Hard Diffraction at HERA & LHC

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on behalf of the H1 and ZEUS collaborations

QCD@LHC 2013
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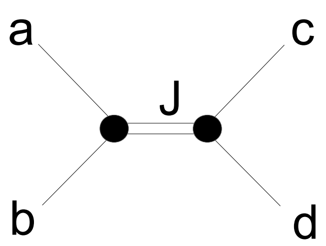
Soft diffractive processes

Hadronic interactions before QCD described by Regge theory

1) analyticity and unitarity of S matrix
2) partial wave analysis
3) extension of partial amplitudes by means of using complex angular momentum



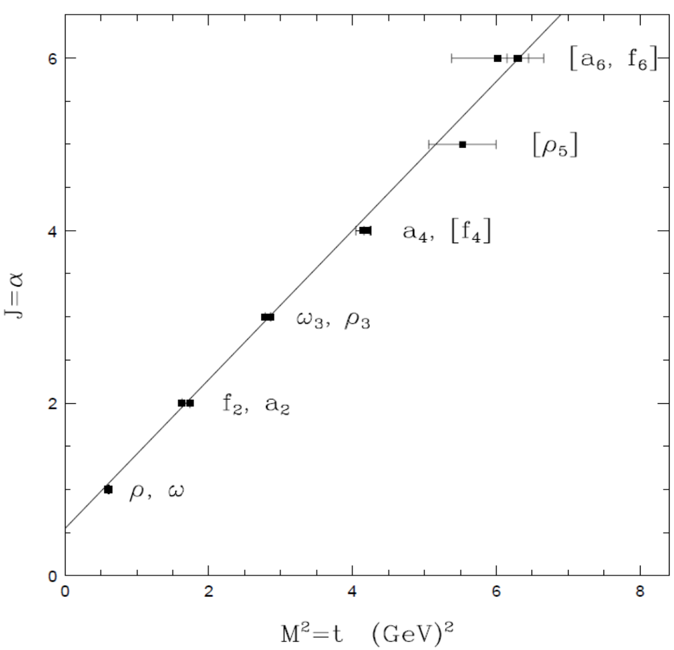
$$A^{ab\rightarrow cd}(s,t) = \sum_J a_J(s) P_J(1-2t/s)$$

crossing symmetry s ↔ t

$$A^{\bar{a}c\rightarrow \bar{b}d}(t,s) \overset{s\rightarrow\infty}{\longrightarrow} \sum_j a_J(t) s^J$$

+ opt. theorem $\longrightarrow$ $\sigma_{tot} \propto \sum_k s^{2(\alpha_k(0)-1)}$

$\alpha_k(t) = \alpha_k(0) + \alpha'_k\, t$ … trajectory in (t,l) plane called Reggeon (IR)



One can think of Regge exchange as of exchange of many particles since the trajectories cross J and m^2 of hadrons.

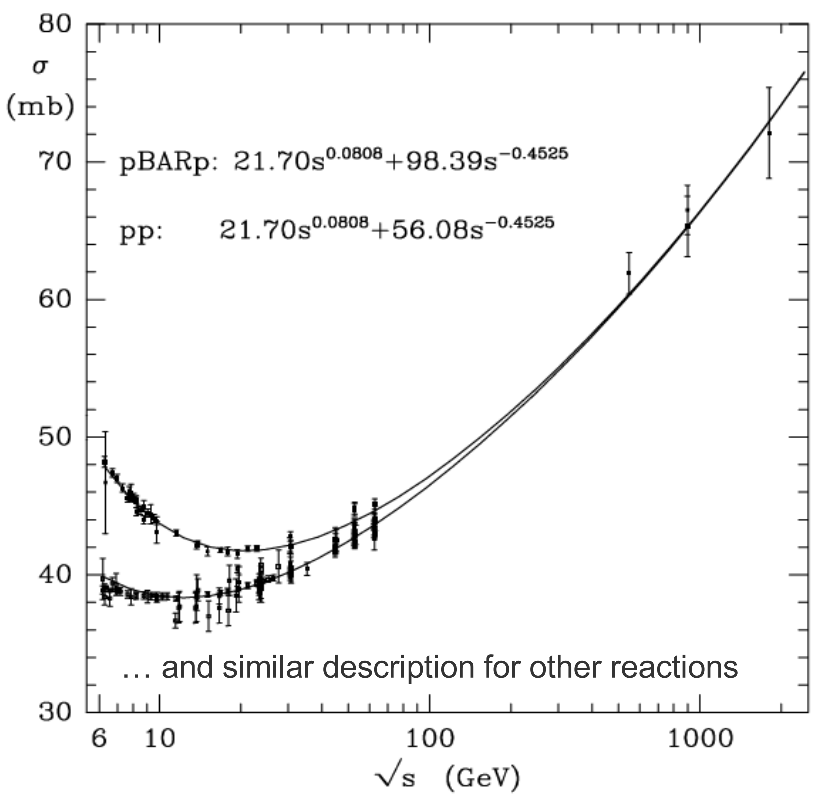
trajectories with non-vacuum quantum numbers have $\alpha(0) < 1$ Okun-Pomeranchuk

if $\alpha(0) \geq 1$ then the exchange must have vacuum quantum numbers Foldy-Peierls

Pomeron (IP) = trajectory with $\alpha(0) \geq 1$, is it needed?

Donnachie-Landshoff

fit of data: $p\,\bar{p},\ pp,\ K^{\pm}p,\ \pi^{\pm}p,\ \gamma\, p$ in form $\sigma^{tot} = X\,s^{0.0808} + Y\,s^{-0.4525}$



energy dependence described with IP of

$$\alpha_{IP}(t) = 1.08 + 0.25\ [\text{GeV}^{-2}]\ .\ t$$

IP is not associated with any hadron

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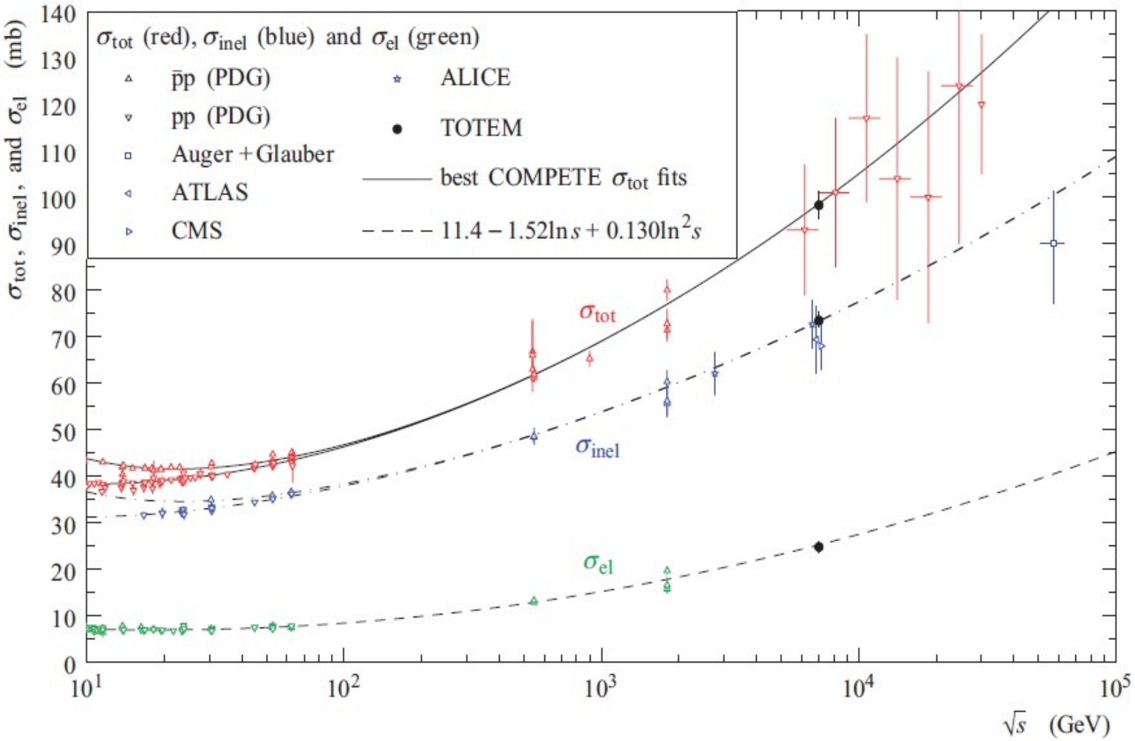

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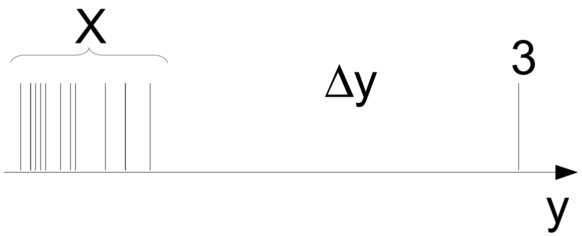
A consequence of IP and IR exchange: 1 + 2 → 3 + X, M = the mass of X.

difference of particle 3 rapidity and rapidity of X edge reads:



$$\Delta y \simeq \ln \frac{s}{M^2}$$

We already know: $\sigma_{tot} \propto \sum_k s^{2(\alpha_k(0)-1)}$ thus $\sigma_{tot} \propto M^2 \sum_k e^{2(\alpha_k(0)-1)\Delta y}$

IP: $\alpha_{IP}(0) \sim 1$ → dσ/dΔy almost independent of Δy

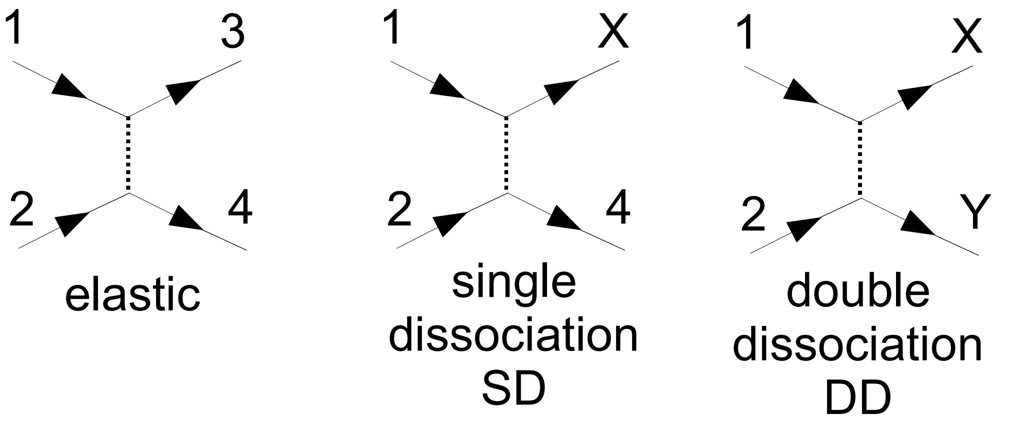
IR: $\alpha(0) < 1$ → dσ/dΔy exponentially suppressed as Δy increases

Hard diffractive processes

Hard scale(s) must be present to make pQCD converging.

Hard diffractive processes are characterized by:

- small momentum transfer between between initial and final state, s >> t
- final state particles may dissociate into states with $M^2 << s$
- they are separated by **Large Rapidity Gap (exponentially non-suppressed)**

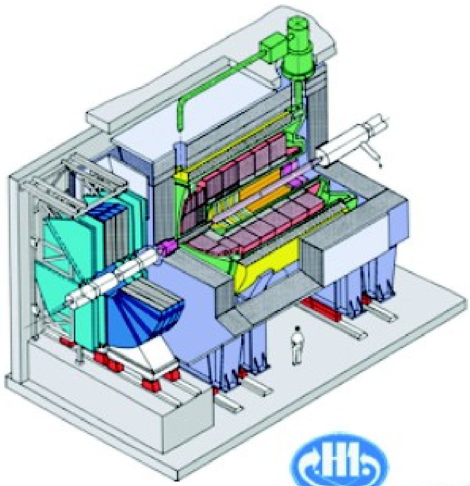


What is IP in QCD?

