The Heavy Quark Parton Dichotomy
or
Heavy Quark - Parton Complementarity in QCD

Scales in Heavy Quark Production at High Energies

Common Calculational Schemes

- The dichotomy:
  - (Zero Mass) Quark Parton Formalism;
  - Heavy Quark (fixed-flavor-number) Scheme
- The Resolution (the physics):
  - Generalized Factorization Theorem
    - $\rightarrow M \neq 0$ Quark Parton Formalism

What Scheme to Use? Depends on:

- Energy scale;
- The Physical Question asked
  -- Complementarity.

"Full Theory" vs. Practical Solution

What is still Missing?

Wu-Ki Tung

Relevant Energy Scales

Scales other then quark masses

Small energy scales: m:

$(m_\pi, m_N, \ldots \Lambda_{QCD}, \ldots)$

Large energy scale: s:

$(s, E, W, \ldots.)$

Typical hard scale:: Q

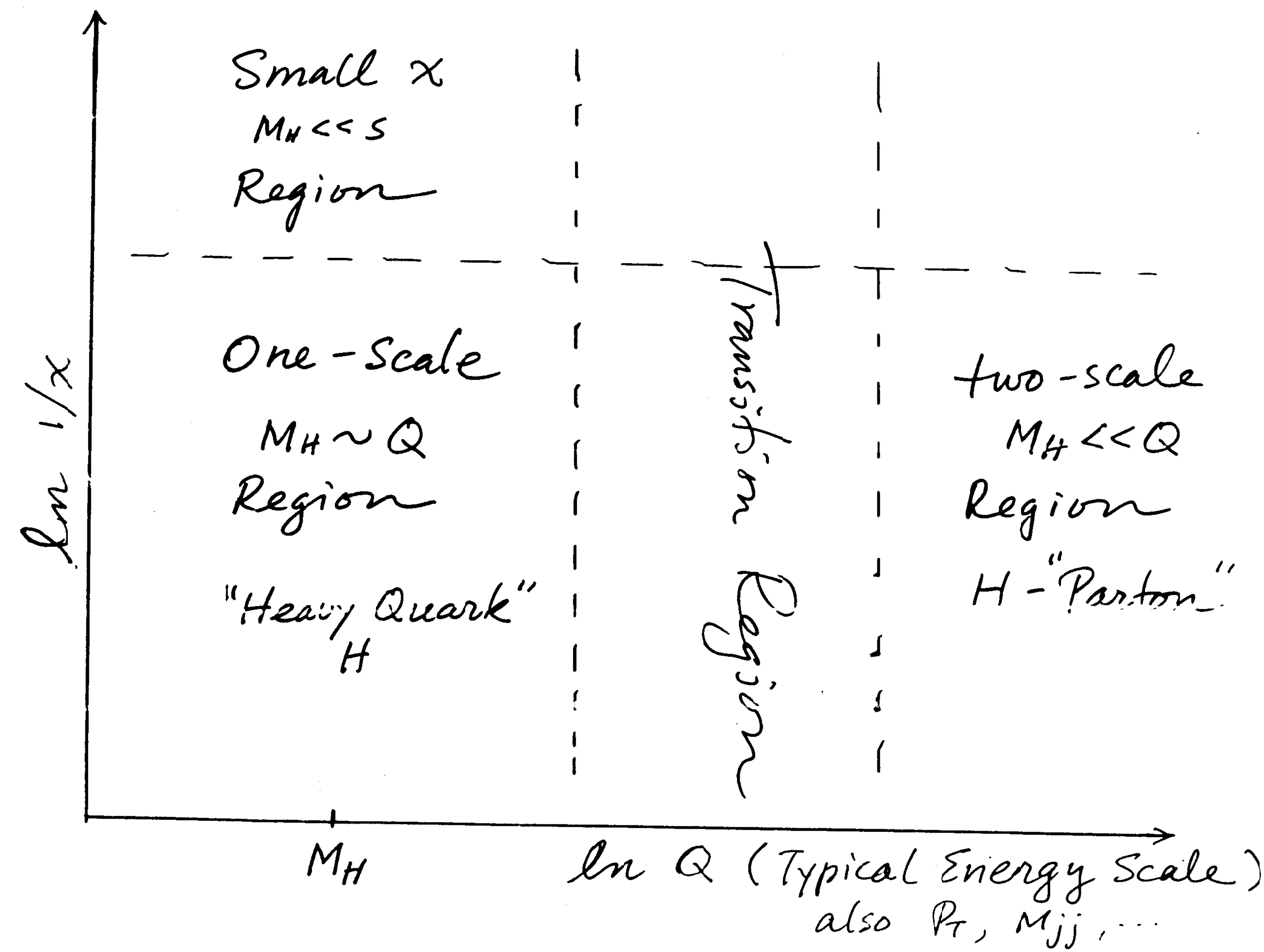
$(Q, P_T, M_{ll}, M_{jj}, \ldots)$

Then, there is the Heavy quark H M_H

If H is "heavy": $m << M_H$

For H to be produced: $M_H^2 < s$

Relative magnitude of typical energy scale Q with respective to M_H is crucial in determining the physics of the production mechanism!!



Small x
MH << s
Region
One-Scale
MH ~ Q
Region
"Heavy Quark" H
Transition Region
two-scale
MH << Q
Region
H-"Parton"
ln 1/x
MH
ln Q (Typical Energy Scale)
also PT, Mjj, ...

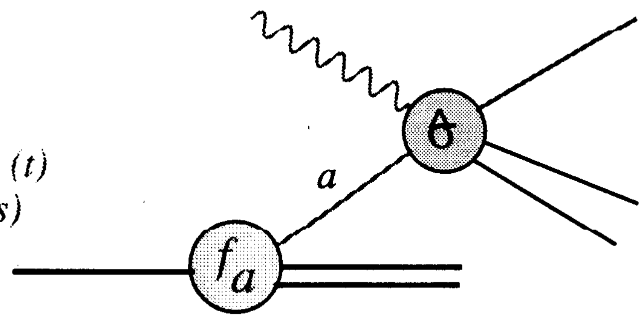
Heavy Quark Production in PCD
- the dichotomy -

<u>Zero-mass parton</u> approach

Zero-mass Factorization Theorem

$$\sum_{a = g,\, u,\, d,\, s,\, c,\, b,\, (t)}$$

(all active flavors)



All parton masses
$m_a = 0$
MSbar Subtr.

