Photoproduction of Events with Rapidity Gaps Between Jets with ZEUS at HERA

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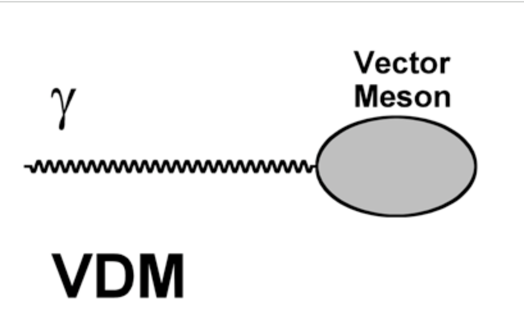
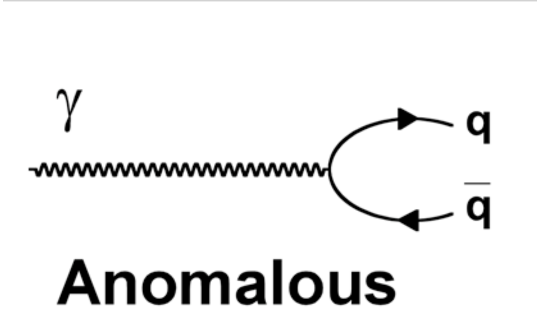
Outline

- Introduction to Rapidity Gaps
  - Photoproduction
  - Diffraction
  - Hard Diffractive Photoproduction
- HERA and ZEUS
- Simulation of photoproduction events
- Reconstruction
- Event Selection
- Comparisons between Data and MC
- Results

Photoproduction in ep Collisions

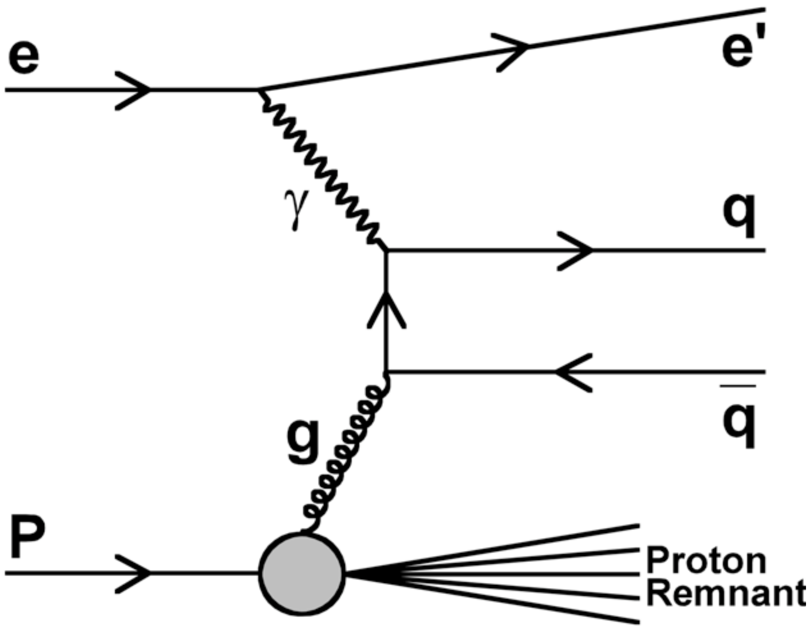




- **$Q^2 \sim 0$ in Photoproduction**
  - **ep cross section has $1/Q^4$ dependence**
  - **Majority of ep events are photoproduction**
- **Time γ has to fluctuate into hadronic object: $t \sim E_\gamma/Q^2$**
  - **Vector Dominance Model (VDM)**
    - Long time: γ forms bound states of mesons
  - **Anomalous**
    - Medium time: γ fluctuates into unbound qq pair
  - **Direct**
    - Short time: γ acts as a point-like object
- **Resolved = VDM + Anomalous**

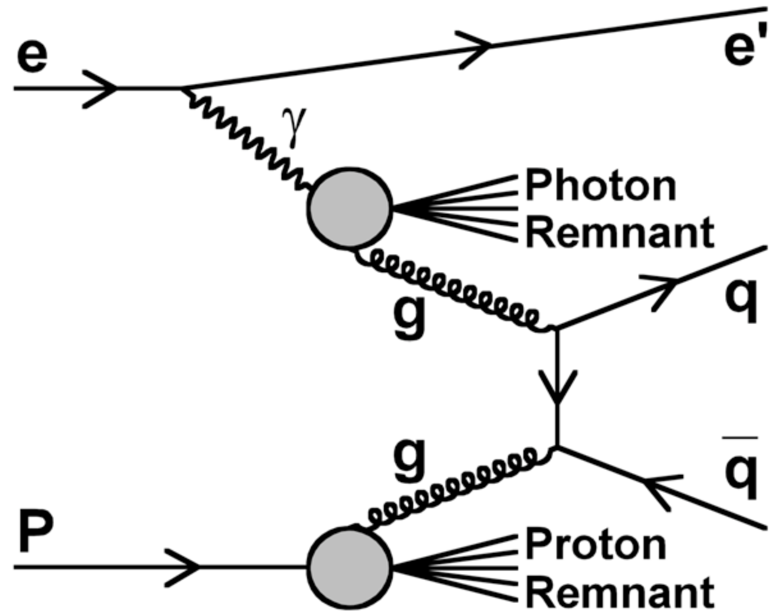
Direct & Resolved Photoproduction

Direct Photoproduction



Boson-Gluon Fusion

Resolved Photoproduction

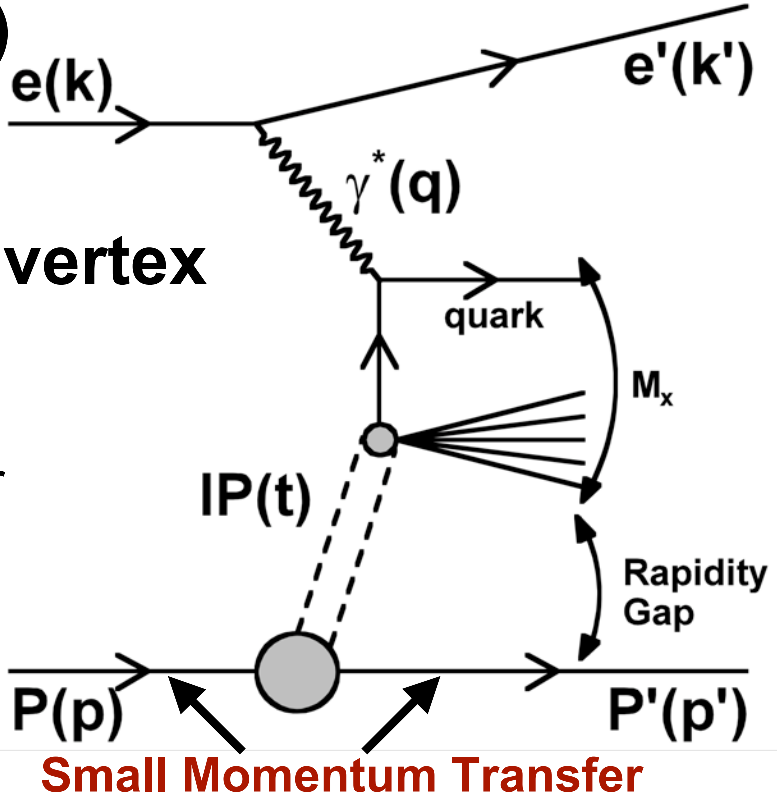


$gg \rightarrow q\bar{q}$

- **Direct: γ couples directly to parton in proton**
- **Resolved: parton from γ couples to parton in proton**

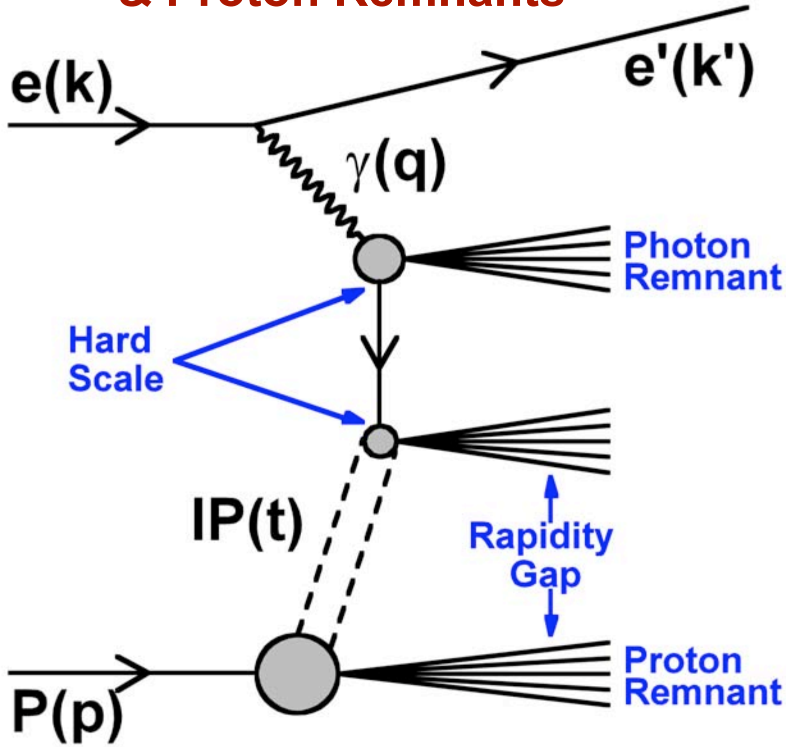
Diffraction in ep Collisions

- **Two "definitions" of diffraction**
  - **Final state particles preserve quantum numbers of associated initial state particles**
  - **Presence of rapidity gap**
- **Exchange object: Pomeron (IP)**
  - **Quantum numbers of vacuum**
  - **Does not radiate color charge**
- **Small momentum transfer at p vertex**
  - **Soft diffraction: No hard scale exists**
  - **Hard diffraction: A hard scale exists**
    - Example: Large momentum transfer between Pomeron and quark
    - Perturbative QCD (pQCD) is applicable

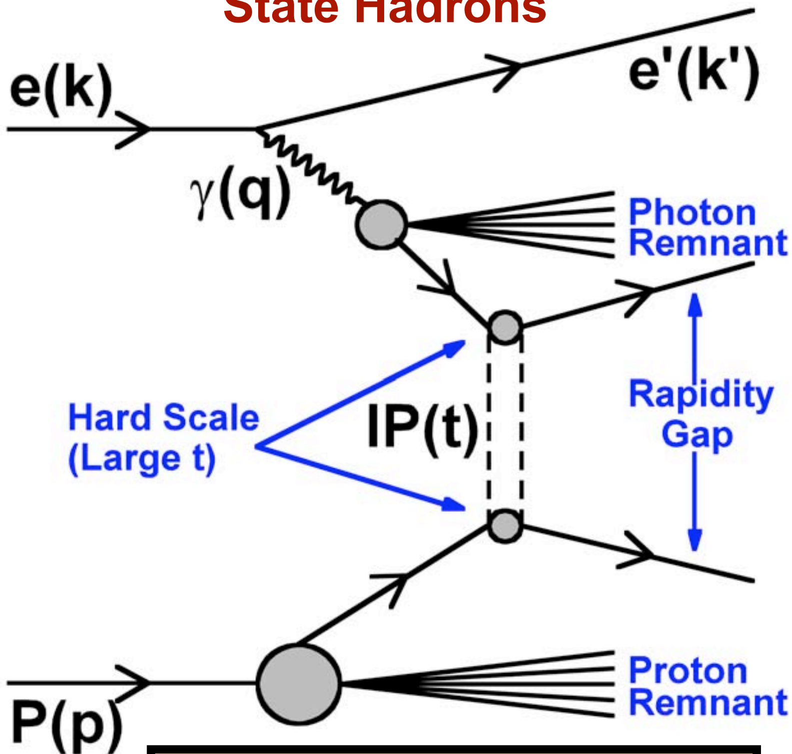


Hard Diffractive Photoproduction

Rapidity Gap Between Hadron & Proton Remnants



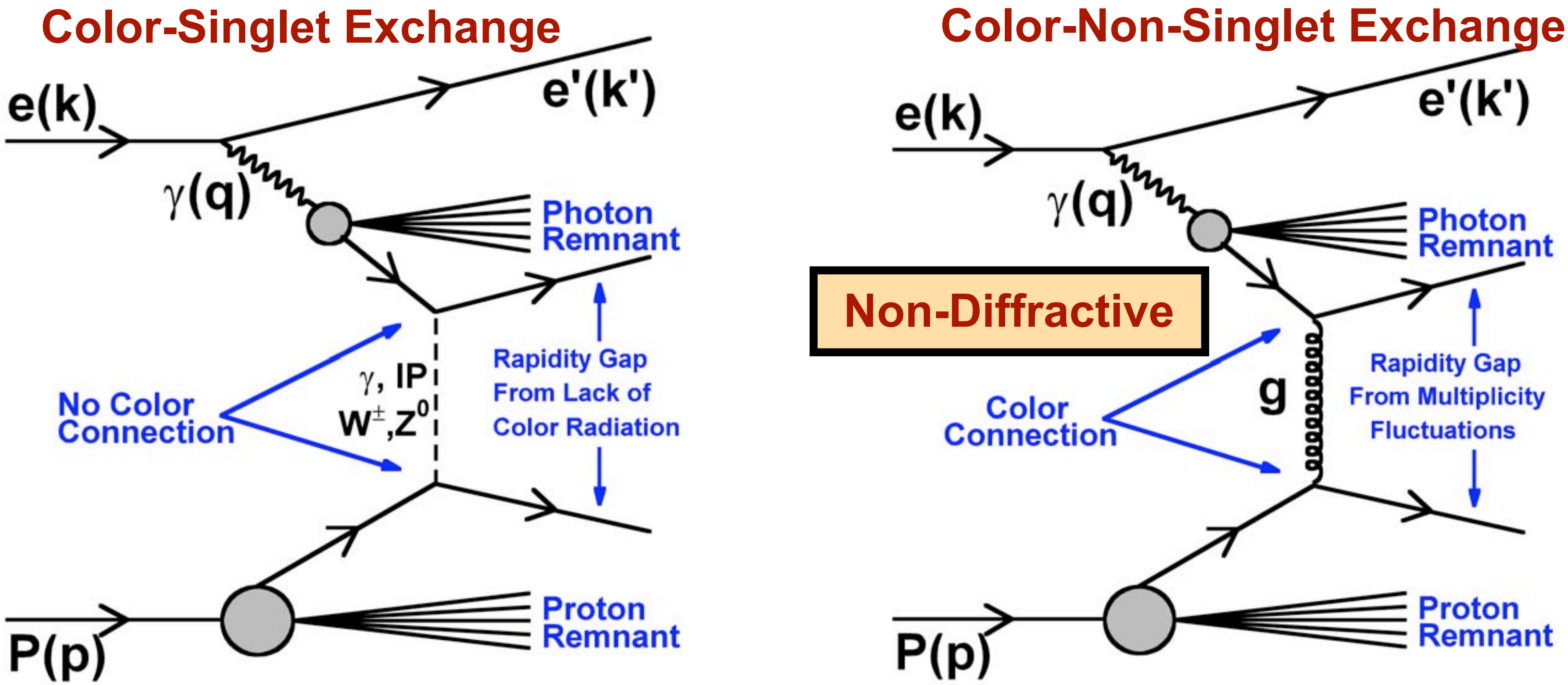
Rapidity Gap Between 2 Final State Hadrons



