Anomalous Single Production of the Fourth Generation Quarks at Future ep and γp Colliders

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The Fourth Generation Fermions

- Standard Model, flavor democracy predicts the existence of a heavy fourth SM generation.
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- The Dirac masses of the new fermions are predicted to be almost degenerate and lie between 300 and 700 GeV, whereas, the masses of known fermions belonging to lighter three generations appear due to small deviations of the democracy.
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- The fourth generation quarks will be produced in pairs copiously at the Large Hadron Collider (LHC).
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- In addition, evidence for the extra SM families may come from the search for the SM Higgs boson due to an essential enhancement in the production of the Higgs boson via gluon-gluon fusion.
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- Linear lepton colliders are the best place for pair production of the fourth generation charged lepton and neutrino.
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Anomalous production at various collider options

The discovery capacity of LHC and lepton collider could be enlarged if the anomalous interactions of the fourth generation fermions with the first three ones exist. Such anomalous interactions seems to be quite natural due to large masses of the fourth generation fermions.

- The anomalous productions of the fourth generation charged lepton and neutrino at future ep colliders are considered.
- Recently, anomalous single productions of the fourth generation quarks at the LHC are published.
- In this study, we will present anomalous single productions of the fourth generation quarks at the future ep and γp colliders.

LINAC-LHC ep COLLIDER OPTIONS

F. Zimmermann, F. Bordry, H.-H. Braun, O.S. Brüning, H. Burkhardt, A. de Roeck, R. Garoby, T. Linnecar, K.-H. Mess, J. Osborne, L. Rinolfi, D. Schulte, R. Tomas, J. Tuckmantel, CERN, Switzerland; A. Eide, EPFL, Switzerland; F.J. Willeke, BNL, U.S.A.; S. Chattopadhyay, Cockcroft I., UK; B.J. Holzer, DESY, Germany; J. Dainton, M. Klein, Liverpool U., UK; A. Vivoli, LAL, France; S. Sultansoy, TOBB ETU, Turkey; A.K. Ciftci, Ankara U., Turkey; H. Aksakal, Nigde U., Turkey

Abstract

We describe various parameter scenarios for a linac-ring ep collider based on LHC and an independent electron linac. Luminosities between 10^{31} and 10^{33} $cm^{-2}s^{-1}$ can be achieved with a s.c. linac, operated either pulsed or in cw mode with optional recirculation, at a total electric wall-plug power of order 20 MW. Higher luminosities of several 10^{33} $cm^{-2}s^{-1}$ can be reached by investing more electric power or by energy recovery. Finally, merits of a linac-ring ep collider are discussed.

SCENARIOS

Colliding the LHC 7-TeV protons with a 25–140 GeV $e^{\pm}$ beam would both extend the discovery reach of the LHC, and enable precision physics with LHC data [1, 2]. $e^{+}p$ collisions are desirable in addition to $e^{-}p$. One way to realize such ep collider is by installing a new lepton ring in the LHC tunnel, implying a new lepton injector too [3, 4]. The THERA study [5] inspired looks at an alternative LHC-based "QCD Explorer" colliding LHC protons with electrons delivered by a linac [6].

Possible linac-ring scenarios include a n.c. linac, a pulsed s.c. linac, and a cw s.c. linac with or without energy recovery in various configurations, as shown in Fig. 1.

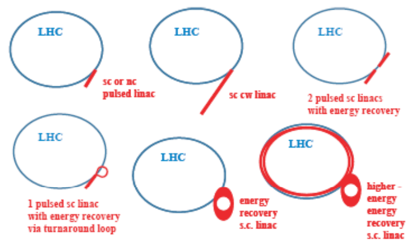


Figure 1: Scenarios for the linac-ring ep collider.

A s.c. linac can accelerate long trains of bunches with 25 or 50 ns spacing, matching the LHC fill pattern. Therefore, its luminosity in collisions with the LHC can be much

Table 1: Proton beam scenarios

	$N_{b,p}$	T_{sep}	$\epsilon_p\gamma_p$	β_p^*
LHC	1.7×10^{11}	25 ns	3.75 μm	0.25 m
LHC*	5×10^{11}	50 ns	3.75 μm	0.10 m

ter is decelerated [8]. More conventional energy recovery is possible by means of a recirculating linac, e.g. similar to ELFE [9], or with a turnaround loop as proposed for a future X-ray FEL [10]. Possible layouts are sketched in Fig. 2. For highest beam energy, the ERL with its recircu-

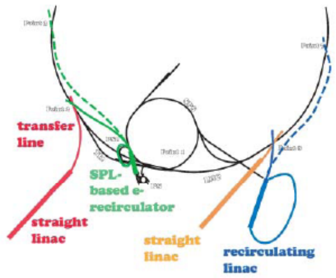


Figure 2: Example linac layouts on LHC site.

