Summary of Heavy Flavour Working Group

Achim Geiser, DESY Hamburg

WG3 convenors:

M. Cacciari, A. Dainese, A.G., H. Spiesberger

contact persons: K. Lipka, U. Uwer

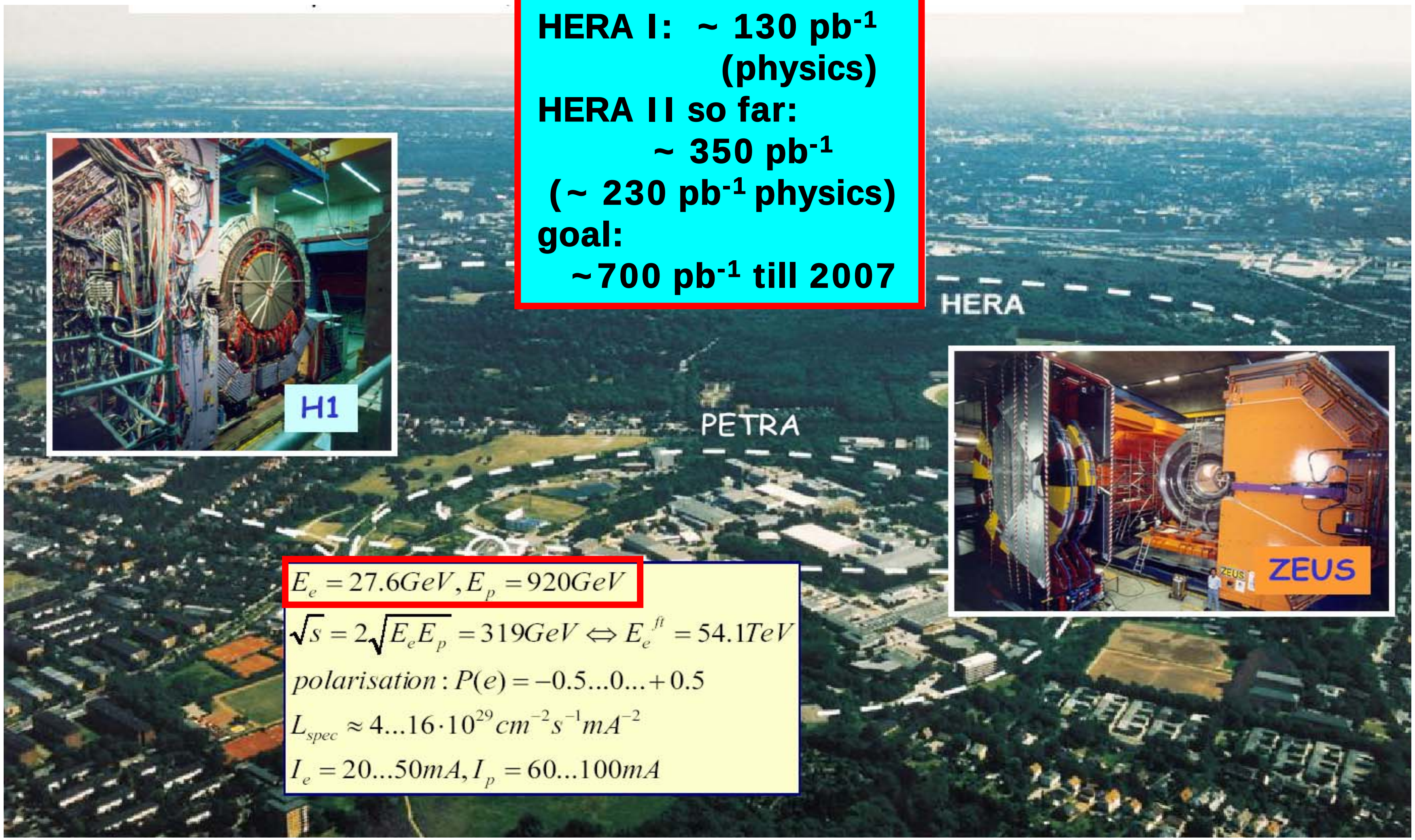
2nd HERA-LHC workshop, CERN, 9.6.06

- introduction
- open heavy flavour production
- parton density functions (joint with WG1)
- fragmentation
- inelastic quarkonium production (J/ψ)
- conclusions

topic selection = subjective choice

thanks to WG3 speakers and O. Behnke for providing slides

The HERA ep collider and experiments



HERA I: ~ 130 pb^{-1} (physics)
HERA II so far: ~ 350 pb^{-1} (~ 230 pb^{-1} physics)
goal: ~700 pb^{-1} till 2007

$E_e = 27.6GeV, E_p = 920GeV$

$\sqrt{s} = 2\sqrt{E_e E_p} = 319GeV \Leftrightarrow E_e^{ft} = 54.1TeV$

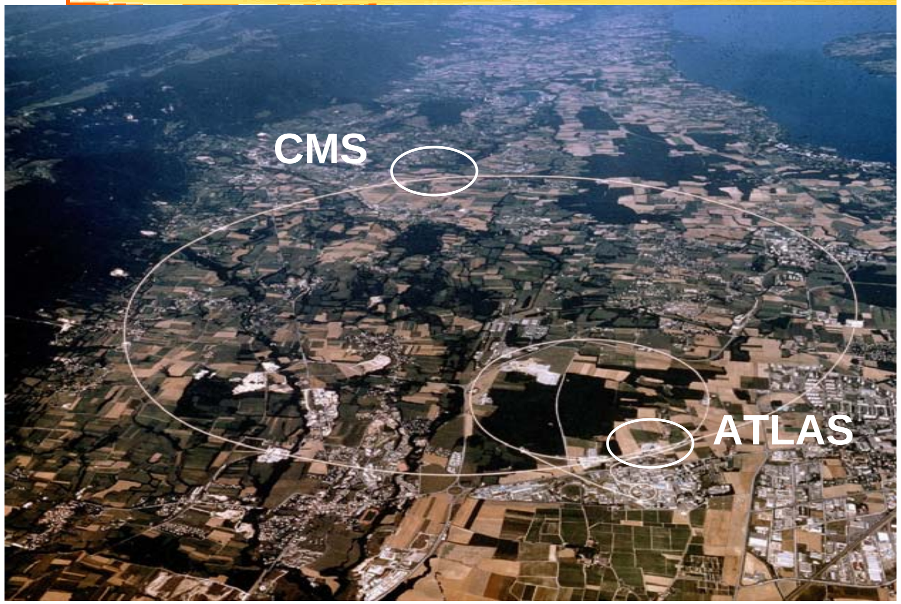
$polarisation: P(e) = -0.5...0...+0.5$

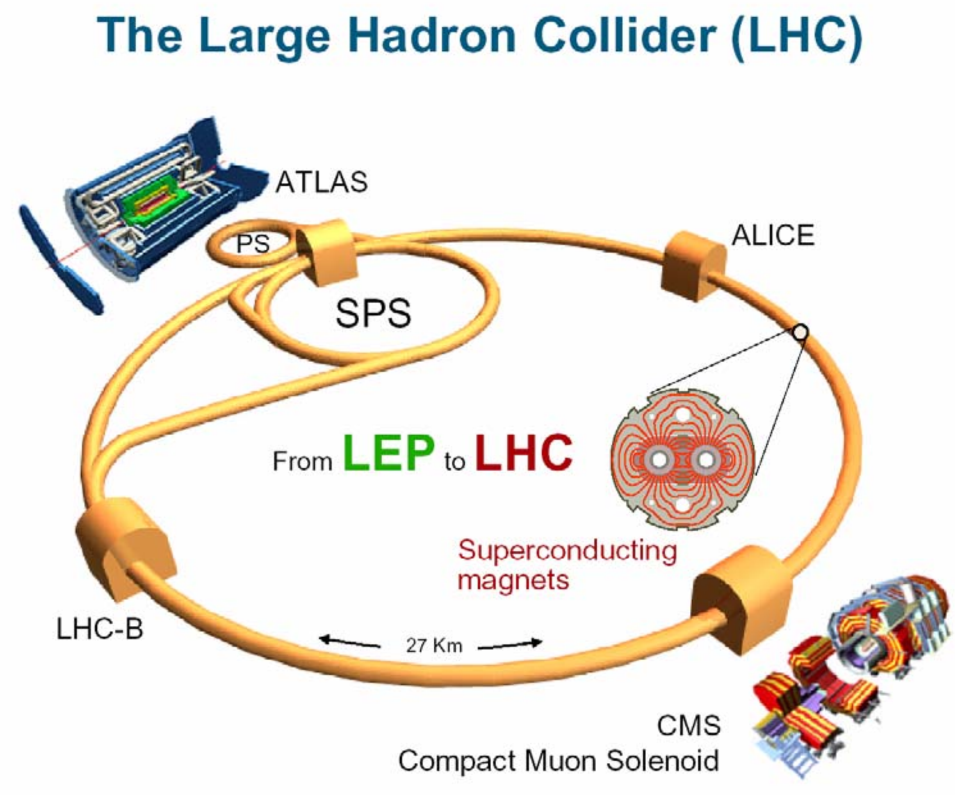
$L_{spec} \approx 4...16\cdot 10^{29} cm^{-2} s^{-1} mA^{-2}$

$I_e = 20...50mA, I_p = 60...100mA$

Large Hadron Collider (LHC)

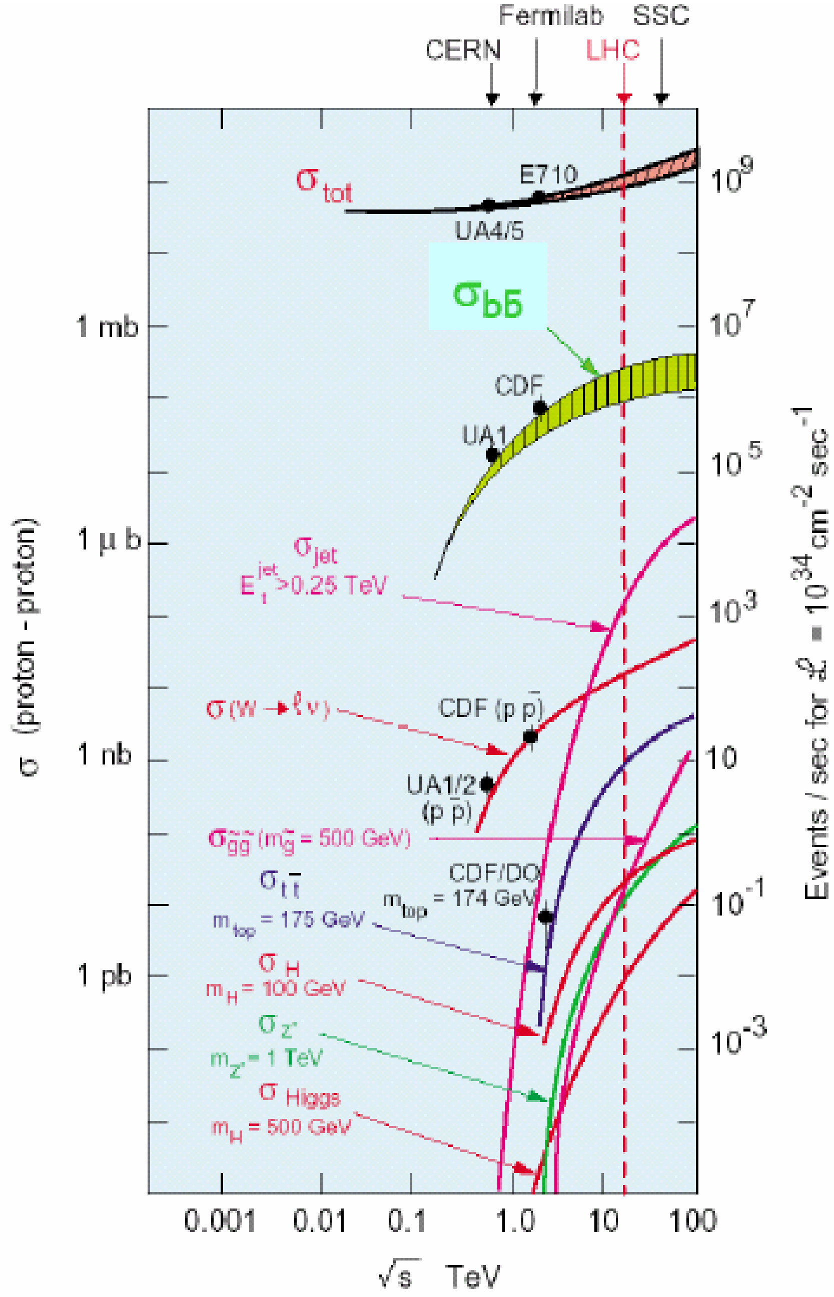
V. Andreev





- Design luminosity L = $10^{34}cm^{-1}s^{-1}$
  ~ 100 fb^{-1}/ year
  Pile up ~ 20 collisions/crossing
  40 MHz pp bunch-crossing rate
- Start-up luminosity L ≈ $10^{33}cm^{-1}s^{-1}$
  ⇒ ~ 10 fb^{-1}/ year
- expected completion : mid 2007

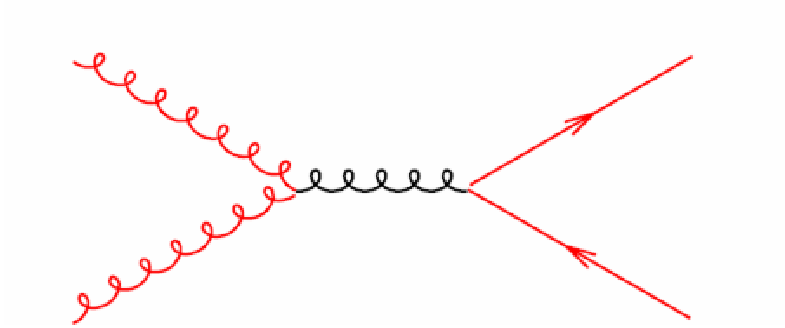
	Beams	Energy		Luminosity
LEP	e^+ e^-	200	GeV	10^{32} $cm^{-2}s^{-1}$
LHC	p p	14	TeV	10^{34} $cm^{-2}s^{-1}$
	Pb Pb	1312	TeV	10^{27} $cm^{-2}s^{-1}$



b production at LHC

V.Andreev

- *b production* at hadron colliders
  - Huge cross section
  - Challenge for perturbative QCD
  - New physics searches: b jets as a signal feature
  - Dominant process: gg fusion

