Studies of dark sector & B decays involving tau @ Belle (Belle II)

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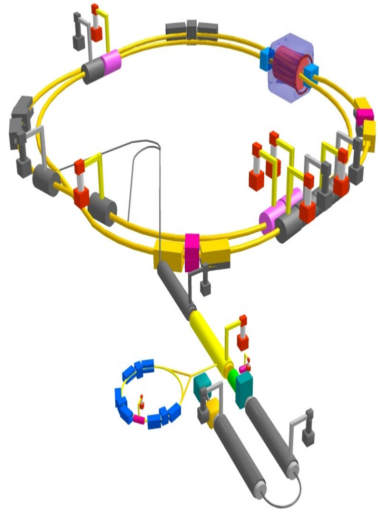

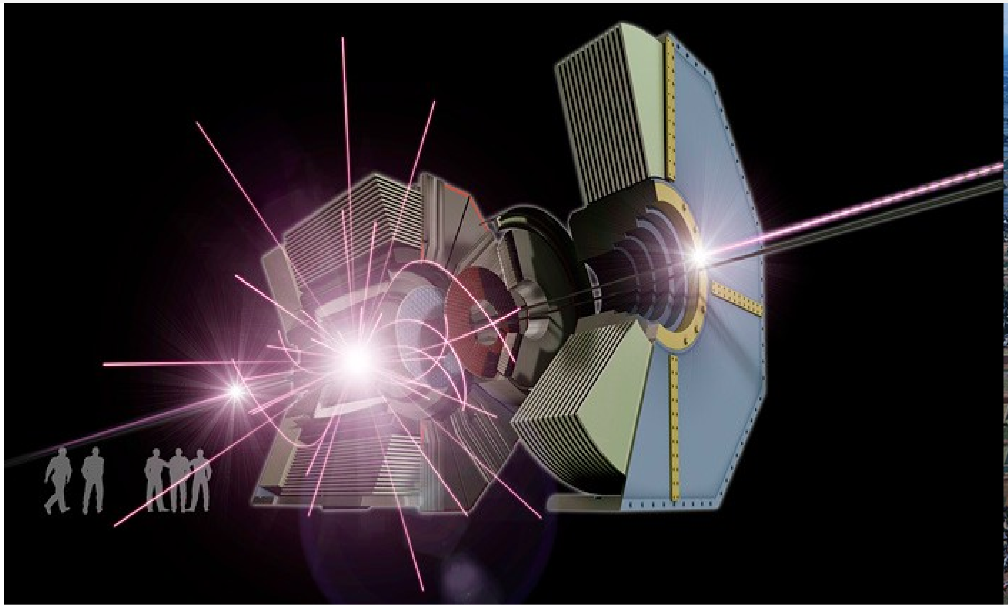

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04/08/2016

HELMHOLTZ ASSOCIATION

BELLE

Belle II

Motivations

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

- A dark sector 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

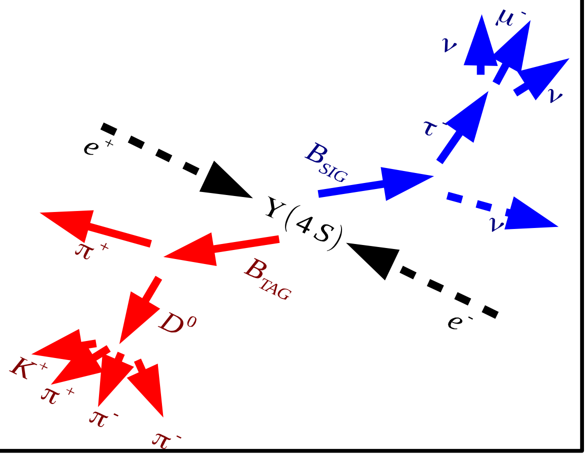
- With 50 ab-1 collected at Belle II experiment one should be able to resolve the observed anomalies and measure rare decays with missing energy. In addition one will have a high discovery potential in searches for the dark photon.

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

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

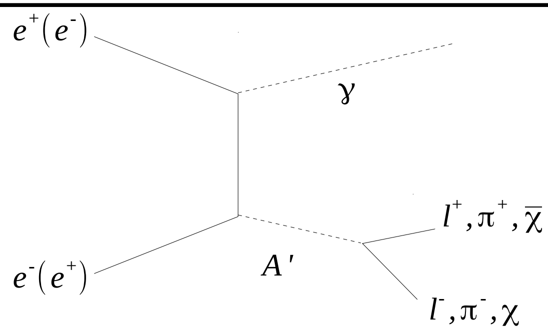
One B meson fully reconstructed: know flavour and momentum of the other

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



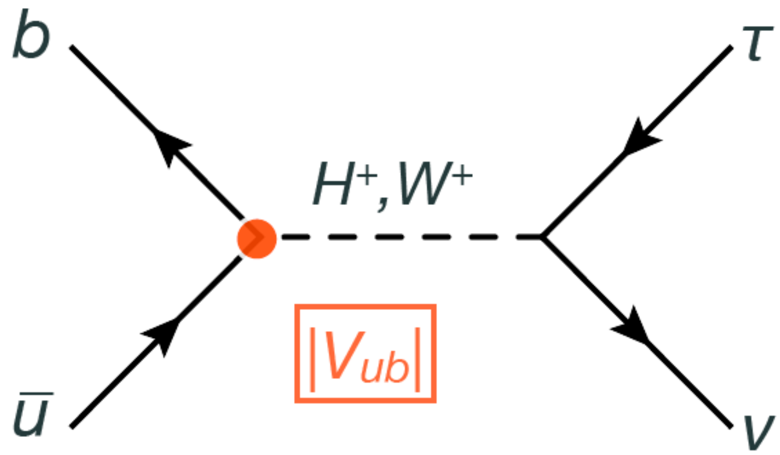
In e+e- collisions the dark photon is produced together with a photon

- Can use Belle data collected at various energies
- Belle II will improve current limits



B → τυ

H⁺ Search: B⁺→τυ, μυ

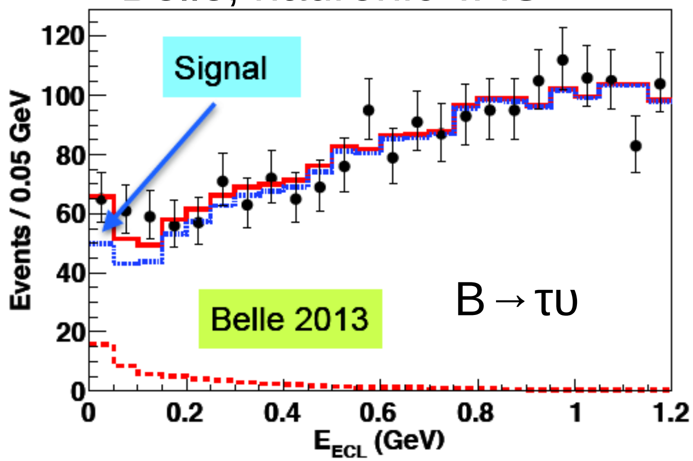


Helicity suppressed - very small in SM.
NP could interfere *e.g.* **charged Higgs.**

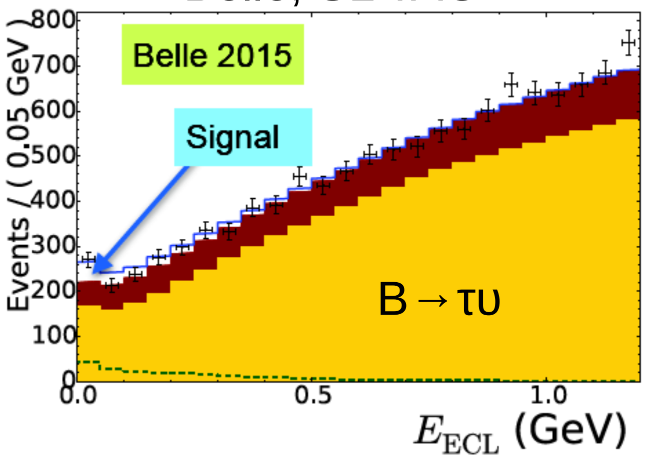
$$\Gamma(B^{\pm} \to \ell^{\pm}\nu) = \frac{G_F^2 m_B m_l^2 f_B^2}{8\pi}|V_{ub}|^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2 \times r_H$$

