See-saw mediators in t-channel

Margherita Ghezzi

PAUL SCHERRER INSTITUT

BSM direct searches at CLIC, 21 February 2018

Outline

Outline

The doubly charged scalar from the $SU(2)_L$-triplet scalar

Type-II see-saw model

$$S = \begin{pmatrix} S^{+} & \sqrt{2}S^{++} \\ \sqrt{2}S^{0} & -S^{+} \end{pmatrix}$$

$$< S >_0 = \begin{pmatrix} 0 & 0 \\ w & 0 \end{pmatrix}$$

Yukawa term with the triplet:

$$\Delta\mathcal{L}_Y = f_{ij} L_i^T C^{-1} i\tau_2 S L_j + \text{h.c.}$$

Majorana mass term for neutrinos:

$$m_{ij}\bar{\nu}^c_{iL}\nu_{jL} \qquad m_{ij} = w\, f_{ij} = m_{ji}$$

T. P. Cheng and L. F. Li, Phys. Rev. D 22 (1980) 2860

W. Grimus, R. Pfeiffer and T. Schwetz, Eur. Phys. J. C 13 (2000) 125

E. Ma, M. Raidal and U. Sarkar, Nucl. Phys. B 615 (2001) 313

A. G. Akeroyd and M. Aoki, Phys. Rev. D 72 (2005) 035011

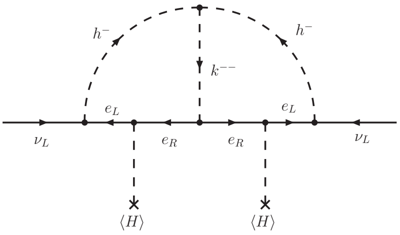
The doubly Charged $SU(2)_L$-singlet scalar

Zee-Babu model

SM + 2 $SU(2)_L$-singlet scalars:

- a singly charged scalar which couples to left-handed leptons: $h^{\pm}$
- a doubly charged scalar which couples to right-handed leptons: $k^{\pm\pm}$

It generates mass terms for the neutrinos at two loops:



A. Zee, Nucl. Phys. B **264** (1986) 99

K. S. Babu, Phys. Lett. B **203**, 132 (1988)

M. Nebot, J. F. Oliver, D. Palao and A. Santamaria, Phys. Rev. D 77 (2008) 093013

The doubly Charged $SU(2)_L$-singlet scalar

Minimal model for neutrino masses

SM + 1 $SU(2)_L$-singlet doubly charged scalar: $S_R^{\pm\pm}$

It couples only with right-handed charged leptons:

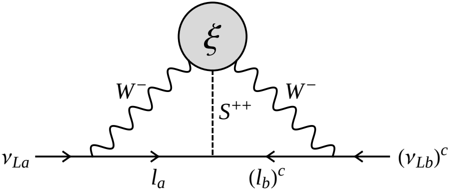
$$\begin{aligned}\mathcal{L}_{UV} &= \mathcal{L}_{\rm SM} + \left(D_\mu S^{++}\right)^\dagger \left(D^\mu S^{++}\right) \\ &+ \left(\lambda_{ab}\, \overline{(\ell_R)^c_a} \ell_{Rb}\, S^{++} + \text{h.c.}\right)\end{aligned}$$

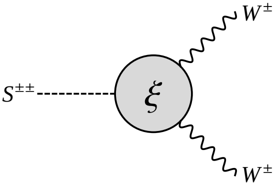
λ_{ab} consist of 6 independent parameters and allow for LFV processes

S. F. King, A. Merle and L. Panizzi, JHEP 1411 (2014) 124

The doubly charged $SU(2)_L$-singlet scalar

Neutrino mass terms are generated at three loop:



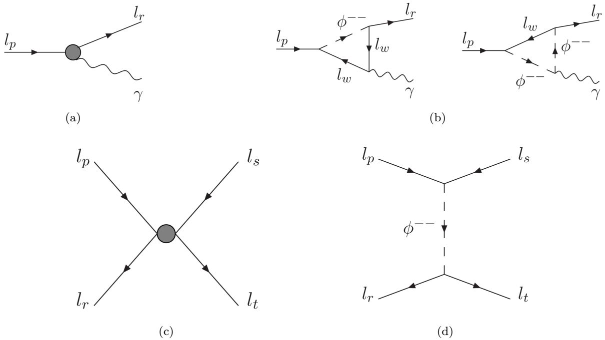


S. F. King, A. Merle and L. Panizzi, JHEP 1411 (2014) 124

Outline

Low-energy effective Lagrangian and the matching

Feynman diagrams representing the UV-complete contributions that match to the dipole and four-fermion operators.



