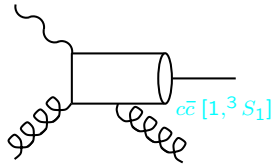
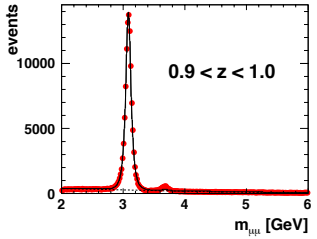
Inelastic J/ψ Production at HERA

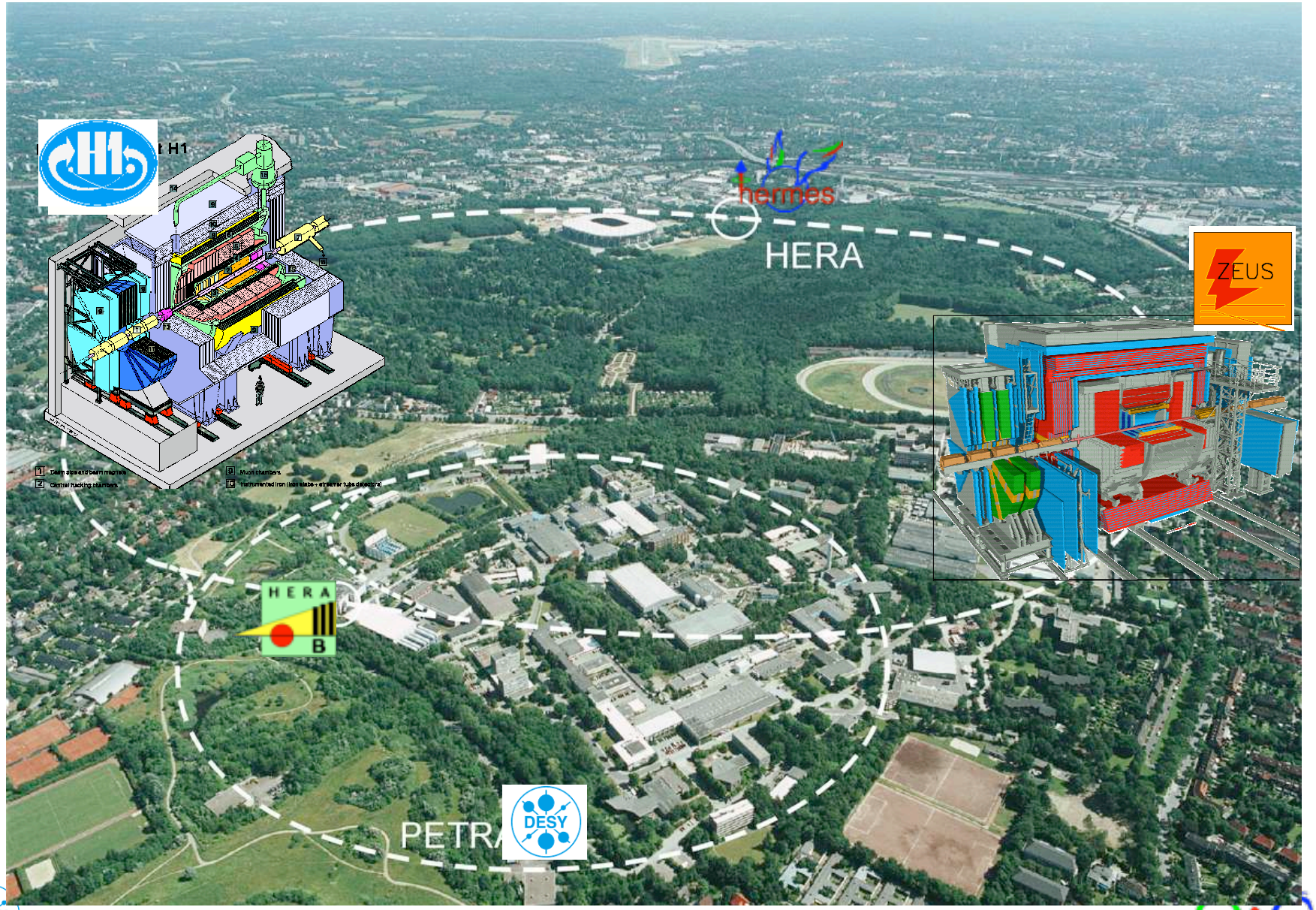




Andreas B. Meyer

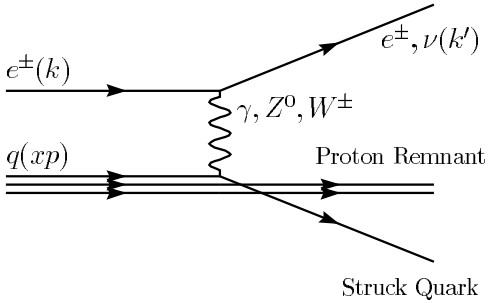
Quarkonium Working Group
21 May 2010

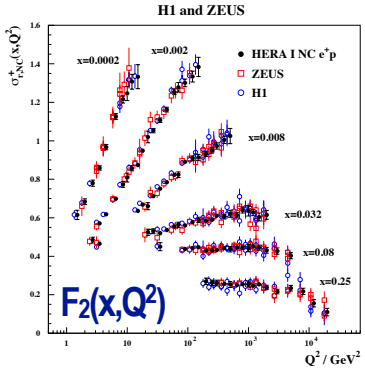
Electron-Proton Collider HERA operated 1992 - 2007

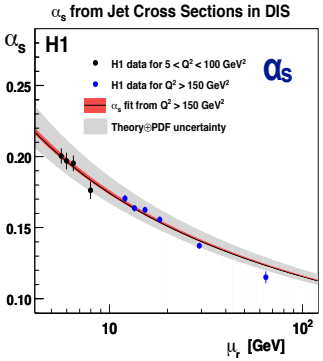


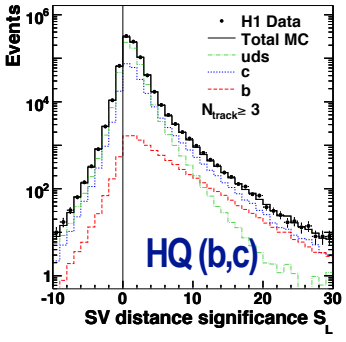
HERA Physics $\sqrt{s_{ep}} \sim 320$ GeV

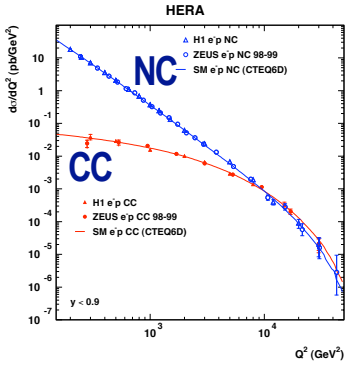
- QCD measurements
- Electroweak physics
- Searches for new physics

