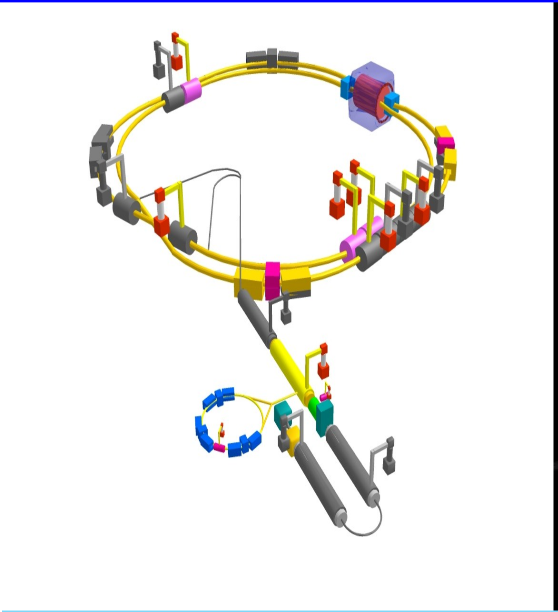
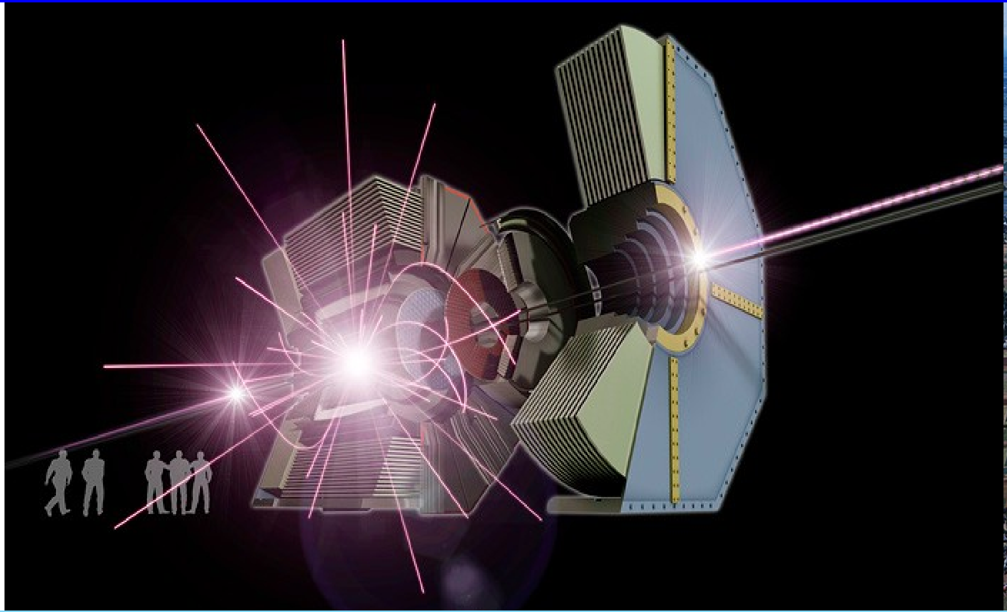
Belle II studies of missing energy decays and searches for dark photon production





DIS16
DESY, HAMBURG 11-15 APRIL 2016

24th International Workshop on Deep-Inelastic Scattering and Related Subjects

11-15 April 2016, DESY, Hamburg

Gianluca Inguglia- DESY
13/04/2016

Motivations

- Leptonic and semileptonic B decays can be used to probe new physics at tree level and in loops
  - Anomalies already observed in data

- The dark photon is proposed in many BSM theories to introduce possible interactions between dark matter particles
  - Can explain many anomalies observed in astrophysical if the mass in the few MeV- few GeV range

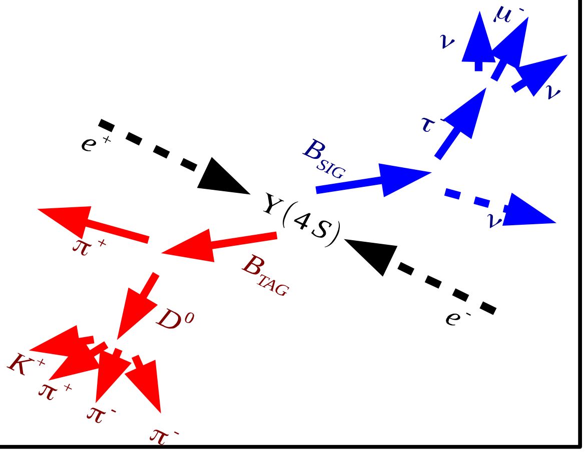
- With 50 ab-1 collected at Belle II experiment one should be able to resolve the observed anomalies and measure rare decays with missing energy. In addition one will have a high discovery potential in searches for the dark photon.

$$Br(\Upsilon(4S)\rightarrow B\overline{B}>96\%)$$

$$p(e^-)+p(e^+)=p(B)+p(\overline{B})$$

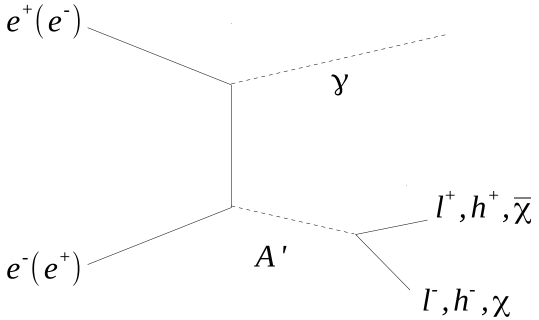
One B meson fully reconstructed: know flavour and momentum of the other

- Allow to study decays with missing energy
- More than 2K hadronic decays available for full reconstruction



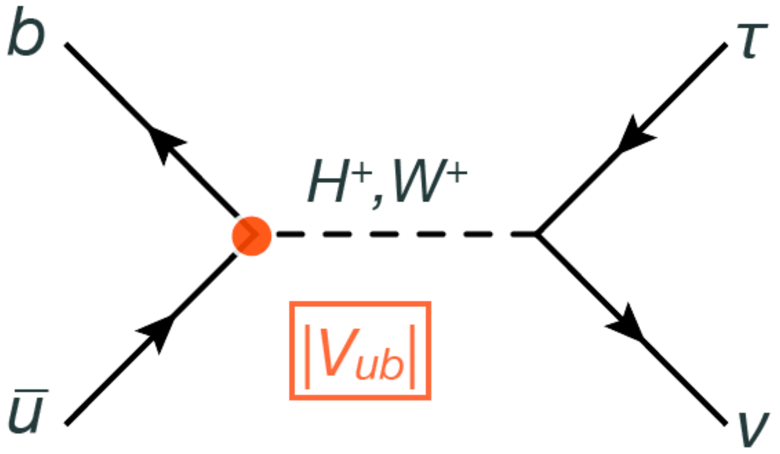
In e+e- collisions the dark photon is produced together with a photon

- Can use data collected at various energies
- Early data will already improve current limits



B →lυ

H⁺ Search: B⁺→τυ, μυ



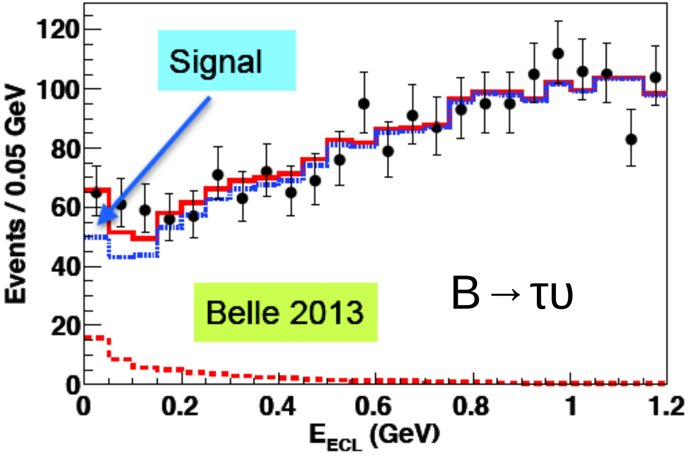
Helicity suppressed - very small in SM.

