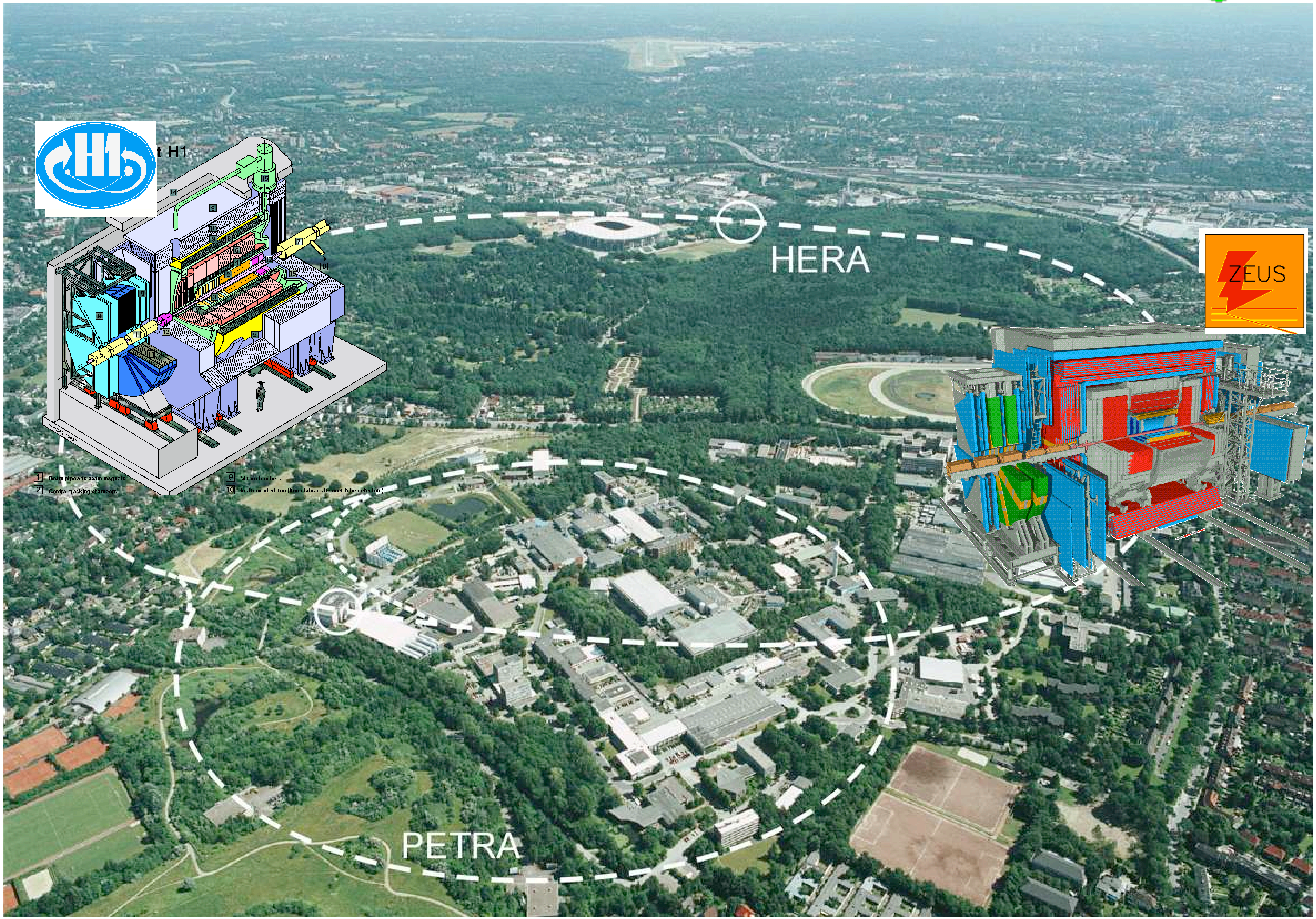
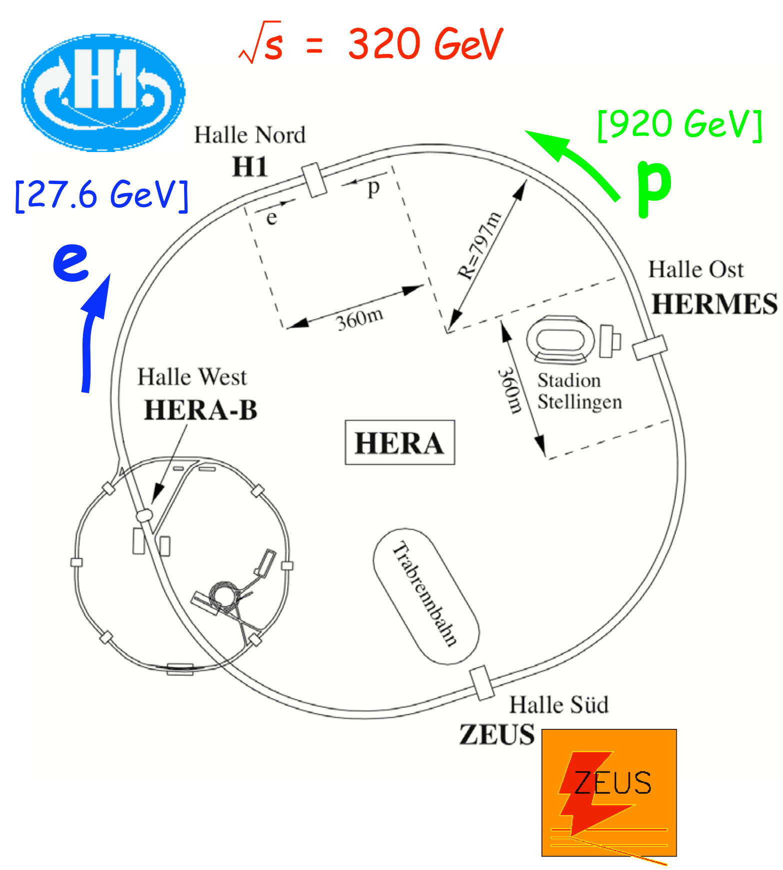
Quarkonium Production at HERA

Andreas B. Meyer
DESY

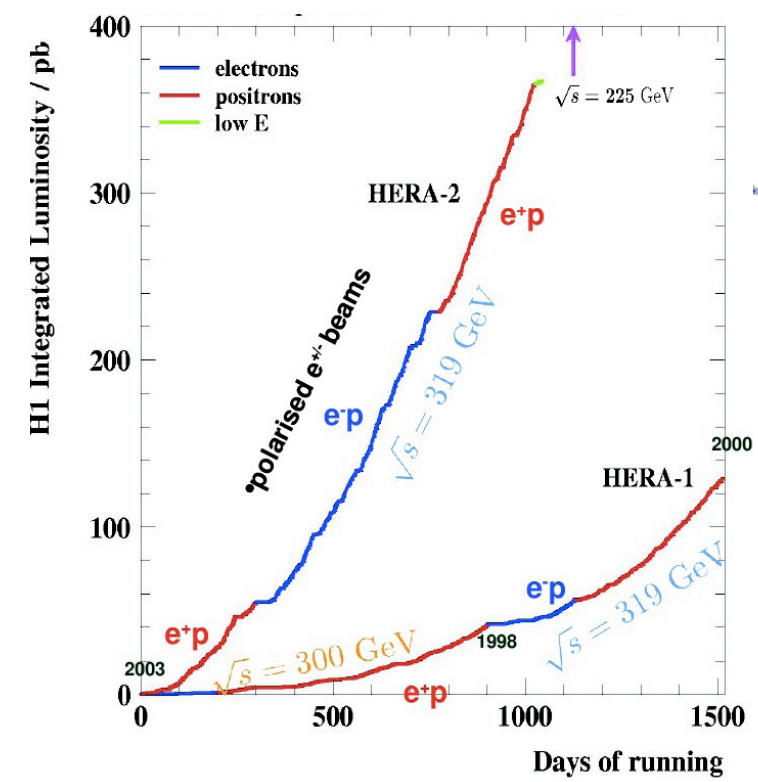
Electron-Proton Collider HERA

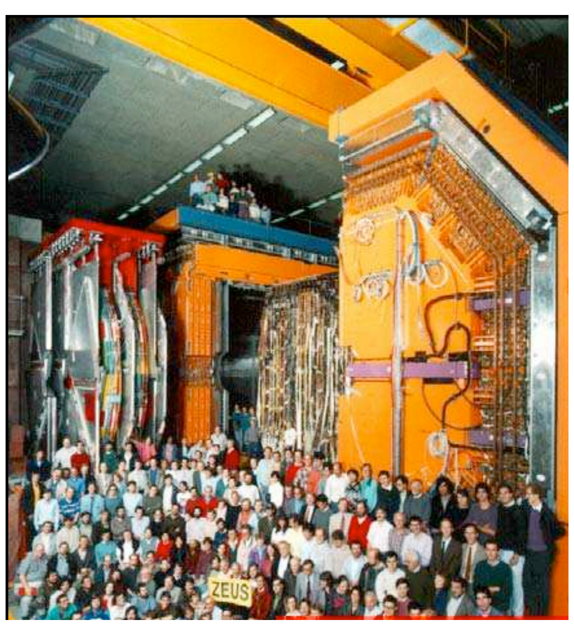


Experiments H1 and ZEUS

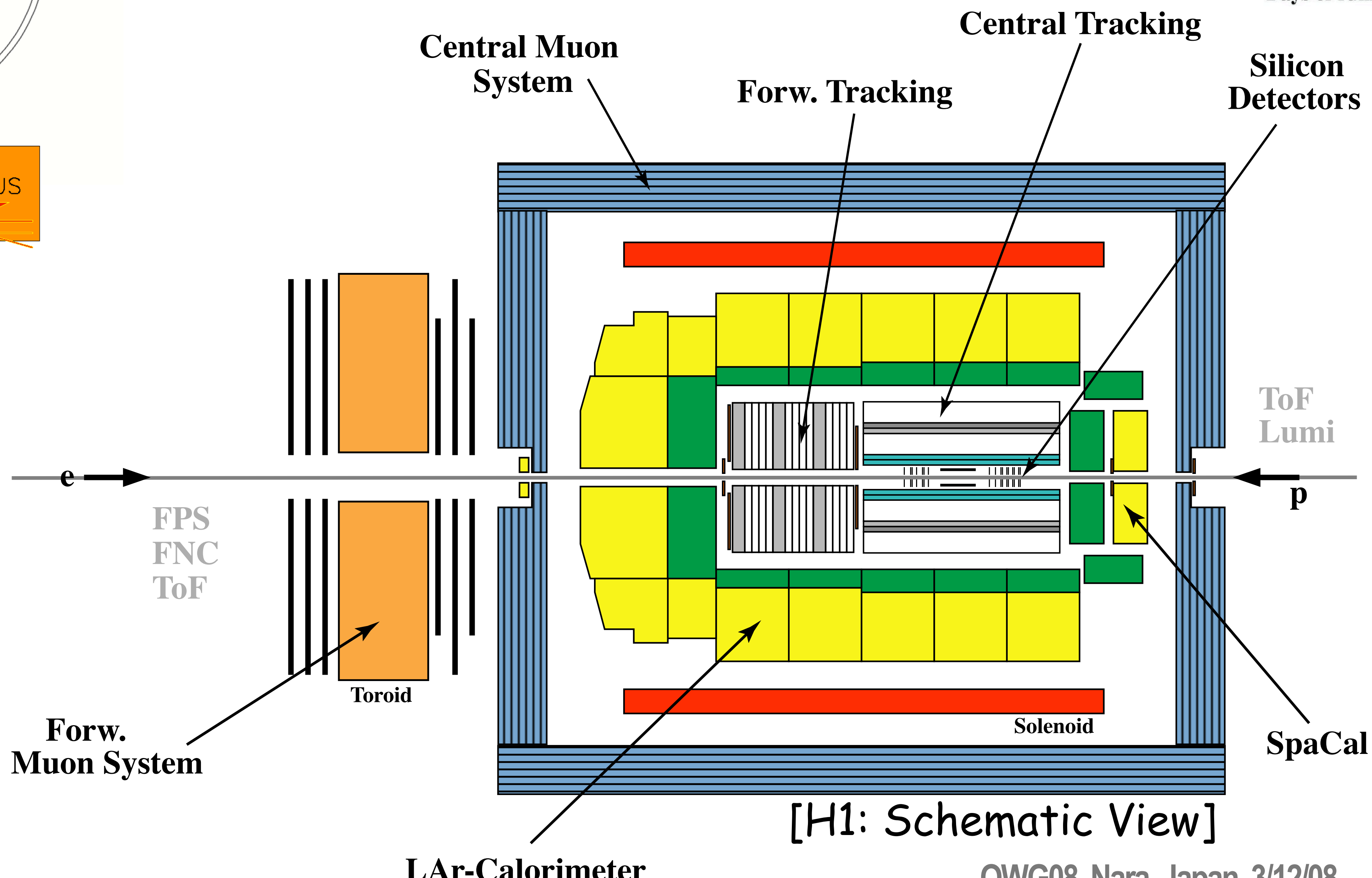


Total integrated Luminosity: ~500pb^{-1} per experiment





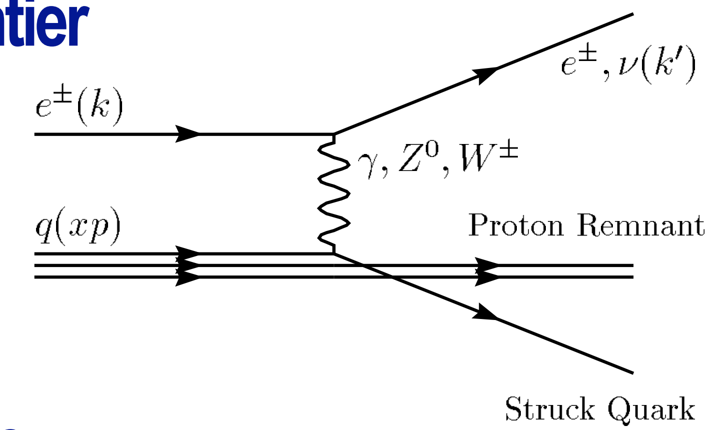
[ZEUS Collaboration]



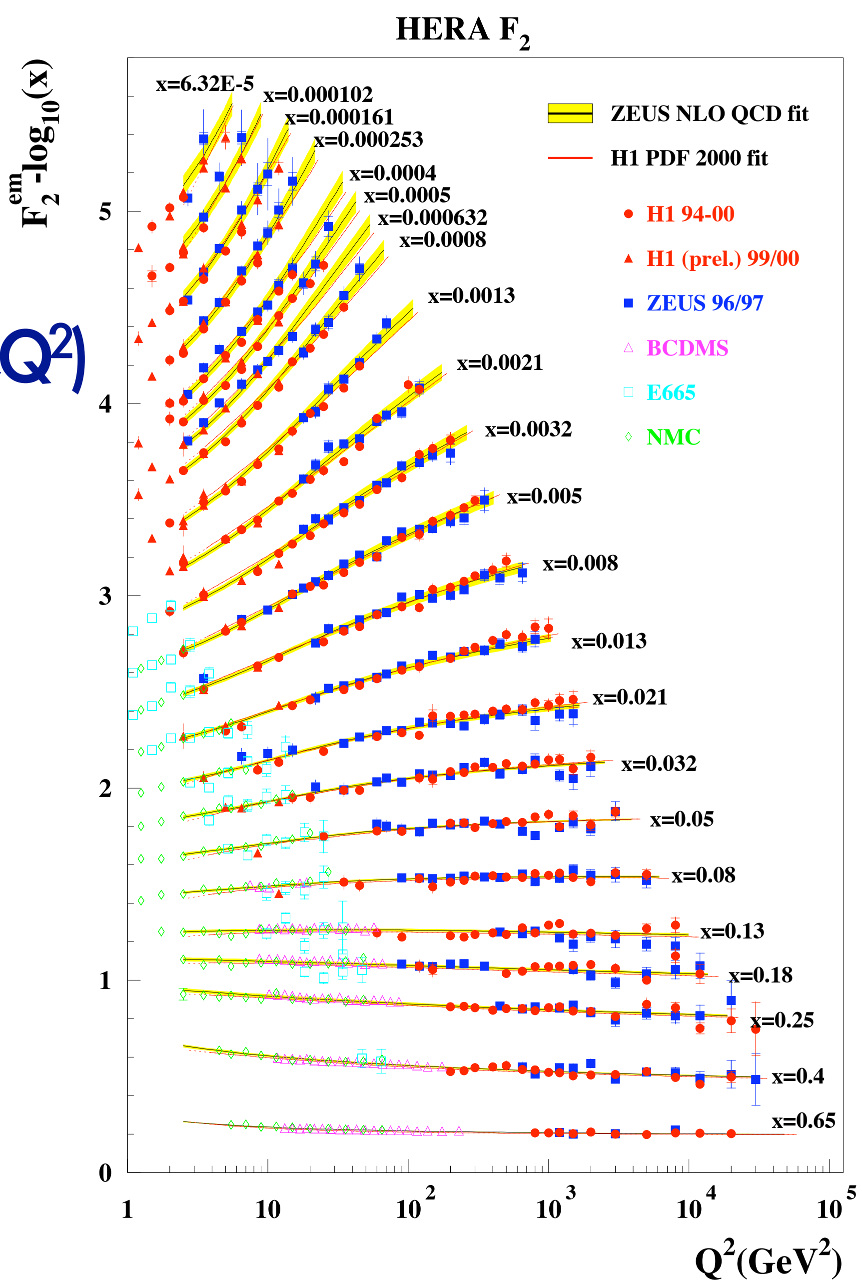
[H1: Schematic View]

HERA Physics $\sqrt{s_{ep}} \sim 320$ GeV

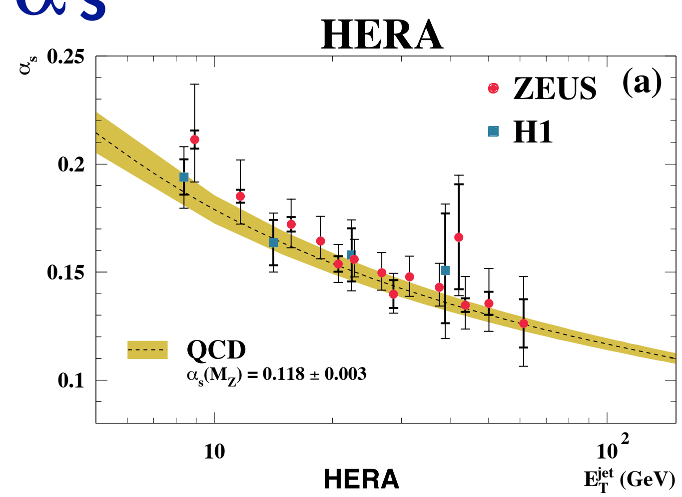
- Measurements at the high energy frontier
  - QCD measurements
  - Electroweak physics
  - Searches for new physics

