Implications of HERA measurements for LHC

M. Diehl

Deutsches Elektronen-Synchroton DESY

13 August 2007

1. Structure functions and parton densities

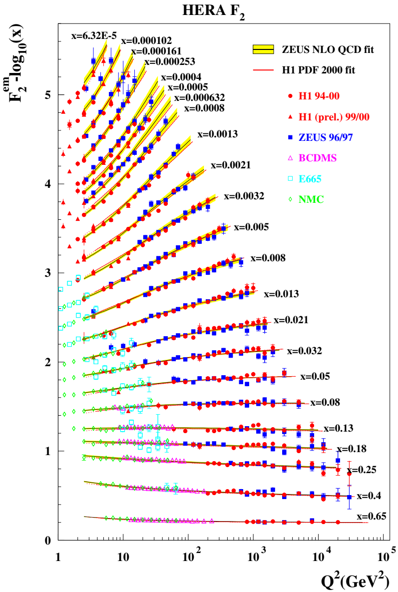
2. Diffraction

3. Summary

(with apologies) will not cover many detailed studies of final state:
jets, charm and bottom production, multiple interactions, ...

detailed recent overview → 3rd HERA/LHC Workshop, March 2007
`http://indico.cern.ch/conferenceDisplay.py?confId=11784`

Thanks to: H. Abramowicz, J. Bartels, O. Behnke, L. Dixon, C. Gwenlan, H. Jung, M. Klein, G. Kramer, S. Moch, L. Motyka



H1+ZEUS, Moriond 2004

- chief discovery of HERA: steep rise of proton structure function
- insight into QCD dynamics → many theory developments
- fits of parton densities (PDFs) → parton luminosities @ LHC
- 2 aspects:
  - precision
  - physics of small-x gluons and sea

Impact of PDF uncertainties on LHC

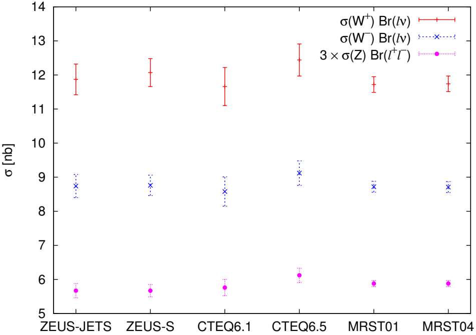
example processes

- Higgs production
- $W^{\pm}$, Z production
  possible luminosity monitors
- most PDFs now with errors
  - reflect error propagation
    fitted data
    $\rightarrow$ PDF parameters
  - not uncertainties from
    theory, parameterization,
    data selection, ...

Impact of PDF uncertainties on LHC

example processes

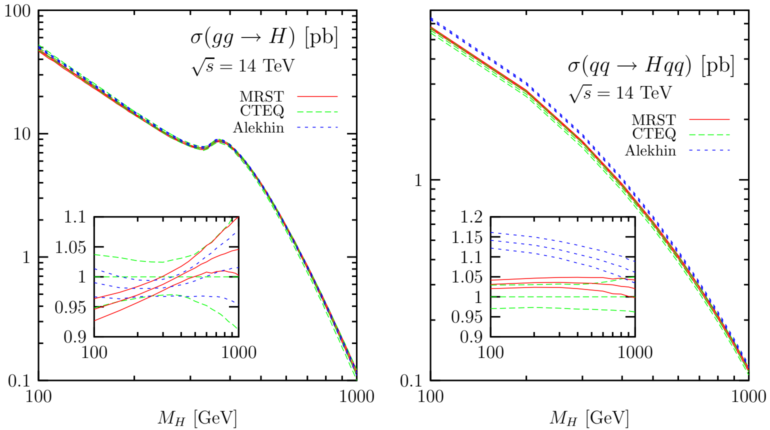
- Higgs production
- $W^{\pm}$, Z production
  possible luminosity monitors
- most PDFs now with errors
  - reflect error propagation
    fitted data
    $\rightarrow$ PDF parameters
  - not uncertainties from
    theory, parameterization,
    data selection, . . .



numbers from A. Cooper-Sarkar
0707.1593 [hep-ph]

