Frontiers of QCD with Precision nPDFs

What lessons can we extract from the last 20 years?

What might the future bring?

Fred Olness

SMU

Thanks to:
A. Kusina, I. Schienbein, F. Lyonnet, K. Kovarik, J.Y. Yu, T. Stavreva, T. Jezo,
J.G. Morfin, J.F. Owens, P. Nadolsky, V. Radescu, C. Keppel, B. Clark, E. Godat

POETIC6
9 September 2015

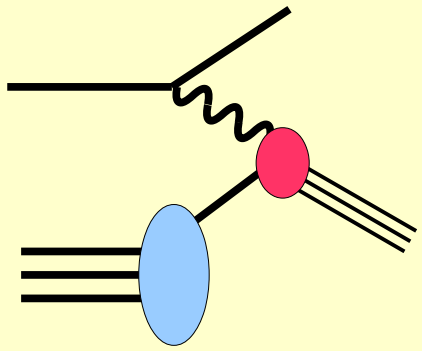
The Parton Model: *Connecting Experiment to Theory*

$$\sigma_{P\gamma \to c} = f_{P \to a} \otimes \hat{\sigma}_{a\gamma \to c}$$

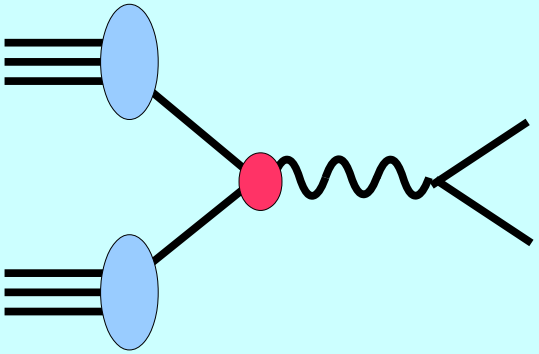
Experimental Observables

Parton Distribution Function (PDF)

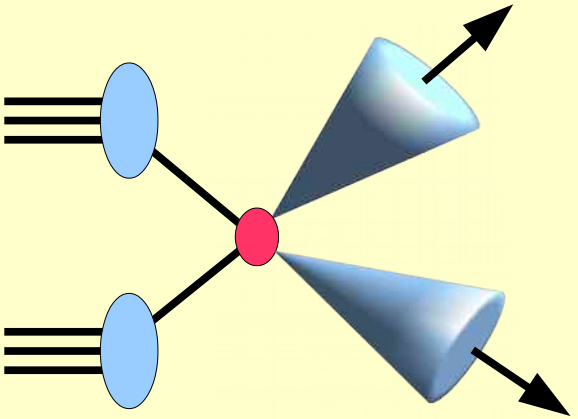
Theoretical Calculations



DIS Production



Drell-Yan



Jet Production

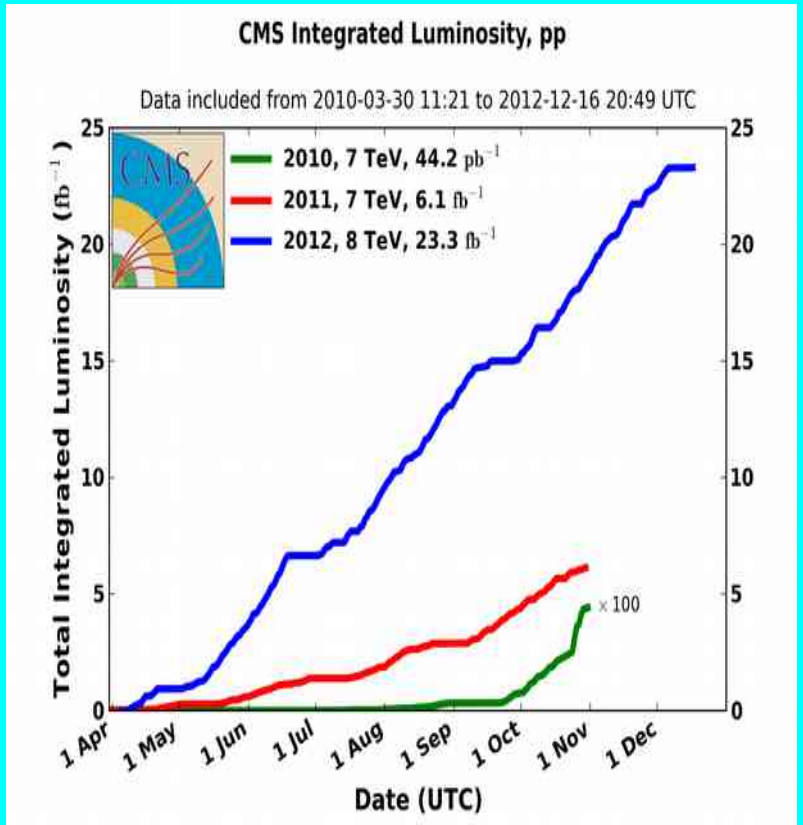
The Parton Model: *Recent Progress ...*

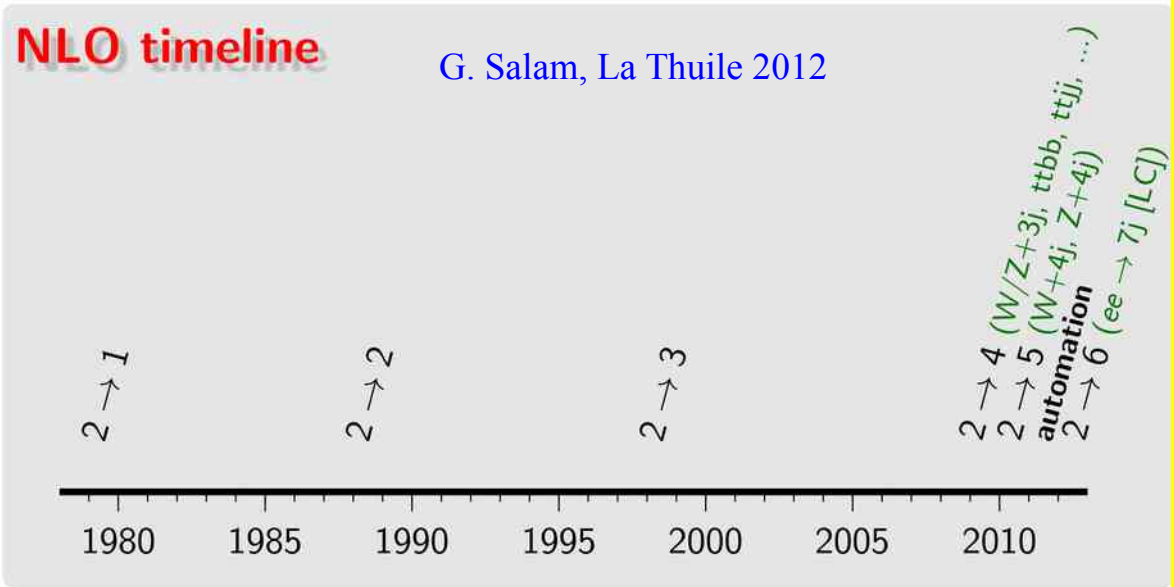
$$\sigma_{P\gamma\to c} = f_{P\to a} \otimes \hat{\sigma}_{a\gamma\to c}$$

Experimental Observables

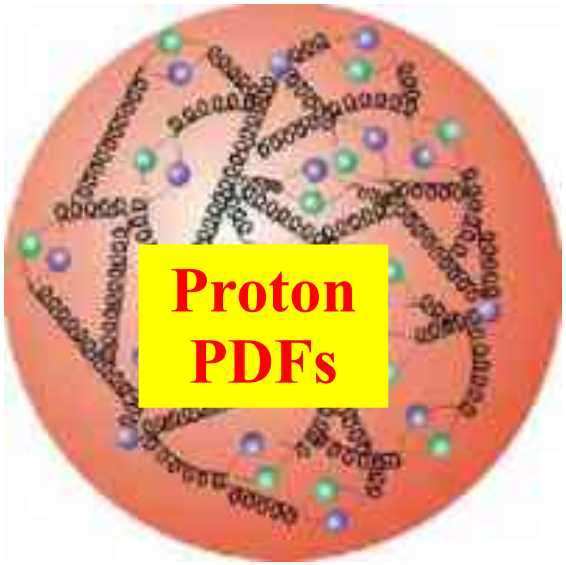
WHAT ABOUT PDF'S ???

Theoretical Calculations

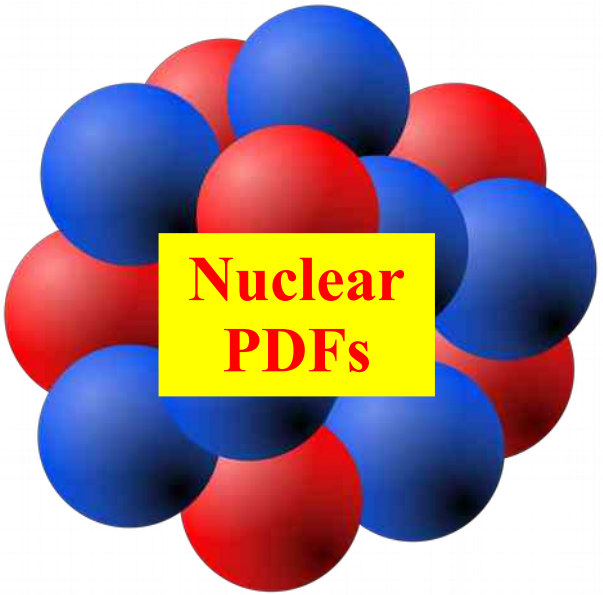


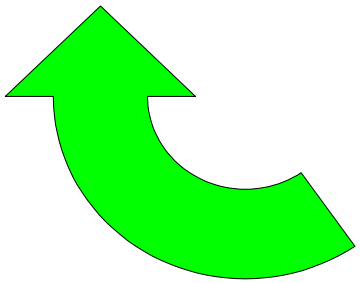


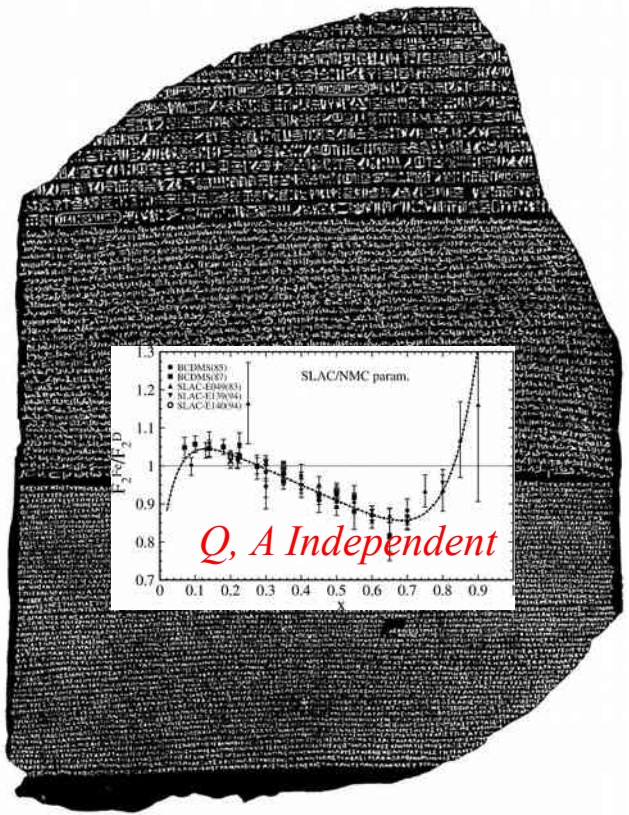
A long time ago in a galaxy far, far away ...

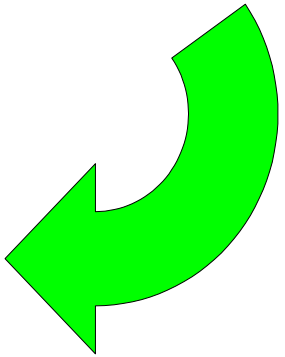


... there was a time when
nuclear corrections
were carved in stone ...