- Diagrams in Fig. (b) match into the diagram in Fig. (a) (dipole interaction)
- Diagram in Fig. (d) matches into the diagram in Fig. (c) (contact interaction)

Crivellin, MG, Panizzi, Pruna, Signer, work in progress

Low-energy effective Lagrangian and the matching

Dipole			
$Q_{e\gamma}$	$em_r(\bar{l}_p\sigma^{\mu\nu}P_L l_r)F_{\mu\nu} + \mathrm{H.c.}$		
Scalar/Tensorial		**Vectorial**	
Q_S	$(\bar{l}_p P_L l_r)(\bar{l}_s P_L l_t) + \mathrm{H.c.}$	Q_{VLL}	$(\bar{l}_p\gamma^\mu P_L l_r)(\bar{l}_s\gamma_\mu P_L l_t)$
		Q_{VLR}	$(\bar{l}_p\gamma^\mu P_L l_r)(\bar{l}_s\gamma_\mu P_R l_t)$
		Q_{VRR}	$(\bar{l}_p\gamma^\mu P_R l_r)(\bar{l}_s\gamma_\mu P_R l_t)$
$Q_{Slq(1)}$	$(\bar{l}_p P_L l_r)(\bar{q}_s P_L q_t) + \mathrm{H.c.}$	Q_{VlqLL}	$(\bar{l}_p\gamma^\mu P_L l_r)(\bar{q}_s\gamma_\mu P_L q_t)$
$Q_{Slq(2)}$	$(\bar{l}_p P_L l_r)(\bar{q}_s P_R q_t) + \mathrm{H.c.}$	Q_{VlqLR}	$(\bar{l}_p\gamma^\mu P_L l_r)(\bar{q}_s\gamma_\mu P_R q_t)$
Q_{Tlq}	$(\bar{l}_p\sigma^{\mu\nu}P_L l_r)(\bar{q}_s\sigma_{\mu\nu}P_L q_t) + \mathrm{H.c.}$	Q_{VlqRL}	$(\bar{l}_p\gamma^\mu P_R l_r)(\bar{q}_s\gamma_\mu P_L q_t)$
		Q_{VlqRR}	$(\bar{l}_p\gamma^\mu P_R l_r)(\bar{q}_s\gamma_\mu P_R q_t)$

Dimension-six operators that allow for effective leptonic transitions below the EW scale

Current low-energy experimental limits

$$
\begin{aligned}
\mathrm{Br}\left[\tau^{\mp} \to e^{\mp} e^{\pm} e^{\mp}\right] &\leq 1.4 \times 10^{-8} \\
\mathrm{Br}\left[\tau^{\mp} \to \mu^{\mp} \mu^{\pm} \mu^{\mp}\right] &\leq 1.2 \times 10^{-8} \\
\mathrm{Br}\left[\tau^{\mp} \to e^{\mp} \mu^{\pm} \mu^{\mp}\right] &\leq 1.6 \times 10^{-8} \\
\mathrm{Br}\left[\tau^{\mp} \to \mu^{\mp} e^{\pm} \mu^{\mp}\right] &\leq 9.8 \times 10^{-9} \\
\mathrm{Br}\left[\tau^{\mp} \to \mu^{\mp} e^{\pm} e^{\mp}\right] &\leq 1.1 \times 10^{-8} \\
\mathrm{Br}\left[\tau^{\mp} \to e^{\mp} \mu^{\pm} e^{\mp}\right] &\leq 8.4 \times 10^{-8} \\
\mathrm{Br}\left[\mu^{\mp} \to e^{\mp} e^{\pm} e^{\mp}\right] &\leq 1.0 \times 10^{-12}
\end{aligned}
$$

