# Heavy Quark Production Issues

**Fredrick Olness**
SMU

## Experimental Examples:

- heavy quark pair production
- di-muon signals of neutrino charm production
- possible signal of intrinsic heavy quarks
- ...

## Theoretical Issues:

- Heavy Quarks are Signal/Background for new physics:

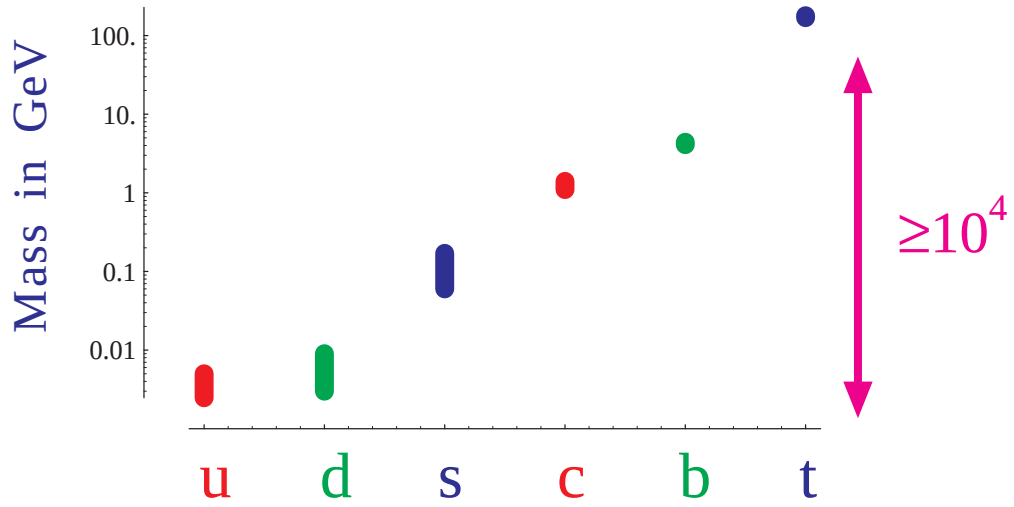
  *Eg.,* $H \to b\,\bar{b}$ *and* $t \to H^{+}\,b$

- Test/Study QCD over large range of scales ...

11 October 1998
HQ‘98

# Heavy Quark Production in QCD

## Wide dynamical range of masses:




*...both a virtue and a challenge*

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## Problems of Multi-Scales:

*We prefer:*

Light Quarks << $\Lambda_{QCD}$ << Q << Heavy Quarks

*What happens when we don't satisfy this condition?*

*..... life gets interesting.*

# Production of Heavy Quarks: *The Problem!*

Factorize the problem into a soft and hard component:

$$\sigma_{a\to c} = f_{a\to b}(x, \mu^2) \otimes \omega_{b\to c}(Q^2/\mu^2, \alpha_s(\mu)) + O(\Lambda^2/Q^2)$$

Where do you draw the line between soft and hard?

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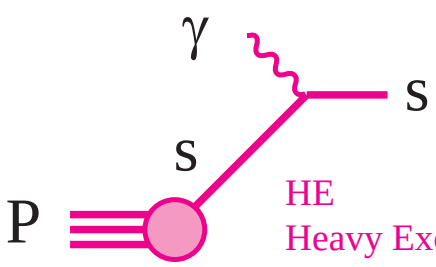
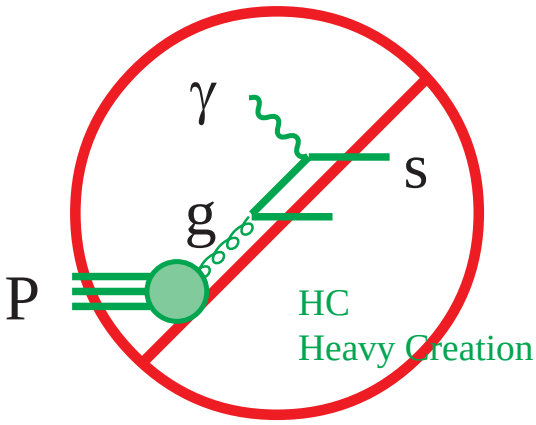
## *Try strange production first:*

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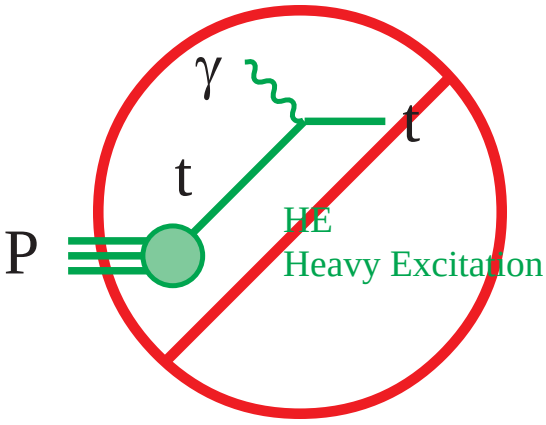
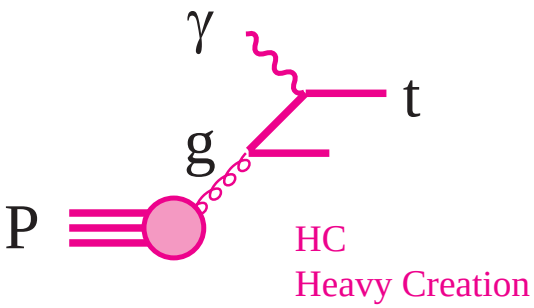
## *Try top production next:*

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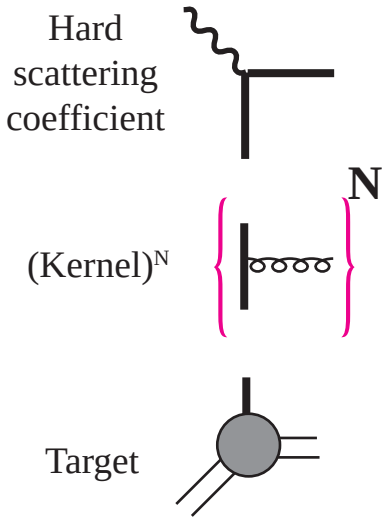
## *What about b and c production???*

- Actually, even s and t production are a problem at high precision.
- Can we combine these ideas into a single consistent calculation?

