Heavy

Quark Production

Fred Olness
SMU

olness@smu.edu

OUTLINE

- Statement of the problem
- Status report:
  - Comparison of Data & Theory
- How do we make heavy quarks
- B-Hadroproduction: A case study
- Single Top Production
  - CKM Quark Mixing Matrix
- Conclusions
- Coffee

Statement of the Problem

A Thought Experiment:

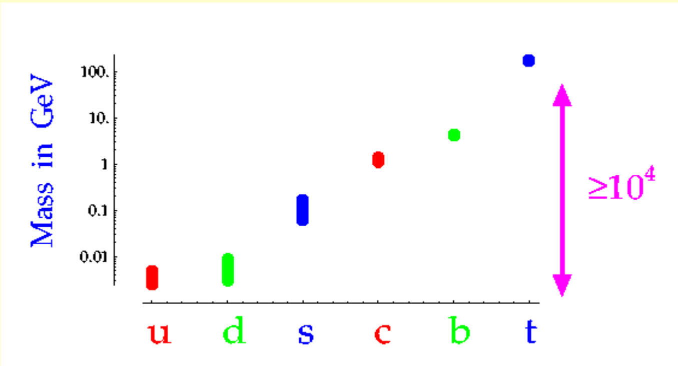
What is the ideal way to learn about quark masses and their effects on a physical process?

As a theorists, I simply run my calculation over the full range of mass values from 0 to ∞, and study the behavior.

Wouldn't it be great
if the experiments could do the same???

The UP Side

Quark Masses Span Wide Dynamical Range ~ 10^4



u	0.008
d	0.015
s	0.300
c	1.300
b	4.500
t	180.000

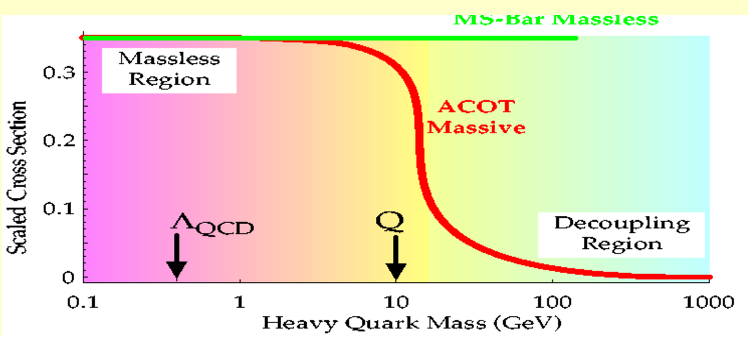
We can't vary the quark mass continuously, but these ``notches" on our control panel give us a lot of flexibility

The DOWN Side

Theorists would much prefer that quark masses only come in 2 varieties:

m = 0: Massless case.
- Mass plays no dynamic role
- Well understood.

m = ∞: Infinite case.
- Mass Decouples.
- We can forget about this object



Welcome to the Multi-Scale Problem

Single-Scale Problem in Perturbation Theory:

$$\sigma = \sum_{N=1}^{\infty} (\alpha_s L)^N = \sum_{N=1}^{\infty} \left\{ \alpha_s(\mu) \log(\frac{E^2}{\mu^2}) \right\}^N$$

... where E is any relevant scale of the problem: Q, P_T, E_T,...

Use RGE to solve this. $\frac{d\sigma}{d \log \mu^2} = \ldots$

Multi-Scale Problem in Perturbation Theory:

What do we do if we have 2 scales???

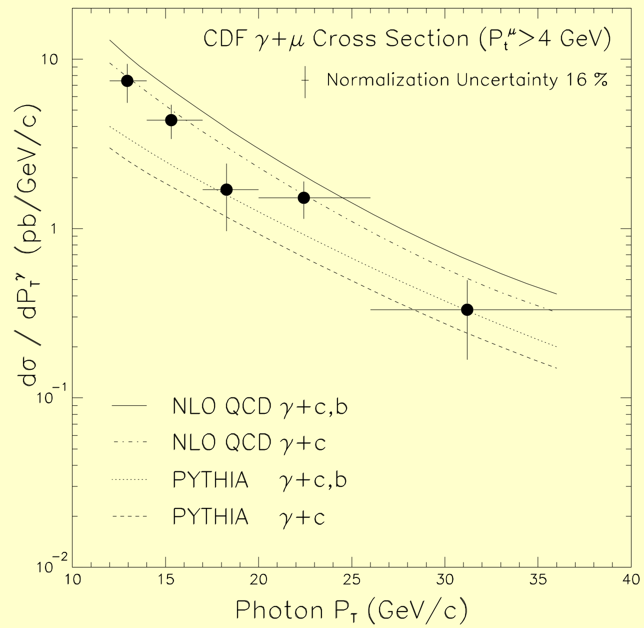
$$\log(\frac{E^2}{\mu^2}) \qquad \log(\frac{M_H^2}{\mu^2})$$

... life gets interesting.

Status Report:

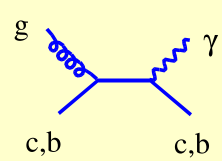
Comparison of Data & Theory

Associated Hadroproduction of Charm (& Beauty) at Tevatron

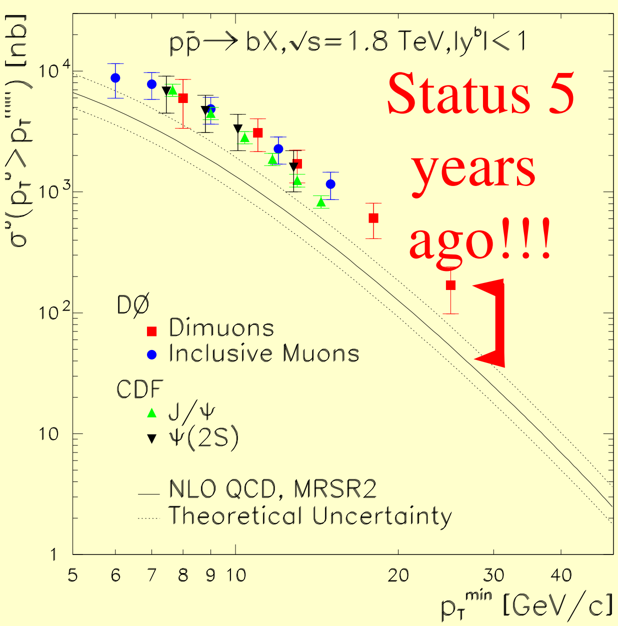


Comparison of Run I Data with NLO Theory

Reasonable agreement within theory uncertainty



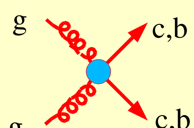
Hadroproduction of Beauty at Tevatron



Comparison of Run I data with NLO Theory

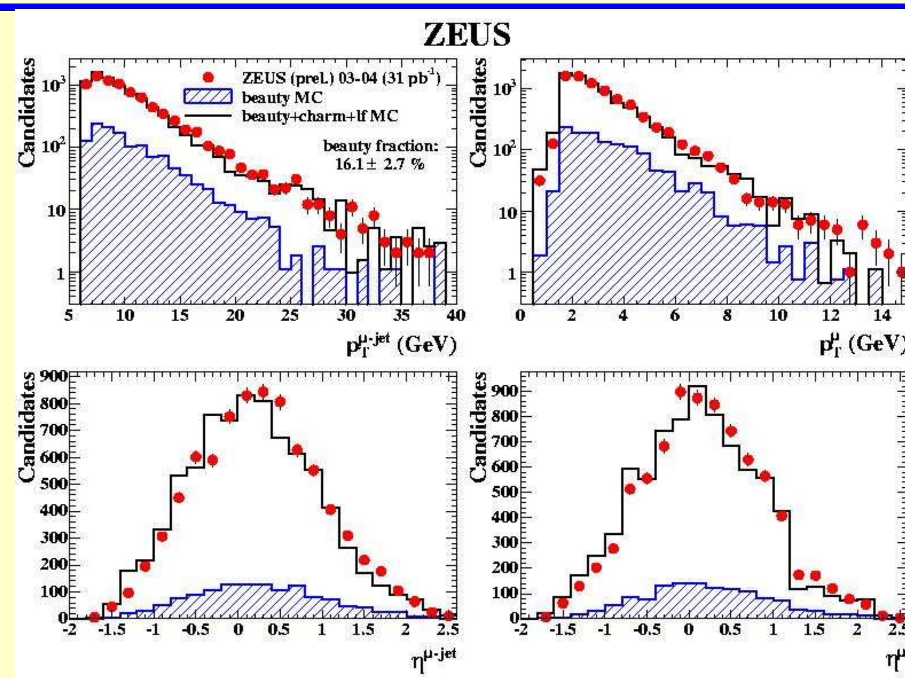
Data is high by factor of 2x or 3x

... even given μ variation

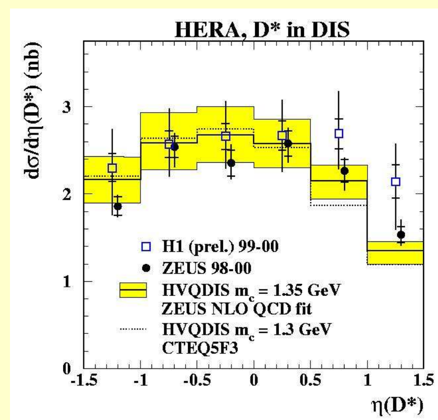


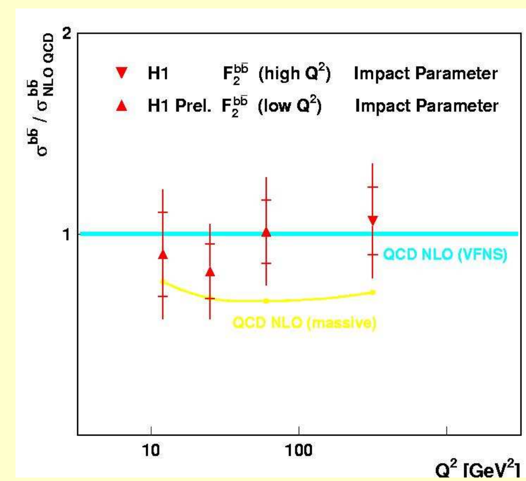
... we'll come back to this...

Charm Production at HERA

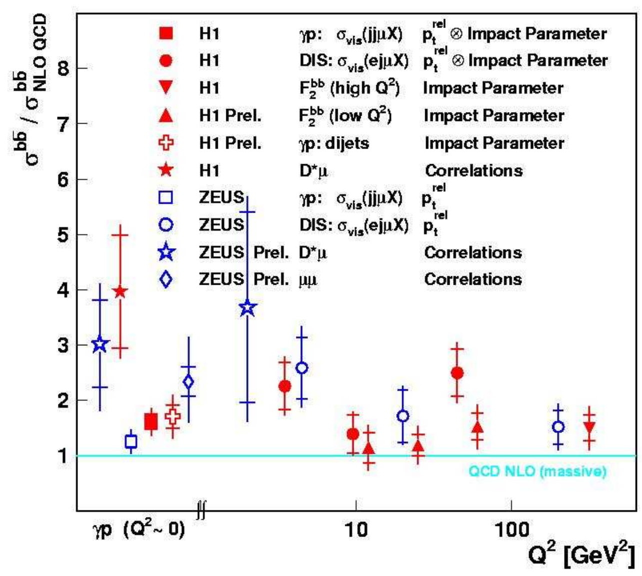


Charm & Beauty Production at HERA

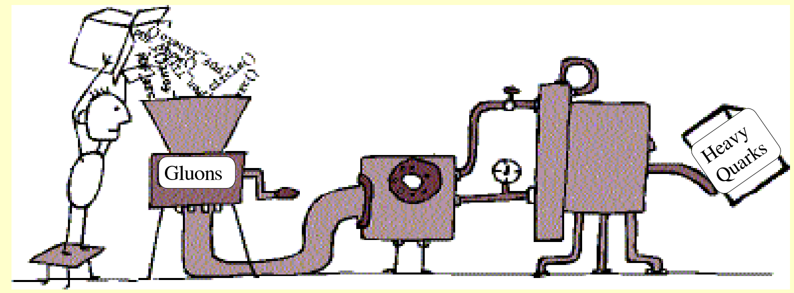




Beauty Production at HERA



How do we make heavy quarks



The Dilemma

General Trend:

Charm: in good shape

Bottom: needs examination

Should Bottom be a problem???