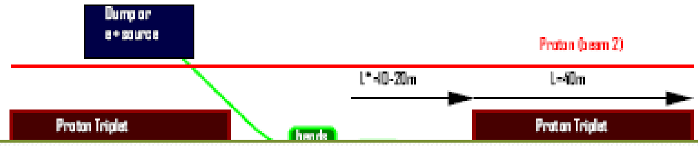
lating arcs could be installed in the LHC tunnel itself, blurring the distinction between ring-ring and linac-ring LHeC options [11].

Two proton scenarios are listed in Table 1: (1) the nominal LHC beam combined with reduced proton interaction-point (IP) beta functions β_p^* of 0.25 m as foreseen for 2013, and (2) a higher brightness beam [corresponding to scenario "LPA" of [12]] available from an upgraded LHC injector chain, including a 5 GeV s.c. proton linac (SPL) and a 50-GeV synchrotron (PS2), by 2017. This second scenario also assumes $\beta_p^* = 0.1$ m, which may be possible by (1) focusing only one of the two proton beams, thereby relaxing aperture constraints, (2) dedicated ep runs, allowing for a chromatic correction twice as strong as for two low-β

Table 2: Electron-beam parameters for various (s.c.) linac-ring LHeC scenarios. The β^* values are calculated for a normalized e- emittance of 20 μm. Parameters marked by asterisks refer to 'LHC*' of Table 1.

energy [GeV]	20	20	60	60	60	120
option	cw 4-pass	cw 4-p. ERL	cw 4-pass	cw 4-p. ERL	pulsed	pulsed
bunch population $N_{b,e}$ [10^9]	0.06, 0.12*	1.3, 2.6*	0.1, 0.2*	0.3, 0.6*	17, 34*	7, 14*
average current [μA]	400	8650	74	2050	820	340
beam power at IP [MW]	8.0	172	4.5	120	49	48
IP beta function [m]	0.25, 0.098*	0.25, 0.098*	0.74, 0.30*	0.74, 0.30*	0.74, 0.30*	1.72, 0.69*
luminosity [10^{31} cm^{-2}s^{-1}]	2.7, 20*	58, 430*	0.5, 3.7*	14, 100*	5.5, 41*	2.3, 17*
total electrical power [MW]	20	20	20	20	100	100

tance between 10 and 100 μm is expected after bunching and acceleration.



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γp Collider

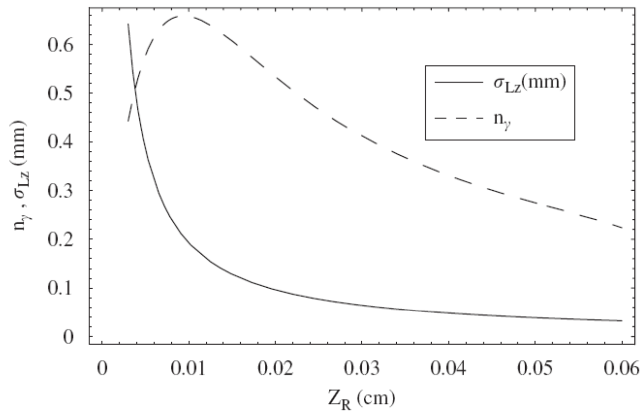

Fig. 2. Conversion efficiency and laser pulse length vs. Z_R for "CLIC-1".

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Conversion efficiency and luminosity for gamma-proton colliders based on the LHC-CLIC or LHC-ILC QCD explorer scheme

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Abstract

Gamma-proton collisions allow unprecedented investigations of the low x and high Q^2 regions in quantum chromodynamics. In this paper, we investigate the luminosity for "ILC" × LHC($\sqrt{s_{ep}} = 1.3$ TeV) and "CLIC" × LHC($\sqrt{s_{ep}} = 1.45$ TeV) based γp colliders. Also we determine the laser properties required for high conversion efficiency.