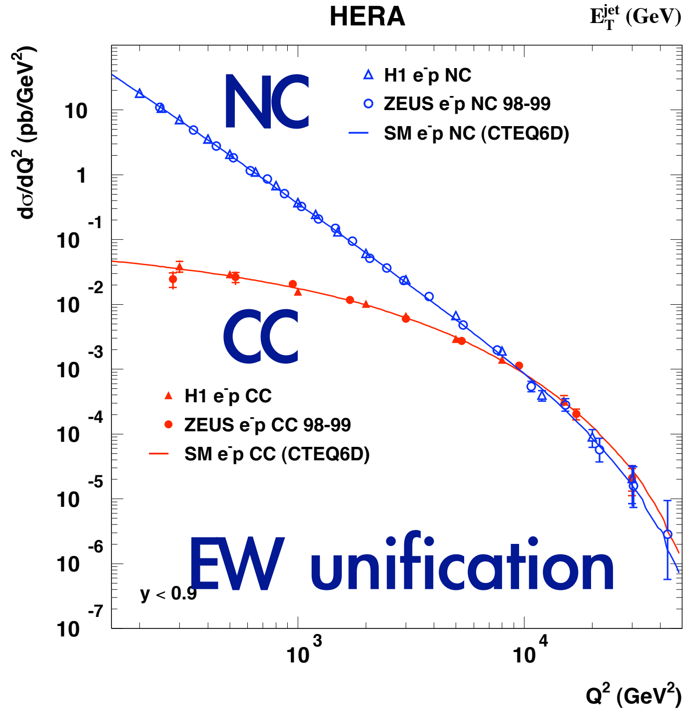


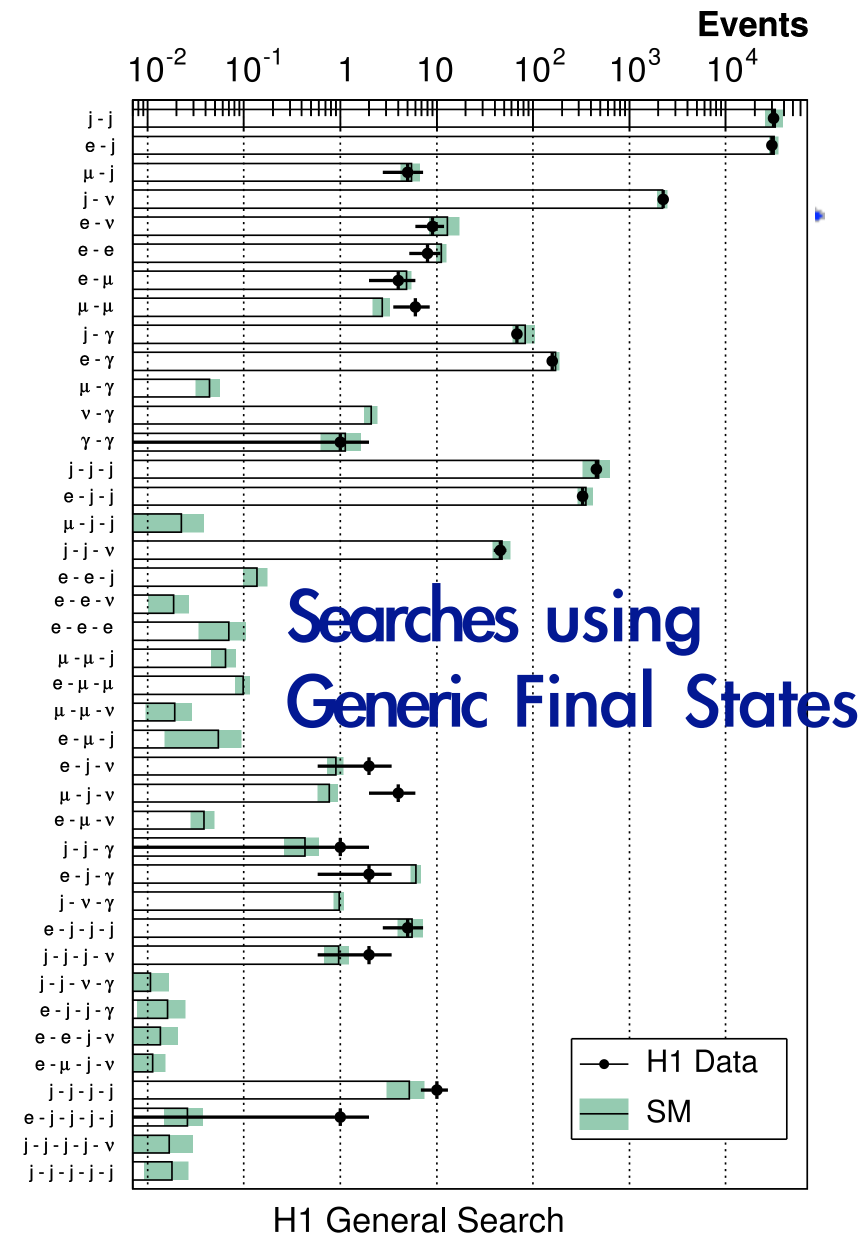
F2(x,Q²)

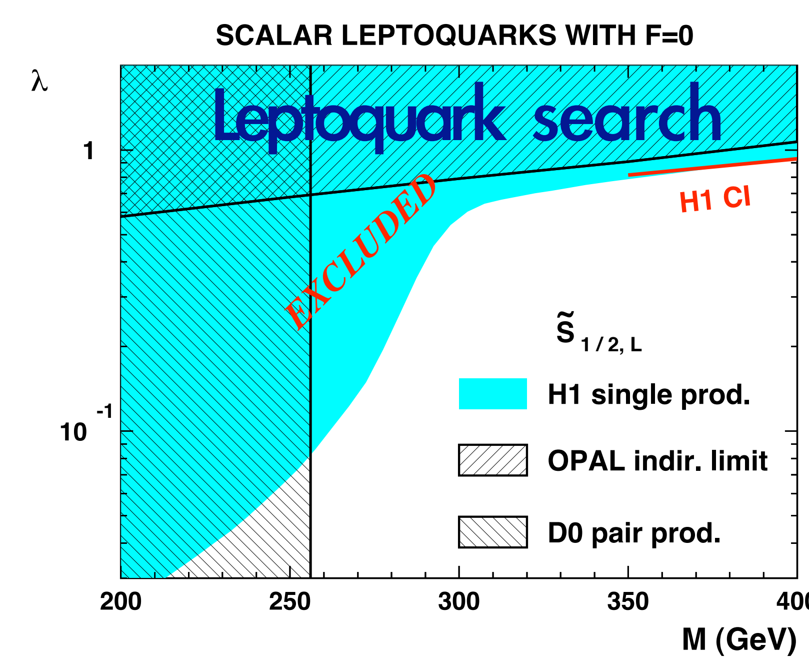


α_s

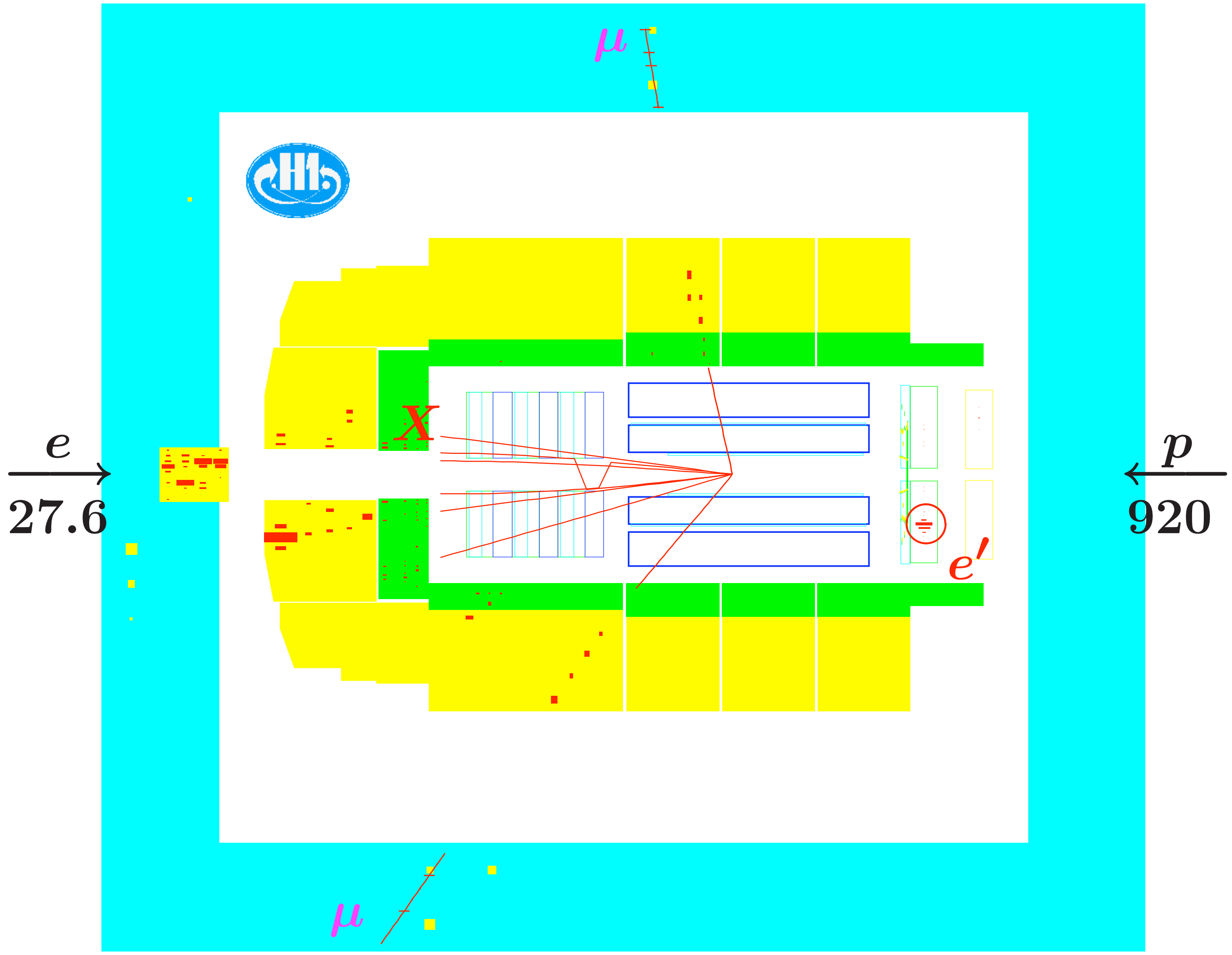


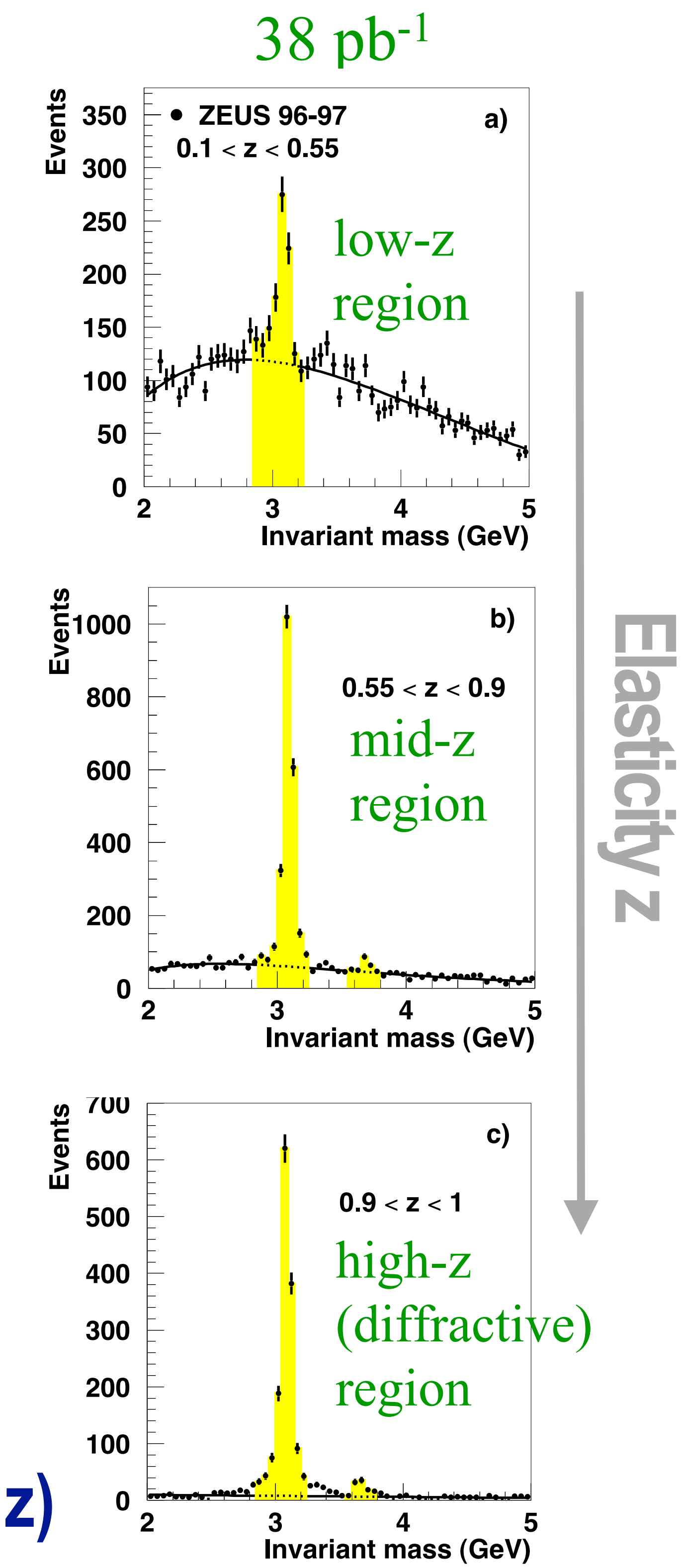






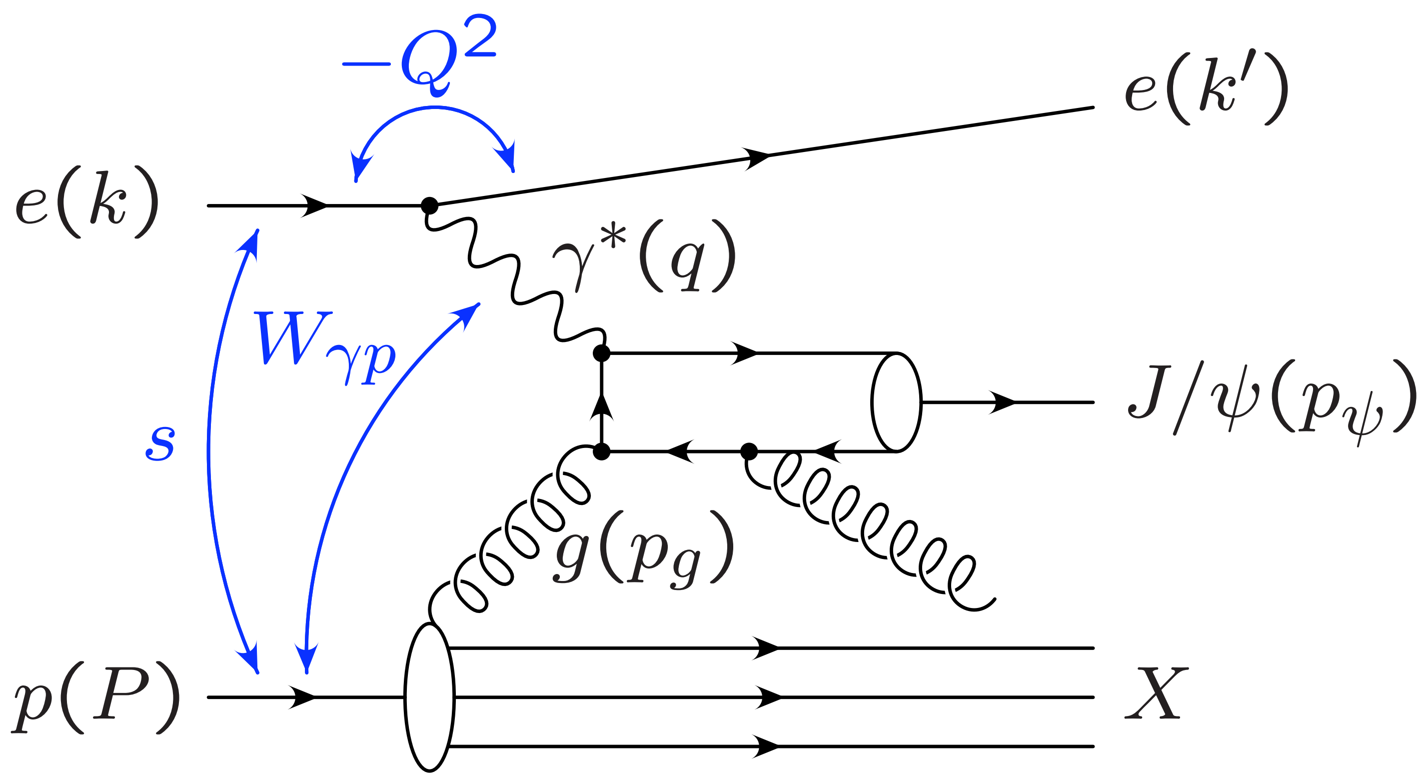
Charmonium at HERA





- Measure J/ψ and ψ(2S) in decays into $\mu^+\mu^-$ (and e^+e^-)
- Trigger and reconstruction down to $p_t \sim 0$
- Moderate backgrounds to inelastic sample (not subtracted):
  - J/ψ from B decays (5% of inelastic, up to 25% at lowest z)
  - J/ψ from χ decays (1% of inelastic, up to 7% at lowest z)

Event Kinematics



kinematic variables

$$Q^2 = -q^2$$
$$s = (P+k)^2$$
$$W_{\gamma p} = \sqrt{(P+q)^2}$$
$$z = \frac{p_\psi \cdot P}{q \cdot P}$$
$$= \frac{E^*_\psi}{E^*_\gamma} \text{ in } p \text{ rest frame}$$

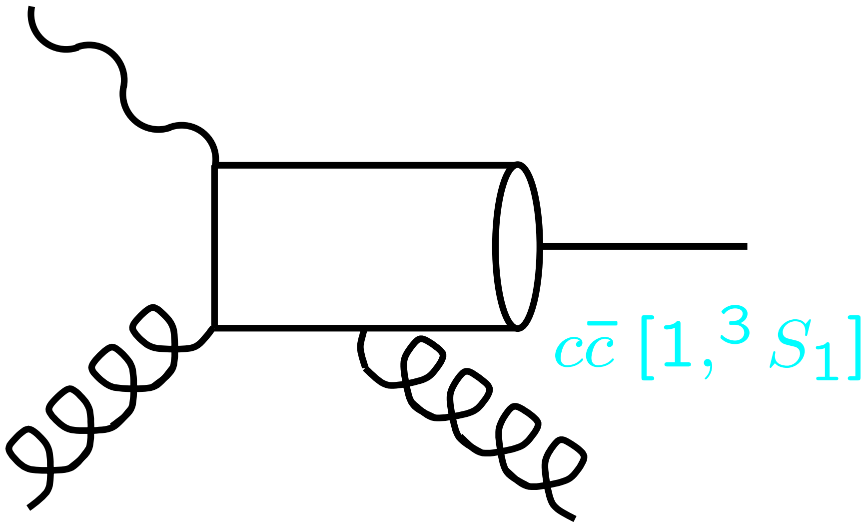
- **Photoproduction (γp):** $Q^2 \sim 0$
  beam electron scattered under low angles, (not detected in main detector)

