B decays as probes of New Physics

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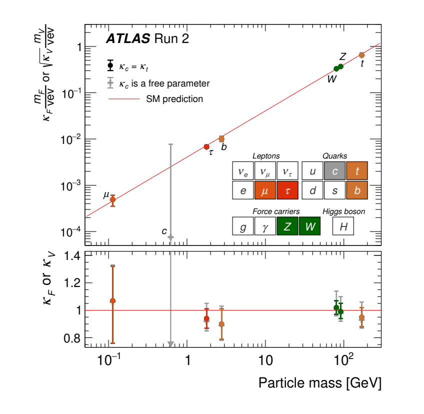
Internal Seminar, Oct 11th 2024

Motivation

The Standard Model is great

Higgs boson



[from ATLAS, 2024]

The Standard Model is great

Top quark

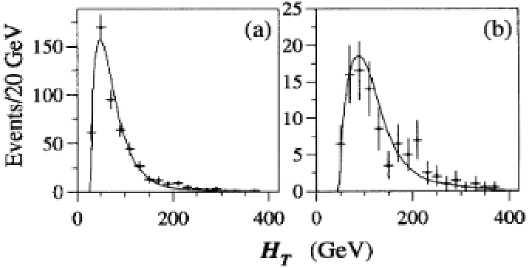


FIG. 2. Observed H_T distributions (points) compared to the distributions expected from background (line) for $\not{E}_T >$ 25 GeV/c and (a) $e+ \geq 2$ jets and (b) $e+ \geq 3$ jets.

[D0 collaboration, 1995]

Electroweak force

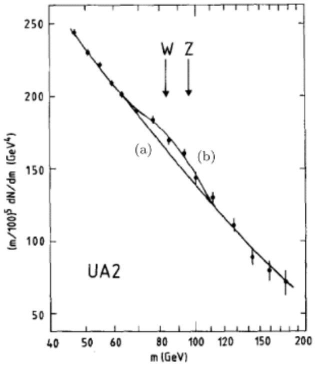


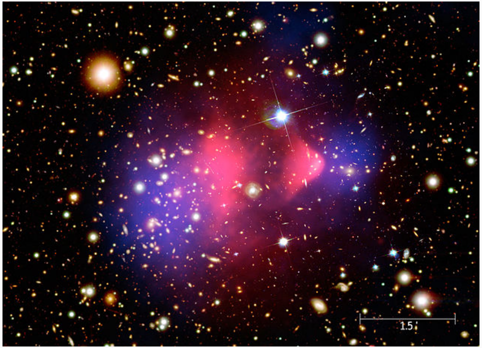
Fig. 24. Two-jet invariant mass distribution, as measured in the UA2 central calorimeter. Curve (a) is a best fit to the data excluding the mass interval $65 < m < 105\,\mathrm{GeV}$. Curve (b) is a fit to all data points with the addition of two Gaussians centred at the nominal W and Z mass values.

[Luigi Di Lella and Carlo Rubbia, 2015]

But...

But...

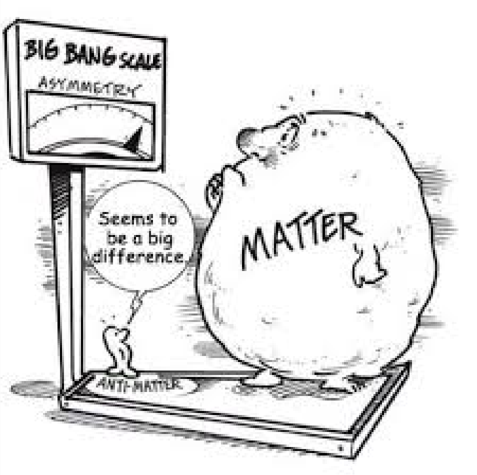
- Can't describe dark matter



[Bullet Cluster]

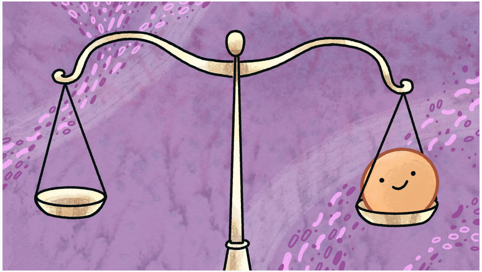
But...

- Can't describe dark matter
- Can't explain baryon asymmetry



But...