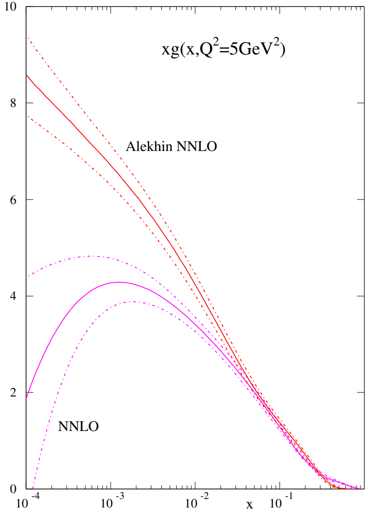
Higgs production

compare MRST 2001, CTEQ6, Alekhin 2002



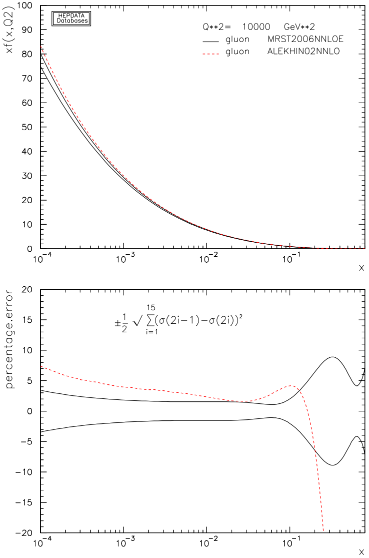
A. Djouadi, S. Ferrag, hep-ph/0310209

MRST2006 vs. Alekhin 06



MSTW, 0706.0459 [hep-ph]

MRST2006 vs. Alekhin 02



$Q^2 = (100\,\mathrm{GeV})^2$

Main constraints on low-x gluon density

- scaling violations in $F_2(x, Q^2)$
  cross talk gluons $\leftrightarrow$ sea quarks

Main constraints on low-x gluon density

- inclusive charm production: $F_2^{c\bar{c}}$
  significant changes in theory used by global parton analyses

Different schemes:

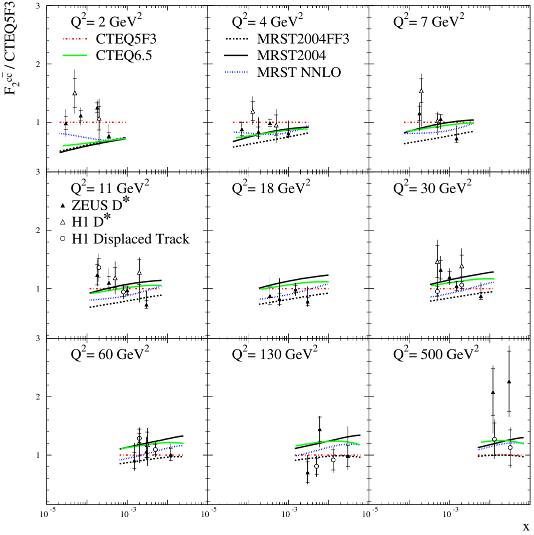
- FFNS (fixed flavor number) :
  $n_f = 3$ PDFs for light q and $\bar{q}$
  c, $\bar{c}$ only from fixed-order hard scattering
  - misses $\alpha_s^n \log^m(m_c^2/Q^2)$ terms from higher orders
  - found to work for HERA $F_2^{c\bar{c}}$ up to rather high Q^2
- ZM-VFNS (zero-mass variable flavor number) :
  change from $n_f = 3$ to $n_f = 4$ quark PDFs at $\mu = m_c$
  quarks treated as massless in hard scattering
  - resums $\alpha_s^n \log^m(m_c^2/Q^2)$ terms via DGLAP evolution
  - adequate for $Q^2 \gg m_c^2$ but not for $Q^2 \sim$ few m_c^2
  - c quark PDFs needed for high-p_T charm production at HERA, Tevatron and LHC

Main constraints on low-x gluon density

- inclusive charm production: $F_2^{c\bar{c}}$
  significant changes in theory used by global parton analyses

Different schemes:

- FFNS (fixed flavor number) :
- ZM-VFNS (zero-mass variable flavor number) :
- GM-VFNS (general mass variable flavor number) :
  interpolate between FFNS at low and ZM-VFNS at high Q^2
  $F_2^{c\bar{c}}$ at HERA and b prod'n at LHC
  technical choices in matching n_f and $n_f + 1$ descriptions
  - m_c in kinematical variables, in hard-scattering coefficients
  - at NNLO discontinuities in both PDFs and coefficient fcts. but not in observables — R. Thorne, '06
- analogous discussion for bottom
  - b quark PDFs needed for LHC



P. Thompson, hep-ph/0703103

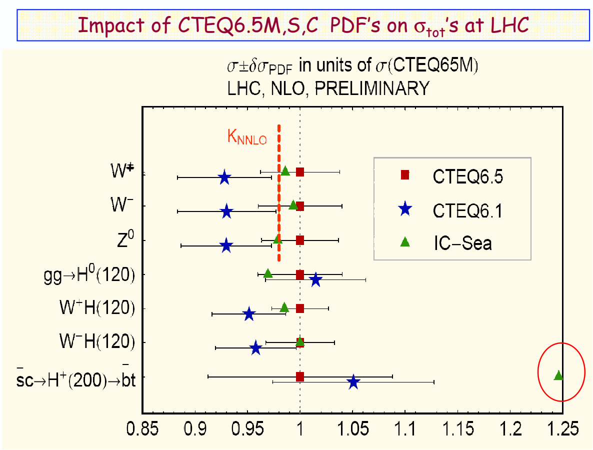
- experimental errors may decrease by factor 2 with full HERA 2 data
  → O. Behnke HERA/LHC Workshop '07
- constraints on theory/PDF fits

