New Physics with N_{eff} in the CMB

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Presentation based on:
arXiv:2404.10077 (Accepted in PRD)
and **arXiv:2312.16304** (EPJC 83 (2023) 9, 880)

with D. K. Ghosh, Sk Jeesun and R. Srivastava

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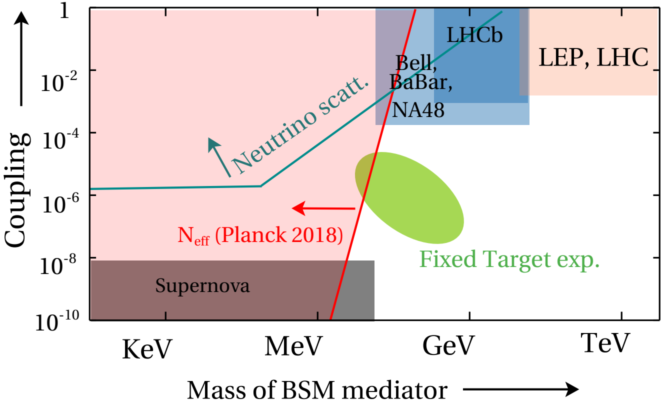
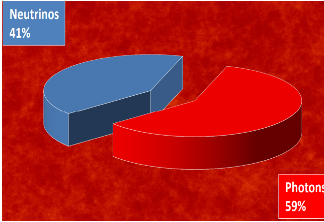
BSM Interactions: Between SM fermions and Light mediators (ALP, light gauge boson, etc.).



Note: The BBN constraint is also applicable here.

- Around BBN (after e^+e^- annihilation): neutrinos are the 2nd most abundant particles in the Universe.



- $N_{\rm eff}$ associated with relativistic DOF.

$$\text{At } T << m_e: \; N_{\rm eff} \;\; \propto \;\; \left(\frac{\rho_{\nu_L}(T_\nu)}{\rho_\gamma(T_\gamma)}\right)$$

It is a crucial parameter in cosmology describing the dynamics of the thermal history of the Universe.

- **CMB :** Planck 2018 data estimates $\boxed{N_{\rm eff}^{\rm CMB} = 2.99^{+0.33}_{-0.34}}$ at 95% CL assuming ΛCDM cosmology.

- **BBN :** $N_{\rm eff} = 2.89^{+0.63}_{-0.57}$ at 2σ (Varying $N_{\rm eff}$ and Y_p).

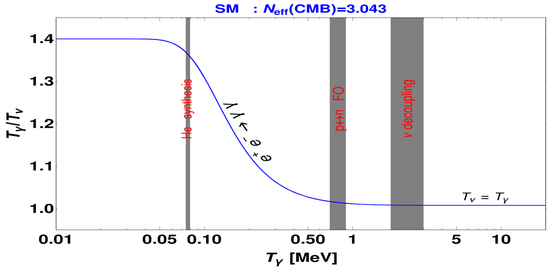
Pisanti et al. 2011.11537

$$N_{\rm eff}^{\rm UL}(\text{BBN}) = 3.51 \text{ and } N_{\rm eff}^{\rm UL}(\text{CMB}) = 3.33.$$

EFT SM Ints. : $\mathcal{L}^{\text{SM}}_{\nu-e} \supset \frac{G_F}{\sqrt{2}} \left[\overline{\nu}\gamma^\mu \nu\right] \left[e^+ \gamma_\mu (g_V - g_A \gamma^5) e^-\right]$

At $T_\gamma \sim$ few MeV : $\boxed{\nu_L, \overline{\nu_L}} \xleftrightarrow{\text{Weak Int.}} \boxed{e^-, e^+} \xleftrightarrow{\text{EM Int.}} \boxed{\gamma} \Rightarrow T_\gamma = T_\nu$

At $T_\gamma \lesssim m_e$: $\boxed{\nu_L, \overline{\nu_L}} \qquad \boxed{e^-, e^+} \longrightarrow \boxed{\gamma} \Rightarrow T_\gamma \neq T_\nu$



- At $T < m_e$: $N_{\text{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\nu_L}(T_\nu)}{\rho_\gamma(T_\gamma)}\right) = 3 \times \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_\nu}{T_\gamma}\right)^4$

- Planck 2018 data: $N_{\rm eff}^{\rm CMB} = 2.99^{+0.33}_{-0.34}$ at 95% CL.
- SM contribution: $N_{\rm eff}^{\rm CMB} \simeq 3.043$. **Escudero, et al. arXiv:2306.05460**

$\boxed{\Delta N_{\rm eff}^{\rm CMB}|_{\rm UL} = N_{\rm eff}^{\rm CMB}(\text{Planck}) - N_{\rm eff}^{\rm CMB}(\text{SM}) \simeq 0.28}$ with 95% CL.

