Towards a measurement of R_{K^*} at high-q^2

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How to find New Physics (NP)? The Holy Grail of particle physics

THIS TALK

Direct searches (*« High Energy Frontier »*):

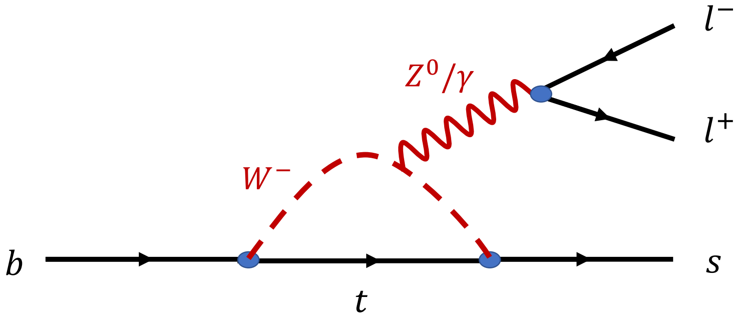
- Produce real NP particles
- Limited by energy of collider

Indirect searches (*« High Luminosity Frontier »*):

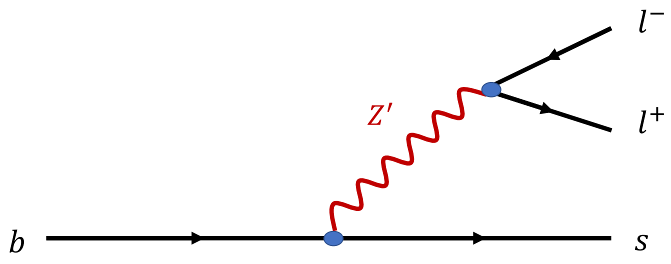
- Study of decays of known particles mediated by virtual intermediary states which can be SM or NP particles
- Rare processes → lot of data needed

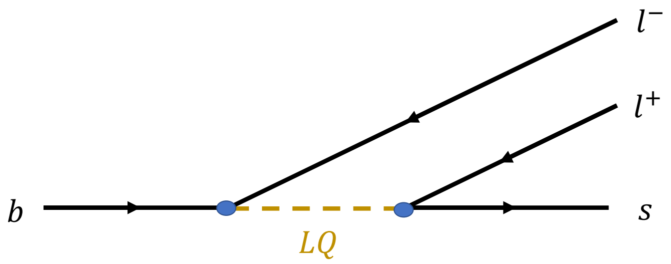
$b \to sll$ transitions as indirect probes of NP

SM



Examples of NP contributions (Z', leptoquarks)





- Electroweak (EW) penguin diagrams allow $b \to sll$ transitions in the SM
- $\mathcal{B} \sim 10^{-6}$ in SM: rare processes!
- NP can significantly alter these processes, such as in:
  - Angular distributions (Janina and Gaelle's talks)
  - **Decay rates (focus on this talk)**

A bit of theory on $b \to sll$ transitions

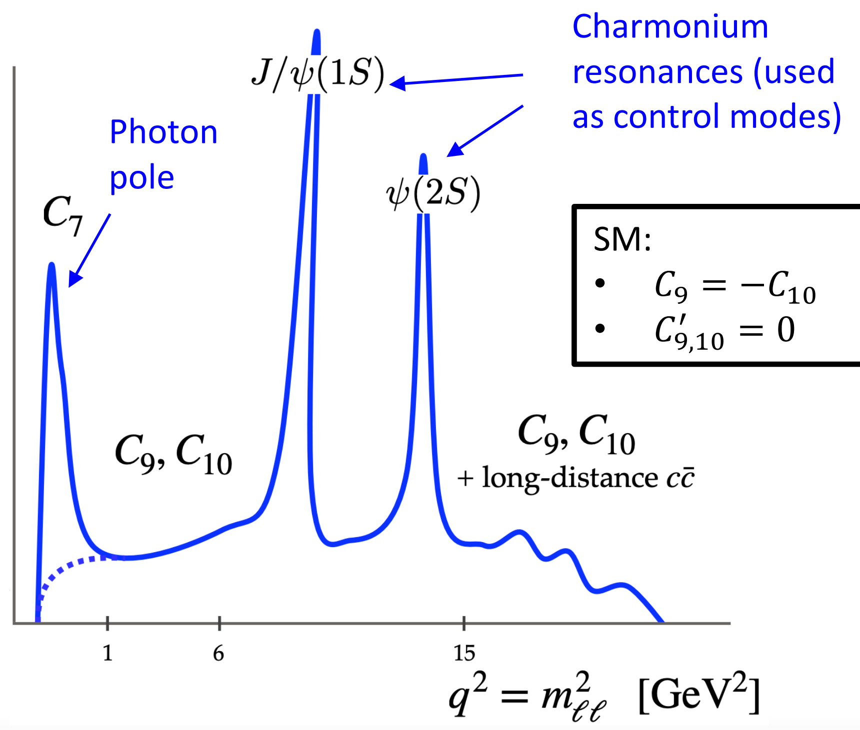
- $b \to sll$ neutral currents can be described by the ***effective*** Hamiltonian:

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{C_i O_i}_{\text{Left chirality}} + \underbrace{C_i' O_i'}_{\text{Right chilarity, suppresed by SM}}]$$

$i = 1, 2$:	Tree
$i = 3-6, 8$:	QCD penguins
$i = 7$:	photon penguins
$i = 9, 10$:	EW penguins
$i = S$:	Higgs penguins
$i = P$:	pseudoscalar penguins

- $C_i^{(\prime)}$ (Wilson coeff.): short-distance physics, sensitive to high energies ($E > \Lambda_{EW}$)
- $O_i^{(\prime)}$ (Operators): long-distance physics, non-perturbative, dependent to hadronic form factors

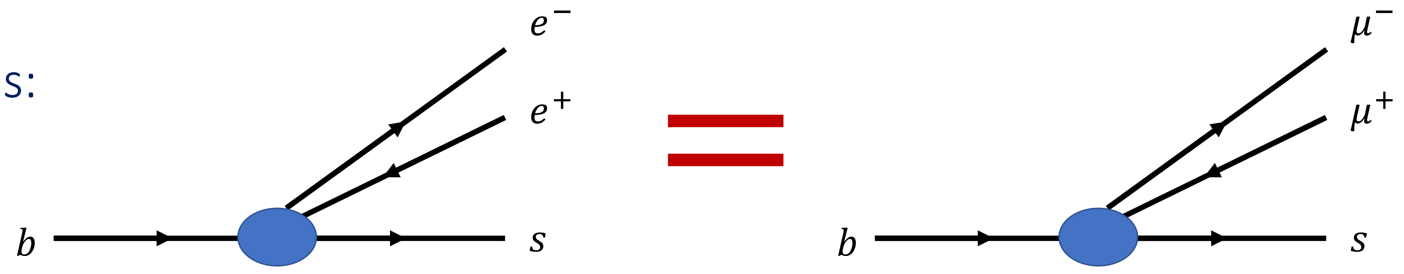
Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$B \to X\gamma$	×			
$B \to Xl^+l^-$	(×)	×	×	
$B_s^0 \to \mu^+\mu^-$			×	×



SM:
- $C_9 = -C_{10}$
- $C'_{9,10} = 0$

Ratios of branching fractions: important tools for NP searches

- Lepton Flavour Universality (LFU) in SM implies:

