

Heavy Flavor Production Overview

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Fermilab

XXXIII International Symposium

on

Multiparticle Dynamics

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Today's Program

Beauty and Charm Production at Fixed-Target Experiments

Erik Gottschalk (Fermilab - FOCUS)

Charmonium Production with $p\bar{p}$ Gas Jet Interactions at FNAL

Matteo Negrini (Ferrara - E835)

Charmonium production with e^+e^-

Pavel Pakhlov (Moscow, ITEP - BELLE)

Heavy Flavor at LEP

Andrea Sciaba (Pisa - ALEPH)

Heavy Flavor Production in ep Collisions

Bob Olivier (DESY - H1)

Heavy Flavor Production and Results from the Tevatron

Kurt Rinnert (Karlsruhe - CDF)

Recent Developments in Heavy Quark and Quarkonium Production

Tom Mehen (Duke)

Themes to Watch For Here

We will see a lot of data in the next six talks, some of it quite new.

Themes of particular interest:

QCD Dynamics

Tests of the Basic Theory and Beyond

Structure of Hadrons

More Than an Input to QCD Calculations

Nature and parameters of quarks in hadrons

By the end of the afternoon, we should see what we have learned and what remains a mystery.

Testing QCD

In his Lepton Photon 2003 review last month, “QCD Theoretical Developments”, Thomas Gehrmann (Institute of Theoretical Physics, Zurich) said

“testing QCD”-era has been over for some time

Nevertheless, a quick search of SPIRES finds the following numbers of papers with titles including “test” of or “testing” QCD:

1998	4	2000	8	2002	11
1999	10	2001	4	2003	3 (so far)

So, testing is not over yet!

Some Recent Surprises

Double charm production in e^+e^- continuum

Production rate of double charm baryons by Σ^+ 's

Better agreement with theory for charm than beauty production
in $\gamma\gamma$ collisions at LEP

Some Remaining Old Mysteries

J/ψ , ψ' production rates at fixed target and collider energies

b quark production rates at Tevatron Collider energies

Double charm production at Belle

$$e^+e^- \rightarrow J/\psi \eta_c:$$

$$e^+e^- \rightarrow J/\psi D^0 X:$$

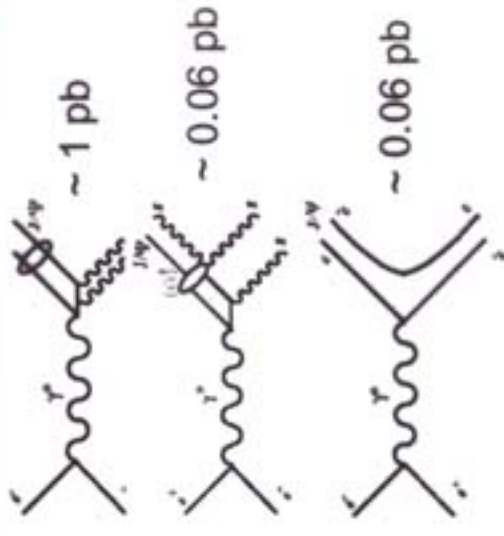
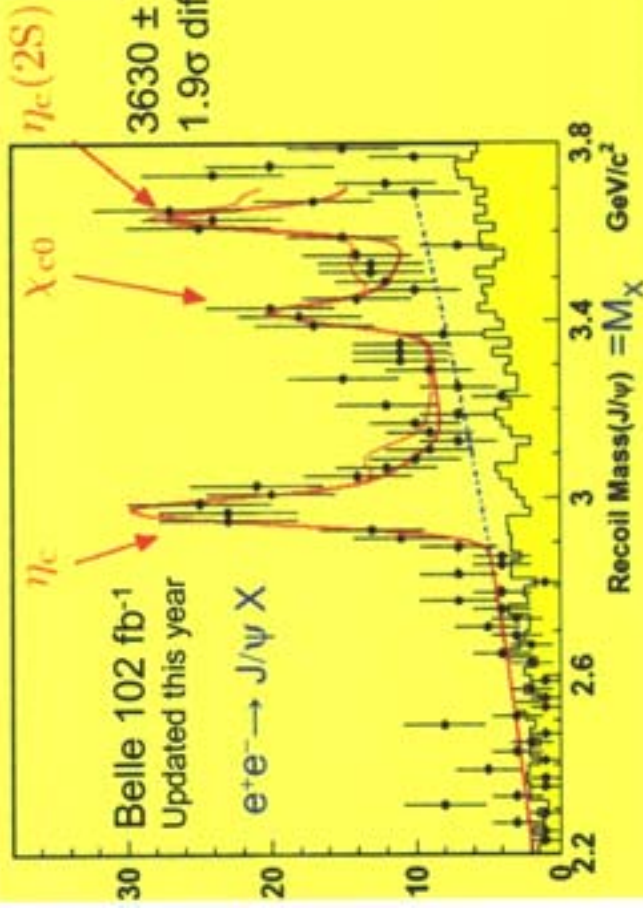
$$e^+e^- \rightarrow J/\psi D^{*+} X:$$

$$\sigma(e^+e^- \rightarrow J/\psi \eta_c) \times \mathcal{B}(\eta_c \rightarrow > 2 \text{ charged}) = (0.033^{+0.007}_{-0.006} \pm 0.009) \text{ pb}$$

$$\sigma(e^+e^- \rightarrow J/\psi c\bar{c}) / \sigma(e^+e^- \rightarrow J/\psi X) = 0.59^{+0.15}_{-0.13} \pm 0.12$$

