High Q^2 Events in ep Collisions

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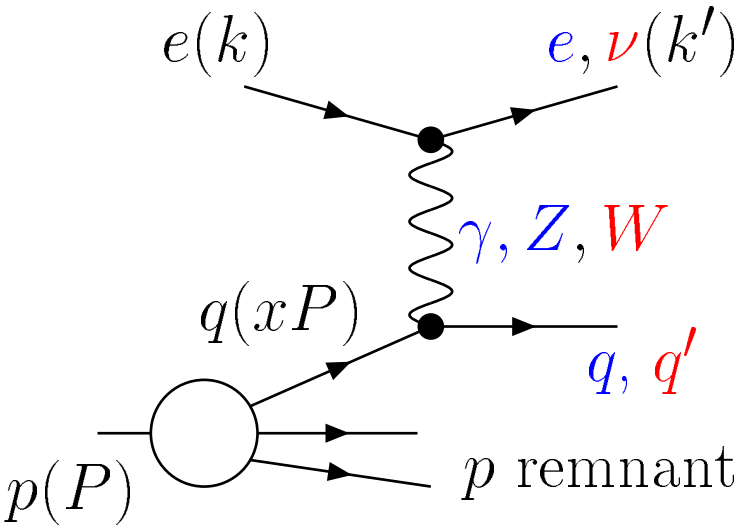
On behalf of the

Collaboration

DIS'97, 15 April 1997

- **Introduction**
- **Reconstruction of Neutral Current DIS Events**
- **Data Selection and Final Data Sample**
- **Systematic Uncertainties and Backgrounds**
- **Significance Analysis**
- **Conclusions**

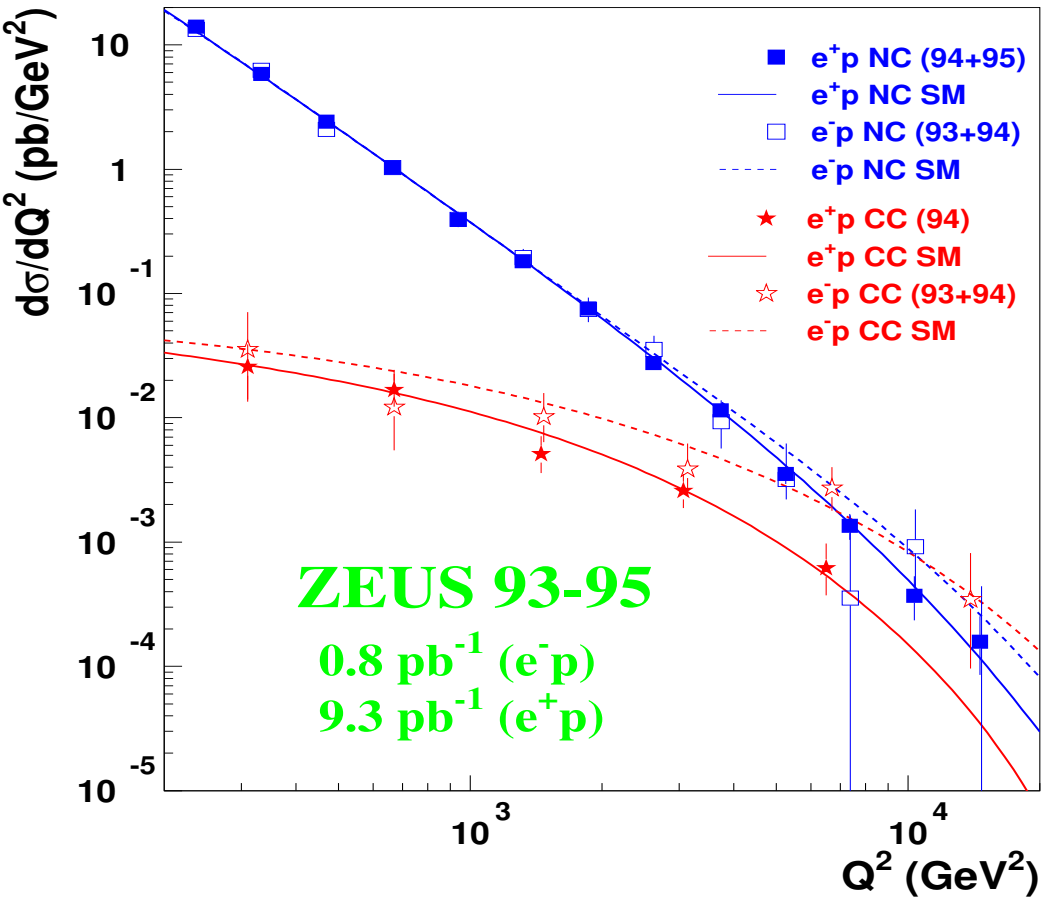
Deep Inelastic ep Scattering



$$Q^2 = -(k - k')^2$$

$$x = \frac{Q^2}{2P \cdot (k - k')}$$

$$y = \frac{P \cdot (k - k')}{P \cdot k}$$



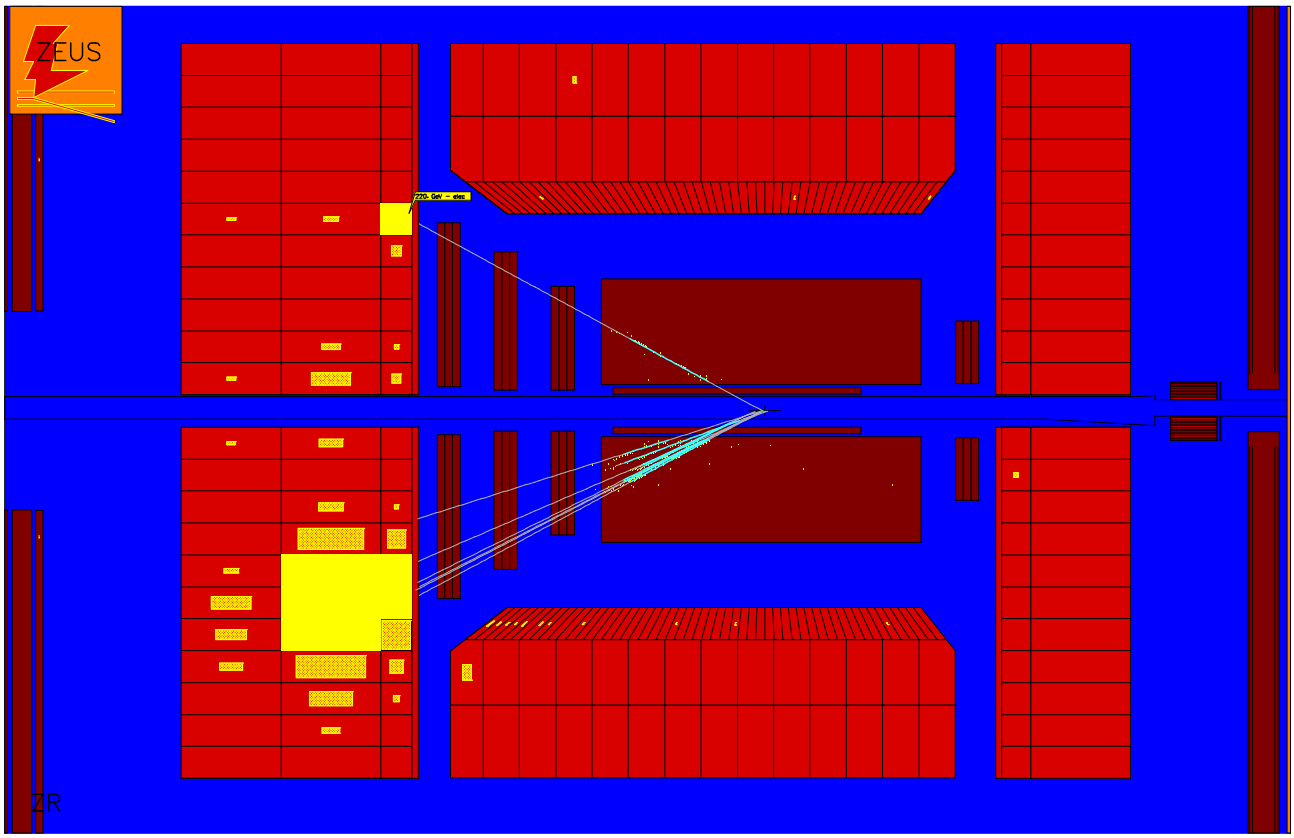
ZEUS 1994–1996 integrated luminosity = $20.1\,\text{pb}^{-1}$

$\rightarrow$ sensitive to $\sigma \sim 50$ fb

$\sqrt{s} = 300$ GeV, $x = 0.5 \rightarrow M = \sqrt{sx} = 212$ GeV

$Q^2 = 10000\,\text{GeV}^2 \rightarrow$ spatial resolution $= 2 \cdot 10^{-16}$ cm

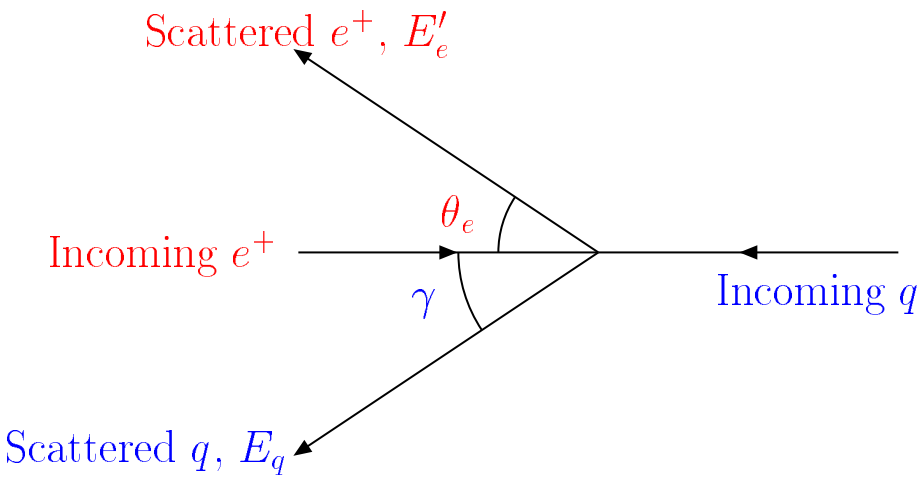
The ZEUS Detector



- **Calorimeter (CAL):**
  - Energy resolution: $\frac{\sigma(E)}{E} = \begin{cases} 18\%/\sqrt{E} & \text{em.} \\ 35\%/\sqrt{E} & \text{hadronic} \end{cases}$
  - Energy scale uncertainty: $\pm 3\%$