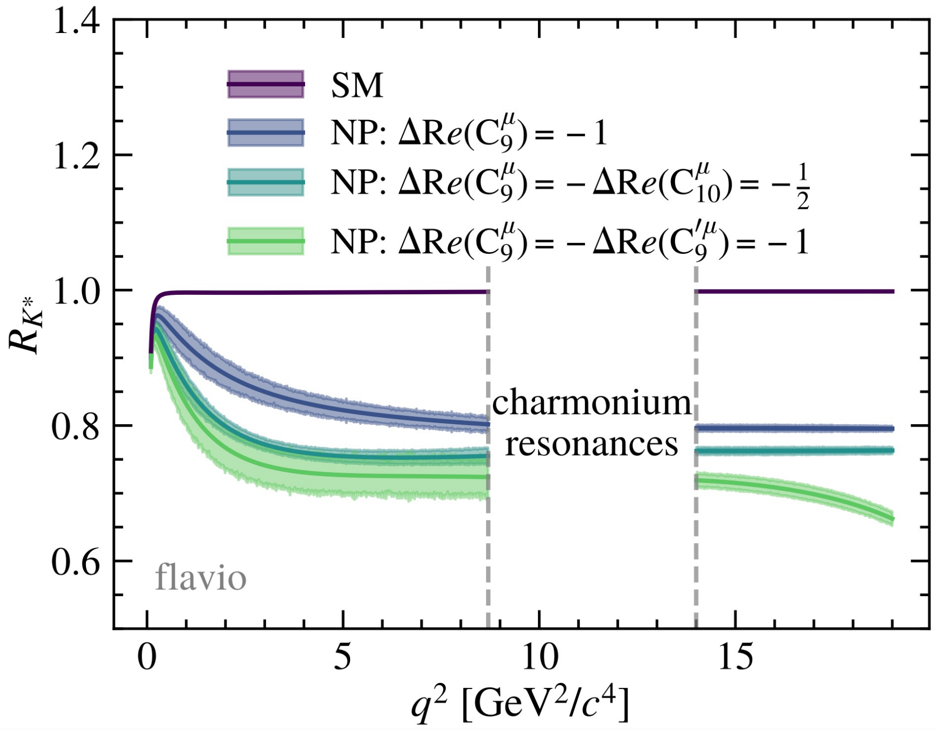


*except for (small) kinematic differences

- Hence (since $B^{+,0} \to K^{+,*0} l^+ l^-$ are described by $b \to sll$ transitions), the SM predicts R_K and R_{K^*} to be equal to 1:

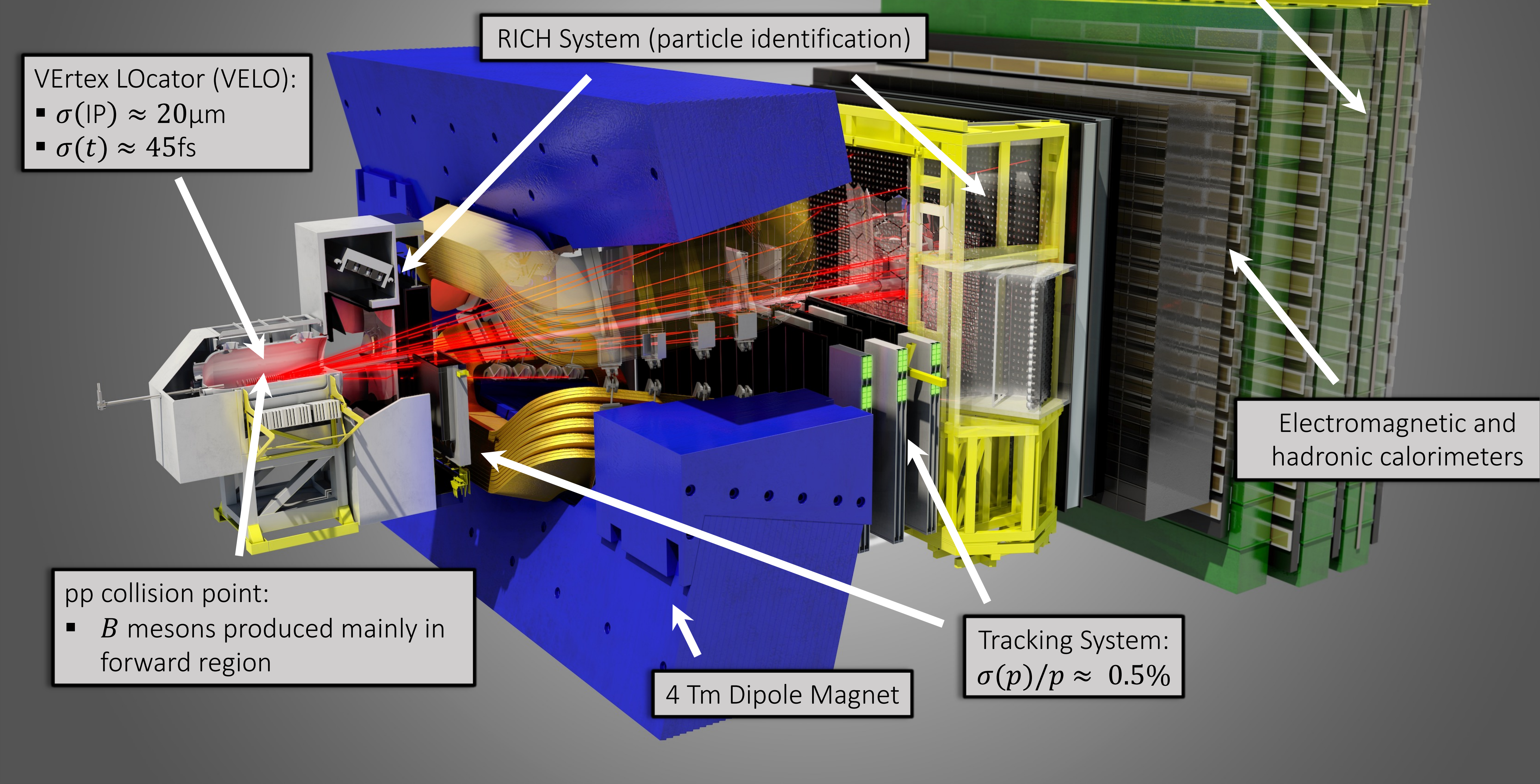
$$R_{K,K^*} = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B^{+,0} \to K^{+,*0}\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B^{+,0} \to K^{+,*0}e^+e^-)}{dq^2} dq^2}$$

with $K^{*0} \to K^+\pi^-$



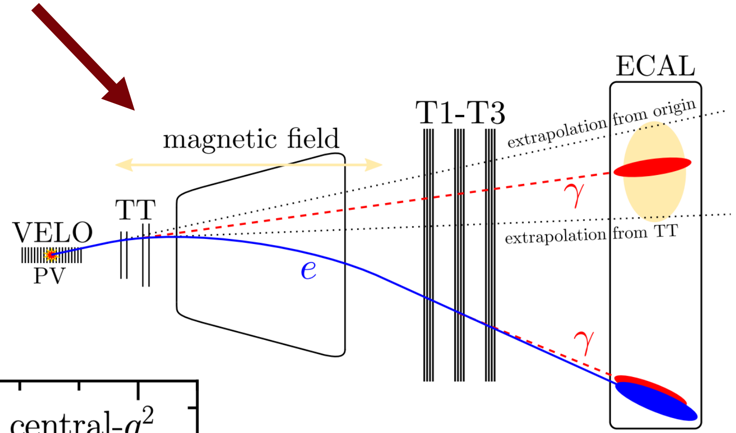
- NP contributions can make R_{K/K^*} depart from 1

The LHCb detector (Run 1+2)

