Search for Excited Quarks at the LHC

Sushil S. Chauhan, Brajesh C. Choudhary, Satyaki Bhattacharya, Debajoyti Choudhury
Dept. of Physics and Astrophysics
University of Delhi, India

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Outline

- Introduction
- Earlier results and limits
- γ+*jet* study for q* search
- Results from $\gamma\gamma$ final state study
- Systematic
- Conclusions

Introduction

$$\mathcal{L}_{int} = \frac{1}{2\Lambda}\bar{q}^*_R\,\sigma^{\mu\nu}\left[\sum_i g_i\, b_i\, T^a_i\, G^a_{i\,\mu\nu}\right] q_L + h.c.,$$

Matrix Element

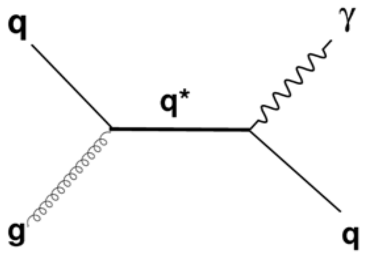
$$\begin{aligned}
\left.\frac{d\sigma}{d\hat{t}}\right|_{qg\to q\gamma} &= \frac{-\pi\,\alpha\,\alpha_s\,e_q^2}{3\,\hat{s}^2}\left[C_{sm} + 2\frac{f_1 f_3}{\Lambda^2}C_I + \frac{f_1^2 f_3^2}{\Lambda^4}C_Q\right]\\
C_{sm} &\equiv \frac{\hat{u}}{\hat{s}} + \frac{\hat{s}}{\hat{u}}\\
C_I &\equiv \frac{\hat{s}^2\,(\hat{s}-M_{q*}^2)\,\mathcal{F}_s}{(\hat{s}-M_{q*}^2)^2+\Gamma^2 M_{q*}^2} + \frac{\hat{u}^2\,\mathcal{F}_u}{\hat{u}-M_{q*}^2}\\
C_Q &\equiv (\hat{s}\hat{u} + M_{q*}^2 t)\\
& \left[\frac{\hat{s}^2\,\mathcal{F}_s^2}{(\hat{s}-M_{q*}^2)^2+\Gamma^2 M_{q*}^2} + \frac{\hat{u}^2\,\mathcal{F}_u^2}{(\hat{u}-M_{q*}^2)^2}\right]\\
&+\ 2M_{q*}^2\frac{\hat{s}\hat{t}\hat{u}}{\hat{u}-M_{q*}^2}\ \frac{(\hat{s}-M_{q*}^2)\,\mathcal{F}_s\,\mathcal{F}_u}{(\hat{s}-M_{q*}^2)^2+\Gamma^2 M_{q*}^2}\\
\mathcal{F}_s &\equiv \left(1+\hat{s}/\Lambda^2\right)^{-(n_1+n_3)}\\
\mathcal{F}_t &\equiv \left(1-\hat{t}/\Lambda^2\right)^{-(n_1+n_3)}\\
\mathcal{F}_u &\equiv \left(1-\hat{u}/\Lambda^2\right)^{-(n_1+n_3)}
\end{aligned}$$

Width of q*

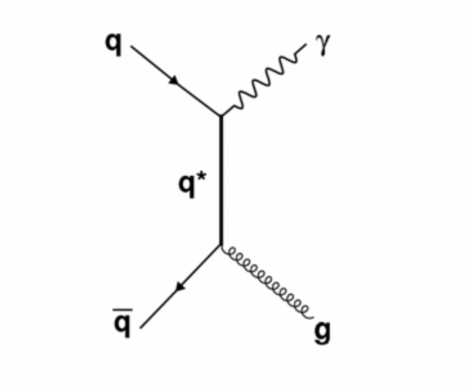
$$\begin{aligned}
\Gamma(q*) &= \Gamma_{q+g} + \Gamma_{q+\gamma}\\
\Gamma_{q+g} &= \frac{2\alpha_s f_3^2}{3}\Gamma_0\\
\Gamma_{q+\gamma} &= \frac{e_q^2\alpha f_1^2}{2}\Gamma_0\\
\Gamma_0 &\equiv \frac{M_{q*}^3}{\Lambda^2}\left(1-\frac{4m_q^2}{M_{q*}^2}\right)\left(1-\frac{m_q^2}{M_{q*}^2}\right)^2
\end{aligned}$$

Signal

- γ+ jet via q*

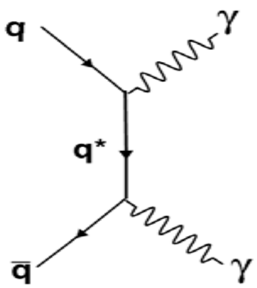


Mass-peak



Flat excess

- $\gamma\gamma$ final state via q*



Flat excess

[PRD 76,115017(2007)]
arXive:0705.347v2[hep-ph]

Earlier results and limits: Exp.

Limits from Tevatron:

CDF

1. Mq* > 570 GeV [from various final states] [PRL72(1994)3004, PRD 76(1995)3538]
2. Λ > 2.4 TeV @ 95% CL (Dijet channel) Preliminary (Nov. 2008)

   [CDF/JET/ANAL/PUB/9609]

D0

1. Mq*> 775 GeV (Dijet channel) [PRD 69(2004)111110]
2. Λ > 2.0 TeV @ 95% CL (Dijet channel) [PRD 62(2000)031101]
3. Λ_+ > 2.75 TeV @ 95% CL (Dijet) Preliminary (July 2008) [D0 Note -5733-Conf]

Earlier results and limits: Phenomenology, Simulations

CMS

- Possible to exclude Λ≈ 6.2 TeV at 95% CL with 100 pb^{-1} of data and 5σ-sensitivity up to Λ≈ 8 TeV with 1 fb^{-1} of data (*Dijet ratio analysis*) [JPCS 110(2008)] 072010]

ATLAS

- Possible to probe up to Λ=10 TeV with ~700 pb^{-1} of data (*Dijet angular distribution study*) [JPCS 110(2008)] 072010]
- With $\gamma + jet$ final state, Mq* = 6.5 TeV can be discovered with 300 fb^{-1} of data (*Mass distribution of γ and jet*) [PRD 60(1999)034004]

Other Studies

- Top compositeness: Possible to probe up to Λ= 2TeV at LHC in pp → t t t-bar t-bar channel (*H_T and Missing E_T*) [JHEP04(2008)087]
- Contact Interaction in diphoton final state: Λ± > 2.81(3.24) TeV possible with 100 (200) fb^{-1} (*Mass Distribution*) [PRD 51 (1995)1064]

Signal and Bkg. Generation

γ+*jet* Case:

Generation of Signal and Background

- pT-hat > 180 GeV, 450 GeV, 950 GeV (due to different mass points)
- Q^2= s-hat , CTEQ5L

Matrix elements of signal were incorporated inside PYTHIA

Signal

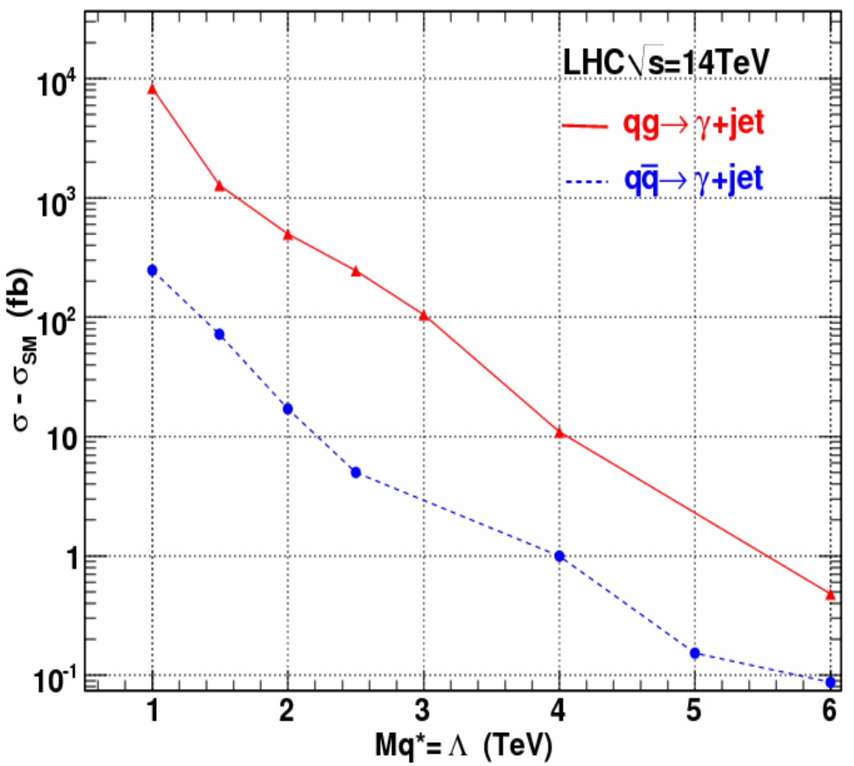
- qg→γ+jet (q*) and qqbar → γ+jet (q*) 11 Points were generated
- with standard coupling(f=1.0) and 5 points with coupling reduced to f=0.5
- Mass points considered from 1TeV- 6TeV

Backgrounds

1. SM γ+jet ← Background for $\gamma\gamma$ case along with SM $\gamma\gamma$
2. QCD di-Jets
3. W/Z(→jj) + γ

X-Section Vs Λ

New Physics Contribution



Width (GeV)