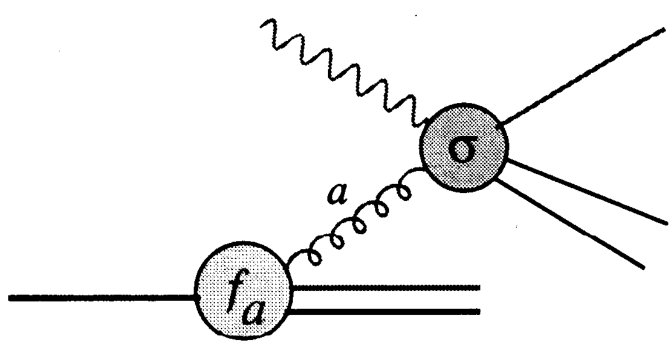
active flavor : all quarks with $m_H < Q$: $n_{fl}(Q)$

<u>Heavy Quark</u> approach

Fixed-flavor-number (<u>FFN</u>) Scheme

$$\sum_{a = g,\, u,\, d,\, s}$$

(light fl. only)

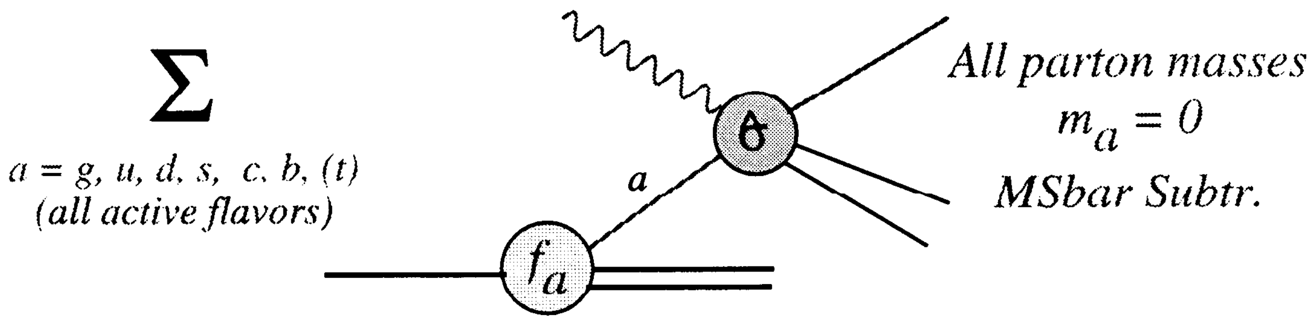


heavy quark:
m_H *"large"*
No col. Subtr.

number of quark flavor $n_{fl} = 3$ *(for c)* <u>*fixed, indep. of Q*</u>

m= 0 Partonic Formalism of Heavy Quarks c, b, (t)

Zero-mass Factorization Theorem



active flavor : all quarks with $m_H < Q$: $n_{fl}(Q)$

Usual parton distributions are generated in this scheme:
EHLQ, ... , MRS, CTEQ

i.e. $F_2(x,q) = u + d + s + c + b + ... +$ NLO

All popular applications are based on this scheme:
Pythia, Herwig, Isajet ; EKS, JetRad, ...
....

Advantage: Simple and intuitive

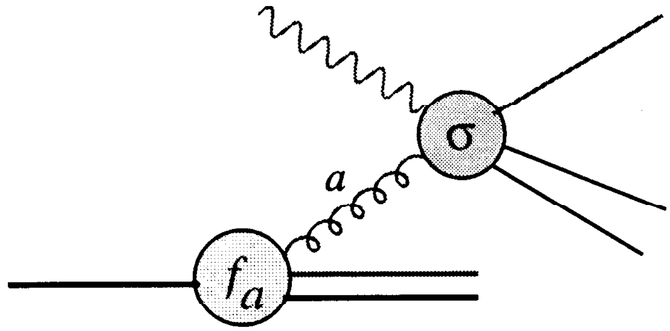
Limitations: mass effects neglected (except for thresholds)
Not appropriate for $Q \sim m_H$

Heavy Quark Formalism of c, b, (t)

Fixed-flavor-number (<u>FFN</u>) Scheme

$\sum_{a = g,\, u,\, d,\, s}$

(light fl. only)

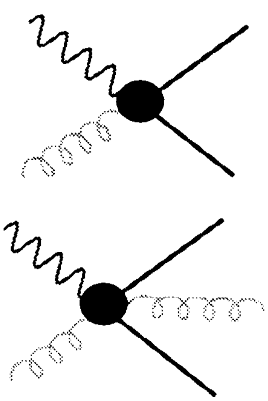


heavy quark:
m_H "large"
No col. Subtr.

number of quark flavor n_{fl} =3 (for c) <u>fixed, indep. of Q</u>

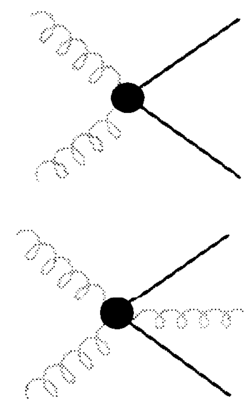
Lepto-production

hadro-production



"Heavy flavor creation"
(HC)

"Gluon-fusion process"



NLO calculation:

Laenen, Smith,
van Neerven ...et.al

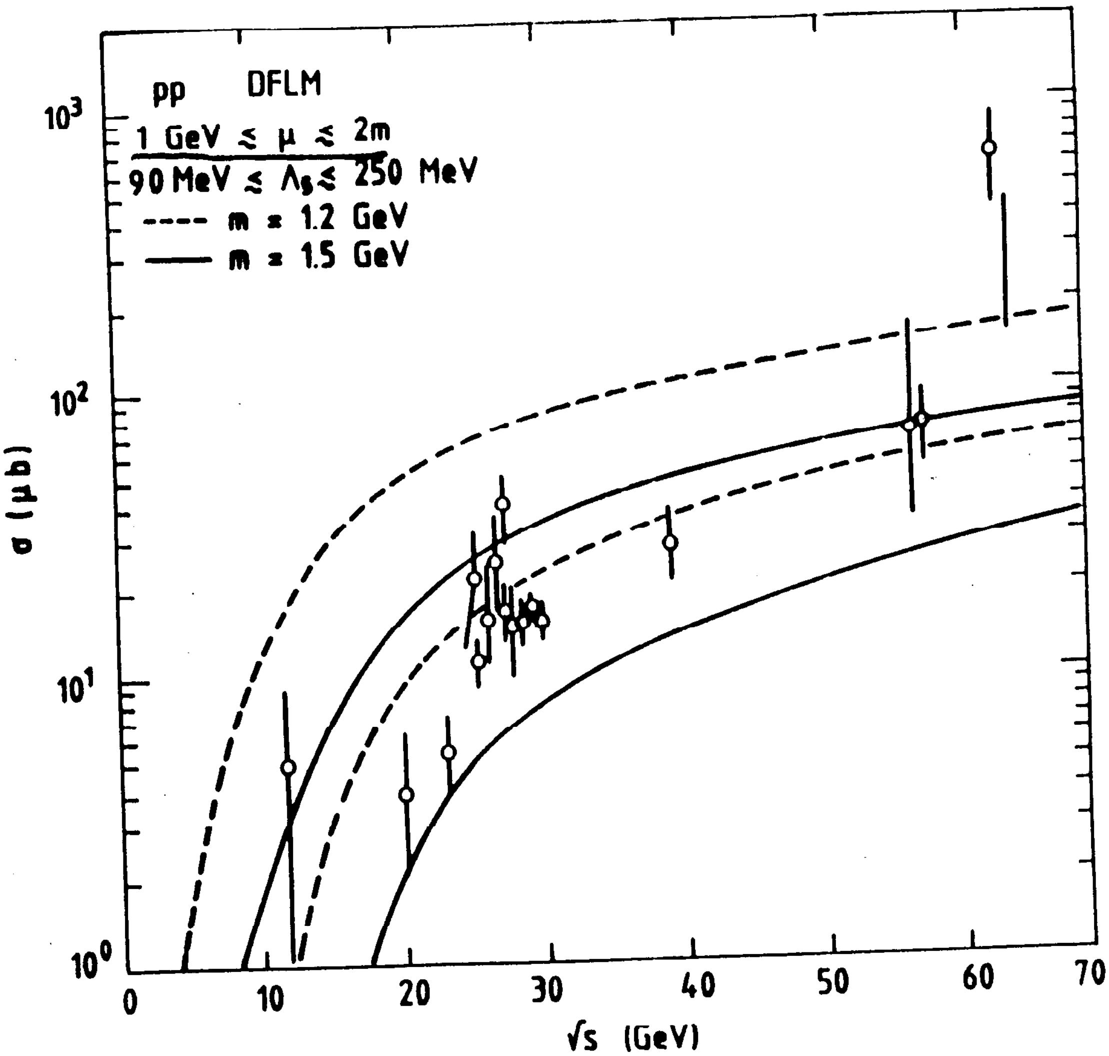
Nason, Dawson, Ellis
Mangano, Ridolfi, Fixione .