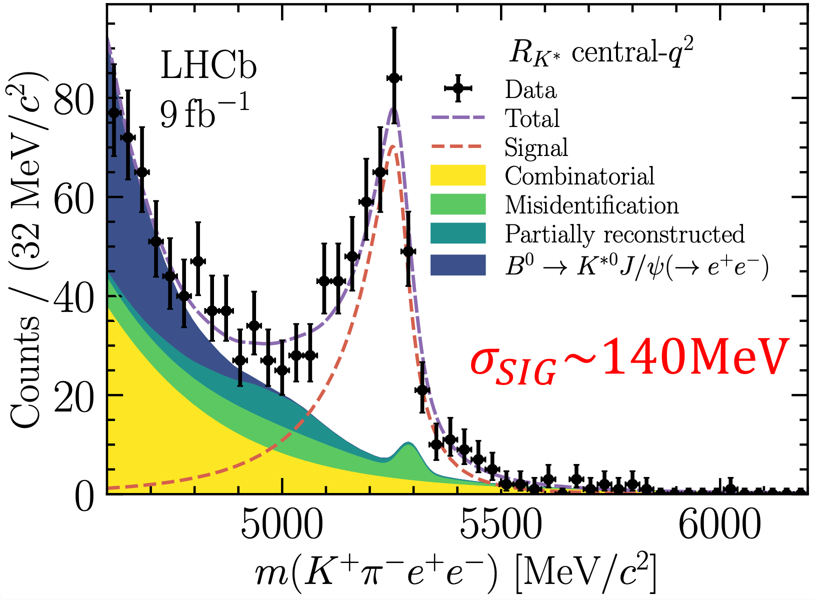


Challenge at LHCb: reconstruction of electrons

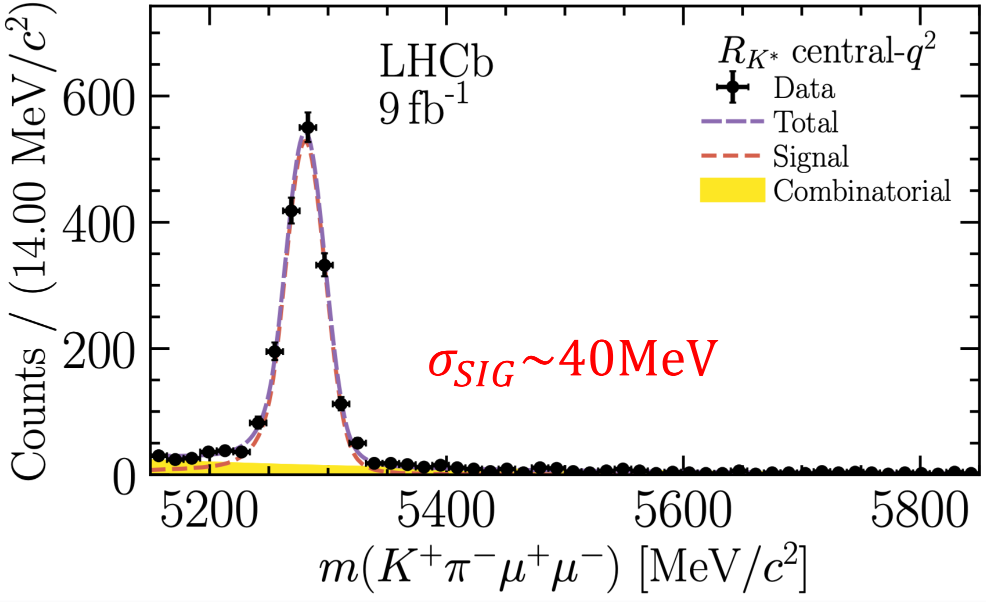
- Electrons emit radiation when interacting with the detector: *bremsstrahlung*
- The measurement of $\vec{p}(e^{\pm})$ is particularly deteriorated by the emission of brem photons before the magnet.
- A *bremsstrahlung photon recovery algorithm* is used to associate electrons to their brem photons



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



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



arXiv:2212.09153

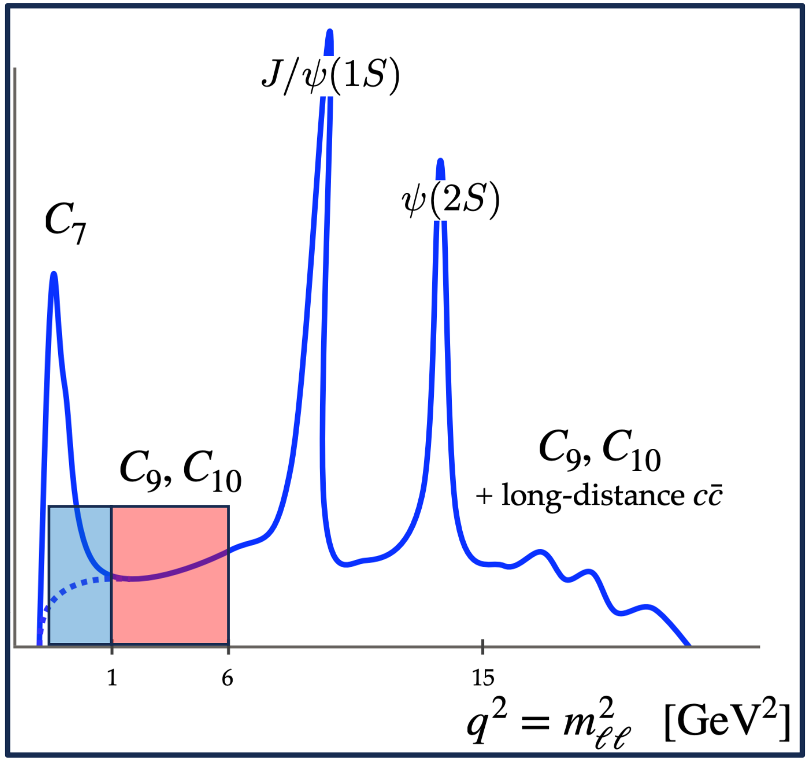
Recent results of R_K and R_{K^*}: the R_X analysis

- Measure R_K and R_{K^*} with full Run 1+2 LHCb data (2011-2018, 9fb^{-1}):

$$R_{K/K^*} = \frac{\frac{N}{\varepsilon}(B^{+,0} \to K^{+,*0}\mu^+\mu^-)}{\frac{N}{\varepsilon}(B^{+,0} \to K^{+,*0}e^+e^-)} \times \underbrace{\frac{\frac{N}{\varepsilon}(B^{+,0} \to K^{+,*0}J/\psi(\to \mu^+\mu^-))}{\frac{N}{\varepsilon}(B^{+,0} \to K^{+,*0}J/\psi(\to e^+e^-))}}_{=1}$$

$\frac{N}{\varepsilon}$: efficiency-corrected yield

- The high-statistics J/ψ resonance allows to cancel out most systematic effects due to e/μ differences
- Yields obtained from mass fits
- Efficiencies obtained from simulation corrected via data-driven techniques
- Analysis in *low-*q^2 ($q^2 \in [0.1,1]\text{GeV}^2$) and *central-*$q^2$ ($q^2 \in [1,6]\text{GeV}^2$)
- Two important cross-checks shown to be compatible with 1:



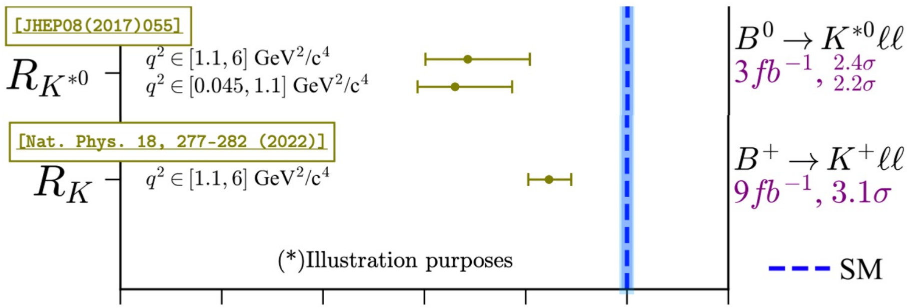
$$r_{J/\psi} = \frac{\frac{N}{\varepsilon}(B^{+,0}\to K^{+,*0}J/\psi(\to\mu^+\mu^-))}{\frac{N}{\varepsilon}(B^{+,0}\to K^{+,*0}J/\psi(\to e^+e^-))}$$

