Single Diquark Searches in $\gamma\, p$ Collisions

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Study with heavy diquarks

- A signal for Compositeness
- Interpretation of di-jet and three-jet signals BSM
- Possibility for diquark charge measurement
- Lower 3j backgrounds compared to pp
- Distinguishing scalar and vector diquarks

Diquarks in superstring-inspired E6 models

Superpotential,

$$W = W_0 + W_1 + W_2 + W_3\,,$$

$$W_0 = \lambda_1 H^c Q u^c + \lambda_2 H Q d^c + \lambda_3 H L e^c + \lambda_4 H^c H S^c + \lambda_5 h h^c S^c\,,$$

$$W_1 = \lambda_6 h u^c e^c + \lambda_7 L h^c Q + \lambda_8 \nu^c h d^c\,, \quad W_2 = \lambda_9 h Q Q + \lambda_{10} h^c u^c d^c\,, \quad W_3 = \lambda_{11} H^c L \nu^c$$

*J.L.Hewett, T.G.Rizzo, PR183, 193 (1989).

SO(10)	SU(5)		Color	T_{3L}	$Y/2$	Q
16	**10**	$Q = \begin{pmatrix} u \\ d \end{pmatrix}_L$	**3**	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	1/6	$\begin{pmatrix} 2/3 \\ 1/3 \end{pmatrix}$
		u_L^c	$\bar{\mathbf{3}}$	0	−2/3	−2/3
		e_L^c	**1**	0	1	1
	$\bar{\mathbf{5}}$	$L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$	**1**	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	−1/2	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
		d_L^c	$\bar{\mathbf{3}}$	0	1/3	1/3
	1	ν_L^c	**1**	0	0	0
10	$\bar{\mathbf{5}}$	$H = \begin{pmatrix} N \\ E \end{pmatrix}_L$	**1**	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	−1/2	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
		h_L^c	$\bar{\mathbf{3}}$	0	1/3	1/3
	5	$H^c = \begin{pmatrix} E \\ N \end{pmatrix}_L^c$	**1**	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	1/2	$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$
		h_L	**3**	0	−1/3	−1/3
1	**1**	S_L^c	**1**	0	0	0

Model independent framework:

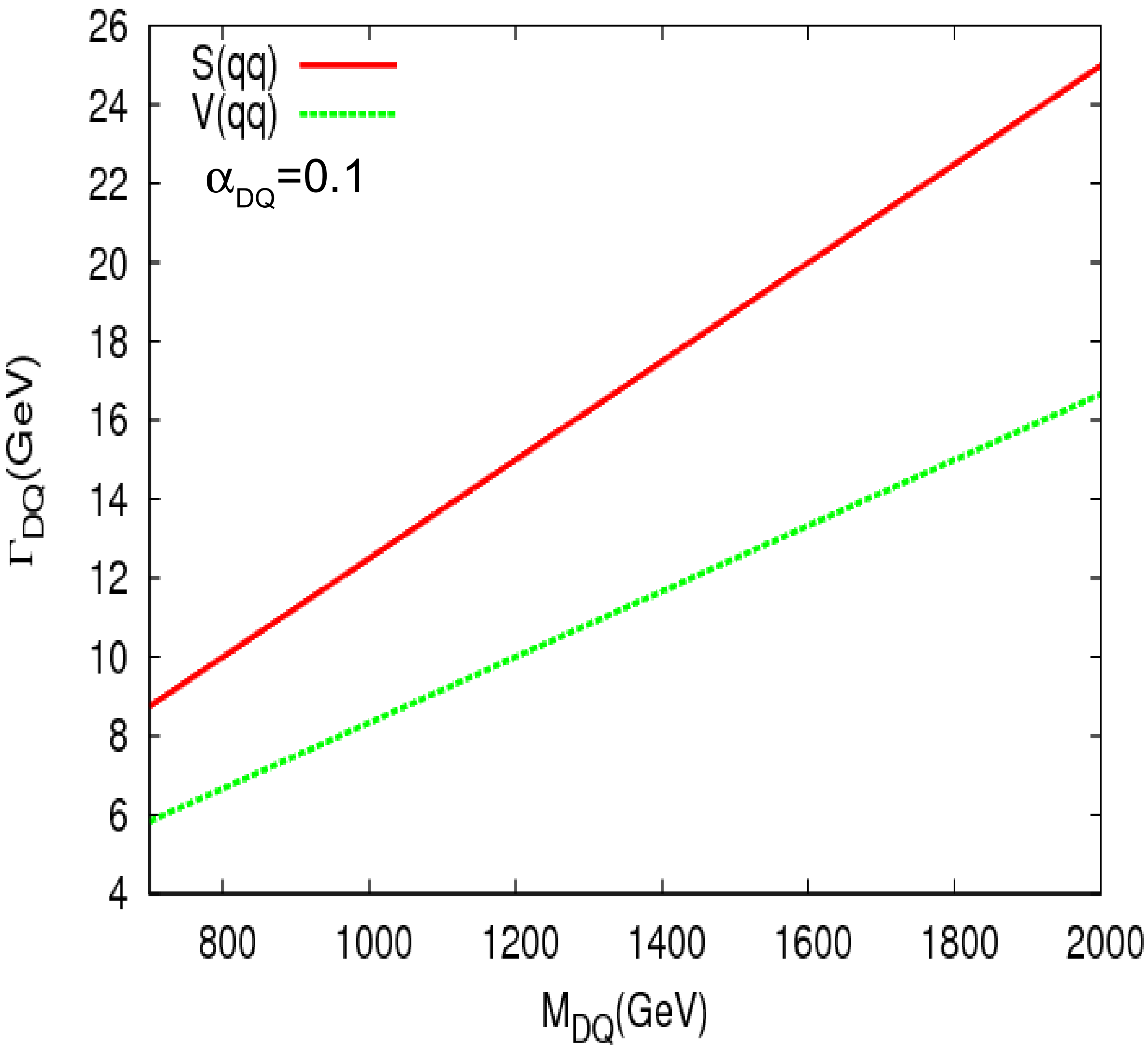
A model independent baryon number conserving, SU(3)xSU(2)xU(1) invariant effective lagrangian for scalar and vector diquarks [*]

$$L_{|B|=2/3} = (g_{1L}\overline{q}_L^c i\tau_2 q_L + g_{1R}\overline{u}_R^c d_R) DQ_1^c + \tilde{g}_{1R}\overline{d}_R^c d_R \widetilde{DQ}_1^c + \tilde{g}'_{1R}\overline{u}_R^c u_R \widetilde{DQ}_1^{\prime c} + g_{3L}\overline{q}_L^c i\tau_2 \tau q_L \cdot \mathbf{DQ}_3^c + g_2 \overline{q}_L^c \gamma^\mu d_R DQ_{2\mu}^c + \tilde{g}_2 \overline{q}_L^c \gamma^\mu u_R \widetilde{DQ}_{2\mu}^c + \text{H.c.}$$

[*] S.Atag, OC, S.Sultansoy, PRD59, 015008 (1999); E.Arik, S.A.Cetin, OC, S.Sultansoy, JHEP09, 024(2002); OC, M.Sahin, PRD72, 115011(2005).

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	Q	Couplings
Scalar diquarks					
DQ_1	3^*	1	2/3	1/3	$u_L d_L(g_{1L}),\ u_R d_R(g_{1R})$
$\widetilde{DQ}_1$	3^*	1	−4/3	2/3	$d_R d_R(\tilde{g}_{1R})$
$\widetilde{DQ}'_1$	3^*	1	8/3	4/3	$u_R u_R(\tilde{g}'_{1R})$
DQ_3	3^*	3	2/3	$\begin{pmatrix} 4/3 \\ 1/3 \\ -2/3 \end{pmatrix}$	$\begin{pmatrix} u_L u_L(\sqrt{2} g_{3L}) \\ u_L d_L(-g_{3L}) \\ d_L d_L(-\sqrt{2} g_{3L}) \end{pmatrix}$
Vector diquarks					
$DQ_{2\mu}$	3^*	2	−1/3	$\begin{pmatrix} 1/3 \\ -2/3 \end{pmatrix}$	$\begin{pmatrix} d_R u_L(g_2) \\ d_R d_L(-g_2) \end{pmatrix}$
$\widetilde{DQ}_{2\mu}$	3^*	2	5/3	$\begin{pmatrix} 4/3 \\ 1/3 \end{pmatrix}$	$\begin{pmatrix} u_R u_L(\tilde{g}_2) \\ u_R d_L(-\tilde{g}_2) \end{pmatrix}$

Decay Widths(DQ-->qq)



Scalar diquark(S):

Γ_{DQ}=8.75 GeV for m_{DQ}=700 GeV and α_{DQ}=0.1.

