Angular analysis of the $B_s \to \phi e^+ e^-$ decay in the very-low q^2 bin in LHCb

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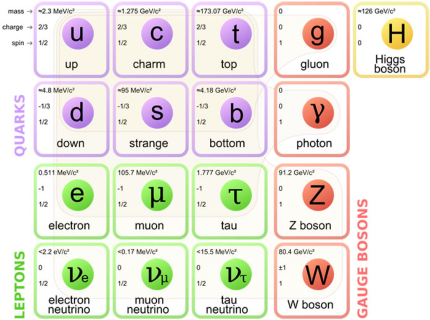
The Standard Model of Particle Physics

Standard Model: the theory describing elementary particles and their interactions

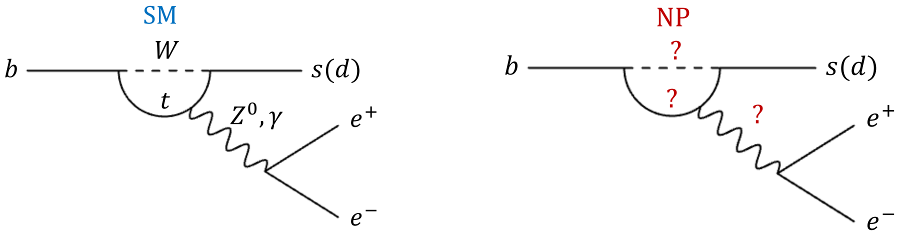
- Extremely powerful: experimentally tested from low-energy phenomena (~ 1 eV) up to the electroweak scale (~ 100 GeV)...
- ...but incomplete! Describes only 5% of the universe
- Many unsolved questions: dark matter, dark energy, neutrino masses, matter-antimatter asymmetry...



Flavour Changing Neutral Current as b$\rightarrow$ sll [1] transitions in the standard model only possible via loop or box diagrams (Penguins Diagrams)

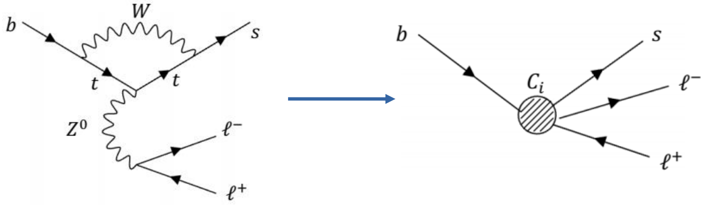
$\rightarrow$ Highly suppressed : Decay Probability in order of $10^{-6} - 10^{-10}$

$\rightarrow$ New particles can enter the loop and modify physics observables



[1] l = e or μ

Effective-Hamiltonian approach



$\sim$ Fermi's description of the neutron decay.

Different $q^2(m^2_{l^+l^-})$ regions probe different processes.

$$\mathcal{H}_{\text{eff}} = \frac{-4G_F}{\sqrt{2}} \cdot \frac{e^2}{16\pi^2} V_{tb} V_{ts}^* \sum_i C_i O_i + \text{h.c.}$$

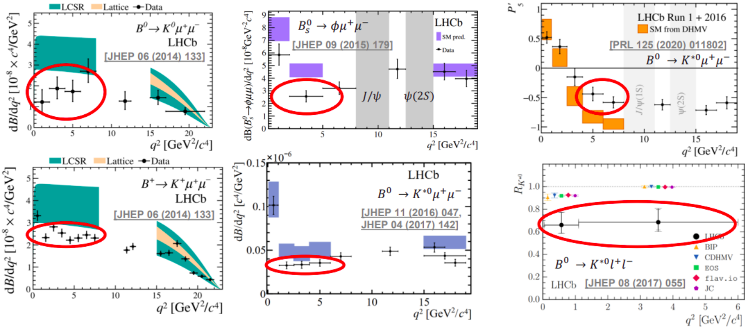
NP enters here $C_i = C_i^{SM} + C_i^{NP}$

