CERN/LHCC 2021-012
LHCb TDR 23
24 February 2022

Framework TDR

LHCb UPGRADE II

Technical Design Report

LHCC-2021-012

Physics benchmarking for Scoping Document

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March 6th 2024

Upgrade 2 TWIKI

1) Luminosity scenarios

- quick recap of what we know from LHC
- present lumi figures for our 3 scenarios

Main LHC parameters

- ***Flat optics*** *(see R. De Maria at LHCb week) would be our target for Scoping Document*

  —> for the moment round optics still remains baseline for the machine, but studies are planned on flat optics

  —> we need to push for swapping the priority (but remain flexible in detector design)

- ***Electron cloud****: baseline assumption from machine is to solve it*

  —> 2574 bunches for LHCb (vs 2748 for ATLAS/CMS)

- ***Luminosity region length*** *with flat optics: ~36mm (~45mm with round beams)*

  —> less separation btw PVs

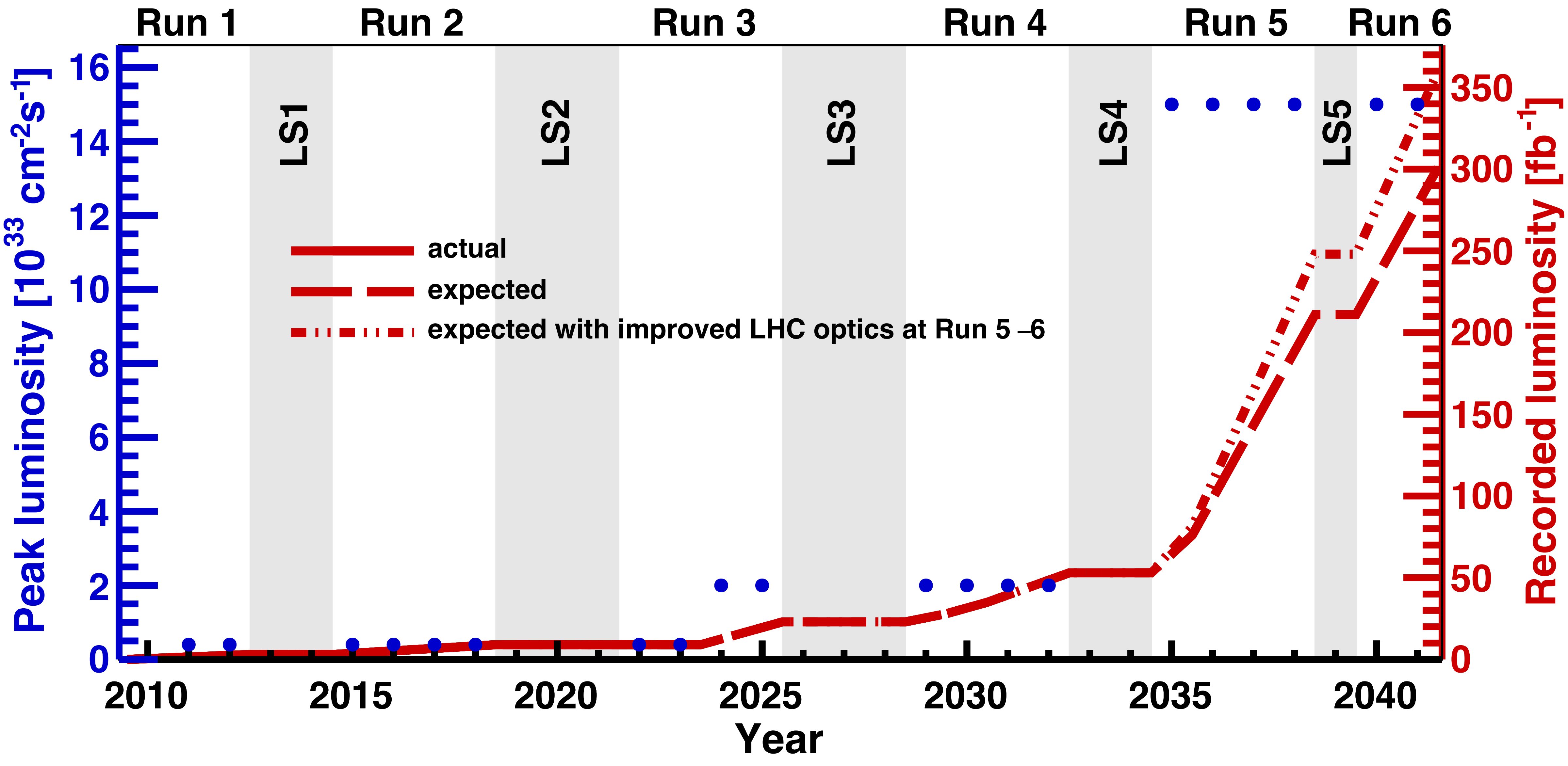
- ***Machine operations:*** *160 pp days/y (average Run5/6 with HI and YETS=15w), fill duration 8h + 3h turn-around, 50% operational efficiency*

- ***Effi(LHCb) for Upgrade II:*** *commissioning year at 50% + 5 nominal years at 90%*
- ***Recorded L_{int} (Run 1 - 4) ~53 fb^{-1}***

LHC note in preparation *we need it!!*

The lumi plot

And this is what we get with levelled L_{peak} = 1.5x10^{34} cm^{-2}s^{-1}



Upgrade 2 TWIKI

Lumi scenarios: all numbers

All numbers to be checked with machine experts!!!

Round beams

	Low	Medium-a	**Medium-b**	**High**
levelled L_{peak} (cm^{-2}s^{-1})	**1.0x10^{34}**	1.2x10^{34}	**1.3x10^{34}**	**1.5x10^{34}**
levelled pile-up	**28**	34	**36**	**42**
levelling time (h)	**3.6**	2.9	**2.3**	**1.3**
delivered L_{int} / y (fb^{-1})	**42.5**	47.0	**48.0**	**49.9**
delivered Run 5-6 (fb^{-1})	**234**	259	**264**	**274**
ratio L_{int} (X) / L_{int} (high)	**0,852**	0,936	**0,962**	**1.0**
total recorded L_{int} Run 1-6	**263**	286	**291**	**300**

for detector

for physics

Flat beams

	Low	Medium-a	**Medium-b**	**High**
levelled L_{peak} (cm^{-2}s^{-1})	**1.0x10^{34}**	1.2x10^{34}	**1.3x10^{34}**	**1.5x10^{34}**
levelled pile-up	**28**	34	**36**	**42**
levelling time (h)	**5.7**	4.7	**4.2**	**3.4**
delivered L_{int} / y (fb^{-1})	**47.8**	54.3	**57.1**	**61.9**
delivered Run 5-6 (fb^{-1})	**263**	299	**314**	**340**
ratio L_{int} (X) / L_{int} (high)	**0,772**	0,877	**0,922**	**1.0**
total recorded L_{int} Run 1-6	**290**	322	**336**	**359**

for detector

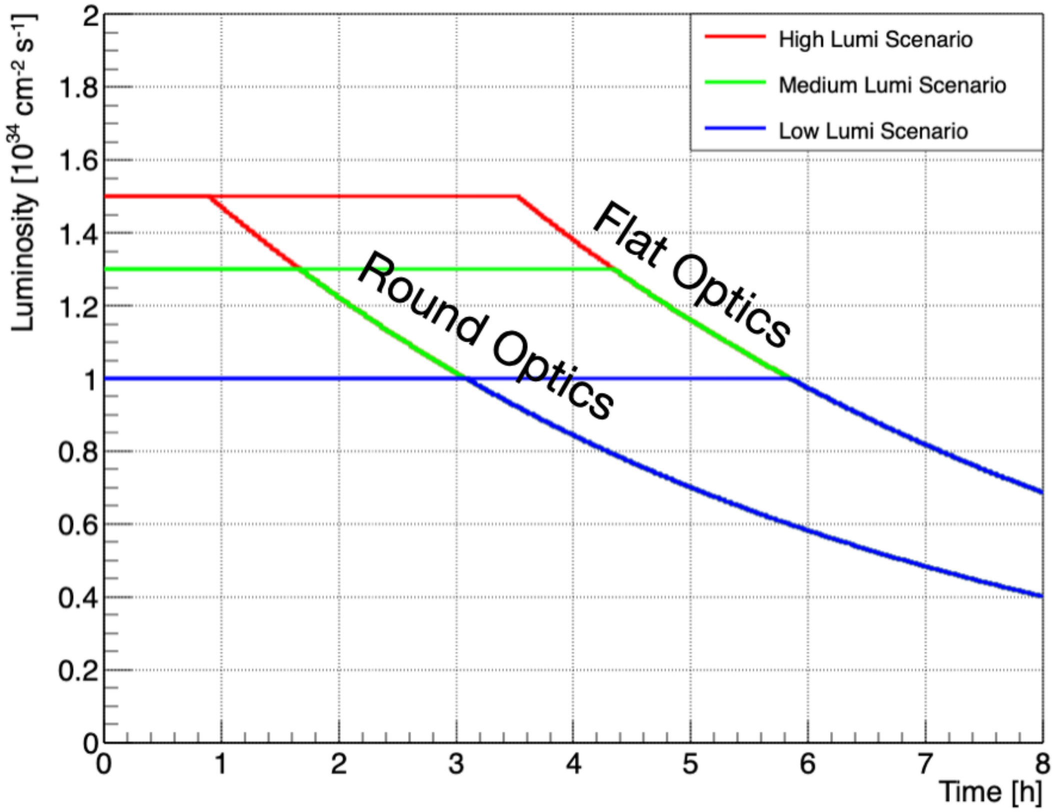
for physics

Scenarios at 1.2 and 1.3 have a small ~5% difference in lumi/occupancy conditions, but 1.3 looks better for FLAT optics, since it makes a better usage of machine improvement —> we've chosen 1.3