- **Central tracking detector (CTD):**
  - Angular acceptance: $15^\circ < \theta < 164^\circ$
  - Resolution: $\frac{\sigma(p_t^{\text{track}})}{p_t^{\text{track}}} = [0.005\, p_t^{\text{track}}\,(\text{GeV})] \oplus 0.016$
    (for full length tracks)

Kinematic Reconstruction



The Electron Method :

$$
\begin{aligned}
x_e &= \frac{E_e}{E_p}\,\frac{E'_e(1+\cos\theta_e)}{2E_e - E'_e(1-\cos\theta_e)} \\
y_e &= 1 - \frac{E'_e}{2E_e}(1-\cos\theta_e) \\
Q^2_e &= s\; x_e\; y_e
\end{aligned}
$$

simple
sensitive
to energy scale
uncertainties

The Double Angle Method :

$$
\begin{aligned}
x_{\mathrm{DA}} &= \frac{E_e}{E_p}\,\frac{\sin\gamma}{(1-\cos\gamma)}\,\frac{\sin\theta}{(1-\cos\theta)} \\
y_{\mathrm{DA}} &= \frac{\sin\theta_e(1-\cos\gamma)}{\sin\gamma + \sin\theta_e - \sin(\gamma+\theta_e)} \\
Q^2_{\mathrm{DA}} &= s\; x_{\mathrm{DA}}\; y_{\mathrm{DA}}
\end{aligned}
$$

insensitive to
energy scale
better
resolution
at low y

ZEUS uses the Double Angle Method

The Electron Method is used as a cross–check

Reconstruction of Event Variables

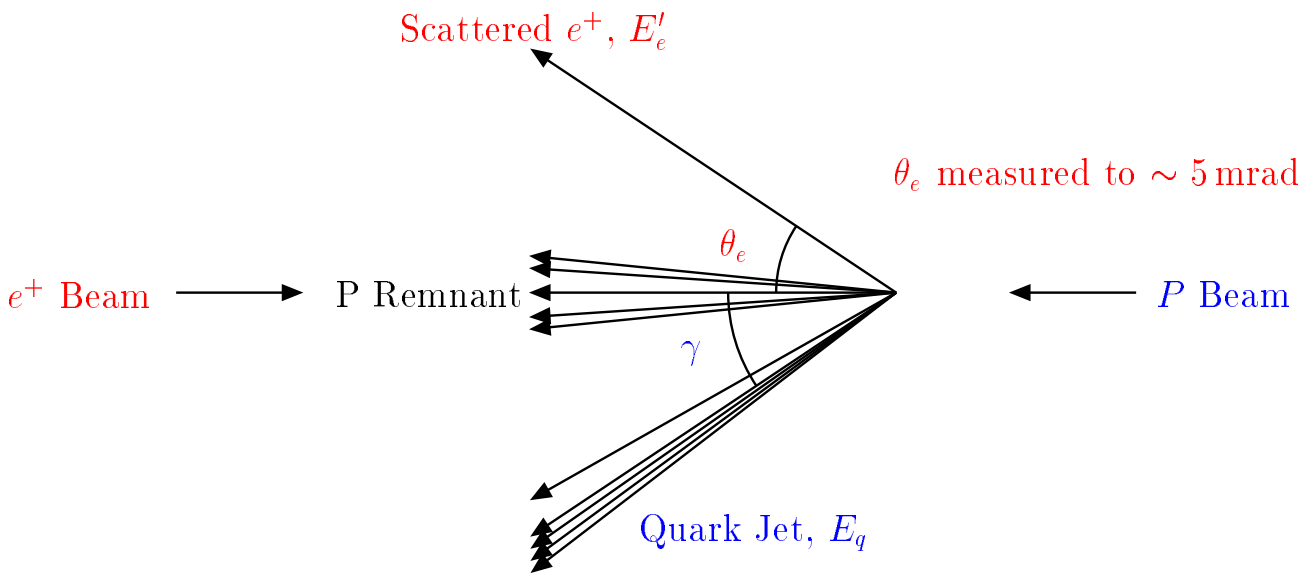
$$\cos\gamma_{\rm raw} = \frac{(p_t)^2_{\rm had} - (E - p_Z)^2_{\rm had}}{(p_t)^2_{\rm had} + (E - p_Z)^2_{\rm had}}$$

$$(p_t)_{\rm had} = \sqrt{\left(\sum_i{}' p^i_X\right)^2 + \left(\sum_i{}' p^i_Y\right)^2}$$

$$(E - p_Z)_{\rm had} = \sum_i{}' \left(E^i - p^i_Z\right)$$

$$E_q = \frac{(p_t)_{\rm had}}{\sin\gamma}$$

$\sum_i{}'$ = sum over all cells excluding e^+



$(E^i, p^i_X, p^i_Y, p^i_Z)$ = measured 4-momentum in calorimeter cell i.

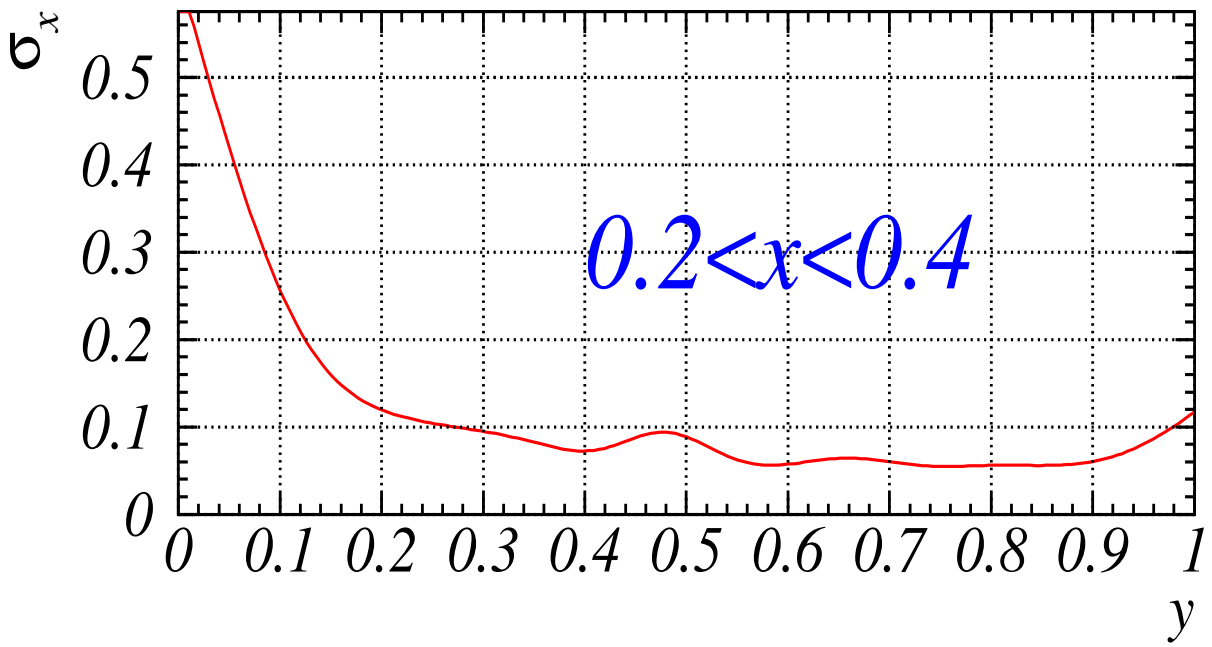
$$p_t = \sqrt{\left(\sum_i p^i_X\right)^2 + \left(\sum_i p^i_Y\right)^2}$$

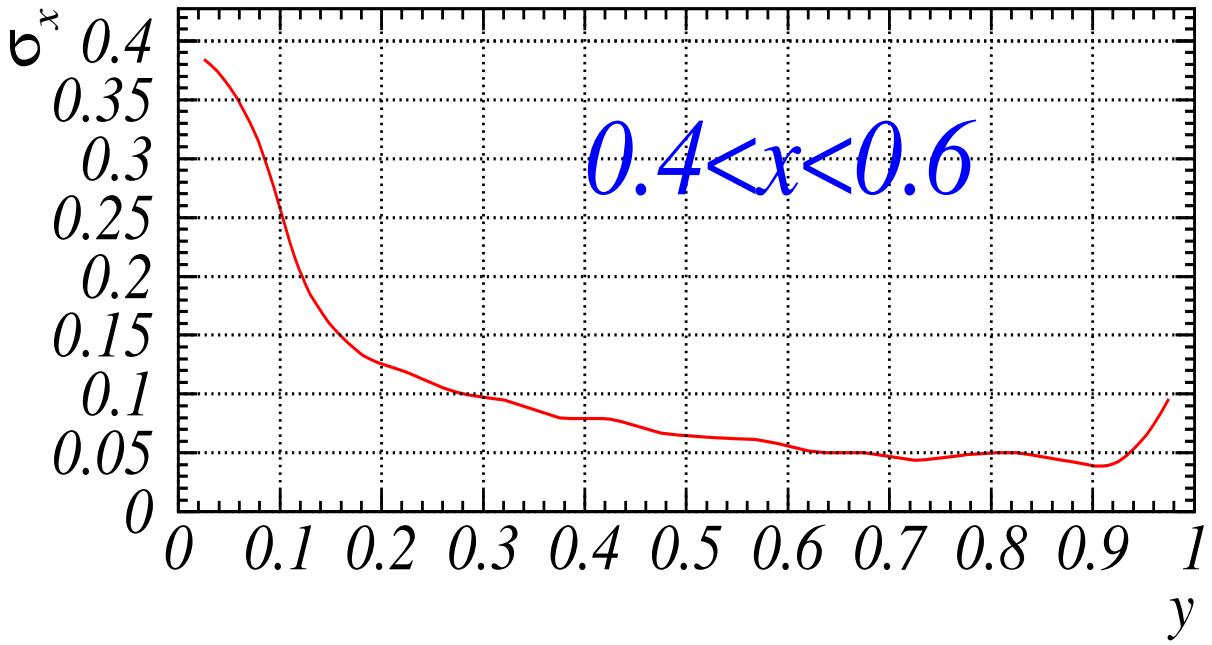
$$E - p_Z = \sum_i \left(E^i - p^i_Z\right)$$