2002
results

~10 times larger than expected



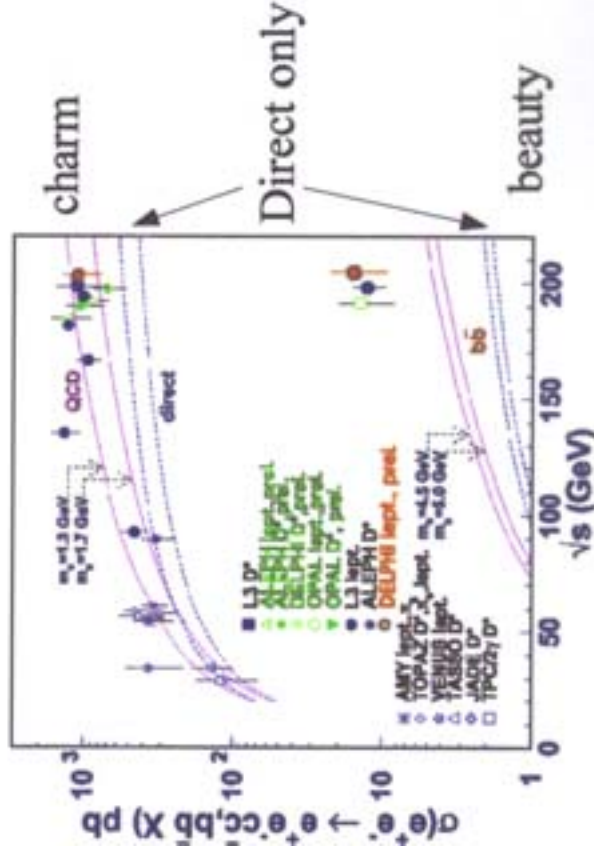
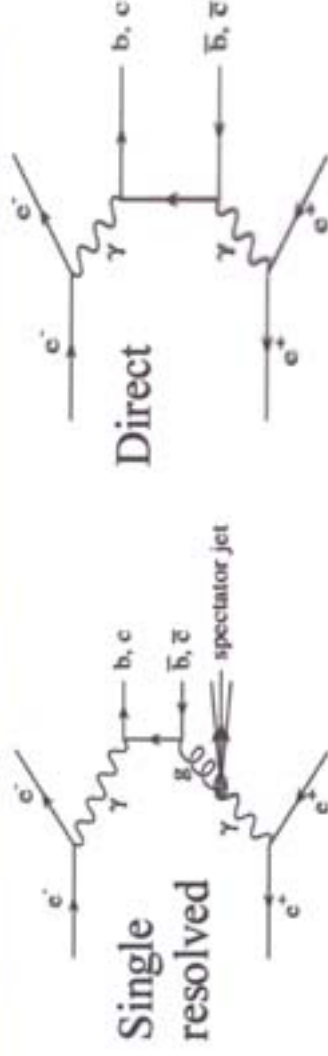
$$\frac{\sigma(e^+e^- \rightarrow J/\psi c\bar{c})}{\sigma(e^+e^- \rightarrow J/\psi X)} \Big|_{P_{J/\psi} > 2.0 \text{ GeV}/c} = \frac{0.5(N_{D^0} + N_{D^+} + N_{D^{*+}} + N_{A_0}) + N_{(c\bar{c})_{res}}}{N_{J/\psi}} = 0.82 \pm 0.15 \pm 0.14$$

Preliminary

- Much debated theoretical puzzle!

Beauty and Charm Production at LEP

Main contributions at LO
both ~ same order at LEP2



Single resolved process
needed to describe b/c data

LEP results consistent

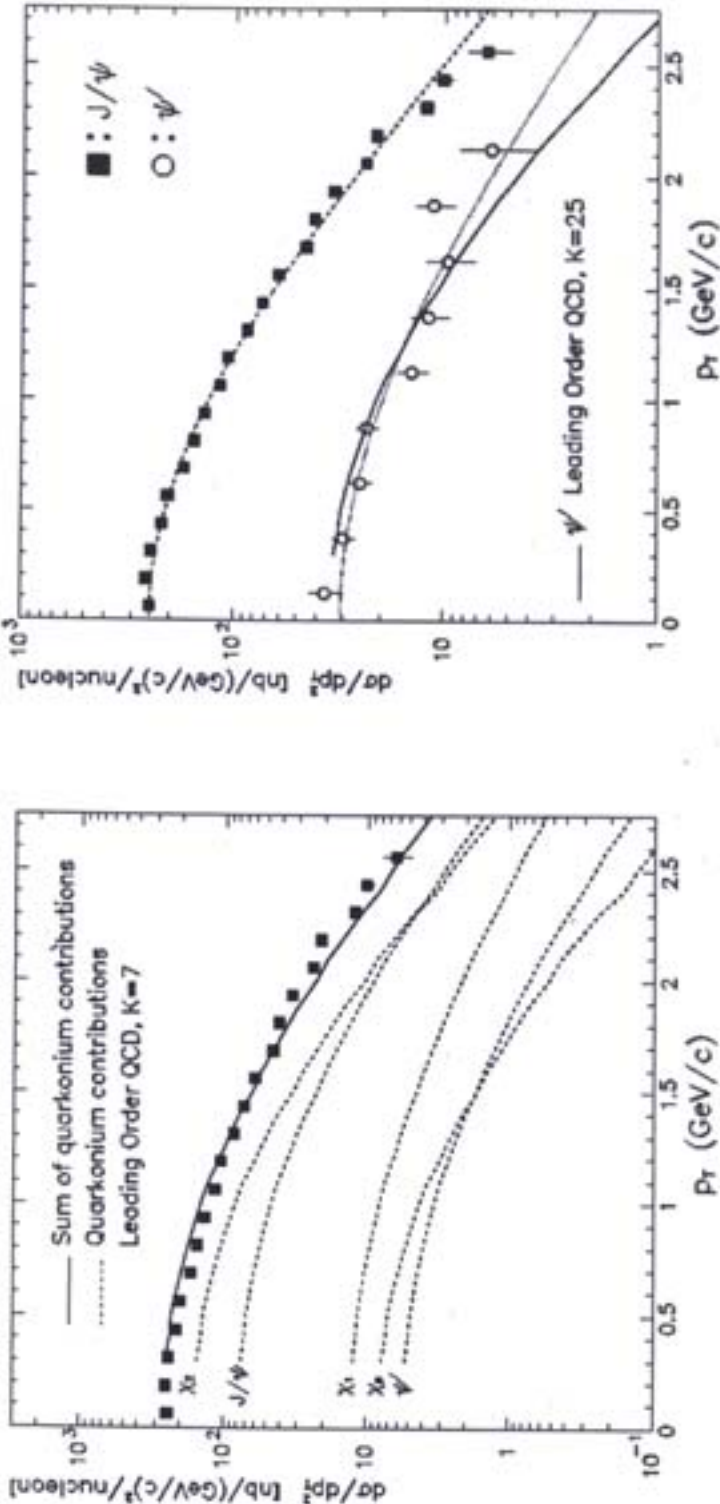
New DELPHI result confirms
L3/OPAL beauty excess

