

Parton Distributions and QCD

Precision QCD in the LHeC Era

Voica Radescu

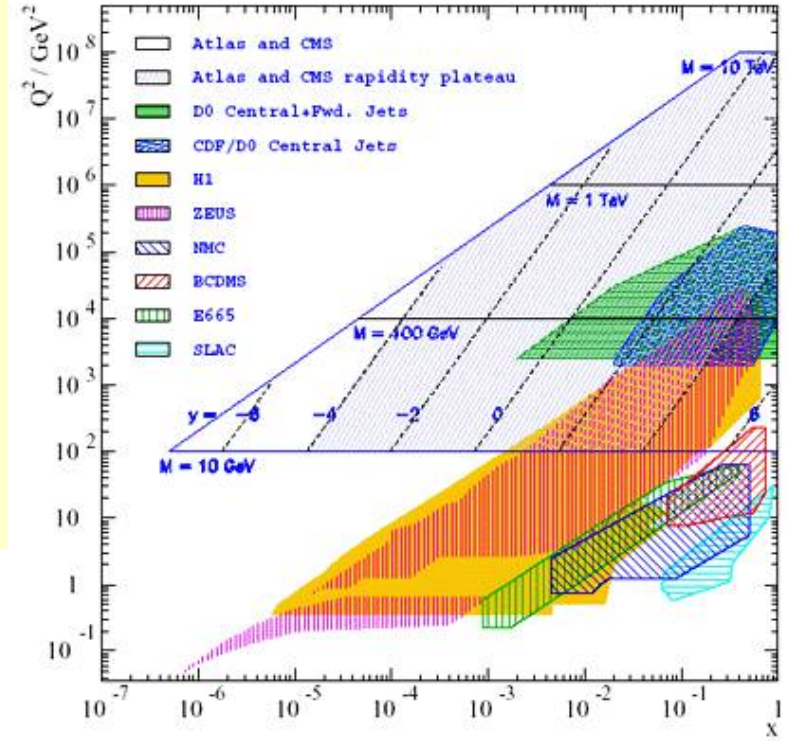
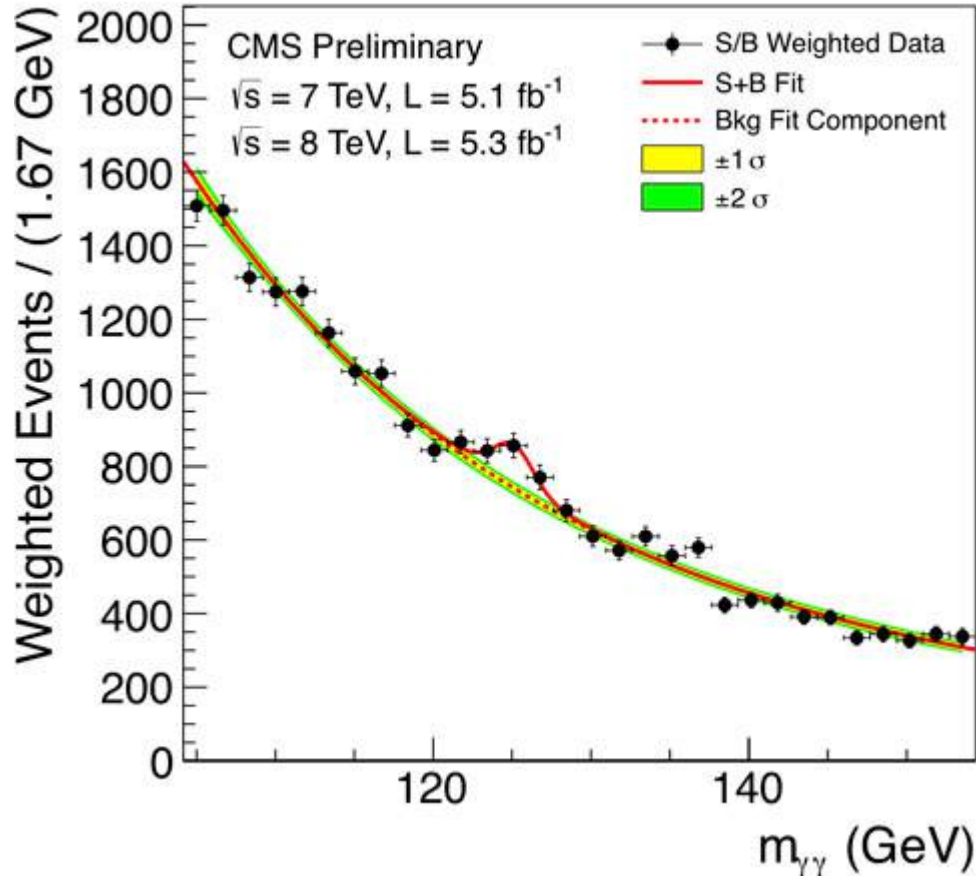
Fred Olness