SN	Mq* (TeV)	Γ (q*) f =1.0	Γ (q*) f = 0.5
1	0.5	34.4	8.61
2	1.0	63.6	15.9
3	2.0	118	29.6
4	3.0	170	42.6
5	4.0	221	55.2
6	5.0	271	67.6
7	6.0	319	79.8
8	7.0	367	91.8

γ and *jet* candidates

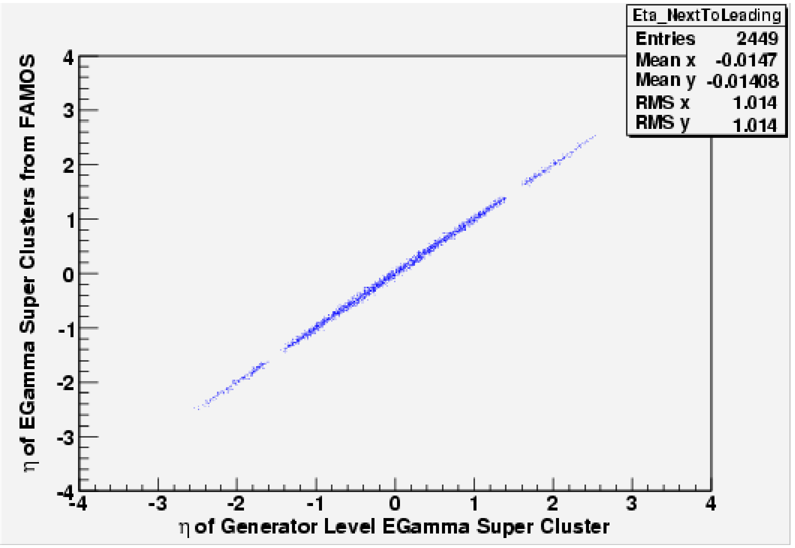
Jet Candidates:

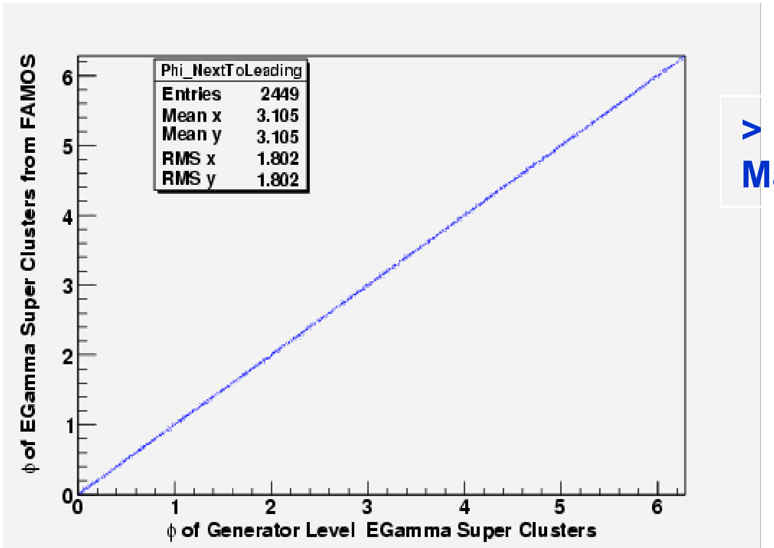
✓ Iterative Cone algorithm is used for jet formation with ΔR=0.5 and seed pT ≥ 1 GeV

Photon Candidates:

✓ Final states em objects are selected as seed with pT> 5 GeV and looked in 10X10 crystal size (i.e. Δη=0.09 & ΔΦ=0.09) around the seed. All em object's 4-mometa are added vectorally to form *photon candidates*. **[CMS IN 2005/018]**

Fake photons (generator level) are matched with fast detector simulated fake photons (old FAMOS)





> 95 % Matched

Smearing Effect

For CMS Set-up

For Photon

$$\frac{\delta E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{a_n}{E} \oplus C$$

$$C = 0.55\%$$

$$a_n = \begin{cases} 2.1 \times 10^{-3}\,\text{GeV} & |\eta| < 1.5 \\ 2.45 \times 10^{-3}\,\text{GeV} & 1.5 \leq |\eta| \leq 2.5 \end{cases}$$

$$a = \begin{cases} 2.7 \times 10^{-2}\,\text{GeV}^{1/2} & |\eta| < 1.5 \\ 5.7 \times 10^{-2}\,\text{GeV}^{1/2} & 1.5 \leq |\eta| \leq 2.5 \end{cases}$$

For high pT(> 100 GeV) Const. term is dominating

For Jet

- Barrel:

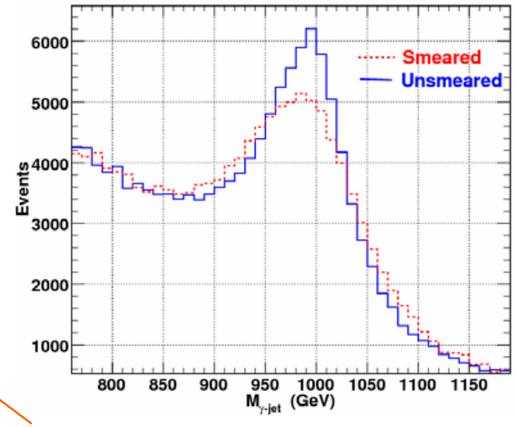
$$\frac{\delta E}{E} = \frac{65\%}{\sqrt{E/\,\text{GeV}}} \oplus 5\%, \Delta\eta = 0.04, \Delta\phi = 0.02$$

- Endcaps:

$$\frac{\delta E}{E} = \frac{83\%}{\sqrt{E/\,\text{GeV}}} \oplus 5\%, \Delta\eta = 0.03, \Delta\phi = 0.02$$

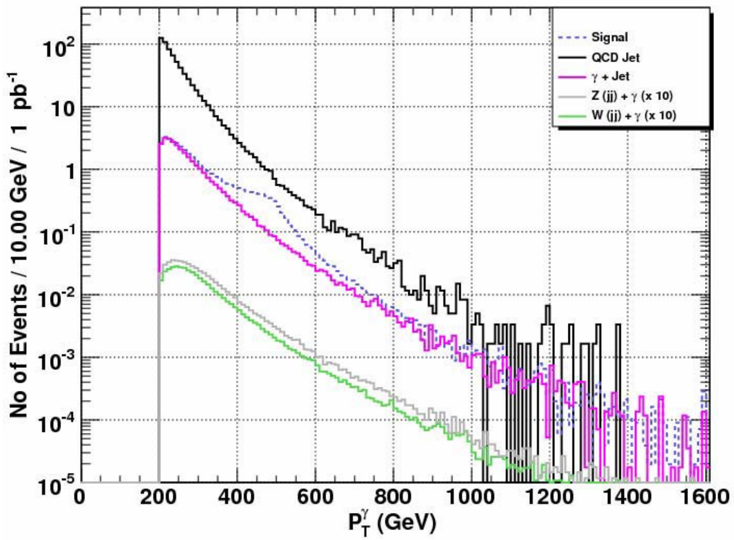
- Forward region:

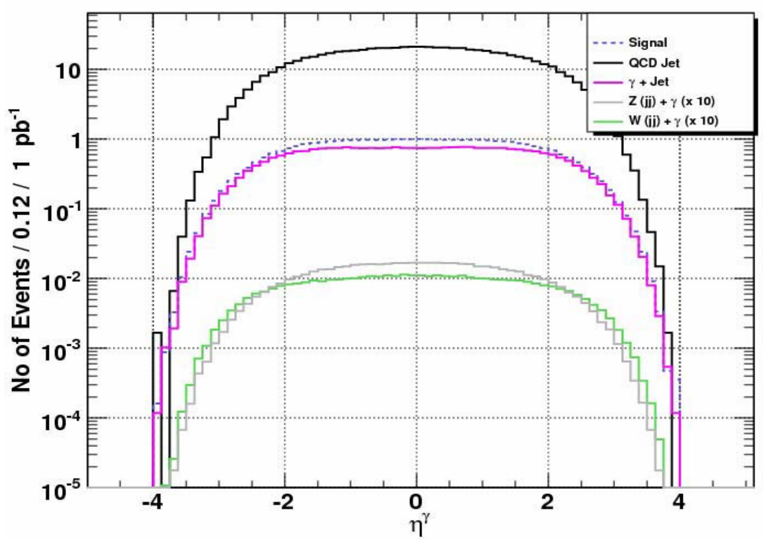
$$\frac{\delta E}{E} = \frac{100\%}{\sqrt{E/\,\text{GeV}}} \oplus 5\%, \Delta\eta = 0.04, \Delta\phi = 0.04$$