Vector diquark(V):

Γ_{DQ}=5.83 GeV for m_{DQ}=700 GeV and α_{DQ}=0.1.

Constraints from DQ searches

A search for narrow two-jet (dijet) resonances at Tevatron experiments with an integrated luminosity of 1.13 fb^{-1},

- The exclusion limit on the scalar ud type E_6-diquark mass, $290 < m_{DQ} < 630$ GeV at 95% CL. [*]

Phenomenological bounds on the diquark couplings from LEP experiments

$\alpha_{DQ} < 0.12$ [**]

[*]CDF/PRD79/ 2009; [**]G.Bhattacharyya et al.,PLB95.

Constraints on DQ couplings to quarks

A major constraint comes from D^0- $\bar{D}^0$ mixing: exchange of DQ. The transition mass Δm_D for this mixing [PDG08]

$$8.5\text{x}10^{-١٥} < \Delta m_D < ١.٩\text{x}١٠^{-١٤}\,\text{GeV}$$

In a DQ model, estimate

$$\Delta m_D \simeq f_{11} f_{22} f_D^2 M_D / (4 M_{DQ}^2) \rightarrow f_{11} f_{22} / (4 M_{DQ}^2) \leqslant 10^{-12}\,\text{GeV}^{-2}$$

taking M_{DQ}=1 TeV one find $f_{11} f_{22} \leq 4\text{x}10^{-6}$. Assume $f_{11} >> f_{22}$, expect $f_{11} \sim 0.1$ for a phenomenological study.

The other constraint comes from $D^0 \dashrightarrow \pi\pi$ decay, which yields Br$\leq 10^{-4}$ and one find $f_{11} f_{12} \leq 4\text{x}10^{-2}$ for a few TeV DQ mass. This converts to $f_{11} \sim f_{12} \sim 0.2$ [*].

[*] R.N.Mohapatra et al.,PRD77(2008).

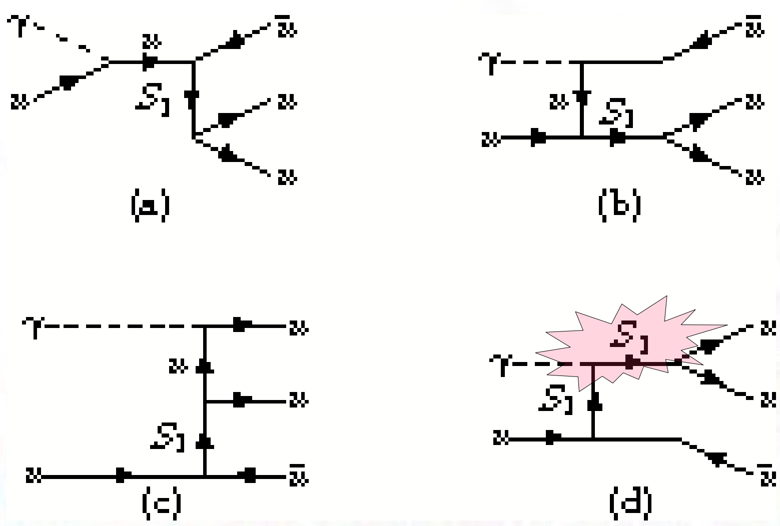
Diquarks at high energy colliders

- If diquarks exist LHC experiments could find them in resonance channel, and measure their masses, spin etc. However, other properties such as their charges and coupling types can be identified at future high energy colliders.

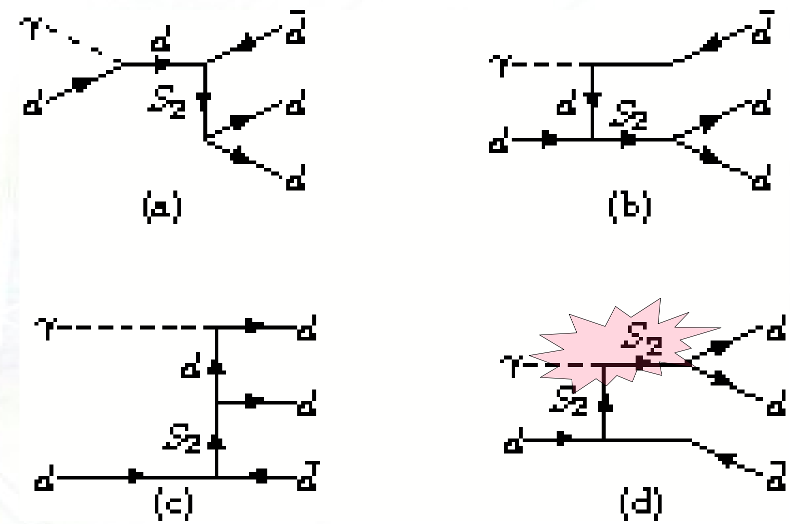
DQ Production (2-->2)	pp/p $\bar{p}$	ep	γ-opt.	resolv.	ee	γ-opt.	resolv.
Resonance	✓	✗	✗	✓	✗	✗	✓
Single	✓	✗	✓	✓	✗	✗	✓
Pair	✓	✓	✓	✓	✓	✓	✓

γ p collider

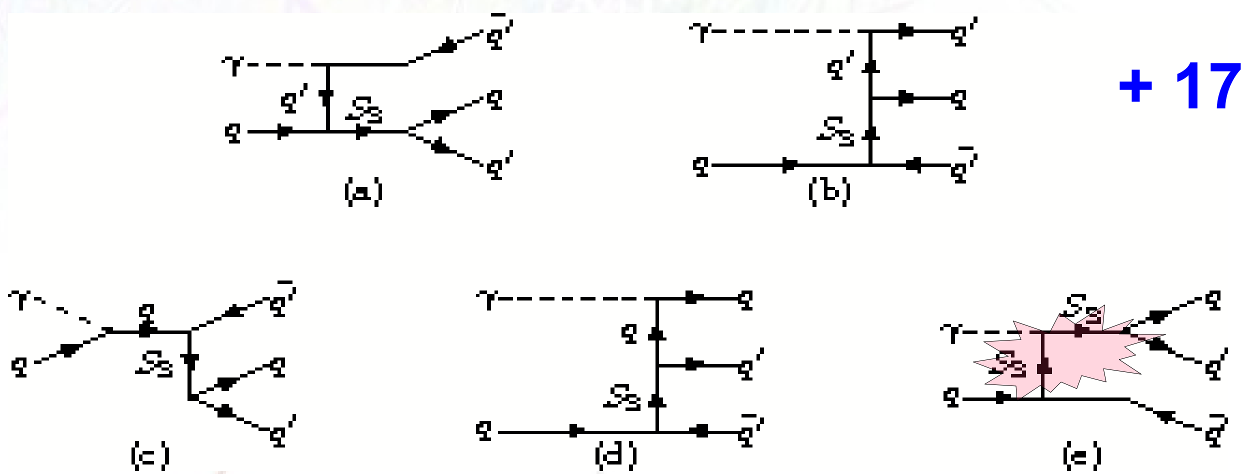
Single productions in γ p collisions: (S1)uu, (S2)dd and (S3)ud type diquarks



