Dark sector and tau physics at Belle II

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on behalf of the Belle II collaboration

Rencontres de Moriond:
Electroweak Interactions & Unified Theories
March 12-19, 2022

Dark-sector and tau physics

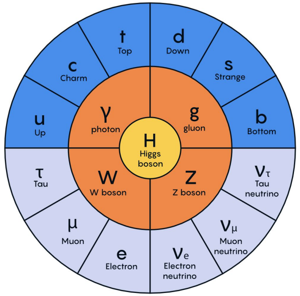
Light dark matter

- dark (hidden) sector coupled to SM only via light meditator (portal)
- portals can take different forms…
  - **Vector portals (dark photon)**
  - (pseudo) scalar, heavy-neutral lepton…
- MeV-GeV scenarios can be probed at B-factories

Tau physics:

- new physics may couple to 3rd gen.
- precision measurements of tau properties
  - deviations from SM **indirect** signs of NP
- searches for forbidden decays
  - observation would be **direct** and unambiguous signs of NP!

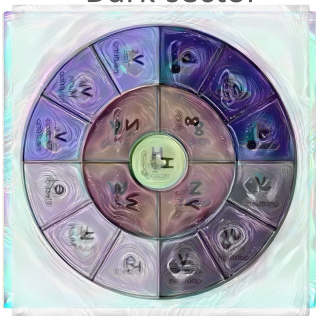
SM



dark portals

A’, Z’, H, ..

Dark-sector



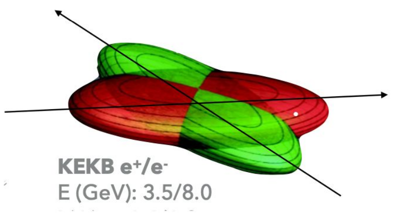
experimental requirements:

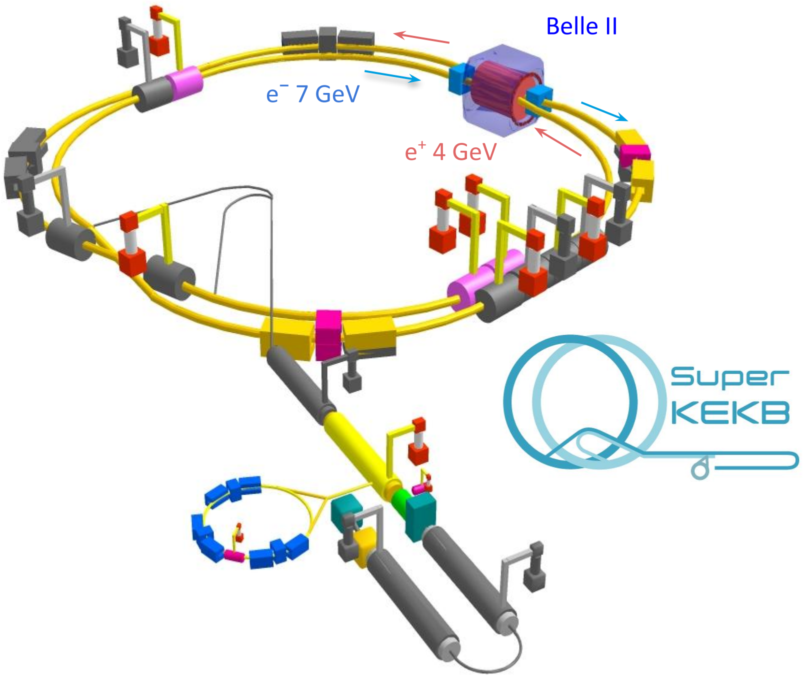
- good missing energy reconstruction
  - hermetic detector
  - clean initial state
- excellent vertexing capabilities
- ability to trigger low-multiplicity events

new for Moriond: search for dark Higgsstrahlung

SuperKEKB

- energy-asymmetric e^+e^- collider in Tsukuba, Japan
- collision energy (mostly) at $\Upsilon(4S)$ $\sqrt{s}$ =10.58 GeV
- target:
  - instantaneous lumi: $6\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
    30 larger than KEKB
  - integrated lumi: 50 ab^{-1}
    50 times larger than KEKB
- improvement achieved via the nanobeam scheme (20x smaller beam spot) and higher beam current





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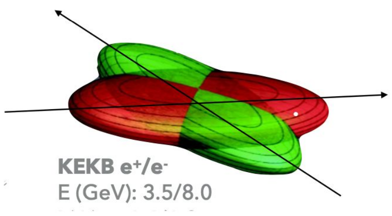
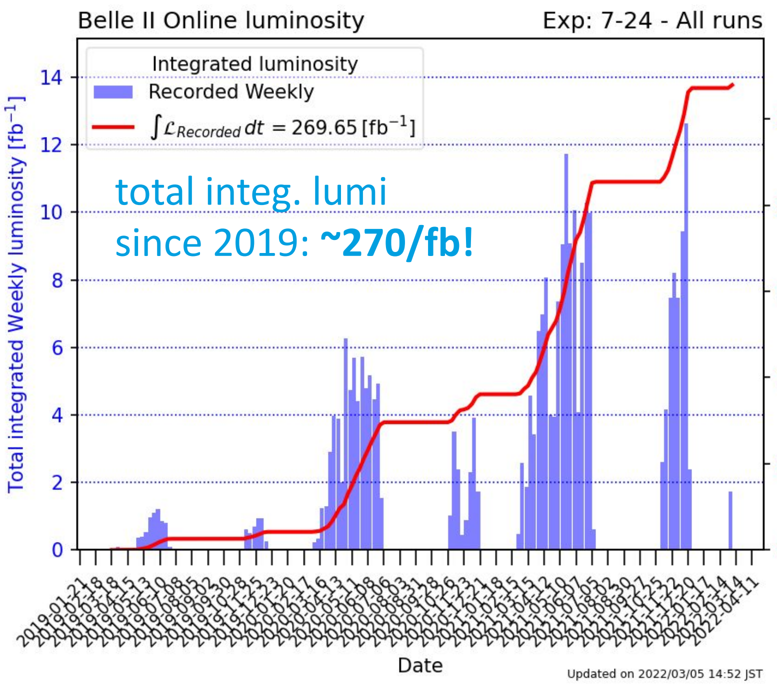
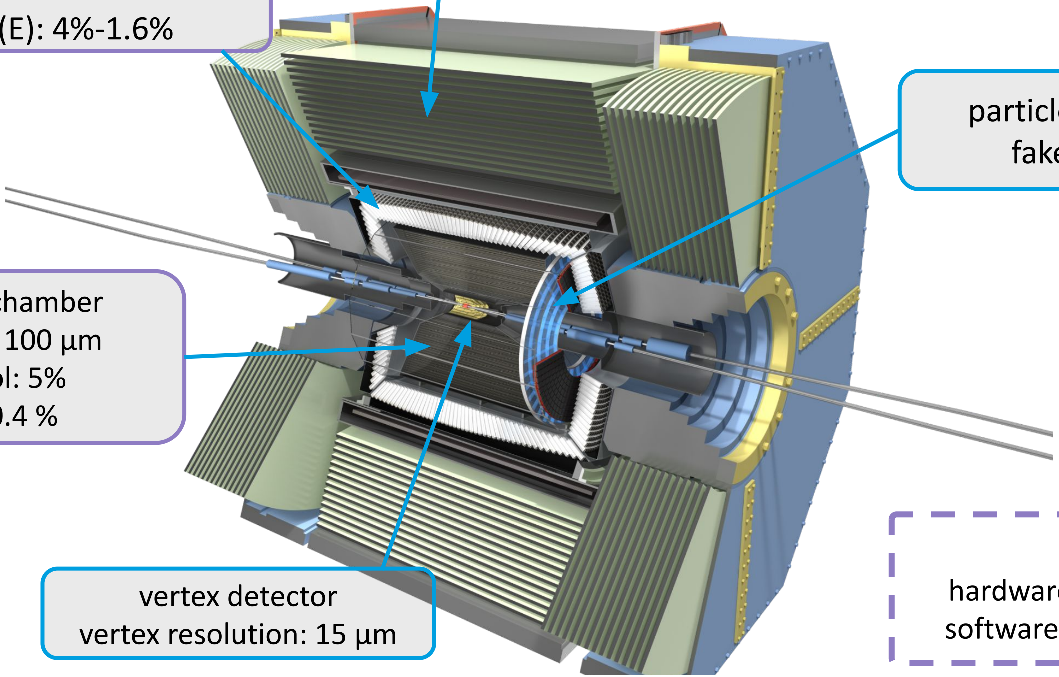




⇒ World record inst. luminosity of $3.8\text{x}10^{34}$ cm^2/s achieved!
(even with smaller beam currents compared to KEKB)

