Prospects for Dark Matter Search at the Super c-tau Factory

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SINP MSU

Workshop on future Super c-tau factories 2021
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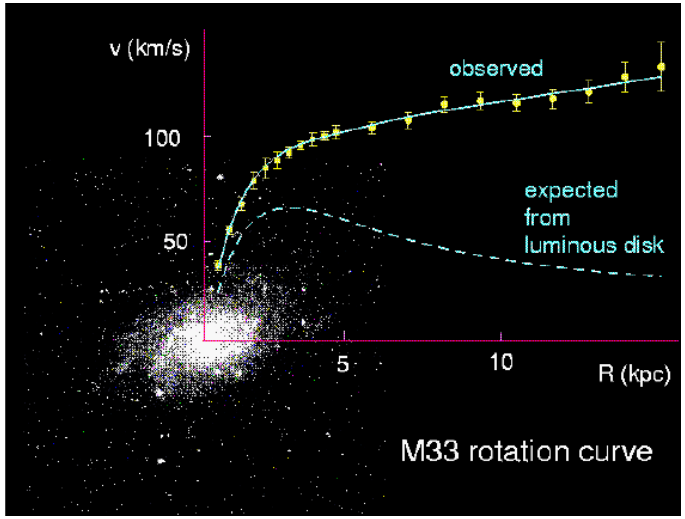
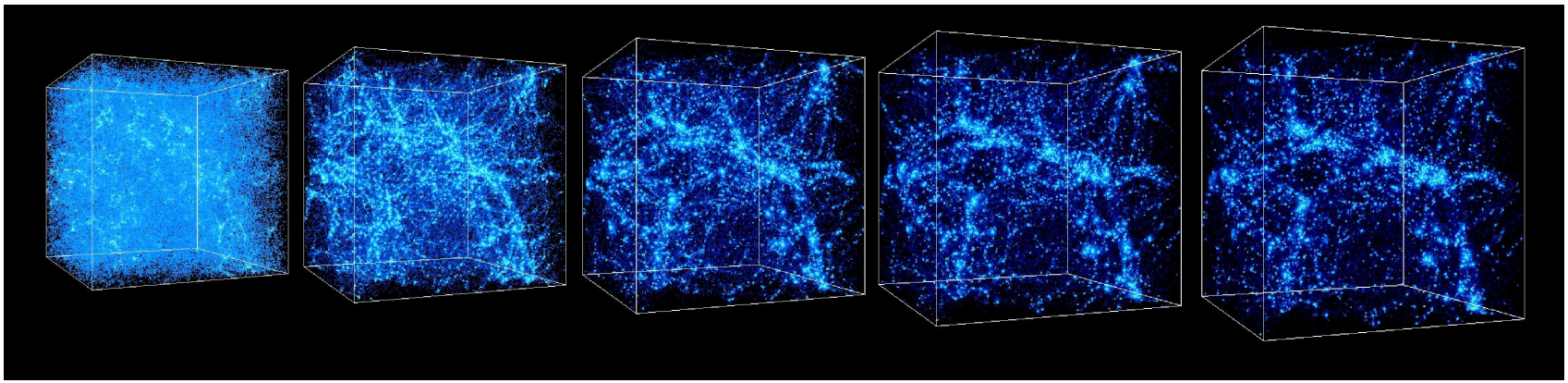
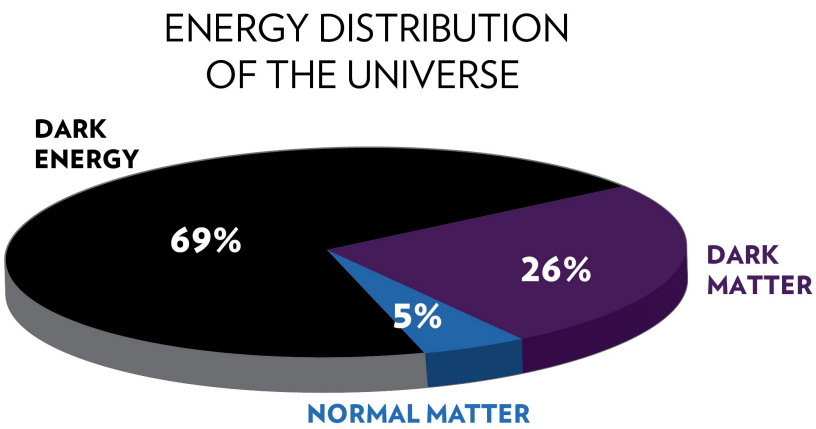
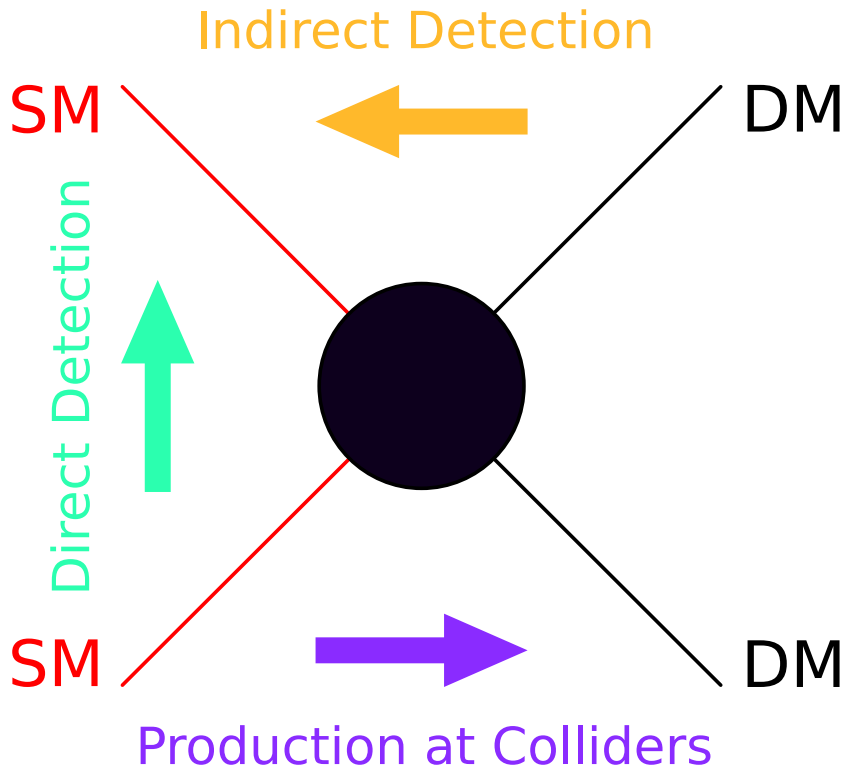
Dark Matter


