# Topology of the Hadronic Final State

# in

# Diffractive Scattering at HERA


**Riko Wichmann**

Santa Cruz Institute for Particle Physics

University of California, Santa Cruz



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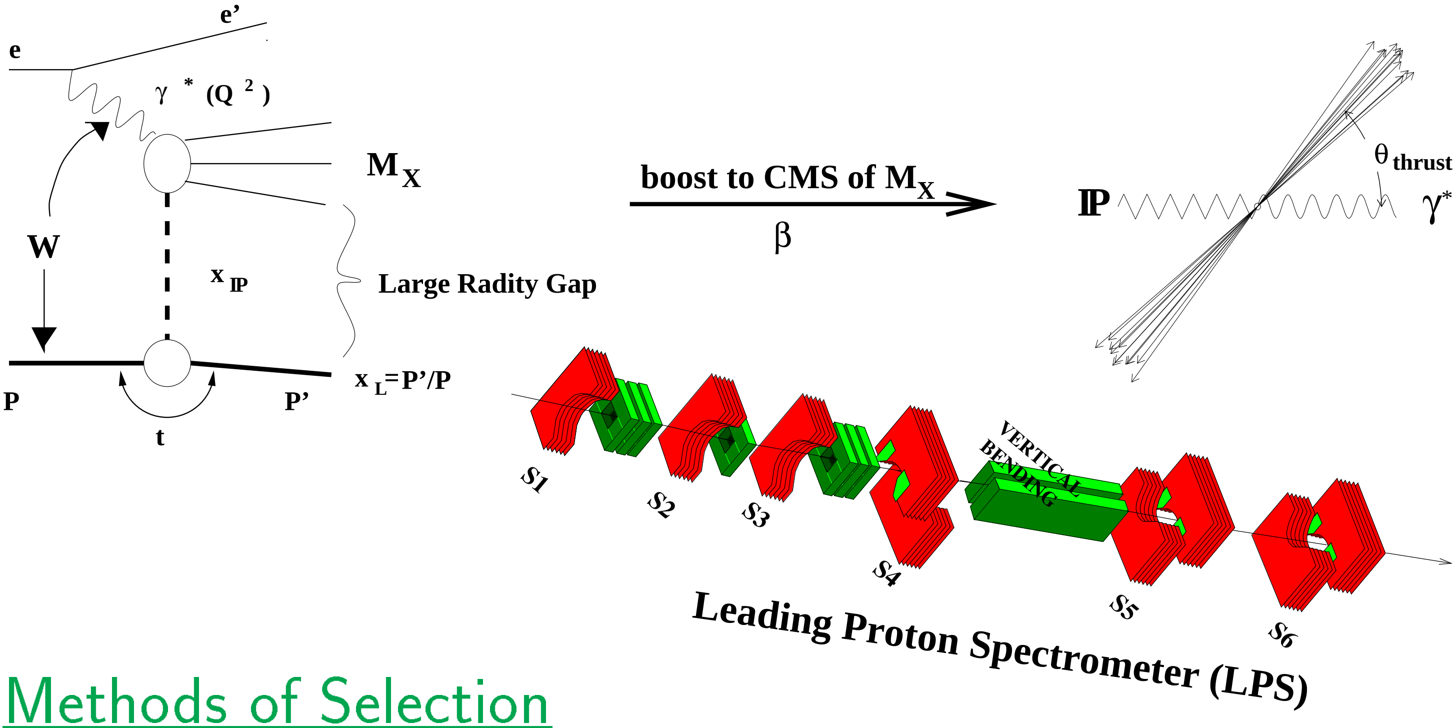
representing the

H1 and ZEUS Collaborations

- Introduction: Hadronic Final State,
  Monte Carlo Models
- Global Event Shapes and
  Inclusive Particle Distributions
- Dijet Production
- 3-Jets Production
- Summary
- Conclusions

# Introduction: Diffraction



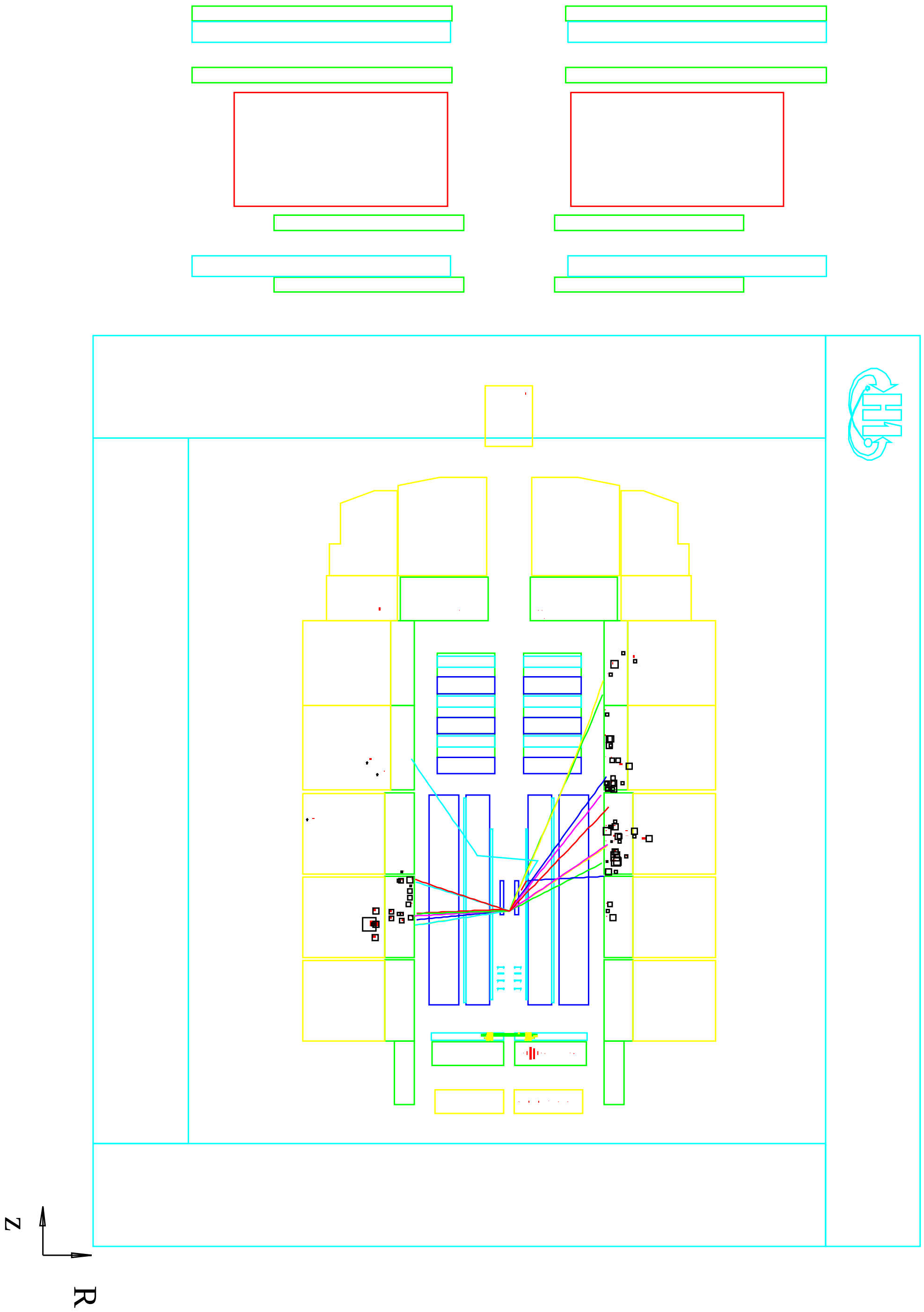

## Methods of Selection

- measure Leading Proton
  (for example LPS proton with $x_L > 0.95$)
- Large Rapidity Gaps (LRG)
- diffractive excess in $\ln M_X^2$ distribution

## Measurements

- Topology of Hadronic Final State $\rightarrow$ nature of $I\!P$ exchange
- Global Shape of Events: $<T>$ , $<S>$ , $<\theta_{Thrust}>$
- Distribution of Particles in the Event:
  energy flow, seagull distribution
- Underlying Parton State: Jet Analysis

