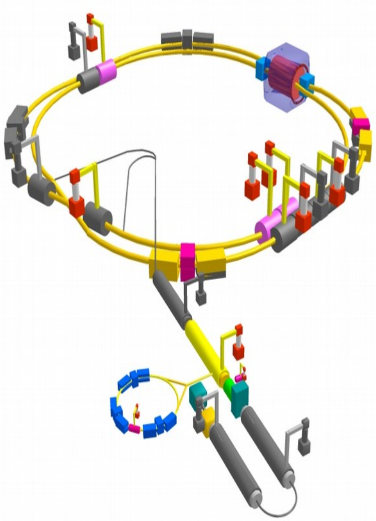
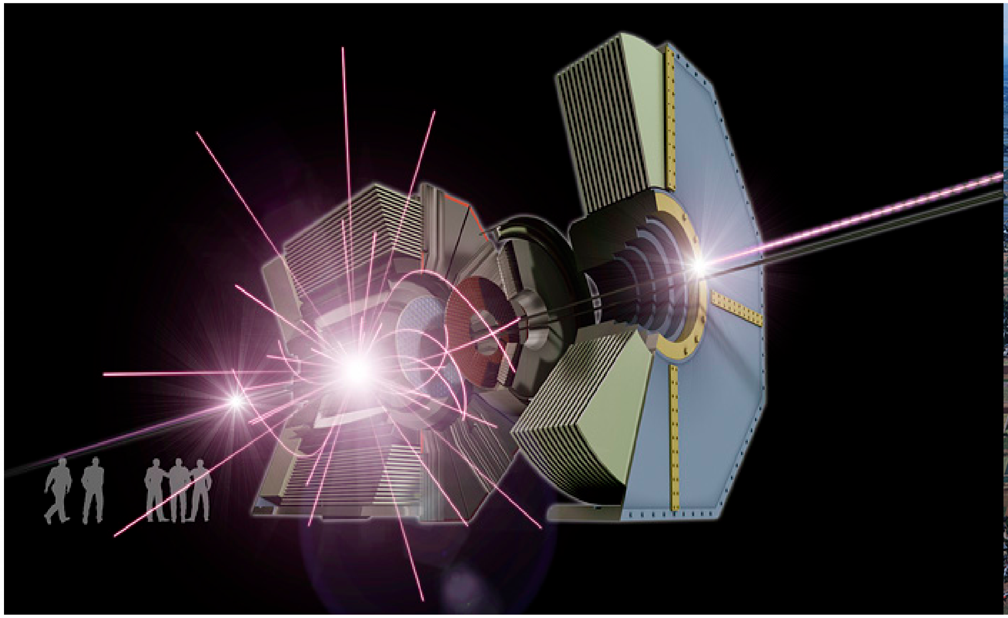
# Prospects for low mass dark matter and T/CPT tests

**JENNIFER Consortium General Meeting**
**KEK 06/10/2017**

**Gianluca Inguglia**

JENNIFER





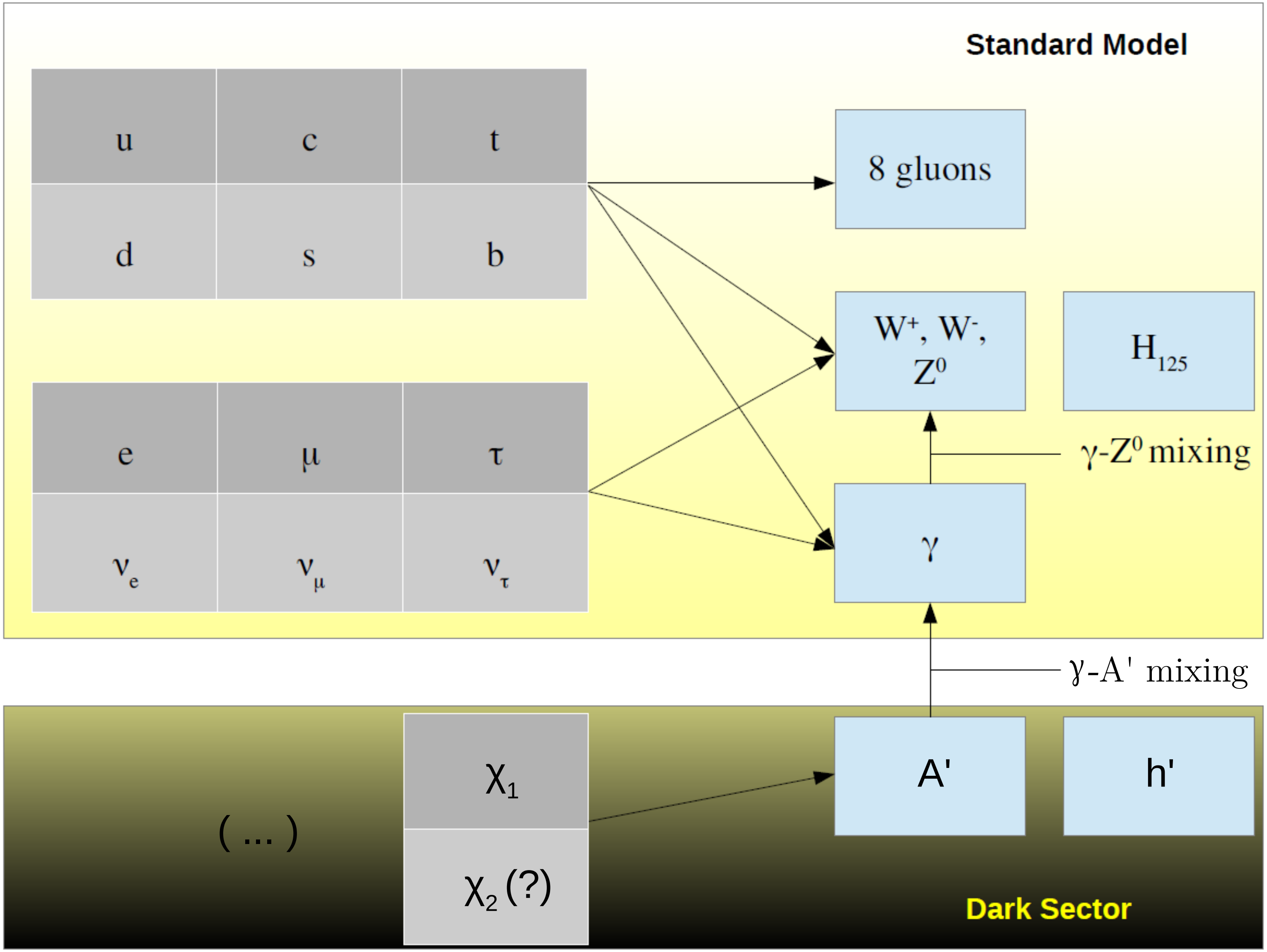
HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

