Things that go bump in the data:

QCD Puzzles, Predictions, and Prognoses

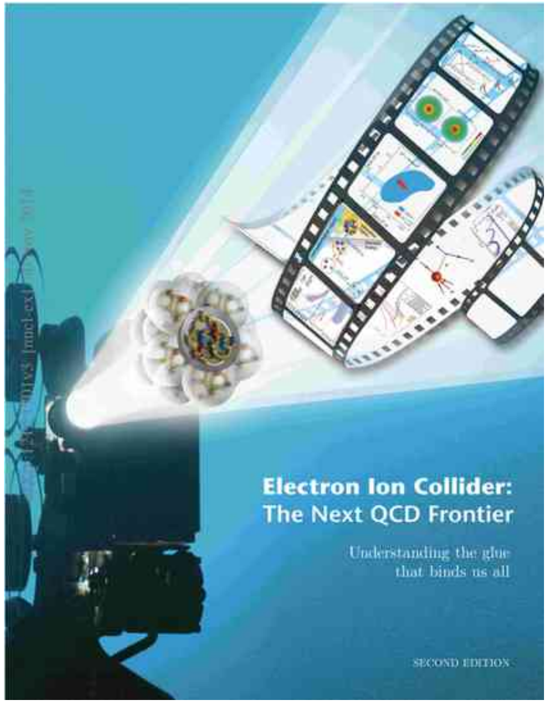
Fred Olness

SMU

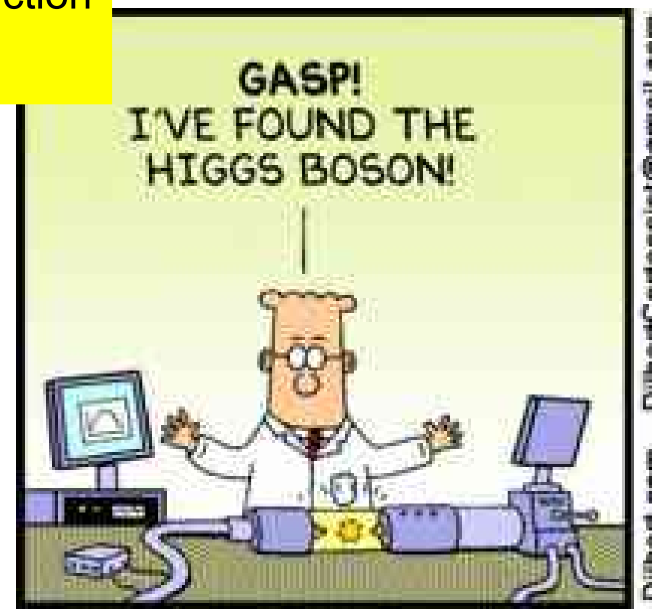
Conspirators:
F. Lyonnet, B. Clark, E. Godat A. Kusina,
S. Berge, I Schienbein, J.-Y. Yu,
P. Nadolsky, J. Owens, J. Morfin, C. Keppel, ...

UVA
29 January 2016

An exciting time for physics



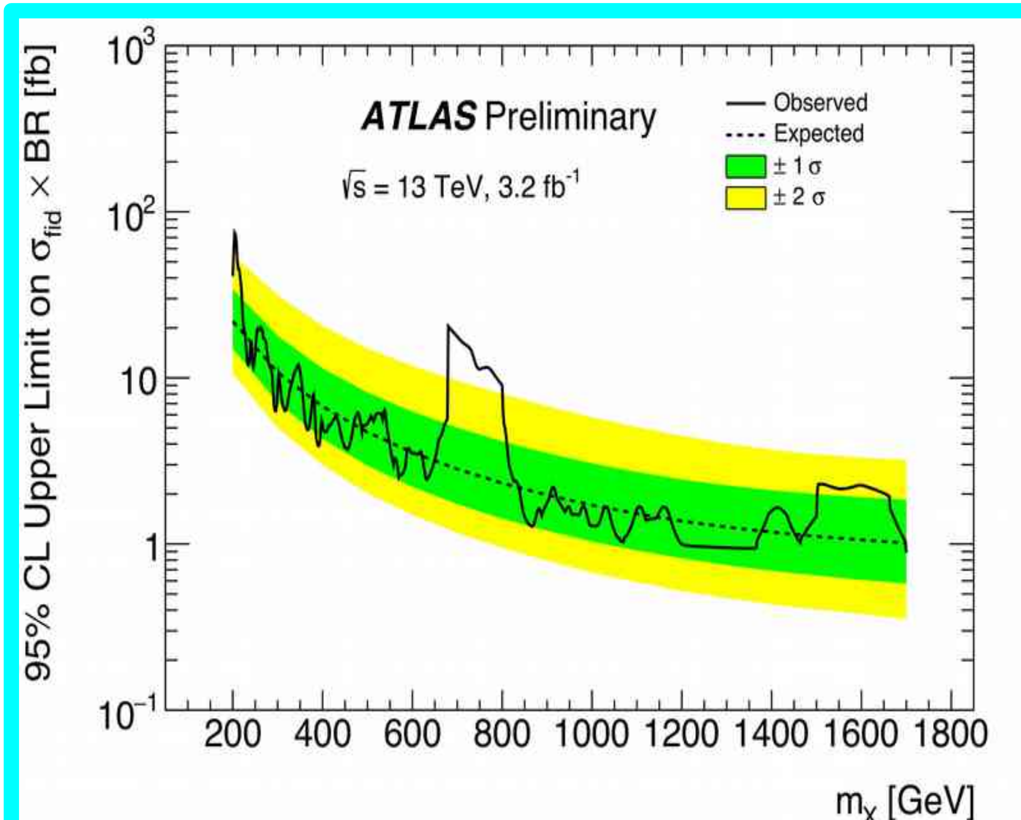
2015 Long Range Plan for Nuclear Science ***15 Oct 2015***
We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.



An early Christmas present from CERN??? 15 December 2015

What is going on at 750 GeV???

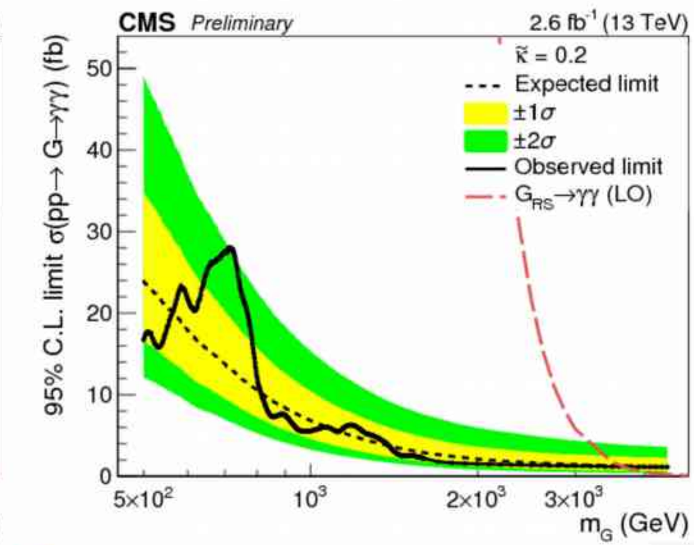
ATLAS and CMS see an excess in $pp \rightarrow \gamma\,\gamma$



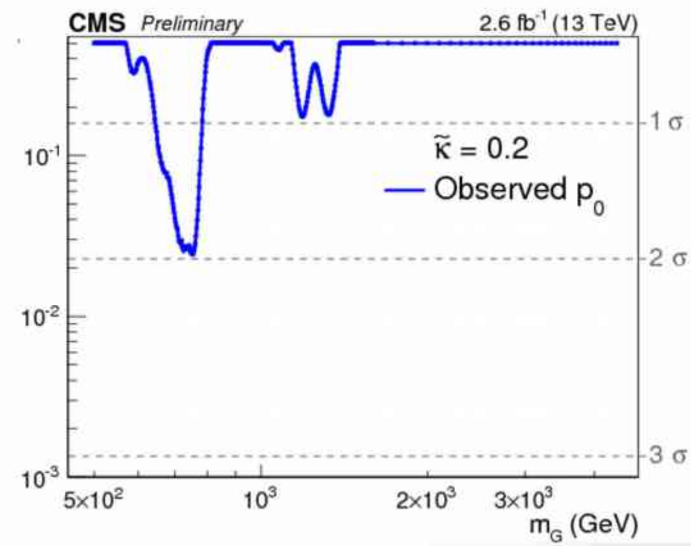
ATLAS: local: 3.6σ global: 2.0σ

CMS: local: 3σ global: 1.2σ

ATLAS-CONF-2015-081



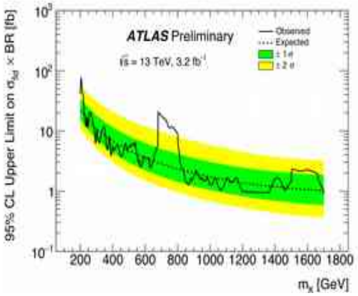
Wide (6%) Width



, global p-value < 1.2σ

CMS Collaboration - 13 TeV Results 15/12/2015

Questions that Physicists Ask



- Is this a real signal or a fake
- Could this be a sign of: *[your favorite theory here]*
- Should we make reservations in Stockholm
- Who will win the Super Bowl

The Key to Discovery: The Parton Model

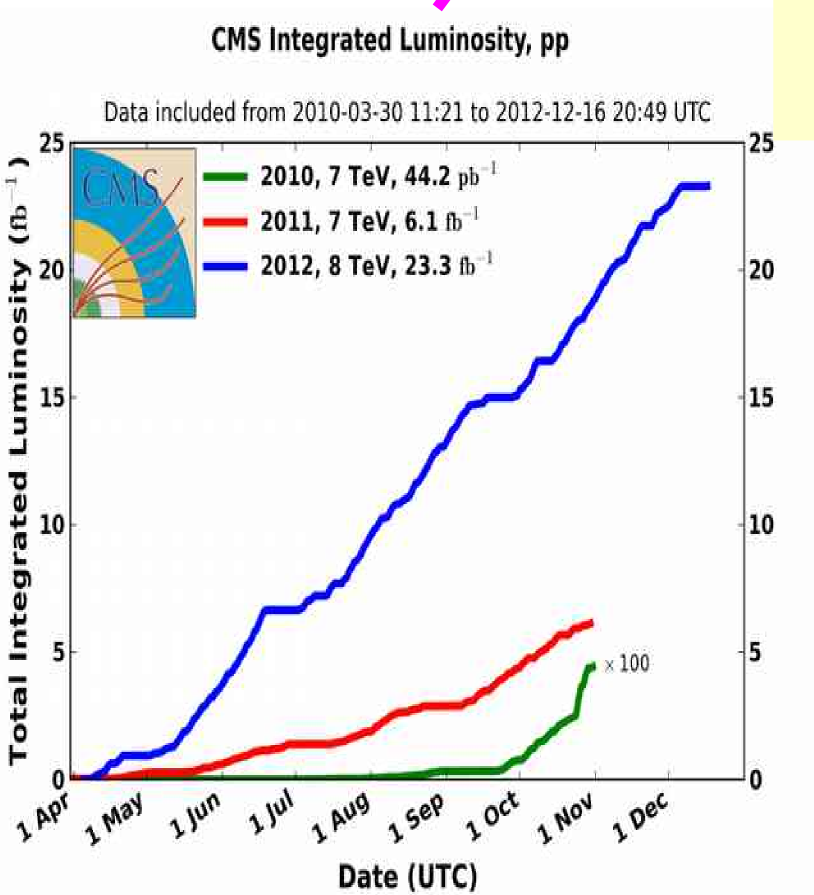
Notation: The "hat" indicates a "quark" cross section

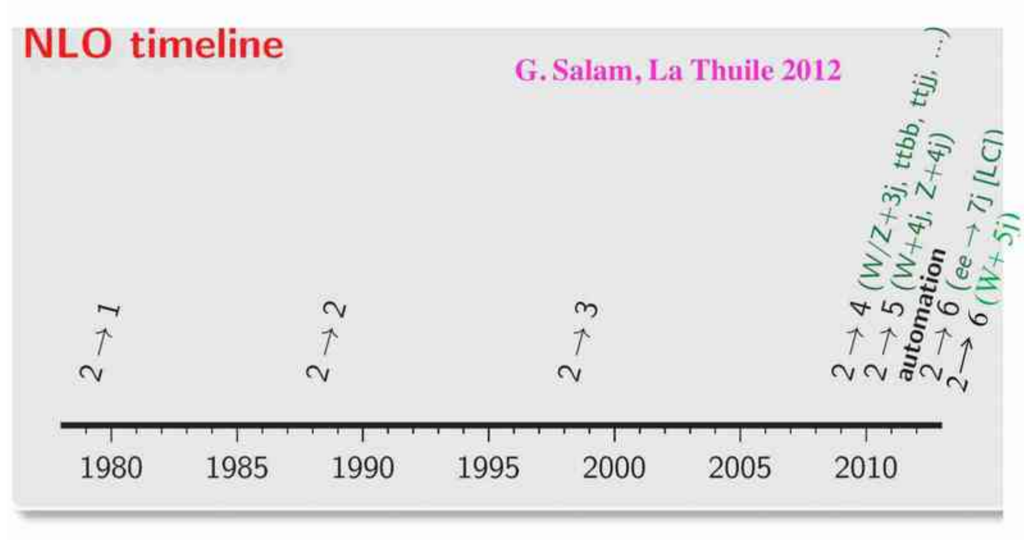
$$\sigma_{P\gamma\to c} = f_{P\to a} \otimes \hat{\sigma}_{a\gamma\to c}$$

Experimental Observables

WHAT ABOUT PDF'S ???

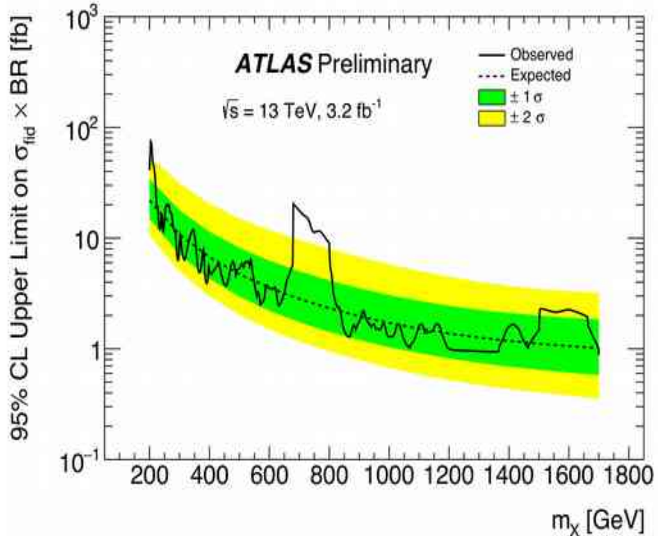
Theoretical Calculations

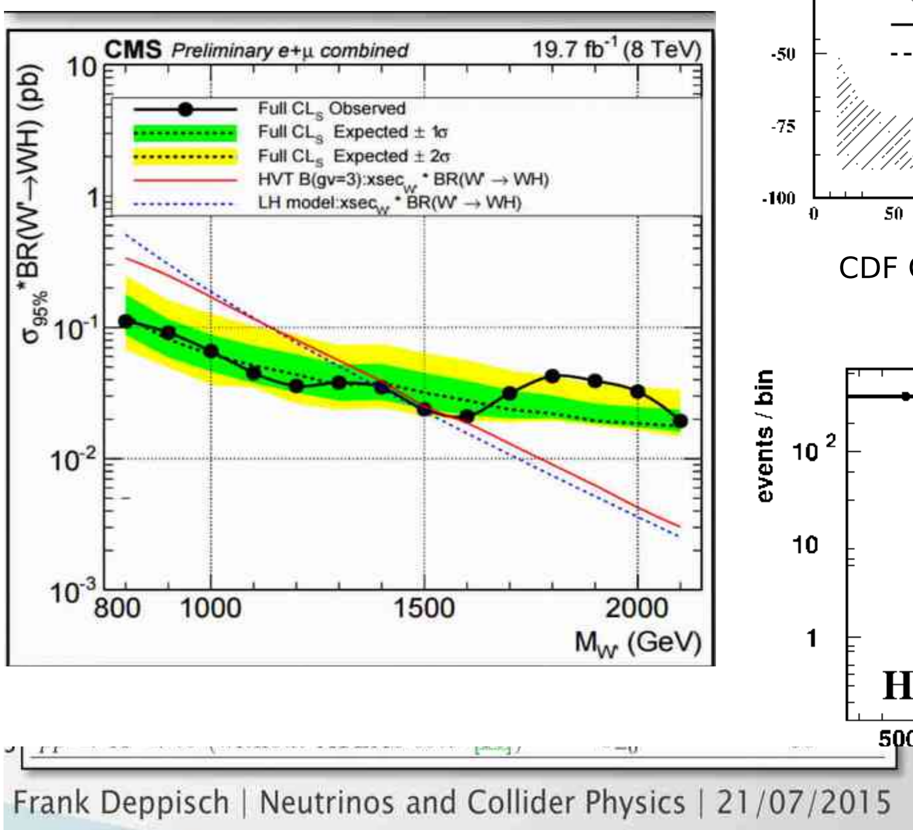


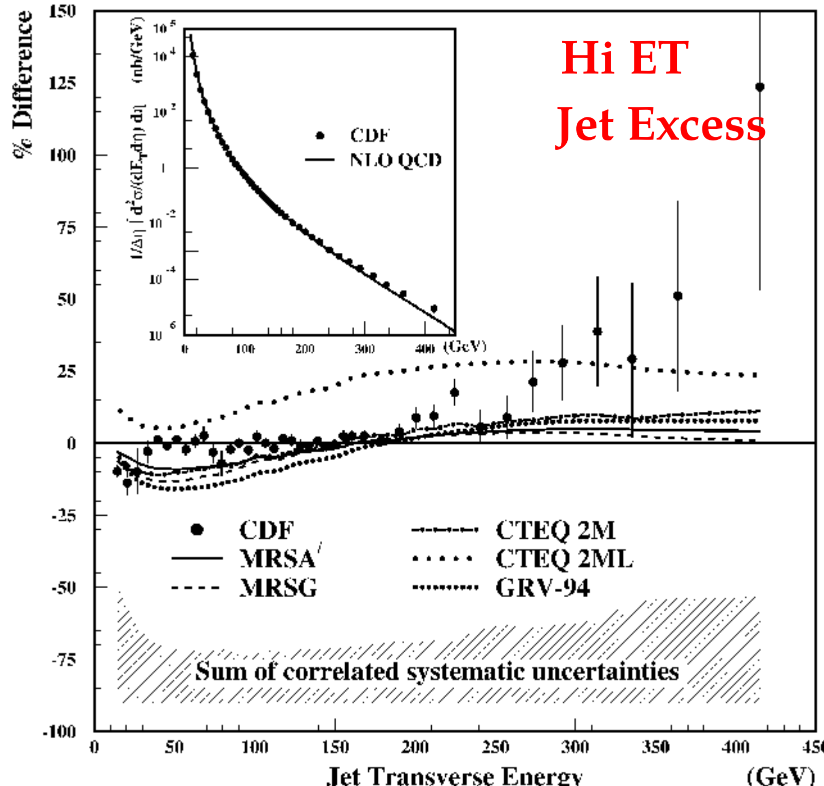


… things that go bump in the data ...

