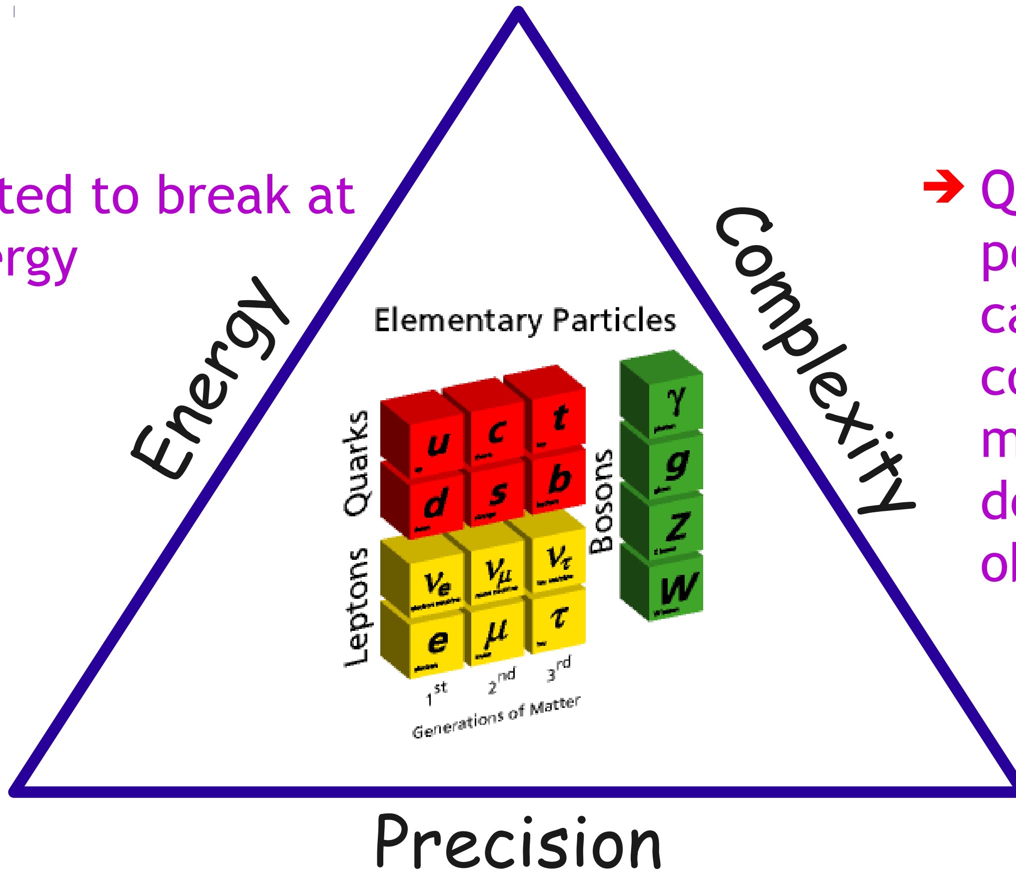
Petit Périple aux confins du modèle standard avec HERA

Emmanuel Sauvan

The experimental frontiers of the Standard model



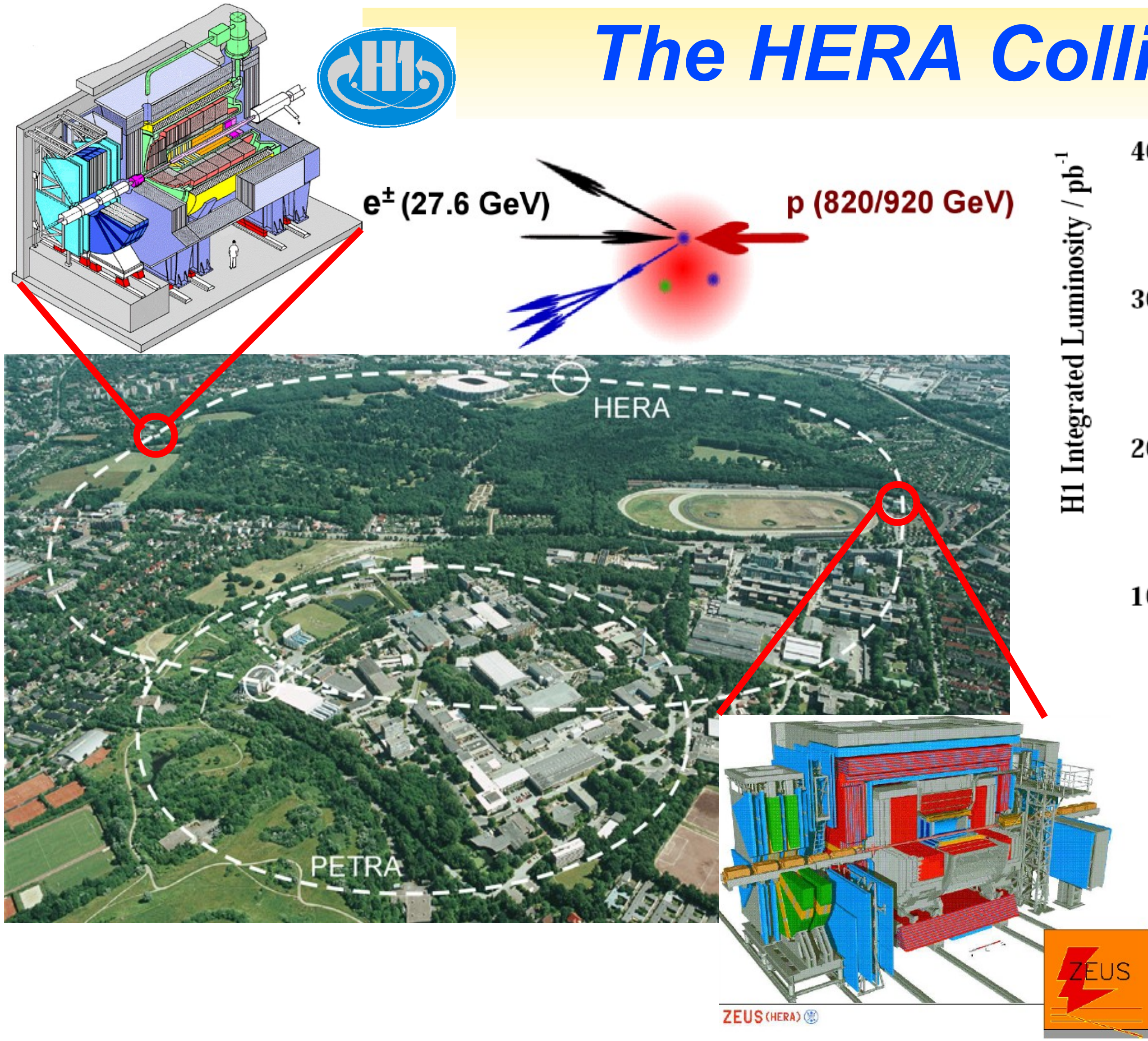
➔ Is expected to break at high energy

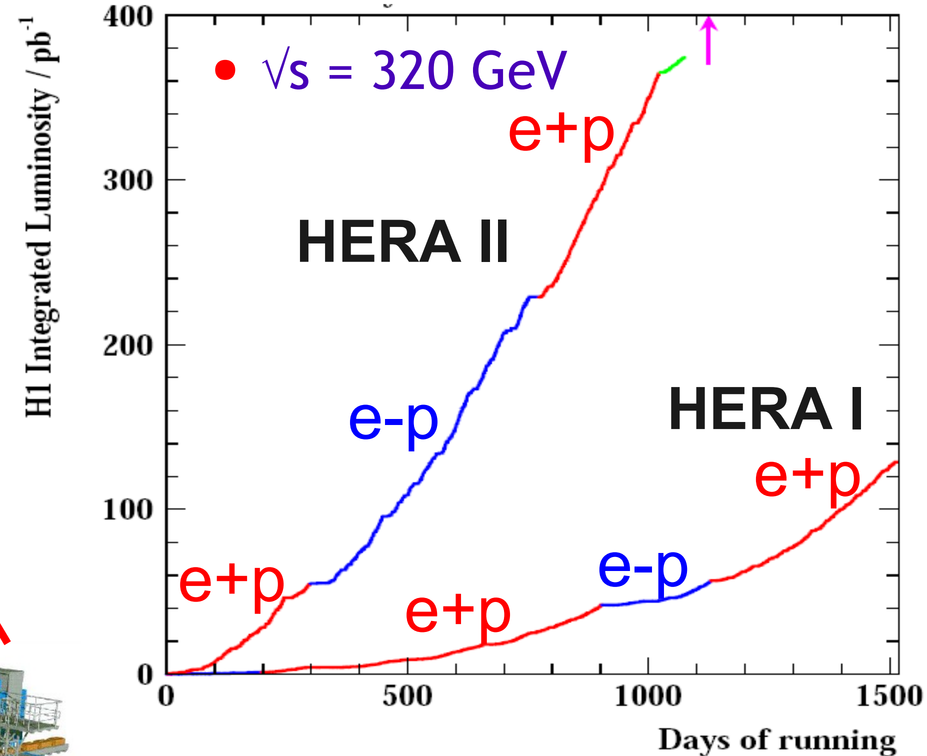
➔ QCD: exact non-perturbative calculations too complex, rely on measurements to describe complex objects (the proton)

➔ Rely on precise measurements of its O(19) parameters

➘ Experiments are needed to explore it

The HERA Collider





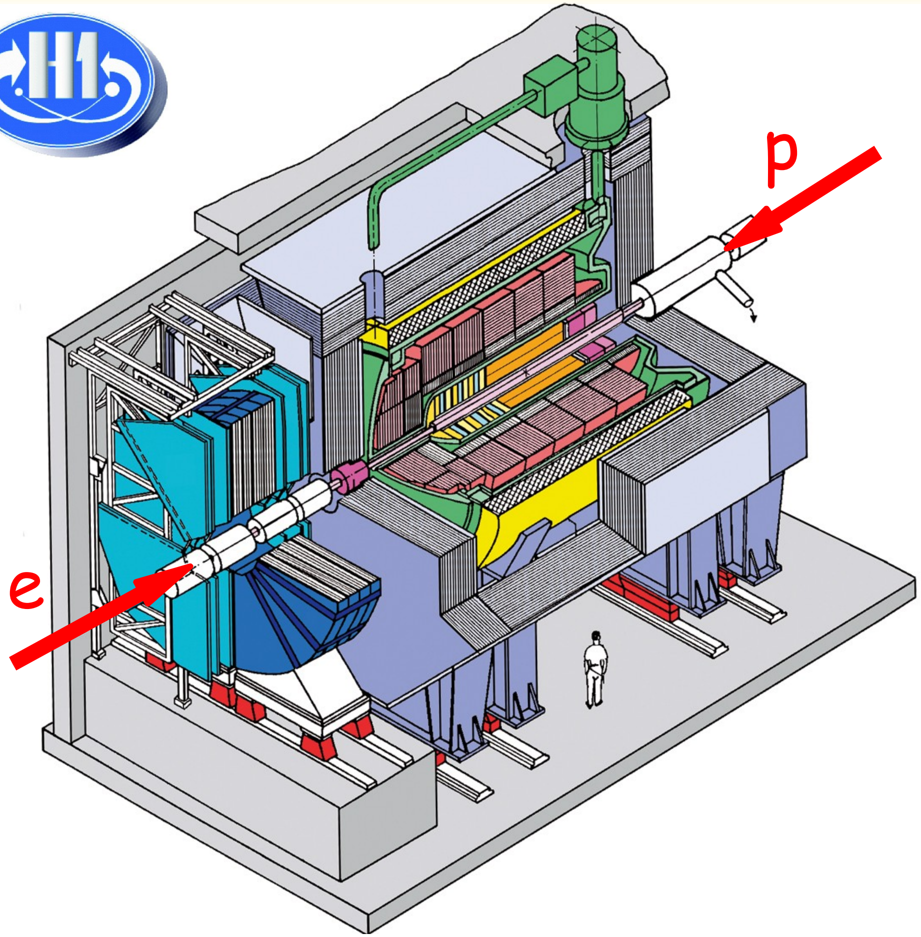
- HERA I: 1992-2000, ~120 pb^{-1} per experiment
- HERA II: luminosity upgrade and polarised lepton beams

➔ End of running: June, 30 2007

➔ HERA II: ~380 pb^{-1} per experiment in $e+_{L,R}$ p and $e-_{L,R}$ p

➘ In total H1+ZEUS together accumulated ~ $1fb^{-1}$

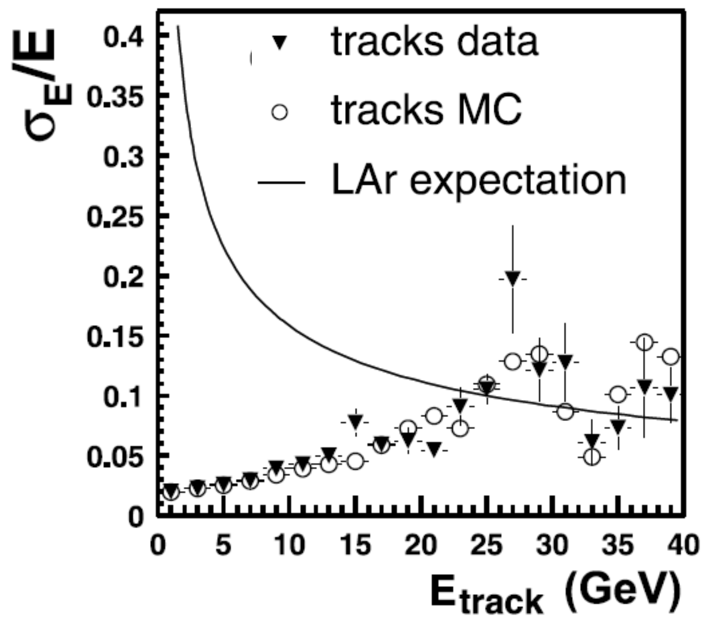
The H1 Detector



- LAr calorimeter:
  - ➔ Electromagnetic: $\frac{\delta E}{E} = \frac{12\%}{\sqrt{E}}$
  - ➔ Hadronic: $\frac{\delta E}{E} = \frac{50\%}{\sqrt{E}}$
- Tracker:
  - ➔ B-field 1.16 T

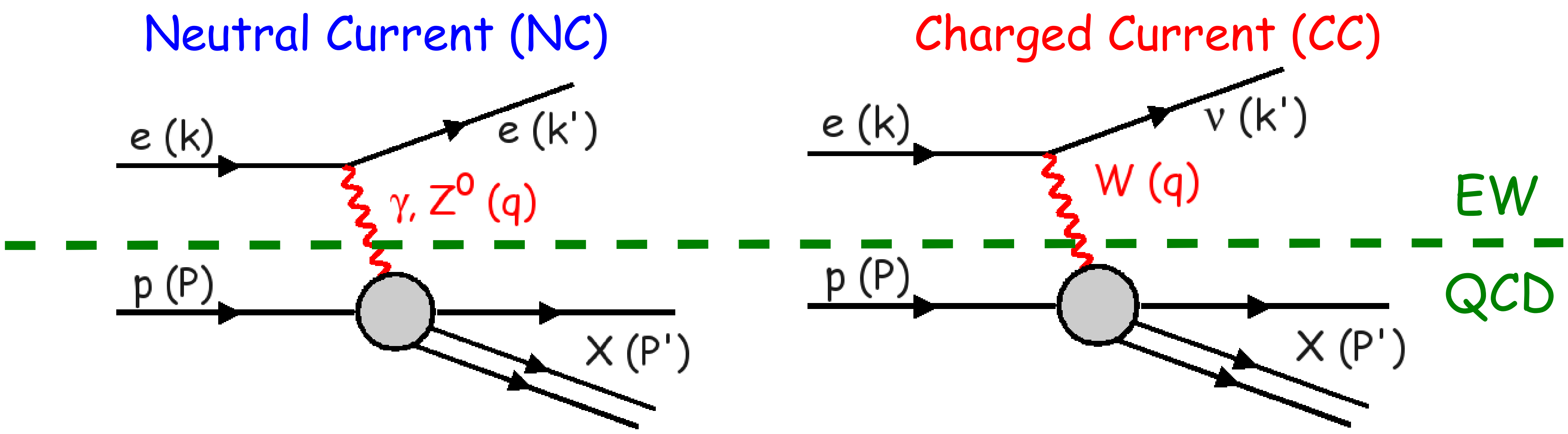
$$\sigma_{P_T}/P_T = 0.002 P_T/\mathrm{GeV} \oplus 0.015$$

- External muon detector



- Electron ID:
  - ➔ A compact em. shower (+track)
- Hadronic final state:
  - ➔ Energy flow algorithm
  - ➔ Combination of track/calo. informations

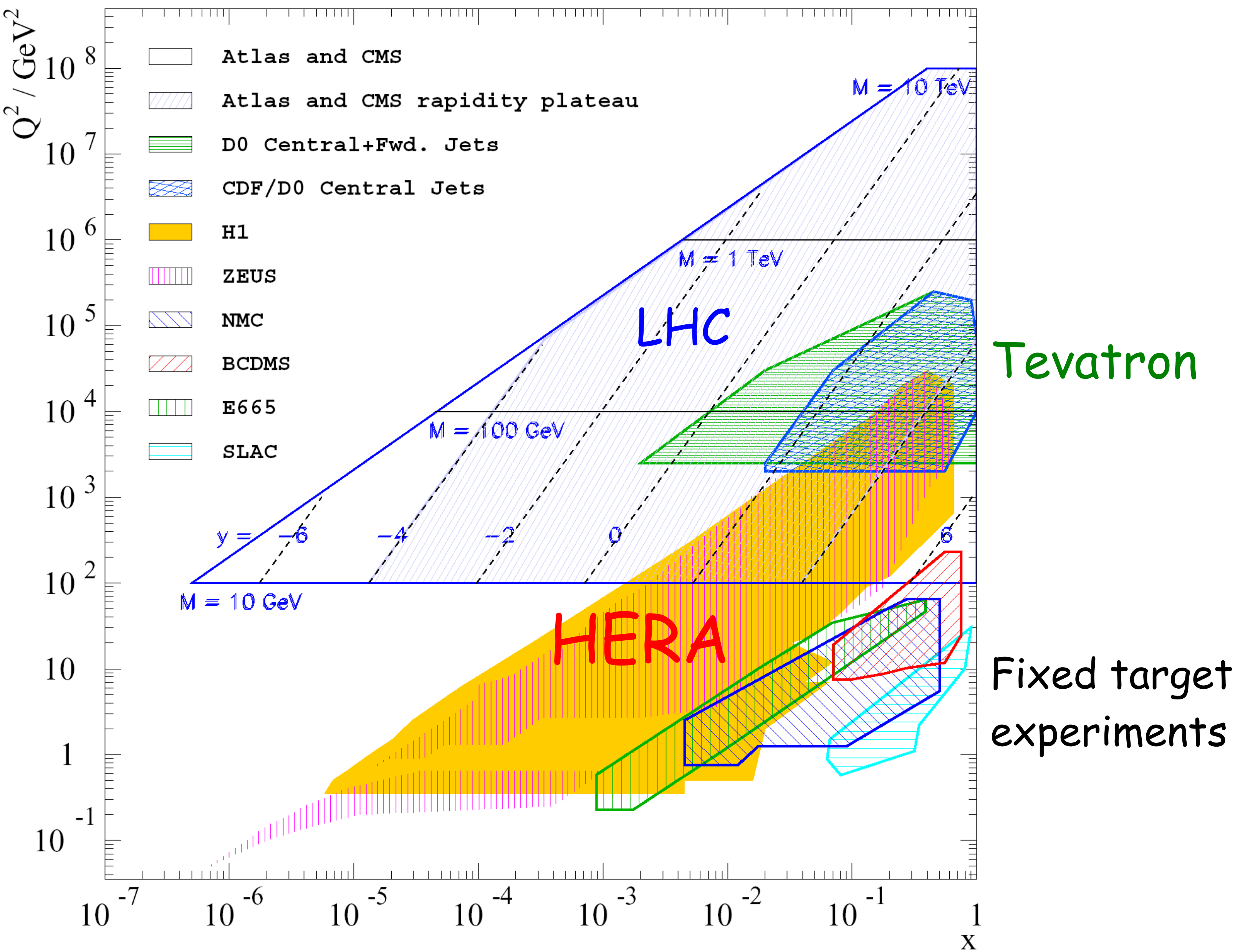
Deep-Inelastic Scattering



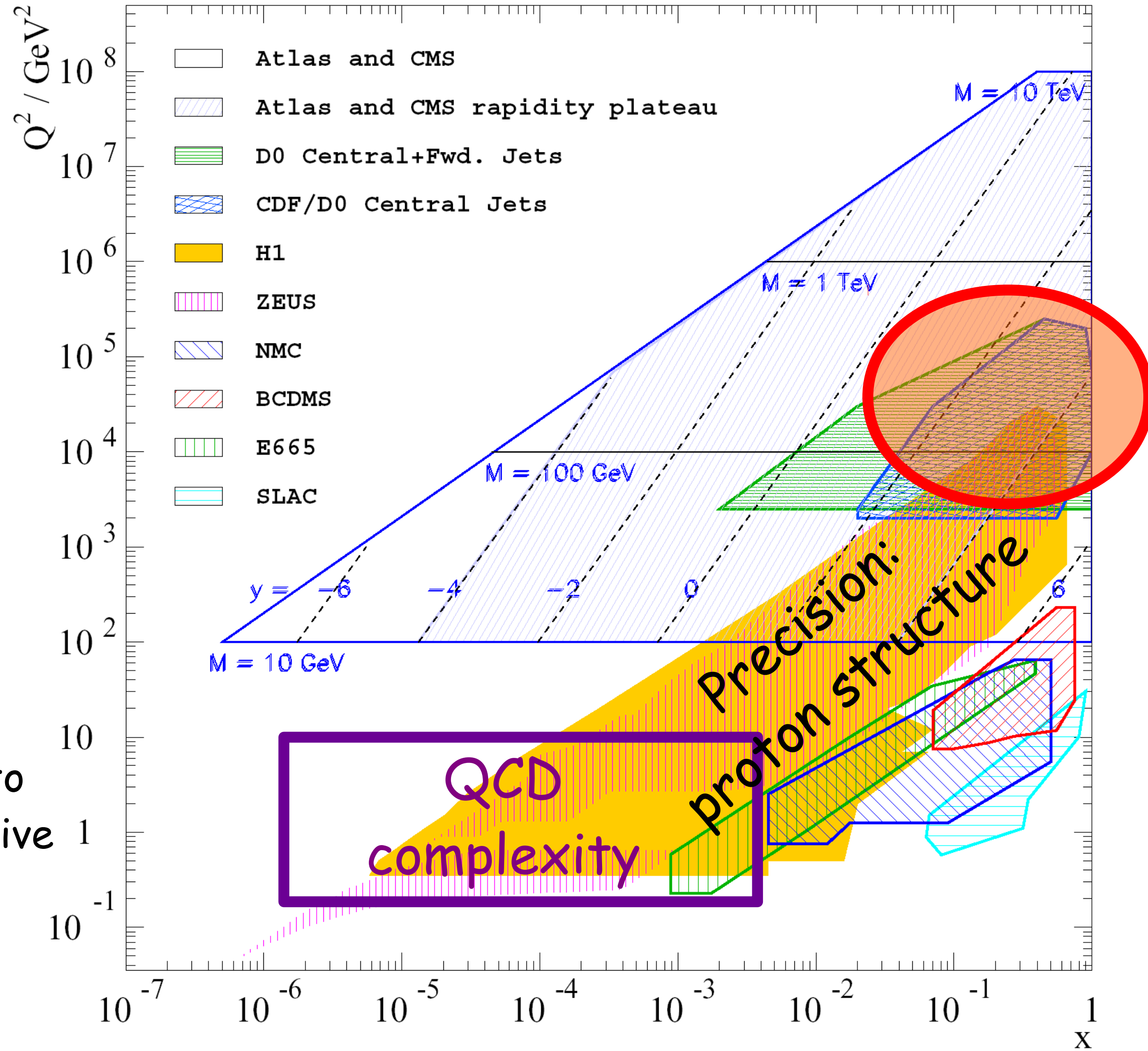
- CMS energy $s = (k+P)^2$
- Boson virtuality (1/resolving power) $Q^2 = -q^2 = -(k-k')^2$
- Momentum fraction of the scattered parton (Bjorken scaling variable) $x = \dfrac{Q^2}{2P \cdot q}$
- Inelasticity $y = \dfrac{Q^2}{xs}$
- Center-of-mass energy of the $\gamma^* p$ system $W^2 = \dfrac{Q^2(1-x)}{x}$

➔ Only 2 independent variables

The Proton Map in the Kinematic Plane



The Proton Map in the Kinematic Plane



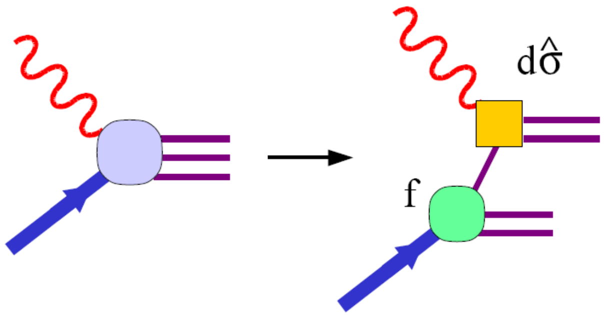
SM high-energy frontier

EW domain

Perturbative to non-perturbative transition

Perturbative QCD and Factorisation

- Internal proton structure not yet calculable in QCD
  - ➔ Factorisation theorem allows to calculate cross sections

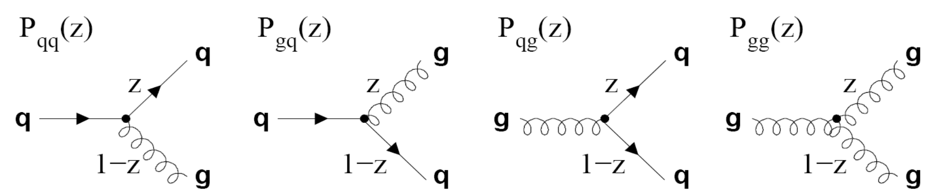


$$\sigma_{ep\to X} \sim \sum_q f_q(x,Q^2) \otimes \hat{\sigma}_{eq\to X}$$

Soft QCD, non-perturbative (PDFs)

Hard cross section, perturbative

  - ➔ DGLAP equations describe evolution of f(x) with Q^2 within perturbative QCD



- Similar for pp collisions:

$$\sigma_{pp\to X} \sim \sum_{q_i}\sum_{q_j} f_{q_i}(x,Q^2) f_{q_j}(x,Q^2) \otimes \hat{\sigma}_{q_i q_j\to X}$$

  - ➘ Proton structure (= PDFs) not known a priori
  - ➘ Need to be measured for any cross section calculation

Measuring the proton structure

- Neutral Currents:

$$\sigma^{\pm}_{r,NC} = \frac{d^2\sigma^{e^{\pm}p}_{NC}}{dx dQ^2}\frac{xQ^2}{2\pi\alpha^2 Y_+} = F_2 - \frac{y^2}{Y_+}F_L \mp \frac{Y_-}{Y_+}xF_3$$

$$Y_{\pm} = 1 \pm (1-y)^2$$

➔ Leading order picture of the proton:

$$\left[F_2^{\gamma}, F_2^{\gamma Z}, F_2^Z\right] = x\sum_i \left[e^2_{q_i}, 2e_{q_i}v_{q_i}, v^2_{q_i} + a^2_{q_i}\right] \; (q_i + \bar{q}_i)$$

↘ F_2: quarks

$$\left[xF_3^{\gamma Z}, xF_3^Z\right] = 2x\sum_i \left[e_{q_i}a_{q_i}, v_{q_i}a_{q_i}\right] \; (q_i - \bar{q}_i)$$

↘ F_3: valence quarks

$$F_L = 0 \; (\sim x\alpha_s g \;\; \text{beyond LO})$$

↘ F_L (+scaling violations): gluons

- Charged Currents:

$$\sigma_{CC}(e^+p) \propto x\left[(1-y^2)(d+s) + (\bar{u}+\bar{c})\right]$$

$$\sigma_{CC}(e^-p) \propto x\left[(u+c) + (1-y^2)(\bar{d}+\bar{s})\right]$$

↘ Quark flavour separation

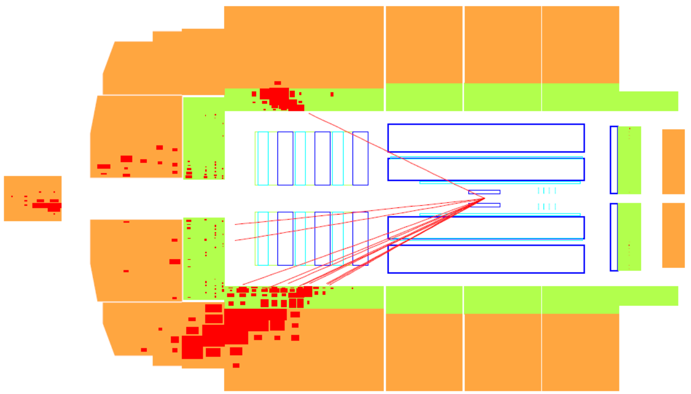
➔ e^+p most sensitive to d

➔ e^-p most sensitive to u

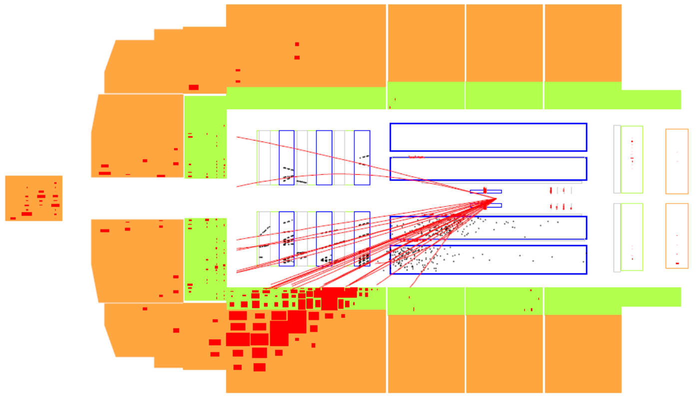
Neutral and Charged Current events

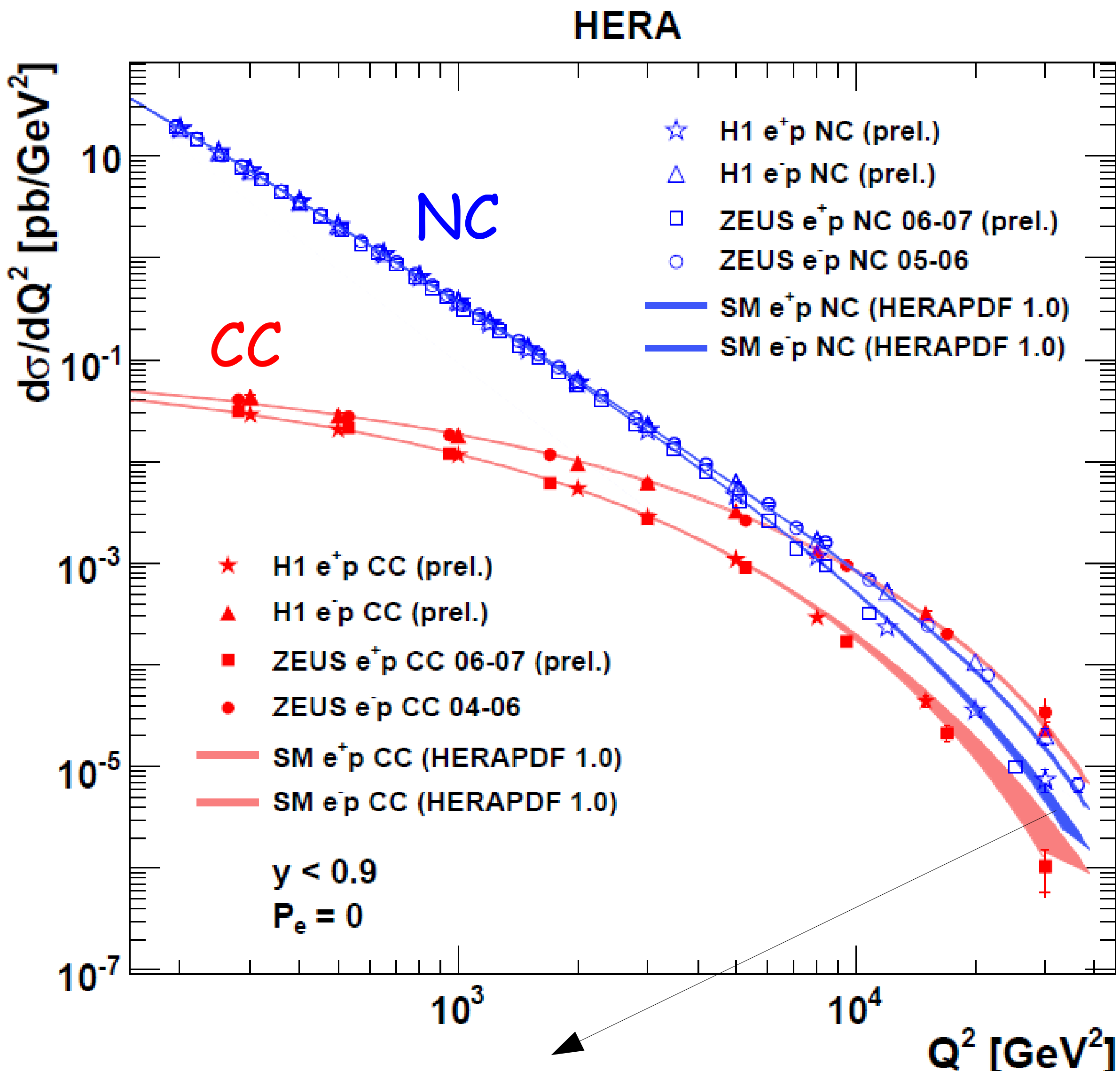
HERA I+II

Neutral Current (NC)



Charged Current (CC)