- **Electroproduction (DIS):** $Q^2 > 2\ \mathrm{GeV}$

z measures softness of final state gluons emitted from $c\bar{c}$ pair

J/ψ Production

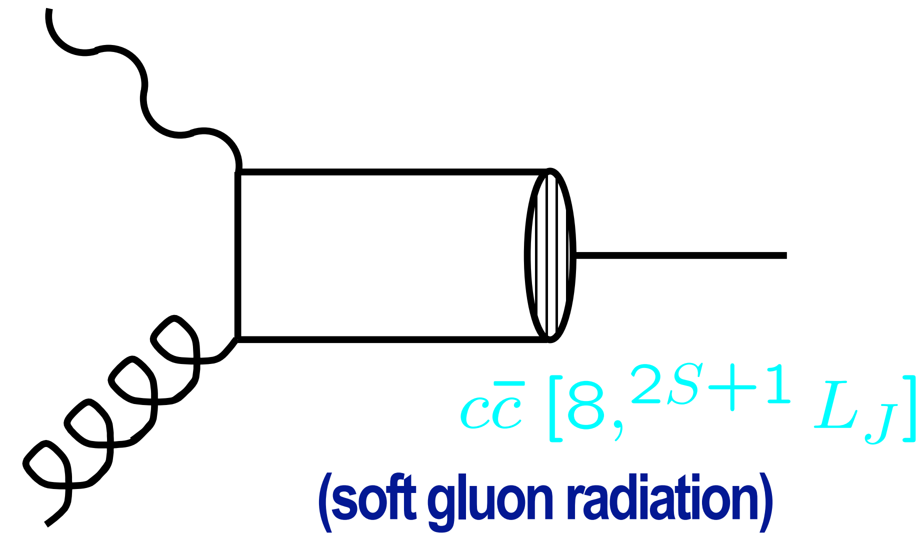
- **Colour Singlet Model**



CS: one parameter
fixed from $\Gamma(J/\psi \rightarrow \ell^+\ell^-)$

LO: Berger et al, Baier et al, 1981
NLO (direct): Kraemer et al, 1995

- **Colour Octet Contributions**



NRQCD-factorization:

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

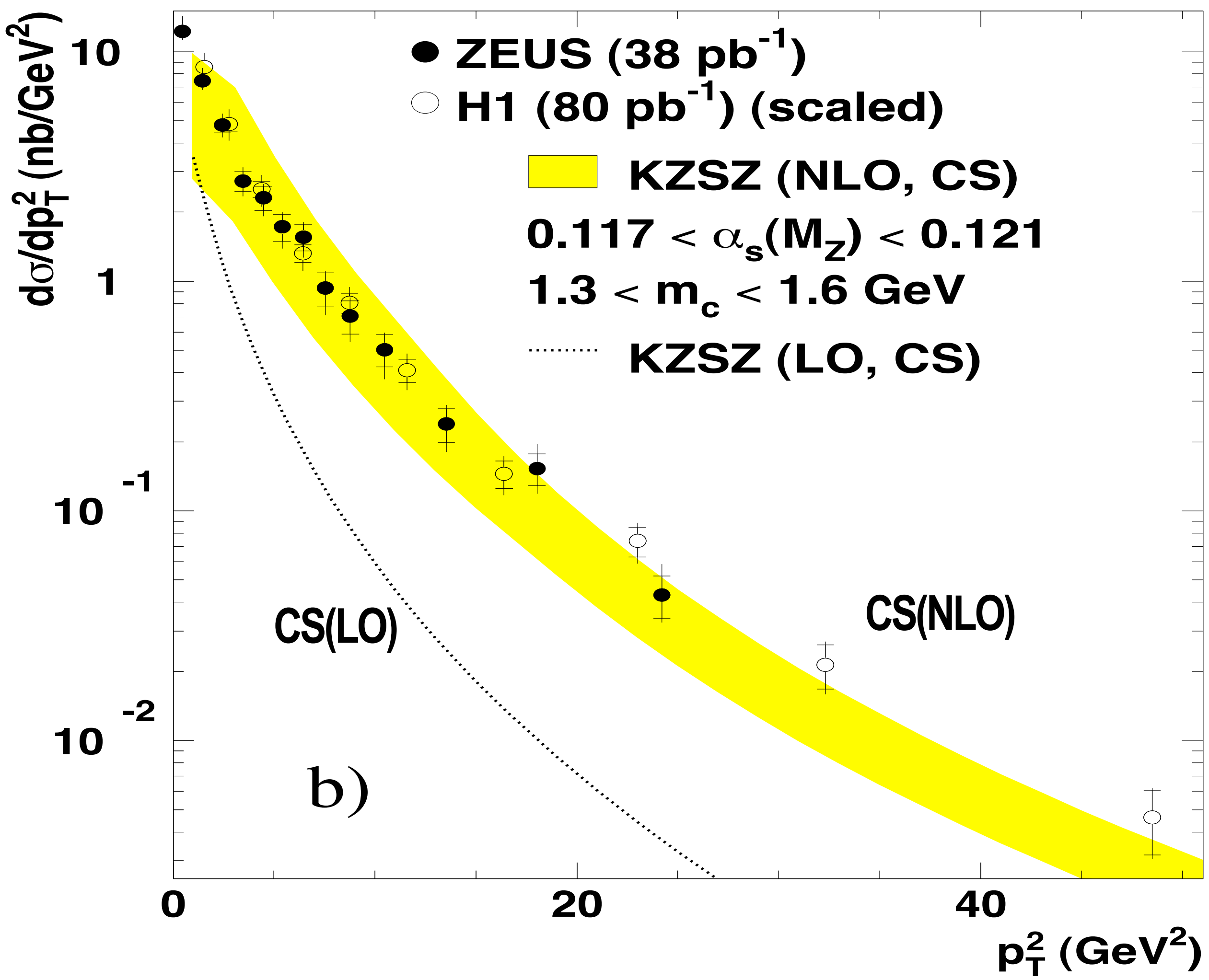
Bodwin, Braaten, Lepage 1995

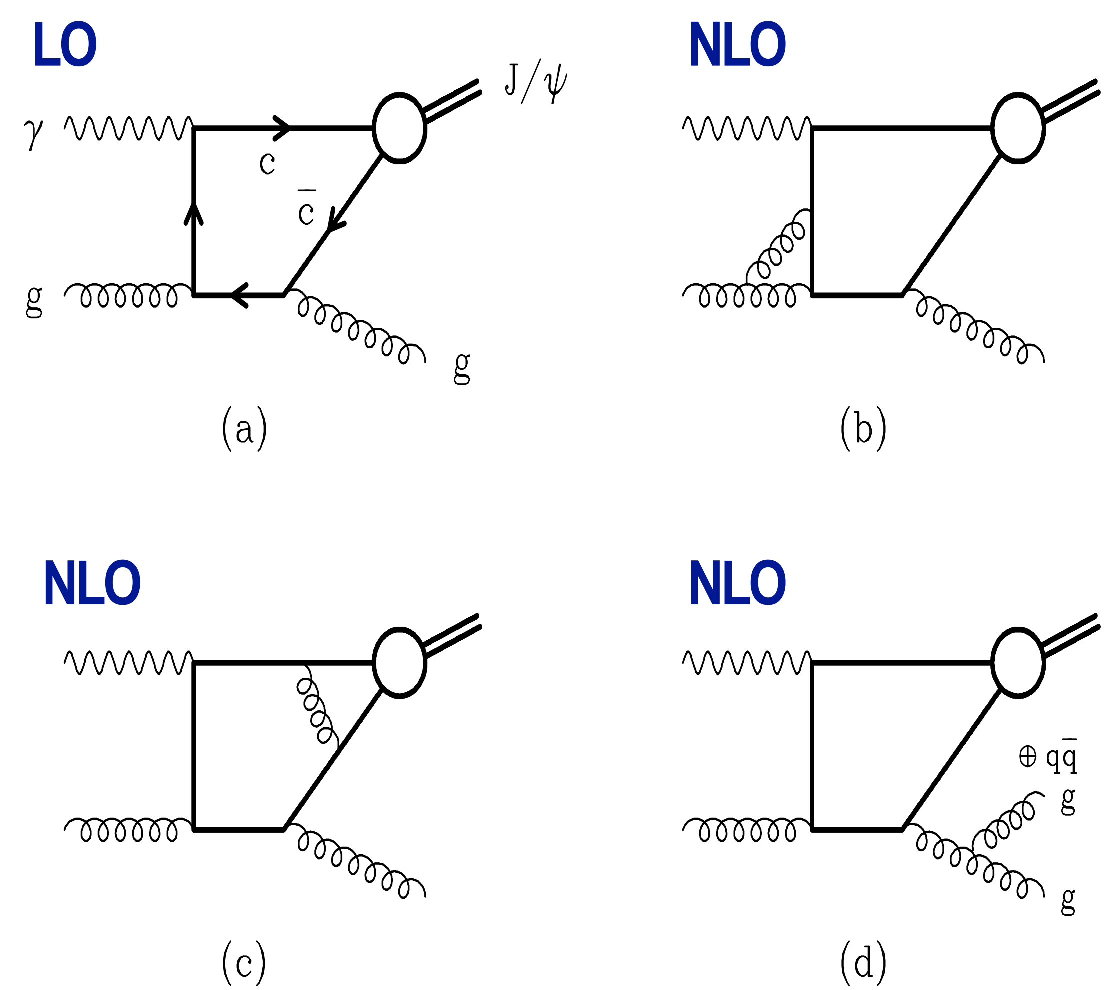
Elasticity z

J/ψ Production in γp

HERA

NLO (direct): Kraemer et al, 1995





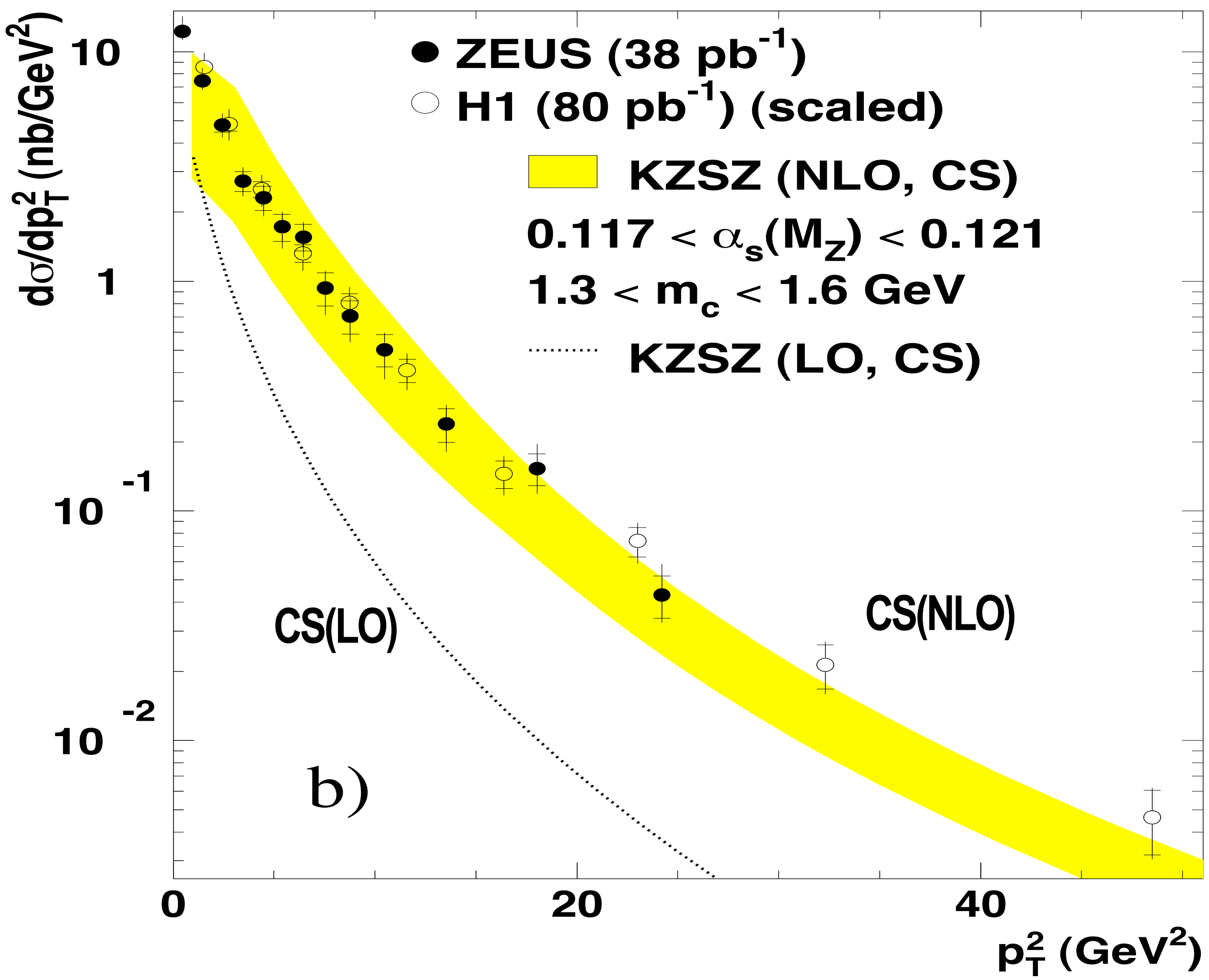
CS (DGLAP, NLO) calculation available for γp since 1995