- in soft regime QCD inapplicable
- in the hard one, exchange of **gluons plays a major role**

HERA and the experiments

ep collider (sleeping somewhere underneath) in DESY, Hamburg

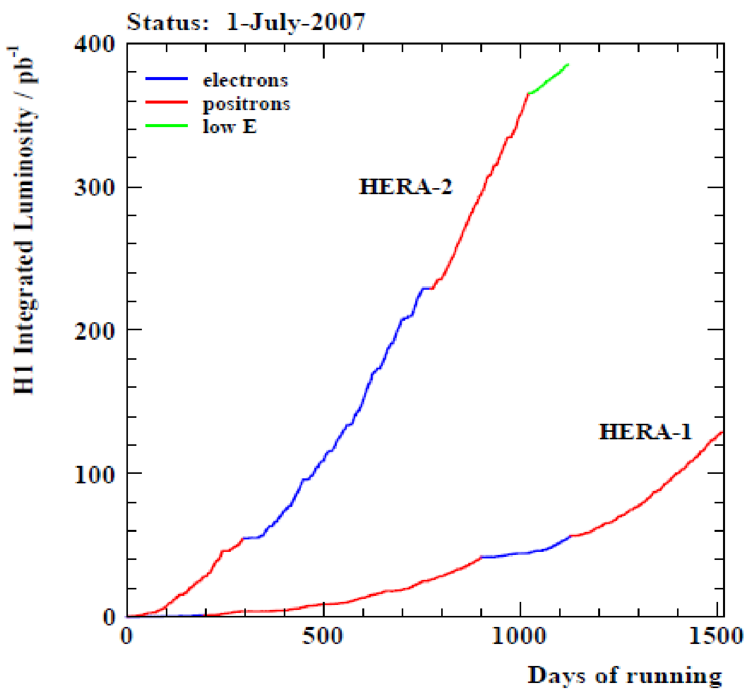


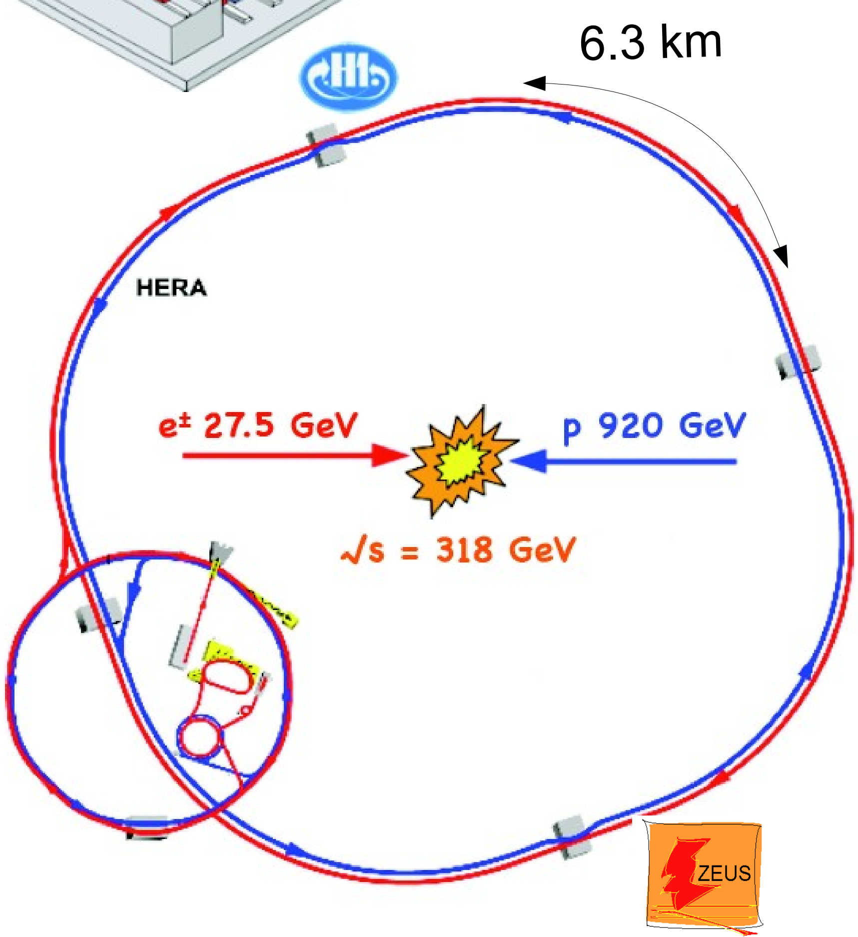
HERA-1 (1993-2000) $\simeq$ 120 pb^{-1}

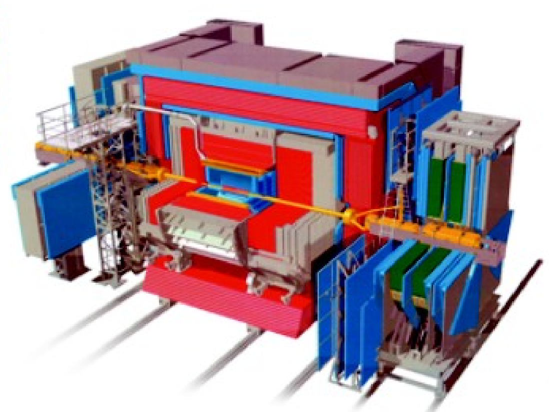
HERA-2 (2003-2007) $\simeq$ 380 pb^{-1}

Final Data samples

H1+ZEUS: $2 \times 0.5\ \text{fb}^{-1}$

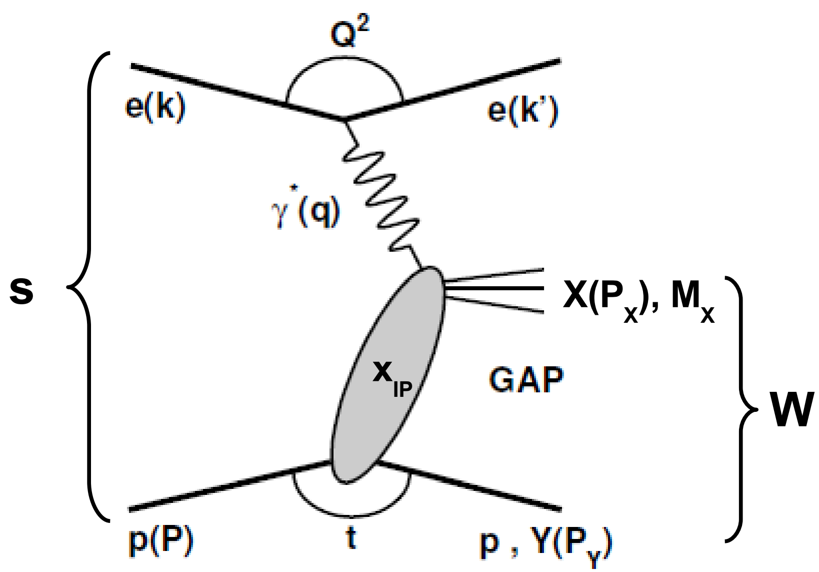






Hard diffraction at HERA

Diffractive Deep Inelastic Scattering (**D**DIS) represents ~ 10% of DIS σ



$$s = (k+P)^2$$
$$Q^2 = -q^2 = -(k-k')^2$$
$$y = \frac{q.P}{k.P}$$
$$x = \frac{Q^2}{2q.P}$$
$$W = \sqrt{(q+P)^2}$$
$$t = (P-P_Y)^2$$
$$M_X = P_X^2$$
$$M_Y = P_Y^2$$
$$x_{IP} = \frac{q.(P-P_Y)}{q.P}$$
$$\beta = \frac{x}{x_{IP}}$$

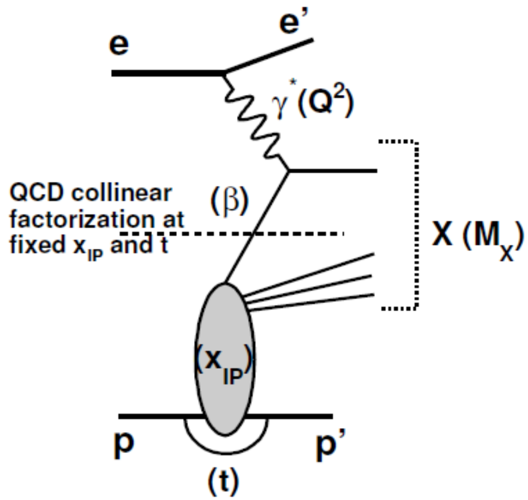
Q^2,t … four-momentum transfers
W … hadronic CMS energy
x … Bjorken x
X … photon dissociative system
Y … leading proton system
x_{IP} … long. fraction of proton momentum carried by IP
β … parton fraction w.r.t. IP

<u>identification of diffractive events</u>

LRG … **large statistics**, **exp. simple** / proton dissociation (p → Y) contamination

leading proton tagging … **clean elastic events /** limited acceptance, dedicated detectors (Roman Pots)

QCD hard factorization in DDIS



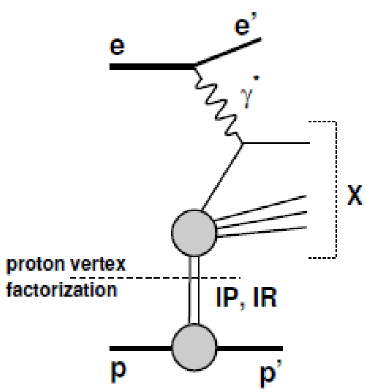
theoretical proof by Collins at. al

hard cross sections factorize from parton distributions

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

hard processes cross sections calculable in QCD
→ parton distributions (PDFs) can be measured
and parametrized in terms of diffractive PDF fits (DPDF)

optionally one may use Ingelman and Schlein proton vertex factorization (Regge factorization):



universal *IP* flux in the *IPp* vertex

$f_{IP/p}(x_{IP}, t)$ … flux controls x_{IP}, t dependence of σ.

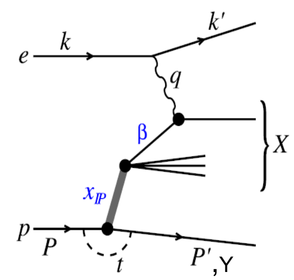
$$F_2^{D(3)}(x_{I\!P}, \beta, Q^2) = f_{I\!P/p} \cdot F_2^{I\!P}(\beta, Q^2)$$

IP with partonic structure is emitted with momentum $x_{IP} . P_{proton}$ and t from the incoming proton and is subject to the hard scattering.

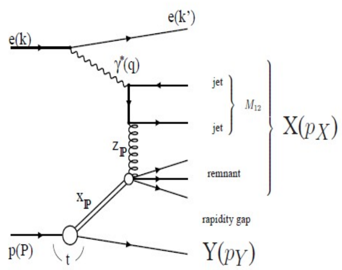
Measurements of DPDFs

measured from

analyses of inclusive data ep → eXY



analyses of data ep → eXY with jets
in the final state
(another constraint on gluon DPDF)



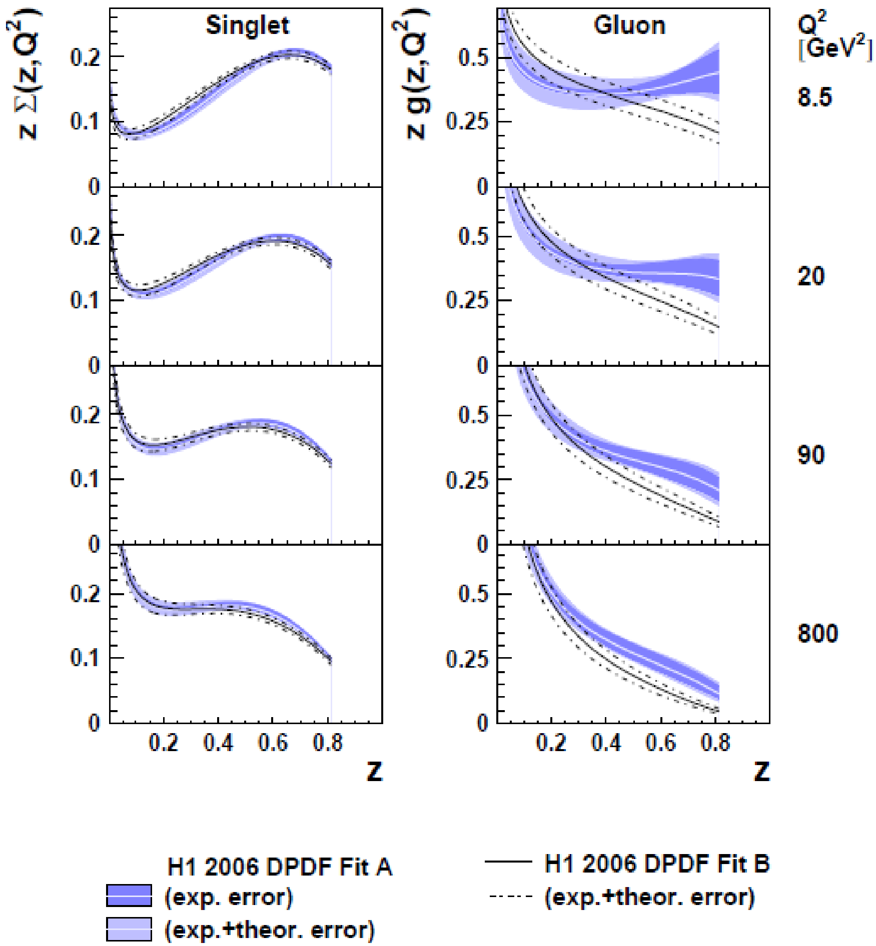
combination of diffraction selection methods