NP could interfere *e.g.* **charged Higgs.**

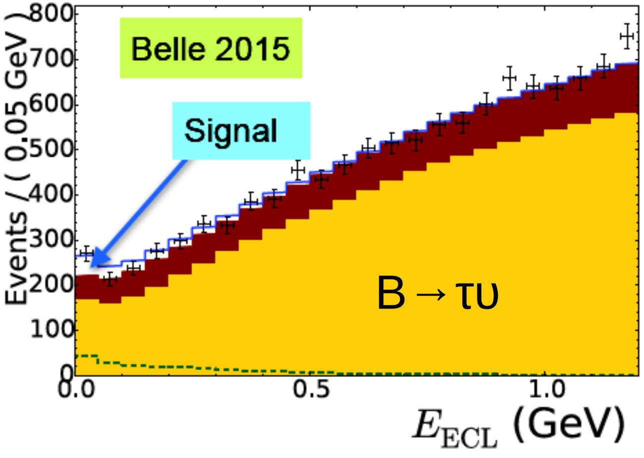
$$\Gamma(B^{\pm} \to \ell^{\pm}\nu) = \frac{G_F^2 m_B m_l^2 f_B^2}{8\pi} |V_{ub}|^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2 \times r_H$$

$$r_H = \left(1 - \frac{\tan^2\beta}{1 + \tilde{\epsilon}_0 \tan\beta} \frac{m_B^2}{m_{H^{\pm}}^2}\right)^2$$

Belle, hadronic TAG



Belle, SL TAG



Belle results

PRD 92, 051102 (2015)

PRD 82, 071101 (2010)

$Br(B^+ \to \tau^+ \upsilon)$=

Hadronic TAG

$[1.25 \pm 0.28 \pm 0.27] \times 10^{-4}$

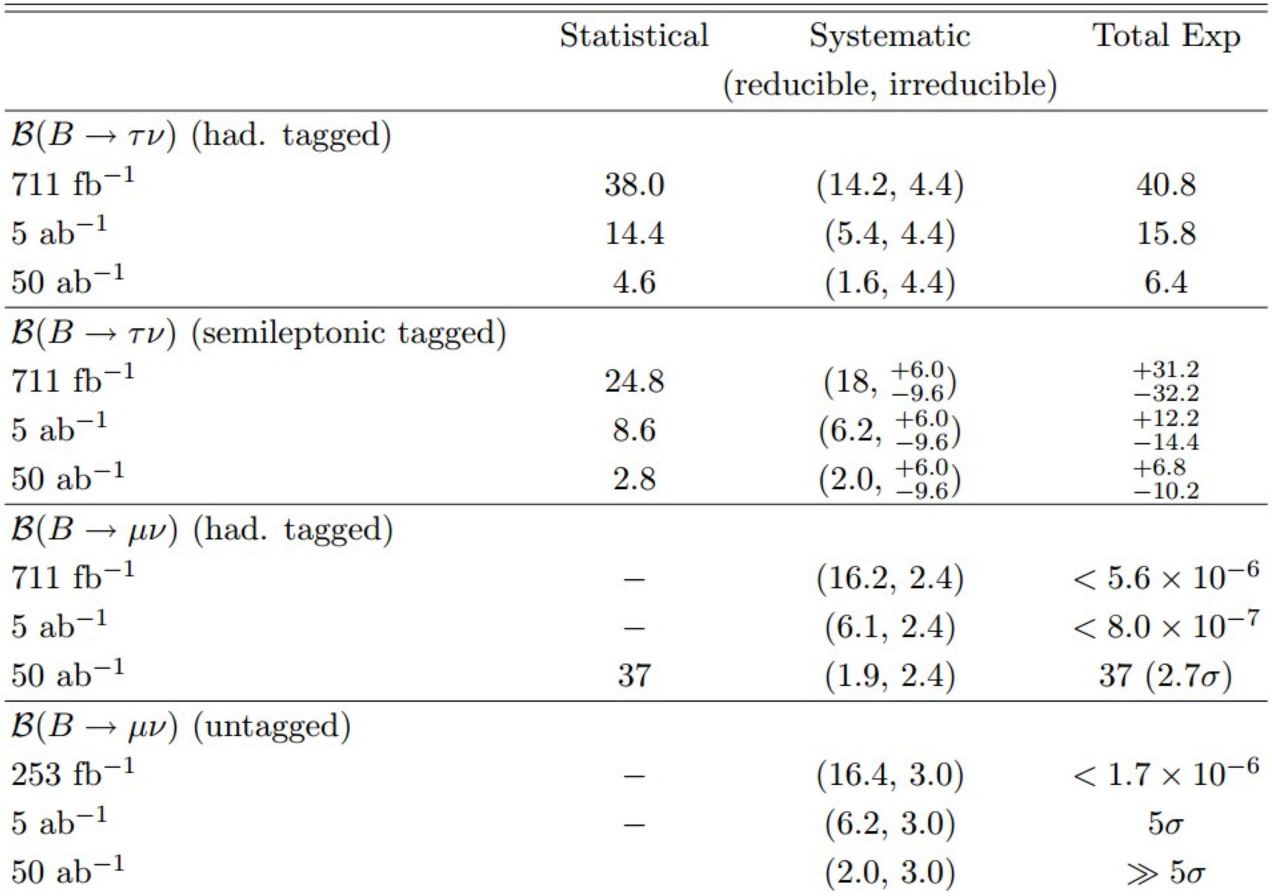
SL TAG

$[1.54 \pm 0.38 \pm 0.37] \times 10^{-4}$

Belle 2 sensitivity (50 ab^{-1})

$Br(B \to \tau\upsilon) \sim 4 * 10^{-5}$

Expected precision in leptonic B decay measurements with the Belle full data sample, and 5 ab^{-1} and 50 ab^{-1} of Belle II data.



	Statistical	Systematic (reducible, irreducible)	Total Exp
$\mathcal{B}(B \to \tau\nu)$ (had. tagged)			
711 fb^{-1}	38.0	(14.2, 4.4)	40.8
5 ab^{-1}	14.4	(5.4, 4.4)	15.8
50 ab^{-1}	4.6	(1.6, 4.4)	6.4
$\mathcal{B}(B \to \tau\nu)$ (semileptonic tagged)			
711 fb^{-1}	24.8	$(18, {}^{+6.0}_{-9.6})$	${}^{+31.2}_{-32.2}$
5 ab^{-1}	8.6	$(6.2, {}^{+6.0}_{-9.6})$	${}^{+12.2}_{-14.4}$
50 ab^{-1}	2.8	$(2.0, {}^{+6.0}_{-9.6})$	${}^{+6.8}_{-10.2}$
$\mathcal{B}(B \to \mu\nu)$ (had. tagged)			
711 fb^{-1}	–	(16.2, 2.4)	$< 5.6 \times 10^{-6}$
5 ab^{-1}	–	(6.1, 2.4)	$< 8.0 \times 10^{-7}$
50 ab^{-1}	37	(1.9, 2.4)	37 (2.7σ)
$\mathcal{B}(B \to \mu\nu)$ (untagged)			
253 fb^{-1}	–	(16.4, 3.0)	$< 1.7 \times 10^{-6}$
5 ab^{-1}	–	(6.2, 3.0)	5σ
50 ab^{-1}		(2.0, 3.0)	$\gg 5\sigma$

B →lυ(γ)

A photon in the final state would remove the helicity suppression enhancing the weak decay amplitude.