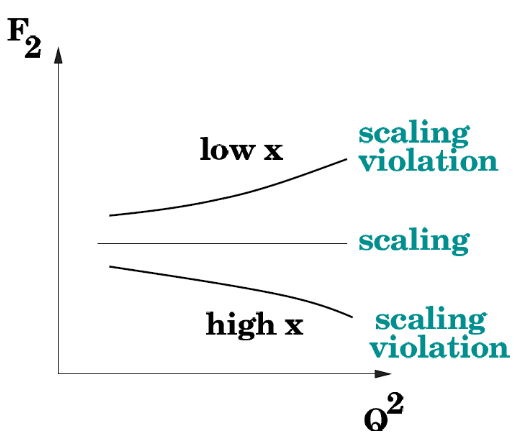
$R_q < 10^{-18}$ m

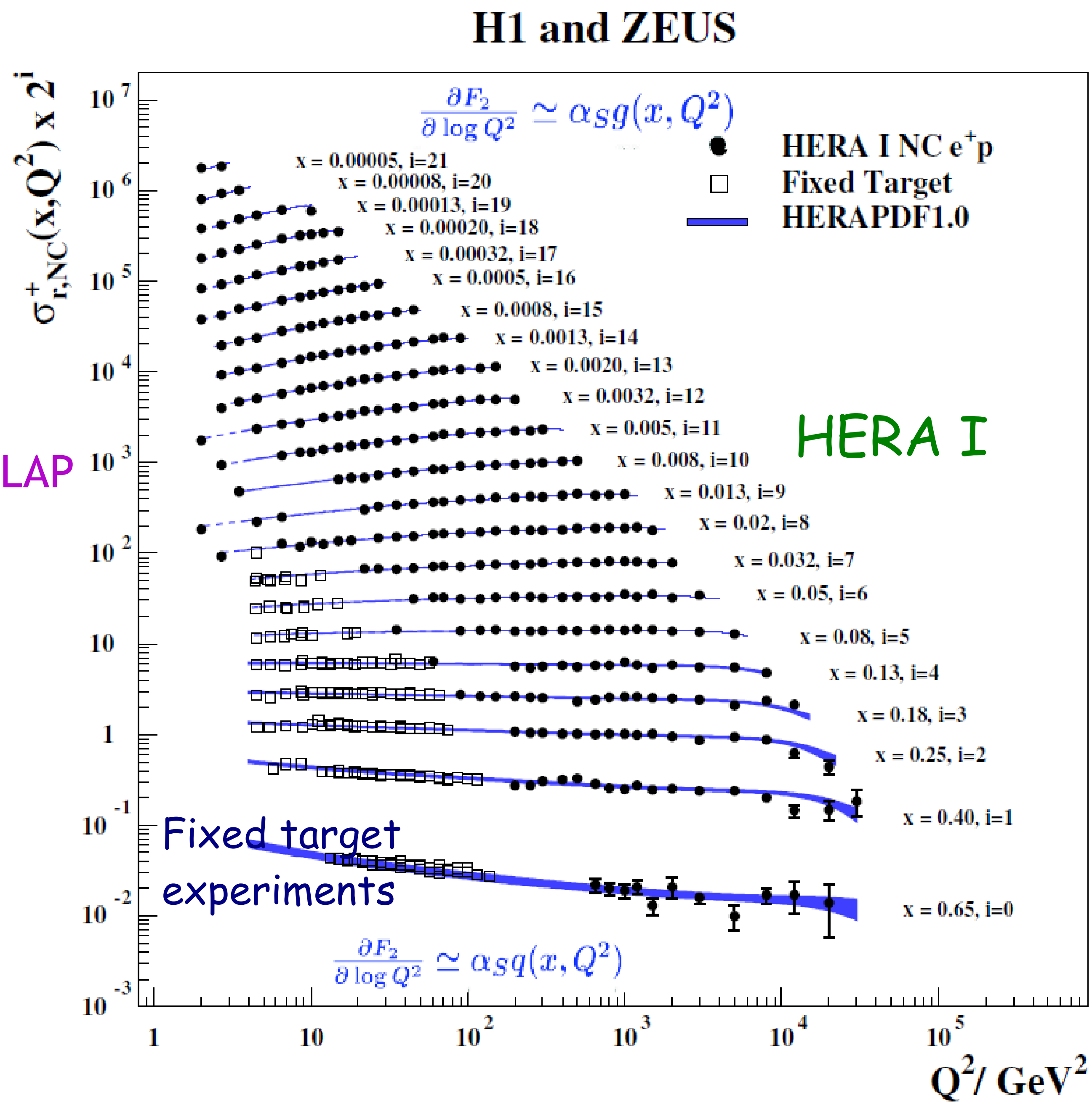
Valence and sea quarks: F_2

- Large coverage of the proton map at HERA
- Precision

➔ Test of QCD in the perturbative regime: DGLAP

➔ Gluon determination via scaling violations





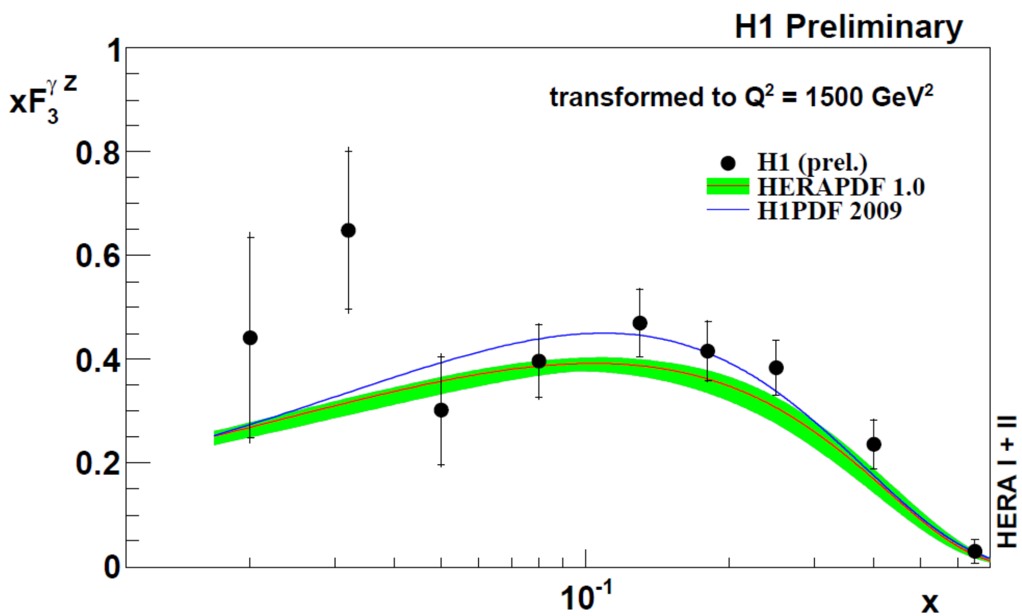
Valence quarks: xF_3

- xF_3: $$xF_3 \sim \sigma(e^- p) - \sigma(e^+ p) \sim (2u_v + d_v)$$

  → Highest Q^2 needed (Z exchange)

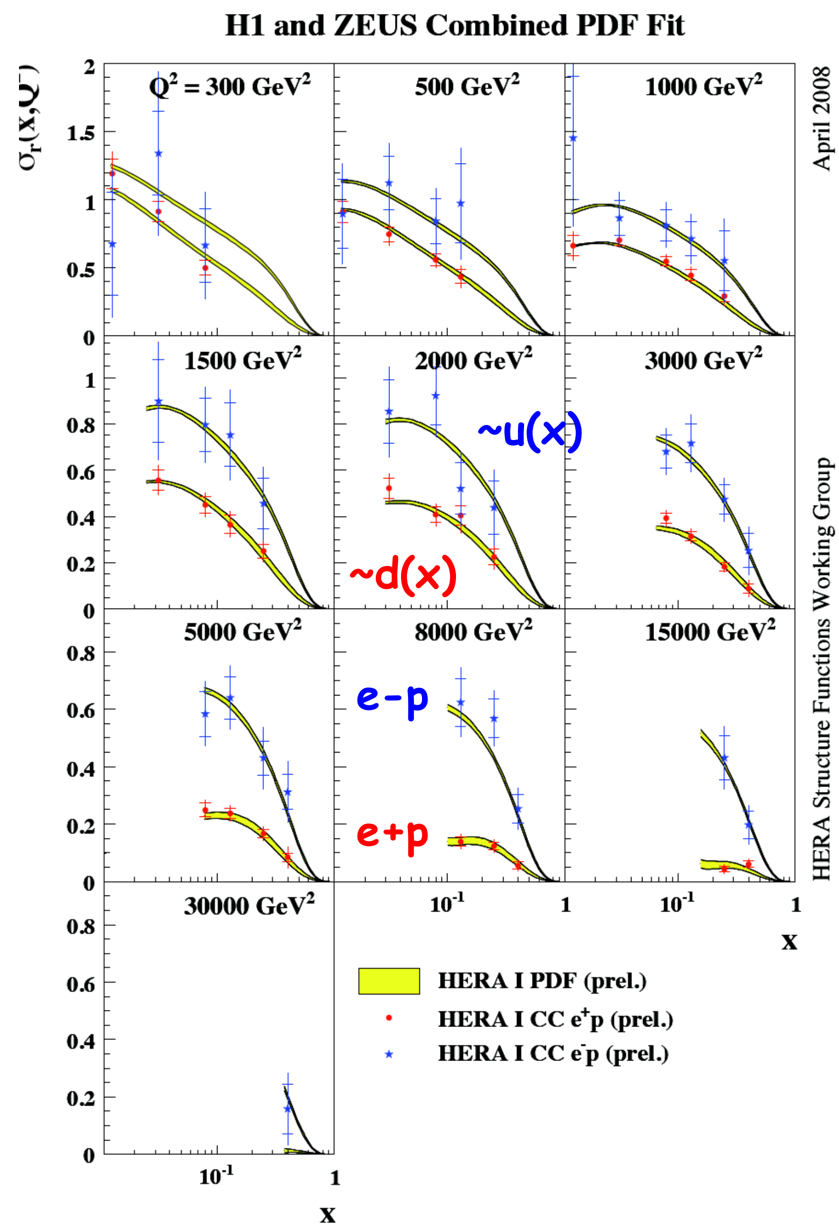
  → Statistically limited

  → Combining a part of H1+ZEUS data



↘ Improvement expected with full H1+ZEUS data (1 fb^{-1})

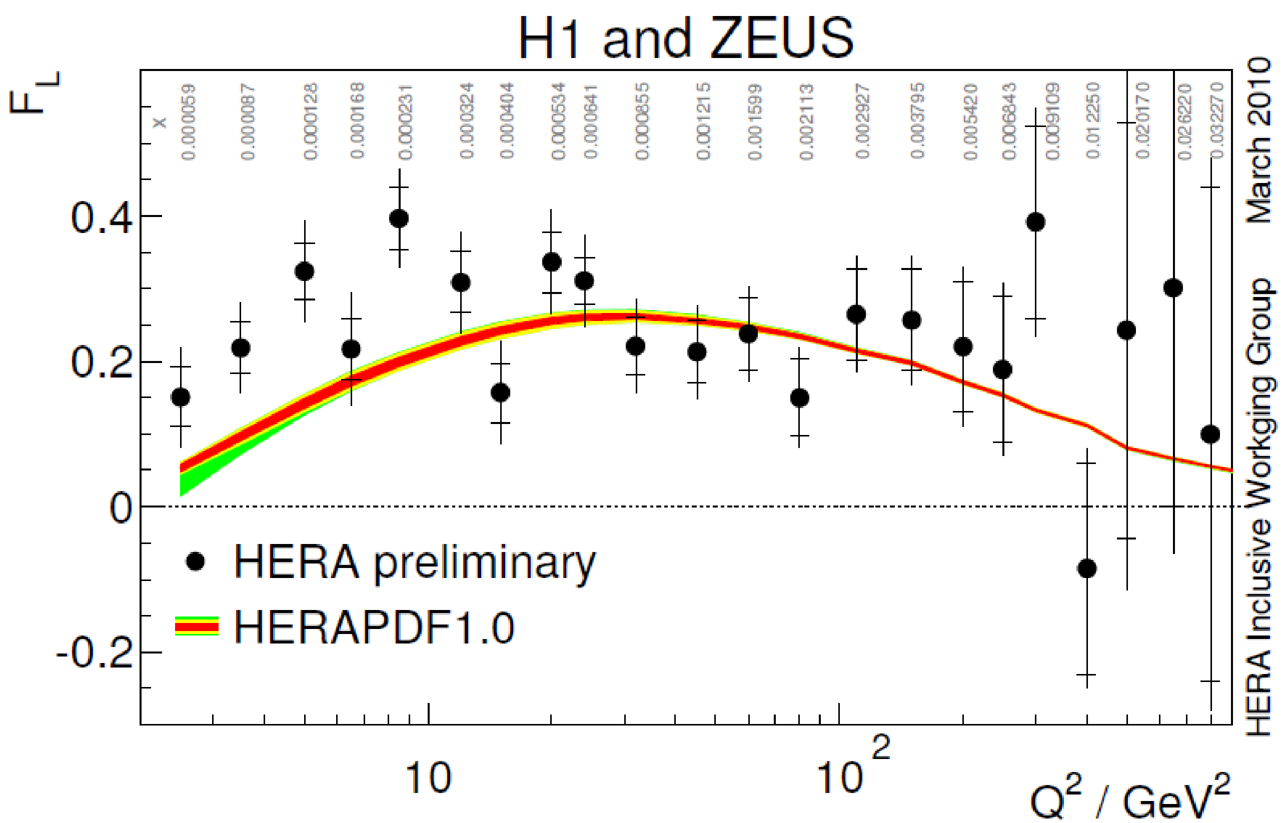
- Charged currents: separation of u and d



Gluons: direct F_L measurement

$$\sigma_{r,NC} = F_2 - \frac{y^2}{1+(1-y)^2} F_L \qquad y = Q^2/sx$$

- Method:
  - ➔ Keep x, Q^2 constant and vary y
  - ➔ Vary s: special runs with E_p = 460, 575 GeV



HERA II

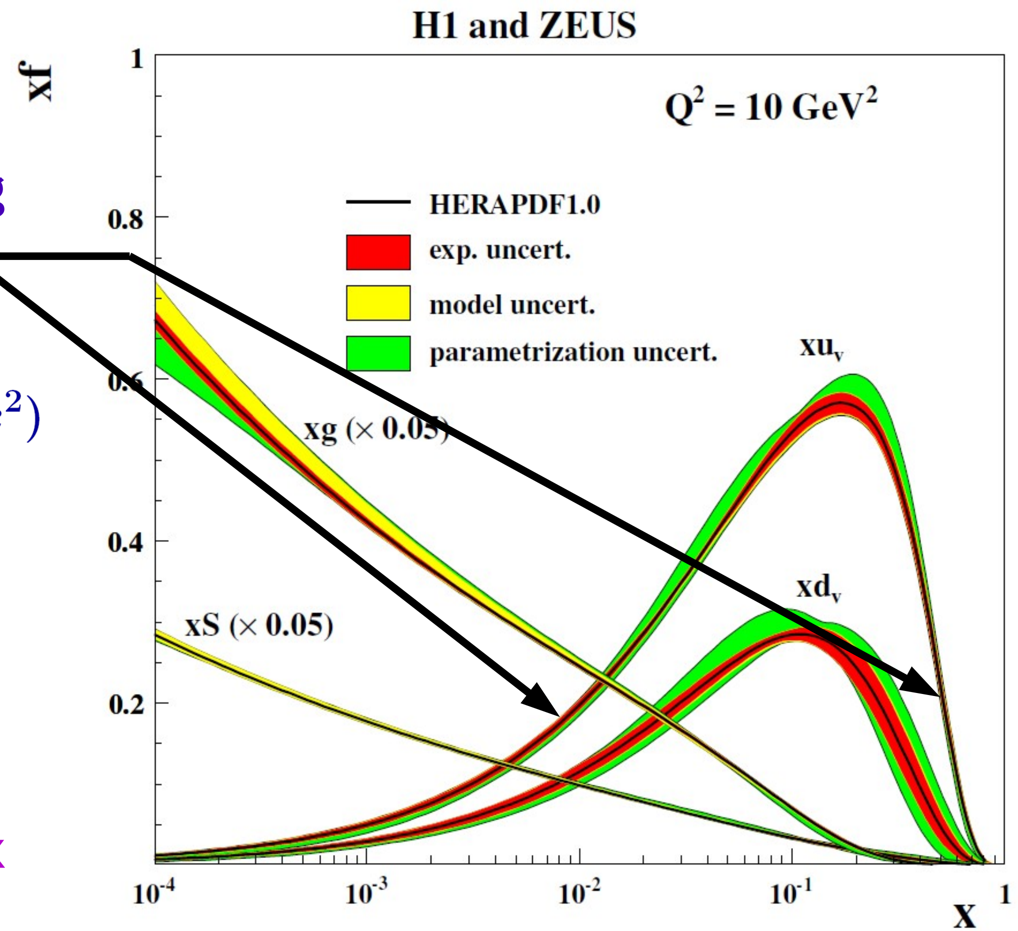
➘ First direct F_L measurement at low x

Parton distribution functions

- A global fit to all HERA NC and CC measurements
- Only HERA data used here
- PDFs parametrised at a starting scale Q_0^2

$$xf(x) = Ax^B(1-x)^C$$
$$(1 + Dx + E\sqrt{x} + Fx^2)$$

$$\int u_v\, dx = 2 \qquad \int d_v\, dx = 1$$

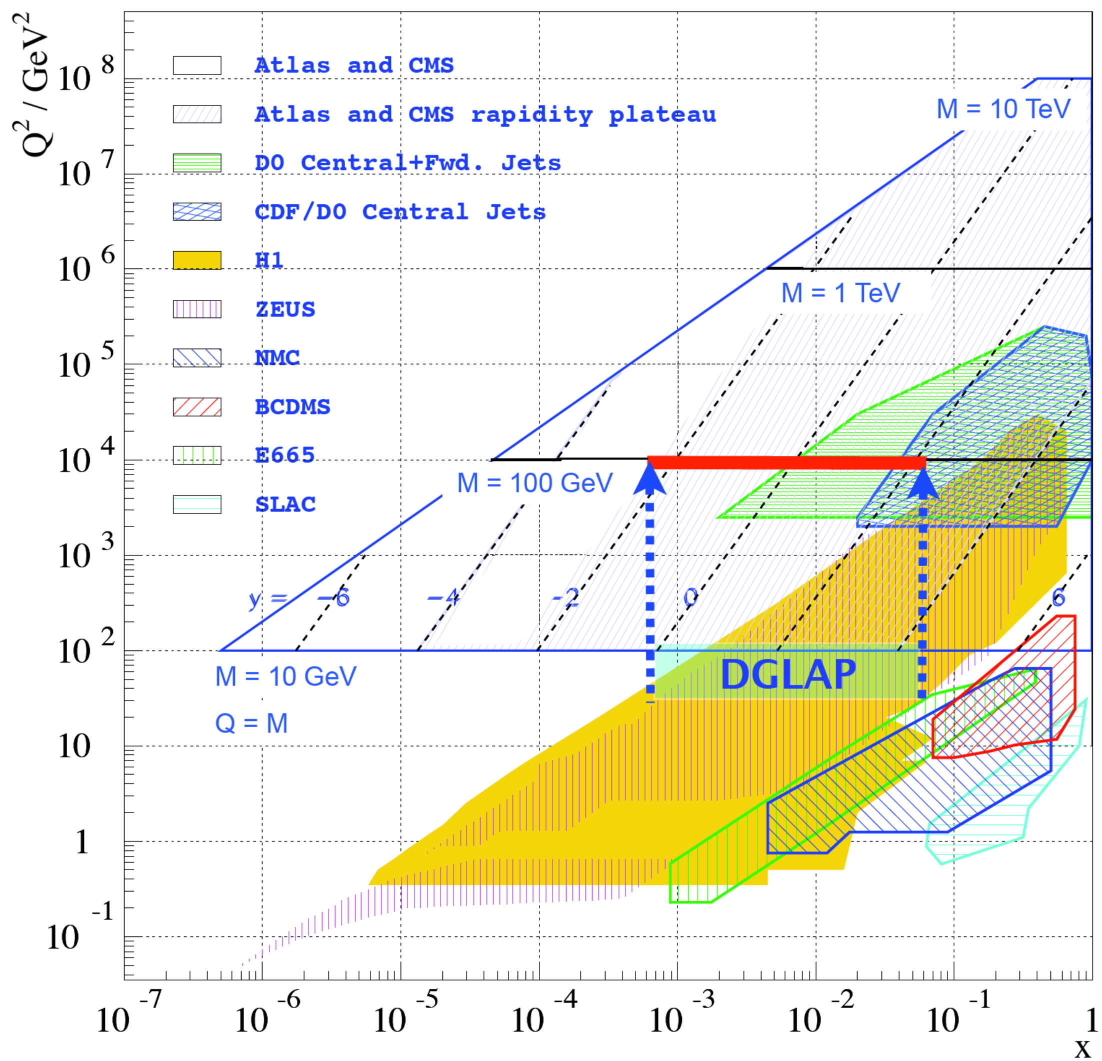


- Uses DGLAP for Q^2 evolution

➔ Dominated by gluons at low x

PDFs and the LHC

- A large fraction of LHC physics is at low x
  - ➔ Crucial needs of HERA PDFs for cross section predictions using DGLAP

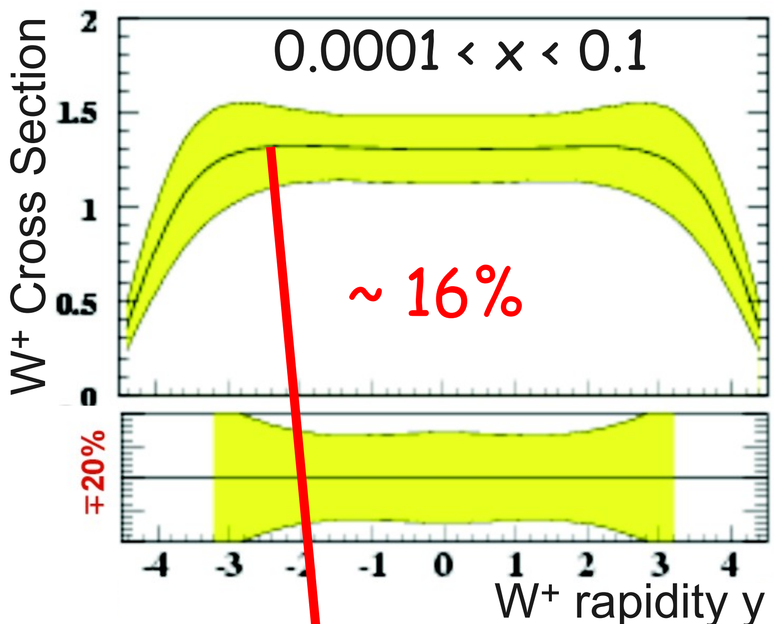


HERA's impact

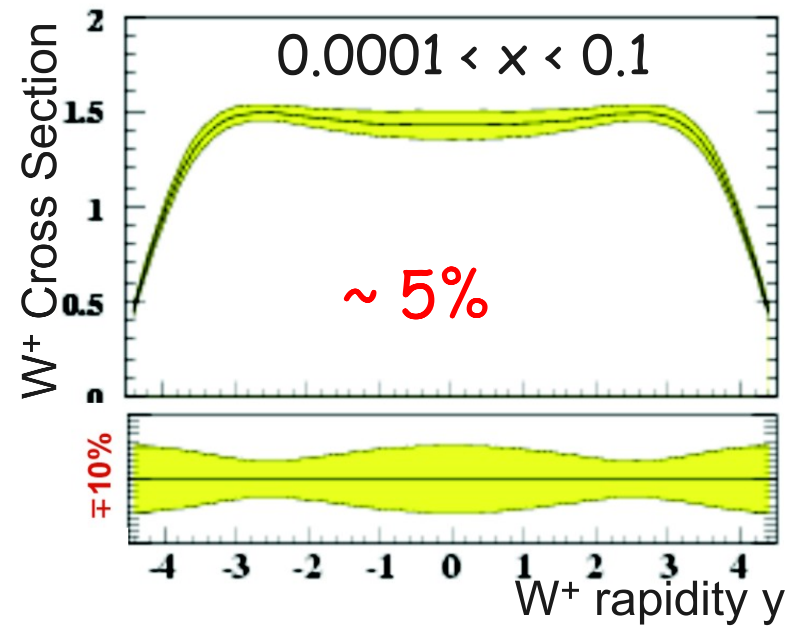
[A.M. Cooper Sakar]

➘ Prediction on W production cross section for LHC: DGLAP at work

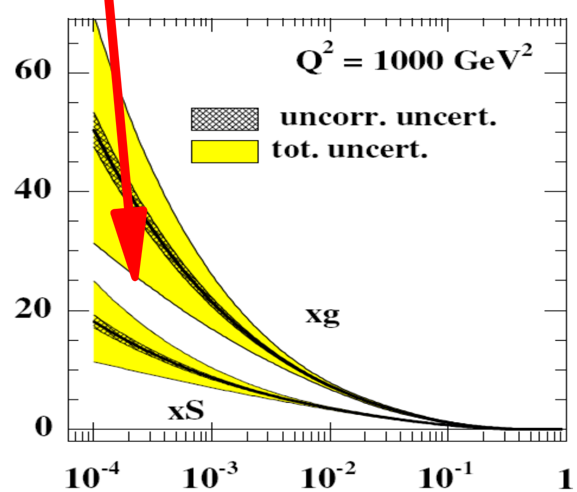
- W prod. at LHC without HERA



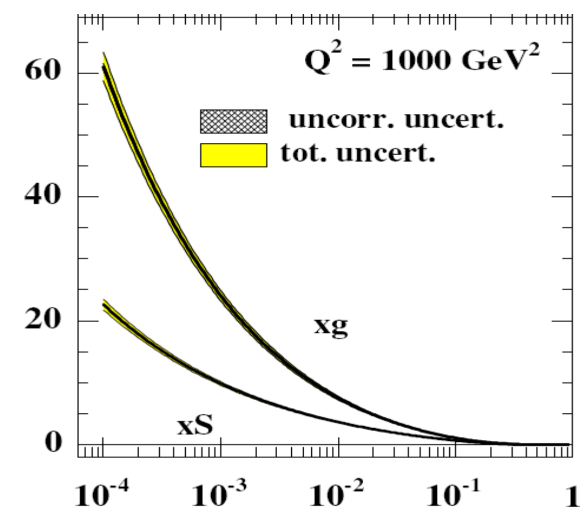
- W prod. at LHC with HERA



- PDFs without HERA

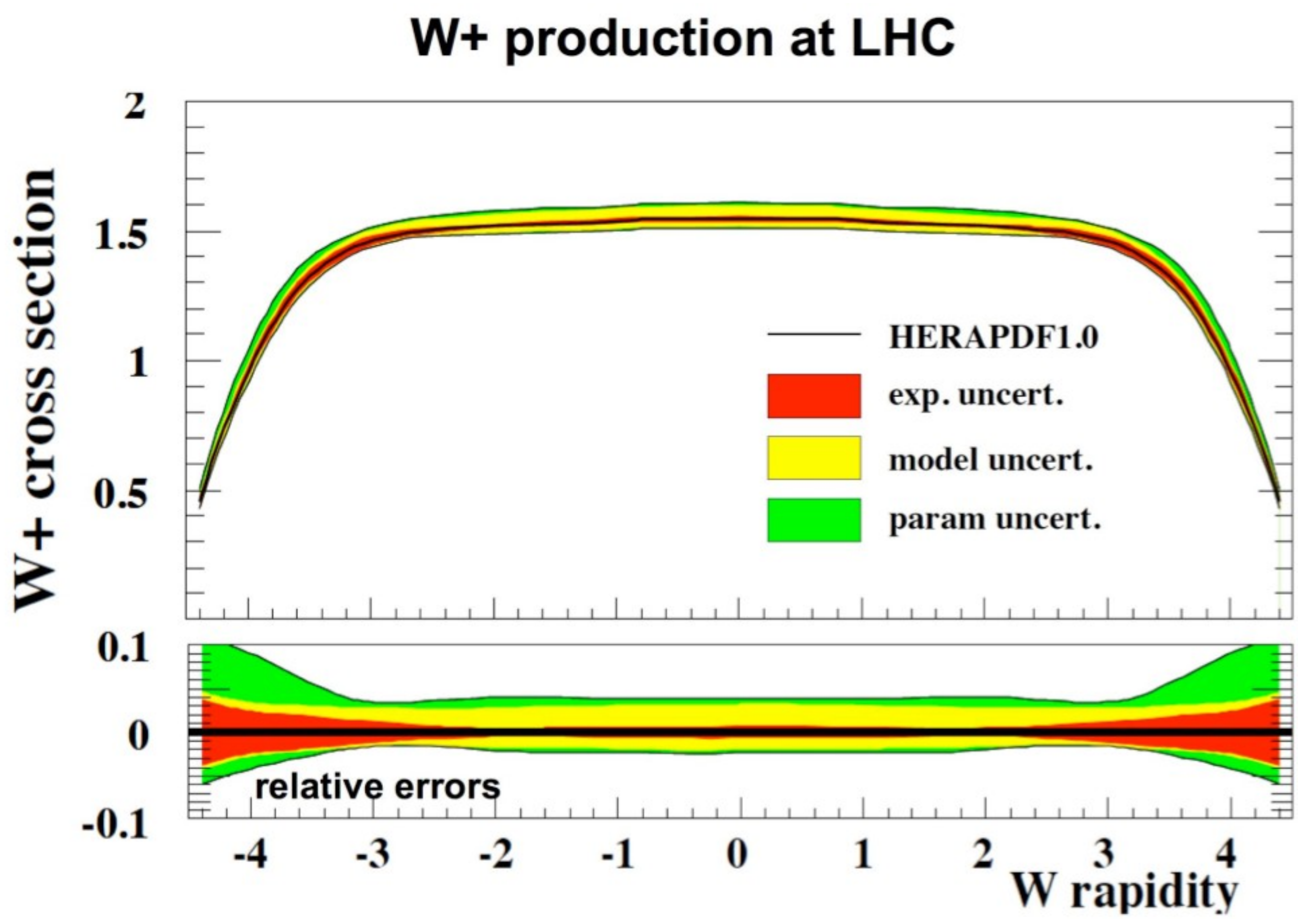


- PDFs including HERA



Predictions for the LHC

[A.M. Cooper Sakar]



- ~5% uncertainty, dominated by model and parametrisation uncertainties

EW: Polarisation effect in CC [H1, PLB 634 (2006) 173]

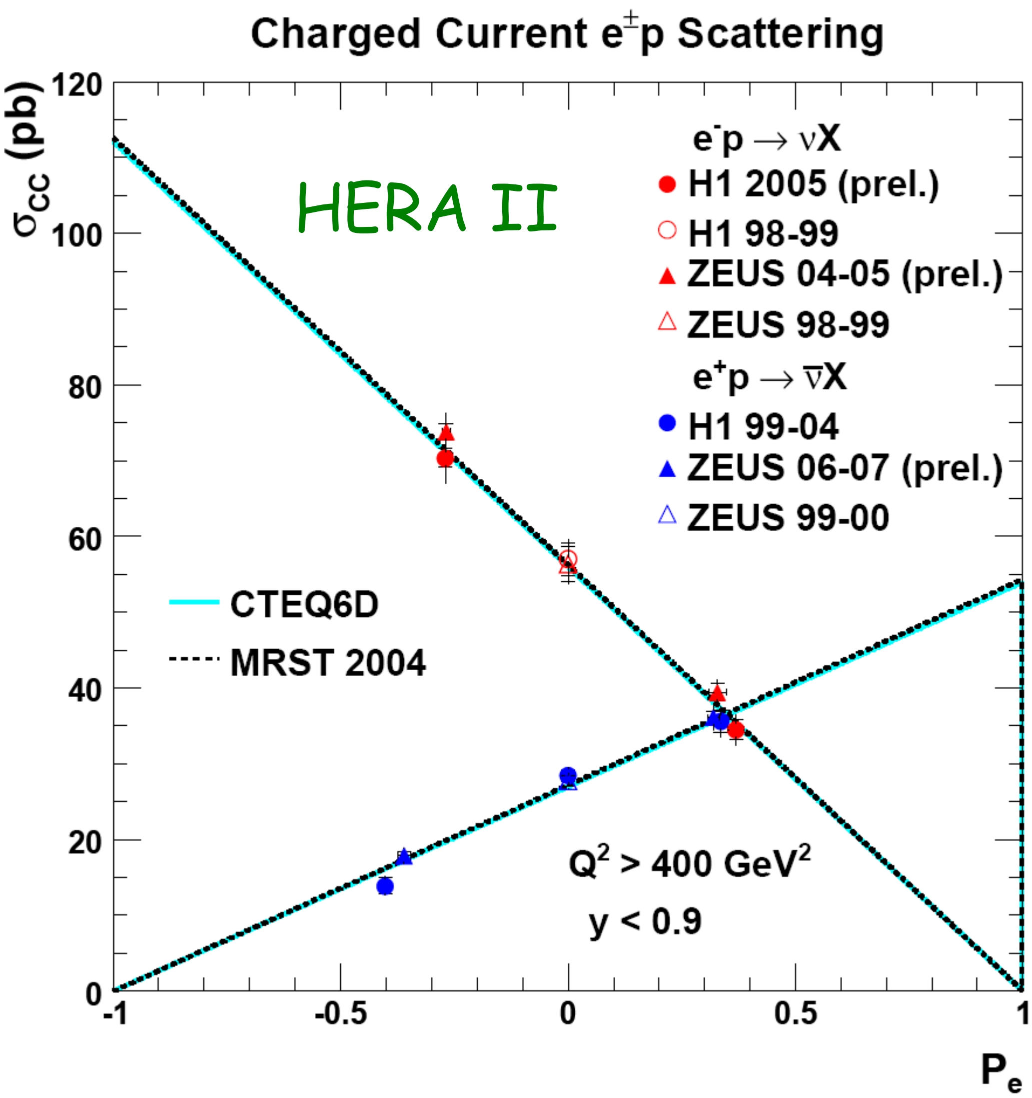
- Exploits e+/e- running and polarisation

$$\sigma_{CC}^{e^{\pm}p}(P) = (1 \pm P)\,\sigma_{CC}^{e^{\pm}p}(P=0)$$

➔ Linear dependence established in DIS at HERA

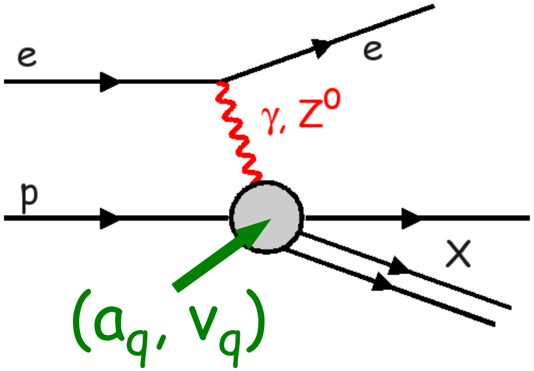
➔ Compatible with V-A structure

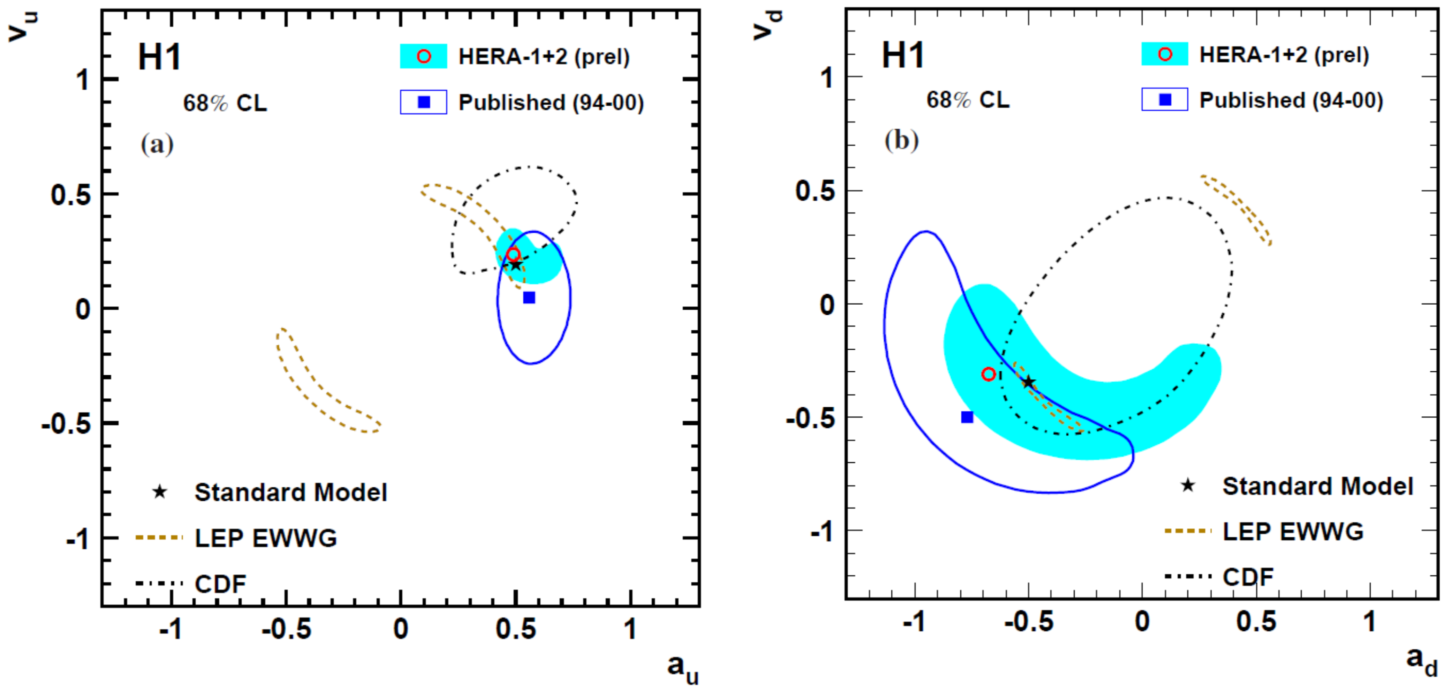
➔ No Right-Handed currents



Light quark couplings to Z

- Fits together QCD proton structure and EW couplings
  - ➔ Takes advantage of the polarisation (for v_q)
  - ➔ Increase of e-p luminosity from HERA II data