$$E_t = \sum_i \sqrt{(p^i_X)^2 + (p^i_Y)^2}$$

$\sum_i$ = sum over all cells

Resolution of the Corrected $x_{\rm DA}$





σ_x = RMS of $\dfrac{x_{\rm DA} - x}{x}$

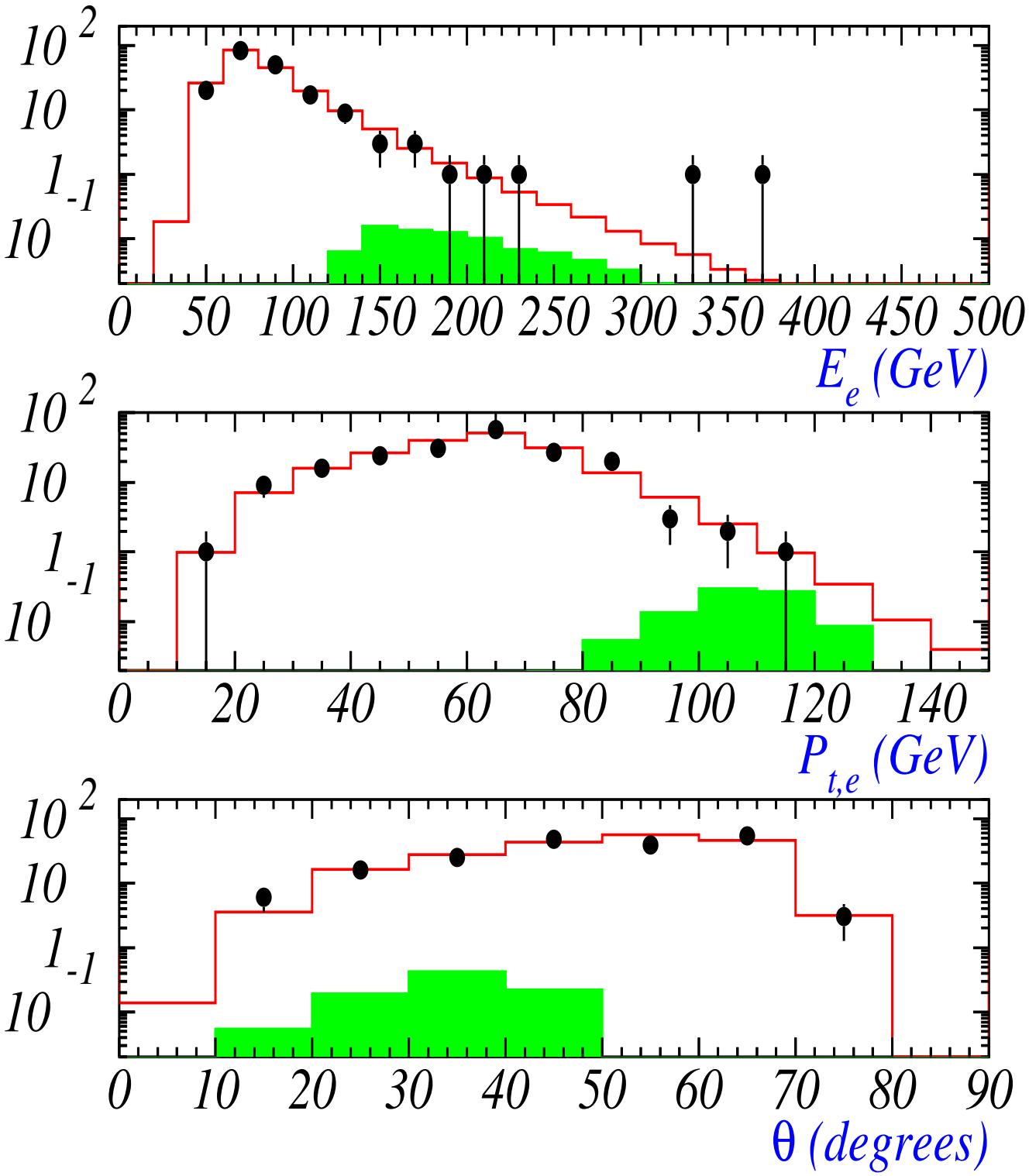
Effects of ISR are included.

Data Selection

Efficiencies are evaluated using NC MC events with $Q^2_{\text{true}} > 5000\,\text{GeV}$

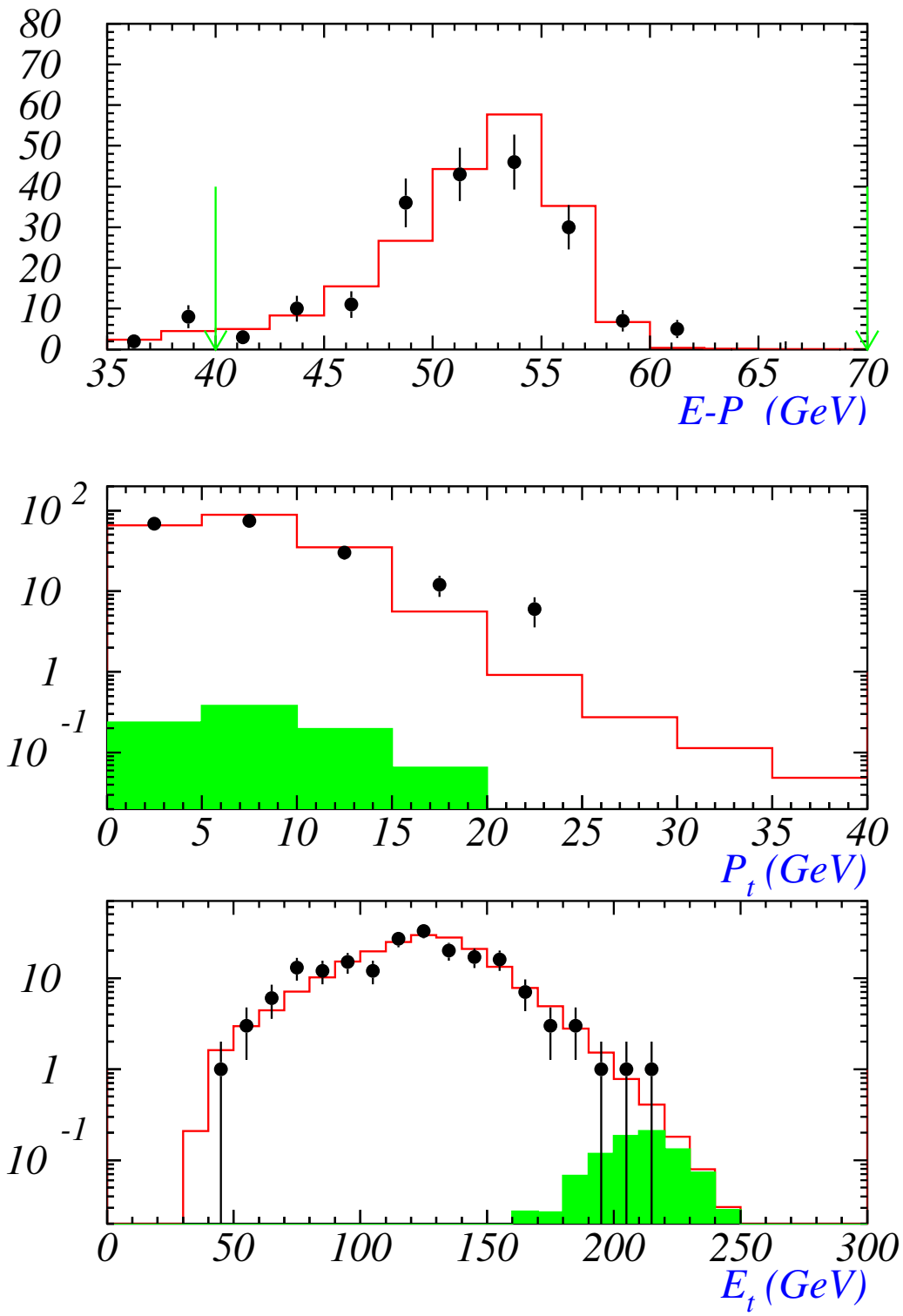
Selection	Efficiency
Vertex found	100.0 %
$\lvert Z_{\text{vtx}}\rvert < 50\,\text{cm}$	94.9 %
$40\,\text{GeV} < E - p_Z < 70\,\text{GeV}$ (lower cut rejects photoproduction or hard ISR)	92.0 %
Positron with $E'_e > 20\,\text{GeV}$ identified in CAL	89.4 %
Positron isolation $E^{R=0.8}_{\text{cone}} < 5\,\text{GeV}$	87.2 %
If $\theta_e > 17.2°$:	
track–cluster match (DCA $< 10\,\text{cm}$)	85.7 %
If $\theta_e < 17.2°$:	
$p_{t,e} > 30\,\text{GeV}$	83.9 %
$E - p_Z > 44$ GeV (tighter Photoproduction rejection)	83.8 %
Reject events with 2 isolated e.m. clusters (Compton rejection)	83.4 %
$Q^2_{\text{DA}} > 5000\,\text{GeV}^2$	81.5 %

Data/MC Comparison for Final–State Positron



Green indicates MC distributions for $x_{\mathrm{DA}} > 0.55$ and $y_{\mathrm{DA}} > 0.25$.