Advantage: "Simple" one-scale calculation

Limitations: no active H parton at any energy; contains powers of $log(Q/m_H)$; Large theoretical uncertainty

Not appropriate for $Q >> m_H$

σ_{Tot} for Charm Production



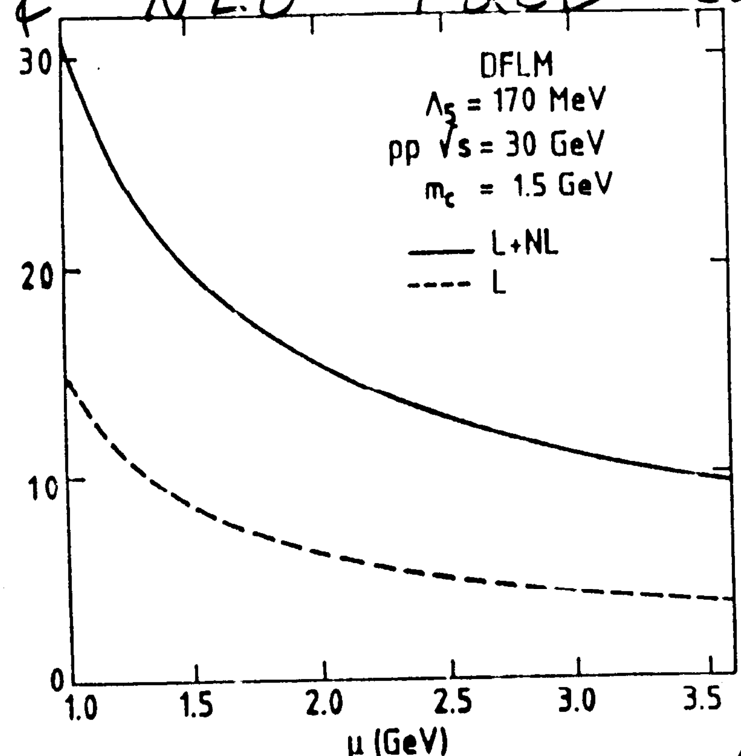
(i) Shape of S-dep. O.K.

Fig. 18

Notes (ii) factor of 3-4 uncertainty due to choice of scale.

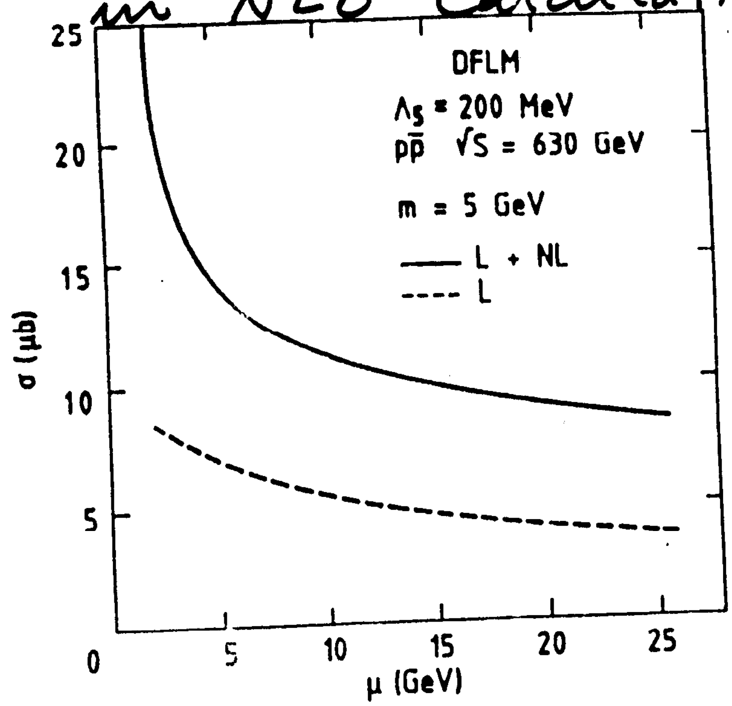
Alterelli et. al. '89

Scale dependence of Fixed N_f^{eff} LO & NLO PQCD calculations



Charm

Note: (i) NLO correction large
(ii) scale dependence not improved in NLO calculation.