# Ingredients of Factorization

Decompose into (t-channel) 2PI amplitudes:

$$\sigma = \Sigma_{N=1}^{\infty} \; C \; (K)^N \; T \; + O(\Lambda_{QCD}^2/Q^2)$$




*New Factorization Proof for Massive Quarks*
Collins,PRD58,1998

After reorganization of the infinite sum:

$$\sigma \approx \overbrace{C\,[1-(1-Z)\,K\,]^{-1}\,Z\;[1-K\,]^{-1}\,T}^{\text{Parton Model}} + \overbrace{C\,[1-(1-Z)\,K\,]^{-1}\,(1-Z)T}^{\text{Remainder}}$$

Wilson Coefficient (Hard Scatt. $\hat{\sigma}$)

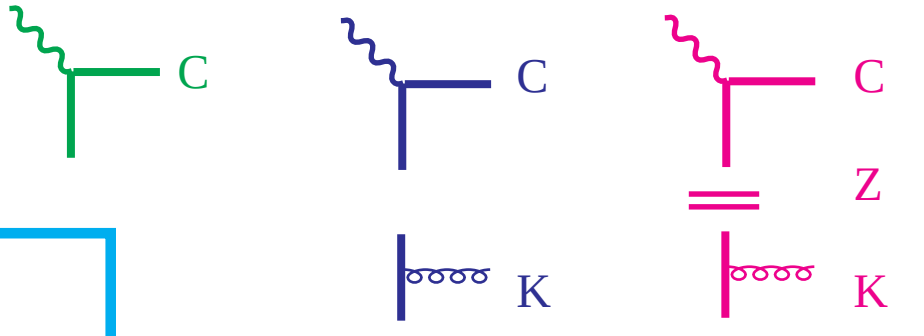
Z collinear projection

Parton Distribution

Power Suppressed

**Wilson Coefficient:**

$$C\,[1-(1-Z)\,K\,]^{-1} \approx \overbrace{C}^{\text{Leading Order}} + \overbrace{C\,K \;-\; C\,Z\,K}^{\text{Next to Leading Order}} + \ldots$$

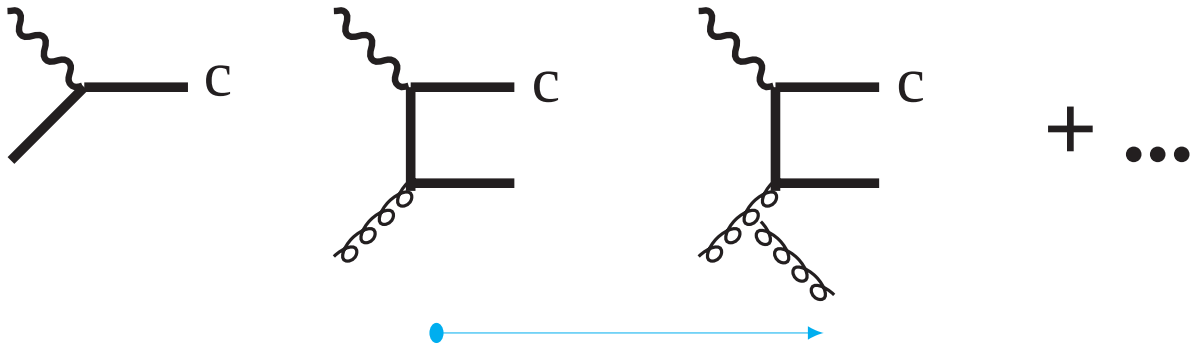



- All orders result
- Valid for all masses

C Z K is the subtraction

# Variable Supersedes Fixed Flavor Scheme

Variable Flavor Number (VFN) Scheme




Fixed Flavor Number (FFN) Scheme

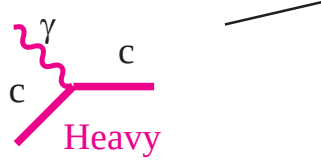
Analogy: Expand f(x) = x in Taylor Series about $x_0$:

$$f(x) \approx f(x_0) + f'(x_0)\,(x-x_0) + \ldots$$

If $x_0 = 0$ then $f(x) = 0 + (x - 0) + \ldots$

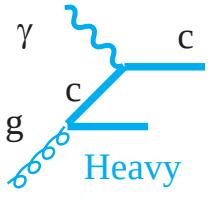
If $x_0 = 1$ then $f(x) = 1 + (x - 1) + \ldots$