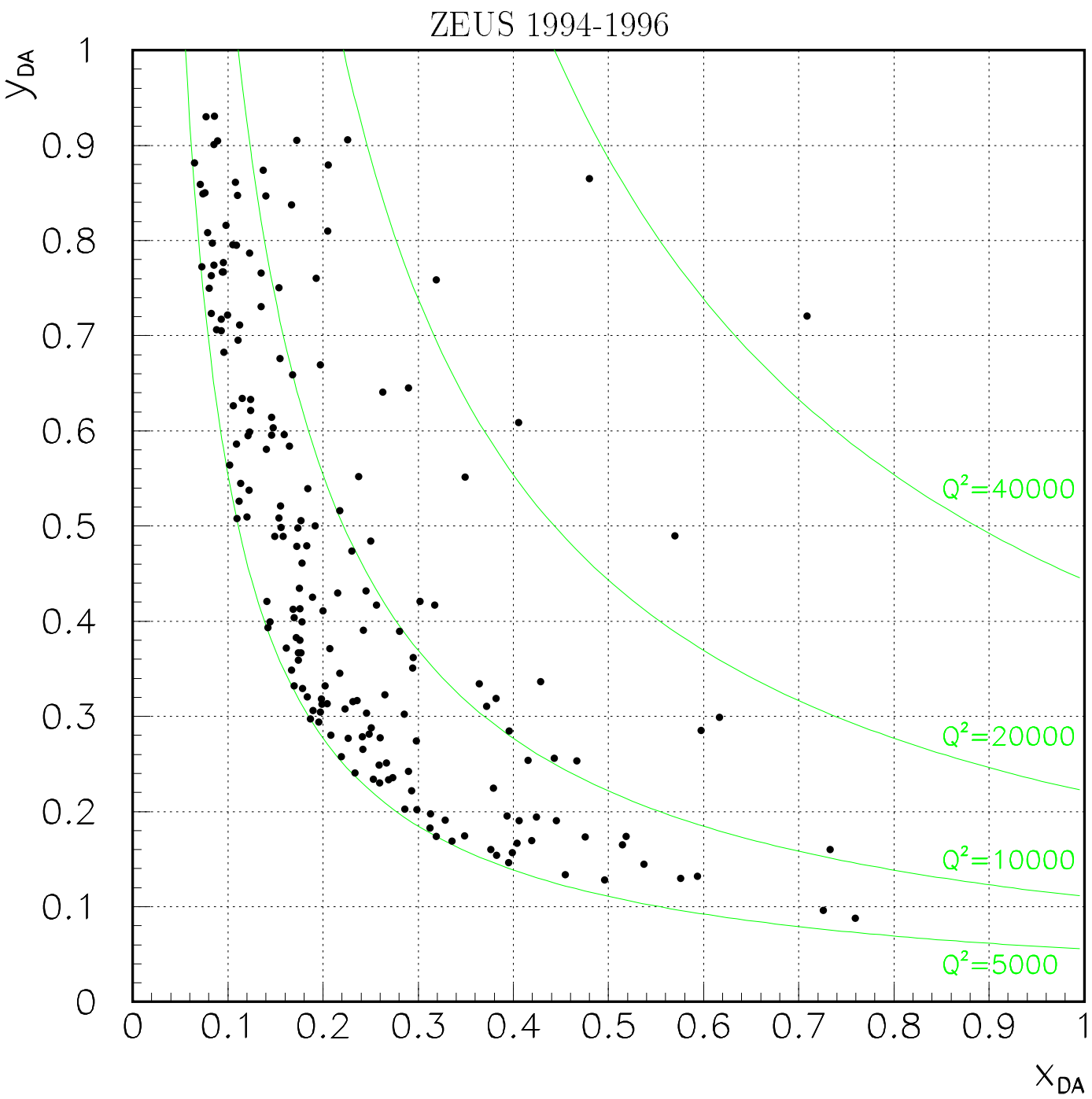
Data/MC Comparison for $E - P_z$, p_t and E_t



Green indicates MC distributions for $x_{\mathrm{DA}} > 0.55$ and $y_{\mathrm{DA}} > 0.25$.

Final Data Sample

The final sample consists of 191 events



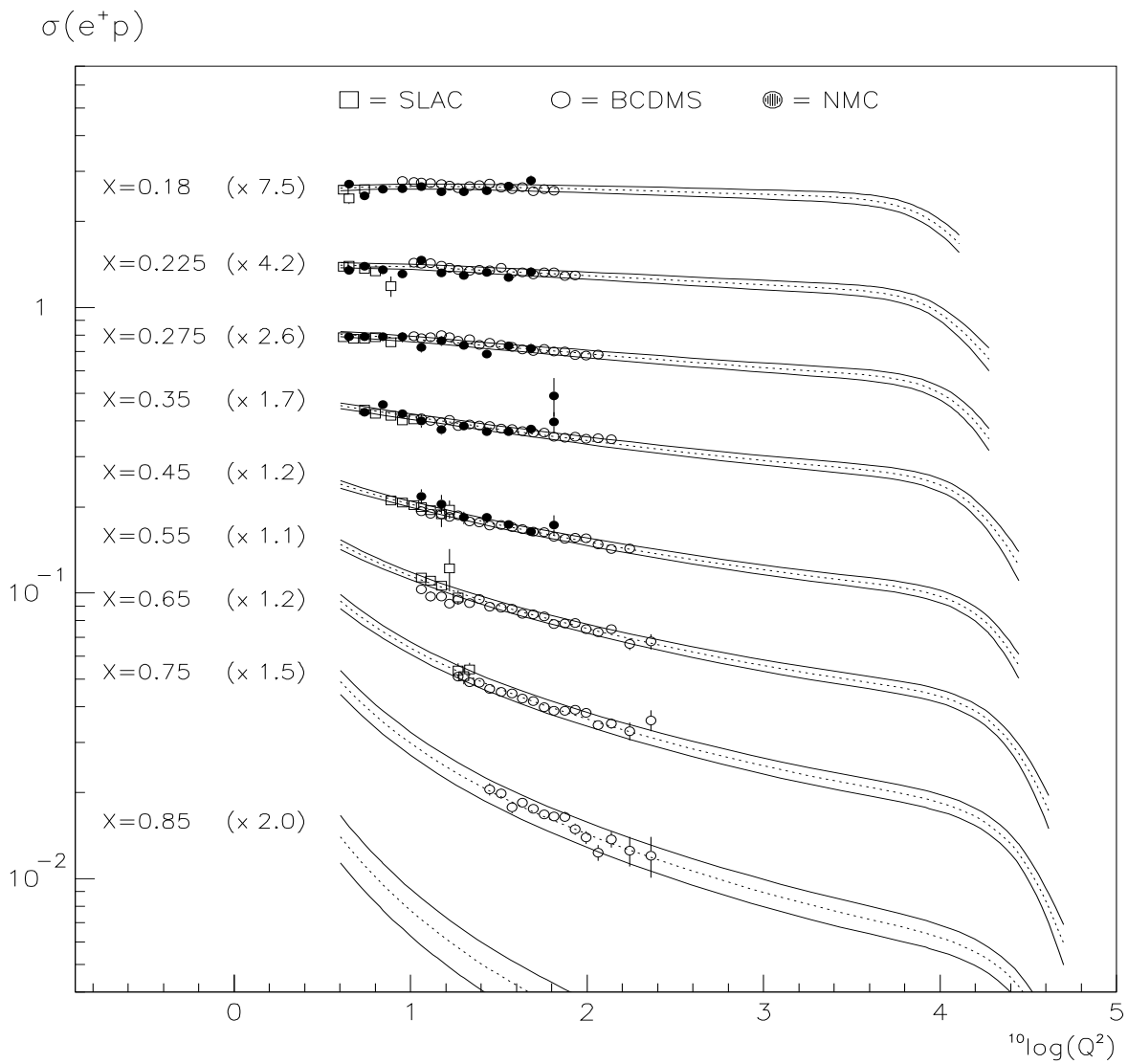
y_{DA} range	x_{DA} range 0.05 – 0.15	0.15 – 0.25	0.25 – 0.35	0.35 – 0.45	0.45 – 0.55	0.55 – 0.65	0.65 – 0.75	0.75 – 0.85	0.85 – 0.95	0.95 – 1.00
0.95 – 1.00	0.15	0.015	0.033	0.013	0.0055	0.0015	0.0012			
0.85 – 0.95	8.8 9	1.2 3	0.32	0.10	0.028 1	0.01	0.0034			
0.75 – 0.85	12 16	2.5 4	0.50 1	0.15	0.050	0.011	0.0039			
0.65 – 0.75	13 10	3.7 3	0.86	0.26	0.082	0.022	0.0054 1	0.0020		
0.55 – 0.65	15 12	6.1 3	1.65 3	0.46 1	0.15	0.046	0.0090	0.0024		
0.45 – 0.55	12 6	11 13	2.5 1	0.85	0.28	0.084 1	0.0208	0.0032		
0.35 – 0.45	4.6 3	18 17	5.5 6	1.75	0.52	0.16	0.0403	0.0093		
0.25 – 0.35		18 23	11 6	3.74 7	1.19 1	0.34 2	0.1104	0.0175	0.0066	
0.15 – 0.25		2.2 1	14 15	9.6 10	3.32 3	1.2	0.2784 1	0.0717	0.0077	
0.05 – 0.15				1.3 1	2.14 3	1.6 2	0.9052 1	0.3022 1	0.1216	

ZEUS 1994–1996 Selected Events

Event Date	11-Oct-94	03-Nov-95	12-Sep-96	12-Oct-96	21-Nov-96
E_t [GeV]	123.	217.	193.	204.	187.
p_t [GeV]	8.9	8.2	2.9	2.2	10.2
$E - p_Z$ [GeV]	47.8	53.2	49.7	50.2	49.1
E_q [GeV]	67.4	235.	270.	151.	276.
$\gamma_{\rm raw}$ [degrees]	69.0	28.1	19.9	40.7	19.7
E'_e [GeV]	324.	220.	149.	366.	134.
θ_e [degrees]	11.9	27.8	39.3	15.4	41.1
$[x_{\rm DA}]_{\rm raw}$	0.468	0.541	0.535	0.668	0.515
$[y_{\rm DA}]_{\rm raw}$	0.868	0.503	0.330	0.733	0.316
$(Q^2_{\rm DA})_{\rm raw}$ [10^4 GeV^2]	3.67	2.45	1.59	4.42	1.47
γ [degrees]	67.6	26.7	17.3	38.6	17.0
$x_{\rm DA}$	0.480	0.570	0.617	0.709	0.597
$\delta x_{\rm DA}$	0.035	0.029	0.054	0.034	0.053
$y_{\rm DA}$	0.865	0.490	0.299	0.721	0.285
$\delta y_{\rm DA}$	0.008	0.010	0.017	0.008	0.017
$Q^2_{\rm DA}$ [10^4GeV^2]	3.75	2.52	1.66	4.61	1.54
$\delta[Q^2_{\rm DA}]$ [10^4GeV^2]	0.26	0.07	0.05	0.16	0.04
x_e	0.525	0.536	0.562	0.605	0.443
δx_e	0.048	0.048	0.102	0.060	0.063
y_e	0.854	0.505	0.319	0.752	0.350
δy_e	0.018	0.024	0.039	0.021	0.032
Q^2_e [10^4GeV^2]	4.05	2.44	1.62	4.10	1.40
$\delta[Q^2_e]$ [10^4GeV^2]	0.31	0.11	0.09	0.30	0.07

ZEUS DGLAP Fit to SLAC, BCDMS, and NMC Data

$$\sigma(e^+p) \equiv \frac{xQ^4}{2\pi\alpha^2 Y_+}\frac{d^2\sigma_{NC}^{e^+p}}{dxdQ^2} = F_2 - \frac{y^2}{Y_+}F_L - \frac{Y_-}{Y_+}xF_3$$



Error Bands include:

$\longrightarrow$ SLAC, BCDMS, NMC statistical and systematic errors

$\longrightarrow$ the effect of varying α_s between 0.112 and 0.122

NC DIS cross section predictions at high x, Q^2 accurate to $\approx 6.5\,\%$

Systematic errors in SM predictions

Structure Functions	6.5%

Uncertainties from structure function fit:

Fixed–target experimental uncertainties	$\pm 6.2\%$
$0.112 < \alpha_s < 0.122$	$\pm 1.9\%$

Cross checks on SF uncertainties include:

$10\% <$ strange fraction $< 30\%$	small
Uncertainties in charm evolution	$< 0.5\%$
GRV94, MRSA, CTEQ3 comparison	$\pm 2.0\%$
GRV94 NLO versus LO	$+1.0\%$
High–x gluon (CDF inspired, CTEQ4 HJ)	$+1.9\%$

Luminosity uncertainty	2.3%
Electroweak parameters	0.25%
Radiative corrections	2%

Evaluated with HERACLES and HECTOR
ISR E_γ spectrum in LUMI monitor agrees well with MC.

