Production of Heavy Flavours in ee, ep and pp Scattering

Leonid Gladilin

(DESY / Moscow University / Weizmann Institute)

Heavy Quarks and Leptons

May 27 - June 1, 2002, Vietri s/m, Salerno, Italy

O U T L I N E :

Introduction

Charm Production

Beauty Production

Top Production

Quarkonium Production

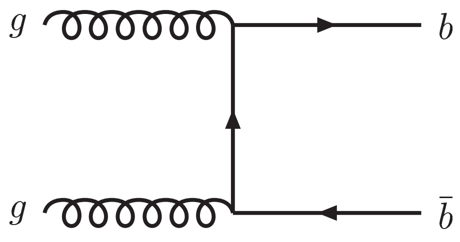
Summary and Prospects

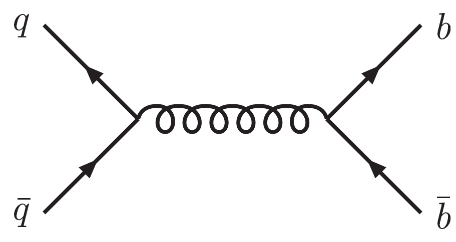
$Q\bar{Q}$ Production Mechanisms in pp, ee $(\gamma\gamma)$ and ep (γp)

$Q\bar{Q}$ **in** pp**:** $gg \rightarrow Q\bar{Q} + \ldots$

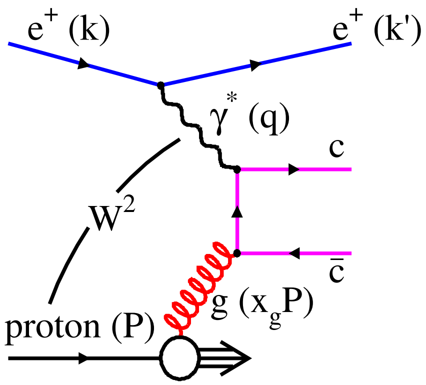
$Q\bar{Q}$ **in** ep**:** $\gamma g \rightarrow Q\bar{Q} + \ldots$

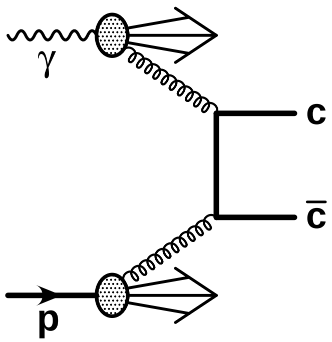
$Q\bar{Q}$ **in** ee**:** $\gamma\gamma \rightarrow Q\bar{Q} + \ldots$

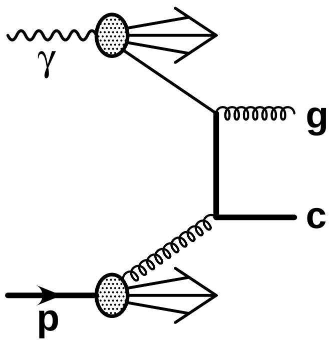




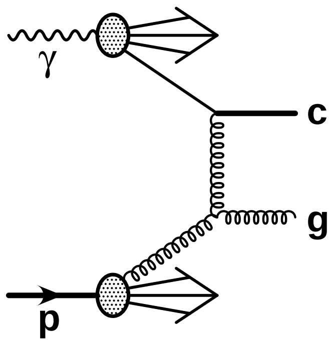
Photon can be either "direct" (no structure, $x_\gamma = 1$) or "resolved" (SF, $x_\gamma < 1$):



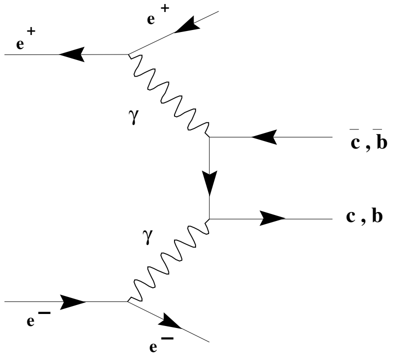




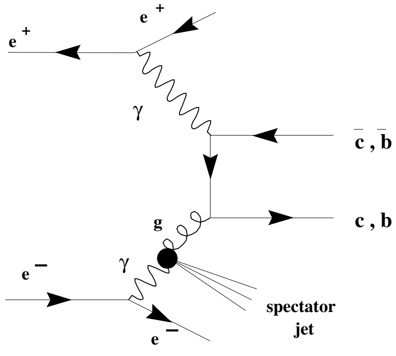
$Qg \rightarrow Qg$, Q **excit.**
(q **propagator)**



$Qg \rightarrow Qg$, Q **excit.**
(g **propagator)**



Direct



Single Resolved

In NLO only sum of direct and resolved is unambiguously defined

Perturbative QCD Calculations

Monte Carlo with LO matrix elements and parton showering

Fixed-order ("massive") NLO calculations (MNR, FMNR, HVQDIS) :

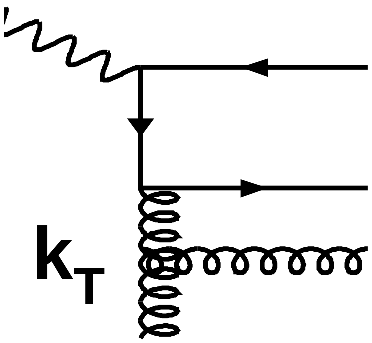
Charm : $n_f = 3$: (u, d, s) are active flavors in p and γ
Beauty : $n_f = 4$: (u, d, s, c) are active flavors in p and γ
not valid for $p_\perp \gg m_Q$ ($Q \gg m_Q$) (large logarithms $\frac{p_\perp}{m_Q}$, $\frac{Q}{m_Q}$)

Resummed ("massless") NLL calculations (Cacciari et al., Kniehl et al.) :

Charm : $n_f = 4$: (u, d, s, c) are active flavors in p and γ
Beauty : $n_f = 5$: (u, d, s, c, b) are active flavors in p and γ
valid only for $p_\perp \gg m_Q$ ($Q \gg m_Q$) (large logarithms are resummed)

Matched calculations (FONLL)

k_t–factorization (semi-hard) calculations (CASCADE, H.Jung et al.) :



non-collinear approach

"unintegrated"

k_t–dependent gluon density

(CCFM-like in CASCADE)

From c(b)-quark to final state hadron (lepton)

Fragmentation (branching) Fractions

universal for all calculations

$$f(c\to D),\ f(c\to l),\ f(b\to B),\ f(b\to l)$$

measured in ee and pp interactions (PDG, hep-ex/9912064, ...)

Fragmentation Functions

dependent from perturbative part

Charm : Peterson's FF : $D_c(x) = N\frac{x(1-x)^2}{[(1-x)^2+\epsilon x]^2}$ $\quad x = \frac{p_{D^*}}{p_c}$

Fixed-order approach (NLO fits of P. Nason and C. Oleari) :

$\epsilon(D^*, D_s) = 0.035$ ARGUS data $\Leftarrow$ Recommended

Resummed approach (LEP data fit):

Kniehl et al. $\epsilon(D^*) = 0.116$

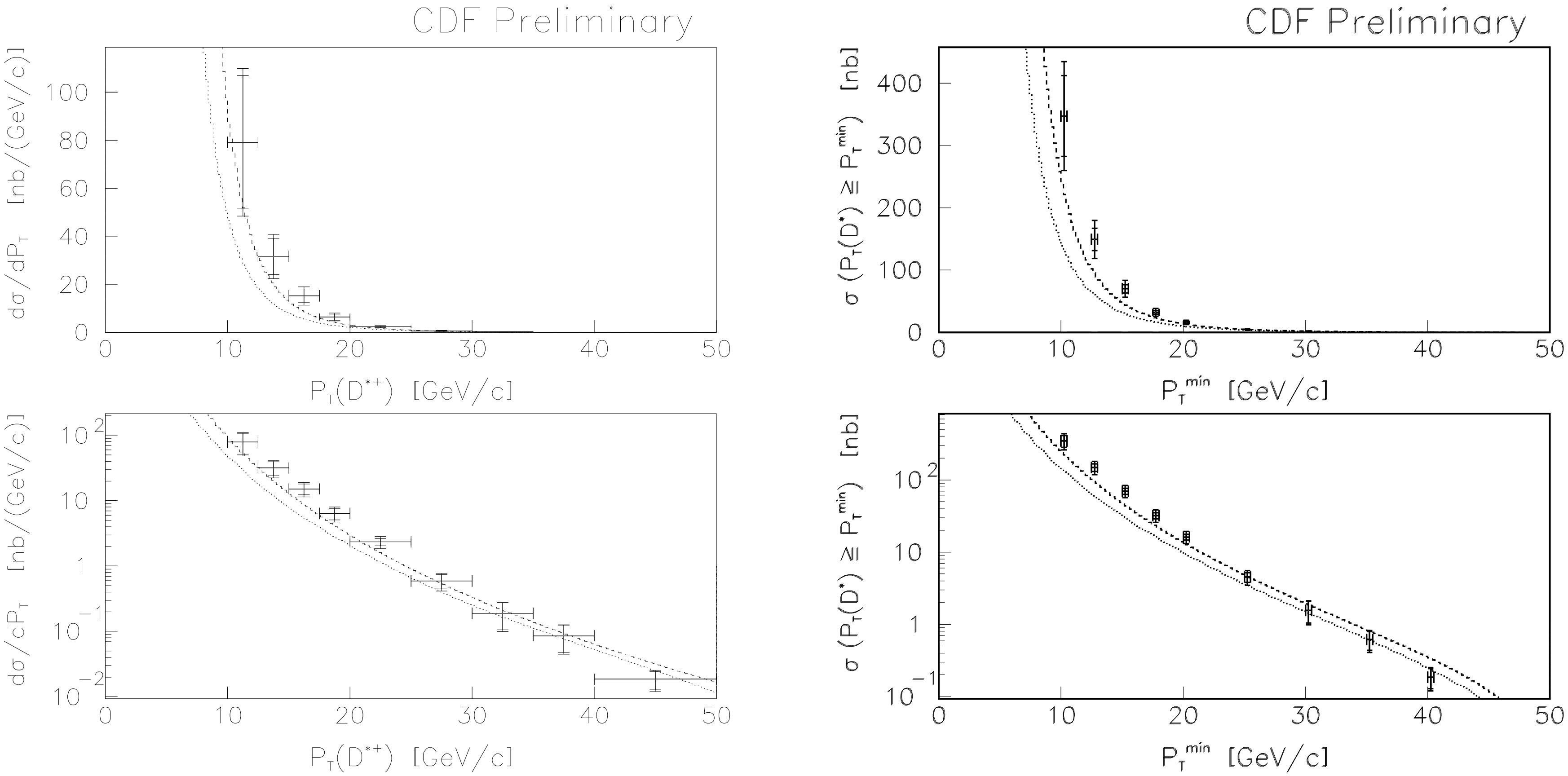
Cacciari et al. $\epsilon(D^*) = 0.020$

Beauty : $\epsilon_b \approx \epsilon_c \cdot (m_c/m_b)^2 \approx 0.0035$ for Peterson's FF

recent measurements (ALEPH, SLD) favor Kartvelishvili et al. FF

Charm in pp Scattering

CDF : $D^{*\pm} \to D^0\pi_S^{\pm},\ D^0 \to K\mu + X,\ P_T(D^*) > 10\,\text{GeV},\ |\eta(D^*)| < 1.0$



dashed (upper) curves - M.Cacciari, NLL, $m_c = 1.5$, $\mu^2 = m_\perp^2 = (p_T^2 + m_c^2)$, CTEQ4M
$f(c \to D^{*+}) = 0.222$, Peterson FF with $\epsilon = 0.02$

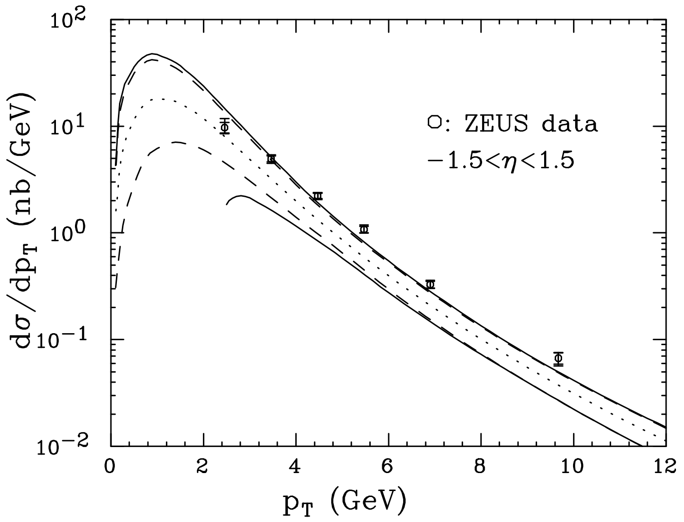
dotted (lower) curves - M.Mangano et al., NLO, $m_c = 1.5$, $\epsilon = 0.078$

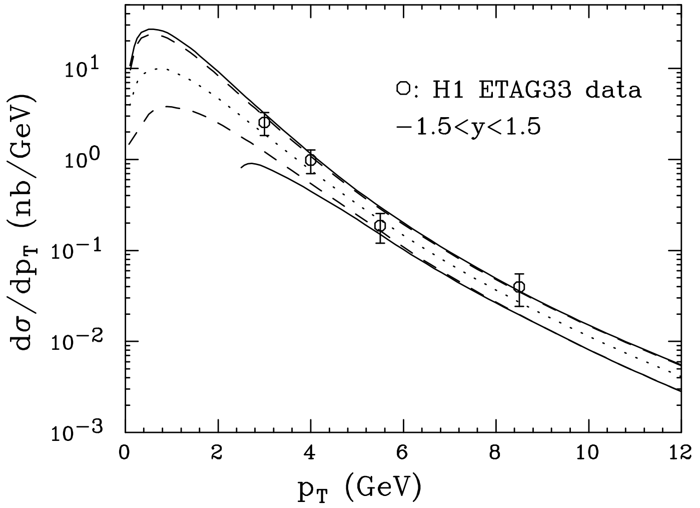
Theoretical predictions are lower than measured cross sections