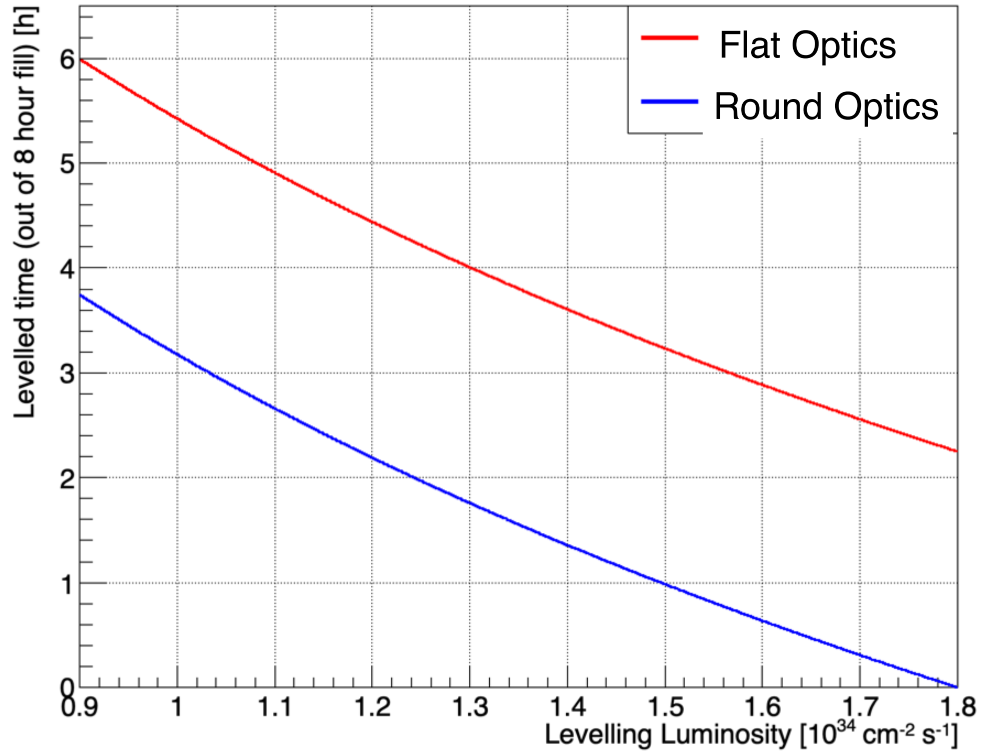
Flat vs Round optics

Paula Collins

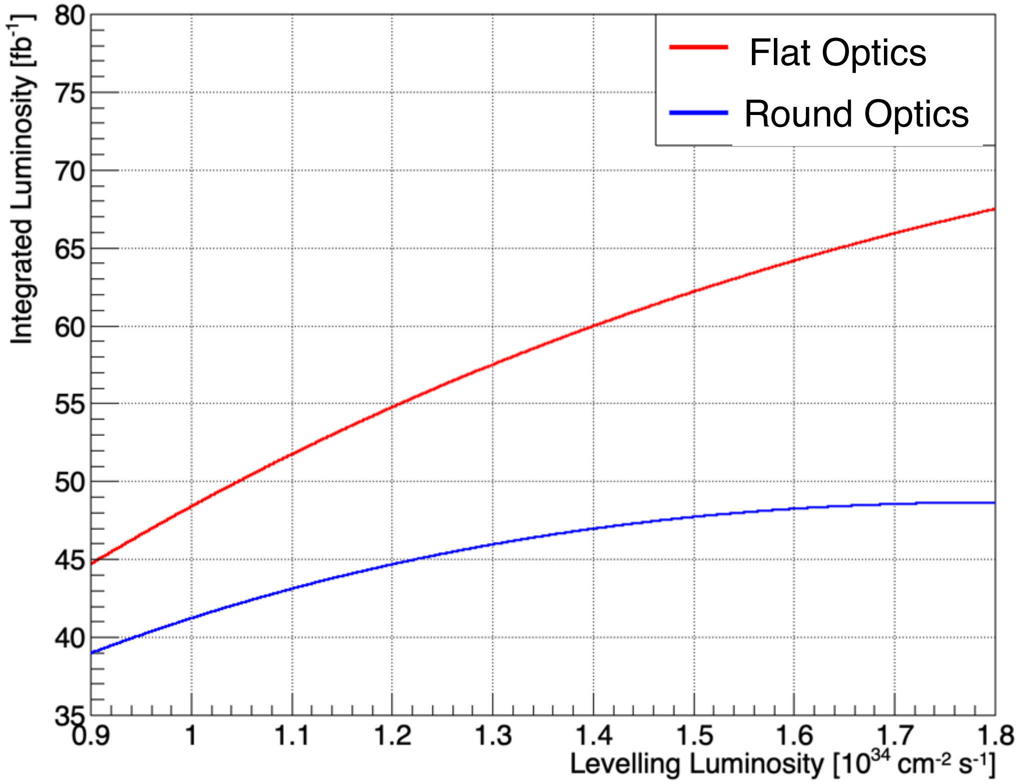
luminosity decay



levelled time vs levelling lumi



Integrated luminosity per year



*Due to its higher virtual peak luminosity ($1.8 \rightarrow 2.8 \times 10^{34}$ cm^{-2}s^{-1}), **flat optics** has much longer levelling times, higher integrated luminosity, and more stable data taking conditions*

Relevant numbers for physics

	Low	*Medium*	***High***
levelled L_{peak} ($cm^{-2}s^{-1}$)	*1.0×10^{34}*	*1.3×10^{34}*	***1.5×10^{34}***
total recorded *ROUND (fb^{-1})*	*263*	*291*	***300***
total recorded *FLAT (fb^{-1})*	*290*	*336*	***359***

- ***Round optics*** *has a larger risk concerning the final integrate lumi target*

- ***Flat optics*** *provides a solid picture for reaching the Upgrade II minimal target of 300 fb^{-1}, with operational risk considerably reduced (very valuable argument in the evaluation phase of our project)*

  To make best use of it, however, we need a detector capable of running at highest possible peak luminosity, and to stand the slightly higher radiation dose

Within the timeline of Scoping Document we will not be certain of final beam configuration, but no show-stoppers are expected for FLAT optics, ***so detector specifications need to be compliant with this***

In summary, we need to define medium and low scenarios at 1.3 and 1.0, respectively, while matching the target cost savings of 15% and 30% of FTDR

2) Physics benchmarking

General considerations

- **High scenario:** *Full breath of our physics programme, with highest possible margins on luminosity.*

- **Medium scenario:** *try to preserve as much as possible the physics programme, small loss in luminosity. But need to decrease some of the detector features in order to generate the target cost decrease.*

- **Low scenario:** *we should propose something that, even sacrificing a fraction of our physics programme, still allows key LHCb flagship measurements, in particular CKM phases, charm CPV and rare muons*