Charm looks OK, beauty
predictions are low.

Difference not understood.

(DELPHI: first analysis w/ K-lepton charge correlations in $\gamma\gamma$)

E789 J/ψ and ψ' Cross Section



J/ψ theory shown 7x LO calculation.

ψ' theory shown 25x LO calculation.

Hadro-production

- NRQCD (leading order)

leading-order colour-singlet: $g + g \rightarrow \alpha_s^3 S_1^{(1)} + g$



$$\sim \alpha_s^3 \frac{(2m_Q)^4}{p_T^4}$$

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



$$\sim \alpha_s^2 \frac{1}{p_T}$$

colour-octet fragmentation: $g + g \rightarrow \alpha_s^3 S_1^{(8)} + g$

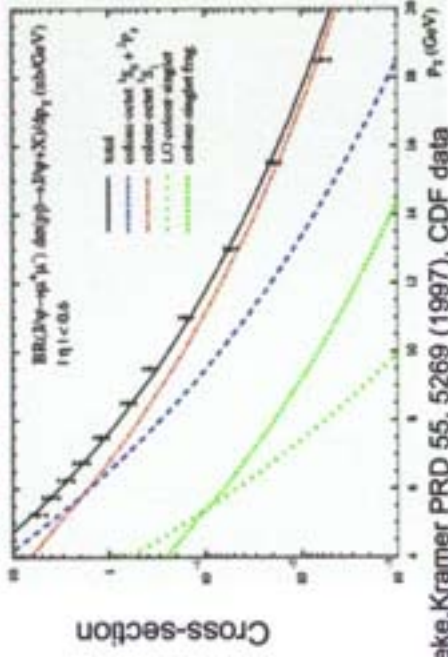


$$\sim \alpha_s^3 \frac{1}{p_T} v^4$$

colour-octet fusion: $g + g \rightarrow \alpha_s^4 [S_0^{(8)} + 3 P_1^{(8)}] + g$

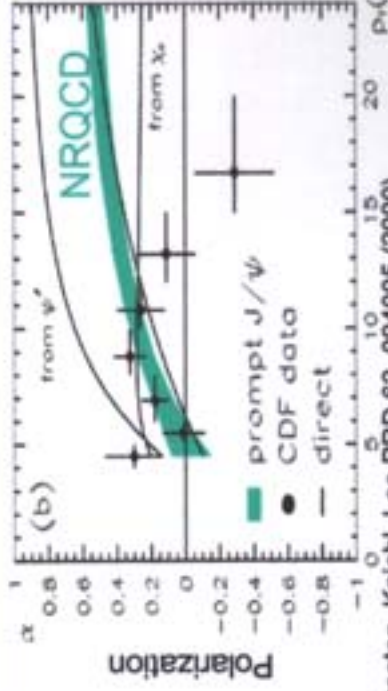


$$\sim \alpha_s^4 \frac{(2m_Q)^2}{p_T^2} v^4$$



Beneke, Kramer PRD 55, 5269 (1997), CDF data

Old news: color-octet contributions are important
potential problem with polarization data



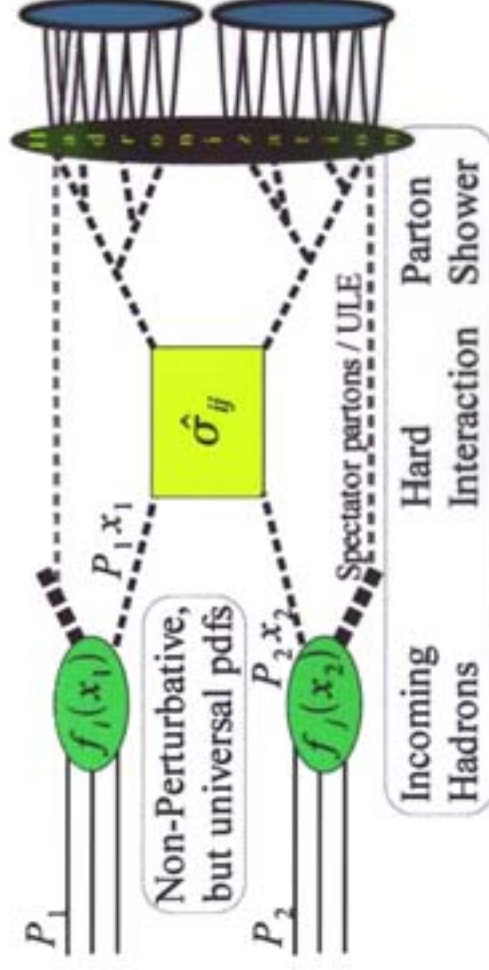
Braaten, Kniehl, Lee PRD 62, 094005 (2000)

new: CDF Run-II data: http://www-cdf.fnal.gov/physics/new/bottom/030327.blessed-jpsixsec/xsec_html/