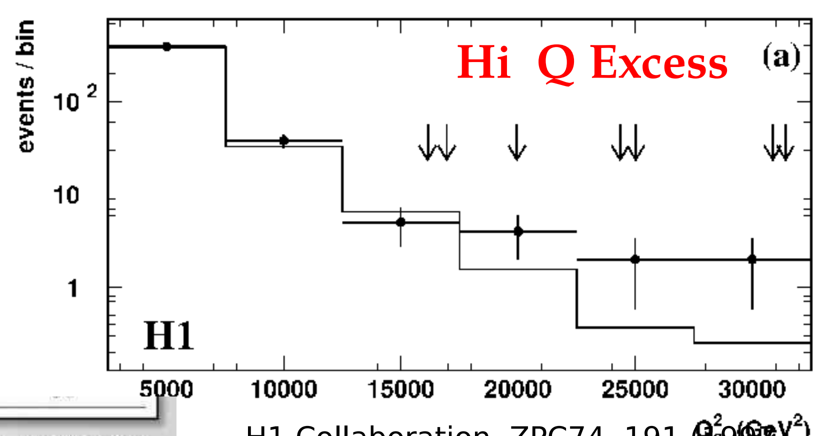
Can you find the Nobel Prize???



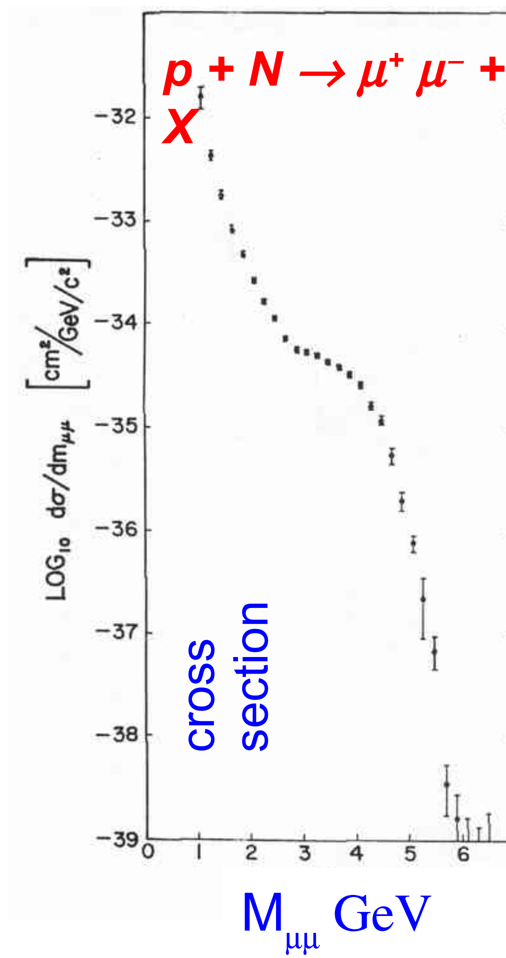




CDF Collaboration, PRL 77, 438 (1996)



H1 Collaboration, ZPC74, 191 (1997)
ZEUS Collaboration, ZPC74, 207 (1997)



What might the new physics be??? … another Higgs???

What lessons might we learn from the Higgs discovery???

Let's get some perspective on where the Higgs fits into our models

Higgs boson wins Physics Nobel Prize:

October 2013

From the official Nobel Prize Press release:

“On 4 July 2012, at the CERN laboratory for particle physics, the theory was confirmed by the discovery of a Higgs particle. CERN’s particle collider, LHC (Large Hadron Collider), is probably the largest and the most complex machine ever constructed by humans. Two research groups of some 3,000 scientists each, **ATLAS** and **CMS**, managed to extract the Higgs particle from billions of particle collisions in the LHC.”

What are the fundamental constituents which comprise the universe?

Periodic Table
Circa 400 BC

"The periodic table."

Sidney
Harris

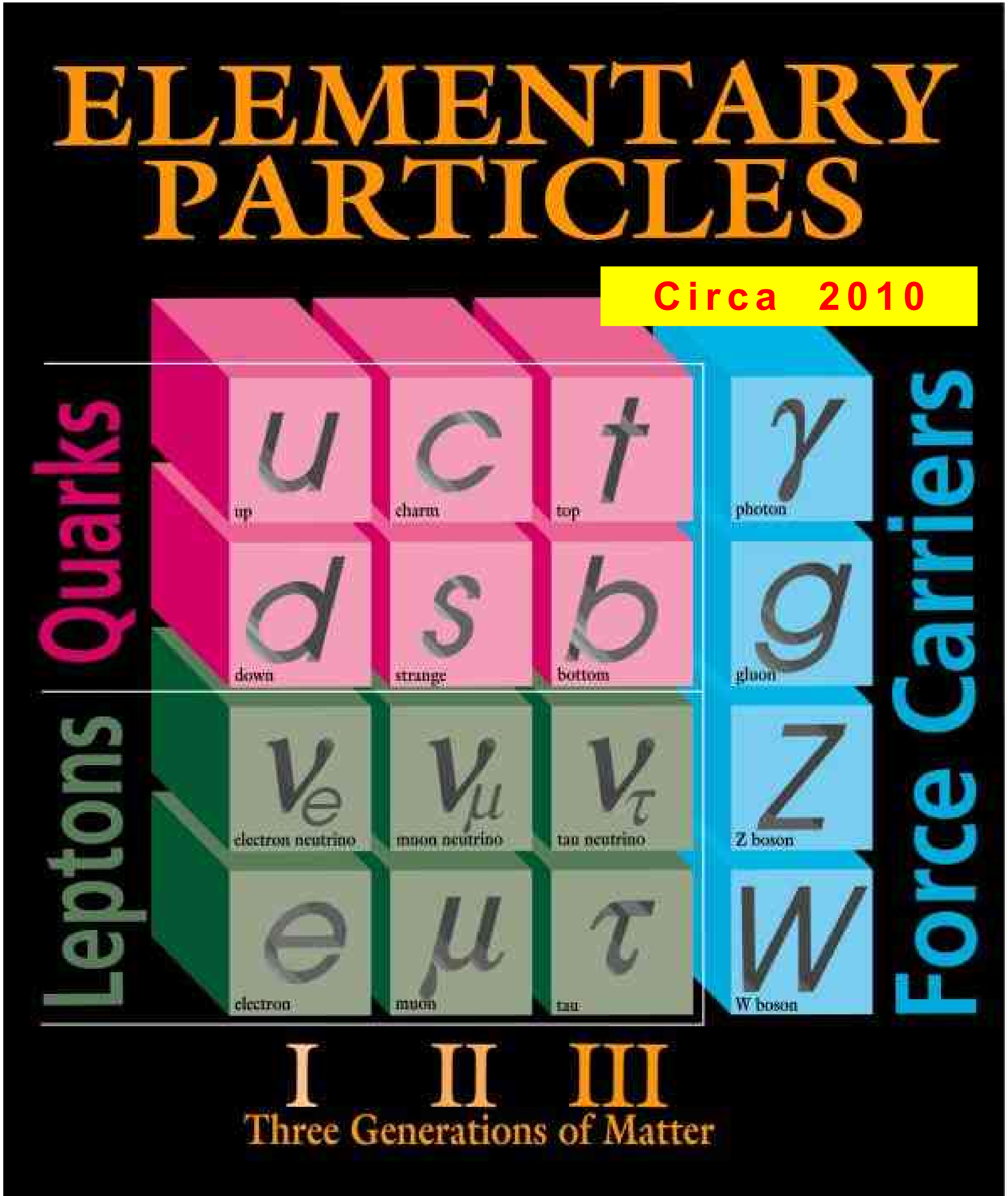
Compact
Easy to remember
Fits on a T-Shirt

Periodic Table

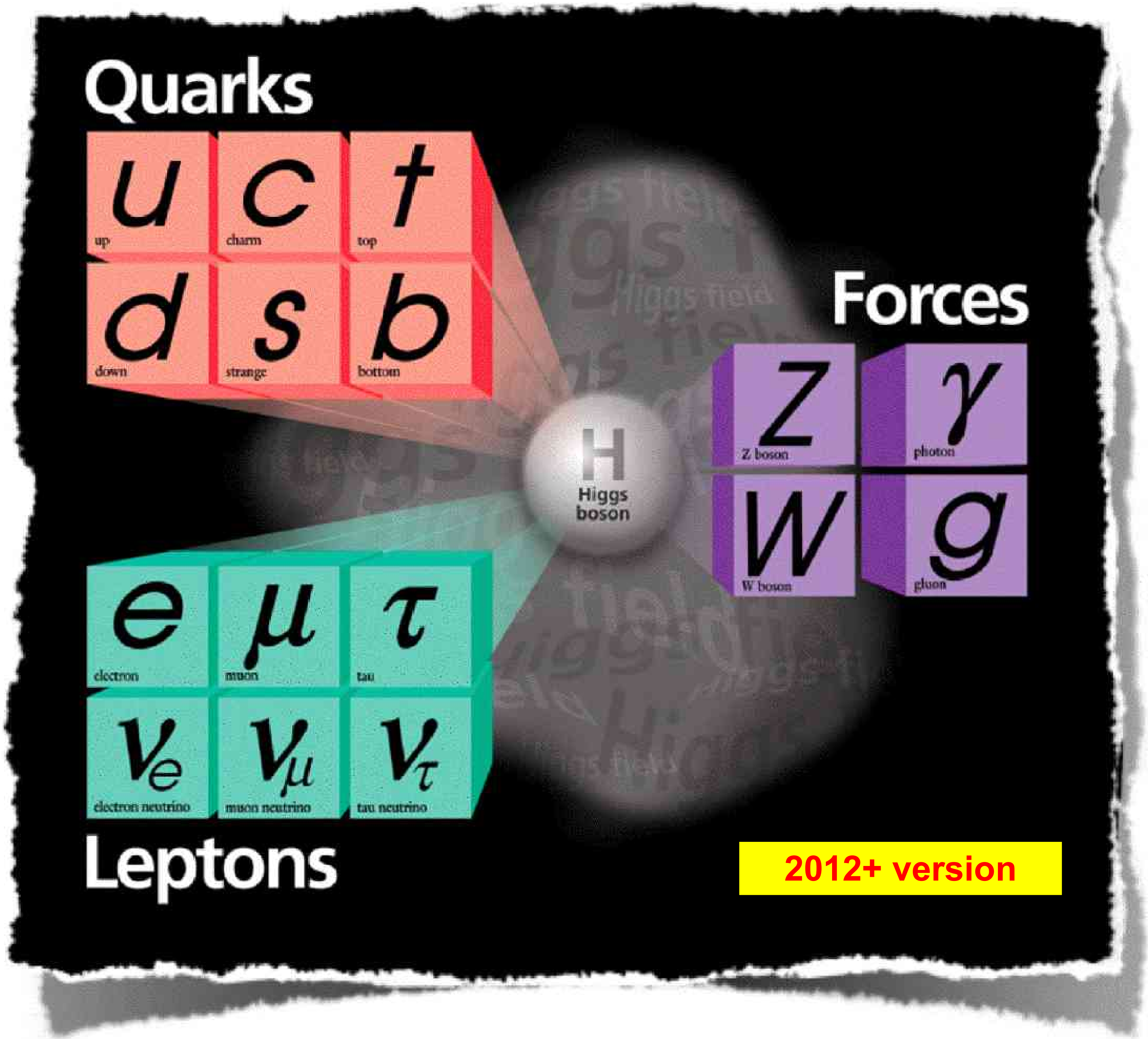
Periodic Table
Circa 1900 AD

1	2											3	4	5	6	7	8
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

Complex
Difficult to remember
Hard to fit on a T-Shirt



Fermilab 95-759



2012+ version

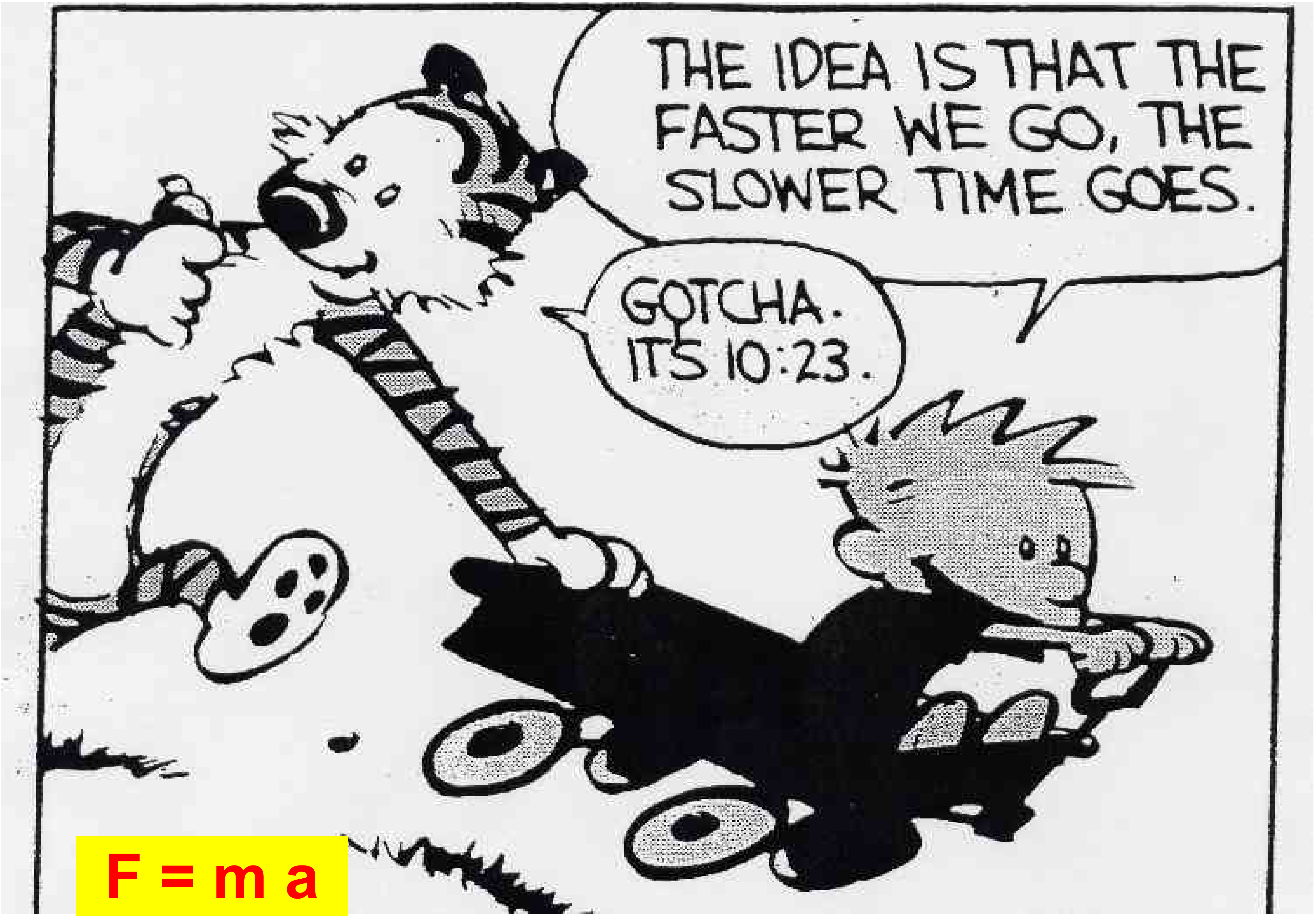
What's so special about the Higgs ?

The Higgs field permeates all space and is the origin of mass

Let's consult the experts

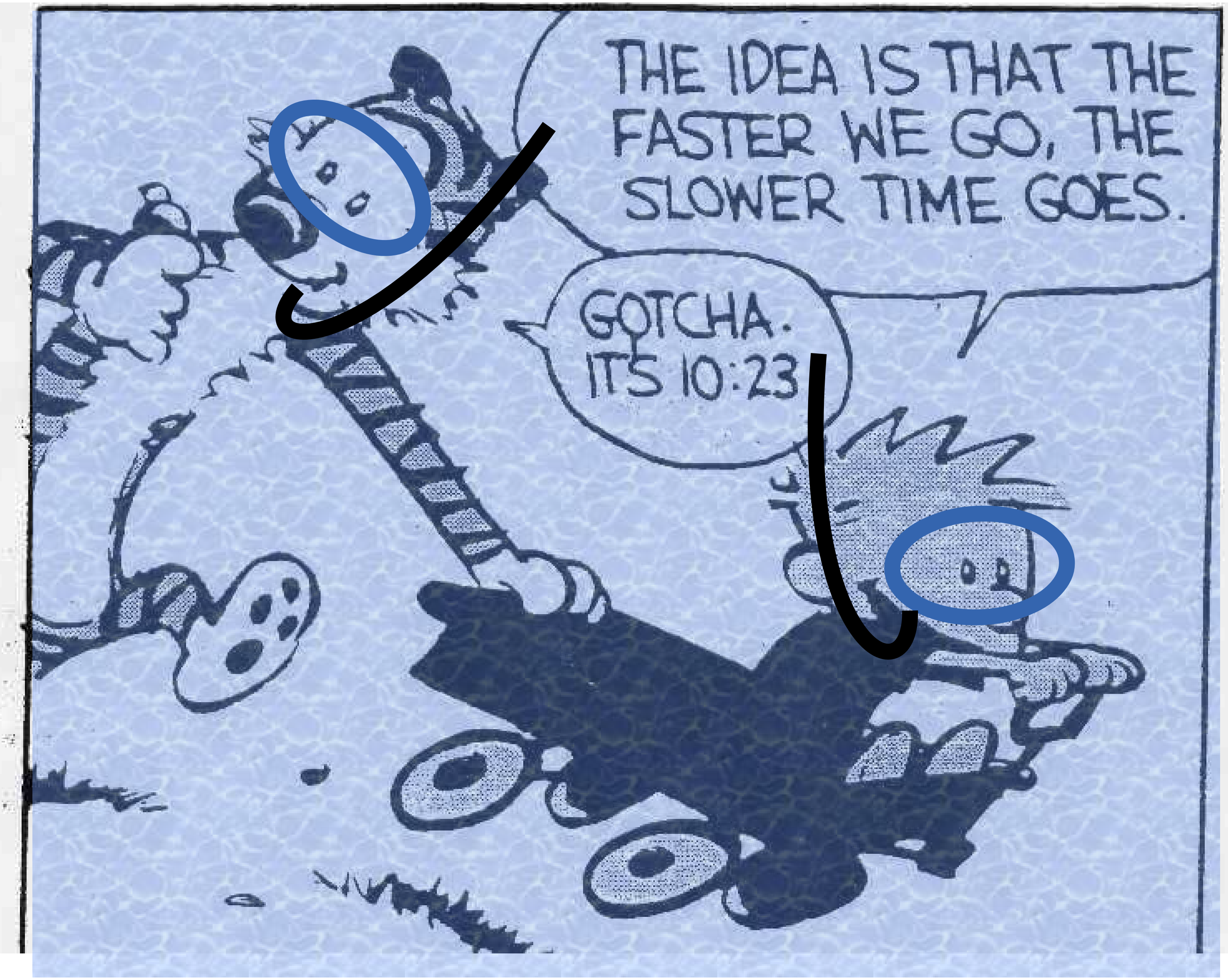

TEN MYTHS ABOUT RUSSIA
JAPAN: HOT GREEN
Newsweek
The Biggest Experiment Ever
(And It's European)
NATIONAL ENQUIRER
The Economist
A giant leap for science
Science
BREAKTHROUGH of the YEAR
The HIGGS BOSON
DER SPIEGEL
DAS TOR ZU EINER ANDEREN WELT
Physiker entschlüsseln das Geheimnis der Anti-Materie
TOM HANKS
ANGELS & DEMONS
FROM THE AUTHOR OF THE DAVINCI CODE
MAY 15
TIME
FABIOLA GIANOTTI

Higgs Bosons: OVER Simplified ...