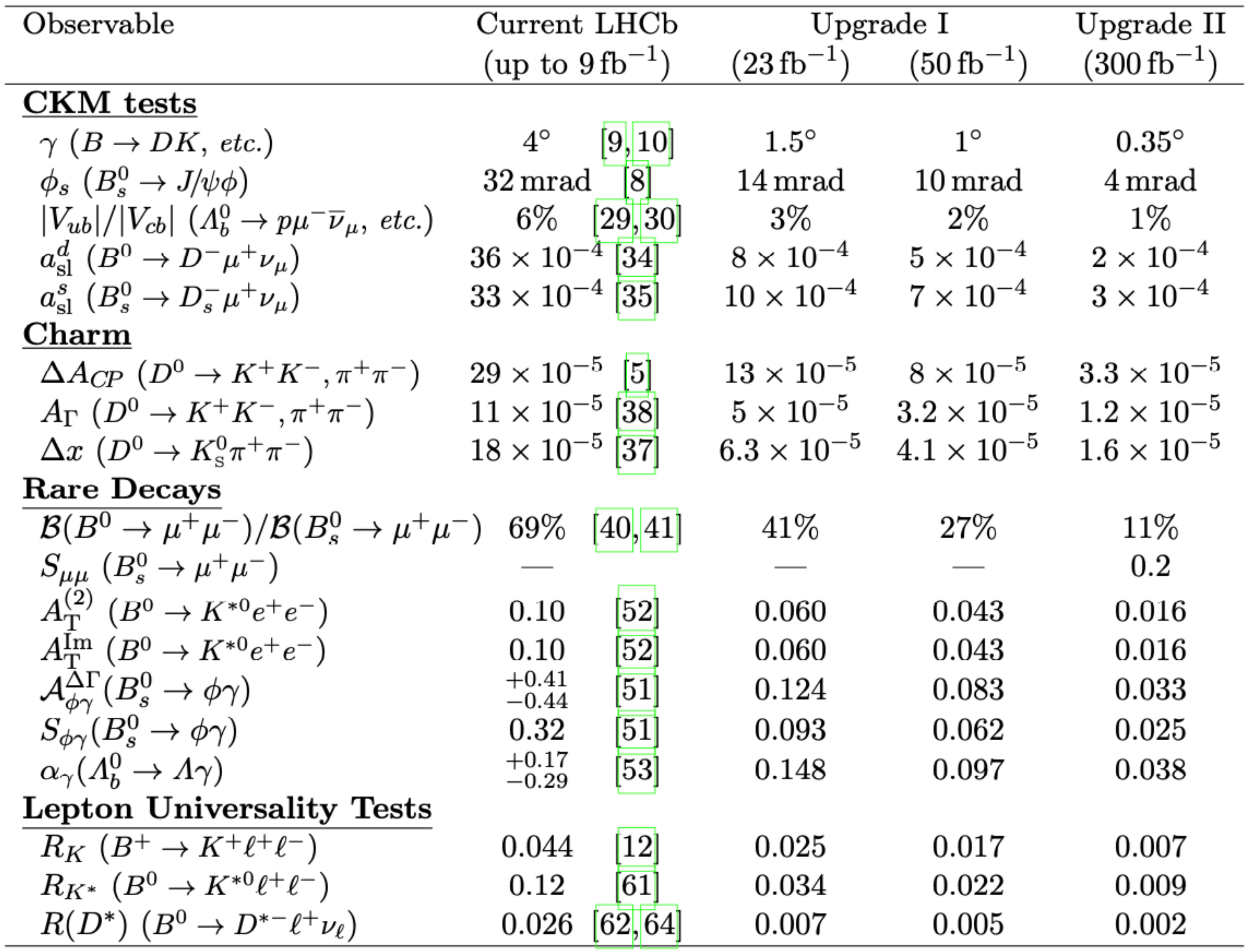
In addition: feedback also received by the CERN Scientific Policy Committee

(december 2023)

Request to better understand which physics goals are truly unique in a global context, and what elements of the proposed upgrade are essential to address them

Physics studies: what we need

This is how we presented so far our Upgrade II case



Observable	Current LHCb		Upgrade I		Upgrade II
	(up to $9\,\mathrm{fb}^{-1}$)		($23\,\mathrm{fb}^{-1}$)	($50\,\mathrm{fb}^{-1}$)	($300\,\mathrm{fb}^{-1}$)
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

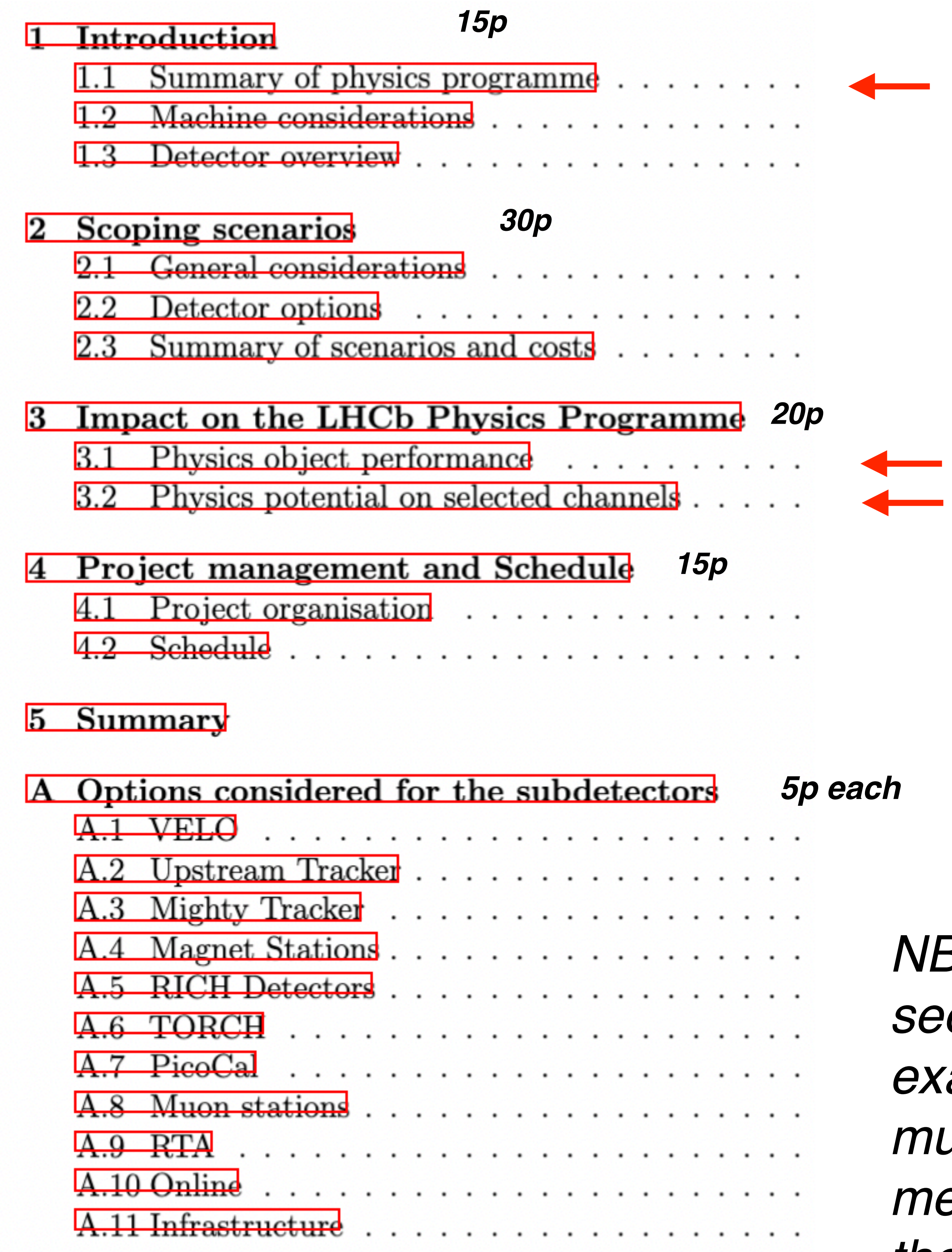
1) Key observables in flavour physics

2) NOT ONLY flavour physics

LHCb, as a general purpose detector in forward region, will keep pursuing an ambitious programme in spectroscopy, EW precision and Higgs physics ($\sim 2-3 \times y_{SM}^c$), dark sector and other exotic searches, heavy ions and fixed target physics ...