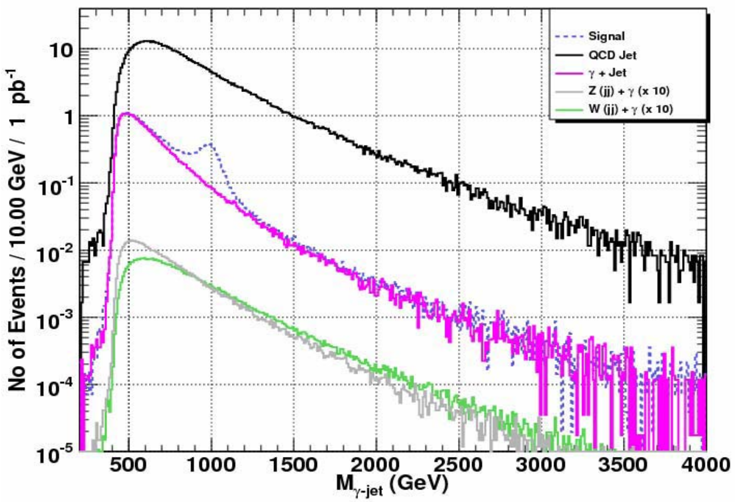


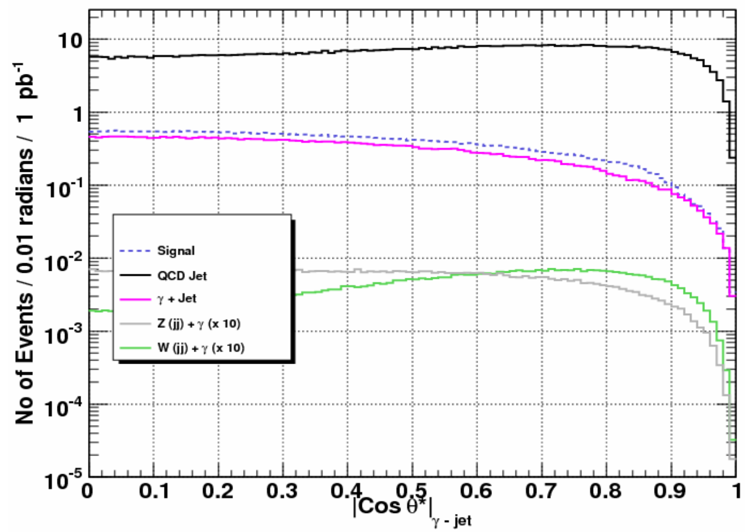
[CMS AN 2008/001]

Kinematical Distributions



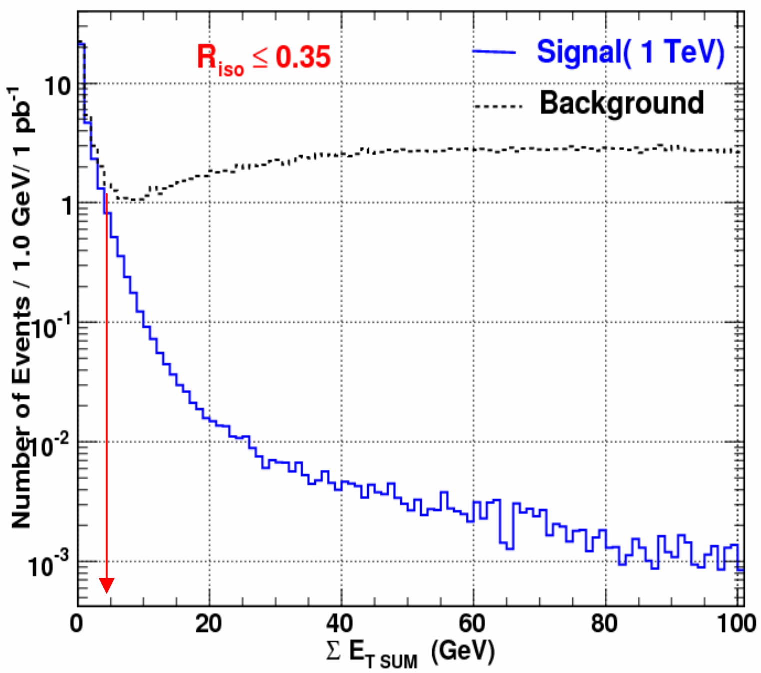


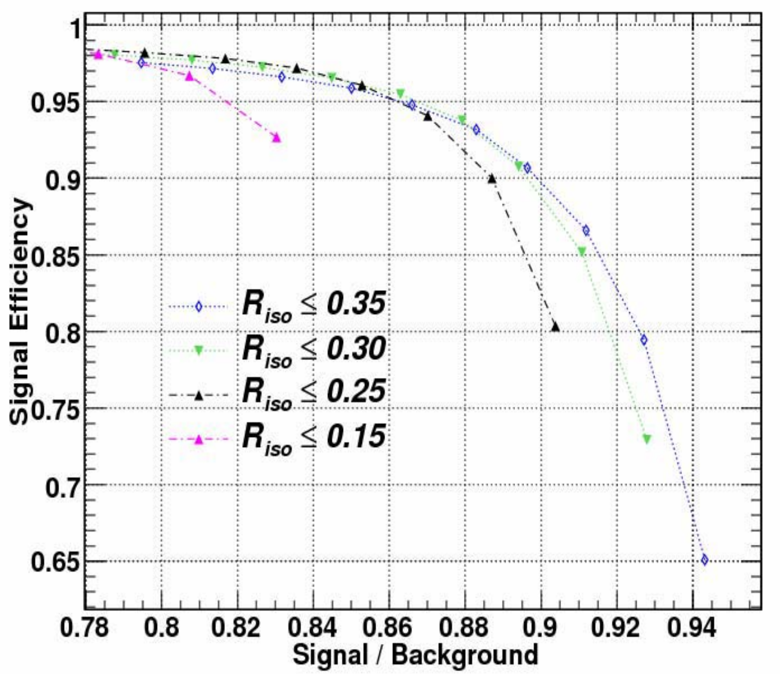




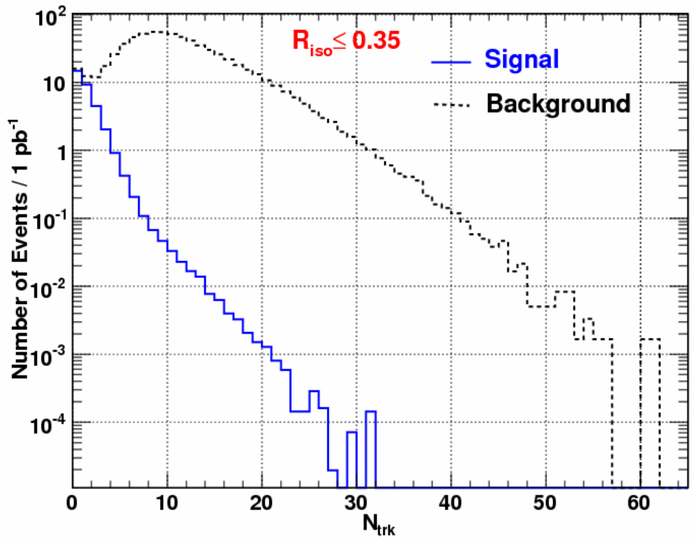
Isolation Variables

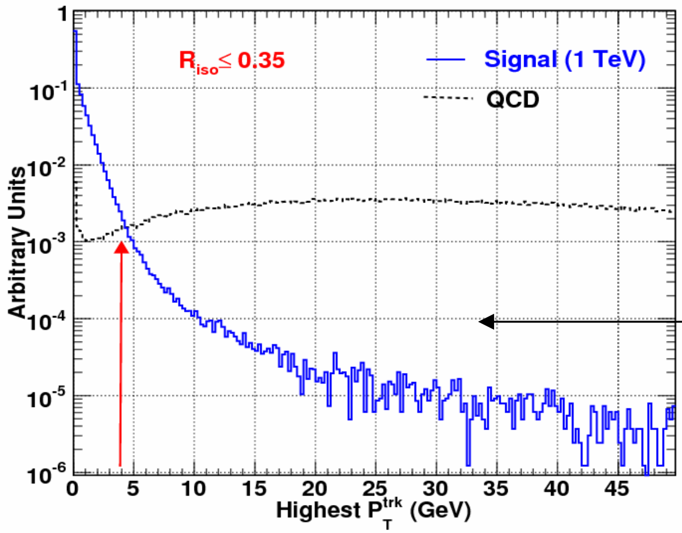
- ✓ Number of tracks (N_{trk}) in a cone around the photon
  - ✓Mini. pT of track (pT_{trk}) to count it as a *track*
- ✓ Scalar sum of transverse energy (E_{Tsum}) around the photon in a cone
- ✓ Isolation cone size (R_{iso}) around the photon

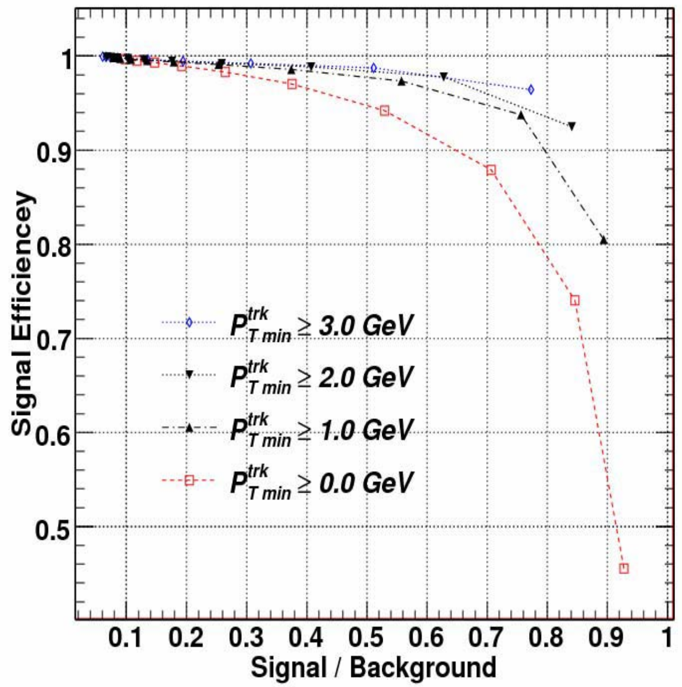




Isolation Variables







To decided min Track pT (found similar result with other Mq* points)

