W/Z/Higgs Production at the LHC
& PDF Uncertainties

Are we ready to make discoveries at the LHC

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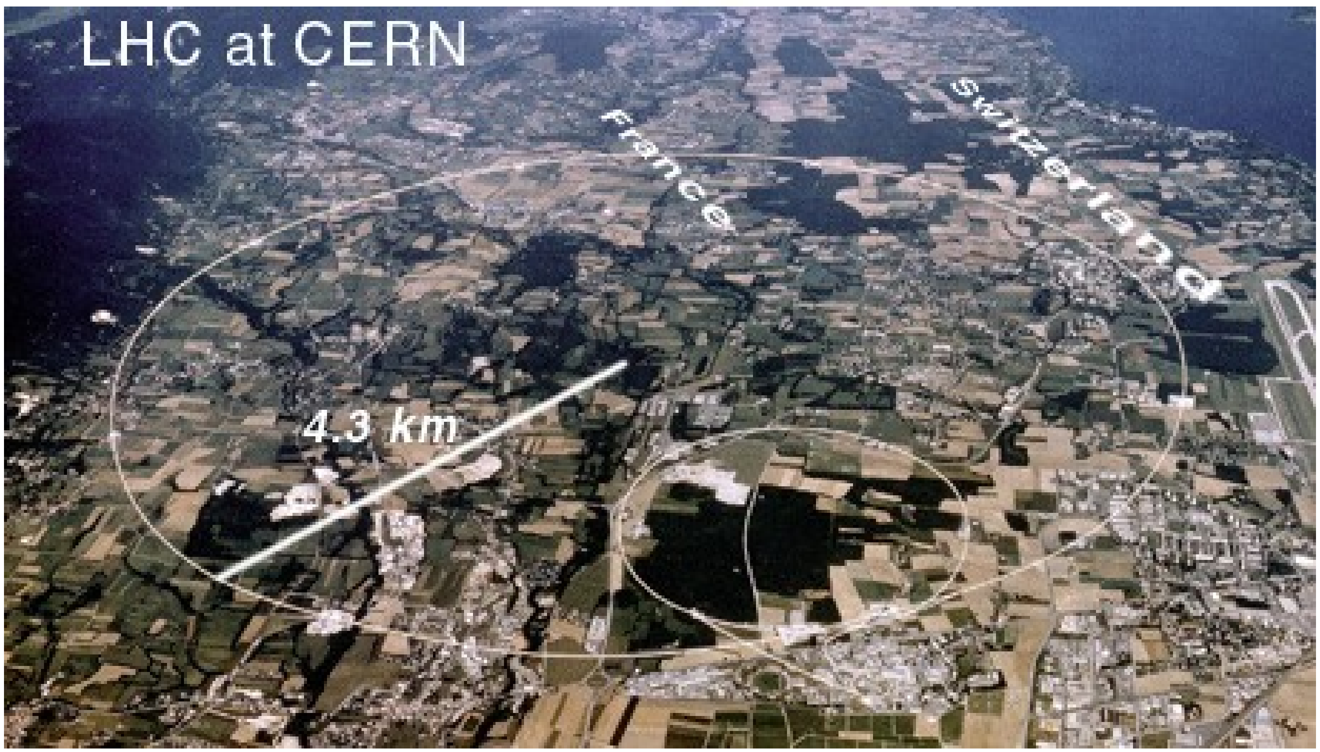
DESY
8 March 2010

Conspirators:
P. Nadolsky, K. Park,
I Schienbein, J.-Y. Yu,
Karol Kovarik, T.P. Stavreva
J. Owens, J. Morfin, C. Keppel, ...