We need some quantitative statements (in the different detector scenarios) about some of the observables belonging to the table above, plus some discussion about the opportunities of extra-physics accessible (or lost) in a given scenario

Scoping Document: the physics content



Sec. 1.1: *give the global context, remind again about unique LHCb capabilities and wide physics breath*

Sec. 3.1: *tracking and PID performance in different scenarios*

~mid April

Sec. 3.2: *quantitative statements on how the above performance reflect into some physics channels, plus info on extra physics opportunities*

~September

NB: both LHCC and FAs are expecting to see discussed quantitatively some physics examples, which they requested explicitly multiple times; they will not argue about the methodology we used to extract numbers, but they want to see some numbers

Benchmark channels

Phoebe, Yasmine,
Tim, Matteo

Proposed list of channels to study in full simulation

- $B^+ \to D[\to K^0_S\pi^+\pi^-]K^+$
  K^0_S reconstruction, PID (K/π), γ
- $B^0_s \to J/\psi[\to \mu^+\mu^-]\phi[\to K^+K^-]$
  muons, PID (K/π), flavour tagging, vertexing, ϕ_s
- $B^0 \to K^{*0}[\to K^+\pi^-]e^+e^-$ [low q^2]
  electron reconstruction, acceptance, PID (e), $C_7^{(\prime)}$
- $\Lambda_b^0 \to \Lambda\gamma$
  non-trivial vertexing, photon reconstruction, acceptance, $C_7^{(\prime)}$
- $D^{*+} \to D[\to K^+K^-]\pi^+$
  slow π acceptance, PID (K/π), A_Γ
- $\Lambda_b^0 \to p\mu\nu$
  single muon, proton ID, missing energy/corrected mass, $|V_{ub}|$

See Tim's presentations at PPG october 12 and in the U2PG october 18

PPG also produced a document with valuable inputs, available here

This list does not define our physics programme. Rather it will be used to demonstrate the impact of different scoping scenarios. There's the attempt to cover a wide spectrum of different detector and reconstruction features

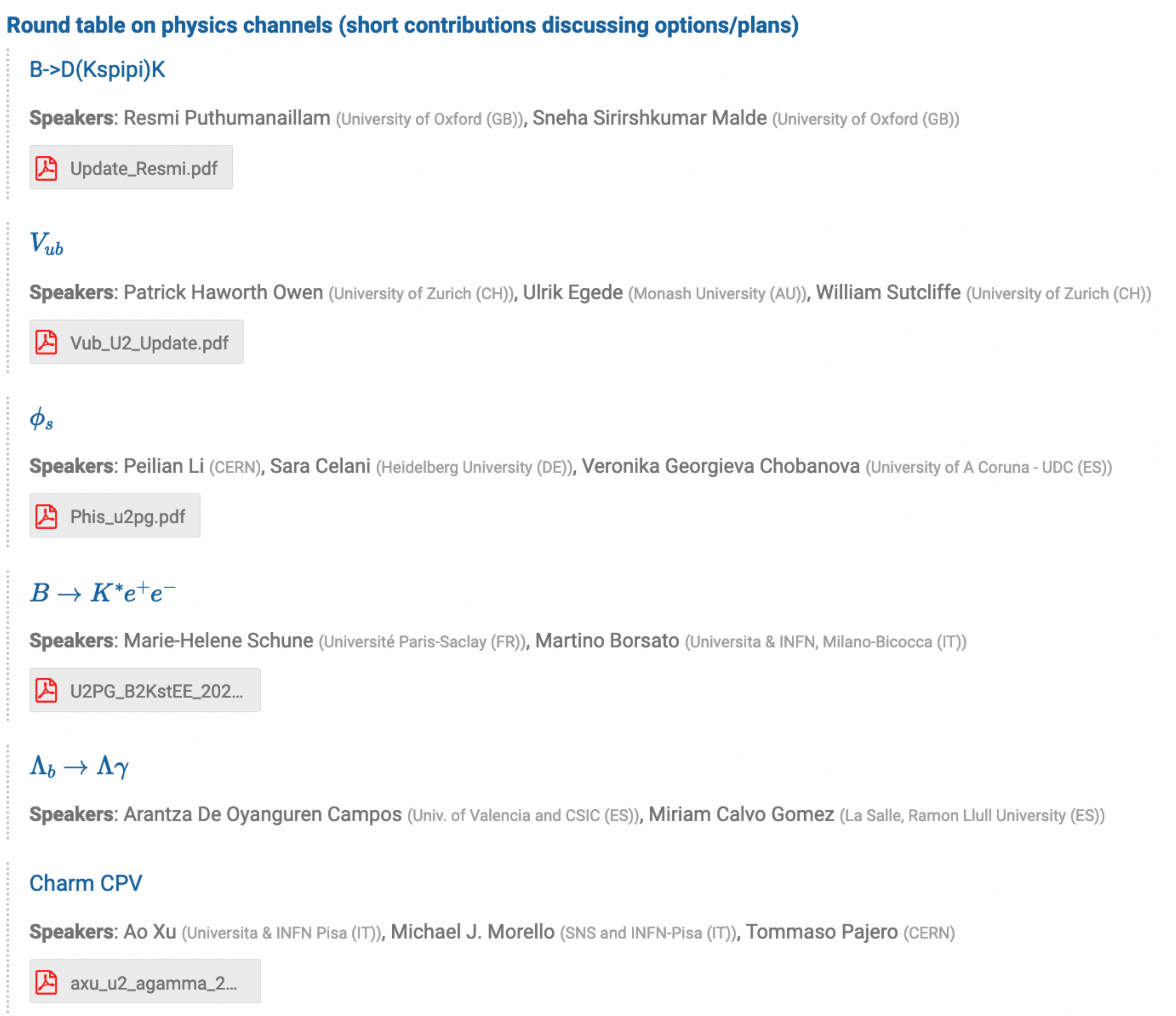
Other inputs are welcome: detectors will add their own specific channels, specific studies will be done for other physics topics, see e.g. U2PG on Heavy Ions nov 15

Planning the work

Volunteers from the analysis groups kindly accepted to follow this task, but this requires strict coordination with people performing detector studies

~monthly U2PG meetings

Last meeting
1 March
https://indico.cern.ch/event/1378464/



Round table on physics channels (short contributions discussing options/plans)

B->D(Kspipi)K

Speakers: Resmi Puthumanaillam (University of Oxford (GB)), Sneha Sirirshkumar Malde (University of Oxford (GB))

Update_Resmi.pdf

V_{ub}

Speakers: Patrick Haworth Owen (University of Zurich (CH)), Ulrik Egede (Monash University (AU)), William Sutcliffe (University of Zurich (CH))

Vub_U2_Update.pdf

ϕ_s

Speakers: Peilian Li (CERN), Sara Celani (Heidelberg University (DE)), Veronika Georgieva Chobanova (University of A Coruna - UDC (ES))

Phis_u2pg.pdf

$B \to K^* e^+ e^-$

Speakers: Marie-Helene Schune (Université Paris-Saclay (FR)), Martino Borsato (Universita & INFN, Milano-Bicocca (IT))

U2PG_B2KstEE_202...

$\Lambda_b \to \Lambda\gamma$

Speakers: Arantza De Oyanguren Campos (Univ. of Valencia and CSIC (ES)), Miriam Calvo Gomez (La Salle, Ramon Llull University (ES))

Charm CPV

Speakers: Ao Xu (Universita & INFN Pisa (IT)), Michael J. Morello (SNS and INFN-Pisa (IT)), Tommaso Pajero (CERN)

axu_u2_agamma_2...

***Present status:** prepare the work while waiting for scenarios to be defined and full simulation to be deployed; simplified approaches also useful in this phases, and to provide preliminary results*

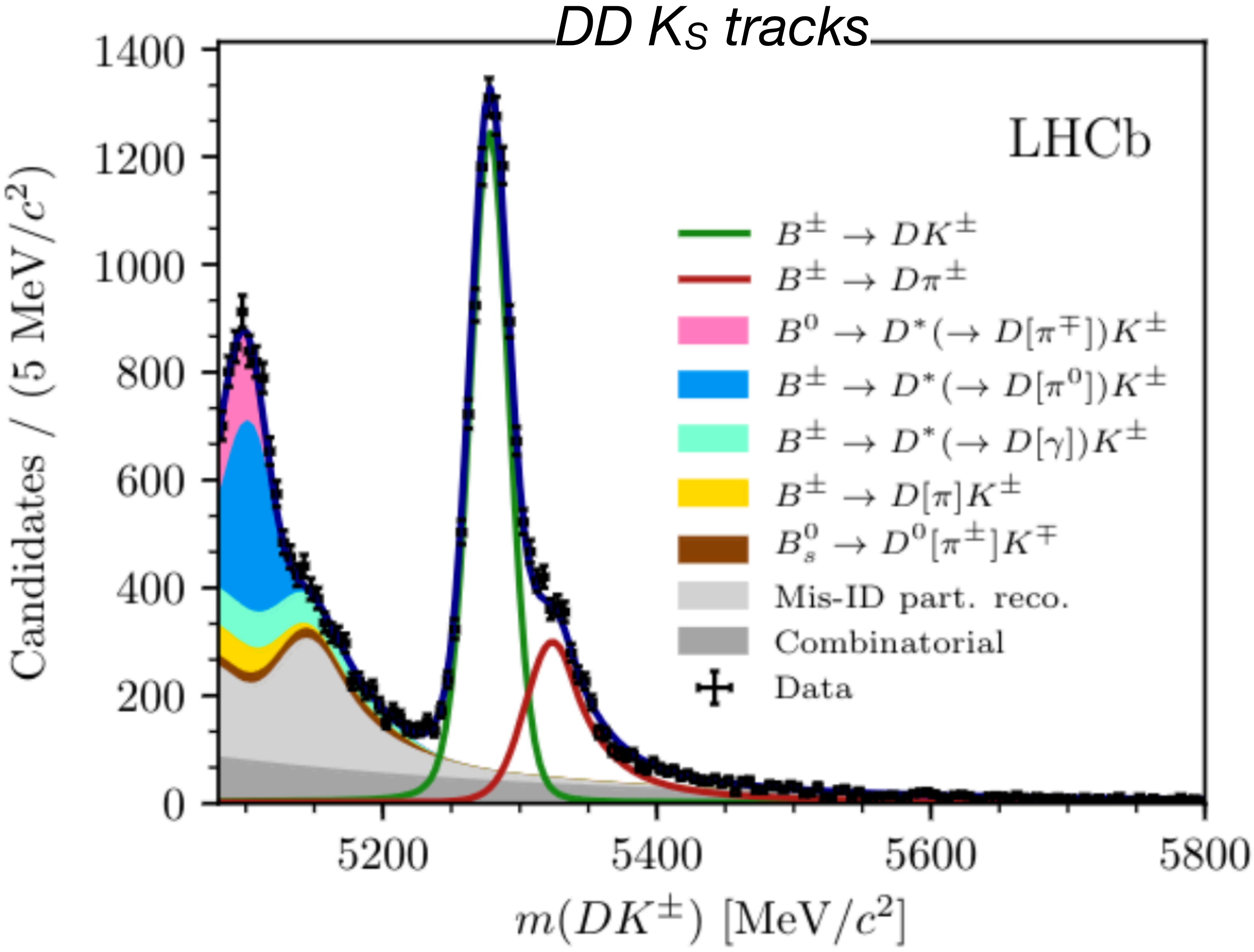
γ from $B^{\pm} \to D(K_S^0 h^+ h^-)K^{\pm}$

