The Hadronic Final State at HERA

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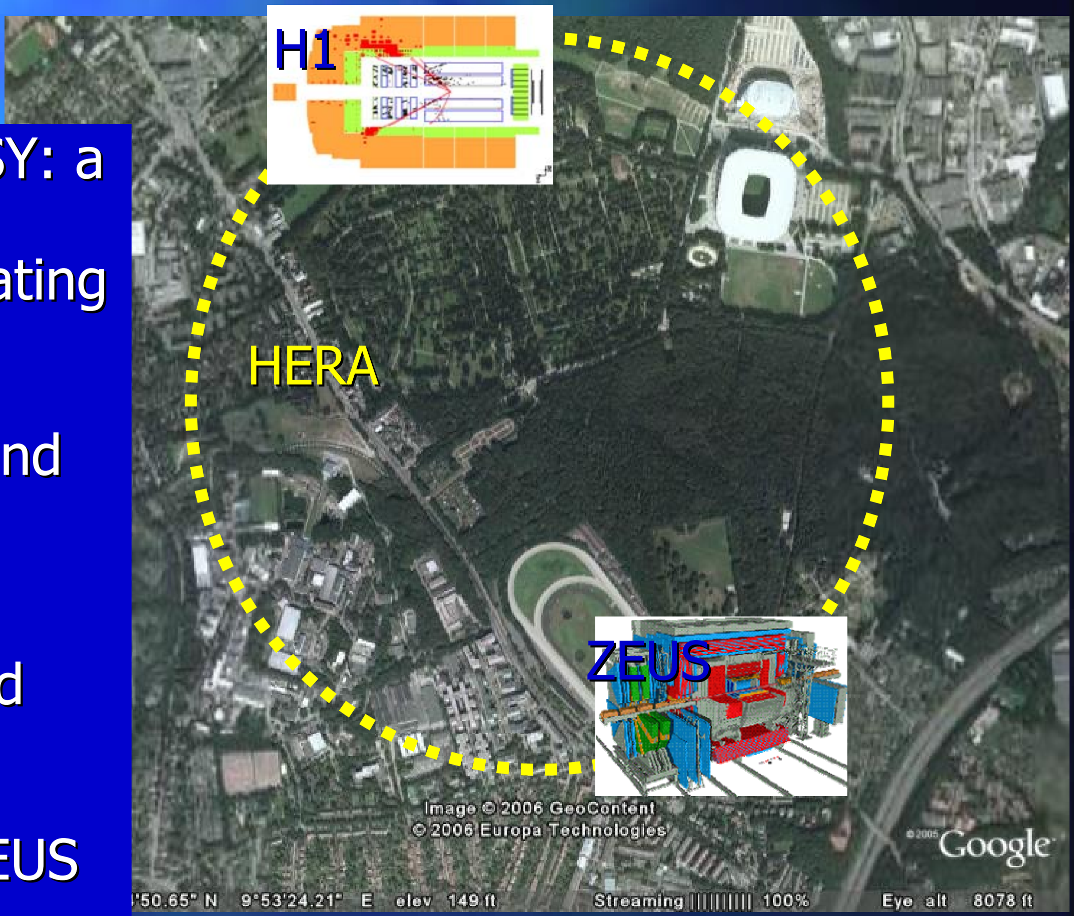
for the H1 & ZEUS collaborations

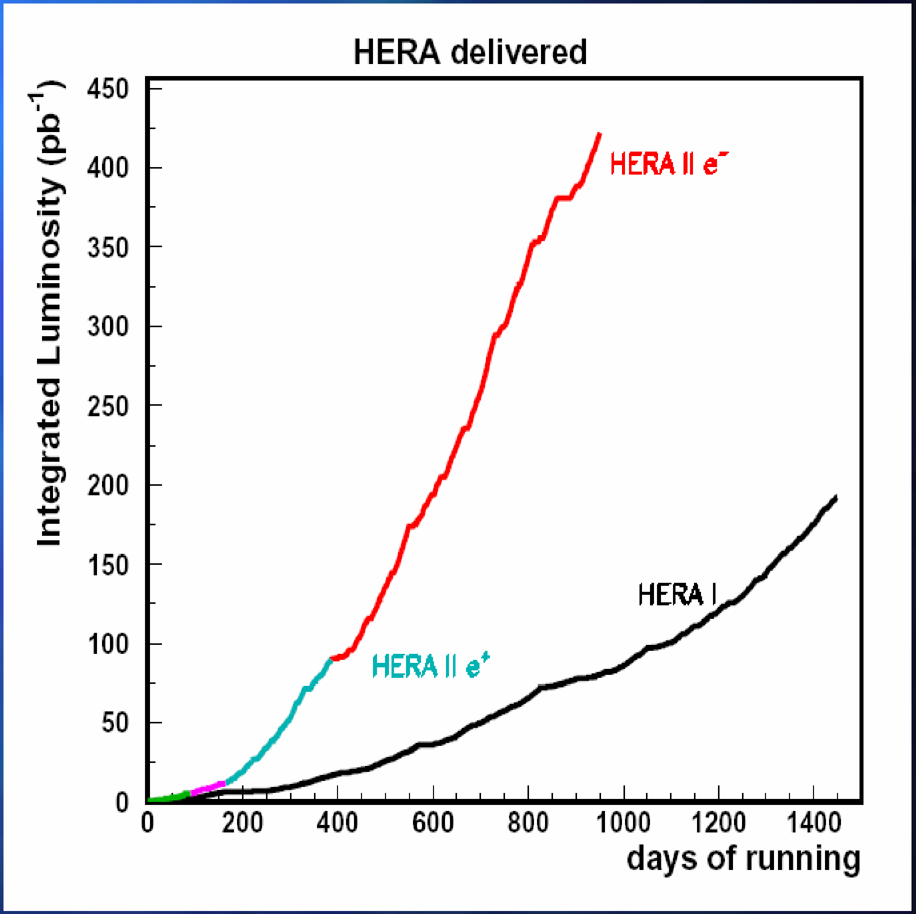
HERA

- HERA ep collider at DESY: a unique machine
- Presently the only operating high energy collider in Europe
- HERA collides protons and electrons/positrons at $\sqrt{s}=318$ GeV
- HERA-II run features upgraded luminosity and polarization
- Colliding beam experiments: H1 and ZEUS

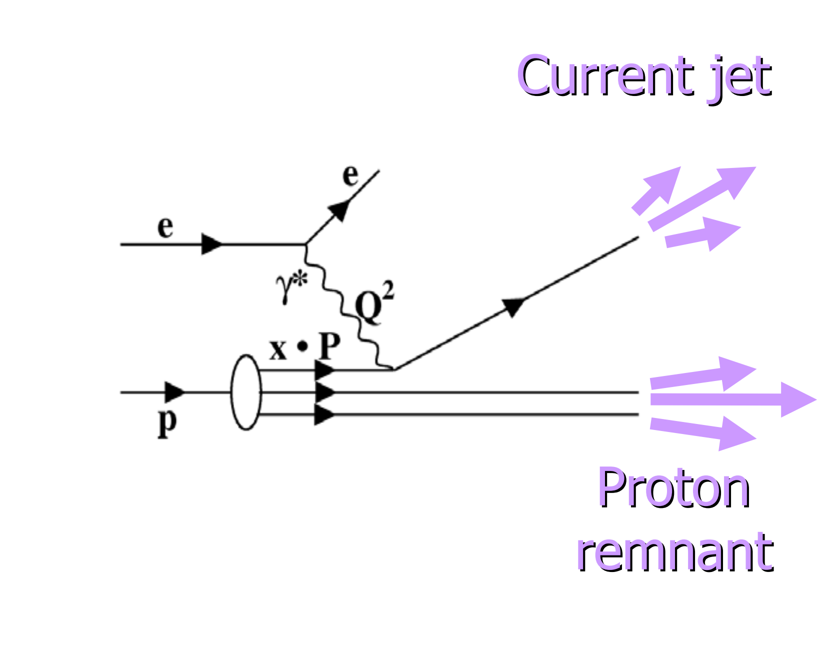


HERA Luminosity

- HERA-II has been surpassing all previous luminosity achievements
- Already the HERA-II e^-p run (Dec 04-Jun 06) has delivered more collisions than six years of HERA-I (1995-2000)
- Since end Jun 06, machine has switched back to e^+p (~40 pb^{-1} since)
- O(500 pb^{-1}) per expt expected by end of data-taking in mid 2007
- Also analysis of HERA-I data is still going strong



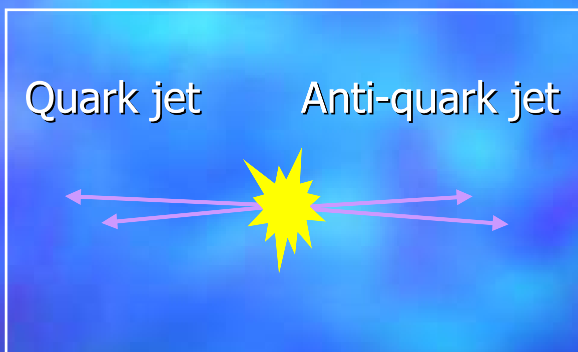
Typical Structure of Hadronic Final States at HERA