Some recent PDF fits

- MSTW 2006 — 0706.0459 [hep-ph]
  global fit, NNLO for DIS and Drell-Yan
  - refined treatment of c, b in GM-VFNS at NNLO
  $\rightsquigarrow$ significant changes w.r.t. MRST 2004 NNLO
- CTEQ6.5 — hep-ph/0702268, hep-ph/0701220, hep-ph/0611254
  global fit, NLO, GM-VFNS
  - previous CTEQ6.1 had ZM-VFNS $\rightsquigarrow$ significant changes
- Alekhin 06 — S. Alekhin, K. Melnikov, F. Petriello, hep-ph/0606237
  DIS and DY data at NNLO with $n_f = 3$ FFNS
  charm and bottom contrib. to F_2 at $O(\alpha_s^2)$
- BBG — J. Blümlein, H. Böttcher, A. Guffanti, hep-ph/0607200
  non-singlet PDFs (no gluon)
  from $F_2^p - F_2^n$ at NNLO and N^{3}LO

- Fits also permit precise determination of α_s
  competitive with e^+e^-

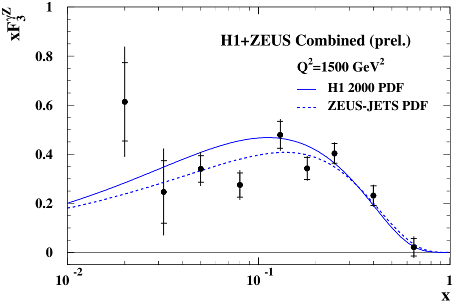
effect of CTEQ6.1 → CTEQ6.5 on LHC cross sections



W.-K. Tung, HERA/LHC workshop, 3/07

separation of quark flavors and of q vs $\bar{q}$

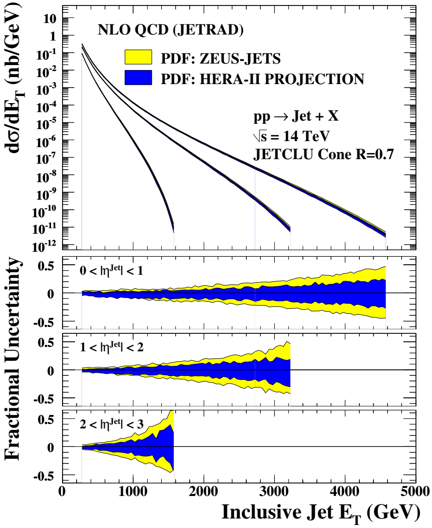
- crucial non-HERA input:
  $\bar{d}$ vs $\bar{u}$: Drell-Yan, CDF $W^{\pm}$ asymmetry (see ABS S2-004)
  s and $\bar{s}$: ν and $\bar{\nu}$ DIS: CDHSW, CCFR, CHORUS, NuTeV
- HERA large Q^2 data ... statistics crucial



H1+ZEUS, ICHEP06
partial HERA II stat.

- ep struct. fcts.: precise theory
  - NC beam charge asy. $\rightarrow F_3^{\gamma Z}$
    $q - \bar{q}$ at small x
  - NC beam pol. asy. $\rightarrow F_2^{\gamma Z}$
    $u + d$ at large x
  - CC: $e^+ p \rightarrow u + c$ and $\bar{d} + \bar{s}$
    $e^- p \rightarrow d + s$ and $\bar{u} + \bar{c}$
    $\bar{s}$, s from charm tagging?

- improved PDFs at medium x
  $\rightarrow$ jet production at LHC
  and heavy new particles ...
- simple estimate of
  HERA II impact
  only statistical errors
  assumed 700 pb^{-1}, have ~ 570 pb^{-1}
  fit only to HERA data



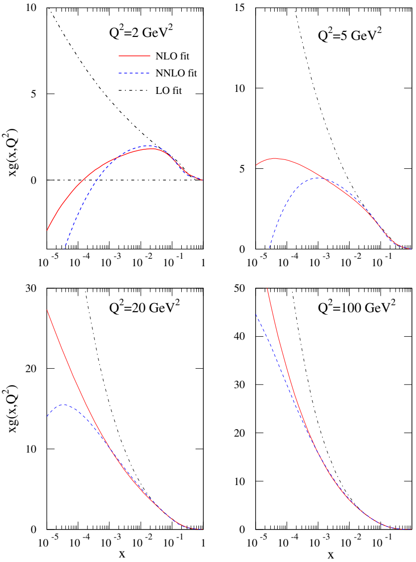
C. Gwenlan et al., hep-ph/0509220

Back to small x

- radiative corrections are important at low x
- see changes of $g(x)$ extracted at LO, NLO, NNLO

  NB: $g(x)$ is not an observable
  but wait a few slides ...

