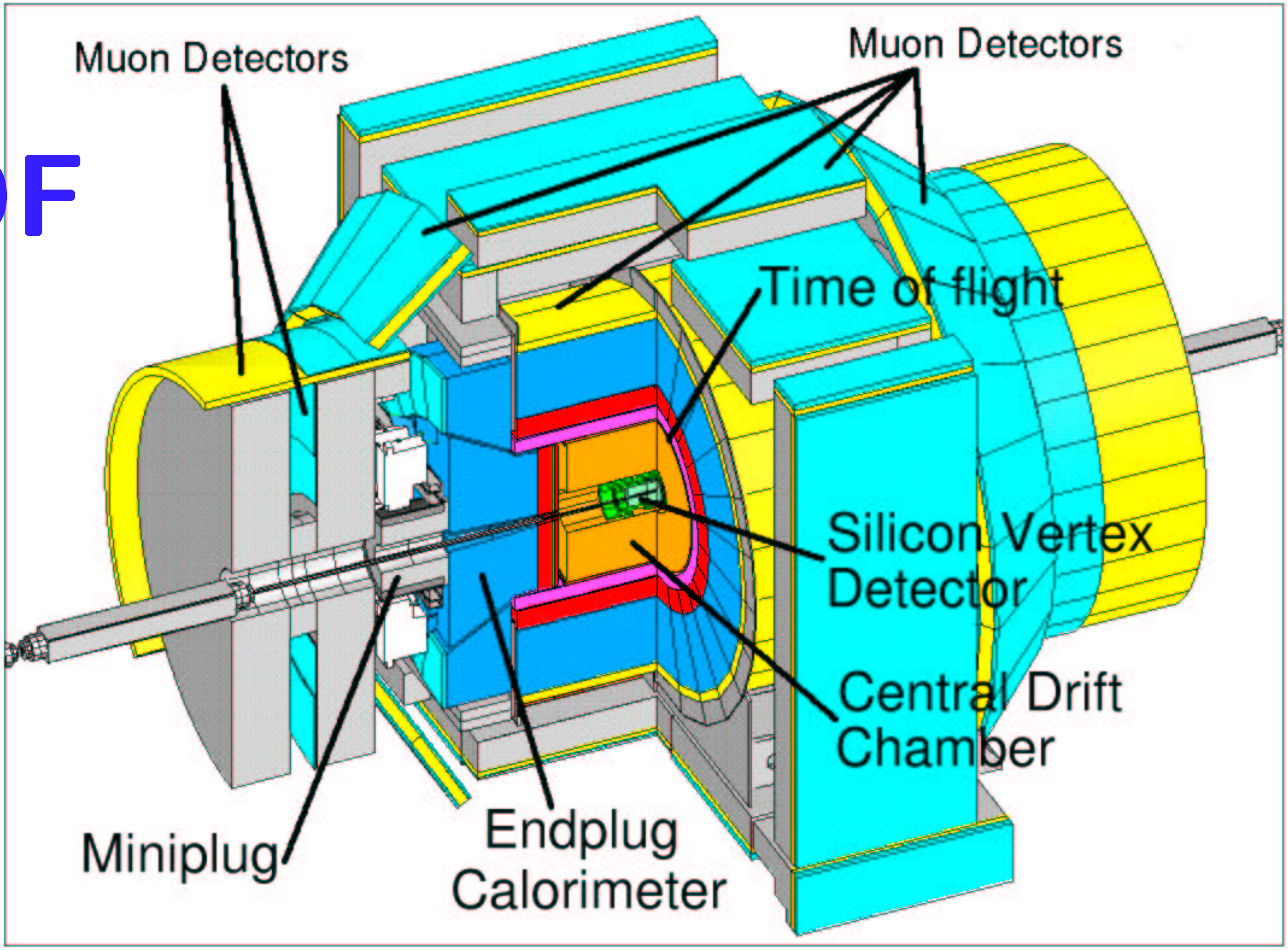
HEAVY FLAVOUR PHYSICS AT HADRON COLLIDERS

PETER J BUSSEY

- Detector upgrades
- Open Charm production
- $c\bar{c}$ production
- Beauty production
- Top production
- Conclusions

The collider detectors have important upgrades for new running

CDF



DETECTOR UPGRADES

Much improved triggers:

CDF

- Level 1 42-clock-cycle pipeline
- Level 2 20 μs decision time (300 Hz accept rate at present)
- Level 3 Full analysis
- L1 XFT (extremely fast tracker) $\rightarrow$ drift chamber tracks
- Powerful Si-based L2 triggers:

  Displaced Track + lepton $= 1\ \mu/e$ + 1 track ($d_0 > 120\mu$ m)

  2-Track Trigger = 2 tracks ($p_T > 2$ GeV, $d_0 > 120\mu$m)

D0

- New Solenoid.
- Silicon inner tracker
- Scintillating fibre tracker
- Forward mini-drift chambers
- Level 1 track trigger (fast using scint. fibres)
- L2 track trigger (track+lepton)
- L2 impact parameter trigger using Si

DETECTOR UPGRADES

H1

- Level 1 Track trigger
- Level 2 Mom. determination
- Level 3 Masses e.g. D^*
- Improved forward tracking (more layers)
- Forward/Backward Si Trackers
- New Central Silicon Tracker

ZEUS

- New Silicon Microvertex Det.
- Forward Straw Tube Tracker
- Global Tracking Trigger (integrates all tracking)
- Improved muon trigger

SCOPE OF TALK

HERA Results from the pre-shutdown data sample

Tevatron Run II now has much more Int. Lum. than Run I!

Here I survey mainly production of heavy flavour states

Compare with QCD-based models, NLO, NLL, etc

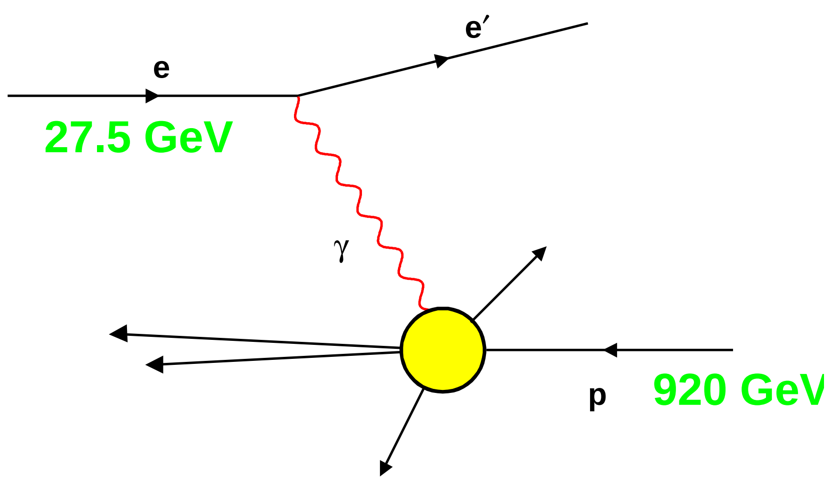
Unfortunately no time for:

- **diffractive physics**
- **decay channel studies**
- **lifetime studies, mass determinations**

Both colliders recently upgraded (and striving for high luminosities)

Tevatron: 1 TeV protons + 1 TeV antiprotons (approx)

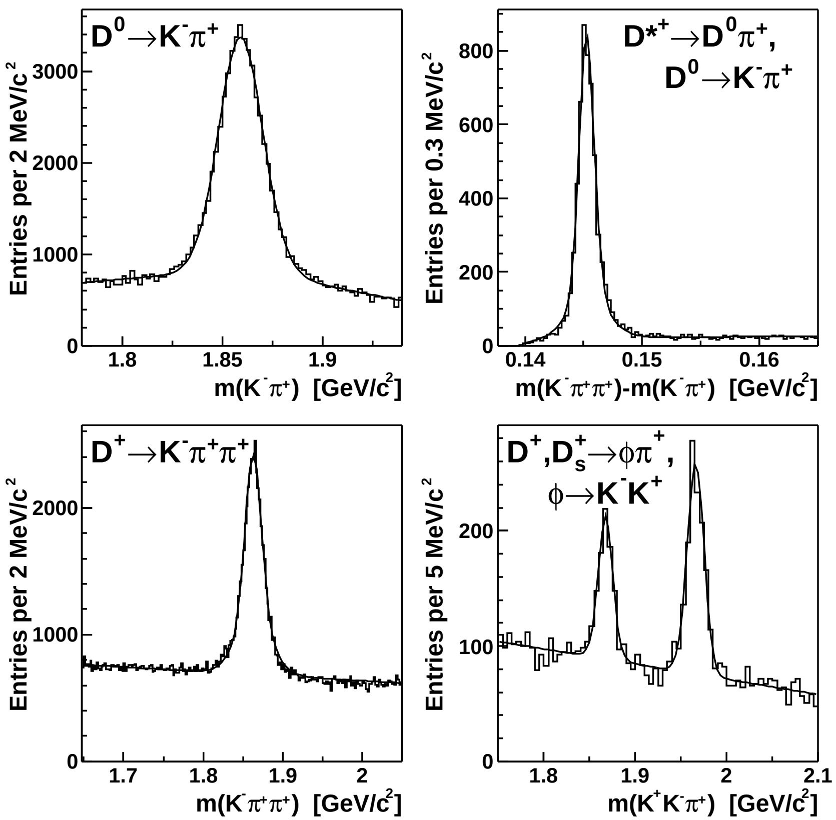
HERA: 27.5 GeV electrons/positrons on 920 GeV protons.

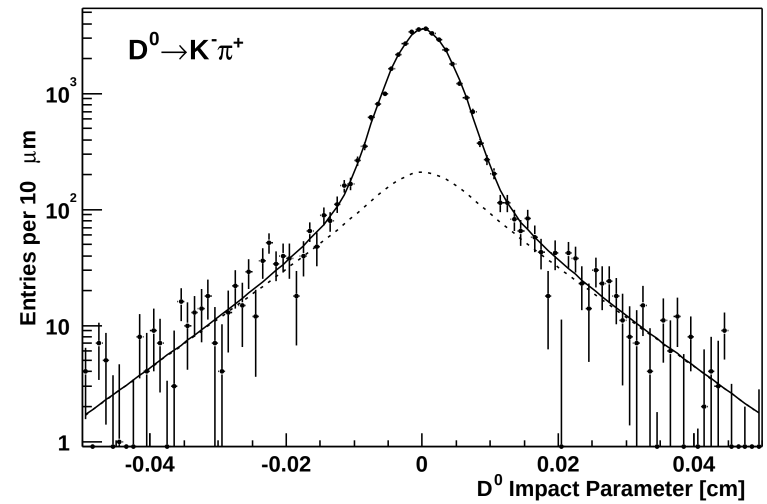


PHOTOPRODUCTION: virtuality Q^2 of exchanged photon ≈ 0
DIS: High Q^2 e.g. many GeV ^{2}

OPEN CHARM PRODUCTION AT TEVATRON

New charm data from CDF, Run II





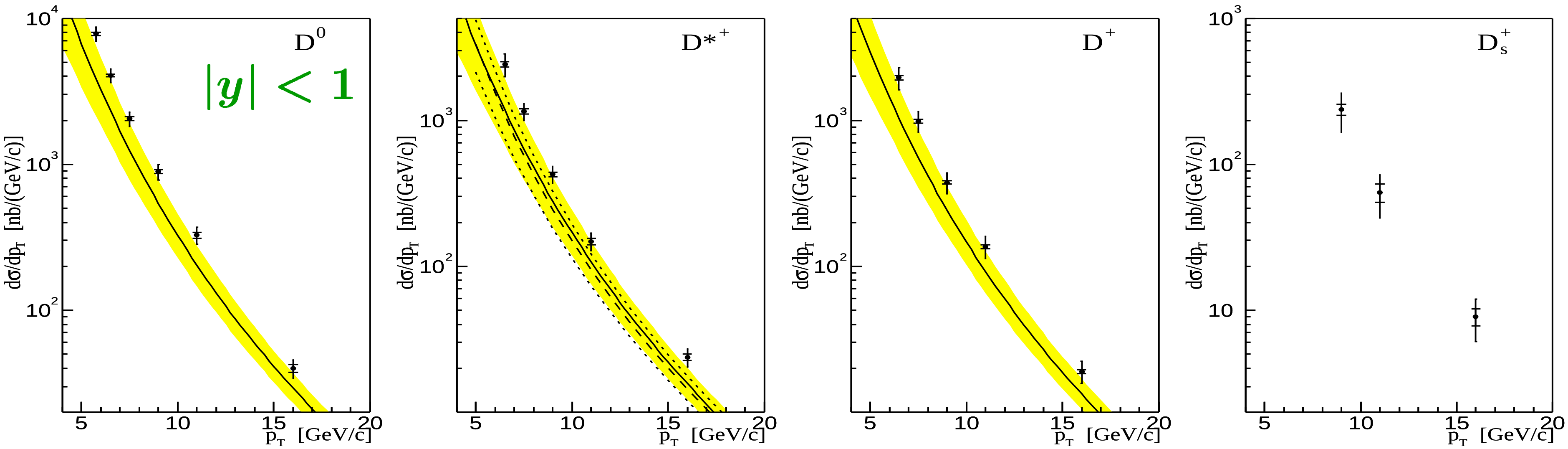
Impact parameter of reconstructed D^0 meson

Prompt D can be evaluated, subtracting contribution from B decay (broader d_0 distribution)

Good signals for D states using two-track trigger

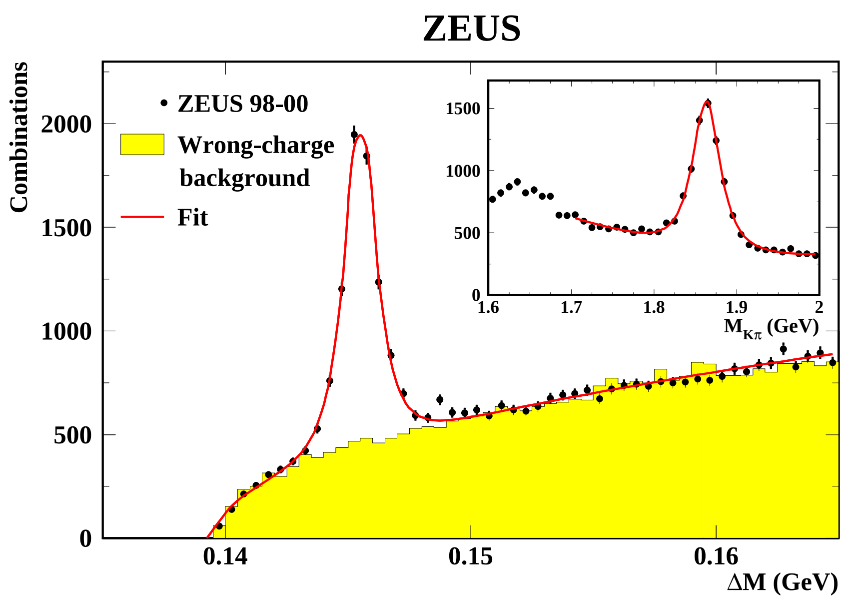
OPEN CHARM PRODUCTION AT TEVATRON

CDF inclusive cross sections for D^0 , D^{*+} , D^+ , D_s^+ vs. p_T

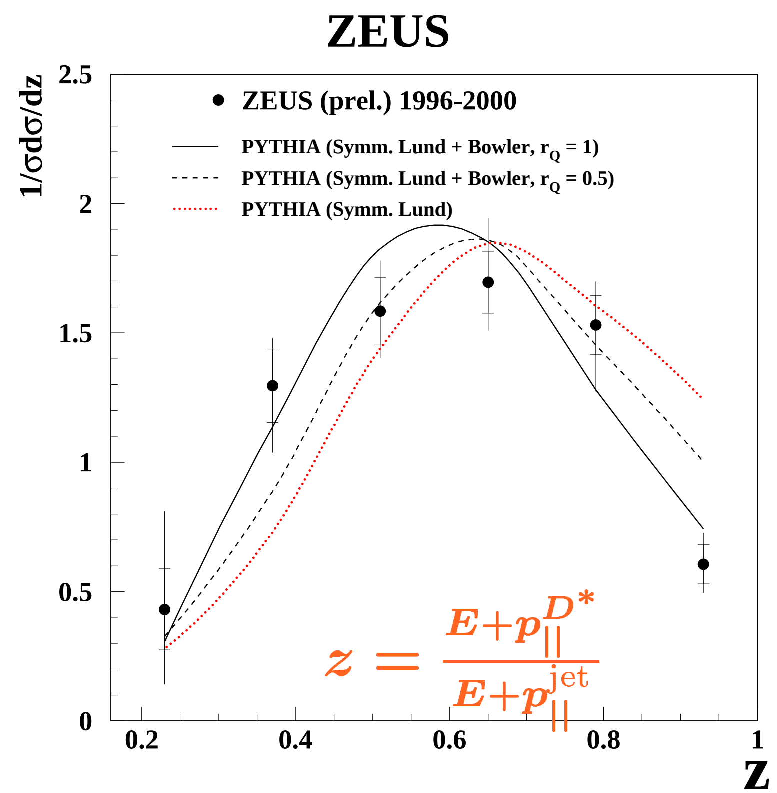


Band: **Cacciari and Nason,** **hep-ph/0306212.** **FONLL** **method**
Fixed Order (NLO) + next-to-leading logs
+ phenom. D fragmentation func. (ALEPH data)
Variable n_F . m_c effects are now included. $m_c = 1.5$ GeV
Error band from renorm/fact. scales. m_c effects "not larger"

Dashed: **Kniehl et al.** **calculation (priv. comm.) for D^{*+}**
Different fragmentation scheme and mass treatment.