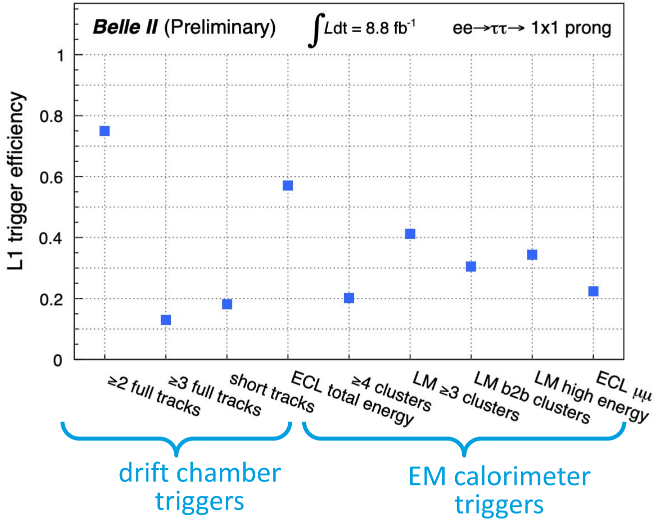
Belle II detector

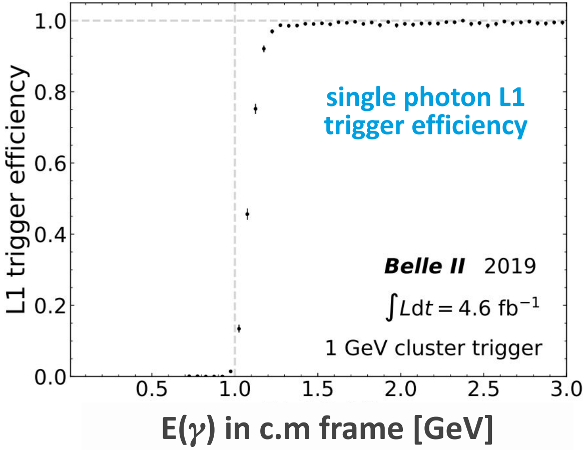


trigger:
hardware rate (L1) < 30 kHZ
software rate (HLT) < 10 kHZ

Trigger performance

- essential for dark-sector and tau physics
  - typical signatures include low-multiplicity of tracks, and energy deposits in EM calorimeter
  - large background from radiative Bhabha and two-photon processes
- some of the dedicated low-multiplicity triggers:
  - single muon
    - combine drift chamber and muon detector information
  - single track:
    - neural-net based hardware trigger
  - single photon:
    - high efficiency for E(γ) > 1 GeV





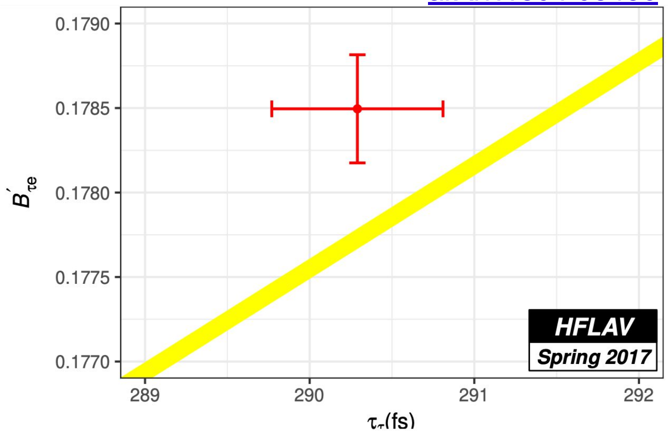
Tau sector

Tau physics: precision measurements

- Precision measurements of the **tau mass** and **tau lifetime** are crucial for lepton flavor universality tests of the SM:

$$B_{\tau\ell}^{SM} = B_{\mu e}\boxed{\frac{\tau_\tau}{\tau_\mu}\frac{m_\tau^5}{m_\mu^5}}\frac{f_{\tau\ell}}{f_{\mu e}}\frac{r_W^\tau r_\gamma^\tau}{r_W^\mu r_\gamma^\mu}$$

arXiv:1804.08436



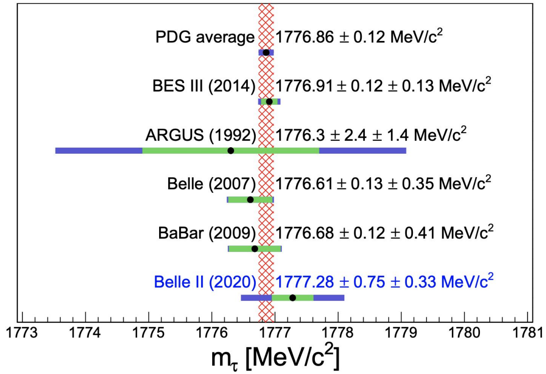
Tau mass

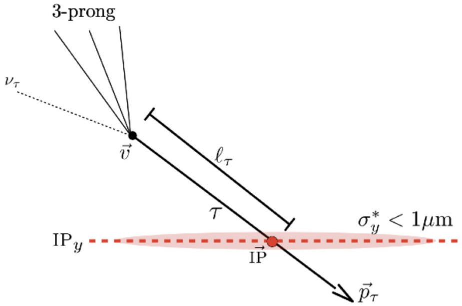
- preliminary measurement, already compatible systematics with Belle

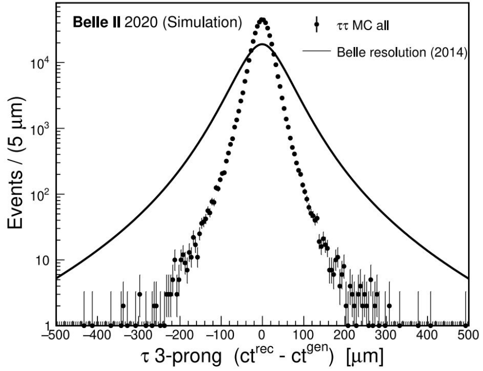
Tau lifetime

- use IP-constraint to get production vertex
- 2x better decay-time resolution compared to Belle

arXiv:2008.04665



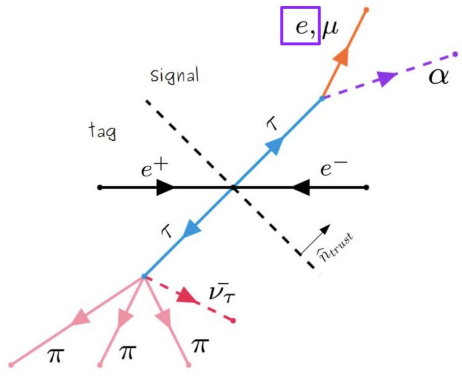




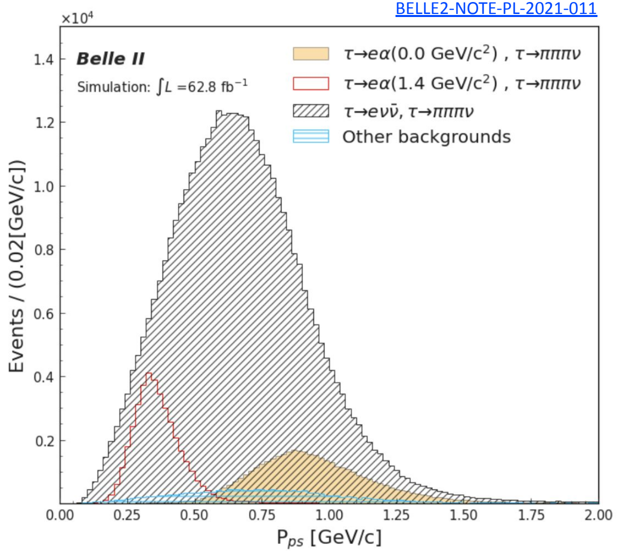
⇒ Challenging systematics!

Tau physics: forbidden decays?

- Lepton flavor violation
  - for charged leptons?
    - allowed within SM (via neutrino osc. in loops) but highly suppressed
    - observation would be clear sign of NP
  - $\tau \to \ell\ell\ell$, $\tau \to \ell V_0$, $\tau \to \ell\gamma$, ….
    - extensively studied at Belle and BaBar
    - but not $\boldsymbol{\tau \to \ell \alpha}$!
- $\boldsymbol{\tau \to \ell \alpha}$:
  - α: any invisible gauge boson (possible DM candidate)
  - best limits are currently by ARGUS
  - p_ℓ expected to peak in the **tau pseudo-rest frame** (approximated tau rest-frame from 3π system)
  - expected limits show we can already improve the sensitivity reach!



BELLE2-NOTE-PL-2021-011



p_e in tau pseudo-rest frame

Dark sector

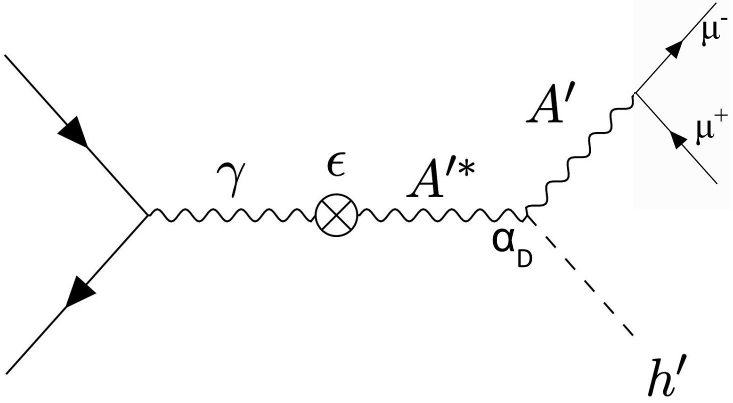
Dark Higgsstrahlung

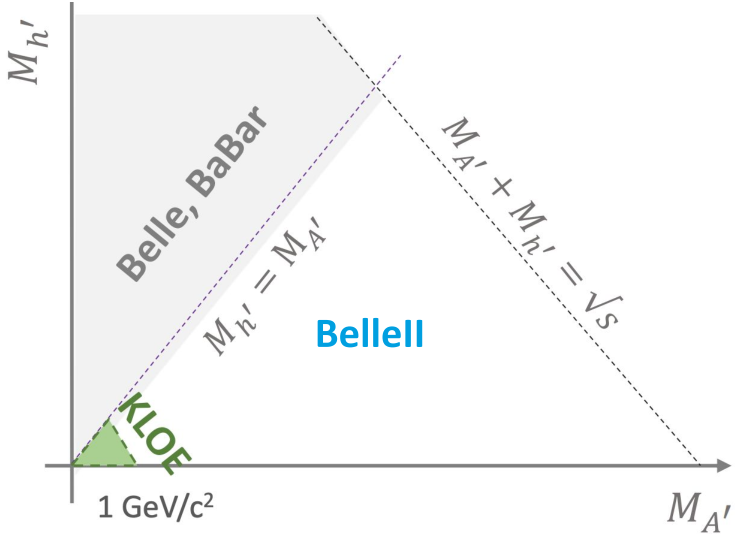
new for Moriond

Dark Higgsstrahlung

New for Moriond

- U(1)' extension of the SM
  - massive dark photon (**A'**) as the mediator
  - spontaneous symmetry breaking (analogous to SM) ⇒ a dark higgs (**h'**)
  - A' couples to SM only via kinetic mixing (ϵ)
  - α_D: dark coupling constant
- Mass hierarchy scenarios:
  - $M_{h'} > M_{A'}$:
    - dominant decay: h' ⟶ A' A'$^{(*)}$
    - signature: 6 charged tracks
    - probed by Belle, BaBar
  - **$M_{h'} < M_{A'}$ (considered in this analysis)**
    - long-lived (invisible) h'
    - signature: **missing energy** and OS charged tracks (here **$\mu^+\mu^-$**)
    - partly probed by KLOE