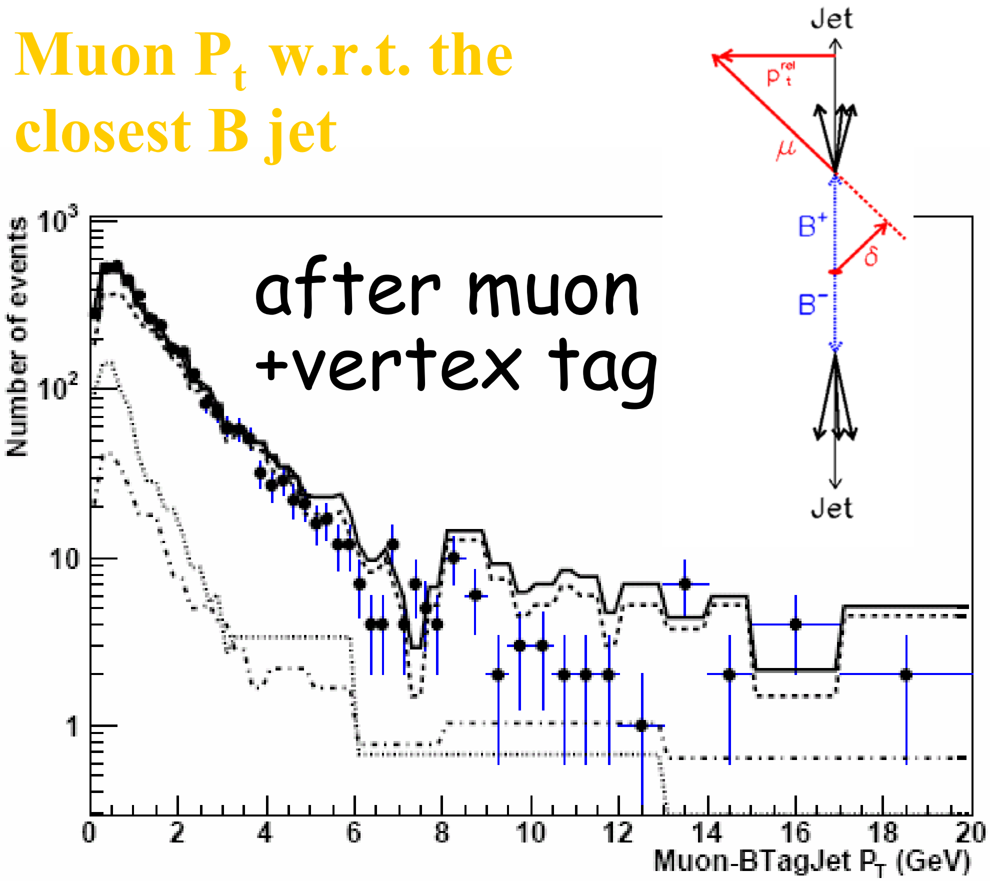


Fit results for b-jets in CMS

QCD events MC: $120 < P_t < 170$ GeV/c

V.Andreev

Muon P_t w.r.t. the closest B jet



b
c
udsg

Nb =2503 (66%)
Nc = 965 (26%)
Nudsg = 299 (8%)

3767 events

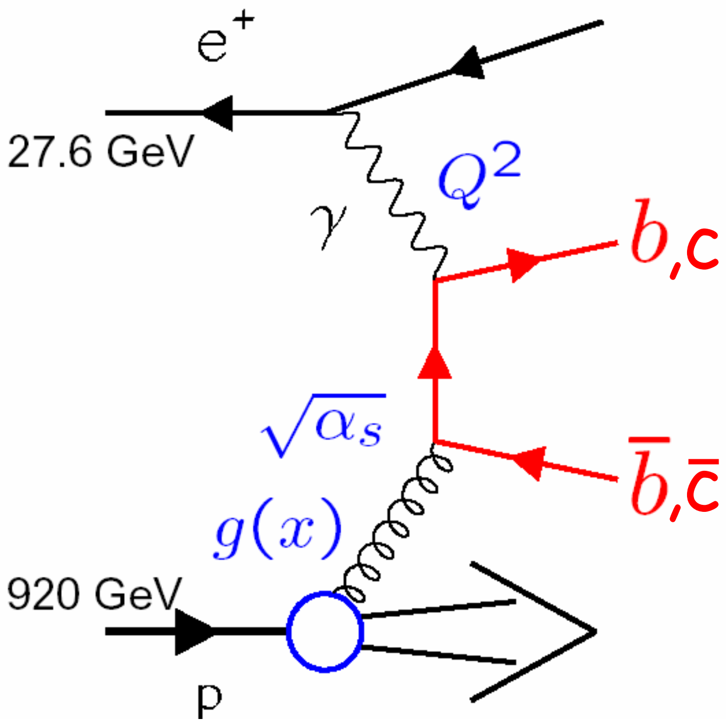
Fit:

Nb $=2750 \pm 346$
Nc $= 702 \pm 513$
Nudsg $= 329 \pm 235$

3781 events

Open Heavy Flavour production in ep scattering

Dominant production process in ep-collisions: Boson-Gluon -Fusion



- Driven by gluons in the proton
- Relevant scales:

m_b $\sim$ 5 GeV, m_c ~ 1.5 GeV

Q^2 $\lesssim$ 1 GeV^2 $\rightarrow \gamma p$

$>$ 2 GeV^2 $\rightarrow$ DIS

$p_T^{b,c}$ Event selection: $p_t^{jet} >$ 6 or 7 GeV

multiscale problem

-> terms $[\alpha_s \ln (Q^2/m_Q^2)]^n$, $[\alpha_s \ln (p_T^2/m_Q^2)]^n$, etc.

in perturbative expansion -> potentially large th. errors

pQCD approximations

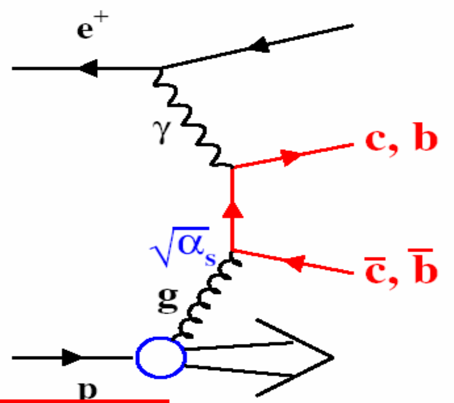
O. Behnke

assume one dominant hard scale:

Massive scheme: $\rightarrow m_b$

- b massive
- neglects $[\alpha_s \ln(Q^2/m_b^2)]^n$

$\rightarrow$ Perturbative production:

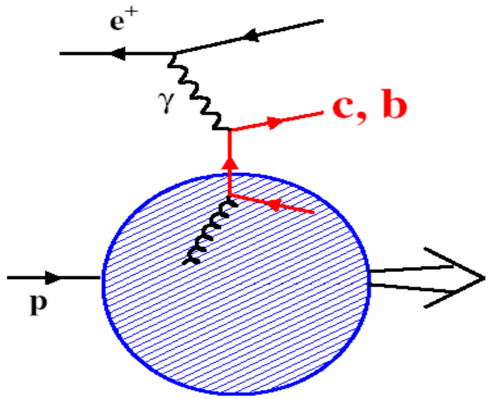


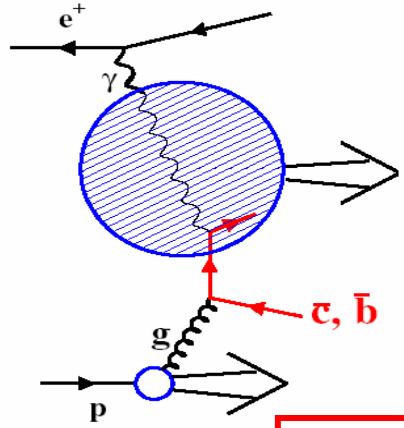
(FO) NLO

Massless scheme: $\rightarrow p_T, Q^2$

- b massless!!!
- Resums $[\alpha_s \ln(Q^2/m_b^2)]^n$

$\rightarrow$ b also in Proton and Photon!





NLL or ZM-VFNS

Variable schemes (VFNS):

$\rightarrow$ at small Q^2 massive, at large Q^2 massless

FONLL or GM-VFNS

which describes HERA data best?

Charm tags

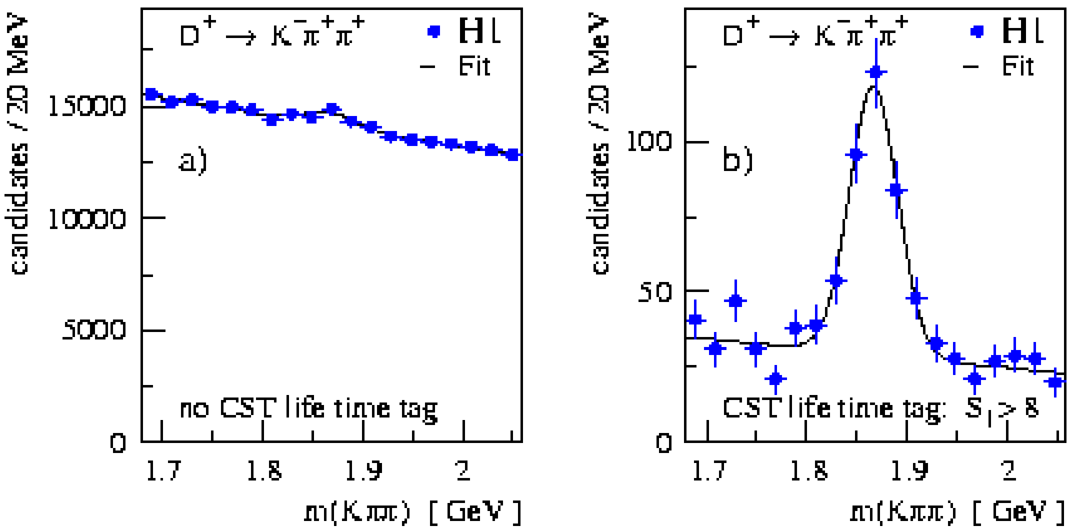
B. Kahle

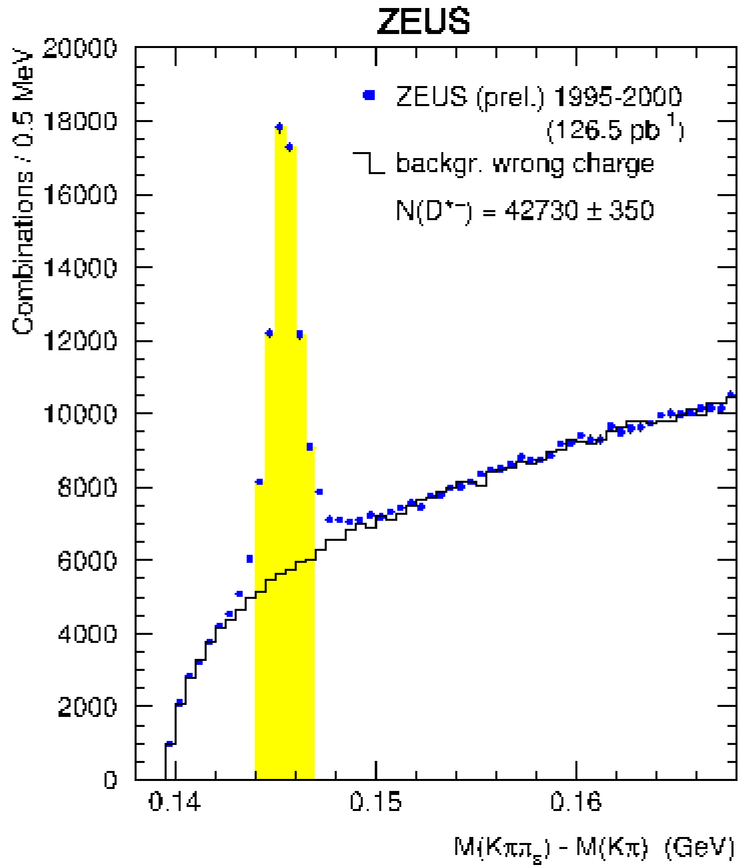
- $\sigma_{uds} : \sigma_{charm} : \sigma_{beauty} \sim 2000 : 200 : 1$

  -> HERA is **charm factory**

- **meson tag**, e.g. $D^* \to K \pi \pi$ →

- **lifetime tag**, e.g. D^+ (or inclusive)

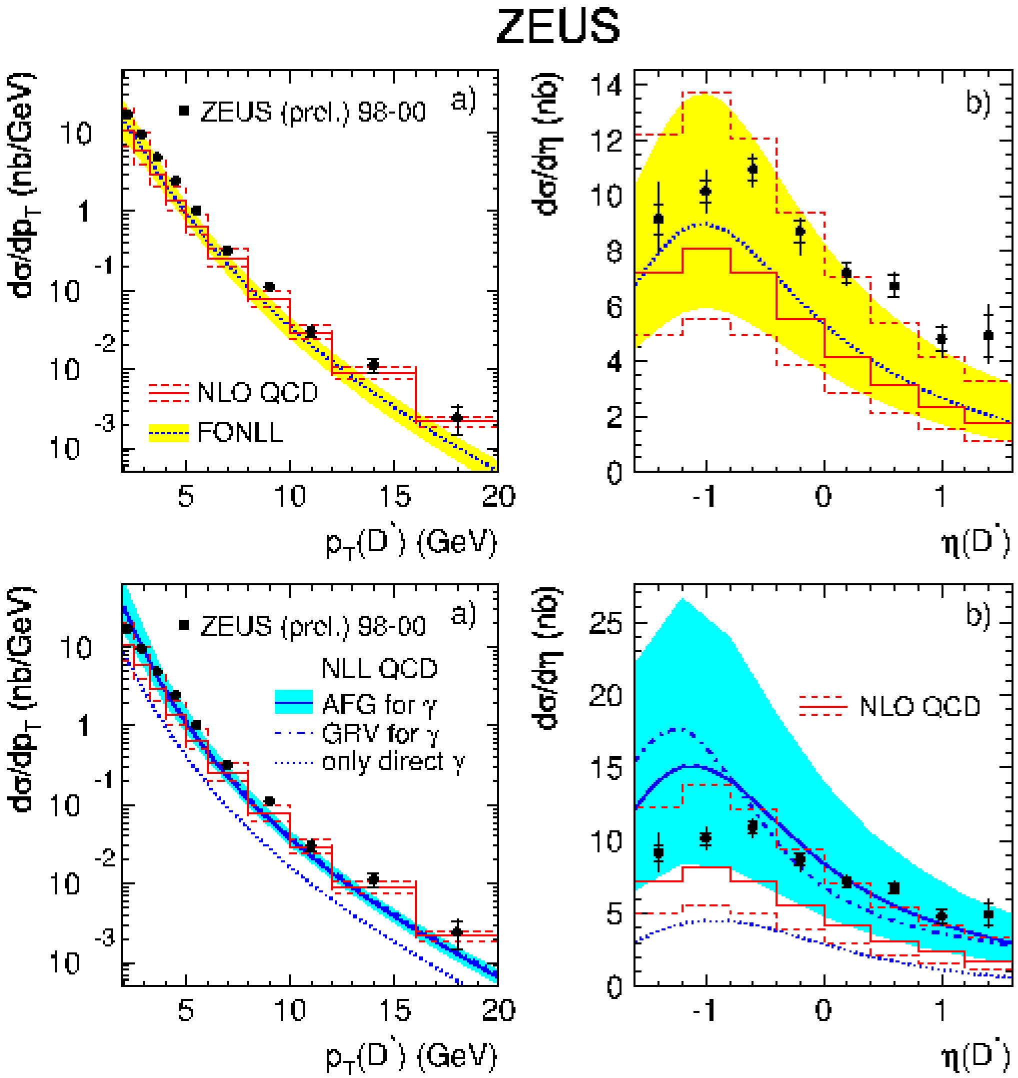




always $p_{Tc} > m_c$!