combinations of data from experiments

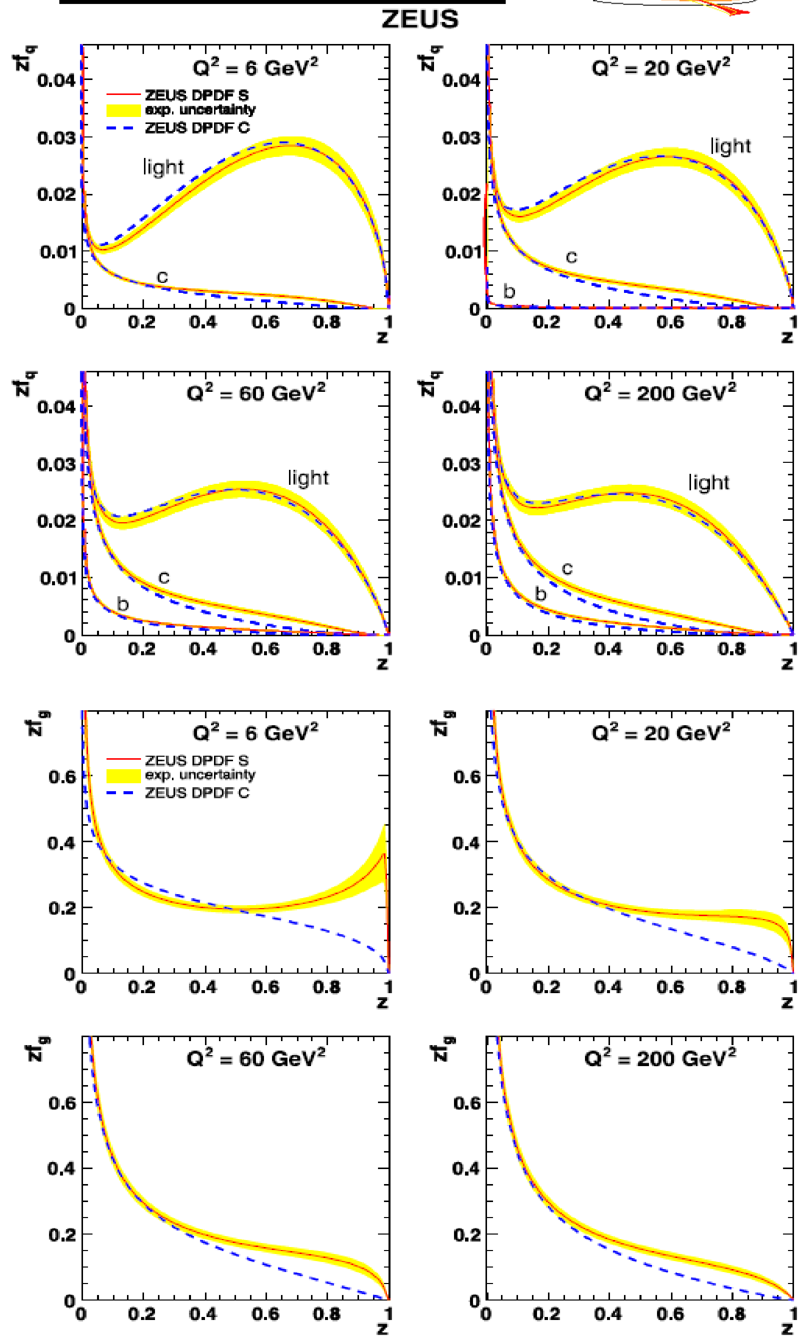
using the DPDFs for predictions → QCD hard factorization is tested

inclusive LRG data

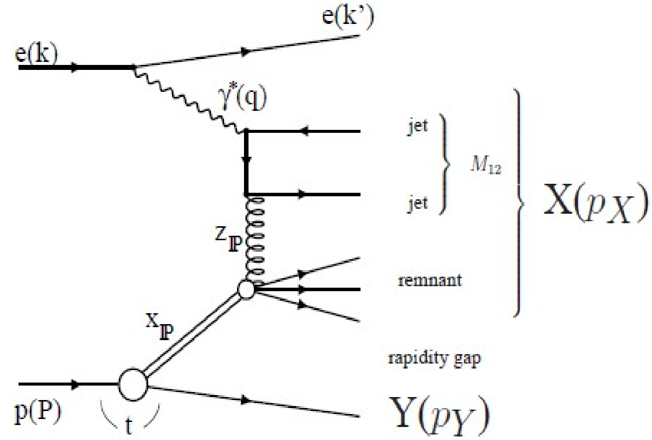
Eur. Phys. J. C48 (2006) 715-748

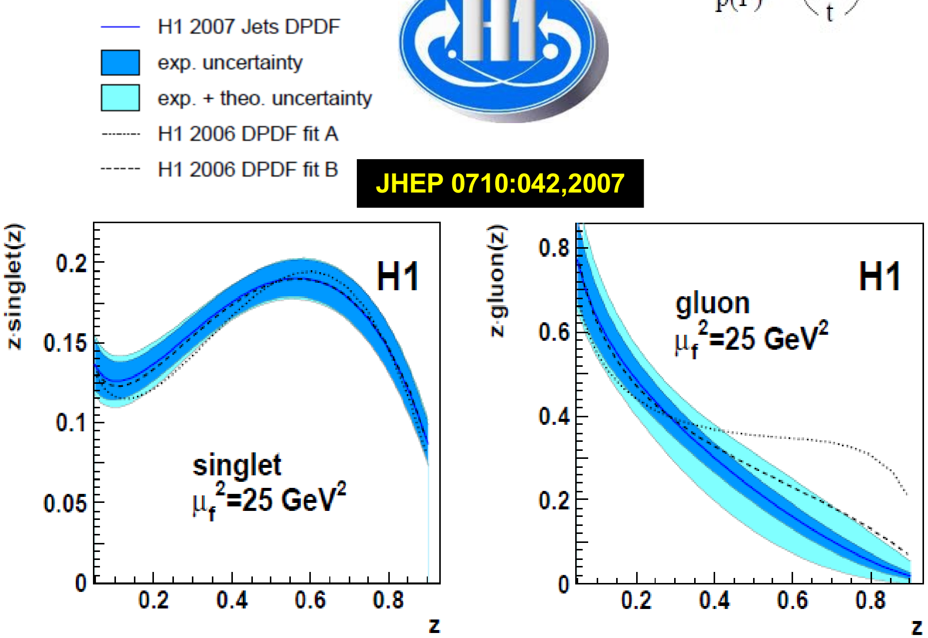


Nucl. Physics B 831 (2010) 1-25



dijet DDIS data





JHEP 0710:042,2007

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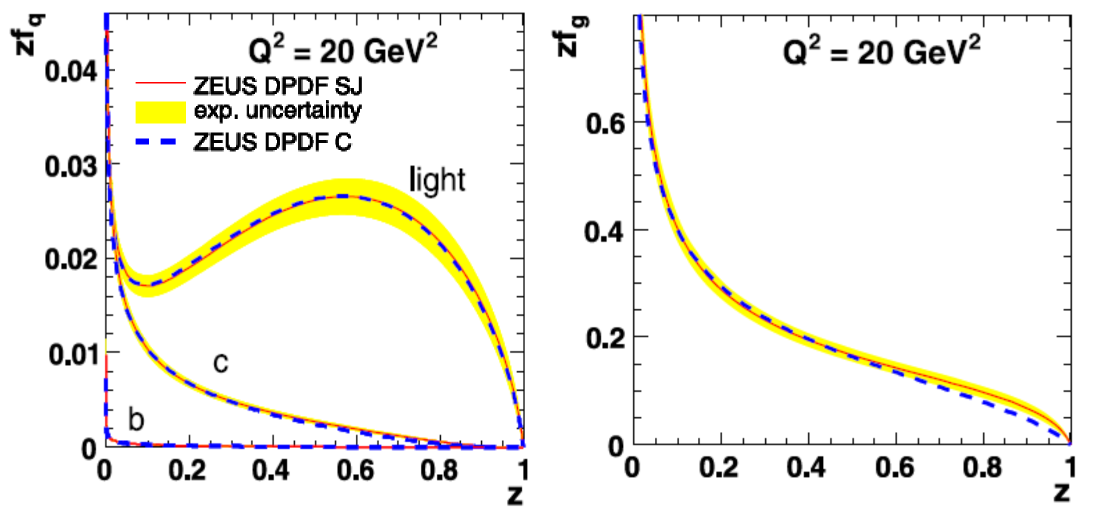
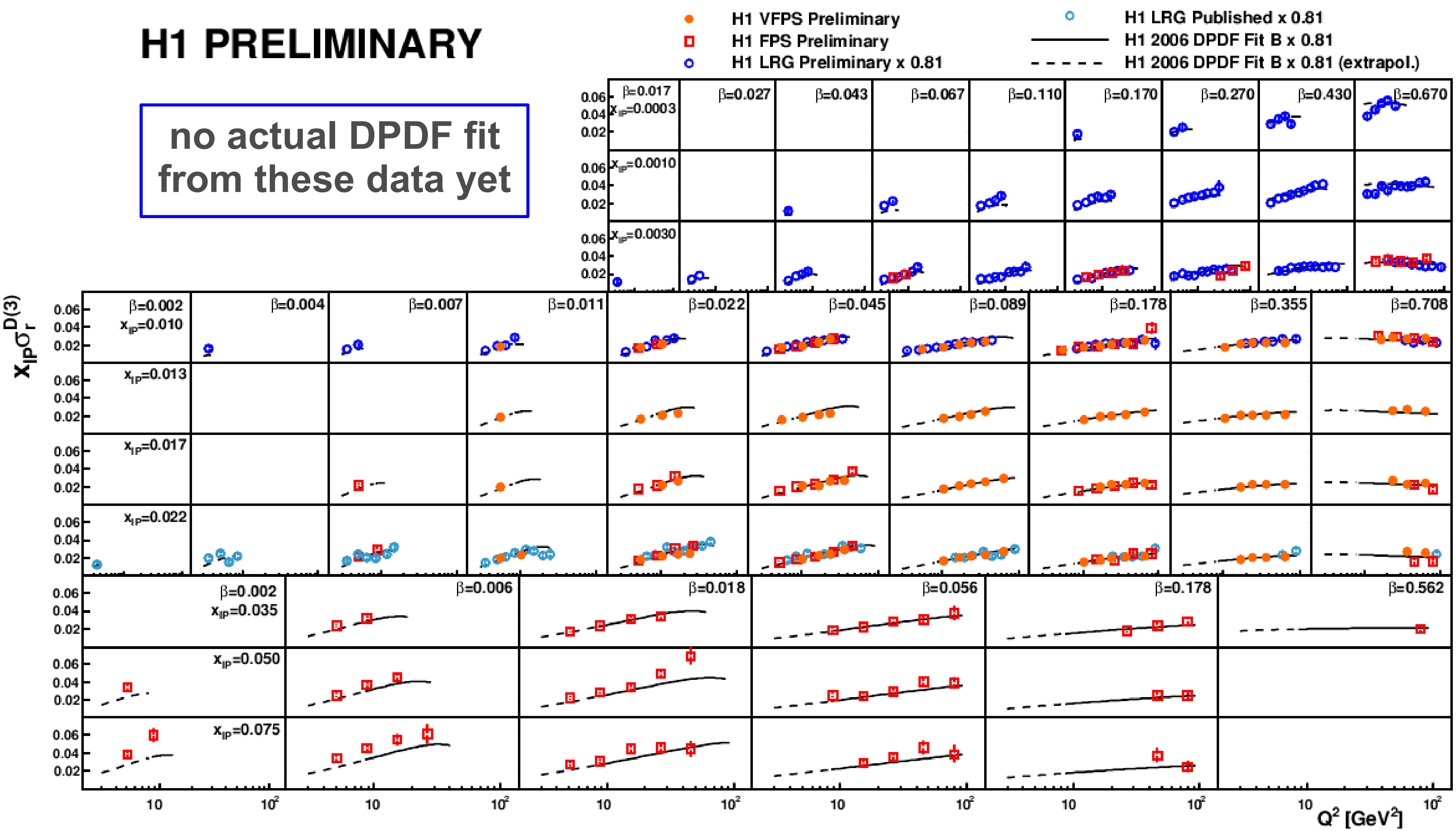


gluon dominates in the diffractive exchange (60-70%)