LHC: Stage 1: High Energy

Use increased ENERGY REACH (2⇒8⇒13 TeV)
to search for new particles

e.g., Higgs Boson discovery
SUSY & Exotic limits



ATLAS SUSY Searches* - 95% CL Lower Limits
Source: SUSY 2013

ATLAS Preliminary
 $\sqrt{s} = 7, 8 \text{ TeV}$

Model	e, μ, τ, γ	Jets	$E_{\text{miss}}^{\text{min}}$	$[L dt] [\text{fb}^{-1}]$	Mass limit	Reference	
Inclusive Searches	MSUGRA/CMSM	0 2-6 jets	Yes	20.3	1.7 TeV	$m(\tilde{g})=m(\tilde{t}_1)$ ATLAS-COBF-2013-047	
	MSUGRA/CMSM	1 e, μ 3-6 jets	Yes	20.3	1.2 TeV	any m0 1308.1841	
	MSUGRA/CMSM	0 7-10 jets	Yes	20.3	1.1 TeV	$m(\tilde{t}_1)=0 \text{ GeV}$ ATLAS-COBF-2013-047	
	$\tilde{q}\tilde{q}, \tilde{q}-\tilde{q}^c$	0 2-6 jets	Yes	20.3	1.2 TeV	$m(\tilde{t}_1)=0 \text{ GeV}$ ATLAS-COBF-2013-047	
	$\tilde{q}\tilde{q}, \tilde{q}-\tilde{q}^c$	0 2-6 jets	Yes	20.3	1.2 TeV	$m(\tilde{t}_1)=0 \text{ GeV}$ ATLAS-COBF-2013-047	
	$\tilde{g}\tilde{g}, \tilde{g}-\tilde{g}^c$	1 e, μ 3-6 jets	Yes	20.3	1.1 TeV	$m(\tilde{t}_1)=200 \text{ GeV}, m(\tilde{t}_2)=0.5m(\tilde{t}_1)+m(\tilde{g})$ ATLAS-COBF-2013-062	
	$\tilde{g}\tilde{g}, \tilde{g}-\tilde{g}^c$	2 e, μ 0-3 jets	-	20.3	1.2 TeV	$m(\tilde{t}_1)=0 \text{ GeV}$ ATLAS-COBF-2013-089	
	GMSB (f NLSP)	2 e, μ 2-4 jets	Yes	4.7	1.2 TeV	$\tan\beta=15$ 1208.4668	
	GMSB (f NLSP)	1 τ, μ 0-2 jets	Yes	20.7	1.4 TeV	$\tan\beta=18$ ATLAS-COBF-2013-026	
	GGM (bino NLSP)	2 γ	Yes	4.8	1.0 TeV	$m(\tilde{t}_1)=50 \text{ GeV}$ 1209.0753	
	GGM (wino NLSP)	1 $e, \mu + \gamma$	Yes	4.8	619 GeV	$m(\tilde{t}_1)=50 \text{ GeV}$ ATLAS-COBF-2012-144	
	GGM (higgsino bino NLSP)	1 τ, μ 1 b	Yes	4.8	900 GeV	$m(\tilde{t}_1)=200 \text{ GeV}$ 1211.1167	
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$m(\tilde{t}_1)=200 \text{ GeV}$ ATLAS-COBF-2012-152	
	Gravitino LSP	0 mono-jet	Yes	10.5	645 GeV	$m(\tilde{g}) > 10^4 \text{ GeV}$ ATLAS-COBF-2012-147	
3rd gen. \tilde{t}_1, \tilde{b}_1	$\tilde{g}-\tilde{t}\tilde{t}^c$	0 3 b	Yes	20.1	1.2 TeV	$m(\tilde{t}_1)=600 \text{ GeV}$ ATLAS-COBF-2013-061	
	$\tilde{g}-\tilde{t}\tilde{t}^c$	0 7-10 jets	Yes	20.3	1.1 TeV	$m(\tilde{t}_1)=350 \text{ GeV}$ 1308.1841	
	$\tilde{g}-\tilde{t}\tilde{t}^c$	0-1 e, μ 3 b	Yes	20.1	1.24 TeV	$m(\tilde{t}_1)=400 \text{ GeV}$ ATLAS-COBF-2013-061	
	$\tilde{g}-\tilde{b}\tilde{b}^c$	0-1 e, μ 3 b	Yes	20.1	1.3 TeV	$m(\tilde{t}_1)=300 \text{ GeV}$ ATLAS-COBF-2013-061	
3rd gen. squarks direct production	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	0 2 b	Yes	20.1	100-820 GeV	$m(\tilde{t}_1)=90 \text{ GeV}$ 1308.2631	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	2 e, μ (SS)	0-3 b	Yes	20.7	$m(\tilde{t}_1)=2 m(\tilde{t}_1)$ ATLAS-COBF-2013-007	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	1-2 e, μ 1-2 b	Yes	4.7	110-167 GeV	1208.4905, 1209.2102	
	$\tilde{t}_1\tilde{t}_1$ (high), $\tilde{t}_1-\tilde{t}_1^c$	2 e, μ 0-2 jets	Yes	20.3	130-220 GeV	$m(\tilde{t}_1)=m(\tilde{t}_1)+m(W)+50 \text{ GeV}, m(\tilde{t}_1) < m(\tilde{t}_1)$ ATLAS-COBF-2013-048	
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1-\tilde{t}_1^c$	2 e, μ 2 jets	Yes	20.3	225-325 GeV	$m(\tilde{t}_1)=0 \text{ GeV}$ ATLAS-COBF-2013-065	
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1-\tilde{t}_1^c$	0 2 b	Yes	20.3	150-880 GeV	$m(\tilde{t}_1)=200 \text{ GeV}, m(\tilde{t}_2)=m(\tilde{t}_1)+5 \text{ GeV}$ 1308.2631	
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1-\tilde{t}_1^c$	1 e, μ 1 b	Yes	20.7	200-610 GeV	$m(\tilde{t}_1)=0 \text{ GeV}$ ATLAS-COBF-2013-037	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	0 2 b	Yes	20.5	320-660 GeV	$m(\tilde{t}_1)=0 \text{ GeV}$ ATLAS-COBF-2013-064	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	0 mono-jet+tag	Yes	20.3	90-200 GeV	$m(\tilde{t}_1)=m(\tilde{t}_1)+85 \text{ GeV}$ ATLAS-COBF-2013-068	