F = m a

Higgs Bosons: OVER Simplified ...



Underwater!!!

$$F = m a$$

$$m = F/a$$

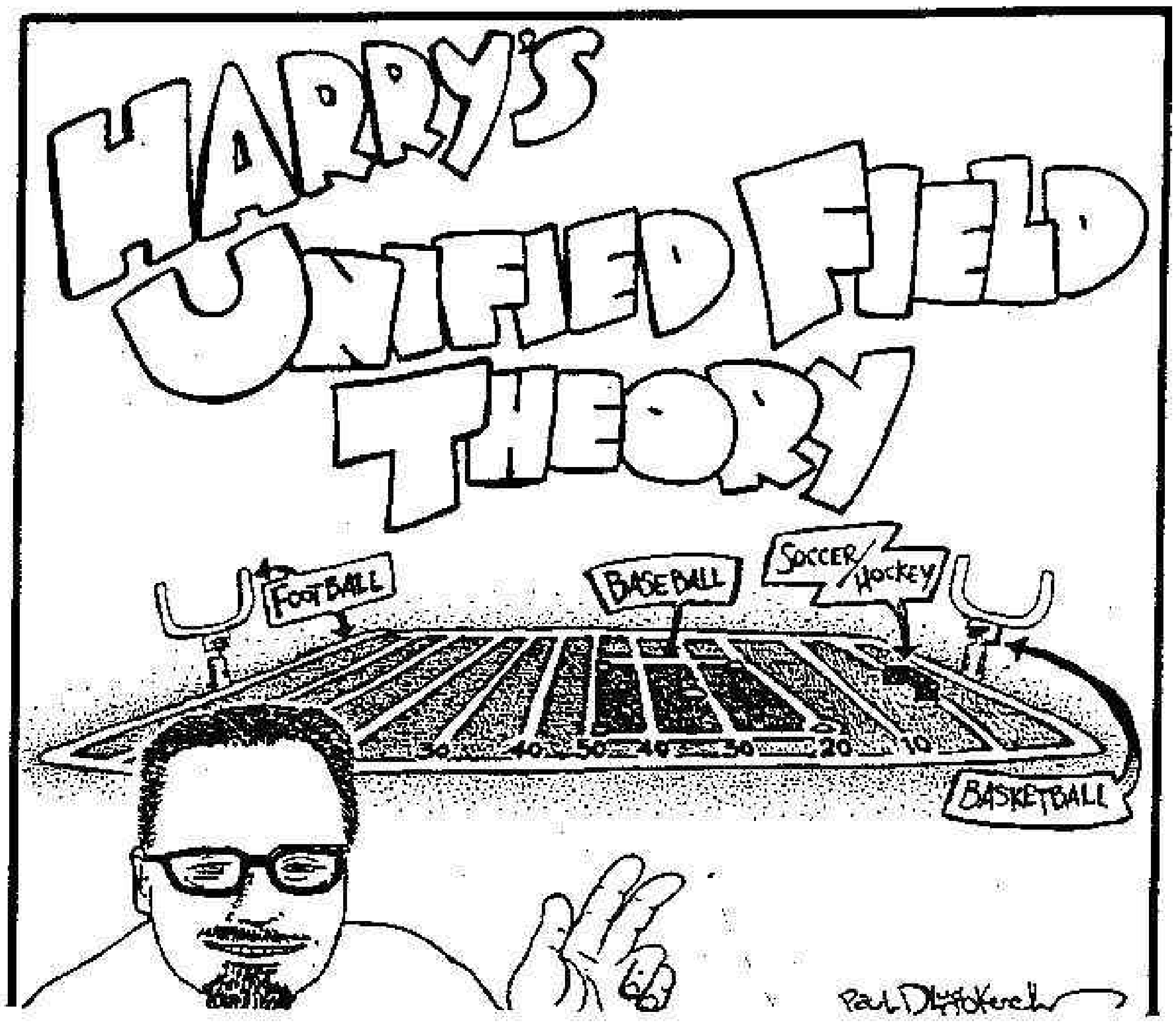
Condensed Matter: Negative electron mass in a semiconductor

Enables the theory to have a mass term AND respect gauge invariance

Could this be 21st Century aether???

What might the new physics be???

There are a variety of Grand Unified Theories



Others predict the existence of:*

SUSY
Extra Higgs Bosons
Extra Gauge Bosons
Extra Dimensions
Composite particles
...

**For more details, ...*

Did we discover the "Garden Variety" Higgs??? Are there extra Higgs Bosons???

Are the branching ratios of the Higgs boson consistent with the standard model? Is there only one type of Higgs boson?

Hierarchy problem:

Why is gravity such a weak force? It becomes strong for particles only at the Planck scale, around 10^{19}GeV, much above the electroweak scale (100 GeV, the energy scale dominating physics at low energies). Why are these scales so different from each other? What prevents quantities at the electroweak scale, such as the Higgs boson mass, from getting quantum corrections on the order of the Planck scale? Is the solution supersymmetry, extra dimensions, or just anthropic fine-tuning?

Supersymmetry:

Is spacetime supersymmetry realized at TeV scale? If so, what is the mechanism of supersymmetry breaking? Does supersymmetry stabilize the electroweak scale, preventing high quantum corrections? Does the lightest supersymmetric particle (Lightest Supersymmetric Particle) comprise dark matter?

Generations of matter:

Why are there three generations of quarks and leptons? Is there a theory that can explain the masses of particular quarks and leptons in particular generations from first principles?

Electroweak symmetry breaking:

What is the mechanism responsible for breaking the electroweak gauge symmetry, giving mass to the W and Z bosons? Is it the simple Higgs mechanism of the Standard Model, or does nature make use of strong dynamics in breaking electroweak symmetry, as proposed by Technicolor?

Dark matter

What is the identity of dark matter? Is it a particle? Is it the lightest superpartner (LSP)? Do the phenomena attributed to dark matter point not to some form of matter but actually to an extension of gravity?

How to make

Higgs

We need high energies to create massive particles

Compare these machines:

LEP	e^+e^-	$\sqrt{s} = 200$ GeV
HERA	ep	$\sqrt{s} = 314$ GeV
RHIC	NN	$\sqrt{s} = N \times 100$ GeV
Tevatron	p p-bar	$\sqrt{s} = 2000$ GeV
LHC	pp	$\sqrt{s} = 13{,}000$ GeV

Hadron beams provide the highest energy

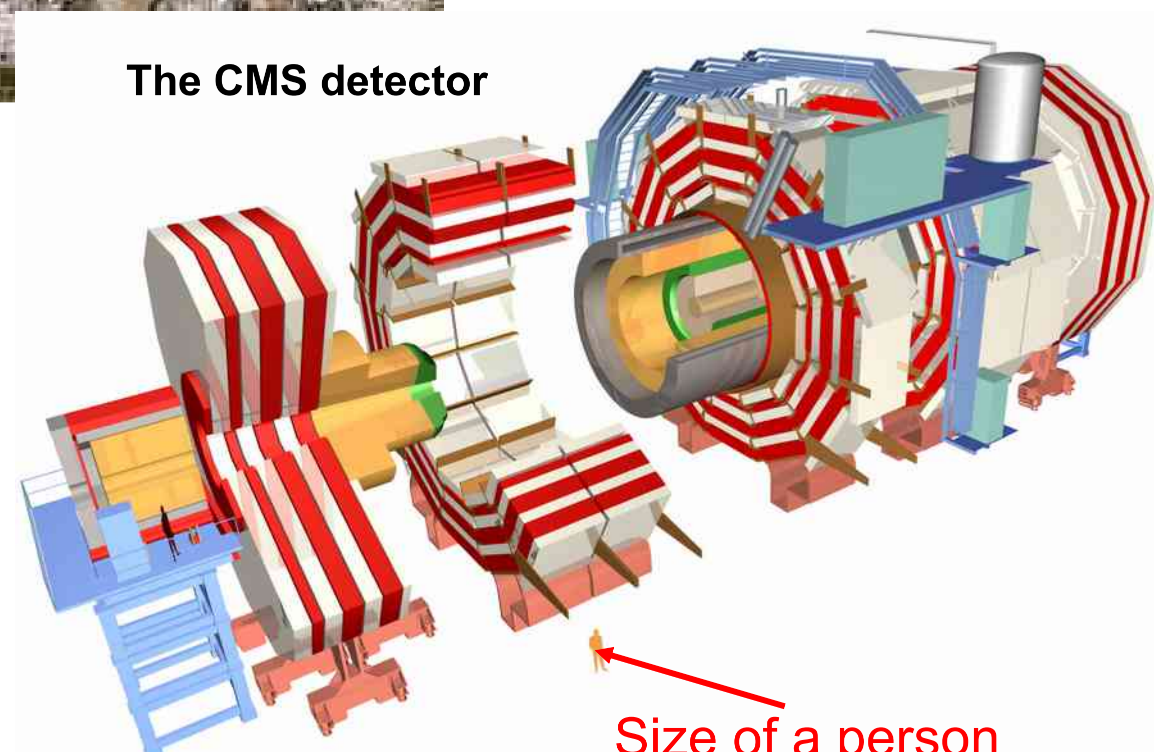
LHC: The High Energy Frontier (2015)

P P collisions

$\sqrt{s}$ = 13,000 GeV

Note: 5 GeV ~ 1 Fermi
∴ 13,000 GeV ~ 3×10^{-19}m

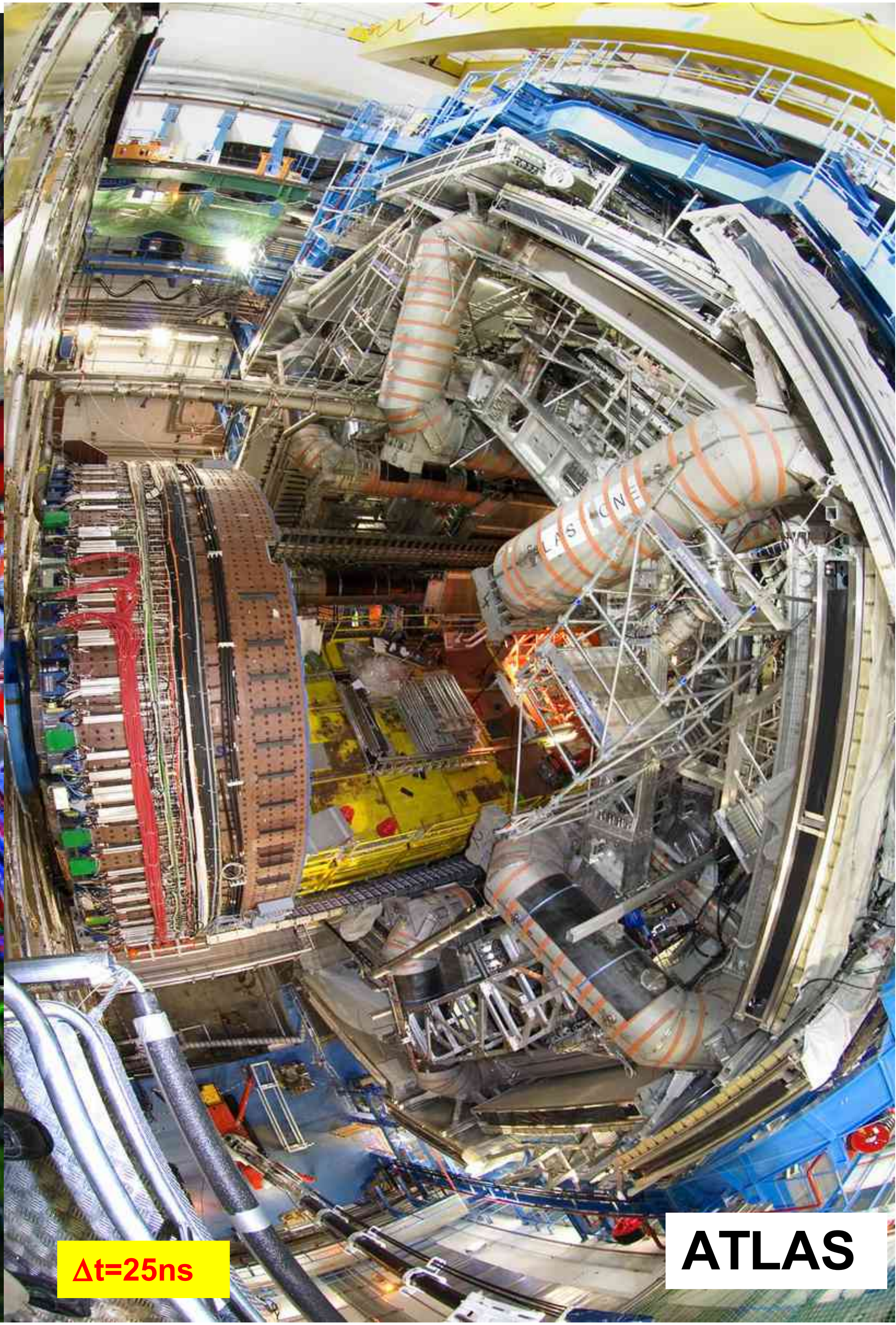
The CMS detector



The LHC has opened up one of the largest kinematic frontiers in many decades

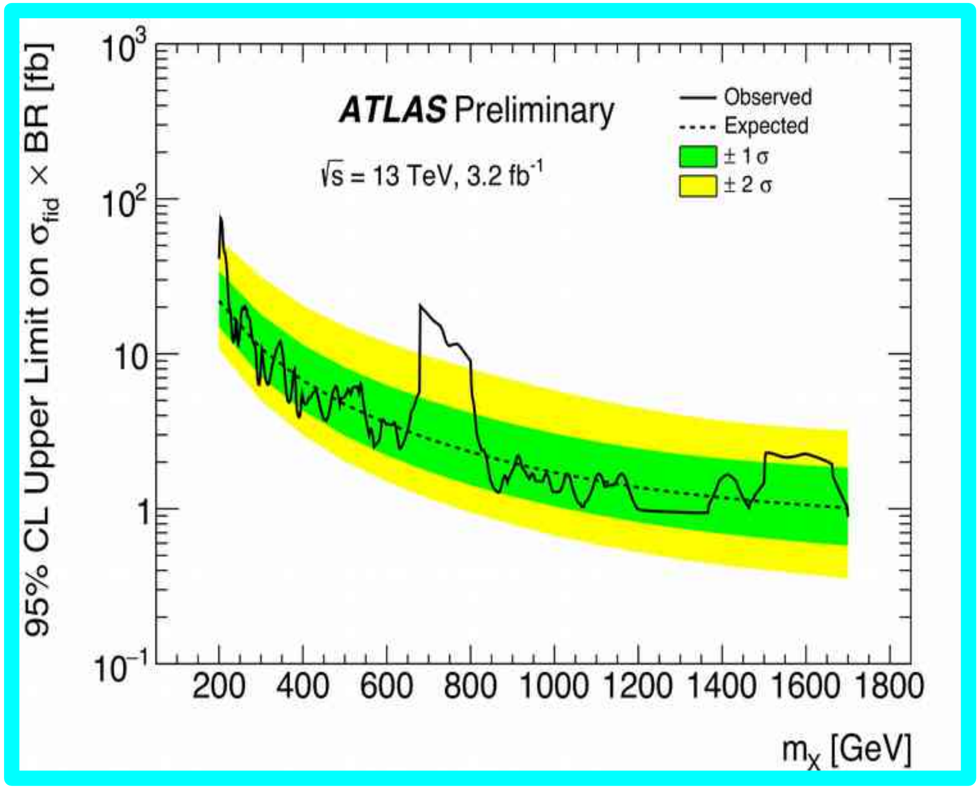
You need big detectors to study small stuff!!!


CMS
You need big detectors to study small stuff!!!


ATLAS
Δt=25ns

The speed of light
is just
too darn slow!!!

How do we make predictions at the LHC



The parton model

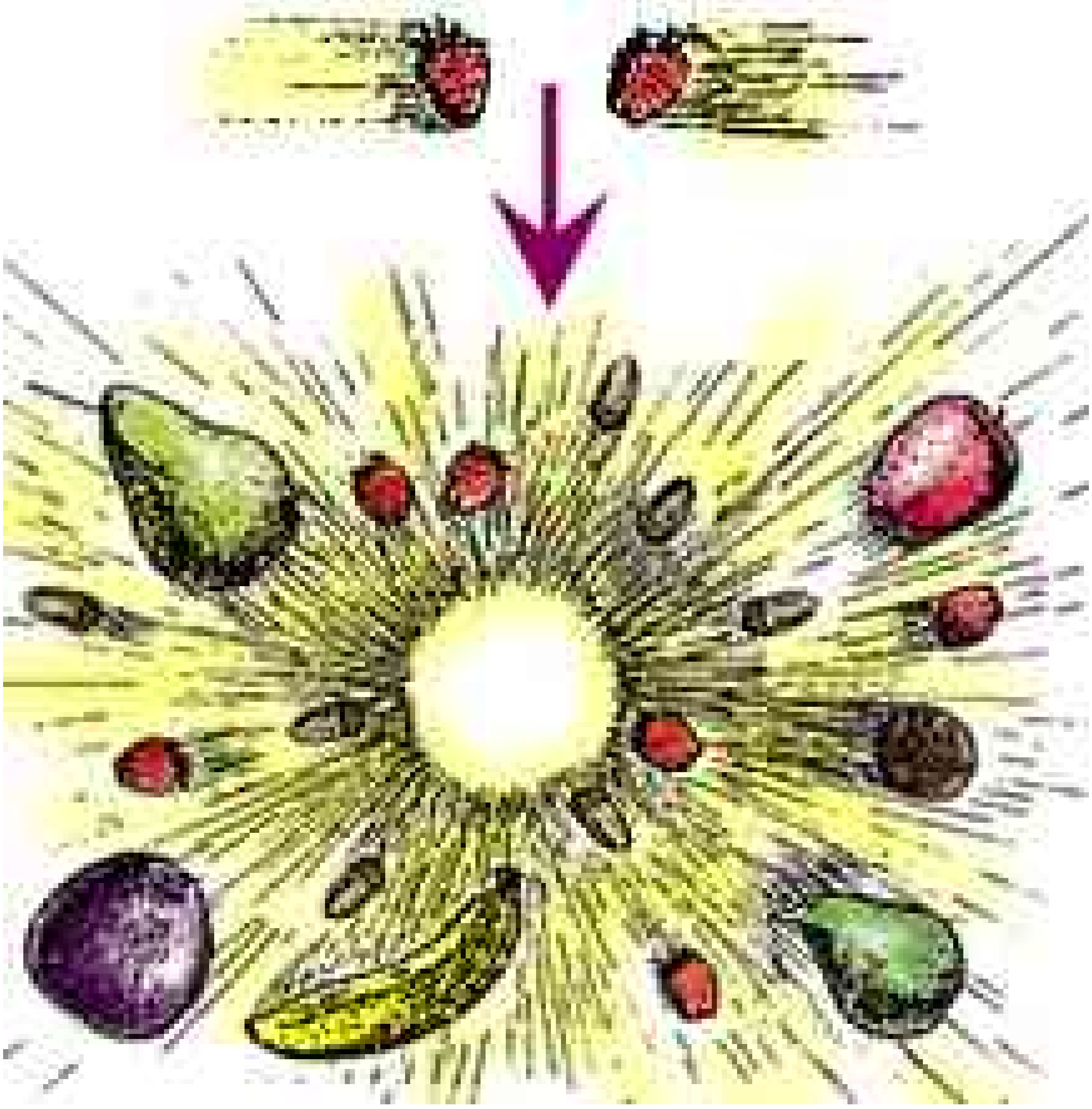
$$\sigma_{P\gamma\to c} = f_{P\to a} \otimes \hat{\sigma}_{a\gamma\to c}$$

