JINR

NEW TRENDS IN HIGH-ENERGY PHYSICS

(experiment, phenomenology, theory)

Alushta, Crimea, Ukraine, September 3 - 10, 2011

BINP

Physics at HERA Collider
Part II

S. Levonian (DESY)

representing

H1 and ZEUS

Physics at HERA

• HERA as Super-microscope

▷ Proton structure at high resolution

▷ Impact for LHC

• HERA as Energy frontier machine

▷ Electroweak unification at work

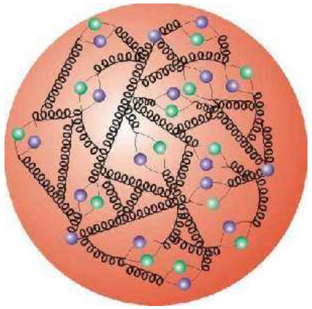
▷ Anything beyond the Standard Model?

• HERA as QCD laboratory

▷ Putting QCD in stringent tests with:
- ∘ Jets (parton evolution schemes, NLO QCD, α_s)
- ∘ Heavy flavor sector (multiscale problem: Q^2, M_Q, E_t)
- ∘ Diffraction (interplay of soft and hard physics)
- ∘ Particle production (parton dynamics and fragmentation)

Physics at HERA

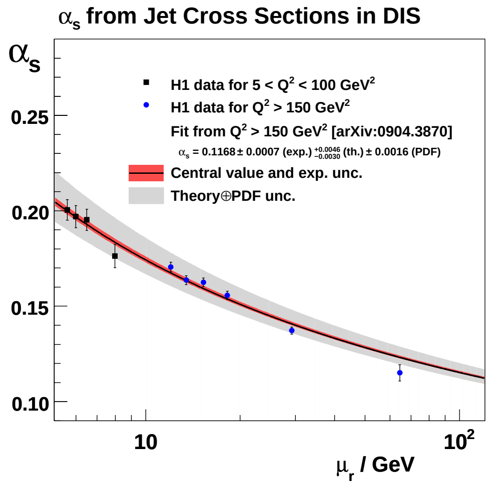
- **HERA as Super-microscope**
  - ▷ Proton structure at high resolution
  - ▷ Impact for LHC



➠ Part I (Monica Turcato)

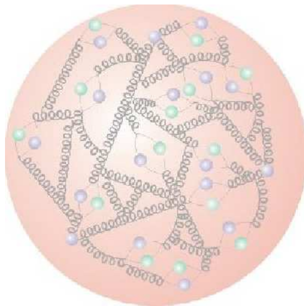
- **HERA as Energy frontier machine**
  - ▷ Electroweak unification at work
  - ▷ Anything beyond the Standard Model?

- **HERA as QCD laboratory**
  - ▷ Putting QCD in stringent tests with:
    - ○ Jets (parton evolution schemes, NLO QCD, α_s)
    - ○ Heavy flavor sector (multiscale problem: Q^2, M_Q, E_t)
    - ○ Diffraction (interplay of soft and hard physics)



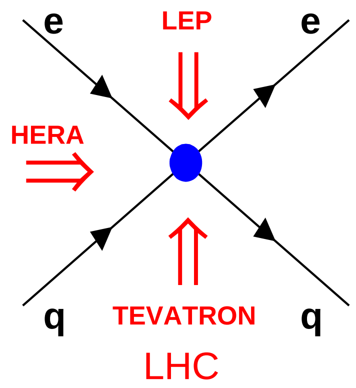
➠ **Precision Measurements (exp. errors $\sim 1\%$)**

Physics at HERA



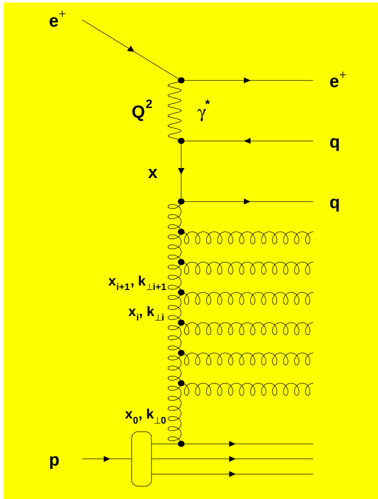
- **HERA as Super-microscope**
  - ▷ Proton structure at high resolution
  - ▷ Impact for LHC

Part I (Monica Turcato)



- **HERA as Energy frontier machine**
  - ▷ Electroweak unification at work
  - ▷ Anything beyond the Standard Model?

- **HERA as QCD laboratory**
  - ▷ Putting QCD in stringent tests with:
    - ○ Jets (parton evolution schemes, NLO QCD, α_s)
    - ○ Heavy flavor sector (multiscale problem: Q^2, M_Q, E_t)
    - ○ Diffraction (interplay of soft and hard physics)
  - ▷ HERA specifics: low x phenomena



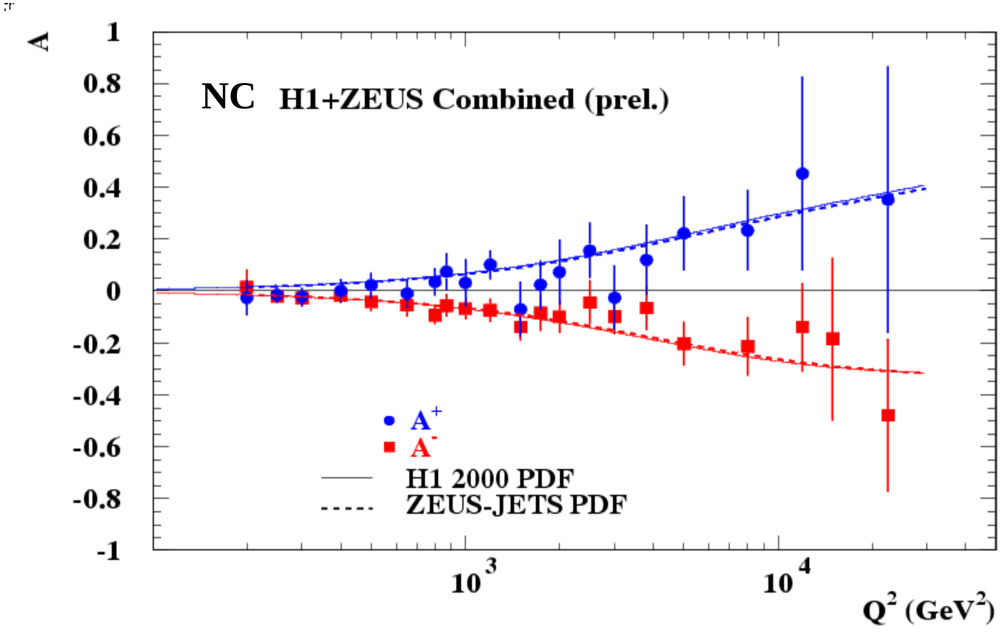
Part II: Search for Novel Phenomena

Parity violation in polarised NC and CC DIS

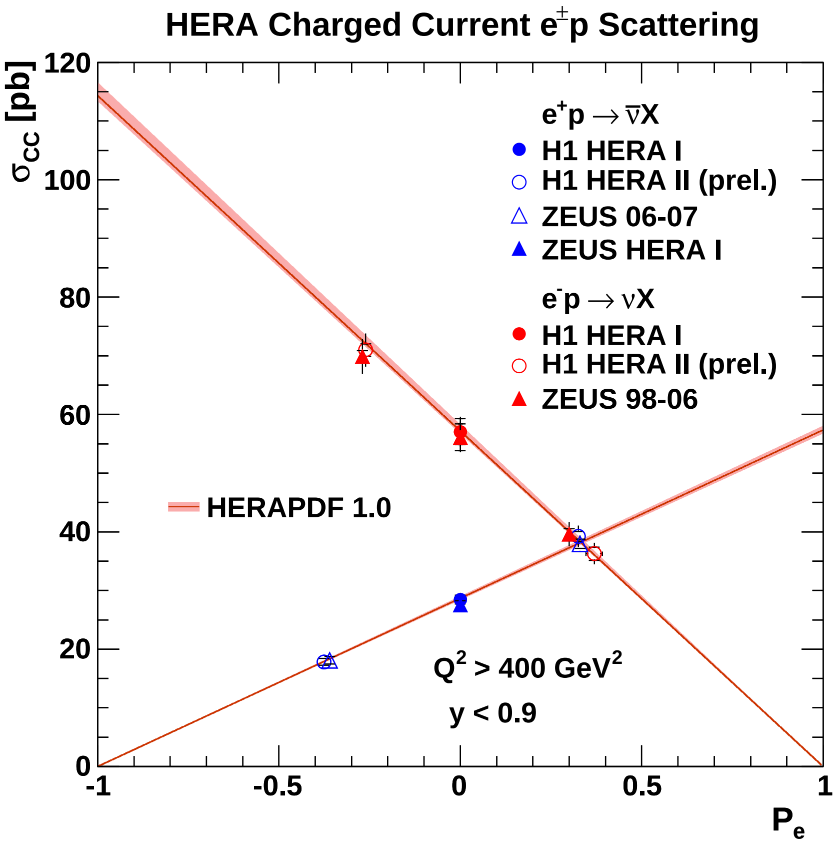
$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$

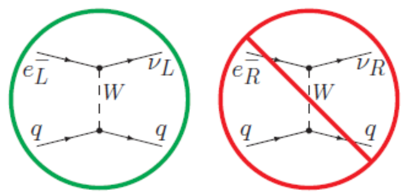
$$A^{\pm} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2} \simeq \pm k \frac{1 + d_v/u_v}{4 + d_v/u_v}$$

$$\sigma^{CC}_{\mathrm{pol}}(\mathrm{e}^{\pm}\mathrm{p}) = (1 \pm \mathrm{P_e}) \cdot \sigma^{\mathrm{CC}}_{\mathrm{unpol}}(\mathrm{e}^{\pm}\mathrm{p})$$



SM expectation is in agreement with data

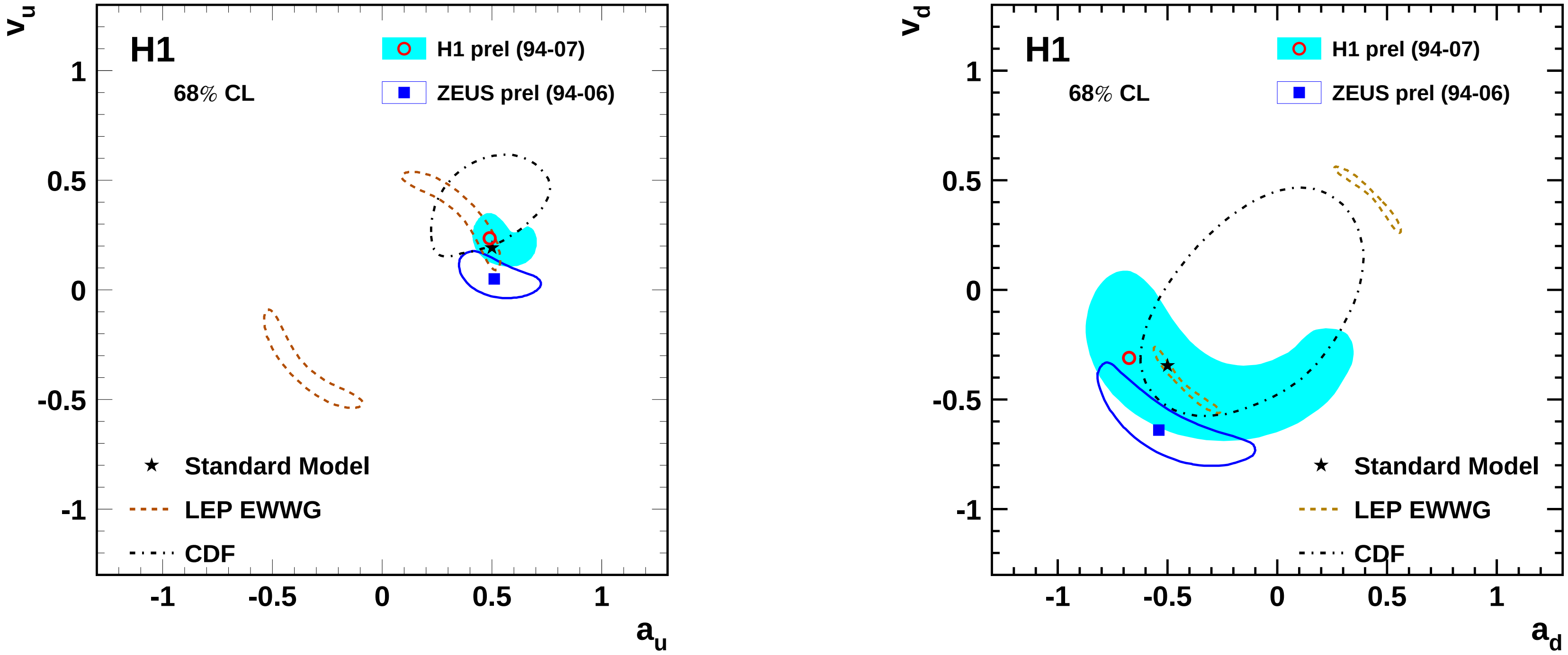




No W coupling to e_R^- and e_L^+

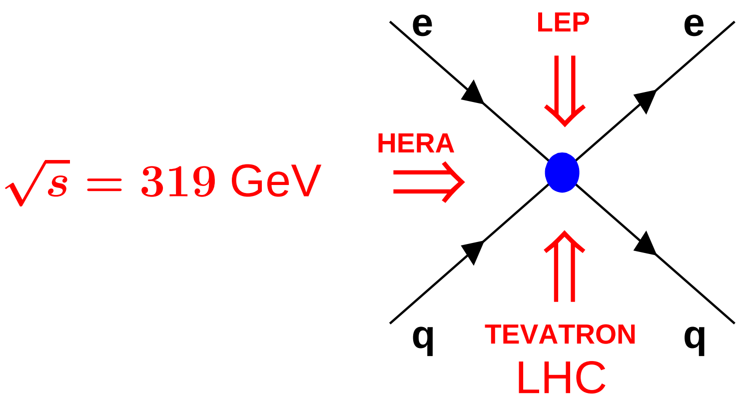
Combined Electroweak and QCD Fit

Combined electroweak quark couplings a_u, v_u, a_d, v_d and PDFs using NC/CC DIS cross sections



- Improved precision wrt HERA-I due to polarisation and statistics
- Consistent with Standard Model (χ^2/dof$= 0.96$)
- Able to resolve ambiguity of e^+e^-
- Results competitive with LEP and Tevatron (especially for v_u-a_u)
- Further improvent expected after ongoing combination of H1+ZEUS data