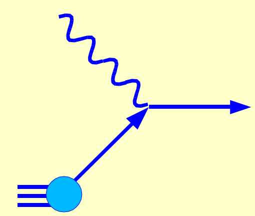
$m_b \approx 4.5$ GeV $\quad m_c \approx 1.5$ GeV

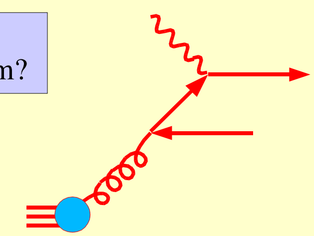
$\text{Log}[m_b/m_c] \approx \text{Log}[3] \approx$ Not a big number!!!

$\alpha_s(m_b) < \alpha_s(m_c)$

Production of Heavy Quarks: The Problem

Which is the correct production mechanism?





Heavy Excitation (HE)

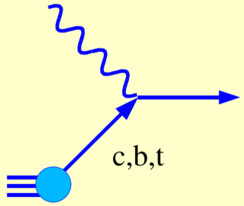
Quark	Channel
s	YES
t	NO
c	???
b	???

Heavy Creation (HC)

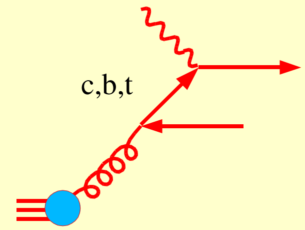
Quark	Channel
s	NO
t	YES
c	???
b	???

If you can't beat 'em, join 'em.

How to Join without ``Double Counting"???

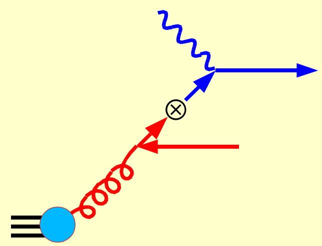


Heavy Excitation (HE)

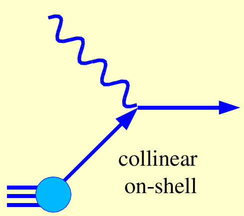


Heavy Creation (HC)

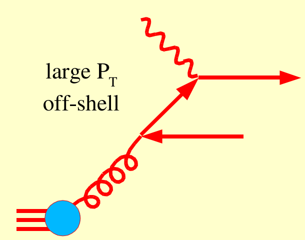
Wait a minute!
Since the heavy quark originally came from a gluon splitting, these diagrams are ***Double Counting***



How to Join without ``Double Counting"???

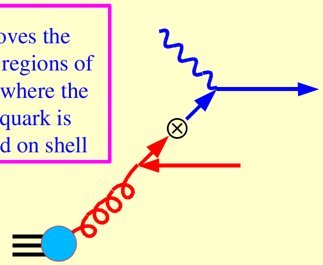


Heavy Excitation (HE)



Heavy Creation (HC)

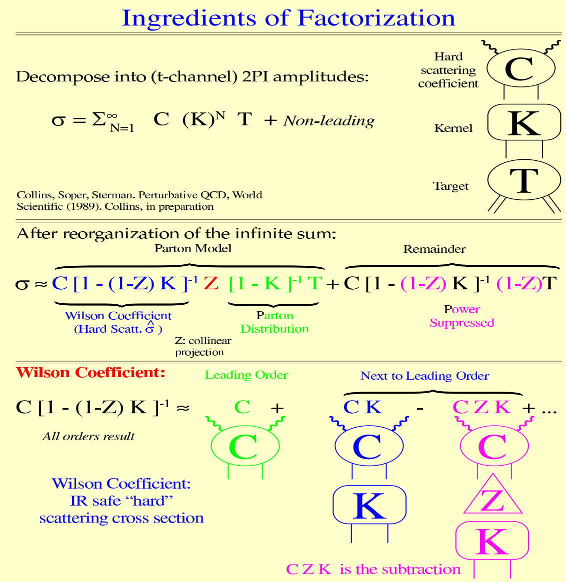
SUB removes the overlapping regions of phase space where the t-channel quark is collinear and on shell



Subtraction (SUB)

$$\textbf{TOT = HE + } \underbrace{\textbf{(HC - SUB)}}_{\textit{Formally, NLO}}$$

There is a rigorous factorization proof ...



A formal proof was constructed by numerous groups.

This proof was explicitly extended to the case of massive quarks

(Collins,1998)

THOUGH EXPERIMENT
To keep things simple, let's consider scattering off a parton target.

Application of Factorization Formula at Leading Order (LO)

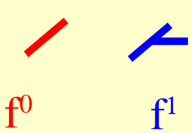
Basic Factorization Formula

$$\boxed{\sigma = f \otimes \omega \otimes d \;\; + O(\Lambda^2/Q^2)}$$

At Zeroth Order:

$$\sigma^0 = f^0 \otimes \omega^0 \otimes d^0 \;\; + O(\Lambda^2/Q^2)$$

Use: $f^0 = \delta$ and $d^0 = \delta$ for a parton target.



Therefore:

$$\sigma^0 = f^0 \otimes \omega^0 \otimes d^0 = \delta \otimes \omega^0 \otimes \delta = \omega^0$$

$$\boxed{\sigma^0 = \omega^0}$$

Warning: This trivial result leads to many misconceptions at higher orders

Basic Factorization Formula

$$\sigma = f \otimes \omega \otimes d \ + O(\Lambda^2/Q^2)$$

At First Order:

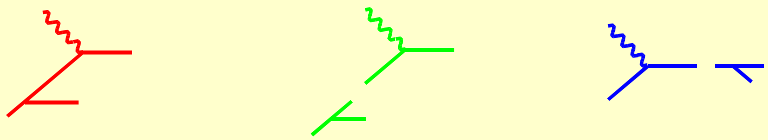
$$\sigma^1 = f^1 \otimes \omega^0 \otimes d^0 + f^0 \otimes \omega^1 \otimes d^0 + f^0 \otimes \omega^0 \otimes d^1$$

$$\sigma^1 = \quad f^1 \otimes \sigma^0 + \omega^1 + \sigma^0 \otimes d^1$$

We used: $f^0 = \delta$ and $d^0 = \delta$ for a parton target.