The additional contribution to $N_{\rm eff}$ → Scope of new physics.

- **Solution**: Non statndard neutrino interactions with the light dark mediator (ALP, light gauge boson, etc.).

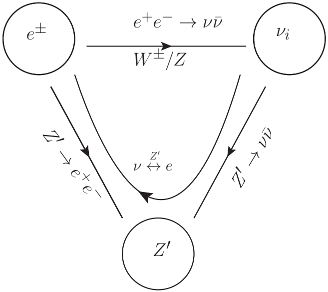
  $U(1)_{L_\mu - L_\tau}$: **JHEP 03 (2019) 071, PLB 834 (2022) 137463** ; $U(1)_{B-L}$: **arXiv:2308.07955** .

Our Contributions: We considered a generic $U(1)_X$ model with arbitrary charge assignments.

- Specific anomaly-free charge assignments →

  X : $B-L$, $L_i - L_j (i \neq j)$, $B - 3L_i$, $B_i - L_j$ etc..

• SM+ light Z' originated from generic $U(1)_X$ model with $T \sim \mathcal{O}(\text{MeV})$



$$\mathcal{L}_{\rm int}^{Z'} \supset g_X \left(X_3\bar{\nu}_\tau\gamma^\alpha P_L\nu_\tau + X_2\bar{\nu}_\mu\gamma^\alpha P_L\nu_\mu\right) Z'_\alpha$$
$$+ g_X \left(X_1\bar{\nu}_e\gamma^\alpha P_L\nu_e + X_1\bar{e}\gamma^\alpha e\right) Z'_\alpha$$

Parameters: Light gauge boson: $\{M_{Z'}, g_X\}$
$U(1)_X$ Lepton Charges : $\{X_1, X_2, X_3\}$

Temperature evolution for the SM $(e^\pm, \gamma, \nu_L)$ and BSM (Z') specices:

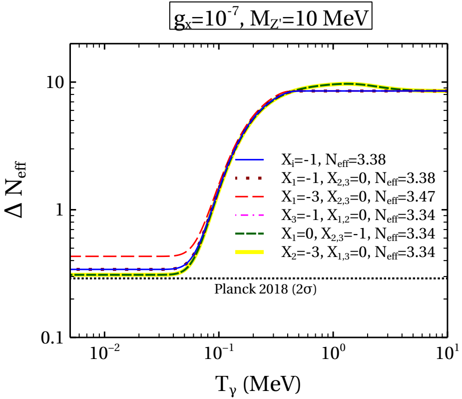
$$\frac{dT_{\nu_L}}{dt} = -\left(4H\rho_{\nu_L} - \frac{\delta\rho_{\nu_L\to e^\pm}}{\delta t} + \frac{\delta\rho_{Z'\to\nu_L}}{\delta t}\right)\left(\frac{\partial\rho_{\nu_L}}{\partial T_{\nu_L}}\right)^{-1}; \quad (T_{\nu_e} = T_{\nu_\mu} = T_{\nu_\tau})$$

$$\frac{dT_{Z'}}{dt} = -\left(3H\left(\rho_{Z'} + P_{Z'}\right) - \frac{\delta\rho_{Z'\to\nu_L}}{\delta t} - \frac{\delta\rho_{Z'\to e^\pm}}{\delta t}\right)\left(\frac{\partial\rho_{Z'}}{\partial T_{Z'}}\right)^{-1}; \quad (Z' : \text{in thermal bath})$$

$$\frac{dT_\gamma}{dt} = -\left(4H\rho_\gamma + 3H\left(\rho_e + p_e\right) + \frac{\delta\rho_{\nu_L\to e^\pm}}{\delta t} + \frac{\delta\rho_{Z'\to e^\pm}}{\delta t}\right)\left(\frac{\partial\rho_\gamma}{\partial T_\gamma} + \frac{\partial\rho_e}{\partial T_\gamma}\right)^{-1},$$

