Quantum Chromodynamics and Jets at the LHC

Herbstschule HEP

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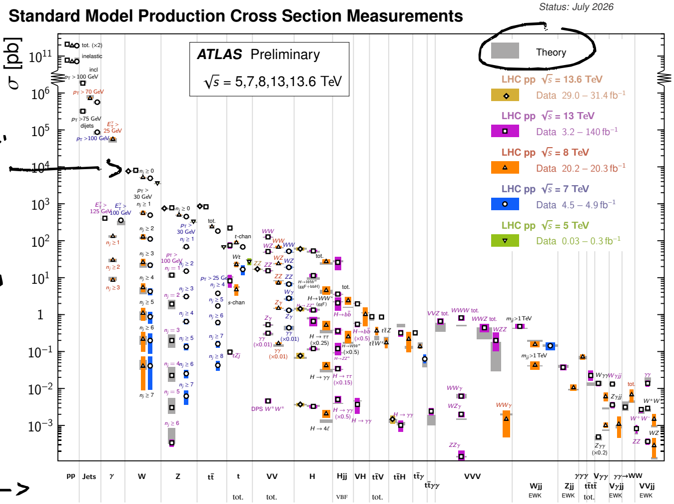
Lecture Overview

- Introduction and motivation } Today
- Basics of QCD
- Higher orders (very brief) } Tomorrow
- Hadronic initial states
- All-order computations: resummation & parton-showers → Thursday
- Jet physics & LHC Phenomenology → Friday

Standard Model measurements

Smaller exp unc.
-> theory unc?
-> QCD plays
dominant role



final state ->

SM
success
story
⇓
QCD

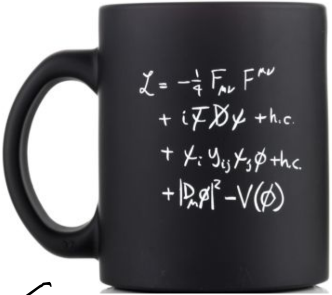
Standard Model measurements

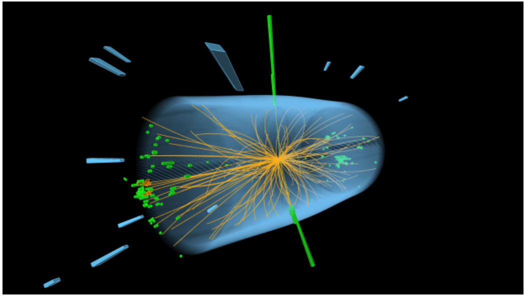
prediction

approximation

QCD

Real data





pQFT : # particles < few

~ 10 @ NLO QCD

~ 3-4 @ NNLO QCD

~ 2 @ N3LO QCD

Event Simulations

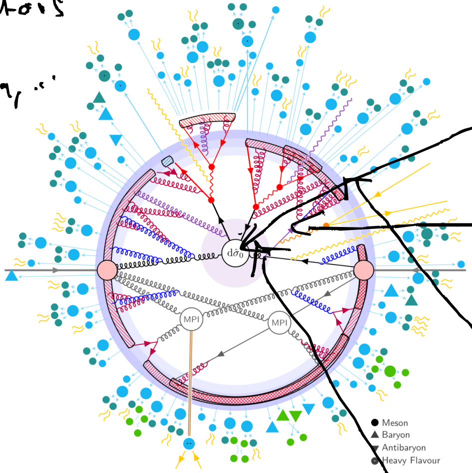
Monte Carlo Event generators

Pythia, Herwig, Sherpa, ...

↓

Scale factorization

"What you see depends on the resolution"



Asymptotic freedom

$\alpha_s(Q) \xrightarrow{Q\to\infty} 0$, pQCD

$\alpha_s(\Lambda_{QCD}) \to 1$, non-pQCD

$Q_0 \to \Lambda_{QCD}$: resummation

→ parton-shower

Λ_{QCD}: non-pQCD

→ pheno models + decays

$Q_0 \gg \Lambda_{QCD}$: hard scattering

pQCD

[Pythia]