Subject of this analysis

- **Study the nature of the Pomeron exchange**
  - Observe Color-Singlet (CS) exchange
- **Hard Scale allows application of pQCD to diffractive process**

Rapidity Gaps between Jets



- **2 Sources of Rapidity Gaps between Jets**
  - **Color-singlet Exchange**
    - Lack of color radiation produces gap
    - Example: Pomeron exchange
  - **Color-Non-Singet Exchange**
    - Fluctuations in particle multiplicity produces gap
    - Non-diffractive

The Gap Fraction f(Δη)

Dijet Events with large Rapidity separation between jets & $E_T^{Gap} < E_T^{Cut}$

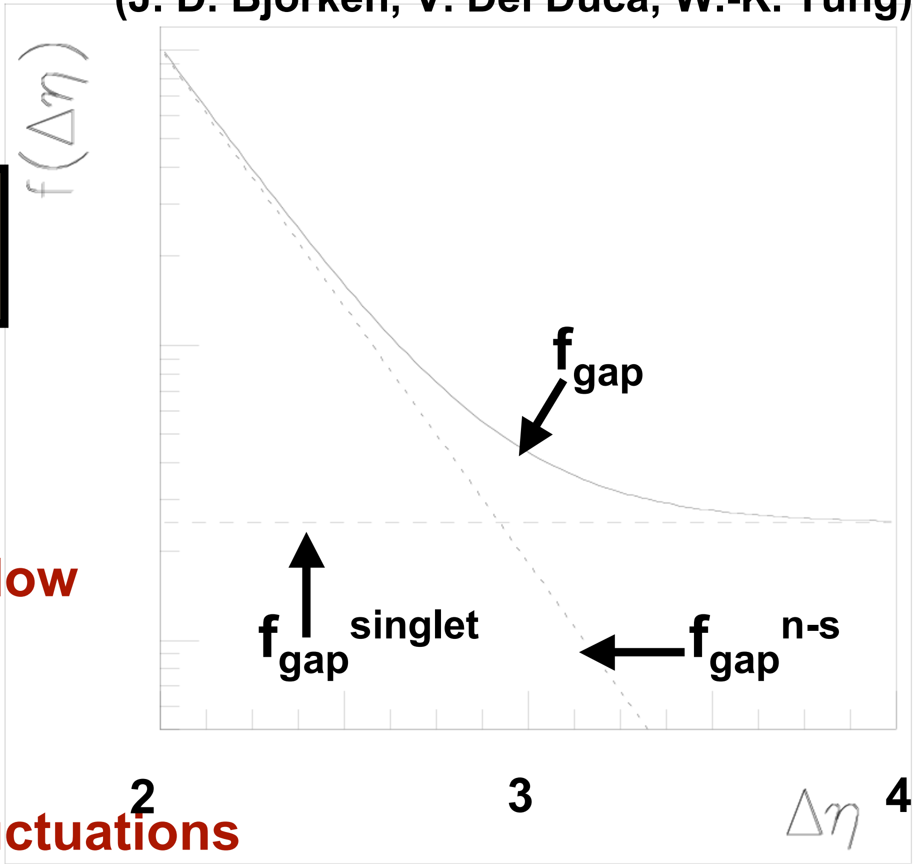
$$f(\Delta\eta) = \frac{d\sigma_{gap} / d\Delta\eta}{d\sigma / d\Delta\eta}$$

All Dijet Events with large Rapidity separation between jets

$$\sigma_{gap} = \sigma_{gap}^{singlet} + \sigma_{gap}^{non-singlet}$$

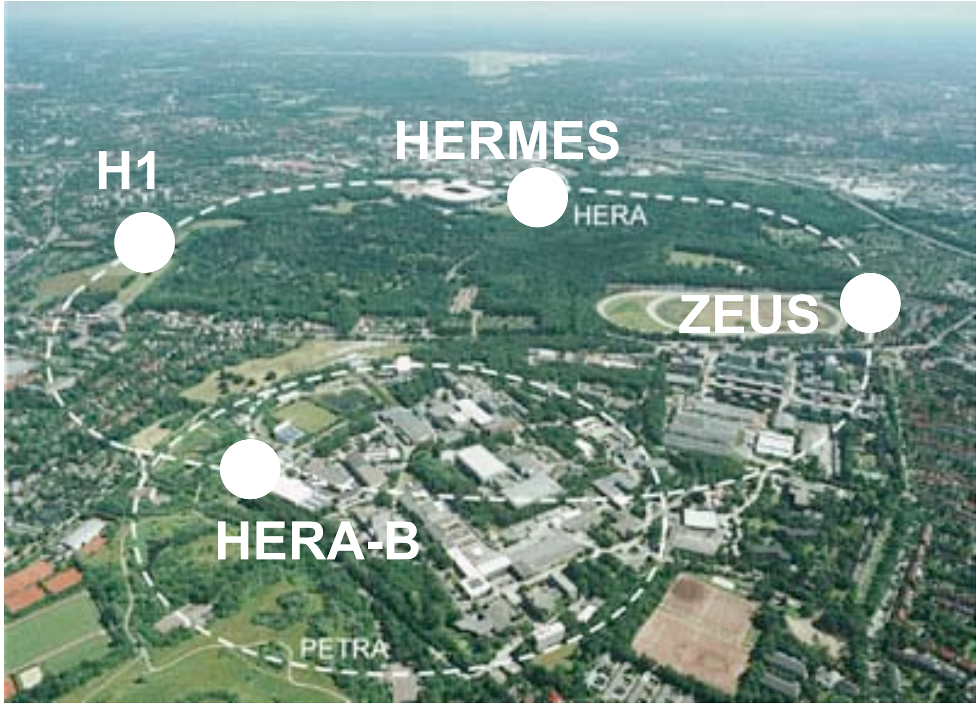
- **Color Singlet**
  - Gap created by lack of color flow
  - f(Δη) constant in Δη
- **Color Non-Singlet**
  - Gap created by multiplicity fluctuations
  - f(Δη) decreases exponentially with Δη

Expectation for Behavior of Gap Fraction (J. D. Bjorken, V. Del Duca, W.-K. Tung)



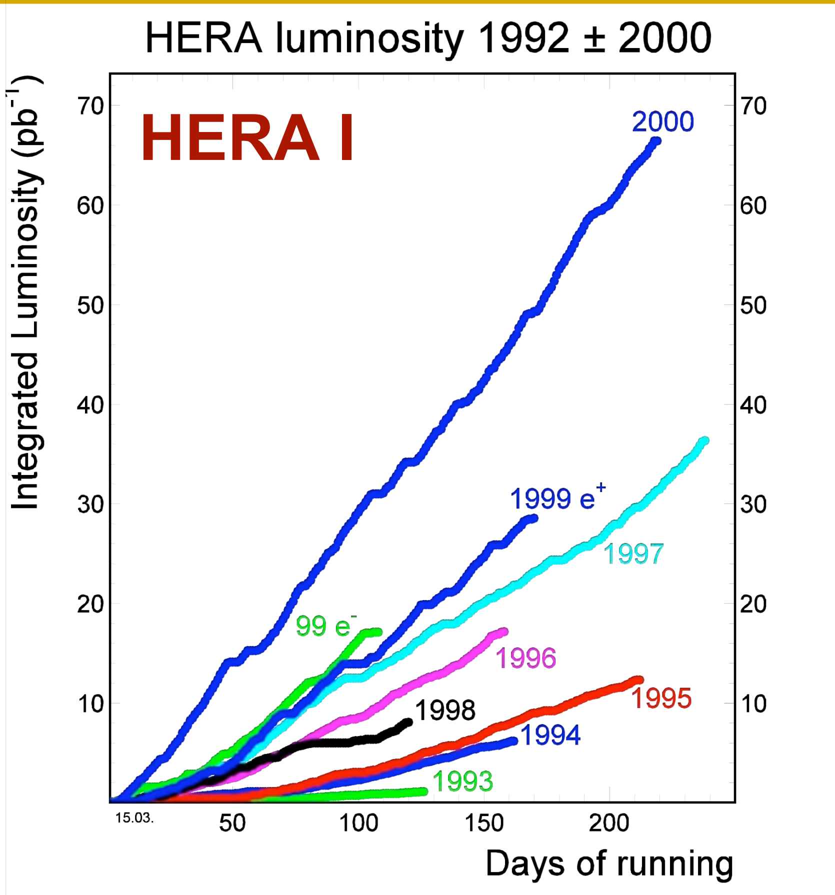
HERA

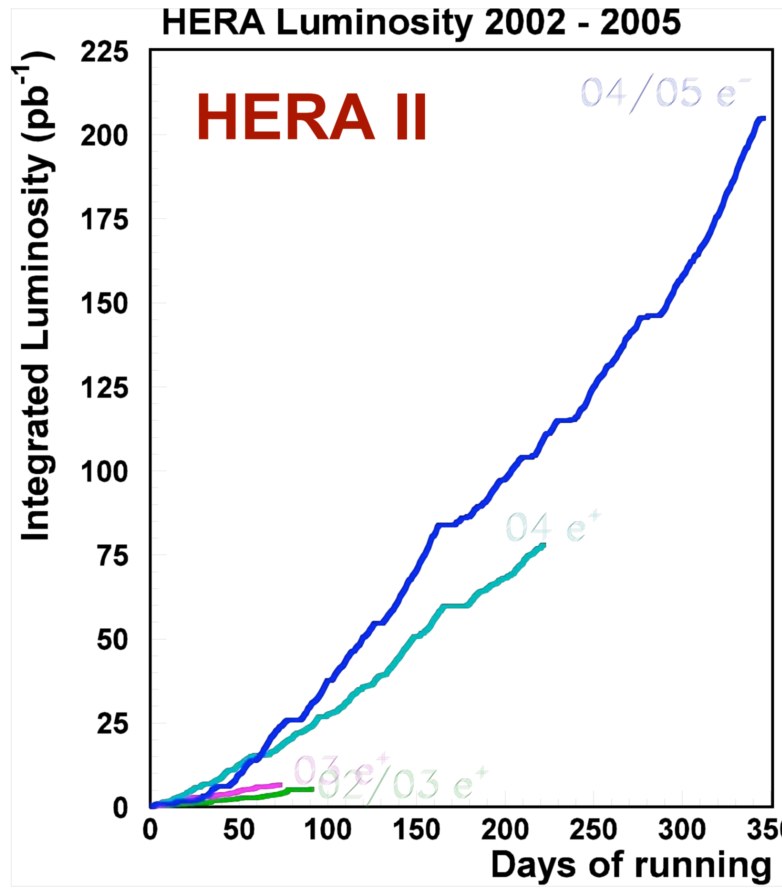
DESY
Hamburg, Germany



- **Beam Energy**
  - **820 GeV Protons (1992-97)**
  - **920 GeV Protons (since 1998)**
  - **27.5 GeV e+ or e-**
  - **CM Energy: ~300/320 GeV**
    - Equivalent to 50 TeV Fixed Target experiment
- **96 ns crossing time**
- **220 bunches**
  - **Not all filled**
- **Currents:**
  - **~90 mA Protons**
  - **~40 mA Leptons**
- **Instantaneous Lumi**
  - **~4x10^{31} cm^{-2} s^{-1}**

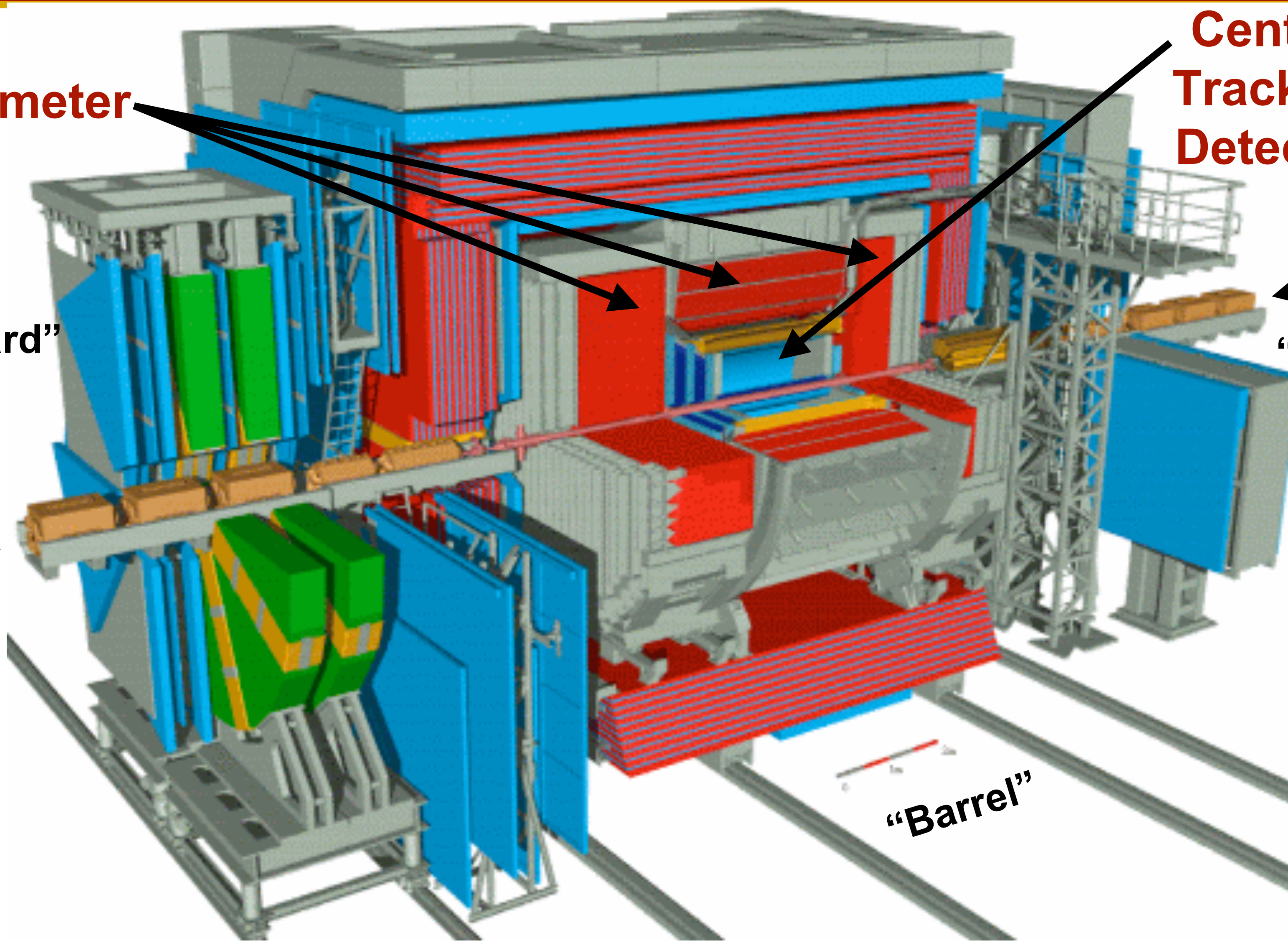
HERA I and II Luminosity





- **HERA I: 1992 – 2000**
  - e^-: 27 pb^{-1} e^+: 166 pb^{-1}
- **HERA II: 2002 – 2007**
  - 5x lumi and polarization
  - e^-: 205 pb^{-1} e^+: 90 pb^{-1}