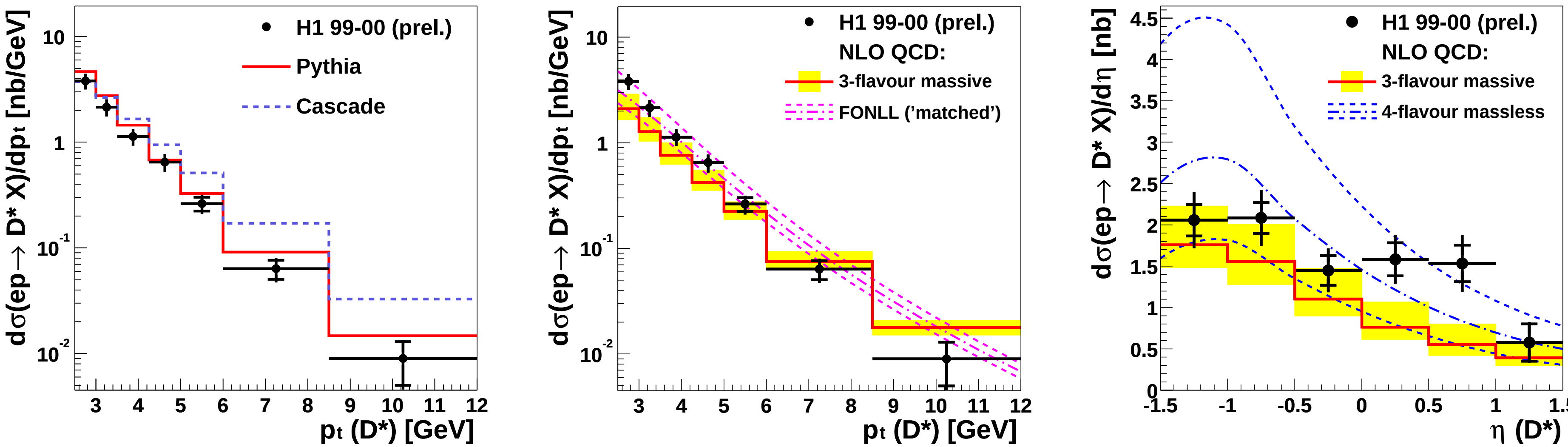
Lots of well-identified D^* mesons.



Charm fragmentation in jets ($E_T > 9$ GeV)

Compare with models.
PYTHIA favoured,
Peterson parameter $\epsilon = 0.064$

OPEN CHARM PHOTOPRODUCTION AT HERA



$p_T > 2.5$ GeV

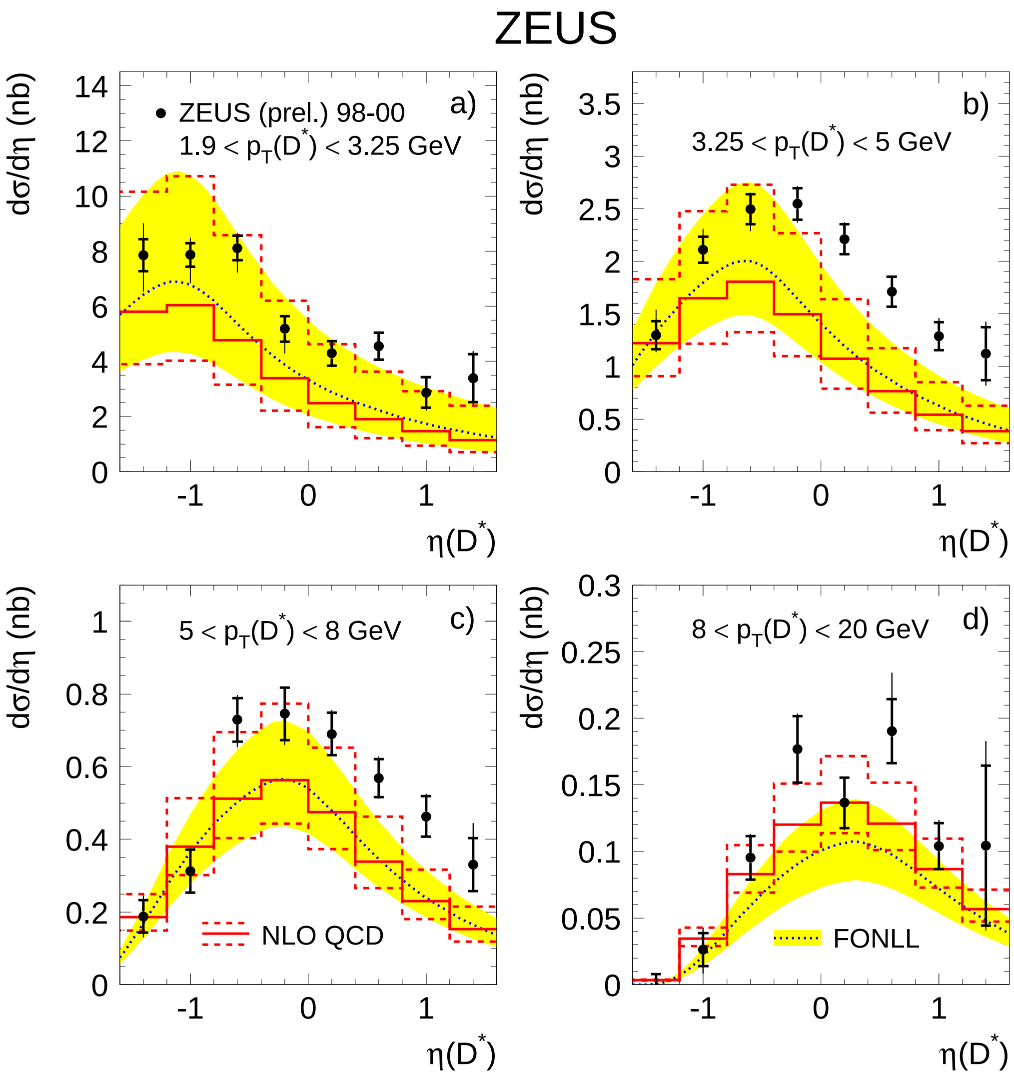
A variety of different models for inclusive D^*

PYTHIA not bad. CASCADE (CCFM scheme) too high

FONLL (Cacciari et al) OK for p_T

NLO (Frixione et al) can be made to work

("3-flavour massive" poor p_T dependence? "4-flavour massless" OK)



Pseudorapidity η in different p_T ranges

FONLL (Cacciari et al):

Fixed Order NLO, mass effects, leading log. resummation:

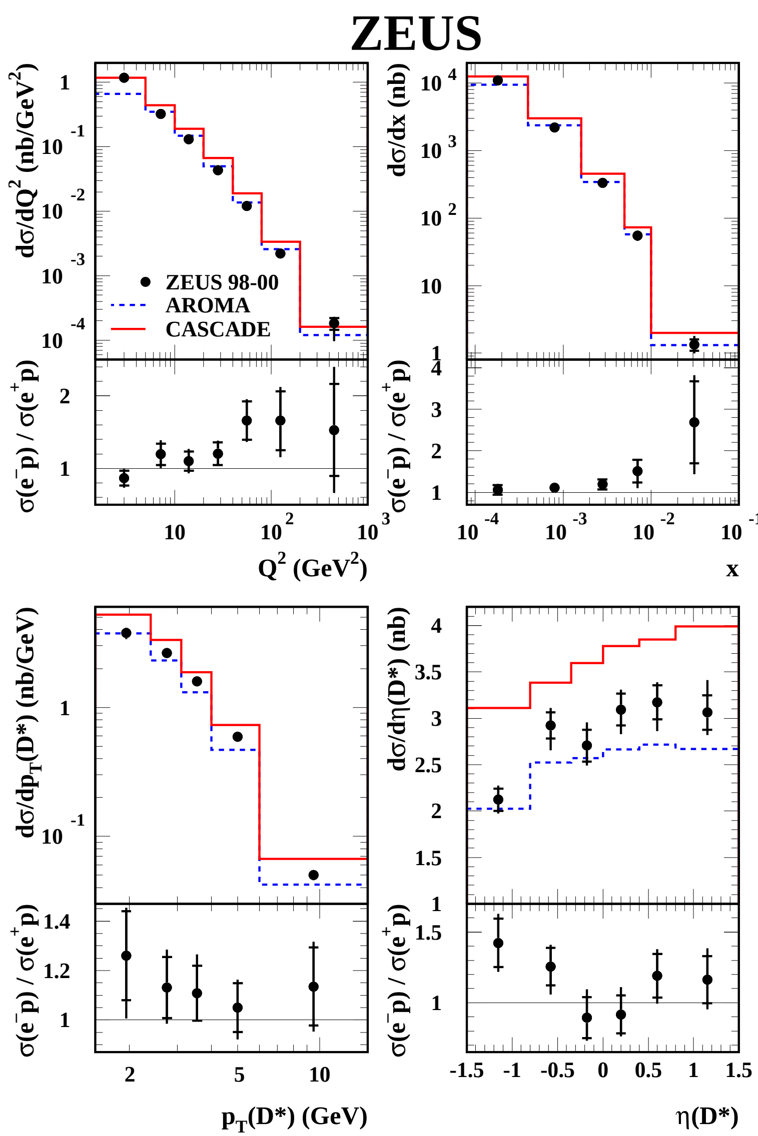
agreement mediocre

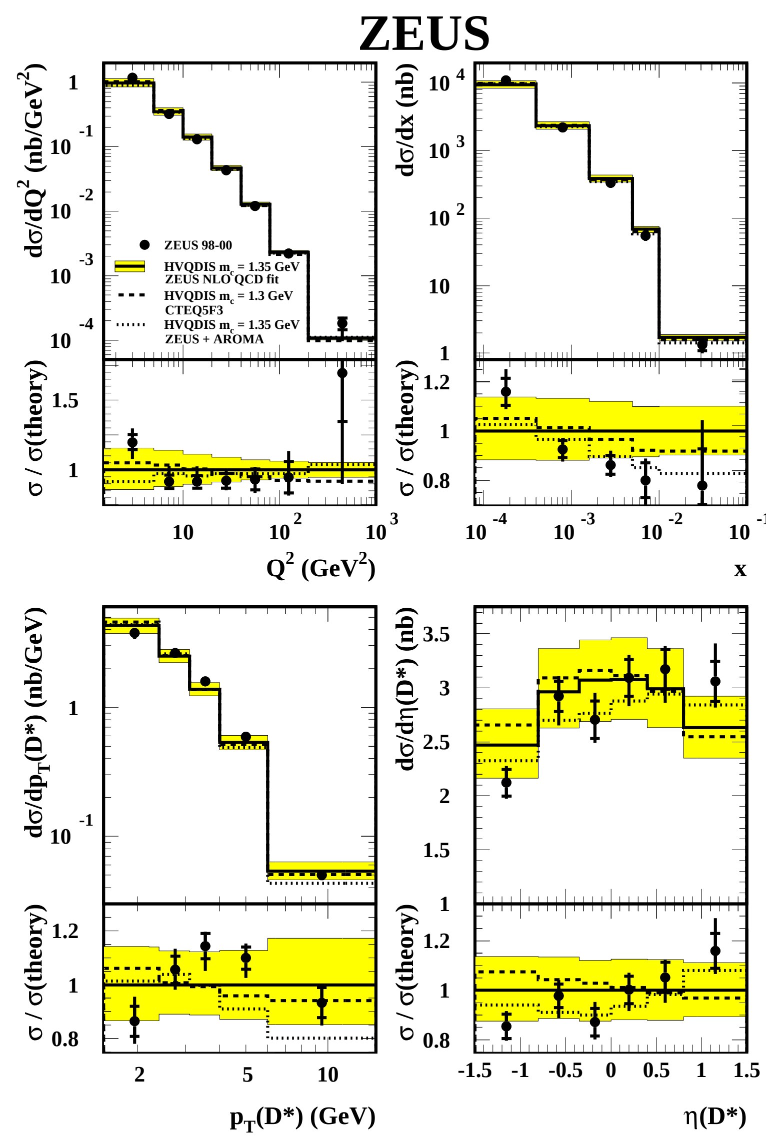
Frixione et al (FMNR)

(NLO 3 active flavours in p, γ)

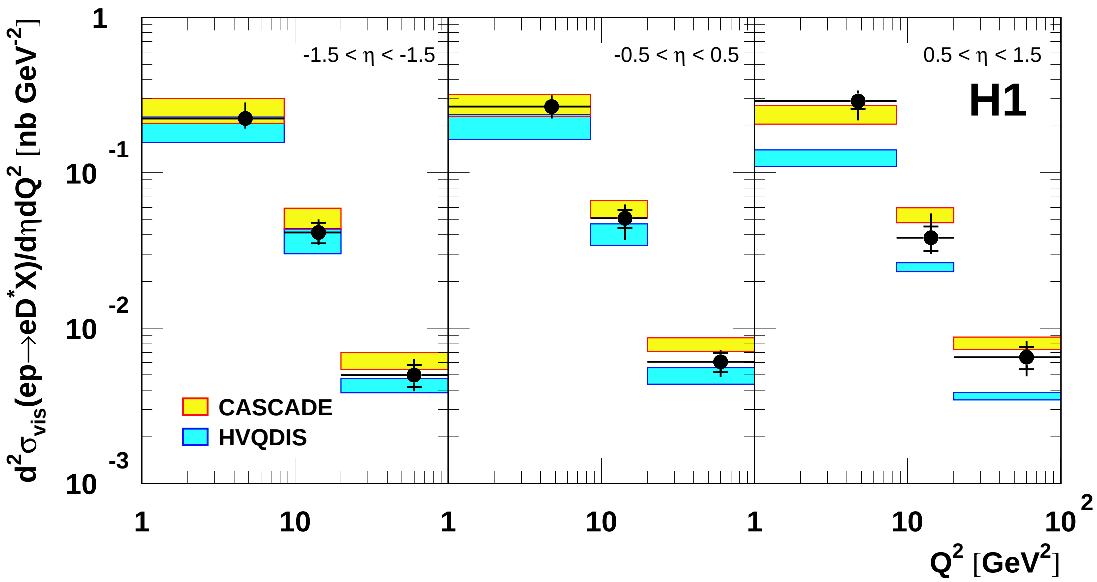
Slight improvement?