In this case:

$$\frac{d\Gamma}{dE_\gamma} = \frac{\alpha_{em} G_F^2 |V_{ub}|^2}{48\pi^2} m_B^4 (1 - x_\gamma) x_\gamma^3 [F_A^2 + F_V^2]$$

$$x_\gamma = 2\frac{E_\gamma}{M_B}$$

$$F_V(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B(\mu)} R(E_\gamma, \mu) + \left[\xi(E_\gamma) + \frac{Q_u m_B f_B}{(2E_\gamma)^2} + \frac{Q_b m_B f_B}{2E_\gamma m_b}\right],$$

$$F_A(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B(\mu)} R(E_\gamma, \mu) + \left[\xi(E_\gamma) - \frac{Q_u m_B f_B}{(2E_\gamma)^2} - \frac{Q_b m_B f_B}{2E_\gamma m_b} + \frac{Q_\ell f_B}{E_\gamma}\right]$$

Belle results
PRD 91, 112009 (2015)

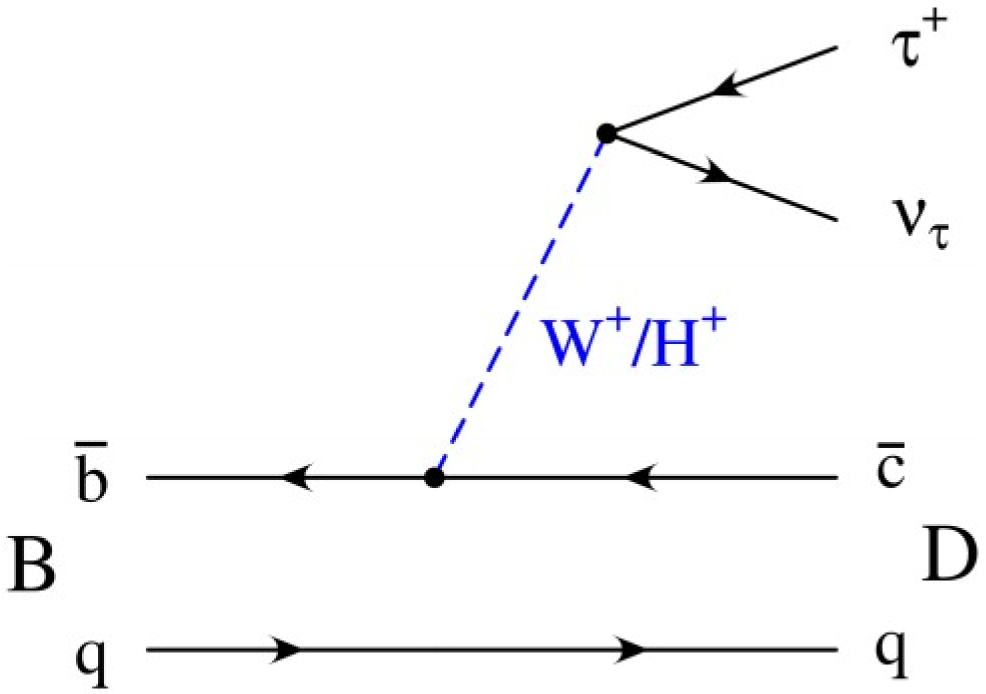
$$\mathcal{B}(B^+ \to e^+ \nu_e \gamma) < 6.1 \times 10^{-6}$$

$$\mathcal{B}(B^+ \to \mu^+ \nu_\mu \gamma) < 3.4 \times 10^{-6}$$

$$\mathcal{B}(B^+ \to \ell^+ \nu_\ell \gamma) < 3.5 \times 10^{-6}$$

Expect to be able to measure standard model BR at 3 sigma level with full Belle II data.

B →D(*)τυ

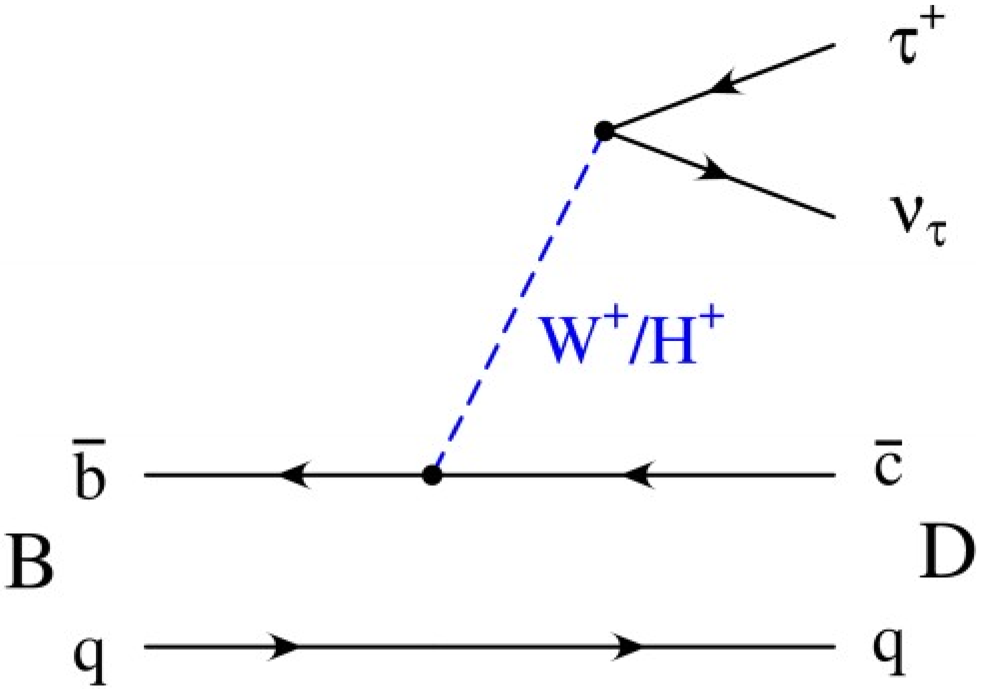


New Physics could affect this decay topology in two ways:
- Branching Fraction
- Tau polarization

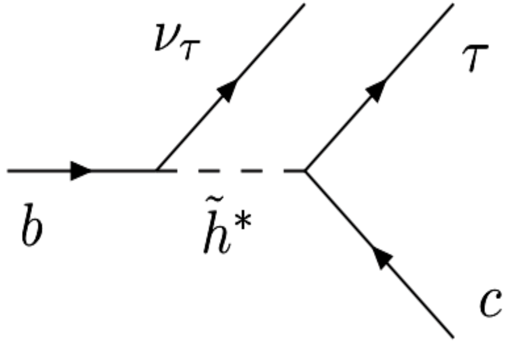
BaBar searches in this topology excluded Type II- 2HDM at 3.4 standard deviations

Experimentally challenging
- 2 missing neutrinos in hadronic tau decays topologies
- 3 missing neutrinos in leptonic tau decay topologies

