Physics with ECAL in Run4 and Run5

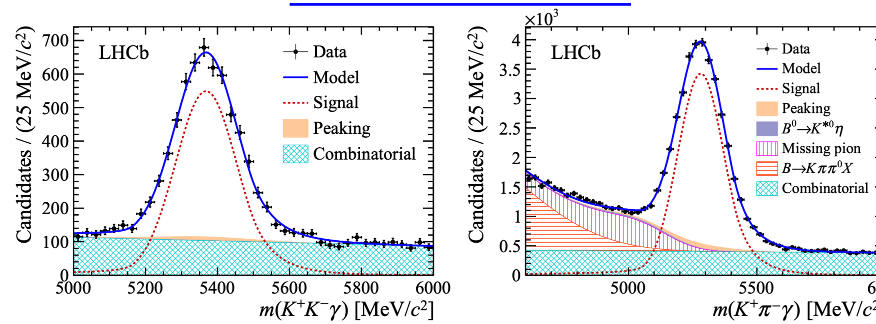
Stefano Perazzini

5th Workshop on LHCb Upgrade II – 1st April 2020

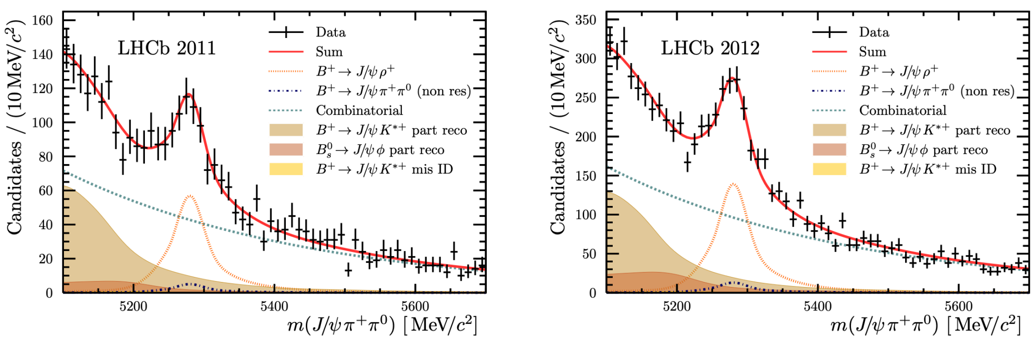
What physics has been done with ECAL

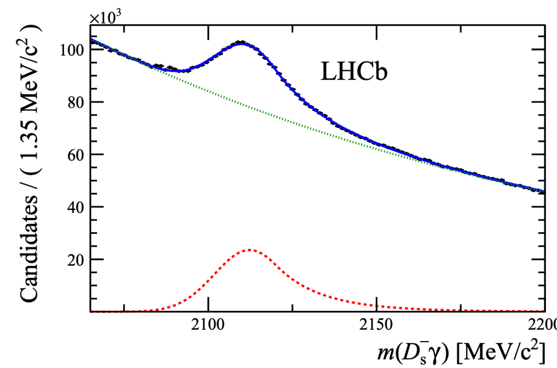
- About 10% of LHCb publications involve final states with γ, π^0 and $e^{\pm}$
  - ECAL is behaving well, but still doing analyses with it is difficult
  - Signal yields are 1/20 with respect to charged modes

arXiv:1905.06284



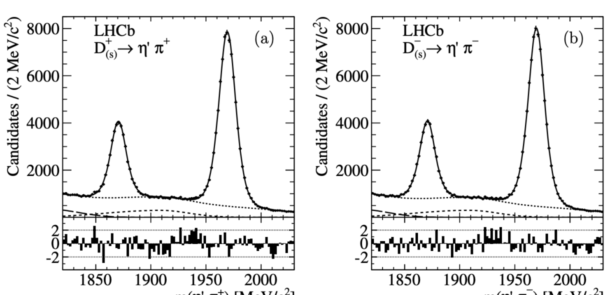
arXiv:1812.07041

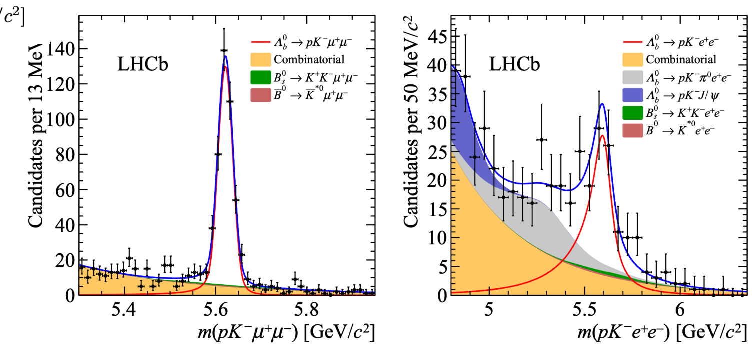




arXiv:2003.08453

arXiv:1701.01871





arXiv:1912.08139

What can be done in the future

- There is some hunger for physics with ECAL objects at LHCb
  - The word “ECAL” appears about 20 times in the document (the same for word “RICH”)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-LHCC-2018-027
LHCB-PUB-2018-009
27 August 2018

Physics case for an LHCb Upgrade II

Opportunities in flavour physics, and beyond, in the HL-LHC era

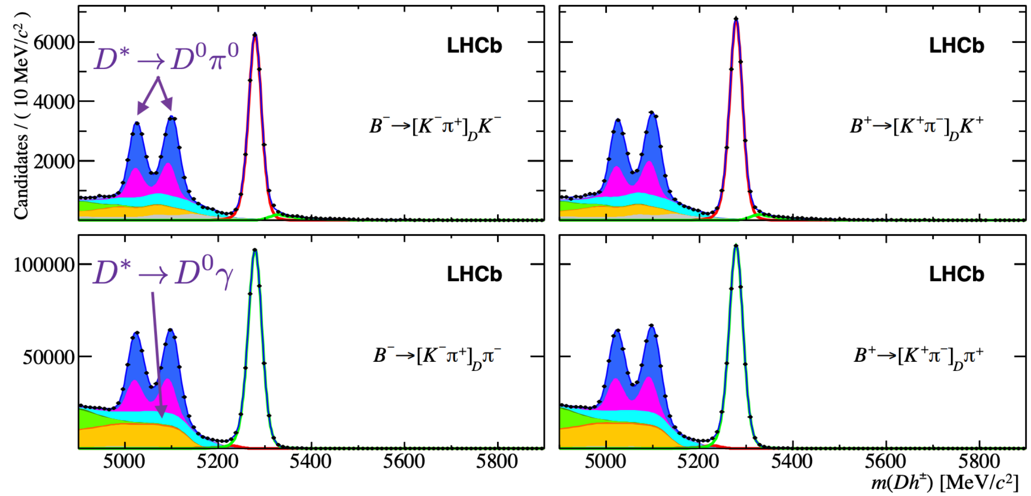
The LHCb collaboration

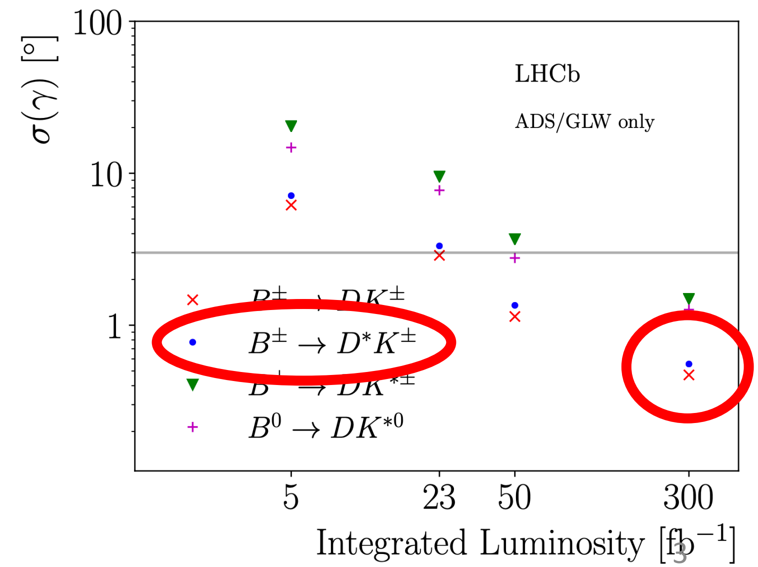
Abstract

The LHCb Upgrade II will fully exploit the flavour-physics opportunities of the HL-LHC, and study additional physics topics that take advantage of the forward acceptance of the LHCb spectrometer. The LHCb Upgrade I will begin operation in 2020. Consolidation will occur, and modest enhancements of the Upgrade I detector will be installed, in Long Shutdown 3 of the LHC (2025) and these are discussed here. The main Upgrade II detector will be installed in long shutdown 4 of the LHC (2030) and will build on the strengths of the current LHCb experiment and the Upgrade I. It will operate at a luminosity up to $2 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$, ten times that of the Upgrade I detector. New detector components will improve the intrinsic performance of the experiment in certain key areas. An Expression Of Interest proposing Upgrade II was submitted in February 2017. The physics case for the Upgrade II is presented here in more depth. *CP*-violating phases will be measured with precisions unattainable at any other envisaged facility. The experiment will probe $b \to s\ell^+\ell^-$ and $b \to d\ell^+\ell^-$ transitions in both muon and electron decays in modes not accessible at Upgrade I. Minimal flavour violation will be tested with a precision measurement of the ratio of $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$. Probing charm *CP* violation at the 10^{-5} level may result in its long sought discovery. Major advances in hadron spectroscopy will be possible, which will be powerful probes of low energy QCD. Upgrade II potentially will have the highest sensitivity of all the LHC experiments on the Higgs to charm-quark couplings. Generically, the new physics mass scale probed, for fixed couplings, will almost double compared with the pre-HL-LHC era; this extended reach for flavour physics is similar to that which would be achieved by the HE-LHC proposal for the energy frontier.

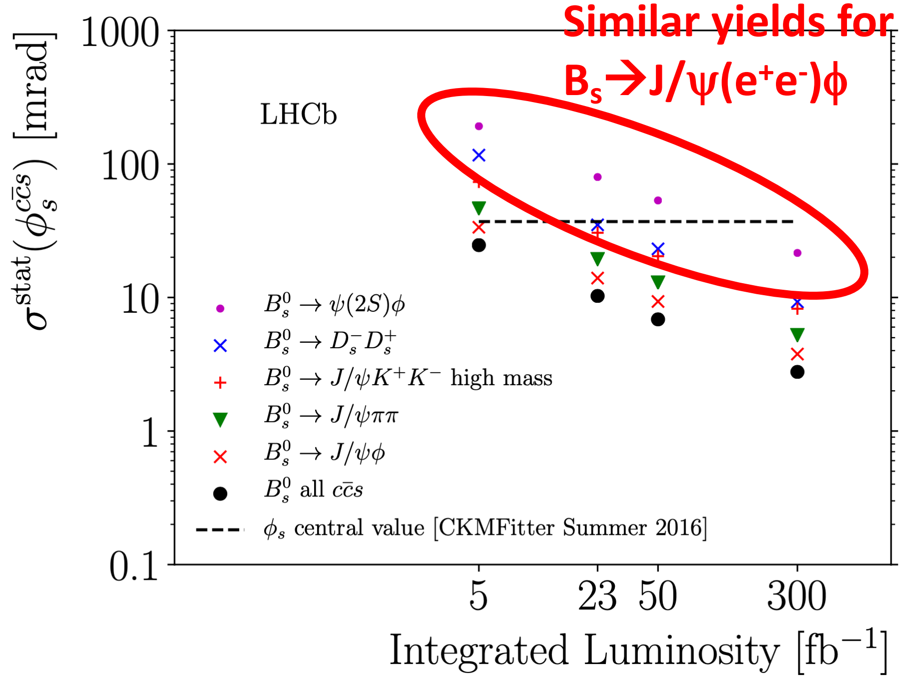
CKM angle γ using photons and π^0

- Very important to combine many different decay modes as each brings different sensitivity to γ arXiv:1708.06370
- One promising case is $B^{\pm} \rightarrow D^{*0}h^{\pm}$ decays:
  - Exploit almost perfect strong phase difference between $D^{*0} \rightarrow D^0\gamma$ and $D^{*0} \rightarrow D^0\pi^0$ [arXiv:hep-ph0409281]
  - Very good sensitivity demonstrated from an analysis exploiting partial reconstruction of D^{*0}
  - Great potential with the inclusion of full reconstructed decays
    - Preliminary studies show comparable sensitivity to γ





Time dependent CPV with B decays

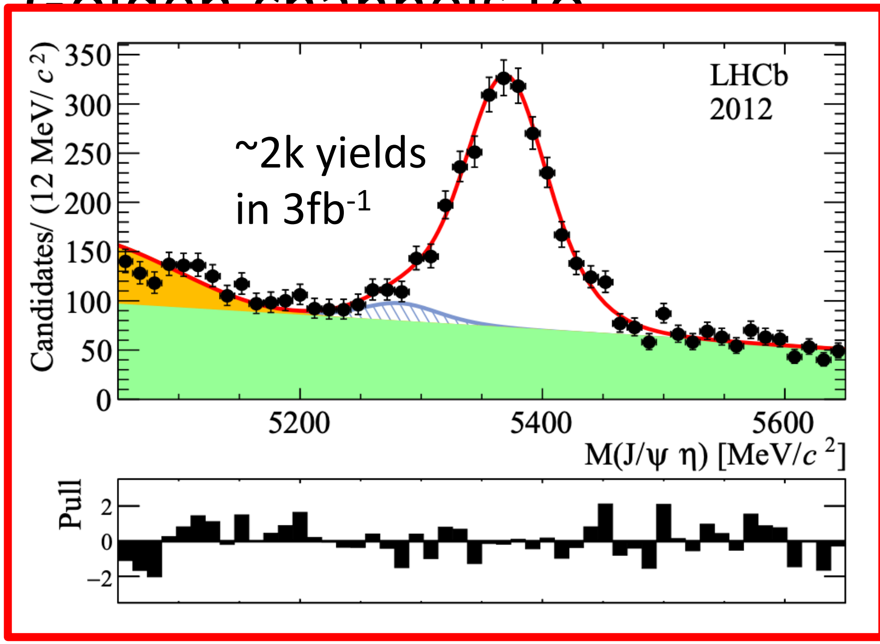


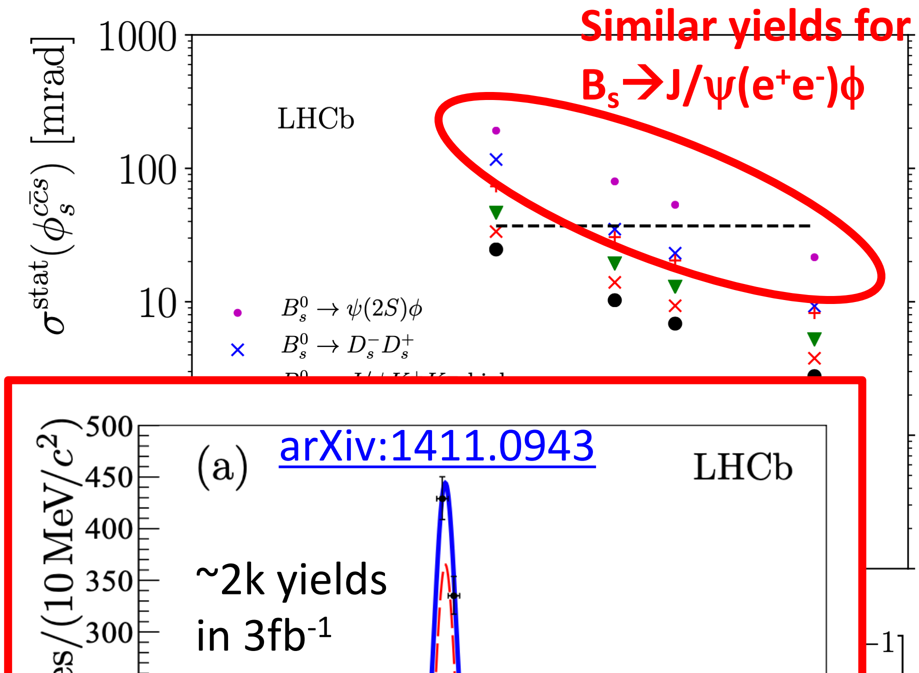
- Golden channels to measure β and β_s are $B_s \to J/\psi(\mu^+\mu^-)K^+K^-$ and $B^0 \to J/\psi(\mu^+\mu^-)K_S$
  - Companion channels with $J/\psi \to e^+e^-$ have a factor 5-10 less than $J/\psi \to \mu^+\mu^-$ channels
    - L0Trigger inefficiency will go away in the future
    - Impact of Bremsstrahlung on mass resolution, decay-time resolution, decay time acceptance
  - Other channels are $B_{(s)} \to J/\psi\{\pi^0,\eta,\eta',\omega\}$ → efficiency is really an issue
    - Some mode useful to constraint penguin pollution