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

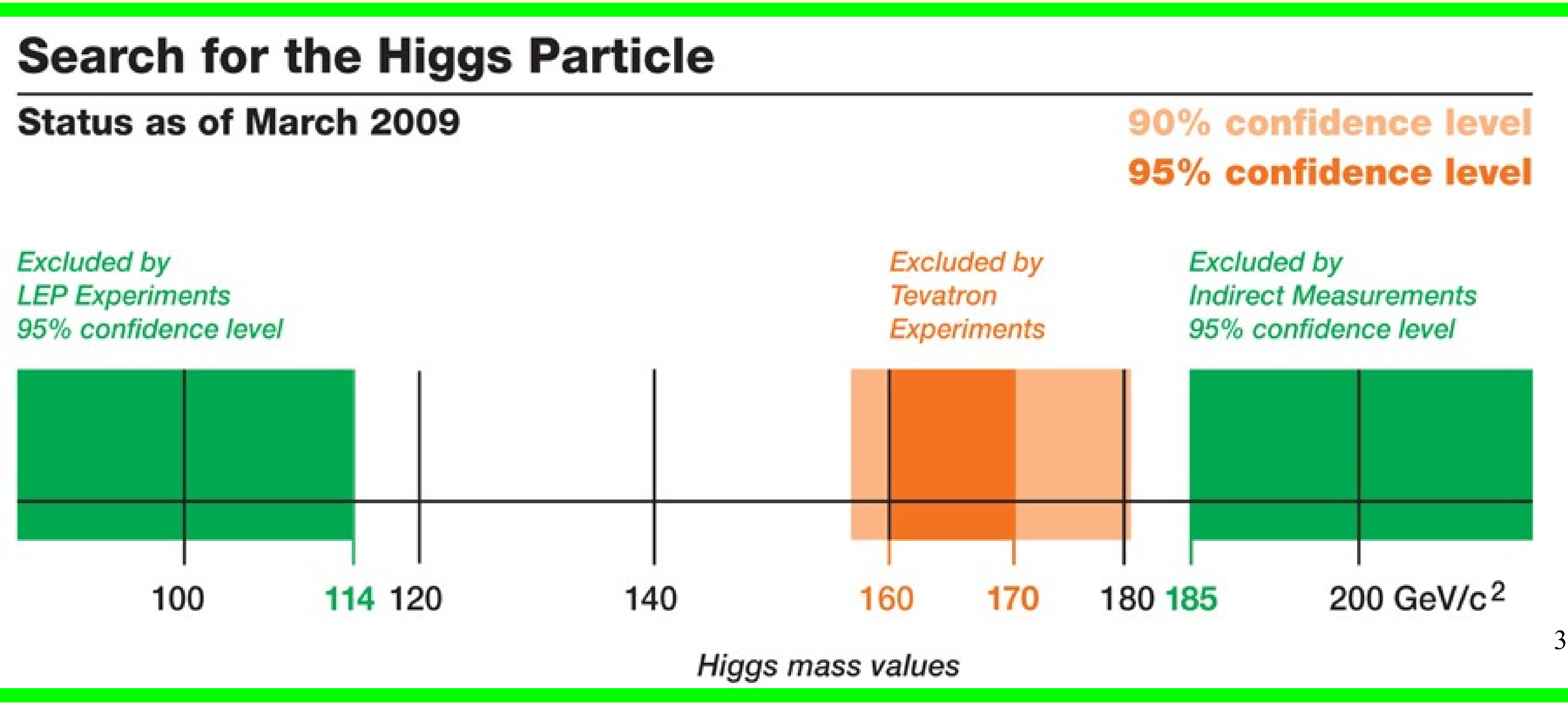
DESY

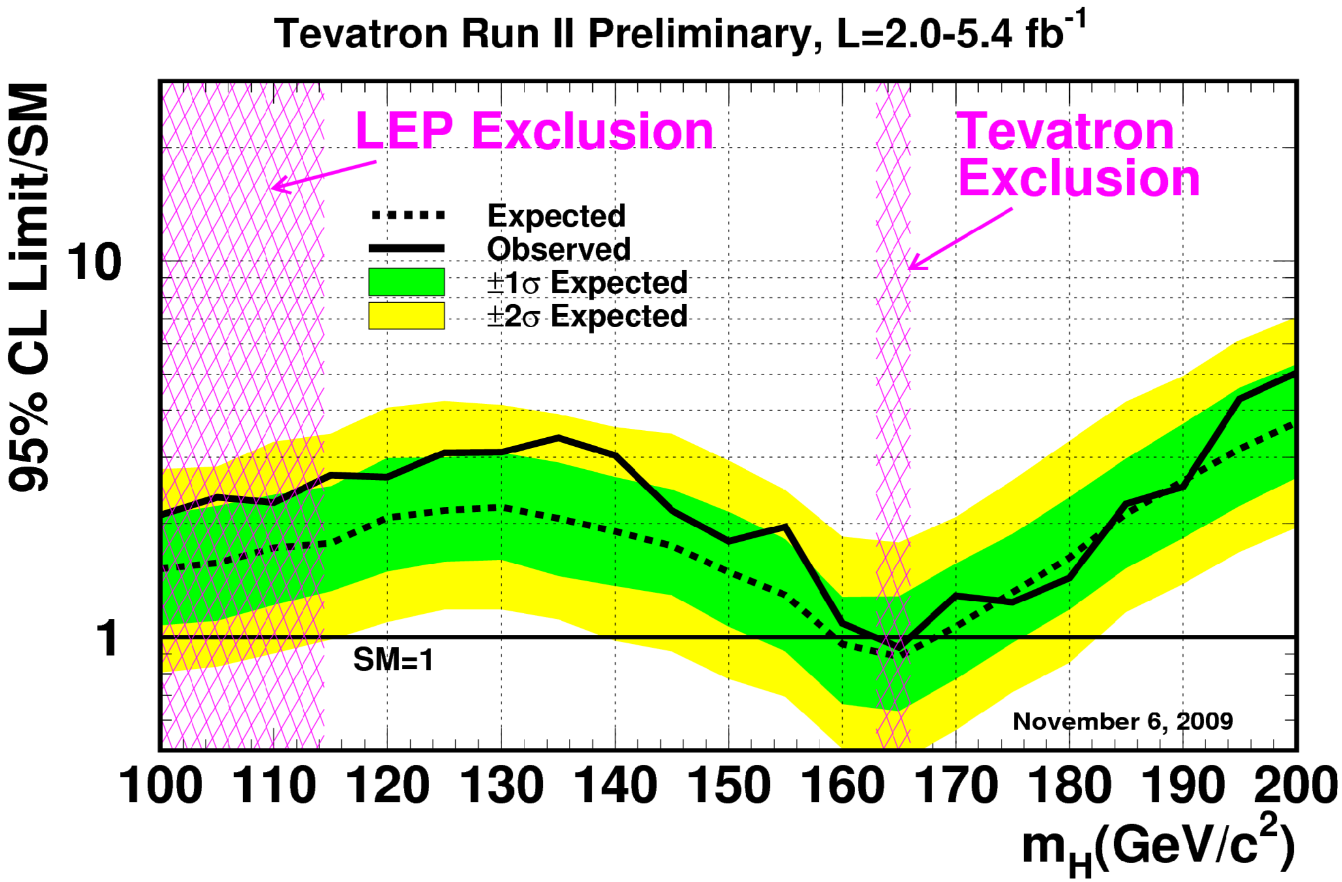
LHC started up in November 2009



W/Z at LHC

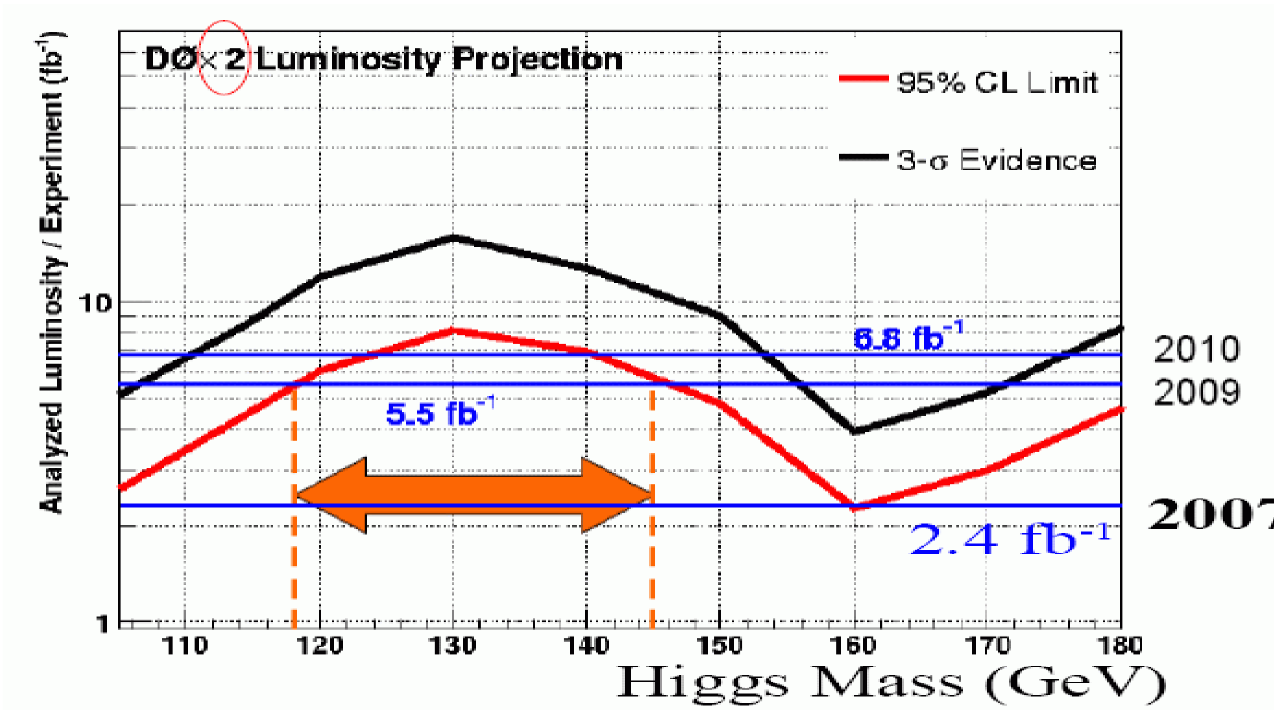
& the race for the Higgs





Combined CDF and DØ Upper Limits on Standard-Model Higgs-Boson Production

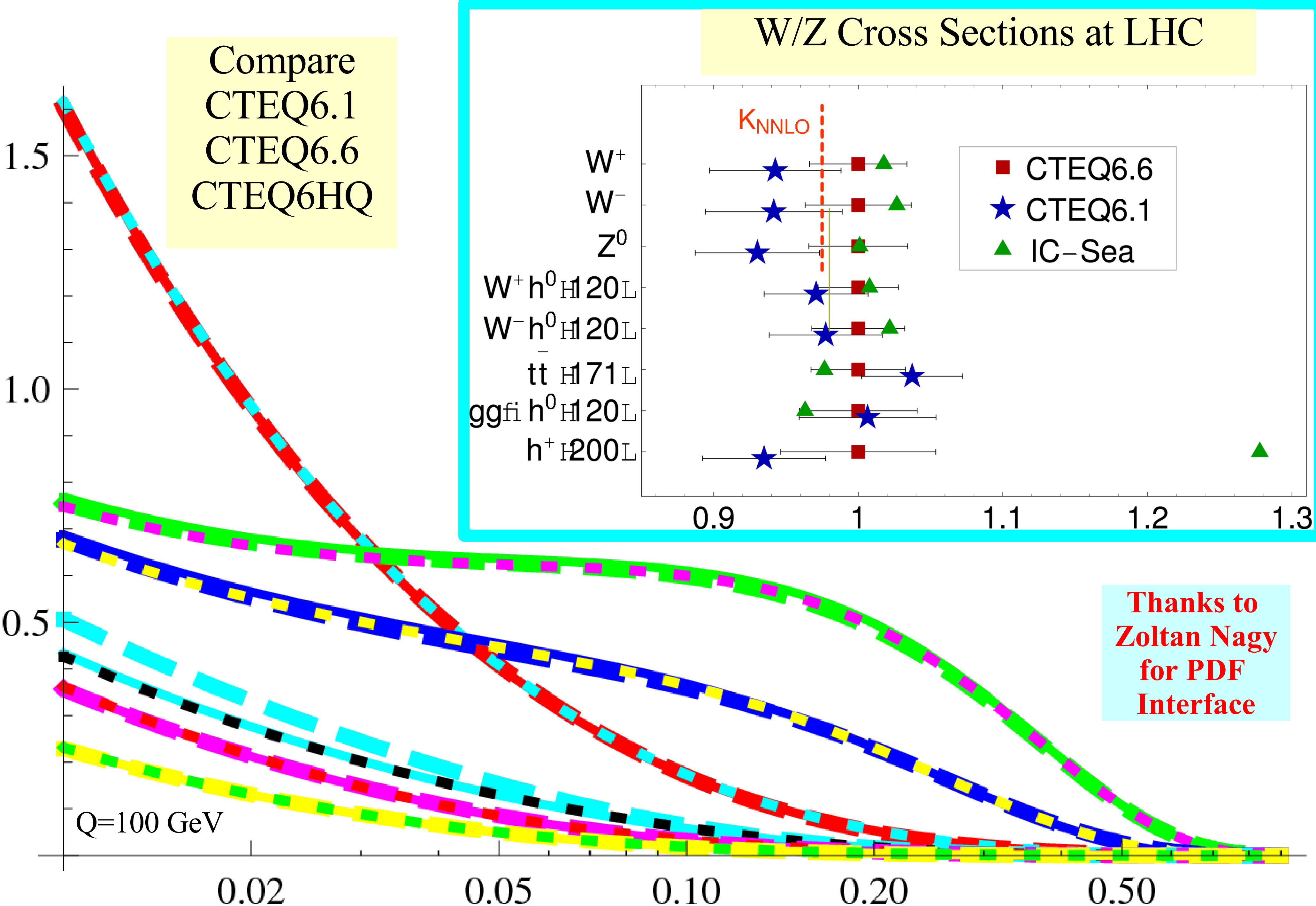
D0 Luminosity Projection



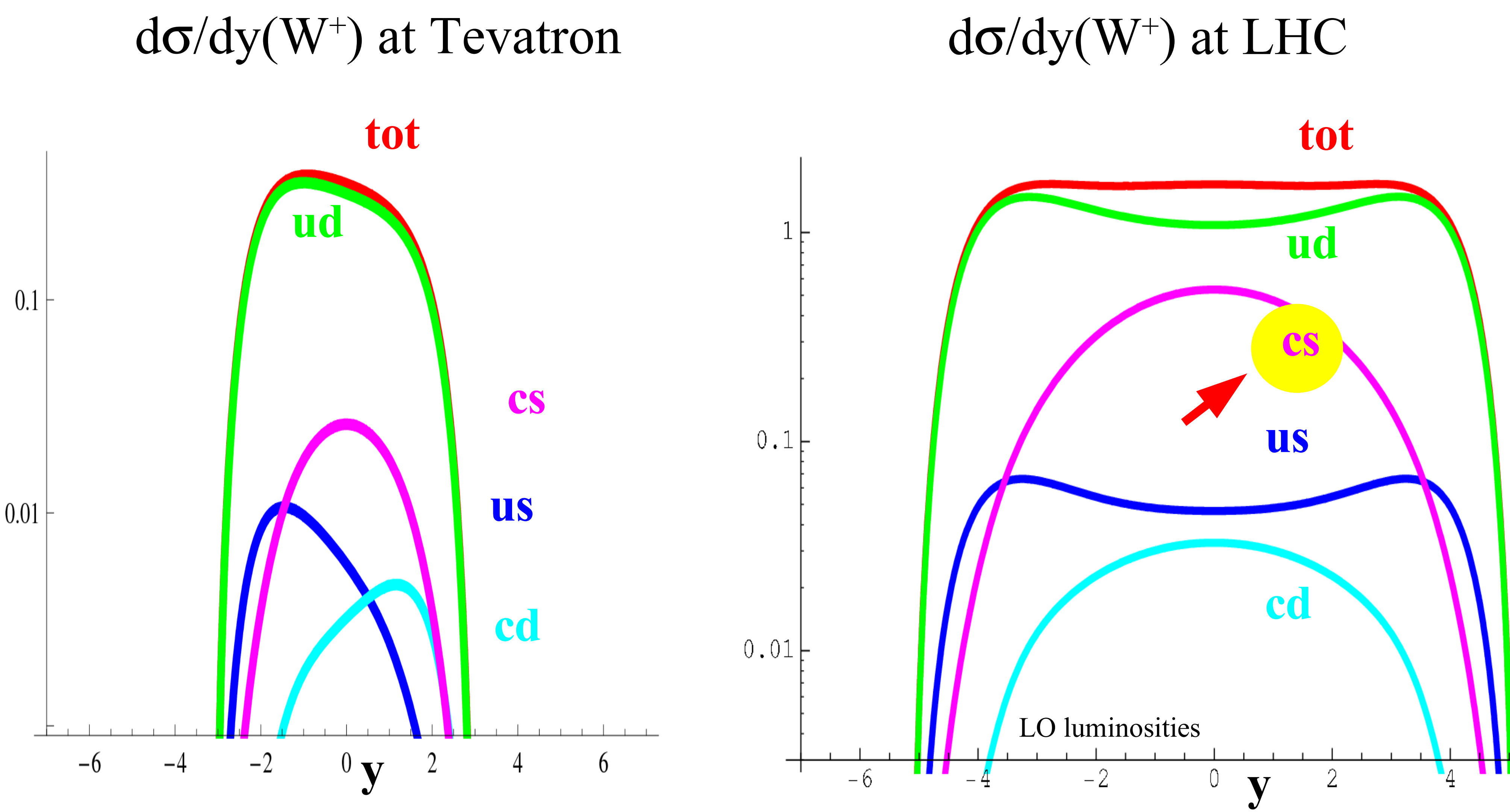
How well can we predict the W/Z

Large Shifts in Benchmark W & Z Cross Sections

Compare
CTEQ6.1
CTEQ6.6
CTEQ6HQ

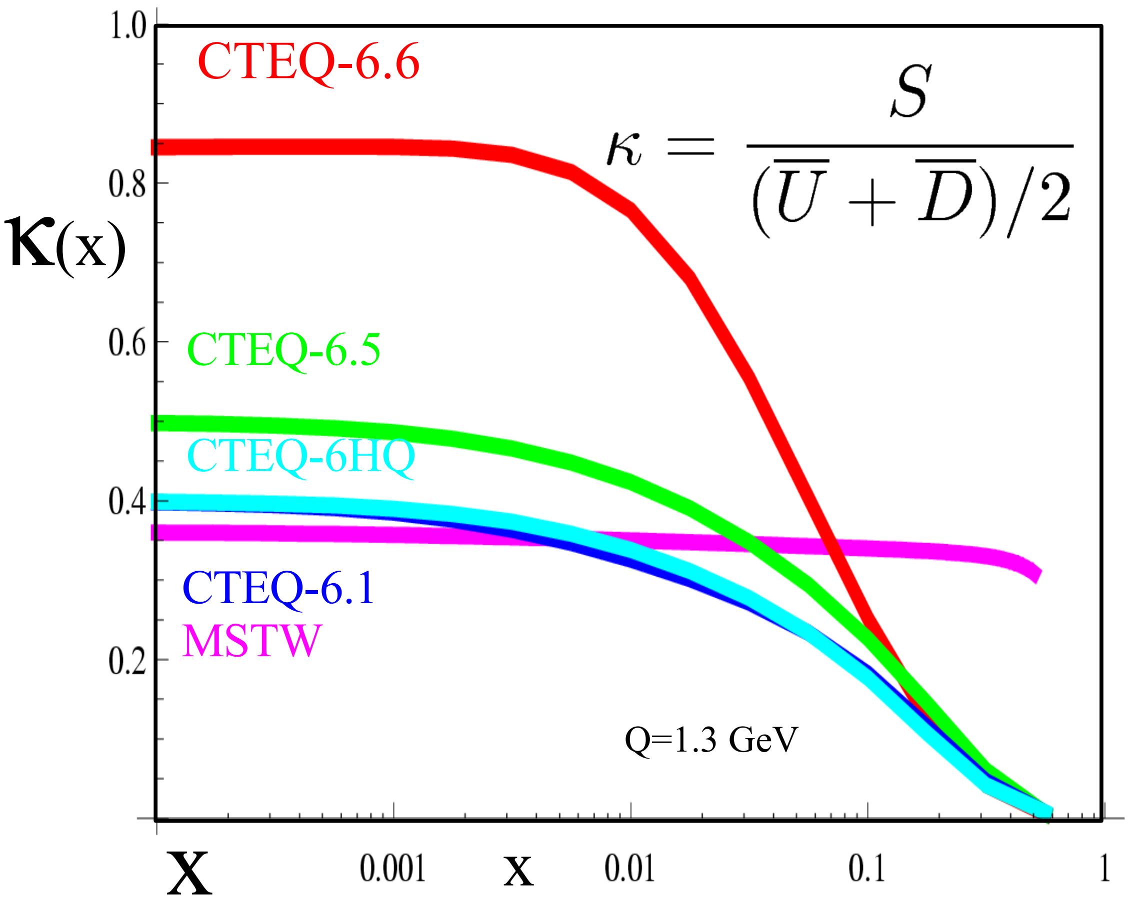


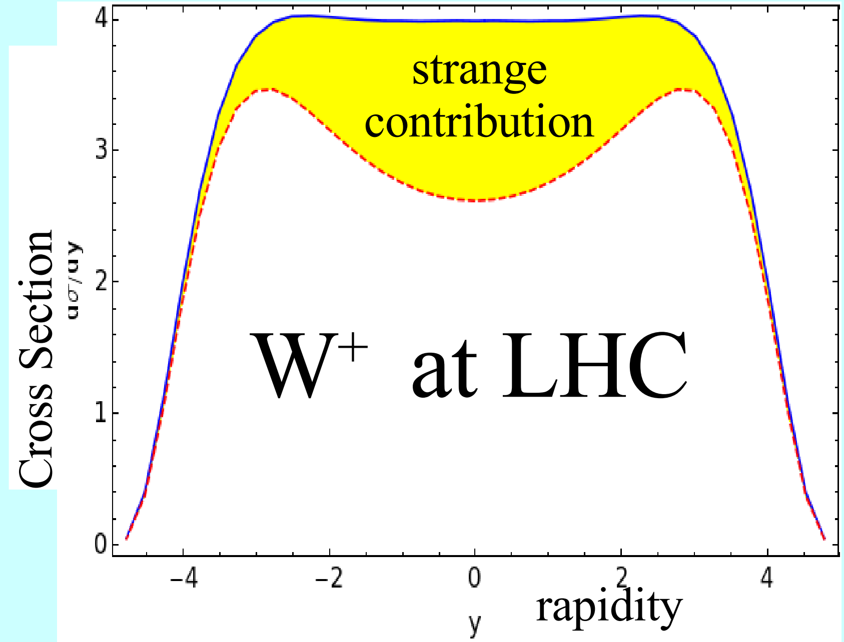
Thanks to Zoltan Nagy for PDF Interface

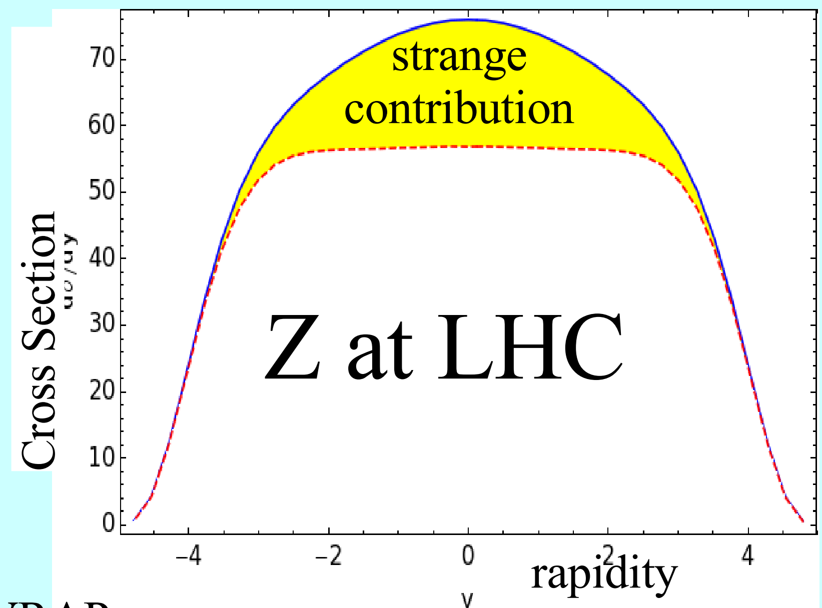


- Larger E $\Rightarrow$ probes PDFs to small x
- Larger Rapidity $\Rightarrow$ probes PDFs to really small x
- **Larger fraction of heavy quarks**

PDF Uncertainties ⇒ S(x) PDF ⇒ W/Z at LHC







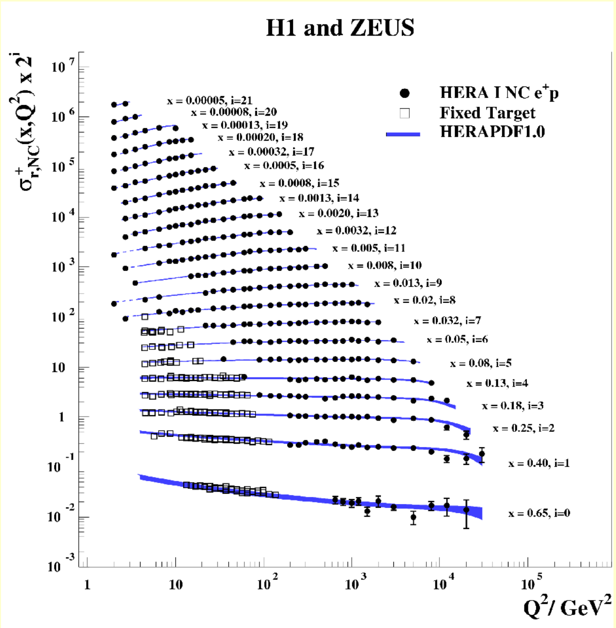
PDF Uncertainties will feed into LHC "Benchmark" processes

VRAP Code

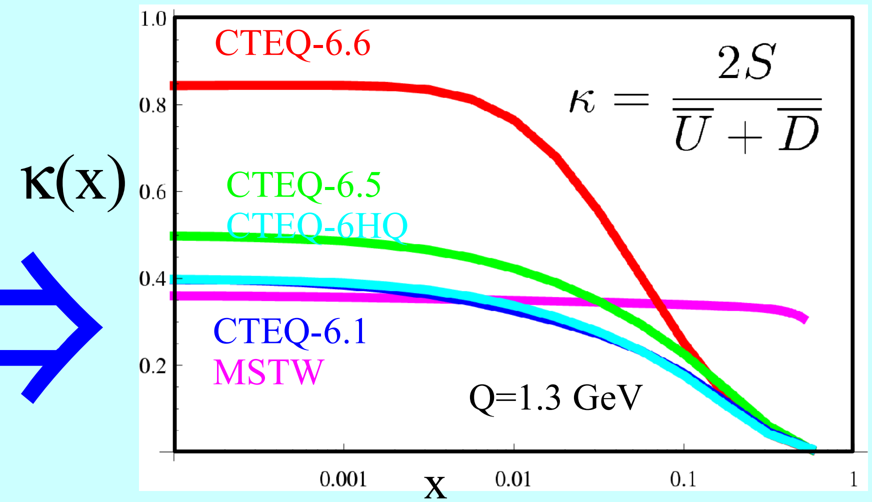
Anastasiou, Dixon, Melnikov, Petriello, Phys.Rev.D69:094008,2004.

What is HERA's Role

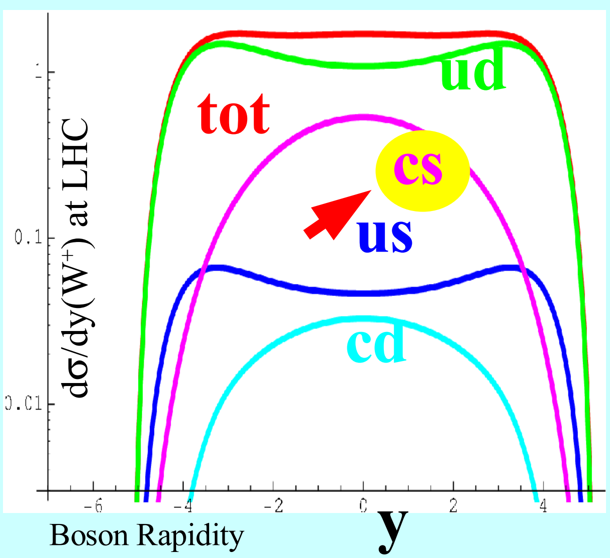
What is HERA's Role



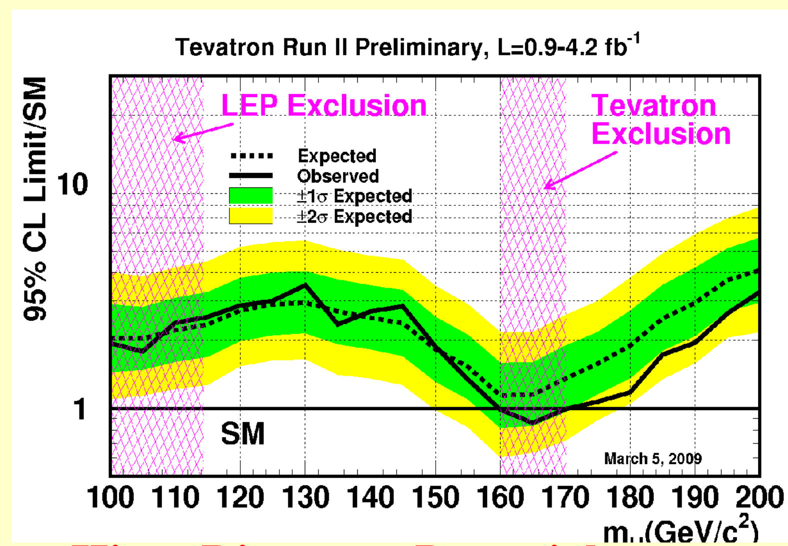
Improved SF Measurements



Improved PDFs and Flavor Differentiation

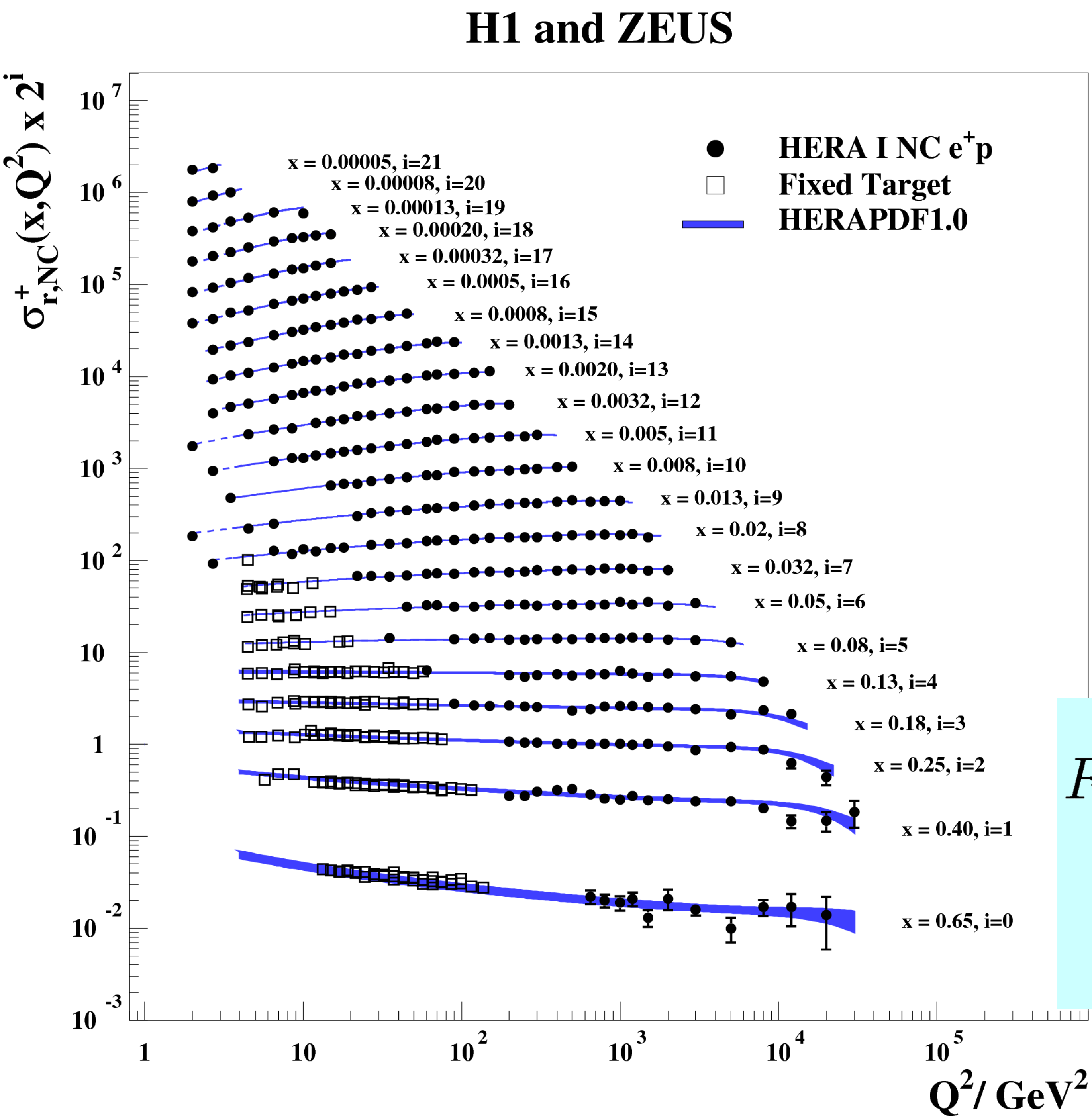


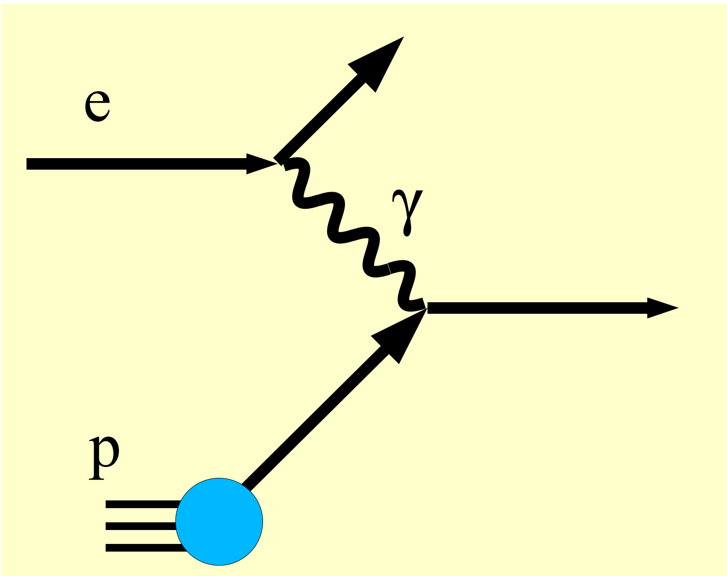
Reduced Uncertainty in W/Z



Higgs Discovery Potential

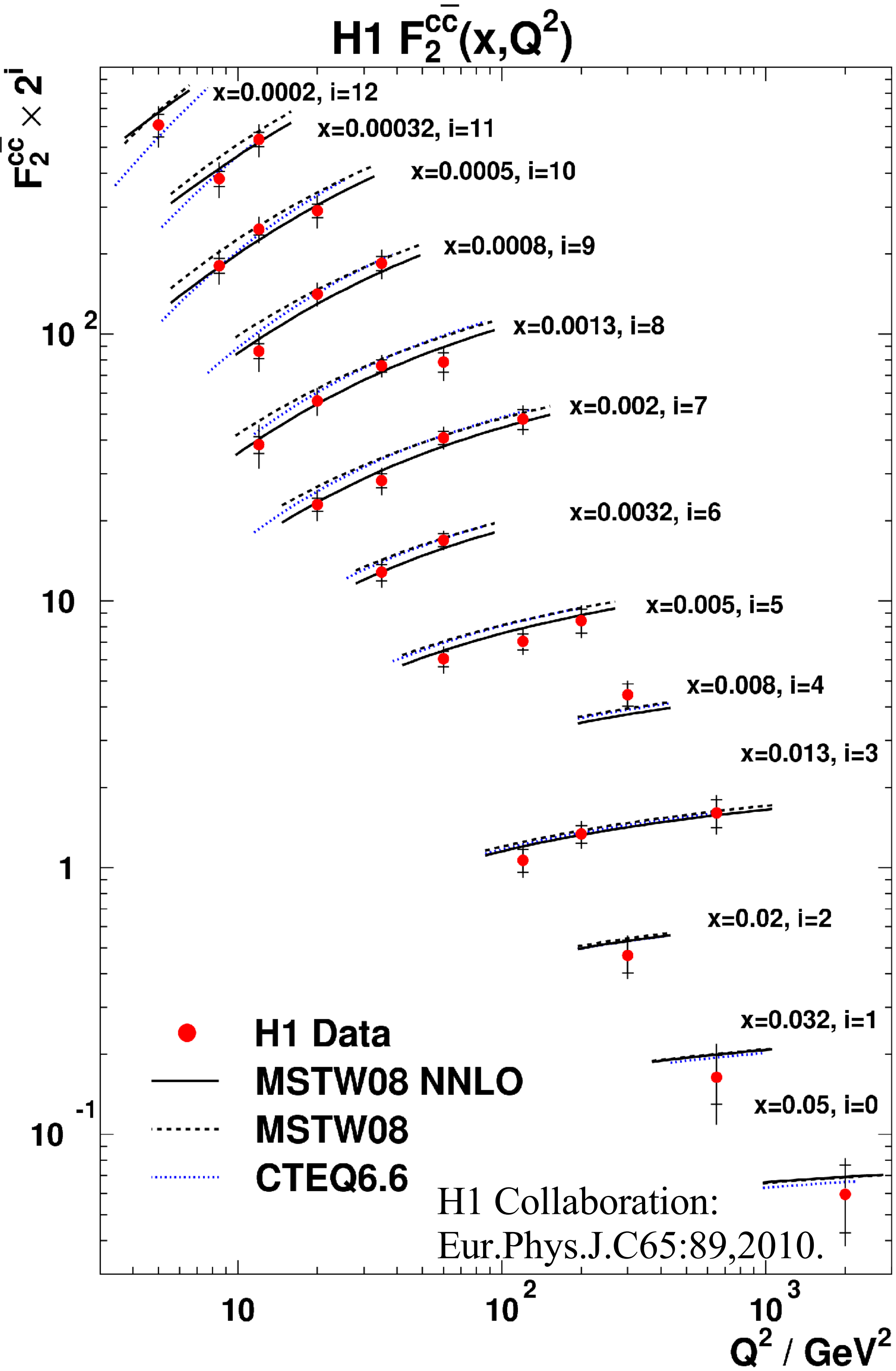
F2: Essential Foundation of LHC Predictions

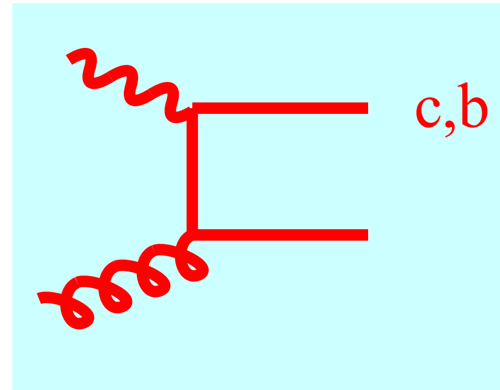


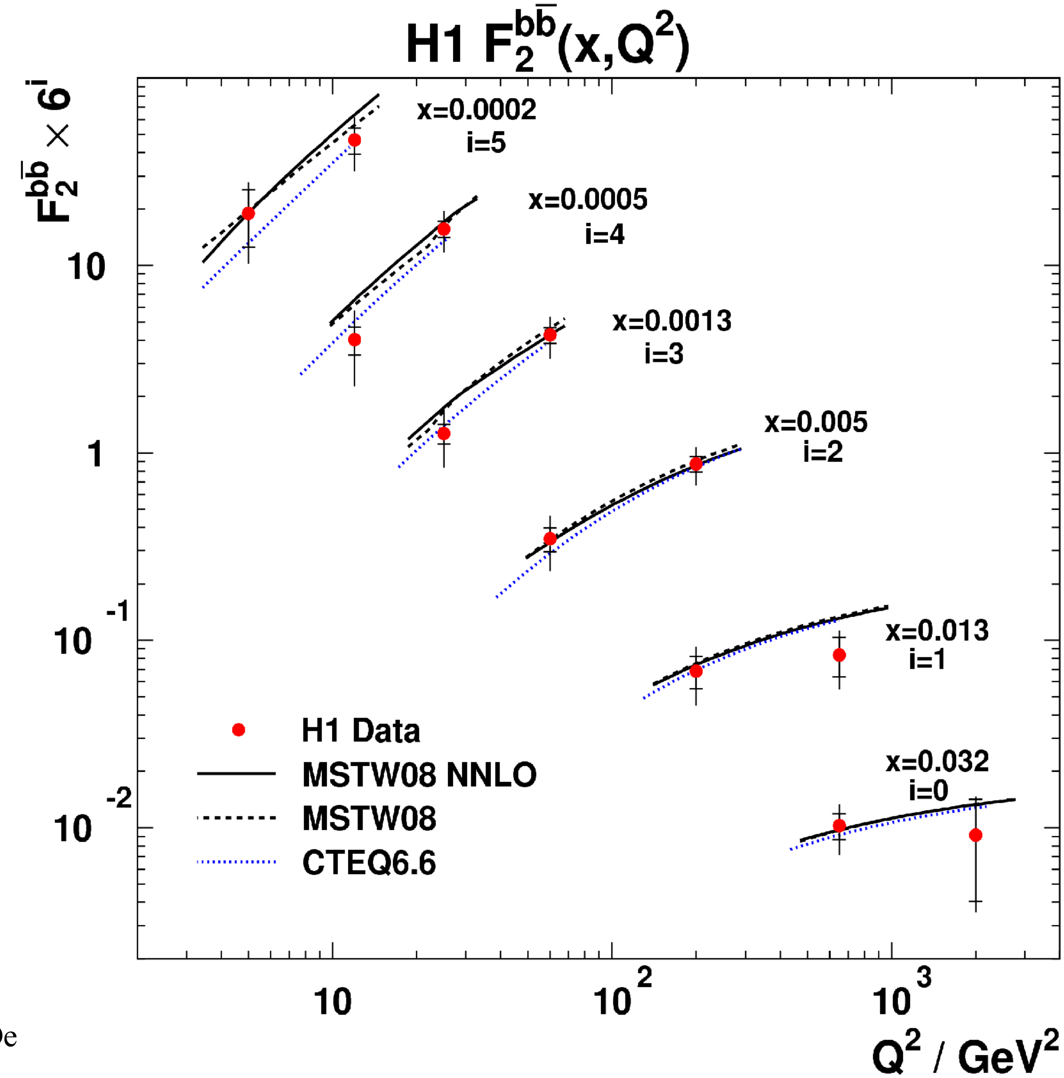


$$F_2^{ep} \sim \frac{4}{9}(u+\bar{u}+c+\bar{c}) + \frac{1}{9}(d+\bar{d}+s+\bar{s})$$

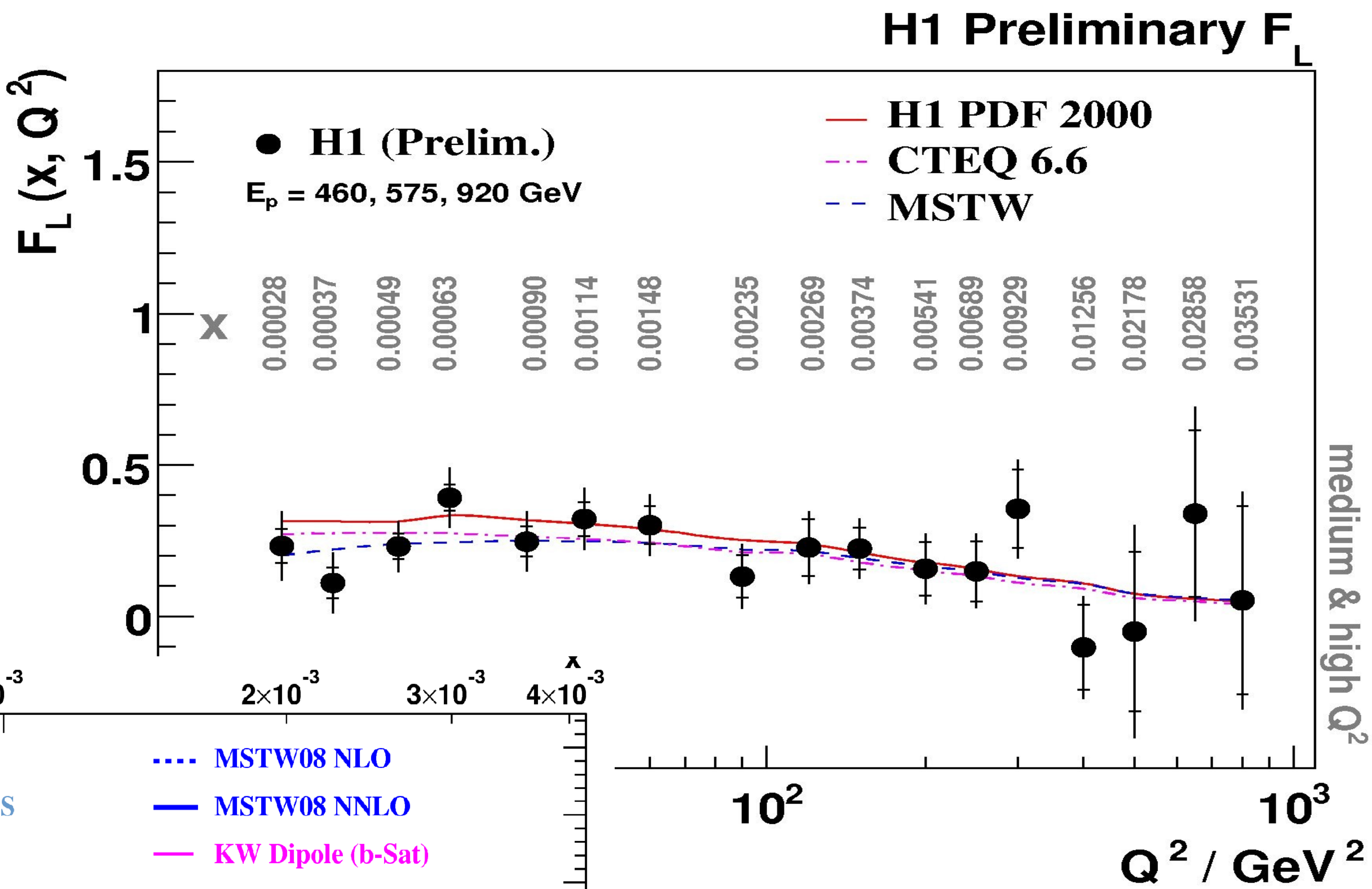
Heavy Flavor Components will play prominent role at LHC