Experimental Observables

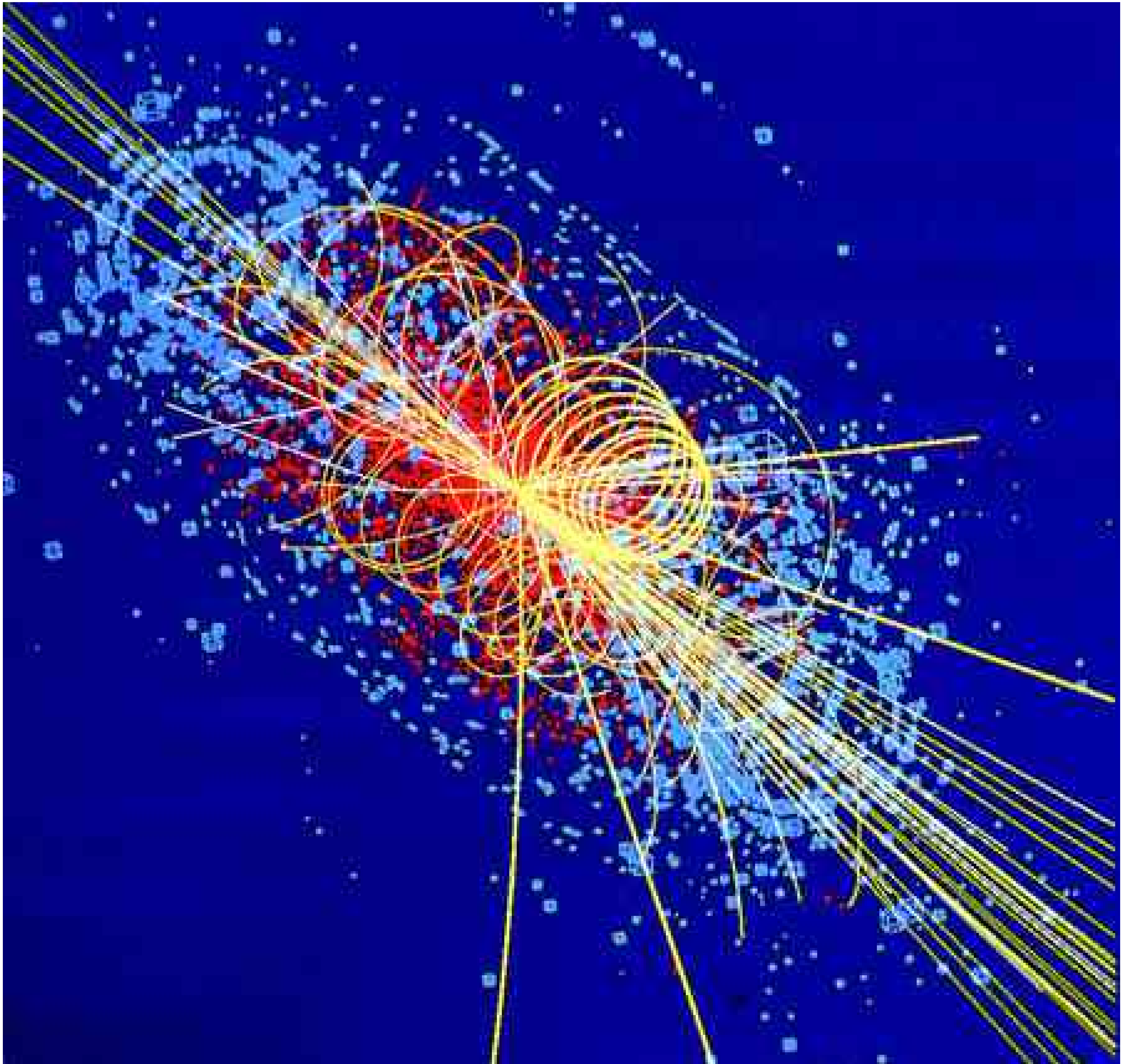
Parton Distribution Functions

Theoretical Cross sections

Artist's interpretation of a hadron-hadron collision



Higgs Simulation from CMS



Statement of the problem

Theorist #1: The universe is completely described by the symmetry group SO(10)

Theorist #2: You're wrong; the correct answer is SuperSymmetric flipped SU(5)xU(1)

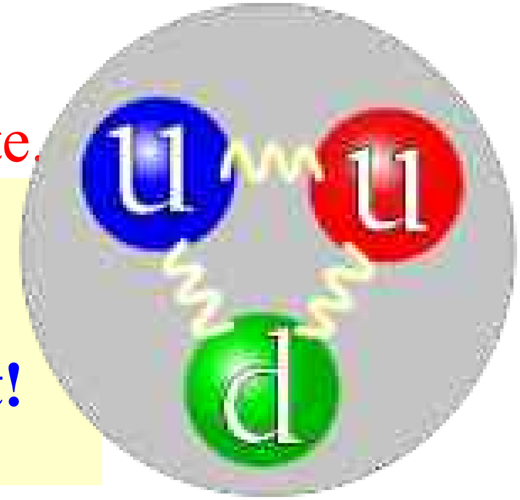
Theorist #3: You've flipped! The only rational choice is E8xE8 dictated by SuperString Theology.

Experimentalist: Enough of this speculative nonsense. I'm going to measure something to settle this question. What can you predict???

Theorist #1: We can predict the interactions between fundamental particles such as quarks and leptons.

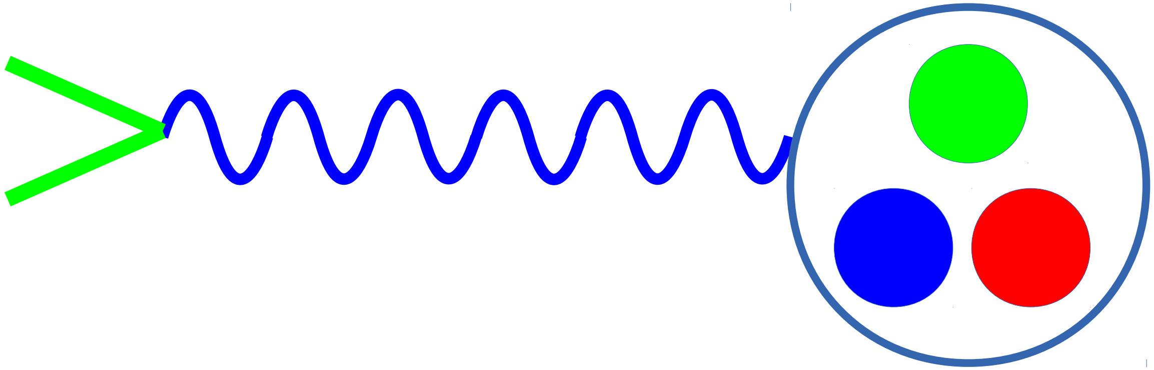
Experimentalist: Great! Give me a beam of quarks and leptons, and I can settle this debate.

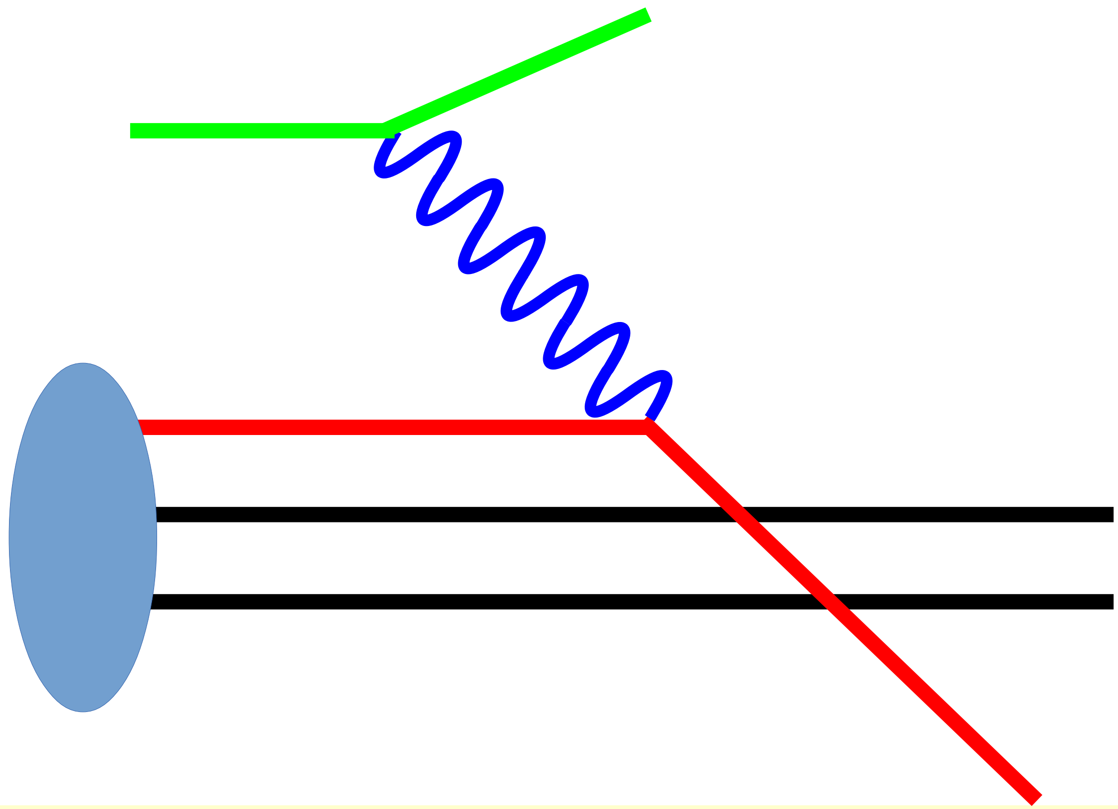
Accelerator Operator: **Sorry, quarks only come in a 3-pack and we can't break a set!**



http://en.wikipedia.org/

Proton as a bag of free Quarks

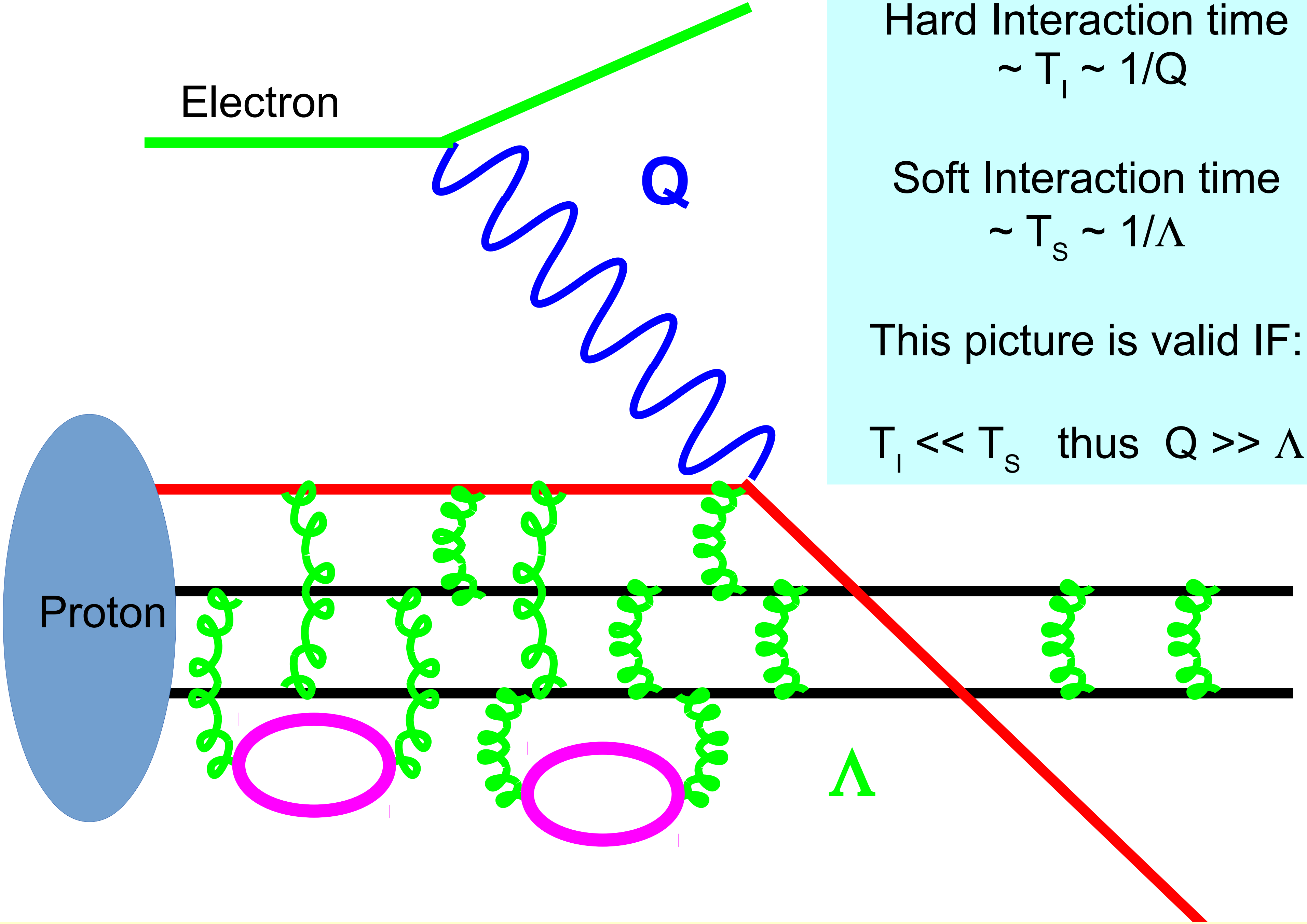




Over Simplified PDFs

$$f(x,Q) = u(x,Q) + d(x,Q) = 2\ \delta(x - \tfrac{1}{3}) + 1\ \delta(x - \tfrac{1}{3})$$

Quarks are not quite free



Hard Interaction time
$\sim T_I \sim 1/Q$

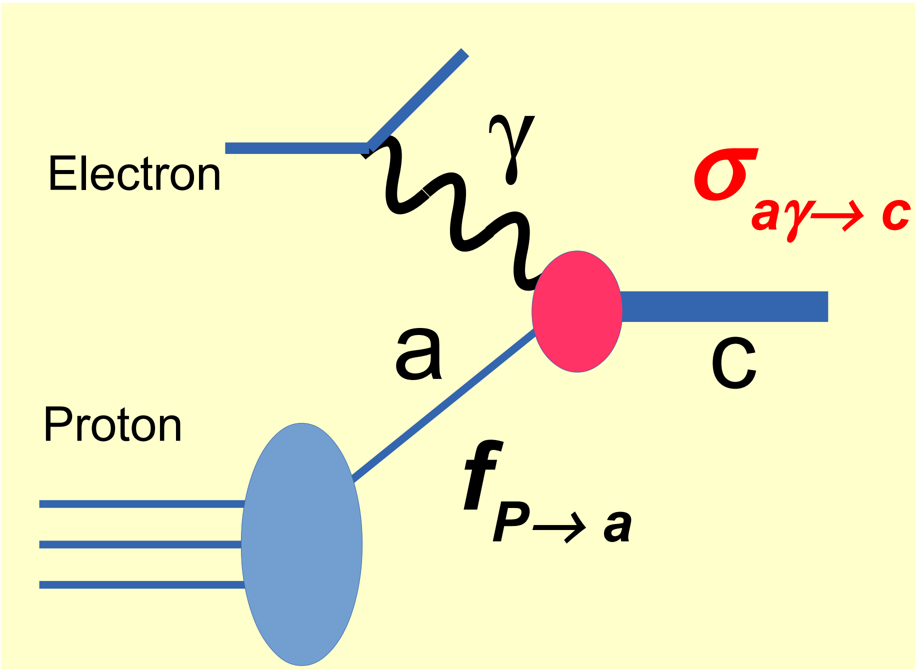
Soft Interaction time
$\sim T_S \sim 1/\Lambda$

This picture is valid IF:

$T_I \ll T_S$ thus $Q \gg \Lambda$

We are going to “absorb” our ignorance of the non-perturbative processes into the PDF

The Parton Model and Factorization



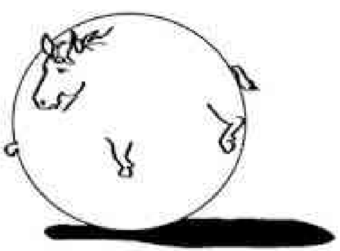
Parton Distribution Functions

(PDFs) $f_{P\to a}$

are the key to calculations

involving hadrons!!!

Notation: The "hat" indicates a "quark" cross section



in the limit of a spherical horse

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

measure in experiment

where do we get these???

calculable from theoretical model

Cross section is product of independent probabilities!!! *(Homework Assignment)*

The Parton Model: *Connecting Experiment to Theory*

$$\sigma_{pp\to X} = f_{p\to a} \otimes f_{p\to b} \otimes \omega_{ab\to X}$$

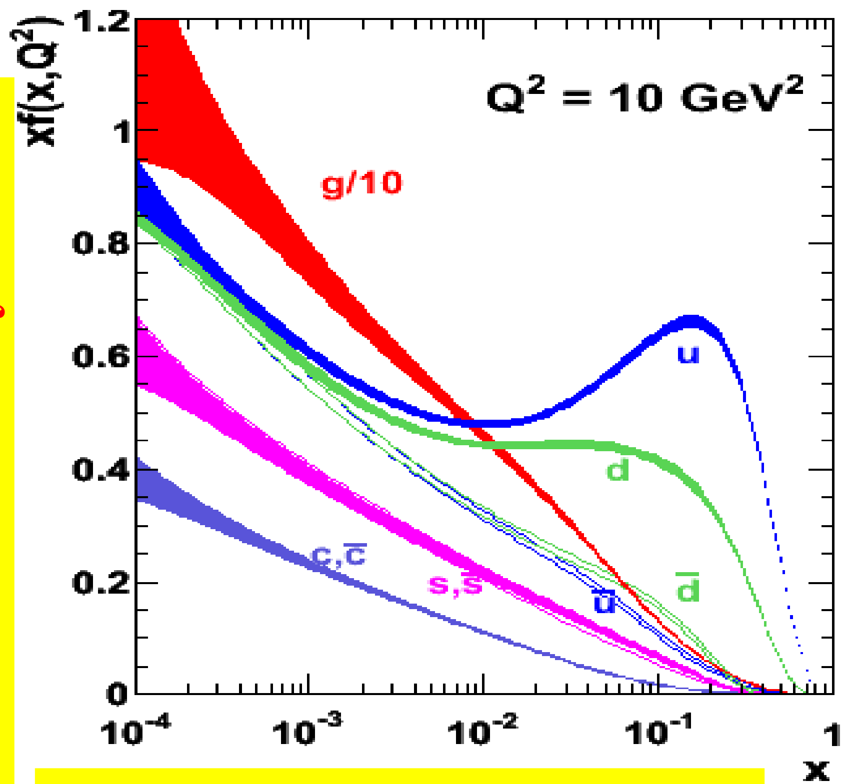
Experimental Observables

WHAT ABOUT PDF'S ???