v (km/s)
observed
100
expected
from
luminous disk
50
5
10
R (kpc)
M33 rotation curve

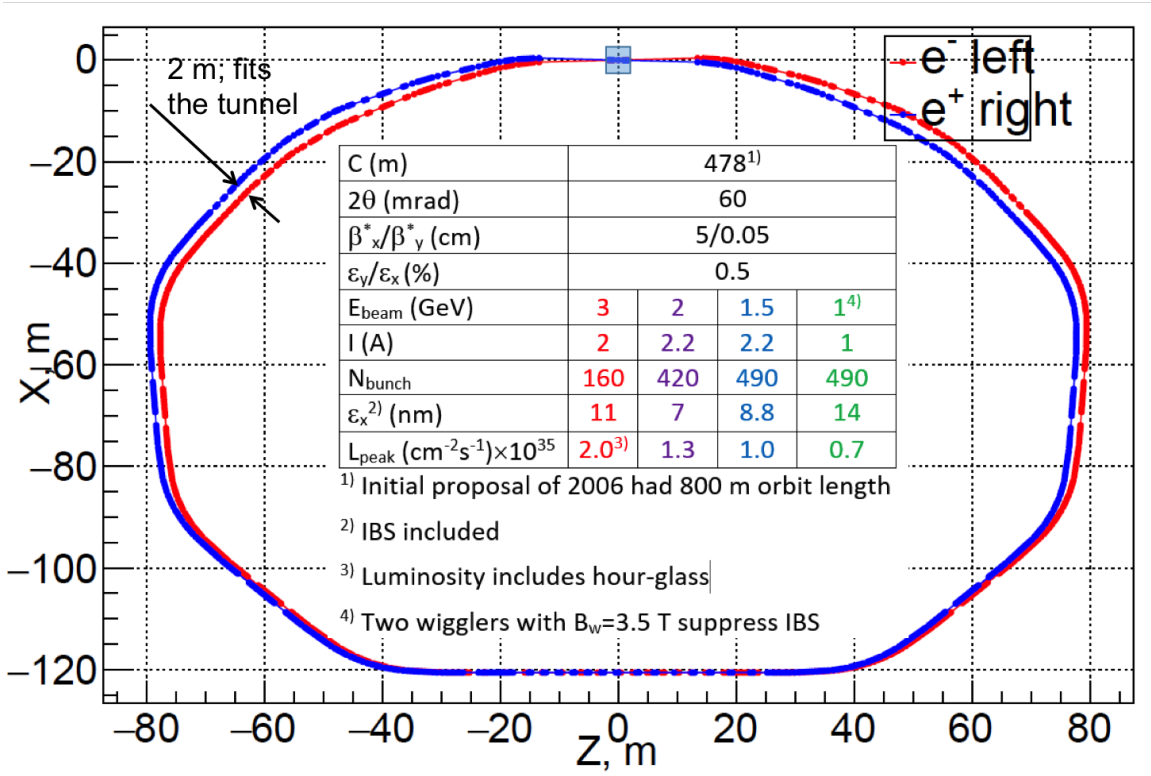

Dark Matter Map in Galaxy Cluster Abell 1689
Hubble Space Telescope ACS/WFC
NASA, ESA, and D. Coe (JPL/Caltech and STScI)
STScI-PRC10-37