# Diffractive Event Display - H1-Detector



# Introduction: Monte Carlo Models

## Resolved $I\!P$ Model: RAPGAP

H. Jung, *Comp. Phys. Comm.* 86 147

- inclusive diffractive cross section

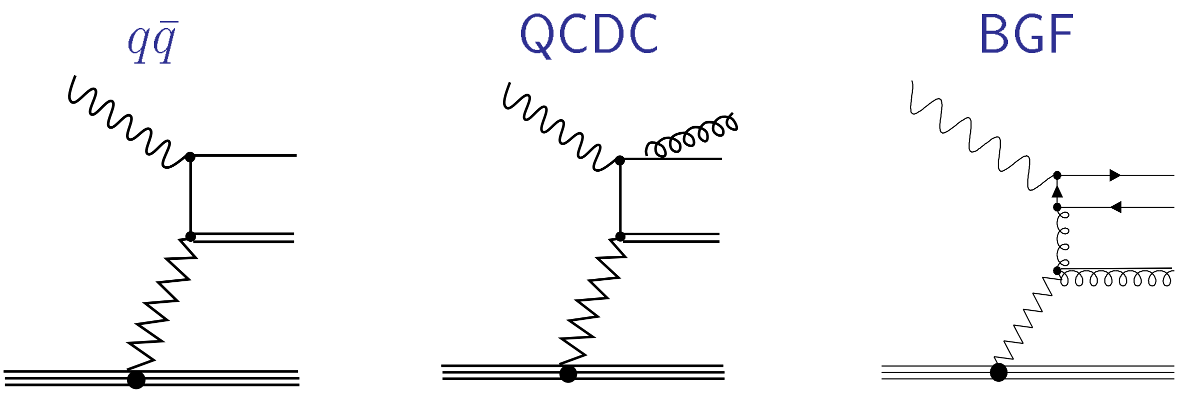
$$\frac{d\sigma(ep->e'Xp')}{dydQ^2dx_{I\!P}dt} = \frac{4\pi\alpha^2}{yQ^4}(1-y+\frac{y^2}{2})\, \mathbf{F_2^{D(4)}(x, Q^2}; x_{I\!P}, \mathbf{t})$$

- $F_2^{D(4)}$ à la Ingelman Schlein

$$F_2^{D(4)}(\beta, Q^2; x_{I\!P}, t) = f_{I\!P/p}(x_{I\!P}, t) F_2^{I\!P}(\beta, Q^2)$$

$$f_{I\!P}(x_{I\!P}) = (\frac{1}{x_{I\!P}})^{2\alpha_{I\!P}(t)-1}\, e^{B_{I\!P}t}$$

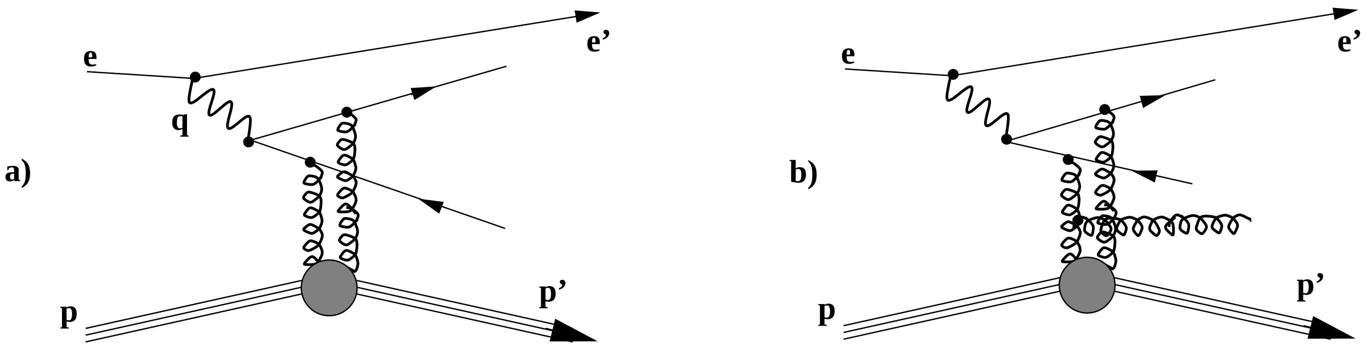
- $I\!P$ intercept: $\alpha_{I\!P}(0) = 1.20$
- $F_2^{I\!P}$ partonic structure of $I\!P$ $\rightarrow$ $\boxed{I\!P \text{ remnant!!}}$
- H1 parameterization of $I\!P$ structure: gluon dominated
- implemented in RAPGAP:



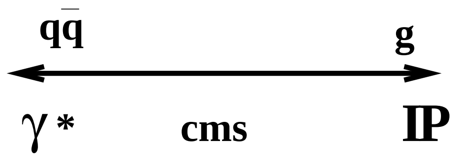

- subleading $I\!R$ exchange (Pion PDF and $\alpha_{I\!R}(0) = 0.57$)
  $\rightarrow$ $q\bar{q}$ events only !

# Introduction: Monte Carlo Models

## Photon-dissociative Models (pQCD)




- $\gamma^*$ fluctuates into $q\bar{q}$ pair $\rightarrow$ no explicit $I\!P$ remnant!!
- interaction with $p$ via gluon ladder
- contributions from transversely and longitudinally polarized photons
- $q\bar{q}g$ events:

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## resolved $\gamma^*$: SaS-2D

- based on PDF for real photon
- non-perturbative (VDM) contribution: $\gamma^* \leftrightarrow V(\rho, \omega, \phi, \cdots)$
- perturbative (anomalous) $\gamma \rightarrow q\bar{q}$ ($q = 5$ flavors) contribution

# Introduction: Monte Carlo Models

## RIDI - SATRAP - BJLW

RIDI: M.G. Ryskin, A. Solano, DESY-PROC-1999-02

- theoretical uncertainty of relative contributions of $q\bar{q}$ and $q\bar{q}g$
- taken into account using $k$-factors
- dominated by $q\bar{q}g$ events

SATRAP: H. Kowalski, DESY-99-141

- similar to BEKW
- saturation of the proton parton density
- model parameter $\leftarrow$ total cross section for $Q^2 \epsilon\ 0.1 \ldots 100$ GeV$^2$
- strong $k_T$ ordering $(k_T^{gluon} \ll k_T^{q,\bar{q}})$

BJWL: J. Bartels, H. Lotter, M. Wüsthoff, *Phys. Lett.* B379 239
J. Bartels, C. Ewertz, H. Lotter, M. Wüsthoff, *Phys. Lett.* B386 389
J. Bartels, H. Jung, M. Wüsthoff, *Eur. Phys. J.* C11 111

- via two-gluon exchange
- $q\bar{q}$ production
- and $q\bar{q}g$ production
  - low-$\beta$ limit
  - all outgoing parton have high $p_T$
  - $\rightarrow$ configurations without strong $k_T$-ordering

# Introduction: Event Shape Variables

- Thrust $T$

$$T = \max \frac{\Sigma_i \left|\mathbf{n} \cdot \mathbf{p}_i\right|}{\Sigma_i \left|\mathbf{p}_i\right|}$$

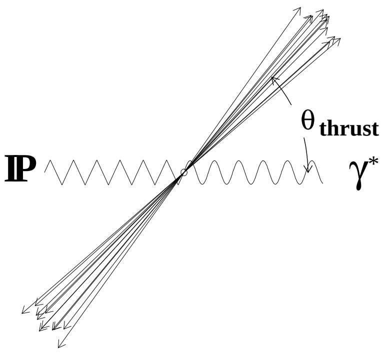
- Sphericity $S$

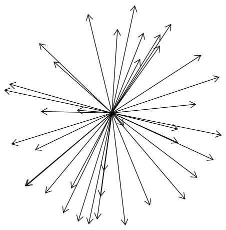
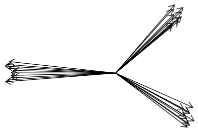
$$S^{\alpha\beta} = \frac{\Sigma_i \, p_i^\alpha p_i^\beta}{\Sigma_i \left|\mathbf{p_i}\right|^2} \qquad \alpha, \beta \in x, y, z \qquad S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

eigenvalues of $S^{\alpha\beta}$ $\quad \lambda_1 \geq \lambda_2 \geq \lambda_3 \quad$ and eigenvectors $\mathbf{v_i}$