B →D$^{(*)}$τυ



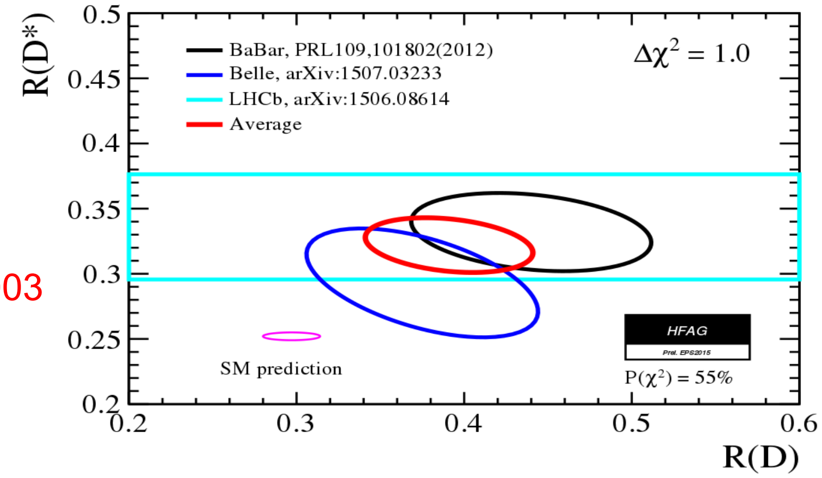
Leptoquark could be a possible explanation for the tension



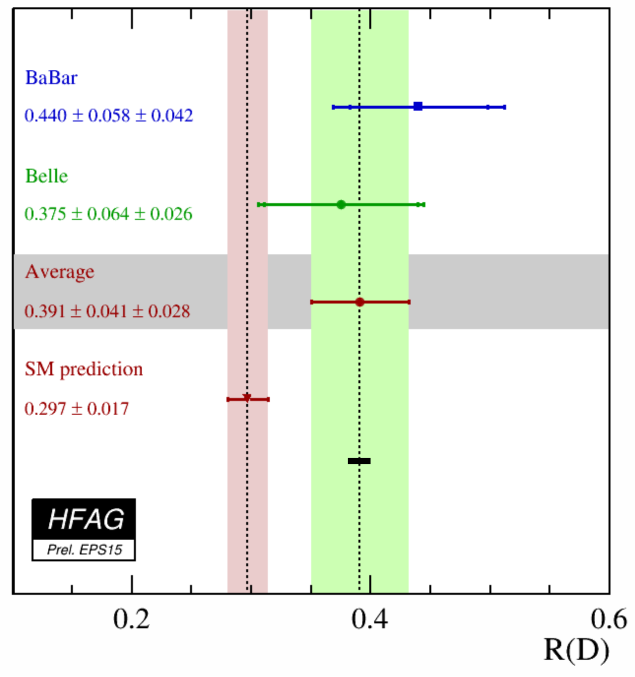
$$R(D^{(*)}) = \frac{\Gamma(B^0 \rightarrow D^{(*)} \tau \nu)}{\Gamma(B^0 \rightarrow D^{(*)} l \nu)_{l=\mu,e}}$$

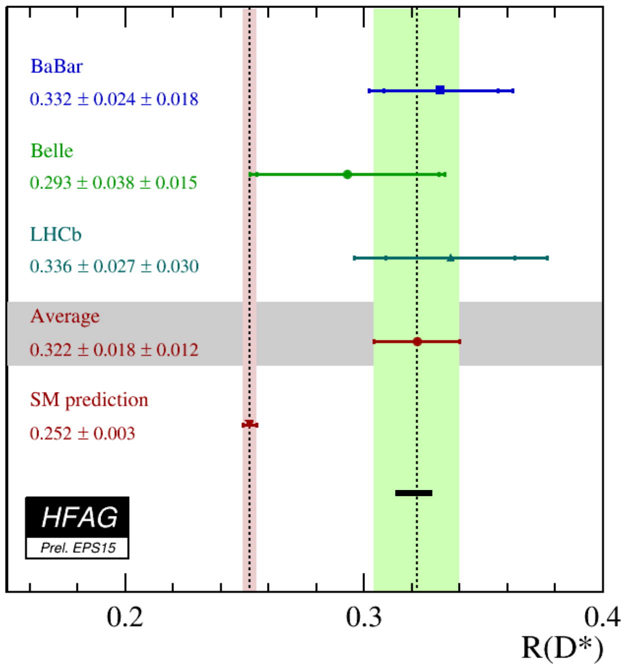
Very precise SM prediction:

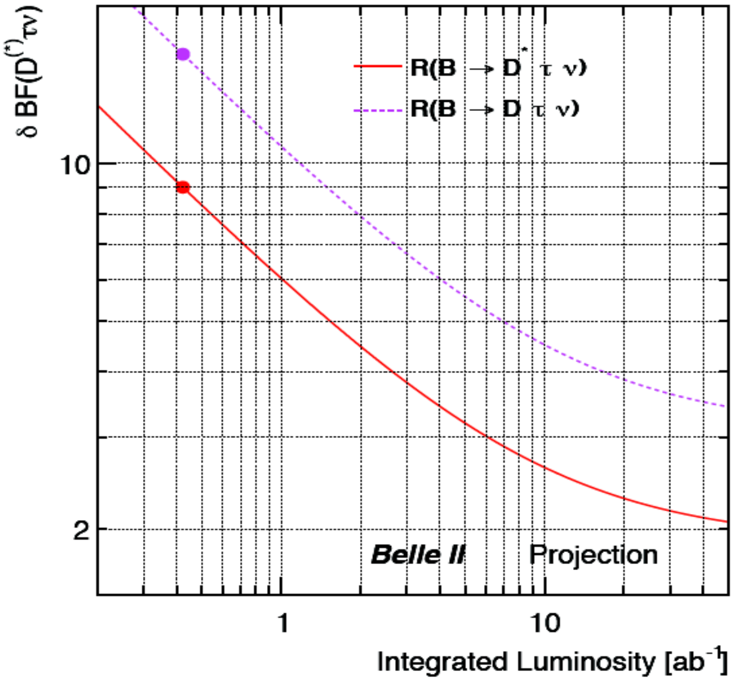
- R(D) =0.297 ± 0.017 Phys.Rev.D78(2008) 014003
- R(D*) = 0.252 ± 0.003 Phys.Rev.D85(2012)



$B \rightarrow D^{(*)}\tau\upsilon$







	Statistical	Systematic (reducible, irreducible)	Total Exp
$R(D)$			
423 fb^{-1}	13.1	(9.1, 3.1)	16.2
5 ab^{-1}	3.8	(2.6, 3.1)	5.6
50 ab^{-1}	1.2	(0.8, 3.1)	3.4
$R(D^*)$			
423 fb^{-1}	7.1	(5.2, 1.9)	9.0
5 ab^{-1}	2.1	(1.5, 1.9)	3.2
50 ab^{-1}	0.7	(0.5, 1.9)	2.1

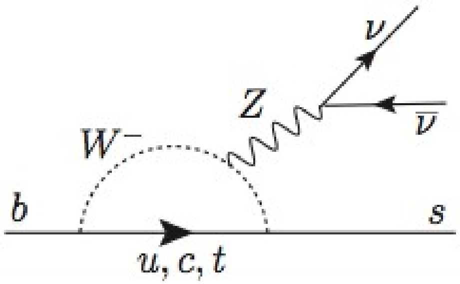
FCNC: B →$K^{(*)}$υυ

B → $K^{(*)}$ νν :

→ b→s flavour-changing neutral current

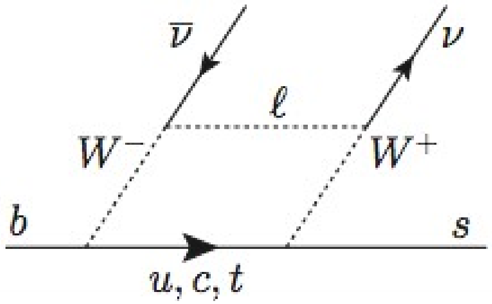
→ suppressed within the SM

→ golden mode of Belle II because theoretically very clean: free of uncertain long-distant hadronic effects



Why at Belle II?