CS alone is able to describe cross sections at HERA

J/ψ Production in γp and p̄p

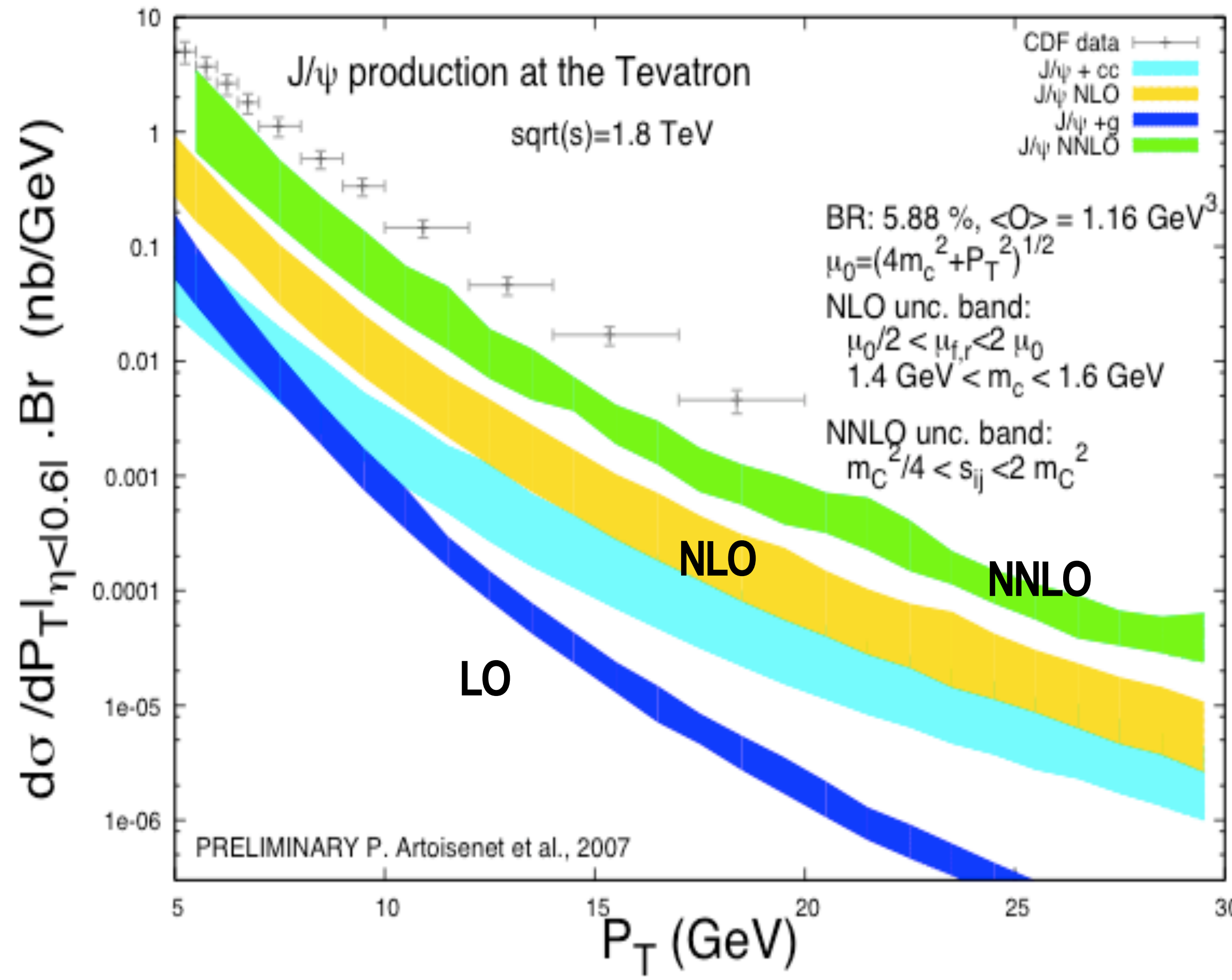
HERA

NLO (direct): Kraemer et al, 1995



Tevatron

Artoisenet, Maltoni et al, 2007



CS (DGLAP, NLO) calculation available for γp since 1995

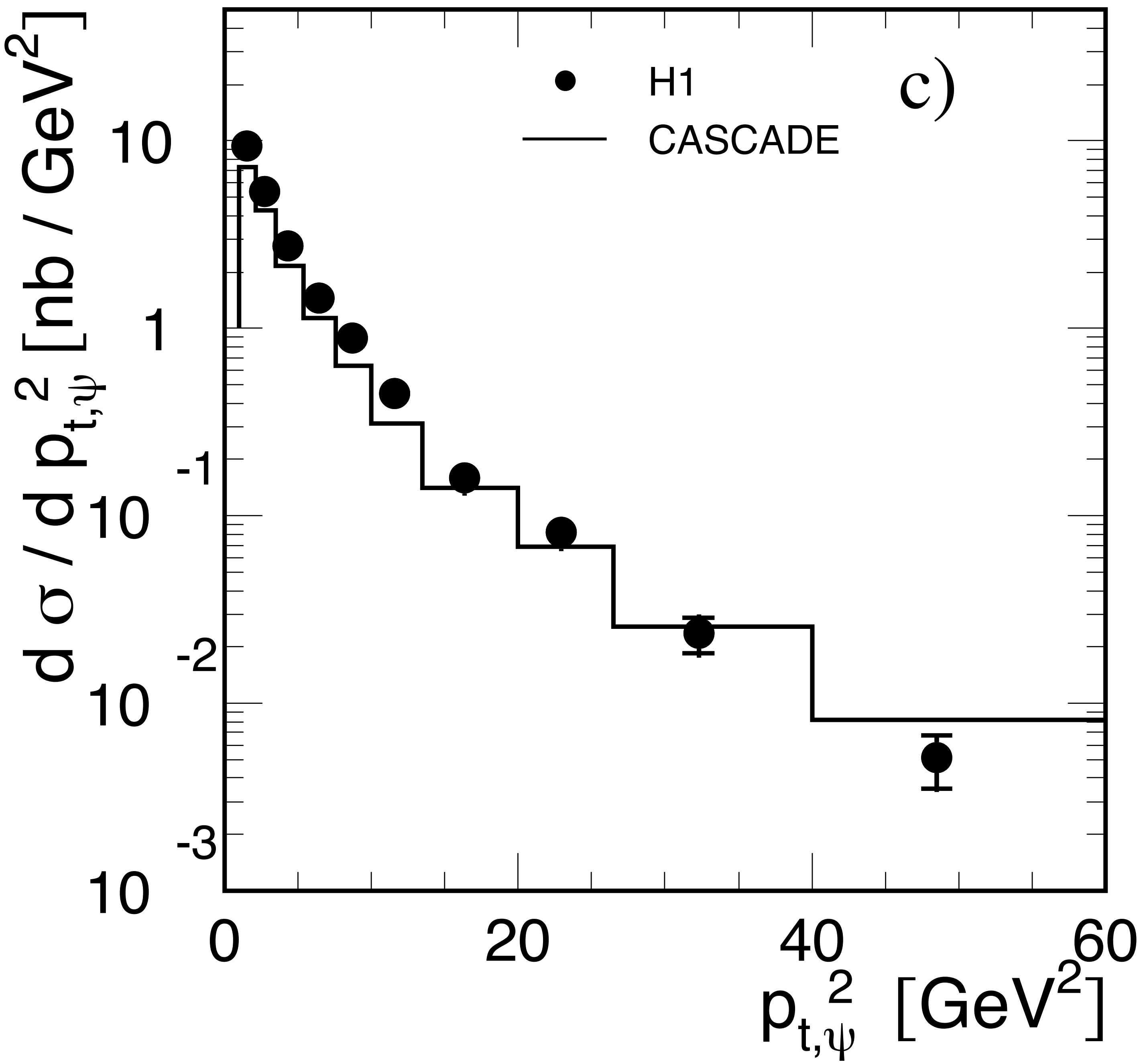
2007: NLO (and NNLO est.) for Tevatron

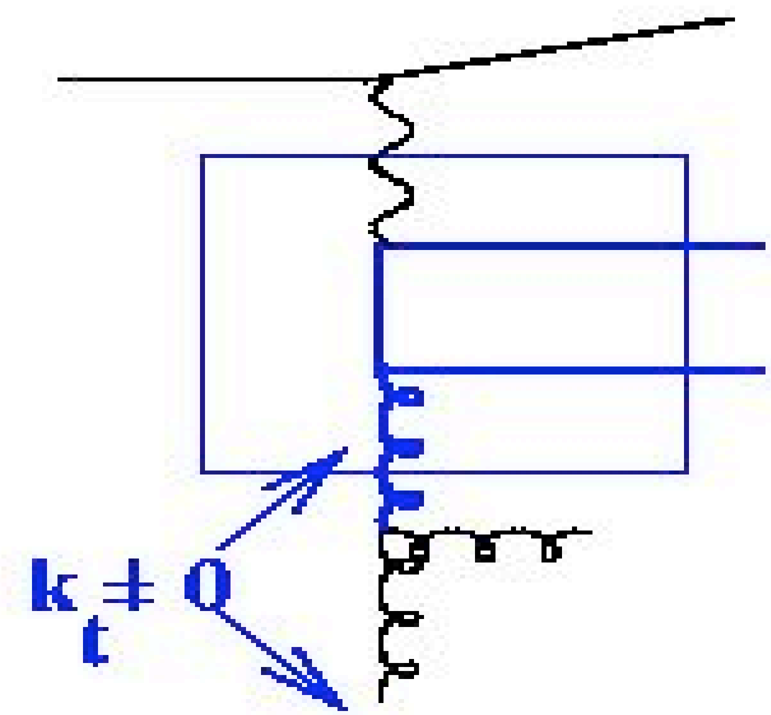
CS alone is able to describe cross sections at HERA

CS alone not able to describe the data alone but situation much less dramatic (Υ ok)

J/ψ Production in k_T-Factorization

HERA-I data comparison with CASCADE MC H.Jung, 2001





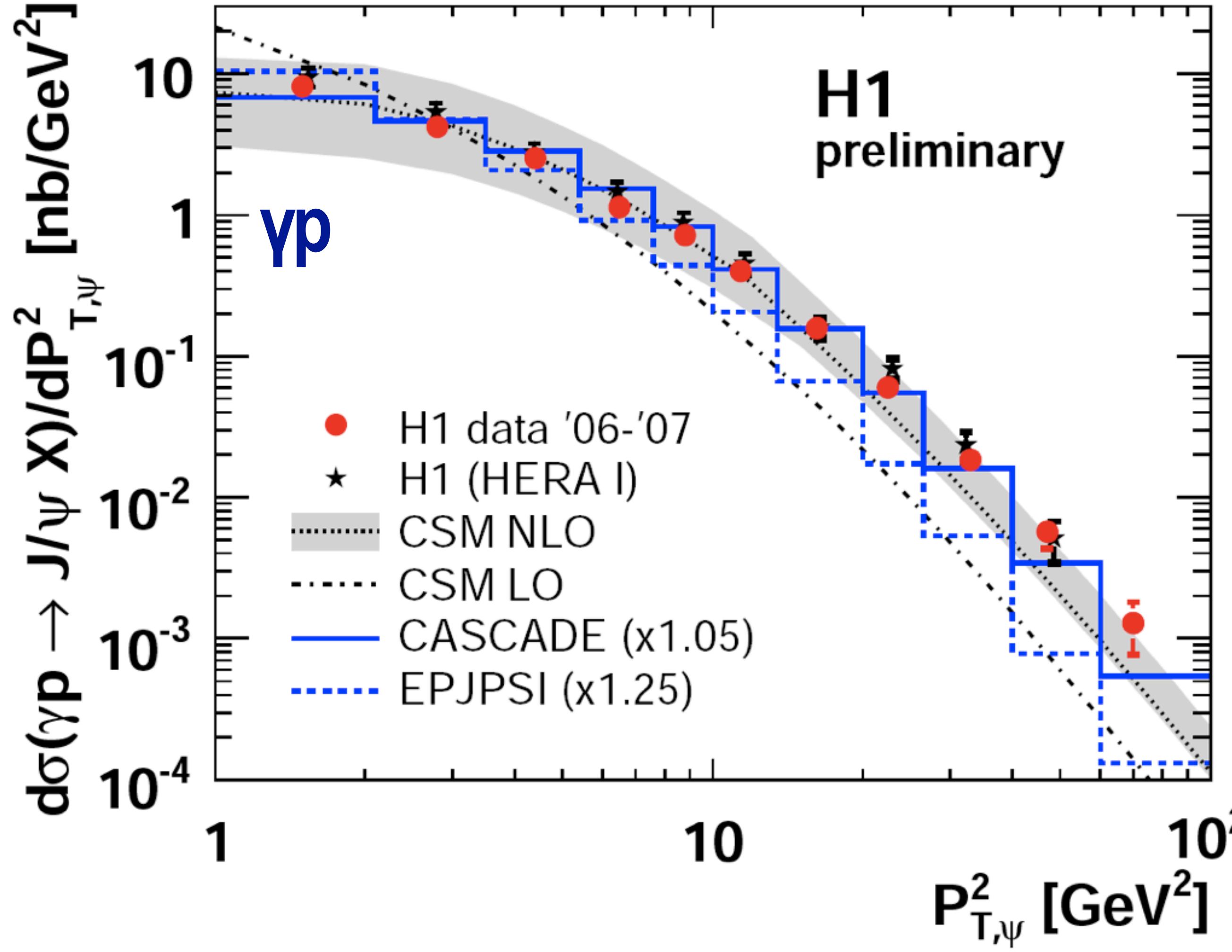
- CCFM evol. eq. M.Ciafaloni et al, 1988
  - k_t - unintegrated gluon density
  - part of NLO corrections

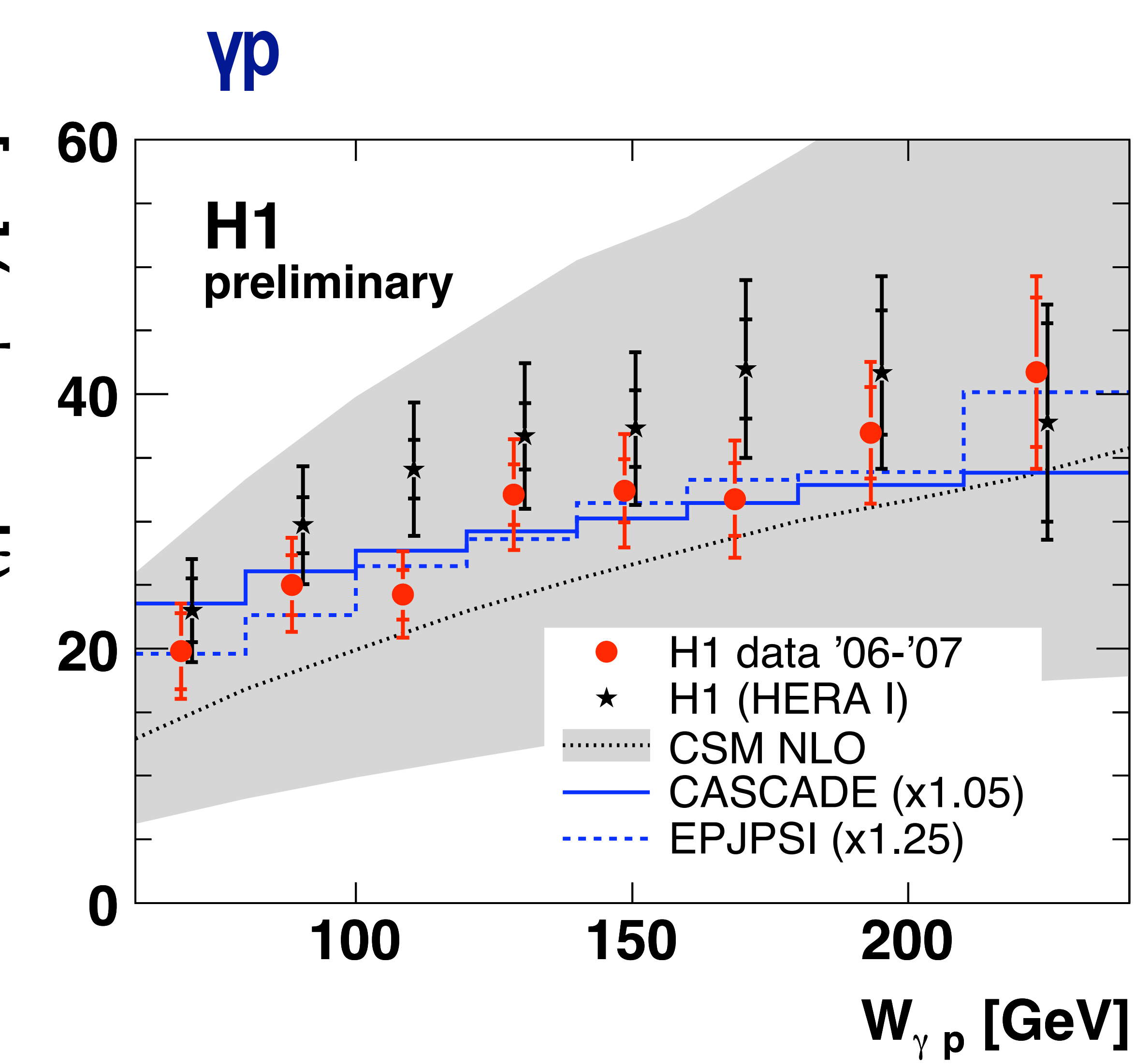
CS model using kt-factorization (CCFM) describes data equally well as NLO

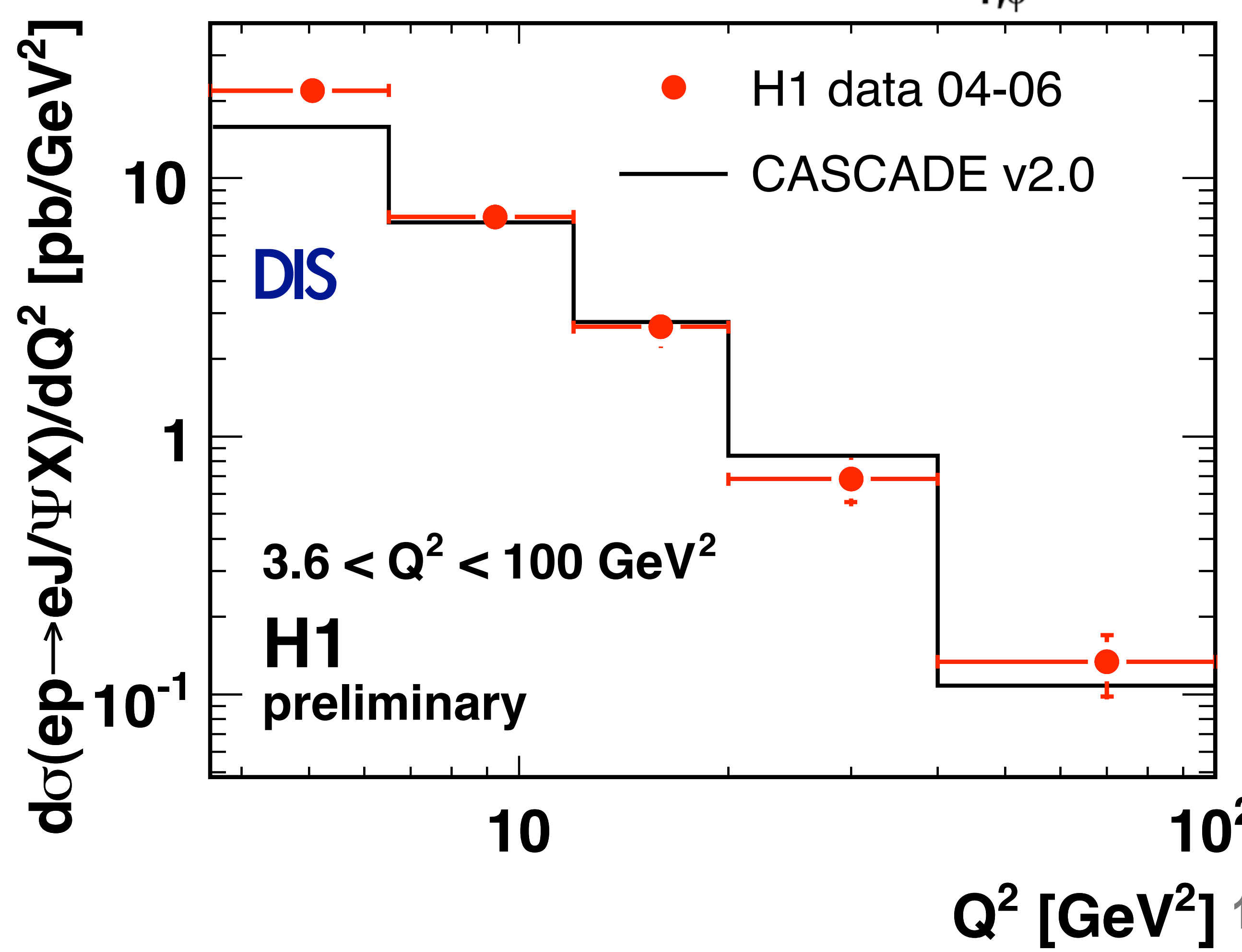
CCFM implemented in Monte Carlo event generator CASCADE

HERA-II Data

- Data presented at QWG07
- Significantly improved precision (stat and syst)
- CS (DGLAP, NLO and CCFM) describe data
- NLO: very large normalization uncertainty
- New CCFM: absolute prediction is correct