Final Selection Cuts

Kinematical:

- $pT^{\gamma} \geq 200$ GeV, 500GeV, 1TeV
- $pT^{jet} \geq 200$ GeV, 500GeV, 1TeV

(For different Mq* point)

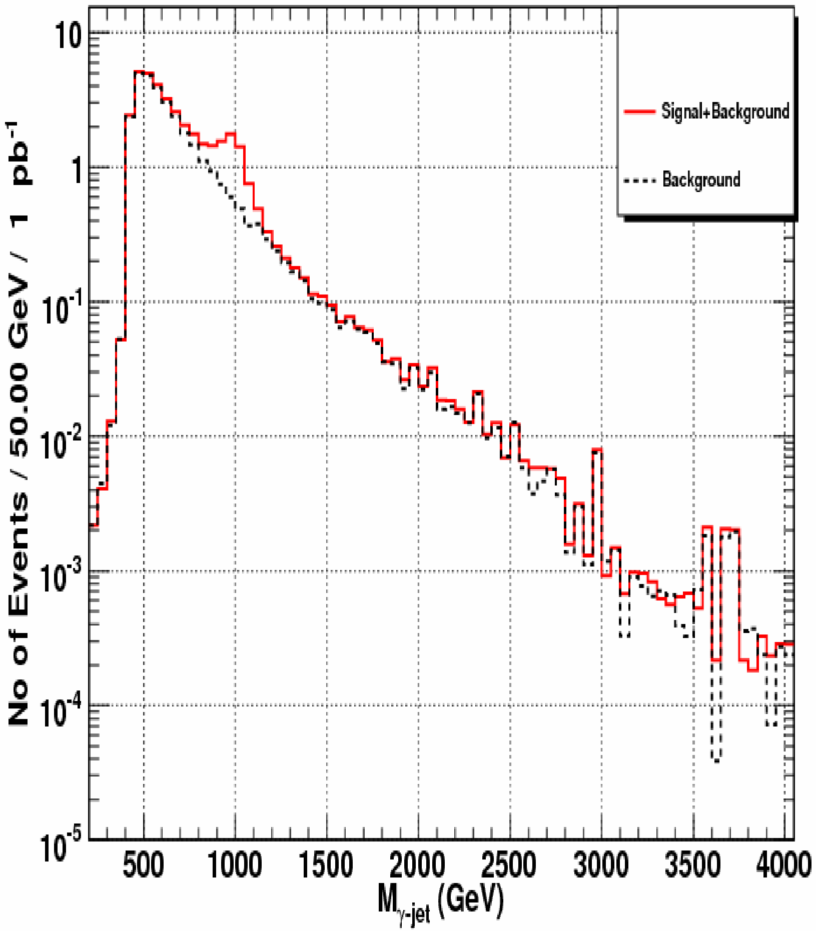
- $|\eta^{\gamma}| \leq 2.5$ and excluding Barrel-Endcap transition region
- $|\eta^{jet}| \leq 3.0$
- $\Delta M_{\gamma j} \approx Mq^* \pm 3\Gamma(q^*)$

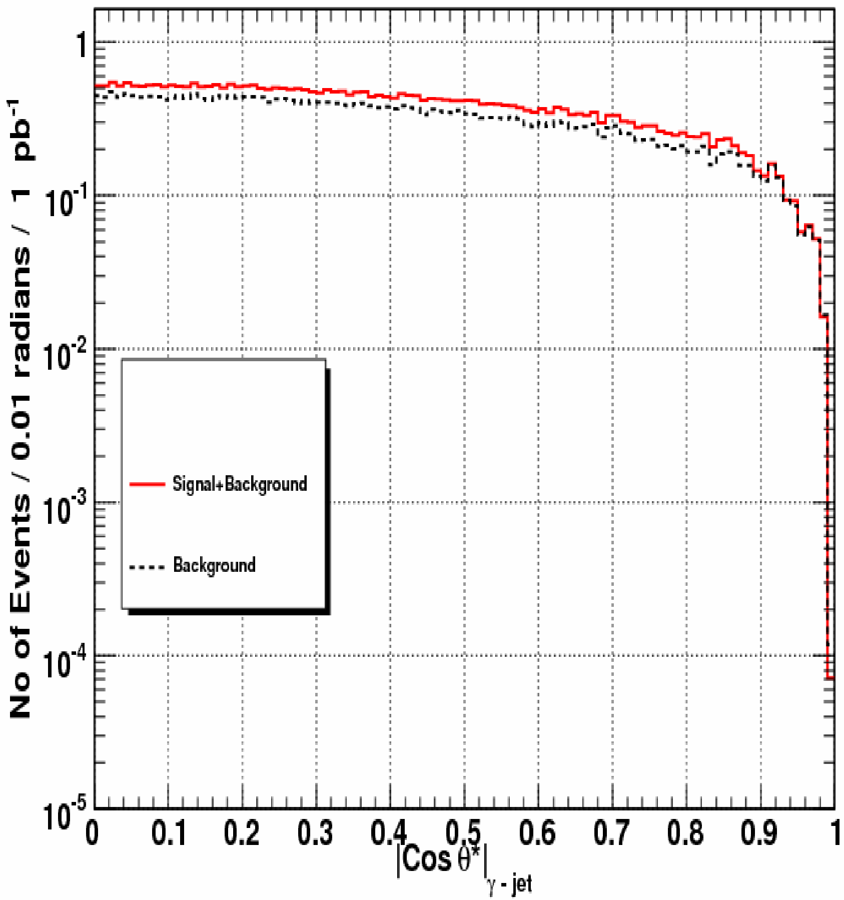
Isolation:

- $\Delta R_{iso} \leq 0.35$
- $N_{trk} = 0$ where tracks are counted if $pT_{trk} \geq 3.0$ GeV
- $E_{T_{sum}} < 5.0$