Gluon LO , NLO and NNLO



R. Thorne, HERA/LHC workshop, 3/07

Small-x resummation

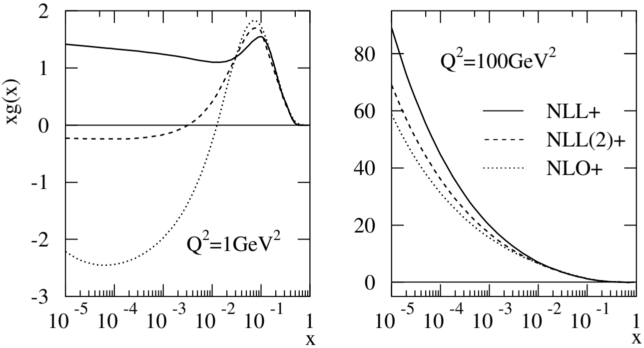
G. Altarelli, R. Ball, S. Forte (ABF); C. White and R. Thorne;
M. Ciafaloni, D. Colferai, G. Salam, A. Stasto (CCSS)

- at small x large logarithms $\alpha_s^n \log^m x$ in
  fixed-order evolution kernels and hard-scattering coefficients
- resum in BFKL approach at NLL, i.e. $\alpha_s(\alpha_s \log x)^n$
  project out leading twist part
  join on to fixed-order results at higher x
- technical issues:
  - running of α_s
  - choice of scheme
  - recent progress: inclusion of quarks

- first application in global PDF fit:

C. White and R. Thorne, hep-ph/0611204

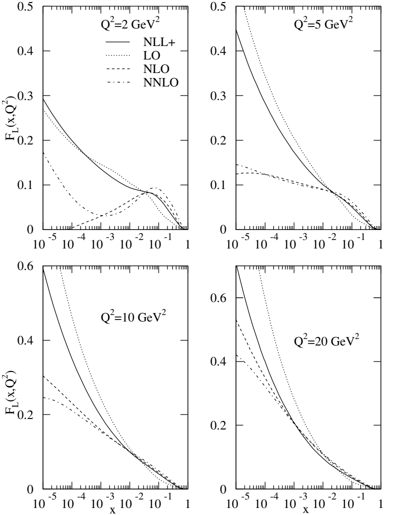
resummed evolution kernel at NNL, coefficient fct. improved LL



C. White, R. Thorne, 0706.2609 [hep-ph]

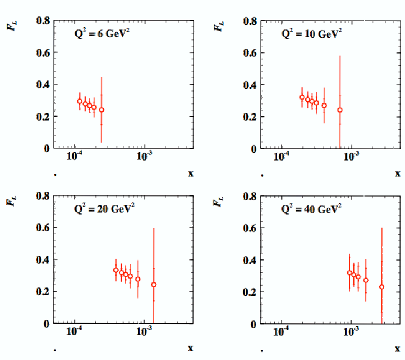
The longitudinal structure function

- F_L is a basic observable
  together with F_2 describes
  inclusive cross section
- starts at order α_s
  $\rightarrow$ directly sensitive to $g(x)$
- discriminates between
  theoretical approaches

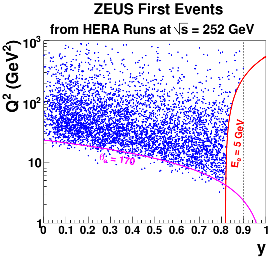


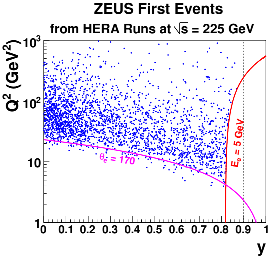
C. White, R. Thorne, 0706.2609 [hep-ph]

HERA low- and medium-energy runs



920 GeV 30 pb^{-1}
575 GeV 7 pb^{-1}
460 GeV 10 pb^{-1}



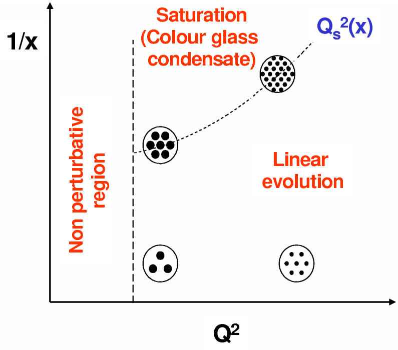


projected errors for low-energy data

M. Klein, DIS, March 07

Non-linear dynamics

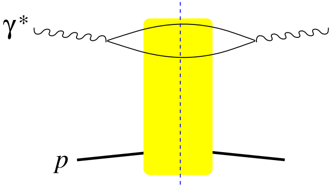
- $1/Q \sim$ transverse size of parton as "seen" by hard probe
- linear evolution: gluons split $\rightarrow$ high density at low x
- very high density: gluons recombine $\rightarrow$ density saturates
- non-linear effects become strong at saturation scale $Q_s(x)$



- non-linear evolution equations various degrees of approximation
  Balitsky-Kovchegov, JIMWLK, pomeron loops, . . .