Systematic errors in SM predictions — continued

Detector simulation 4.4%

$\sim 2\%$ for $y_{\rm DA} > 0.2$

$4 - 7\%$ for $y_{\rm DA} > 0.5$

Effects included:

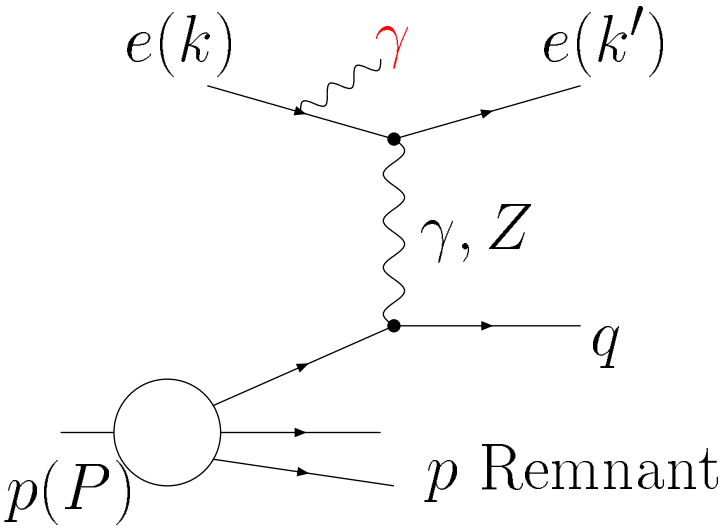
- variation of $\pm 3\%$ in the FCAL, BCAL energy scales
- smearing of the electron scattering angle (5 mrad)
- variation in the electron finding efficiency
  - variation of HAC fraction of electron candidate
  - variation of lateral energy profiles of the electron
  - variation of non–electron energy in the cone
  - variation of track–cluster matching angles
  - variation of track momentum resolution

Summary of systematic errors in SM predictions

for $x > 0.55$ and $y > 0.25$

Structure Functions	6.5%
Luminosity measurement	2.3%
Electroweak parameters	0.25%
Radiative corrections	2%
Detector simulation	4.4%
Total	8.4%

Initial State Radiation and Kinematic Reconstruction



Initial State Radiation (ISR):

- mostly collinear with e beam
- can escape detection
- effectively reduces E_e
- events with ISR photons with $E_\gamma \gtrsim 7.5\,\text{GeV}$ rejected by cuts

$$f_\gamma = \frac{E_\gamma}{E_e} = \text{fractional energy carried by } \gamma$$

$$x_{\text{DA}} = x\,\frac{1}{1-f_\gamma} \qquad Q^2_{\text{DA}} = Q^2\,\frac{1}{(1-f_\gamma)^2}$$

$$x_e = x\,\frac{(1-f_\gamma/y_e)}{(1-f_\gamma)} \qquad Q^2_e = Q^2\,\frac{1}{(1-f\gamma)}$$

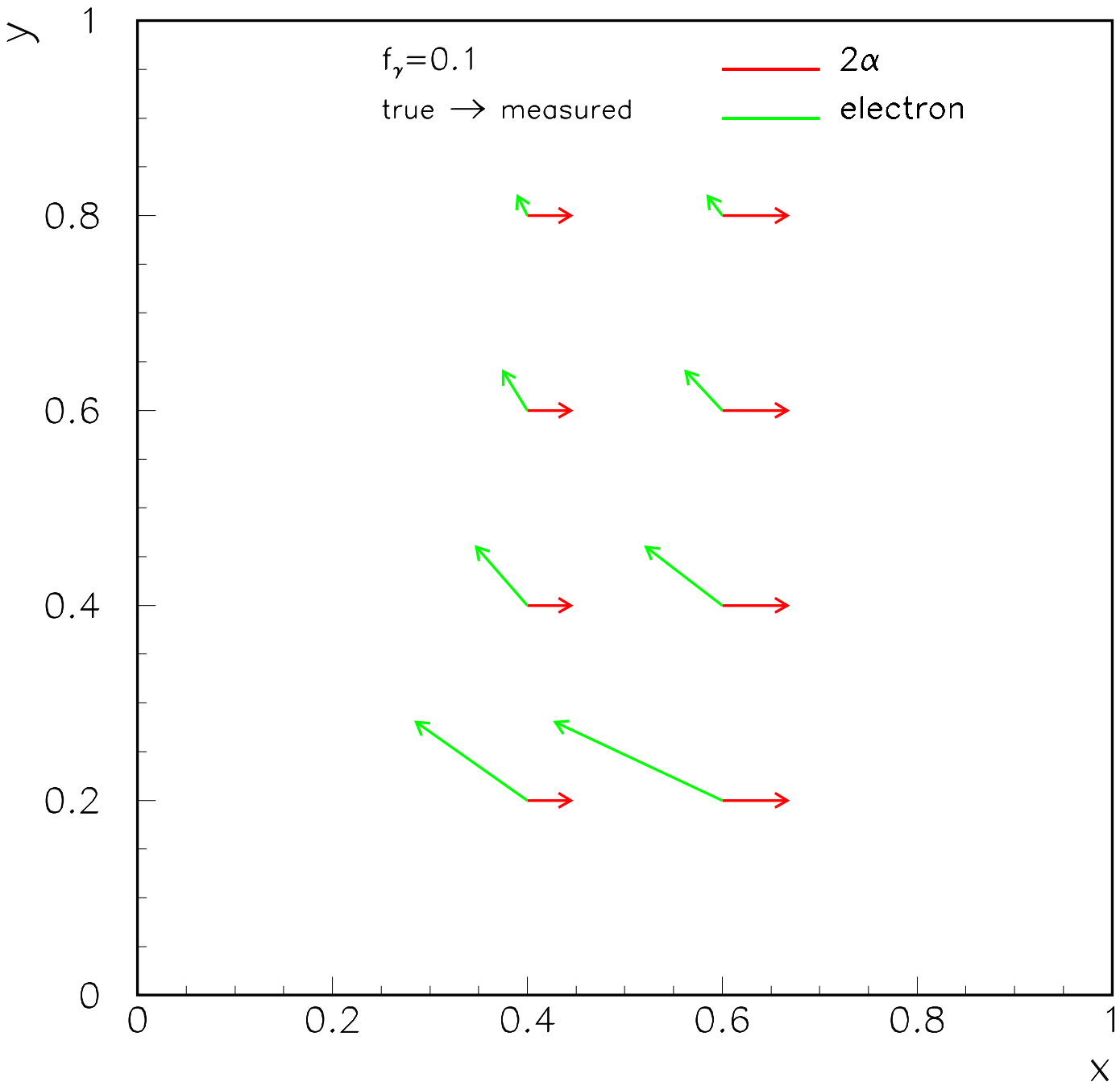
Average shifts of true kinematic variables due to ISR
for events passing all cuts and having $0.4 < x < 0.6$, $y > 0.25$

$$\langle \delta x_{\text{DA}} \rangle = \left\langle \frac{x_{\text{DA}} - x}{x} \right\rangle = +1.7\% \qquad \langle \delta Q^2_{\text{DA}} \rangle = \left\langle \frac{Q^2_{\text{DA}} - Q^2}{Q^2} \right\rangle = +2.5\%$$

$$\langle \delta x_e \rangle = \left\langle \frac{x_e - x}{x} \right\rangle = -2.5\% \qquad \langle \delta Q^2_e \rangle = \left\langle \frac{Q^2_e - Q^2}{Q^2} \right\rangle = +1.8\%$$

Initial State Radiation and Kinematic Reconstruction

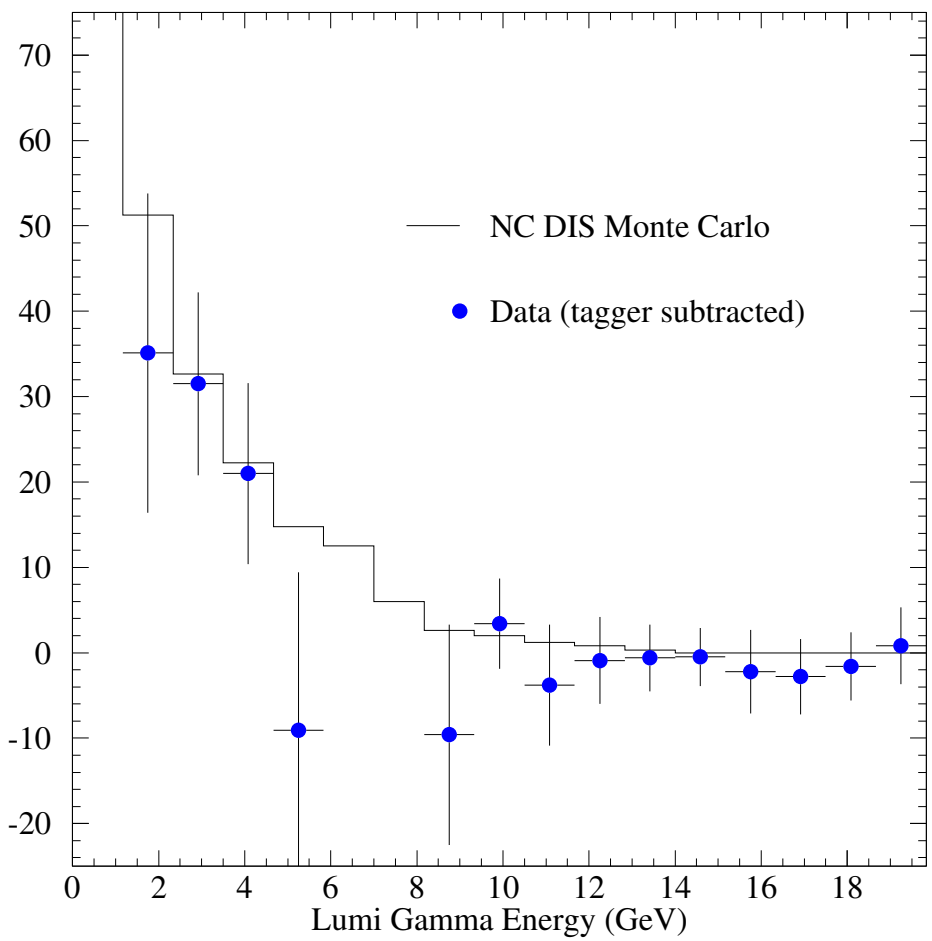
Possible influence of hard ISR on event reconstruction