- Can be measured only in e^+e^-, experimentally challenging
- Existing limits from BABAR and Belle leave room for NP

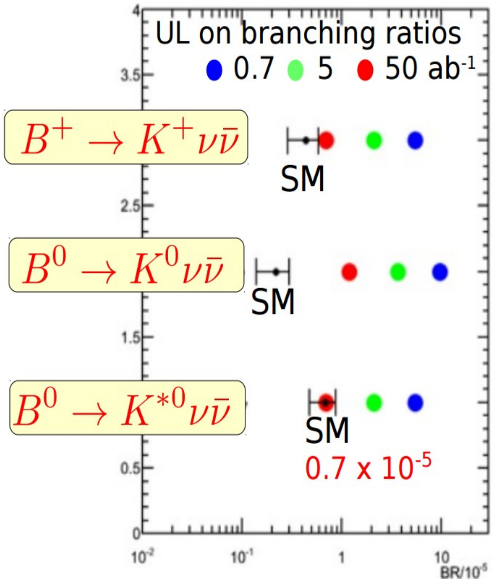


$$BABAR: BR\left(B^+ \to K^+ \nu\bar{\nu}\right) < 1.7\times10^{-5}$$
$$BELLE: BR\left(B^0 \to K^{*0} \nu\bar{\nu}\right) < 5.5\times10^{-5}$$

Babar, B → K(*) ν ν , PRD 87, 112005 (2013)
Belle, B → K(*)/π/ρ ν ν, PRD 87, 111103(R) (2013)

Sensitivity with full Belle II data

- SM expectation for exclusive
- $B \to K^{(*)}\nu\nu$ can be probed at 5σ level



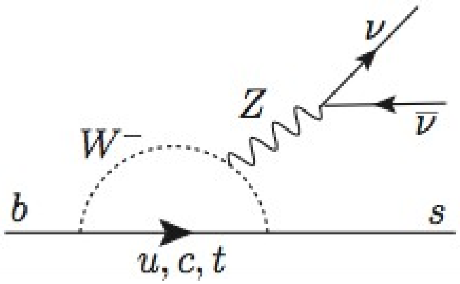
FCNC: $B \rightarrow K^{(*)}\upsilon\upsilon$

$B \rightarrow K^{(*)} \nu\nu$:

→ $b \rightarrow s$ flavour-changing neutral current

→ suppressed within the SM

→ golden mode of Belle II because theoretically very clean:
free of uncertain long-distant hadronic effects



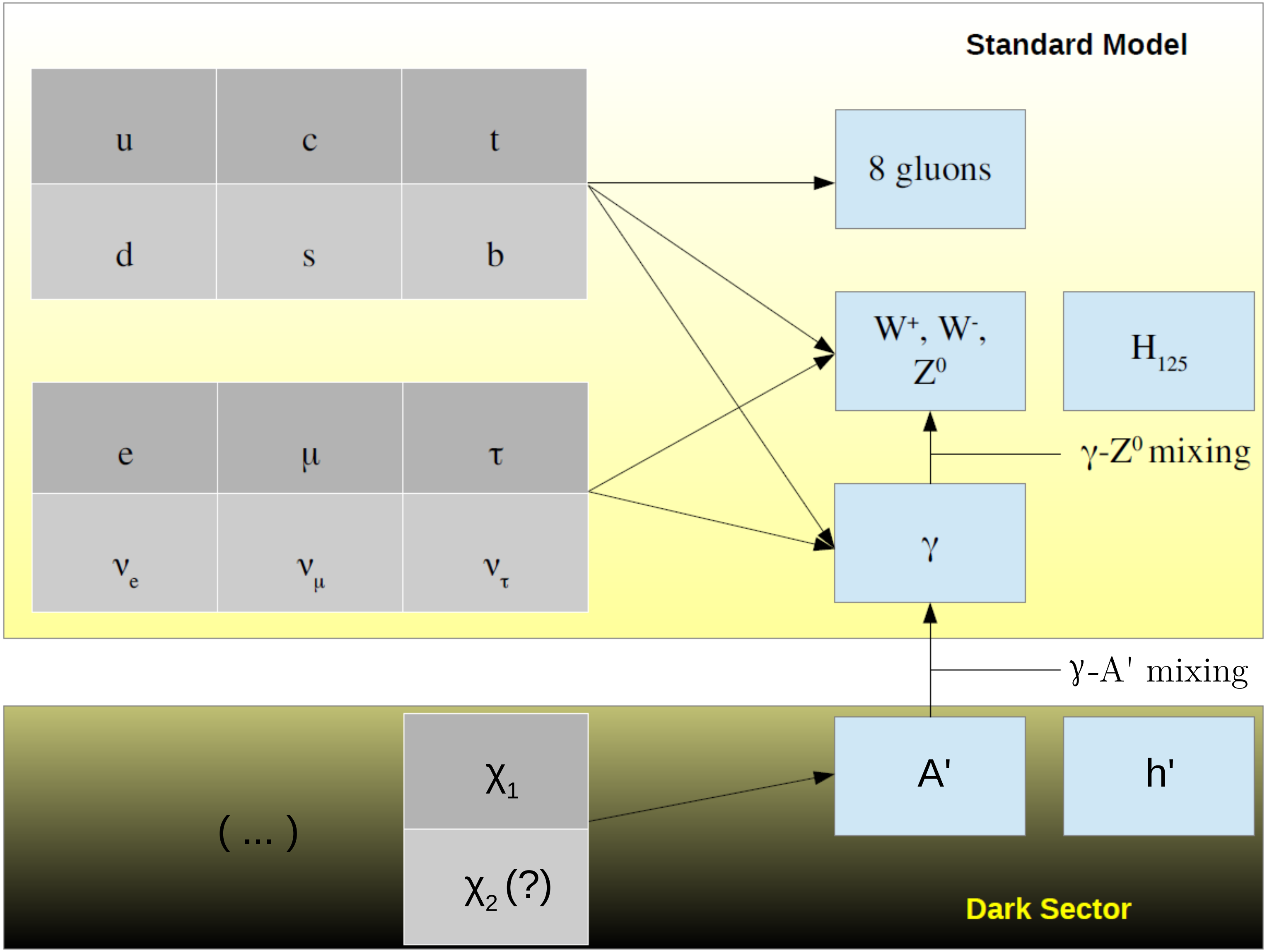
Searched signal:
K^+
K_s
$K^{*+} \rightarrow K_s \pi^+$
$K^{*+} \rightarrow K^+ \pi^0$
$K^{*0} \rightarrow K^+ \pi^-$

Fake signal: $B \rightarrow f'_2 K^*$
With $f'_2 \rightarrow K^0_L K^0_L$ (22%)
$B \rightarrow \eta_c K^+$
With $\eta_c \rightarrow K^0_L K^0_L$
B decays to D^0:
$D0 \rightarrow K^0_L \pi^0$

Separation between signal and fake signal requires very good signal-selection/background-rejection algorithms → K^0_L VETO

*Ongoing work with promising preliminary results
*Algorithm to be implemented into Belle II Full Event Interpretation (FEI) module

Dask sector: how does it look like?



Standard Model

u c t

d s b

e μ τ

ν_e ν_μ ν_τ

8 gluons

W^+, W^-, Z^0

H_{125}

γ-Z^0 mixing

γ

γ-A' mixing

(...)

χ_1

χ_2 (?)