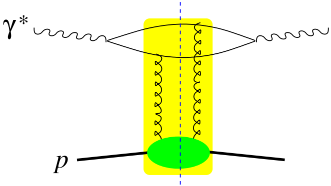
intense theoretical activity

- description of DIS processes in color dipole picture
  $\rightarrow$ dipole scattering amplitude $N_{q\bar{q}-p}$



- description of DIS processes in color dipole picture
  $\rightarrow$ dipole scattering amplitude $N_{q\bar{q}-p}$
- in non-saturated regime connect with leading-twist description

$$N_{q\bar{q}-p} \leftrightarrow g(x)$$



- parameterizations of $N_{q\bar{q}-p}$ incorporating saturation attempts to derive/motivate from non-linear evolution eqs.
  Golec-Biernat, Wüsthoff; Itakura, Iancu, Munier; Marquet, Peschanski, Soyez; Kowalski, Motyka, Watt; Forshaw, Sandapen, Shaw; ...
- successful fits to HERA F_2 down to low Q^2 and of $F_2^{c\bar{c}}$
- geometric scaling: $F_2(x, Q^2) \approx$ only function of $Q^2/Q_s^2(x)$
- with same $N_{q\bar{q}-p}$ describe HERA diffraction $\rightarrow$ next section

no proof of saturation at HERA, but strong indications

Where does saturation become important?

recent estimates of $Q_s^2(x)$ in GeV^2

$x = 10^{-4}$	$x = 10^{-6}$	Ref.
0.7	1.9	G. Soyez, 0705.3672 [hep-ph]
0.8	4.0	H. Kowalski, L. Motyka, G. Watt, hep-ph/0606272
0.8	2.0	K. Golec-Biernat, S. Sapeta, hep-ph/0607276

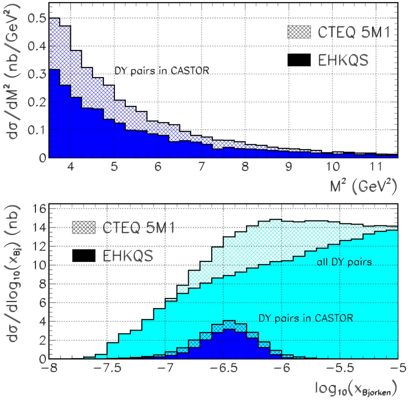
- at HERA typical $Q_s^2(x) \lesssim 1\,\mathrm{GeV}^2$
- HERA data have driven efforts to validate and quantify saturation
- impact on heavy-ion collisions $\rightarrow$ RHIC, ALICE theory of color glass condensate
- prospects to study saturation in pp at LHC $\rightarrow$ forward detectors

Forward DY and saturation

Rise of F_2 tamed by saturation?

- CTEQ 5M1: standard, "non-saturated" pdf
- EHKQS: "saturated" pdf with nonlinear terms in gluon evolution
  [A. Dainese et al., HERA-LHC Workshop proc.]

→ Saturation effects cause a 30% decrease in the DY cross section!



[PVM, CMS-note 2007/002]

Event yield: ~2 million events/fb^{-1} in CASTOR

F_L once more

- expect bigger saturation effects than in F_2
  J. Bartels, K. Golec-Biernat, K. Peters, hep-ph/0003042

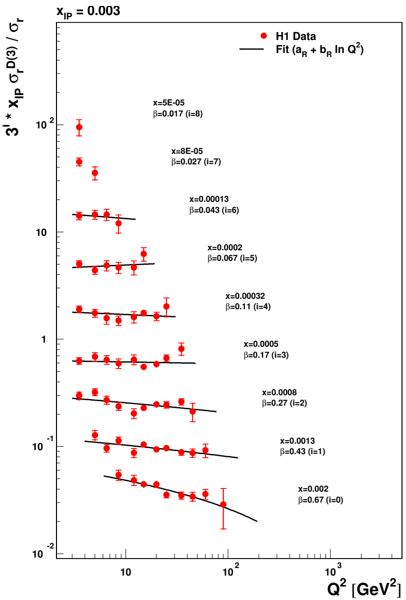
  study in saturation model:
  ratio of full result and twist-two part:
  at $Q^2 = 5\,\mathrm{GeV}^2$ and $x = 2.5 \times 10^{-4}$

$$\frac{F_2^{\text{full}}}{F_2^{t=2}} \approx 0.94 \qquad\qquad \frac{F_L^{\text{full}}}{F_L^{t=2}} \approx 0.66$$

caveat: uses old model parameters, no update of study
but: trend follows from general considerations