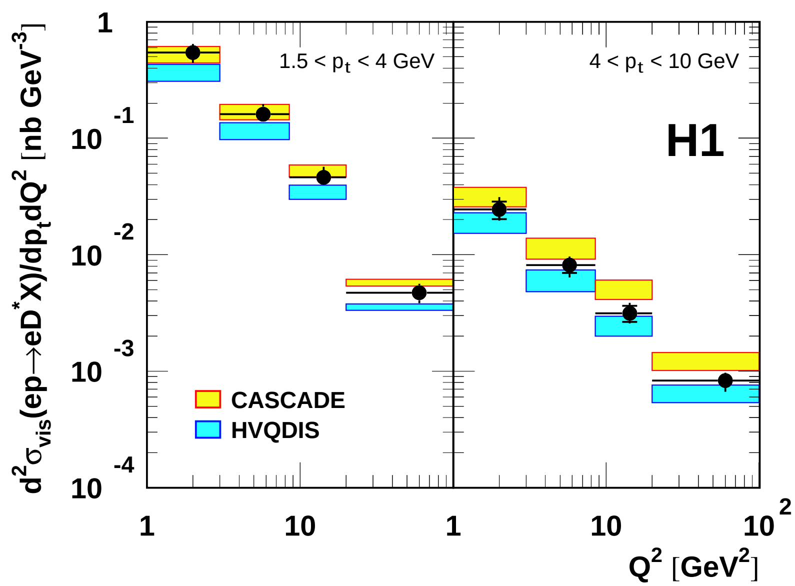
OPEN CHARM IN DIS AT HERA





AROMA seems better than CASCADE. HVQDIS based models best.

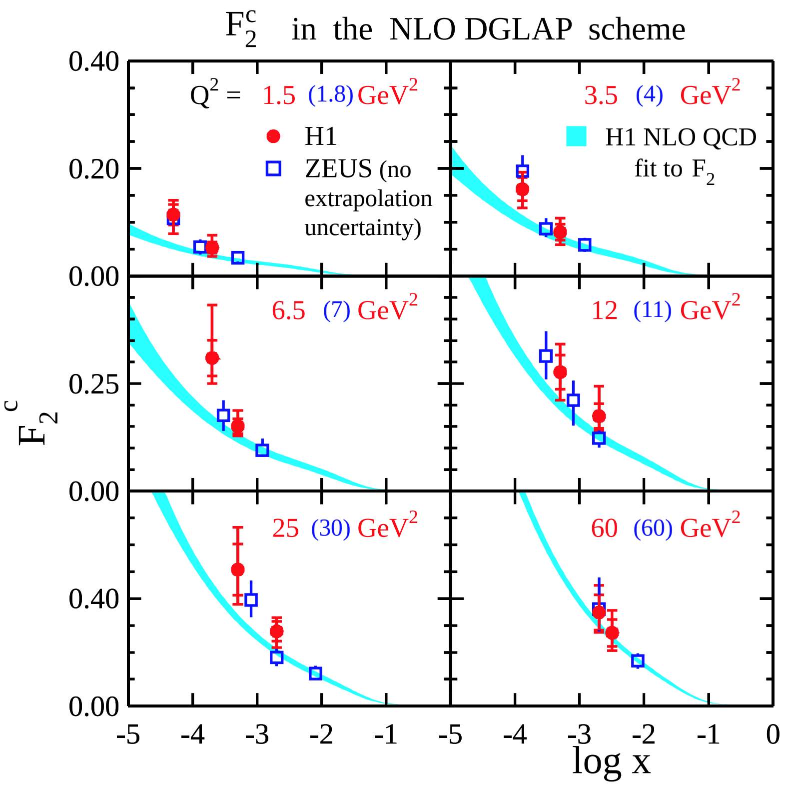


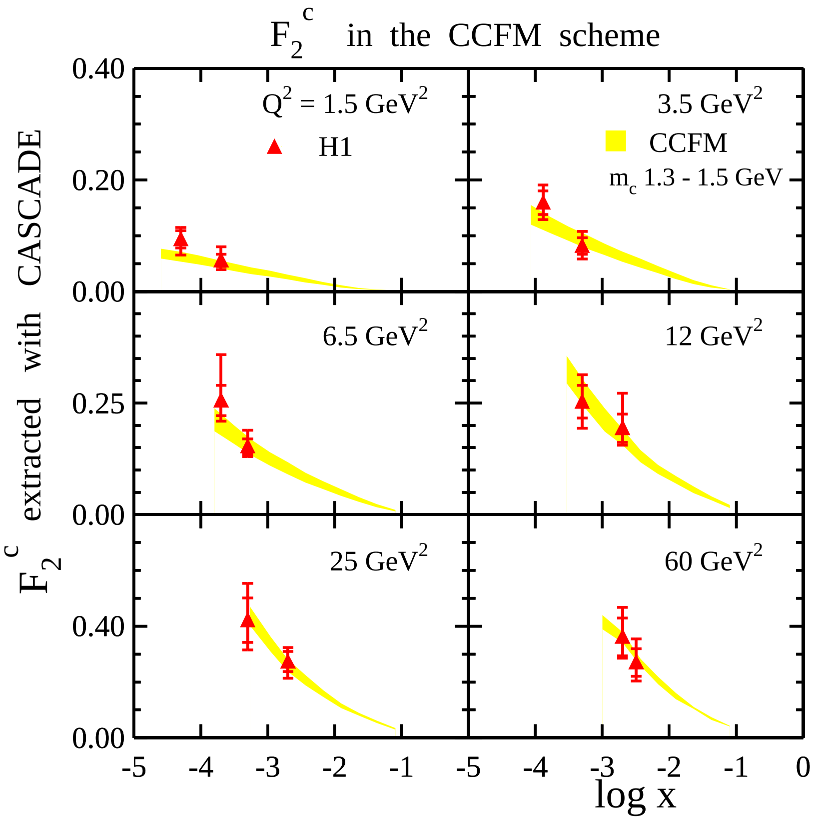


H1 have good general description of D^* data in η , p_T bins.

HVQDIS and CASCADE similar quality.

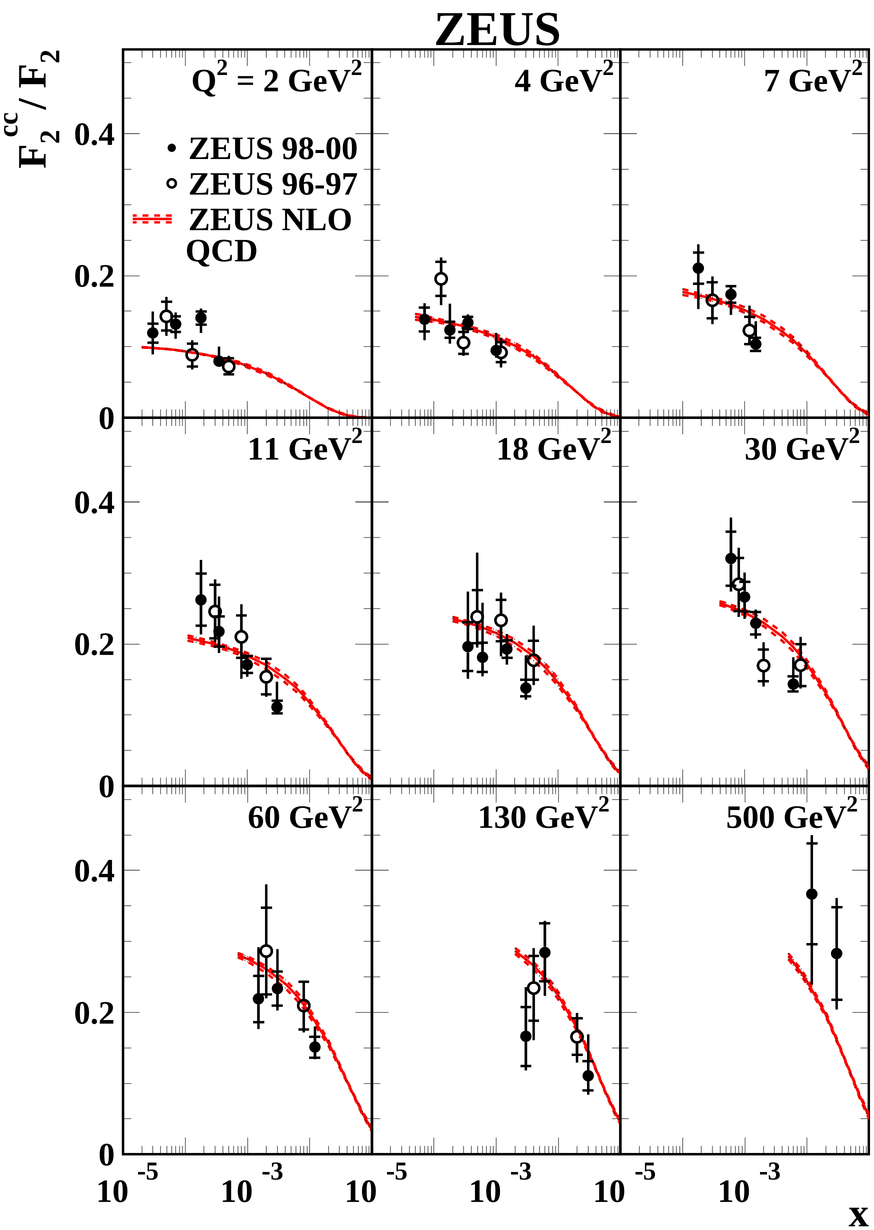
OPEN CHARM IN DIS AT HERA





Charm Structure Functions well described. CCFM perhaps a bit better than DGLAP scheme for fit.

OPEN CHARM IN DIS AT HERA



Fraction of the proton structure function with charm

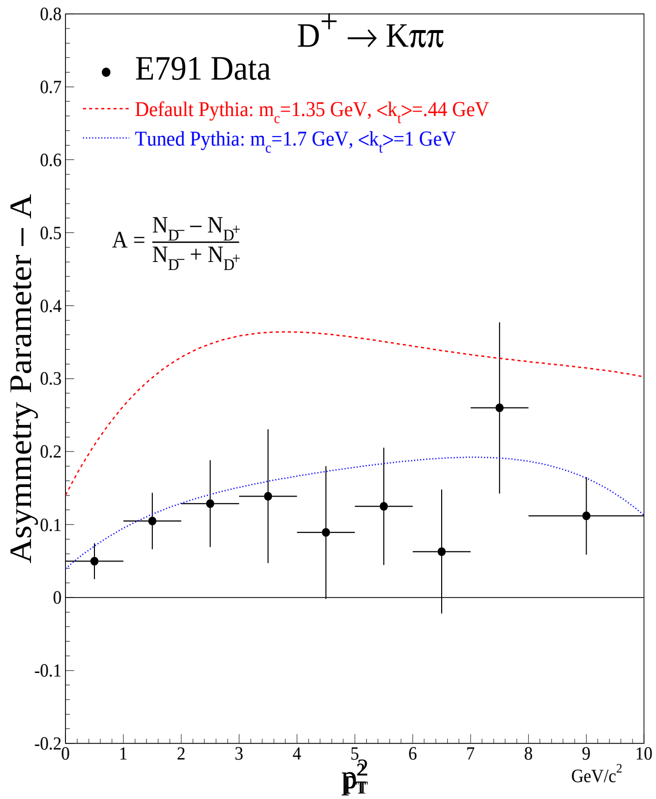
plateauing at low x :

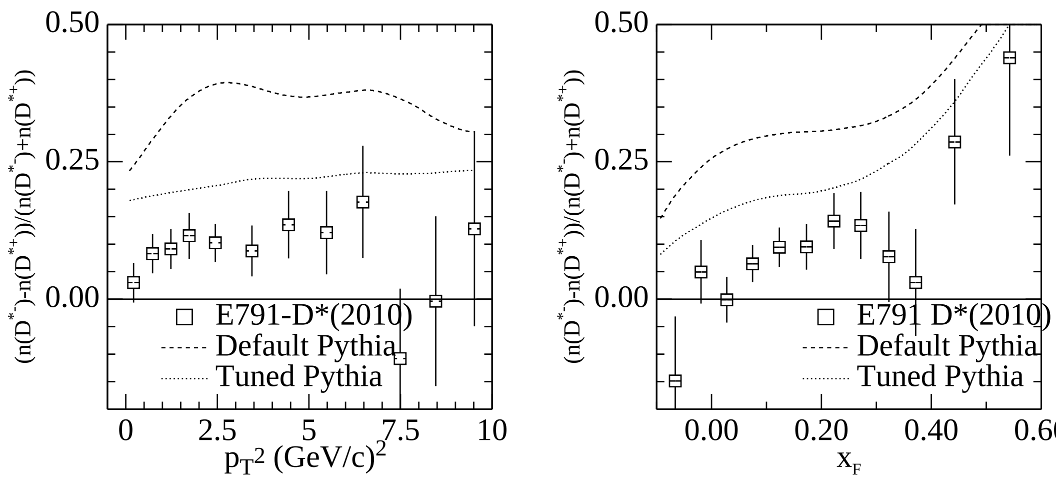
— low-x c quarks arise from gluon splitting

— charm behaves like light flavours at low x

OPEN CHARM PRODUCTION AT TEVATRON

Asymmetries $A = (N(D^-) - N(D^+)) \, / \, (N(D^-) + N(D^+))$
are a challenge (E791 Spectrometer)





Look at p_T^2 **and** x_F **using** $D^{\pm *}(2010)$.

Same PYTHIA tuning this time fails.

NLO QCD gives zero asymmetry anyway!

D^+ **data for** $0 < p_T^2 < 10$
compared with PYTHIA
default, and tuned. The tuning works

States studied: J/ψ , ψ' , χ_c

NRQCD factorisation model

(Krämer, Bodwin, Braaten, Lepage et al.)

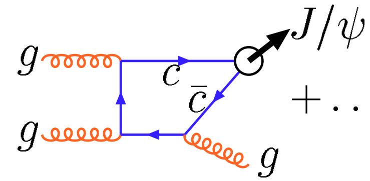
Two stages:
(a) hard perturbative QCD subprocess $\rightarrow c\bar{c}$ pair in Colour Singlet (CS) or Octet (CO) state.

(b) soft hadronisation stage $\rightarrow$ prob. of given hadron $\mathcal{O}^H$.

(soft gluon radiation ensures colour-neutrality of final-state particles.)

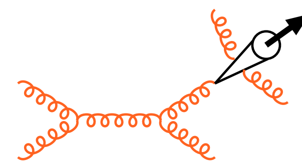
$$d\sigma(\gamma^* p \rightarrow HX) = \sum_n d\sigma(\gamma^* p \rightarrow c\bar{c}(n) + x)\, \mathcal{O}^H(n)$$

Leading-order CS



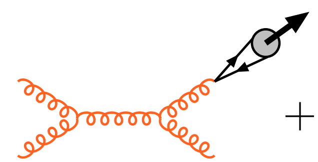
$$+\ldots \qquad \sim \alpha_s^3 \frac{(2m_c)^4}{p_t^8}$$

CS fragmentation



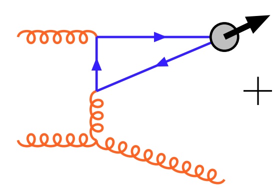
$$+\ldots \qquad \sim \alpha_s^5 \frac{1}{p_t^4}$$

CO fragmentation



$$+\ldots \qquad \sim \alpha_s^3 \frac{1}{p_t^4} v^4$$

CO fusion



$$+\ldots \qquad \sim \alpha_s^3 \frac{(2m_c)^2}{p_t^6} v^4$$

History of the subject:

(c.f. Krämer, Prog. Part. Nuc. Phys. 47 (2001) 141; Ringberg 2003)

1977 – Colour-Evaporation Model (Fritzsch, Glück et al): S-wave matrix elements $\mathcal{O}^H(n)$ dominate.