PACS: 13.60.Fz; 41.75.–i; 42.55.–f

Keywords: Photon–Proton collisions; Luminosity

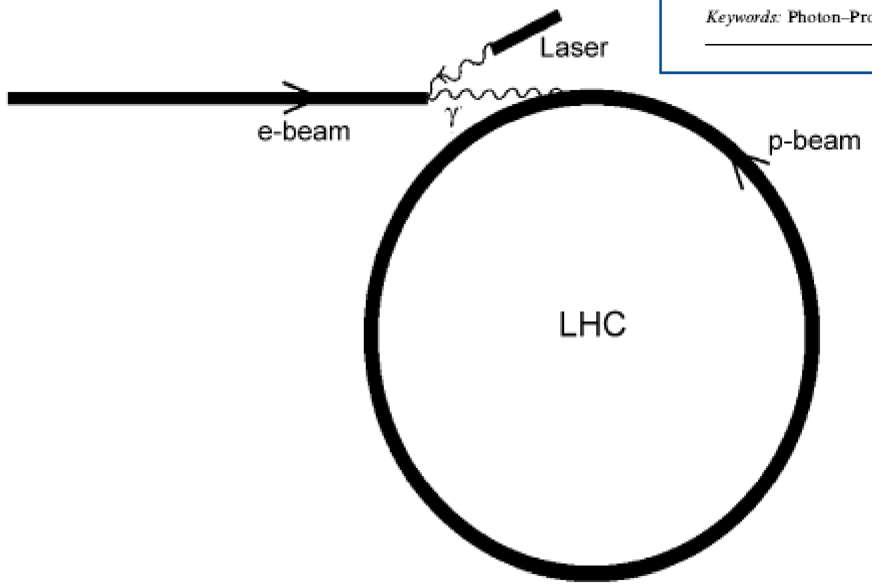
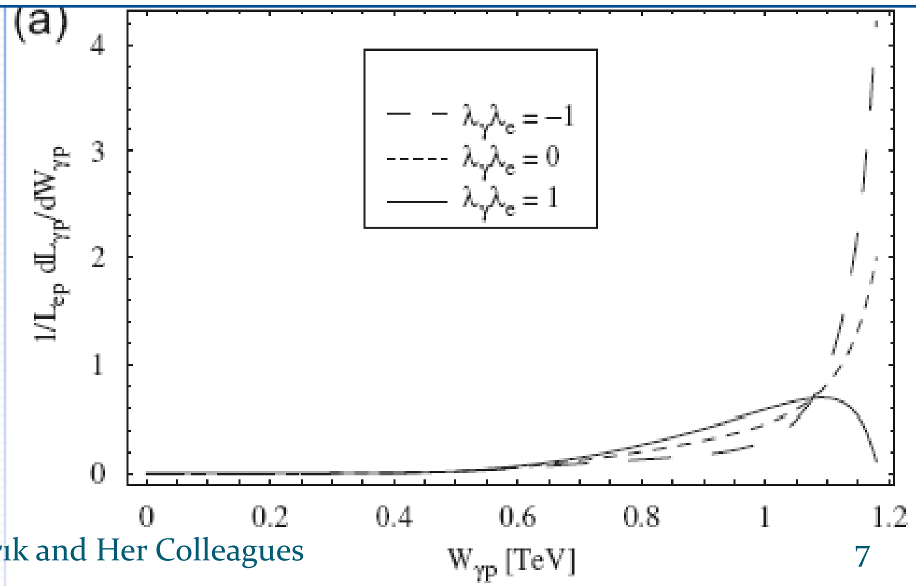


Fig. 1. Schematic of the proposed colliders.