Operator encoding Lorentz structure

i =1,2	Tree
i=3-6,8	Gluon penguin
i=7	Photon Penguin
i=9,10	Electroweak penguin
i=S,P	Scalar/ Pseudoscalar Penguin

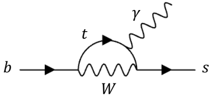
Rich phenemology:

- Branching Ratios (but large theoretical uncertainties)
- Angular observables
- Ratios of BF (test of Lepton Universality)

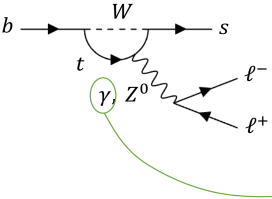


The Gamma Penguin

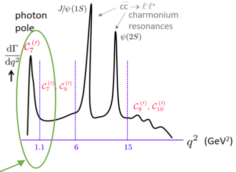
One very interesting $b \to s$ process is the penguin diagram with a photon



You can find the Gamma Penguin with a real photon (radiative decay) or with a virtual photon in $b \to sll$ processes



Contributes a **very low** $q^2 \to$ **go as low as possible in** q^2 **to select it**

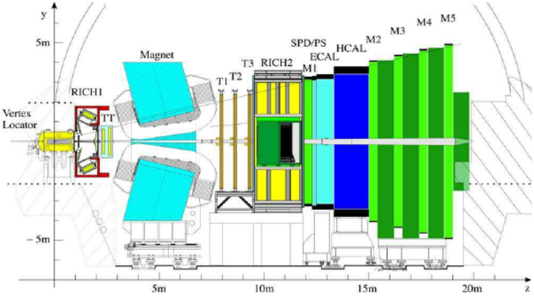


Muons need at least $\sqrt{q^2} = 2\ m_\mu$

$\to$ With electrons you can go lower in q^2 and isolate the gamma penguin

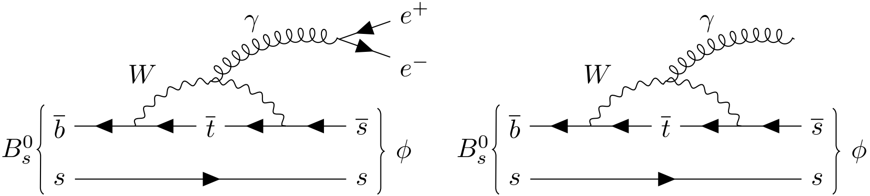
LHCb detector

- It's a detector in the forward region
- Oriented to studies of the B-physics
- It's composed by (Run1-Run2):
  - Tracking System: VELO, Trigger Tracker, Dipole Magnet and 3 Tracking stations.
  - Particle Identification System: RICH, ECAL, HCAL and Muon stations



The Analysis - $B_s^0 \to \phi(\to K^+K^-)e^+e^-$

Angular observables are predicted more precisely than Banching Fractions.



✓ Angular Analysis at low q^2 gives access to photon polorazition, a sensitive probe for New Physics.

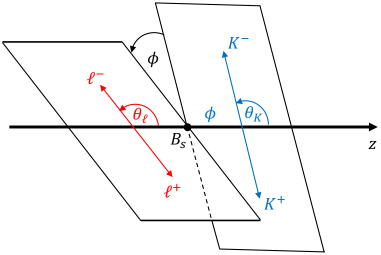
The Analysis- 3 Angles

The direction of the four outgoing particles can be described by three angles.

θ_l: defined as the angle between the direction of the e^- and the direction of flight of the B_s^0 in the dielectron rest frame.

θ_K: defined as the angle between the direction of K^- and the direction of flight of B_s^0 in the K^-K^+ rest frame.

ϕ: defined as the angle between the plane containing the two leptons and the plane containing the two hadrons of the final state in the B_s^0 rest frame.