Diffraction

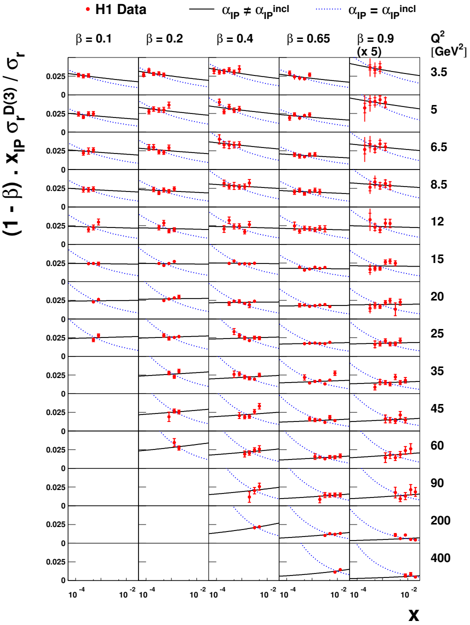
- in DIS have large fraction of events with leading proton/large rapidity gap: $\gamma^* p \to X + p$
- overall fraction in DIS $\sim 10\%$



H1, hep-ex0606004

- $\sigma_{\text{diff}}/\sigma_{\text{tot}}$ flat in Q^2
  $\rightarrow$ leading twist phenomenon

- twist-two descript. of inclusive F_2 ok for large Q^2
  factorization theorems
- but twist-two hard scattering
  $\oplus$ parton showers
  $\oplus$ hadronization models
  can miss important aspects of final state



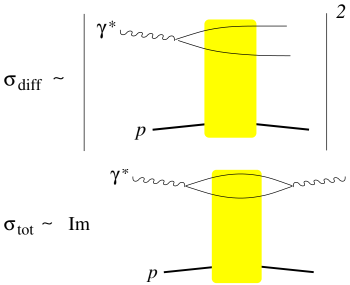
- σ_{diff} and σ_{tot} have very similar energy dep'ce in full Q^2 range

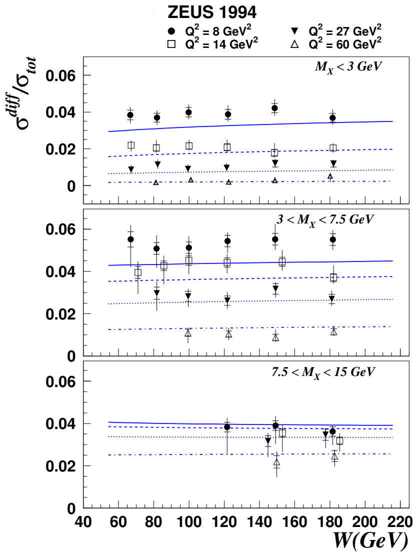
← H1, hep-ex0606004

- naturally explained in dipole models with saturation
- caveat: in restricted kinematics models without saturation work as well

J. Forshaw et al., hep-ph/0608161

→ kinematic reach important

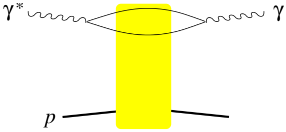


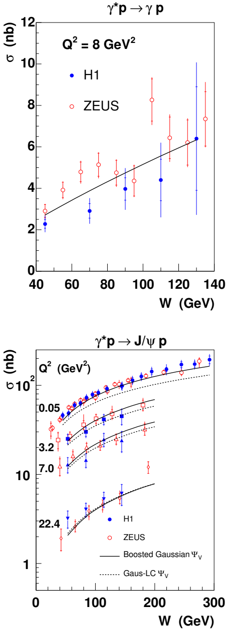


K. Golec-Biernat, M. Wüsthoff hep-ph/9903358

Vector mesons and virtual Compton scattering

- for large Q^2 or with heavy quarks
  σ rises much faster than σ_{tot}
- also well described in saturation models

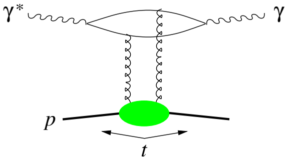




H. Kowalski, L. Motyka, G. Watt, hep-ph/0606272 →

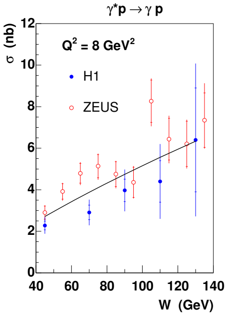
Vector mesons and virtual Compton scattering

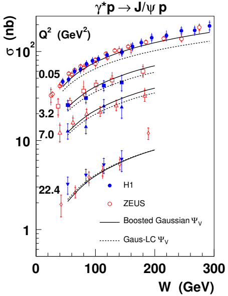
- for large Q^2 or with heavy quarks
  σ rises much faster than σ_{tot}
- also well described in saturation models



- in non-saturated regime have again leading twist factorization theorems
  $\longrightarrow$ generalized gluon distribution
- t dependence $\rightsquigarrow$ spatial distribution of gluons in plane $\perp$ to hadron momentum

