VERY RARE AND RADIATIVE DECAYS

3RD WORKSHOP ON LHCB UPGRADE II

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DISCLAIMER

The prospects for very rare and radiative decays were covered in detail by J. Prisciandaro and P. Pais in the Elba workshop (slides here and here).

These two types of decays will be in a very different situation in Run 5: ones will still be **statistically limited**, while the others will have been long limited by **systematic (detector)** effects.

In this talk, I plan to summarize some their prospects (sorry, no time to discuss everything) and also focus on particular decays to try to give an idea of what detector improvements could be useful for the LHCb upgrade II.

Therefore, expect a lot of hand waving arguments and not so many numbers. I hope this is helpful!

VERY RARE DECAYS

VRD IN RUN 5

Need as **much statistics as possible**

- Most of these analyses are not systematically limited, and won't be with the HL-LHC.
- Many observables have very precise SM predictions

SM predictions or NP region **within reach** with 300 fb^{-1}

Benefit from the **full software trigger** starting in the upgrade I, especially when studying low-p_{T} tracks

Potential improvements with an **upgraded detector in Run 5**

- Better electron reconstruction/selection, Bremsstrahlung recovery, magnet side stations (?)
- Improved downstream track reconstruction

PROSPECTS FOR $B \to \mu^+\mu^-$ AT 300 fb^{-1}

Uncertainty on BF for B_s^0 mode down to 0.16×10^{-9} with the same systematics, close to the uncertainty of the theoretical prediction (dominated by the B_s^0 decay constant and CKM matrix elements).

- Currently, main systematics come from f_s/f_d (5.8%) and the BF of normalisation modes (3%)
- Could go to 0.13×10^{-9} with an overall systematic of 3%

Ratio of BF between B_s^0 and B^0 down from current 90% to 10%.

New observables: **effective lifetime** (2% uncertainty) and **time-dependent *CP* asymmetry**, with a sensitivity of $\sigma(\mathcal{S}_{\mu^+\mu^-}) \sim 0.2$

PROSPECTS FOR $B \to e^+e^-$ AND $B \to \tau\tau$ AT 300 fb^{-1}

$B \to e^+e^-$ (similar considerations as $B_s^0 \to \mu^+\mu^-$)

- BF is enhanced in many NP models, search ongoing with expected limit in Run 1 at $\mathcal{O}(10^{-8})$. Expect limit at $\mathcal{O}(10^{-9})$ at the end of Run 5.
- **Sensitivity will be enhanced** in the upgrade~I thanks to the removal of L0, provided we can deal with the removal of PS and the SPD. Could be improved for the in upgrade II with **better electron reconstruction**.

$B \to \tau^+\tau^-$

- Current LHCb limits far from theoretical predictions (10^{-3} vs $10^{-7(8)}$), will stay **far from SM prediction** even at the end of Run 5.

PROSPECTS FOR LFV AT 300 fb^{-1}

Many models explaining LFU violation also predict the **existence of LFV**. Therefore, the search for LFV will be a cornerstone of the LHCb physics programme if the anomalies are confirmed.

LHCb has set limits on $B \to e\mu$ [JHEP03 (2018) 078] and $D^0 \to e\mu$ [PLB 754 (2016)], with more to follow ($B^+ \to K^+ e(\tau)\mu$, $B \to \tau\mu$, $B \to K^{*0} e(\tau)\mu$).

Predictions for many modes are **experimentally reachable in Run 5**, although some, like $B \to e\mu$ will stay out of reach.

- With measurements expected to be statistics limited, improvements in electron reconstruction (maybe magnet side stations?) will allow to probe even lower BFs.

EXAMPLE: $\tau \to \mu\mu\mu$

Limit set at $< 4.6 \times 10^{-8}$ with 1 fb^{-1} of data [JHEP 02 (2015) 121], thus expect $< 3 \times 10^{-9}$ with 300 fb^{-1} (comparable to BELLE II).