Theoretical Calculations

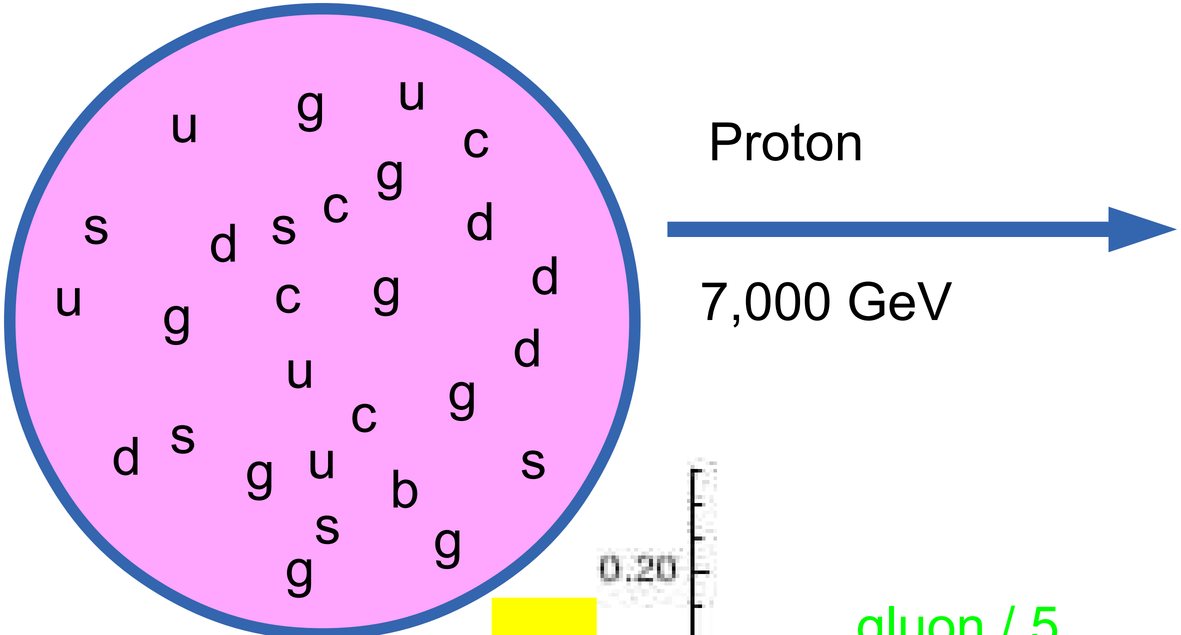
If we can accurately determine *f(x,Q)* for all the quarks & gluon, then the problem is solved

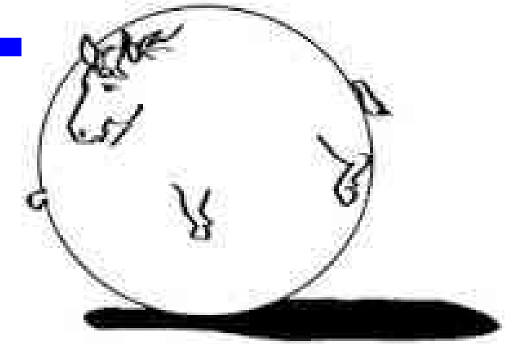
Probability



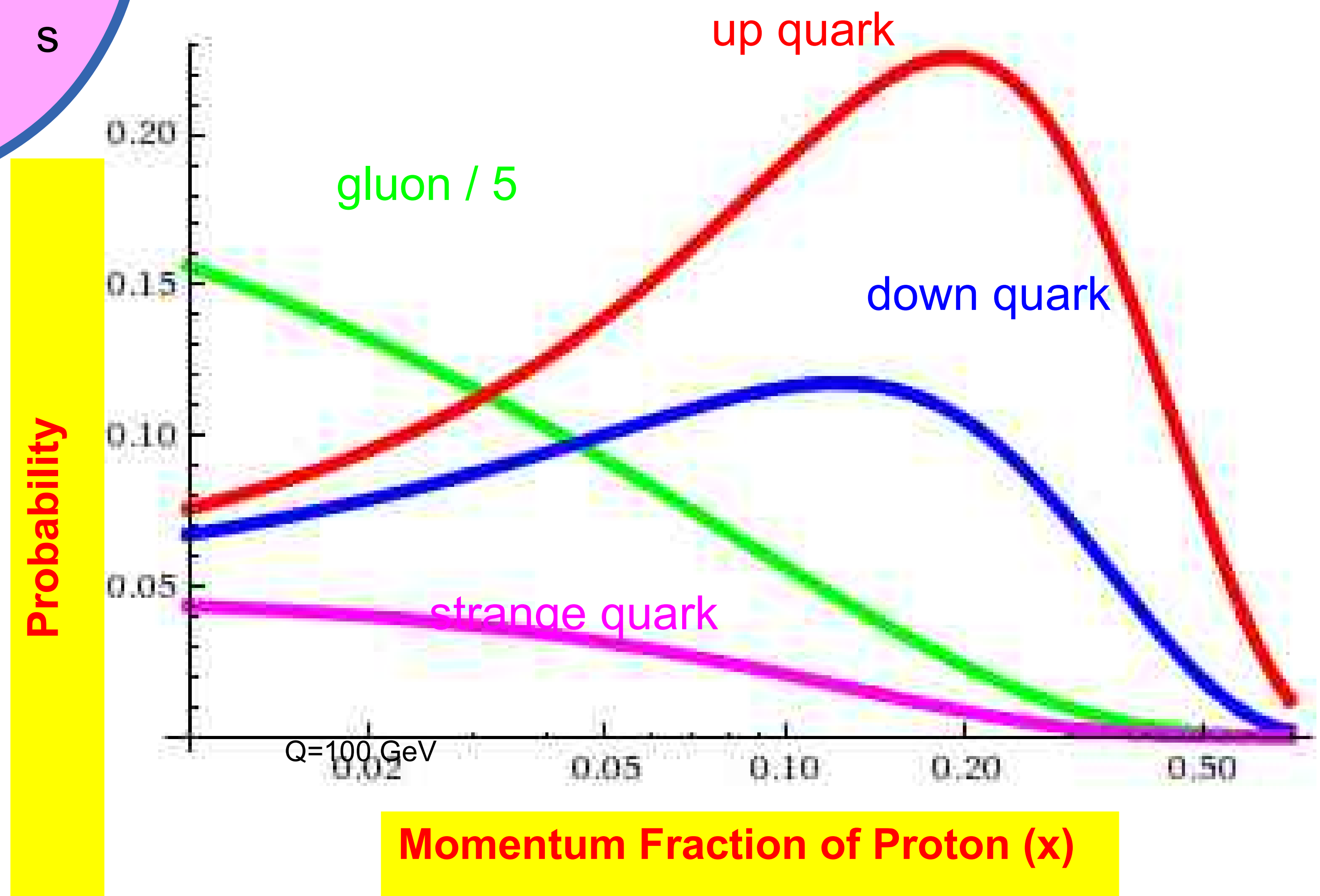
Momentum Fraction (x)

How do we parameterize our ignorance?

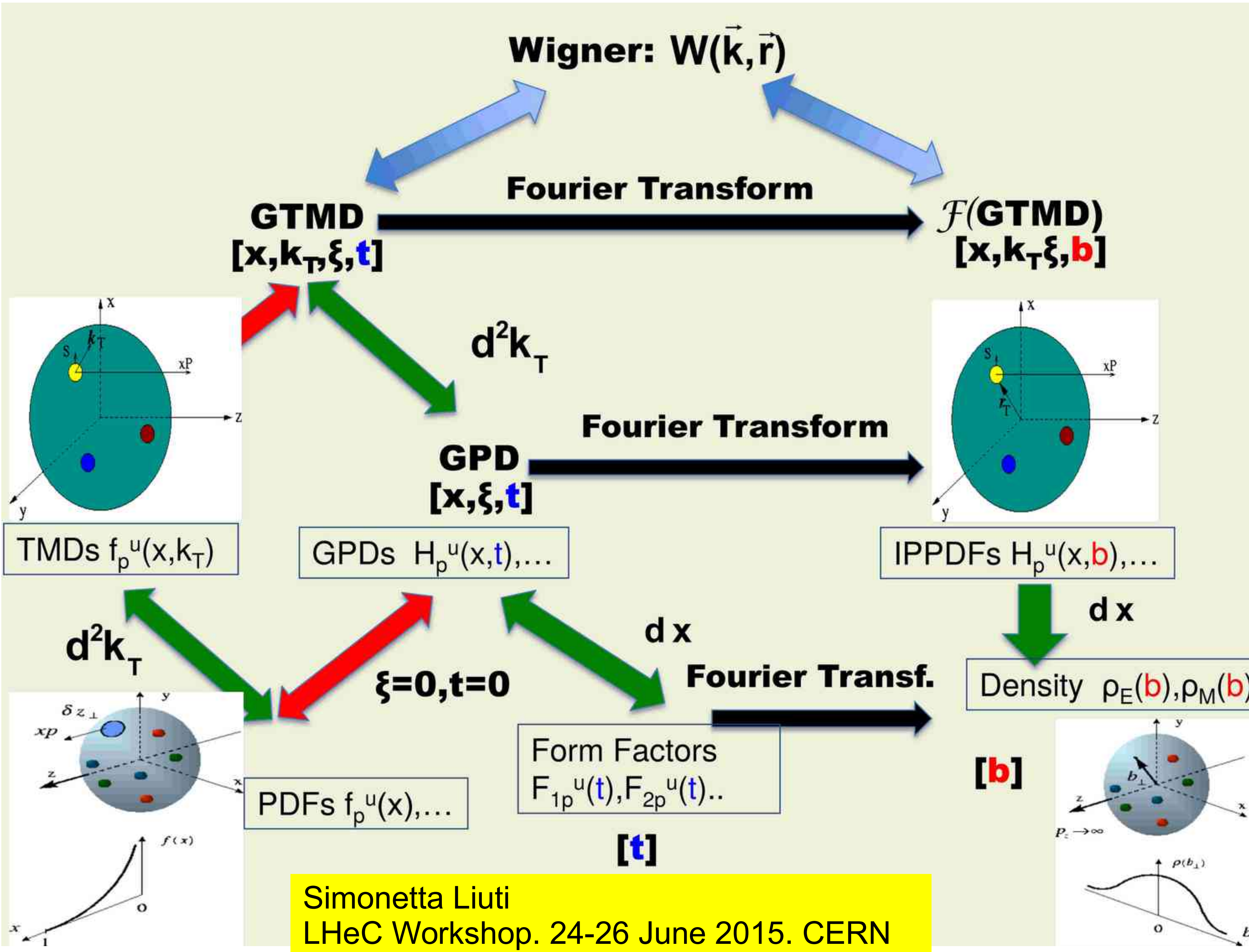




in the limit of a spherical horse



Generalized Parton Distribution Functions



All is not lost ...

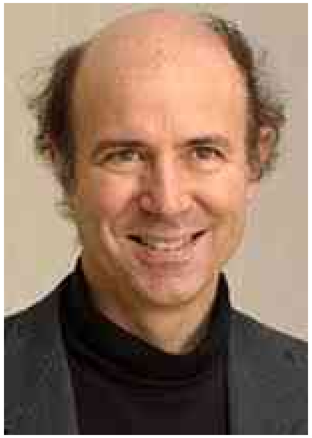
What QCD Tells Us About Nature – and Why We Should Listen

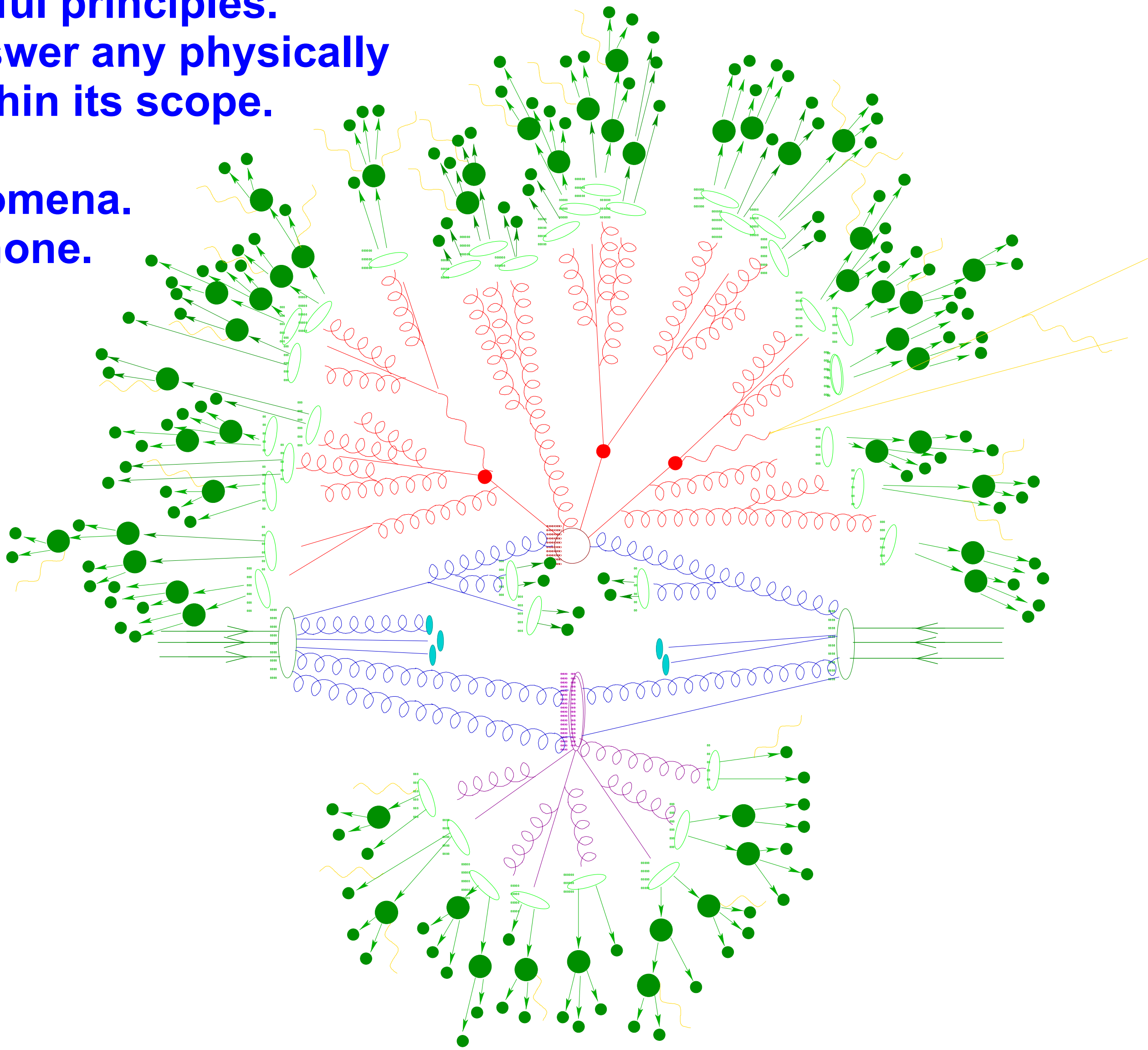
Frank Wilczek *(arXiv:hep-ph/9907340)*

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





The Renormalization Group Equation

Parton Model

Experimental cross section — Parton Distribution Function — Theoretical Cross section

$$\sigma = f(\mu) \otimes \hat{\sigma}(\mu)$$

$f(\mu)$: **Non-perturbative** — $\hat{\sigma}(\mu)$: **Perturbative**

μ is an energy scale

Notation: Sorry, I switched from sigma-hat to omega

Renomalization Group Equation

$$\frac{d\sigma}{d\mu} = 0 = \frac{df(\mu)}{d\mu}\,\omega(\mu) + f(\mu)\,\frac{d\omega(\mu)}{d\mu}$$

Chain Rule

$$\frac{1}{f(\mu)}\frac{df(\mu)}{d\mu} = \gamma = \frac{-1}{\omega(\mu)}\frac{d\omega(\mu)}{d\mu}$$

Non-perturbative — **Separation Constant** — **Perturbative**

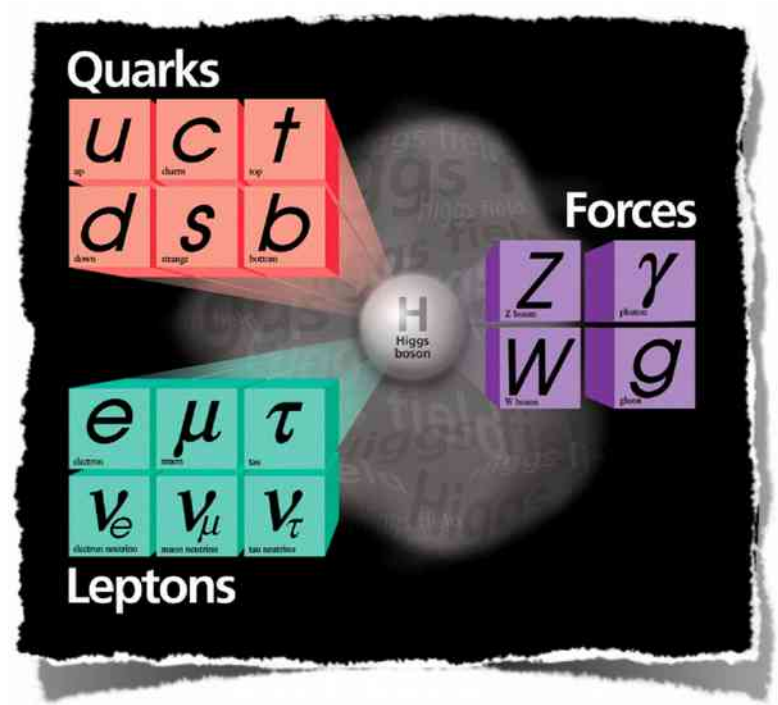
QCD is an elegant theory

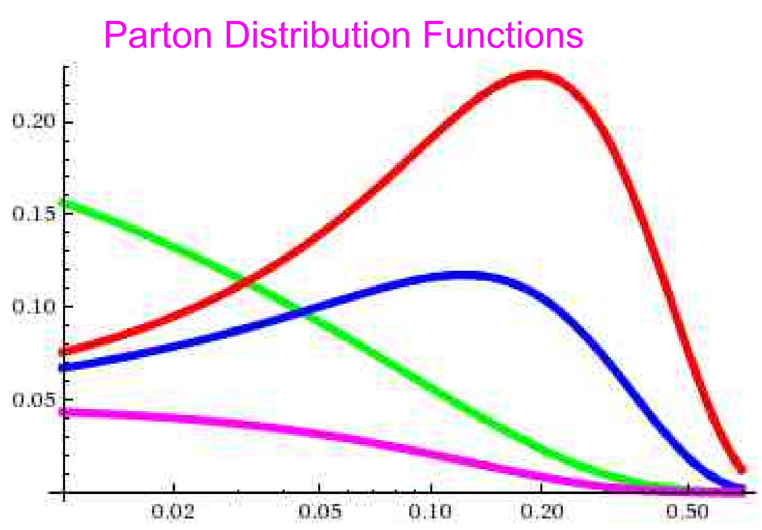
Recap

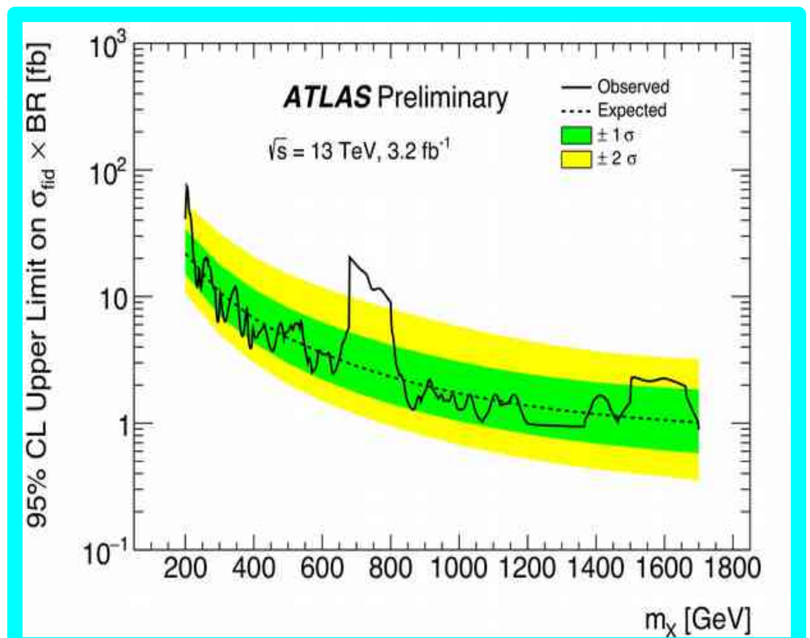
Parton Model

$$\sigma = f \otimes \hat{\sigma}$$

Experimental cross section — Parton Distribution Function — Theoretical Cross section







ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

$\sqrt{s} = 7, 8$ TeV

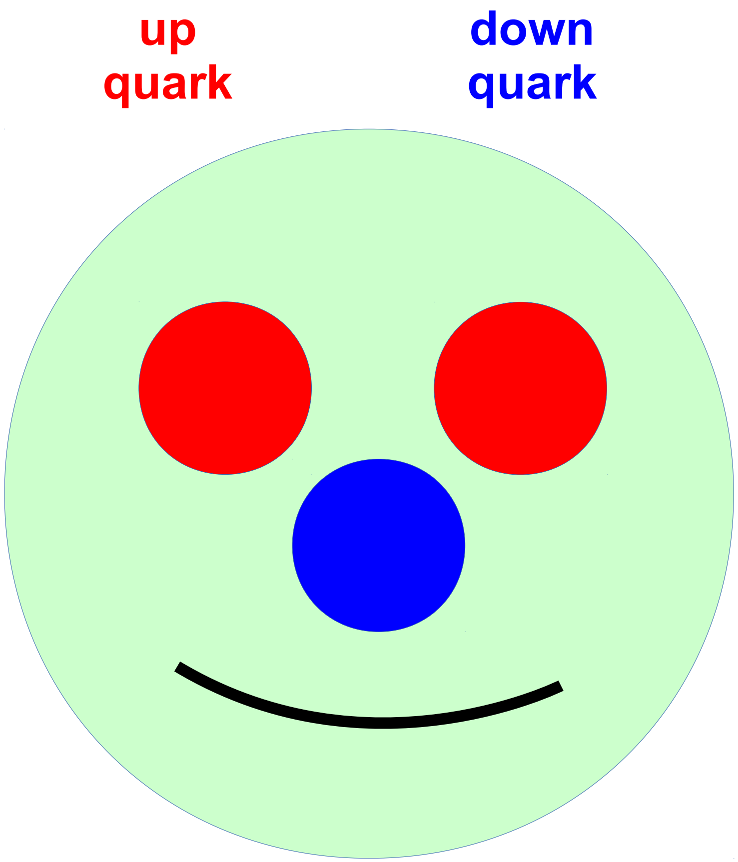
$\sqrt{s} = 7$ TeV | $\sqrt{s} = 8$ TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.8 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	20.3	$\tilde{q}$	100-440 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<10 GeV	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$	780 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1503.03290
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	0-1 e,μ	2-6 jets	Yes	20	$\tilde{g}$	1.26 TeV	m($\tilde{\chi}_1^0$)<300 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	1507.05525
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$	1.32 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$	1.6 TeV	tanβ>20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.29 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<900 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$	1.25 TeV	m($\tilde{\chi}_1^0$)<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$	850 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	m($\tilde{G}$)>1.8 × 10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$	275-440 GeV	m($\tilde{\chi}_1^\pm$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$	110-167 GeV; 230-460 GeV	m($\tilde{\chi}_1^\pm$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$	90-191 GeV; 210-700 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$	100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	700 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	420 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	250 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	620 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	$\tilde{W}$	124-361 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^\pm$)=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$	482 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^\pm$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$	1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	435 GeV	2<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	7 <$c\tau$($\tilde{\chi}_1^0$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	6 <$c\tau$($\tilde{\chi}_1^0$)< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$	1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$	750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), λ_{121}≠0	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$	450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), λ_{133}≠0	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}, \tilde{g}\to q\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	870 GeV	m($\tilde{\chi}_1^0$)=600 GeV	1502.05686
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	850 GeV		1404.250
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$	100-308 GeV		ATLAS-CONF-2015-026
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$	0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$	490 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

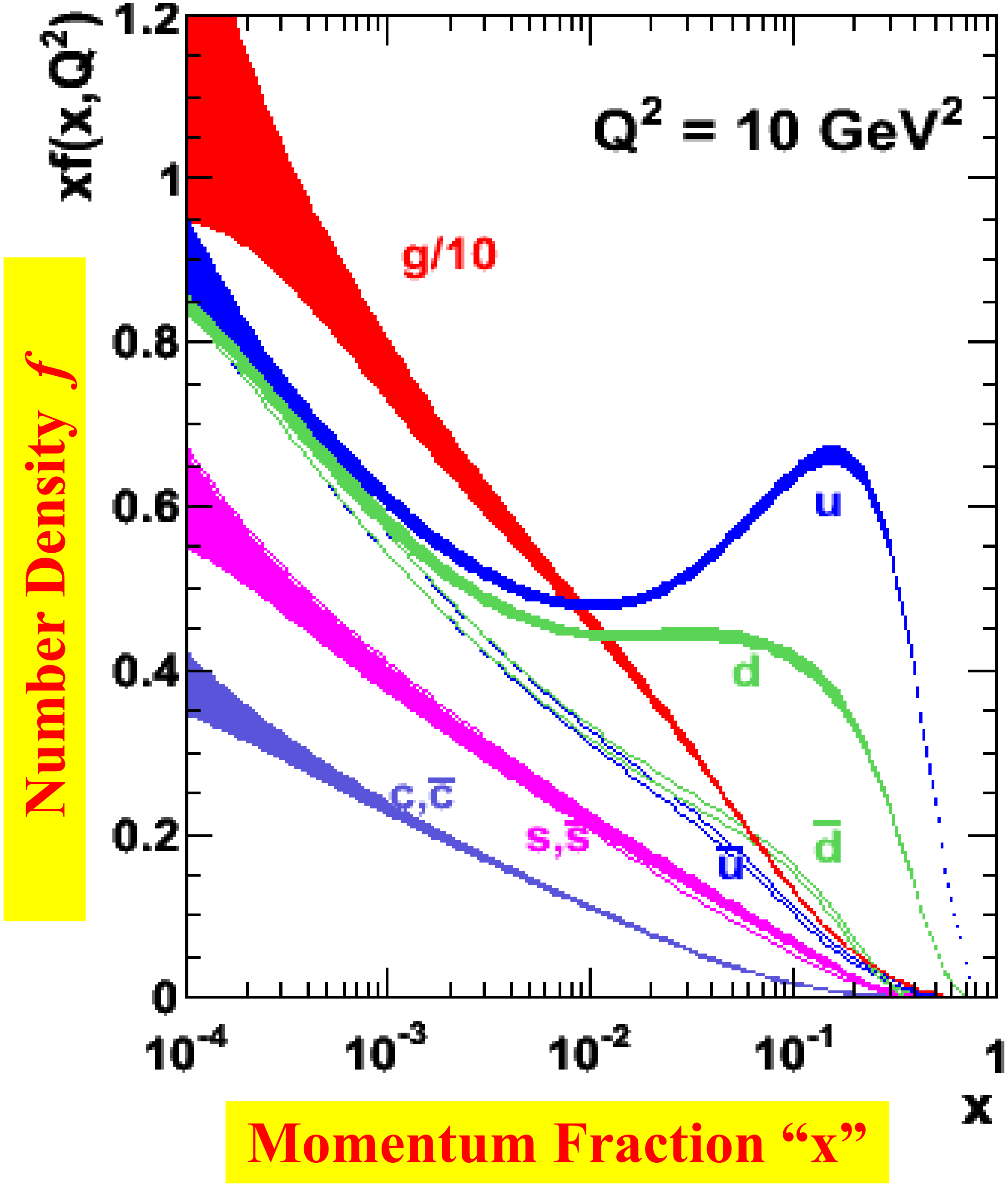
10^{-1} 1 **Mass scale [TeV]**

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

f(x,Q)

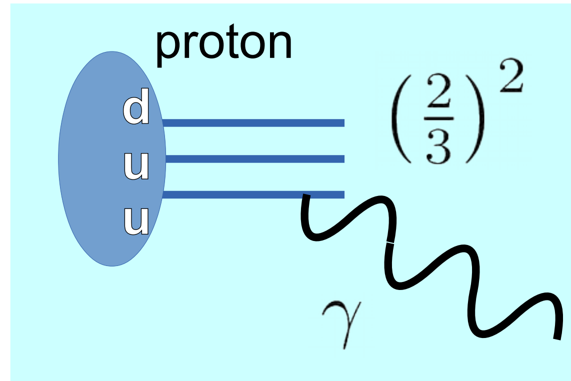


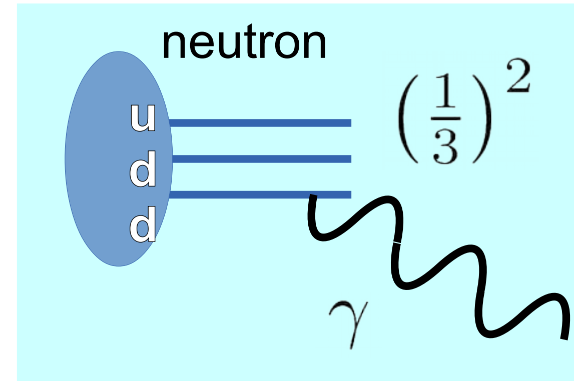
Proton = uud

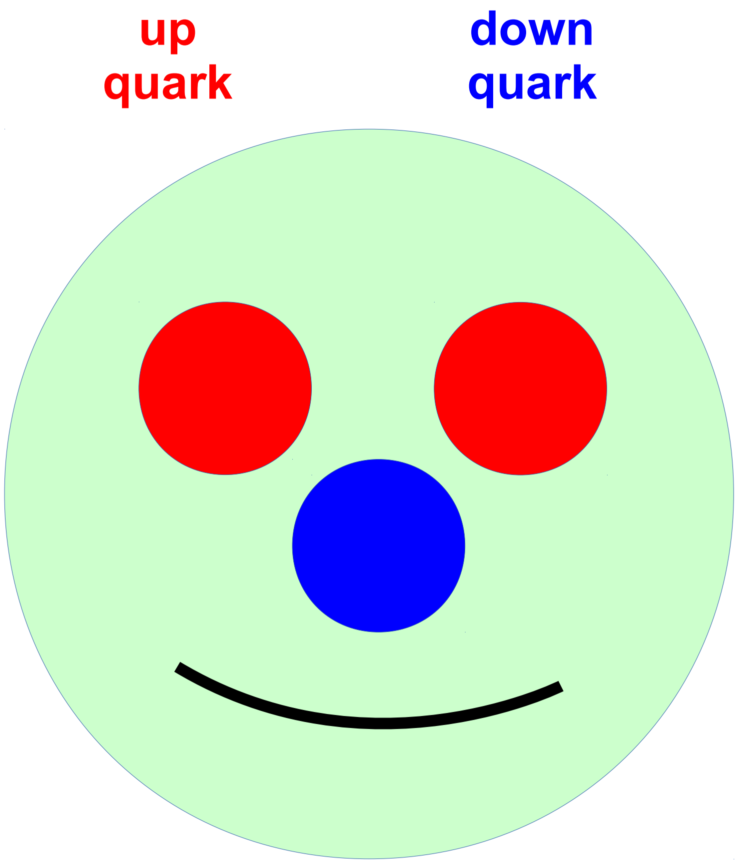


Up and Down Quark: *... not as easy as it looks*

$f(x,Q)$







Proton = uud

Up quarks couple with 4 times the strength of down quarks

more difficult to determine down quarks

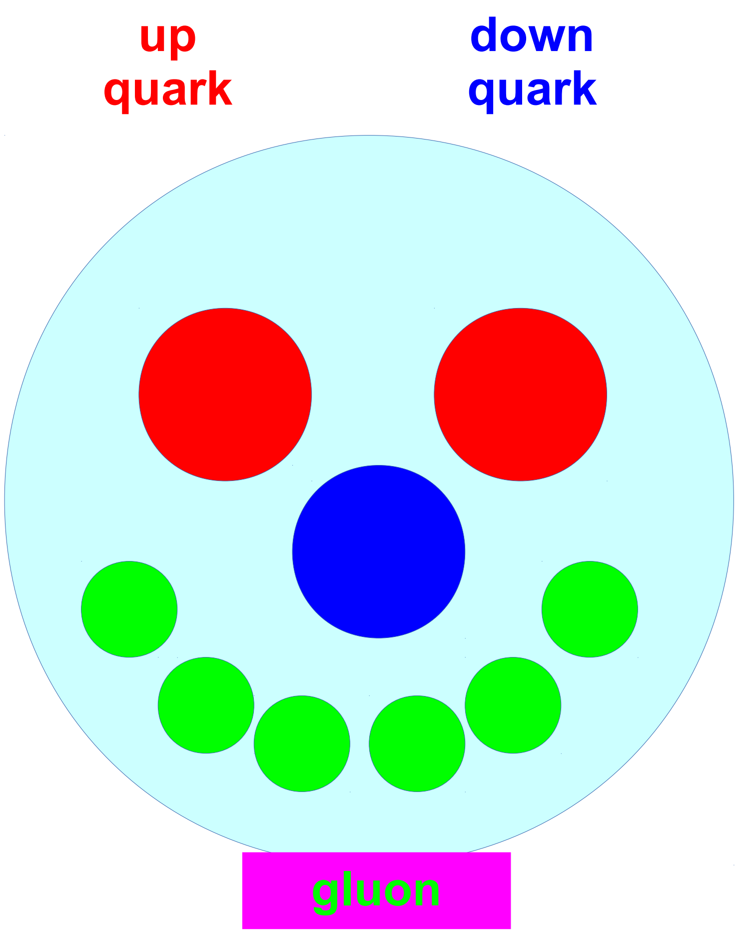
BoNuS @ JLab

Isospin terms are comparable to NNLO QCD

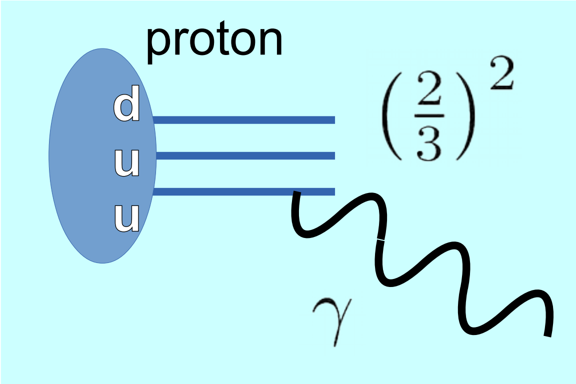
$$\alpha_S \sim \frac{1}{10} \qquad \alpha \sim \frac{1}{137} \qquad \alpha_S^2 \sim \alpha$$

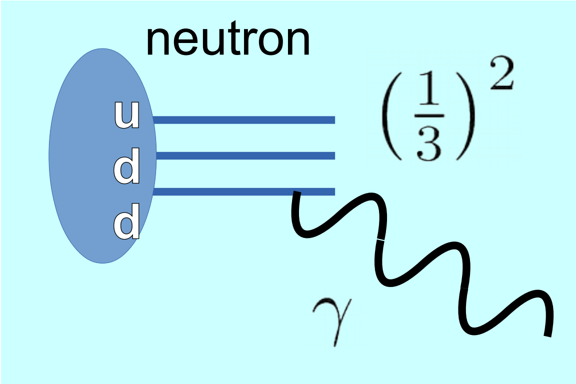
Gluons: *... carry 50% of the momentum fraction of the proton*

f(x,Q)