ÖAW
ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

BELLE

Belle II

# Dask sector: how does it look like?



# Low mass dark matter @ Belle (II): Υ(1S) → invisible

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

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

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

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

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

$$e^+e^-\rightarrow\Upsilon(2S)$$
↓(18.1%)
$$\Upsilon(2S)\rightarrow\pi^+\pi^-\Upsilon(1S)$$
↓
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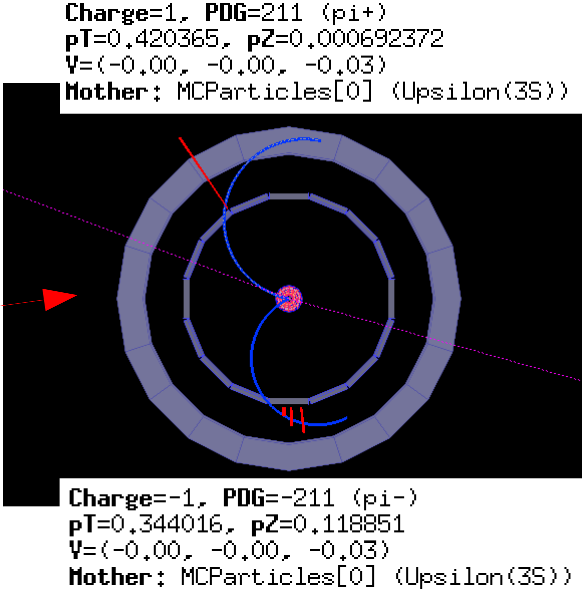
*Belle2 Simulation*
$\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$,
$\Upsilon(1S)\rightarrow\nu\nu$




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

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

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

# Low mass dark matter @ Belle (II): Υ(1S) → invisible

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

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$$e^+e^-\rightarrow Y(3S)$$
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- 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]
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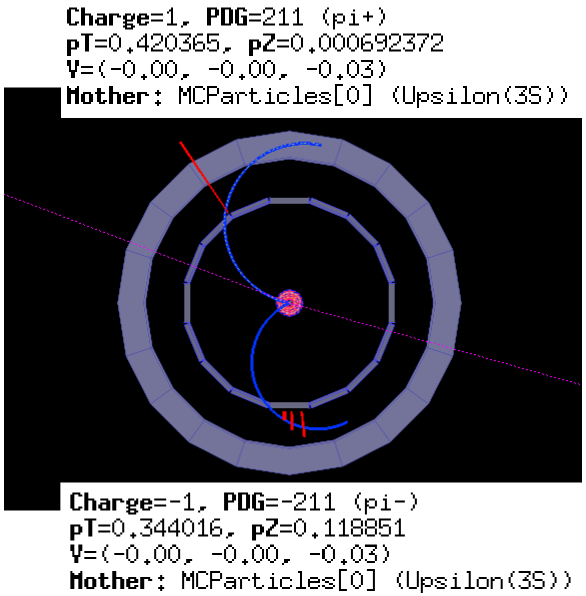
Υ(3S)→$\pi^+\pi^-$Υ(1S),
Υ(1S)→ νν




A signal of Υ(1S)→*invisible* is an excess of events over the background in the $M_r$ distribution at a mass equivalent to that of the Υ(1S) (9.460 GeV/c²)

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

# Low mass dark matter @ Belle II: Y(1S) → invisible

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

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

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

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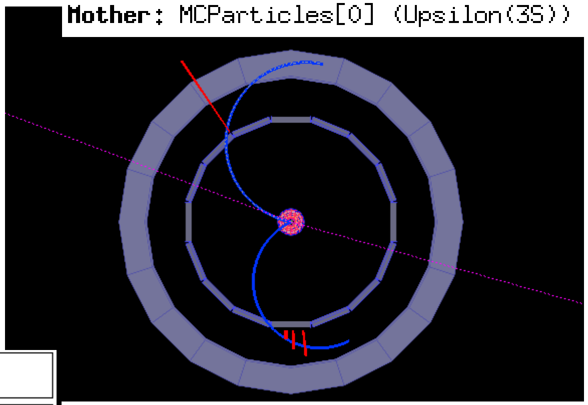
- Low mass dark matter particles however might might play a role in the decays of Y(1S), having Y(1S)→χχ if kinematic allowed. [Phys. Rev. D **80**, 115019, 2009]
- Also, new mediators (Z', $A^0$, $h^0$) or SUSY particles might enhance Y(1S)→νν(γ). [Phys. Rev. D **81**, 054025, 2010]
- In absence of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

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




No signal was observed over the expected background and upper limits have been obtained: BR(Y→νν) < $3\times10^{-4}$ (BaBar) and BR(Y→νν) < $3.0\times10^{-3}$(Belle).