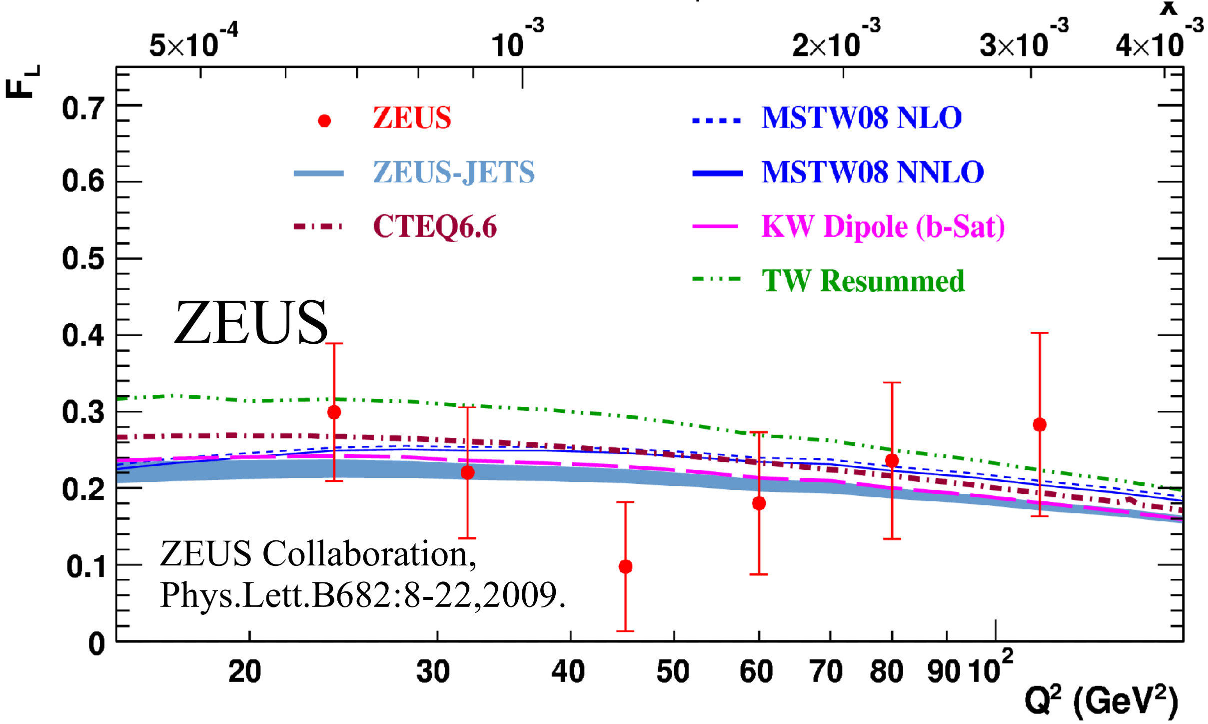






New F_L Measurements: New Perspective





H1 Collaboration and ZEUS Collaboration
(S. Glazov for the collaboration).
Nucl.Phys.Proc.Suppl.191:16-24,2009.

Why is F_L so special ???

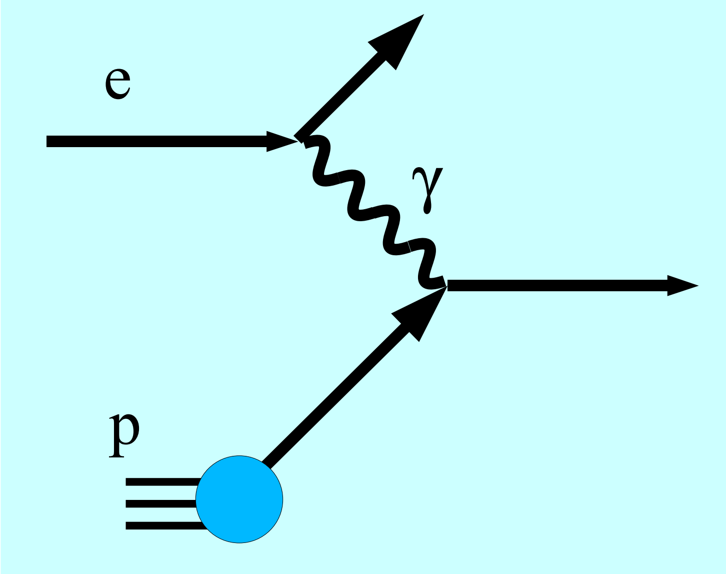
$$\frac{d\sigma^{\nu\, DIS}}{dx\, dy} = (1-y)^2\, \bar{q}(x) + (1-y)\, \phi(x) + q(x)$$

$$\frac{d\sigma^{\nu\, DIS}}{dx\, dy} = (1-y)^2\, F_+(x) + (1-y)\, F_0(x) + F_-(x)$$

$$F_0 = \frac{F_2}{2x} - F_1$$

$$F_0 = 0 \quad \Longrightarrow \quad F_2 = 2xF_1$$

Callan-Gross



$$F_L \sim \frac{m^2}{Q^2}\, q(x) + \alpha_S \left\{ c_g \otimes g(x) + c_q \otimes q(x) \right\}$$

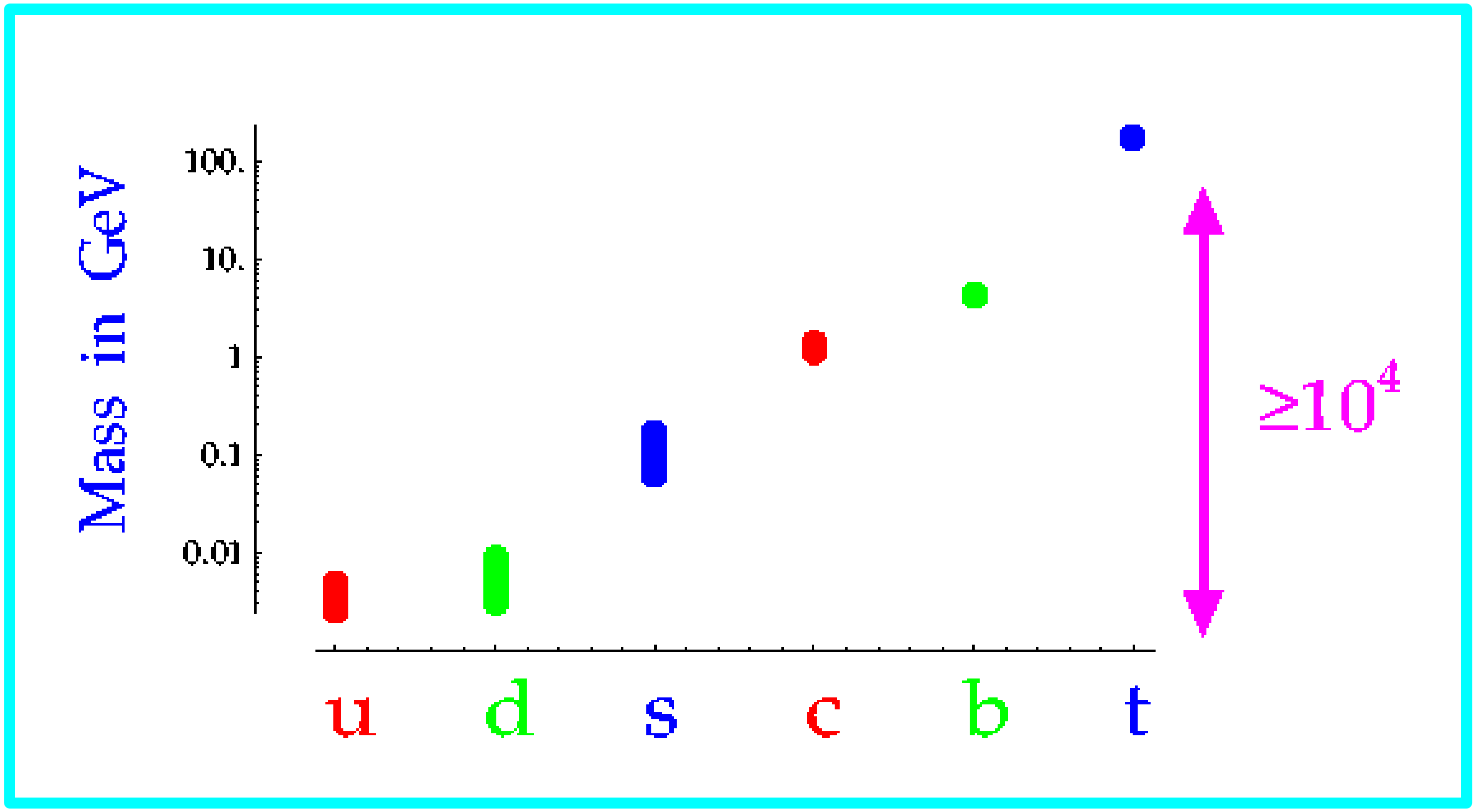
Masses are important

Masses are important

for a number of reasons

Quark Masses: Pros & Cons

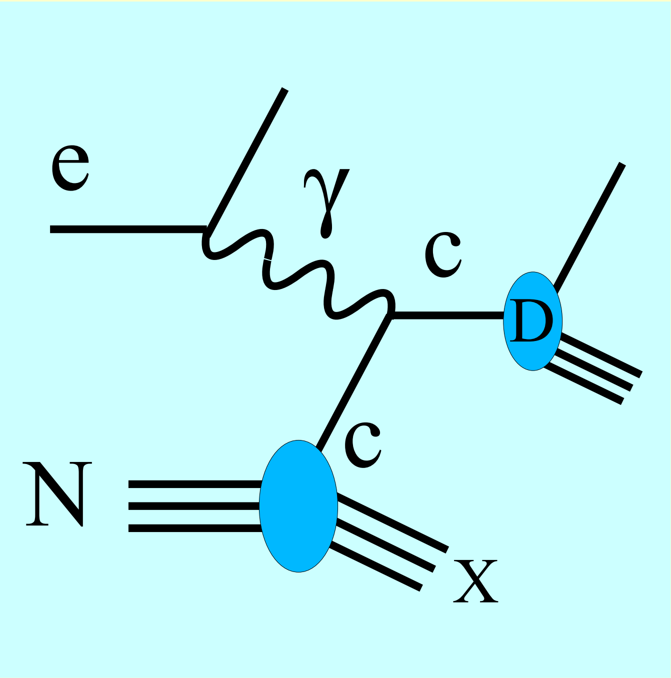
The UP side: Quark Masses Span Wide Dynamical Range ~ 10^4



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

The DOWN side: Quark Masses Span Wide Dynamical Range ~ 10^4

How do we accommodate mass scales over such a large range ???



Heavy Quarks PDF's

Essential for disparate mass scales

Heavy Quarks: How do we deal with disparate scales???

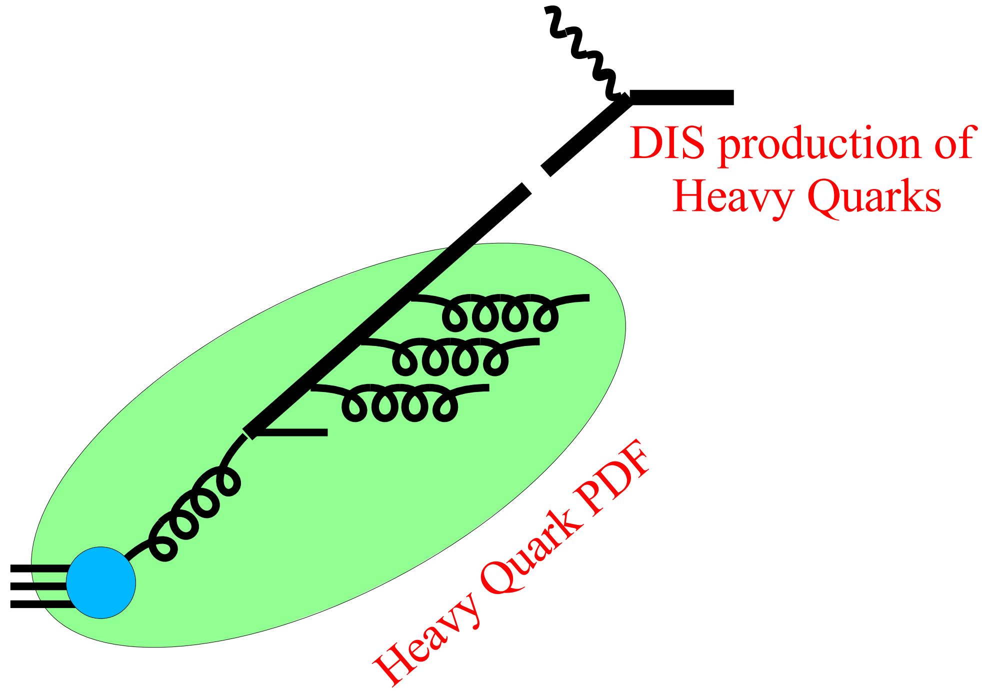
Problem: Heavy Quark introduces new scale: $\log(\frac{Q^2}{\mu^2})$ $\log(\frac{M_H^2}{\mu^2})$

... life gets interesting.

Solution: Resum $Log(M_H)$ in the Heavy Quark PDF's:

...include charm and bottom in the PDFs

DGLAP equation
Resums iterative splittings
inside the proton

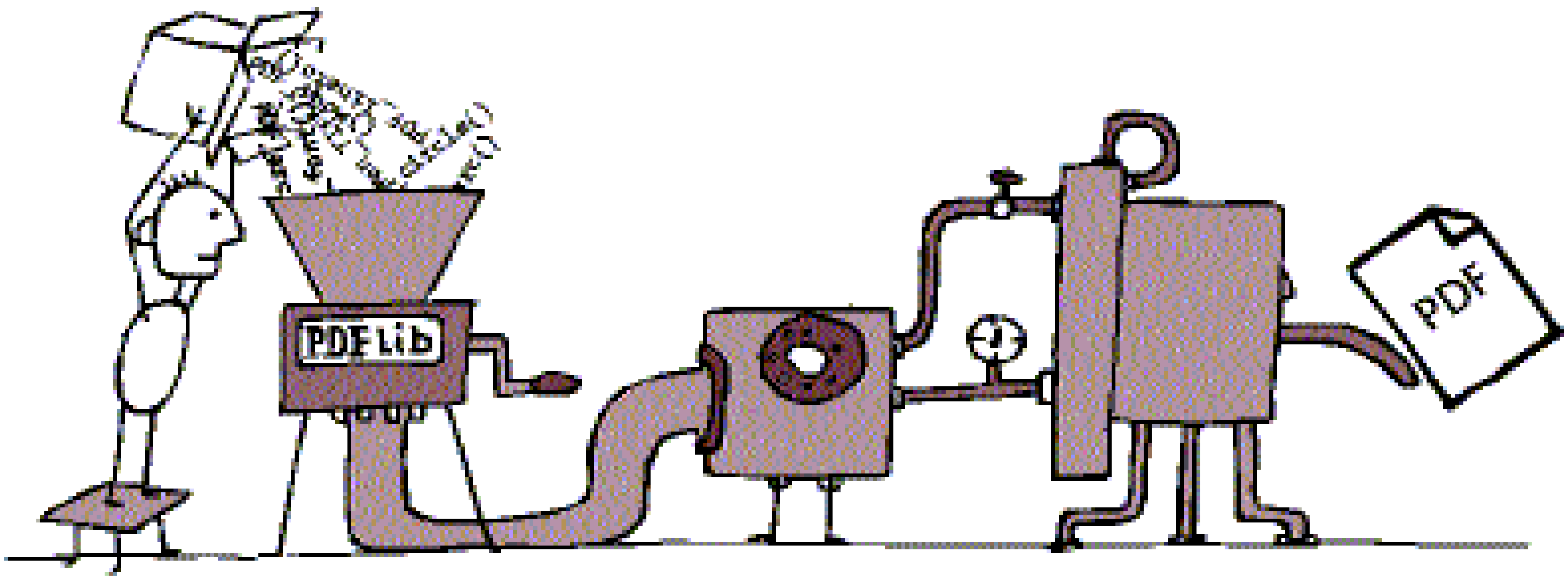


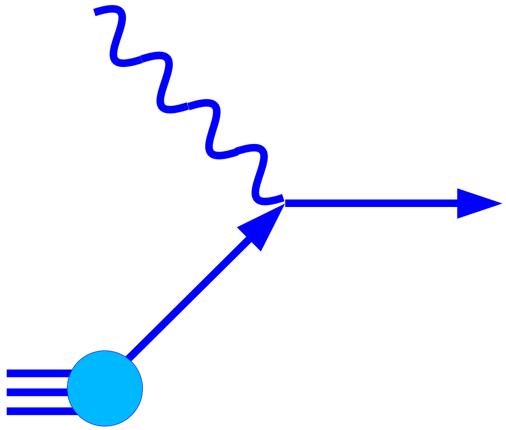
Result: We can describe the full kinematic range from low to high

this is the essence of the ACOT renormalization scheme

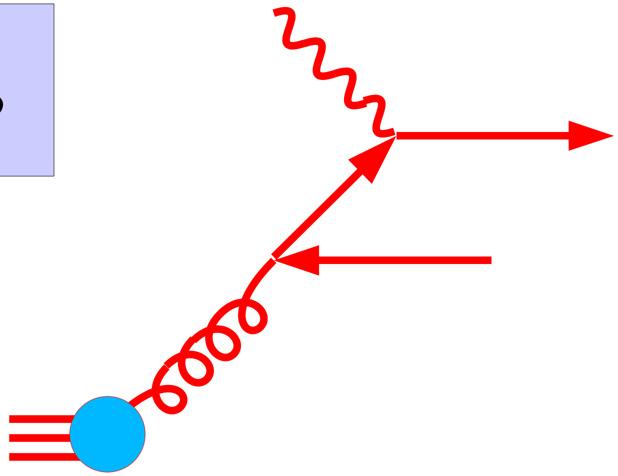
ACOT, PRD 50, 3102

How do calculate with heavy quarks PDFs





Which is the correct production mechanism?



Heavy Excitation (HE)

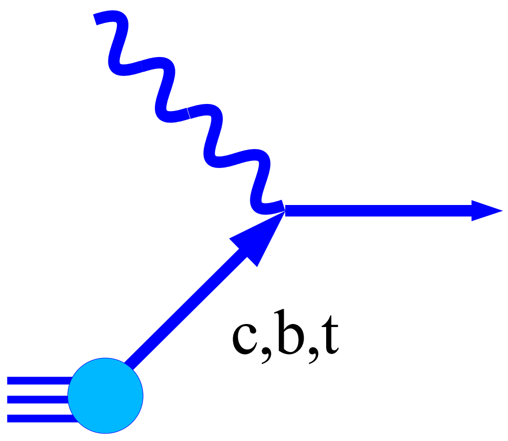
Quark	Channel
s	YES
t	NO
c	???
b	???

Heavy Creation (HC)

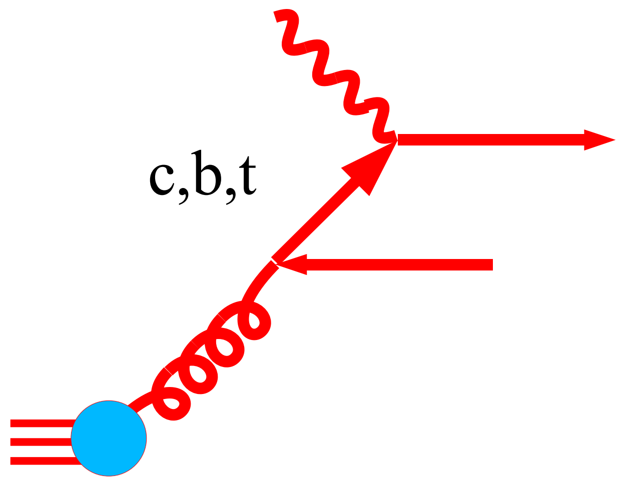
Quark	Channel
s	YES
t	NO
c	???
b	???