+ 12 SM diagrams



+ 12 SM diagrams

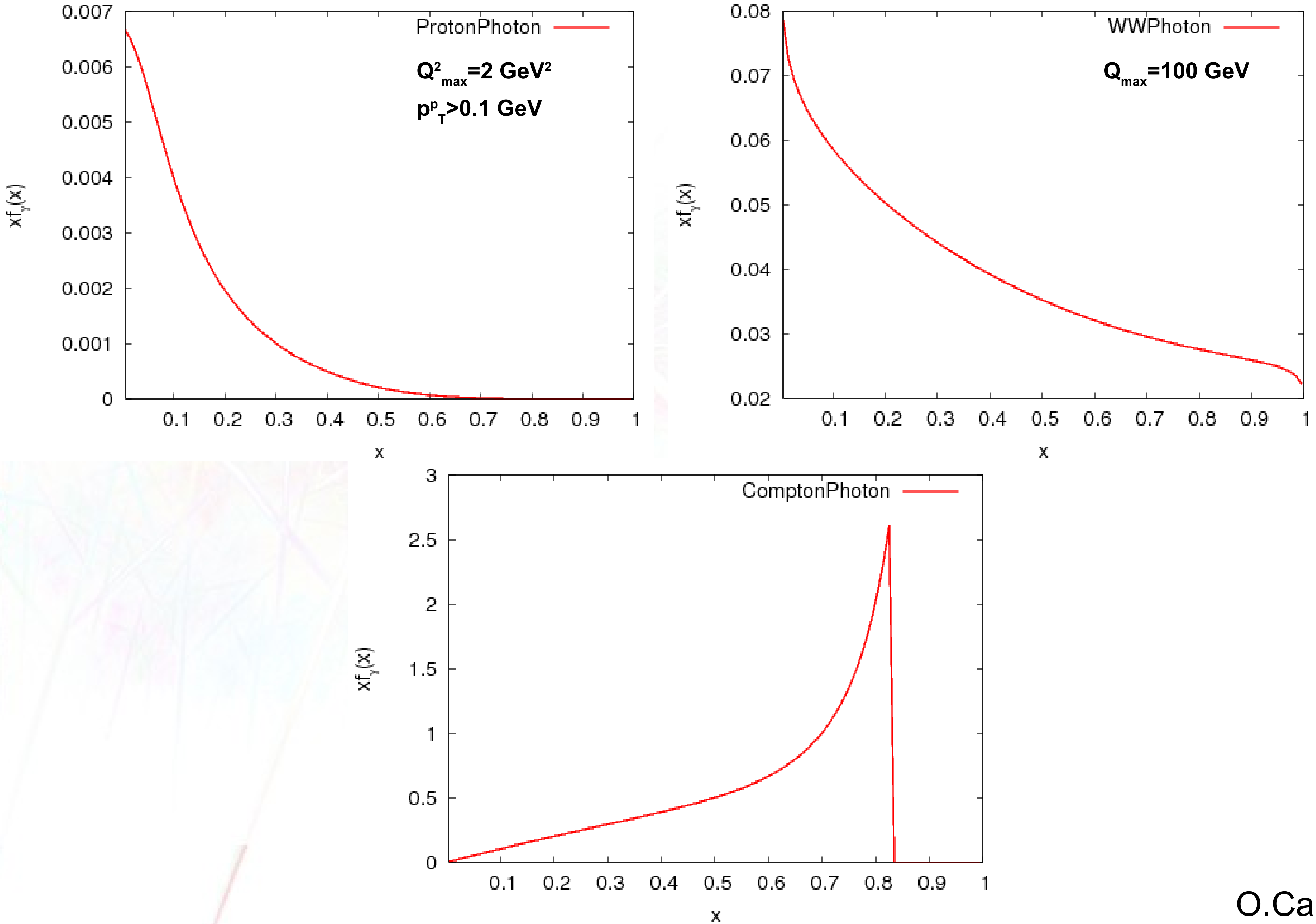


+ 17 SM diagrams

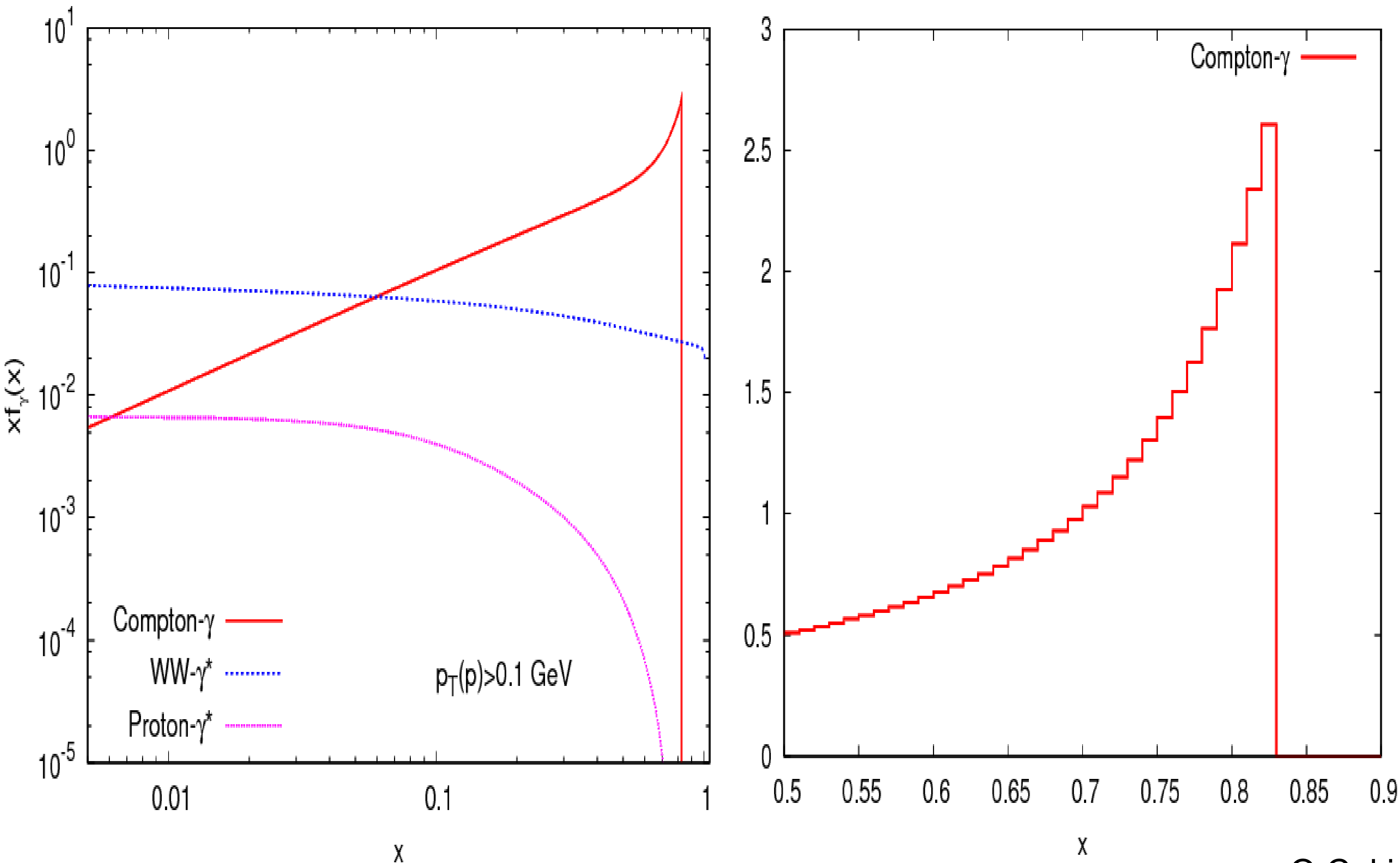
All these signal diagrams interfere with the SM ones(irreducible). Others (reducible) contribute to 3j events.

Diquark model is implemented in CalcHEP2.5[Pukhov04]