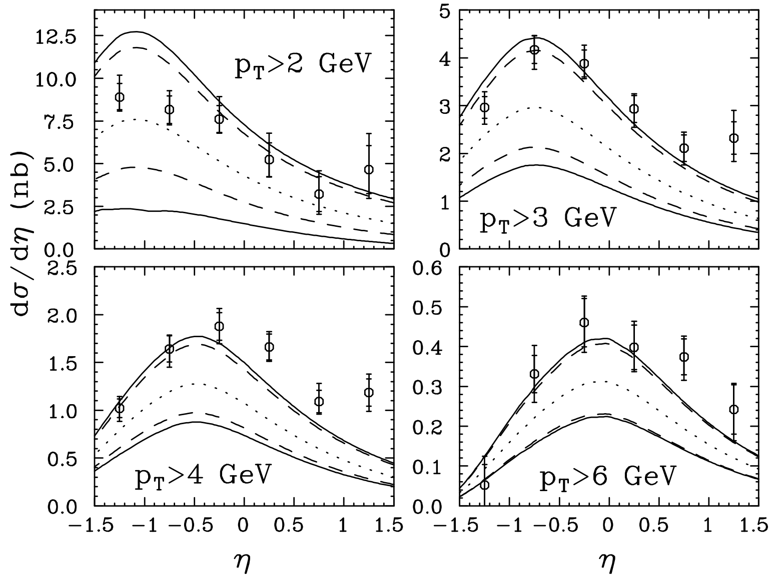
Data show more steeply falling transverse momentum spectrum

Charm in ep Scattering, Photoproduction

H1, ZEUS : $D^{*\pm} \to D^0 \pi_S^\pm$, $D^0 \to K^\mp \pi^\pm$, Photoproduction: $Q^2 \sim 0$







curves - S.Frixione et al., FONLL

dotted - central prediction : $m_c = 1.5$, $\mu^2 = m_\perp^2$
$f(c \to D^{*+}) = 0.235$, Peterson with $\epsilon = 0.02$

solid - all uncertainties added linearly
$m_\perp^2/2 < \mu^2 < 2 \cdot m_\perp^2$, $1.2 < m_c < 1.8$

dashed - w/o factorization scale uncertainties

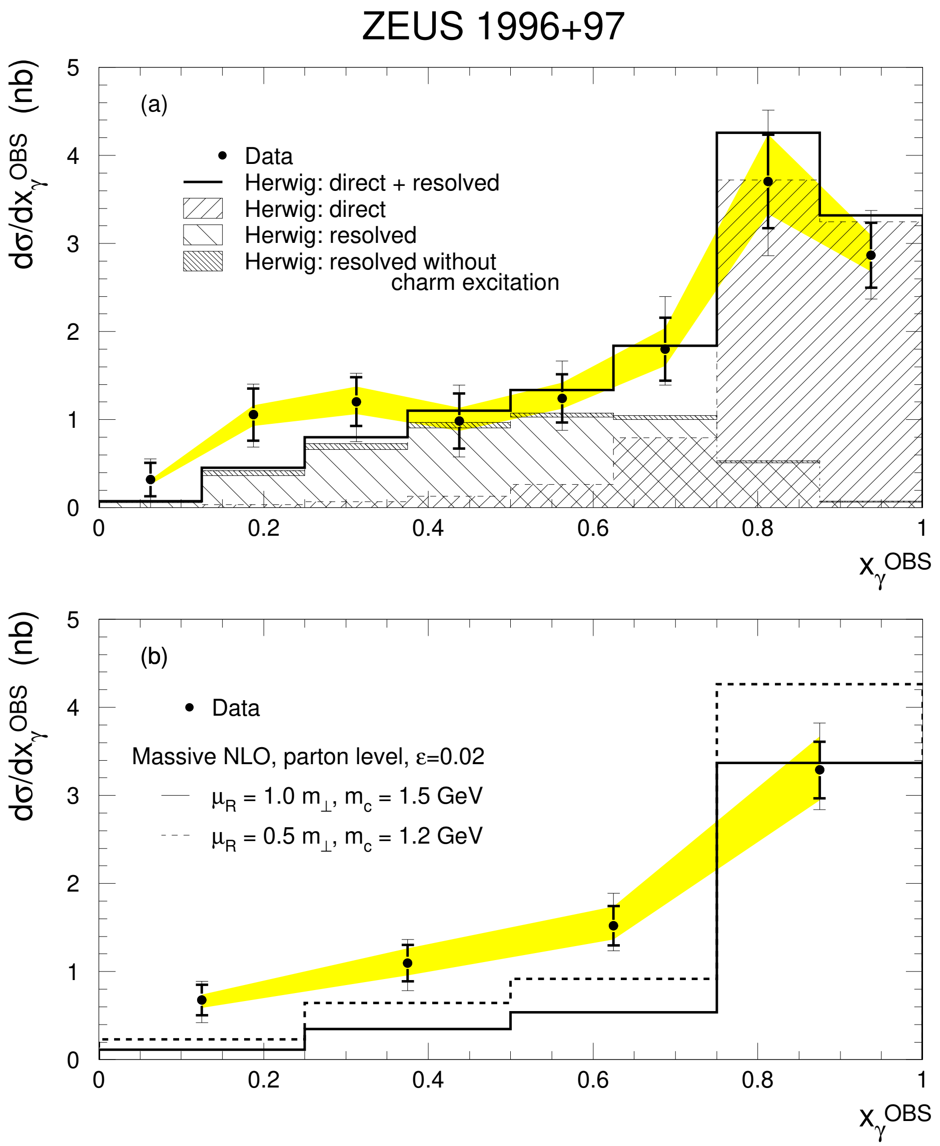
The uncertainties are too large ! NNLO ?

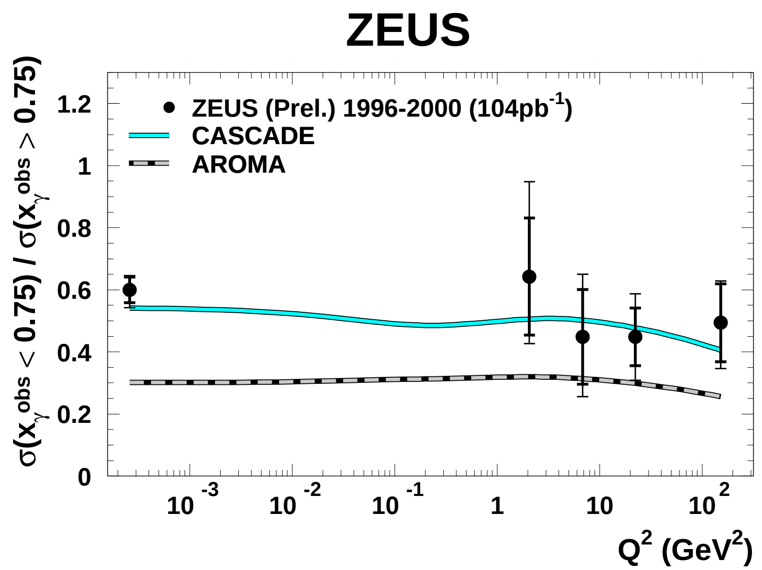
Theoretical predictions are marginally consistent with data (upper band)

Disagreement in positive-η region (proton direction). Fragmentation or NNLO ?

Charm in ep Scattering, Dijet Photoproduction and DIS

ZEUS : $D^{*\pm}$ and at least two jets, $x_\gamma^{OBS} = \frac{E_T^{jet1} e^{-\eta^{jet1}} + E_T^{jet2} e^{-\eta^{jet2}}}{2yE_e}$





Sizable LO resolved γ contribution

Charm excitation in photon (≈ 40 %)

No strong suppression with Q^2

CASCADE describes reasonably well w/o explicit resolved γ component

⟵ NLO are below data at low x_γ^{OBS}

NNLO ? NLL ? FONLL ? CCFM gluon ?

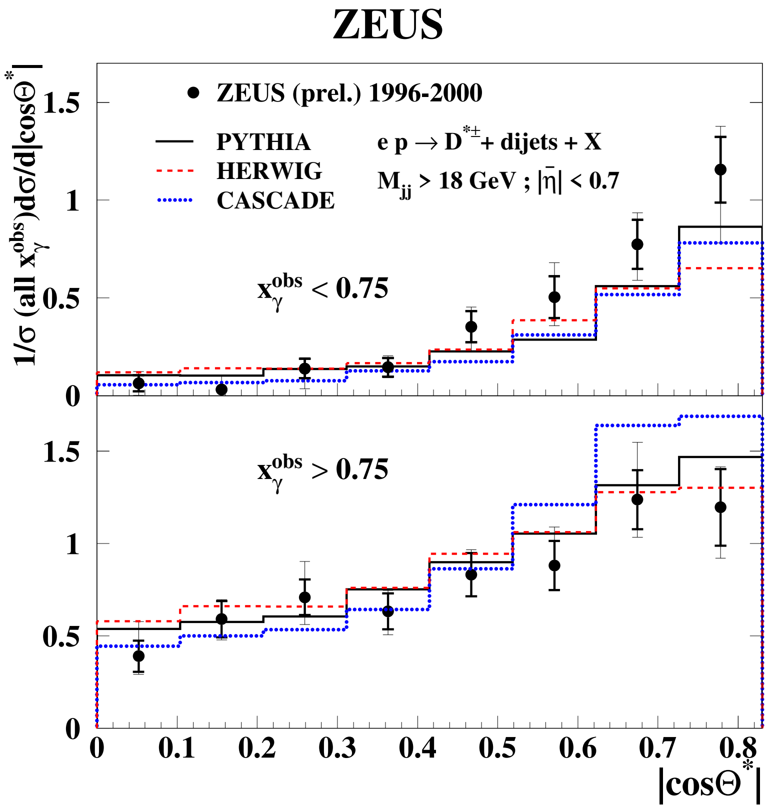
Charm in *ep* Scattering, Dijet Photoproduction

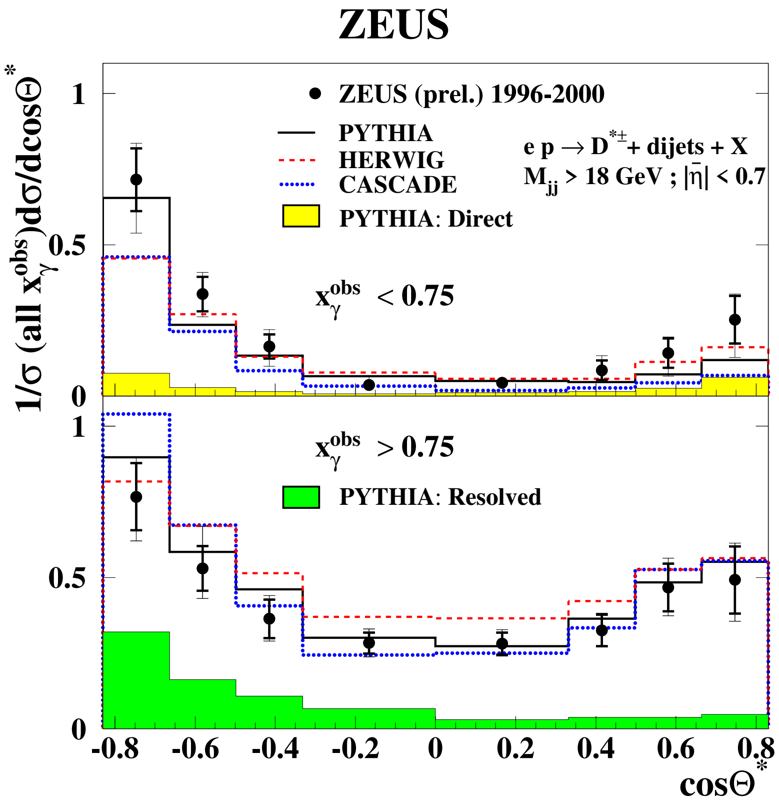
Observable : the angle between jet-jet axis and beam axis in the dijet rest frame

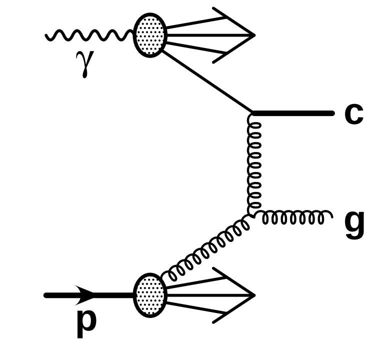
$$\cos\theta^* = \tanh\frac{\eta^{jet1}-\eta^{jet2}}{2}$$

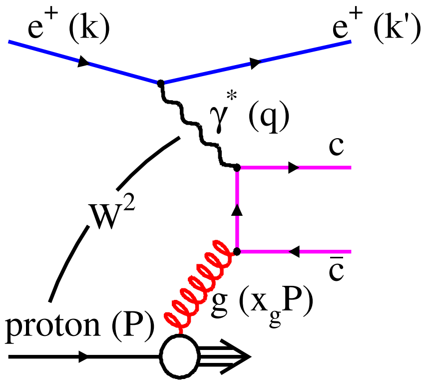
"q propagator" $\propto (1-|\cos\theta^*|)^{-1}$

