Latest Results on Dark Sector and τ Physics from Belle II

Petar Rados (HEPHY)
on behalf of the Belle II Collaboration

Moriond QCD
La Thuile, Italy
March 23, 2022

HEPHY
INSTITUTE OF
HIGH ENERGY PHYSICS

EUROPEAN COMMISSION

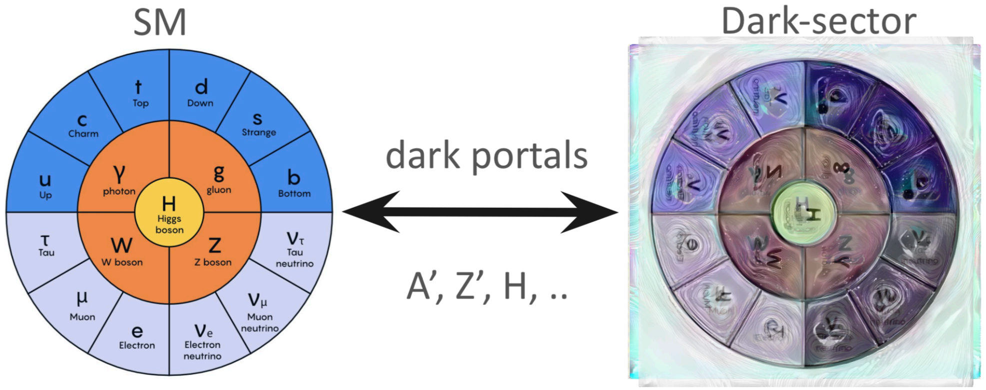
erc
European
Research
Council

Belle II

since 1966
Rencontres
de Moriond

Light Dark Matter

- B-factories have a unique and world-leading reach in searches for mediators particles and DM at the MeV-GeV scale.
- e.g. a massive dark photon (A') that obtains its mass through SSB introducing a dark Higgs boson (h')

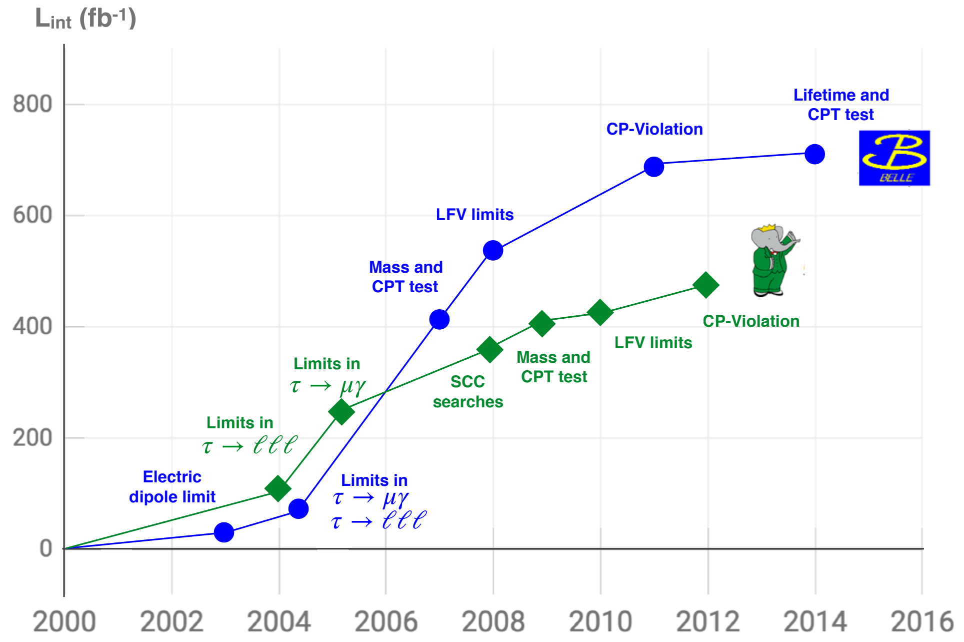


This talk will focus on a new result shown for the first time at Moriond 2022:

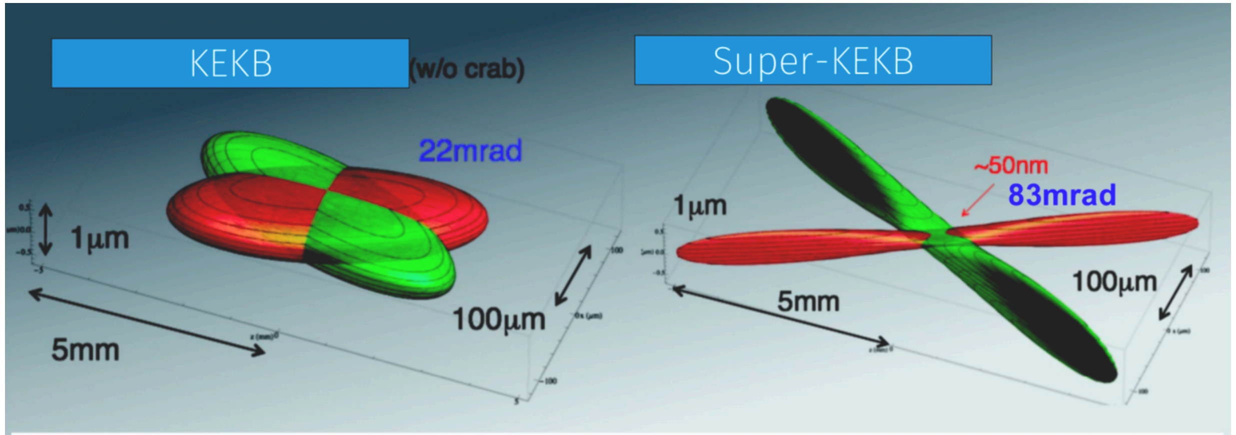
Search for the simultaneous production of a dark photon and dark Higgs in the dark Higgsstrahlung process.

Tau Lepton Physics

- B-factories are also τ-factories!
- Belle II will deliver the world's largest sample of τ- pair events, enabling a rich program of precision SM measurements and direct searches for new physics.

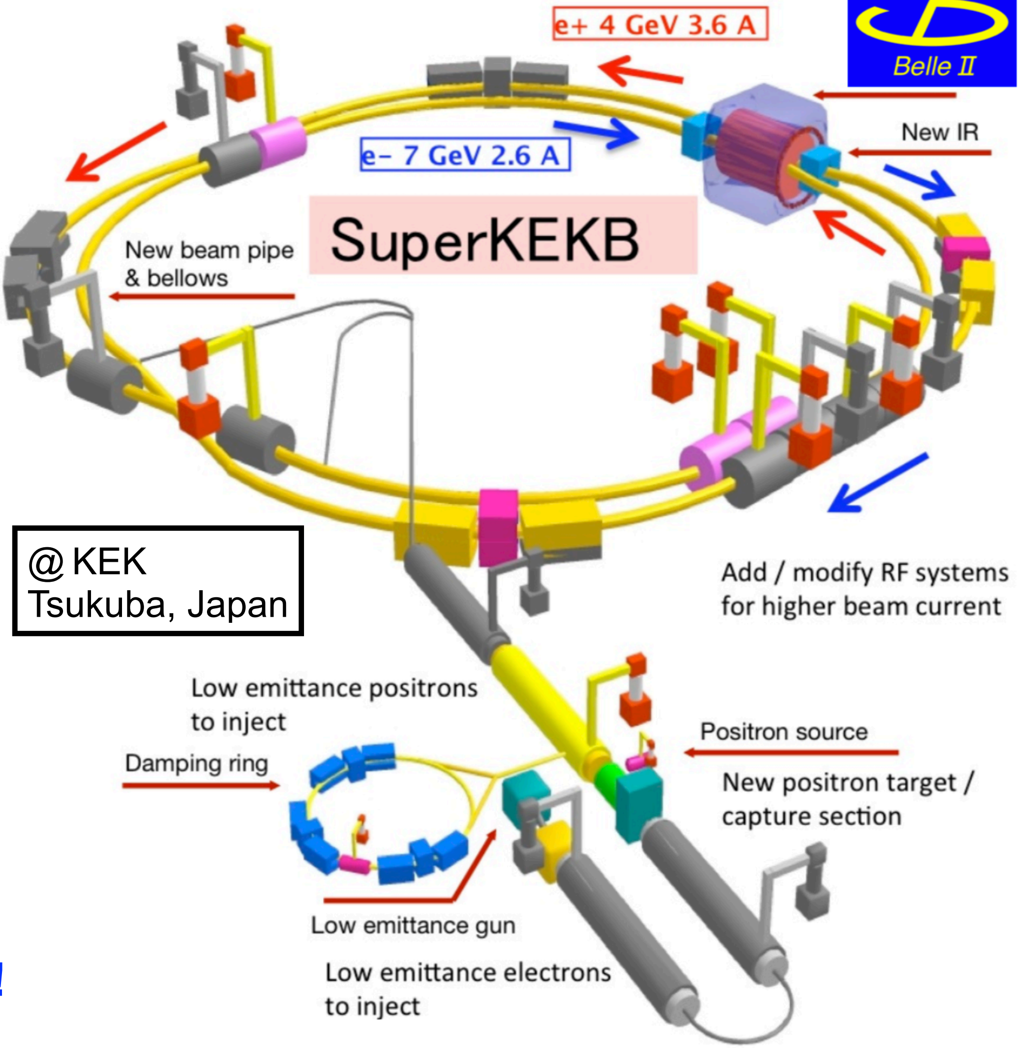


- Next generation B-factory: $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$, $\sqrt{s} \approx 10.58$ GeV
  + rich program of tau, dark sector and other low-multiplicity physics



	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	60 x 10^{34}

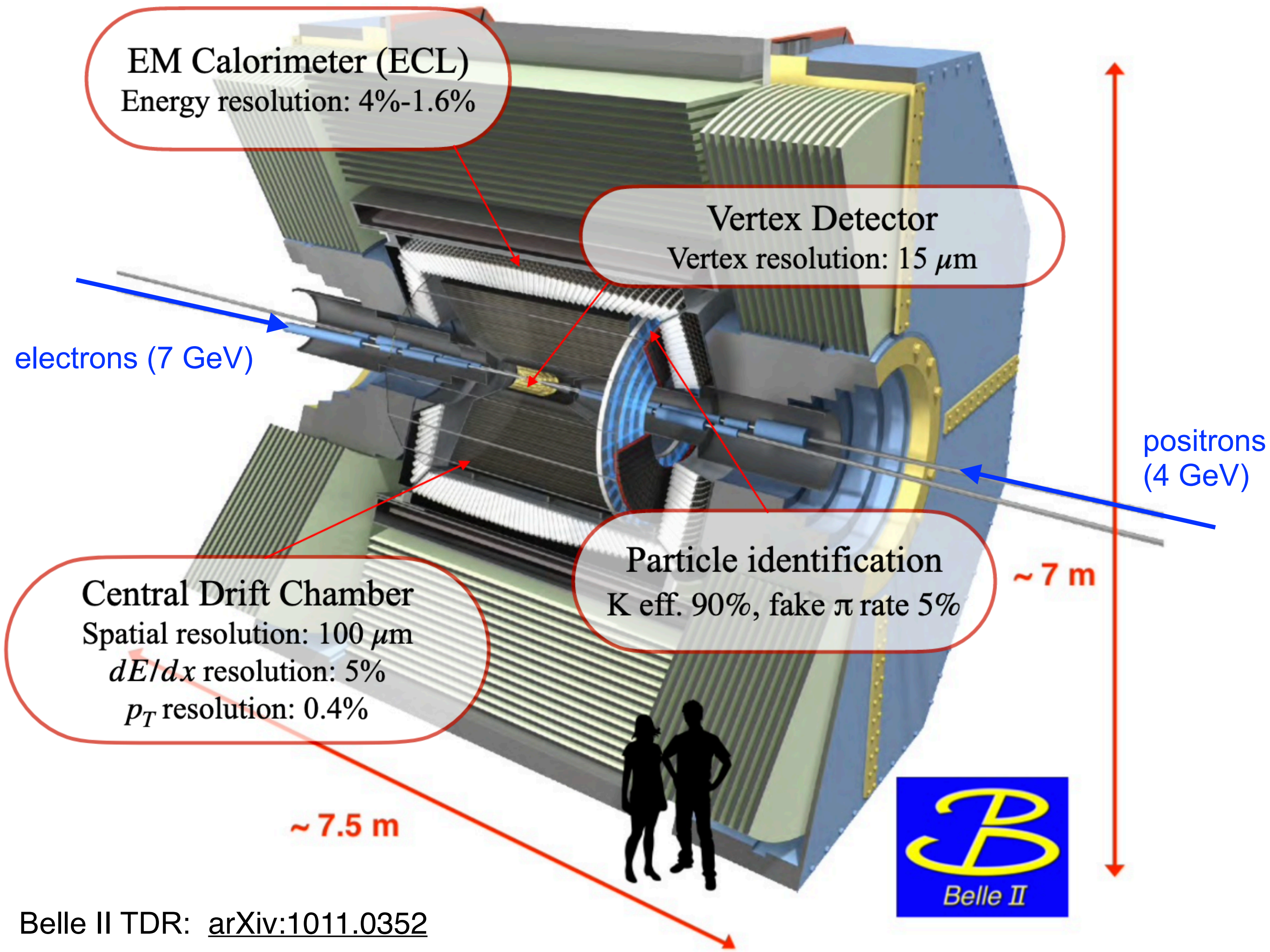
factor 20 factor 2-3



- Unprecedented design luminosity of ~6×10^{35} $cm^{-2}s^{-1}$

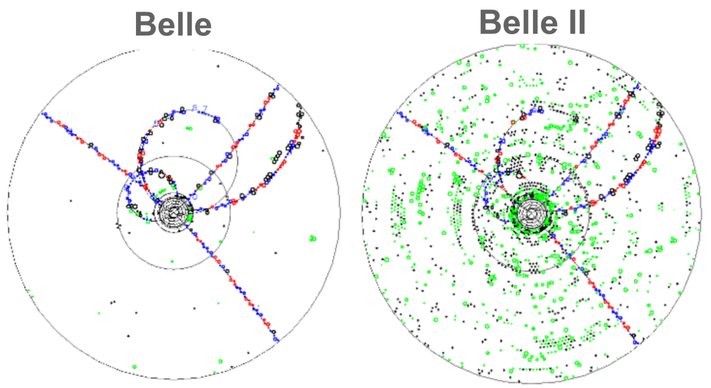
- **World record inst. luminosity of 3.8×10^{34} $cm^{-2}s^{-1}$ achieved!**
  (even with smaller beam currents wrt KEKB)

Belle II Detector



Belle II TDR: arXiv:1011.0352

- Increased beam backgrounds



⇒ upgraded trigger system and sub-detectors

- $\beta\gamma$ = 0.28 (vs 0.42 @ Belle)