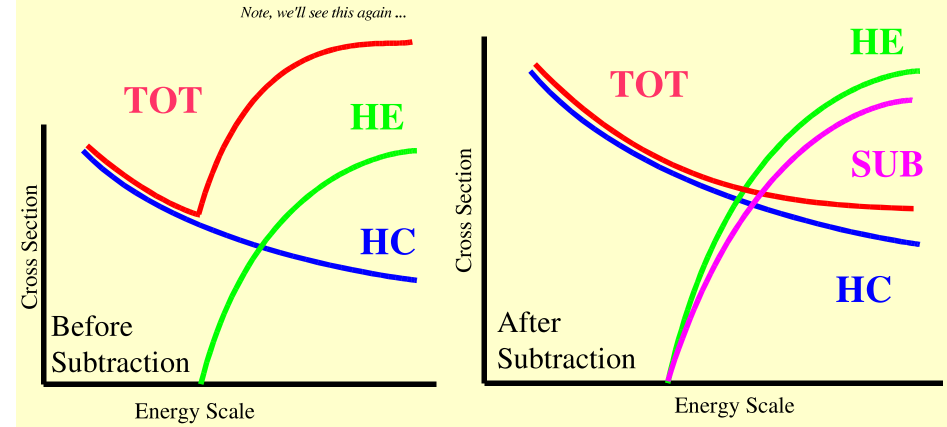
f^0 f^1

Therefore: $\omega^1 = \sigma^1 - f^1 \otimes \sigma^0 - \sigma^0 \otimes d^1$

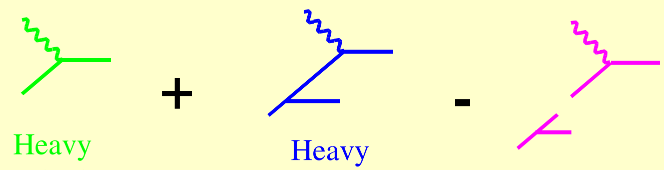


σ^1 $f^1 \otimes \sigma^0$ $\sigma^0 \otimes d^1$

Note, we'll see this again ...



TOT =

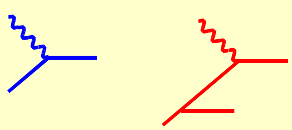


Heavy Excitation + Heavy Excitation - Subtraction

Combined Result:

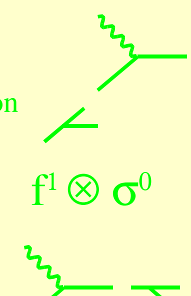
$$\omega^0 + \omega^1 = \sigma^0 + \sigma^1 - \underbrace{\left\{ f^1 \otimes \sigma^0 + \sigma^0 \otimes d^1 \right\}}_{\text{SUB}}$$

TOT **HE** **HC**



Heavy Excitation Heavy Excitation

SUB Subtraction



$f^1 \otimes \sigma^0$

$\sigma^0 \otimes d^1$

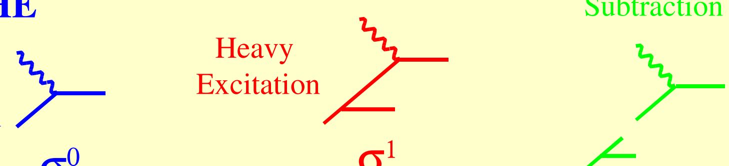
TOT = HE + HC – SUB

Expand f(x)=x in Taylor Series about x_0.

For $x_0=0$: $f(\varepsilon) = 0 + (\varepsilon - 0) + \ldots = \varepsilon$

For $x_0=1$: $f(\varepsilon) = 1 + (\varepsilon - 1) + \ldots = \varepsilon$

TOT **HE** **HC** **SUB** Subtraction



Heavy Excitation σ^0 Heavy Excitation σ^1 $f^1 \otimes \sigma^0$

TOT = HE + HC – SUB

It doesn't matter which expansion point you use; QCD will compensate (if you go to high enough order).

In practice ...

we are often limited to low-order calculations, so it is wise to choose your expansion point carefully.

Use the Basic Factorization Formula $\sigma = f \otimes \omega \otimes d \; + O(\Lambda^2/Q^2)$

At Second Order:

$$\sigma^2 = f^2 \otimes \omega^0 \otimes d^0 + \ldots$$
$$f^1 \otimes \omega^1 \otimes d^0 + \ldots.$$

Therefore:

$$\omega^2 = ???$$

- Compute ω^2 at second order.
- Make a diagrammatic representation of each term.

Part 1) Show these 3 definitions are equivalent; work out the limits of integration.

$$f \otimes g = \int f(x) g(y) \delta(z - x * y)\, dx\, dy$$
$$f \otimes g = \int f(x) g\left(\frac{z}{x}\right) \frac{dx}{x}$$
$$f \otimes g = \int f\left(\frac{z}{y}\right) g(y) \frac{dy}{y}$$

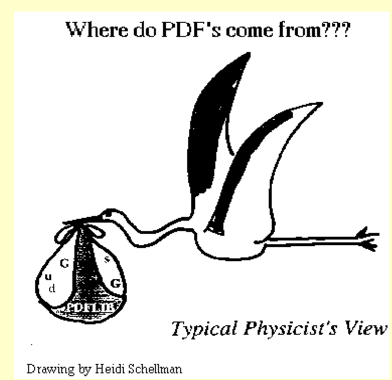
Part 2) Show convolutions are the ``natural'' way to multiply probabilities.

If f represents the heads/tails probability distribution for a single coin flip, show that the distribution of 2 coins is $f \oplus f$ and 3 coins is $f \oplus f \oplus f$.

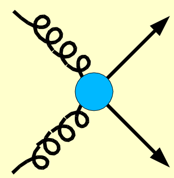
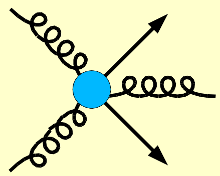
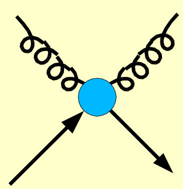
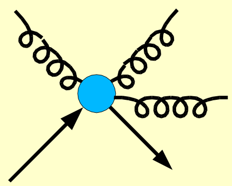
$$f \oplus g = \int f(x) g(y) \delta(z - (x+y))\, dx\, dy$$
$$f(x) = \frac{1}{2}(\delta(1-x) + \delta(1+x))$$

BONUS: How many processes can you think of that don't factorize?