| Process | $L_{int}(ab^{-1})$ | $\epsilon$ | $N(\Upsilon(1S))$ | $N_{\Upsilon(1S)\to\nu\bar{\nu}}$ | $N_{NP}$ |
|---|---|---|---|---|---|
| $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ | 0.2, $\Upsilon(2S)$ | 0.1-0.2 | $2.3\times10^8$ | 230-460 | 6900-13800 |
| $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ | 0.2, $\Upsilon(3S)$ | 0.1-0.2 | $3.2\times10^7$ | 32-64 | 945-1890 |
| $\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S)$ | 50.0, $\Upsilon(4S)$ | 0.1-0.2 | $5.5\times10^6$ | 5.5-11 | 165-310 |
| $\Upsilon(5S)\to\pi^+\pi^-\Upsilon(1S)$ | 5.0, $\Upsilon(5S)$ | 0.1-0.2 | $7.6\times10^6$ | 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 | $1.5\times10^8$ | 150-300 | 4500-9000 |
| $\gamma_{ISR}\Upsilon(3S)\to(\gamma_{ISR})\pi^+\pi^-\Upsilon(1S)$ | 50.0, $\Upsilon(4S)$ | 0.1-0.2 | $3.5\times10^7$ | 35-70 | 1050-2100 |

# Low mass dark matter @ Belle II: Y(1S) → invisible

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If we collect >200fb$^{-1}$ of data @ Y(3S) [Y(2S)] we should reconstruct between 30 and 300 [~200 and ~2000] events , assuming $10^{-5}$ (SM)<$BR_{Y\to invisible}$< $10^{-4}$ (NP) and $\varepsilon_{tot}$=10%.

However trigger is not yet taken into considerations and preliminary studies have shown that the trigger (only) efficiency currently is of ~50%.
Work also during phase II data taking is needed to perform test on exotic triggers (for the two low momentum π's).

Another thing that need to be clarified is the data taking at other energies than Y(4S). If the luminosity is too high the bkgd levels increase as well and triggers have to be scaled accordingly, this is in conflict with the need of low momentum pions trigger: data taking must happen in the early period of phase 3.

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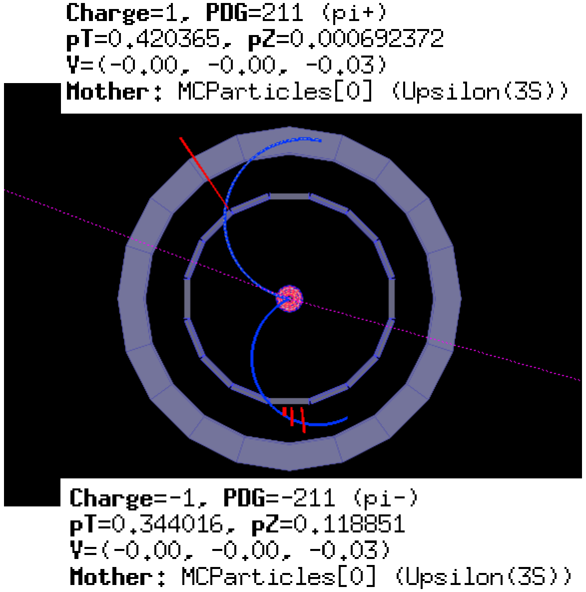
$Y(3S)\to\pi^+\pi^-Y(1S)$,
$Y(1S)\to\nu\nu$



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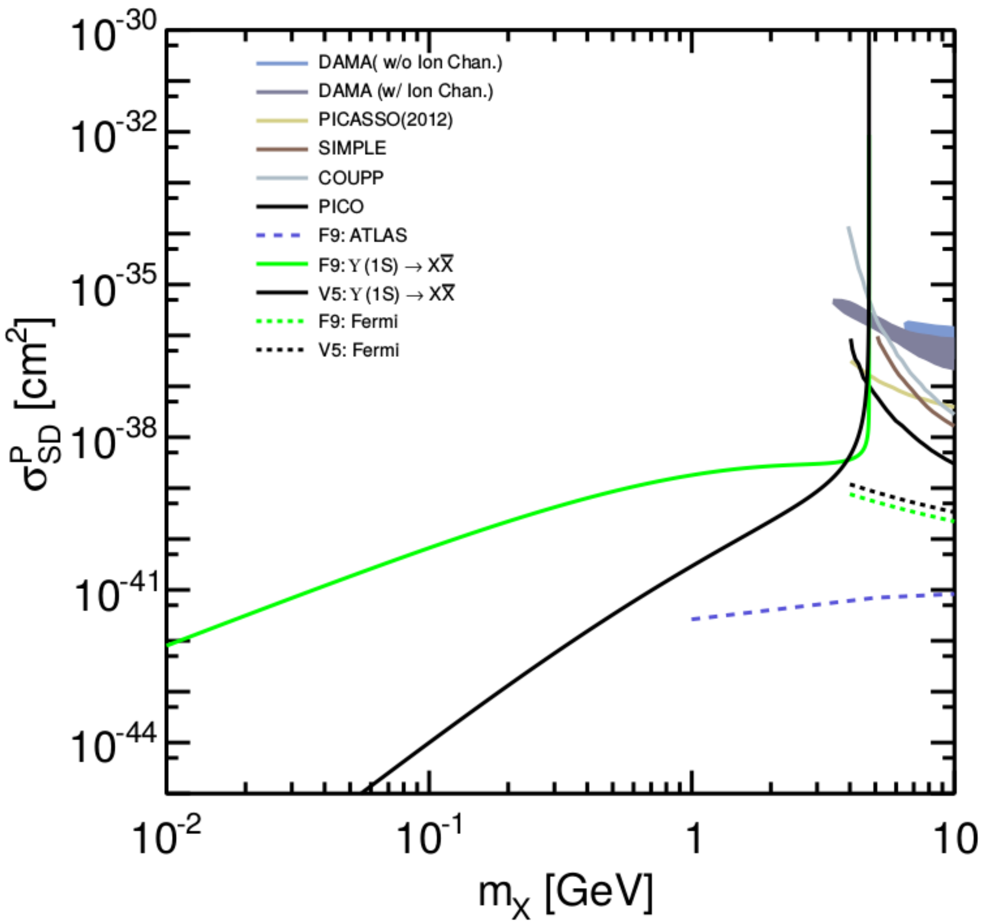