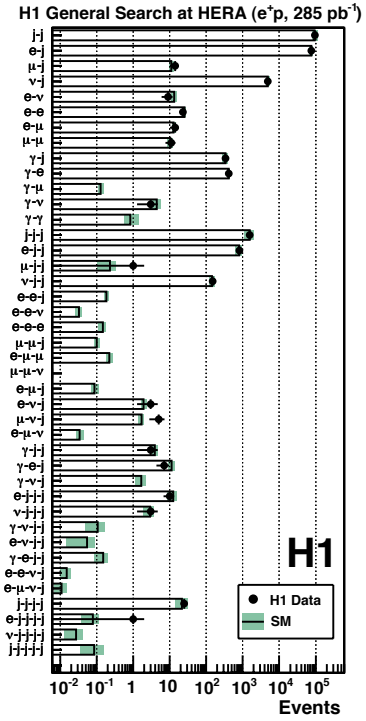


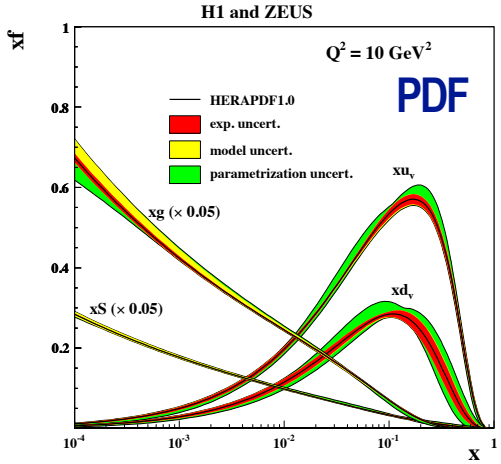


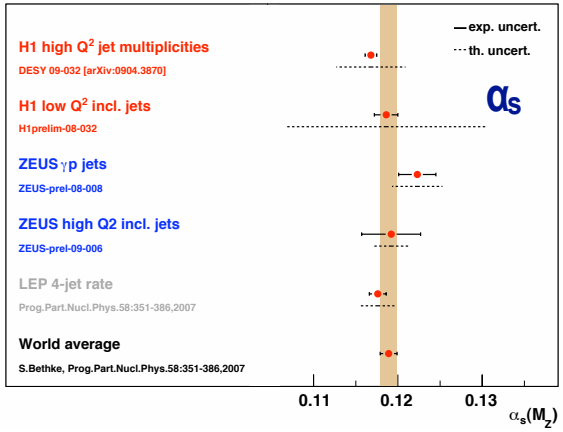


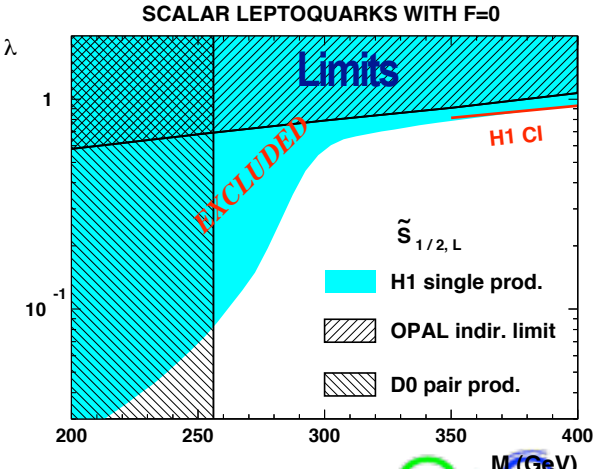






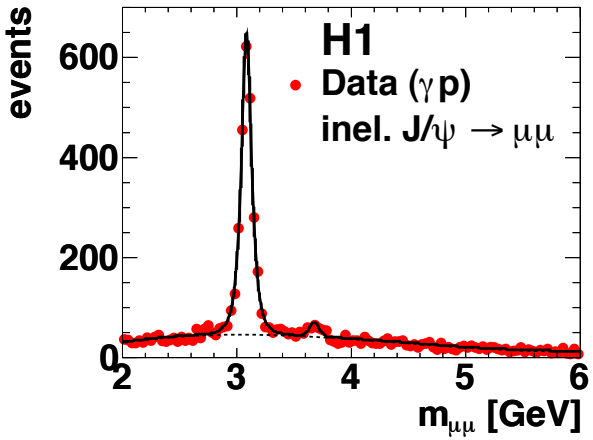




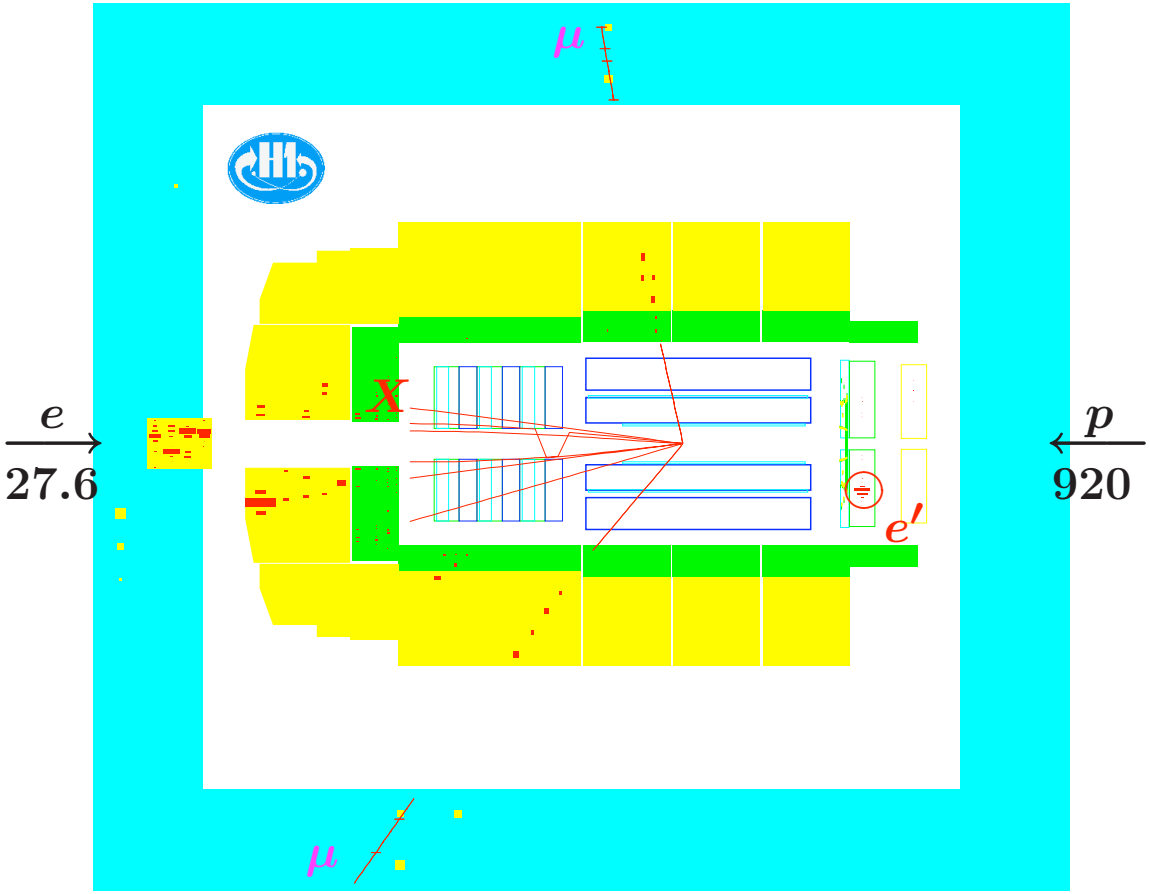


J/ψ Event Signature

H1 Collaboration, 2010 1002.0234 [hep-ex]

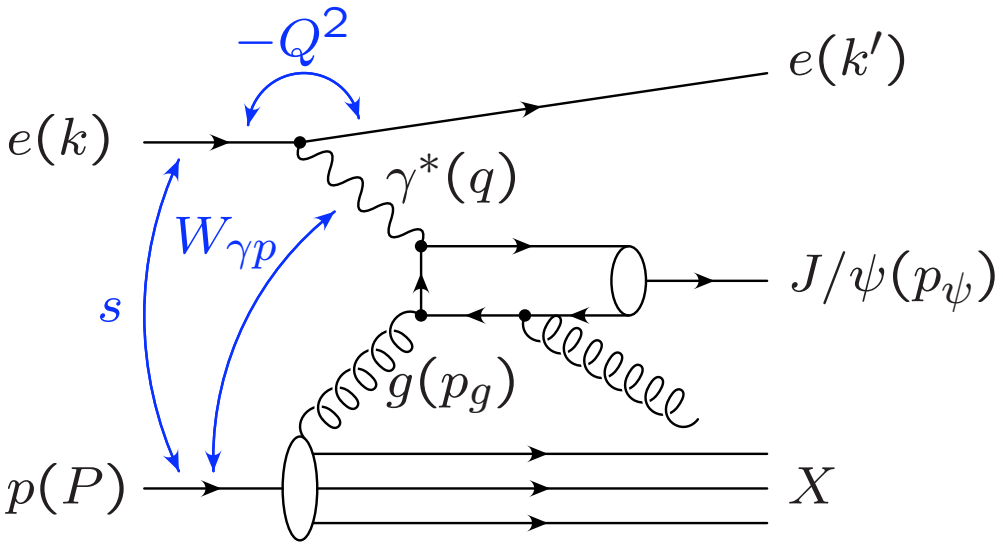


J/ψ $\rightarrow \mu^+\mu^-$ candidate event in H1 Detector:

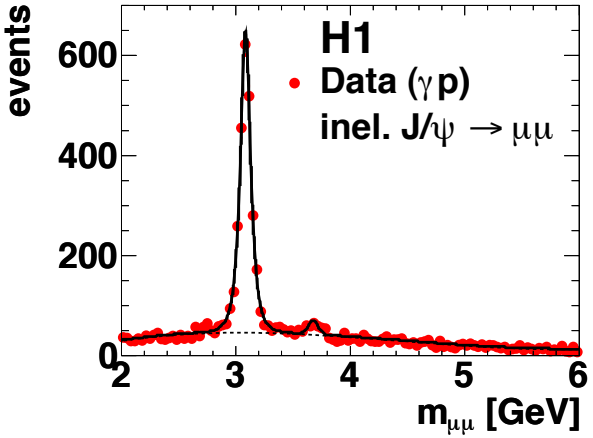


- J/ψ, ψ(2S), ϒ measurements:
  - use decays into $\mu^+\mu^-$ or e^+e^-
  - Trigger and reconstruction down to $p_t \sim 0$
- Feed down contributions (not subtracted from data):
  - ψ(2S): ~15 %
  - B, X_c: few % in measured range

Event Kinematics



H1 Collaboration, 2010 1002.0234 [hep-ex]



$$Q^2 = -q^2$$

$$s = (P+k)^2$$

$$W_{\gamma p} = \sqrt{(P+q)^2}$$

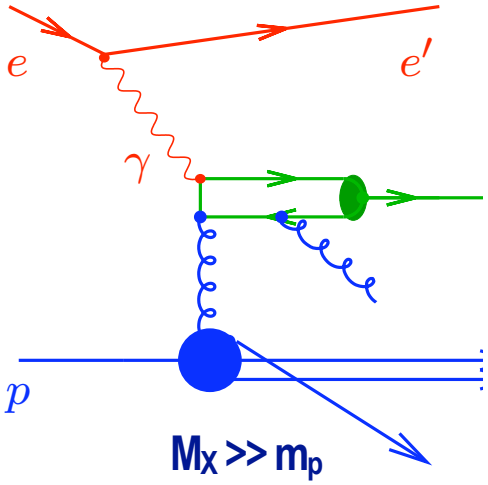
$$z = \frac{p_\psi \cdot P}{q \cdot P} = \frac{E^*_\psi}{E^*_\gamma} \text{ in } p \text{ rest frame}$$

- **Photoproduction (γp):** $Q^2 \sim 0$
  beam electron scattered under low angles, (not detected in main detectors)
- **Electroproduction (ep):** $Q^2 \gtrsim 2\ \mathrm{GeV}^2$

elasticity observable z → sensitivity to final state radiation details

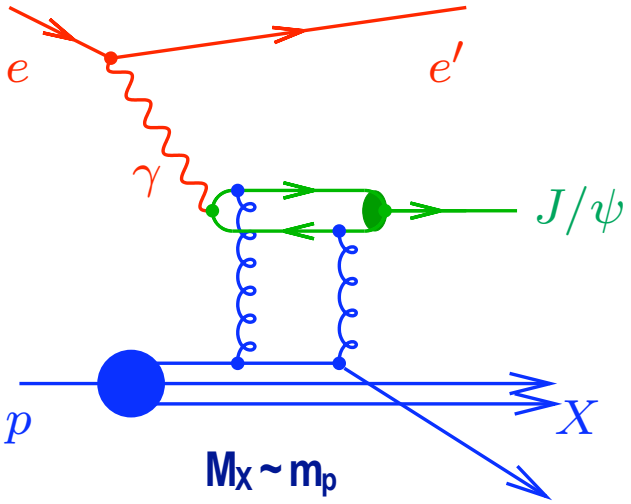
Production Mechanisms

boson-gluon fusion
inelastic



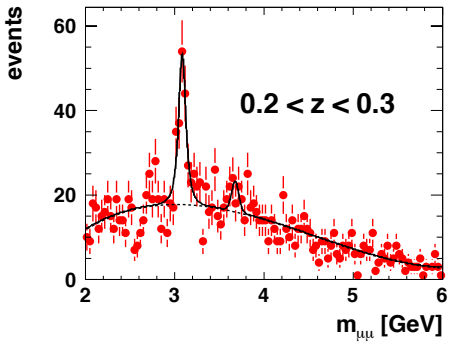
$M_X \gg m_p$

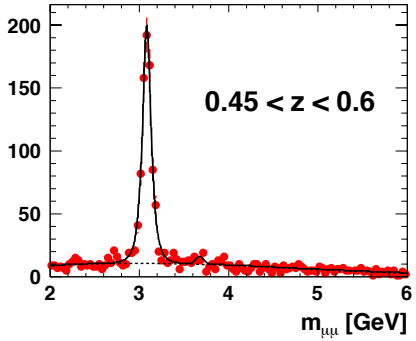
exchange of colourless state
elastic / diffractive