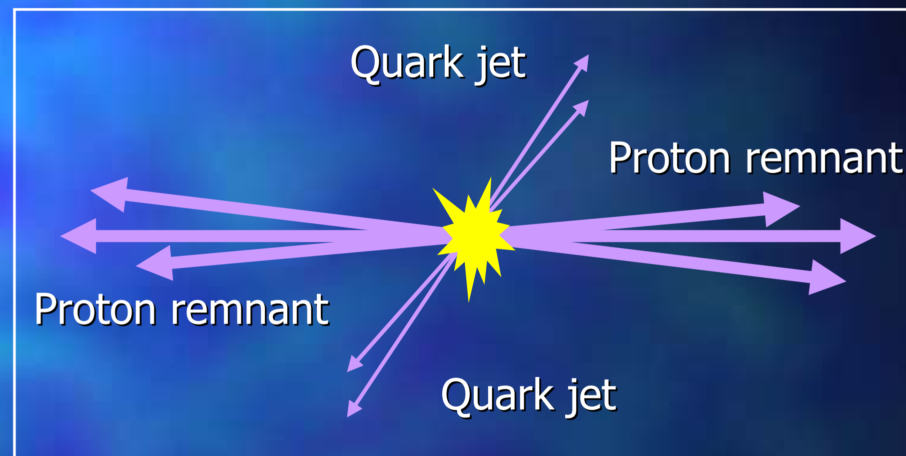
- Q^2: virtuality of exchanged photon (boson)
  - $Q^2 > 1\ \text{GeV}^2$: deep-inelastic scattering (DIS)
  - $Q^2 < 1\ \text{GeV}^2$: photo-production (PHP)
- x (x_{Bj}): fraction of proton momentum carried by struck quark

Comparison of Hadronic Final State Structure

e^+e^- interaction



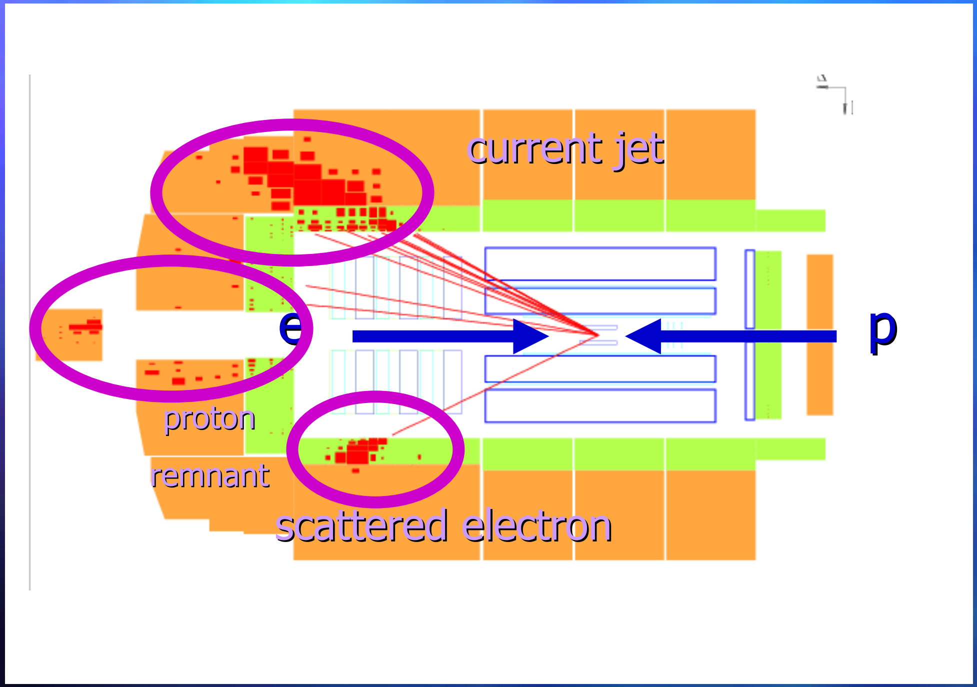
hadron-hadron interaction



$e^\pm p$ interaction

- ➔ contains main features of energetic hadron interaction (proton remnant)
- ➔ less complex than hadron-hadron interaction
- ➔ clean reconstruction of kinematic variables
- ➔ ideal laboratory for studying QCD

Colliding Beam Detectors

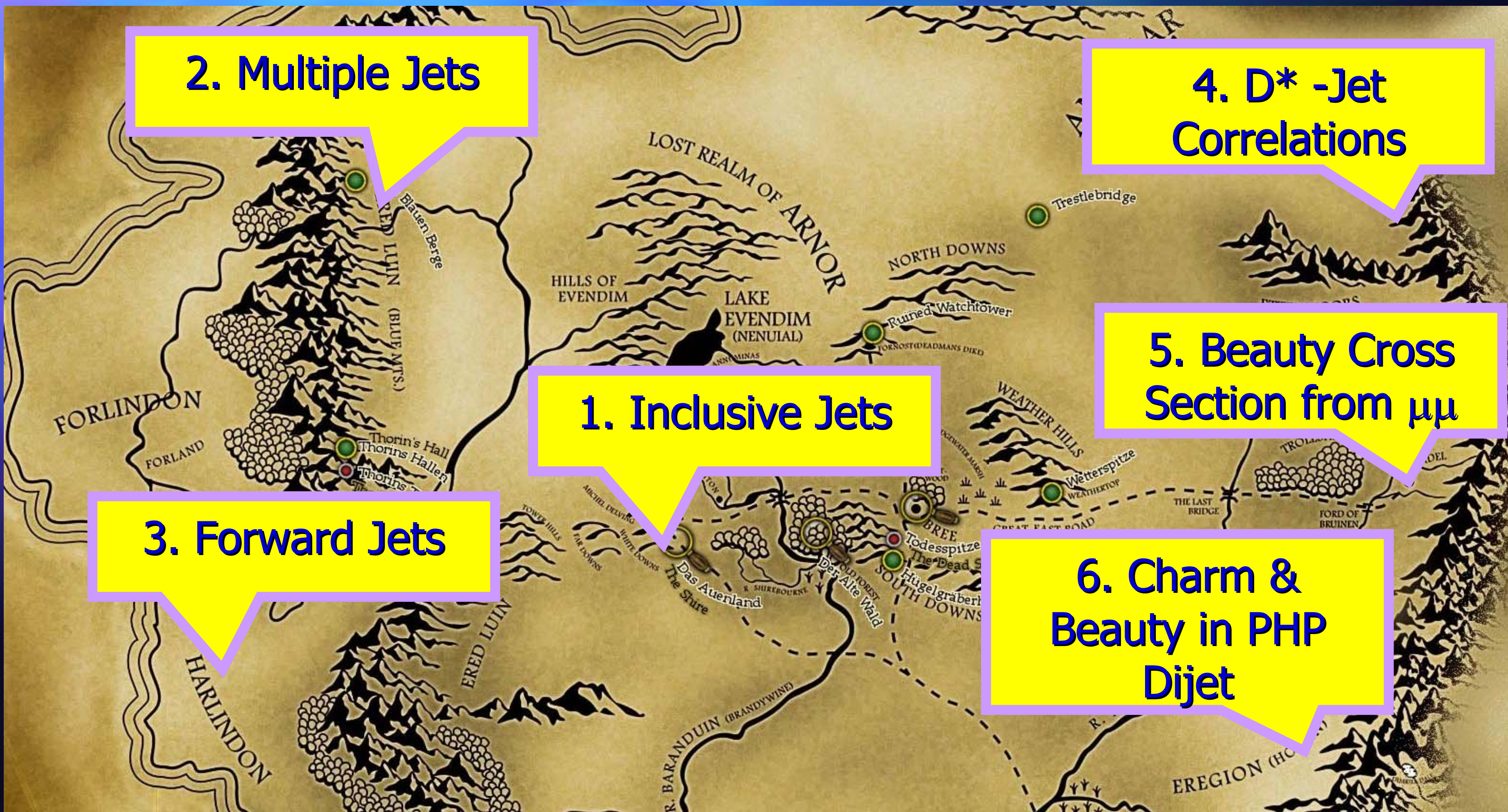


- Colliding mode detectors can generally measure current jet & scattered electron very well ("central region")
  - in these areas, also theoretical approaches are tested & tuned best
  - in PHP, the scattered electron usually escapes along the beam pipe
- The proton remnant emerges close to beam pipe & is less accessible
  - these areas also pose big challenges to theory
- Additional jets can arise from more complex processes

Some “Frontier” Questions Related to Hadronic Final State

- How relevant are higher orders in perturbative QCD?
- How well do we understand the workings of QCD in the forward area?
- Can we distinguish evolution schemes in parton cascades?
- At which accuracy can we describe production of heavy flavor?

Outline

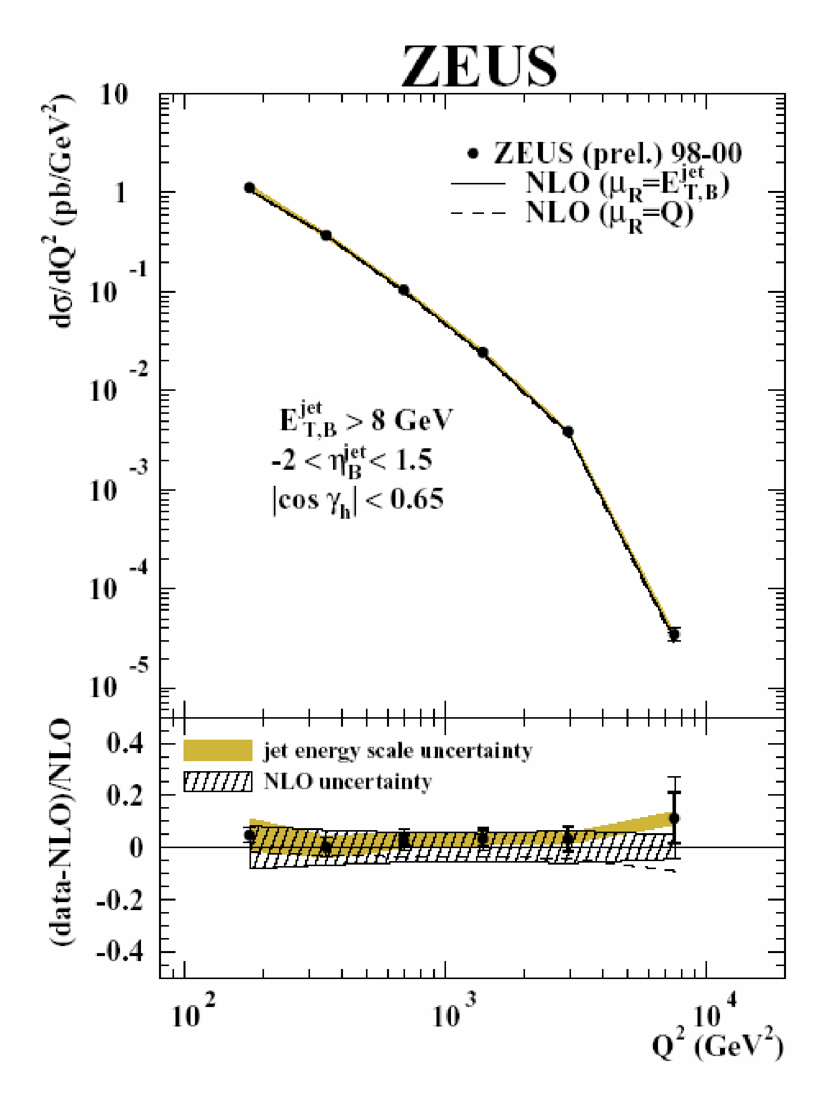


1. Inclusive Jets
2. Multiple Jets
3. Forward Jets
4. D* -Jet Correlations
5. Beauty Cross Section from μμ
6. Charm & Beauty in PHP Dijet

