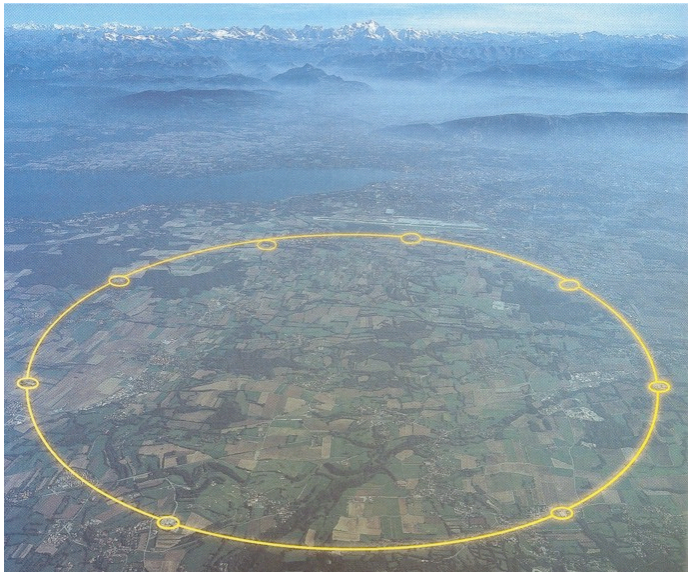
Help Wanted:
A DEWSB Wish List

R. Sekhar Chivukula
Michigan State University

Lattice Gauge Theory for the LHC
May 2-3, 2008

An Experimenter's Wishlist



- Missing many needed NLO computations — Campbell

An experimenter's wishlist

- Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

Single boson	Diboson	Triboson	Heavy flavour
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} + \leq 3j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 3j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 5j$	$ZZ + \leq 5j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 3j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + \leq 2j$
$Z + c\bar{c} + \leq 3j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 2j$
$\gamma + \leq 5j$	$\gamma\gamma + \leq 5j$		$b\bar{b} + \leq 3j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + \leq 5j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + \leq 3j$		
	$Z\gamma + \leq 3j$		

7 years on, and none finished ...

B. Knuteson, 2001

More realistic

NLO calculation priority list from Les Houches 2005
G. Heinrich and J. Huston

process ($V \in \{Z, W, \gamma\}$)	relevant for	
1. $pp \to VV + \text{jet}$	$t\bar{t}H$, new physics	*
2. $pp \to H + 2\,\text{jets}$	H production by vector boson fusion (VBF)	*
3. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$	+
4. $pp \to t\bar{t} + 2\,\text{jets}$	$t\bar{t}H$	
5. $pp \to VV\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics	
6. $pp \to VV + 2\,\text{jets}$	VBF$\to H \to VV$	
7. $pp \to V + 3\,\text{jets}$	various new physics signatures	+
8. $pp \to VVV$	SUSY trilepton	*

pp->bBbB
pp->4 jets (added in 2007)
gg->W*W*

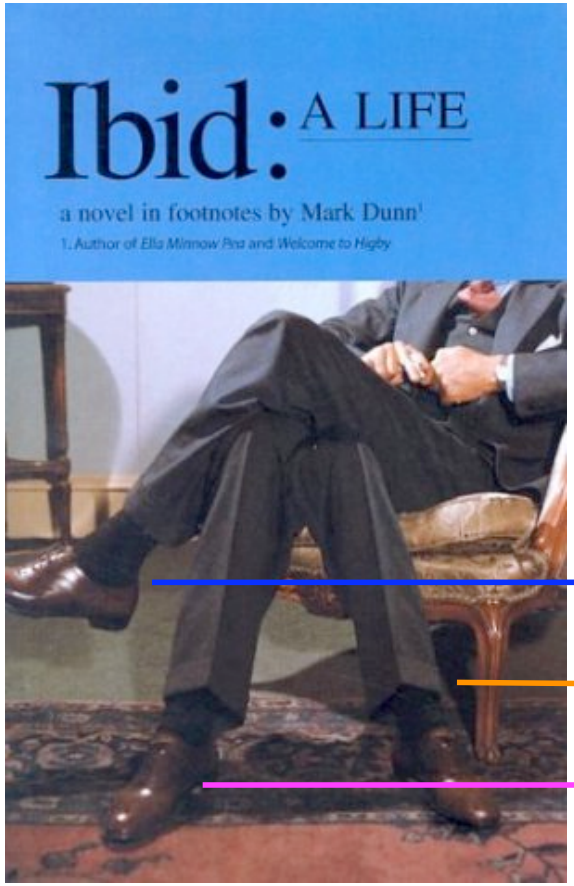
*completed since list
+ people are working