LEP: ee → qq at Z peak (a^2v^2, a^2+v^2)

Tevatron: qq → ee from Drell-Yann (A_{FB})

➘ Best precision for u-couplings

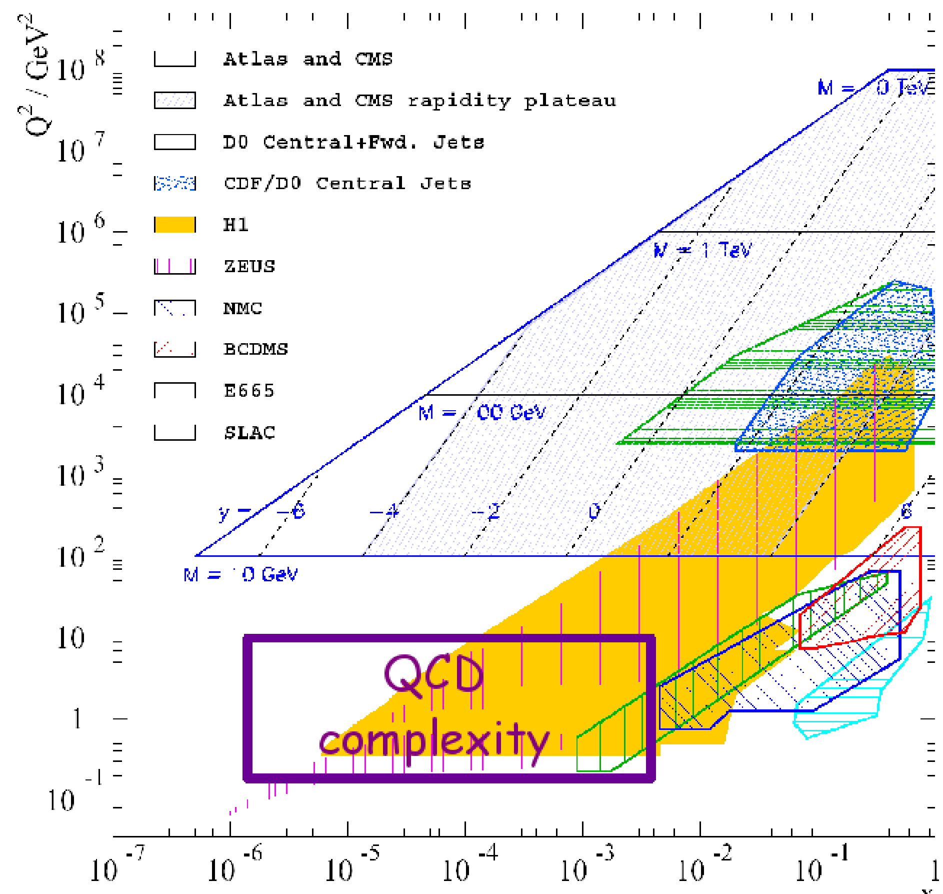
➘ Still to go: H1/ZEUS combination

Complexity in the SM: QCD

- DIS: only probes longitudinal momentum content of the proton
  - ➘ Incomplete picture
    - ➔ Proton's transverse size ?
    - ➔ Correlations between partons ?
    - ➔ High parton (gluon) densities ?

➘ New windows provided by Low x QCD interactions at HERA

➘ Diffractive interactions

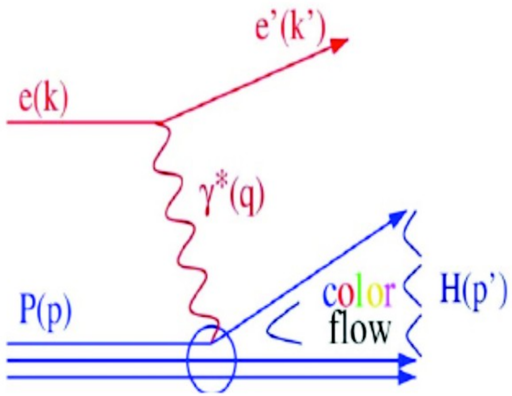


Diffractive interactions

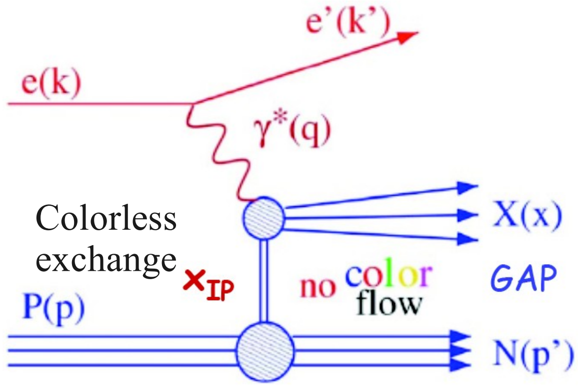
- Diffractive interactions: a colorless exchange

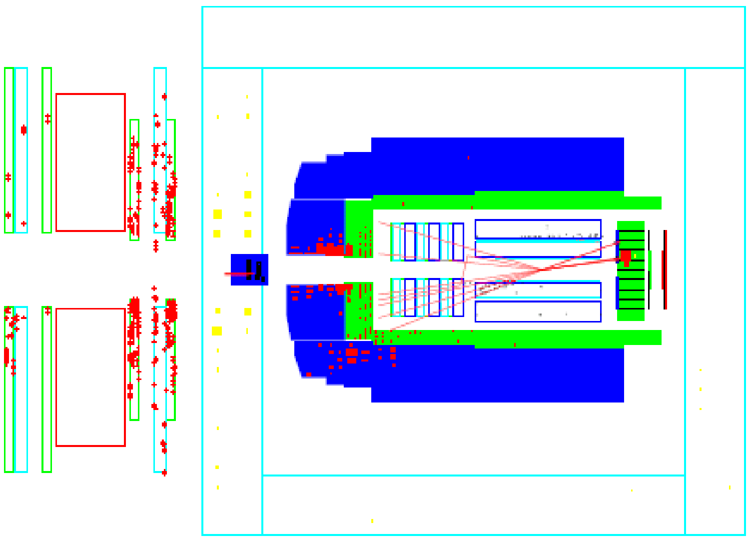
➔ The proton stays intact
(or in a low excitation state)

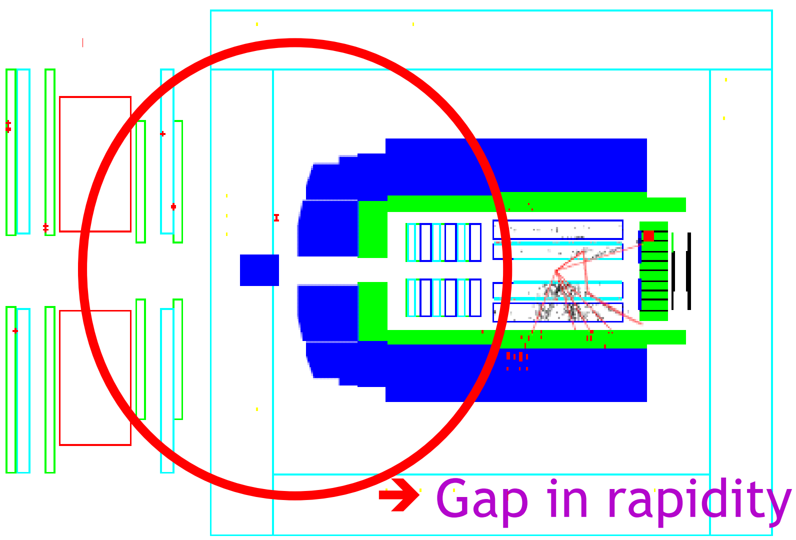
DIS



Diffractive DIS





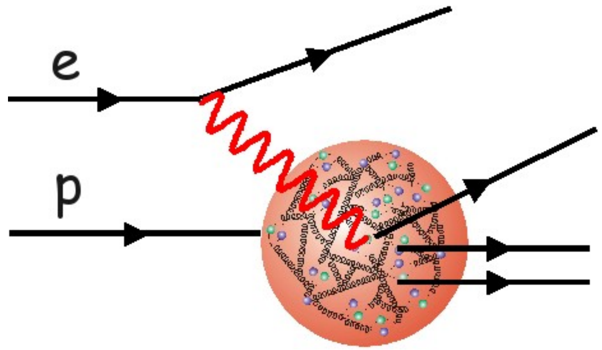


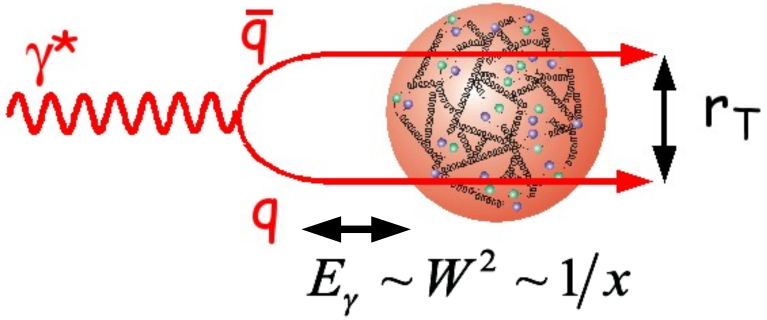
➔ Gap in rapidity observed

➘ ~ 10% of all DIS events

Different points of view of DIS

- Infinite momentum frame
- Proton rest frame





➔ A "frozen" proton seen by the electron

➔ Electrons as probes for quark structure

➔ At low x, rapid photon (50 TeV) seen by the proton

➔ γ^* splits in a $q\bar{q}$ pair, long life time due to lorentz boost

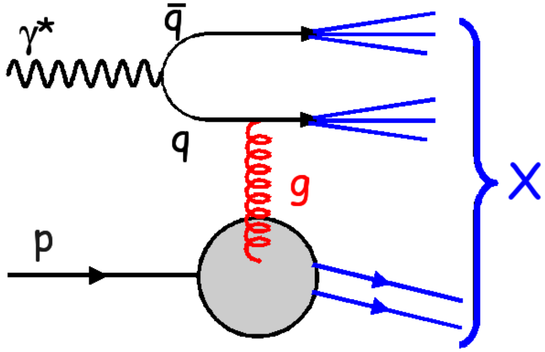
➔ Transverse size: $r_T \sim 1/Q$ = 1 to 0.01 fm

➔ Hadronic interaction with the p

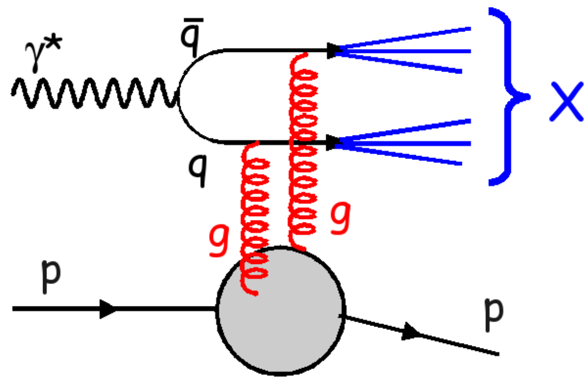
➘ Q^2 steers the transition from hard collisions (perturbative QCD) to soft hadron physics

The dipole model

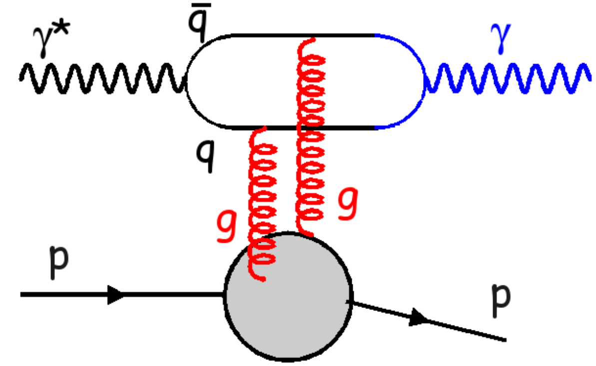
- Deep inelastic scattering



- Diffractive interactions
  - Diffractive DIS

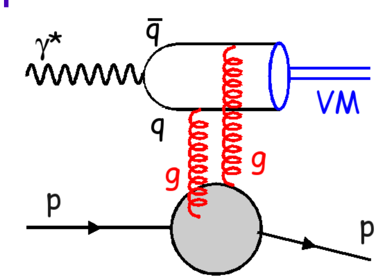


  - Deeply Virtual Compton Scattering



➔ Cross section proportional to the probability of finding 2 gluons in the proton

  - Or vector meson production



➘ *Allows a unified description in the low x domain*

- Then

$$\sigma^{\mathrm{tot}}_{\gamma^* p} \sim C \otimes \left[x\, g(x, Q^2)\right]$$

$$\sigma^{\mathrm{diff}} \sim C' \otimes \left[x\, g(x, Q^2)\right]^2$$

$$x\, g(x, Q^2) \propto x^{-\lambda(Q^2)}$$

(λ ~ 0.3)

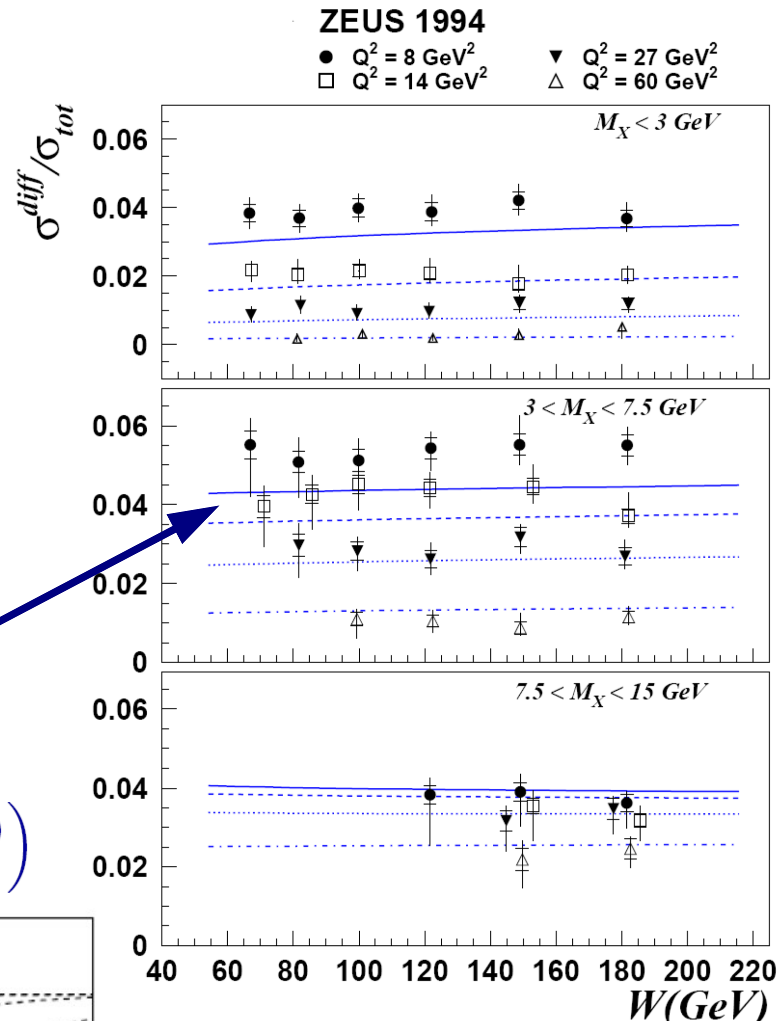
$$W \sim \frac{Q^2}{x}$$

$$\sigma^{\mathrm{tot}}_{\gamma^* p} \propto W^{2\lambda(Q^2)}$$

$$\sigma^{\mathrm{diff}} \propto W^{4\lambda(Q^2)}$$

Saturation

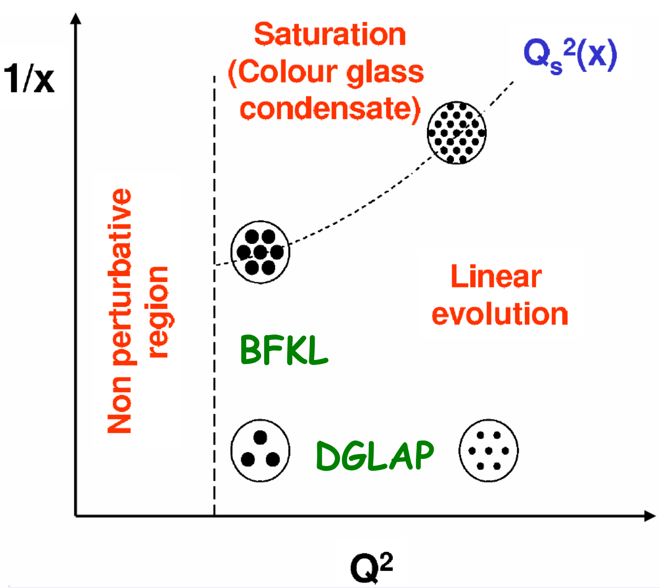
- ➔ We expect a strong dependence $\sigma^{\text{diff}} / \sigma^{\text{tot}}_{\gamma^* p} \propto W^{2\lambda}$
- ➔ But a flat ratio with W is observed instead
  - ➘ Limitation of the gluon distribution extent as W increase
  - ➘ Gluon density saturates (as gluons re-interact with each other)

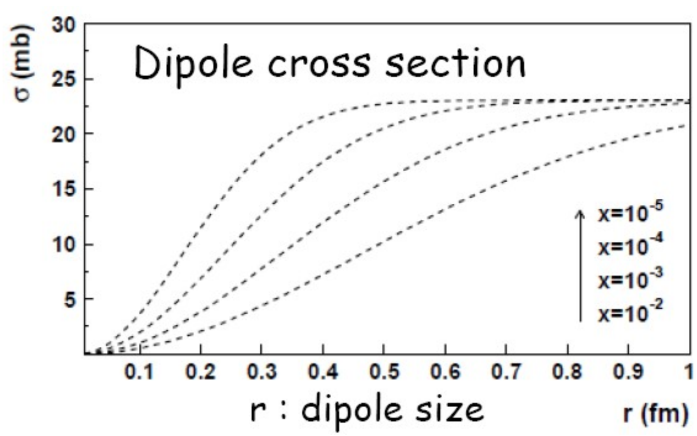


- Can be described by dipole models including saturation

(Qs = saturation scale)

$$\hat{\sigma}_{q\bar{q}} = \sigma_0 \left(1 - e^{(-r^2 Q_s^2(x))}\right)$$



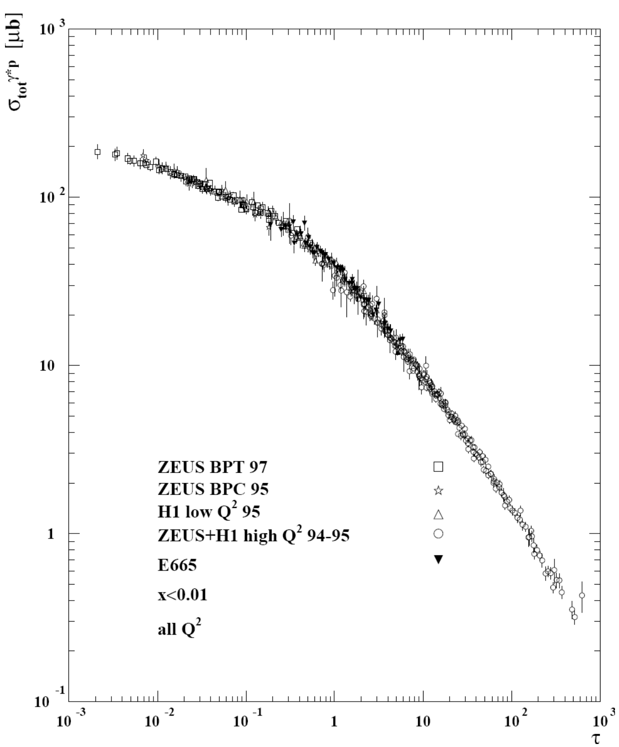


$r \equiv 1/Q$

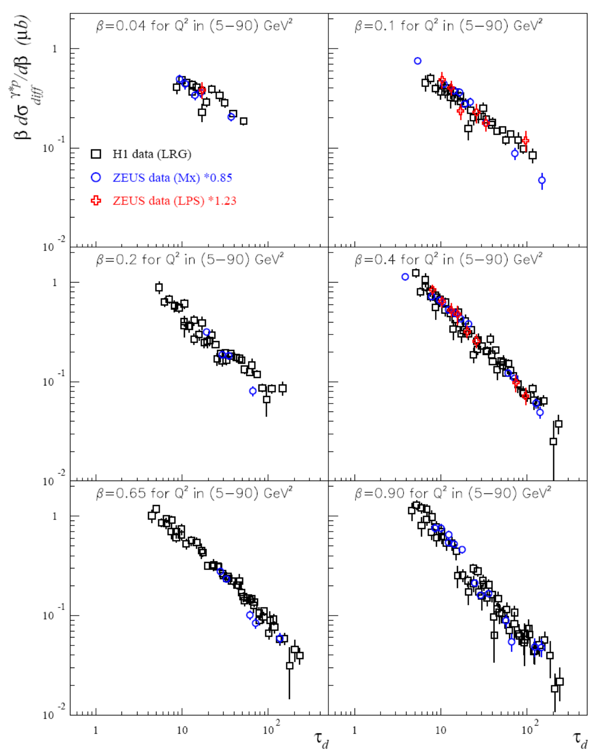
Geometric Scaling

- A consequence of saturation:
  - ➔ Cross section depends on a single variable $\tau = Q^2/Q_s^2(x)$
  - ➔ Property called "geometric scaling"

- DIS

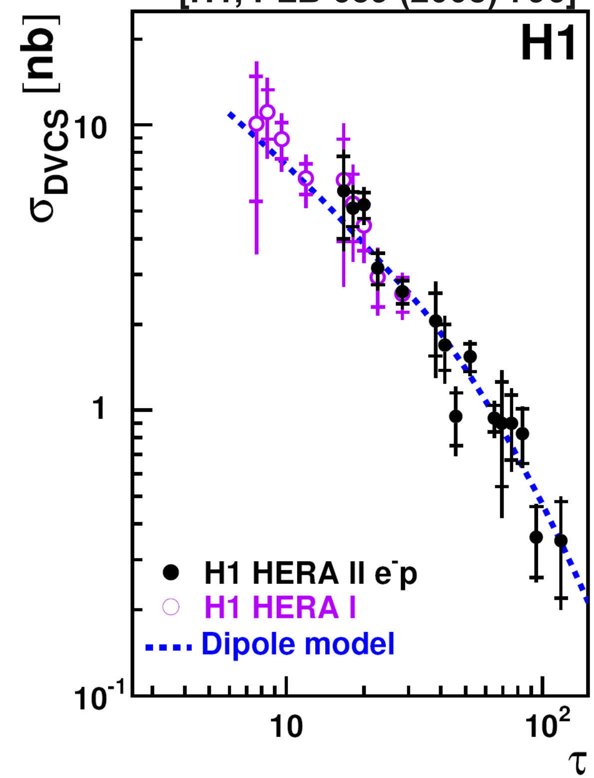


- Diffractive DIS



- DVCS

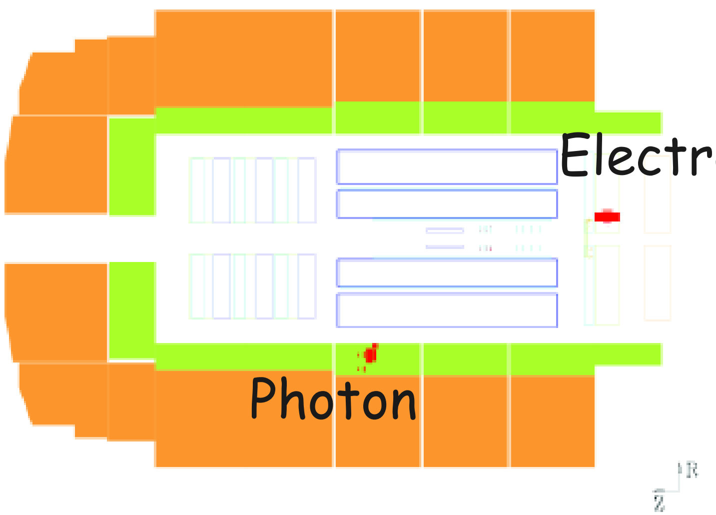
[H1, PLB 659 (2008) 796]

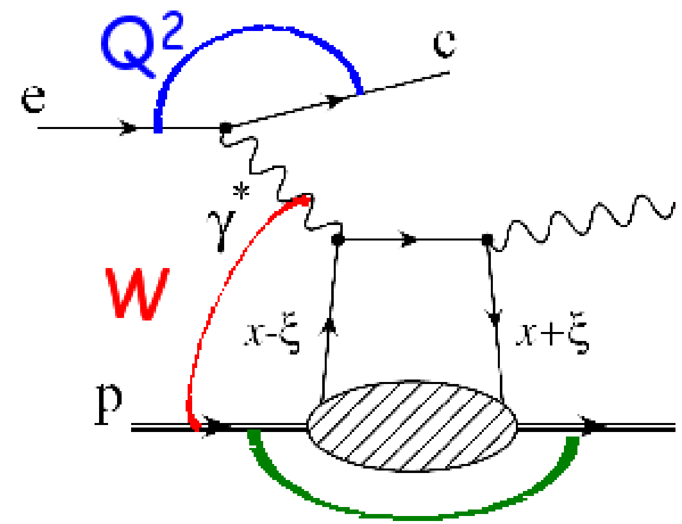


- ➘ Universal saturation scale $Q_s^2(x)$
- ➘ Can also be connected to effects observed in heavy ion physics

Deeply Virtual Compton Scattering

- Elastic production of a real photon
  - ➔ A pure QCD process
  - ➔ The cleanest process to study QCD effects at HERA





t

Q^2: virtuality of the exchanged photon

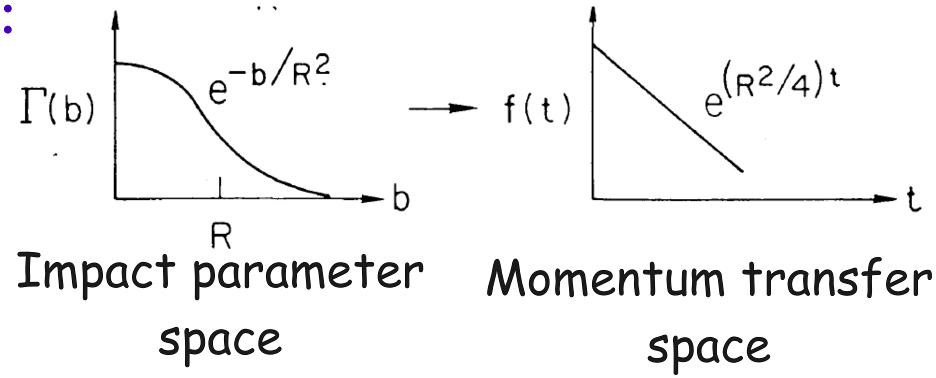
W: center of mass energy of the γ^*p system

t: squared momentum transfer at the proton vertex

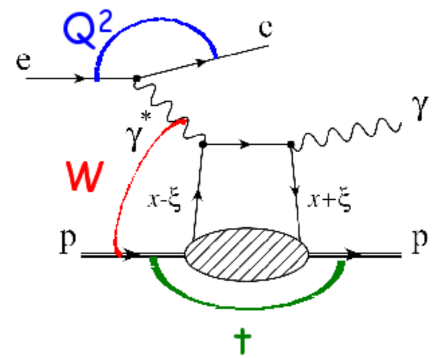
- Involves 2 partons of different momentum fractions
  - ➔ Allows to access correlations between partons

t-dependence of DVCS cross section

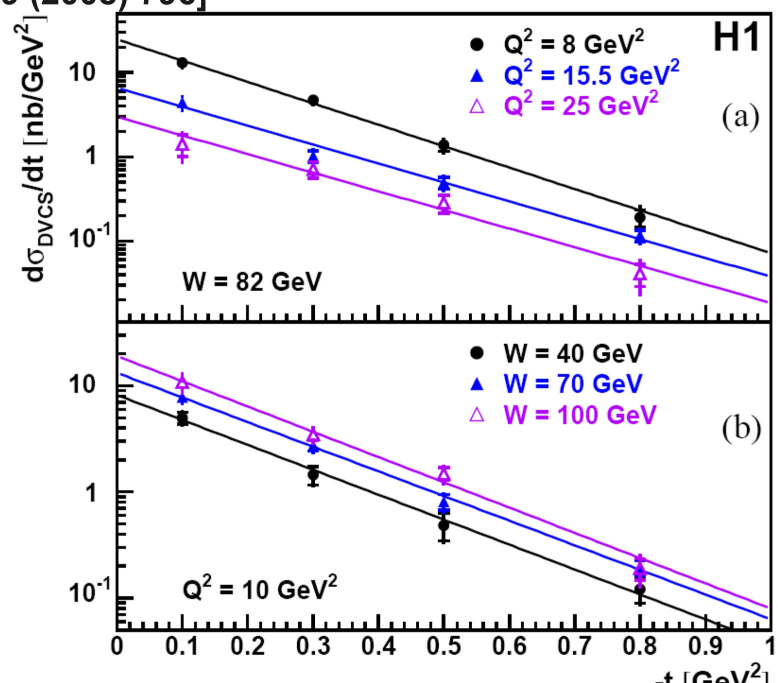
- Quantum analogue of optical diffraction:
  - ➔ Momentum and coordinate are conjugate variables
  - ➔ Diffraction pattern in momentum if coordinates restricted to a finite region



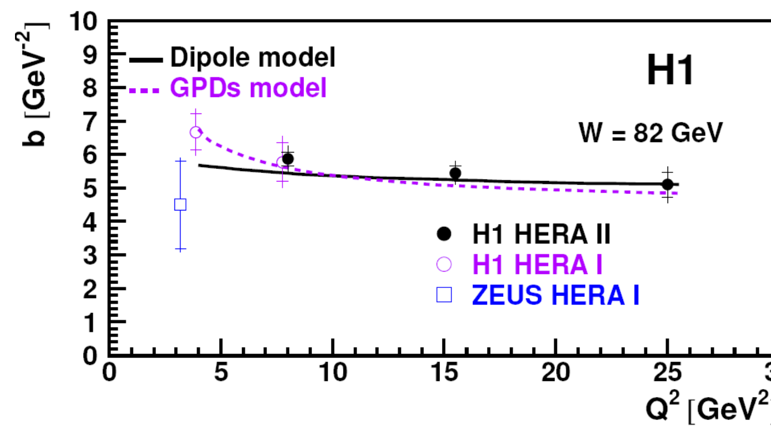
- Measurement of t-dependence of DVCS cross section performed at different values of Q^2 and W