Photon spectrum



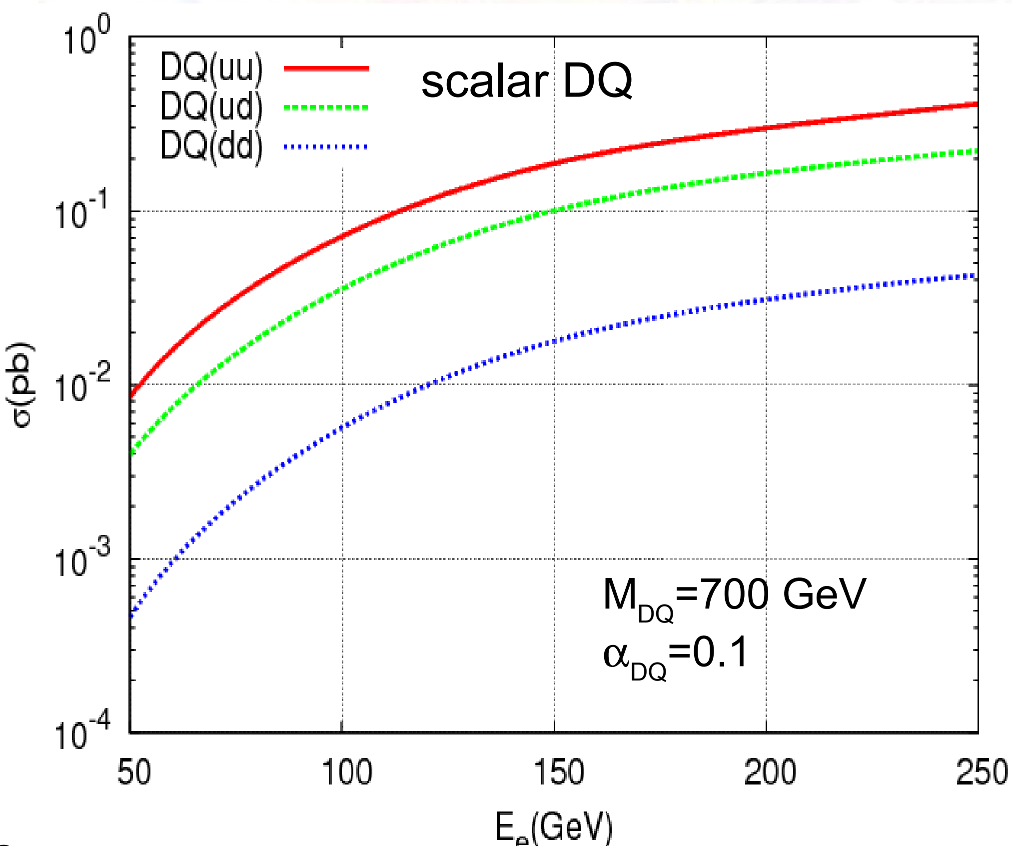
Comparison of the spectra

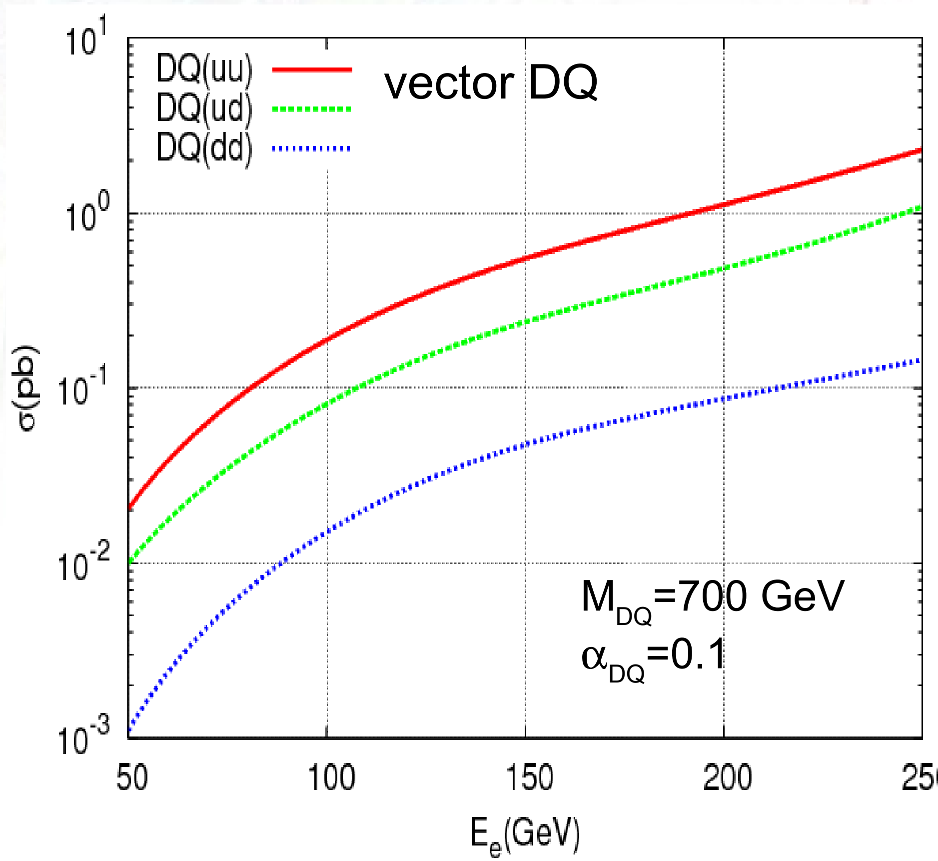


Hadronic cross section

For the γp collisions, the cross section

$$\sigma = \int_{m_{DQ}^2/s}^{0.83} d\tau \int_{\tau/0.83}^{1} \frac{dx}{x} f_{\gamma/e}\left(\frac{\tau}{x}\right) f_{q/p}(x, Q_p^2)\, \hat{\sigma}(\hat{s})$$





Cross sections for scalar DQ uu(dd)-type, with p_T^q>20 GeV

γp collisions σ(fb)	LHeC(γp) Ee(GeV)		LHC(γp) (10TeV)	LHC(γp) (14TeV)
M_{DQ} (GeV)	70	140	5+5	7+7
700	36.56 (2.53)	189.37 (18.57)	8.29 (1.13)	12.23 (2.04)
800	10.04 (0.58)	93.21 (8.51)	5.94 (0.69)	8.61 (1.32)
900	2.31 (0.12)	42.97 (3.50)	3.51 (0.49)	6.65 (0.85)
1000	0.53 (0.03)	19.84 (1.39)	2.62 (0.30)	4.58 (0.64)

For the signal, the pdf CTEQ6M with $Q^2=m_{DQ}^2$ is used.

Three-jet background:

- **3j events at LHC(10)[14] → σ=(10094.34)[23090.56] pb for p_T^{jet}>100 GeV**
- **3j events at LHeC based γp(1.4)[1.9] --> σ=0.99[3.26] pb for p_T^{jet}>100 GeV.**

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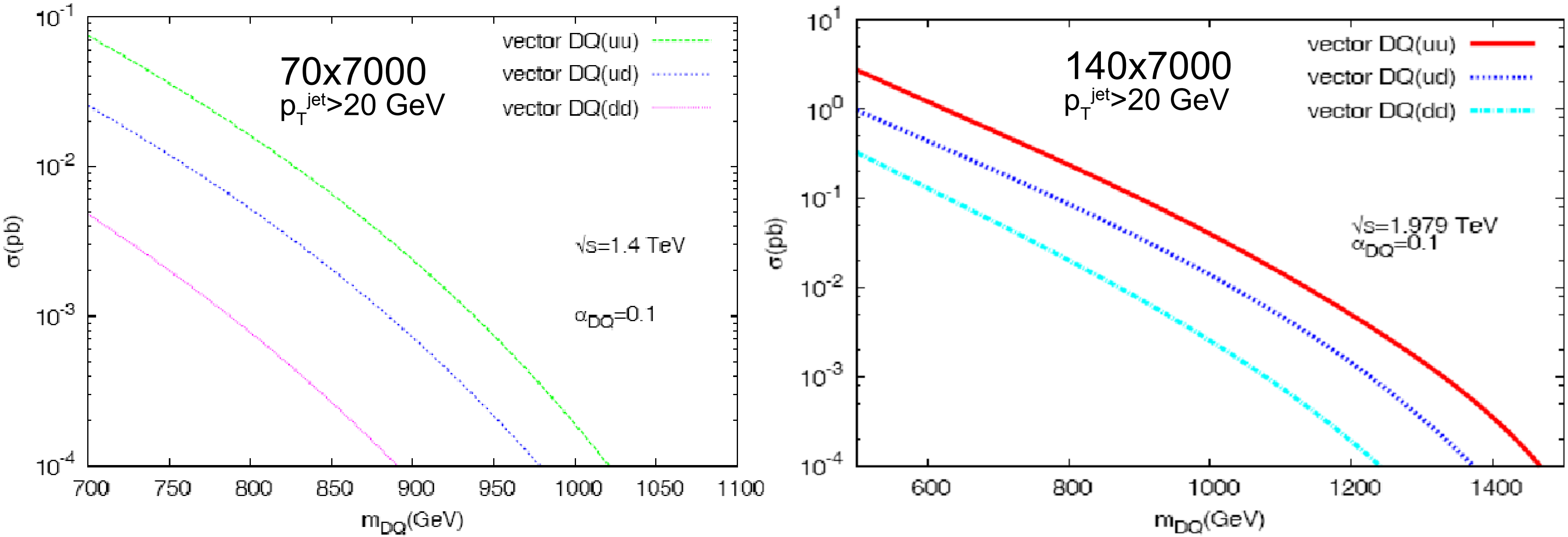
Vector diquark production at LHeC based γ p