  ⇒ reduced boost requiring improved vertex reconstruction

- Solid angle coverage > 90%

  ⇒ high hermeticity for E_{miss} measurements

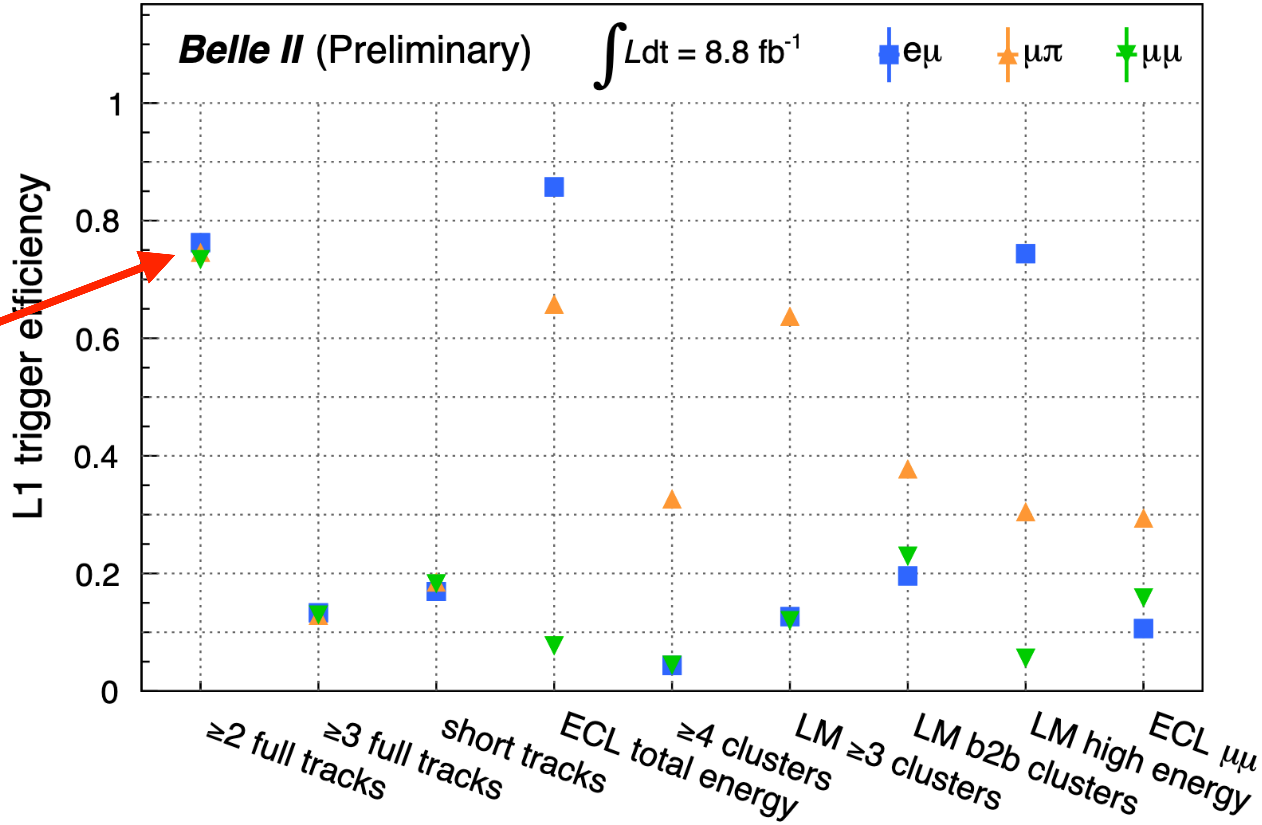
Triggers

- Belle II hardware-based (Level 1) trigger combines information from CDC, ECL, TOP and KLM.
  - Designed to reduce rate to at most 30 kHz, while delivering ~100% efficiency for $\Upsilon(4S) \to B\bar{B}$ events
  - **Novel menu of triggers unavailable in Belle enable a compelling low-multiplicity program!**

- Main trigger types for Tau & Dark Sector physics:
  - CDC number of full tracks
  - CDC number of short tracks
  - ECL total energy threshold
  - ECL number of isolated clusters
  - ECL low multiplicity
  - ECL di-muon

- In the **dark Higgsstrahlung** analysis events are required to fire the so-called "**ffo**" trigger:

  $\geq$ 2 full tracks, pair with $\Delta\varphi > 90°$, bhabha-veto



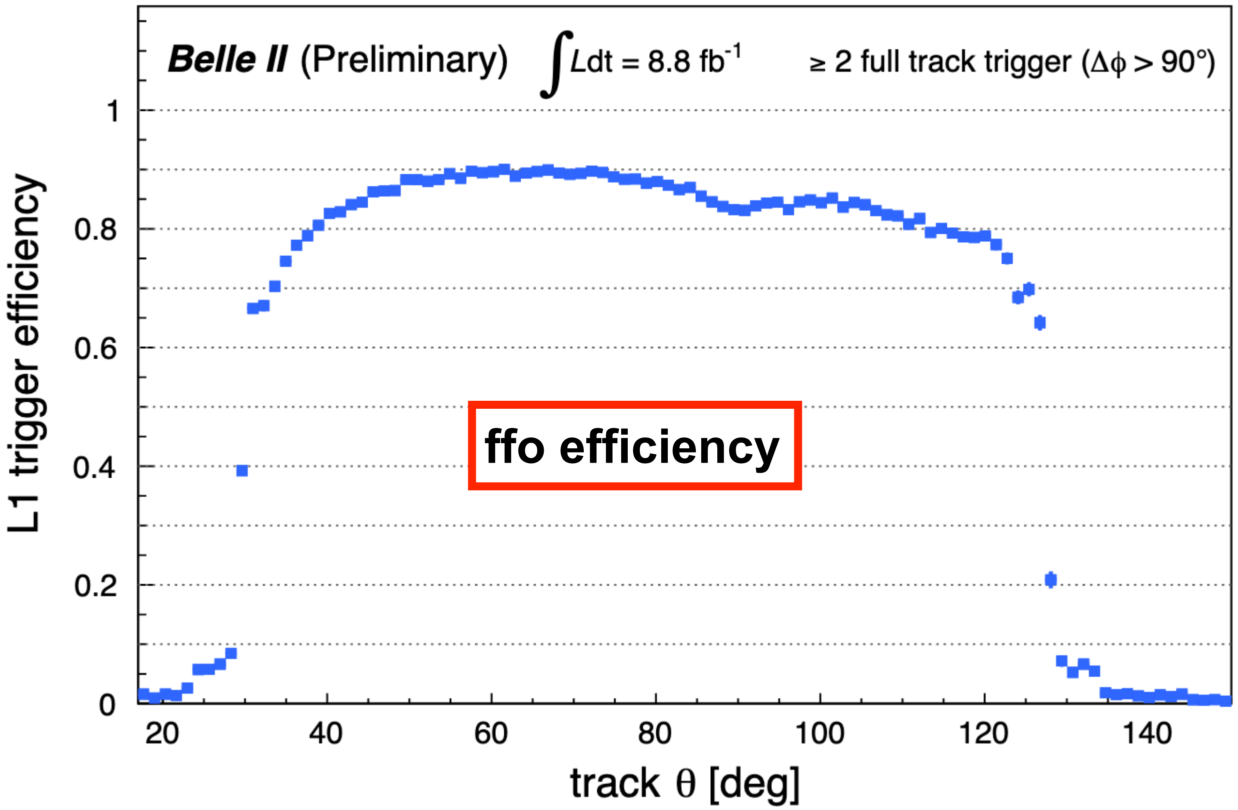
Triggers

- Belle II hardware-based (Level 1) trigger combines information from CDC, ECL, TOP and KLM.
  - Designed to reduce rate to at most 30 kHz, while delivering ~100% efficiency for $\Upsilon(4S) \to B\bar{B}$ events
  - **Novel menu of triggers unavailable in Belle enable a compelling low-multiplicity program!**

- Main trigger types for Tau & Dark Sector physics:
  - CDC number of full tracks
  - CDC number of short tracks
  - ECL total energy threshold
  - ECL number of isolated clusters
  - ECL low multiplicity
  - ECL di-muon

- In the **dark Higgsstrahlung** analysis events are required to fire the so-called "**ffo**" trigger:

  $\geq$ 2 full tracks, pair with $\Delta\varphi > 90°$, bhabha-veto

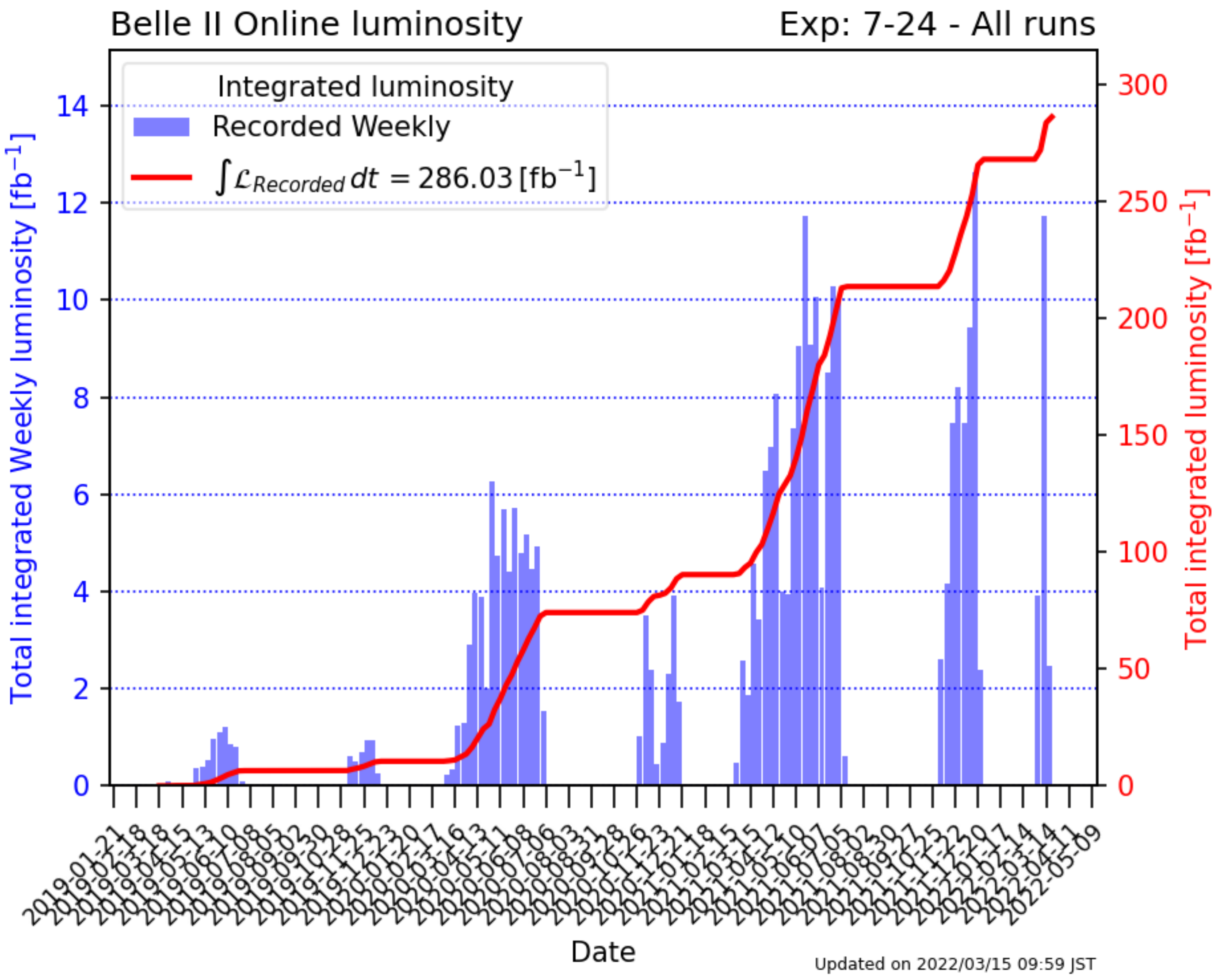


Luminosity Status and Goals

- Since 2019 Belle II has recorded **~286 fb^{-1}** of data.

- Aiming for a similar data sample size as BABAR by summer 2022.

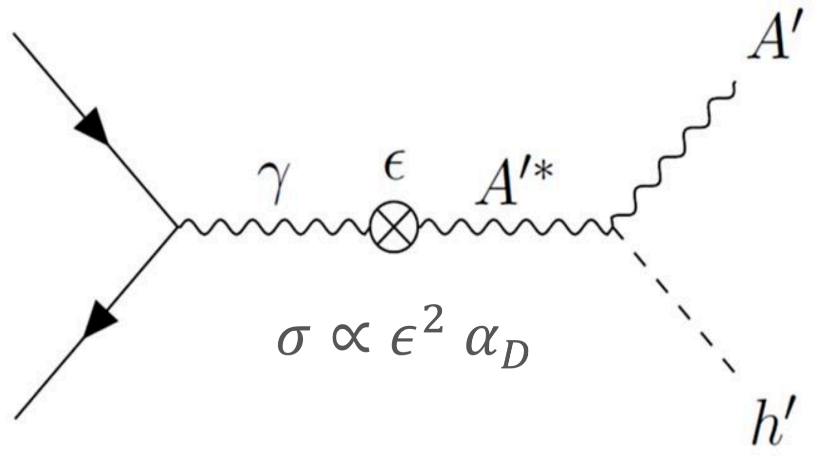
- Over the next ~10 years our goal is to accumulate **50 ab^{-1}** (50 x Belle dataset).



New for Moriond!

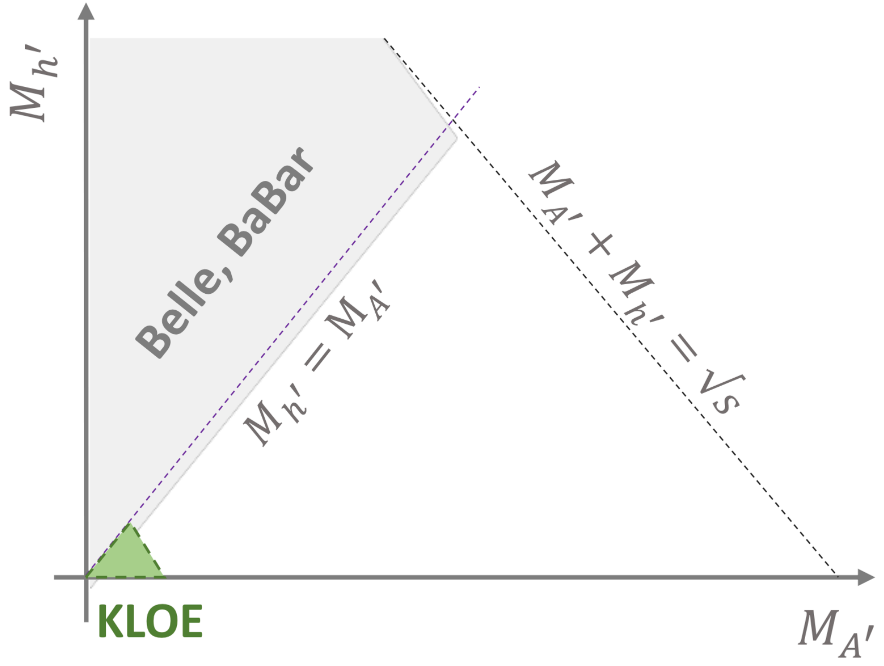
Next to minimal dark photon model

- Dark photon (**A'**) couples to SM photon via kinetic mixing parameter ϵ
- A' mass can be generated via a spontaneous symmetry breaking mechanism, adding a dark Higgs boson (**h'**) to the theory.
  Phys. Rev. D 79, 115008 (2009)
- No dark Higgs mixing with SM Higgs.
- Both particles can be produced via **dark Higgsstrahlung process**.