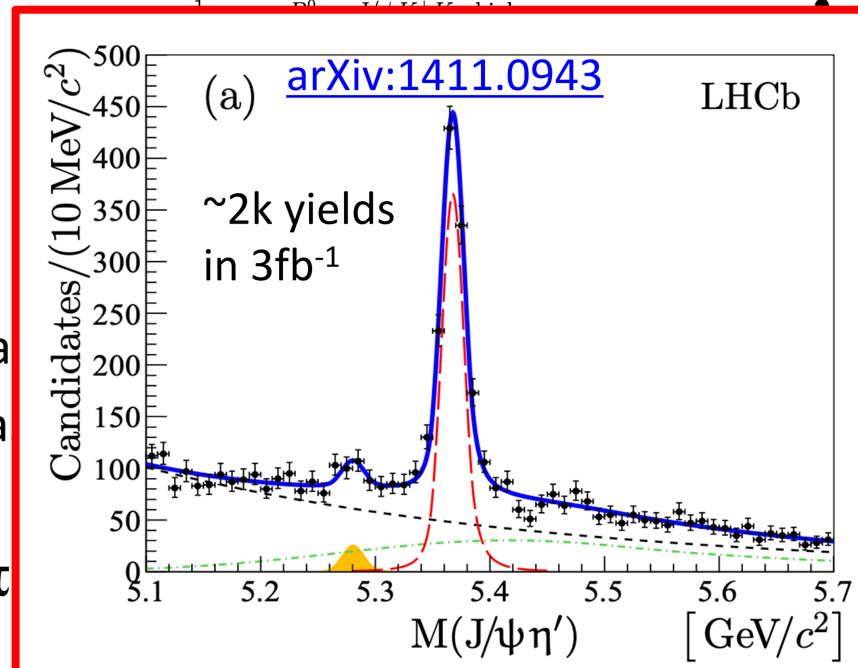
Time dependent CPV with B decays

- Golden channels to

arXiv:1607.06314







a

  - Impact of Bremsstrahlung on ma
    decay time acceptance

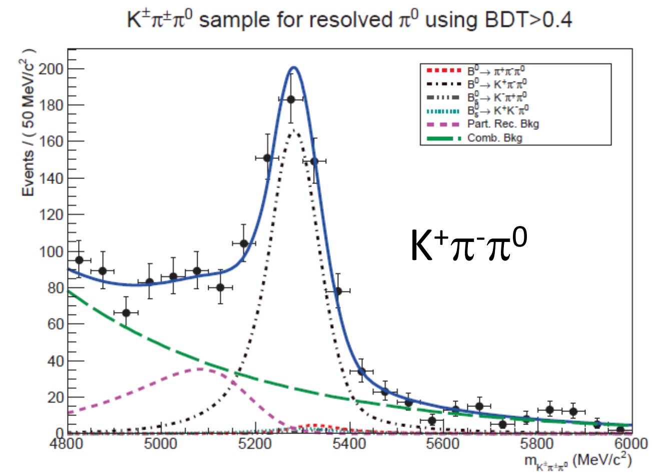
– Other channels are $B_{(s)} \to J/\psi\{\pi$
issue

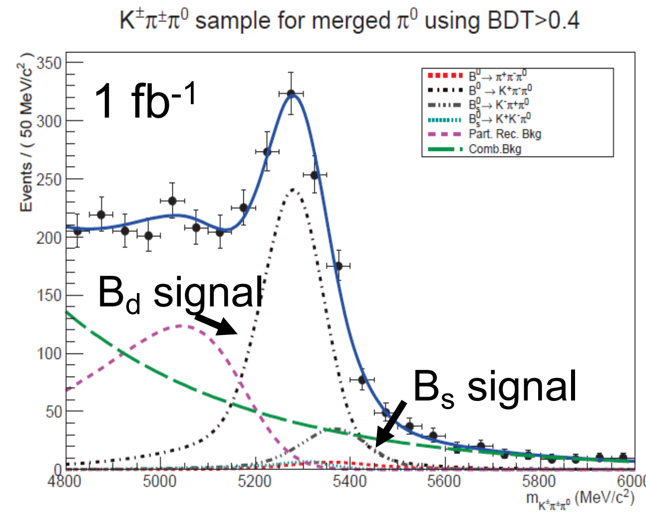
  - Some mode useful to constraint penguin pollution

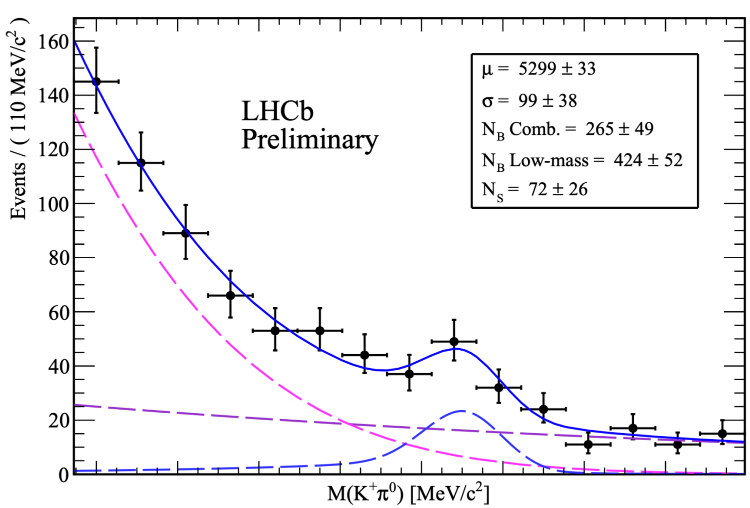
Charmless decays

[Diego Romero, CERN-THESIS-2013-051]

- Golden channels for the determination of CKM angel α
  - $B^0 \rightarrow \pi^0\pi^0$ ➔ Need decay vertex, use $\pi^0 \rightarrow \gamma e^+e^-$
  - $B^+ \rightarrow \pi^+\pi^0$ ➔ already investigated with $B^+ \rightarrow K^+\pi^0$ but limited by BF of normalisation channel
  - $B^0 \rightarrow \rho^+\rho^-$ ➔ two π^0 in the final state
  - $B^0 \rightarrow \pi^+\pi^-\pi^0$ ➔ enough to determine α alone, but require tagged time-dependent analysis
- Reminder: α determination is affected by a 1° theoretical uncertainty → Belle-II can achieve it
- B_s modes are unique to LHCb

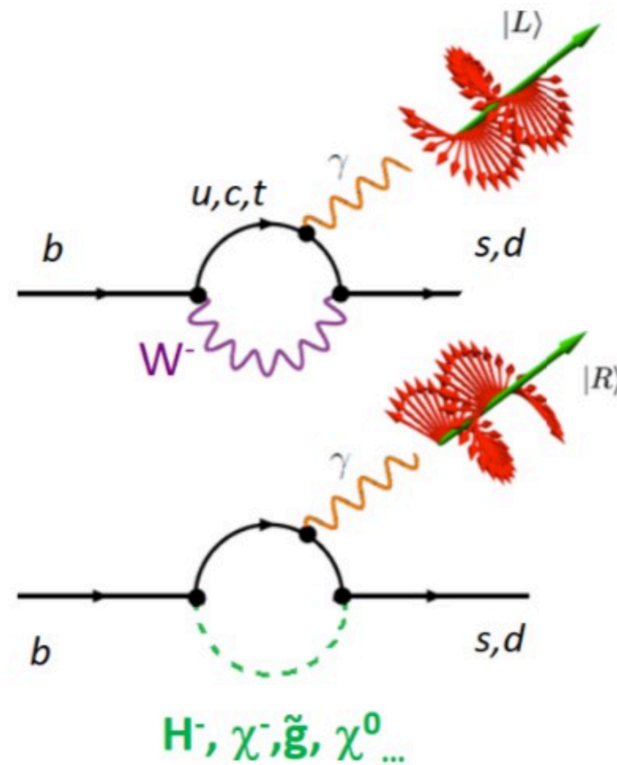






Radiative penguins

- Radiative b→sγ transitions are FCNC
  - Sensitive to NP
  - Several interesting observables
    - Branching fractions: $|C_7|^2 + |C_7'|^2$
    - Photon polarisation: C_7'
    - CP asymmetries: $Im(C_7)$

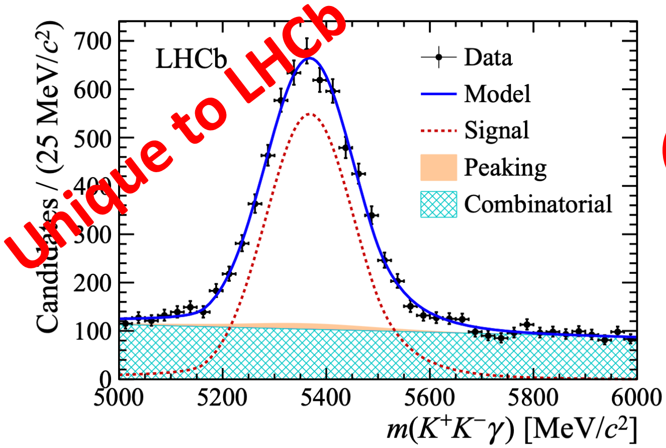


Wilson Coefficient

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big[\underbrace{\mathcal{C}_i(\mu)\, \mathcal{O}_i(\mu)}_{\text{left-handed part}} + \underbrace{\mathcal{C}_i'(\mu)\, \mathcal{O}_i'(\mu)}_{\text{right-handed part suppressed in SM}} \Big]$$

Radiative penguins

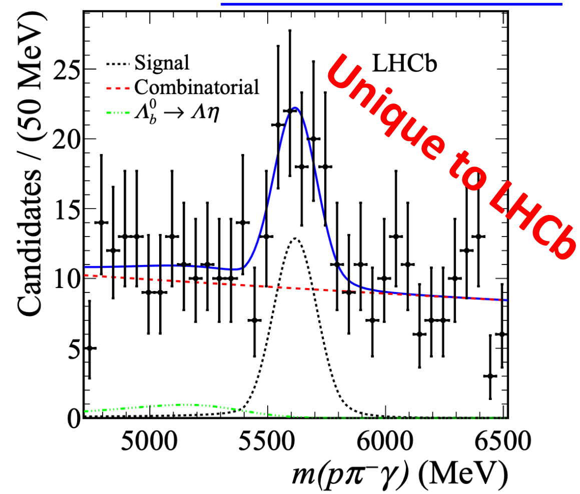
arXiv:1905.06284



Time-dependent CPV with $B_s \to \phi\gamma$

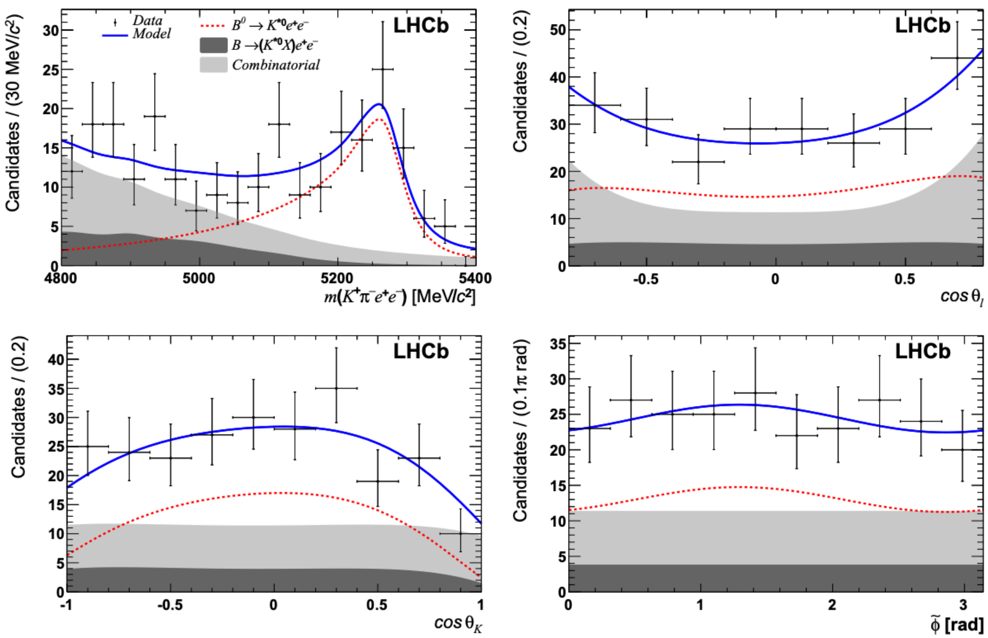
$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11,$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11,$$
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41} \pm 0.17$$

arXiv:1904.06697



$$\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma) = (7.1 \pm 1.5) \times 10^{-6}$$

arXiv:1501.03038



Angular analysis $B^0 \to K^* e^+e^-$ for $q^2 \to 0$ gives information on γ polarisation

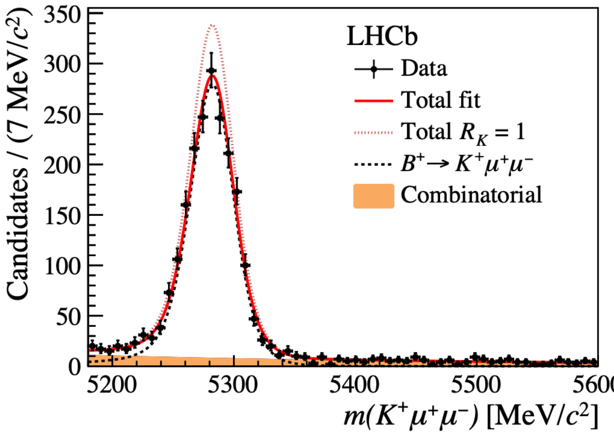
$$F_L = 0.16 \pm 0.06 \pm 0.03$$
$$A_T^{(2)} = -0.23 \pm 0.23 \pm 0.05$$
$$A_T^{Im} = +0.14 \pm 0.22 \pm 0.05$$
$$A_T^{Re} = +0.10 \pm 0.18 \pm 0.05,$$

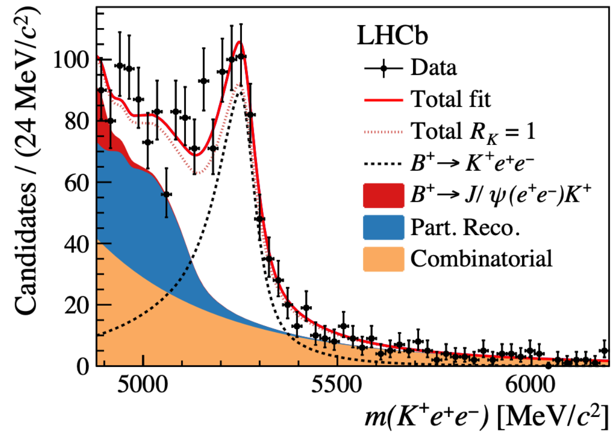
$$A_T^{Im}(q^2 \to 0) \simeq 2\frac{\mathcal{I}m(C_7'^*)}{|C_7|} \qquad A_T^{(2)}(q^2 \to 0) \simeq 2\frac{\mathcal{R}e(C_7'^*)}{|C_7|}$$

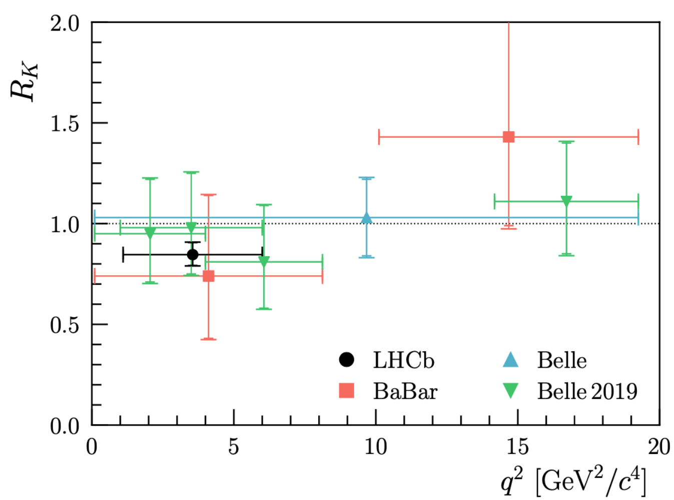
FCNC in b→sl$^+$l$^-$

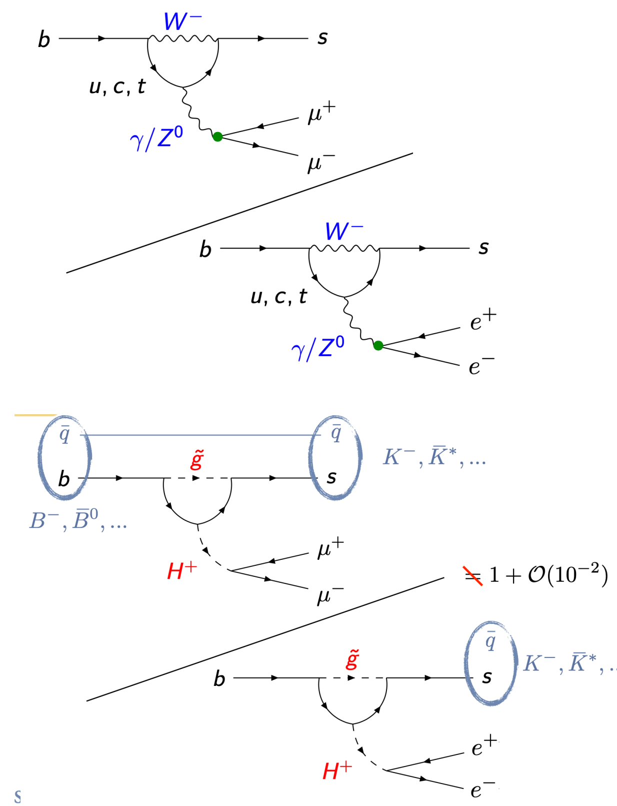
arXiv:1903.09252

$\mathcal{L}$ = 5 fb^{-1}







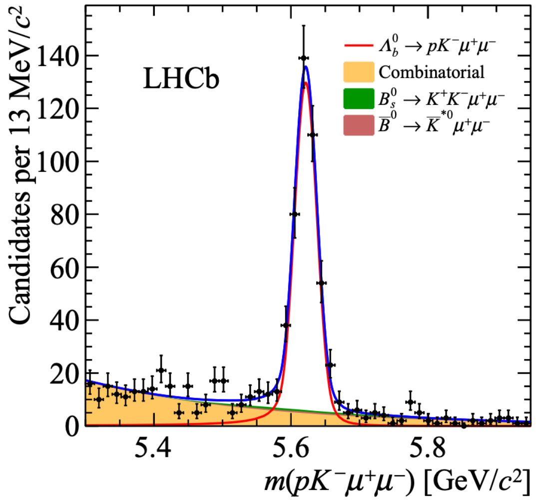


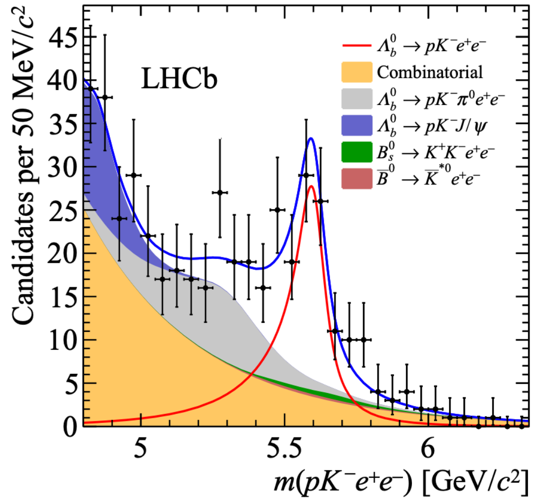
$$\mathcal{R}_K = 0.846^{+0.060}_{-0.054}{}^{+0.016}_{-0.014}$$