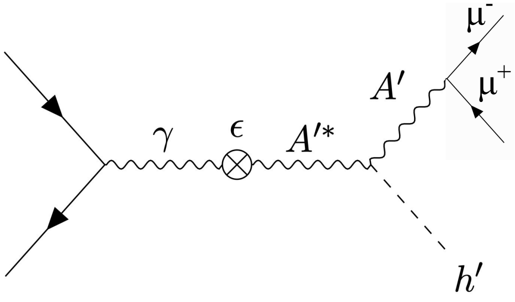


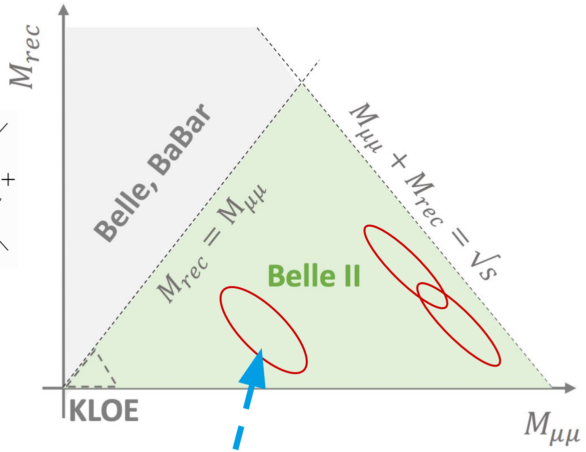
⇒ Exploring unconstrained territories at BelleII!

Dark Higgsstrahlung: signature and strategy

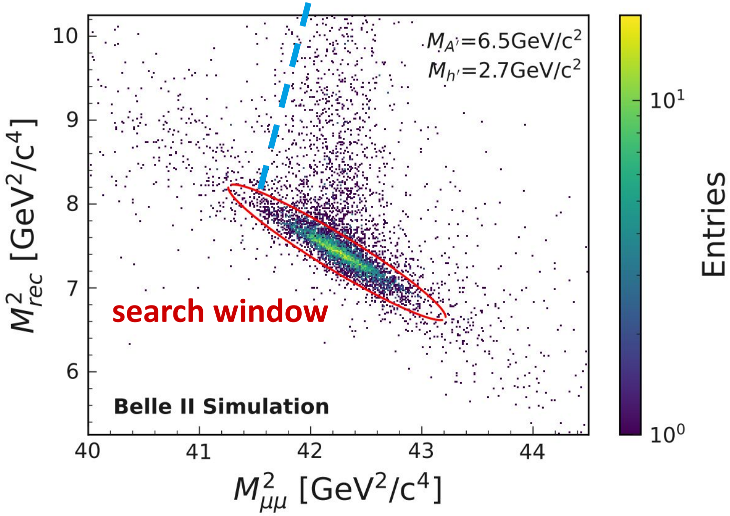
- **Signature:**
  - 2D peak in $M_{\mu\mu}$ vs M_{rec}:
    - dimuon invariant mass ($M_{\mu\mu}$)
    - invariant mass of the system recoiled against dimuons (M_{rec})

$$M_{rec}^2 = s + M_{\mu\mu}^2 - 2\sqrt{s}E_{\mu\mu}$$





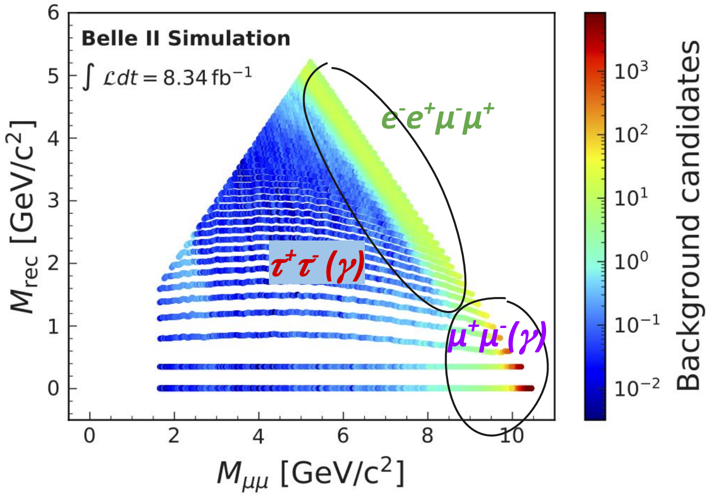
- **Search strategy: scan and count**
  - exploit correlations: M_{reco} & $M_{\mu\mu}$ ($M_{h'}$, $M_{A'}$ dependant)
  - search windows:
    - **~9000 2D elliptical mass windows in M^2_{reco} & $M^2_{\mu\mu}$**
      $\Rightarrow$ large look-elsewhere effect
    - overlapping windows to maximize signal efficiency
    - on average, one event in ~3 windows

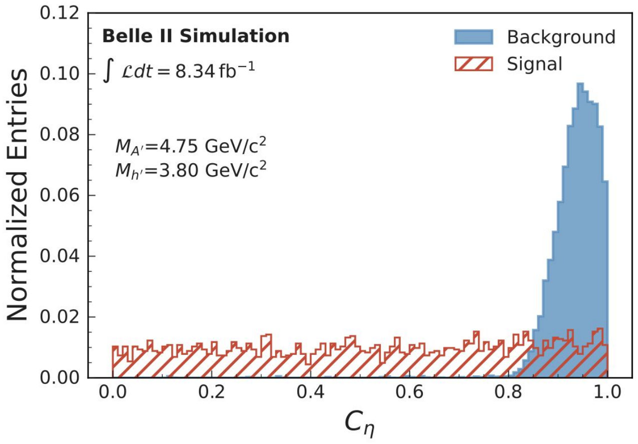


Dark Higgsstrahlung

- Backgrounds
  - dominant backgrounds:
    - ***$\mu^+\mu^-(\gamma)$ (79%)***
    - ***$\tau^-\tau^+(\gamma)$ (18%)***
    - ***$e^-e^+\mu^-\mu^+$ (3%)***
  - different contributions in different regions

- Background suppression:
  - helicity angle (C_η = cos($\theta_{helicity}$))
    - flat for signal
    - peak at 1 for bkg
    - cut value optimized in each search window ([Punzi F.o.M](#))

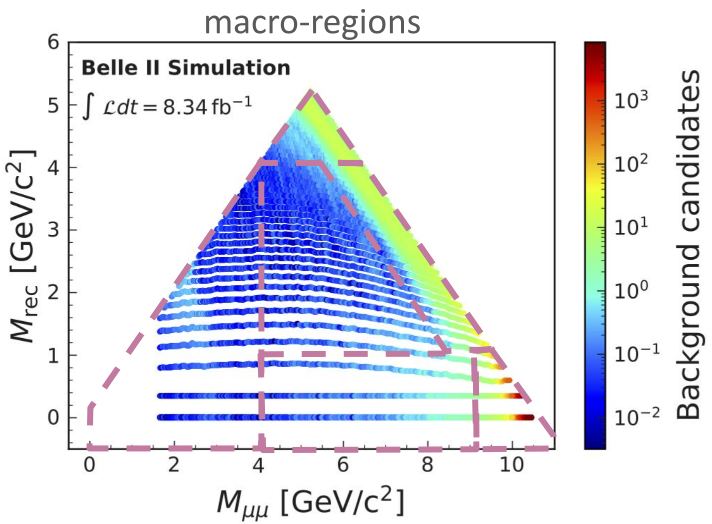


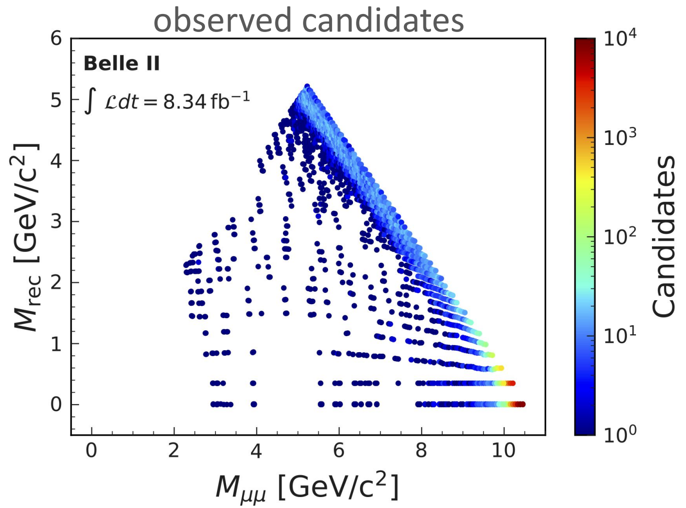


Dark Higgsstrahlung: systematics

- Control studies:
  - **$\mu^+\mu^-$ (γ):** require an energetic photon (instead of vetoing γ's)
  - **eμ:** require an electron instead of muon
  - Split mass-plane in non-overlapping “macro-regions”
    - each mostly dominated by a single source of bkg
    - Check for global agreement, bkg shape modelling, recoil mass resolution
    - discrepancies are assigned as systematics
- Systematics:
  - impacting both signal and background: 2.2%-12.7%
  - impacting signal only:
    - differences in M resolution in data/MC (1-5%), BR theory uncert. 4%
- Results: interpreted as $N = \epsilon_{sig} \times L \times \sigma + B$