ENERGY DISTRIBUTION
OF THE UNIVERSE
DARK
ENERGY
69%
26%
DARK
MATTER
5%
NORMAL MATTER


Indirect Detection
SM
DM
Direct Detection
SM
DM
Production at Colliders

Super c-tau Factory



C (m)	478[1]			
2θ (mrad)	60			
β^*_x/β^*_y (cm)	5/0.05			
$\varepsilon_y/\varepsilon_x$ (%)	0.5			
E_{beam} (GeV)	3	2	1.5	1[4]
I (A)	2	2.2	2.2	1
N_{bunch}	160	420	490	490
ε_x[2] (nm)	11	7	8.8	14
L_{peak} ($cm^{-2}s^{-1}$)×10^{35}	2.0[3]	1.3	1.0	0.7

[1] Initial proposal of 2006 had 800 m orbit length

[2] IBS included

[3] Luminosity includes hour-glass

[4] Two wigglers with B_w=3.5 T suppress IBS

- Energy range in centre of mass $2 - 5\,(7?)\,\mathrm{GeV}$;
- High luminosity, up to $2 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ — at least in 50 times more than at BES-III;
- It is supposed to record data with an integral luminosity of $10\,\mathrm{ab}^{-1}$ during the entire operation of the SCTF;
- Longitudinal electron polarization;
- Good energy and momenta resolution in detector;

http://ctd.inp.nsk.su

Many BSM theories predict the existence of additional scalars, which could mediate the interactions between the SM and DM in the $\mathrm{MeV} - \mathrm{GeV}$ range.

If the coupling of the scalar to quarks is suppressed and the scalar interacts preferentially with heavy-flavor leptons, we refer to such a particle as a leptophilic scalar ϕ.

It's interaction Lagrangian with leptons can be written as

$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell}\, \phi\, \ell, \tag{1}$$

where ξ denotes the flavor-independent coupling strength to leptons and $v = 246\,\mathrm{GeV}$ is the SM Higgs vacuum expectation value.

arXiv:1606.04943
arXiv:1106.0034

The most minimal vector portal interaction:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{DS}} - \frac{1}{2}\frac{\varepsilon}{\cos\theta_{\mathrm{W}}} B^{\mu\nu} F'_{\mu\nu}, \tag{2}$$

where $\mathcal{L}_{\mathrm{SM}}$ is the SM Lagrangian, $B^{\mu\nu}$ and $F'_{\mu\nu}$ are the field strength tensors of the SM hypersharge and the new $U_{\mathrm{D}}(1)$ gauge groups; ε is the kinetic mixing parameter and $\mathcal{L}_{\mathrm{DS}}$ is the dark sector Lagrangian that may include new matter fields χ charged under the $U_{\mathrm{D}}(1)$ group.

After electroweak symmetry breaking and with the gauge boson kinetic terms diagonalized, the relevant terms for $m_{A'} \lesssim 10\,\mathrm{GeV}$ in the Lagrangian including the dark photon coupling suppressed by ε to the SM electromagnetic current J^{μ}_{EM} are

$$\mathcal{L} \supset -\frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} m^2_{A'} A'^{\mu} A'_{\mu} - \varepsilon\, e\, J^{\mu}_{\mathrm{EM}} A'_{\mu} - e_{\mathrm{D}} J^{\mu}_{\mathrm{D}} A'_{\mu}, \tag{3}$$

where the dark current J^{μ}_{D} is depending on the type of DM candidate.

https://doi.org/10.1016/0370-2693(86)91377-8
arXiv:2102.12143

If kinematically allowed dark photons are expected to decay predominantly into invisible dark-sector final states. If no such decays are allowed, e.g. if $m_{A'} < 2m_{\chi}$, then the dark photon will decay into visible SM final states.