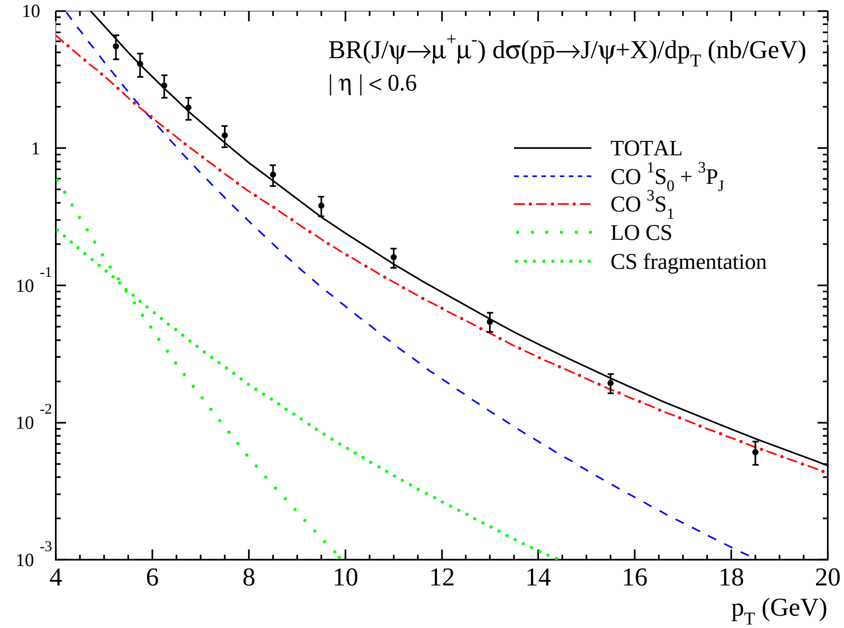
1981 – Colour-Singlet Model (Berger, Baier et al): leading CS term dominates.

NRQCD – $\mathcal{O}^H(n)$ terms universal, i.e. factorisation.

$\rightarrow$ determine the $\mathcal{O}^H(n)$ from experiment – e.g. fit FNAL data – and see if it works in other regimes, e.g. HERA!

NB possible importance of NLO!

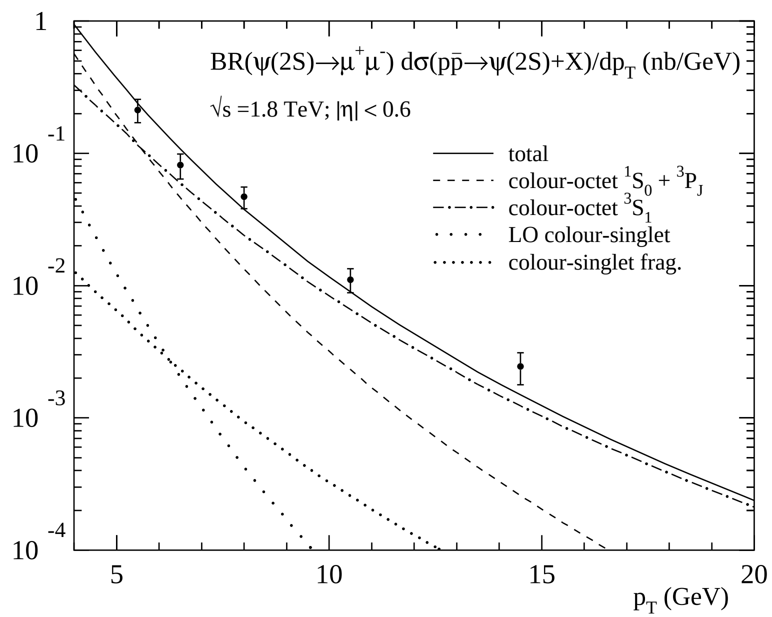
CDF J/ψ Data, Run I

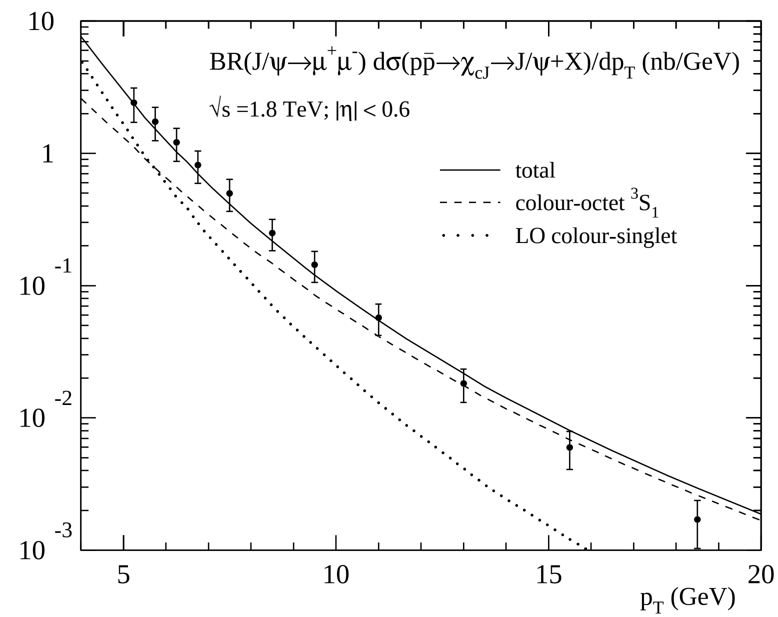


Appears that CO is needed, dominates at high p_T.

These data used to FIT CO matrix elements.

CDF Data on ψ' (2S) and χ_c (3415)+(3510)



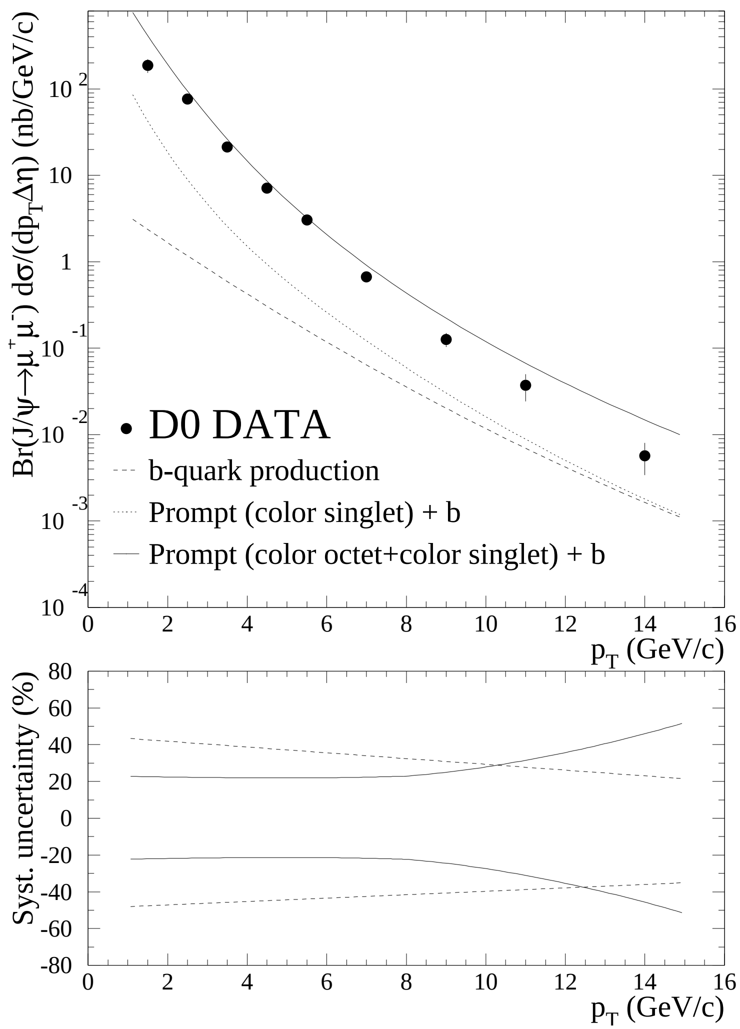


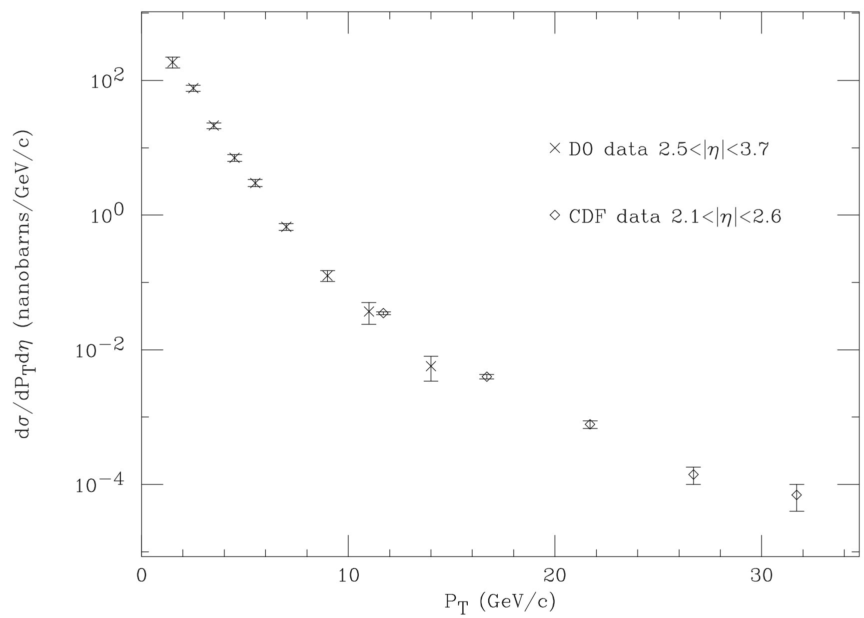
Again the fit (Krämer 2001) **requires a CO contribution.**

Large NLO effect in CS due to new channels $\rightarrow$ t -channel gluon exchange — will affect fit for $p_T < 10$ GeV in the ψ states.
Calculation needed for Tevatron data.

However this would not affect the conclusions, based on higher p_T , that CO is needed for the Tevatron data. (M Krämer, priv. comm.)

Run I forward J/ψ production

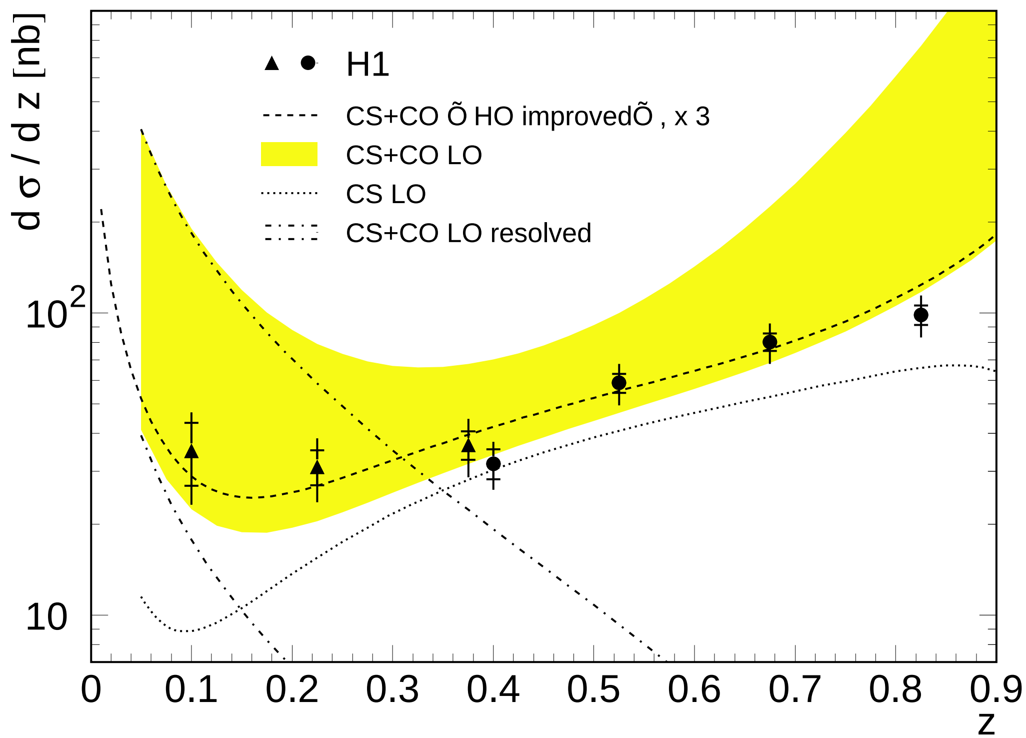




D0 and CDF have measured J/ψ at forward angles $2.5 < \eta < 3.7$ (D0), $2.1 < \eta < 2.6$ (CDF).

Consistent results, agreement with CS+CO theory within sys. err.

J/ψ IN PHOTOPRODUCTION AT HERA

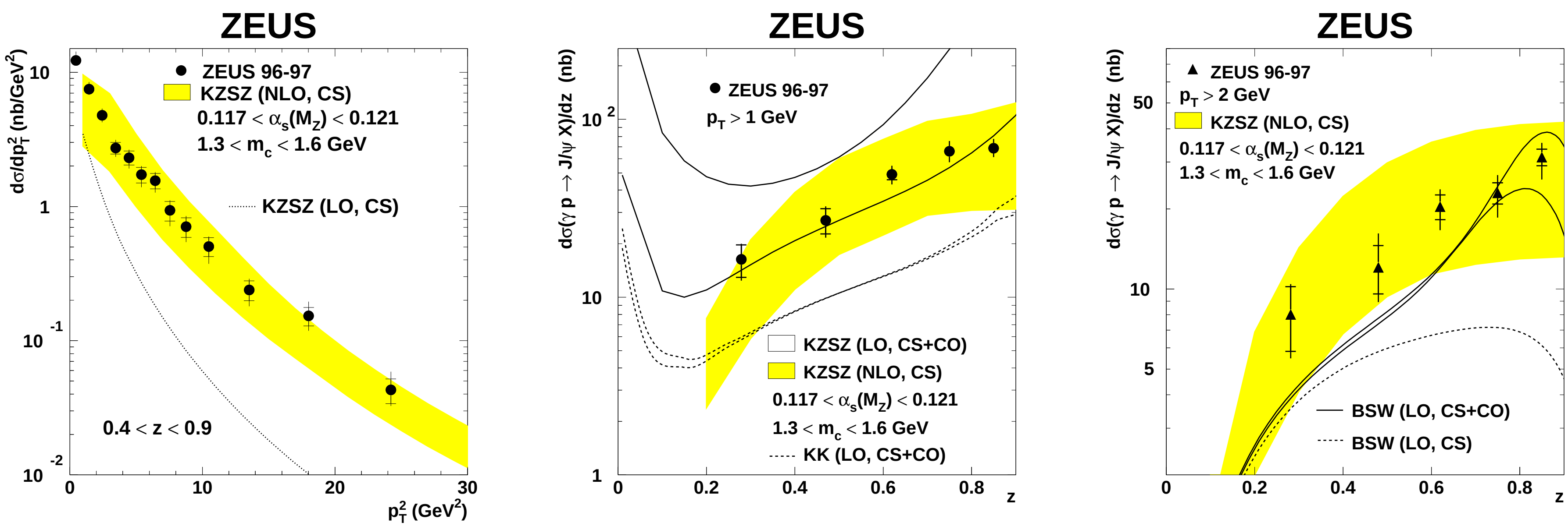


$$z = \frac{p_\psi \cdot p_p}{q_\gamma \cdot p_p}$$

H1 - Krämer et al (band) **Kniehl & Krämer (KK) (dots).**

LO - CS not OK, but LO - CS + CS + CO will work.