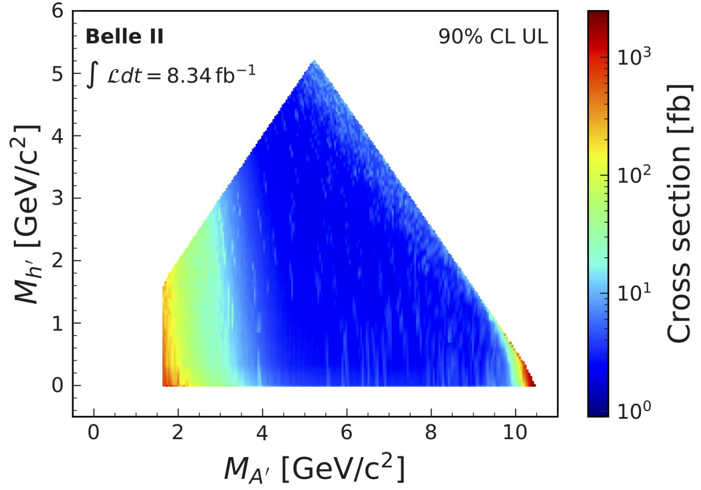
⇒ No significant deviation from the SM bkg expectation is observed

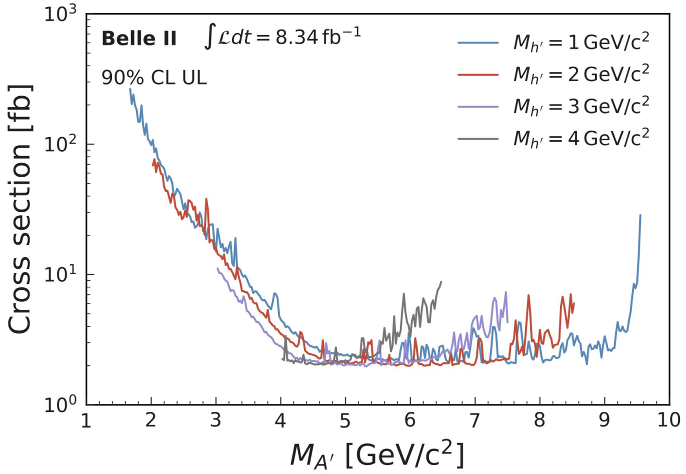


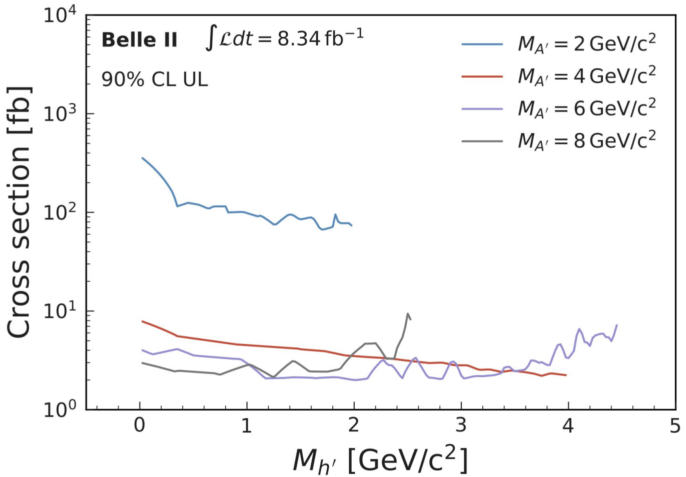


Dark Higgsstrahlung: results

- Upper limits are set on σ and $\epsilon^2 \alpha_D$:
  - covered region: $1.65 < M_{A'} < 10.51$ GeV and $M_{h'} < M_{A'}$
  - **90% CL UL on σ ranges from 1.7 to 5 fb**
    - in the most sensitive regions ($4 < M_{A'} < 9.7$ GeV)
  - for $M_{A'} < 4$ GeV: low sensitivity due to trigger efficiency
  - for $M_{A'} > 9$ GeV: large dimuon background







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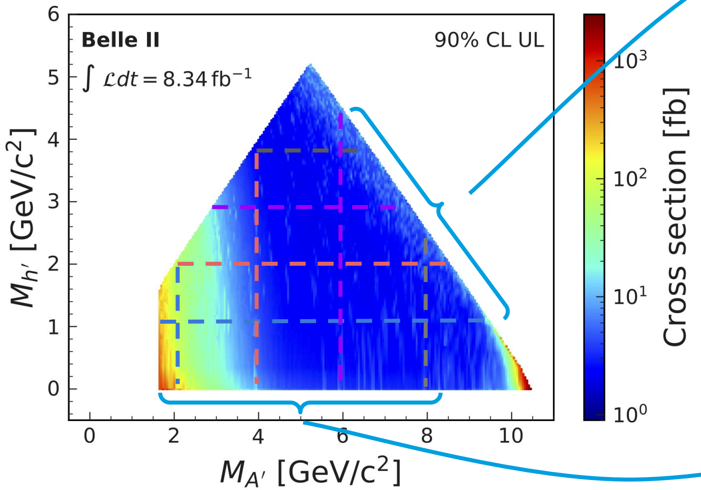
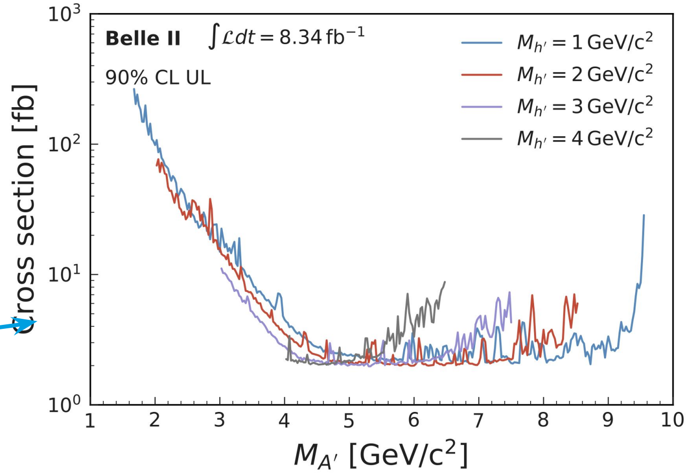
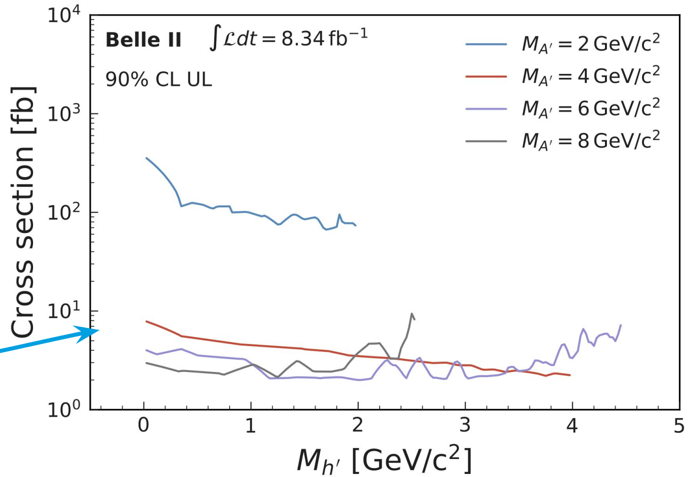






⇒ World-leading results, in previously unexplored regions!

Summary

- Tau physics at Belle II:
  - may provide direct and indirect insights into new physics
  - Belle II will be the leading tau factory in the coming years
- Dark-sector at Belle II:
  - dark-sector mediators in the MeV-GeV range are being explored at Belle II
  - brand-new results: **search for dark Higgsstrahlung**
    - large previously-unexplored regions of parameter space are probed
    - world's most stringent limits on ϵ^2 for a wide range of α_D values!
- More results in the pipelines:
  - Invisible Z' search, $\tau \to \ell \alpha$, tau mass measurement …

Thank you!

See more from Belle II:

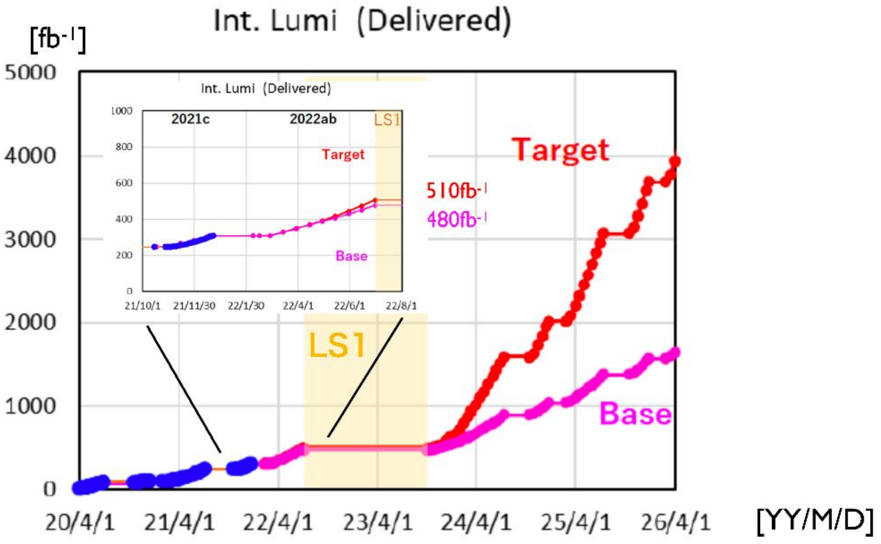
- **Time-dependent CP violation and charmless decays** (Thibaud Humair)
- **Charm and B to charm decays at Belle II** (Riccardo Manfredi)
- **EW penguins and radiative B decays at Belle II** (Elisa Manoni)
- **Semileptonic B decays at Belle II** (William Sutcliffe)

Backup

Projection of integrated luminosity delivered by SuperKEKB to Belle II

Target scenario: extrapolation from 2021 run including expected improvements.