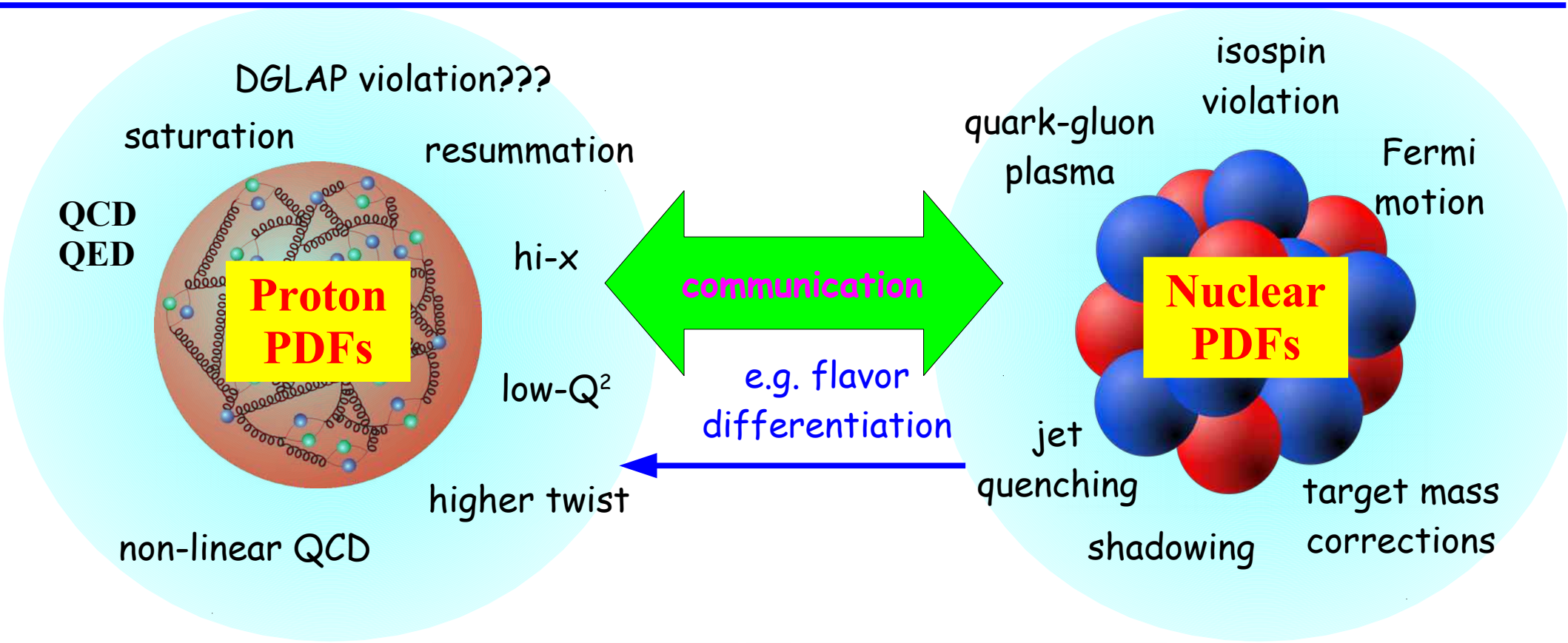


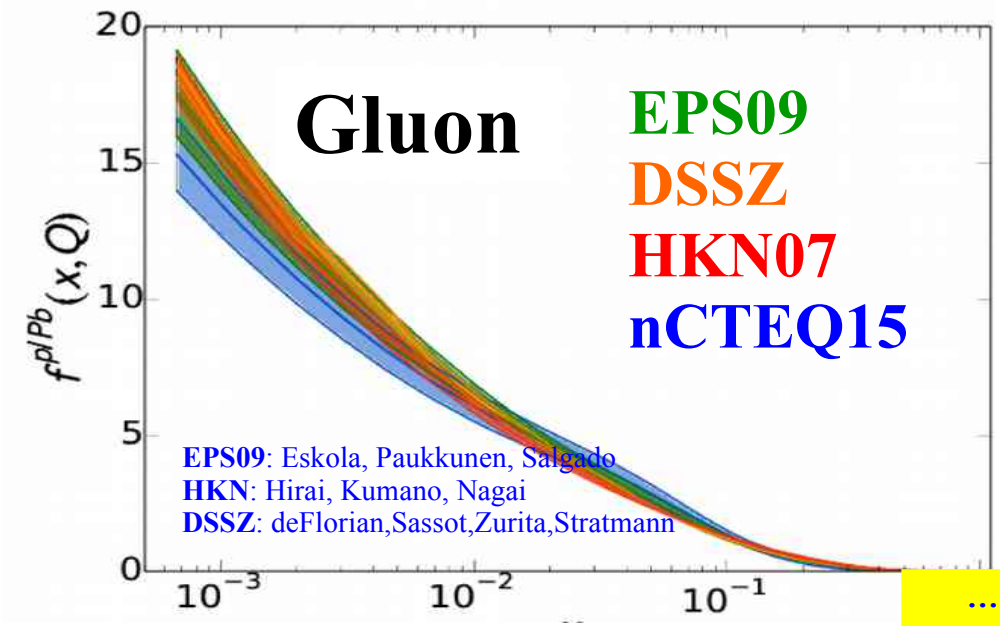




... the original motivation for nCTEQ15

Moving Into The 21st Century





… the original motivation for nCTEQ15

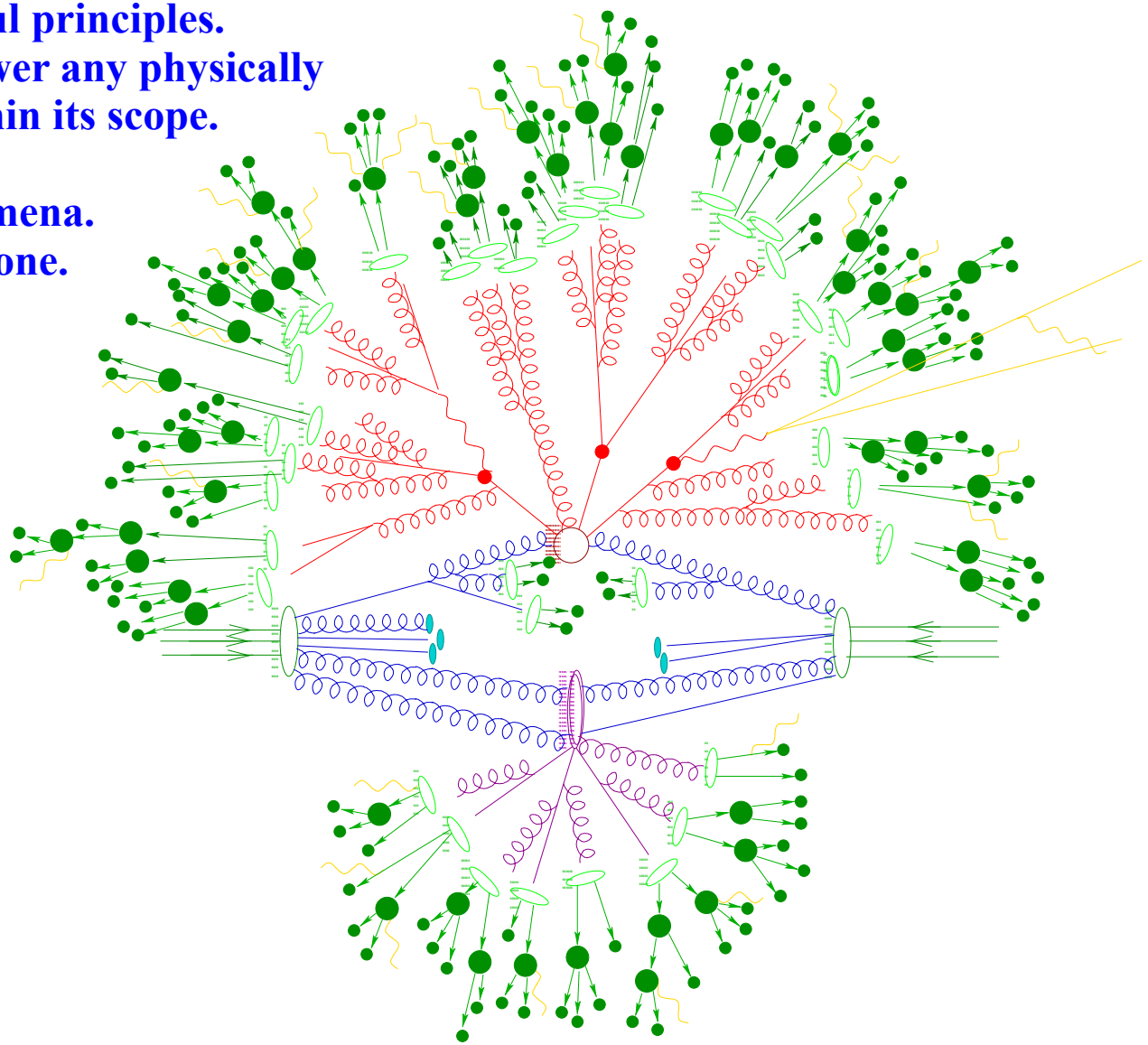
What QCD Tells Us About Nature – and Why We Should Listen

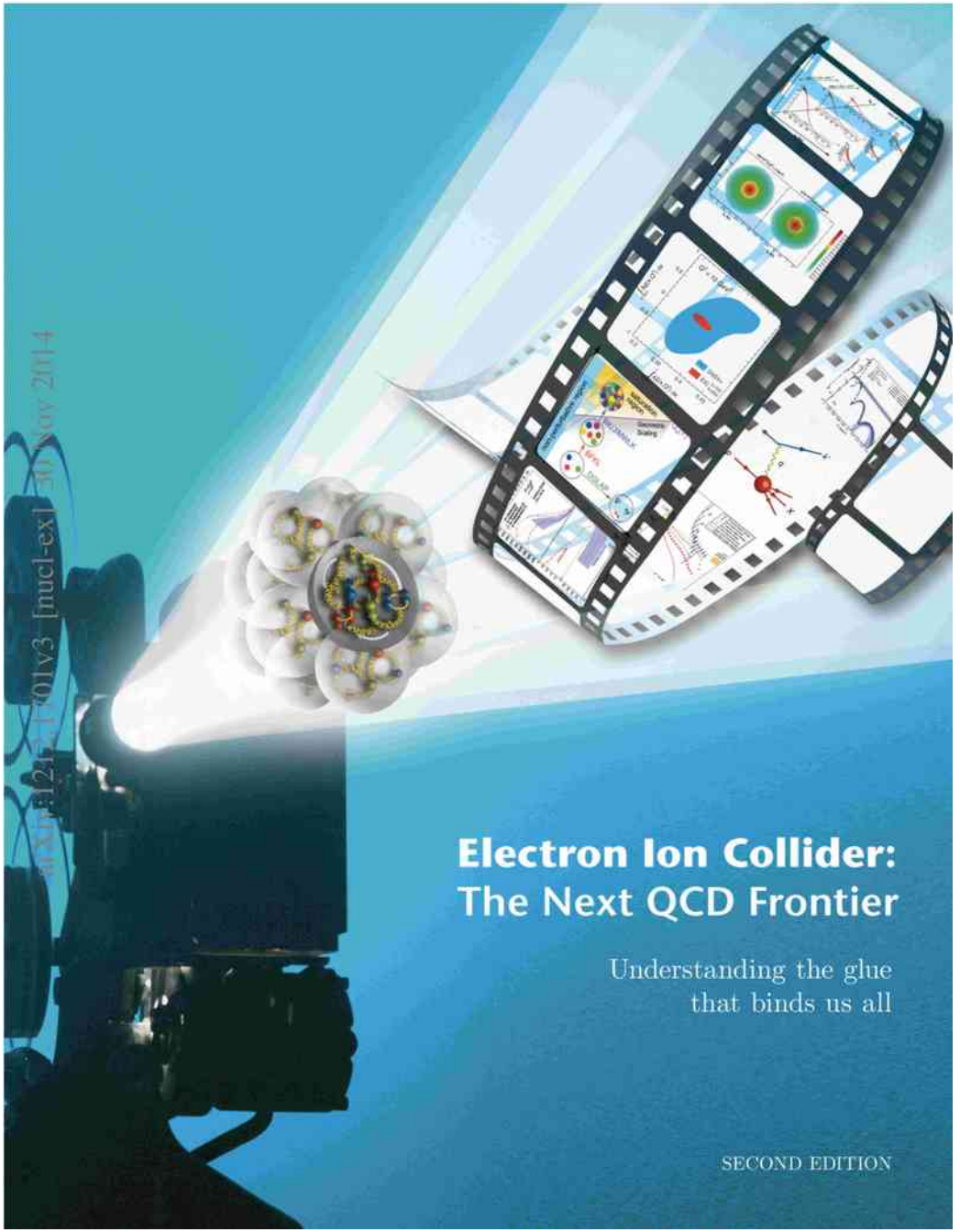
Frank Wilczek *(arXiv:hep-ph/9907340)*

QCD is our most perfect physical theory

It embodies deep and beautiful principles.
It provides algorithms to answer any physically meaningful question within its scope.
Its scope is wide.
It contains a wealth of phenomena.
It has few parameters … or none.
It is true.
It lacks flaws.

Lessons: The Nature of Nature
… alien, simple, beautiful, weird, & comprehensible





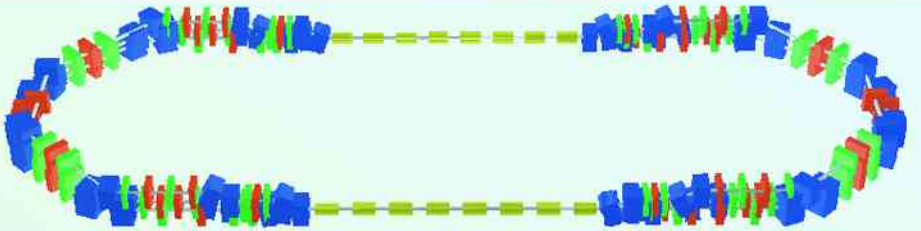
http://cern.ch/lhec lhec.ws@cern.ch

Workshop on the LHeC

Electron-proton and electron-ion collisions at the LHC

24 June 2015 CERN

25-26 June 2015 Chavannes-de-Bogis, Switzerland



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CERN EuCARD² XBEAM LHeC

Challenges: … past, present,& future

The CTEQ List of Challenges in Perturbative QCD

~1995

Welcome to the CTEQ List of Challenges in Perturbative QCD! Although QCD has successfully passed many tests, there are still areas where there are problems when comparing theory and experiment or where additional data or calculations are needed. Here is our current list of Challenges in Perturbative QCD. This is expected to be a dynamic list, so check back often. It is expected that existing entries will be periodically updated and that new entries will be added.

1. Direct photon production
2. Heavy quark production cross sections
3. Jet cross sections and xt scaling
4. Determining the gluon distribution
5. Large-x behavior of parton distributions
6. Determining the flavor dependence of pdf's
7. Extracting Charged & Neutral Current Cross Sections

`http://www.hep.fsu.edu/~owens/qcd/QCD_list.html`

1) Flavor Differentiation & Nuclear Corrections

2) Multi-scale problems: Heavy Quarks Resummation

3) Hi-Order Corrections

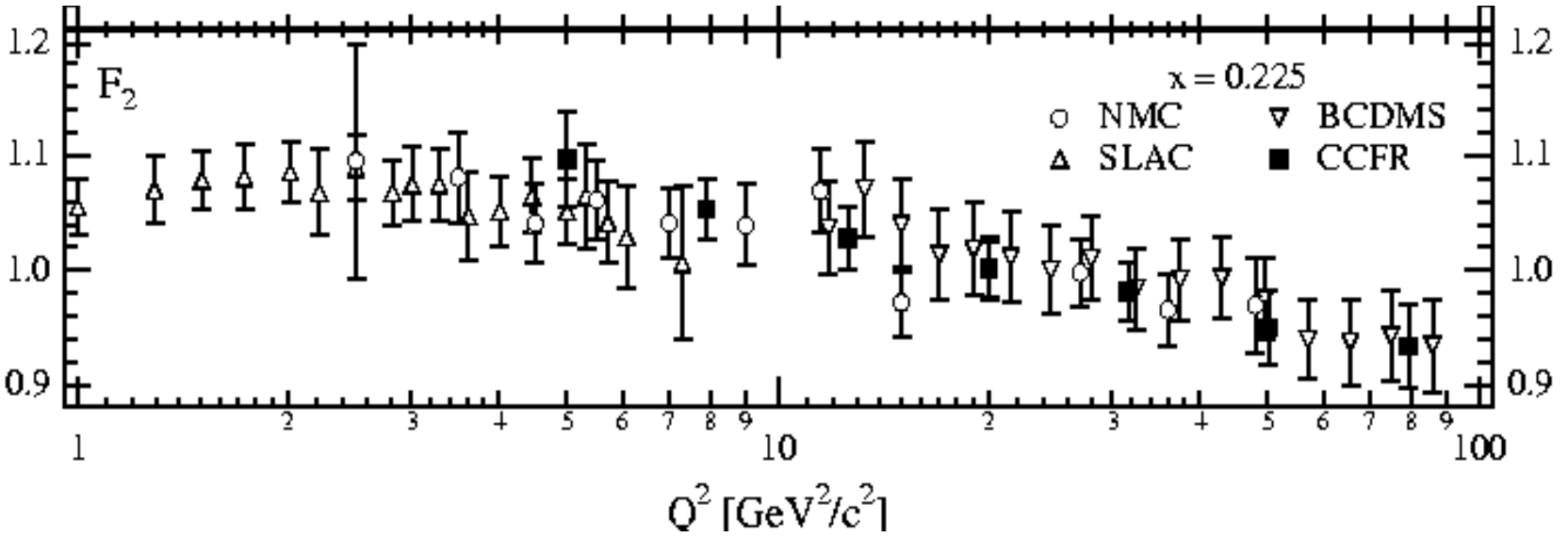
FLAVOR DIFFERENTIATION

Di-muon production ⇒ Extract s(x) Parton Distribution

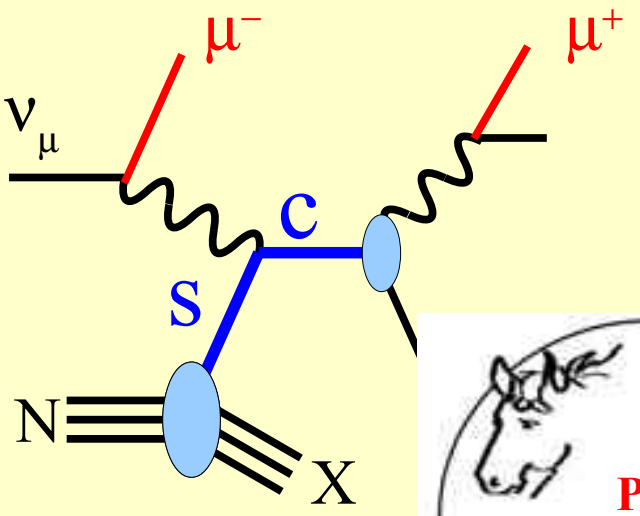
The CTEQ List of Challenges in Perturbative QCD