Charm in photoproduction

J.Loizides



QCD calculations using

CTEQ5M1 + AFG structure functions

m_c = 1.5 +- 0.2 GeV, $\mu_0^2 = m_c^2 + p_T^2$,

$\mu_r = \mu_f = \mu$, $\mu_0/2 < \mu < 2\mu_0$

f(c->D*) = 0.235

$e_{Peterson}$ = 0.035 (FO NLO), 0.02 (FONLL)

NLO (FMNR)

reasonable agreement
some deviations at forward η

FONNL (Cacciari et al.)

similar, not better at large p_T

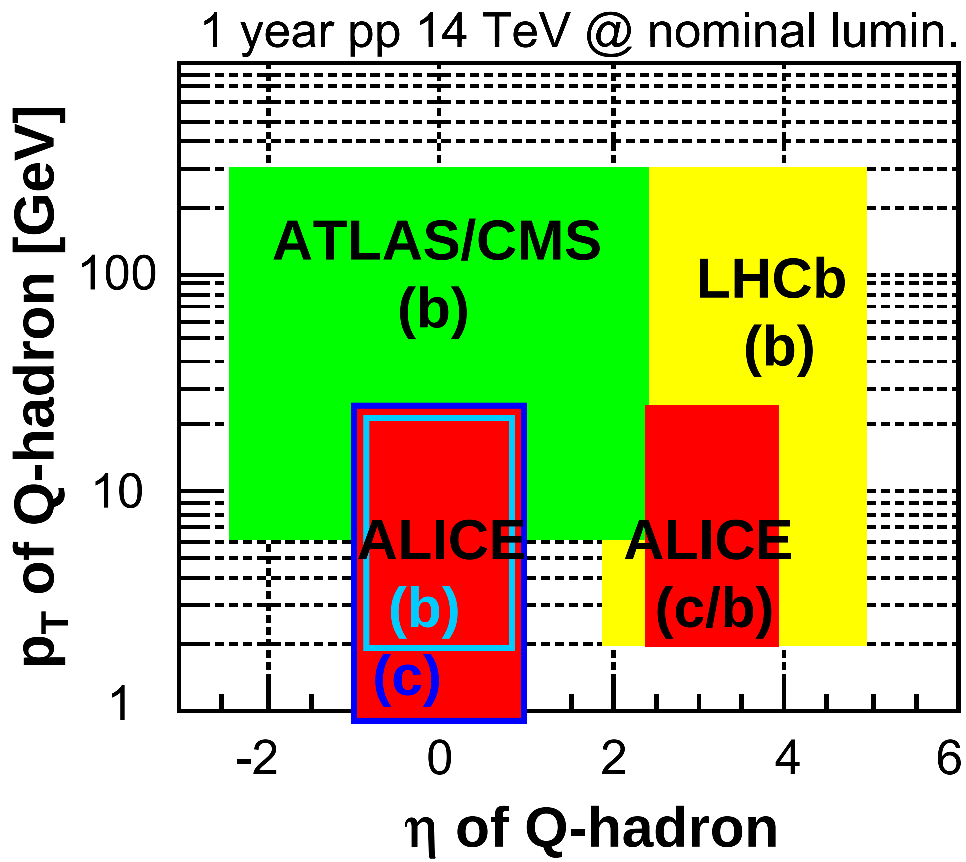
NLL (Kniehl et al.)

larger norm., shape not better

ALICE heavy-flavour potential

C.Bombonati

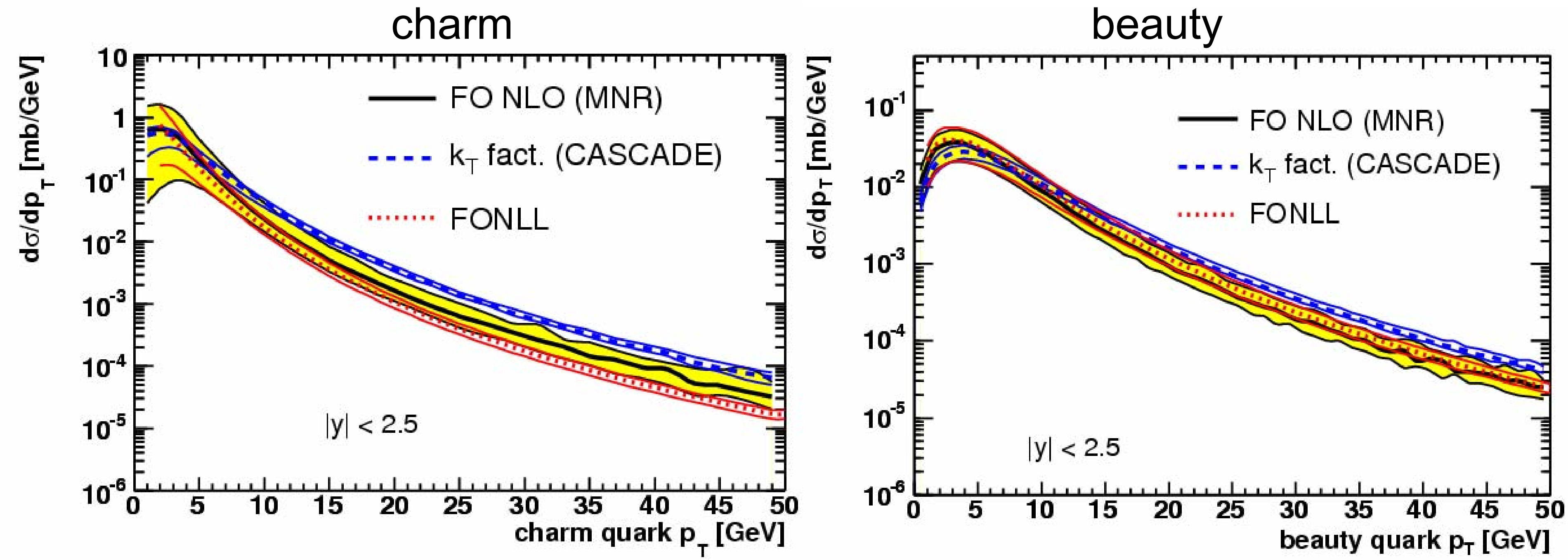
- ALICE combines **electronic** (|η|<0.9), **muonic** (-4<η<-2.5), **hadronic** (|η|<0.9) channels
- ALICE covers **low-p_T region** (similar to HERA)
- ALICE covers **central and forward regions**



Model comparisons

C.Bombonati

CERN/LHCC 2005-014
hep-ph/0601164



⇨ Good agreement between FO NLO and FONLL

⇨ k_T factorization + LO (CASCADE) higher at large p_T

Conclusions for HERA/LHC

- LHC: b production at LHC kinematically similar to c production at HERA.

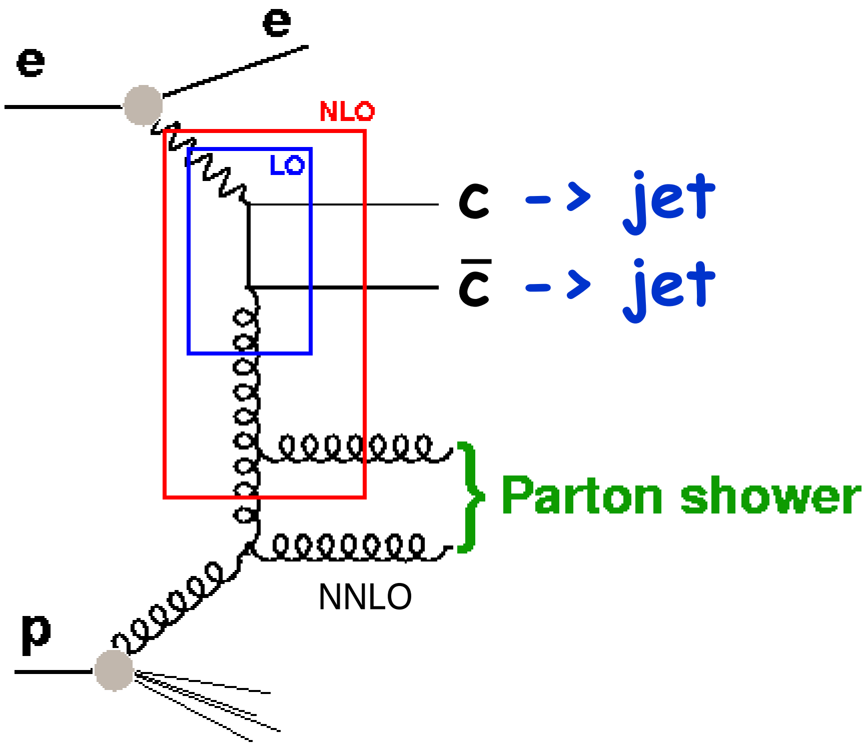
  spread of predictions between NLO and NLL schemes gives indication of theoretical uncertainties

- HERA: both NLO and NLL schemes give reasonable predictions

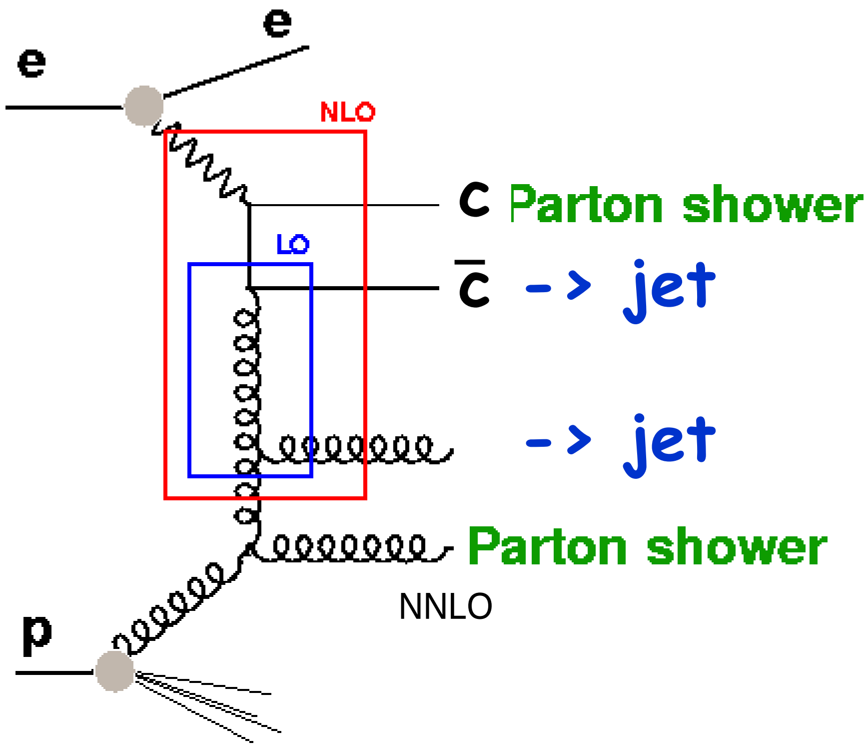
  need more statistics at high pT

  need reduction of theoretical uncertainties

NLO vs. LO + parton shower at HERA



"direct γ"

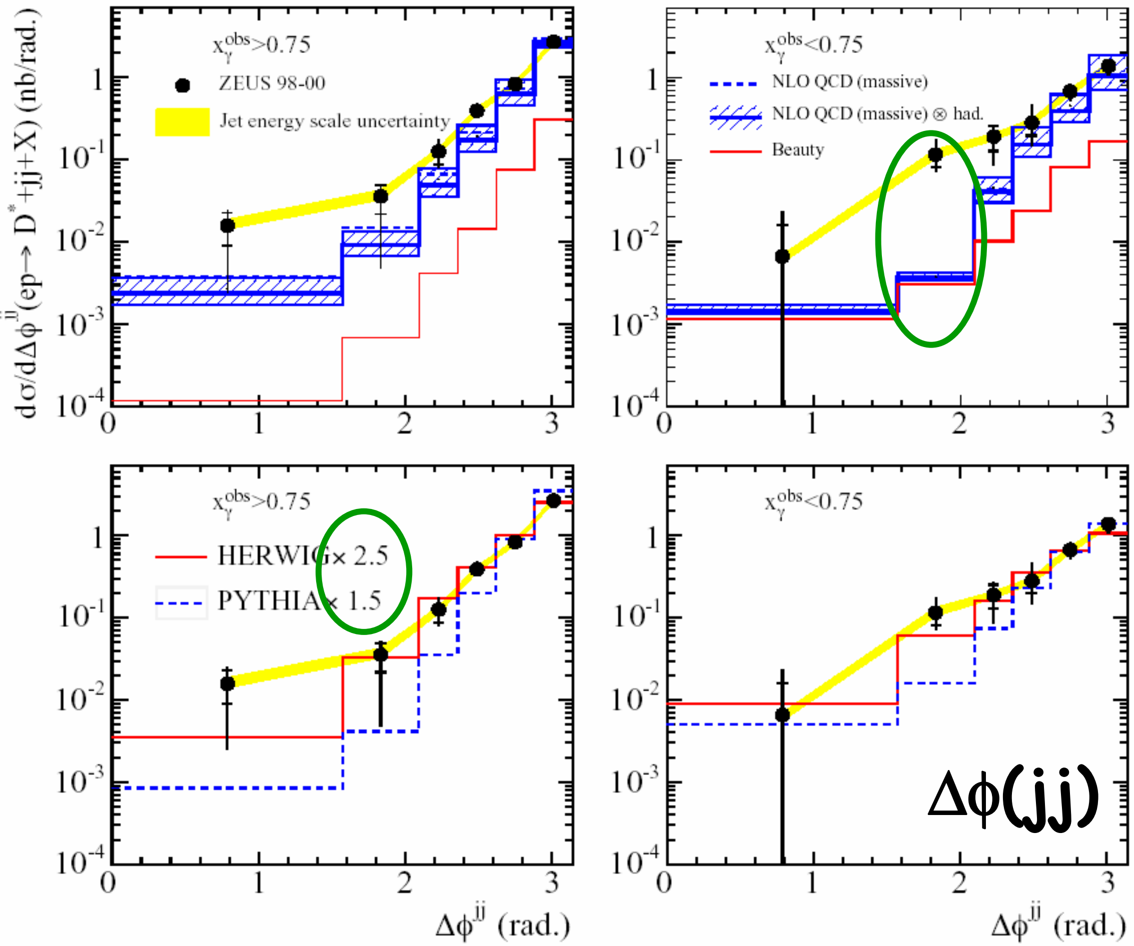


"resolved γ"

NLO vs. LO + parton shower

direct enriched — ZEUS — resolved enriched

J.Loizides



NLO

norm. OK
shape X

LO+PS

shape OK
norm. X

data:

charm
+ dijet

need
NNLO

or

NLO+PS
(MC@NLO)

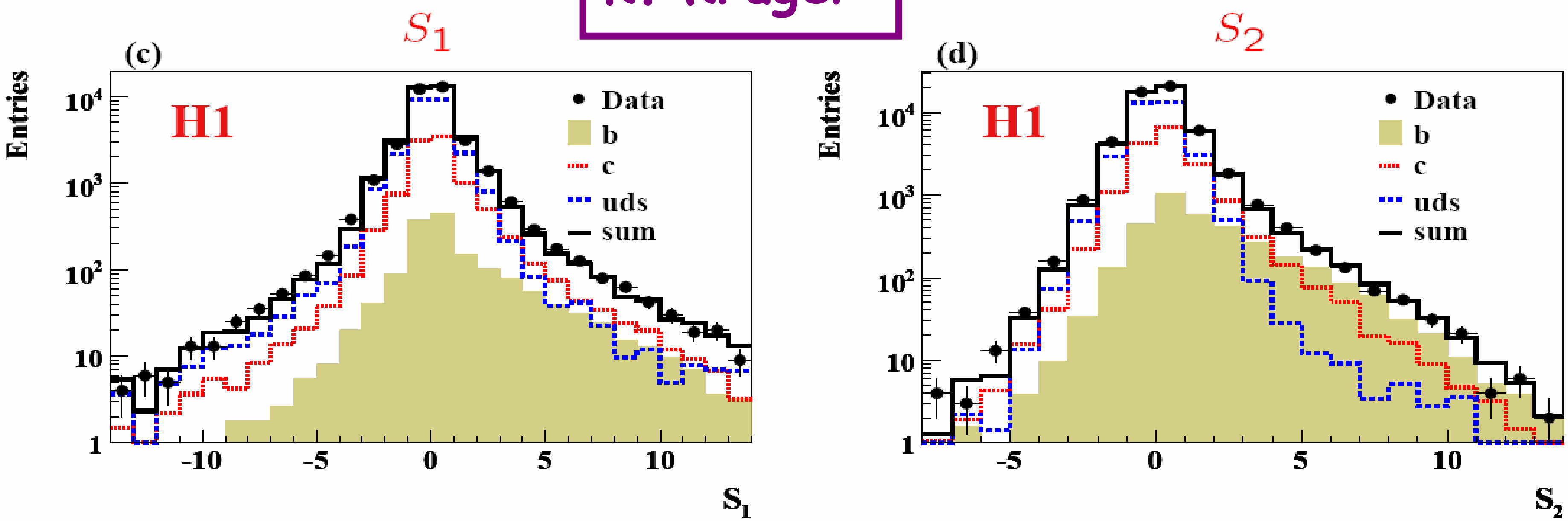
Conclusions for HERA/LHC

- LHC: MC@NLO (NLO+PS) exists,
  whenever higher order topologies are important, use it!