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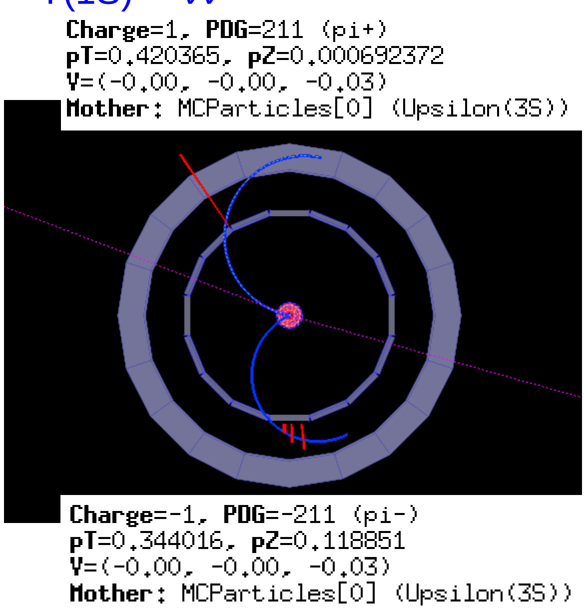

# Low mass dark matter @ Belle II: a dark Z'

Partial width results and BR not published, derived from eqn. 2.12 of Essig et al. JHEP02(2015)157, arXiv:1412.0018 [hep-ph] (contact: Brian Shuve).

The model is a new gauge boson, $Z'$, which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

$$\mathcal{L} = -g'\bar{\mu}\gamma^\mu Z'_\mu \mu + g'\bar{\tau}\gamma^\mu Z'_\mu \tau - g'\bar{\nu}_{\mu,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\mu,\mathrm{L}} + g'\bar{\nu}_{\tau,\mathrm{L}}\gamma^\mu Z'_\mu \nu_{\tau,\mathrm{L}}.$$

The equations for the partial widths are,

$$\Gamma(Z' \to \ell^+\ell^-) = \frac{(g')^2 M_{Z'}}{12\pi}\left(1 + \frac{2M_\ell^2}{M_{Z'}^2}\right)\sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}}\,\theta(M_{Z'} - 2M_\ell),$$

$$\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) = \frac{(g')^2 M_{Z'}}{24\pi}.$$

$$Br(Z' \to invisible) = \frac{2\Gamma(Z' \to \nu_l\bar{\nu}_l)}{2\Gamma(Z' \to \nu_l\bar{\nu}_l) + \Gamma(Z' \to \mu^+\mu^-) + \Gamma(Z' \to \tau^+\tau^-)}$$

1) The branching fraction to one neutrino species is half of the branching fraction to one charged lepton flavour. The reason is, of course, that the *Z'* only couples to left-handed neutrino chiralities whereas it couples to both left- and right-handed charged leptons.

For $M_{Z'} < 2M_\mu$ Br(Z' → invisible) =1.
For $2M_\mu < M_{Z'} < 2M_\tau$ Br(Z' → invisible)~1/2
For $M_{Z'} > 2M_\tau$ Br(Z' → invisible)~1/3

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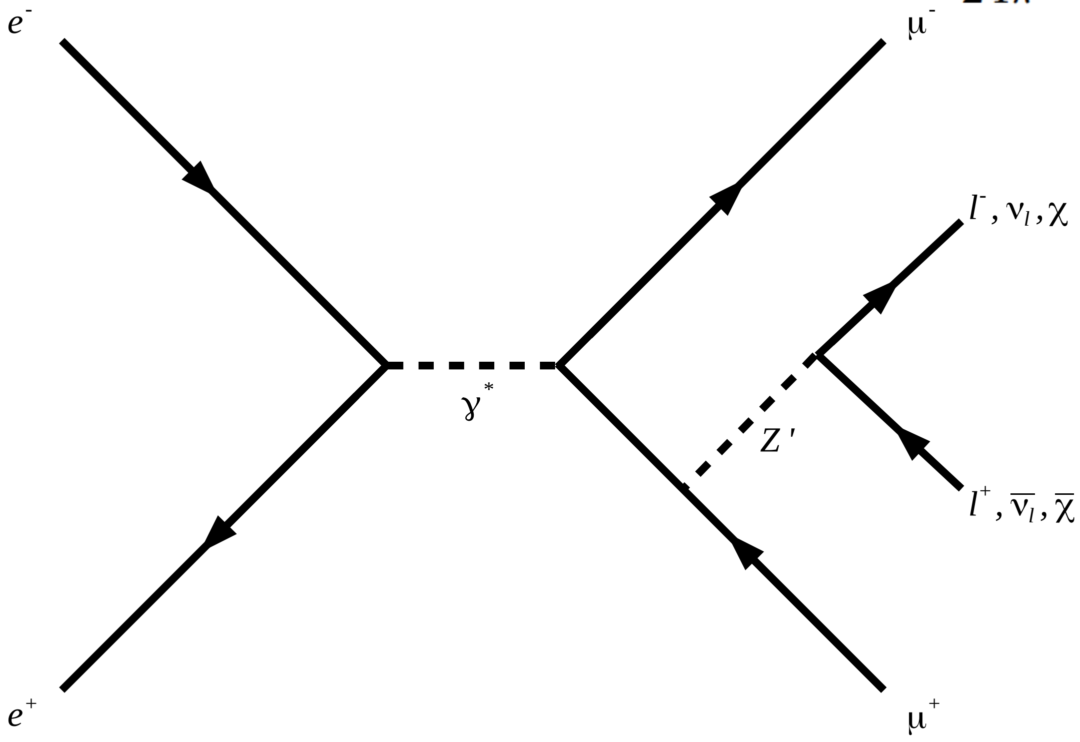
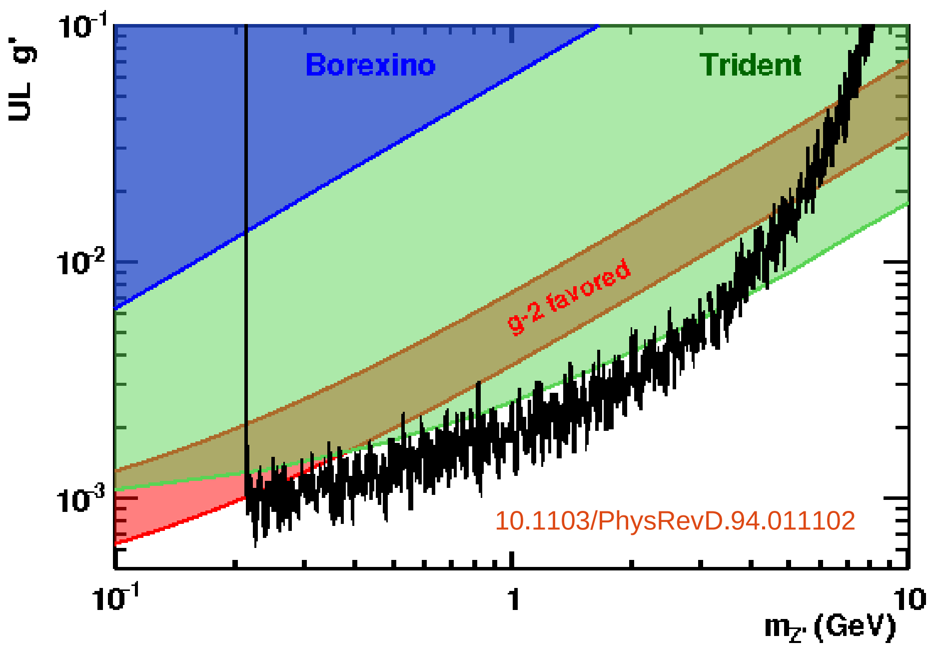
The equations for the partial widths are,