combination of detection methods

inclusive data obtained by LRG and proton tagging … biggest H1 dataset

no actual DPDF fit from these data yet



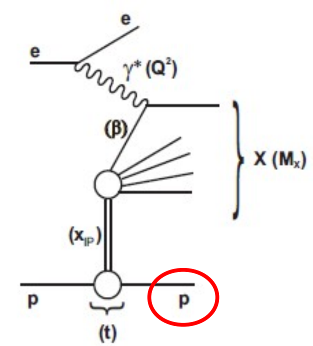
Era of combinations of H1 and ZEUS data

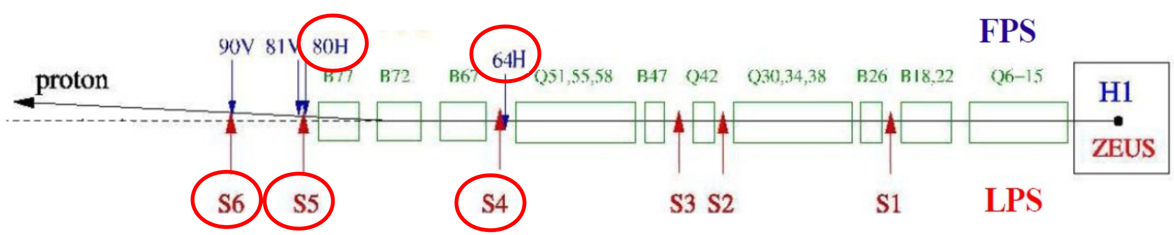
(D)PDF fits will profit from statistics increase and independent systematics

successful combination of inclusive data with leading proton

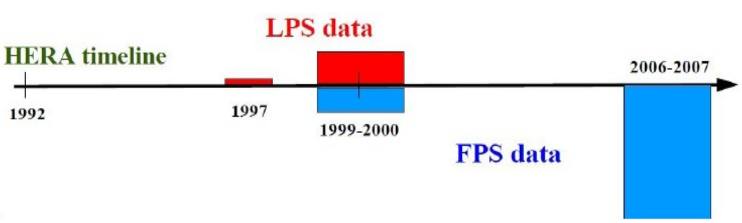
Combined inclusive diffractive cross sections measured with forward proton spectrometers in deep inelastic ep scattering at HERA

Eur. Phys. J. C72 (2012) 2175 , 07/12





ep → eXp, selected with leading protons in Roman Pots (H1-FPS, ZEUS-LPS)



common phase space:

$2.5 < Q^2 < 200$ GeV^2 $\quad 0.00035 < x_{I\!P} < 0.09$

$0.09 < |t| < 0.55$ GeV^2 $\quad 0.0018 < \beta < 0.816 \quad \beta = x/x_{I\!P}$

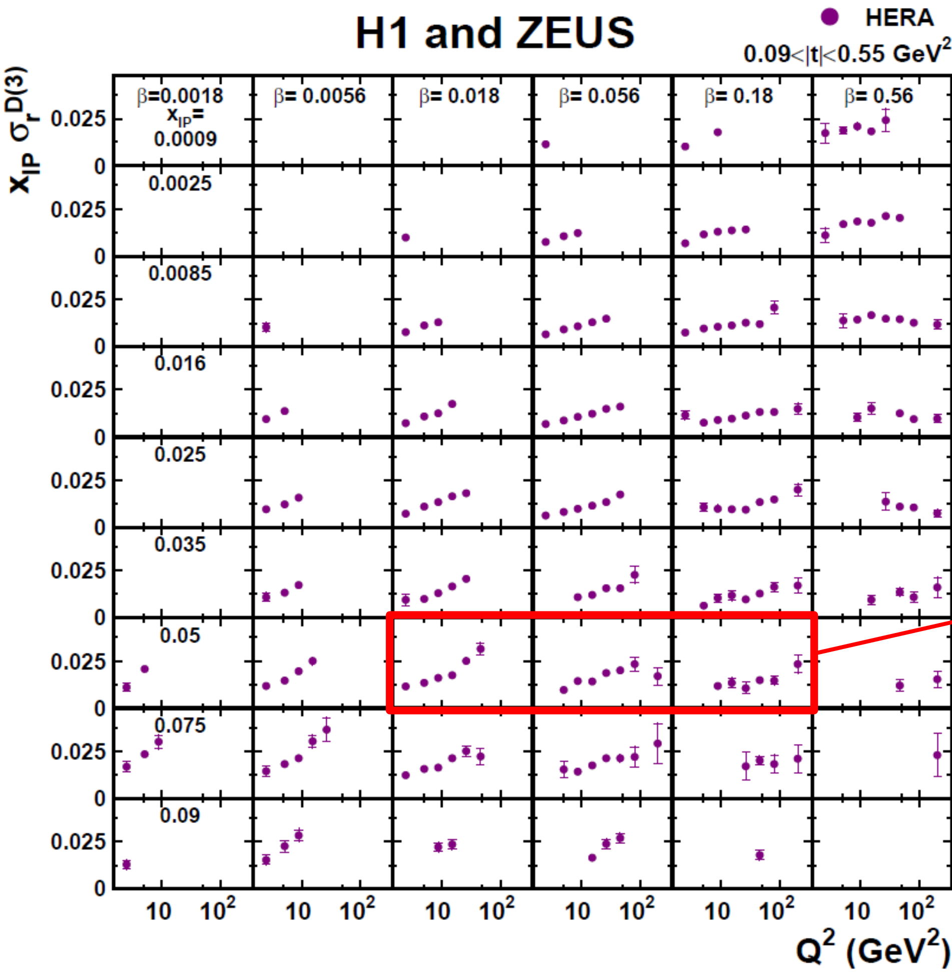
combined cross section values obtained by iterative χ^2 minimization, full error correlations taken into account

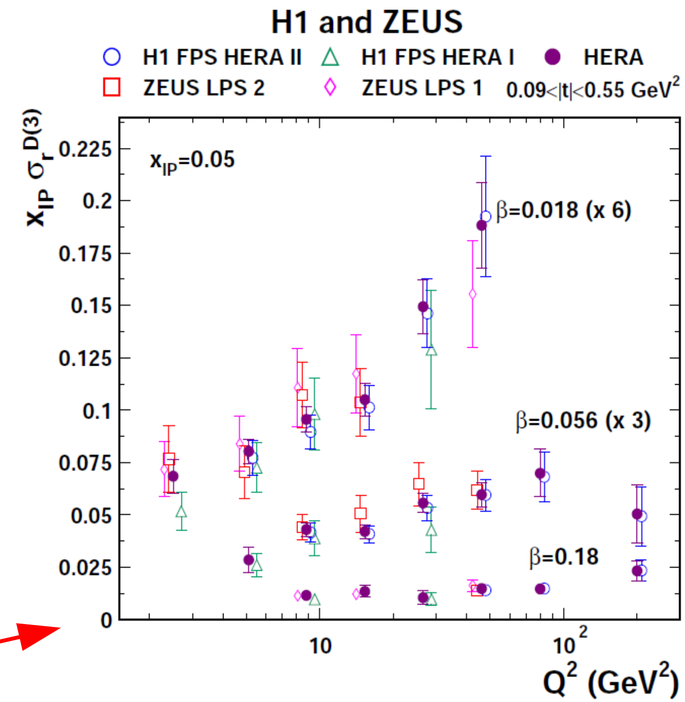
[A. Glazov, AIP Conf. Proc. 792 (2005) 237]

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

reduced cross section measured $\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{1+(1-y)^2} F_L^{D(4)}$

integrated over t $\sigma_r^{D(3)}(\beta, Q^2, x_{I\!P}) = \int \sigma_r^{D(4)}(\beta, Q^2, x_{I\!P}, t)dt$





Reduction of syst. errors (two detectors).

Consistency between H1 and ZEUS.

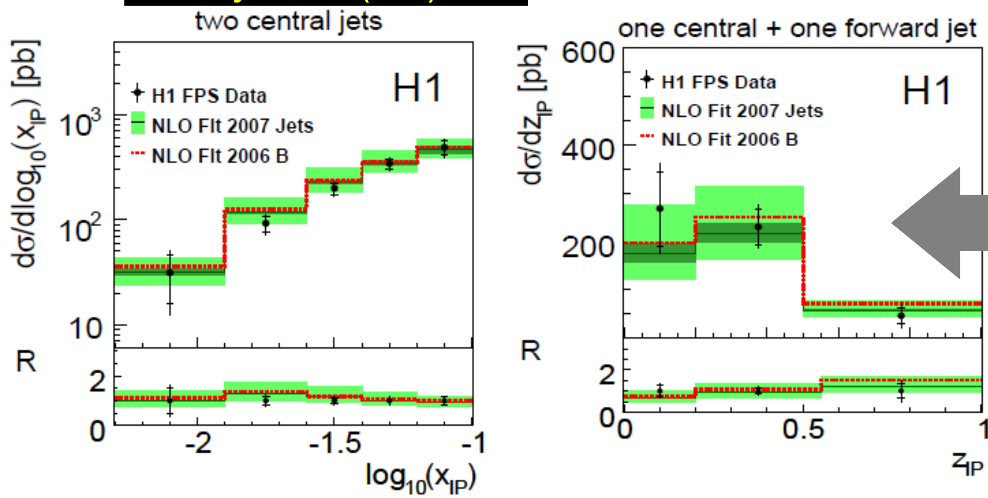
Most precise normalization of ep→eXp σ.

Combined data more precise than single data of either experiment alone.

Tests of HERA DPDFs in DDIS

DPDFs obtained (under assumption of validity of QCD hard factorization) are used for predictions

Eur. Phys. J. C72 (2012) 1970



jets

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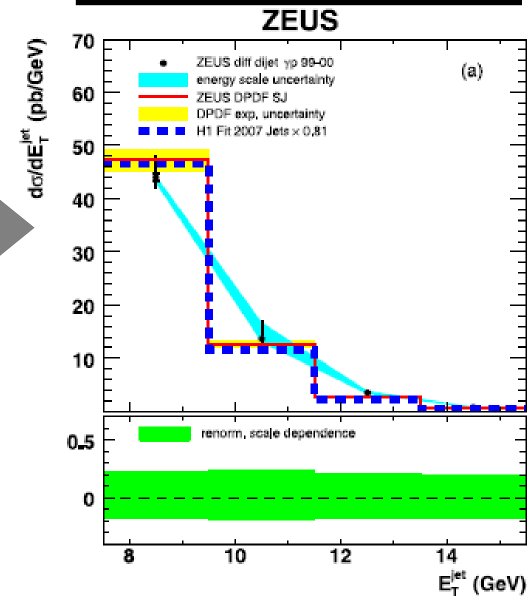

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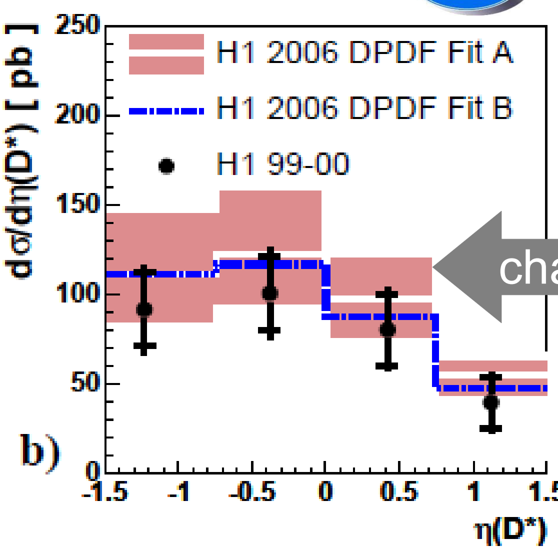
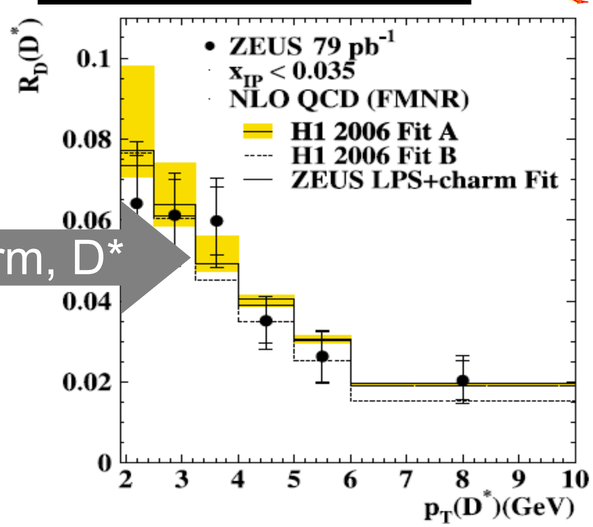


charm, D*

Eur. Phys. J. C51 (2007) 301-315



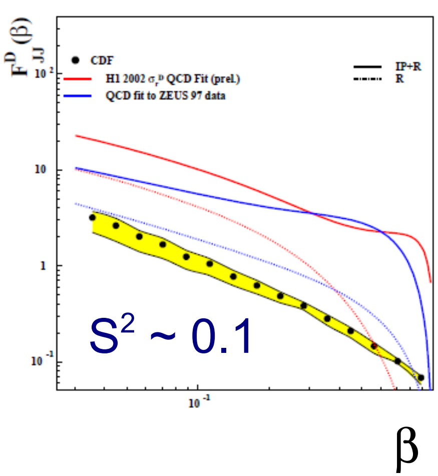
Tests DPDFs from HERA in Photoproduction