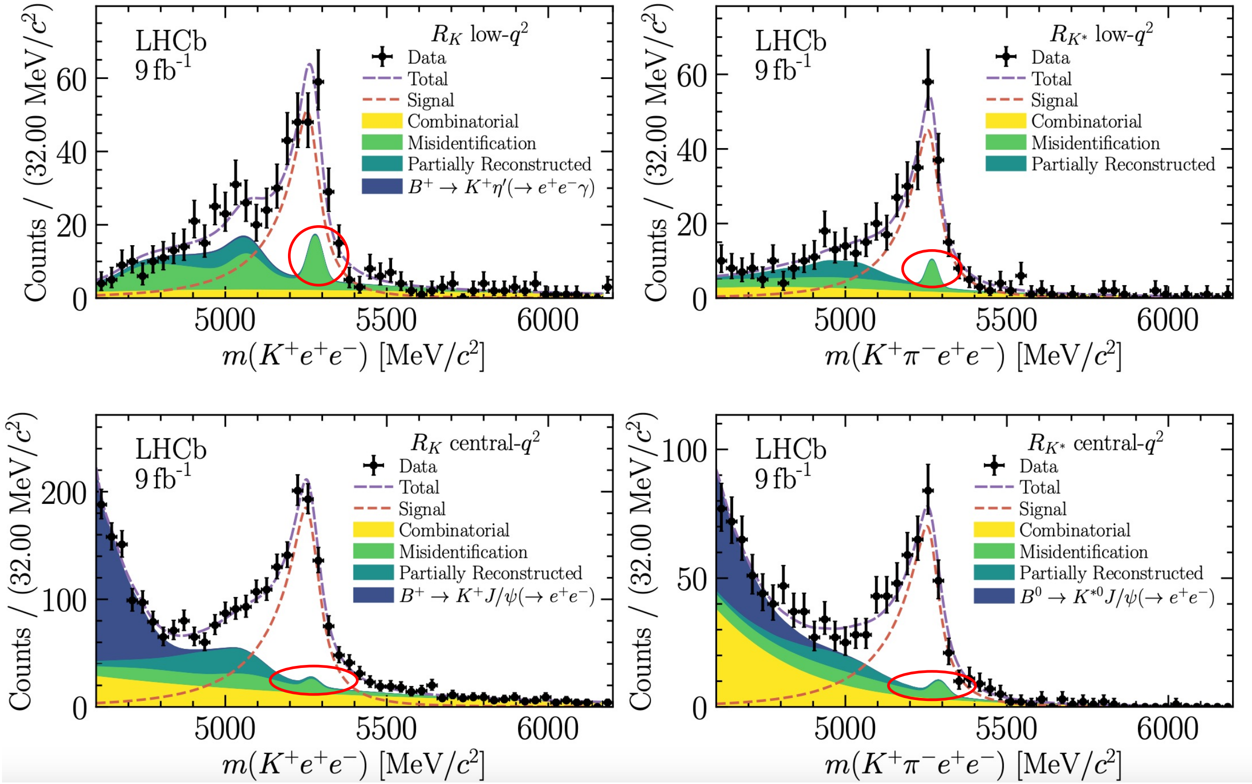
$$R_{\psi(2S)} = \frac{\frac{N}{\varepsilon}(B^{+,0} \to K^{+,*0}\psi(2S)(\to \mu^+\mu^-))}{\frac{N}{\varepsilon}(B^{+,0} \to K^{+,*0}\psi(2S)(\to e^+e^-))} \times \frac{\frac{N}{\varepsilon}(B^{+,0} \to K^{+,*0}J/\psi(\to \mu^+\mu^-))}{\frac{N}{\varepsilon}(B^{+,0} \to K^{+,*0}J/\psi(\to e^+e^-))}$$

Recent results of R_K and R_{K^*}: results

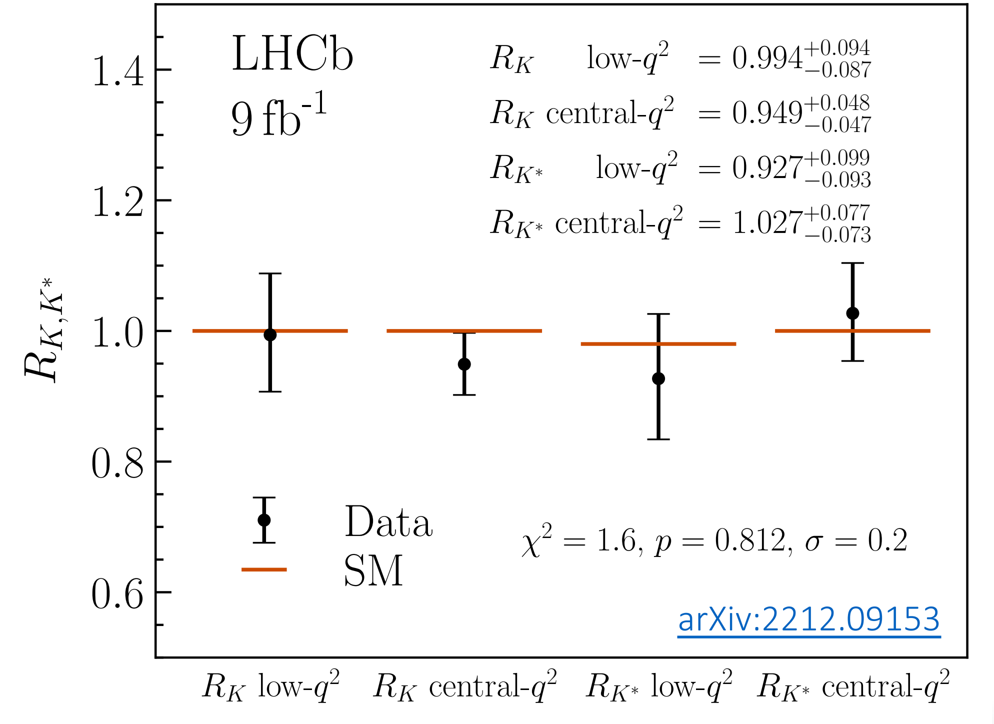
- Previous measurements indicated discrepencies from SM predictions.
- R_X: extensive studies of hadronic misidentified background (bkg) components in the electron mode, which can hide below the signal peak!

Previous measurements





R_X measurement

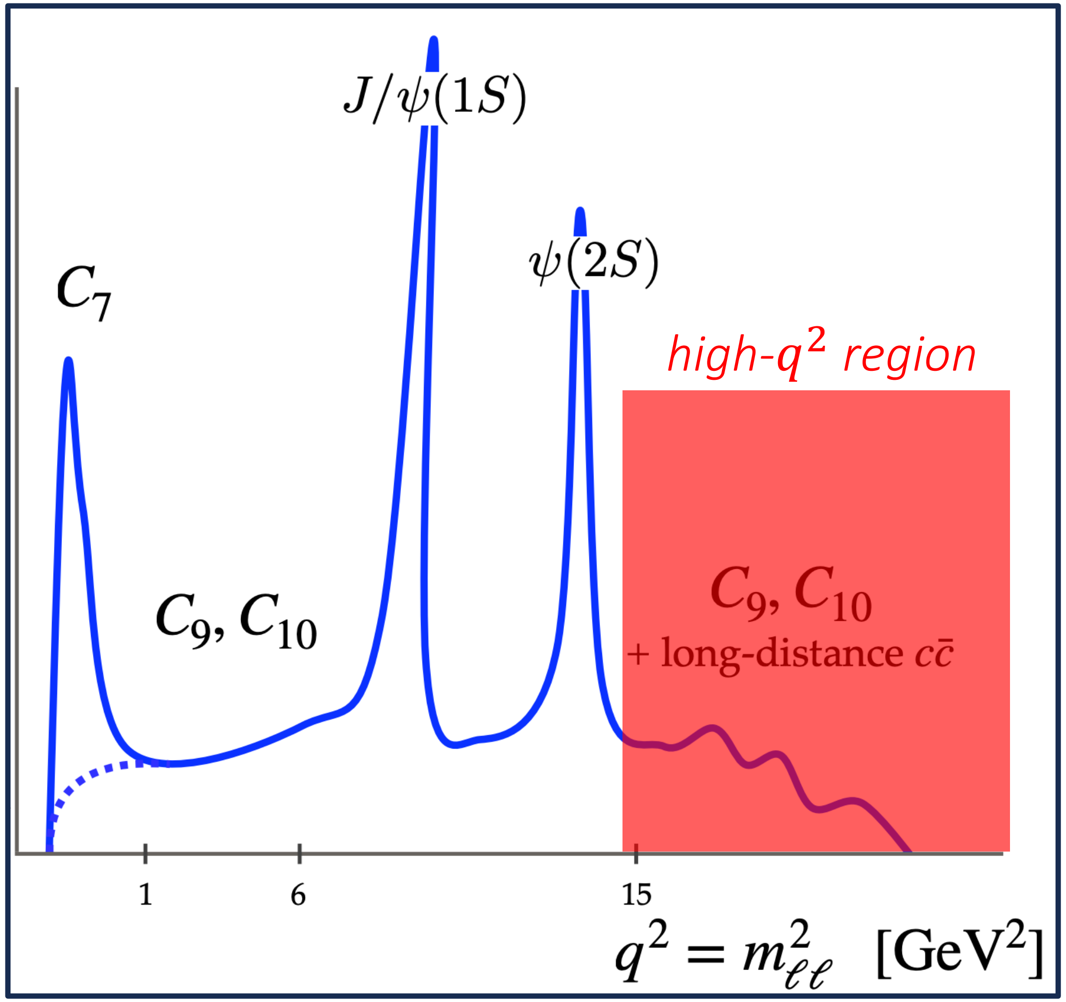


- When considering these bkg, R_K and R_{K^*} are compatible with 1

Measurement of R_{K^*} at high-q^2 values

Measurement of R_{K^*} at high-q^2 values

- Still no measurement of R_{K^*} above the $c\bar{c}$ resonances (*high-q² region*)
- Analysis performed using the framework and knowledge of the R_X analysis