$\sim 2.5\,\sigma$ from SM

FCNC in b→sl⁺l⁻

arXiv:1912.08139





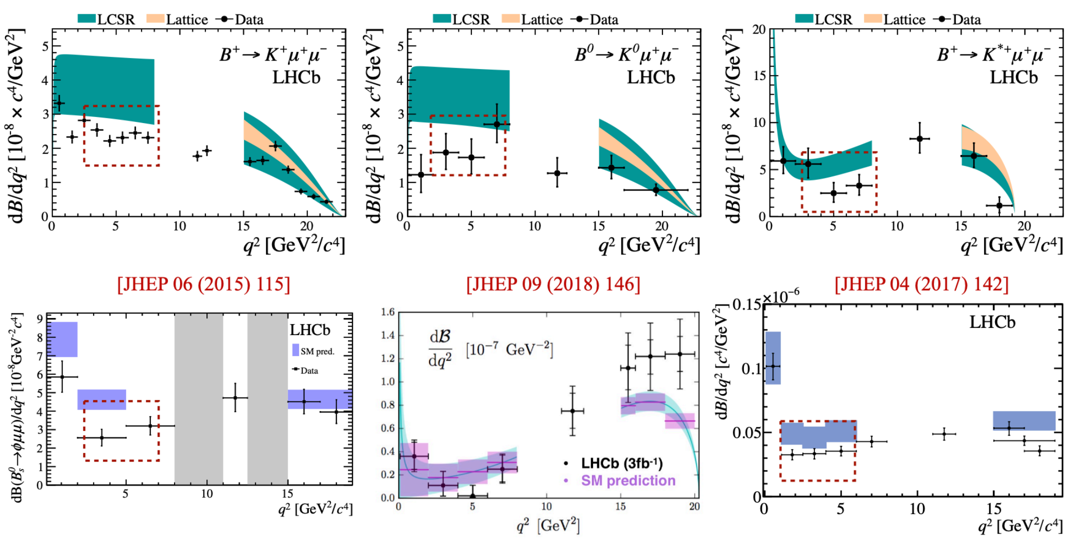
$$R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

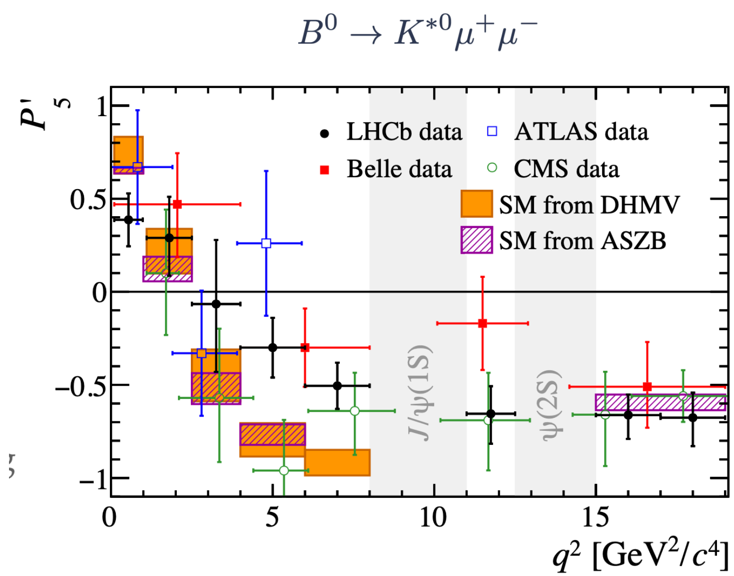
$0.1 < q^2 < 6$ GeV^2/c^4

Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to K^+e^+e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0}e^+e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B_s^0 \to \phi e^+e^-$	–	80	230	530	3 300
$\Lambda_b^0 \to pKe^+e^-$	–	120	360	820	5 000
$B^+ \to \pi^+e^+e^-$	–	20	70	150	900
R_X precision	**Run 1 result**	**9 fb^{-1}**	**23 fb^{-1}**	**50 fb^{-1}**	**300 fb^{-1}**
R_K	0.745 ± 0.090 ± 0.036 [274]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	0.69 ± 0.11 ± 0.05 [275]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

FCNC in b→sl$^+$l$^-$

- Not only R(X) are sensible quantities
  - To really understand the picture, it is important to combine more measurements
  - Several hints of discrepancies with theory coming from b→s$\mu^+\mu^-$ analyses
  - Larger statistics fundamental to repeat the analyses with the b→se$^+$e$^-$
  - Angular analyses, differential BF, effective lifetime, CP asymmetries



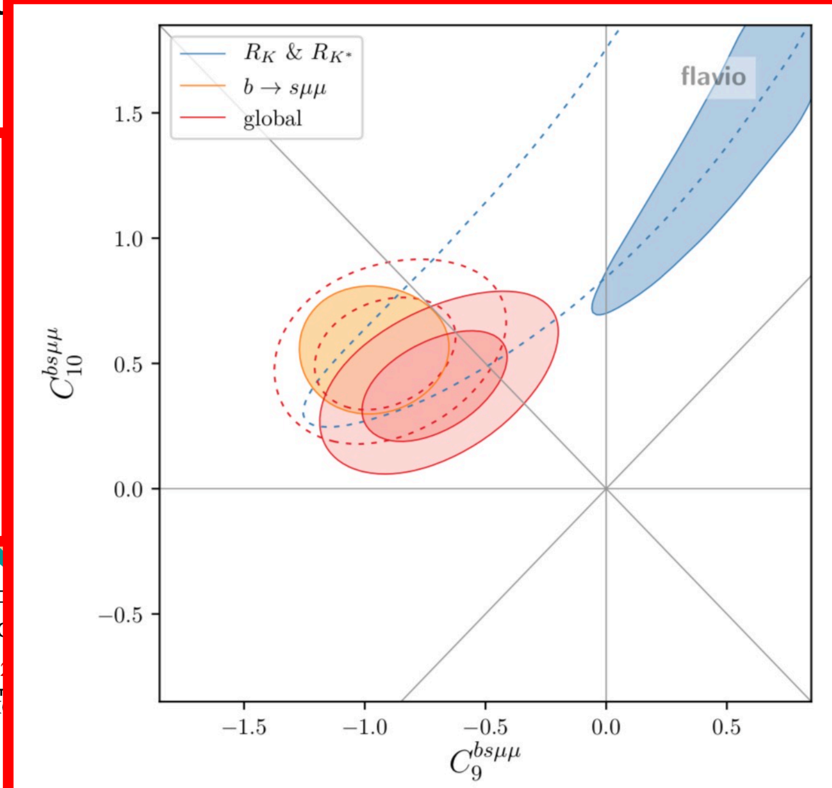


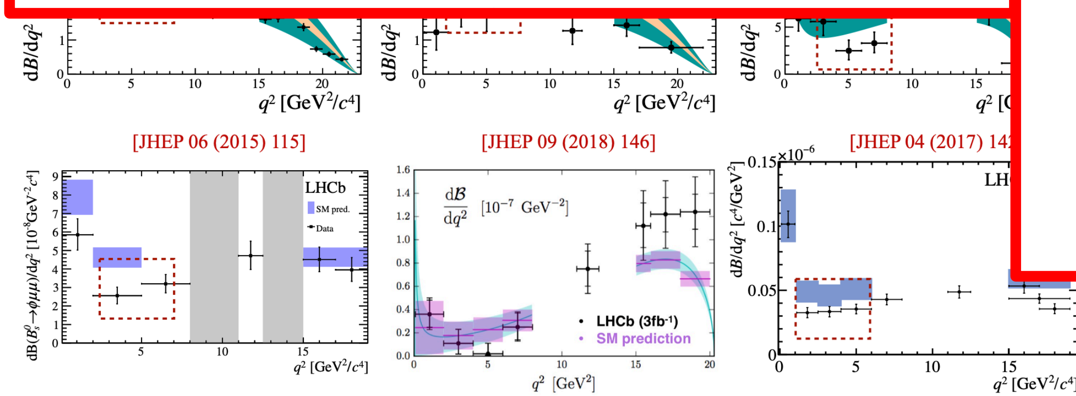
FCNC in b→sl⁺l⁻

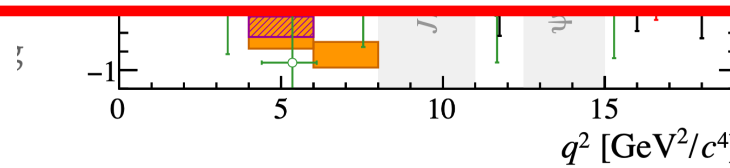
- Not only R(X) are sensible quantities
  - To really understand the the picture, it is important to combine more measurements

[J. Aebischer *et al*, arXiv:1903.10434]

Coeff.	Dirac structure	best fit	1σ	pull
$C_9^{bs\mu\mu}$	$L \otimes V$	-0.95	$[-1.10, -0.79]$	5.8σ
$C_9^{\prime bs\mu\mu}$	$R \otimes V$	$+0.09$	$[-0.07, +0.24]$	0.5σ
$C_{10}^{bs\mu\mu}$	$L \otimes A$	$+0.73$	$[+0.59, +0.87]$	5.6σ
$C_{10}^{\prime bs\mu\mu}$	$R \otimes A$	-0.19	$[-0.30, -0.07]$	1.6σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$L \otimes R$	$+0.20$	$[+0.05, +0.35]$	1.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$L \otimes L$	-0.53	$[-0.62, -0.45]$	6.5σ



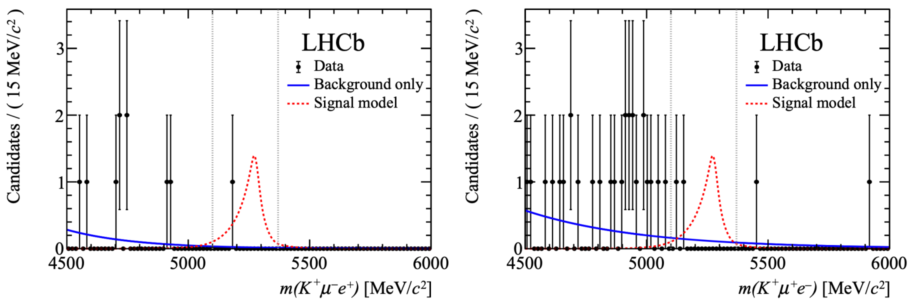




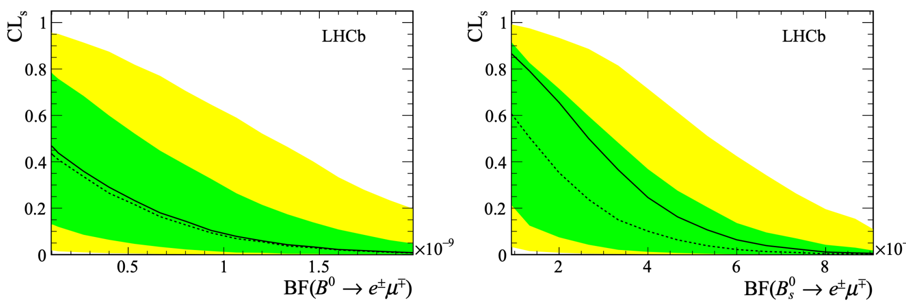
More on LFV and very rare decays

- Searches for forbidden decays is a powerful and complementary tool to R(X) analyses

arXiv:1909.01010 B→Keμ

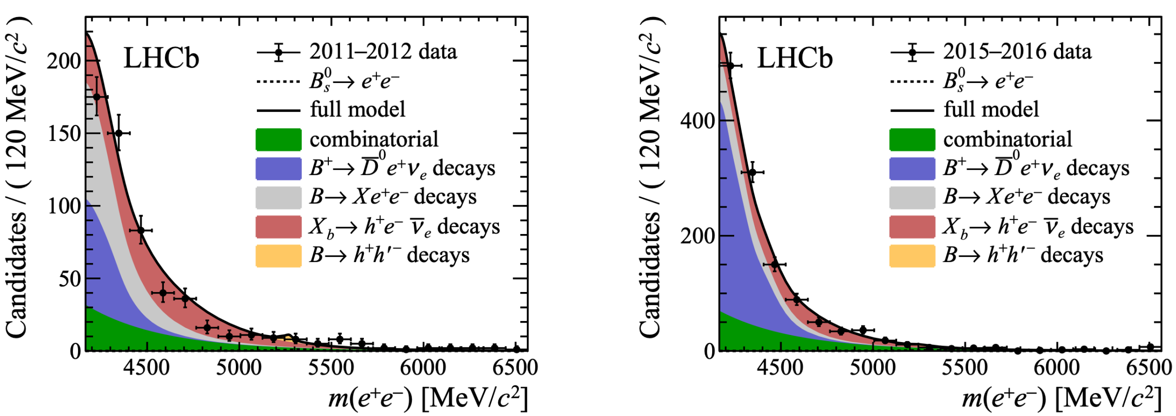


arXiv:1710.04111 $B_{(s)}$→eμ



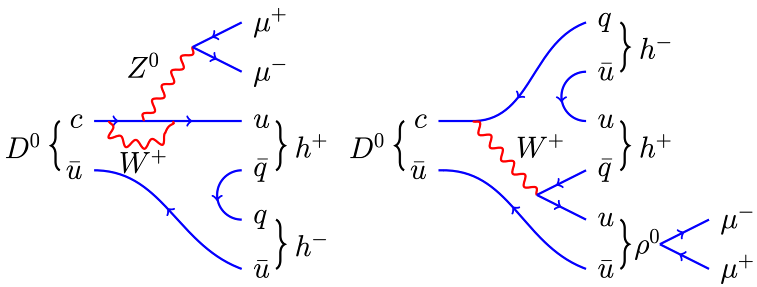
- But also search for allowed but very rare decays

arXiv:2003.03999 B→e^+e^-

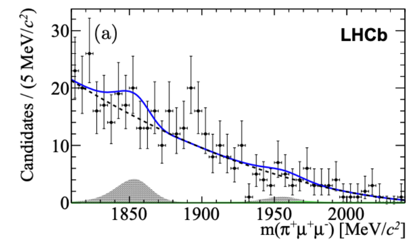


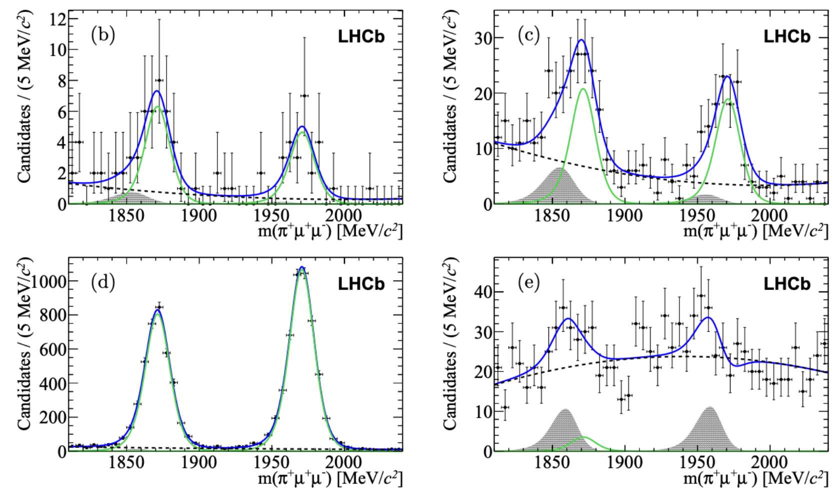
What about charm

- Already investigated the decays with muons and will be natural to follow-up with electrons