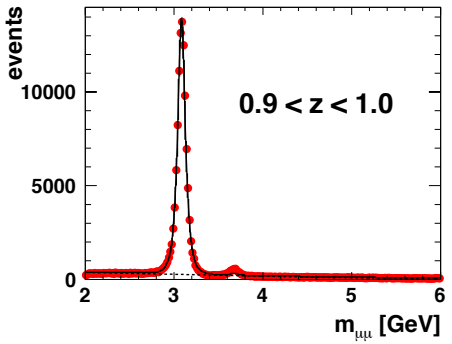


$M_X \sim m_p$

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

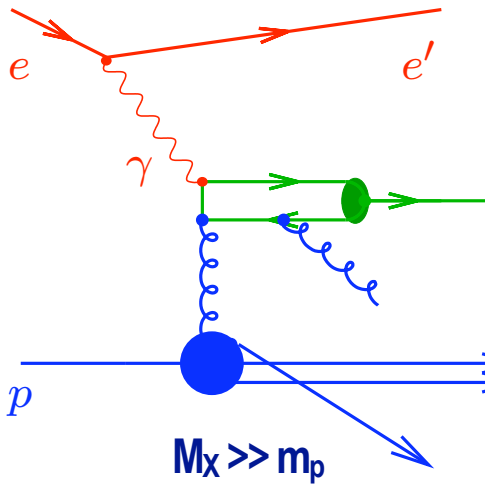






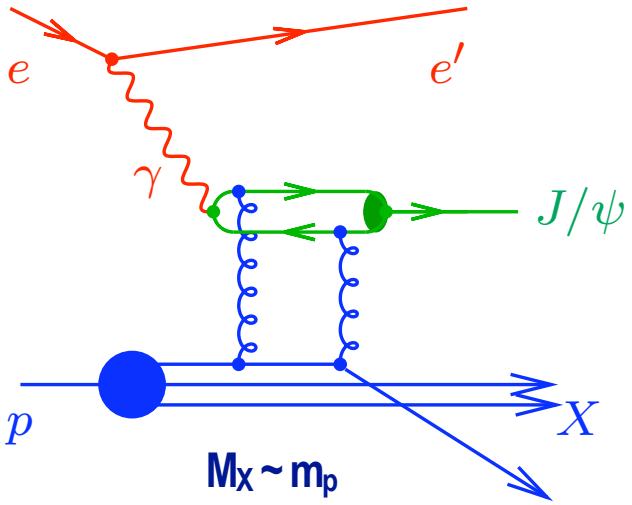
Production Mechanisms

boson-gluon fusion
inelastic



$M_X \gg m_p$

exchange of colourless state
elastic / diffractive



$M_X \sim m_p$

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

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

$$\sigma \propto |xg(x)|$$

HERA, Tevatron, LHC:
universality of quarkonium production models

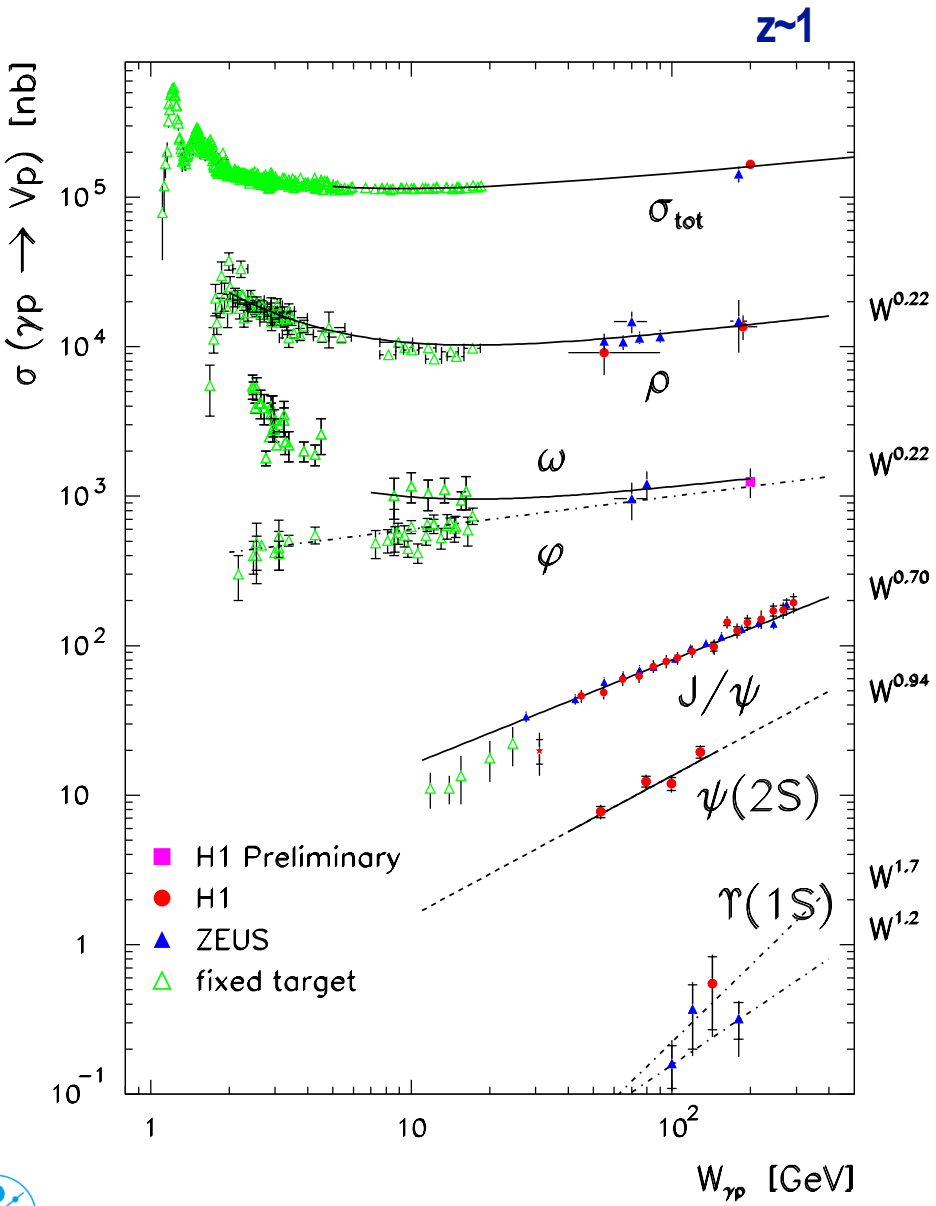
$$\Psi(\gamma \to c\bar{c}) \otimes \sigma^2_{dipole} \otimes \Phi(J/\psi)$$

$$\sigma \propto |xg(x)|^2$$

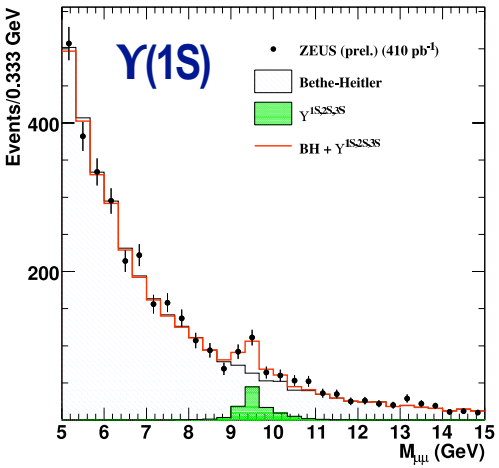
sensitivity to square of gluon

Measure partonic structure of diffraction

Elastic Quarkonium Production

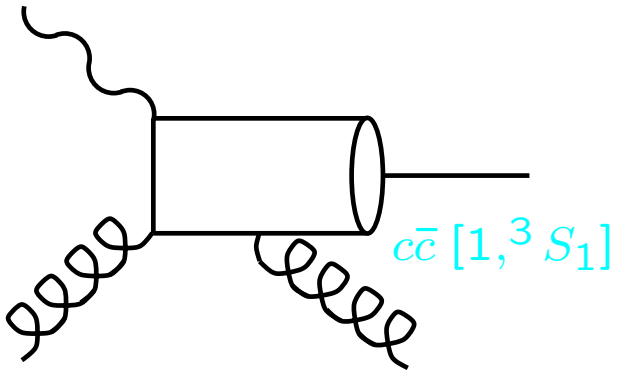


- Elastic VM production has been measured for ρ^0, ω, ϕ, J/ψ, ψ(2S) and Υ(1S)
- Controled variation of up to 4 different scales (m_{VM}, Q^2, W_{gp} and t) in the same experiment:
  - unique multi-scale problem
  - study interplay between soft and hard QCD
- Test of QCD concepts, e.g. Generalized Parton Distributions, BFKL,



Inelastic Heavy Quarkonium Production

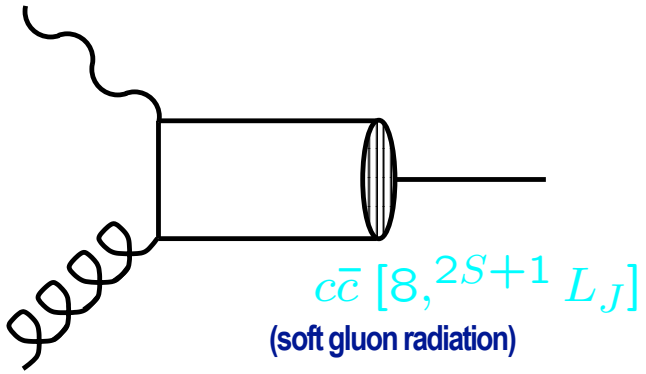
- **Colour Singlet Model**



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

LO: Berger et al, Baier et al, 1981
NLO: Kraemer et al, 1995

- **Colour Octet Contributions**



NRQCD-factorization:

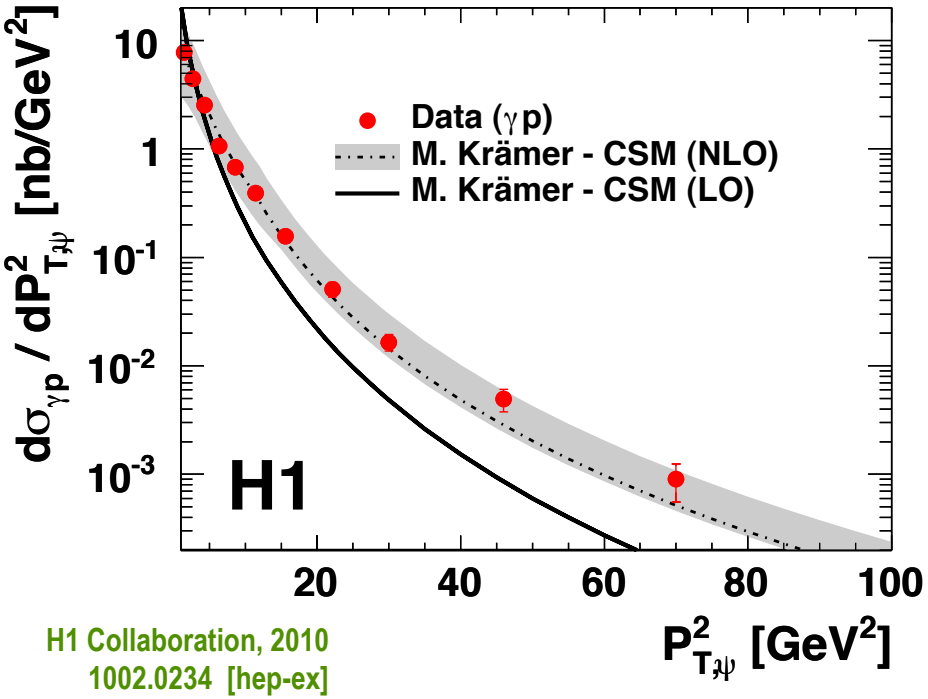
$$\sigma_{J/\psi X} = \sum \hat{\sigma}(p\bar{p} \to c\bar{c}[n]X) \times \mathrm{LDME}[n]$$