J. Huston, KITPC 2008

What is a realistic goal for BSM/DEWSB Lattice Calculations in the next decade?

"Computation has become an important tool throughout the physical sciences. Computer simulations can bridge intellectual gaps, such as the relationship between quantum-scale models and continuum-scale models of a physical process or material; moreover, computer simulations can be the most convenient channel for communications from theory to the design of experiments."

NSF Theory Workshop Report, 2004



Computation

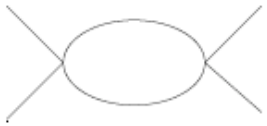
Theory

Experiment

Lattice Contribution to EWSB

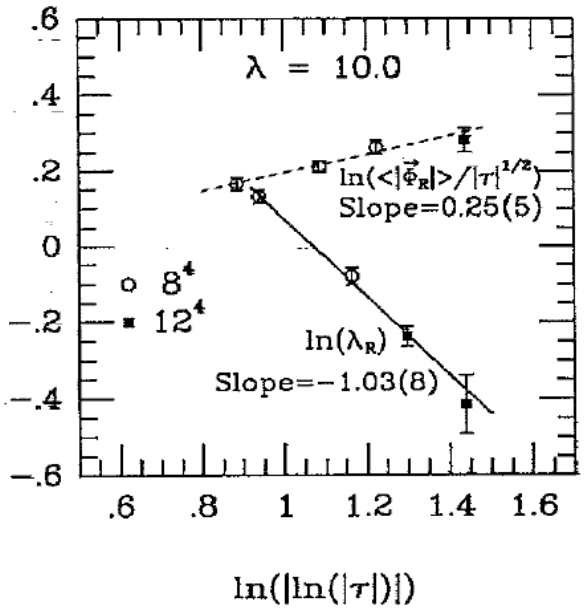
Higgs Lagrangian: $$\frac{1}{2}\mathrm{Tr}\left(D^{\mu}\Phi D_{\mu}\Phi^{\dagger}\right)+\frac{\lambda}{4}\left(\mathrm{Tr}\left(\Phi\Phi^{\dagger}\right)-v^{2}\right)^{2}$$

Triviality Problem . . .



$$\Rightarrow \beta=\frac{3\lambda^{2}}{2\pi^{2}}>0$$

$$\lambda(\mu)<\frac{3}{2\pi^{2}\log\frac{\Lambda}{\mu}} \quad .$$



Kuti, et. al. PRL 61 (1988) 678

Dashen & Neuberger PRL 50 (1983) 1897

Technicolor: Higgsless since 1976!

Eliminate Scalars: Electroweak gauge symmetry broken by the nonzero expectation value of a fermion bilinear, driven by new strong interactions.

Understanding of strongly-interacting gauge theories is extremely limited $\Rightarrow$ theories constructed by analogy!

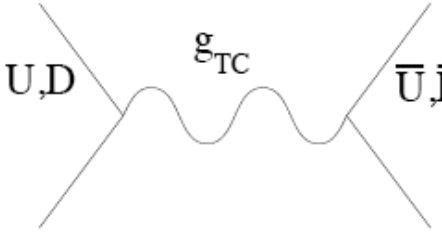
(New Models in this decade from Extra D)

Strong Dynamics/Technicolor

$SU(N_{TC})$ strong/confining theory,

$$\Psi_L = \begin{pmatrix} U \\ D \end{pmatrix}_L \qquad U_R, D_R$$

with massless fermions



$$\rightarrow \langle \bar{U}_L U_R \rangle = \langle \bar{D}_L D_R \rangle \neq 0$$