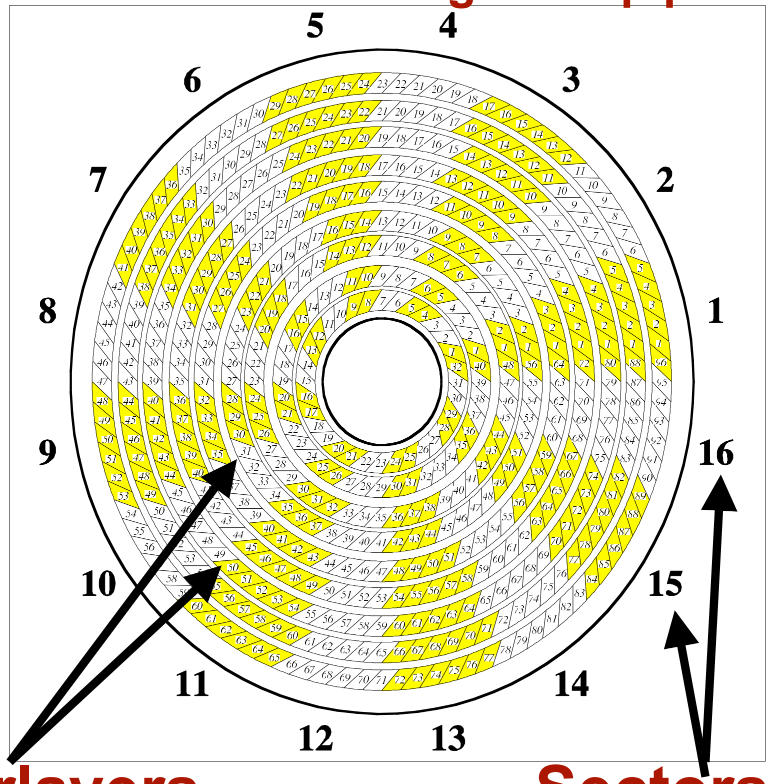
ZEUS Detector



Central Tracking Detector

- **Cylindrical Drift Chamber in 1.43 T magnetic field**
- **Covers 15° < θ < 164° (-1.96 < η < 2.04)**
- **Organization**
  - **16 azimuthal sectors**
  - **9 concentric superlayers**
  - **8 radial layers in a superlayer**
  - **Between 32-96 cells in a superlayer**
- **Resolutions**
  - **Track transverse momentum**
    - $\sigma/p_T = [(0.005p_T)^2 + (0.0016)^2]^{1/2}$
  - **Vertex Position**
    - x and y: accurate to 1 mm
    - z: accurate to 4 mm

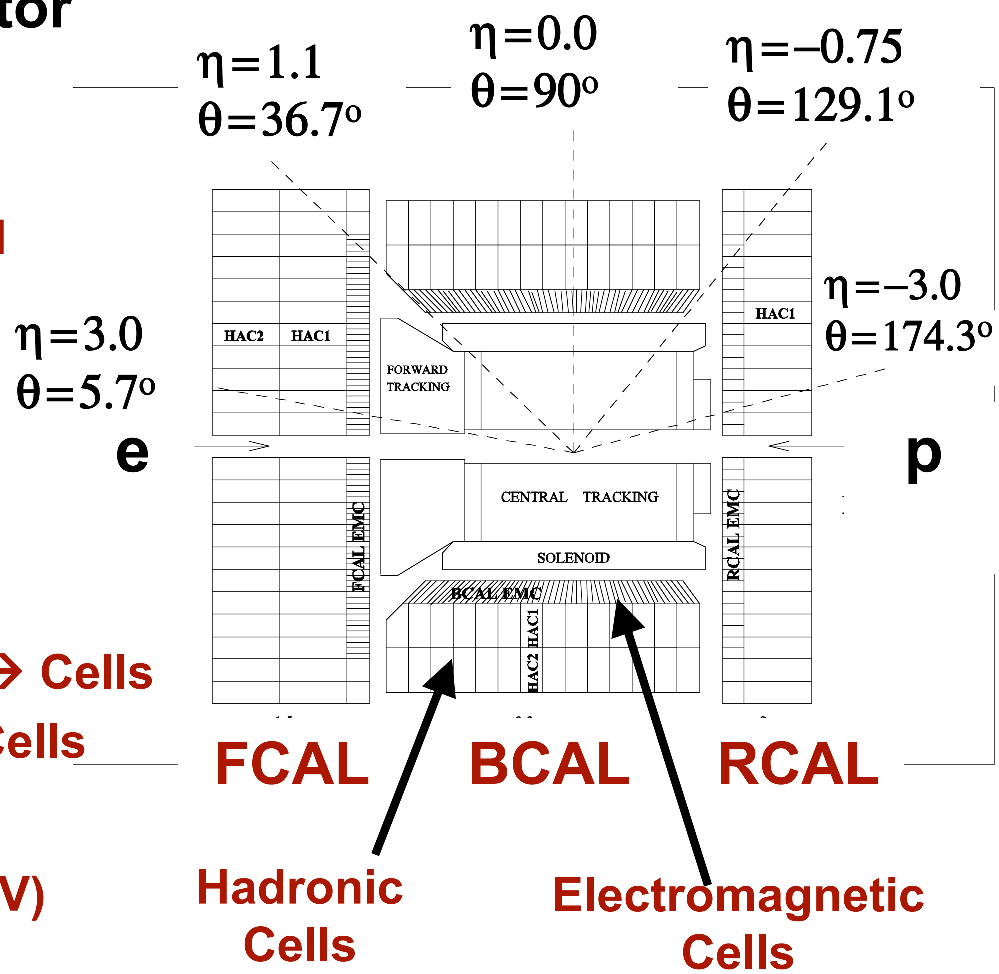
View of CTD along Beampipe



Superlayers **Sectors**

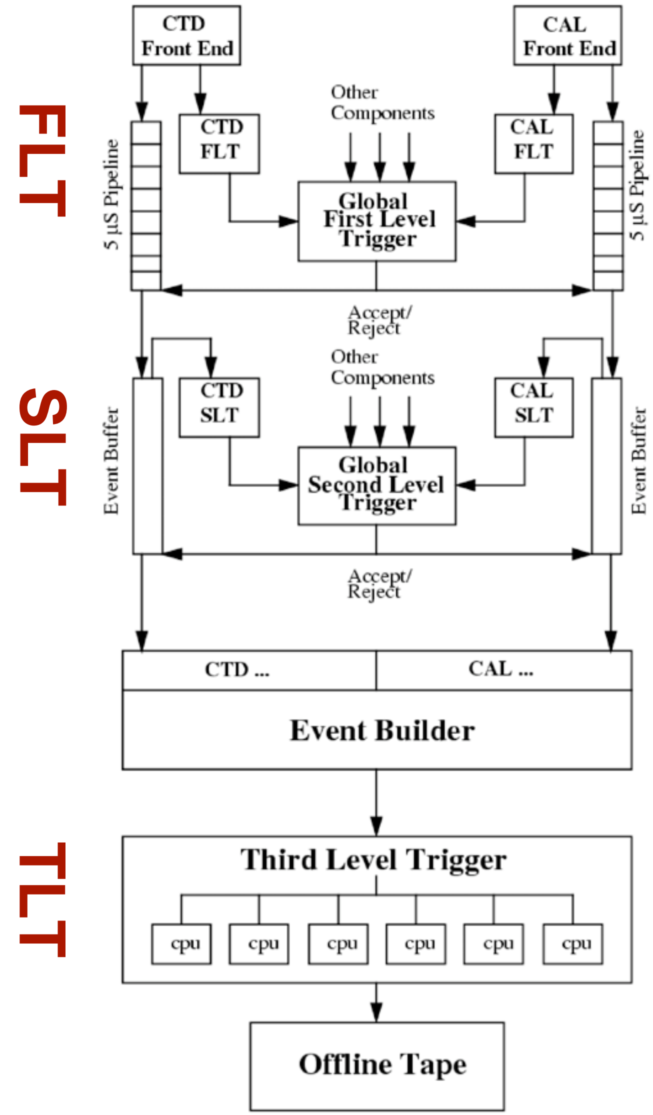
Uranium Calorimeter

- **Composed of plastic scintillator and depleted uranium**
- **Compensating**
  - Equal response to electrons and hadrons of same energy
- **Sampling**
  - Most energy absorbed by U
- **Segmented**
  - 3 Regions: FCAL, BCAL, RCAL
  - Regions → Modules → Towers → Cells
  - Hadronic and Electromagnetic Cells
- **Resolution (from test beam)**
  - Electromagnetic: $\sigma = 0.18/\sqrt{E(GeV)}$
  - Hadronic: $\sigma = 0.35/\sqrt{E(GeV)}$



ZEUS Trigger

- **First Level (4.4 μs)**
  - Dedicated custom hardware
  - Pipelined without deadtime
  - Global & regional energy sums
  - Isolated e and μ recognition
  - Track quality information
- **Second Level (6 ms)**
  - Commodity transputers
  - Calorimeter timing cuts
  - Cuts on $E\text{-}p_z$ and E_T
  - Vertex and tracking information
  - Simple physics filters
- **Third Level (0.3 s)**
  - Commodity processor farm
  - Full event info available
  - Refined jet and lepton finding
  - Advanced physics filters



Crossing: 10^7 Hz

After FLT: ~1000 Hz

After SLT: ~100 Hz

After TLT: ~1 Hz

Simulation of γp Events PYTHIA

- **Accurate hadronization model**
  - Many input parameters
- **Adjustable p_T^{Min1} and p_T^{Min2}**
  - p_T^{Min1}: p_T^{Min} of hardest interaction
  - p_T^{Min2}: p_T^{Min} of soft secondary interactions (Multi-Parton Interactions)
- **QCD Radiation: Matrix Element+Parton Shower (MEPS)**
- **Hadronization: String Model**
- **Multi-Parton Interactions in resolved MC**
- **Color-singlet exchange in PYTHIA**
  - No Pomeron exchange model in PYTHIA
  - Use high-t γ exchange for qq scattering in LO resolved process
  - Reproduce topology of rapidity gap events
  - Not a source of events with rapidity gaps in hard diffractive γp

Simulation of γp Events HERWIG

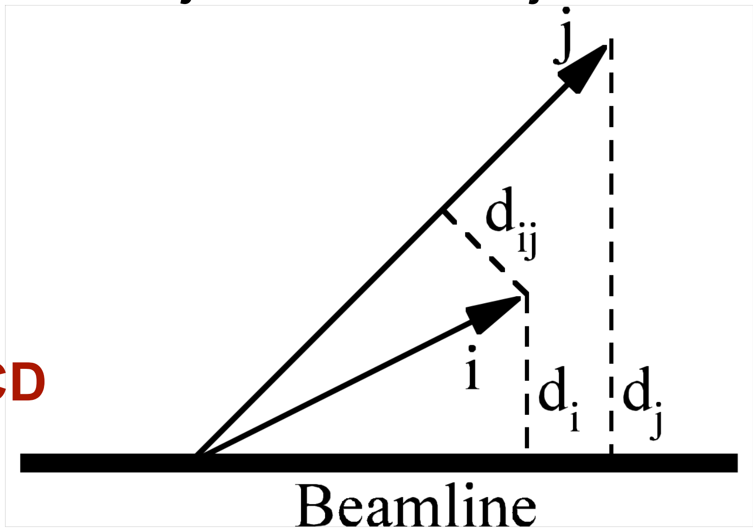
- **Simple universal hadronization model**
  - **Few input parameters**
- **Adjustable p_T^{Min1} (but not p_T^{Min2})**
- **QCD Radiation: MEPS**
- **Hadronization: Cluster Model**
- **JIMMY package used to simulate MPIs**
  - **Multi-Parton Interactions in resolved & CS MC**
- **Color-singlet exchange in HERWIG**
  - **BFKL pomeron as exchange object**
    - Resummation of leading log diagrams in 1/x

Reconstruction

- **Tracks: Use only information from CTD**
- **Vertex: Use CTD tracks fit to 5-parameter Helix model**
- **Calorimeter**
  - **Use cell position, magnitude of PMT pulse, time of PMT pulse**
  - **Island formation: Cells merged based on location and size of energy deposits**
- **e^-/e^+: SINISTRA95 Neural Network electron finder**
- **Energy Flow Objects (EFOs)**
  - **Combine track and calorimeter information for hadrons**
    - CTD has better angular resolution than CAL
    - CTD has better energy resolution at low energy than CAL

k_T Cluster Jet Algorithm

- **Historically used in e^+e^- experiments**
- **Procedure**
  - **For every object *i* and pair of objects *i,j* compute**
    - $d_i^2 = E^2_{T,i}$ (distance to beamline in momentum space)
    - $d_{i,j}^2 = \min\{E^2_{T,i}, E^2_{T,j}\}[\Delta\eta^2 + \Delta\phi^2]^{1/2}$ (distance between objects)
  - **Calculate $\min\{d_i^2, d_{i,j}^2\}$ for all objects**
    - If $d_{i,j}^2$ is the smallest, combine objects *i* and *j* into a new object
    - If d_i^2 is the smallest, object *i* is a jet
- **Advantages**
  - **Collinear and infrared safe**
  - **No problems with overlapping jets**
  - **Distributions can be predicted by QCD**



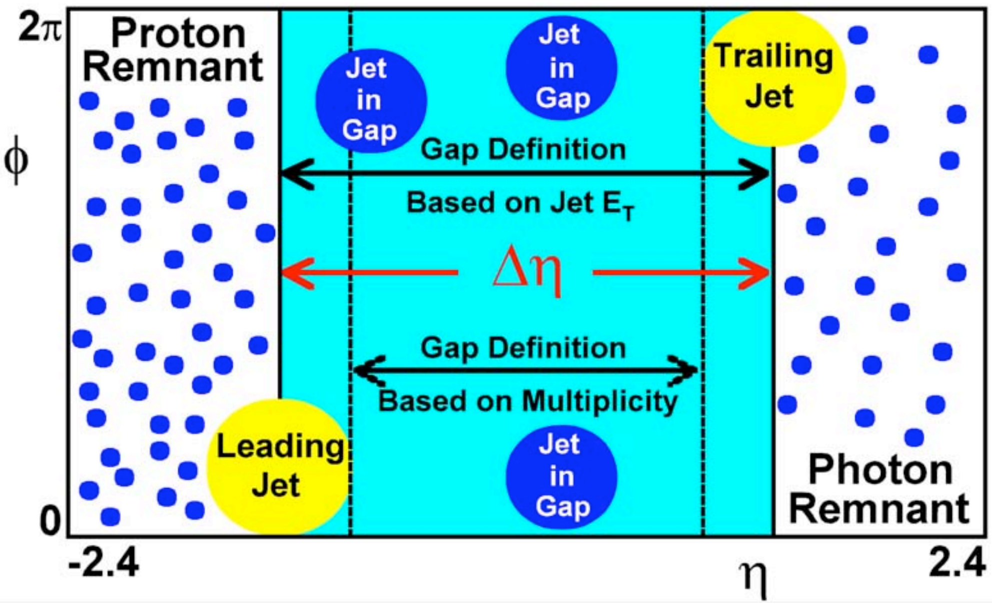
Kinematic Variables

Variable	Electron Method	Jacquet-Blondel Method
y	$1-\frac{E_e'}{2E_e}(1-\cos\theta_e)$	$\frac{\sum_i (E_i - p_{z,i})}{2E_e}$
Q^2	$2E_eE_e'(1+\cos\theta_e)$	$\frac{(\sum_i p_{z,i})^2 + (\sum_i p_{y,i})^2}{1-y_{JB}}$