[H1, PLB 659 (2008) 796]



$$\frac{d\sigma}{d|t|} \propto e^{-b|t|}$$



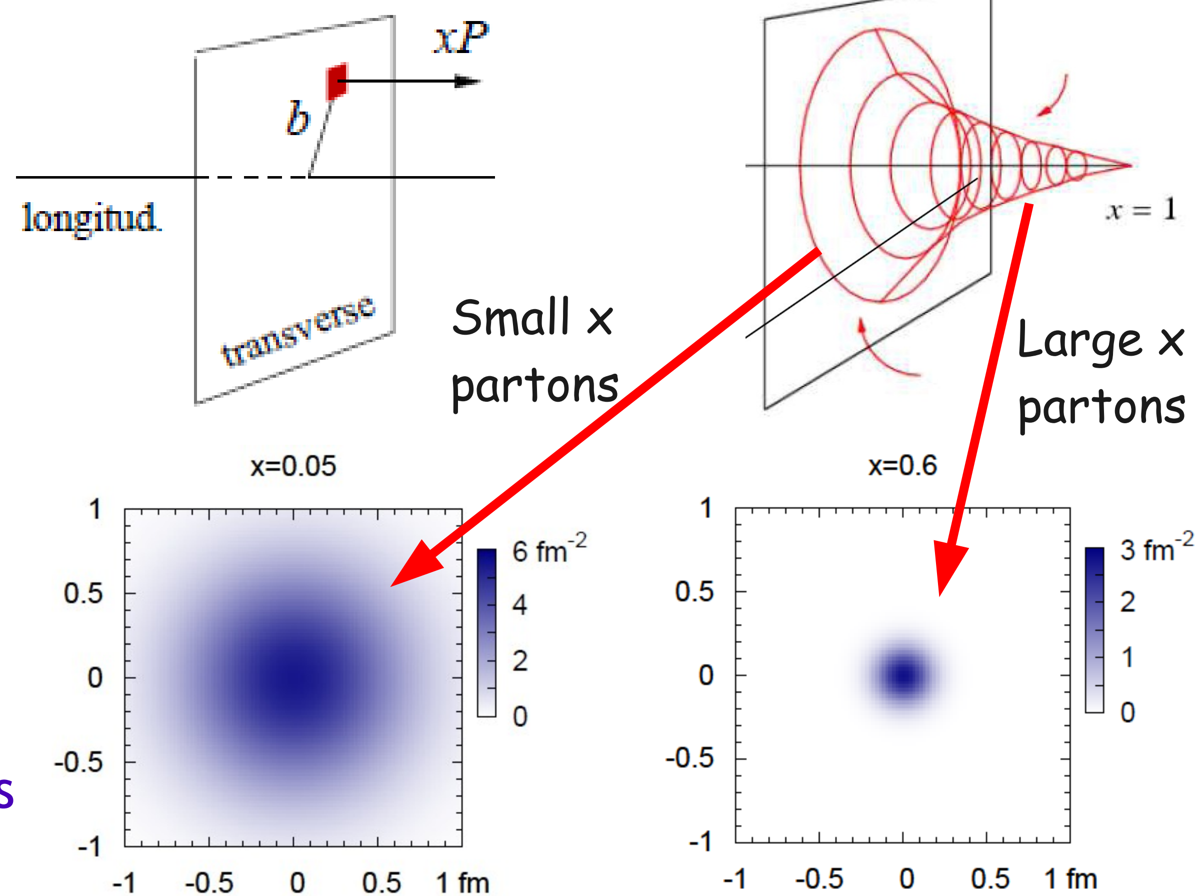
- No dependence with W observed

3D imaging of the proton

- From $\frac{d\sigma}{d|t|} \propto e^{-b|t|}$ via Fourrier transform to impact parameter
  - ➔ In analogy with 2D from factor measurements, is related to transverse extension of the proton

➘ $\sqrt{< r_T^2 >} = 0.64 \pm 0.02 \text{ fm}$

Extension of sea and gluons at low x



- A core of “fast” valence quarks
- Surrounded by a cloud of “slow” gluons and sea quarks

➘ Direct measurement performed for x ~ 1.2 10^{-3}

➘ Only indirect determinations exists for high x

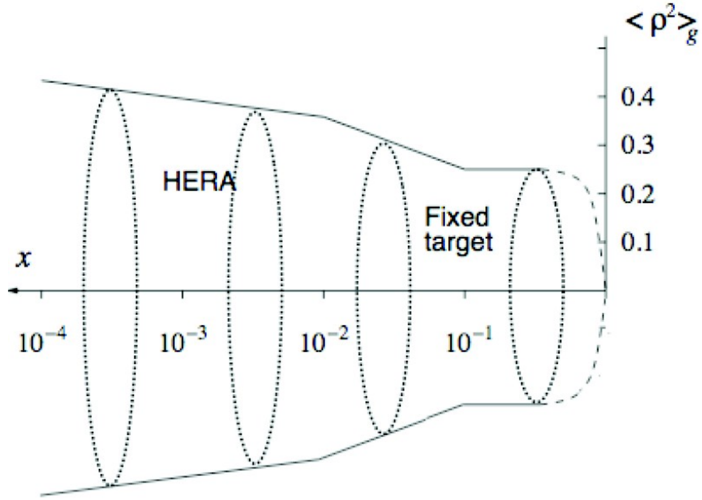
3D structure of the proton and the LHC

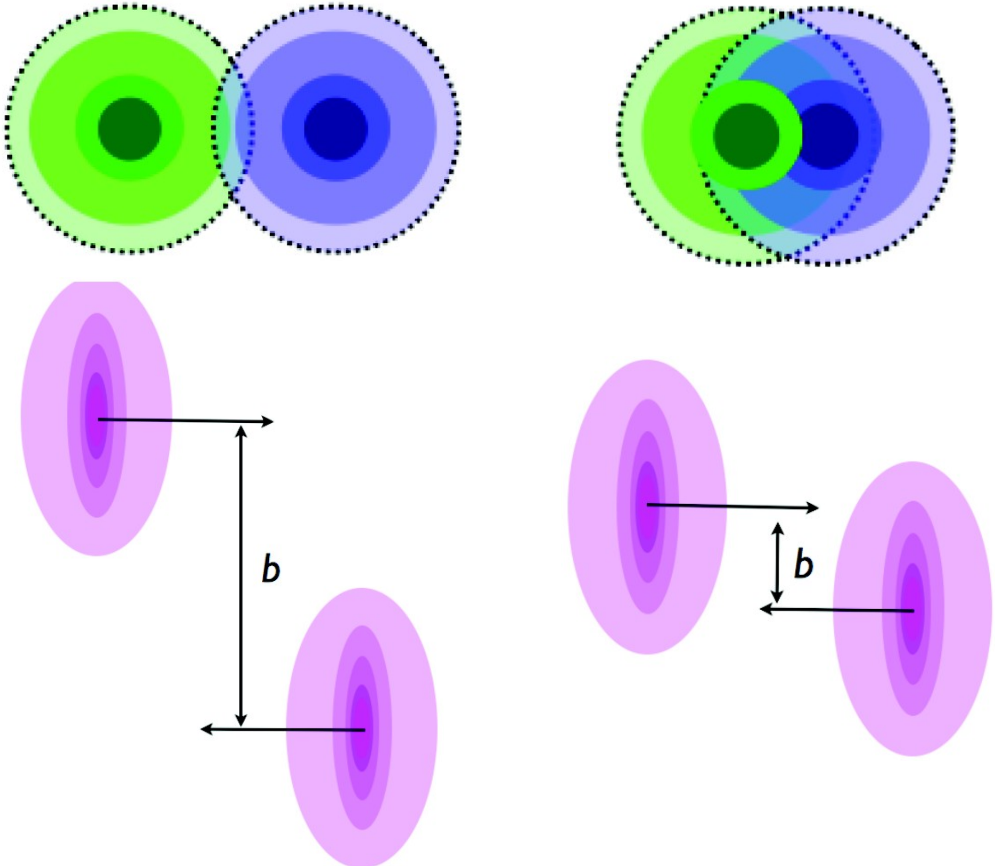
- In pp collisions: secondary interactions, besides the hard one

➔ High x needed to produce high mass particles

➔ Central collisions

➔ Increased probability of multiple interactions



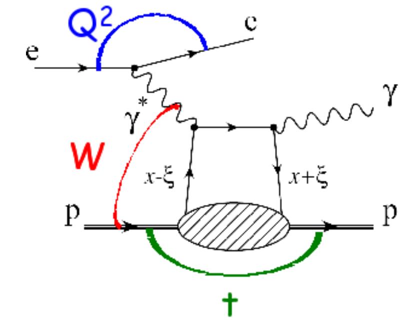


Peripheral pp collision Central pp collision

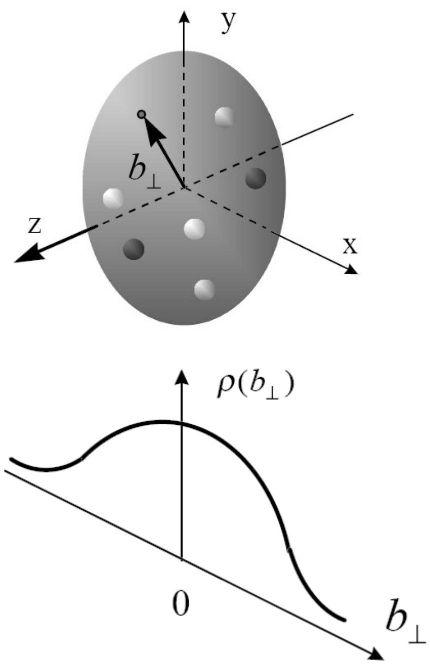
➘ The harder the collision, the bigger the probability of another collision

Generalised Parton Distributions

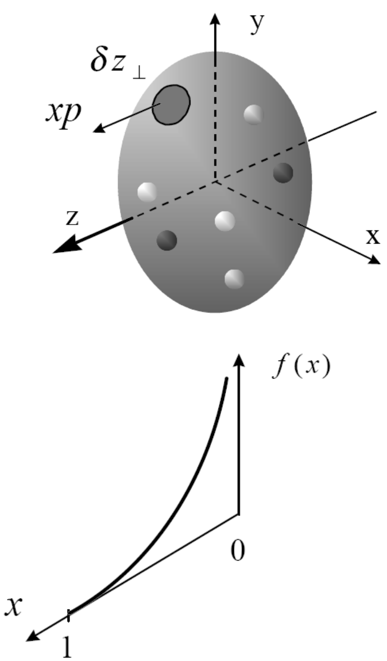
- A 3D description of the proton
- Interpolates between form factors and PDFs
- Includes correlation between partons



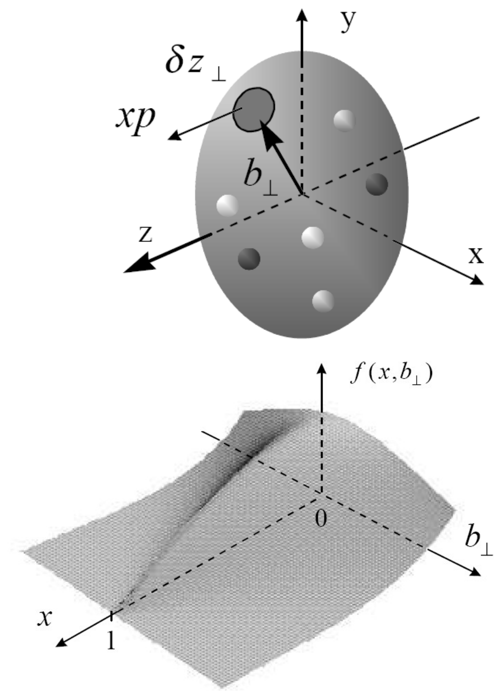
- Form factor



- Parton density



- Generalised parton distributions (at η=0)



➘ Total DVCS cross section related to imaginary part of GPDs

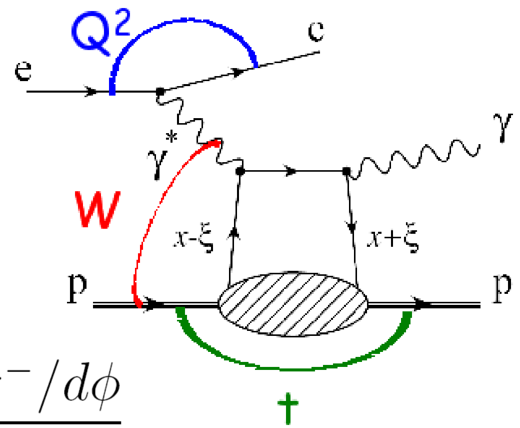
$$\sigma_{DVCS}(Q^2,W) \equiv \frac{[\mathcal{I}mA(\gamma^* p \to \gamma p)_{t=0}(Q^2,W)]^2\,(1+\rho^2)}{16\pi\, b(Q^2,W)}$$

DVCS Beam Charge Asymmetry

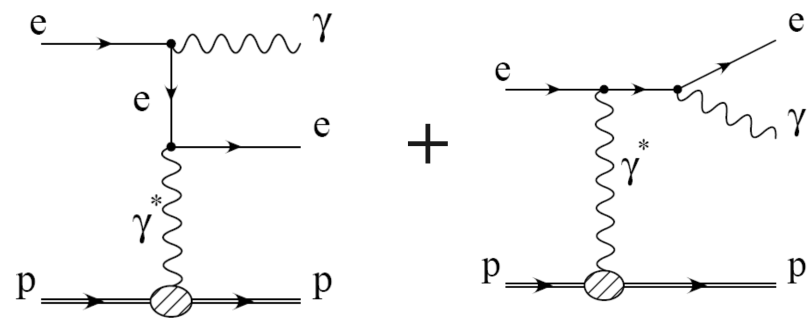
[H1, arXiv:0907.5289]

- Interference between DVCS and Bethe-Heitler

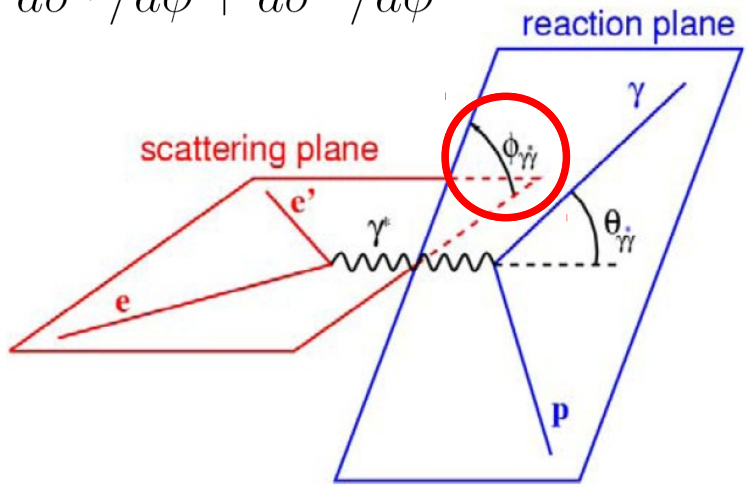
DVCS:
QCD process

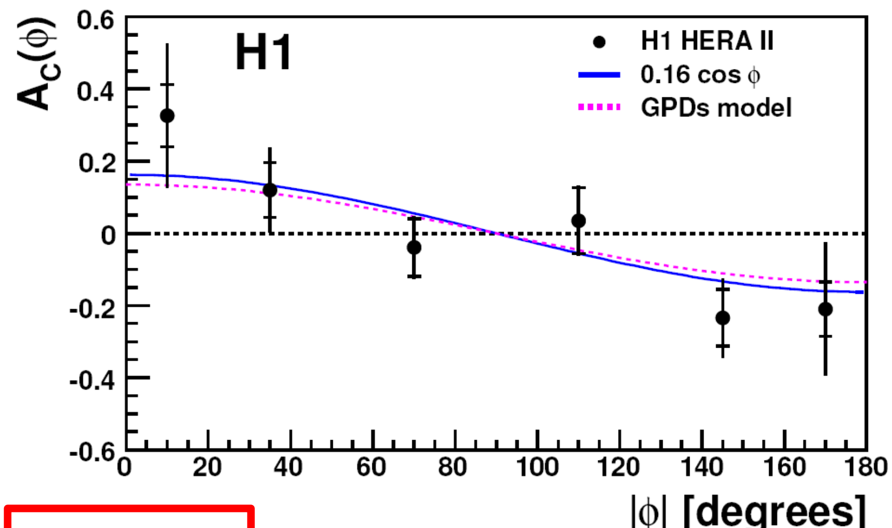


Bethe-Heitler: QED process



$$A_C(\phi) = \frac{d\sigma^+/d\phi - d\sigma^-/d\phi}{d\sigma^+/d\phi + d\sigma^-/d\phi}$$





$$A_C(\phi) = p_1 \cos\phi = 2A_{BH} \frac{\boxed{\mathrm{Re} A_{DVCS}}}{|A_{DVCS}|^2 + |A_{BH}|^2} \cos\phi$$

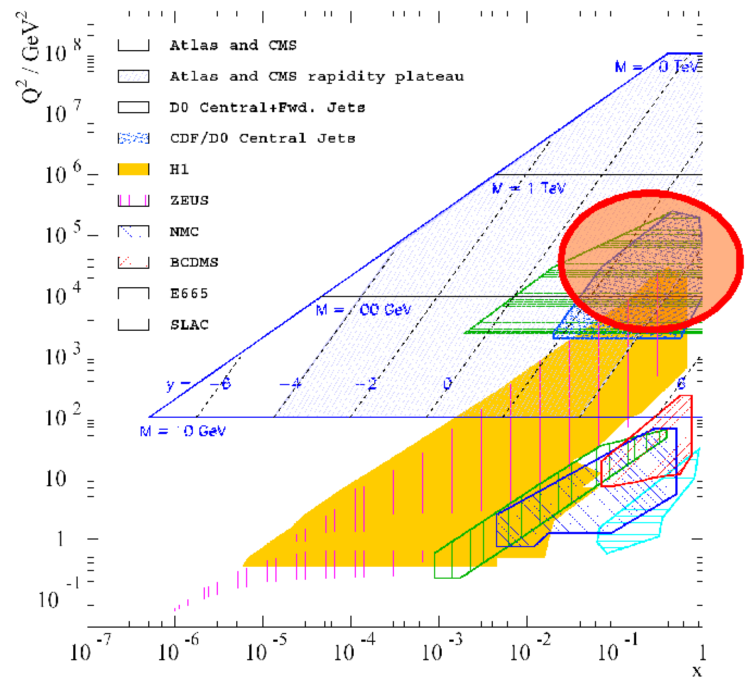
➔ Related to the real part of the DVCS amplitude

➘ $\mathrm{Re}A_{DVCS}$ = integral of GPDs over the whole x domain

The high energy frontier of the SM

- New physics is expected to appear at ~ 1 TeV
  - ➔ Effects could be visible at highest energy colliders: LEP, HERA and Tevatron

- ep interactions complementary to e^+e^- or pp
  - ➔ $\mathscr{L}$ ~ 0.5 fb^{-1}: search for processes with σ < 1 pb
  - ➔ Parton luminosity: HERA collides beyond LEP
  - ➔ Backgrounds: HERA has less than Tevatron



➘ 2 complementary approaches:

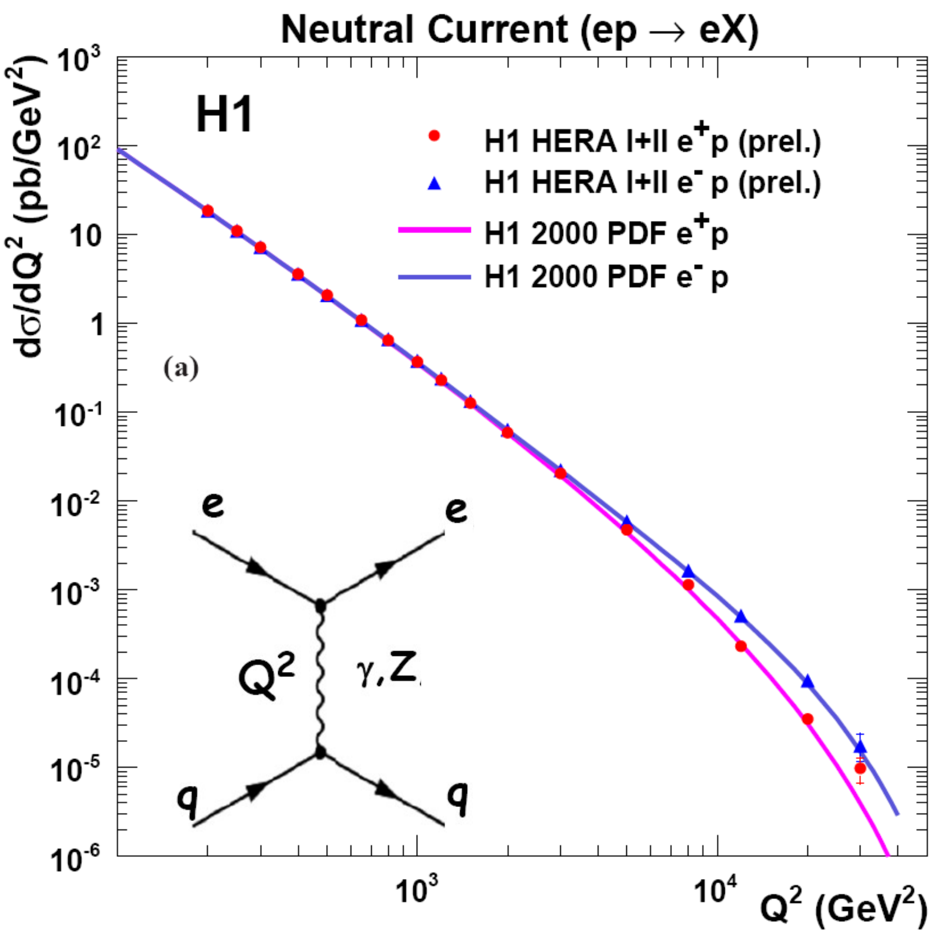
- ➔ Model-driven searches
- ➔ Model-independent searches

Deeper into Matter Structure

➘ Repeat the history: diffusion of point-like particles on matter

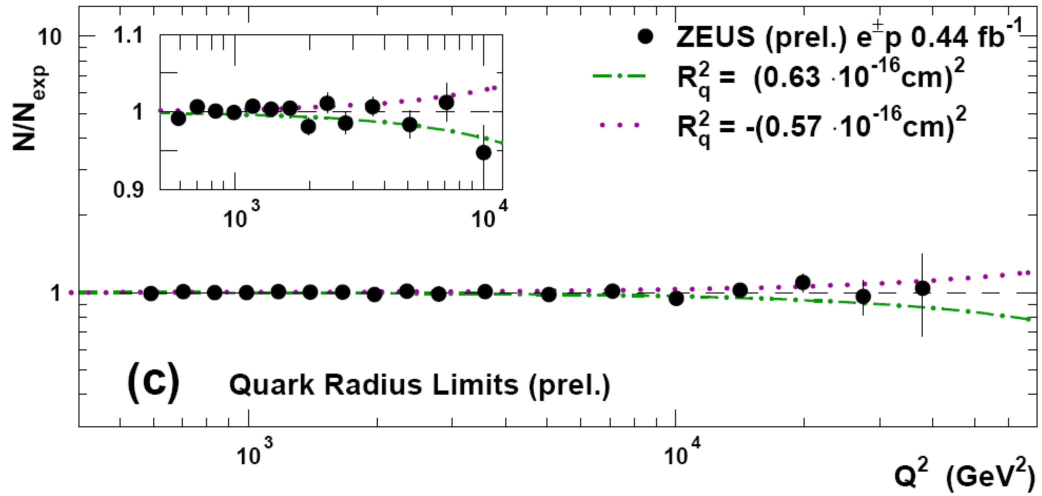
- Atom → Nucleus → Nucleon → Quark (→ ?)

➔ DIS scattering of e on q



➔ A finite size of quarks EW charge distribution

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



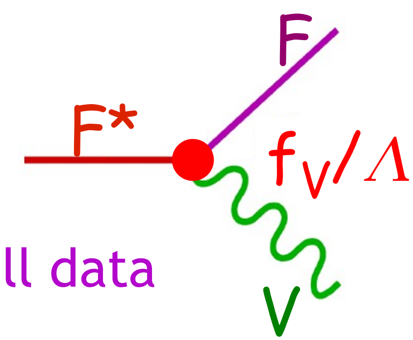
➘ $R_q < 0.63\ 10^{-18}$ m (ZEUS)

➘ $R_q < 0.74\ 10^{-18}$ m (H1)

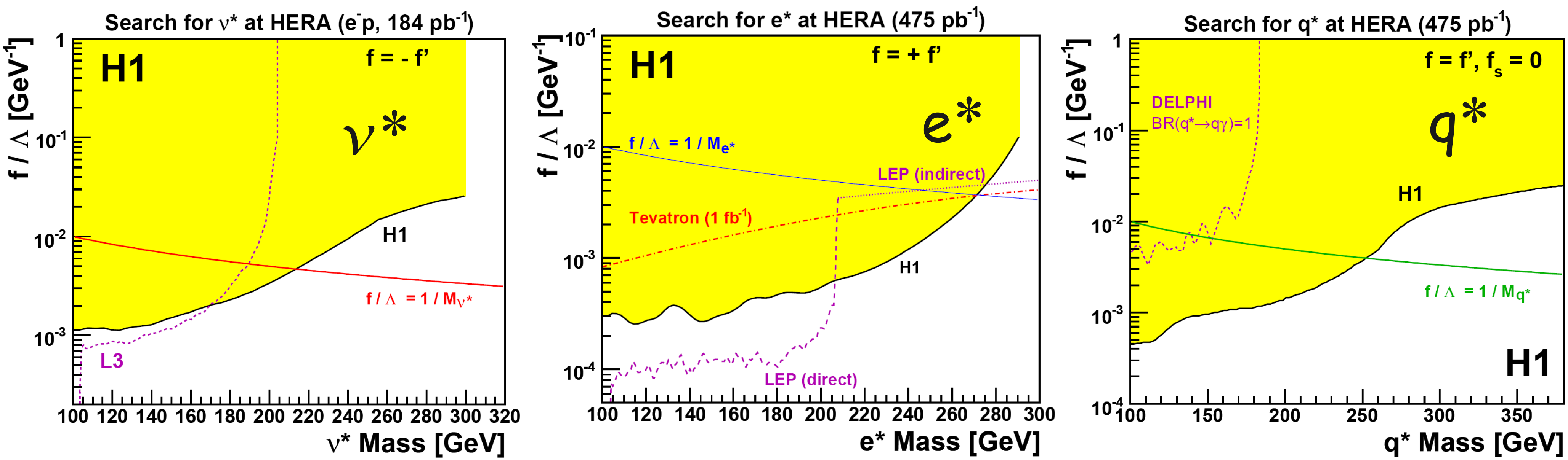
Compositness

[H1, PLB 663 (2008) 382]
[H1, PLB 666 (2008) 131]
[H1, PLB 678 (2008) 335]

- A direct manifestation of new substructures
  - ➔ Existence of fermion excited states
  - ➔ Searches via decays to fermion+ boson



- ep colliders well suited
  - ➔ A complete scan performed by H1 at HERA, using all data
  - ➔ ν*, e* and q* searched for

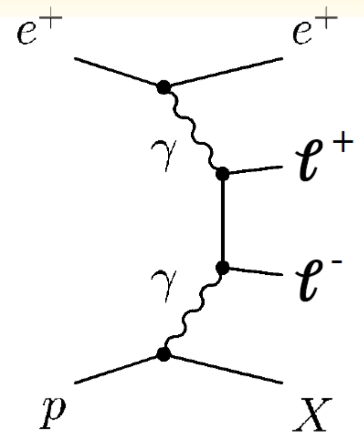


➘ For l*: HERA has the best sensitivity in $\sqrt{s_{LEP}}$ = 200 < M_{l^*} < 300 GeV

➘ For q*: complementary to Tevatron for small fs

Multi-Leptons Final States

[H1, EPJC 31 (2003) 17]
[H1, PLB 638 (2006) 432]
[H1, PLB 668 (2008) 268]
[H1 and ZEUS, JHEP 10 (2009) 013]



σ ~ 1 pb (high P_T)

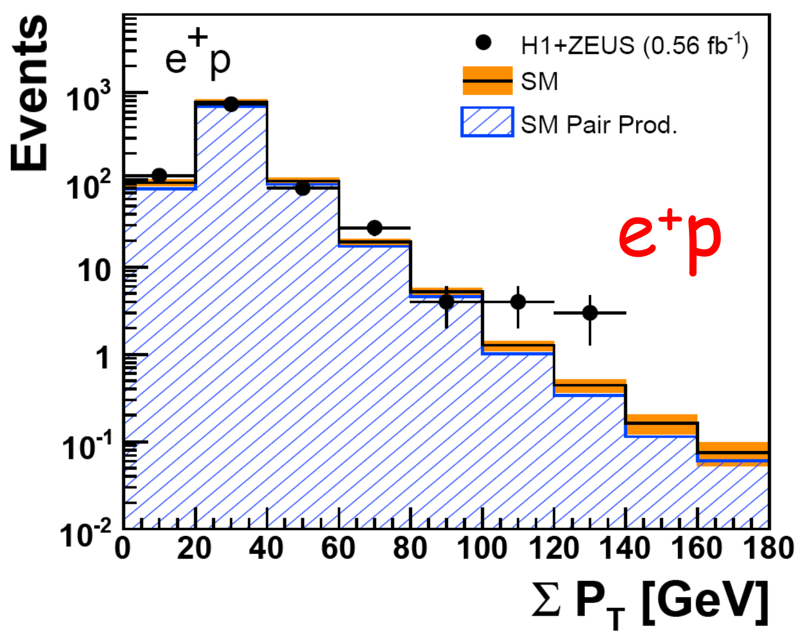
↘ Low and well controlled SM contribution

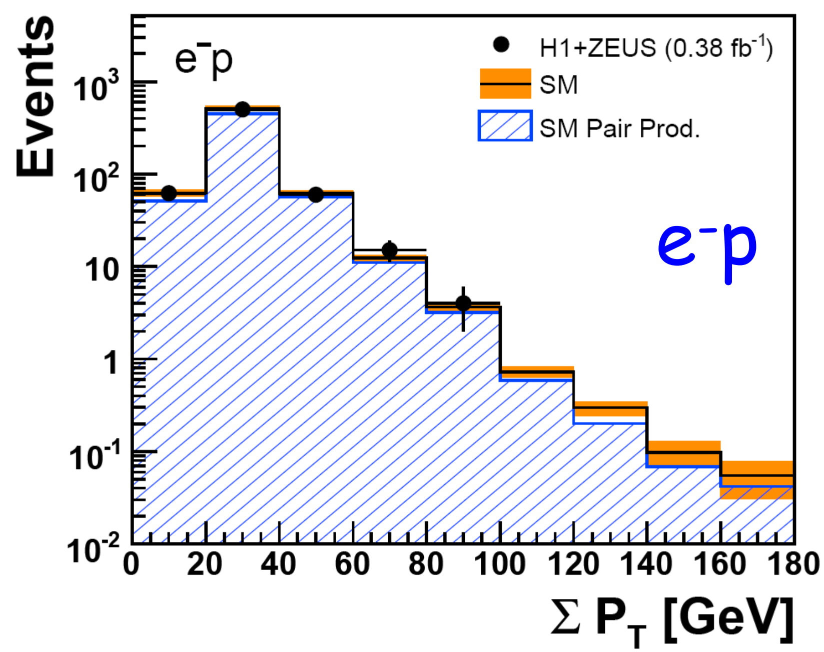
- Mainly produced via γ-γ in the SM
- Look for events with at least 2 isolated high-P_T leptons (e,μ)

  ➔ ee, eee, eμ, $\mu\mu$, e$\mu\mu$

- H1+ZEUS combined analysis (0.94 fb^{-1})

  ➔ ΣP_T : hardness of the events





➔ Striking events observed for ΣP_T > 100 GeV by H1 and ZEUS

➔ Only in e+p : 7 / 1.94 ± 0.17 ↘ Probability of 0.4% (2.6σ)

A General Search at HERA

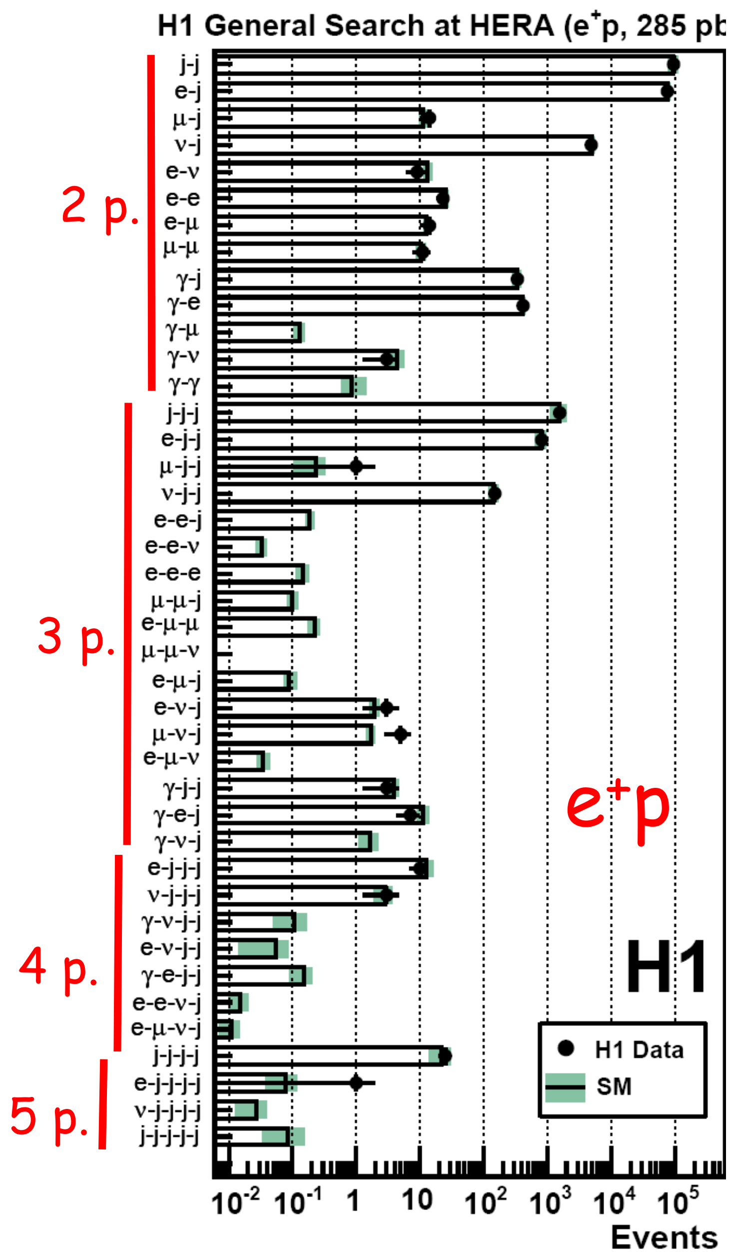
[H1, PLB 602 (2004) 14]
[H1, PLB 674 (2009) 257]

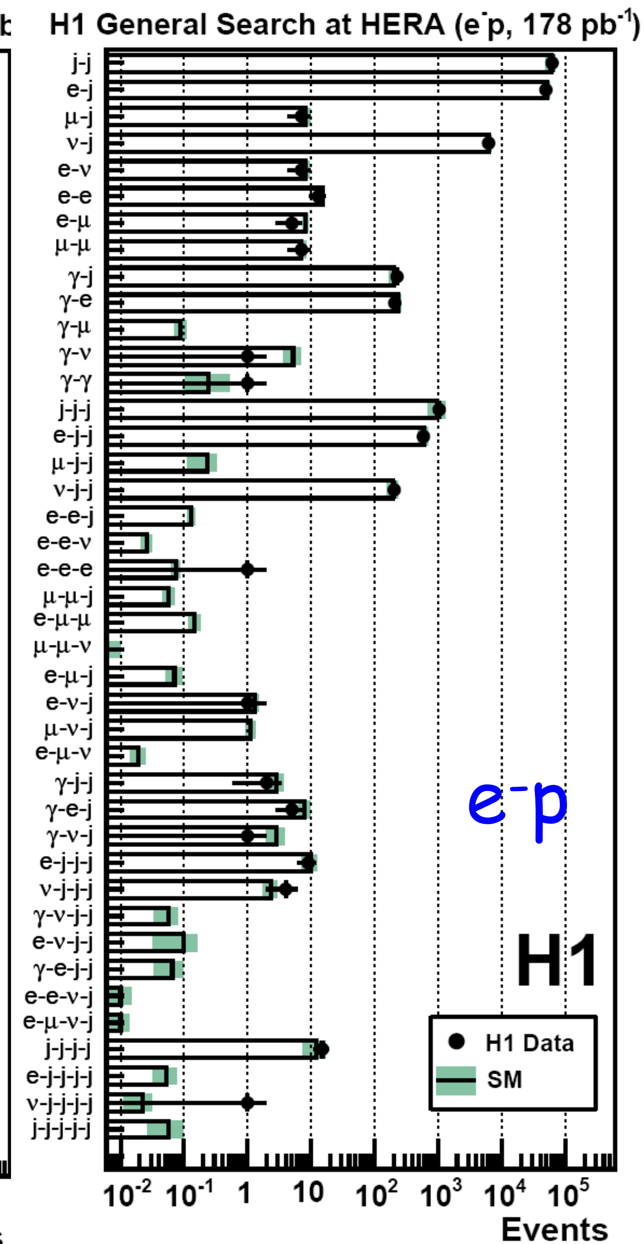
➘ Investigate all high P_T topologies

- Pioneered by H1, full HERA data, 463 pb^{-1}
- Isolated particles
  ➔ e, γ, μ, jet, ν
- A common phase space
  ➔ P_T^{part} > 20 GeV
  ➔ 10 < θ^{part} < 140 deg.