B-Hadroproduction: A Case Study



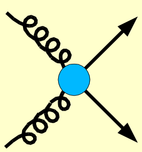
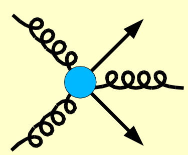
The Basic Contributions to Heavy Flavor Production

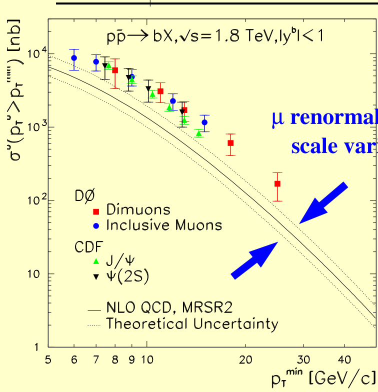
	Leading Order	Next to LO
Heavy Creation		
Heavy Excitation		

Fixed-Flavor Scheme

Variable-Flavor Scheme

NLO Fixed-Flavor Scheme

	Leading Order		Next to LO
Heavy Creation		Surprise <<	

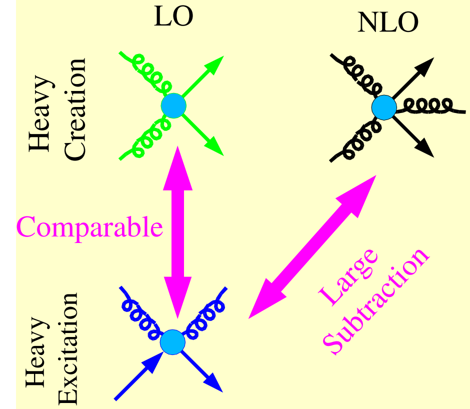


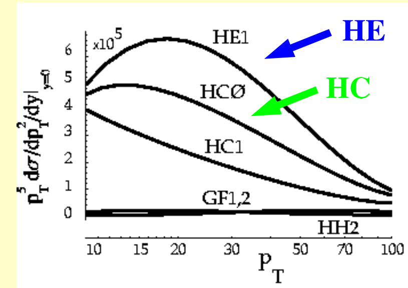
Surprise: NLO / LO ~ 2

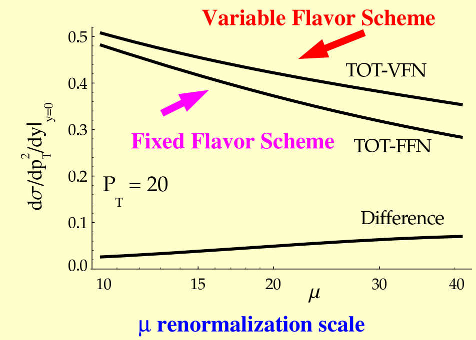
But, theory still below data

Nason, Dawson, Ellis
Beenakker, Kuijf, Van Neerven, Smith

NLO Variable Flavor Scheme



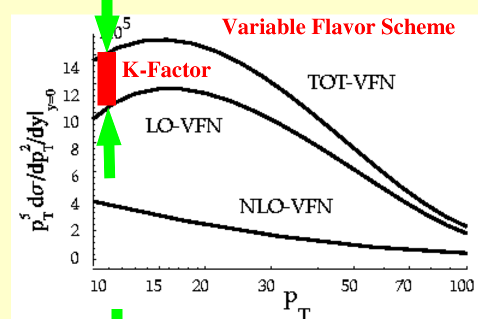


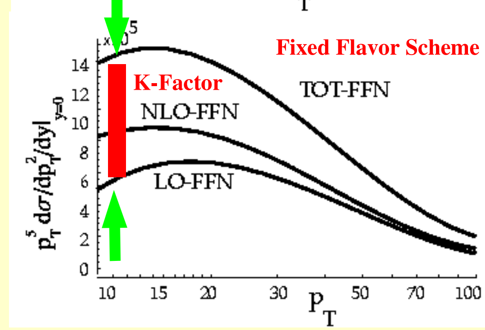


Net result:
- Reduction of μ-dependence
- 30% to 50% increase in σ

Aivazis, Collins, Olness, Tung
Olness, Scalise, Tung

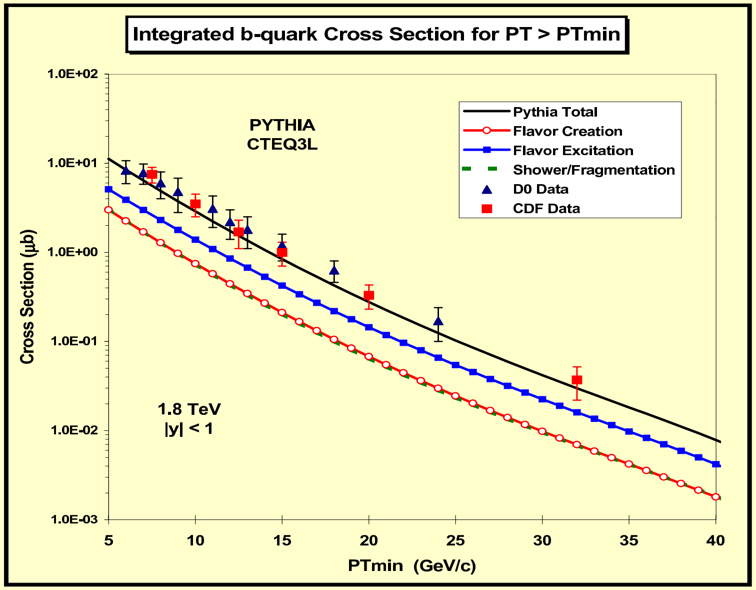
Compare Fixed & Variable Flavor Scheme



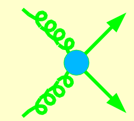


- To NLO, different schemes are comparable.
- K-Factor very different.
- Suggestion: VFS may provide more efficient organization of perturbation series than FFS.
- Recall: Choice of expansion point x_0 in Taylor series.