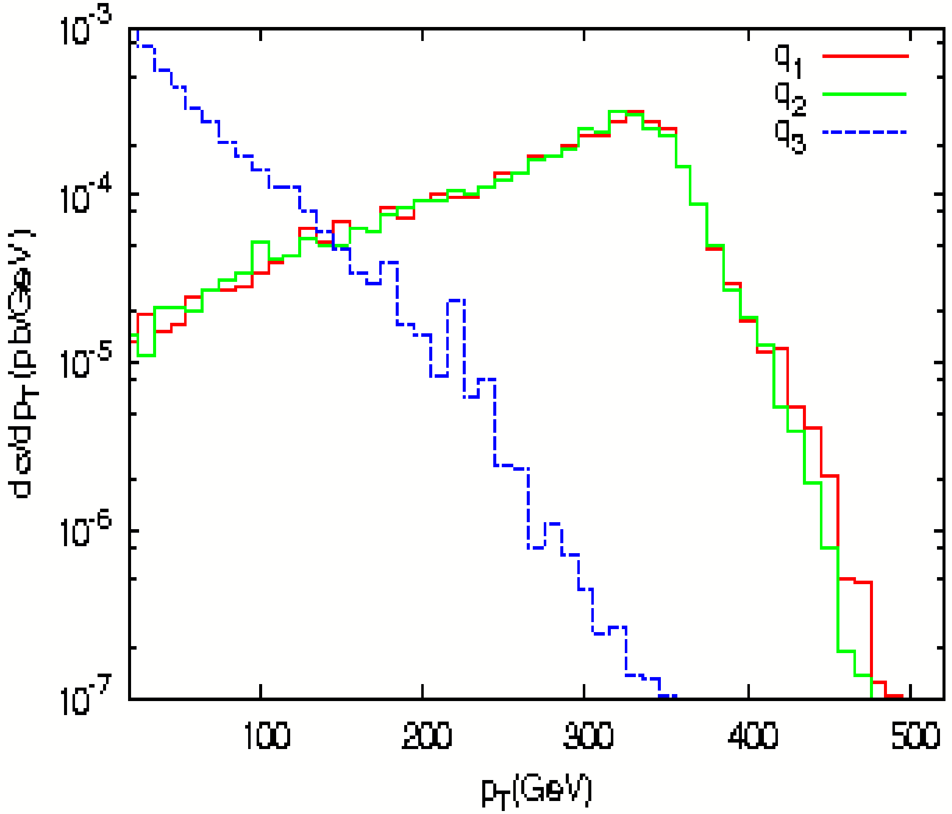


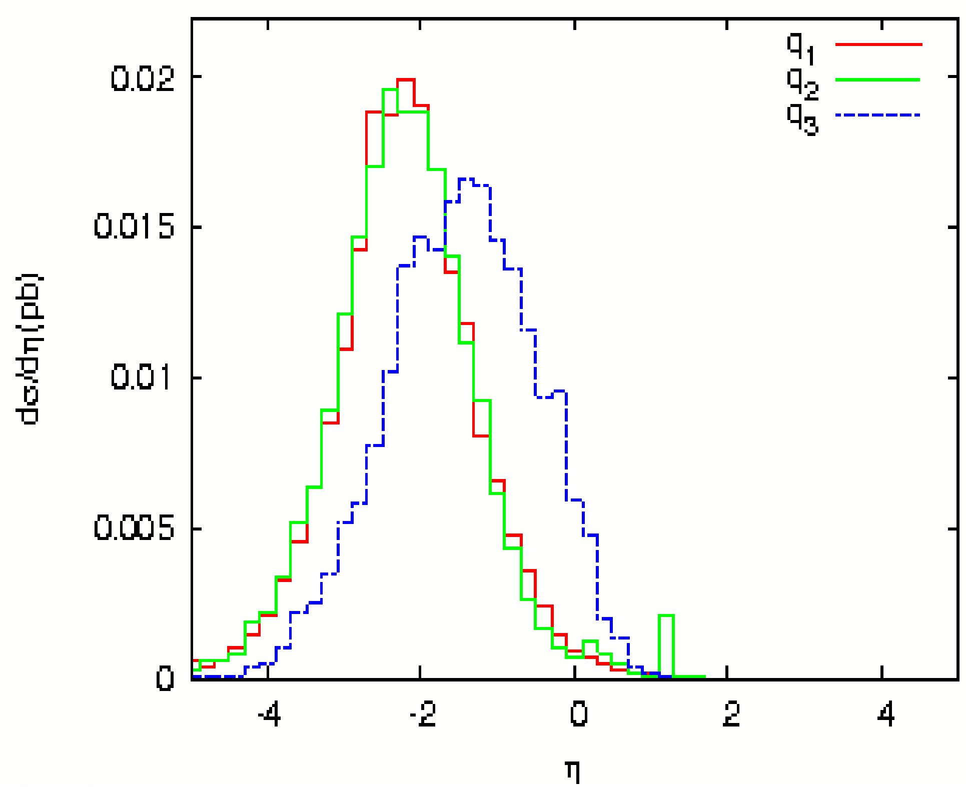
Cross sections for S_1 and V_1 at E(140x7000)

Event generation with p_T^{jet}>50 GeV, and the cross sections in pb

m_{DQ}(GeV)	Scalar DQ(uu)-S_1	Vector DQ(uu)-V_1
700	1.11×10^{-1}	2.98×10^{-1}
900	2.38×10^{-2}	5.51×10^{-2}
1100	4.19×10^{-3}	9.59×10^{-3}
1300	4.46×10^{-4}	1.07×10^{-3}

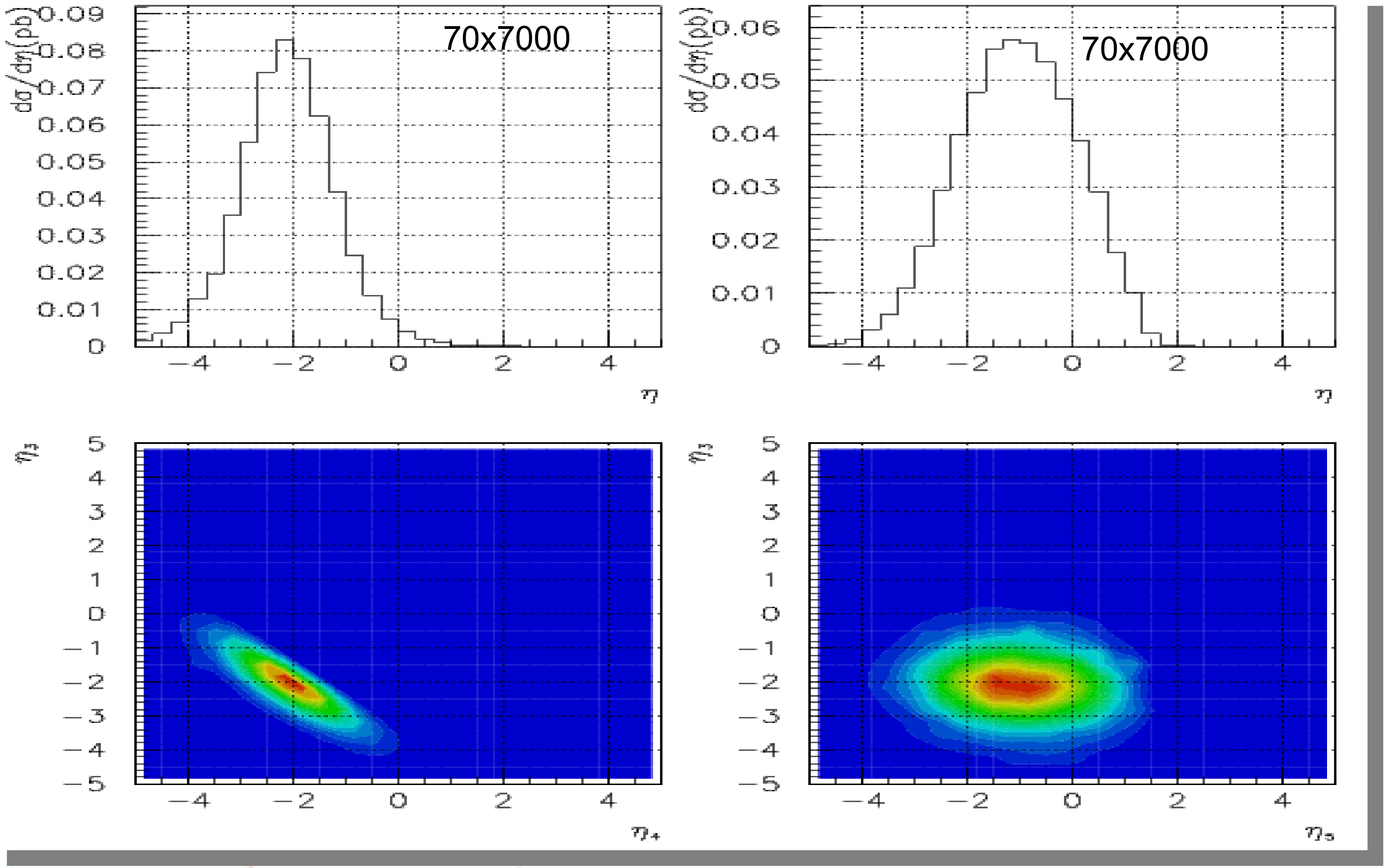
Signal DQ-->qq: partonic level distributions