1. Inclusive Jets

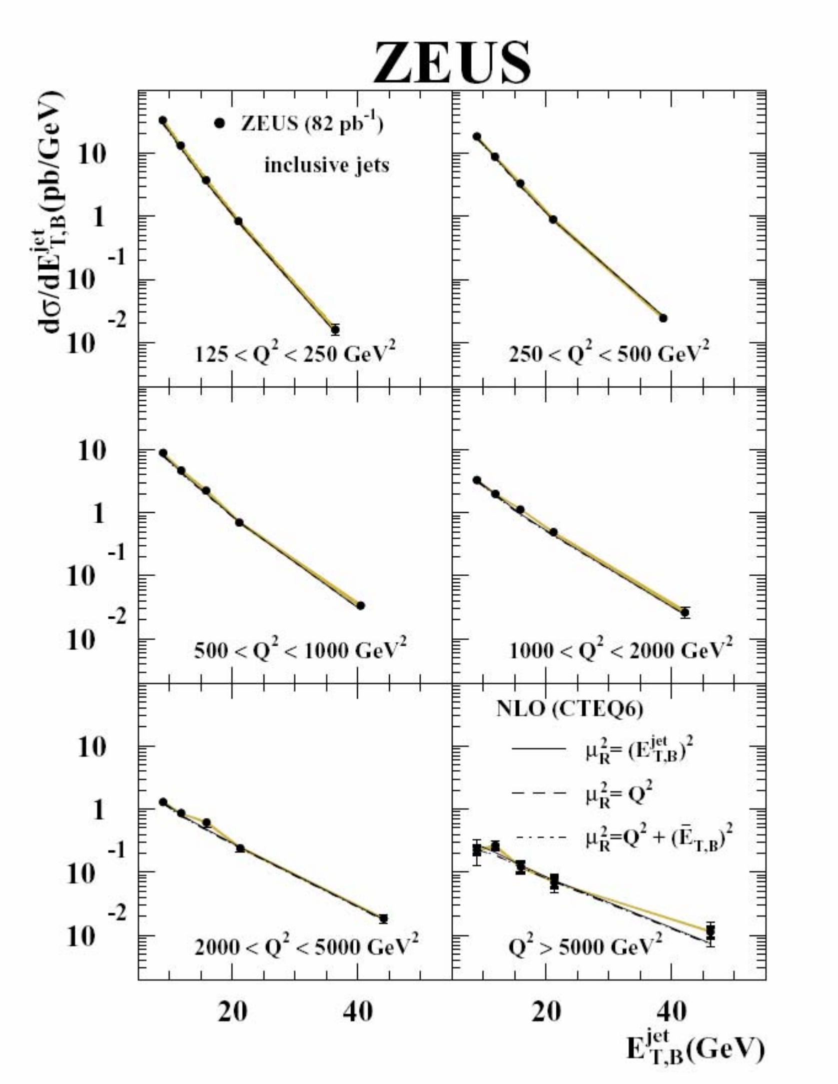
Inclusive Jet Production in NC DIS

- Jet search in Breit frame
  - virtual photon purely space-like, defines longitudinal direction
  - optimal separation of proton remnant & recoiling parton
- High $E^{jet}_{T,B}$
  - ➔ mainly sensitive to hard QCD processes
  - ➔ ideal testing ground for pQCD
- ➔ Experiment and NLO calculations agree over five orders (!) of magnitude in the Q^2 spectrum
- ➔ Impressive success for QCD theory
- ➔ Experimental uncertainty (mainly jet energy scale) tends to be smaller than theoretical uncertainly of NLO calculations



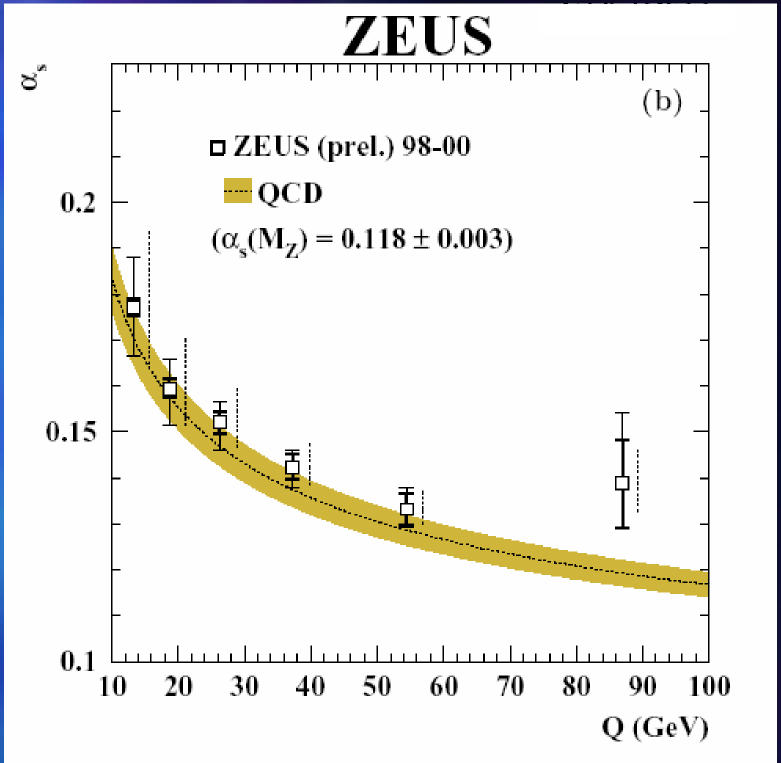
Inclusive Jet Production in NC DIS (cont'd)

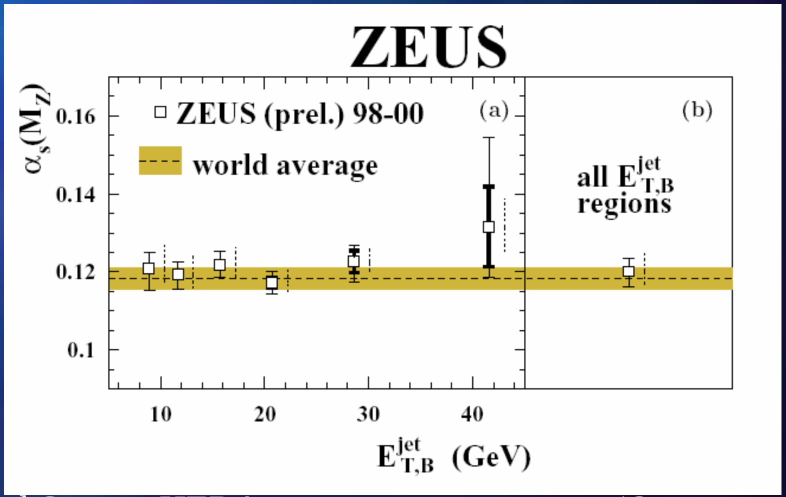
- $E^{jet}_{T,B}$ dependence becomes less steep as Q^2 increases
- ➔ Measurements well described by NLO QCD



Inclusive Jet Production (cont'd)

- Differential cross sections vs $E_{T,B}^{jet}$ and Q^2 can be used to extract strong coupling constant
  - ➔ Running of α_s clearly seen
  - ➔ Shape agrees with theoretical expectation
  - ➔ Value of $\alpha_s(M_Z)$ in accord with world average
    - ➔ competitive precision
- Measuring whole Q range in one analysis avoids systematic uncertainties that arise when combining different experiments

