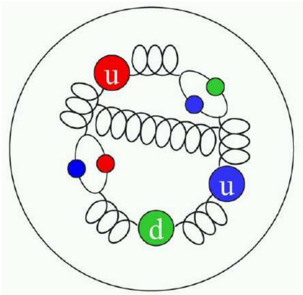
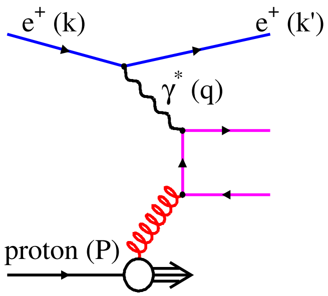
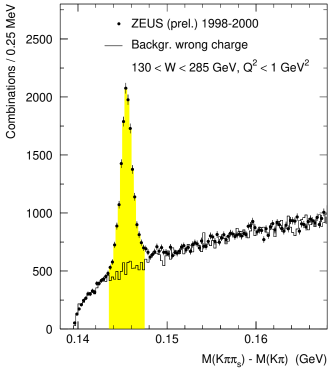
Graduiertenkolleg Elementarteilchenphysik, 6.-9.10.03

# Heavy Quark Production at HERA





Andreas B. Meyer

Hamburg University

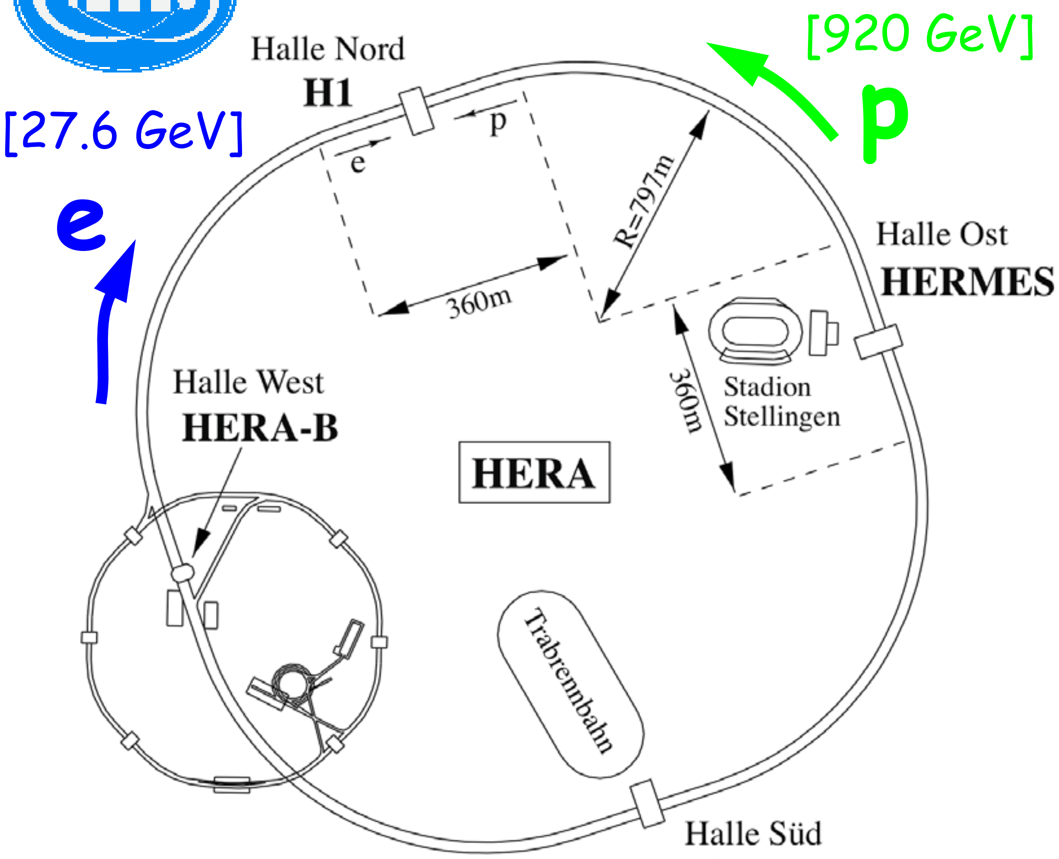

Concepts | Experiments | Recent Results | Future Plans

# The $ep$ Collider HERA at DESY

# The HERA ep-Collider

## @ DESY/Hamburg

$\sqrt{s}$ = 320 GeV




**HERA I** [1994 -2000]

$e^+p$ Scattering: $L \sim 100\ pb^{-1}$

$e^-p$ Scattering: $L \sim 15\ pb^{-1}$

**HERA II** [2003++]

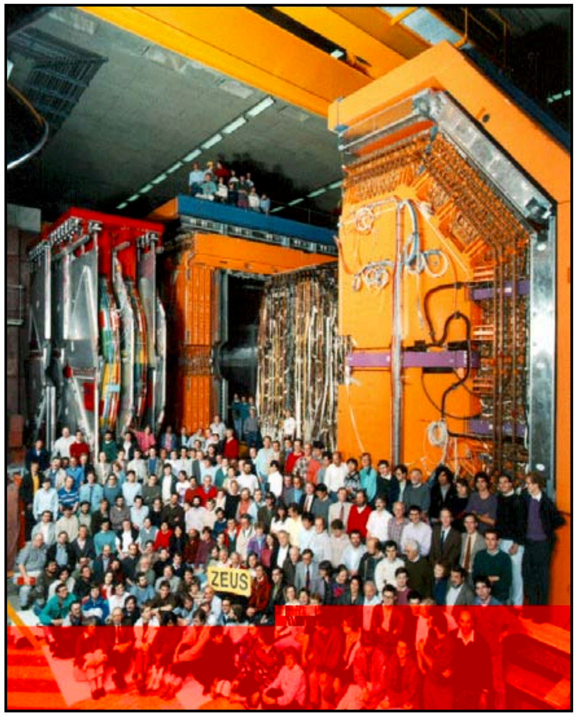
Int. Luminosity: $1000\ pb^{-1}$

$e^{\pm}$-Polarisation ~50%

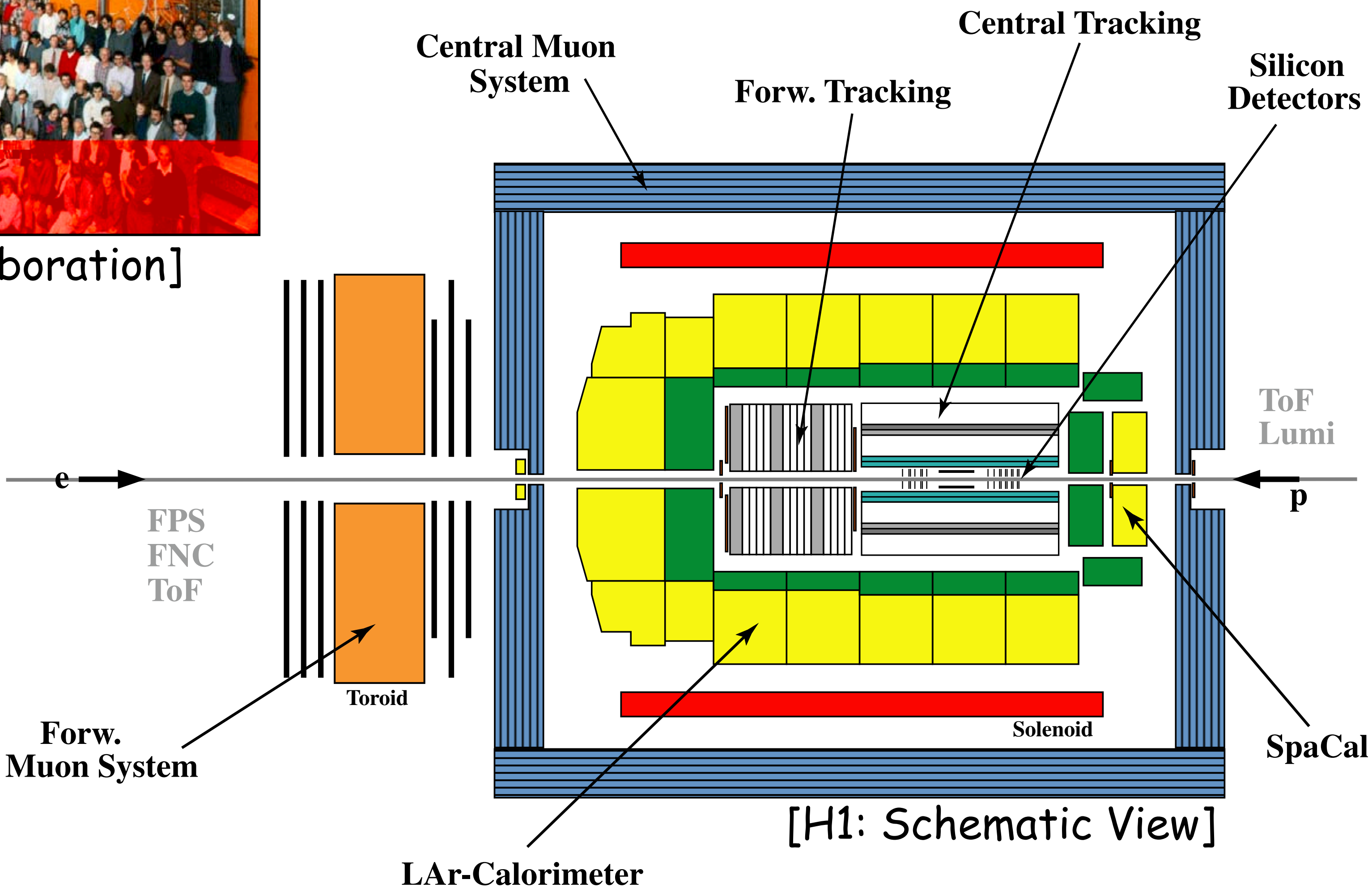
[+ low energy ep-data]

# HERA Detectors

| ZEUS | H1 |
|---|---|
| Uranium Calorimeter | LAr Calorimeter |
| • $\sigma(E)/E = 18\%/\sqrt{E}$ for electrons | • $\sigma(E)/E = 12\%/\sqrt{E}$ for electrons |
| • $\sigma(E)/E = 35\%/\sqrt{E}$ for hadrons | • $\sigma(E)/E = 50\%/\sqrt{E}$ for hadrons |
| Central Tracker Resolution | Central Tracker Resolution |
| • $\sigma(p_t)/p_t = 0.0058\, p_t/\mathrm{GeV} \oplus 0.0065$ | • $\sigma(p_t)/p_t = 0.006\, p_t/\mathrm{GeV} \oplus 0.02$ |



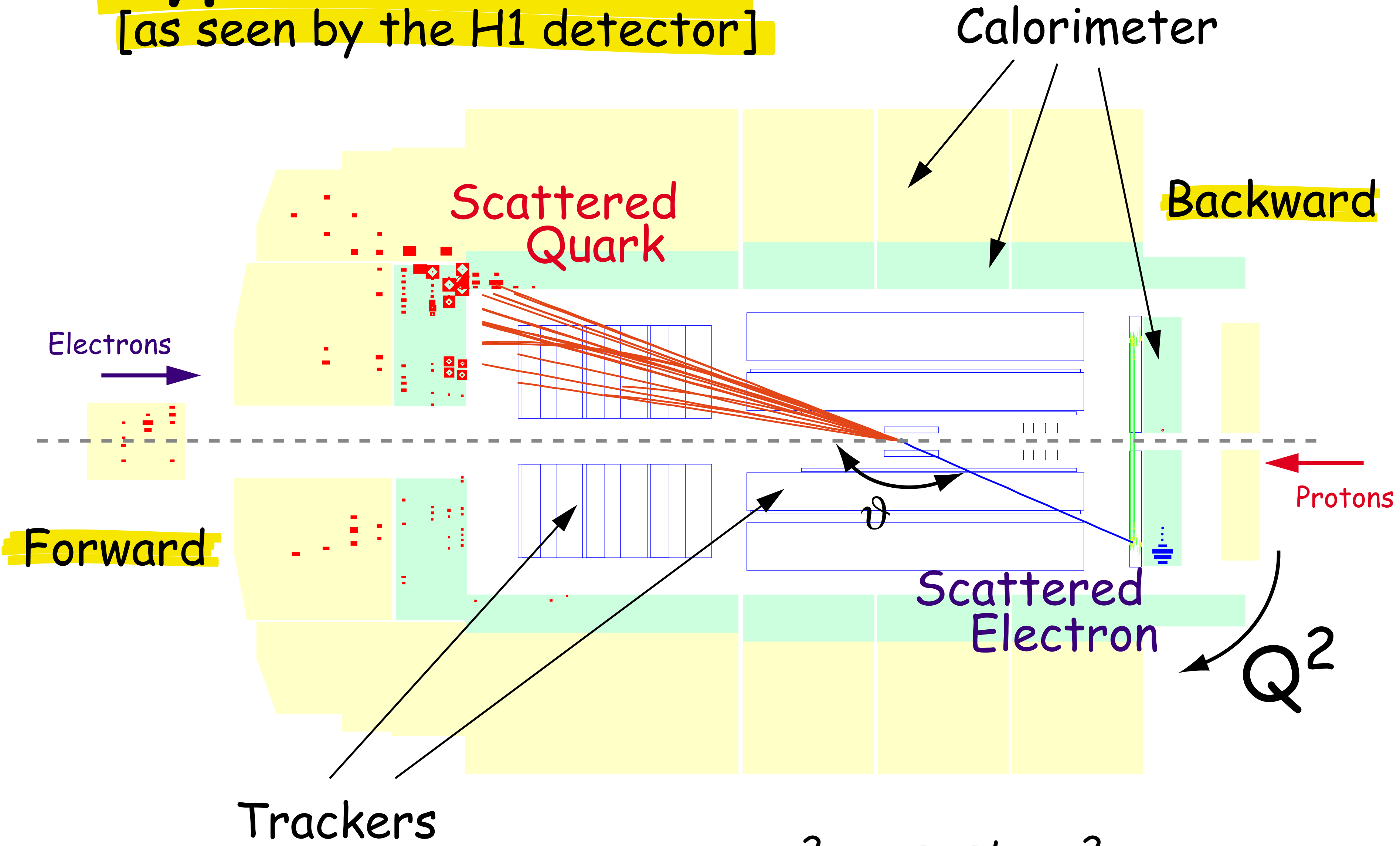

[ZEUS Collaboration]




[H1: Schematic View]

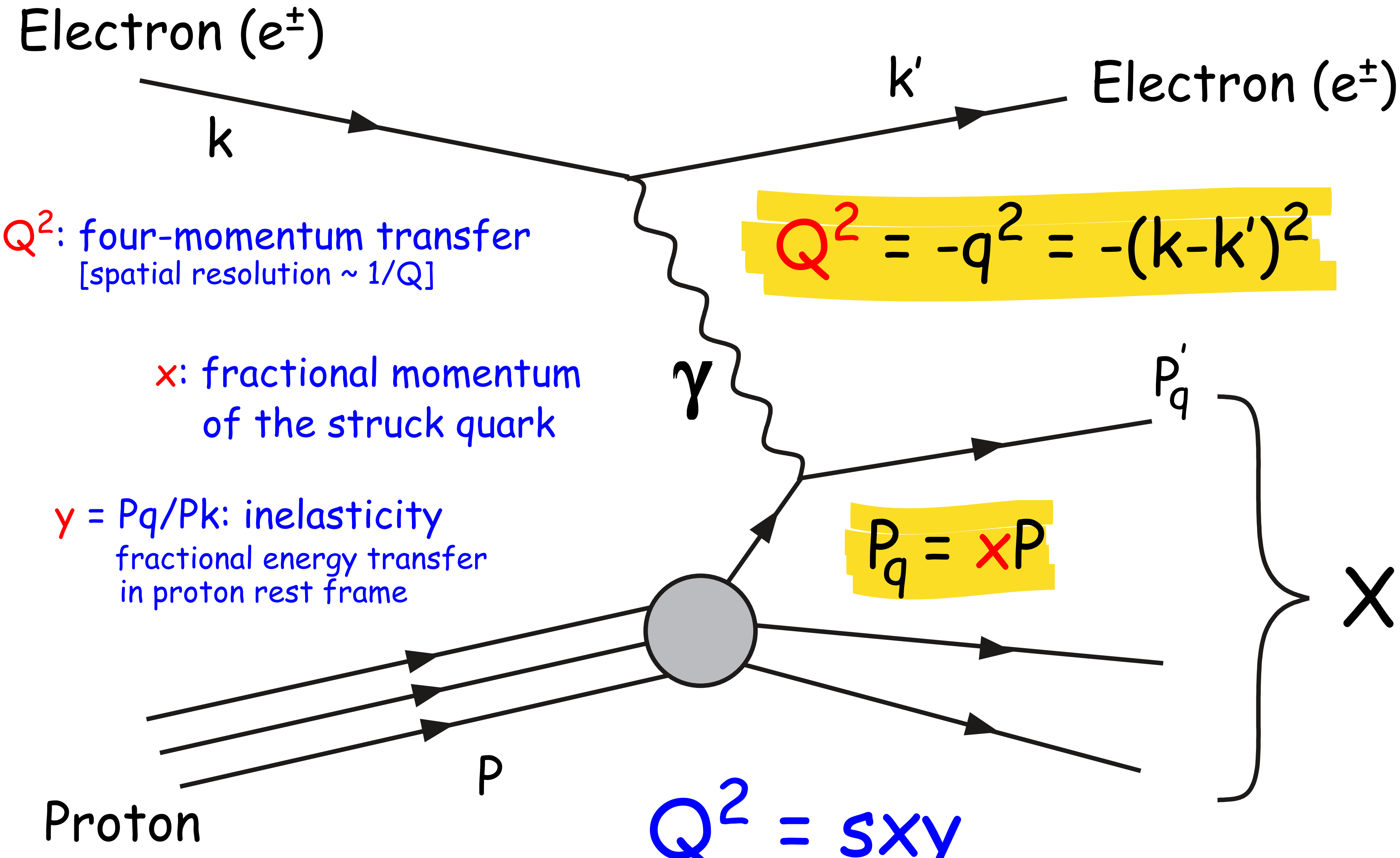
# Typical DIS-Event

[as seen by the H1 detector]




$$Q^2 = 4E_eE_e'\cos^2(\vartheta/2)$$

# DIS Kinematics




$Q^2$: four-momentum transfer
[spatial resolution ~ 1/Q]

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

x: fractional momentum of the struck quark

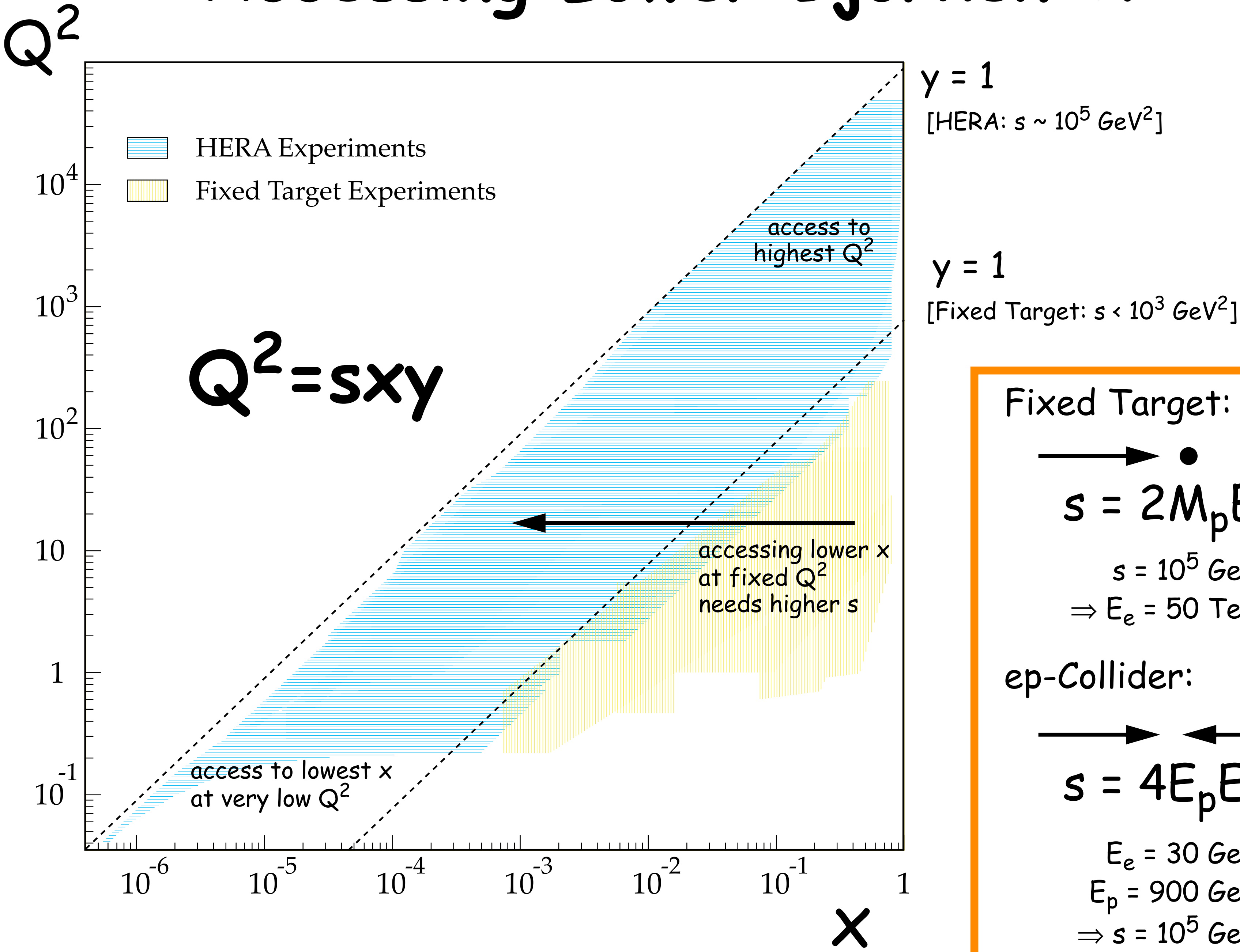
$$P_q = xP$$

y = Pq/Pk: inelasticity
fractional energy transfer in proton rest frame

$$Q^2 = sxy$$

[$\sqrt{s}$: cms-energy]
[$0 \le x \le 1$; $0 \le y \le 1$]