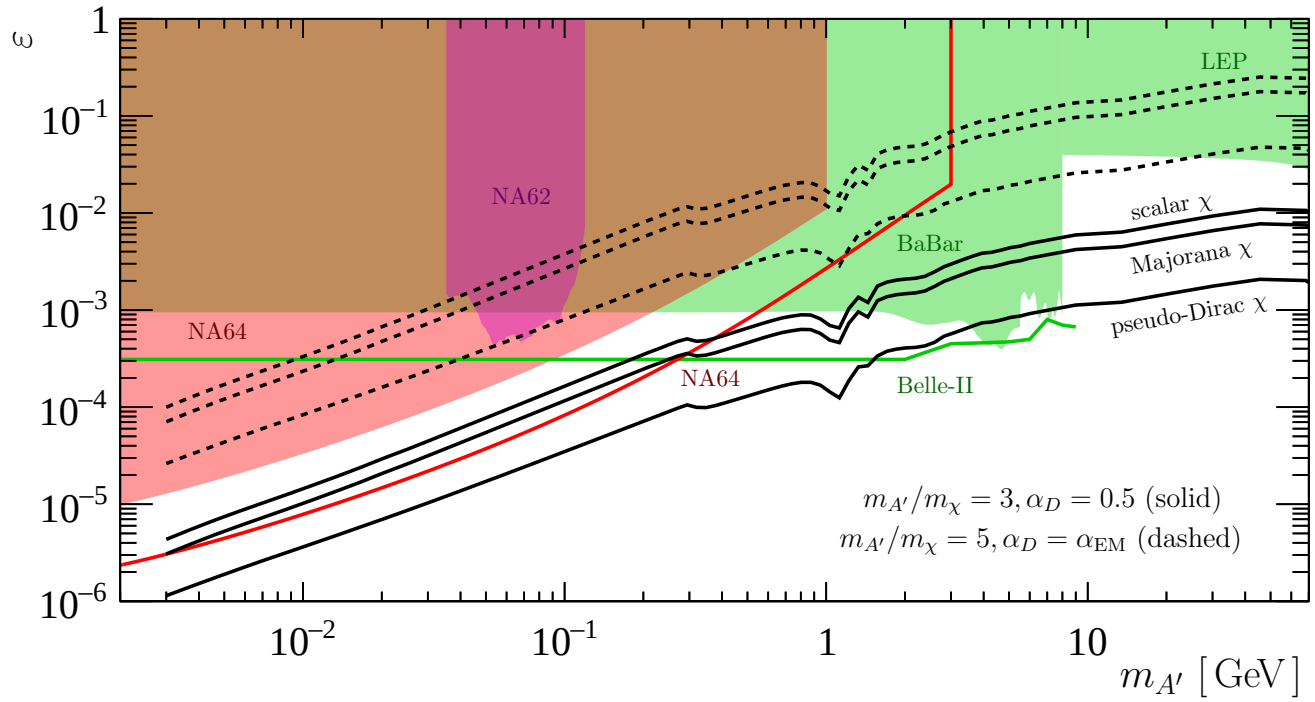
$$\Gamma_{A' \to \chi\chi} = \frac{1}{3}\alpha_{\mathrm{D}} m_{A'} \left(1 + 2\frac{m_{\chi}^2}{m_{A'}^2}\right) \sqrt{1 - 4\frac{m_{\chi}^2}{m_{A'}^2}}; \tag{4}$$

$$\Gamma_{A' \to \ell^+\ell^-} = \frac{1}{3}\varepsilon^2 \alpha m_{A'} \left(1 + 2\frac{m_{\ell}^2}{m_{A'}^2}\right) \sqrt{1 - 4\frac{m_{\ell}^2}{m_{A'}^2}}; \tag{5}$$

$$\Gamma_{A' \to \mathrm{hadrons}} = \frac{1}{3}\varepsilon^2 \alpha m_{A'} \left(1 + 2\frac{m_{\mu}^2}{m_{A'}^2}\right) \sqrt{1 - 4\frac{m_{\mu}^2}{m_{A'}^2}} R, \tag{6}$$

$$R \equiv \frac{\sigma_{e^+e^- \to \mathrm{hadrons}}}{\sigma_{e^+e^- \to \mu^+\mu^-}}. \tag{7}$$

Searches for Invisible Dark Photons

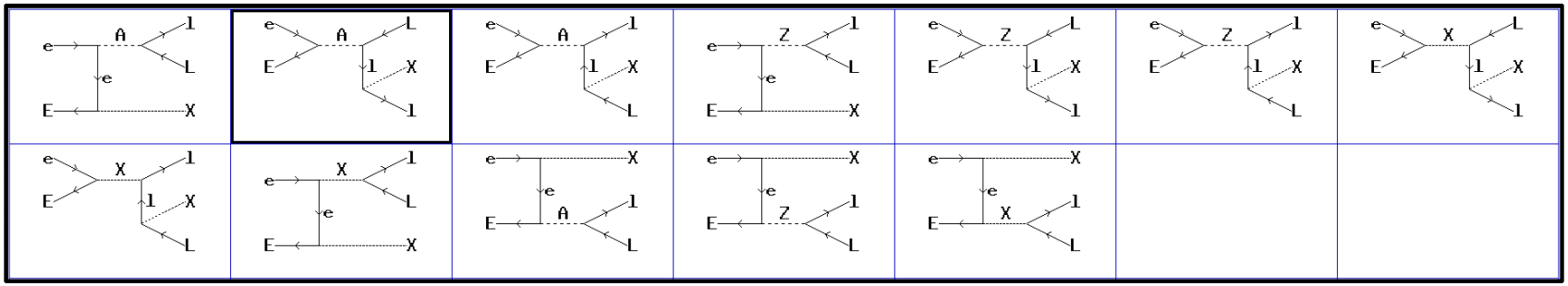


Constraints on invisible A' decays.