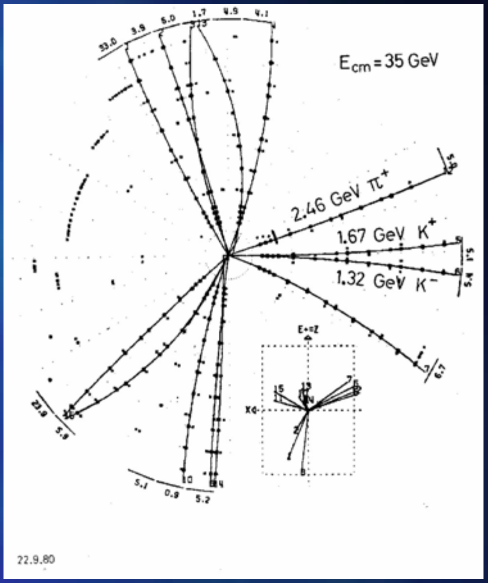


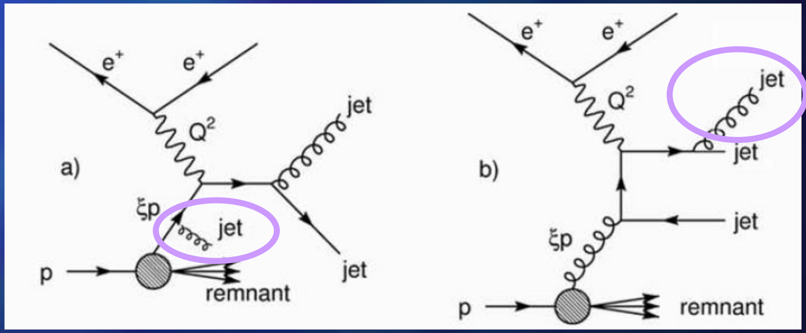


2. Multi-Jet Final States

Multijet Final States

- Historical note: in 1979, the first direct observation of the gluon was made at DESY, as a third jet in e^+e^- annihilation
  - resulting from hard gluon radiation
  - could estimate α_s from relative rate
- Three-jet signatures can be seen as the modern HERA equivalent of this measurement
  - in Breit frame similar quite picture as in e^+e^-
  - one jet emerging from hard gluon radiation
  - can measure α_s from ratio of 3-jet : 2-jet production

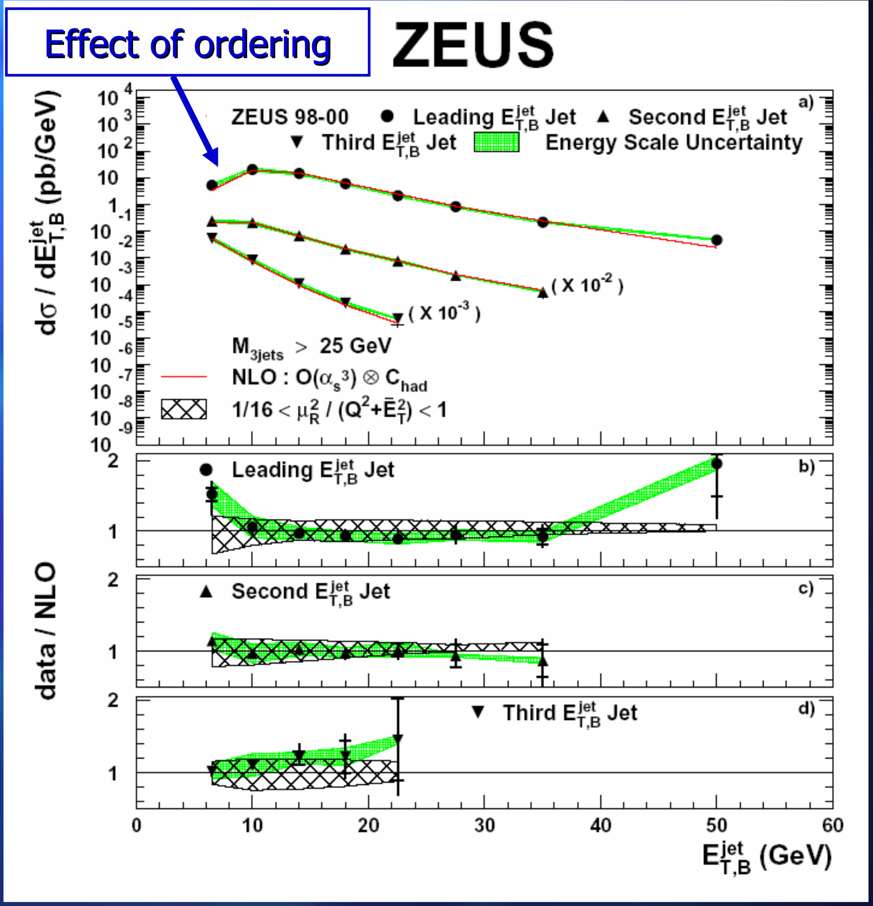




Tri-Jet Final State: Jet Energy Spectra

- Jets classified according to decreasing transverse energy $E_{T,B}^{jet}$

➔ Good description by NLO* in $O(\alpha_s^3)$, even at low $E_{T,B}^{jet}$

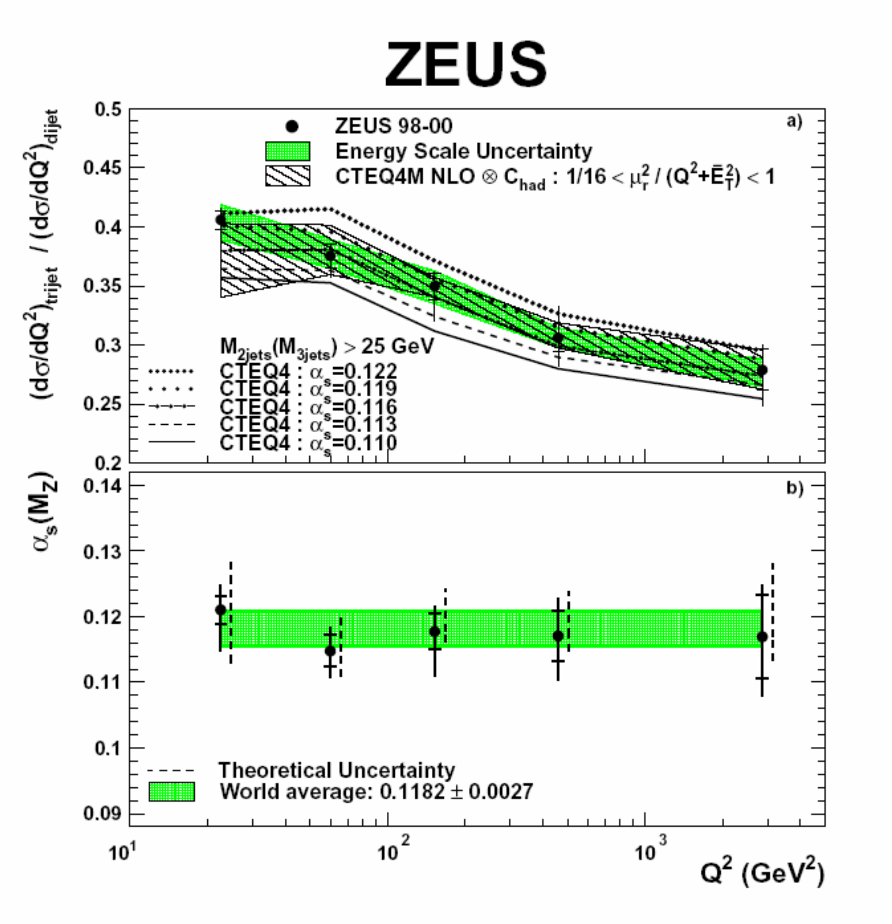


*NLOJET with CTEQ6

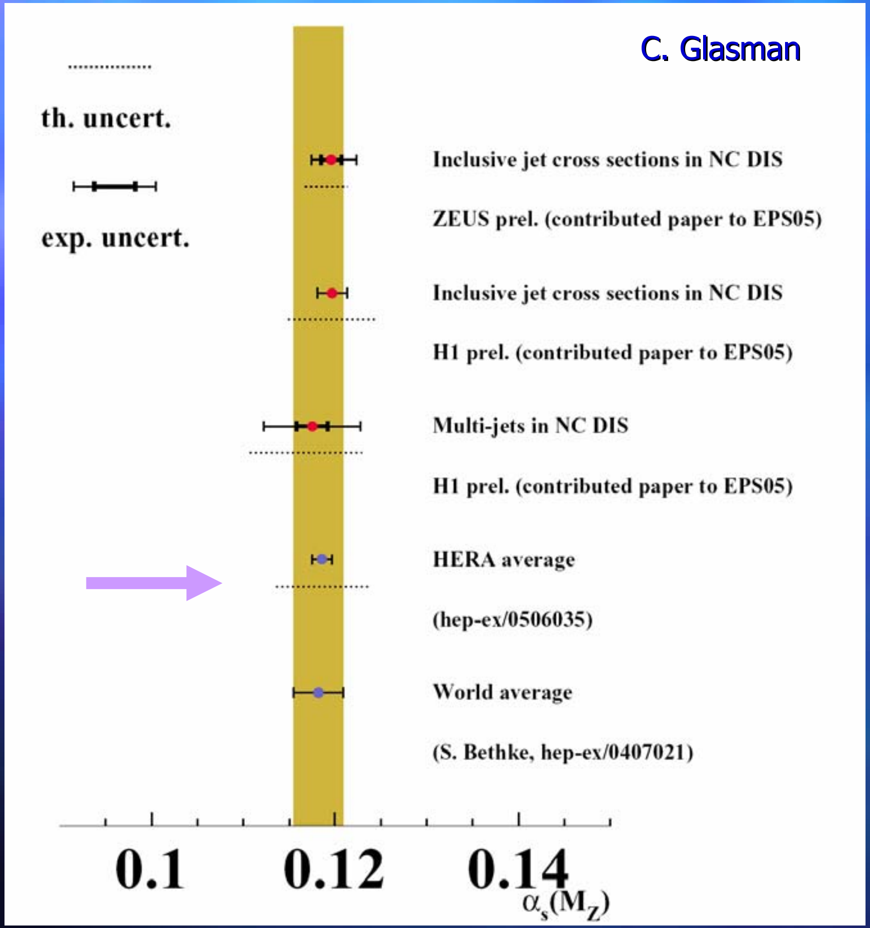
Ratio of Tri-Jet to Di-Jet Production

- Correlated uncertainties largely cancel in ratio
- Ratio decreases with increasing Q^2
  - ➔ reflects decreasing strength of coupling
  - ➔ well described by theory
- Absolute ratio can be used to determine $\alpha_s(m_Z)$
  - systematics complementary to inclusive jet measurement

$$\alpha_s = 0.1179 \pm 0.0013(stat.)\,^{+0.0028}_{-0.0046}(\text{exp.})\,^{+0.0064}_{-0.0046}(th.)$$