HE + HC - SUB



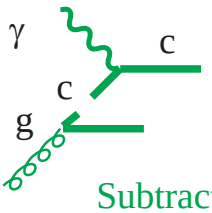

Heavy Excitation

$$f_{P\to c} \otimes \sigma^{0}_{c\to c}$$




Heavy Creation

$$f_{P\to g} \otimes \sigma^{1}_{g\to c}$$




Subtraction

$$\underbrace{f_{P\to g} \otimes f^{1}_{g\to c}} \otimes \sigma^{0}_{c\to c}$$

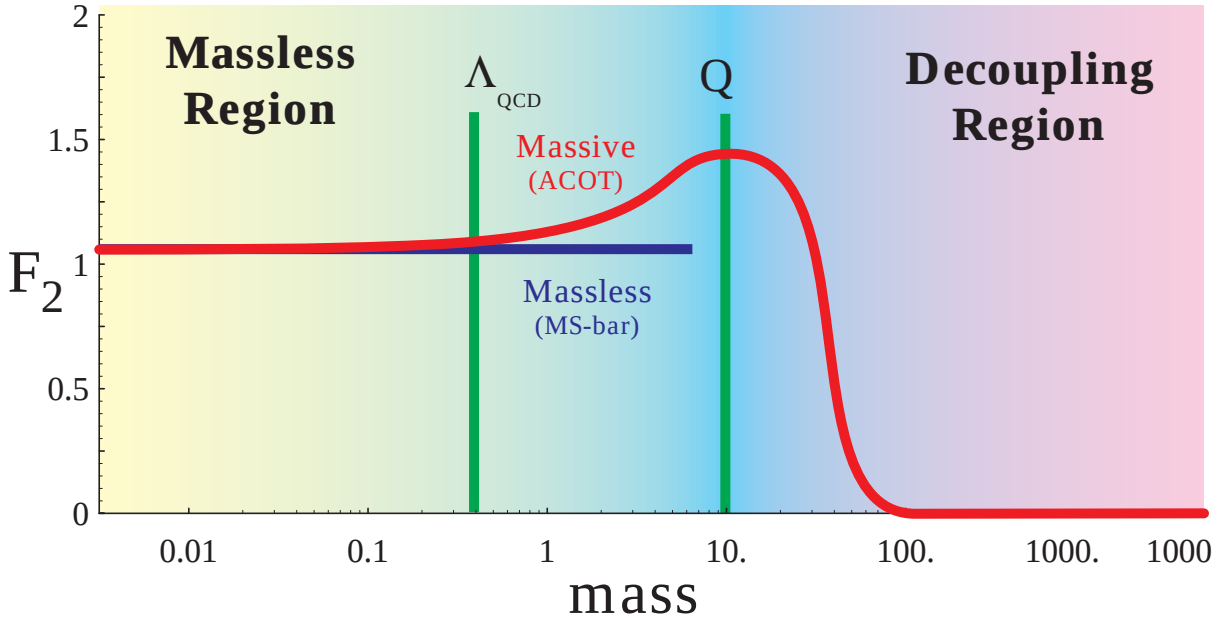
Perturbatively generated charm distribution

- VFN Formalism uses HC and HE *together* in consistent manner
- VFN uses 2-orders ($\alpha$ and $\alpha\alpha_s$) to minimize $\mu$-variation
- VFN uses heavy quark PDF's to resums large $\log(m_H)$ terms

# Valid From Small to Large Scales

## Verify appropriate limits are obtained:

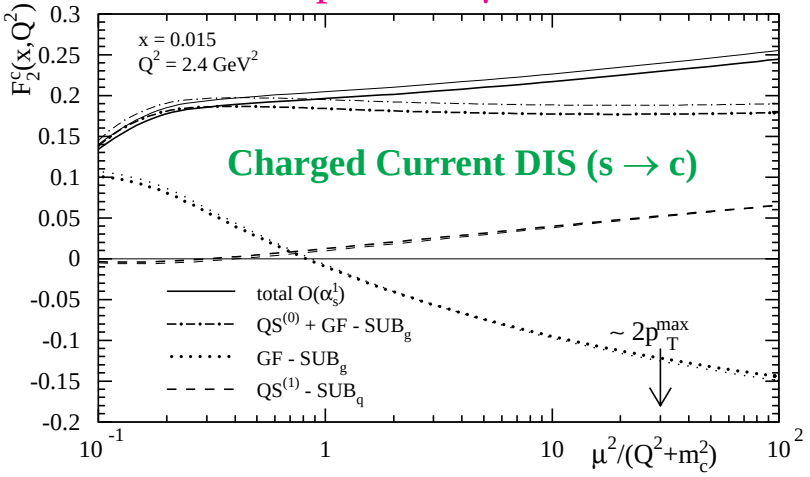
- $M \to 0$, result reduces to massless MS-bar formulas
- $M \to \infty$, result exhibits manifest decoupling




*ACOT: Aivazis, Collins, Olness, Tung. PRD 50, 3102 (1994).*

## Example: Charged Current $F_2^C$

- For $M \leq \Lambda_{QCD}$, M is a regulator without dynamical significance
- Compare M= 500 MeV with M=0 MS-bar results
- M variation is small compared to μ variation




*S. Kretzer, hep-ph/9808464; S. Kretzer, I. Schienbein, hep-ph/9808375*

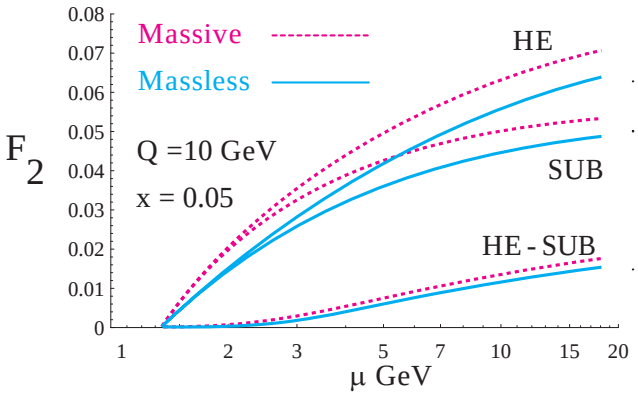
# Massive vs. Massless Evolution

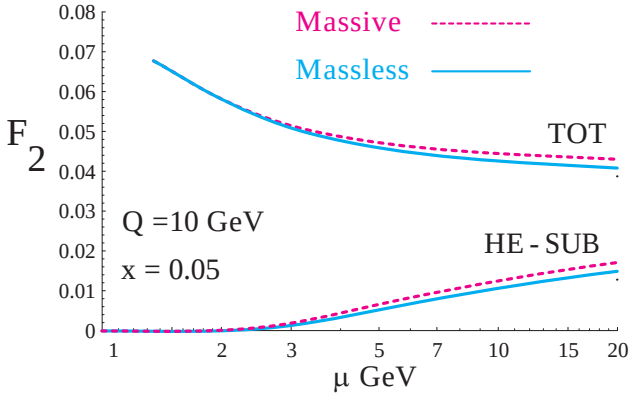
Should we include $m_H$ in the evolution equations???

$$P_{g\to H}(x, \mu, m_H) = \frac{(1-x)^2 + x^2}{2} + \left(\frac{m_H^2}{\mu^2}\right)(1-x)\,x$$