✓ Also evaluated limits for $|\eta^{\gamma,j}| \leq 1.5$

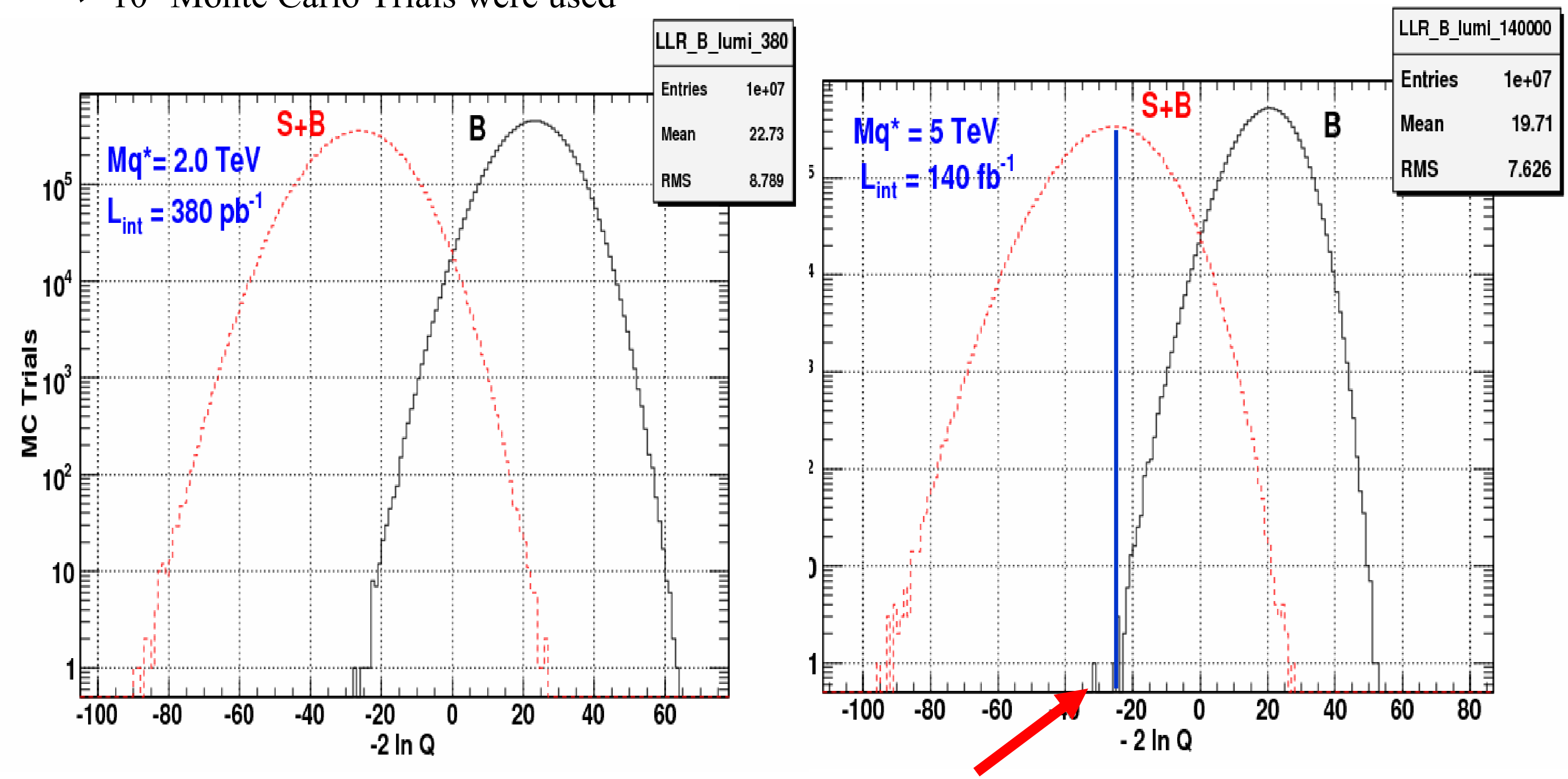
After All Cuts





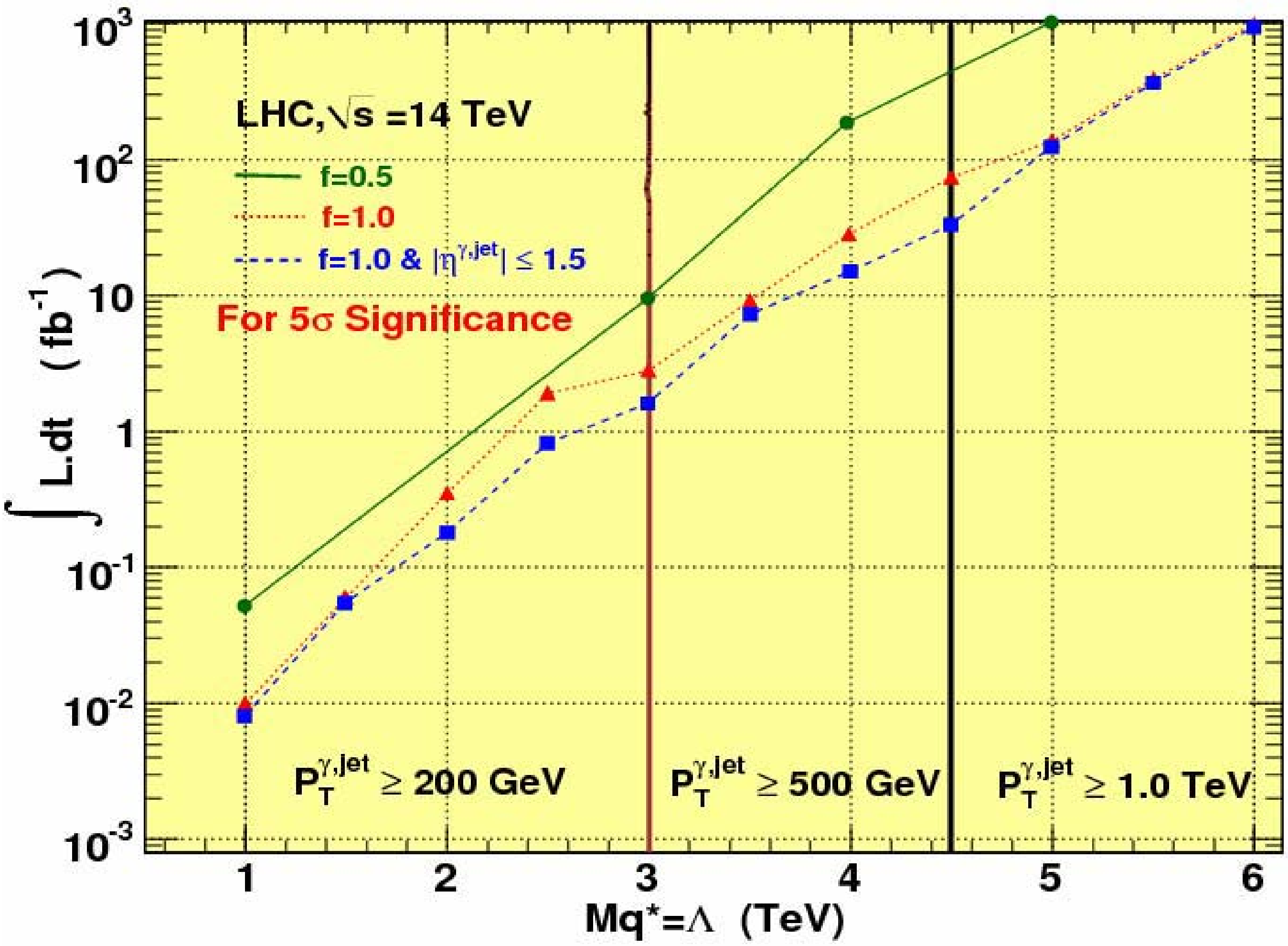
Log Likelihood Ratio (LLR)

- ✓ Test *statistics*: ***-2 ln Q***
- ✓ Consider $M_{\gamma j}$ discriminating variable for LLR
- ✓ 10^7 Monte Carlo Trials were used



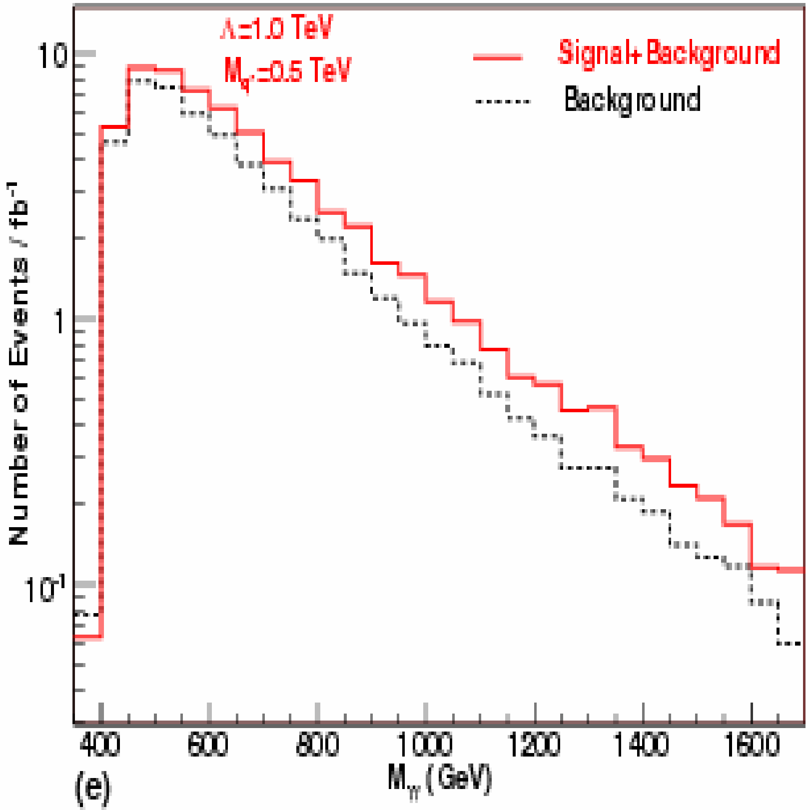
For "5σ", B-Type Fraction < 2.8 x 10^{-7}

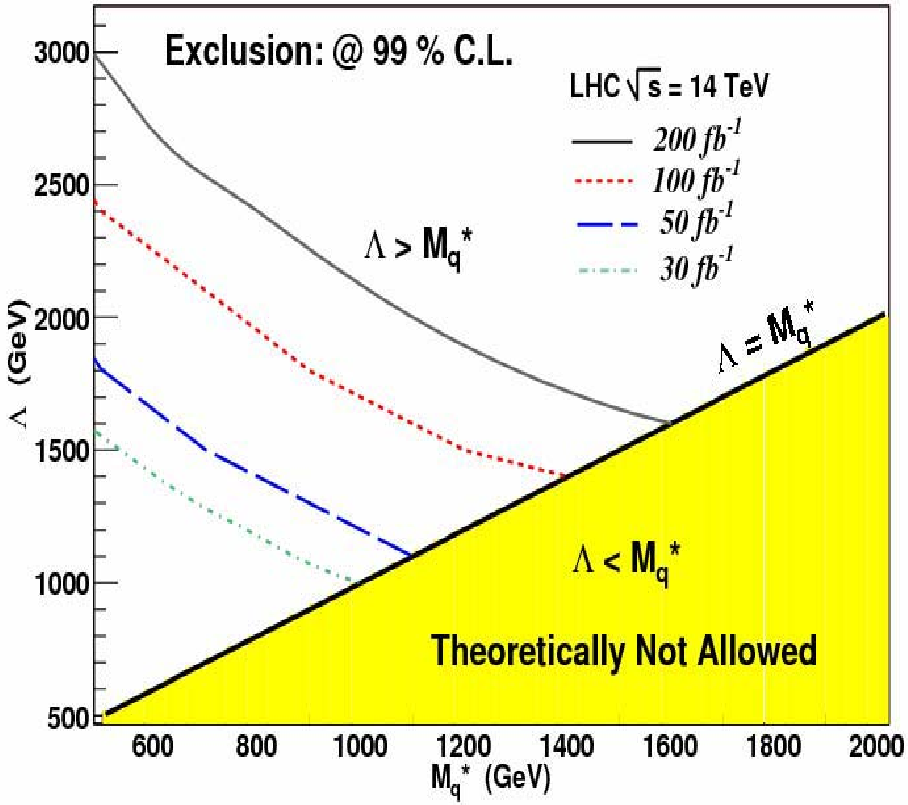
Result: γ+jet


LHC,√s =14 TeV
f=0.5
f=1.0
f=1.0 & |η^γ,jet| ≤ 1.5
For 5σ Significance
P_T^γ,jet ≥ 200 GeV
P_T^γ,jet ≥ 500 GeV
P_T^γ,jet ≥ 1.0 TeV
∫L.dt (fb^-1)
Mq*=Λ (TeV)
10^3
10^2
10
1
10^-1
10^-2
10^-3
1
2
3
4
5
6