Bottom

Alterelli et.al. '89

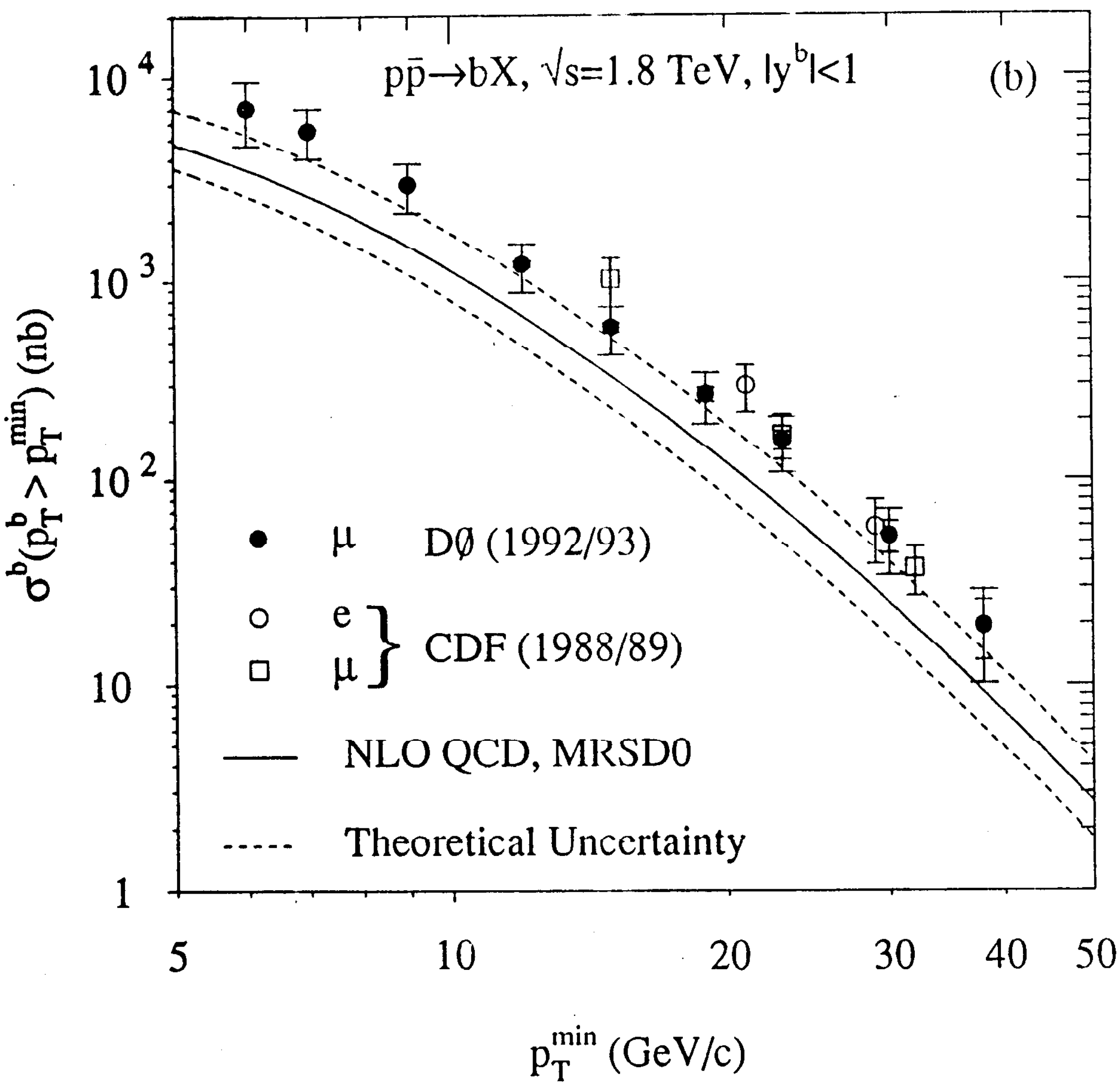


FIG. 3. b) *b*-quark production cross section compared to NLO QCD predictions (see text).

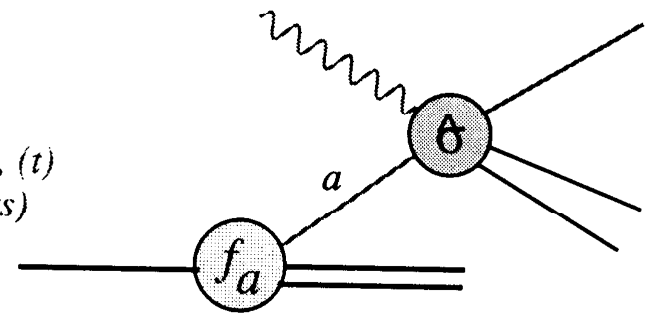
General Formalism of Heavy Quark Partons c, b, (t)

(Witten, Collins-Wilczek-Zee, Aivazis-Collins-Olness-Tung, ...)

Generalized ($m \neq 0$) Factorization Theorem

$\sum$

$a = g, u, d, s, c, b, (t)$
(all active flavors)



quark mass
$m_H \neq 0$
Mass Subtr.

***active flavor : all quarks with** $m_H < Q$: $n_{fl}(Q)$*

Key features:

* $f_a(x,Q)$ *obey the usual (MSbar) evolution eqs.*

* $\sigma(Q,m_H)$ *is free from large* $\log(Q/m_H)$ *after mass subtr.*

Proper limits:

* for $Q \sim m_H$ *: reduces to the FFN heavy quark scheme;*

* for $Q >> m_H$ *: reduces to the zero-mass parton model*

Advantage: intuitively "obvious"; theoretically more complete

price to pay: more complicated to implement; mass subtr. needs to be calculated.

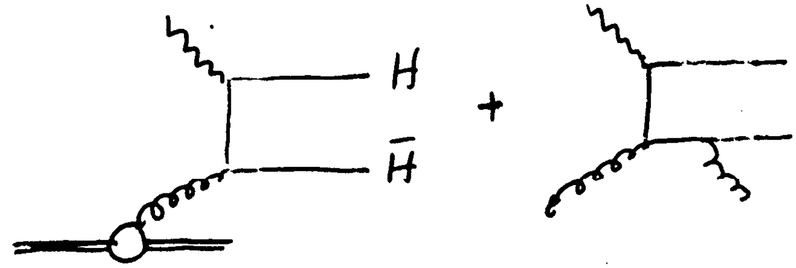
Example

Lepto-production of H (c/b)

FFN Scheme

α^0 α^1 α^2

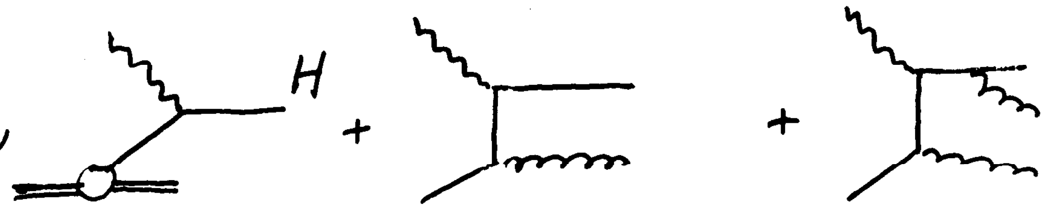
"Heavy Flv. Creation" HC

+ 

+ virtul

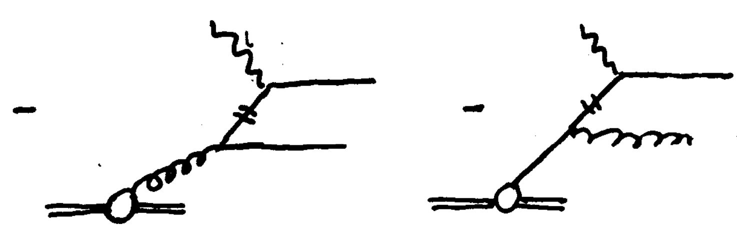
Parton Formalism : Additional contribution

"Heavy Flv Excitation" HE



+ virtual

Subtraction terms due to overlap (mixing)



. . . .