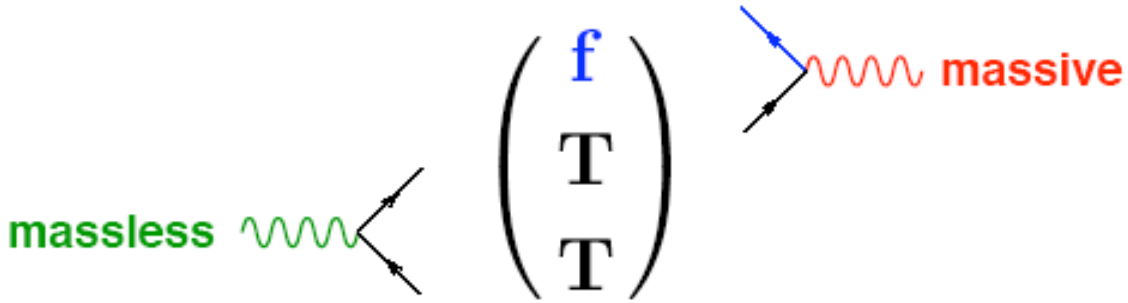
- Pions: $\pi^{\pm}, \pi^0 \Leftrightarrow W_L^{\pm}, Z_L$

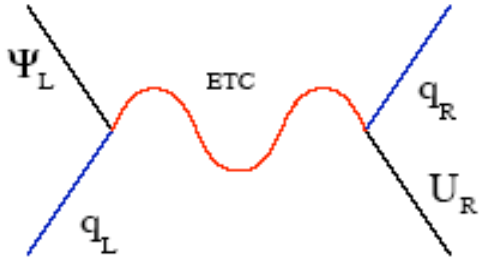
(We know too much … this simplest theory is ruled out!)

Weinberg (1976) & Susskind (1979)

Fermion Masses & ETC Interactions

Extended Technicolor Interactions — Connect chiral-symmetries of TFs to quarks & leptons.





$$\Rightarrow \frac{g^2_{ETC}}{M^2_{ETC}}(\overline{\Psi}_L U_R)(\overline{q}_R q_L)$$

$$m_q \approx \frac{g^2_{ETC}}{M^2_{ETC}}\langle \overline{U}U \rangle_{ETC}$$

Dimopoulos and Susskind & Eichten and Lane (1979)

$$\langle \overline{U}U \rangle_{ETC} = \langle \overline{U}U \rangle_{TC} \exp\left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu} \gamma_m(\mu) \right)$$

For QCD-like TC ("precociously" asymptotically free), γ_m is small over this range:

$$\langle \overline{U}U \rangle_{ETC} \approx \langle \overline{U}U \rangle_{TC} \approx 4\pi F_{TC}^3$$

$$\frac{M_{ETC}}{g_{ETC}} \approx 40\,\mathrm{TeV} \left(\frac{F_{TC}}{250\,\mathrm{GeV}} \right)^{\frac{3}{2}} \left(\frac{100\,\mathrm{MeV}}{m_q} \right)^{\frac{1}{2}}$$

FCNCs and Walking Technicolor

Quark mixing implies transitions between different generations: $q \to \Psi \to q'$. ETC algebra:

$$[\overline{q}\gamma\Psi, \overline{\Psi}\gamma q'] \supset \overline{q}\gamma q' \,.$$

$|\Delta S| = 2$ interactions:

$$\mathcal{L}_{|\Delta S|=2} = \frac{g_{ETC}^2\,\theta_{sd}^2}{M_{ETC}^2}\ (\overline{s}\Gamma^\mu d)\ (\overline{s}\Gamma'_\mu d) + \text{h.c.}$$

$$\Delta M_K \;<\; 3.5 \times 10^{-12}\ \text{MeV} \Rightarrow$$

$$\frac{M_{ETC}}{g_{ETC}\sqrt{\text{Re}(\theta_{sd}^2)}} \;>\; 600\ \text{TeV}$$

$$m_{q,\ell} \simeq \frac{g_{ETC}^2}{M_{ETC}^2}\langle \overline{T}T\rangle_{ETC} < \frac{0.5\ \text{MeV}}{N_D^{3/2}\,\theta_{sd}^2}$$

Difficult to get s & c, let alone b & t!