Result: γγ final state

PRD 76,115017(2007)





✓**Mass range of 450- 1500 GeV is used to evaluate 99% CL limits**
✓**Weak dependence on stronger kinematical cuts**

Uncertainties-I

γ+jet Case: Similar estimates for $\gamma\gamma$ final state

PDFs

✓ We used MRST2001, CTEQ6L and CTEQ6M to compare with CTEQ5L

For Signal : CTEQ6L shows a decrease in X-Section up to 7 %
CTEQ6M and MRST2001 shows X-Section up by 2-12 %

For Backg.: With CTEQ6L the X-Section can decrease by 12 %
CTEQ6M and MRST2001 shows X-Section up by 2-12 %

- Uncertainty due to Errors on Fit Parameters of PDF

Signal: ± 10%, QCD dijet: ± 13%, $\gamma + jet$ (SM):±10%

Scale (Q^2)

✓ Signal X-Section: use of – t_hat or pT^2 gives +(2-20) % compare to s-hat. Although the shape of the distribution do not change significantly (check with pT^2 and s-hat)

✓ Background X-Section: Corresponding numbers are +(5-39) %
Here the main uncertainties comes from QCD di-jets. For $qg \rightarrow \gamma + jet$ it is up to 22 %

Uncertainties-II

LLR uncertainties:

- ✓ Bin width of $M_{\gamma j}$ affects sensitivity negligibly above 99 % CL (compared with 20 GeV, 50 GeV and 100 GeV bin width)
- ✓ # of MC Trials have ~1% effects on discovery limits

Jet Energy Resolution:

- ✓ If we increase jet energy resolution to 100 % in Barrel and Endcap and 150 % in Forward region then it changes the $\int L.dt$ by ~2% for 5σ significance

Effect of Uncertainties:

- ✓ 5% decrease in signal x-section increases the required luminosity for 5σ-significance by ~11%
- ✓ 5% increase in background x-section increases the required luminosity for 5σ by ~9%

Conclusions-I

γ+*jet* Case:

- ✓ **With ~ 200 pb^{-1} up to Λ= 2 TeV q* state can be discovered at LHC**
- ✓ **With 2fb^{-1}, probe up to Λ= 3 TeV is possible with $|\eta^{\gamma,jet}| \leq 1.5$**
- ✓ **Central η region gives better chance of discovery up to 4 TeV**
- ✓ **Beyond 5.5 TeV 3σ evidence is possible**
- ✓ **If coupling strength is f=0.5 still Mq* up to 4 TeV is possible to discover at LHC**

Conclusions-II

$\gamma\gamma$ Final State Case:

- ✓ **With ~ 30 fb^{-1} of integrated luminosity, Mq*= 0.5TeV and Λ=1.55 TeV can be excluded at 99% CL**

- ✓ **Mq*=Λ=1.6 TeV can be excluded at 99% CL with 200fb^{-1} of luminosity**

- ✓ **Complementary to direct searches e.g. dijet and γ+jet mass peak searches**

Thank You

Backup Slides

Couplings to SM q and g

Couplings to SM q, g and γ

$$\overline{q^*}\, q\, \gamma_\mu(p): \quad \frac{e\, e_q\, f_1}{\Lambda} \left(1 + \frac{Q^2}{\Lambda^2}\right)^{-n_1} \sigma_{\mu\nu}\, p^\nu$$

$$\overline{q^*}\, q\, g_\mu(p): \quad \frac{g_s f_3}{\Lambda} \left(1 + \frac{Q^2}{\Lambda^2}\right)^{-n_3} \sigma_{\mu\nu}\, p^\nu\, T_\alpha$$

- ✓n1=n3=1 for unitarity condition
- ✓F1=f3= 1 for Standard couplings

Background and X-sections

Cross Section (pb) for backgrounds in different P_T-hat bin

Type-1: SM γ+jet Background – Non-Reducible

Pt – hat	50-100 GeV	100-200 GeV	200-400 GeV	400-600 GeV	600-1000 GeV	1000-1500 GeV	>1500 GeV
qg	4458	425.3	33.2	1.517	2.22×10^{-1}	1.19×10^{-2}	7.6×10^{-4}
qqbar	375.4	47.44	5.01	3.15×10^{-1}	5.66×10^{-2}	3.77×10^{-3}	2.77×10^{-4}
gg	1.528	8.01×10^{-2}	3.08×10^{-3}	7.02×10^{-5}	6.33×10^{-6}	1.75×10^{-6}	5.81×10^{-9}

Interested above 200 GeV onwards.

Background and X-Section

Type-2: From Z(jj)+γ & W(jj)+γ - small & reducible but comparable to gg → γ+jet)

Pt –hat	50-100 GeV	100-200 GeV	200-400 GeV	400-600 GeV	600-1000 GeV	1000-1500 GeV	>1500 GeV
Z(jj)+γ	2.80	6.18×10^{-1}	8.61×10^{-2}	6.18×10^{-3}	1.20×10^{-3}	8.47×10^{-5}	$6.54 X 10^{-6}$
W(jj)+γ	2.54	4.81×10^{-1}	6.06×10^{-2}	4.09×10^{-3}	7.39×10^{-4}	4.68×10^{-5}	2.9×10^{-6}

Type-3: SM Jet-Jet background where one of the Jet(s) fakes a Photon – Largest Background – Reduce with isolation requirements

Cross-Section

S.N	Mq* (TeV) qg→γ+jet via (q*)	Pre-Selected Events	σ (pb)
1	1.0	500 k	67.29
2	1.5	500 k	60.64
3	2.0	500 k	59.46
4	2.5	500 k	59.20
5	3.0	500 k	59.00

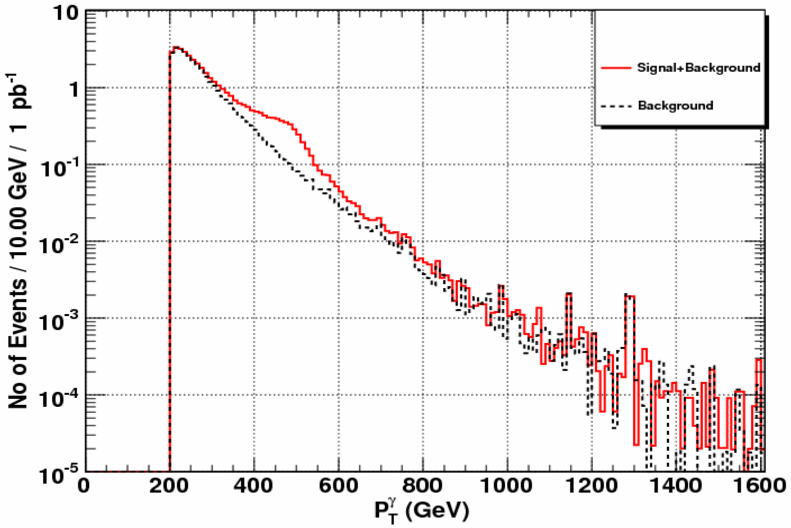
S.N	Process	Pre-Selected Events	σ (pb)
1	QCD Jet	404761	74770
2	qg→γ+Jet qqbar→γ+Jet gg → γ+Jet	241853 211808 157868	58.96 8.789 $5.43\ 10^{-3}$
3	Z(jj)+ γ	197137	$1.47\ 10^{-1}$
4	W(jj) + γ	203203	$1.08\ 10^{-1}$

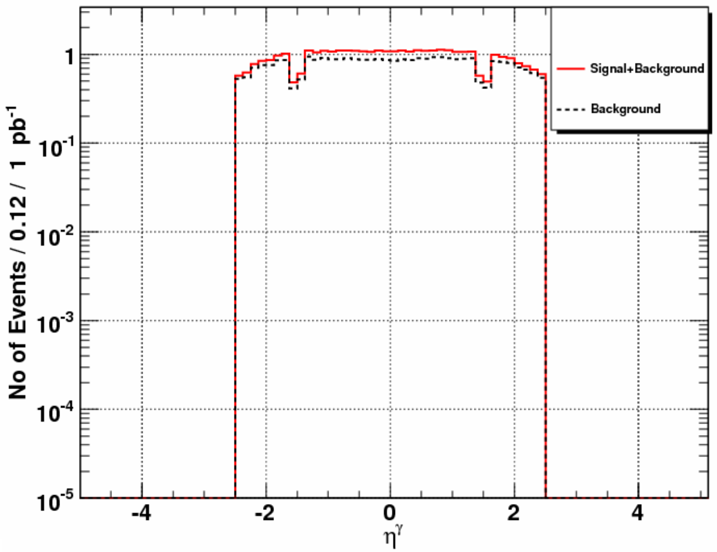
Pre-Selection: pT ≥ 200 GeV, 500 GeV, 1 TeV