J/ψ IN PHOTOPRODUCTION AT HERA

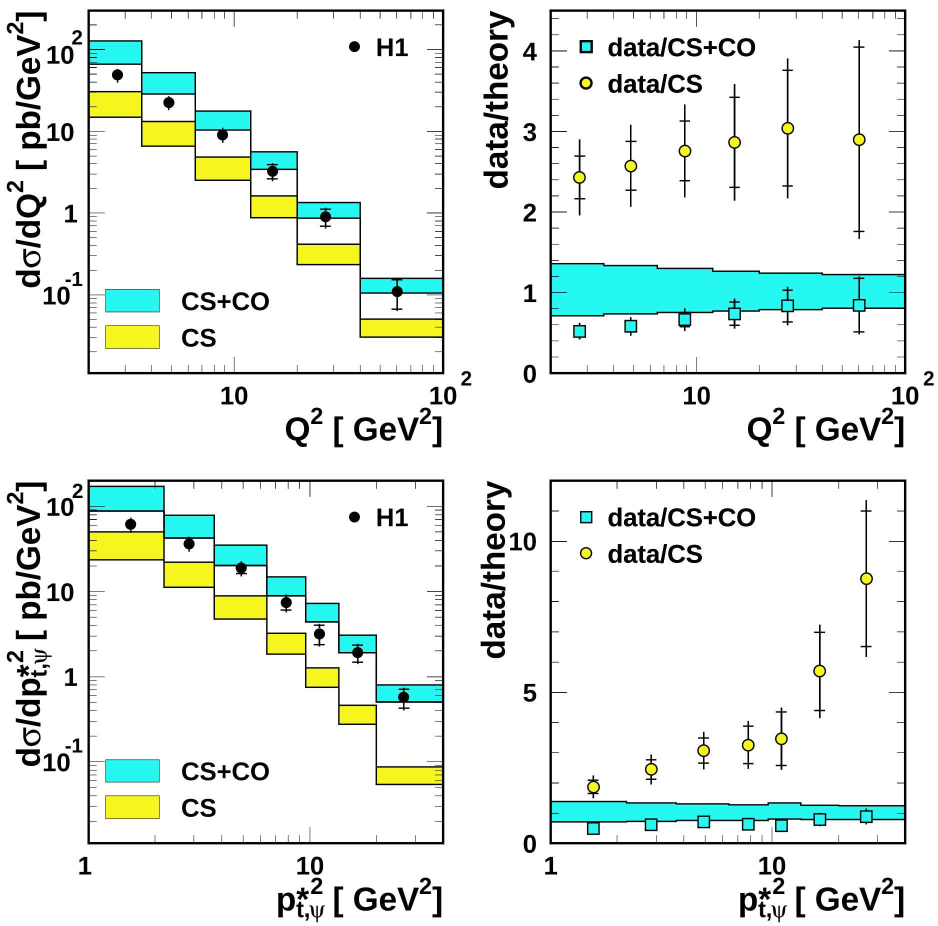


$$z = \frac{p_\psi \cdot p_p}{q_\gamma \cdot p_p}$$

Theory: Krämer et al (KZSZ); Beneke et al (BSW); Kniehl & Krämer (KK) NRQCD

NLO - CS is sufficient, but LO - CS is not.
LO - CS + CO will work
No convincing evidence for CO !

J/ψ IN DIS AT HERA

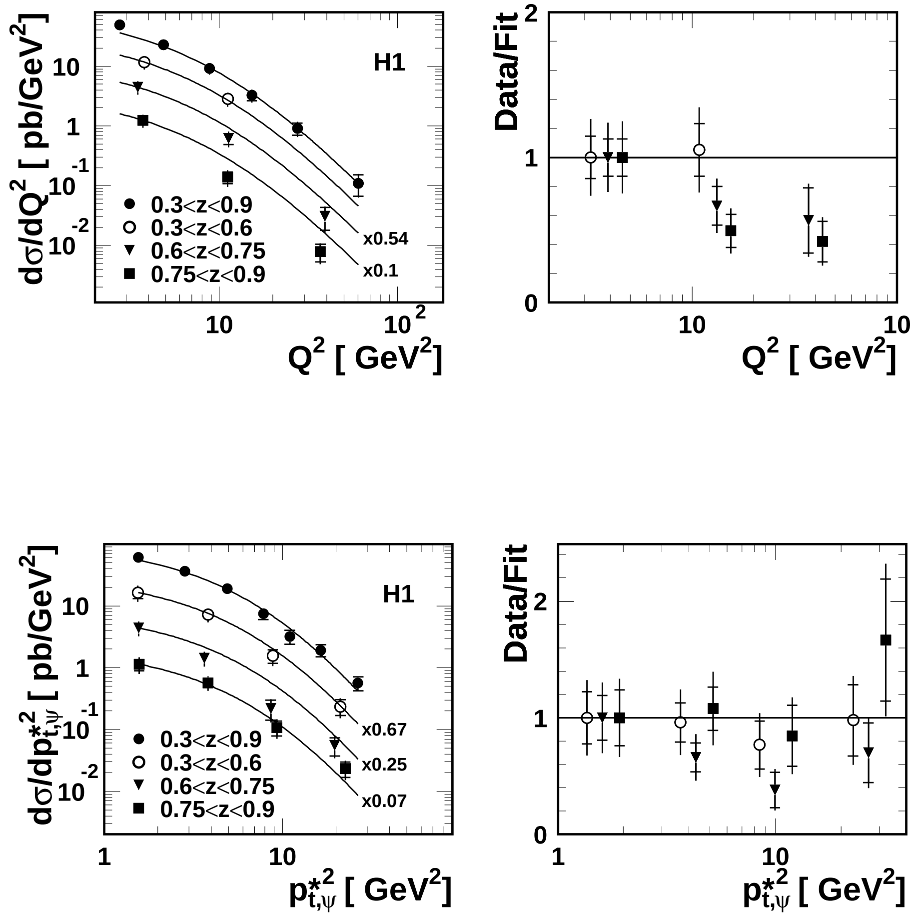


H1 measurements in DIS

Compare with NRQCD calc. using CS and CS+CO versions.
CS alone is insufficient.
CS+CO is OK.

n.b. NLO is available only for photoproduction, where NLO+CS alone is sufficient.

J/ψ IN DIS AT HERA

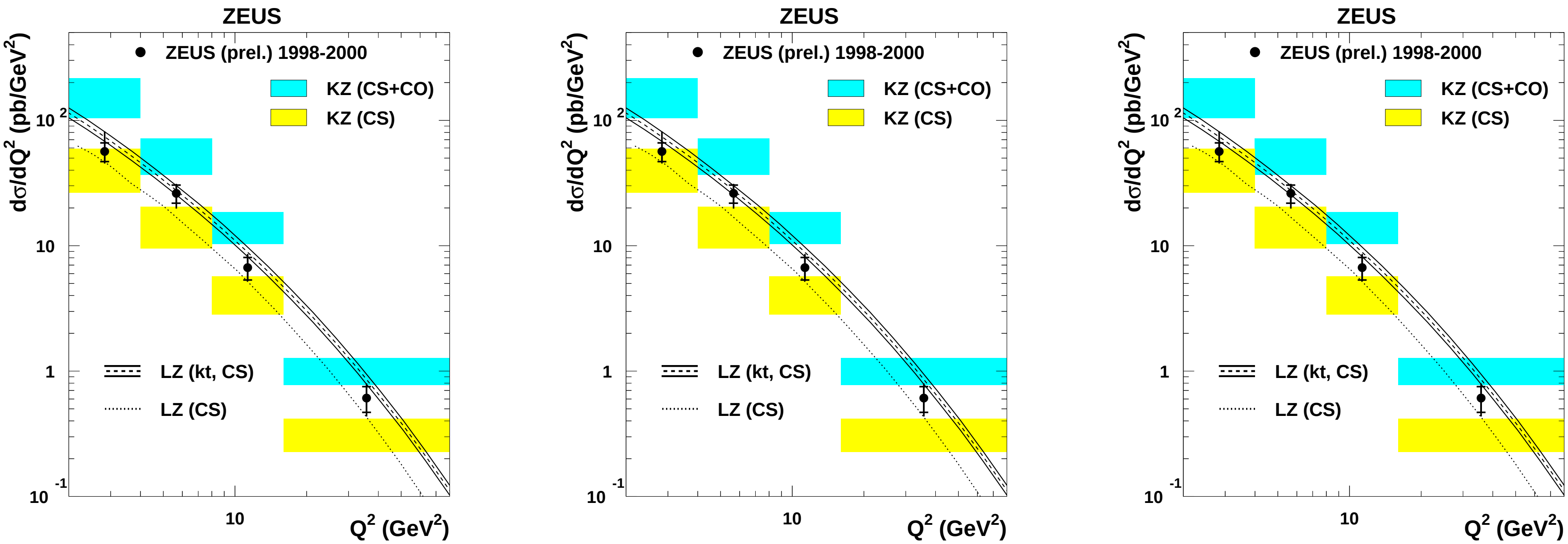


H1 compare J/ψ Xsecs as function of Q^2 and P_t^{*2} with fitted curves of form

$$(\mu^2 + m_{J\psi}^2)^{-M,N}$$

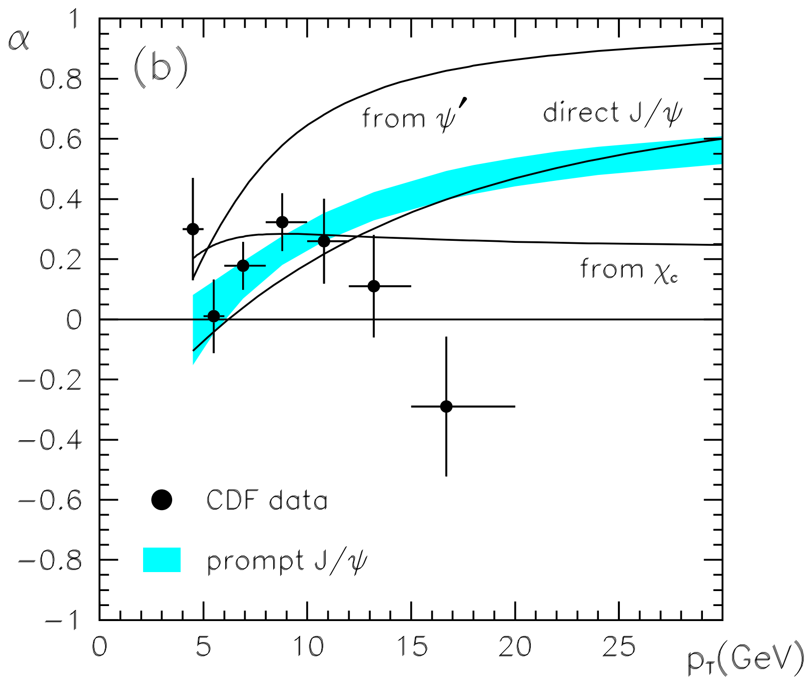
where μ = respective hard scale.

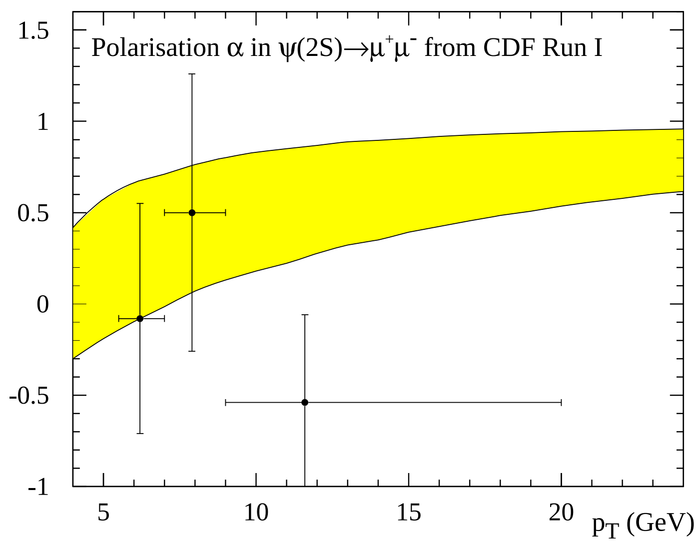
Fair fit, except at high Z
No conclusions attempted.



Theory: Kniehl+ Zwirner (KZ) CS, KZ CS+CO, Lipatov&Zotov (LZ)

OK but KZ are somewhat high.





Polarisation tests NRQCD theory:

$$I(\cos\theta^*) = \frac{3}{2(\alpha+3)}(1+\alpha\cos^2\theta^*)$$

Prompt J/ψ (not from B decay)
= sum of direct production
+ feed-down from higher $c\bar{c}$ states.

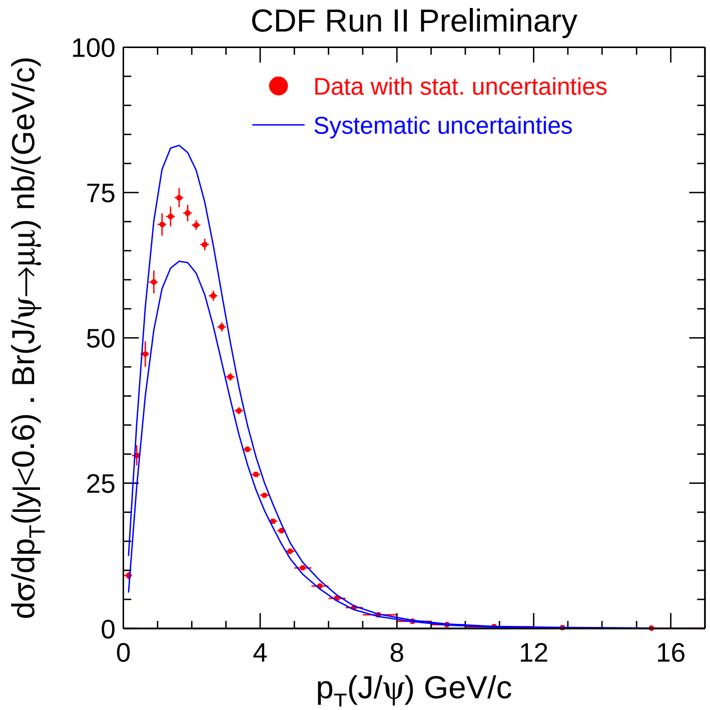
Prediction of high α at high p_T (Braaten et al) apparently not seen.

c.f. CEM predicts little polarisation at high p_T .

Krämer: invoke higher order QCD effects or different power counting schemes?

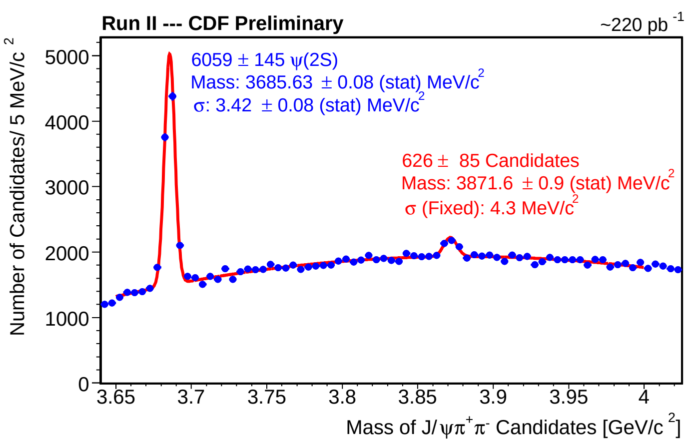
Need for better Tevatron measurements, and at HERA.