"g propagator" $\propto (1-|\cos\theta^*|)^{-2}$









A signature of g propagator

More charm in γ direction

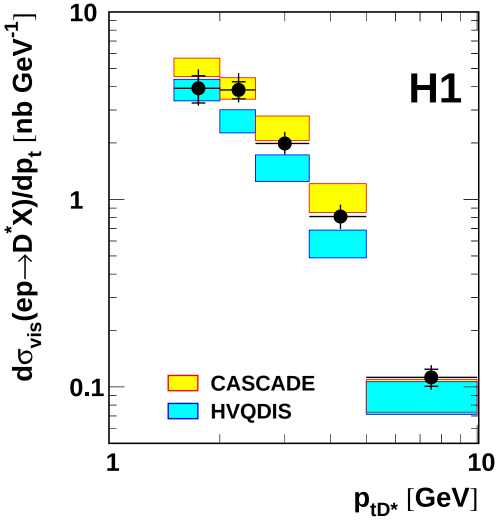
LO generators (HERWIG, PYTHIA) with charm excitation describe well

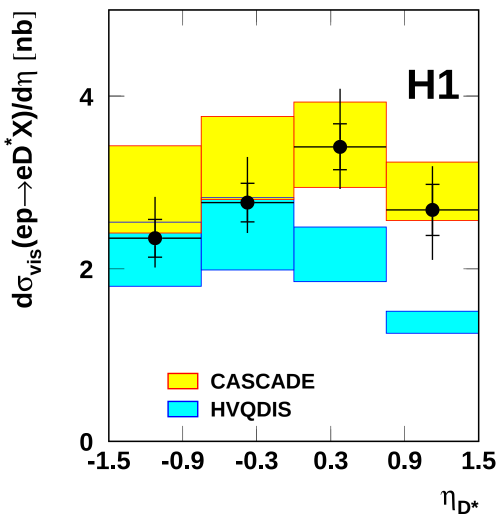
CASCADE describes worse (steeper for $x_\gamma^{obs} > 0.75$) but still reasonably well

Comparison with NLO is really important (and possible)

Charm in *ep* Scattering, DIS

H1, ZEUS : $D^{*\pm}$, $D^{\pm}$, e^- from s-l decays ; DIS: $Q^2 > 1 - 2\,\mathrm{GeV}^2$





$1 < Q^2 < 100\,\mathrm{GeV}^2$; $0.05 < y < 0.7$

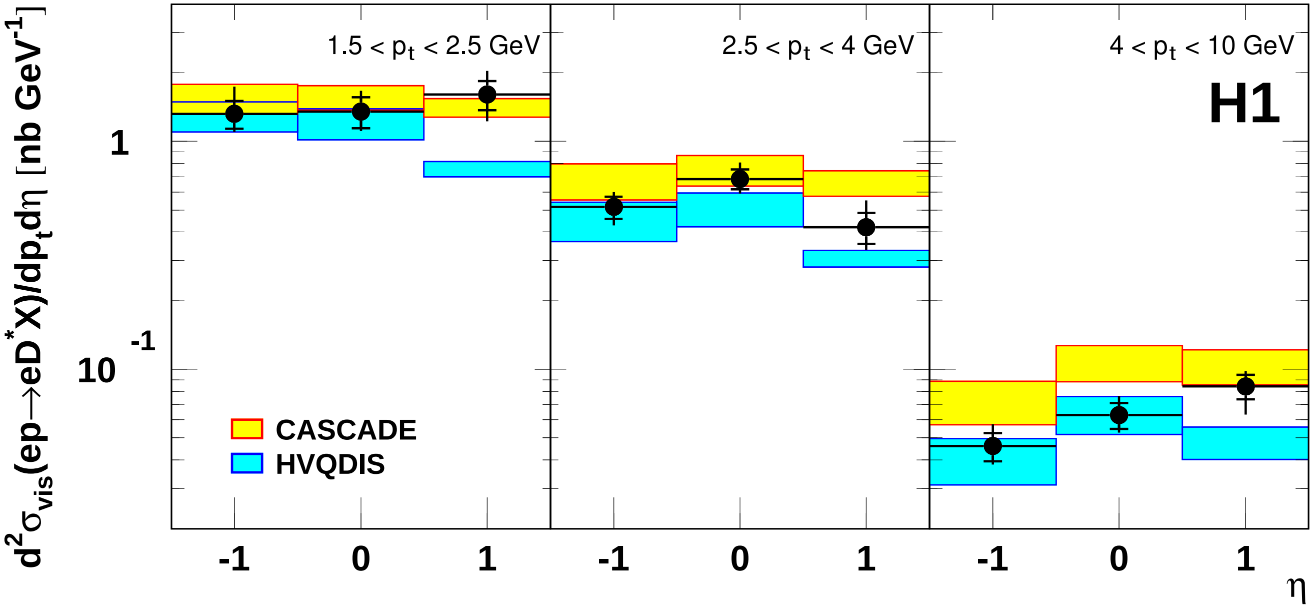
$P_\perp^{D^*} > 1.5\,\mathrm{GeV}$; $-1.5 < \eta^{D^*} < 1.5$

Bands : $1.3 < m_c < 1.5\,\mathrm{GeV}$
and fragmentation

Blue : NLO (HVQDIS, GRV98)

Yellow: CASCADE

CASCADE agrees better



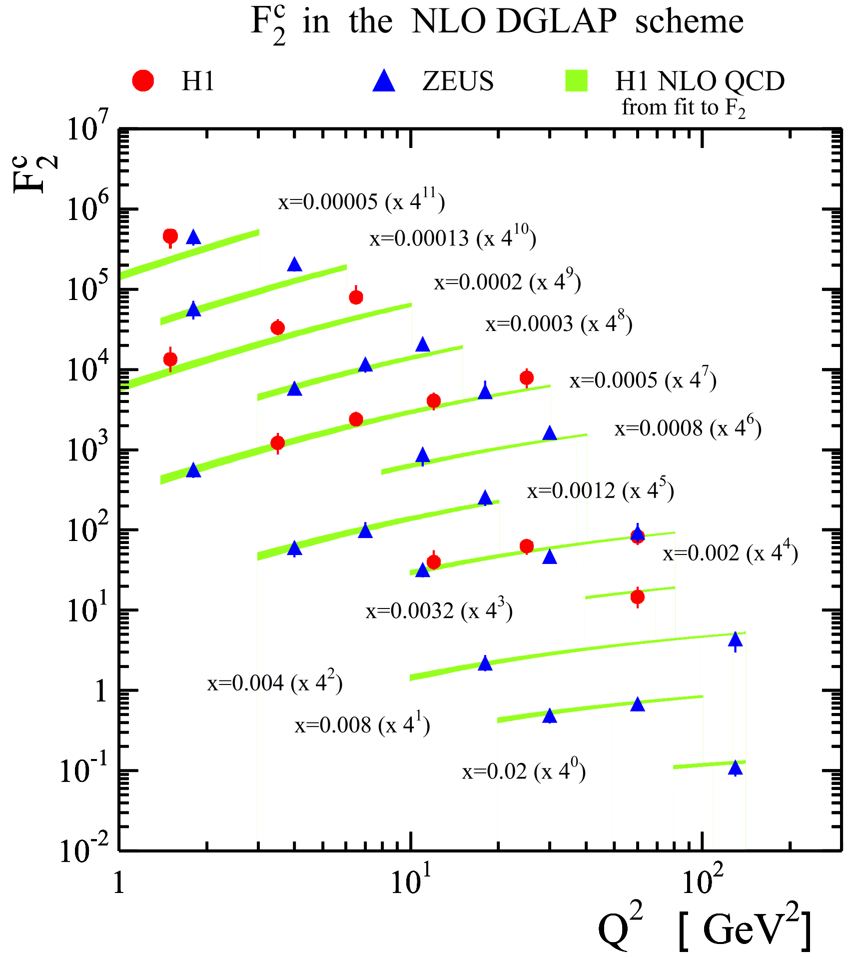
NLO is too low
in positive-η region
(proton direction)

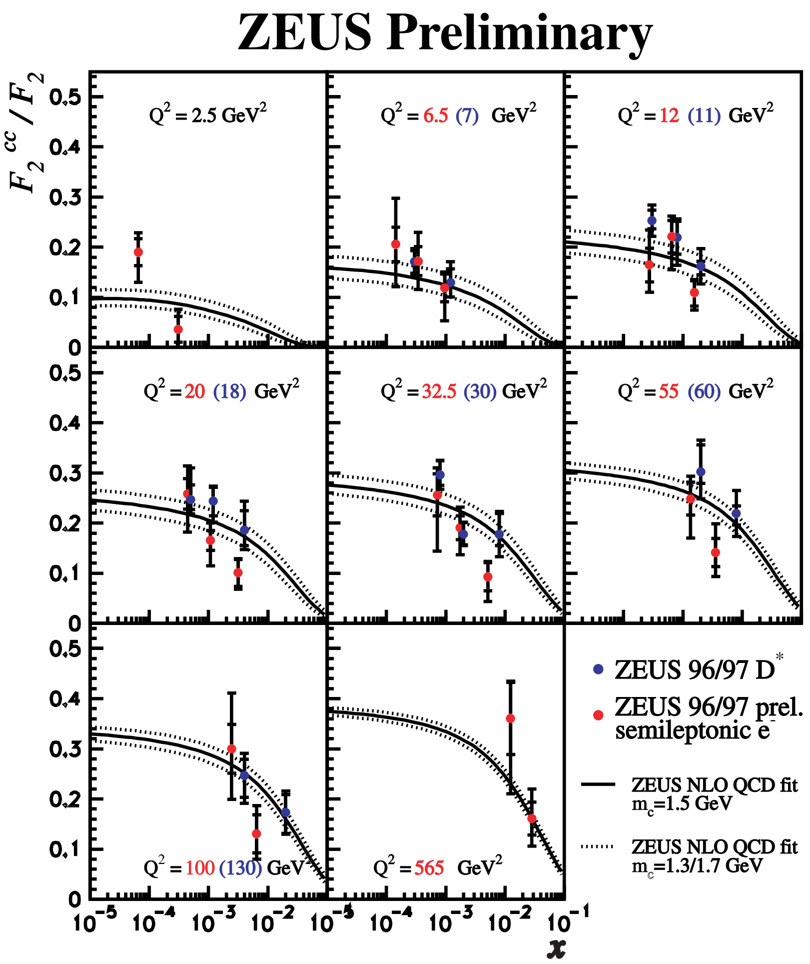
CASCADE is too high
at large $P_\perp^{D^*}$

Predictions have large
uncertainties

Charm in ep Scattering, DIS

Charm contribution to proton SF: $$\frac{d^2\sigma_{c\bar{c}}(x,Q^2)}{dxdQ^2} = \frac{2\pi\alpha^2[1+(1-y)^2]}{xQ^4} F_2^c(x,Q^2)$$



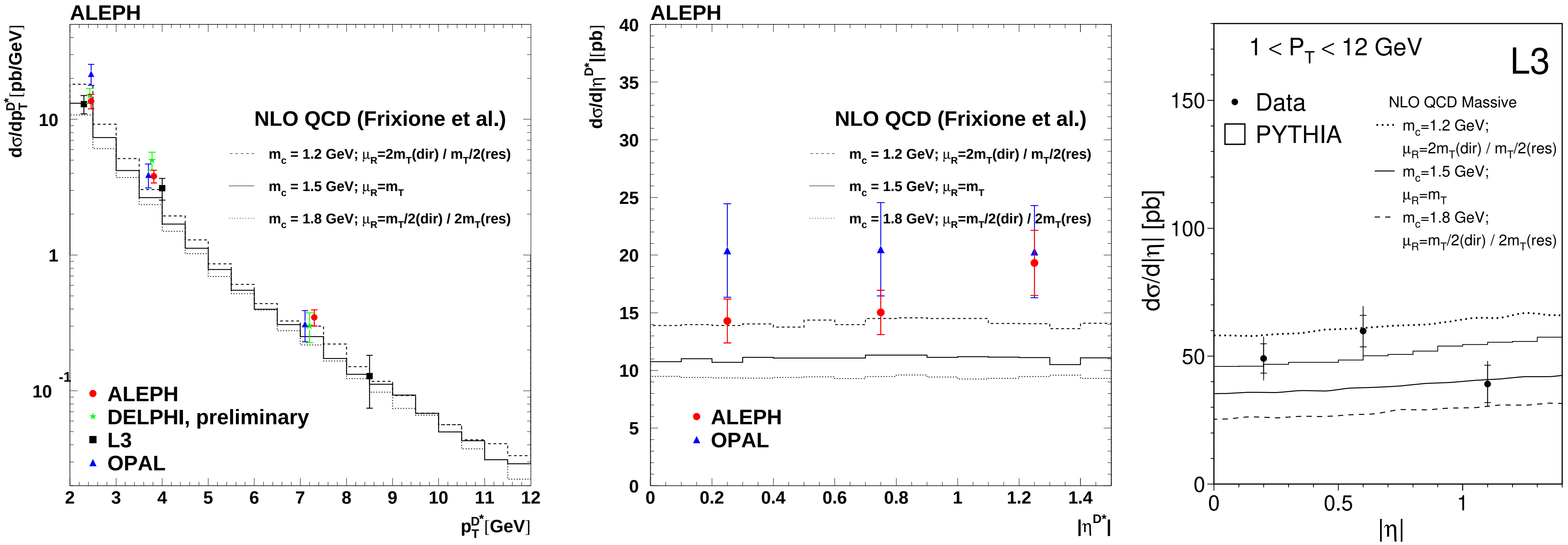


Data tend to be higher and steeper at low x

F_2^c/F_2 is near 40% limit at large Q^2 and small $x_{Bjorken}$ values

Charm in ee Scattering

ALEPH, DELPHI, L3, OPAL : $D^{*\pm}$ in $\gamma\gamma$ Collisions



$\eta(D^{*\pm})$ distributions are flat

curves - S.Frixione et al., NLO (direct + resolved)