Bodwin, Braaten, Lepage 1995

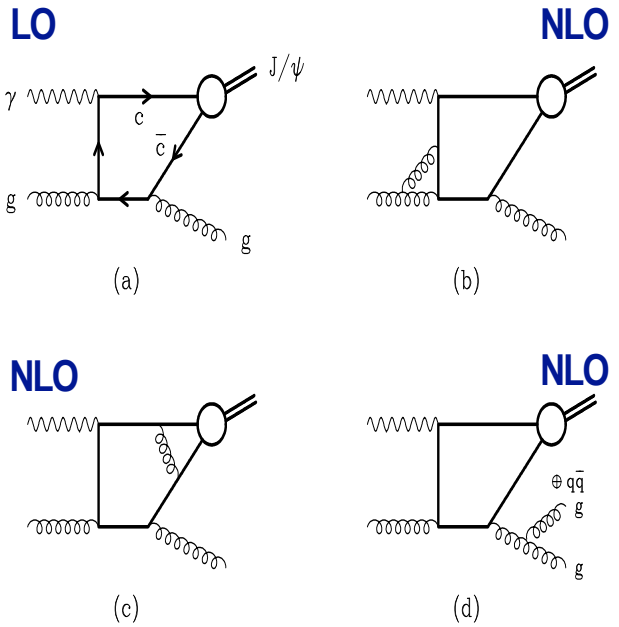
LDME determined from Tevatron data
(NLO not yet available for $p\bar{p}$ or pp)

J/ψ Production at HERA

Kraemer et al, 1995



H1 Collaboration, 2010
1002.0234 [hep-ex]

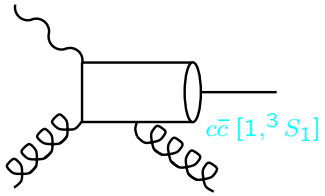


CSM: NLO available for γp already since 1995

good description of HERA data

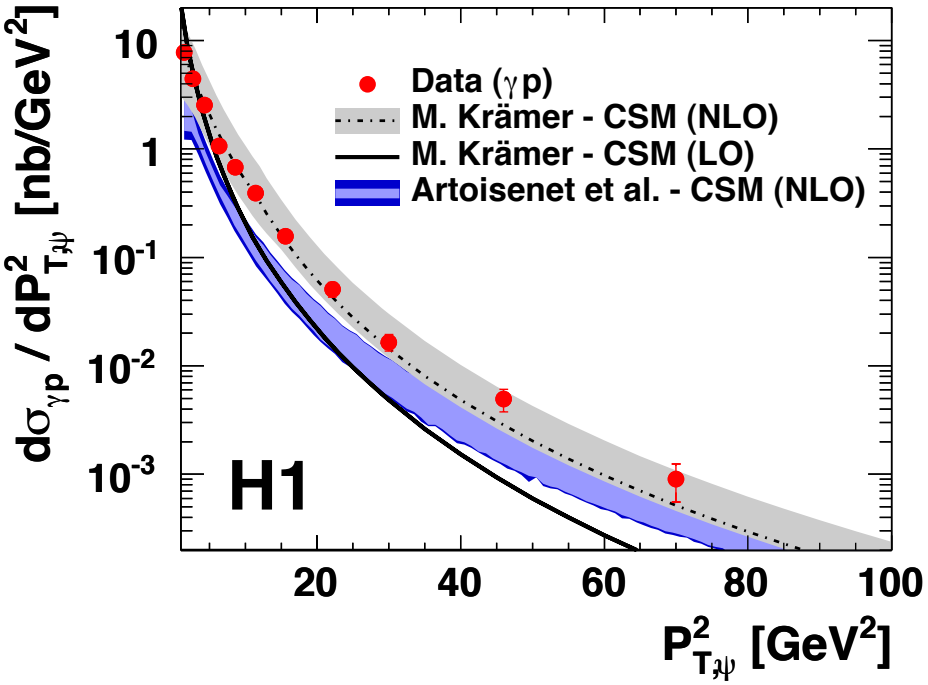
However, NLO corrections are very large - with large scale uncertainties → need for NNLO

J/ψ Production at HERA



Kraemer et al, 1995

Artoisenet, Maltoni et al, 2009



- Kraemer et al
  - $m_c = 1.3$ GeV
  - MRST
  - $\mu_r = \mu_f = \dfrac{\sqrt{m_c^2 + p_t^2}}{2}$
- Artoisenet et al
  - $m_c = 1.5$ GeV
  - CTEQ6M
  - $\mu_r = \mu_f = 4m_c$

CSM (NLO): re-calculated recently

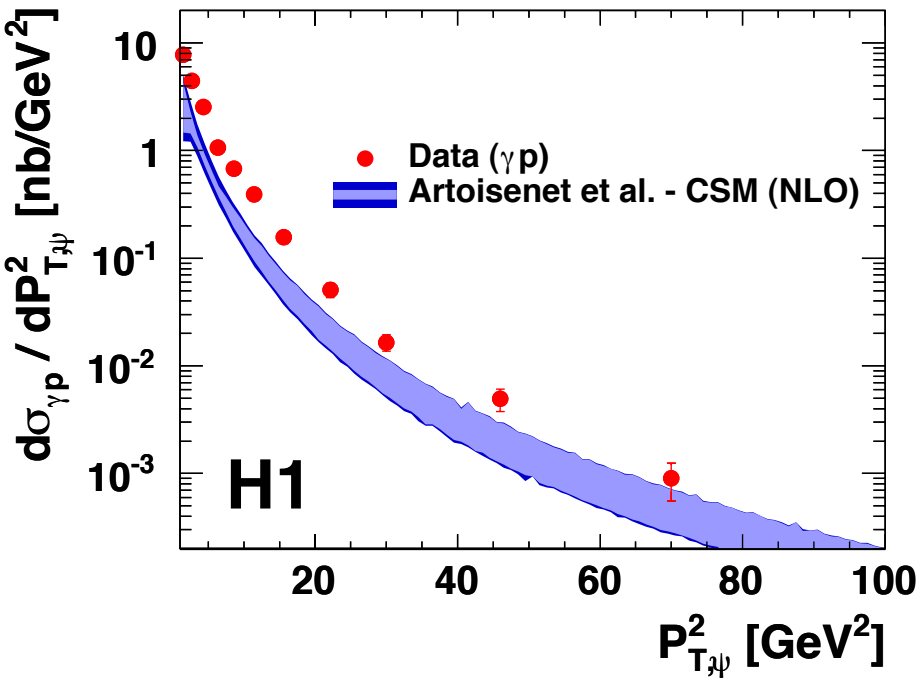
New calculation factor ~2-3 lower than previous results - due to use of different scales

No discrepancies between calculations / choice of scales is "matter of taste" (!?)