HERA at the Energy Frontier

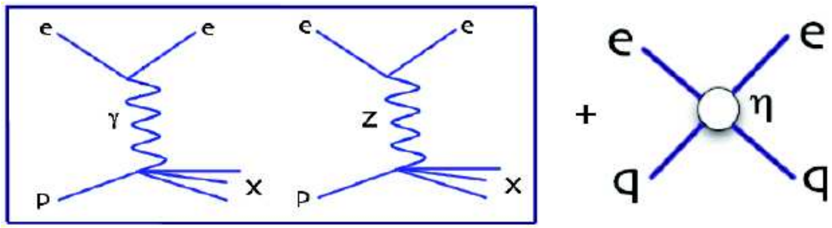


So far all NC and CC HERA data were in good agreement with the SM.
Try now to look more carefully at the tails, using two strategies:

1. Specific BSM signals search (LQ, LFV, SUSY, ...) – guided by theory

2. Model independent generic search (data vs SM) – guided by data

Search for Contact Interactions at HERA



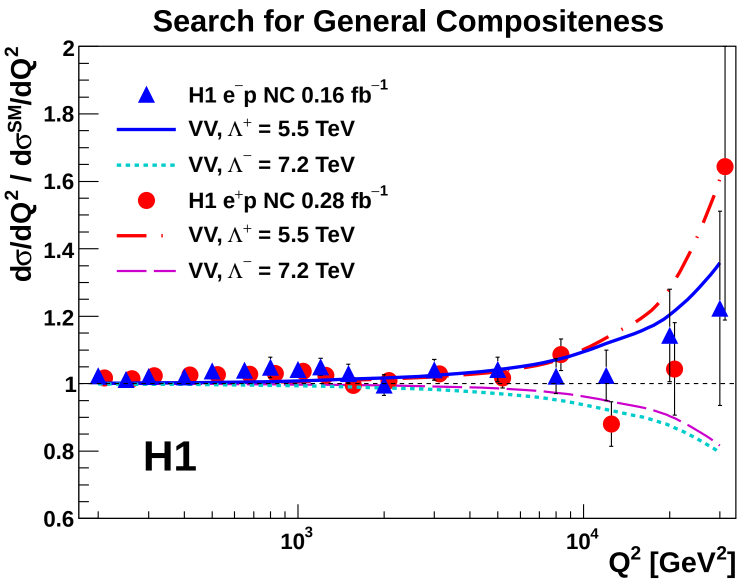
$$L = L_{SM} + L_{CI}$$

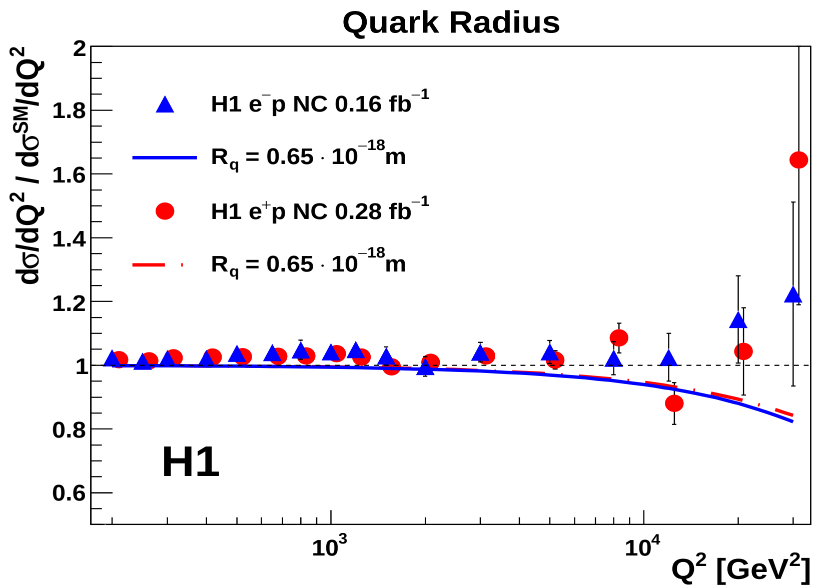
$$L_{CI} = \sum_{i,j=L,R} \eta_{ij}^{eq} (\overline{e}_i \gamma_\mu e_i)(\overline{q}_j \gamma^\mu q_j)$$

4 possible couplings for each q flavor

$$\eta_{ab}^{eq} = \frac{\pm 4\pi}{\Lambda^2}$$

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma_{SM}}{dQ^2} \cdot \left(1 - \frac{R^2}{6} \cdot Q^2\right)^2$$





Limit on effective mass scale:

$$\boxed{\Lambda > 3.2 - 7.2\ \mathrm{TeV}}$$

At 95% CL

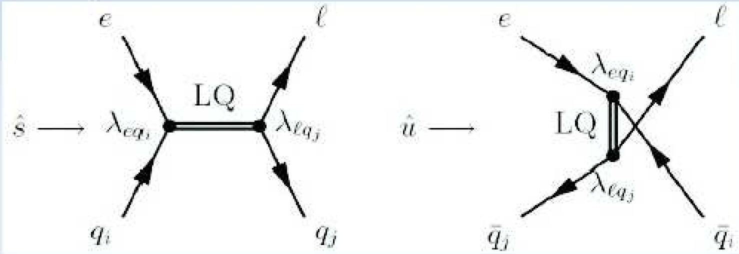
Upper limit on quark radius:

$$\boxed{R < 0.65 \cdot 10^{-18}\ \mathrm{m}}$$

Search for Leptoquarks at HERA

- Leptoquarks ***(LQ),*** compound states of leptons and quarks

  Fermion number ***F = L+3B*** ***F = 2 (e^-p)*** ***F = 0 (e^+p)***
- ***Buchmüller-Rückl-Wyler*** framework: 14 different types (7 scalar, 7 vector)
- LQ at HERA:



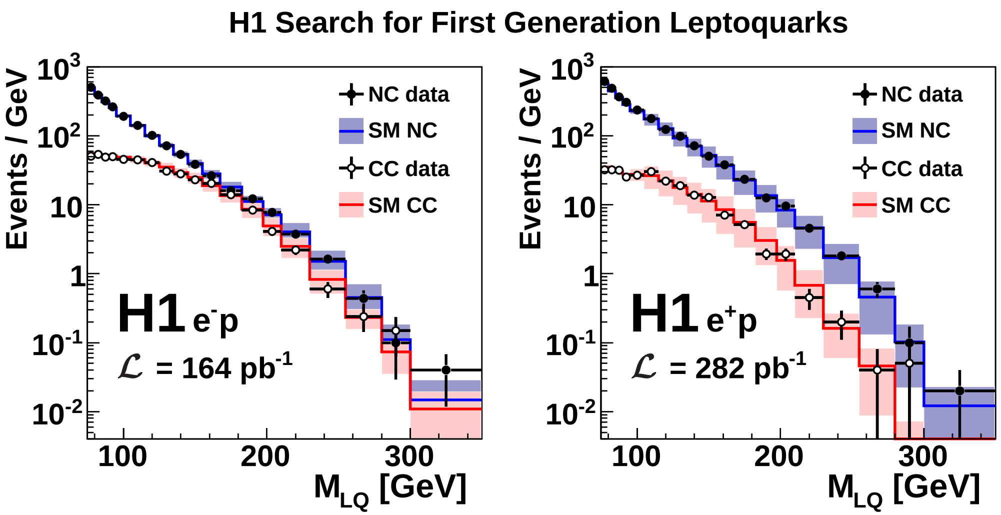
1st gen: eq → LQ → e(ν)q ***(LFC)***

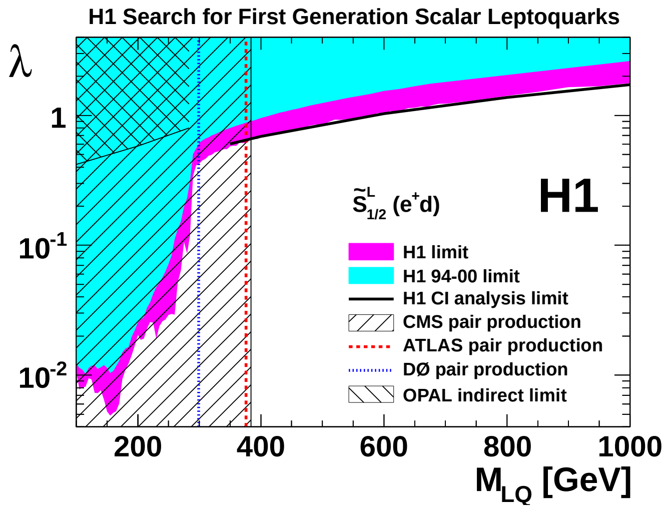
2nd gen: eq → LQ → μ(ν)q ***(LFV)***

3rd gen: eq → LQ → τ(ν)q ***(LFV)***

s-channel: (resonant production)

u-channel: (LQ exchange)

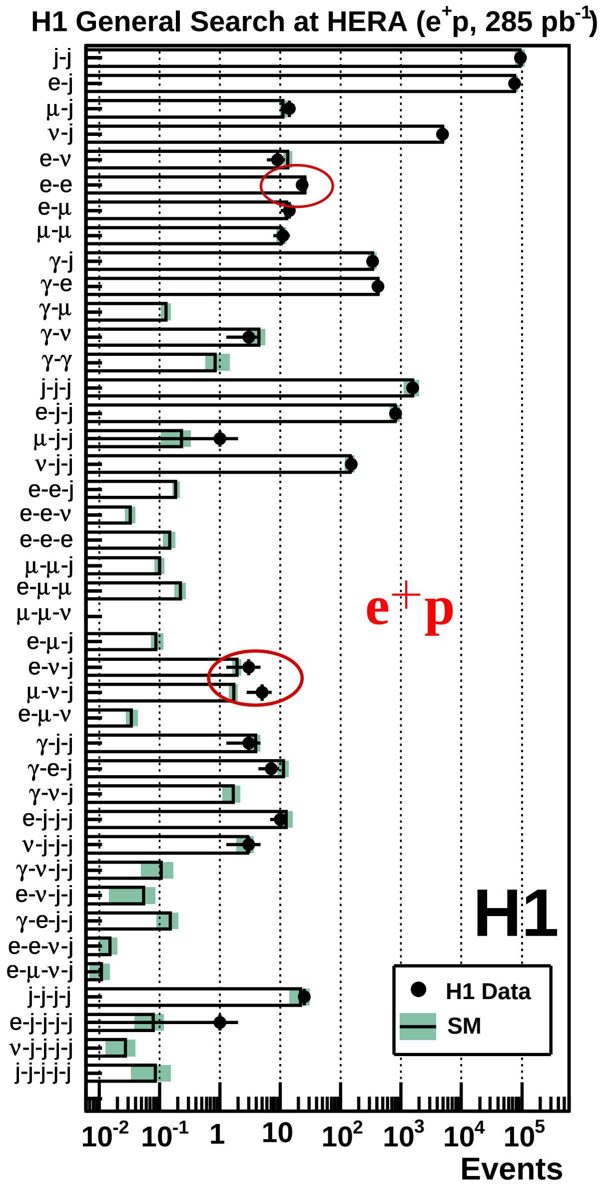




Model independent search for New Phenomena

- Identify isolated ($D(\eta\phi) > 1$) particles (objects): e, μ, γ, j, ν
- Select events, having at least two objects with high $P_T > 20$GeV in the detector acceptance ($10^o < \theta < 140^o$)
- Classify into exclusive channels containing from 2 to 5 objects
- Compare with SM predictions
  $\Rightarrow$ **good overall agreement**
- Find interesting regions with greatest deviations from SM in kin. distributions ($M_{\rm all}$, ΣP_T)

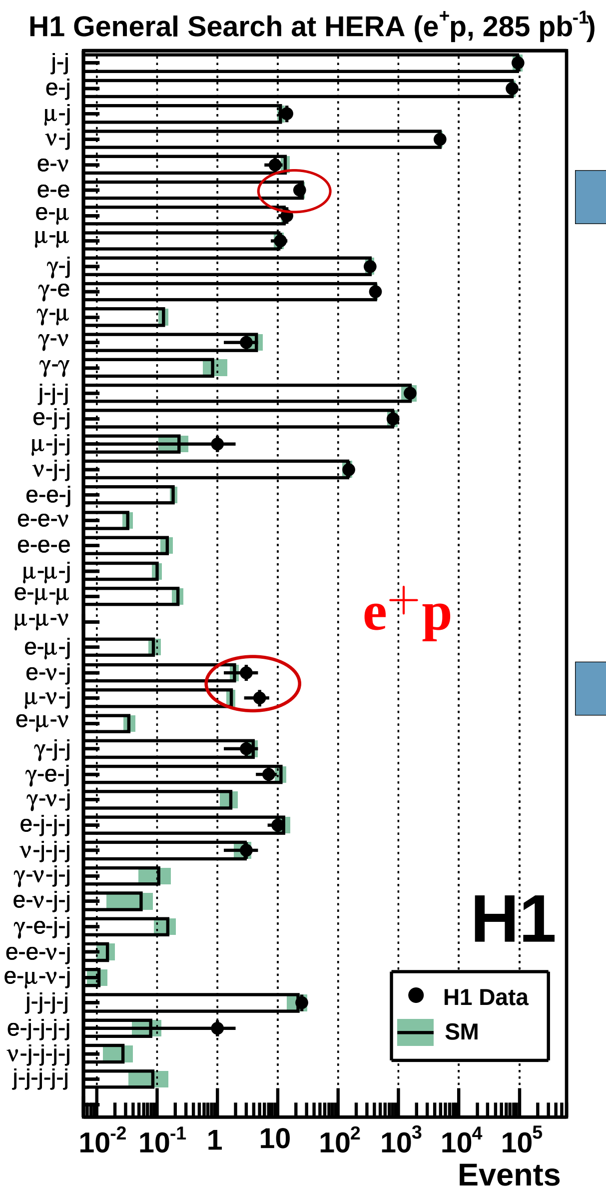
  $\Rightarrow$ **Combine H1 and ZEUS data**



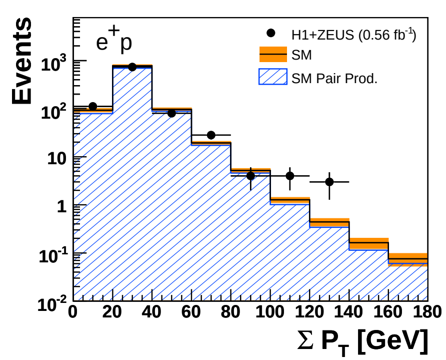
Model independent search for New Phenomena

- Identify isolated ($D(\eta\phi) > 1$) particles (objects): e, μ, γ, j, ν
- Select events, having at least two objects with high $P_T > 20\text{GeV}$ in the detector acceptance ($10^o < \theta < 140^o$)
- Classify into exclusive channels containing from 2 to 5 objects
- Compare with SM predictions
  $\Rightarrow$ **good overall agreement**
- Find interesting regions with greatest deviations from SM in kin. distributions (M_{all}, ΣP_T)