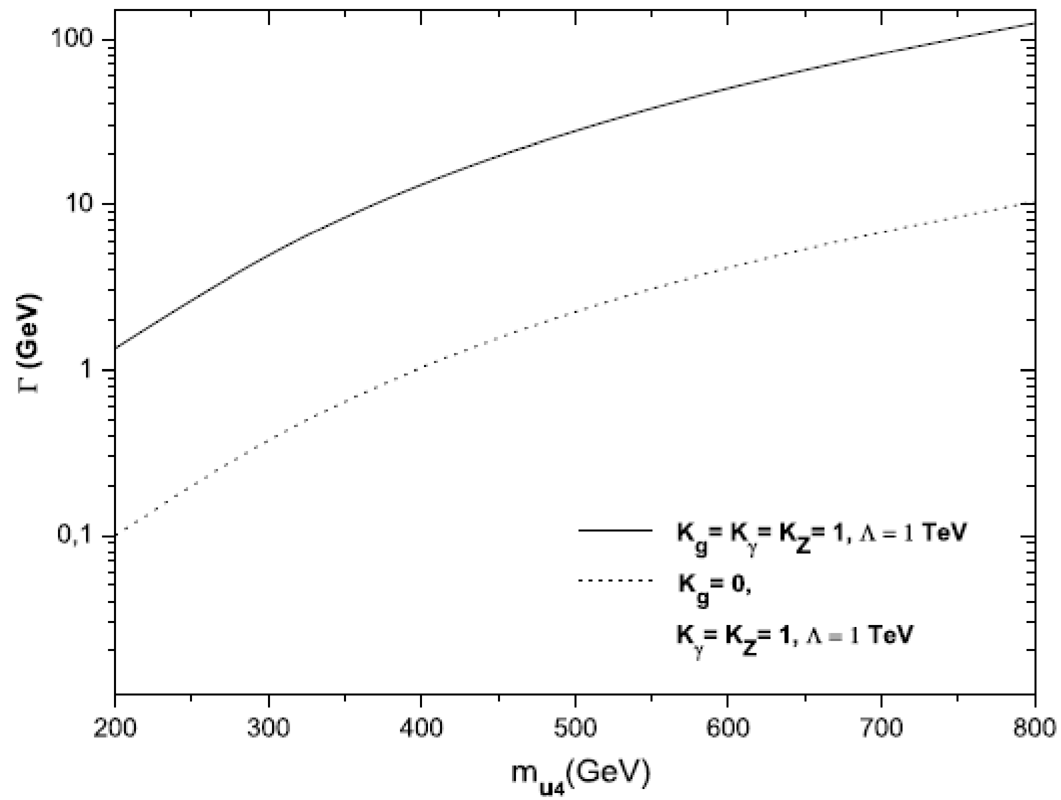


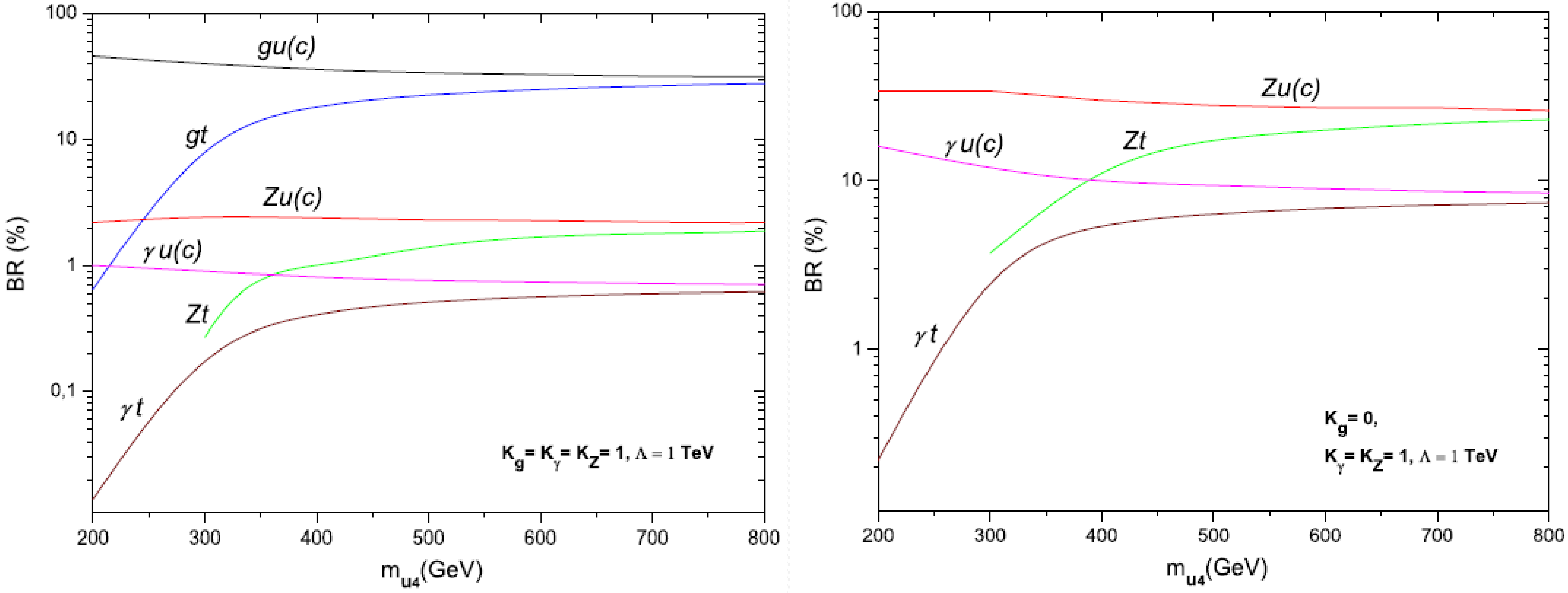
$$\mathcal{L} = \left(\frac{\kappa_\gamma^{q_i}}{\Lambda}\right) e_q g_e \bar{q}_4 \sigma_{\mu\nu} q_i F^{\mu\nu} + \left(\frac{\kappa_Z^{q_i}}{2\Lambda}\right) g_Z \bar{q}_4 \sigma_{\mu\nu} q_i Z^{\mu\nu}$$

$$+ \left(\frac{\kappa_g^{q_i}}{\Lambda}\right) g_s \bar{q}_4 \sigma_{\mu\nu} T^a q_i G_a^{\mu\nu} + \text{H.c.},$$