- transverse momentum with respect to the thrust axis

$$p_{T,thrust} = \frac{1}{2} \cdot M_X sin(\theta_{thrust})$$




| Particle Trajectories | Thrust | Sphericity |
|---|---|---|
|  | $\to \frac{1}{2}$ | $\to 1$ |
|  | $\to 1$ | $\to 0$ |
|  | $\simeq \frac{3}{4}$ | $\simeq \frac{1}{2}$ |

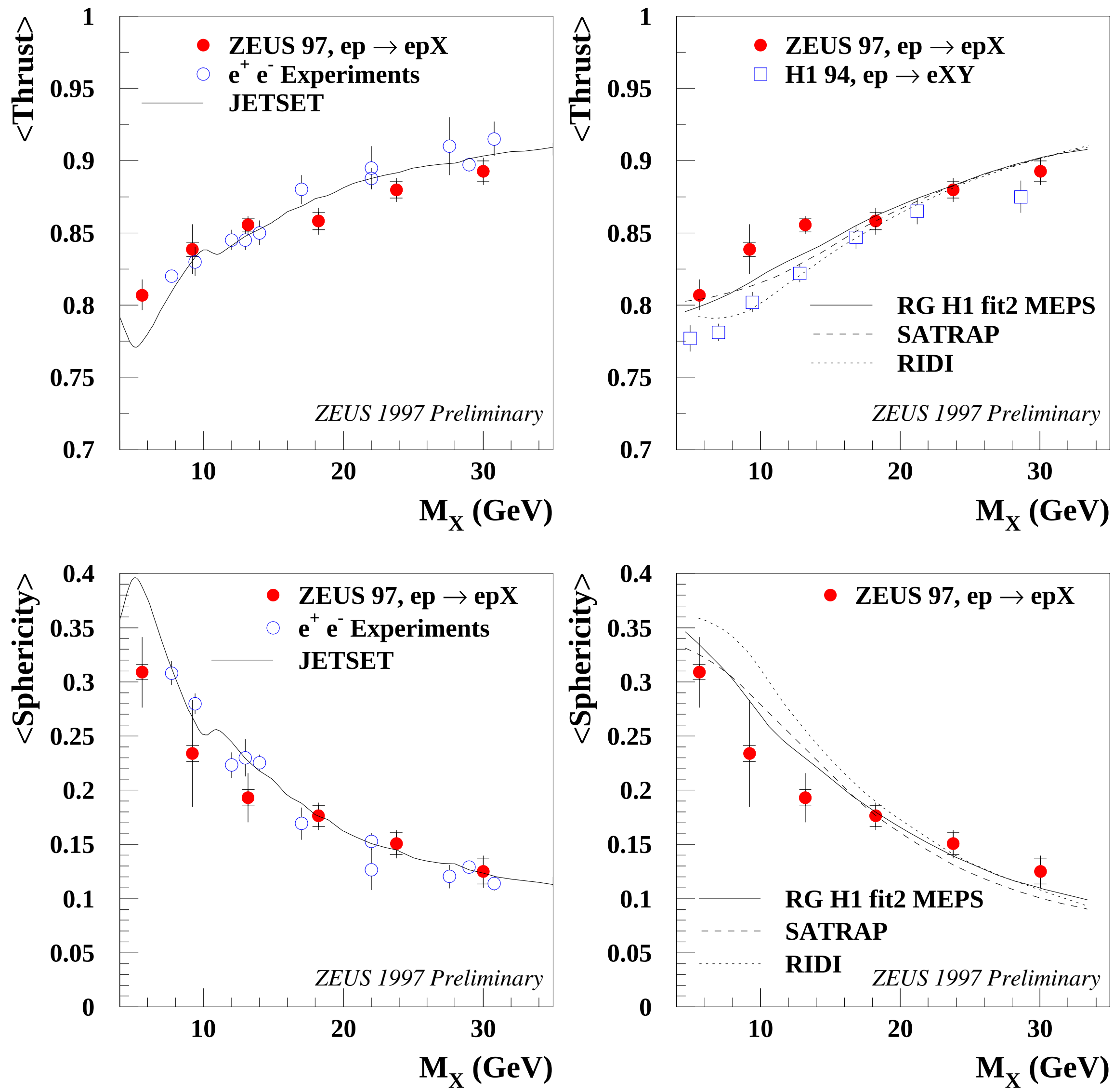
**ZEUS Event Shape Analysis**

$4 < M_X < 35$ GeV $\qquad 0.0003 < x_{I\!P} < 0.03$

$4 < Q^2 < 150$ GeV$^2$ $\qquad 70 < W < 250$ GeV

# $<T>$ and $<S>$ vs $M_X$ - ZEUS

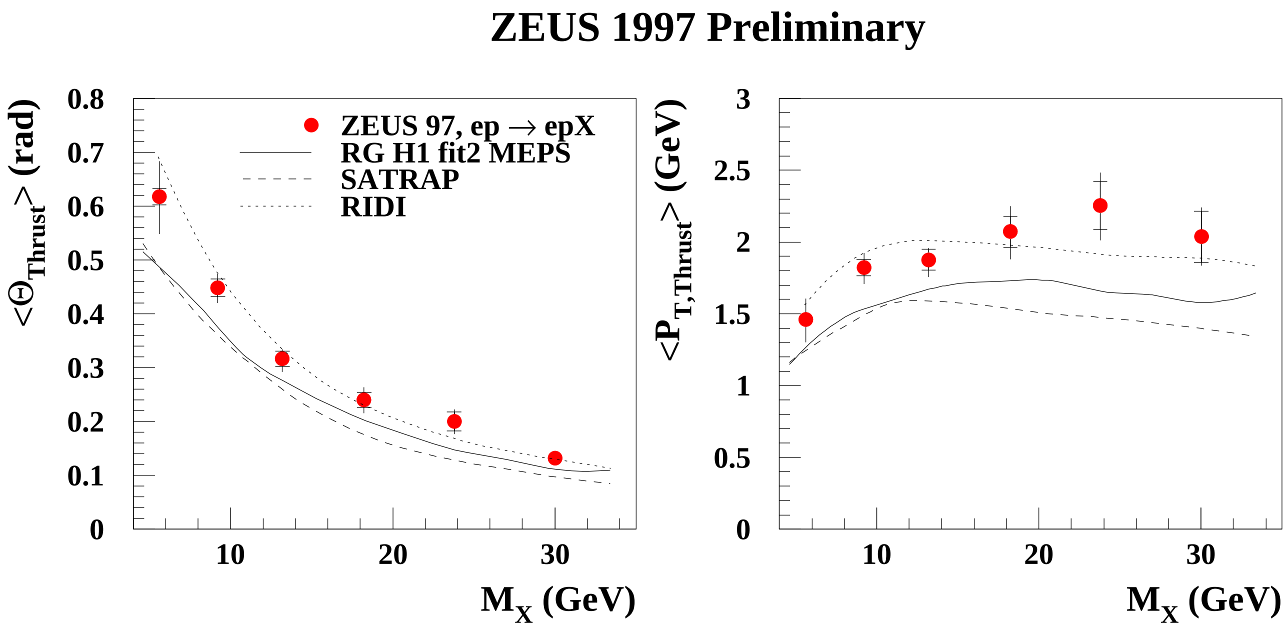
- sample selected: LPS to tag the scattered proton
- $<T>$ and $<S>$ similar to $e^+e^-$ over the full $M_X$ range
- MC models: problems at low $M_X$
- disagreement with H1: different way to select diffractive events

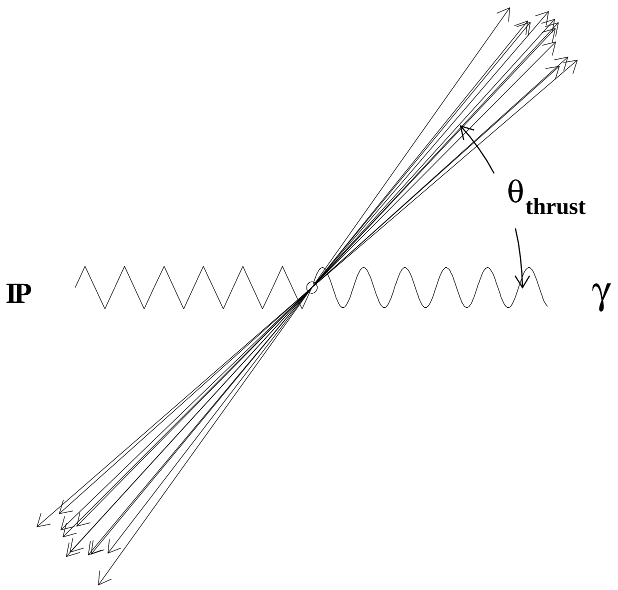



No Model was tuned to the HFS measured with the LPS!