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$m(\tilde{t}_1)=150 \text{ GeV}$ ATLAS-COBF-2013-025	
	$\tilde{t}_1\tilde{t}_2, \tilde{t}_2-\tilde{t}_1+Z$	3 e, μ (Z)	1 b	Yes	20.7	$m(\tilde{t}_1)=m(\tilde{t}_2)+180 \text{ GeV}$ ATLAS-COBF-2013-025	
EW direct	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	2 e, μ 0	Yes	20.3	85-315 GeV	$m(\tilde{t}_1)=0 \text{ GeV}$ ATLAS-COBF-2013-049	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	2 e, μ 0	Yes	20.7	124-450 GeV	$m(\tilde{t}_1)=0 \text{ GeV}, m(\tilde{t}_2)=0.5m(\tilde{t}_1)+m(\tilde{t}_1)$ ATLAS-COBF-2013-049	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	2 τ, μ	Yes	20.7	180-330 GeV	$m(\tilde{t}_1)=0 \text{ GeV}, m(\tilde{t}_2)=0.5m(\tilde{t}_1)+m(\tilde{t}_1)$ ATLAS-COBF-2013-028	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	3 e, μ 0	Yes	20.7	600 GeV	$m(\tilde{t}_1)=0 \text{ GeV}, m(\tilde{t}_2)=0.5m(\tilde{t}_1)+m(\tilde{t}_1)$ ATLAS-COBF-2013-035	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	3 e, μ 0	Yes	20.7	315 GeV	$m(\tilde{t}_1)=m(\tilde{t}_2), m(\tilde{t}_2)=0$, stauons decoupled ATLAS-COBF-2013-035	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	1 e, μ 2 b	Yes	20.3	285 GeV	$m(\tilde{t}_1)=m(\tilde{t}_2), m(\tilde{t}_2)=0$, stauons decoupled ATLAS-COBF-2013-093	
Long-lived particles	Direct $\tilde{t}_1\tilde{t}_1$ prod., long-lived \tilde{t}_1^c	Disapp. trk	1 jet	Yes	20.3	$m(\tilde{t}_1)=160 \text{ MeV}, \tau(\tilde{t}_1^c)=0.2 \text{ ns}$ ATLAS-COBF-2013-069	
	Stable, stopped \tilde{g} R-hadron	0 1-5 jets	Yes	22.9	100 GeV, $10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$ ATLAS-COBF-2013-057		
	GMSB, spale $\tilde{t}_1-\tilde{t}_1^c \rightarrow \tilde{t}_1, \tilde{t}_1^c \rightarrow \tilde{t}_1, \tilde{t}_1^c$	2 γ	-	4.7	475 GeV	$10^{-10} \text{ s} < \tau(\tilde{t}_1^c) < 10^{-9} \text{ s}$ 1304.6310	
	GMSB, $\tilde{t}_1^c \rightarrow \tilde{t}_1, \tilde{t}_1^c \rightarrow \tilde{t}_1, \tilde{t}_1^c$	1 μ , displ. vtx	-	20.3	230 GeV	$1.5 < c\tau < 156 \text{ mm}, \text{BR}(\tilde{t}_1 \rightarrow \mu) > 108 \text{ GeV}$ ATLAS-COBF-2013-092	
RPV	LFV $pp \rightarrow \tilde{t}_1 + X, \tilde{t}_1 \rightarrow e + \mu$	2 e, μ	-	4.6	1.8 TeV	$\tilde{t}_1 \rightarrow 0.10, \tilde{t}_1 \rightarrow 0.05$ 1212.1272	
	Bilinear RPV CMSM	1 e, μ, τ	-	4.6	1.1 TeV	$m(\tilde{t}_1)=m(\tilde{t}_2), \text{cr}_{\text{up}} < 1 \text{ mm}$ ATLAS-COBF-2012-140	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	1 e, μ 7 jets	Yes	4.7	1.2 TeV	$m(\tilde{t}_1)=300 \text{ GeV}, \tilde{t}_1 \rightarrow 0$ ATLAS-COBF-2013-036	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	4 e, μ	Yes	20.7	760 GeV	$m(\tilde{t}_1)=80 \text{ GeV}, \tilde{t}_1 \rightarrow 0$ ATLAS-COBF-2013-036	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	3 $e, \mu + \tau$	Yes	20.7	350 GeV	$\text{BR}(\tilde{t}_1 \rightarrow \text{RPV}) < 10\%$ ATLAS-COBF-2013-091	
	$\tilde{g}-\tilde{t}_1\tilde{t}_1$	0 6-7 jets	Yes	20.3	916 GeV	ATLAS-COBF-2013-091	
	$\tilde{g}-\tilde{t}_1\tilde{t}_1, \tilde{t}_1-\tilde{t}_1^c$	2 e, μ (SS)	0-3 b	Yes	20.7	880 GeV	ATLAS-COBF-2013-007
Other	Scalar gluon pair, sgluon→ $q\bar{q}$	0 4 jets	-	4.6	100-287 GeV	incl. limit from 110.2693 1210.4826	
	Scalar gluon pair, sgluon→ $t\bar{t}$	2 e, μ (SS)	1 b	Yes	14.3	800 GeV	ATLAS-COBF-2013-051
	WIMP interaction (DS, Direct)	0 mono-jet	Yes	10.5	794 GeV	$m(\tilde{t}_1)=80 \text{ GeV}$, limit of 487 GeV for DS ATLAS-COBF-2012-147	