- Searches at e^+e^- colliders for $m < 10\,\mathrm{GeV}$, $e^+e^- \to A'A$: BaBar, Belle II, KLOE2, LEP;
- Searches at Electron Beam Dumps, $e^- Z \to e^- Z\, A'$: NA64, LDMX, BDX;
- Searches in Meson Decays, $K^+ \to \pi^+\pi^0, \pi^0 \to A'A$: NA62, KLEVER.

arXiv:2104.10280

Modeling the Process of Dark Scalar and Dark Photon Production on CompHEP at the Energies of the Future SCTF



Diagrams contributing to the ϕ production in the reaction $e^+e^- \to \tau^+\tau^-\phi, \phi \to \text{dark sector}$. The produced ϕ decays invisibly into dark sector particles.

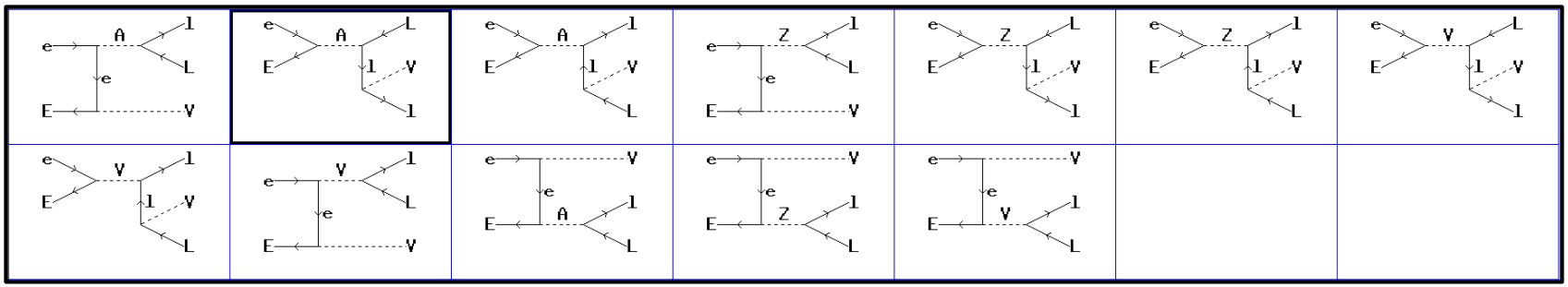
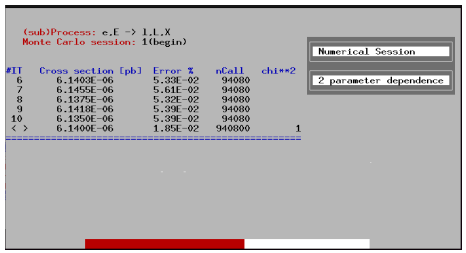
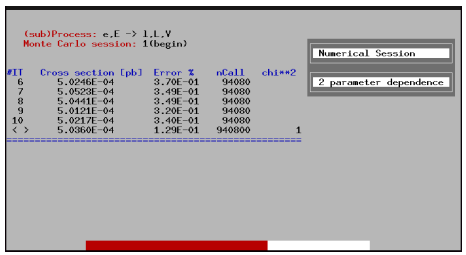


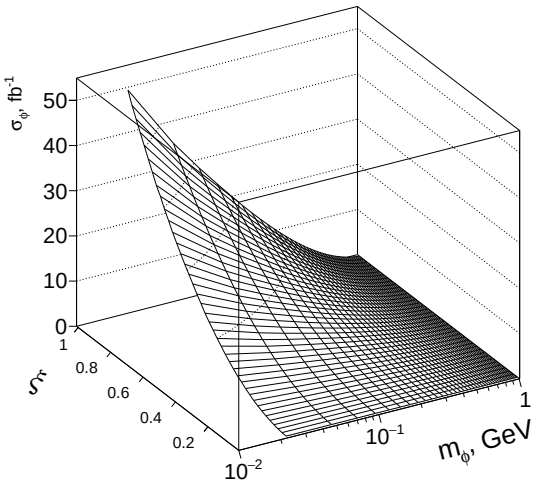
Diagram contributing to the A' production in the reaction $e^+e^- \to \tau^+\tau^- A', A' \to \text{dark sector}$. The produced A' decays invisibly into dark sector particles.

