New standard physics at the LHC

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Measuring quark polarization

- It will be really cool if we can measure polarization of quarks
  - Examples include $H \to b\bar{b}$ and $\tilde{b} \to b\tilde{g}$
  - Polarization carries information about the Dirac structure of the couplings, not only their strengths
- It seems impossible since hadronization washes away the polarization of the quarks
- Think of b quark that hadronized into B meson
- Can we measure the polarization of b quarks?

Heavy baryons!

- Despite hadronization, bottom baryons partly retain the polarization of the b quark

- Evidences observed at LEP in $Z \to b\bar{b}$

- About 8% of the b quarks hadronized into baryons

- How to measure the b and c polarizations at the LHC?

- Can we calibrate the measurement on SM samples?

- Can we use it for discovering/characterizing new physics?

Theory of polarization loss

Time scales of polarization loss

Start with the known statement:

"The top quark decays before it hadronized and thus it keeps its polarization"

- Is that statement correct?

- How large are the corrections?

- What is the situation for $\Gamma_t = 30 \text{ MeV}$?

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The relevant depolarization scale is

$$\frac{\Lambda_{\text{QCD}}^2}{m_t} \sim 1 \text{ MeV}$$

Recall the Hydrogen atom

- The 21 cm line measures the hyperfine splitting

- Consider a proton with spin up that "meets" an electron with spin down

  - Very fast the electron decay to the $n = 1$ state
  - Then the atom is in a superposition of a $J = 0$ and $J = 1$ state
  - The atom then oscillates between the two states, and the proton depolarizes at time scale of $1/\Delta E$

- What is the situation when a proton with spin up "meets" an electron with spin up?

- Hyperfine interactions in bound states lead to depolarization

b and c quarks

We now move to bound states of QCD, $Q\bar{q}$

- In the heavy quark limit (we use $Q = b$)
  - No polarization is retained for mesons
  - All baryons decay strongly to Λ_b
  - For baryons in the Heavy quark limit $\mathcal{P}(Q) = \mathcal{P}(\Lambda_b)$
  - There are corrections of order $\Lambda_{\mathrm{QCD}}/m_b$

- Open questions
  - How large are these corrections?
  - Can we understand them theoretically?
  - Can we measure them?

Determining the depolarization

How much polarization is retained?

For interpreting polarization measurement, we need to know

$$r \equiv \frac{\mathcal{P}(\Lambda_b)}{\mathcal{P}(b)}$$

Bottom line:

- We can calculate it, but the result involves unknown hadronic parameters and thus we cannot predict it

- We hope that r can measured in some decay modes

- We can show, theoretically, that r is universal (up to a known, small running)

- Thus, measuring r once, we can use the value of r to probe the b polarization in other processes

Calculation of r

$$r \equiv \frac{\mathcal{P}(\Lambda_b)}{\mathcal{P}(b)}$$

- Main $1/m_b$ effect is due to $\Sigma_b - \Sigma_b^*$ oscillation

- The light DOFs in a $\Sigma_b^{(*)}$ (Λ_b) are a $J = 1$ ($J = 0$) state

- We need $x \equiv \Delta M / \Gamma_\Sigma$ with $\Delta M \equiv m(\Sigma_b^*) - m(\Sigma_b)$.
  - $\Delta M \sim \Lambda_{QCD}^2 / m_b \sim 20$ MeV
  - $\Gamma(\Sigma \to \Lambda_b + \pi) \sim \# \times \Lambda_{QCD} \sim 10$ MeV

- While formaly $O(1/m_b)$ effect, it is numerically $O(1)$

- $\Sigma_b - \Sigma_b^*$ oscillation washes out the b polarization

Calculations

- With some approximation we get

$$r = \frac{1 + (1 + 4w_1)A/9}{1 + A}$$

- r depends on two hadronization parameters

$$A = \frac{P(\Sigma_b)}{P(\Lambda_b)} \qquad w_1 = \frac{P(|S_Z^{\text{light}}| = 1)}{P(S^{\text{light}} = 1)}$$

- No direct measurement of A yet.
  - Statistical hadronization model: $A \sim 2.6$
  - Pythia tunes (light hadron data): $A = 0.35 \pm 0.10$
- DELPHI $w_1 = -0.36 \pm 0.44$ and CLEO $w_1 = 0.71 \pm 0.13$

Determining A and w_1

If b is polarized transversely, r is different

$$r_L \approx \frac{1 + (0.23 + 0.38w_1)A}{1 + A} \qquad r_T \approx \frac{1 + (0.62 - 0.19w_1)A}{1 + A}$$

- In principle we can measure both A and w_1

- Yet, it involves measuring r, so it will not help us to determined r

- The bottom line, it will be very hard to calculate r

Universality

Why we like universality

While we cannot calculate r we can measure it

- Consider a decay where, assuming the SM, we know the initial polarization of the b quark

- The point is that r is almost the same in any high energy process

- Basically, the b does not care much about the overall energy, just the fact that it is in a jet

- We can in fact hope to measure r in several processes and compare them to verify univerasilty

Where to measure it at the LHC?

- Top decay
  - Maximal polarization; Large cross section; Clean sample

- $Z \to b\bar{b}$
  - Large polarization; Large cross section; Large QCD background ($S/B \approx 1/15$)
  - LEP data gave about 30% uncertainty in the value of r

- QCD production
  - Large cross section; Small and only transverse polarization; Good for LHCb
  - Looking for correlation between the two bs to get r_L

How to measure it?

$$b \to X \ell \nu$$

- Large rate (about 10%) and high sensitivity to θ, the angle between the polarization and the lepton direction

$$\frac{d\Gamma}{d\cos\theta} \propto (1 + \alpha \mathcal{P} \cos\theta)$$

where

$$\alpha_\ell \approx 0.26 \qquad \alpha_\nu = 1$$

- B mesons only dilute the effect, no need to veto on them. Maybe we can still do better by demanding a Λ?

- Can we use neutrinos? (probably yes)

- Can we use exclusive decay? (need to study it)

What about charm?

- Same formalism ensures polarization retention as in b

- Potentially promising decay mode: $\Lambda_c \to PK\pi$ with 6.7% BR (vs 3% for semileptonic)

- About 6% of charms end up inside baryons

- Can we do it with charms from $W \to c\bar{s}$ decays?

- Can also be done at Belle2 using $e^+e^- \to \Lambda_c \bar{\Lambda}_c$

- Can be done also using D^*. We do not need baryons to keep polarization information

Conclusions

Conclusions

- Measuring b and c polarizations is interesting

- We need calibrations from known SM processes

- It seems possible at the LHC

- Maybe can also be done with B^* and D^* decays

- Maybe possible also for s quarks   Y. Kats,