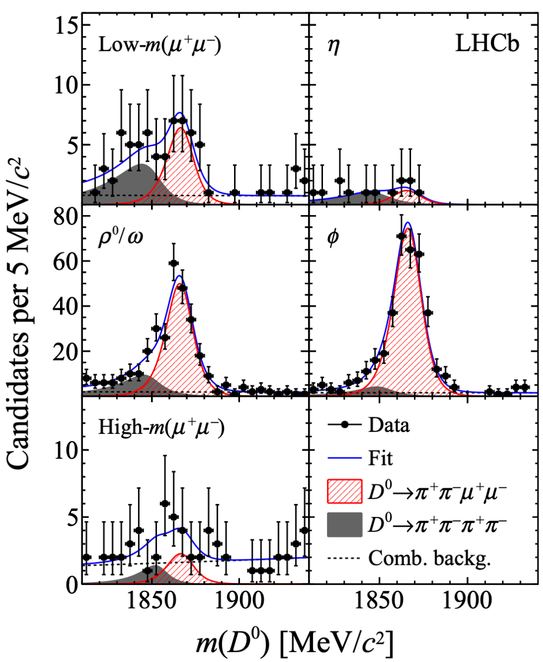


arXiv:1304.6365



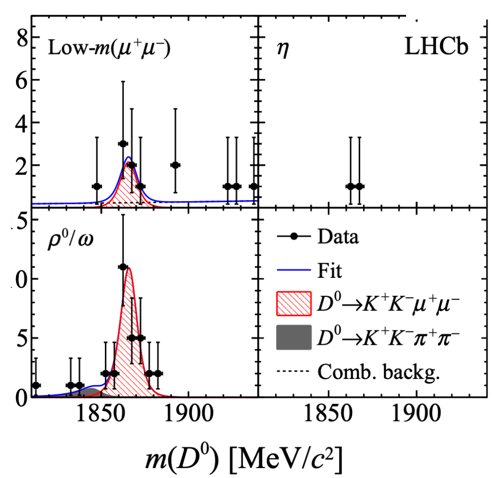


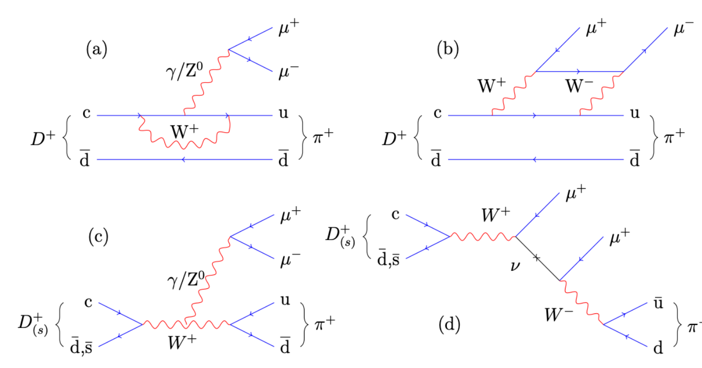
$\pi^+\pi^-\mu^+\mu^-$



arXiv1707.08377

$K^+K^-\mu^+\mu^-$

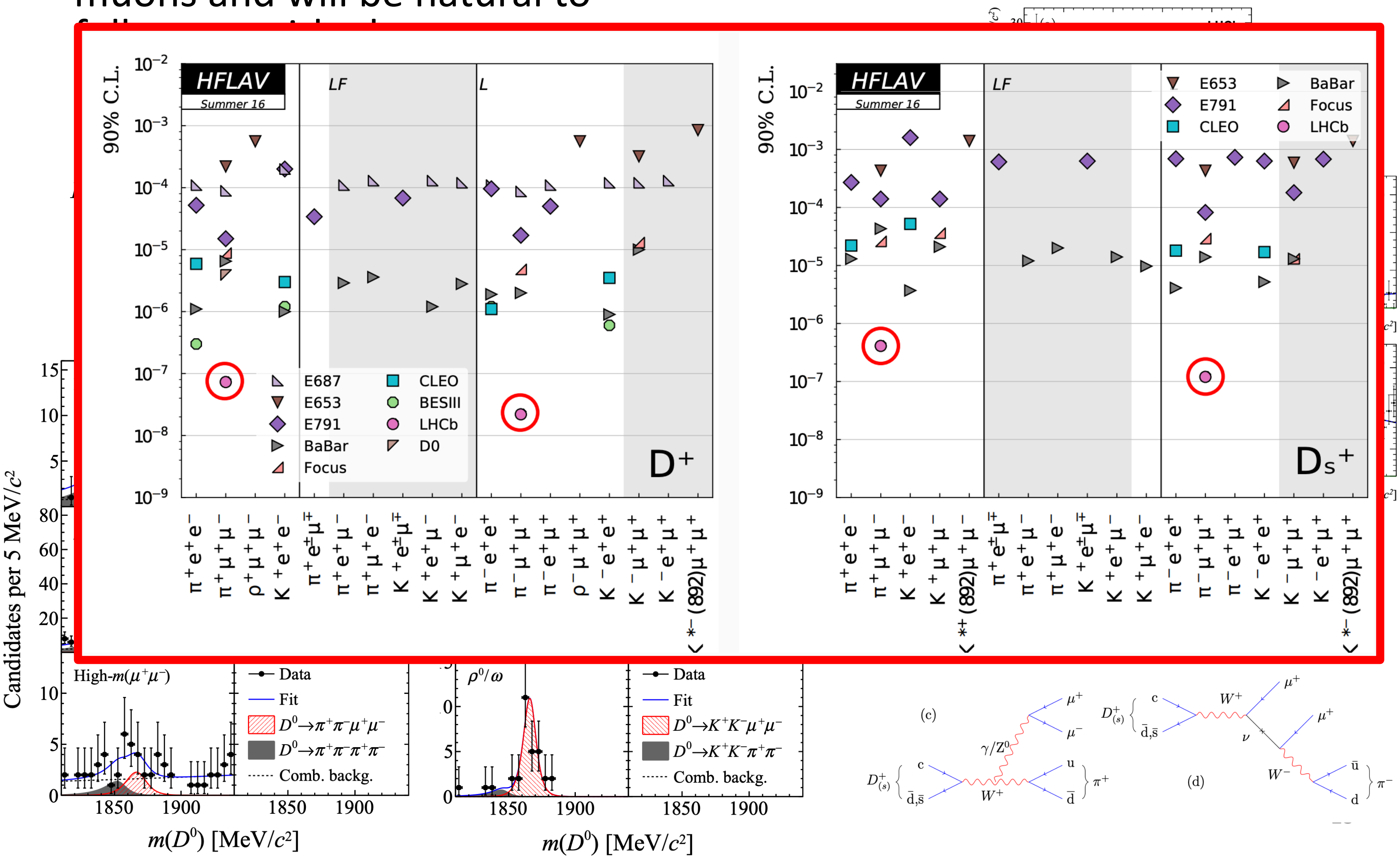




What about charm

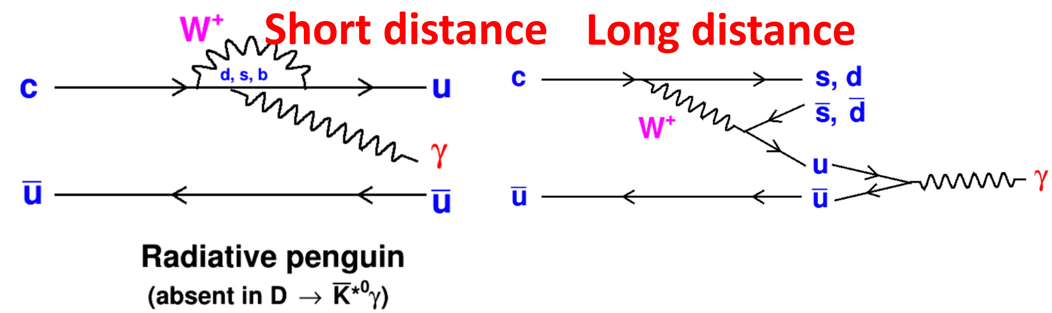
- Already investigated the decays with muons and will be natural to

[arXiv:1304.6365](https://arxiv.org/abs/1304.6365)



Charm decays with neutrals

- Radiative decays $D \rightarrow \{K^{*0}, \rho^0, \phi\}\gamma$ receive contributions from short- and long-distance
  - BF and A_{CP} can be enhanced by NP in loops
  - Test for QCD calculation of long-distance

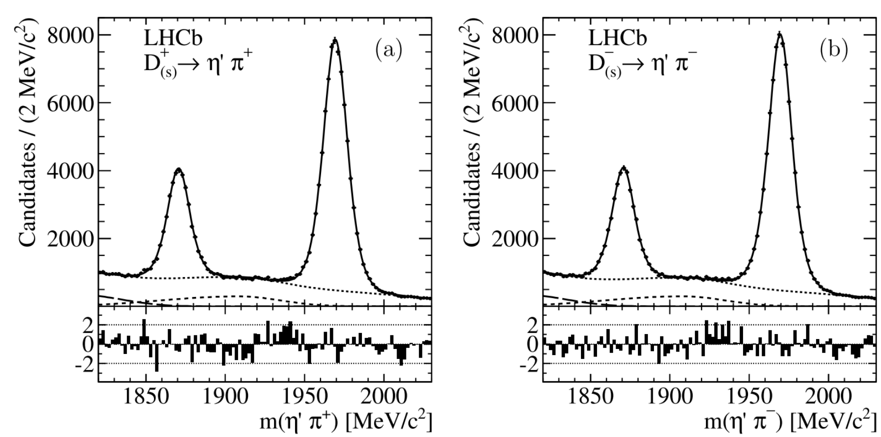


- Hadronic $D^0 \rightarrow h^+h^0$ decays

PRD85,034036

Decay	Mode	Experimental A_{CP} (%)	Theory A_{CP} (%)
$D^+ \to \pi^+\pi^0$	SCS	2.4 ± 1.2	0
$D^+ \to K^+\pi^0$	DCS	4 ± 11	
$D_s^+ \to \pi^+\pi^0$	-	-	-
$D_s^+ \to K^+\pi^0$	SCS	-27 ± 24	0.088
$D^+ \to \pi^+\eta$	SCS	1.0 ± 1.5	-0.065
$D^+ \to K^+\eta$	DCS	-	
$D_s^+ \to \pi^+\eta$	CF	1.1 ± 3.1	
$D_s^+ \to K^+\eta$	SCS	9 ± 15	-0.019

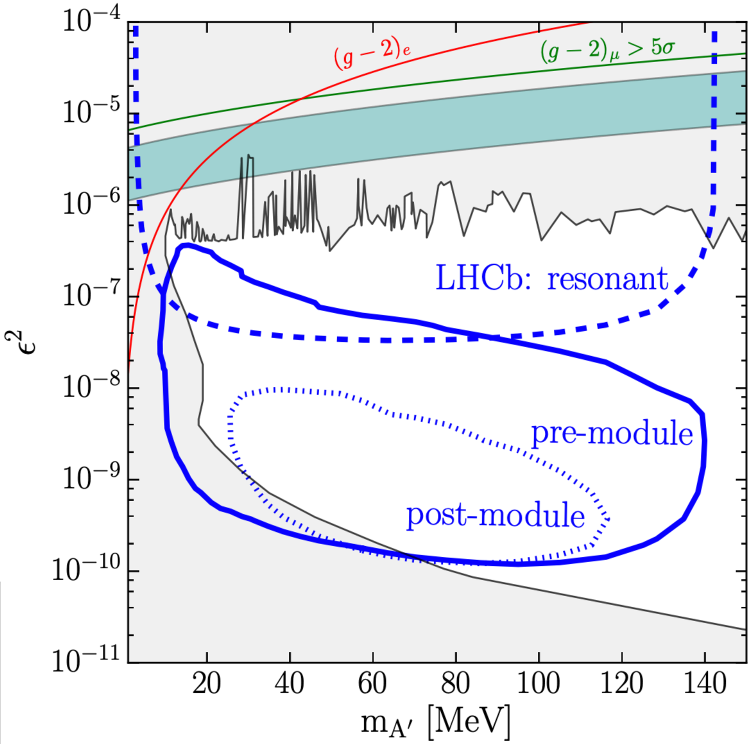
arXiv:1701.01871

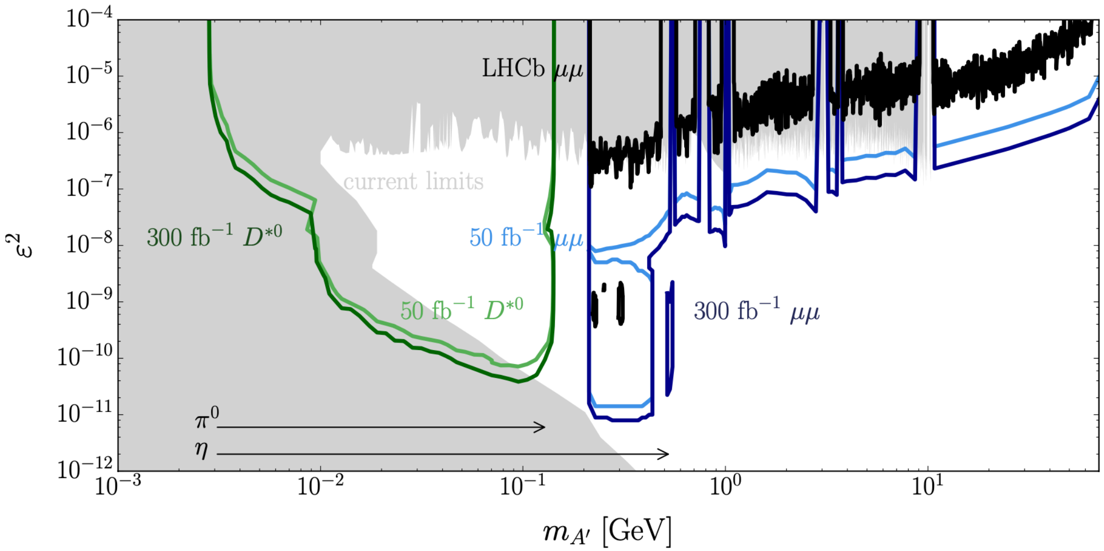


Dark photons below $2m_\mu$

- Possible to cover region below $2m_\mu$ using charm decays $D^{*0} \to D^0 A'(e^+e^-)$
  - About 300×10^9 $D^{*0} \to D^0\gamma$ per fb^{-1}
  - Can use $D(*)$ mass constraint to correct bremsstrahlung
  - Very low momentum: electrons emit light in RICH while pions don't
  - Both displaced and prompt searches

arXiv:1509.06765





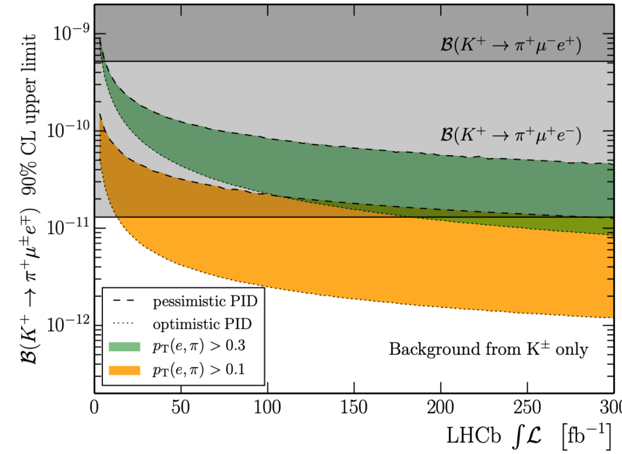
Physics with strange and ECAL

arXiv:1808.03477

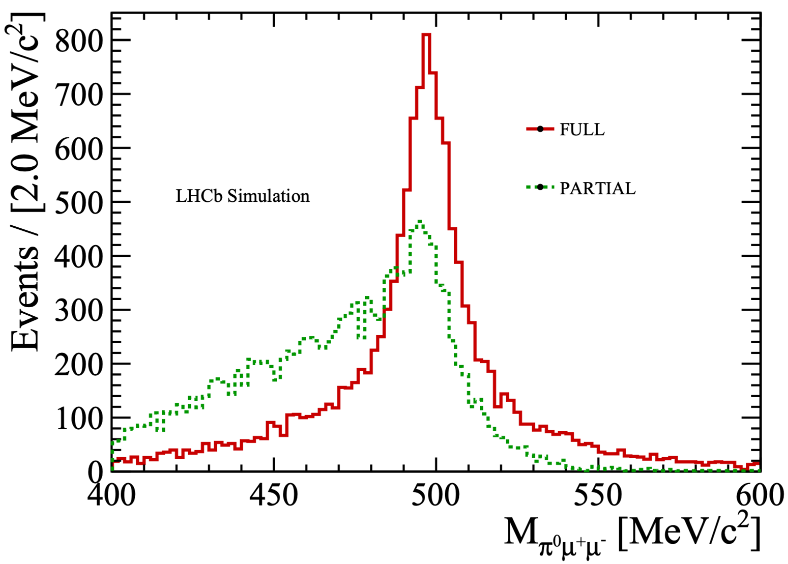
Channel	$\mathcal{R}$	ϵ_L	ϵ_D	σ_L(MeV/c^2)	σ_D(MeV/c^2)
$K^0_S \to \pi^+\pi^-e^+e^-$	1	1.0 (0.18)	2.83 (1.1)	~ 2.0	~ 10
$K^0_S \to \mu^+\mu^-e^+e^-$	1	1.18 (0.48)	2.93 (1.4)	~ 2.0	~ 11
$K^+ \to \pi^+e^+e^-$	~ 2	0.04 (0.01)	0.17 (0.06)	~ 3.0	~ 13
$\Sigma^+ \to pe^+e^-$	~ 0.13	1.76 (0.56)	3.2 (1.3)	~ 3.5	~ 11
$\Lambda \to p\pi^-e^+e^-$	~ 0.45	$< 2.2 \times 10^{-4}$	~ 17 (< 2.2) $\times 10^{-4}$	–	–

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	σ_L(MeV/c^2)	σ_D(MeV/c^2)
$K^0_S \to \mu^+e^-$	1	1.0 (0.84)	1.5 (1.3)	~ 3.0	~ 8.0
$K^0_L \to \mu^+e^-$	1	3.1 (2.6) $\times 10^{-3}$	13 (11) $\times 10^{-3}$	~ 3.0	~ 7.0
$K^+ \to \pi^+\mu^+e^-$	~ 2	3.1 (1.1) $\times 10^{-3}$	16 (8.5) $\times 10^{-3}$	~ 2.0	~ 8.0

arXiv:1812.07638



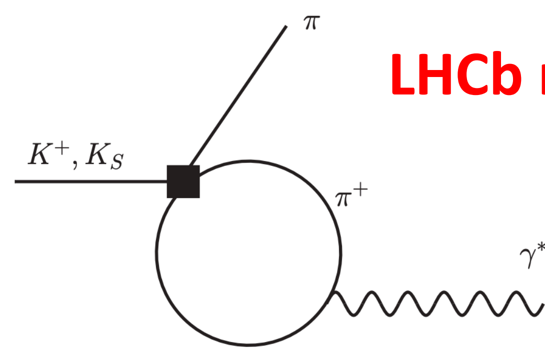
LHCb-PUB-2016-017



arXiv:hep-ex/0409011 (NA48)

$$\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-) = (2.9^{+1.5}_{-1.2}(\text{stat}) \pm 0.2(\text{syst})) \times 10^{-9}.$$

LHCb reach is ~ 10^{-10}

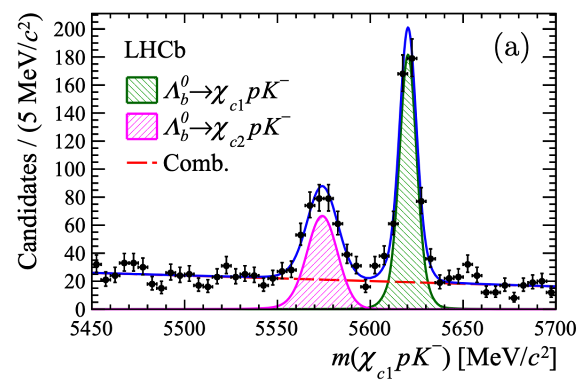


s→d transition for $K_S \to \pi^0\mu^+\mu^-$

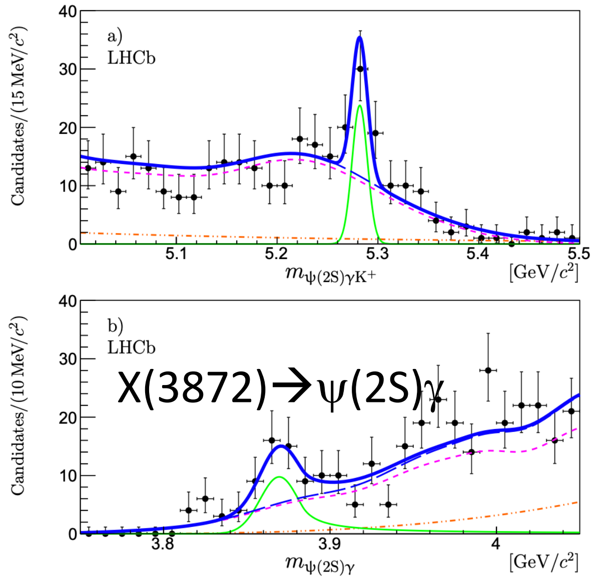
Spectroscopy and production

- A lot of spectroscopy and production measurements to do with photons and π^0
  - Radiative decays are a gold mine to study energy levels of excited states and compare their BF, aiming to understand quantum numbers
  - Study decays of exotics to final states with photons
  - Measure production cross-sections of heavy states, e.g. $\chi_b \rightarrow \Upsilon\gamma$
  - Very difficult since soft photons → viable to use γ-conversion or Dalitz decays