S. Malde,
R.Puthumanaillam

Statistically limited at 9 fb^{-1}: $\gamma = (68.7^{+5.2}_{-5.1})^{\circ}$*; syst* $\sim 1^{\circ}$

Key point: syst will remain under control if bkg is kept LOW

- *2/3 of statistics from DD K_S tracks*
- *misID bkg: PID performance checks with scoping scenarios*
- *Comb bkg: from toys 40% error increase on CP observables with* $10\times$ *comb. bkg*
- *Part reco: plan to look at the effect of resolution*



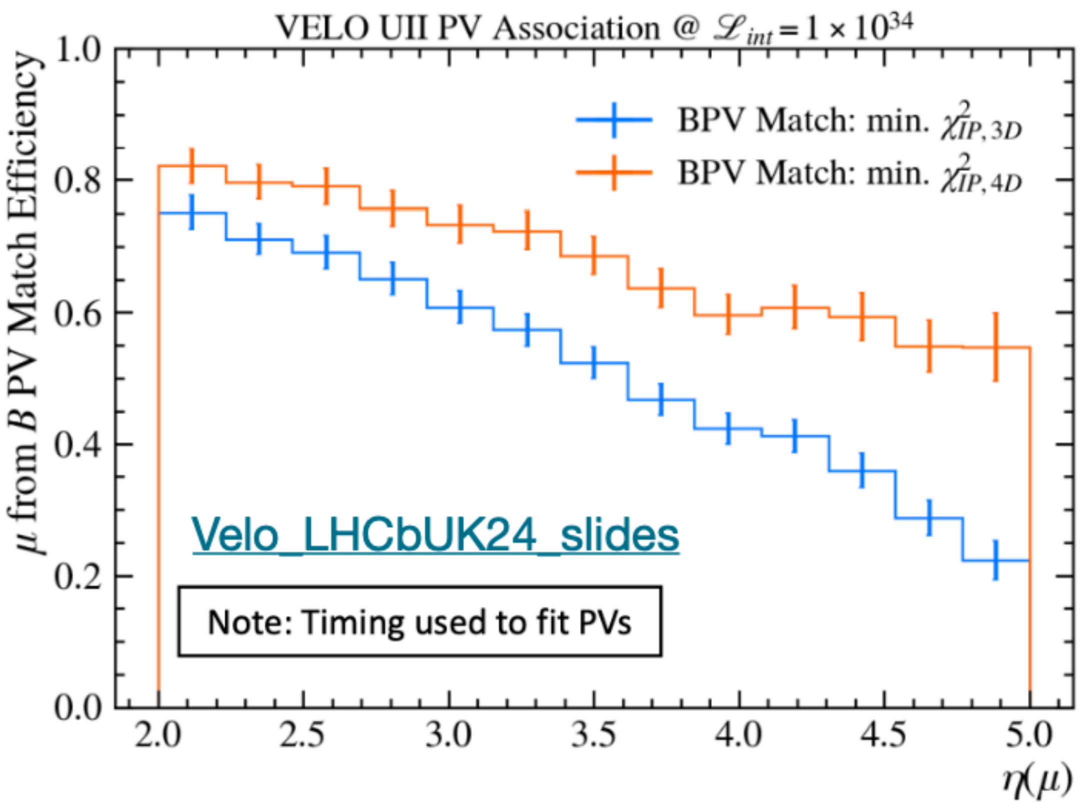
DD K_S tracks

ϕ_s from $B_s^0 \to J/\psi\phi$

P.Li, S.Celani, Q.Fuehring, S.Menzemer, C.Langenbruch, V.Chobanova, D.M.Santos, C.Prouve, L.Uecker, M.Olocco

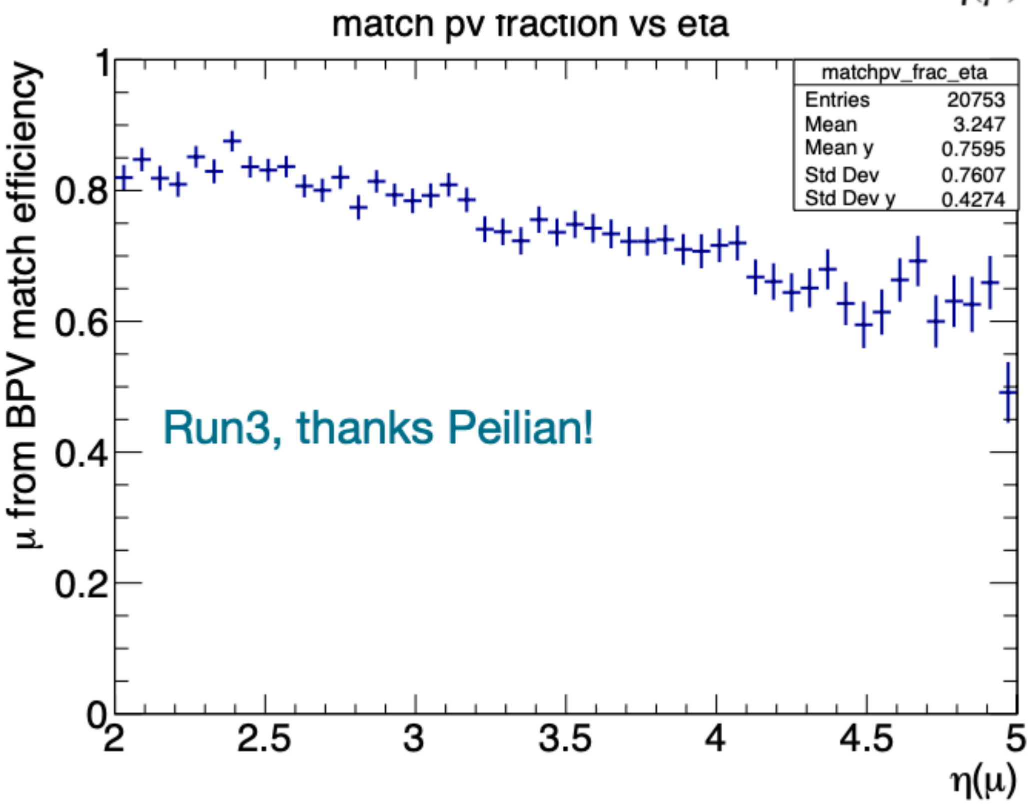
Key point to study: flavour tagging

- ‘Short’ term plan: provide $\varepsilon_{\mathrm{tag}}, \omega, \bar{\varepsilon}$ as a function of possible U2 conditions (ghost probability, IP resolution, tracking efficiencies….)
- Starting using Run3 MC
  - But this means making some assumptions…
    - **PV matching** efficiency comparable to Run3
    - **IP resolution** of U2 at least as good as in Run3
      - If not, needed to smear the IP accordingly
    - **PID** efficiencies at least as good as Run3
      - If not, mis-identification ROC curves / efficiency maps wrt to p, p_T, η are needed to simulate the response



Velo_LHCbUK24_slides

Note: Timing used to fit PVs



Run3, thanks Peilian!