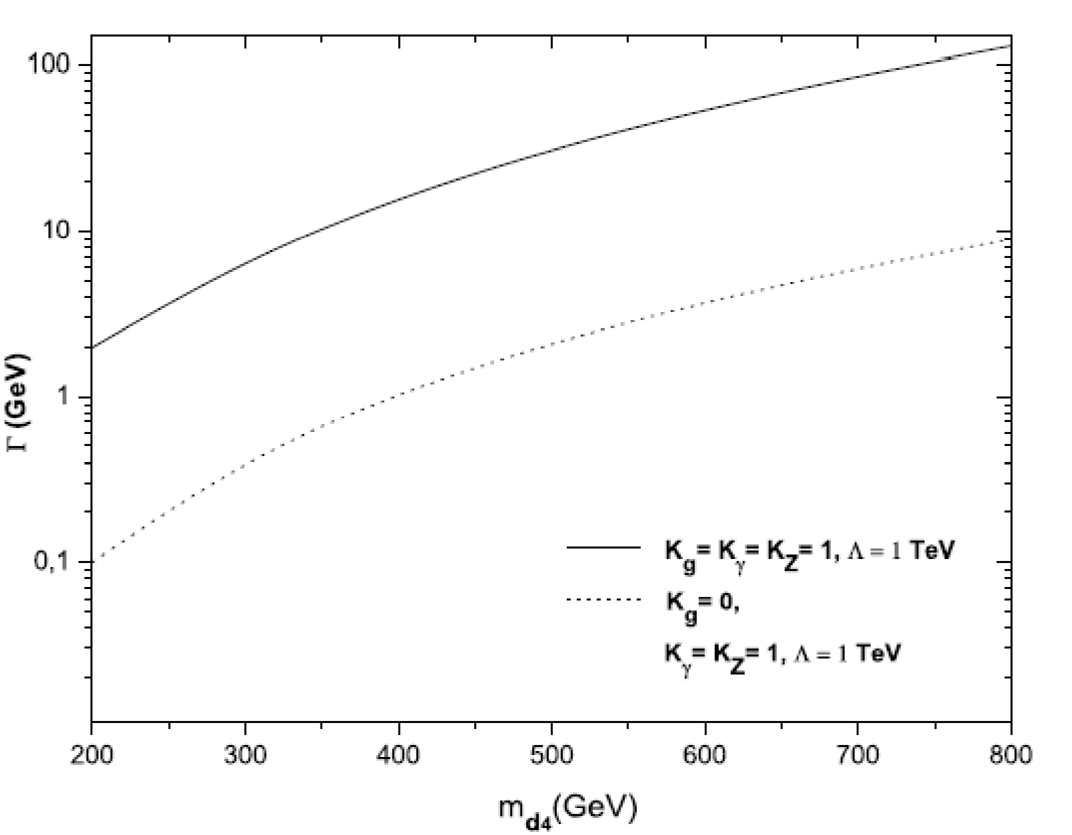
where $i = 1, 2, 3$ denotes the generation index. $\kappa_\gamma^{q_i}$, $\kappa_Z^{q_i}$, and $\kappa_g^{q_i}$ are anomalous couplings for the electromagnetic, the weak (neutral current), and the strong interactions, respectively, (in numerical calculations, $\kappa_\gamma^{q_i} = \kappa_Z^{q_i} = \kappa_g^{q_i}$ is assumed). Λ is the cutoff scale for the new physics and e_q is the quark charge. g_e, g_Z, and g_s are the electroweak and the strong coupling constants. In the above equation, $\sigma_{\mu\nu} = i(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)/2$. $F^{\mu\nu}$, $Z^{\mu\nu}$, and $G_a^{\mu\nu}$ are field strength tensors of the photon, the Z boson and gluons, respectively. T_a is the Gell-Mann matrices.

Total widths and branching ratios of fourth generation quarks under anom. interactions