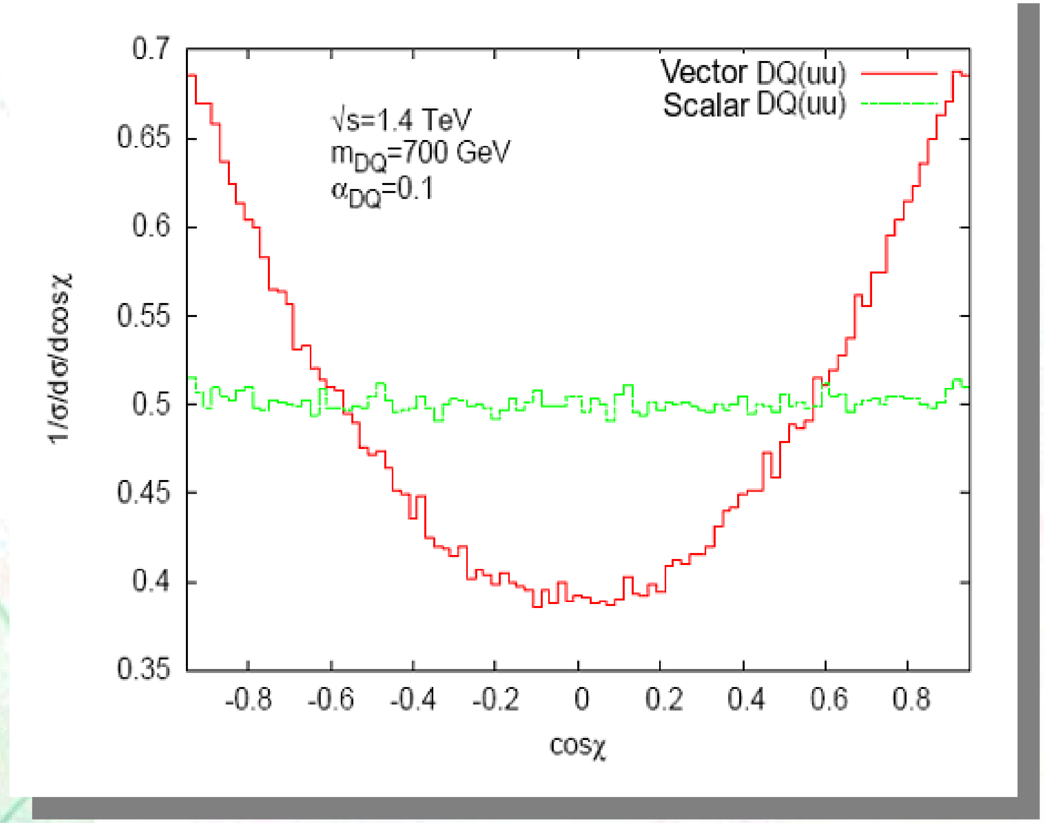


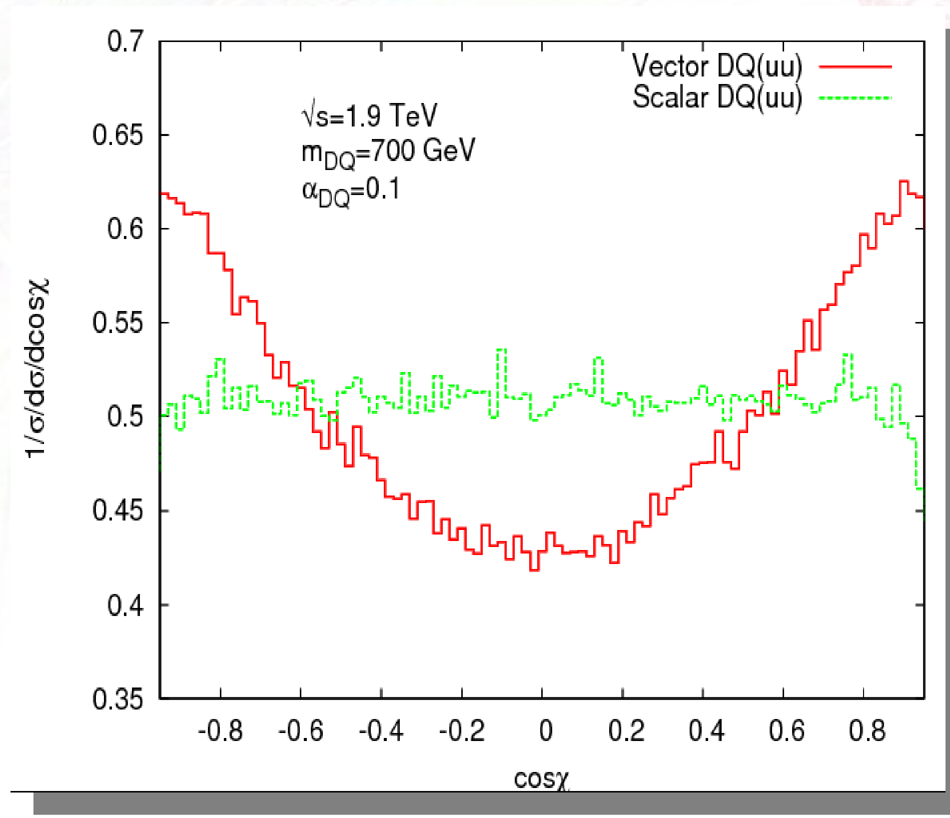
Differential cross sections for $\gamma p \to q_1 q_2 q_3 X$ at Ecm=1.4 TeV, scalar DQ with M_{uu}=700 GeV, $\alpha_{uu} = 0.1$