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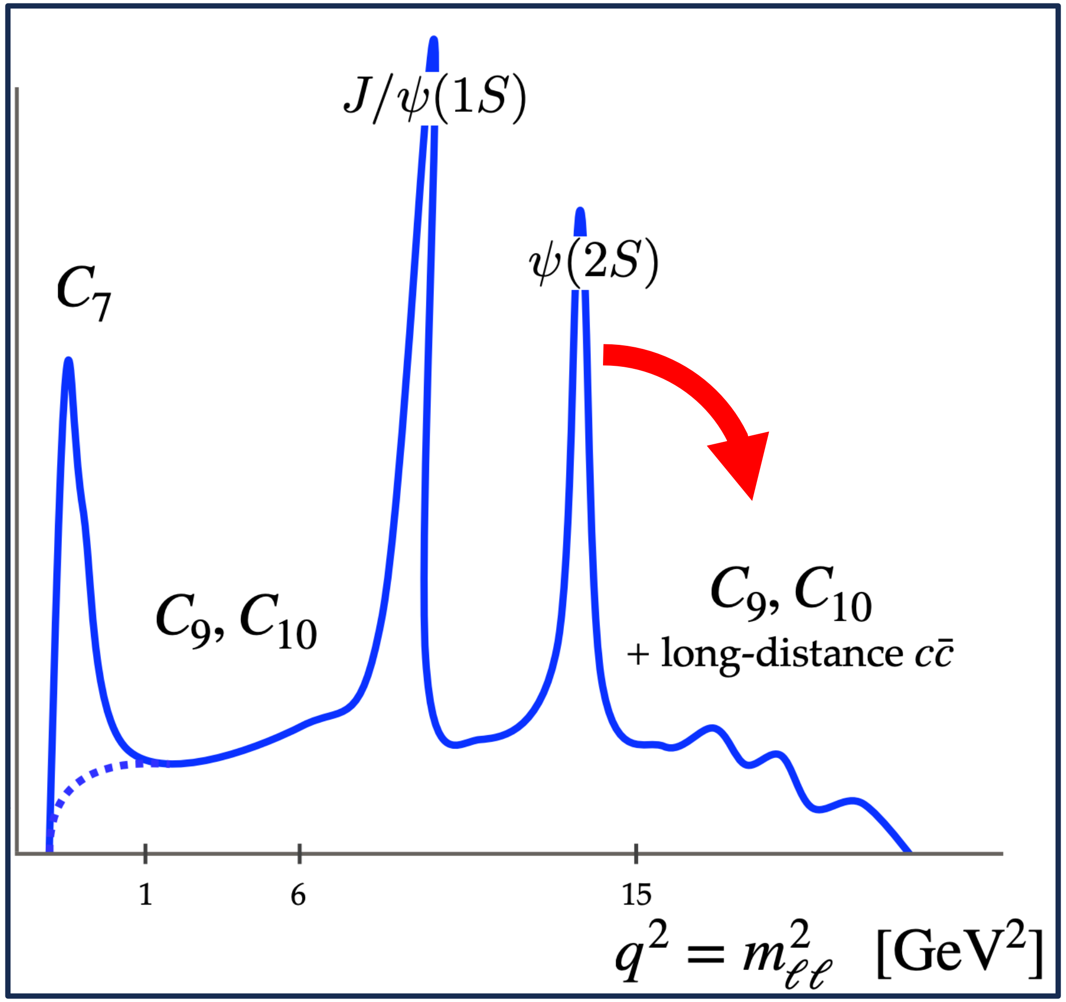
- Still no measurement of R_{K^*} above the $c\bar{c}$ resonances (*high-q^2 region*)
- Challenging electronic backgrounds at *high-q^2*:
  1. $\boldsymbol{B^0 \to K^{*0}\psi(2S)(\to e^+e^-)}$: an unrelated photon is sometimes considered as *bremsstrahlung* photon → q^2 is increased and makes $\boldsymbol{B^0 \to K^{*0}\psi(2S)}$ leak to high-q^2.



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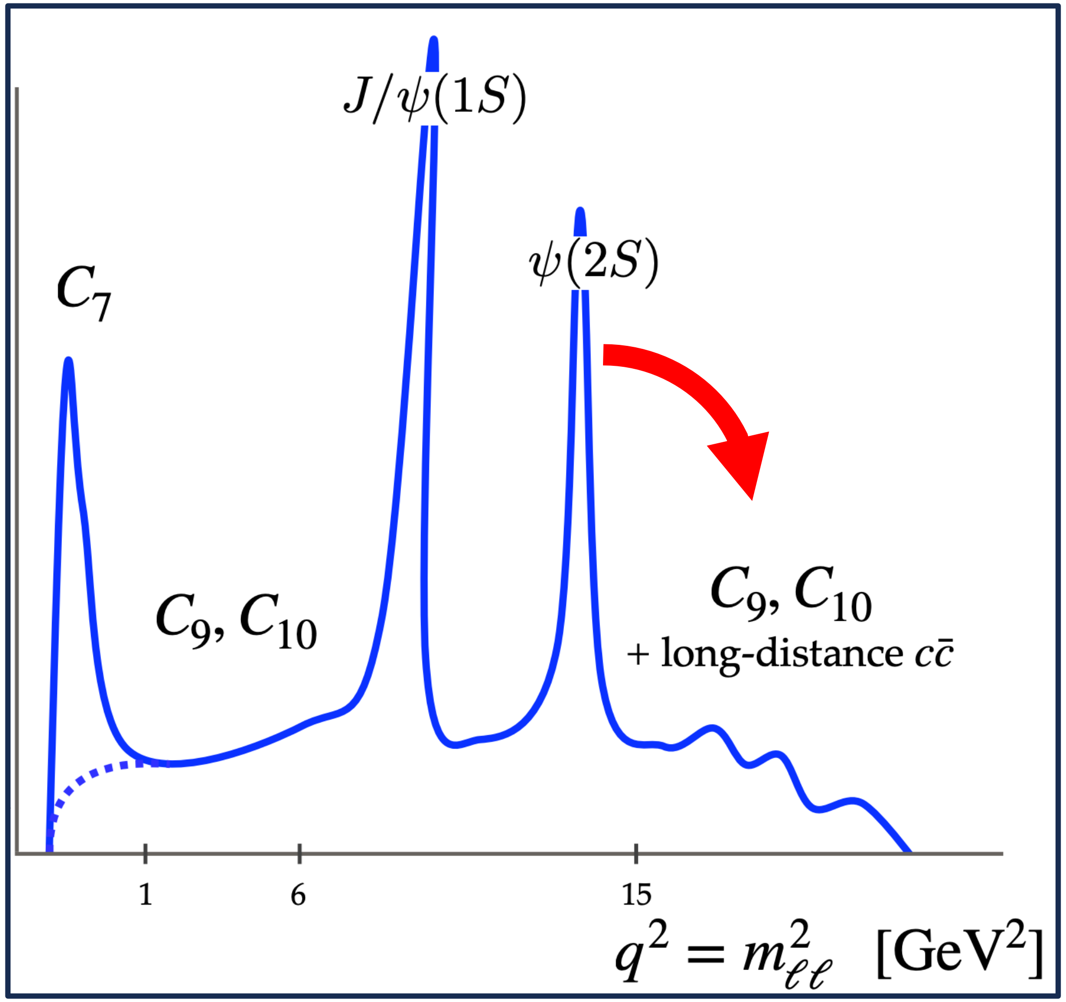
  2. $\boldsymbol{B \to X(\to YK^{*0})\psi(2S)(\to e^+e^-)}$, where Y is lost. Same logic as for $\boldsymbol{B^0 \to K^{*0}\psi(2S)}$ but the missing energy can make it peak below the signal peak (dangerous!)