A'

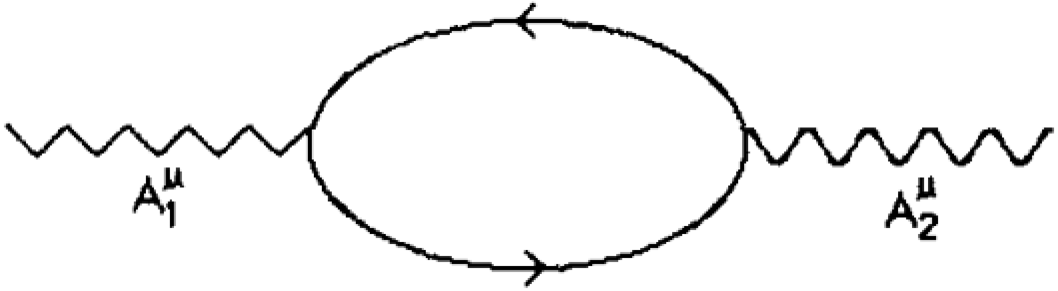
h'

Dark Sector

Dark photon: The general idea of kinetic mixing γ-A'

Dark photon first proposed in P. Fayet, Phys. Lett. B **95**, 285 (1980),
P. Fayet Nucl. Phys. B **187**, 184 (1981).

- (Holdom, 1986) A boson belonging to an additional U(1)' symmetry would mix kinetically with the photon:

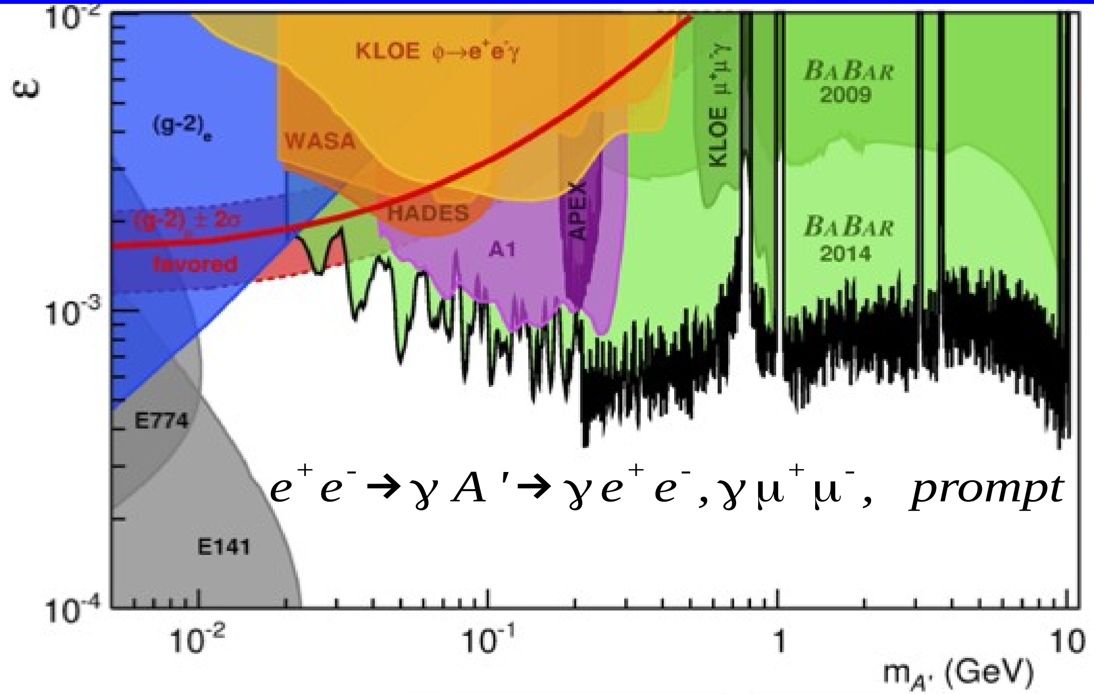


- The kinetic mixing is a term in the Lagrangian expressed by $\frac{1}{2}\epsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$
- For the dark photon to acquire mass an extended Higgs sector is required to break the new U(1)' symmetry

Note: ϵ is the strength of the kinetic mixing and it is supposed to be small, 10^{-5}-10^{-2}, **the smaller the value of ϵ the longer A' lifetime** (i.e. **long lived**).

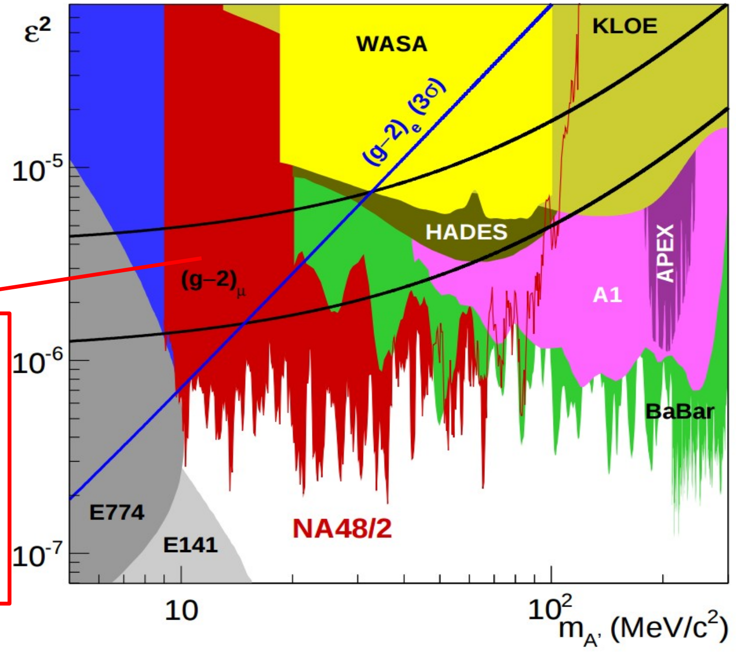
The Mass of the new boson should be in the range few MeV to few Gev allowing for the Sommerfeld enhancement that would also explain anomalies observed in astrophysical data (Nima Arkani-Hamed et al. Phys. Rev. D **79,** 015014, 2009).

Dark photon: current limits



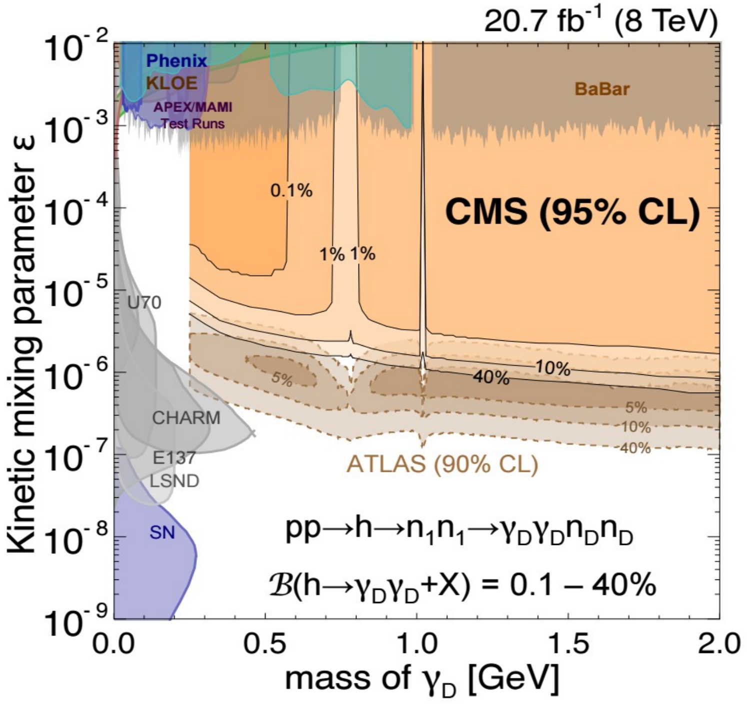
$e^+e^- \rightarrow \gamma A' \rightarrow \gamma e^+e^-, \gamma \mu^+\mu^-, \;\; prompt$