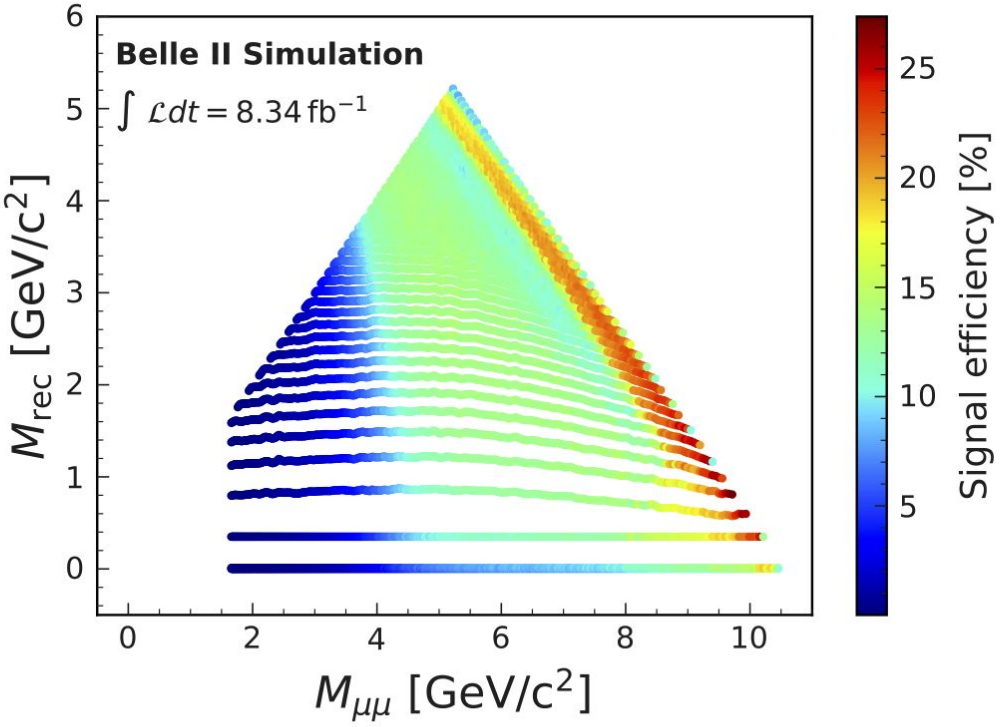
Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run



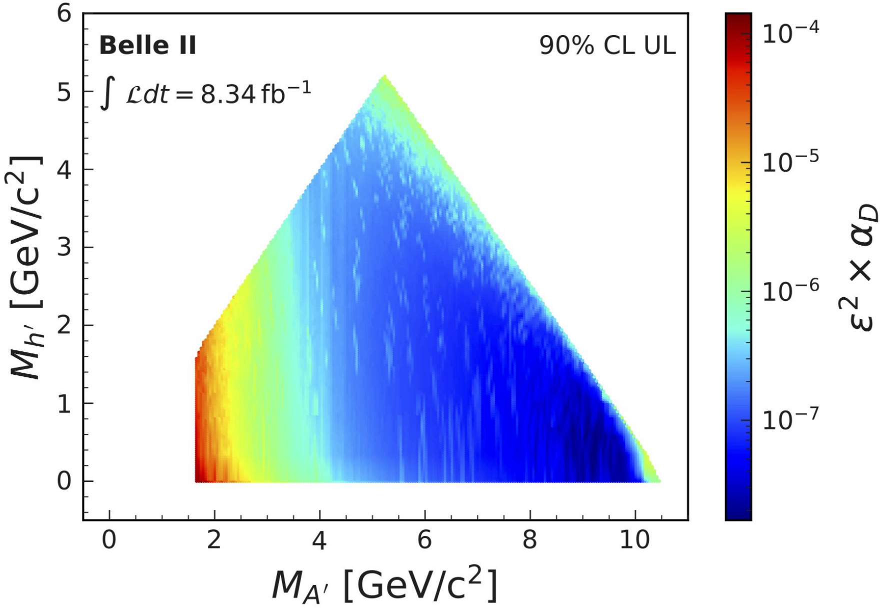
- We start long shutdown 1 (LS1) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement works of machine and detector.
- We resume physics running from Fall 2023.
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.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

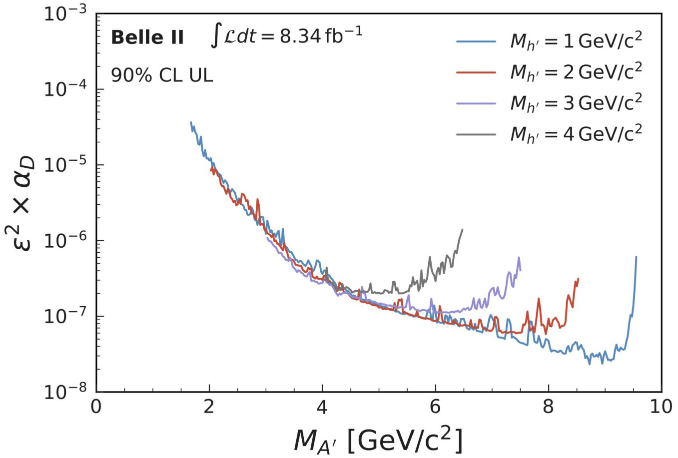
Dark Higgsstrahlung

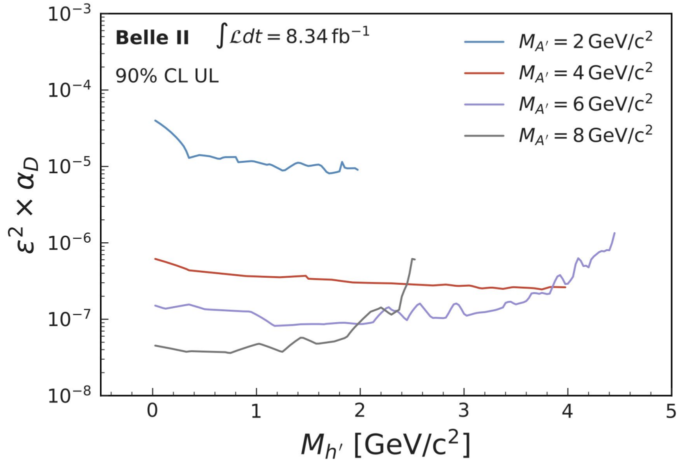
Dark Higgsstrahlung: signal efficiency



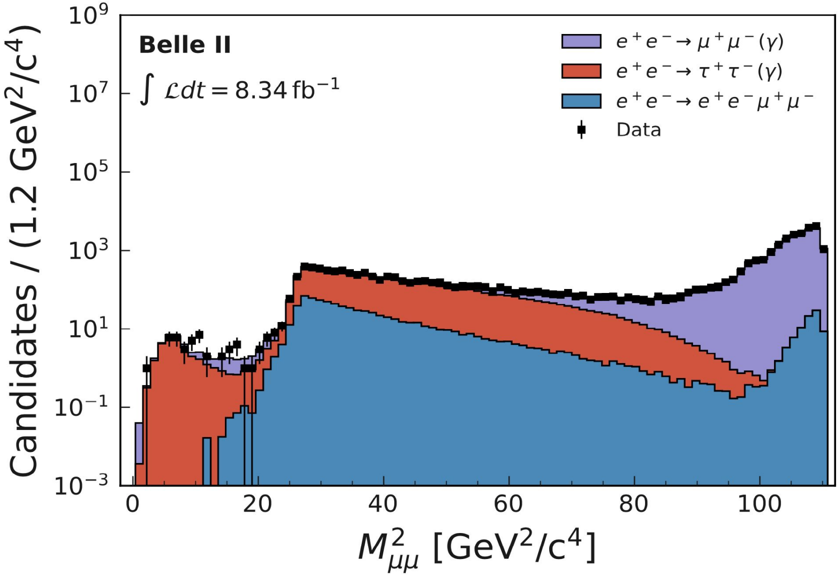
Limits on effective coupling ϵ^2 x σ

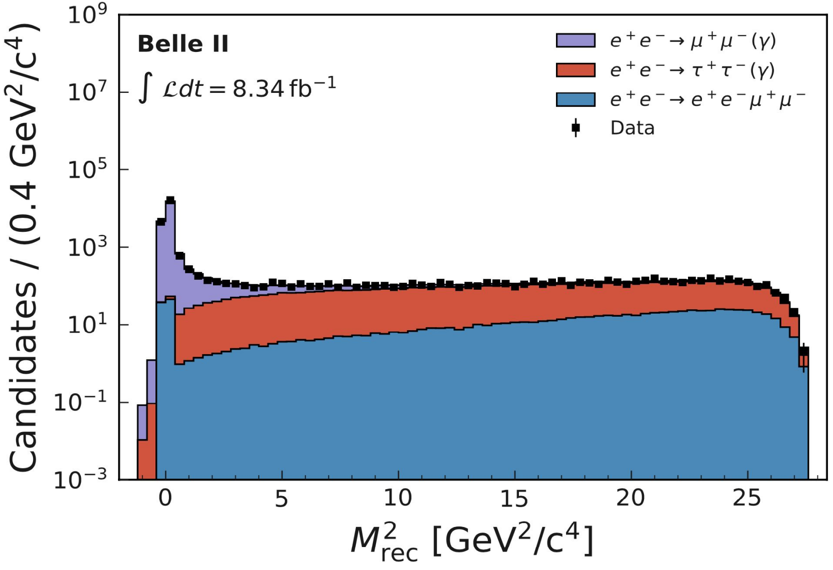






Dark Higgsstrahlung



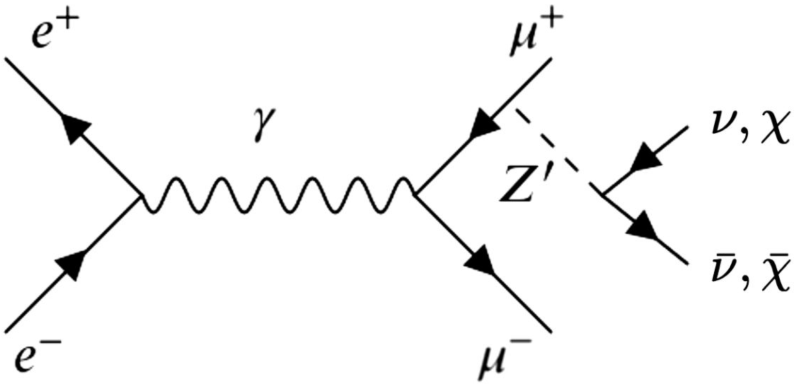


Invisible Z'