In addition

- study dependence on event must by assigning random tracks from other events

- if FT found to be sensitive to ghost rates, take these into account

V_{ub} from $\Lambda_b \rightarrow p\mu\nu$

W.Sutcliffe,
P.Owen,
U.Egede

Key point to study: M_{corr} and q^2 resolution

$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$

Dominated by PV and SV resolution;

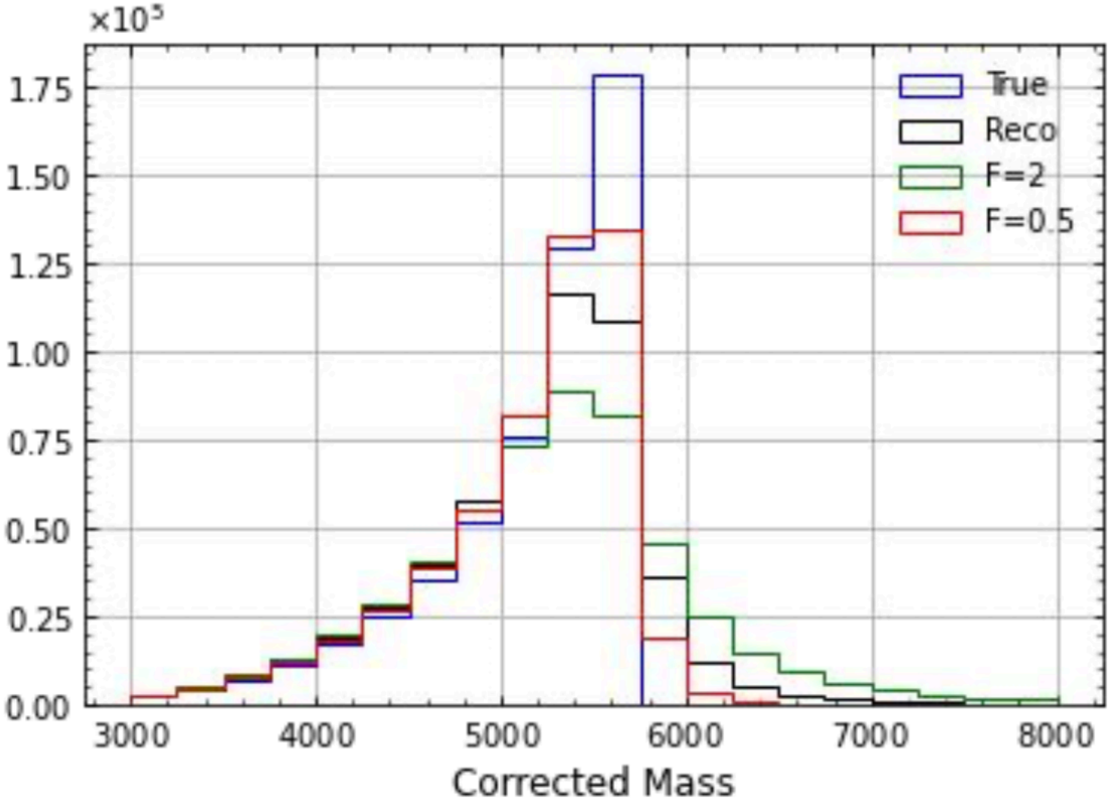
also important PV mis-association

- *both effects have been studied with toy sim, ready to be updated with specific U2 scenario inputs*
- *can extend to include dominant bkg like $\Lambda_b \rightarrow \Lambda_c \mu\nu$ and $\Lambda_b \rightarrow N^* \mu\nu$*

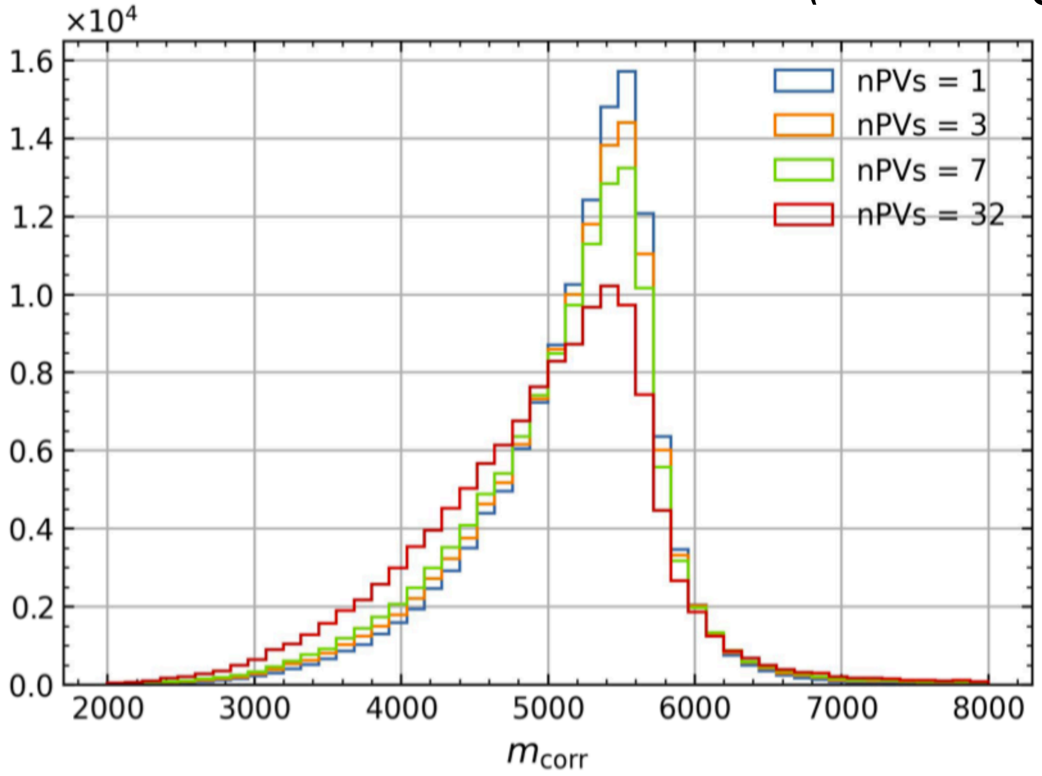
More studies:

- *impact of proton PID at low momenta, muon trigger efficiency*
- *more difficult: isolation, combinatorial $p\mu$*

effect of vertex resolution



effect of PV misassoc. (no timing)

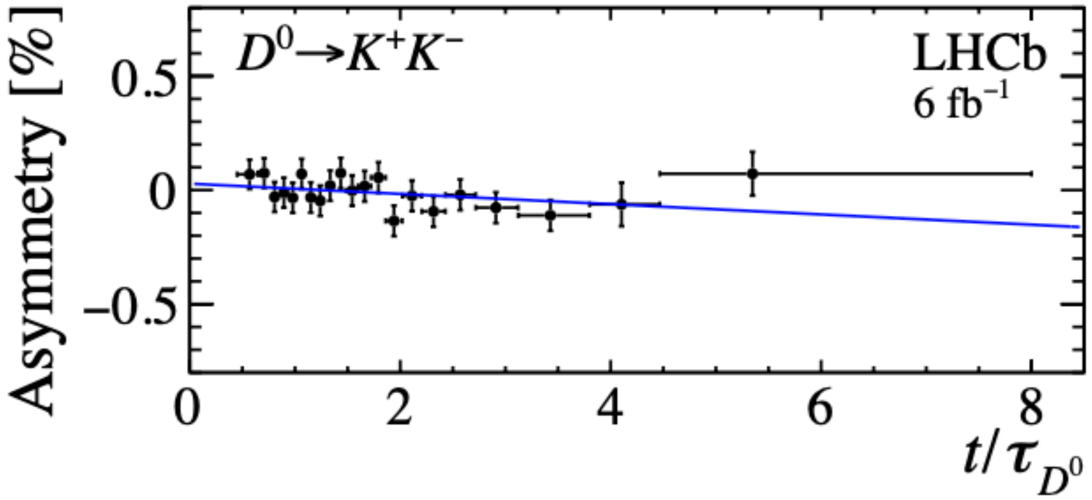


A_Γ from $D^0 \to K^+K^-$

M.Morello, T.Pajero, G.Punzi, A.Xu

Slope of time-dependent asymmetry -> time reso of 0.1 $\tau(D^0)$ is enough

precision of 10^{-4} already reached in Run 2



Key points to address

- background level
- separation of primary and secondary (from-B) decays (mostly based on IP/IPCHI2)
- PV mis-ID (large time biases)
- size of detection asymmetries