Basic of QCD

-> quick history

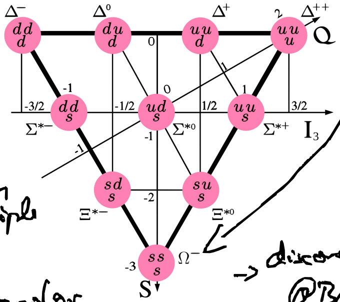
-> Lagrangian

-> LO example: $t\bar{t}$ @LHC LO

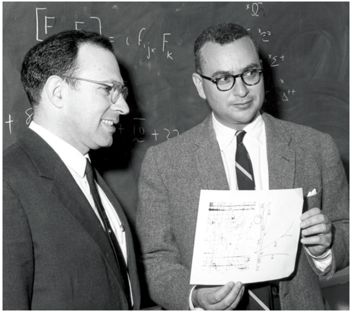
Zoo particle $3/2$-spin → 3 quarks of $\frac{1}{2}$ spin ← proposal

violation Pauli exclusion principle

→ new quantum number → color

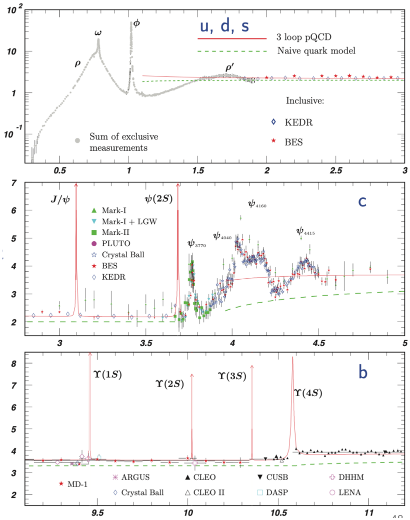


→ discovered '64 @BNL



[8-foldway & Yuval Ne'eman (left) and Gell-Mann March 1964 (CERN Courier'19)]

→ further evidence : DIS experiments @SLAC



→ R-ratio in e^+e^-

$$R = \frac{\sigma(e^+e^- \to had.)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c \sum_f q_f^2$$

$R = 2 \quad Q < 2m_c \quad \& \quad R = 3,67 \quad Q > 2m_b$

→ $\pi^0 \to \gamma\gamma$ decay

$$\Gamma(\pi^0 \to \gamma\gamma) = \left(\frac{N_c}{3}\right)^2 \frac{\alpha_{EW}^2 m_\pi^3}{64\pi^3 f_\pi^2}$$

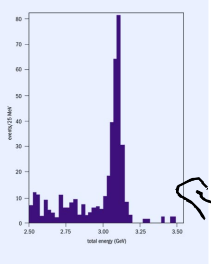
→ agrees with exp. data

→ countless jet meas.

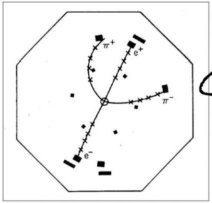
QCD origins - the charm quark

-> Puzzle of ~~FCNC~~

-> GIM mechanism



BNL

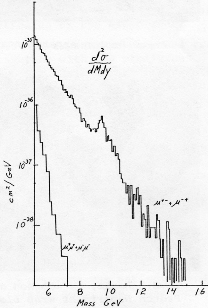


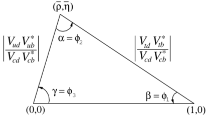
SLAC

} J/ψ -> particle

[CERN Courier 04]

QCD origins - the bottom quark





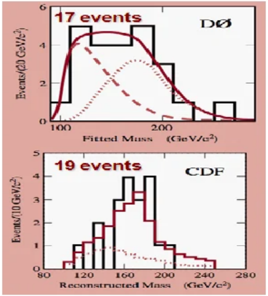
[E228 experiement'77]

-> similar for bottom

-> CP violation via CKM matrix

-> 3rd generation

-> directly produced @ Fermilab '77

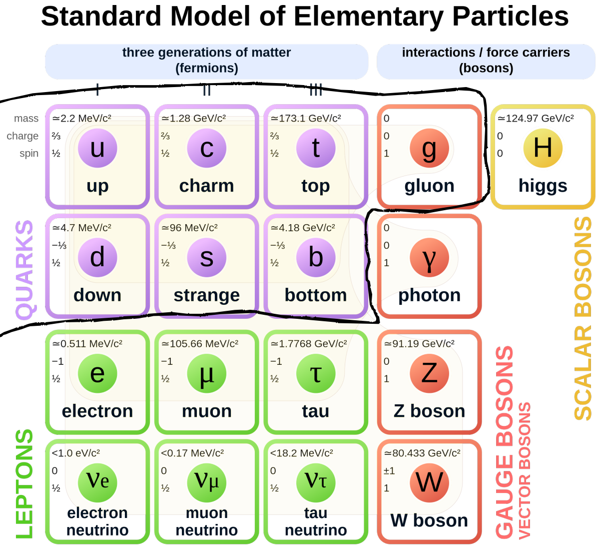


1995, CDF and DØ experiments, Fermilab

Indirect evidence

- -> CKM matrix
- -> B meson oscillation
- -> Precision EW measurements
- -> top-quark was measured @ 170 GeV