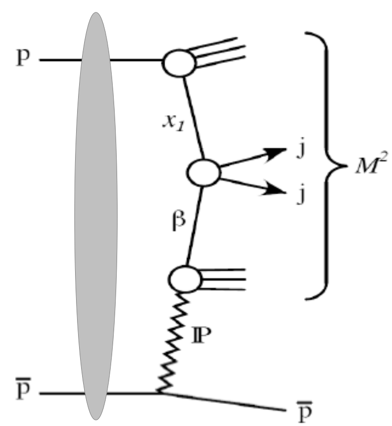
QCD hard factorization **does not hold** in diffractive **hadron-hadron** interactions Kaidalov et al. [hep- ph/0302091]

soft scatterings between spectator partons fill the gap, leads to suppression of observed rate of diffractive events → gap survival probability, S^2

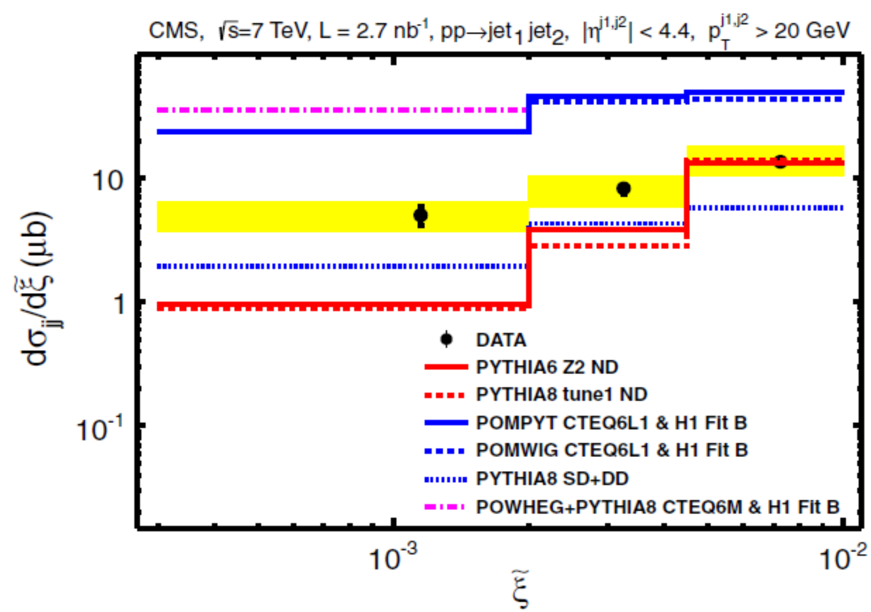
can be illustrated with dijets in pp at Tevatron
and newly by diffractive contribution to dijet production in CMS

Tevatron vs HERA





Phys. Rev. D 87, 012006 (2013)



$$\tilde{\xi}^{\pm} = \frac{\sum(E^i \pm p_z^i)}{\sqrt{s}}$$

There are hadron-hadron like interactions at HERA too.

$S^2_{\text{(LO MC, HERA DPDF)}} \sim 0.12\text{-}0.2$

$S^2_{\text{(NLO MC, HERA DPDF)}} \sim 0.08\text{-}0.14$

photoproduction in ep … $Q^2 \sim 0\ \mathrm{GeV}^2$

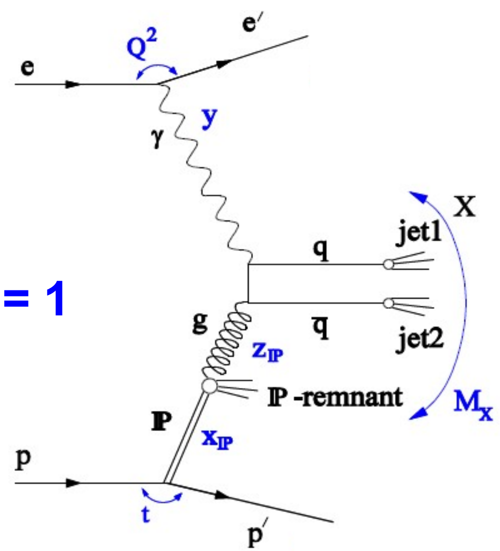
in LO we distinguish between:

direct (DIS-like) photon interactions

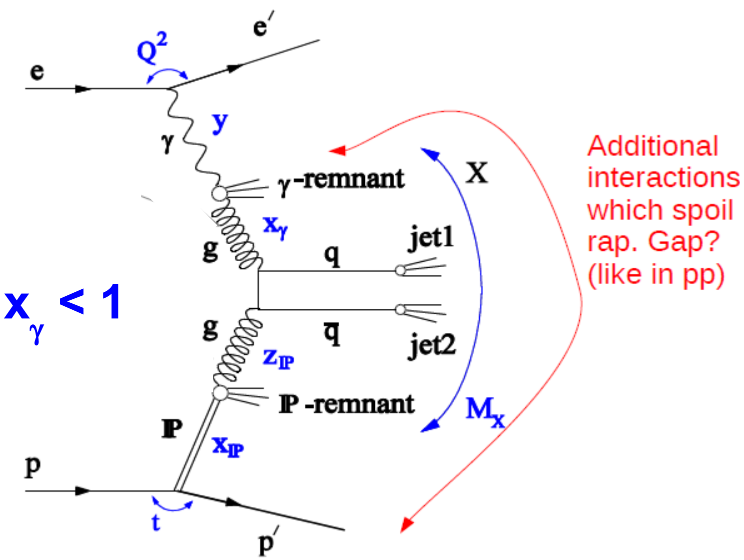
resolved photon interactions (h-h-like) … photon structure function used

x_γ = fraction of γ 4-momentum in the hard process, direct/resolved discriminator

$x_\gamma = 1$



$x_\gamma < 1$



direct processes, DIS-like

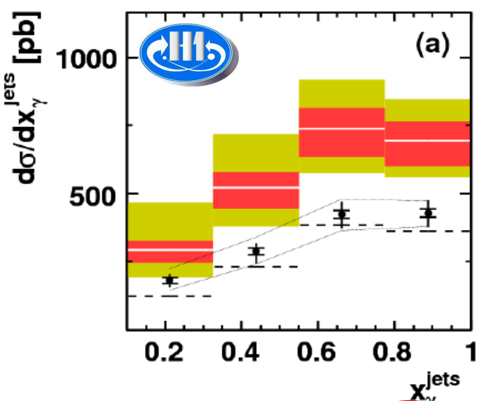
resolved γ processes, hadron-like

Previous HERA results not fully decisive.

- LRG method used for diffractive selection
- different phase space
- different selection of photoproduction, tagged electron H1 vs. untagged ZEUS
- survival probability studied by comparison of data with NLO QCD prediction

Eur. Phys. J. C68 (2010) 381

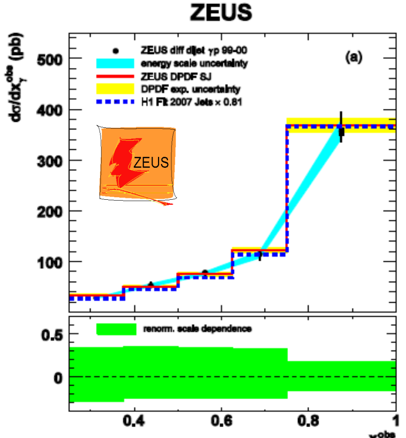
$E_T^{jet1(2)} > 5(4)\,\text{GeV}$



$\sigma_{data}^{H1} / \sigma_{NLO}^{H1} \approx 0.6$

Nucl. Phys. B381 (2010)

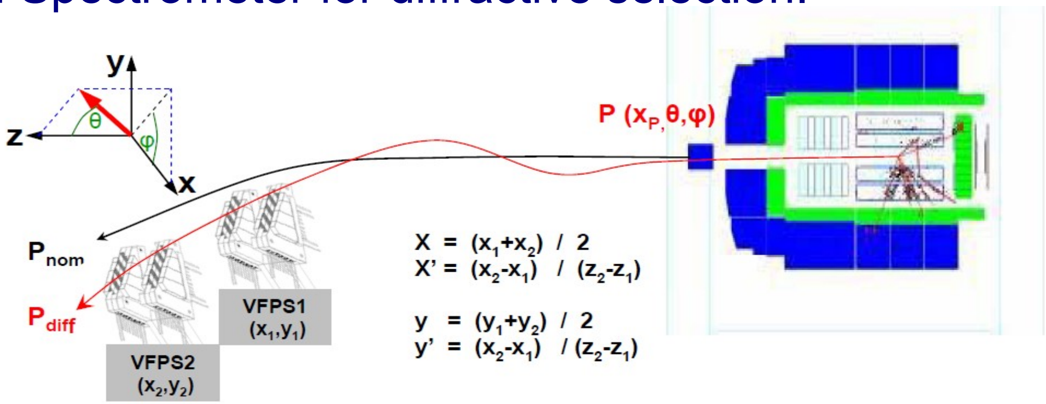
$E_T^{jet1(2)} > 7.5(6.5)\,\text{GeV}$



$\sigma_{data}^{ZEUS} / \sigma_{NLO}^{ZEUS} \approx 1.0$

New analysis uses **V**ery **F**orward **P**roton **S**pectrometer for diffractive selection.

- located at 218 and 222 m from I.P.
- profits from different systematics
- reasonable statistics ~ 4800 ev.



Phase-space definition

$Q^2 < 2\,\mathrm{GeV}^2$

$0.2 < y < 0.8$

k_T jet algorithm:

$E_T^{\mathrm{jet1}(2)} > 5.5(4)\,\mathrm{GeV}$

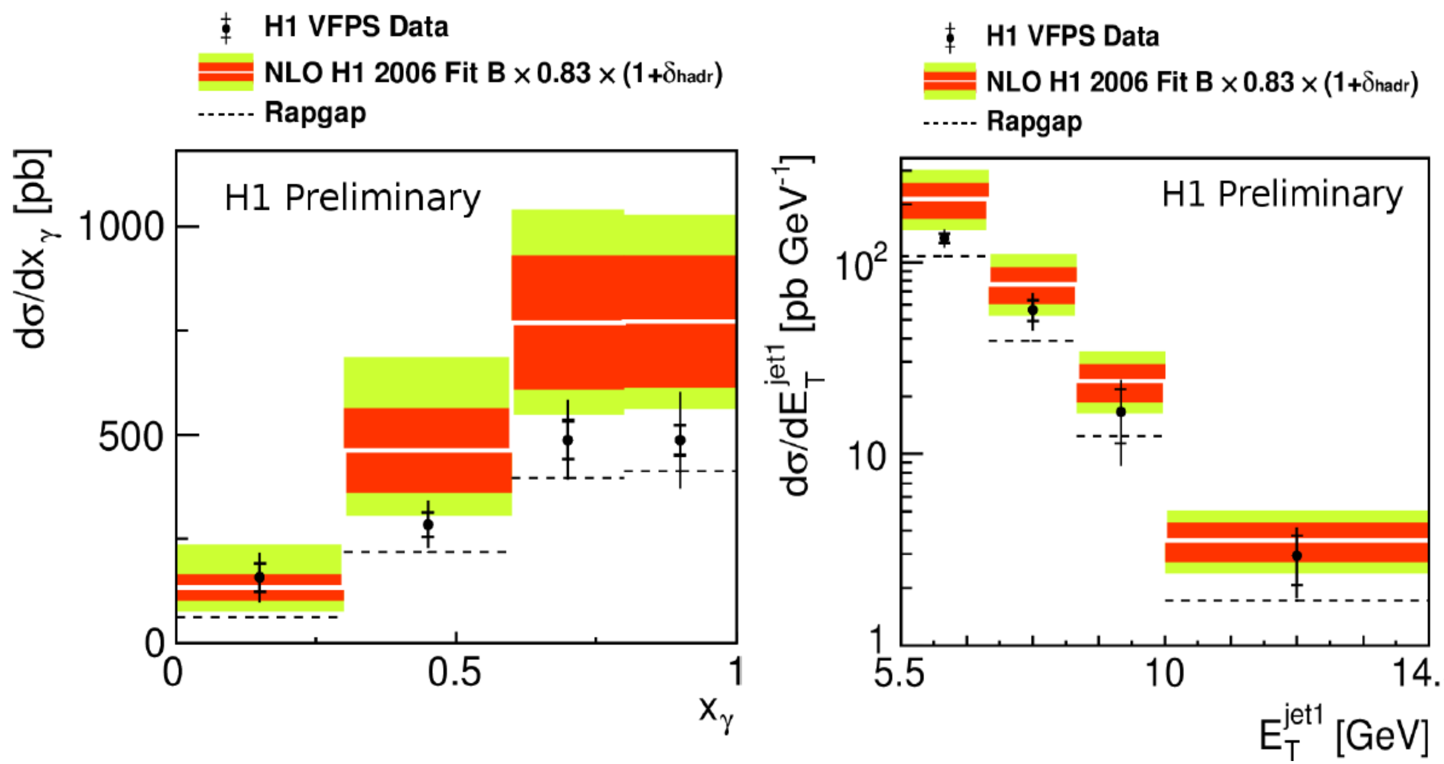
$-1 < \eta^{\mathrm{jet1,2}} < 2.5$

Diffractive:

$0.010 < x_{IP} < 0.024$

$|t| < 0.6\,\mathrm{GeV}^2$

$M_Y = M_p$



$$\sigma_{DATA}/\sigma_{NLO} = 0.67 \pm 0.04(\mathrm{stat.}) \pm 0.09(\mathrm{syst.}) \pm 0.20(\mathrm{scale}) \pm 0.14(\mathrm{DPDF})$$

Measured suppression factor $\sigma_{DATA}/\sigma_{NLO}$ consistent with previous H1 analysis.