$\Rightarrow$ TC Dynamics is NOT like QCD.

Walking Technicolor

If $\beta(\alpha_{TC}) \simeq 0$ all the way from Λ_{TC} to M_{ETC},
i.e. if the TC-coupling "walks" $\Rightarrow \gamma_m(\mu) \cong 1$

$$m_{q,l} = \frac{g^2_{ETC}}{M^2_{ETC}} \times \left(\langle \overline{T}T \rangle_{ETC} \cong \langle \overline{T}T \rangle_{TC} \frac{M_{ETC}}{\Lambda_{TC}} \right)$$

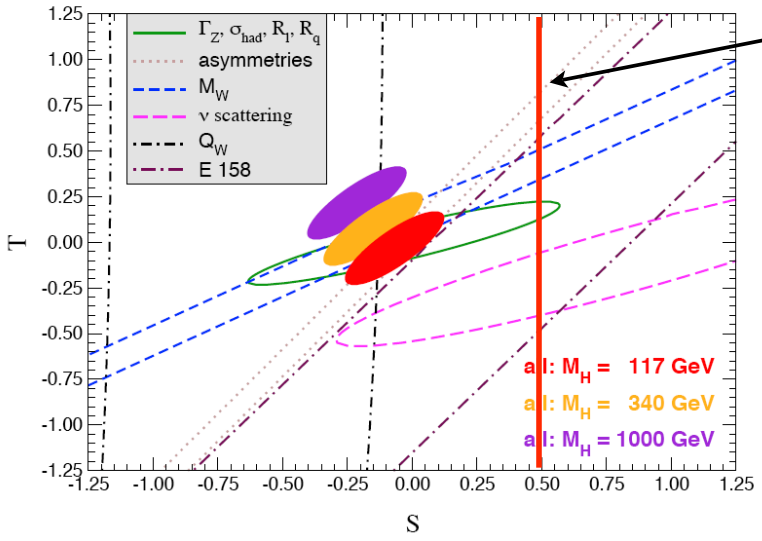
$$\text{FCNCs} \Rightarrow M_{ETC}/\Lambda_{TC} \gtrsim 100 - 1000$$

$$m_{q,l} \lesssim \frac{50 - 500\,\text{MeV}}{N_D^{3/2}\theta^2_{sd}}$$

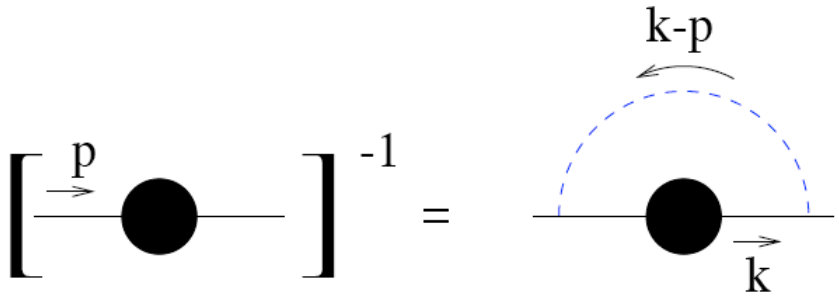
enough to accommodate s and c quarks.

Does $\gamma_m = 1$ in a walking theory?

- Chiral symmetry breaking in an approximately conformal theory
- Large anomalous dimension of $\bar{\psi}_L \psi_R$
- Can we calculate αS?
- What is the spectrum? PNGB masses?