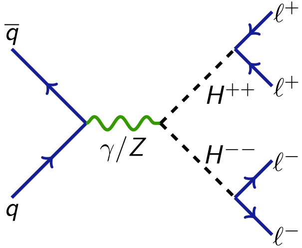
$$
\begin{aligned}
\mathrm{Br}\left[\tau \to e\gamma\right] &\leq 3.3 \times 10^{-8} \\
\mathrm{Br}\left[\tau \to \mu\gamma\right] &\leq 4.4 \times 10^{-8} \\
\mathrm{Br}\left[\mu \to e\gamma\right] &\leq 4.2 \times 10^{-13}
\end{aligned}
$$

$$
\mathrm{BR}(l_p^{\pm} \to l_r^{\pm}\gamma) \simeq \frac{\alpha\, m_p^5}{(24\pi^2)^2 m_\phi^4 \Gamma_p} \left| \sum_{w=1}^{3} \lambda_{pw} \lambda_{rw}^* \right|^2
$$

$$
\mathrm{BR}(l_p^{\pm} \to l_r^{\pm} l_s^{\mp} l_t^{\pm}) \simeq \frac{m_p^5 |\lambda_{ps}|^2 |\lambda_{rt}|^2}{s_{rt} 6(4\pi)^3 m_\phi^4 \Gamma_p}
$$

Outline

Direct searches at LHC



- Signature: same-sign lepton pairs
- Assumptions on the branching ratios
- Narrow width approximation

ATLAS 7 TeV:

- Eur.Phys.J. C72 (2012) 2244

CMS 7 TeV:

- Eur.Phys.J. C72 (2012) 2189

ATLAS 13 TeV:

- CERN-EP-2017-198

CMS 13 TeV:

- CMS-PAS-HIG-16-036

Current limits from LHC

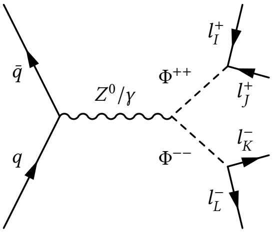
CMS searches

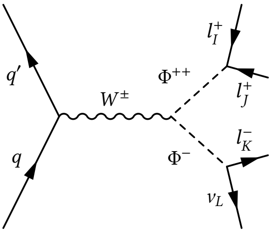
Search for a scalar triplet $S = \begin{pmatrix} S^+ & \sqrt{2}S^{++} \\ \sqrt{2}S^0 & -S^+ \end{pmatrix}$ with degenerate masses.

$12.9\,\mathrm{fb}^{-1}$ of integrated luminosity at 13 TeV

Channels:

- Pair production with decays $S^{++}S^{--} \to \ell^+\ell^+\ell^-\ell^-$
- Associated production with decays $S^{\pm\pm}S^{\mp} \to \ell^\pm\ell^\pm\ell^\mp\nu$





CMS-PAS-HIG-16-036

Current limits from LHC

CMS searches

- $S_L^{\pm\pm}$ decaying at 100% to ee, $\mu\mu$, $\tau\tau$, $e\mu$, $e\tau$, $\mu\tau$;
- Benchmark points:

Benchmark Point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	1/2	0	0	1/8	1/4	1/8
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

Lower bounds on the mass of the $S_L^{\pm\pm}$ - observed (expected) 95% CL:

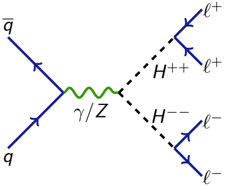
Benchmark	AP [GeV]	PP [GeV]	Combined [GeV]
100% $\Phi^{\pm\pm} \to ee$	734 (720)	652 (639)	800 (785)
100% $\Phi^{\pm\pm} \to e\mu$	750 (729)	665 (660)	820 (810)
100% $\Phi^{\pm\pm} \to \mu\mu$	746 (774)	712 (712)	816 (843)
100% $\Phi^{\pm\pm} \to e\tau$	568 (582)	481 (543)	714 (658)
100% $\Phi^{\pm\pm} \to \mu\tau$	518 (613)	537 (591)	643 (708)
100% $\Phi^{\pm\pm} \to \tau\tau$	479 (483)	396 (419)	535 (544)
Benchmark 1	613 (649)	519 (548)	723 (715)
Benchmark 2	670 (671)	465 (554)	716 (723)
Benchmark 3	706 (682)	531 (562)	761 (732)
Benchmark 4	639 (639)	496 (539)	722 (704)

$S_R^{\pm\pm}$ may have similar kinematic properties, but potentially very different production cross sections. No associate production.