- Can't describe dark matter
- Can't explain baryon asymmetry
- Can't explain neutrino masses



What can we do?

Search Directly

Search Indirectly

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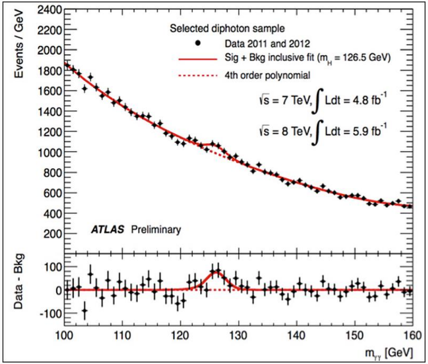
Search Directly



[ATLAS collaboration, 2013]

Search Indirectly

What can we do?

Search Directly

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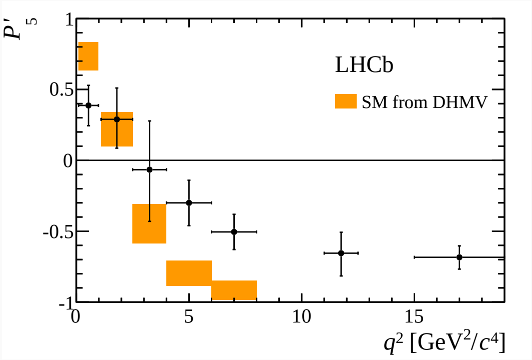

[LHCb collaboration, 2016]

Indirect Searches

Combine at low energy:

- Precise measurements
- Precise predictions

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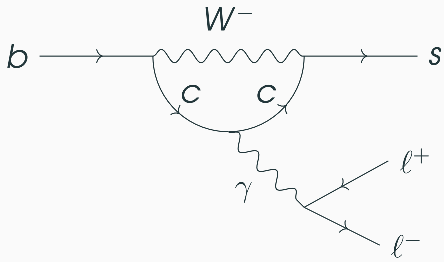
$$\Lambda_{hadronic} \ll m_b^2 \ll m_W^2$$

- Precise measurements
- Precise predictions

Which b decays?



Flavour changing neutral currents only emerge at 1 loop level

Indirect Searches

Precise measurements

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Precise measurements

- dedicated experiments e.g. LHCb,Belle II

Indirect Searches

Precise measurements

- dedicated experiments e.g. LHCb,Belle II
  - dedicated components
    - to differentiate p, π, K, μ
    - to locate vertices

Indirect Searches

Precise predictions

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Precise predictions

- multi-scale problem

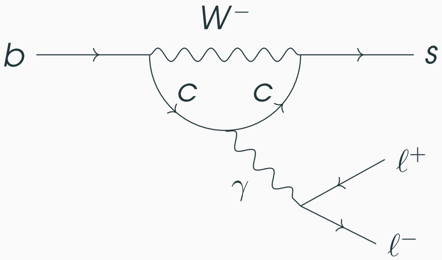
Indirect Searches

Precise predictions

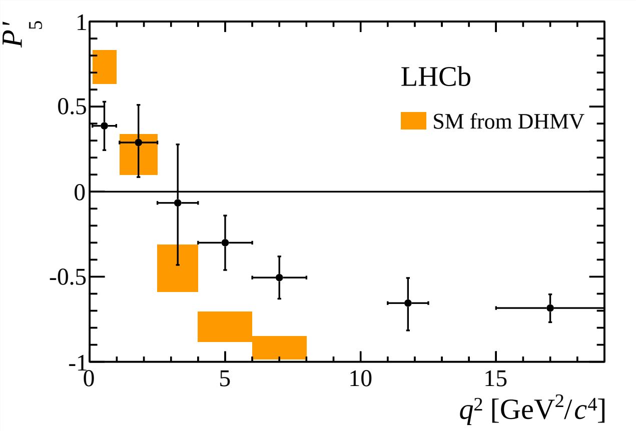
- multi-scale problem
- hadronic matrix elements

Precise predictions

- multi-scale problem
- hadronic matrix elements
- perturbation theory



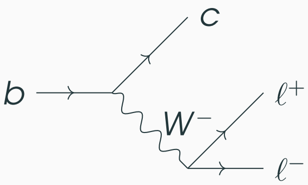
Why talk about them?