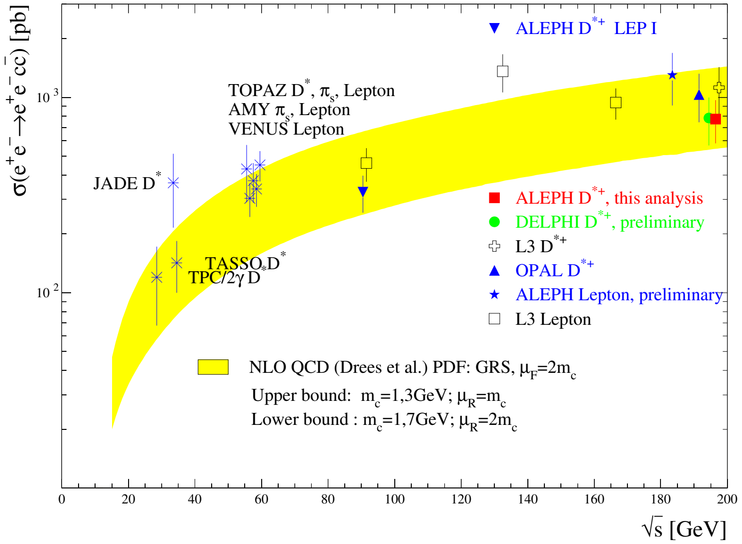
solid - central prediction ($m_c = 1.5$, $\mu^2 = m_\perp^2$) below data

upper - $m_c = 1.2$, $\mu_R = 2m_\perp(\mathrm{dir})/m_\perp/2(\mathrm{res})$ agree reasonably well

experimental and theoretical uncertainties are compatible (and not small)

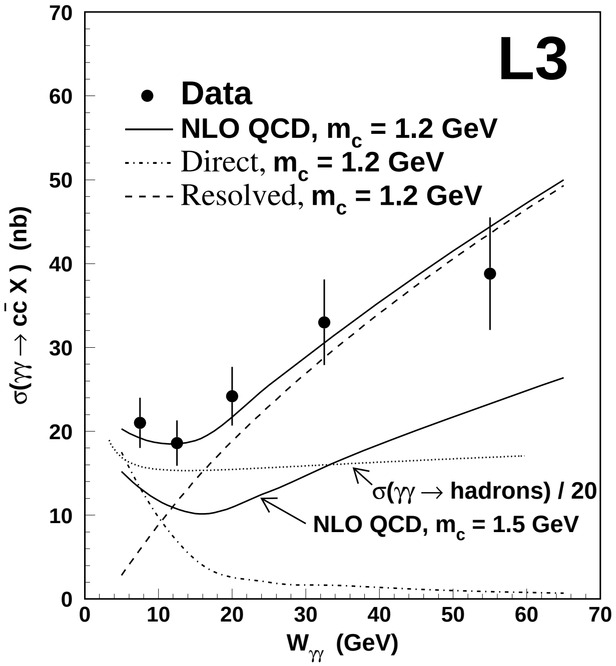
Charm in *ee* Scattering

ALEPH, DELPHI, L3, OPAL : total charm x-section in $\gamma\gamma$ collisions



yellow band - Drees et al., NLO
(direct + resolved)

reasonable agreement with data



L3 : $\sigma(\gamma\gamma\to c\bar{c}X)$ vs $W_{\gamma\gamma}$, $e^{\pm}$ from s-l decays

curves - S.Frixione et al., NLO (direct + resolved)

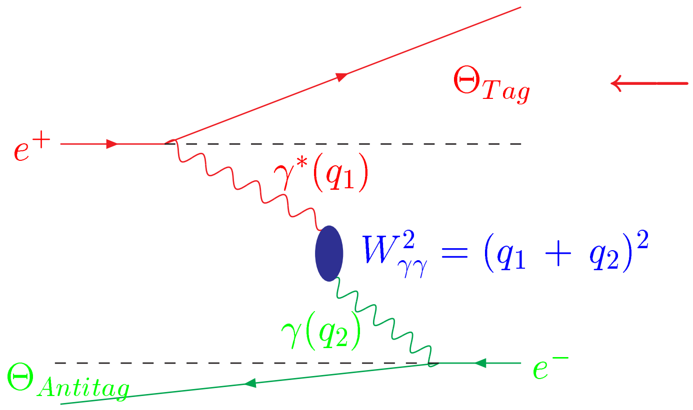
good agreement using $m_c = 1.2$, $\mu_R = m_c$, $\mu_F = 2m_c$
$\Lambda_5^{QCD} = 227.5$, GRS-HO

too low using $m_c = 1.5$, especially for large $W_{\gamma\gamma}$

resolved contribution dominates large-$W_{\gamma\gamma}$ range

Charm in ee Scattering, DIS

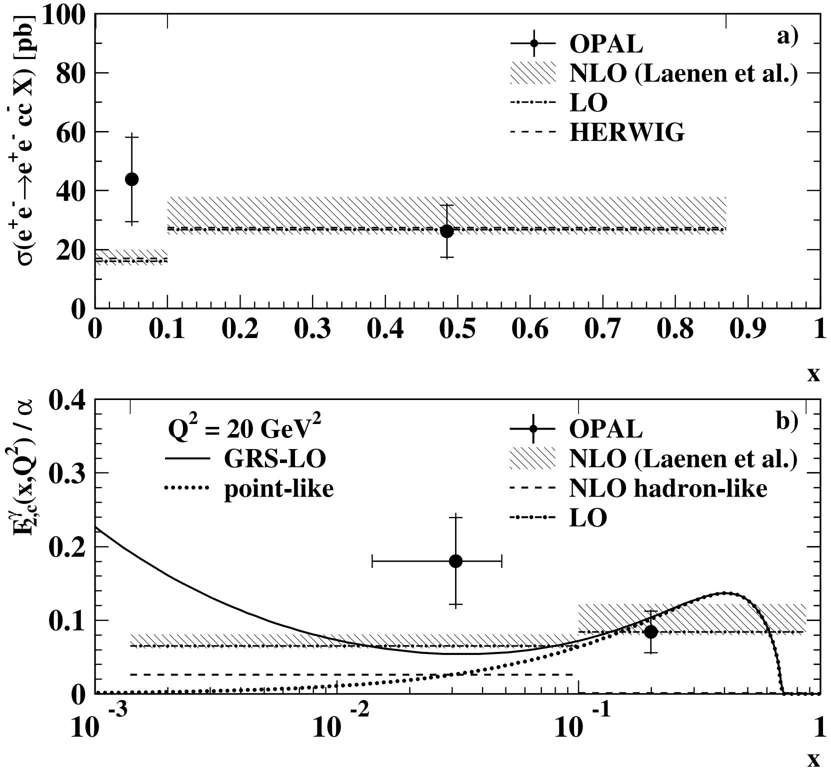
Charm contribution to photon SF: $$\frac{d^2\sigma_{c\bar{c}}(x,Q^2)}{dx\,dQ^2} = \frac{2\pi\alpha^2[1+(1-y)^2]}{xQ^4}\,F^{\gamma}_{2,c}(x,Q^2)$$



$\longleftarrow$ single-tag events (electron or positron detected)

$N(D^{*\pm}) = 55 \pm 10$

$5 < Q^2 < 100\,\mathrm{GeV}^2$, $0.0014 < x < 0.87$



band - E.Laenen et al., NLO (dir + res)
GRV-G HO

$1.3 < m_c < 1.7,\ Q^2/4 < \mu_R = \mu_F < 4Q^2$

$x > 0.1$: perfect agreement
dominated by direct contribution

$x < 0.1$: $\sigma^{EXP} = 43.8 \pm 14.3 \pm 6.3 \pm 2.8\,\mathrm{pb}$

$\sigma^{NLO} = 17.0^{+2.9}_{-2.3}\,\mathrm{pb}$

hadron-like contribution to $F^{\gamma}_{2,c}/\alpha$:

EXP : $0.154 \pm 0.059 \pm 0.029$

NLO : $0.026^{+0.007}_{-0.005}$ too small !

Summary for Charm in *ee* ($\gamma\gamma$), *ep* and *pp* Scattering

pp **, TEVATRON : only one measurement. More results are needed.**

ep **, HERA : wide spectrum of measurements. New results from HERA I and HERA II will come soon.**

ee **, LEP : very interesting results. And statistics are not really high.**

pQCD predictions (NLO, NLL, FONLL) with central choice of parameters typically underestimate cross sections.

Theoretical uncertainties are large. They are larger than experimental errors in many cases.

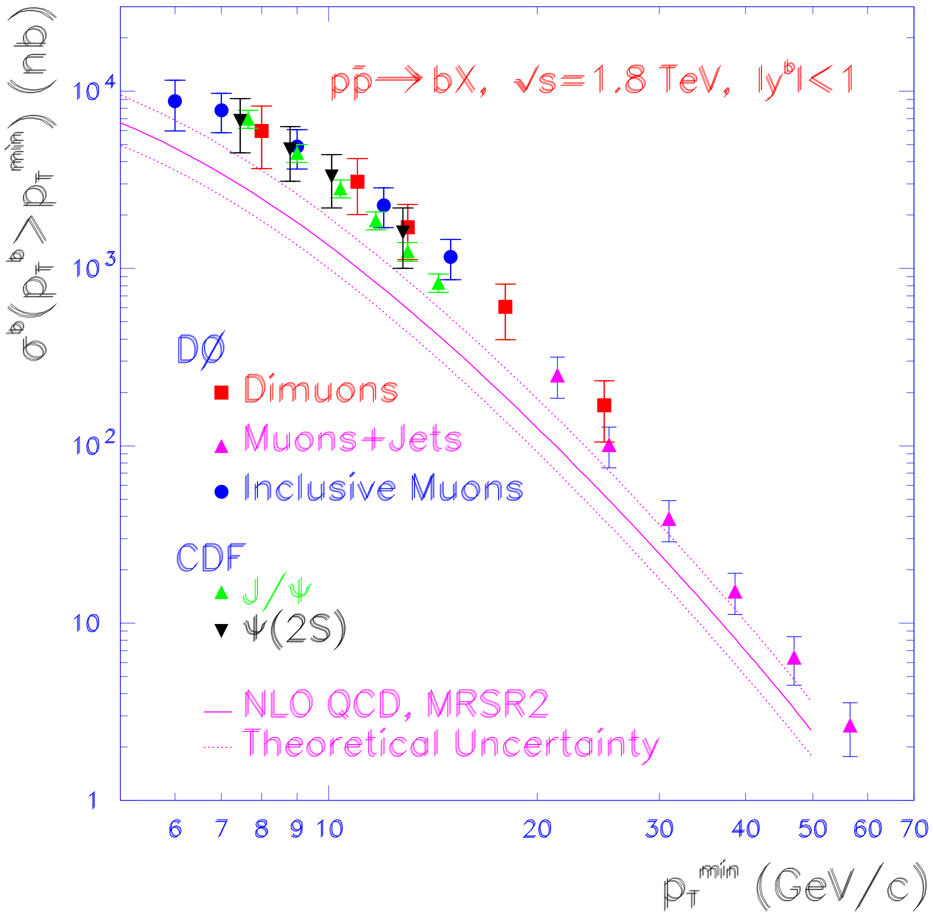
Using small values of m_c and μ_R it is usually possible to describe experimental cross sections.

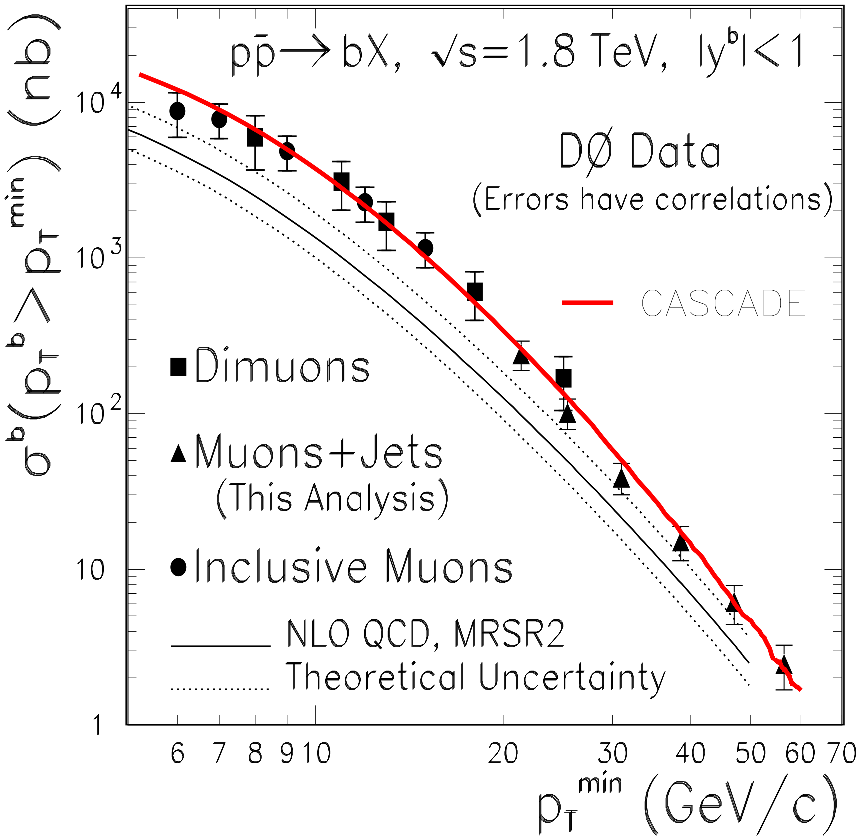
Resolved (hadronic) photon component is the most problematic for NLO.

Will NNLO help ?