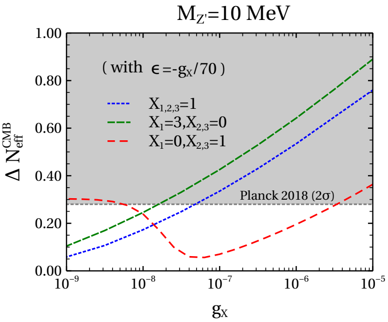
$$\mathcal{L}_{\rm int}^{Z'} \supset g_X \left(X_{2(3)} \bar{\nu}_{\mu(\tau)} \gamma^\alpha P_L \nu_{\mu(\tau)} \right) Z'_\alpha + g_X \left(X_1 \bar{\nu}_e \gamma^\alpha P_L \nu_e + X_1 \bar{e} \gamma^\alpha e \right) Z'_\alpha$$

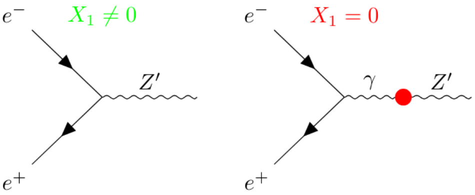
Light gauge boson: $\{M_{Z'}, g_X\}$ :: Lepton Charges : $\{X_1, X_2, X_3\}$

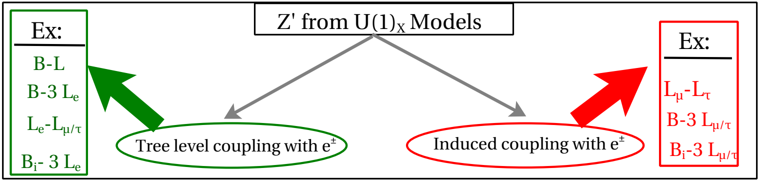


Any increase in the effective coupling $(X_1 g_X)$ leading to an increment in $N_{\rm eff}$.

$$\mathcal{L}_{\rm int}^{Z'} \supset g_X \left(X_{2(3)} \bar{\nu}_{\mu(\tau)} \gamma^\alpha P_L \nu_{\mu(\tau)} \right) Z'_\alpha + g_X \left(X_1 \bar{\nu}_e \gamma^\alpha P_L \nu_e + X_1 \bar{e} \gamma^\alpha e \right) Z'_\alpha$$