The Analysis - 4 Angular Parameters

$$\left\langle \frac{d^3\Gamma}{d\cos\theta_l d\cos\theta_k d\phi} \right\rangle = \frac{9}{16\pi} \left\{ \frac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k \right.$$
$$+ \left[\frac{1}{4}(1-F_L)\sin^2\theta_k - F_L\cos^2\theta_k\right]\cos 2\theta_l$$
$$+ \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_k\sin^2\theta_l\cos 2\phi$$
$$+ (1-F_L)A_T^{ReCP}\sin^2\theta_k\cos\theta_l$$
$$\left. + \frac{1}{2}(1-F_L)A_T^{ImCP}\sin^2\theta_k\sin^2\theta_l\sin 2\phi \right\}$$

$F_L, A_T^{(2)}, A_T^{ImCP}$ and A_T^{ReCP} [2] are related to Wilson Coefficients

[2] F_L is the longitudinal polarisation, $A_T^{(2)}, A_T^{ImCP}$ are sensitive to the photon polarization and A_T^{ReCP} related to the forward-backward asymmetry

Key Observables

A_T^{Im} and A_T^{ReCP} are our key observables:

- They are sensitive to the photon polarization.
- They are predicted to be close to zero in the Standard Model.
- Can be large in the presence of New Physics contributions.

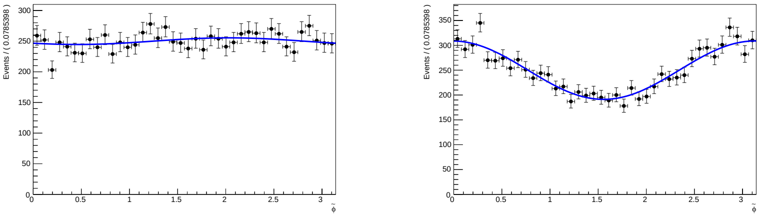
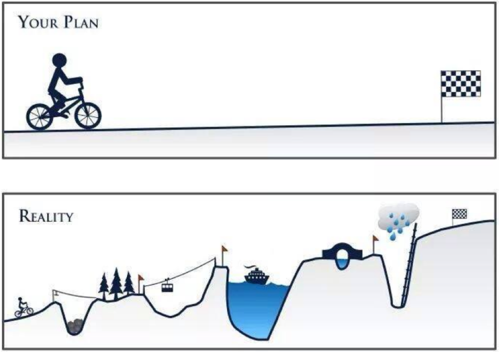


Figure 5: Distributions of the ϕ angle from pseudo-experiments, generated with the SM predictions on the left ($A_T^{(2)} = 0$) and with a different value of $A_T^{(2)}$ (=0.5) on the right.

Way Towards the Measurement



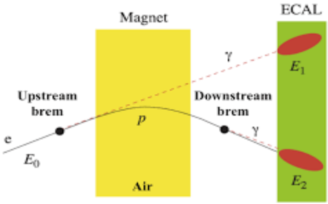
Looks simple? But many things to consider:

- Bremsstrahlung effects
- Different types of Background
- Corrections to the simulation
- Systematic uncertainties

Problem 1: Bremsstahlung

- It's the interaction with the detector material
- Probability goes with $E/m^2 \rightarrow$ mainly affecting electrons

A recovery procedure is in place to improve the momentum reconstruction:

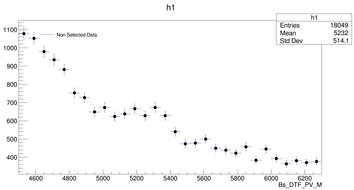


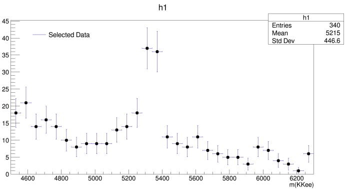
Drawbacks:
$\longrightarrow$ The Calorimeter energy resolution is worse than tracking resolution
$\longrightarrow$ Presence of energy deposits mistaken as bremsstrahlung photons
$\longrightarrow$ Some unrecovered Bremstrahlung photons.