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

LHC: Stage 2: High Precision

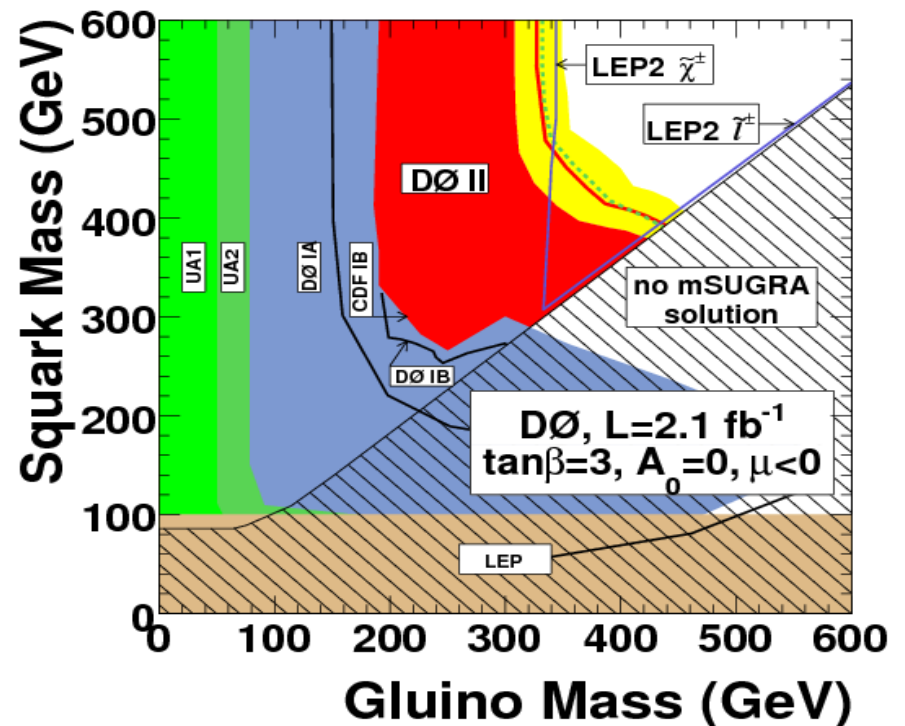
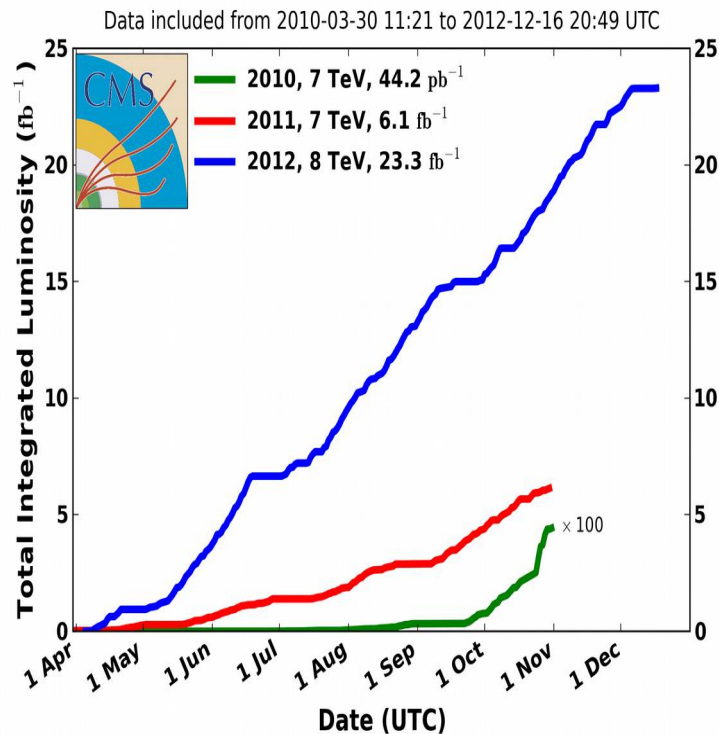
Enter LHeC: provides important complement to LHC:

Use increased INTENSITY (stats + upgrades) for improved precision
-- this allows us to probe new physics beyond the machine energy

e.g., as Tevatron+HERA did for Higgs/SUSY/exotics searches

Note: HERA essential for PDFs at both Tevatron and LHC

CMS Integrated Luminosity, pp



Make use of LHeC to probe kinematic “corners” to look at QCD under extreme conditions:

Small-x:

saturation, BFKL, $\ln(1/x)$

Large-x:

TMC,
Higher-Twist,
fermi motion

Low Q:

Strong coupling
Non-perturbative effects

TMD PDFs:

Soft gluon resummation
(now in HERA-Fitter)

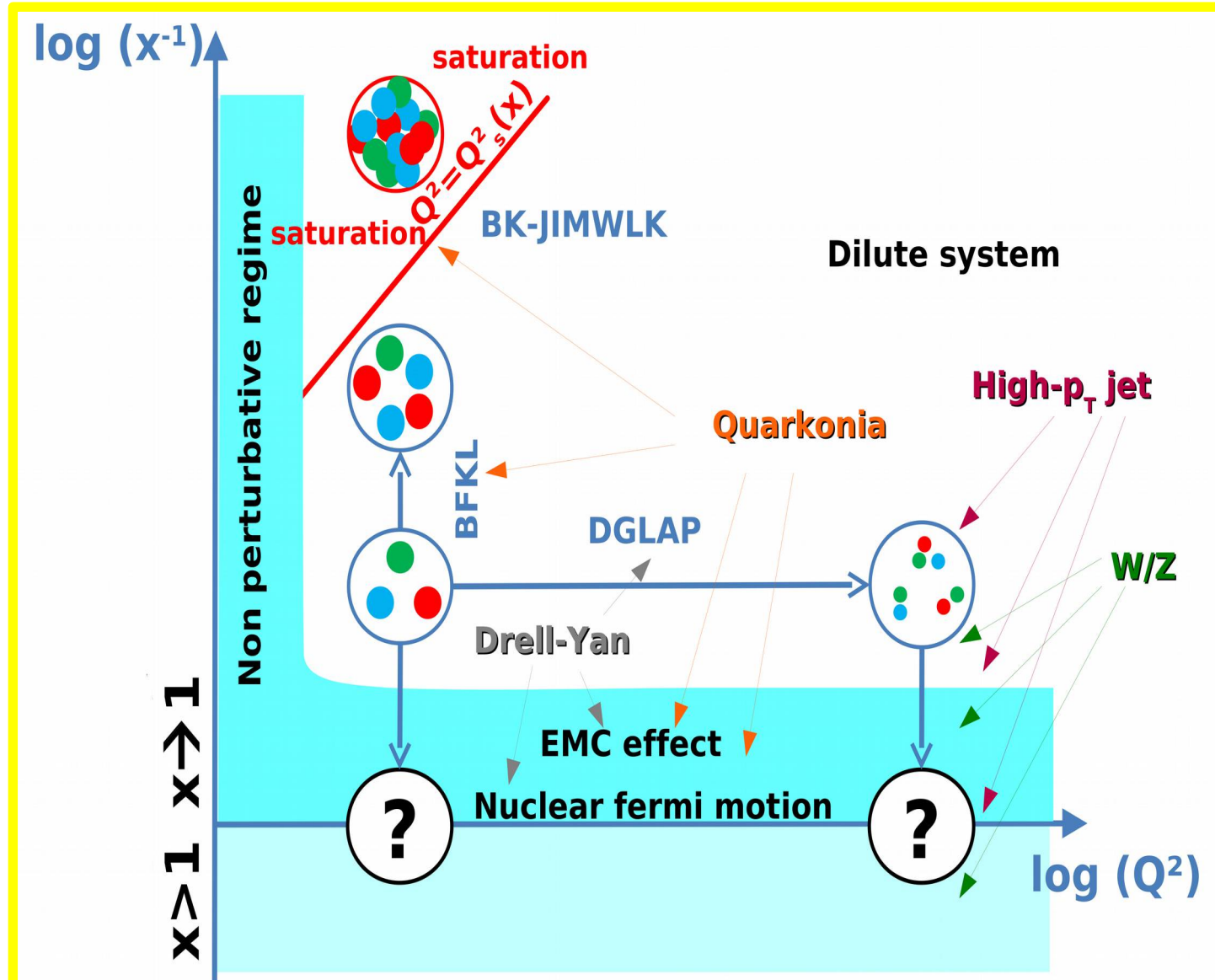
Heavy Quarks:

Multi-scale issues

Nuclear Dimension:

Nuclear Corrections
High Temperature
QGP, deconfinement

QED Corrections:



Nuclear Correction:

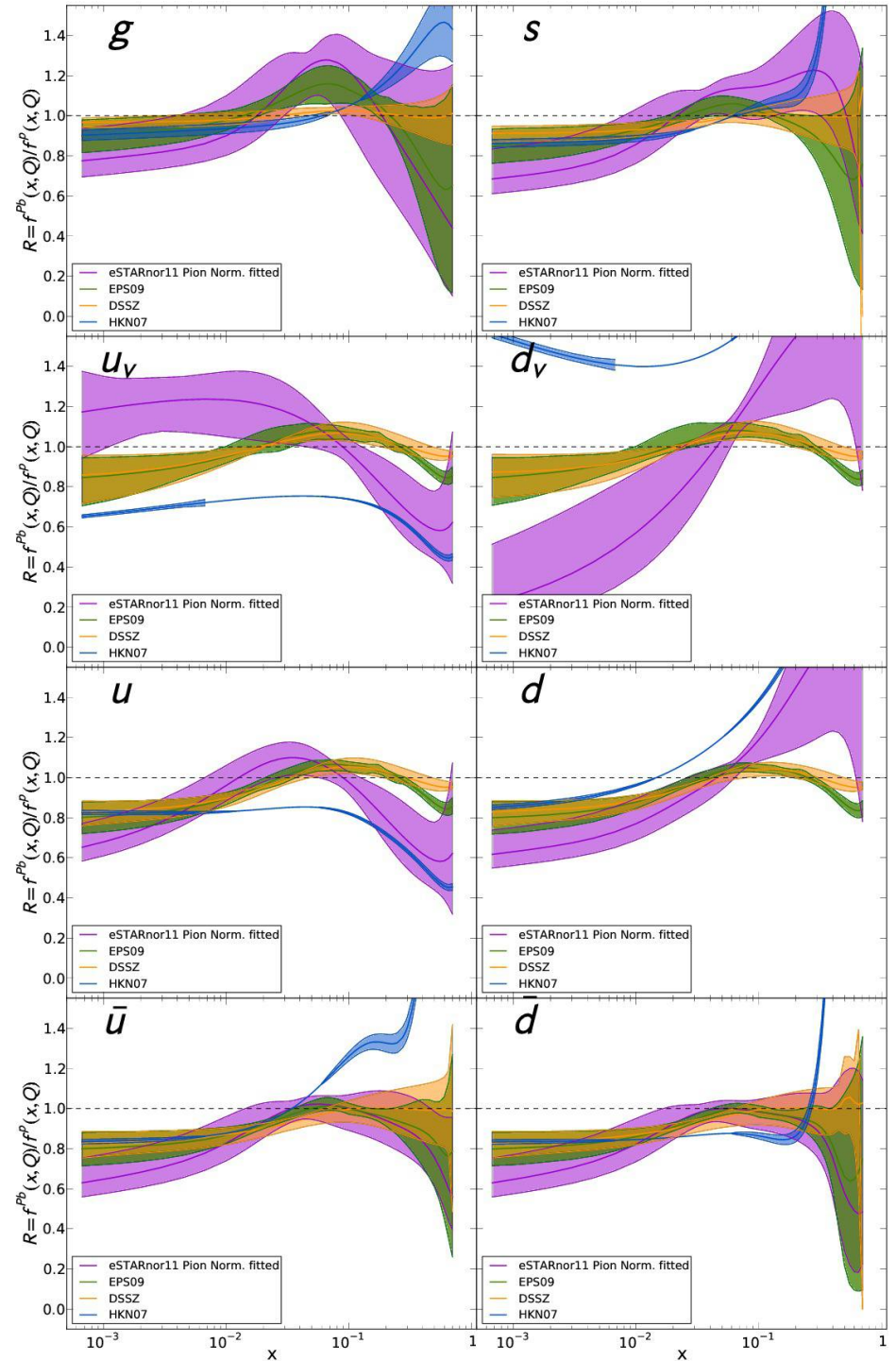
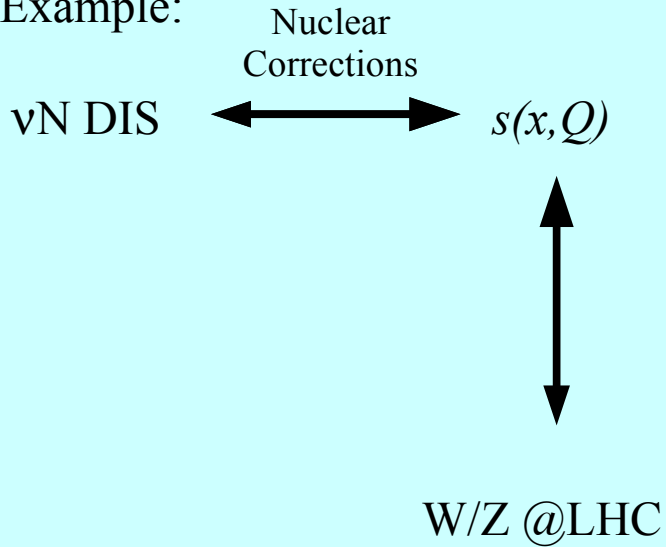
Comparisons:

Preliminary

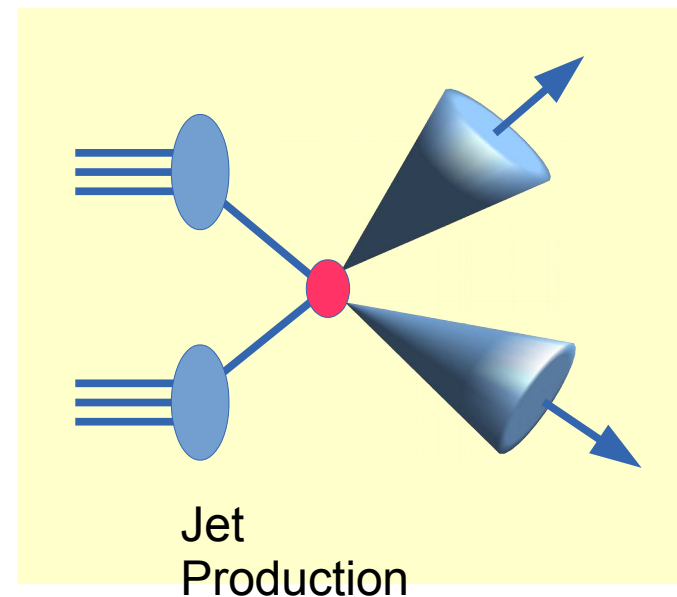
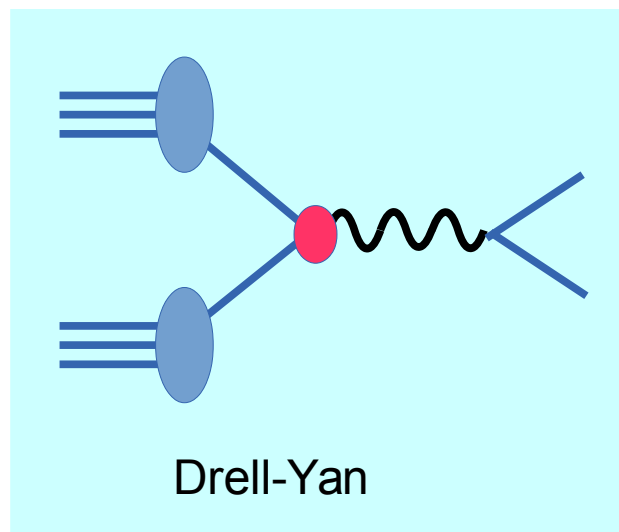
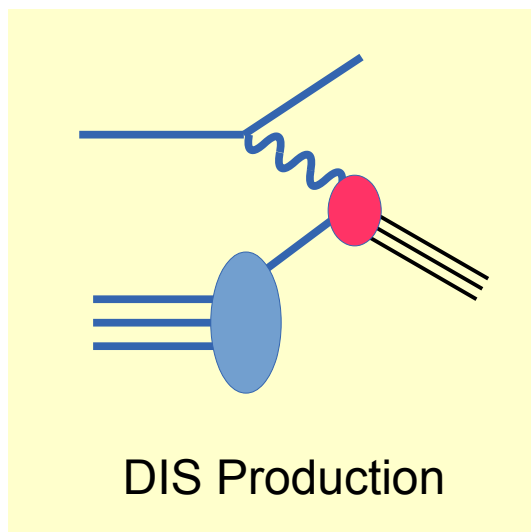
$$\frac{f^{Pb}(x, Q^2)}{f^p(x, Q^2)}$$

Large uncertainties,
especially when compared to proton

Example:



Leftover



$$F_2^\nu \sim [d + s + \bar{u} + \bar{c}]$$

$$F_2^{\bar{\nu}} \sim [\bar{d} + \bar{s} + u + c]$$

$$F_3^\nu = 2 [d + s - \bar{u} - \bar{c}]$$

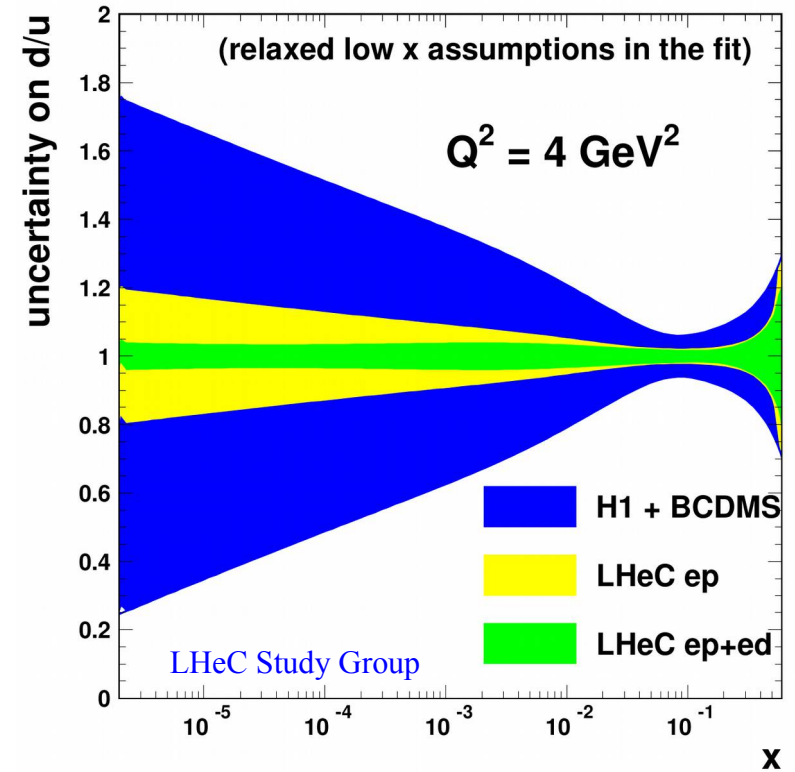
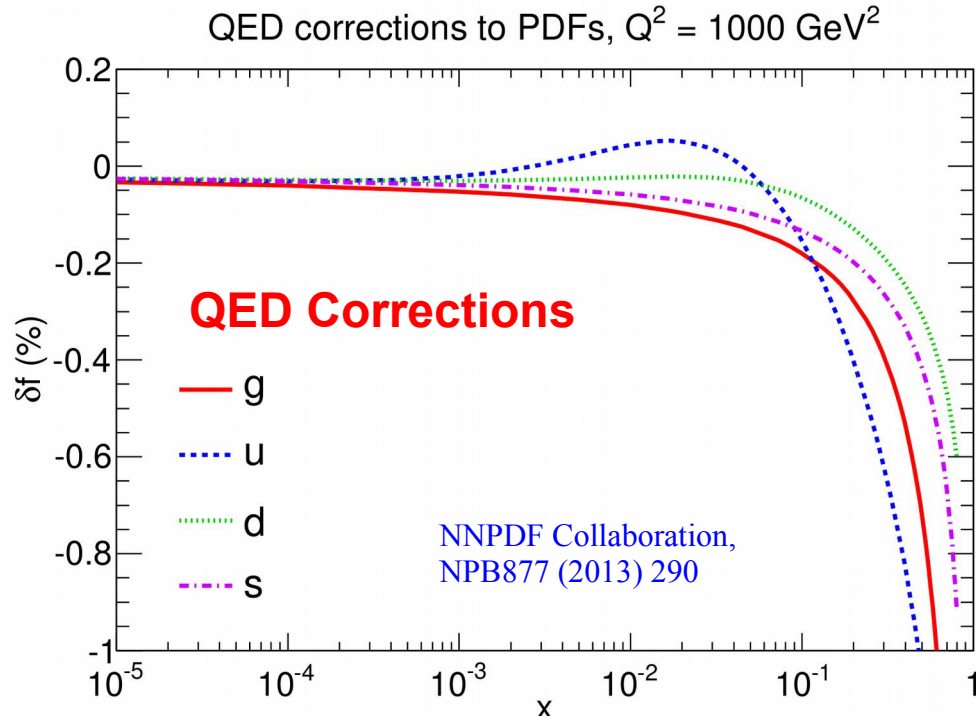
$$F_3^{\bar{\nu}} = 2 [u + c - \bar{d} - \bar{s}]$$