Mass hierarchy scenarios

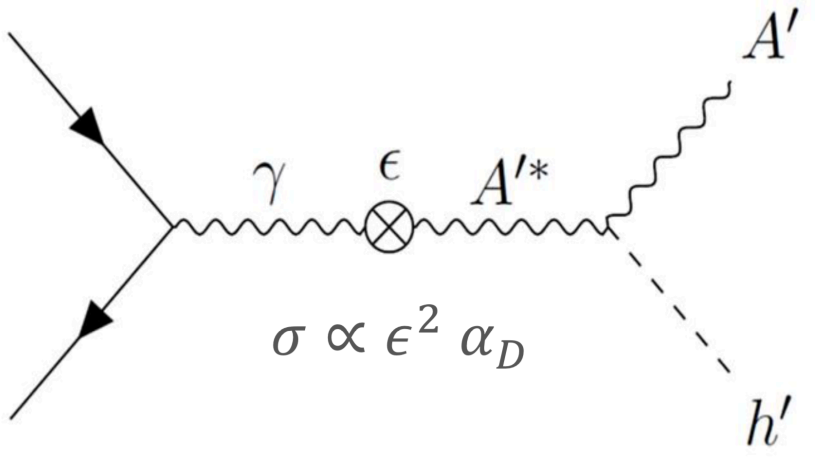
- $m_{h'} > m_{A'}$: $h' \to A'A' \to 4\ell$, 4had, 2ℓ + 2had ⇒ 6 charged tracks
  Investigated by BaBar (2012) and Belle (2015).
- $m_{h'} < m_{A'}$: h' is long-lived and thus invisible ⇒ 2 charged tracks
  Partially constrained by KLOE (2015).



Dark Higgsstrahlung

Next to minimal dark photon model

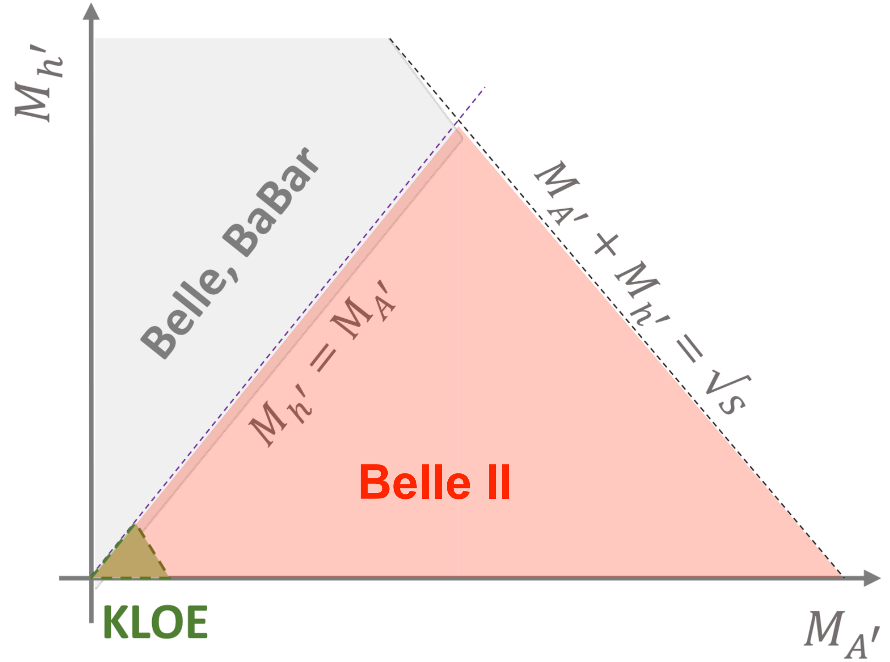
- Dark photon (**A'**) couples to SM photon via kinetic mixing parameter ϵ
- A' mass can be generated via a spontaneous symmetry breaking mechanism, adding a dark Higgs boson (**h'**) to the theory.
  Phys. Rev. D 79, 115008 (2009)
- No dark Higgs mixing with SM Higgs.
- Both particles can be produced via **dark Higgsstrahlung process**.



Mass hierarchy scenarios

- $m_{h'} > m_{A'}$: $h' \to A'A' \to 4\ell$, 4had, 2ℓ + 2had ⇒ 6 charged tracks
  Investigated by BaBar (2012) and Belle (2015).
- $m_{h'} < m_{A'}$: h' is long-lived and thus invisible ⇒ 2 charged tracks
  Partially constrained by KLOE (2015).

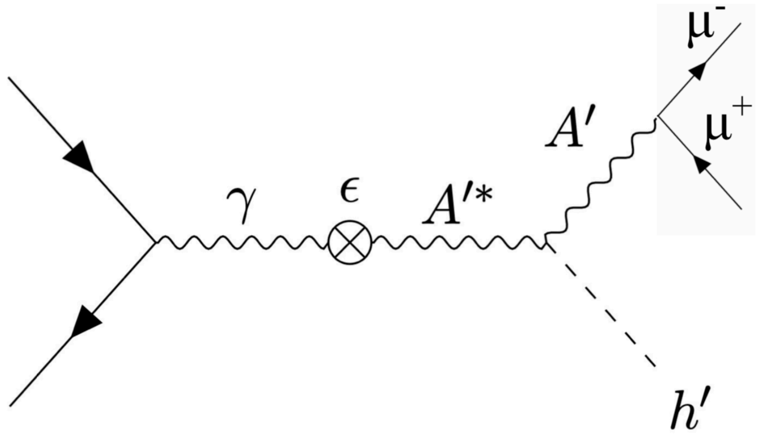
Exploring unconstrained territories at BelleII !



Analysis Strategy

New for Moriond!

Data sample: 2019 dataset ⇒ 8.34 fb-1

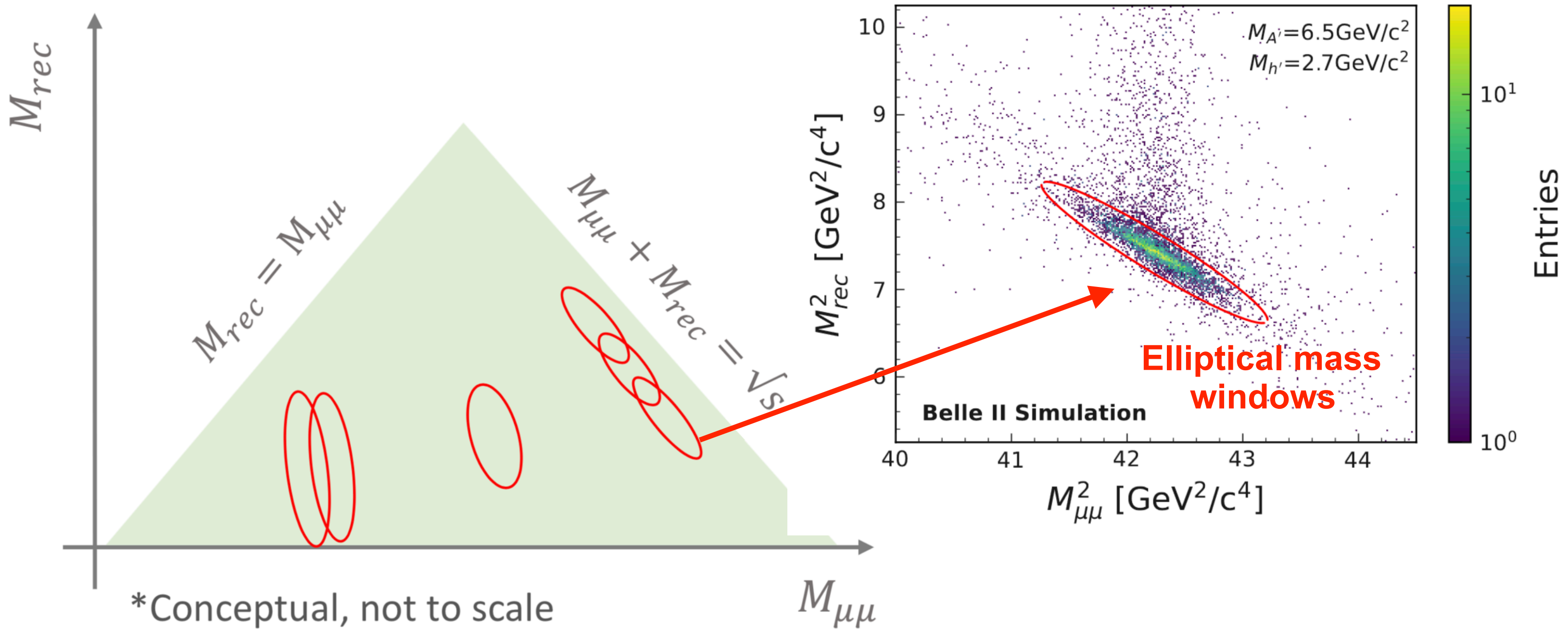


Detector signature

- Looking for invisible h' with $A' \rightarrow \mu^+\mu^-$ ⇒ μμ + missing energy
- 2D peak in in $M_{\mu\mu}$ vs M_{rec}
  M_{rec} = invariant mass of the system recoiled against μμ.

Search strategy:

- $M_{\mu\mu}$ & M_{rec} are correlated ⇒ search in tilted elliptical mass windows
- Spacing α M^2 resolution in the two directions
- ~9000 overlapping windows (large look-elsewhere effect)
- Counting experiment in each window (on average, 1 event in ~3 windows)



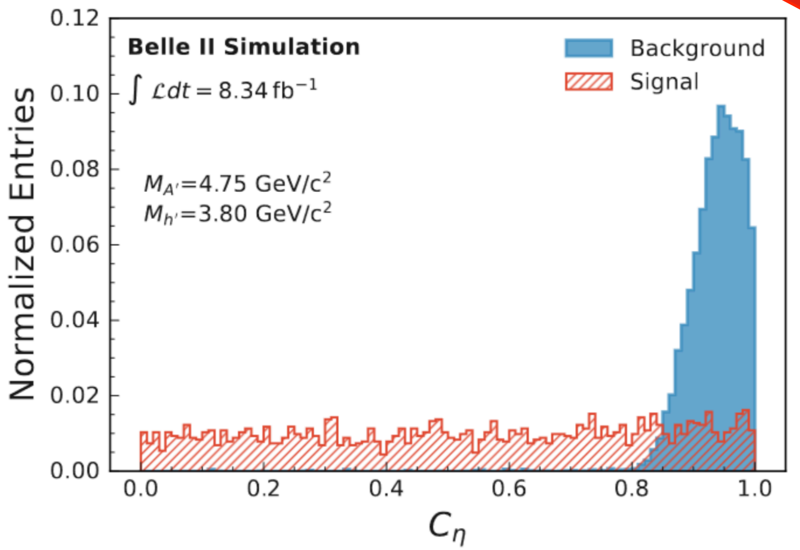
Background suppression

Trigger & pre-selections:

- Events fire ffo trigger
- 2 good quality tracks
- Muon ID, $p_T^{\mu\mu} > 0.1$ GeV
- Recoil points in ECL barrel, no nearby ɣ
- ROE extra energy < 0.4 GeV

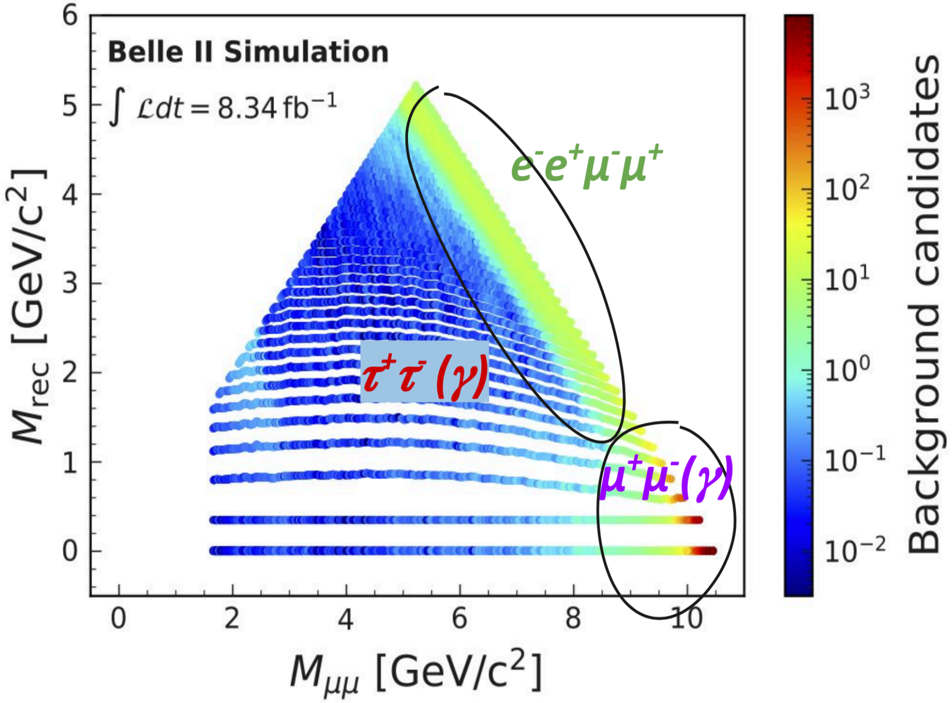
Helicity angle (C_η):

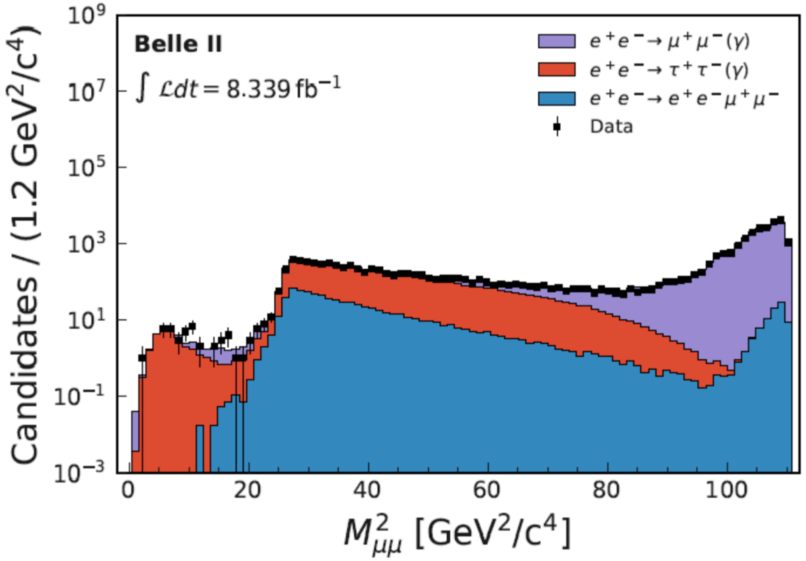
- Cut on angle b/w flight direction of A′ in the CMS and the μ in the A′ rest frame (Punzi FOM in each search window)
- Signal eff. 10-25% for $M_{\mu\mu}$ > 4 GeV (rapidly drops below due to trigger)