Final precision crucially depends on the trigger requirements that we can afford (S/B, bandwidth) with HLT1 playing the most important role until now

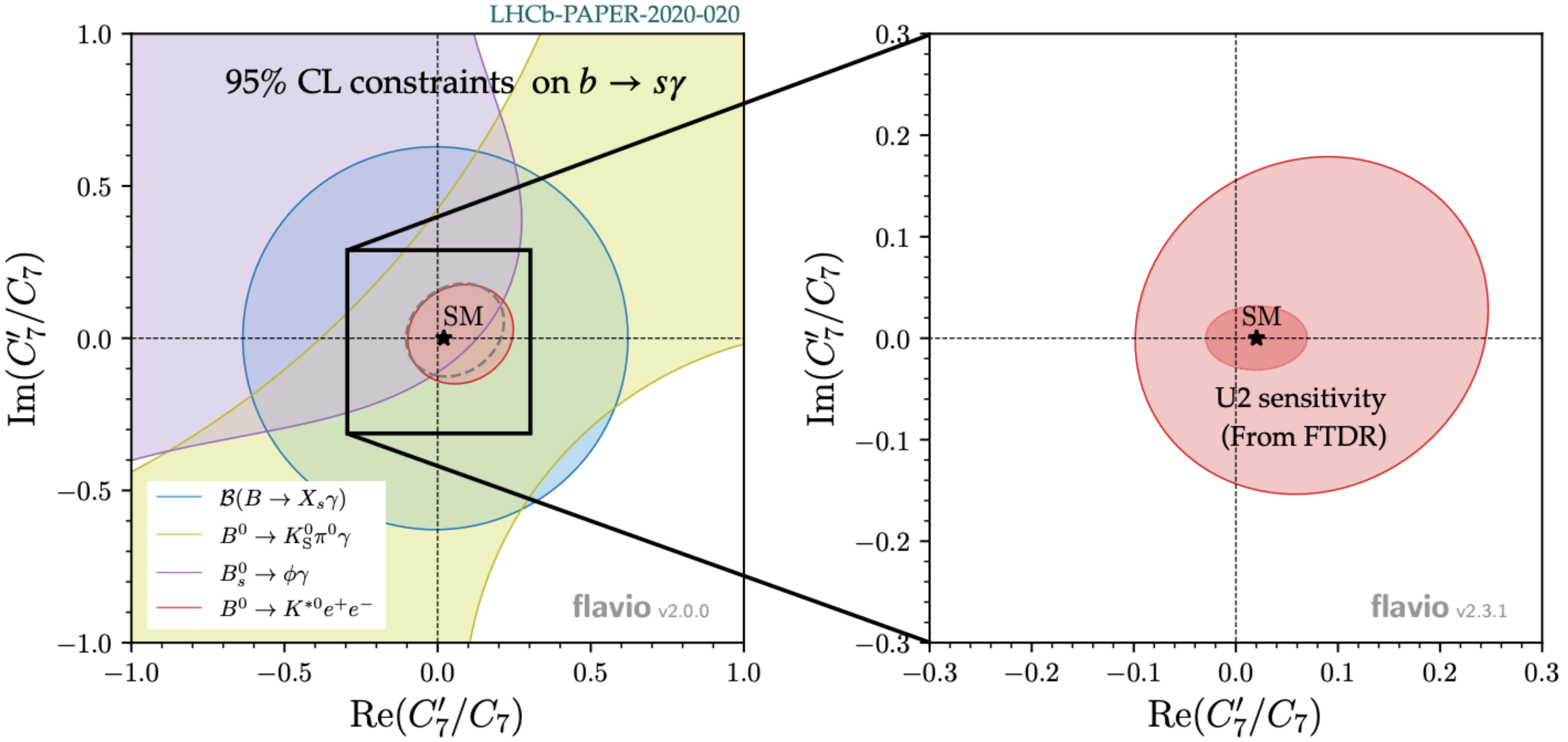
How

- RapidSim + U2 momentum resolution smearing (Renato)
  - Mass resolution of D^0 and D^*
  - Inner/outer/MS geometrical acceptance
- Full simulation + Rec and Moore @ `velo_upgrade2` branch (Tim)
  - Efficiency vs. signal purity: IP/momentum thresholds, PID performance, MS
  - Prompt/secondary separation vs. IP resolution
  - Decay-time bias: PV association
  - Detection asymmetry

$B^0 \to K^* e^+ e^-$

M.Borsato,
M.H.Schune

Strong potential for improved constraints at U2



Key points

1. Electron **tracking** and PID (**ECAL**)
2. Low brem loss (upstream **material**)
3. Good brem recovery (**ECAL**)
4. Measurement of e^+e^- decay plane
   - Small e^+e^- angle (**VELO** resolution)
   - Multiple scattering in **VELO material**
5. Minimise bkg from γ conversions
   - **VELO material** budget
   - **VELO material** causes multiple scattering and worsens $m(ee)$ resolution

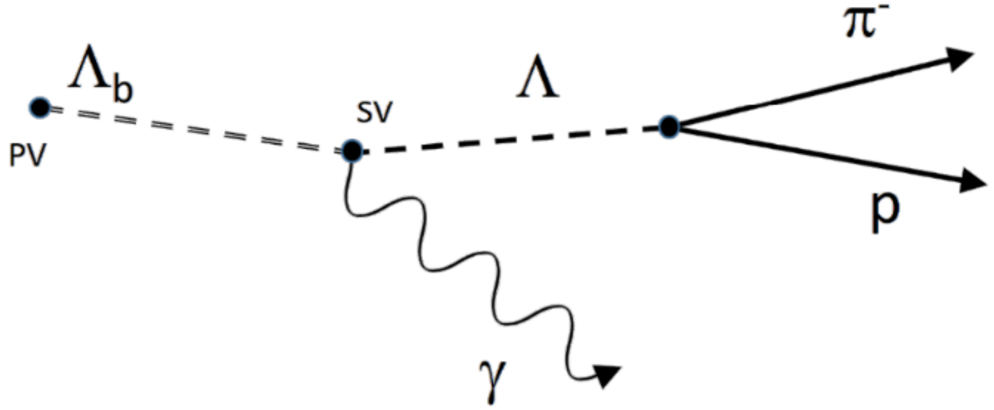
Many of these will discussed at this workshop

$\Lambda_b \to \Lambda\gamma$

M.C.Gomez,
A.Oyanguren

Key points

Non trivial vertexing, photon reconstruction, acceptance



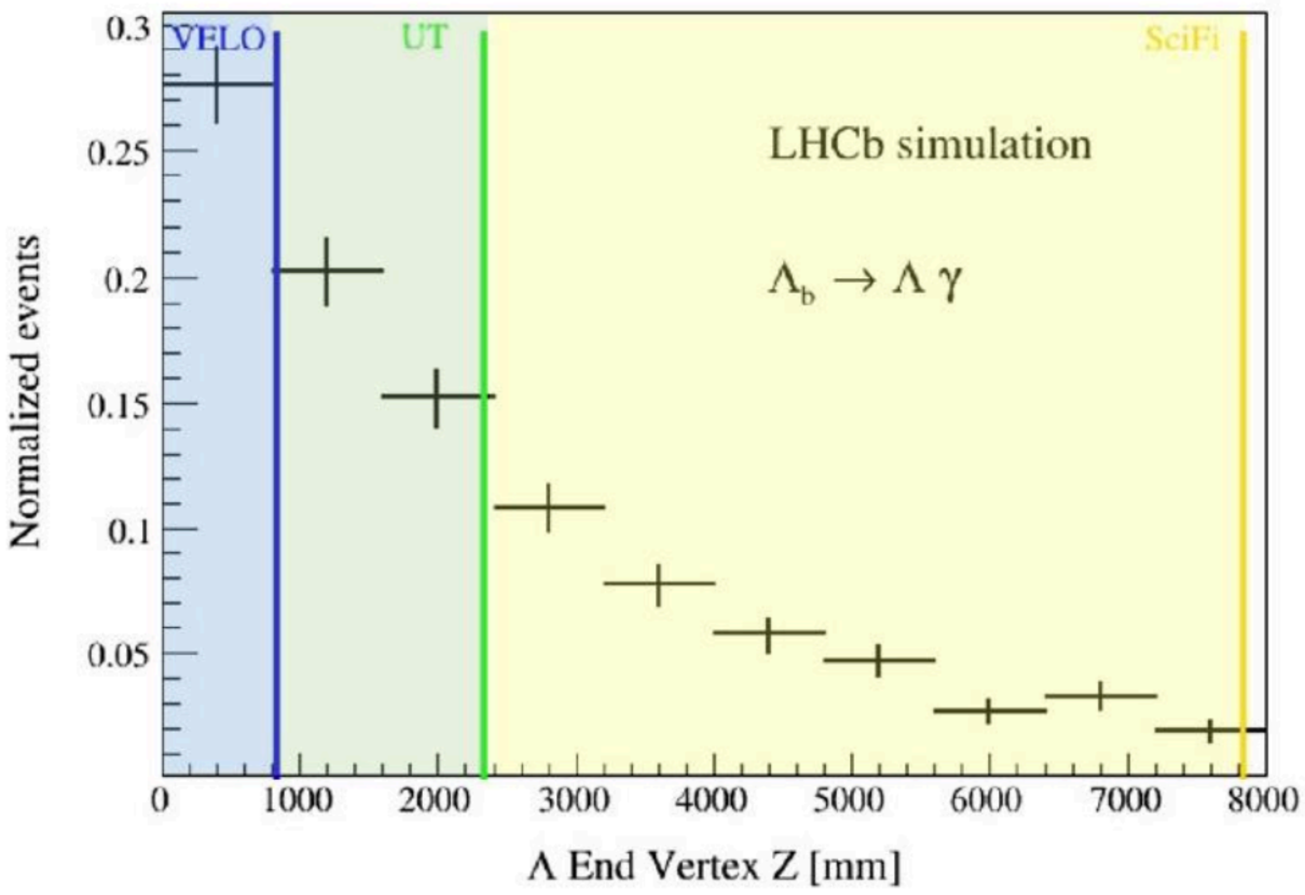
- *efficiency limited by track reconstruction*