- HERA: MC@NLO being worked on (T. Toll)
  -> hope for progress by next meeting
  -> will greatly enhance possibilities for comparisons with perturbative QCD

Beauty and Charm at HERA with lifetime tag

K. Krüger

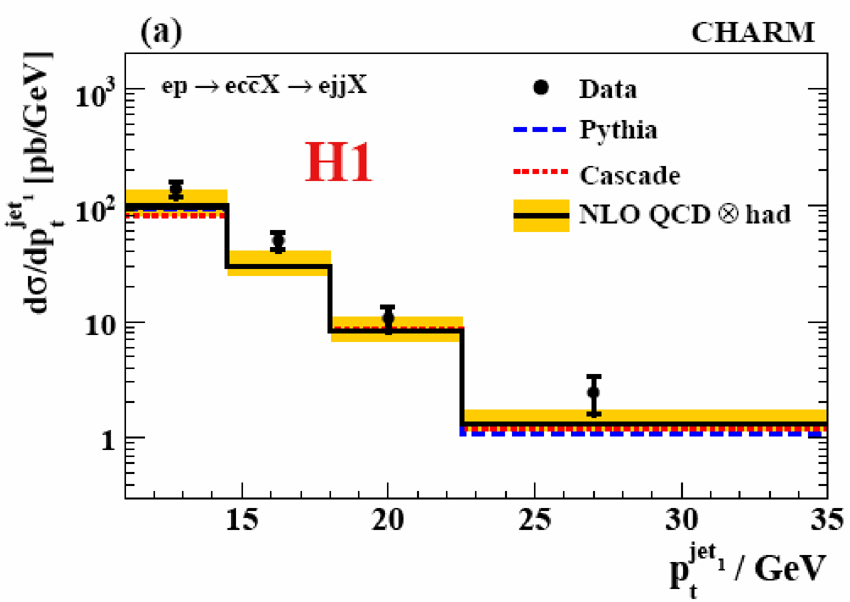


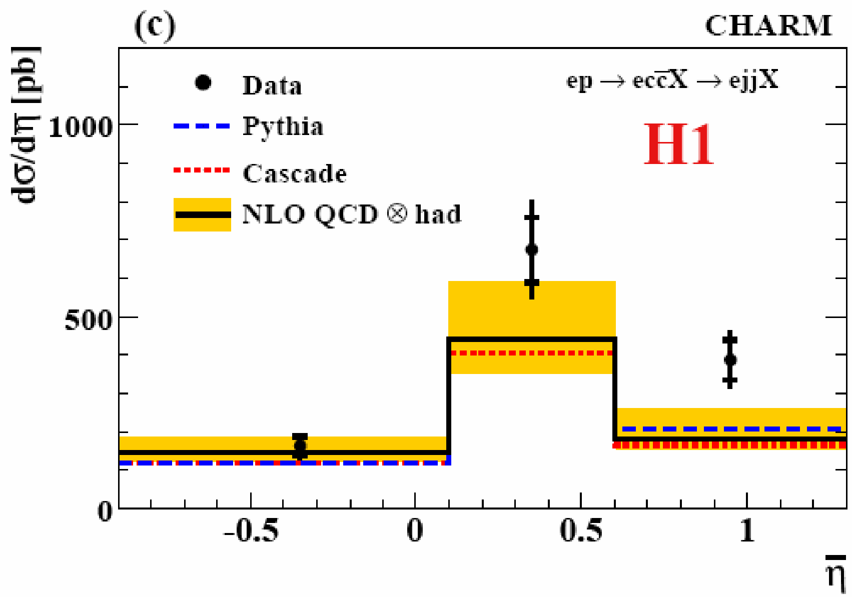
- S_1 significance of highest significance track (1 track events)
- S_2 significance of 2nd highest significance track with same sign as S_1 ($\geq$ 2 track events)

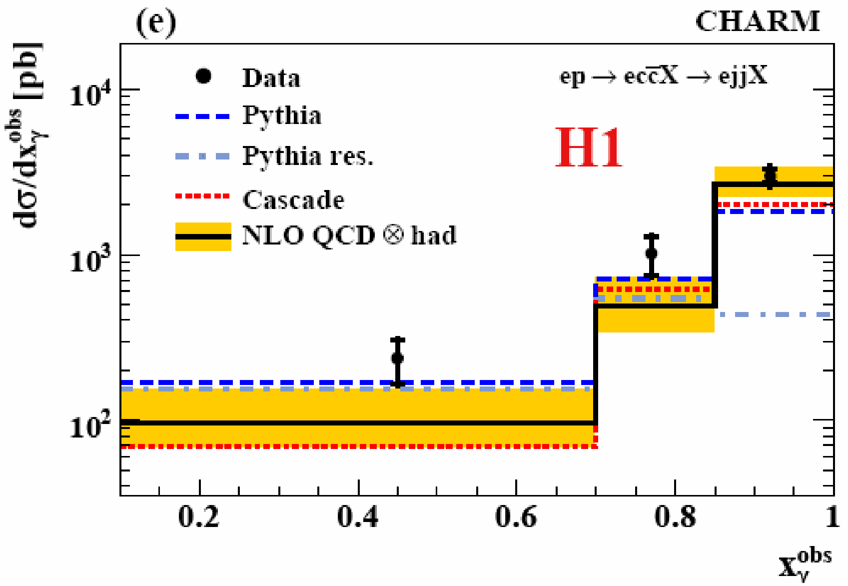
$\Rightarrow$ S_2 provides separation power between charm and beauty

Charm in photoproduction

K. Krüger







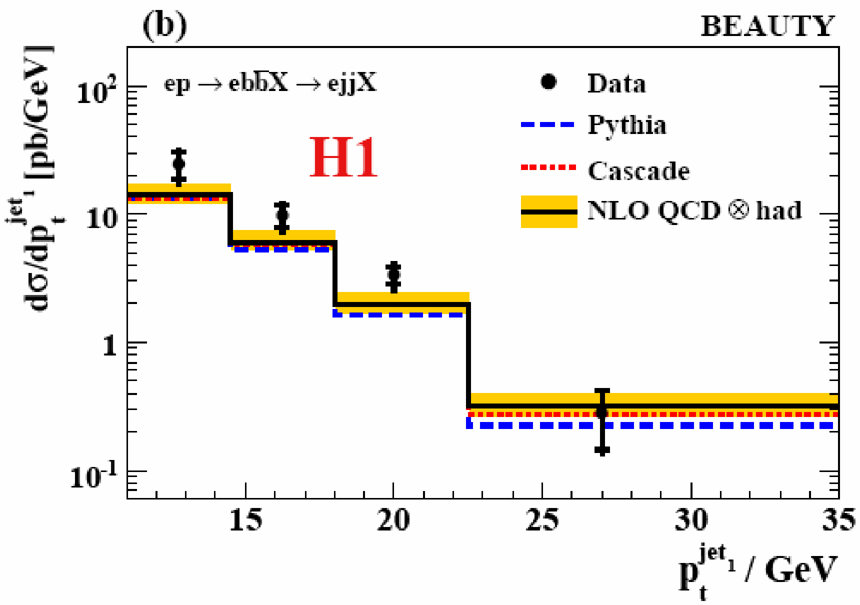
NLO calculation describes data reasonably well

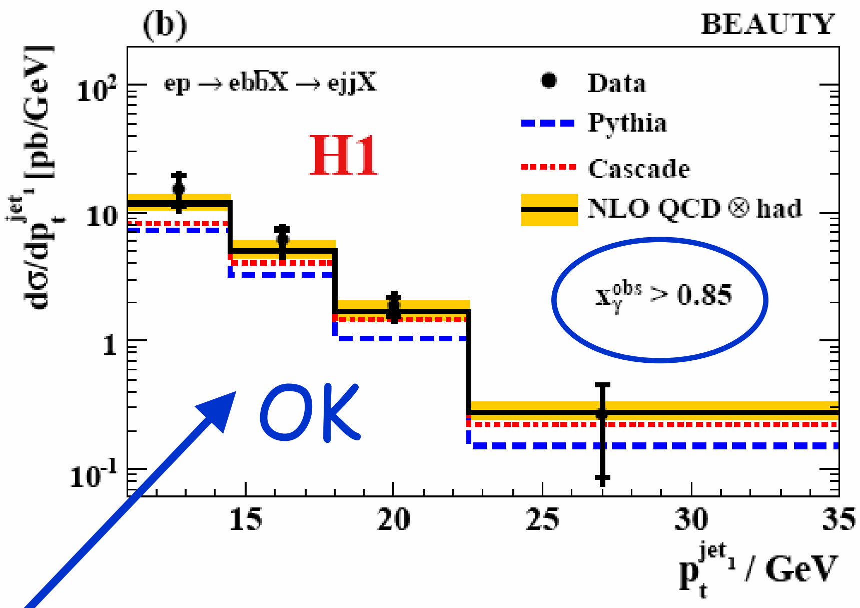
PYTHIA is too low

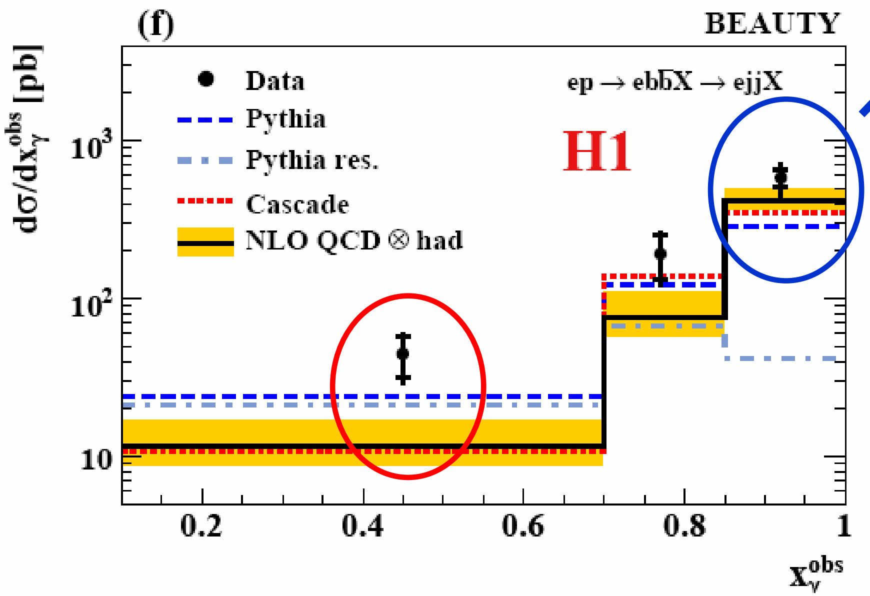
CASCADE is too low at small x_γ^{obs}

Beauty in photoproduction

K. Krüger







NLO calculation is somewhat too low, mainly at small x_γ^{obs} (resolved)

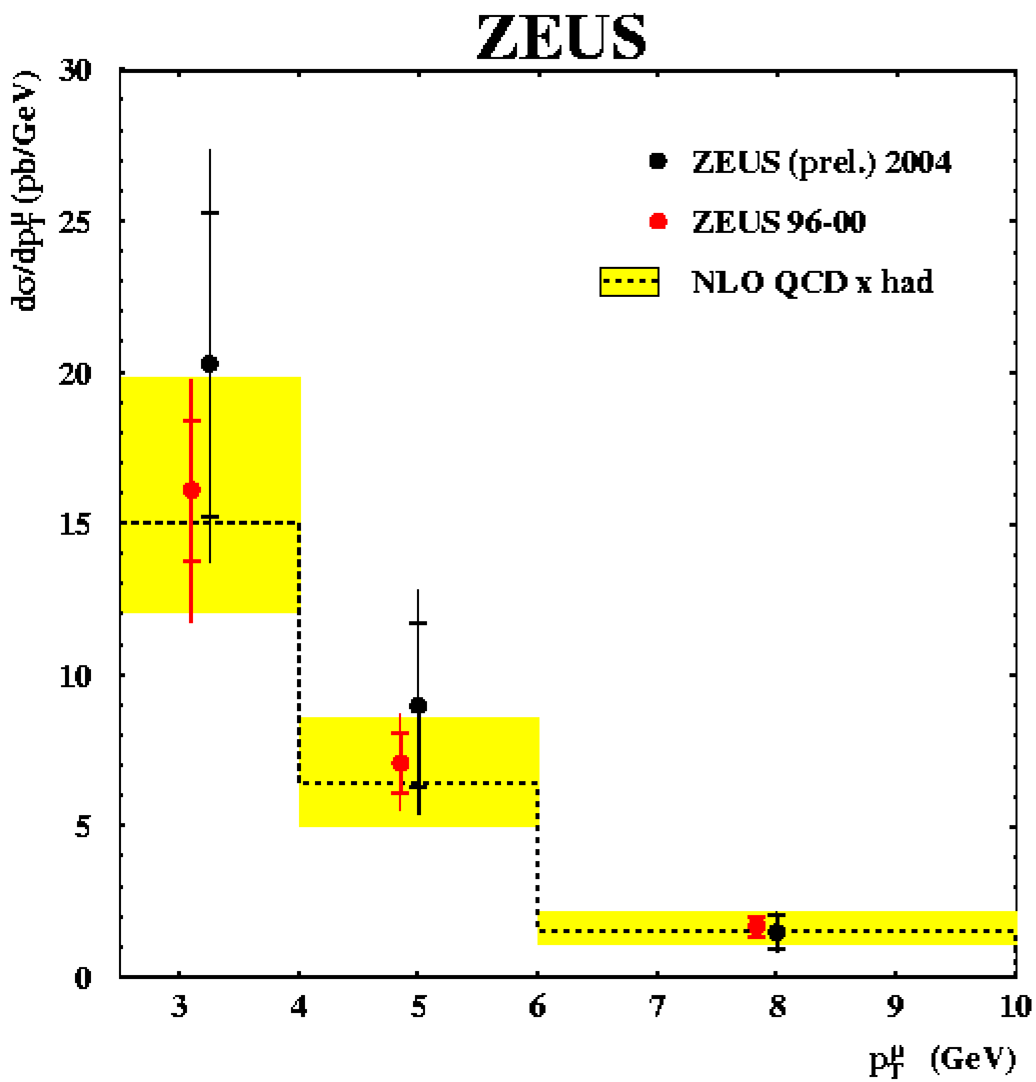
PYTHIA is too low
but shape OK

CASCADE is too low
at small x_γ^{obs}

Beauty in HERA II data

B. Kahle

- First preliminary results using new ZEUS MVD:
  - first 30 pb^{-1} of HERA II data
  - combine muon p_{Trel} with impact parameter (muon+dijet events)
- **Outlook:** **improve by ~ order of magnitude**
  + new double differential measurements