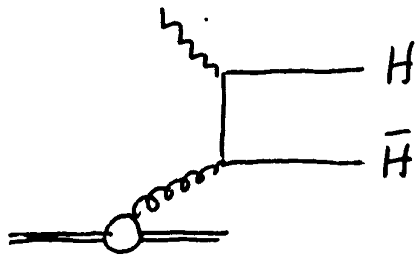
Example

Lepto-production of H (c/b)

FFN Scheme

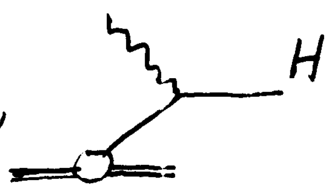
α^0 α^1

"Heavy Flv. Creation" HC +

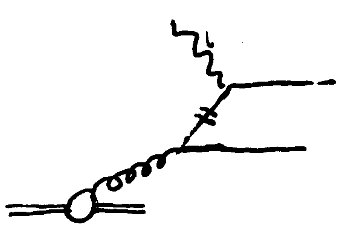


Parton Formalism : Additional contribution

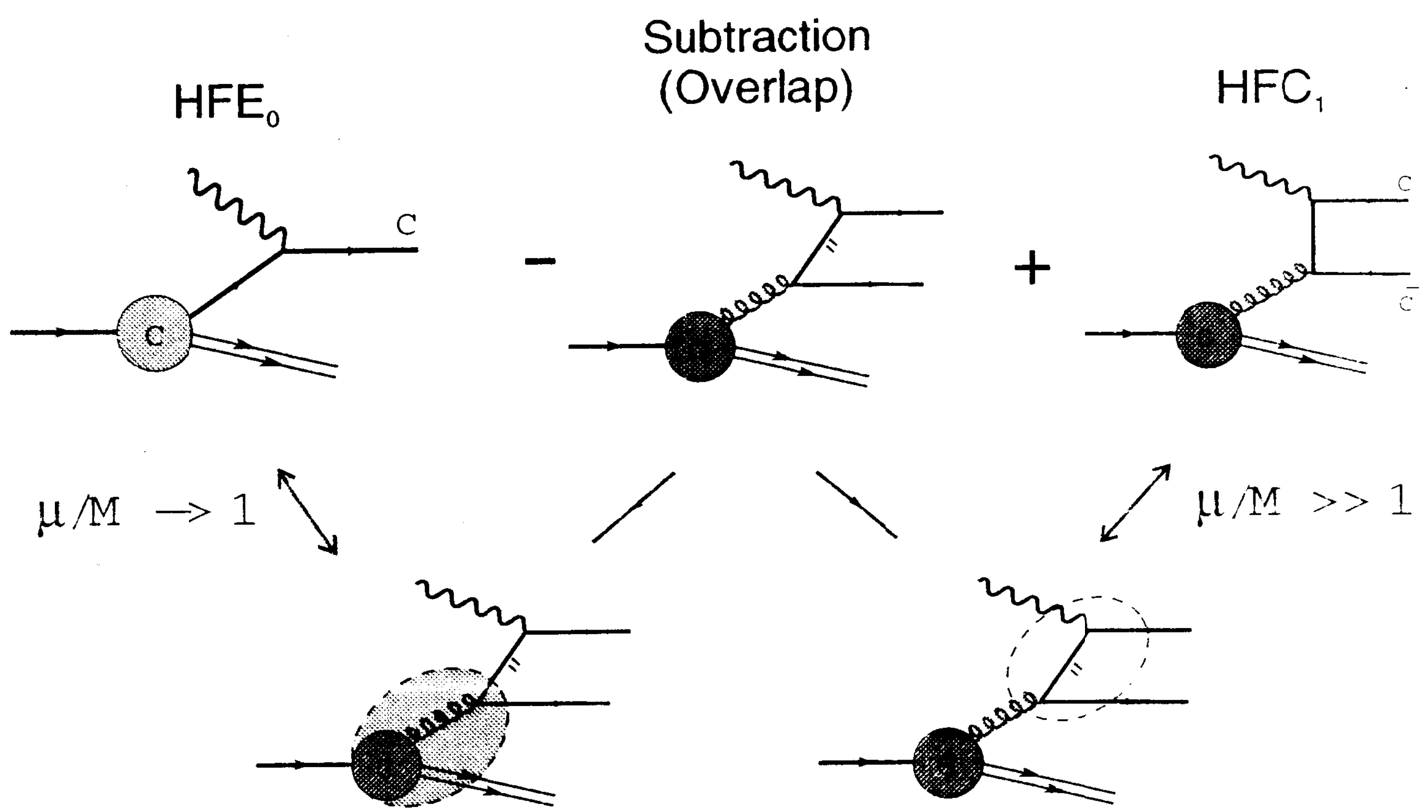
"Heavy Flv Excitation" HE