α_s Summary

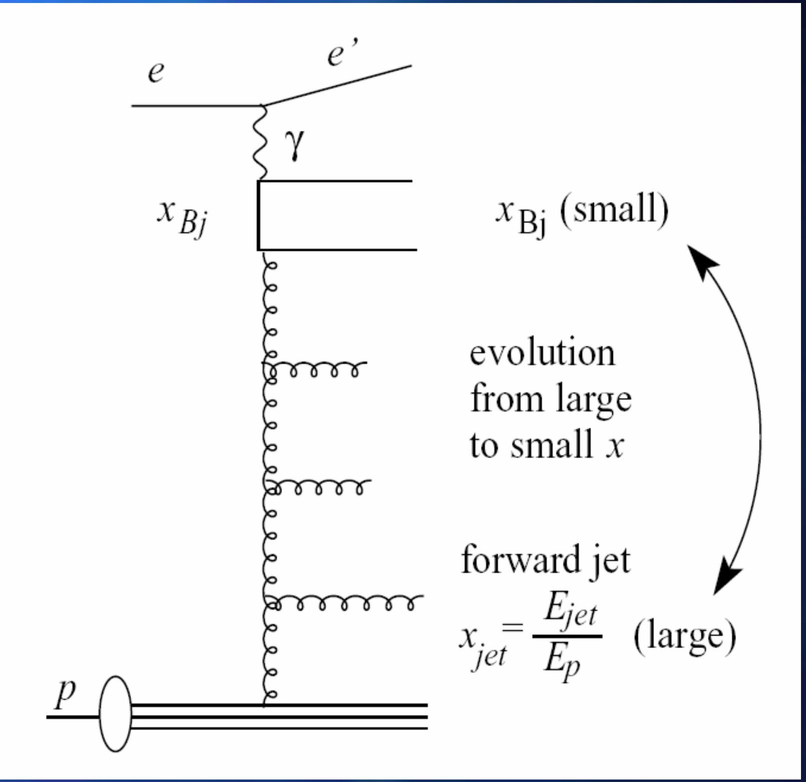


- α_s measurements from HERA have reached an impressive level of precision
  - need help from theory
- Consistent both internally & with other experiments
- With more data to come from HERA-II → further improvement expected

3. Forward Jets

Forward Jets

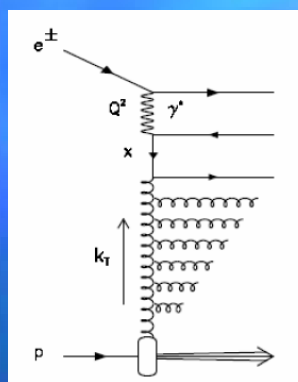
- Forward area is particularly sensitive to details in evolution of parton cascade
- At low x, we do not probe the valence structure of the proton, but rather see universal structure of QCD radiation at work
  - signature: forward jet
- This enables us to examine different mechanisms of parton cascade evolutions



Dynamics of Parton Evolution

DGLAP

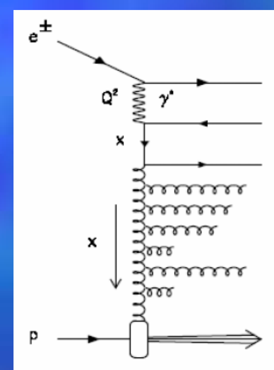
Dokshitzer-Gribov-Lipatov-Altarelli-Parisi



- Evolution in powers of ln Q^2
- Strongly ordered in k_T
- Well established at high x and Q^2, but expected to break down at low x

BFKL

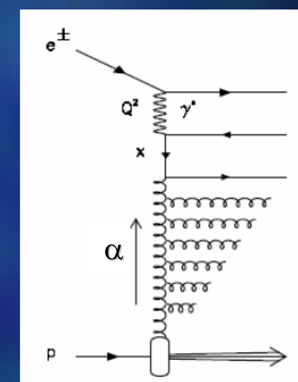
Balitsky-Fadin-Kuraev-Lipatov



- Evolution in powers of ln 1/x
- Strongly ordered in x
- May be applicable at low x

CCFM

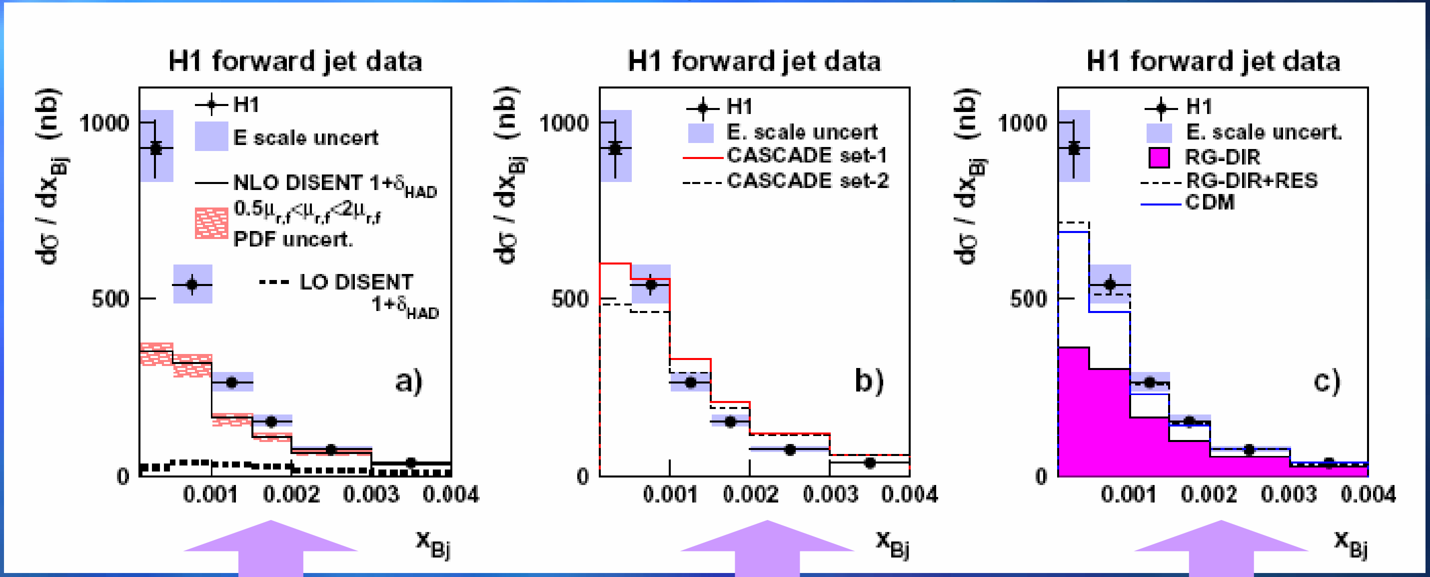
Ciafaloni-Catani-Fiorani-Marchesini



- Evolution in both ln Q^2 and ln 1/x
- Bridge between DGLAP and BFKL
- Angular ordering
- May be applicable at low x

Forward Jet Measurements (DIS)

$x_{Bj}<0.004$, $7^o<\theta_{jet}<20^o$, $x_{jet}>0.035$ ← Cuts designed to enhance BFKL effects



DGLAP
- leading order suppressed by kinematics
- even with NLO, factor 2 below data at low x
- need for higher orders?

CCFM
- distribution too hard
- comparatively poor description of the data

CDM (similar to BFKL)
- generally good

DGLAP with resolved virtual photon similar to CDM, but fails to describe forward+dijet sample

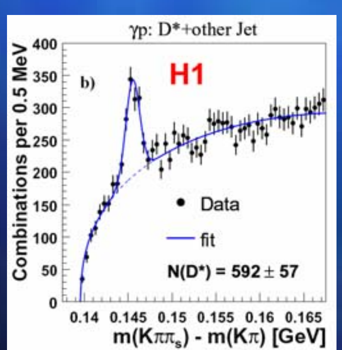
Forward Jets Summary

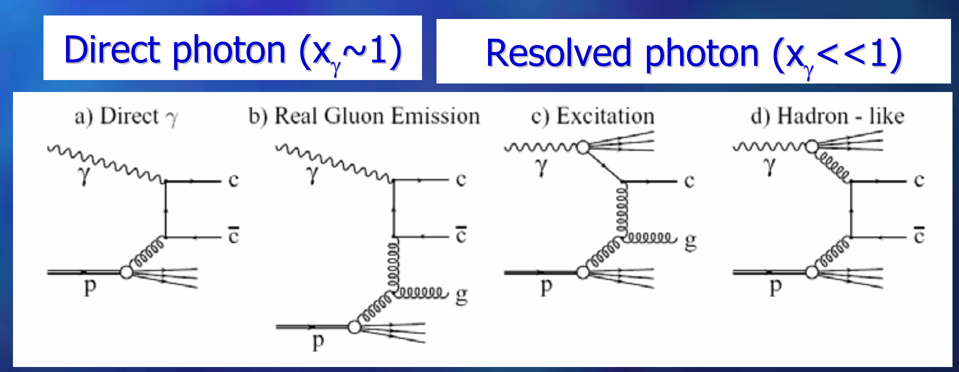
- Limitations of the pure DGLAP approach clearly seen in the forward area
  - higher order parton emissions break ordering scheme
- Calculations which include such processes (CDM) achieve better description of the data

4. Charm & Jets in Photo-Production

D*-Jet Correlations in Photo-Production

- Charm quark mass provides hard scale even for quasi-real photon ($Q^2 \sim 0$)
  - perturbative QCD (pQCD) applicable over full phase space
- Several basic processes expected to contribute to photo-production of charm
- Correlations between D* and a separate additional jet, or between two jets (one of them tagged by a D*) allow a very fine-grained comparison of different theoretical approaches