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

Belle, hadronic TAG



Belle, SL TAG

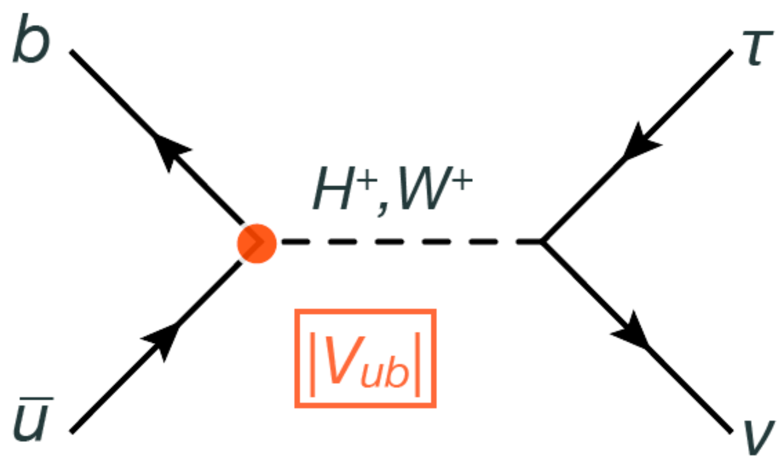


Belle results
PRD 92, 051102 (2015)
PRD 82, 071101 (2010)
$Br(B^+ \to \tau^+ \upsilon)$=
Hadronic TAG
$[0.72 \pm 0.27 \pm 0.11] \times 10^{-4}$
SL TAG
$[1.54 \pm 0.38 \pm 0.37] \times 10^{-4}$

Belle 2 sensitivity (50 ab^{-1})
$Br(B \to \tau\upsilon) \sim 4*10^{-5}$

B → τυ

H^+ Search: $B^+ \rightarrow \tau\upsilon$, $\mu\upsilon$



Helicity suppressed - very small in SM.
NP could interfere *e.g.* **charged Higgs.**

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

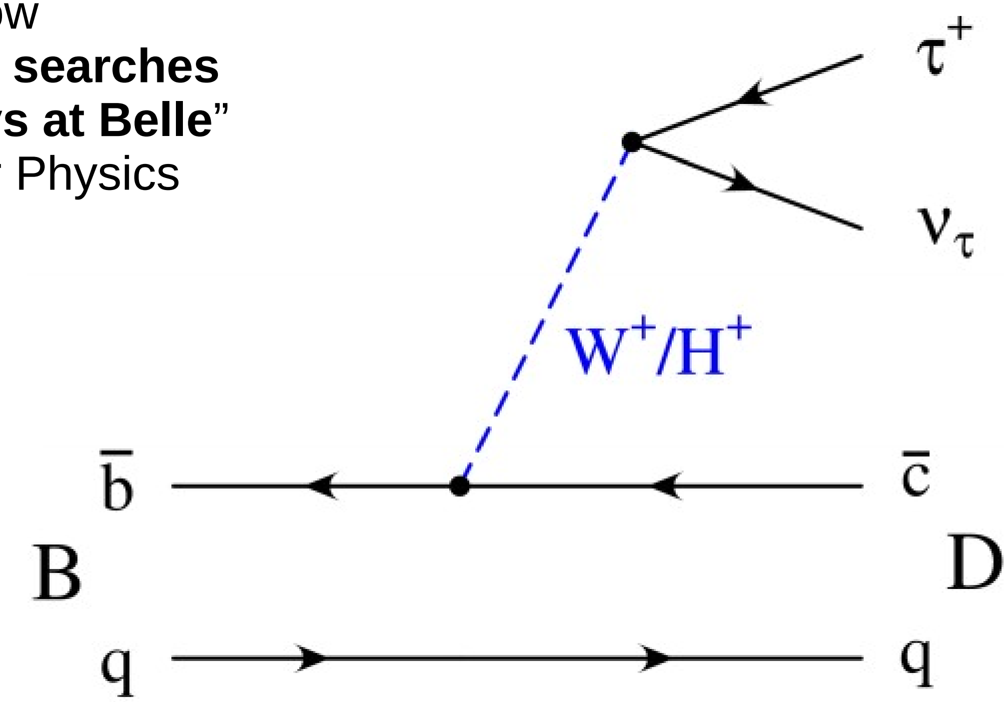
$$r_H = \left(1 - \frac{\tan^2\beta}{1+\tilde{\epsilon}_0 \tan\beta} \frac{m_B^2}{m_{H^\pm}^2}\right)^2$$

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

(x10^{-6})	Statistical	Systematic (reducible, irreducible)	Total Exp
$\mathcal{B}(B \rightarrow \tau\nu)$ (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
$\mathcal{B}(B \rightarrow \tau\nu)$ (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	$(2.0, {}^{+6.0}_{-9.6})$	${}^{+6.8}_{-10.2}$

B → D$^{(*)}$τυ

See Y. Sato's talk tomorrow
"**Tree-level New Physics searches in semileptonic B decays at Belle**"
-Quark and Lepton Flavor Physics Session-



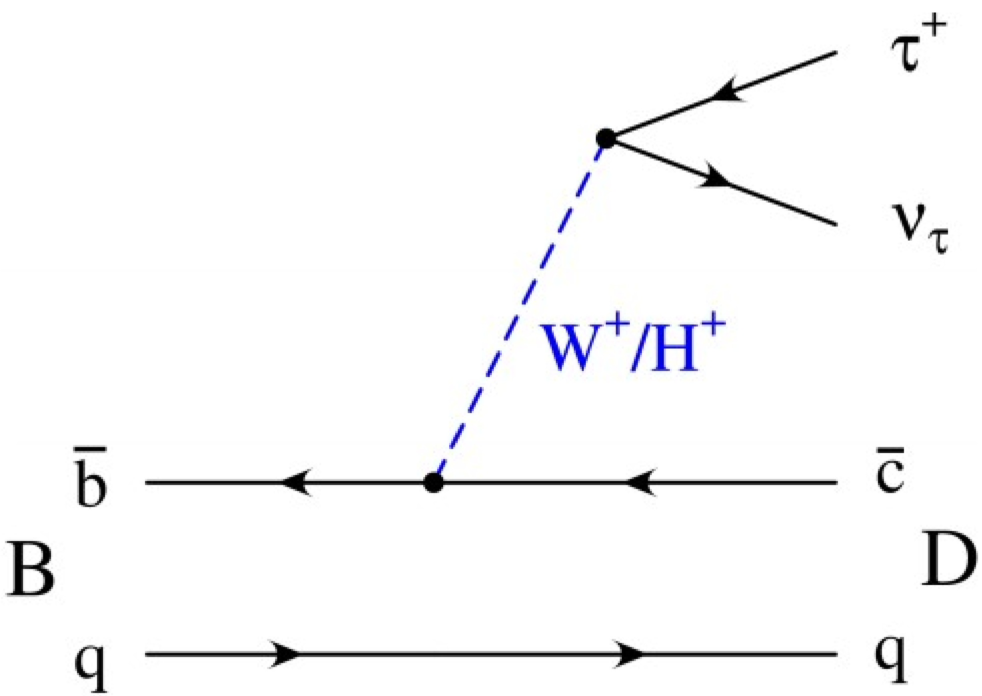
New Physics could affect this decay topology in different ways including effects on the branching fraction.