← @ Tevatron '95



$SU(3)_c \boxed{\times SU(2)_L \times U(1)}$

→ Yukawa coupling determine quark m

but they are parameters in QCD

QCD lagrangian

$$\mathcal{L}_{QCD} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \sum_{f=1}^{n_f} \bar{\Psi}_{f,i} \left(i \not{D}_{ij} - m_f \delta_{ij} \right) \Psi_{f,j}$$

$j = 1,2,3$ color dofs of quarks

SU(3) gauge theory: $\Psi(x) \to \Psi'(x) = U(x)\Psi(x)$

$$= \exp\left(i g_s \Theta^a(x) T^a\right)\Psi(x)$$

SU(3) has $3^2 - 1 = 8$ → generator

$$[T^a, T^b] = i f^{abc} T^c$$

antisymmetric constant

$$(D_\mu)_{ij} = \partial_\mu \mathbb{1}_{ij} - i g_s (T^a)_{ij} A^a_\mu$$

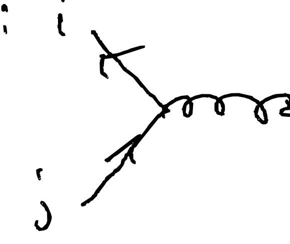
gluon field

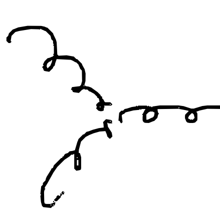
$$F^a_{\mu\nu} = \underbrace{\partial_\mu A^a_\nu - \partial_\nu A^a_\mu}_{\sim \text{QED, abelian}} + \underbrace{g_s f^{abc} A^b_\mu A^c_\nu}_{\text{non-abelian}}$$

-> can't solve this theory in general

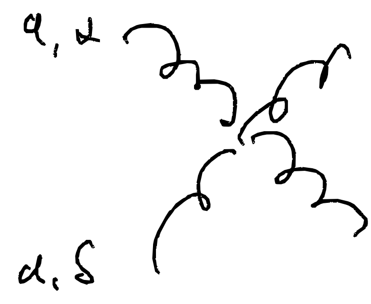
-> Lattice QCD : -> putting everything on space-time lattice spacing is a
- -> take limit $a \to 0$
- -> good at low energies <-> large distance
- -> bad at high energies <-> short distance

-> perturbation theory:
- -> small coupling g_s
- -> expand around free theory
- -> Feynman calculus

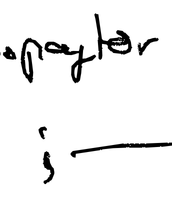
Vertices:  $-i g_s (T^a)_{ij} \gamma^\mu$

 $-i g_s f^{abc} V_{\alpha\beta\gamma}(p_1, p_2, p_3)$

$$V_{\alpha\beta\gamma} = (p_1 - p_2)_\gamma g_{\alpha\beta} + (p_2 - p_3)_\alpha g_{\beta\gamma} + (p_3 - p_1)_\beta g_{\alpha\beta}$$

 $-i g_s^2 \left[f^{xac} f^{xbd} (g_{\alpha\beta} g_{\gamma} \ldots) + \ldots \right]$

quark propagator

 $\delta_{ij} \frac{i(\not{p} + m)}{p^2 - m^2 + i\epsilon}$

gluons: 

-> req. gauge fixing cov. R_ξ $(\partial_\mu A^\mu) = 0$ $\frac{-i\delta^{ab}}{p^2 + i\epsilon}\left[g^{\mu\nu} - (1-\xi) \frac{p^\mu p^\nu}{p^2}\right]$

axial gauge

Color

-> T^a, f^{abc}
- -> always sum over external color indices
- -> trace

$$\mathrm{Tr}(T^a T^b) = T_F \delta^{ab} \qquad T_F = 1$$

Casimirs

$$(T^a T^a)_{ij} = C_F \delta_{ij} \qquad C_F = \frac{4}{3}$$

$$f^{acd} f^{bcd} = C_A \delta^{ab} \qquad C_A = 3$$

Useful: $i T_F f^{abc} = \mathrm{Tr}(T^a T^b T^c) - \mathrm{Tr}(T^c T^b T^a)$

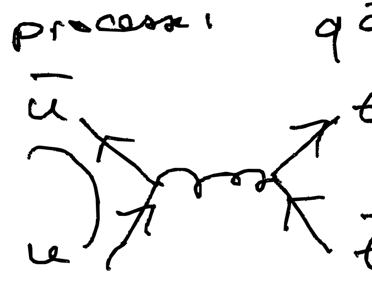
Fierz Identity: $T^a_{ij} T^a_{kl} = \frac{1}{2}\left(\delta_{il}\delta_{jk} - \frac{1}{N_c}\delta_{ij}\delta_{kl}\right)$