  ⇒ evaluate per category (LL/DD/TT)

- *mass resolution limited by photon reconstruction*

  ⇒ evaluate impact of PicoCal downscoping on resolution and photon ID

12% (LL), 51% (DD), and 37% (TT)



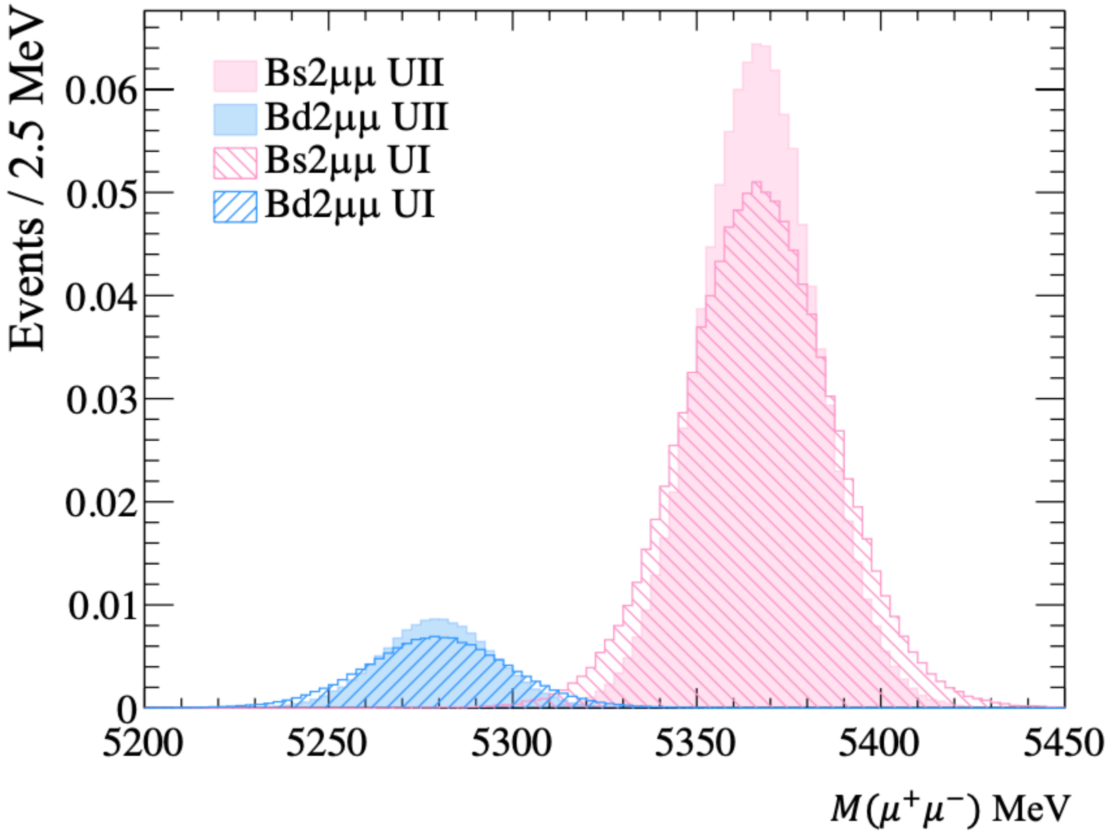
…and there's more

Example 1

Flagship channels like $B_{d,s} \rightarrow \mu^+\mu^-$ can illustrate very well the power of an improved momentum resolution

Very good selling point for the project in ALL scenarios

$B_{d,s} \rightarrow \mu^+\mu^-$ with U1/U2 mass resolution

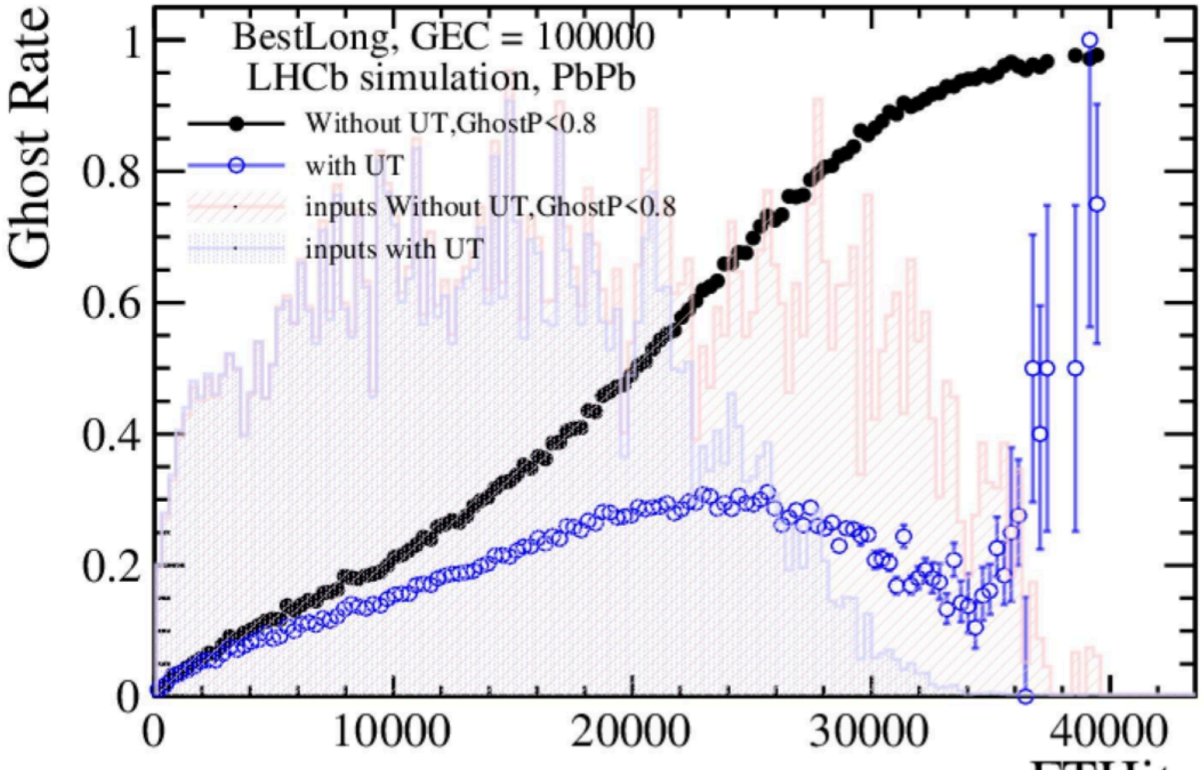


Mary Richardson-Slipper

Example 2

Tracking with heavy ions down to very low centrality: critical metric ghost rate

Very good selling point for the HIGH scenario



Conclusions

We need quantitative statements on the impact of the detector scenarios on selected physics channels

Results are needed in time for the Scoping Document, which is supposed to be circulated within the collaboration end of June, and sent to LHCC beginning of September

Preliminary figures (e.g. effect of momentum resolution improvement) could be also shown at the April LHCC/RRB meetings, where we're supposed to present the U2 detector scenarios ⇒ this would have a positive impact on the discussion

Effort ongoing , needs good coordination with detector studies

A HUGE thanks to all people involved, and especially to the SIMULATION TEAM!!!