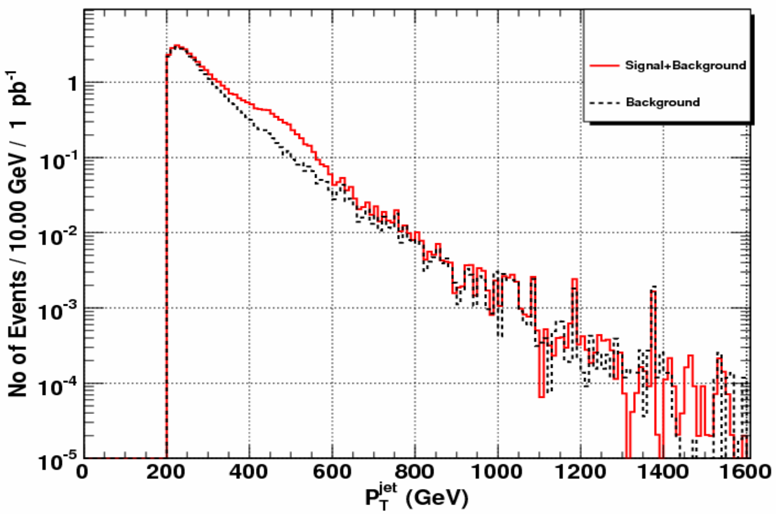
Preselection & Geometrical Acceptance

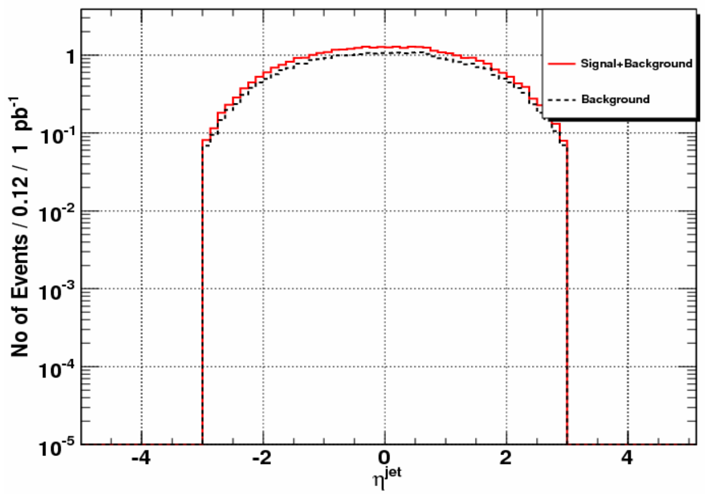
Selection Cut	Signal (%)	γ+Jet (%)	QCD (%)	Z+γ (%)	W+γ (%)
pT ≥ 200 GeV	48.69 (1 TeV)	44.22	0.9	38.39	37.14
$\lvert\eta^{\gamma}\rvert$<2.5, BE-Gap , $\lvert\eta^{j}\rvert$≤3.0	42.41	38.19	0.81	32.8	33.22
pT ≥500 GeV	40.19 (4 TeV)	39.8	0.41	50.43	50.57
$\lvert\eta^{\gamma}\rvert$≤2.5, BE-Gap , $\lvert\eta^{j}\rvert$≤3.0	38.22	37.83	0.39	47.42	48.41
pT ≥ 1000 GeV	47.42 (5 TeV)	46.02	0.51	58.84	59.86
$\lvert\eta^{\gamma}\rvert$ ≤2.5, BE-Gap , $\lvert\eta^{j}\rvert$≤3.0	46.42	45.04	0.50	56.30	58.73

After All Cuts



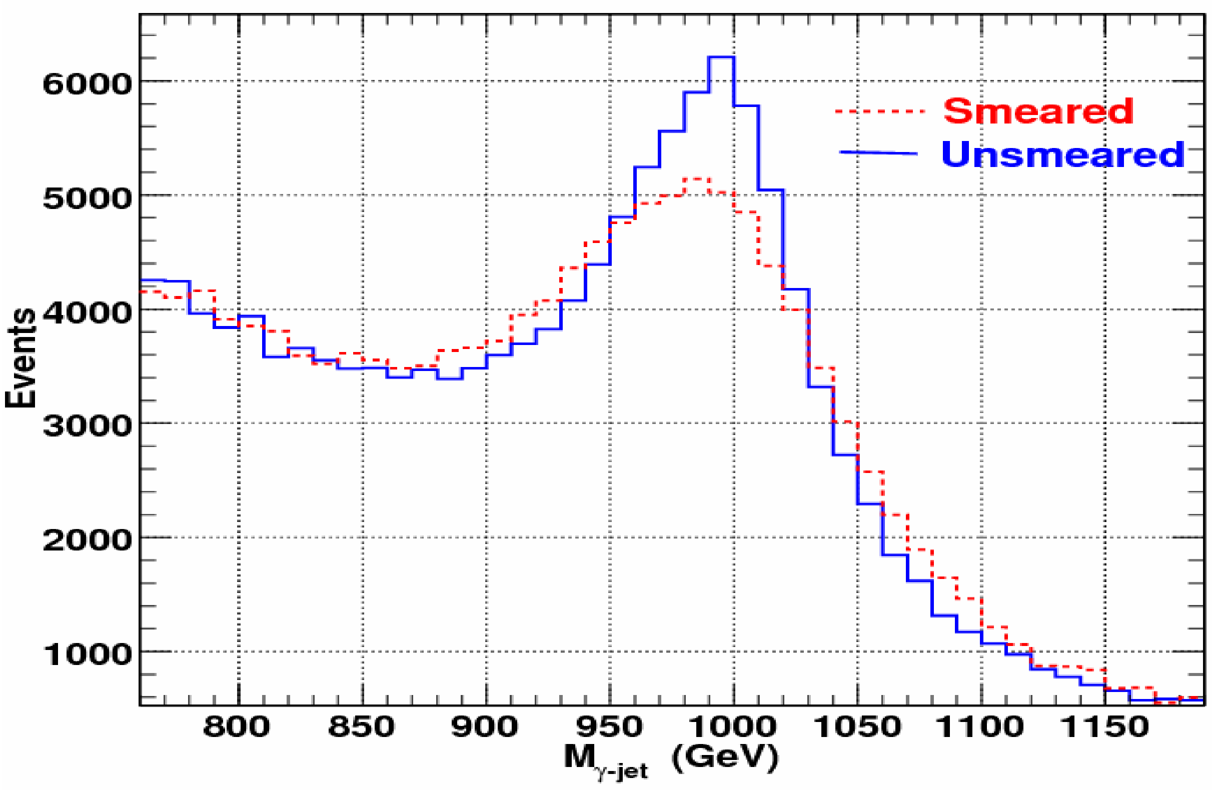






Smearing Effects on Mass

- Smeared the 4-momentas of Photon and Jets.



Results

Mq*	Mass Window (GeV) ~ 3* Γ (q*)	σ (S+B) pb	σ (B) pb	σ (S*) pb	"5-Sigma" Discovery Luminosity
1.0 TeV	800-1200	9.27	4.92	4.34	~ 15 pb^{-1}
1.5 TeV	1200-1800	2.03	1.34	0.695	~ 60 pb^{-1}
2.0 TeV	1600-2400	0.672	0.511	0.162	~ 380 pb^{-1}
3.0 TeV	2450-3550	0.078	0.064	0.014	~2.8 fb^{-1}
4.0 TeV	3300-4700	4.90 x 10^{-3}	3.40 x 10^{-3}	1.50 x 10^{-3}	~ 28 fb^{-1}
5.0 TeV	4100-5850	4.60 x10^{-4}	2.47 x 10^{-4}	2.12 x 10^{-4}	~ 140 fb^{-1}
5.5 TeV	4500-6450	2.18 x 10^{-4}	1.30 x 10^{-4}	8.82 x 10^{-5}	~ 350 fb^{-1}
6.0 TeV	5000-7000	8.40 x 10^{-5}	5.14 x 10^{-5}	3.25 x 10^{-5}	≥ 10^3 fb^{-1}

Results: With $|\eta^{\gamma, j}| \leq 1.5$

Mq*	Mass Window (GeV) ~3 Γ(q*)	σ (S+B) pb	σ (B) pb	σ (S*) pb	"5-Sigma" Disc. Luminosity
1.0 TeV	800-1200	4.75	2.14	2.61	~ 8 pb^{-1}
1.5 TeV	1200-1800	0.871	0.416	0.456	~ 54 pb^{-1}
2.0 TeV	1600-2400	0.227	0.110	0.116	~ 180 pb^{-1}
3.0 TeV	2450-3550	2.21×10^{-2}	1.27×10^{-2}	9.4×10^{-3}	~ 1.6 fb^{-1}
4.0 TeV	3300-4700	2.65×10^{-3}	1.30×10^{-3}	1.34×10^{-3}	~ 15.0 fb^{-1}
5.0 TeV	4100-5850	3.99×10^{-4}	2.00×10^{-4}	1.98×10^{-4}	~ 123.0 fb^{-1}
5.5 TeV	4500-6450	1.79×10^{-4}	9.78×10^{-5}	8.15×10^{-5}	~ 340.0 fb^{-1}
6.0 TeV	5000-7000	6.51×10^{-5}	3.44×10^{-5}	3.07×10^{-5}	~ 920 fb^{-1}