HERA-II Data

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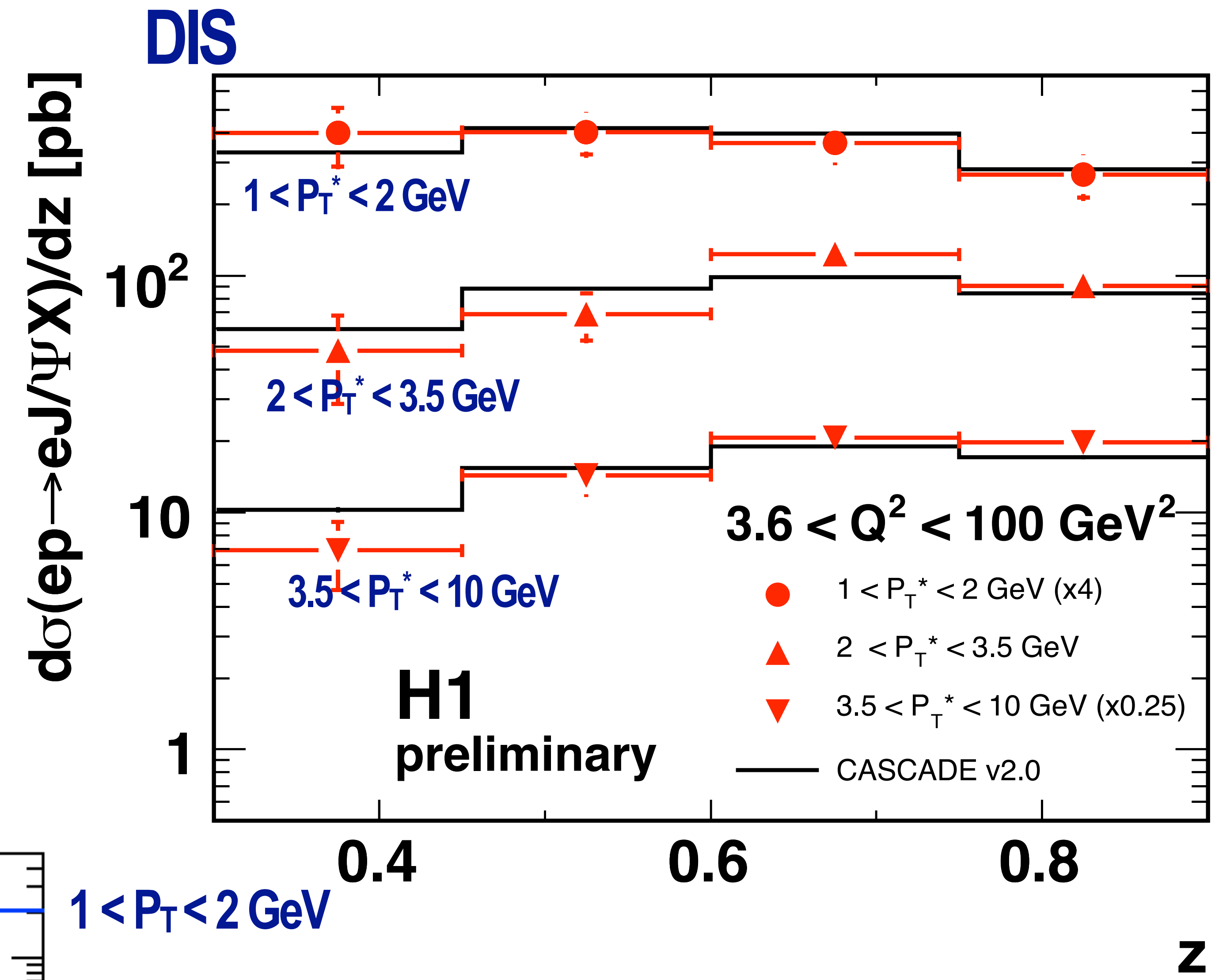
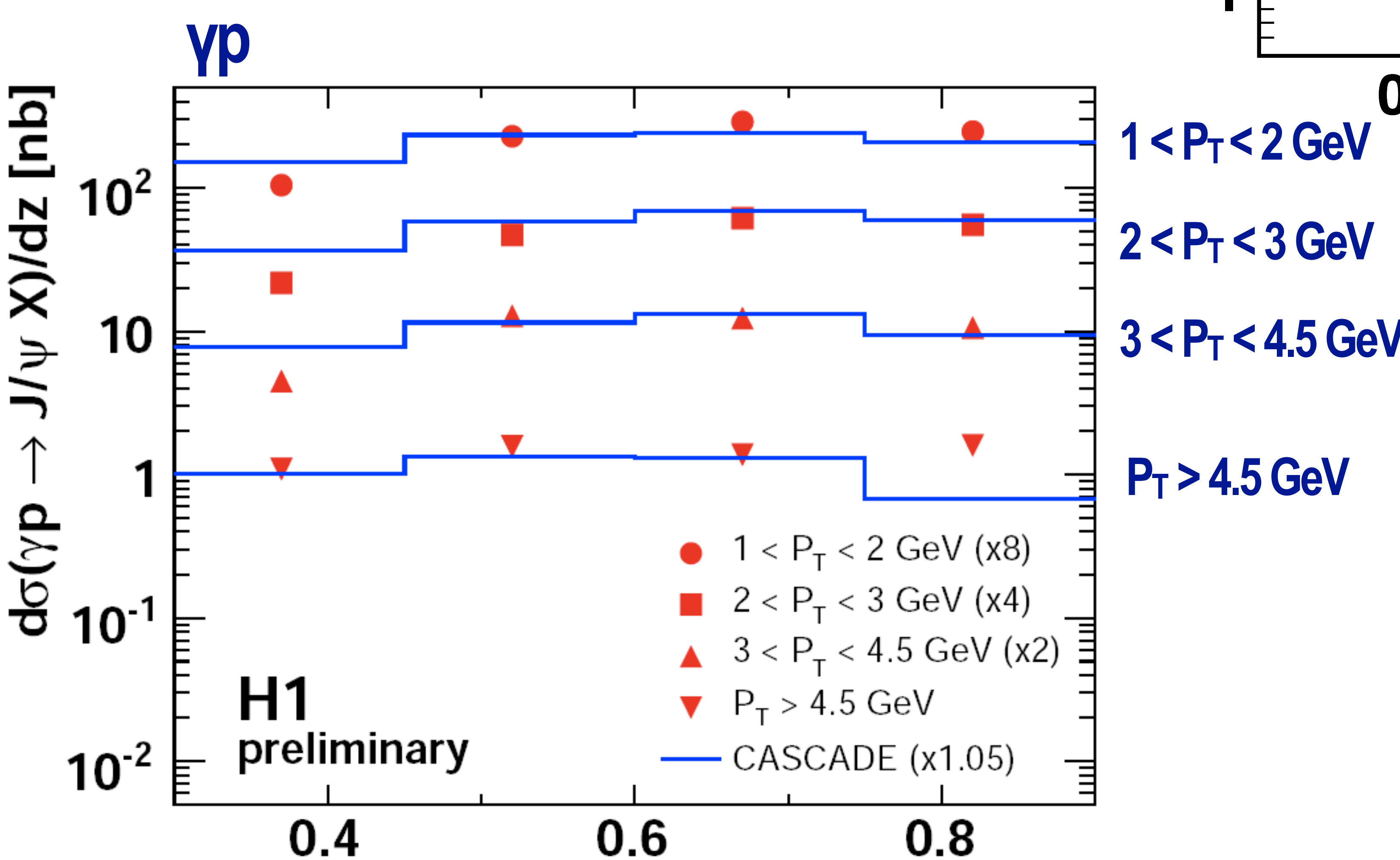
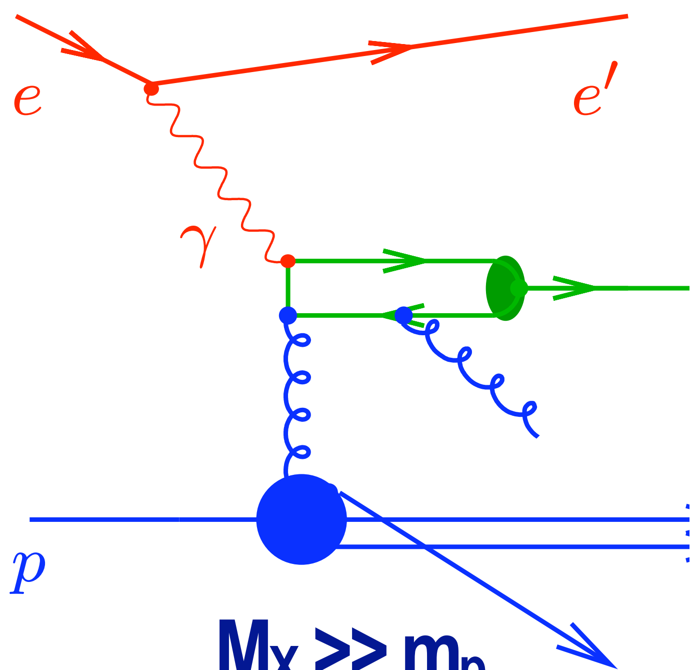




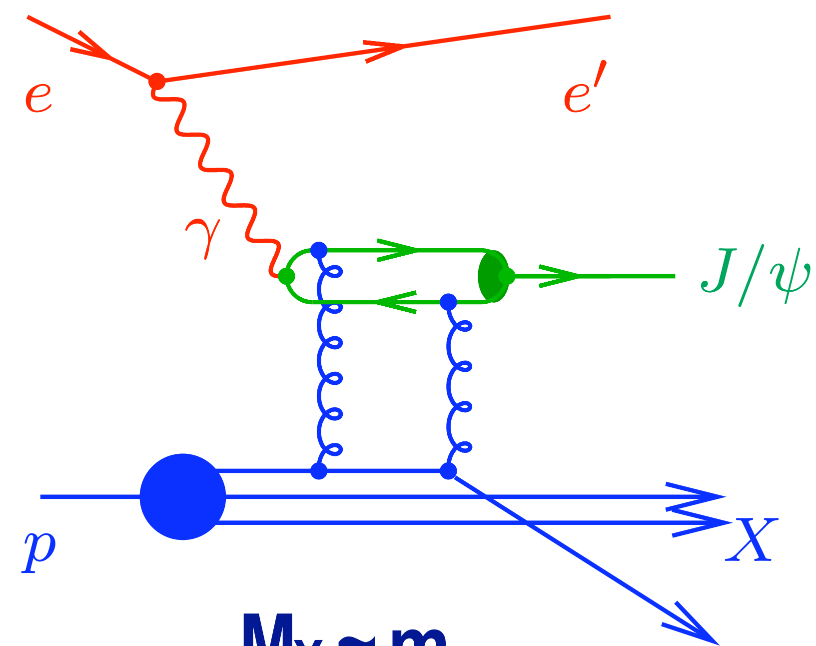
Elasticity z

inelastic
boson-gluon fusion



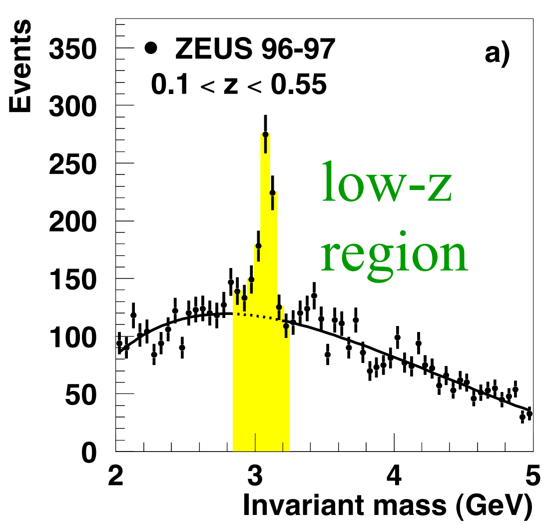
$M_X \gg m_p$

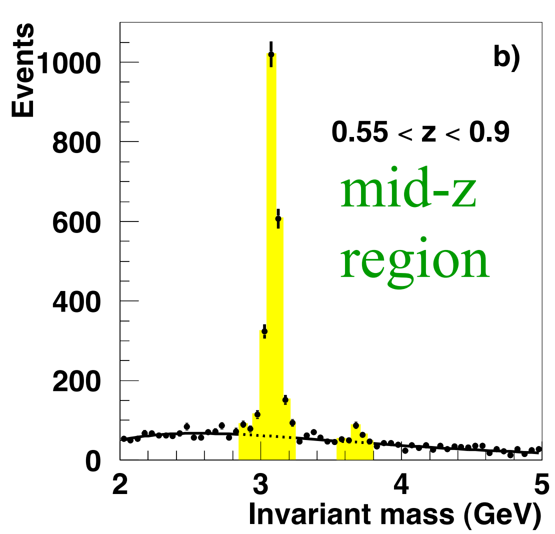
diffractive
exchange of colourless state

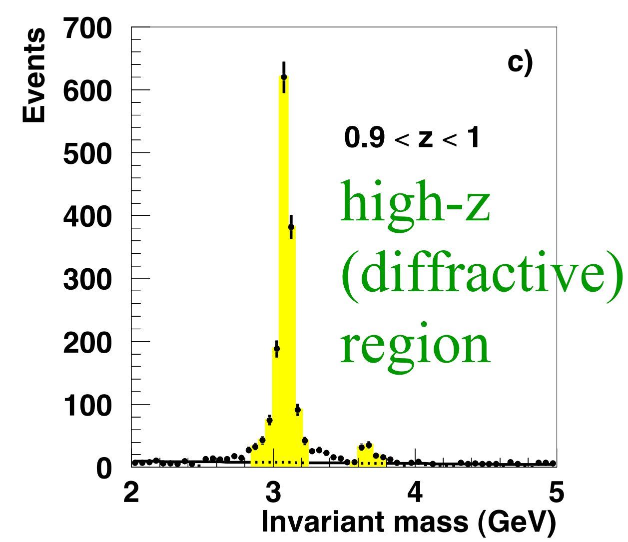


$M_X \sim m_p$

z>0.05 — **z~0.9** — Elasticity z — **z~1**







Elasticity z

inelastic
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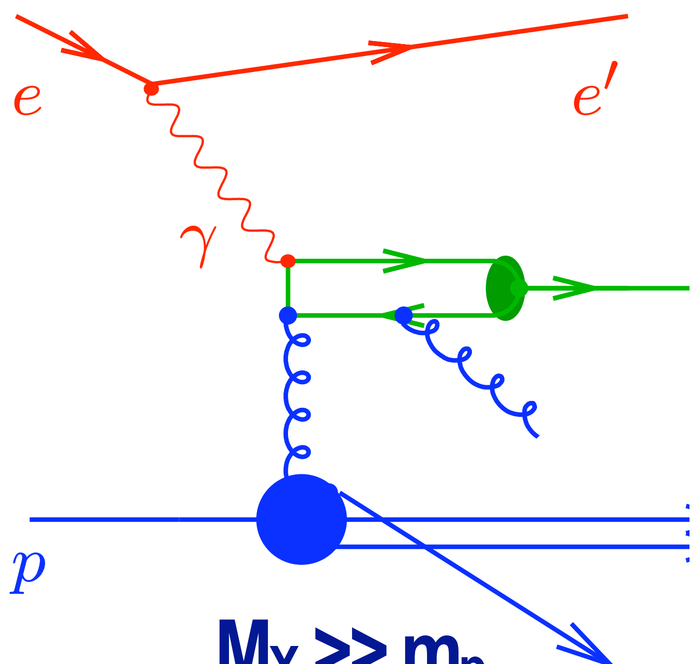
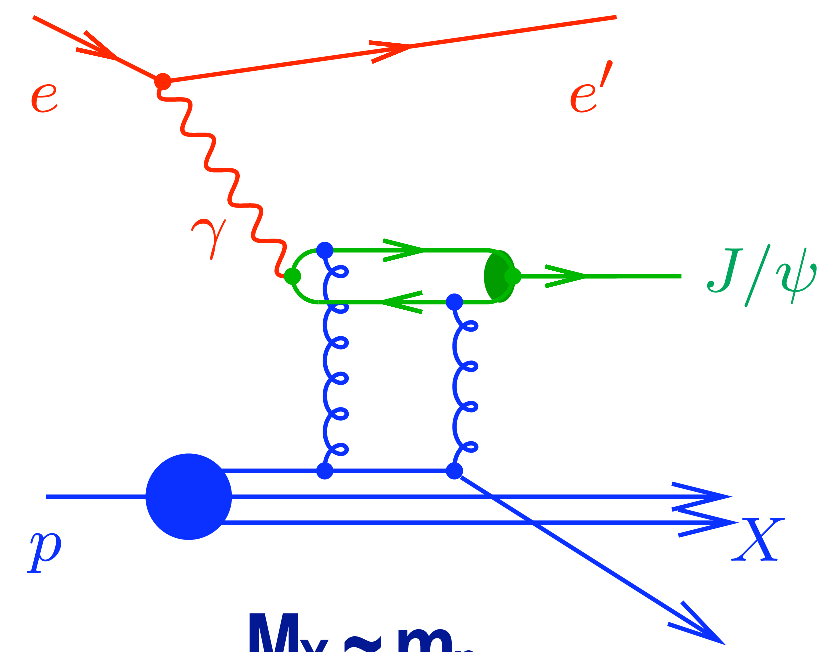


$M_X >> m_p$

diffractive
exchange of colourless state



$M_X \sim m_p$

z>0.05 **z~0.9** Elasticity z **z~1**

$\sum \hat{\sigma}(\gamma p \to c\bar{c}[n]X) \times \mathrm{LDME}[n])$

$\sigma \propto |xg(x)|$ **moderate rise with $W_{\gamma p}$**

$d\sigma/dp_{t,\psi}^2 \propto (p_{t,\psi}^2 + M_\psi^2)^{-4...5}$

$\Psi(\gamma \to c\bar{c}) \otimes \sigma_{dipole}^2 \otimes \Phi(J/\psi)$

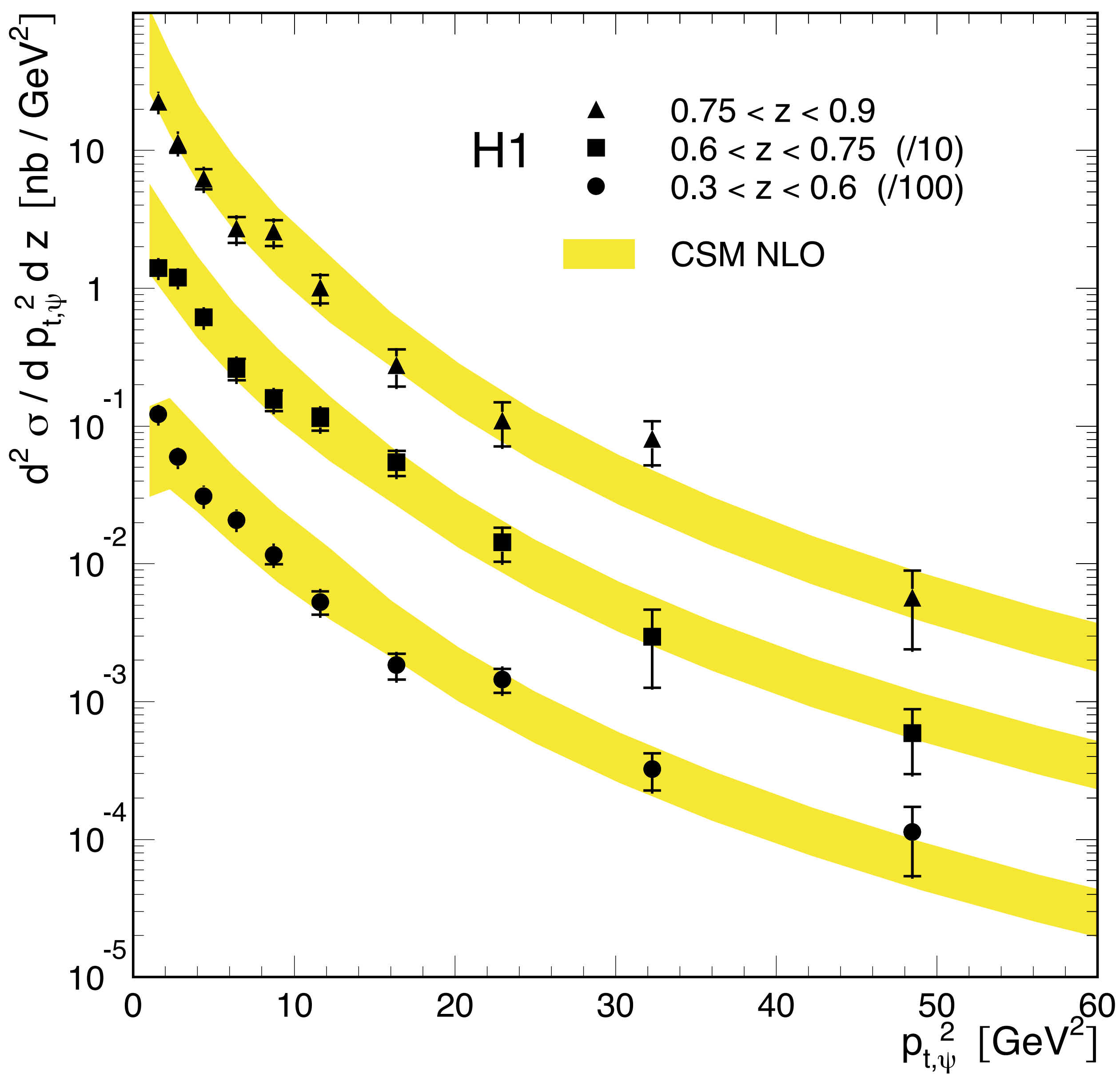
$\sigma \propto |xg(x)|^2$ **faster rise with $W_{\gamma p}$**

$d\sigma/dt \propto -t^{-3}$ **somewhat steeper**

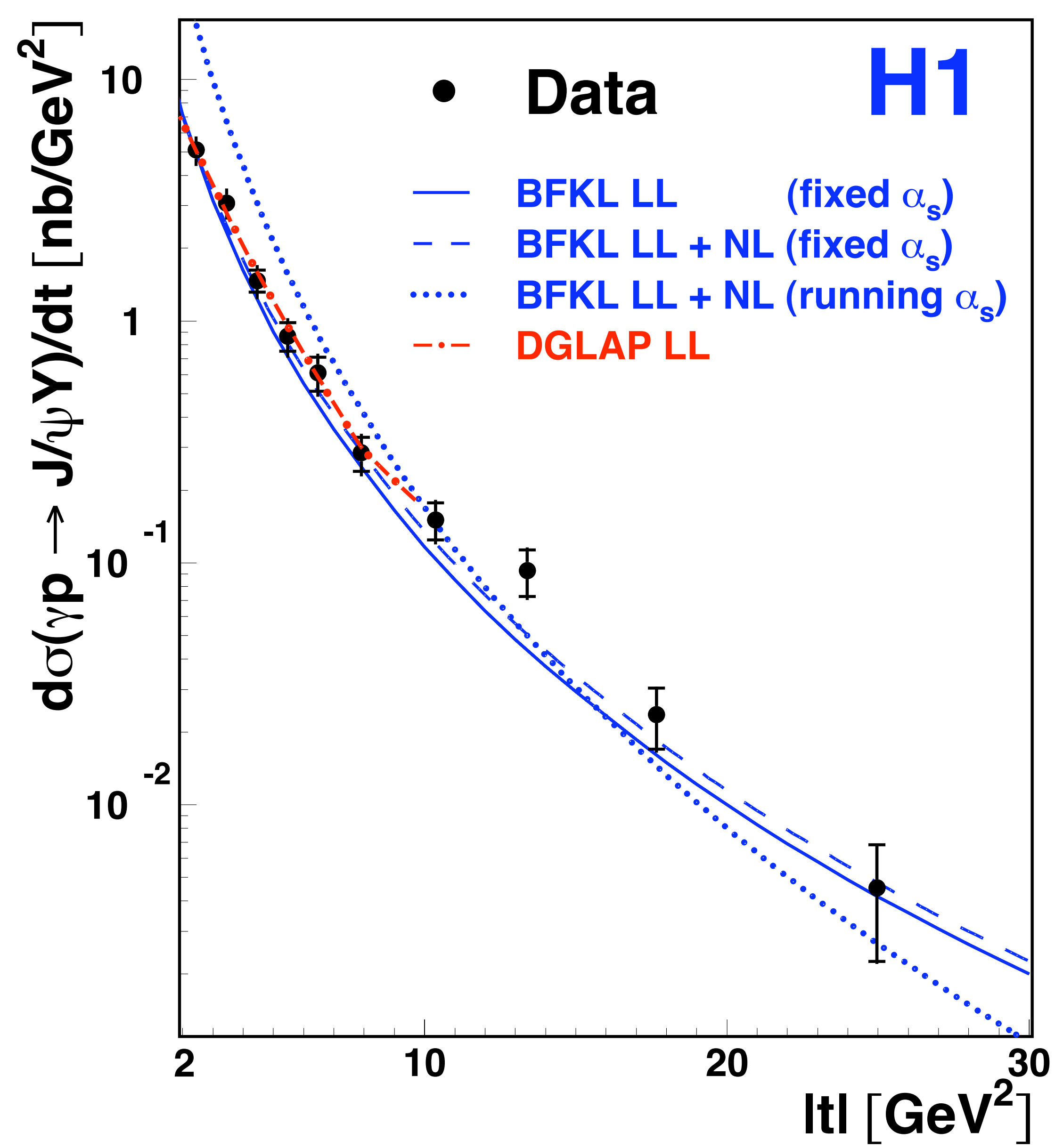
Transition between inelastic and diffractive production regimes ?