# $<\theta_{Thrust}>$ and $<p_{t,Thrust}>$ vs $M_X$

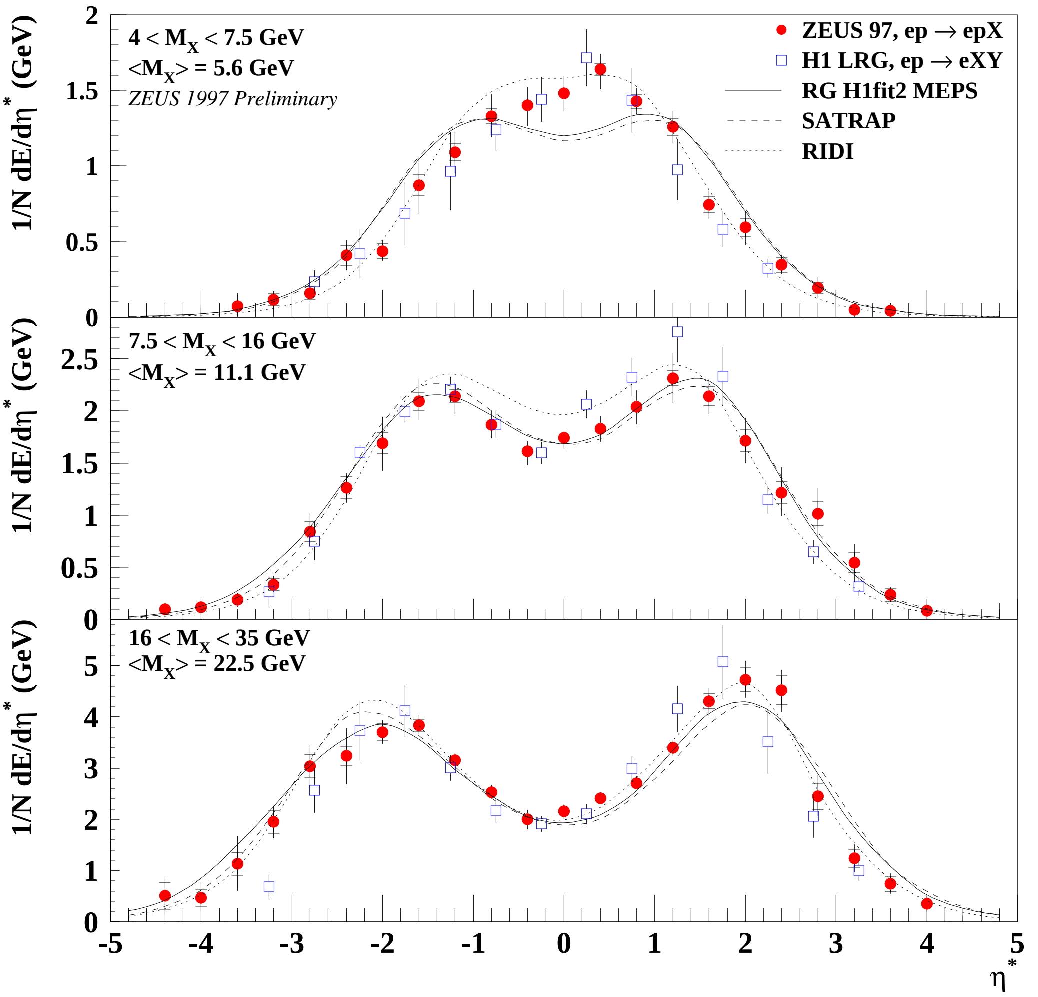
- events are more aligned with $\gamma^* IP$ axis at high $M_X$
- SATRAP and RAPGAP do not produce enough $p_T$
- $q\bar{q}g$ contribution already important at low $M_X$

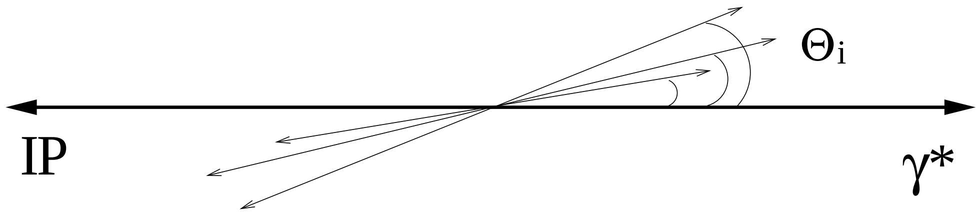


# Energy Flow

- low $M_X$: not well described
- high $M_X$: RAPGAP gives largest asymmetry
- asymmetry in data even larger?
- mostly fair agreement with H1