Difference of the suppression w.r.t. ZEUS analysis remains.

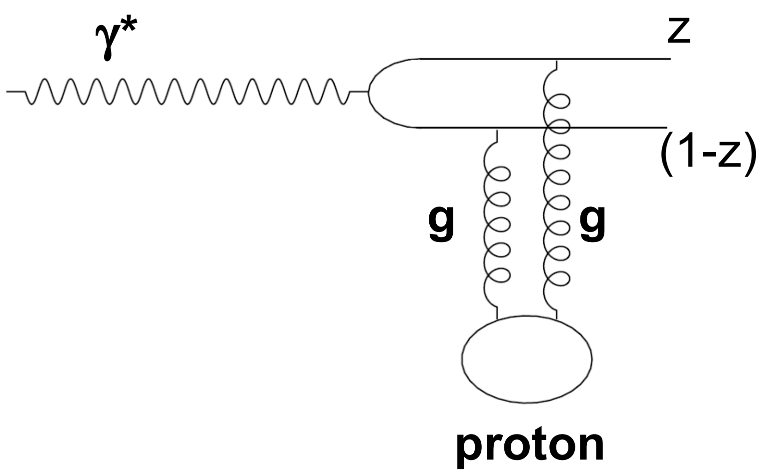
Non-dependence on the x_γ fraction consistent with both previous analyses.

Hard diffractive processes in proton rest frame

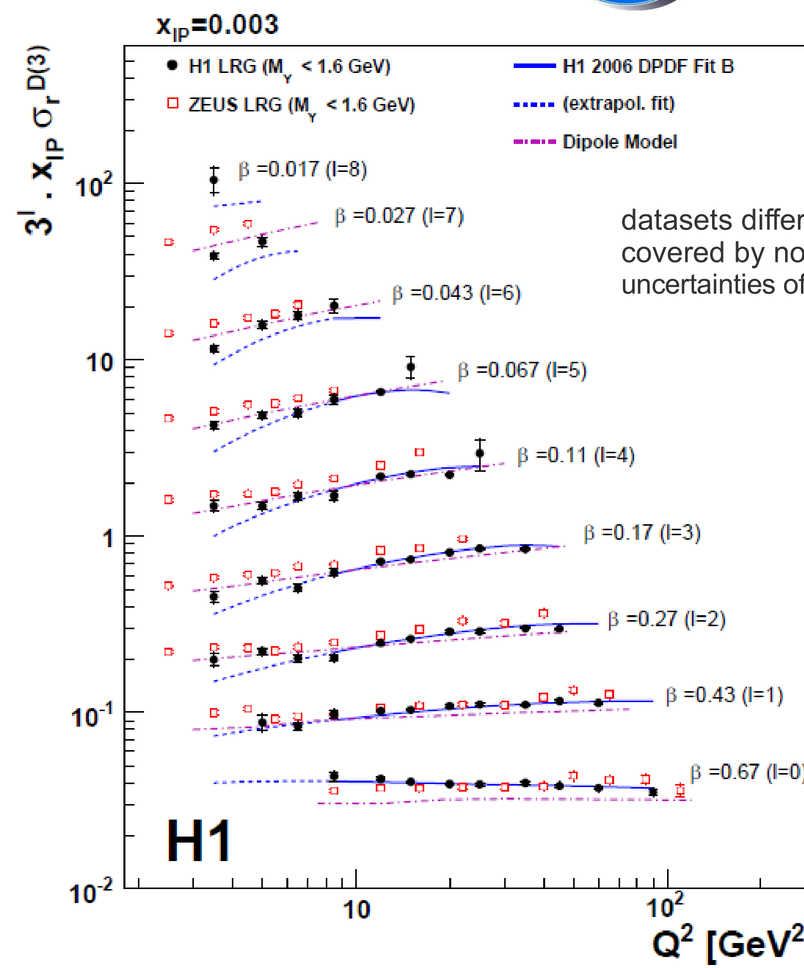
QCD hard factorization valid if proton is fast (infinite momentum frame)

interpretation in proton rest frame:

long living color dipole of virtual photon scatters on static proton
… **color dipole model (CDM)**



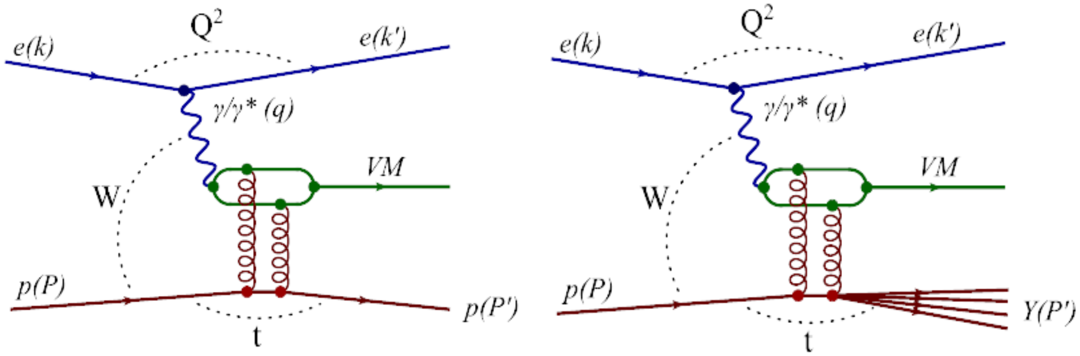
Eur. Phys. J. C72 (2012) 2074



datasets differ by ~10%
covered by normalization
uncertainties of both

shapes: CDM better at low Q^2 … DPDF at high Q2

Production of vector mesons (in proton rest frame)



Soft production:

parton dipole forms a vector meson and elastically scatters from proton

Regge based prediction: $\sigma \sim W^{0.22}$

Transition from soft to hard with hard scale present

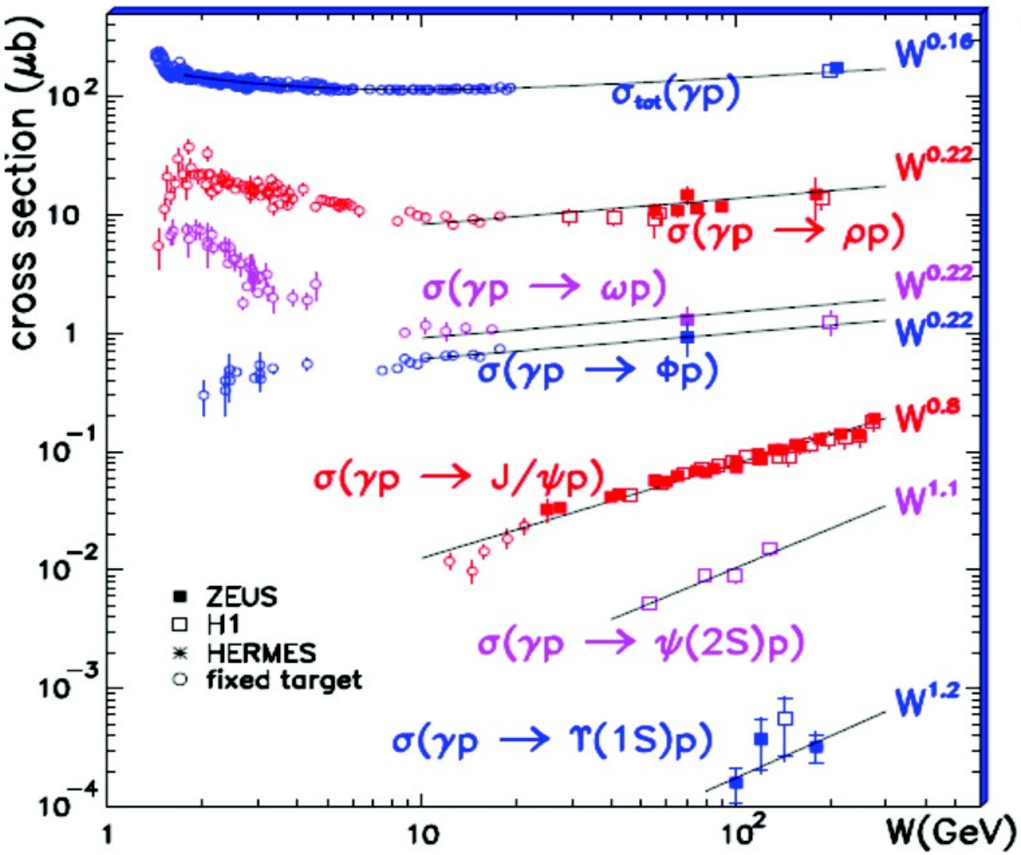
$\sigma \sim W^{\delta}$ the power δ expecting to grow to, driven by $\sigma \propto \left[\alpha_s(\mu^2)\, x\, g(x, \mu^2)\right]^2$

Vector meson production is particularly interesting also due to

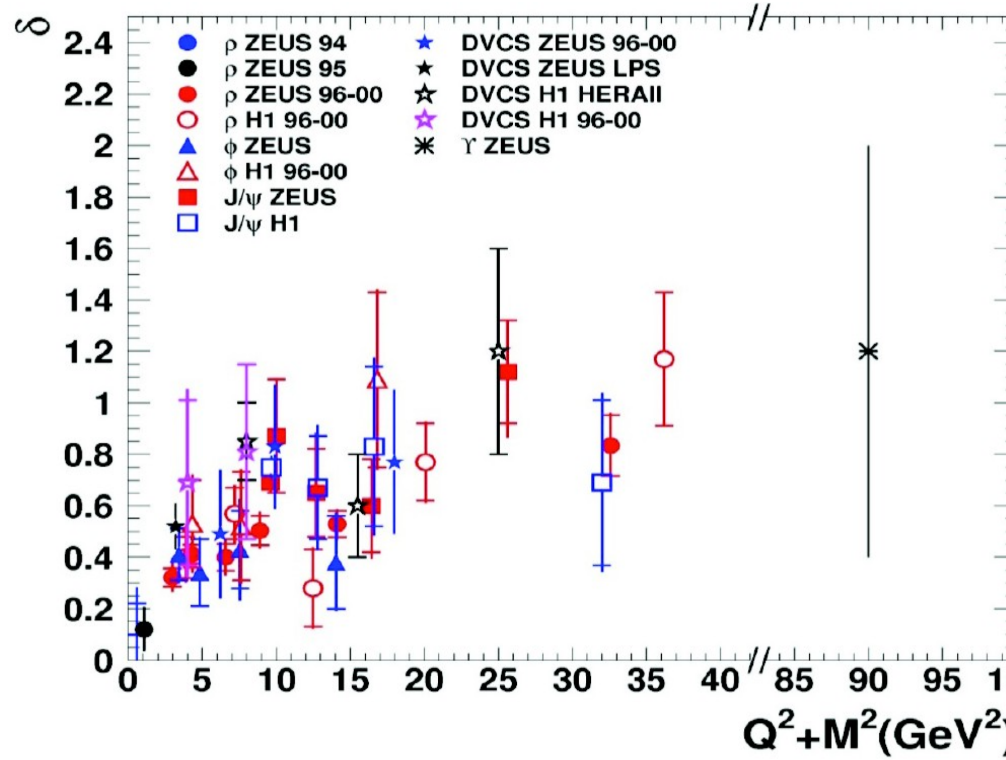
clear signature, decay of VM + empty detector otherwise (proton undetected)