➔ Good agreement with SM in most classes

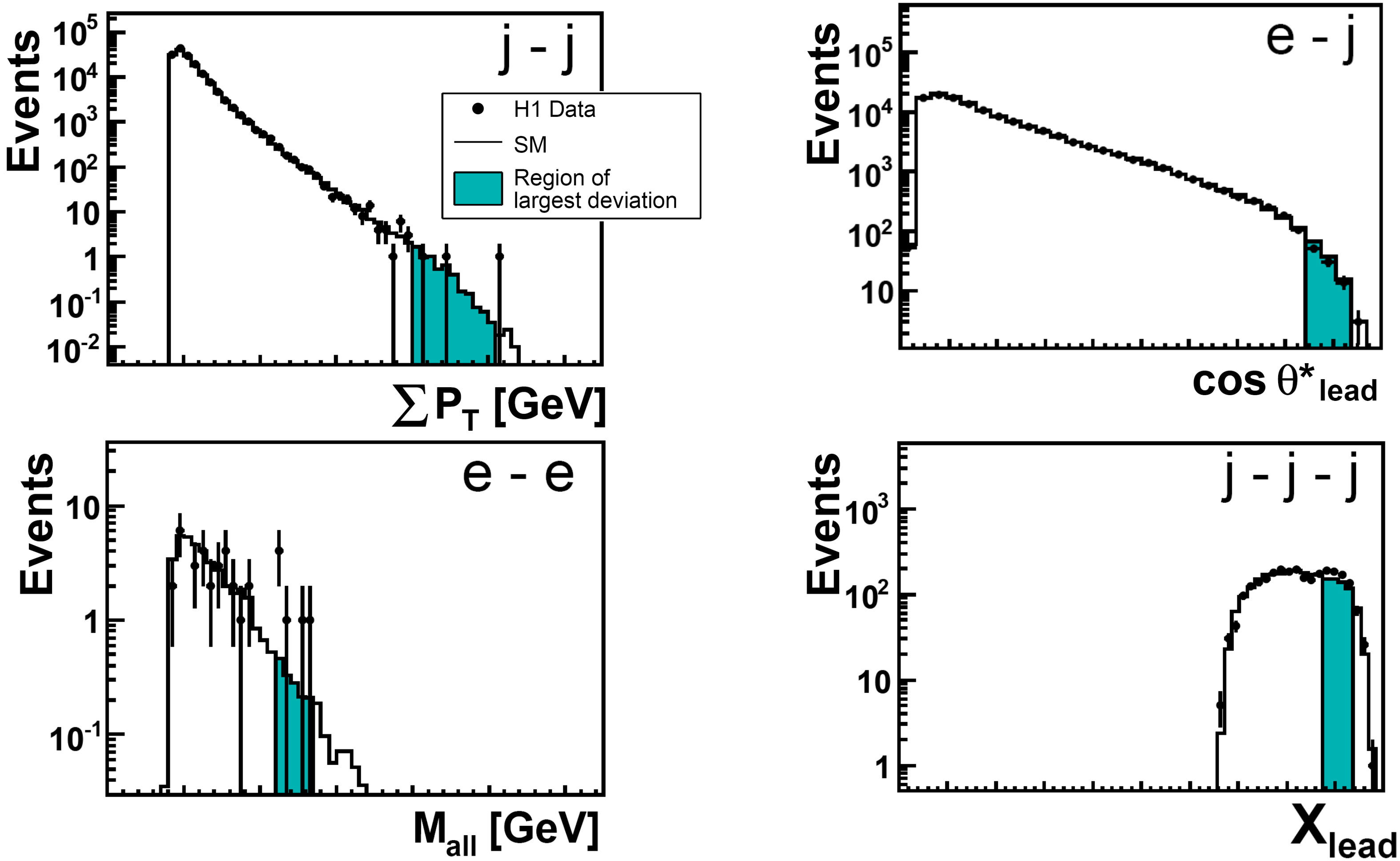
➘ Good understanding of the detector and of SM processes





A General Search at HERA

- Look for regions of data/SM discrepancies in 1D distributions:
  - ➔ ΣP_T, M_{all}
  - ➔ Topological variables: angle and energy sharing



$$X_{\mathrm{lead}} = \frac{2E^*_{\mathrm{lead}}}{\sum_i E^*_i}$$

↘ Largest deviation observed in e+p, in e-e channel for M_{all} (~2.5σ)

↘ Global probability to observe such deviation in one of the channels: 12%

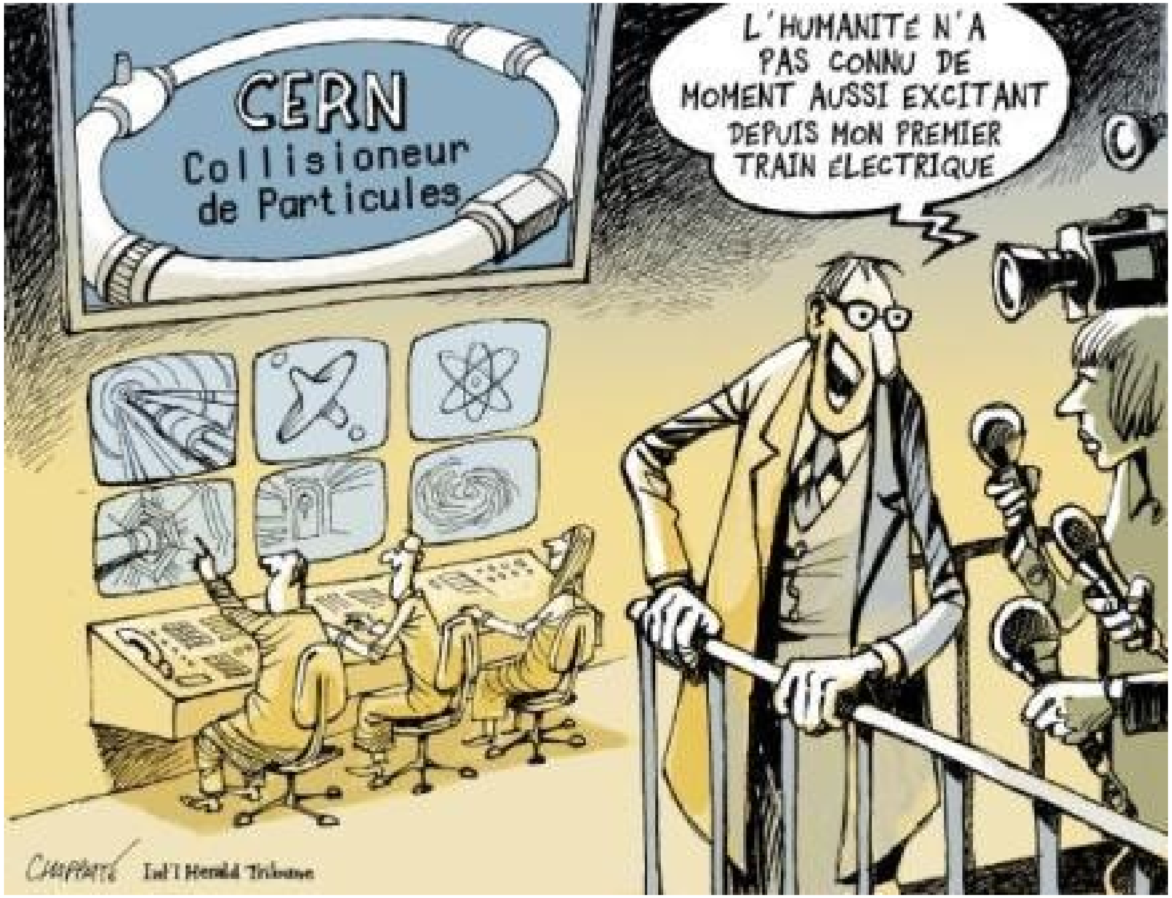
Summary

- The SM is still a largely unknown territory (QCD, ...)

- HERA was a unique machine, allowing to improve our knowledge of the SM

- LHC: primarily intended to attack the high energy frontier of the SM

➘ The understanding of the proton structure will be necessary for the study of LHC collisions

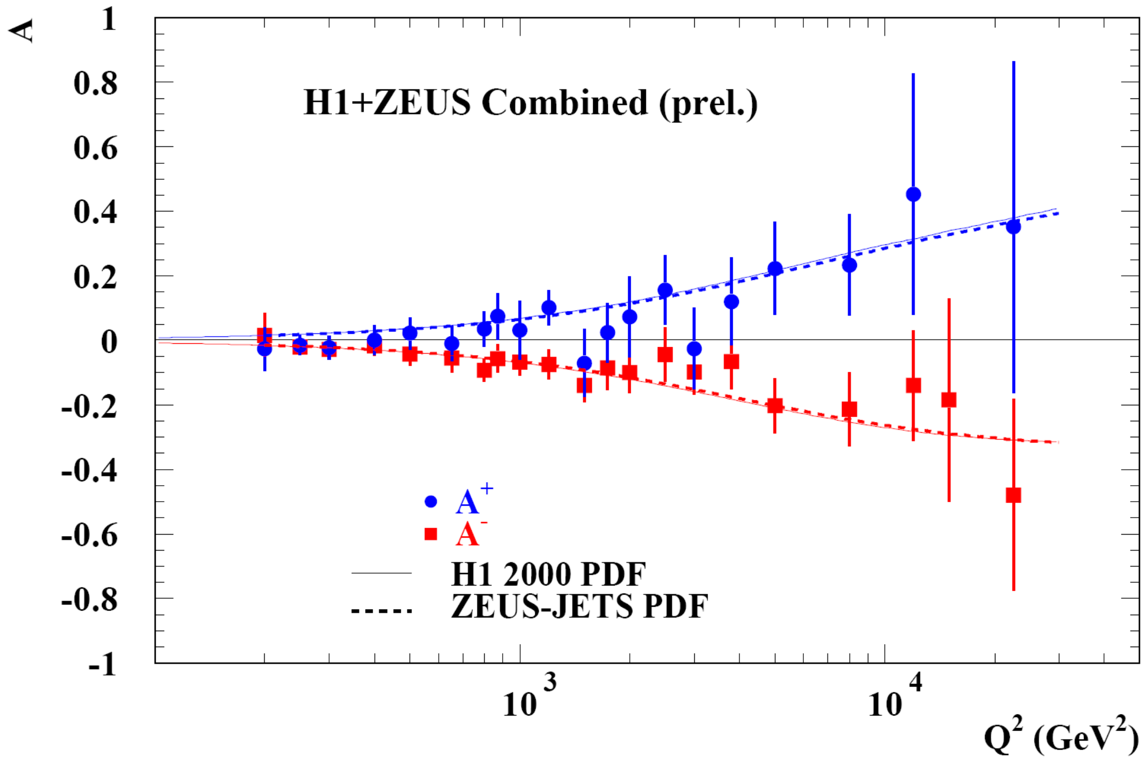


Additional Material ....

EW: Polarisation effects in NC

- Exploits e+/e- running and polarisation
  - ➔ Probes parity violation in γ-Z interference

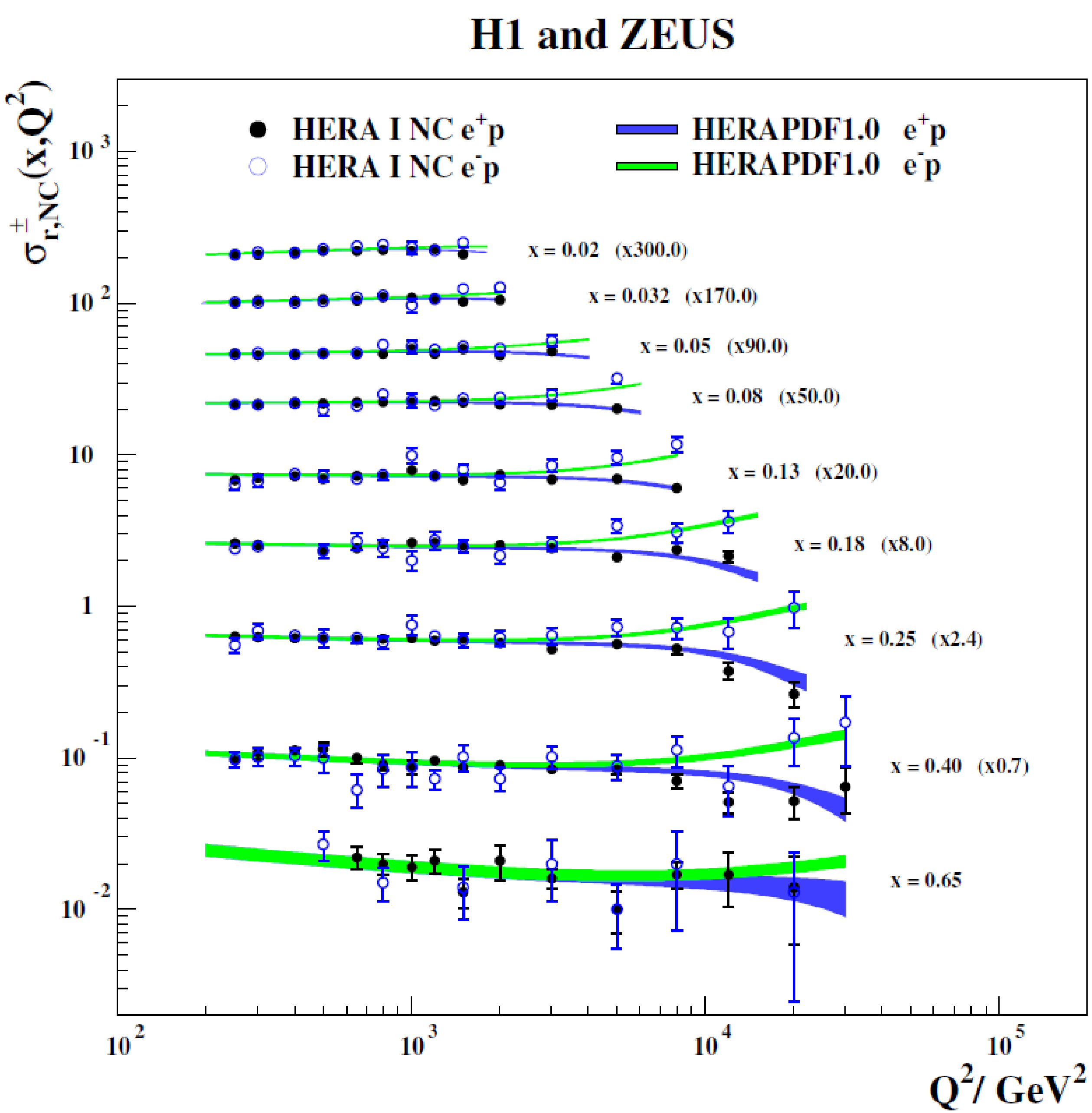
$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$



➘ First observation of parity violation in NC data down to 10^{-18} m

➘ Improvement foreseen with full H1+ZEUS data

XF_3 effect at high Q^2 in NC



EW-QCD fit

NC structure functions (SFs) have 3 or 2 well defined contributions from

γ exchange γZ interference Z exchange

$$\tilde{F}_2 = F_2 - (v_e + \underline{P_e a_e}) K_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 + 2P_e v_e a_e) K_Z^2 F_2^Z$$

$$x\tilde{F}_3 = -(a_e + P_e v_e) K_Z x F_3^{\gamma Z} + [2 v_e a_e + P_e (v_e^2 + a_e^2)] K_Z^2 \, x F_3^Z$$

$$K_Z = \frac{Q^2}{Q^2 + M_Z^2} \frac{1}{4 \sin^2\theta_W \cos^2\theta_W}$$

$$[F_2, F_2^{\gamma Z}, F_2^Z] = x \sum [e_q^2, 2 e_q v_q, v_q^2 + a_q^2](q + \bar{q})$$

$$[xF_3^{\gamma Z}, xF_3^Z] = 2x \sum [e_q a_q, v_q a_q] \underbrace{(q - \bar{q})}_{\text{Valence quarks } u_v,\, d_v}$$

PDFs: Parton Distribution Functions
q=u,d,c,s,b & gluon g

Unpolarized e± (HERA I): coupling constrains mainly from F_2^Z and $xF_3^{\gamma Z}$ terms

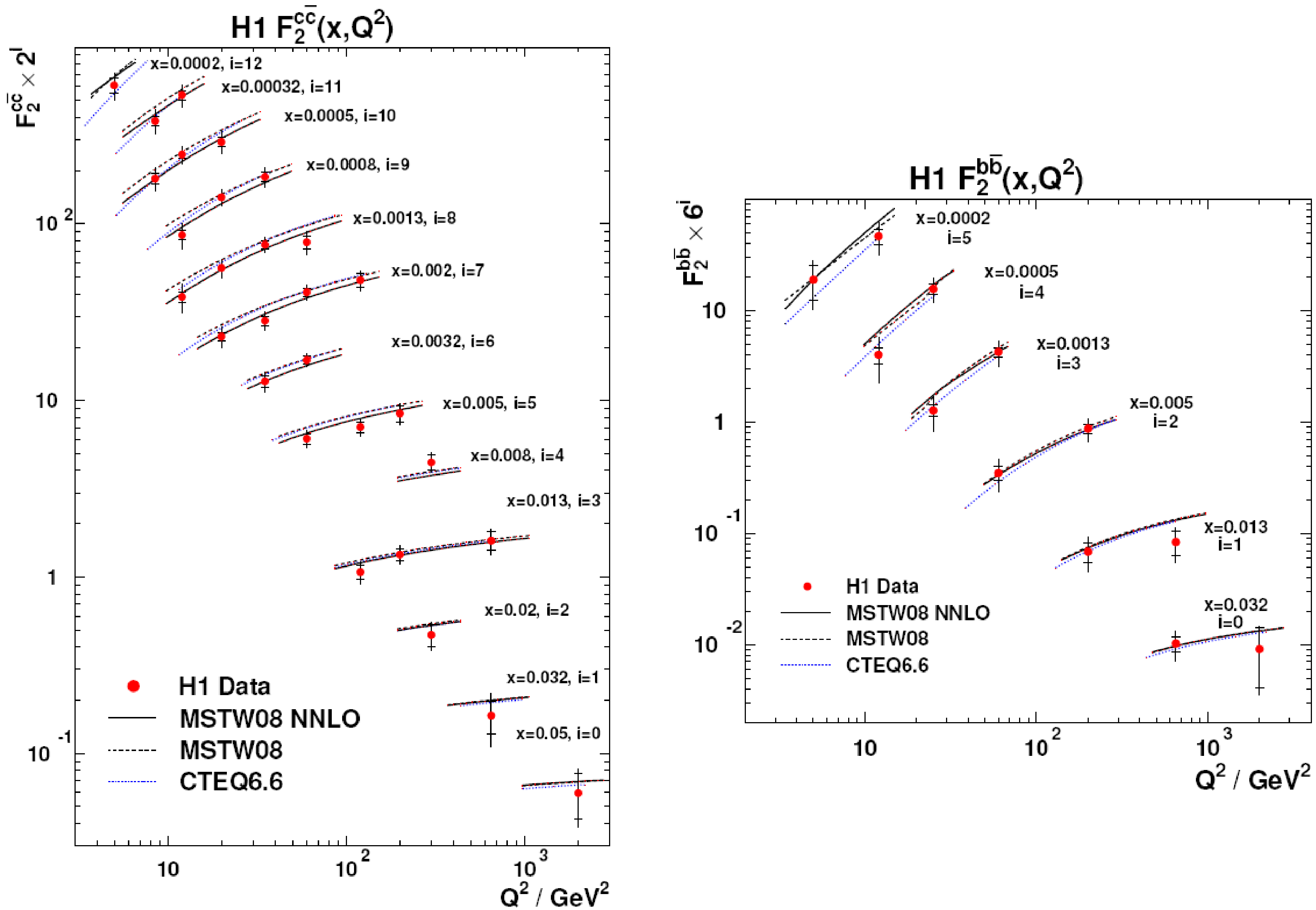
Polarized e± (HERA II): helps to constrain v_q

Other PDF constraints

- Fixed targets: valence quarks (d_v)
- Fixed target Drell-Yann ($pN \rightarrow \mu\mu$): $x\bar{d} - x\bar{u}$ at high x
- Muon pairs in neutrino-nucleon scattering: s and $\bar{s}$
- Gluons: jets at HERA (middle x), jets at Tevatron (high x)
- W^+/W^- at Tevatron: d/u ratio at medium x

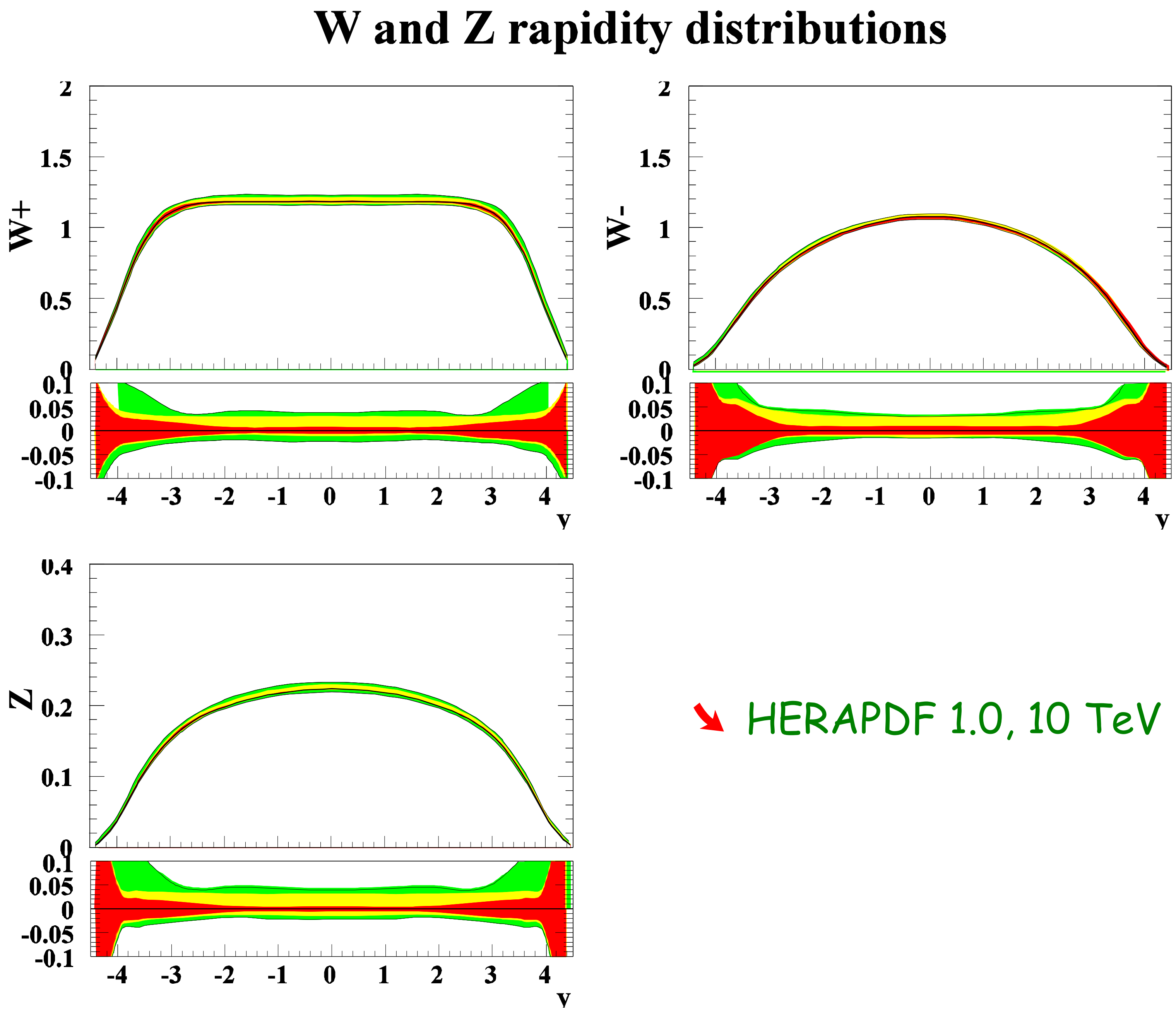
- LHC: Z production may reduce pdf uncertainties for W
- Asymmetries in W production: for the first time constraints on valence quarks at low x

Charm and Beauty PDFs



W, Z predictions for LHC

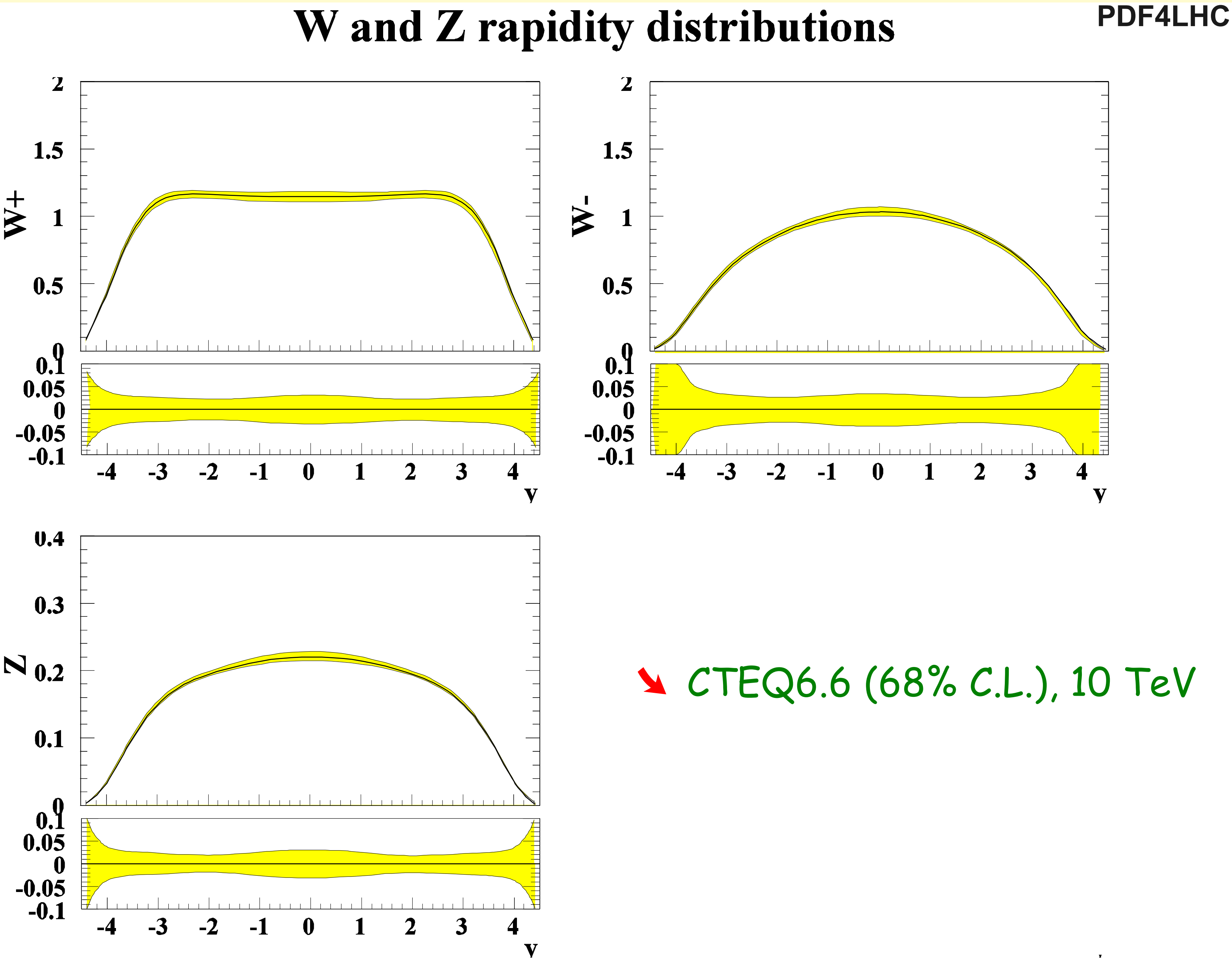
[A.M. Cooper Sakar, PDF4LHC Workshop]



➘ HERAPDF 1.0, 10 TeV

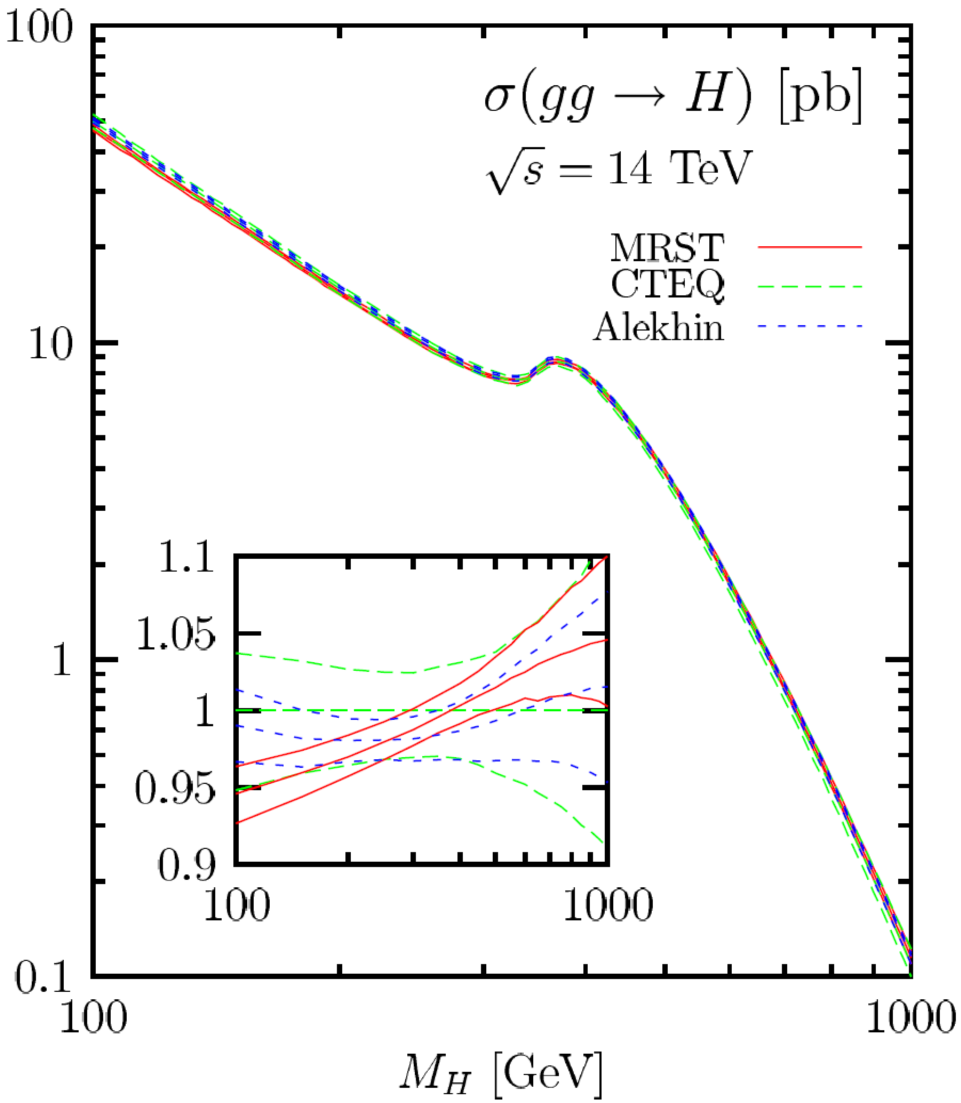
W, Z predictions for LHC

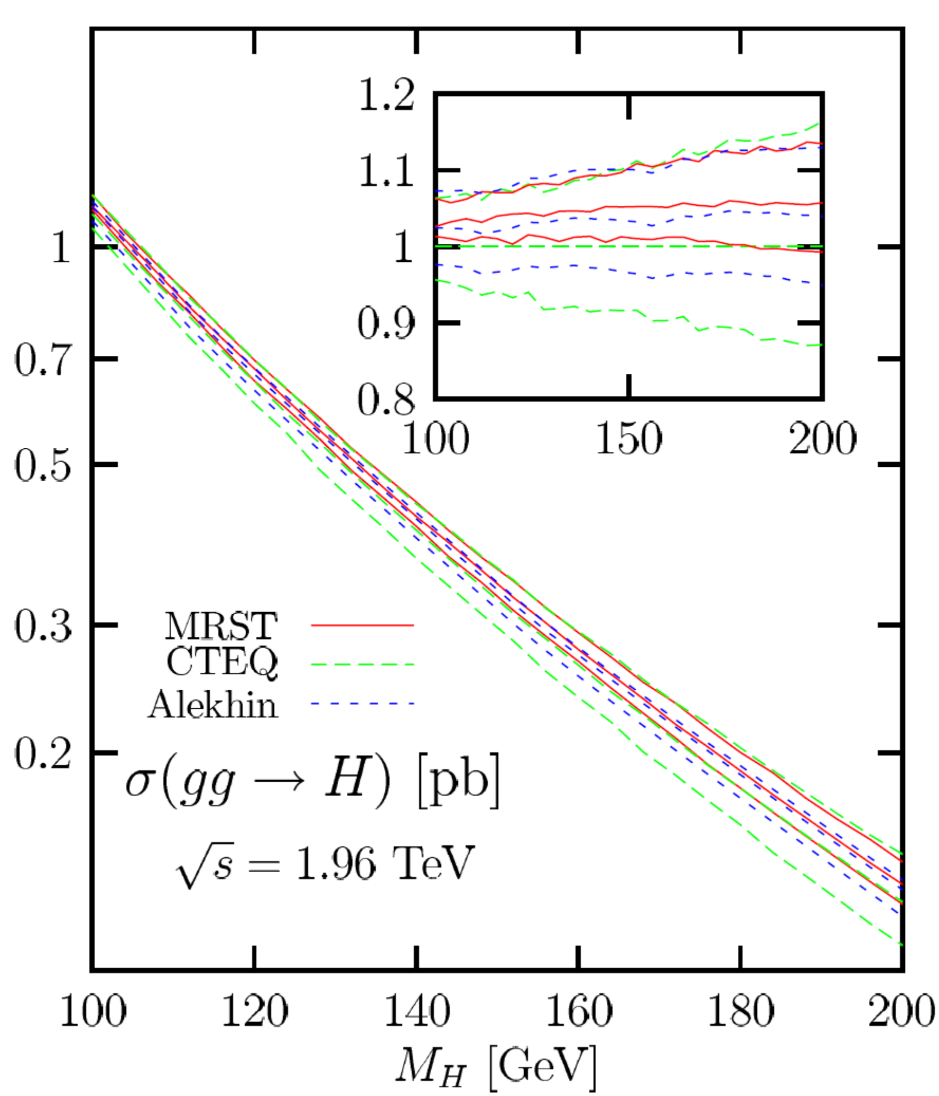
[A.M. Cooper Sakar, PDF4LHC Workshop]