For hard interactions in QCD

General applicability of perturbation theory

- non abelian gauge theory, running coupling constant $\alpha_s \propto \frac{1}{\ln(\sim Q^2/\Lambda^2)} \dots$
- extremely rich phenomenology
- short distances / large p scales: α_s small allowing perturbative calcs.
- factorization of short (pert.) and long (non-pert.) scales



Calculable at (N)NLO w/ scale dependencies: $\alpha_s(Q^2), f(x, Q^2)$

Heavy Flavor Cross Sections

Typically, cross sections are much larger than LO QCD predictions, even

when renormalization and factorization scales and masses set low.

Cross sections are still larger than NLO predictions, typically by factors

~ 2 , at least in some kinematic regions.

Recently, adding resummation effects (Next to Leading Log, NLL in p_t)

and refined fragmentation functions are helping with agreement.

How should we interpret this progression? Real progress. Yes. But,

notice that data is typically in a limited kinematic region and any

Standard Model effect which increases predicted σ_{QCD} is kept.

Charmonium Issues

Direct charmonium is a small fraction of the total charm production.

Large factors larger than color singlet production predictions.

Color octet hard scattering is a possible contribution, color evaporation, too.

Non-Standard Model sources – e.g., light SUSY?

Need data over broader kinematic ranges (e.g., lower p_t where σ is large – noting p_t dependence of resummation in p_t).

Theory is only credible when terms are universal, non-process specific.

Direct charmonium production “K factors” don’t look like “simple” higher order effects to me.

1. Supersymmetry and Bottom Quark Production

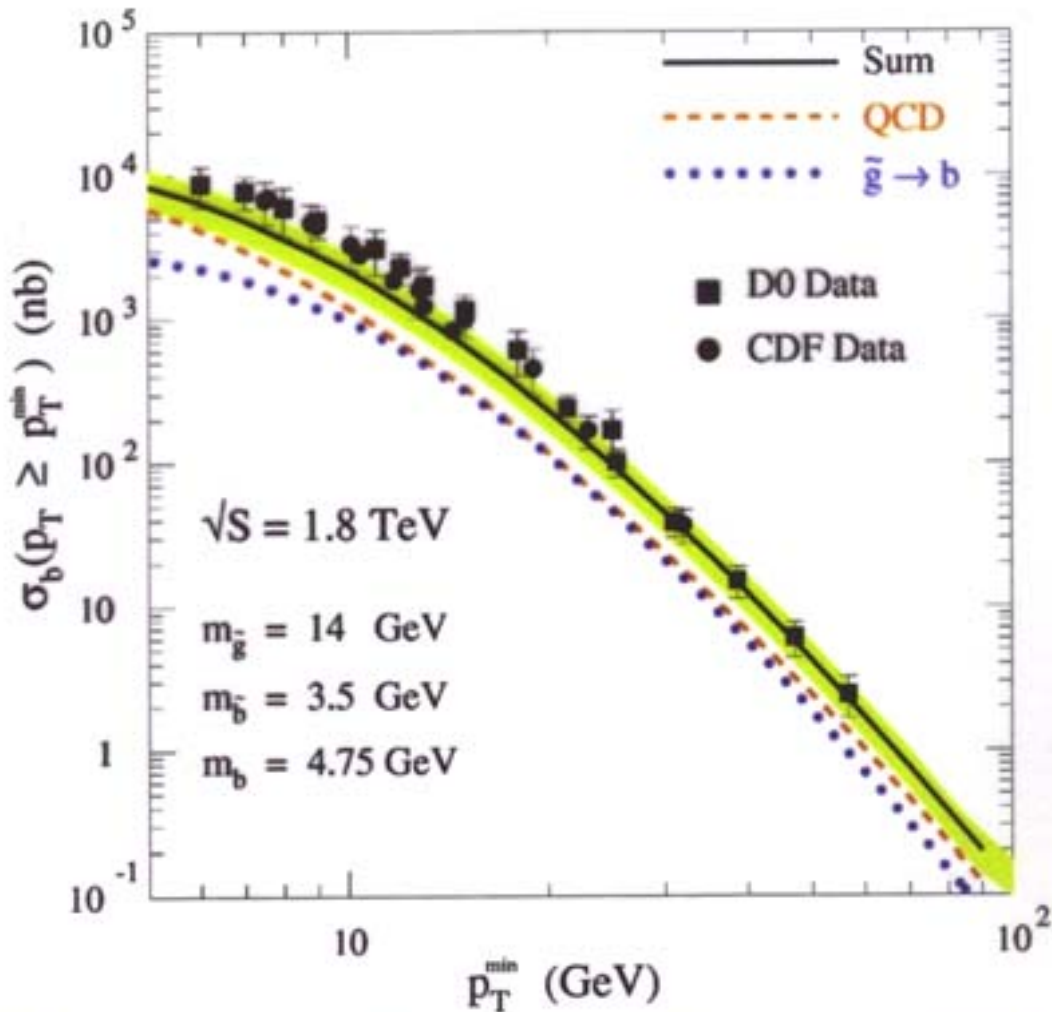
- Motivation: Cross section for bottom quark production exceeds the central value of predictions of NLO QCD by a factor of **2 to 3** at the Tevatron ($p\bar{p} \rightarrow b\bar{b}X$) [$\rightarrow$ Fig.]
- **New Physics:** within the minimal supersymmetric standard model (MSSM), assume the existence of a low-mass color-octet, spin-1/2 gluino ($\tilde{g}$) and a low-mass color-triplet spin-0 bottom squark ($\tilde{b}$) **Pair production of $\tilde{g}$:**