QCD-like, N_D=2 & N_C=3



Current Understanding from
"Gap Equation" in "Rainbow Approximation"

PDG2006: Erler and Langacker

Extended TechniColor

$$SU(N_{TC}+3)$$

$$\Lambda_1 \quad \downarrow \quad m_1 \approx \frac{4\pi F^3}{\Lambda_1^2}$$

$$SU(N_{TC}+2)$$

$$\Lambda_2 \quad \downarrow \quad m_2 \approx \frac{4\pi F^3}{\Lambda_2^2}$$

$$SU(N_{TC}+1)$$

$$\Lambda_3 \quad \downarrow \quad m_3 \approx \frac{4\pi F^3}{\Lambda_3^2}$$

$$SU(N_{TC})$$

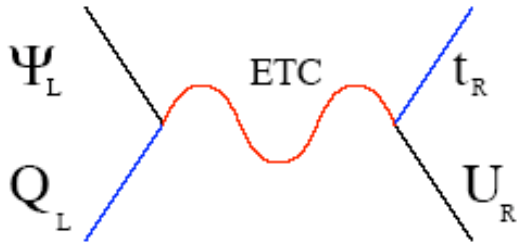
Self-breaking through "tumbling":

"Most Attractive Channel"

Chiral Symmetry Breaking @ Critical Coupling

Does tumbling occur, and in the pattern predicted by this method?

Top Quark Mass Generation



$$\Rightarrow \frac{g_{ETC}^2}{M_{ETC}^2}(\overline{\Psi}_L U_R)(\bar{t}_R Q_L)$$

$$m_t \approx \frac{g_{ETC}^2}{M_{ETC}^2}\langle \overline{U}U \rangle_{ETC}$$

$$\frac{M_{ETC}}{g_{ETC}} \approx 1\,\mathrm{TeV}\left(\frac{F_{TC}}{250\,\mathrm{GeV}}\right)^{\frac{3}{2}}\left(\frac{175\,\mathrm{GeV}}{m_t}\right)^{\frac{1}{2}}$$

Are new interactions required to explain top-quark mass?

Topcolor-Assisted Technicolor† (TC2)

- Strong Technicolor dynamics at 1 TeV dynamically generates most of EWSB.
- Extended Technicolor dynamics at scales much higher than 1 TeV generate the light quark and lepton masses.
- Strong Topcolor dynamics also at a scale of 1 TeV generates $\langle \bar{t}t \rangle \neq 0$, $m_t \sim 170$ GeV.

Hill, hep-ph/9411426

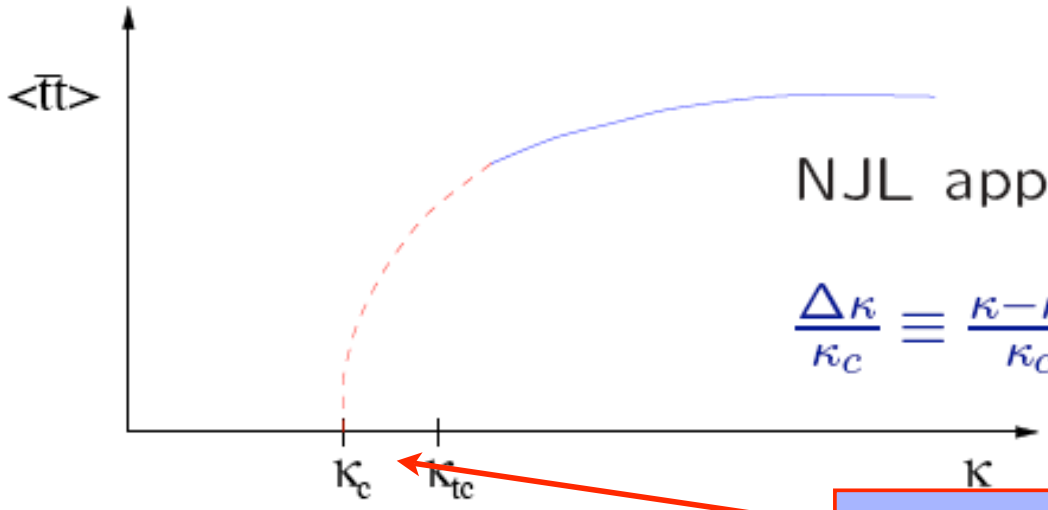
Can we realize the NJL dynamics?