LO: example : $pp \to t\bar{t}$

-> $d\sigma = \frac{1}{F} |M|^2 d\Phi_2$

$F \hookrightarrow 2\hat{s}$

2 partonic processes: $q\bar{q} \to t\bar{t}$, $gg \to t\bar{t}$

$q\bar{q} \to t\bar{t}$ 

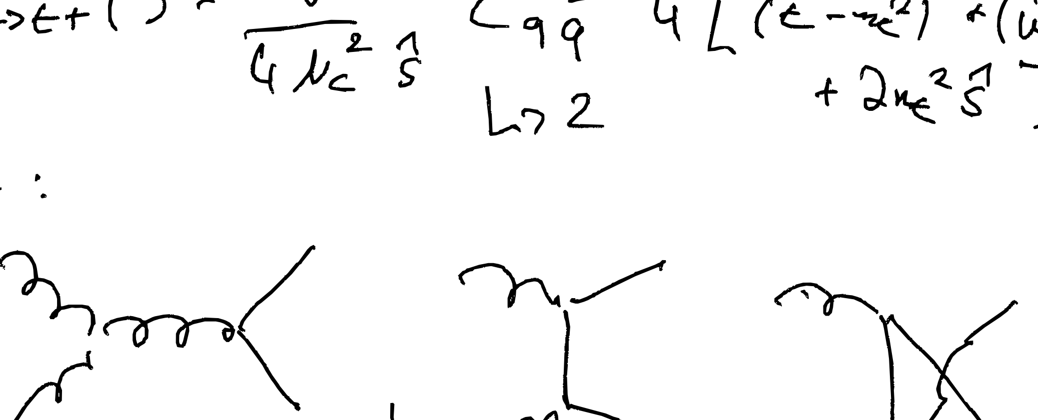
Mandelstam:

$$\left.\begin{aligned} \hat{s} &= (p_1 + p_2)^2 \\ \hat{t} &= (p_1 - p_3)^2 \\ \hat{u} &= (p_2 - p_3)^2 \end{aligned}\right\} \hat{s} + \hat{t} + \hat{u} = 2m_t^2$$

$$i M_{q\bar{q} \to t\bar{t}} = [\bar{v}(p_2)(-i g_s \gamma^\mu T^a) u] [\bar{u}(p_3)(-i g_s \gamma^\nu T^b) v(p_4)] \left(\frac{-i g_{\mu\nu}}{\hat{s}} \delta^{ab}\right)$$

$$\langle |M_{q\bar{q} \to t\bar{t}}| \rangle = \frac{g_s^4}{4 N_c^2 \hat{s}} \underbrace{C_{q\bar{q}}}_{\hookrightarrow 2} 4\left[(\hat{t} - m_t^2)^2 + (\hat{u} - m_t^2)^2 + 2 m_t^2 \hat{s}\right]$$

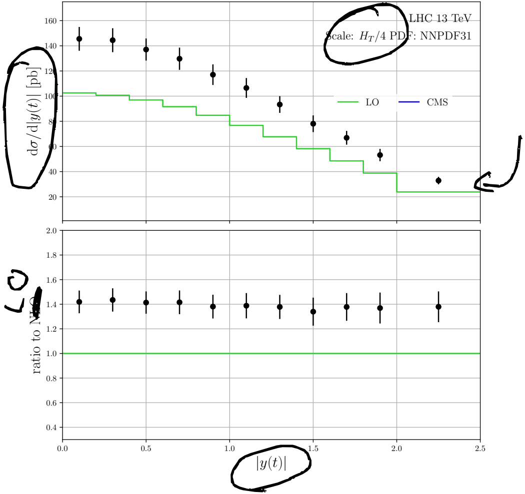
$gg \to t\bar{t}$:



$$d\sigma_{pp \to t\bar{t}} = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1) f_b(x_2) d\hat{\sigma}_{ab}(x_1, x_2)$$

-> numerically

LHC top-quark pair at leading order



40%

→ higher-order will help us to resolve this