HE: Heavy Excitation: $\gamma c \to c$
HC: Heavy Creation: $\gamma g \to c\bar{c}$
SUB: Subtraction

Neutral current charm production: $m_c$=1.35 GeV




How does the cancellation work?

$$\sigma_{HE} \simeq \frac{\alpha_S}{2\pi} f_g \otimes \int \frac{d\mu^2}{\mu^2} P_{g\to H} \otimes {}^0\sigma_{H\to H} + O(\alpha_S^2)$$

$$\sigma_{SUB} \simeq \frac{\alpha_S}{2\pi} f_g \otimes \int \frac{d\mu^2}{\mu^2} P_{g\to H} \otimes {}^0\sigma_{H\to H} + 0$$

***No new physical information is obtained by using a massive evolution***

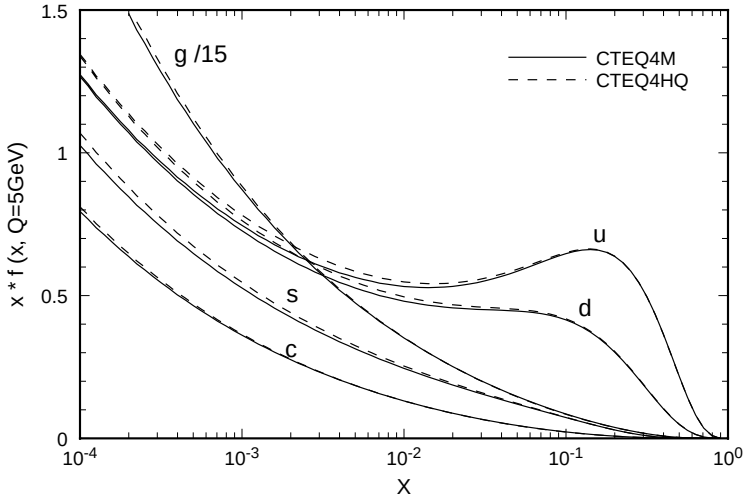
- Scheme for $\sigma$ must match scheme for PDF's
- Massless evolution yields a valid scheme
  (evolution kernels are $\gamma$ obtained from the renormalization counterterms
  $\therefore$ mass independent to all orders)

*Olness, Scalise. PRD57, 241 (1998)*

# Global Fitting Heavy Quarks

How does the massive calculation affect the global fitting?

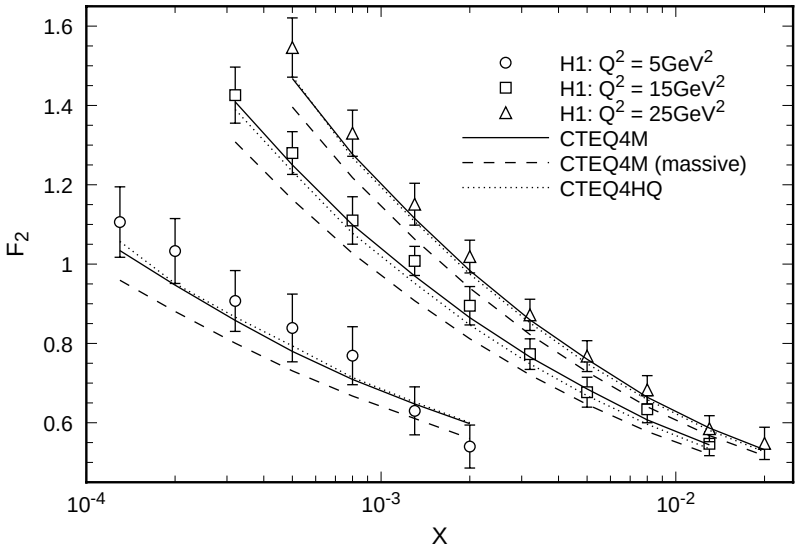
- Change appears minimal
- More significant at small x




Let's look at the effect in a real calculation.

*Lai, Tung, Z.Phys.C74:463,1997*

| | | |
|---|---|---|
| CTEQ4M: | $\sigma(m=0) \otimes f(m=0 \text{ fit})$ | valid calculation |
| CTEQ4M massive: | $\sigma(m\neq0) \otimes f(m=0 \text{ fit})$ | scheme mismatch |
| CTEQ4HQ: | $\sigma(m\neq0) \otimes f(m\neq0 \text{ fit})$ | valid calculation |