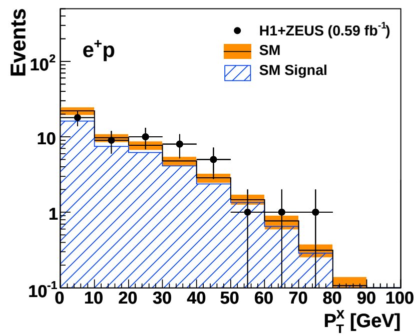
  $\Rightarrow$ **Combine H1 and ZEUS data**



H1+ZEUS, $0.59\ \text{fb}^{-1}$



2.6σ

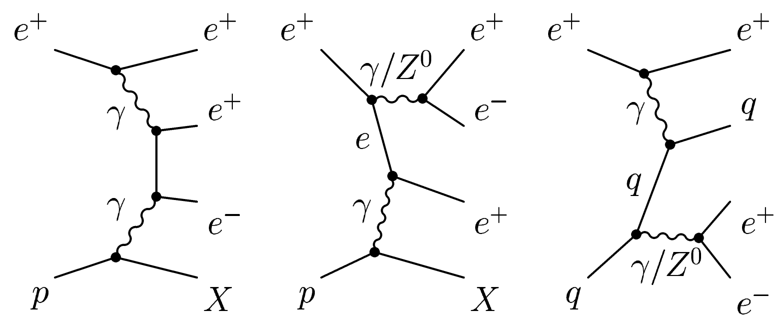


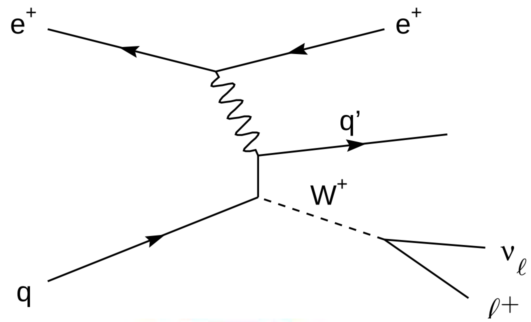
1.9σ

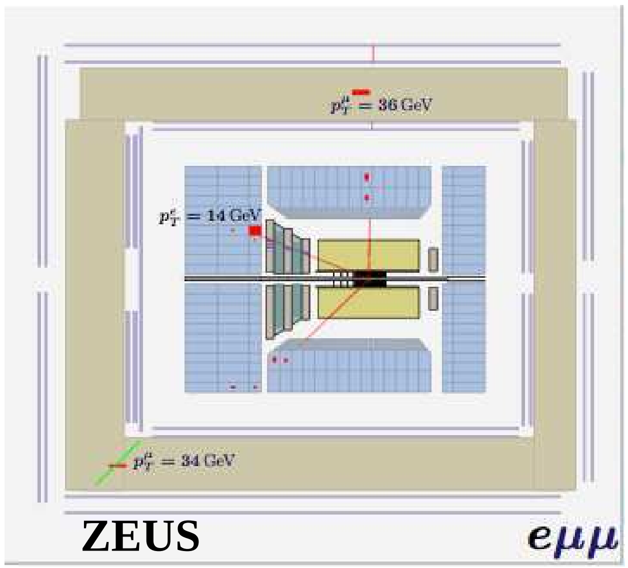
Largest observed deviations from the SM at HERA

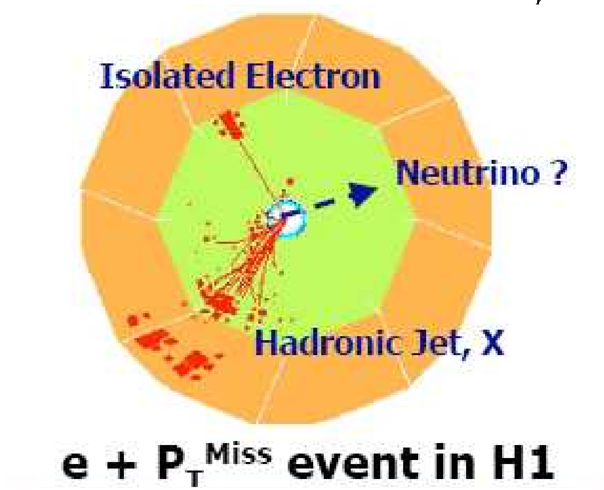
JHEP 0910:013 (2009)
JHEP 1003:035 (2010)

Multi-lepton Events and Isolated Lepton Events with $\not{P}_T$









Multi-Leptons at HERA (0.94 fb^{-1})

$\sum P_T > 100$ GeV

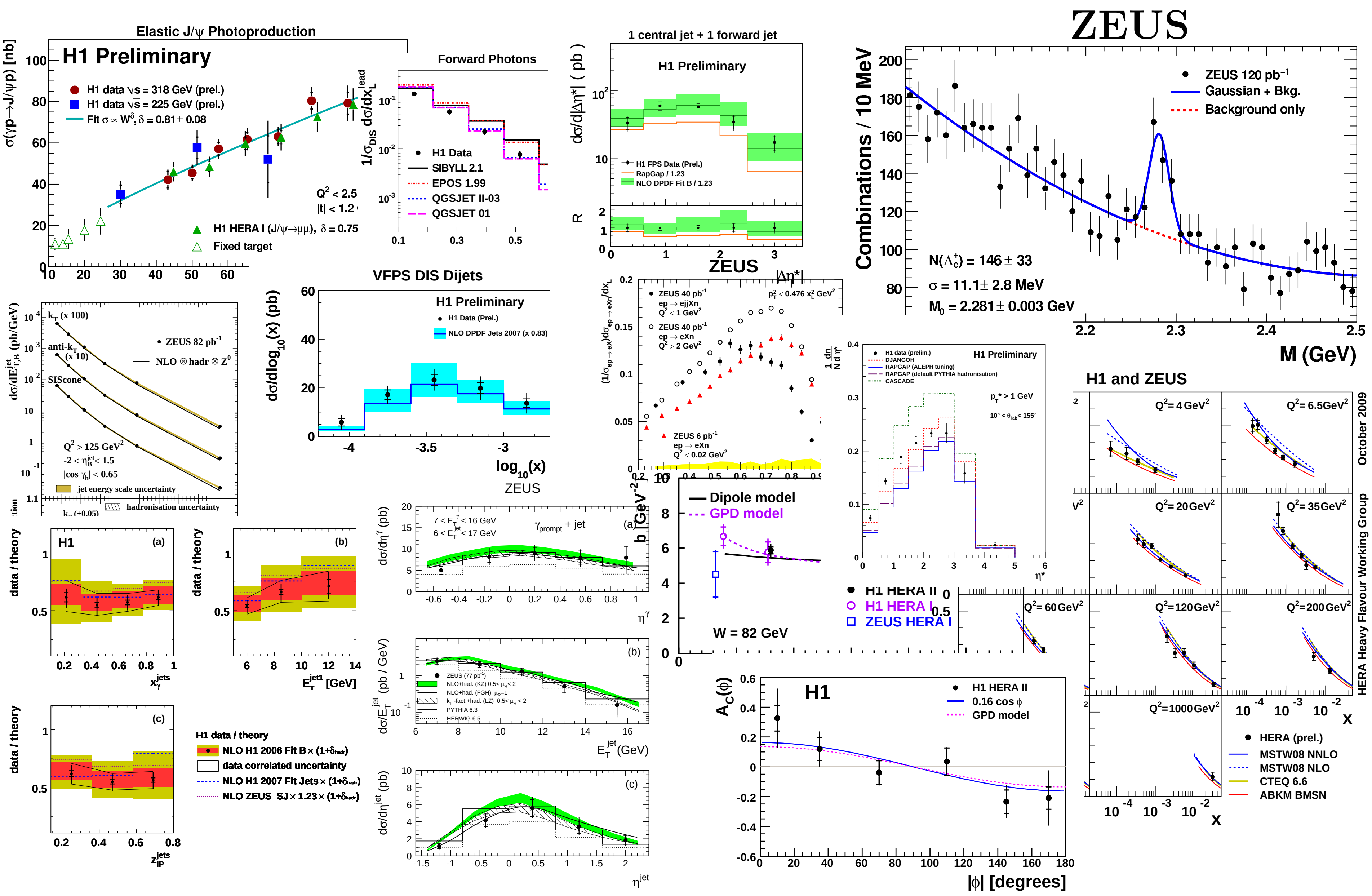
Data sample	Data	SM	Pair Production (GRAPE)	NC DIS + QEDC
e$^+$p (0.56 fb^{-1})	7	1.94 ± 0.17	1.52 ± 0.14	0.42 ± 0.07
e$^-$p (0.38 fb^{-1})	0	1.19 ± 0.12	0.90 ± 0.10	0.29 ± 0.05
All (0.94 fb^{-1})	7	3.13 ± 0.26	2.42 ± 0.21	0.71 ± 0.10

H1+ZEUS 1994–2007 e^+p 0.59 fb^{-1}		Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	37	38.6 ± 4.7	28.9 ± 4.4	9.7 ± 1.4
	$P_T^X > 25$ GeV	12	7.4 ± 1.0	6.0 ± 0.9	1.5 ± 0.3
Muon	Total	16	11.2 ± 1.6	9.9 ± 1.6	1.3 ± 0.3
	$P_T^X > 25$ GeV	11	6.6 ± 1.0	5.9 ± 0.9	0.8 ± 0.2
Combined	Total	53	49.8 ± 6.2	38.8 ± 5.9	11.1 ± 1.5
	$P_T^X > 25$ GeV	23	14.0 ± 1.9	11.8 ± 1.9	2.2 ± 0.4

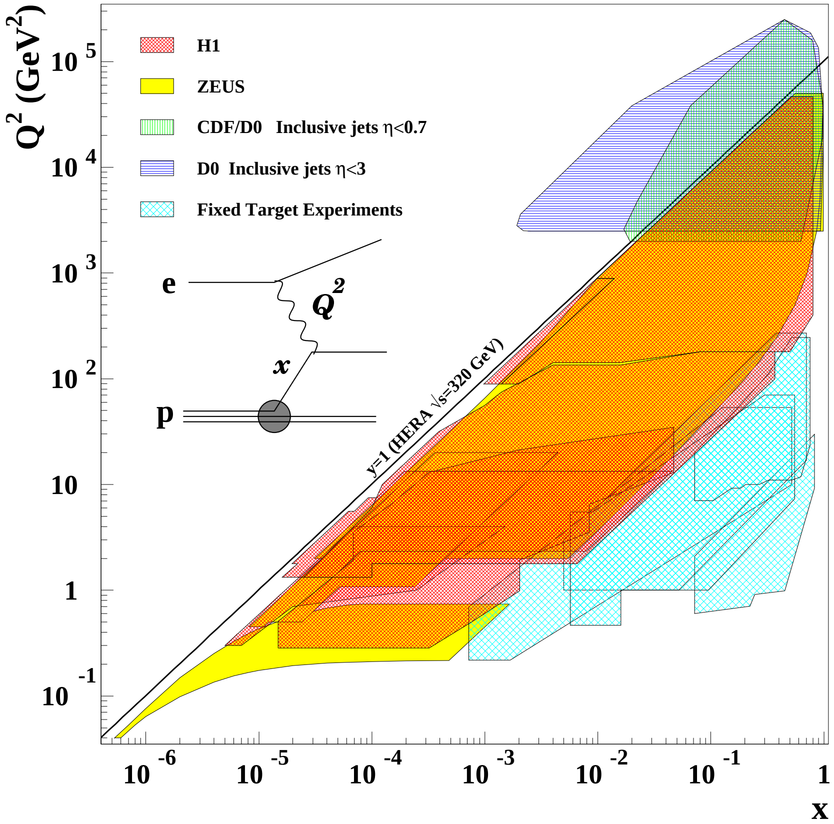
e^+p : 7 obs. vs 2 expected events

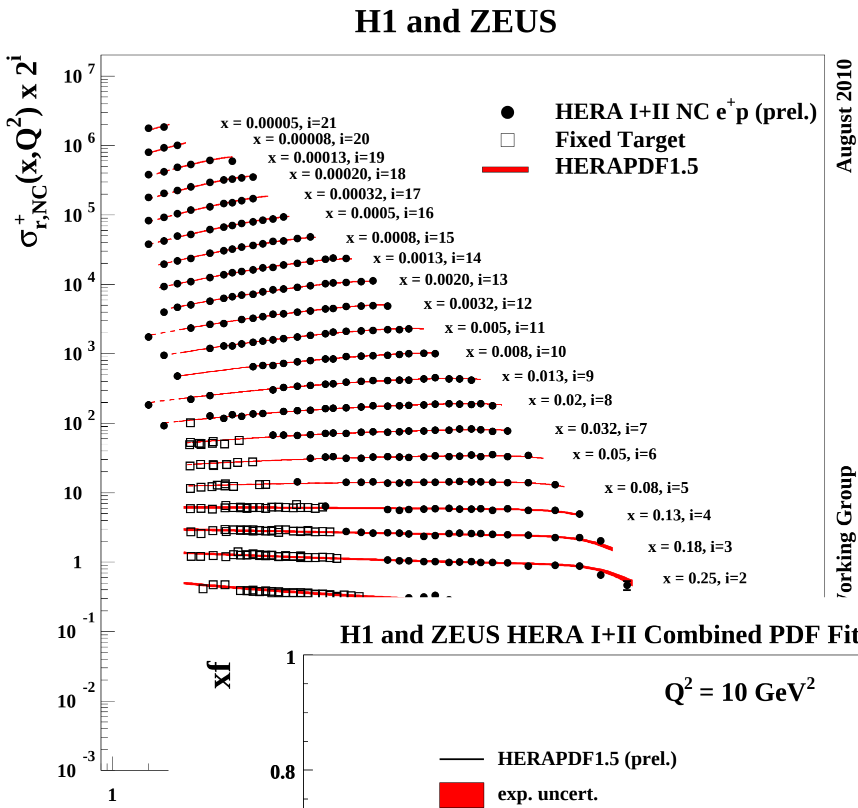
23 obs. vs 14 expected events

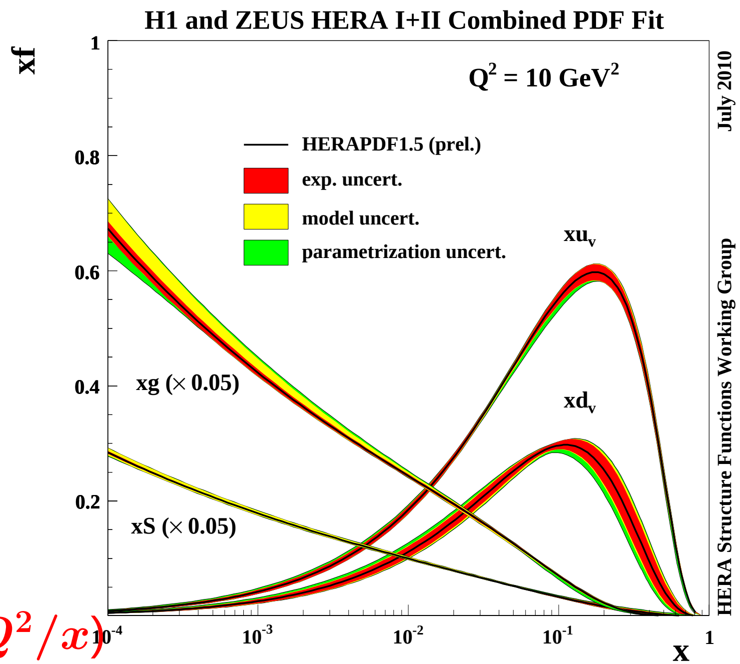
HERA as QCD factory



Small x domain of HERA





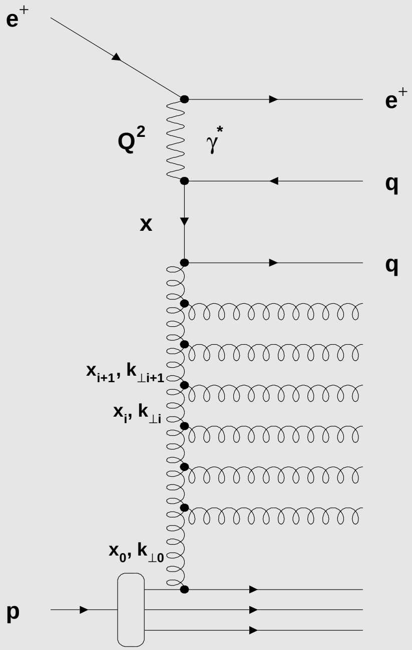


- ep DIS: clean QCD laboratory
  with high resolving power $Q^2 \Rightarrow 0.001$fm
- Low $x \leq 10^{-3}$: new kinematic domain at HERA
- NLO DGLAP is perfectly OK for F_2^p (too inclusive?)
- There is a lot of glue in proton at low x!
  $\Rightarrow$ gluodynamics in high energy limit of QCD ($W^2 \approx Q^2/x$)