$B^0 \to K^{*0}\mu^+\mu^-$

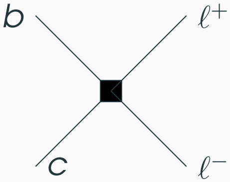
Effective Field Theory tangent

Four Fermi theory



An electroweak interaction

$\rightarrow$



A Four Fermi theory interaction

Operators

$$\mathcal{L}_{WET} \supset \mathcal{L}_{QCD+QED}^{\{\text{all fermions}, \cancel{top}\}} + \frac{1}{\Lambda^2} \sum_i \mathcal{C}_i^{(6)} \mathcal{O}_i^{(6)}$$

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$$\mathcal{O}_i^{(6)} \supset [c\gamma_\mu P_L b][\ell^+ \gamma^\mu P_L \ell^-]$$

Weak Effective Theory Sectors

Sector: Complete set of operators so that at leading order in G_F they can only mix into each other

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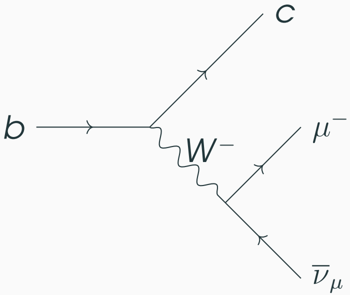
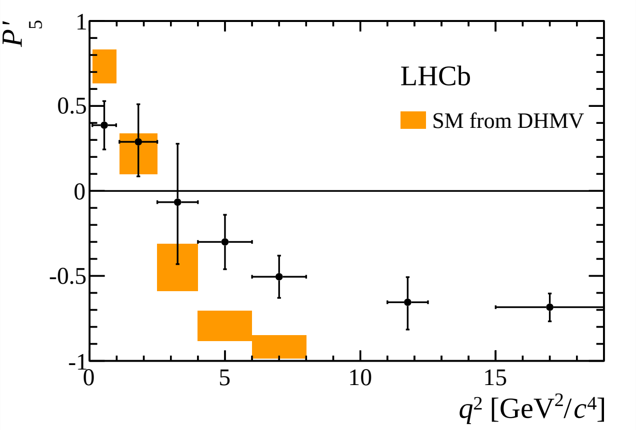
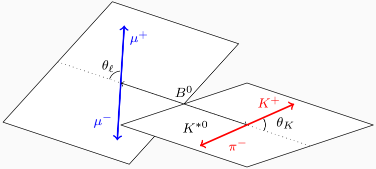
e.g. $cb\mu\nu_\mu$.



My work

Recall P'_5





(a) θ_K and θ_ℓ definitions for the B^0 decay

$B^0 \to K^{*0}\mu^+\mu^-$

What could cause the tension?

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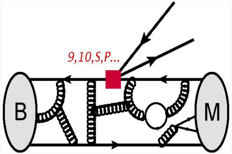
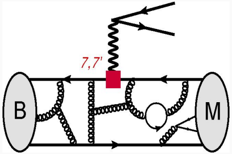
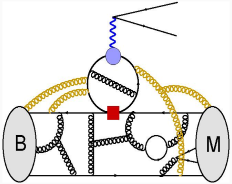
- Issues with hadronic form factors (local and non-local)?
- New physics in $sb\{\gamma, \ell\ell, qq\}$ sector?

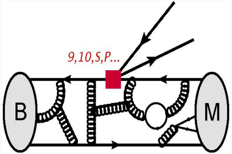
Form Factors

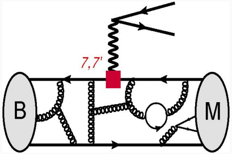




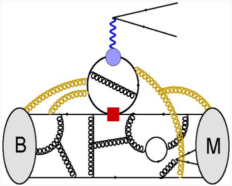


Form Factors





- Local $\mathcal{P}_\mu \langle \overline{M}(k) | \bar{s}\Gamma^\mu b | \overline{B}(k+q) \rangle$



- Non-local $i\mathcal{P}_\mu \int d^4x e^{iq.x} \langle \overline{M}(k) | T\{ J^\mu_{em}(x), \mathcal{C}_i^{sbcc} \mathcal{O}_i^{sbcc} \} | \overline{B}(k+q) \rangle$

New Physics

- $sb\{\gamma, \ell\ell, qq\}$

- $sb\{\gamma, \ell\ell, qq\}$
- Prevaling assumption is that *sbqq* operators are SM-like
  - We're going to test this