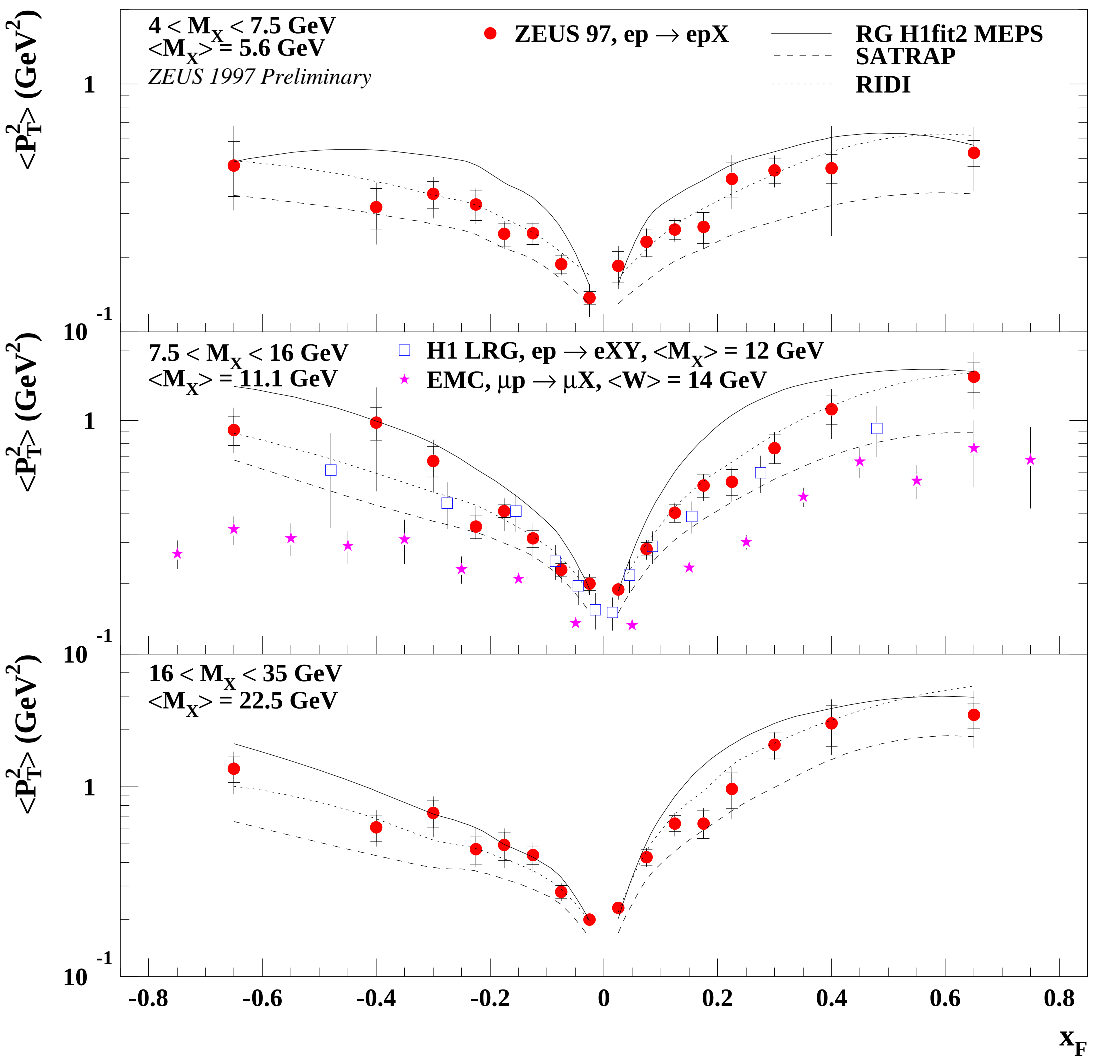


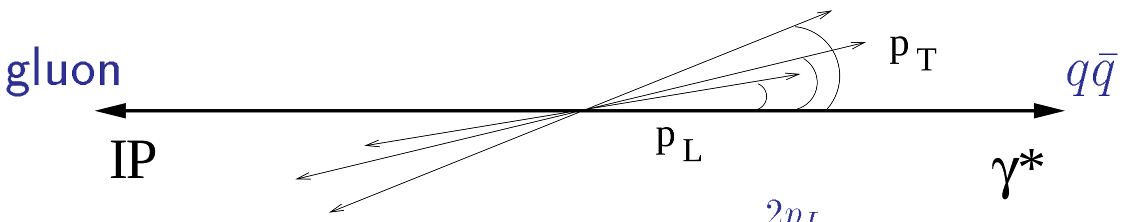




$$\eta^* = -\ln\left(\tan\left(\theta_i/2\right)\right)$$

# Seagull Plot

- asymmetry at large $M_X$
- asymmetry of $IP$ remnant too large (RAPGAP)
- RIDI: OK $\rightarrow$ asymmetry due to $q\bar{q}$ ($\gamma^*$ side) vs gluon ($IP$ side)



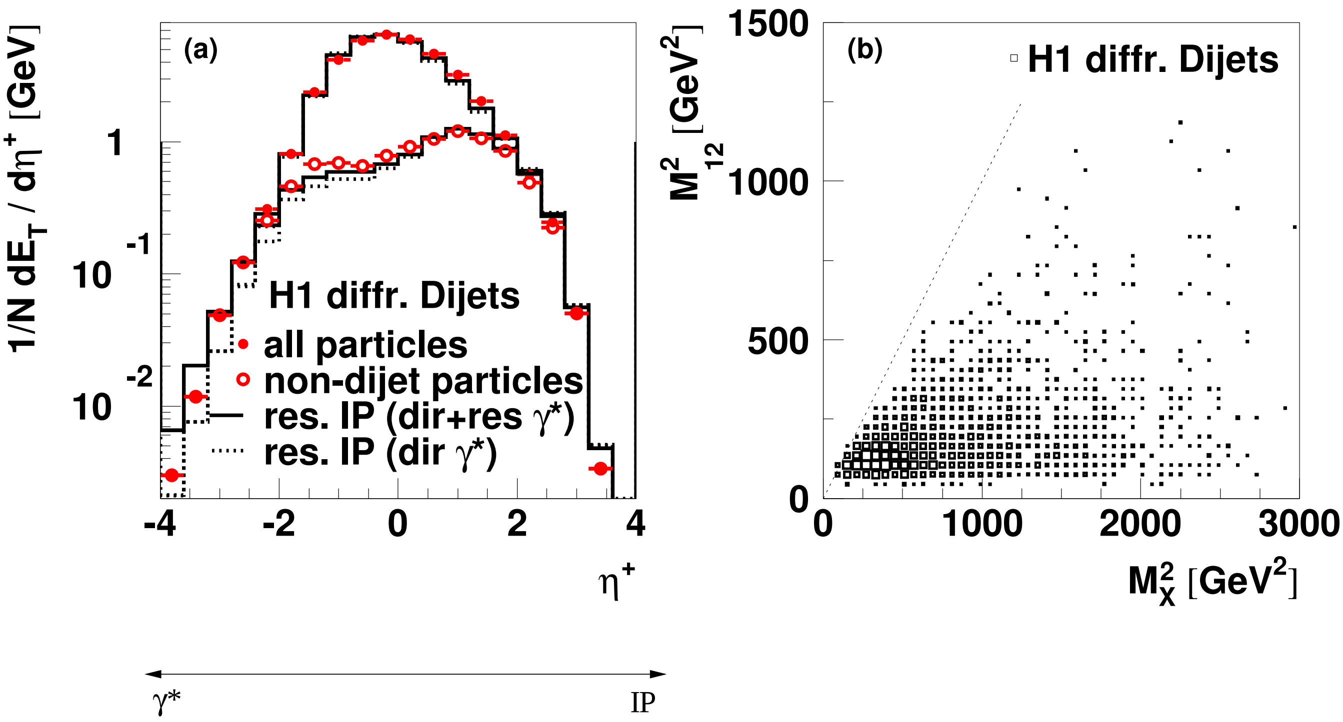




$$x_F = \frac{2p_L}{M_X}$$

# Diffractive Dijets Sample - H1

- Cone Algorithm (R = 1.0) on LRG events
- Dijets: at least 2 jets with $P^*_{T,jet} > 4$ GeV, $-3 < \eta^*_{jet} < 0$

H1 Preliminary




- considerable hadronic activity outside the Dijets

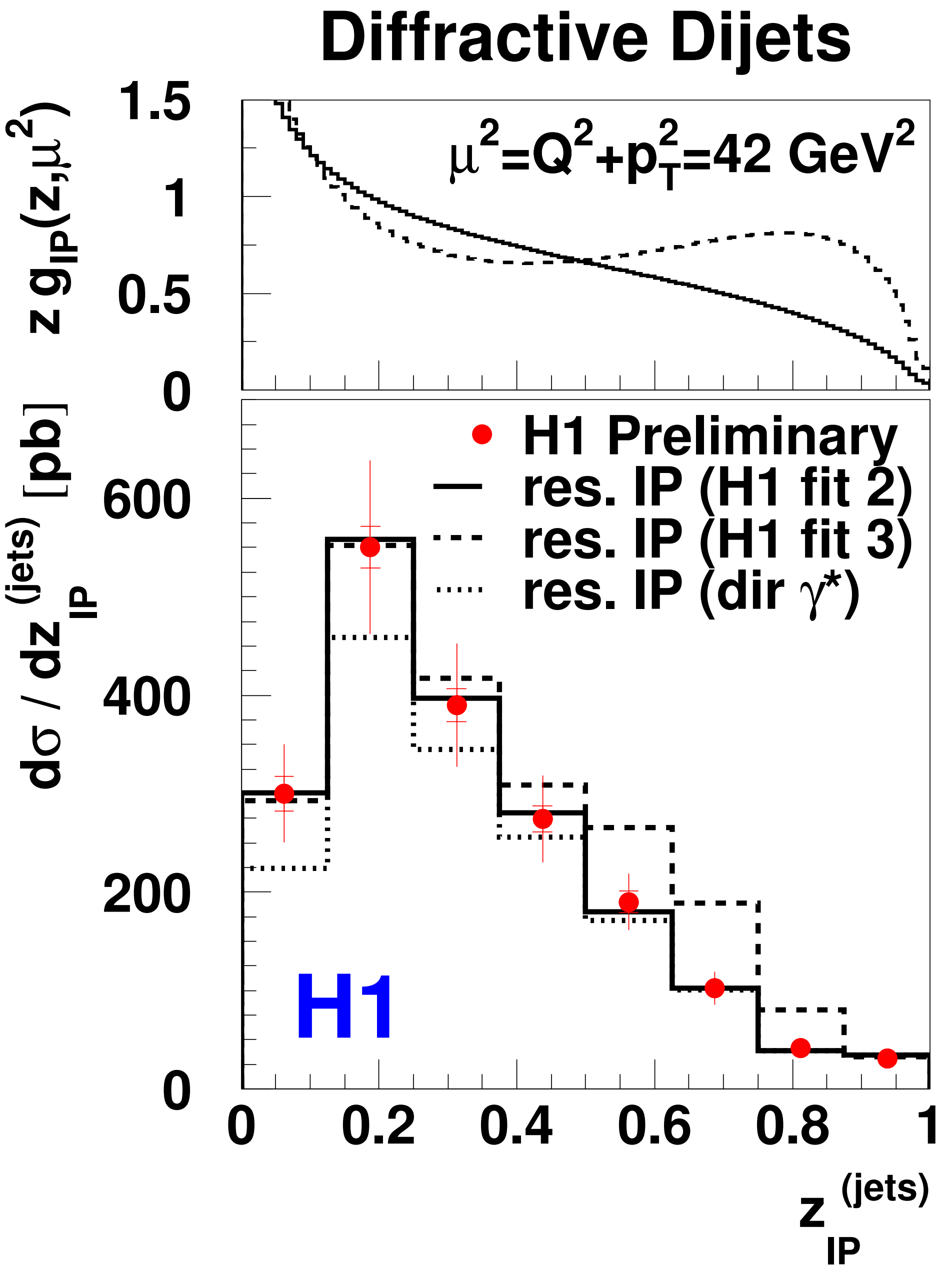
$$4 < Q^2 < 80 \text{ GeV}^2 \qquad 0.1 < y < 0.7$$
$$x_{I\!P} < 0.05$$
$$M_Y < 1.6 \text{ GeV} \qquad |t| < 1.0 \text{ GeV}^2$$