H. Kowalski, L. Motyka, G. Watt, hep-ph/0606272 →





Rapidity gaps in hard pp or $p\bar{p}$ collisions

- at Tevatron $\sim$ order of magnitude more rare than in DIS

Diffractive fractions for forward and central gap processes at CDF

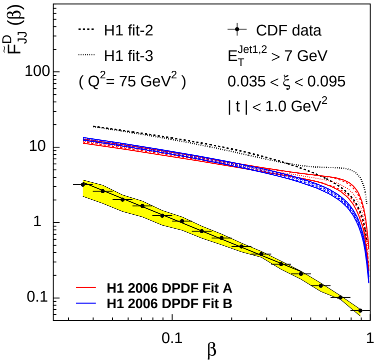
Hard process	$\sqrt{s}$ (GeV)	$R = \frac{\text{DIFF}}{\text{TOTAL}}$ (%)	Kinematic region
$W(\to e\nu)$+G	1800	1.15 ± 0.55	E_T^e, $\not{E}_T > 20$ GeV
Jet+Jet+G	1800	0.75 ± 0.1	$E_T^{jet} > 20$ GeV, $\eta^{jet} > 1.8$
$b(\to e + X)$+G	1800	0.62 ± 0.25	$\lvert\eta^e\rvert < 1.1$, $p_T^e > 9.5$ GeV
$J/\psi(\to \mu\mu)$+G	1800	1.45 ± 0.25	$\lvert\eta^\mu\rvert < 0.6$, $p_T^\mu > 2$ GeV
Jet-G-Jet	1800	1.13 ± 0.16	$E_T^{jet} > 20$ GeV, $\eta^{jet} > 1.8$
Jet-G-Jet	630	2.7 ± 0.9	$E_T^{jet} > 8$ GeV, $\eta^{jet} > 1.8$

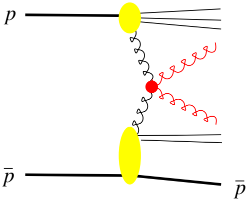
G= gap in rapidity

Table from: K. Goulianos, hep-ph/0407035

- gaps in hard $p\bar{p}$ proc's: strong suppression w.r.t. calculation using diffractive PDFs from HERA → A. Rostovtsev

$$\widetilde{F}^{D}_{JJ} \propto \sigma(p\bar{p} \to \text{dijet} + X + \bar{p})$$

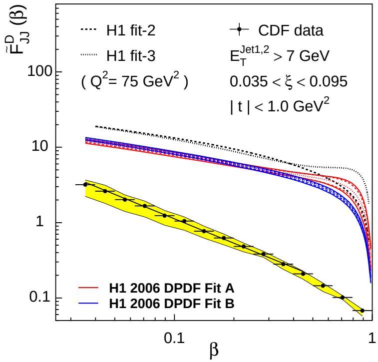


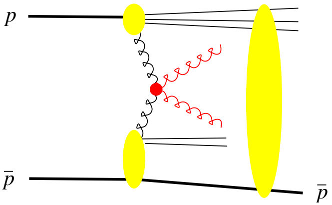


P. Newman and F.-P. Schilling
HERA/LHC workshop, March '07

- gaps in hard $p\bar{p}$ proc's: strong suppression w.r.t. calculation using diffractive PDFs from HERA → A. Rostovtsev
- diffractive factorization in $p\bar{p}$ broken by spectator interactions

$\widetilde{F}^{D}_{JJ} \propto \sigma(p\bar{p} \to \text{dijet} + X + \bar{p})$

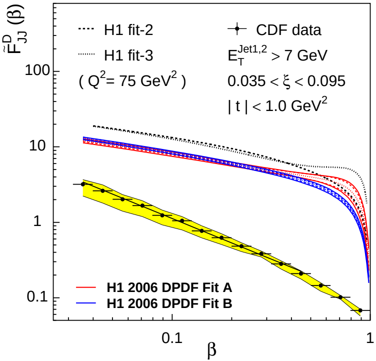




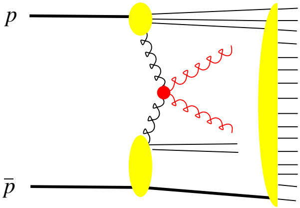
P. Newman and F.-P. Schilling
HERA/LHC workshop, March '07

- gaps in hard $p\bar{p}$ proc's: strong suppression w.r.t. calculation using diffractive PDFs from HERA → A. Rostovtsev
- diffractive factorization in $p\bar{p}$ broken by spectator interactions

$\widetilde{F}^D_{JJ} \propto \sigma(p\bar{p} \to \text{dijet} + X + \bar{p})$



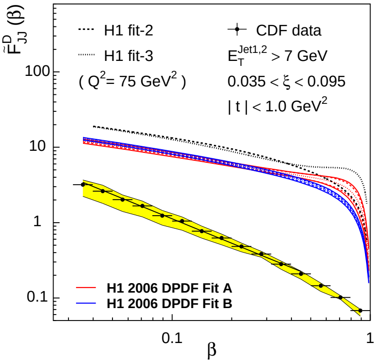
P. Newman and F.-P. Schilling
HERA/LHC workshop, March '07



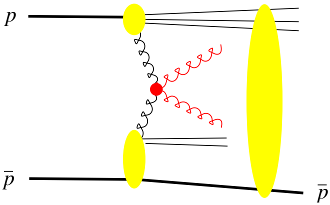
- same interactions can populate final state
- physics of underlying event and multiple interactions