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

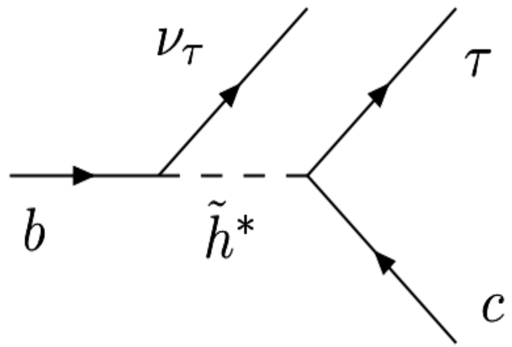
Experimentally challenging

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

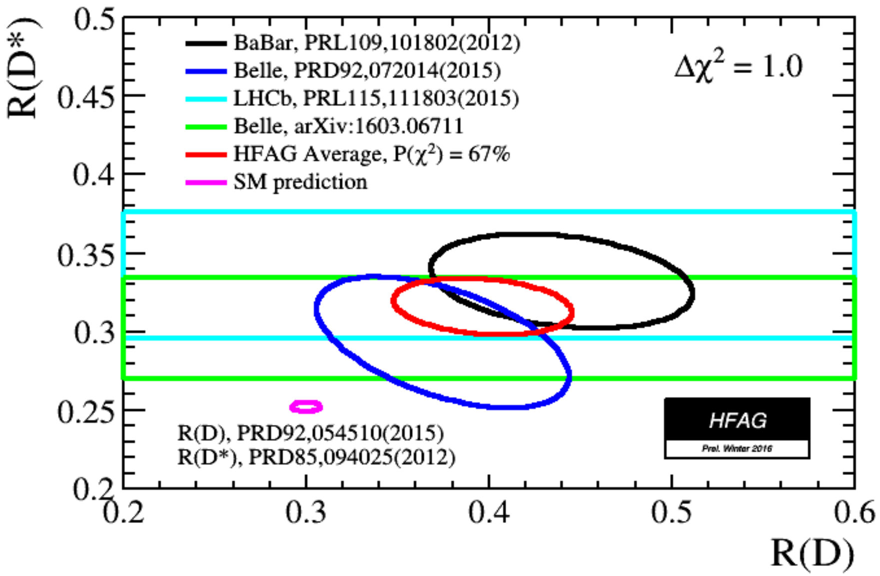


$$R(D^{(*)}) = \frac{\Gamma(B^0 \to D^{(*)} \tau \nu)}{\Gamma(B^0 \to D^{(*)} l \nu)_{l=\mu,e}}$$

Very precise SM prediction:

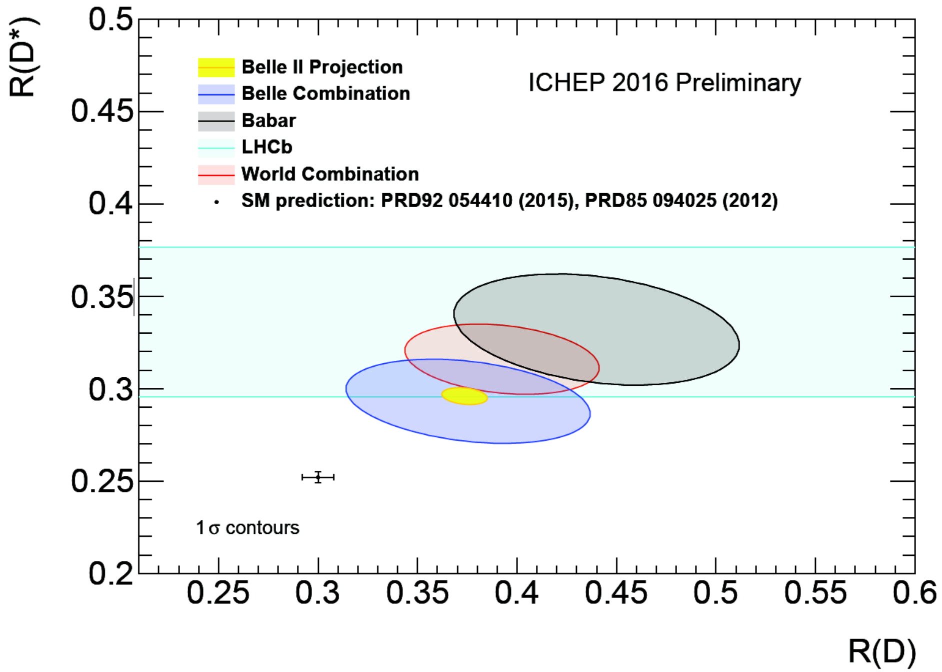
- R(D) =0.297 ± 0.017 Phys.Rev.D78(2008) 014003
- R(D*) = 0.252 ± 0.003 Phys.Rev.D85(2012)

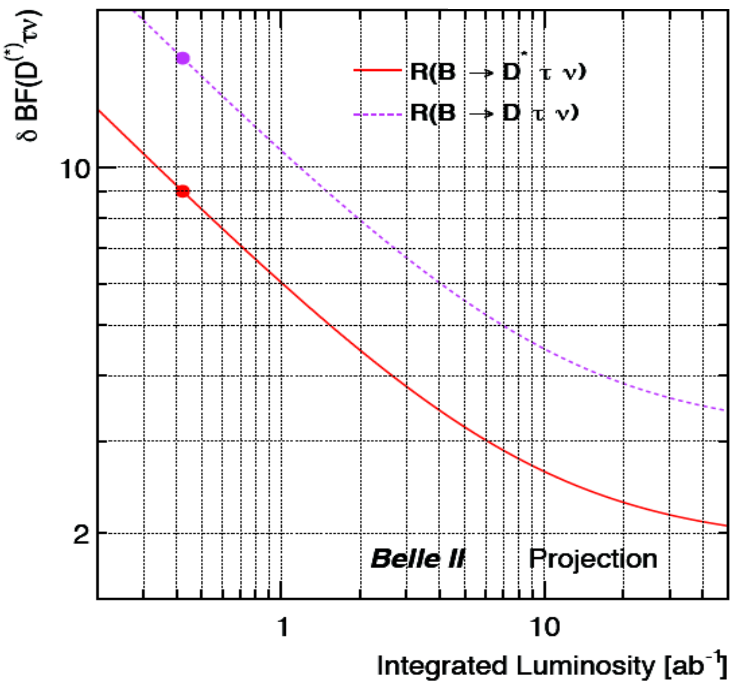
HFAG 2016:
R(D)=0.397±0.040±0.028
R(D*)=0.316±0.016±0.010