~1995

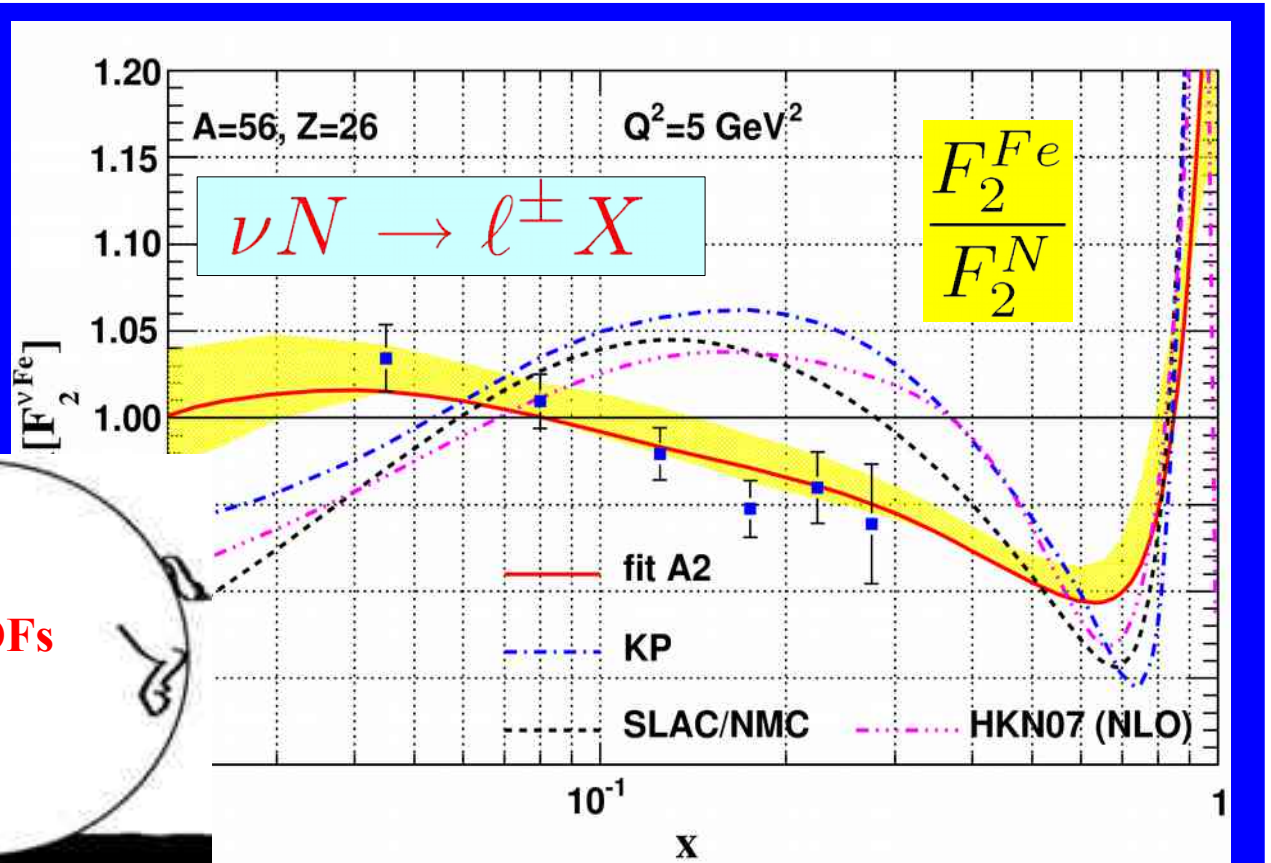
C T E Q



Extract s(x)



Depends on nuclear corrections

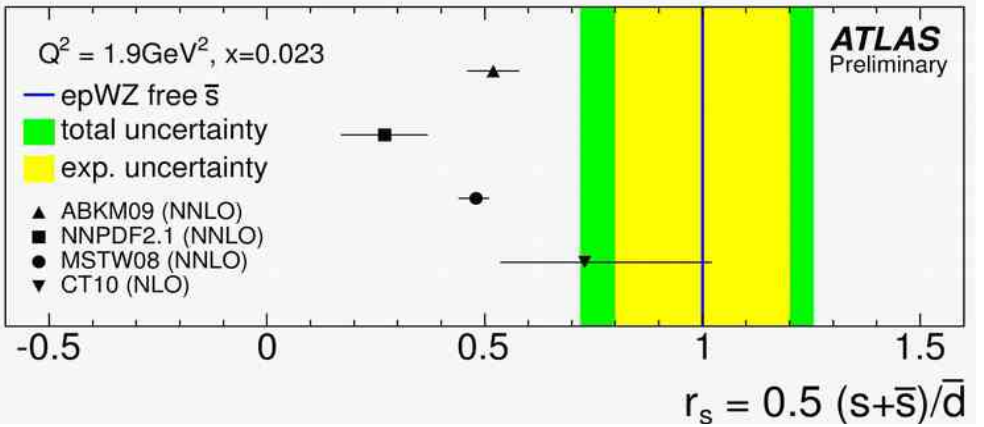


Use LHC data to constrain Strange Quark

W, Z data sensitivity to strange sea

- ATLAS performed NNLO QCD fit to Z, W^+, W^- + HERA ep DIS cross sections: significant tension for Z observed when suppressing strange by 50% at low scale $1.9\,\mathrm{GeV}^2$
- Fit with free strange sea gives no supression

$$r_s = 1.00 \pm 0.20_{\mathrm{exp}}\ ^{+0.16}_{-0.20}\ \mathrm{sys}$$



DIY: Do It Yourself: Strange Quark from LHC Data

... what about the

Heavy Quarks

c & b: Extrinsic & Intrinsic

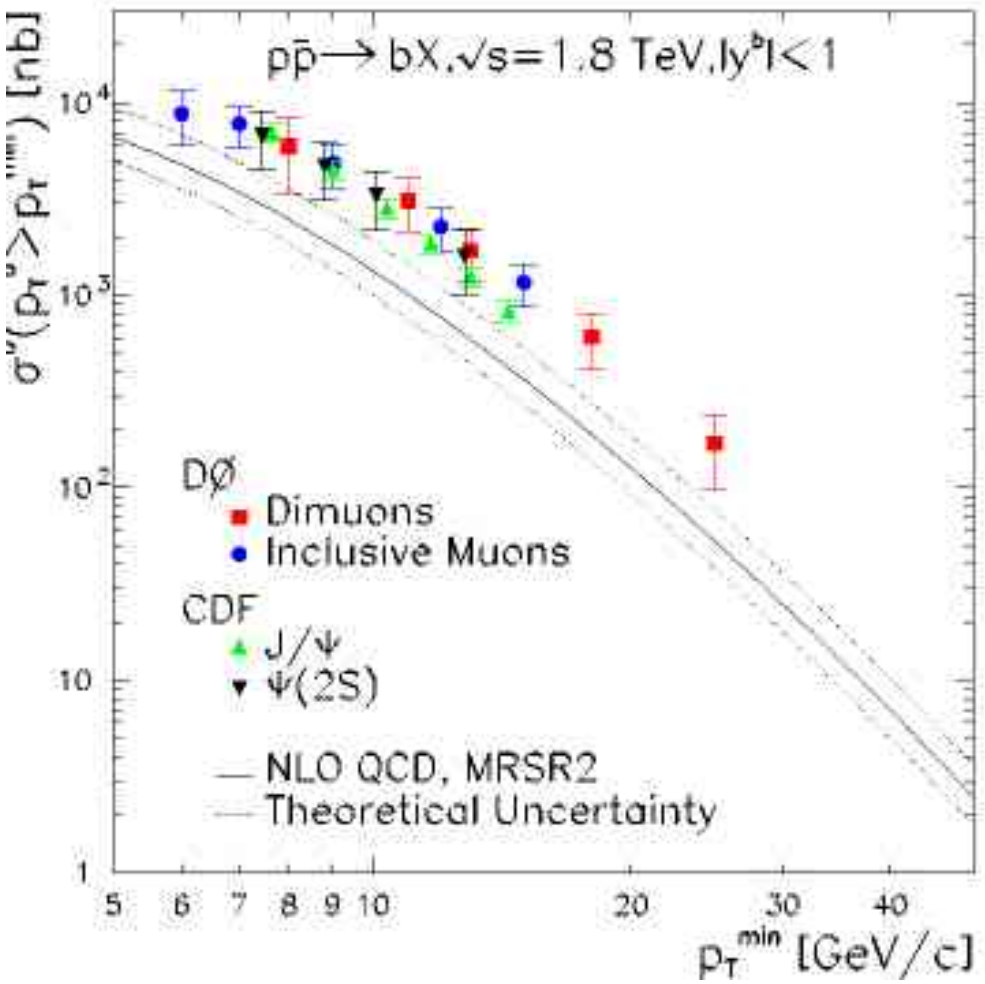
Historically, these have been a challenge because $Q \sim m_{c,b}$