Transv. Momentum Distributions

$0.3<z<0.9$



$z>0.95$, $|t|>2$ GeV^2



$(p_{t.\psi}^2 + M_\psi^2)^{-n}$: $n = 4.49 \pm 0.15$

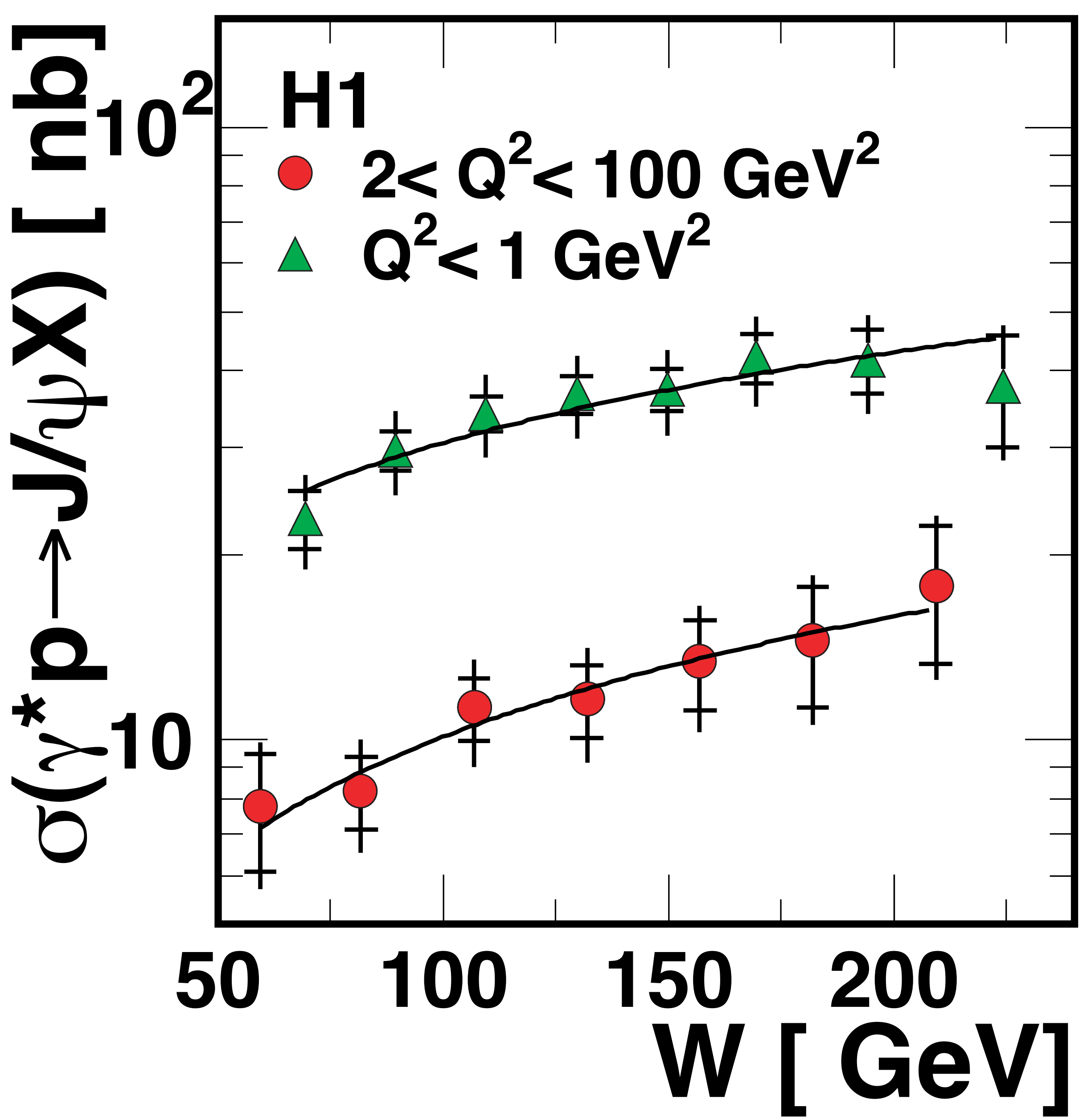
$n = 6.63 \pm 0.13 \pm 0.08$

Behaviour is significantly, but not drastically different:

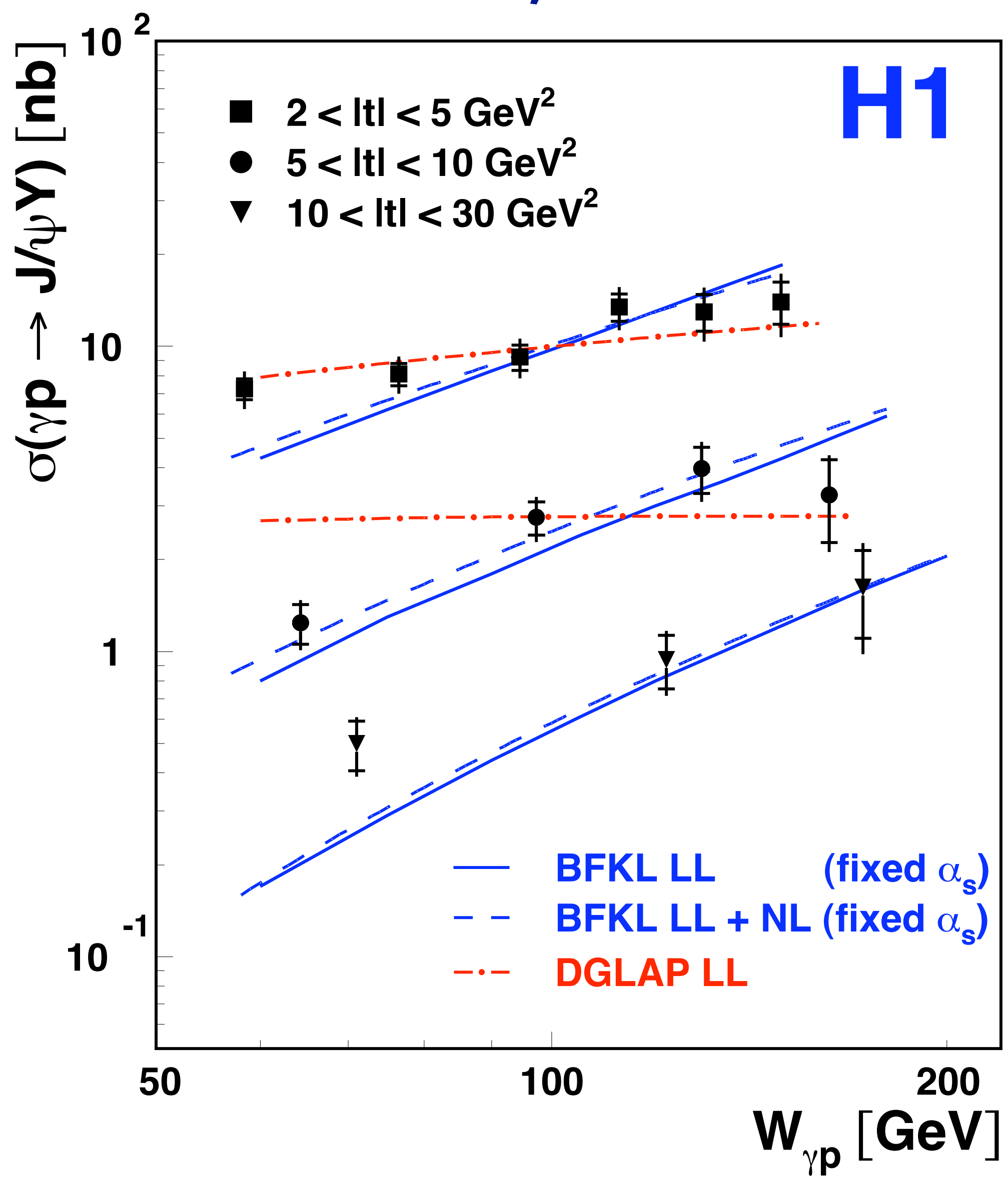
Cut in p_t does not provide clean experimental handle

Energy Dependence

0.3<z<0.9



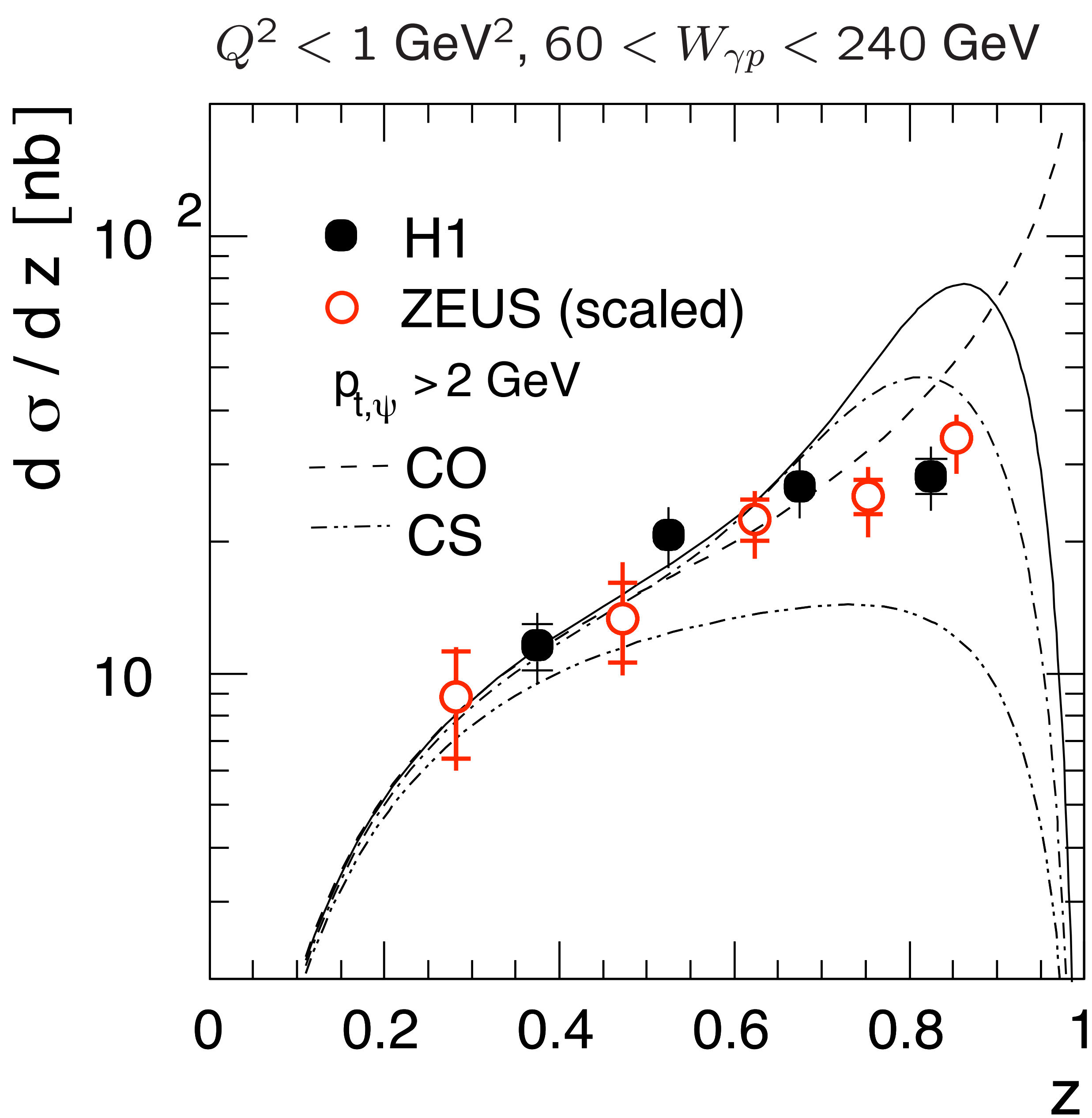
z>0.95, |t|>2 GeV²



Fit W^{δ}: $\delta \sim 0.49 \pm 0.16$ $\delta \sim 0.77 \pm 0.14 \pm 0.10$ (lowest t-bin)

Large z: steeper energy dependence

Elasticity Distribution



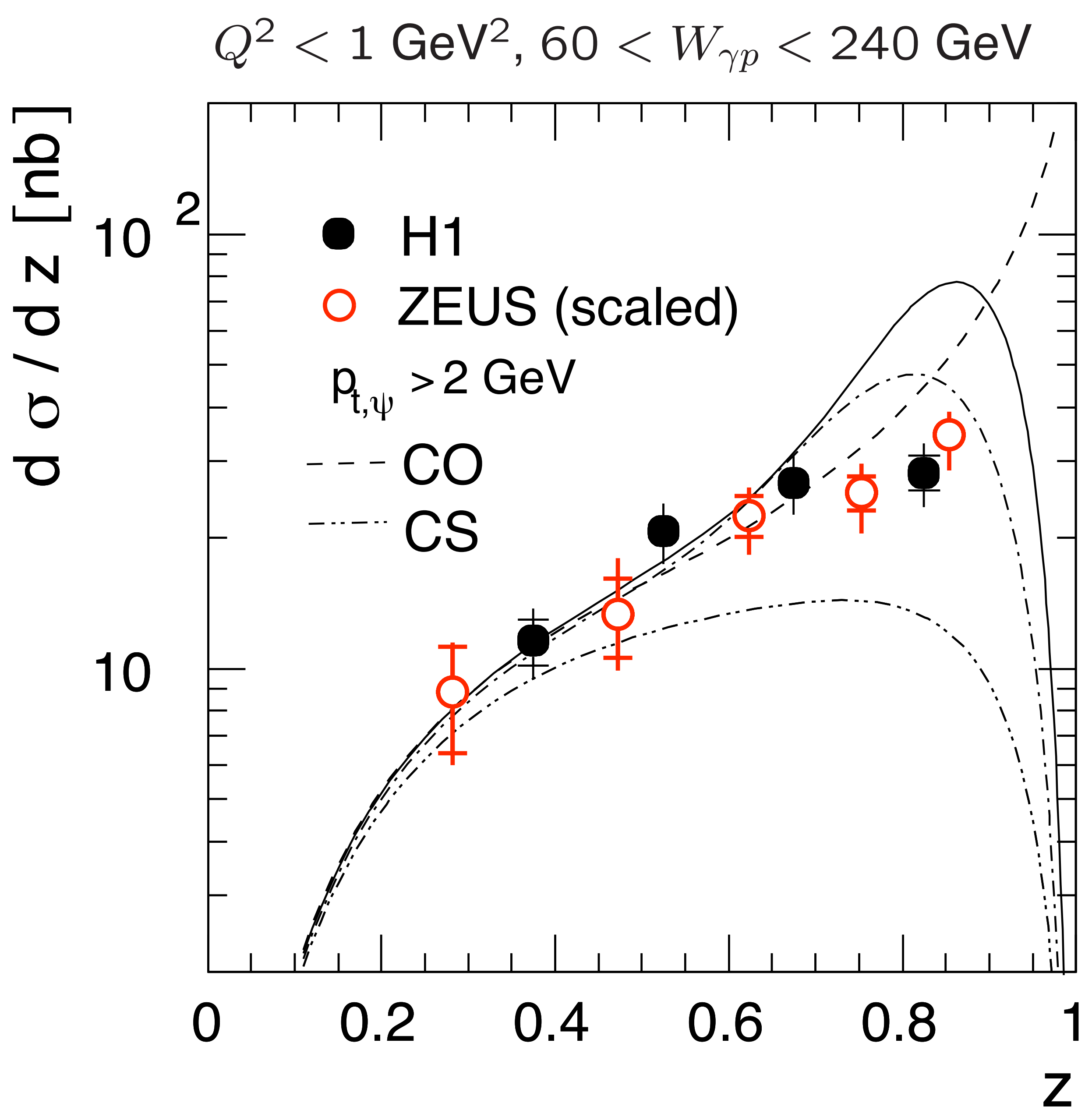
LO Color-Octet Contribution
→no hard gluon
→rises to large z

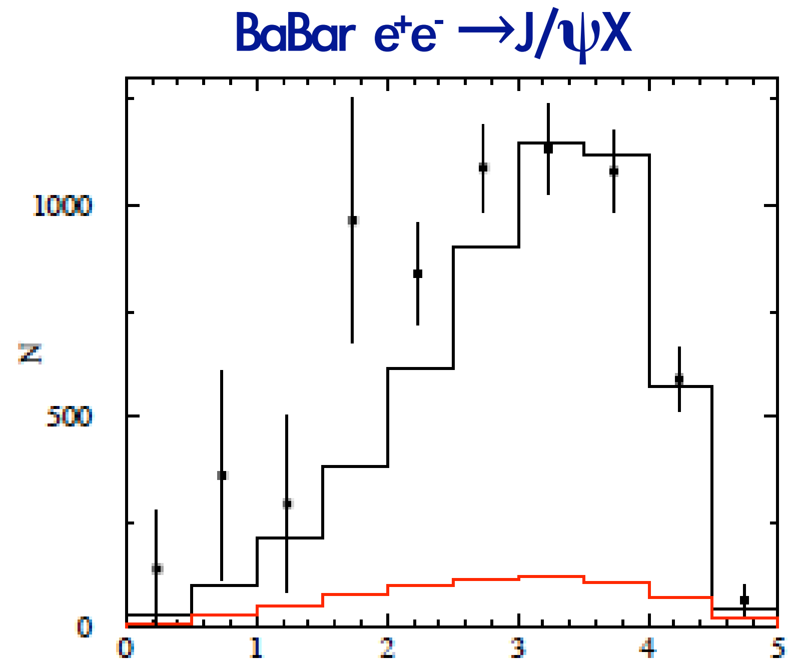
Color Singlet contribution:
→hard gluon
→falling off at large z

soft Color Octet gluons resummed:
→reasonable description of shape
for data at z < 0.9 !!!