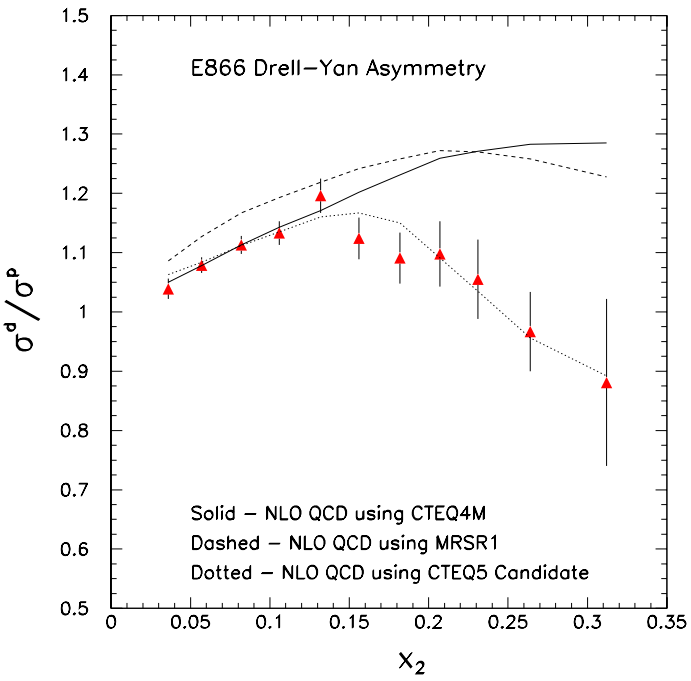

Could there be an intrinsic charm component of (0.86±0.60)%

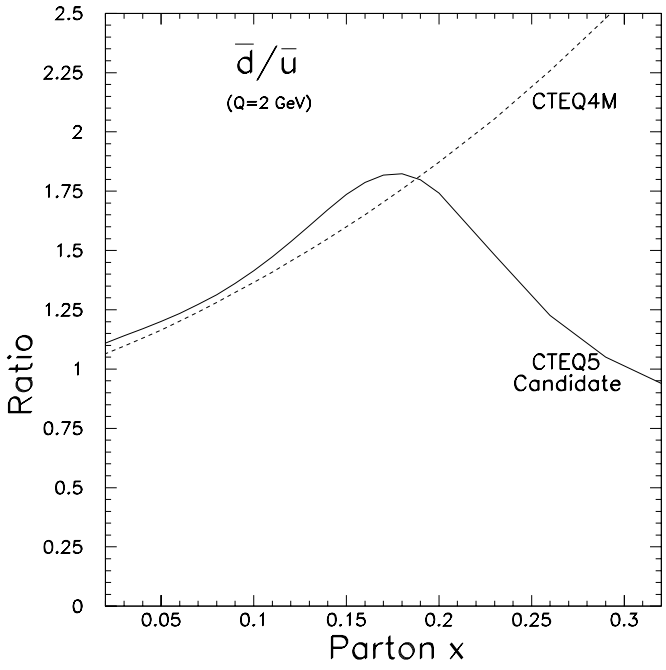
*Harris & Smith, Nucl.Phys.B461:181,1996*

| Expt. | #pts | CTEQ4M | CTEQ4HQ | CTEQ4F4 | CTEQ4F3 |
|---|---|---|---|---|---|
| $BCDMS+NMC+E665$ | 691 | 725 | 716 | 716 | 721 |
| $CCFR$ | 126 | 130 | 125 | 120 | 135 |
| $HERA$ | 351 | 362 | 350 | 409 | 410 |
| $CDFA_W$ | 9 | 4 | 5 | 4 | 11 |
| $NA51$ | 1 | 0.6 | 0.7 | 0.8 | 0.7 |
| $E605$ | 119 | 98 | 96 | 99 | 101 |
| Total | 1297 | 1320 | 1293 | 1349 | 1380 |

# Drell-Yan Asymmetry

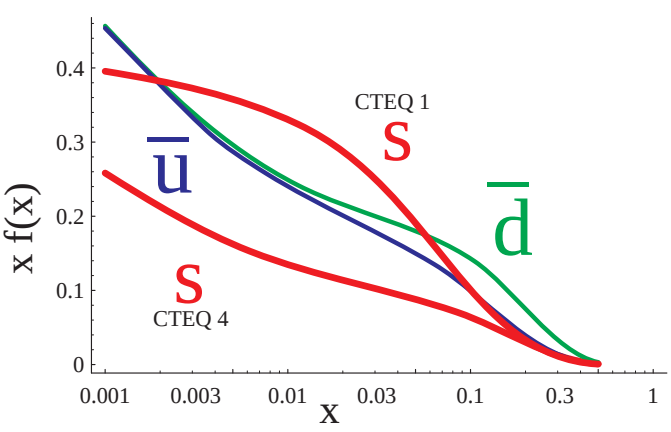
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_1 \ll x_2} \simeq \frac{1}{2} \frac{\left(1 + \frac{1}{4}\frac{d_1}{u_1}\right)}{\left(1 + \frac{1}{4}\frac{d_1}{u_1}\frac{\bar{d}_2}{\bar{u}_2}\right)} \left(1 + \frac{\bar{d}_2}{\bar{u}_2}\right)$$