Surviving backgrounds:

- Main contributions:
  $\mu^+\mu^-(\gamma)$ (79%)
  $\tau^+\tau^- \to \mu^+\mu^-, 4\nu$ (18%)
  $e^+e^-\mu^+\mu^-$ (3%)
- Mostly localised near the kinematic limit, especially for $M_{\mu\mu}$ > 9 GeV





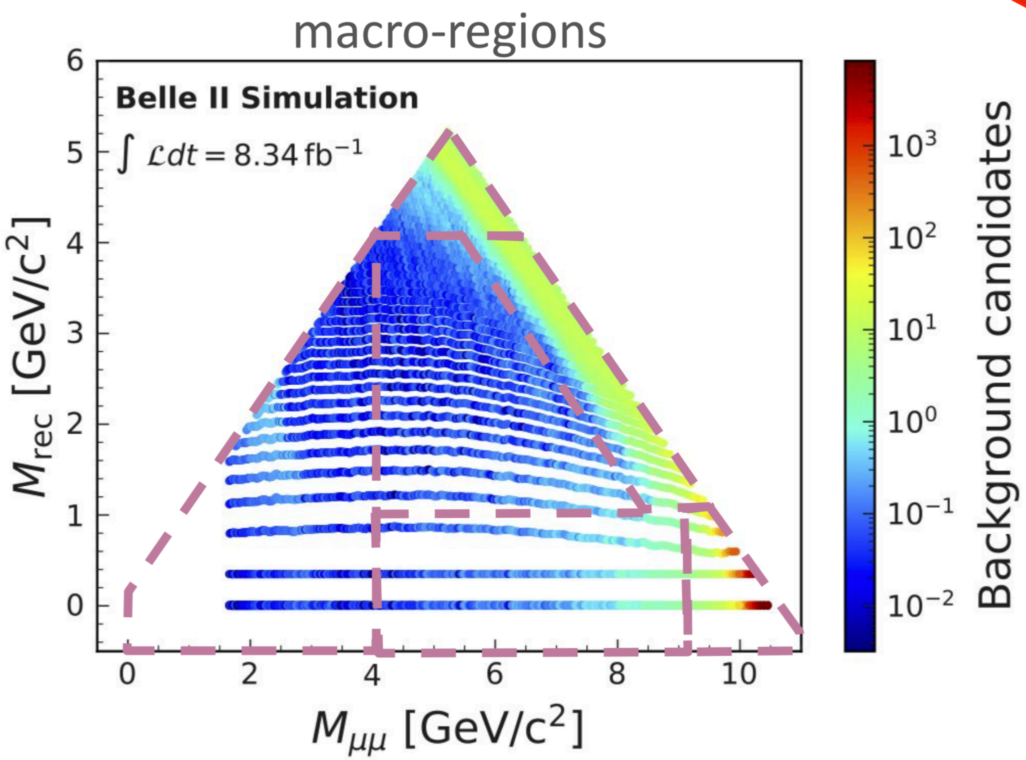
Systematic Uncertainties

New for Moriond!

Data validation in control samples:

- $\mu^+\mu^-\gamma$: require an energetic photon (instead of veto)
- $\tau^+\tau^- \to e^+\mu^-, 4\nu$: require an electron instead of muon

- Split mass-plane into orthogonal macro-regions
  - Each enriched by a single source of background
  - Data vs MC: normalisation, bkg shape modelling, recoil mass resolution.
  - Overall good agreement observed.
    Discrepancies assigned as systematic uncertainties.



source	uncertainty	target
Pre-selections	**2 - 9.1%**	BKG & signal
BKG shape	**9.3%** (region specific)	BKG
C_η cut	**1%**	BKG
Mass resolution	**2.4%** (on average)	signal
Eff. Inside windows	**2 - 5%**	signal
Theory (BR A')	**4%**	signal

Total uncertainties	**2.2 - 12.7%**	BKG
	5.4 - 11.3%	signal

- Almost all of the search plane is statistically limited (impact of systematics on ULs < 1%, see next slide)
- Exception is $M_{A'}$ > 9 GeV (~25% impact on ULs)

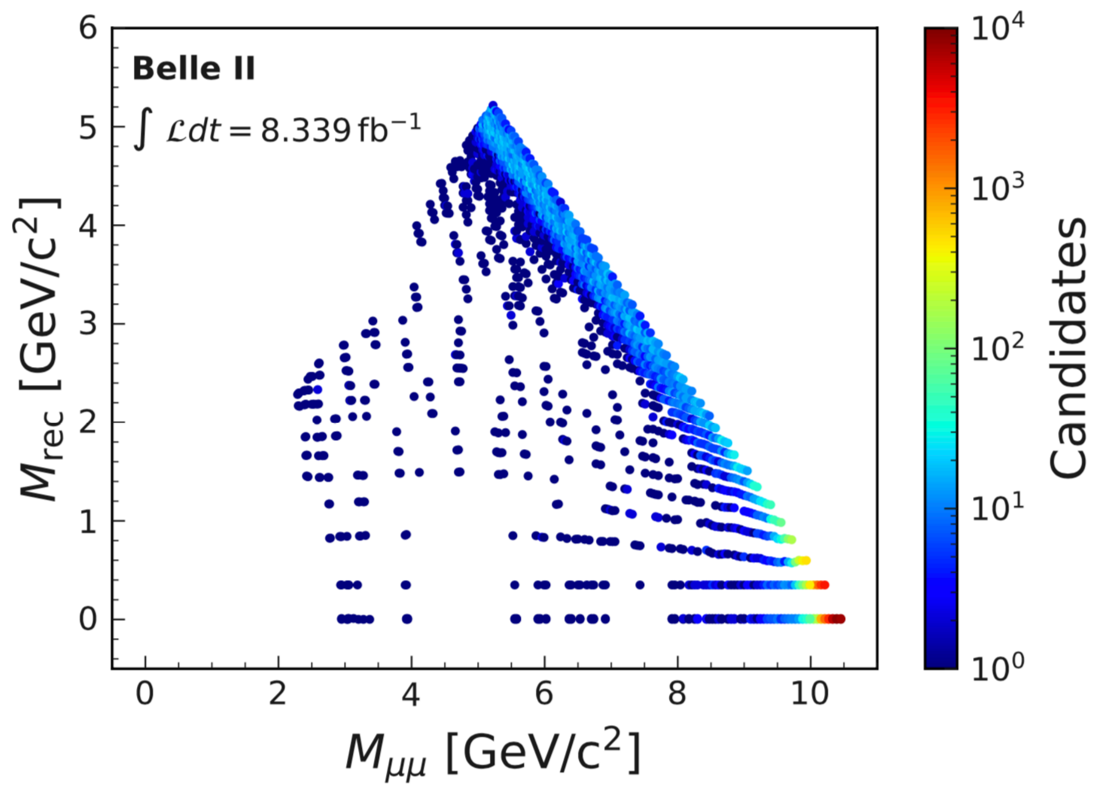
New for Moriond!

Search for excesses above expected background independently in the ~9k search windows

- Event counts in a single window interpreted as:

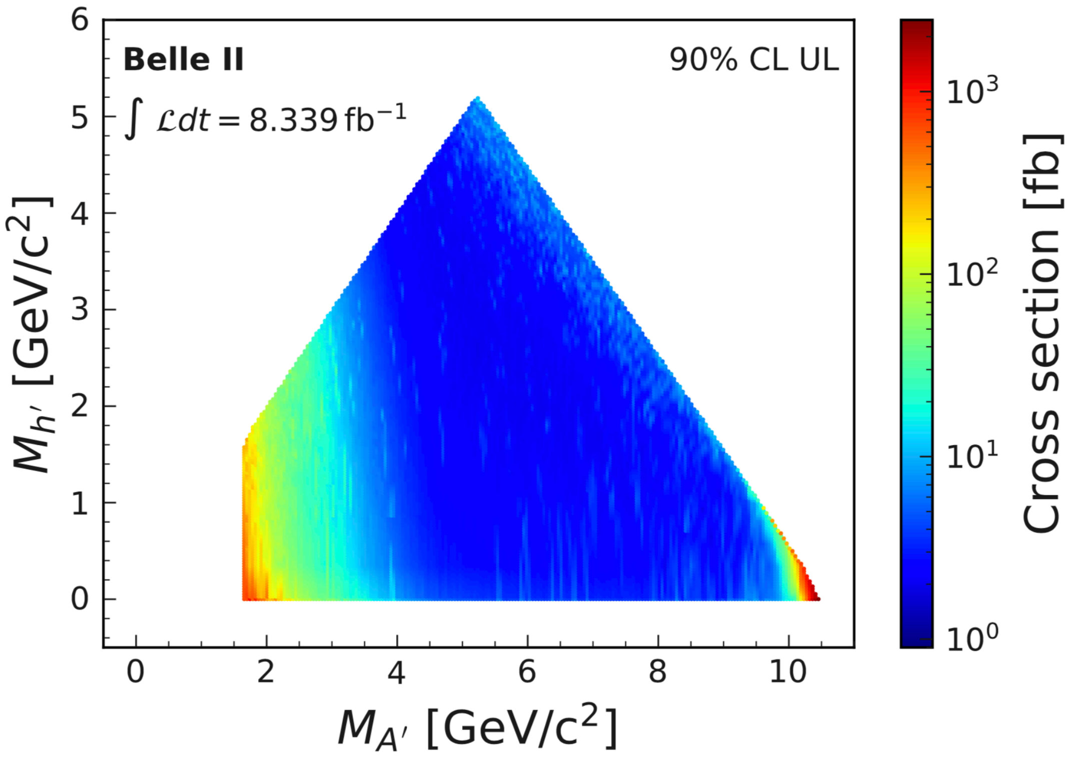
$$N = \epsilon_{sig} \times L \times \sigma_{DH} + B$$

with systematic uncertainties taken into account.



- Find no significant excess above background.

90% upper limits computed in a Bayesian approach on the cross section from 1.65 - 10.51 GeV in $M_{A'}$ ($M_{h'} < M_{A'}$)

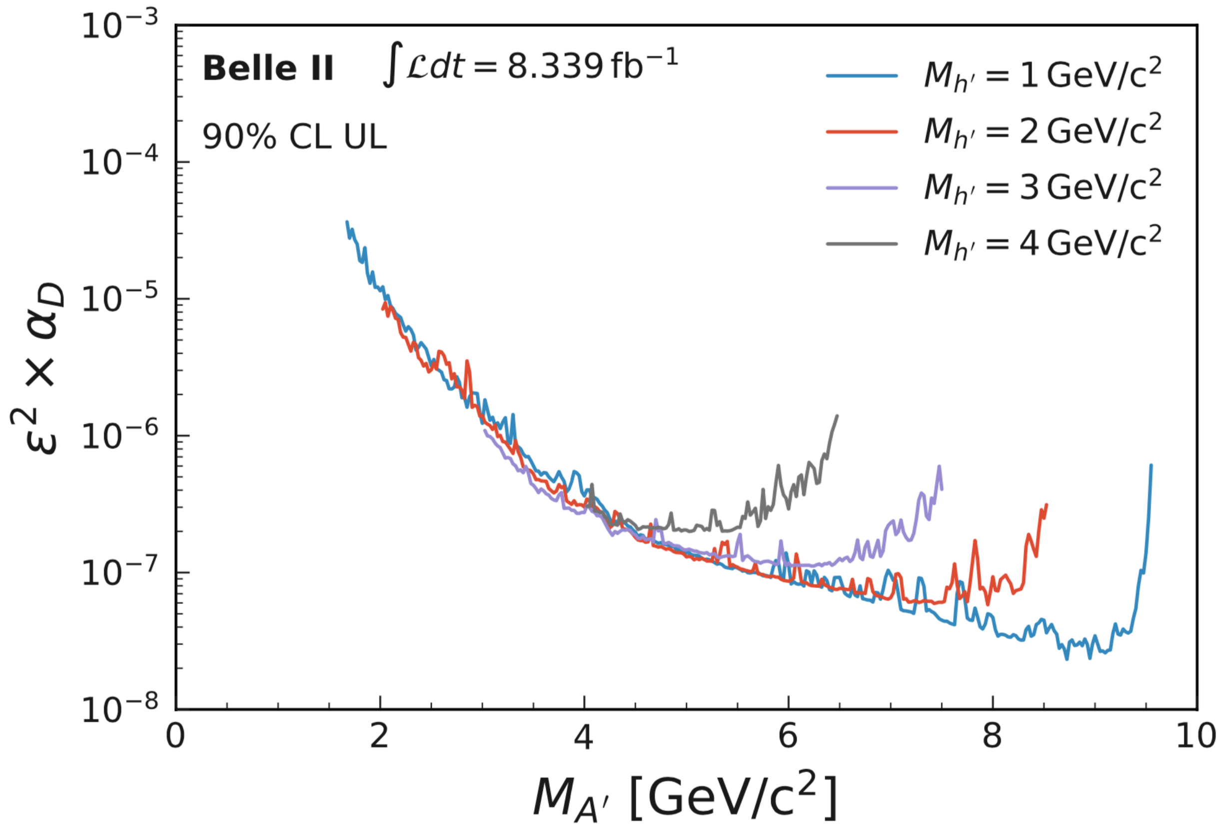


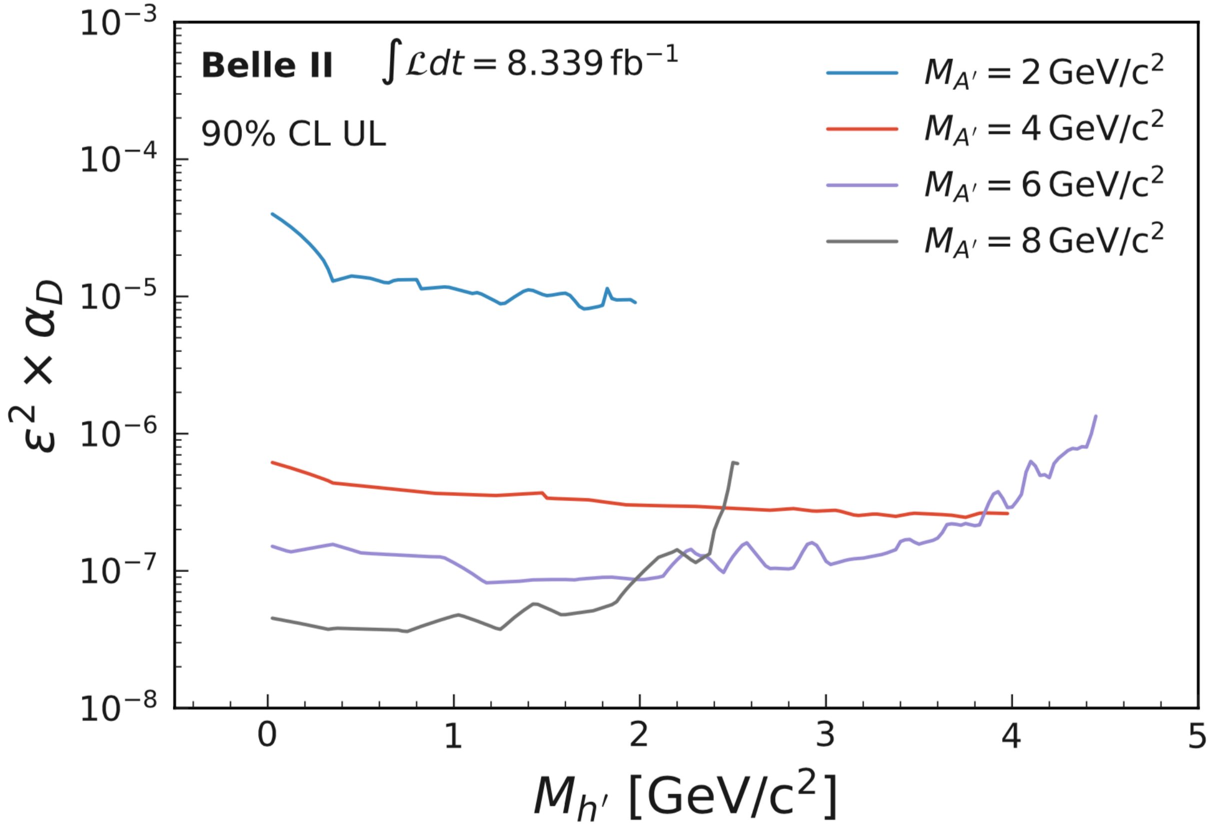
World's first ULs for 4 GeV < $M_{A'}$ < 9.7 GeV

Results

New for Moriond!