HFAG 2016:
R(D*)=0.316±0.016±0.010

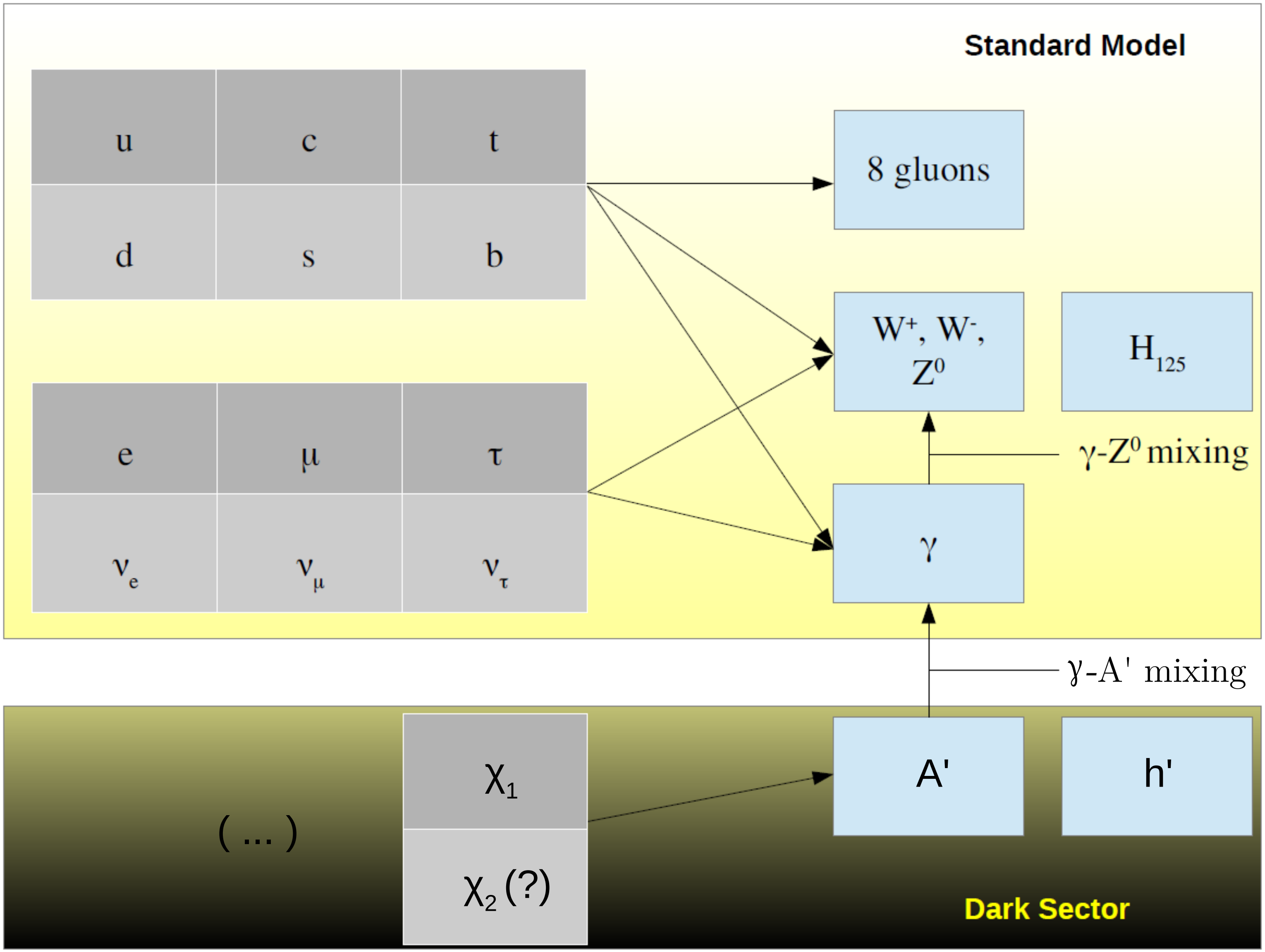
$B \to D^{(*)}\tau\upsilon$





	Statistical (x10^{-3})	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

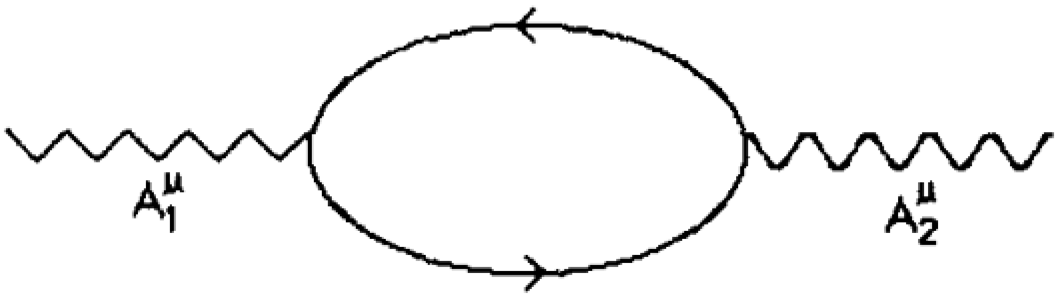
Dask sector: how does it look like?



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**).

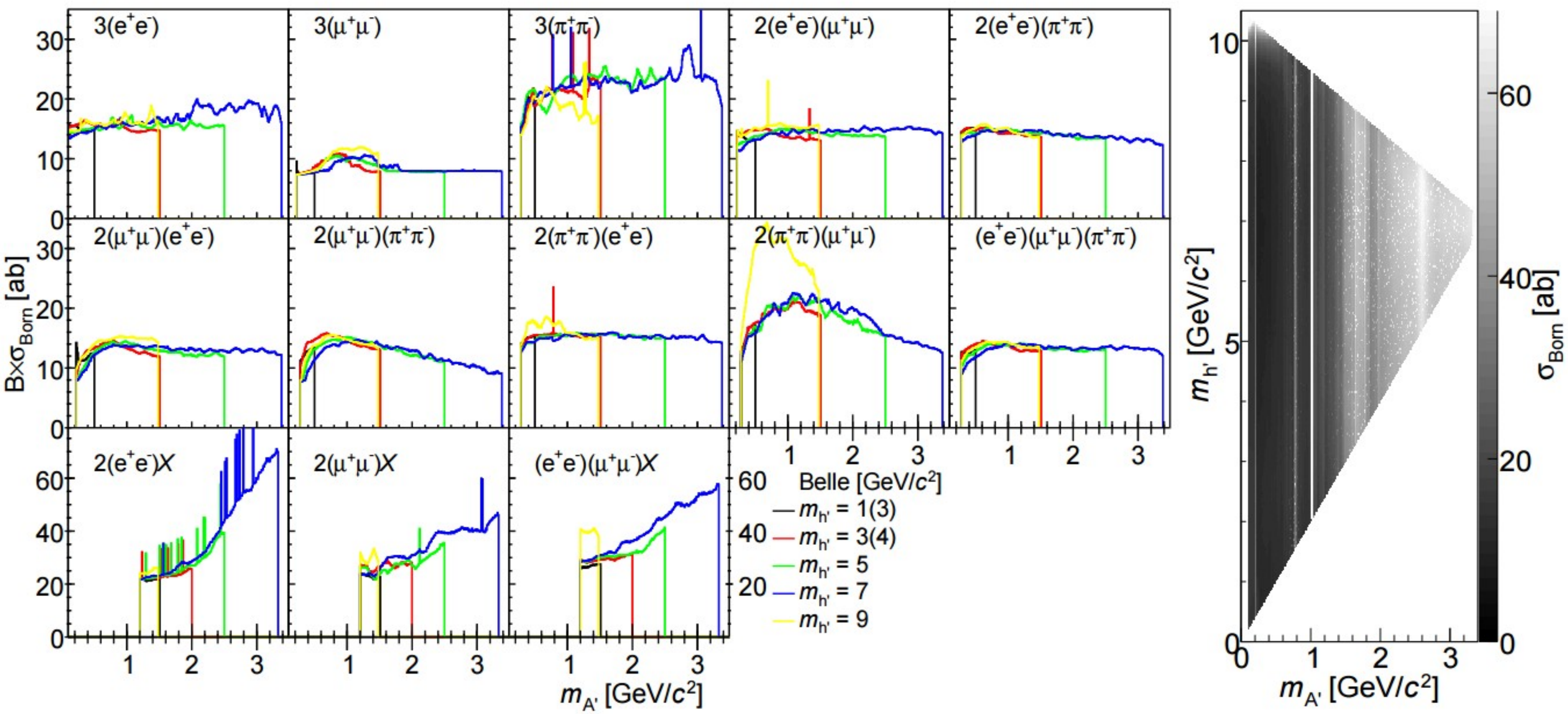
The Mass of the new boson should be in the range few MeV to few Gev allowing for the Sommerfeld enhancement that would also explain anomalies observed in astrophysical data (Nima Arkani-Hamed et al. Phys. Rev. D **79,** 015014, 2009).

Dark Higgs-strahlung at Belle

$$e^+e^- \rightarrow A'h', \quad h' \rightarrow A'A'$$
$$A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$$
$$2(e^+e^-)A', \quad 2(\mu^+\mu^-)A', \quad A' \rightarrow invisible$$

Phys. Rev. Lett. **114**, 211801 (2015)

- Belle limits for $\mathcal{L} = 977\ \mathrm{fb}^{-1}$ on $\mathcal{B} \times \sigma_{\mathrm{Born}}$ and σ_{Born}
  - 90% CL upper limit for each of the 13 final states
  - 90% CL upper limit on the combined Born cross section



- 90 % Credibility Level (CL) upper limit determined by Bayesian inference method with the use of Markov Chain Monte Carlo A'. Caldwell et al., CPC 180 (2009) 2197-2209

Limits from $3(\pi^+\pi^-)$ and $2(e^+e^-)X$ are the first placed by any experiment