$$\Gamma(Z' \to \ell^+\ell^-) = \frac{(g')^2 M_{Z'}}{12\pi}\left(1 + \frac{2M_\ell^2}{M_{Z'}^2}\right)\sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}}\,\theta(M_{Z'} - 2M_\ell),$$

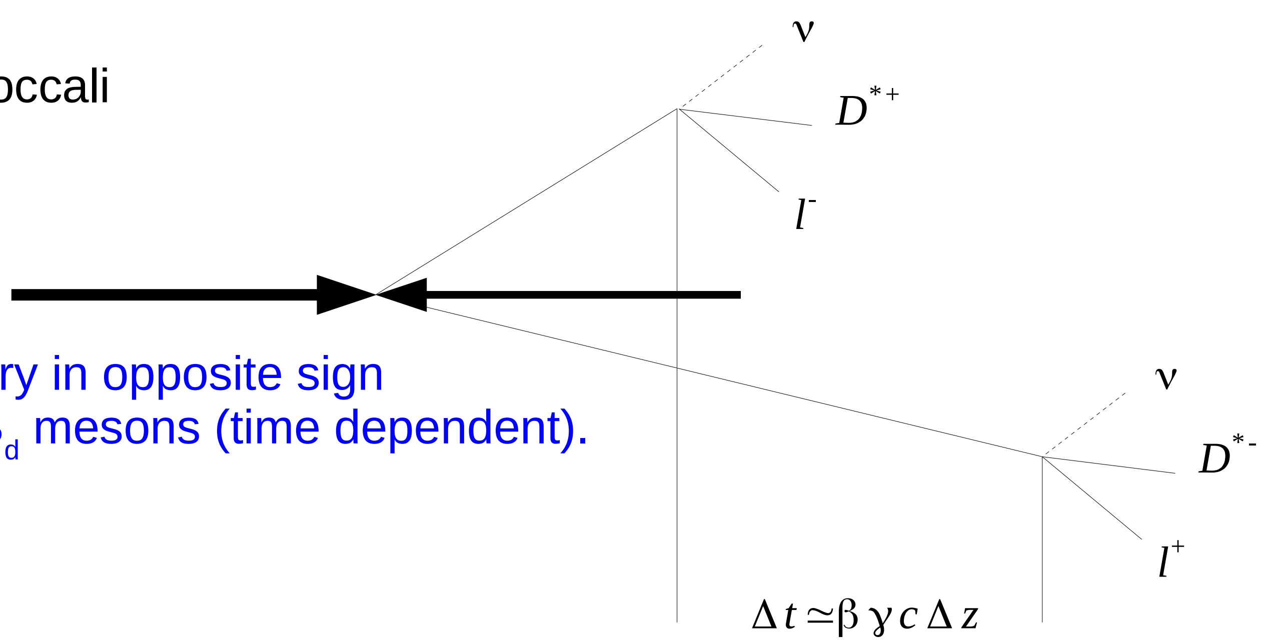
$$\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) = \frac{(g')^2 M_{Z'}}{24\pi}.$$



# Beside CP, can Belle II look for T/CPT non invariance?

1203.0930 Belle, CPT
1207.5832 BaBar, T+CPT
1302.4191 A. Bevean, G.I., M. Zoccali
1605.04545 BaBar, CPT




Dual CP/CPT violating asymmetry in opposite sign dilepton events with entangled $B_d$ mesons (time dependent).