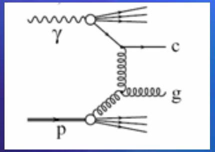


How Models Treat Charm Production

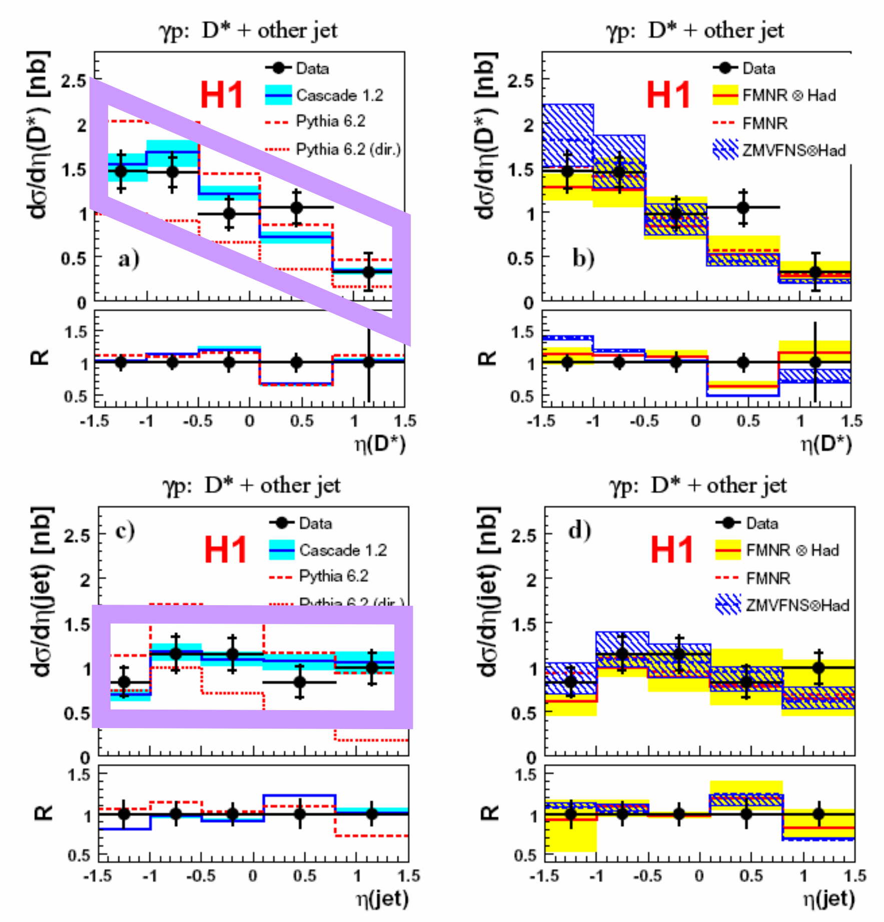
- PYTHIA: LO direct photon-gluon fusion, charm excitation & hadron-like. Higher order contributions simulated with leading-log parton showers in collinear approach.
- CASCADE: LO in k_T factorization approach. Higher order corrections simulated with initial state parton showers (CCFM evolution)
- FMNR (Frixione-Mangano-Nason-Ridolfi): NLO calculation ($O(\alpha_s^2)$), massive scheme in collinear factorization approach
- ZMVFNS (Zero mass variable flavor number scheme) : NLO calculation ($O(\alpha_s^2)$) in collinear approach, neglecting charm mass

D*-Jet Correlations: η Spectra

- Data show marked difference in shape: jets on average more forward than D*
  - indicates presence of a hard non-charm parton in the forward direction
  - dominant mechanism: hard gluon radiation from proton
  - [a PYTHIA variant with only direct photon does not show this difference]
- All models include this & describe effect well

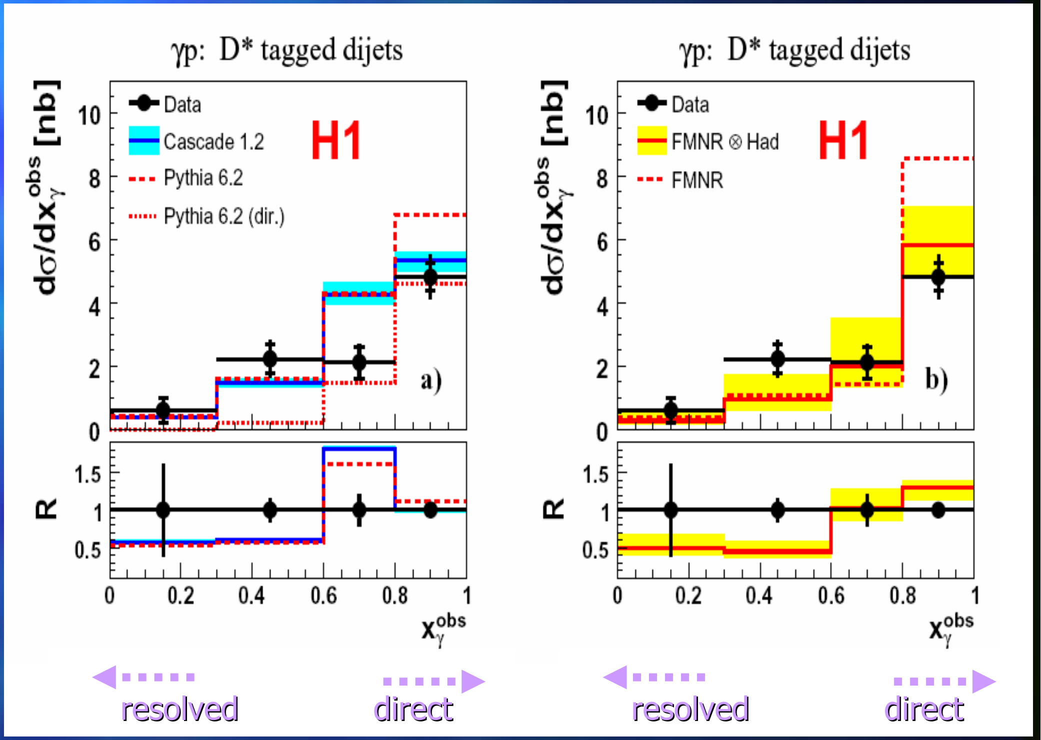


$$R = \frac{\frac{1}{\sigma_{vis}^{calc}} \frac{d\sigma^{calc}}{dY}}{\frac{1}{\sigma_{vis}^{data}} \frac{d\sigma^{data}}{dY}}$$



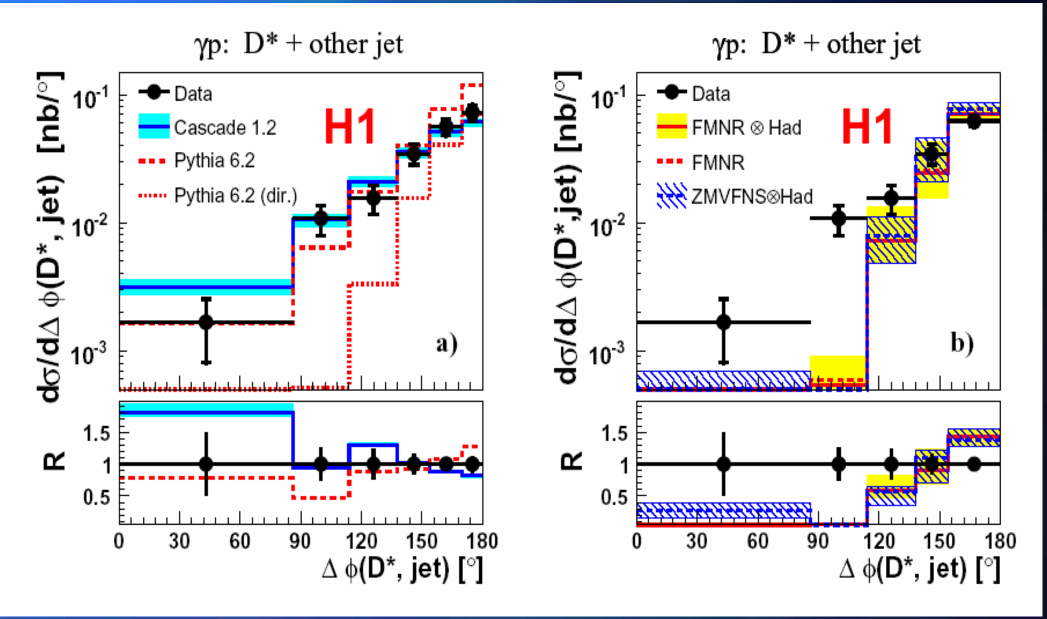
D*-Tagged Dijets: Transition from Resolved to Direct PHP

- x_γ^{obs} = fraction of photon energy participating in hard interaction
  - x_γ^{obs} ~1 : direct PHP
  - x_γ^{obs} <<1 : resolved PHP
- Sensitive to gluon emission in initial state
- All calculations underestimate relative contribution in x_γ^{obs} <0.6 region



D*-Jet Correlations: Relative Azimuth Angle

- In collinear approximation, process γg→cc should lead to back-to-back topology
- But data show: only 25% of cross section are strictly back-to-back
- Remainder can only be described with significant contributions from higher order QCD radiation
- ➔ Neither PYTHIA nor CASCADE describe full range
- ➔ NLO calculation too low for $\Delta\varphi<120^o$ → relevance of higher order contributions