Beauty in pp Scattering

CDF, D0 : $\mu^{\pm}$, **dimuons,** $\mu^{\pm}$**+jets,** J/ψ, $\psi(2S)$





NLO - **M. Mangano et al.**
$m_b = 4.75$, $\mu = m_\perp$
MRSR2

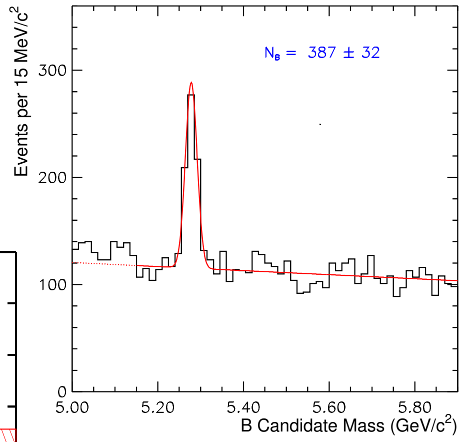
central prediction ∼ 2.5 lower

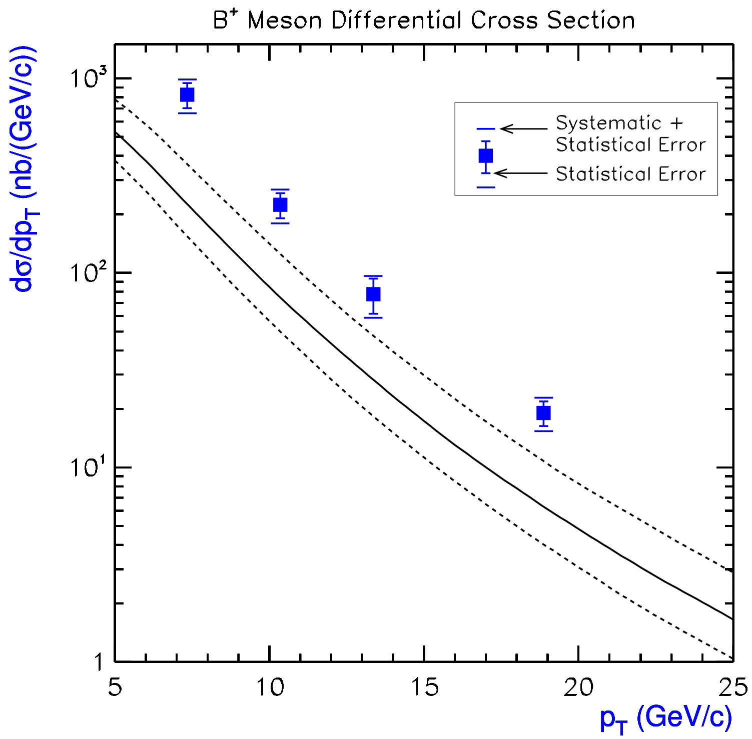
CASCADE - **H. Jung et al.**
$m_b = 4.75$, $\mu = m_\perp$
CCFM gluon from HERA F_2 data

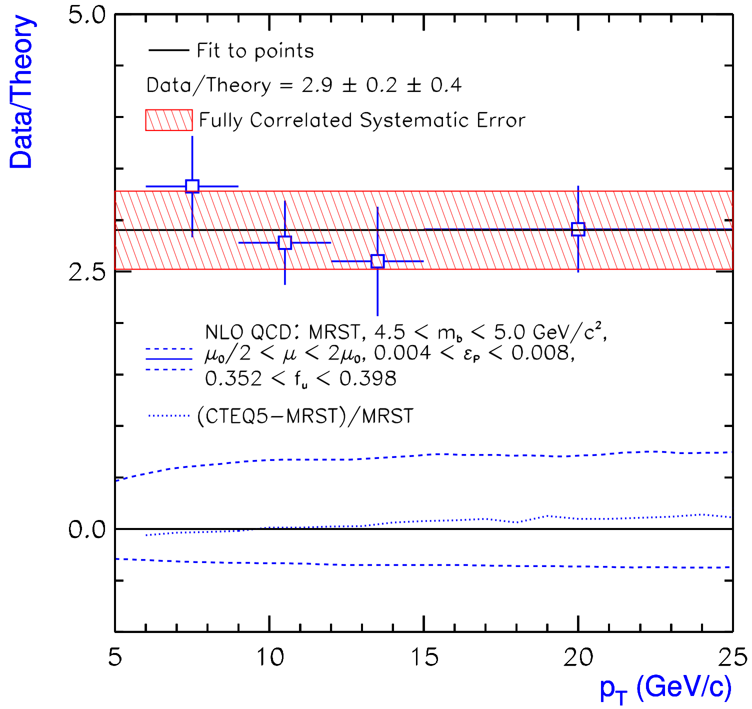
describes measurements

Beauty in pp Scattering

CDF : $B^{\pm} \to J/\psi K^{\pm}$, $p_T(B) > 6\,\mathrm{GeV}$, $|y(B)| < 1.0$







NLO - P. Nason et al., $m_b = 4.75$, $\mu = m_\perp$, MRST

good agreement in shape

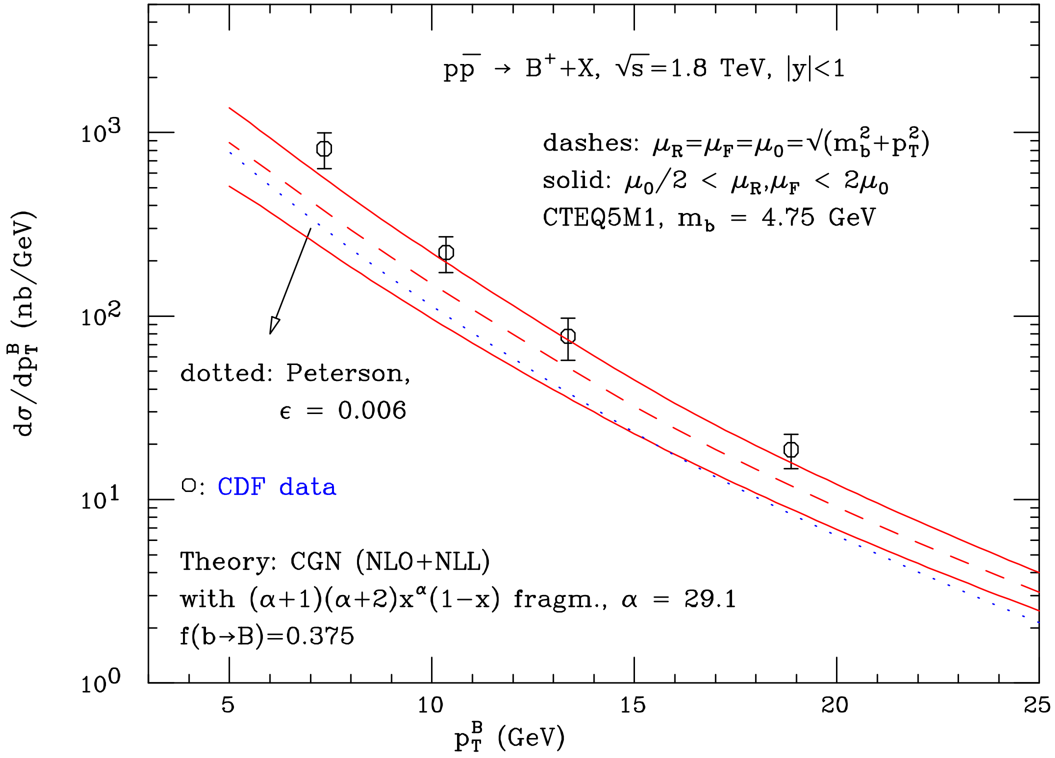
disaster with normalization

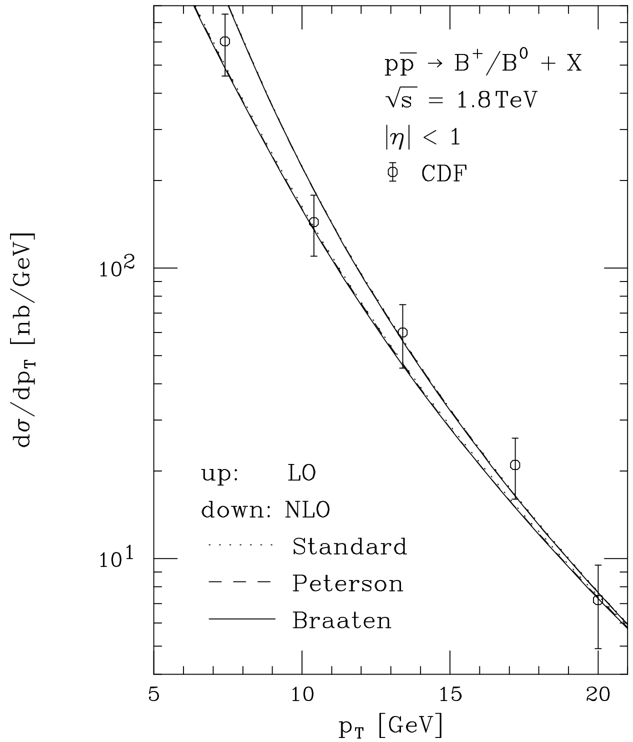
NNLO ? NLL ? Fragmentation ? CCFM gluon ?

Beauty in pp Scattering

CDF : $B^{\pm} \rightarrow J/\psi K^{\pm}$

the same measurement | **preliminary version**





FONLL - M. Cacciari et al.
FF fitted to ALEPH moments space

$\boxed{\text{borderline agreement}}$

NLL - J. Binnewies et al.
FFs fitted to OPAL (3)

$\boxed{\text{reasonable agreement}}$

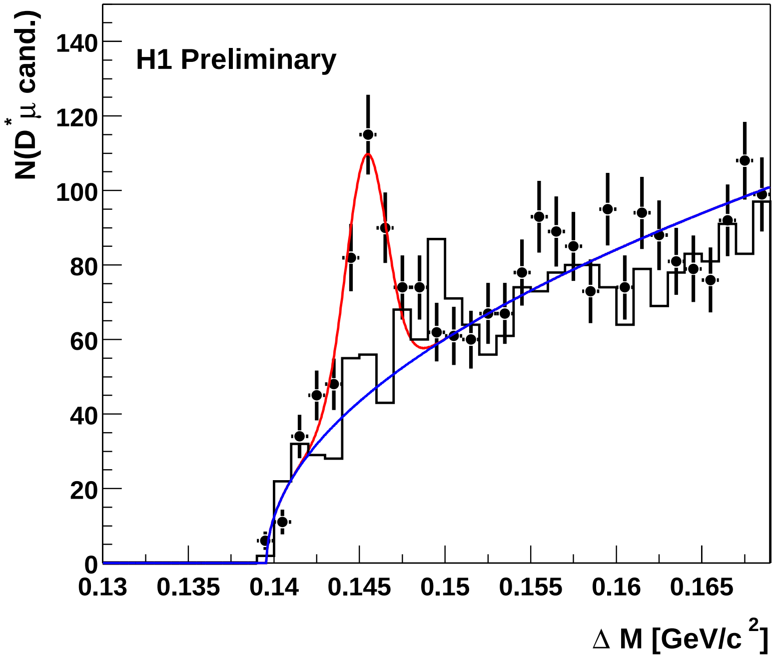
$$\text{Data/Theory} \simeq 1.7 \pm 0.5(exp) \pm 0.4(theor)$$

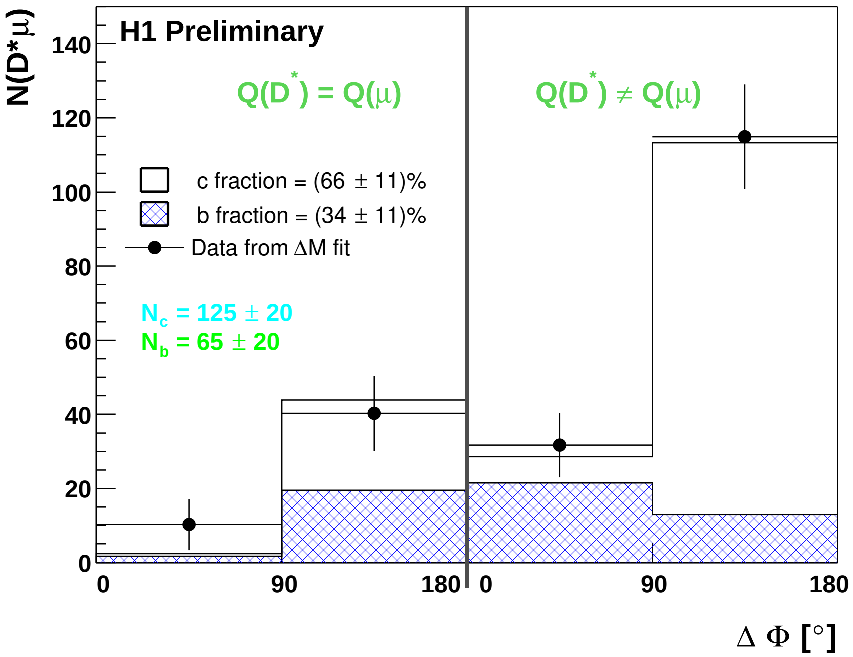
Good enough ? NNLO ?