Many constraints for different region of the parameter space from different experiments.
Shown here:
-top left: BaBar ,
-bottom left NA48,
-bottom right CMS (containing ATLAS) [highly model dependent]



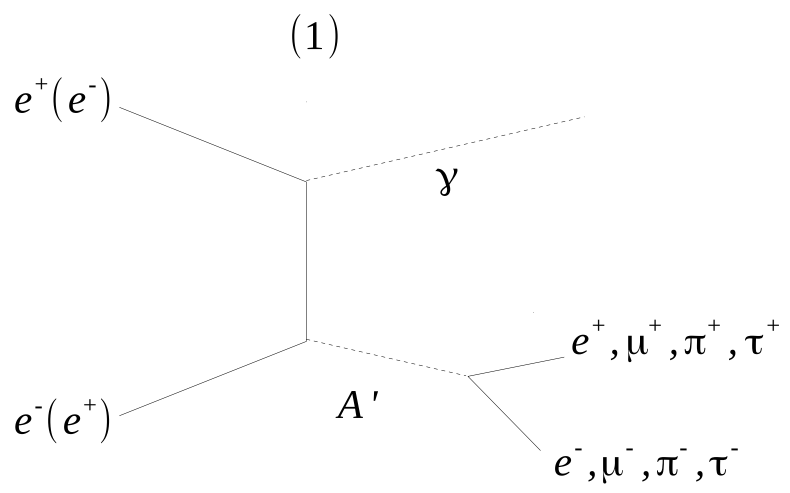
dark photon explanation of $(g\text{-}2)_\mu$ ruled out for $A' \rightarrow e^+e^-$

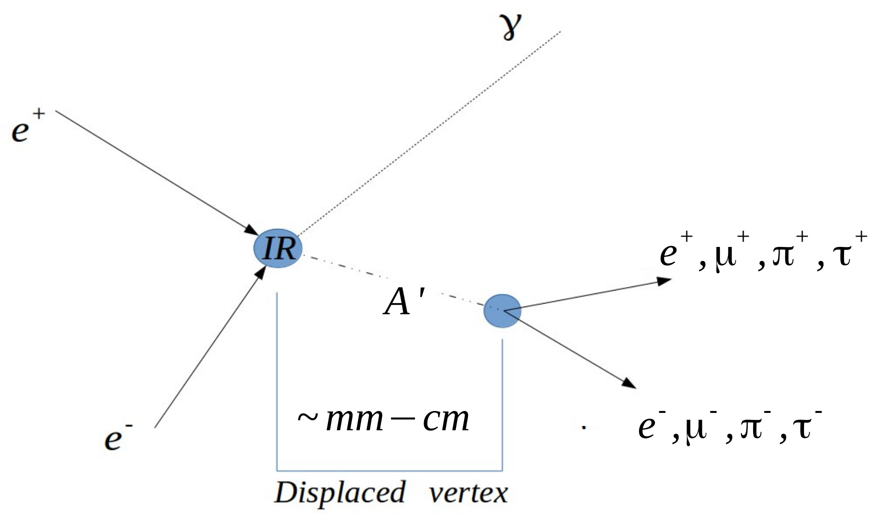
NA48 arXiv:1504.00607
π^0 decays



arXiv:1506.00424 [hep-ex]
Long lived, decays to leptons

Dark photon searches @ BELLE II

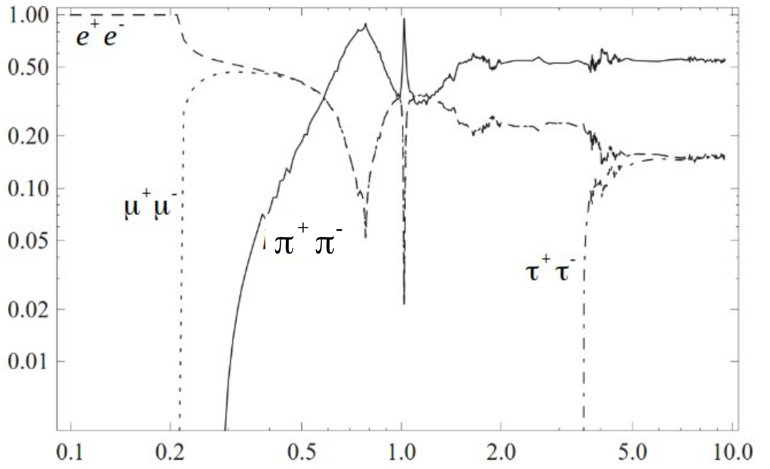




A'= dark photon.
A' decays to SM final states through kinetic mixing (if allowed by kinematics). Low multiplicity final states. 2 charged tracks and 1 photon, prompt or displaced vertex. Require dedicated trigger to increase efficiencies, especially for the displaced vertex case.

"*A'* " decays depend on $M_{A'}$:

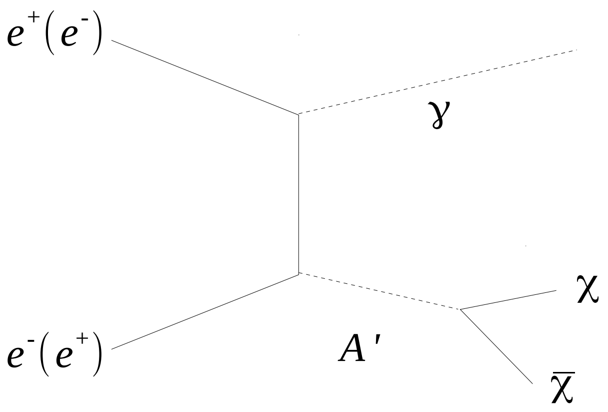
-Decays to leptons require $M_{A'}>1.02$ MeV/c^2
-Decays to hadrons require $M_{A'}>0.36$ GeV/c^2
Currently ongoing analyses at Belle for e^+e^-, $\mu^+\mu^-$,h^+h^- final sates (including displaced vtx), results expected this year.

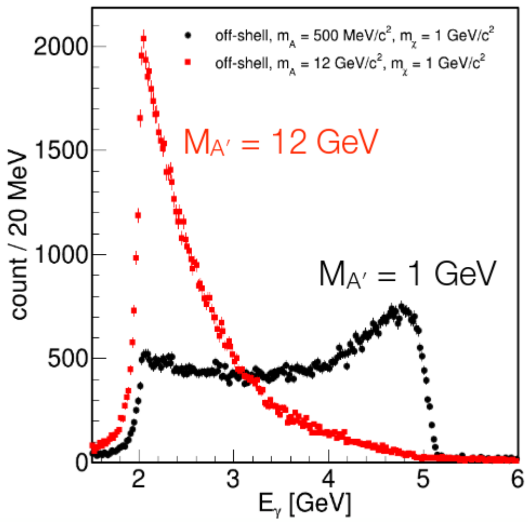


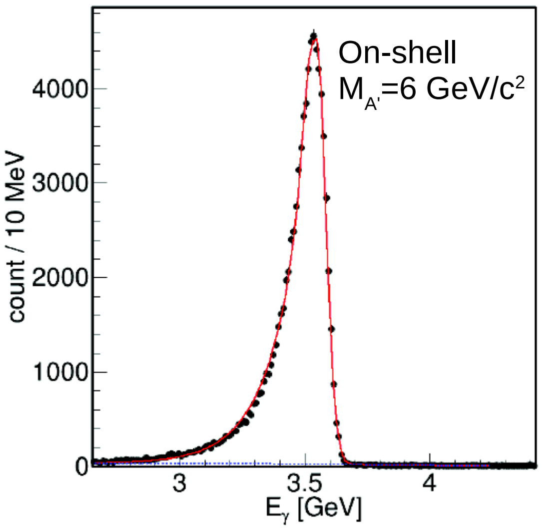
ArXiv:0903.0363 [hep-ph]

Dark photon searches @ BELLE II

See *R. Essig et al. JHEP11 (2013) 167.*







A'= dark photon, χ= dark matter particle (neutral under SU(3)xSU(2)xU(1))
A' decays to dark matter. On-shell or off-shell with different gamma spectrum .