QCD at low x

Lots of glue in the proton $\Rightarrow$ long gluon cascade at low x. Perturbative expansion of evolution equations $\sim \sum_{mn} A_{mn} \ln(Q^2)^m \ln(1/x)^n$ hard to calculate explicitely

$\Rightarrow$ approximations needed



DGLAP: resums $\ln(Q^2)^n$ terms, neglecting $\ln(1/x)^n$ terms
strong k_T ordering in partonic cascade

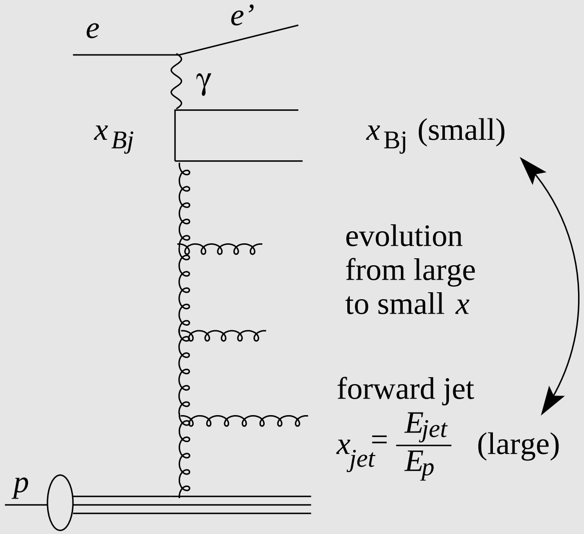
BFKL: resums $\ln(1/x)^n$ terms
no k_T ordering in partonic cascade $\Rightarrow$ more hard gluons are radiated far from the hard interaction vertex

CCFM: angular ordered parton emission $\Rightarrow$
reproduces DGLAP at large x and BFKL at $x \to 0$

- How long is partonic cascade at HERA, at small x?
- Do the $\ln(1/x)^n$ terms play a major role in parton dynamics as suggested by BFKL?

$\Rightarrow$ Look at (multi)jet final states at low x in different configurations

Forward jets



Strategy $(E_t^{jet})^2 \approx Q^2 \Rightarrow$ suppress phase space for DGLAP evolution

large $x_{jet} >> x_{Bj} \Rightarrow$ enhance BFKL evolution

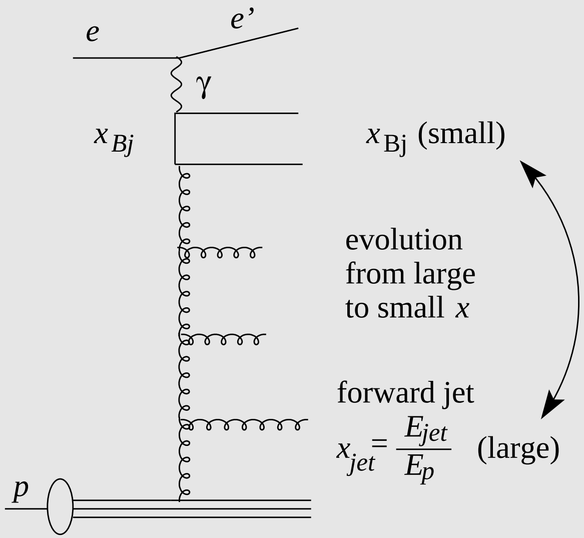
Event selection

$10^{-4} < x < 4 \cdot 10^{-3}$ $5 < Q^2 < 85\text{GeV}^2$

$E_t^{jet} > 3.5\text{GeV}$ $7^o < \theta_{jet} < 20^o$

$x_{jet} > 0.035$ $0.5 < (E_t^{jet})^2/Q^2 < 2$

Forward jets



Strategy $(E_t^{jet})^2 \approx Q^2 \Rightarrow$ suppress phase space for DGLAP evolution

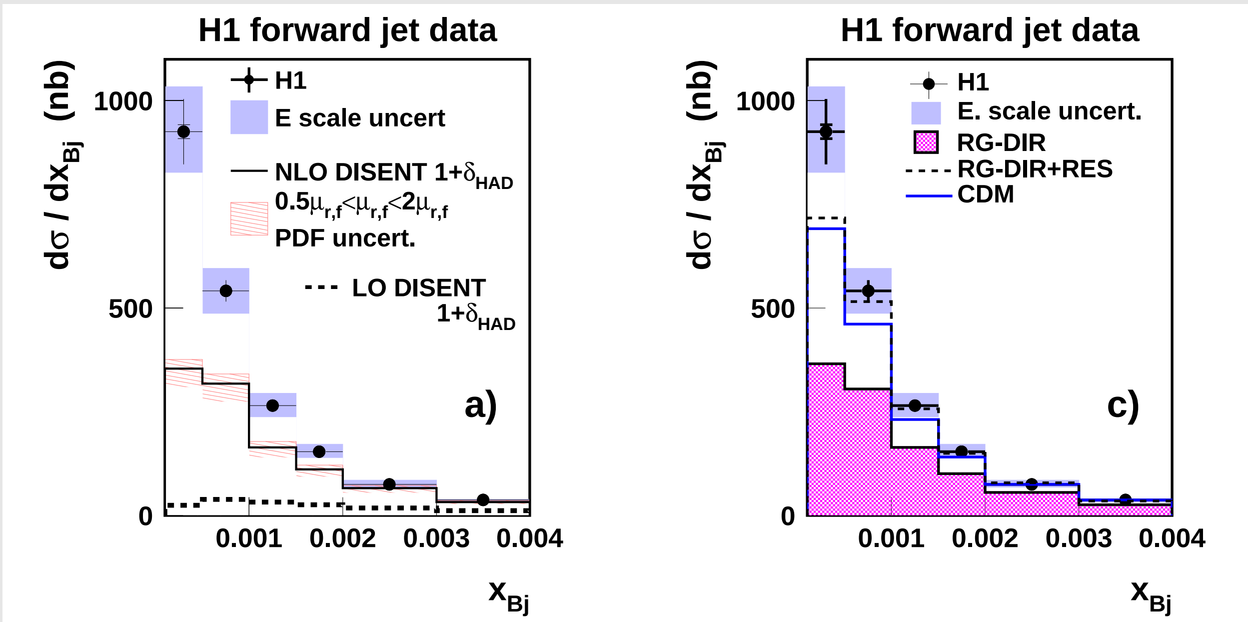
large $x_{jet} >> x_{Bj} \Rightarrow$ enhance BFKL evolution

Event selection

$10^{-4} < x < 4 \cdot 10^{-3}$ $\quad 5 < Q^2 < 85\text{GeV}^2$

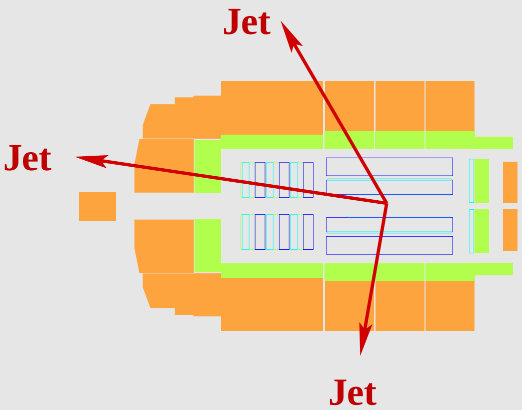
$E_t^{jet} > 3.5\text{GeV}$ $\quad 7^o < \theta_{jet} < 20^o$

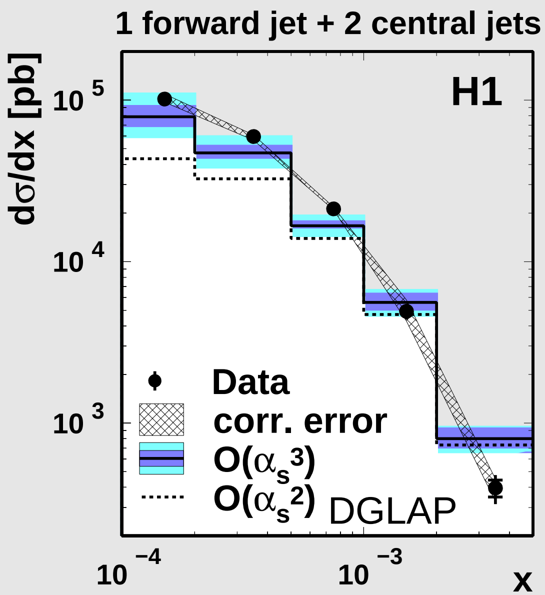
$x_{jet} > 0.035$ $\quad 0.5 < (E_t^{jet})^2/Q^2 < 2$



- Huge improvement from LO to NLO, but still insufficient at low x
- Resolved γ component in DGLAP MC helps ("breaks" k_t ordering)
- CDM and RG(d+r) provide similar description $\Rightarrow$ inconclusive

3-jet samples with different topologies





Central jets:

$-1 < \eta_{jet} < 1$

Forward jets:

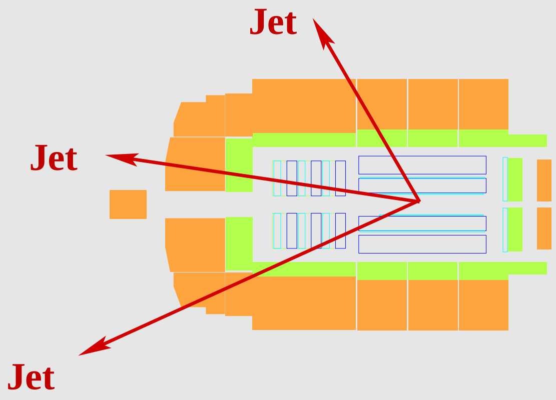
$\eta_{fj1} > 1.73$

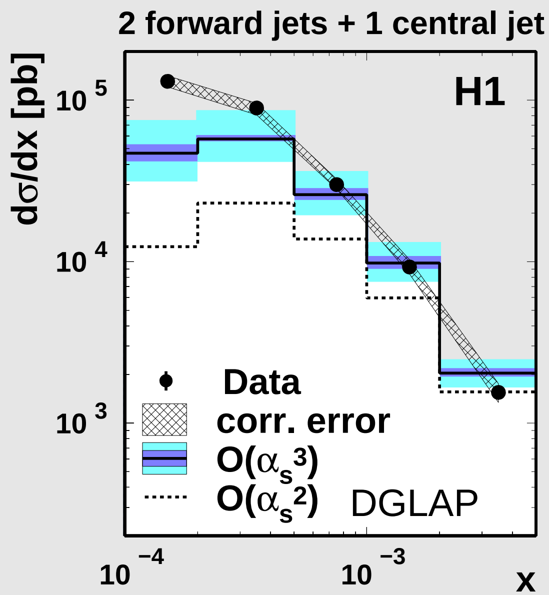
$x_{fj1} > 0.035$

$\eta_{fj2} > 1$

All jets:

$E^*_{t,jet} > 4$ GeV



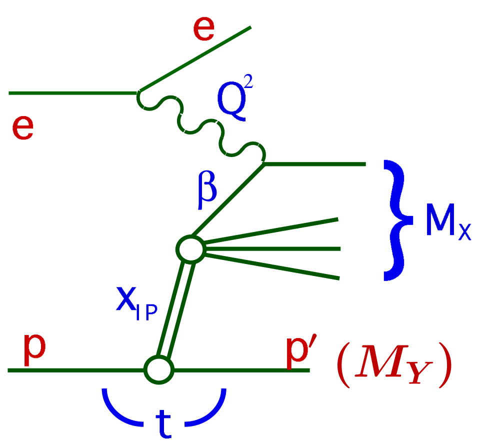


- **Large deficit at small x for 2-forward jet topology! There $\mathcal{O}(\alpha_s^3)$ calculation is insufficient**

$\Rightarrow$ room for non-DGLAP dynamics!