Work ongoing to improve the analysis by removing the `IsMuon` requirement from one of the muons (20% more signal)

In high lumi conditions, one needs

- Shielding to reduce muon background
- Installation of Pad chambers to mitigate losses in the upgrade I
- Improved PID on the non-`IsMuon` track with RICH and calo

Background from $D_s^- \to \eta(\to \mu^+\mu^-\gamma)\mu^-\overline{\nu}_\mu$ is expected to be the main systematic Improved calorimeter performance to veto it $\eta \to \mu^+\mu^-\gamma$ will be crucial.

PROSPECTS FOR RARE STRANGE AT 300 FB^{-1}

Strange decays have a very different signature compared to B physics: lower momentum, larger lifetime (behave as a background)

- So far, search for $K^0_S \to \mu^+\mu^-$ [EPJC 77 10 (2017) 678] and evidence of $\Sigma \to p\mu^+\mu^-$ [1712.08606], as well as prospects for several modes.

Prospects for Run 5 put $K^0_S \to \mu^+\mu^-$ at $\mathcal{O}(10^{-11})$, close to the SM prediction and in the region sensitive to NP.

- Once removed the hurdle of the L0 in the upgrade I, reconstruction of low-p_{T} particles will be essential for the rare strange programme.

Further studies include hyperons, K^+ decays (access to $K^+ \to \pi^+\ell^+\ell^-$ with BF of $\mathcal{O}(10^{-7})$), use kaons from ϕ to exploit kinematic constraints to study decays with neutrinos...

RADIATIVE DECAYS

Main **challenges**:

- Mass resolution dominated by photon energy resolution, causing large contamination from partially reconstructed decays
- Background from $\pi^0 \to \gamma\gamma$ reconstructed as a single cluster in the calorimeter (currently for $E_{\mathrm{T}} > 4\ \mathrm{GeV}$)
- Crossfeed, especially in the case of $b \to d\gamma$ transitions

Without any detector improvements,

- many analyses will be systematics-limited by Run 5 (mainly due to contamination/knowledge of peaking and partially reconstructed backgrounds)
- some analyses will be impossible due to the B mass resolution, *e.g.*, $B_s^0 \to K^{*0}\gamma$

PHOTON POLARISATION MEASUREMENTS (I)

Time-dependent measurements

- $B_s^0 \to \phi\gamma$ (tagged and untagged). Statistical sensitivity from ~80k events of $\mathcal{O}(0.02)$ with 300 fb^{-1}, but systematics limited (lifetime acceptance, lifetime distribution of backgrounds, proper time resolution).
- Tagged neutral $B^0 \to hhh\gamma$ decays, with potentially comparable sensitivity to $B_s^0 \to \phi\gamma$, as suppression from $\Delta\Gamma/\Gamma$ is lifted (under study).

Angular analyses of b-baryon decays, still unobserved. Expect ~1.5k (150) events for Λ_b^0 (Ξ_b) decays, with sensitivities of $\mathcal{O}(5\%)$, at the limit of being systematics-limited.

- Improvements in downstream tracking could be very beneficial, especially for the Λ_b^0 decay.

Amplitude analyses of $B^+ \to K^+\pi^-\pi^+\gamma$ decays, with ~300k signal events expected with 300 fb^{-1}. Sensitivity still under study, but could be $\sim 5\%$ with Run 1 only. Therefore, expect to be dominated by systematics from acceptance, backgrounds and model by the end of Run 3 (maybe even before).

Angular analysis of $B^0 \to K^{*0} e^+ e^-$ at very low q^2. Measurement with Run 1 currently one of the best constraints on the C_7.

Same type of constraint as $B_s^0 \to \phi\gamma$ untagged, expect statistical uncertainty of 4% with 50 fb^{-1} and 2% with 300 fb^{-1}

Improvements in electron reconstruction are essential to limit systematic uncertainties and to improve statistical power.

$\mathcal{A}^{CP}$ **for** $B^0 \to K^{*0}\gamma$ systematics limited by the end of Run 2, BELLE II much better than LHCb.

Isospin asymmetry in $B \to K^{*}\gamma$ is currently not competitive due to low reconstruction efficiency of B^+ mode

Study of $b \to d\gamma$ **transitions** ($|V_{td}/V_{ts}|$, $\mathcal{A}^{CP}$):

- More suppressed, backgrounds from π^0 larger and thus need to be controlled
- Runs 4–5 will allow to study in detail decays not reachable before: $B \to \omega\gamma$, $B \to \pi\pi\pi\gamma$ ...