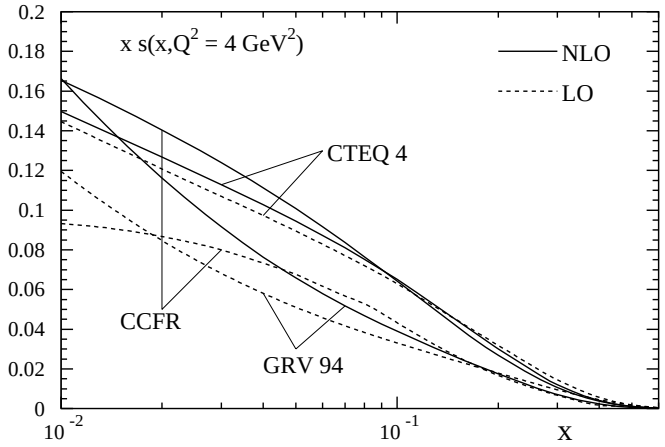



*E866/NuSea Collaboration. E.A.Hawker, et al., Phys.Rev.Lett.80:3715,1998.*

# What do we know about s(x)



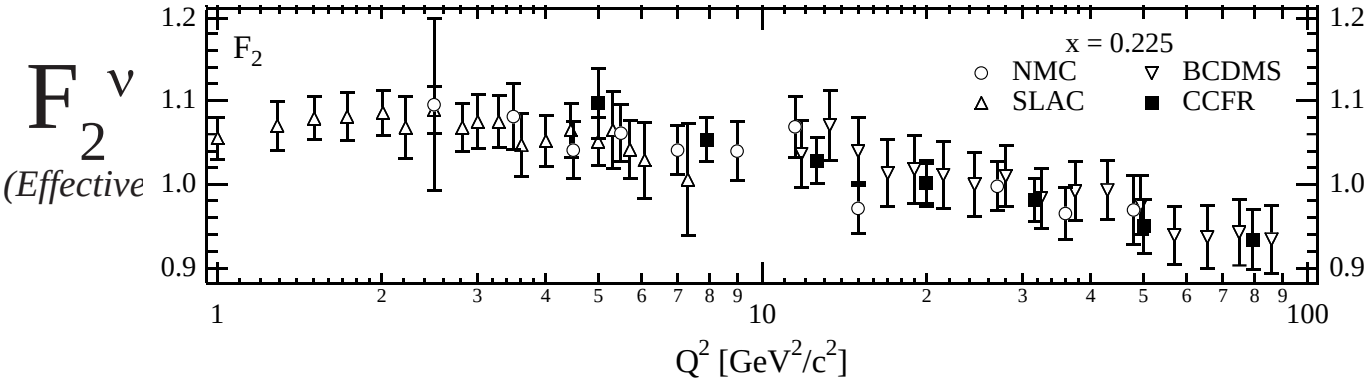




*Lai, et al., PRD55, 1280 ('97); Botts et al., PL B304, 159 ('93)*

*from S. Kretzer, hep-ph/9808464*

## Indirect Evidence:

$$\frac{F_2^{NC}}{F_2^{CC}} \simeq \frac{5}{18}\left\{1 - \frac{3}{5}\,\frac{(s+\bar{s}) - (c+\bar{c}) + \ldots}{q+\bar{q}}\right\}$$

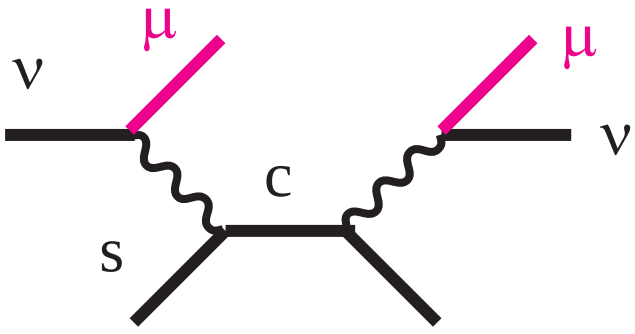



*W. G. Seligman, et al., hep-ex/9701017*

## Direct Evidence:

Need to analyze NuTeV di-muon data dynamically in global fit.

Extract κ, $m_c$, B(c→μ), s(x)



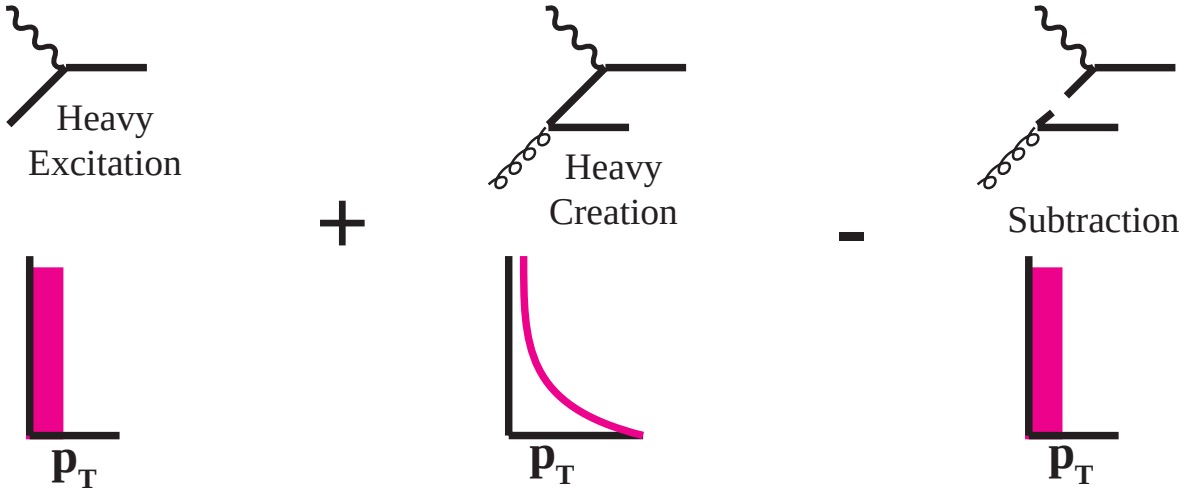

*T. Adams, This meeting*

*A. O. Bazarko, et al., Z.Phys.C65, 189 (1995)*

# $P_T$ Distributions for DIS Production

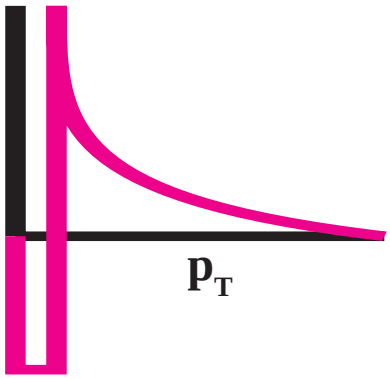
Detector acceptance is not uniform
Need to compute $P_T$ distribution of final state heavy quark

## Compute $P_T$ distribution in Parton-Boson CMS

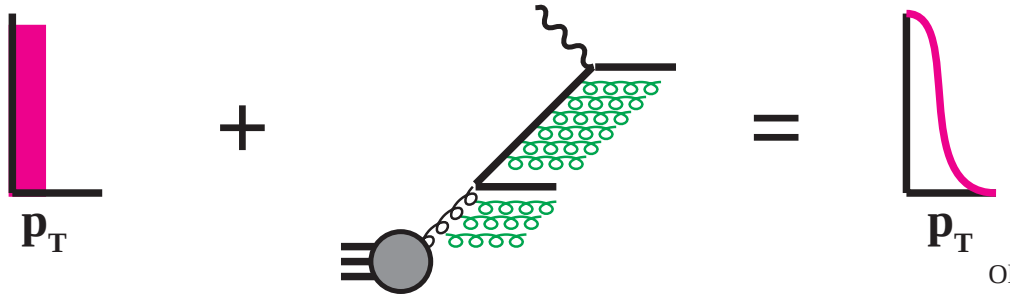



## The result is not a physical distribution:

- Formally, a mathematical “distribution”
- Must convolute with smooth test function