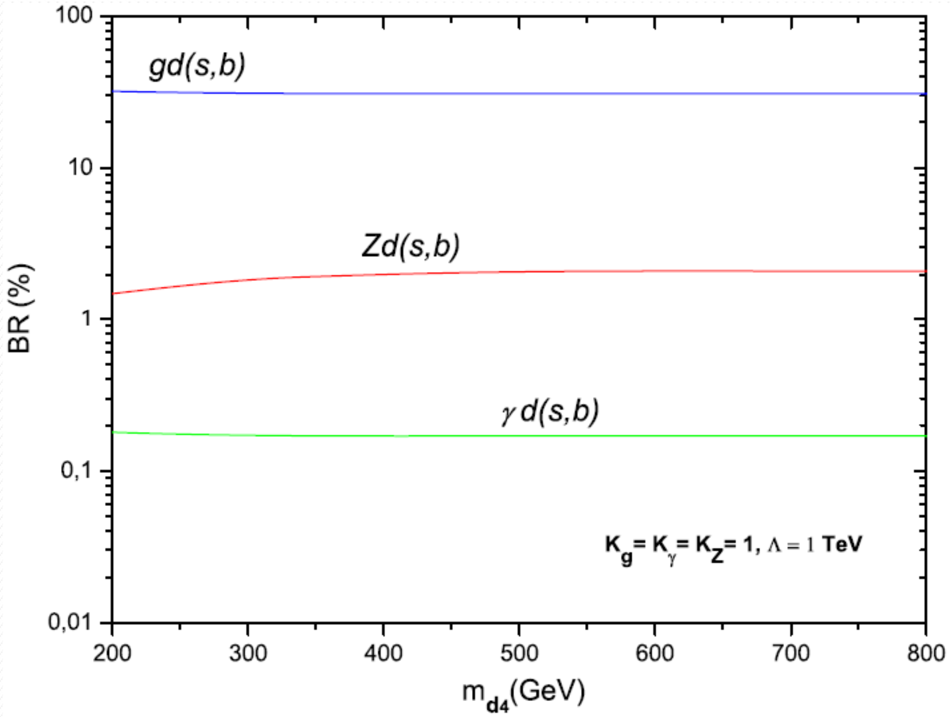


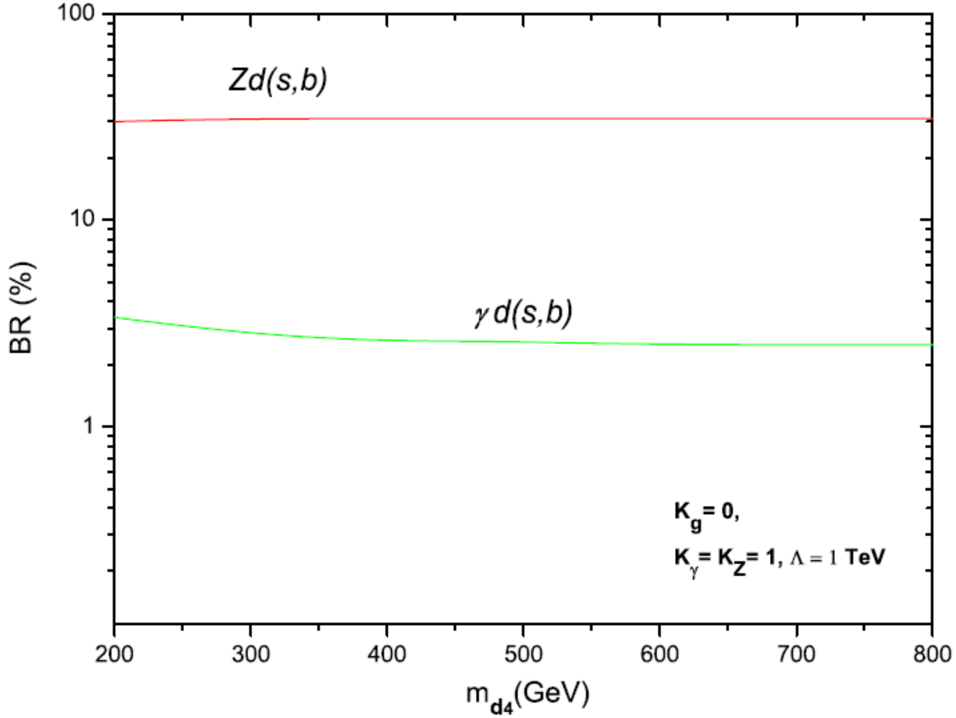


gu(c)
gt
Zu(c)
γ u(c)
Zt
γ t
BR (%)
m_u4(GeV)
K_g = K_γ = K_Z = 1, Λ = 1 TeV
Zu(c)
γ u(c)
Zt
γ t
BR (%)
m_u4(GeV)
K_g = 0,
K_γ = K_Z = 1, Λ = 1 TeV



100
10
1
0,1
Γ (GeV)
200
300
400
500
600
700
800
m_d4(GeV)
K_g = K_γ = K_Z = 1, Λ = 1 TeV
K_g = 0,
K_γ = K_Z = 1, Λ = 1 TeV


gd(s,b)
Zd(s,b)
γ d(s,b)
$K_g = K_\gamma = K_Z = 1, \Lambda = 1$ TeV
BR (%)
100
10
1
0,1
0,01
200
300
400
500
600
700
800
m_{d4}(GeV)