Signal: $q(\eta_3)q(\eta_4)q'(\eta_5)$, rapidity distribution of quarks



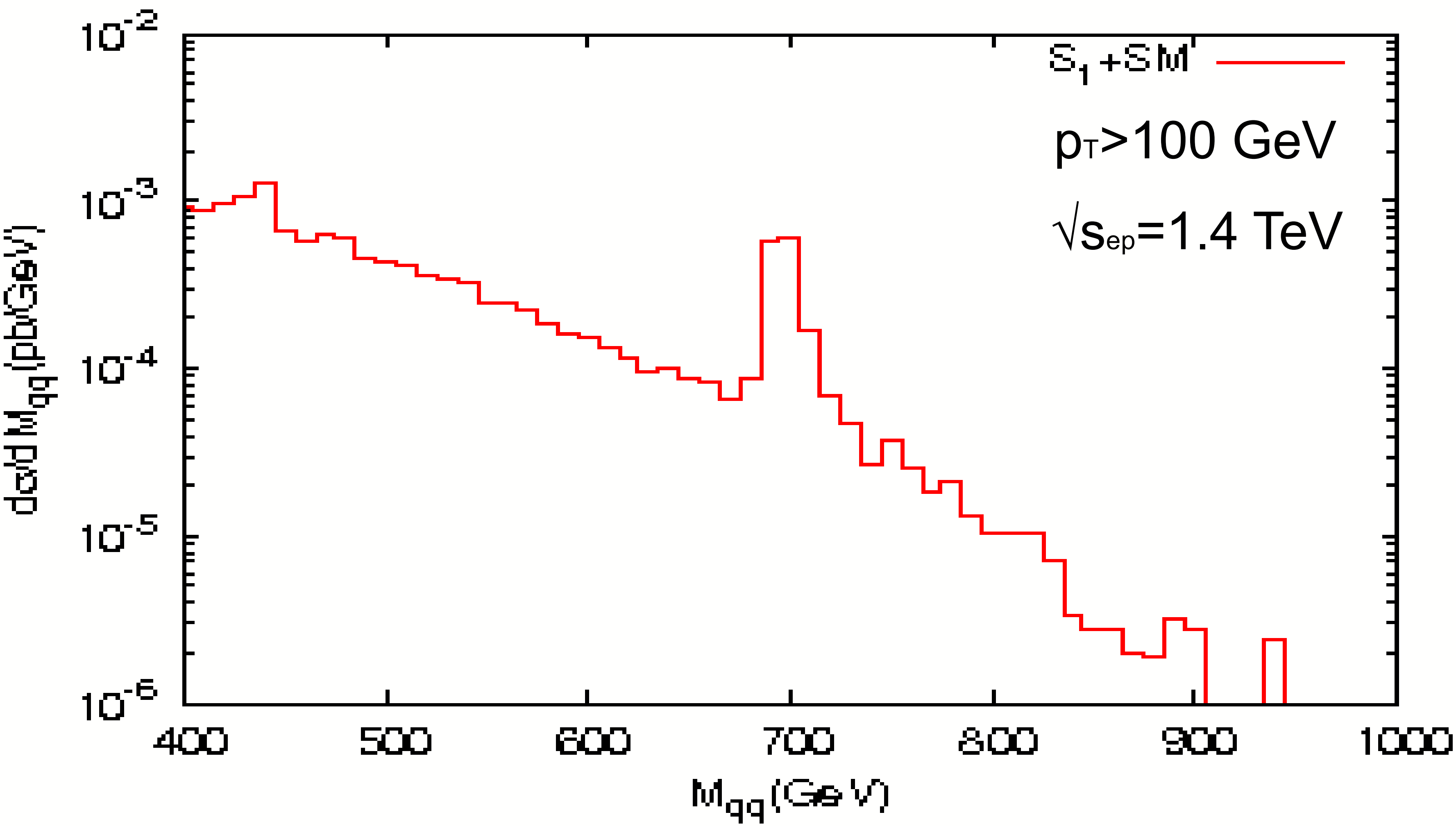
Angular distributions ($P_{34} \equiv \cos\chi$)





P_{34} is the cosine in the rest frame of particles uu in the final state

Invariant mass distribution: $S_1(uu)$+SM(IrB)



Background 3jet: cross sections at 70x7000

p_T^{jet} cut	σ (pb)	p_T and η cut	σ (pb)
p_T>20 GeV	1.866×10^3	p_T>20 GeV, η<0	6.402×10^2
p_T>50 GeV	4.016×10^1	p_T>20 GeV, -3<η<-1	6.475×10^1
p_T>100 GeV	9.987×10^{-1}	p_T>50 GeV, η<0	3.379×10^1
p_T>200 GeV	2.858×10^{-3}	p_T>50 GeV, -3<η<-1	7.904×10^0

Event generation and simulation

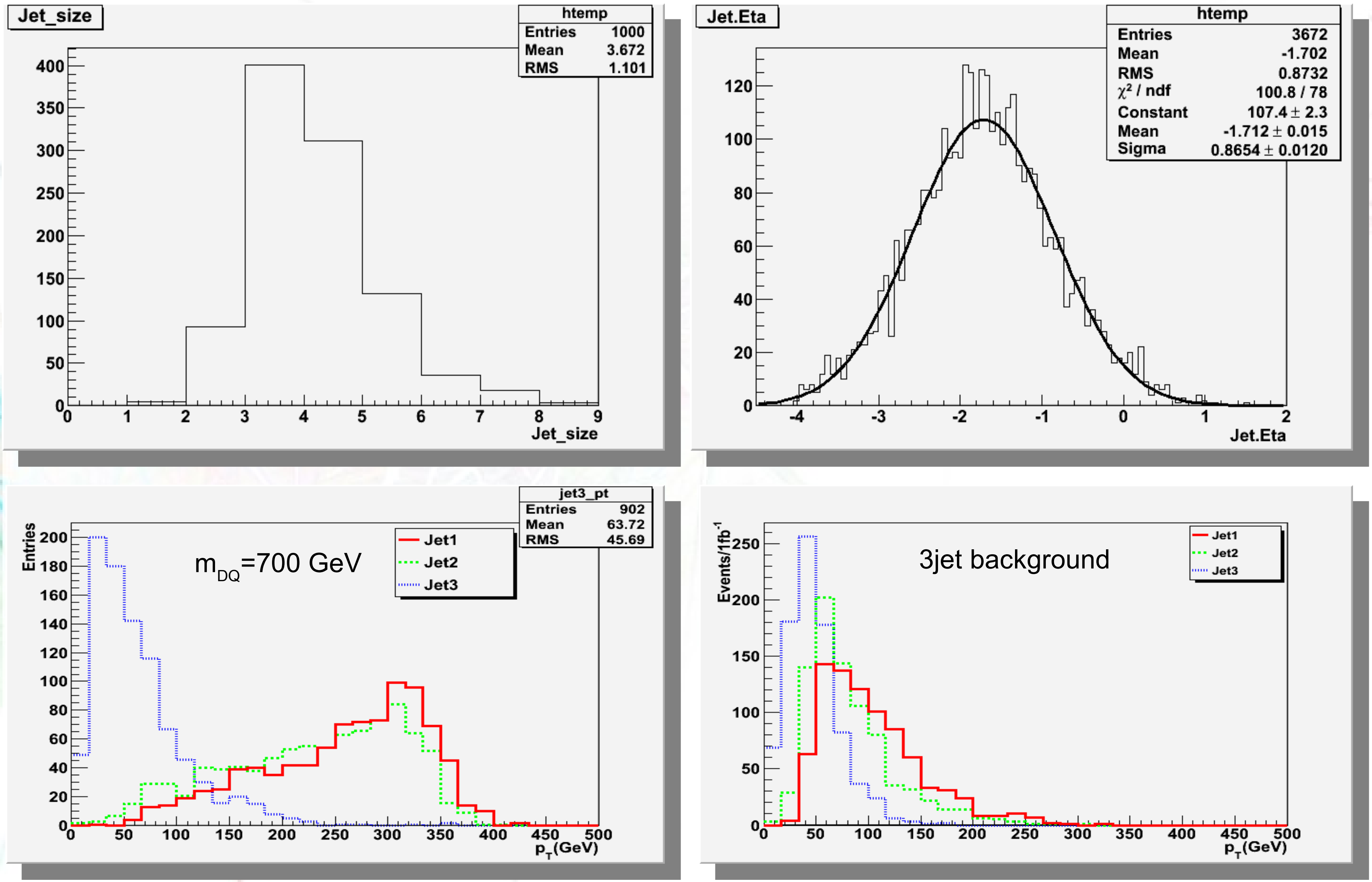
Events are generated with CalcHEP2.5[Pukhov04] with full implementation of scalar and vector diquark interaction vertices.

A modified version of Cpyth[Belyaev01] interface for CalcHEP2.5 + PYTHIA6.4[Sjostrand06] is used for hadronization and decay.

Simulation performed with PGS4[Conley09] for the parameters of a generic HCD. The PGS4 parameter file allows one to specify the maximum eta range of jet reconstruction, jets in PGS are based on the calorimeter.

Preliminary analysis for signal and background events (10k) with ROOT (ExRootAnalysis).