CHARMONIUM PRODUCTION AT TEVATRON

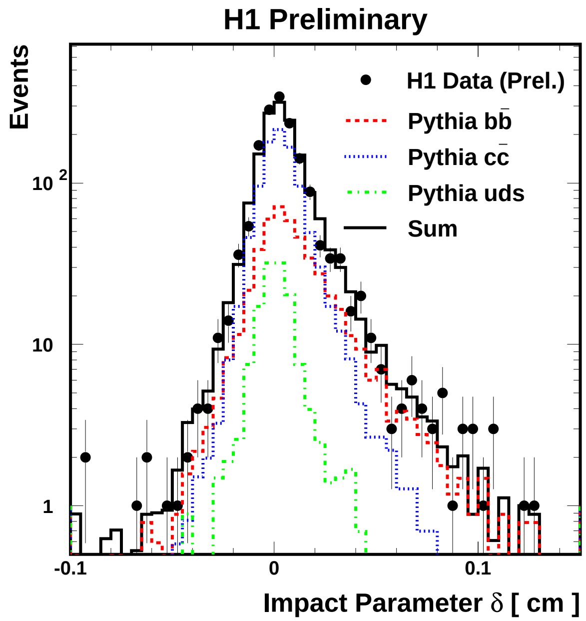


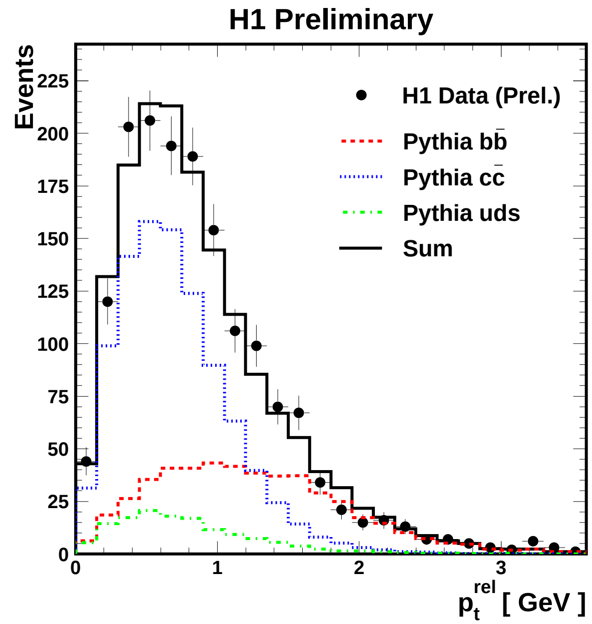
Preliminary Run II results:

Using better trigger, CDF measure J/ψ down to zero p_T in $\mu^+\mu^-$ decays. (prelim. data include feed-down)



CDF confirm BELLE's recent announcement of a narrow state at 3872 decaying to $J/\psi\pi\pi$. Could be perhaps a $^3D_2$ state (rather heavy), or a $D^0\bar{D}^{*0}$ "molecule".



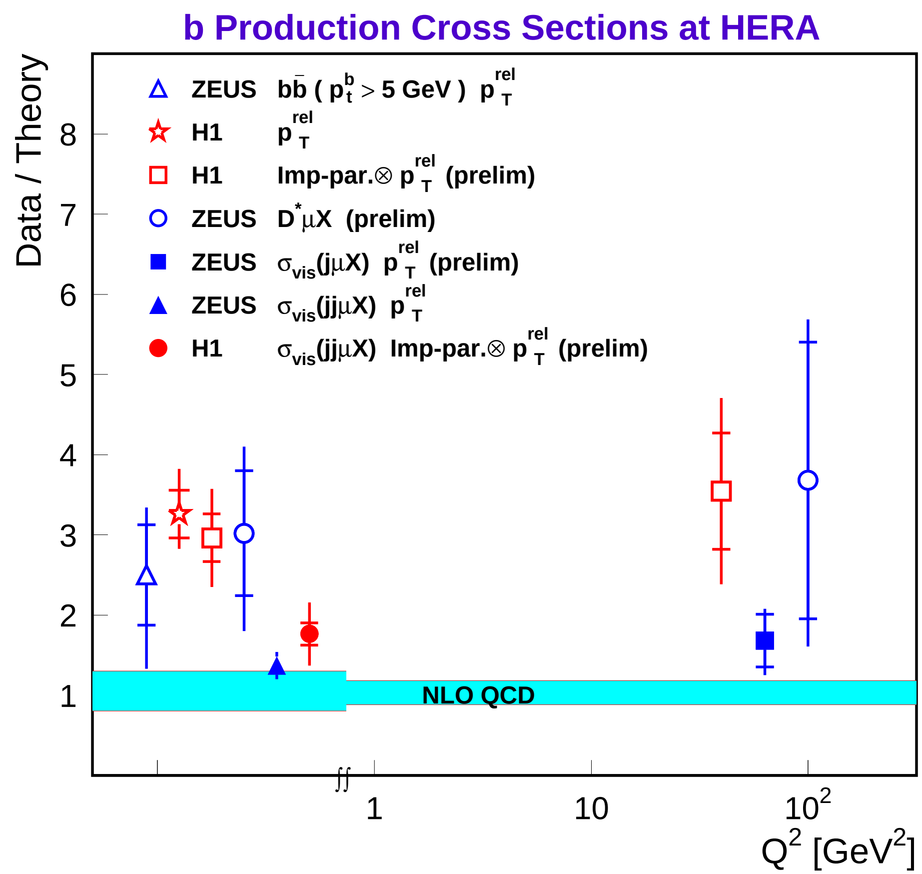


Selection method for B hadrons:

— Use presence of muon to enhance heavy flavour signal
— Impact parameter of μ track larger for B decays
— p_T^{rel} of μ larger for B decays
— Apply fit to extract B signal.

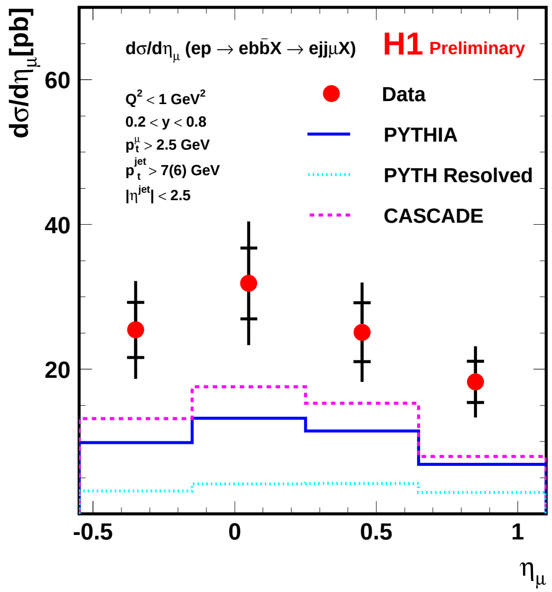
HERA

OVERVIEW



Conflicting results from H1 and ZEUS over past few years

both in photoproduction and DIS



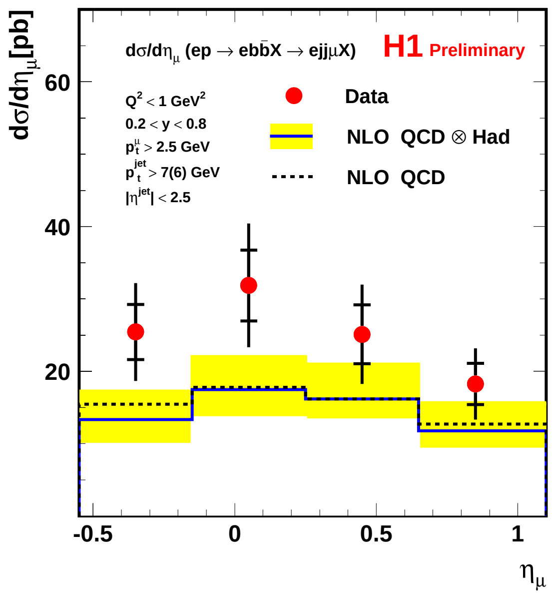
H1 RESULTS

Events with 2 jets + μ

Plot pseudorapdity of μ tagging B

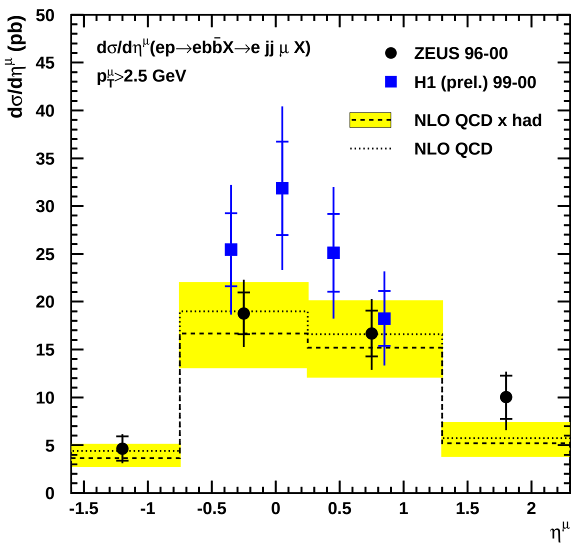
Disagreement with PYTHIA

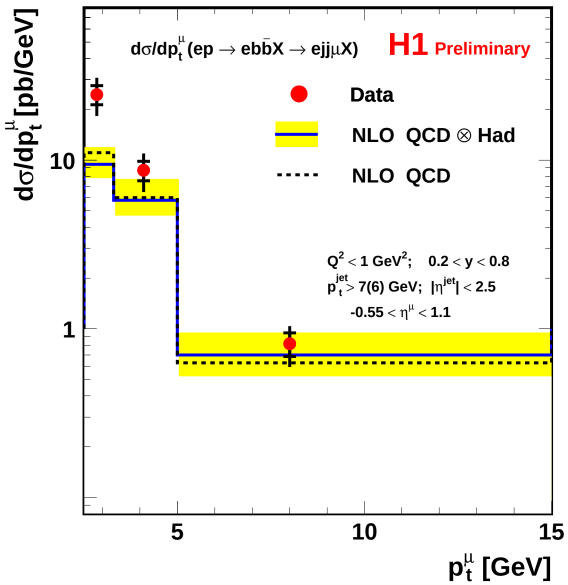
Disagreement with CASCADE

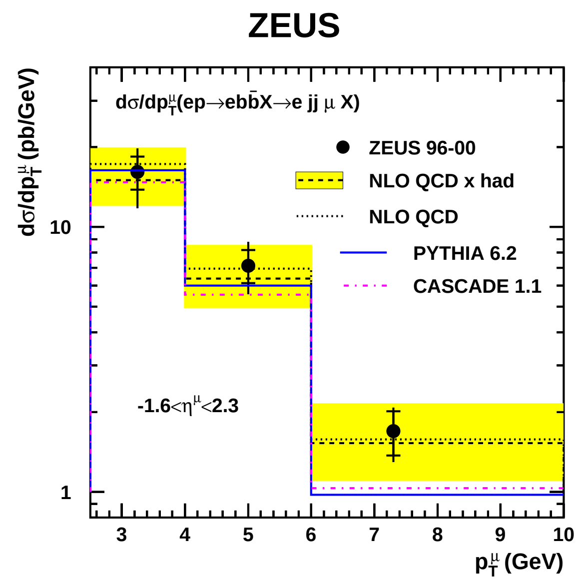


Fair agreement with NLO QCD (Frixione et al)

Comparison between ZEUS and H1: η , p_T of muon





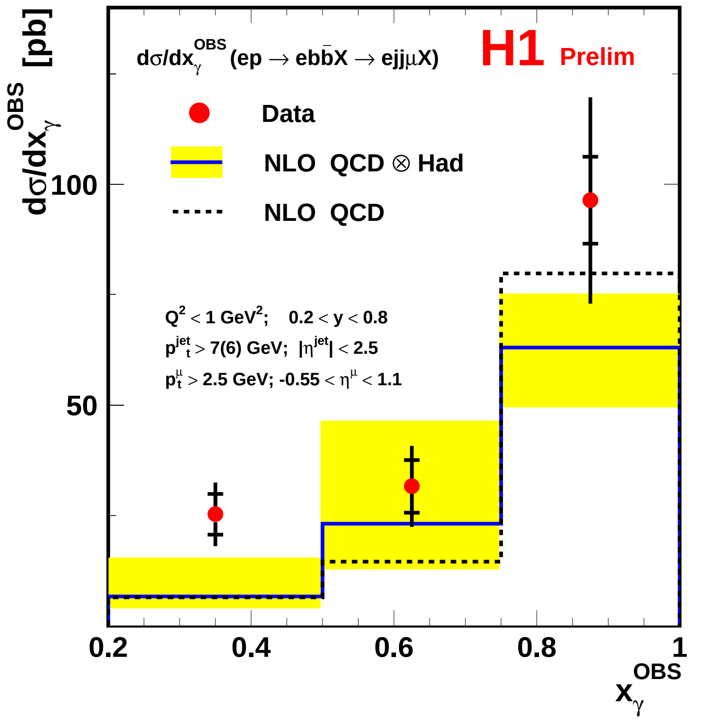


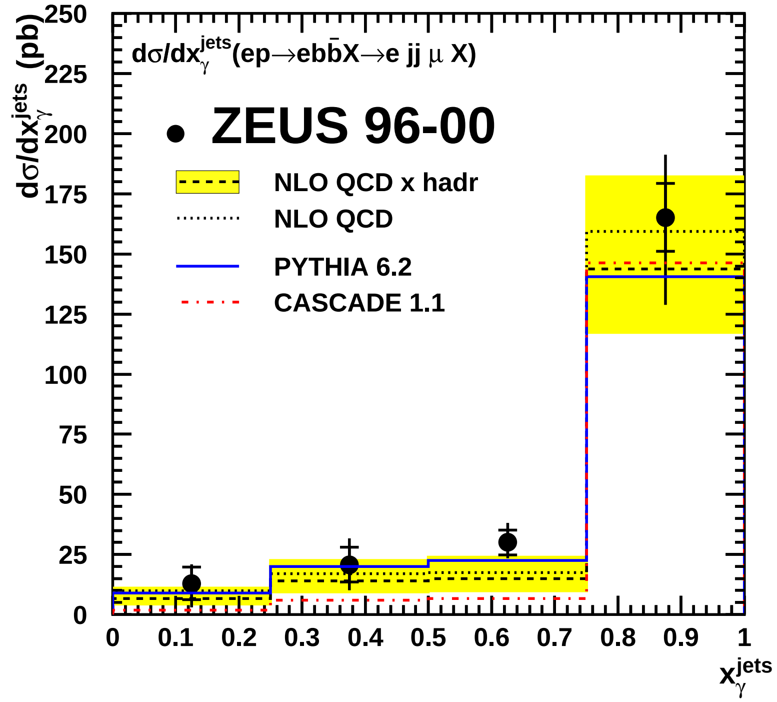
ZEUS have used a broader muon acceptance.