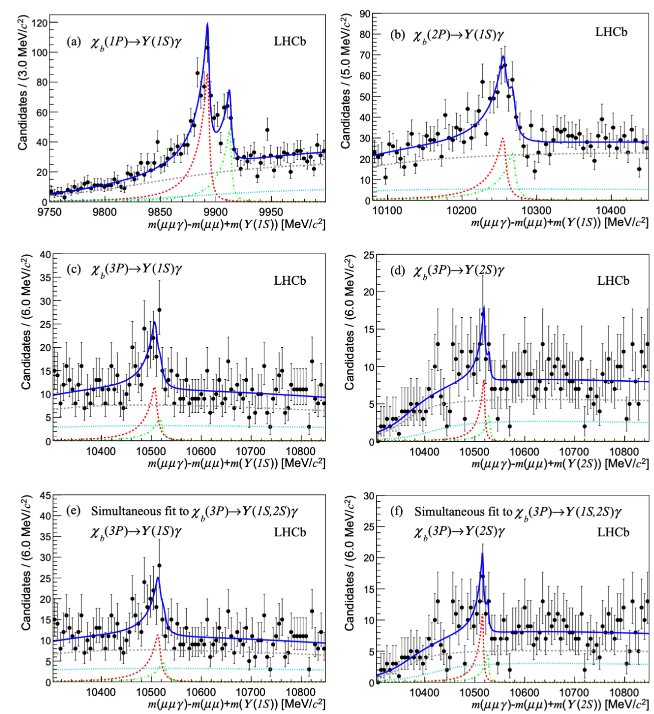
arXiv:1704.07900 $\chi_c \rightarrow J/\psi\gamma$



arXiv:1404.0275



arXiv:1409.1408 $\chi_b \rightarrow \Upsilon\gamma$



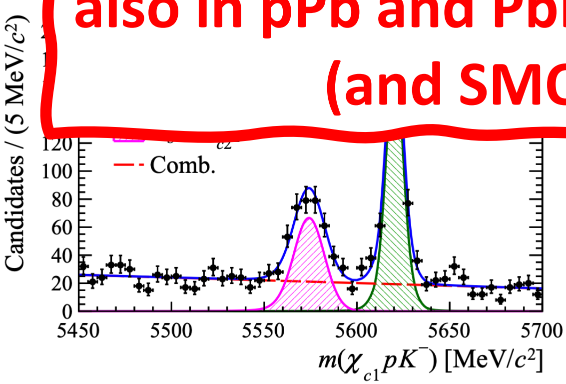
Spectroscopy and production

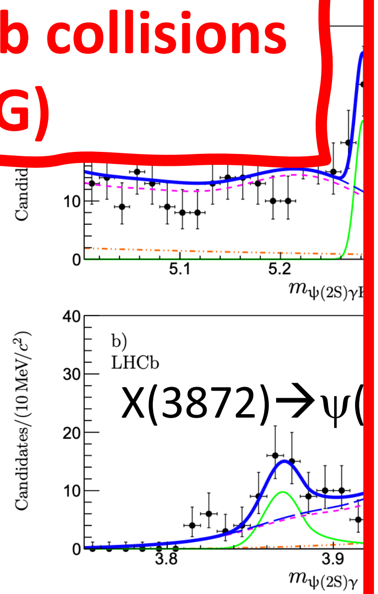
- A lot of spectroscopy and production measurements [arXiv:1812.07638] s and π^0
  - Radiative decays are a gold mine to study e... e their BF, aiming to understand quantum nu...
  - Study decays of exotics to final states with ...

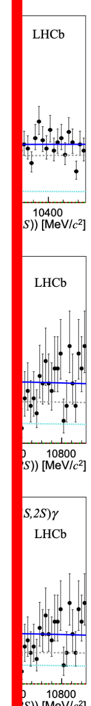
States/structures	Channels	Observables	Further comments
$D_{s0}^*(2317)$	$D_s\pi^0$, $D_s^*\gamma$	Width upper limit; branching fractions	π^0 is difficult
$D_{s1}^*(2460)$	$D_s^{*+}\pi^0$, $D_s^+\pi^+\pi^-$, $D_s^{(*)+}\gamma(\to\mu^+\mu^-)$	see above	May use the Dalitz decay to probe photons
Broad D_0^*, D_1 structures	$\bar{B}\to D^{(*)}\pi^-\pi^-$, $D_s^{(*)}\bar{K}\pi$, $D_s^{(*)}\bar{K}K$, $\bar{B}_s\to D^{(*)}\bar{K}\pi$	$D^{(*)}\pi$ angular moments; $D_s^{(*)}\bar{K}$ invariant mass distribution	$\langle P_1\rangle - \frac{14}{9}\langle P_3\rangle$ is particularly sensitive to the $D^{(*)}\pi$ S-wave; possible enhancement above $D_s\bar{K}$ threshold
B_{s0}^* (?)	$B_s\pi^0$, $B_s^*\gamma$		$M\sim 5.72$ GeV; not seen yet
B_{s1} (?)	$B_s^*\pi^0$, $B_s\pi^+\pi^-$, $B_s^{(*)}\gamma$		$M\sim 5.77$ GeV, lower than $B_{s1}(5810)$; not seen yet
Excited single-heavy baryons			A whole SU(3) family; determination of spin and parity
$X(3872)$	$D^0\bar{D}^0\pi^0$, $D\bar{D}\gamma$, $J/\psi\pi^+\pi^-$, $J/\psi 3\pi$, $J/\psi\gamma$, $\psi'\gamma$	Line shapes; decay width; production rates	
X_2 (?)	$D\bar{D}$, $D\bar{D}^*$ + c.c., $J/\psi\omega$		$J^{PC}=2^{++}$, $M\sim 4$ GeV, $\Gamma\lesssim 50$ MeV; existence unknown
$\chi_{c1}(2P)$ (?)	$D\bar{D}^*$ + c.c., $J/\psi\omega$		$M\sim 3.9$ GeV, broad; existence unknown
$h_c(2P)$ (?)	$D\bar{D}^*$ + c.c., $J/\psi\eta$, $\eta_c\omega$		$M\sim 3.9$ GeV, broad; not seen yet
X_b (?)	$\Upsilon\omega$, $\chi_{bJ}\pi^+\pi^-$, $B\bar{B}\gamma$, $\Upsilon\gamma$		Bottom analogue of $X(3872)$; existence unknown
X_{b2} (?)	$B\bar{B}$, $\Upsilon\omega$		Bottom analogue of X_2; existence unknown
Z_c structures	$(c\bar{c})\pi^\pm$, $(D^{(*)}\bar{D}^{(*)})^\pm$	Line shapes; production rates; Argand plots	Sensitivity to kinematics
Z_{cs} (?)	$(c\bar{c})K$, $D_s^{(*)}\bar{D}^{(*)}$		Existence unknown
Z_b structures	$(b\bar{b})\pi^\pm$, $(B^{(*)}\bar{B}^{(*)})^\pm$	Line shapes	Not seen at LHC yet
W_{bJ} (?)	$\Upsilon\pi^+\pi^-$, $\Upsilon\gamma$		$I^G(J^{PC})=1^-(J^{++})$, possible spin partners of Z_b states; existence unknown
P_c and relatives	$J/\psi p$, $\chi_{cJ}p$, $\Lambda_c\bar{D}^{(*)}$, $\Sigma_c\bar{D}^{(*)}$		Hidden-charm pentaquarks
Doubly-heavy baryons			Displaced B_c as an inclusive signature of weakly decaying double-beauty hadrons
$\bar{b}\bar{b}ud$ (?); $\bar{b}\bar{b}qs$ ($q=u,d$) (?)	$B^+\bar{D}^0$, $J/\psi B^+K^0$; $B\bar{D}_s$, $B_s\bar{D}$, $J/\psi B\phi$, $J/\psi B_sK$		Ground states likely stable against strong decays; not seen
$cc\bar{c}\bar{c}$ (?); $bb\bar{b}\bar{b}$ (?)	$H_Q\bar{H}_Q$+anything, $J/\psi(\Upsilon)\mu^+\mu^-$, $\mu^+\mu^-$, 4μ		Widths: tens of MeV if below double-$(Q\bar{Q})$ thresholds; H_Q denotes any heavy hadron; existence unknown

av... e t... arX... 02...

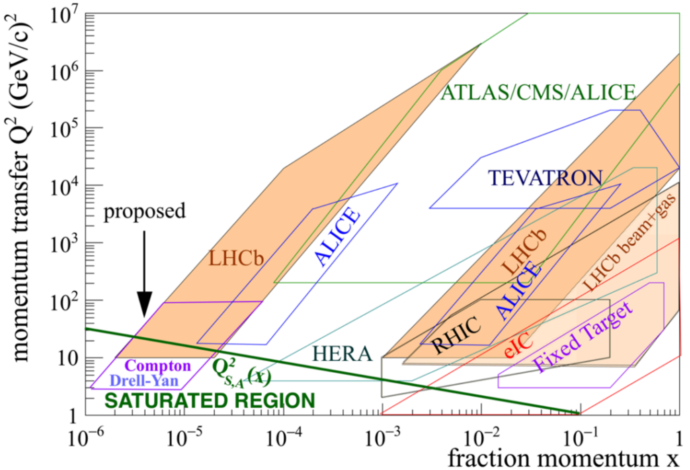
Considerations on production studies are very interesting also in pPb and PbPb collisions (and SMOG)

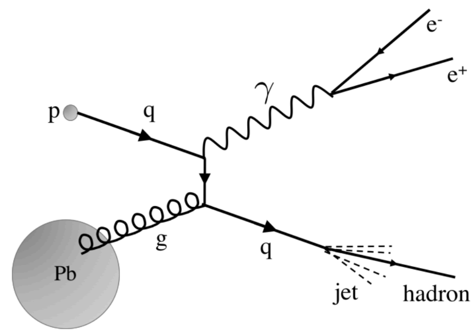


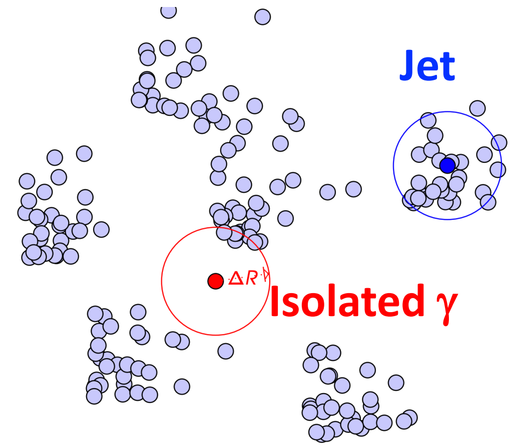




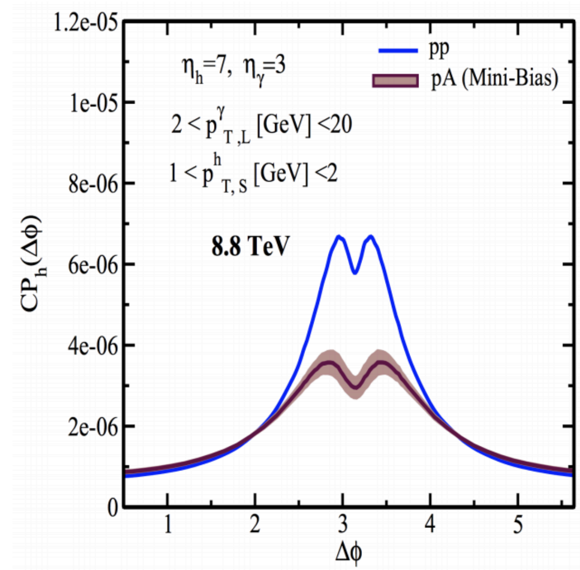
Photon-hadron correlation





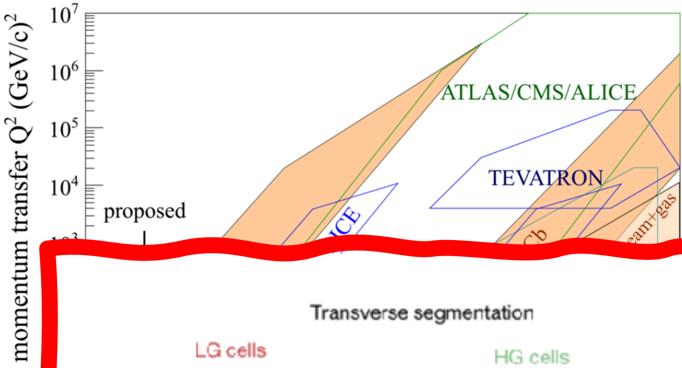


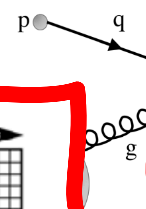
PRD 86, 094016, 2012

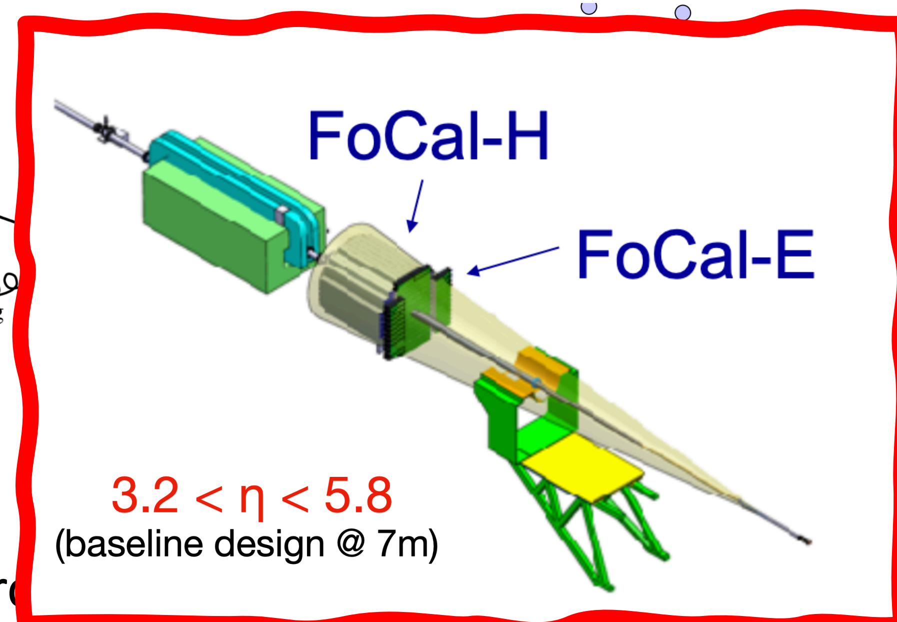


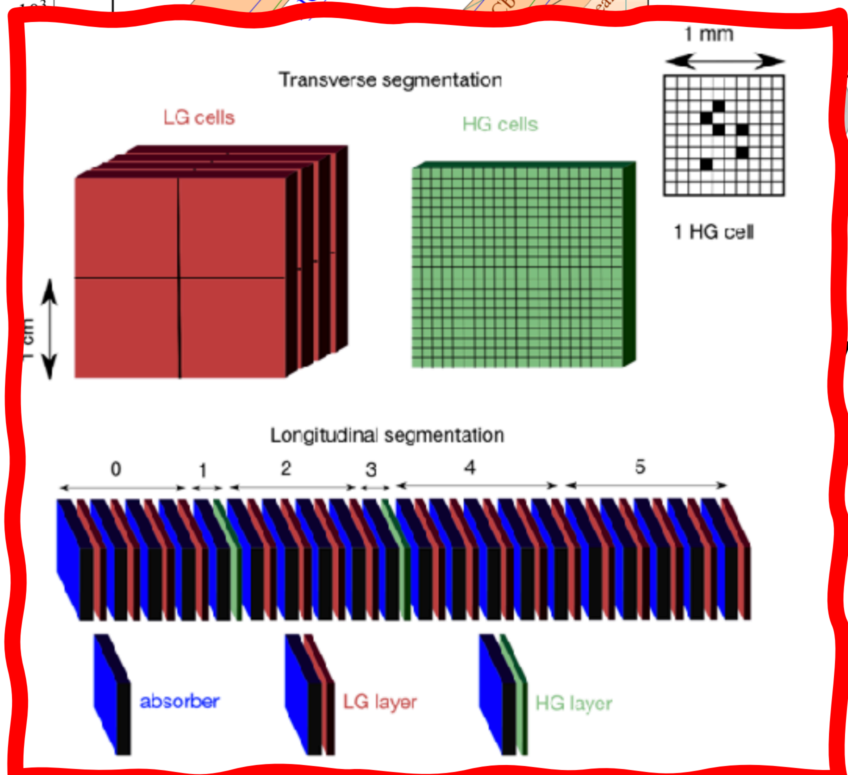
- Measure photons coming directly from gluons in a region where gluon distributions are expected to be saturated
  - direct photon production: clean probe of parton densities
  - LHCb acceptance is unique to access gluon saturation
- ALICE is proposing to build a W-Si ECAL with very high granularity for this (but not only) measurement → ALICE-PUBLIC-2019-005