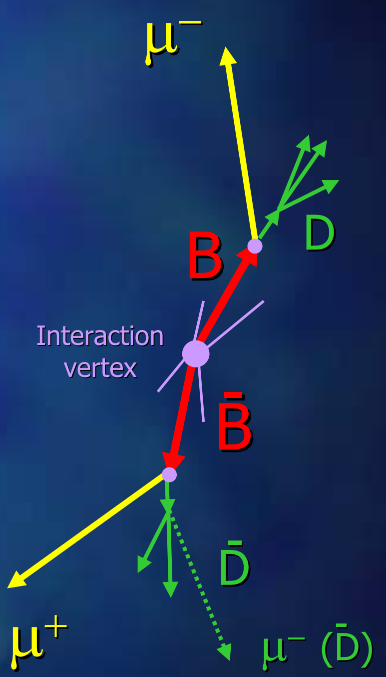


➔ Rich testing ground for QCD, challenging for theory

5. Total Beauty Cross Section

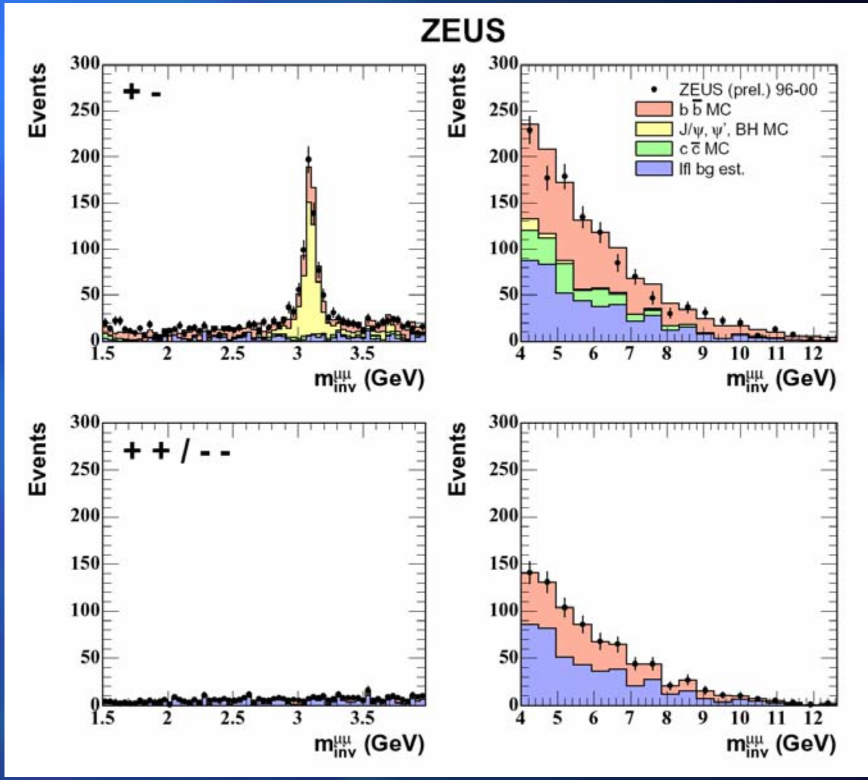
Total Beauty Cross Section

- Very stringent QCD test
  - large m_b → pQCD reliable in full phase space?
- Measurements in pp, $\gamma\gamma$, πN and pN have shown large discrepancies
- Experimental challenge:
  - beauty often tagged with high p_T electron or muon (secondary vertex, or p_T relative to jet)
  - measurement restricted to high p_T b quark → extrapolation uncertainty
- Alternative: correlation signature
  - example: di-muon
- Study of di-muon event signatures allows to use low p_t^μ thresholds
  - ➔ measure the total bb cross section



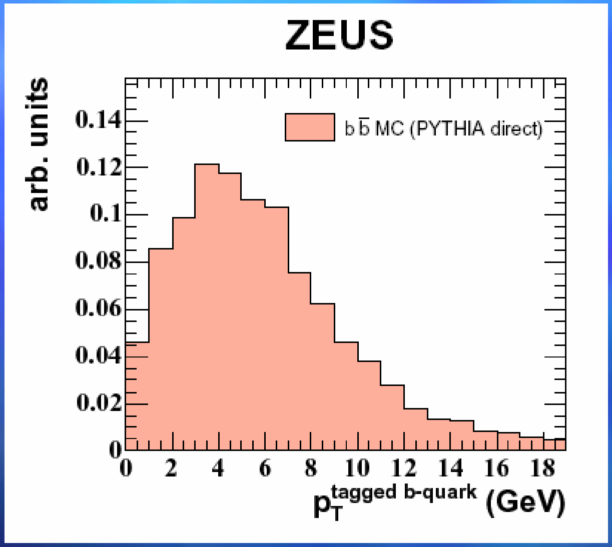
Extraction of Beauty Signal

- Light flavor background similar in (+-) and (±±) mass spectra → exploit for subtraction
- Bethe-Heitler and quarkonia background suppressed by non-isolation requirement
- Bethe-Heitler, quarkonia and cc background subtracted using MC (PYTHIA, RAPGAP, HERWIG, GRAPE)



Beauty from Di-Muons: Accessible Quark p_T Range

p_T distribution of tagged b quarks



- Method is sensitive down to $p_T(b)$~0
- Small extrapolation uncertainty

–

$b\bar{b}$ Cross Section from Di-Muon Events

$$\sigma_{tot}(ep \to b\bar{b}X)(\sqrt{s} = 318\,GeV) = 16.1 \pm 1.8(stat)^{+5.3}_{-4.8}(syst)\ nb$$

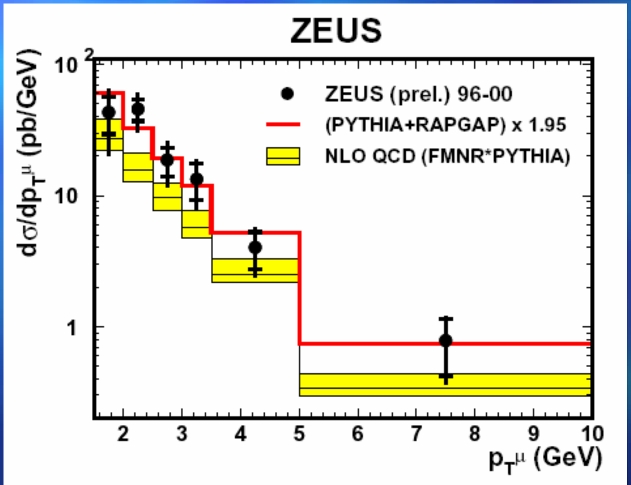
$$NLO\ QCD\ \ prediction:\ 6.8^{+3.0}_{-1.7}\ nb$$

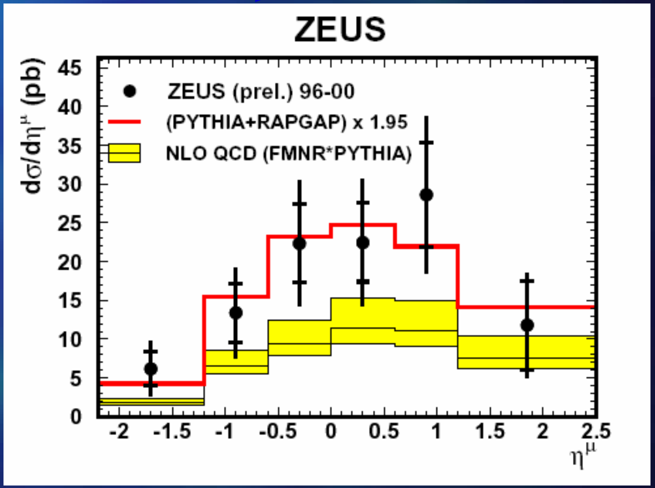
PHP: 5.8 nb (FMNR,CTEQ5M)

DIS: 1.0 nb (HVQDIS,CTEQ5F4)

Note:
PYTHIA+RAPGAP
scaled by 1.95x

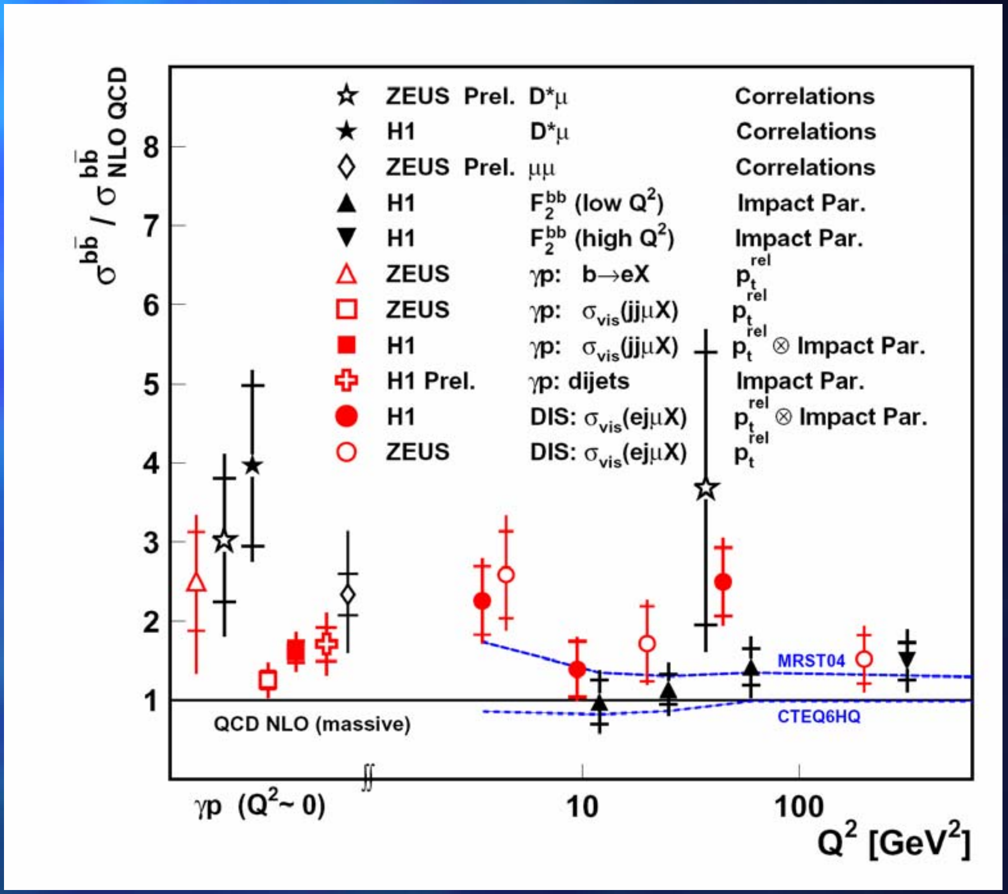
- For muons from b decays
  - ➔ Wide phase space
  - ➔ Good agreement in shape
  - ➔ Normalization underestimated by theory