Good overall agreement with H1

But H1 have a larger Xsec at low muon p_T.

x_γ measurements distinguish resolved from direct



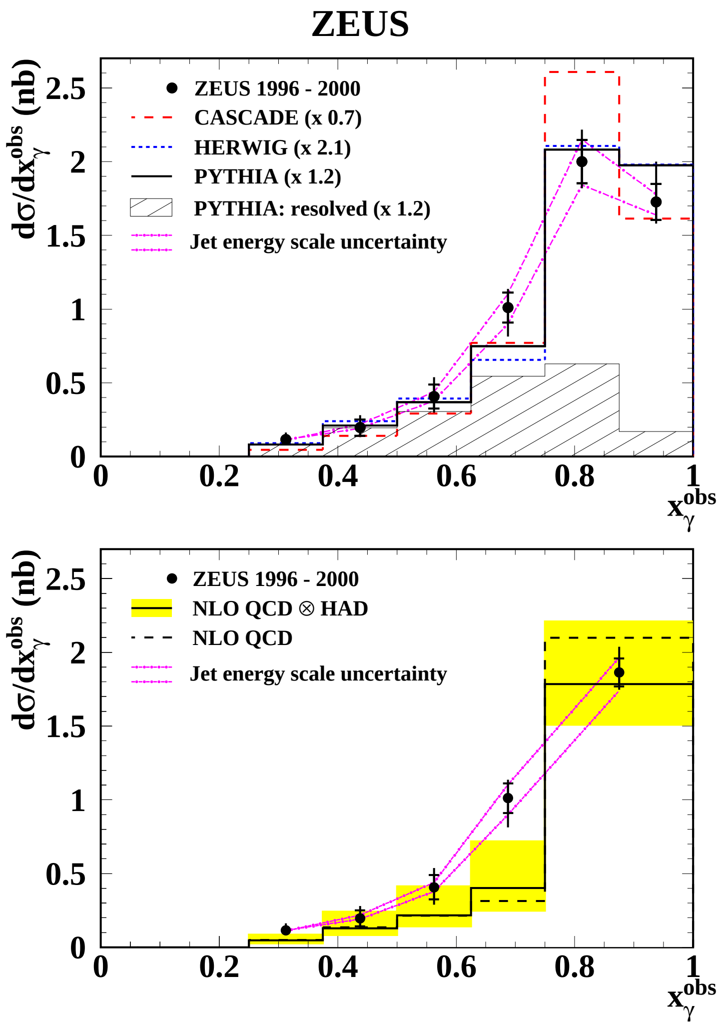


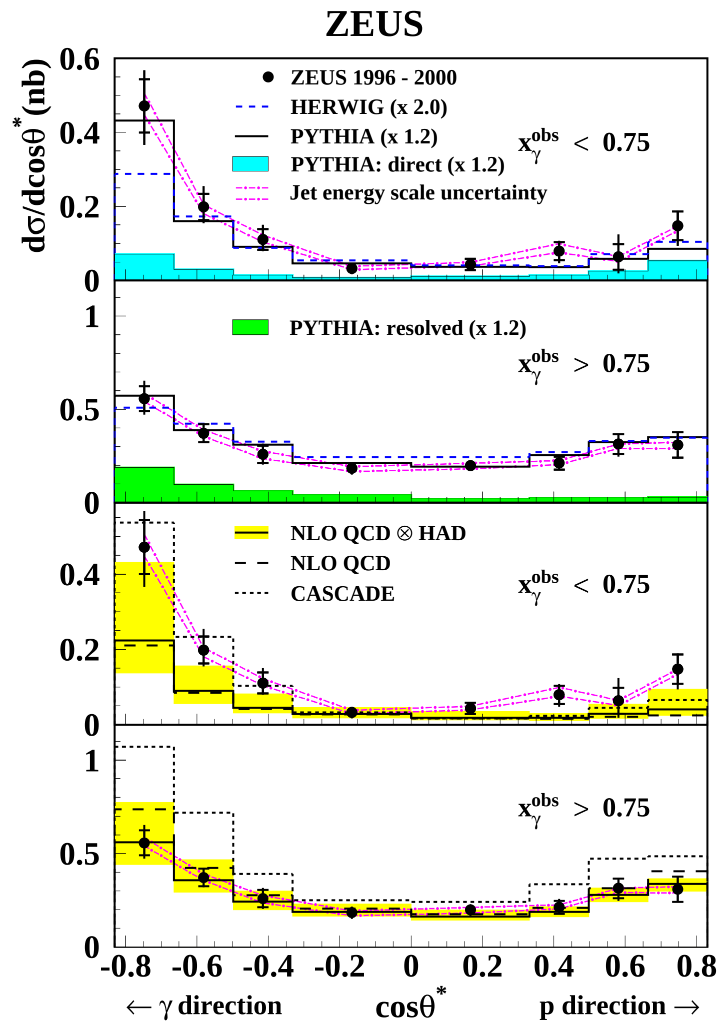
(Different acceptances → different cross sections)

PYTHIA 6.2 OK for ZEUS, CASCADE resolved is poor

NLO (Frixione et al) gives good agreement with ZEUS and fair with H1.

CHARM PHOTOPRODUCTION

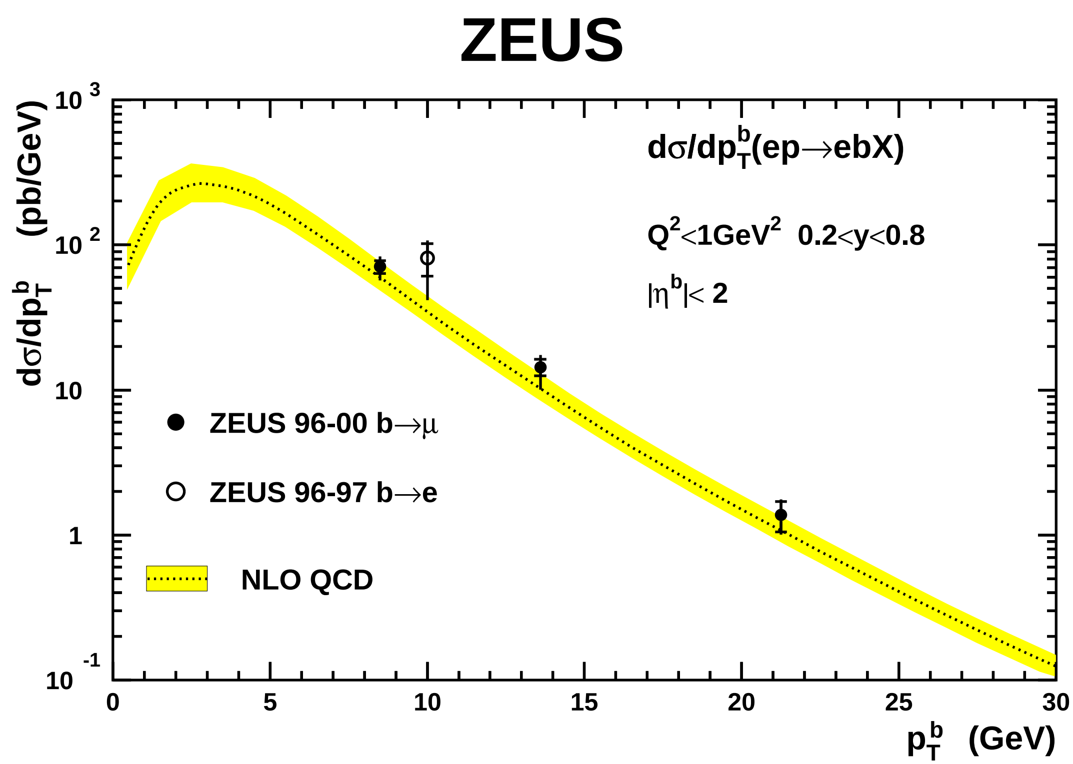




Compare with CHARM + dijets !

All models get x_γ shape approx. right

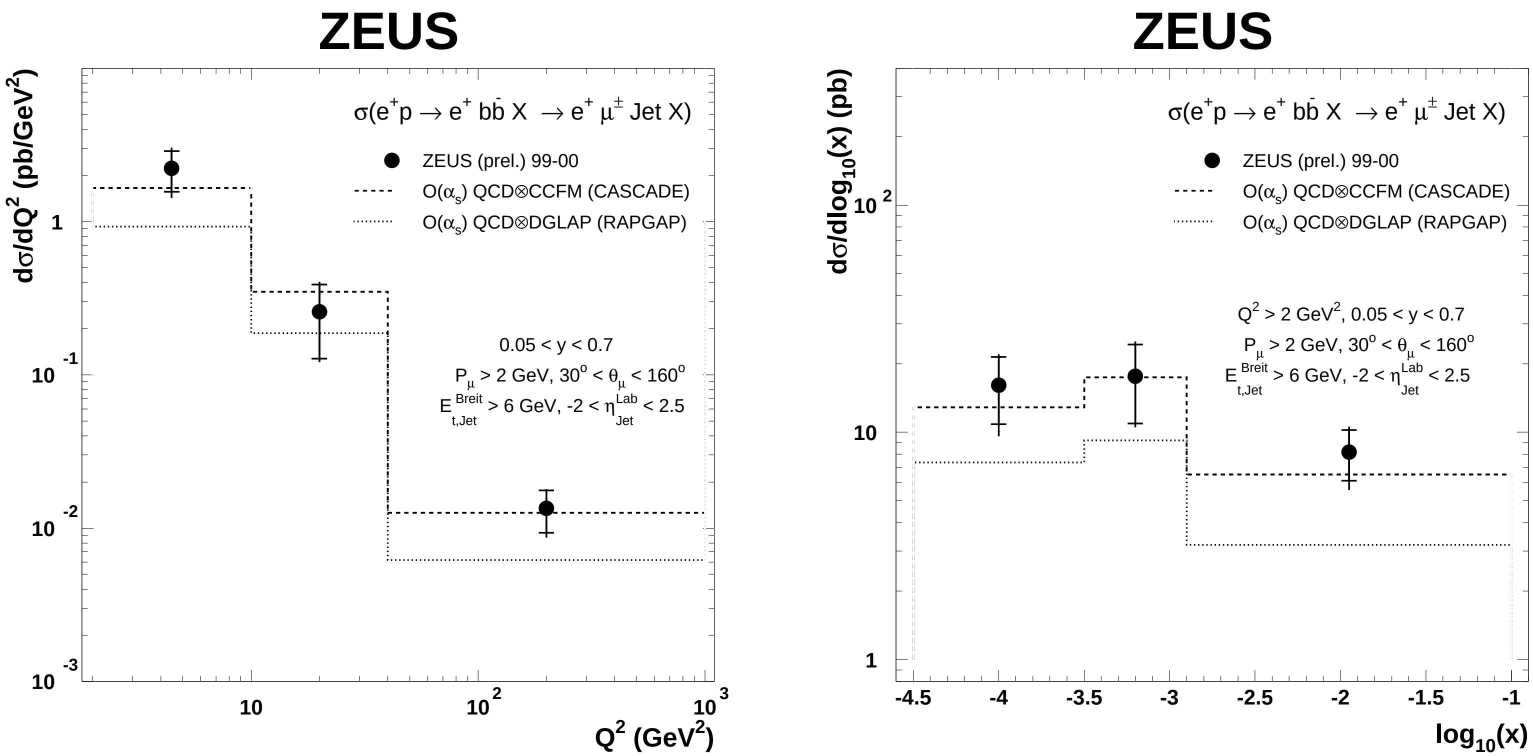
Jet angular distributions: NLO gets Xsec right, CASCADE DIRECT off!



ZEUS data corrected to p_T of b quark

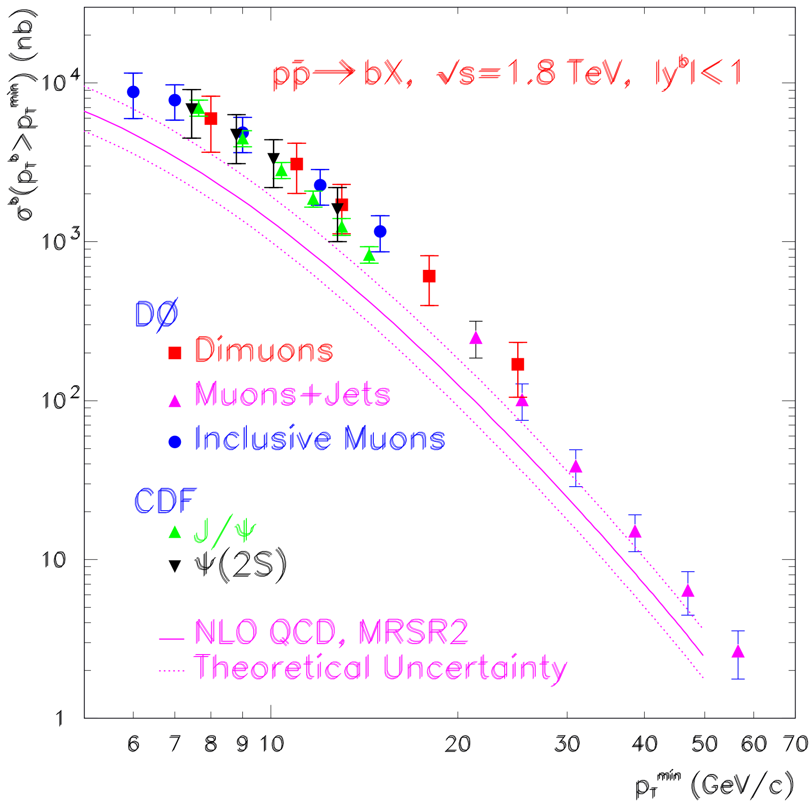
Good agreement with NLO QCD.

BEAUTY IN DIS



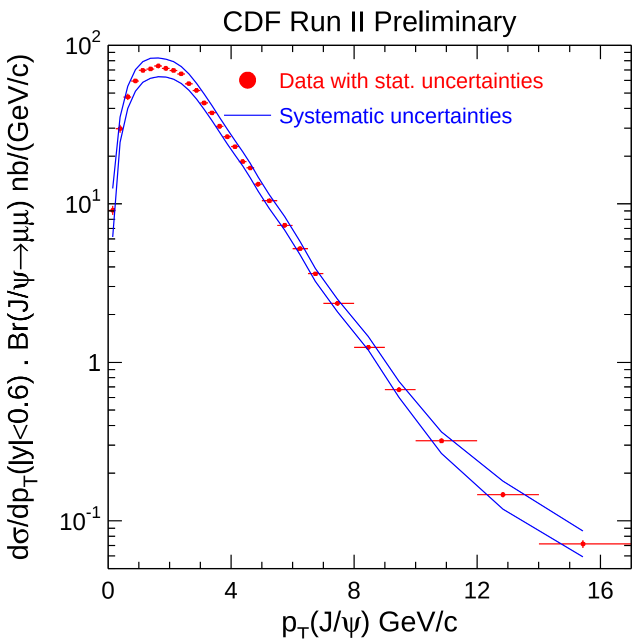
Preliminary DIS results from ZEUS

Xsecs in Q^2 , x prefer CASCADE to RAPGAP



B data at Tevatron Run 1 gave problems for theory

NLO theory undershot the data substantially except at high p_T

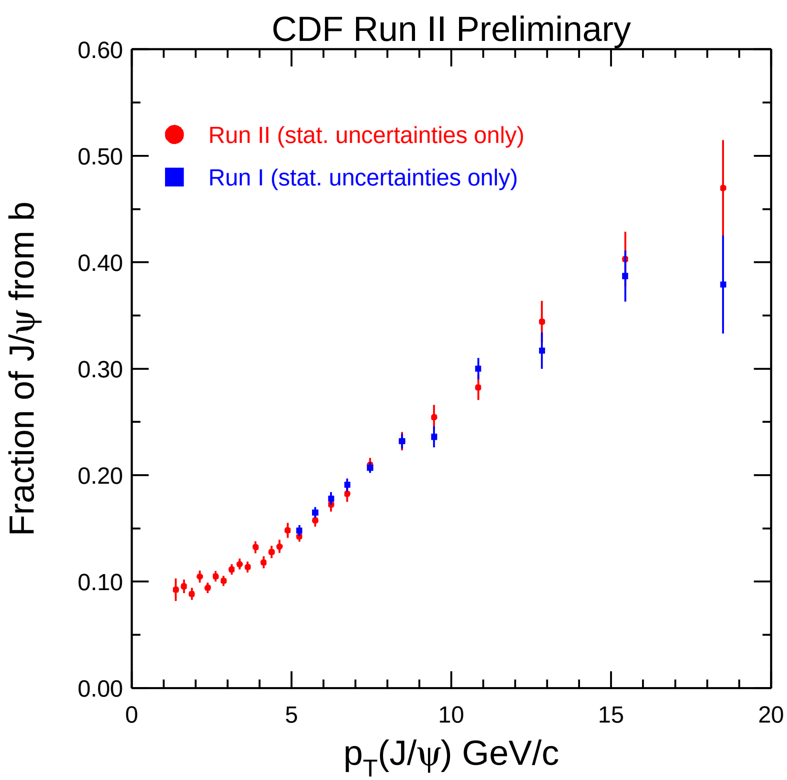


New CDF B cross sections

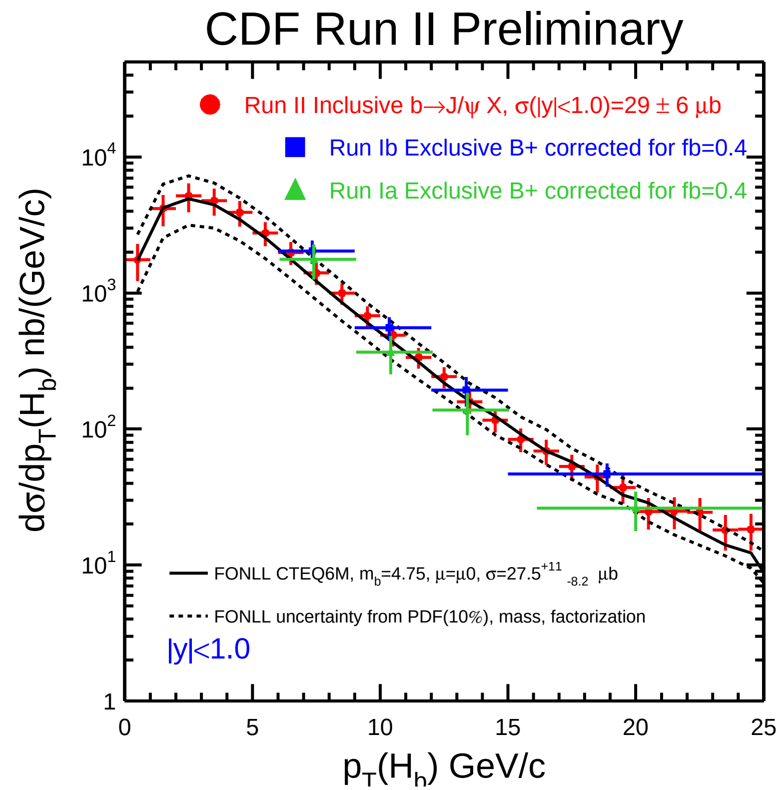
Method:

- **Start with $J/\psi \rightarrow \mu\mu$ signal**
- **Measure decay path L_{xy} in x, y**
- **Model known b-hadron $\rightarrow J/\psi$ processes**
- **Max likelihood fit to $L_{xy}/p_T(J/\psi)$ evaluates b-hadron fraction**
- **Include effects of acceptance etc.**
- **Unfold to get b-hadron distribution.**

Fraction of J/ψ from H_b



Final cross sections



Good agreement with the Run I results (corrected to B-hadrons)

FONLL theory from Cacciari et al. fits the data well!