$$\Psi = \frac{1}{\sqrt{2}} \left( B_1^0 \bar{B}_2^0 - \bar{B}_1^0 B_2^0 \right)$$

$$i \frac{d}{dt} \begin{pmatrix} |B_{1,H}\rangle \\ |B_{2,L}\rangle \end{pmatrix} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M_{22}^* - \frac{i}{2}\Gamma_{22}^* \end{pmatrix} \begin{pmatrix} |B^0\rangle \\ |\bar{B}^0\rangle \end{pmatrix}$$

$$|B_{1,H}\rangle = p\sqrt{1-z}|B^0\rangle + q\sqrt{1+z}|\bar{B}^0\rangle$$

$$|B_{2,L}\rangle = p\sqrt{1-z}|B^0\rangle - q\sqrt{1+z}|\bar{B}^0\rangle$$

$$z = \frac{(m_{11} - m_{22}) - \frac{i}{2}(\Gamma_{11} - \Gamma_{22})}{\Delta m - \frac{i}{2}\Delta\Gamma}$$

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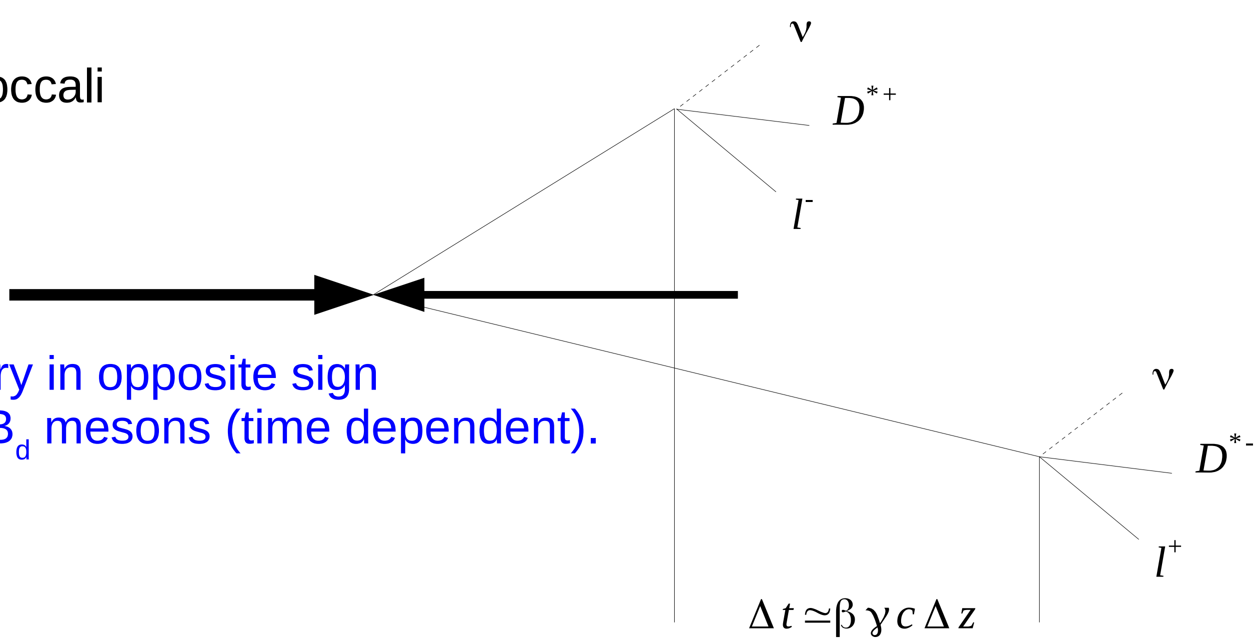


Dual CP/CPT violating asymmetry in opposite sign di-lepton events with entangled $B_d$ mesons (time dependent).

$$\Psi = \frac{1}{\sqrt{2}}\left(B_1^0 \bar{B}_2^0 - \bar{B}_1^0 B_2^0\right)$$

$$N^{2l} \propto \frac{e^{-\Gamma|\Delta t|}}{2}\left\{\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right) - 2\Re z \sinh\left(\frac{\Delta\Gamma\Delta t}{2}\right) + \cos(\Delta m\Delta t) + 2\Im z\, sin(\Delta m \Delta t)\right\}$$

$$A_{CPT,CP}(|\Delta t|) = \frac{P(B^0 \to B^0) - P(\bar{B}^0 \to \bar{B}^0)}{P(B^0 \to B^0) - P(\bar{B}^0 \to \bar{B}^0)} = \frac{N^{2l}(\Delta t > 0) - N^{2l}(\Delta t < 0)}{N^{2l}(\Delta t > 0) - N^{2l}(\Delta t < 0)} \simeq 2\frac{\Im z \sin(\Delta m \Delta t) - \Re z \sinh(\frac{\Delta\Gamma\Delta t}{2})}{\cosh(\frac{\Delta\Gamma\Delta t}{2}) + \cos(\Delta m \Delta t)}$$