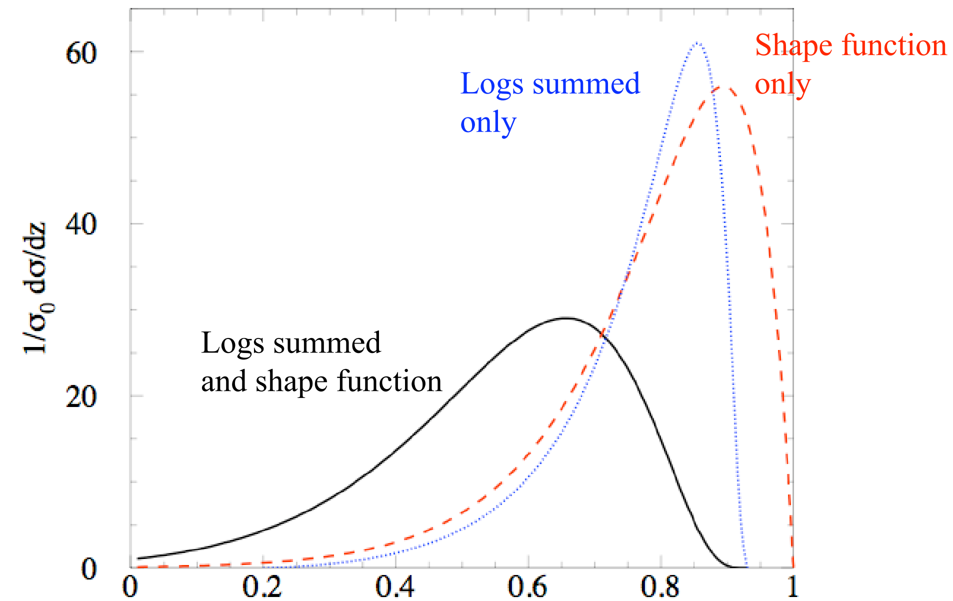
M.Beneke, G.A. Schuler, S.Wolf, 2000

Elasticity Distribution





Adam Leibovich, Sean Fleming, Thomas Mehen, QWG, FNAL 2003

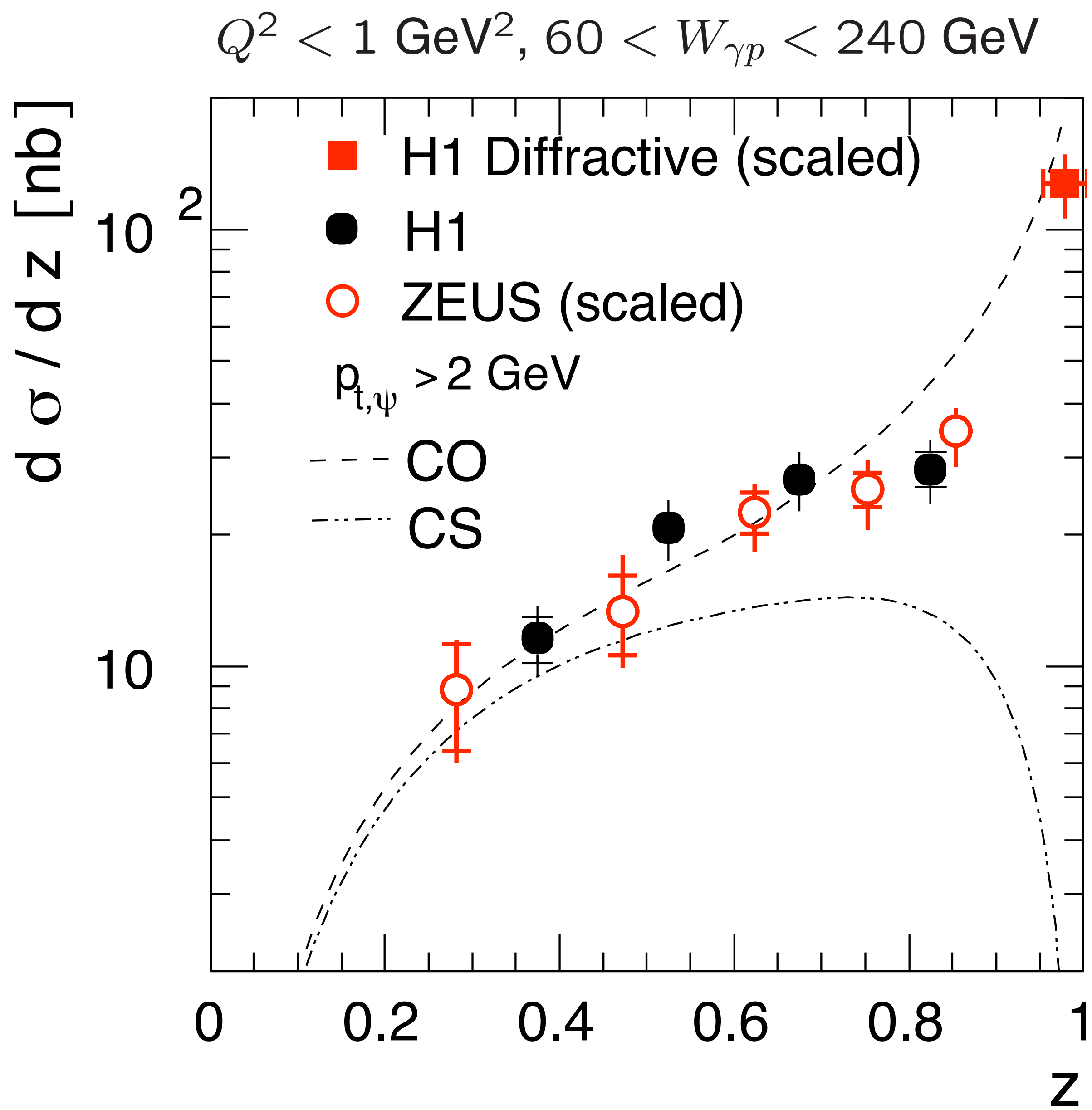


Adam Leibovich, Sean Fleming, Thomas Mehen, QWG, DESY 2007

Description of CO endpoint behaviour (B-factories ↔ HERA)

Elasticity Distribution

My extrapolation of H1 published result



Total cross section for $z > 0.95$:

$|t| > 4$ GeV^2 and $60 < W_{\gamma p} < 240$ GeV

$$\sigma = 6.04 \pm 0.35 \pm 0.95 \text{ nb}$$

Measured z-distribution of events:

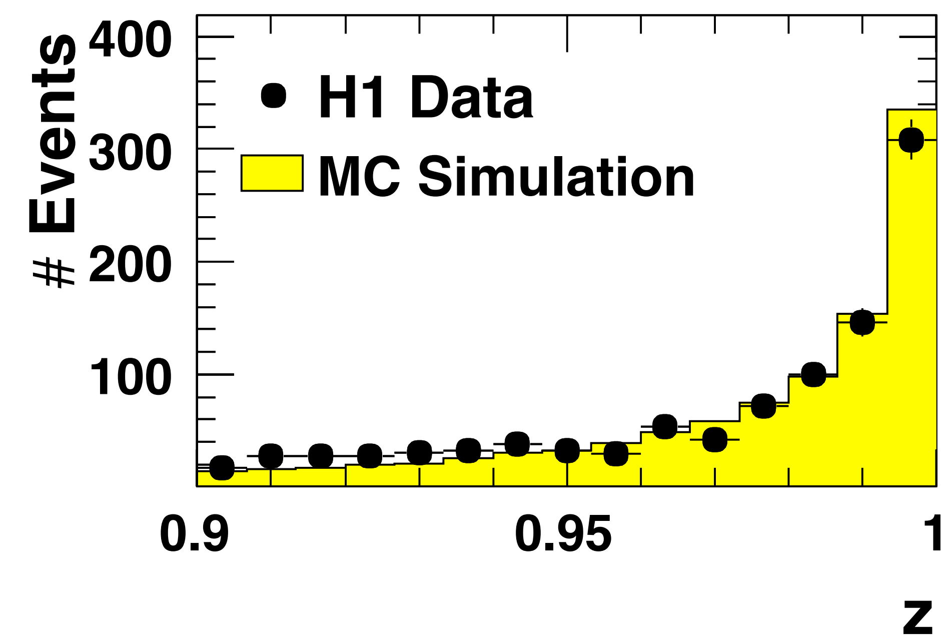


Figure Caveats: 'H1 Diffractive'

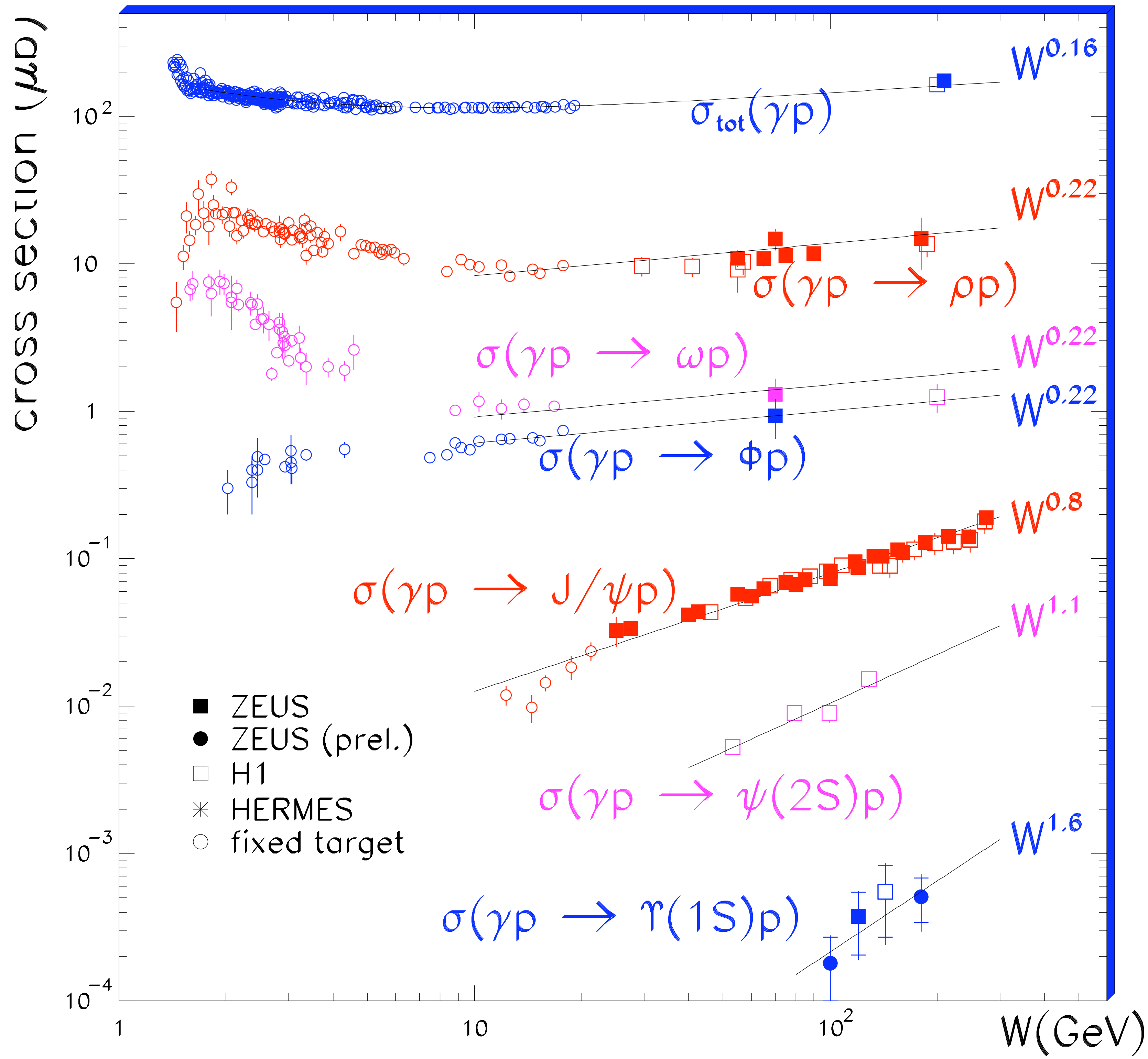
data point after scaling in W assuming $\sigma(W) \propto W^{\delta}$ with $\delta = 0.77 \pm 0.14 \pm 0.10$

$d\sigma/dz$ averaged over $0.95 < z < 1$, although event distribution in z is steep

At HERA, cross section does actually rise steeply due to diffractive process

Elastic VM Production

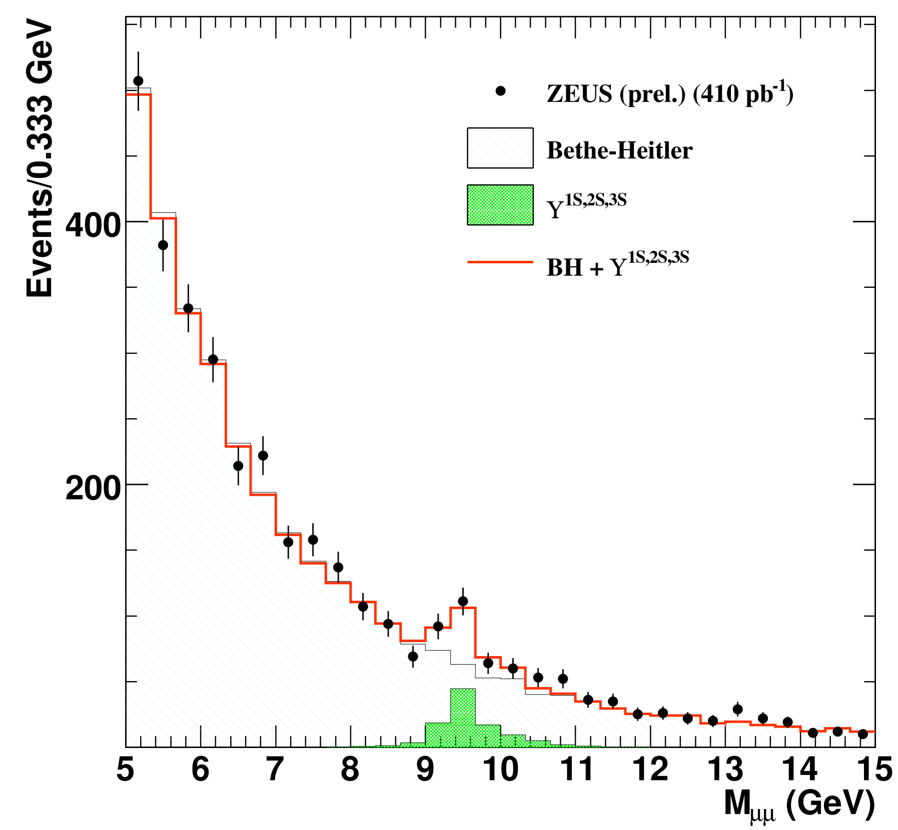
z=1



Slope rising with m_{VM}

Elastic VM production has been measured for ρ^0, ω, ϕ, J/ψ, ψ(2S) and ϒ(1S)

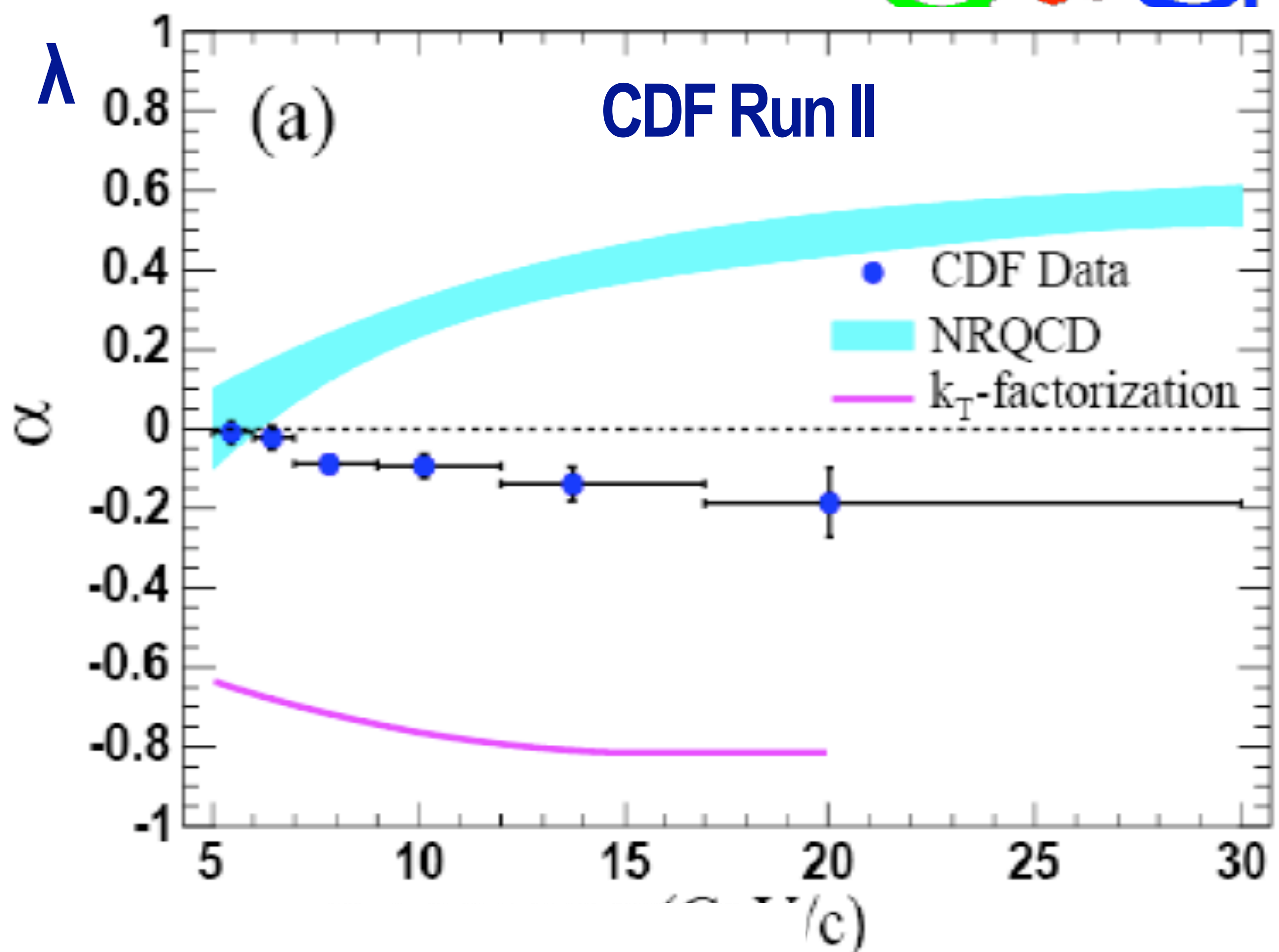
ZEUS: New measurement of elastic production of Upsilon