The invisible Z' and dark Higgsstrahlung searches

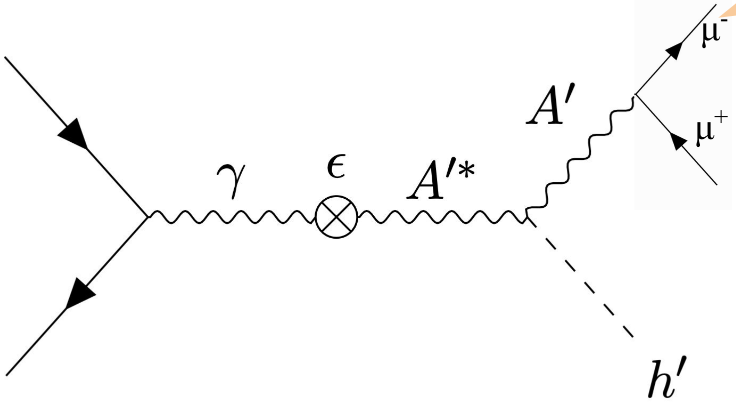
- (next-to) minimal U(1) extensions of SM
- Signature:
  - pair of OS leptons and missing energy
- Strategy: bump search $M^2_{rec} = s + M^2_{\mu\mu} - 2\sqrt{s}E_{\mu\mu}$
  - invisible Z': peak in $\mathbf{M_{recoil}}$
  - dark Higgsstrahlung: **2D peak in $\mathbf{M_{recoil}}$ vs. $\mathbf{M_{\mu\mu}}$**
- Backgrounds:
  - $\mu^+\mu^-(\gamma)$, $\tau^-\tau^+(\gamma)$, $e^-e^+\mu^-\mu^+$
- Common challenge…. Trigger!
  - trigger on events w/ two CDC tracks
  - opening angle in transverse plane larger than 90°

Invisible Z' search



Dark Higgsstrahlung

New!!

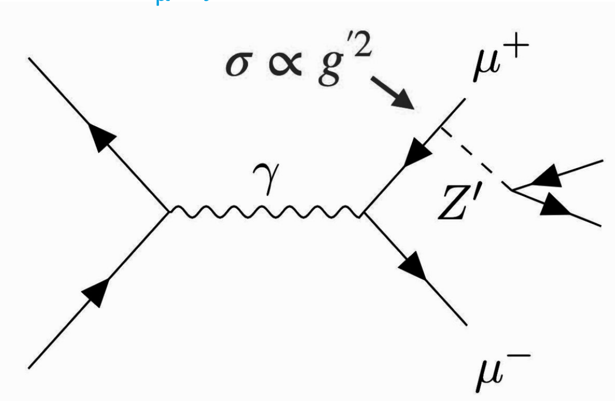


Invisible Z' (L_μ-L_τ and LFV)

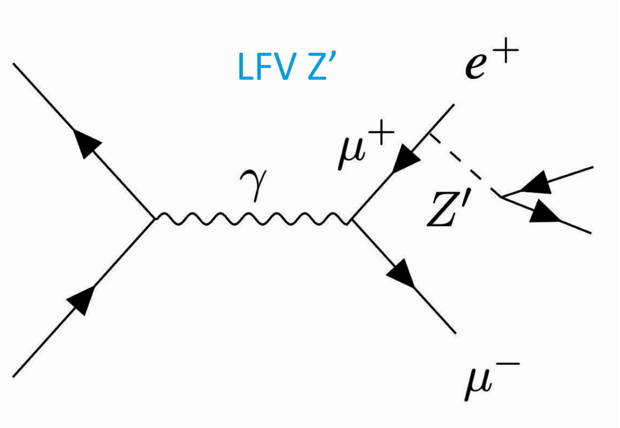
PhysRevLett.124.141801

- New light gauge boson Z'
  - L_μ-L_τ Z' (standard Z'):
    - only interacts with 2nd and 3rd gen. leptons
    - may explain: DM, (g-2) anomaly, b−>sℓℓ anomalies
  - LFV Z': e-μ coupling
- Signature:
  - **standard Z':** $\mu^+\mu^-$ + missing energy
  - **LFV Z':** μ^+e^- + missing energy
  - bump search in M_{recoil}
- First physics publication by BelleII
  - 2018 pilot-data taking run ($276 pb^{-1}$)
  - sensitivity $M_{Z'}$ < 5-6 GeV/c2

L_μ-L_τ Z' (standard)



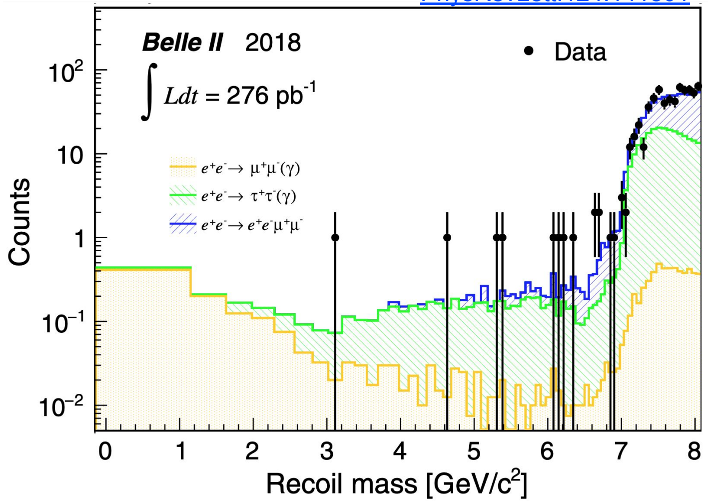
LFV Z'

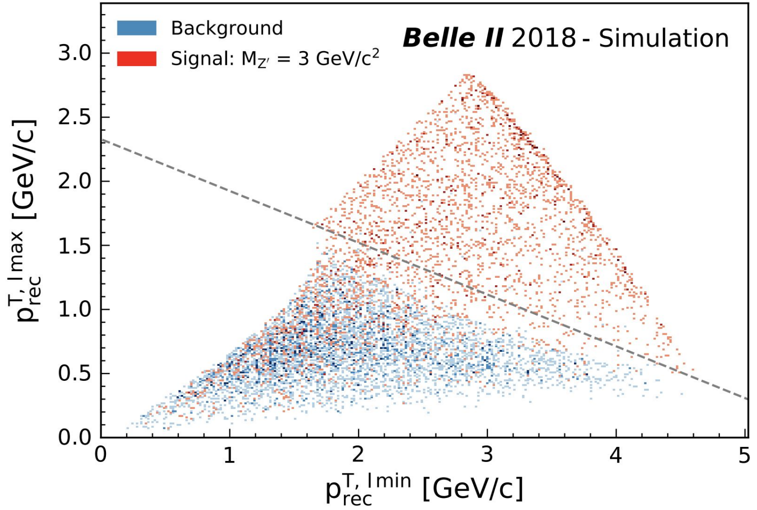


Invisible Z’: strategy

PhysRevLett.124.141801

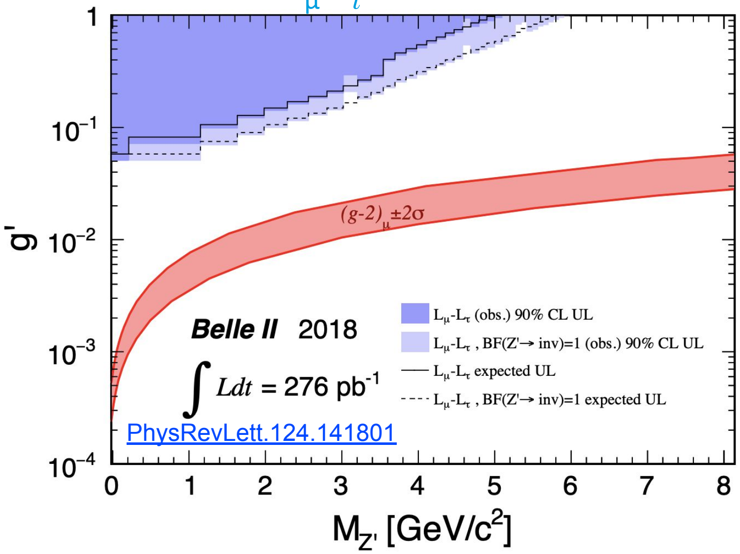
- Mass windows in M_{recoil}
  - selected as ±2σ of M_{recoil} resolution of Z’ signal
  - data/MC resolutions validated in $\mu\mu\gamma$, $e\mu\gamma$ and ee
- Background suppression
  - optimized using a Punzi F.o.M in each mass window
  - exploit differences in recoil kinematics
    - transverse components of P_{recoil} w.r.t to the leptons
- Systematics:
  - tracking/trigger efficiency, PID (1-6%)
  - data/MC agreements in control samples (12.5-22%)