$SU(3)_h \times SU(3)_\ell \xrightarrow{M} SU(3)_{QCD}$

where (t,b) feel the first SU(3)
and (u,d,c,s) feel the second

Below the scale M

- massive topgluons exchanged by top quarks
- $\mathcal{L} \supset -\frac{4\pi\kappa}{M^2}\left(\bar{t}\gamma_\mu\frac{\lambda^a}{2}t\right)^2$



NJL approximation

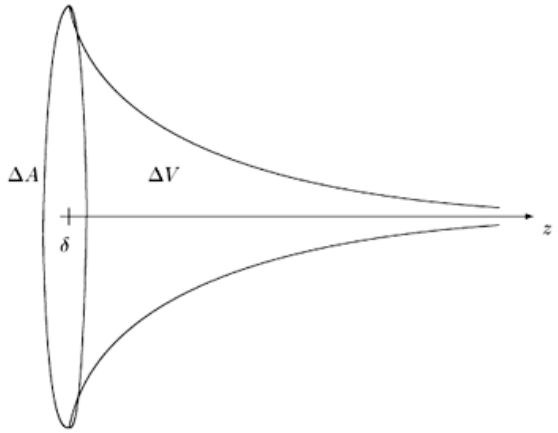
$$\frac{\Delta\kappa}{\kappa_c} \equiv \frac{\kappa-\kappa_c}{\kappa_c} \propto \frac{\langle\bar{t}t\rangle}{M^3}$$

Is this truly 2nd order?

Note:
M >> 1 TeV
implies fine
tuning

AdS/CFT Duality

Conjecture: Equivalence of 5D theory in AdS and 4D CFT



UV ⟶ IR

$$ds^2 = \left(\frac{R}{z}\right)^2 \left[\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right]$$

$$R < z < R'$$

NB: Rescaling Invariance!

Strong evidence for N=4 SUSY YM string theory on AdS

Strongly-coupled CFT ⇔ Weakly-coupled 5D Theory!

AdS/CFT Dictionary

Bulk of AdS	$\leftrightarrow$	CFT
Coordinate (z) along AdS	$\leftrightarrow$	Energy scale in CFT
Appearance of UV brane	$\leftrightarrow$	CFT has a cutoff
Appearance of IR brane	$\leftrightarrow$	conformal symmetry broken spontaneously by CFT
KK modes localized on IR brane	$\leftrightarrow$	composites of CFT
Modes on the UV brane	$\leftrightarrow$	Elementary fields coupled to CFT
Gauge fields in bulk	$\leftrightarrow$	CFT has a global symmetry
Bulk gauge symmetry broken on UV brane	$\leftrightarrow$	Global symmetry not gauged
Bulk gauge symmetry unbroken on UV brane	$\leftrightarrow$	Global symmetry weakly gauged
Higgs on IR brane	$\leftrightarrow$	CFT becoming strong produces composite Higgs
Bulk gauge symmetry broken on IR brane by BC's	$\leftrightarrow$	Strong dynamics that breaks CFT also breaks gauge symmetry

Csaki hep-ph/0510275

Duality and Higgsless Models

A Higgsless Theory on AdS could be "dual" to a conformally-invariant model of dynamical EWSB : like walking TC!

Can we find a 4-D Conformal Higgless Theory?