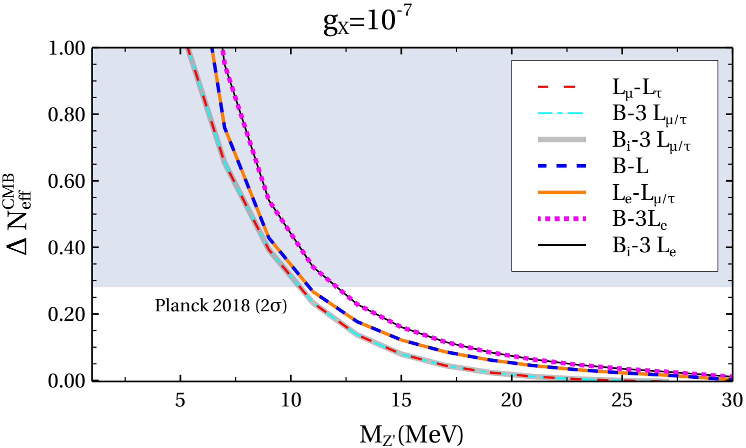




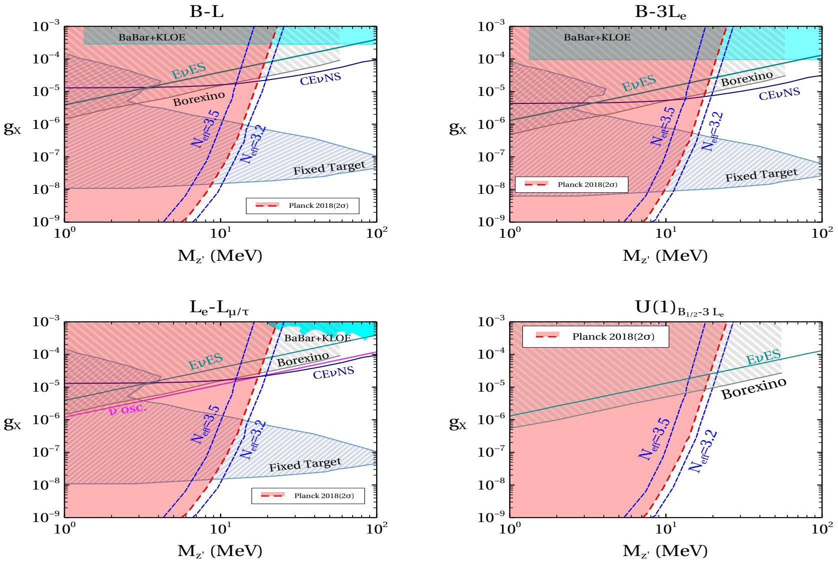


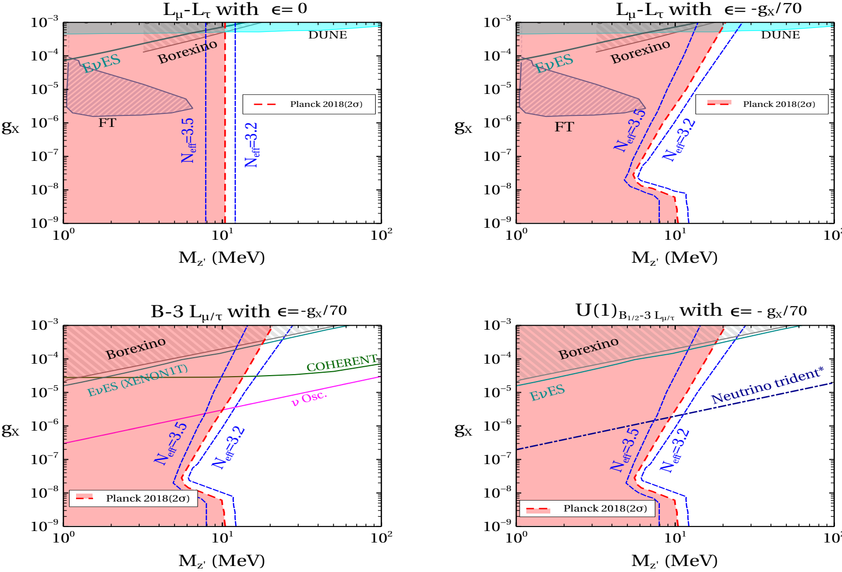
Models	$\mathbb{X}_{Q_i}(\mathbb{X}_{u_i}=\mathbb{X}_{d_i})$	X_1	X_2	X_3
$\mathbf{B-L}$	$(1/3,\ 1/3,\ 1/3)$	-1	-1	-1
$\mathbf{B-3L_e}$	$(1/3,\ 1/3,\ 1/3)$	-3	0	0
$B-3L_\mu$	$(1/3,\ 1/3,\ 1/3)$	0	-3	0
$B-3L_\tau$	$(1/3,\ 1/3,\ 1/3)$	0	0	-3
$\mathbf{L_e-L_\mu}$	$(0,0,0)$	1	-1	0
$\mathbf{L_e-L_\tau}$	$(0,0,0)$	1	0	-1
$L_\mu-L_\tau$	$(0,0,0)$	0	1	-1
$\mathbf{B_1-3L_e}$	$(1,0,0)$	-3	0	0
$\mathbf{B_2-3L_e}$	$(0,1,0)$	-3	0	0
$\mathbf{B_3-3L_e}$	$(0,1,0)$	-3	0	0
B_1-3L_μ	$(1,0,0)$	0	-3	0
B_2-3L_μ	$(0,1,0)$	0	-3	0
B_3-3L_μ	$(0,1,0)$	0	-3	0
B_1-3L_τ	$(1,0,0)$	0	0	-3
B_2-3L_τ	$(0,1,0)$	0	0	-3
B_3-3L_τ	$(0,1,0)$	0	0	-3