First signal for top announced 1995

Measurements gradually improving since then.

Sought in various channels

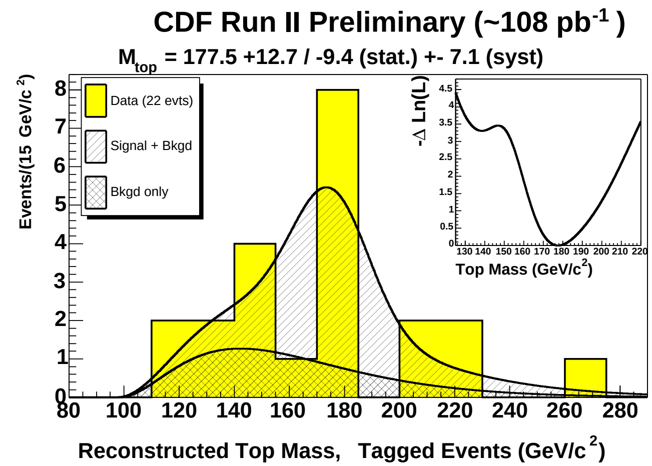
Seen only at Tevatron

Collected mass results from Run I (P. Azzi, hep-ex/0312052)

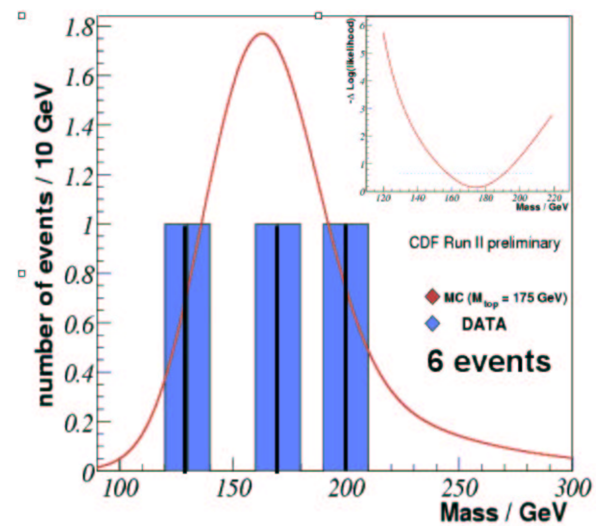
Channel	CDF	D0
Dilepton	167.4 ± 11.4	168.4 ± 12.8
Lepton+jets	175.9 ± 7.1	173.3 ± 7.8
All jets	186.0 ± 11.5	–
Combined	176.0 ± 6.5	172.1 ± 7.1
CDF+D0 Combined	174.3 ± 5.1	
Lepton+jets (New)	–	180.1 ± 5.4

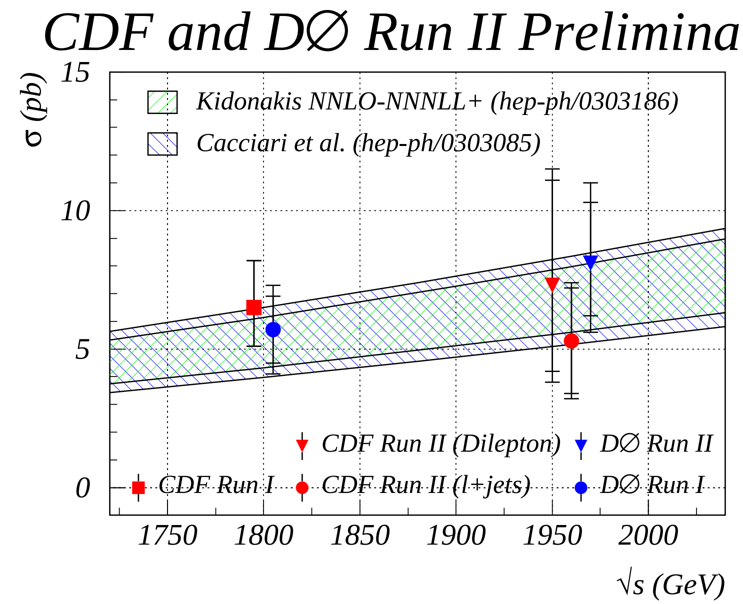
Some top-mass plots from Run II Method – minimise background!

(a) Lepton + jets, b-tagged jet



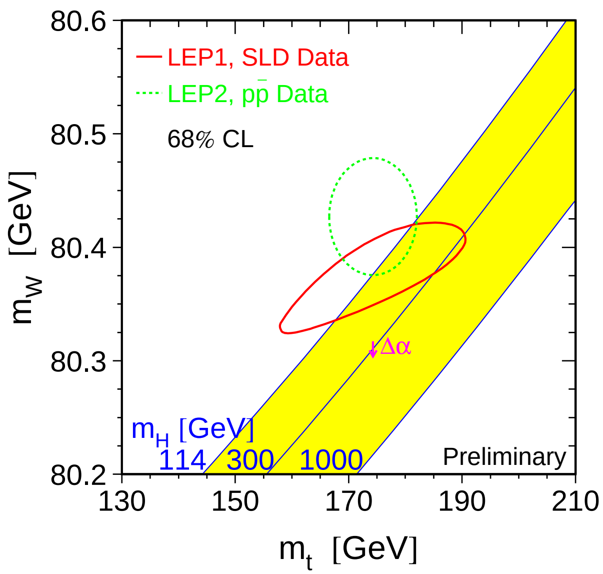
(b) Dilepton channel



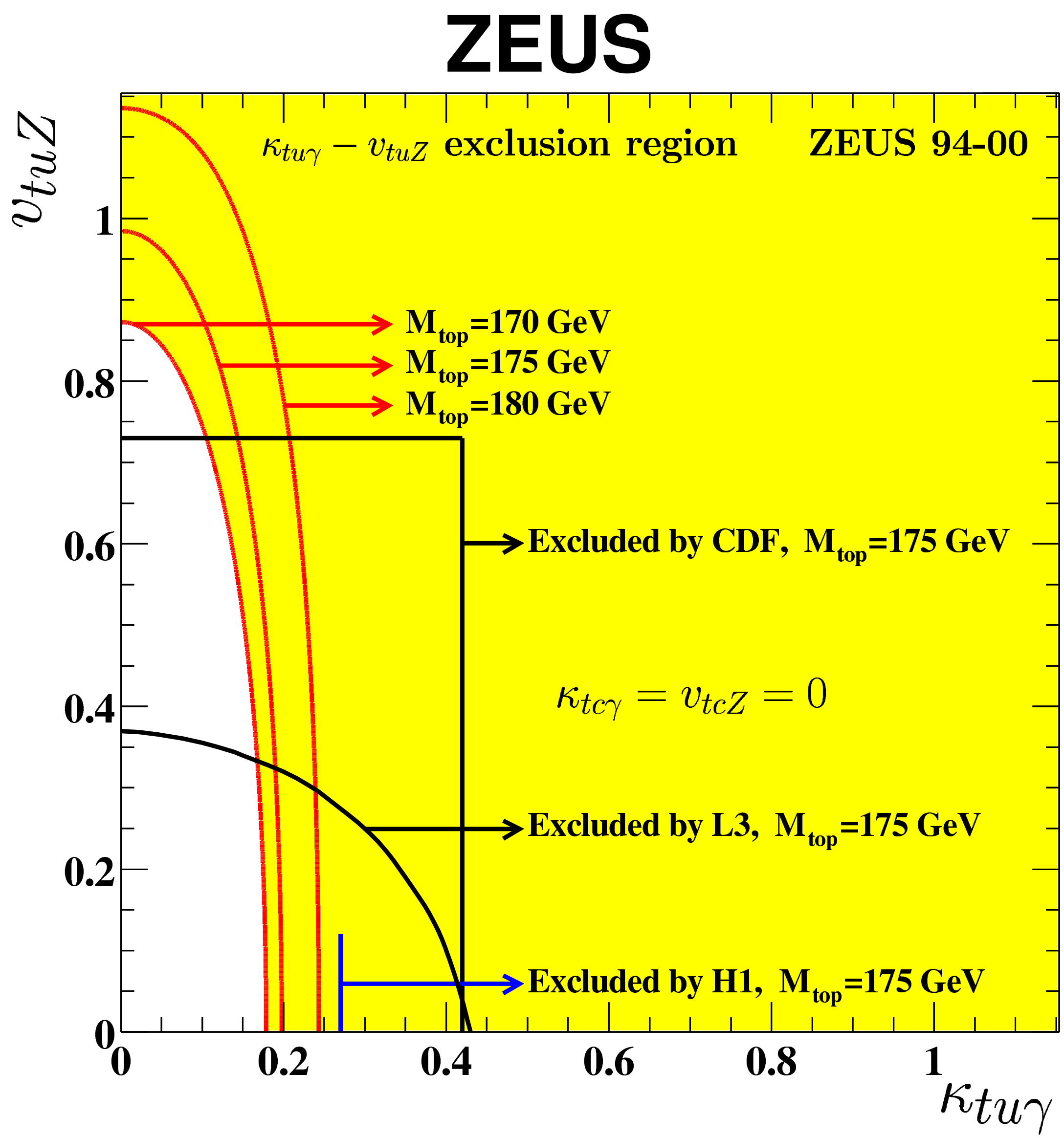


Cross sections agree with models of Kidonakis, and Cacciari et al.

M_t : important correlation with Higgs parameters



Single top searches at HERA place competitive limits on vector and magnetic coupling parameters (very small in Standard Model).



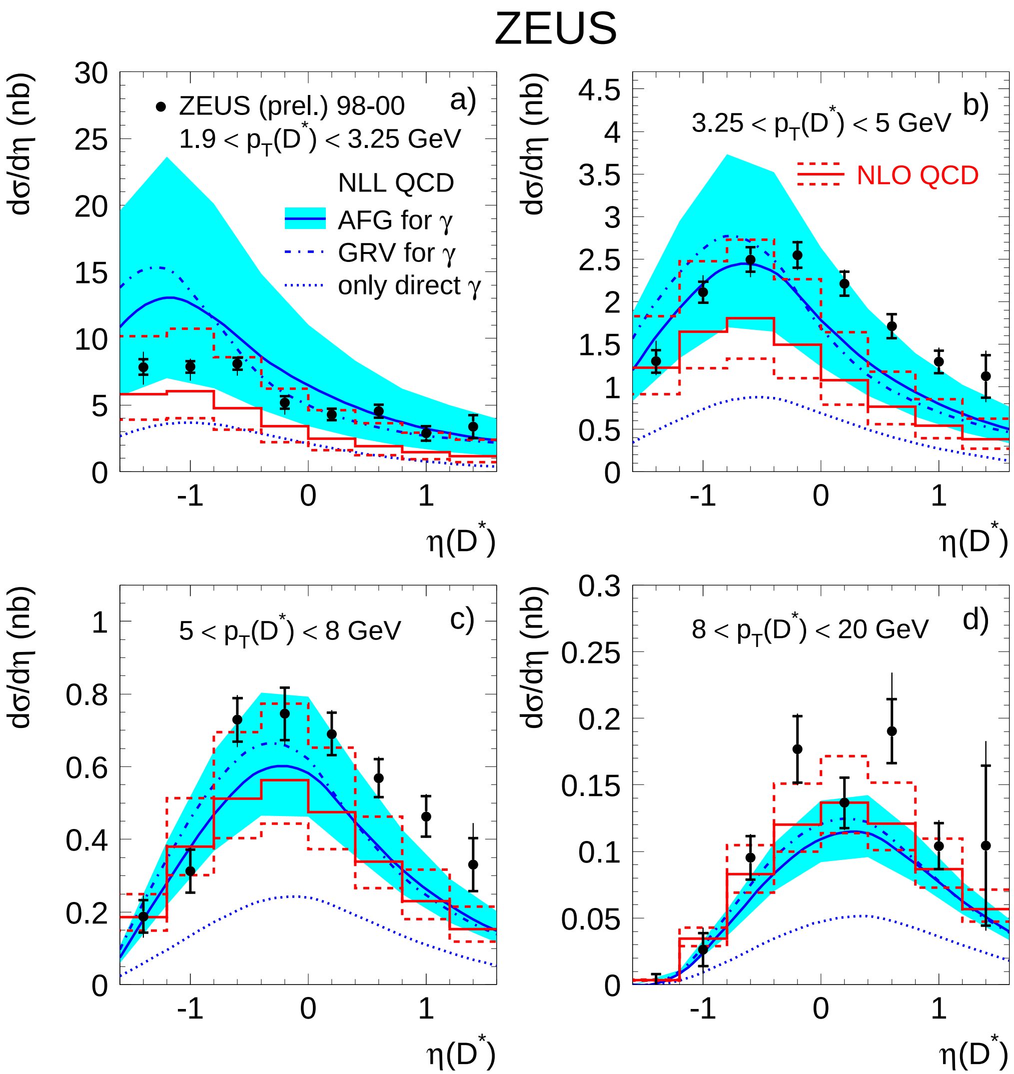
FUTURE PLANS

- **HERA – Improved cross section studies, b and c.**
- **Searches for new final states**
- **Charm structure of photon, proton.**
- **Charm, beauty in diffractive processes.**
- **Tevatron: Cross sections, b, c and t.**
- **Branching ratios of decays**
- **New final states.**
- **Lifetimes and masses.**
- B **mixing including** B_s

CONCLUSIONS

- **The fixed-target and collider experiments at FNAL and HERA have produced a prolific variety of heavy flavour physics.**
- **Data present a challenge to many aspects of the theory.**
- **Charm theory models are improving**
- **Beauty ditto – problems disappearing?**
- **Overall, perturbative QCD is very successful.**
- **Top physics: also coming along. . . high luminosity is critical!**
- **The two colliders compliment each other.**
- **With improving integrated luminosity, the experiments will be able to produce many more definitive results.**

OPEN CHARM PHOTOPRODUCTION AT HERA



Predictions from

Kniehl et al

(NLL)

massless, 4 active flavours in p and γ

Frixione et al (FMNR)

(NLO)

3 active flavours in p, γ

No clear preference?

Some sensitivity to γ structure