Subtraction terms due to overlap

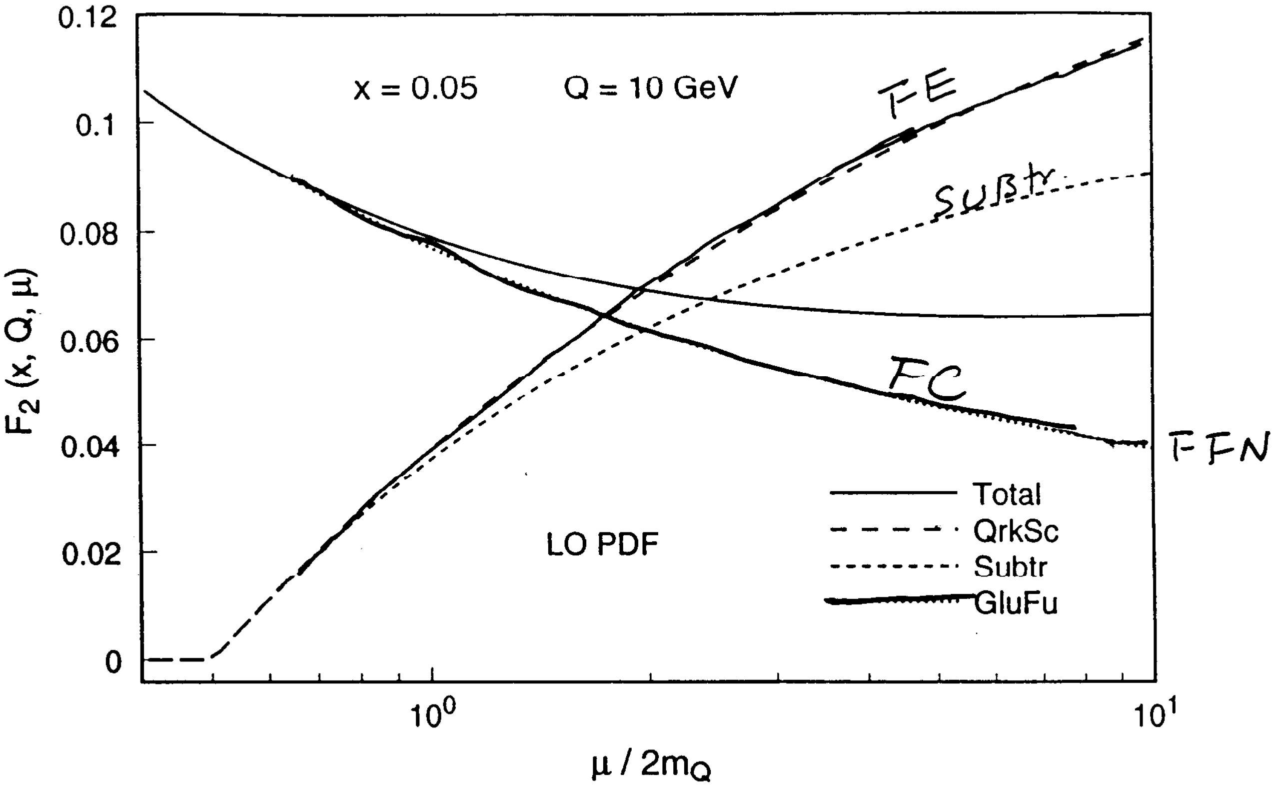


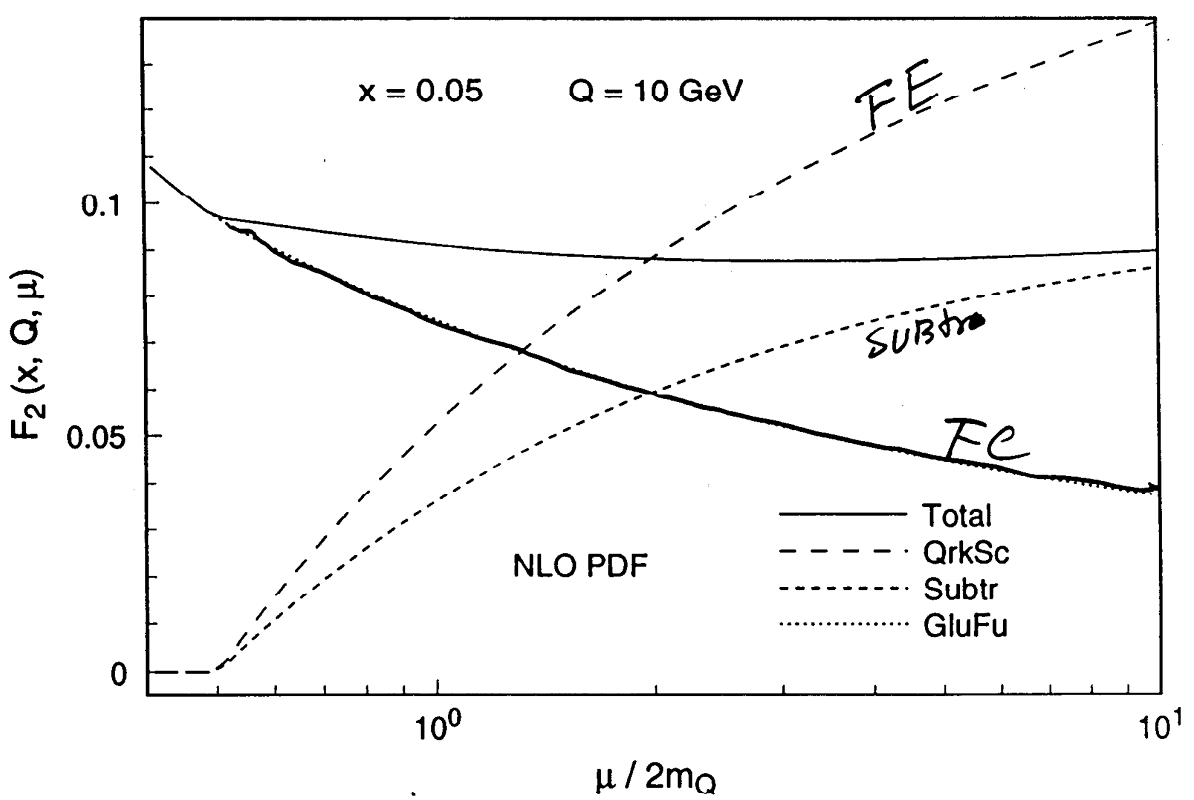
Complementarity of the "Partonic" and "Heavy Quark" Aspects of c-quark



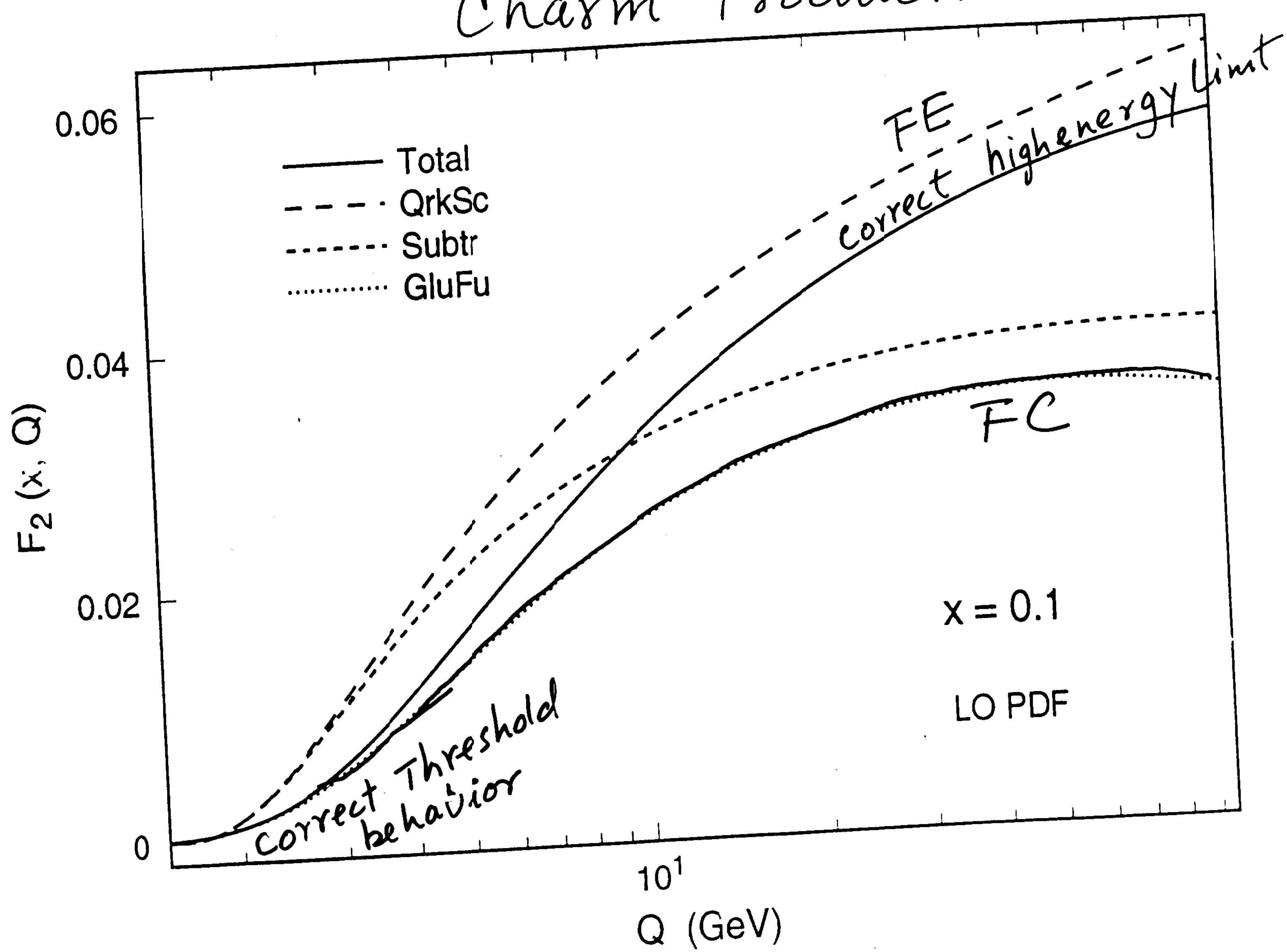
Sub. term: $f^G \times {}^1f_G^{\,H} \times HFE_0$; ${}^1f_G^{\,H} = \alpha_S\, P_{G\text{->}H}\, \ln(\mu/m_H)$