Beauty in ep Scattering

H1, ZEUS : e^-, $\mu^\pm$

New H1 measurement: $D^{*\pm} + \mu$ $\quad \mathcal{L}_{int} = 91.2\,\mathrm{pb}^{-1}$ (≈all HERA I data)





$$N(D^{*\pm}\mu) = 195 \pm 21 \qquad\qquad f_b = (34 \pm 11)\%$$

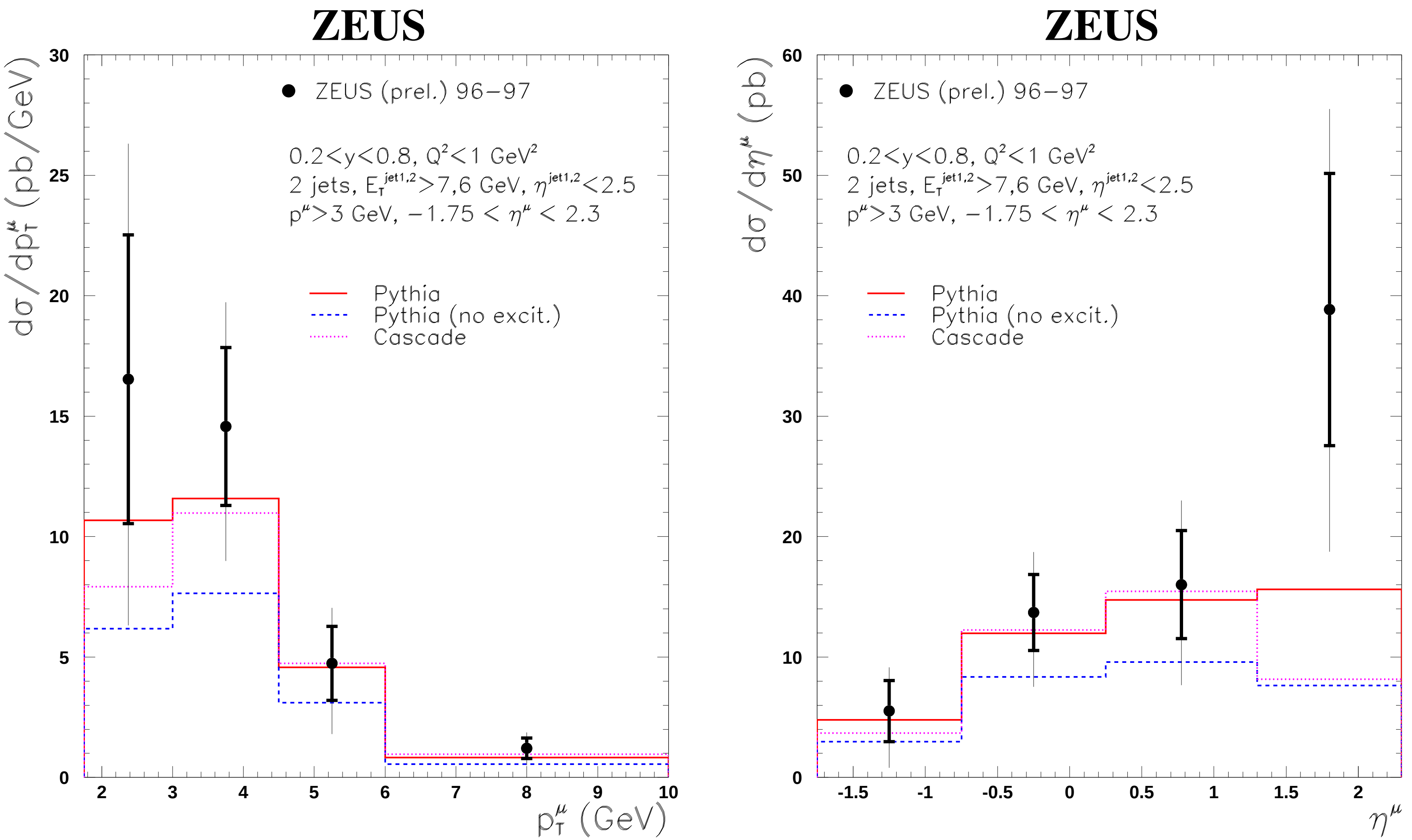
visible range: all Q^2 values, $0.05 < y < 0.75$
$p_T(D^*) > 1.5\,\mathrm{GeV}$, $|\eta(D^*)| < 1.5$
$p_T(\mu) > 1.0\,\mathrm{GeV}$, $20^\circ < \theta(\mu) < 160^\circ$

$$\boxed{\sigma^b_{vis}(ep \rightarrow e' D^* \mu X) = (380 \pm 120 \pm 130)\,\mathrm{pb}}$$

AROMA (direct, LO+PS): $\approx 100\,\mathrm{pb}$ $\longleftarrow$ well below

Beauty in *ep* Scattering

ZEUS : differential cross sections for $\mu^{\pm}$ from beauty s-l decays ($\mathcal{L}_{int} = 38\,\mathrm{pb}^{-1}$)



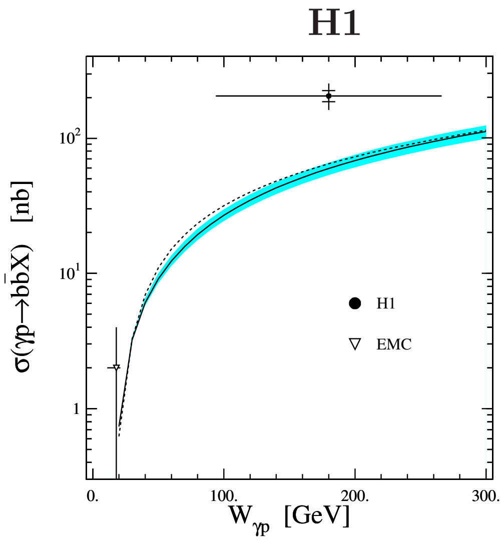
PYTHIA (dir+res, LO+PS) with b-excitation component describes

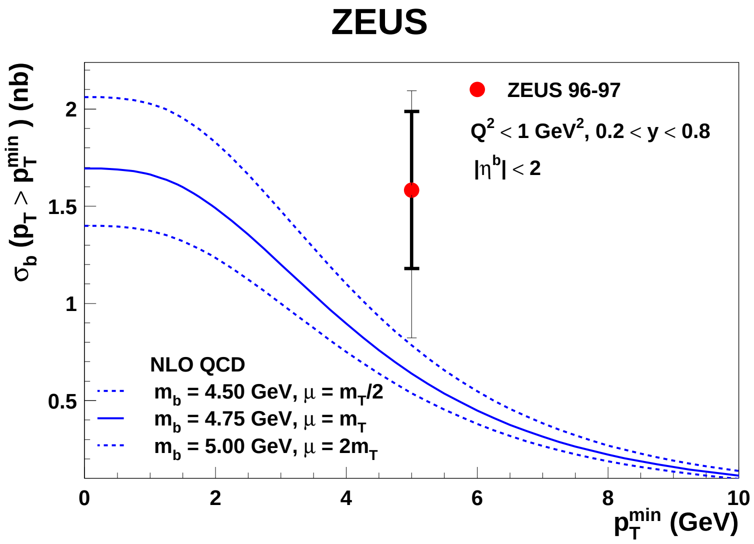
In forward (proton) direction data are above PYTHIA and CASCADE

experimental uncertainties are too large ... will be reduced !

Beauty in *ep* Scattering

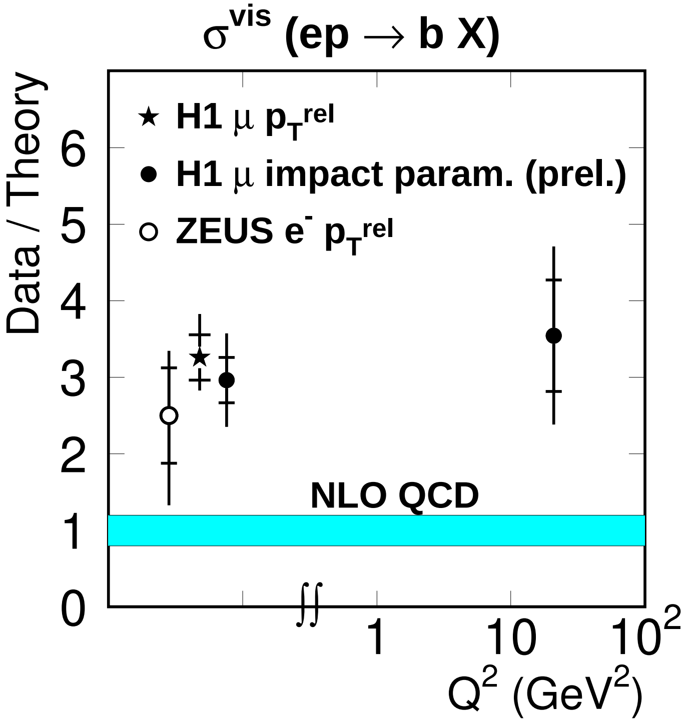
H1, ZEUS : comparison with NLO (S. Frixione et al.)





H1 : well above NLO

ZEUS : somewhat above (less precise though)



$\Longleftarrow$ all σ_B at HERA exceed NLO QCD

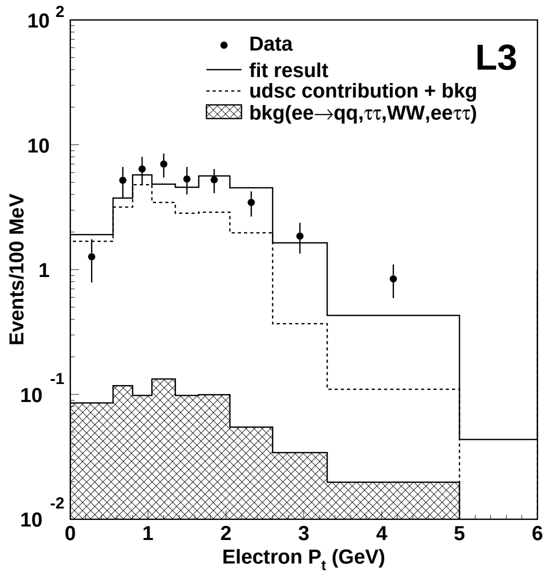
also in DIS : $Q^2 > 2\,\mathrm{GeV}^2$

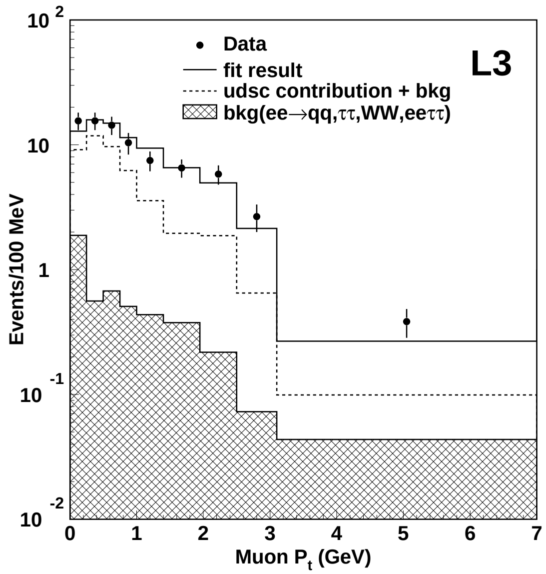
CASCADE $\sim$ 1.3 higher NLO
matches ZEUS but below H1 data

new and more precise
measurements to come soon

Beauty in ee Scattering

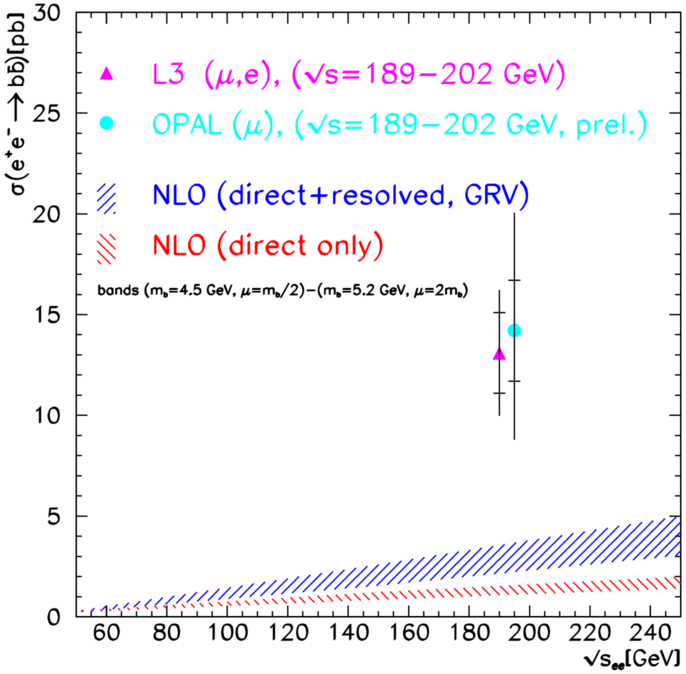
L3, OPAL : $e^{\pm}$, $\mu^{\pm}$ total beauty x-section in $\gamma\gamma$ collisions





$p^{l}_{T.rel}$ wrt jet axis

clear evidence for beauty contribution



bands - NLO, M.Drees et al. (dir+res)
with GRV for γ SF

$(m_b = 4.5,\ \mu = m_b/2) \Longleftrightarrow (m_b = 5.2,\ \mu = 2m_b)$

Data/Theory $\simeq$ 3

CASCADE predicts ... nothing
no unintegrated g for γ yet

Serious problem for pQCD ?

Summary for Beauty in ee ($\gamma\gamma$), ep and pp Scattering

pp , TEVATRON : certainly best place to measure $b\bar{b}$ production. Results from Run I are extensive. Results from Run II will come soon.

ep , HERA : first results obtained. Final results from HERA I and high-statistics results from HERA II will come.

ee , LEP : great results. Will wait new ee collider for new results.

