New standard physics at the LHC

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Two papers

Learn about QCD using the weak interaction

- Measuring the polarization of heavy quarks
    - M. Galanti, A. Giammanco, YG, Y. Kats, E. Stamou, J. Zupan, 1505.02771
- Hadronic Z decays
    - YG, M. Konig, M. Neubert, 1501.06569

Measuring heavy quark polarization

Motivation

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

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The relevant depolarization scale is

$$\frac{\Lambda^2_{\mathrm{QCD}}}{m_t} \sim 1~\mathrm{MeV}$$

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 $\Lambda_{\rm QCD}/m_b$
- 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 prove 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 mainly 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 $\Delta M \equiv m(\Sigma_b^*) - m(\Sigma_b)$.
- x is of $O(1)$
    - $\Delta M \sim \Lambda_{QCD}^2/m_b \sim 20 \text{ MeV}$
    - $\Gamma(\Sigma) \sim \Lambda_{QCD}^2/m_b \sim 10 \text{ MeV}$
- $\Sigma_b - \Sigma_b^*$ 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
- The ultimate plan is to measure r in several processes and compare them

Where to measure it in 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 $e^+e^- \to \Lambda_c\bar{\Lambda}_c$

Conclusions (part I)

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- In general, measuring b and c polarizations is interesting
- For that we need to get some “calibration” from known SM processes
- It seems possible at the LHC

Exclusive Z decays

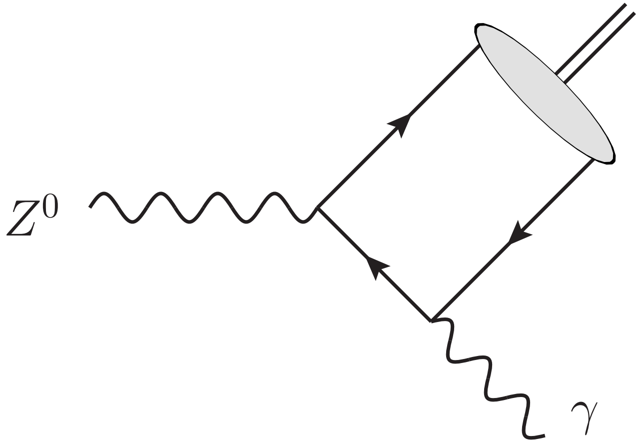
Bottom line

- Theoretically, we can learn a lot from decays like $Z \to \psi\gamma$ and $W \to D_s\gamma$
- It will be really nice if the decay rates for such exclusive decays can be measured
- The BRs are up to 10^{-7}
- Looking for some of them may require novel experimental ideas
- We can measure some interesting hadronic parameters
- Can also be used in Higgs decays to probe Higgs couplings

Bodwin et. al., 1306.5770; Kagan et. al., 1406.1722

The very basic theory: $Z \to \psi\gamma$

- We usually think of $Z \to q\bar{q}$ as $Z \to 2j$
- At some rare cases the $q\bar{q}$ hadronized into one hadron



- For example, $\mathcal{A}(Z \to M\gamma) \sim \phi_M(k) \sim \langle q\bar{q}|M\rangle(k)$
- ϕ_M is a leading-twist LCDA
- We cannot calculate this amplitude from first principles

More theory

- One can get some handle on QCD when the decaying particle is heavy: QCD factorization
- QCD factorization was developed for B physics, but higher order effects are important there
- Can we find a really heavy particle to test QCD factorization?
  - Top, Higgs, W, Z
- It turns out that higher order effects in Z decays are down by

$$\left(\frac{\Lambda_{\rm QCD}}{m_Z}\right)^2 \sim 10^{-4}$$

- Z decays are good testing ground for factorization

Calculations

Using some models for the matrix elements we can estimate the rates

Decay mode	BR	Decay mode	BR
$Z^0 \to \pi^0\gamma$	$1 \cdot 10^{-11}$	$W^\pm \to \pi^\pm\gamma$	$4 \cdot 10^{-9}$
$Z^0 \to \rho^0\gamma$	$4 \cdot 10^{-9}$	$W^\pm \to \rho^\pm\gamma$	$9 \cdot 10^{-9}$
$Z^0 \to \omega\gamma$	$3 \cdot 10^{-8}$	$W^\pm \to K^\pm\gamma$	$3 \cdot 10^{-10}$
$Z^0 \to \phi\gamma$	$9 \cdot 10^{-9}$	$W^\pm \to K^{*\pm}\gamma$	$5 \cdot 10^{-10}$
$Z^0 \to J/\psi\,\gamma$	$8 \cdot 10^{-8}$	$W^\pm \to D_s\gamma$	$4 \cdot 10^{-8}$
$Z^0 \to \Upsilon(1S)\,\gamma$	$5 \cdot 10^{-8}$	$W^\pm \to D^\pm\gamma$	$1 \cdot 10^{-9}$
$Z^0 \to \Upsilon(4S)\,\gamma$	$1 \cdot 10^{-8}$	$W^\pm \to B^\pm\gamma$	$2 \cdot 10^{-12}$

Very optimistically we can hope to get 10^{11} Zs and 5×10^{11} Ws at CMS and at Atlas

Specific decays

$Z \to \psi\gamma$

- $BR \sim 10^{-7}$
- Already been looked for at Atlas, with a bound of order 3×10^{-6}
- Trigger on the photon and the muons from the ψ
- Theoretically, one can add the ψ and ψ'
- Similar idea for $\Upsilon(nS)$ with $n = 1, 2, 3$

$Z \to \Upsilon(4S)\gamma$

- $BR \sim 10^{-8}$
- $\Upsilon(4S)$ decays to $B\bar{B}$ all the time
- Can these isolated B mesons be identified?
- The photon and the known invariant mass can help
- Similarly for $\psi(3770)$ but with D and not B

$Z \to X\gamma$

- $BR \sim 10^{-8}$ with $X = \phi, \omega, \rho$ (no numbers yet for η, η')
- Is the a way to trigger and identify such events?
  - Can we use the kaons for the ϕ?
  - Can we identified π^0 or few π^0 using converted photons?
  - Can we use charged pions?

$W \to D_s\gamma$

- $BR \sim 4 \times 10^{-8}$
- The most promising decay in terms of number of events (given that we have 5 more Ws than Zs)
- Again, can we trigger on and identify a D_S?
- It is probably best to use Ws from top decay?

M. Mangano and T. Melia, arXiv:1410.7475

- Any other W decays that may be possible to look at?

Conclusions

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- We can learn about QCD form the weak interaction
  - We hope to be able to measure b and c polarizations
  - Exclusive Z and W decays can check QCD factorization
  - Eventually, this provide tools for look for BSM