Comparison between data and MC of the ISR photon energy spectrum

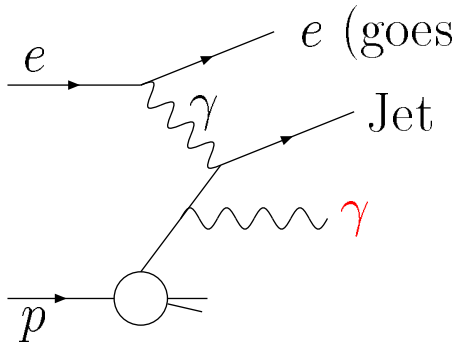
- Select NC events with $Q^2_{\rm DA} > 400\,{\rm GeV}^2$ and the energy measured in the photon calorimeter of the luminosity monitor $E_{\rm LUMI-\gamma} > 1.2\,{\rm GeV}$ (460 events out of 5630).
- Subtract rate of random bremsstrahlung conincidences using events in which the positron is tagged in the 44 m ($\rm E_\gamma < 6\,GeV$) or 35 m ($\rm E_\gamma \approx 7 - 25\,GeV$) calorimeters.

The resulting E_γ spectrum agrees well with the MC prediction, with 88 ± 24 events measured and 105 expected in the range $1.2\,{\rm GeV} < E_{\rm LUMI-\gamma} < 4.8\,{\rm GeV}$.



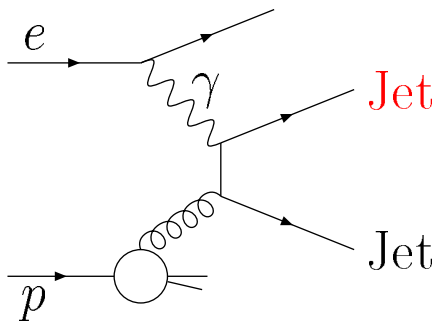
Backgrounds

Prompt Photon Production:

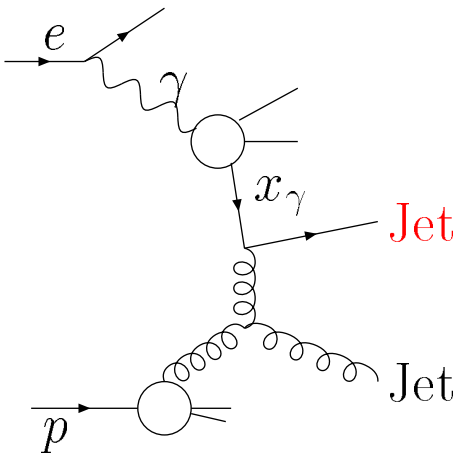


γ can have large energy, and P_T. Mostly a background for $\theta_e < 17.2°$ where no track is required.

Photoproduction of Dijets:



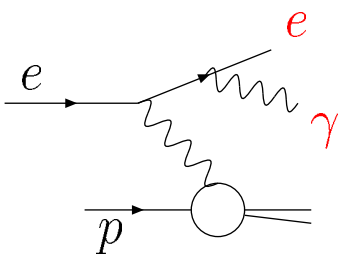
Direct Photoproduction



Resolved Photoproduction

Background when jet satisfies electron requirements

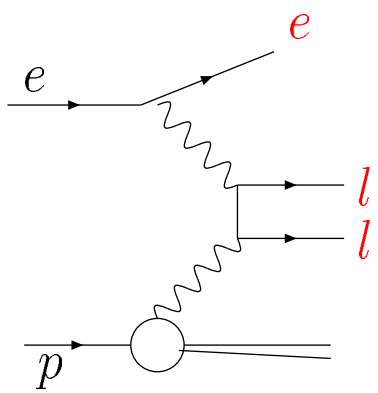
QED Compton:



e, γ can be produced with large transverse momentum

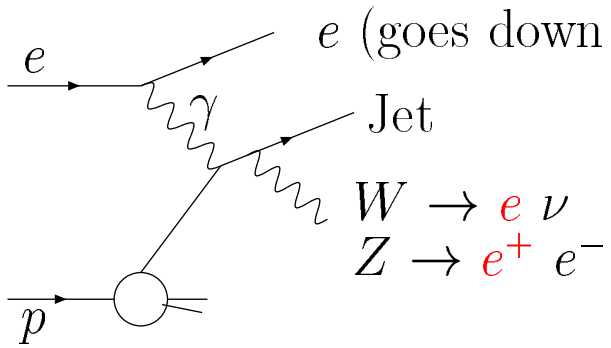
Backgrounds — continued

Dilepton Photoproduction:



l can have large P_T.
Background if e or l misidentified

Weak Boson Production:



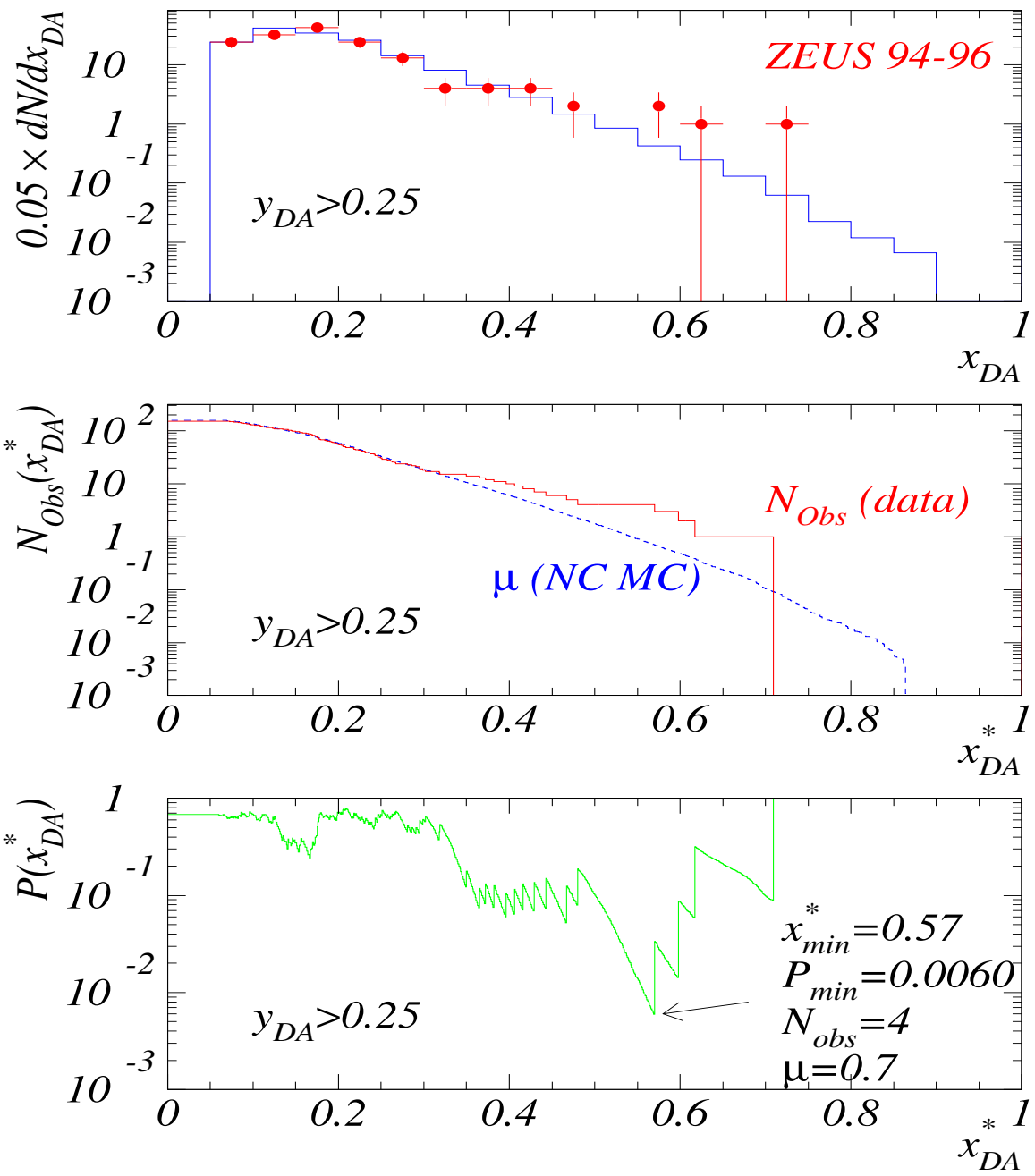
Can produce e with large transverse momentum

Expected cross sections for backgrounds
(< indicates 90% confidence level upper limit)

Background Process	Cross–section [fb] $x > 0.45$	$x > 0.55$
$\gamma p \to \gamma X$	0.28	0.28
$\gamma p \to$ dijets	< 1.8	< 1.8
$ep \to e\gamma X$	< 0.2	< 0.2
$\gamma\gamma \to \ell\ell$	< 0.1	< 0.1
$W \to e\nu$	< 0.5	< 0.5
Accepted NC DIS	165	46