Proton = uud



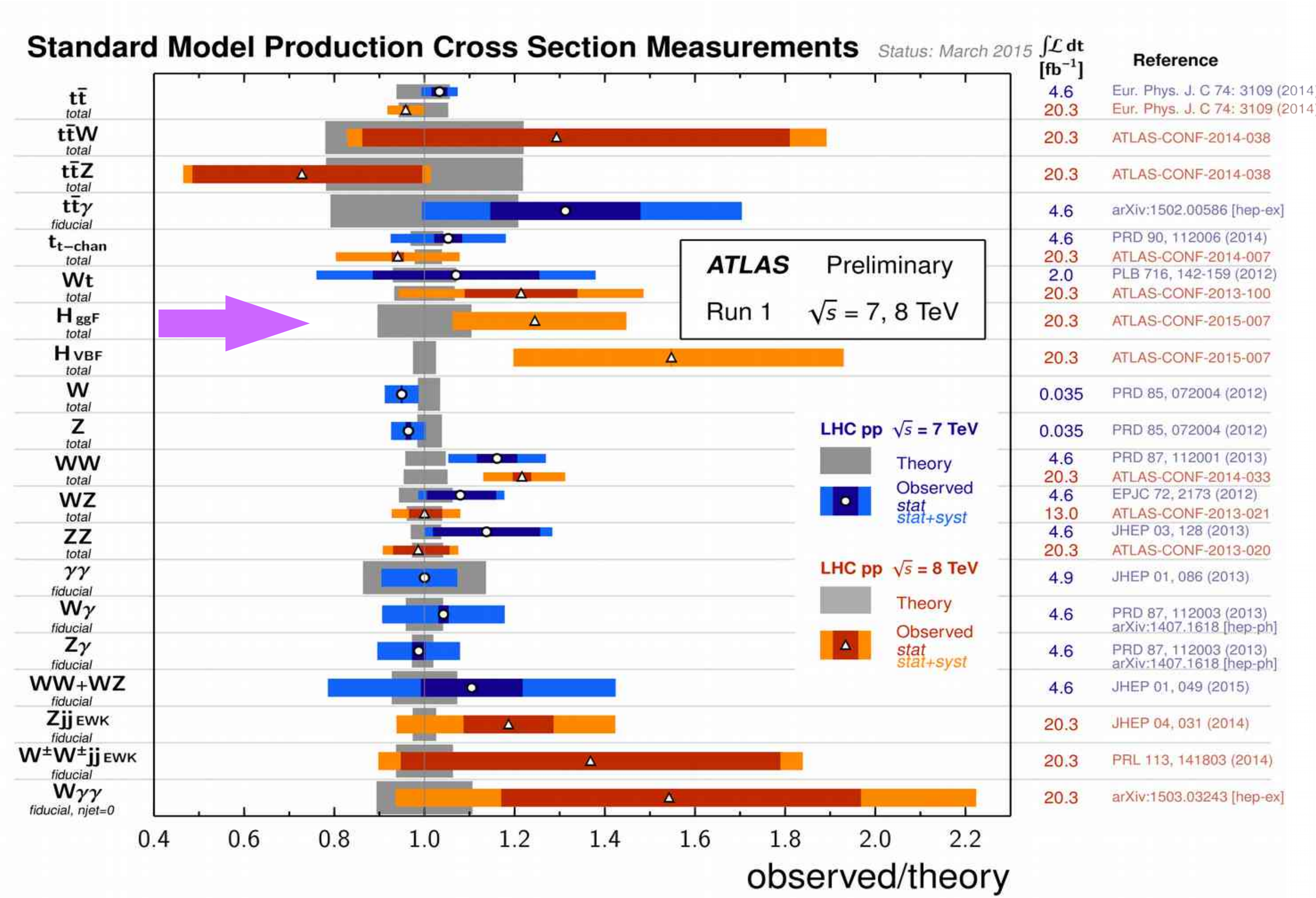


Carry 50% the momentum fraction, but not measured by γ

more difficult to determine than quarks

Important for Higgs production

LHC Results: *Incredible Progress*

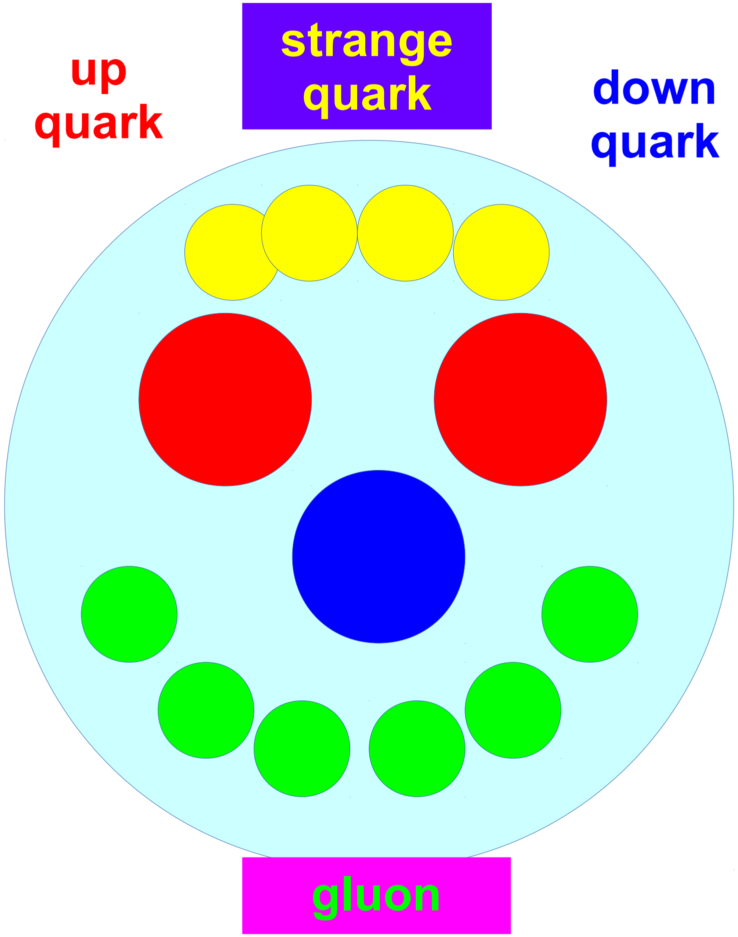


Much of theory error from PDFs N^{3}LO gg->H **PDF error 2x of Theory Error**

Strange Quarks: *... difficult to distinguish Down and Strange*

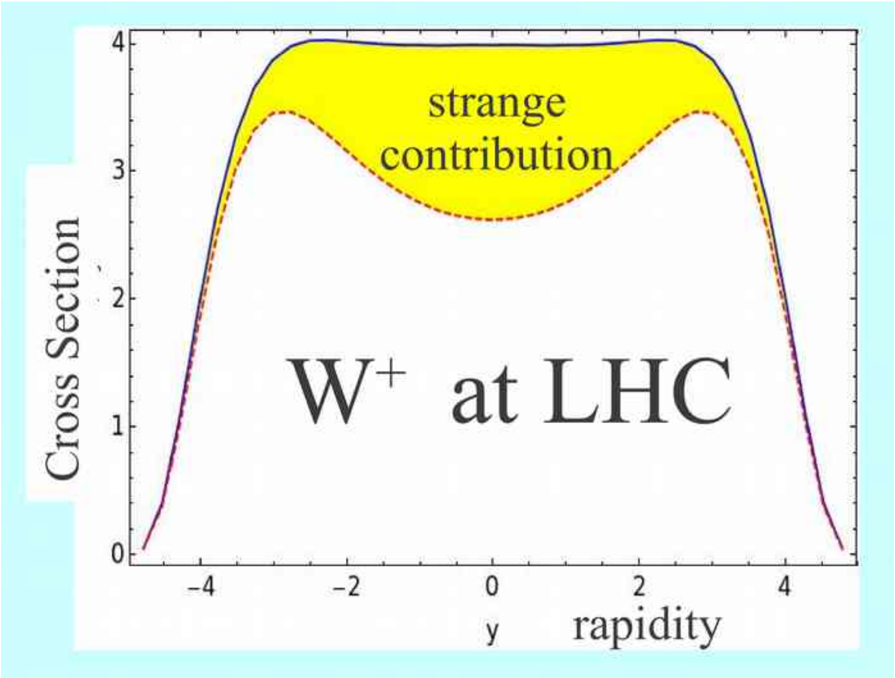
f(x,Q)

{u, c, t}	{d, s, b}
Charge 2/3	Charge 1/3



Proton = uud

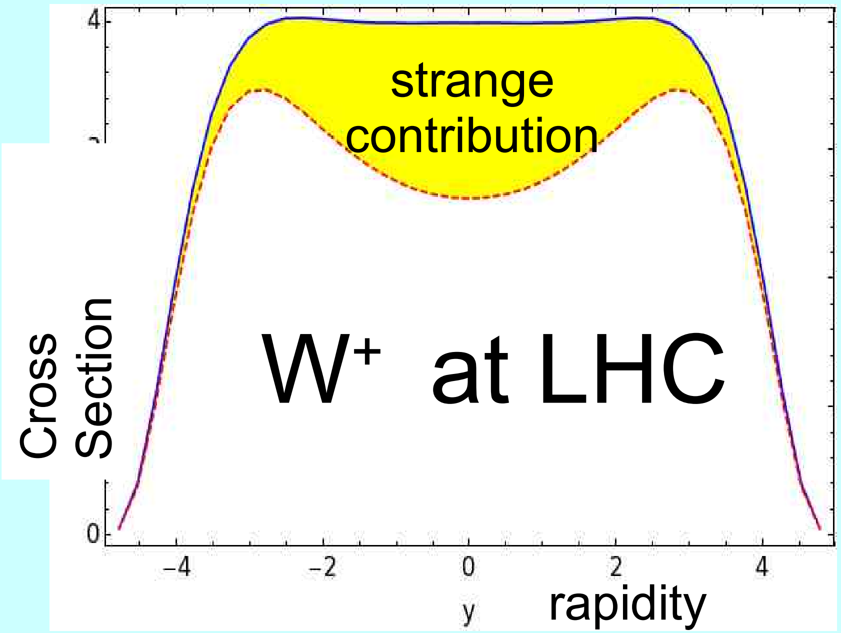
Strange Quark can give large contributions at the LHC

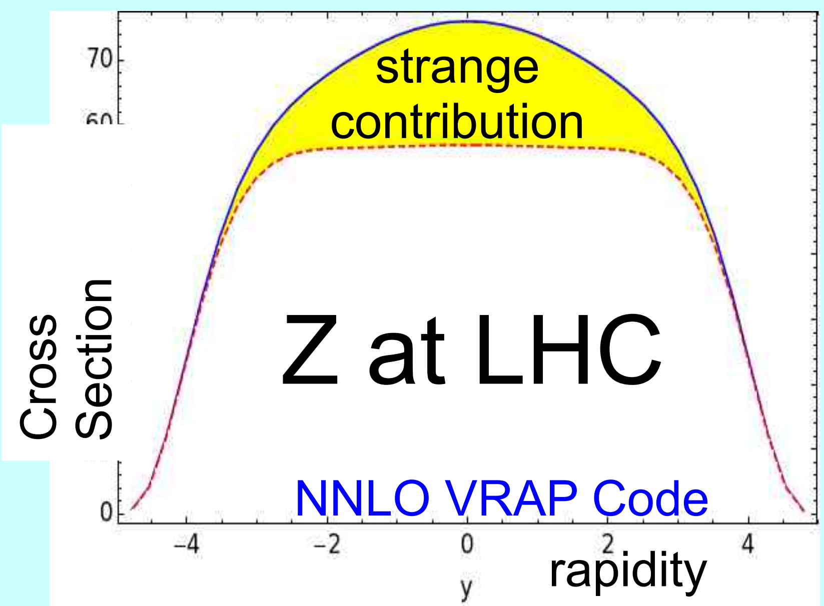


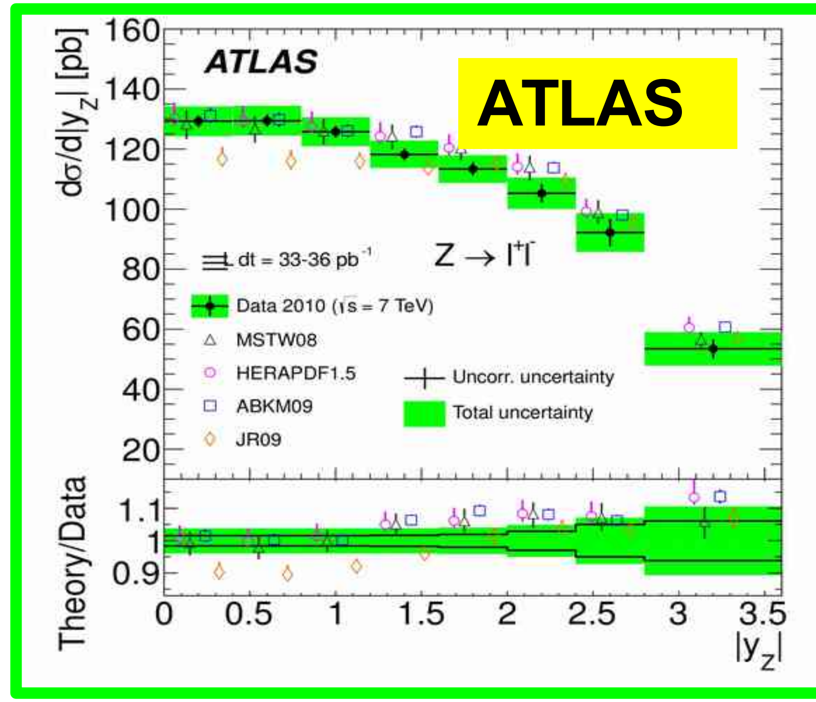
Very different from Tevatron case

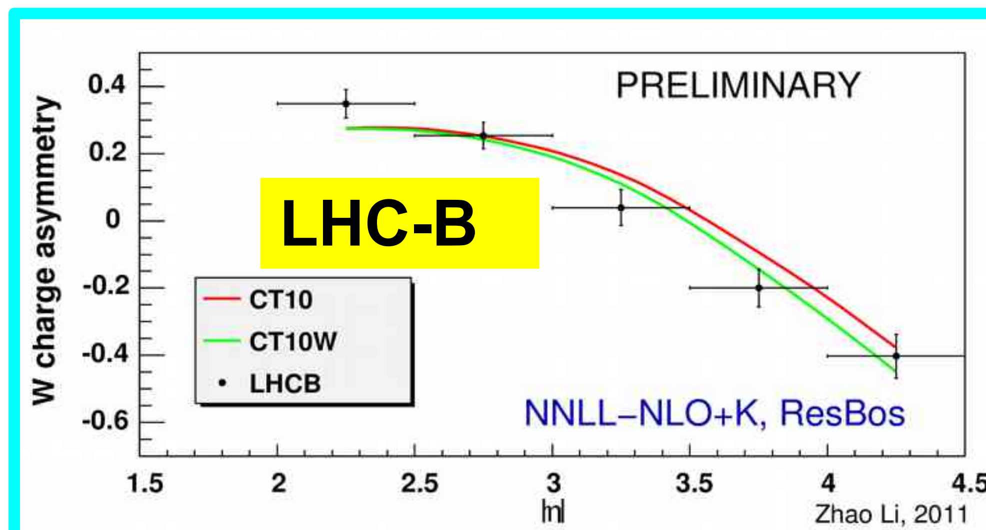
strange content at LHC different from Low Energy

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









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

Kusina, Stavreva, Berge, Olness, Schienbein, Kovarik, Jezo, Yu, Park
Phys.Rev. D85 (2012) 094028

y distribution shape can constrain s(x) PDF

Slide from Carl Schmidt 19 October 2015: INT Workshop

CT14 strange quark PDF

- Conflicting results from experiments:

- ATLAS $$r^s = \frac{\bar{s}(x,Q)}{\bar{d}(x,Q)} = 0.96^{+0.26}_{-0.30} \text{ at } x = 0.023, \quad Q = 1.4 \text{ GeV}$$

$$r^s_{\text{CT14NNLO}} = 0.53 \pm 0.20$$
$$r^s_{\text{CT10NNLO}} = 0.76 \pm 0.17$$

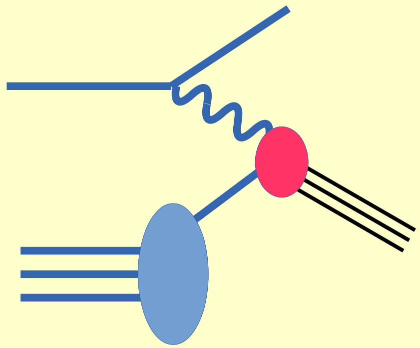
- CMS $$\kappa^s = \frac{\int_0^1 x\left[s(x,Q)+\bar{s}(x,Q)\right]dx}{\int_0^1 x\left[\bar{u}(x,Q)+\bar{d}(x,Q)\right]dx} = 0.52^{+0.18}_{-0.15} \text{ at } Q^2 = 20 \text{ GeV}^2$$

- NOMAD $$\kappa^s = 0.591 \pm 0.019$$

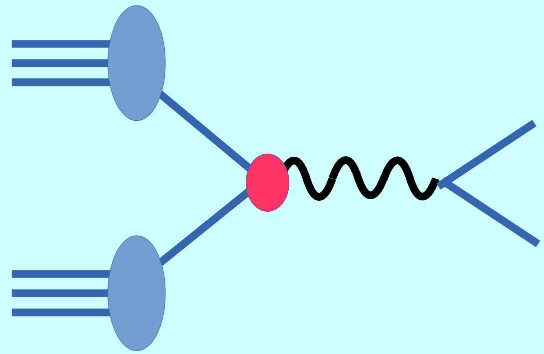
$$\kappa^s_{\text{CT14NNLO}} = 0.62 \pm 0.14$$
$$\kappa^s_{\text{CT10NNLO}} = 0.73 \pm 0.11$$

A man with one watch ...

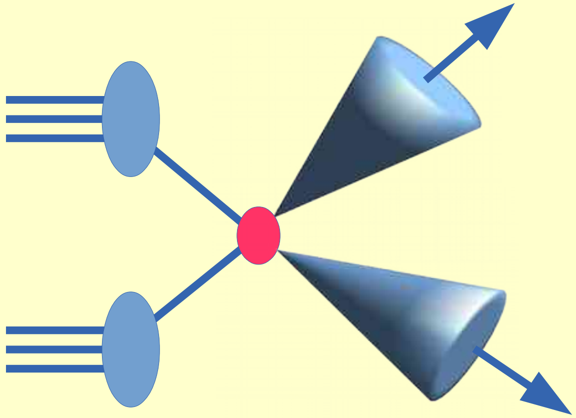
PDF Flavor Differentiation: *A difficult problem*



DIS Production



Drell-Yan



Jet Production

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

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

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

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

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

The DIS combinations have historically been particularly useful

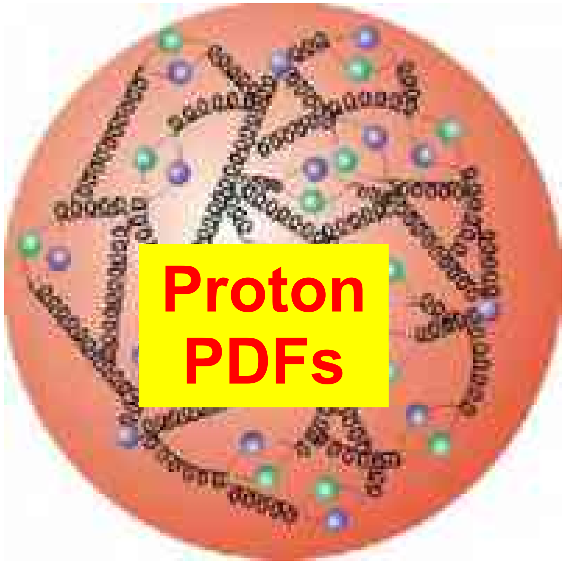
Different linear combinations – key for flavor differentiation

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

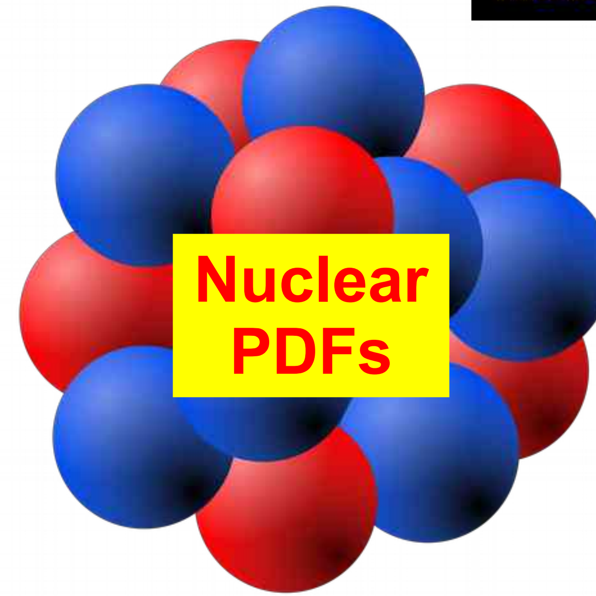
Nuclear data is key for flavor differentiation

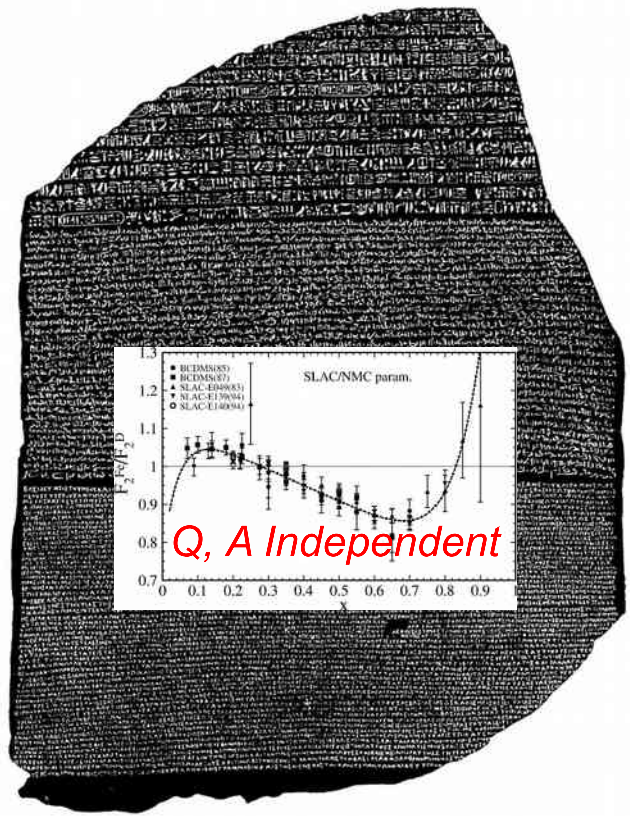
... motivation for

nCTEQ Project



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

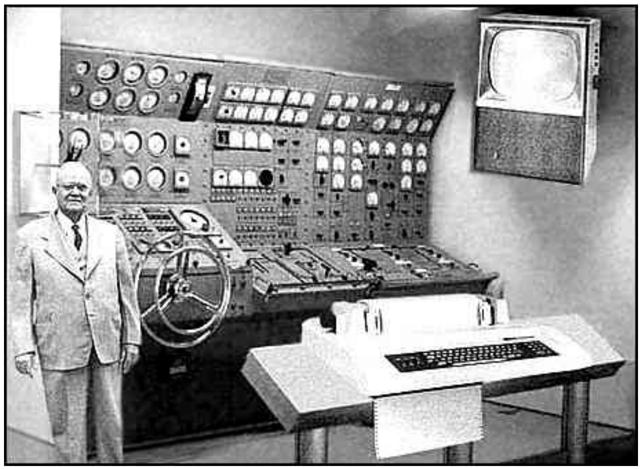




Now & Then

Things can change a bit over the years

PAST	PRESENT	FUTURE
Bubble Chambers	**LHC**	**LHC Run 2**



?