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

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

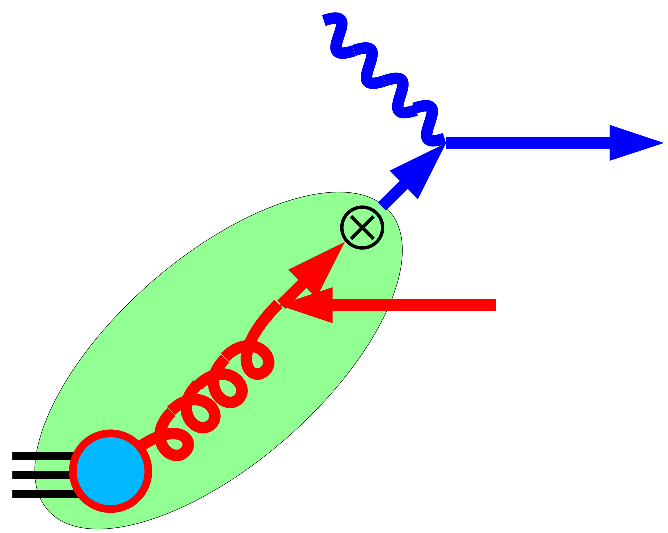


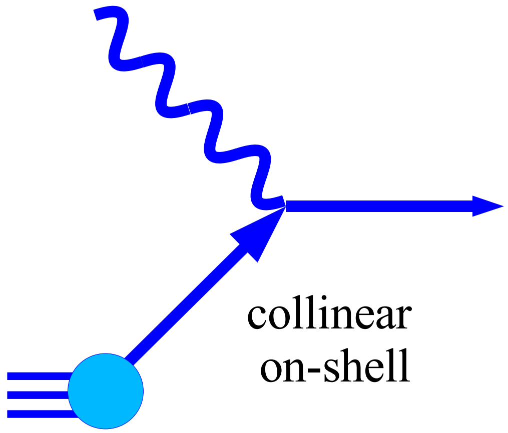
Heavy Excitation (HE)



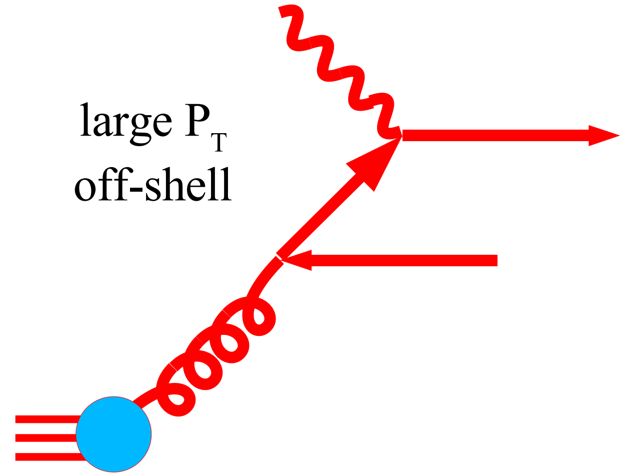
Heavy Creation (HC)

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



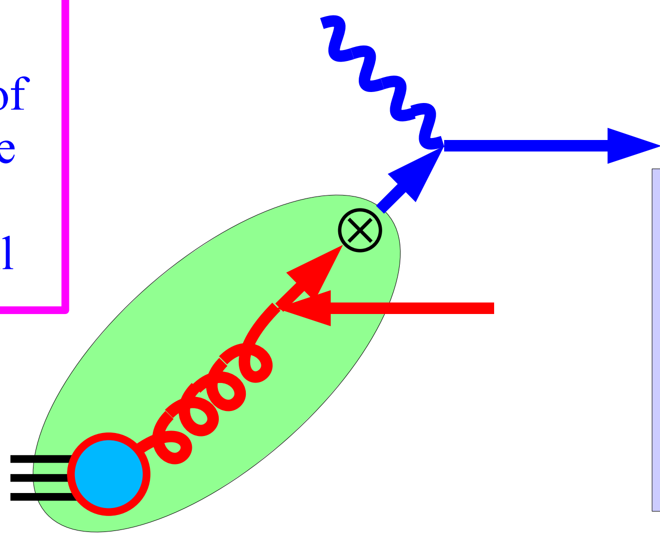


Heavy Excitation (HE)



Heavy Creation (HC)

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

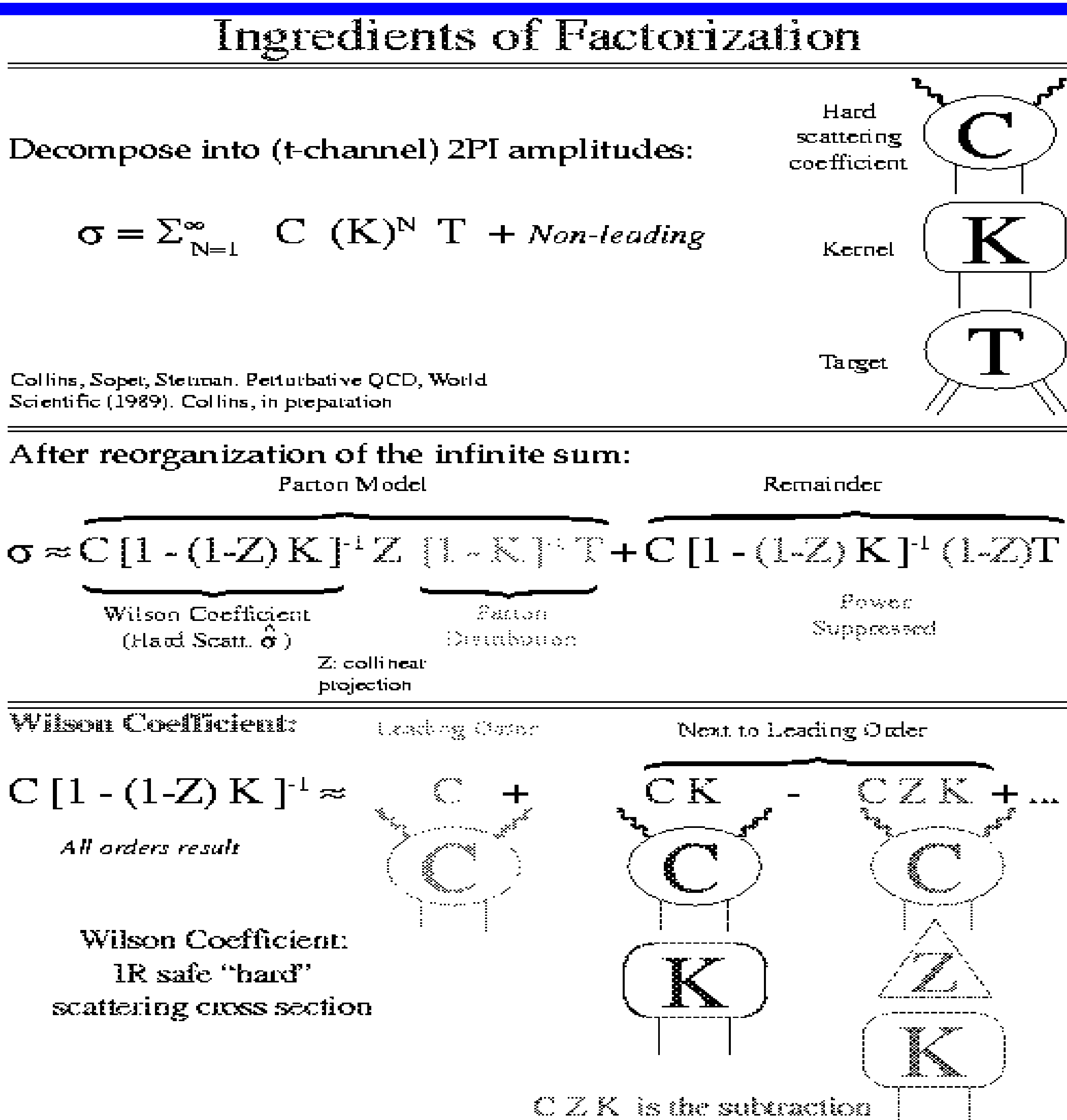


Subtraction (SUB)

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

How do we actually derive???

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

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

Note: not m^2/Q^2

At Zeroth Order:

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

f^0 f^1

for parton target

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

Therefore:

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

$$\sigma^0 = \omega^0$$

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

Basic Factorization Formula

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

At First Order:

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

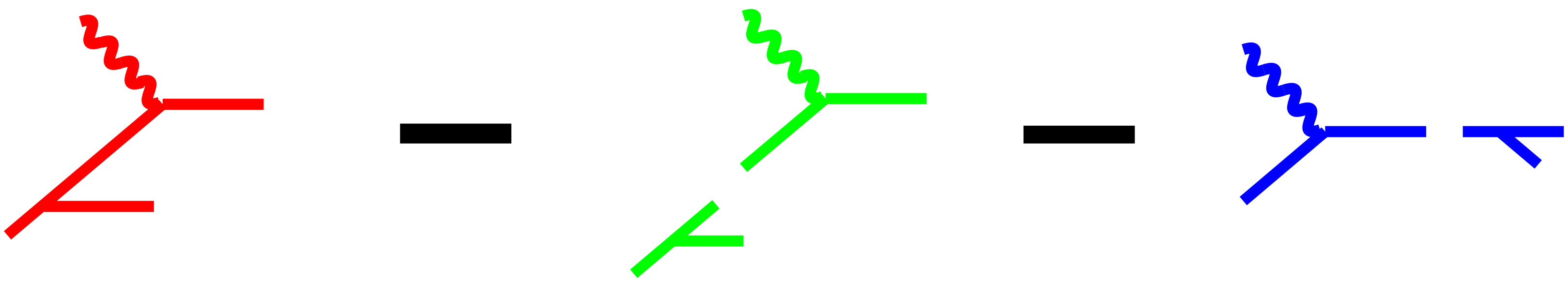
$$\sigma^1 = \quad f^1 \otimes \sigma^0 + \omega^1 + \sigma^0 \otimes d^1$$

f^0 f^1

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

Therefore:

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

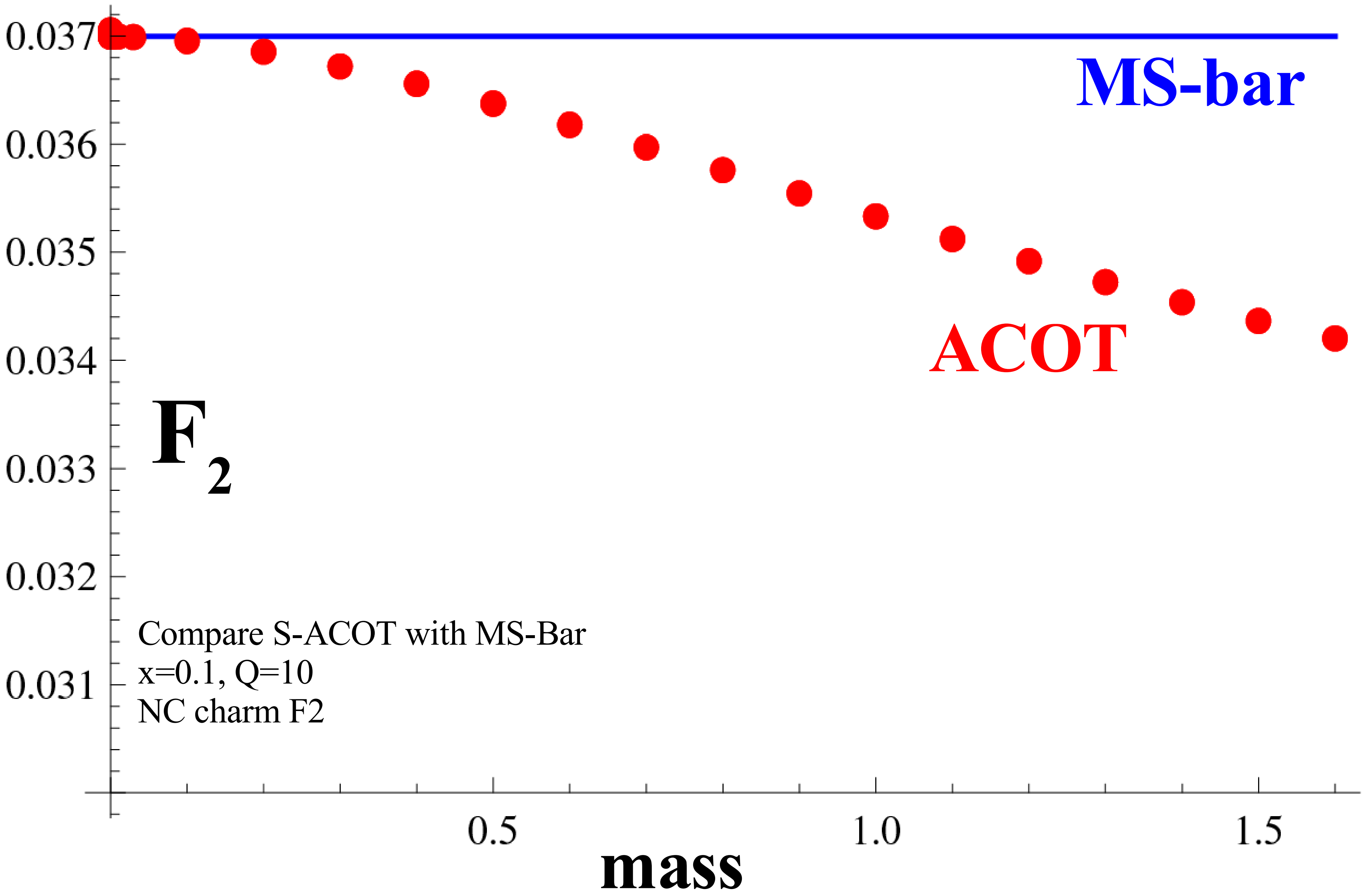


σ^1 $f^1 \otimes \sigma^0$ $\sigma^0 \otimes d^1$

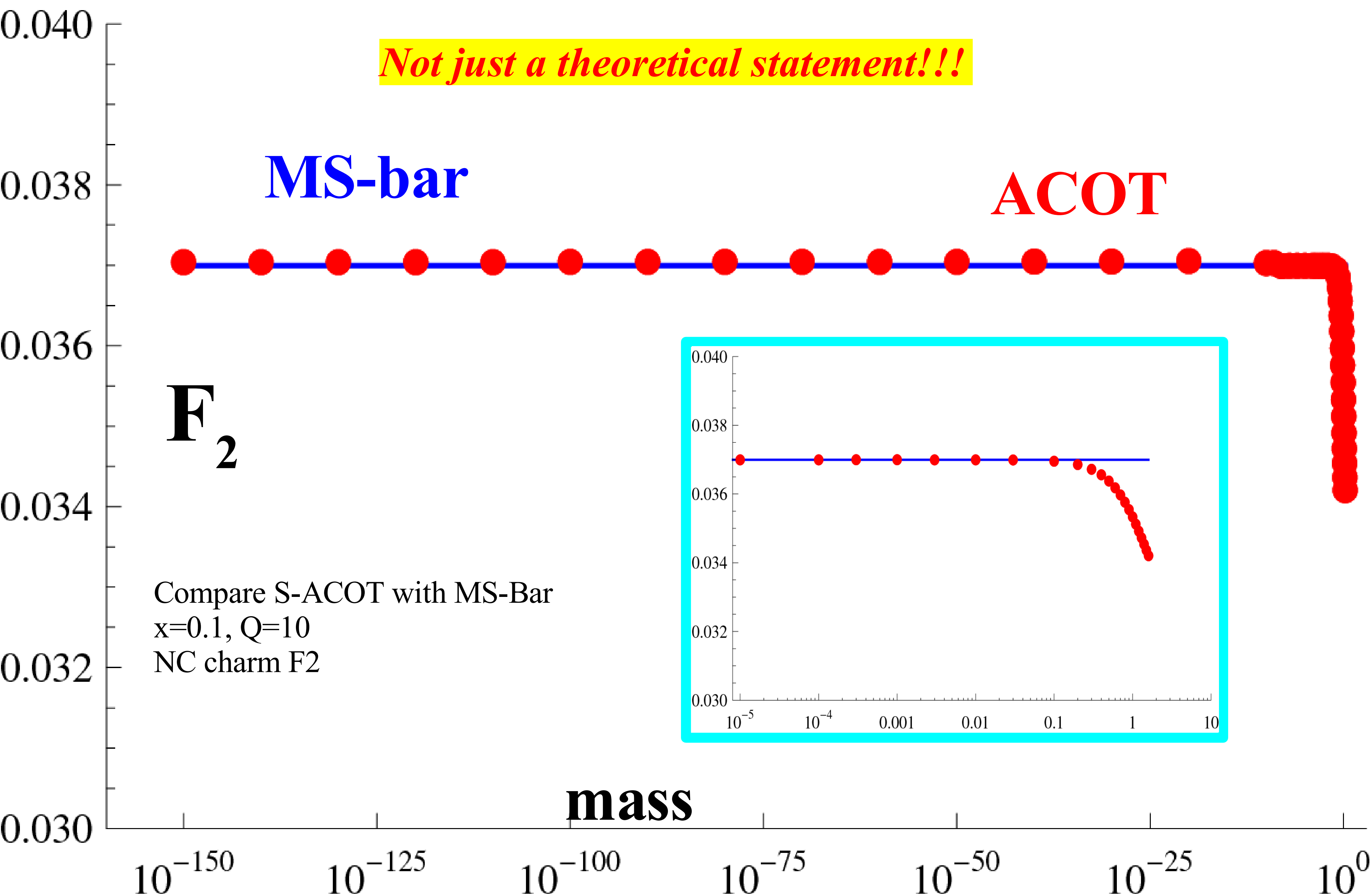
ACOT
m$\rightarrow$ 0 limit
yields MS-Bar

no finite renormalization

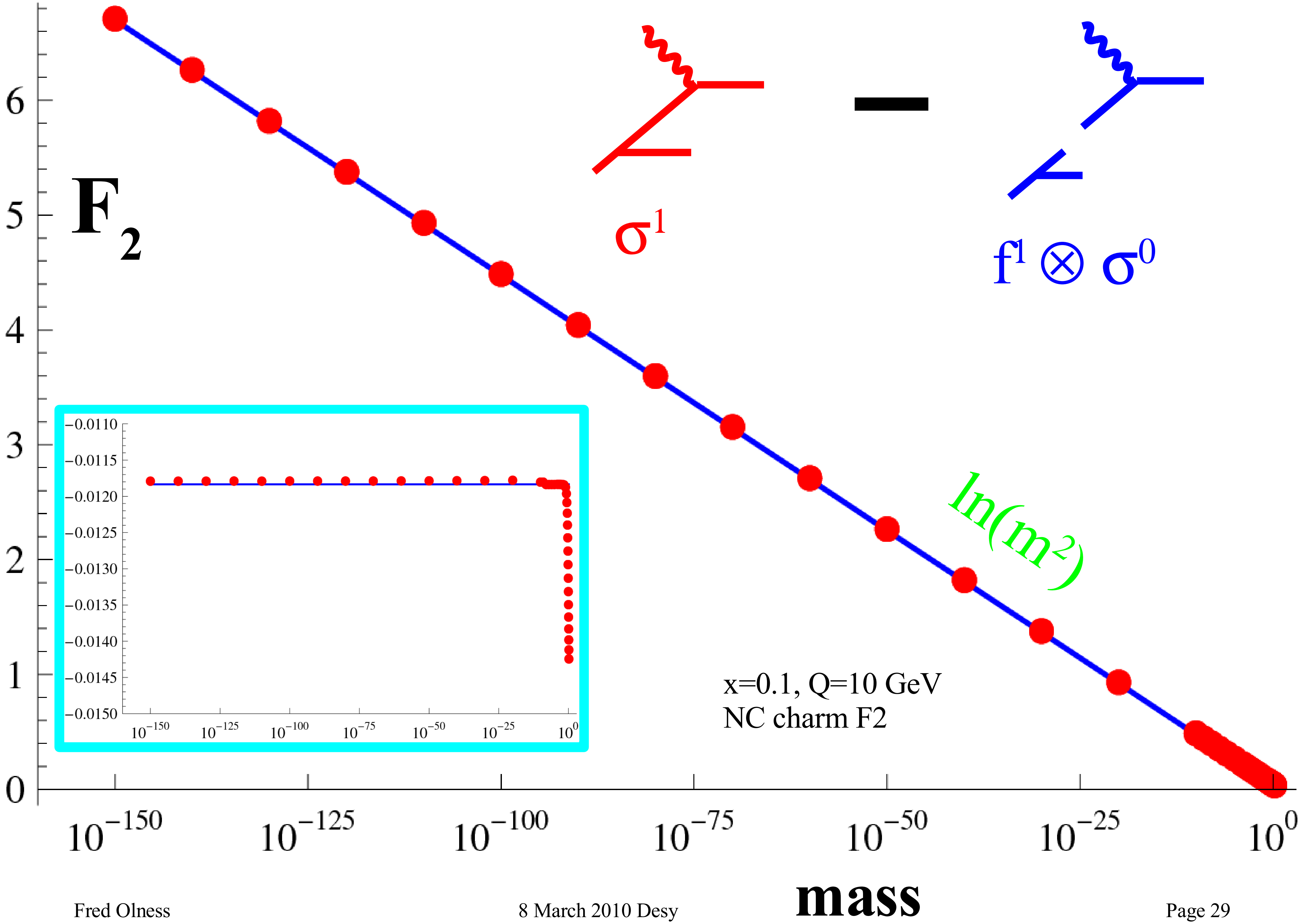
ACOT m→ 0 limit yields MS-Bar: *No finite renormalization*



ACOT m→ 0 limit yields MS-Bar: *No finite renormalization*



ACOT m→ 0 limit yields MS-Bar: *No finite renormalization*

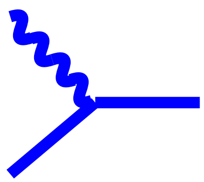


Combined Result:

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

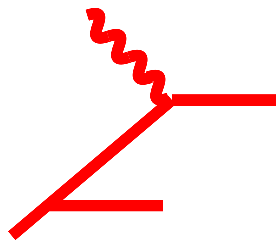
TOT

HE



Heavy Excitation

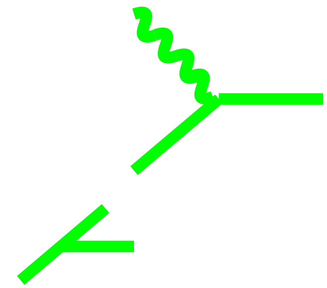
HC



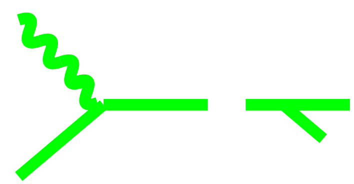
Heavy Excitation

SUB

Subtraction



$f^1 \otimes \sigma^0$

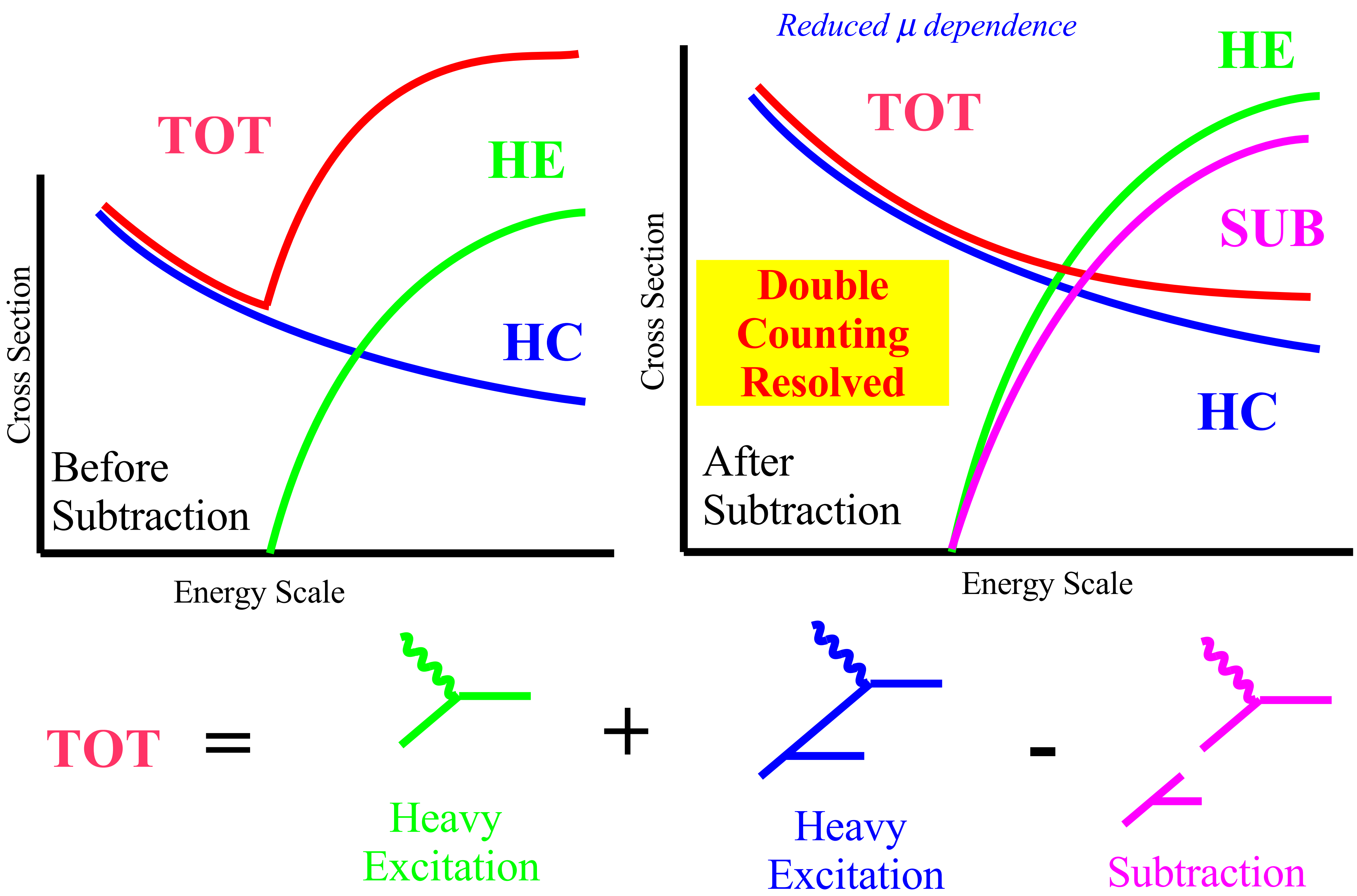


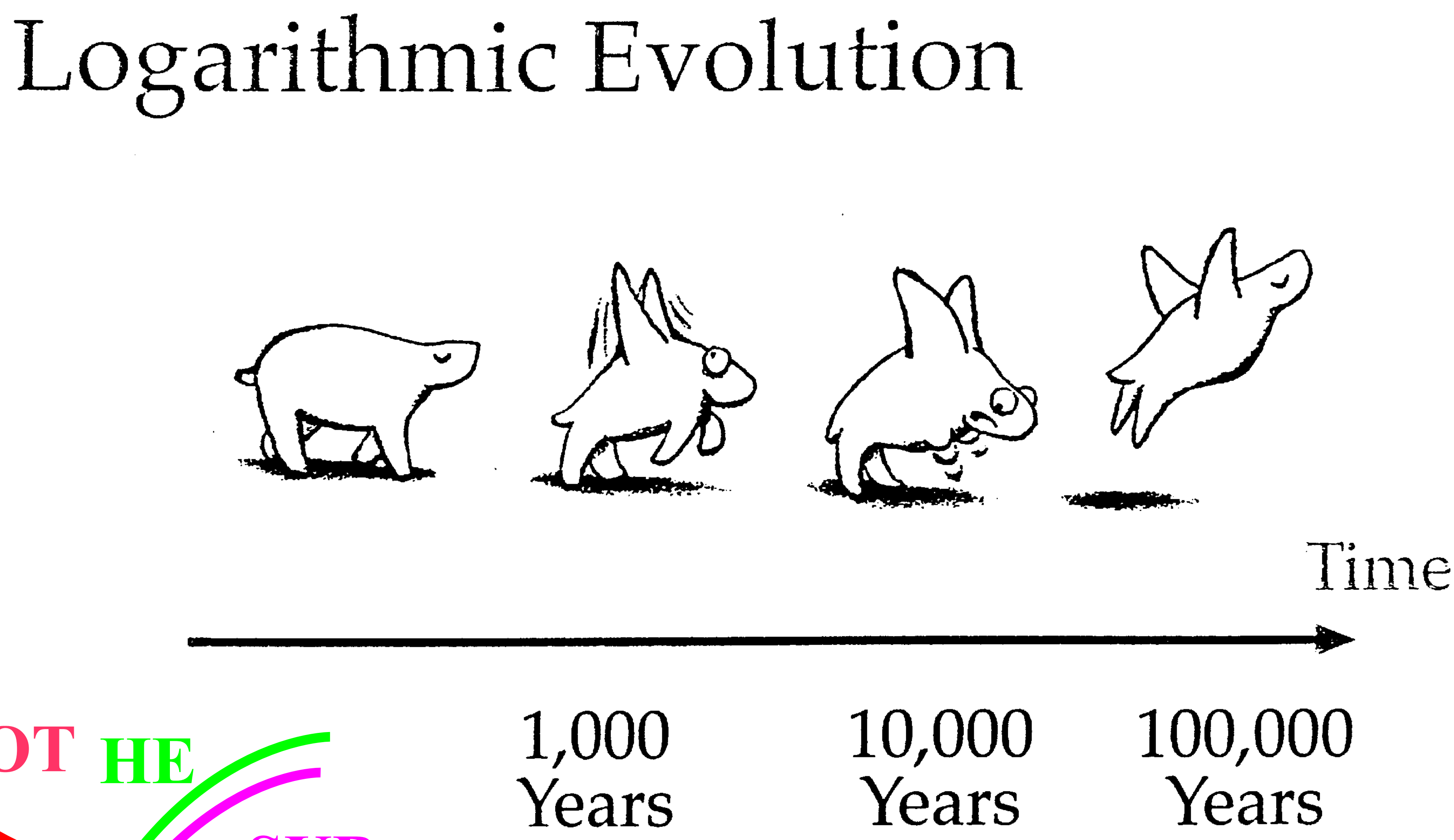
$\sigma^0 \otimes d^1$

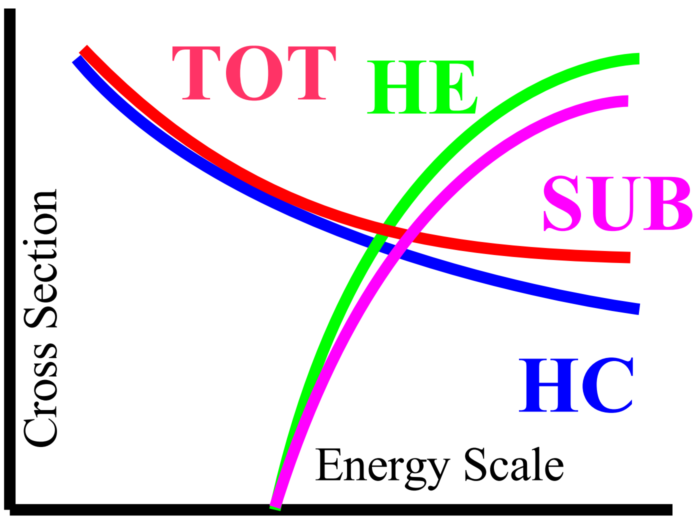
TOT = HE + HC – SUB

Double Counting Resolved

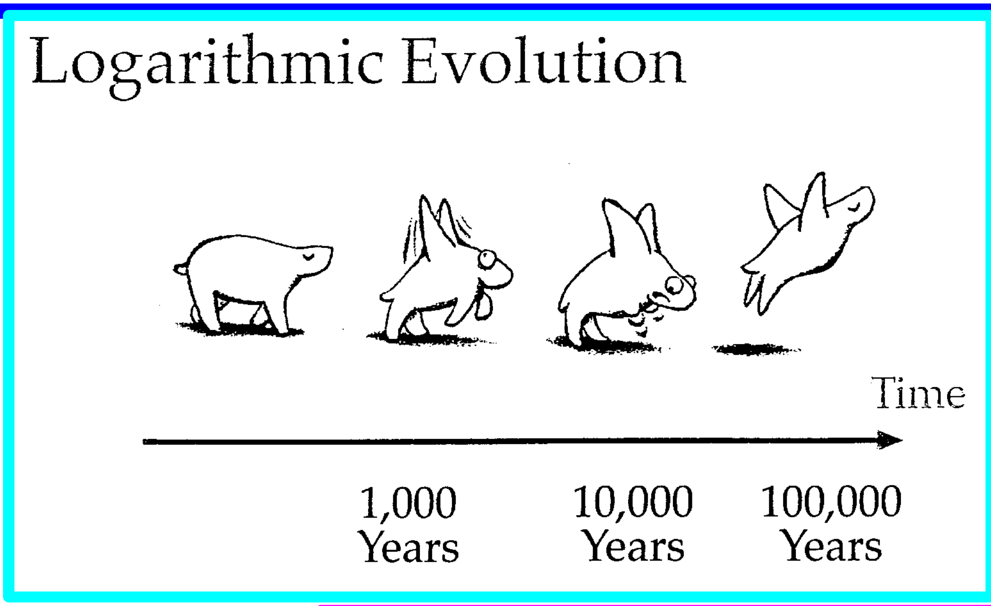
Interaction of the separate contributions vs. energy scale



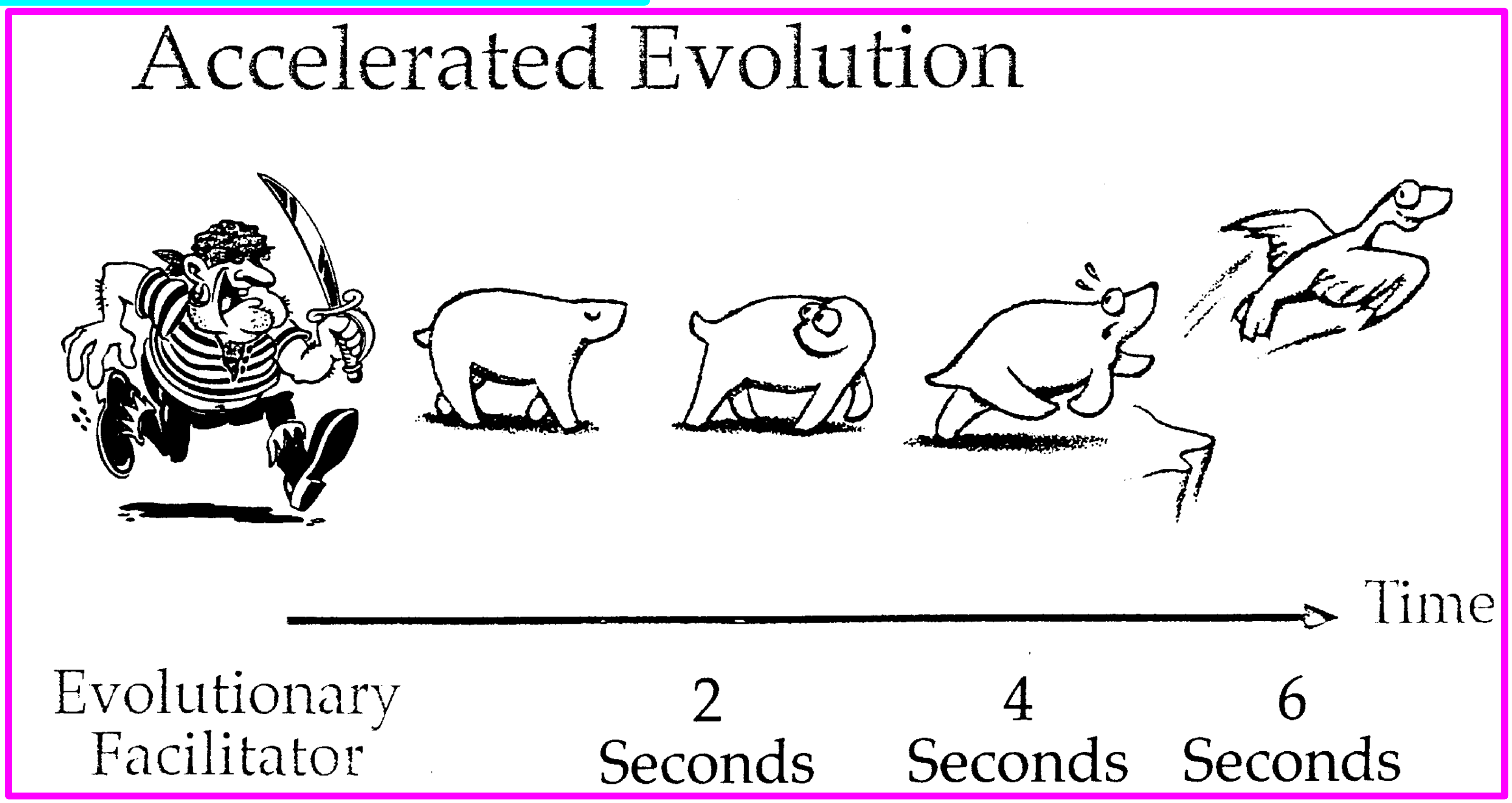

Logarithmic Evolution
Time
1,000 Years
10,000 Years
100,000 Years


TOT
HE
SUB
HC
Cross Section
Energy Scale

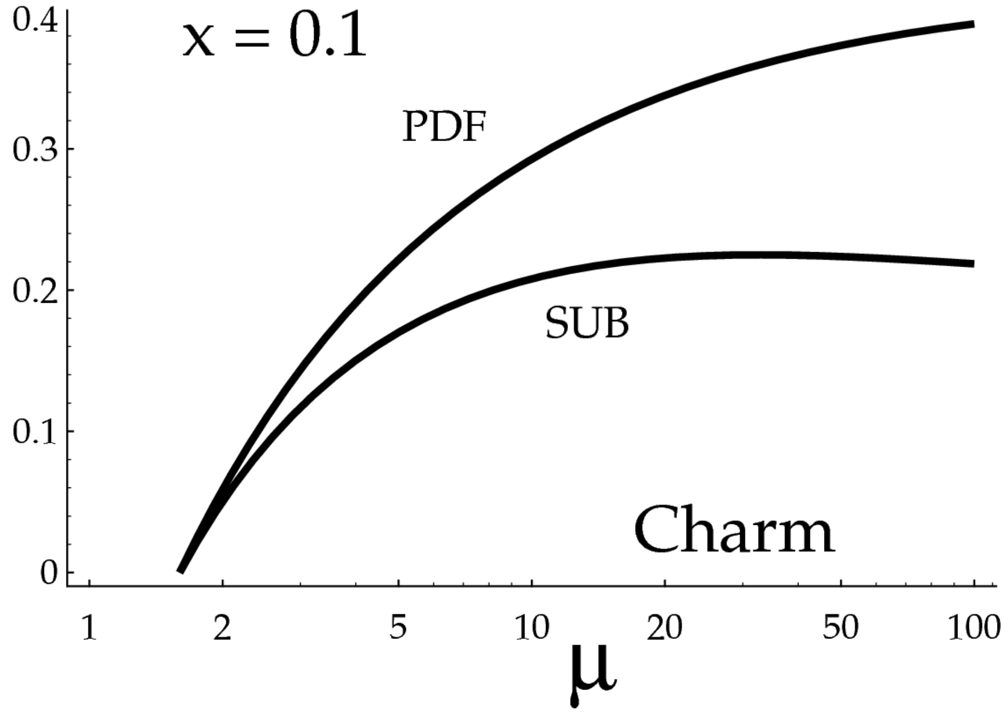
Why does $f_b(x,\mu)$ increase so quickly???

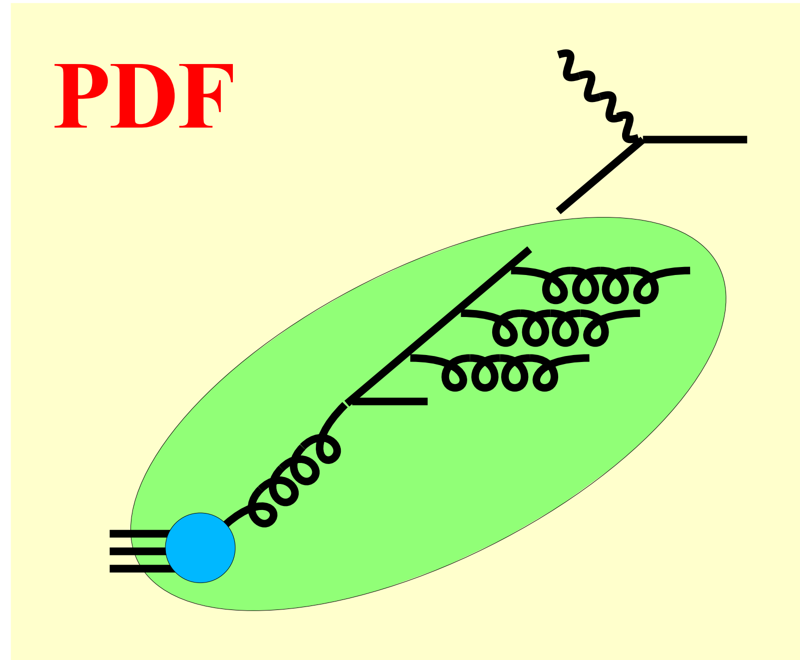


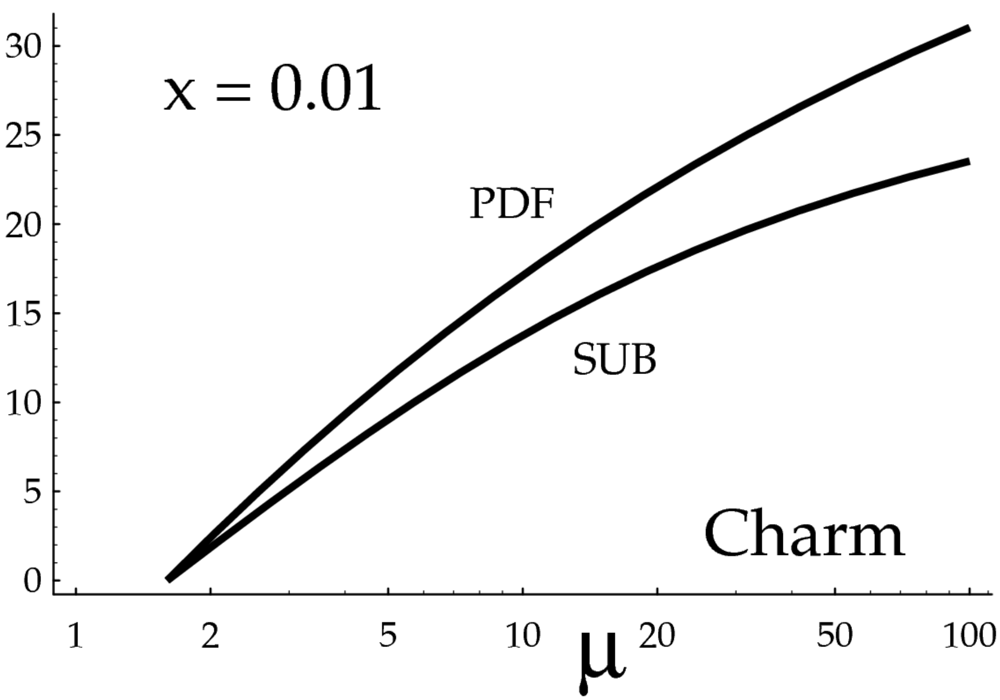
On occasion,
certain factors can accelerate
evolution

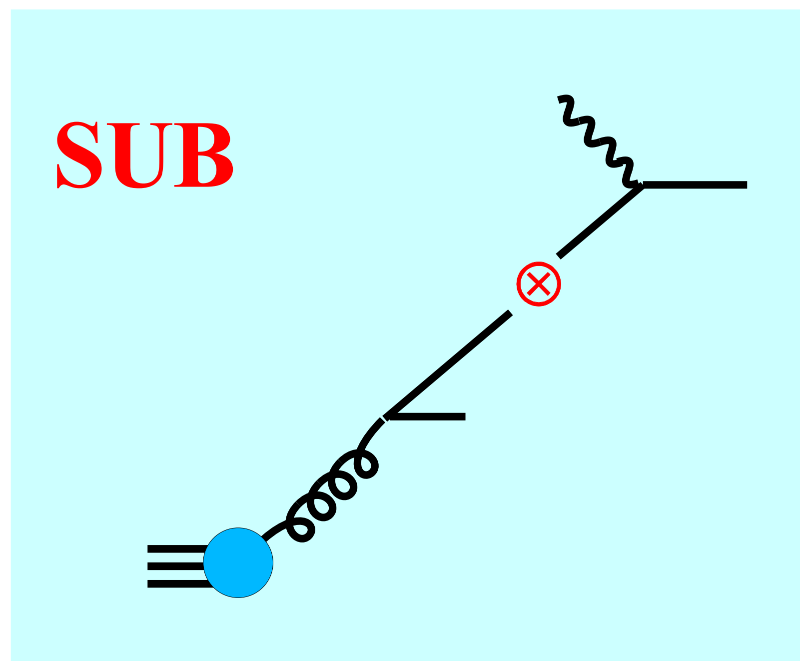


When do we need to consider heavy quark PDF evolution ???









An Example: How the separate pieces can conspire

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

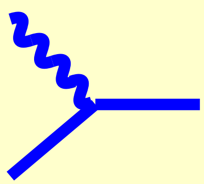
For $x_0=0$: $f(\varepsilon) = 0 + (\varepsilon - 0) + \ldots = \varepsilon$

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

TOT

HE

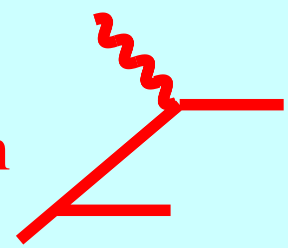
Heavy Excitation



σ^0

HC

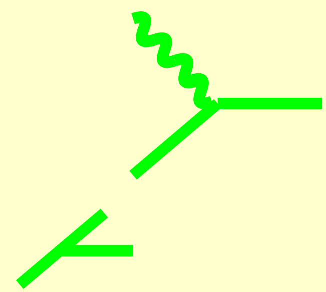
Heavy Excitation



σ^1

SUB

Subtraction



$f^1 \otimes \sigma^0$

TOT = HE + HC – SUB

The Moral

You don't have to choose which expansion point you use; by using the Heavy Quark PDF, QCD will compensate

In practice ...

Using the heavy quark PDF's we can accommodate quark masses of any values: e.g., 10^{-150} to 10^{+150}

Use the Basic Factorization Formula

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

At Second Order *(NNLO):*

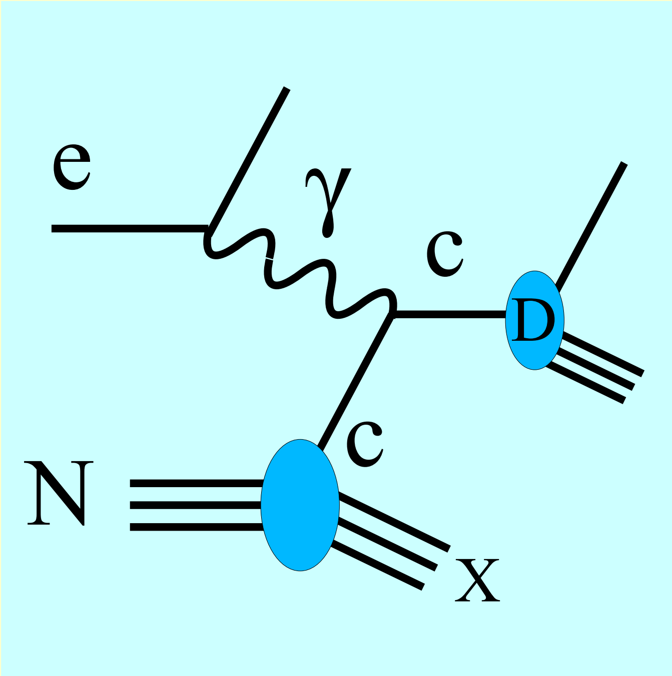
Therefore:

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

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

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

Heavy Quarks



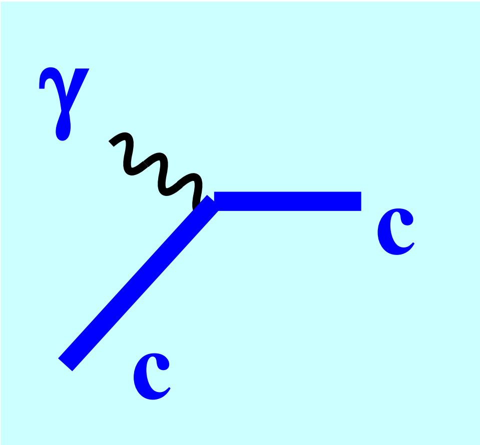
Dynamics & Kinematics

Effect of Kinematic Mass Re-Scaling

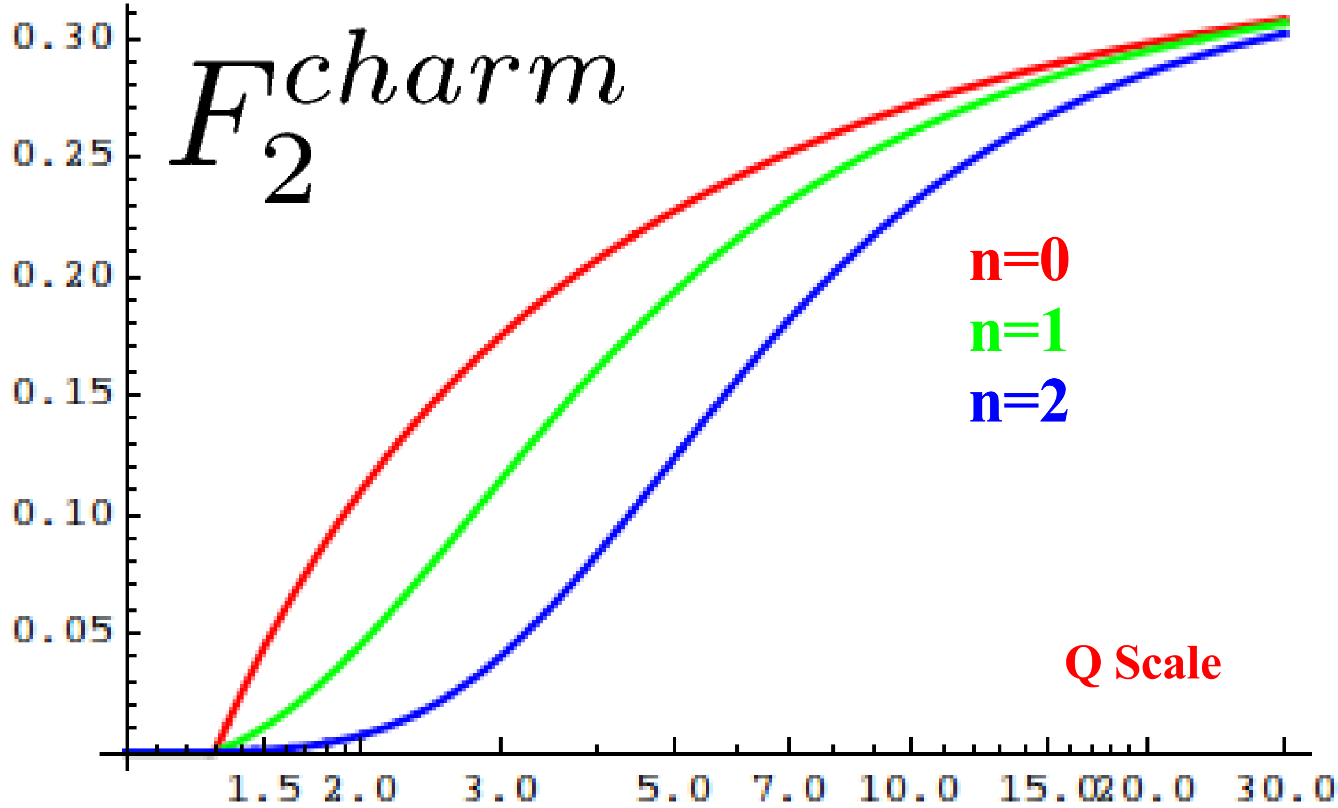
ACOT (Aivazis, Collins, Olness, Tung) A general framework for including the heavy quark components.
Phys.Rev.D50:3102-3118,1994.