Mixing

$sbqq$ mixes into $sb\ell\ell$ through non-local operator.

$$\int d^4x e^{iq.x} T\{J^{\mu}_{em}(x-y), \mathcal{C}_i^{\mathrm{sbcc}} \mathcal{O}_i^{\mathrm{sbcc}}(y)\}$$

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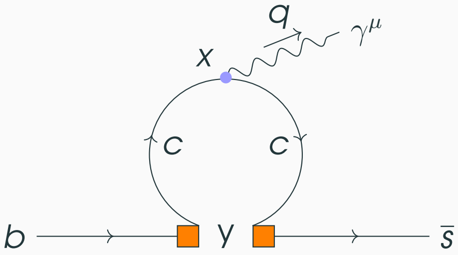
$$\int d^4x e^{iq.x} T\{J^\mu_{em}(x-y), \mathcal{C}_i^{sbcc}\mathcal{O}_i^{sbcc}(y)\}$$

for example:

- $J^\mu = Q_c \bar{c}\gamma^\mu c$
- $\mathcal{O}_2^{sbcc} = [\bar{s}\gamma_\nu P_L c][\bar{c}\gamma^\nu P_L b]$



Operator Product Expansion

Technical point:

⌜**Pertubation constraints:** $|q^2 - 4m_c^2| > \Lambda^2_{hadronic}$⌟

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$$\int d^4x e^{iq.x} T\{J^{\mu}_{em}(x), \mathcal{C}_i^{sbcc}\mathcal{O}_i^{sbcc}\}$$

$$= \sum F_{ij}\, \mathcal{C}_i^{sbcc}\, [\bar{s}\Gamma_j^{\mu} b]$$

Example

$$F_{29}\, \mathcal{C}_2^{\text{sbcc}}\, [\bar{s}\Gamma_9^{\mu} b]$$

$$= \frac{2}{9}(4\pi e^{-\gamma})^{\epsilon}\left[\frac{12m_c^2}{q^2} + \left(2 + \frac{3}{\epsilon} + 3\log\frac{\mu^2}{m_c^2}\right) + 3\text{DiscB}(q^2, m_c, m_c)\frac{(2m_c^2 + q^2)}{q^2}\right]$$

$$\times\, \mathcal{C}_2^{\text{sbcc}}(q^2 g^{\mu\nu} - q^{\mu} q^{\nu})[\bar{s}\gamma_{\nu} P_L b]$$

Current Status of work:

- I've done $F_{1\ldots10,j}$ (all c quarks operators) to 1 loop (LO)

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Next tasks:

- $F_{1\ldots10,j}$ to 2 loops (NLO)

- $F_{i>10,j}$ at 1 and 2 loop level (u, d;(hopefully) s, b)

- Reduce to minimum number of independent propagators (solve algebraic equations)
- Reduce to scalar integrals (Passarino-Veltman)
- Reduce to minimum number of master integrals (Integration by parts identities)

$$\int d^d k_1 \dots d^d k_L \left[\frac{\partial}{\partial k_i^\mu} \left(\frac{N^\mu}{P_1 P_2 \dots} \right) \right] = 0$$

Conclusions

- B decays are an important and interesting area of work
- There are some interesting challenges involved in the work
- I'm looking at 1 and 2 loop calculations (where SM in not assumed)

Backup Slides

P_5'

The angular distribution of $B^0 \to K^{*0}\mu^+\mu^-$ decay is given by

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})\,\mathrm{d}q}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}}\bigg|_P = \frac{9}{32\pi}\bigg[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + \frac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell$$
$$+S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\bigg]$$

F_L is a fraction of longitudinal polarization of K^{*0};

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

$sb\{\gamma, \ell\ell\}$ basis

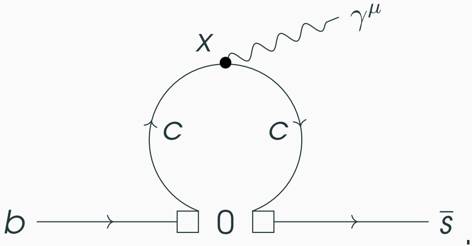
$$J_7 = 2im_b q_\nu [\bar{s}\sigma^{\mu\nu} P_R b]$$