Table 1

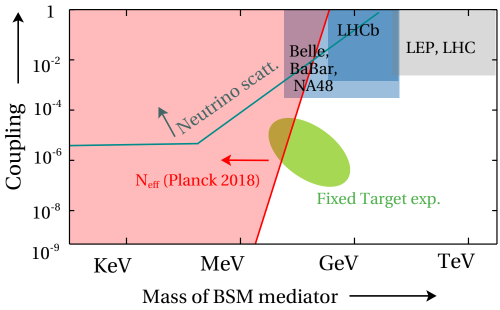


$$
\begin{aligned}
|X_1| = 0 : &\quad L_\mu - L_\tau,\ B - 3L_{\mu/\tau},\ B_i - 3L_{\mu/\tau} \\
|X_1| = 1 : &\quad B - L,\ L_e - L_{\mu/\tau} \\
|X_1| = 3 : &\quad B - 3L_e,\ B_i - 3L_e
\end{aligned}
$$


B-L
BaBar+KLOE
EνES
CEνNS
Borexino
Neff=3.5
Neff=3.2
Fixed Target
Planck 2018(2σ)
B-3Le
BaBar+KLOE
EνES
Borexino
CEνNS
Neff=3.5
Neff=3.2
Planck 2018(2σ)
Fixed Target
Le-Lμ/τ
BaBar+KLOE
EνES
Borexino
CEνNS
ν osc.
Neff=3.5
Neff=3.2
Fixed Target
Planck 2018(2σ)
U(1)B1/2-3 Le
Planck 2018(2σ)
EνES
Borexino
Neff=3.5
Neff=3.2
gX
Mz' (MeV)


Lμ-Lτ with ϵ= 0
DUNE
Borexino
EνES
FT
Neff=3.5
Neff=3.2
Planck 2018(2σ)
gX
MZ' (MeV)
Lμ-Lτ with ϵ= -gX/70
DUNE
Borexino
EνES
FT
Neff=3.5
Neff=3.2
Planck 2018(2σ)
gX
MZ' (MeV)
B-3 Lμ/τ with ϵ=-gX/70
Borexino
EνES (XENON1T)
COHERENT
ν Osc.
Neff=3.5
Neff=3.2
Planck 2018(2σ)
gX
MZ' (MeV)
U(1)B1/2-3 Lμ/τ with ϵ= - gX/70
Borexino
EνES
Neutrino trident*
Neff=3.5
Neff=3.2
Planck 2018(2σ)
gX
MZ' (MeV)

- The new interaction of Z' with both $e^{\pm}$ and ν_i, can potentially impact the neutrino decoupling consequently altering $N_{\rm eff}$.
- In some $M_{Z'}$ region, the $N_{\rm eff}$ bound from Planck 2018 is more stringent than the low energy experimental constraints.
- These $U(1)_X$ models are widely used used in particle physics as well as cosmology. The bound from $N_{\rm eff}$ derived by us will be extreamly relevant for the community.



thank you!

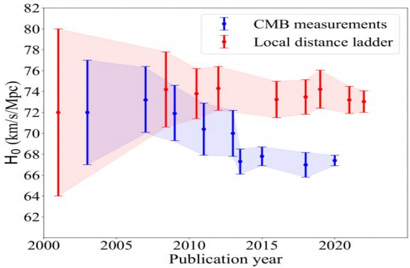
Email id pghoshiitg@gmail.com

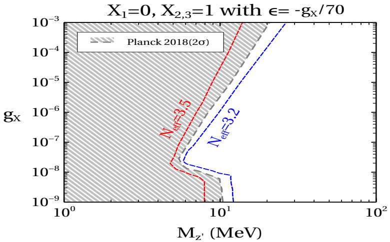
H_0 Tension: Discrepancy between the values of expansion rate H_0 obtained from CMB and local measurement.

- CMB measurement (PLANCK 2018) : $H_0 = 67.36 \pm 0.54$ Km s^{-1} Mpc^{-1}
- Distance measurement (SHOES) : $H_0 = 73.04 \pm 1.04$ Km s^{-1} Mpc^{-1}

Riess et al. (arXiv:2112.04510)

- Discrepancy of around 6σ between two measurements.