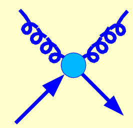
b-Quark Hadroproduction via Monte Carlo



Flavor Creation



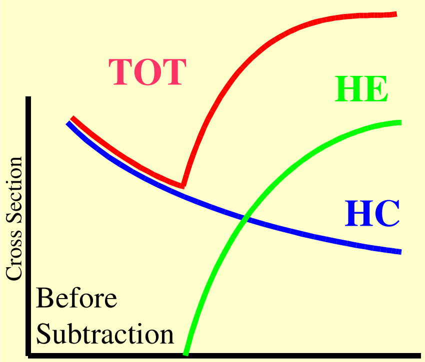
Flavor Excitation

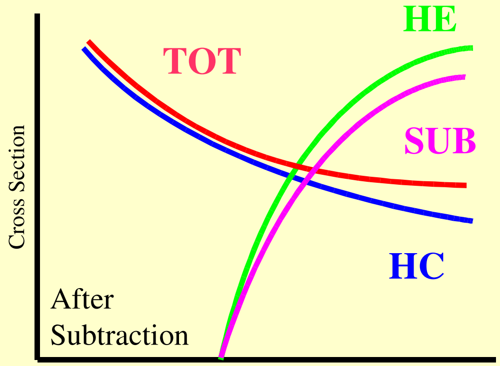


R. Field, hep-ph/0201112

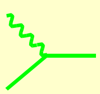
Recall

Note, we told you you'll see this again ...



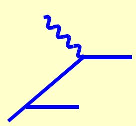


TOT =



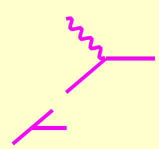
Heavy Excitation

+



Heavy Excitation

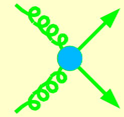
-



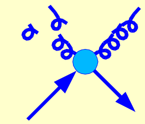
Subtraction

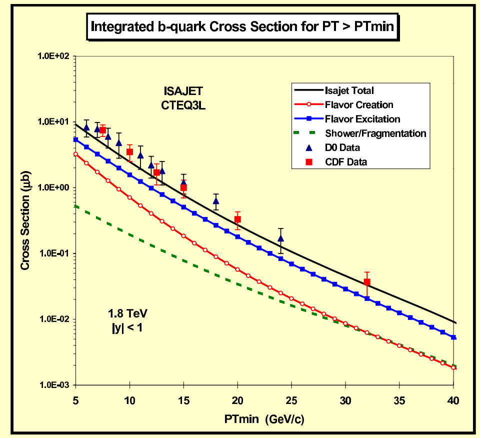
b-Quark Hadroproduction via Monte Carlo

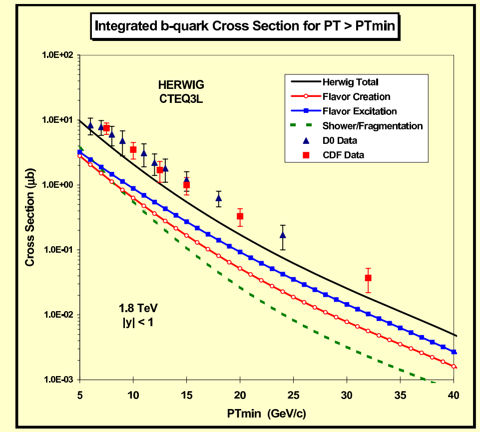
Flavor Creation



Flavor Excitation

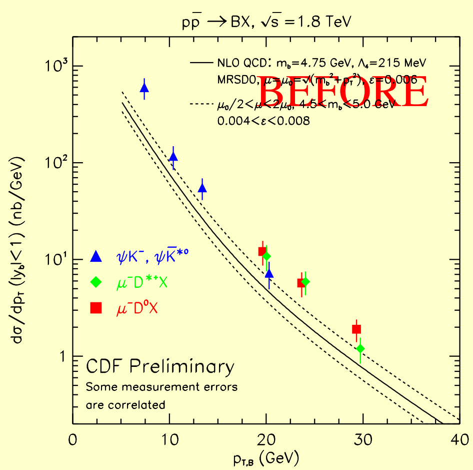


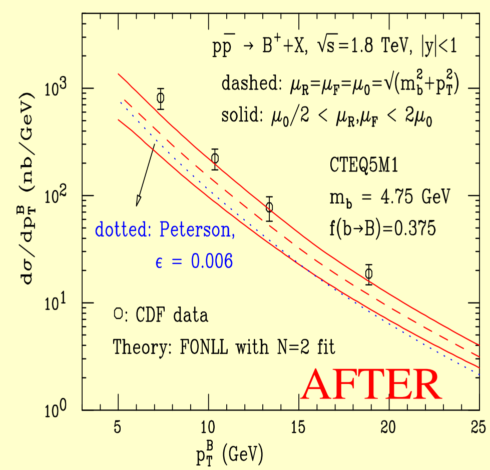




R. Field, hep-ph/0201112

B production with modified fragmentation function



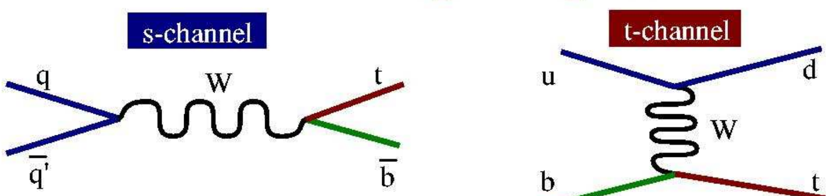


Cacciari & Nason hep/ph-0204025
Cacciari, Greco, Nason, JHEP 9805:007, 1998
Cacciar & Greco, Nuc.Ph.B421:530, 1994

The effect of modifying the bottom fragmentation function raises theory predictions in the range of data.
Note, we observe b-hadron, not b-quark!!!

Single Top Production

Tevatron Single Top Goals



- Observe single top quark production
  - Separately in the s-channel and t-channel
- Measure production cross sections
  - CKM matrix element V_{tb}
- Look for physics beyond the Standard Model
- Study top quark spin correlations – probe V-A
- Irreducible background to associated Higgs production

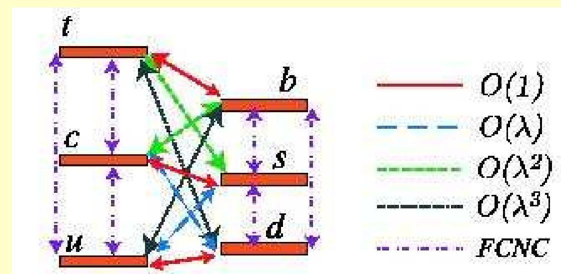
Reinhard Schwienhorst, Michigan State University 3