leading proton kinematics reconstructed from VM products

Vector meson production soft → hard transition



Phys. Lett. B 708 (2012) 14-20

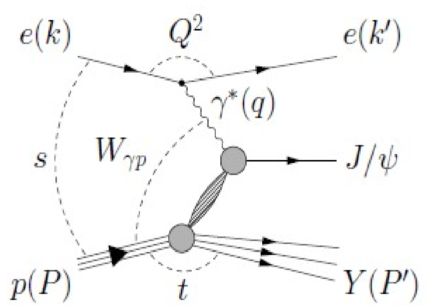


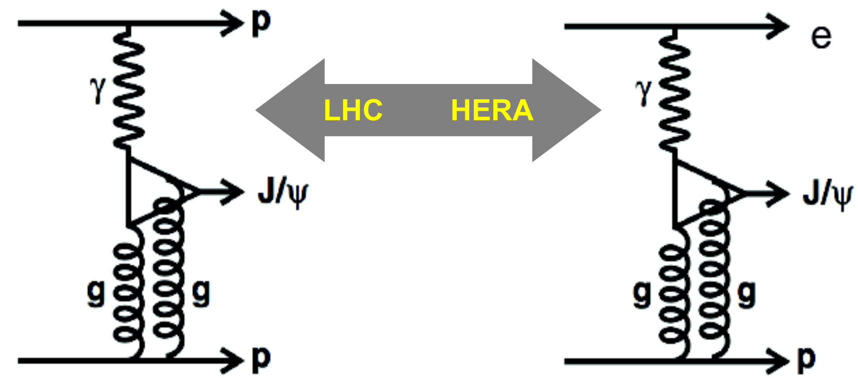
hardening of σ's W dependence for hard scale increasing (... from ρ to ϒ(1S))

New “complementary” measurement of J/ψ … in H1 and LHCb

Eur. Phys. J. C73 (2013) 2466 , 04/13

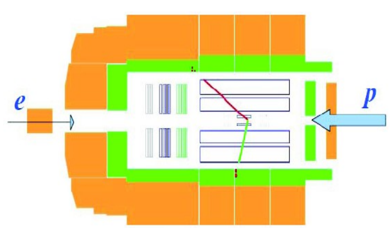
J. Phys. G: Nucl. Part. Phys. **40** (2013) 045001 (17pp)



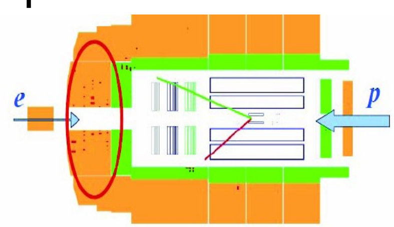


pp ep

elastic



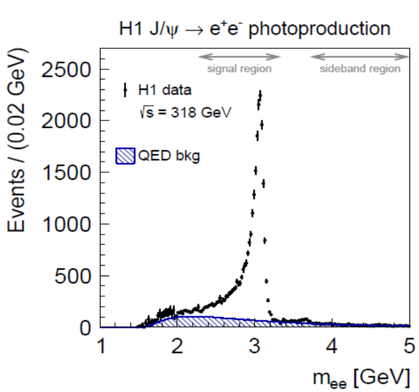
proton dissociative

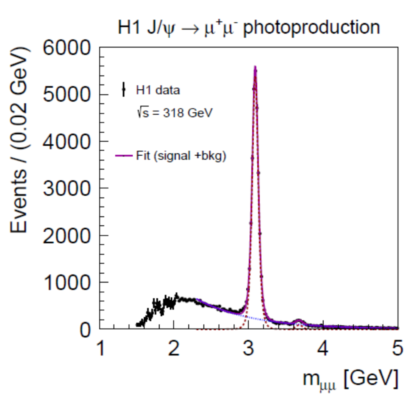


LHCb c/s is HERA c/s weighted by photon spectrum + gap survival factor (r)

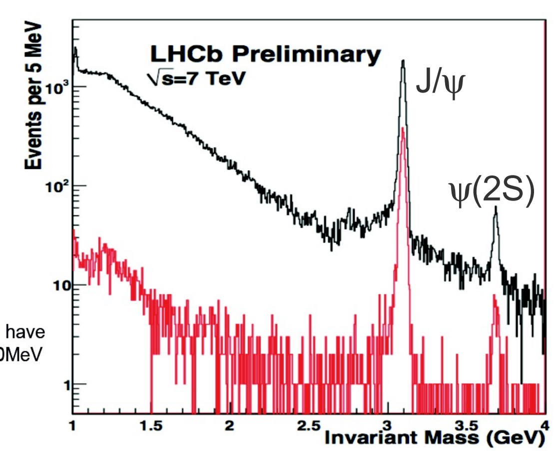
$$\frac{d\sigma}{dy}_{pp\to pVp} = a(2\sqrt{s})^{\delta/2} r(y) \left[\frac{dn}{dk_+} k_+^{\,1+\delta/2} + \frac{dn}{dk_-} k_-^{\,1+\delta/2}\right]$$

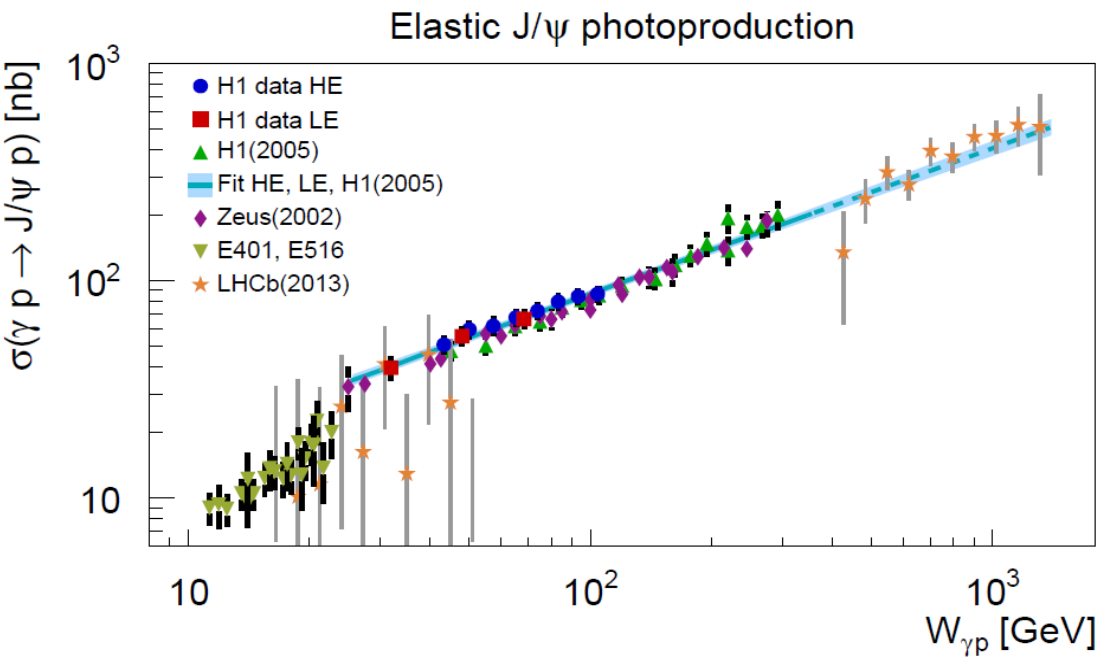
$$k_\pm \approx (m_V/2)\exp(\pm|y|).$$





Tracks have p_T>400MeV 2<η<5



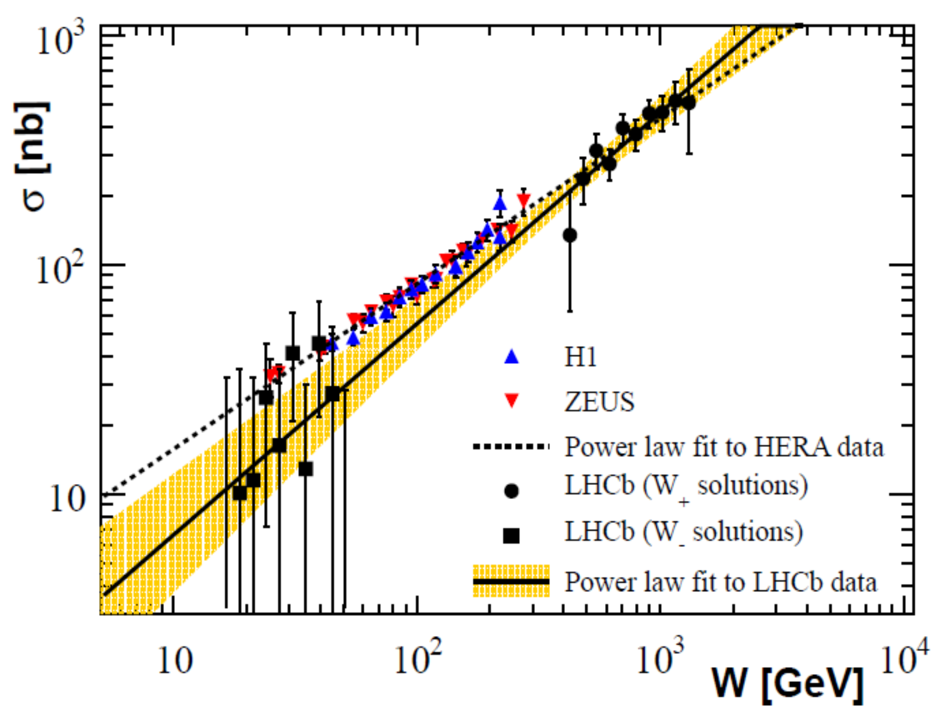


H1

Consistent with previous HERA results.

Steeper slope and lower normalization of the fixed target data.

Extrapolation to new LHCb data seems OK.



LHCb

LHCb data consistent with a power law dependence $\sigma(W) = aW^{\delta}$.

LHCb	HERA
$a = 0.8^{+1.2}_{-0.5}\,nb$	a ~ 3 nb
$\delta = 0.92 \pm 0.15$	$\delta = 0.72 \pm 0.03$

Eur. Phys. J. **C46** (2006) 585
Eur. Phys. J. **C24** (2002) 345

The parametric form is in broad in agreement with HERA (older H1 result).

Summary

Hard diffraction is present in ep, and pp data ... dominated by gluon

Efficient diffractive selection achieved by LRG and proton tagging.

HERA provides valuable input for LHC in terms of diffractive PDFs.

- … extracted from inclusive data
  - … **combination** of experiments
  - … **combination** detection methods
- … extracted from dijet data to constrain gluon contribution

QCD hard factorization holds in DDIS (jets, D*) and not in pp

- … **new:** gap suppression observed with diff. dijets in CMS
- … situation not clear in diffractive photoproduction, **global** suppression observed different for H1 and ZEUS

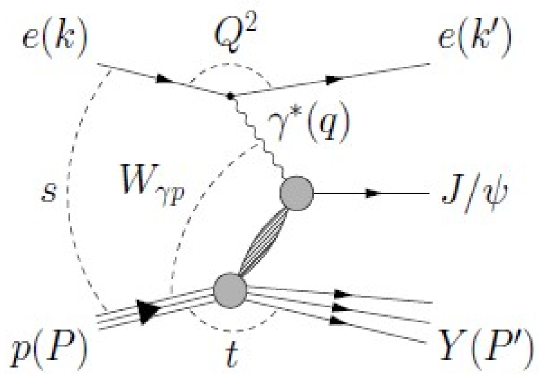
Color Dipole Model

- … describes low Q^2 inclusive σ better than DPDF fits
- … used for predictions in VM analyses
  - … soft to hard (Regge to QCD) transition observed in terms of hardening the energy dependence of σ