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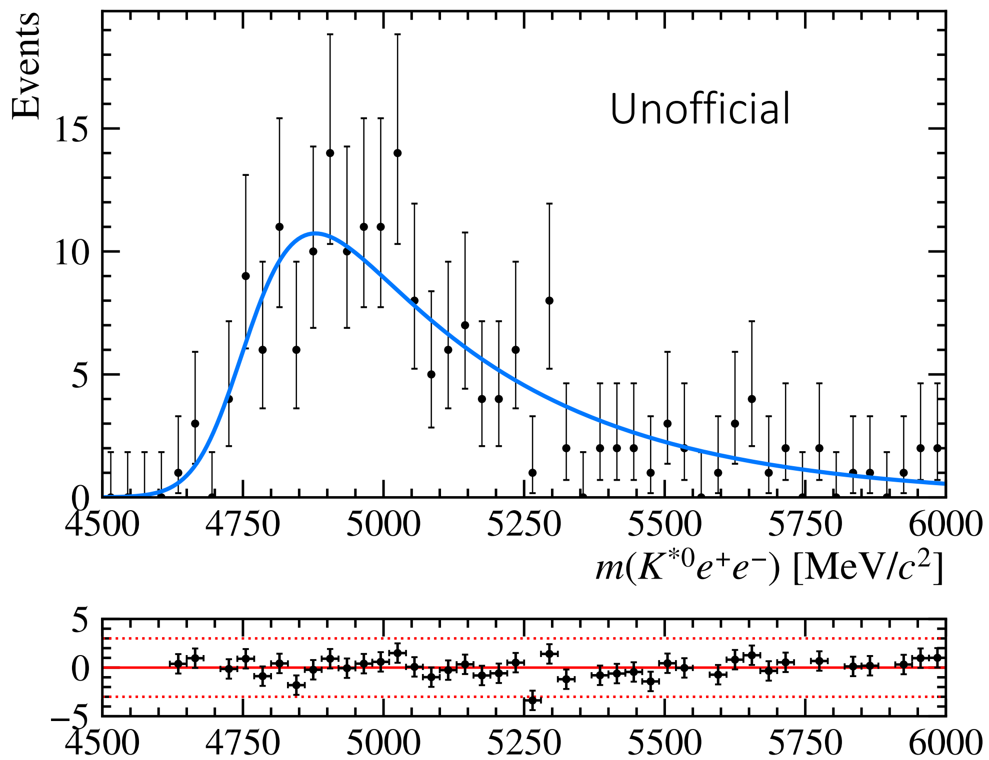
  3. Combinatorial background: does not follow an usual exponential shape because of the kinematic limit at high q^2 values. A Boosted Decision Tree (BDT) is used to reduce this bkg.

Combinatorial background



Measurement of R_{K^*} at high-q^2 values

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- Challenging electronic backgrounds at *high-q^2*:

  1. $\boldsymbol{B^0 \to K^{*0}\psi(2S)(\to e^+e^-)}$: an unrelated photon is sometimes considered as *bremsstrahlung* photon → q^2 is increased and makes $\boldsymbol{B^0 \to K^{*0}\psi(2S)}$ leak to high-q^2.
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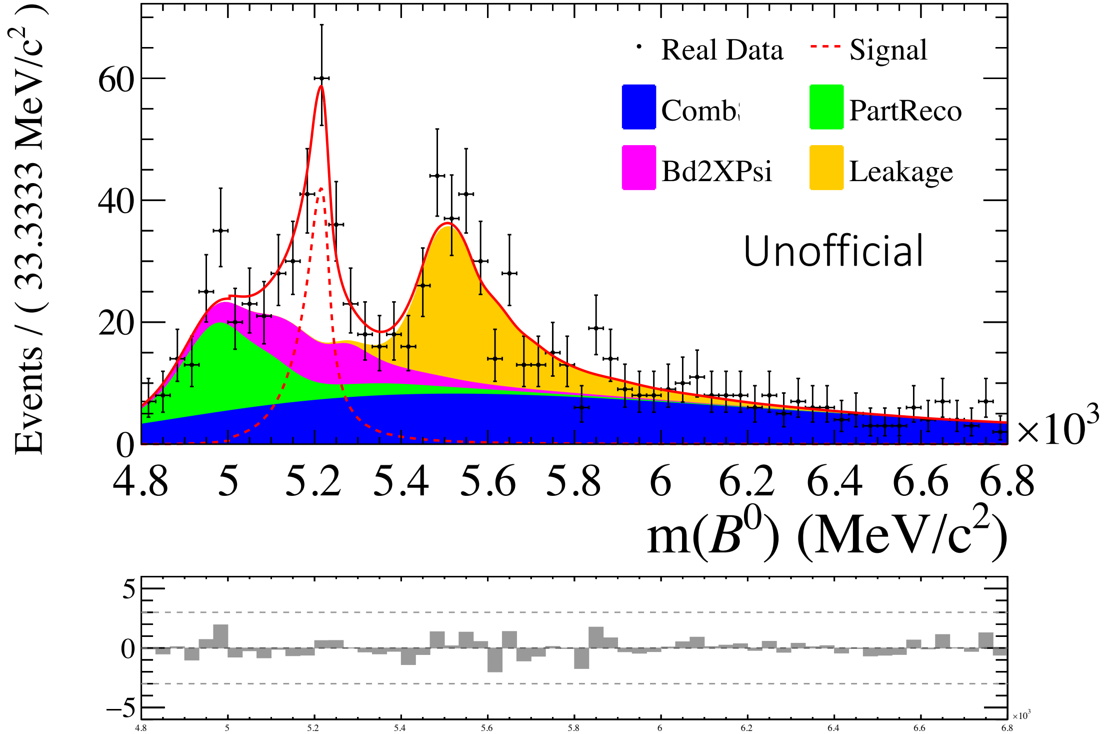
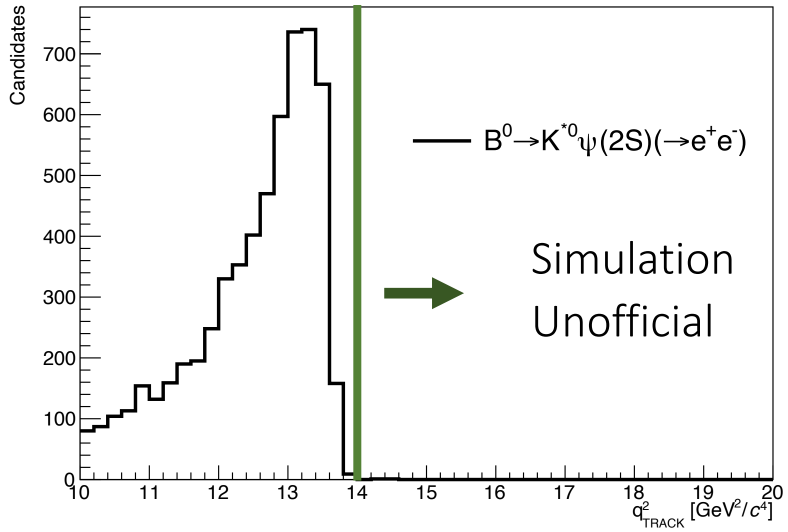
  3. Combinatorial background: does not follow an usual exponential shape → sculpted because of high q^2 values. A Boosted Decision Tree (BDT) is used to reduce it.