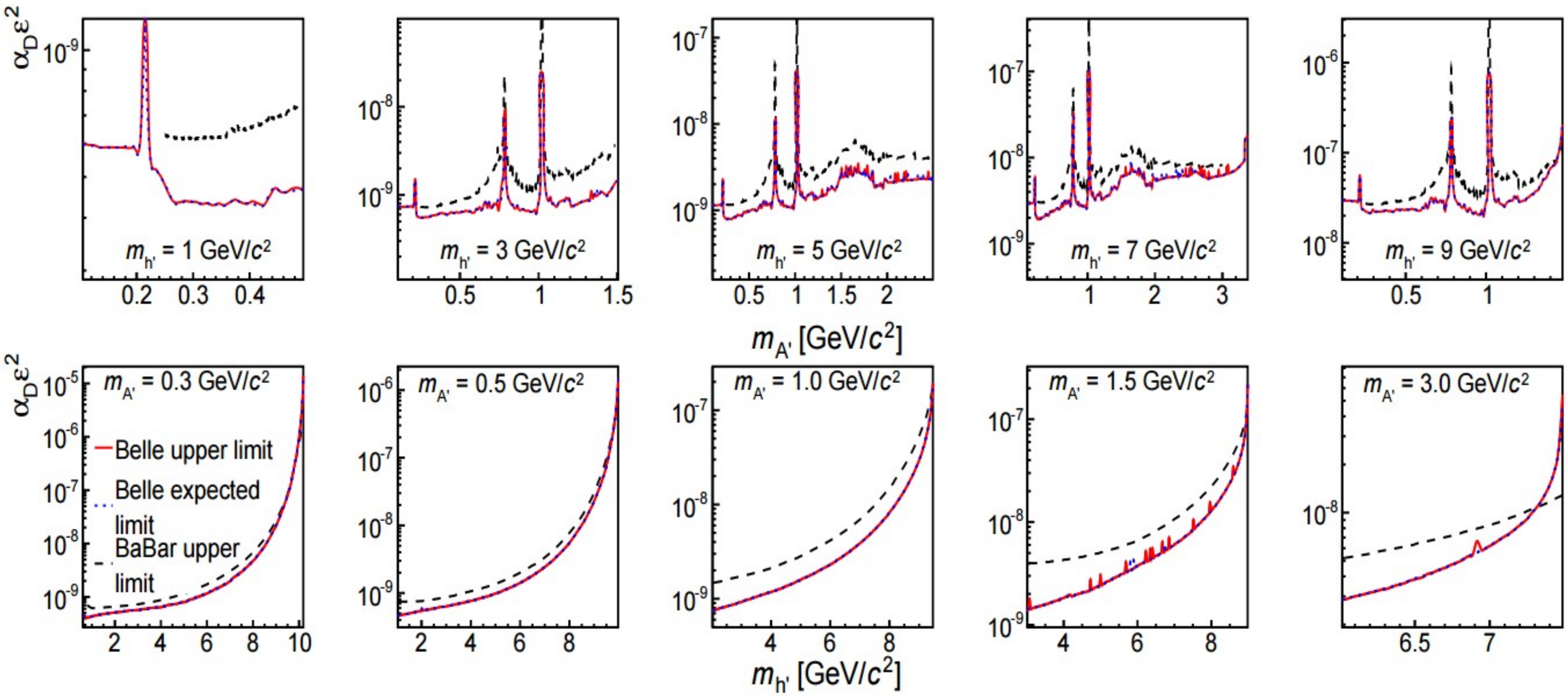
Dark Higgs-strahlung at Belle

$$e^+e^- \to A'h',\ \ h' \to A'A'$$
$$A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$$
$$2(e^+e^-)A',\ \ 2(\mu^+\mu^-)A',\ \ A' \to invisible$$

Phys. Rev. Lett. **114**, 211801 (2015)

Belle combined limits compared to BaBar combined limits

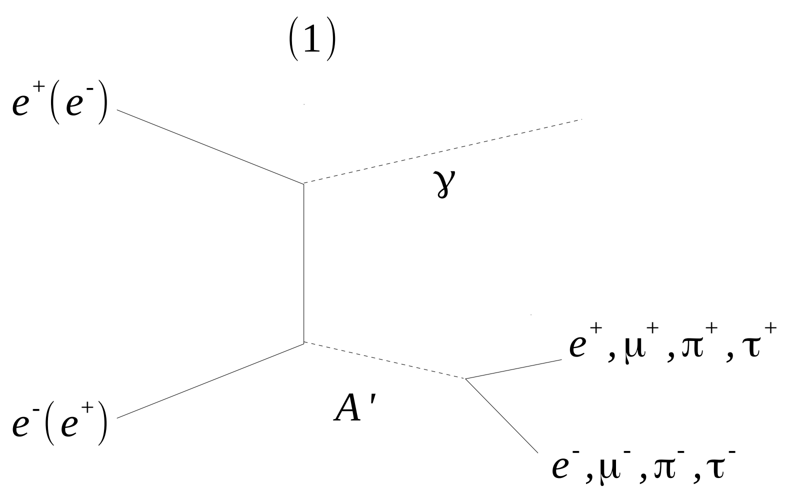
- Belle limits for $\mathcal{L} = 977\ \text{fb}^{-1}$ based on the Born cross section, ISR effect non negligible
- BaBar limits for $\mathcal{L} = 520\ \text{fb}^{-1}$ based on the visible cross section PRL 108 211801 (2012)

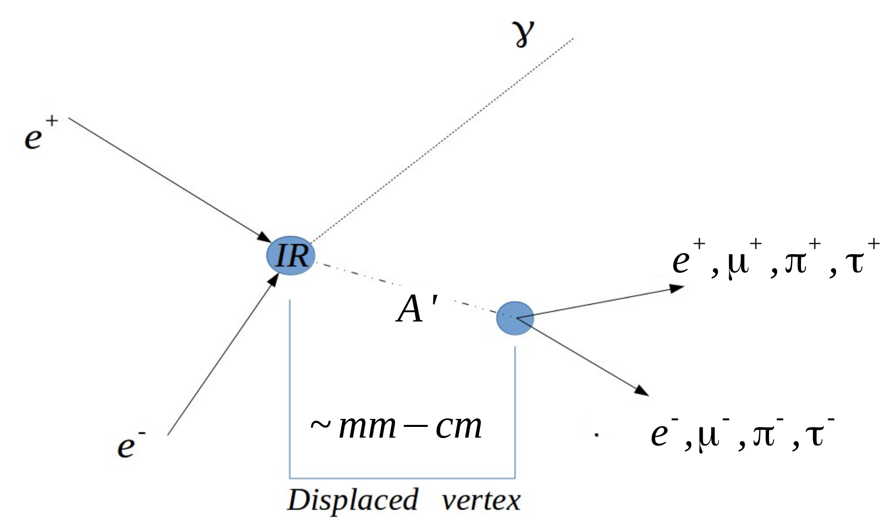


90% CL upper limit on the product $\alpha_D \times \varepsilon^2$ versus dark photon mass (top row) and dark Higgs boson mass (bottom row)

- Assuming branching fractions and couplings versus cross section from B. Batell et al. PRD 79 (2009) 115008

Dark photon searches @ BELLE II





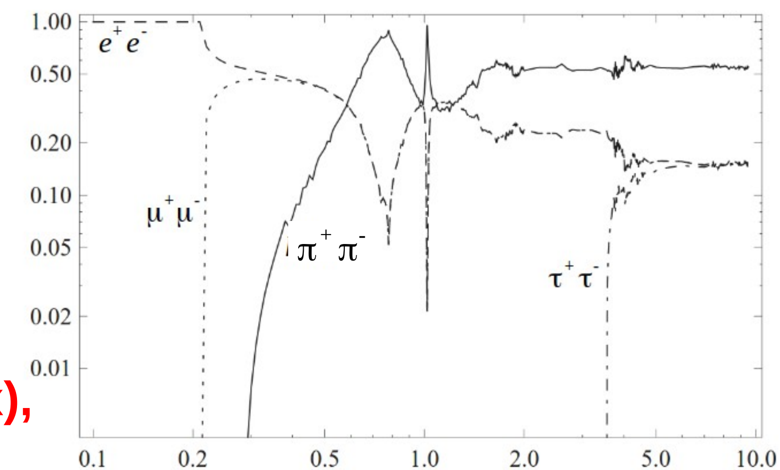
A'= dark photon.
A' decays to SM final states through kinetic mixing (if allowed by kinematics). Low multiplicity final states. 2 charged tracks and 1 photon, prompt or displaced vertex. Require dedicated trigger to increase efficiencies, especially for the displaced vertex case.