J/ψ Production at HERA and Tevatron

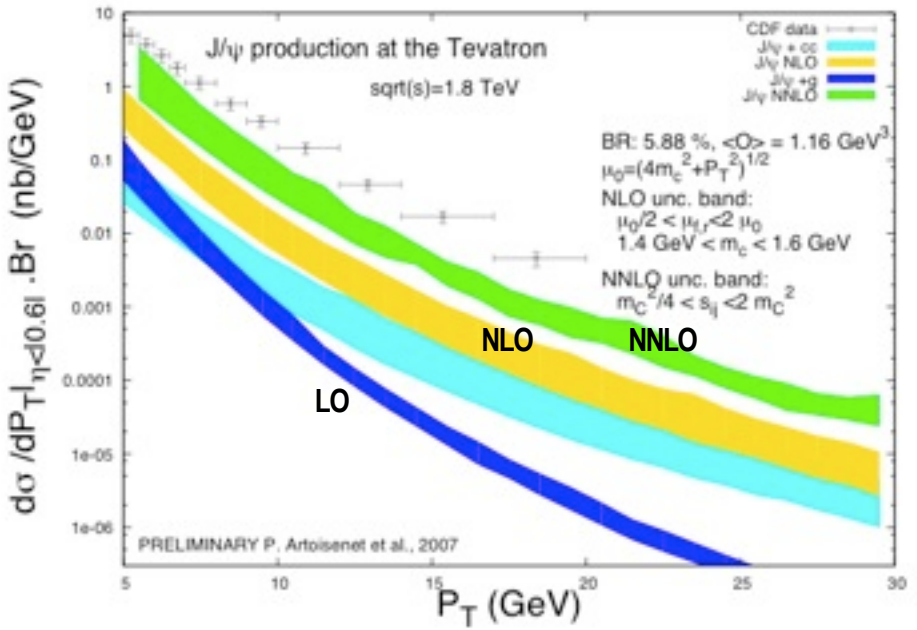
HERA

Artoisenet, Maltoni et al, 2009



Tevatron

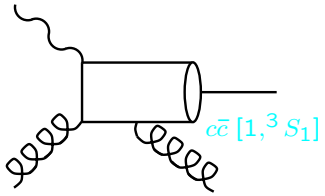
Artoisenet, Maltoni et al, 2007

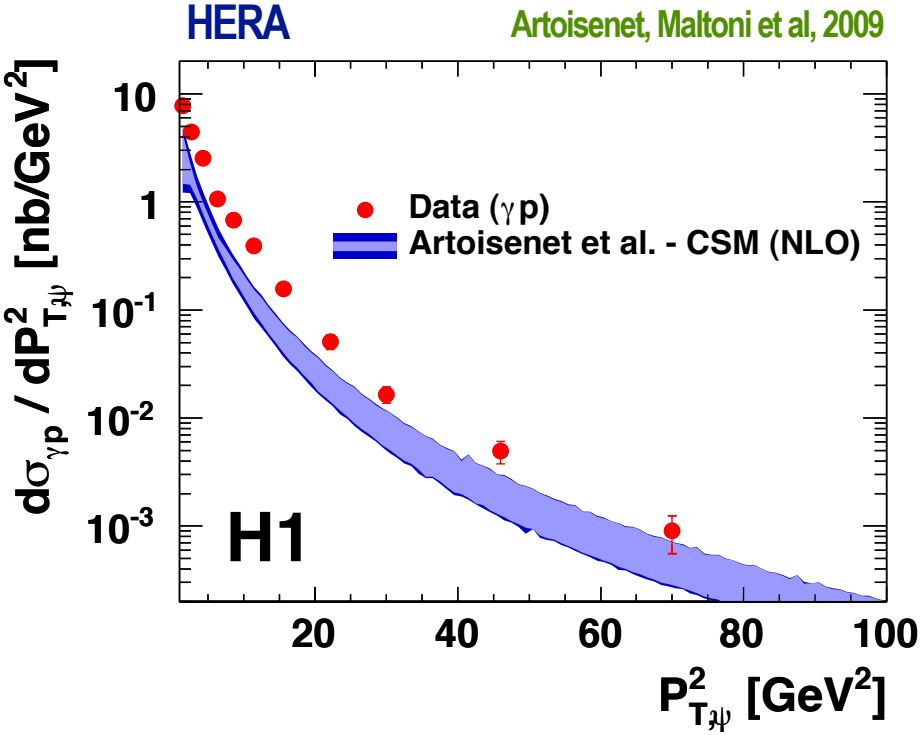


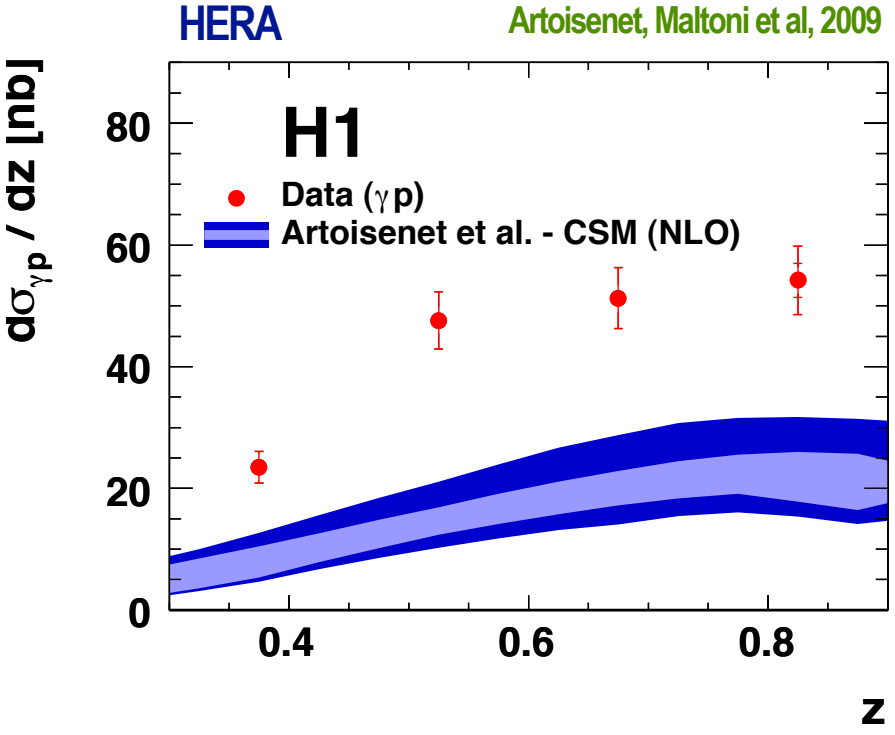
CSM (NLO) calculations for HERA and Tevatron by same authors

looking consistent, i.e. shape ok, normalization off

J/ψ Production at HERA







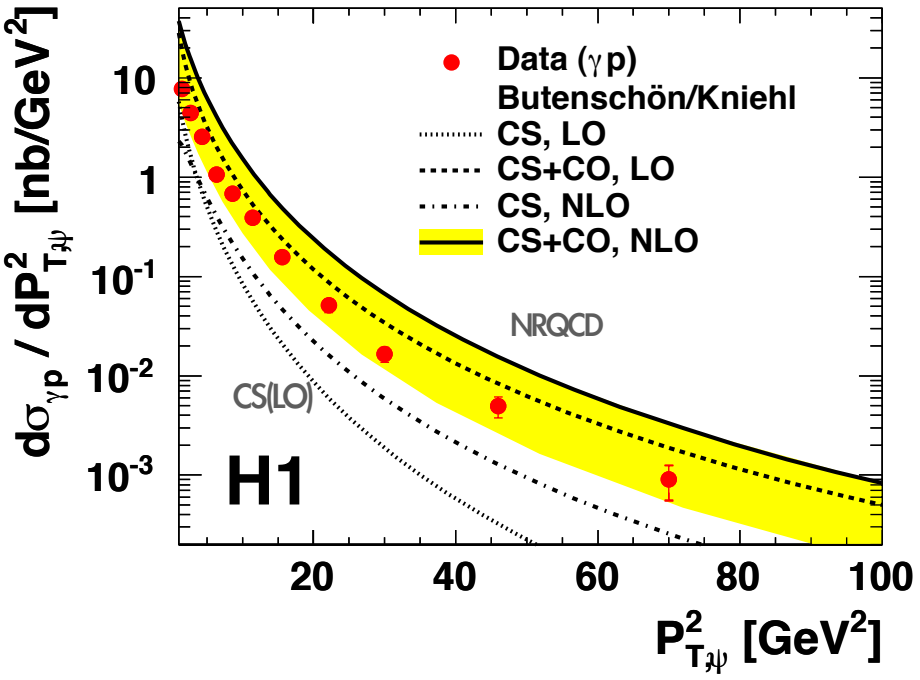
Test against elasticity distribution z:

Shape well described

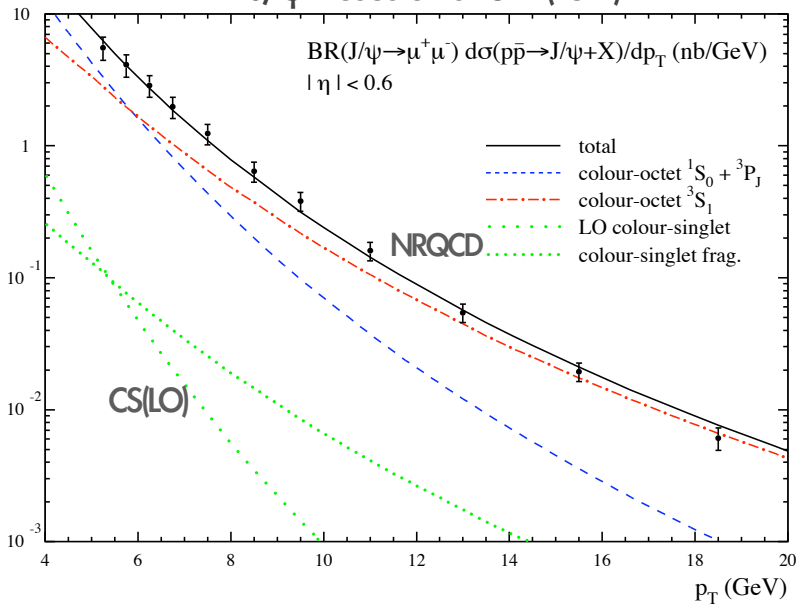
Color Octet Contributions

HERA

Kniehl, Butenschoen, 2009



Tevatron



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

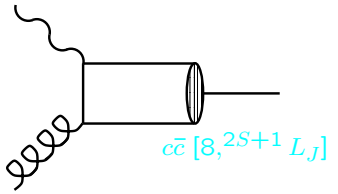
HERA photoproduction CO perturbative matrix elements now calculated to NLO

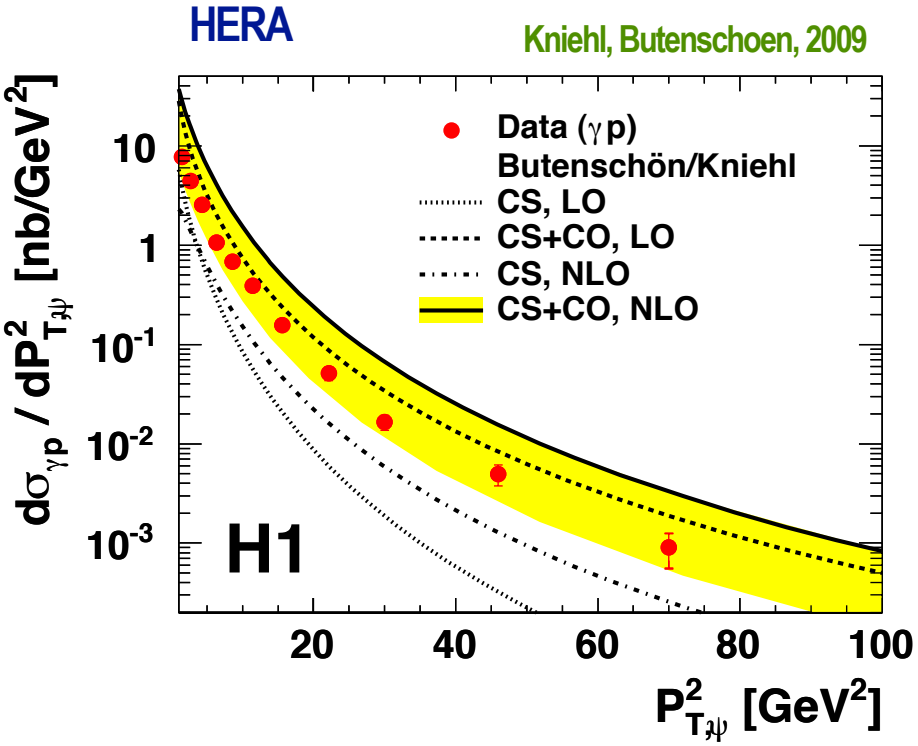
LDME (not yet at NLO) determined from Tevatron data

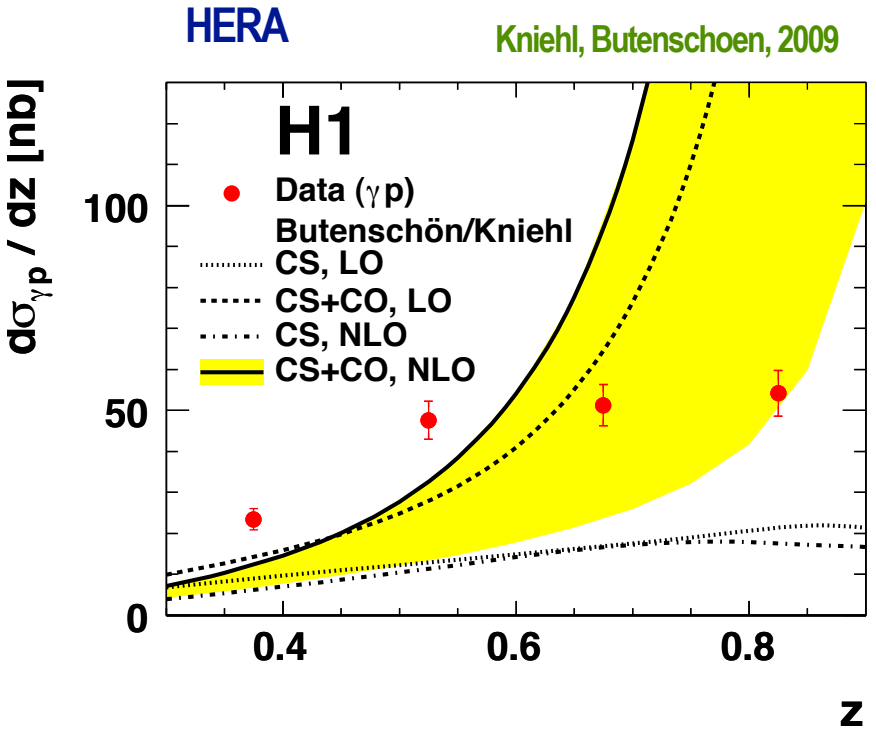
Kniehl, Kramer, 1998

Error band: difference between LDME (LO) and LDME (LO higher order improved)