The CKM Quark Mixing Matrix

The CKM Quark Mixing Matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\begin{pmatrix} 0.97 & 0.22 & 0.003 \\ 0.22 & 0.97 & 0.04 \\ 0.003 & 0.04 & 0.999 \end{pmatrix}$$



stolen from Michael Luke, TASI-02

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

3-Generations:
4 real parameters;
η controls Im part
$\Rightarrow$
CP-violation

CLNS 94/1314
CLEO 94–25
December 13, 1994

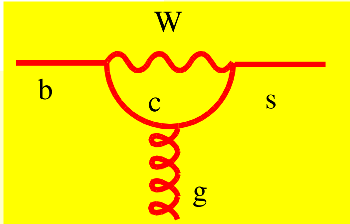
First Measurement of the Rate for the Inclusive Radiative Penguin Decay $b \to s\gamma$

M.S. Alam,[1] I.J. Kim,[1] Z. Ling,[1] A.H. Mahmood,[1] J.J. O'Neill,[1] H. Severini,[1] C.R. Sun,[1] F. Wappler,[1] G. Crawford,[2] C. M. Daubenmier,[2] R. Fulton,[2] D. Fujino,[2] K.K. Gan,[2] A. Wolf,[2] A. Wood [3] M

Abstract

We have measured the inclusive $b \to s\gamma$ branching ratio to be $(2.32 \pm 0.57 \pm 0.35) \times 10^{-4}$, where the first error is statistical and the second is systematic. Upper and lower limits on the branching ratio, each at 95% CL, are $\mathcal{B}(b \to s\gamma) < 4.2 \times 10^{-4}$ and $\mathcal{B}(b \to s\gamma) > 1.0 \times 10^{-4}$. These limits restrict the parameters of extensions of the Standard Model.

PACS numbers: 13.25Hw, 14.40.Nd



$$Br(b \to s\gamma) = 2.32 \pm 0.57 \pm 0.35 \times 10^{-4}$$

SLAC Press Release

July 23, 2002

Contact: Neil Calder
SLAC
(650) 926-8707
Neil.Calder@SLAC.Stanford.edu

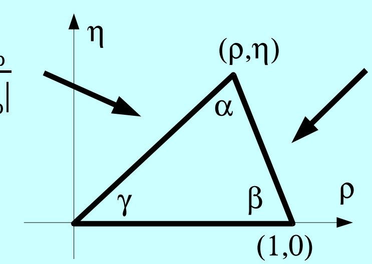
From Theory to Certainty. BaBar announces new result on Charge Parity violation

At the International Conference on High Energy Physics in Amsterdam on July 25, the BaBar collaboration working at the the Department of Energy's Stanford Linear Accelerator Center (SLAC) announced their new measurement of a parameter known as sine two beta, that expresses the degree of asymmetry between matter and antimatter. This result is the product of three years of intense research and is a classic example of how understanding of our universe advances through high energy physics research.

if η (or β) is zero, no CP-violation

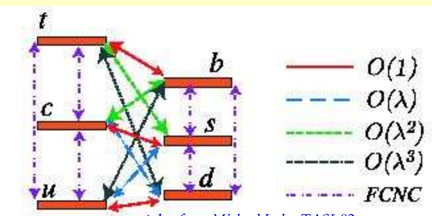
$\sin(2\beta) = 0.59 \pm 0.14 \pm 0.05$

$$\frac{V_{ud}V_{ub}^*}{|V_{cd}V_{cb}^*|} \qquad \frac{V_{td}V_{tb}^*}{|V_{cd}V_{cb}^*|}$$



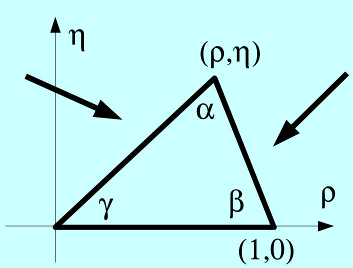
CP Violation in the CKM Mixing Matrix

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



stolen from Michael Luke, TASI-02

$$\frac{V_{ud}V_{ub}^*}{|V_{cd}V_{cb}^*|} \qquad \frac{V_{td}V_{tb}^*}{|V_{cd}V_{cb}^*|}$$



See talks by V. Sharma, M. Neubert

if η (or β) is zero, no CP-violation

The Mixing Matrix

Neu^trino

$$U = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\text{Atmospheric}} \times \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{\text{Cross-Mixing}} \times \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Solar}}$$

$$c_{ij} \equiv \cos\theta_{ij} \qquad s_{ij} \equiv \sin\theta_{ij} \qquad \times \underbrace{\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Majorana } \cancel{CP} \text{ phases}}$$

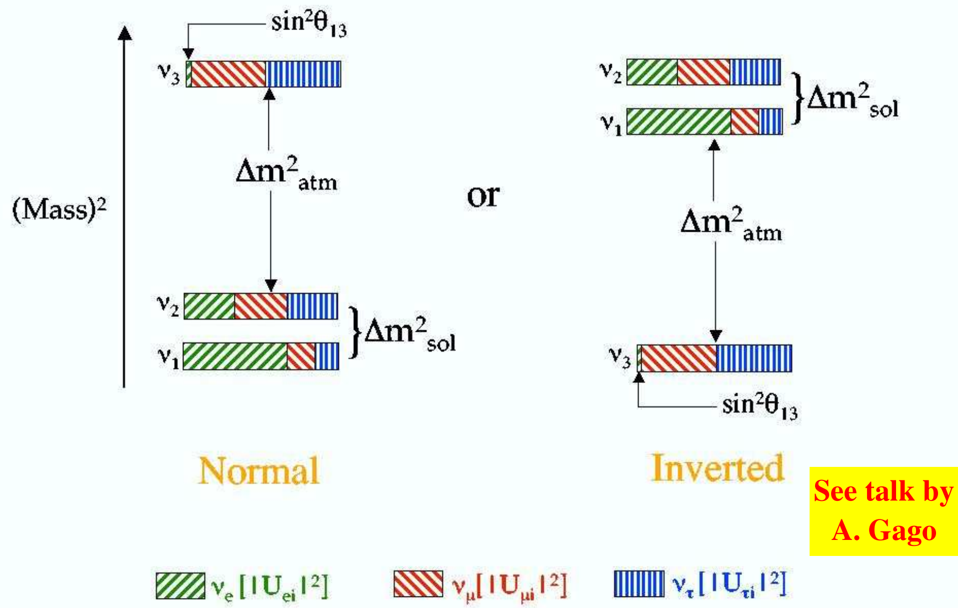
$\theta_{12} \approx \theta_{sol} \approx 33°$, $\theta_{23} \approx \theta_{atm} \approx 37\text{-}53°$, $\theta_{13} \lesssim 12°$