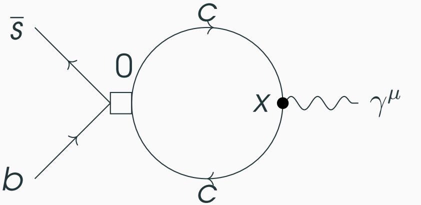
$$J_9 = (q^\mu q^\nu - q^2 g^{\mu\nu})[\bar{s}\gamma_\nu P_L b]$$

sbcc operators

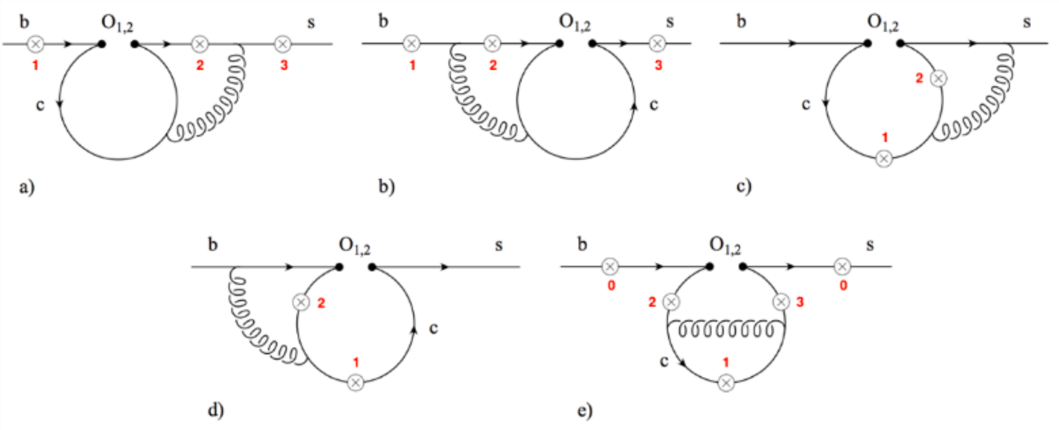
$$
\begin{aligned}
\mathcal{O}_1^{\text{sbcc}} &= [\bar{s}\gamma_\mu t^a P_L c][\bar{c}\gamma^\mu t^a P_L b] & \mathcal{O}_6^{\text{sbcc}} &= [\bar{s}\gamma_{\mu\nu\rho} t^a P_L b][\bar{c}\gamma^{\mu\nu\rho} t^a c] \\
\mathcal{O}_2^{\text{sbcc}} &= [\bar{s}\gamma_\mu P_L c][\bar{c}\gamma^\mu P_L b] & \mathcal{O}_7^{\text{sbcc}} &= [\bar{s}\gamma_\mu P_L b] Q_c [\bar{c}\gamma^\mu c] \\
\mathcal{O}_3^{\text{sbcc}} &= [\bar{s}\gamma_\mu P_L b][\bar{c}\gamma^\mu c] & \mathcal{O}_8^{\text{sbcc}} &= [\bar{s}\gamma_\mu t^a P_L b] Q_c [\bar{c}\gamma^\mu t^a c] \\
\mathcal{O}_4^{\text{sbcc}} &= [\bar{s}\gamma_\mu t^a P_L b][\bar{c}\gamma^\mu t^a c] & \mathcal{O}_9^{\text{sbcc}} &= [\bar{s}\gamma_{\mu\nu\rho} P_L b] Q_c [\bar{c}\gamma^{\mu\nu\rho} c] \\
\mathcal{O}_5^{\text{sbcc}} &= [\bar{s}\gamma_{\mu\nu\rho} P_L b][\bar{c}\gamma^{\mu\nu\rho} c] & \mathcal{O}_{10}^{\text{sbcc}} &= [\bar{s}\gamma_{\mu\nu\rho} t^a P_L b] Q_c [\bar{q}\gamma^{\mu\nu\rho} t^a q].
\end{aligned}
$$

1 loop diagrams





2 loop diagrams



VErtex LOcator (VELO)

VELO is extremely close to beams to allow precision measurement of b quark location (10^{-5}m).

It is mechanically moved into place once the beams have been stabilsed so that they are not damaged when the beams are injected

DiscB

$$\mathrm{DiscB}(q^2, m_c, m_c) = \frac{\sqrt{q^2(q^2 - 4m_c^2)}}{q^2} \log\left(\frac{2m_c^2 - q^2\sqrt{q^2(q^{-}4m_c^2)}}{2m_c^2}\right)$$