S-ACOT (Simplified-ACOT) ACOT with the initial-state heavy quark masses set to zero.
Phys.Rev.D62:096007,2000.

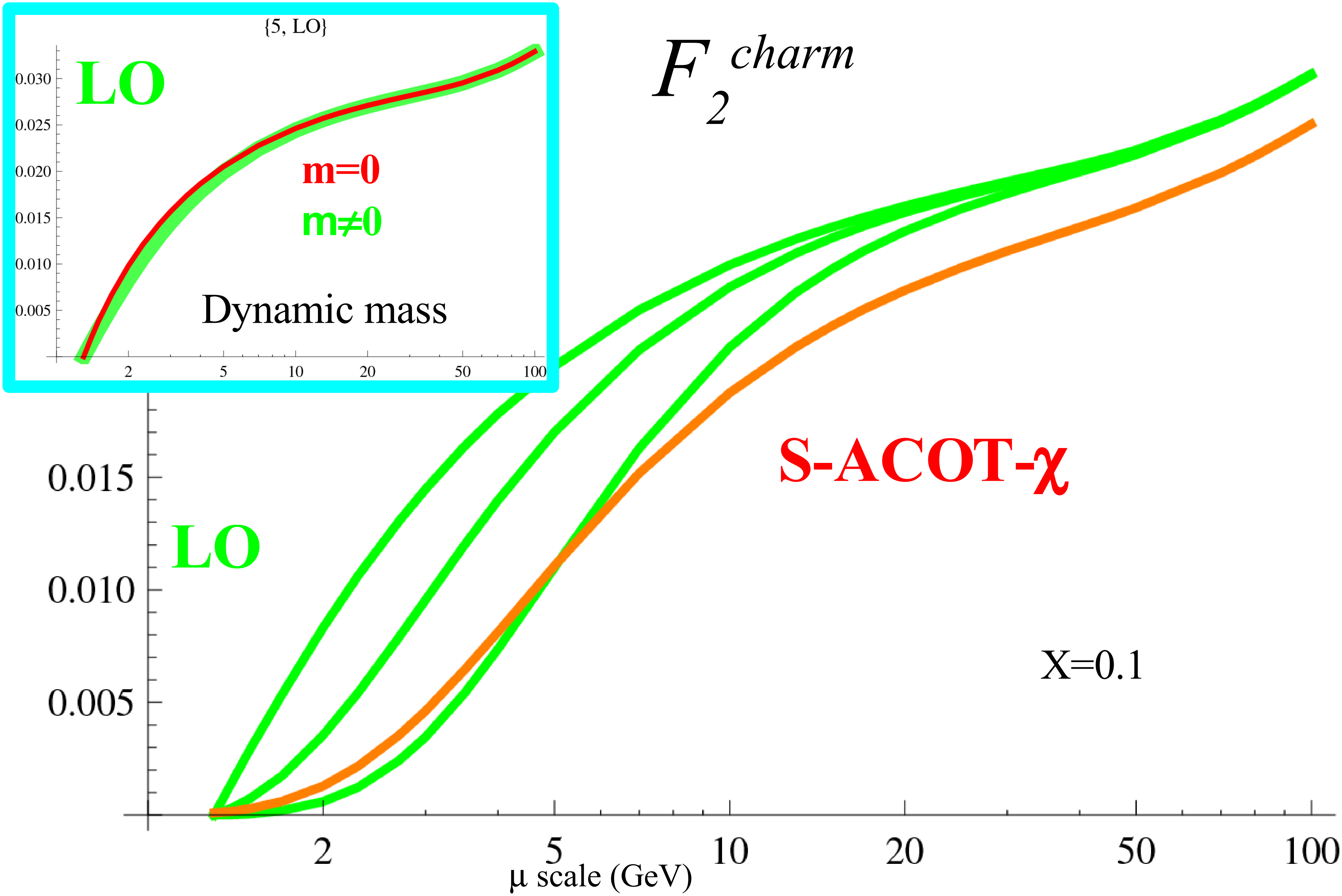
ACOT-χ & **S-ACOT-χ:** As above with a generalized slow-rescaling
Phys.Rev.D62:096007,2000.



$$\chi = x\left[1 + \frac{(\mathbf{n}m_c)^2}{Q^2}\right]$$

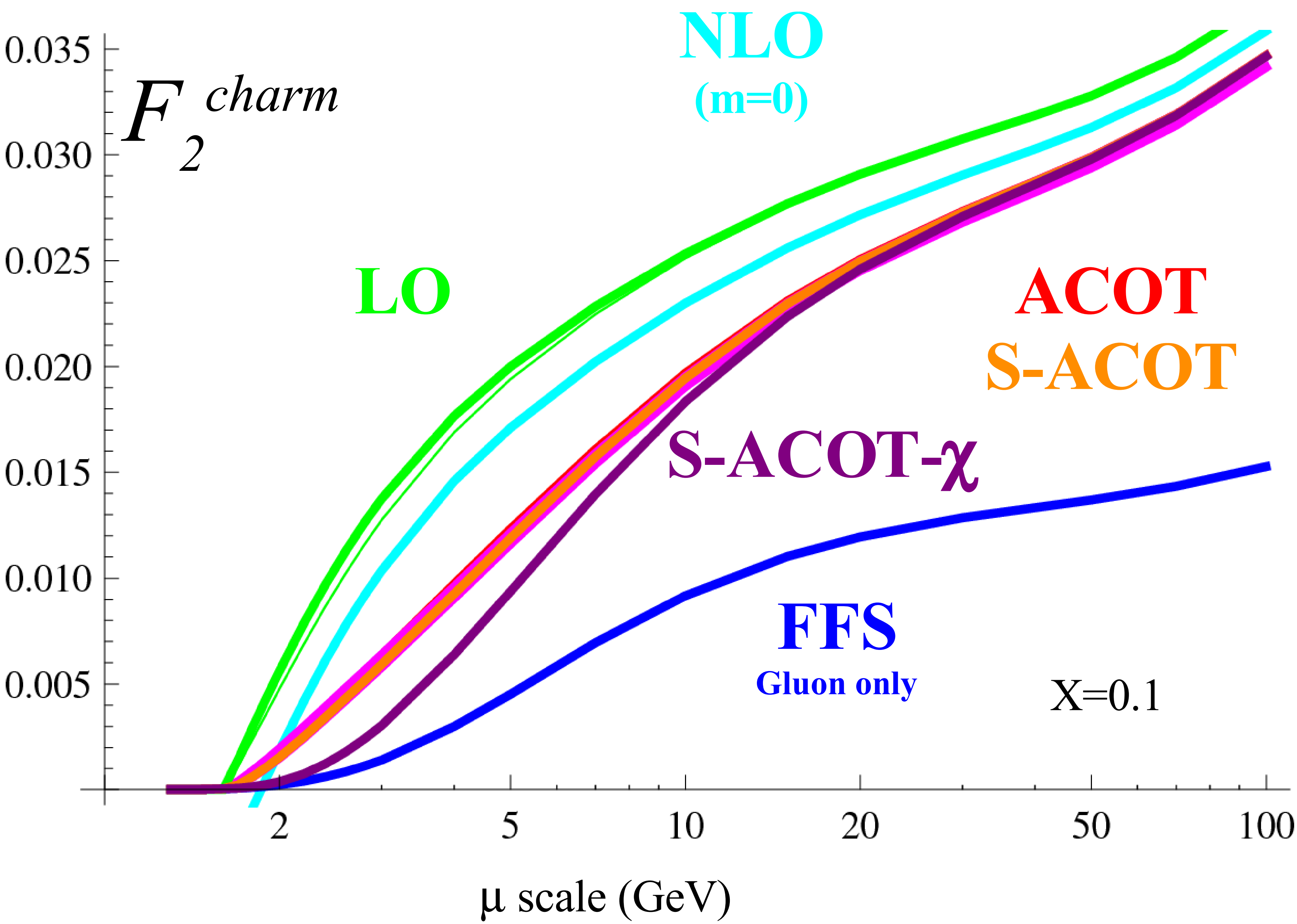


Kinematic Masses are more important than Dynamical Masses ***(in general)***



Kinematic Masses are more important than Dynamical Masses ***(in general)***

F_2 Charm in the threshold region



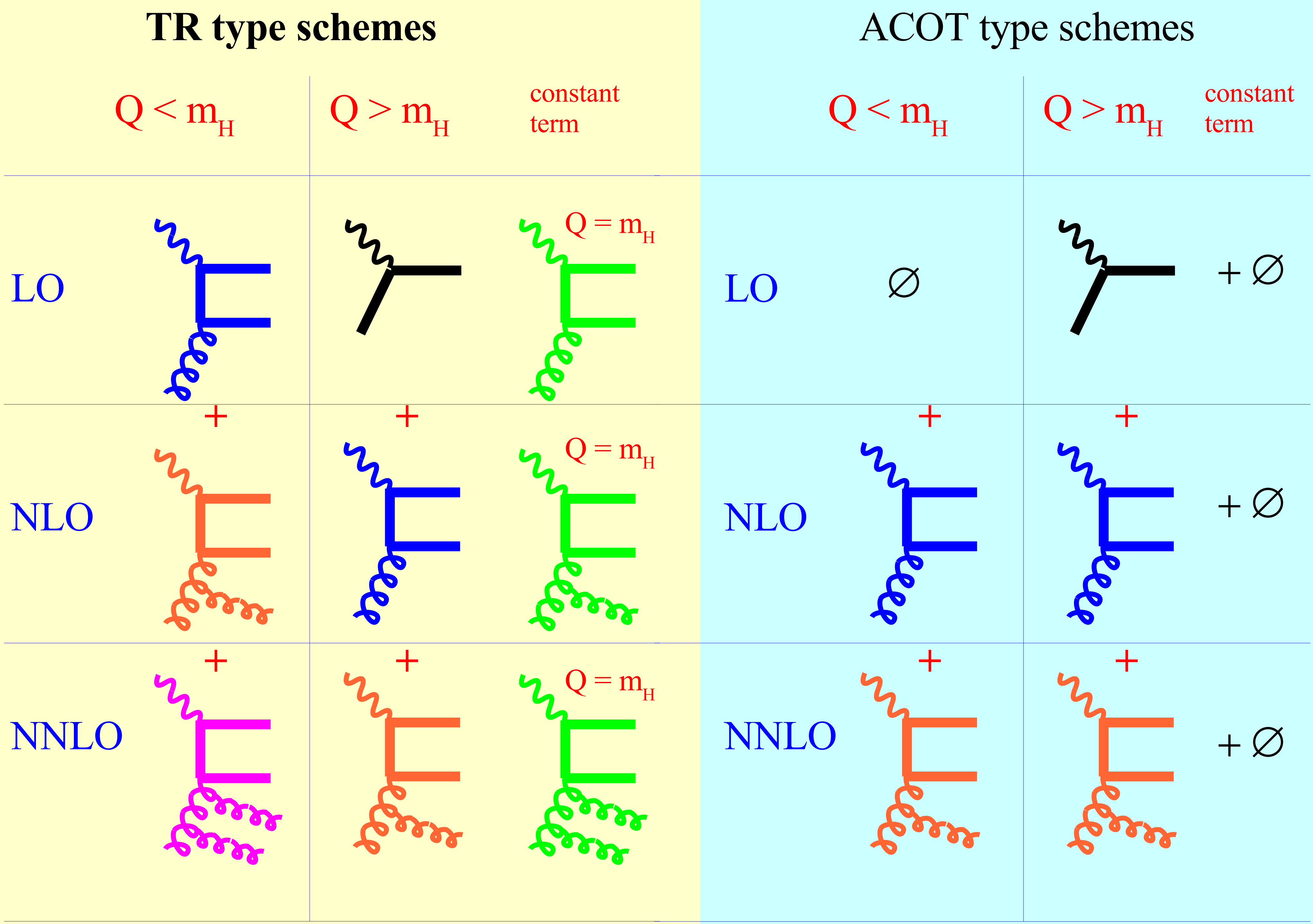
A man with one watch knows what time it is; a man with two is never sure.

Compare Schemes

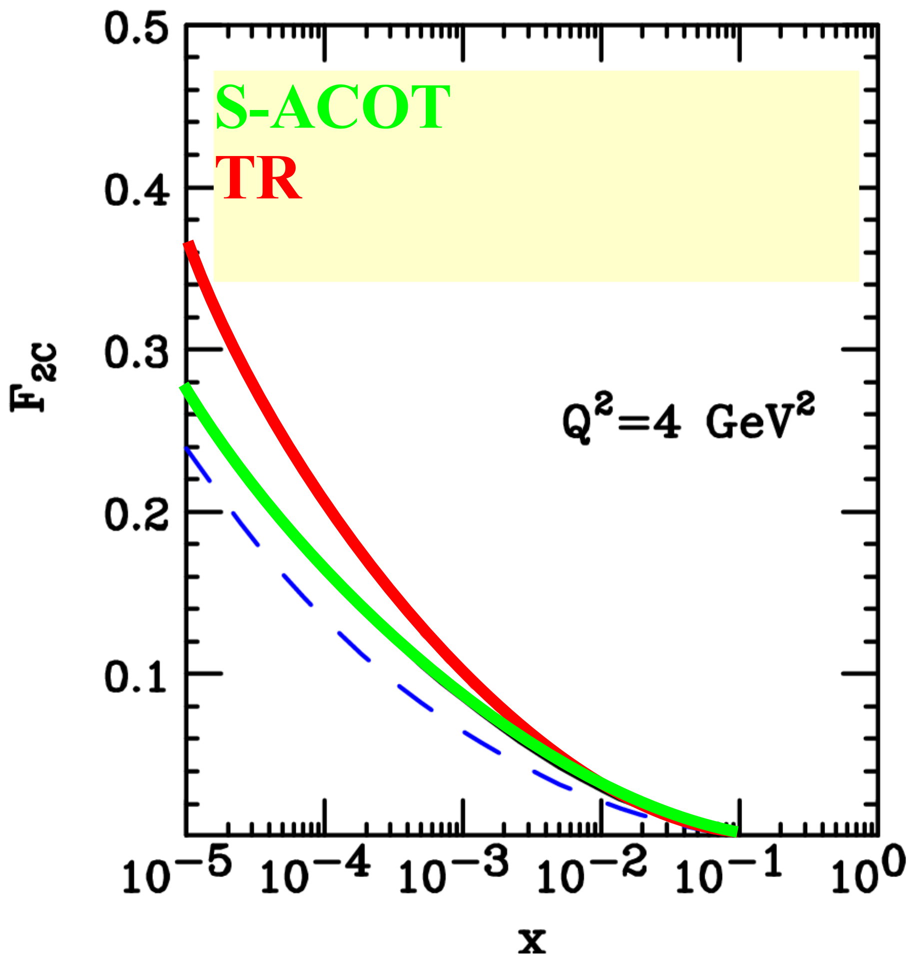
ACOT, TR, FONLL

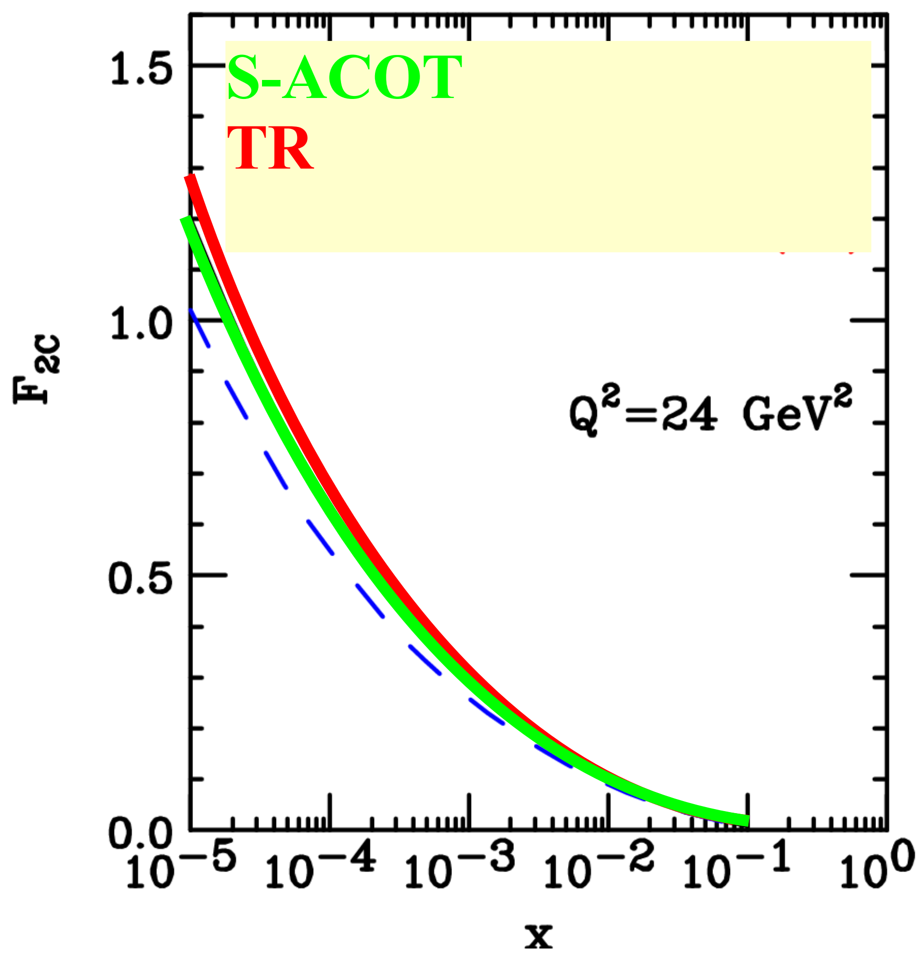
(NNPDF)

Schematic Summary of ACOT & TR Schemes



Comparison of ACOT & TR Schemes





Les Houches 2009

Comparative Studies

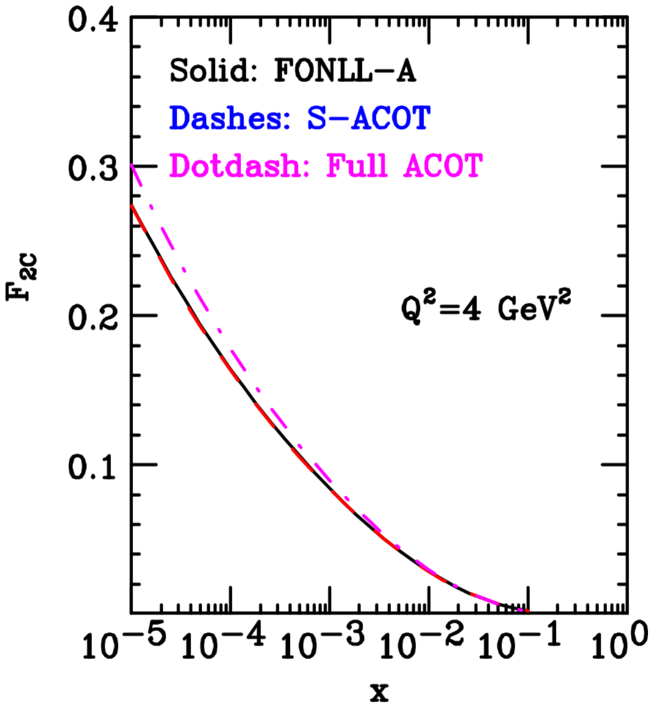
TeV 2009

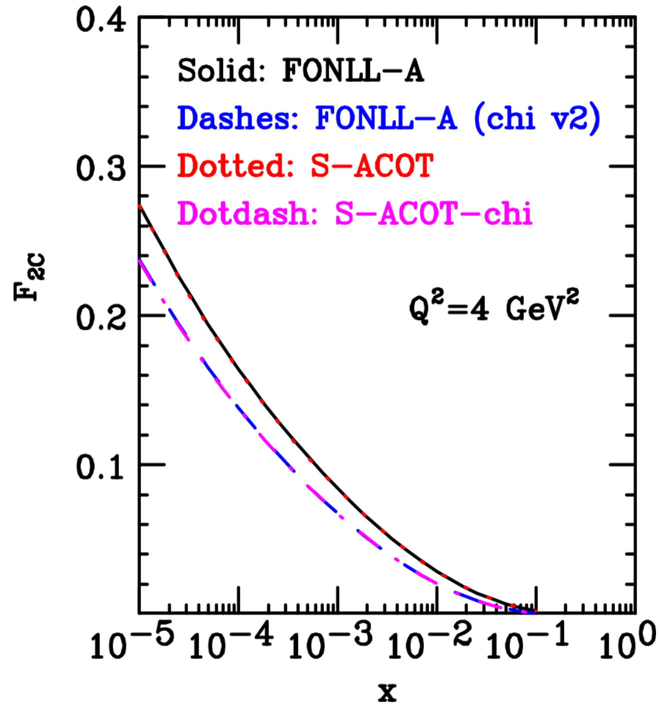
Physics at TeV Colliders

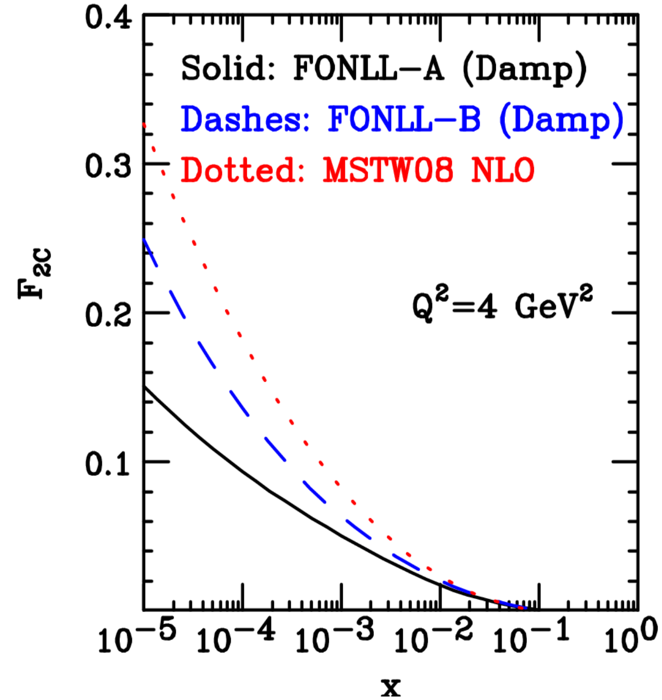
Les Houches 8-26 June 2009

LES HOUCHES

centre de physique







ACOT & S-ACOT essentially identical

... it's all in the kinematics

FONNL & S-ACOT numerically similar

chi(χ) prescription enforces threshold

MSTW09 uses different threshold definition

different scheme different intermediate result

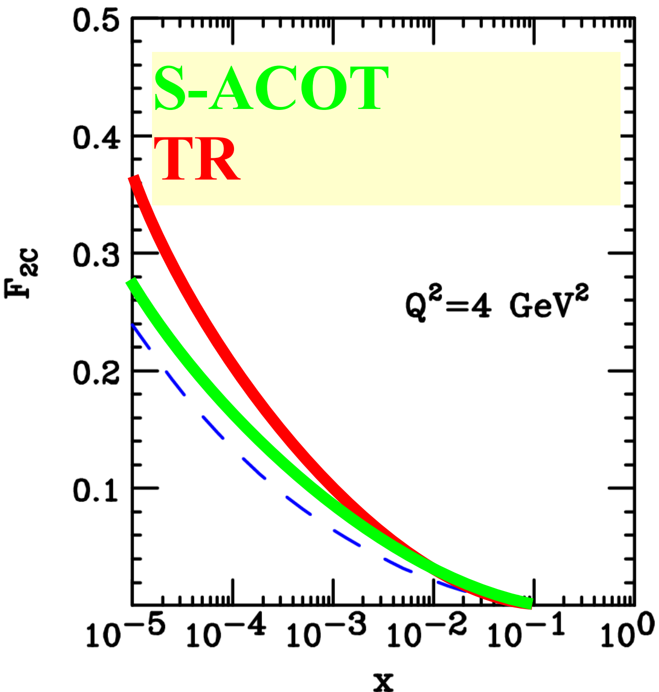
A comment about schemes

Essential to match PDF with (hard) cross section in proper schemes!!!