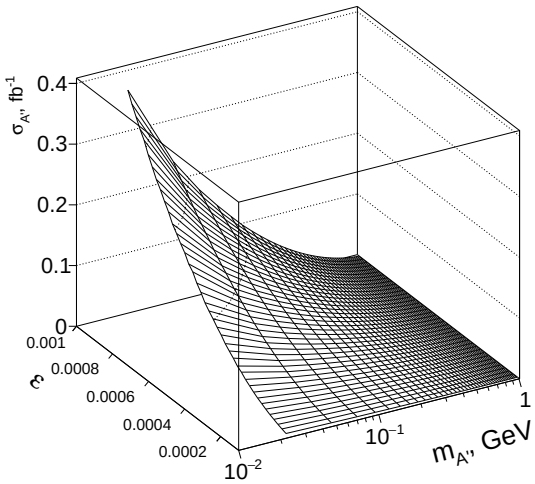
Modeling the Process of Dark Scalar and Dark Photon Production on CompHEP at the Energies of the Future SCTF





	E_{tot}, GeV	L, fb^{-1}
$\psi(2S)$	3.686	200
$\psi(3770)$	3.770	300
$\psi(4160)$	4.170	100
Λ_c, max	4.650	100



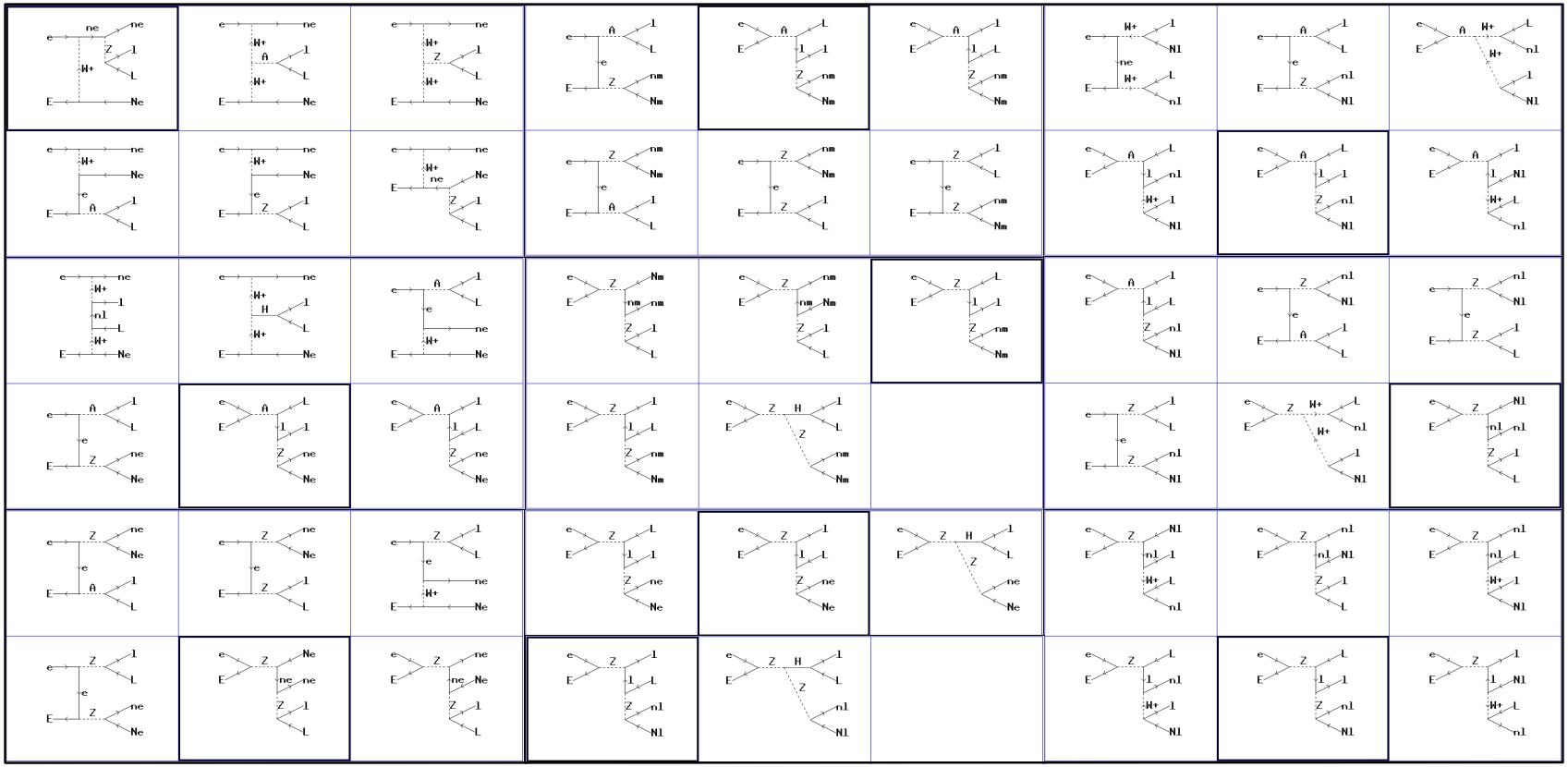


arXiv:hep-ph/0403113
http://comphep.sinp.msu.ru

Background for ϕ and A' Production Processes

SM background processes for $e^+e^- \to \tau^+\tau^- A', A' \to$ dark sector and $e^+e^- \to \tau^+\tau^-\phi, \phi \to$ dark sector are