Conclusions for HERA/LHC

- LHC: perturbative QCD should yield reasonably reliable predictions of b production, in particular for „leading order" topologies

- HERA: exploit HERA II potential for more precise comparisons

Small-x Effects

($x < 10^{-4}$, Q^2 in perturbative regime)

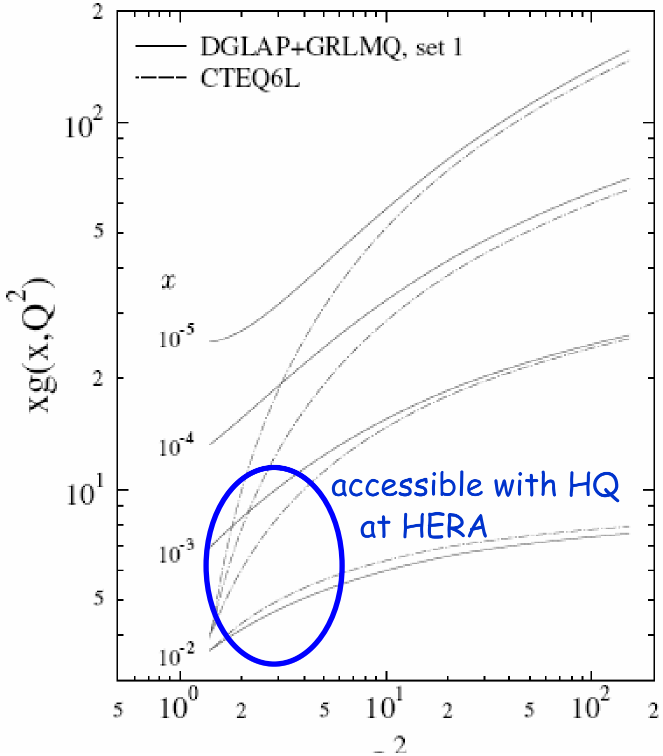
H. Spiesberger

GLRMQ

DGLAP + non-linear g recombination

→ enhanced gluon

→ enhanced b production at LHC



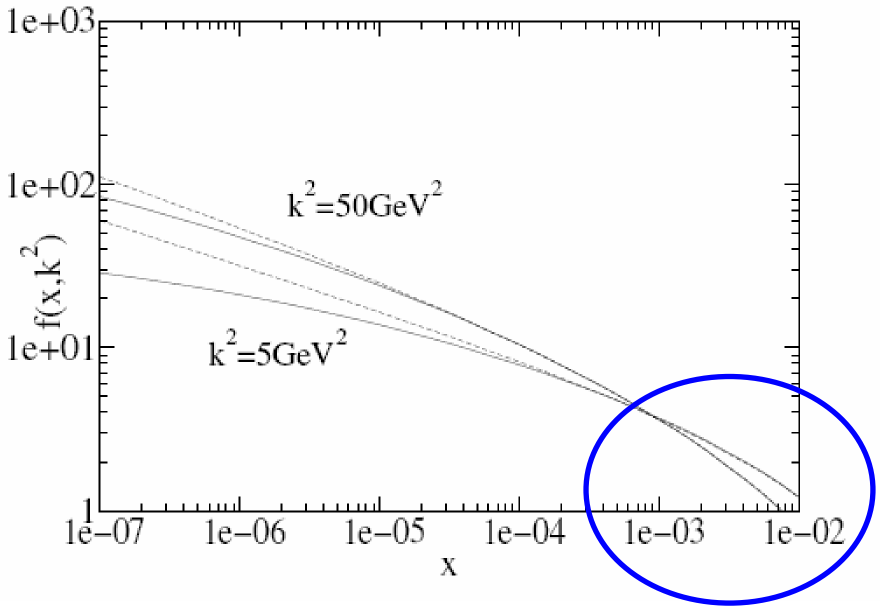
KKMS

DGLAP + BK saturation effects

k_T-factorization (unintegrated PDF)

→ suppressed gluon

→ suppressed b production at LHC ?



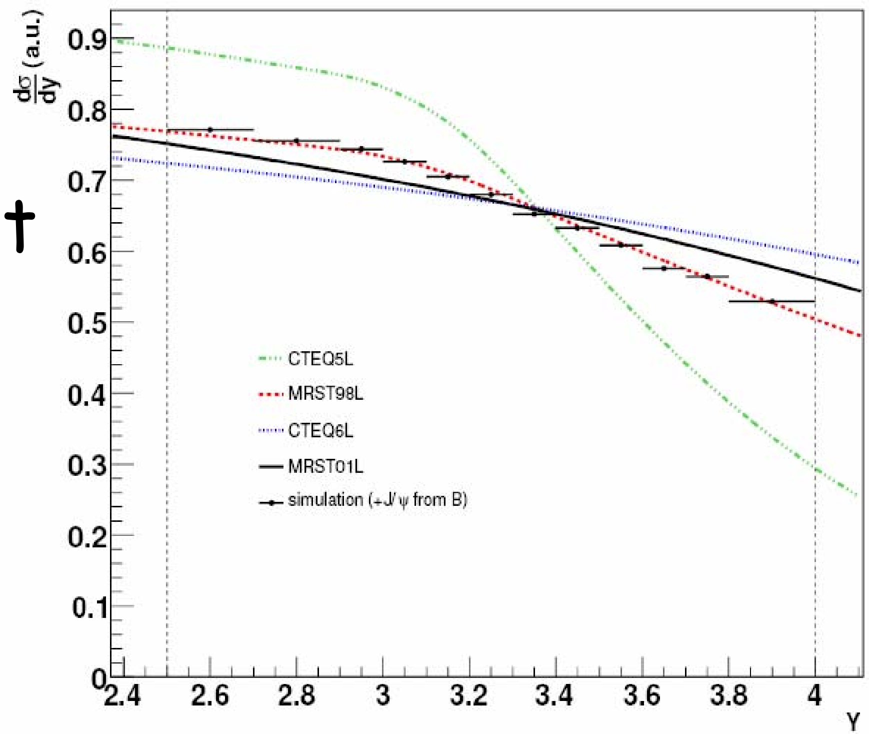
Forward J/ψ production at ALICE

D. Stocco

gg contribution dominant

normalized to 1

=> study shape only



...put some constraints on gluon distribution functions
in the low x region

Conclusions for HERA/LHC

- LHC: low x effects potentially very important for heavy flavour production

- HERA: exploit non-heavy flavour measurements to investigate this region (see WG1 and WG2)

Double tagging of $b\bar{b}$ pair

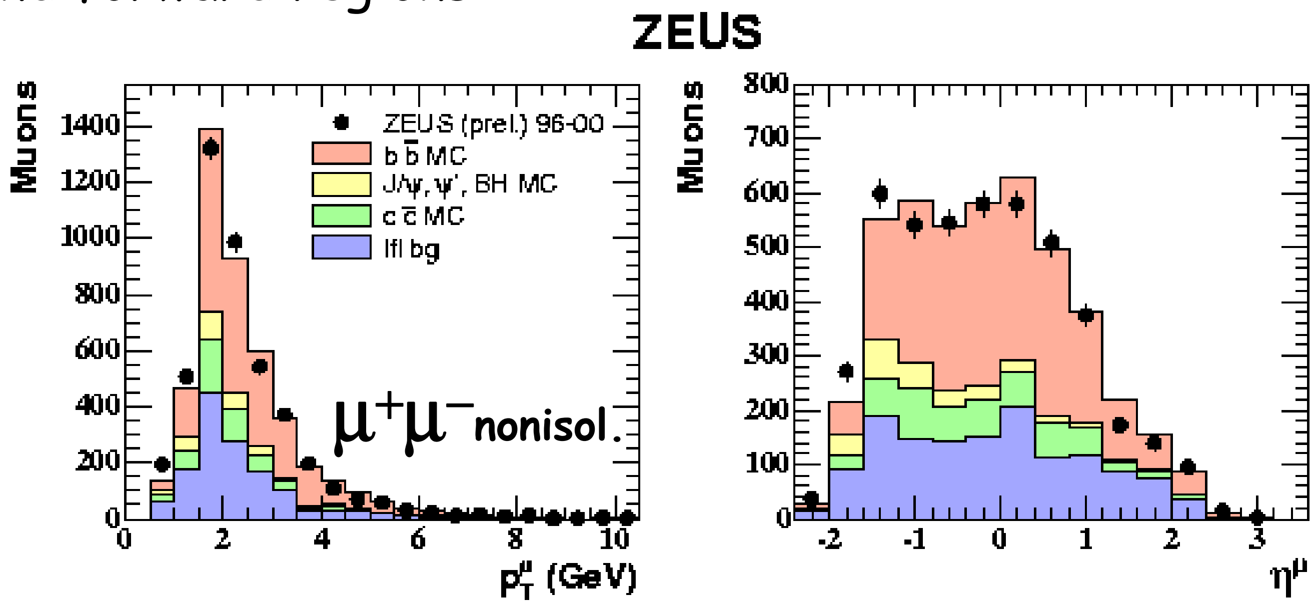
A.-E. Nuncio-Quiroz

- two direct flavour tags, e.g. $D^*+\mu$ or $\mu+\mu$

-> large bg reduction, do not need jets

-> access low p_T and forward regions (proton direction)

~50% beauty



-> measure **total beauty production cross section** at HERA:

$$\sigma(ep \to b\bar{b} + \text{anything}) = 16.1 \pm 1.8_{stat} {}^{+5.3}_{-4.8,sys} \text{ nb}$$

$$\sigma_{NLO} = 6.8 {}^{+3.0}_{-1.7} \text{ nb}$$ (FMNR+HVQDIS)

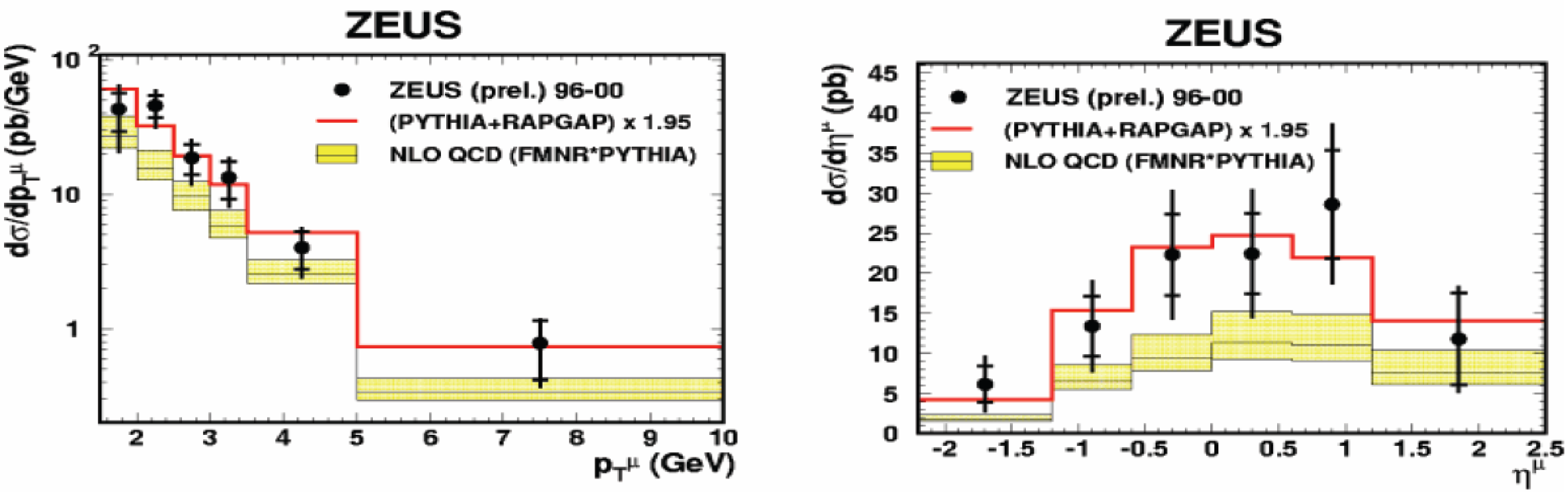
New interface FMNR NLO -> PYTHIA

for complicated final states

A.-E. Nuncio-Quiroz

Results

Visible Beauty cross sections from μμ

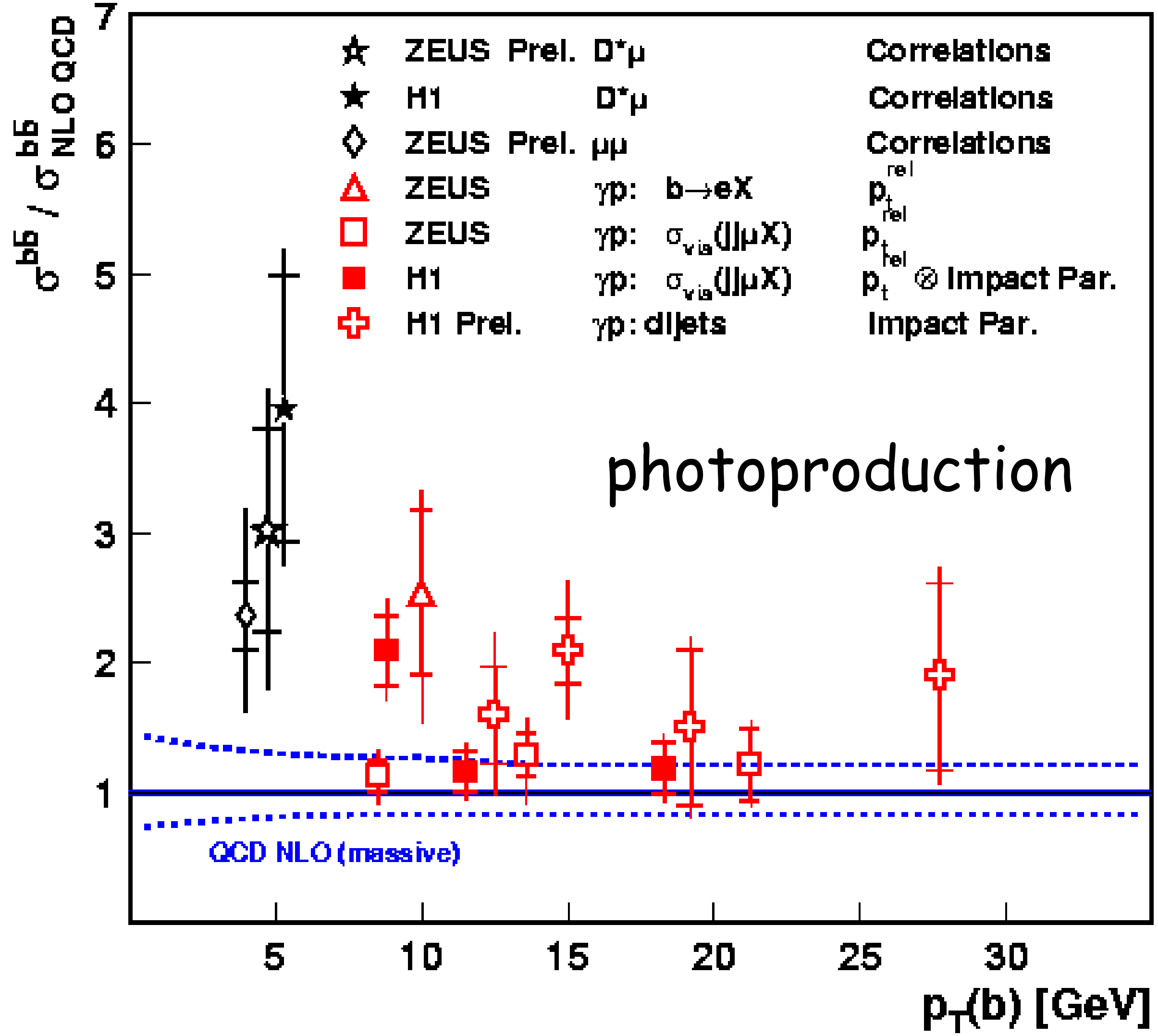


- **Shape well described**

NLO low, but still compatible

Beauty cross sections vs. p_{Tb}

$p_{Tb} >> m_b$
better
described
than
$p_{Tb} \sim m_b$?