		Consistent Schemes		Mixed Schemes	
Set	# pts	6HQ	6M	6M⊗GM	6HQ⊗ZM
ZEUS	104	0.91	0.98	2.84	3.72
H1	484	1.02	1.04	1.50	1.22
TOTAL	1925	1.04	1.06	1.26	1.30

χ^2/DOF

$\delta\chi^2 \approx 420$ $\delta\chi^2 \approx 500$



Just because the PDFs or (hard) cross sections do not match, for a consistent scheme, the physical observable should be invariant to $O(\alpha_S^{N+1})$

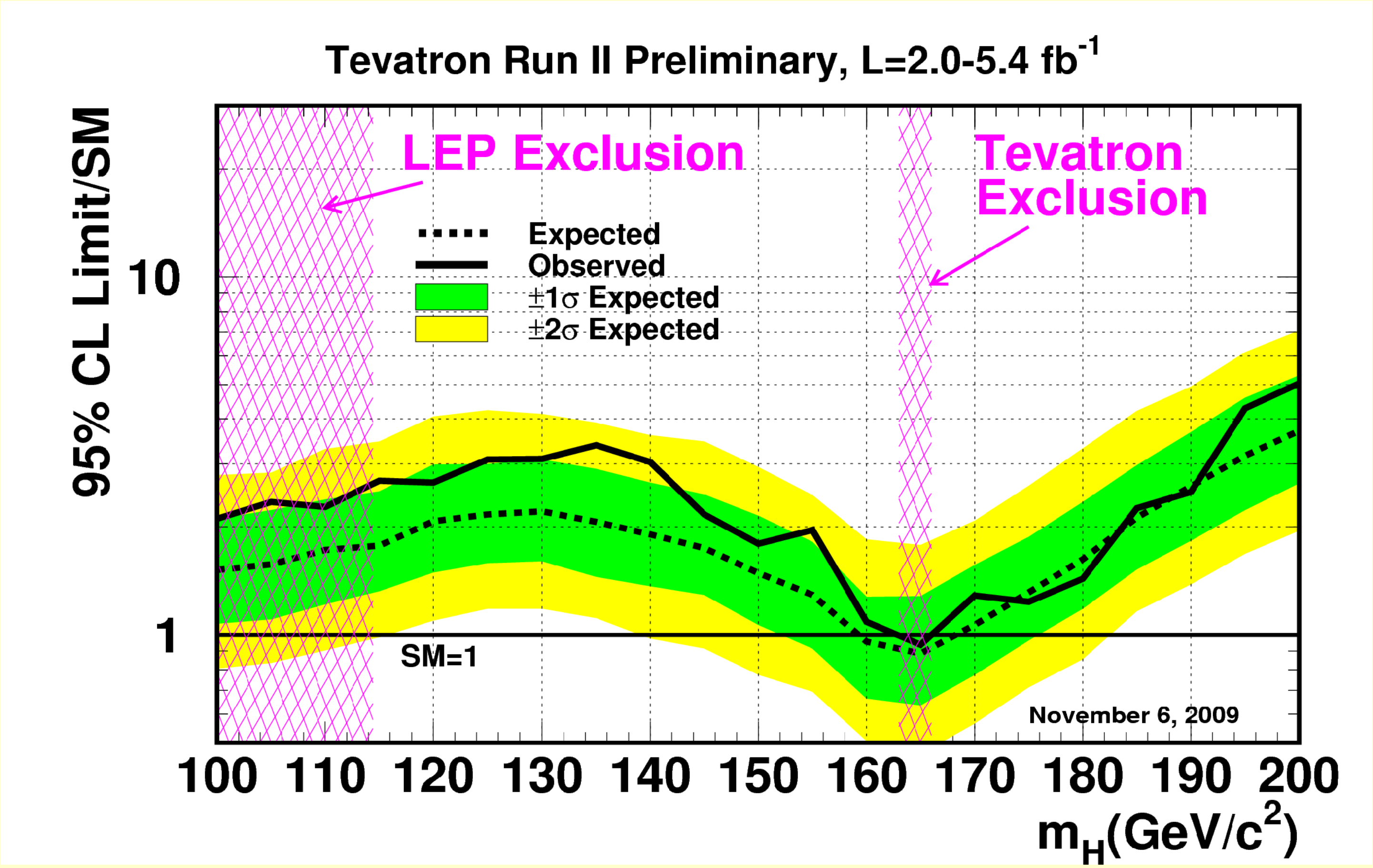
NNLO

A proposal for NNLO PDF implementation

Mass-Independent Evolution.

Why is it valid?

Conclusions



Conclusions

HERA measurements are foundation for PDFs

Any "new physics" must be calibrated against "old physics"

Combination of H1 & Zeus data sets:

Improved measurements of F^2, F^{cc}, F^{bb}, and F_L:

Improved precision for LHC benchmarks

At LHC, heavy flavors play a prominent role: ⇒ *{s,c,b...}*,

... key in W/Z production ⇒ Higgs Discovery

Theoretically, we can now compute full dynamic mass range $[10^{-150}, 10^{+150}]$

ACOT natural massive extension of MS-bar

Mass effects are essential:

Separate roles of dynamic and kinematic masses illustrated

Improvement programs & understanding on theoretical side:

Les Houches benchmark comparisons enlightening

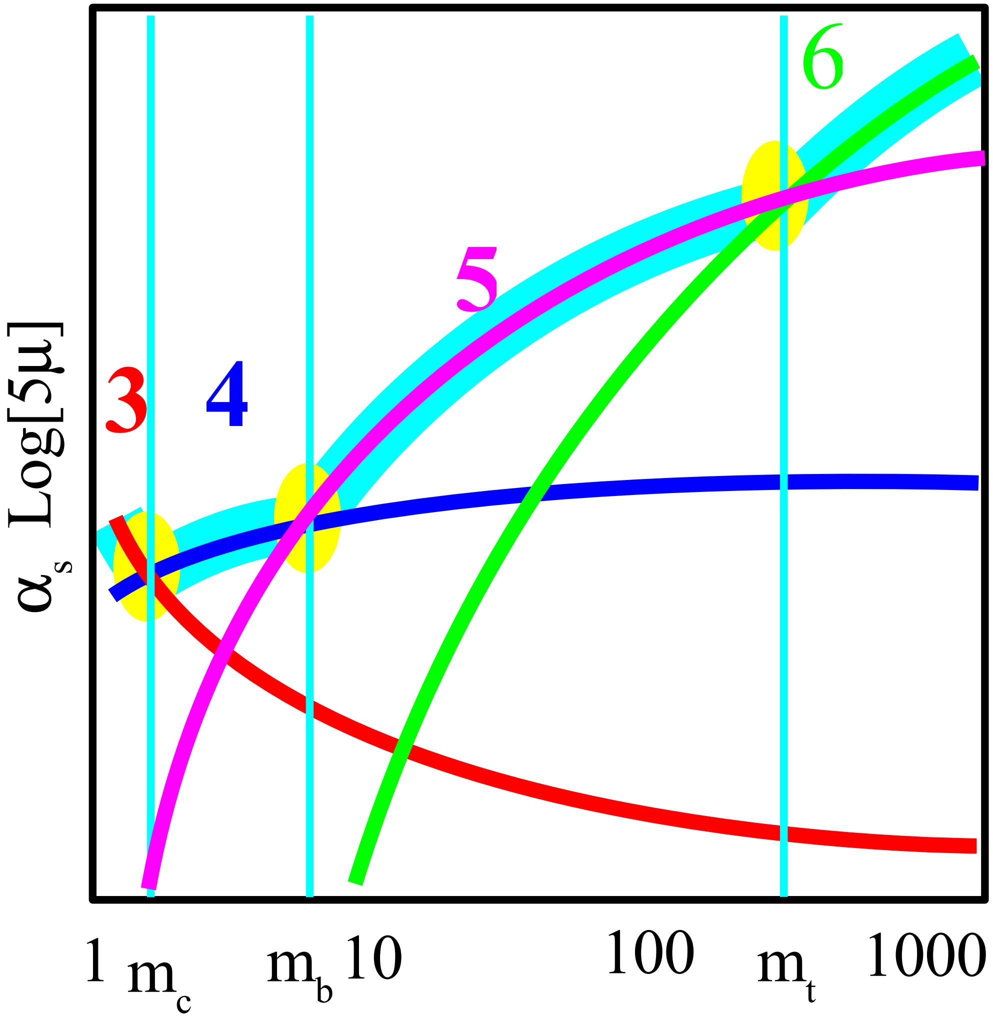
Essential ingredient for LHC discoveries

NNLO

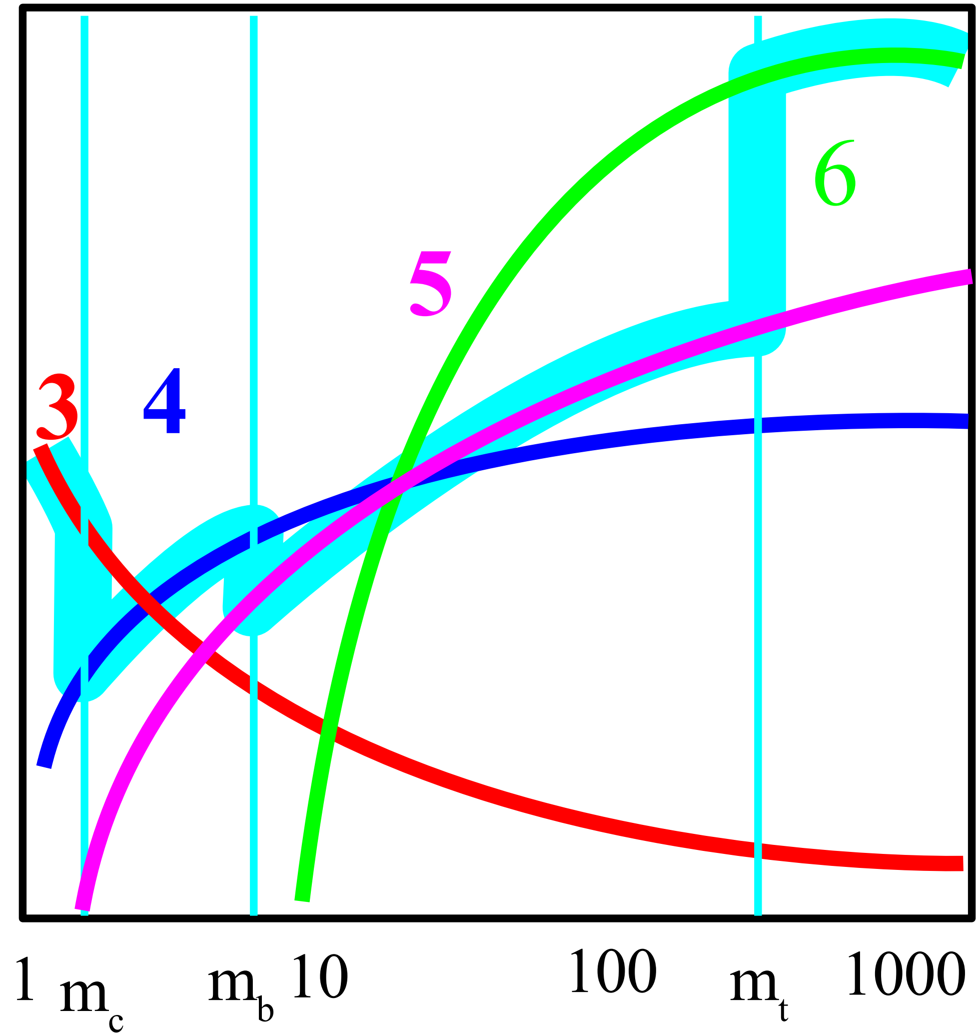
A proposal for NNLO PDF implementation

α_s as a function of μ for various flavor numbers

At 1-loop and 2-loops, continuous at thresholds

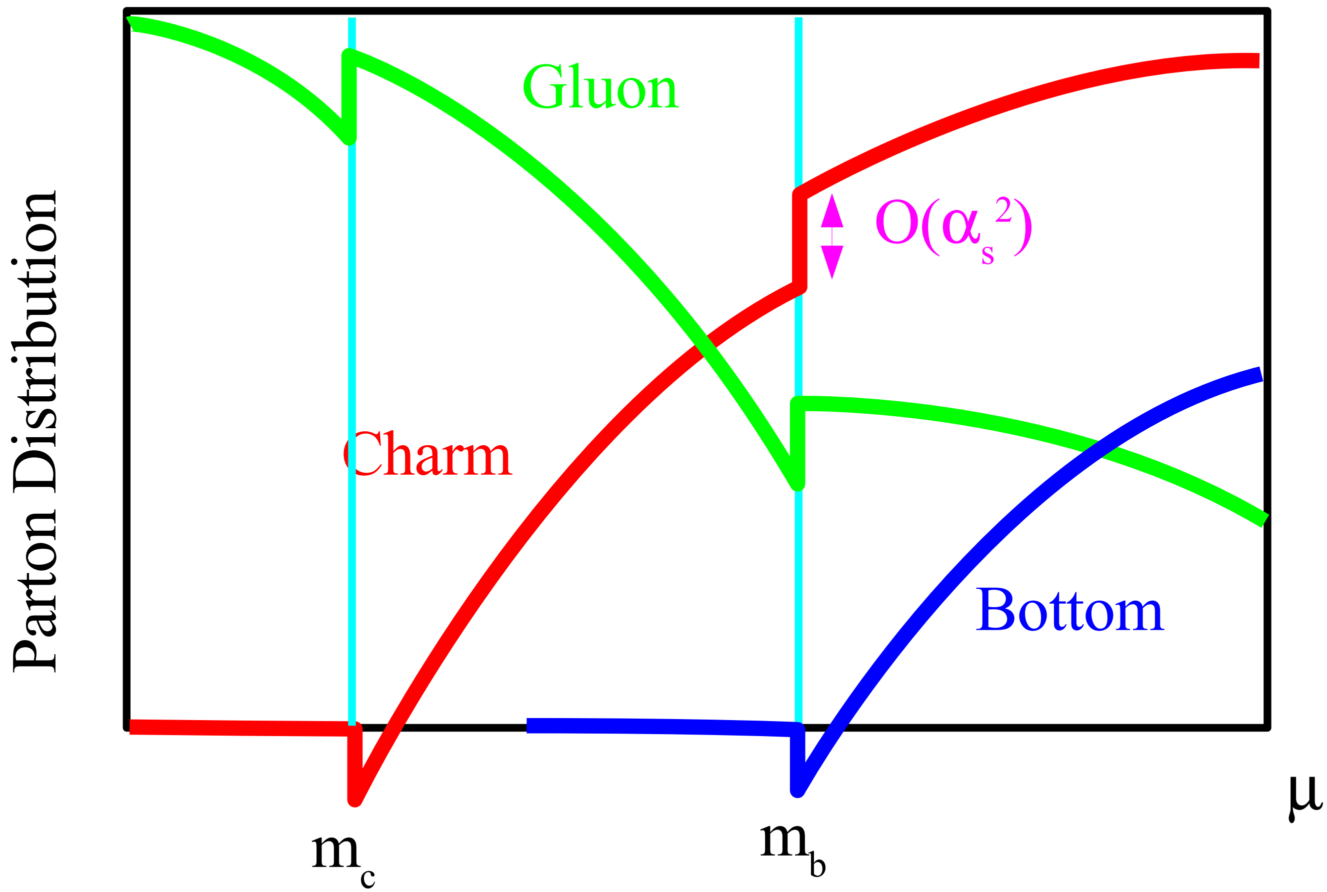


At $O(\alpha_s^3)$, not even continuous at thresholds



$$\alpha_{(n_f)}(M) = \alpha_{(n_f-1)}(M) - \frac{11}{72\pi^2}\,\alpha^3_{(n_f-1)}(M) + \mathcal{O}(\alpha^4_{(n_f-1)})$$

f(x,μ) as a function of μ for various flavor numbers



Not continuous at $O(\alpha_s^2)$

$$f_k^{n_f+1}(\mu^2, m_H^2) = A_{kj}(\mu^2/m_H^2) \otimes f_j^{n_f}(\mu^2),$$

relate N and N+1 PDF's

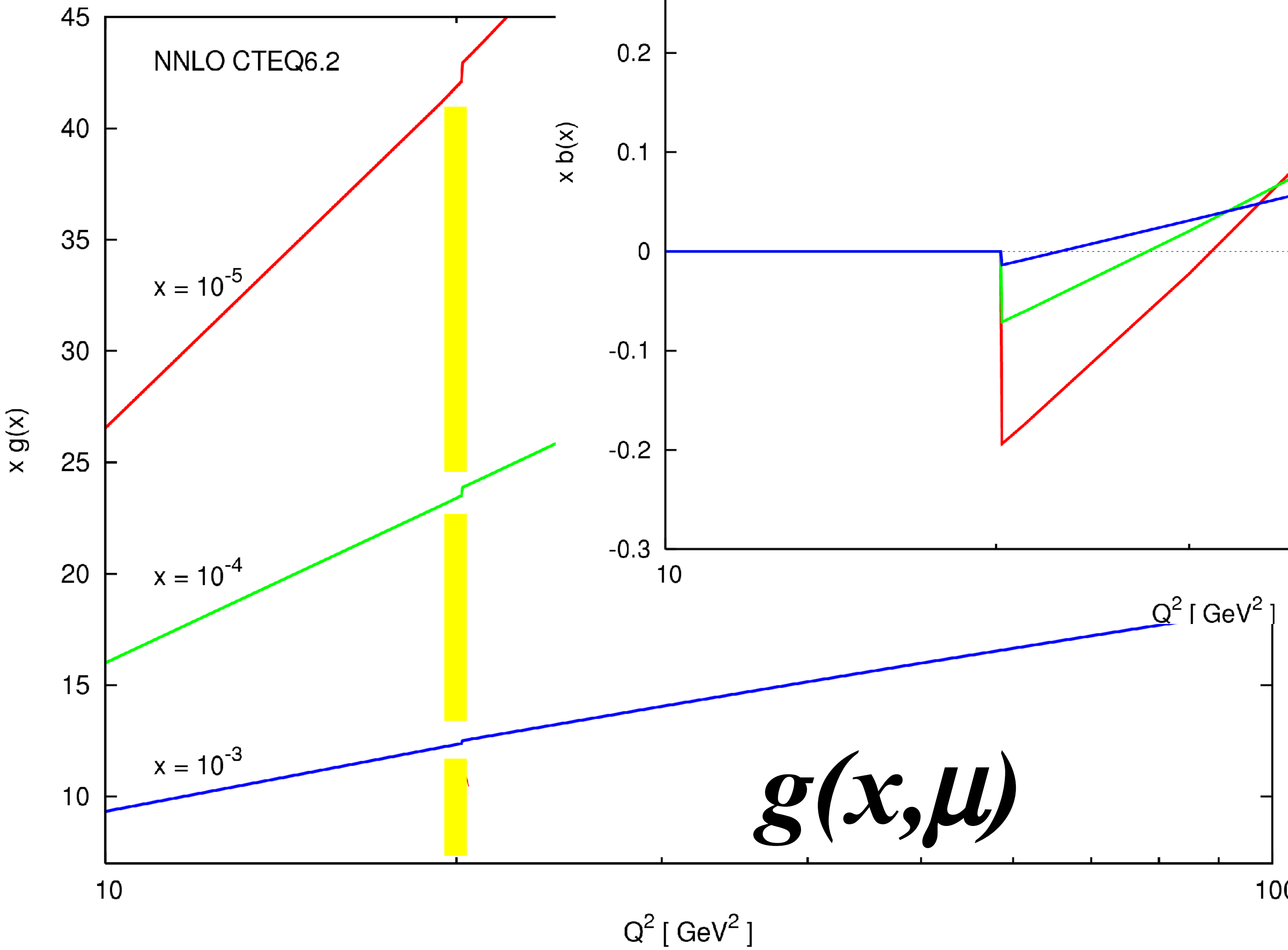
Note:
FFNS ~ N
VFNS ~ N+1

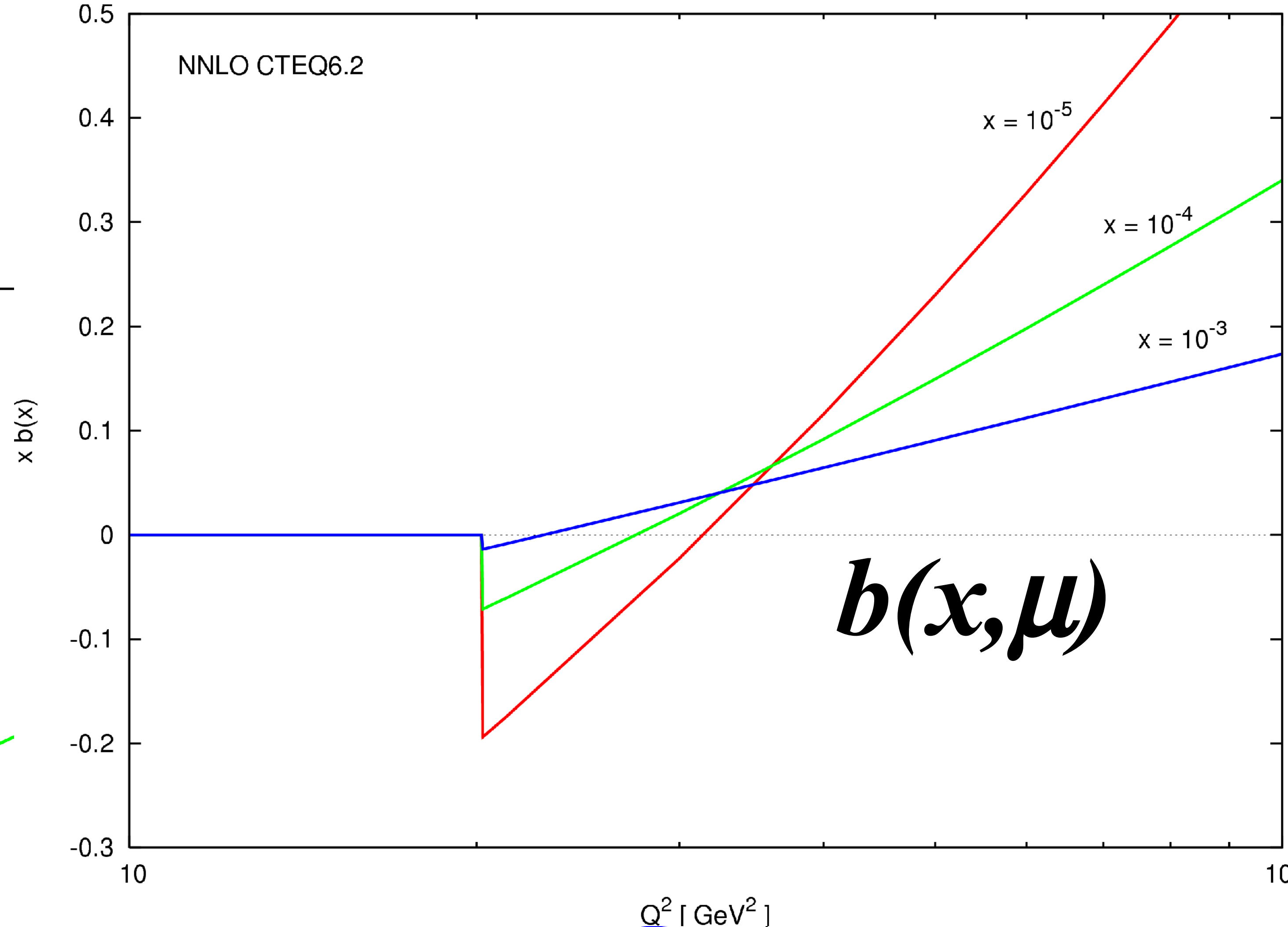
implied relation of C's

$$F(x,Q^2) = C_k^{FFNS}(Q^2/m_H^2) \otimes f_k^{n_f}(Q^2)$$
$$= C_j^{VFNS}(Q^2/m_H^2) \otimes f_j^{n_f+1}(Q^2) \equiv C_j^{VFNS}(Q^2/m_H^2) \otimes A_{jk}(Q^2/m_H^2) \otimes f_k^{n_f}(Q^2)$$