- Upper limits also computed in terms of the effective coupling:



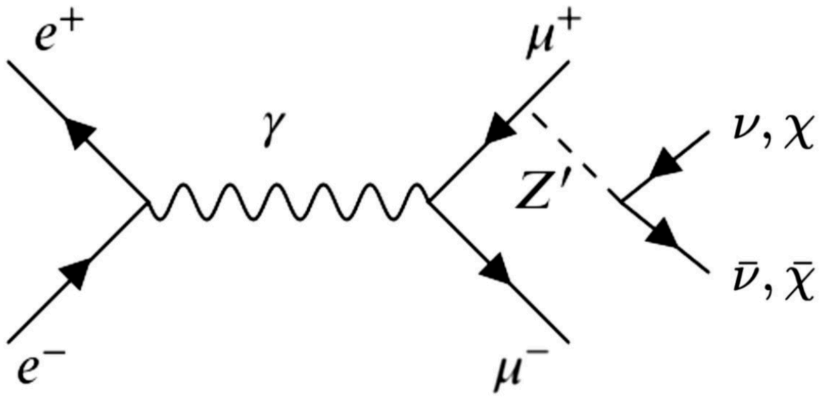


World's first ULs for 4 GeV < $M_{A'}$ < 9.7 GeV

Upcoming results from Dark Sector

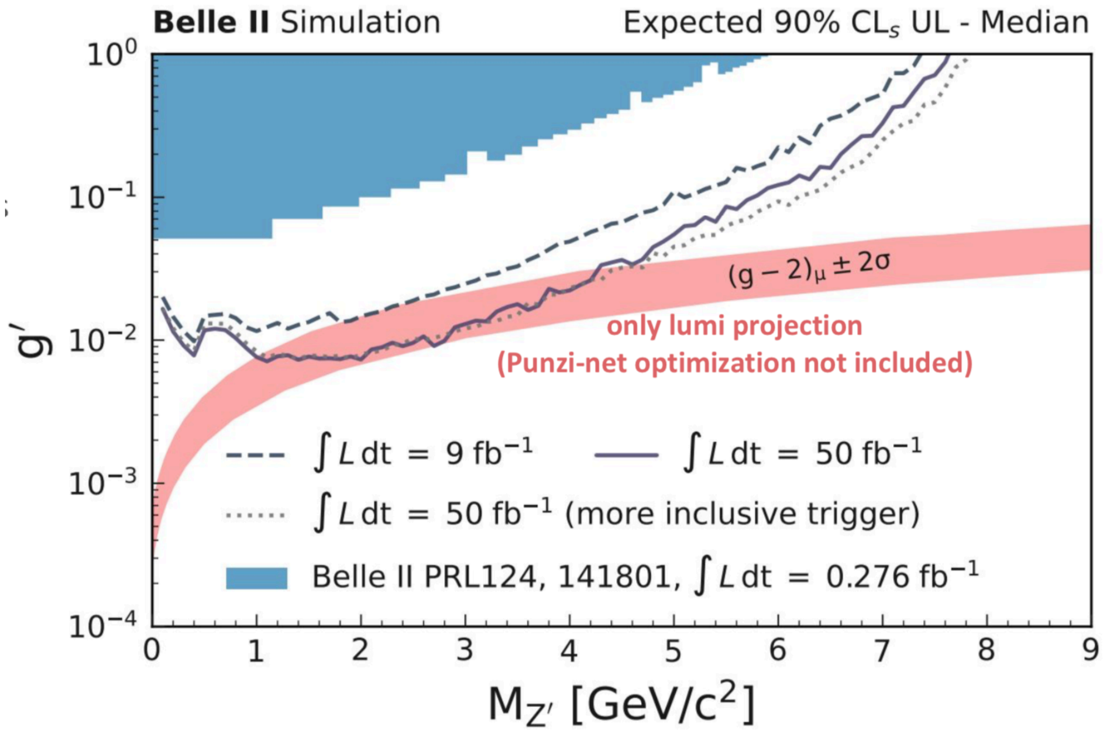
Paper on updated Z’ invisible search coming soon!

- Novel “Punzi-net” approach: Eur.Phys.J.C(2022) 82:121
- More inclusive trigger, muonID
- ~300 times larger dataset wrt to previous result PhysRevLett.124.141801



Aiming for summer conferences:

- Searches for visible Z’ with μμ and ττ decays

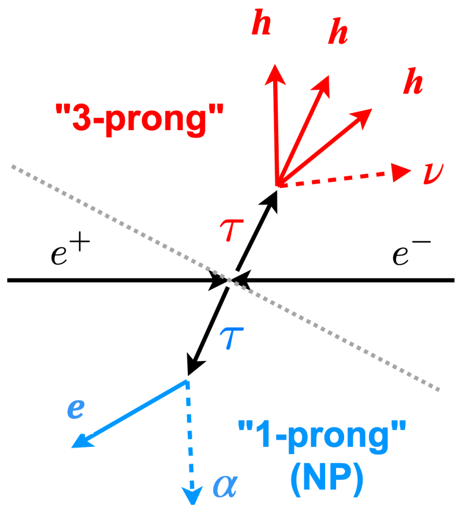


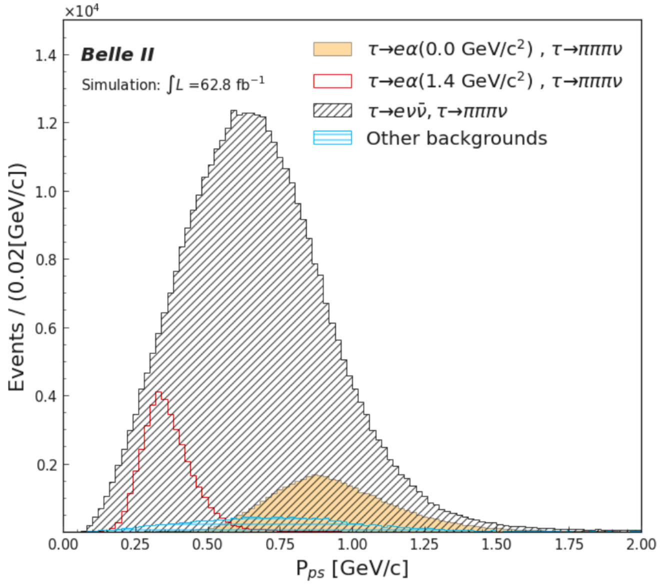
Longer term:

- Heavy QCD axion search
- LLP in b→s transitions
- Single photon search
- Dark showers
- $\pi^+\pi^-\pi^0$ contributing to $(g-2)_\mu$
- \+ more!

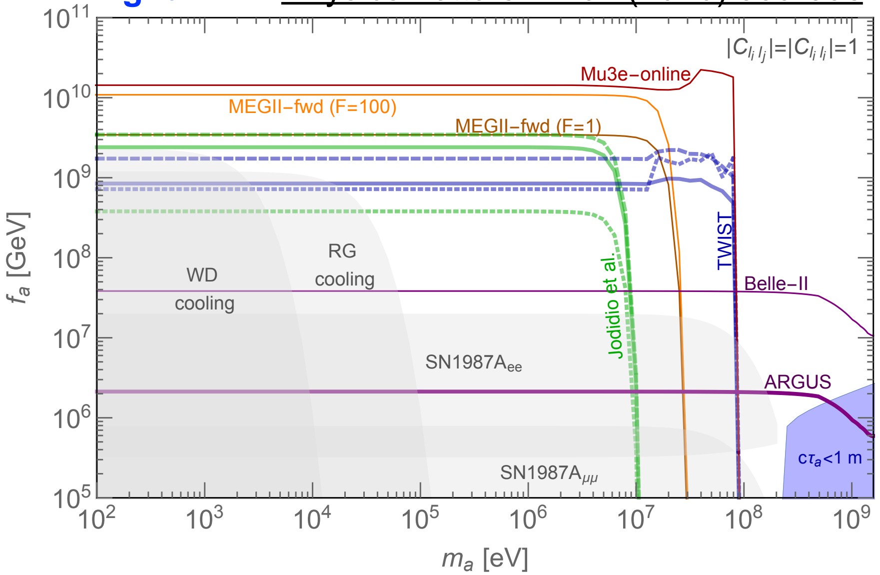
Tau Physics: search for $\tau \to \ell\alpha$

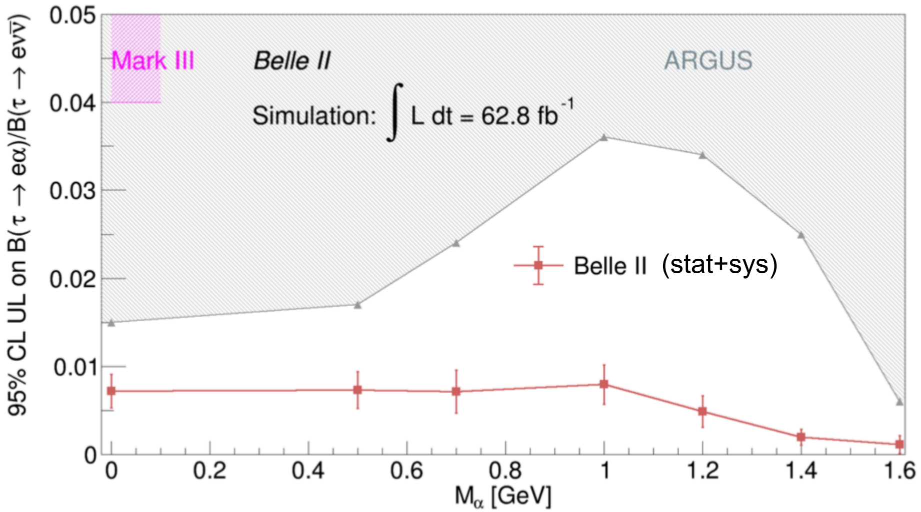
- Search for LFV $\tau^{\pm} \to \ell^{\pm}\alpha$, ($\ell^{\pm} = e^{\pm}/\mu^{\pm}$) and α is an invisible boson.
- α could enter from several different New Physics models
  - light ALP, LFV Z' + many more





Light ALP: Physics Letters B 762 (2016) 389-398





Signature:
2-body $\tau \to \ell\alpha$ decay will manifest as a bump in the p_ℓ distribution in the τ pseudo-rest frame, against the SM 3-body $\tau \to \ell\nu\bar{\nu}$ background.

$\Rightarrow$ With 62.8 fb^{-1} of data, Belle II can provide **world leading ULs** on B($\tau \to \ell\alpha$) / B($\tau \to \ell\nu\bar{\nu}$).

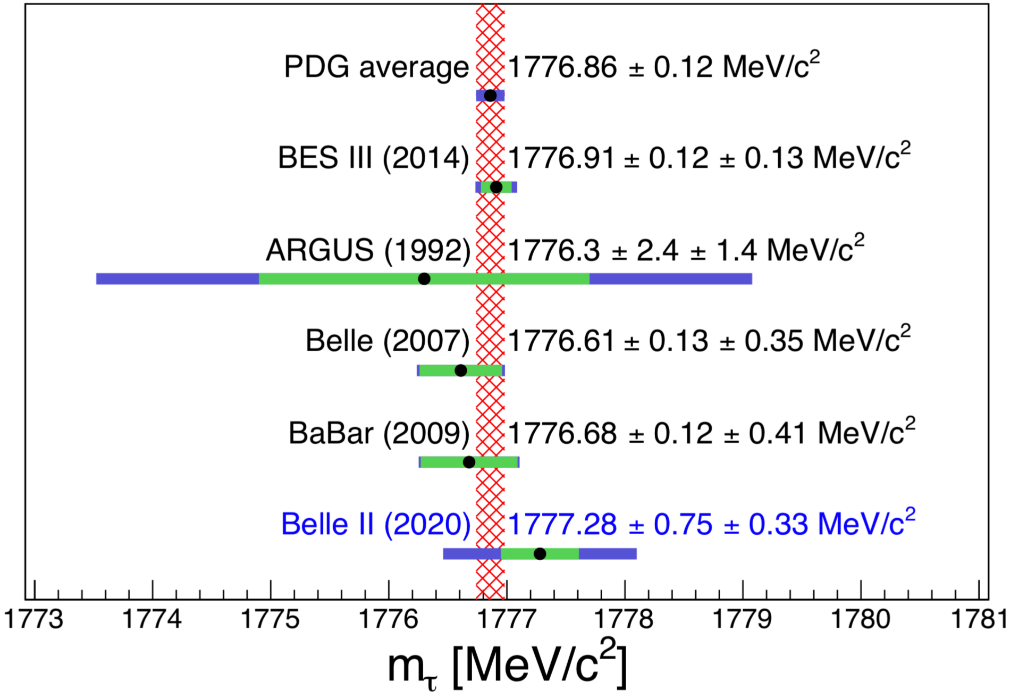
Upcoming results from Tau Physics

Paper on search for LFV $\tau \to l\alpha$ expected soon!