Conclusions for HERA/LHC

- HERA: improve both measurements (statistics) and theory (fragmentation, HO corrections) for b production near threshold

- LHC: top at LHC kinematically similar to b at HERA.
  any lessons to be learnt from this?
  e.g. threshold effects?

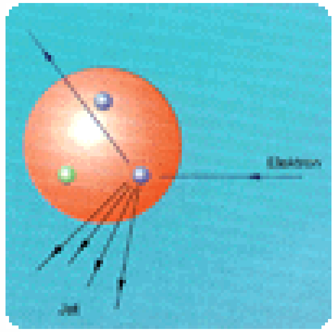
The structure of the proton

- Measure cross section

~negligible

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left\{\left[1+(1-y)^2\right] F_2(x,Q^2) - y^2 F_L(x,Q^2) \;+\ldots xF_3\right\}$$

at high Q^2



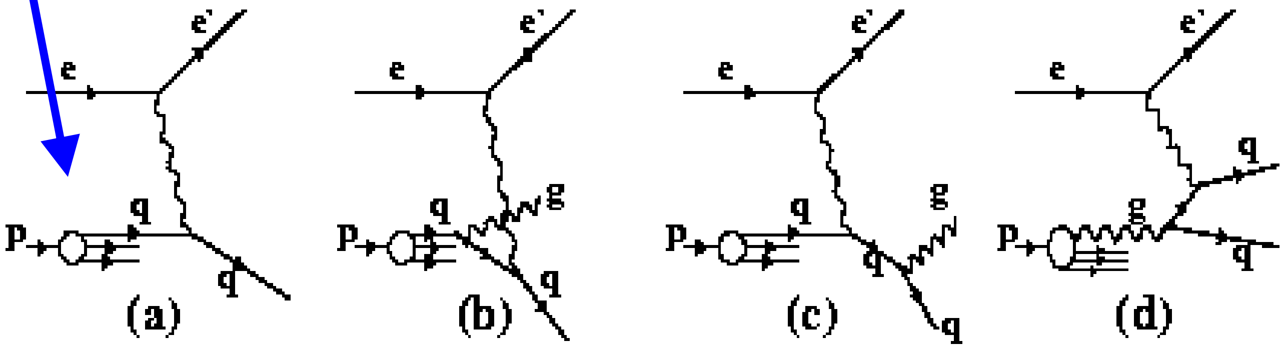
to **0th order QCD** ($Q^2 \gg m_q$ only!!):

- Parton distribution functions (PDF) in pQCD

$$F_2^{em}(x,Q^2) = x\sum_i e_i^2[q_i(x,Q^2)+\bar{q}_i(x,Q^2)]$$

q_i – probability to find quark with flavour i in proton

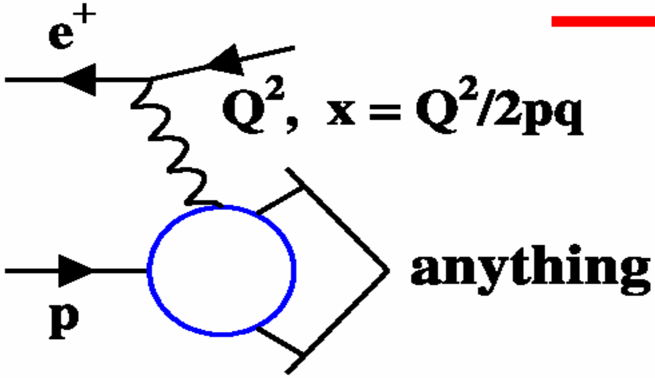
b,c pair production is "higher" order QCD correction



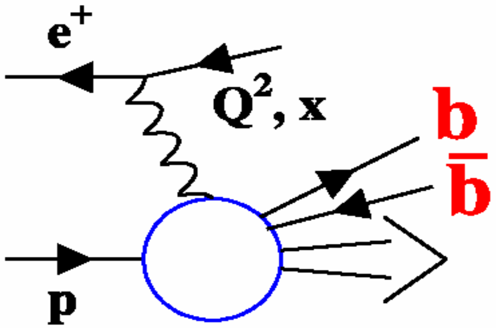
in general: F_2 **structure function** is **not** PDF

Beauty contribution to F_2

Beauty contribution to inclusive DIS



$$\frac{d^2\sigma^{ep}}{dQ^2dx} \propto F_2(x, Q^2)$$

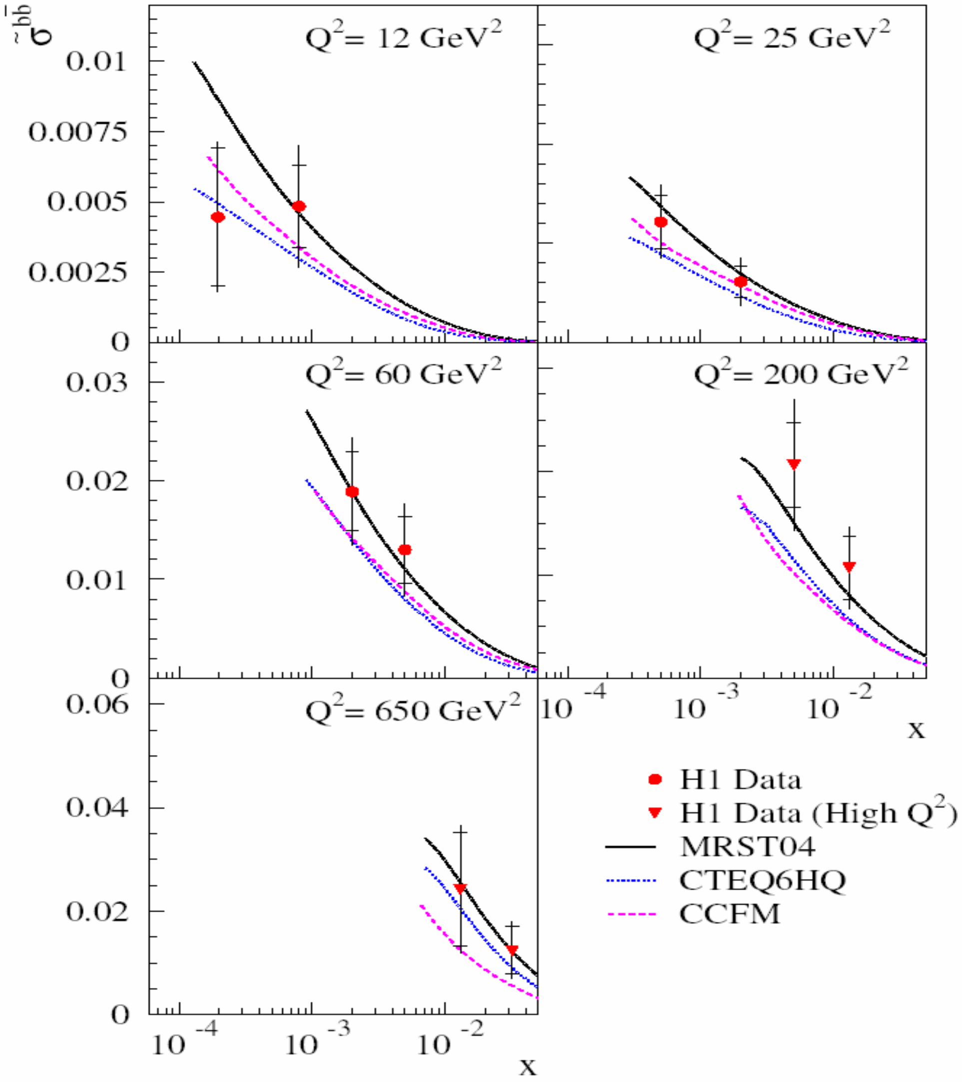


$$\frac{d^2\sigma^{ep\to b\bar{b}x}}{dQ^2dx} \propto F_2^{b\bar{b}}(x, Q^2)$$

Use inclusive lifetime tagging to determine fraction of b quark events $\to F_2^{b\bar{b}}$

Beauty contribution to F_2

P. Thompson

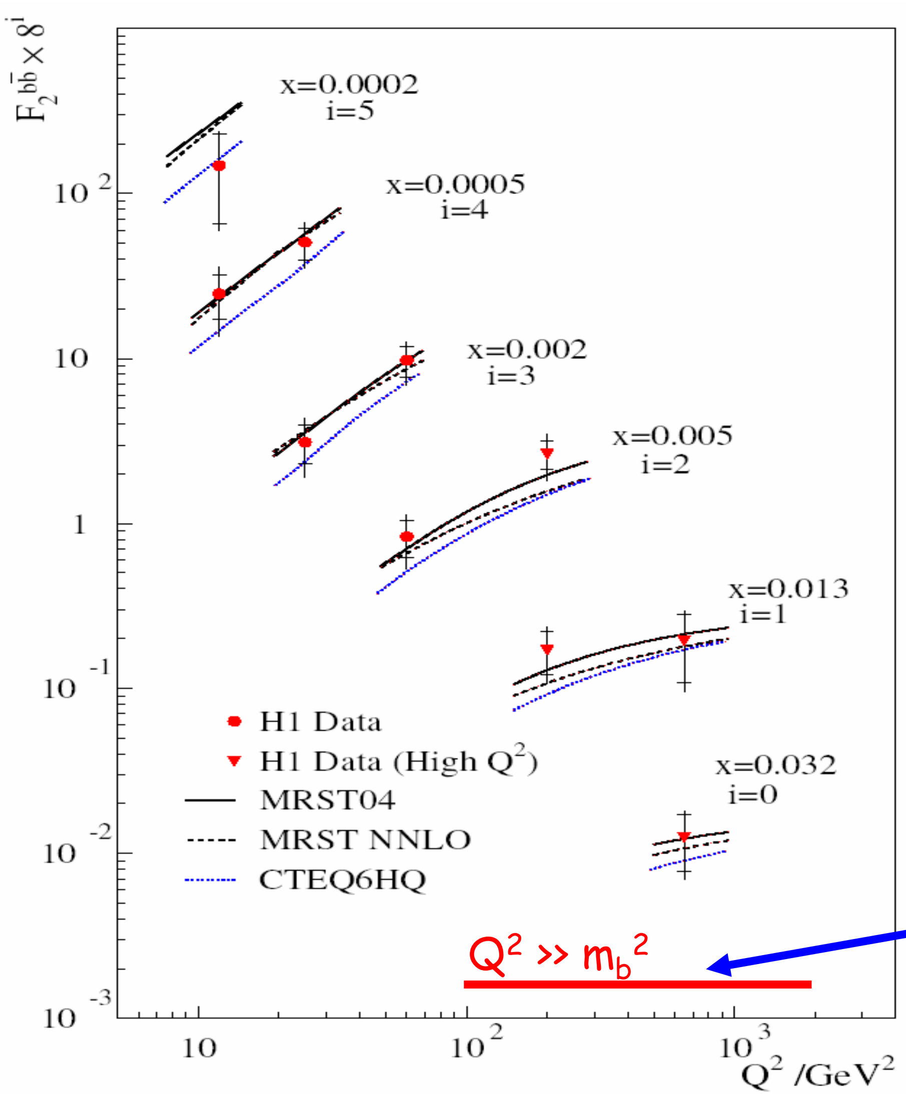


$F_2^{b\bar{b}}$ vs x in bins of Q^2

- **First measurements at all!**
- **Rise towards smaller x and larger Q^2 $\leftrightarrow$ gluon density**
- **MRST04 and CTEQ6HQ differ up to factor two!**
- **Data described well by calculations**

Beauty contribution to F_2

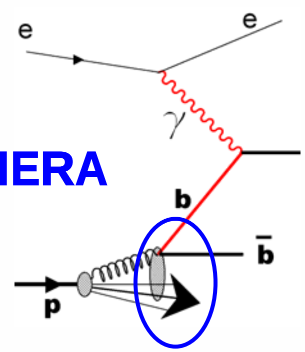
P. Thompson



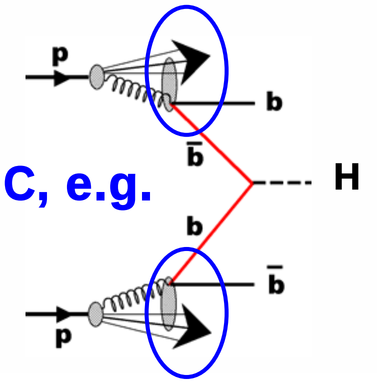
$F_2^{b\bar{b}}$ vs Q^2 in bins of x

- **Large scaling violations**
- **First NNLO calculation, from Robert Thorne: → mostly lower than NLO (max. 40%)**
- **Data in agreement also with NNLO**

HERA



LHC, e.g.