Considerable Improvement compare to larger η region

Results: f=0.5

Mq*	Mass Window (GeV) ~3 Γ(q*)	σ (S+B) pb	σ (B) pb	σ (S*) pb	"5-Sigma" Discovery Luminosity
1.0 TeV	940-1060	2.18	1.31	0.873	~50 pb^{-1}
3.0TeV	2860-3140	1.74×10^{-2}	1.43×10^{-2}	3.04×10^{-3}	~ 9.4 fb^{-1}
4.0 TeV	5820-4180	8.46×10^{-4}	5.98×10^{-4}	2.48×10^{-4}	~180 fb^{-1}
5.0 TeV	4780-5220	7.36 x 10-5	4.07 x 10-5	3.30 x 10-5	≥ 10^{3} fb^{-1}
6.0 TeV	5740-6260	1.34×10^{-5}	8.63×10^{-6}	4.79×10^{-6}	NOT POSSIBLE

s/√b Vs llr

f =1.0

Mq*	LLR Significance	S/√b
1.0 TeV	5.0	7.5
1.5 TeV	5.0	4.64
2.0 TeV	5.0	4.4
3.0 TeV	5.0	3.0
4.0 TeV	5.0	4.3
5.0 TeV	5.0	5.0
5.5 TeV	5.0	4.57
6.0 TeV	5.0	4.52

f = 0.5

Mq*	LLR Significance	S/√b
1.0 TeV	5.0	5.3
3.0 TeV	5.0	2.46
4.0 TeV	5.0	4.3
5.0 TeV	5.0	5.1
6.0 TeV	----	----

Efficiency (f =1.0)

Mq* (TeV)	ε (S+B) %	ε (B) %	ε* (S) %
1.0	1.30	0.70	60.28
1.5	0.29	0.19	46.71
2.0	0.10	0.07	37.23
2.5	0.036	0.03	40.67
3.0	0.011	0.01	75.95
3.5	0.27	0.17	24.7
4.0	0.121	0.084	15.60
4.5	0.055	0.039	11.48
5.0	0.63	0.34	22.49
5.5	0.30	0.18	14.91
6.0	0.11	0.07	7.85

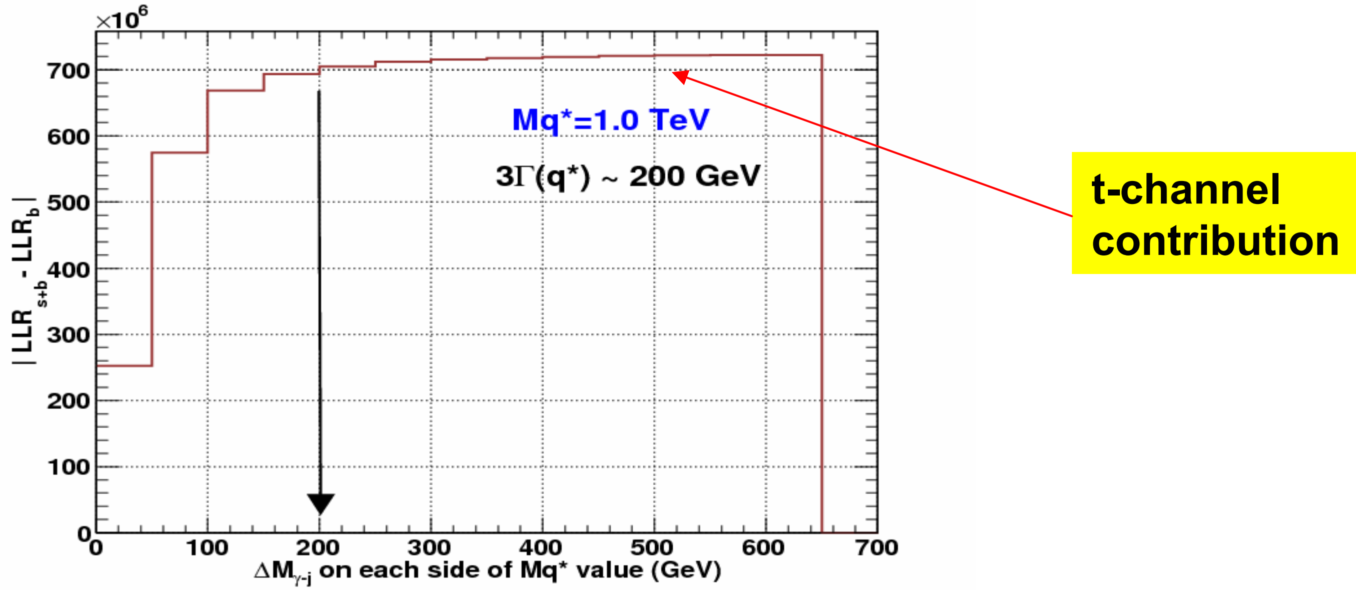
Bands are for 3-different phase space region (namely : pT> 200 GeV, 500 GeV and 1 TeV)

*Pure New Physics

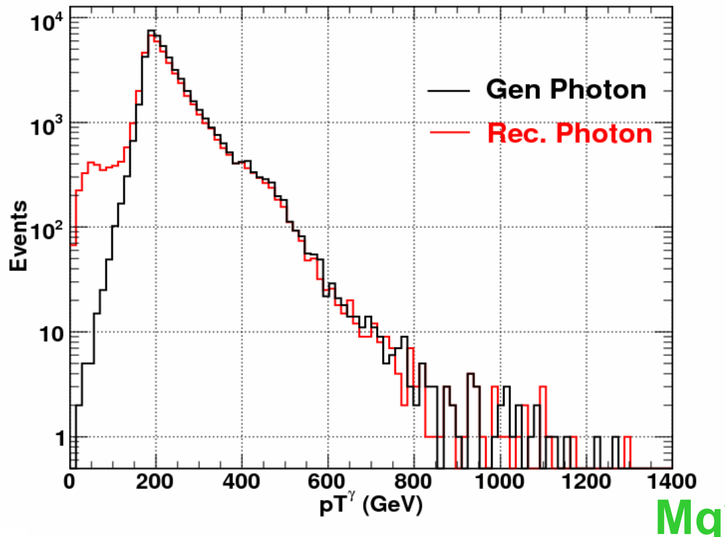
Mass Window Selection

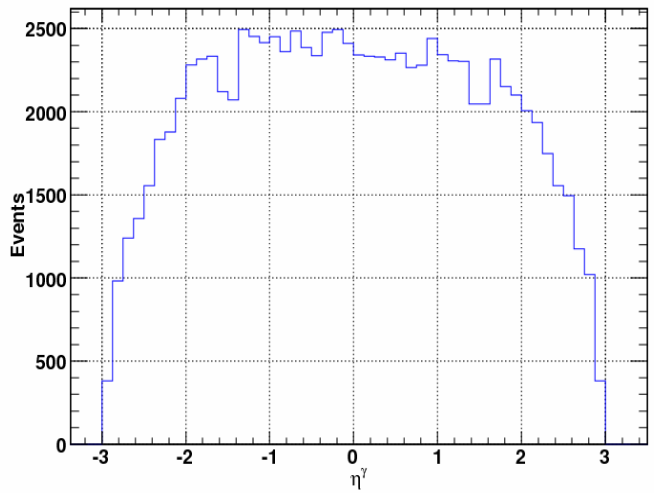
Test Statistics: $-2lnQ = 2\sum_{i=1}^{n_{bins}} s_i - 2\sum_{i=1}^{n_{bins}} n_i ln(1+\frac{s_i}{b_i})$

- ✓ Instead of fitting sidebands of Mγj, we take the expected number of events as LLR input.
- ✓ So to decide the mass window we use LLR difference of S+B and B type-hypothesis (for luminosity at which B-Type rejection is 99 % CL!!) as guiding rule to decided $\Delta M_{\gamma j}$ size.

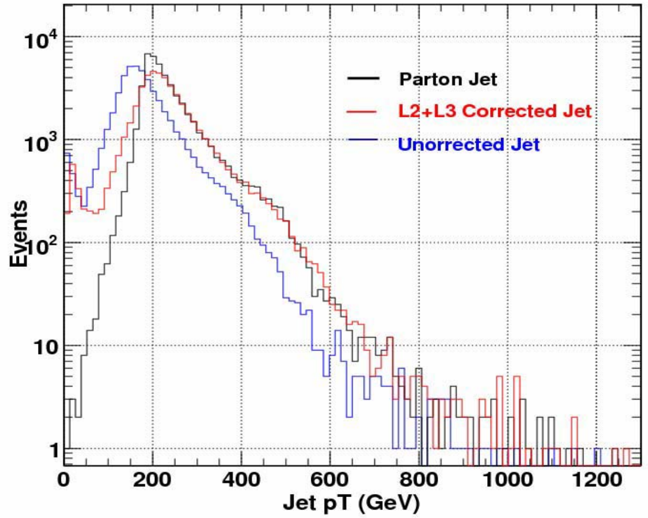


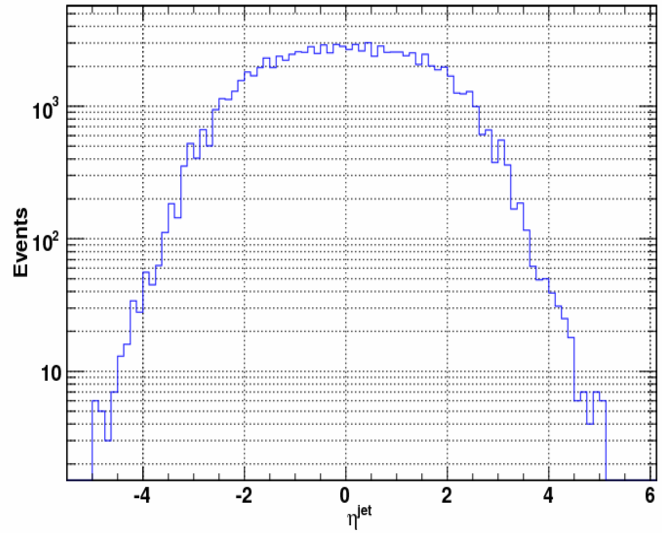
Distributions





Mq*= 1TeV





Distributions..