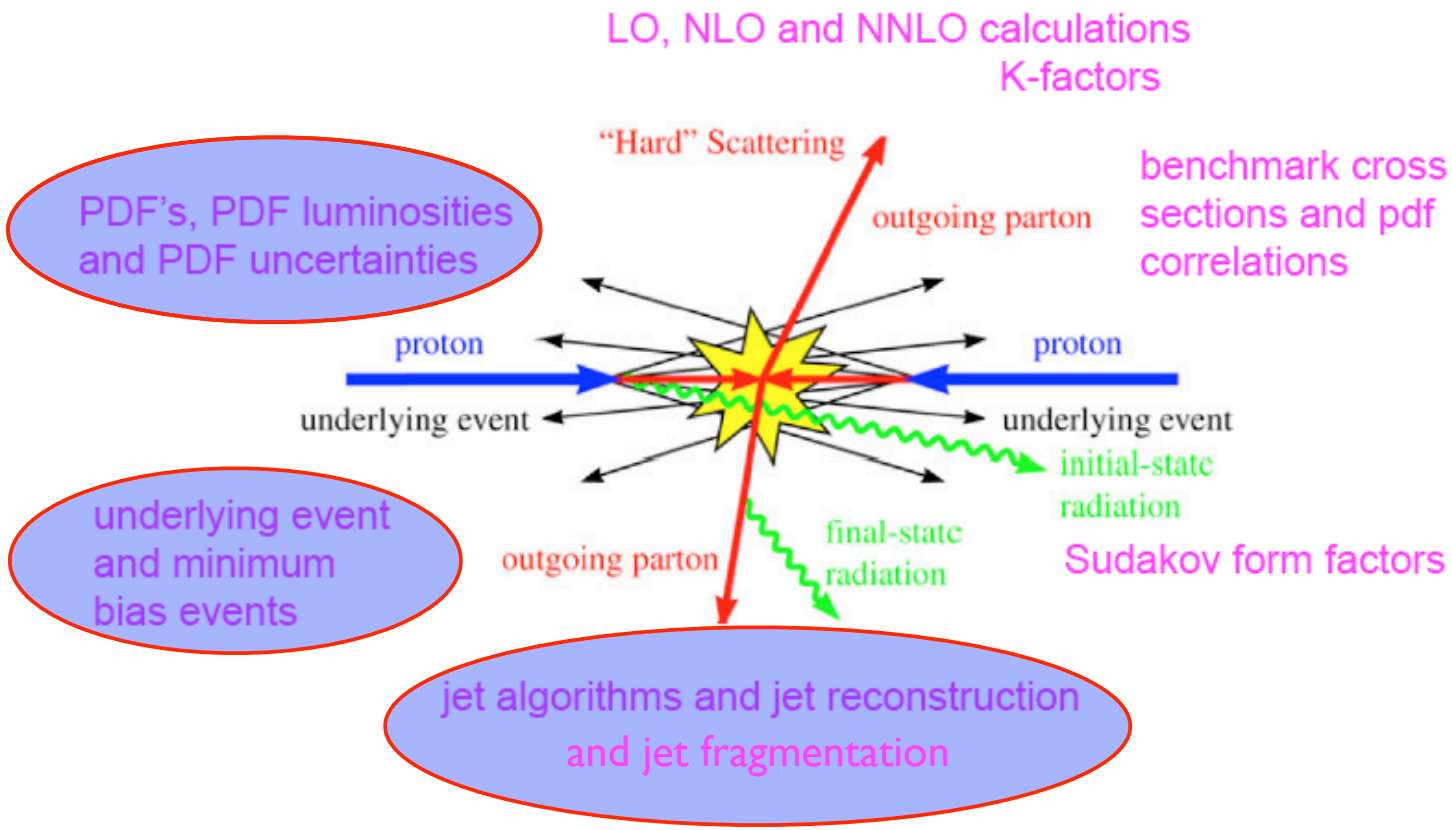
See talks by E. Neil, A. Martin, D. Nogradi, & M. Luty

Inspiration: Symmetries in QCD

	Symmetry	Anomaly?	Fate
✔	Color (gauged)	no	unbroken (confined)
✔	Scale Invariance	yes	not a symmetry
✔	$SU(3)_V \times U(1)_B$	no	unbroken
✔	$SU(3)_A$	no	spontaneously broken
?	$U(1)_A$	yes	not a symmetry
??	CP	no?!	not a symmetry!?

QCD: Unsolved Problems @ LHC

Understanding SM predictions at the LHC



The Holy Grail

A complete Yang-Mills Phase Diagram:

for any group (will settle for SU(N)), any fermion representation(s), arbitrary gauge-symmetry breaking

and

relevant scaling dimensions, spectrum,
& correlation functions

see Sanino, arXiv:0804.0182 for a recent review (analytic)