"*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

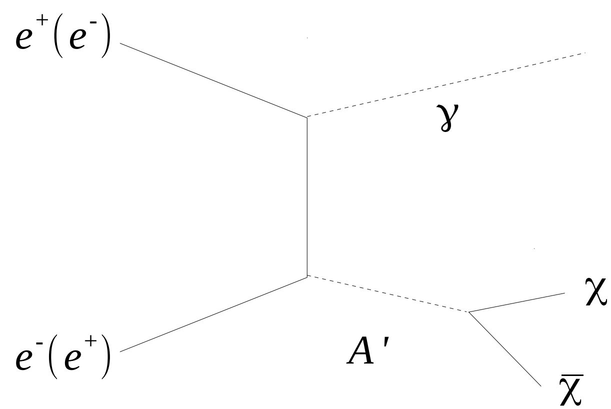
Currently ongoing analyses at Belle for e^+e^-, $\mu^+\mu^-$,$\pi^+\pi^-$ final sates (including displaced vtx), results expected this year.

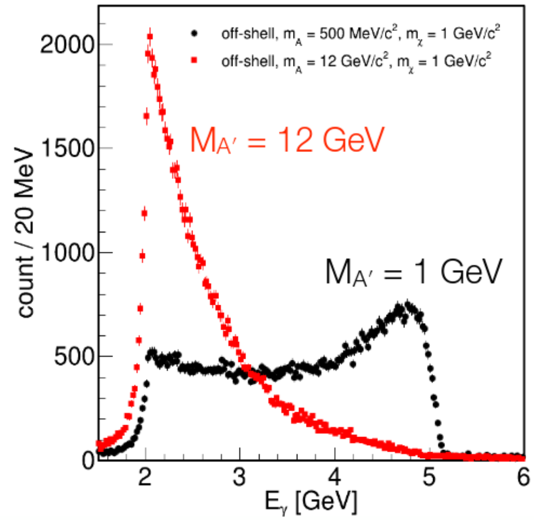


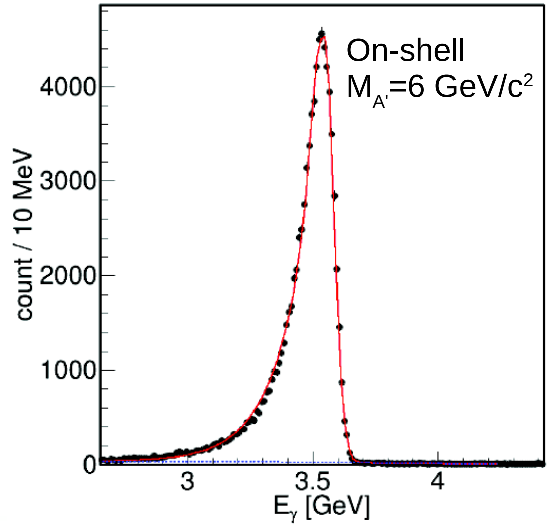
ArXiv:0903.0363 [hep-ph] $M_{A'}[GeV/c^2]$

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 .

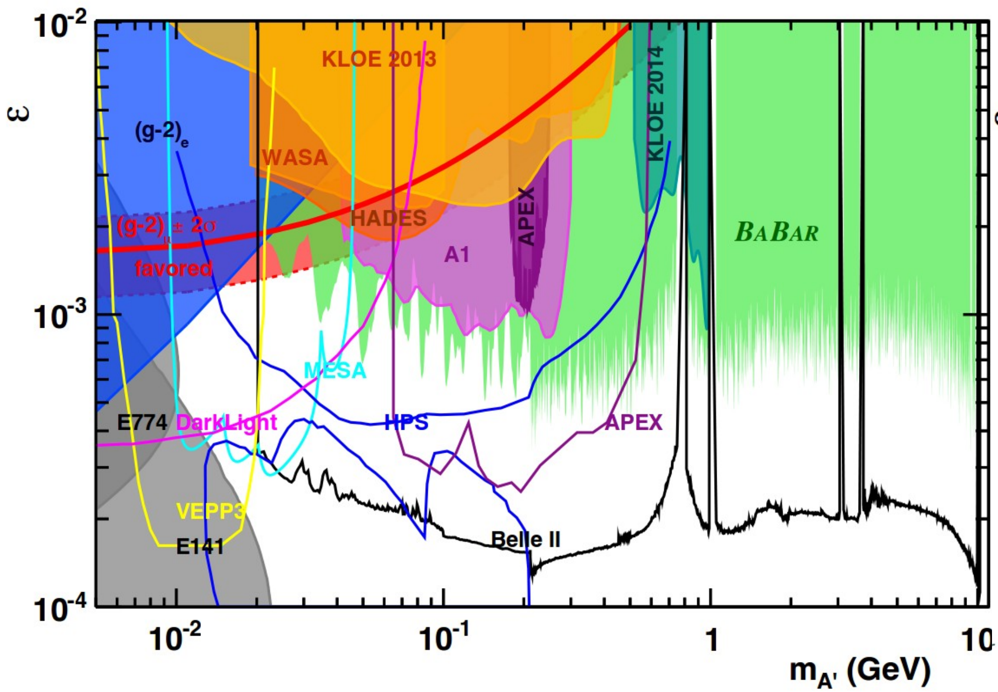
radiative production in e+e- collisions
only one photon in the final state with $E^*_\gamma = (s - M^2_{A'})/2\sqrt{s}\,(on-shell)$
No existing limits

- 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.
- Plans to study e+e- $\rightarrow \mu^+\mu^- A'$, followed by $A' \rightarrow \chi\chi$ (no special trigger required).

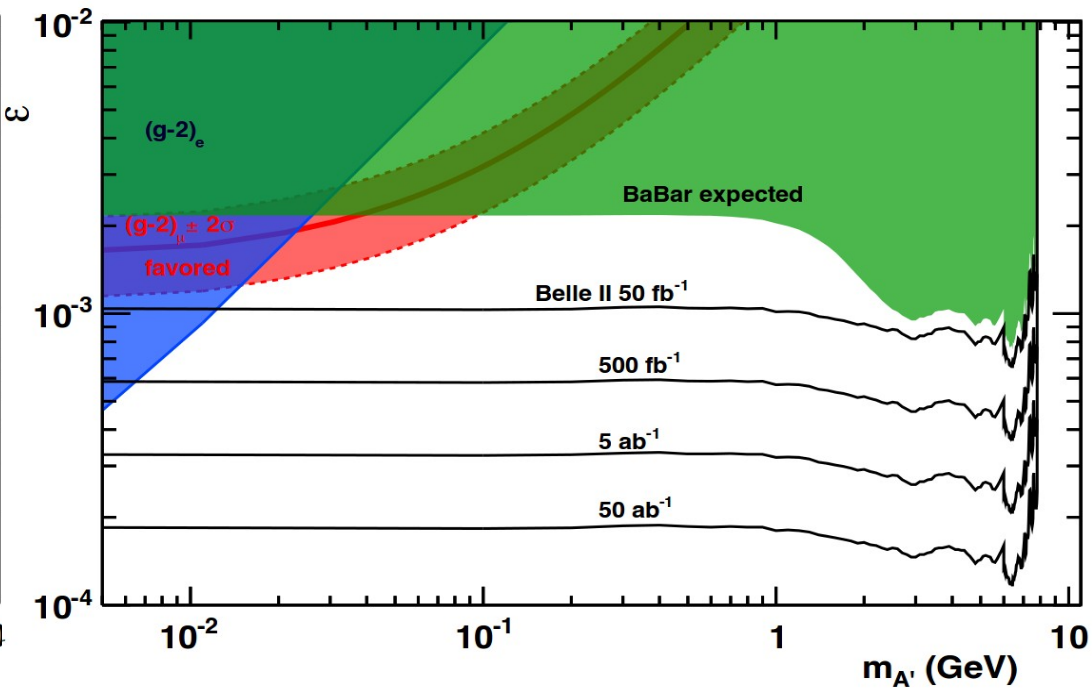
Dark photon, decays to SM particles and dark matter: expected limits at Belle II compared to other experiments

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

Low mass dark matter @ Belle (II)