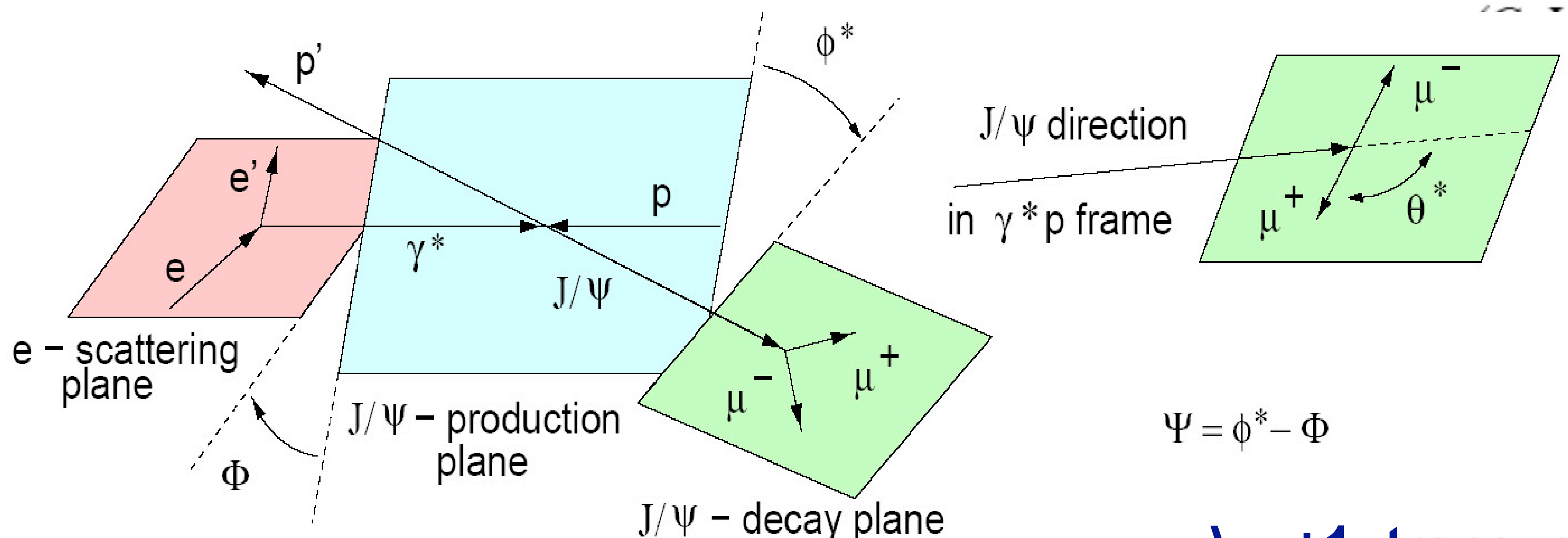


J/ψ Polarization

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} \propto 1 + \lambda\cos^2\theta^*$$

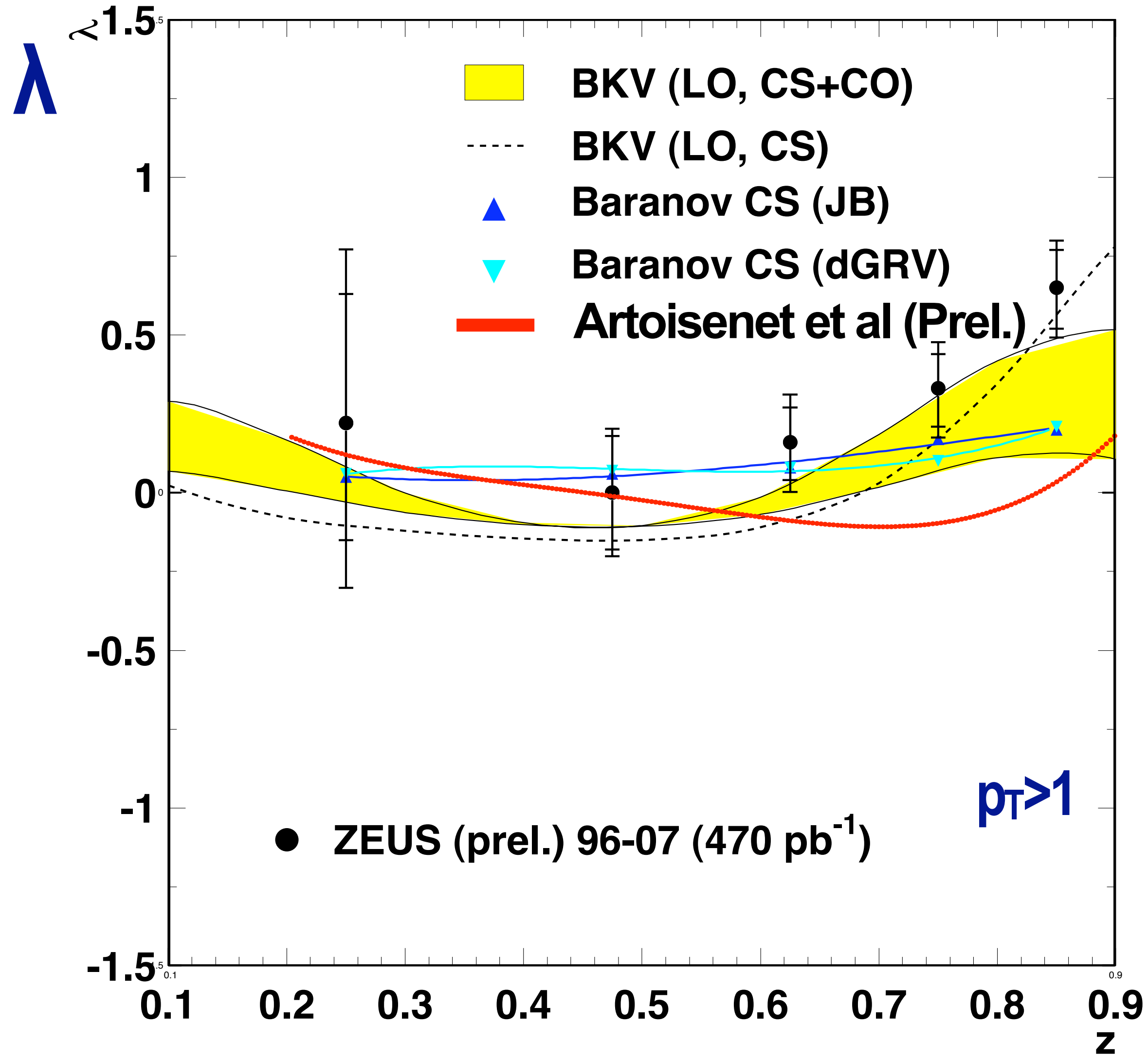
$$\frac{1}{\sigma}\frac{d\sigma}{d\Phi^*} \propto 1 + \frac{\lambda}{3} + \frac{\nu}{3}\cos 2\Phi^*$$

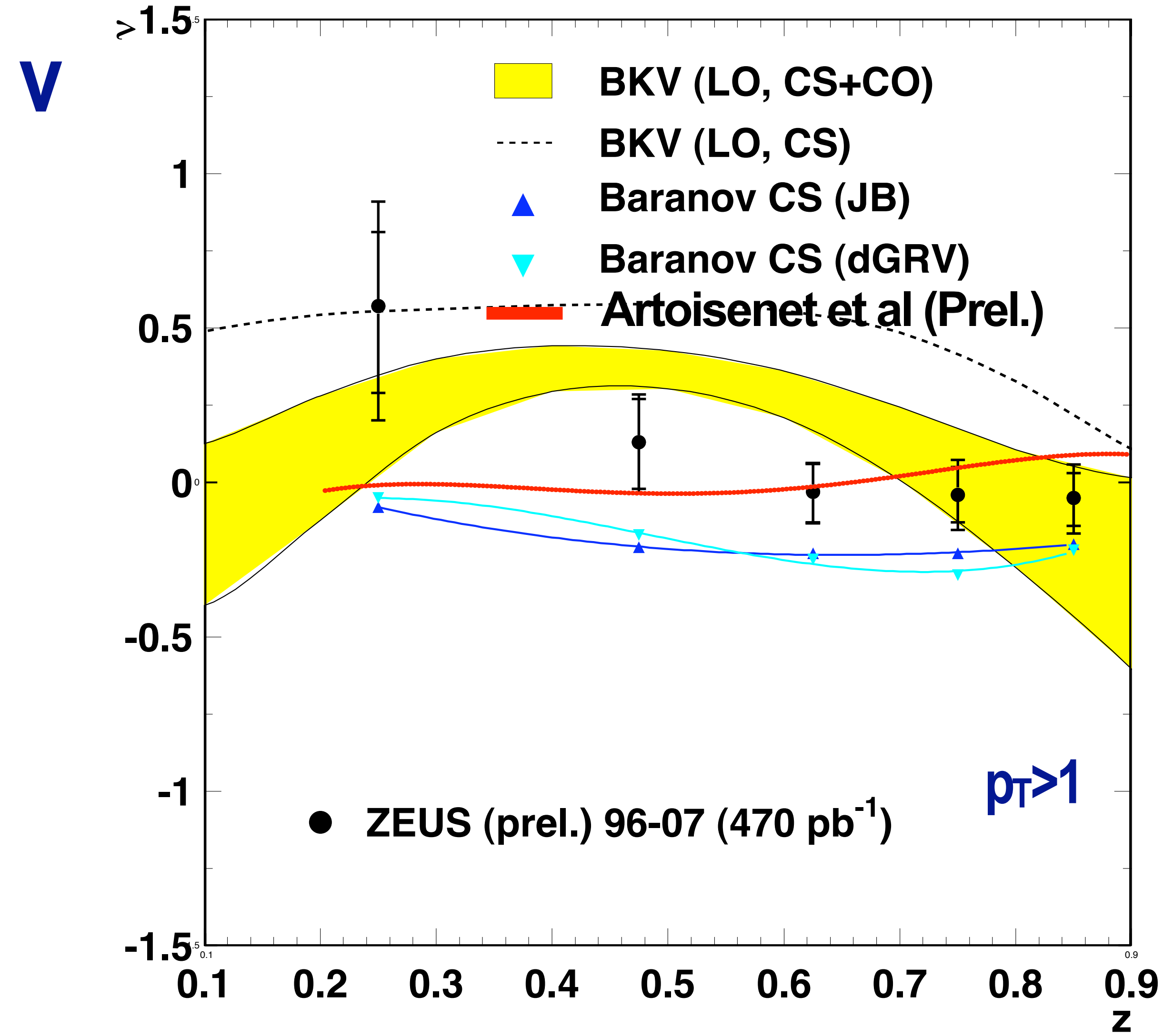




λ = +1: transverse polarisation

J/ψ Polarization





- CS (DGLAP, LO): λ ok, ν too high
- CS+CO (DGLAP, LO): ok
- New CS (CCFM): ok
- New CS (DGLAP, NLO): ok

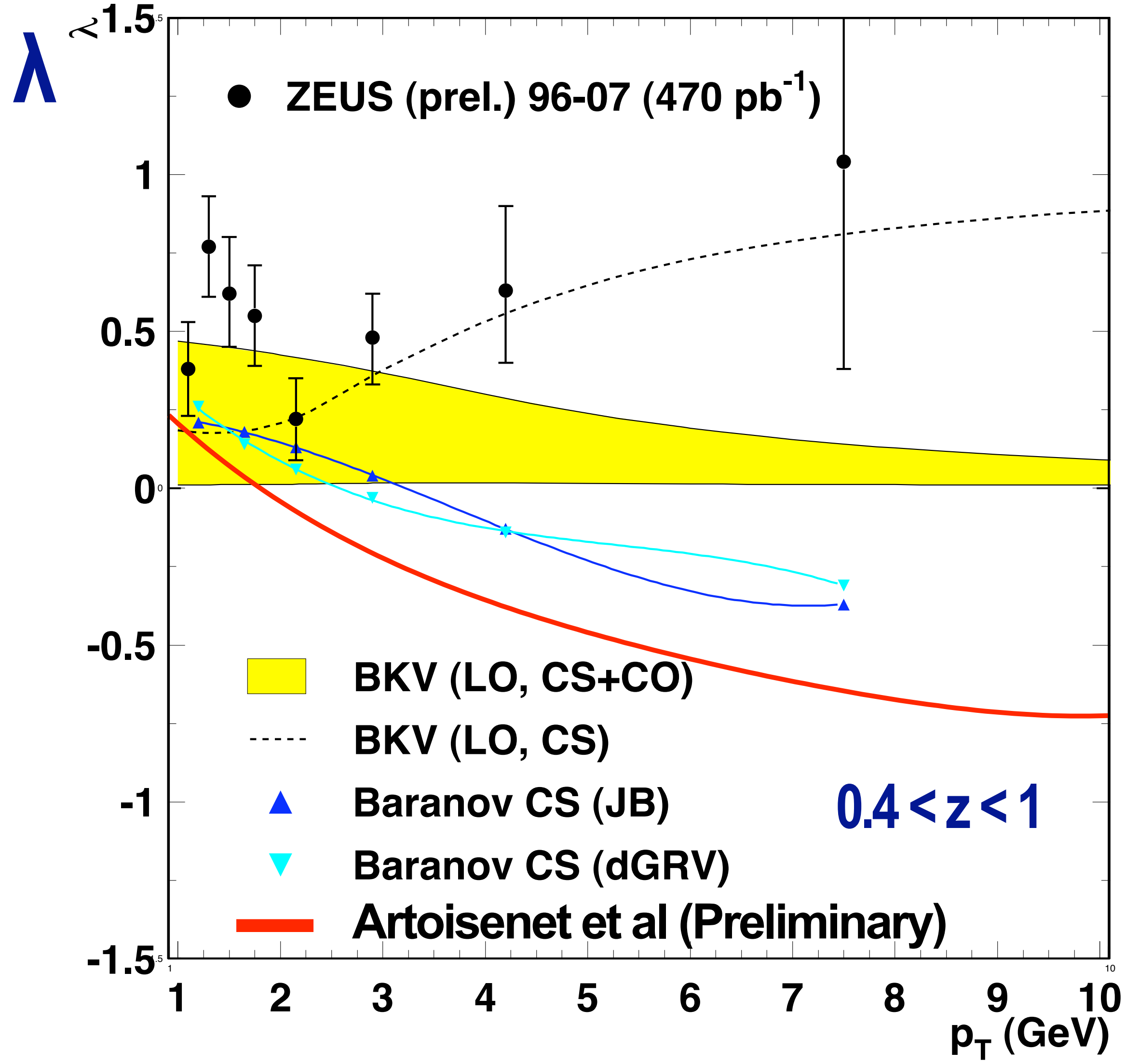
Beneke, Krämer, Väntinnen, 1998

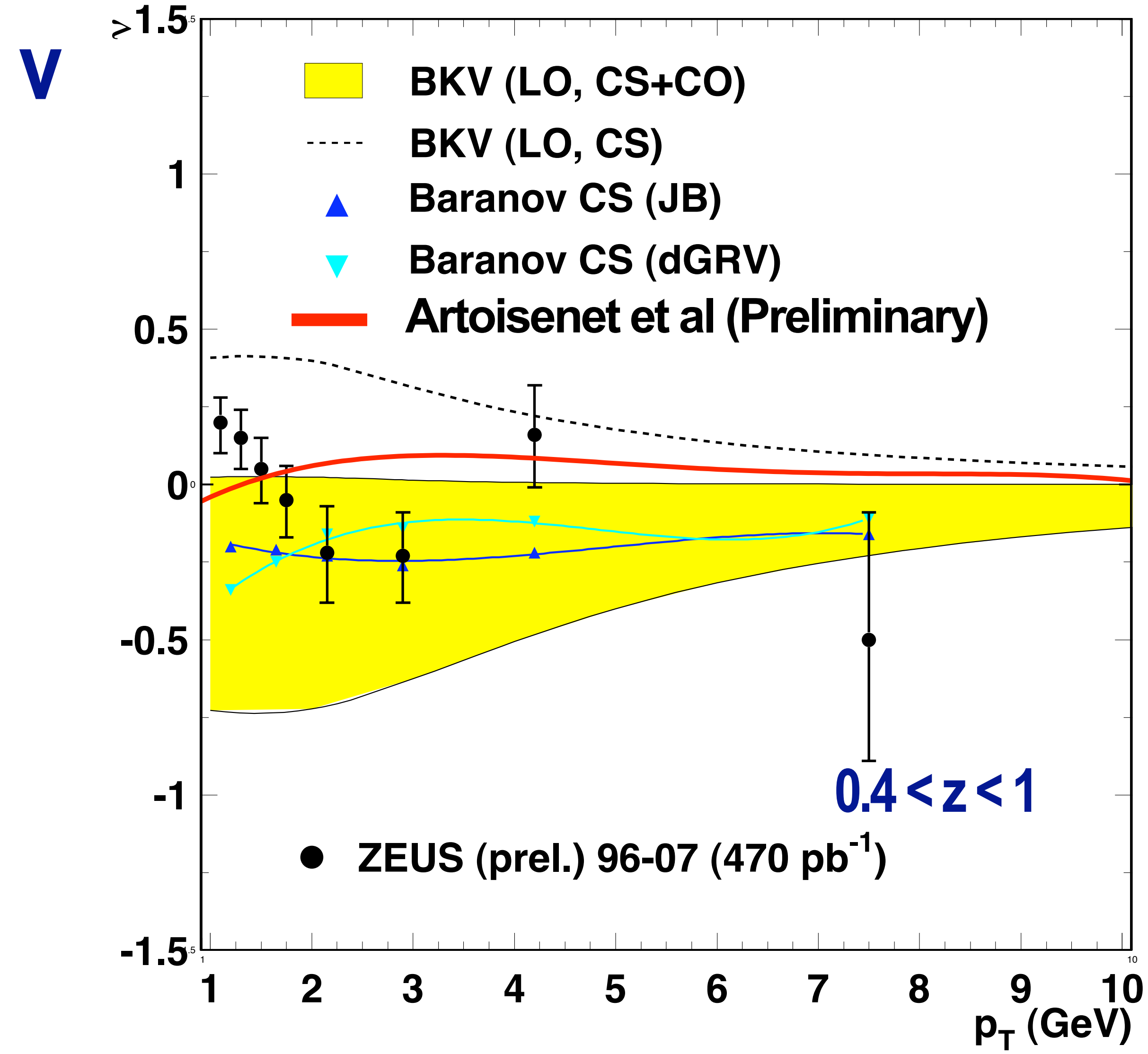
Baranov, 2008

Artoisenet, Lansberg et al, 2008

new calculations available

J/ψ Polarization





- Similar behaviour for CS (DGLAP, NLO) and CS (CCFM)
- ZEUS data show opposite trend, CS (DGLAP, LO) describing data best
- Contributions from diffractive backgrounds at low p_T and high z being evaluated

Conclusions

- New HERA data-to-theory comparisons:
  - Several new calculations have become available recently (CCFM and DGLAP, NLO)
  - Both CS (DGLAP, NLO) and CS (CCFM) describe the data rather well
  - Higher order calculations remove need for colour octet contributions
- Inelasticity distributions
  - Diffractive VM production is the dominant production process for ψ(nS) and also for Υ(nS)
  - Can not distinguish production processes at large z experimentally
  - Transition between inelastic and diffractive VM production regimes to be understood
- Upcoming final publications from HERA:
  - H1: cross sections and polarization (DIS and γp)
  - ZEUS: polarization (γp) (cross section measurements planned for later)
  - Looking out for theoretical and experimental input and suggestions