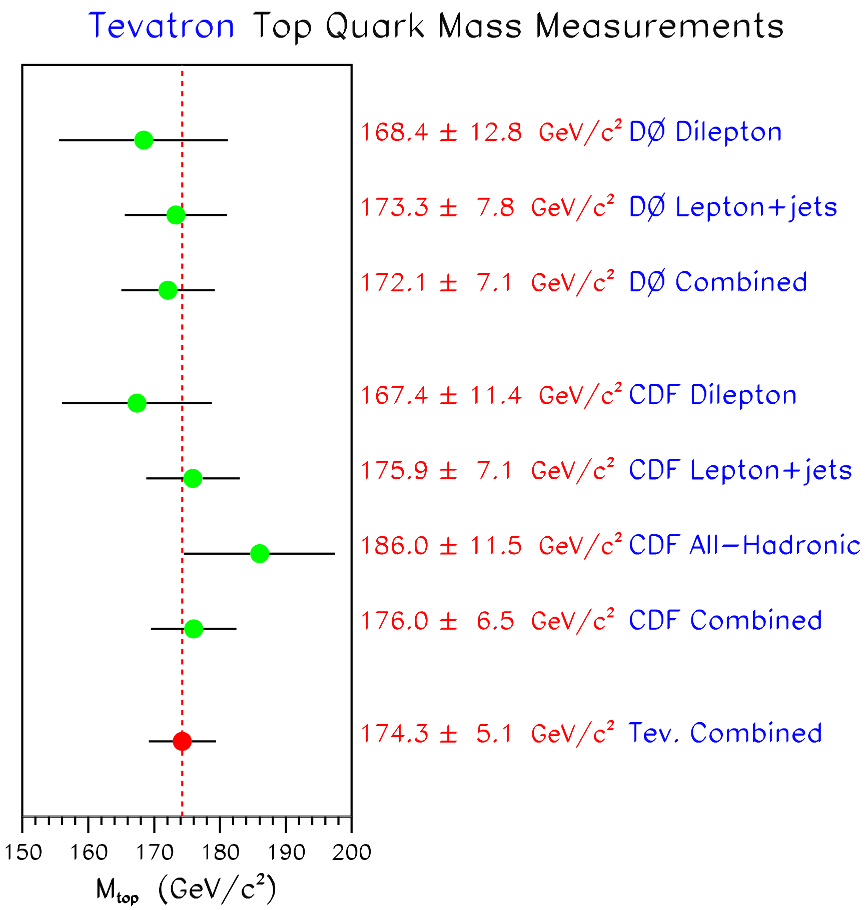
Old good "NLO+Peterson" failed to describe beauty x-sections normalization.

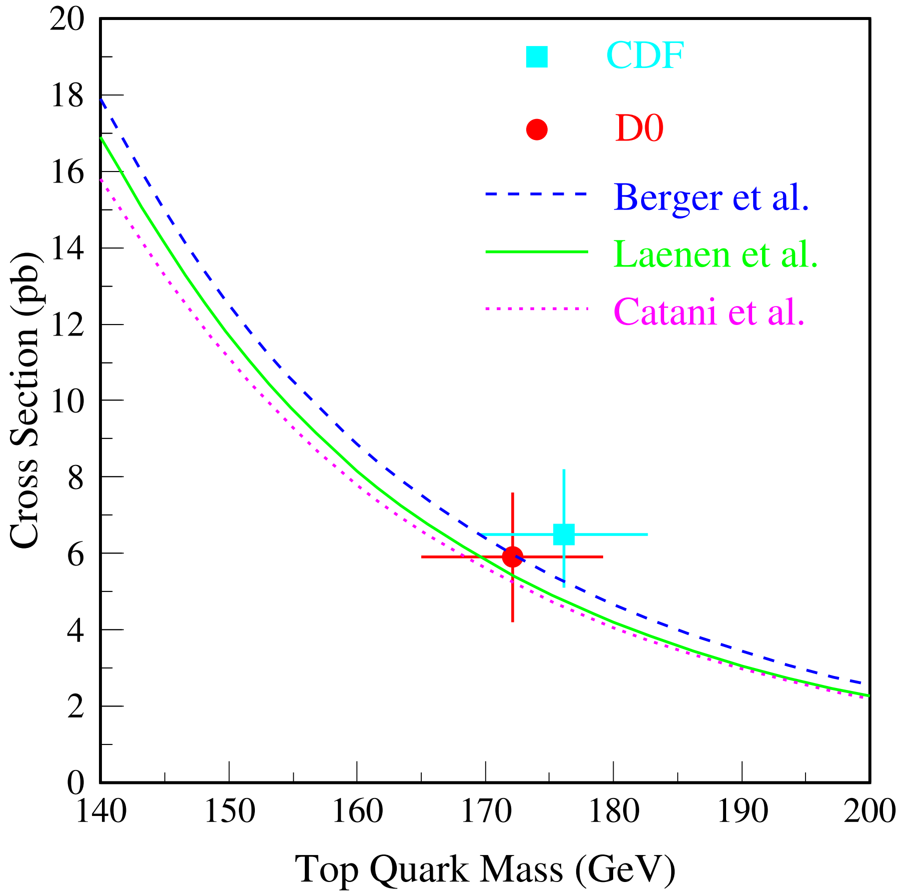
New theoretical developments are promising (NLL, FONLL, Fragmentation, CCFM gluon). Theoretical land-shaft is rather complicated at now.

Can NNLO clarify the picture ?

Top in pp (only) Scattering

CDF, D0 : measure m_t and $\sigma(pp \to t\bar{t}X)$ ("asymptotically" large m_Q)





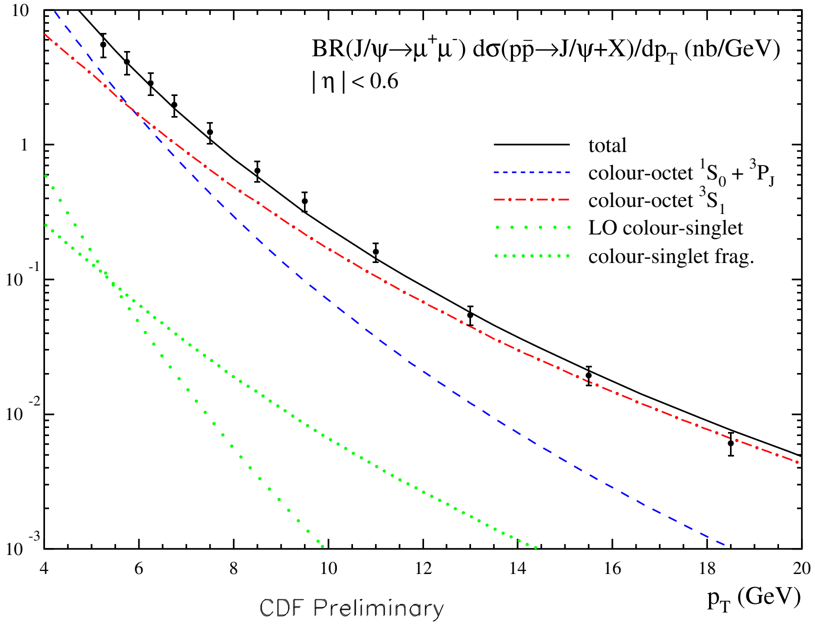
m_t is known with precision 3%

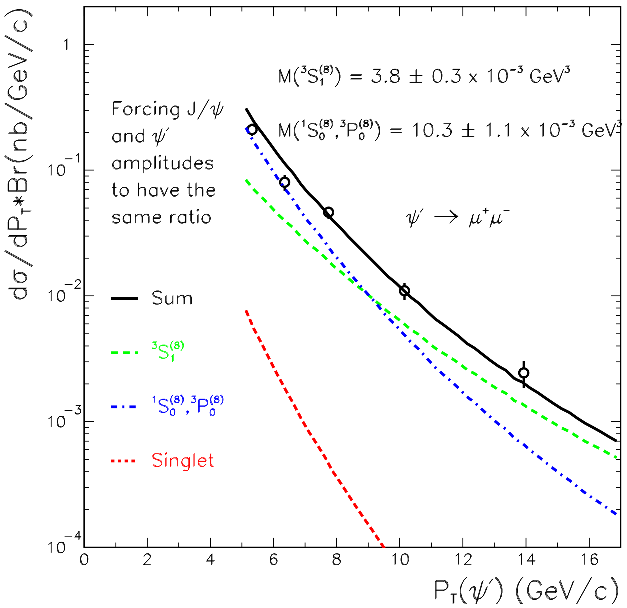
No problems for pQCD yet

More results from TEVATRON Run II and LHC, TESLA, THERA

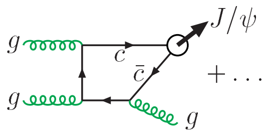
Quarkonium in pp Scattering

CDF: prompt $J/\psi, \psi'$ production



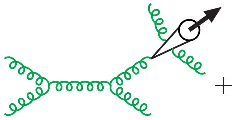


leading-order colour-singlet: $g+g \to c\bar{c}[{}^3S_1^{(1)}]+g$



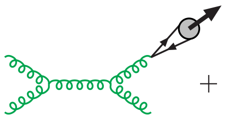
$+\ldots \qquad \sim \alpha_s^3 \frac{(2m_c)^4}{p_t^8}$

colour-singlet fragmentation: $g+g \to [c\bar{c}[{}^3S_1^{(1)}]+gg]+g$



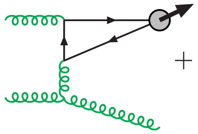
$+\ldots \qquad \sim \alpha_s^5 \frac{1}{p_t^4}$

colour-octet fragmentation: $g+g \to c\bar{c}[{}^3S_1^{(8)}]+g$



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

colour-octet fusion: $g+g \to c\bar{c}[{}^1S_0^{(8)}, {}^3P_J^{(8)}]+g$



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

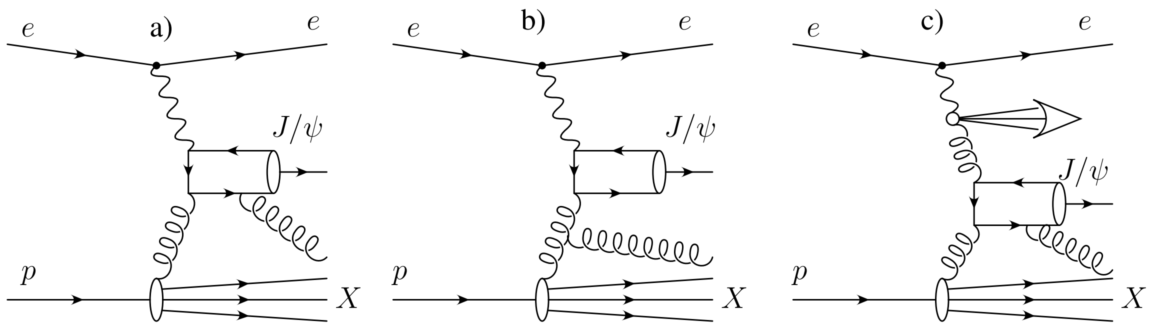
Colour-Singlet predictions 1-2 orders below data

Braaten et al : Colour-Octet based on NRQCD perfectly describes data with 3 non-pert. ME

These Matrix Elements are universal in NRQCD

Quarkonium in ep Scattering

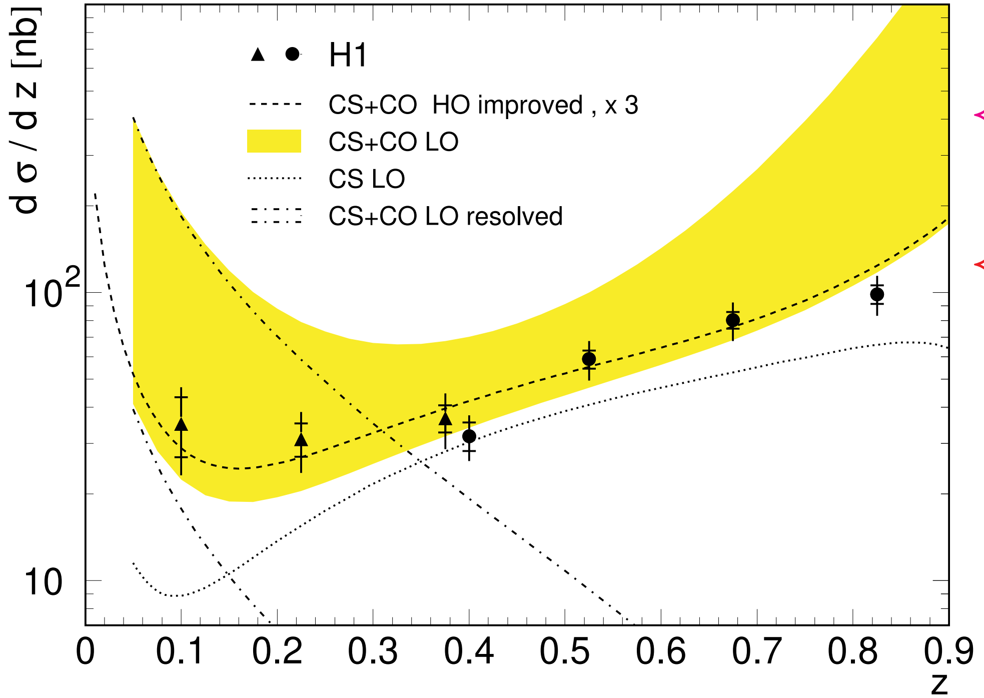
H1, ZEUS : J/ψ (ψ') in photoproduction



$$z \equiv \frac{P_p \cdot P_{J/\psi}}{P_p \cdot P_\gamma}$$

$$= \frac{E_{J/\psi}}{E_\gamma} \text{ in proton cms}$$

Published H1 measurement (ZEUS prel. results agree)