Aiming for summer: Tau mass measurement

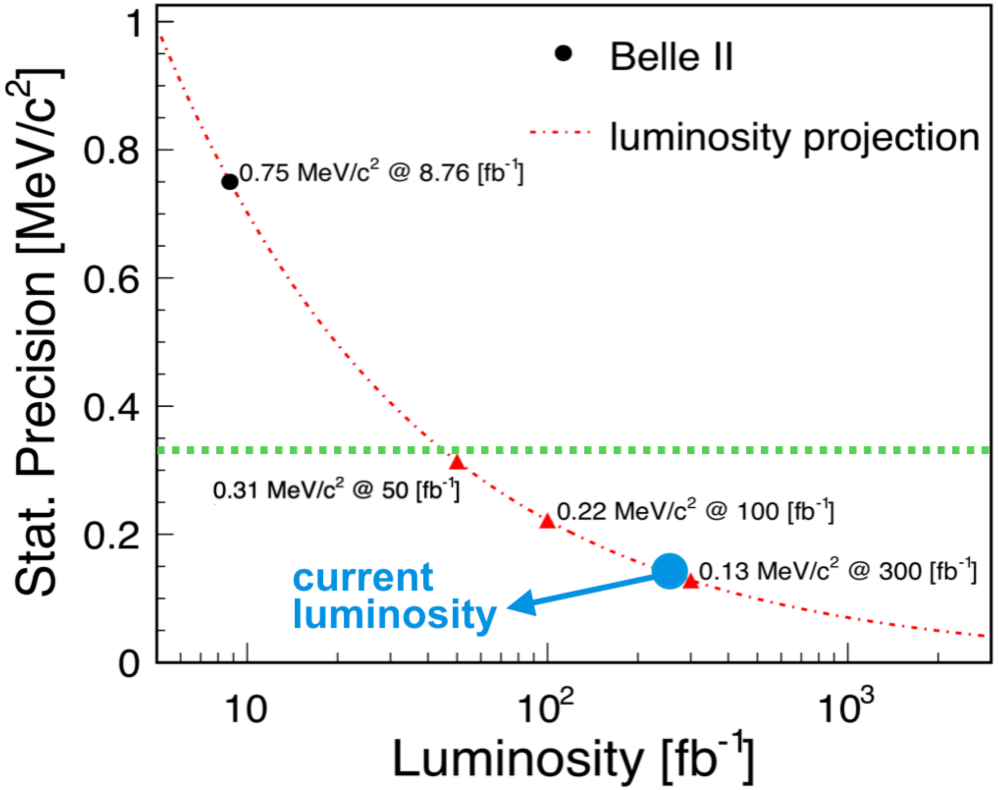
- Belle II already has comparable systematic errors to Belle/BABAR
- Expect to exceed statistical precision with **~200-300 fb^{-1}**

arXiv:2008.04665



Longer term:

- Tau lifetime measurement, tests of LFU
- V_{us} determination in hadronic decays
- Search for other LFV modes ($\tau \to \ell\ell\ell, \ell V^0, \ell\gamma, ...$)
- Anomalous magnetic and electric moments
- CP violation in $\tau \to K_S \pi \nu$, + more!



Conclusion

- **Dark sector at Belle II**
  - Dark-sector mediators in the MeV-GeV range are being explored at Belle II
  - New results shown for the first time at Moriond: search for dark Higgsstrahlung ($M_{h'} < M_{A'}$)
    - **world's first upper limits** on cross section and couplings for 4 GeV < $M_{A'}$ < 9.7 GeV

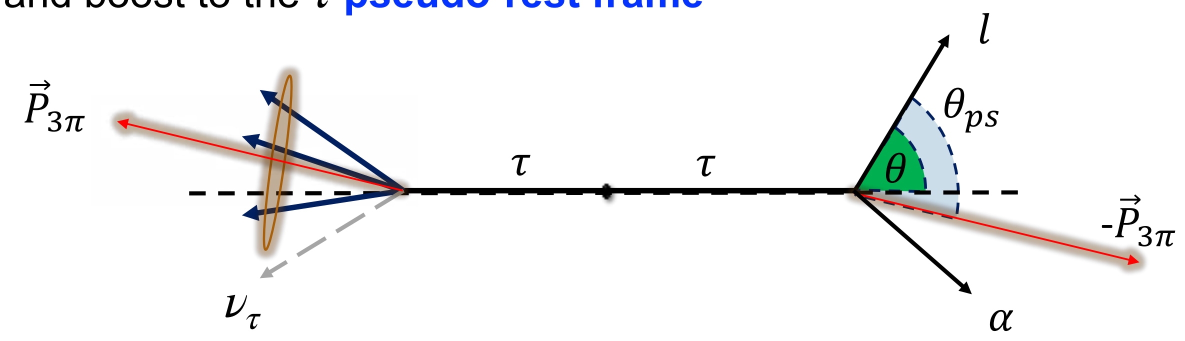
- **Tau physics at Belle II**
  - Belle II will be the leading tau factory in the coming years, and may provide direct and/or indirect insights into new physics.

- **More results in the pipeline**
  - Update on invisible Z', first results on $\tau \rightarrow l\alpha$, visible Z', tau mass measurement, …

BACKUP

- In an ideal world we would search for $\tau \to \ell\alpha$ in the *true* τ rest frame, where the p_ℓ spectrum is a monochromatic peak at the value corresponding to the α mass.

- However we cannot access τ rest frame directly due to ν_τ, and so we *approximate* the signal τ momentum under some assumptions and boost to the τ **pseudo-rest frame**

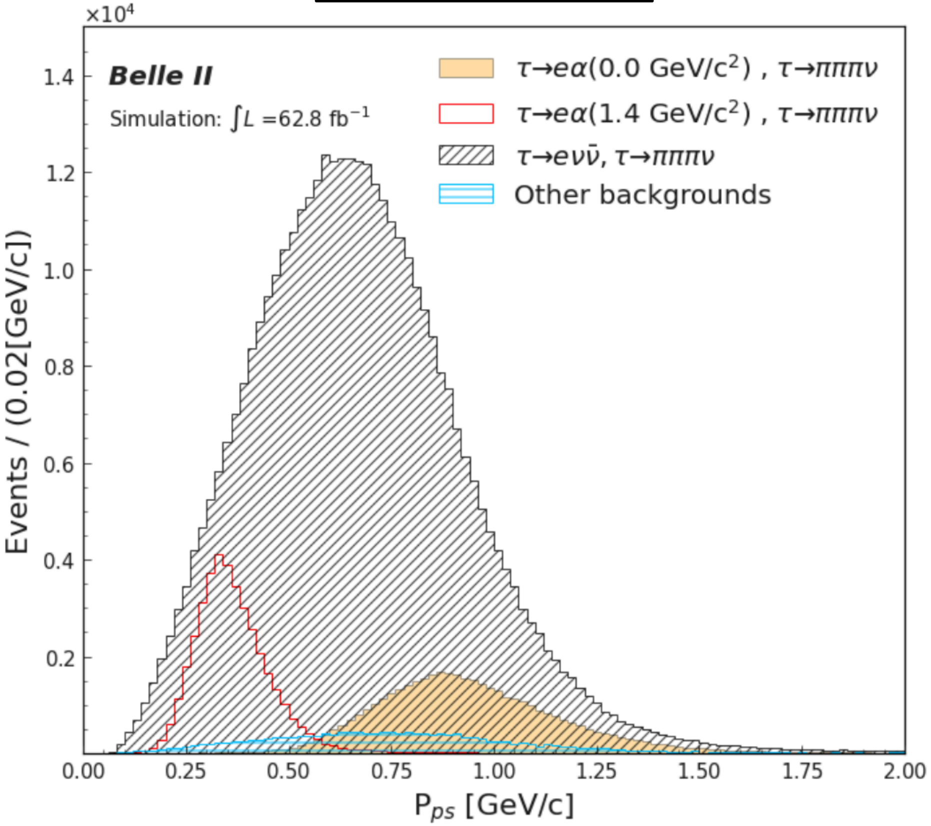


- Two assumptions: (1) $E_\tau = \sqrt{s}/2$

$$\text{(2)} \quad \vec{n}_\tau \approx -\vec{n}_{3\pi} = -\sum_{i=1}^{3} \frac{\vec{p}_\pi^{\,i}}{|\vec{p}_{3\pi}|}$$

Signature:
2-body $\tau \to \ell\alpha$ decay will manifest as a bump in the p_ℓ distribution in the τ pseudo-rest frame, against the SM 3-body $\tau \to \ell\nu\bar{\nu}$ background.

$\tau \to e\alpha$ channel

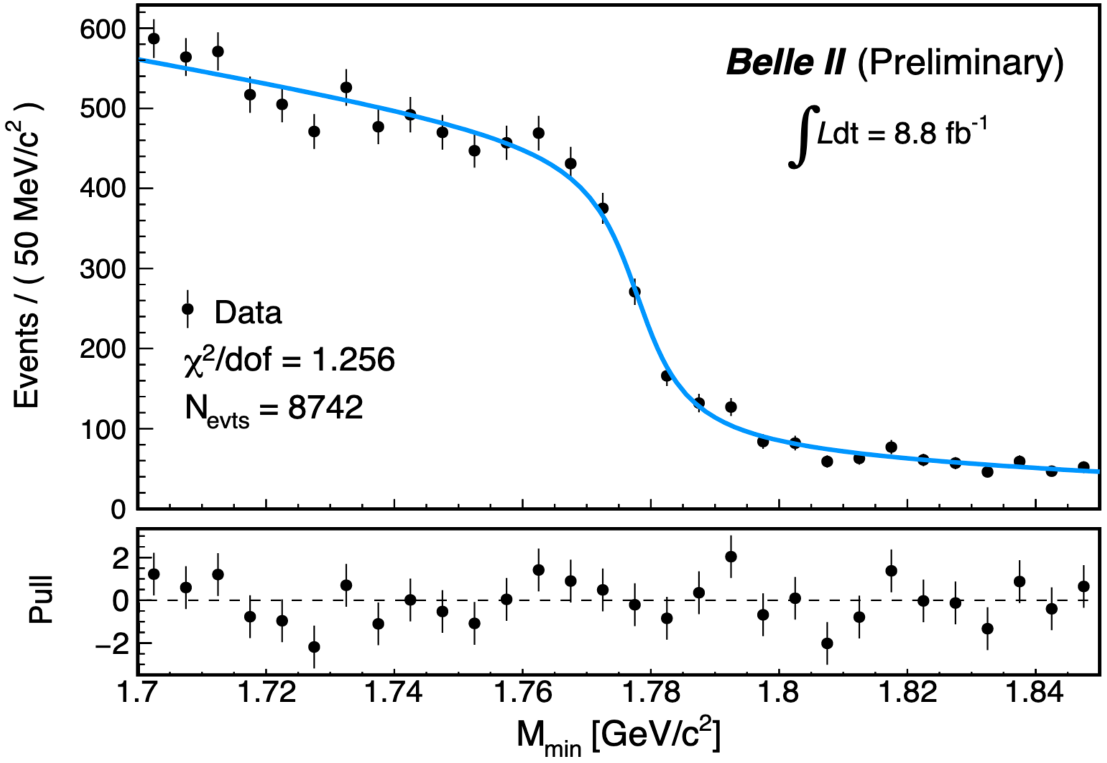


Tau Mass

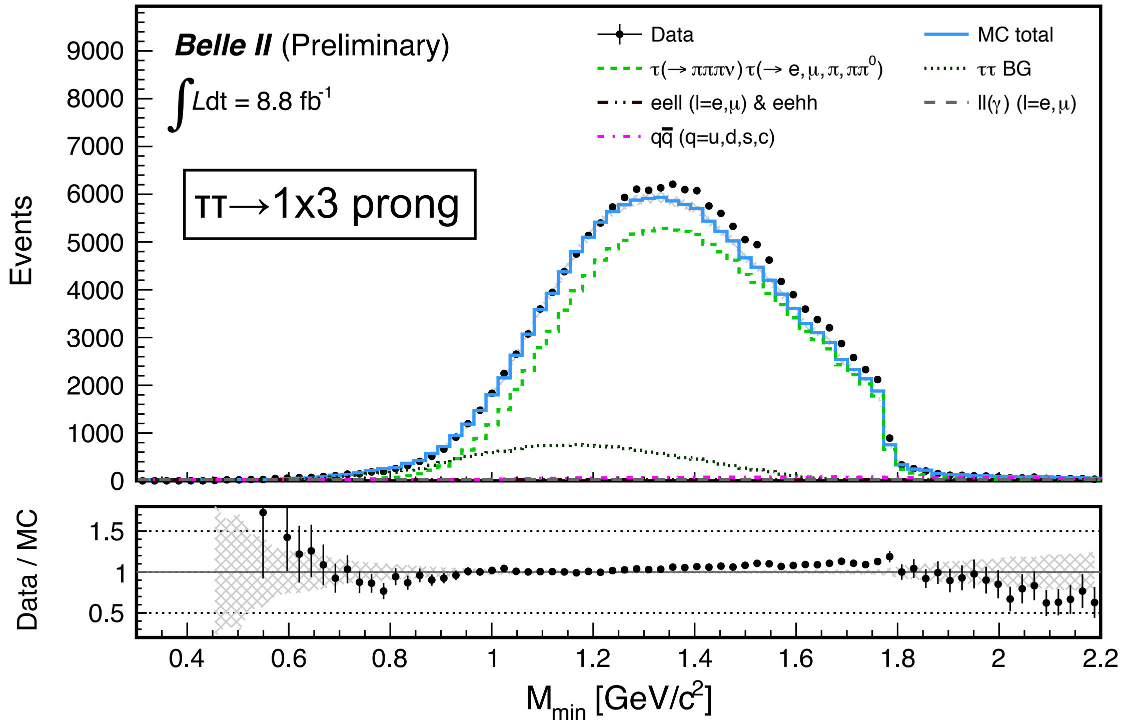
- Tau mass measurement in early Belle II data (8.8 fb^{-1})
- Using a pseudomass technique on $\tau \to 3\pi\nu$ decays

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

- sharp threshold behaviour in region close to m_τ



arXiv:2008.04665



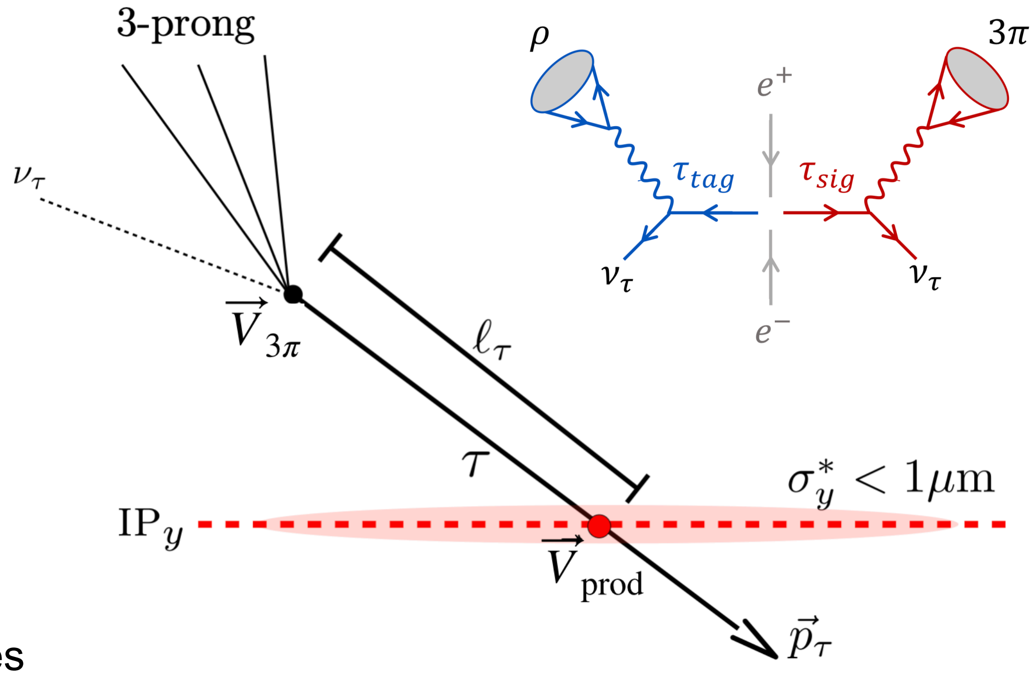
- M_{min} is fitted to an empirical mass function ($P_1 \Rightarrow m_\tau$) within a 1.7-1.85 GeV window:

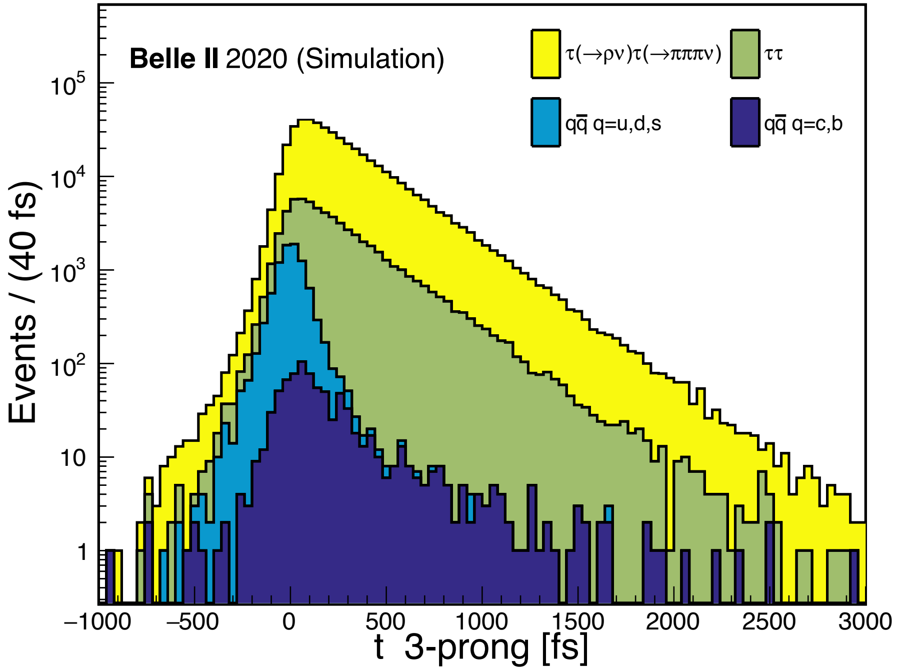
$$F(M, \vec{P}) = (P_3 + P_4 M) \cdot \tan^{-1}[(M - P_1/P_2)] + P_5 M + 1$$

$$\boxed{m_\tau = 1777.28 \pm 0.75\ (\mathrm{stat}) \pm 0.33\ (\mathrm{sys})\ \mathrm{MeV/c^2}}$$

Tau Lifetime

- Can relate proper time to flight distance and momentum in lab frame: $t = \frac{l_\tau}{\beta\gamma c} = m\frac{l_\tau}{p_\tau}$ measure these!
- Reconstruct 3-prong vertex and estimate p_τ using decay products
- Exploit the tiny beam spot size near IP $\Rightarrow$ estimate production vertex as the intersection of p-direction with plane = IP_y



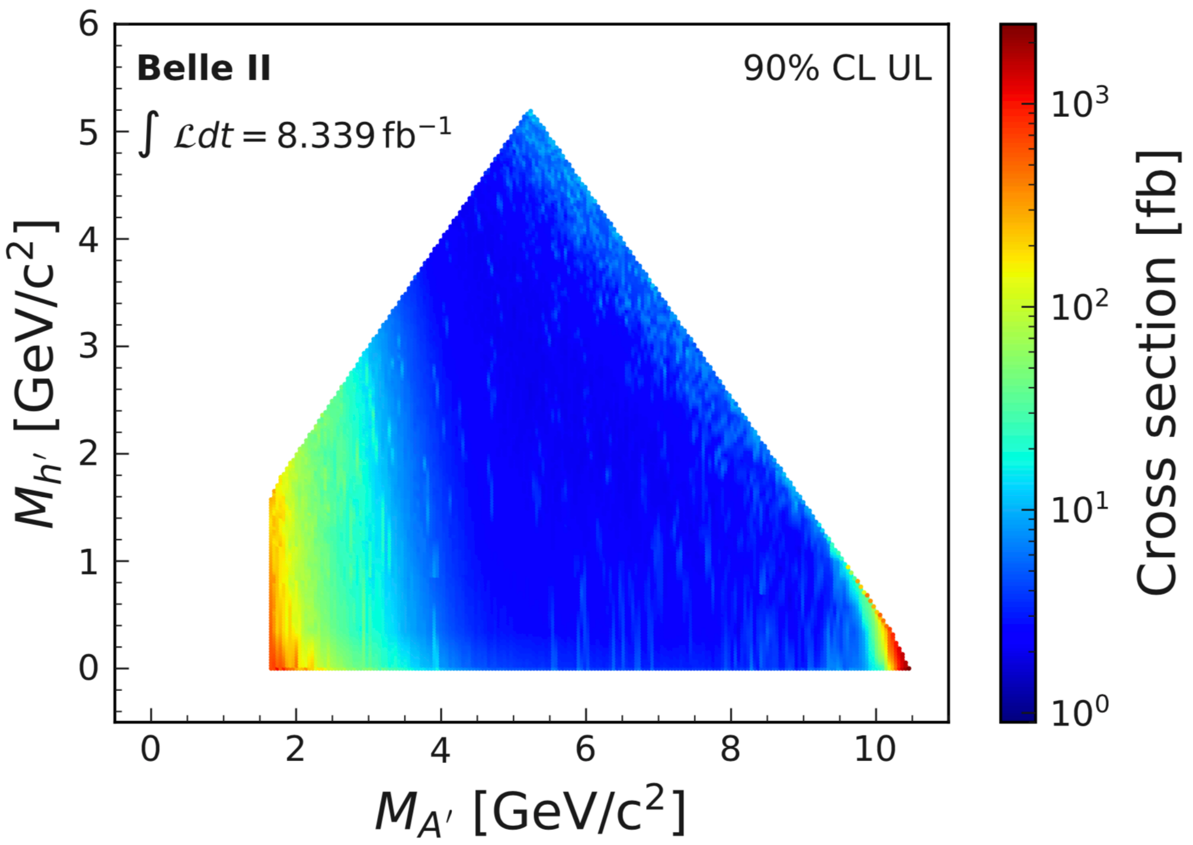


- World-best measurement comes from Belle (711 fb^{-1}):

τ_τ = 290.1 ± 0.53 (stat) ± 0.33 (sys) fs   Phys. Rev. Lett. 112, 031801

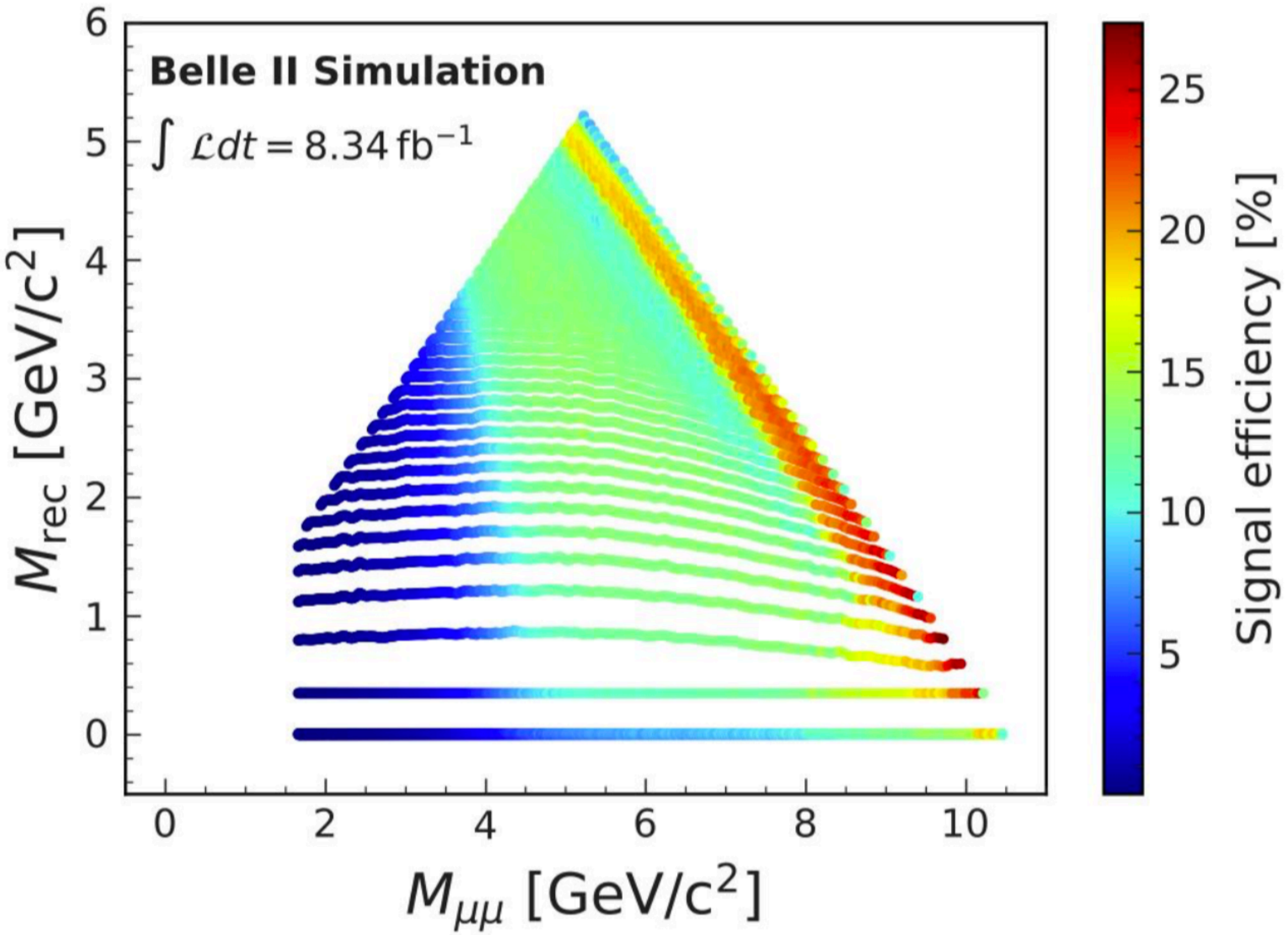
- Belle II has **5x higher efficiency** (1x3 vs 3x3 prong @ Belle), and **2x better proper decay time resolution**

$\Rightarrow$ **expect competitive results with only ~150 fb^{-1}**

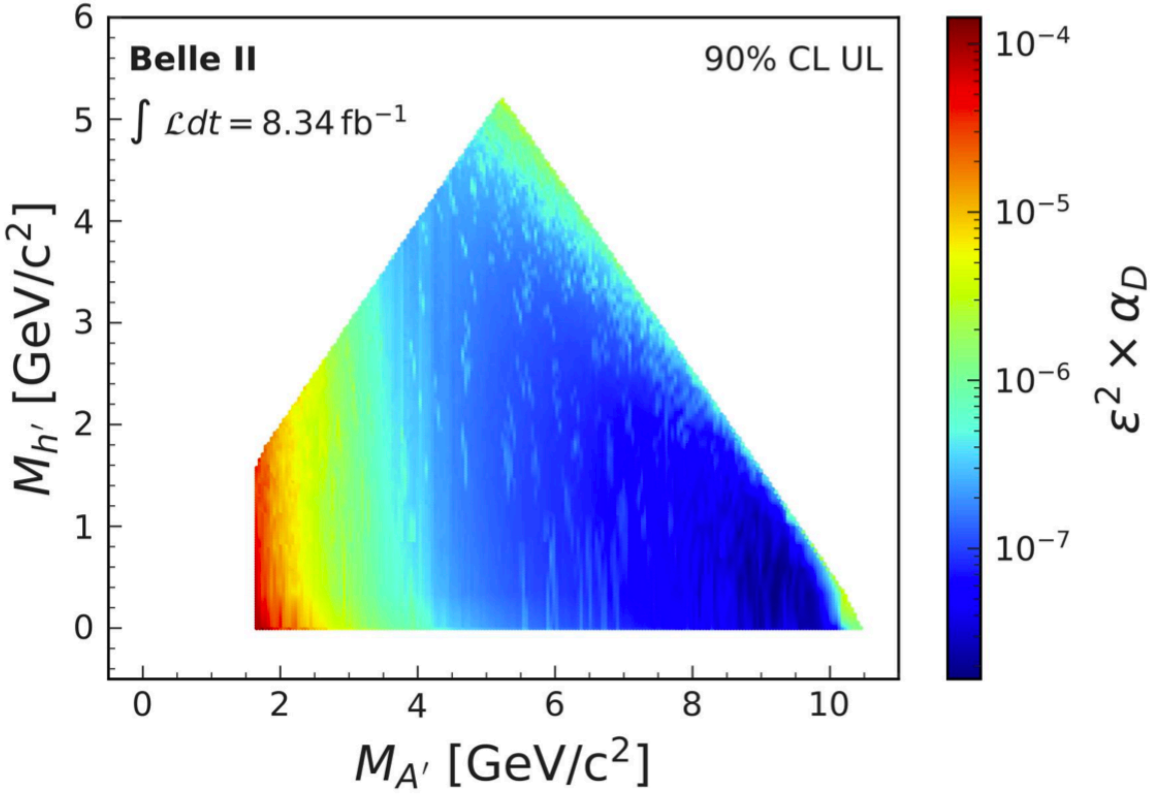


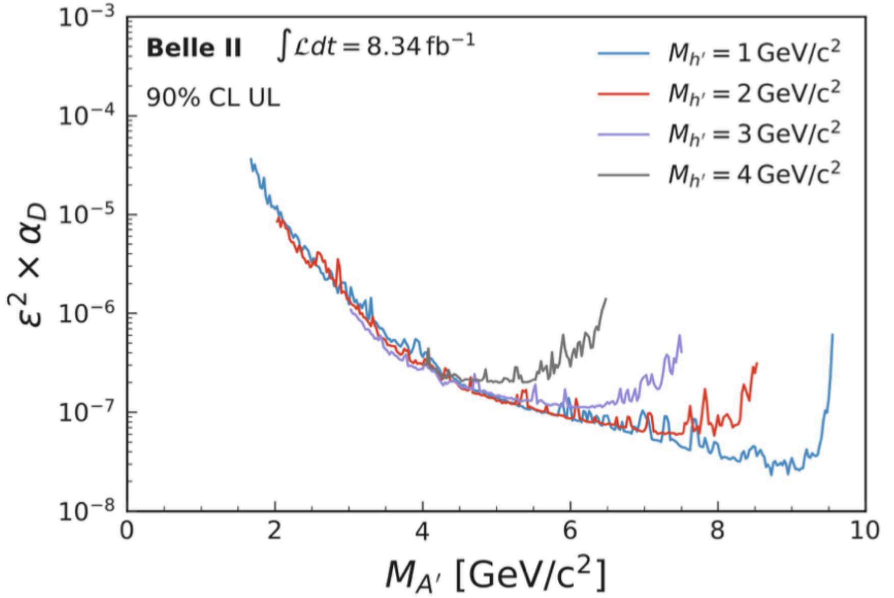
We compute 90% Bayesian credibility level (CL) upper limits on the cross section for the dark Higgsstrahlung process $e^+e^- \to A'h'$ with $A' \to \mu^+\mu^-$ and h' invisible as a function of $M_{A'}$ and $M_{h'}$ using the Bayesian Analysis Toolkit software package [46]. We assume flat priors for all positive values of the cross section, Poissonian likelihoods for the number of observed and simulated events and Gaussian smearing to model the systematic uncertainties, accounting for their correlations.