Significance Analysis

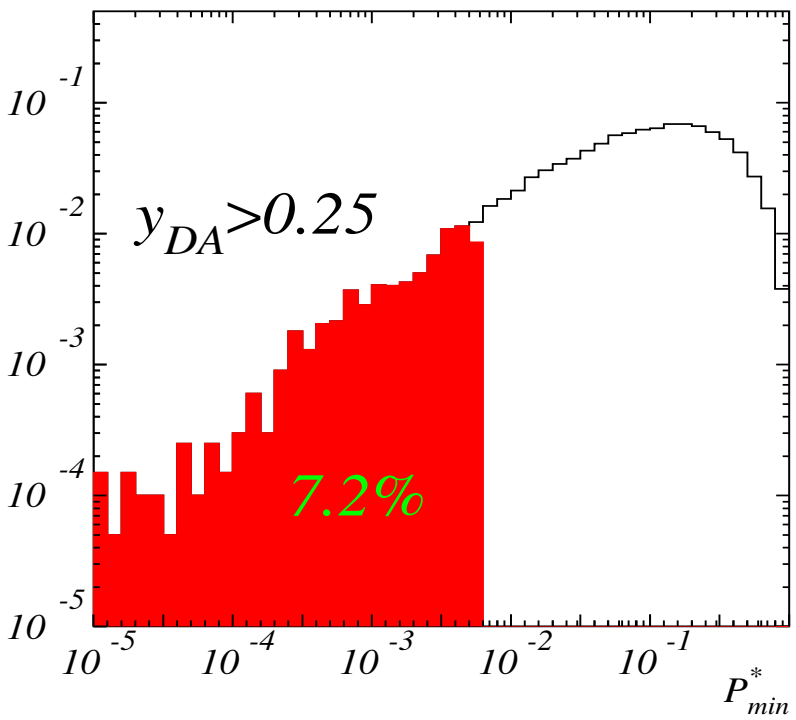
Excess in x



$$N_{\rm obs}(x^*_{\rm DA}) = \int_{x^*_{\rm DA}}^{1} dx_{\rm DA}\; dN/dx_{\rm DA}$$

$$\mathcal{P}(x^*_{\rm DA}) = \sum_{n=N_{obs}}^{\infty} e^{-\mu}\,\frac{\mu^n}{n!}$$

Excess in x — continued



Minimal Poisson probabilities of the $x_{\rm DA}$ distributions for different $y_{\rm DA}$ cuts

$y_{\rm DA}$ range	$\mathcal{P}_{min}(x^*_{\rm DA})$ [%]	$x^*_{\rm DA}$	$N_{\rm obs}$	μ	$P_{\rm SM}$ [%]
$y_{\rm DA} > 0.05$	1.61	0.708	4	0.95	16.0
$y_{\rm DA} > 0.15$	2.57	0.708	2	0.25	23.0
$y_{\rm DA} > 0.25$	0.60	0.569	4	0.71	7.2
$y_{\rm DA} > 0.35$	3.38	0.708	1	0.034	26.6
$y_{\rm DA} > 0.45$	1.32	0.569	2	0.17	12.7
$y_{\rm DA} > 0.55$	0.96	0.708	1	0.010	9.5
$y_{\rm DA} > 0.65$	0.50	0.708	1	0.005	5.0

$\mathcal{P}_{min}(x^*_{\rm DA})$ = the minimal probability

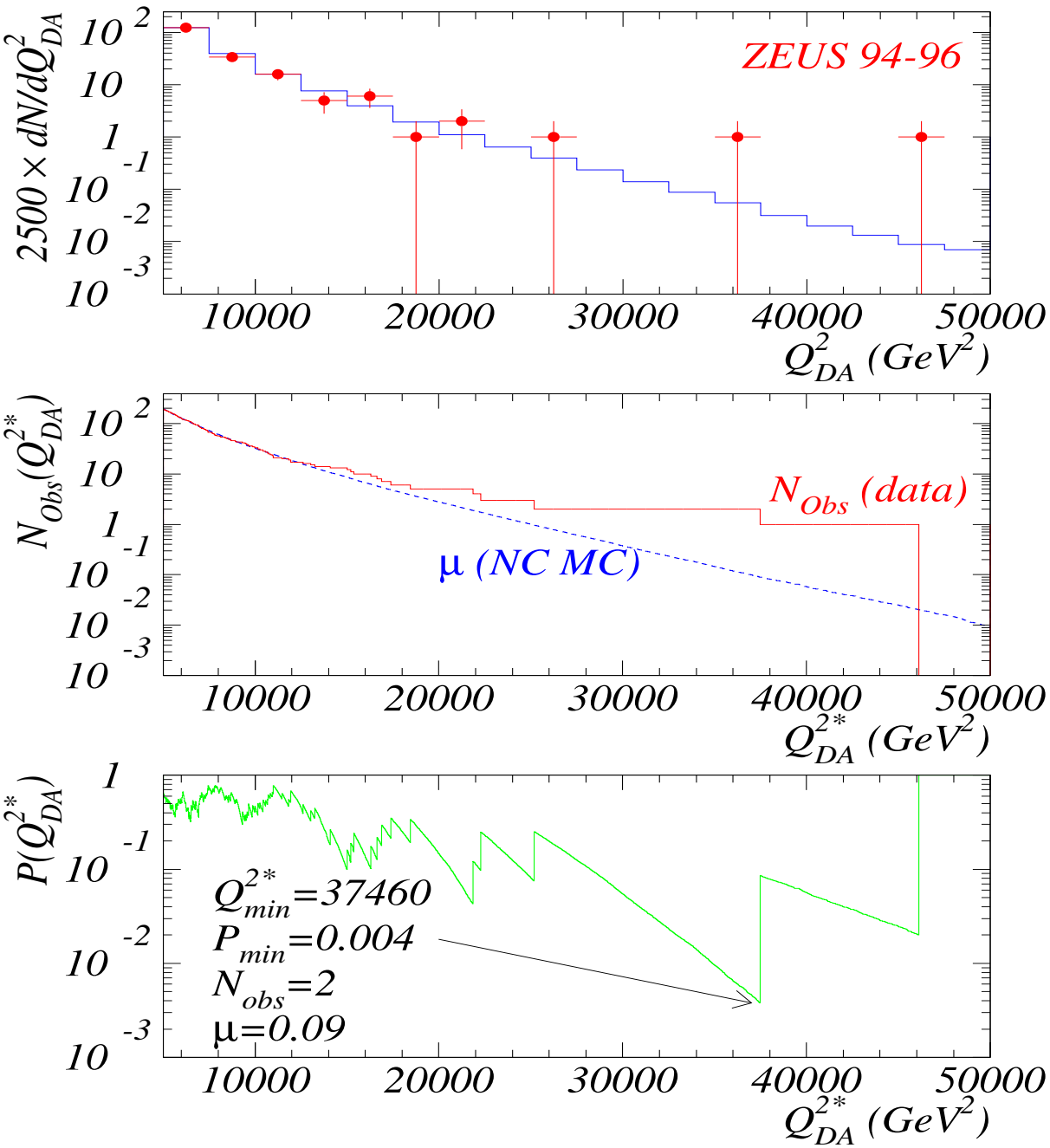
$x^*_{\rm DA}$ = the value of $x_{\rm DA}$ where it occurs

$N_{\rm obs}$ = number of events observed with $x_{\rm DA} > x^*_{\rm DA}$

μ = expected number of events with $x_{\rm DA} > x^*_{\rm DA}$

$P_{\rm SM}$ = prob. that a simulated experiment yields a lower $\mathcal{P}_{min}(x^*_{\rm DA})$ than observed

Excess in Q^2



The probability for a simulated experiment to obtain $\mathcal{P}_{min}((Q^2_{\rm DA})^*) < 0.004$ is 6.0%.

2–Dimensional Likelihood Test

- Divide x-y plane into 10×10 grid
- Assign Poisson probability to i^{th} bin

$$\mathcal{P}_i = e^{-\mu_i} \frac{\mu_i^{N_i}}{N_i!} \qquad \begin{array}{l} N_i = \text{Number observed} \\ \mu_i = \text{Number expected} \end{array}$$

- Form likelihood over a subset of bins $\mathcal{R}$

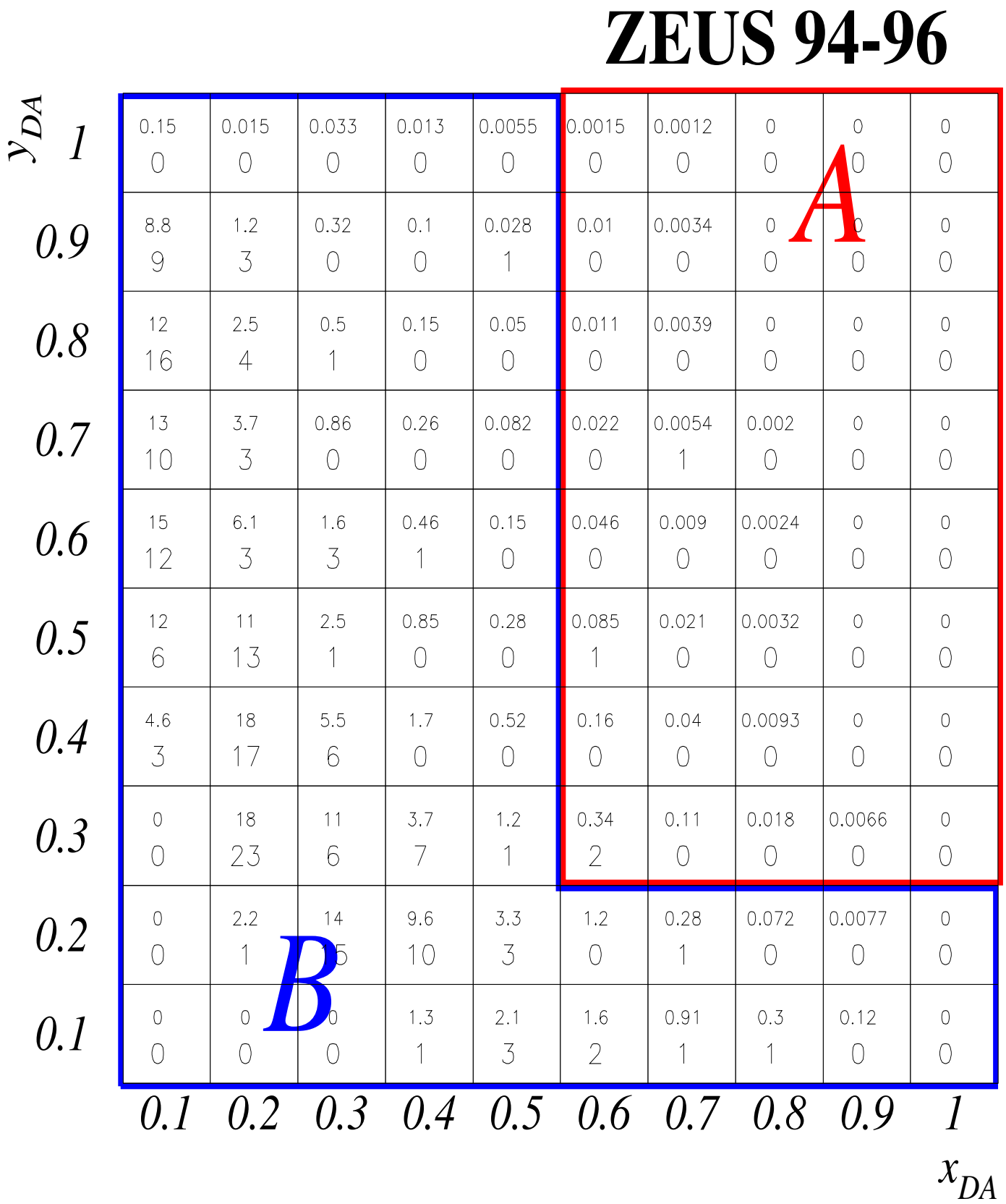
$$\mathcal{L}_{\mathcal{R}} = \Pi_{i \in \mathcal{R}} \, \mathcal{P}_i$$