Converted photons not competitive with calo photons due to low reconstruction efficiency

Further ideas: $B_s^0 \to \gamma\gamma$, $B^0 \to pp\gamma$, ...

limitations/improvements for run 5

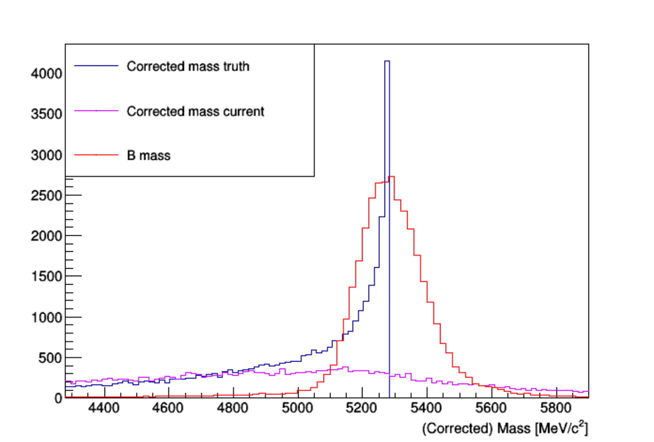
The main issues with radiative decays are the signal mass peak width and the contamination from π^0 backgrounds.

Assuming calorimeter energy resolution stays the same, study the impact of other improvements on radiative measurements using $B^0 \to K^{*0}\gamma$ as a test channel

- Improvements in vertexing to allow partial reconstruction
- Addition of fast timing to the calorimeter
- Improvement of spatial resolution or addition directionality information in the calorimeter
- Improved cluster granularity, smaller Molière radius

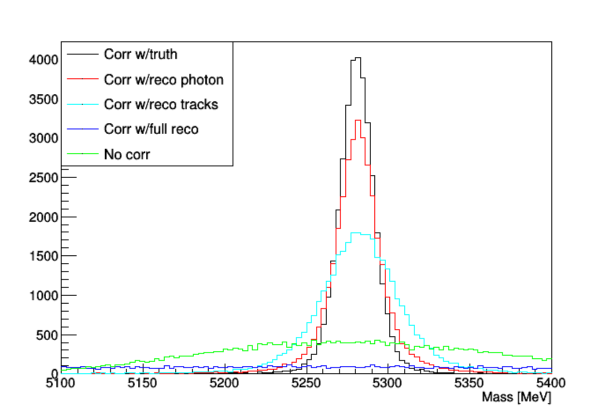
PARTIAL RECONSTRUCTION: CORRECTED MASS

First, look at $m_{\text{corrected}} = \sqrt{m^2 + p_{\text{T,missing}}^2} + p_{\text{T,missing}}$



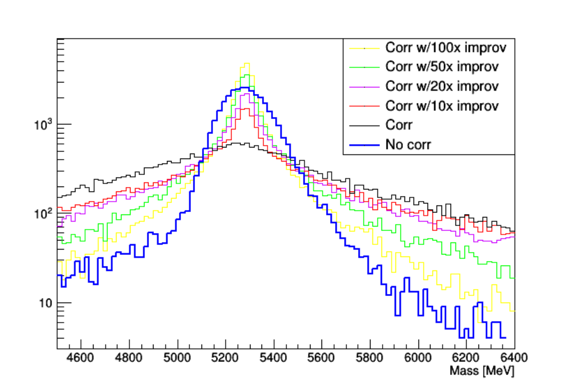
Missing p_{T} due to photon is too large for the correction to be approximate enough

Correct the energy of the photon using the ratio of p_{T} of the γ and the K^{*0} along the direction of the PV–SV, going from full MC truth to fully reconstructed quantities