$$p + \bar{p} \rightarrow \tilde{g} + \tilde{g} + X,$$

$$\tilde{g} \rightarrow b + \tilde{b}^* \text{ or } \tilde{g} \rightarrow \bar{b} + \tilde{b} \quad \text{100\% BR}$$

- Masses obtained by “fit” to the hadron collider b data:
 - $m_{\tilde{g}} \simeq 12$ to 16 GeV; $m_{\tilde{b}} \simeq 2$ to 5.5 GeV
- $\tilde{b}$ is the lightest SUSY particle; other than $\tilde{b}$ and $\tilde{g}$, masses of most other SUSY particles may be arbitrarily large; $m_{\tilde{t}} \simeq m_t$; this scenario is **NOT** mSUGRA, GMSB,
- Consistent with all available constraints from precision measurements at the Z , from low-energy e^+e^- experiments, etc.; recent ALEPH analysis requires the lifetime $\tau_{\tilde{b}} < 1$ ns.

2. Comparison of b -Quark Cross Section with Data



- Values of $m_{\tilde{g}} \simeq 12$ to 16 GeV produce p_{Tb} spectra that are enhanced near $p_{Tb}^{\min} \simeq m_{\tilde{g}}$ where data deviate most from pure QCD; light $\tilde{g}$ is necessary to obtain a b cross section comparable to the pure QCD rate
- Theoretical uncertainty of roughly $\pm 30\%$ (yellow band) may be assigned to the final curve from variations of the renormalization and factorization scales μ , the b mass, and the parton densities

E. Berger, B. Harris, D. Kaplan, Z. Sullivan, T. Tait, and C. Wagner,

Phys.Rev.Lett. 86,4231 (2001) [hep-ph/0012001]

3. Predictions and Implications

- $\tilde{g}$ decays to $b\tilde{b}$. $\tilde{b}$ is the LSP, and $\tilde{g}$ is the NLSP
- Since $\tilde{g}$ is a Majorana fermion, it decays with equal probability to a b quark or a $\bar{b}$. There will be an apparent **increase of the time-averaged mixing** of B^0 and $\bar{B}^0$ in hadron collisions
- In DIS or in photoproduction at HERA, and in $\gamma\gamma$ processes at LEP, the process $g + g \rightarrow \tilde{g} + \tilde{g}$ feeds from the resolved component of the real or virtual γ . There should therefore be much less excess rate of $b\bar{b}$ at HERA and in $\gamma\gamma$ processes with respect to NLO QCD
- Bottomonium decays: $\Upsilon \rightarrow \tilde{b}^* \tilde{b}$. If the $\tilde{b}$ is light enough, expect an increase of the hadronic widths of $\Upsilon(nS)$.
 - $BR(\Upsilon(1S) \rightarrow \tilde{b}\tilde{b}^*) \simeq 10\%$ for $m_{\tilde{g}} \simeq 16$ GeV and $m_{\tilde{b}} \simeq 4$ GeV

Berger and Clavelli, Phys.Lett. B512 (2001) 115-120

- If $\tilde{b}$ is relatively stable, **$\tilde{b}\tilde{b}^*$ bound states** can exist. Suppose $\tilde{b}$ is stable enough that $\tilde{S} = S$ -wave bound state exists; $\tilde{S} \rightarrow gg$ ($\Gamma_{\text{had}} < 10$ MeV). **$\tilde{S}$ could be produced in radiative decays: $\Upsilon \rightarrow \gamma\tilde{S}$** . Branching fraction $\sim 10^{-4}$ Berger, Bodwin, and Lee, Phys. Lett. B552, 223 (2003)
- Higgs boson decays primarily to hadronic jets Berger, Chiang, Jiang, Tait, and Wagner, Phys. Rev. D66, 095001 (2002)

Partons in the Light Hadrons

Fixed-Target measurements of charm quarks
tell us about the nature and details of

light hadrons

HERA measurements of charm quarks tell us
about the charm content of
resolved γ 's.