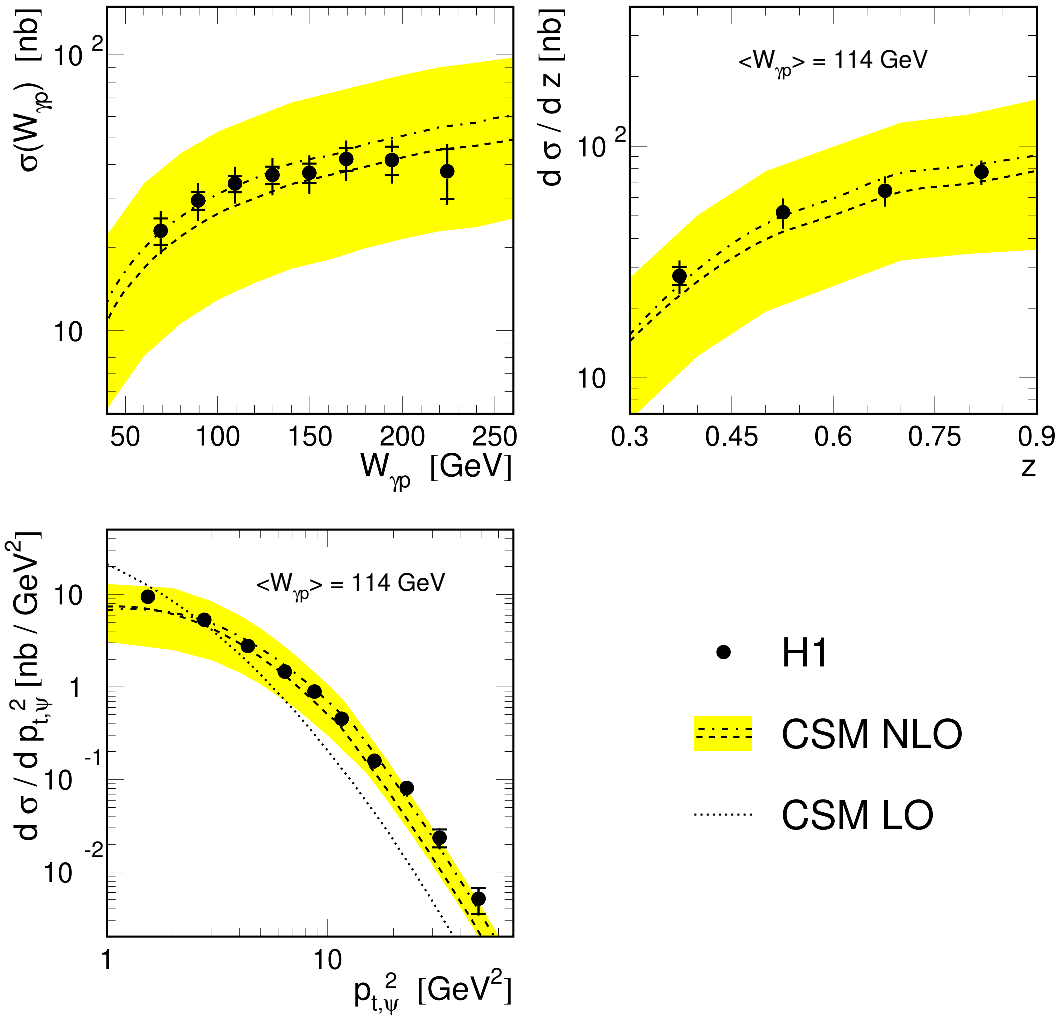


⟸ large uncertainties in CO ME values

⟸ data favor low values of the ME

Quarkonium in ep Scattering

J/ψ photoproduction vs CSM NLO, M.Kraemer et al.



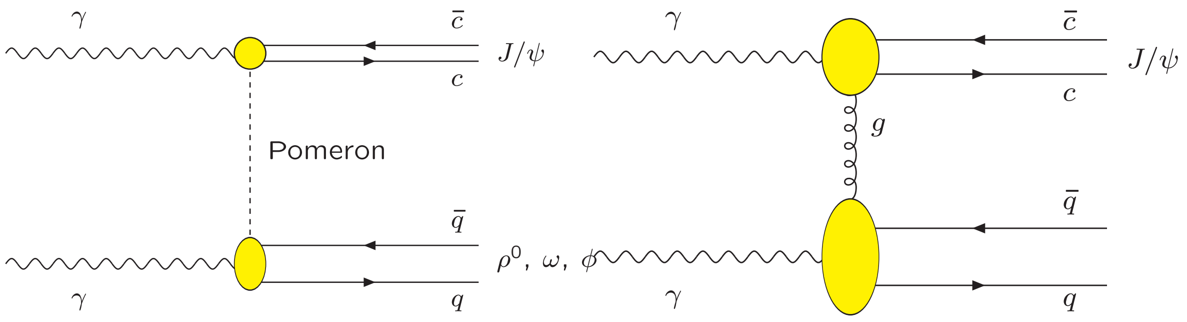
large theor. uncertainties (m_c, α_s)

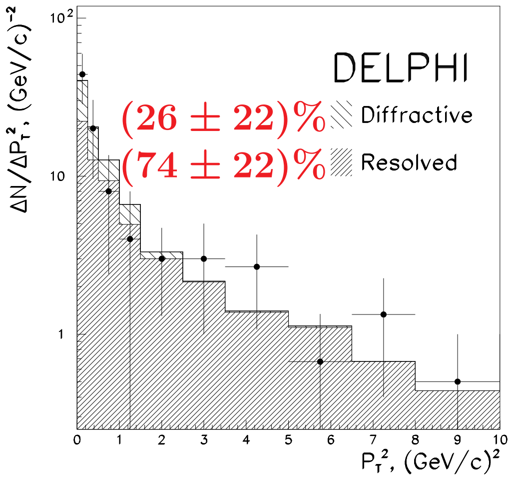
CSM LO too steep in $P_T(J/\psi)$

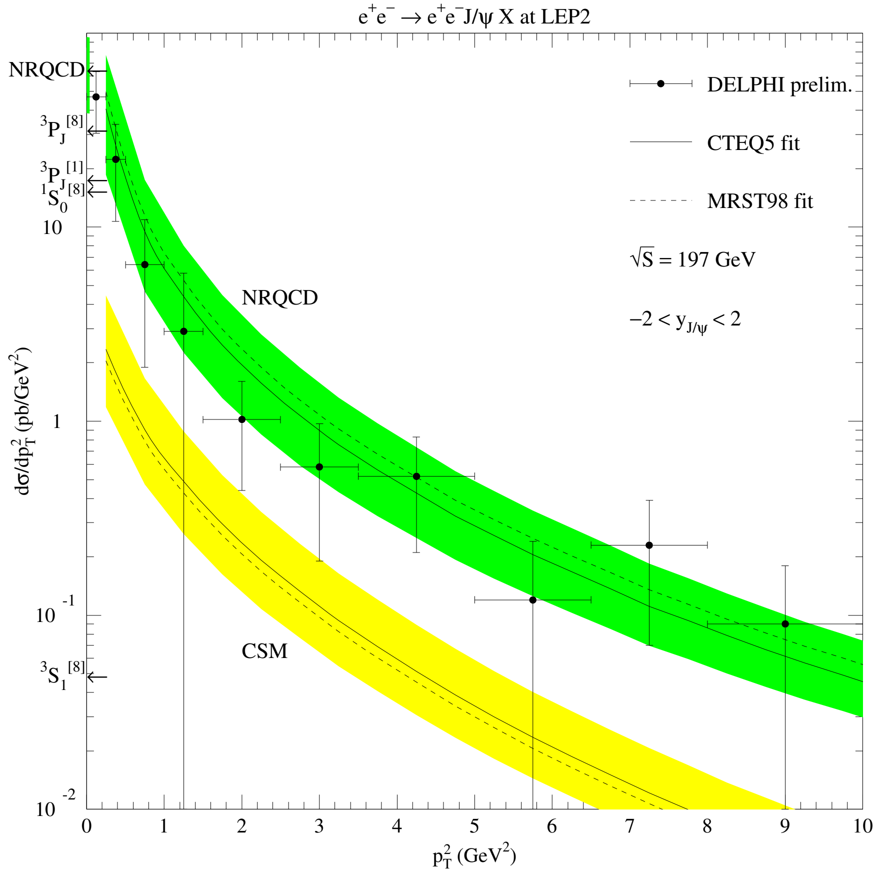
$\boxed{\text{CSM NLO describes data not worse than CO+CS LO}}$

Quarkonium in ee ($\gamma\gamma$) Scattering

DELPHI : $\gamma\gamma \to J/\psi X$, $J/\psi \to \mu^+\mu^-$ $\quad N(J/\psi) = 36 \pm 7$







M. Klasen et al., CO ME fit to CDF and D0

$$m_\perp/2 < \mu < 2m_\perp,\ m_\perp = \sqrt{(2m_c)^2 + p_T^2}$$

$$m_c = 1.5 \pm 0.1,\ \text{GRV-G LO}$$

$\Longleftarrow$ NRQCD CO+CS describes measurement

$\Longleftarrow$ CSM LO is too low

Summary for Quarkonium in *ee*, , *ep* and *pp* Scattering

pp , TEVATRON : results from Run I are extensive. Results from Run II will come soon.

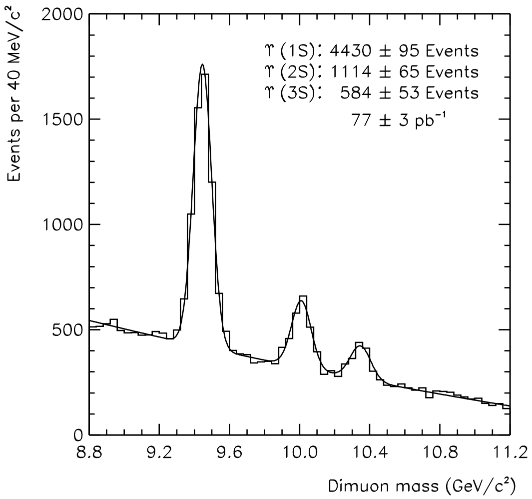
ep , HERA : rather detailed results obtained. New results from HERA I and HERA II will come.

ee , LEP : only one (and very interesting) measurement on $\gamma\gamma \rightarrow J/\psi X$.

ee , Babar, Belle : results on prompt $e^+e^- \rightarrow J/\psi X$ somewhat different but both favor NRQCD.

NRQCD CS+CO predictions are compatible with all J/ψ cross sections.

HERA measurements of direct photon J/ψ production are also described by CSM NLO calculations (although theoretical uncertainties are large).



$\Longleftarrow$ there are also nice results

on Υ production from CDF

can be described by NRQCD (Braaten et al.)

should be complemented by others (HERA II)

Summary and Prospects

Production of Heavy Flavours in *ee*, *ep* and *pp* Scattering is real laboratory for:

- quantitative tests of pQCD
- studies of proton and photon structures

Not all measurements satisfied to predictions that triggered (and continue to trigger) new theoretical developments

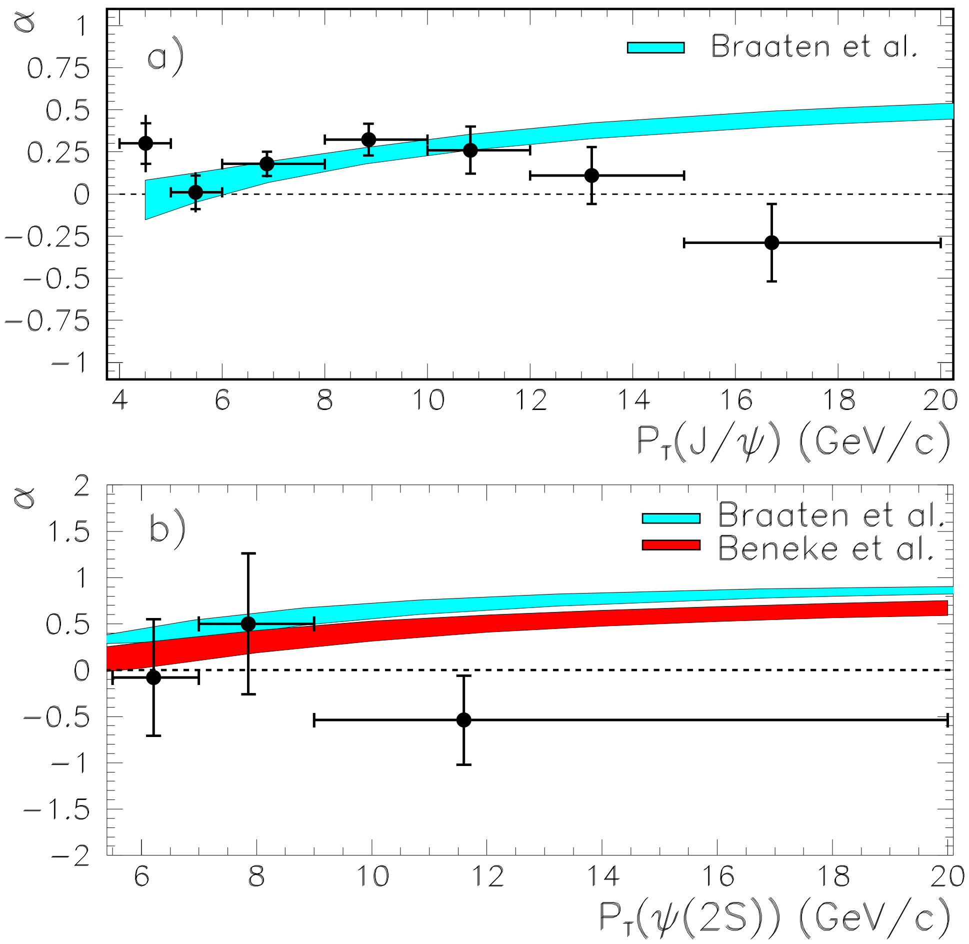
New results from TEVATRON Run II and HERA II will come soon. In addition to ~ 1 order increase in statistics they will gain from detector upgrades

- e.g., ZEUS microvertex detector:

It is a good time to make new (precise) predictions

Backup

CDF: $J/\psi, \psi'$ polarization



$\Longleftarrow$ transverse polarization

$\alpha = +1$

$\alpha = -1$

$\Longleftarrow$ longitudinal polarization

$$dN/d\cos\theta^* \propto 1 + \alpha\cos^2\theta^*$$

θ^* is μ^+ angle in J/ψ rest frame wrt J/ψ in the lab.

No increasing transverse polarization at $P_T \gtrsim 12\,\mathrm{GeV}$ in disagreement with NRQCD predictions. Higher-order QCD effects ?