Color Octet Contributions





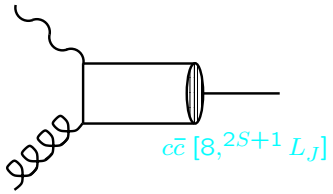


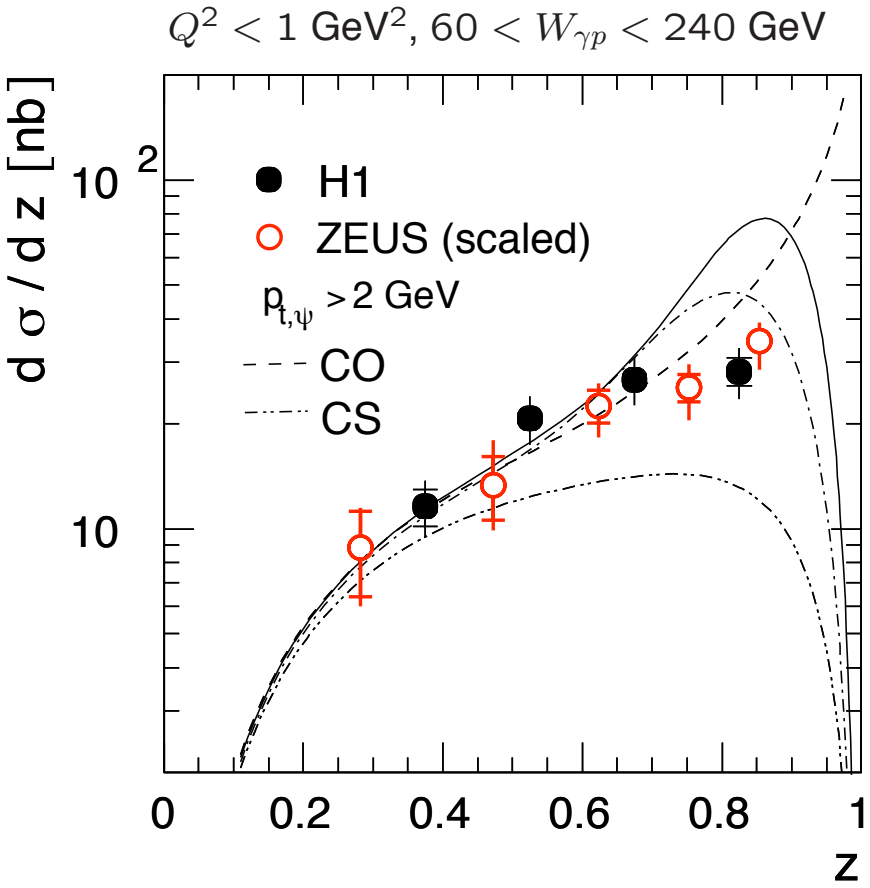
Test against elasticity distribution z:

Shape wrong

Possibly due to LO - LDME (NLO) requires full NLO calculation of all NRQCD components to hadroproduction

Color Octet Contributions





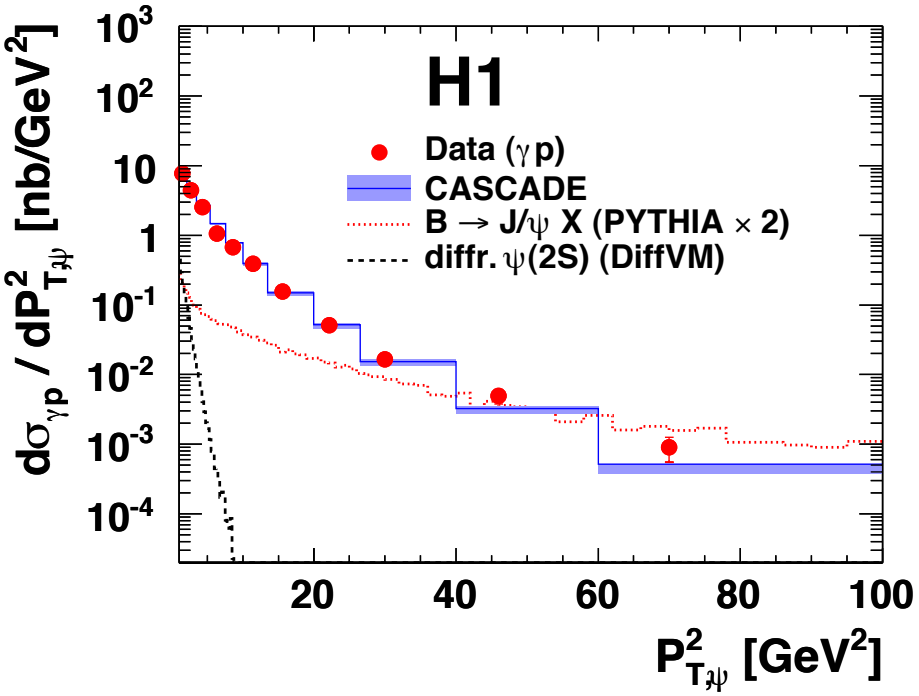
Color-Octet Contribution
→no hard gluon
→rises to large z

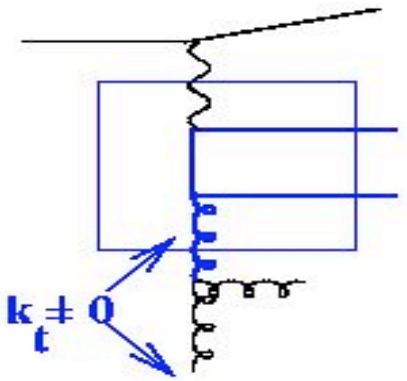
Color Singlet contribution:
→hard gluon
→falling off at large z

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

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

J/ψ Production in k_T-Factorization





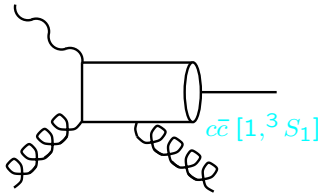
- CCFM evolution equation M.Ciafaloni et al, 1988
  - k_t - unintegrated gluon density
  - contains NLO components

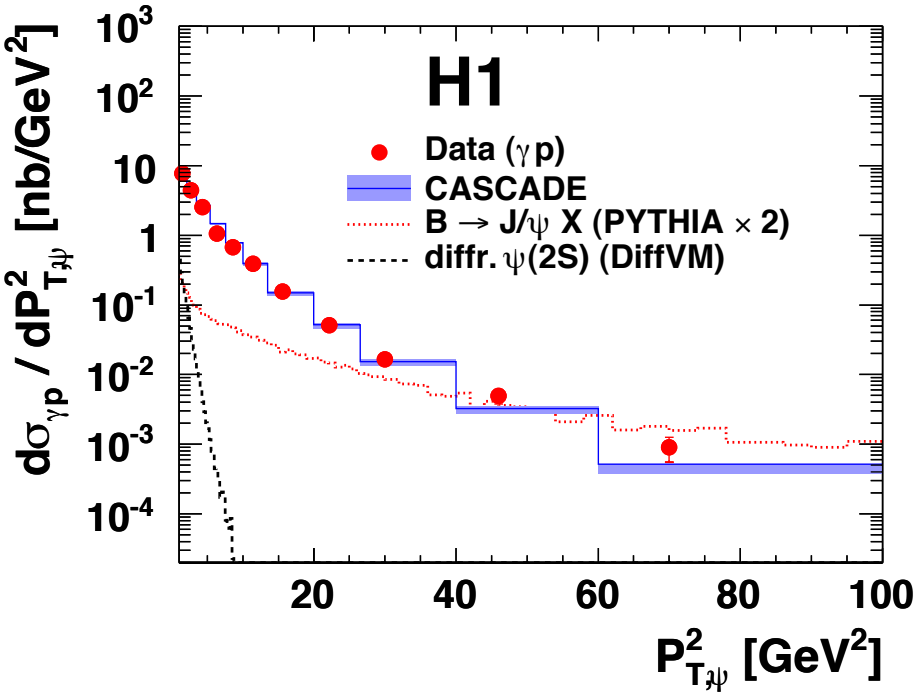
CCFM implemented in Monte Carlo event generator CASCADE H.Jung, 2001

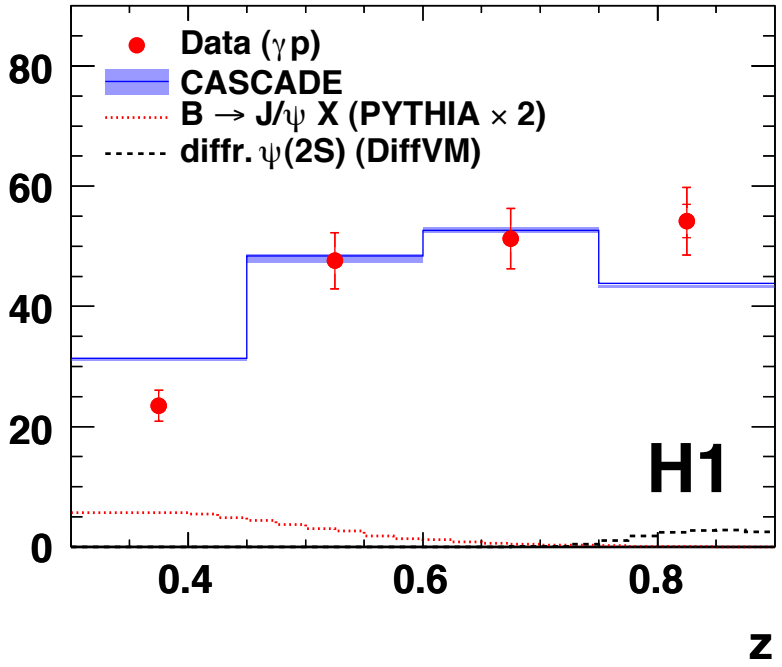
K_t-factorization (CSM) as implemented in CASCADE describes HERA data very well

out of the box match with data / no need for CO and/or complex reweighting etc.

J/ψ Production in k_T-Factorization







Test against elasticity distribution z:

Shape well described, normalization also ok

out of the box match with data / no need for CO, reweighting etc.