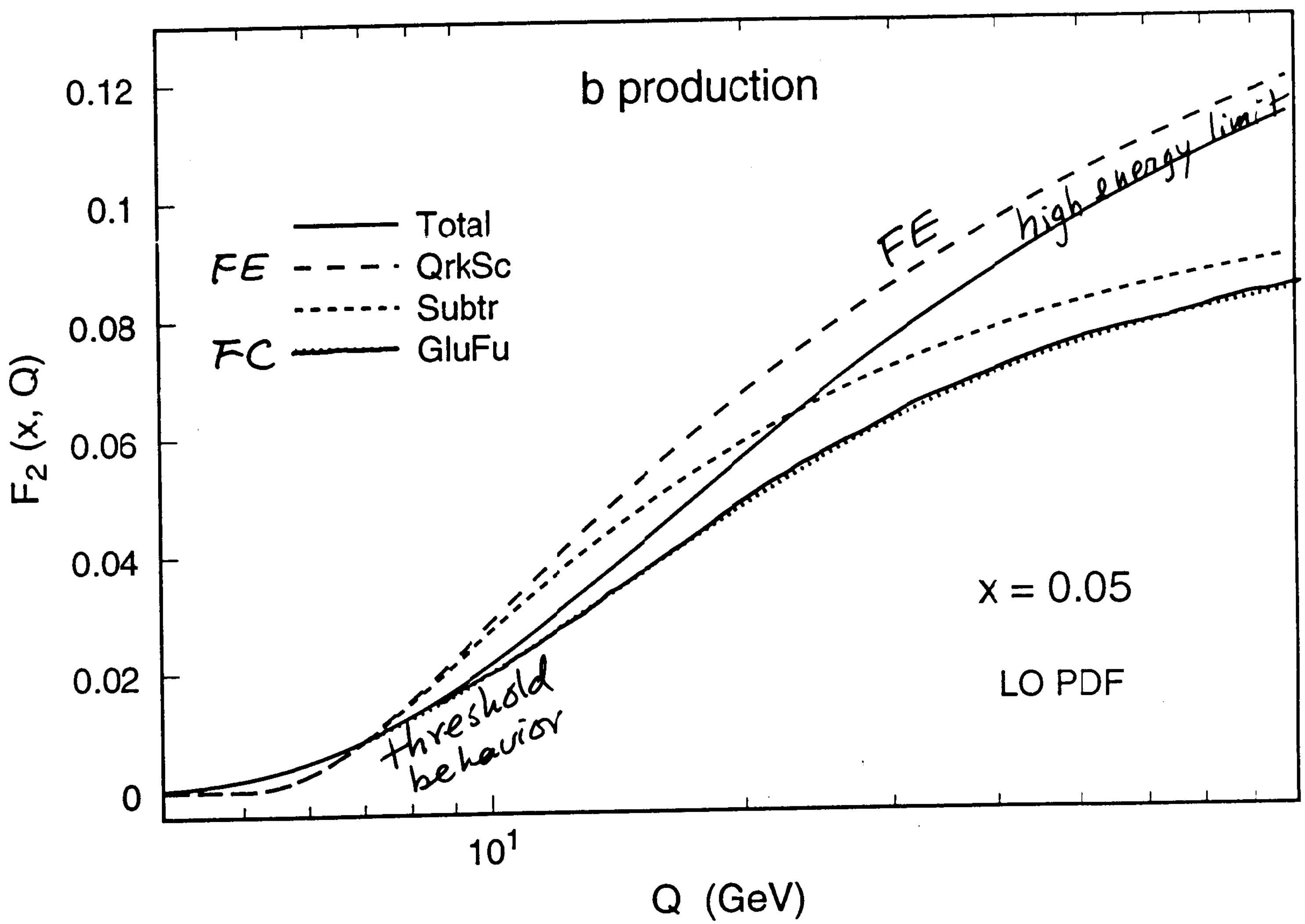
μ dependence





Charm Production




b production
Total
FE QrkSc
Subtr
FC GluFu
FE
high energy limit
threshold behavior
x = 0.05
LO PDF
0.12
0.1
0.08
0.06
0.04
0.02
0
F2 (x, Q)
10¹
Q (GeV)

In General:

($m \neq 0$) Parton Formalism

$$\sigma_{th.} = \sigma_{HE} - \sigma_{SUB} + \sigma_{HC}$$

$Q \sim M_H$ → $\underbrace{\sigma_{HE} - \sigma_{SUB}}_{\text{(Small Corr.)}} + \sigma_{HC}$ (FFN → σ_{HC}) — Heavy Quark Picture

$Q \gg m_H$ → $\hat{\sigma}_{HE} + \hat{\sigma}_{HC} + \text{(higher order corr.)}$ — ($m=0$) Parton Picture

* Correct physical picture & results in both limits
  consistent theory in transition region
* Can be proved order-by-order in α_s to all orders

Phenomenological Gain:

* More accurate X-section formula
* Less theoretical uncertainties (scale dependence)

Price to pay:

* more terms to calculate ; .... (?? →)

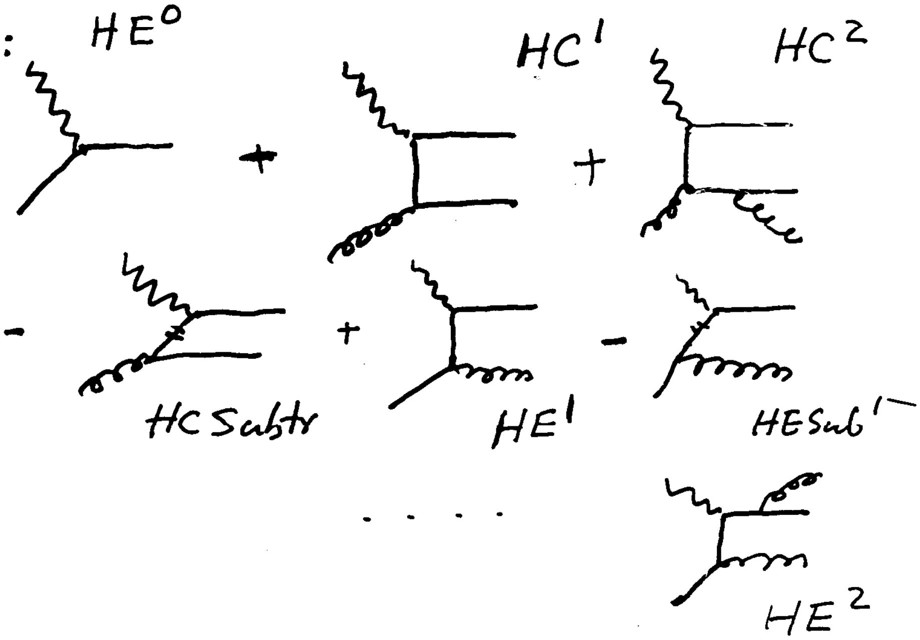
What is the Most Efficient Scheme for calculating Heavy Quark Prod.?