Zd(s,b)
γ d(s,b)
$K_g = 0,$
$K_\gamma = K_Z = 1, \Lambda = 1$ TeV
BR (%)
100
10
1
200
300
400
500
600
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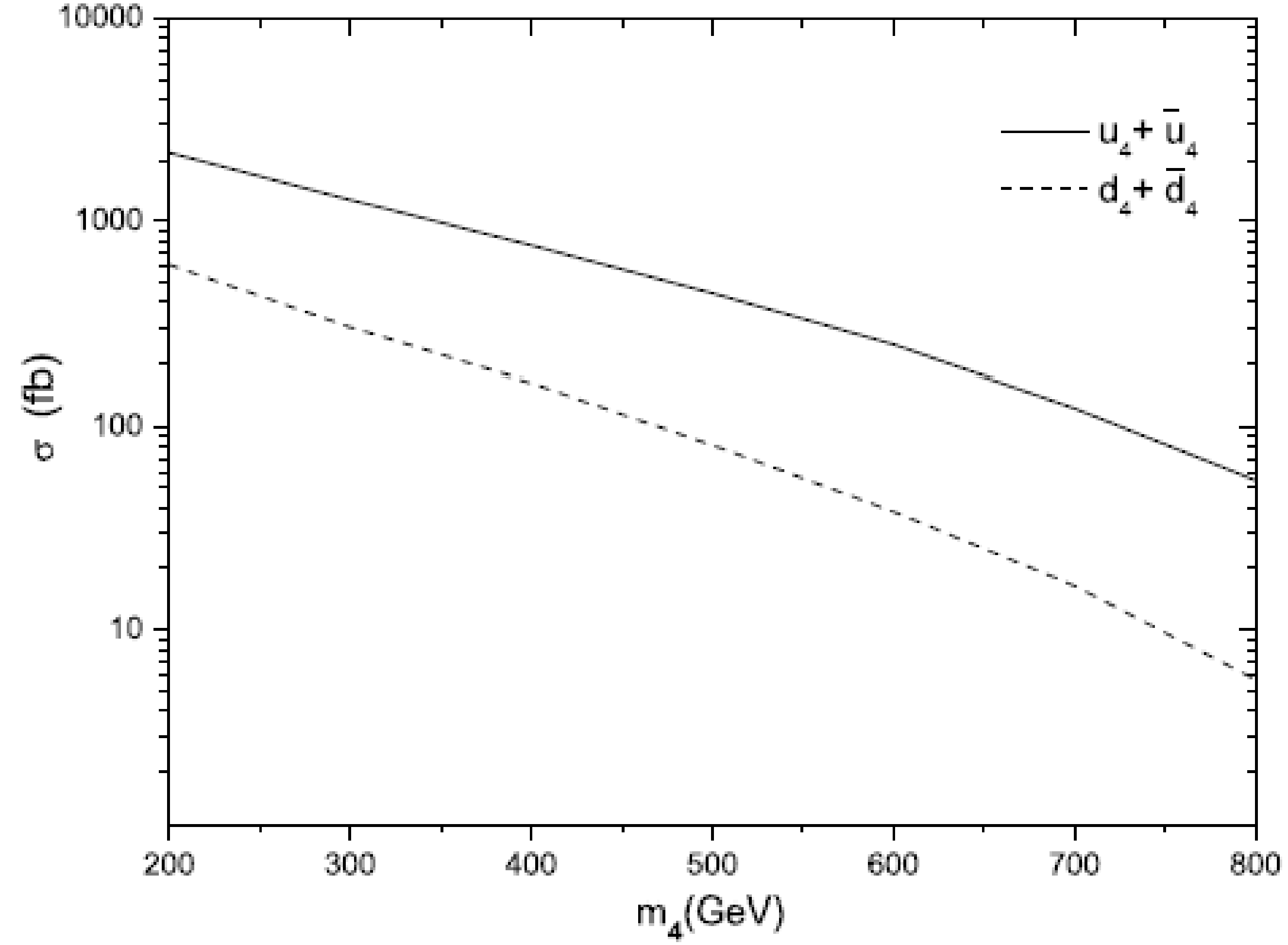
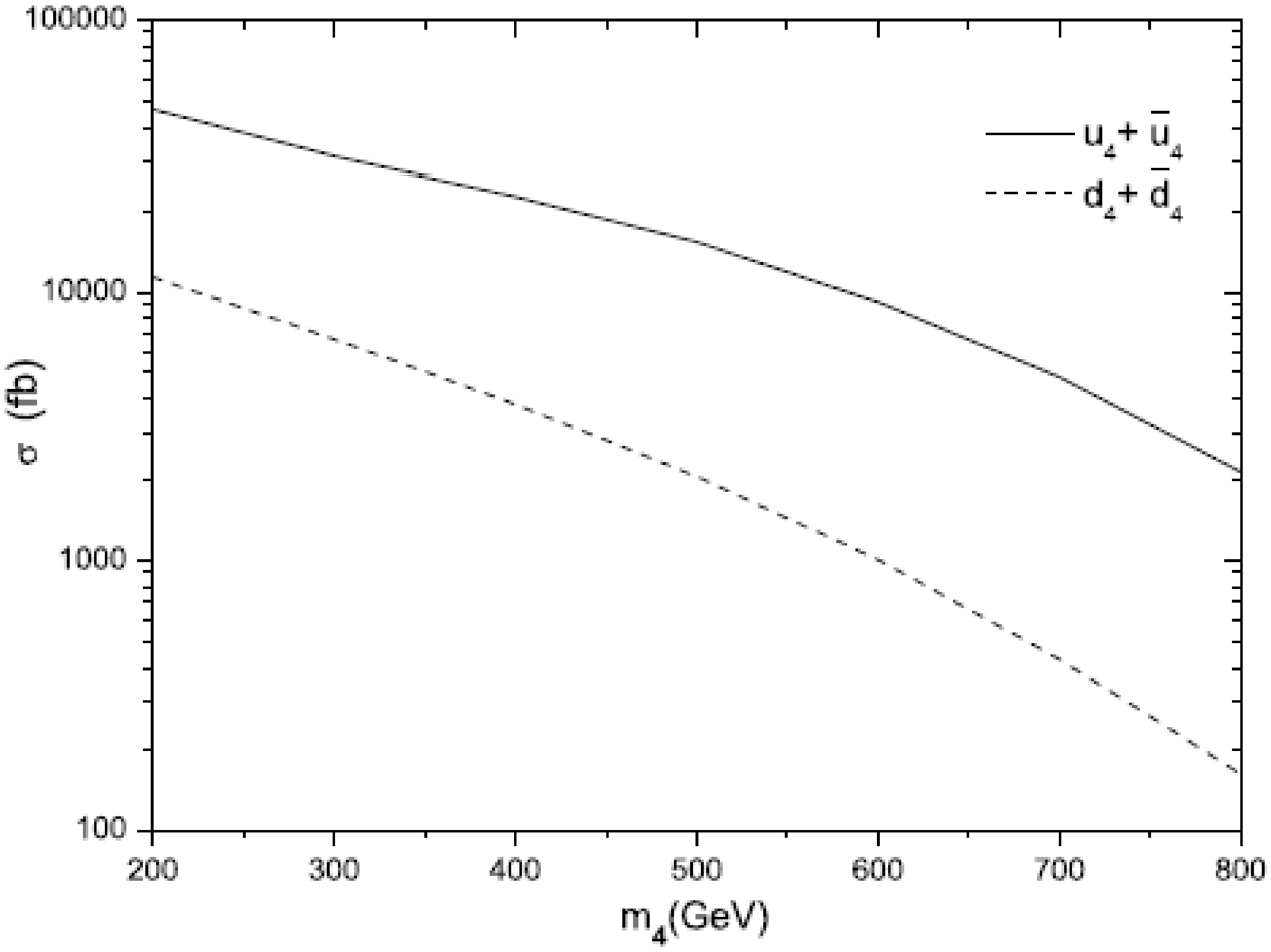
m_{d4}(GeV)