CMS-PAS-HIG-16-036

Current limits from LHC

ATLAS searches



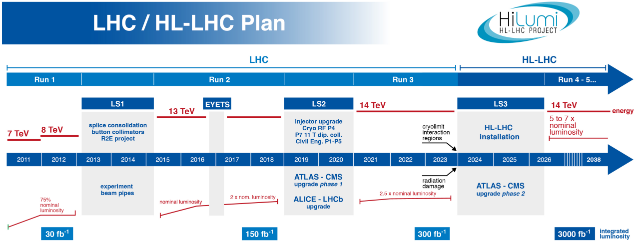
36.1 fb^{-1} of integrated luminosity at 13 TeV.

Scenarios:

- $\sum_{i,j=e,\mu} \mathcal{B}(S^{\pm\pm} \to \ell_i \ell_j) = 100\%$
  - $m\left(S_L^{\pm\pm}\right)$ between 770 GeV and 870 GeV @ 95% C.L.
  - $m\left(S_R^{\pm\pm}\right)$ between 660 GeV and 760 GeV @ 95% C.L.
- $\mathcal{B}(S^{\pm\pm} \to \ell_i \ell_j) > 10\%$ (decays to τ and W are possible)
  - $m\left(S_L^{\pm\pm}\right)$ larger than 450 GeV @ 95% C.L.
  - $m\left(S_R^{\pm\pm}\right)$ larger than 320 GeV @ 95% C.L.

CERN-EP-2017-198

Expected discovery power of HiLumi-LHC



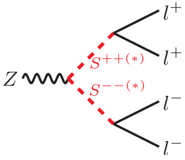
Expected lower limits on the mass - projections at 3000 fb^{-1}

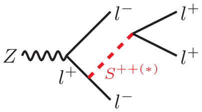
CMS 12.9 fb^{-1}	$S_L^{\pm\pm}$	$[600, 800]$ GeV	$\to$	$[2400, 3200]$ GeV:
	$S_L^{\pm\pm}$, PP only	$[400, 700]$ GeV	$\to$	$[1600, 2800]$ GeV
ATLAS 36.1 fb^{-1}	$S_L^{\pm\pm}$, $\mathcal{B}_{\ell\ell} = 100\%$	~ 800 GeV	$\to$	~ 2400 GeV
	$S_L^{\pm\pm}$, $\mathcal{B}_{\ell\ell} > 10\%$	~ 450 GeV	$\to$	~ 1350 GeV
	$S_R^{\pm\pm}$, $\mathcal{B}_{\ell\ell} = 100\%$	~ 700 GeV	$\to$	~ 2100 GeV
	$S_R^{\pm\pm}$, $\mathcal{B}_{\ell\ell} > 10\%$	~ 300 GeV	$\to$	~ 900 GeV

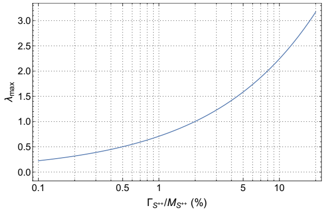
Width effects

- No *production* × *decay* approximation;
- some topologies that are negligible in the NWA can become relevant;
- assumption: gauge sector not modified, i.e. $S_R^{\pm\pm}$ coupling to Z is not a free coupling;
- Γ_S is considered as a free parameter and $\sum_{ab,cd} \Gamma_S^{\text{part}} \leq \Gamma_S$

$$\sigma_{PP\to l_a^+ l_b^+ l_c^- l_d^-}(M_S, \Gamma_S, \lambda_{ab}, \lambda_{cd}) = \lambda_{ab}^2 \lambda_{cd}^2 \hat{\sigma}(M_S, \Gamma_S)$$