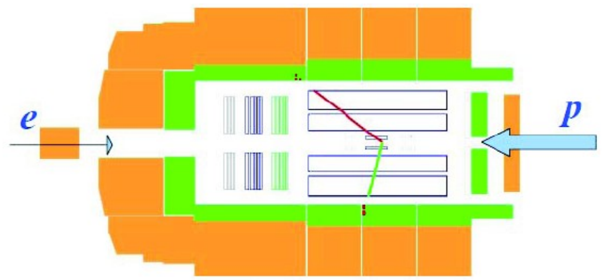
Backup

Elastic and Proton-Dissociative Photoproduction of J/ψ Mesons at HERA

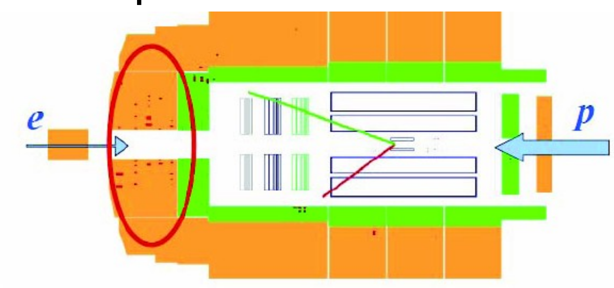
Eur. Phys. J. C73 (2013) 2466 , 04/13

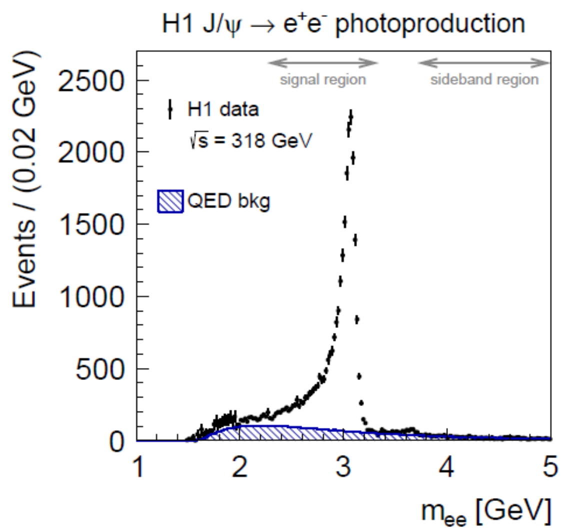


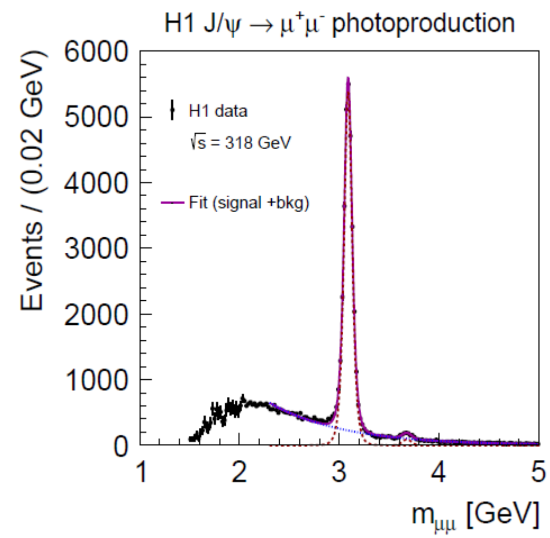
elastic



proton dissociative

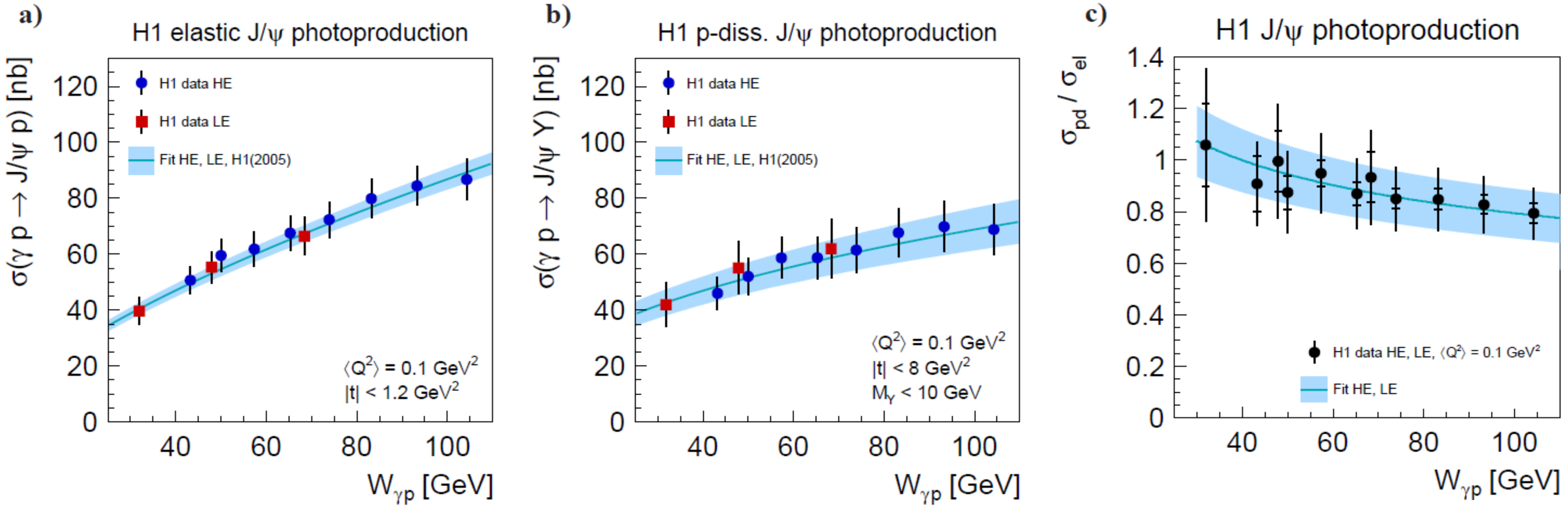






Using HERA 2 data at 318 GeV and 225 GeV where the lower energy data provide transition to previous HERA and to fixed targed data, **30 < W < 100 GeV**.

Elastic and Proton-Dissociative Photoproduction of J/ψ Mesons at HERA

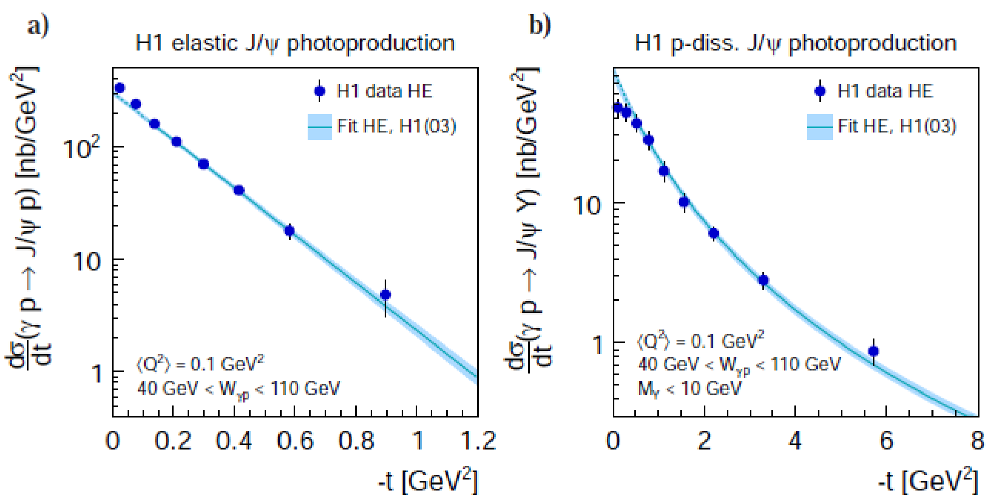


fitted W dependence: $\sigma = N\left(\frac{W_{\gamma p}}{W_0}\right)^{\delta}, W_0 = 90\,GeV$

decreasing ratio of $\sigma_{PD} / \sigma_{EL}$

$\delta_{EL} = 0.67 \pm 0.03$

$\delta_{PD} = 0.42 \pm 0.05$ … **both stronger than Regge $W^{0.22}$ … i.e. pQCD "hard" Pomeron**



$$\frac{d\sigma_{EL}}{dt} \sim e^{-b_{EL}|t|}$$

$$\frac{d\sigma_{PD}}{dt} = N_{PD}\left(1 + \frac{b_{PD}}{n}|t|\right)^{-n}$$

$b_{EL} = 4.88 \pm 0.15$ GeV^2

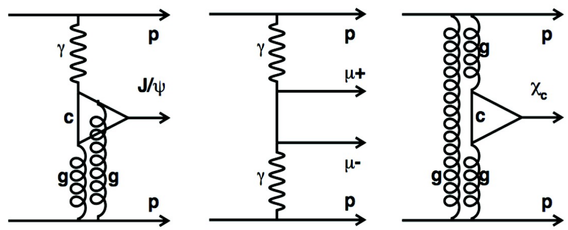
$b_{PD} = 1.79 \pm 0.12$ GeV^2

Exclusive J/ψ and ψ(2S) production in pp collisions at √s = 7 TeV

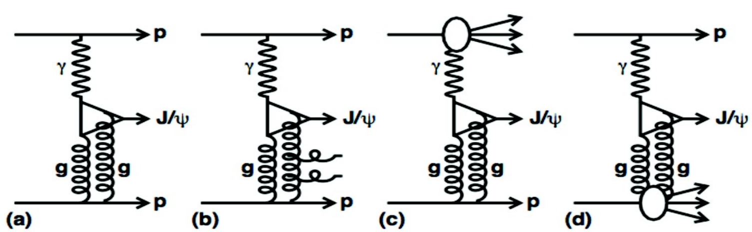
J. Phys. G: Nucl. Part. Phys. 40 (2013) 045001 (17pp)

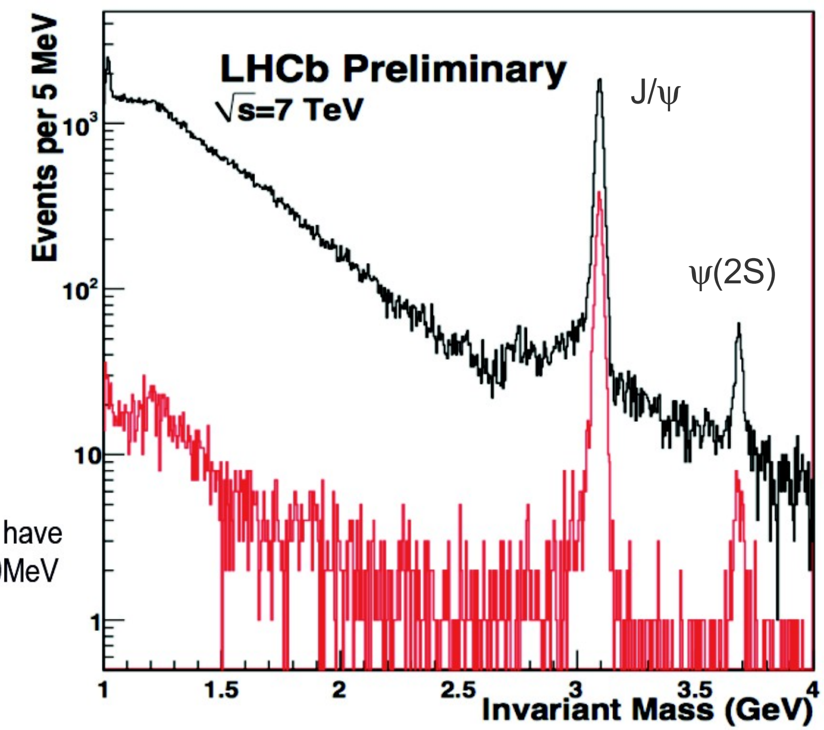
Signal extracted from di-muon decays:

contributions to central prod. of di-muons



+ inelastic background

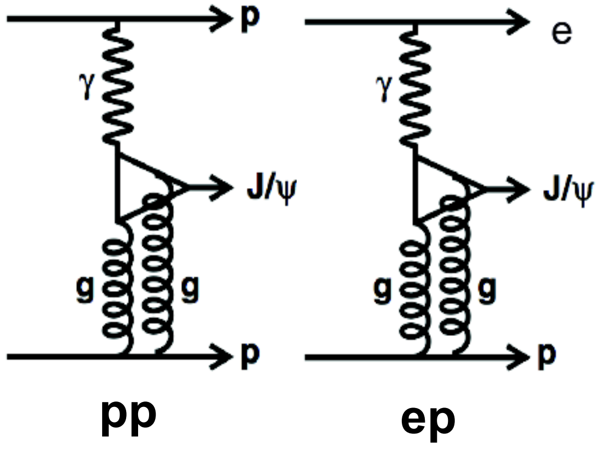




Tracks have
p_T>400MeV
2<η<5

based on 37 pb^{-1} 2010 data
with about ~1500 J/ψ and ~40 ψ events

LHCb compared with HERA (photoproduction) J/ψ results



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HERA Eur. Phys. J. **C46** (2006) 585
Eur. Phys. J. **C24** (2002) 345

a ~ 3 nb

δ = 0.72 ± 0.03

HERA Eur. Phys. J. C73 (2013) 2466

a ~ 4 nb

δ = 0.67 ± 0.03