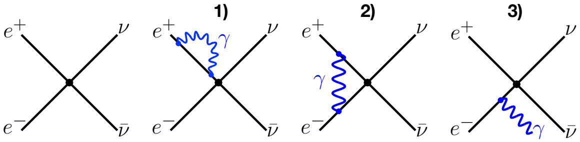


Additional $\Delta N_{\rm eff}$: reduce the H_0 tension from 6σ to 4.6σ

Riess et al. JCAP10(2016)019

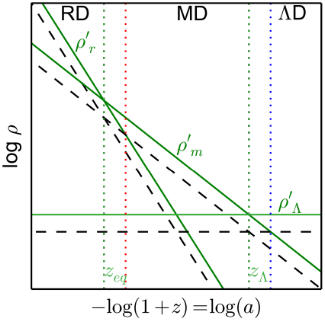
Physical Scenario	$N_{\rm eff}^{\rm SM} - 3$
Instantaneous ν decoupling	0
residual $e^+e^- \to \bar{\nu}\nu$	0.03
QED corrections to $\rho_{e^+e^-}$ and ρ_γ	0.01
NO	0.0007
NLO QED coorections ($e^+e^- \leftrightarrow \bar{\nu}\nu$ rates) Escudero, M., et al. (2023). arXiv:2306.05460	-0.0007

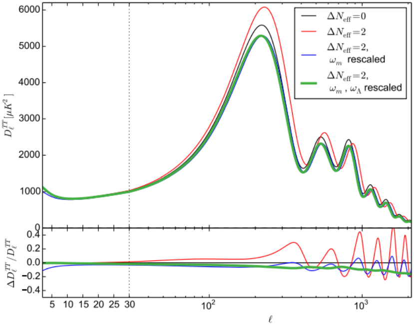
Contributions to $N_{\rm eff}$ in the SM. $N_{\rm eff}^{\rm SM} = 3.0432(2) \simeq 3.043$ (arXiv:2306.05460).



NLO QED Contributions to $N_{\rm eff}$ in the SM. (Escudero, M., et al. arXiv:2306.05460).

Impact of $N_{\rm eff}$ on CMB and $P_m(k)$: Increase $N_{\rm eff}$ and rescal ω_m and ω_Λ to fix $z_{\rm eq}$ and z_Λ.





Ref.: Taken From Julien Lesgourgues's Presentation.

Experiments	Upper bound on $N_{\text{eff}}(2\sigma)$
Planck 2018 [4]	$N_{\text{eff}} < 3.33$
Simon Observatory [61]	$N_{\text{eff}} < 3.14$
CMB-S4 [62]	$N_{\text{eff}} < 3.10$
CMB-HD [63]	$N_{\text{eff}} < 3.07$

Experiments	Process	Observations	Refs.
EνES (elastic electron-neutrino scattering)	$\nu\ e \to \nu\ e$ incoming particle: solar ν (ν_e)	recoil rate of e^-	XENON [21, 50], LZ[22], Borexino [19, 20, 51]
CEνNS (coherent elastic neutrino -nucleus scattering)	$\nu\ N \to \nu\ N$ nuclei N: {CsI, Ar}	recoil rate of nucleus	CsI and Ar [35, 43, 52] XENON [21, 22]
Fixed target experiments	$e(p)\ N \to e(p)\ N\ Z'$ $Z' \to e^+e^-$	displaced vertex with di-electron	E137 [53], E141 [54], E774 [34] etc.
Neutrino trident	$\nu\ N \to \nu\ N\ \mu^+\ \mu^-$	di-muon final state	LBNE [55], CCFR [56], DUNE [57]
ATLAS and CMS	(i) $pp \to Z' \to \mu^+\mu^-$ (ii) $pp \to h, \phi \to Z^* Z'$, $Z^*\ Z' \to 4\ell$	(i) oppositely charged muons (ii) 4ℓ final state	(i) [58] (ii) [59, 60]
BaBar, Belle	$e^+\ e^- \to \gamma_{\rm ISR}\ Z'$, $Z' \to \ell^+\ell^-(\ell = e, \mu)$	lepton charged tracks with γ	BaBar [17, 33] Belle [32]
KLOE	$e^+\ e^- \to \gamma_{\rm ISR} Z'$, $Z' \to \mu^+\mu^-, \pi^+\pi^-$	charged tracks with γ	KLOE [61]