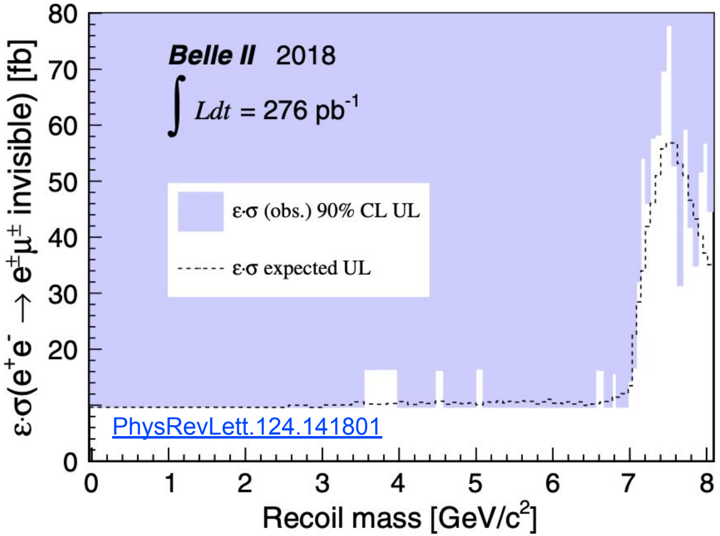


Invisible Z’: results

L_μ-L_τ Z’ (standard)



LFV Z’



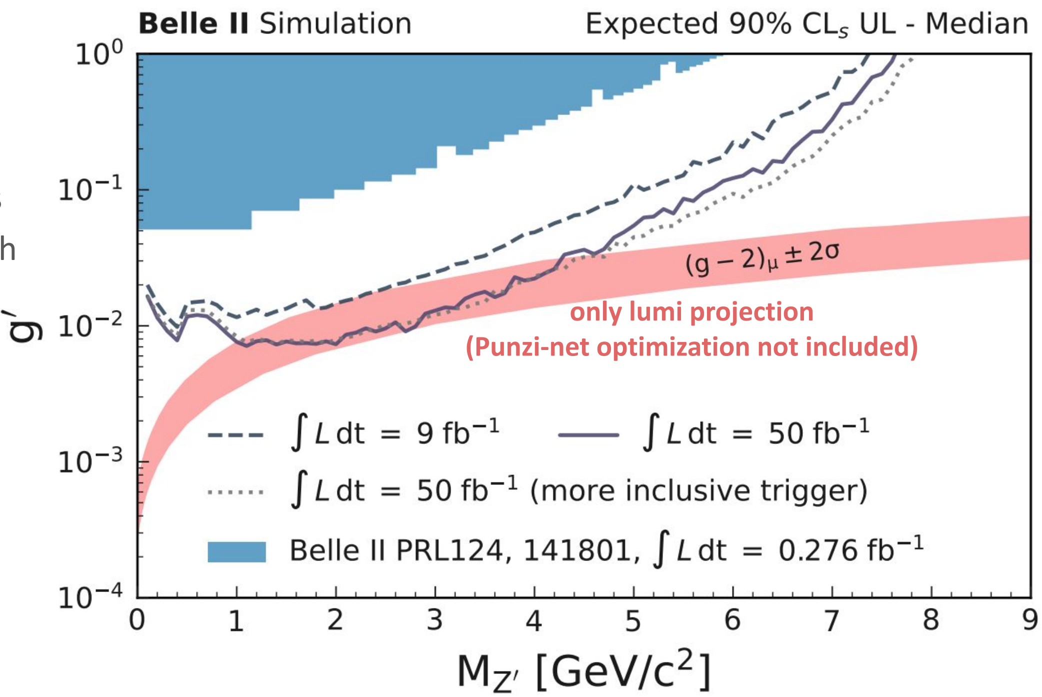
No significant deviations are observed

⇒ Limits are set for the g’ for the standard Z’ and the $\epsilon\sigma$ for LFV Z’

Z’: future

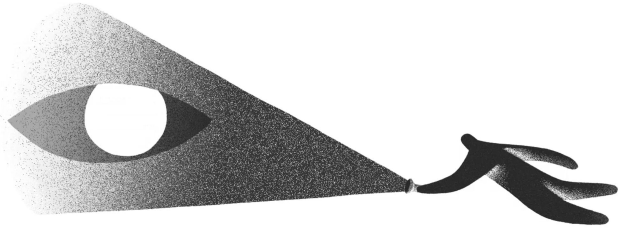
- Invisible Z’:
    - New optimized analysis in the pipelines
        - using a novel “Punzi-net” approach ([Eur. Phys. J. C (2022) 82: 121](#))
        - more inclusive trigger
        - much larger data set (almost 300 times larger)

[BELLE2-NOTE-PL-2020-012](#)

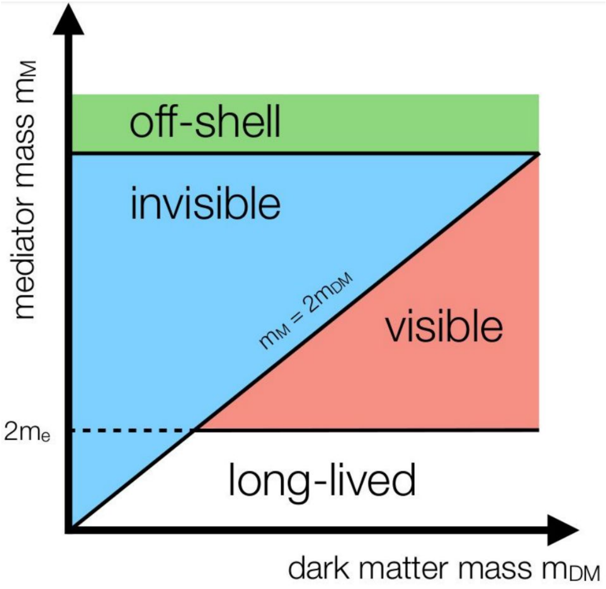


⇒ Updated Z’ results expected very soon!!

Probing the dark-sector at Belle II



- Why at Belle II?
  - relatively “clean” initial e^+e^- state
  - Hermetic detector
  - vertex identification capabilities
  - dedicated low multiplicity triggers (single γ, single track, ECL trigger…)
- portals to the dark-sector can take different forms…
  - **Vector portals (dark photons, Z’)**
  - Scalar portals
  - pseudo-scalar portal (ALPs)
  - heavy-neutral-lepton portals
  - and many more!



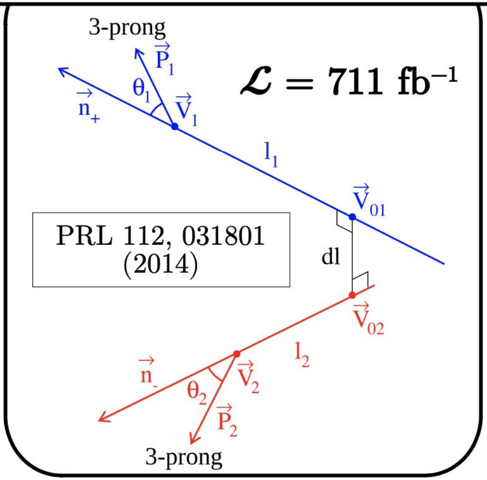
⇒ BelleII can probe scenarios in MeV-GeV with wide range of signatures!

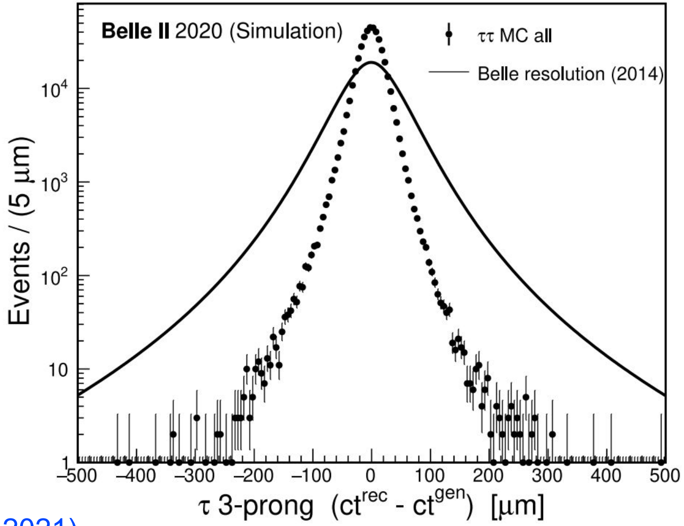
Tau lifetime, teaser

- at Belle:
  - the 3x3 tau decays
  - 700/fb
- at BelleII:
  - Factor 5 gain in stat. by using 3x1 instead of 3x3
  - With 200/fb already statistically compatible with Belle results
  - Systematics still to be studied… but, proper time resolution already 2x better than Belle!

World-best measurement

$$\tau_\tau = (290.17 \pm 0.53_{\text{stat}} \pm 0.33_{\text{syst}})\ \text{fs}$$





Stefano Moneta (EPIPHANY 2021)

Belle II → Factor ≃2 narrower

Tau Mass: Systematics

- Important systematics include:
  - Dominant systematic is the momentum SF
    - expected to improve with updated b-field map and momentum corrections
  - Beam energy systematics reduced significantly (w.r.t to Belle)
    - Belle: BE correction of 1 MeV
    - BelleII: BE uncertainty of 0.2 MeV (stat only)
  - Remaining systematics come from estimator bias mostly due to limited MC samples which also affects fit function and fit window

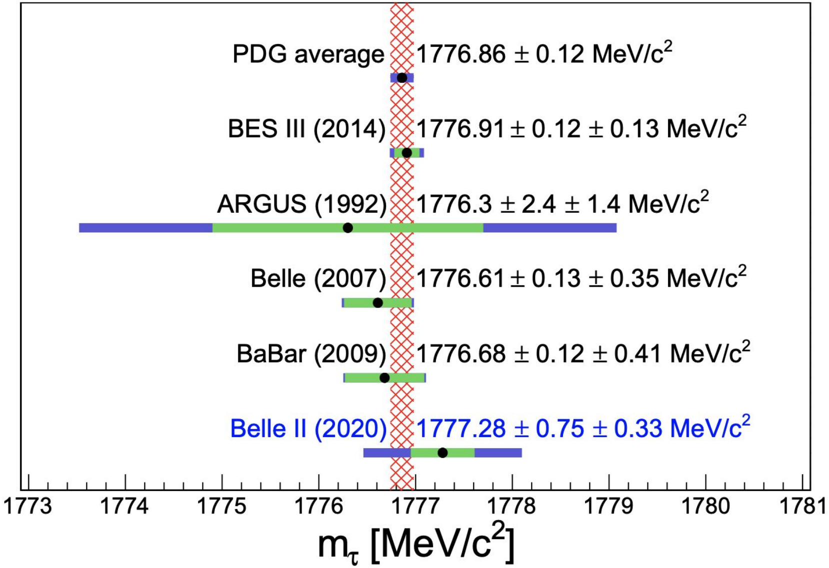
Systematic uncertainty	MeV/c^2
Momentum shift due to the B-field map	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	$\leq$ 0.01
Initial parameters	$\leq$ 0.01
Background processes	$\leq$ 0.01
Tracking efficiency	$\leq$ 0.01