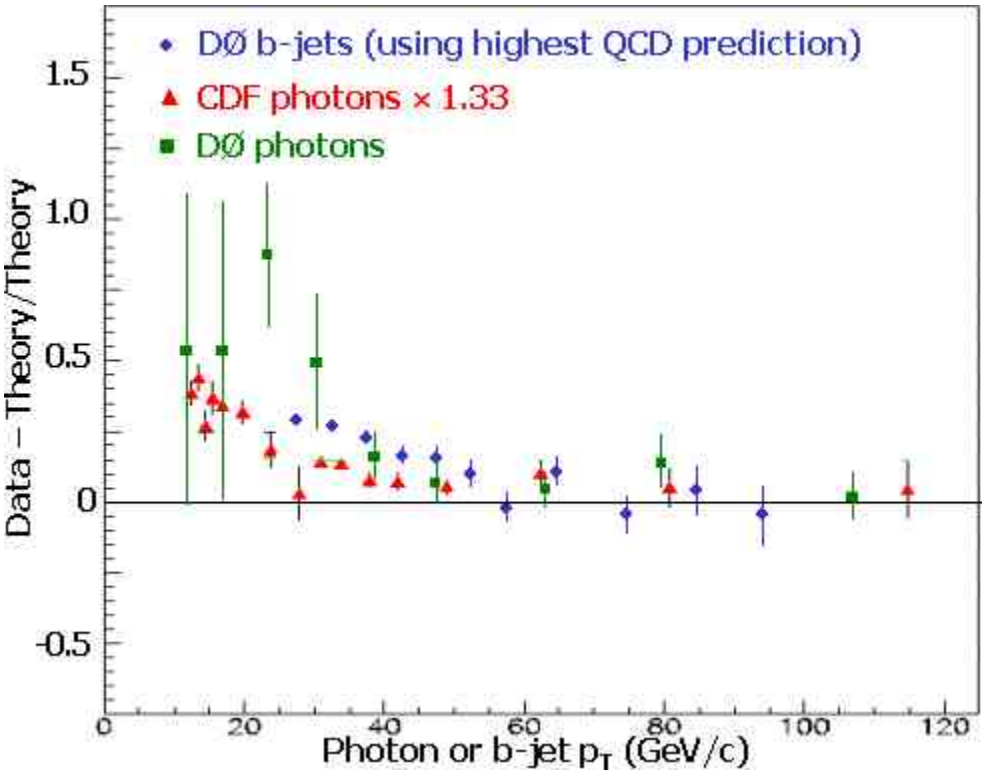
Heavy Quarks : … past challenges

The CTEQ List of Challenges in Perturbative QCD

Calculating b-quark production cross sections at hadron-hadron colliders

C T E Q





~1995

Multi-Scale Problems are Challenging

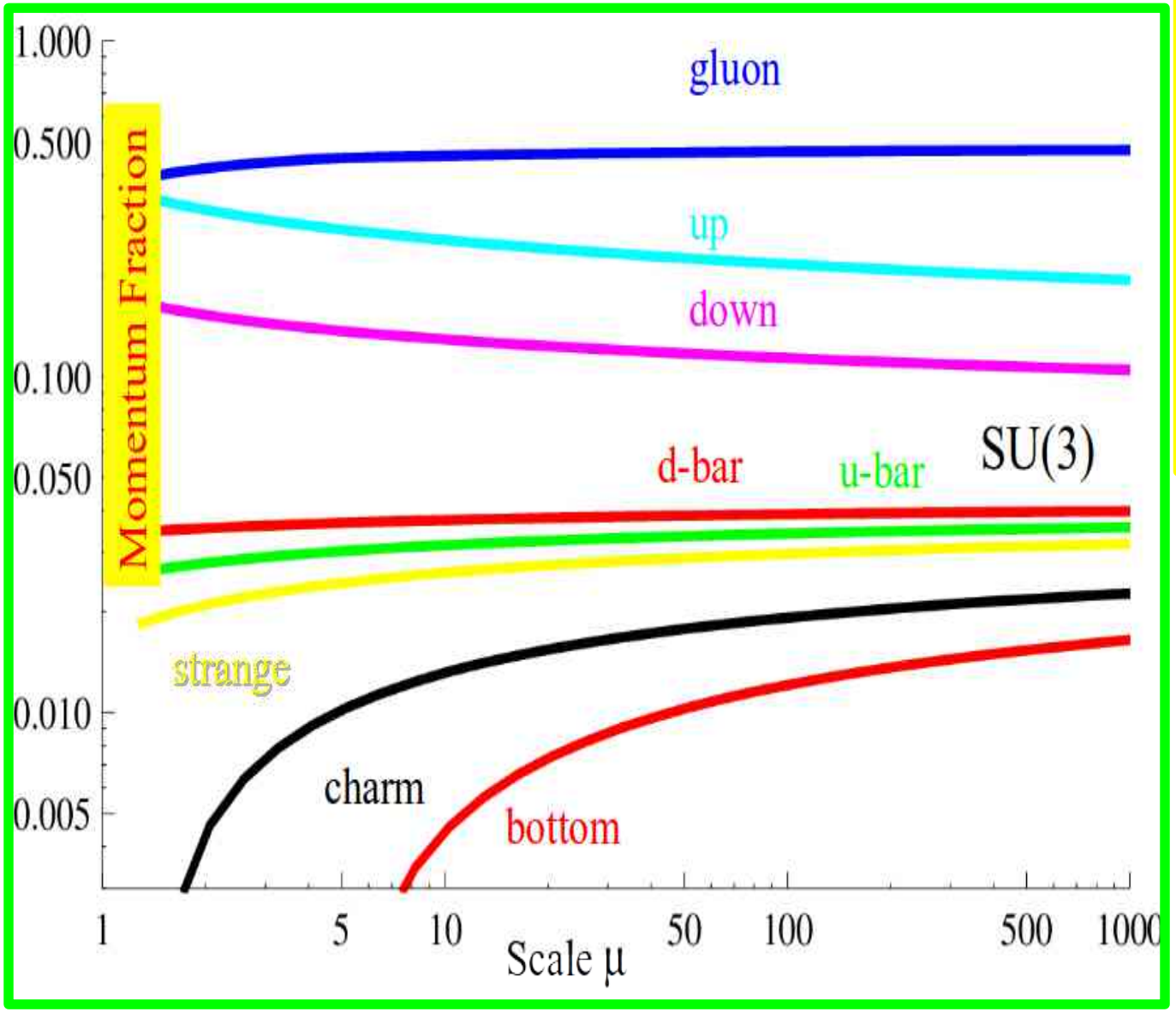
Two-Loop Total Cross Section: One Scale

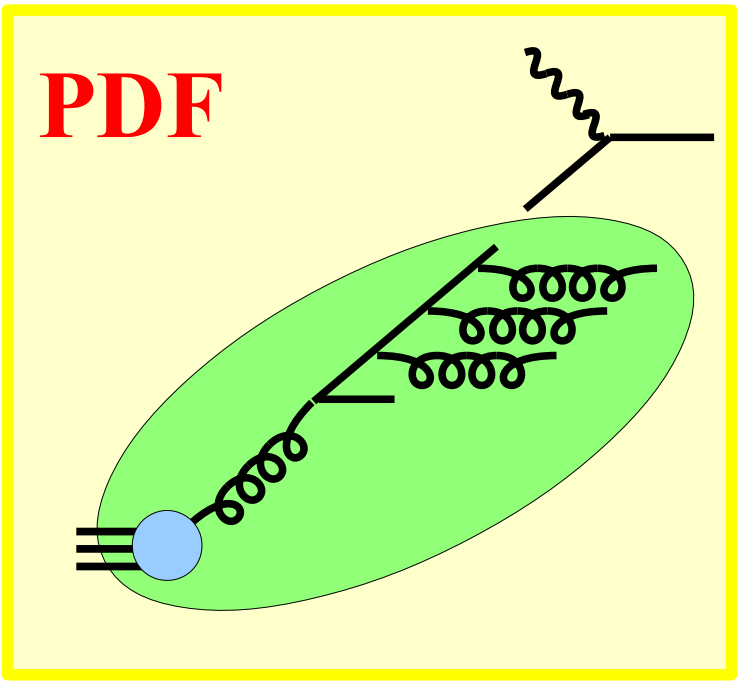
$$\sigma(Q^2)=\sigma_0\left\{1+\frac{\alpha_s(Q^2)}{4\pi}(3C_F)+\left[\frac{\alpha_s(Q^2)}{4\pi}\right]^2\left[-C_F^2\left[\frac{3}{2}\right]+C_FC_A\left[\frac{123}{2}-44\zeta(3)\right]+C_FTn_f(-22+16\zeta(3))\right]\right.$$

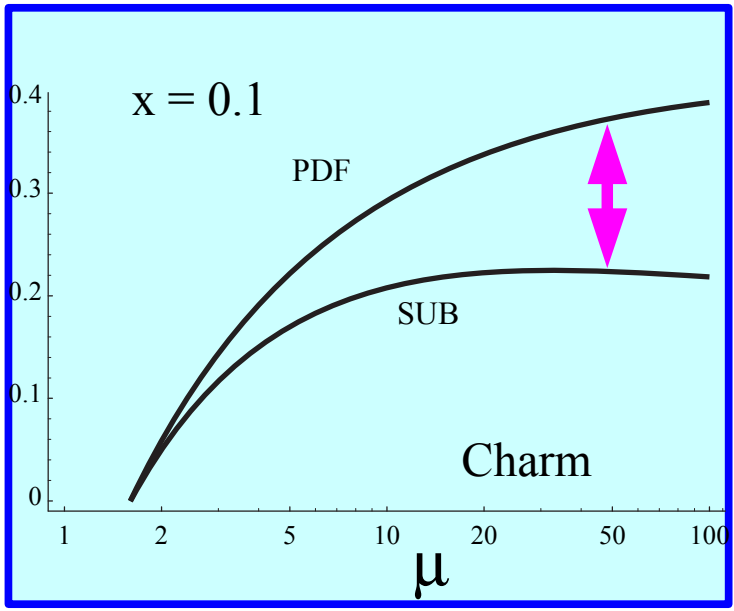
Two-Loop Drell-Yan Cross Section: Two Scales

$$\begin{aligned}
H_{q\bar{q}}^{(2),S+V}(z)=&\left[\frac{\alpha_s}{4\pi}\right]^2\delta(1-z)\left\{C_AC_F\left[\left[\tfrac{193}{3}-24\zeta(3)\right]\ln\left[\frac{Q^2}{M^2}\right]-11\ln^2\left[\frac{Q^2}{M^2}\right]-\tfrac{12}{5}\zeta(2)^2+\tfrac{592}{9}\zeta(2)+28\zeta(3)-\tfrac{1535}{12}\right]\right.\\
&+C_F^2\left[\left[18-32\zeta(2)\right]\ln^2\left[\frac{Q^2}{M^2}\right]+\left[24\zeta(2)+176\zeta(3)-93\right]\ln\left[\frac{Q^2}{M^2}\right]\right.\\
&\left.\left.+\tfrac{8}{5}\zeta(2)^2-70\zeta(2)-60\zeta(3)+\tfrac{511}{4}\right]\right.\\
&\left.+n_fC_F\left[2\ln^2\left[\frac{Q^2}{M^2}\right]-\tfrac{34}{3}\ln\left[\frac{Q^2}{M^2}\right]+8\zeta(3)-\tfrac{112}{9}\zeta(2)+\tfrac{127}{6}\right]\right\}\\
&+C_AC_F\left[-\tfrac{44}{3}\mathcal{D}_0(z)\ln^2\left[\frac{Q^2}{M^2}\right]+\left\{\left[\tfrac{536}{9}-16\zeta(2)\right]\mathcal{D}_0(z)-\tfrac{176}{3}\mathcal{D}_1(z)\right\}\ln\left[\frac{Q^2}{M^2}\right]\right.\\
&\left.-\tfrac{176}{3}\mathcal{D}_2(z)+\left[\tfrac{1072}{9}-32\zeta(2)\right]\mathcal{D}_1(z)+\left[56\zeta(3)+\tfrac{176}{3}\zeta(2)-\tfrac{1616}{27}\right]\mathcal{D}_0(z)\right]\\
&+C_F^2\left[\left[64\mathcal{D}_1(z)+48\mathcal{D}_0(z)\right]\ln^2\left[\frac{Q^2}{M^2}\right]+\left\{192\mathcal{D}_2(z)+96\mathcal{D}_1(z)-\left[128+64\zeta(2)\right]\mathcal{D}_0(z)\right\}\ln\left[\frac{Q^2}{M^2}\right]\right.\\
&\left.+128\mathcal{D}_3(z)-\left(128\zeta(2)+256\right)\mathcal{D}_1(z)+256\zeta(3)\mathcal{D}_0(z)\right]\\
&+n_fC_F\left[\tfrac{8}{3}\mathcal{D}_0(z)\ln^2\left[\frac{Q^2}{M^2}\right]+\left[\tfrac{32}{3}\mathcal{D}_1(z)-\tfrac{80}{9}\mathcal{D}_0(z)\right]\ln\left[\frac{Q^2}{M^2}\right]+\tfrac{32}{3}\mathcal{D}_2(z)-\tfrac{160}{9}\mathcal{D}_1(z)+\left[\tfrac{224}{27}-\tfrac{32}{3}\zeta(2)\right]\mathcal{D}_0(z)\right].
\end{aligned}$$

Resum $\alpha_s \ln(m/Q)$



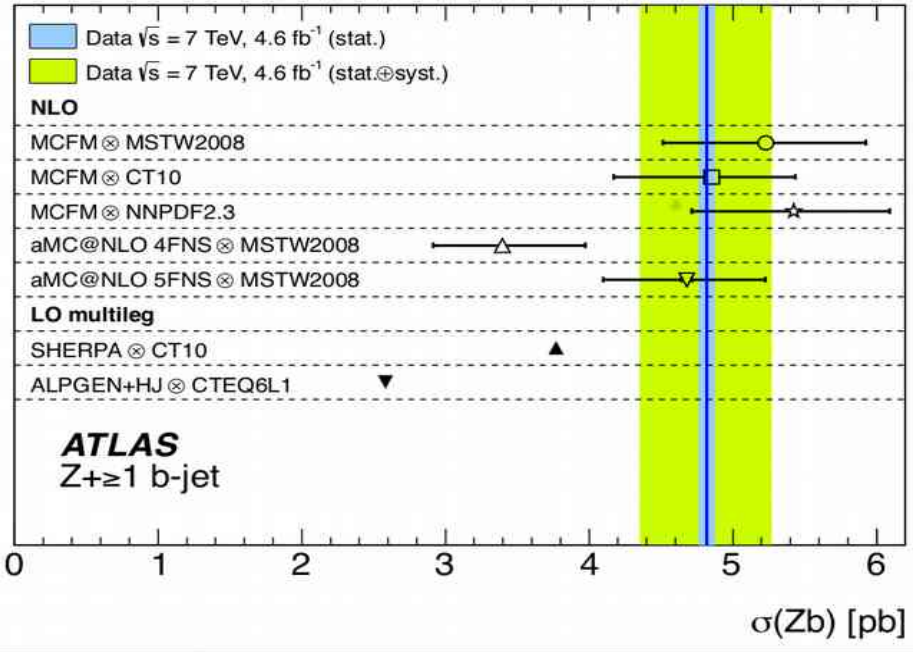


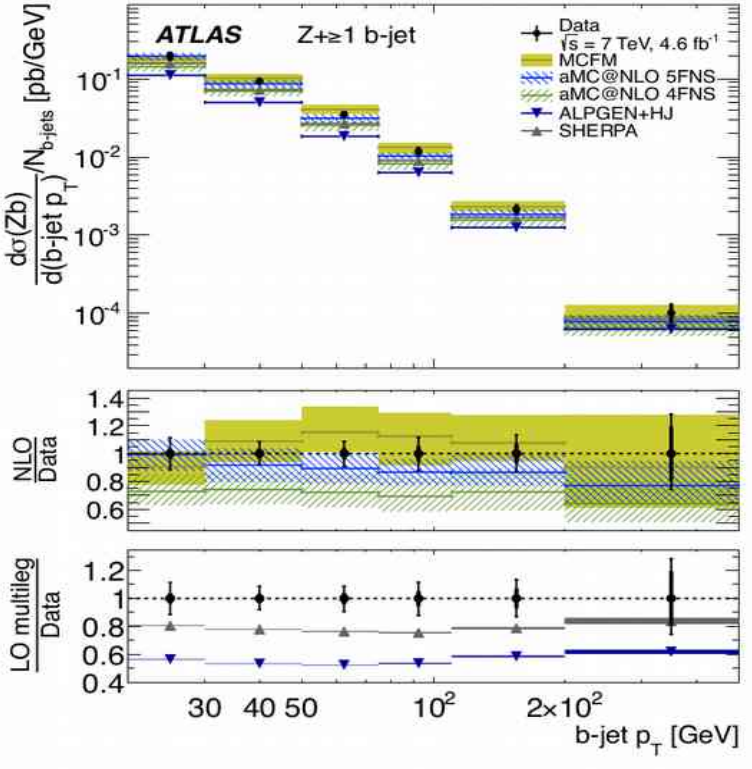


Heavy flavor: Z+b-jets

JHEP 10 (2014) 141

- Good agreement with NLO MCFM and aMC@NLO
  - Seems to favor scheme where b-quark is taken from PDF (5 FNS)
  - LO+PS generators are underestimating the cross section
  - Can't constrain PDF yet due to too large uncertainty
- Good description of b-jet p_T shape
  - Normalization is off





W/Z/γ Production

“Benchmark Calculations”

Recall Direct Photon

… the fine print:

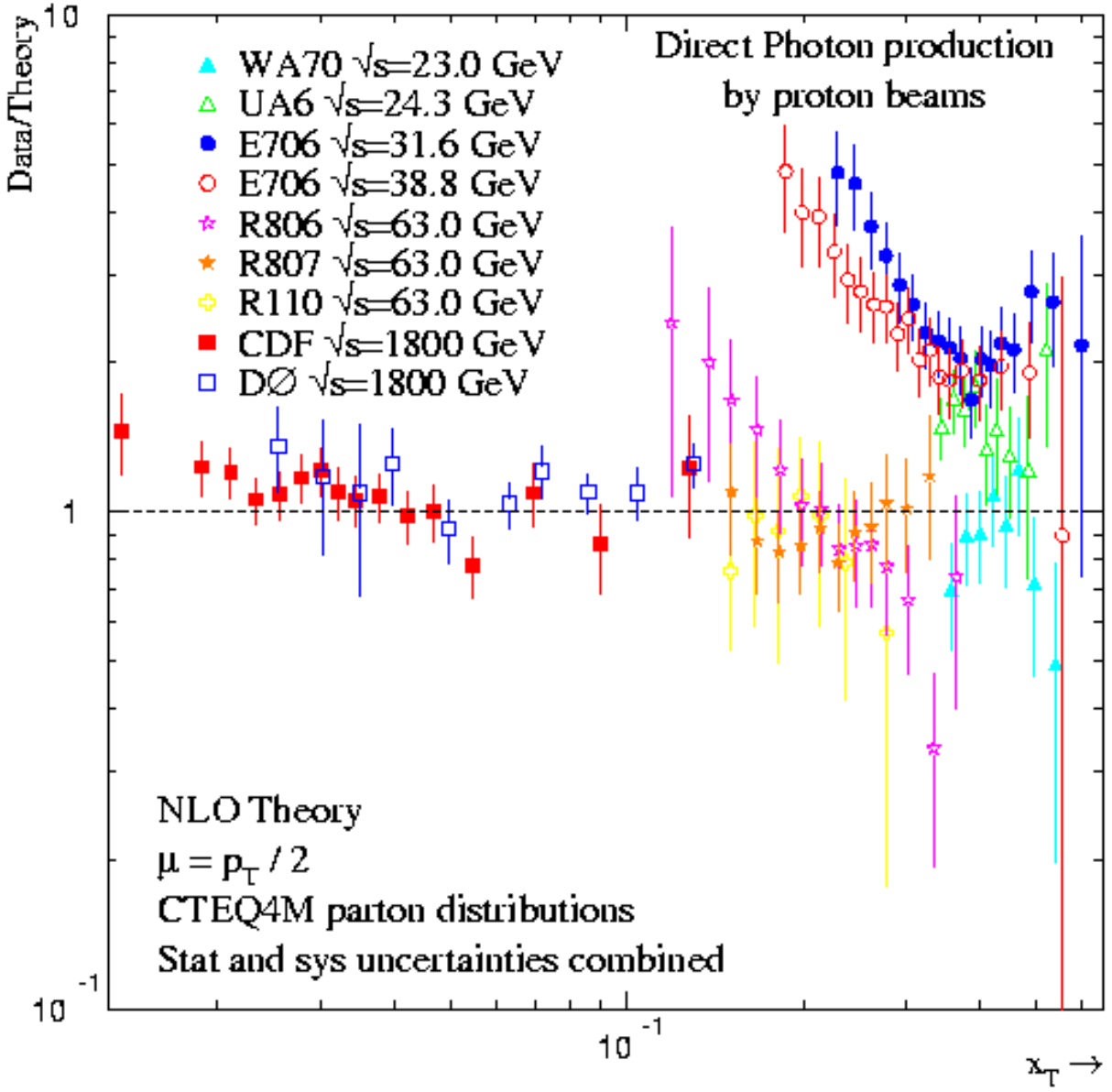
……

The CTEQ List of Challenges in Perturbative QCD

Understanding Direct Photon Production

C T E Q

~1995

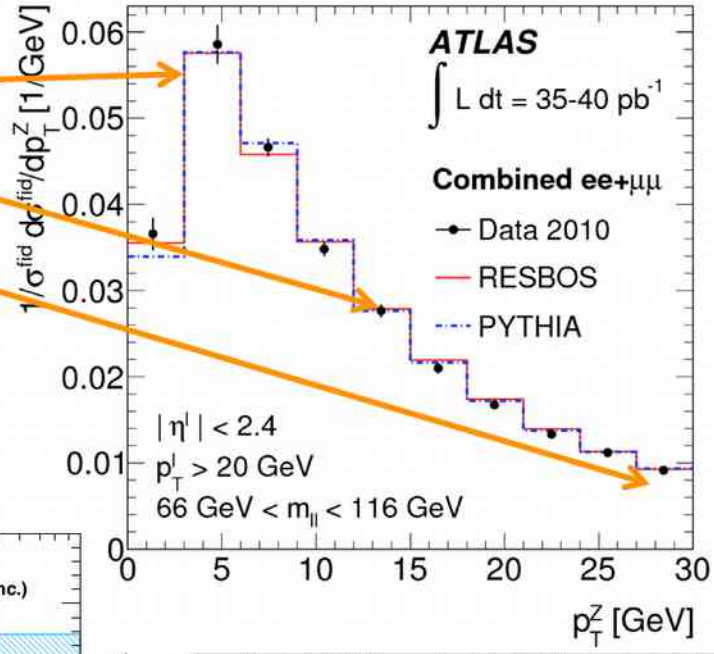


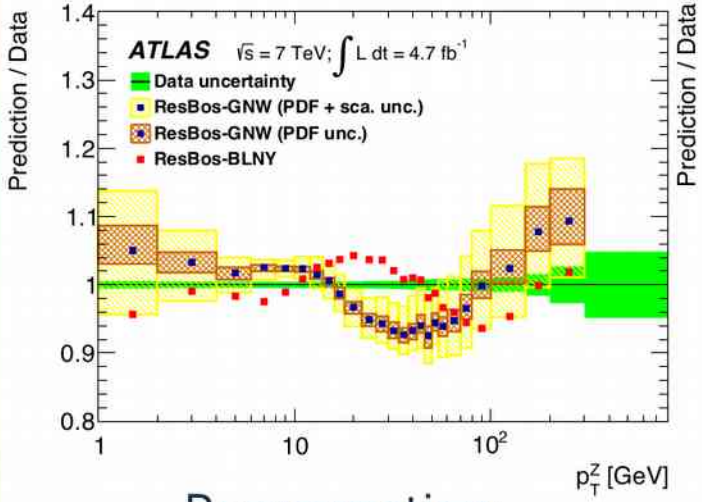
QCD bremsstrahlung: Vector Boson P_T

Phys. Lett. B705 (2011) 415-434

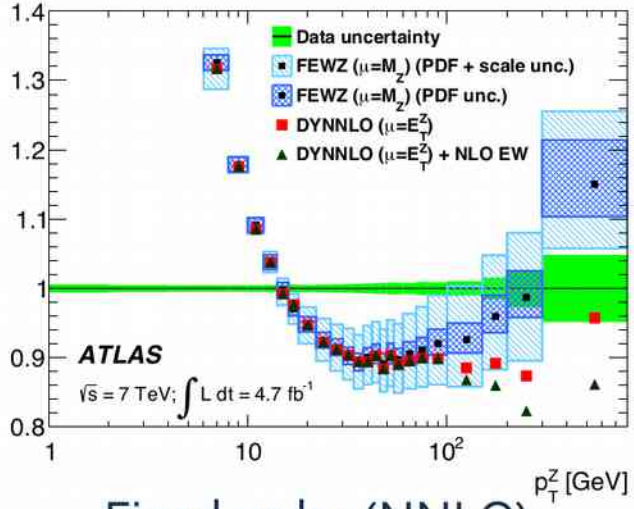
JHEP 09 (2014) 145

- Test multiple aspect of QCD predictions
  - Intrinsic-K_T
  - Low-PT (W,Z): logarithmic resummations
  - High-PT (W,Z): (N)NLO perturbative QCD
  - Important test of parton shower tuning
    - No color flow between initial and final state

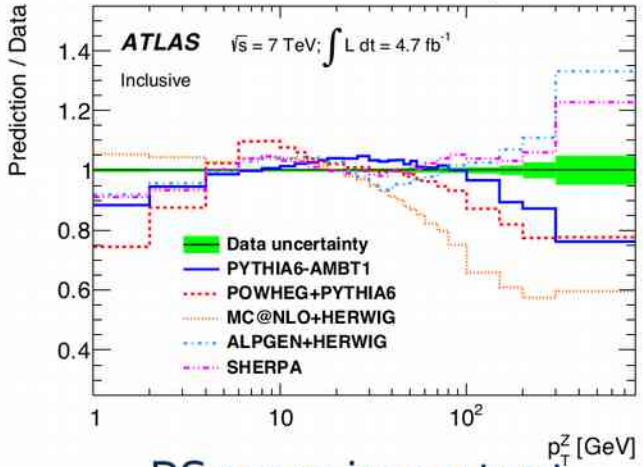




Resummation: Good description at low and average P_T



Fixed order (NNLO): Poor description at average P_T



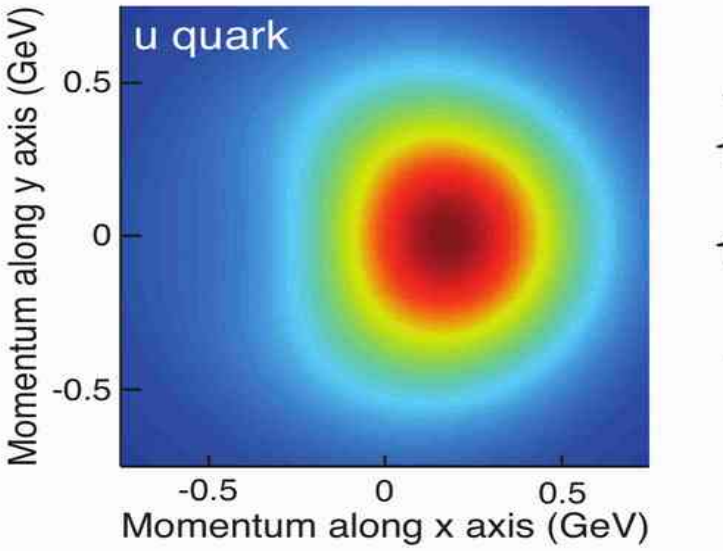
PS more important than NLO ME

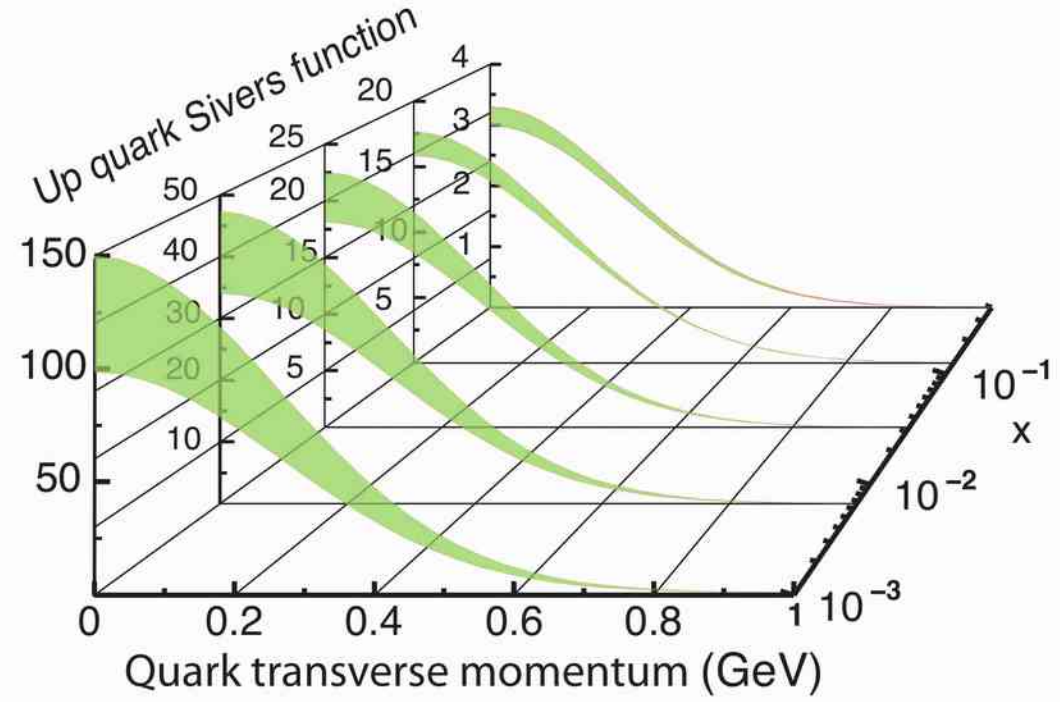
TMD & Generalized PDFs

previously discussed by: Rolf Ent & Michael Engelhardt

Kresimir Kumericki
Curse of dimensionality

Lattice Calculations





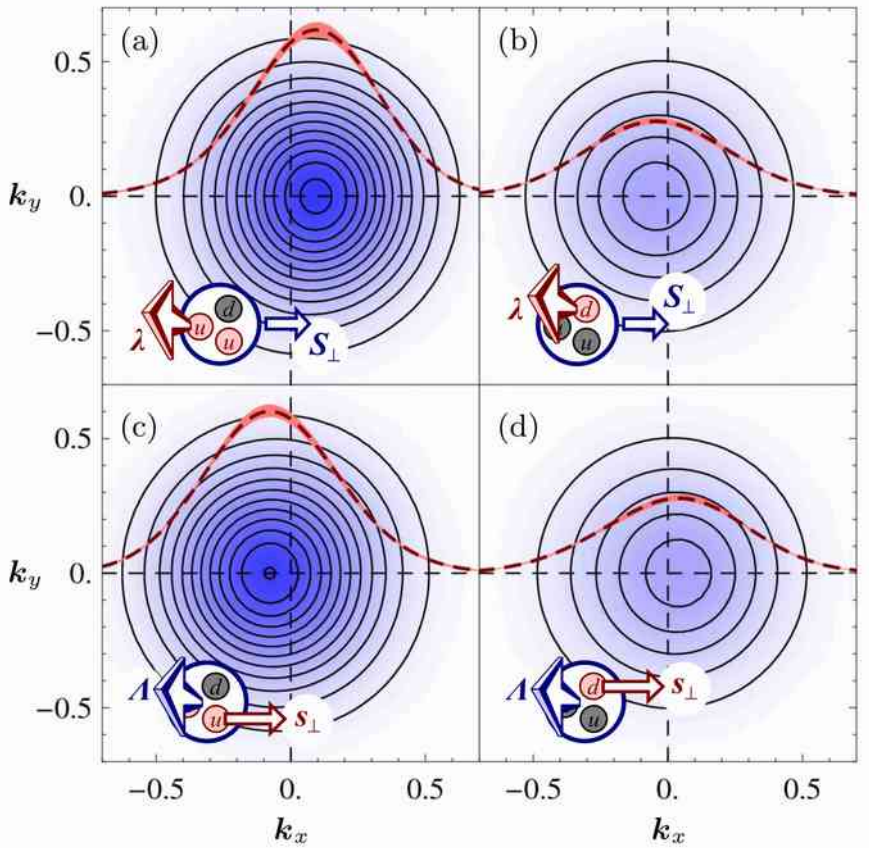


FIG. 3: Quark densities in the $\boldsymbol{k}_\perp$-plane, for $m_\pi \approx 500\,\mathrm{MeV}$. (a) ρ_L for u-quarks and $\lambda = 1$, $\boldsymbol{S}_\perp = (1,0)$, (b) the same for d-quarks, (c) ρ_T for u-quarks and $\Lambda = 1$, $\boldsymbol{s}_\perp = (1,0)$, (d) the same for d-quarks. The error bands show the density profile at $\boldsymbol{k}_y = 0$ as a function of $\boldsymbol{k}_x$ (scale not shown).

Intrinsic quark transverse momentum in the nucleon from lattice QCD
Hagler et al., TUM/T39-09-08

Higher Orders

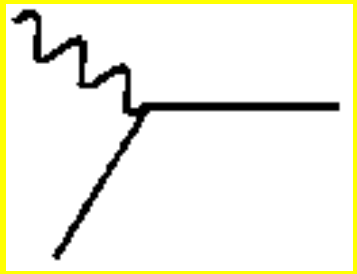
An example...