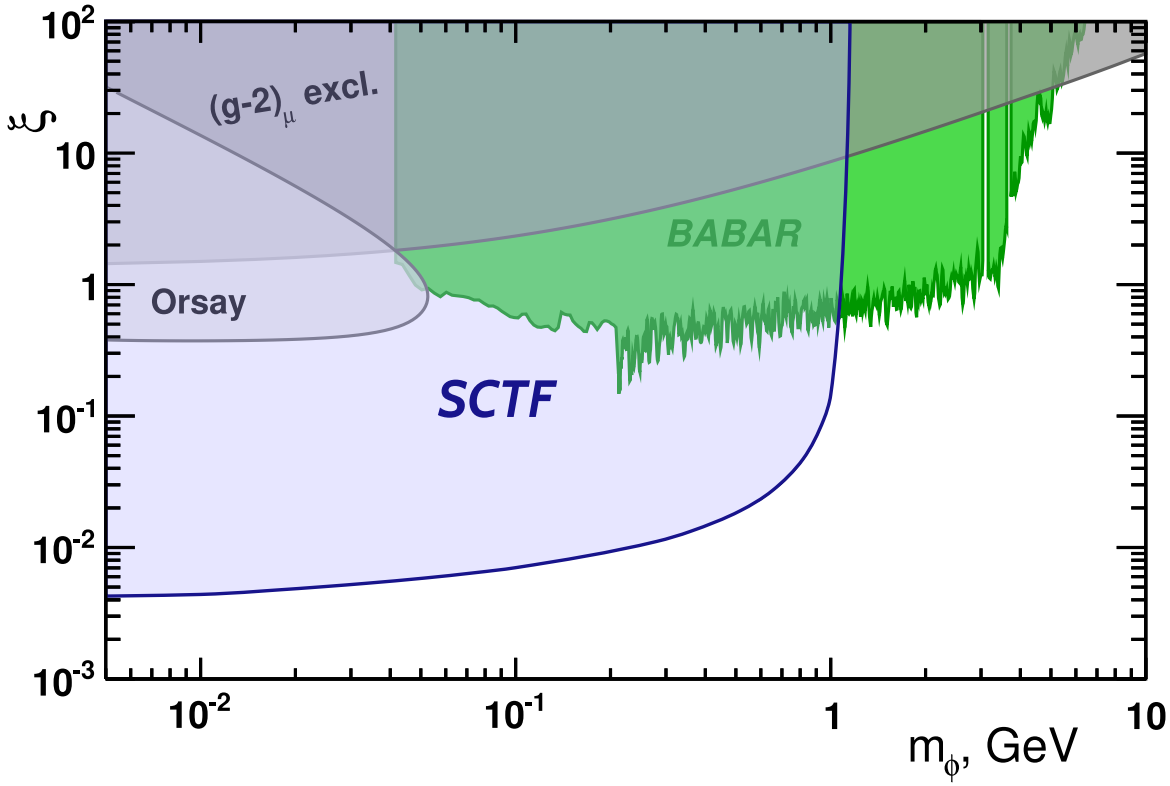
$$e^+e^- \to \tau^+\tau^- + \widetilde{\nu}_\ell \nu_\ell, \qquad \ell = e, \mu, \tau. \tag{8}$$



Significance is $S = 2\left(\sqrt{N_{signal} + N_{background}} - \sqrt{N_{background}}\right)$.