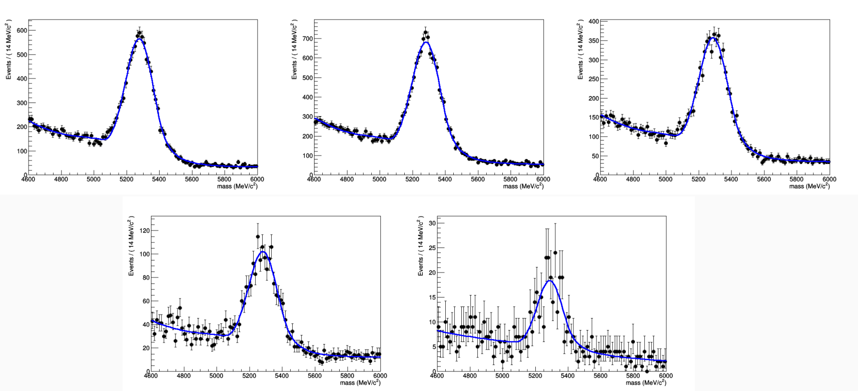
Currently limited by SV z resolution (K^{*0} vertex)

How much would we need to improve SV resolution to be able to use this technique? Test improving the resolution by a factor $x \in [10, 20, 50, 100]$.

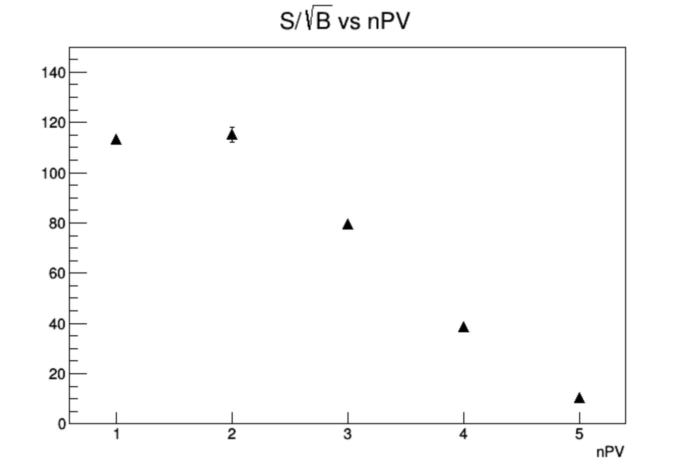


Narrower peak but wider tails...

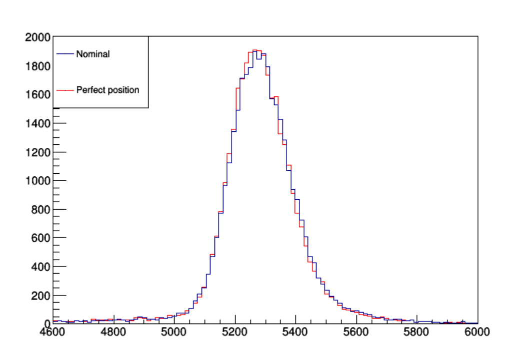
Fast timing could allow to isolate single PVs. Measure $S/\sqrt{B}$ as a function of nPVs in $B^0 \to K^{*0}\gamma$ (use the full fit mass range for simplicity).



FAST TIMING



Can the improvement of the spatial resolution (for example by using the timing layer) or the addition of directionality information through segmentation help in improving the mass peak resolution? Compare reconstructed mass peak with mass peak with perfect photon direction.



Even if the mass resolution does not improve, better spatial resolution and directionality can help when combined with improved granularity and smaller Molière radius.

The combination of improved granularity and smaller Molière radius will allow **better separation of the photons coming from π^0 decays**, thus allowing to reduce the contamination from these peaking backgrounds.

Use of directionality and more fine-grained cluster shape will allow, using ML techniques, to better **distinguish between showers coming from merged π^0 and high-E_{T} photons**.

CONCLUSIONS

Very rare decays will be mostly limited by statistics at the end of Run 5, but physics reach will put us in the interesting region for NP.

Rare strange decays provide a rich programme to study NP.

Radiative decays already systematics limited at the end of the upgrade, so an improved detector will be crucial to further develop the programme.

From the detector side, improvements in electron reconstruction will be crucial for LFV modes, while calorimeter improvements will be needed to reduce systematic uncertainties in measurements of the photon polarisation.

And let’s not forget rare charm, searches for Majorana neutrinos, etc