Expected sensitivity with 5 $ab^{-1}$ ~3-4 x $10^{-3}$

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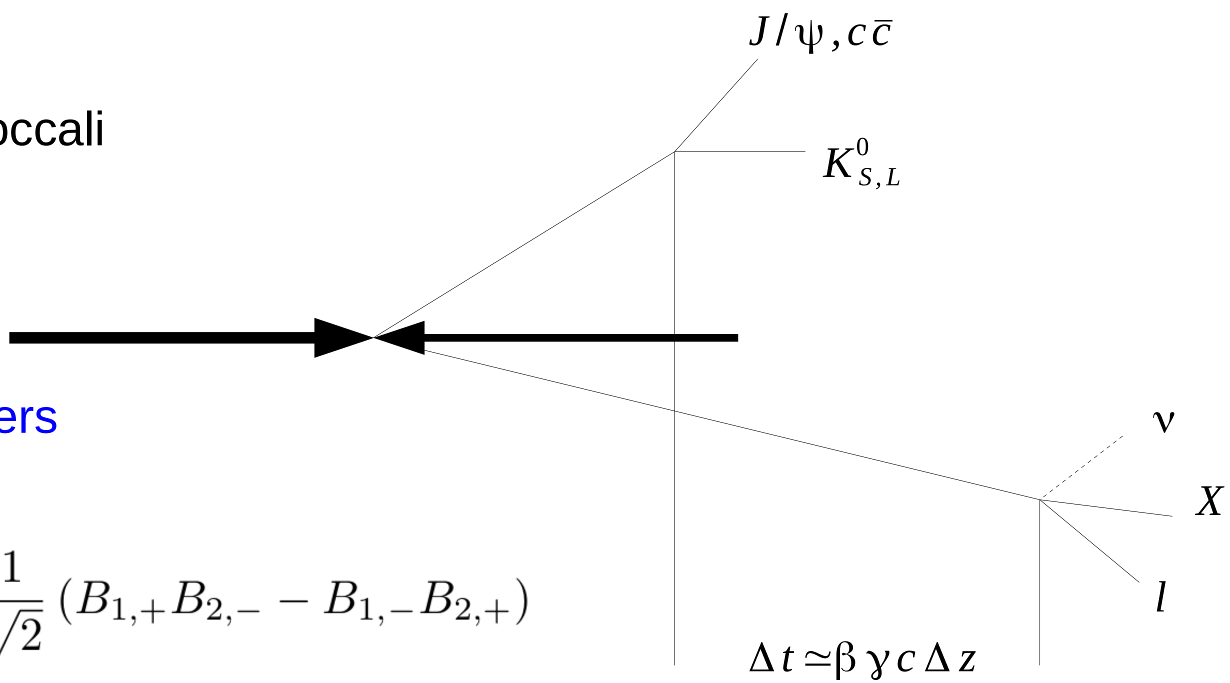


Test of T invariance using CP filters

$$\Psi = \frac{1}{\sqrt{2}}\left(B_1^0 \bar{B}_2^0 - \bar{B}_1^0 B_2^0\right) = \frac{1}{\sqrt{2}}\left(B_{1,+}B_{2,-} - B_{1,-}B_{2,+}\right)$$

$$A_T = \frac{\Gamma(|1\rangle \to |2\rangle) - \Gamma(|2\rangle \to |1\rangle)}{\Gamma(|1\rangle \to |2\rangle) + \Gamma(|2\rangle \to |1\rangle)}$$

$$g^{\pm}_{\alpha,\beta} \propto \left[1 + C^{\pm}_{\alpha,\beta}\cos\Delta m\Delta t + S^{\pm}_{\alpha,\beta}\sin\Delta m\Delta t\right]$$

$$S^{\pm}_{\alpha,\beta} = \frac{2Im\lambda}{1+|\lambda|^2} \text{ and } C^{\pm}_{\alpha,\beta} = \frac{1-|\lambda|^2}{1+|\lambda|^2}$$

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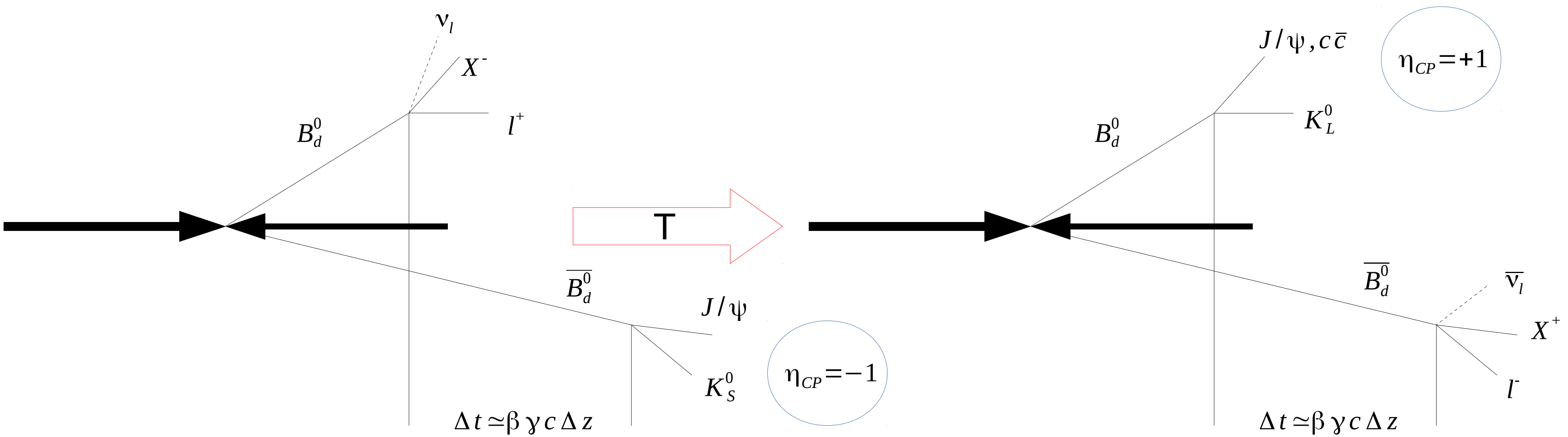