Problem 2: Background

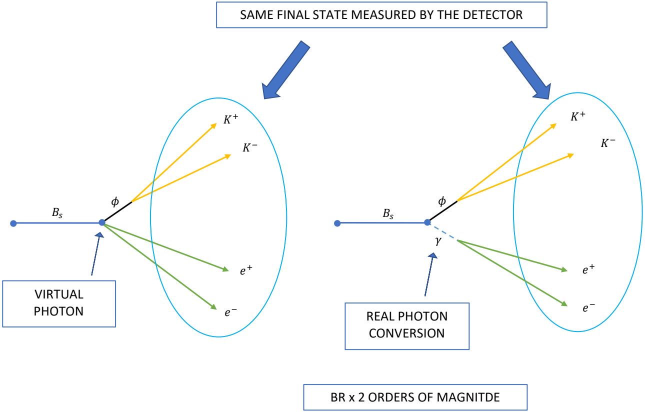
Several sources of Background:

- Combination of random tracks ($\rightarrow$ Machine Learning Technique?)
- MisIdentification of the final-state particles ($\rightarrow$ Particle identification and Kinematics requirements?)
- Peaking Background ($\rightarrow$ Veto or Include their distribution in your fitting model?)





Photons can interact with the material of the detector and convert into an e^+e^- pair.



Solution?

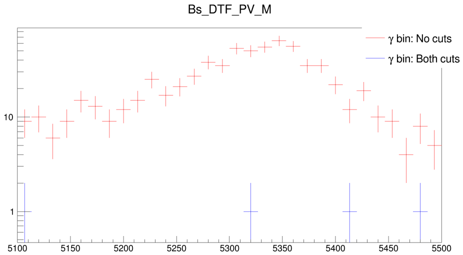
Two cuts to remove these photons

Velo Cut

Conversion happens when the photon interacts with the material of the detector
→ remove events having the dielectron vertex compatible with being in the detector material.

DEDX cut

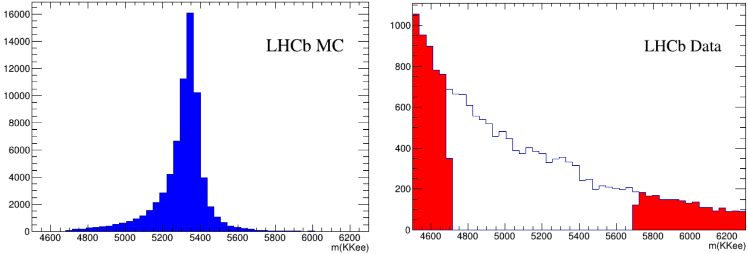
$2e$ tracks from γ conversion end up in the same VELO strips (almost co-linear)
→ reject events having twice the ADC count of usual charged tracks.



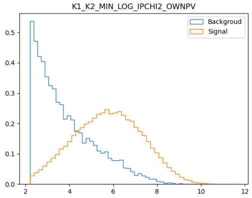
Reducing to ≈ 1% contamination

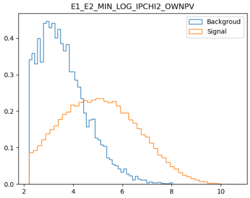
Problem 2: Background (Combinatorial)

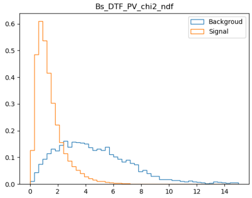
The most significant background is coming from random combinations of final-state particles.
→ Solution? Train a Boosted Decision Tree to distinguish between the Signal (From Simulation) and the Background (From Data Sidebands) events



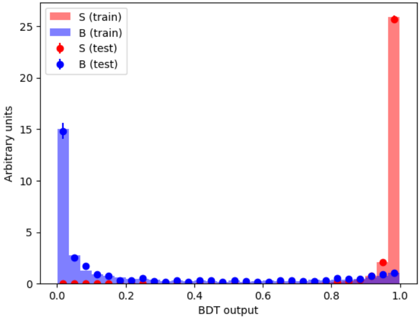
Input: 8 Kinematics and geometery variables