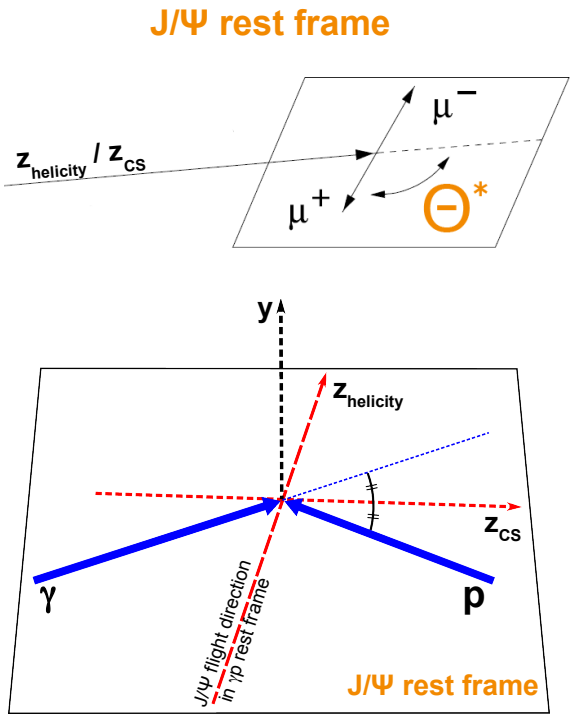
J/ψ Helicity Distributions

- α and ν from angular distributions

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

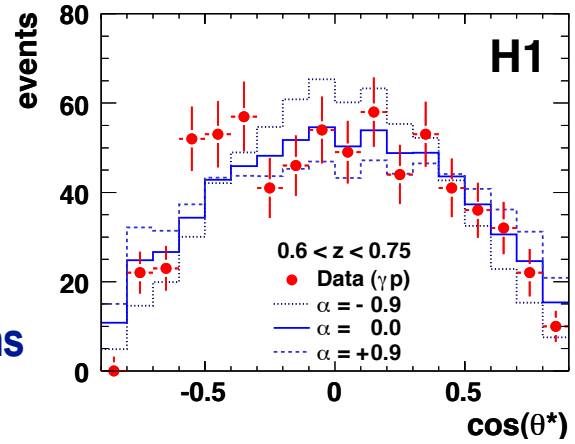
$$\frac{1}{\sigma}\frac{d\sigma}{d\phi^*} \propto 1+\frac{\alpha}{3}+\frac{\nu}{3}\cos^2 2\phi^*$$

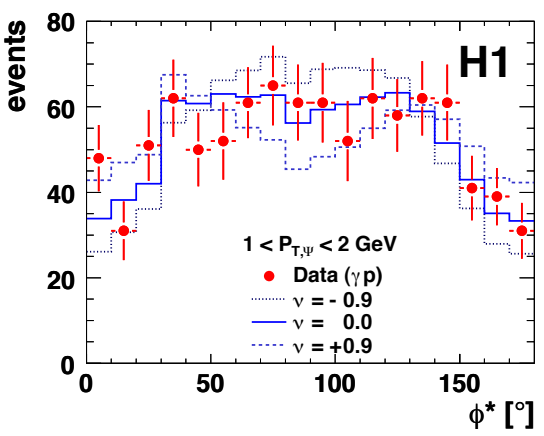
- Two complementary frames:
  - Helicity: z defined by J/ψ direction in γp rest frame
  - Collins Soper: z defined by bisector of γ and p in J/ψ rest frame



- Projections onto x,y,z give:
  - z $\propto \cos\theta^*$
  - y $\propto \sin\theta^*\sin\phi^*$
  - x $\propto \sin\theta^*\cos\phi^*$

- Measurement: minimize X^2 by variation of angular distributions at generator level

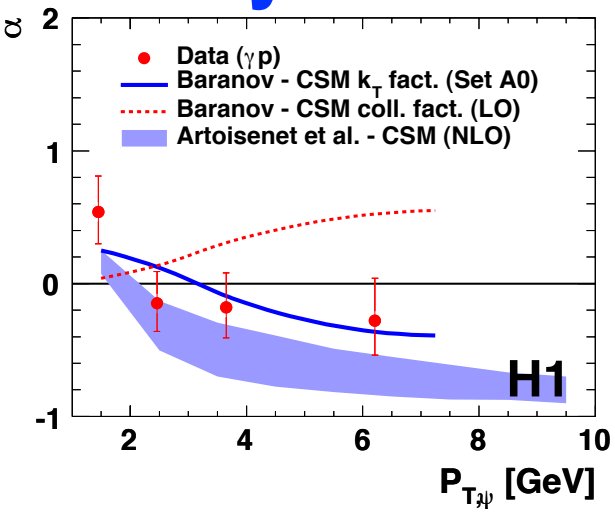


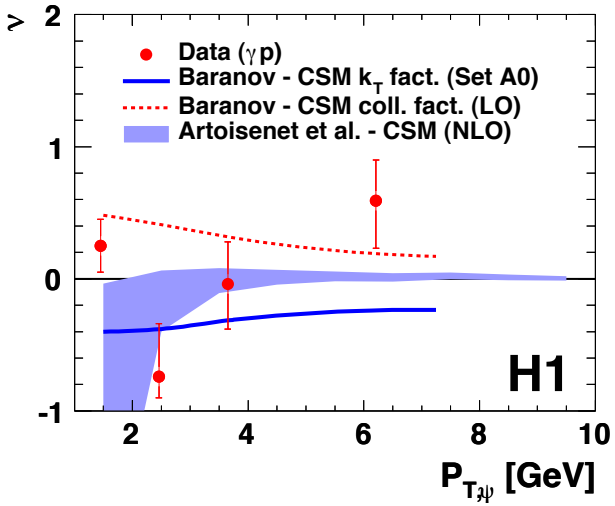


J/ψ Helicity Distributions

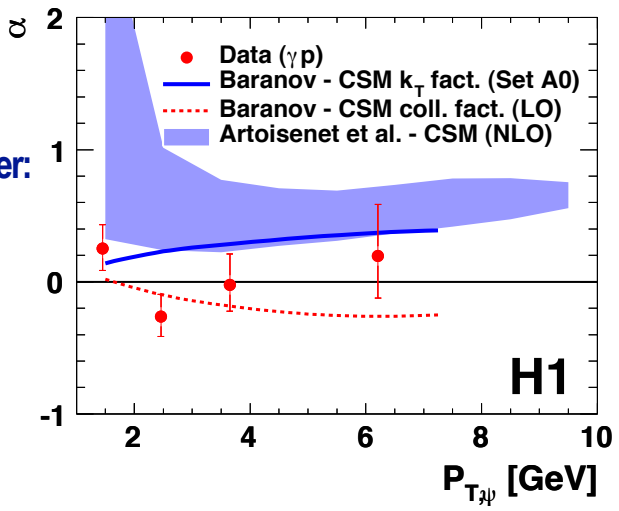
kinematic range 0.3 < z < 0.9

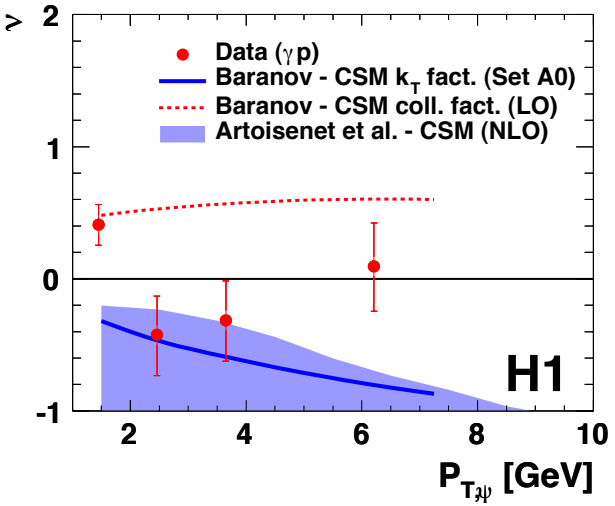
Helicity:





Collins Soper:





New calculations in NLO and k_t-factorization available

K_t-factorization and CSM (NLO) show correct trends - within large errors

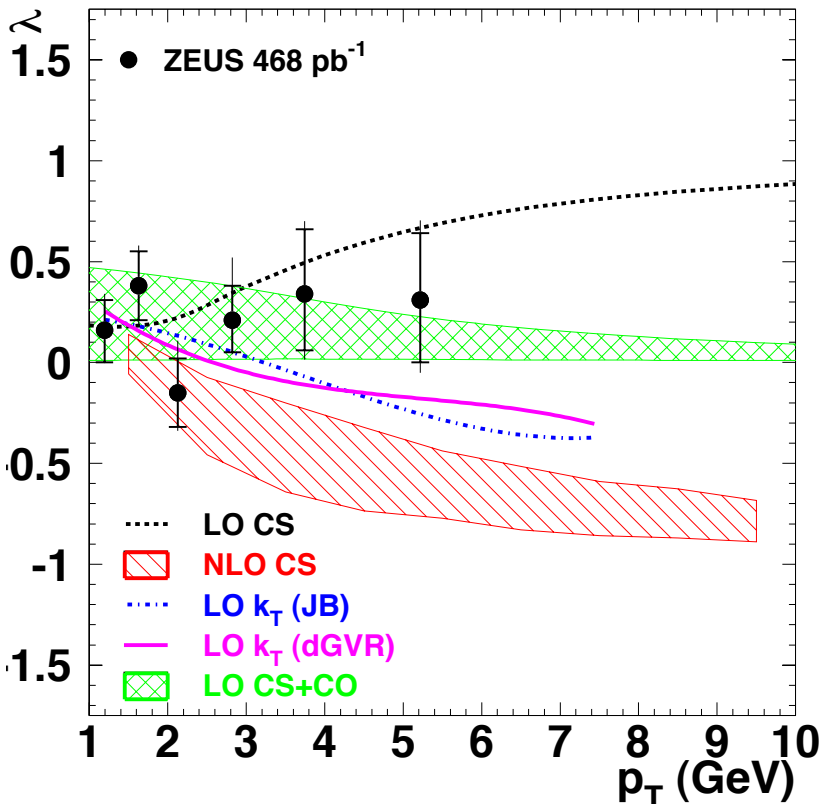
Note: α changing sign going from LO to NLO

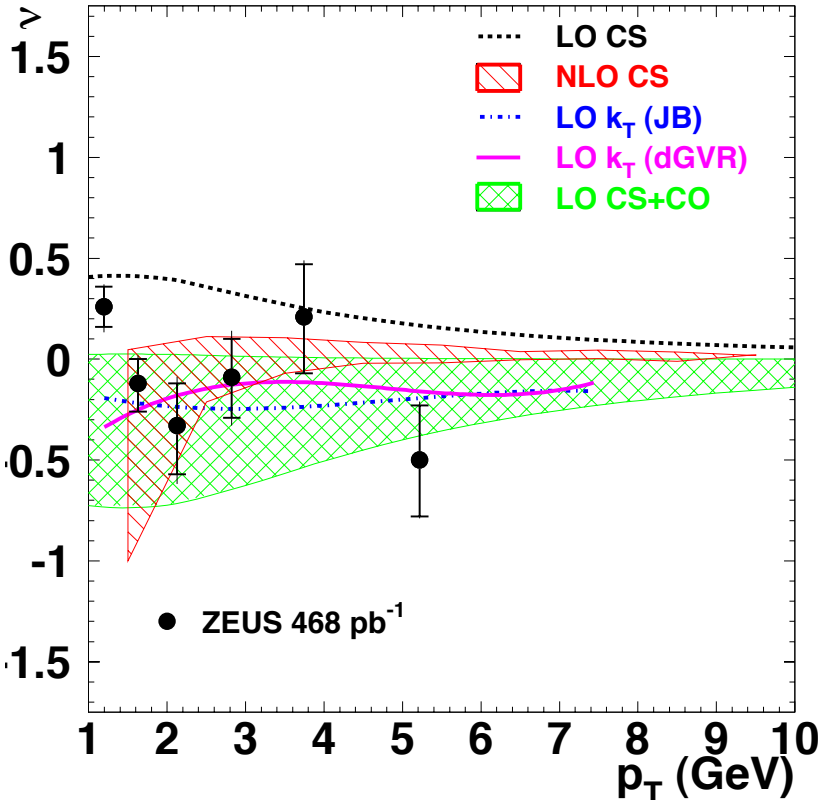
J/ψ Helicity Distributions

kinematic range 0.4 < z < 1.0

ZEUS

Helicity frame





Note: ZEUS and H1 measurements in somewhat different kinematic region
(ZEUS: diffractive contribution suppressed requiring extra energy deposit in central calorimeter)