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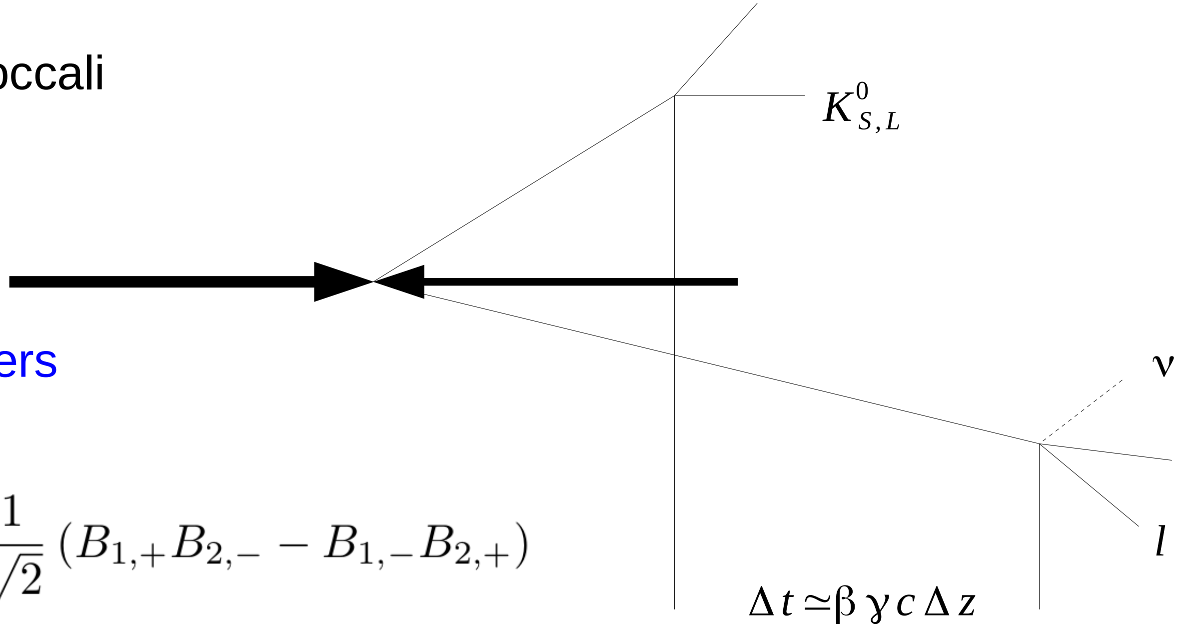


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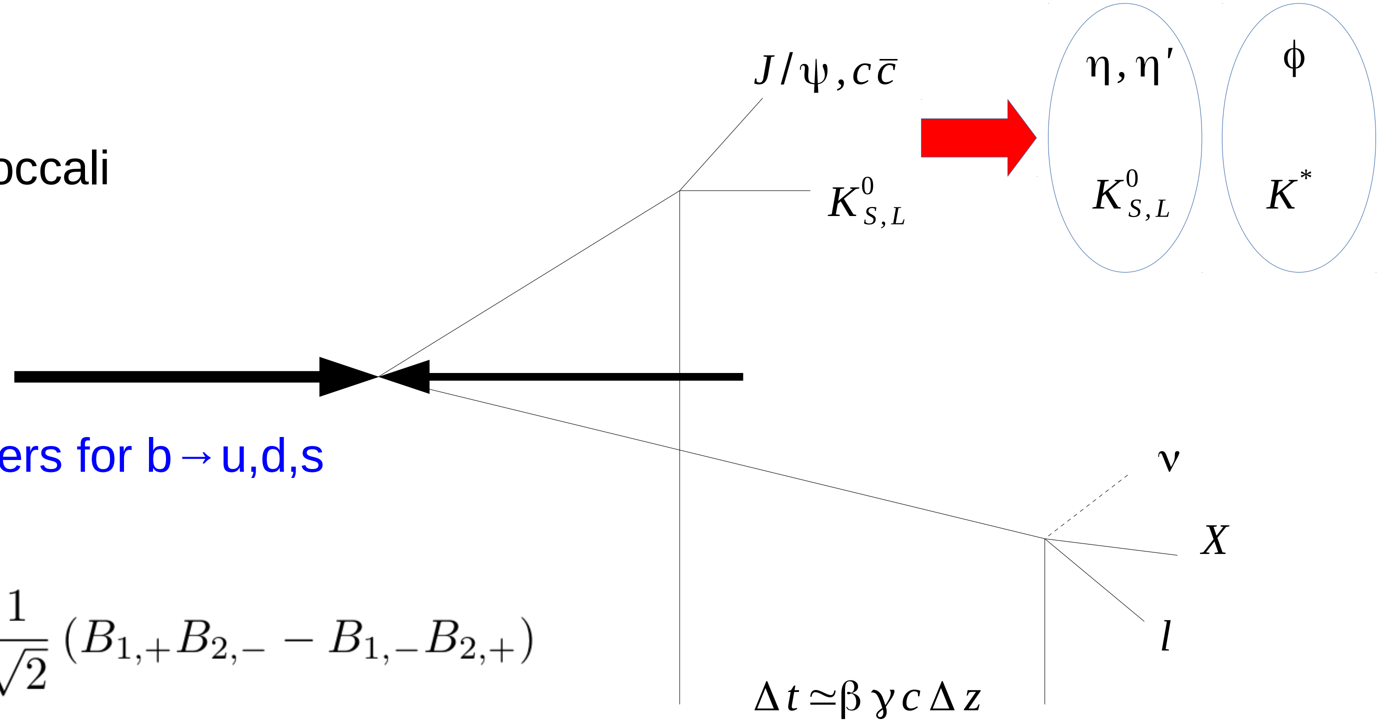


Test of T invariance using CP filters for b→u,d,s

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$$A_T \simeq \frac{\Delta C^{\pm}_T}{2}\cos\Delta m\Delta t + \frac{\Delta S^{\pm}_T}{2}\sin\Delta m\Delta t$$

Channel suppressed by a factor 10, but considering ~5ab-1 of data one can expect similar precision on b→uds as obtained by BaBar for b→c transitions
($\Delta S_T^+ = -1.37 \pm 0.14$ (stat.)$\pm 0.06$(syst.),
$\Delta S_T^- = 1.17 \pm 0.18$ (stat.)$\pm 0.11$ (syst.))

# Conclusions

- Important opportunities for new physics searches ahead.
- For invisible Υ(1S) decays we need to have precise plan for data taking at the Υ(3S), and this is still missing. Triggers will depend also on when data are taken, ideally the sooner the better..In general tests of exotics triggers will be performed during data taking from phase 2.
- T/CPT tests could and should be performed during the operation of Belle II, and a few channels have been identified to complement and improve existing measurements.
- JENNIFER contribution will have a high impact on these projects:
  - 4-5 people (including myself, excluding undergraduates) are expected to work on these studies starting in mid 2018 to ~2022
  - For Υ(3S) data taking 1-2 people should be based at KEK.

**Thank you for your attention!**