Charm Production

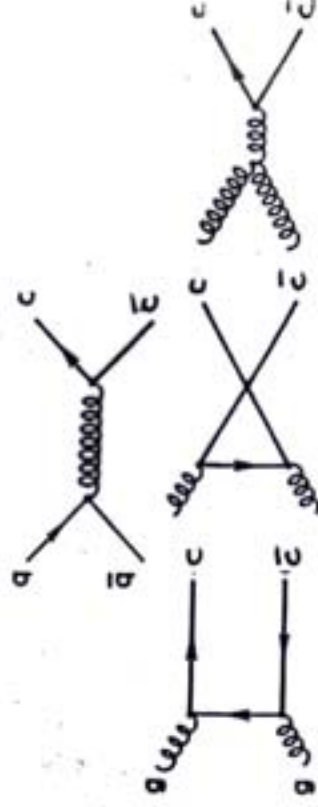
By Neutrinos



By Photons

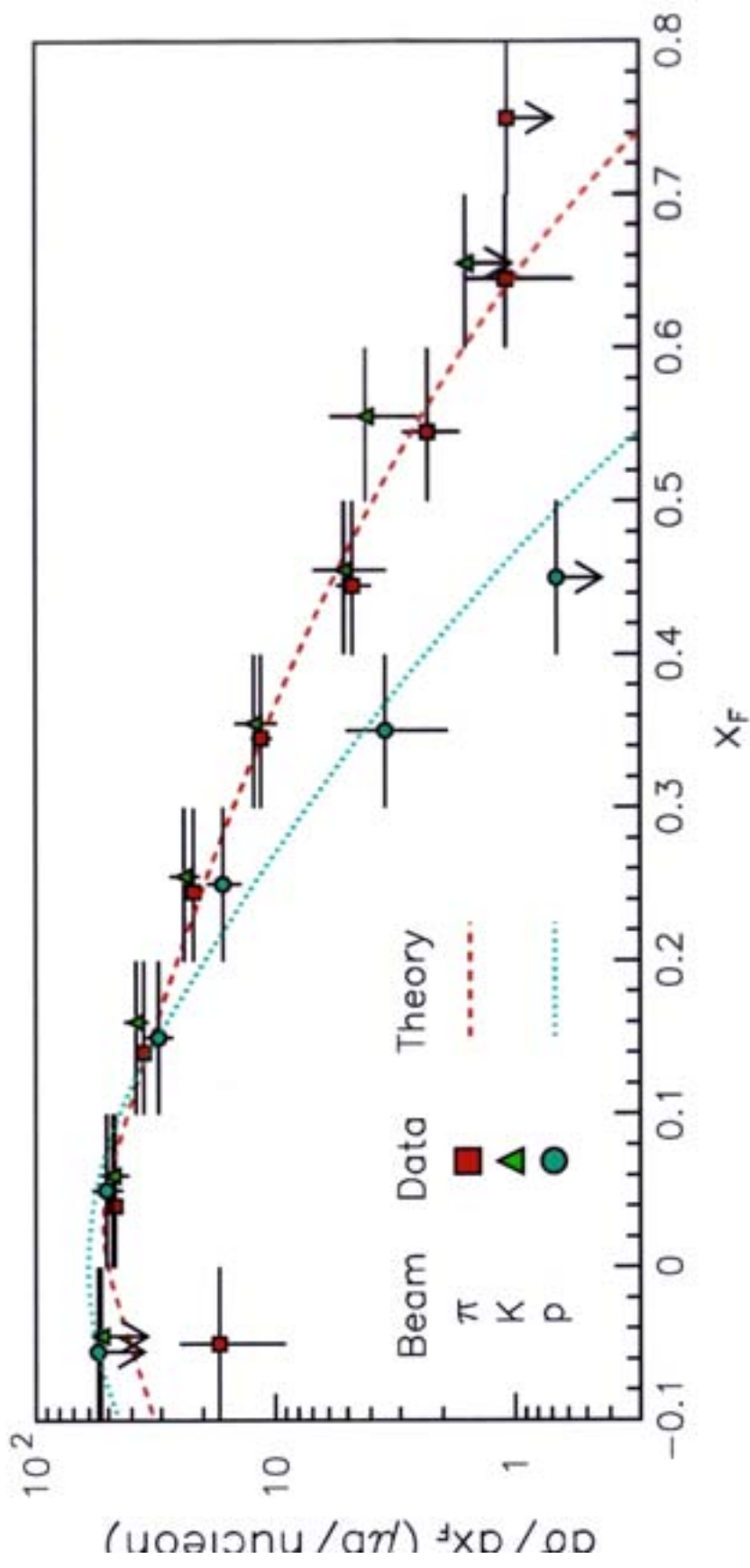


By Hadrons



Observed charm particles are sensitive to the parton distributions in the incident particles, as well as to hadronization effects and the hard scattering $\sigma_{c,\text{anti-}c}$ which produces the charm quarks in the first place.

Gluons Softer in Nucleons than Mesons



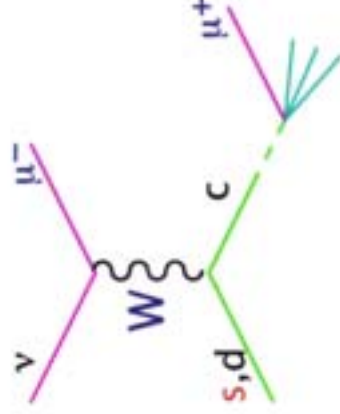
D meson production in Fermilab E769.

G.A. Alves, *et al.*, Phys. Rev. Lett. 77, 2392 (1996).

Strange Quarks and Antiquarks in the Nucleon Sea

$$\nu N \rightarrow \mu^- \mu^+ X$$

$$\bar{\nu} N \rightarrow \mu^+ \mu^- X$$

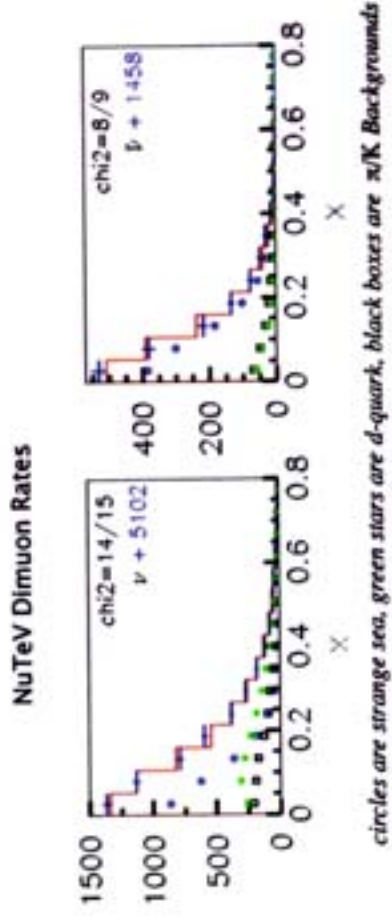


Dimuon signal (one muon from the charged-current interaction, one from a charm semileptonic decay).