- gaps in hard $p\bar{p}$ proc's: strong suppression w.r.t. calculation using diffractive PDFs from HERA → A. Rostovtsev
- diffractive factorization in $p\bar{p}$ broken by spectator interactions

$\widetilde{F}^D_{JJ} \propto \sigma(p\bar{p} \to \text{dijet} + X + \bar{p})$

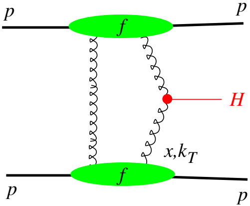


P. Newman and F.-P. Schilling
HERA/LHC workshop, March '07



- spect. interactions at least partly soft → models
- HERA + Tevatron
  → validate models
  → extrapolate to LHC

Exclusive production at LHC



- produce Higgs (or other particles) in clean environment
- need forward detectors
  Totem, FP220, FP420
- expt'l challenge: triggers, low rates

Why interesting?

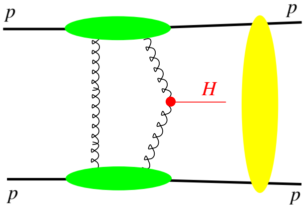
- tagged protons → precise mass/width meas't $\sim$ 2 to 3 GeV
- selects $CP = ++$ states ($CP = +-$ strongly suppressed)
- good signal/background ratio

How to calculate?

- HERA vector meson prod'n → generalized gluon distribution
- hard QCD corrections Sudakov suppression factor

Exclusive production at LHC

- produce Higgs (or other particles) in clean environment
- need forward detectors
  Totem, FP220, FP420
- expt'l challenge: triggers, low rates



Why interesting?

- tagged protons → precise mass/width meas't $\sim$ 2 to 3 GeV
- selects $CP = ++$ states ($CP = +-$ strongly suppressed)
- good signal/background ratio

How to calculate?

- HERA vector meson prod'n → generalized gluon distribution
- rescattering corrections: models checked against Tevatron
  ongoing CDF studies: $p\bar{p} \to p + \text{dijet} + \bar{p}$, $p\bar{p} \to p + \gamma\gamma + \bar{p}$

- light SM Higgs $\to W^+W^-$ (one W off shell)
  - very low background

B. Cox et al., hep-ph/0505240

Excl. DPE H->WW: Event yield for L=30 fb-1
ExhuMe 1.3 and new RP acceptances

			fully-lept		semi-lept		
Mh[GeV]	σXBR[fb]	Acc.[%]	cms	atlas	cms	atlas	Total
120	0.37	57	0.2	0	1.2	1	1.3
135	0.77	62	0.6		3.1		3.4
140	0.87	63	0.6	1	3.5	3	3.8
150	1.00	66	1.0		4.9		5.3
160	1.08	69	1.0	1	6.0	5	6.6
170	0.94	71	1.0		5.4		5.9
180	0.76	74	0.8	1	4.5	4	4.9
200	0.44	78	0.6	1	2.9	2	3.2

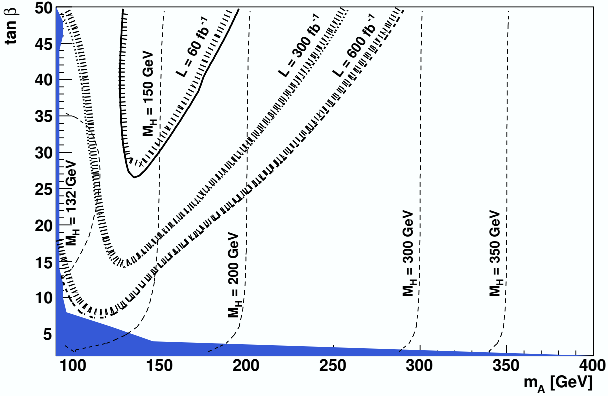
M. Taševski, HERA/LHC workshop, 3/06

8

- light Higgs $\to b\bar{b}$
  - very low rate in SM with triggers and cuts
    must remove $gg \to b\bar{b}$ background
    (although is much lower than in inclusive case)
    detailed background calculations V. Khoze, M. Ryskin, J. Stirling, '06

- light Higgs $\to b\bar{b}$
  - strongly enhanced rate in MSSM scenarios with high $\tan\beta$

Stat.sig=5 for H→bb, mhmax sc.,μ=-500 GeV



M. Taševski, HERA/LHC workshop, 3/07

Summary

HERA has pioneered study of DIS at small x and at large Q^2

- precision PDFs
- theory of low x dynamics
  high fixed orders, resummation, non-linear dynamics
- diffraction: subtle QCD dynamics in final state
- HERA $\oplus$ Tevatron $\rightsquigarrow$ exclusive production at LHC
  in some >SM scenarios could become discovery channel

important results still to come from HERA II data

- statistics and kinematic reach
- longitudinal structure function F_L