Summary

- **Measurements of Inelastic Charmonium Production:**
  - H1: cross sections and polarization (ep and γp) final publication just out / reported here
  - ZEUS: polarization (γp) published - final cross section measurements to come

- **Reconstruction of final state kinematics: elasticity z (fractional photon energy carried by J/ψ in p rest frame): Sensitivity to final state QCD radiation, distinguish between different models and production regimes**

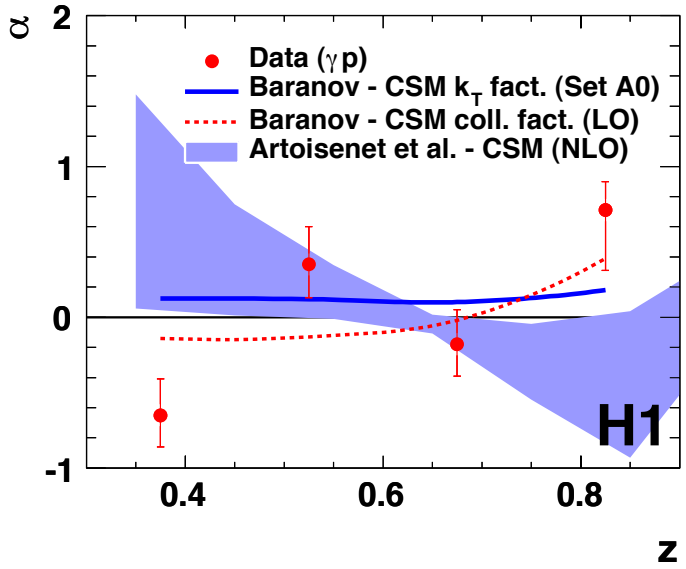
- **Detailed comparisons of H1 data with several recent calculations:**
  - CSM (NLO) describes shape of data rather well, polarization ok
  - Normalization too low - recent choice of scale - large normalization uncertainties
  - This picture is largely consistent between HERA and Tevatron

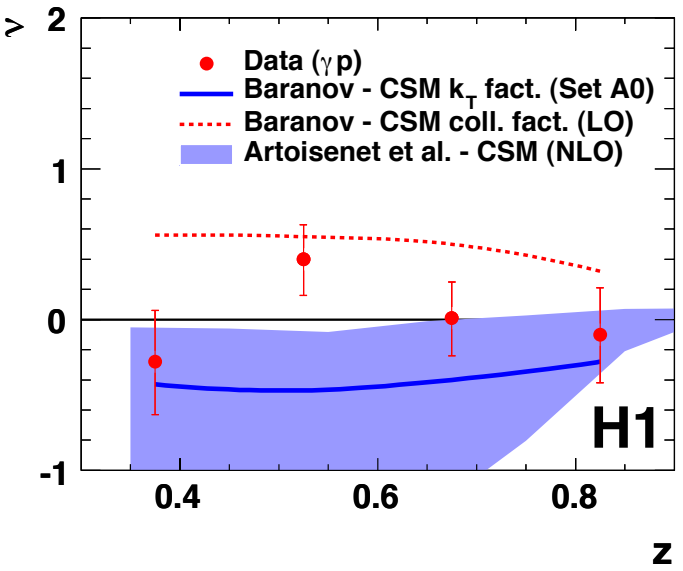
  - CS+CO (NLO): first x-sec. calculations of color octet contributions to next-to-leading order are available now for HERA.
  - Failure describing the elasticity distribution z
  - Full determination of LDME (NLO) requires full calc. of ME for Hadroproduction + fit of Tevatron data (underway)
  - Test of NRQCD factorization / universality of LDME still to be done

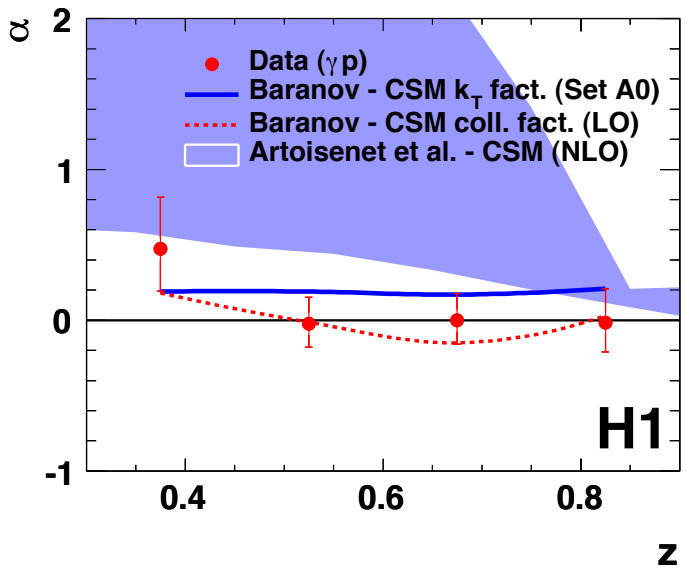
  - Kt-factorization (CSM) does a good job describing the HERA data out-of-the box
  - Similar in shape as CSM (NLO), normalization and polarization ok.
  - The multi-purpose MC generator CASCADE implements k_t-factorization (CCFM), available for ep, γp, pp

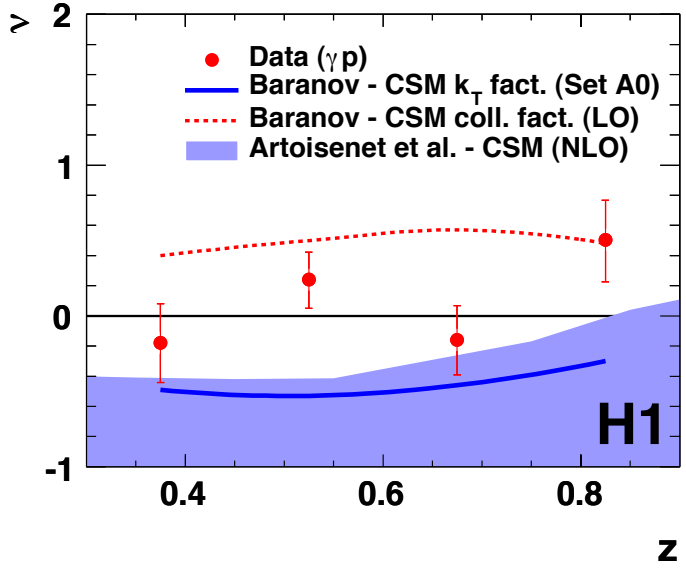
Backup

Polarization Measurements as fct of z

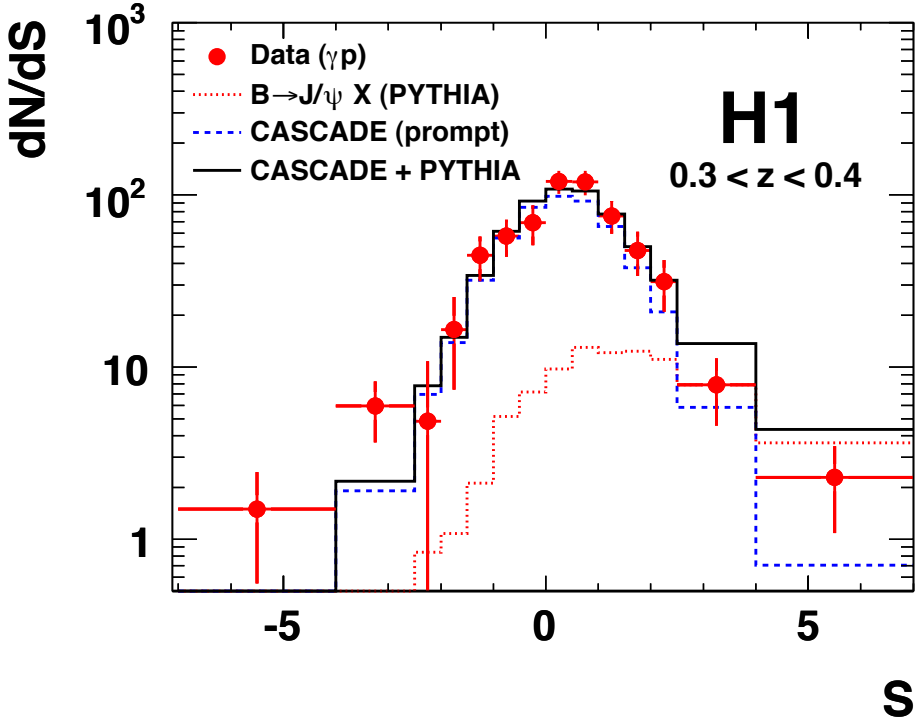


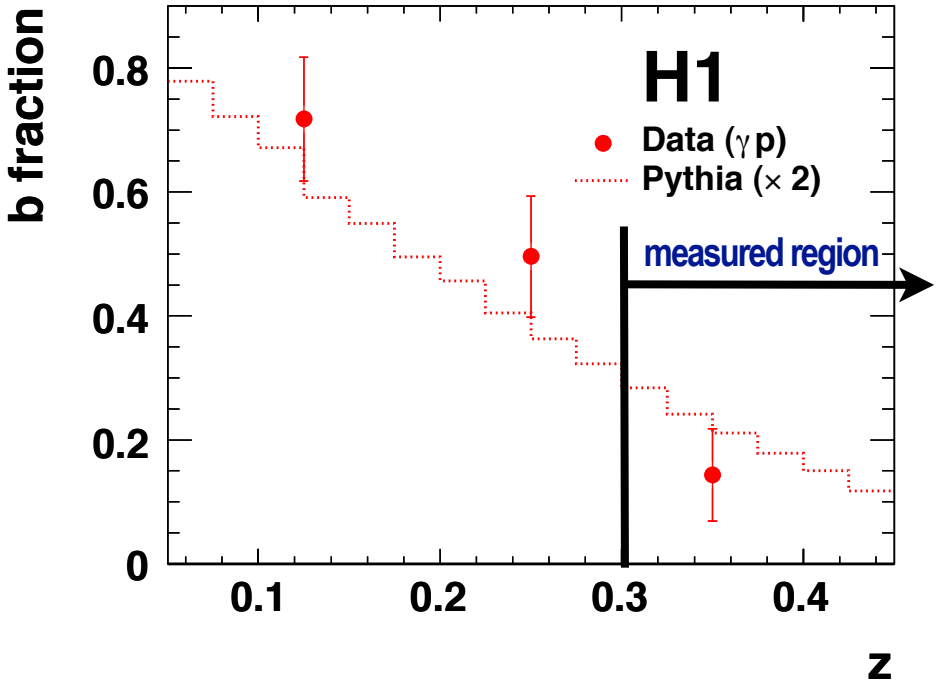






Lifetime Distribution / Feed Down from B decays





Fraction of J/ψ coming from B decays measured to be small
(~15 % in lowest bin of the prompt production measurement, z > 0.3)