Next generation computer

?

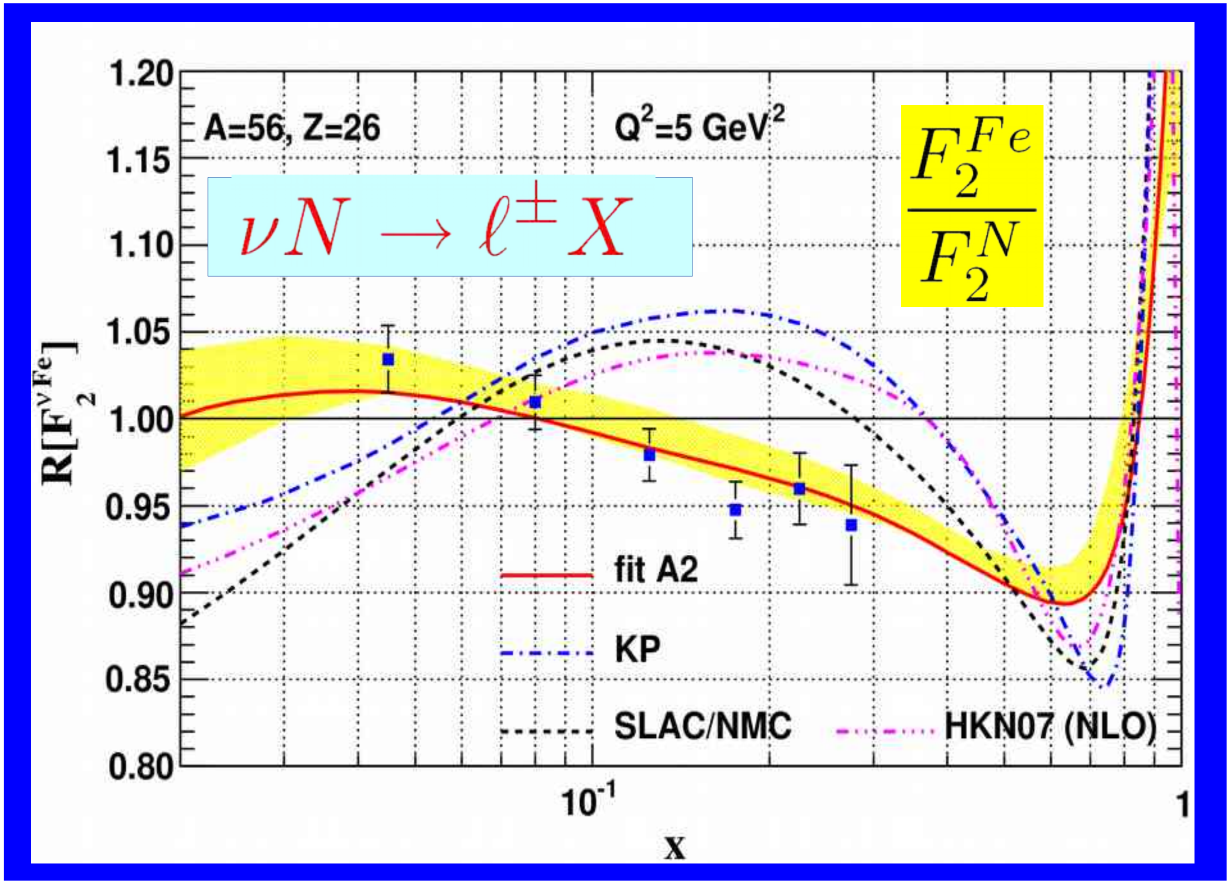
Next generation phone

the same is true for PDFs
not just a Tevatron re-do

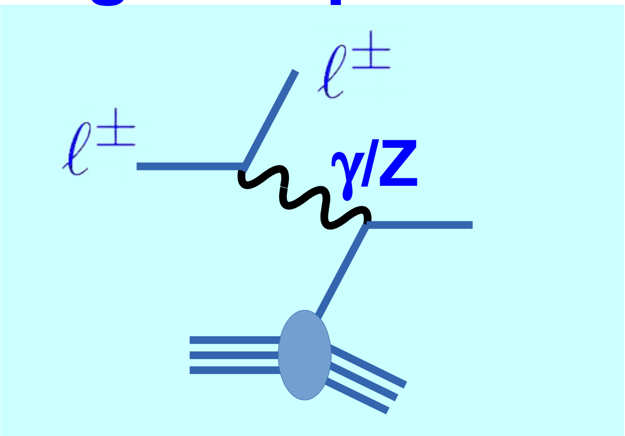
… with a bit of exaggeration

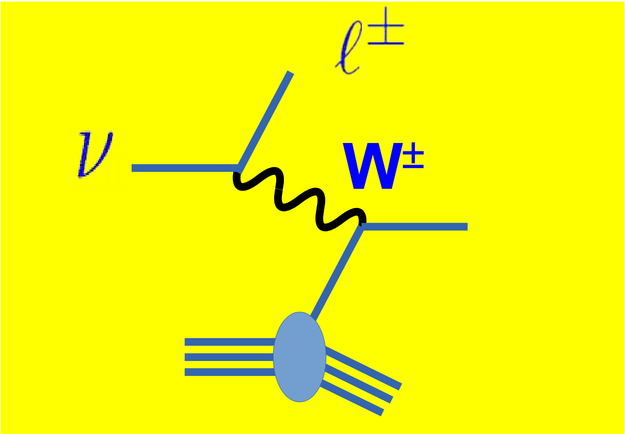
Nuclear Corrections: Compare Neutrino and Charged Lepton DIS

There is tension between the data sets



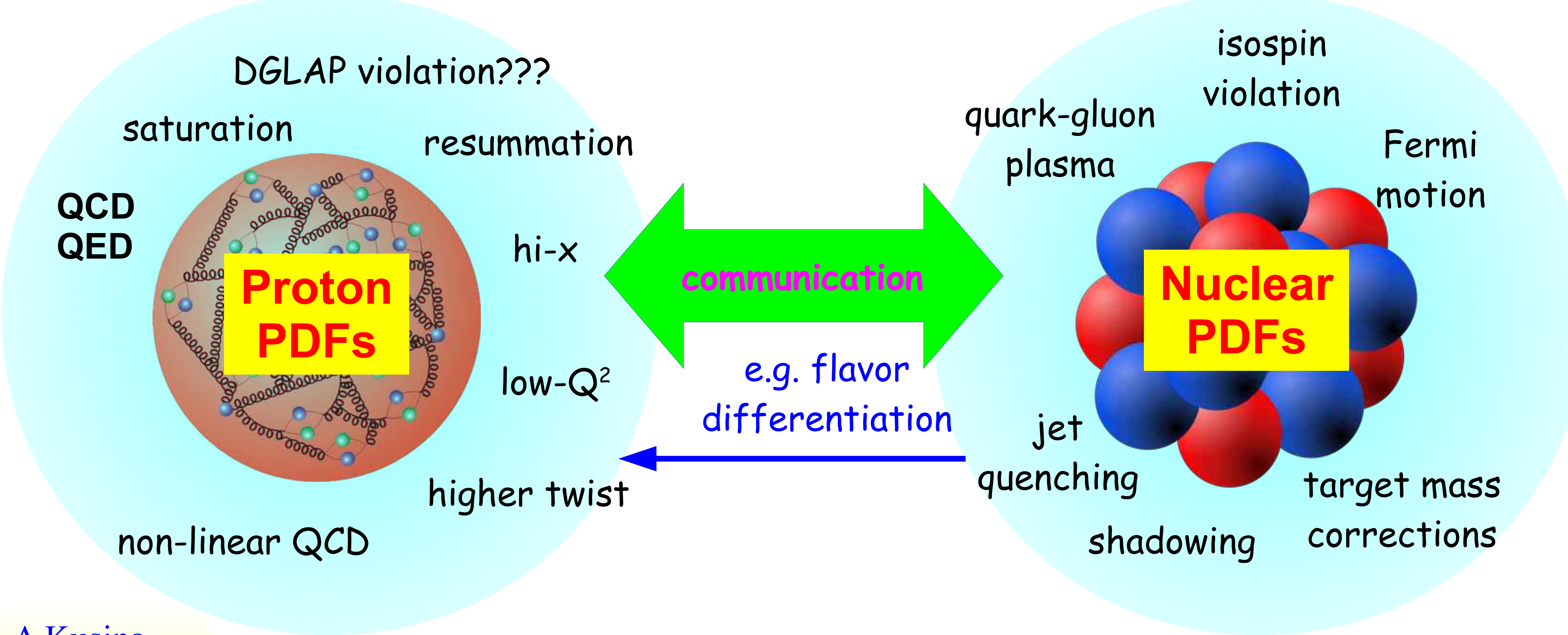
Charged Lepton DIS





Neutrino DIS

Moving Into The 21st Century



A Kusina,
K. Kovarik
T. Jezo,
D. Clark,
C. Keppel,
F. Lyonnet,
J. Morfin,
F. Olness
J. Owens,
I. Schienbein,
J. Yu
E. Godat

Data from nuclear targets play a key role in the flavor differentiation

nCTEQ-15

nuclear parton distribution functions

… the original motivation for nCTEQ15

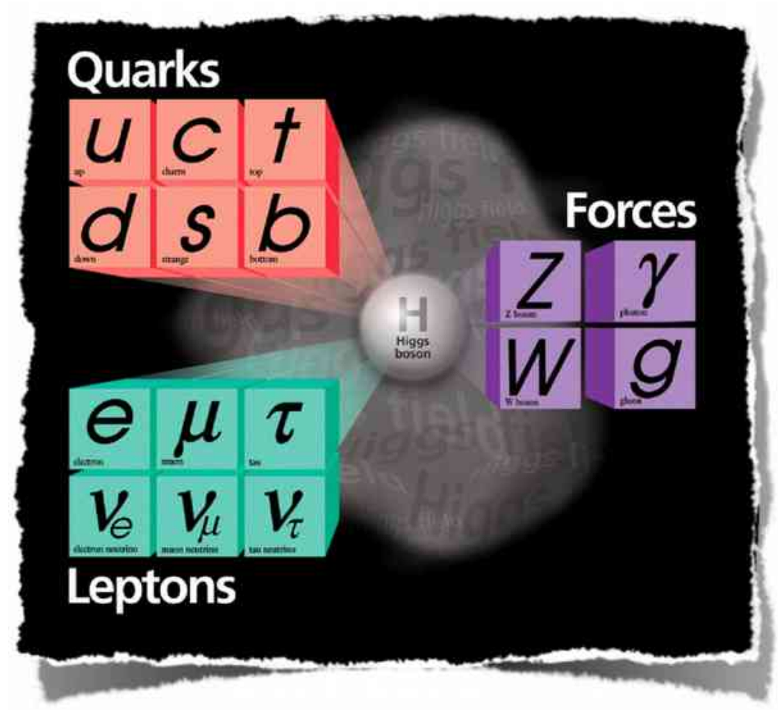
Conclusions

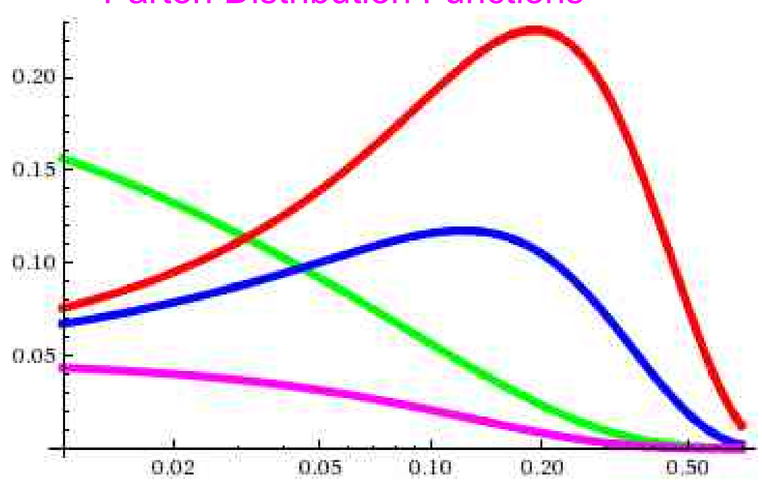
Recap

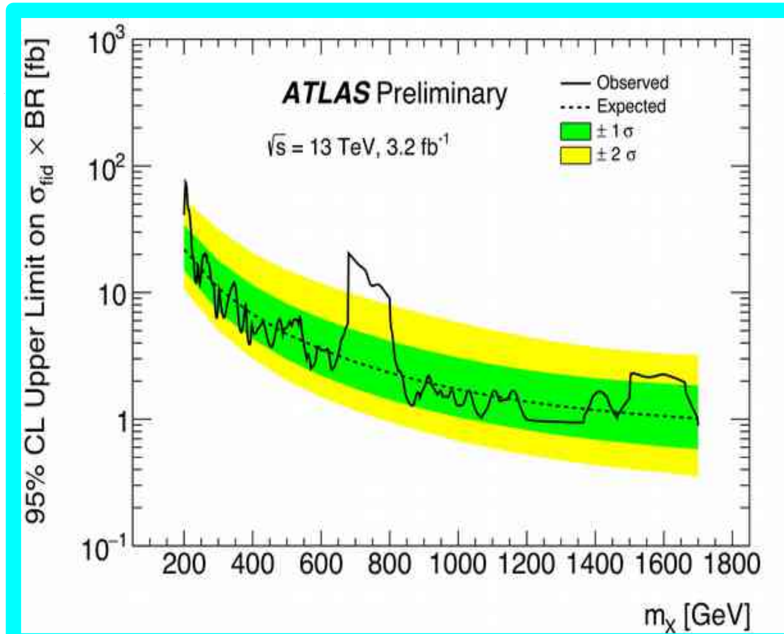
Parton Model

$$\sigma = f \otimes \hat{\sigma}$$

Experimental cross section — Parton Distribution Function — Theoretical Cross section







Our field is data driven!!!

CERN

Google

Fermilab

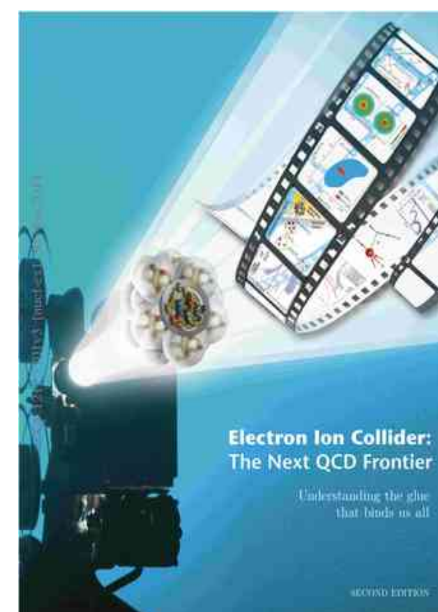
RHIC
relativistic heavy ion collider

Jefferson Lab
Thomas Jefferson National Accelerator Facility

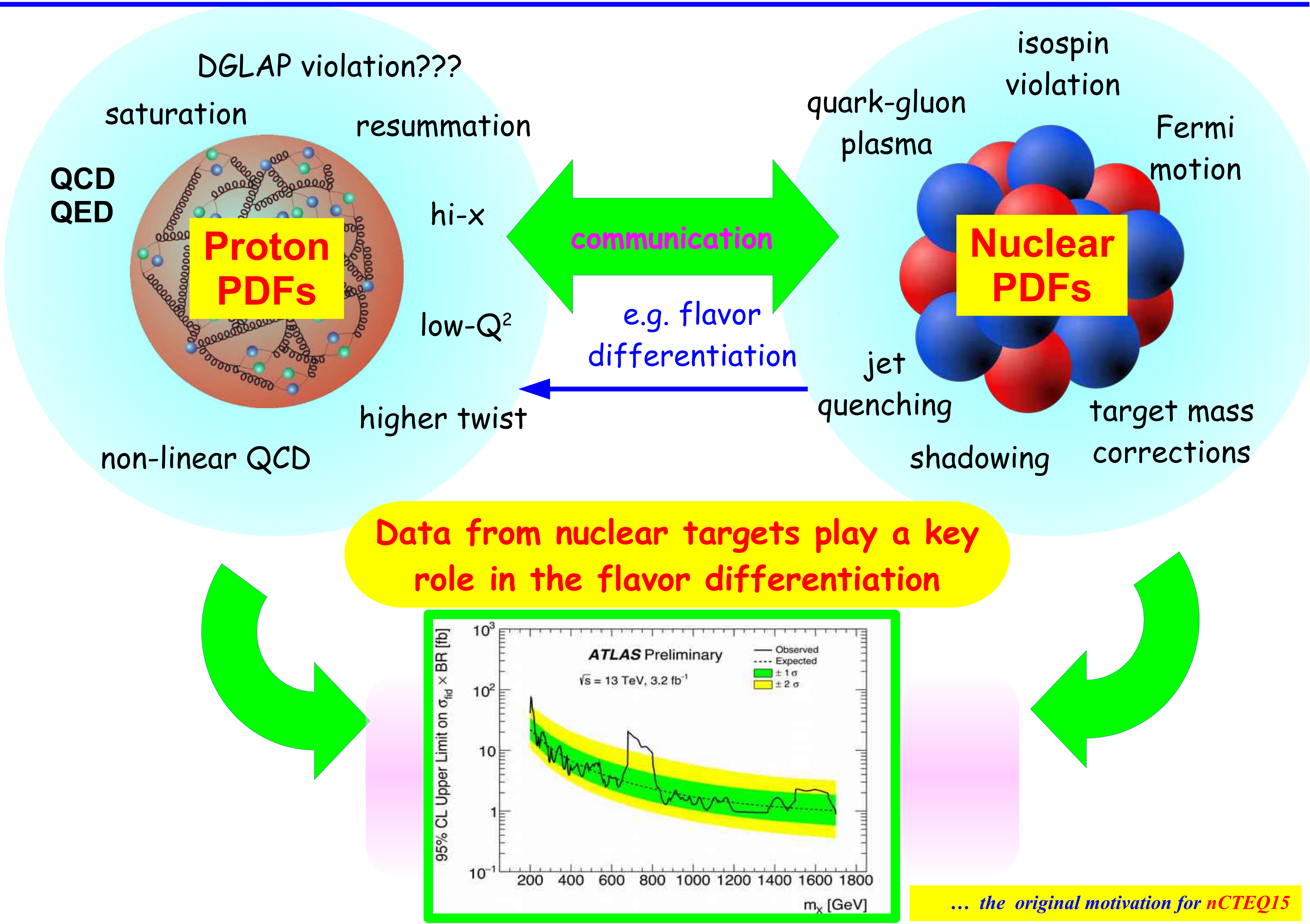
BROOKHAVEN
NATIONAL LABORATORY

FCC
hh ee he

LHeC



Many inputs are needed for the PDFs and nPDFs



Data from nuclear targets play a key role in the flavor differentiation

… the original motivation for nCTEQ15

THE END