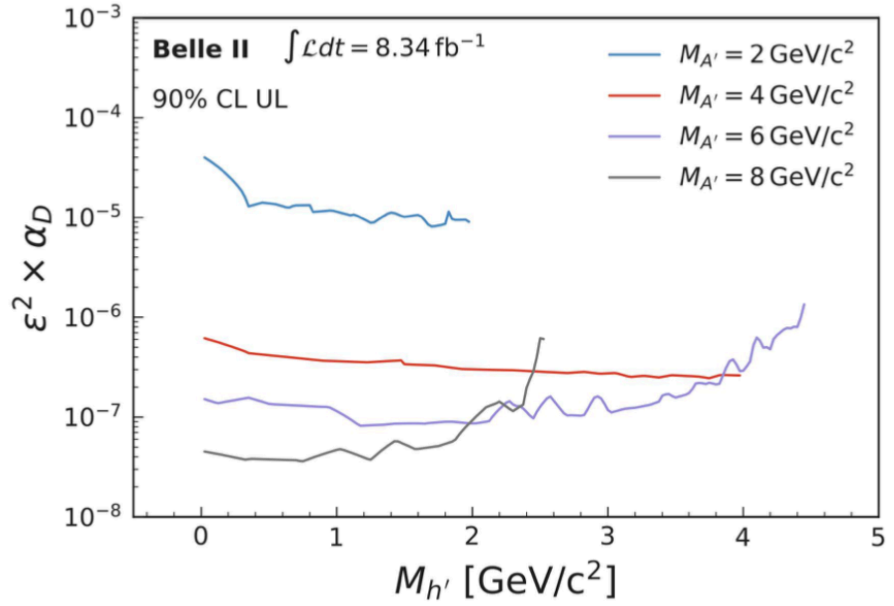
Dark Higgsstrahlung: signal efficiency



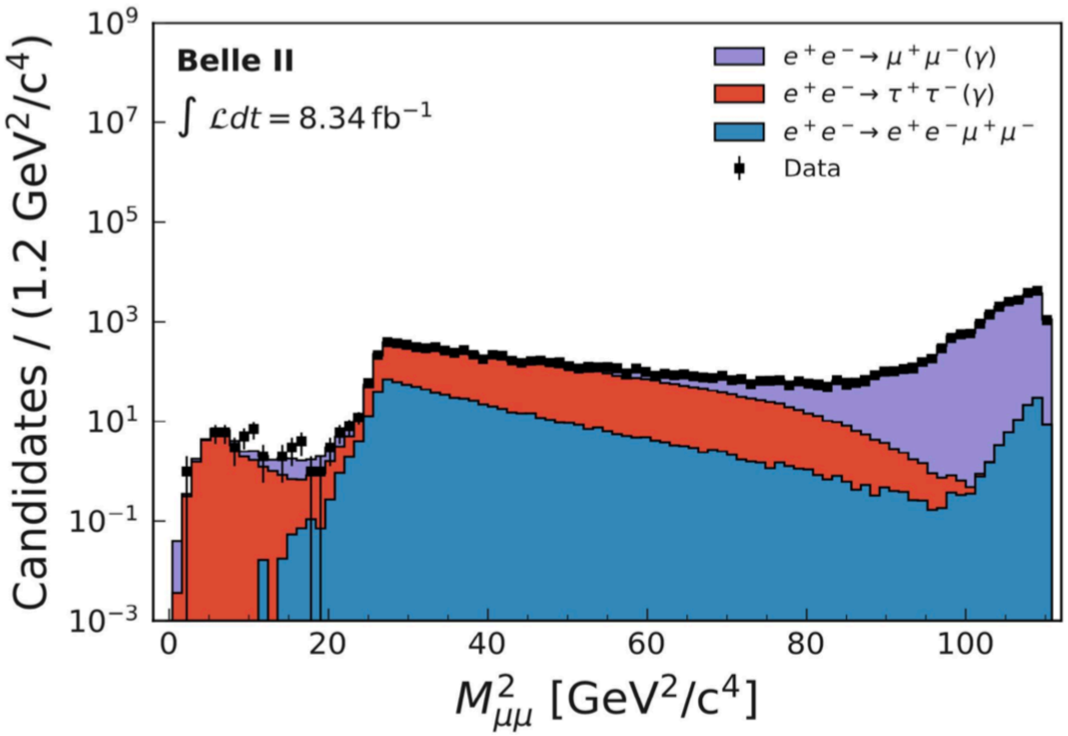
Limits on effective coupling ϵ^2 x σ

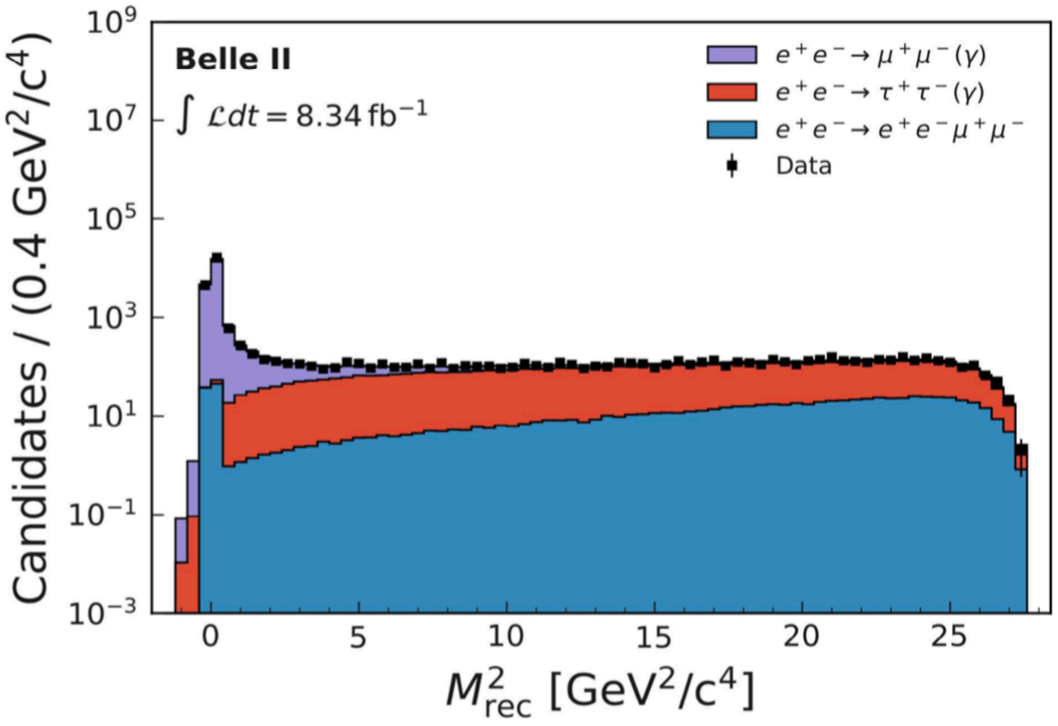






Dark Higgsstrahlung

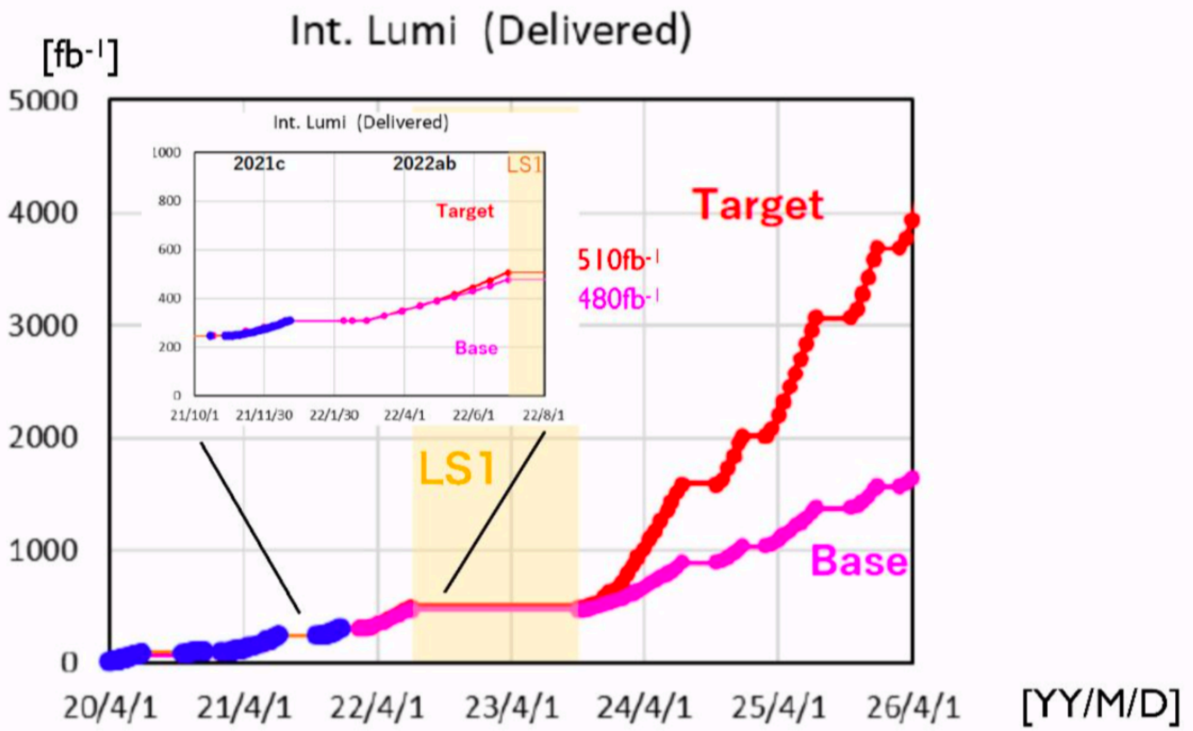




Projection of integrated luminosity delivered by SuperKEKB to Belle II

Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run

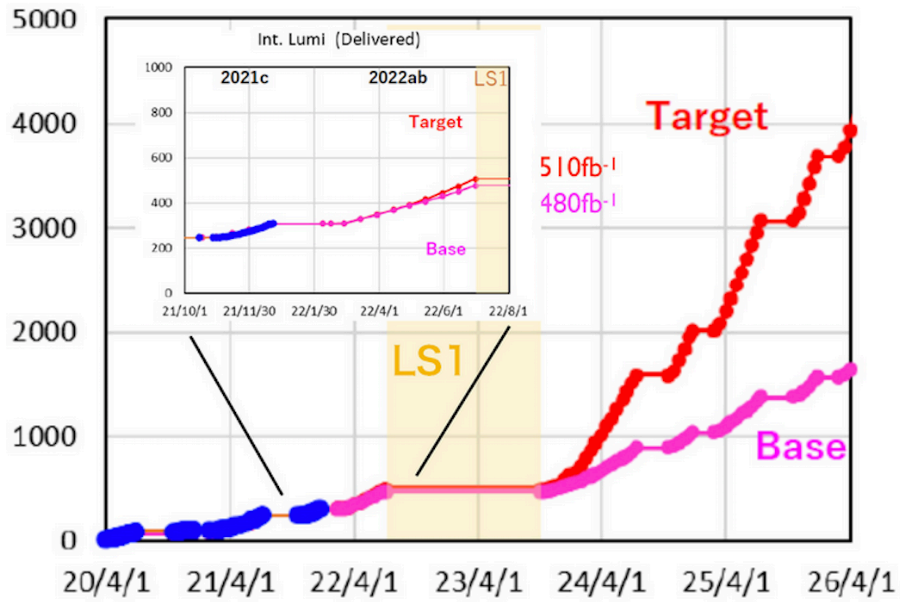


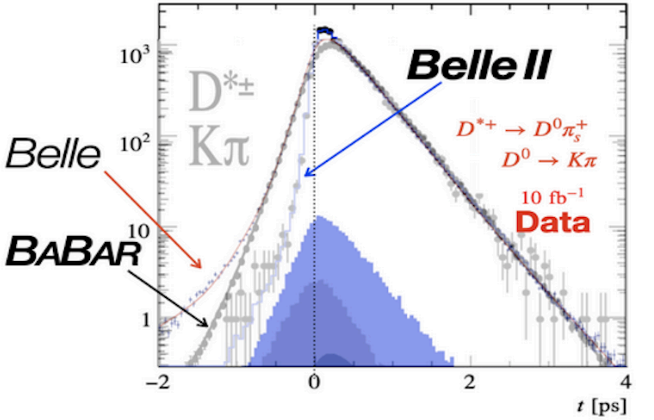
- We start long shutdown 1 (LS1) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement works of machine and detector.
- We resume physics running from Fall 2023.
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.
- An LS2 for machine improvements could happen on the time frame of 2026-2027

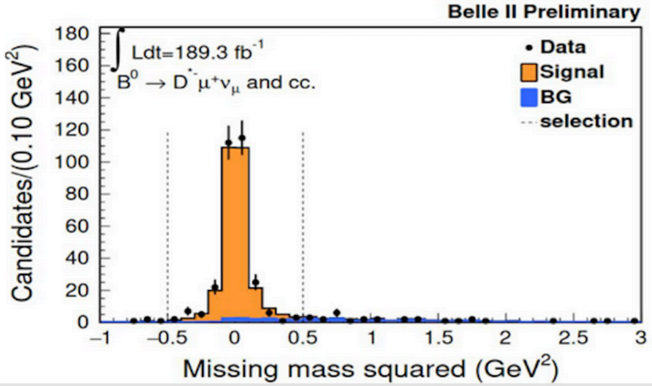
Belle II performances

SuperKEKB performance below expectations, but common when exploring **uncharted territory**

- Lint = 190 fb-1 (¼ Belle full dataset)
- **world-record Linst** = 3.81*10^34 cm-2 Hz
- divide between expectation/achievement shrunk in 2021, also thanks to International Task Force
- Long shutdown 1 (LS1) starting summer 22







Good detector performance, allowing precision physics results and measurements with challenging final states

- **Tracking and vertexing:** working nominally, as shown with B0 mixing and charmed hadrons lifetime measurements
- **Neutral performance:** Good, Belle-like performances
- **PID performance:** μ-ID superior to Belle, K-ID not there yet but improving
- **Flavour tagger** performance comparable to Belle (efftag=30%) and **tag-side reconstruction** (for missing energy analyses) has 30-50% better efficiency than Belle at same purity
- Novel menu of triggers unavailable in Belle enable compelling **low-multiplicity/dark-sector program**

SuperKEKB designed machine parameters

Machine Parameters

2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.20×10^{-4}	4.55×10^{-4}		
σ_δ	$7.92(7.53)\times10^{-4}$	$6.37(6.30)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	():zero current
ν_s	-0.0245	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	