- Evaluate the significance by performing many Monte Carlo experiments

$$\mathcal{L}_{\mathcal{R}} = \Pi_{i \in \mathcal{R}} \, \mathcal{P}_i^{(m)} \qquad \text{for } m^{\text{th}} \text{ experiment}$$

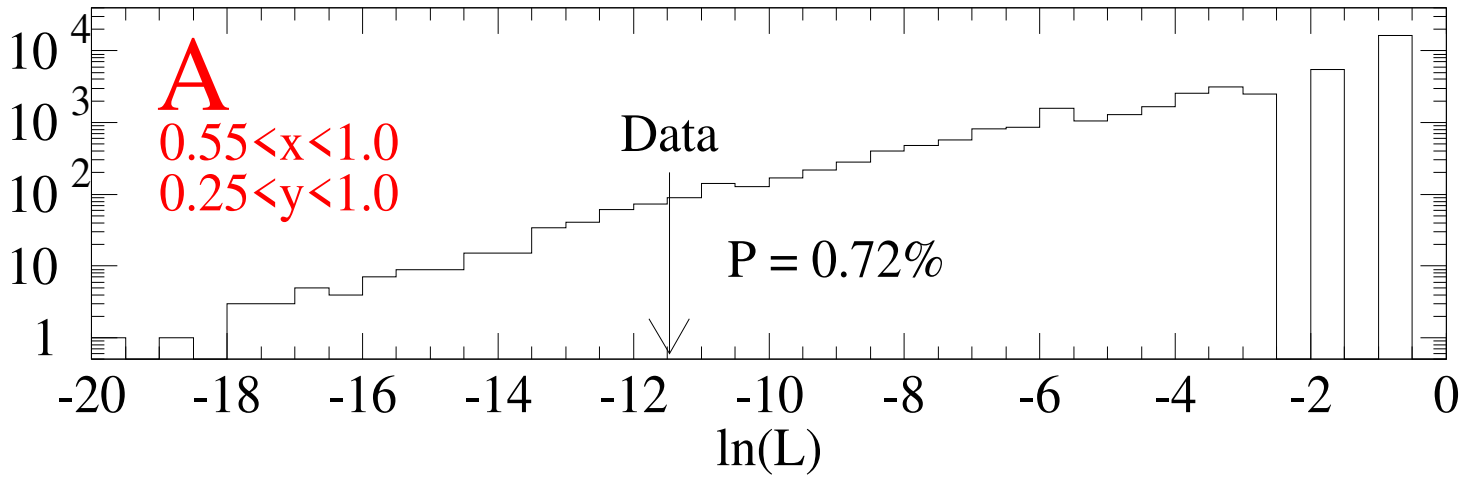
- Significance $\equiv$ Probability $(\mathcal{L}_{\mathcal{R}} \leq \mathcal{L}_{\mathcal{R}}{}^{\text{obs}})$

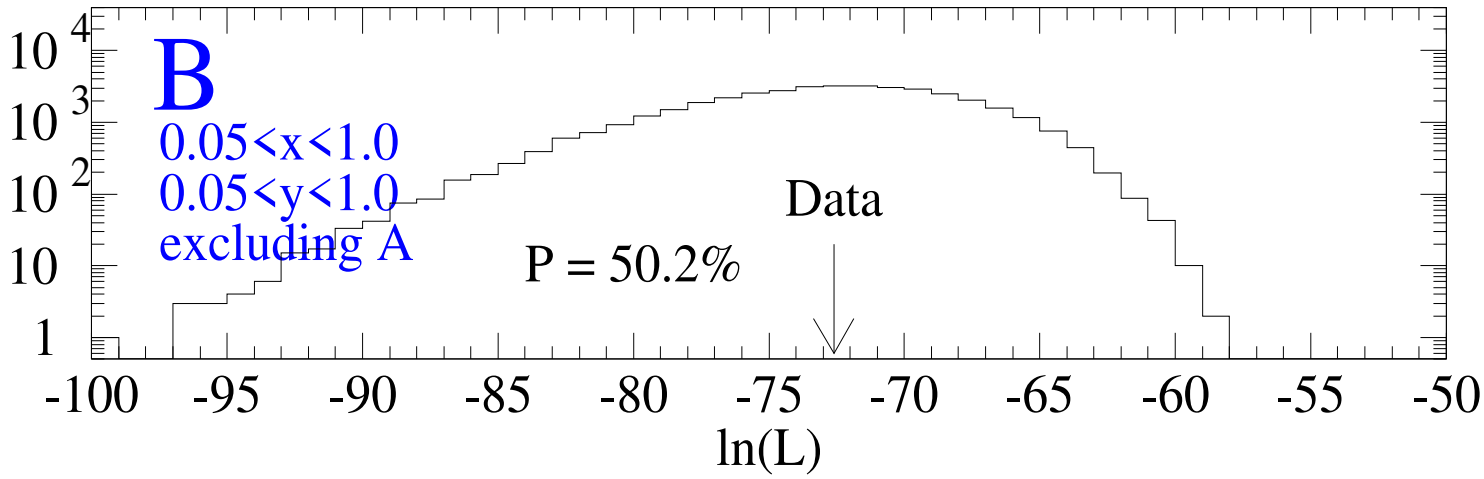
2–Dimensional Likelihood Test – continued

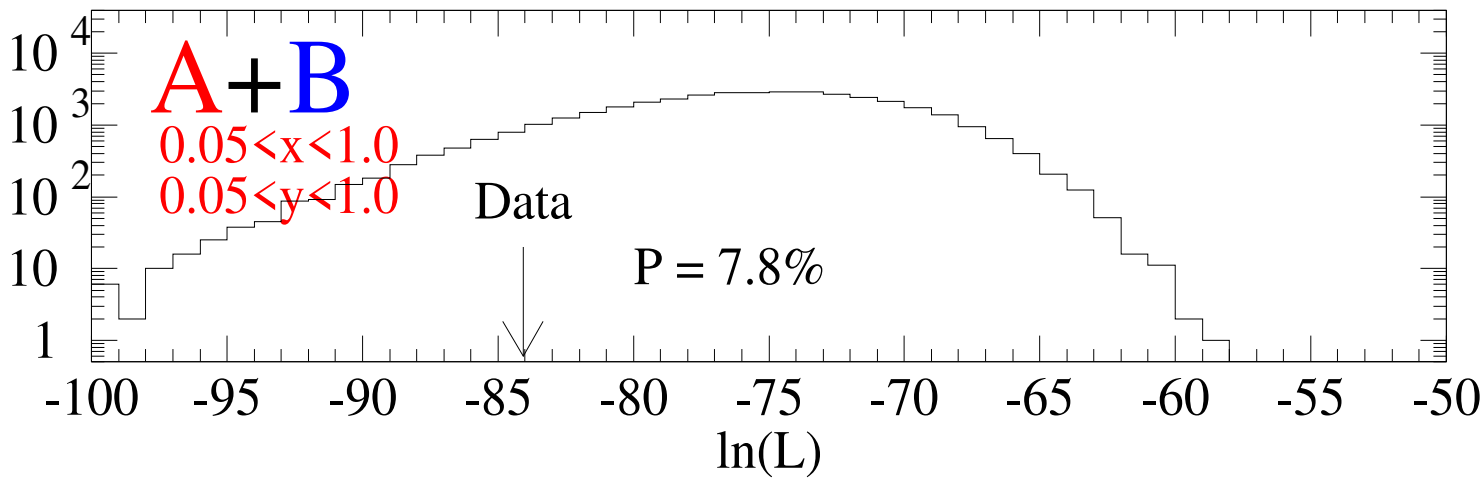


2–Dimensional Likelihood Test – continued

Likelihood Distributions







Conclusions

1. We have searched for deviations from Standard Model expectations in $eP \to eX$ scattering at high Q^2 and high x.
   - The Neutral Current DIS cross section predictions are known to an accuracy at the level of 6%.
   - The events are experimentally very clean. There are no significant backgrounds.

2. In a sample with integrated luminosity 20.1 pb^{-1}, we find:

   2 events with $Q^2 > 35\,000\,\text{GeV}^2$ where only 0.145 ± 0.013 are expected, corresponding to a Poisson probability of 0.96 %.

   4 events for ($x > 0.55$, $y > 0.25$) where only 0.91 ± 0.08 are expected, corresponding to a Poisson probability of 1.4 %.

   An analysis using a large ensemble of simulated Standard Model experiments indicates that statistical fluctuations at these levels would occur

   at *some* Q^2 for ($Q^2 > 5000$ GeV^2) in 6 % of all experiments;

   at *some* x for ($y > 0.25, Q^2 > 5000$ GeV^2) in 7.6 % of all experiments.

3. A likelihood analysis sensitive to the event distribution in (x, y) gives probabilities of

   0.72 % for the events in the region ($x > 0.55$, $y > 0.25$),

   50.2 % for the events in the region ($x > 0.05$, $y > 0.05$), excluding the region ($x > 0.55$, $y > 0.25$), indicating that the data are in good agreement with Standard Model expectations at lower x and Q^2.

4. The effect is particularly interesting because it occurs in an unexplored kinematic region.