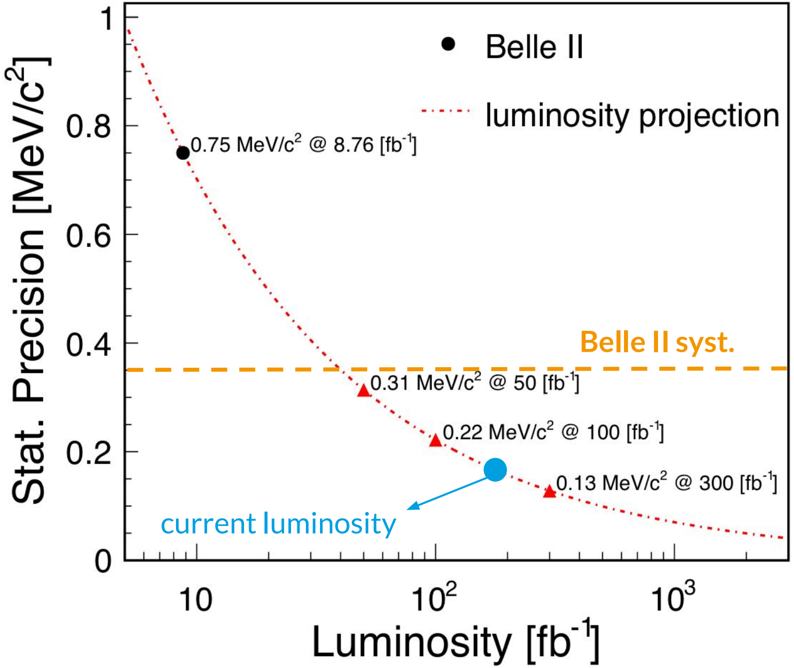
⇒ Total systematic uncertainty = 0.33 MeV

Belle Systematics: hep-ex/0608046v2

Source of systematics	σ, MeV/c^2
Beam energy and tracking system	0.26
Edge parameterization	0.18
Limited MC statistics	0.14
Fit range	0.04
Momentum resolution	0.02
Model of $\tau \to 3\pi\nu_\tau$	0.02
Background	0.01
Total	0.35

Tau Mass: Systematics

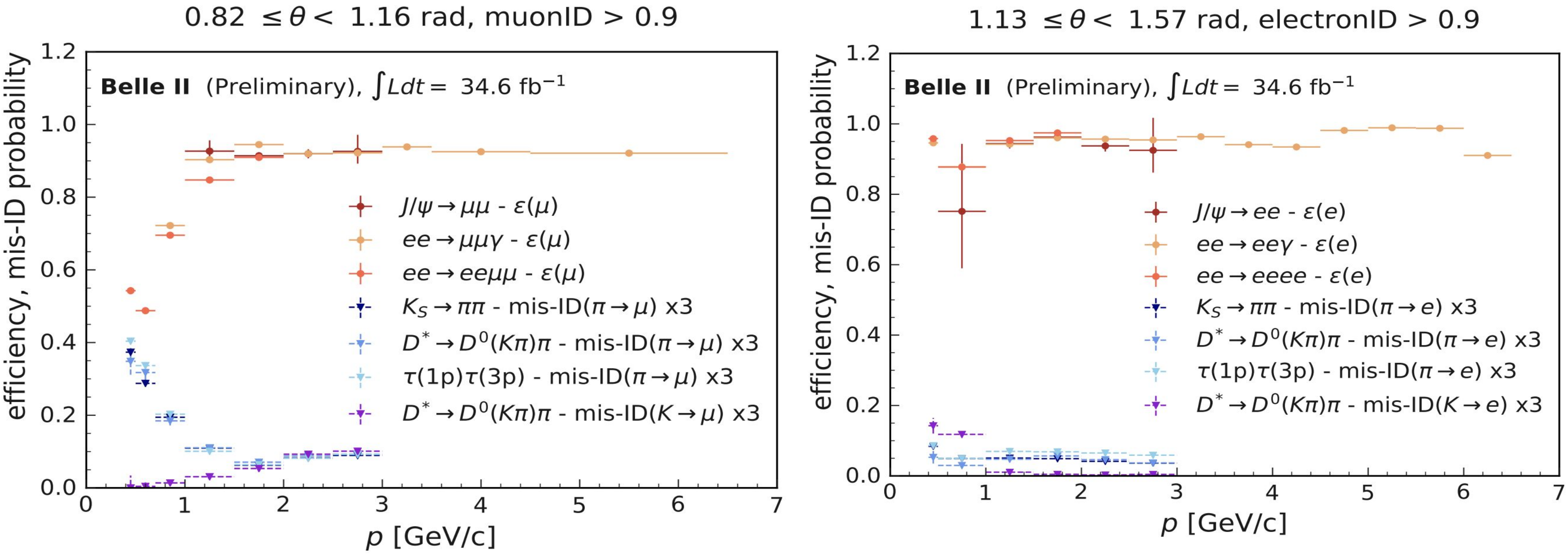




Lepton ID

BELLE2-NOTE-PL-2020-027

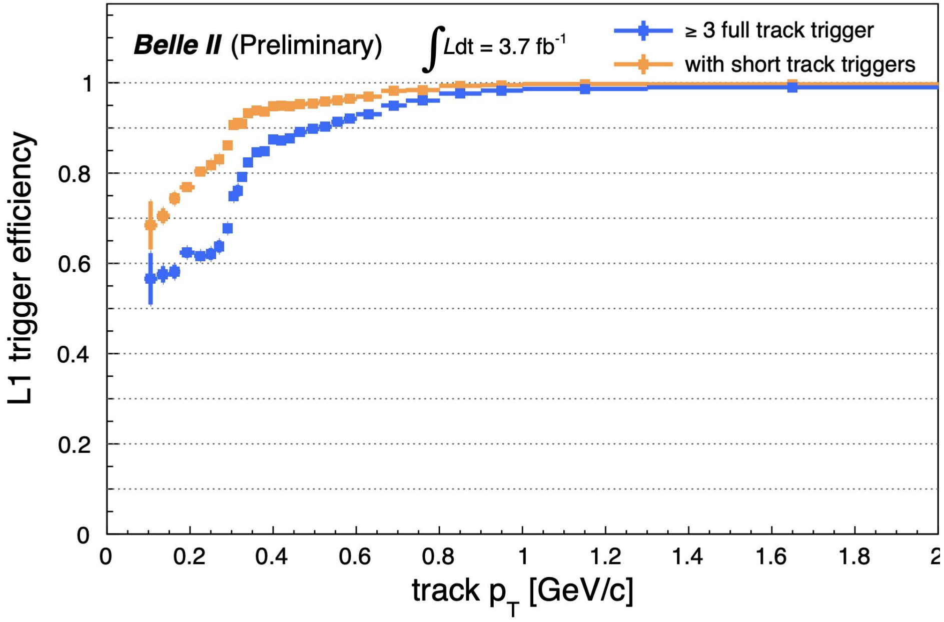
- electron and muon identification efficiencies measured in data

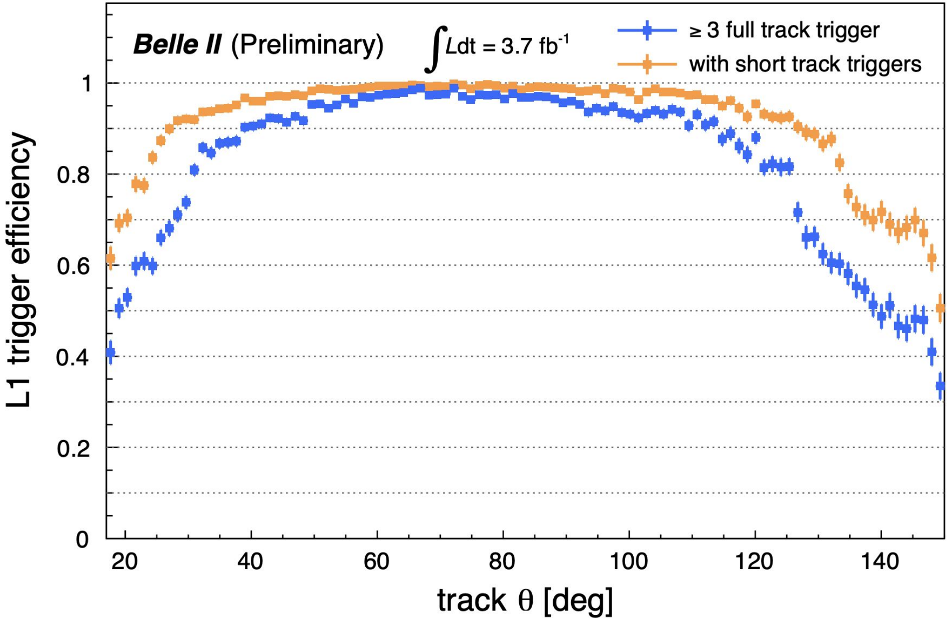


Trigger Efficiency

- Measured in 3x1 tau decays:
  - CDC track trigger efficiencies measured w.r.t to ECL trigger

BELLE2-NOTE-PL-2020-015





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	$7.92(7.53) \times 10^{-4}$	$6.37(6.30) \times 10^{-4}$		():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}		$cm^{-2}s^{-1}$	