- Jet $E_T = [p_x^2 + p_y^2]^{1/2}$
- Jet η = -ln (tan θ/2) where $\theta = \tan^{-1}(E_T/p_z)$
- x_γ: Fraction of γ momentum involved in collision
  - Direct γp: $x_\gamma \sim 1$
  - Resolved γp: $x_\gamma < 1$

$$x_\gamma^{OBS} = \frac{\sum_{jets} E_T e^{-\eta}}{2yE_e}$$

Rapidity Gap Topology



- Distance between leading and trailing jet centers: $\Delta\eta$
- E_T^{Gap}: Total E_T of jets between leading and trailing jet centers
- Gap Event has small energy in Gap: $E_T^{Gap} < E_T^{Cut}$
- Gap definition based on E_T better than that based on multiplicity
  - Collinear and infrared safe
  - Gap spans between centers of leading & trailing jets (increased statistics)

Monte Carlo Tuning

- **PYTHIA and HERWIG parameters modified**
  - Tuning based on JetWeb parameters (Global fit to collider data)
  - Tuned p_T^{Min} to ZEUS E_T^{GAP} distributions
- **Tuned PYTHIA 6.1**
  - Proton PDF: CTEQ 5L (Set 46)
  - Photon PDF: SaS-G 2D
  - p_T^{Min1}= 1.9 GeV p_T^{Min2}= 1.7 GeV (default 2.0 GeV, 1.5 GeV)

$p_T^{Min\ 1}$: p_T of hardest interaction

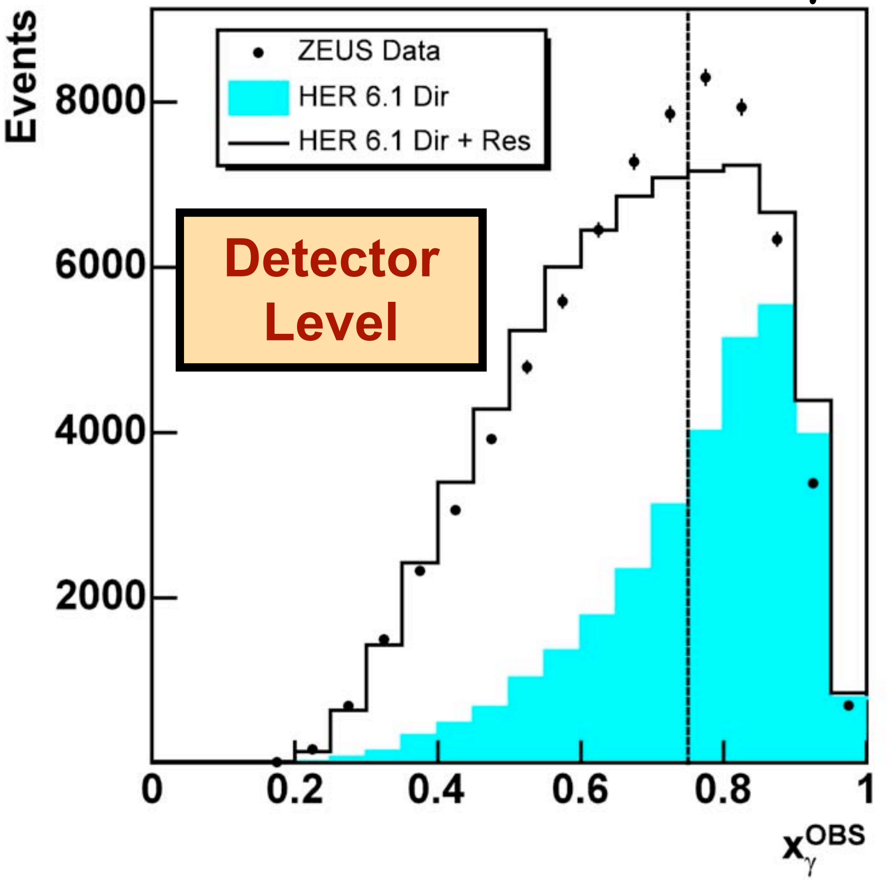
$p_T^{Min\ 2}$: p_T of all secondary interactions

- **Tuned HERWIG 6.1**
  - Proton PDF: CTEQ 5L (Set 46)
  - Photon PDF SaS-G 2D
  - Square of factor to reduce proton radius: 3.0 (default 1.0)
  - Probability of Soft Underlying Event: 0.03 (default 1.0)
  - p_T^{Min1} = 2.7 GeV (default 1.8 GeV)

Acceptance Correction Direct + Resolved MC

- **Correct data for acceptance: Detector → Hadron level**
- **Dir & Res relative amounts fit to Data**
  - x_γ^{OBS} distribution
- **PYTHIA – Detector Level**
  - 28% Direct
  - 72% Resolved
- **HERWIG – Detector Level**
  - 44% Direct
  - 56% Resolved
- **Non-Color-Singlet (NCS)**
  - Direct and Resolved only

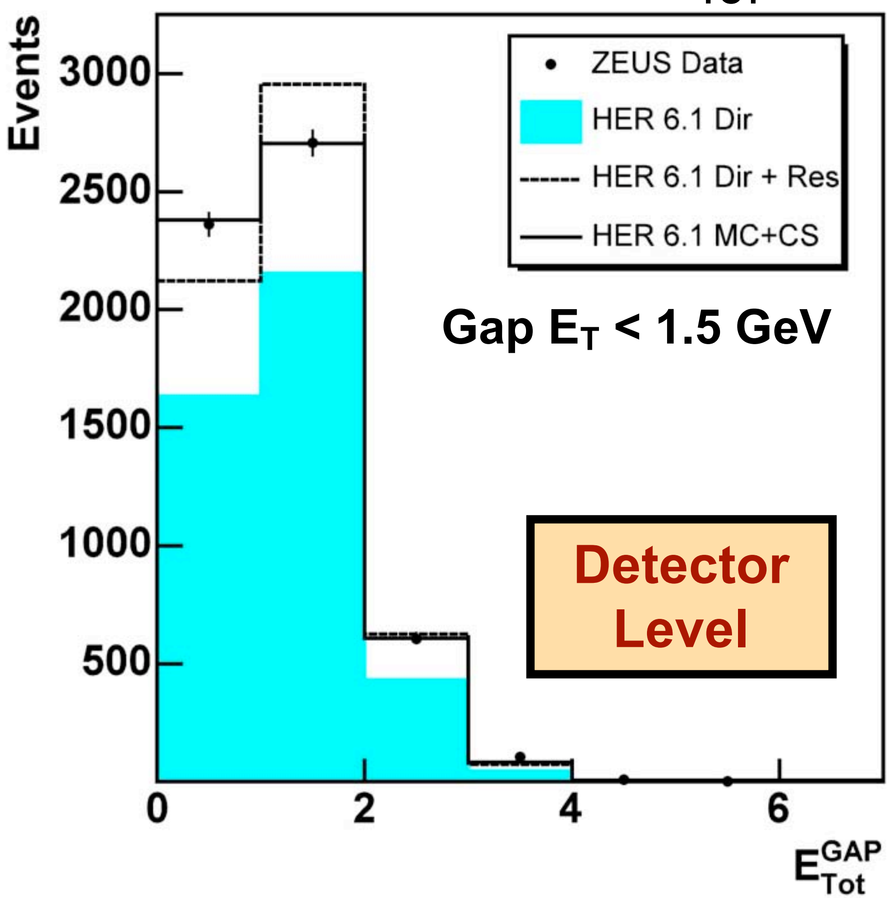
Fit of HERWIG to Data for x_γ^{OBS}



Acceptance Correction Direct + Resolved + Color Singlet

- **Correct data for acceptance: Detector → Hadron level**
- **NCS & CS relative amounts fit to Data**
  - **Dir and Res fractions fixed from x_γ^{OBS} fit**
  - **E_{TOT} for E_T^{GAP} < 1.5 GeV**
- **For Inclusive Sample**
  - **PYTHIA – Detector Level**
    - 96% NCS (Direct + Resolved)
    - 4% CS (Direct + Resolved)
  - **HERWIG – Detector Level**
    - 94% NCS
    - 6% CS
- **Compare to other methods**
  - **Fit to Num Jets for E_T^{GAP} < 1.5 GeV**
  - **Hadron level E_T^{GAP}**
  - **Similar results**