Diffraction at HERA

- Fundamental aim: understand high energy limit of QCD (gluodynamics; CGC ?)
- Novelty: for the first time probe partonic structure of diffractive exchange
- Practical motivations: study factorisation properties of diffraction; try to transport to hh scattering (e.g. predict diffractive Higgs production at LHC)



$$x_{I\!P} = \xi = \frac{Q^2+M_X^2}{Q^2+W^2}$$

(momentum fraction of colour singlet exchange)

$$\beta = \frac{Q^2}{Q^2+M_X^2} = x_{q/I\!P} = \frac{x}{x_{I\!P}}$$

(fraction of exchange momentum, coupling to γ^*)

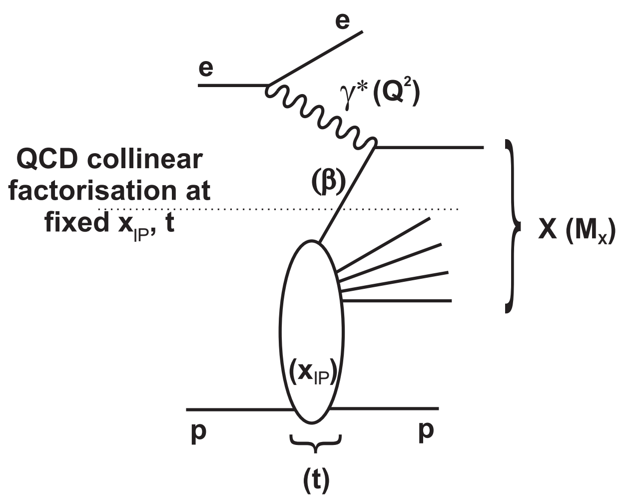
$$t = (p-p')^2$$

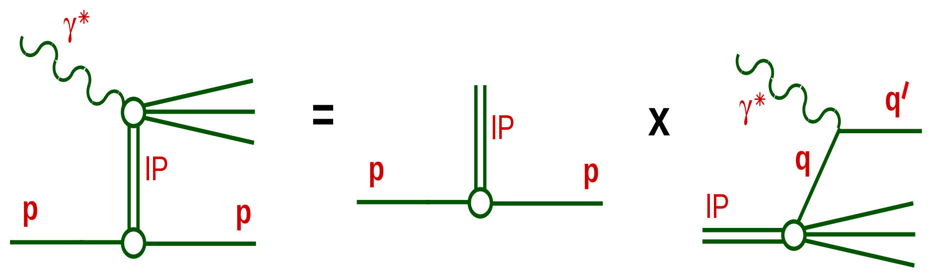
(4-momentum transfer squared)

$$\frac{d^4\sigma}{dx_{I\!P}\,dt\,d\beta\,dQ^2} = \frac{4\pi\alpha^2}{\beta Q^4}\left(1-y+\frac{y^2}{2}\right)\sigma_r^{D(4)}(x_{I\!P},t,\beta,Q^2)$$

$$\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{2(1-y+y^2/2)}F_L^{D(4)} \quad \Rightarrow \quad F_2^{D(3)} = \int dt F_2^{D(4)}$$

Factorisation properties in diffraction





QCD versus Regge factorisation

QCD factorisation

(rigorously proven for DDIS by Collins et al.):

$$\sigma_r^{D(4)} \propto \sum_i \hat{\sigma}^{\gamma^* i}(x, Q^2) \otimes f_i^D(x, Q^2; x_{I\!P}, t)$$

- $\hat{\sigma}^{\gamma^* i}$ – hard scattering part, same as in inclusive DIS
- f_i^D – diffractive PDF's, valid at fixed $x_{I\!P}, t$ which obey (NLO) DGLAP

Regge factorisation

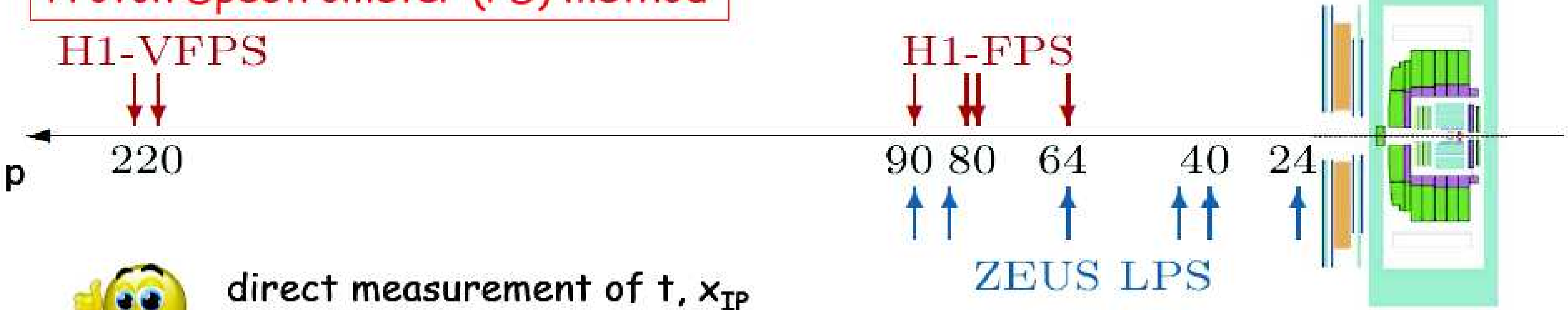
(conjecture, e.g. RPM by Ingelman,Schlein):

$$F_2^{D(4)}(x_{I\!P}, t, \beta, Q^2) = \Phi(x_{I\!P}, t) \cdot F_2^{I\!P}(\beta, Q^2)$$

- In this case shape of diffractive PDF's is independent of $x_{I\!P}, t$ while normalization is controlled by Regge flux $\Phi(x_{I\!P}, t)$

Selecting Diffraction at HERA

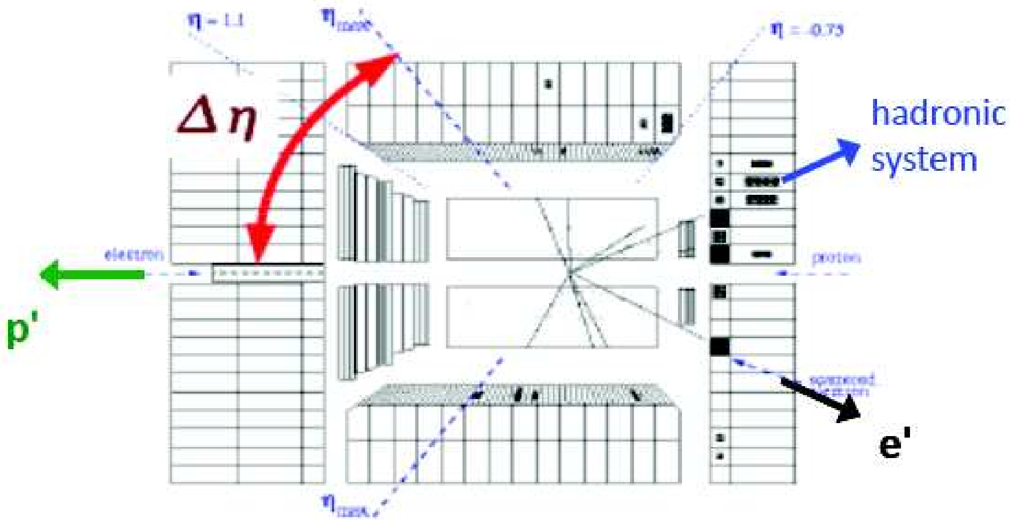
Proton Spectrometer (PS) method



direct measurement of t, x_{IP}
high x_{IP} accessible
no p-diss contribution

low statistics

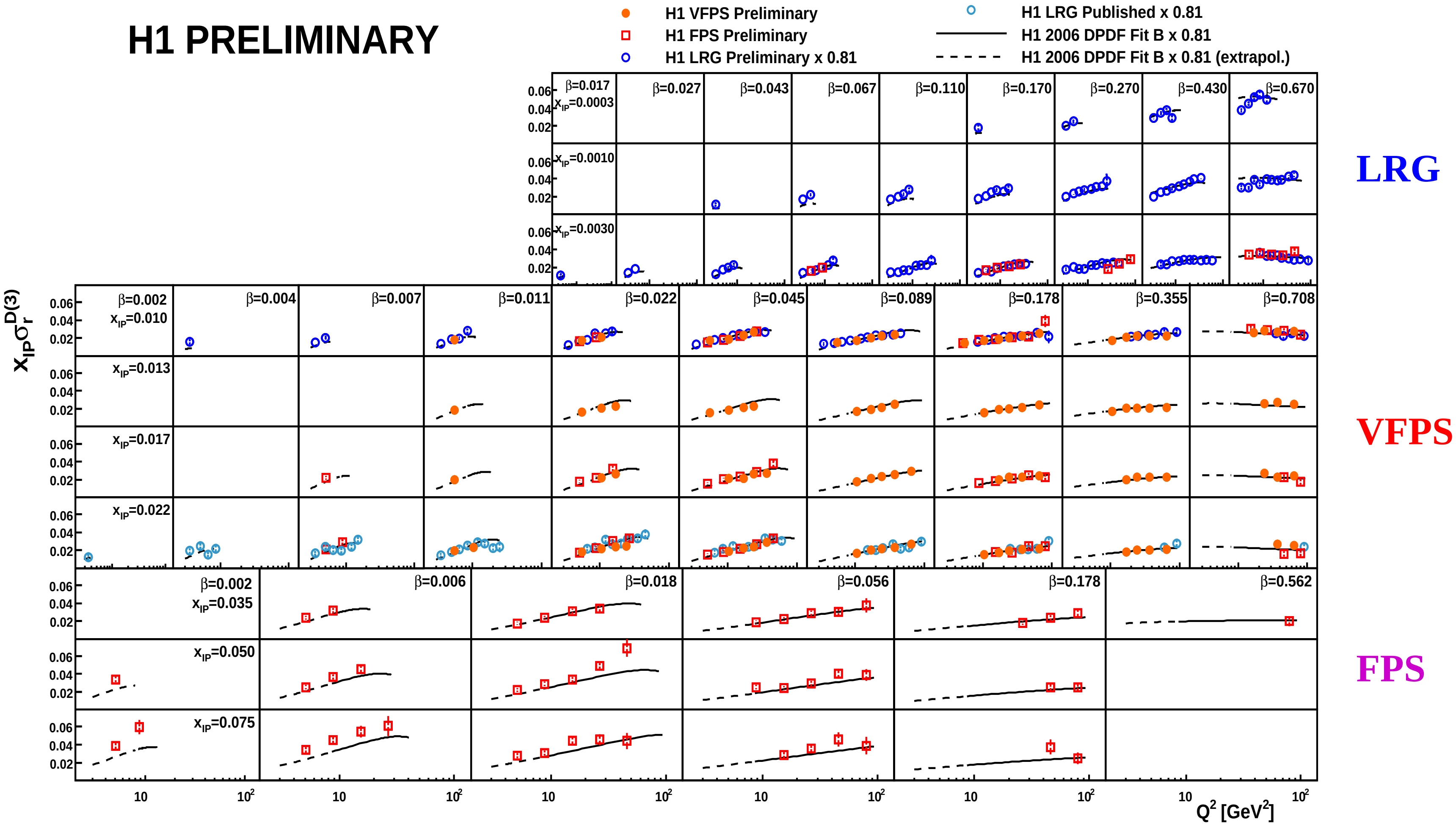
Large Rapidity Gap (LRG) method



near perfect acceptance at low x_{IP}

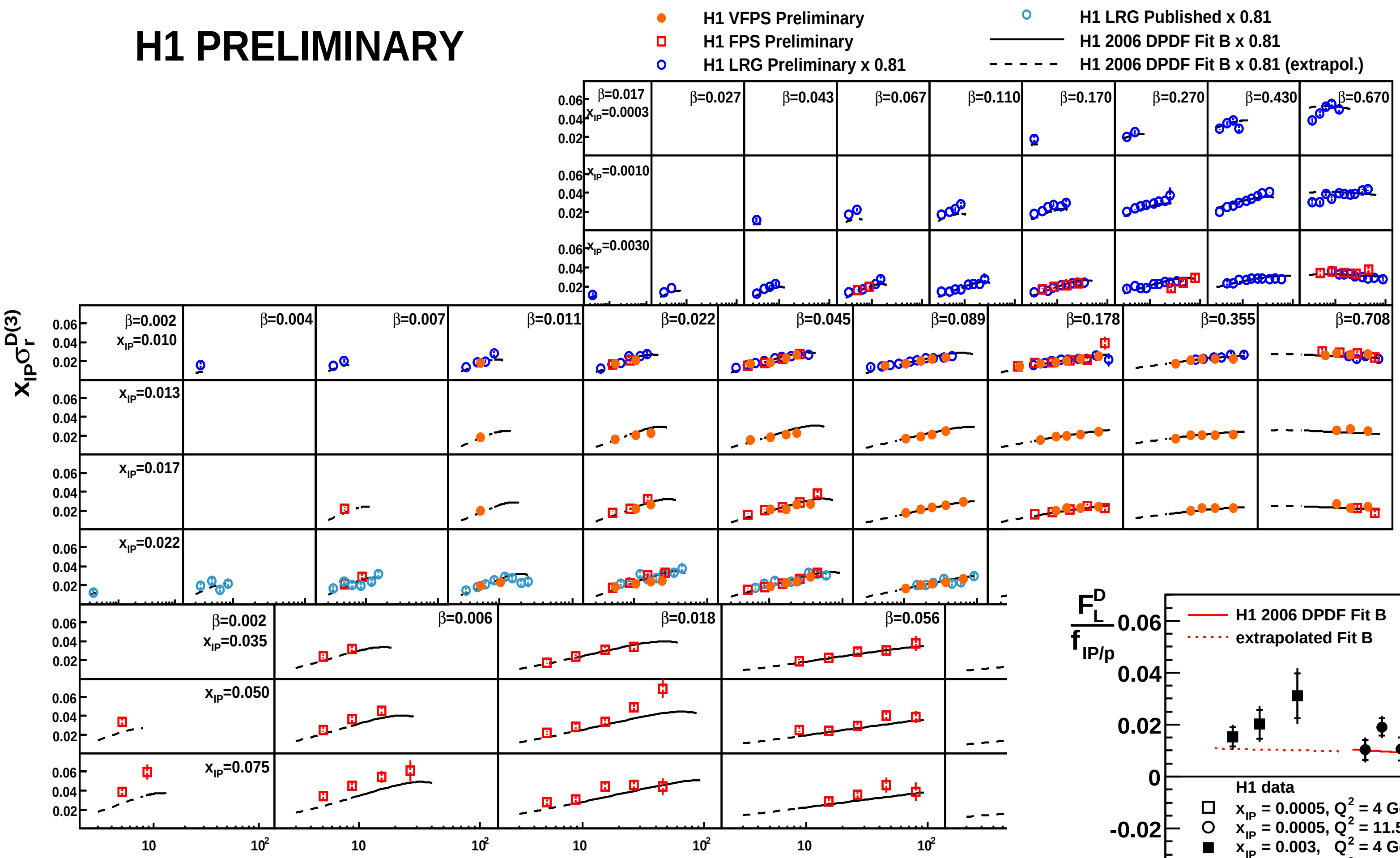
p-diss contribution
no t measurement

Inclusive Diffraction Summary

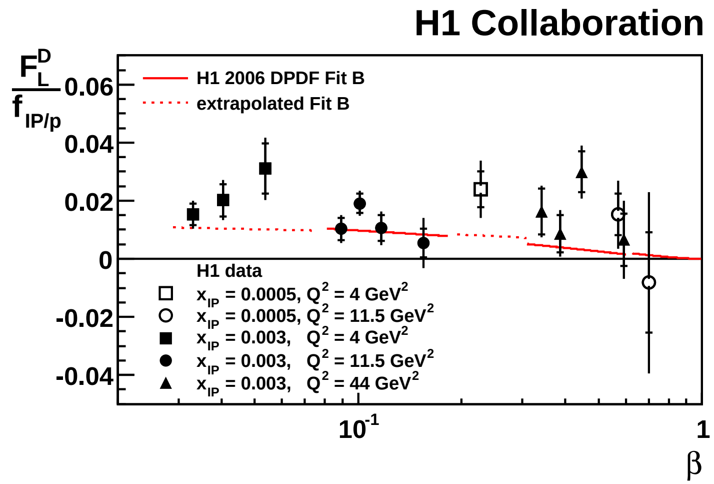


- Compelling confirmation of the NLO QCD picture of diffraction over a wide kinematic range!