# Diffractive Dijets: Gluon Content

- momentum fraction transferred to dijet system:

$$z_{I\!P}^{jets} = \frac{Q^2+M_{12}^2}{Q^2+M_X^2}$$

- sensitive to gluon distribution of colorless exchange




- flat gluon (fit 2) is preferred
- colorless exchange dominated by gluon

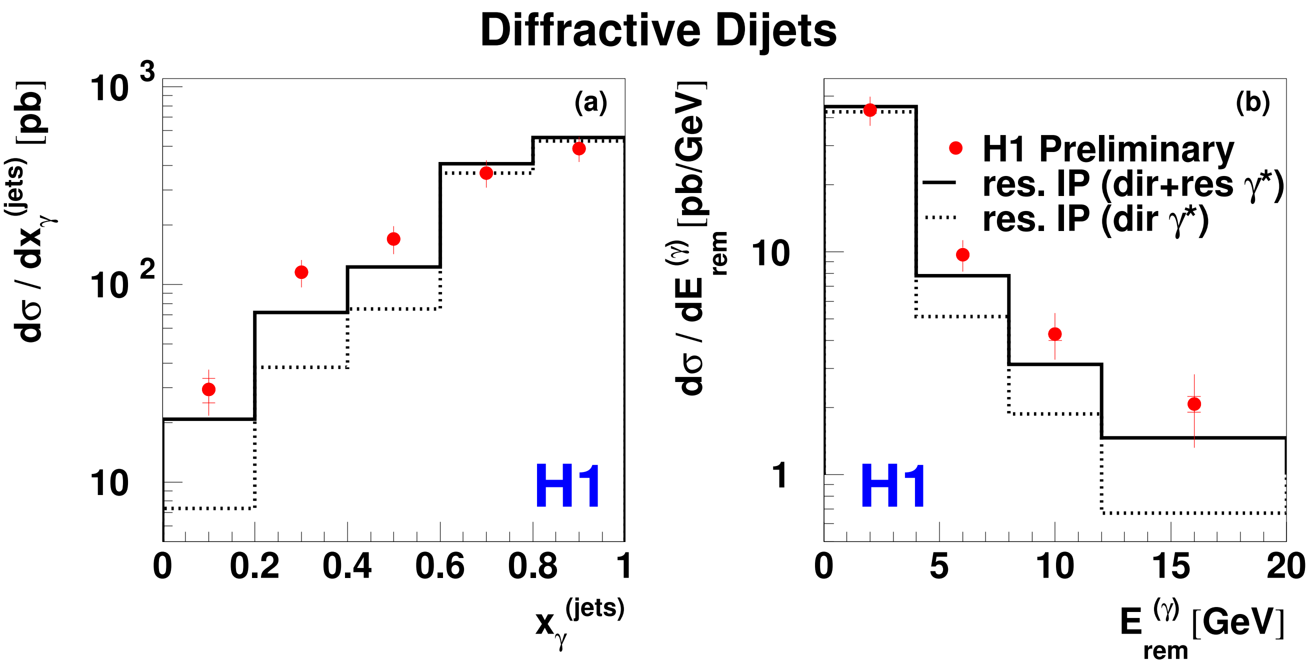
# Diffractive Dijets: Resolved $\gamma^*$

- momentum fraction of $\gamma^*$ entering the hard scattering

$$x_\gamma^{jets} = \frac{\Sigma_{jets}\, E - pz}{\Sigma_{all}\, E - pz}$$

- $\gamma^*$ remnant energy

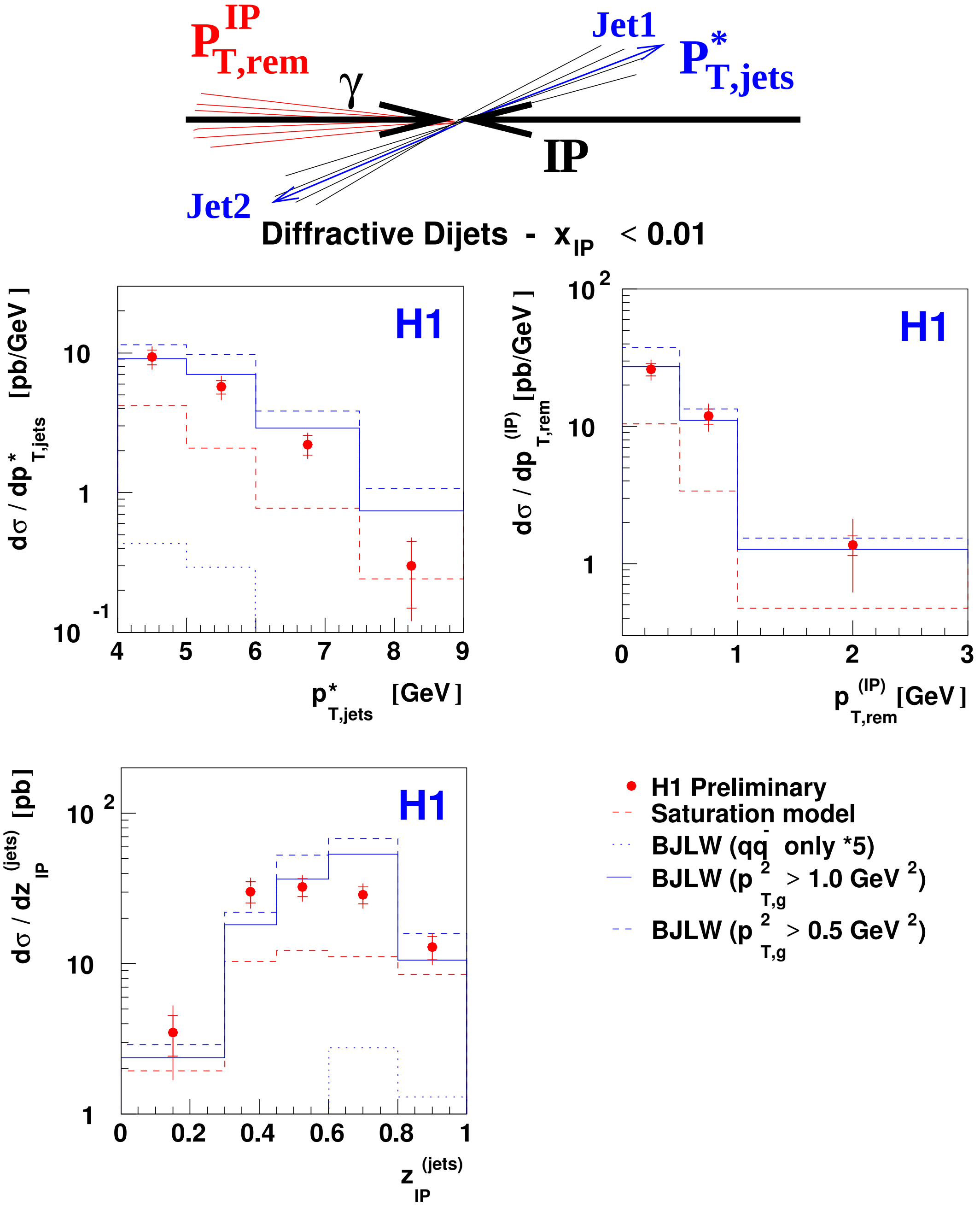
$$E_{rem}^{\gamma} = \sum_{\eta^+ < 0} E - \sum_{jets} E$$