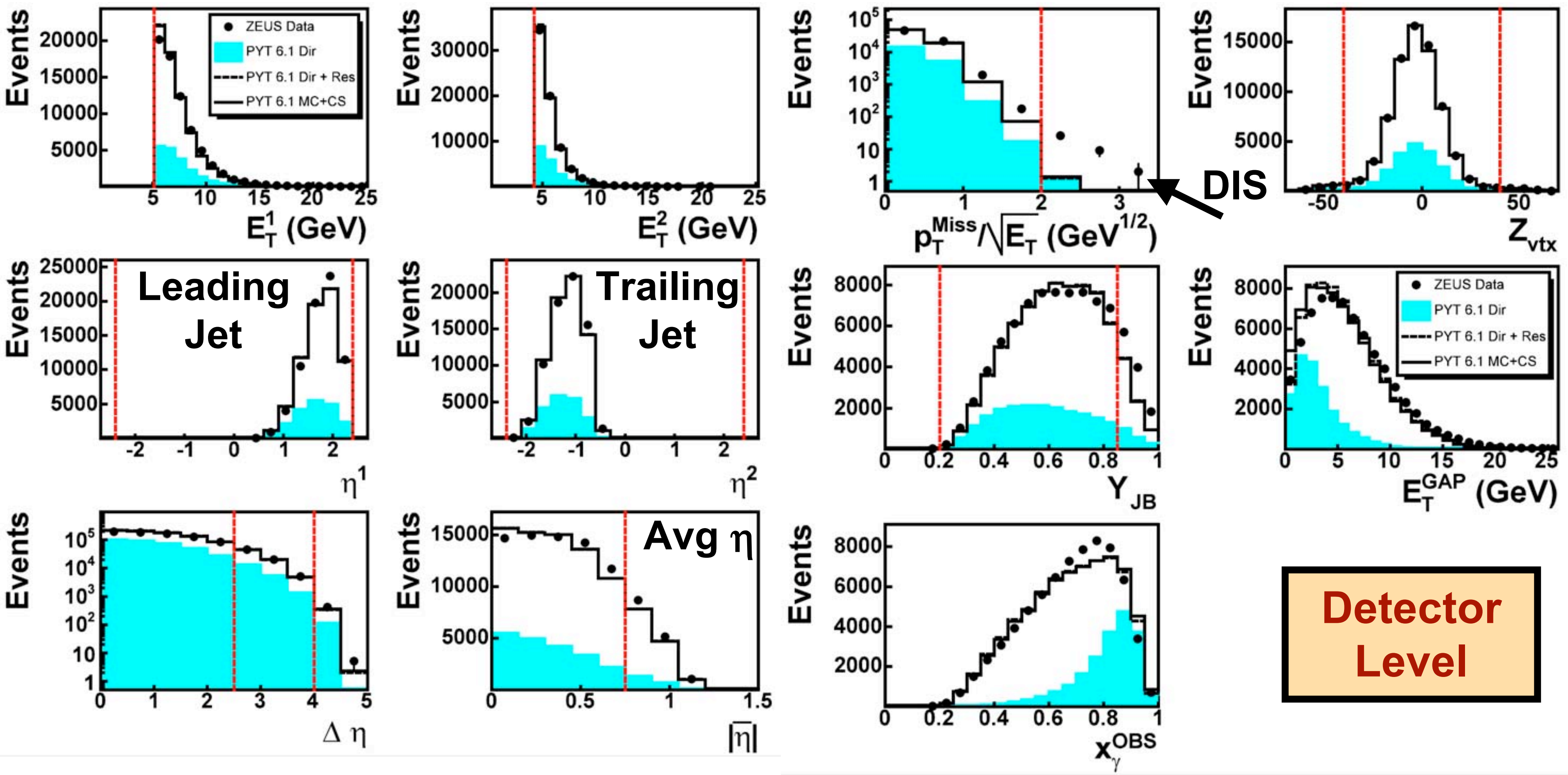
Fit of HERWIG to E_{TOT}



Rapidity Gap Event Selection

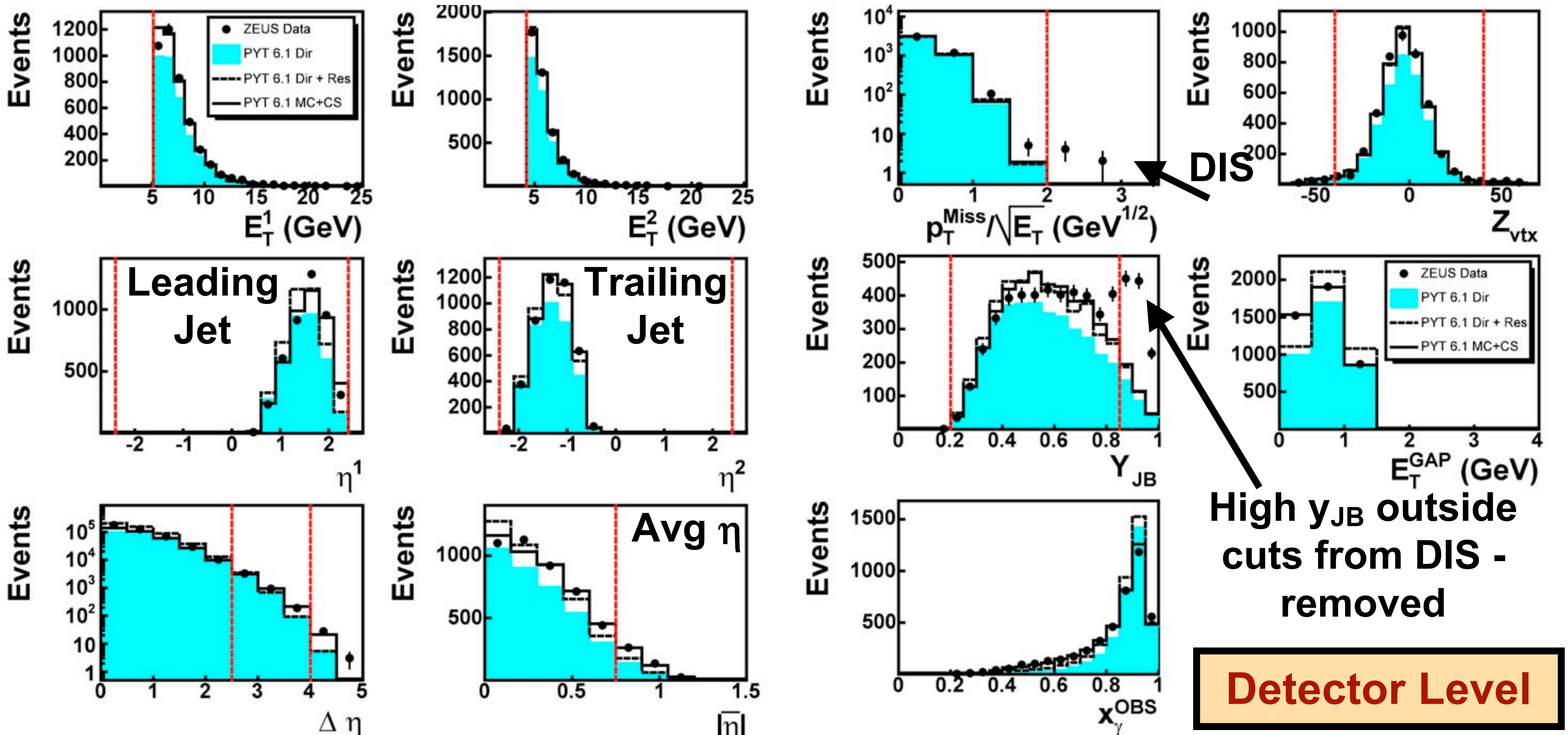
ZEUS 1996-97 Data (38 pb^{-1})	
Trigger Selection:	
FLT, SLT, and TLT requirements to select dijet photoproduction events	
Clean Photoproduction Sample:	
Reject events having Electron with $E_e > 5$ GeV **AND** $y_e < 0.85$	
$\Sigma p_T / \Sigma\sqrt{E_T} < 2$ GeV$^{1/2}$	
$\lvert z_{vtx}\rvert < 40$ cm	$0.2 < y_{JB} < 0.85$
Dijets with Large Rapidity Separation:	
$E_T^{1,2} > 5.1, 4.25$ GeV (corresponds to $E_T^{1,2} > 6.0, 5.0$ GeV at hadron level)	
$\lvert\eta^{1,2}\rvert < 2.4$	$\frac{1}{2}\lvert\eta^1+\eta^2\rvert < 0.75$
$2.5 < \lvert\eta^1-\eta^2\rvert < 4.0$ (Gap Definition)	
~70,000 Events in Inclusive Sample	
4 Samples of Gap Events:	
$E_T^{CUT} = 0.6, 1.2\ 1.8, 2.4$ GeV (corr. to $E_T^{CUT} = 0.5, 1.0, 1.5, 2.0$ at hadron level)	

Inclusive Kinematic Variables
Data vs. PYTHIA



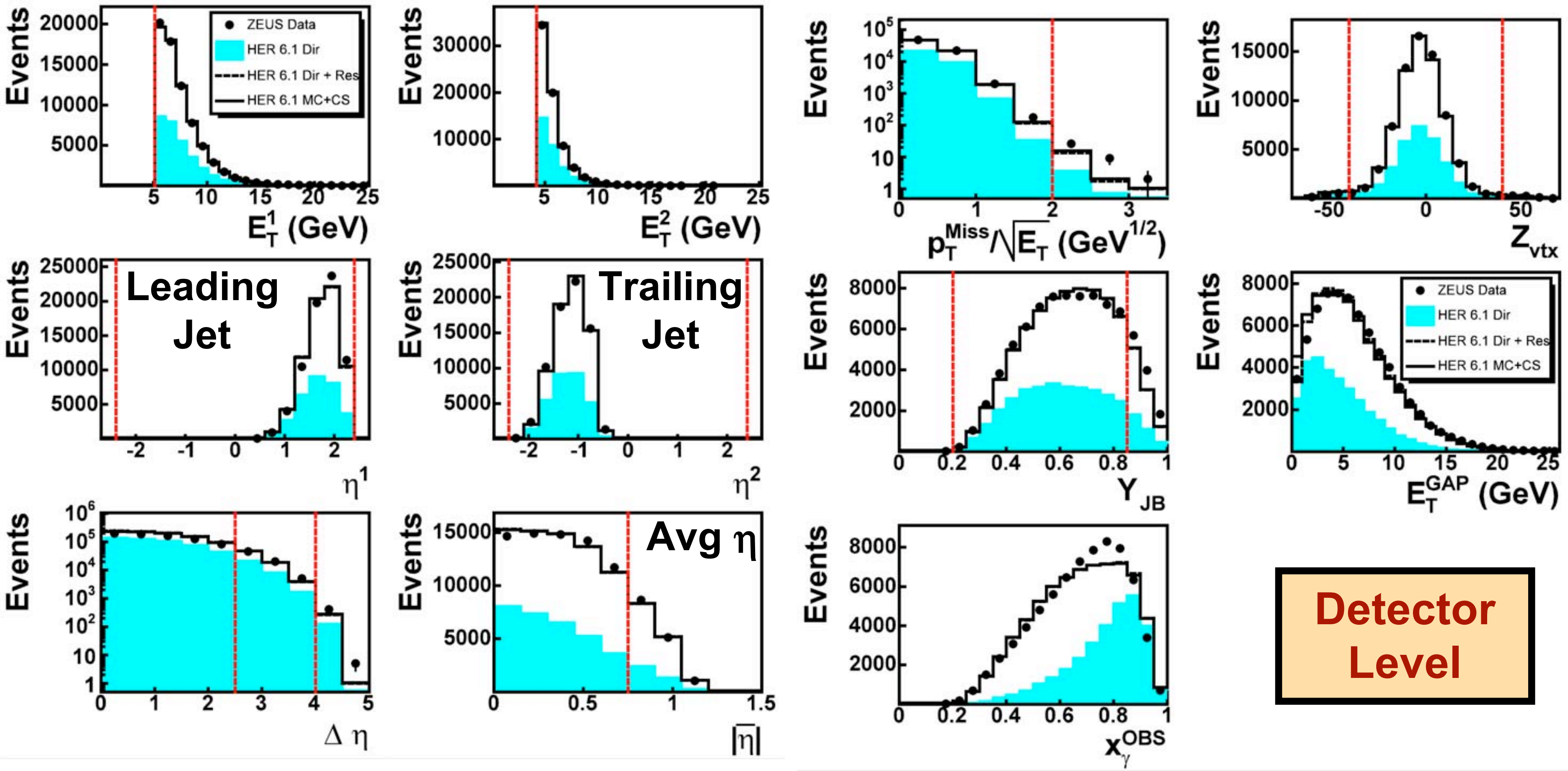
- **PYTHIA describes the inclusive variables**
- **Addition of CS makes small improvement for inclusive sample**

Gap Kinematic Variables Data vs. PYTHIA (E_T^{CUT} = 1 GeV)



- PYTHIA describes the gap variables (E_T^{Cut} = 1 GeV)
- Addition of CS makes substantial improvement for gap sample

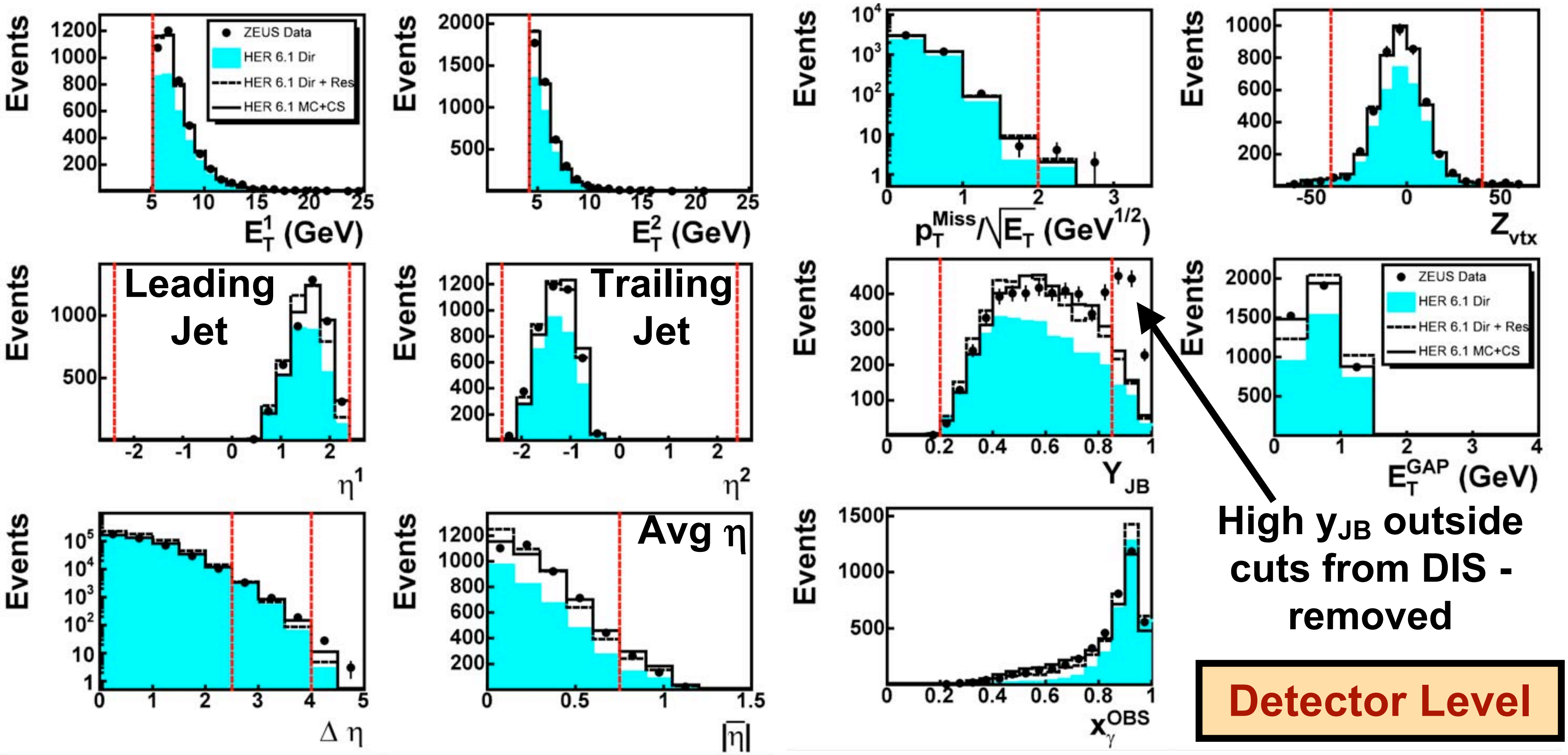
Inclusive Kinematic Variables Data vs. HERWIG



Detector Level

- **HERWIG describes the inclusive variables**
- **Addition of CS makes small improvement for inclusive sample**

Gap Kinematic Variables
Data vs. HERWIG (E_T^{CUT} = 1 GeV)



- HERWIG describes the gap variables (E_T^{Cut} = 1 GeV)
- Addition of CS makes substantial improvement for gap sample

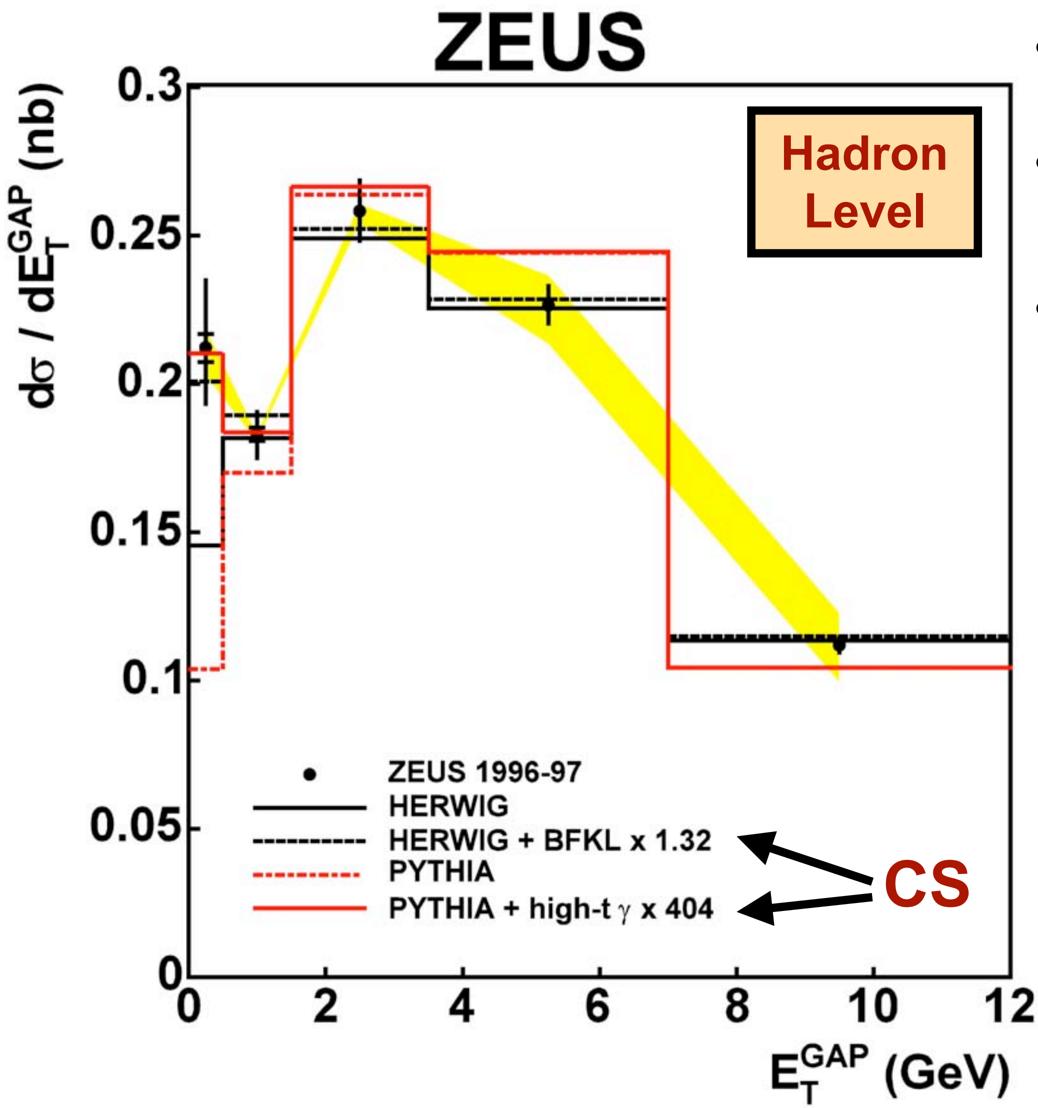
Systematics

- Kinematic Cuts: +/- HERWIG Resolutions
- Amount of CS in unfolding varied by 25%
- CAL Energy Scale varied by 3%
- Difference between PYT and HER acceptance correction