Inclusive Diffraction Summary



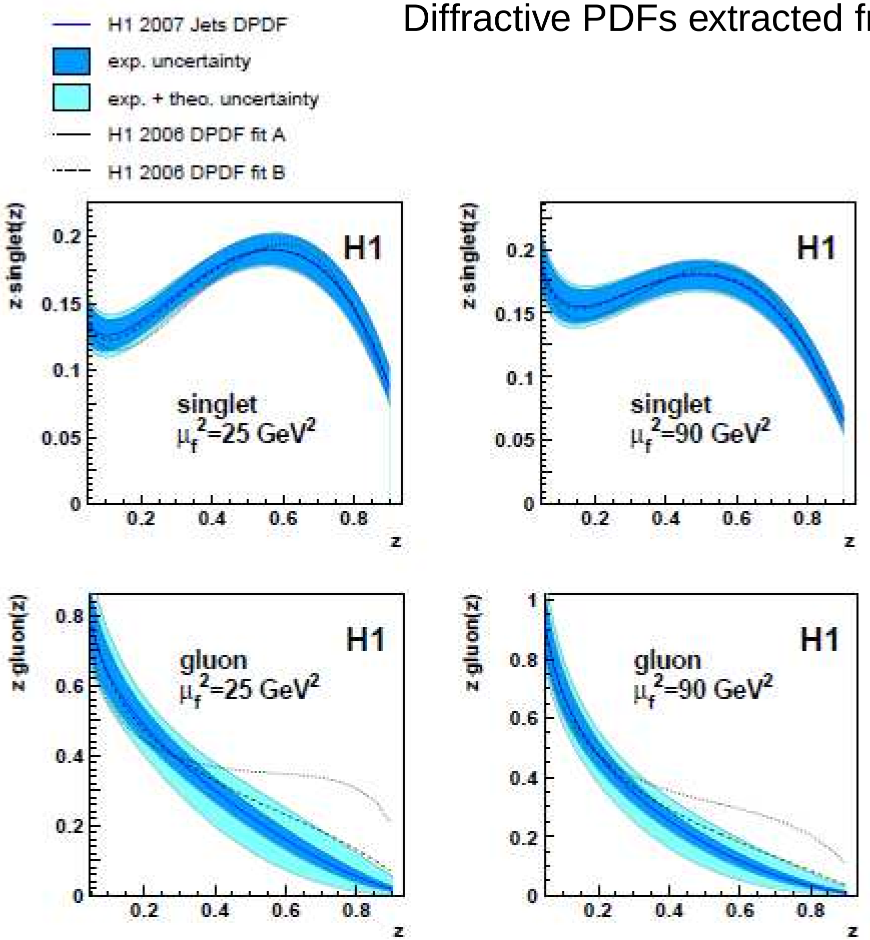
- Compelling confirmation of the NLO QCD picture of diffraction over a wide kinematic range!

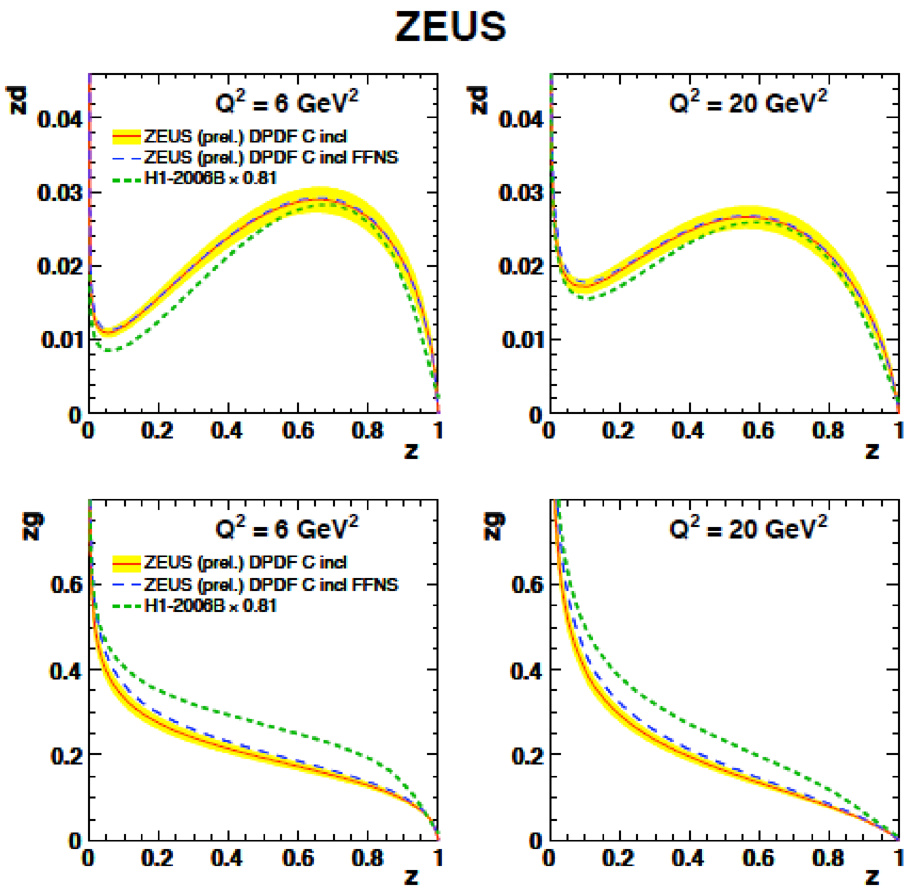


First ever measurement of F_L in diffraction

Diffractive PDFs as determined by H1 and ZEUS

Diffractive PDFs extracted from NLO DGLAP fit, using Regge factorisation



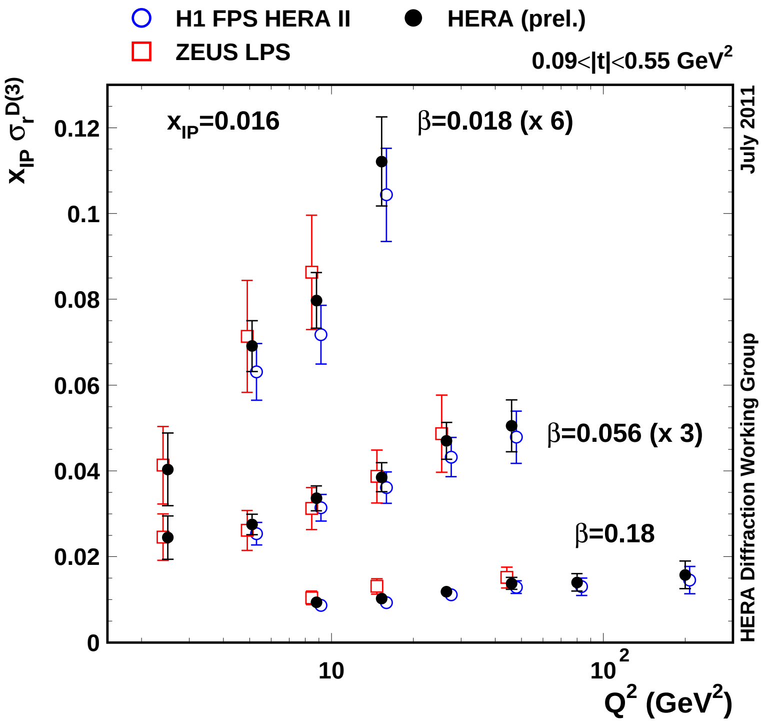


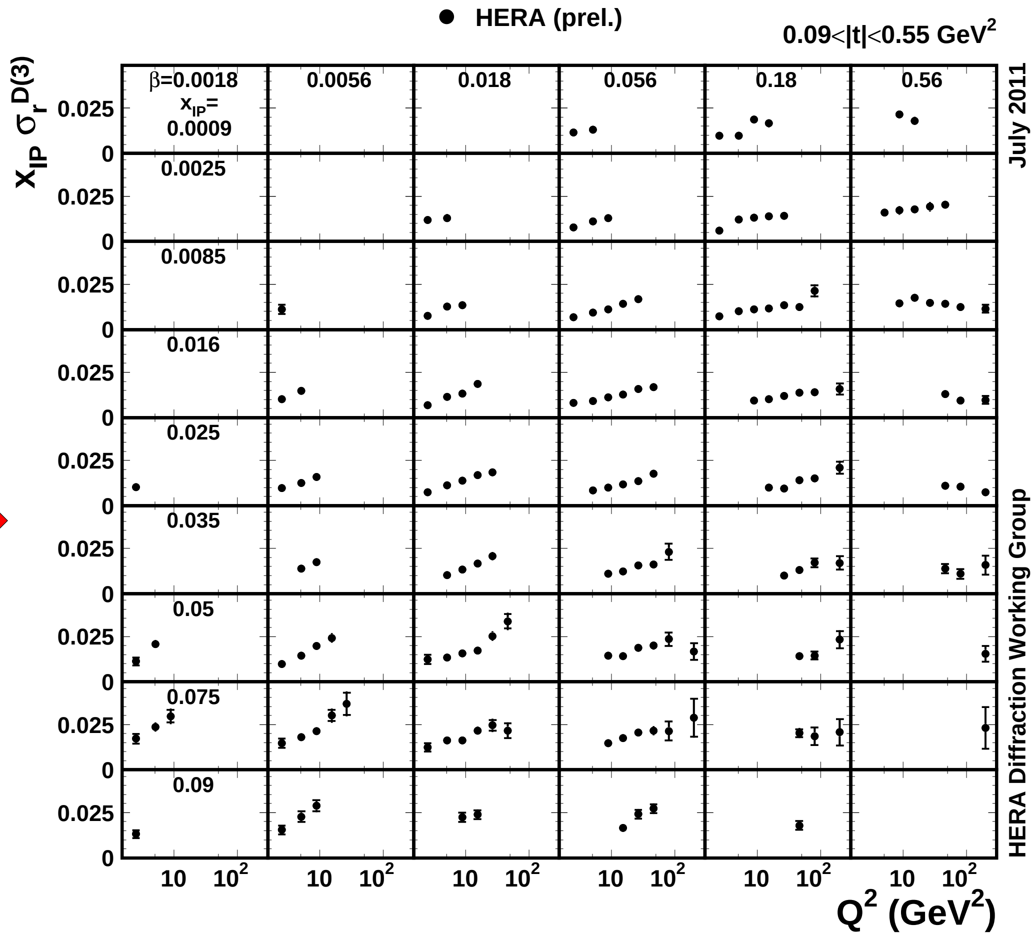
- Combine H1 and ZEUS measurements to improve precision
- Determine DPDF (eventually without Regge factorisation assumption)

H1 FPS and ZEUS LPS Combination

- Select common phase space $(x_{I\!P}, t; Q^2, \beta)$

- 121 H1 and 106 ZEUS measurements give 169 H1+ZEUS combined points

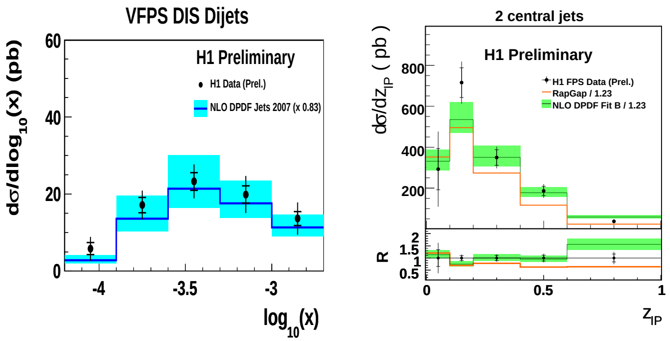




- Significant improvement in precision. Work in progress for other samples

QCD Factorisation Tests in Diffraction at HERA

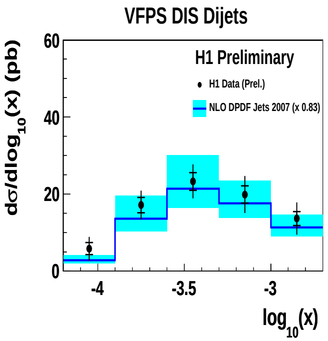
QCD Factorisation holds in DIS regime, e.g.:

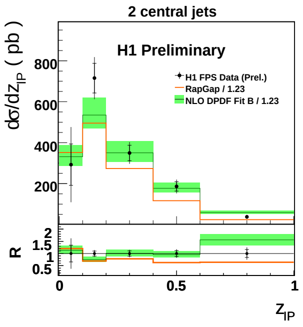


However, it breaks down at Tevatron ($S \sim 0.1$)
(due to soft remnant rescattering)

QCD Factorisation Tests in Diffraction at HERA

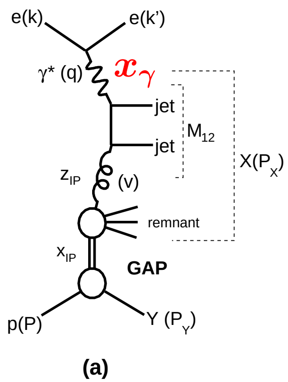
QCD Factorisation holds in DIS regime, e.g.:

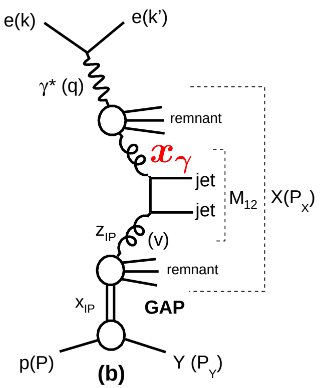




However, it breaks down at Tevatron ($S \sim 0.1$)
(due to soft remnant rescattering)

$\Rightarrow$ Test it in photoproduction:



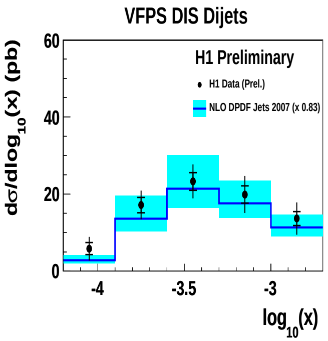


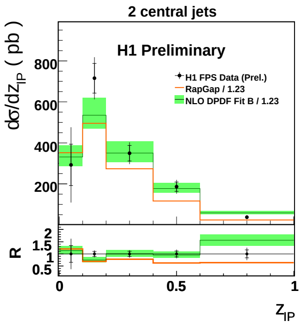
direct, $x_\gamma = 1$
(DIS-like)

resolved, $x_\gamma < 1$
(hadron-like)

QCD Factorisation Tests in Diffraction at HERA

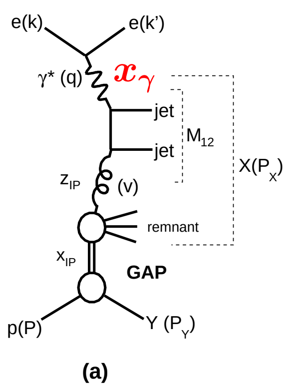
QCD Factorisation holds in DIS regime, e.g.:

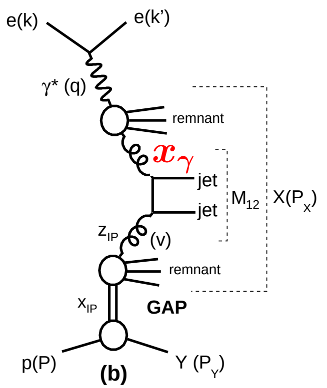




However, it breaks down at Tevatron ($S \sim 0.1$)
(due to soft remnant rescattering)

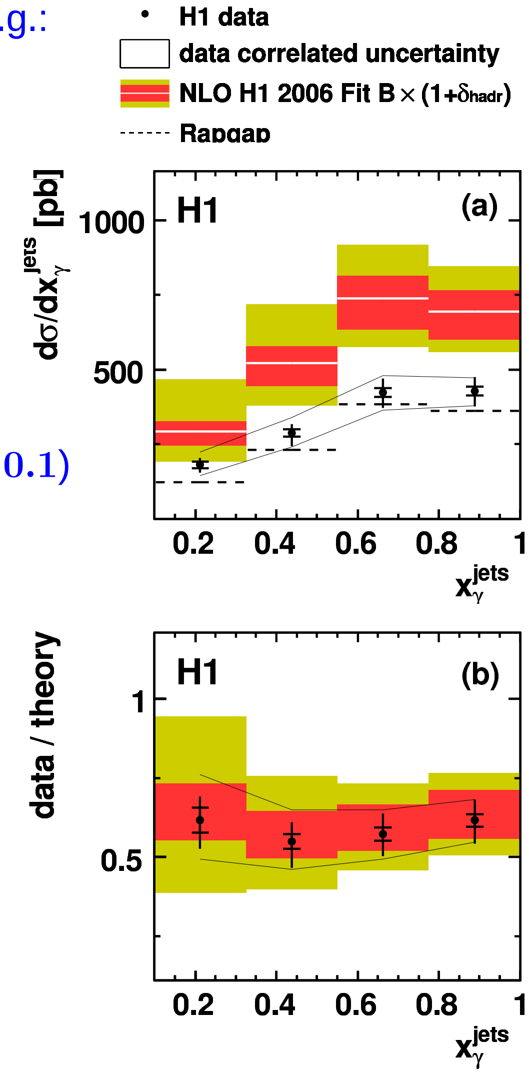
⇒ Test it in photoproduction:



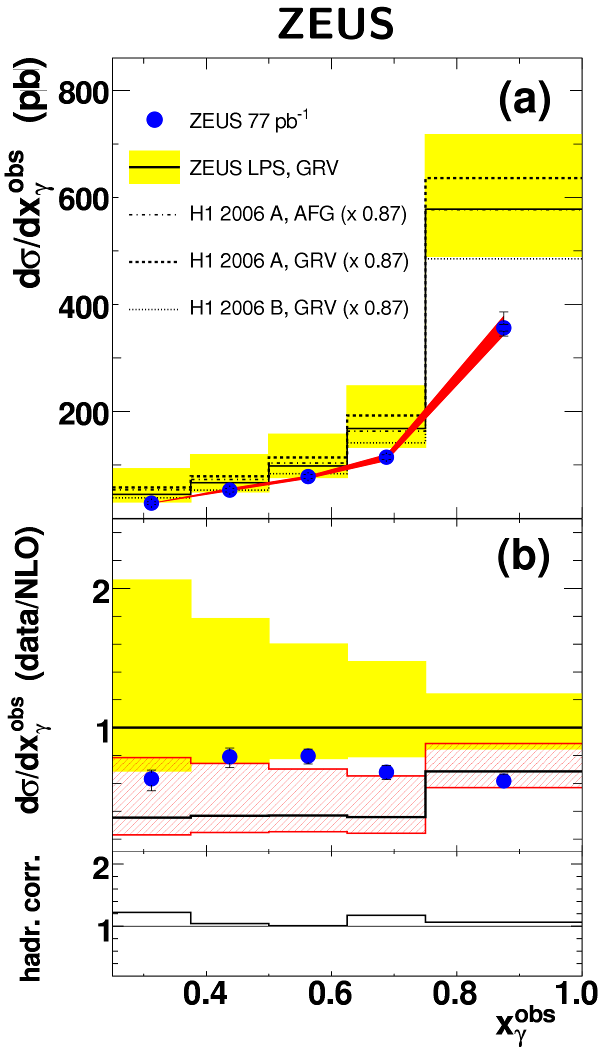


direct, $x_\gamma = 1$
(DIS-like)

resolved, $x_\gamma < 1$
(hadron-like)



$S = 0.58 \pm 0.21$



$S \simeq 0.7 - 0.9$ (DPDF dep.)

- Both H1 and ZEUS observe global, x_γ-independent suppresion factor – somewhat unexpected
  ⇒ Details of factorisation breaking mechanism in γp at HERA are not fully understood yet

Summary

- Standard Model survived 1 fb^{-1} of **HERA** data and is still in a good shape. Next challenge will come from the **LHC** - stay tuned!

- Combining H1 and ZEUS data allowed proton structure to be measured with unprecedental precision

- NLO DGLAP is surprisingly successful down to low Q^2 and low x in describing bulk of HERA data. However, some room for parton evolution beyond DGLAP is found at specific phase space corners $\Rightarrow$ important message for LHC.

- Gained new insights into high energy diffraction:
  Pomeron under the HERA microscope shows complicated interplay of soft and hard phenomena. Start combining H1 and ZEUS diffractive data

Summary

- Standard Model survived 1 fb^{-1} of **HERA** data and is still in a good shape. Next challenge will come from the **LHC** - stay tuned!

- Combining H1 and ZEUS data allowed proton structure to be measured with unprecedental precision

- NLO DGLAP is surprisingly successful down to low Q^2 and low x in describing bulk of HERA data. However, some room for parton evolution beyond DGLAP is found at specific phase space corners $\Rightarrow$ important message for LHC.

- Gained new insights into high energy diffraction:
  Pomeron under the HERA microscope shows complicated interplay of soft and hard phenomena. Start combining H1 and ZEUS diffractive data

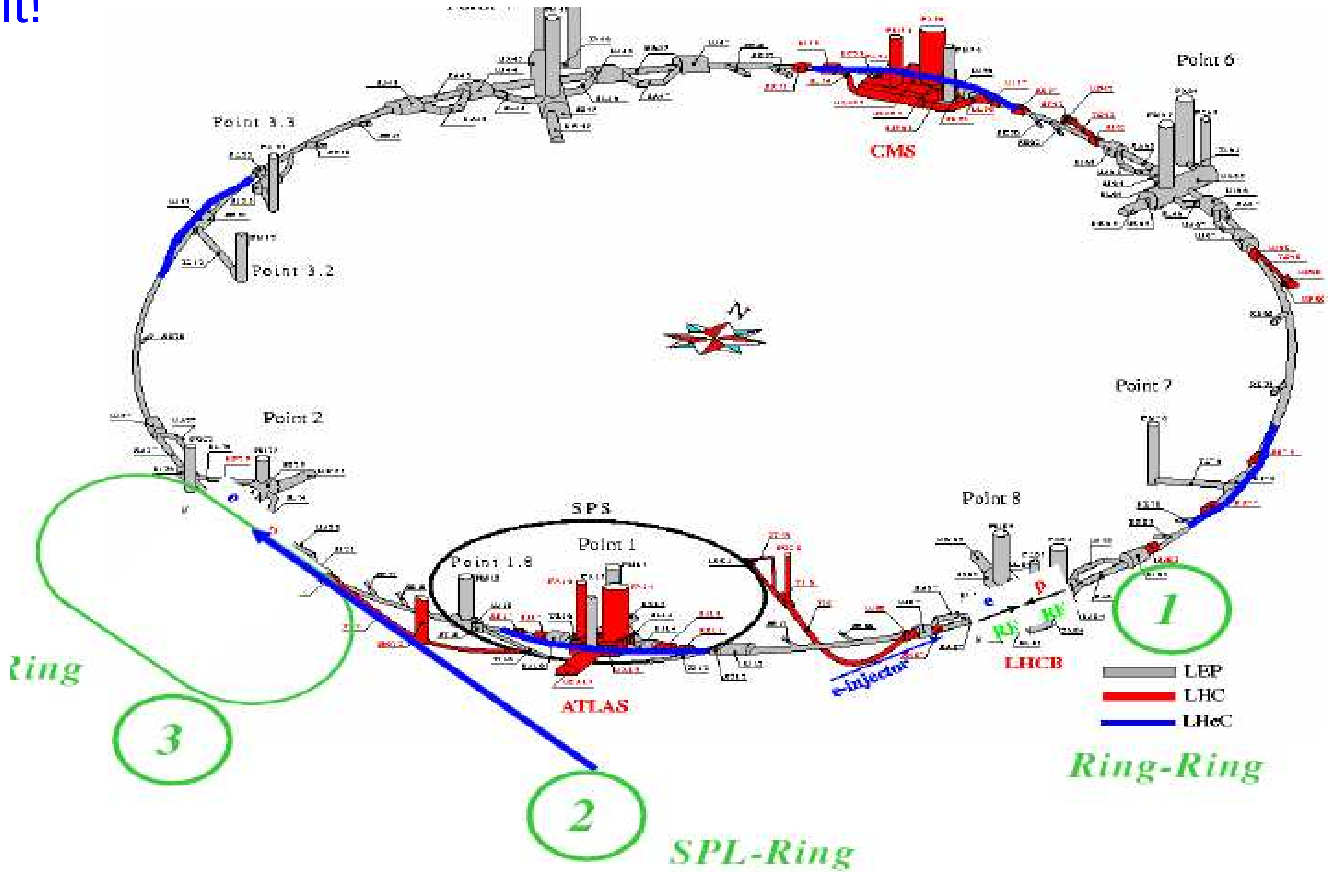
- Is this the end of DIS experiments at the colliders? Or what's next?

Project under discussion

For late LHC period:

Support it!

$\sim 2022 - 2032$



$$e^{\pm}p$$

$(60 - 140)$GeV $\times$ 7000 GeV

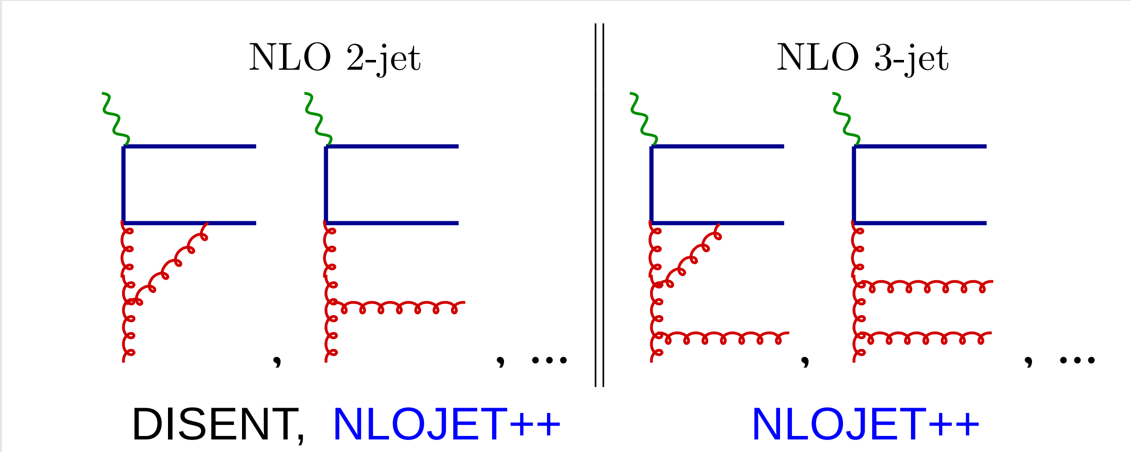
talk by Peter Kostka on Sept.9

BACKUP SLIDES...

Low x phenomenology

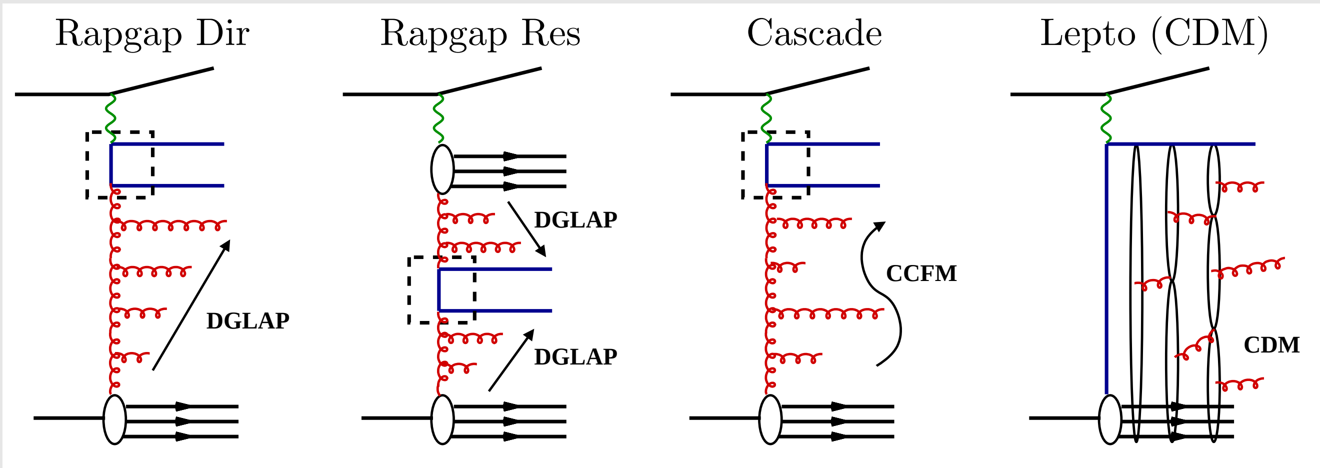
Fixed order

QCD calculations



LO ME + PS

MC models



k_t-ordered gluon radiation (DGLAP)

angular ordering (DGLAP $\Longleftrightarrow$ BFKL)

random walk in k_t (BFKL like)

‘Soft’ or ‘Hard’ Pomeron ?