Conclusions for HERA/LHC

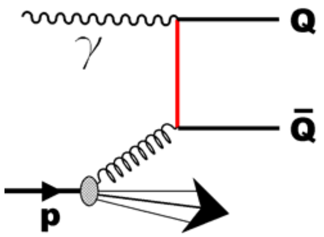
- HERA: first measurement of F_2^{bb} achieved

  to do: improve with HERA II,

  derive b PDF from high Q^2 ($\gg m_b^2$) data

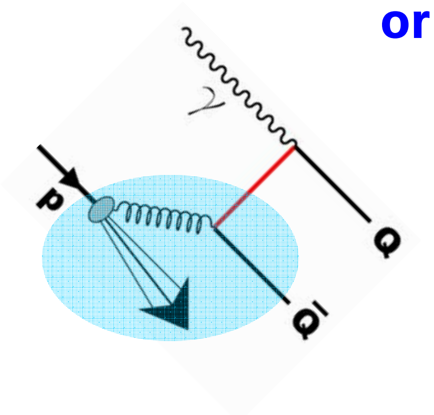
- LHC: b PDF important input for H and Z production at LHC

charm contribution to F_2



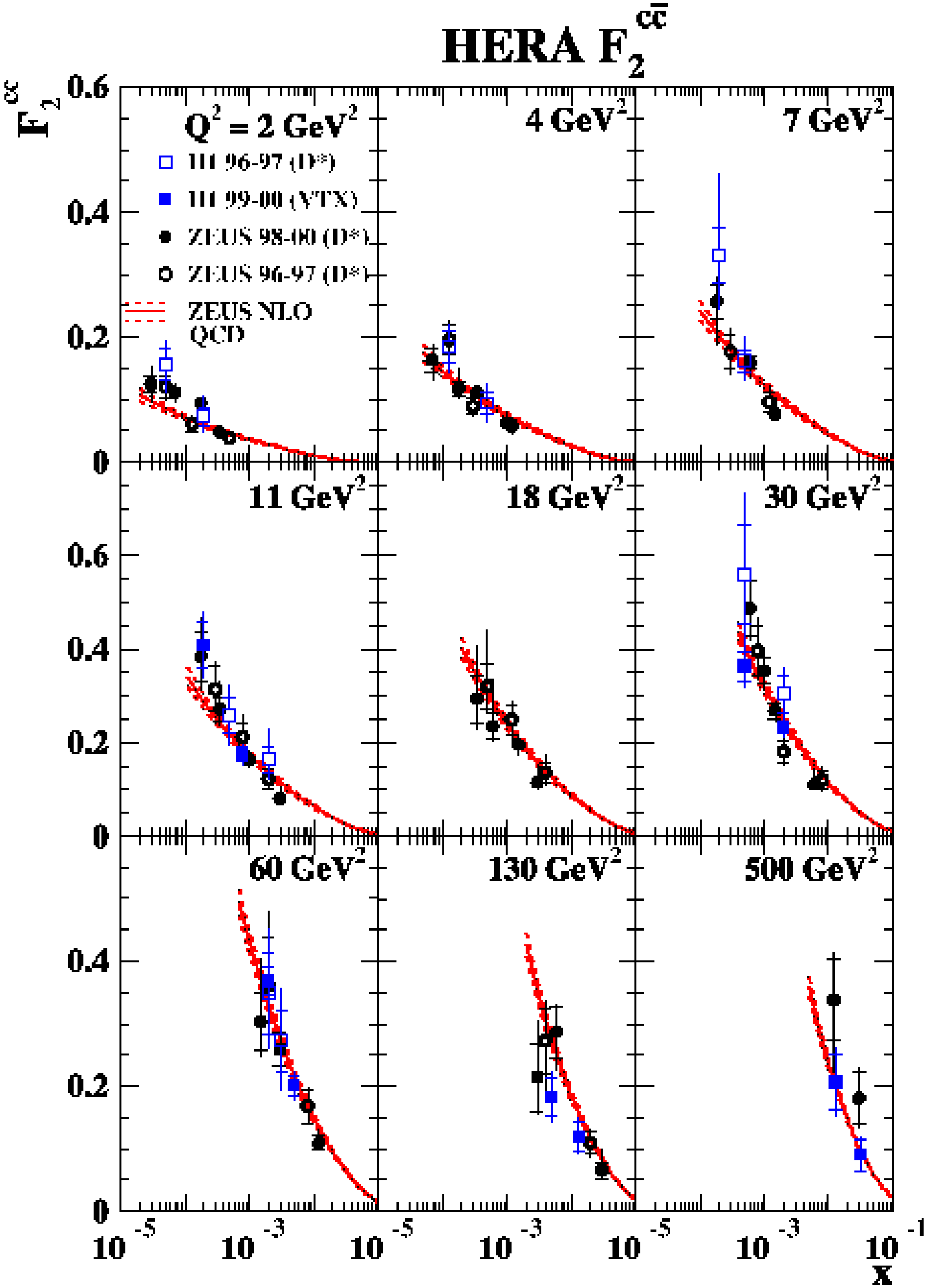
-> test/constrain gluon density

or



($Q^2 \gg m_c^2$)

-> obtain virtual charm content (PDF) of proton



Conclusions for HERA/LHC

- HERA: to do: converge towards quantitative direct measurement of gluon distribution from charm production

- LHC: gluon distribution determined by HERA is basis for many cross section predictions

Charm fragmentation fractions

	ZEUS (γp) $p_T(D,\Lambda_c) > 3.8\,\mathrm{GeV}$ $\lvert\eta(D,\Lambda_c)\rvert < 1.6$	Combined e^+e^- data [7]	H1 (DIS) [6]
	stat. syst. br.	stat.$\oplus$syst. br.	total
$f(c \to D^+)$	$0.217 \pm 0.014 \,^{+0.013}_{-0.005}\,^{+0.014}_{-0.016}$	$0.226 \pm 0.010 \,^{+0.016}_{-0.014}$	0.203 ± 0.026
$f(c \to D^0)$	$0.523 \pm 0.021 \,^{+0.018}_{-0.017}\,^{+0.022}_{-0.032}$	$0.557 \pm 0.023 \,^{+0.014}_{-0.013}$	0.560 ± 0.046
$f(c \to D_s^+)$	$0.095 \pm 0.008 \,^{+0.005}_{-0.005}\,^{+0.026}_{-0.017}$	$0.101 \pm 0.009 \,^{+0.034}_{-0.020}$	0.151 ± 0.055
$f(c \to \Lambda_c^+)$	$0.144 \pm 0.022 \,^{+0.013}_{-0.022}\,^{+0.037}_{-0.025}$	$0.076 \pm 0.007 \,^{+0.027}_{-0.016}$	
$f(c \to D^{*+})$	$0.200 \pm 0.009 \,^{+0.008}_{-0.006}\,^{+0.008}_{-0.012}$	$0.238 \pm 0.007 \,^{+0.003}_{-0.003}$	0.263 ± 0.032

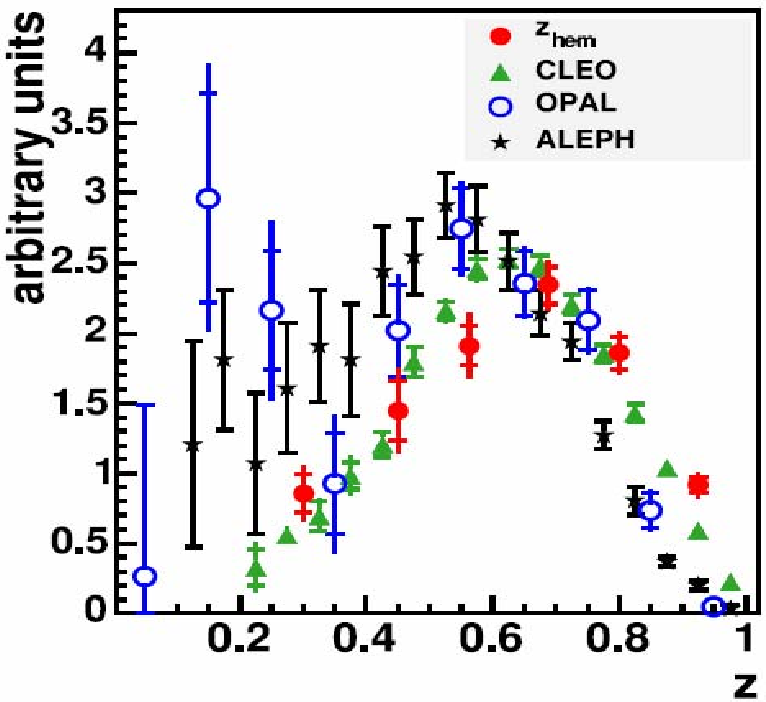
Table 4: *The fractions of c quarks hadronising as a particular charm hadron, $f(c \to D, \Lambda_c)$. The fractions are shown for the D^+, D^0, D_s^+ and Λ_c^+ charm ground states and for the D^{*+} state.*

- consistent with universality of charm fragmentation
- HERA competitive with e^+e^-

Charm fragmentation functions

Z. Rurikova

Comparison of Experimental results I



H1 hemisphere method
$<\sqrt{\hat{s}}>\approx 8$ GeV,
$z = \frac{(E+p_L)_{D^*}}{\sum_{\text{hem}}(E+p)}$

CLEO $\sqrt{s} = 10.6$ GeV,
$z = p_{D^*}/p_{\max}$

OPAL $\sqrt{s} = 91.2$ GeV,
$z = 2E_{D^*}/\sqrt{s}$

ALEPH $\sqrt{s} = 91.2$ GeV,
$z = 2E_{D^*}/\sqrt{s}$

- ▷ different observable definitions
- ▷ different center of mass energies, thus different pert. components as well

$\Longrightarrow$ **Direct shape comparison impossible!**

Conclusions for HERA/LHC

- HERA: more work needed on the influence of the perturbative part of heavy quark fragmentation, where universality is NOT expected

- LHC: universality of nonperturbative part can be safely assumed

Beauty fragmentation

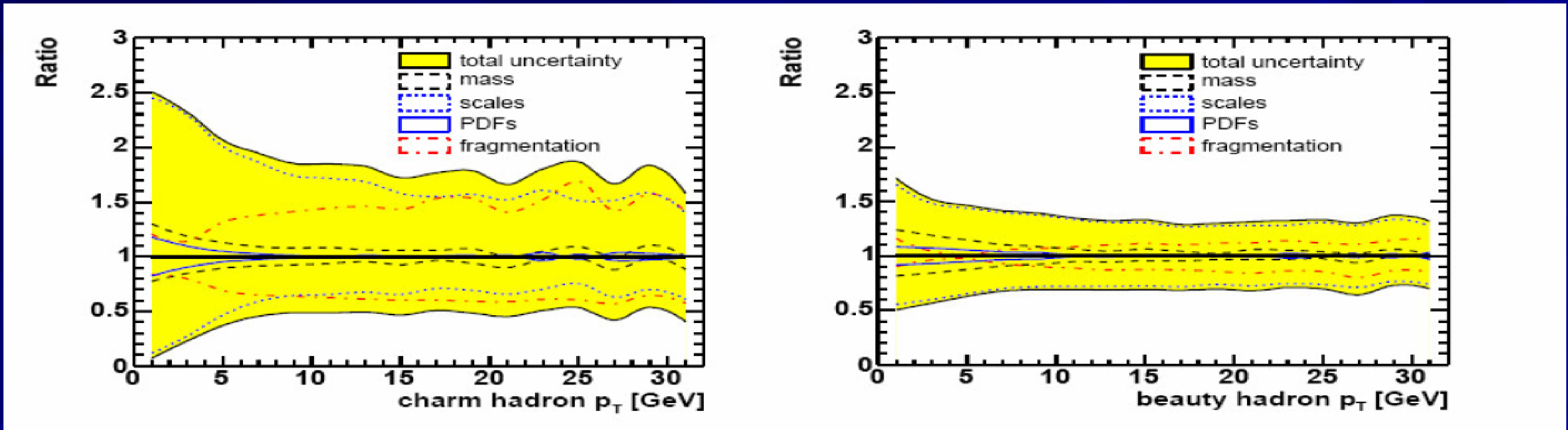
A. Mitov

Fragmentation at NNLO?

expected soon!

From the previous HERA-LHC workshop hep-ph/0601164 ...

fragmentation is second largest uncertainty



QCD predictions from NLO QCD (fixed order only)

Mangano, Nason, Ridolfi (1992)

Conclusions for HERA/LHC

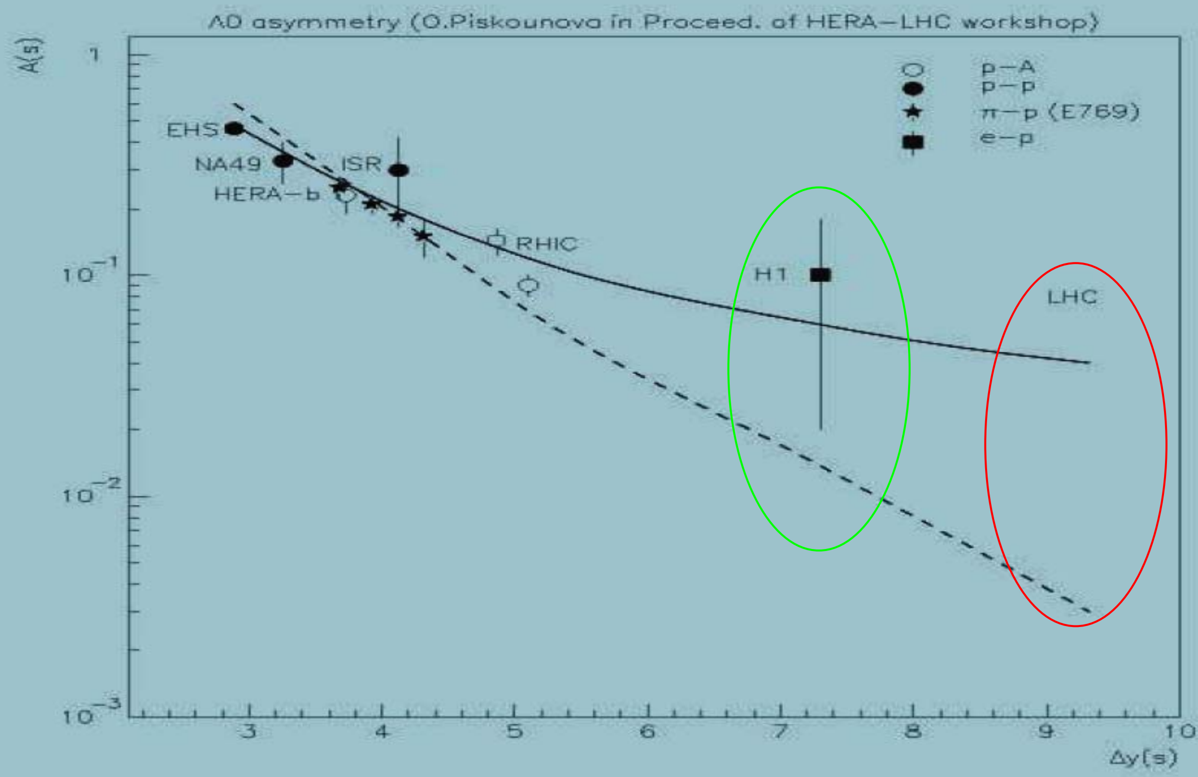
- expect improved predictions, in particular for LHC
  - p_{Tb} distributions
  - top mass measurements
  - …
- test at HERA

Baryon asymmetries

O. Piskounova

$\Lambda^0/\overline{\Lambda}^0$ asymmetry

$\Lambda_c/\overline{\Lambda}_c$ asymmetry should be the same!