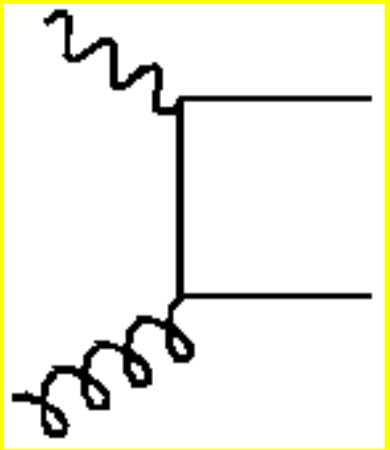
ACOT@ NNLO + N^3LO

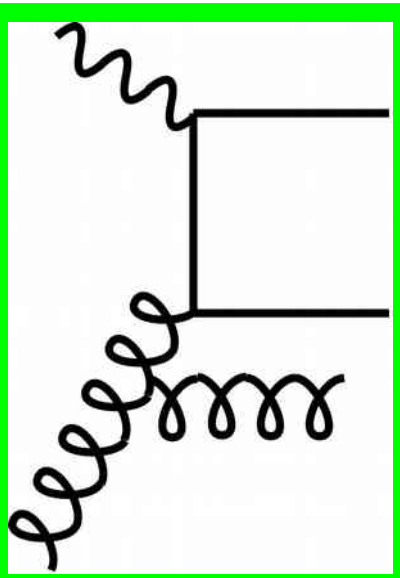
Stavreva, Olness, Schienbein, Jezo, Kusina, Kovarik, Yu
Phys.Rev. D85 (2012) 114014

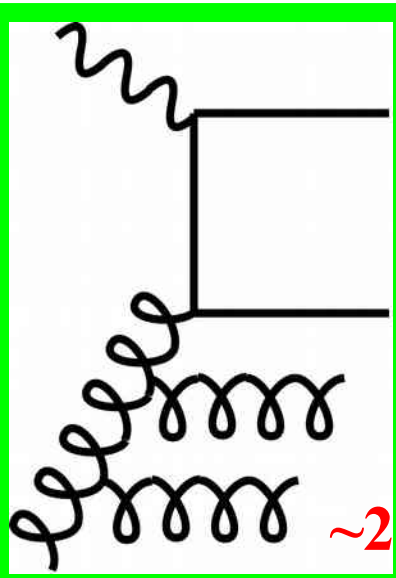
ACOT Extension to Higher Orders

LO **NLO** **N2LO** **N3LO**









~1995 ~2015

Full ACOT

Based on the Collins-Wilczek-Zee (CWZ) Renormalization Scheme
... hence, extensible to all orders

DGLAP kernels & PDF evolution are pure MS-Bar
Subtractions are MS-Bar

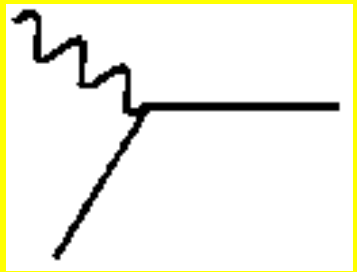
ACOT: $m \to 0$ limit yields MS-Bar
with no finite renormalization

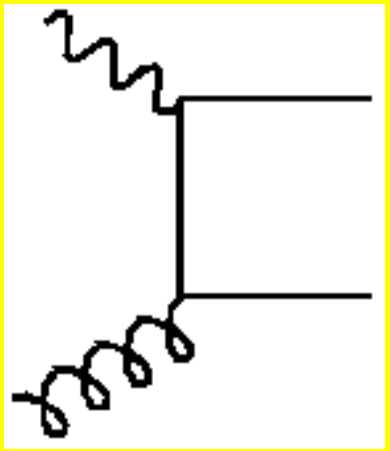
PDFs Discontinuous at N2LO

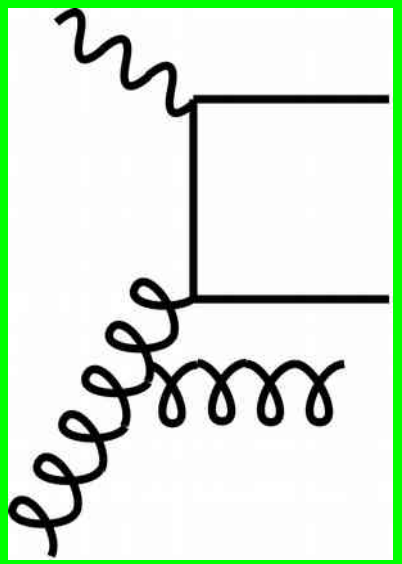
α_s Discontinuous at α_s^3

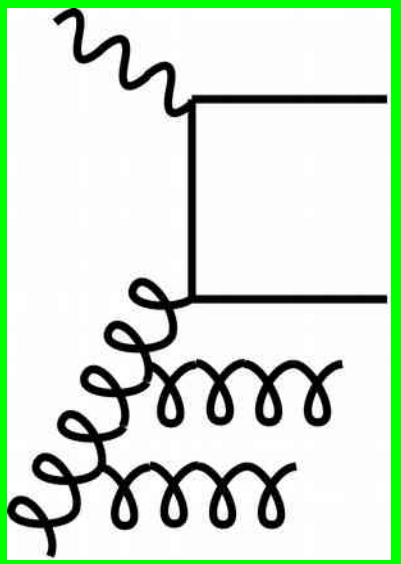
ACOT Extension to Higher Orders

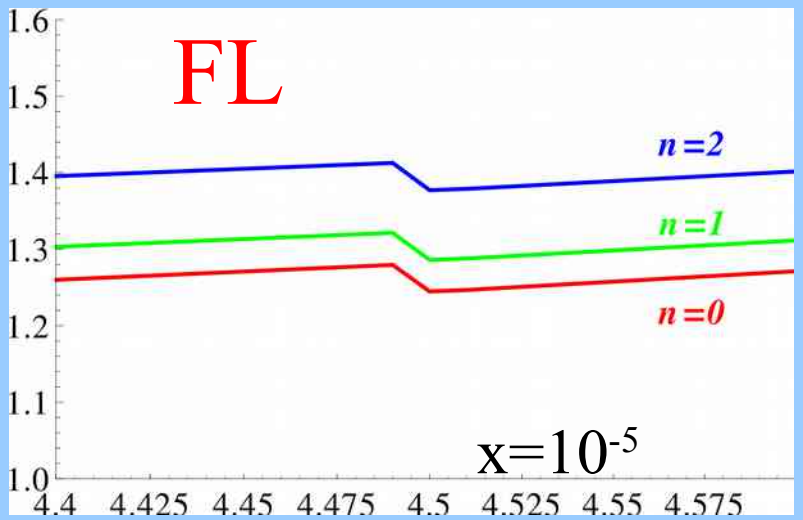
LO **NLO** **N2LO** **N3LO**











Quark & Gluon have opposite discontinuities

PDFs Discontinuous at N2LO

α_s Discontinuous at α_s^3

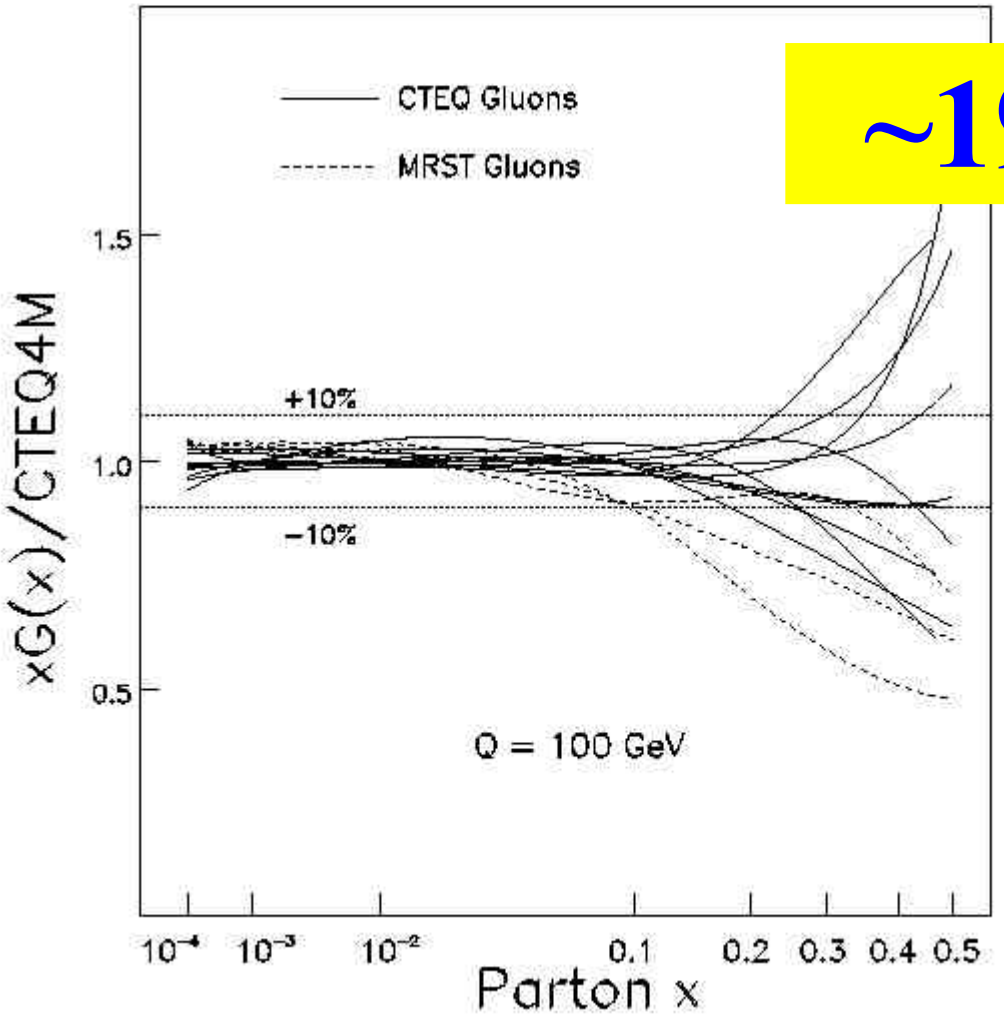
$$\sigma_{TOT}^{N_F+1} = \sigma_{TOT}^{N_F} + \mathcal{O}(\alpha_S^{m+1})$$

... this is really cool!!!