arXiv:physics/9811025v1
https://doi.org/10.22323/1.070.0118

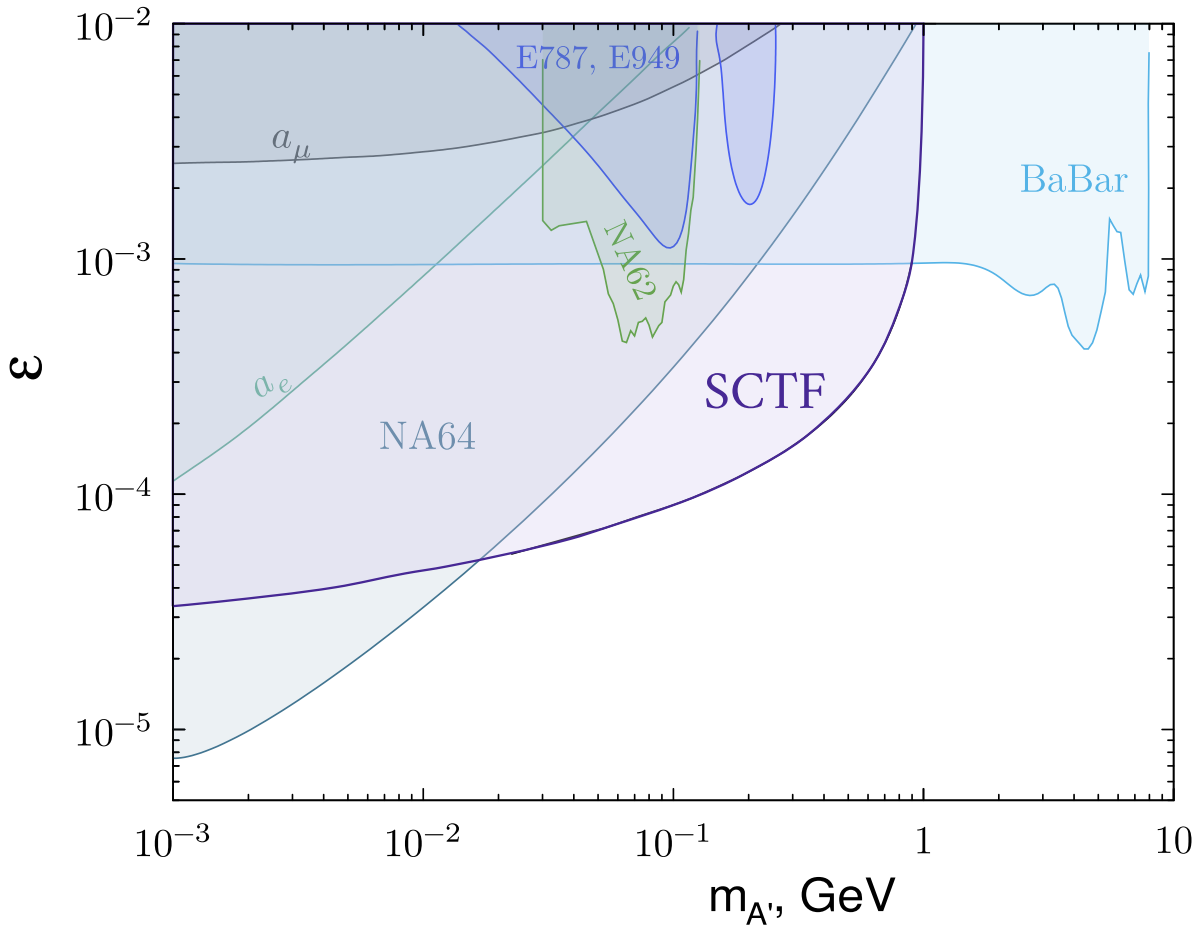
The Expected Region for Dark Scalar Search at the SCTF



The expected 90% C.L. region in the (m_ϕ, ξ) plane for dark scalar search at the SCTF. The BABAR and Orsay exclusion regions are also shown.

arXiv:2005.01885
https://doi.org/10.1016/0370-2693(89)90174-3

The Expected Region for Dark Photon Search at the SCTF



The expected 90% C.L. region in the $(m_{A'}, \varepsilon)$ plane for dark photon search at the SCTF. The NA64 exclusion region [arXiv:1906.00176], constraints from the E787 and E949, BABAR and NA62 experiments are also shown.

Dark Photon vs. Dark Scalar

— The dark scalar coupling strength to fermions is proportional to fermion masses.

— The kinetic mixing strength does not depend on the fermion masses.

In the $e^+e^- \to \tau^+\tau^- X$ process at the collider operating energies, we have

- the high values of the τ leptons production cross sections,
- good τ detection,
- the high luminosity of the collider,

which allows us

- to perform an accurate study of the channel,
- to analyze the processes not only considering missing energy and transverse momentum, but also to comparing the types of mediators, vector or scalar boson, taking into account spin dependencies by hadron modes of τ lepton decay.

Conclusion and Future Tasks

Based on the analysis of the results of modeling the associative production of new bosons and τ leptons at the energies of the future SCTF in the scenarios with an extra scalar boson and a dark photon, the possibility of searching in the non-excluded region of the parameter space was found.

Thus, the obtained cross sections values in the 90% C.L. region of mass range from few MeV to $1\,\mathrm{GeV}$ demonstrate the power of the future collider for the light dark matter search in the parameter space range that is inaccessible for experiments at the LHC and other e^+e^- colliders.

Future tasks:

- Taking into account kinematic cuts to improve the signal-to-background rate;
- Using other collider operation energy and integral luminosities points;
- Studying hadron modes of τ leptons decay to analyze spin correlations to compare the vertices of mediators in processes $e^+e^- \to \tau^+\tau^- X$.