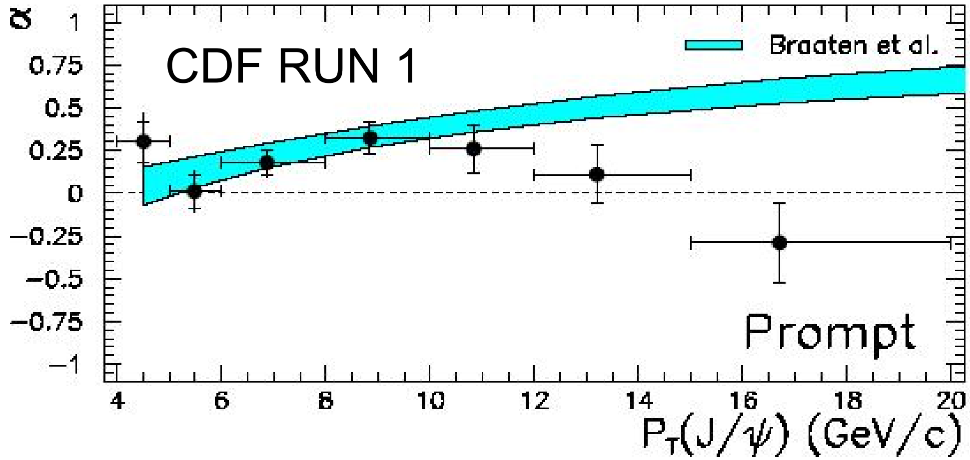
Conclusions for HERA/LHC

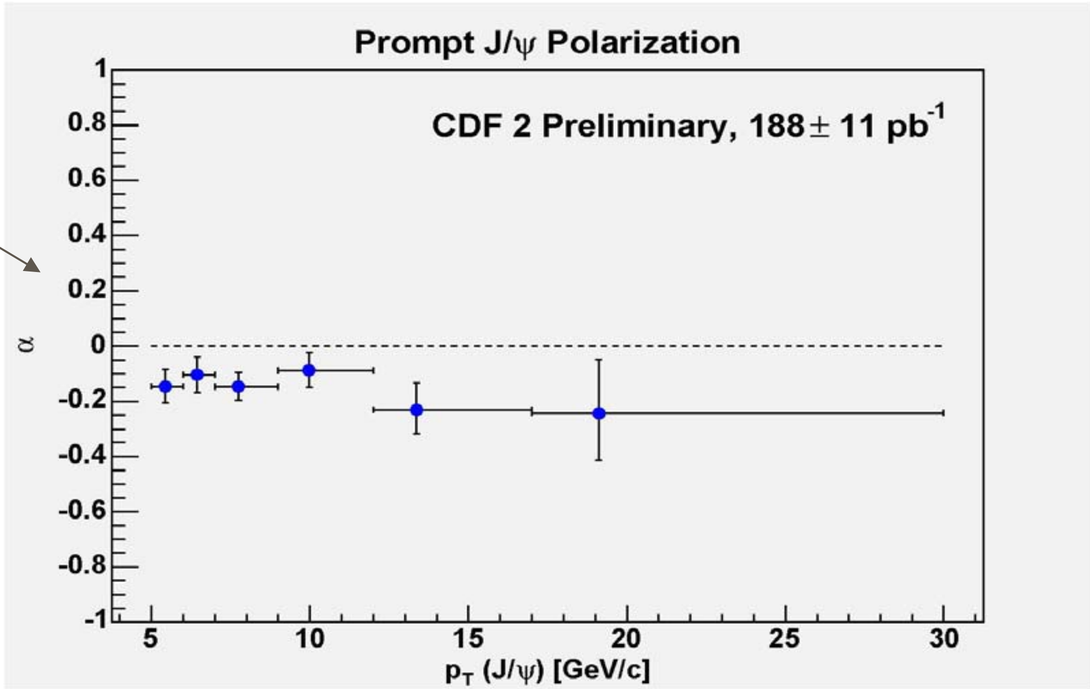
- try to measure Lambda_c asymmetry at HERA
- LHC can discriminate even better

J/ψ production at Tevatron->LHC

J. Ginzburg

- Measurements done at CDF are not consistent with the predictions of the J/ψ polarization P_T dependence.
- *Recent measurements* April 28, 2005
  [http://www-cdf.fnal.gov/physics/new/bottom/05 0428.blessed-jpsi-polarization/](http://www-cdf.fnal.gov/physics/new/bottom/050428.blessed-jpsi-polarization/)
- ***LHC can improve this!***



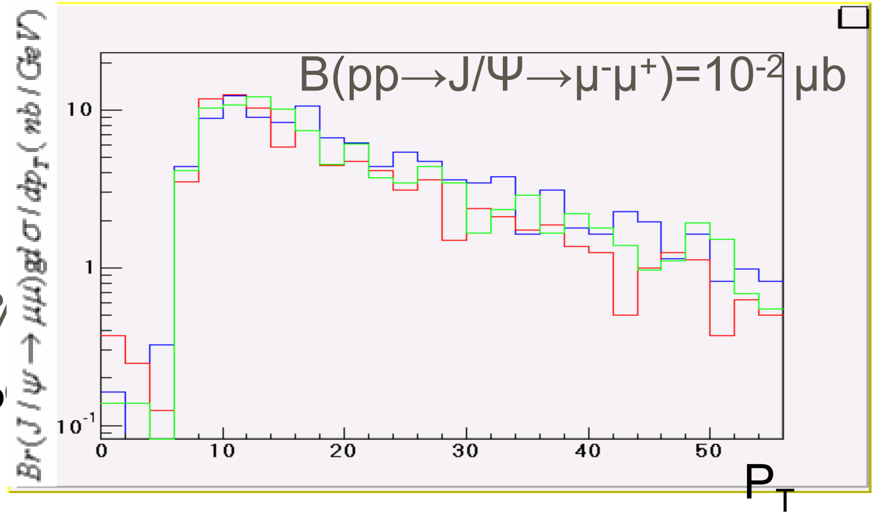


Cross Sections (g+g→J/Ψ +g)

J. Ginzburg

The prompt J/Ψ direct production using 3 different parton distribution functions.
CTEQ3L-Green
CTEQ5L-Red
CTEQ6M-Blue

ATLAS



- Trigger efficiency (low luminosity) to select pp→ J/Ψ → μ(6GeV)μ(3GeV) is~10
- Reconstruction algorithm efficiency ~6
- First year run ~ 100 days

$$10^{33}[bar^{-1}\sec^{-1}]\bullet 10^{-24}[particles/cm^2]\bullet 10^{-8}[bar]\bullet 10^{7}[\sec/run\_year] = 10^{8}[events/year]$$

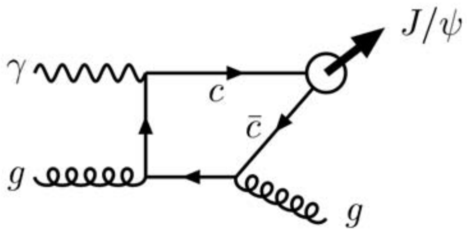
$$10^{8}[events/year]\times 0.1\times 0.6 \approx 6\times 10^{6}[events/year]$$

After one year we expect 6 million events of $pp\to J/\Psi\to\mu^-\mu^+$

inelastic J/ψ production at HERA

(a) leading-order colour-singlet:

direct γ: $\gamma + g \to c\bar{c}[{}^3S_1^{(1)}] + g$



$+\ldots$

- **Colour Singlet (CS)** contribution

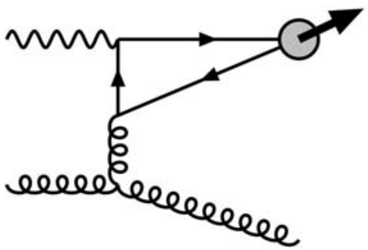
  directly calculable

  (see e.g. talk G. Bodwin)

  available at LO and NLO

(b) inelastic colour-octet:

direct γ: $\gamma + g \to c\bar{c}[{}^1S_0^{(8)}, {}^3P_J^{(8)}] + g$

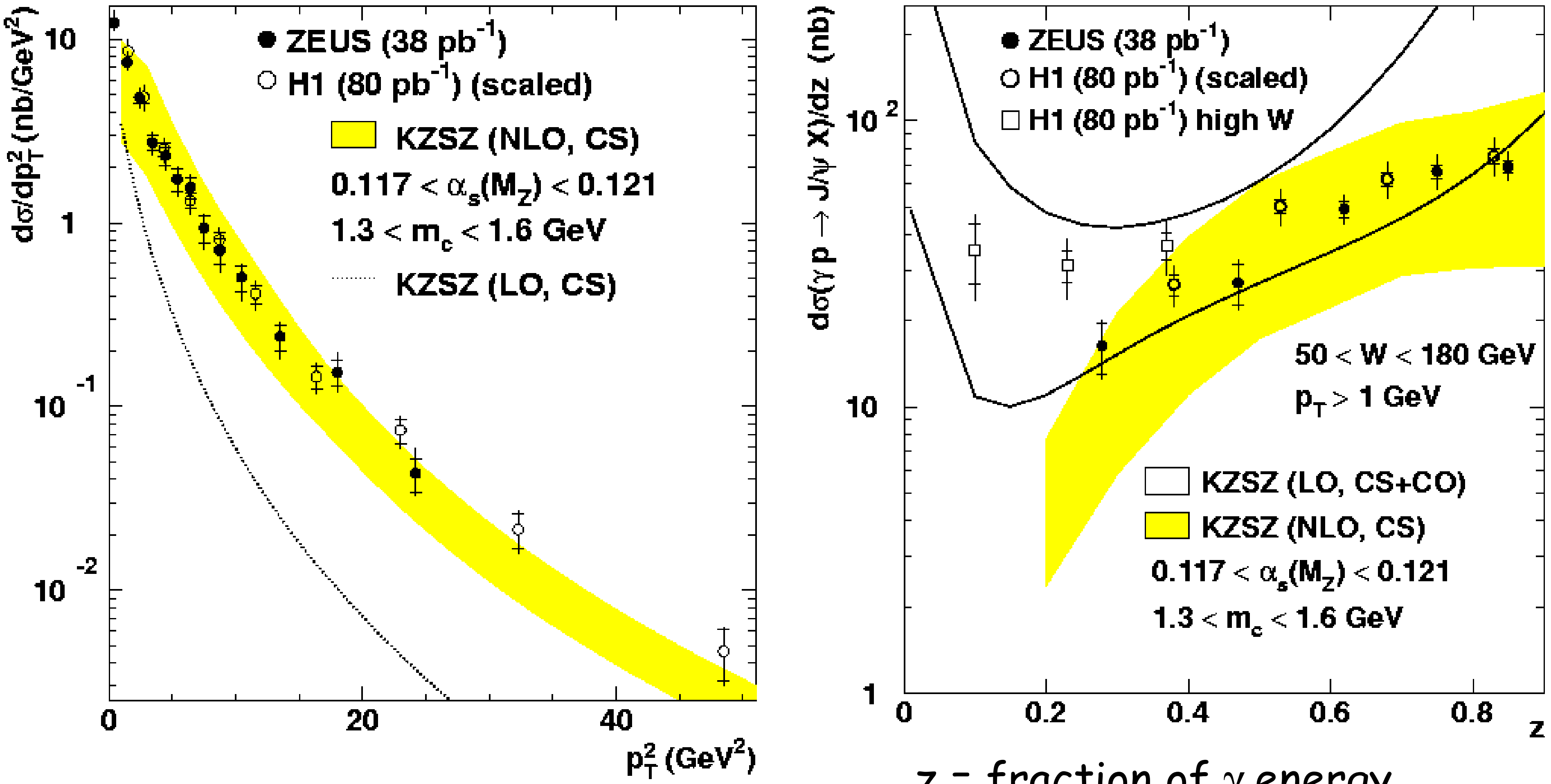


$+\ldots$

- **Colour Octet (CO)** contribution

  introduced in NRQCD to describe Tevatron data,
  not directly calculable,
  parametrized from Tevatron
  -> prediction for HERA, LO only

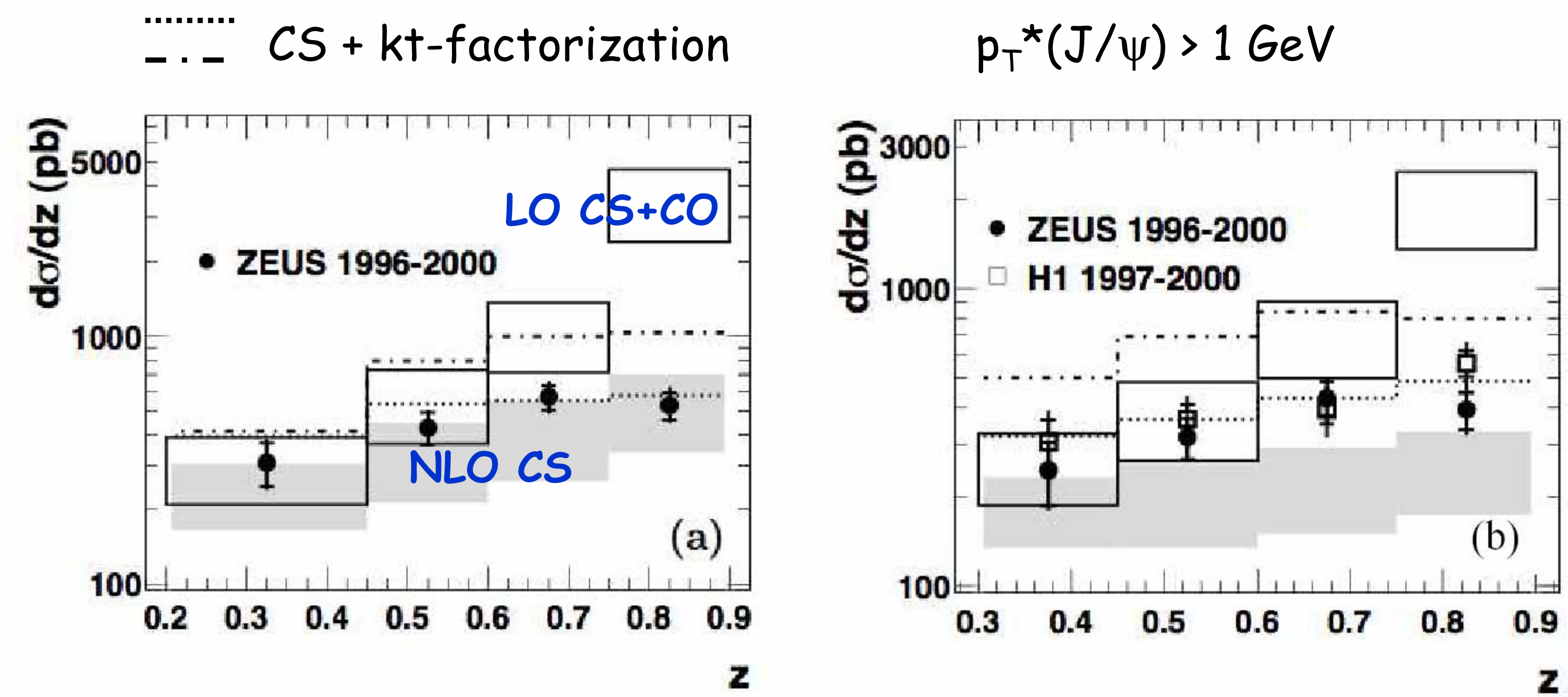
inelastic J/ψ photoproduction



z = fraction of γ energy
carried by J/ψ (in p rest frame)

- CS LO->NLO ~factor 3-10!

inelastic J/ψ electroproduction



Color Octet contribution not really needed to describe HERA data

Does NLO CS contain part of CO?

Conclusions for HERA/LHC

- HERA: status of CO contribution (NRQCD) unclear -> need HERA II measurements

- LHC: since J/ψ production mechanism potentially not yet fully understood: can theoretical predictions (extrapolation Tevatron -> LHC) be trusted?

Summary and Conclusions

- Heavy Flavour production in ep and pp collisions is good testing ground for perturbative QCD
- charm production: reasonably described, no clear preference between "massive" NLO and "massless" NLL calculations.
  NNLO or NLO+PS needed for some regions of phase space.
  HERA charm fragmentation measurements competitive with e^+e^-.
- beauty production: reasonable description at high p_{Tb} -> **OK for LHC**
  getting worse (but still acceptable) at low p_{Tb}?
  problem with „resolved“ region? -> higher orders!
- DIS (F_2): both charm and beauty well described
  first measurement of F_2^{bb} -> extract b and gluon for LHC
- inelastic J/ψ production at HERA: data acceptably described by both LO CS+CO, and NLO CS only. CO not really needed. LHC??
- HERA II performing well. Expect improved results soon!