$$F_2^{\ell^\pm} \sim \left(\frac{1}{3}\right)^2 [d + s] + \left(\frac{2}{3}\right)^2 [u + c]$$

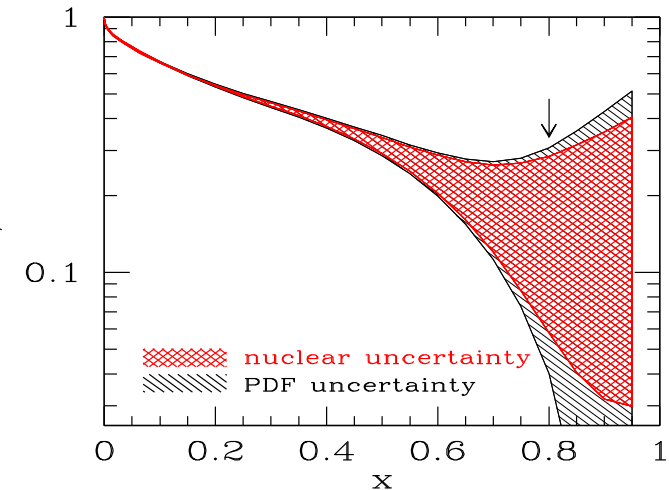
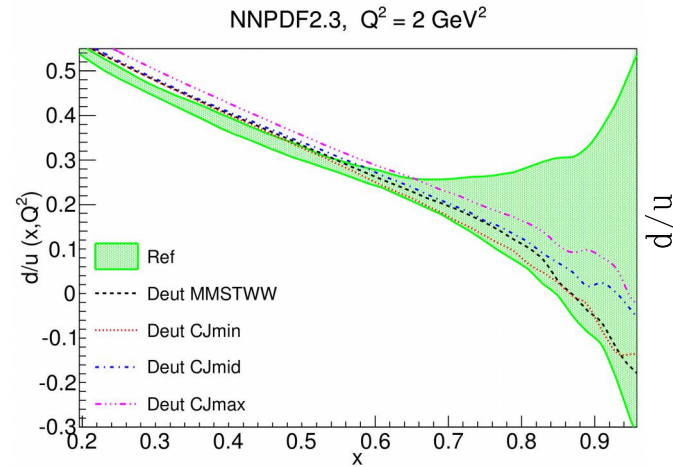
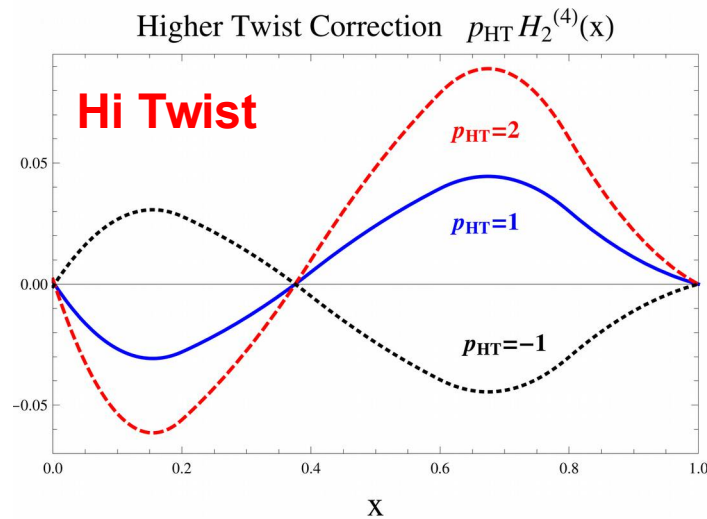
The DIS combinations have historically been particularly useful