δ would lead to $P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$. $\cancel{CP}$

But note the crucial role of $s_{13} \equiv \sin\theta_{13}$.

stolen from Boris Kayser, Pheno 2005

The spectrum, showing its approximate flavor content, is

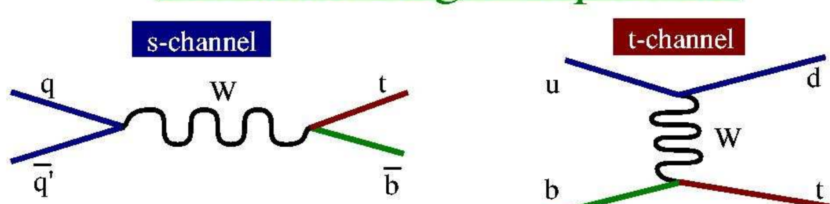


See talk by A. Gago

... not very diagonal

stolen from Boris Kayser, Pheno 2005

Tevatron Single Top Goals



- Observe single top quark production
  - Separately in the s-channel and t-channel
- Measure production cross sections
  - CKM matrix element V_{tb}
- Look for physics beyond the Standard Model
- Study top quark spin correlations – probe V-A
- Irreducible background to associated Higgs production

Conclusions

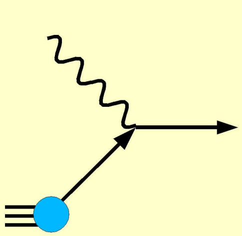
- DØ Run II single top analysis with 230pb^{-1} completed
  - Detector, trigger, software etc working and understood
  - 95% CL cross section limits of $\sigma_s < 6.4$ pb, $\sigma_t < 5.0$ pb
  - Factor 2 improvement over previous limits
  - Reaching sensitivity to new physics
  - Could discover SM single top with this method with ~3fb^{-1}
- Single Top is an exciting opportunity for Run II
  - New and old (SM) physics
- This is just the beginning
  - Expect ×3 dataset by end of year
  - Improve all aspects of the analysis

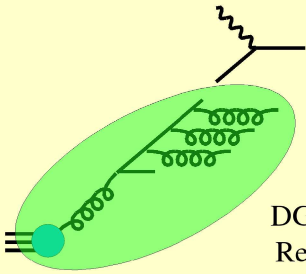
Dawn of Run II Discoveries

Mass-Independent Evolution.

Why is it valid?

DGLAP Equation and the Heavy Quark PDF





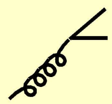
$$HE = \int f(P\to a)\otimes\sigma(a\to c)$$

DGLAP equation Resums iterative splittings inside the proton

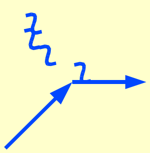
DGLAP Equation $$\frac{df_i}{d\log\mu^2} = \frac{\alpha_s}{2\pi}\ {}^1P_{j\to i}\otimes f_j + \ldots$$

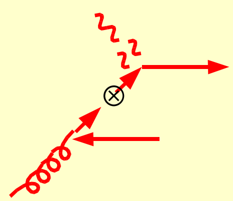
Splitting Function

$${}^1P_{g\to q} = \frac{1}{2}[x^2+(1-x)^2] + \left(\frac{M_H^2}{\mu^2}\right)[x(1-x)]$$



Effect of Heavy Quark Mass in the Calculation





$$HE = \int f(P\to a)\otimes\sigma(a\to c)$$

$$\approx f(P\to g)\otimes{}^1P(g\to a)$$

valid near threshold (M_H~Q)

$$SUB = \int f(P\to g)\otimes{}^1P(g\to a)\otimes\sigma(a\to c)$$

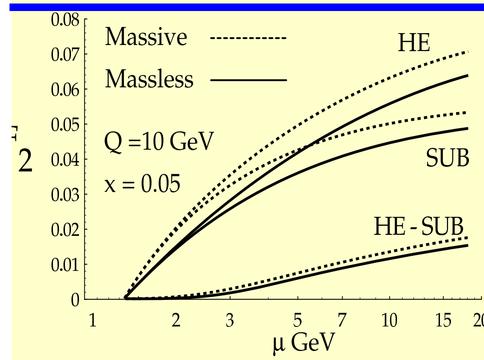
${}^1P$ splittings must match

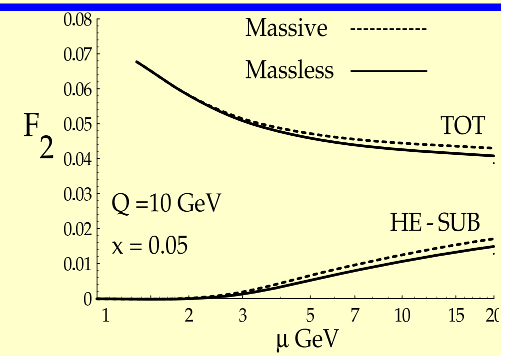
In Summary:

Near threshold(M_H~Q), mass effects cancel between HE and SUB

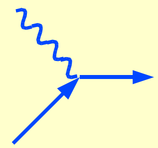
Above threshold(M_H<<Q), mass effects can be ignored

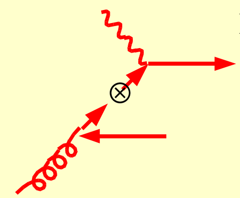
Effect of Heavy Quark Mass in the Calculation is Trivial



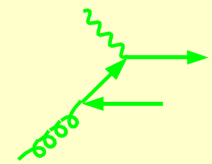


$$HE = \int f(P\to a)\otimes\sigma(a\to c)$$





$$HC = \int f(P\to g)\otimes\sigma(g\to c)$$



$$SUB = \int f(P\to g)\otimes{}^1P(g\to a)\otimes\sigma(a\to c)$$

Conclusions

... or, coffee is just around the corner

Heavy Quark Production

An interesting subject because:

- Lots of data at present; more in near future
- Theoretical issues of multi-scale problem

A fascinating subject because:

- Theory & data often not consistent
- This should be a region we can compute

Fred Olness olness@smu.edu