Distributions of jets from scalar DQ(uu) signal and 3jet background



Analysis and Results

Some cuts on jets:

- Transverse momentum of jet p_T>50 GeV (initial), and then check
- Invariant mass of dijet $m_{DQ}-\Delta m<m_{jj}<m_{DQ}+\Delta m$

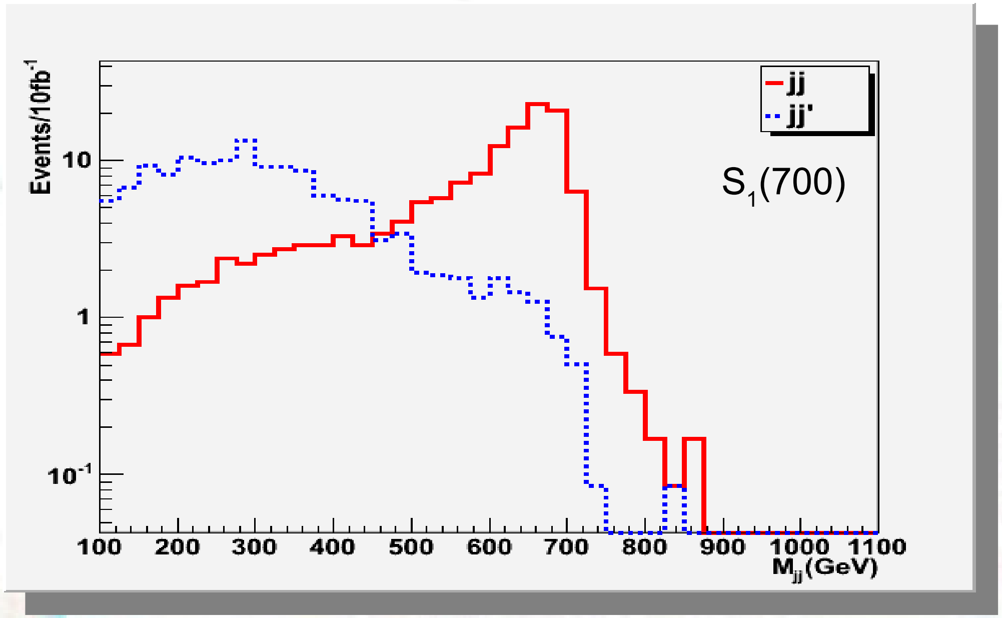
  $\Delta m=\max(2\Gamma,\delta m)$ where δm is the dijet invariant mass resolution

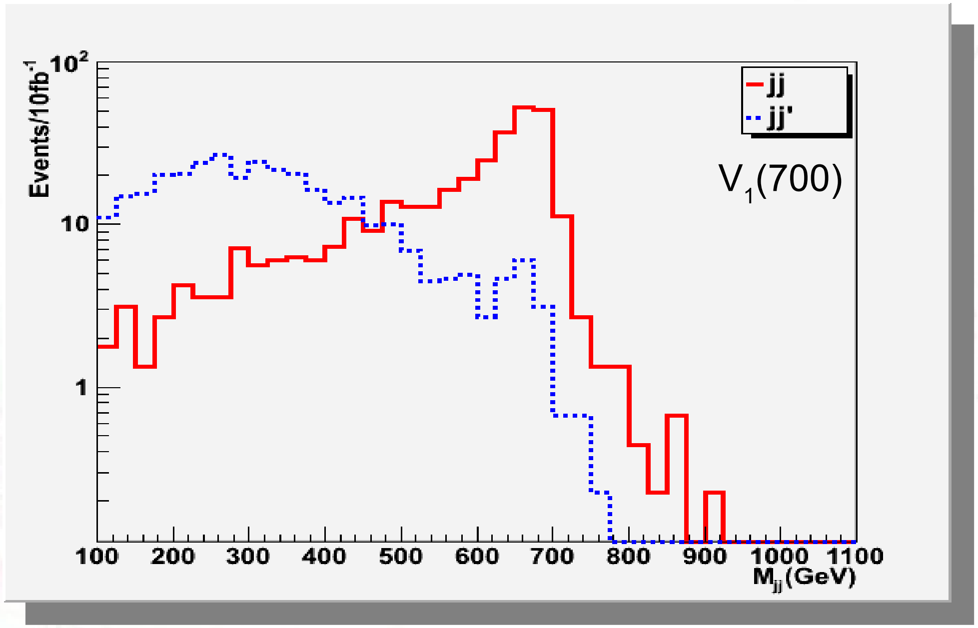
- Count signal events within the inv. mass bin
- Count background events in the same interval
- Find statistical significance (SS) for the signal

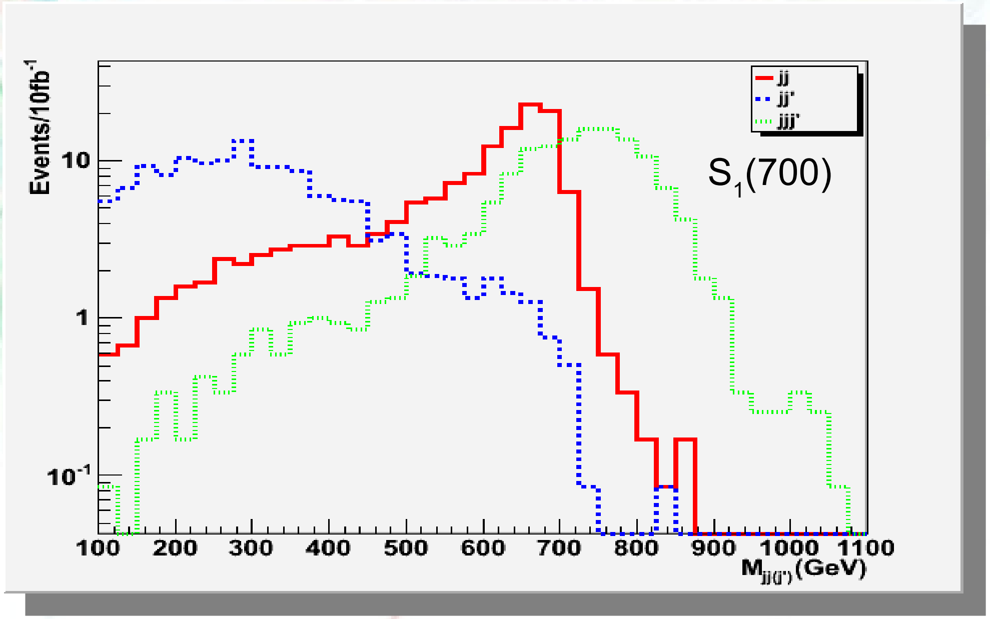
$$SS=\sqrt{(N_s+N_b)\ln(1+\frac{N_s}{N_b})-N_s}$$

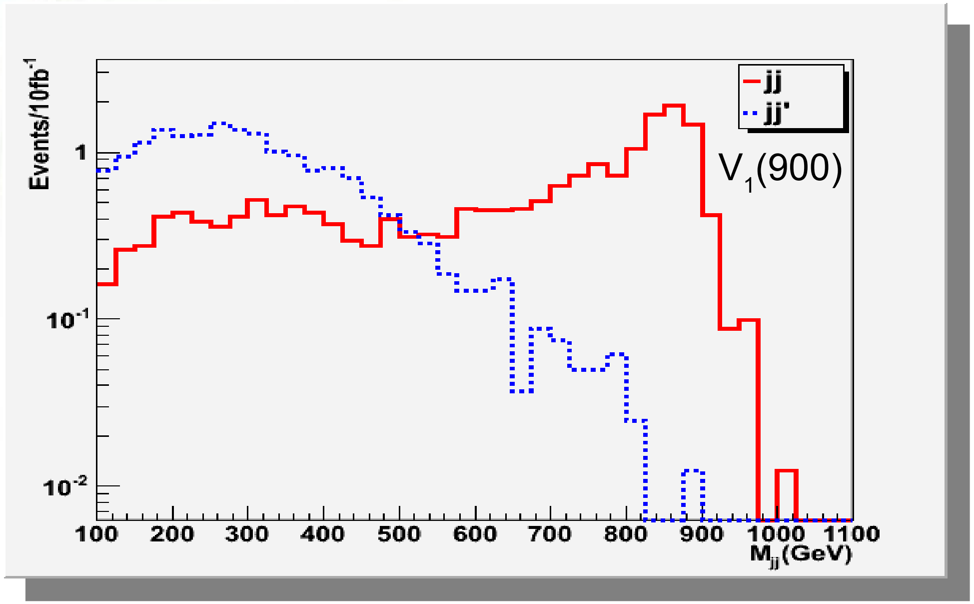
- Taking at least 10 signal events after the cuts and requiring SS>3 we find the attainable limits for the DQs

Reconstructed dijet mass (Ecm=1.4 TeV)









Signal Significance for Scalar(vector) diquarks

	70x7000			140x7000		
m_{DQ}(GeV)	NS	NB	SS	NS	NB	SS
700	52(119)	30	5.5(10.9)	379(637)	125	17.9(27.2)
900	2(4)	5	0.6(1.1)	70(105)	32	6.9(9.7)

Signal and background events are calculated in the mass interval $m_{DQ} \pm 50$ GeV, where integrated luminosity L=10 fb^{-1}.

Conclusion

- If diquarks exist, LHC could find them in resonance channel, however their charges and coupling types can be identified at a LHeC based γp collider.
- Up to 1 TeV mass of diquarks can be studied at LHeC based γp collider.
- Scalar and vector diquarks can be distinguished with the angular distribution in single production.