Variable	+/- Change	Variable	+/- Change
$E_T^{1,2}$	13%	$\eta^{1,2}$	2%
$\frac{1}{2}\lvert\eta^1+\eta^2\rvert$	9%	$\Delta\eta$	2%
y_{JB}	5%	$p_T^{Miss}/\sqrt{E_T}$	10%
y_e	6%	Z_{vtx}	25%
E_T^{Cut}	36%		

- Same systematics used for all bins
- Systematic variation in cross section dependent on E_T^{Gap}, $\Delta\eta$, W, and x_γ^{OBS} bins

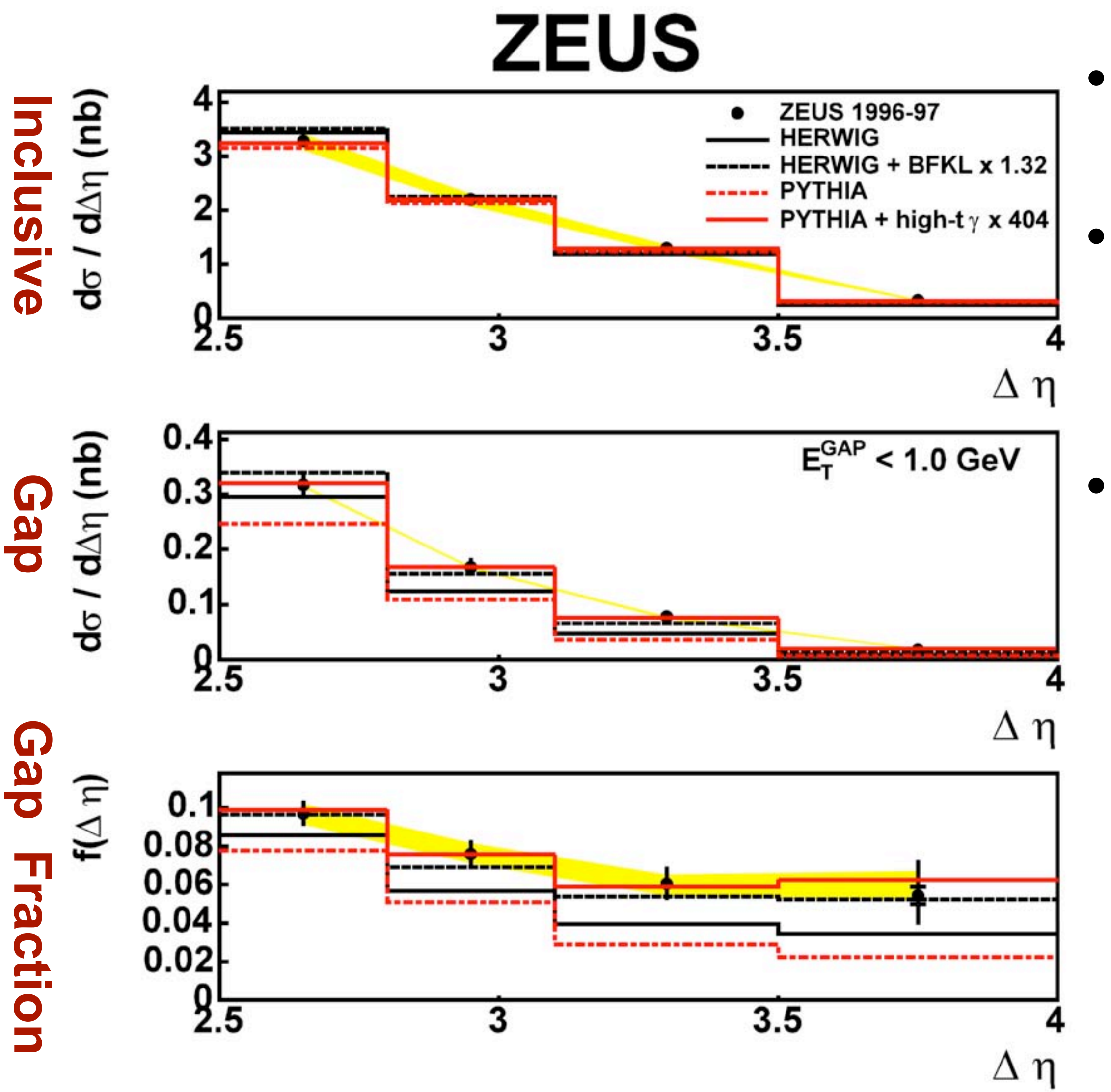
Acceptance Corrected Data vs MC E_T^{Gap} Cross Section



- **Acceptance Correction**
  - Average of PYT & HER
- **Systematic Errors from HER**
  - Difference between HER & PYT values added to systematic
- **MCs fit to Data**
  - χ^2 Minimization
  - Yield Scale Factors
    - HER: 1.01*NCS + 1.32*CS
    - PYT: 1.25*NCS + 404*CS
  - High CS Scale Factor in PYTHIA due to High-t γ exchange
  - Same scale factors used in all following plots

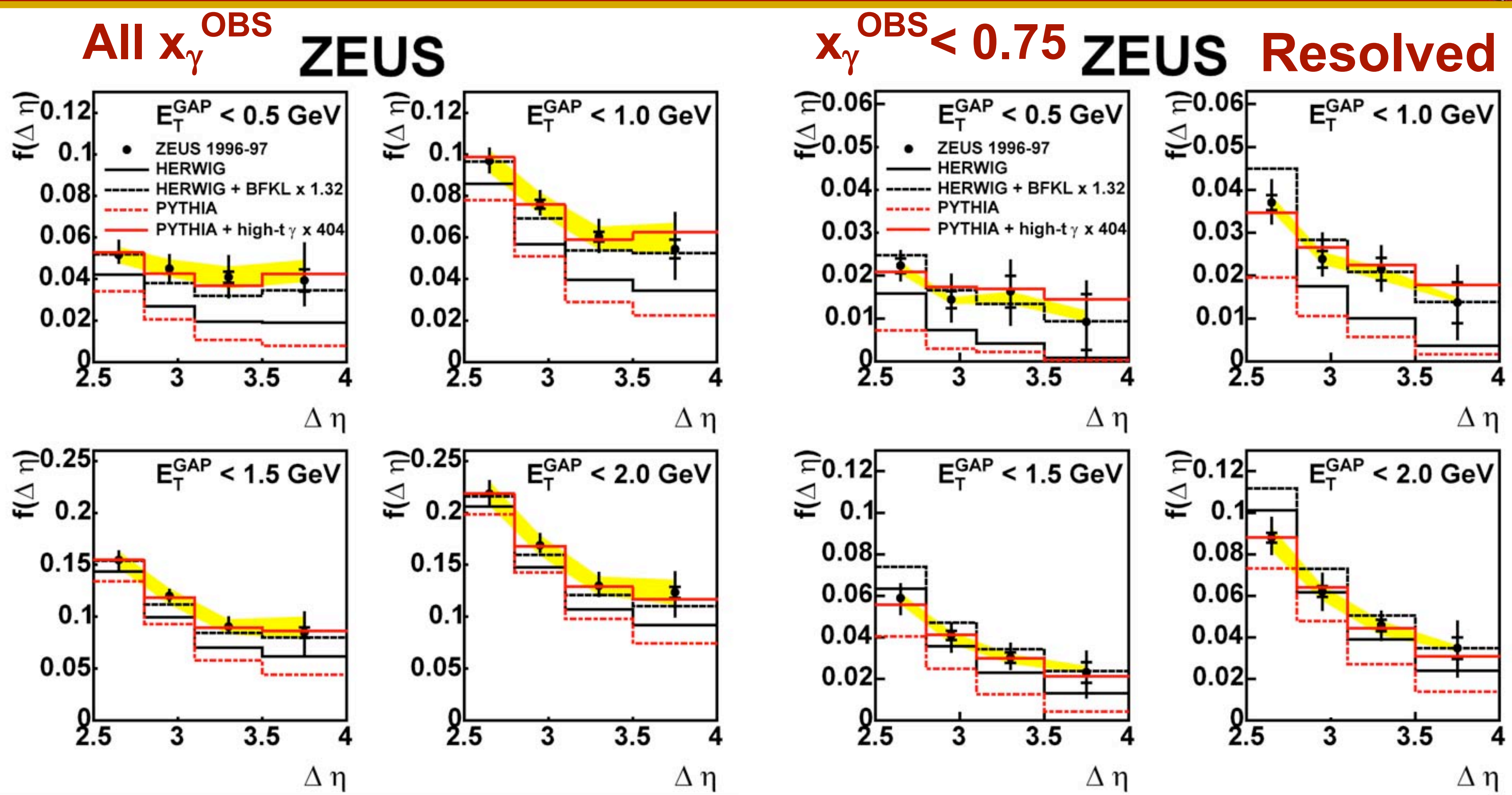
Fit to E_T^{GAP} Cross Section results in ~3% CS contribution for both PYTHIA & HERWIG

Acceptance Corrected Data vs MC Δ η Cross Sections



- **Inclusive Cross Section**
  - MC with and without CS added describes data
- **Gap Cross Section**
  - MC without CS disagrees with data
  - MC with CS added describes data
- **Gap Fraction**
  - MC without CS disagrees with data
  - MC with CS added describes data

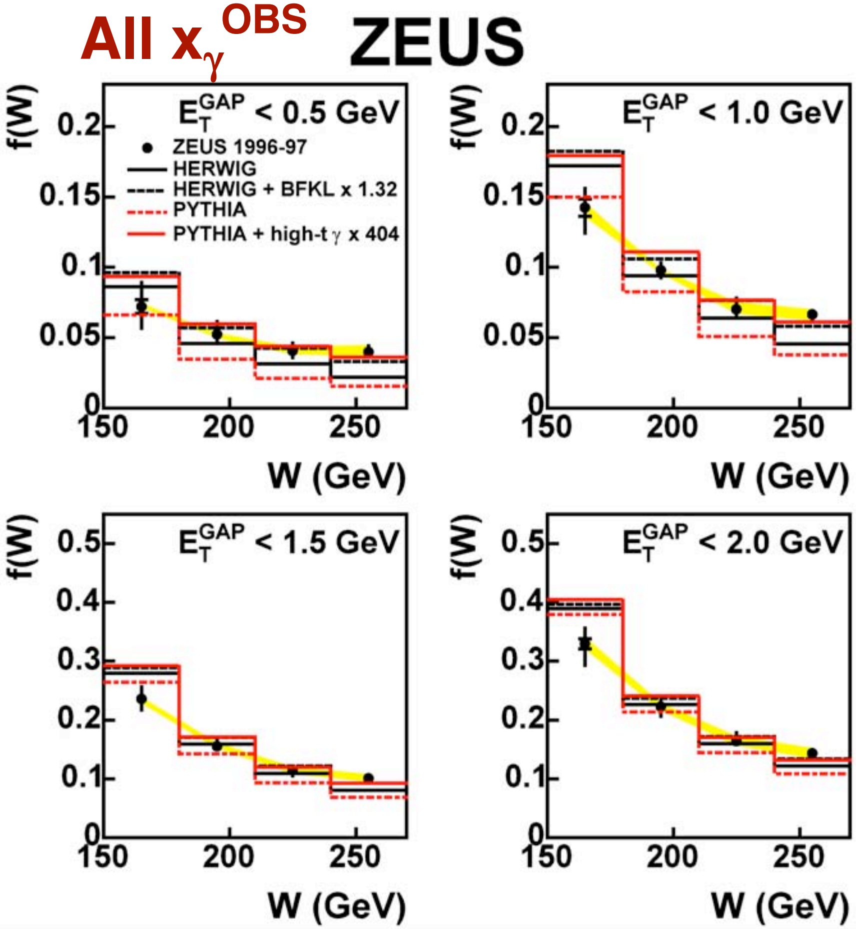
Δη for Different Gap Fractions Unfolded with AVG of PYT & HER



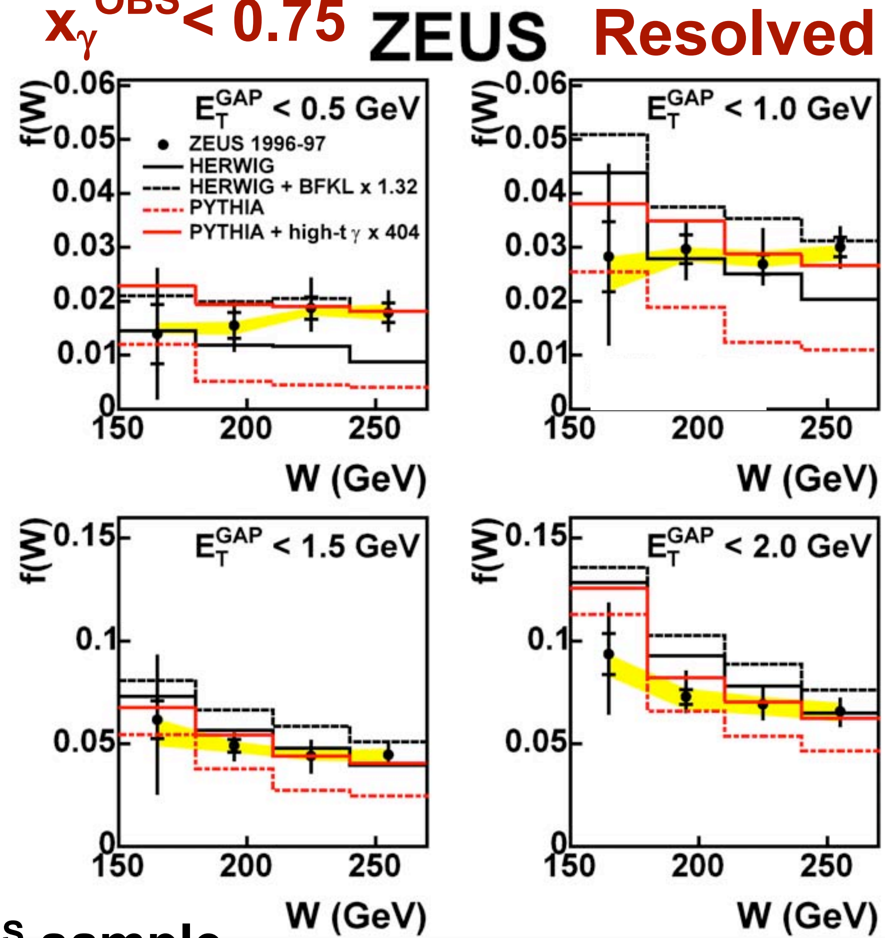
- MC with CS added describes data for entire x_γ^{OBS} region
- CS contribution in <u>resolved region</u> is 1-2% from Gap Fraction
  - Resolved region should allow comparison to Tevatron (1-1.5% CS)