# Accessing Lower Bjorken-x




**Fixed Target:**

$$s = 2M_pE_e$$

$s = 10^5$ GeV

$\Rightarrow E_e = 50$ TeV

**ep-Collider:**

$$s = 4E_pE_e$$

$E_e = 30$ GeV

$E_p = 900$ GeV

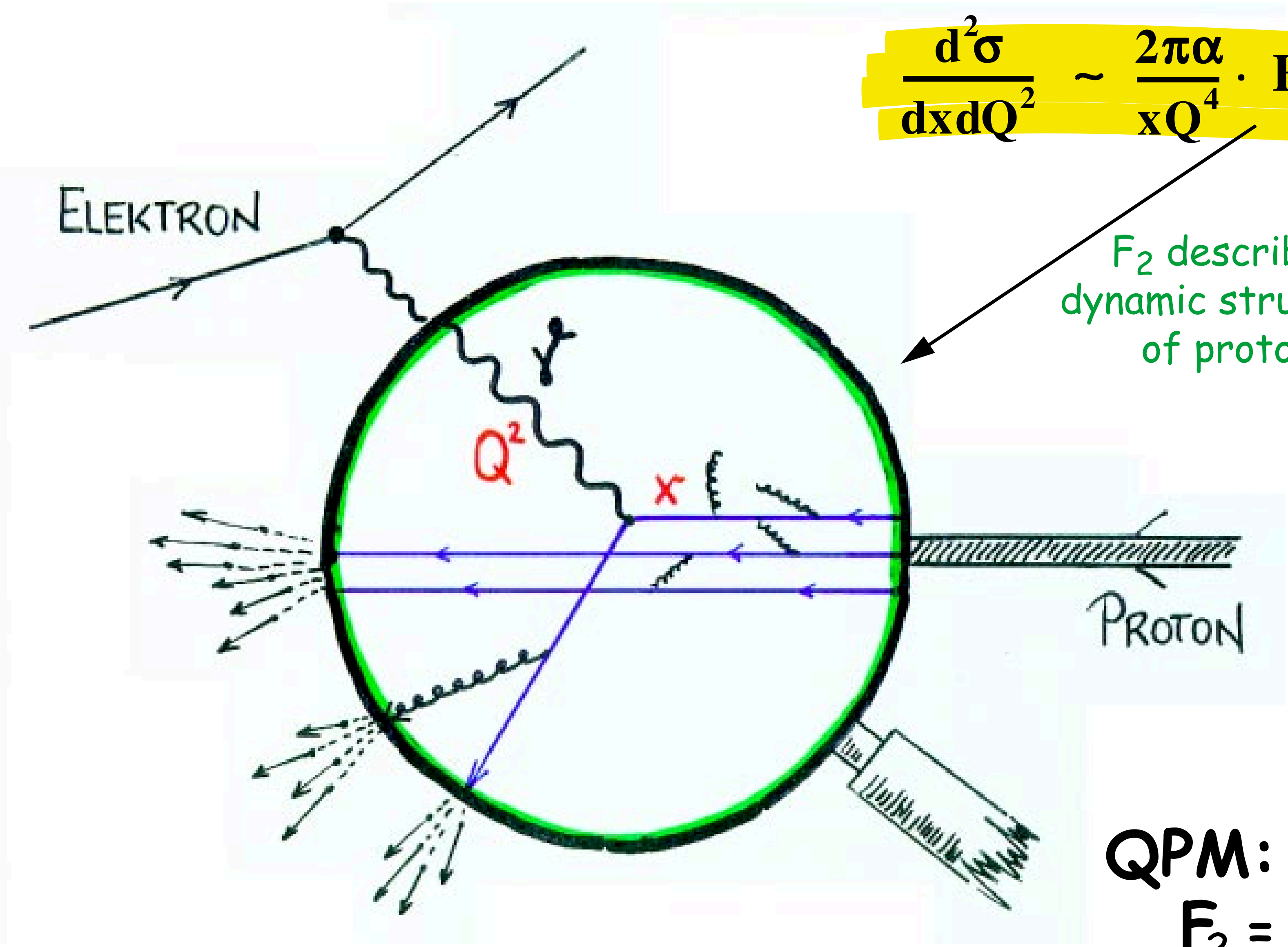
$\Rightarrow s = 10^5$ GeV

Investigating the

# Structure of the Proton

$$\frac{d^2\sigma}{dx\,dQ^2} \sim \frac{2\pi\alpha}{xQ^4} \cdot F_2(x, Q^2)$$

$F_2$ describes dynamic structure of proton



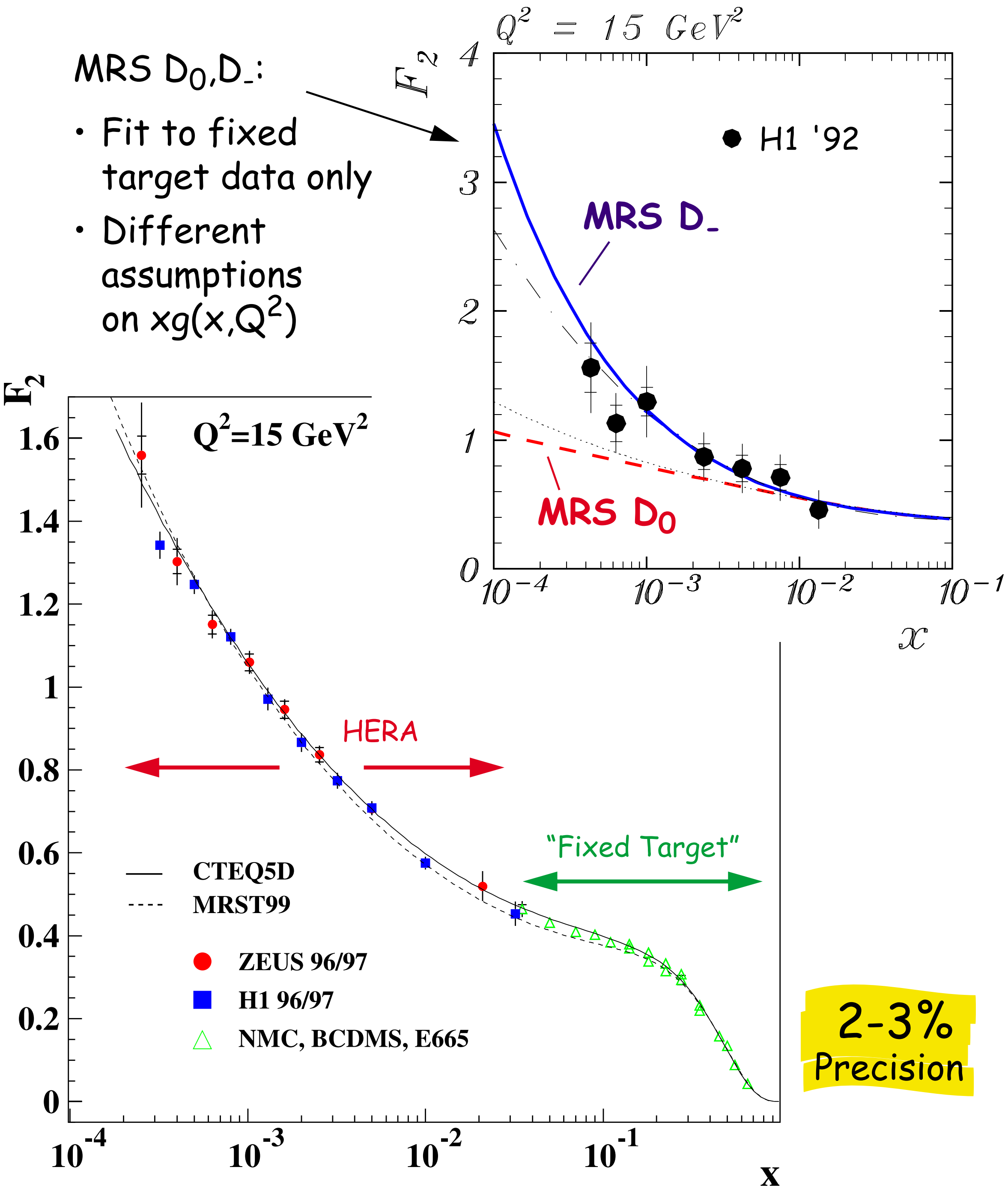

**QPM:**

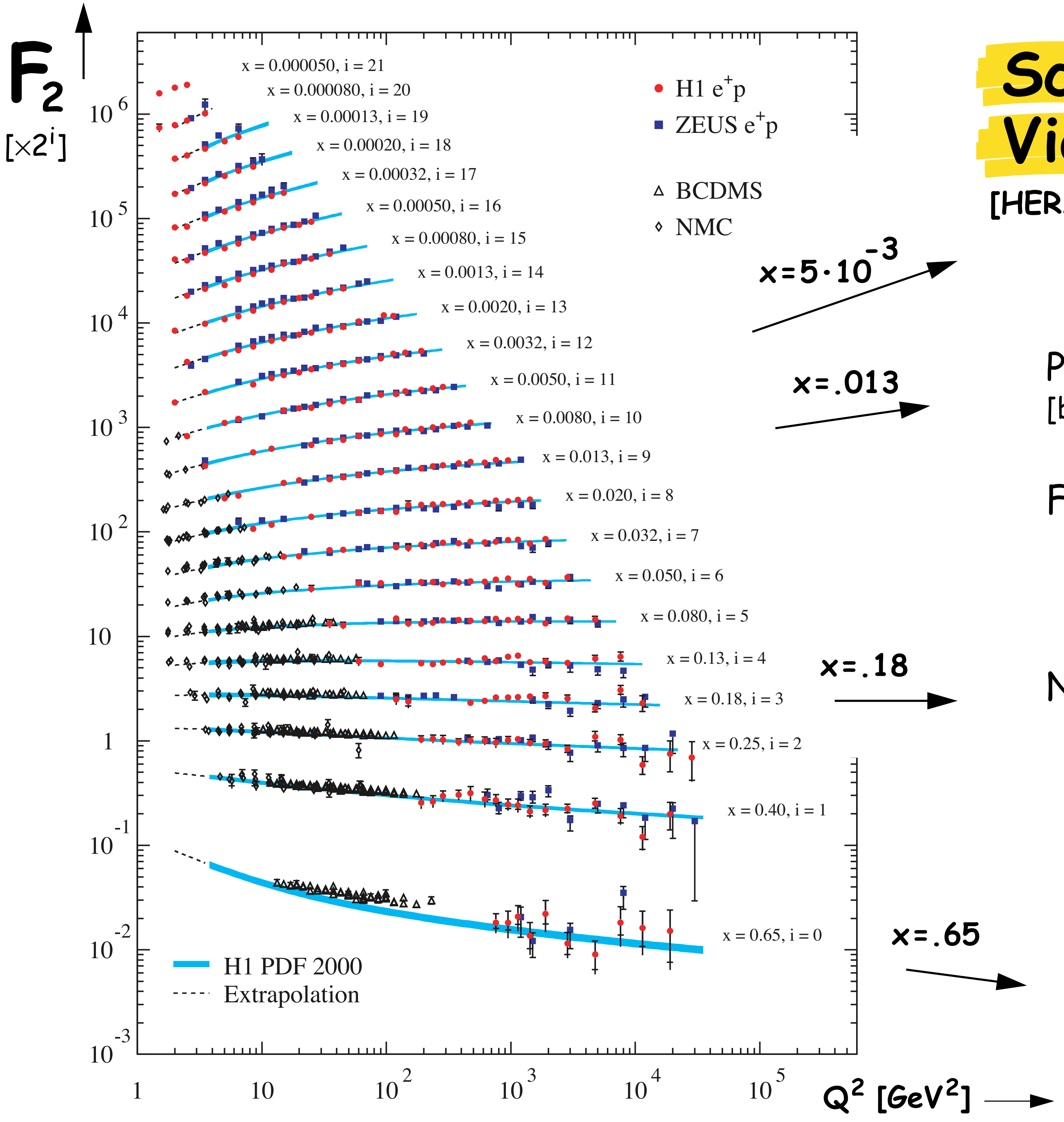
$$F_2 = \sum e_q^2\, x q(x)$$

# HERA early findings:

- $F_2$ steeply rising towards small $x$

Unexpected!






# Scaling Violations

[HERA & fixed target data]

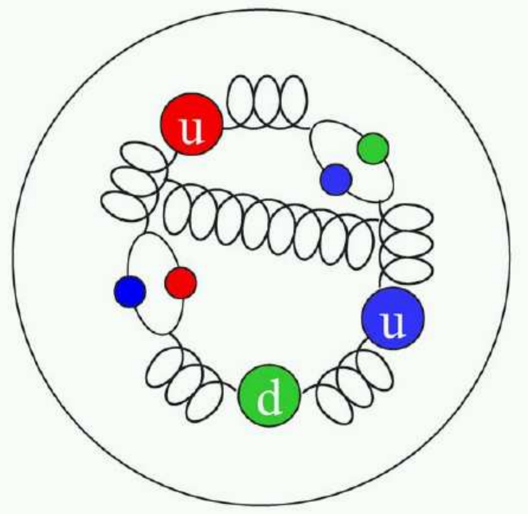
Precision: 2-3%
[bulk region]

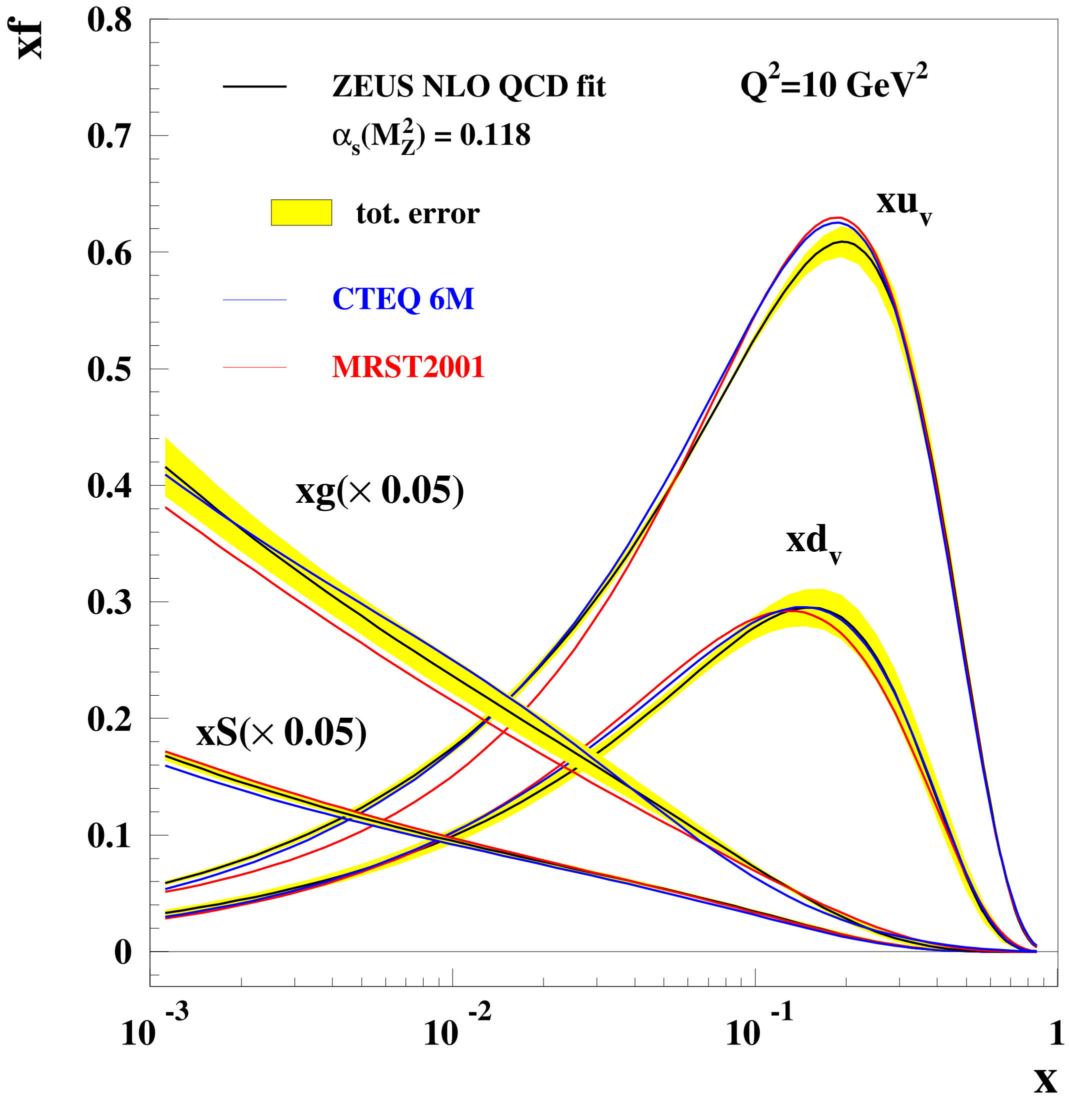
For $x < 10^{-2}$:

$$\frac{dF_2}{d\log Q^2} \sim g(x,Q^2)\cdot\alpha_s(Q^2)$$

NLO QCD Fits:

Quark densities
Gluon density
Strong coupling $\alpha_s$



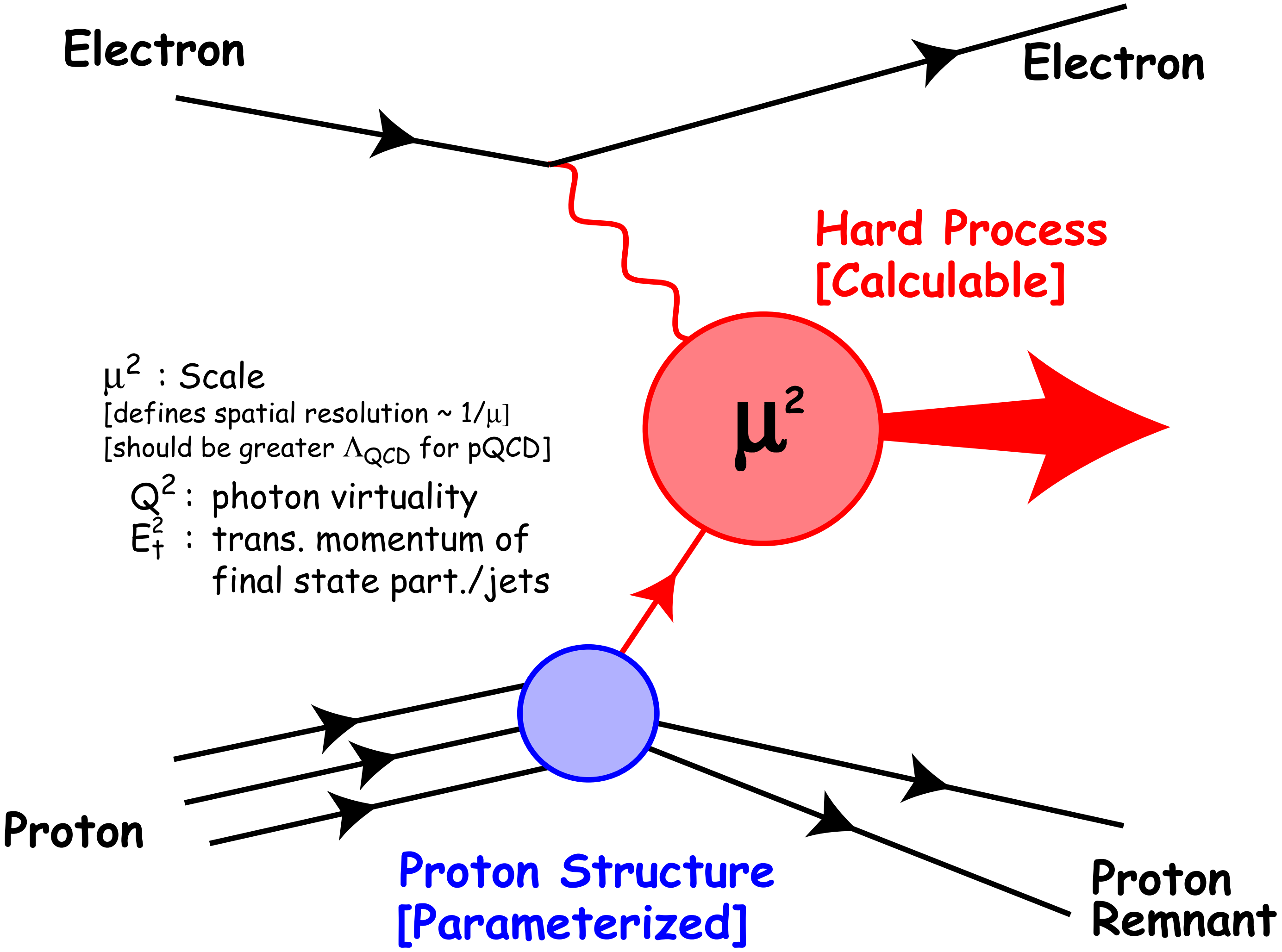

Small $x$:

- Scaling Violations → Gluons

Large $x$:

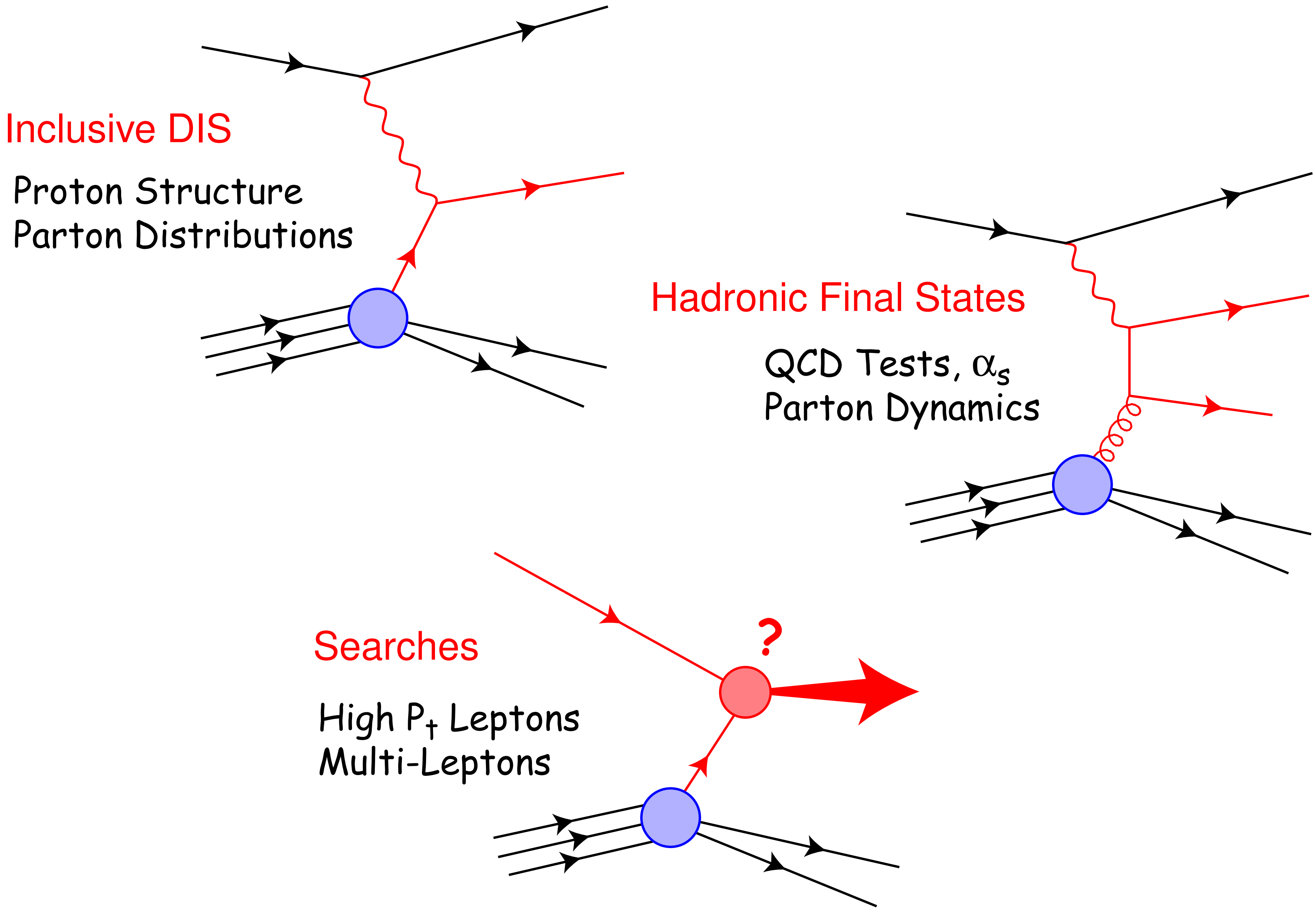
- Valence Quarks → still some uncertainties

# HERA: Multi purpose physics at the high energy frontier ($\sqrt{s} = 320$ GeV)

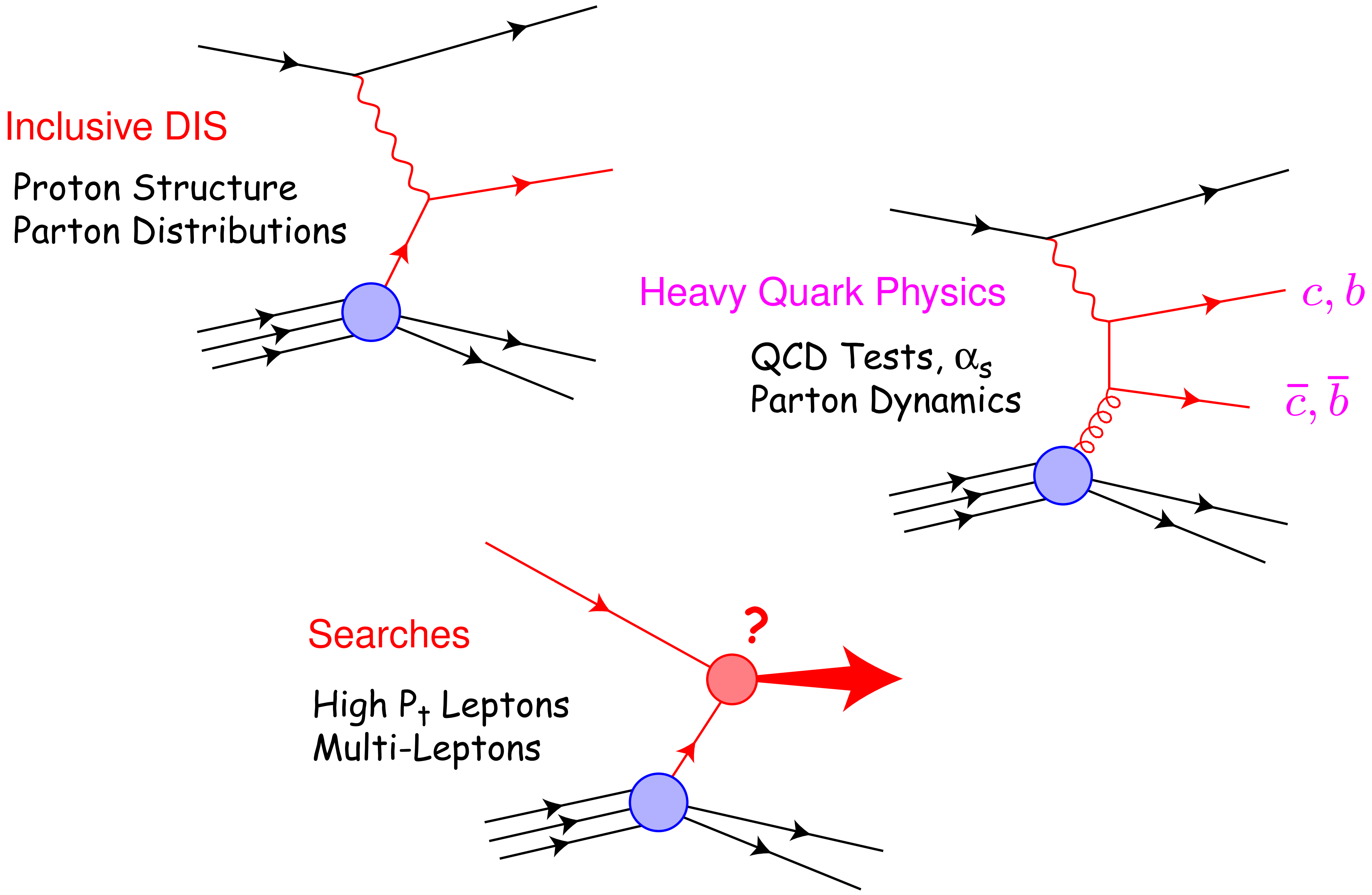



- QCD studies
- EW physics
- Searches

Proton used as a source of partons (small $x$: mostly gluons)

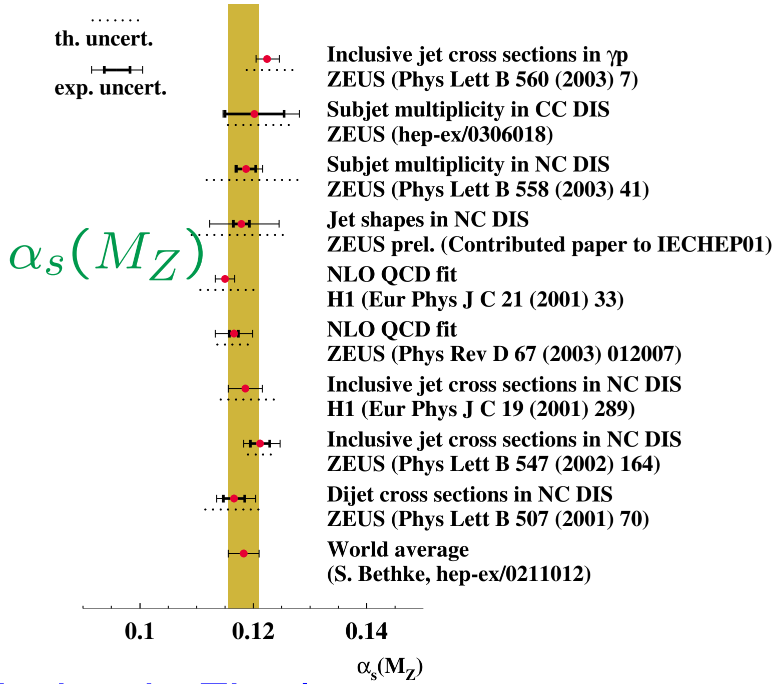


Inclusive DIS
Proton Structure
Parton Distributions
Hadronic Final States
QCD Tests, $\alpha_s$
Parton Dynamics
Searches
?
High $P_t$ Leptons
Multi-Leptons

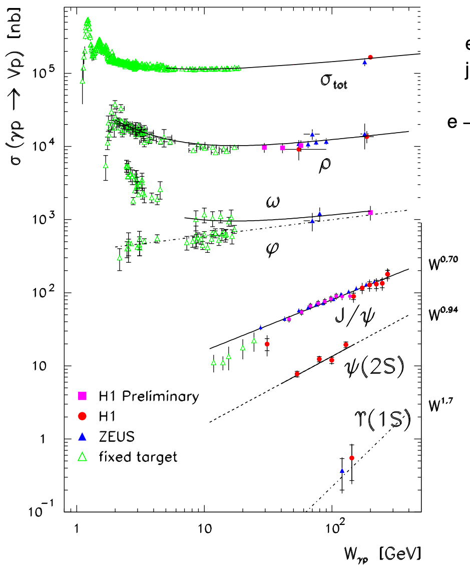


Inclusive DIS
Proton Structure
Parton Distributions
Heavy Quark Physics
QCD Tests, $\alpha_s$
Parton Dynamics
$c, b$
$\bar{c}, \bar{b}$
Searches
?
High $P_t$ Leptons
Multi-Leptons