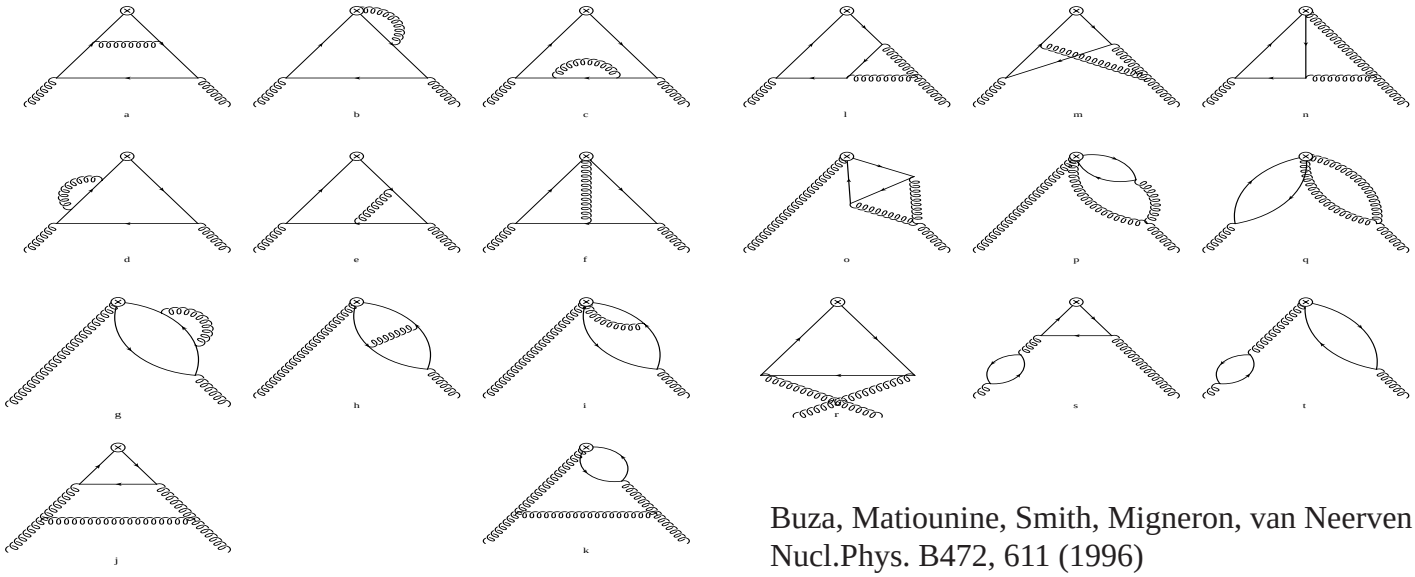



QUICK ANSWER: Smear distribution with a detector $P_T$ resolution
COMPLETE ANSWER: Resum soft gluon emissions




Olness, Reno, Scalise. In progress

# 2-Loop Matching of PDF's



Buza, Matiounine, Smith, Migneron, van Neerven
Nucl.Phys. B472, 611 (1996)

$$f_i(x,\mu,N+1) = \sum_j A_{ij} \otimes f_j(x,\mu,N)$$

$$A_{ij} = \sum_{n=0} \left(\frac{\alpha_s}{\pi}\right)^n A_{ij}^{(n)} \qquad A_{ij}^{(0)} \simeq \delta_{ij}$$

$$A_{Qg}^{(1)} \simeq P_{Qg}^{(0)} \ln\left|\frac{m^2}{\mu^2}\right| + 0$$

$$A_{Qg}^{(2)} \simeq P_{Qi}^{(0)} \otimes P_{ig}^{(0)} \ln^2\left|\frac{m^2}{\mu^2}\right| + P_{Qg}^{(1)} \ln\left|\frac{m^2}{\mu^2}\right| + a_{Qg}^{(2)}$$

Discontinuity in the 4-flavor vs. 5-flavor Gluon PDF

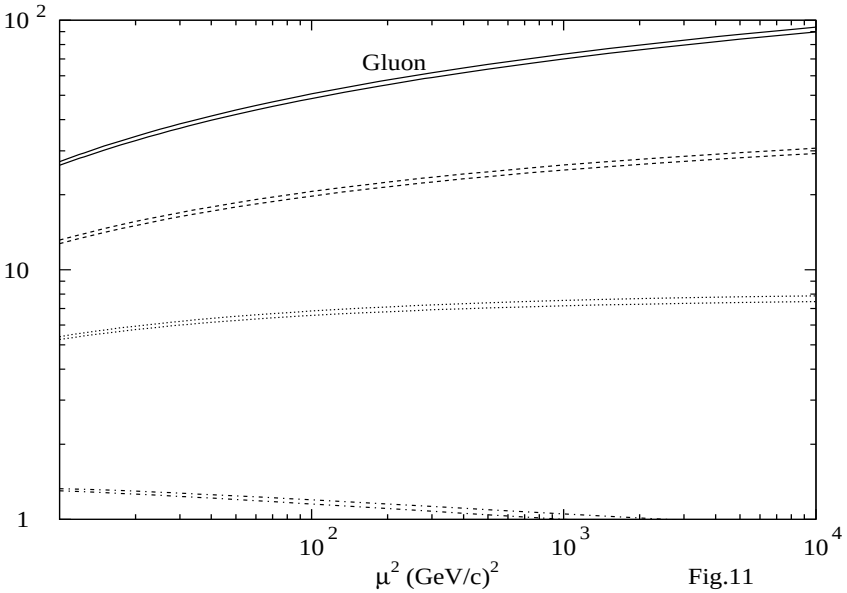
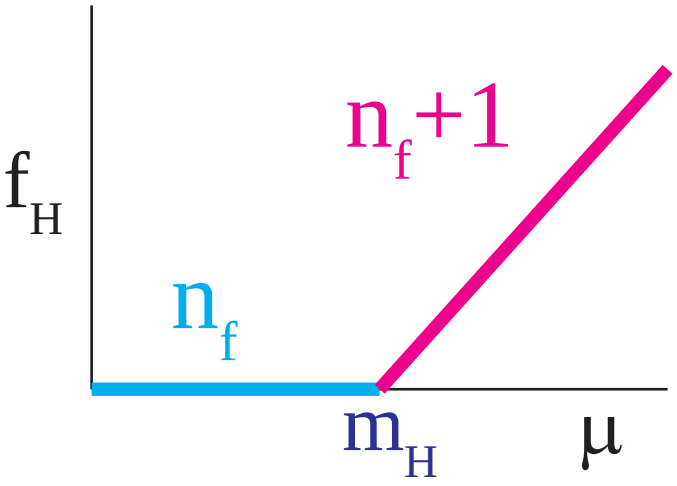