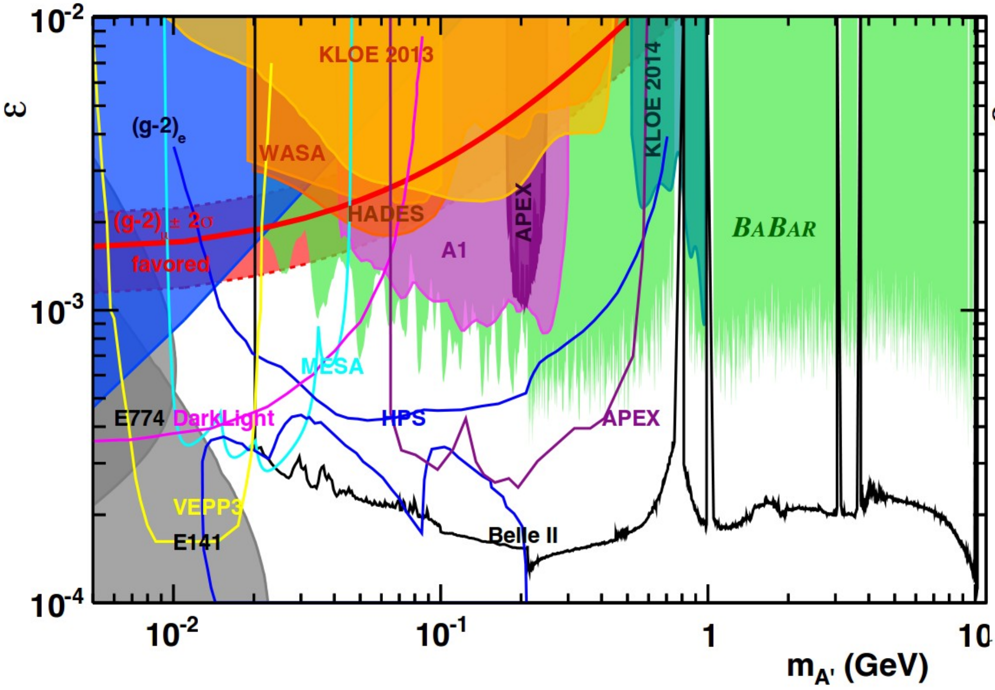
radiative production in e+e- collisions
only one photon in the final state with $E^*_\gamma = (s - M^2_{A'})/2\sqrt{s}\,(on-shell)$
No existing limits

Requires high rate single photon trigger, not available in Belle. The BaBar Collaboration implemented a single photon trigger (arXiv:0808.0017 [hep-ex]). Single photon trigger will be implemented at Belle II.

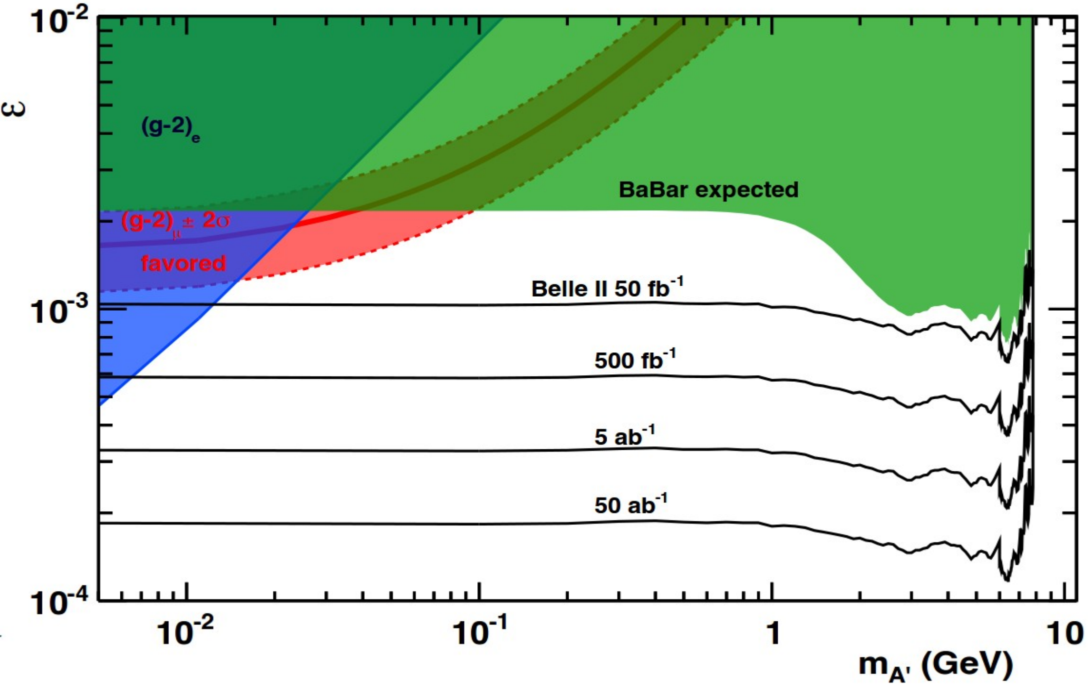
Dark photon, decays to SM particles and dark matter: expected limits at Belle II compared to other experiments

Projection from BaBar results to Belle 2 luminosity assuming same trigger/detector/reconstruction efficiencies

$e^+e^- \to \gamma A' \to \gamma e^+e^-, \gamma\mu^+\mu^-,$ *prompt*



$e^+e^- \to \gamma A' \to \gamma\chi\bar{\chi}$



From Christopher Hearty, University of British Columbia/IPP
Belle II Theory Interface Platform meeting 2014
Belle II limits scaled from BABAR

Conclusions

- Decays of B meson with large missing energy can only be studied at e^+e^- colliders
- Belle II will have the capability to perform studies of B meson decays with large missing energy in the final state (N_υ>1) with unprecedented precision:
  - $B \to K^{(*)}\upsilon\upsilon$, $B \to l\upsilon$, $B \to D^{(*)}\tau\upsilon$
  - Previously observed anomalies (such those observed in $B \to D^{(*)}\tau\upsilon$) can be resolved with few ab^{-1} of data, while very rare decays (such as $B \to K^{(*)}\upsilon\upsilon$)can be observed at 5σ level with the full Belle II data set.

- Lack of experimental evidence for WIMPs
  - Ongoing searches of the dark photon with Belle data, results planned to be ready by the end of the year
  - Belle II will cover additional regions of the parameter space of the dark photon mass vs. mixing parameter with high discovery potential; a high rate single photon trigger during Belle II data taking will enable the search for decays of the dark photon to dark matter.

- Belle II will have a strong impact in the searches for new physics from 2018 for the next decade

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Thank you for your attention!

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Belle II