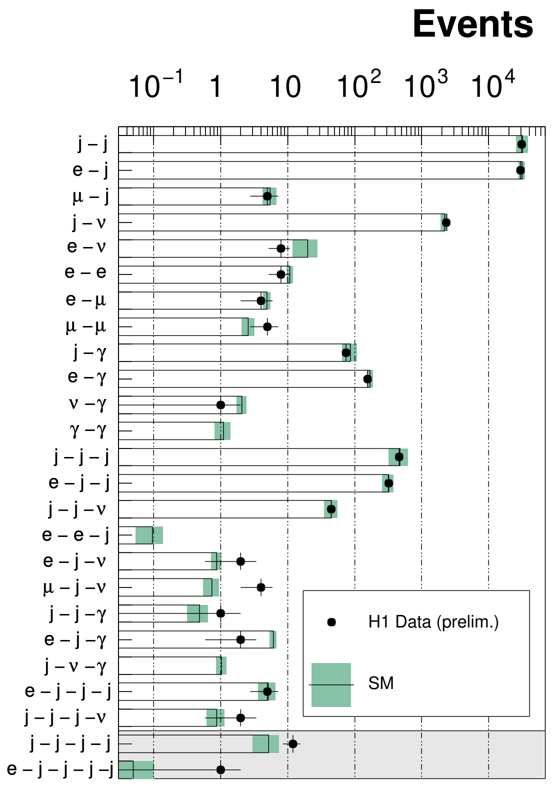
# Physics Results Overview




## Hadronic Final States



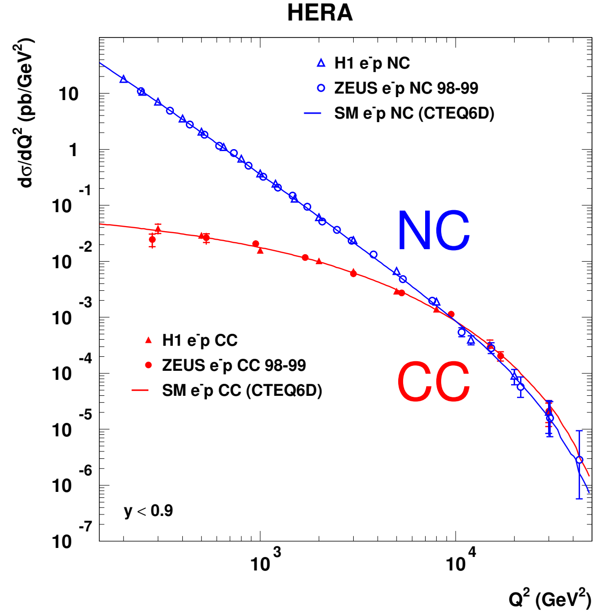

## Diffraction

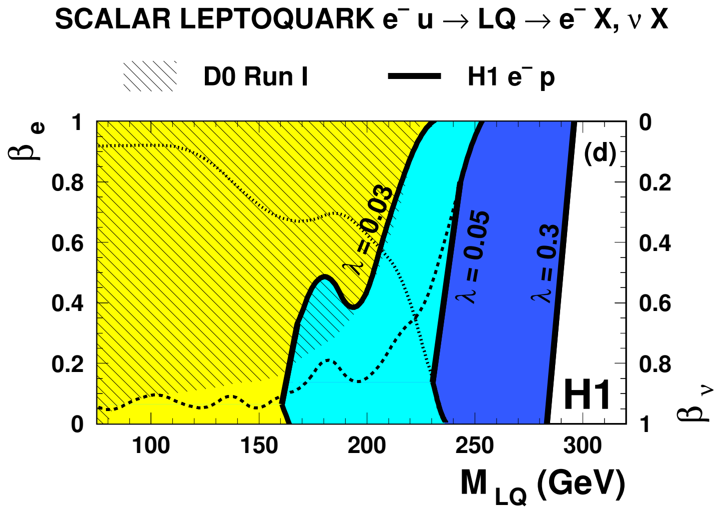


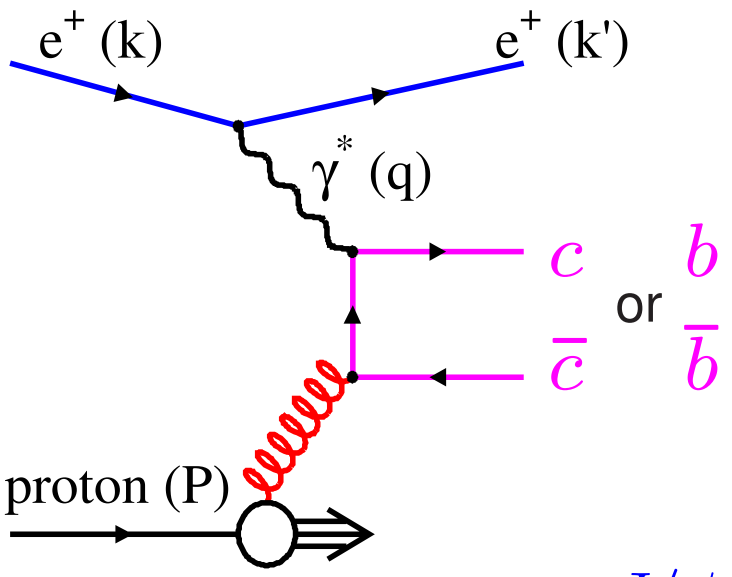

H1 General Search

## Searches

## Inclusive Measurements





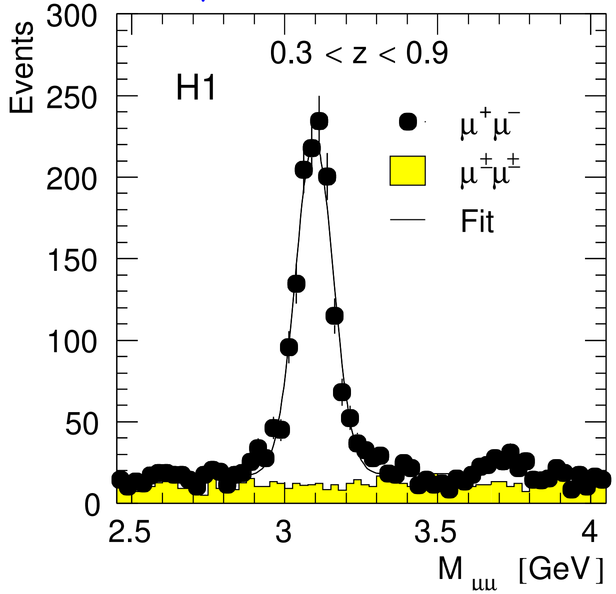

Dominant Process: Boson-Gluon-Fusion

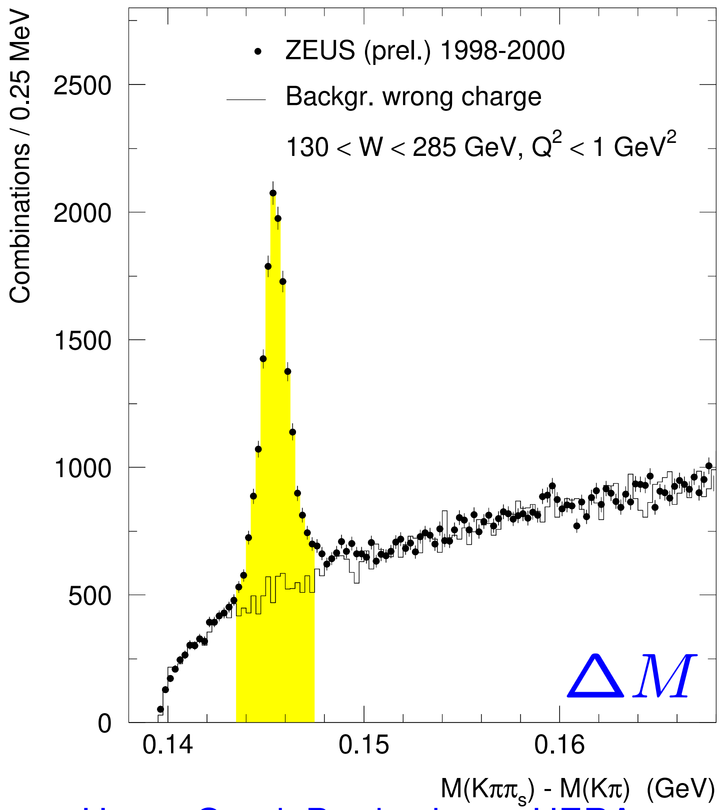
$$\gamma g \longrightarrow c\bar{c} \text{ or } b\bar{b}$$

Charm fraction at large $Q^2$: 20 – 30%

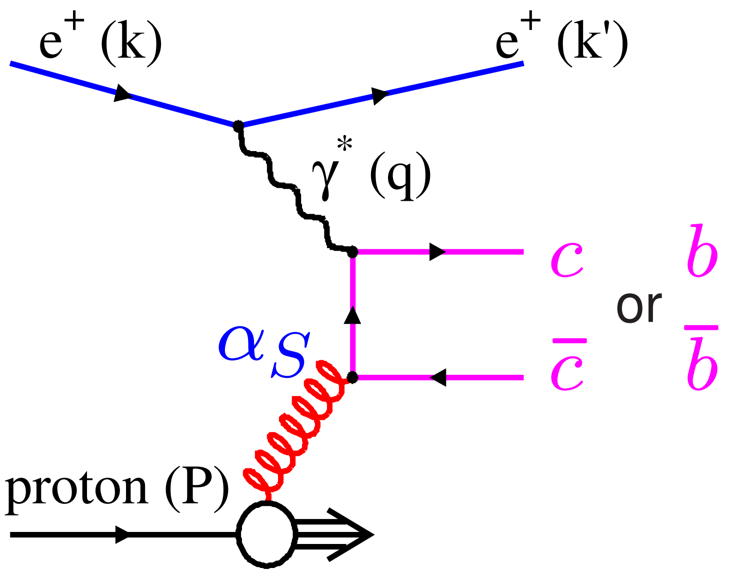
$$D^{*\pm} \rightarrow D^0 \pi_s^{\pm}$$
$$\hookrightarrow K^{\mp}\pi^{\pm}$$

$$J/\psi \rightarrow \mu^+\mu^-$$



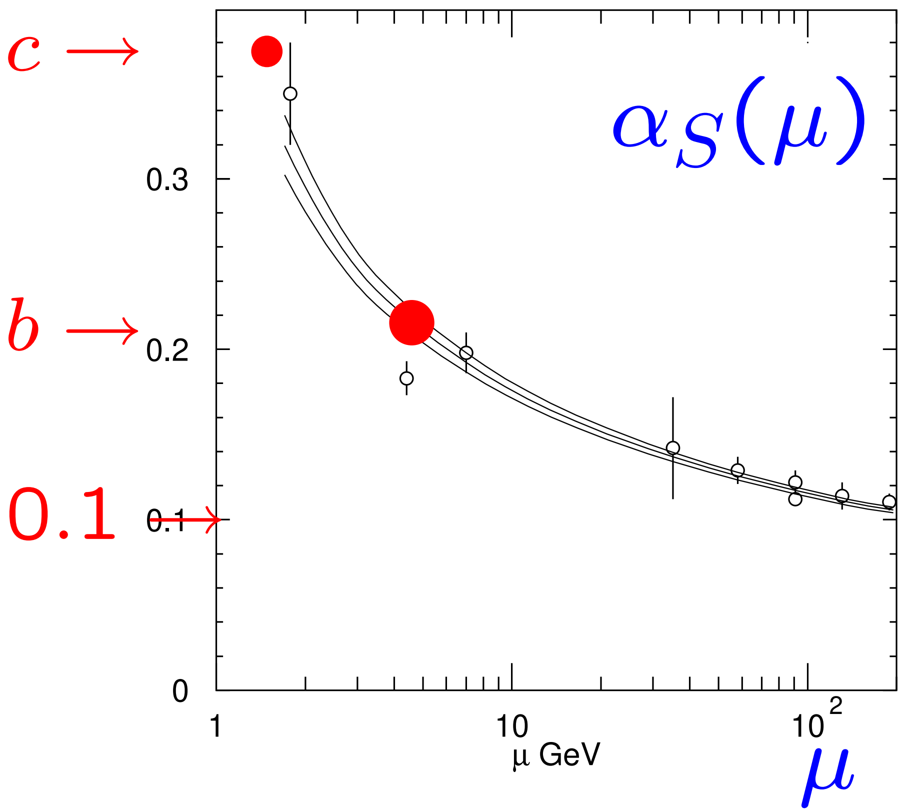



# Factorization Ansatz and perturbative QCD




## QCD: Running coupling constant $\alpha_S(\mu)$

Confinement $\longleftrightarrow$ Asymptotic Freedom




Factorization:

Proton Structure

⊗ Perturbative QCD

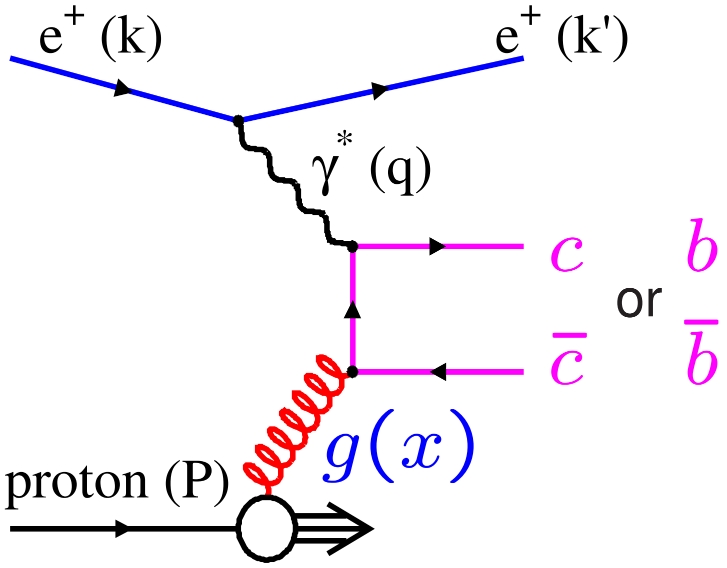
⊗ Photon Structure

⊗ Fragmentation

– Hard processes calculable in perturbation theory

– Heavy quarks: $m^2_{c,b}$ provide an energy scale

Other scales: $Q^2$, $p_T^2$ $\rightarrow$ multiscale problem

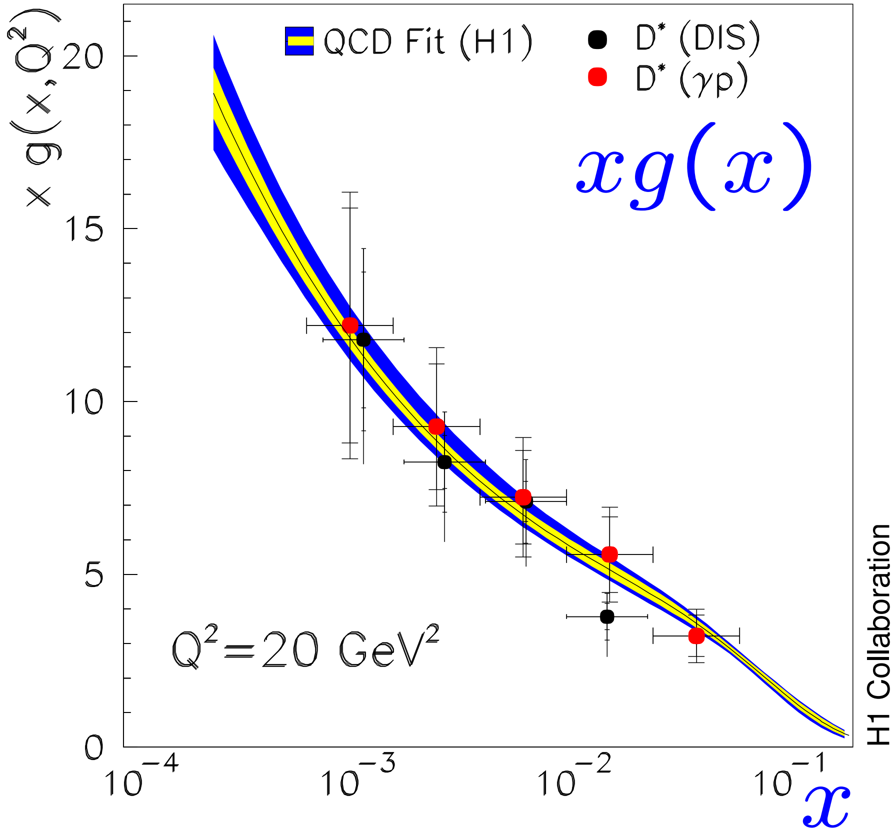



Factorization:

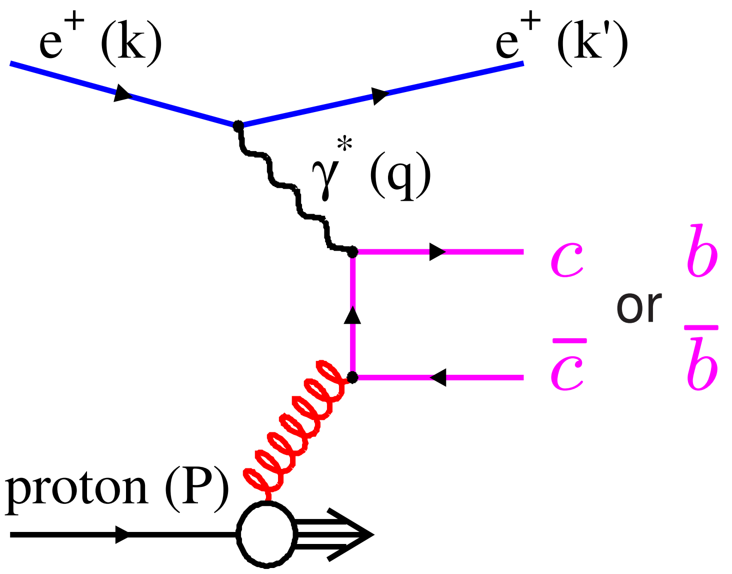
Proton Structure
⊗ Perturbative QCD
⊗ Photon Structure
⊗ Fragmentation

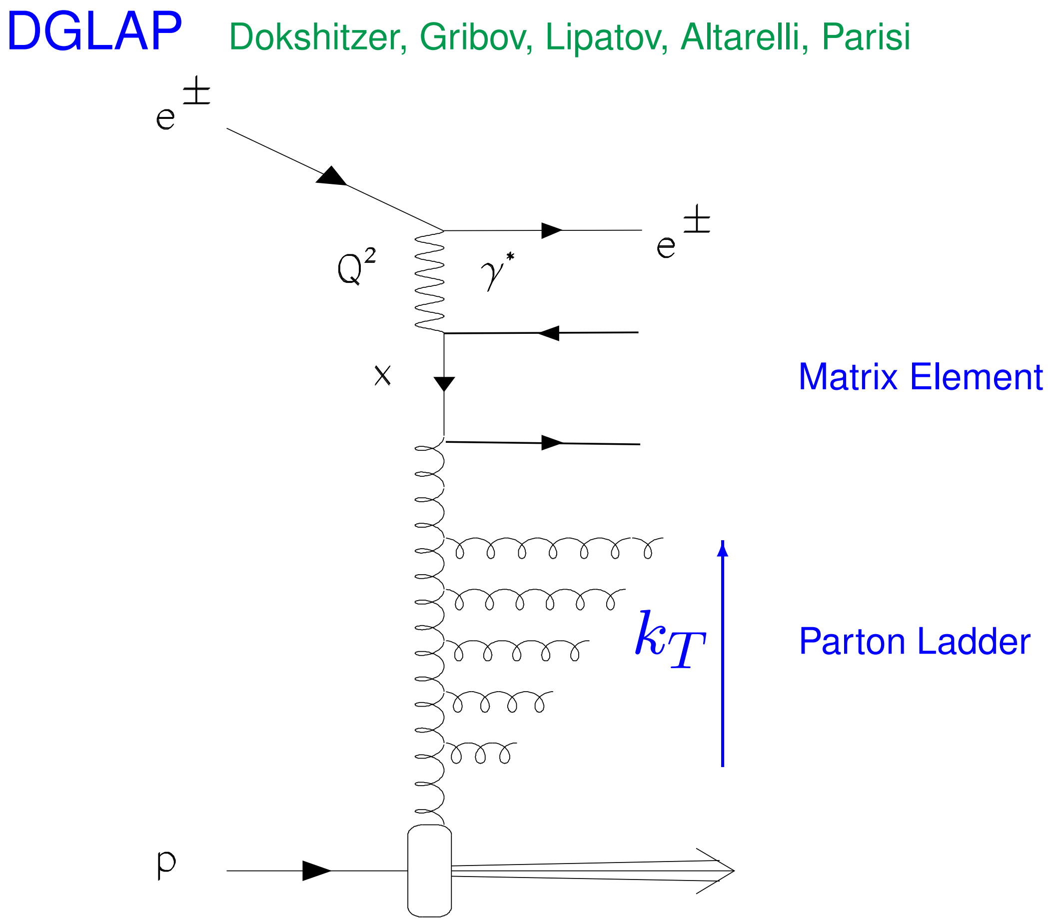
Gluon distribution:

$c\bar{c}$-production is directly sensitive




Good agreement with results from $F_2(x, Q^2)$

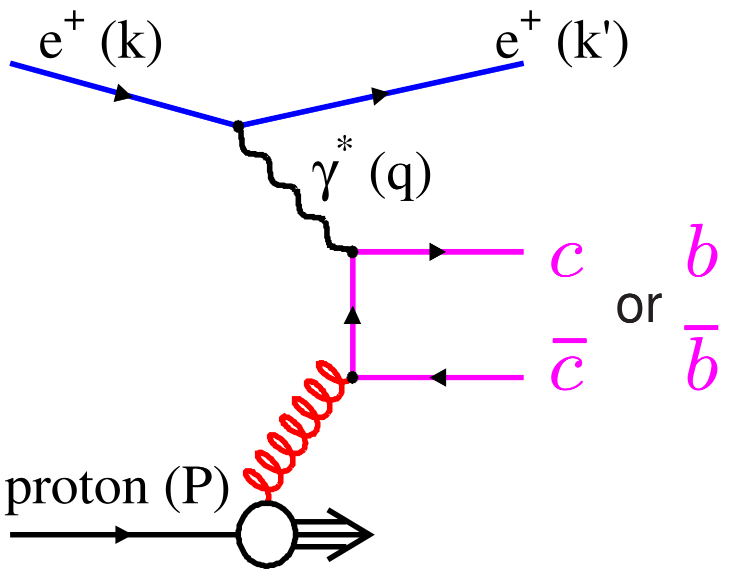



Factorization:

Proton Structure
⊗ Perturbative QCD
⊗ Photon Structure
⊗ Fragmentation

– Evolution in $Q^2$ ($\sim k_t^2$)
– Valid at large $Q^2$ and medium $x$
– MC programs (LO+PS) and NLO calculations




Factorization:

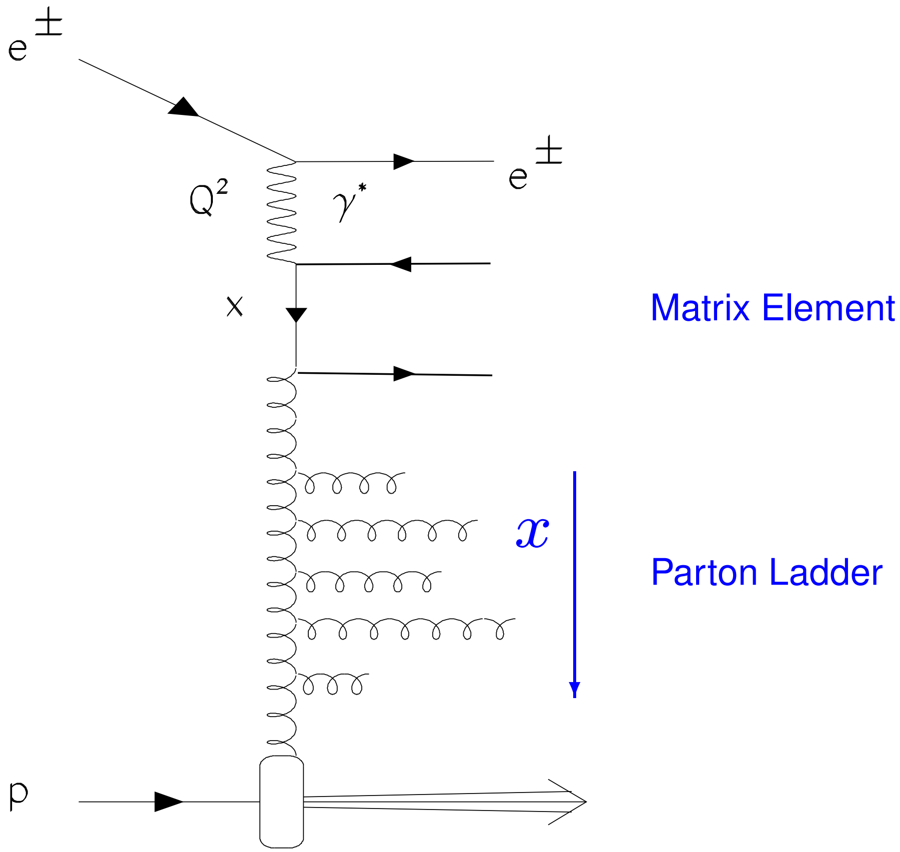
Proton Structure

⊗ Perturbative QCD

⊗ Photon Structure

⊗ Fragmentation

**BFKL** Balitsky, Fadin, Kuraev, Lipatov

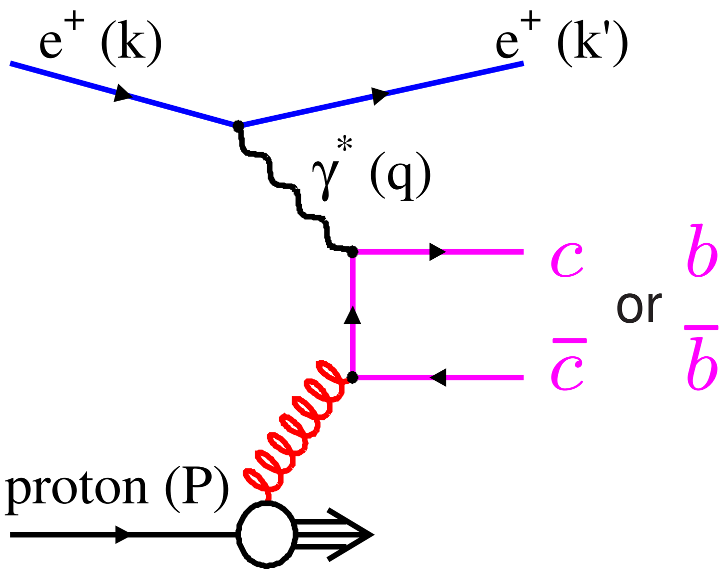



Alternatively:

– Evolution in $x$

– Valid at small $x$ and medium $Q^2$

– $k_t$-unintegrated gluon distribution




Factorization:

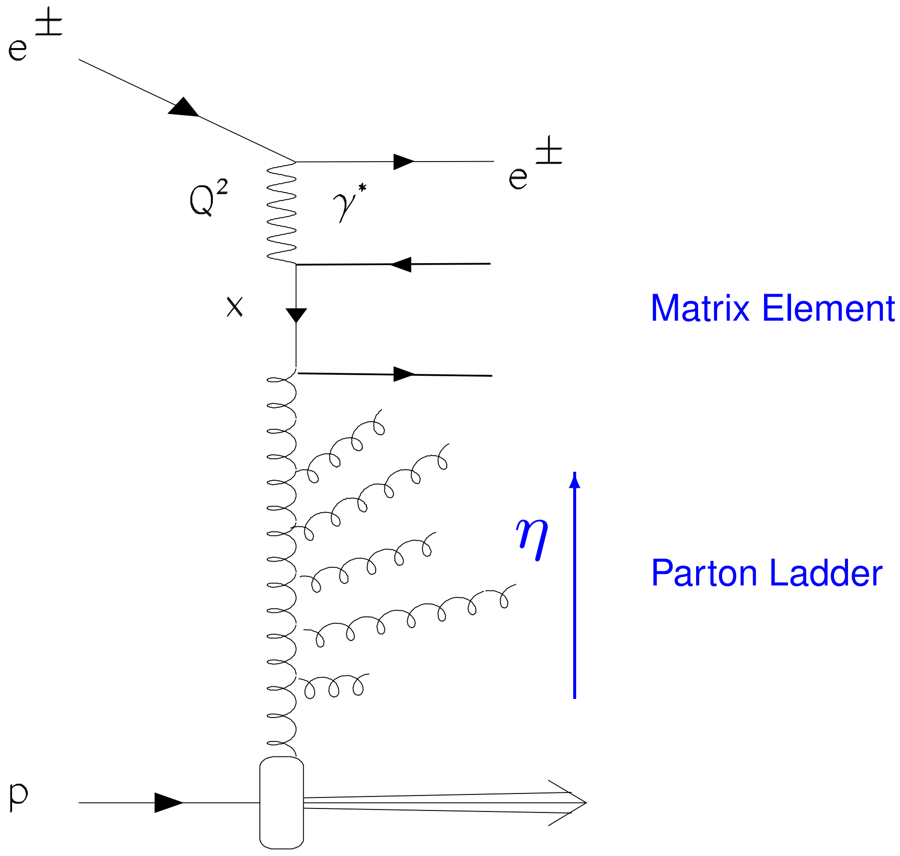
Proton Structure

⊗ Perturbative QCD

⊗ Photon Structure

⊗ Fragmentation

**CCFM** Catani, Ciafaloni, Fiorani, Marchesini

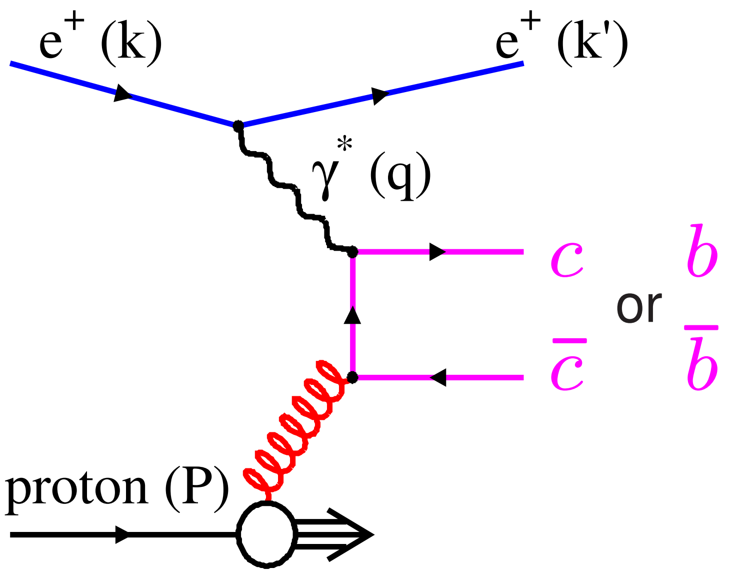


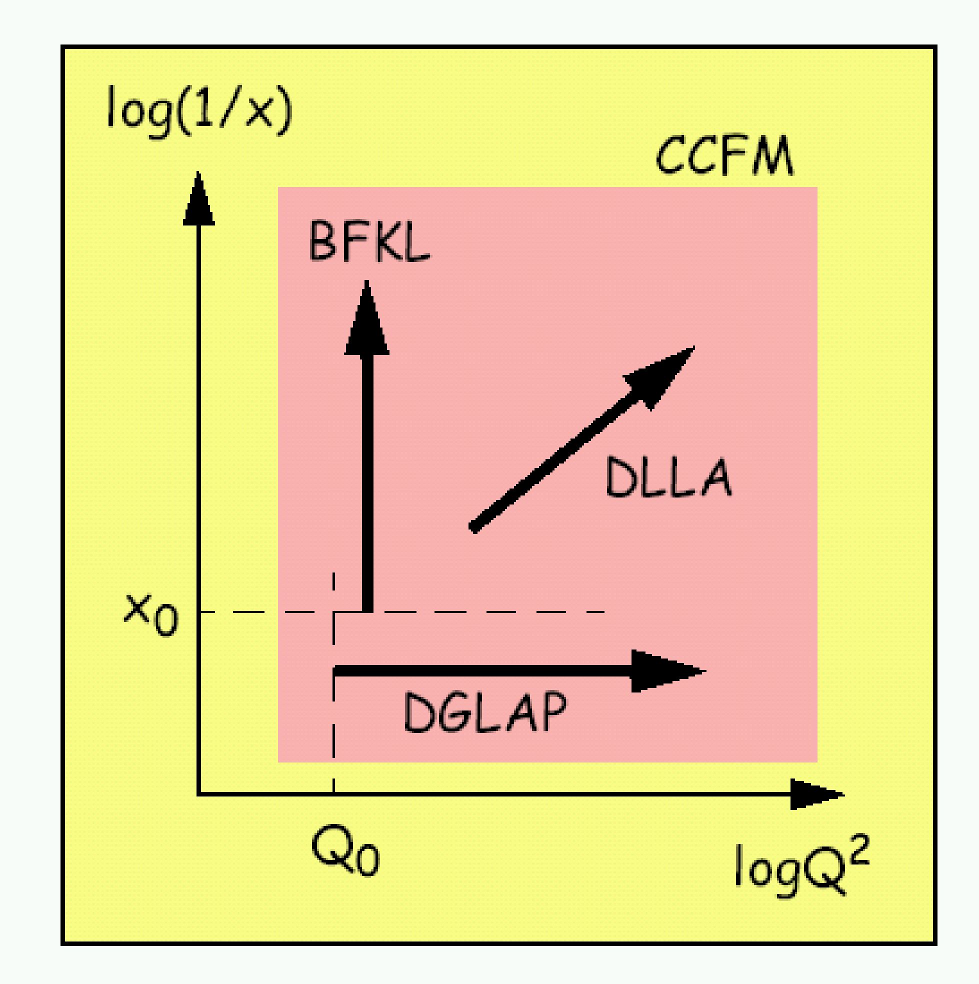

Interpolates between DGLAP und BFKL

– Ordering in rapidity (Polar Angle)

– MC program CASCADE

Use $ep$-data to discriminate between evolutions




Factorization:

Proton Structure

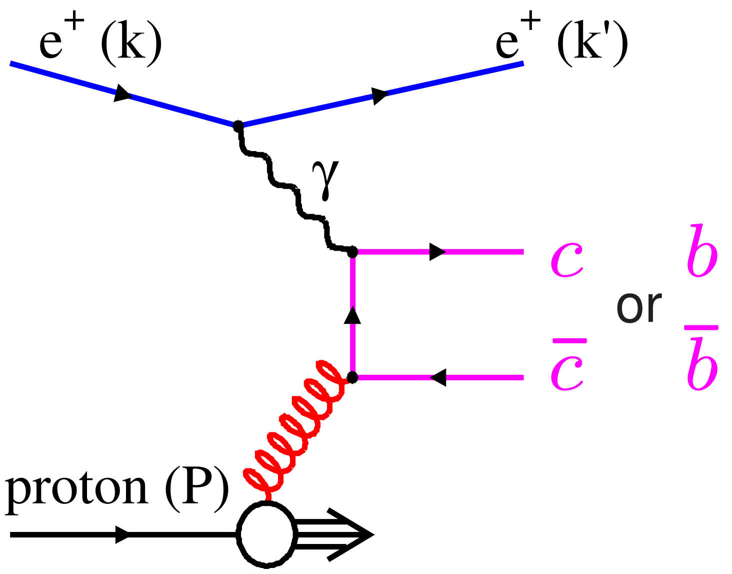
⊗ Perturbative QCD

⊗ Photon Structure

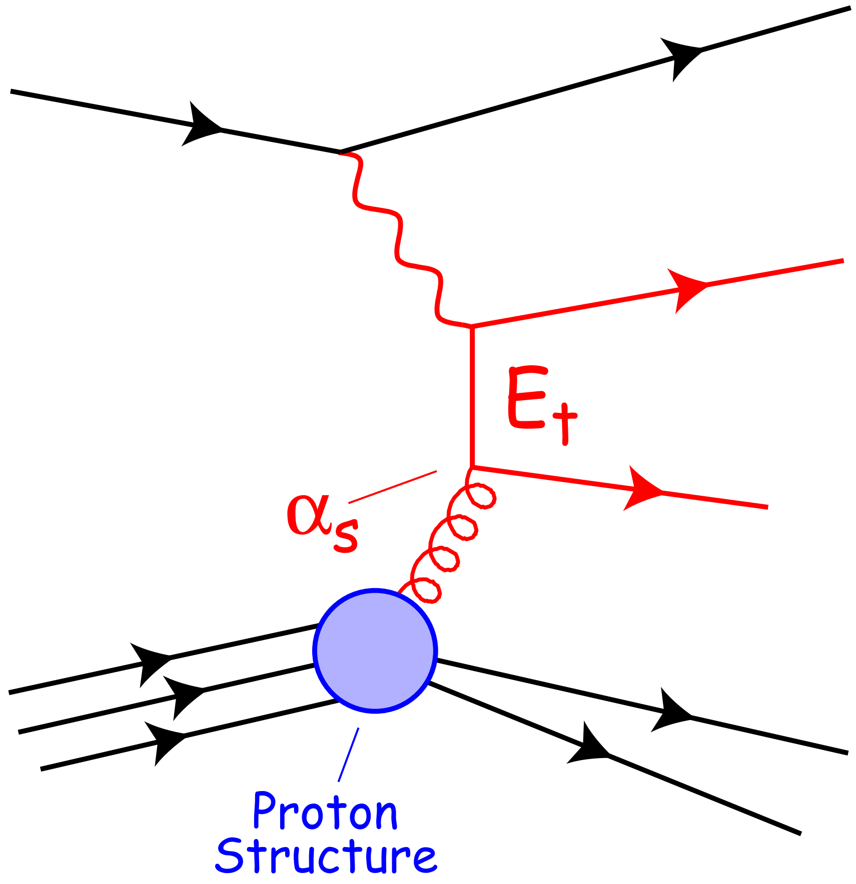
⊗ Fragmentation

DGLAP, BFKL, CCFM:

Approximations for different kinematic regions




Photon-Gluon Fusion: Direct Process



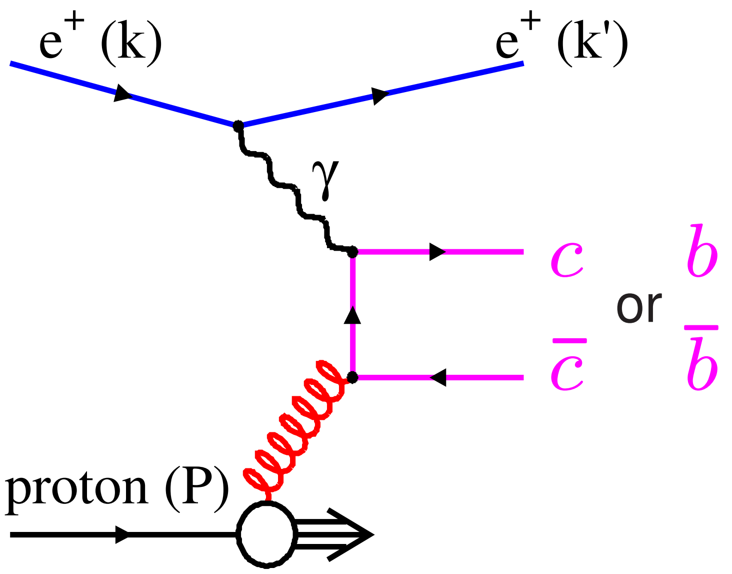

Factorization:

Proton Structure

⊗ Perturbative QCD

⊗ Photon Structure

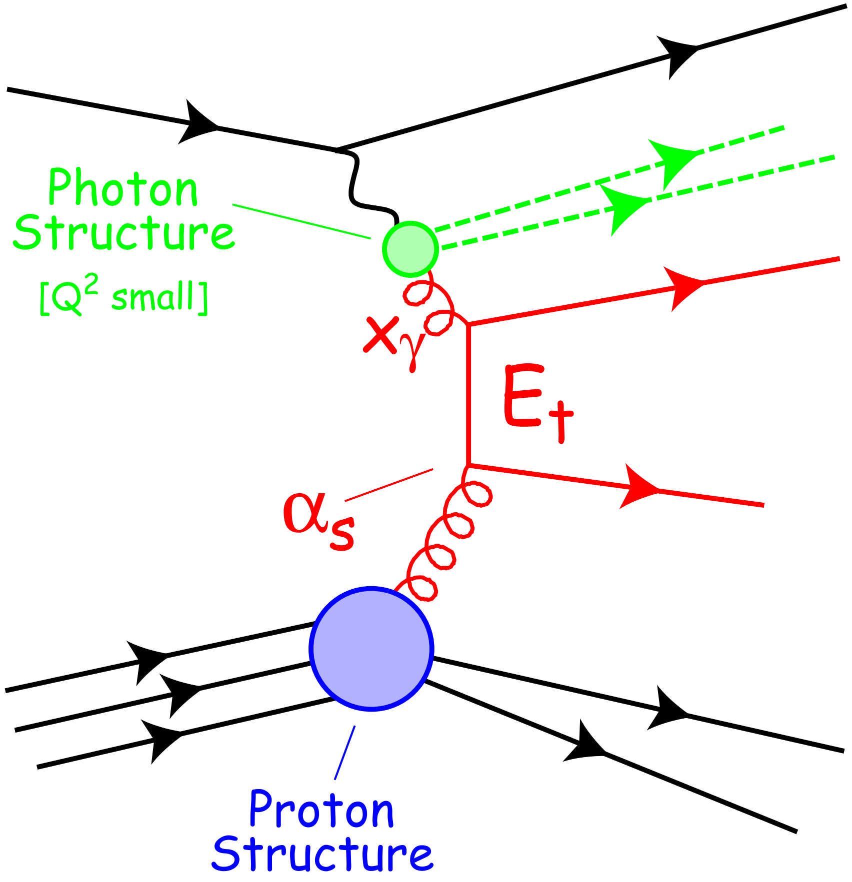
⊗ Fragmentation




Photoproduction ($Q^2 \sim 0$): Photon is real

$\longrightarrow$ Fluctuates into hadronic states

'Resolved-$\gamma$':



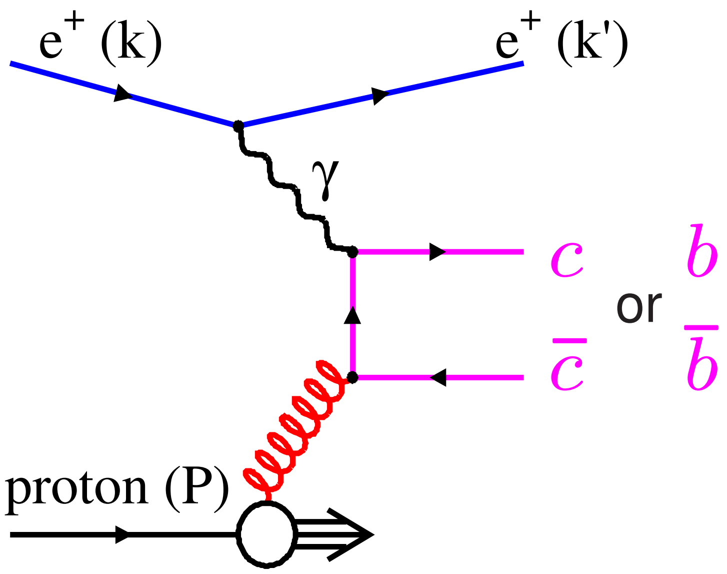

Factorization:

Proton Structure

$\otimes$ Perturbative QCD

$\otimes$ Photon Structure

$\otimes$ Fragmentation




Factorization:

Proton Structure

⊗ Perturbative QCD

⊗ Photon Structure

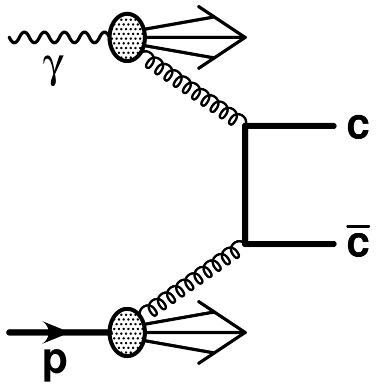
⊗ Fragmentation

Photoproduction ($Q^2 \sim 0$): Photon is real

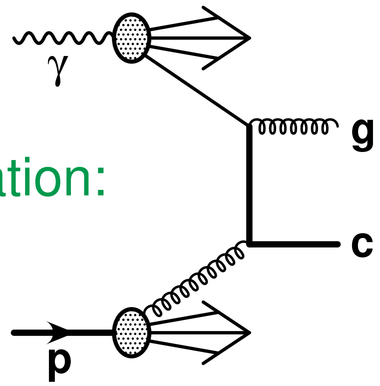
$\longrightarrow$ Fluctuates into hadronic states

'Resolved-$\gamma$':

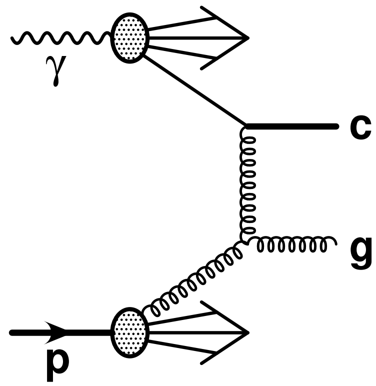
– Hadron-like:




– $c$-Excitation:

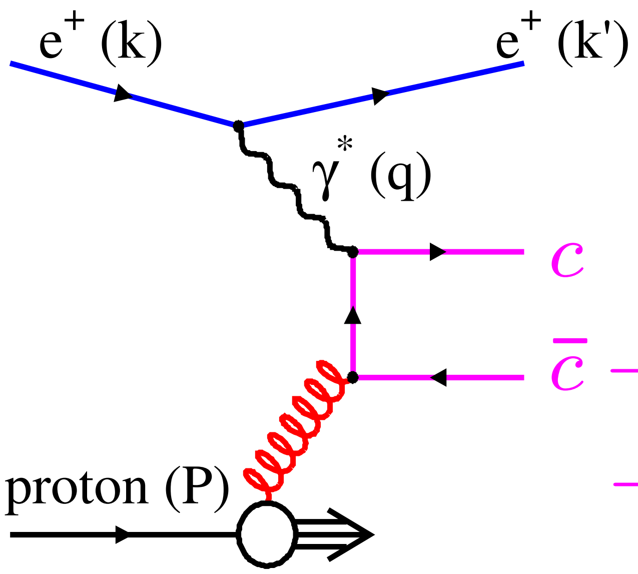



$q$-Propagator




$g$-Propagator

How much charm is there in the photon?




$c$ or $b$

$\bar{c} \rightarrow D$ $\bar{b} \rightarrow B$

$\rightarrow J/\psi$

Factorization

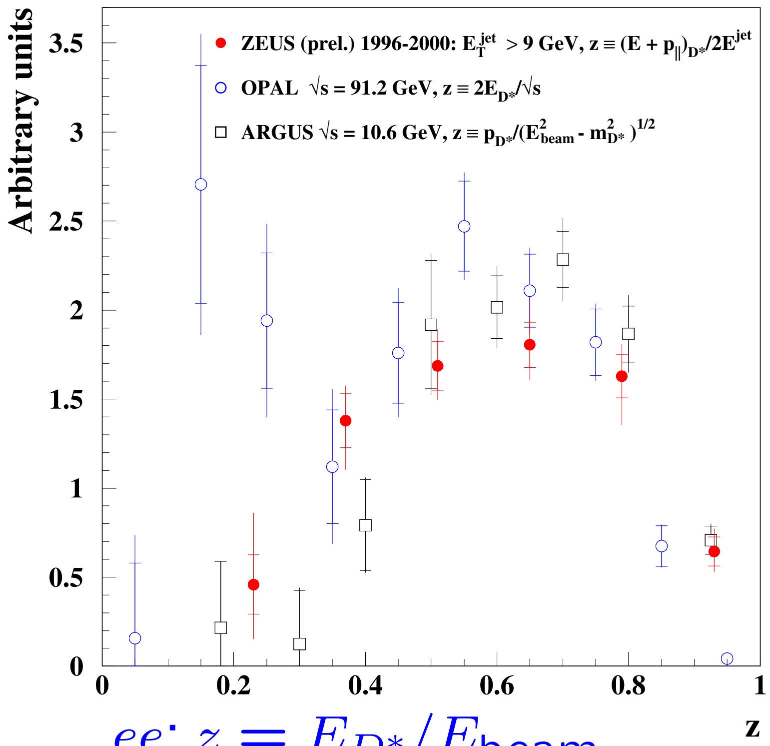
Proton Structure

$\otimes$ Perturbative QCD

$\otimes$ Photon Structure

$\otimes$ Fragmentation

Fragmentation function: $f(c \rightarrow D^*)$ in $ep$ and $ee$

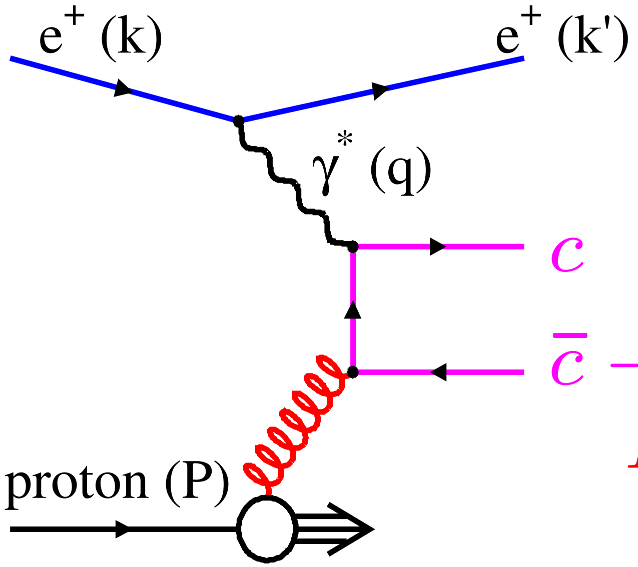



$ee$: $z = E_{D^*}/E_{\text{beam}}$

$ep$: $z = (E + p_{||})_{D^*}/2E_{\text{jet}}$

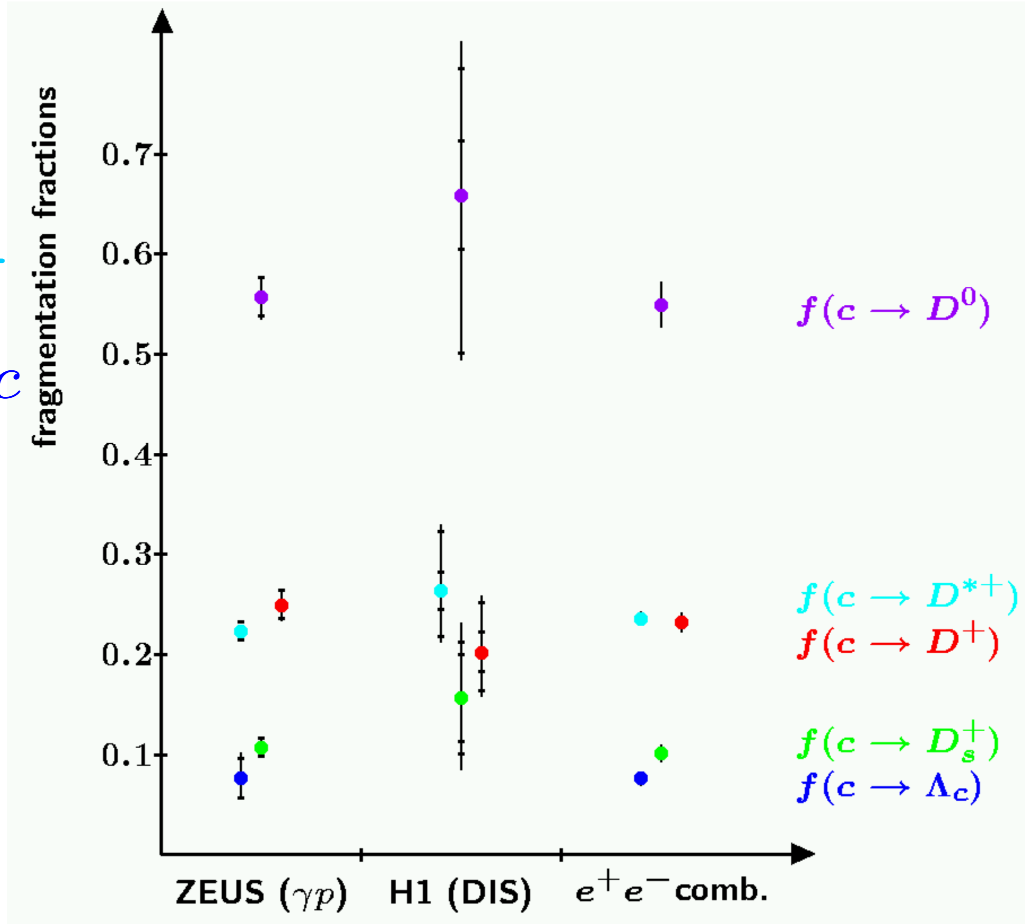
Fit an MC (LO+PS): $\epsilon_c^{\text{Peterson}} = 0.064 \pm 0.006^{+0.011}_{-0.008}$

$ep$ in agreement with $e^+e^-$




$\bar{c} \rightarrow D^0 \; D^{*+}$
$D^+ \; D_s^+ \; \Lambda_c$

Fragmentation fractions for charmed hadrons:




Factorization

Proton Structure

⊗ Perturbative QCD

⊗ Photon Structure

⊗ Fragmentation

$ep$ in agreement with $ee$, similar precision

Fragmentation functions and ratios appear to be universal

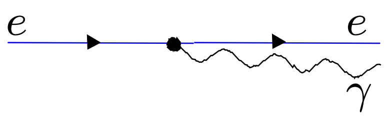
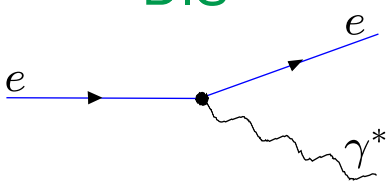
Comparison Theory – Experiment:

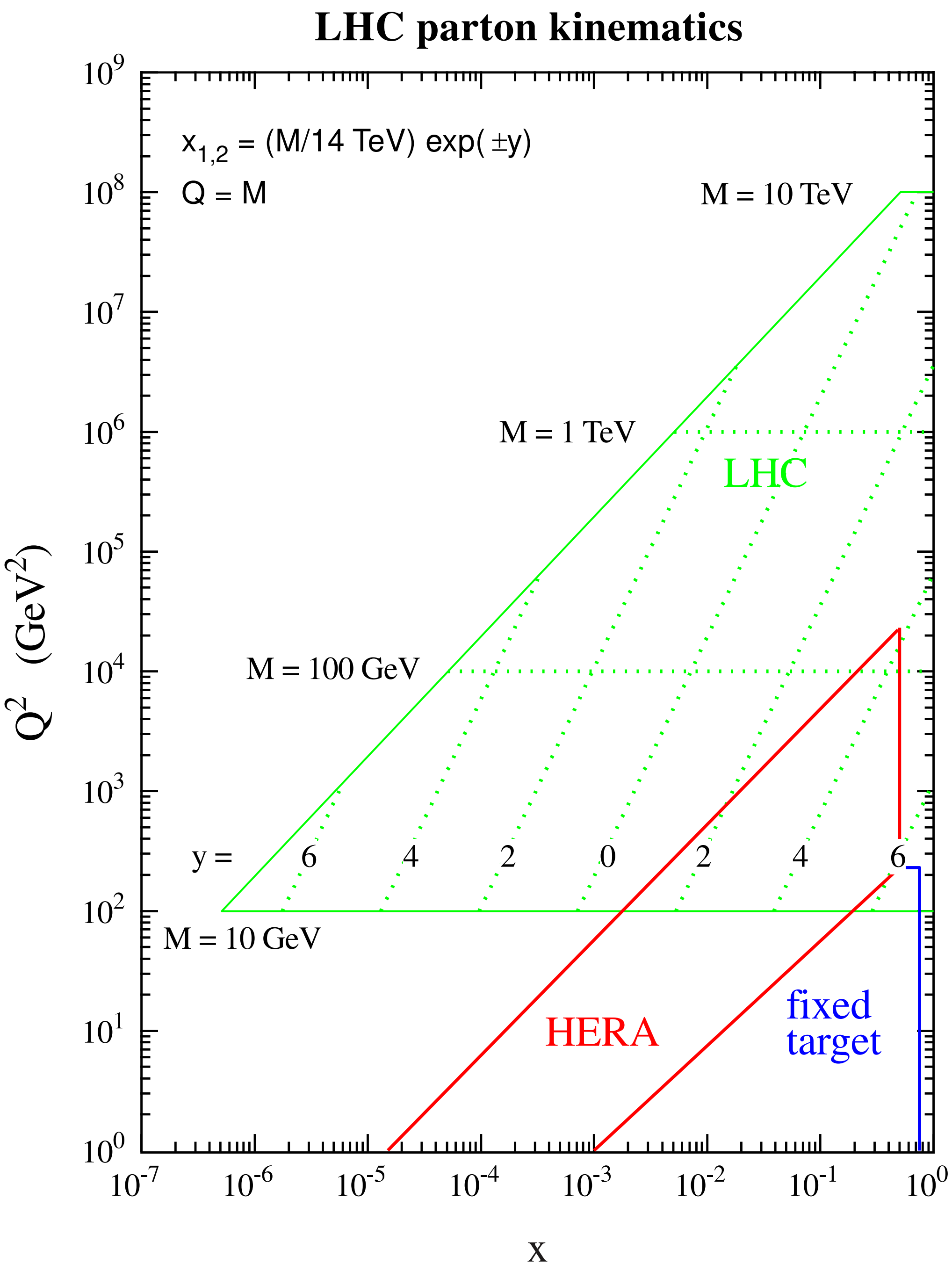
## Proton Structure $\otimes$ Photon Structure $\otimes$ QCD-Dynamics $\otimes$ Fragmentation

$\Rightarrow$ Test of factorization and all ingredients $\Rightarrow$ Progress understanding confinement

$\Rightarrow$ Precise quantitative calculations $\Rightarrow$ Predictions for future experiments

Menu:

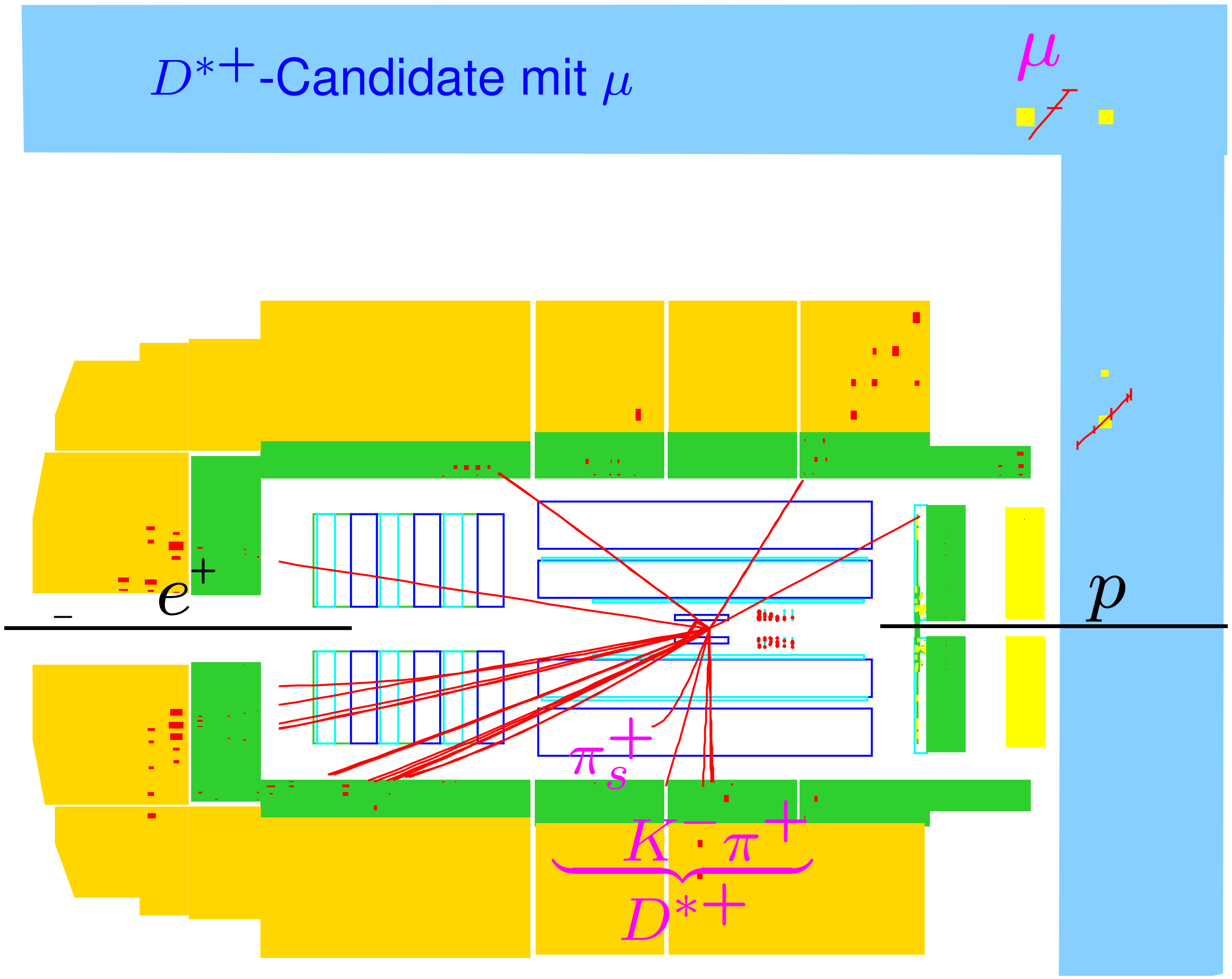
| $m_q \downarrow$ \ $Q^2 \longrightarrow$ | | | $Q^2 \sim 0$ Photoproduction | $Q^2 \gtrsim 2$ GeV$^2$ DIS |
|---|---|---|---|---|
| | | |  |  |
| $\sim$ 1.5 GeV | c | • | $D^{*+}$, Jets, $J/\psi$ | $D^+$ |
| $\sim$ 4.75 GeV | b | ● | $D^*\mu$, $B \to \mu X$ | $B \to \mu X$ |



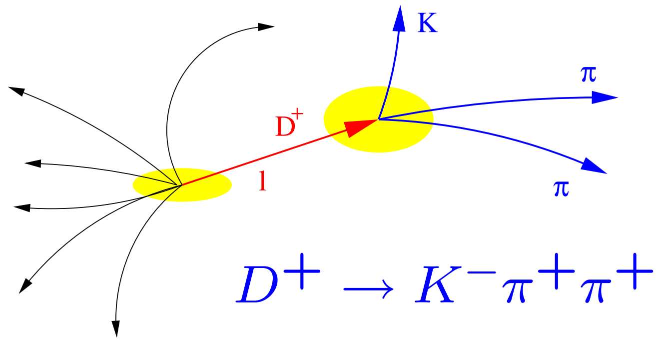

# LHC needs:

- knowledge on parton densities
- extrapolation over orders of magnitude

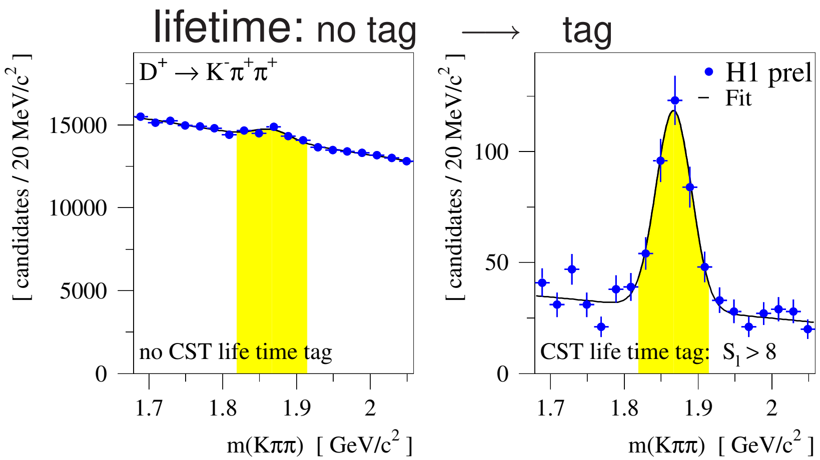
# The Experiments H1 and ZEUS




## $D^+$-Reconstruction



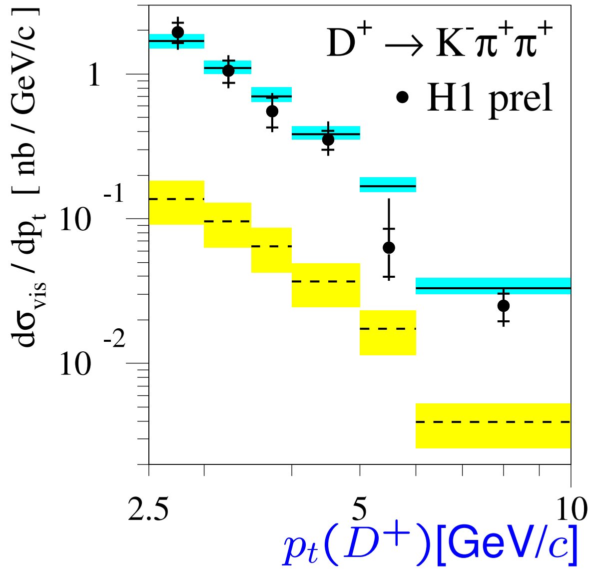

$$D^+ \rightarrow K^-\pi^+\pi^+$$

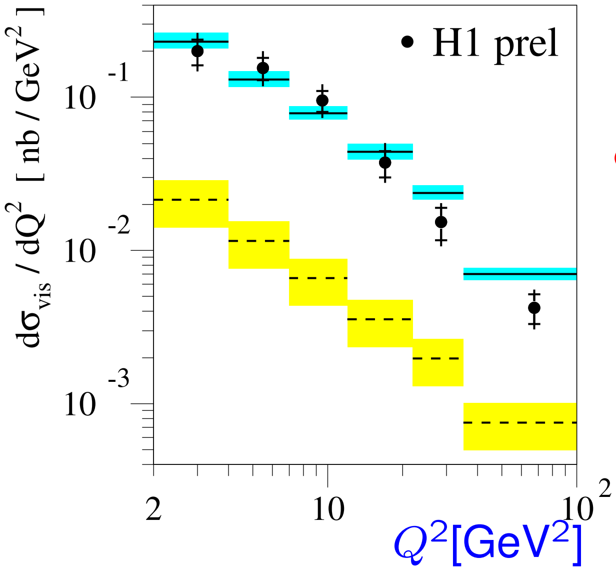



HERA: $E_e = 27.5$ GeV, $E_p = 920$ GeV, $\sqrt{s} = 320$ GeV

# $D$-Meson Production

$Q^2 > 2$ GeV$^2$: Scale: $Q^2$

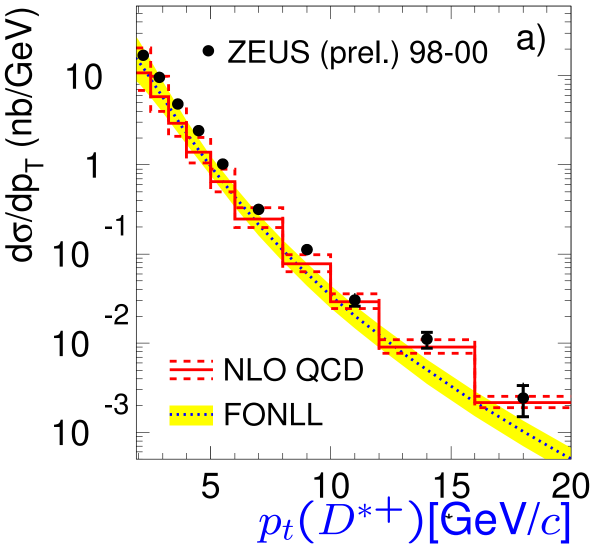


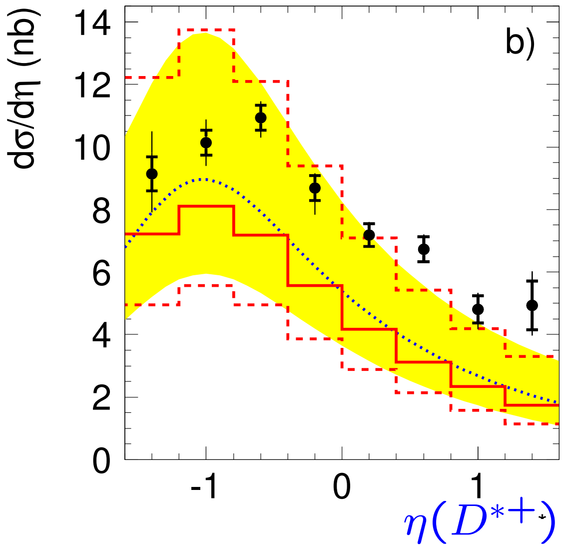




$D^+ \rightarrow K^-\pi^+\pi^+$

- DGLAP (LO+PS):
  Distributions correctly described

$Q^2 \sim 0$: Scales: $m_c$, $p_t$

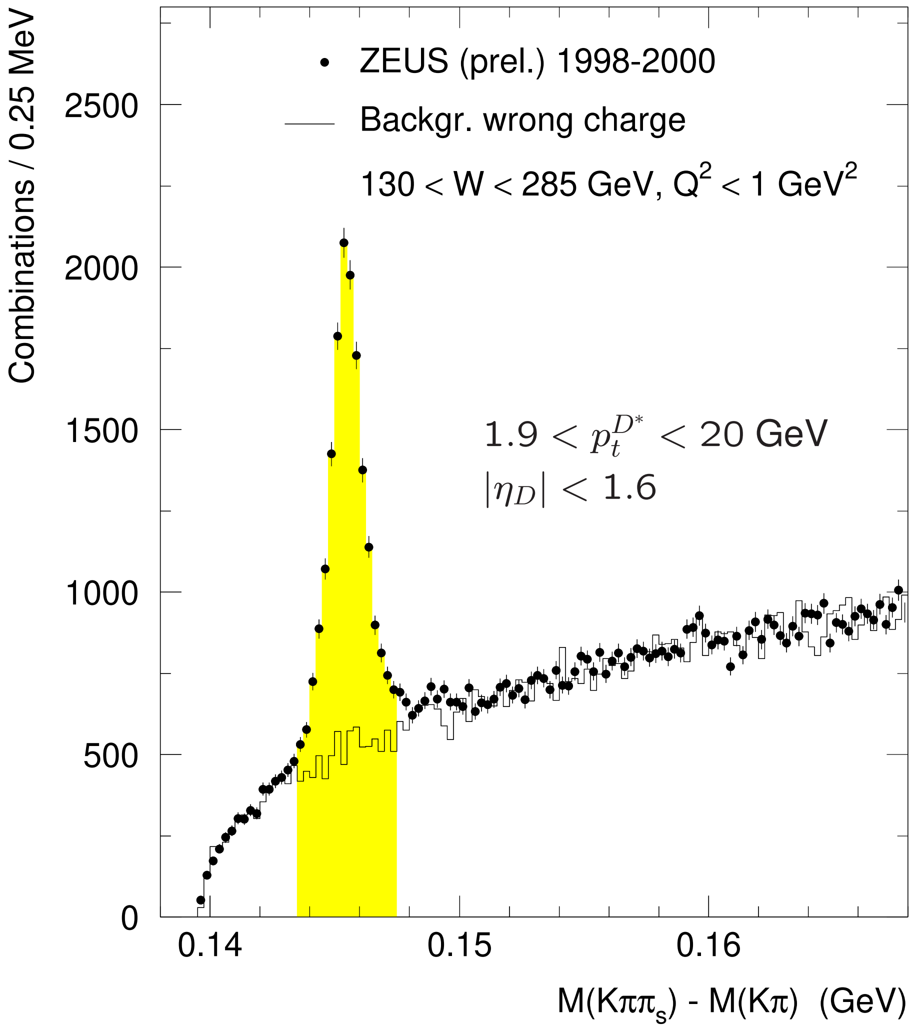


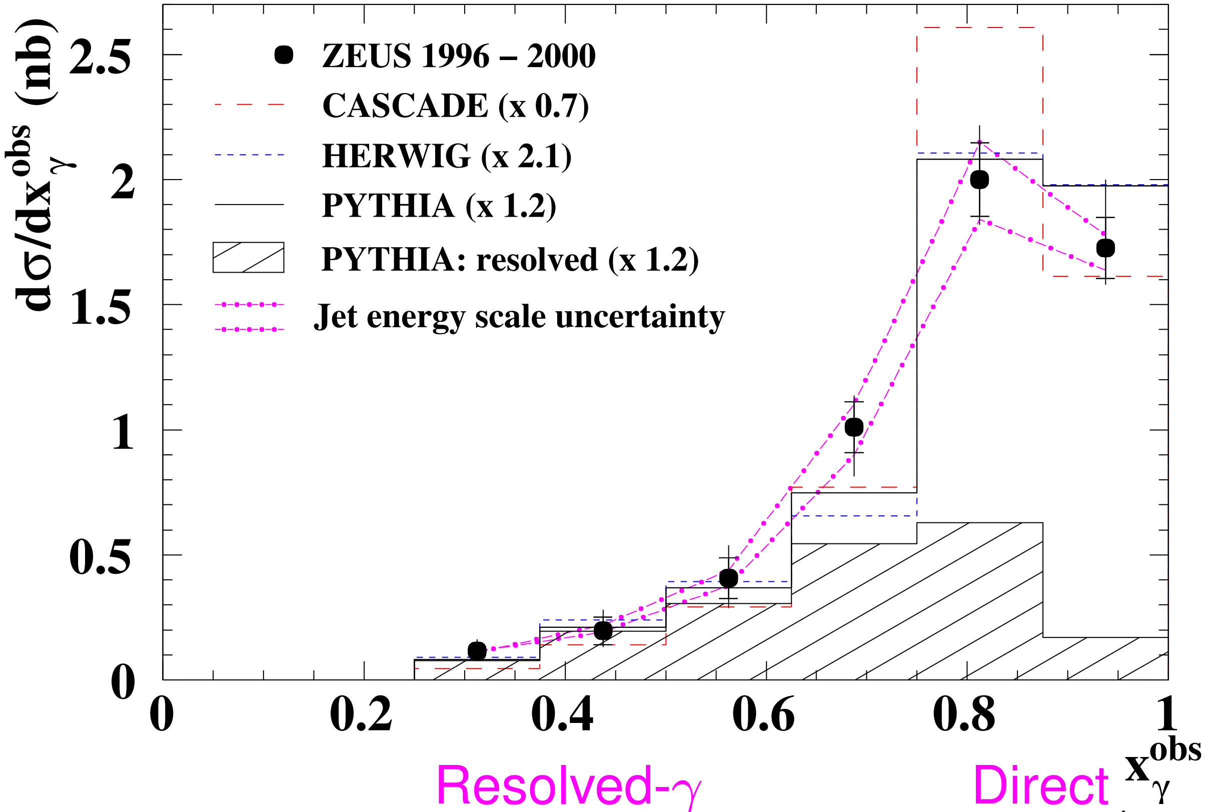

$D^{*+} \rightarrow D^0\pi^+$
$\hookrightarrow K^-\pi^+$

- DGLAP (NLO):
  – Shape ok
  – Normalization too low

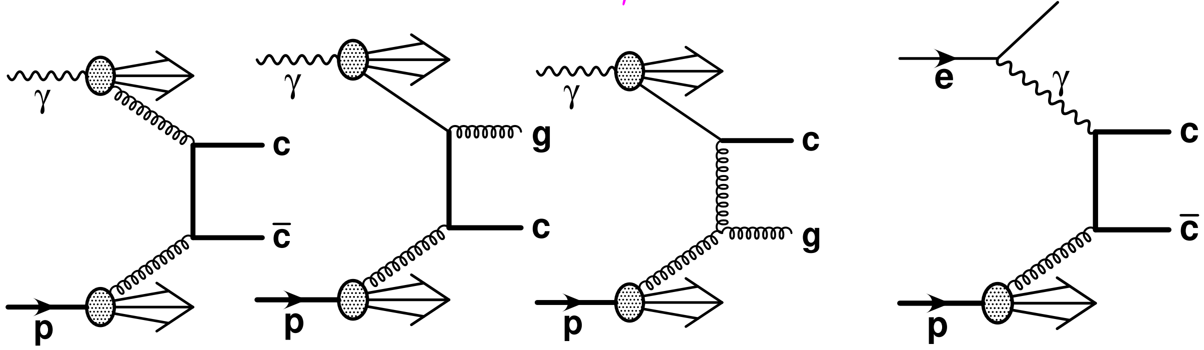
$$D^{*\pm} \to (K^{\mp}\pi^{\pm})\pi^{\pm}$$



# Charm: Two-Jet-Events




Resolved-$\gamma$ Direct




$Q^2 \sim 0 \quad M_{jj} > 18$ GeV

$\gamma p \rightarrow D^{*\pm} + jj + X$

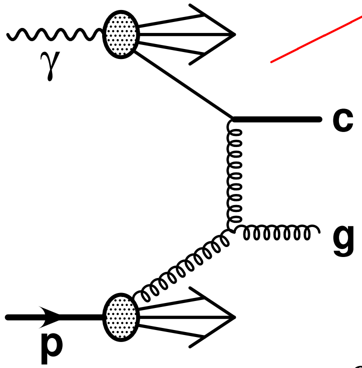
$$x_\gamma^{\text{obs}} = \frac{\sum_{j_1,j_2}(E_T^j e^{-\eta^j})}{2yE_e}$$

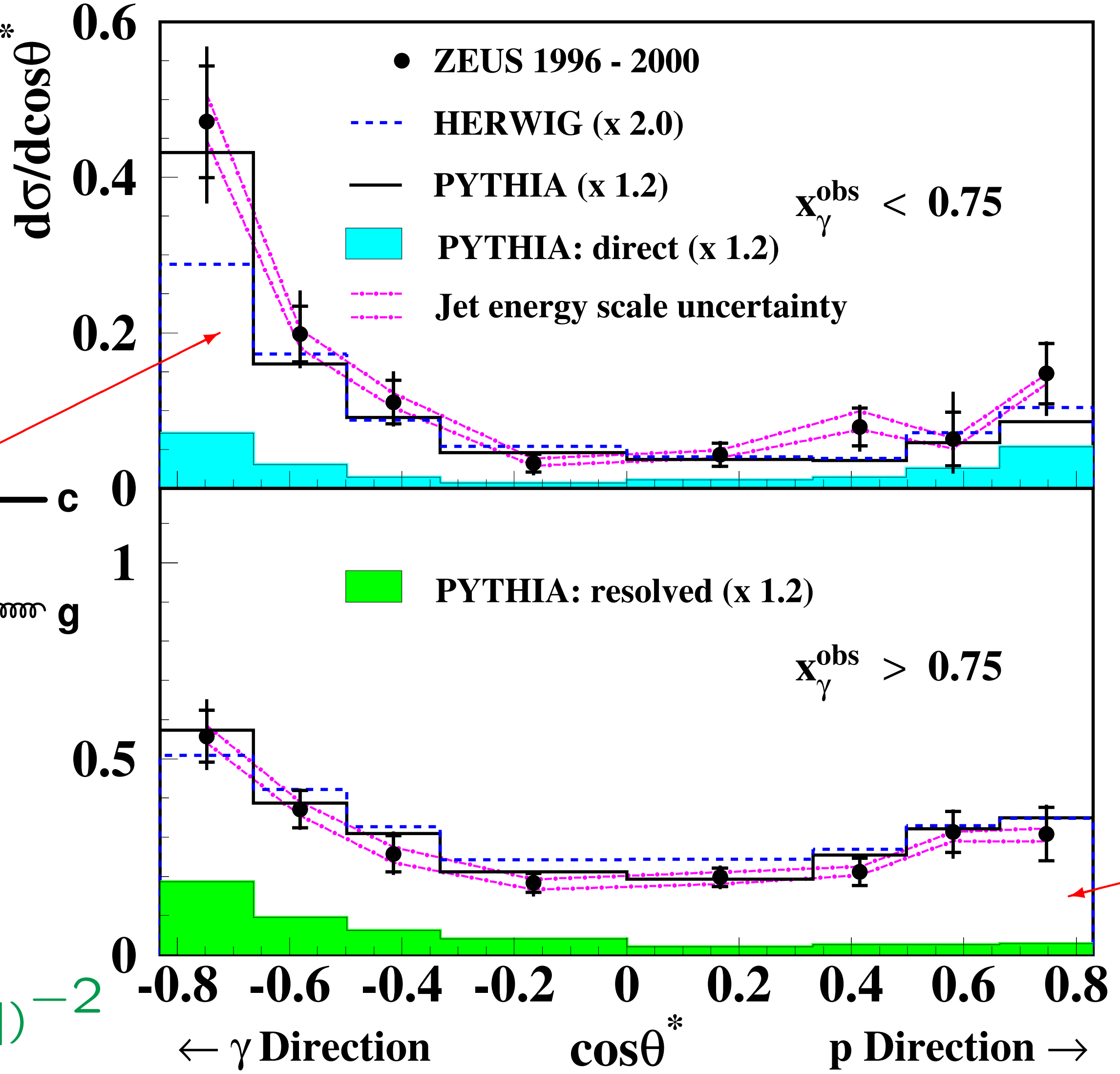
Momentum fraction of parton from photon

Resolved-$\gamma$: $x_\gamma \lesssim 0.75$

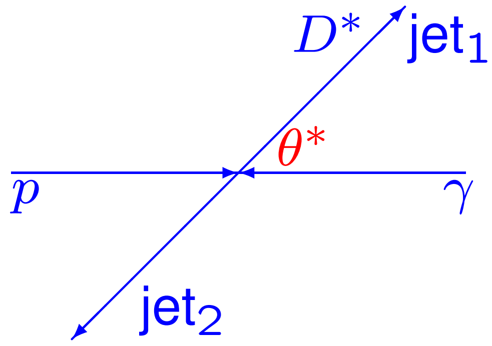
Significant contributions from resolved-$\gamma$