Photon-hadron correlation

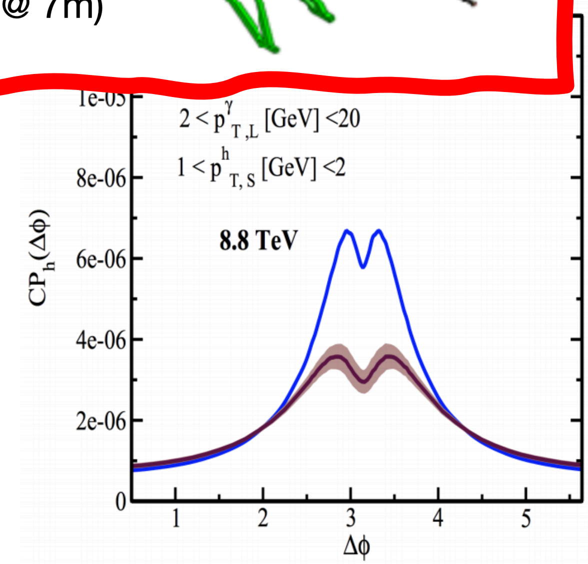








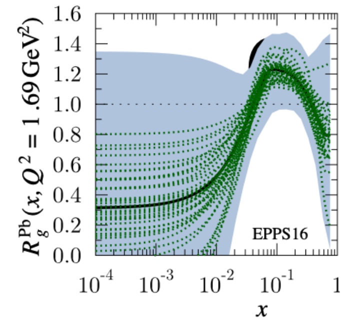
- … fr…
  …s are expected
  …probe of parton
  …cess gluon
- … ECAL with very high granularity for this (but not only) measurement → ALICE-PUBLIC-2019-005

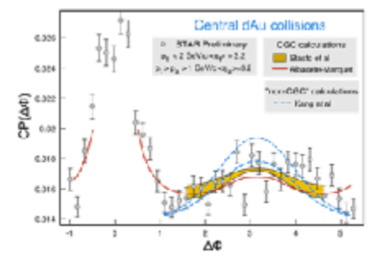


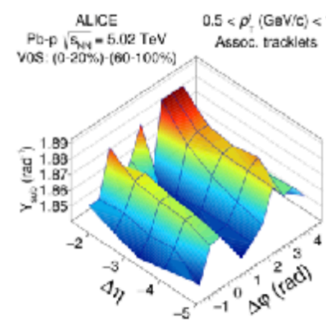
Photon-hadron correlation

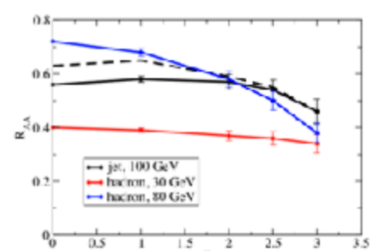
Physics goals

- Quantify nuclear modification of the gluon density at small-x
  - Isolated photons in pp and pPb collisions
- Explore non-linear QCD evolution
  - Azimuthal π^0-π^0 and isolated photon-π^0 (or jet) correlations in pp and pPb collisions
- Investigate the origin of long range flow-like correlations
  - Azimuthal π^0-h correlations using FoCal and central ALICE (and muon arm?) in pp and pPb collisions
- Explore jet quenching at forward rapidity
  - Measure high p_T neutral pion production in PbPb
- Other measurements need (more) study
  - Jets and dijets in pp/pPb and UPC
  - Quarkonia in UPC (and pp?)
  - Photon and pion HBT
  - W,Z in pp/pPb?
  - Measurements at 14 TeV
    - Universality at small-x
    - Saturation in pp
    - High-x (>0.1) gluon constraints?









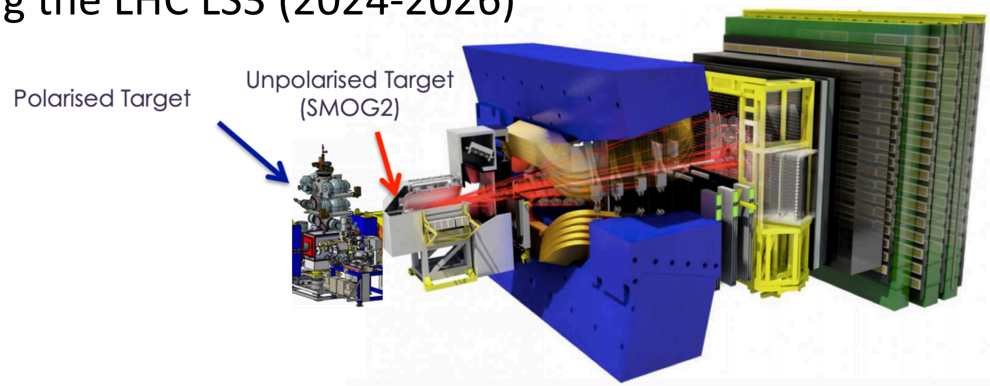
Constantin Loizides – LPC Workshop

Polarised SMOG

aiming to install during the LHC LS3 (2024-2026)

LHC spin

[arXiv:1901.08002]



F. Murgia – 2nd LHCb Heavy Ion Workshop

The LHCSpin physics case - 1

- Quark TMD distributions, in particular at medium-large light-cone momentum fraction
- Mainly Sivers function, transversity and tensor charge; Boer-Mulders function, Collins FF,...
- Polarized hydrogen and deuterium targets at $\sqrt{s}$ = 115 GeV

Two-particle production in the same hemisphere:

- $pp^{\uparrow} \to (h_1 h_2) + X$ - di-hadron fragmentation functions, collinear factorization
- $pp^{\uparrow} \to (h + jet) + X$ – azimuthal moments as in SIDIS, TMDs in fragmentation, Collins FF
- Polarized Drell-Yan process, change of sign of the Sivers function as compared to SIDIS

Two-particle production in the opposite hemisphere, with small transv. momentum imbalance:

$$pp^{\uparrow} \to h_1 + h_2 + X, \quad pp^{\uparrow} \to h + jet + X, \quad pp^{\uparrow} \to h + \gamma + X$$

TMD factorization could be violated; still useful and relevant to possibly assess the (unknown) relative size of factorization breaking terms in different kinematical regimes

The LHCSpin physics case - 2

- Quarkonium production as a tool for studying gluon TMDs
- Unpol. and linearly polarized gluon TMDs (first stage, SMOG2) [Talk by Cristian Pisano]
- Gluon Sivers function (needs transv. polarized target, 2nd stage)

- Quarkonium and isolated photons in opposite hemispheres (relative $p_T \ll M_Q$)

$$pp^{\uparrow} \to J/\psi + \gamma + X; \quad pp^{\uparrow} \to \psi' + \gamma + X; \quad pp^{\uparrow} \to \Upsilon + \gamma + X; \quad etc.$$

- Associated back-to-back quarkonium production

$$pp^{\uparrow} \to J/\psi + J/\psi + X; \quad pp^{\uparrow} \to J/\psi + \psi' + X; \quad pp^{\uparrow} \to \Upsilon + \Upsilon + X$$

- Single inclusive Quarkonium, D meson, pion and photon production
  Unpolarized and transversely polarized cases

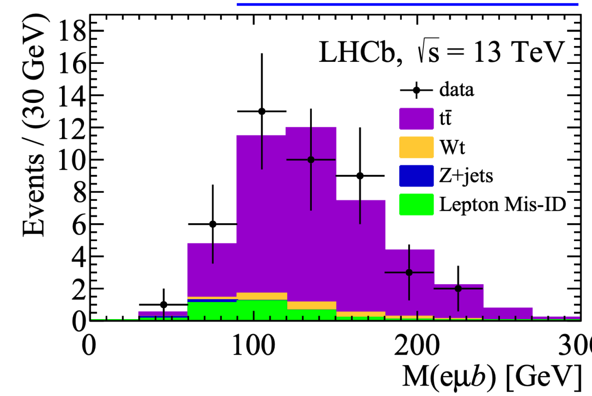
$$pp^{\uparrow} \to J/\psi, \Upsilon + X; \quad pp^{\uparrow} \to D + X; \quad pp^{\uparrow} \to \pi + X; \quad pp^{\uparrow} \to \gamma + X$$

Open points:
Factorization, universality, process dependence, evolution with scale, TMD + NRQCD,...

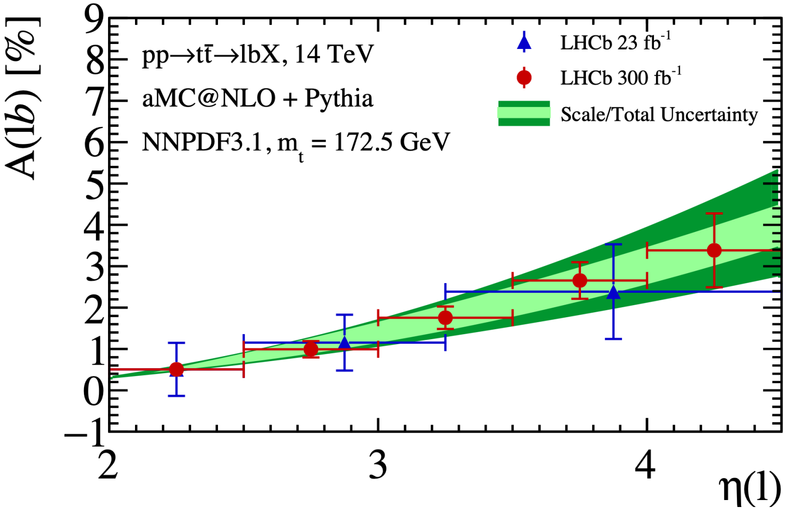
Forward and high-p_T physics

- LHCb is in a unique forward region at the LHC
  - Channels with electrons represent about 50% of potential statistics

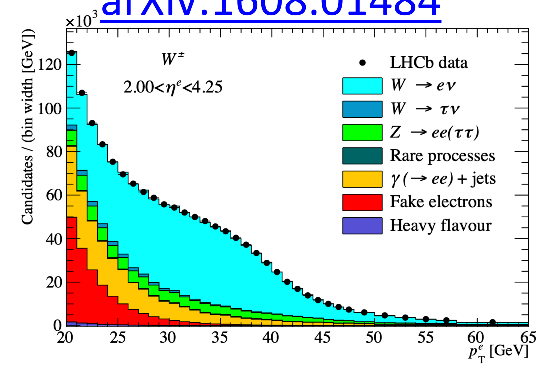
arXiv:1803.05188

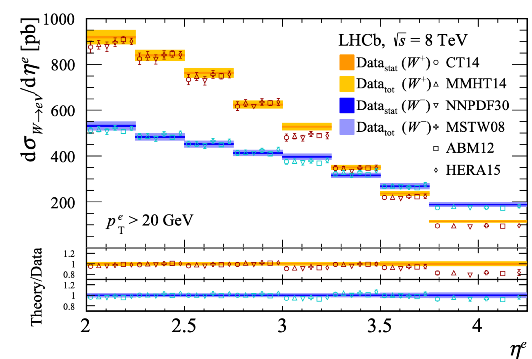


arXiv:1808.08865



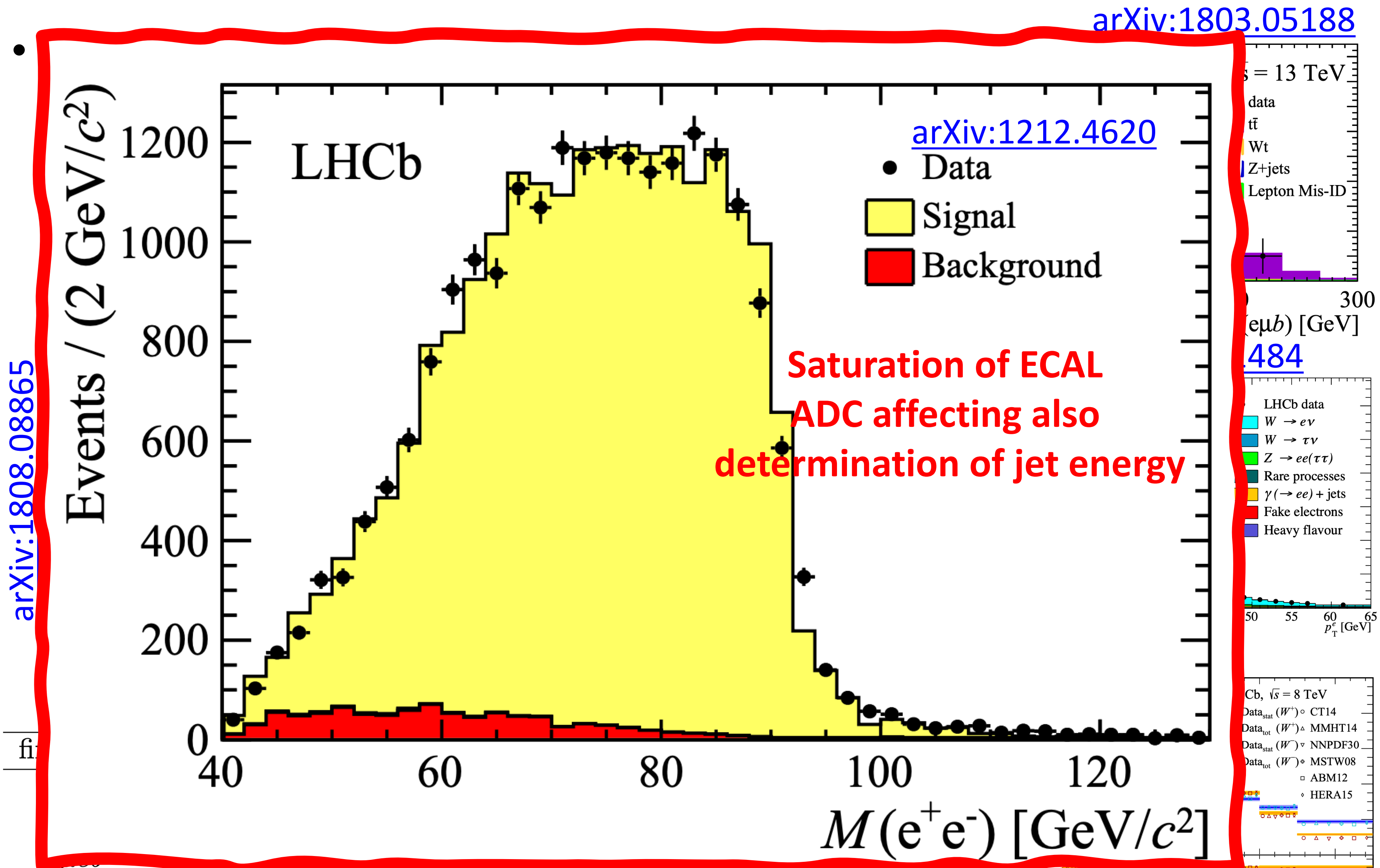
arXiv:1608.01484





final state	current	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}	$< x >$
ℓb	220 [414]	54k	117k	830k	0.295
$\ell b\bar{b}$	24 [415]	8k	17k	130k	0.368
$\mu e b$	38 [416]	1k	2k	12k	0.348
$\mu e b\bar{b}$	-	120	260	1.5k	0.415

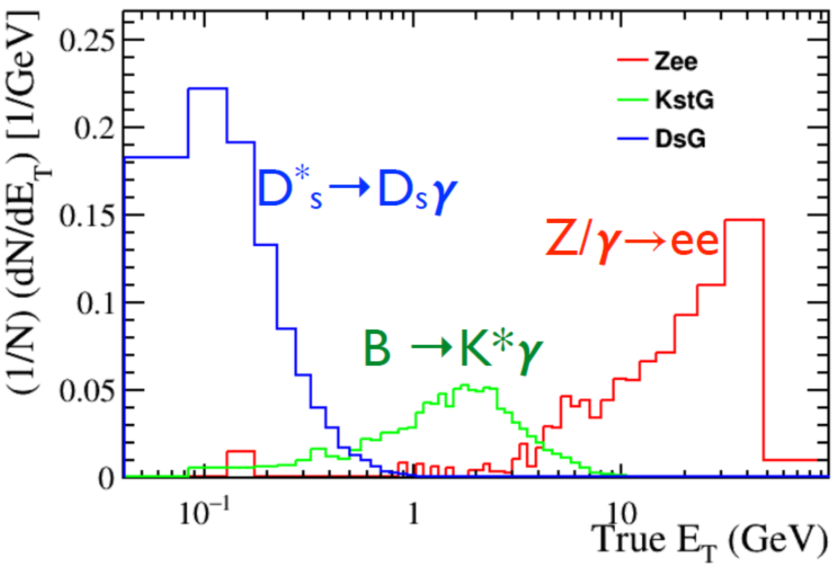
Forward and high-p_T physics



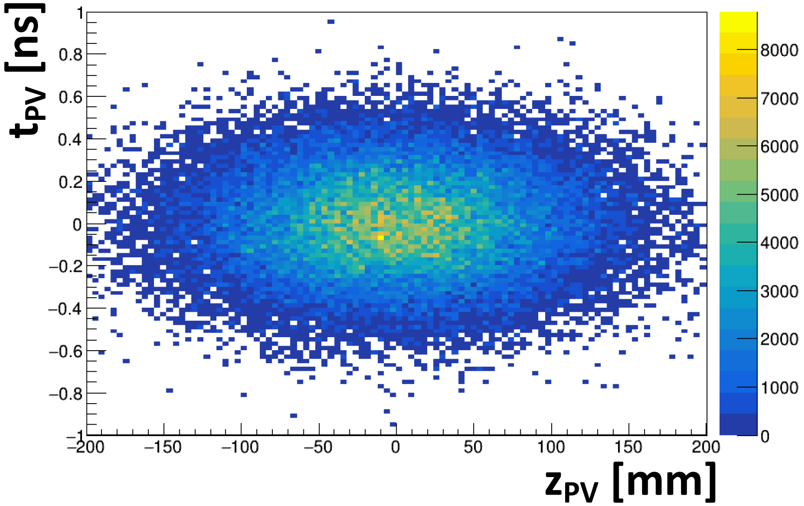
$\mu e b\bar{b}$	-	120	260	1.5k	0.415

Experimental considerations

- The just outlined physics programme is a very wide and interesting one
  - Difficult to cope with the requests from all physics cases
  - Channels with $\pi^0/e^\pm$ instead of $\pi^+/\mu^\pm$ have about 10-20 times less yields and worse resolutions (mass, decay time…)
  - Removing L0Trigger in Run3 will help with efficiency
- What can be done to improve current ECAL to cope with Run4 and Run5 conditions?
- Outcome of discussion with several people:
  - Better energy resolution
  - Finer granularity
  - Extended dynamic range
  - **Time information**

