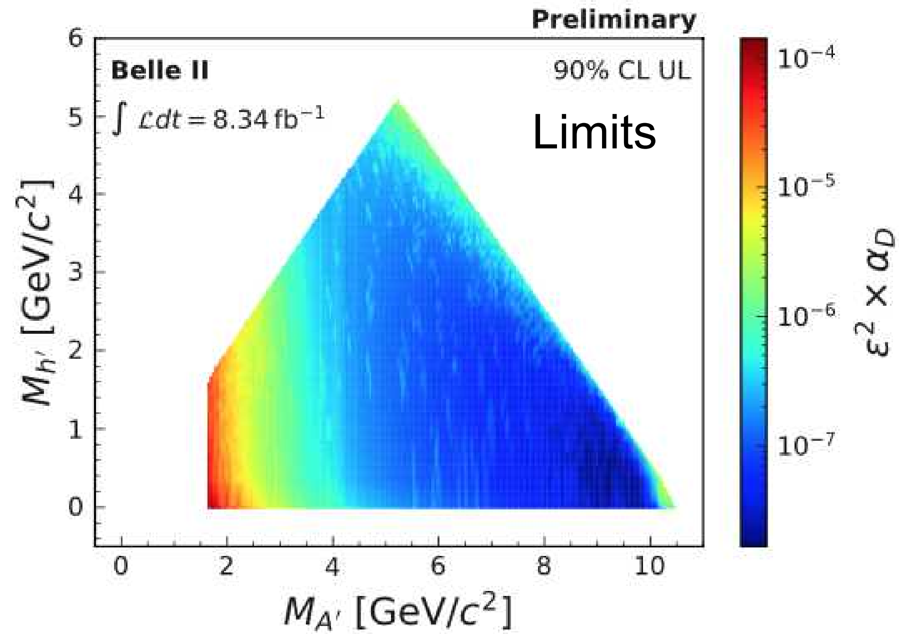
Phys.Rev.Lett. 130 (2023) 7, 071804
Based on 8.34 fb^{-1}





Scan ~9000 overlapping 2D elliptical mass windows

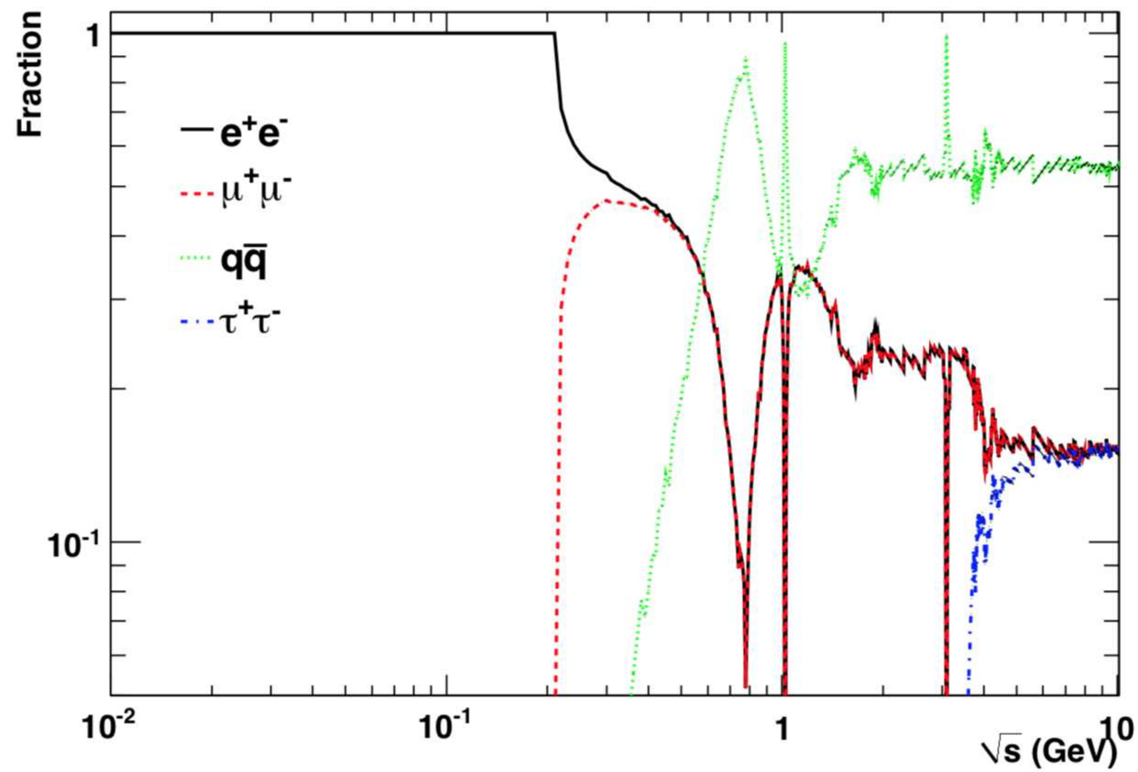




Dark photon

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

- Models are highly predictive:

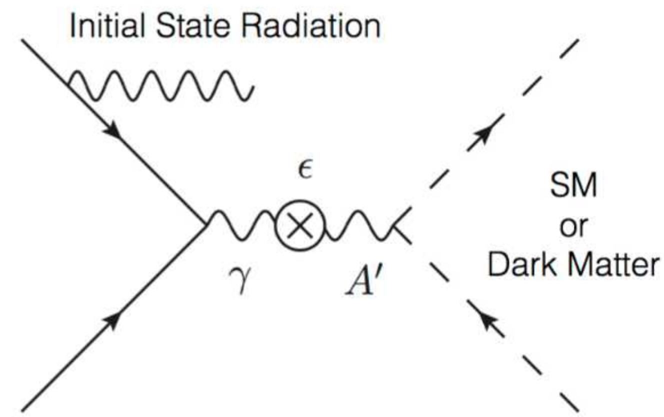


Experimentally, the important feature is a reconstructable narrow A' resonance in a clearly defined topology, i.e a "bump hunt"

- 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

Dark Forces

Dark matter interactions mediated by new U(1) gauge boson A' “dark photon” which can mix with SM photon



- Search for decay of $e^+e^- \to \gamma A'$ via $A' \to \chi\bar{\chi}$ or into SM particles
  - “visible” $A' \to l^+l^-$, or
  - “Invisible” A' decays, with A' mass determined from photon energy

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

Can potentially be detected via one of a number of “portals” coupling the Dark Sector to the SM:

Vector Portal → *Dark Photon, Z'*
Scalar Portal → *Higgs/Dark Scalars*
Pseudoscalar Portal → *Axion-like Particles*
Neutrino Portal → *Sterile Neutrinos*

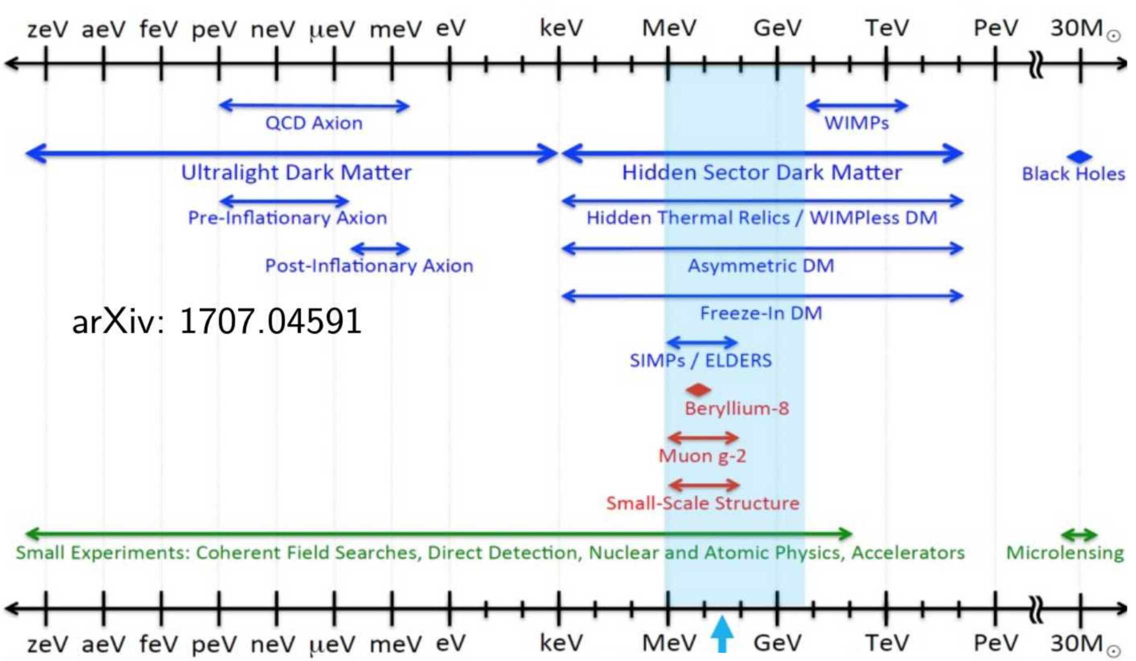
- Sensitivity studies performed in the context of “Belle II physics book” (B2TiP): arXiv:1808.10567 [hep-ex]; ALP sensitivity studies: arXiv:1709.00009[hep-ph]

Typically, these are narrow resonance (“bump hunt”) searches in low-multiplicity data samples

Dark Sector @ B Factories

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



B Factory direct searches