W for Different Gap Fractions Unfolded with AVG of PYT & HER

All x_γ^{OBS}



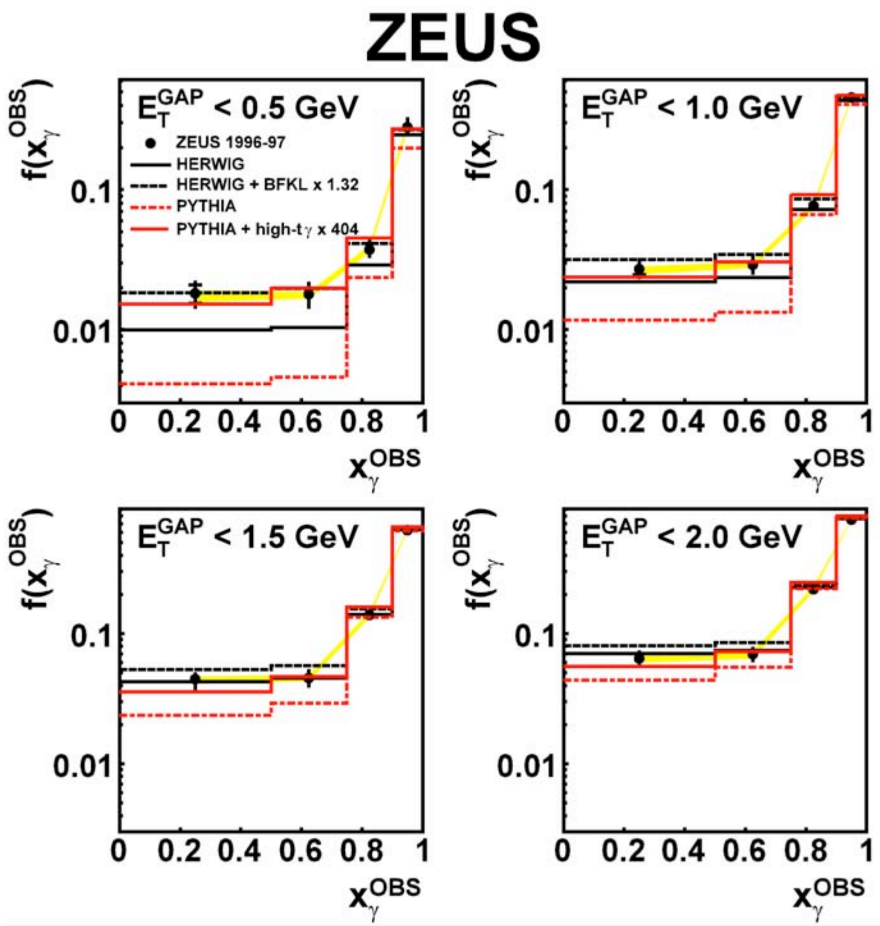
$x_\gamma^{OBS} < 0.75$ Resolved



- Disagreement at low W for All x_γ^{OBS} sample
- CS contribution in <u>resolved region</u> is 1-2% from Gap Fraction
  - Resolved region should allow comparisons to Tevatron

x_γ^{OBS} for Different Gap Fractions Unfolded with AVG of PYT & HER

$$x_\gamma^{OBS} = \frac{\sum_{jets} E_T e^{-\eta}}{2yE_e}$$



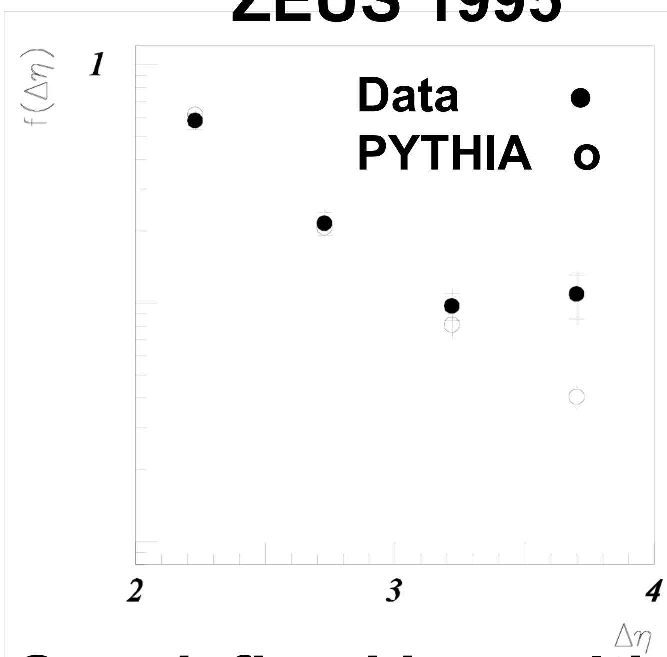
Resolved region: $x_\gamma^{OBS} < 0.75$

Should allow comparison to Tevatron

- **PYTHIA and HERWIG with CS describes the data well**
- **HERWIG agreement remains better than PYTHIA agreement**
- **PYTHIA agreement in resolved region improved compared to $\Delta\eta$**

Comparisons to Previous ZEUS Measurement

ZEUS 1995



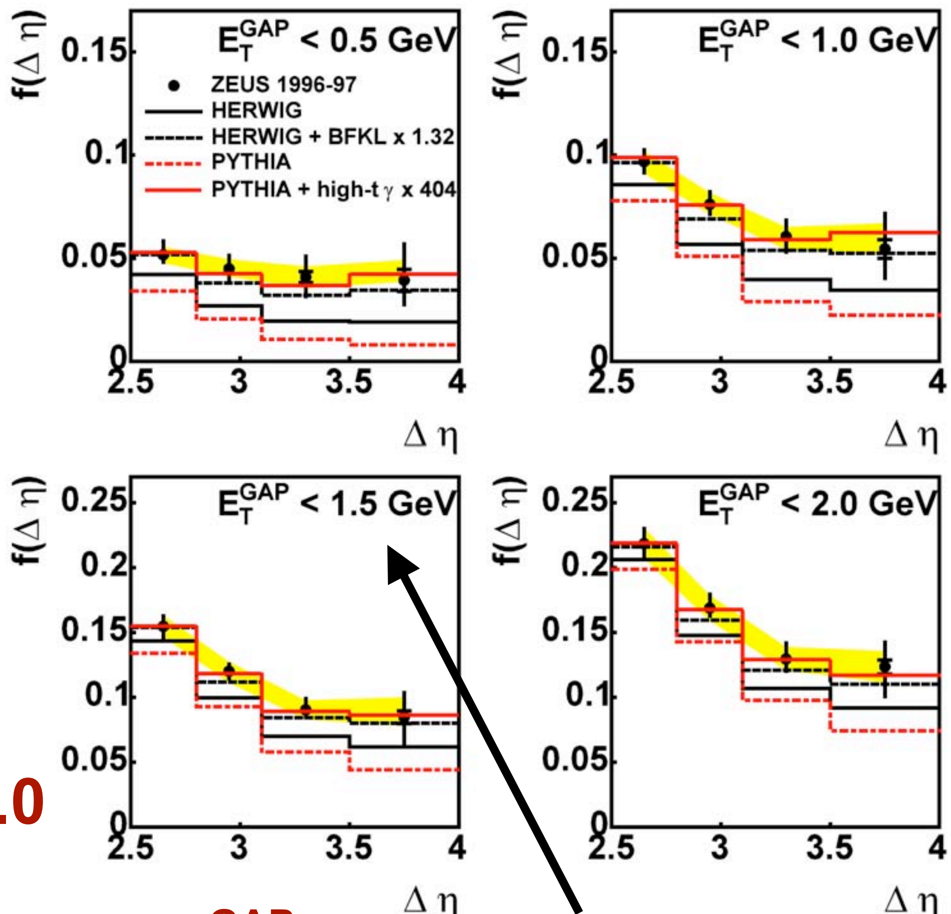
Gap defined by multiplicity (not E_T)

$f(\Delta\eta) = 0.11$ for $3.5 < \Delta\eta < 4.0$

1-4% CS from 2-4 in $\Delta\eta$

Measurements consistent

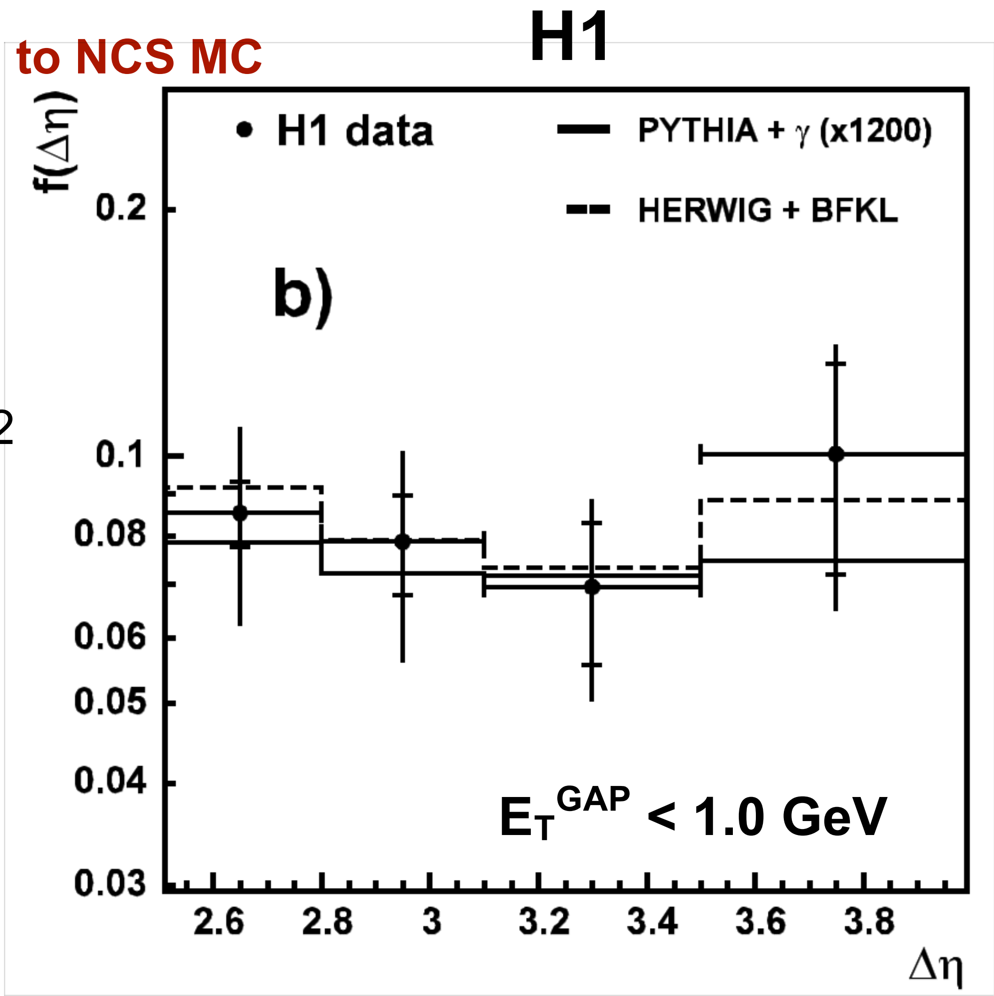
ZEUS (this analysis)



$E_T^{GAP} < 1.5$ GeV closest to previous results

Comparison to H1 Measurement

- **Gap Fraction for $E_T^{Gap} < 1.0$ GeV**
  - **6.6 pb^{-1} of Lumi**
  - **Excess of data when compared to NCS MC**
  - **Data described by NCS+CS MC**
  - **Consistent with ZEUS within errors**
  - **Reference**
    - C. Aldoff et al.
    - Eur.Phys.J C24:517-527 2002



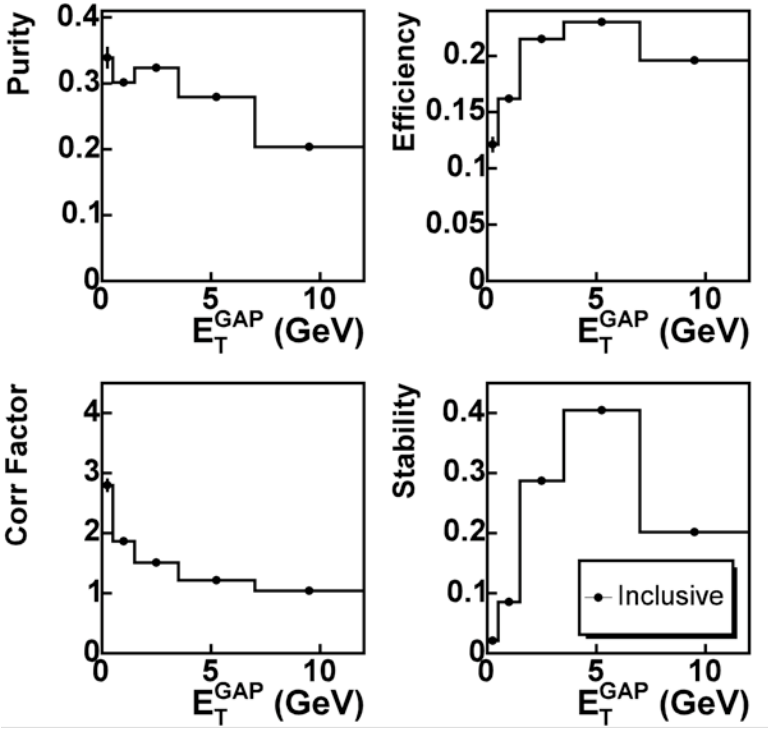
Rapidity Gap Between Jets Summary

- **Conclusions**
  - **Data demonstrate evidence of ~3% Color-Singlet contribution estimated at the cross section level for entire phase space**
    - Observe ~1-2% Color-Singlet in resolved region
  - **Data consistent with published ZEUS and H1 results**
  - **PYTHIA and HERWIG describe data well after the Color-Singlet contribution is added**
- **In Progress**
  - **Examine W dependence**
  - **Explore comparisons with Tevatron**