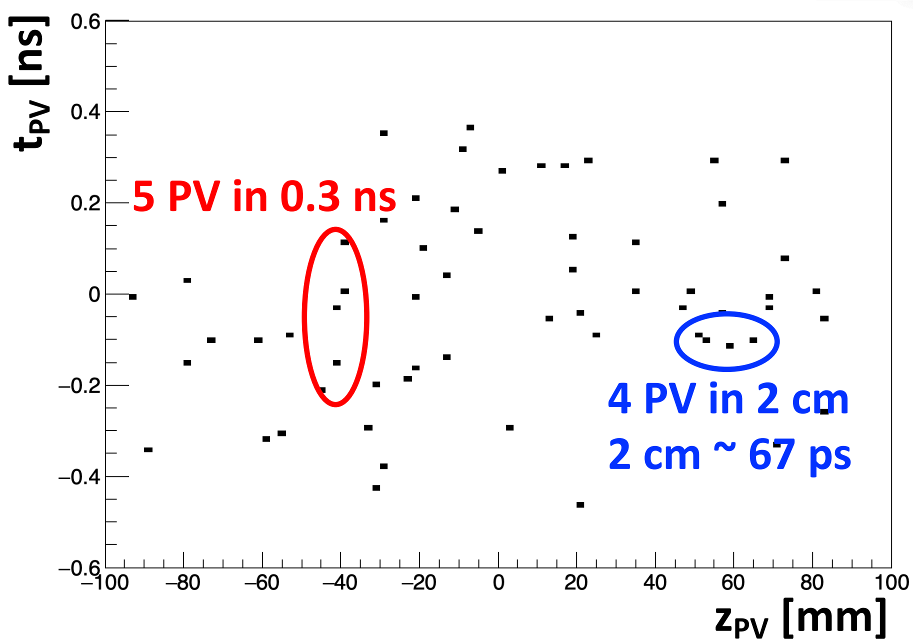


Considerations on time information



Primary vertices are distributed on a 2D gaussian → σ_z ~ 6 cm
→ σ_t ~ 0.2 ns

Single event example – $\mathcal{L}$ = 2x10^{34} cm^{-2}s^{-1}

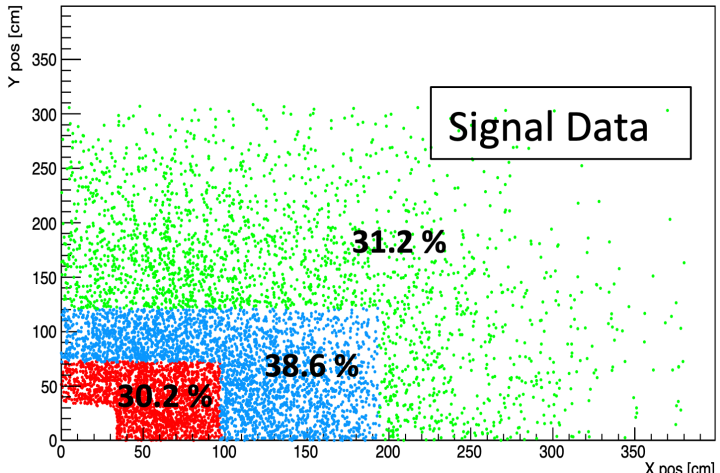


Time information is fundamental to separate PVs

Resolutions of O(10-20) ps is necessary for a good sparation of PVs

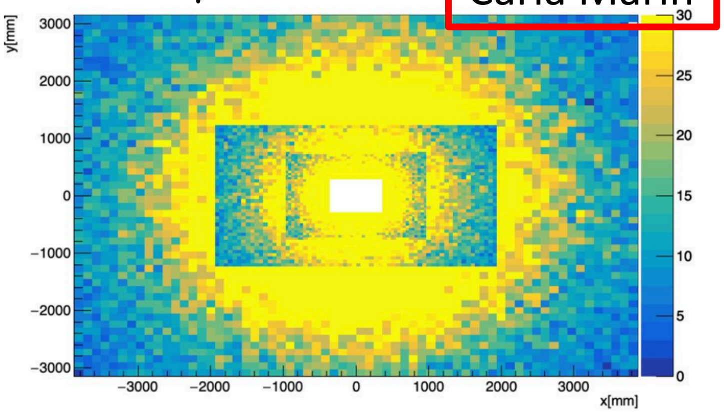
Importance of ECAL regions

B⁺→η′K⁺ Simulation



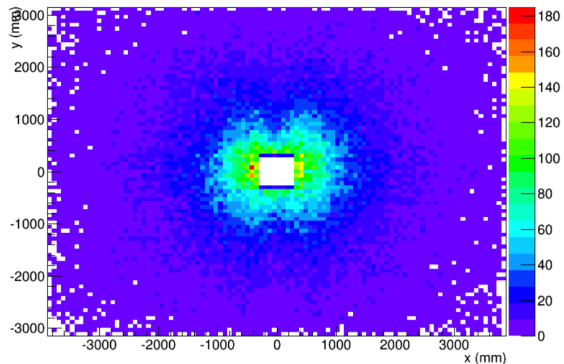
$B^0 \to K^*\gamma$ Simulation

Carla Marin

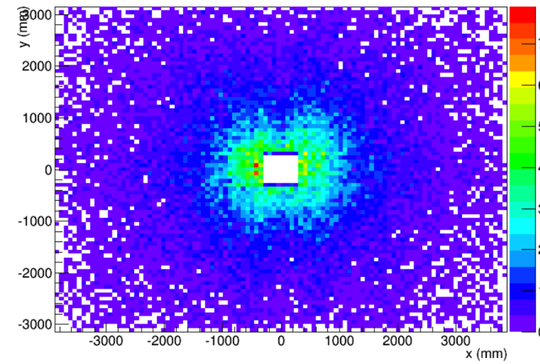



```
in InMost ECAL: 6.26 %
in Inner  ECAL: 33.69 %
in Middle ECAL: 27.54 %
in Outer  ECAL: 38.77 %
```

$B^+ \to K^+\pi^0$ Simulation



pi0 pT > 0

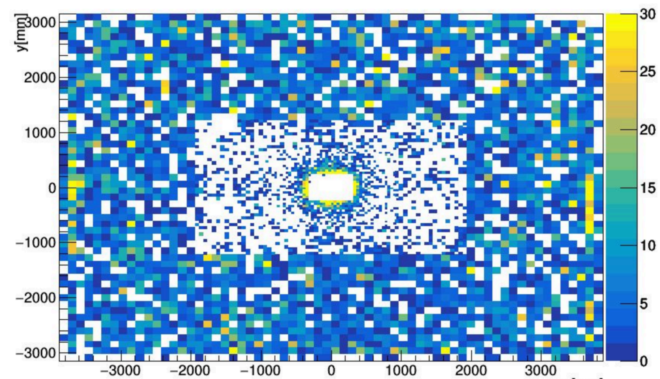


pi0 pT > 3500 MeV

From simulation

Jason Andres

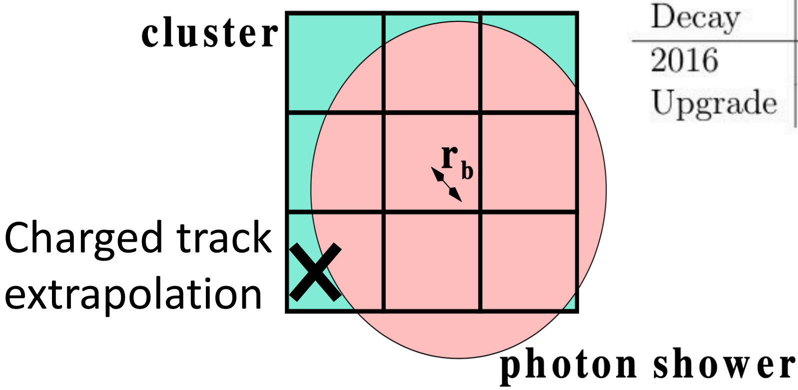
	Inner (%)	Middle (%)	Outer (%)	
* Bu → eta' K+	30.2	38.6	31.2	*
* Bu → K+ pi0	27.4	28.4	44.3	*
* Bu → rho+ rho0	28.7	30.1	41.3	*
Bd → K* eta (eta → pi pi pi0)	32.2	39.8	28.0	
Bd → K* eta' (eta' → pi pi gamma)	35.5	35.2	29.3	
Lb → p K eta' (eta' → pi pi gamma)	33.6	37.0	29.3	
Lb → p K eta (eta → pi pi pi0)	30.9	41.0	28.1	



Comb. Bkg. reconstructed as $B^0 \to K^*\gamma$

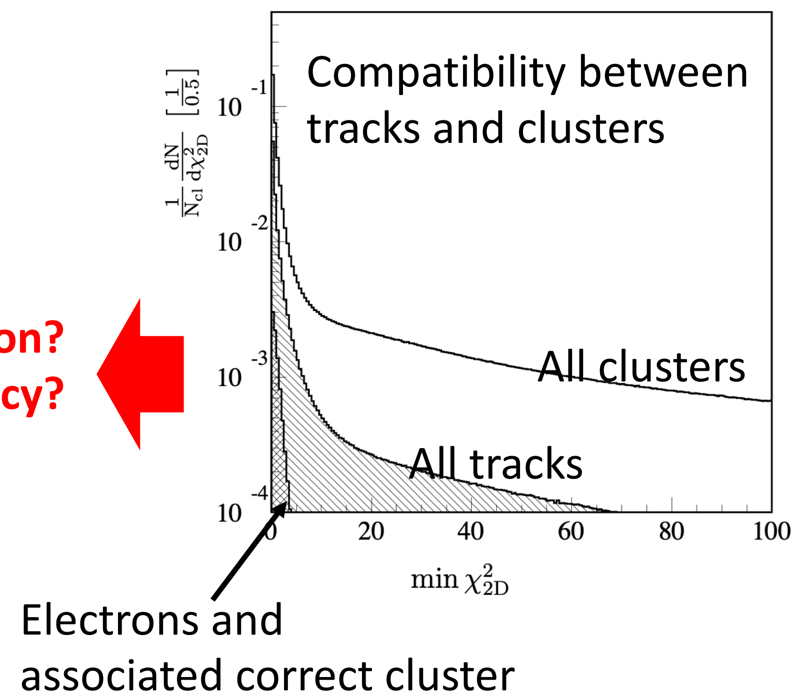
Reconstruction efficiency

- From simulation 15-30% loss in reconstruction efficiency is observed for several decays moving from Run1 to Run3 conditions
  - Clusters compatible with charged tracks are rejected → more tracks more rejected clusters



Decay	$B^0 \to K^*\gamma$	$B^0 \to \pi^+\pi^-\pi^0$ [merged]	$B^0 \to \pi^+\pi^-\pi^0$ [resolved]
2016	22.43	6.13	3.58
Upgrade	18.84	3.98	4.24

What if 3D χ^2 including timing information?
Possible to recover lost efficiency?

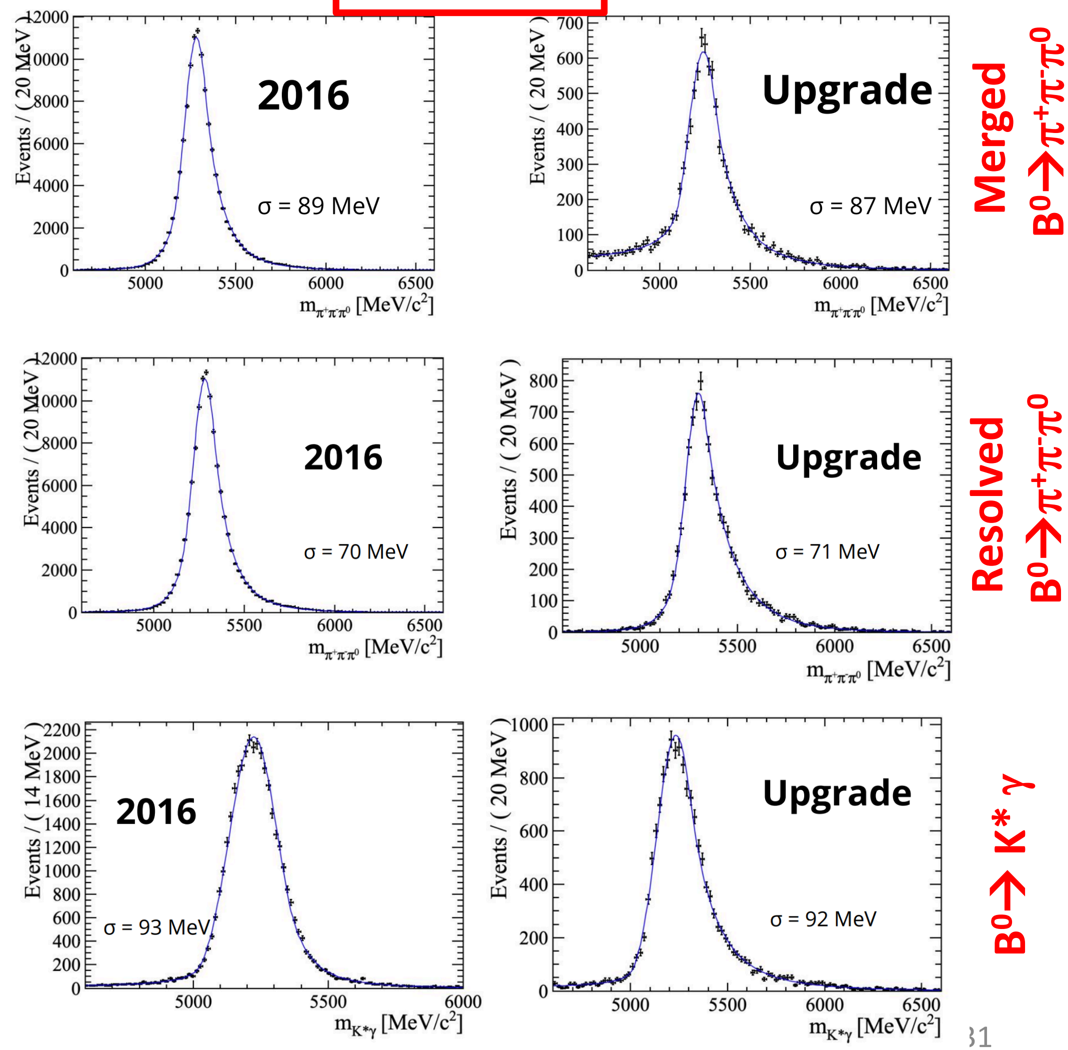


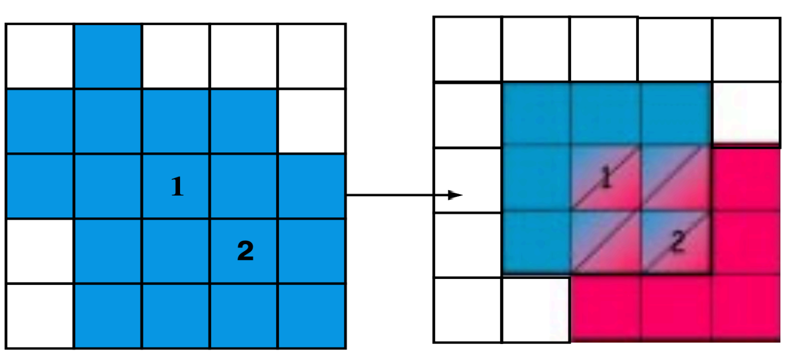
Energy resolution

- Energy resolution is the main contributor to mass resolution
  - B^0/B_s separation
  - Spectroscopy
- Similar core resolution for different occupancies
  - Core resolution intrinsic to ECAL technology
  - Larger occupancy is main responsible for larger tails → **granularity**
  - Include time information in reconstruction may help to separate overlapping clusters

Carla Marin

Simulation



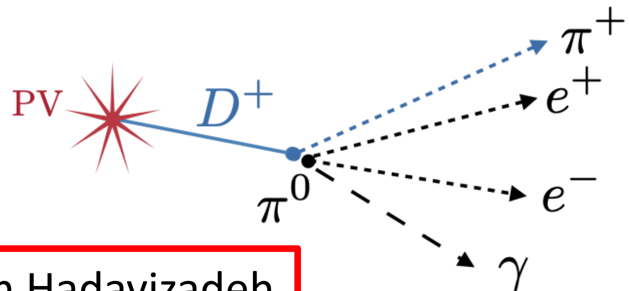


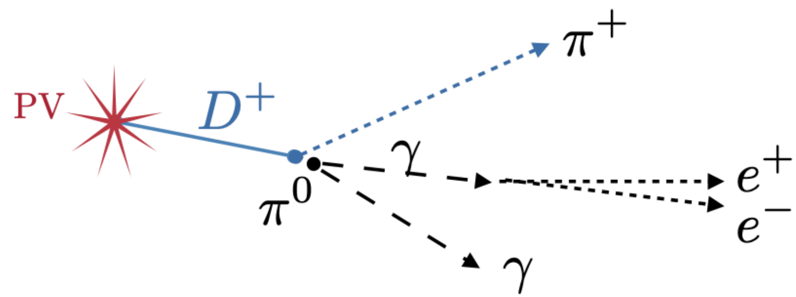
Single cluster **2 interleaved subclusters**

Usage of converted phtons

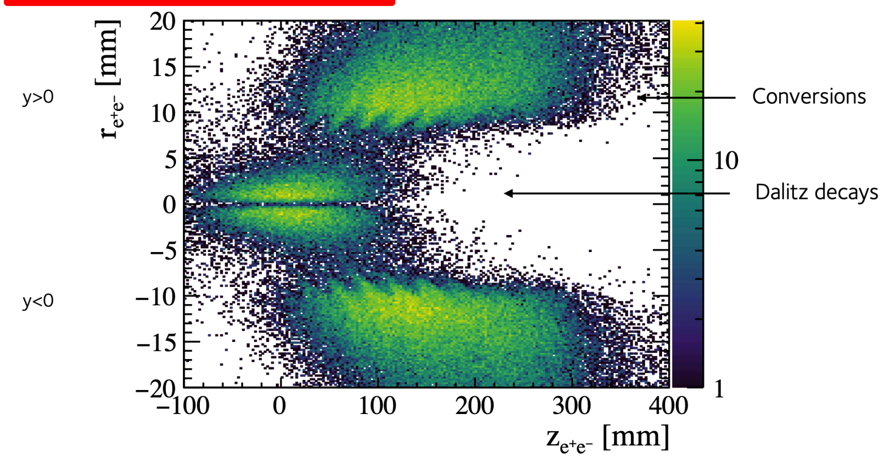
- Possibility to use $\gamma \rightarrow e^+e^-$ conversions or $\pi^0 \rightarrow \gamma e^+e^-$ Dalitz decay
  - Studies going on with charm decay