Dimuon cross section is dominated by strange quarks:

$$\text{d-quark term small, } |V_{cd}|^2 / |V_{cs}|^2 \approx 1/20$$

Measurement of Strange Sea



M. Goncharov *et al.*, *PRD64* 112006(2001).

Strange sea measured to be $\sim 40\%$ of the non-strange sea:

	from neutrinos	from antineutrinos
$\kappa = 2s/(u+d)_{\text{sea}}$	0.36 ± 0.05	0.38 ± 0.04

LO Strange Sea Model in fits so far (Buras and Gaemers)

Experimental Evidence on Intrinsic Charm

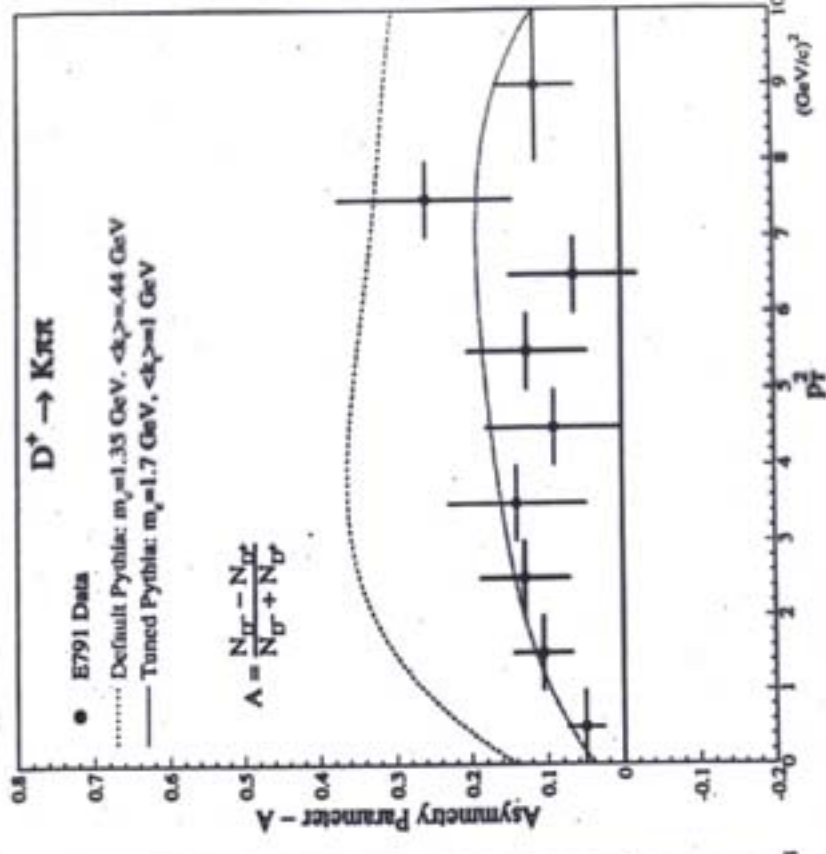
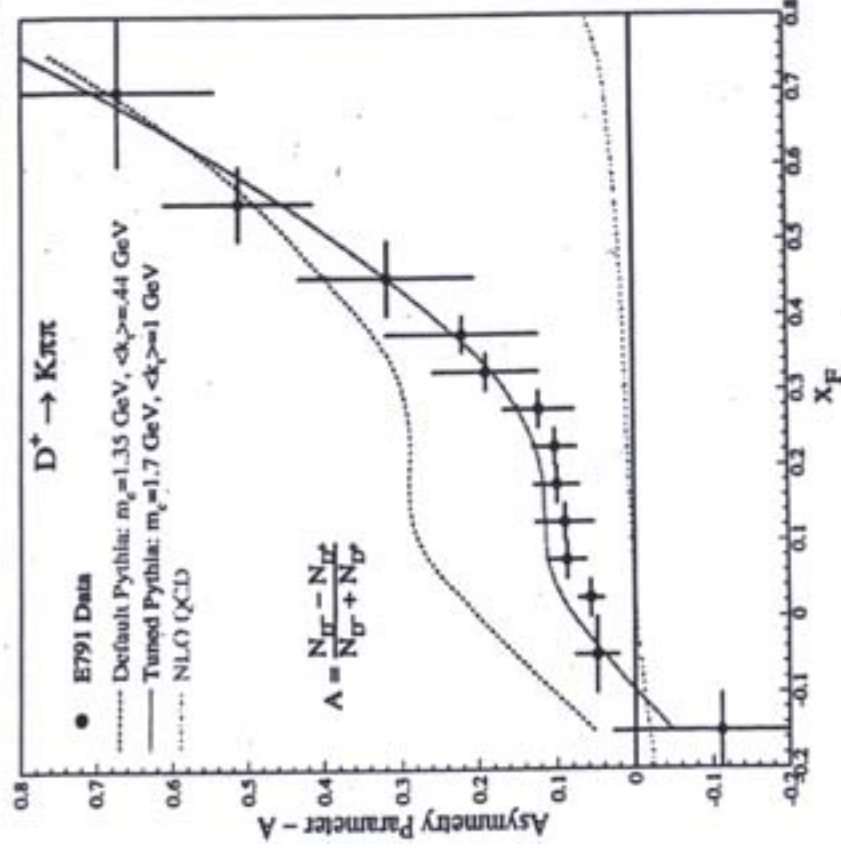
Initially, proposed to explain apparently very large Λ_c production at CERN ISR experiments – 1-2% of the proton.