CTEQ6.6 (68% C.L.), 10 TeV

Impact of PDF on H at the LHC



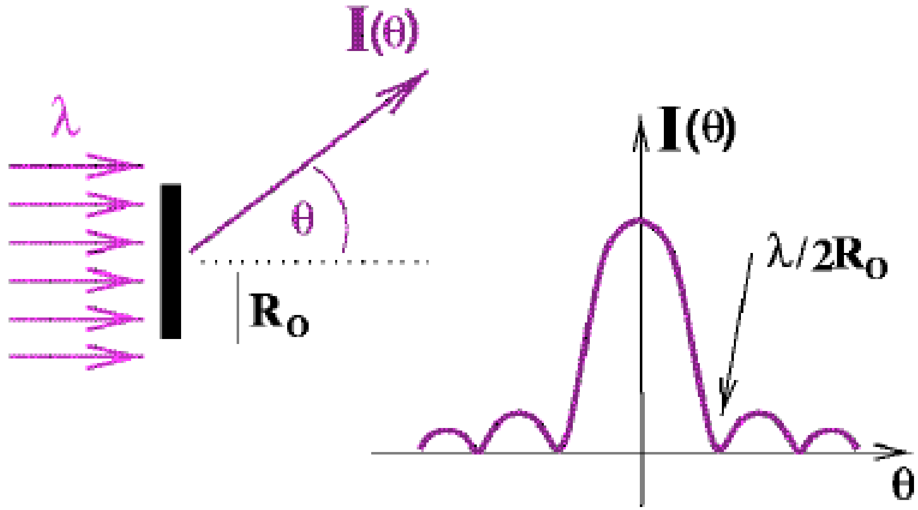


A. Djouadi, S. Ferrag, *Phys. Lett.* **B586**, 345 (2004)

Why "Diffraction"

[M. Ruspa]

Term introduced in nuclear high-energy physics in the 50's, used in strict analogy with optics

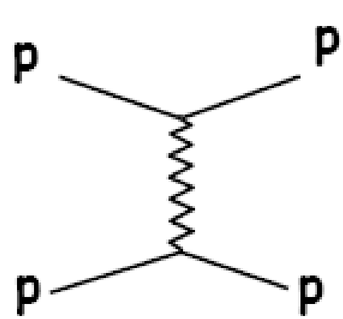


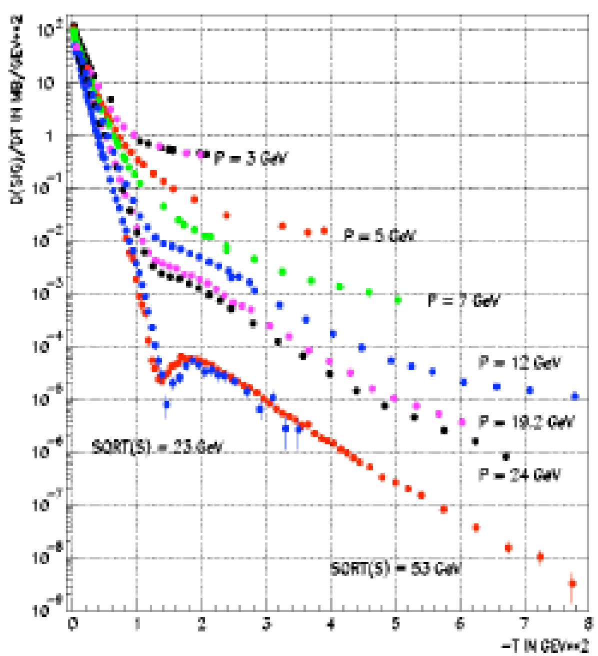
$$\frac{I(\vartheta)}{I(\vartheta=0)} \approx 1 - \frac{R_0^2}{4}(k\vartheta)^2 \qquad k = \frac{2\pi}{\lambda}$$

Forward peak for $\theta=0$ (diffraction peak)

Diffraction pattern related to size of target and wavelength of beam

Propagation/interaction of a a hadron → absorption of its wave function





$$\frac{d\sigma/dt(t)}{d\sigma/dt(t=0)} \approx \exp(bt) \approx 1 - b(p\theta)^2$$

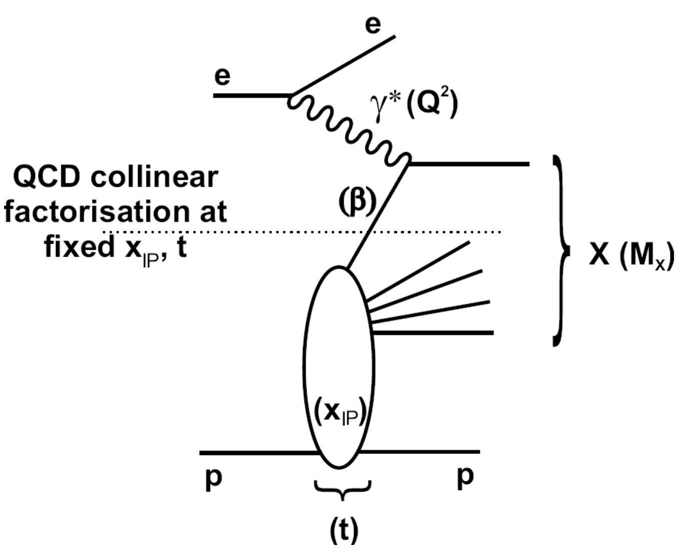
$|t| \approx (p\theta)^2$ 4-momentum transfer

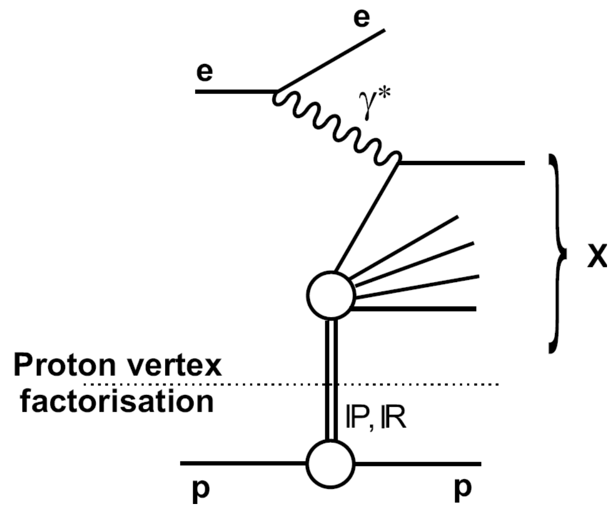
ϑ scattering angle

$b = R^2/4$

R transverse distance projectile-target

“Regge” Factorisation

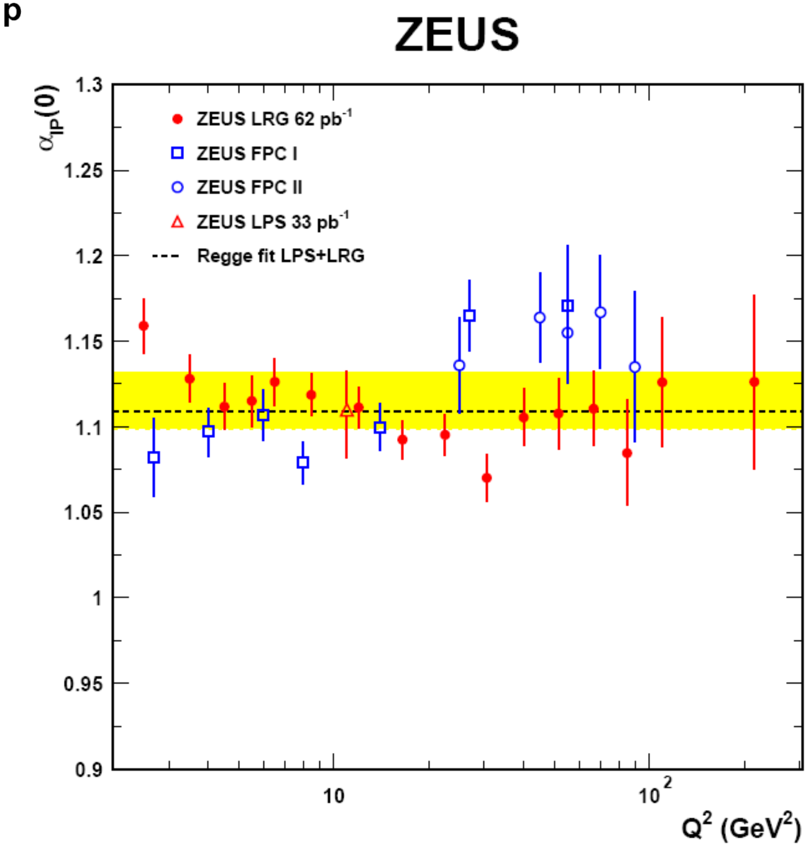




$$f_i^D(x_{I\!P}, t; \beta, Q^2) = f(x_{I\!P}, t)\, f_i^{I\!P}(\beta, Q^2)$$

$$f(x_{I\!P}, t) = \frac{B^2(t)}{8\pi^2}\, x_{I\!P}^{1-2\alpha_{I\!P}(1)}$$

$$\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha' t$$



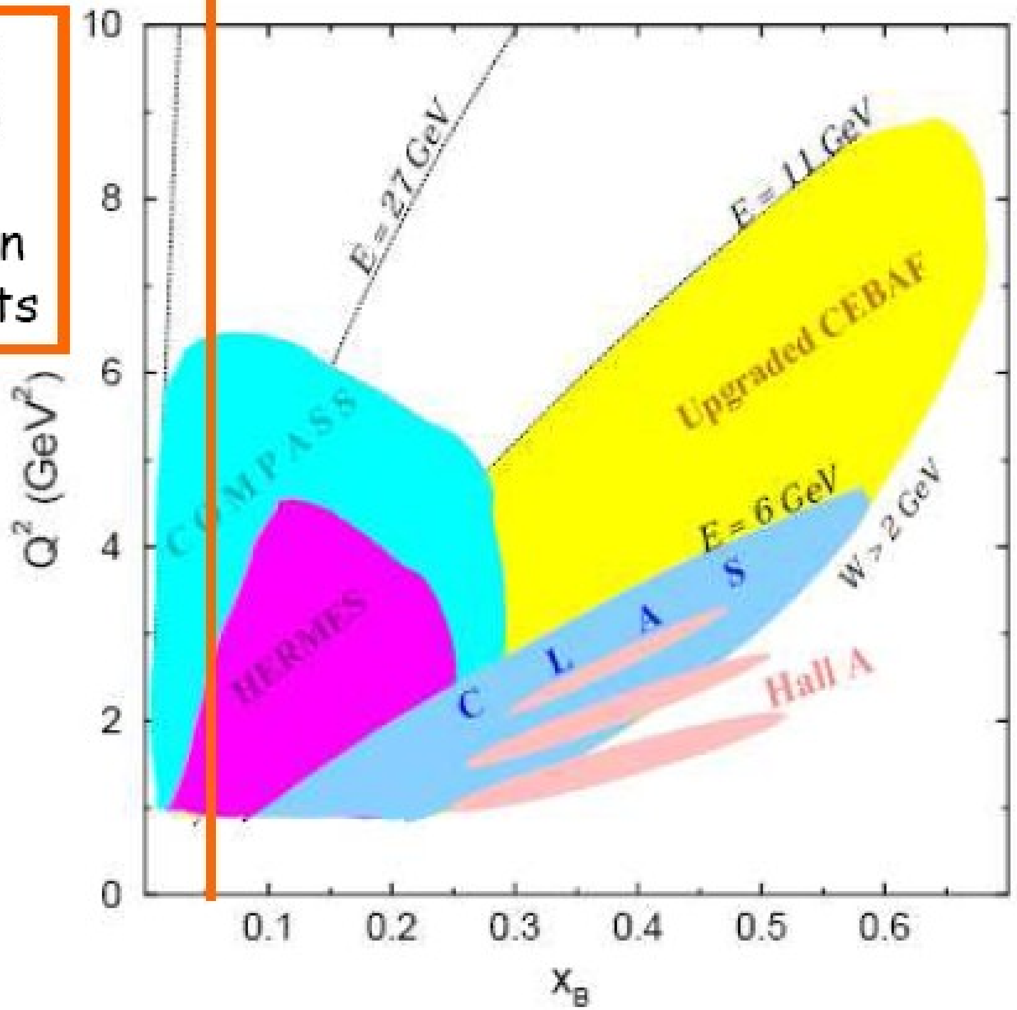
DVCS: HERA and other experiments

tests of the Q^2 evolution and pQCD : GPDs + dipole models

H1/ZEUS

BH >> DVCS => asymetries

DVCS > BH
f(topology)
=>
cross section
measurements



DVCS Beam Charge Asymmetry study

$$|\mathcal{T}_{\rm BH}|^2 = \frac{e^6}{x_{\rm B}^2 y^2 (1+\epsilon^2)^2 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\rm BH} + \sum_{n=1}^{2} c_n^{\rm BH} \cos(n\phi) + s_1^{\rm BH} \sin(\phi) \right\}$$

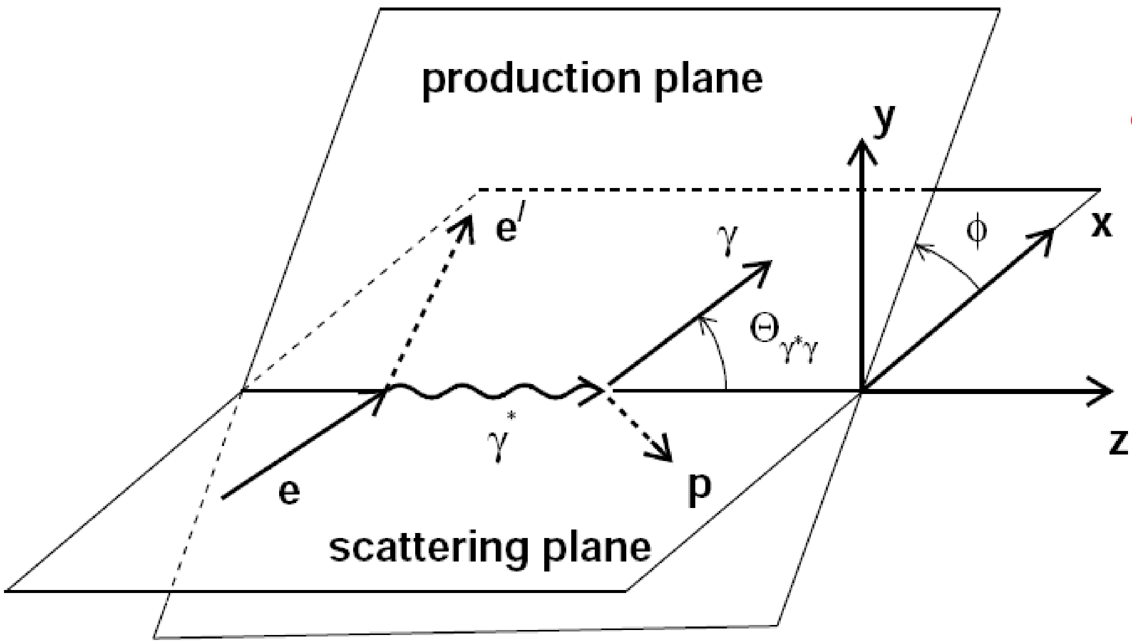
$$|\mathcal{T}_{\rm DVCS}|^2 = \frac{e^6}{y^2 \mathcal{Q}^2} \left\{ c_0^{\rm DVCS} + \sum_{n=1}^{2} \left[c_n^{\rm DVCS} \cos(n\phi) + s_n^{\rm DVCS} \sin(n\phi) \right] \right\}$$

$$\mathcal{I} = \frac{\pm e^6}{x_{\rm B} y^3 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} \left[c_n^{\mathcal{I}} \cos(n\phi) + s_n^{\mathcal{I}} \sin(n\phi) \right] \right\}$$

Beam Spin asymetry

Beam Charge asymetry

➔ Need to build asymmetries to disentangle the different contributions of the interference



- $\phi_{\rm bel}$ is the azimuthal angle between the lepton scattering plane (incoming/outgoing leptons) and photon production plane (virtual/real photon)

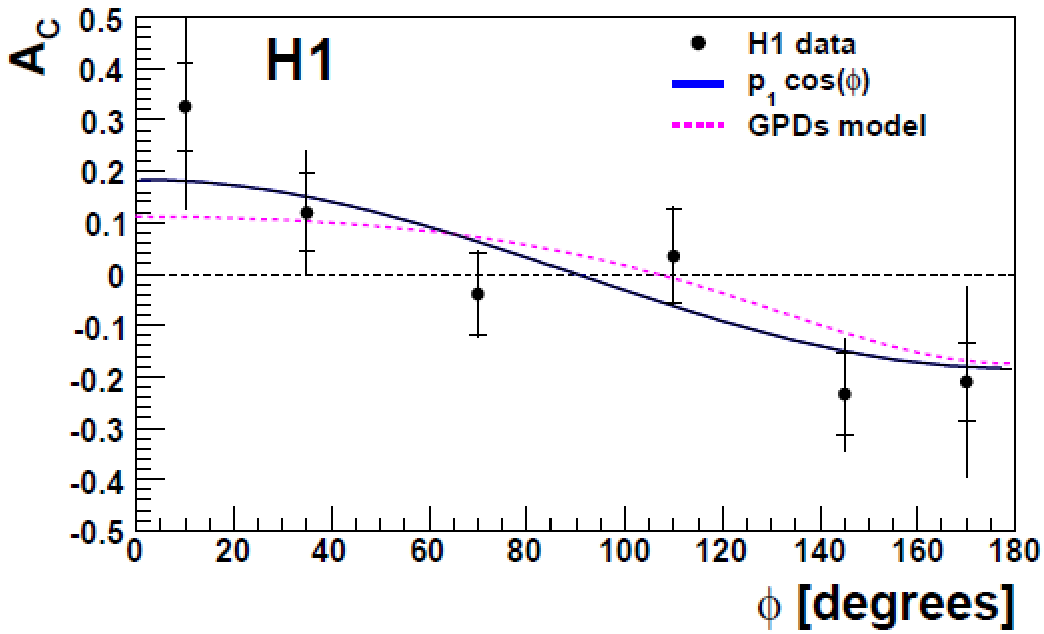
➔ Around z-axis defined by the γ^*

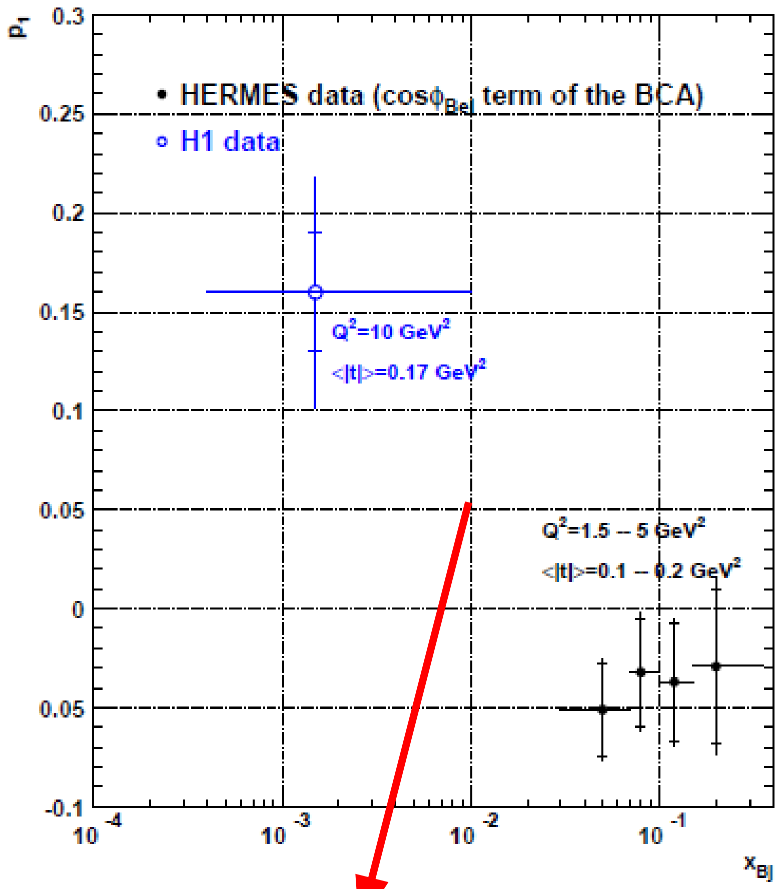
DVCS: Beam Charge Asymmetry

Compilation HERMES & H1 for p1 [BCA~p1 cos(Φ)]

Recent result from H1 (x_{Bj} ~10^{-3})

BCA ~ p1 cos(Φ) ~ 0.16 cos(Φ)



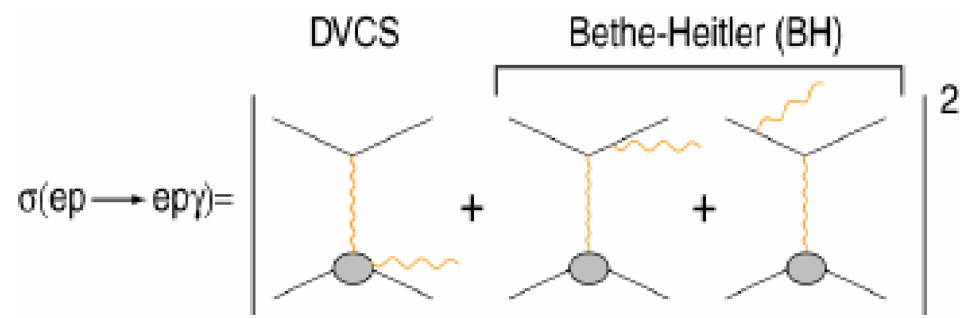


Without details: GPDs provide already a good description of data… work in progress…

Future COMPASS program

More complete expression

Belitsky, Müller, Kirchner '01



Let's neglect polarisation effects

$$d\sigma_{(\mu p\to\mu p\gamma)} = d\sigma^{BH} + d\sigma^{DVCS}{}_{unpol} + a^{BH}\,\mathcal{R}e\,A^{DVCS}$$

$$d\sigma^{BH} = \frac{\Gamma(x_B, Q^2, t)}{P_1(\varphi)P_2(\varphi)}\left(c_0^{BH} + c_1^{BH}\cos\varphi + c_2^{BH}\cos 2\varphi\right) \leftarrow \text{Known expression}$$

$$d\sigma^{DVCS}_{unpol} = \frac{e^6}{y^2 Q^2}\left(c_0^{DVCS} + c_1^{DVCS}\cos\varphi + c_2^{DVCS}\cos 2\varphi\right)$$

Sign of the incident lepton charge

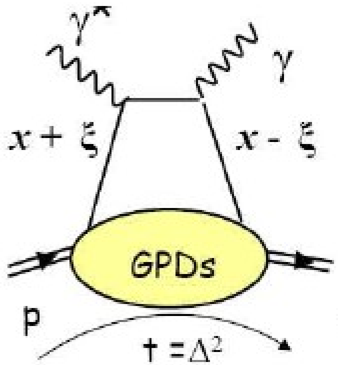
$$a^{BH}\Re e\,A^{DVCS} = \frac{+/-\ e^6}{xy^3 t P_1(\varphi)P_2(\varphi)}\left(c_0^{Int} + c_1^{Int}\cos\varphi + c_2^{Int}\cos 2\varphi + c_3^{Int}\cos 3\varphi\right)$$

== expected to be negligeable (for indication)

Twist-2 M^{11} — Twist-3 M^{01} — Twist-2 gluon M^{-11}

Interest of BCA measurement

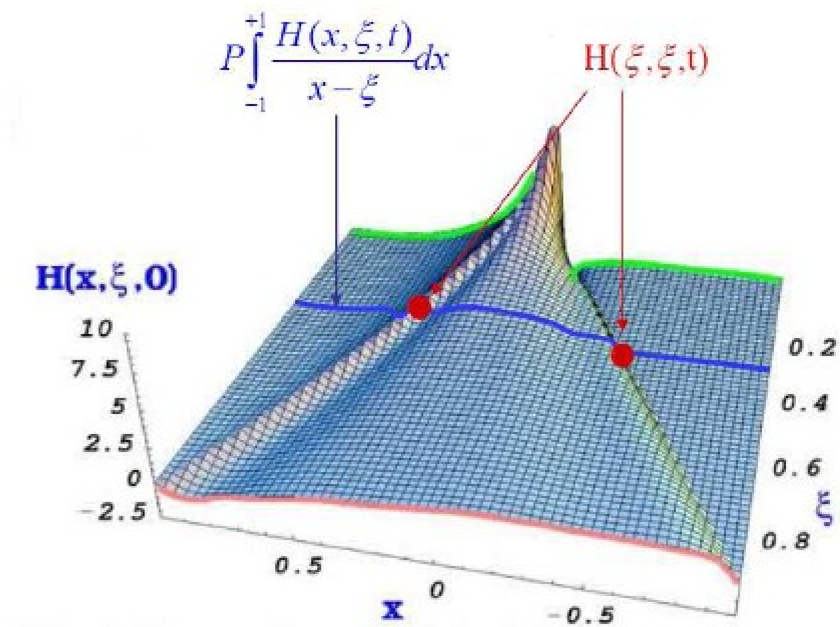
$$T^{DVCS} \approx \int_{-1}^{+1} \frac{H(x,\xi,t)}{x-\xi+i\varepsilon}\,dx \quad + \quad \cdots$$



Dominant term in the DVCS xs measurement : C_0^{DVCS}

$$C_0^{DVCS} \equiv \boxed{\Im m\, H^2 [= H^2(x=\xi,\xi,t)]}\,.\,(1 + \text{small Re part corr}^2)$$

H : GPD singlet (H1) (note : NLO corrections are large)

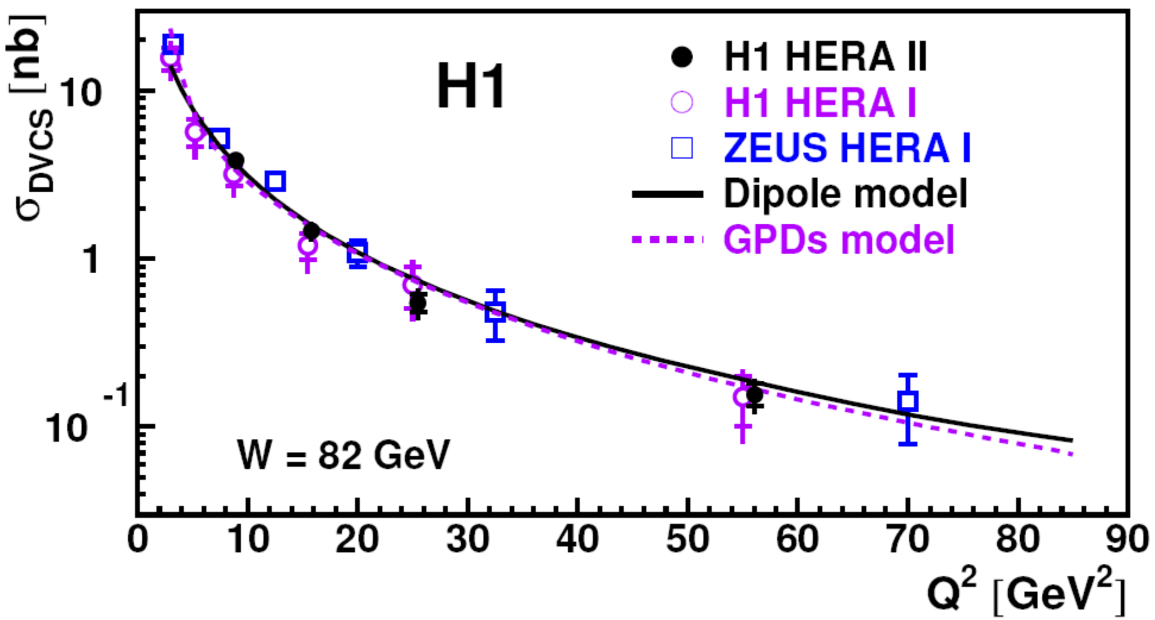


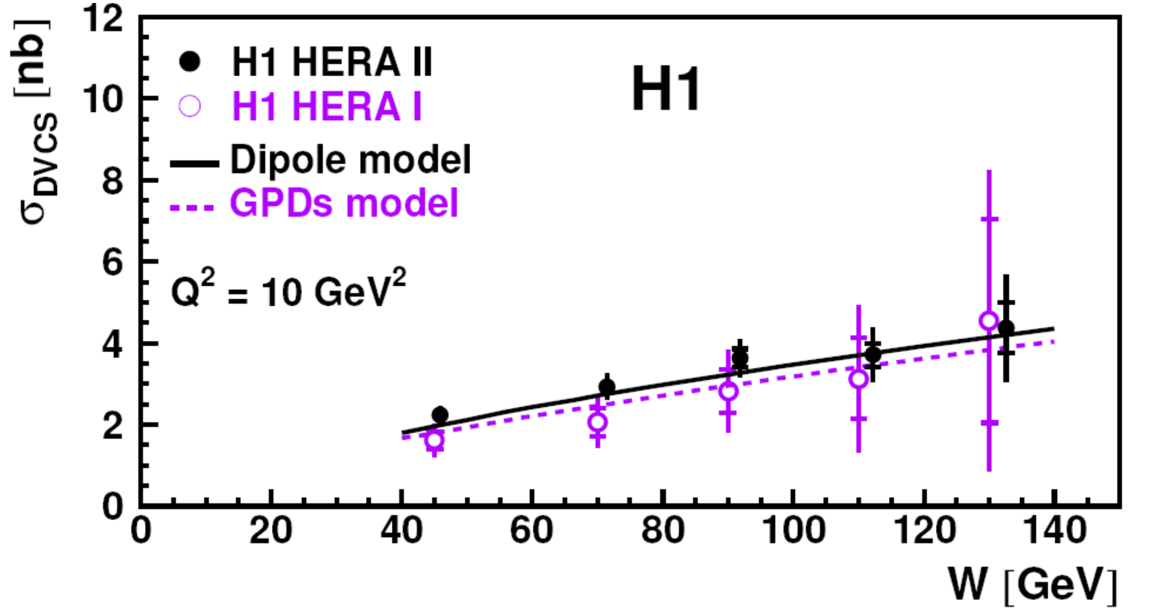
Dominant term(s) in the BCA : C_1^{Int} and C_3^{Int}

$$C_1^{Int} \equiv \boxed{\Re e\, H \;=\; \mathcal{P}\int_{-1}^{+1} dx\, \frac{H(x,\xi,t)}{x-\xi}} \;+\text{c.t.}$$

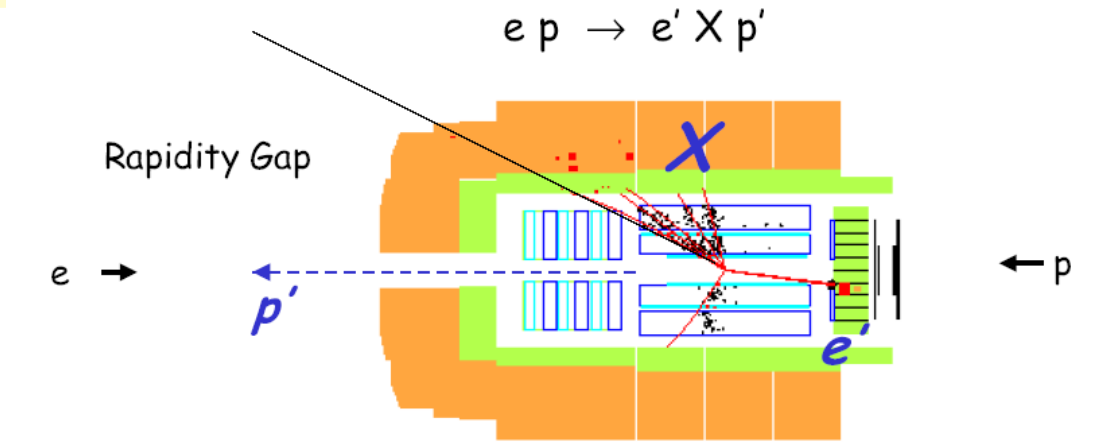
- DVCS xs measurement : GPD in one point @ x=ξ
  BCA measurement : integration along the x line

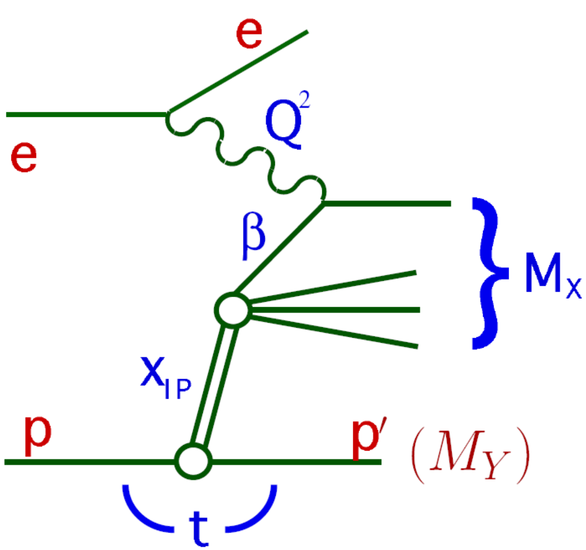
DVCS Cross Section





Diffractive DIS: kinematics





Invariant mass of the diffractive final state

- Momentum fraction of colour singlet exchange:

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

- Fraction of exchange momentum of q coupling to γ^*:

$$\beta = \frac{Q^2}{Q^2 + M_X^2} = \frac{x}{x_{\mathbb{P}}}$$

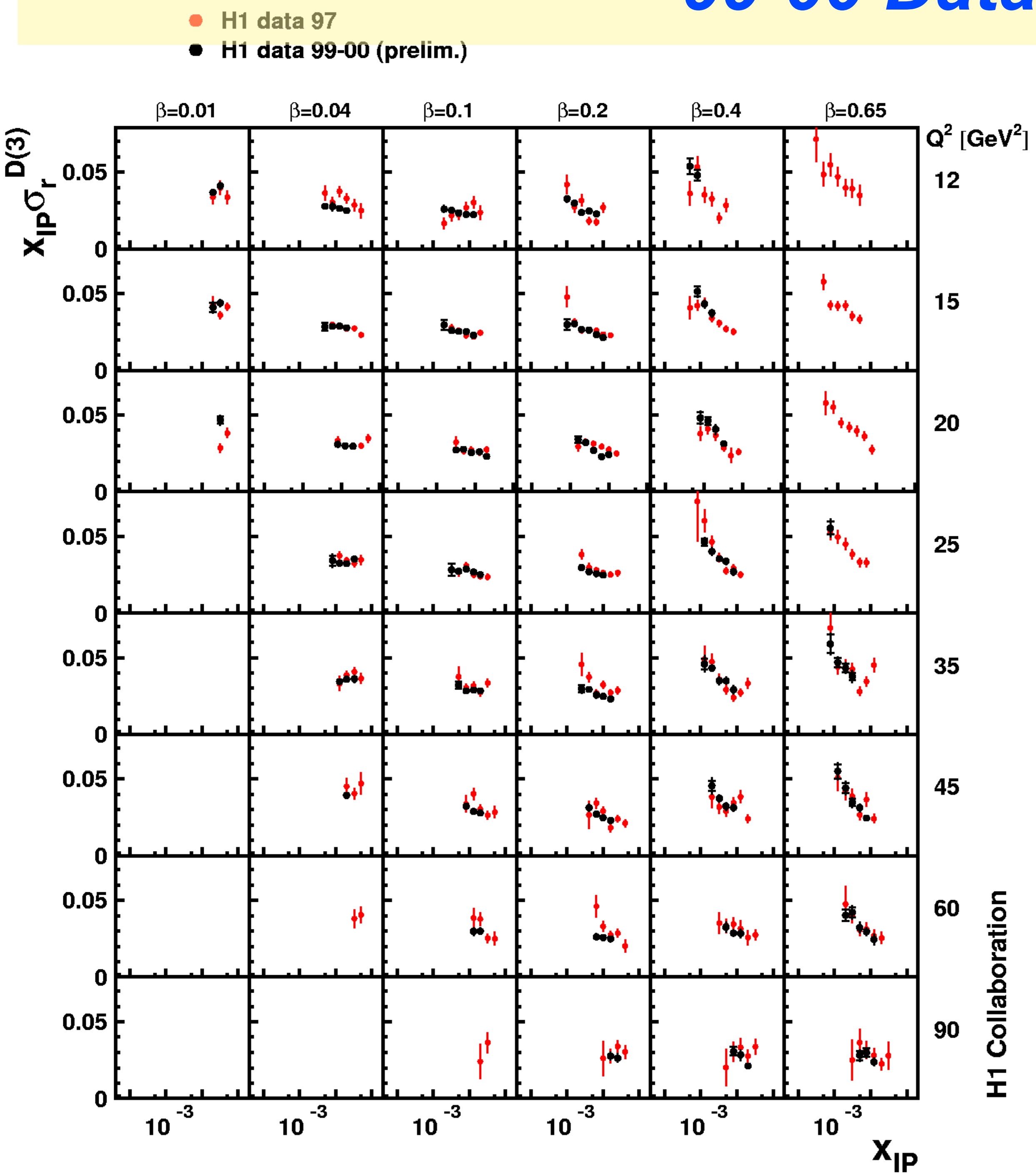
- 4-momentum transfer squared:

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

- Diffractive cross-section (integrated over t):

$$\frac{\mathrm{d}^3\sigma^D}{\mathrm{d}x_{\mathbb{P}}\,\mathrm{d}\beta\,\mathrm{d}Q^2} = \frac{2\pi\alpha_{em}^2}{\beta Q^4}\left(1 - y + \frac{y^2}{2}\right)\sigma_r^{D(3)}(x_{\mathbb{P}}, \beta, Q^2)$$

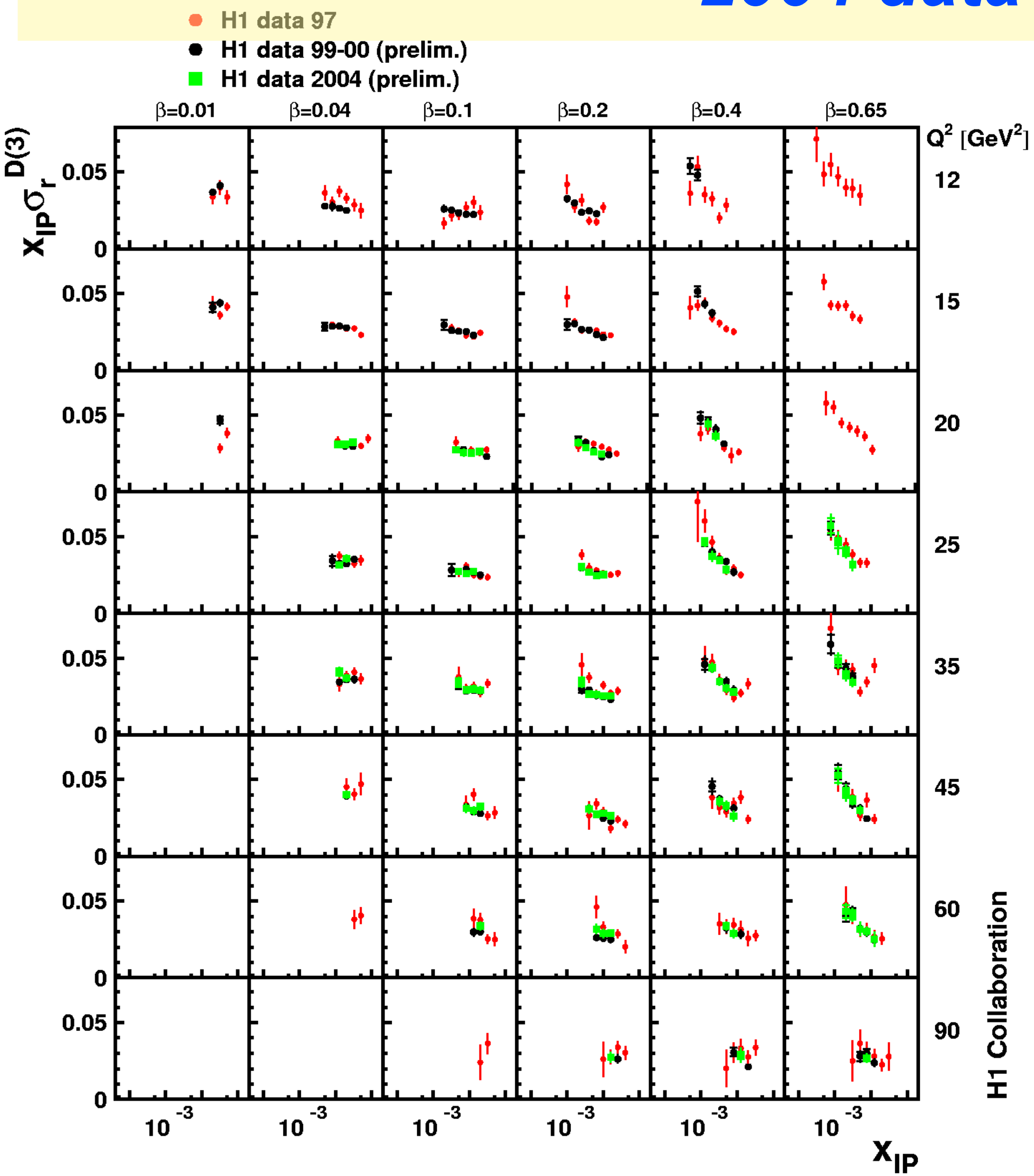
99-00 Data



- In middle Q^2 region: Q^2 = 10-105 GeV^2
- Mx >4 GeV
- LRG: η_{max} <3.2
- No activity above noise in forward detectors
- Correction to M_Y < 1.6 GeV, $|t|$ < 1.0 GeV^2 : 1.09 ± 0.06
  → Normalisation uncertainty of ~5%

➘ *Good agreement between 97 and 99-00 data sets*

2004 data



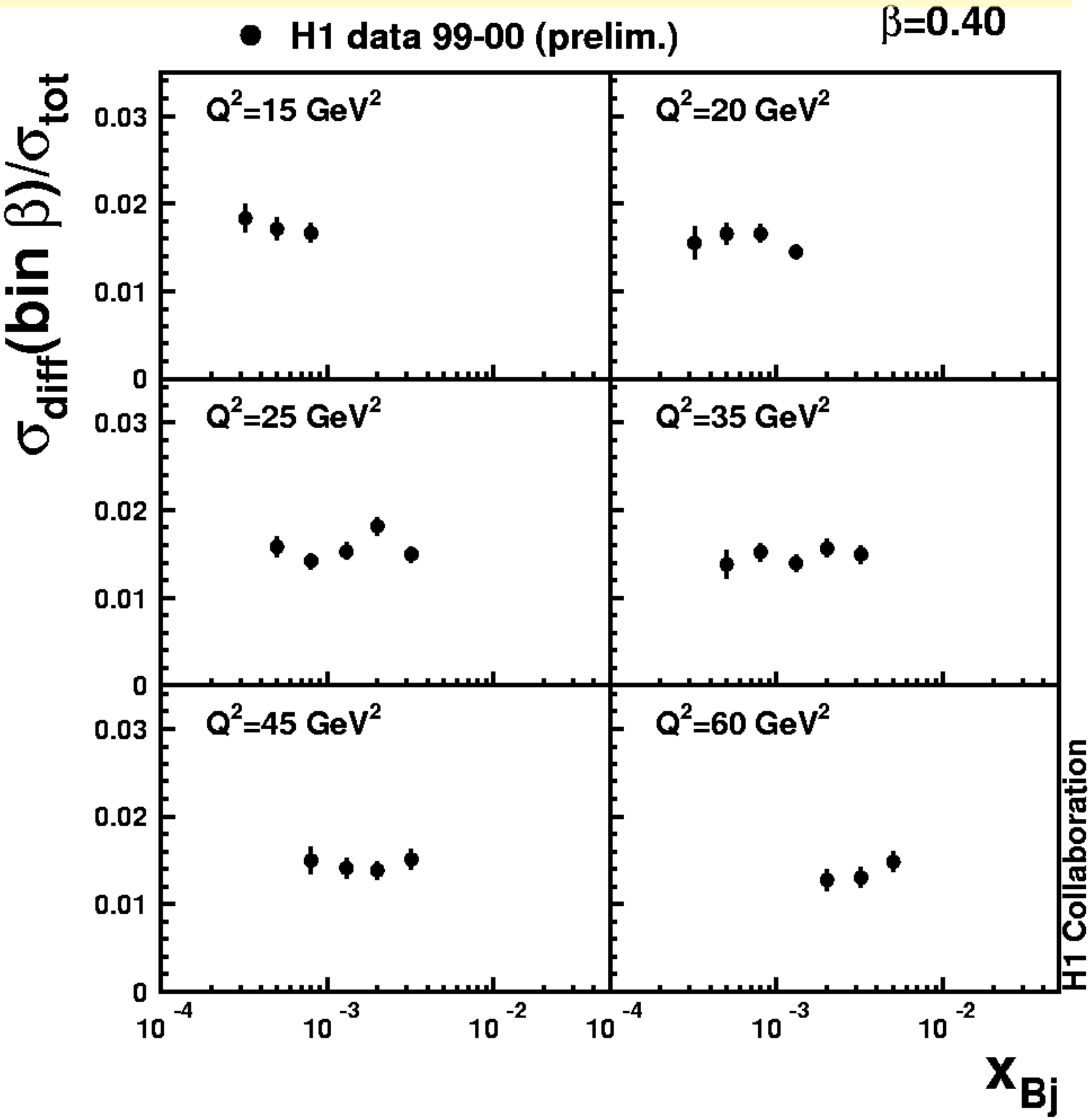
- Analysis of this sample more focused to larger Q^2 (17.5 – 105 GeV^2)
- Correction to M_Y < 1.6 GeV, $|t|$ < 1.0 GeV^2 : 1.18 ± 0.10
  - ➔ Normalisation uncertainty of ~8%

➘ Confirms 97 and 99-00 measurements

Diffractive contribution of the total cross-section

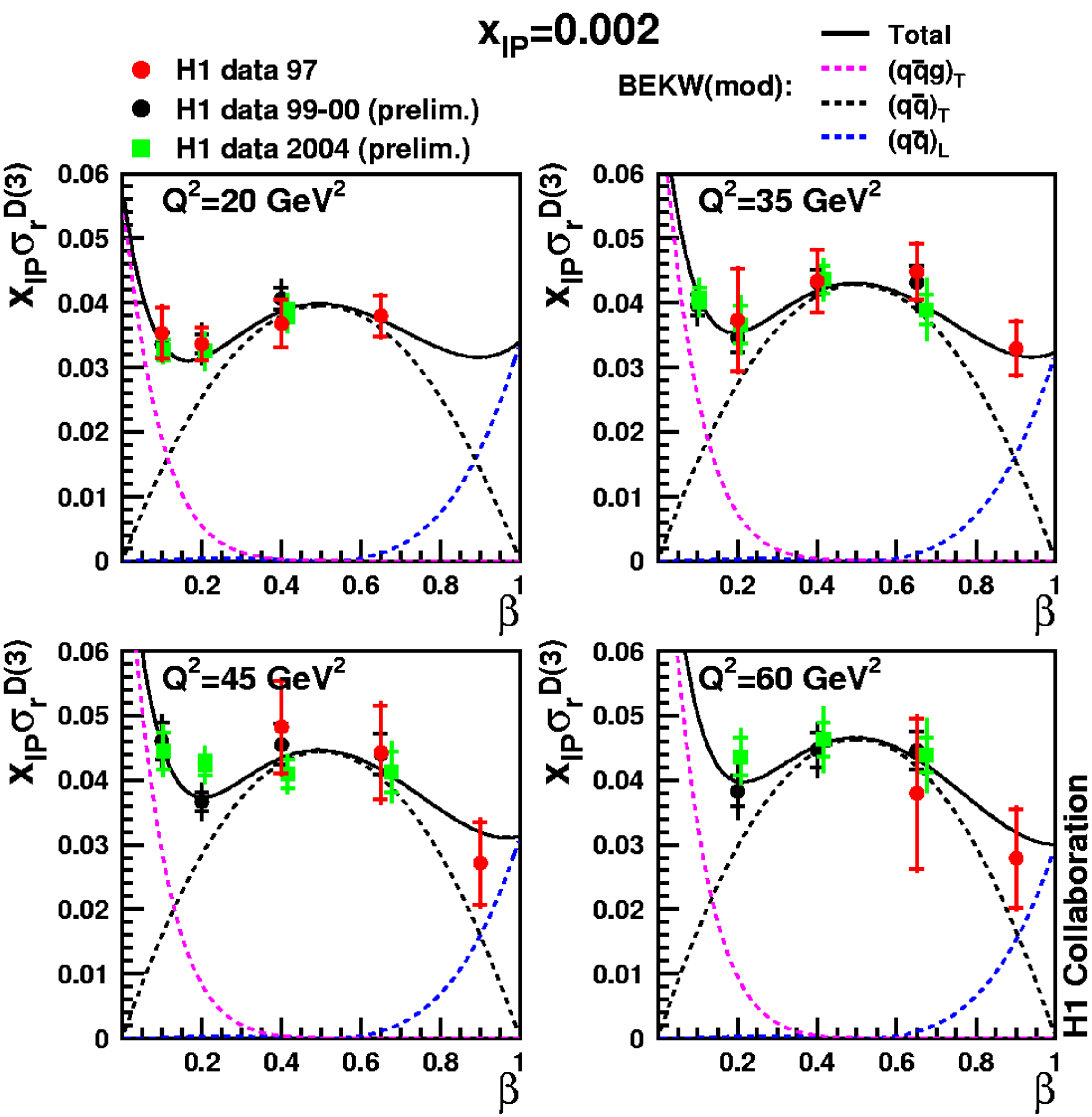
$$\frac{d\sigma^{diff}}{d\beta} = \frac{1}{\beta}\,\frac{4\pi^2\alpha_{em}}{Q^2}\;x_{\mathbb{P}}F_2^D$$

$$\sigma_{tot} = \frac{4\pi^2\alpha_{em}}{Q^2}\;F_2$$



- F_2^D / F_2 ~1-2% in each bin
  - ➔ Integrated over β : F_2^D ~ 10% F_2
  - ➔ Diffraction is a non-negligible fraction of F2
- Similar x dependencies for F_2^D and F_2
  - ➔ A unique factor between F_2^D and F_2 ?

BEKW fit result



- Fit all H1 data together: 97, 99-00, 2004

  → 672 points

  → χ^2/points = 1.26

↘ Good overall description of data

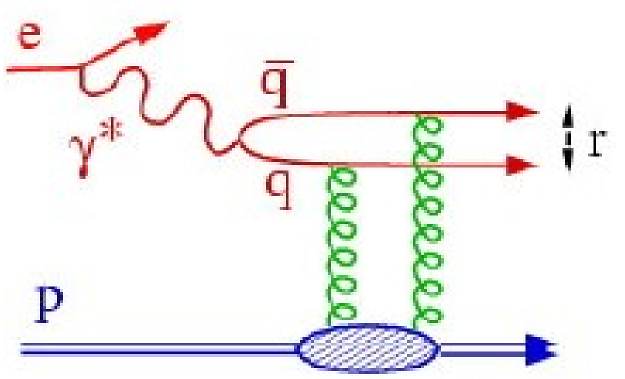
↘ β decomposition consistent over the full data set

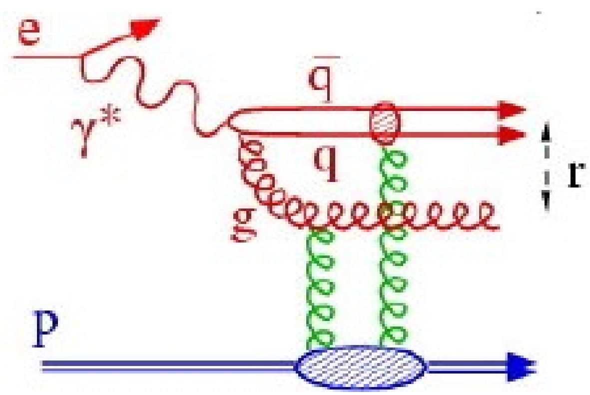
2 gluons exchange model

- LO realisation of the Singlet Exchange
- BEKW parametrisation: **[J. Bartels at al., Eur.Phys.J. C7, 443 (1999)]**

  → Modified form used **[ZEUS coll., Nucl. Phys. B713 (2005)]**

$$x_{\mathbb{P}} F_2^{D(3)} = c_T \cdot F^T_{q\bar{q}} + c_L \cdot F^L_{q\bar{q}} + c_g \cdot F^T_{q\bar{q}g}$$





- Dominant terms:

$$F^T_{q\bar{q}} \;\; \alpha \;\; \beta\,(1-\beta)$$

↘ At medium β

$$F^L_{q\bar{q}} \;\; \alpha \;\; \frac{Q_0^2}{(Q^2+Q_0^2)} \;\; \log^2\left(\frac{7}{4}+\frac{Q^2}{4\beta Q_0^2}\right)\beta^3\,(1-2\beta)^2$$

↘ At large β

$$F^T_{q\bar{q}g} \;\; \alpha \;\; \log(1+\frac{Q^2}{Q_0^2})\,(1-\beta)^\gamma$$

↘ At low β

↘ Compare to data

The dipole model

$$F_2(x,Q^2) = \frac{Q^2}{4\pi^2\alpha_{em}}(\sigma_T + \sigma_L)$$

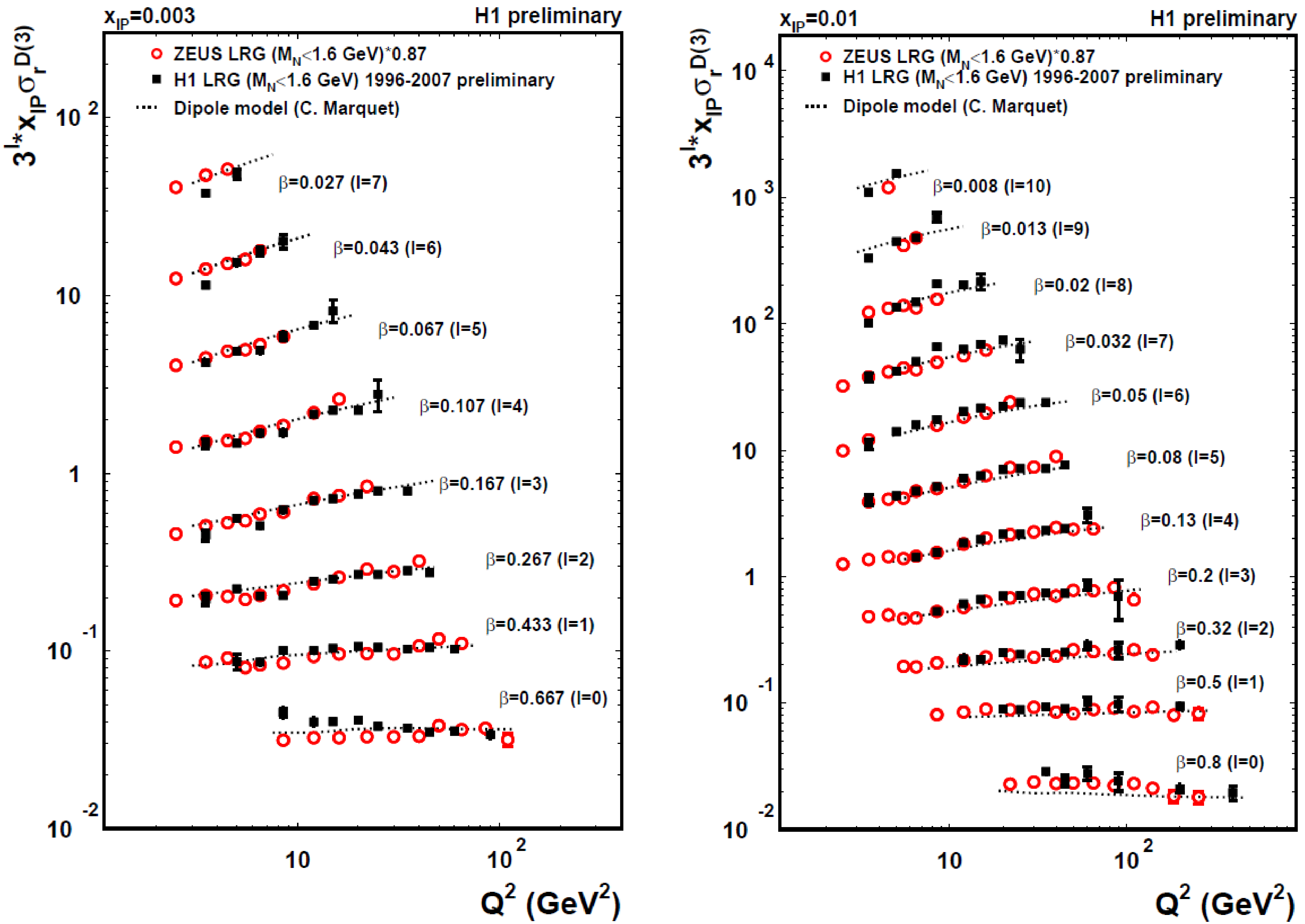
$$\sigma_{T,L}(x,Q^2) = \int \mathrm{d}z\mathrm{d}^2r \left|\Psi_{L,T}(z,r,Q^2)\right|^2 \hat{\sigma}(x,r)$$

Photon wave function (in light cone)

Non-perturbative effects

$$\hat{\sigma}(x,r) = \sigma_0 \left(1 - e^{(-r^2 Q_s^2(x))}\right)$$

DDIS and the dipole model



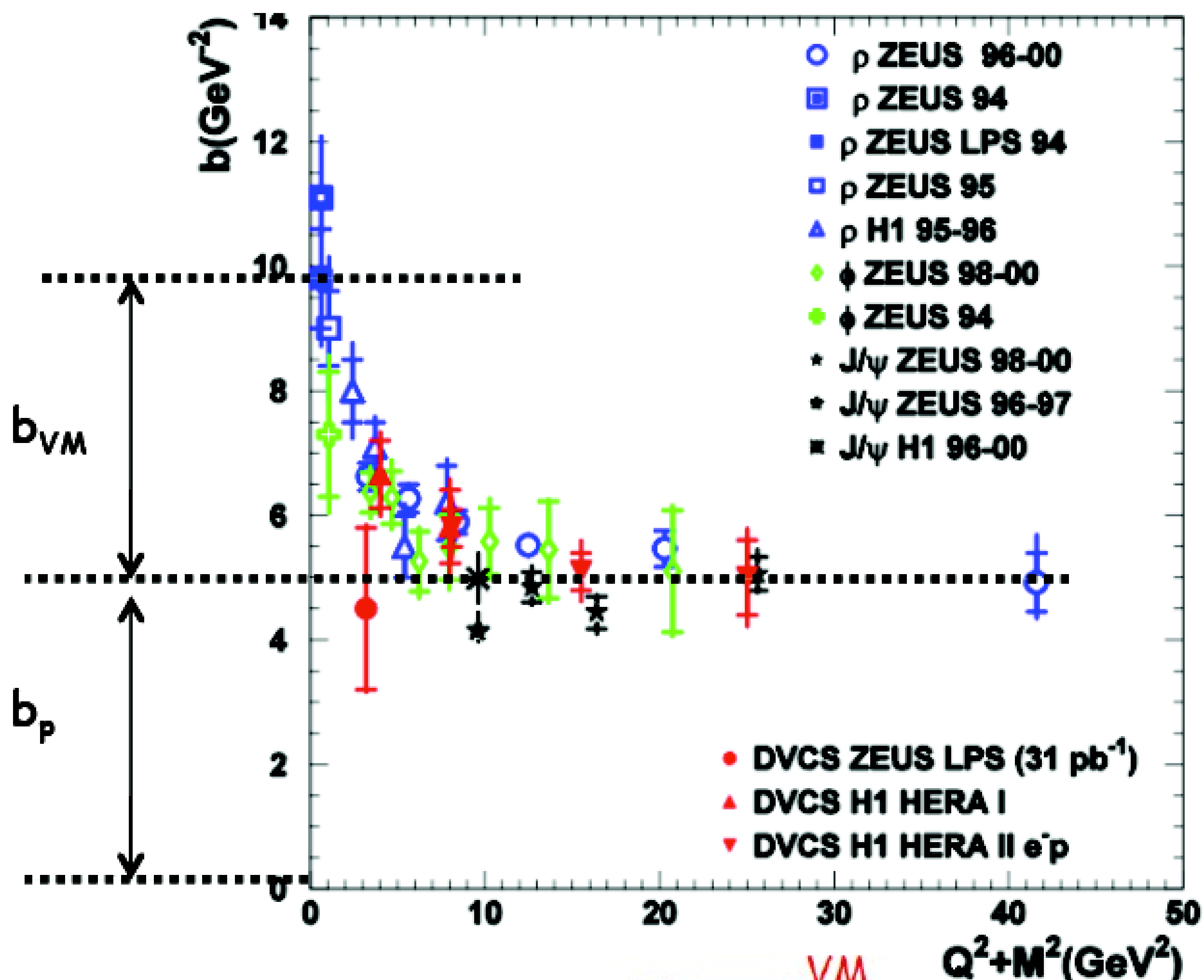
Exclusive processes at HERA: soft → hard

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

Slope b smaller as scale increases

As in optical diffraction, size of diffractive cone related to size of interacting objects

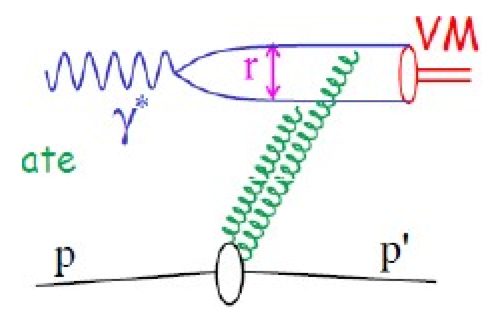
$b \sim b_{VM} + b_P$



$\langle r^2 \rangle = b(hc)^2$

→ r_g ~0.6 fm, radius of gluon density in proton

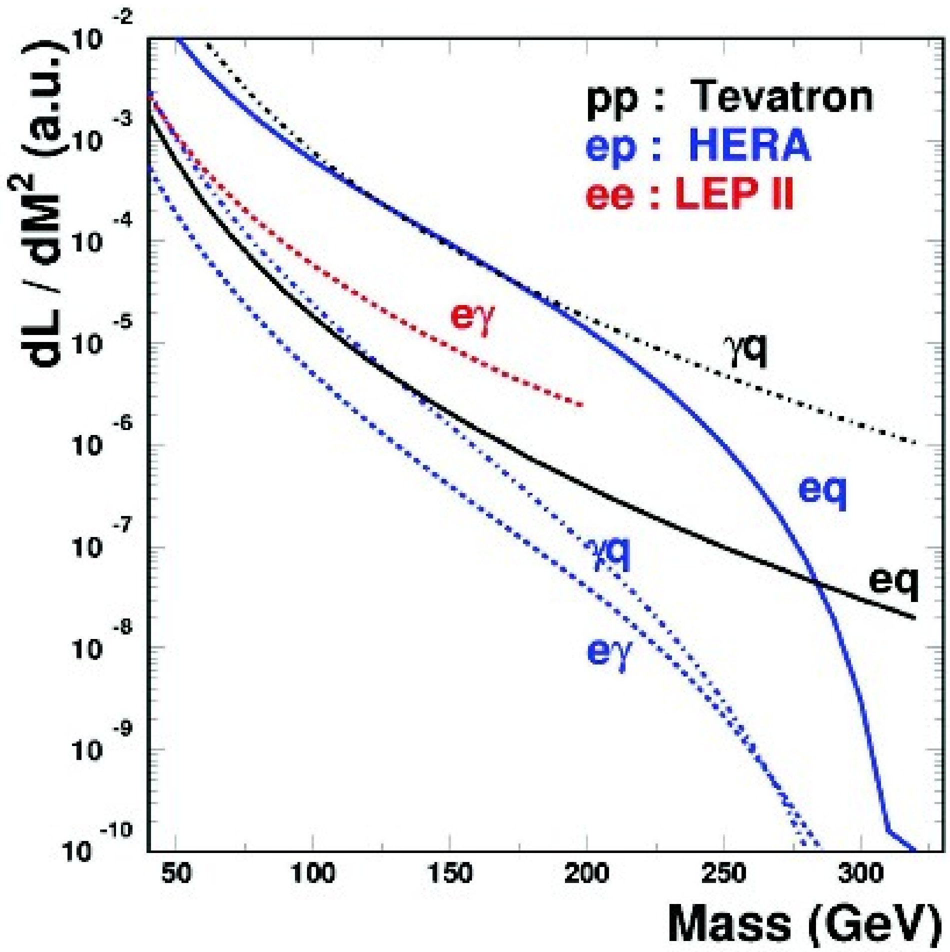
r_p ~ 0.8 fm, charge density in the proton



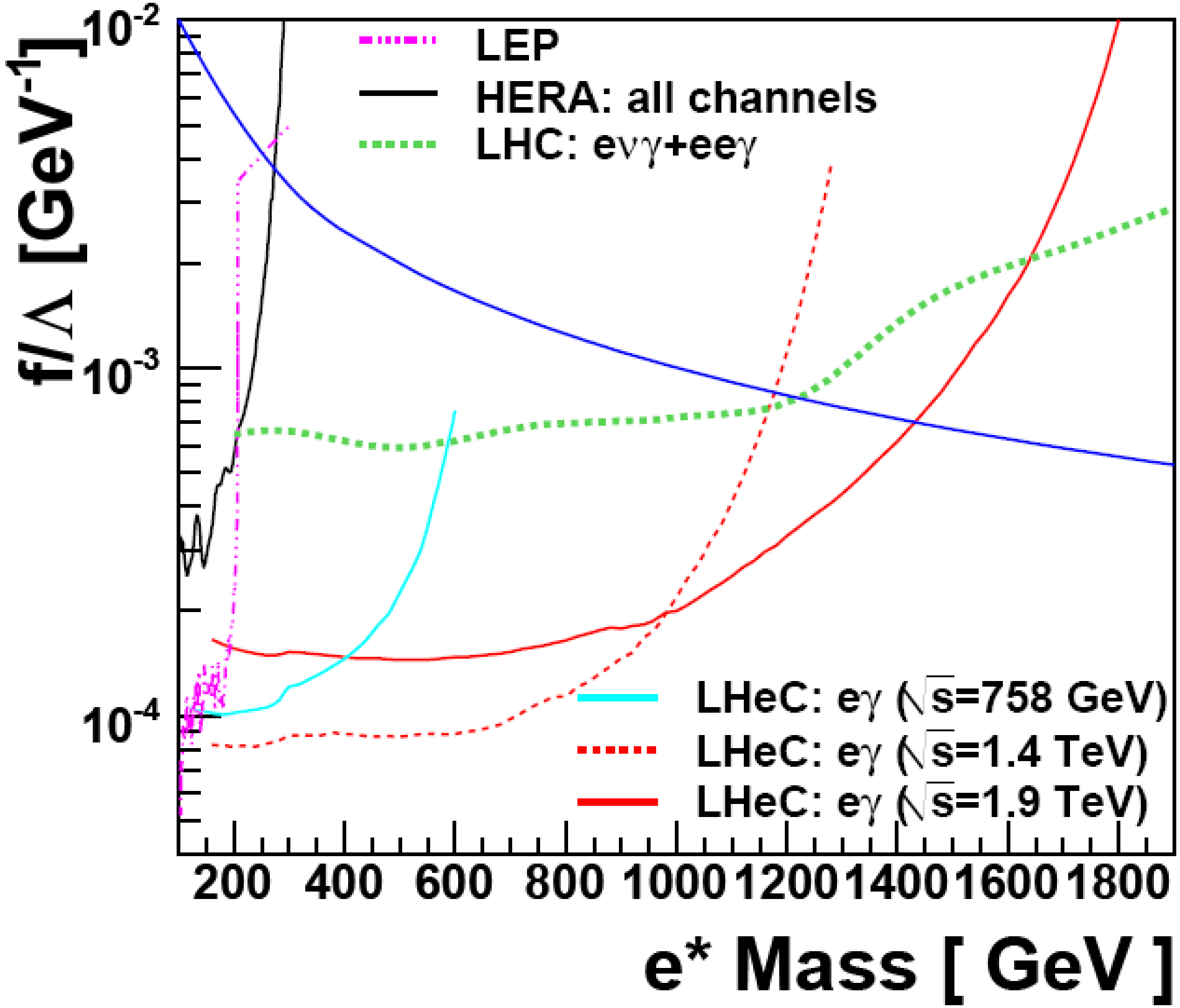
Partonic luminosities

[C. Diaconu, E. Perez]