Decay	BF
$\pi^0 \rightarrow \gamma\gamma$	98.8%
$\pi^0 \rightarrow e^+ e^- \gamma$	1.2%
$\eta \rightarrow \gamma\gamma$	39.41%
$\eta \rightarrow e^+ e^- \gamma$	0.69%





Tom Hadavizadeh



With the statistics of Upgrade2 might be a viable option also for B decays

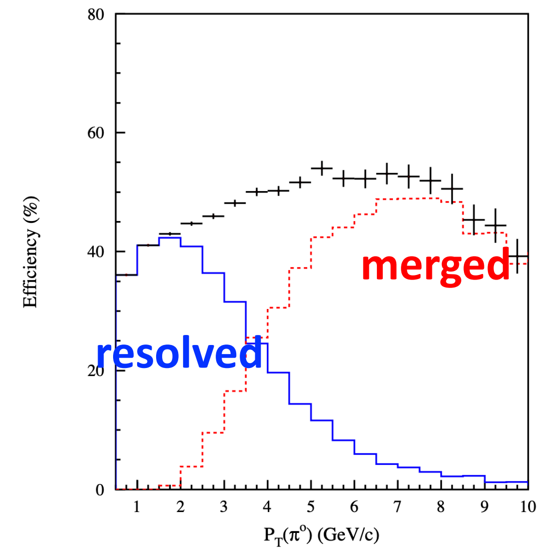
Better mass resolution

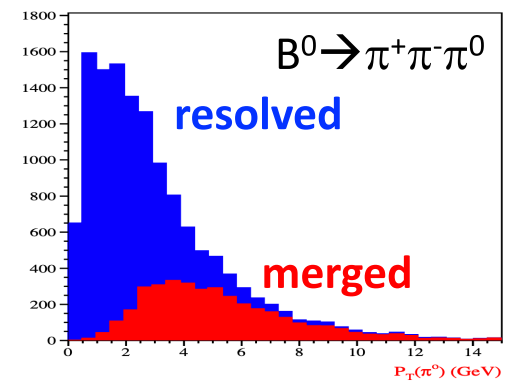
Not clear actual improvement in signal yields

Neutral PID and γ/π^0 separation

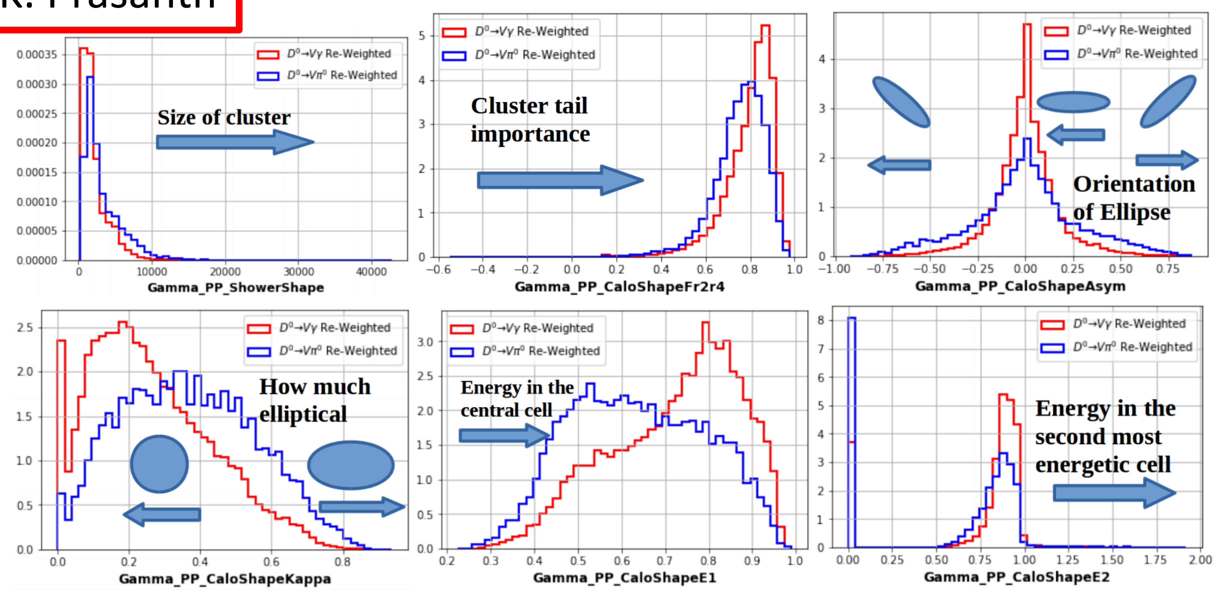
- Photons are one of main background to merged π^0 and vice versa
  - 30% of π^0 from $B^0 \rightarrow \pi^+\pi^-\pi^0$ are merged
- A lot of work going on to improve γ/π^0
  - Granularity is fundamental
  - Z-segmentation

LHCb-PUB-2003-091





K. Prasanth



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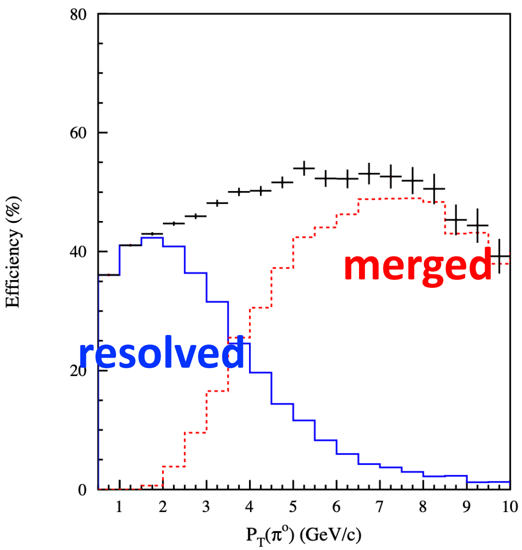
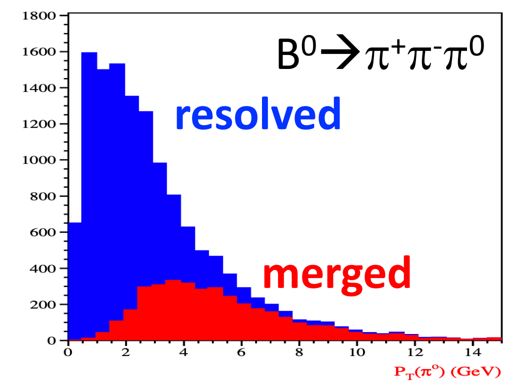
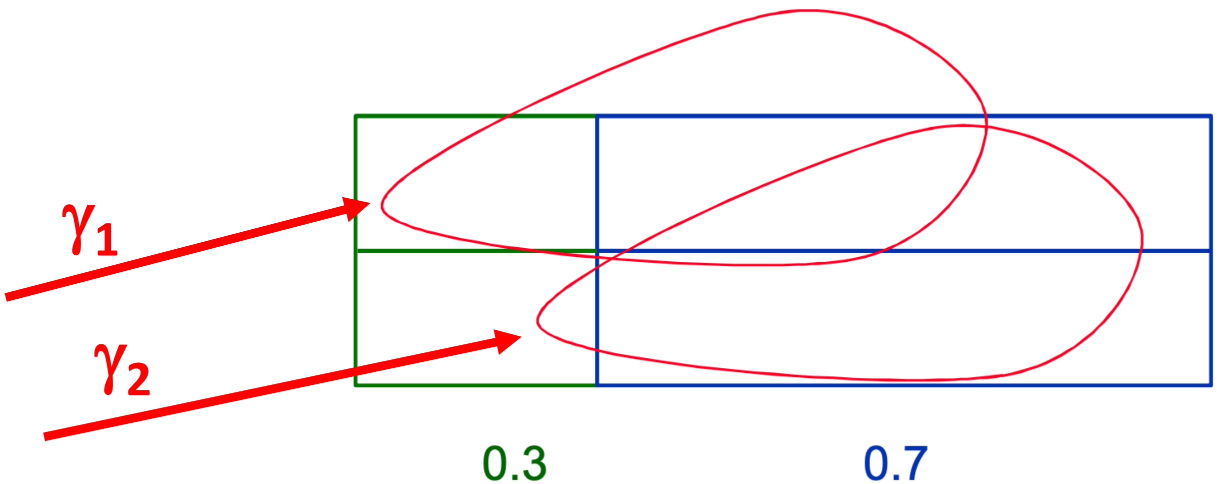


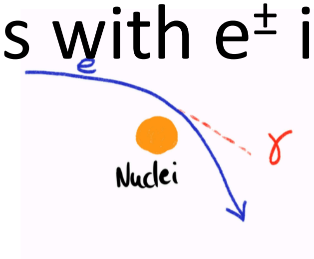


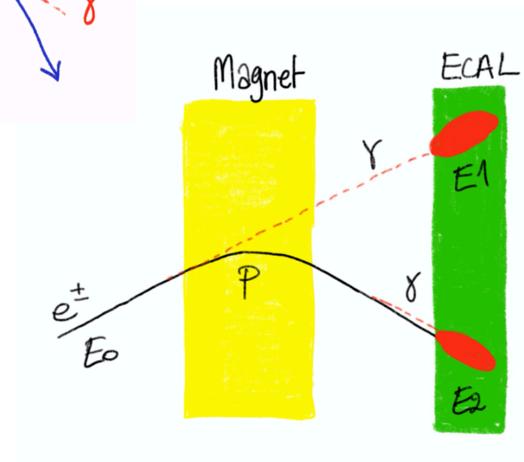


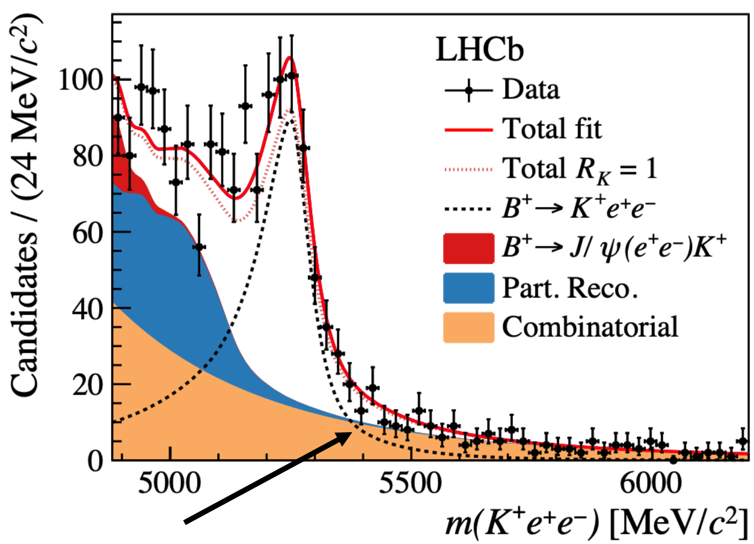
Electron/positron reconstruction

- Main problem affecting channels with $e^{\pm}$ is bremsstrahlung of electrons
  - Larger backgrounds due to wider tails
  - Difficult to discriminate between brem. γ and $e^{\pm}$ produced in secondary interactions and not reconstructed

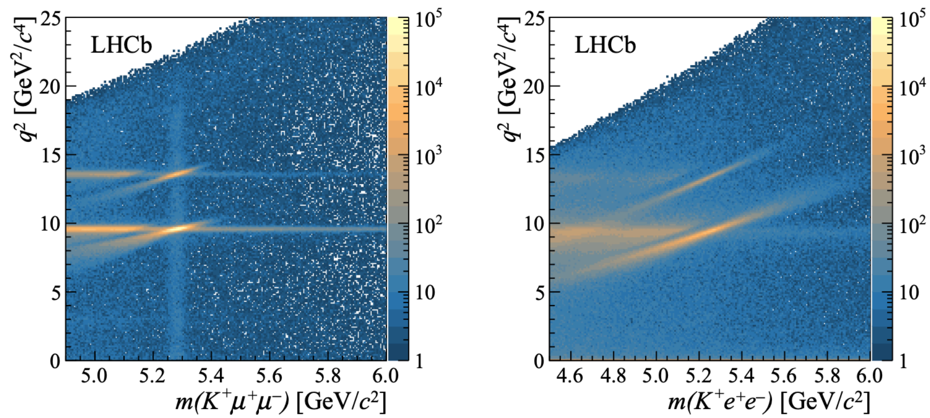
Ene
Ene







Brem. recovery



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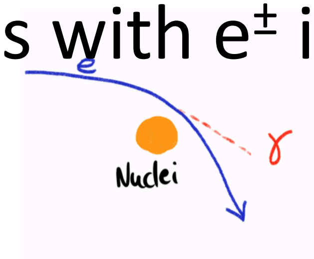
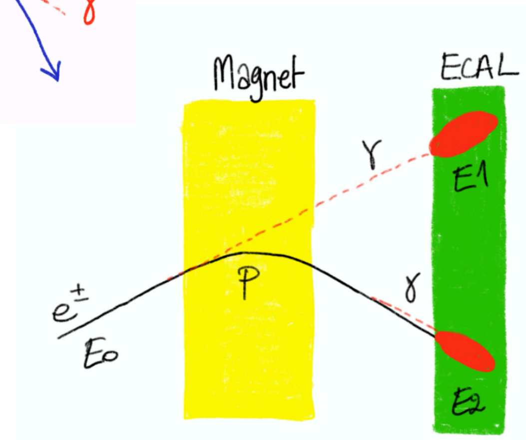
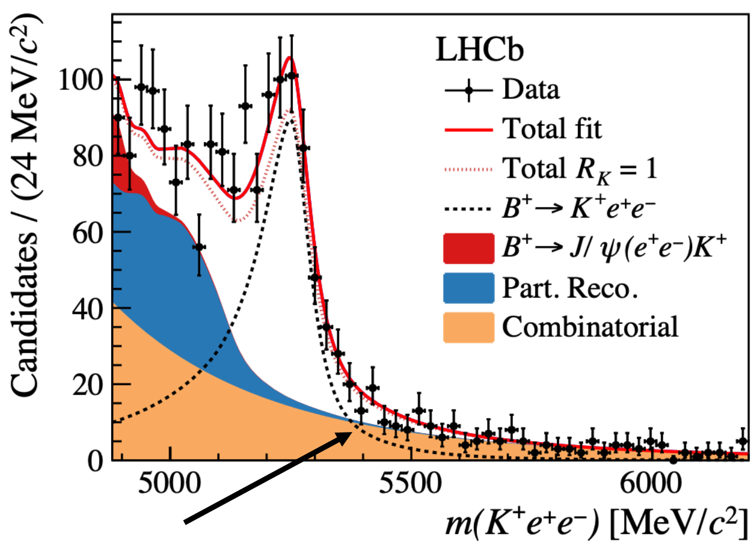


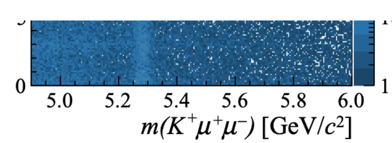


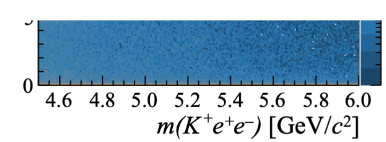


Brem. recovery

Reduce material budget in trackers looks the easies solution

What can be achieved with time information to associate brem. γ and reject backgrounds?

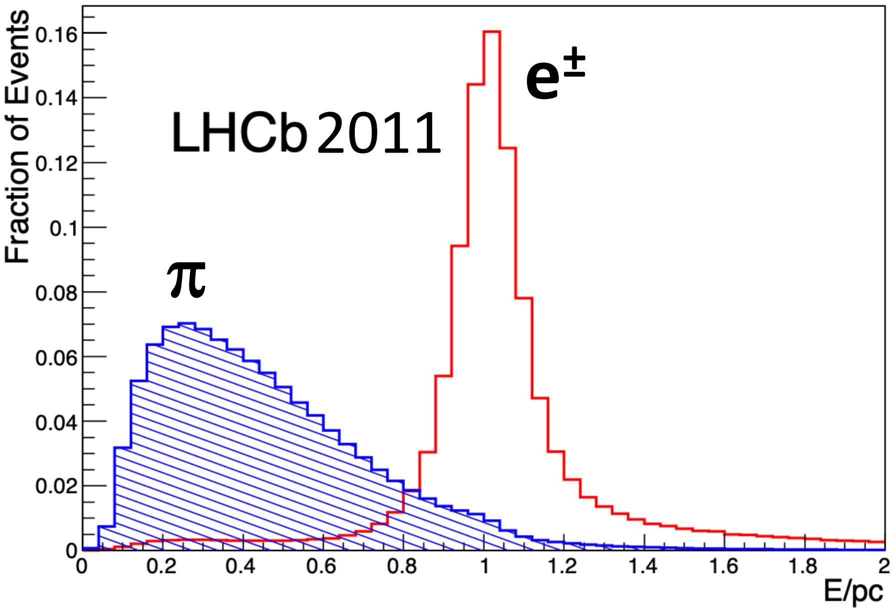




Charged PID for e/π discrimination

- Fundamental ingredient to discriminate between π and $e^{\pm}$ is E/p
  - Better energy resolution is important but **tails due to occupancy** could be a problem → feed from soft photons into π-cluster
  - Z-segmentation might be also an important leverage since pions release energy at the end of ECAL

arXiv:1412.6352



arXiv:1705.05802

	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ ratio	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

Conclusions

- The physics programme that requires ECAL is very wide and interesting
  - So far ECAL behaved as expected and gave important contributions
  - Nevertheless performances are far from those obtained for charged tracks
  - Important to work on limiting factor of current ECAL
- Making a better ECAL is mandatory to cope with harder conditions in future Runs
  - Energy resolution and granularity
  - Z-segmentation
  - Inclusion of time information
- Already in Run3 and Run4 conditions will be hard
  - Some improvement could be implemented already in LS3