- Resolved $\gamma^*$ improves description of data
- other possible interpretation:
  - NLO contributions
  - contributions without strong $k_T$ ordering

# Diffractive Dijets: $k_T$ ordering

- Analysis performed in restricted phase space: $x_{I\!P} < 0.01$




- Saturation Model (SATRAP): factor 2 too low (strong $k_T$ ordering, gluon distribution ...)
- non-$k_T$-ordered contributions could be important

# Diffractive 3-Jets - ZEUS

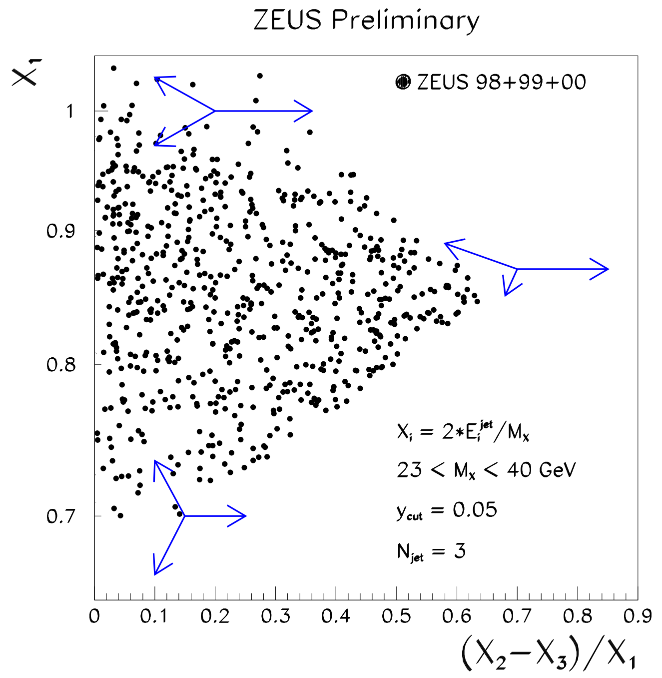
- exclusive $k_T$ algorithm with $y_{cut} = 0.05$ using LRG events clustering for

$$y_{ij} = \frac{2 \cdot \min(E_i^2, Ej^2)(1 - \cos\theta_{ij})}{M_X^2} < y_{cut} \qquad (E_{jet} \gtrsim 4 \text{ GeV})$$

- $|\eta_{lab}^{jet}| < 2.3$

- fractional jet energy:

$$x_i = \frac{2 \cdot E_i^{jet}}{M_X} \text{ sorted according to } x_1 \geq x_2 \geq x_3$$

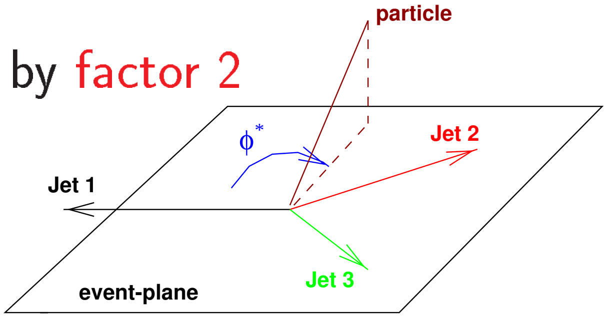


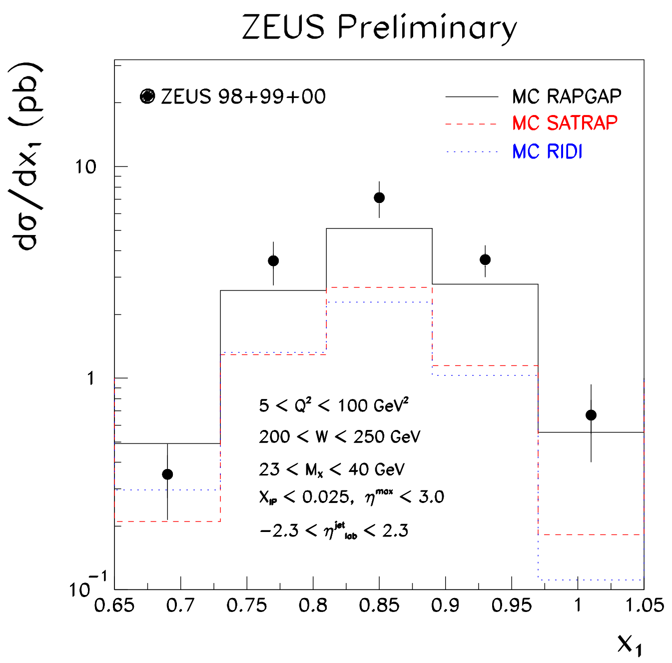

- three different 3-jet configurations

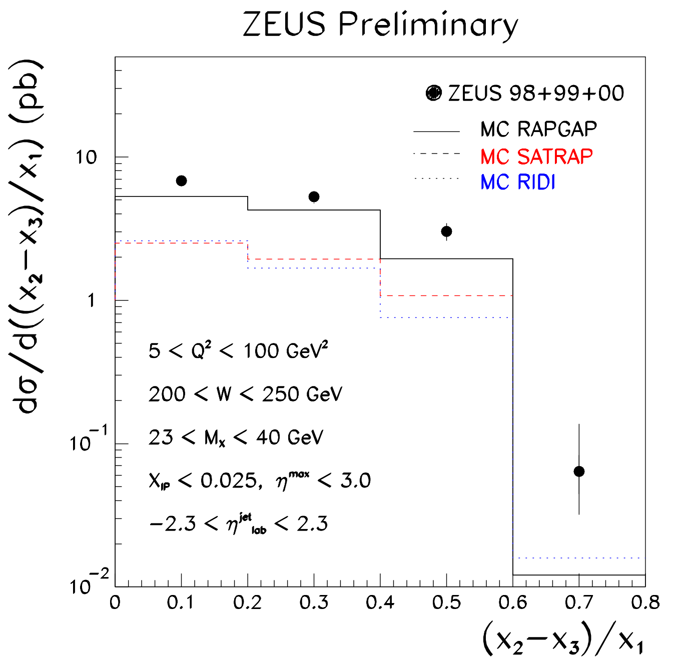
| | |
|---|---|
| $5 < Q^2 < 100$ GeV$^2$ | $200 < W < 250$ GeV |
| $4 < M_X < 40$ GeV | $x_{I\!P} < 0.025$ |
| | $\eta_{hadron}^{max} < 3.0$ |

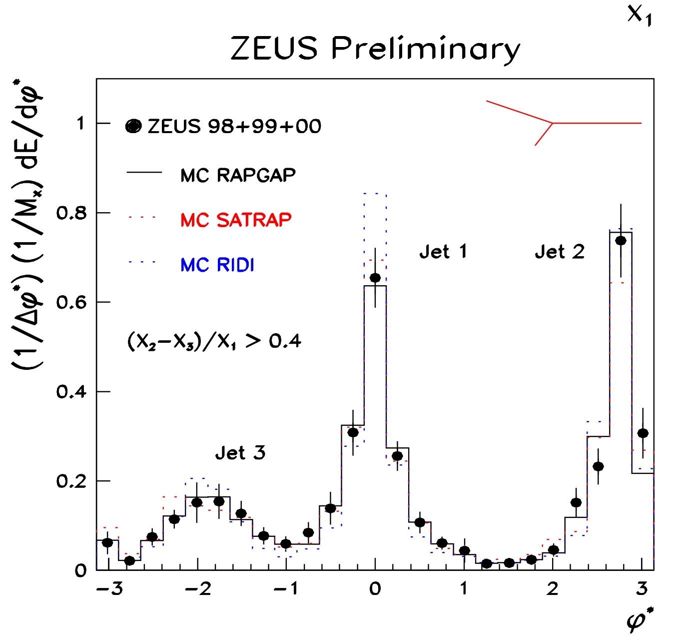
# Diffractive 3-Jets

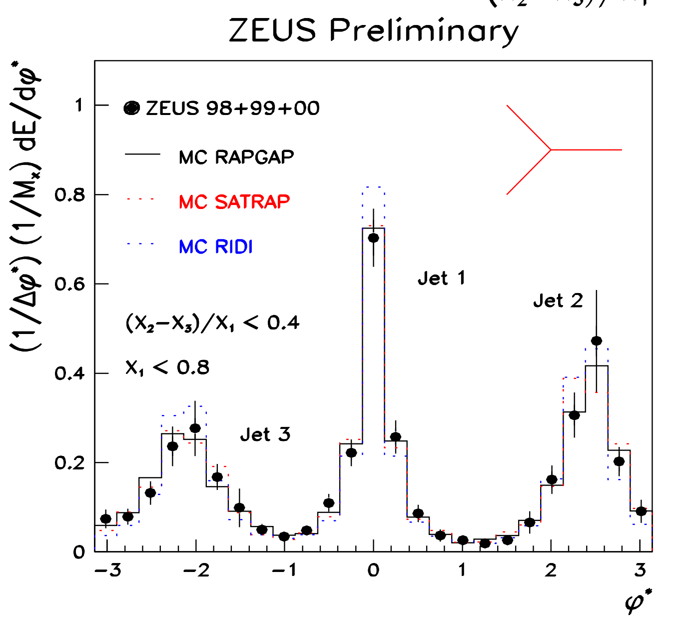
- no configuration seems to be preferred
- described by all models
- Normalization of SATRAP, RIDI off by factor 2