Y(nS): bound state of a b quark and a b antiquark

$$\frac{BR(Y(1S)\to\nu\bar{\nu})}{BR(Y(1S)\to e^+e^-)}=\frac{27G^2M^4_{Y(1S)}}{64\pi^2\alpha^2}\left(-1+\frac{4}{3}\sin^2\theta_W\right)^2=4.14\times10^{-4}$$

$$BR(Y(1S)\to\nu\bar{\nu})\sim 9.9\times10^{-6}$$

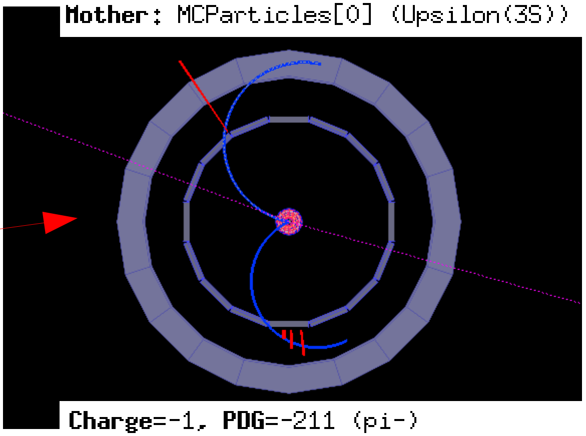
- Low mass dark matter particles however might might play a role in the decays of Y(1S), having $Y(1S)\to\chi\chi$ if kinematic allowed. [Phys. Rev. D **80**, 115019, 2009]
- Also, new mediators (Z', A^0, h^0) or SUSY particles might enhance $Y(1S)\to\nu\nu(\gamma)$. [Phys. Rev. D **81**, 054025, 2010]
- In absence of new physics enhancement, Belle2 should be able to observe the SM $Y(1S)\to\nu\nu$

$$e^+e^-\to Y(3S)$$
$\downarrow$ (4.4%)
$$Y(3S)\to\pi^+\pi^-Y(1S)$$
$\downarrow$
$$Y(1S)\to invisible$$

$$e^+e^-\to Y(2S)$$
$\downarrow$ (18.1%)
$$Y(2S)\to\pi^+\pi^-Y(1S)$$
$\downarrow$
$$Y(1S)\to invisible$$

Belle2 Simulation
$Y(3S)\to\pi^+\pi^-Y(1S)$,
$Y(1S)\to\nu\nu$

Charge=1, PDG=211 (pi+)
pT=0.420365, pZ=0.000692372
V=(-0.00, -0.00, -0.03)
Mother: MCParticles[0] (Upsilon(3S))



Charge=-1, PDG=-211 (pi-)
pT=0.344016, pZ=0.118851
V=(-0.00, -0.00, -0.03)
Mother: MCParticles[0] (Upsilon(3S))

$\sim 900\ MeV$ *available for* $P_{\pi\pi}$

$$M_{Y(3S)}=10.355\,GeV/c^2,\quad M_{Y(2S)}=10.023\,GeV/c^2,\quad M_{Y(1S)}=9.460\,GeV/c^2$$

$\sim 540\ MeV$ *available for* $P_{\pi\pi}$

Low mass dark matter @ Belle (II)

$$\frac{BR(Y(1S)\rightarrow\nu\bar{\nu})}{BR(Y(1S)\rightarrow e^+e^-)}=\frac{27G^2M^4_{Y(1S)}}{64\pi^2\alpha^2}\left(-1+\frac{4}{3}\sin^2\theta_W\right)^2=4.14\times10^{-4}$$

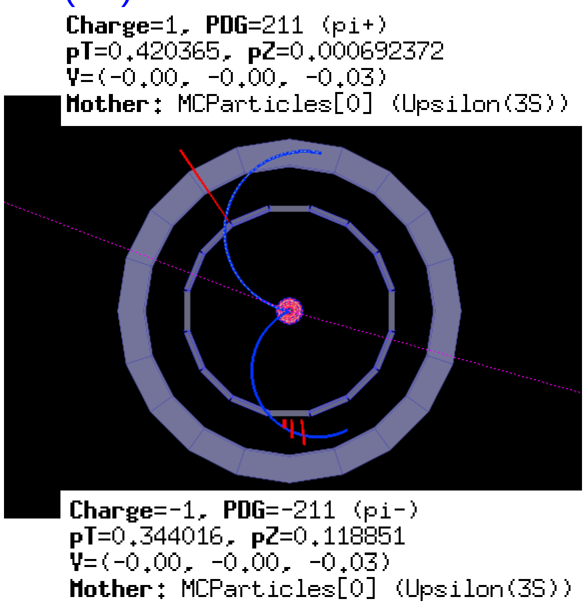
$$BR(Y(1S)\rightarrow\nu\bar{\nu})\sim9.9\times10^{-6}$$

$e^+e^-\rightarrow Y(3S)$
↓(4.4%)
$Y(3S)\rightarrow\pi^+\pi^-Y(1S)$
↓
$Y(1S)\rightarrow invisible$

$e^+e^-\rightarrow Y(2S)$
↓(18.1%)
$Y(2S)\rightarrow\pi^+\pi^-Y(1S)$
↓
$Y(1S)\rightarrow invisible$

- Low mass dark matter particles however might might play a role in the decays of Y(1S), having Y(1S)→χχ if kinematic allowed. [Phys. Rev. D **80,** 115019, 2009]
- Also, new mediators (Z', A^0, h^0) or SUSY particles might enhance Y(1S)→νν(γ). [Phys. Rev. D **81**, 054025, 2010]
- In absence of new physics enhancement, Belle2 should be able to observe the SM Y(1S)→νν

Belle2 Simulation
$Y(3S)\rightarrow\pi^+\pi^-Y(1S)$,
$Y(1S)\rightarrow\nu\nu$



A signal of Y(1S)→*invisible* is an excess of events over the background in the M_r distribution at a mass equivalent to that of the Y(1S) (9.460 GeV/c^2)

$$M_r^2=s+M_{\pi^+\pi^-}-2\sqrt{s}E^{CMS}_{\pi^+\pi^-}$$

Low mass dark matter @ Belle II: Expected Yields

$$\frac{BR(Y(1S)\to\nu\bar{\nu})}{BR(Y(1S)\to e^+e^-)}=\frac{27G^2M^4_{Y(1S)}}{64\pi^2\alpha^2}\left(-1+\frac{4}{3}\sin^2\theta_W\right)^2=4.14\times10^{-4}$$

$$BR(Y(1S)\to\nu\bar{\nu})\sim9.9\times10^{-6}$$

$e^+e^-\to Y(3S)$

↓(4.4%)

$Y(3S)\to\pi^+\pi^-Y(1S)$

↓

$Y(1S)\to invisible$

$e^+e^-\to Y(2S)$

↓(18.1%)

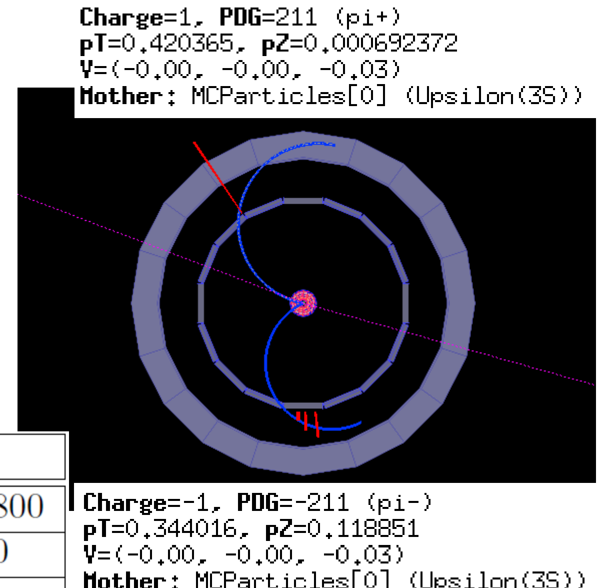
$Y(2S)\to\pi^+\pi^-Y(1S)$

↓

$Y(1S)\to invisible$

- Low mass dark matter particles however might might play a role in the decays of Υ(1S), having Υ(1S)→χχ if kinematic allowed. [Phys. Rev. D **80,** 115019, 2009]
- Also, new mediators (Z', A^0, h^0) or SUSY particles might enhance Υ(1S)→νν(γ). [Phys. Rev. D **81**, 054025, 2010]
- In absence of new physics enhancement, Belle2 should be able to strongly constrain the SM Υ(1S)→νν

Belle2 Simulation
Υ(3S)→$\pi^+\pi^-$Υ(1S),
Υ(1S)→ νν



No signal was observed over the expected background and upper limits have been obtained: BR(Υ→νν) < 3x10^{-4} (BaBar) and BR(Υ→νν) < 3.0x10^{-3}(Belle).