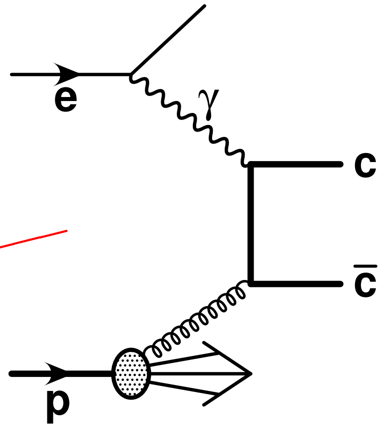
# Charm: Di-Jet-Angular Distributions




$\theta^* = \measuredangle(p, D^*\text{-Jet})$:




$g$-Exchange:

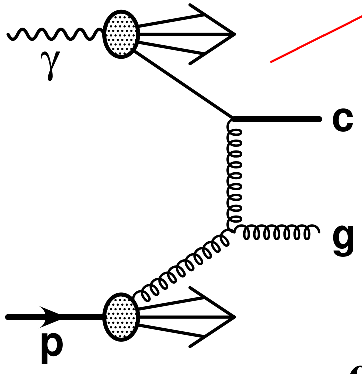
$\propto (1 - |\cos\theta^*|)^{-2}$

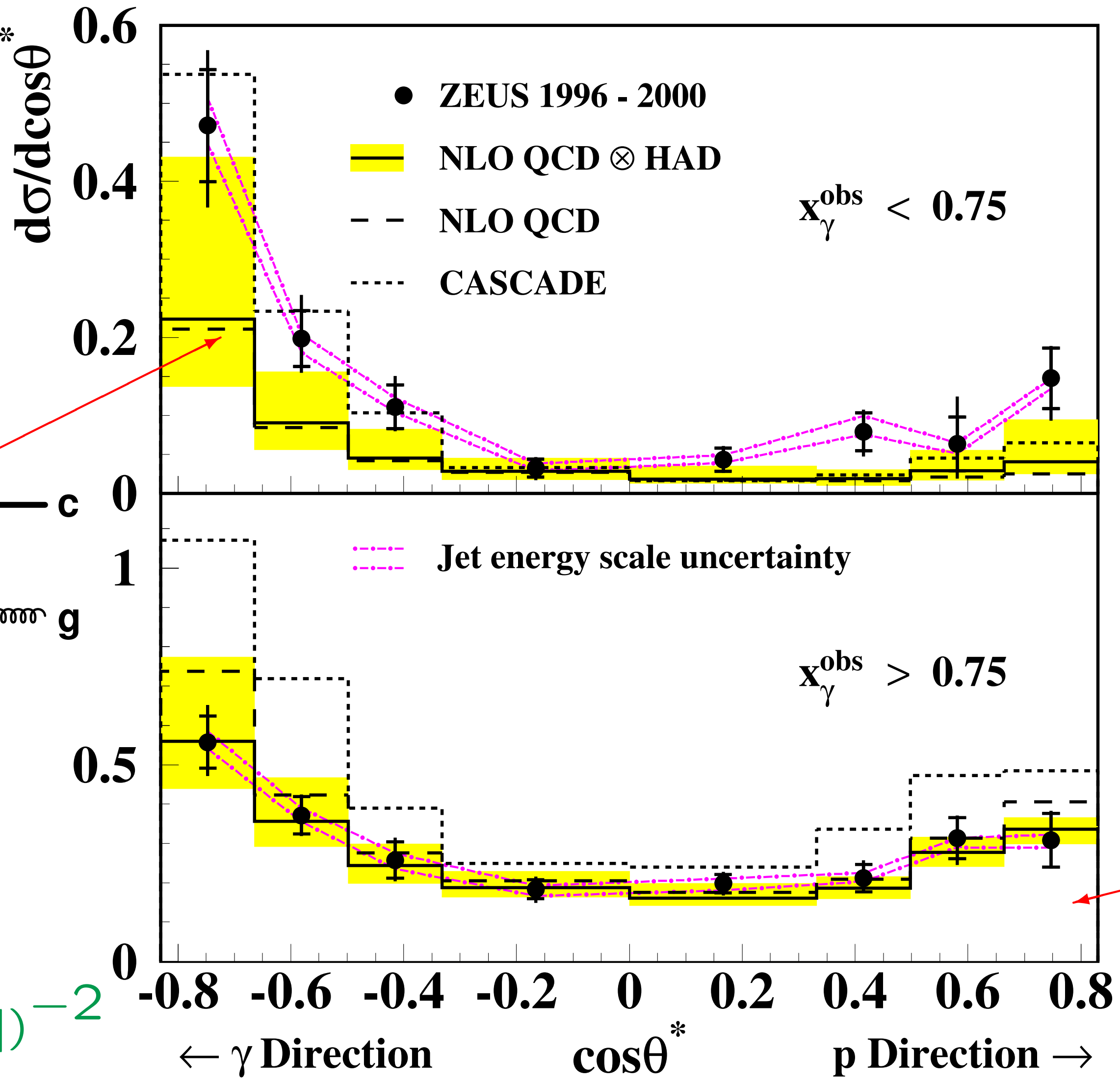
$q$-Exchange:

$\propto (1 - |\cos\theta^*|)^{-1}$

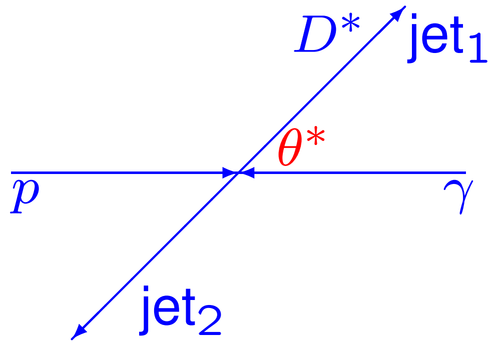
- $D^*$ in photon-direction: charm quark comes from photon
- Increase in photon direction: Gluon exchange signature

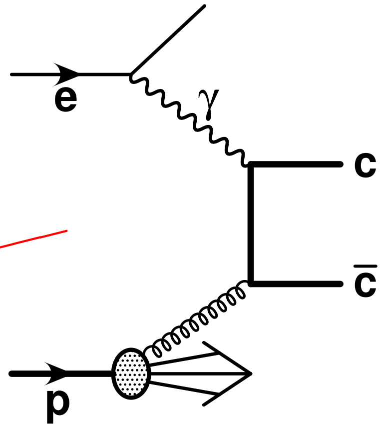
# Charm: Di-Jet-Angular Distributions




$\theta^* = \measuredangle(p, D^*\text{-Jet})$:



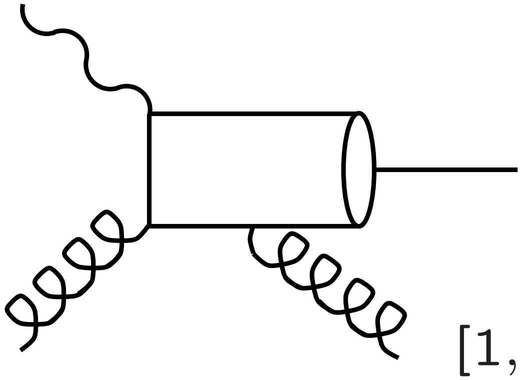




$g$-Exchange:
$\propto (1 - |\cos\theta^*|)^{-2}$

$q$-Exchange:
$\propto (1 - |\cos\theta^*|)^{-1}$

- DGLAP (NLO): shape ok, $x_\gamma < 0.75$: Normalization too low
- CCFM: shape ok, $x_\gamma > 0.75$: Normalization too high

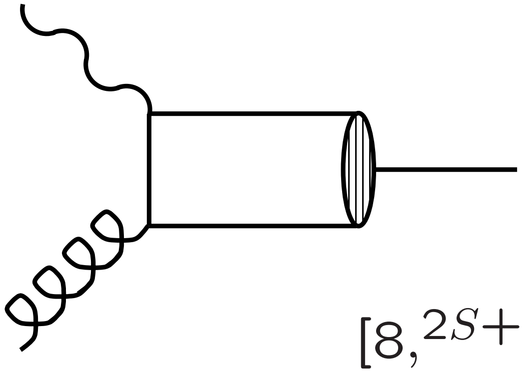
$J/\psi$ formed from a $c\bar{c}$ singlet



$[1,^3S_1]$

**Colour Singlet (CS)**

$c\bar{c} \rightarrow J/\psi$ + gluon



$[8,^{2S+1}L_J]$

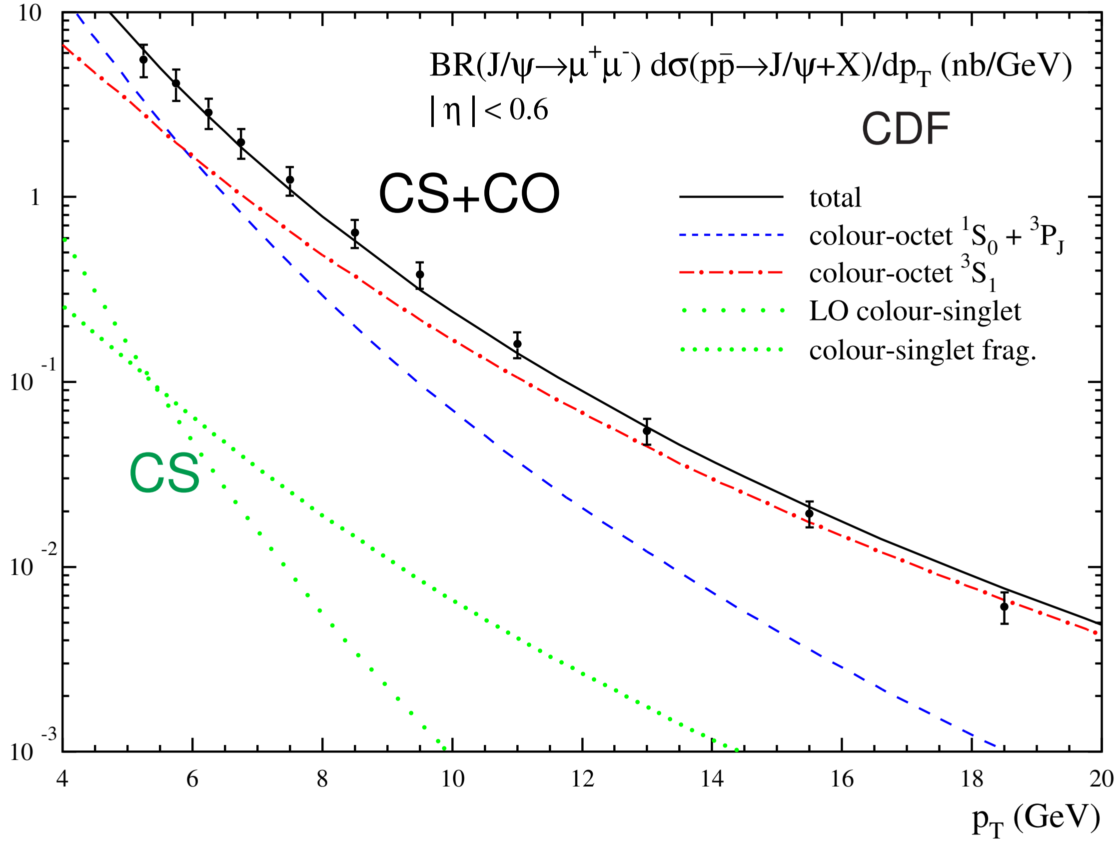
**Colour Octet (CO)**

$c\bar{c} \rightarrow J/\psi$ + soft gluons

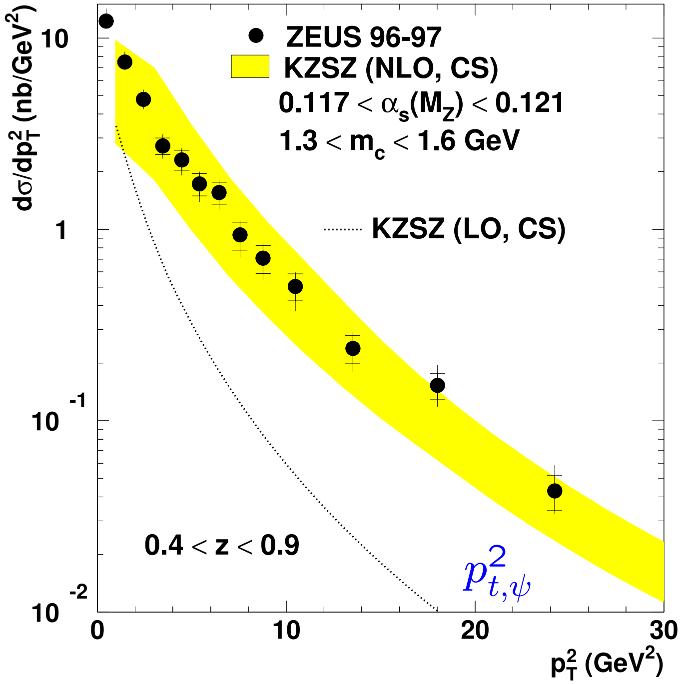
**NRQCD + Factorization:**

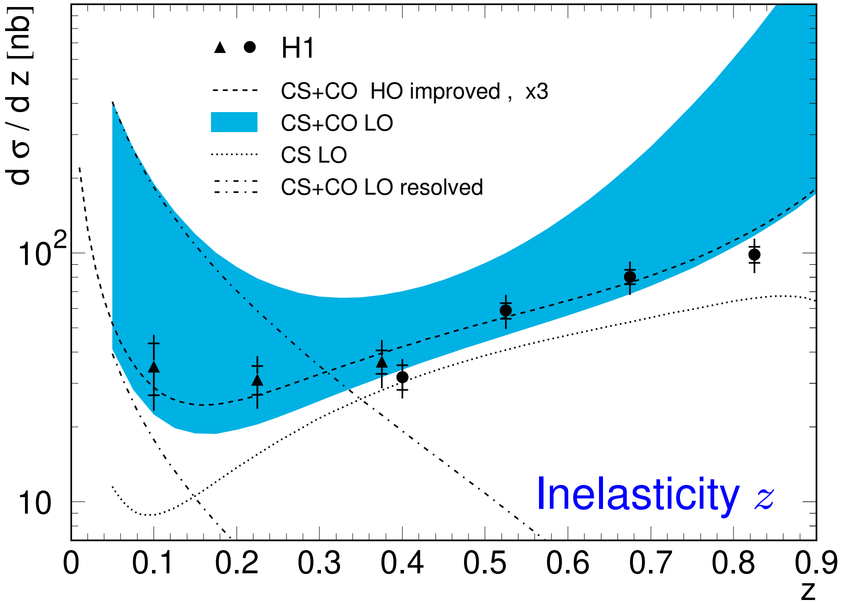
$$\sigma_{J/\psi X} = \sum \hat{\sigma}(\gamma p \rightarrow c\bar{c}[n]X) \times \text{LDME}[n])$$

LDME from NRQCD-fit to $p\bar{p}$ data




**Universality of LDME?** **Tevatron → HERA**




$Q^2 \sim 0$

- Colour Singlet:
  - NLO (available for photoproduction): ok
  - LO: too steep in $p^2_{t,\psi}$

$\Rightarrow$ NLO corrections are crucial

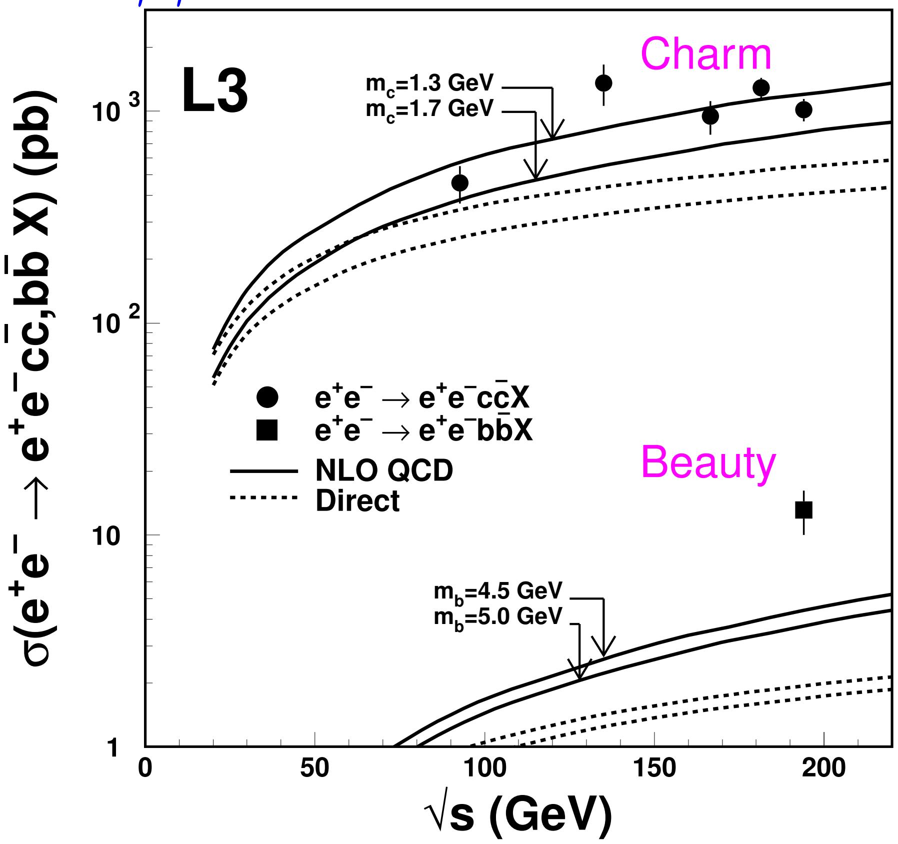
$\Rightarrow$ No indication of Colour-Octet contributions

- NRQCD CS+CO (LO):
  - Good description in $z$
    (assuming small LDME)

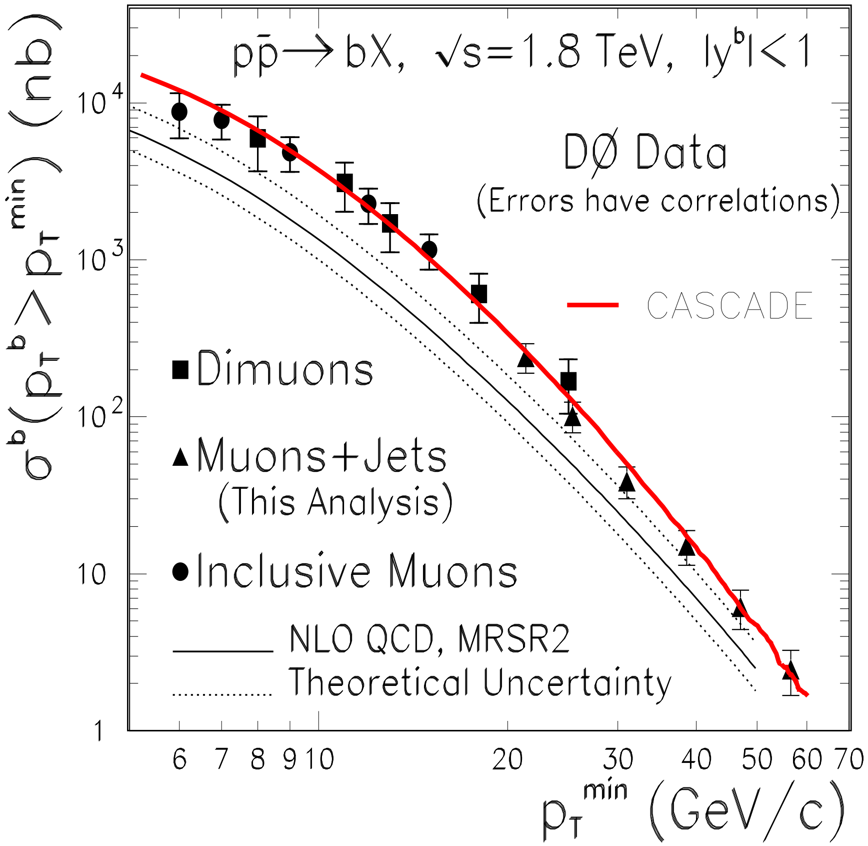
$z = E^*_\psi / E^*_\gamma$

# Beauty-Production: Overview LEP and Tevatron

$\gamma\gamma$ LEP




$p\bar{p}$ Tevatron



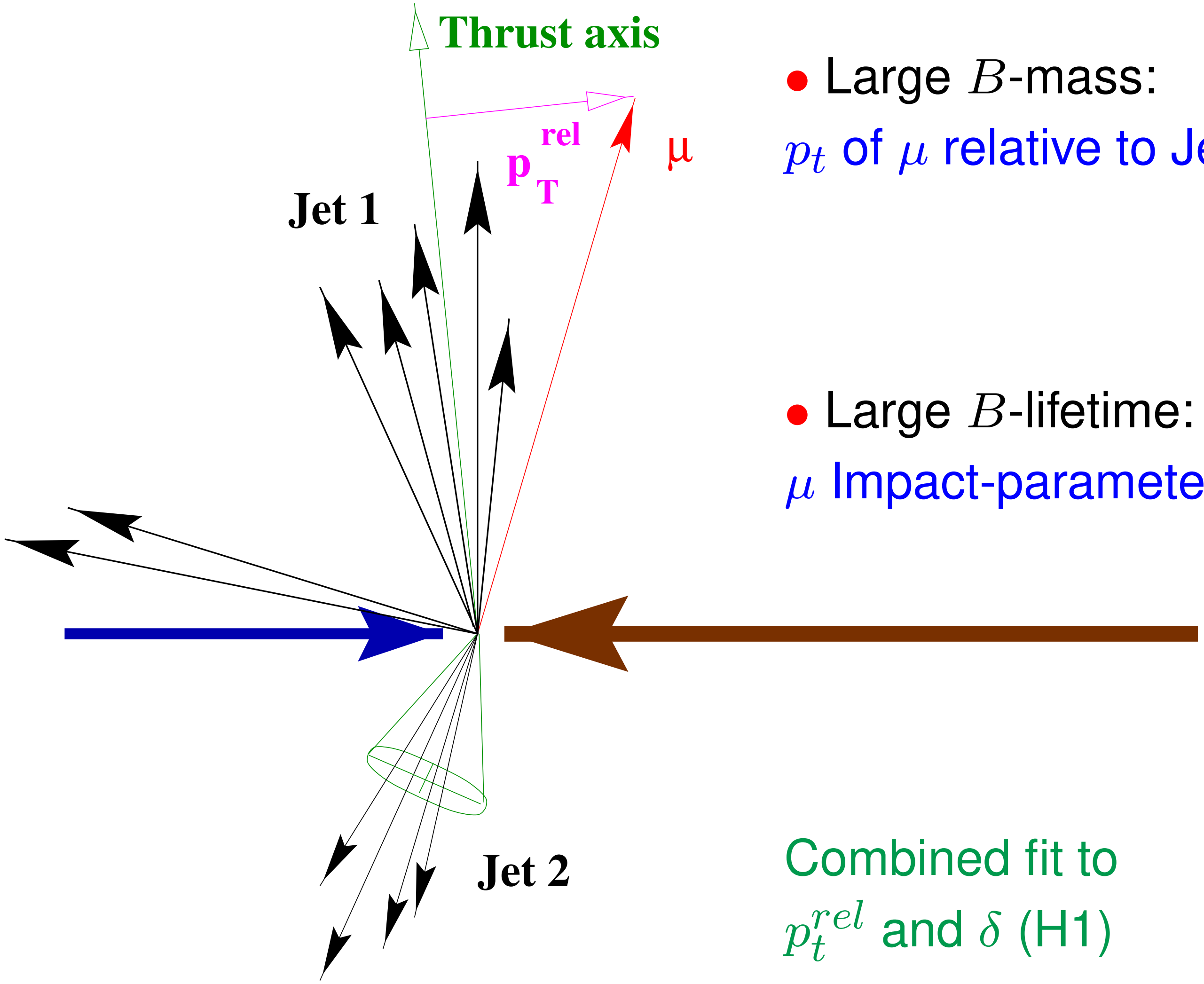

- NLO-expectations low compared to data
- $p\bar{p}$: Improved calculations are closer

What about $b$ at HERA?