Soft diffraction: no hard scale present

$$hh, \gamma p$$

Hard diffraction: some hard scale present

$$(Q^2, M_Q, t, jets)$$

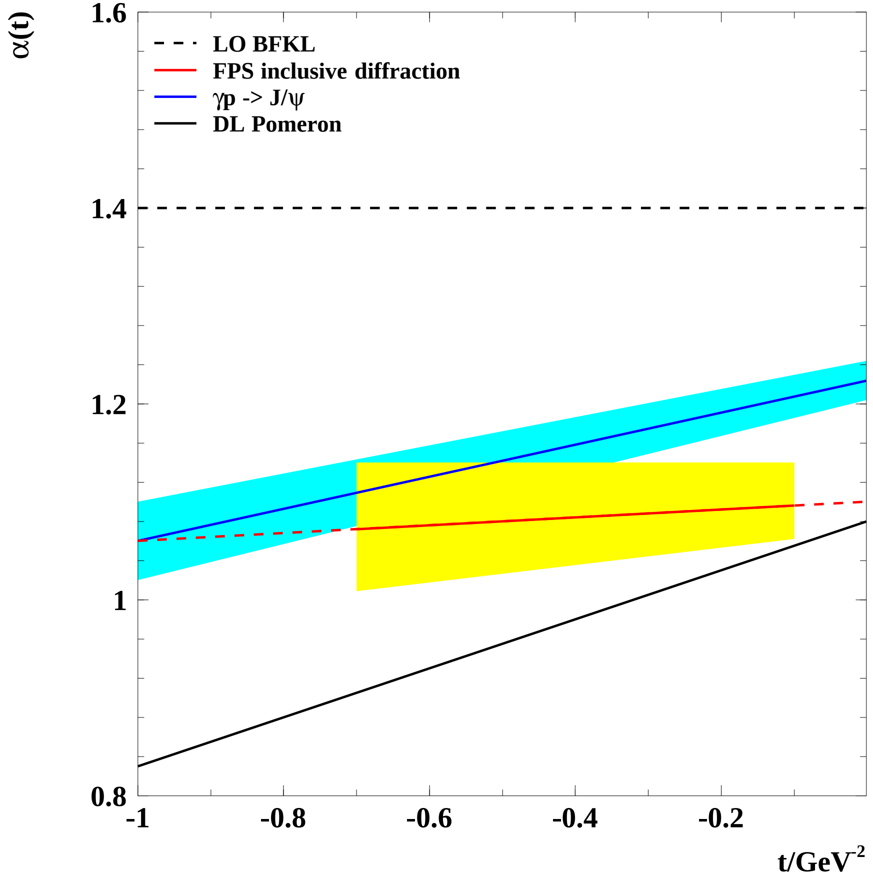
Soft $I\!P$: $\alpha_{I\!P} = 1.08,\ \alpha'_{I\!P} = 0.25$

Universal in all $hh\ \sigma_{tot}, \sigma_{el}$

Hard $I\!P$: $\alpha_{I\!P} \geq 1.20,\ \alpha'_{I\!P} = 0.0$

hard scale on both ends of $I\!P$

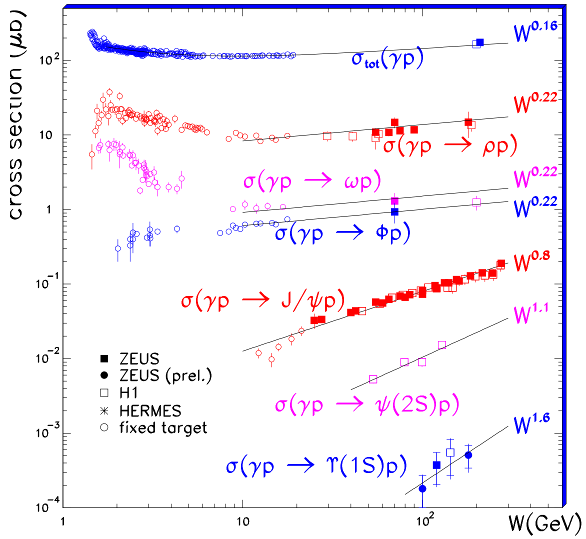
(jet$-I\!P-$jet, $\gamma^*\gamma^*$)



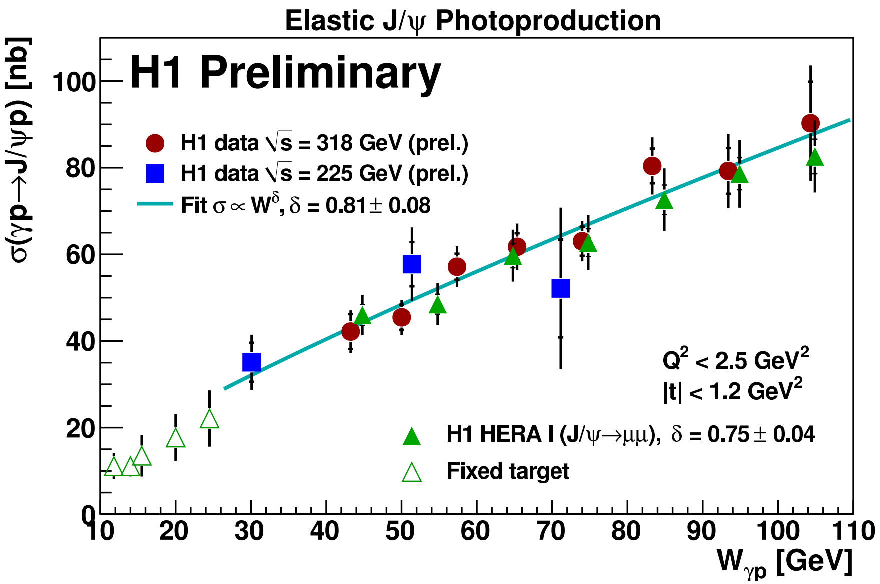
We cannot really tell...

Complicated interplay of soft and hard phenomena

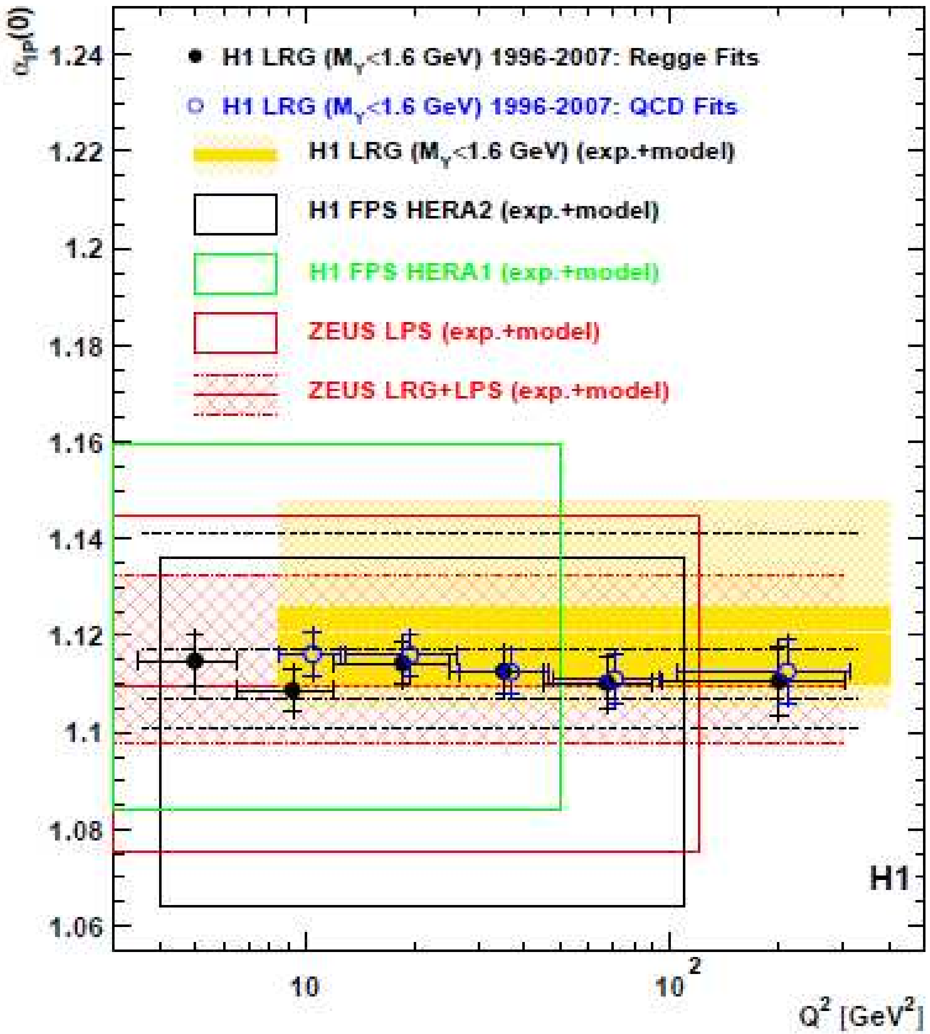
$\alpha_{I\!P}(t)$ in different reactions at HERA



$$\gamma p \Rightarrow V p$$

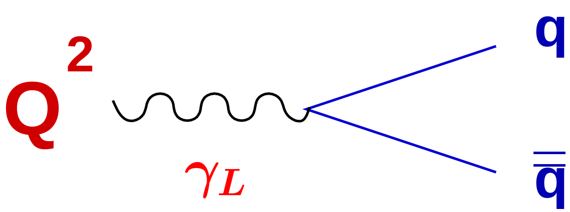


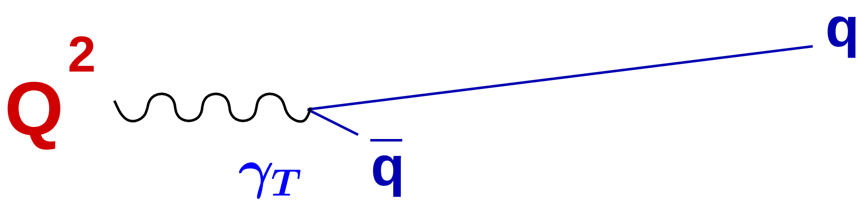
Elastic J/ψ Photoproduction



$\alpha_{I\!P}(0)$ from Inclusive Diffraction

Interplay of soft and hard contributions





$$\gamma_L\ (z \simeq 0.5):\ \langle r_t^2\rangle \simeq (z(1-z)Q^2 + m_q^2)^{-1} \simeq 1/[(Q/2)^2 + m_q^2]$$

$$\gamma_T\ (z \simeq 0;1):\ \langle r_t^2\rangle \simeq (z(1-z)Q^2 + m_q^2)^{-1} \simeq 1/m_q^2$$

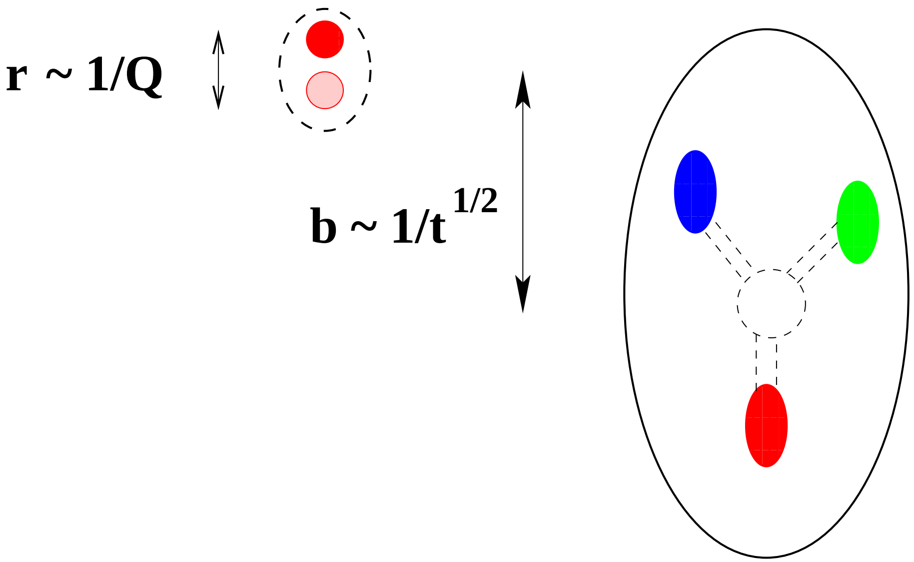
Small dipole

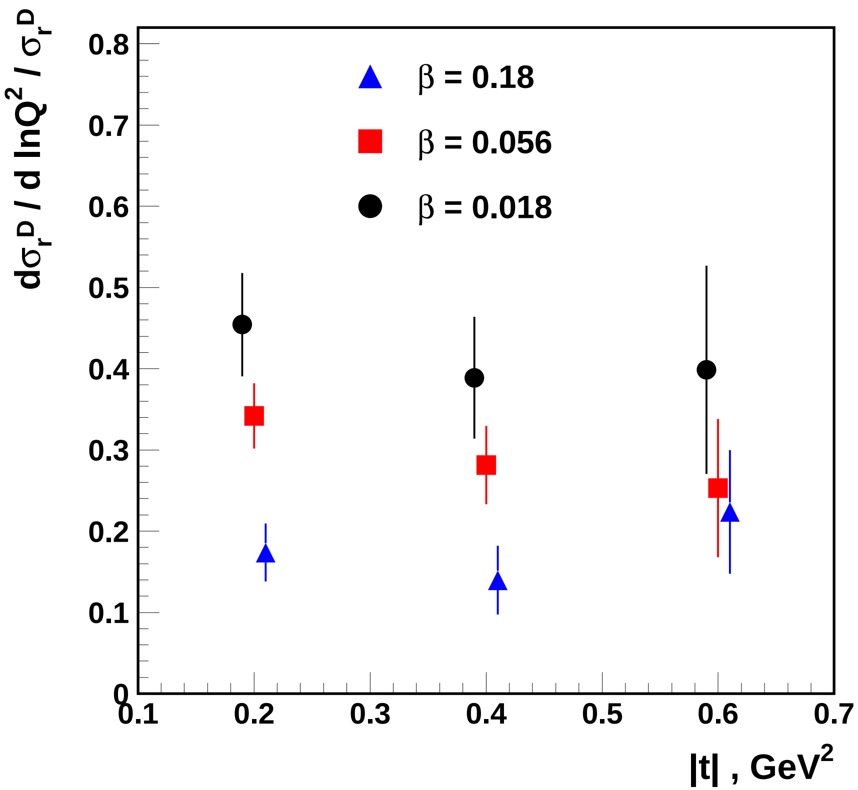
Large dipole

TABLE I: Interplay between the probabilities of hard and soft fluctuations in a highly virtual photon and the cross section of interaction of these fluctuations.

	$\lvert C_\alpha\rvert^2$	σ_α	$\sigma_{tot} = \sum_{\alpha=soft}^{hard} \lvert C_\alpha\rvert^2 \sigma_\alpha$	$\sigma_{sd} = \sum_{\alpha=soft}^{hard} \lvert C_\alpha\rvert^2 \sigma_\alpha^2$
Hard	~ 1	$\sim \frac{1}{Q^2}$	$\sim \frac{1}{Q^2}$	$\sim \frac{1}{Q^4}$
Soft	$\sim \frac{m_q^2}{Q^2}$	$\sim \frac{1}{m_q^2}$	$\sim \frac{1}{Q^2}$	$\sim \frac{1}{m_q^2 Q^2}$

Can we see t-dependent gluons in the proton?





⇒ Need larger t-range for definite conclusion