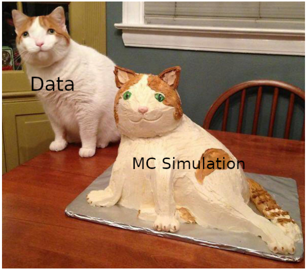




Output:

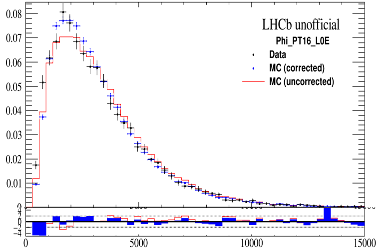


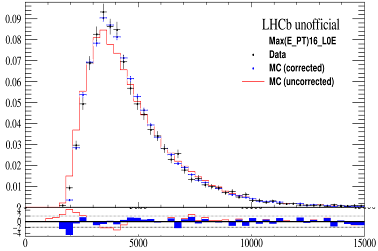
The analysis relies on MC simulation for some tests and studies.
BUT the LHCb MC is known to not perfectly reproduce the data.

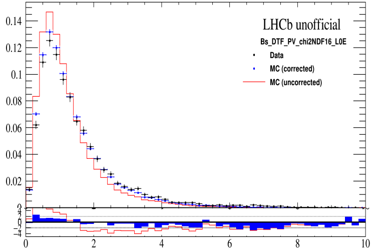


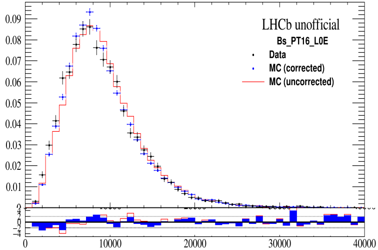
→ the simulated samples have to be corrected.

Problem 3: Simulation









Towards the Angular Analysis

The aim of our angular analysis is to measure the four observables $F_L, A_T^{(2)}, A_T^{ReCP}$ and A_T^{ImCP}.
The total fit PDF is:

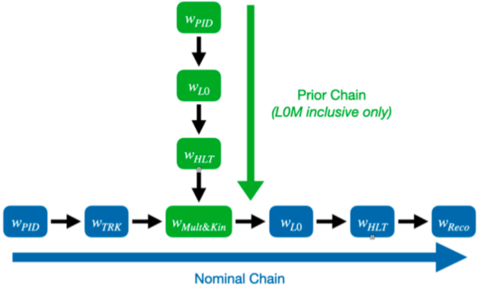
$$fs \times PDF_{Signal}(m, \theta_l, \theta_K, \phi) + (1 - fs) \times PDF_{Background}(m, \theta_l, \theta_K, \phi)$$

The reconstruction and selection of signal candidates induces a distortion in the angular distributions.

- Get the Angular Acceptance from MC that is generated with flat angles after applying the selection
- Multiply the signal angular PDF by this acceptance
  $$PDF_{Signal}(m, \theta_l, \theta_K, \phi) \rightarrow PDF_{Signal}(m, \theta_l, \theta_K, \phi) \times \epsilon(\theta_l, \theta_K, \phi)$$

What needs to be done

- Investigate specific backgrounds.
- Optimize the Selection and the BDT.
- Continue with the mass and Angular PDFs.



- **Nominal chain** of corrections to simulation:

w_{PID}	`PIDCalib` package for kaons, pions and muons, and `Fit&Count`[1] tool for electrons
$w_{Tracking}$	Correct for electron detection efficiency using tag and probe method
$w_{Mult\&Kin}$	BDT-based reweighting of B kinematics and multiplicity, evaluated from `L0M` samples
w_{L0}	Data/simulation ratios of `L0` efficiencies evaluated with the `TISTOS` method
w_{HLT}	Data/simulation ratios of `HLT` efficiencies evaluated with the `TISTOS` method
w_{Reco}	BDT-based reweighting of B reconstruction properties (χ^2_{VTX} and χ^2_{IP})