# Beauty Production

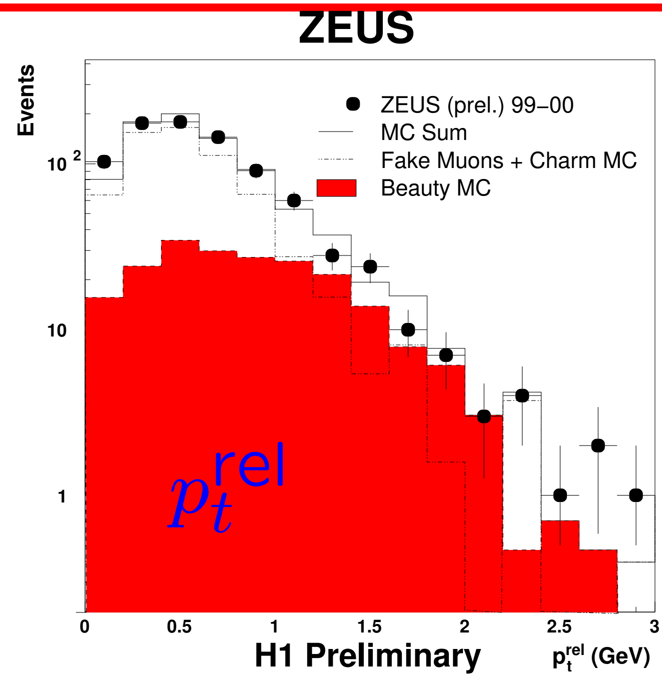
$\sigma(b\bar{b})$ : Factor $\sim$ 200 smaller than $\sigma(c\bar{c})$

$\rightarrow$ Use semileptonic $B$-decays



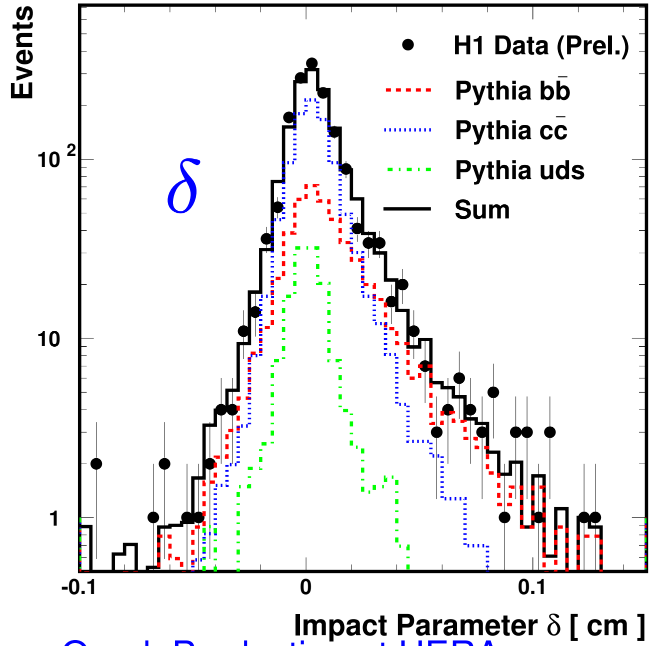

- Large $B$-mass:

$p_t$ of $\mu$ relative to Jet



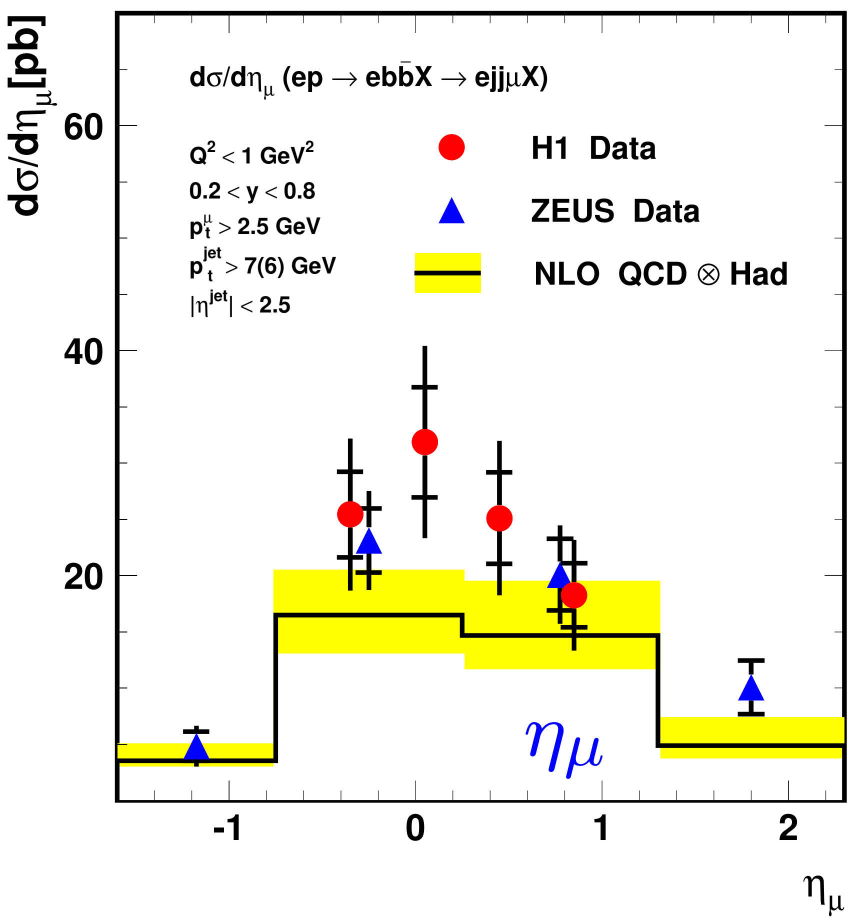

- Large $B$-lifetime:

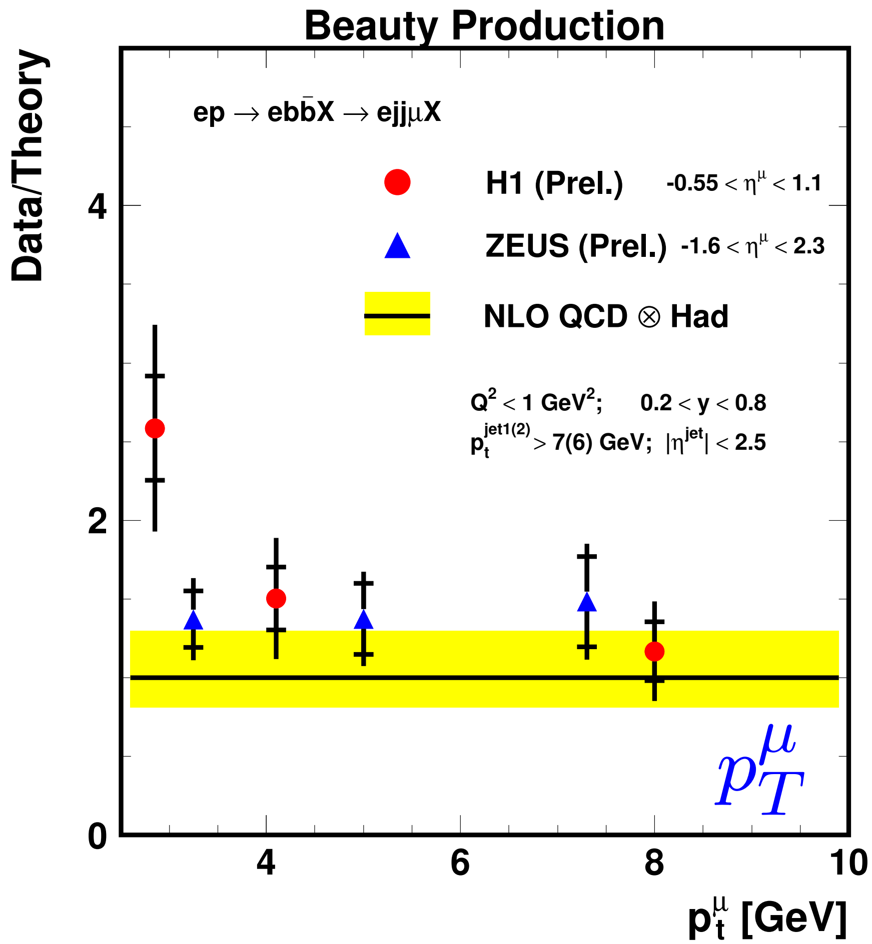
$\mu$ Impact-parameter




Combined fit to $p_t^{rel}$ and $\delta$ (H1)

$Q^2 \sim 0$ $b\bar{b} \to jj\mu X$

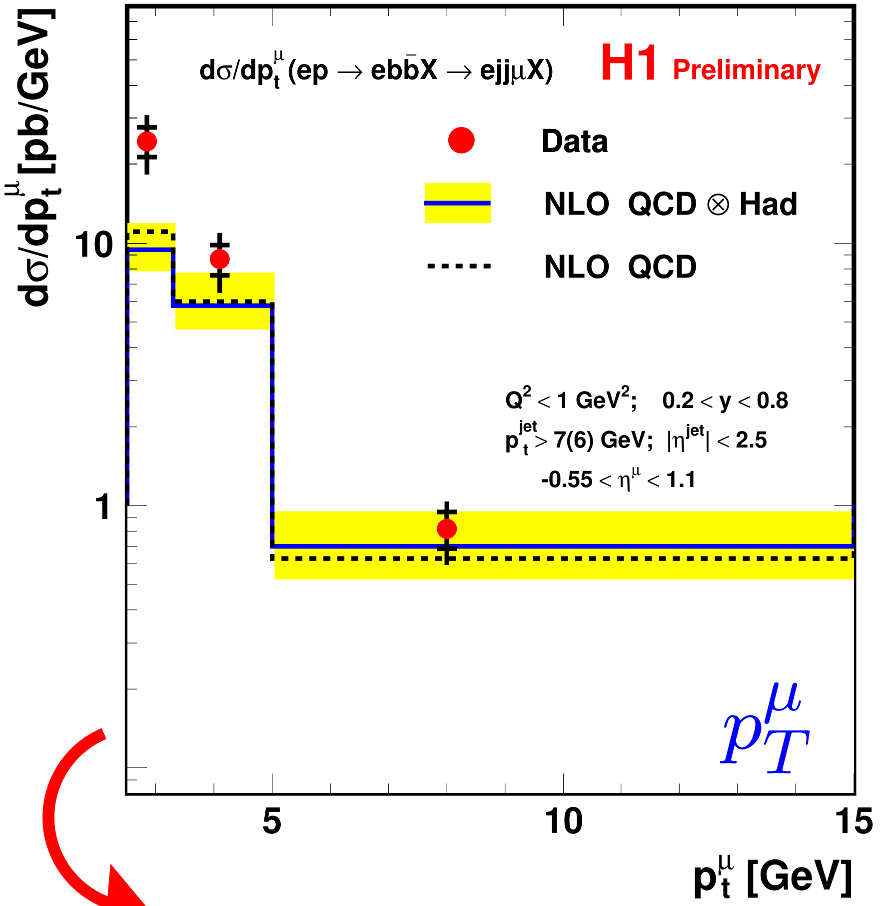


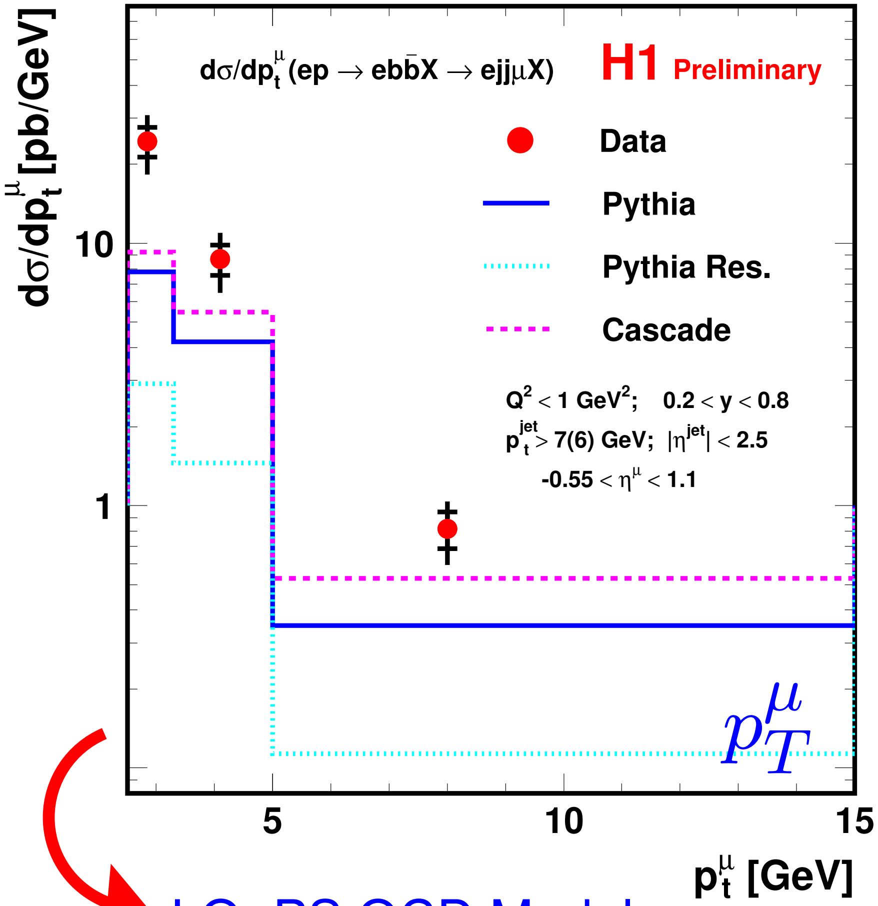




- Agreement between H1 and ZEUS
- All data points above NLO QCD
- Exp. and theory errors fairly large $\to$ agreement within errors

# $d\sigma/dp_T^{\mu}$ compared with QCD models

$Q^2 \sim 0$ $b\bar{b} \rightarrow jj\mu X$

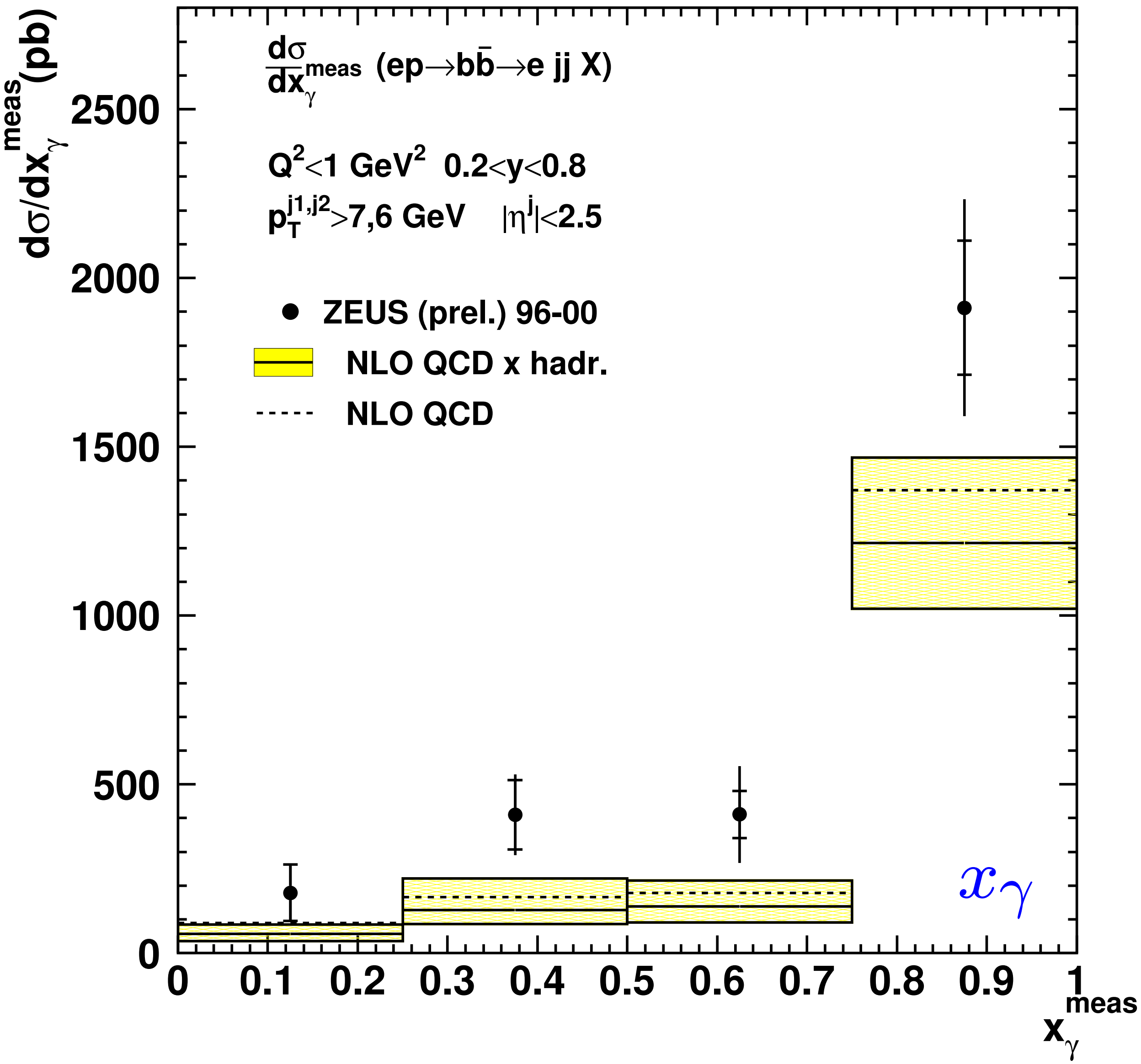



NLO QCD: Too low at low $p_T^{\mu}$

LO+PS QCD Models
Too low in normalization

$Q^2 \sim 0$ ZEUS $b\bar{b} \to jjX$




$p_t^{rel}$-Method

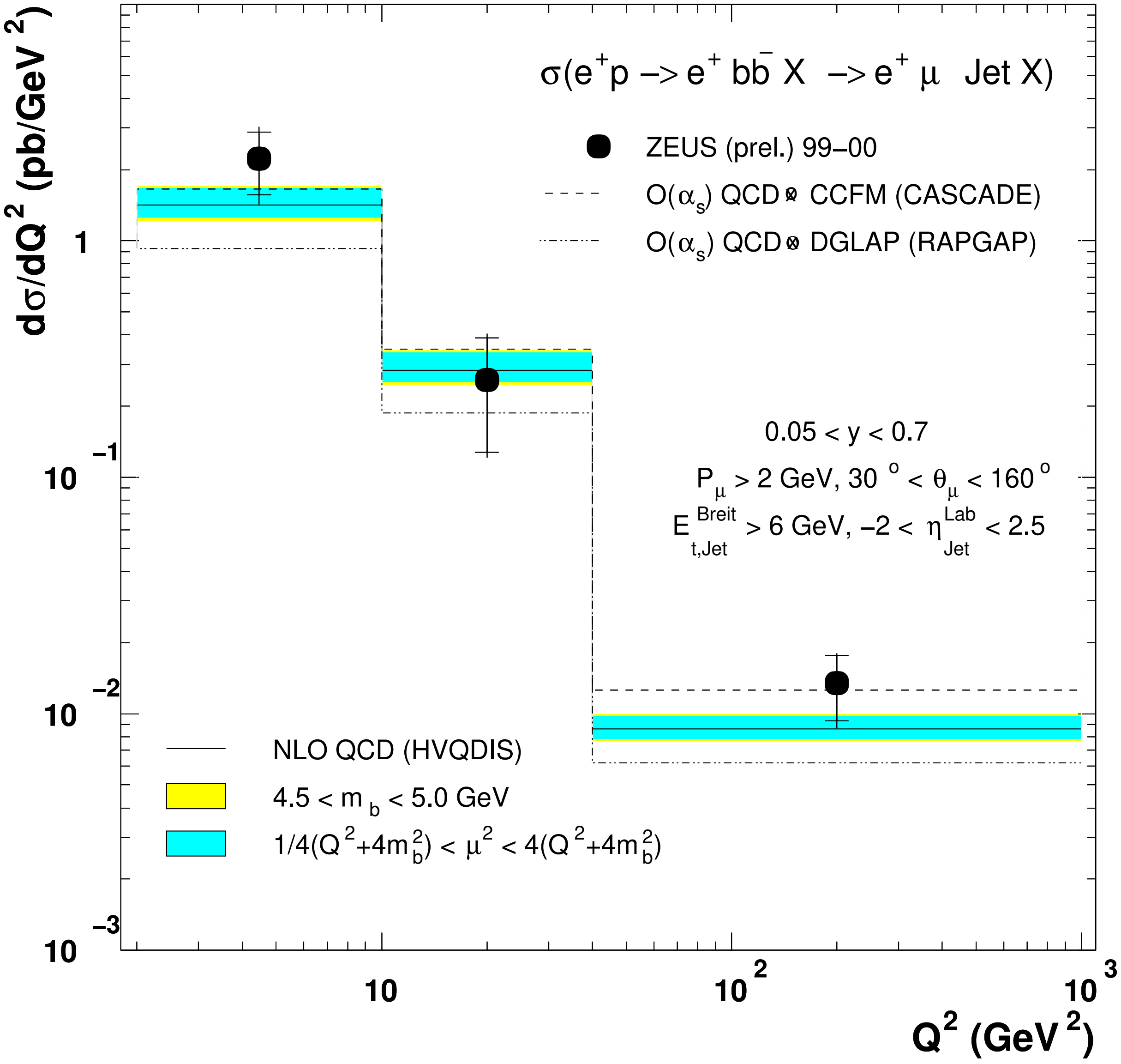
- DGLAP (NLO):
  – lower than data

ZEUS: $\sigma^{\text{vis}} = (733 \pm 61 \pm 104)$ pb
NLO (Frixione et al): $\sigma^{\text{vis}} = (381^{+117}_{-78})$pb

- Significant contribution from
  'Resolved-$\gamma$' cf. charm

# Beauty-Spectra in DIS

$Q^2 > 2$ GeV$^2$ $\qquad ep \rightarrow b\bar{b} \rightarrow ej\mu X$

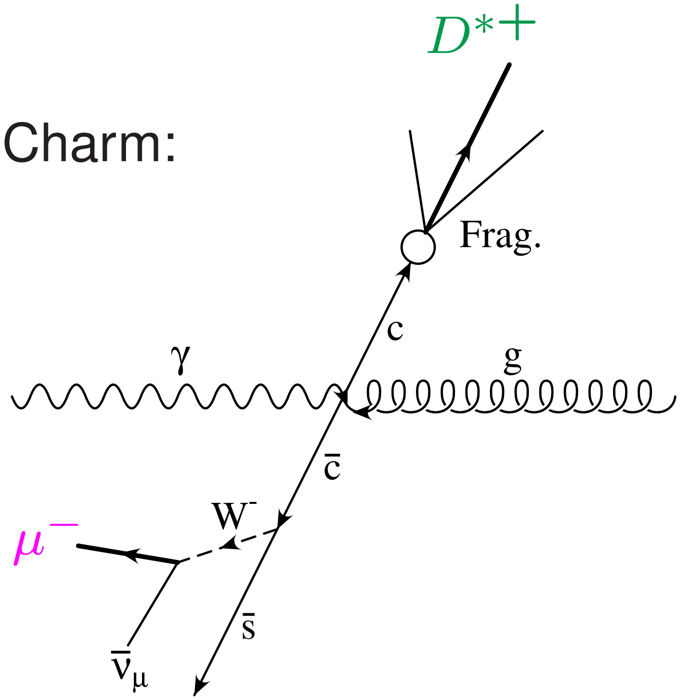



$\sigma^{\mathrm{vis}} = (38.7 \pm 7.7^{+6.1}_{-5.0})$ pb

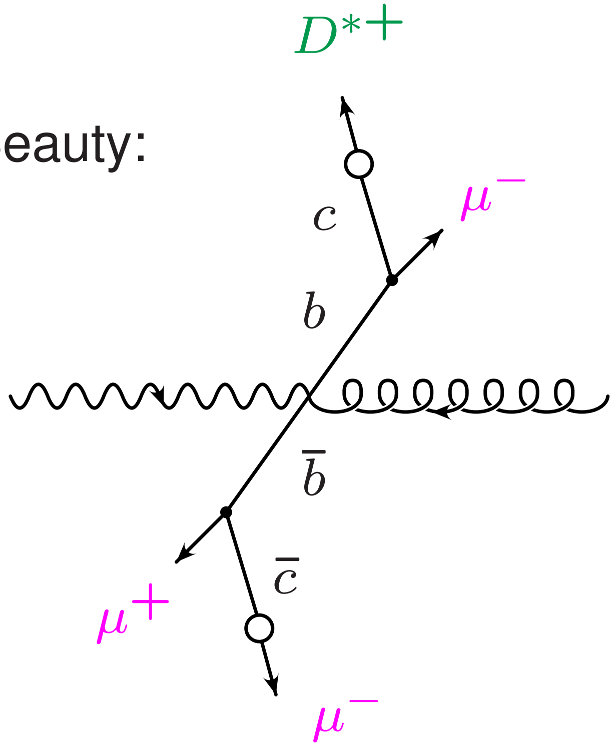
- DGLAP (NLO):
  – ok within errors
  NLO (Harris et al): $\sigma^{\mathrm{vis}} = (28^{+5.3}_{-3.5})$pb
- CCFM:
  – Good description
  CASCADE-MC: $\sigma^{\mathrm{vis}} \approx 35$pb
- DGLAP (LO+PS):
  – too low

$\gamma g$-Center of Mass System:

Charm:




Beauty:




$\Delta\Phi \approx 180^\circ$

$Q(D^*) \neq Q(\mu)$

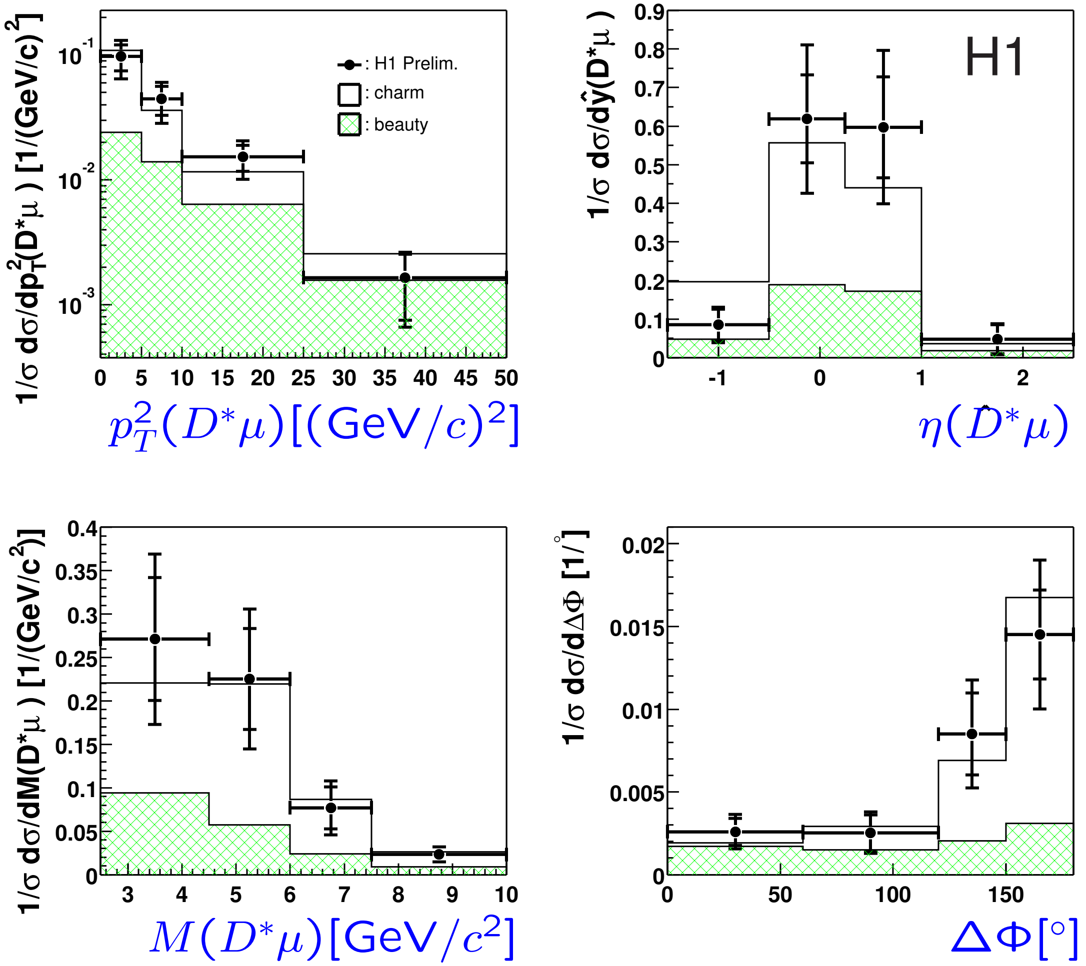
$\Delta\Phi \approx 0^\circ$ ; $Q(D^*) \neq Q(\mu)$

$\Delta\Phi \approx 180^\circ$; $Q(D^*) \neq Q(\mu)$

$\Delta\Phi \approx 180^\circ$; $Q(D^*) = Q(\mu)$

Separation of $c$ and $b$ via charge and angular correlations

## Heavy-Flavour Double-Tag




- Both quarks measured:

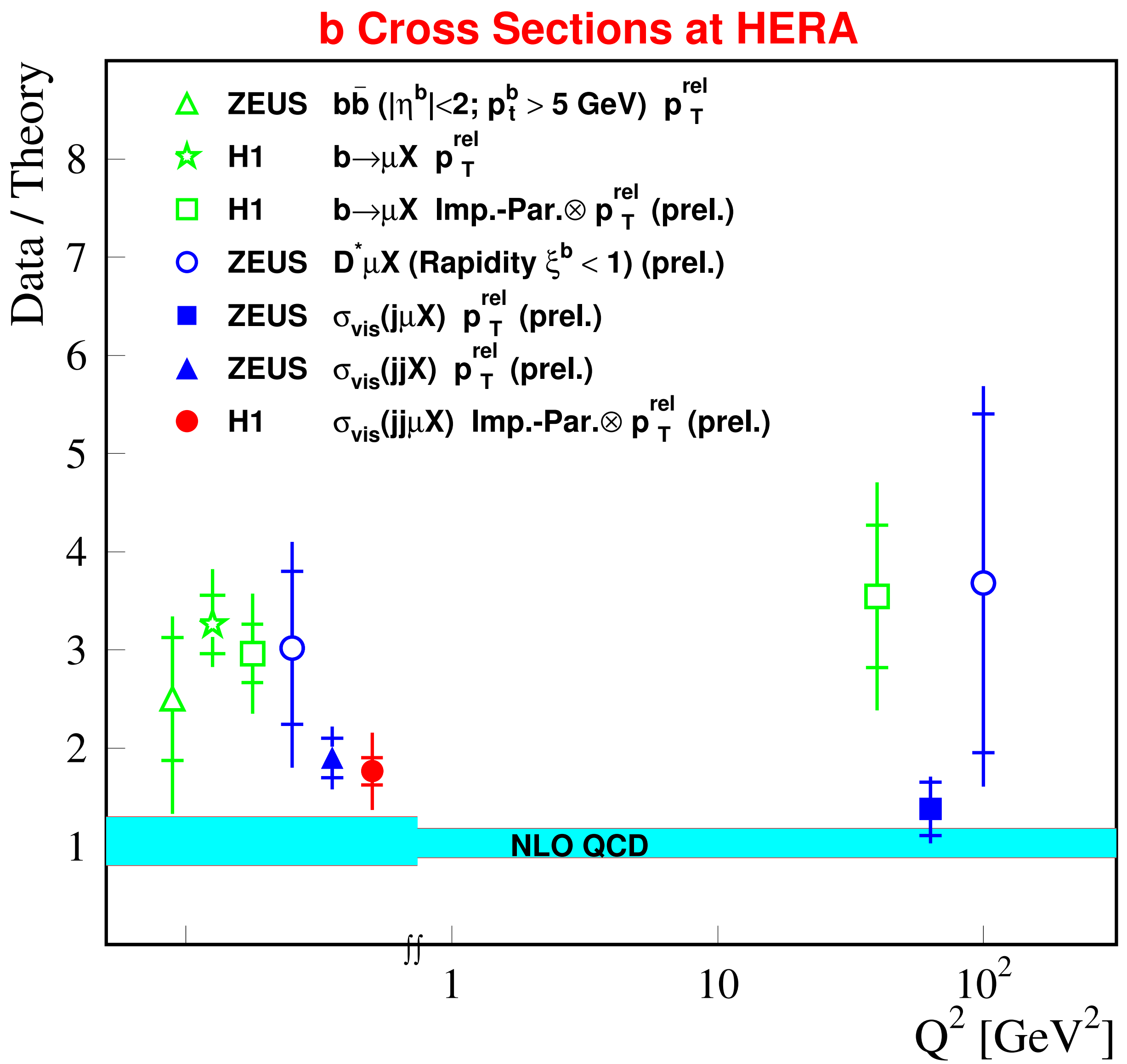
$\rightarrow$ Full reconstruction of event

$\rightarrow$ Higher order effects ?