Anomalous single production of fourth generation quarks at ep colliders



Anomalous single production of fourth generation quarks at γp colliders



Signal and corresponding SM background cross-section values

m_4 (GeV)	Quark Type	Signal σ (fb) for $ep \to d_4(u_4)X \to q\ell^+\ell^-X$		Signal σ (fb) for $\gamma p \to d_4(u_4)X \to q\gamma X$	
		$\kappa/\Lambda = 1$ TeV^{-1}	$\kappa_g/\Lambda = 0$	$\kappa/\Lambda = 1$ TeV^{-1}	$\kappa_g/\Lambda = 0$
No Cut					
300	u_4	8.68	163	564	7340
	d_4	2.44	40	33.9	540
600	u_4	1.45	19	136	1820
	d_4	0.32	5	5.13	81
SM Background σ (fb)		1954		$3.19 \cdot 10^8$	
Cut2					
300	u_4	–	3.37	380	4940
	d_4	–	1.75	–	390
600	u_4	–	0.94	61	800
	d_4	–	0.35	–	38
SM Background σ (fb)		0.64		1220	

Cut selection

Some kinematic cuts have been applied in order to extract the signal and to suppress the SM background. The following selection of cuts is chosen: $P_T > 80$ GeV for photons and leptons (coming from Z boson), $P_T > 20$ GeV for jet; $|\eta_{j,\gamma}| < 2.5$, where η denotes the pseudorapidity; a minimum separation of $\Delta R = \left[(\Delta\phi)^2 + (\Delta\eta)^2\right]^{1/2} > 0.4$ (ϕ is the azimuthal angle) between the leptons and jet.

Statistical Significances and observation limits

m_4 (GeV)	Quark Type	SS for $ep \to d_4(u_4)X \to q\ell^+\ell^-X$		SS for $\gamma p \to d_4(u_4)X \to q\gamma X$
		$L = 10$ fb^{-1}	$L = 4.1$ fb^{-1}	$L = 2.665$ fb^{-1}
300	u_4	13.3	8.5	231
	d_4	6.9	4.4	18.2
600	u_4	3.7	2.4	37.4
	d_4	1.4	0.9	1.8

m_4 (GeV)	Quark Type	Min(κ_Z) values for observation at $ep \to d_4(u_4)X \to q\ell^+\ell^-X$		Min(κ_γ) values for observation at $\gamma p \to d_4(u_4)X \to q\gamma X$
		$L = 10$ fb^{-1}	$L = 4.1$ fb^{-1}	$L = 2.665$ fb^{-1}
300	u_4	0.47	0.59	0.34
	d_4	0.66	0.82	0.64
	$u_4 + d_4$	0.38	0.48	0.33
600	u_4	0.90	–	0.53
	d_4	–	–	–
	$u_4 + d_4$	0.76	0.95	0.52

Conclusion

- When anomalous coupling for strong interactions is close to one, ep and γp colliders are almost blind to anomalous interactions;

- The ep and γp colliders give possibility to investigate effects of both anomalous couplings of electromagnetic and weak interactions for $\kappa_g^{q_i} = 0$.