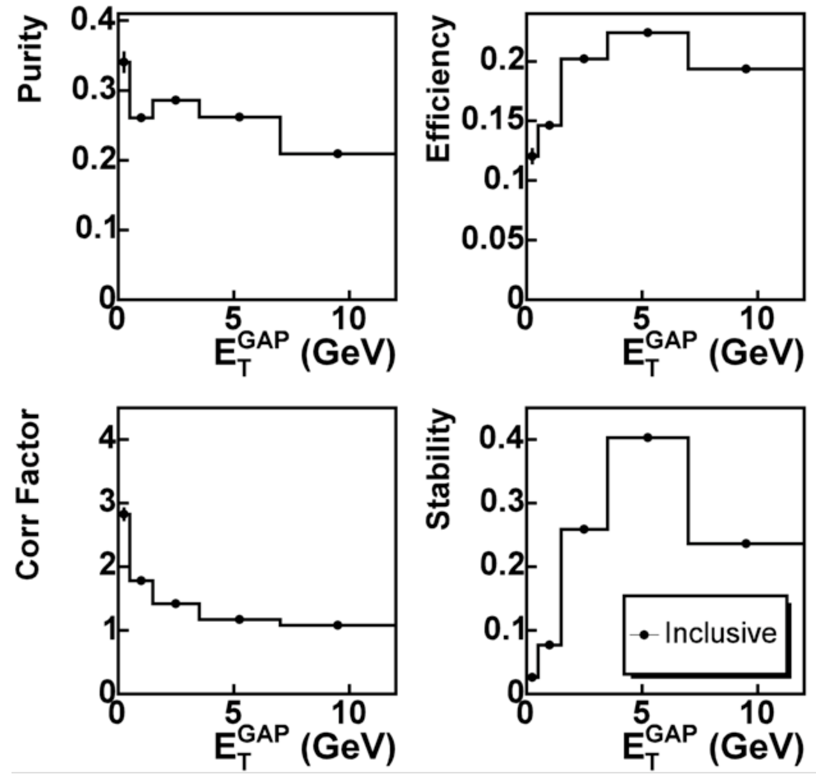
Extra Slides

Purities and Efficiencies
E_T Gap

PYTHIA



HERWIG

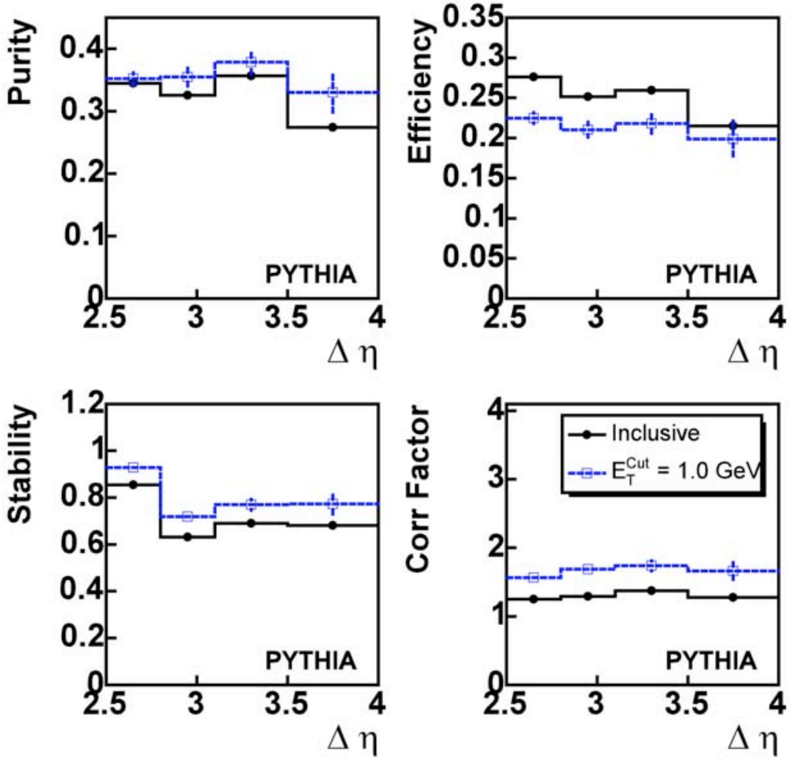


- **Purity: (Detector && Generator)$_i$ / (Detector)$_i$**
- **Efficiency: (Detector && Generator)$_i$ / (Generator)$_i$**
- **Correction Factor: (Generator / Detector)$_i$ = (Purity / Efficiency)$_i$**
- **Stability: (Detector && Generator)$_i$ / Reconstructed in any bin**

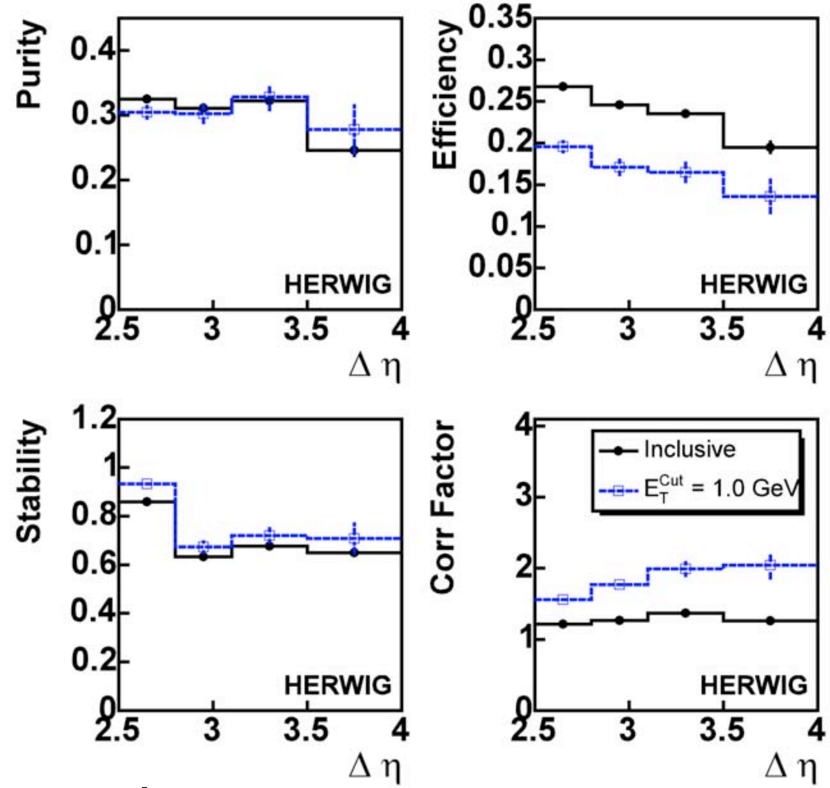
i: Bin i

Purities and Efficiencies
Δη

PYTHIA



HERWIG



- **Purity: (Detector && Generator)$_i$ / (Detector)$_i$**
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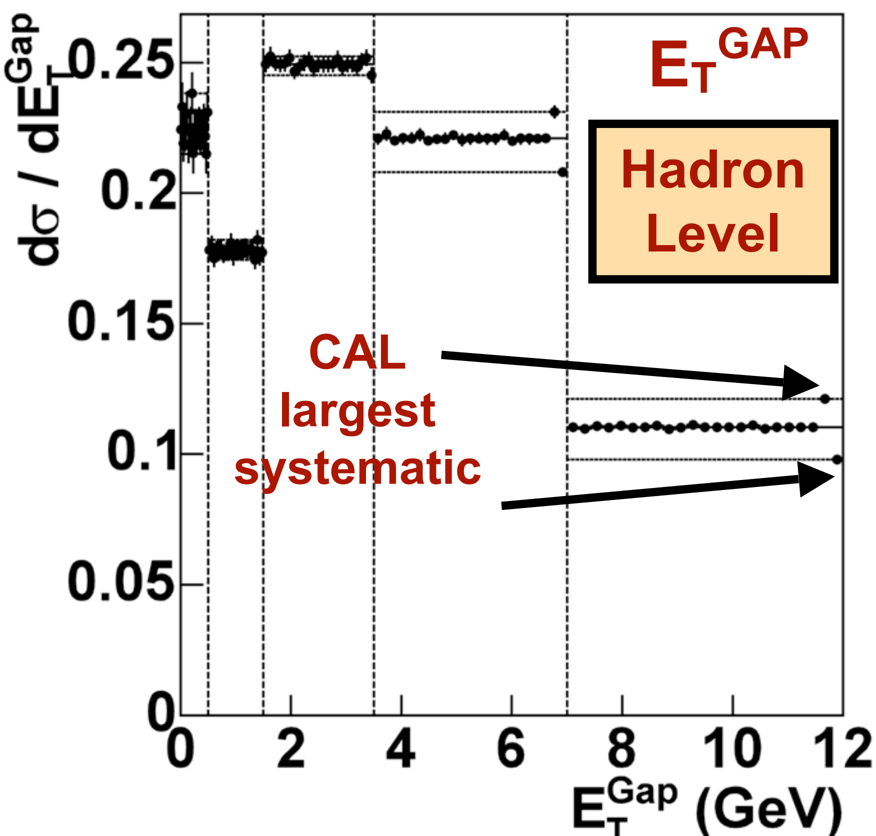
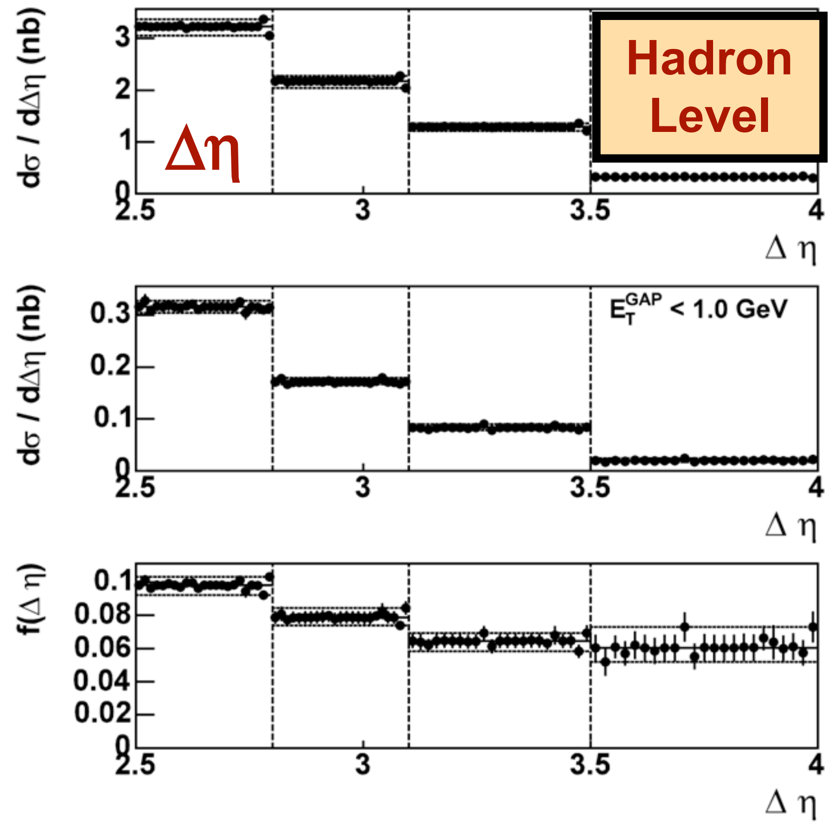
Cross Section Systematics Unfolded with HERWIG

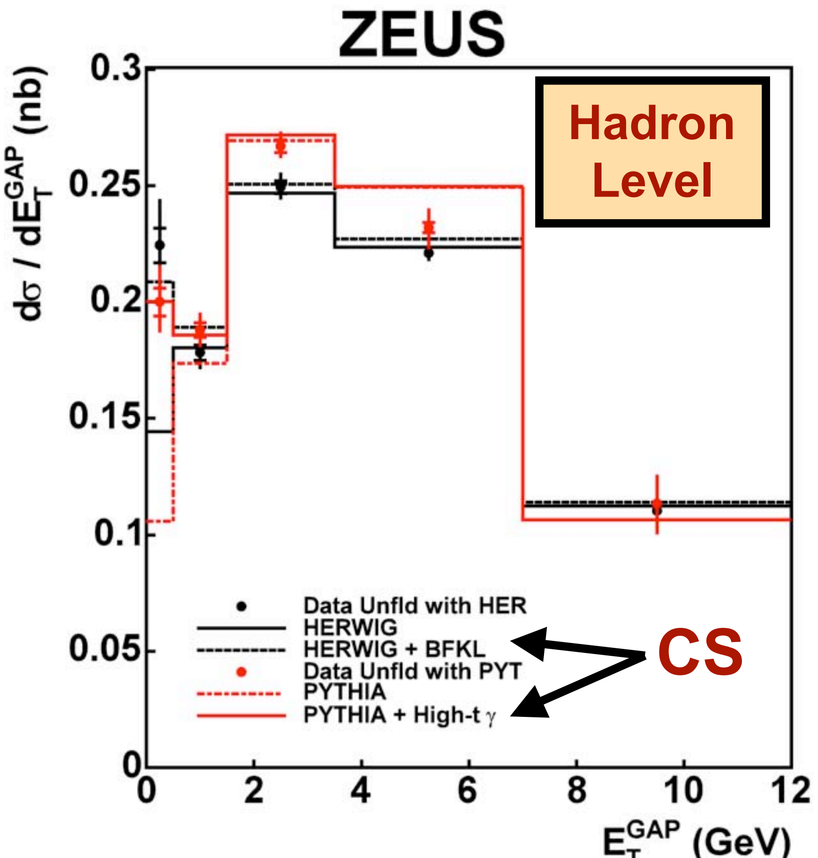


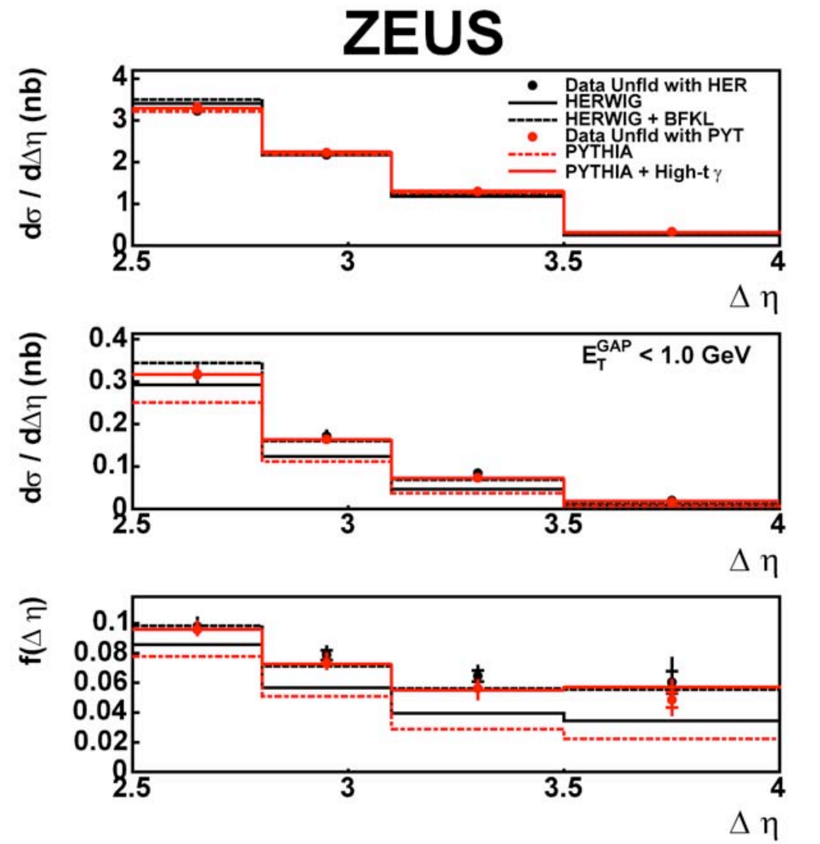


Order of Systematics (left to right in each bin)

+	1.E_T	3.η	5.Av η	7.$\Delta\eta$	9.y_{JB}	11.$p_T^M/\sqrt{E_T}$	13.y_e	15.Z_v	17.E_T^{Cut}	19.%CS	21.CAL
-	2.E_T	4.η	6.Av η	8.$\Delta\eta$	10.y_{JB}	12.$p_T^M/\sqrt{E_T}$	14.y_e	16.Z_v	18.E_T^{Cut}	20.%CS	22.CAL

Cross Sections Unfolded with PYT & HER





- **Data unfolded separately with PYT & HER**
- **NCS MC fit to data in E_T^{GAP} cross section**
- **CS MC added by fitting NCS+CS to E_T^{Gap}**
  - **Addition of CS maximizes agreement with Data for PYT and HER**