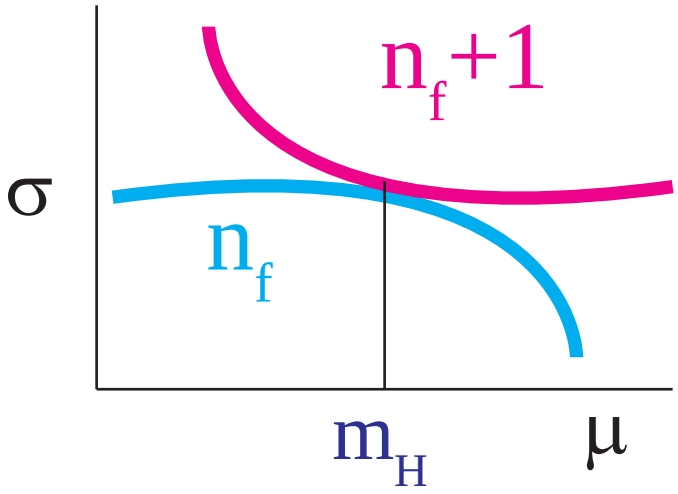

Fig.11

Discontinuities in quark PDF's are imperceptible

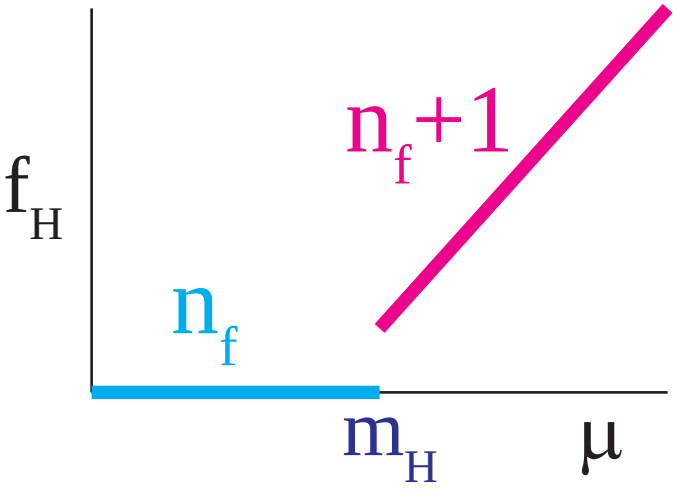
# Two-Loop Matching Condition

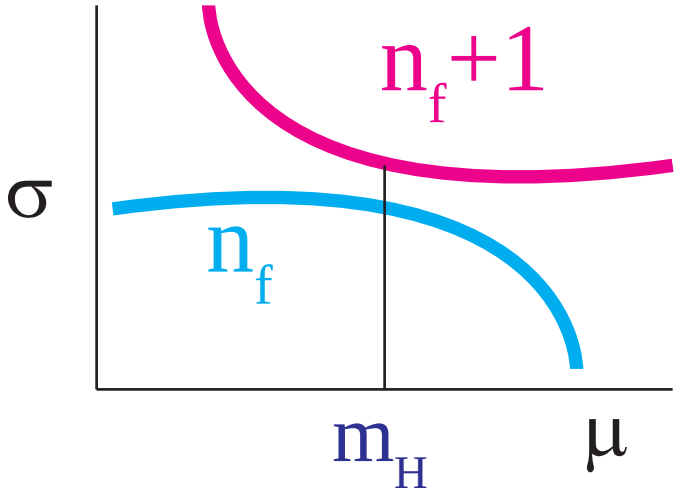
**One Loop:** $\mu = m_H$ is a special point



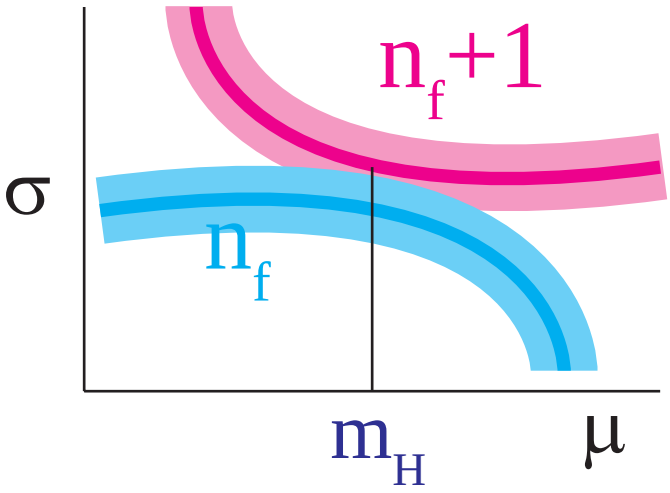

**Two Loop:** Matching at any $\mu \sim m_H$ is equivalent. *Can't avoid gap.*




Results:

- $\mu = m_H$ *not* special
- Match at any $\mu \sim m_H$
- $\Delta f_H \sim O(\alpha_s^2)$
- $\Delta\sigma \sim O(\alpha_s^3)$



# Conclusions

Heavy quark production:

- Challenges:
  - Multi-scale problem $\{Q, m_H\}$
  - Requires extension of factorization theorems
  - Resummation issues:
    - $ln(m_H)$ via heavy quark PDF's

- Subtleties of $O(\alpha_s^2)$ Calculation:
  - Matching of PDF's
  - Subtractions of PDF's *and* Fragmentation

Addressing these challenges & puzzles will:

- provide incisive tests of the QCD
- broaden the applicability of QCD
- and help in the search for new physics

***We are making steady progress toward these goals***