The CTEQ List of Challenges in Perturbative QCD

Large-x behavior of parton distributions

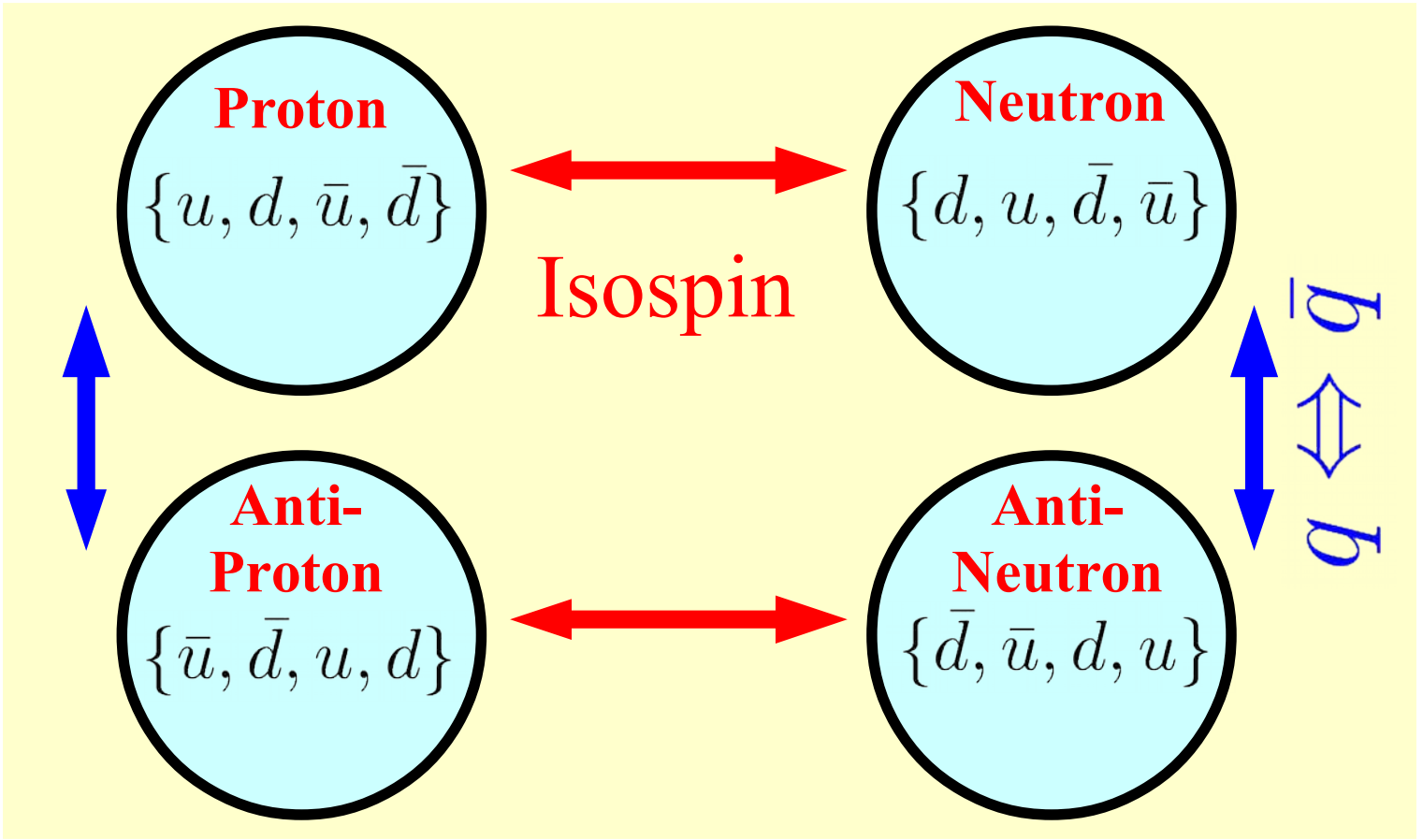
C T E Q

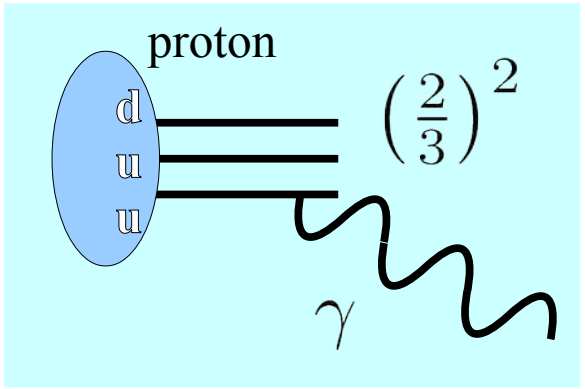


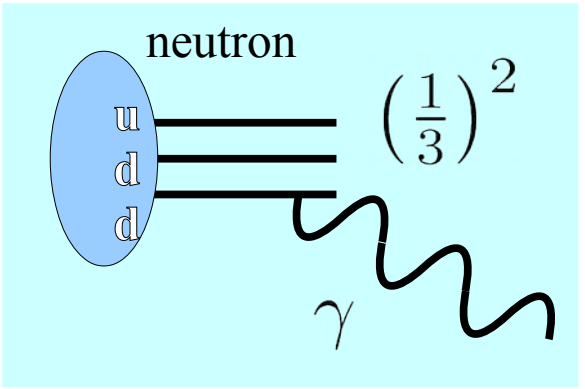
Isospin Symmetry

... taken for granted

Isospin Symmetry used to relate PDFs





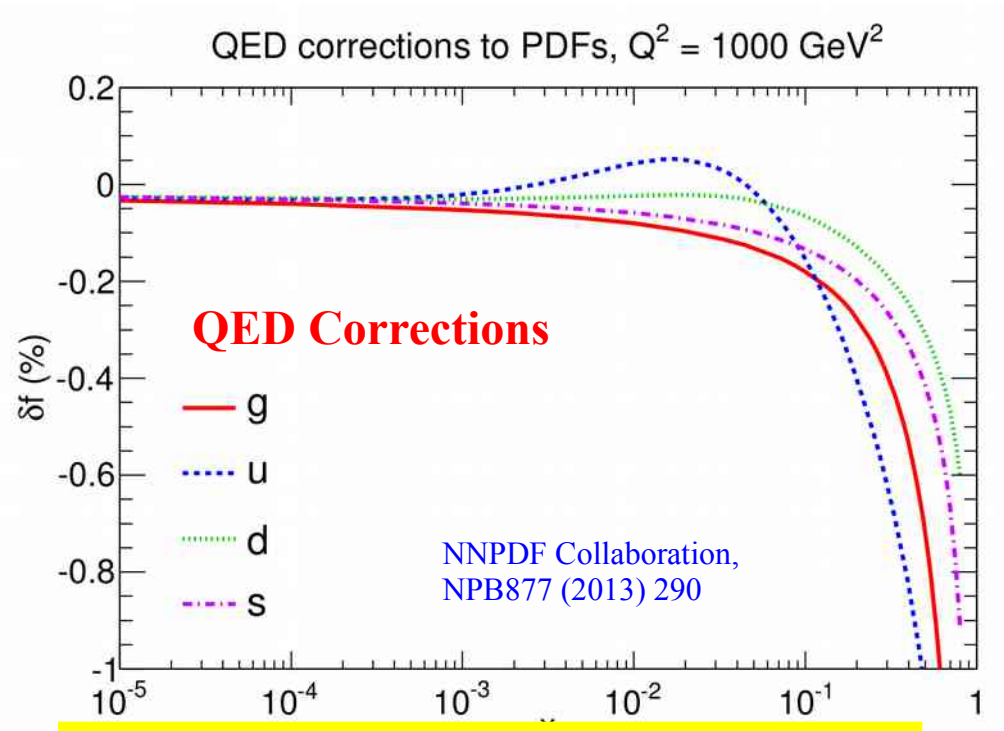


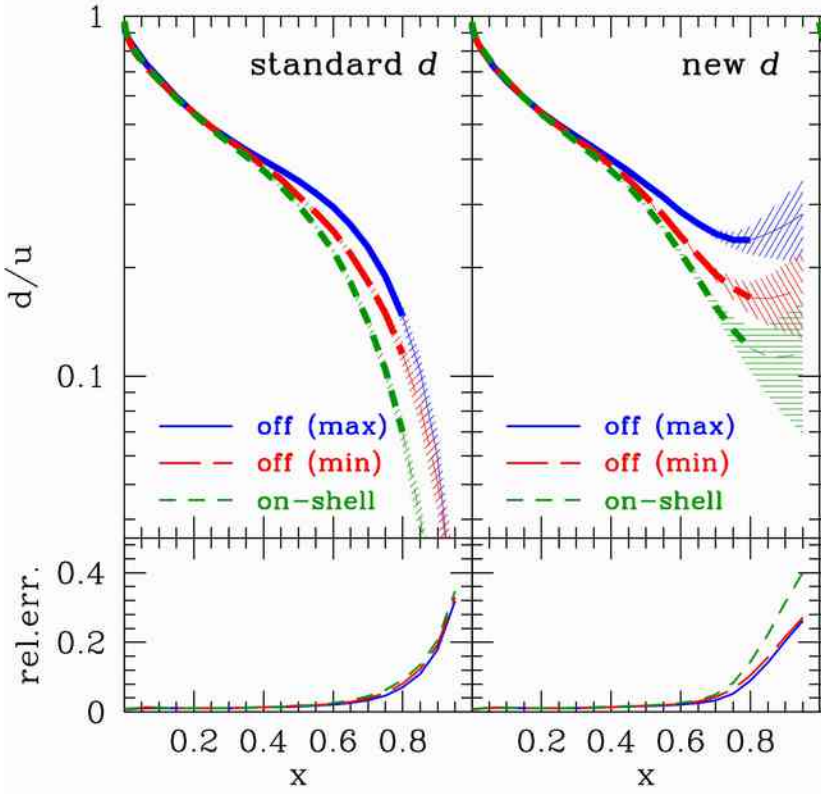
Isospin terms are comparable to NNLO QCD

QCD & EW Corrections do NOT factorize

A Review of Target Mass Corrections.
Ingo Schienbein et al,
J.Phys.G35:053101,2008.

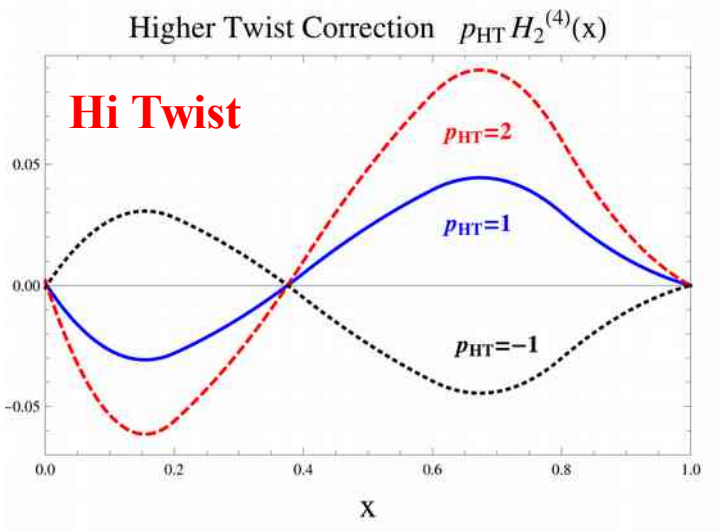
Hi-x Issues: Isospin Symmetry Violation, Higher Twist, ...

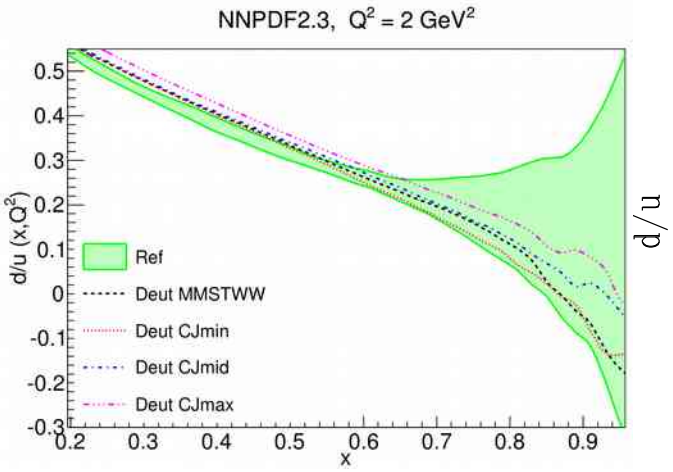


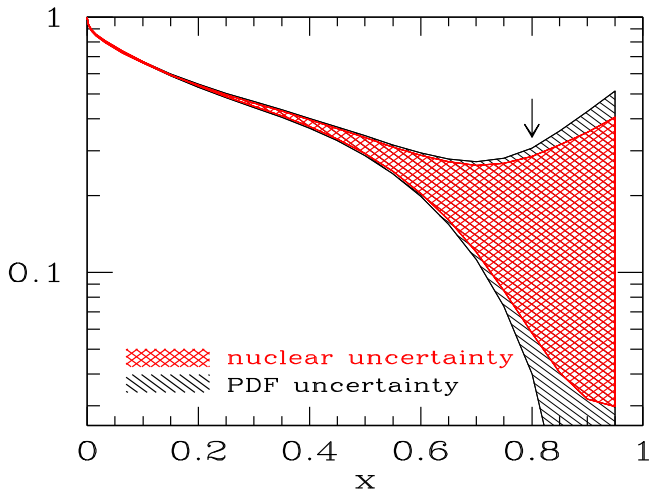


Hi-x is a "Gold Mine" for EIC

Nuclear Corrections or Parameterization???







The NNPDF Collaboration, PLB723 (2013) 330

CTEQ-CJ: Phys.Rev. D84 (2011) 014008

other effects

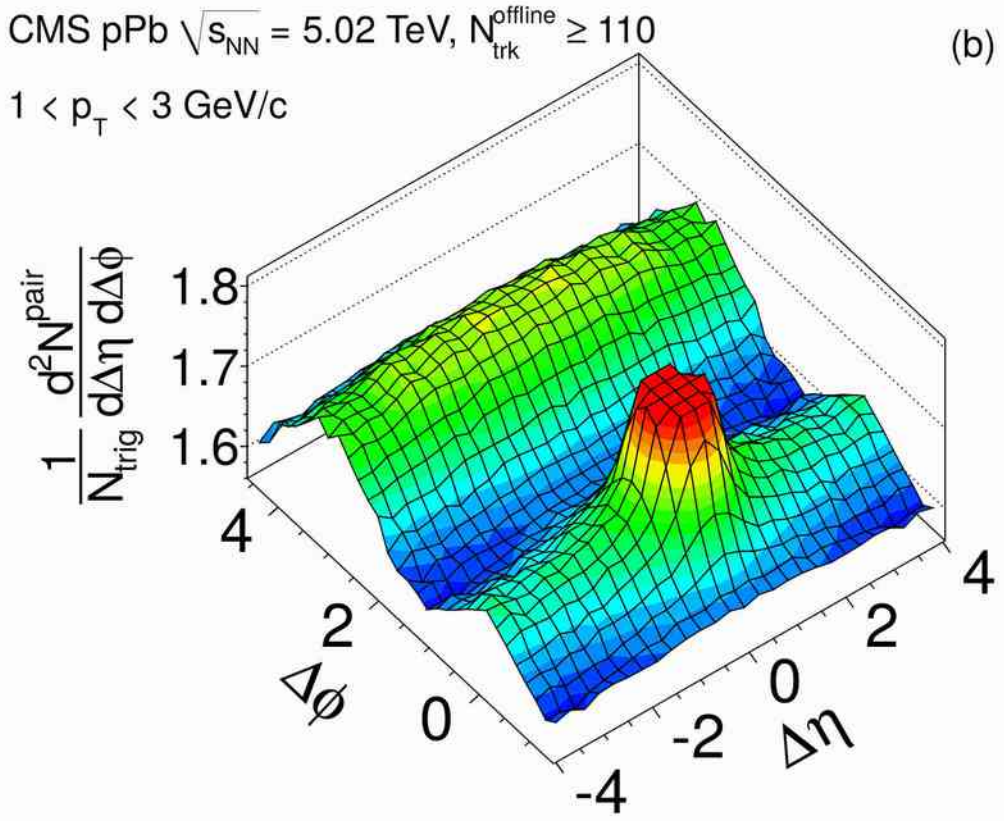
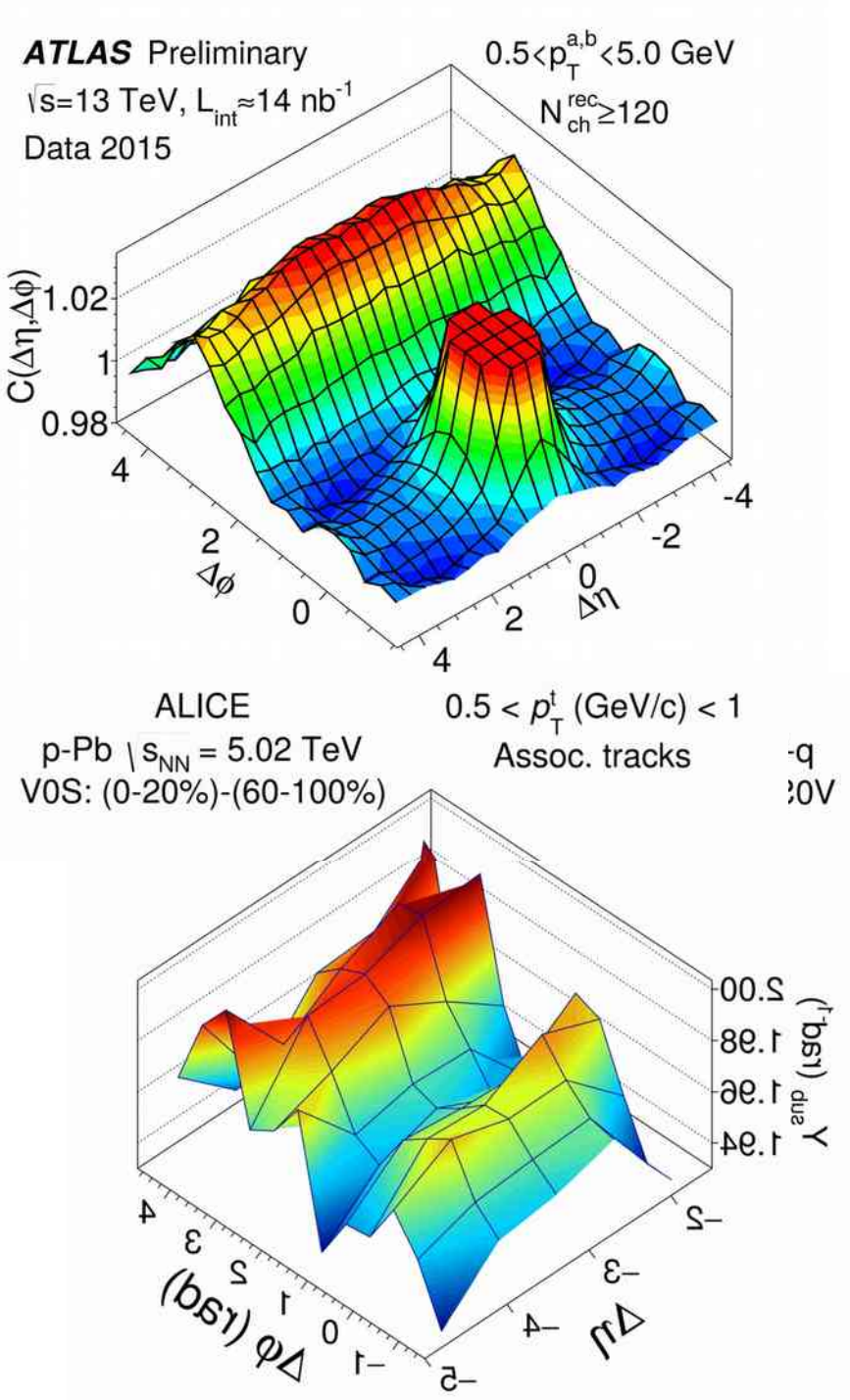


Figure 3.33: The two-particle correlation function in high-multiplicity p+Pb collisions as a function of $\Delta\phi$ and $\Delta\eta$ reported by the CMS collaboration [252]. The 'ridge' structure is seen as a correlation near $\Delta\phi = 0$ stretching over many units of rapidity $\Delta\eta$.