Intrinsic charm pairs co-moving with the valence quarks of the parent projectile – making coalescence with them easy, and producing large particle/antiparticle asymmetries in the forward direction at low p_t .

Differential cross section for forward J/ψ production at high x_F from E789[†] limits intrinsic charm to less than 1% of prediction (corresponding to less than 0.02% of proton).

[†]E789 Collaboration, M.S. Kowitt et al., Phys. Rev. Lett. 72, 1318 (1984).

P_t Dependence of Prod. Asymmetry



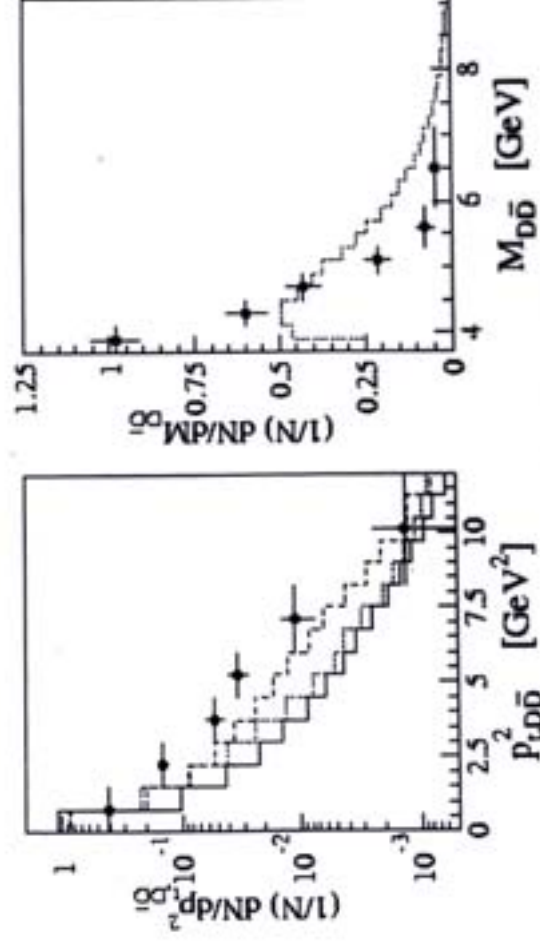
E791 Collaboration, E.M. Aitala, et al, Phys. Lett. B371 (1996).

Intrinsic k_t

Term to account for the transverse momentum of initial partons.

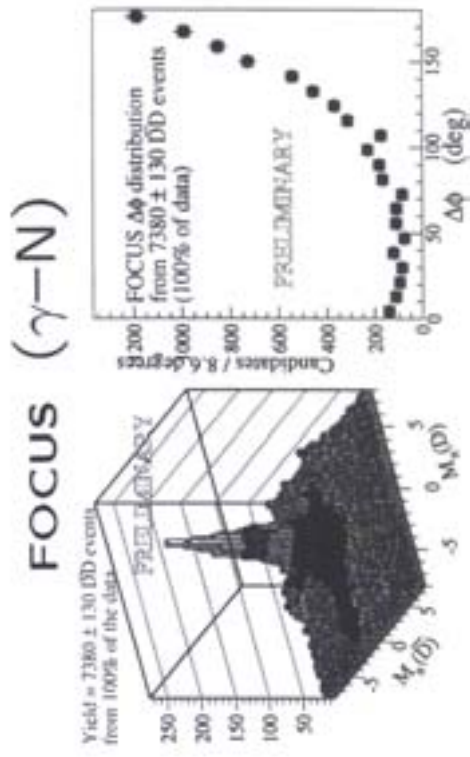
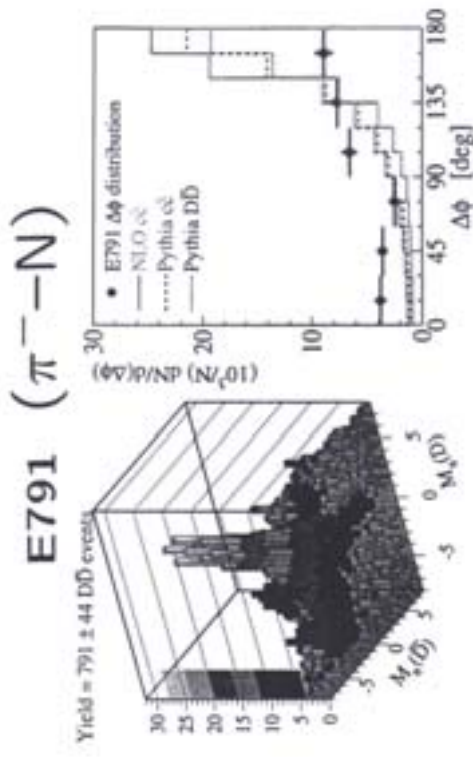
Unphysically large k_t needed to explain p_t and correlations.

Is it a misnomer for something else? What?



E791 Collaboration, E.M. Aitala, et al., EPJdirect C4, 1 (1999).

Comparing Photo- and Hadroproduction Correlations



Summary

A lot to learn from heavy flavor production in a large variety of environments.

We will see tests of QCD – the processes that matter, and how they contribute.

We will see fundamental quantities entering each process, and use the heavy quark to tag the process of interest.

On to the data and its interpretations!