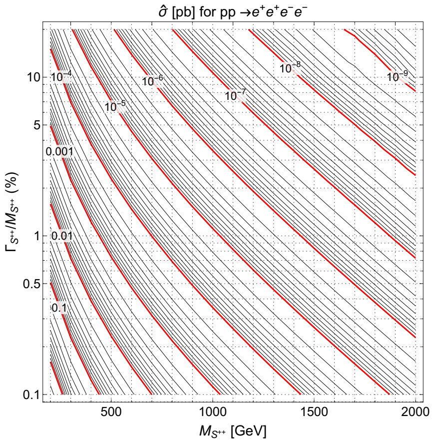


Crivellin, MG, Panizzi, Pruna, Signer, work in progress

Width effects: results

Very good approximation for light leptons:

$$\sigma_{PP\to l_a^+ l_b^+ l_c^- l_d^-}(M_S, \Gamma_S, \lambda_{ij}) = \kappa_{ab,cd}\ \lambda_{ab}^2 \lambda_{cd}^2 \hat{\sigma}_{PP\to 2e^+2e^-}(M_S, \Gamma_S)\ ,$$



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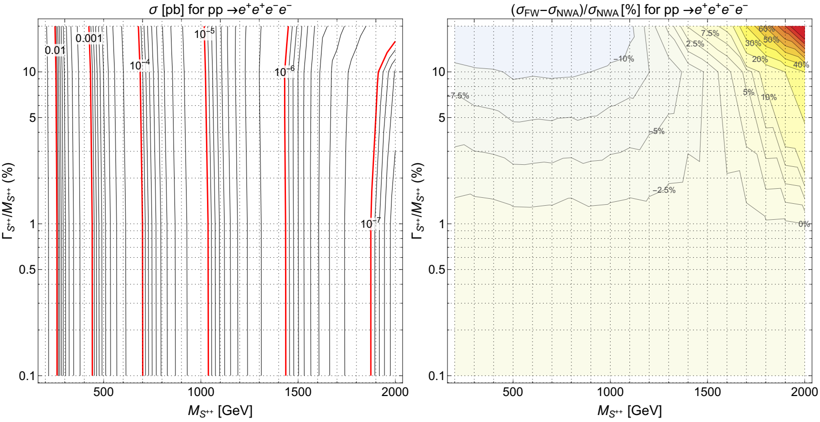
Width effects: results

- Cross-section corresponding to the maximum coupling values;
- relative ratio between cross-sections in the FW regime and NWA.



Crivellin, MG, Panizzi, Pruna, Signer, work in progress

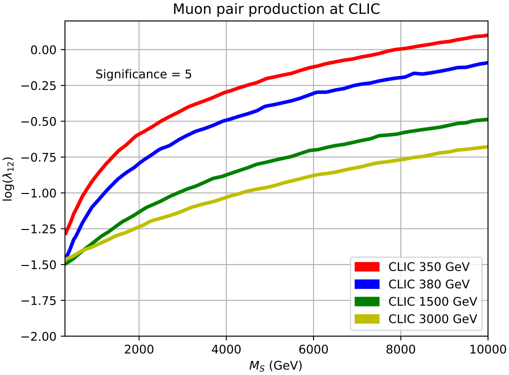
Outline

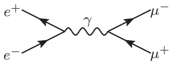
Perspective of searches at future colliders

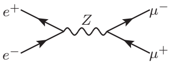
Crivellin, MG, Panizzi, Pruna, Signer, work in progress (Preliminary plot)

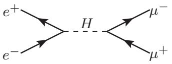
- $S = \frac{N_s}{\sqrt{N_s + N_b}}$
- Beamstrahlung
- Standard acceptance cuts:

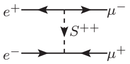
$$E(\mu^\pm) > 10\,\mathrm{GeV}$$
$$|\cos(\theta)| < 0.95$$











Perspective of searches at future colliders

Crivellin, MG, Panizzi, Pruna, Signer, work in progress

(Preliminary plot)

- Electron beam polarization:

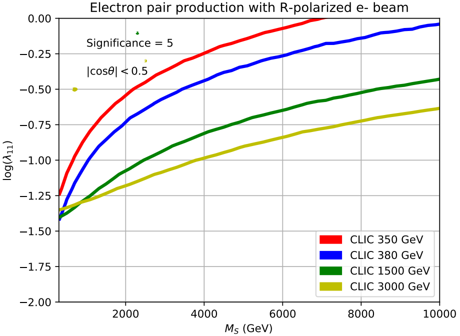
$$P_{e^-} = 0.4$$
$$P_{e^+} = 0$$

- Angular cut:

$$|\cos(\theta)| < 0.5$$

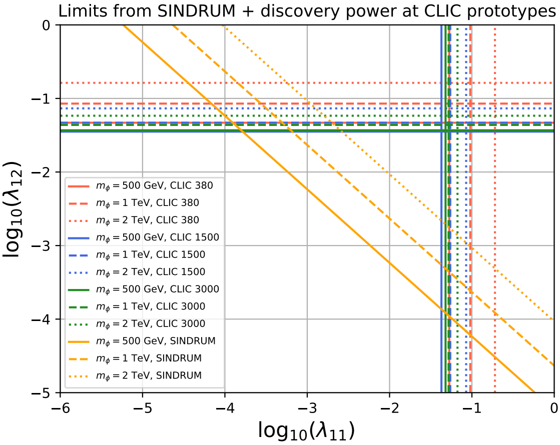
- Integrated luminosity:

350 GeV	380 GeV	1.5 TeV	3 TeV
100 fb^{-1}	500 fb^{-1}	1500 fb^{-1}	3000 fb^{-1}



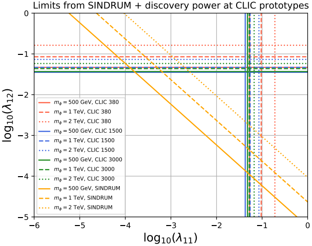
Limits from low energy and discovery power of CLIC

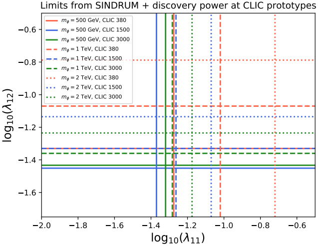
(Preliminary plot)

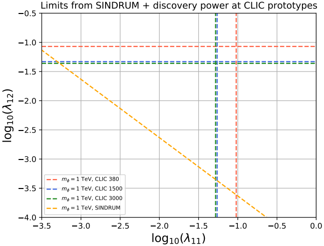


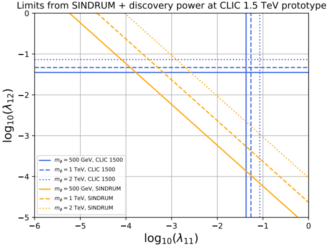
Crivellin, MG, Panizzi, Pruna, Signer, work in progress

Limits from low energy and discovery power of CLIC









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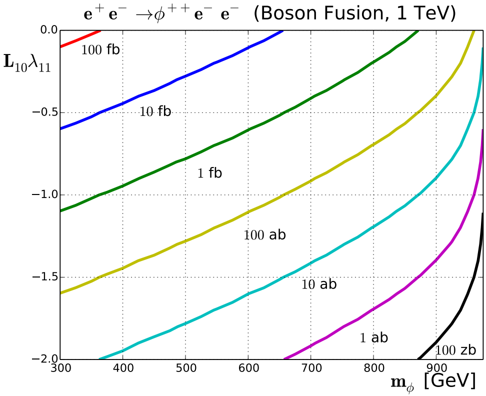
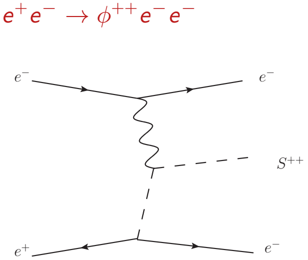
Direct production

Single production at ILC

(Preliminary plot)





Crivellin, MG, Panizzi, Pruna, Signer, work in progress

Outline

Summary

- Doubly charged scalars arise in many BSM models, in triplets or singlets under $SU(2)_L$, often in connection with the neutrino masses;
- LFV low energy processes set strong limits on combination of the DCS couplings to leptons;
- future e^+e^- colliders can provide complementary bounds;
- due to the production of the DCS in the t-channel, future e^+e^- colliders can be sensitive to mass scales of several TeV;
- direct searches have been performed at LHC by both ATLAS and CMS, setting limits on the DCS mass in the range (320, 870) GeV depending on the assumptions;
- a moderately large width ($\Gamma_S/m_S \sim$ few%) can have 10-20% effect on the cross section compared to the NWA;
- further investigations of the DCS phenomenology are ongoing and the results will be published soon.