Distribution of $m(K^+\pi^-e^+e^-)$ from pseudoexperiments, representative of 2017-2018 data

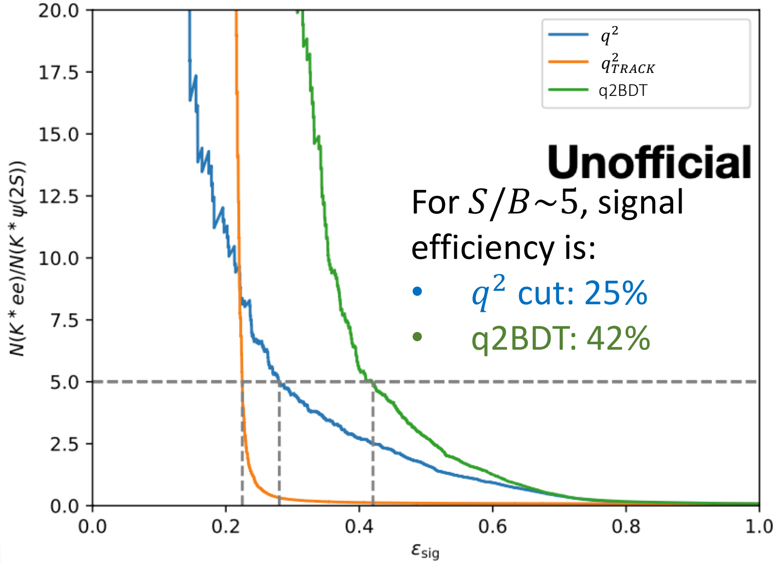


Reducing the nasty $\psi(2S)$ backgrounds

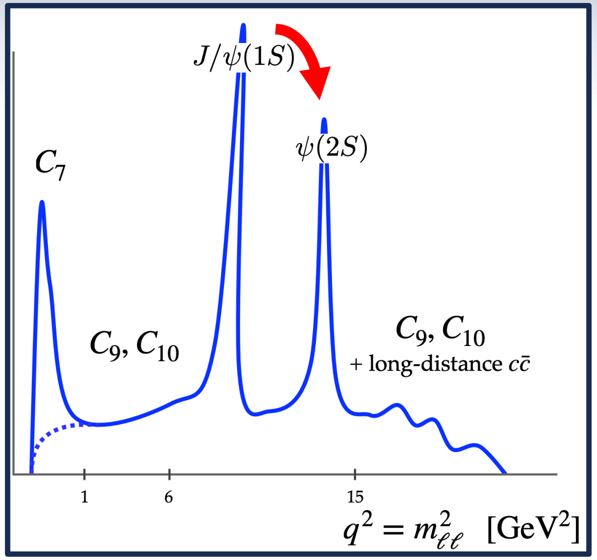
- Method 1: cut on q^2 calculated with no *bremsstrahlung* correction (called q^2_{TRACK})
  - Removes all $\psi(2S)$ pollution 👍
  - Reduces quite a bit of signal 👎
- Method 2: Create a BDT (called q2BDT) designed to reduce $\psi(2S)$ pollution while keeping a good fraction of the signal. The BDT is trained with only 3 variables:
  1. q^2
  2. q^2_{TRACK}
  3. Number of bremsstrahlung photons
- Method 2 is still challenging because it still requires a very precise modelling of the $\psi(2S)$ pollution → good trust in simulation!
- Studying actively which method to use for the final analysis!



q^2 calculated with no bremsstrahlung correction [GeV^2/c^4]

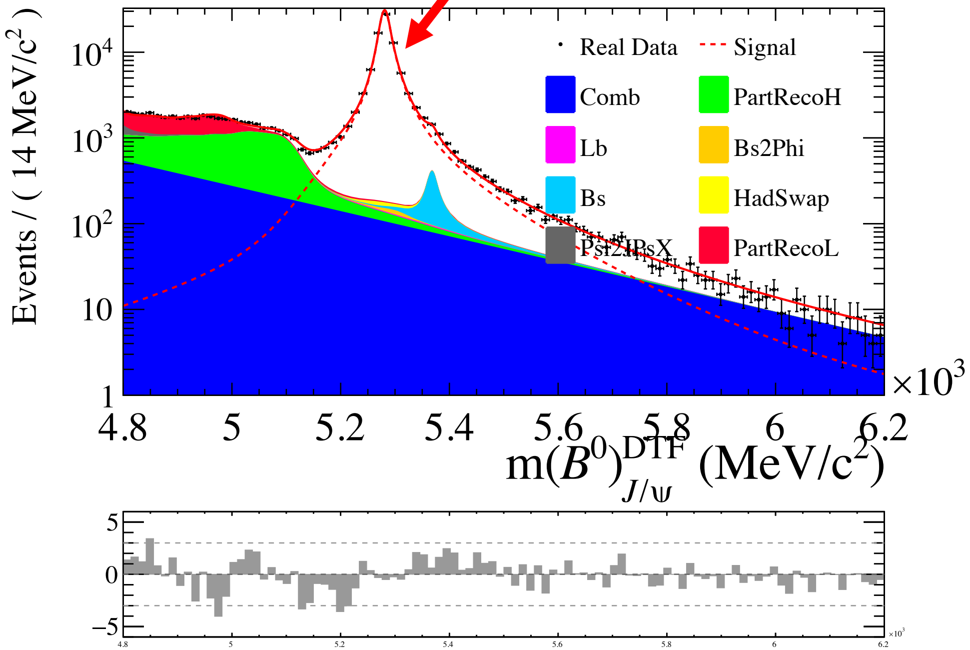


Electronic mass fits in the J/ψ and $\psi(2S)$ region

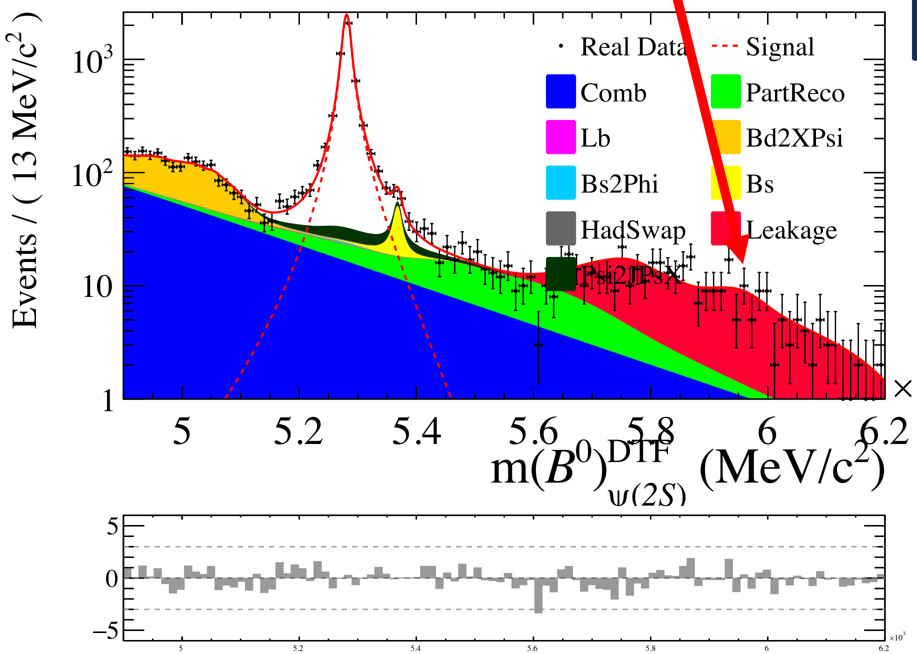


- Just like $\psi(2S)$ polutes the high-q^2 region, J/ψ polutes the $\psi(2S)$ region!
- We rescale the q2BDT so that it can be used in the $\psi(2S)$ fit

J/ψ fit: 91K signal J/ψ candidates



$\psi(2S)$ fit: only ~50 J/ψ candidates remain!