Conclusion

Thinking Outside the PDF

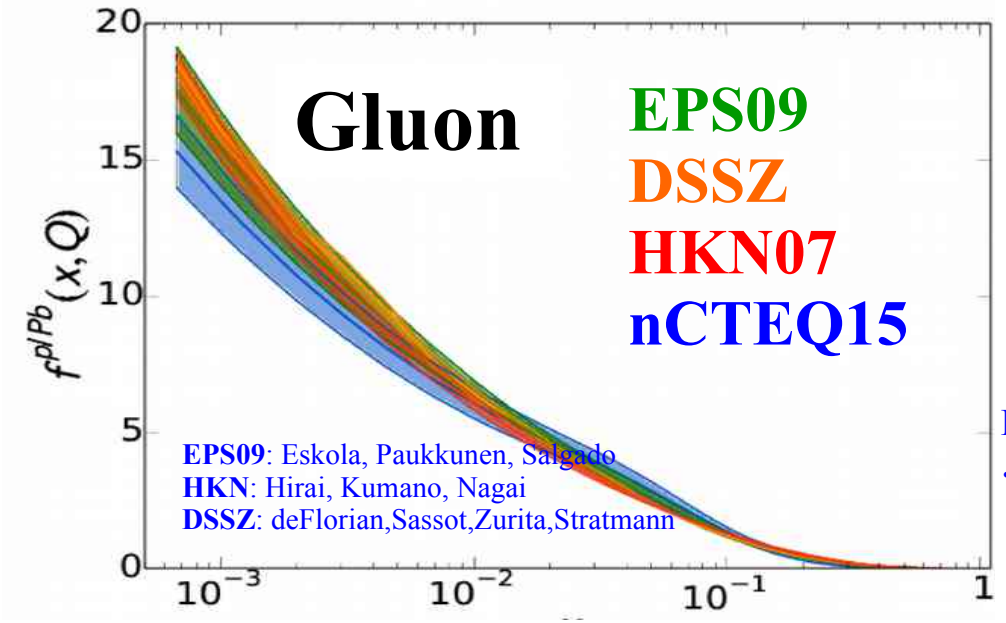
"QCD is our most perfect physical theory"

DGLAP violation???
saturation
resummation
QCD
QED
hi-x
low-Q^2
higher twist
non-linear QCD
Proton PDFs

communication

e.g. flavor differentiation

isospin violation
quark-gluon plasma
Fermi motion
Nuclear PDFs
jet quenching
target mass corrections
shadowing



1) Flavor Differentiation & Nuclear Corrections
2) Multi-scale problems: Heavy Quarks Resummation
3) Hi-Order Corrections

Lessons: The Nature of Nature … alien, simple, beautiful, weird, & comprehensible

W/Z/γ Production

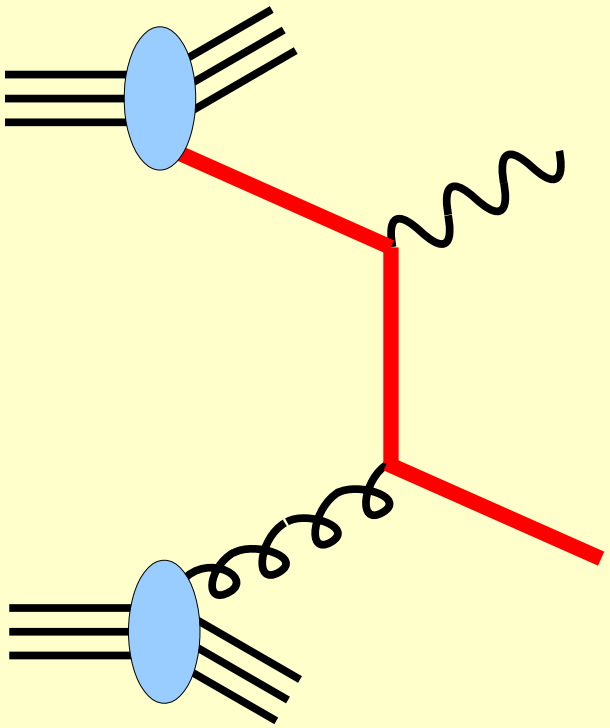
"Benchmark Calculations"

... how stable are these

... the fine print:

.....

Tevatron & LHC can Access Heavy Flavor Components Directly



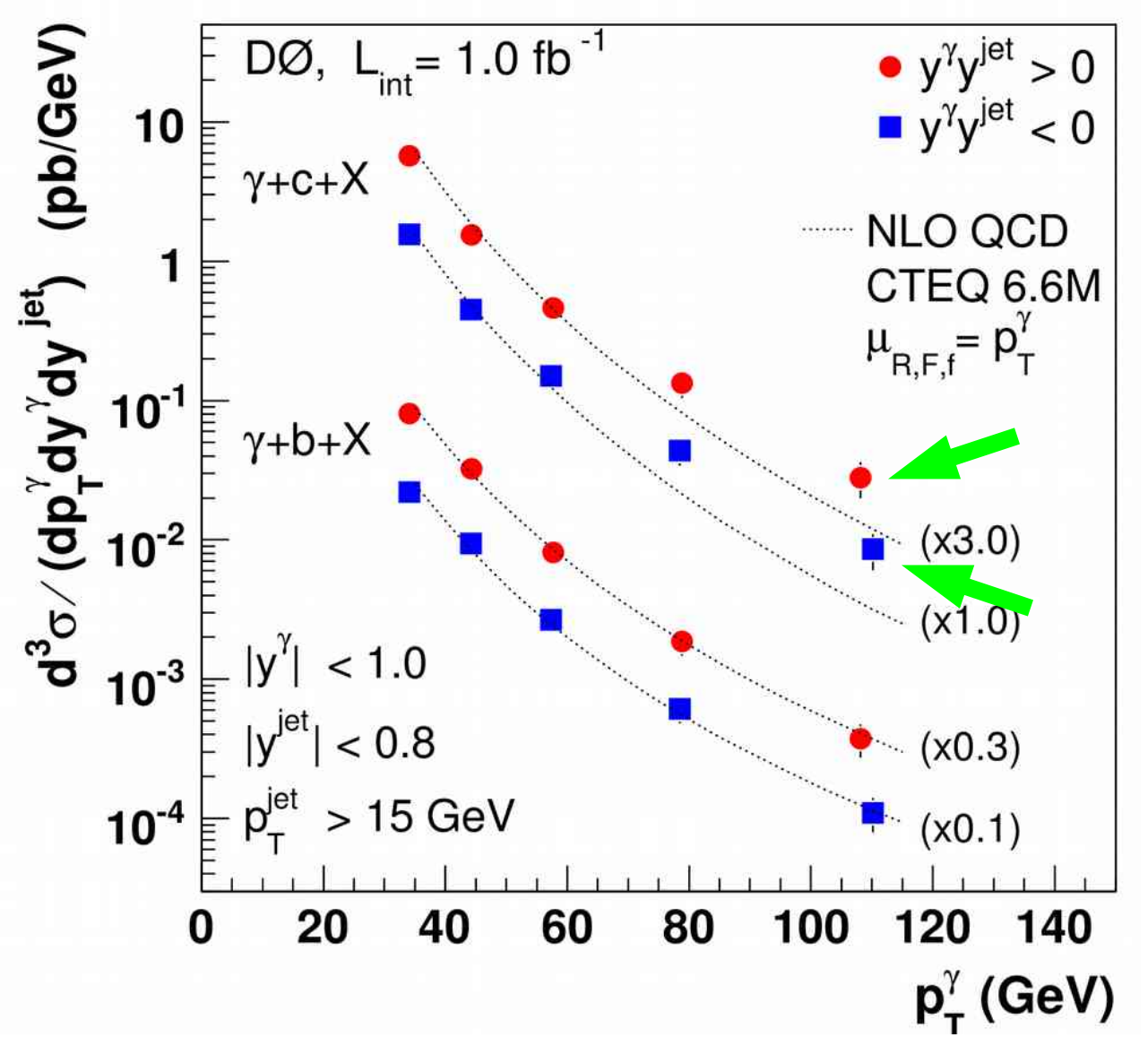
$$c\ g \rightarrow c\ \gamma$$

$$b\ g \rightarrow b\ \gamma$$

$$s\ g \rightarrow c\ W$$

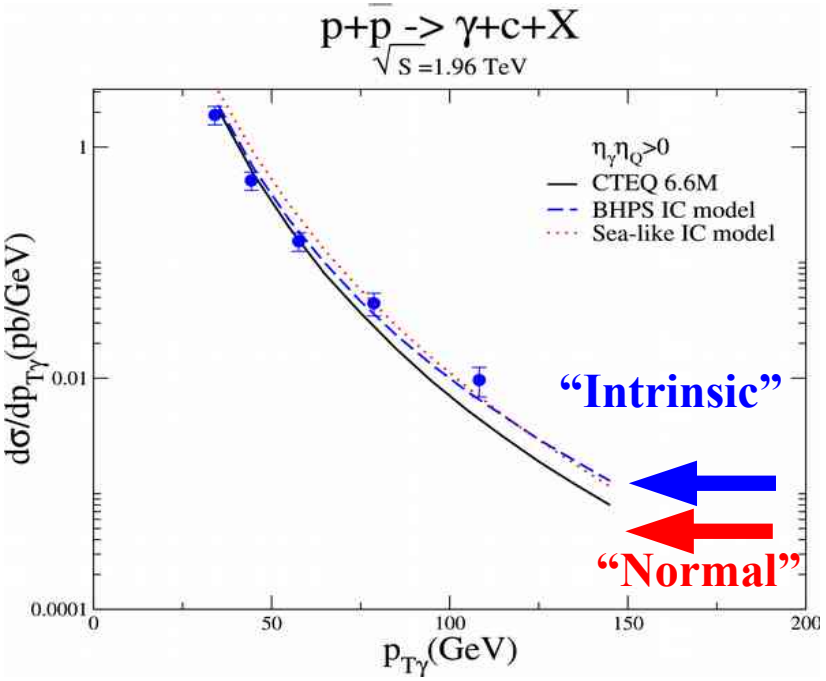
$$c\ g \rightarrow b\ W$$

Heavy Quarks at the Tevatron: … "intrinsic" charm???



Excess in Charm,
NOT Bottom

only at high PT



D. Duggan (D0) arXiv:0906.0136

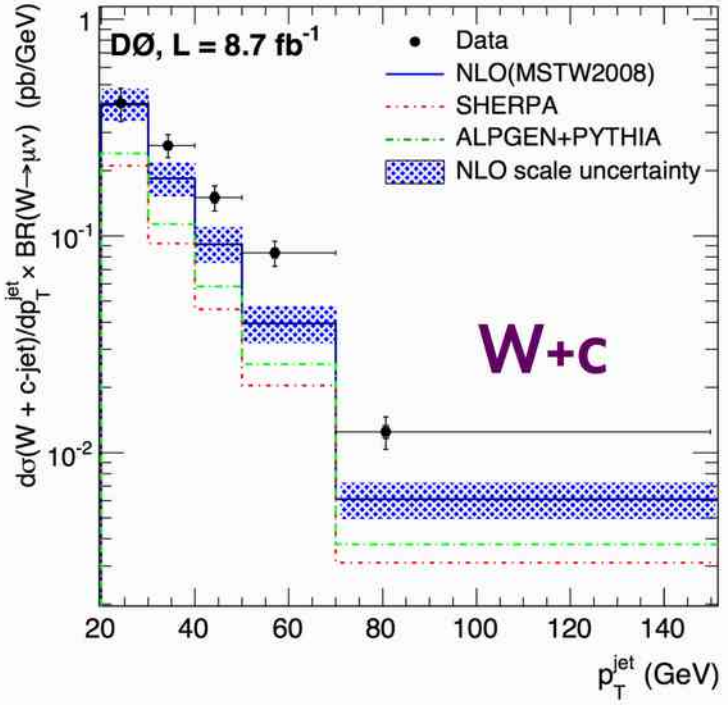
T. Stavreva, I. Schienbein, F. Arleo, K. Kovarik, F. Olness, J.Y. Yu, J.F. Owens, JHEP 1101 (2011) 152

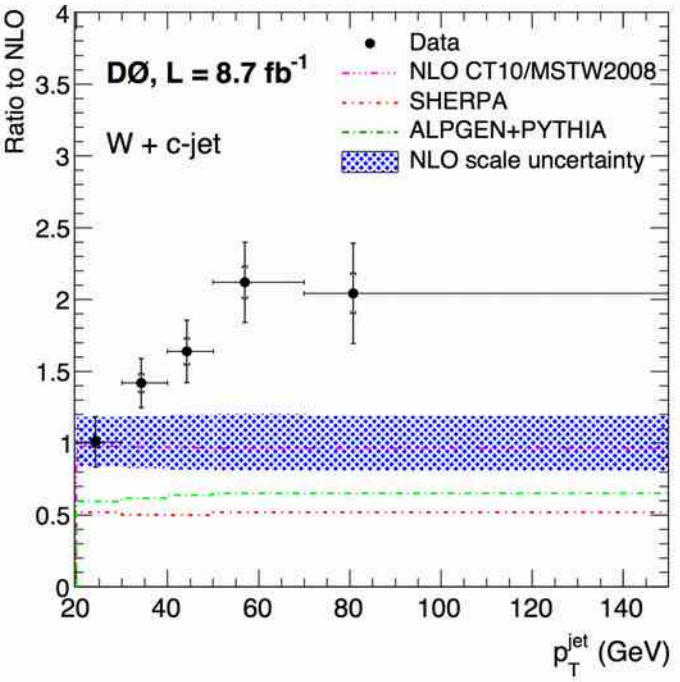
W+c production

Phys. Lett. B 743 (2015) 6; arXiv:1412.5315

Extracted W+c production rates corrected for efficiency and acceptance:

4–7% statistical and 12–17% systematic uncertainties, dominantly from c/b-jet ID, selection efficiency, and luminosity





Cross-section compared to predictions from NLO pQCD (corrected for non-perturbative effects), and Sherpa/Alpgen+Pythia MC models.

Unlike W+b, see a clear trend developing to higher jet p_T

High p_T range where gluon splitting becomes increasingly important.