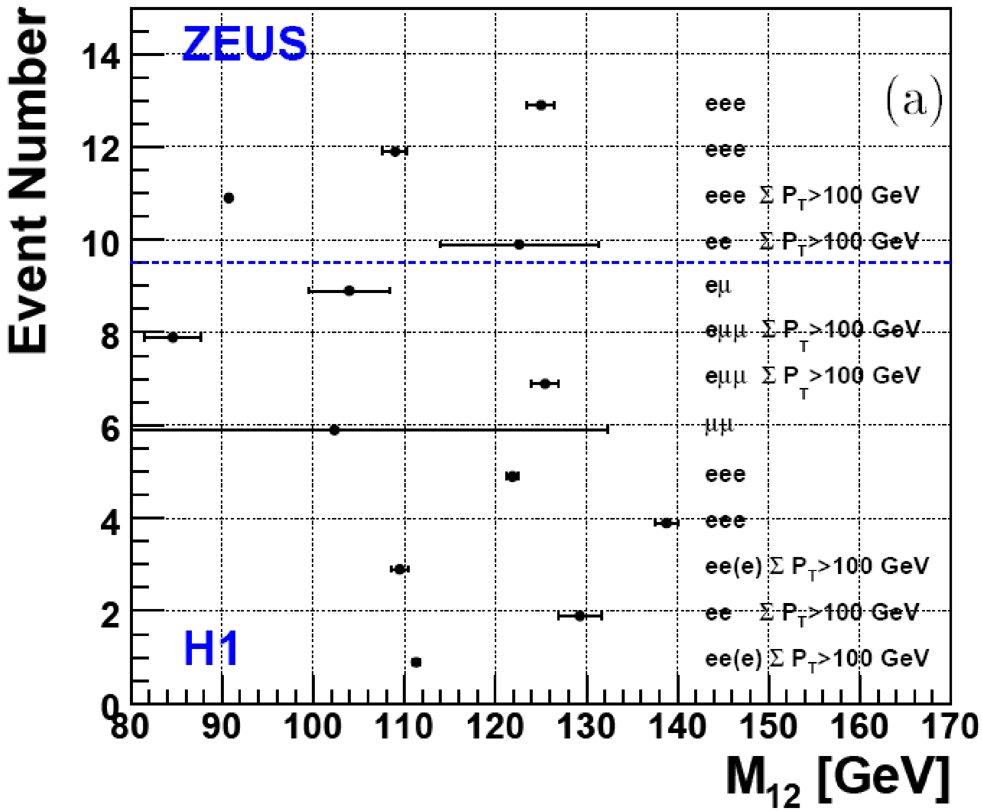
$$\sigma_c \sim \hat{\sigma}_{ab\to c}\frac{dL}{d\hat{s}} \qquad \frac{dL}{ds} = \frac{1}{s}\int_{\frac{\hat{s}}{s}}^{1}\frac{dx_a}{x_a} f_A(x_A,\hat{s}) f_B(\frac{\hat{s}}{s x_A},\hat{s})$$

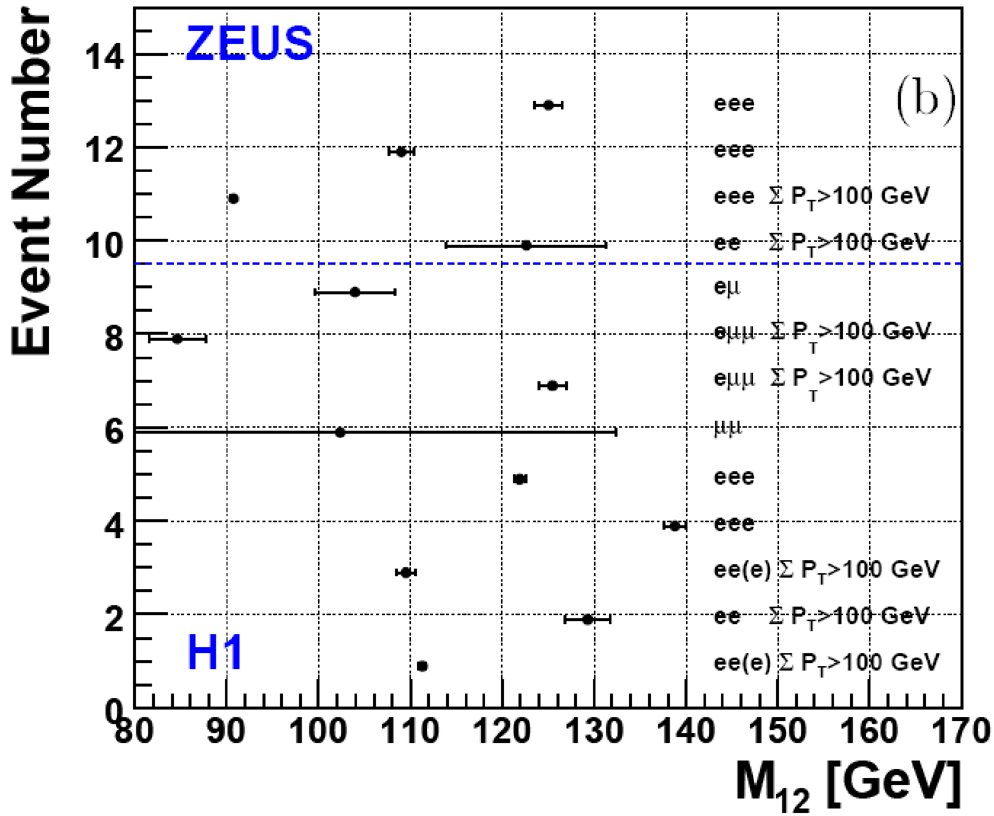


e* at the LHC and LHeC

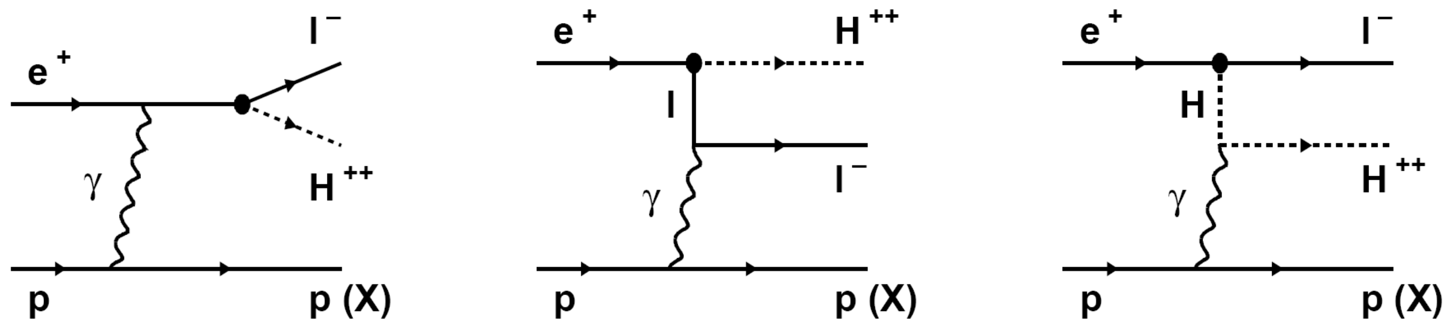


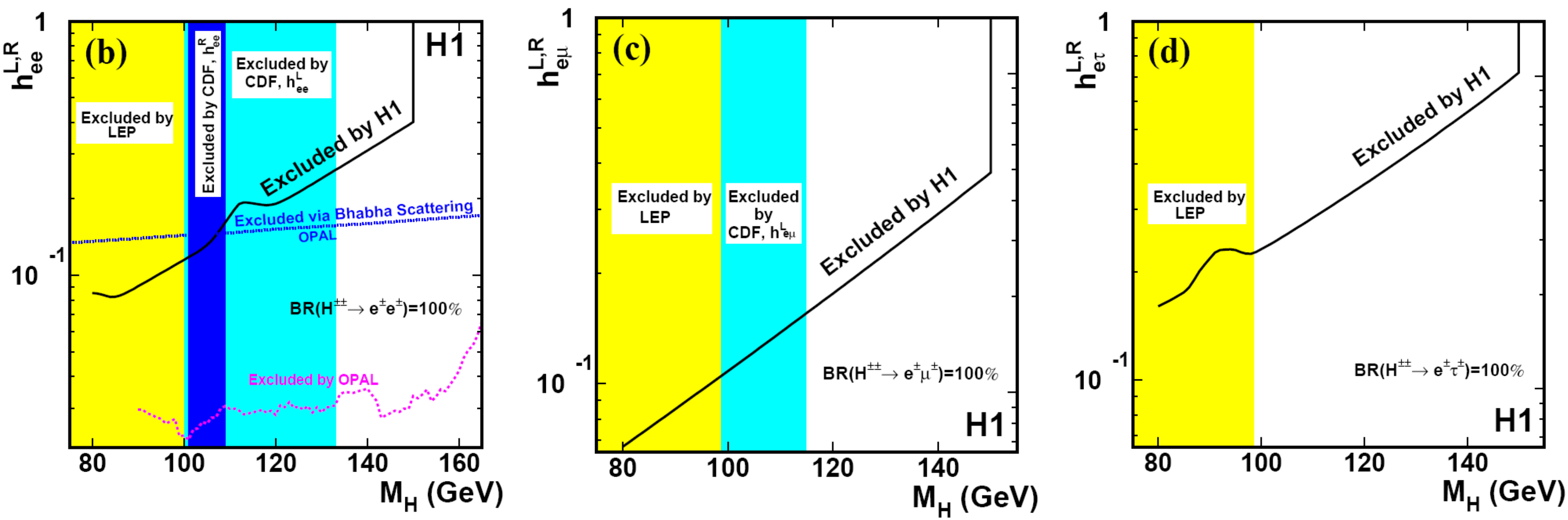
High-mass multi-lepton events





Doubly-Charged Higgs boson



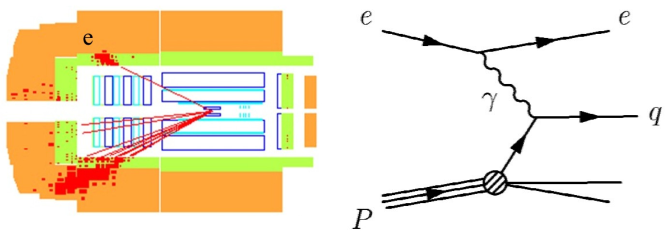


SM processes

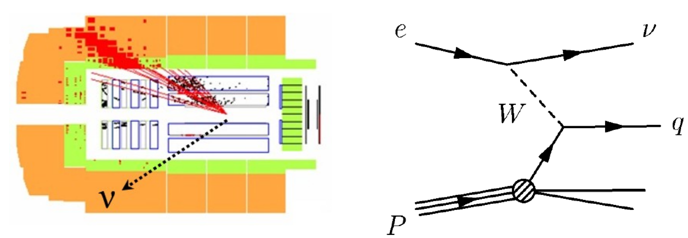
➔ Need simulation of all ep processes

➔ Large MC statistic required (multi-particle classes)

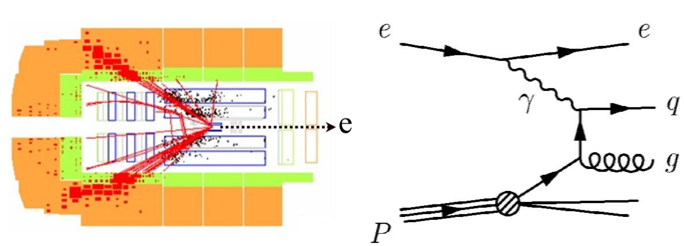
- Neutral Current DIS $ep \rightarrow eX$



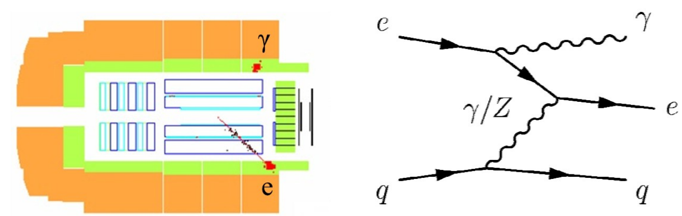
- Charged Current DIS $ep \rightarrow \nu X$



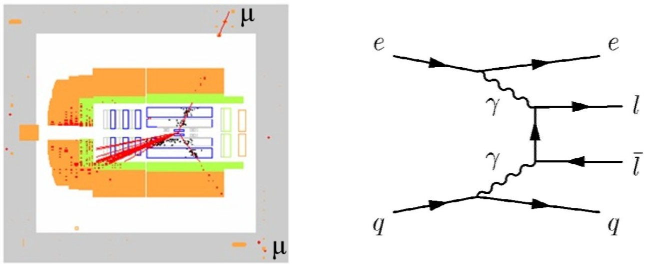
- Photoproduction $\gamma p \rightarrow X$



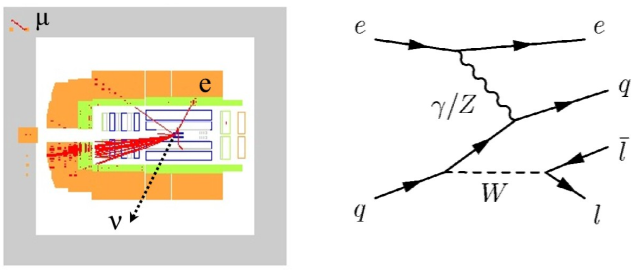
- QED Compton $ep \rightarrow e\gamma X$



- Lepton pair production $ep \rightarrow ellX$



- W production $ep \rightarrow eWX$



➔ QCD processes: O(α_s) + PS QED processes: O(α^2) + PS

Search for deviations

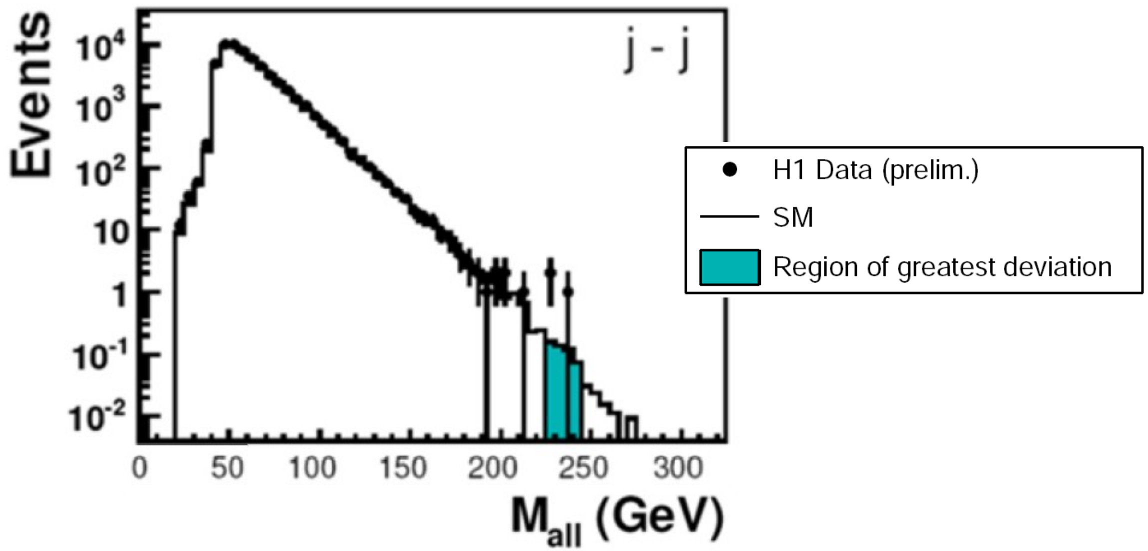
➘ Identify regions of largest deviations between data / SM

- Investigate 1D ΣP_T and M_{all} distributions
- Probability p of up or down fluctuations in each regions:

$$p = \begin{cases} A \int_0^\infty db\, G(b; N_b, \delta N_b) \sum_{i=N_{obs}}^{\infty} \frac{e^{-b} b^i}{i!} & \text{if } N_{obs} \geq N_b \\ A \int_0^\infty db\, G(b; N_b, \delta N_b) \sum_{i=0}^{N_{obs}} \frac{e^{-b} b^i}{i!} & \text{if } N_{obs} < N_b \end{cases}$$

(A = normalisation constant)

- Most interresting region: p minimum -> p_{min}^{data}



Quantify the deviation

➘ Quantify the significance of each deviation found

- What is the probability ($\hat{P}$) to observe somewhere else in the histogram a region with $p < p_{min}^{data}$?

➔ Pull random histograms H_{ran} according to the SM expectation

$$\hat{P} = \frac{\text{number of } H_{ran} \text{ with } p_{min}^{ran} < p_{min}^{data}}{\text{number of } H_{ran}}$$

➔ $\hat{P}_{data}$ = significance of p_{min}^{data}

➔ $\hat{P}_{data}$ can be used to compare results of different event class

➔ p_{min} = "5 σ" corresponds to ~ $-\log_{10} \hat{P}_{data}$ = 5-6

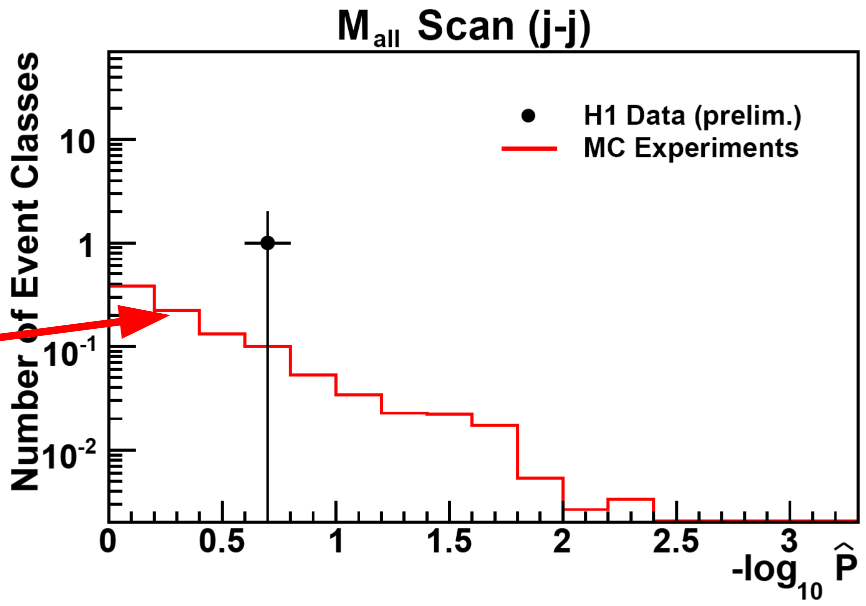
➘ Smallest $\hat{P}_{data}$ → most interresting channel

Determine the global significance

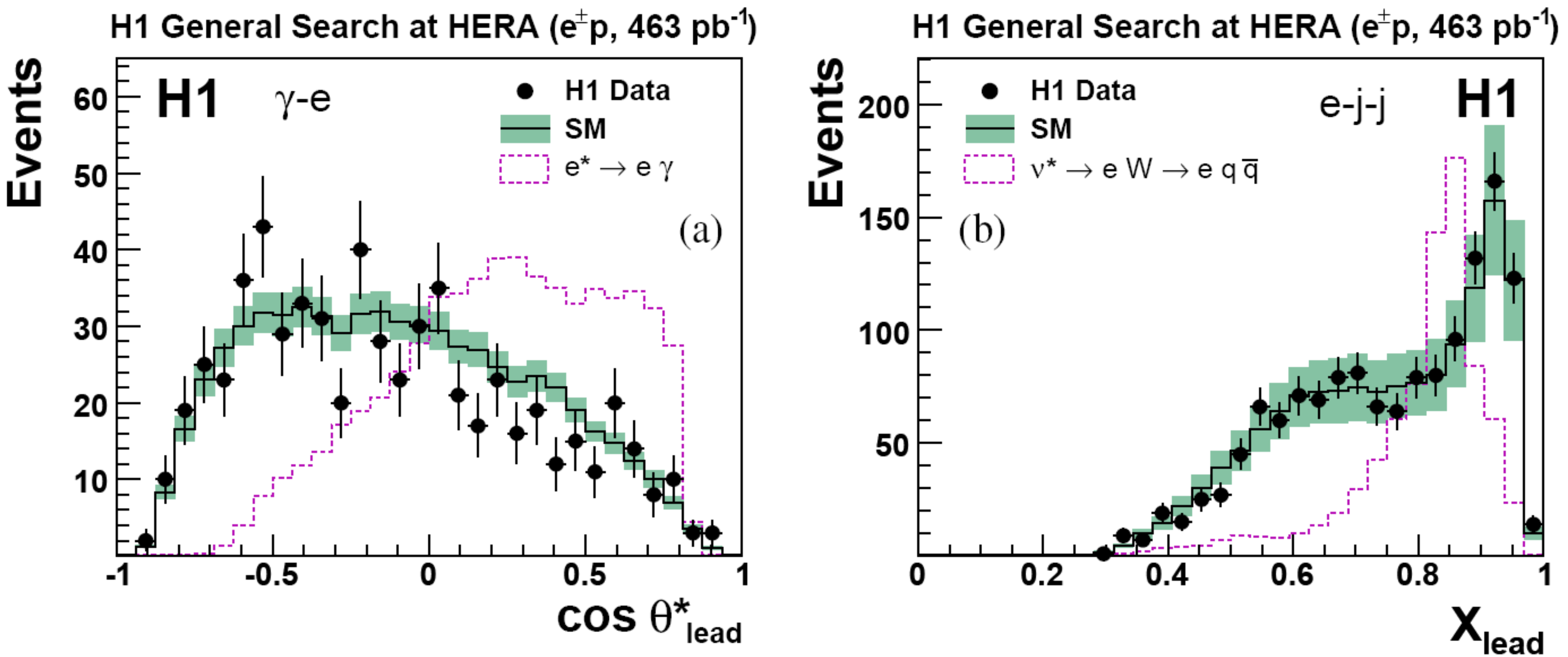
➘ Multiple classes studied, limited statistic: small $\hat{P}$ values can occur

- What is the expectation for $\hat{P}$ using this method and if we redo an experiment ?

  - ➔ Replace data by many "HERA MC experiments" with the luminosity of the data
  - ➔ Apply the same algorithm
  - ➔ $\hat{P}_{MC}$

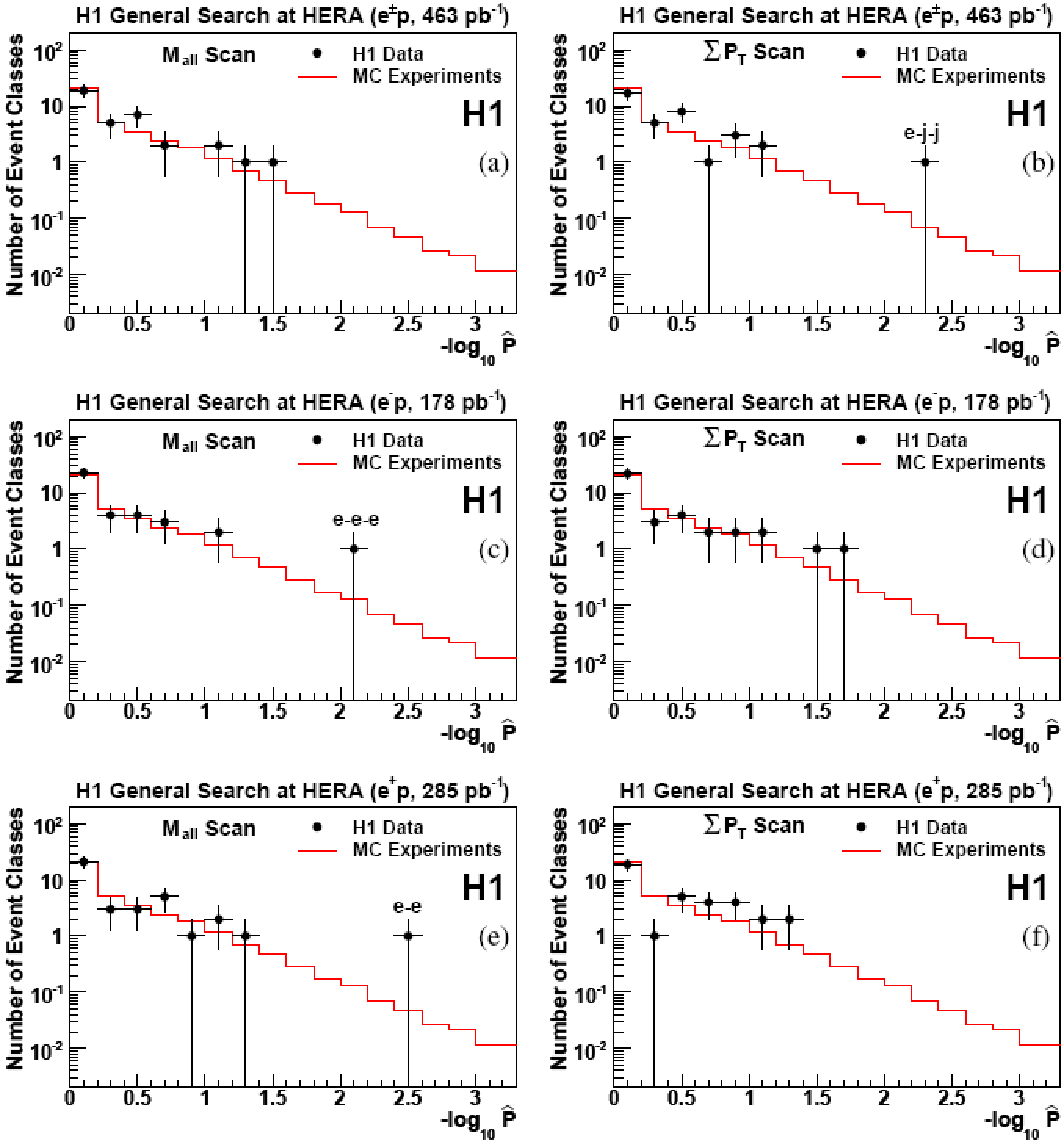


General Search: topological variables



$$X_{\text{lead}} = \frac{2E^*_{\text{lead}}}{\sum_i E^*_i}$$

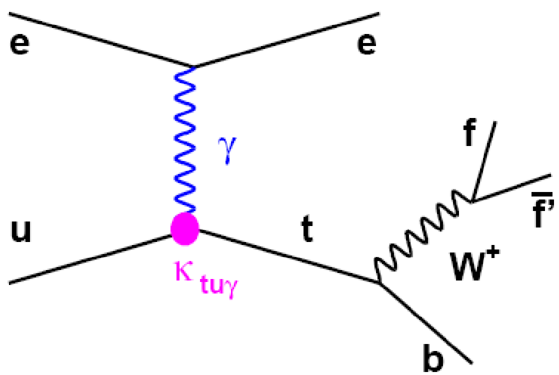
General Search: statistical analysis

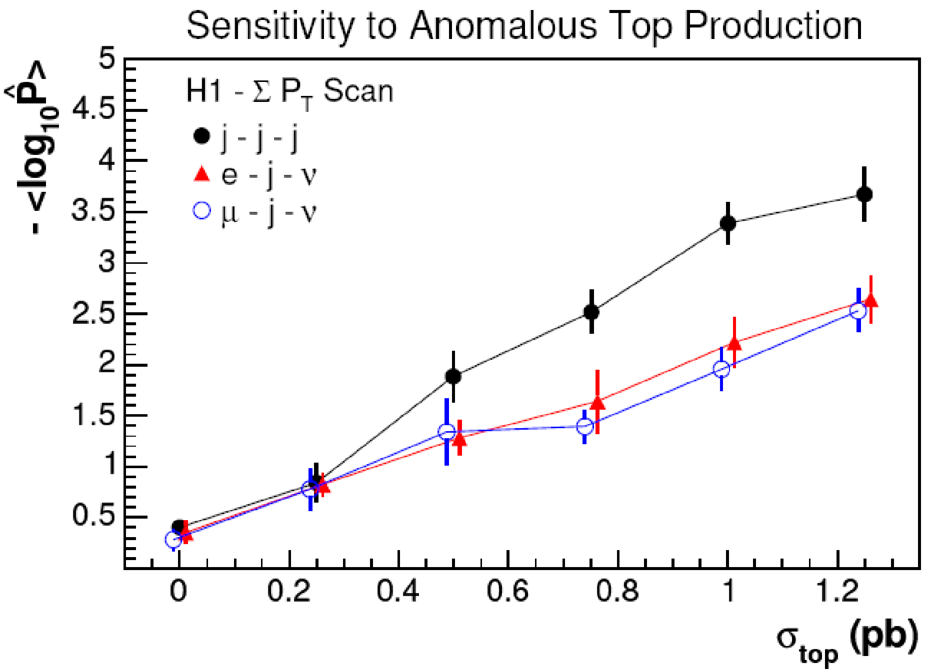


Sensitivity to new physics

➘ Test the sensitivity of the method to new physics

- Anomalous top production via FCNC
  - ➔ A decay $t \to bW$ would appear mostly in j-j-j, e-j-ν and μ-j-ν
  - ➔ Evolution of $-\log_{10} \hat{P}$ as a function of σ_{top}





- In j-j-j: $-\log_{10} \hat{P}$ ~2 for σ_{top} = 0.5 pb
  - ➔ From H1 dedicated analysis in hadronic channel: σ_{top} < 0.48 pb at 95% C.L.
- $-\log_{10} \hat{P} \geq 3$ for σ_{top} ~ 1.5 pb

➘ Sensitivity equivalent or slightly lower than dedicated searches

General Search at the Tevatron

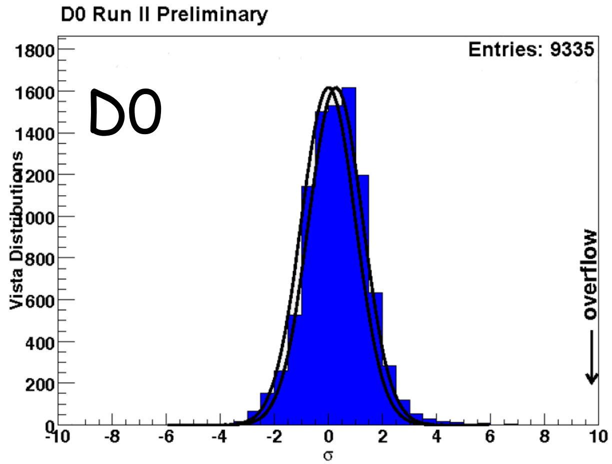
- Also performed by CDF and D0
  - ➔ A common framework used by CDF and D0
  - ➔ CDF: all topologies (399)
  - ➔ D0: only topologies with 1 lepton (180)

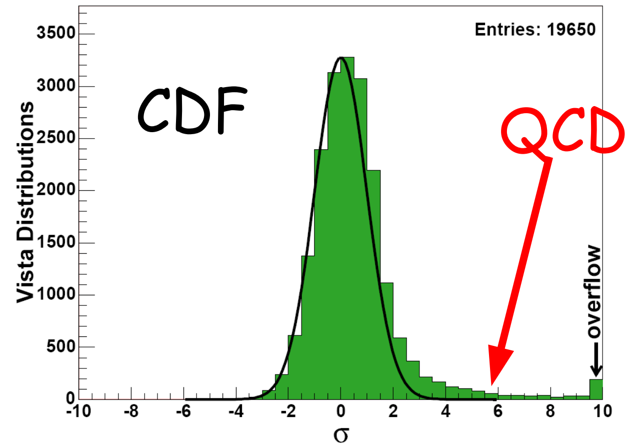
- Adjust the SM simulation to data at low energies
  - ➔ O(40) k-factors used, determined in a dedicated algorithm
  - ➔ Check data/SM discrepancies at high energies

General Search at the Tevatron

[CDF, PRD 79(2009)011101]

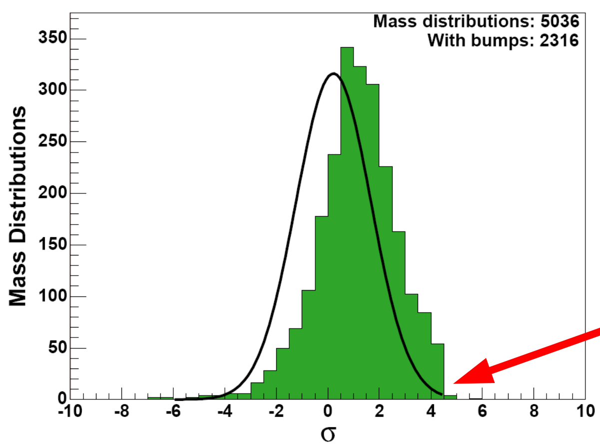
- Check data/SM in rate and shape of distribution

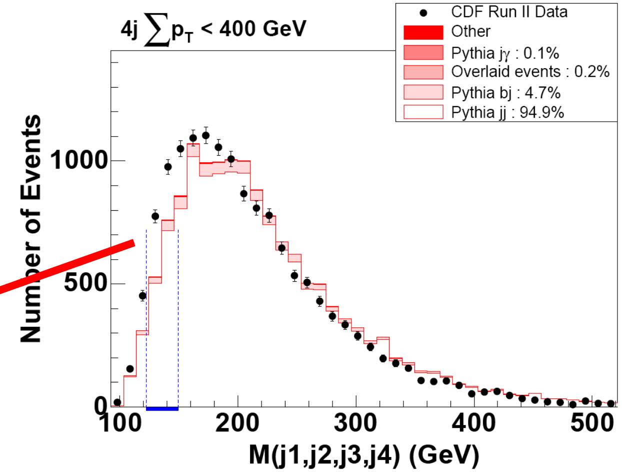




QCD mis-modeling

- Look for bumps in ΣP_T distributions





➘ Most significant discrepancies found:
attributed to QCD and detector simulation deficits

Title