* It depends on the relevant energy scale;
* It depends on the physical question asked.

In Principle:

σ =

"Full Theory"



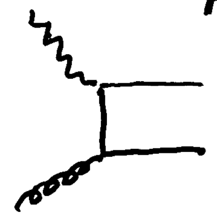
What is the Most Efficient Scheme for Calculating Heavy Quark Prod.?

* It depends on the relevant energy scale;

* It depends on the physical question asked.

For Total Inclusive:

HE^0 HC^1

$\sigma_{inclu.}$ =  + 

"Partonic" approx.: − 

HC Subtr.

gives a very good approximation. Most higher order contributions are resummed into the parton distribution of the heavy quark. Error ~ $O(\alpha^2$, __no__ large logs) ⟹ small "K-factor"

For final state particle distributions: (e.g. P_t^c)
HE^0 and HC sub terms are not appropriate. They are generalized functions $\delta(P_T)$ which must be integrated!

What is the Most Efficient Scheme for calculating Heavy Quark Prod.?

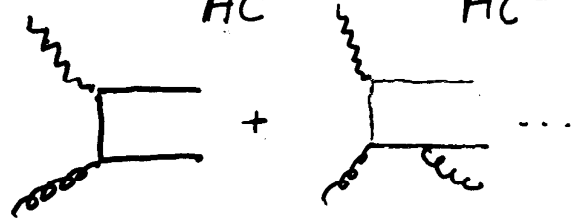
* It depends on the relevant energy scale;

* It depends on the physical question asked.

For final state Distributions:

HC[1] HC[2]

σ =



LO NLO

"Fixed-flavor-number" scheme

gives realistic predictions on final state particle correlations.

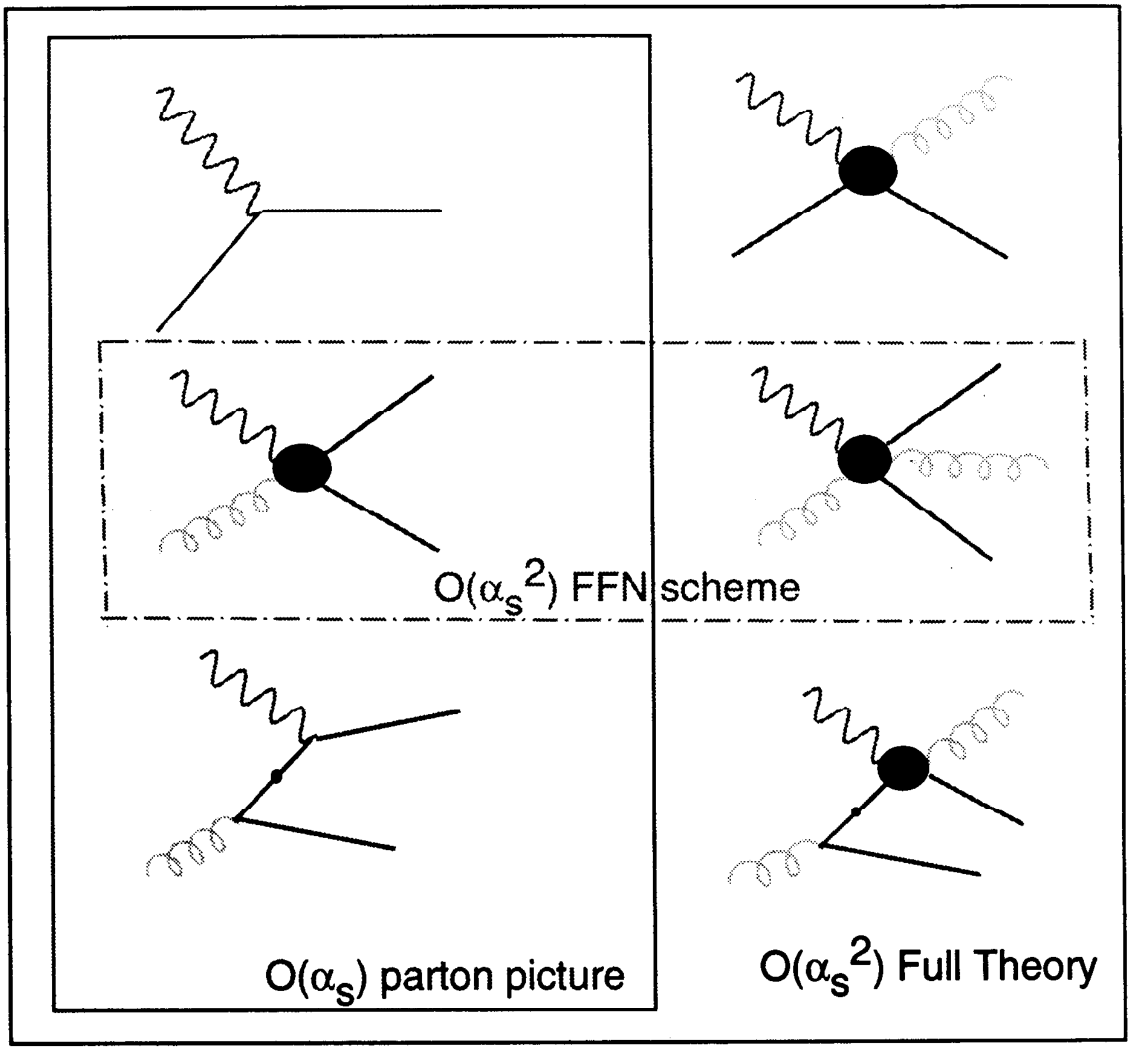
Also turns out to give fairly good approx. to $\sigma_{inclusive}$ over a wide range, but ...

* $\frac{NLO}{LO} \gtrsim 1$ → Large "K-factor"

* large μ-dep.

} uncertainties large and hard to estimate

Complementarity between the Parton picture and Heavy Quark scheme for Lepto-Production of H



	$F_2^H(x,Q)$	dF_2^H / dp_t
$O(\alpha_s)$ Parton	Good Approx.	Insufficient info.
$O(\alpha_s^2)$ FFN	OK, but Large Uncertainties, lengthy calculations	Good Approx.

Lessons and Additional Remarks

* Heavy flavor creation (HC) and Heavy flavor excitation (HE, or heavy parton picture) are *not* mutually exclusive production mechanisms.

* In a full theory, they must co-exist; otherwise the theory will not be infra-red safe (free of large logs).

* "Dynamically generated" heavy quarks (by QCD evolution) can be treated, at least approximately, either as partons or as heavy particles, depending on the physical observables.

* "Intrinsic heavy flavor" (non-perturbative) is completely incompatible with the FFN scheme.

* The full theory is required to study the possible presence of intrinsic *c* or *b*.