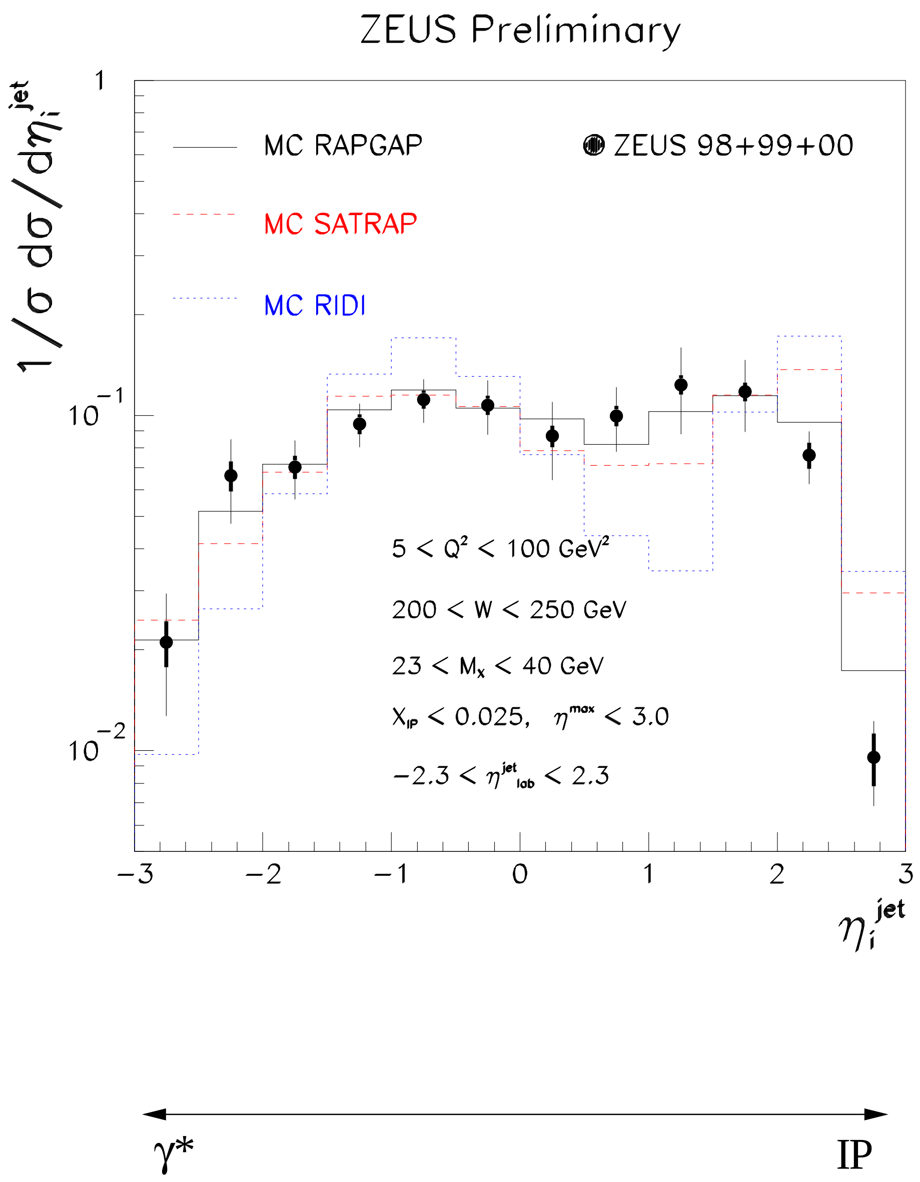



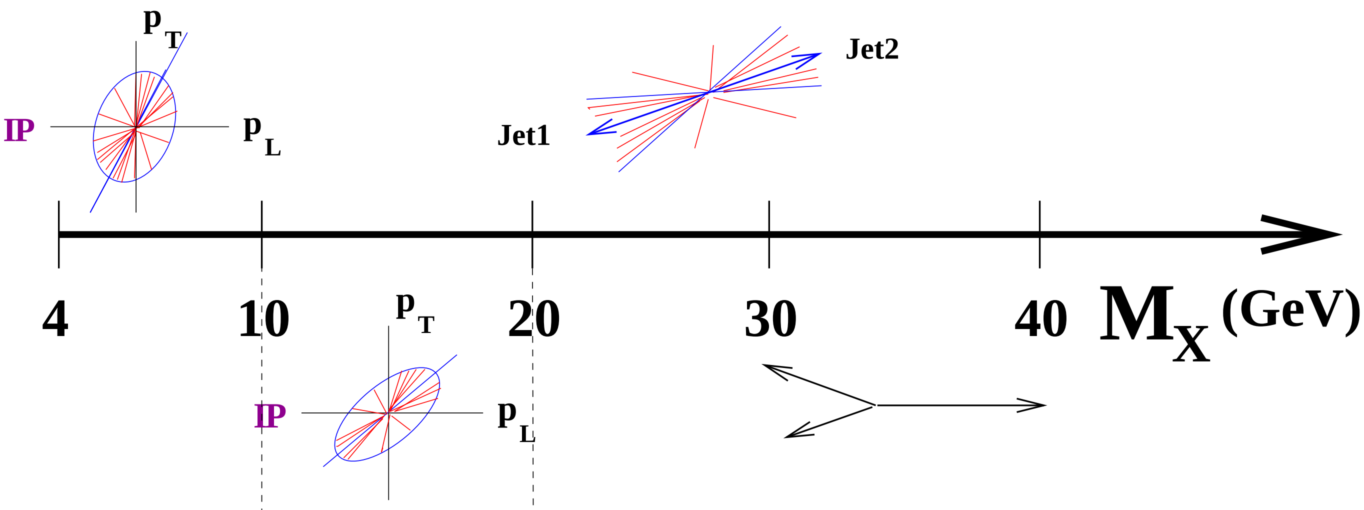



# Diffractive 3-Jets

- distribution normalized to cross section
- Gluon-dominated resolved $IP$ consistent with data
- SATRAP and RIDI: asymmetric double peaks
  $\rightarrow$ indication for non-$k_T$-ordered contribution being necessary



# Summary of Final State Topology




| | | |
|---|---|---|
| $<T>$ | $<T>$ | Jet Analysis |
| $<\theta_{Thrust}>$ | $<\theta_{Thrust}>$ | Dijets |
| E-Flow | Seagull | 3-Jets |

- Global Event Shape Analysis
  - Thrust, Sphericity: superficially similar to $e^+e^-$
  - final state is more collimated at high $M_X$
  - and more aligned with $\gamma^* I\!P$ axis
  - slight asymmetry: more $p_T$ in $\gamma^*$ hemisphere for high $M_X$
- clear Dijet structure
  - considerable hadronic activity outside the jets
- evidence for 3-Jet production
  - no 3-Jet configuration dominates

# Conclusions

- no MC model describes all aspects of the final state
- resolved $I\!P$ (RAPGAP) gives overall best description
- flat gluon (fit 2) preferred
- photon dissociative model (RIDI) produce shape correctly but normalization too low
- final state appears dominated by $q\bar{q}g$
- some contribution from resolved $\gamma^*$?
  $\rightarrow$ need more $q\bar{q}$
- indication for non-strong-$k_T$ ordering or some other source of extra $k_T$