f(x,μ) as a function of μ for various flavor numbers

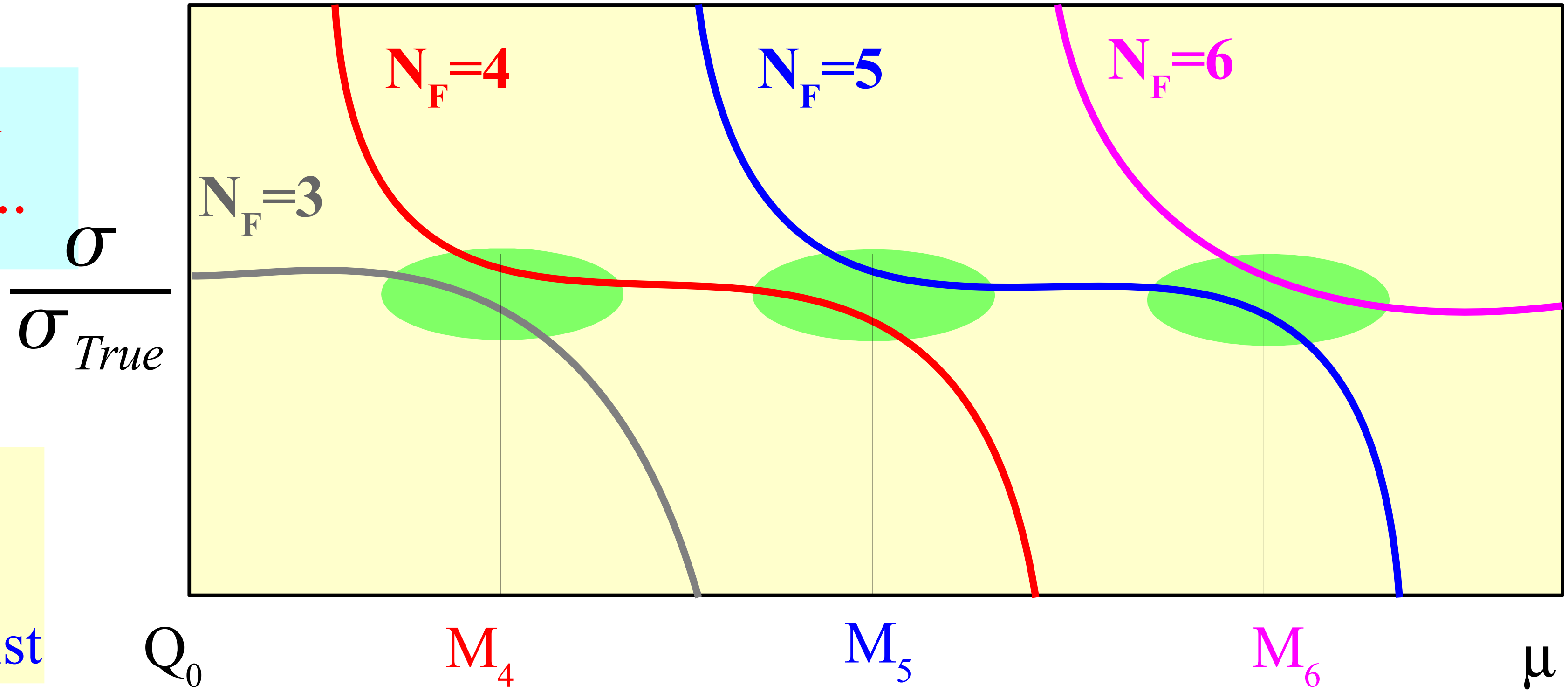
NNLO





A Proposal for PDFs at NNLO

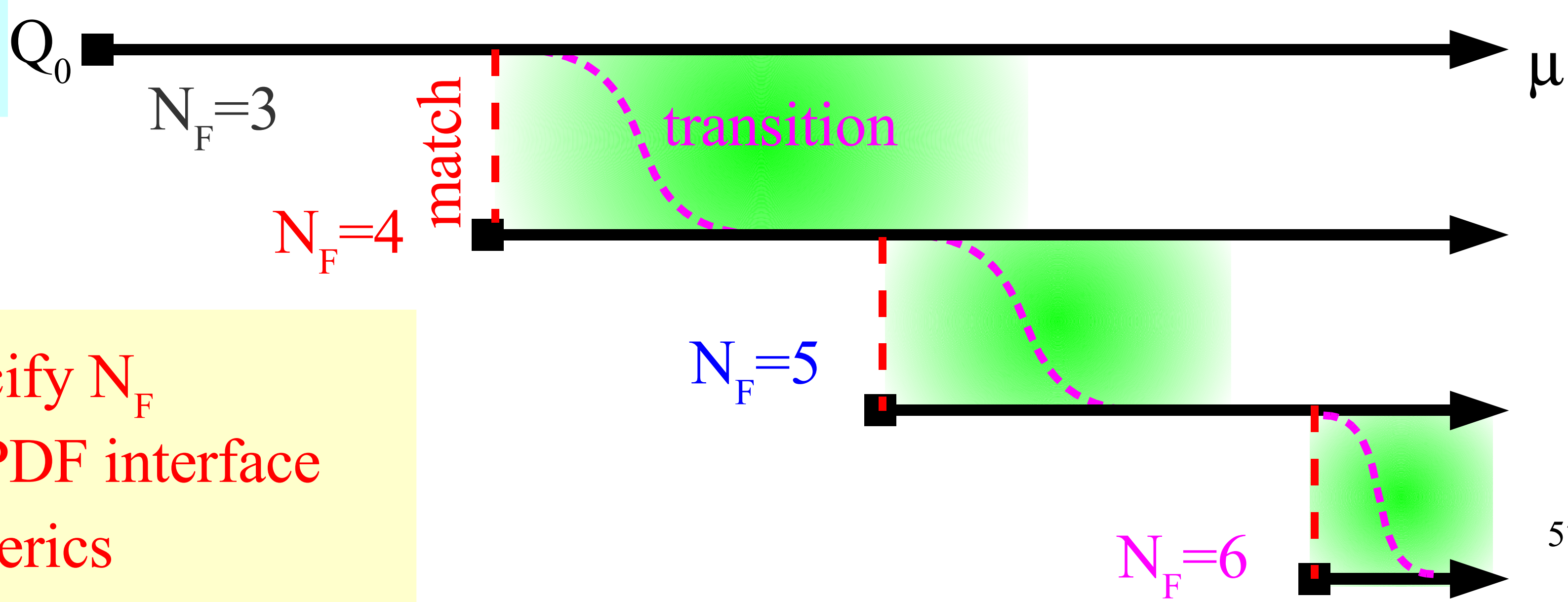
Match at μ=m
Transition at ...



For μ~m,
N and N+1
Schemes Co-exist

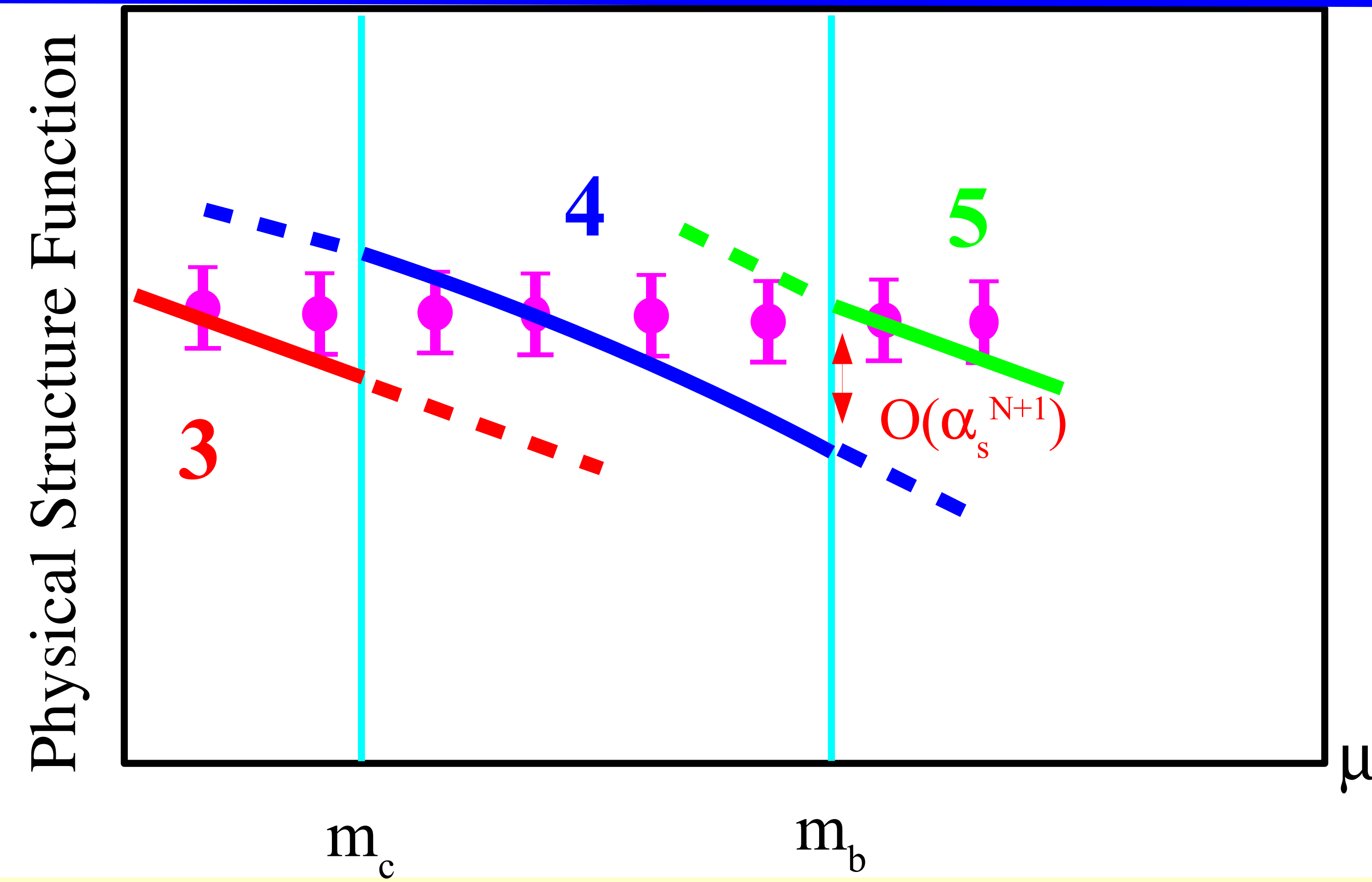
$f_{a/p}(x, Q, N_F)$

new



- Freedom to specify N_F
- Requires N_F in PDF interface
- Simplified Numerics

A multi-flavor scheme is truly a patchwork



* Difference represents the theoretical uncertainty
* Gaps will decrease with higher orders *(they must as physical quantities)*

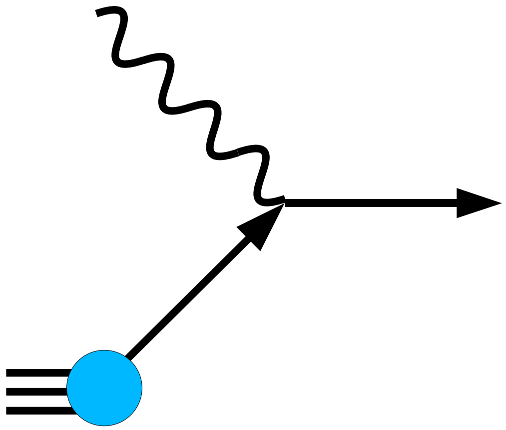
  (note: gaps of PDF's and α_s do not--these are unphysical quantities)

* If data prefers one scheme ⇒ optimal perturbative organization
* Gaps between schemes reflects limit of theory uncertainty

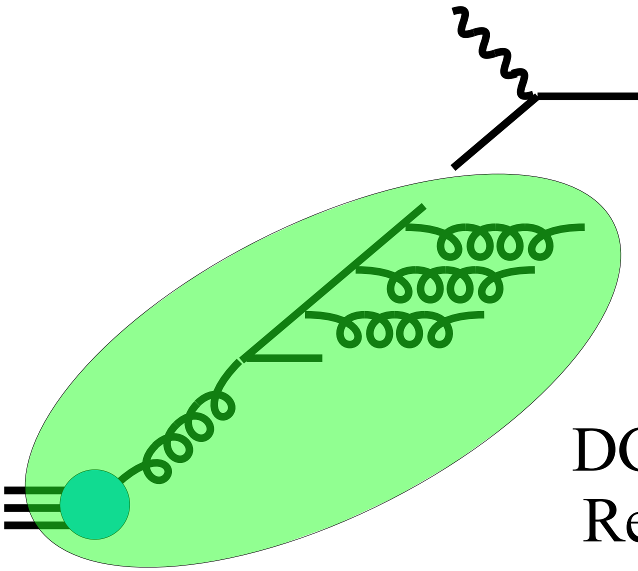
Mass-Independent Evolution.

Why is it valid?

DGLAP Equation and the Heavy Quark PDF



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

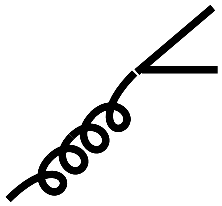


DGLAP equation Resums iterative splittings inside the proton

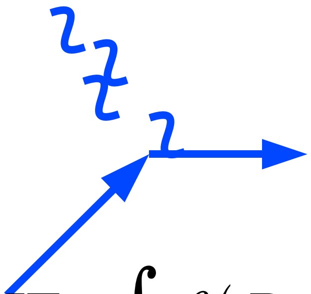
DGLAP Equation $$\frac{df_i}{d\log\mu^2} = \frac{\alpha_s}{2\pi}\ {}^1P_{j\to i} \otimes f_j + \ldots$$

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

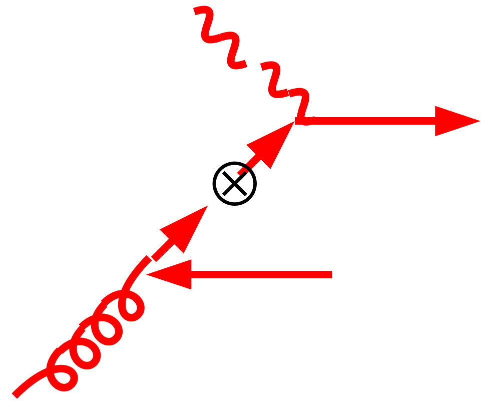


$$HE = \int f(P \to a) \otimes \sigma(a \to c)$$

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

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

valid near threshold ($M_H \sim Q$)



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

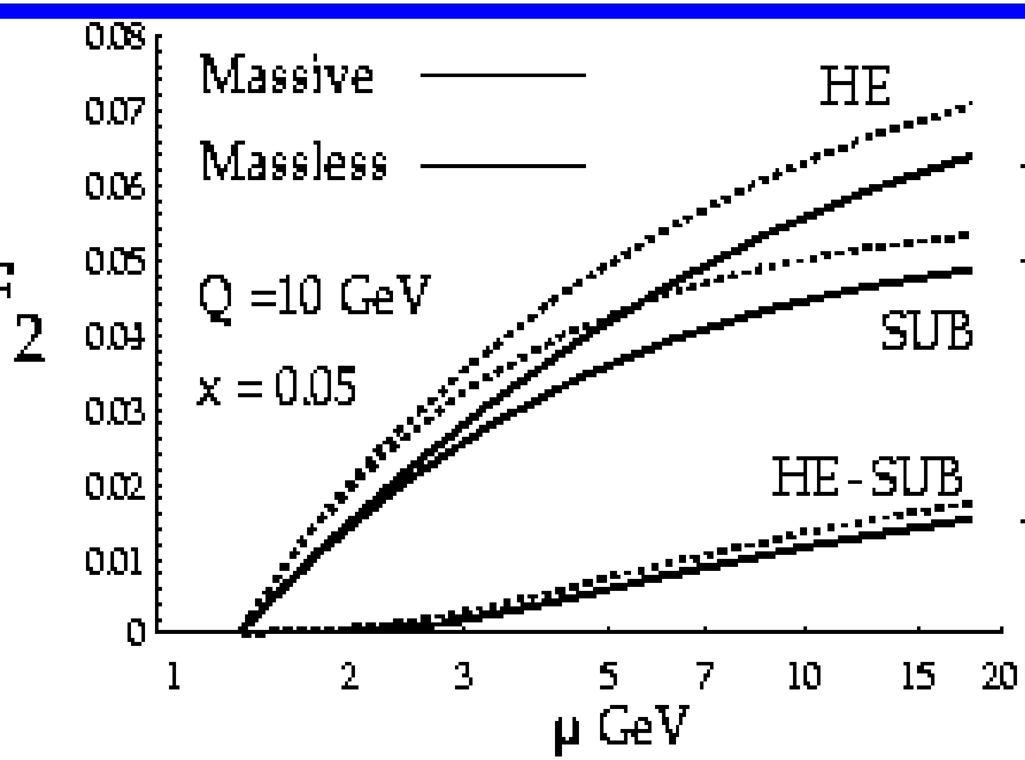
${}^{1}P$ splittings must match

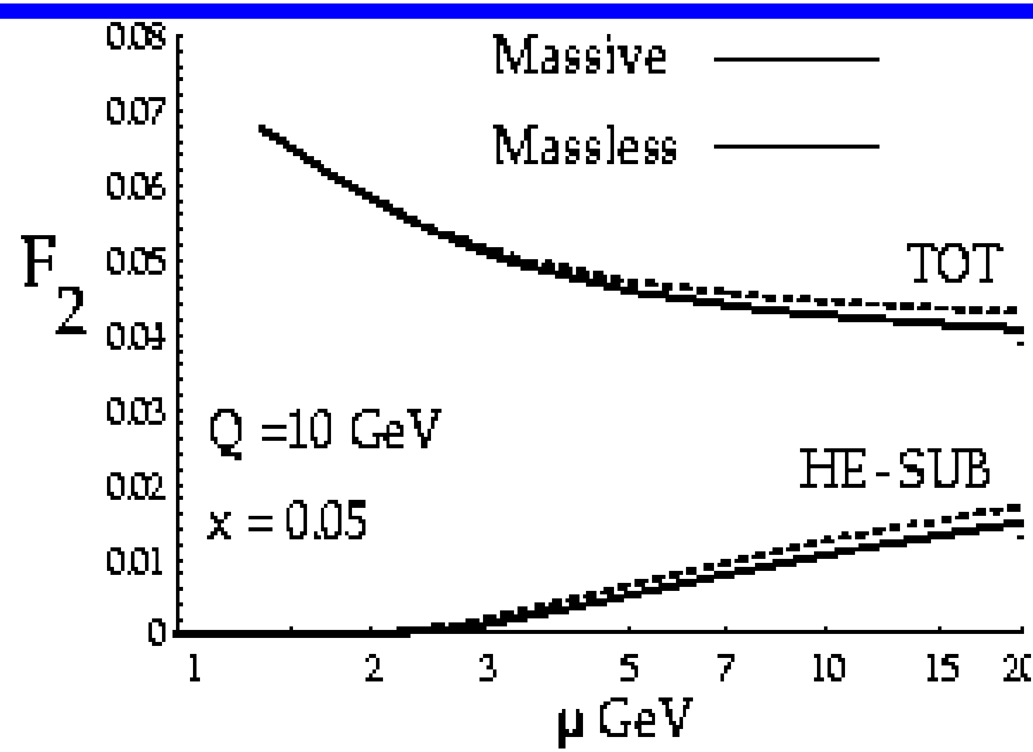
In Summary:

Near threshold($M_H \sim Q$), mass effects cancel between HE and SUB

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

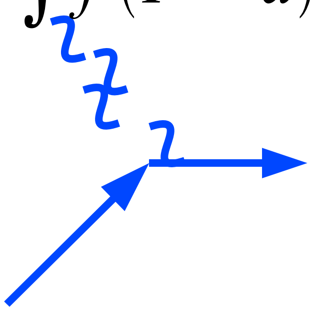
Effect of Heavy Quark Mass in the Calculation is Trivial

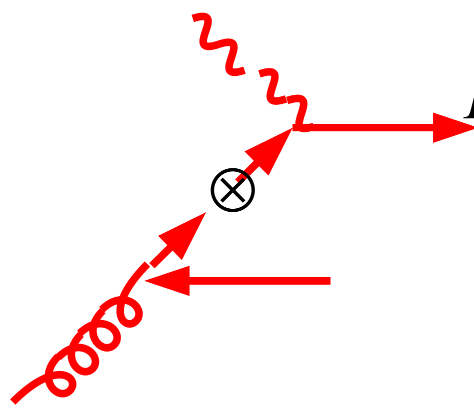


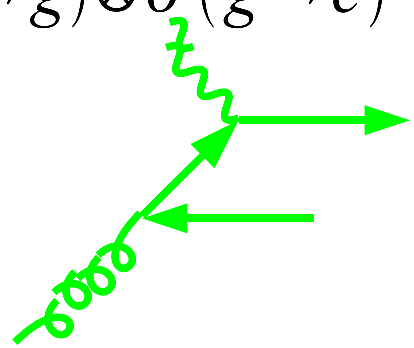


$$HE = \int f(P \to a) \otimes \sigma(a \to c)$$

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

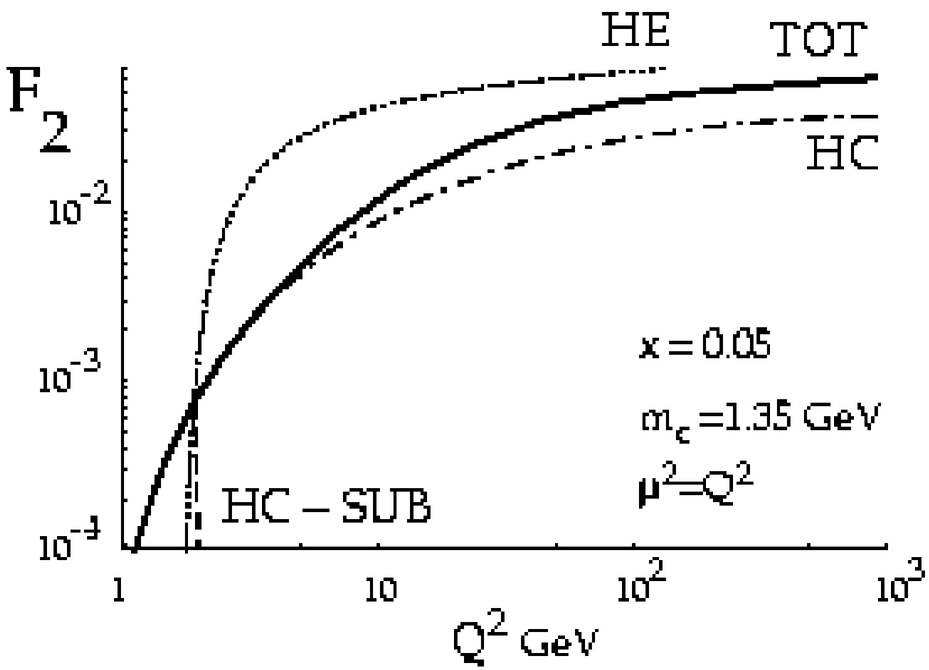


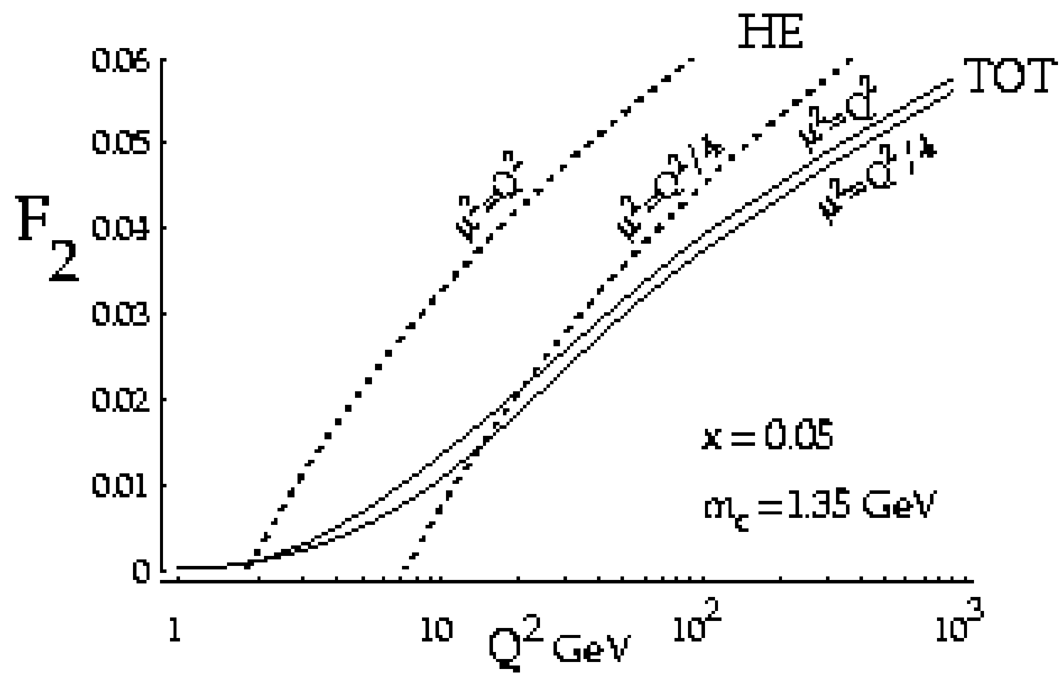




$$SUB = \int f(P \to g) \otimes {}^{1}P(g \to a) \otimes \sigma(a \to c)$$

Variation of σ vs. renormalization scale μ





LO = HE result is very sensitive to the choice of scale (i.e., μ^2=Q^2 or $Q^2/4$)
TOT result (higher order) is stable w.r.t. the choice of scale

An accurate calculation must be stable as the renormalization scale varies