$\sigma(ep \rightarrow eb\bar{b}X)$ :
ZEUS: $15.1 \pm 3.9^{+3.8}_{-4.7}$ pb
NLO (Frixione et al): $5.7^{+1.7}_{-1.1}$ pb

- Factor $\sim$ 3 above NLO-expectation
  – statistical uncertainty still large
  – confirms previous $b$-results

Figures: LO Monte Carlo, Cross sections normalized

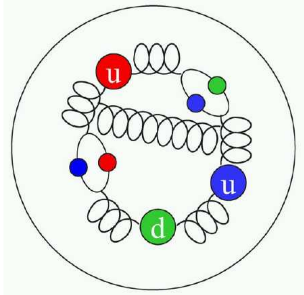

b Cross Sections at HERA
ZEUS bb̄ (|η^b|<2; p_t^b > 5 GeV) p_T^rel
H1 b→μX p_T^rel
H1 b→μX Imp.-Par.⊗ p_T^rel (prel.)
ZEUS D*μX (Rapidity ξ^b < 1) (prel.)
ZEUS σ_vis(jμX) p_T^rel (prel.)
ZEUS σ_vis(jjX) p_T^rel (prel.)
H1 σ_vis(jjμX) Imp.-Par.⊗ p_T^rel (prel.)
NLO QCD
Data / Theory
1
2
3
4
5
6
7
8
1
10
10^2
Q^2 [GeV^2]

# Summary of Heavy Quark Measurements

HERA-I:

– Proton properties revealed at small $x$:

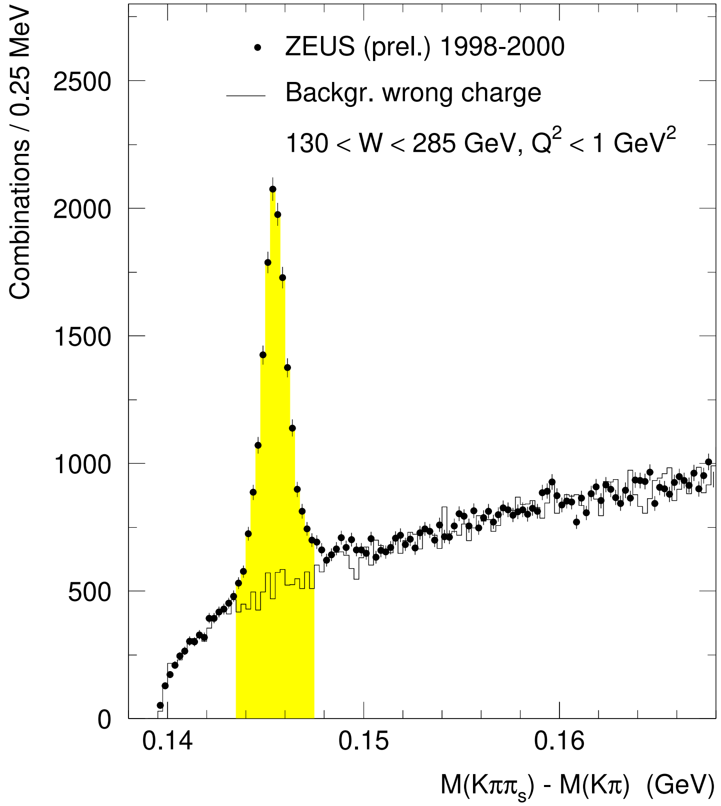
– Crucial contributions to quant$^{\text{ive}}$ understanding of strong interactions




- Data modeled reasonably well by QCD

  Proton Structure $\otimes$ Photon Structure $\otimes$ QCD-Dynamics $\otimes$ Fragmentation

  – Successful factorization of the many ingredients




- Charm:

  – Cross sections adequately described

- Beauty:

  – NLO lower than data (ZEUS, DIS ok)

  situation similar to $p\bar{p}$ und $\gamma\gamma$

- Much more results available, not reported here

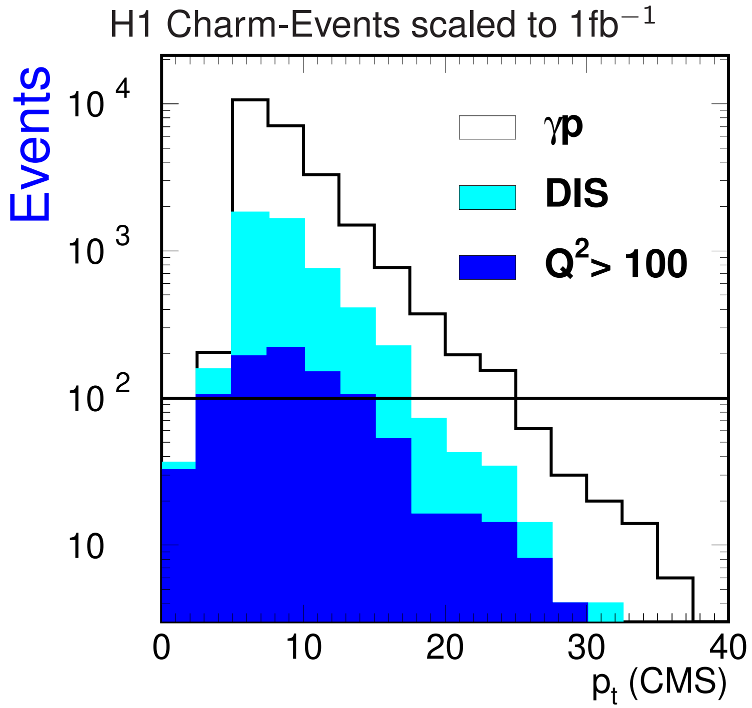
## HERA-II:

## Go for precision answers to open questions

- Factor of 10 in luminosity
- Improved detectors
  (z.B. Trigger, tracking, angular coverage)

## Extend precision and physics reach:

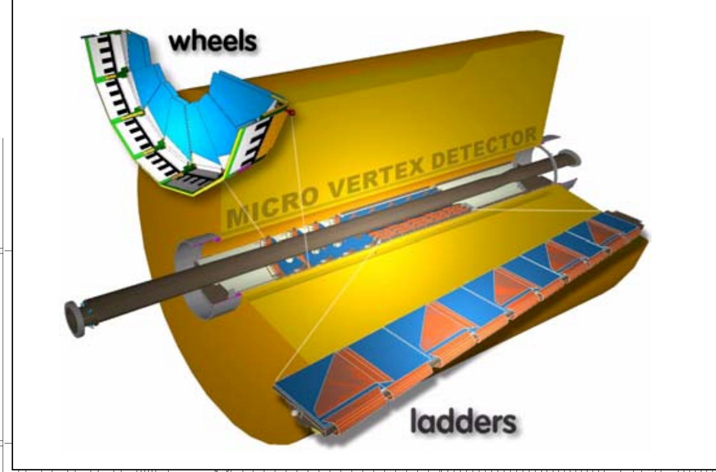
- Understanding / handling of QCD
- Determination of EW parameters
- Searches beyond the Standard Model

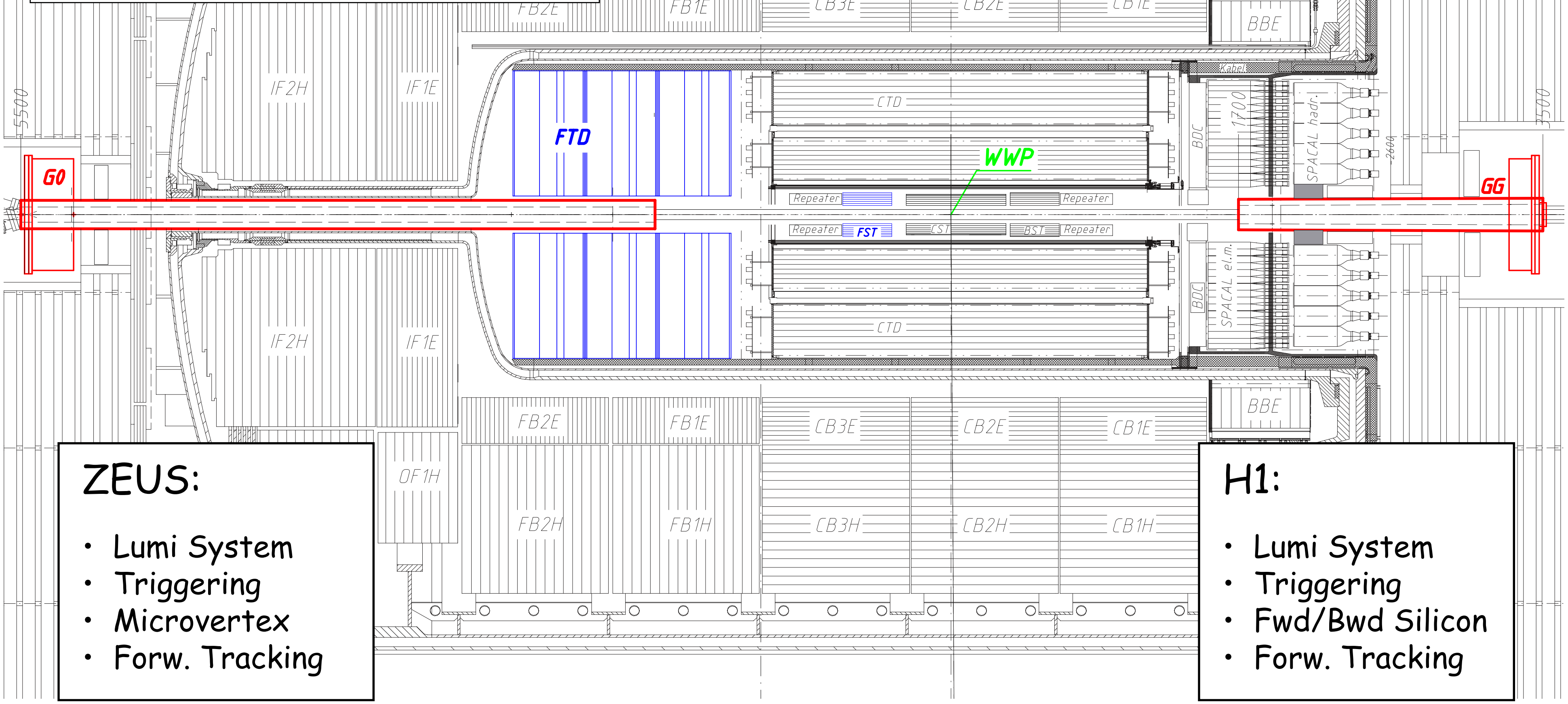



ZEUS Microvertex-Detector

# HERA Upgrade

ZEUS Microvertex Detector



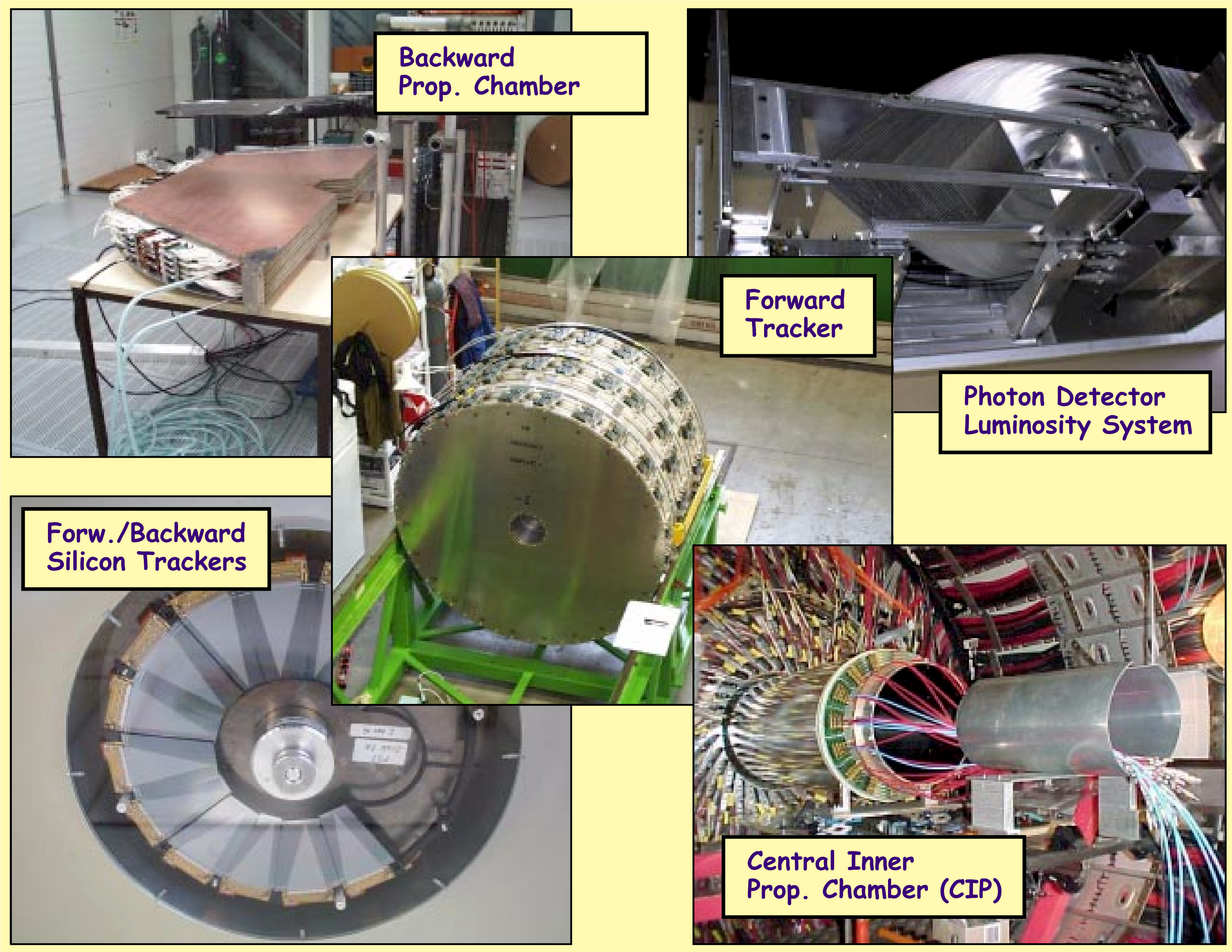




## ZEUS:

- Lumi System
- Triggering
- Microvertex
- Forw. Tracking

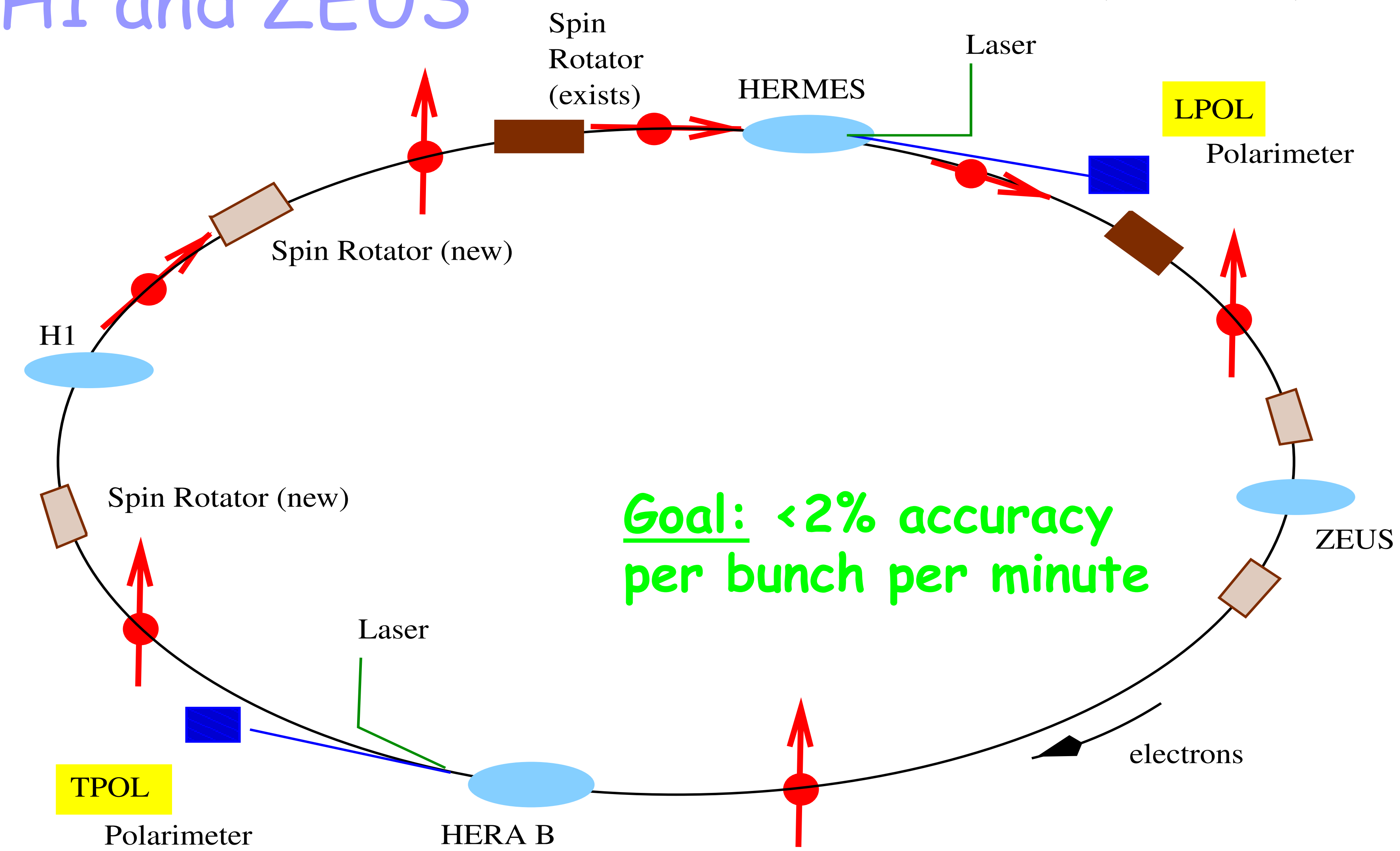
## H1:

- Lumi System
- Triggering
- Fwd/Bwd Silicon
- Forw. Tracking


Backward Prop. Chamber
Forward Tracker
Photon Detector Luminosity System
Forw./Backward Silicon Trackers
Central Inner Prop. Chamber (CIP)

# Polarization for H1 and ZEUS

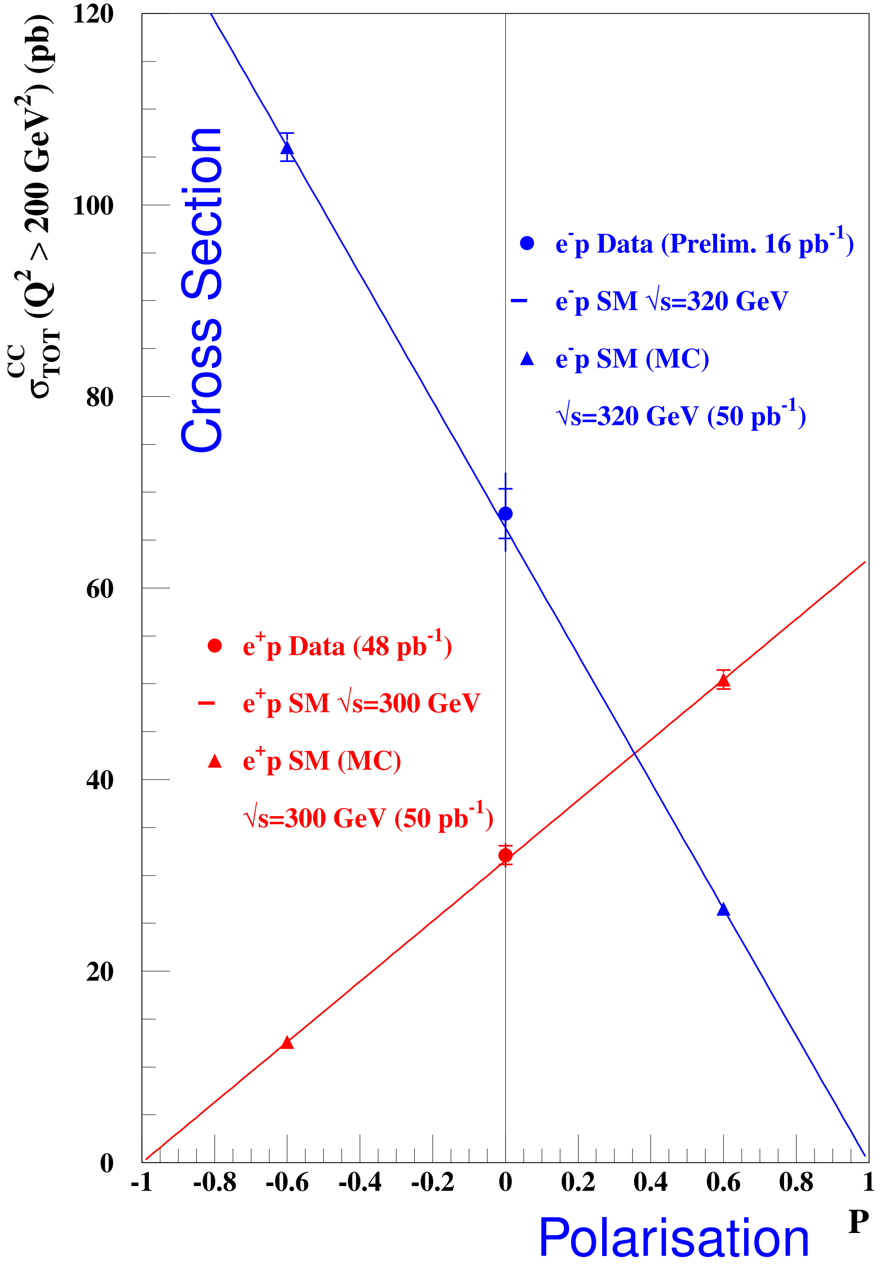
- utilises Compton scattering
- measures energy weighted asymmetry

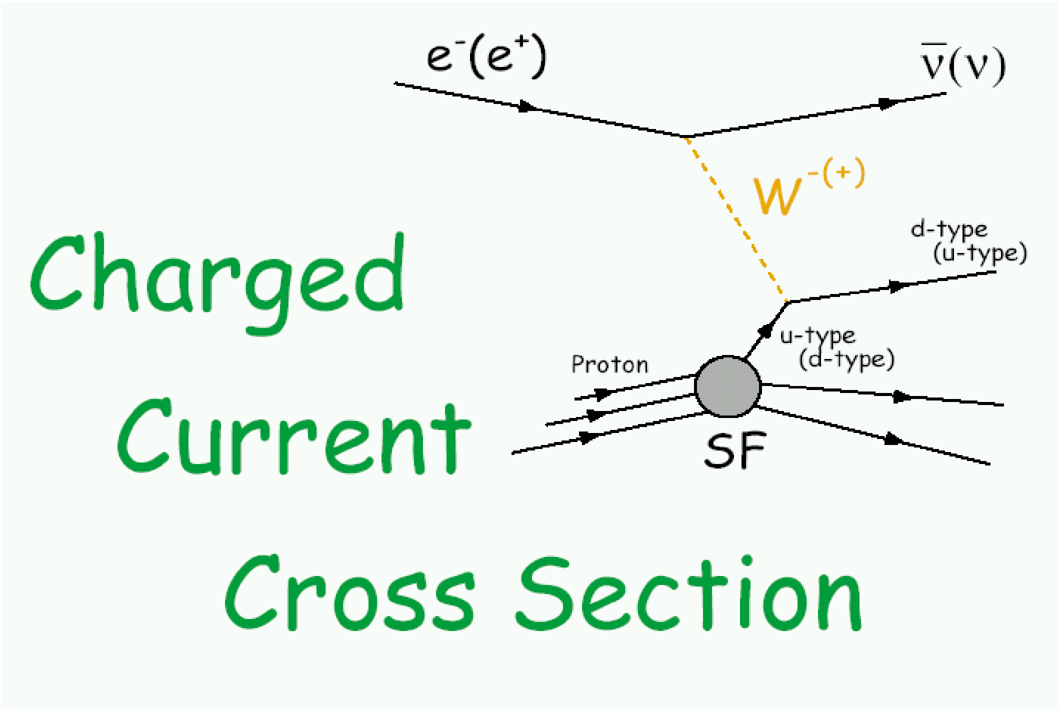



**<u>Goal:</u> <2% accuracy per bunch per minute**

- utilises Compton scattering
- measures spatial asymmetry

# Polarisation of Lepton Beams ($e^+$ and $e^-$)




- Look for right handed charged currents
- Any deviation from straight line
  $\rightarrow$ New physics

*"I got what I wanted, but it wasn't what I expected."*