Process	$L_{int}(ab^{-1})$	ϵ	$N(\Upsilon(1S))$	$N_{\Upsilon(1S)\to\nu\bar{\nu}}$	N_{NP}
$\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$	0.2, $\Upsilon(2S)$	0.1-0.2	2.3×10^8	230-460	6900-13800
$\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$	0.2, $\Upsilon(3S)$	0.1-0.2	3.2×10^7	32-64	945-1890
$\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S)$	50.0, $\Upsilon(4S)$	0.1-0.2	5.5×10^6	5.5-11	165-310
$\Upsilon(5S)\to\pi^+\pi^-\Upsilon(1S)$	5.0, $\Upsilon(5S)$	0.1-0.2	7.6×10^6	7.6-15.2	228-456
$\gamma_{ISR}\Upsilon(2S)\to(\gamma_{ISR})\pi^+\pi^-\Upsilon(1S)$	50.0, $\Upsilon(4S)$	0.1-0.2	1.5×10^8	150-300	4500-9000
$\gamma_{ISR}\Upsilon(3S)\to(\gamma_{ISR})\pi^+\pi^-\Upsilon(1S)$	50.0, $\Upsilon(4S)$	0.1-0.2	3.5×10^7	35-70	1050-2100

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:
  - $B \to l\upsilon$, $B \to D^{(*)}\tau\upsilon$
  - Previously observed anomalies (such those observed in $B \to D^{(*)}\tau\upsilon$) can be resolved with few ab^{-1} of data.

- 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; plan to search for decays of the dark photon to dark matter.

- Search for low mass dark matter in $\Upsilon(1S) \to$ invisible (+gamma) planned at Belle II.

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

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_ν>=1) with unprecedented precision:
  - $B \to l\nu$, $B \to D^{(*)}\tau\nu$
  - Previously observed anomalies (such those observed in $B \to D^{(*)}\tau\nu$) can be resolved with few ab^{-1} of data.

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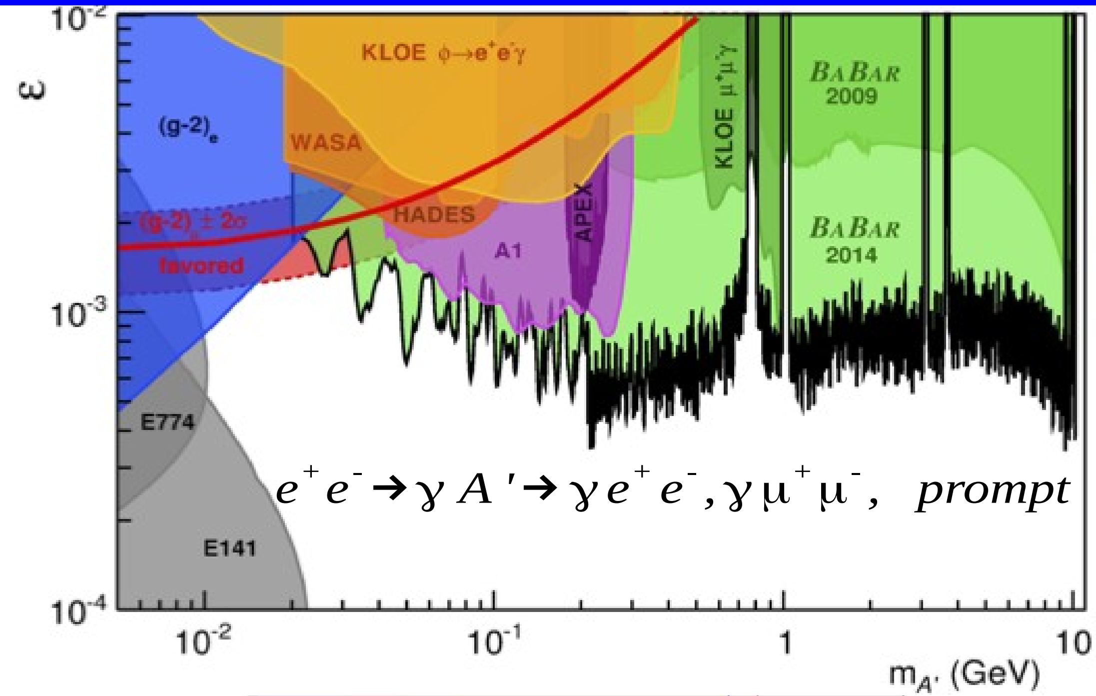
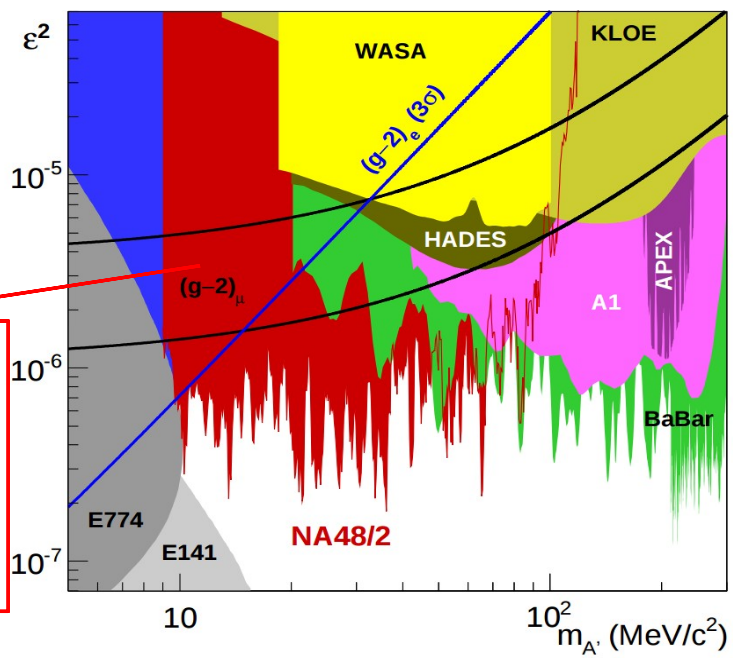
- Belle II will have a strong impact in the searches for new physics from 2018 for the next decade

Thank you for your attention!

Dark photon: current limits

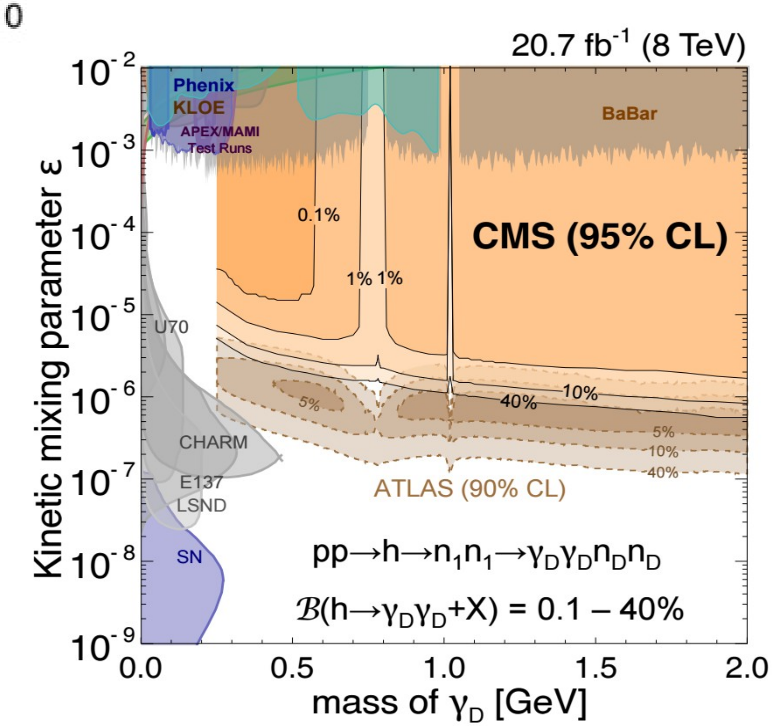


Many constraints for different region of the parameter space from different experiments.
Shown here:
- top left: BaBar ,
- bottom left NA48,
- bottom right CMS (containing ATLAS) [highly model dependent]



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

NA48 arXiv:1504.00607
π^0 decays



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