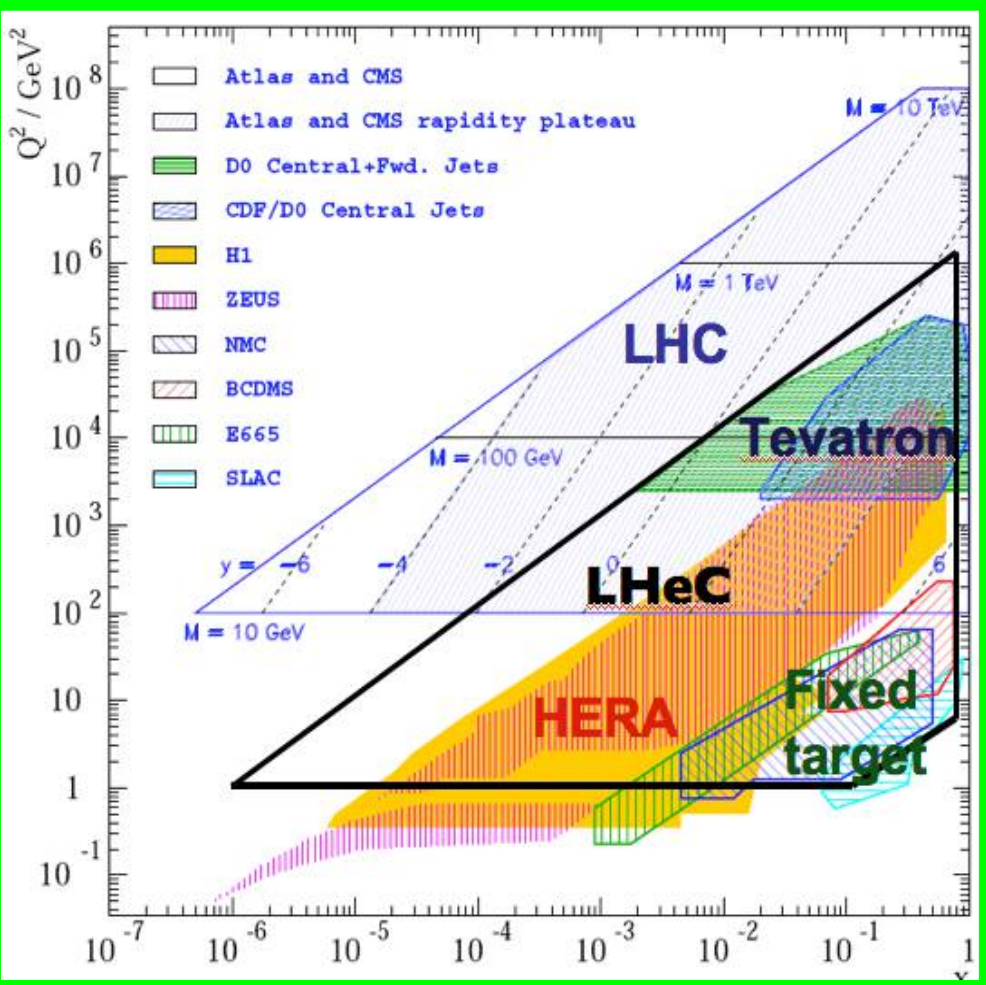
Different linear combinations – key for flavor differentiation

*The n-DIS data typically use heavy targets, and this requires the application of **nuclear corrections***



Nuclear Corrections or Parameterization???

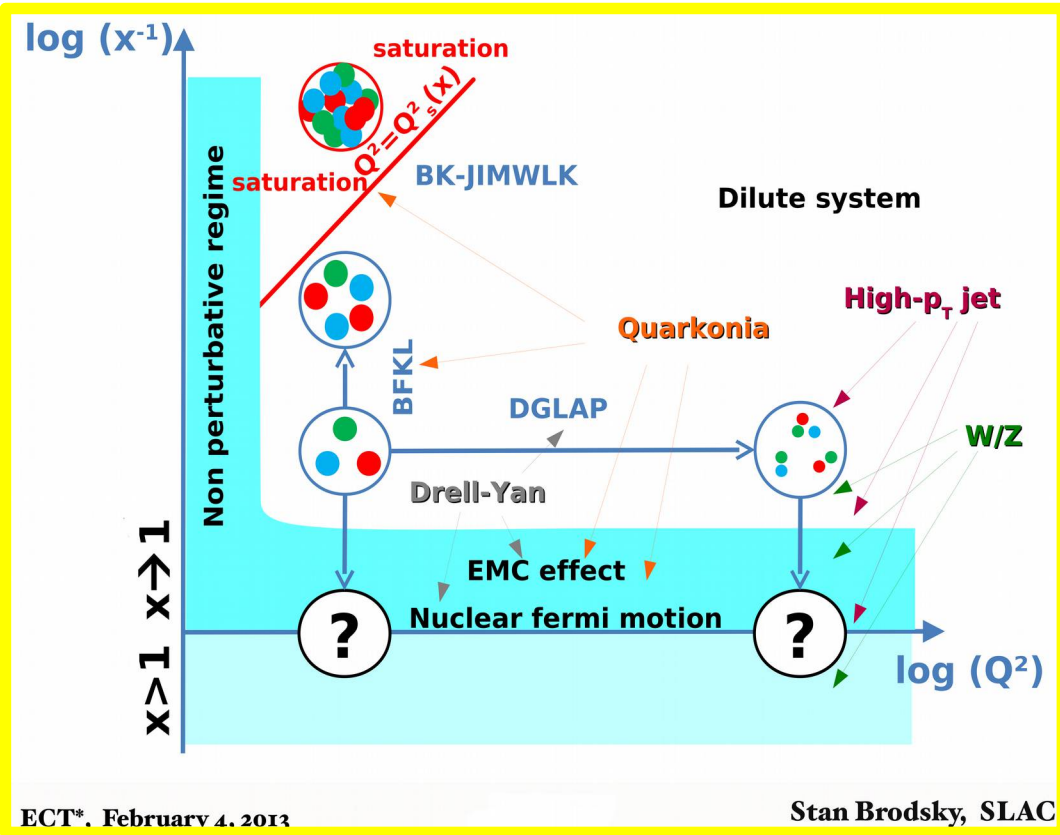




DGLAP: $\ln(Q^2)$

HQ: $\ln(m^2/Q^2)$

BFKL: $\ln(1/x)$



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

Experimental Observables

WHAT ABOUT PDF'S ???

Theoretical Calculations