HERA $b\bar{b}$ Cross Section vs Theory

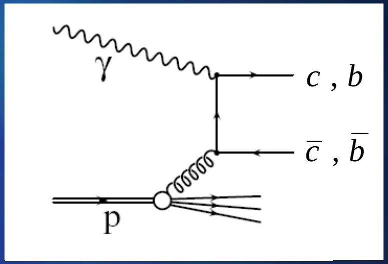
- Wide range of measurements available
- Measurements tend to be larger than NLO

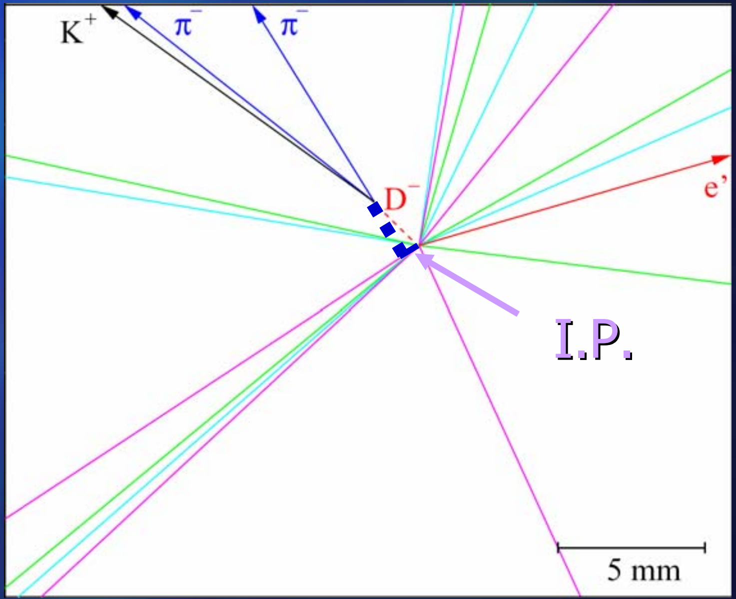


6. Charm & Beauty Di-Jet

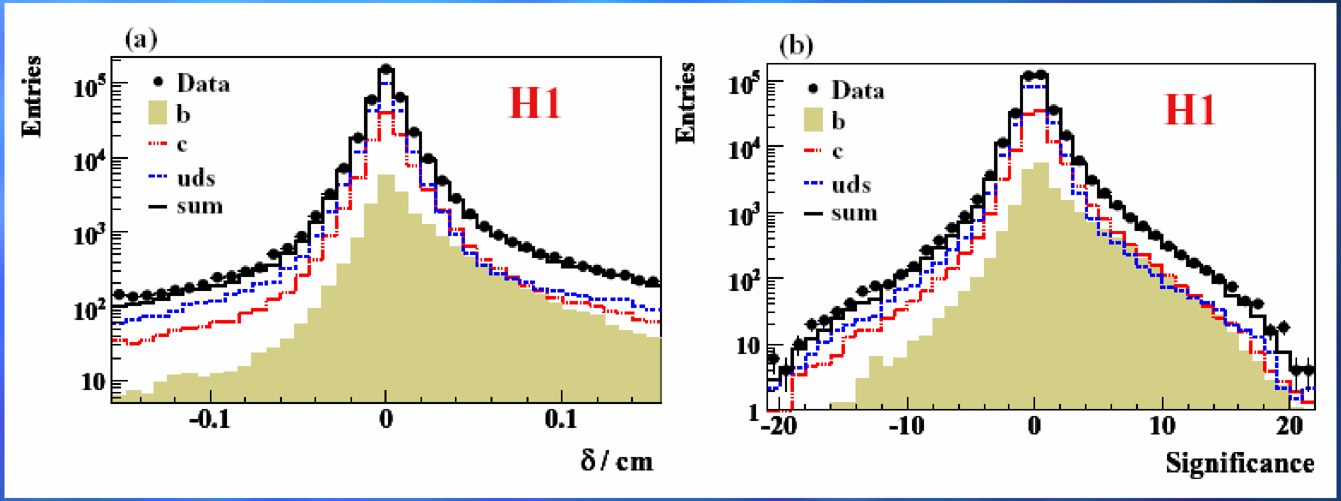
Charm & Beauty Di-Jet Cross Sections in PHP

- Typical topology for charm & beauty production: ≥2 jets
- A very elegant way to identify heavy quark production is to use lifetime tags
  - c+b lifetime leads to significantly positive values of impact parameter δ of charged tracks
  - can be measured with high resolution silicon vertex detectors
  - signed according to jet direction
- Allows simultaneous determination of charm & beauty rates in PHP





Charm & Beauty in PHP Di-Jet (cont'd)



Tracks with $p_T > 0.5$ GeV, $30^o < \theta < 150^o$, #CST hits $(r\varphi) \geq 2$

$$Significance = \frac{\delta}{\sigma(\delta)}$$

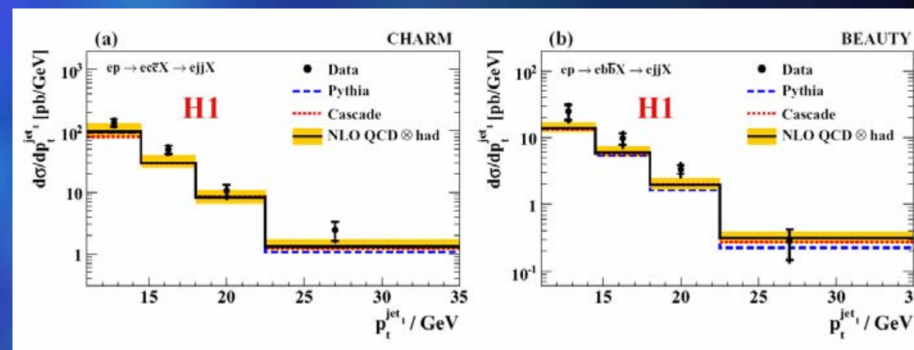
- ➔ Clear excess at positive impact parameter (significance)
- Since $m_b >> m_c$, decays of beauty hadrons have significantly higher number of tracks on average
- Divide into 2 samples according to tracks associated to jet:
  - #tracks=1 : charm enriched
  - #tracks>1 : beauty enriched

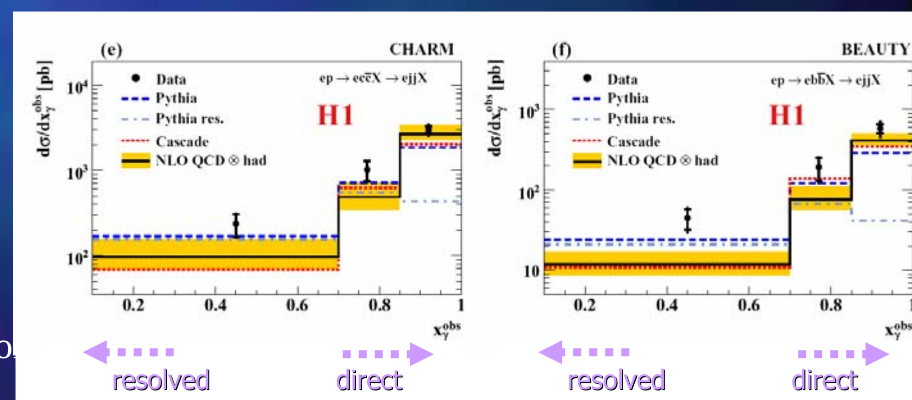
Charm & Beauty in PHP Di-Jet: Cross Sections

$Q^2<1$ GeV^2, $0.15<y<0.8$,
$p_T^{jet1(2)}>11(8)$ GeV, $-0.9<\eta^{jet1(2)}<1.3$

	Charm [pb]	Beauty [pb]
Data	$702 \pm 67(stat.) \pm 95(syst.)$	$150 \pm 17(stat.) \pm 33(syst.)$
FMNR	500^{+173}_{-99}	83^{+19}_{-14}
PYTHIA	484	76
CASCADE	438	80

- Cross section:
  - NLO (FMNR) agrees for charm, but factor 1.8 too low for beauty
  - PYTHIA, CASCADE similar
- Shapes of p_T^{jet} and η^{jet} (not shown) reasonably well described
- x_γ^{obs} = fraction of photon energy participating in hard interaction
- At low x_γ^{obs} (resolved photon regime), NLO calculation strongly underestimates the beauty cross section
  - PYTHIA agrees in shape
- At x_γ^{obs} >0.85 (direct photon regime), models work generally well (↔photon gluon fusion)





Summary

- Wealth of measurements from HERA on structure of hadronic final state
  - only a small selection presented
  - unique facility for QCD studies
- NLO largely successful in describing experimental data
- Some challenging frontiers identified
  - QCD dynamics in vicinity of proton remnant (low x regime)
  - resolved photo-production
  - beauty cross section
- With large HERA-II data sample, and improvements in theory, expect further insights in QCD frontiers regarding the hadronic final state