- Similarly, the obtained $\psi(2S)$ yields are used to estimate how many leak at high-q^2

Conclusion

Done

- Simulation corrections
- Efficiencies calculations
- Fits to control $c\bar{c}$ channels
- Modelisation of most of the background components

Under study

- Final decision on best strategy to reduce the $\psi(2S)$ backgrounds
- Modelisation of hadronic misidentified background

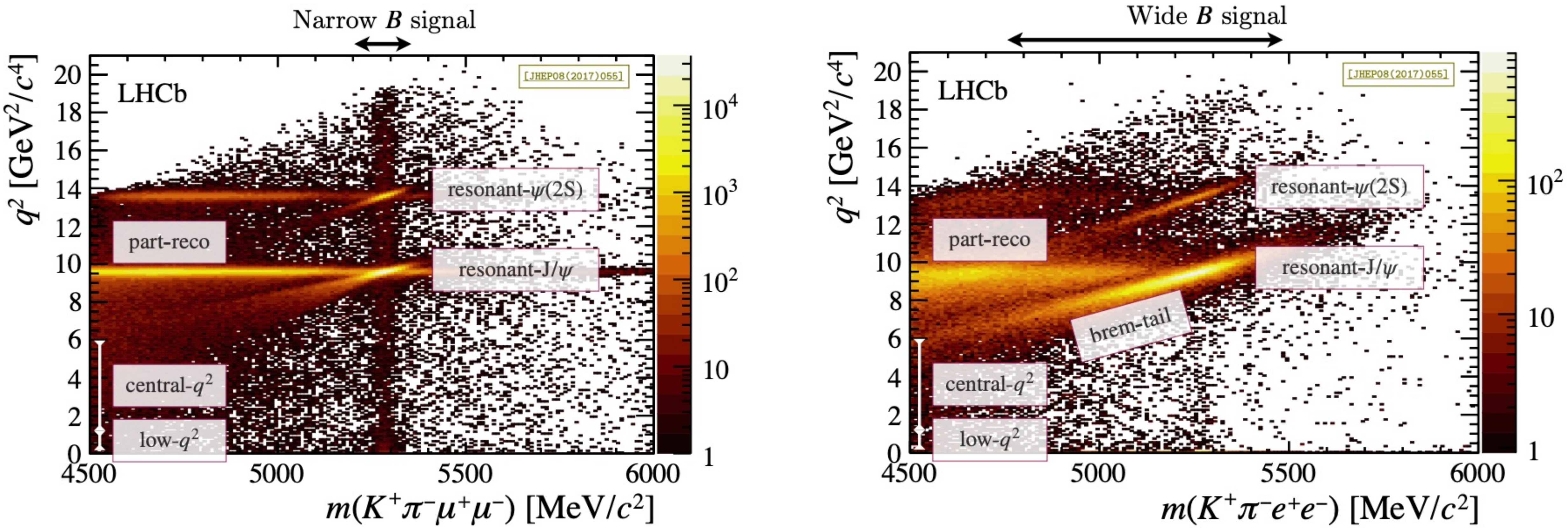
To be done

- Validate measurements of $r_{J/\psi}$ and $R_{\psi(2S)}$
- Model the muonic high-q^2 region
- Compute systematic uncertainties

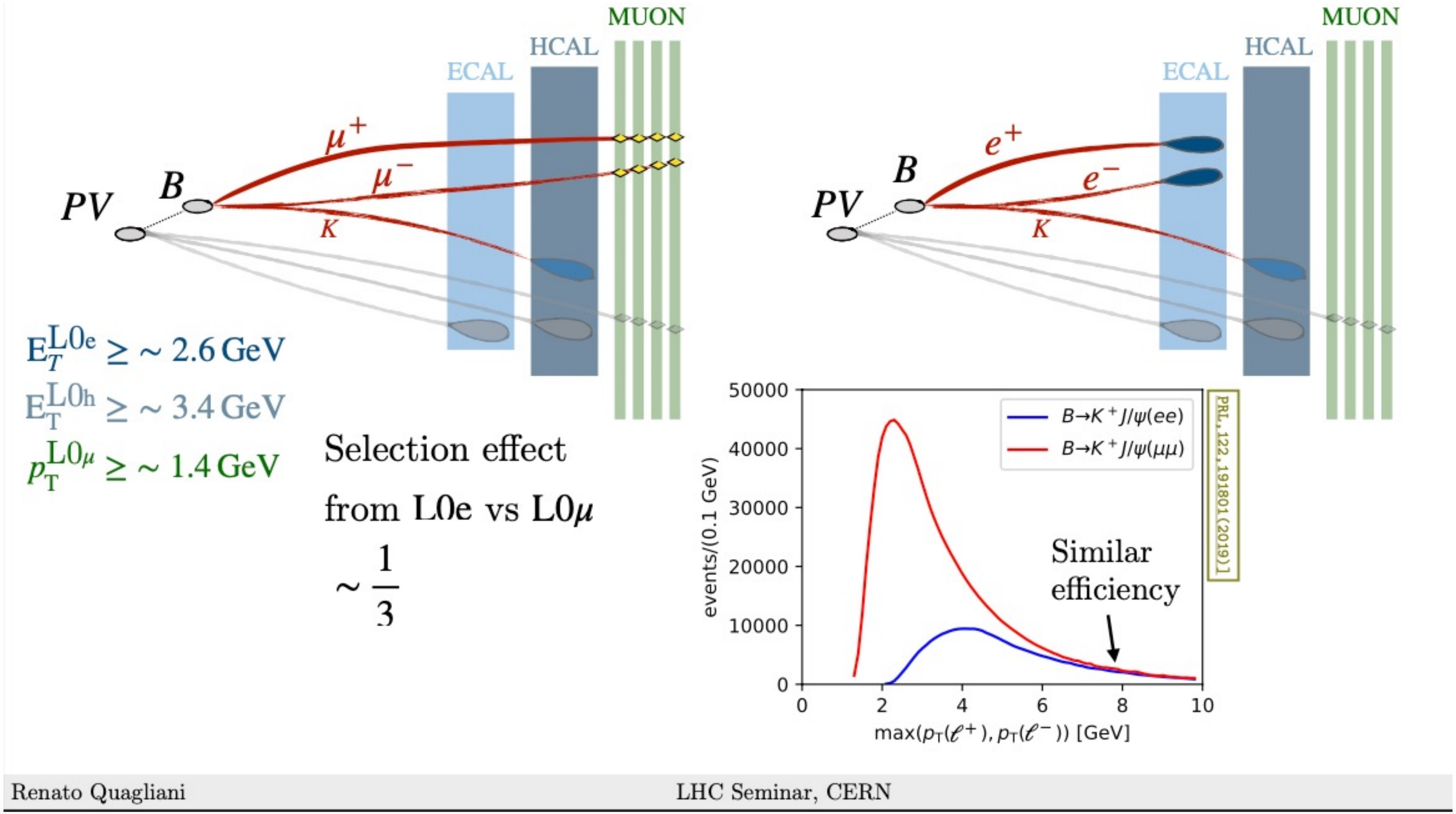
- Challenging electronic bkg make this analysis complicated
- The measurement of R_{K^*} at high-q^2 will be an important addition LFU tests

BACKUP

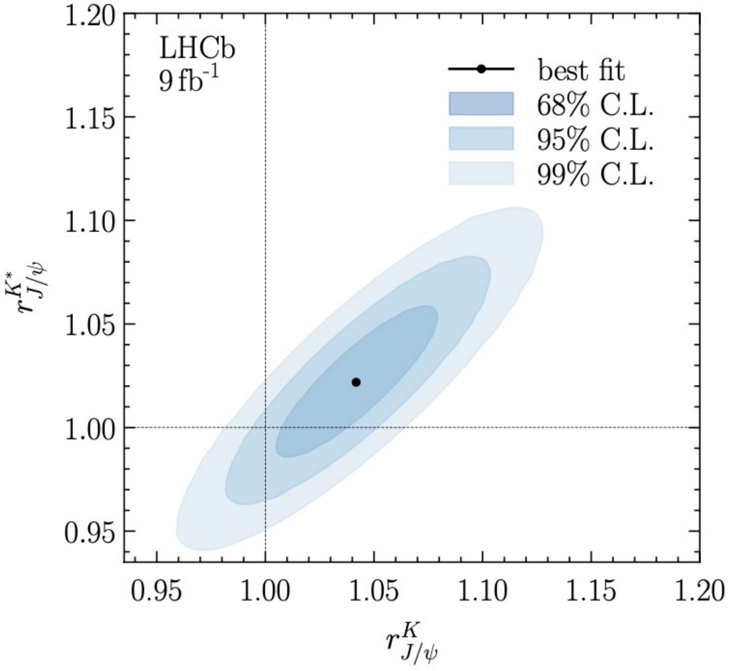
Comparison of $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$

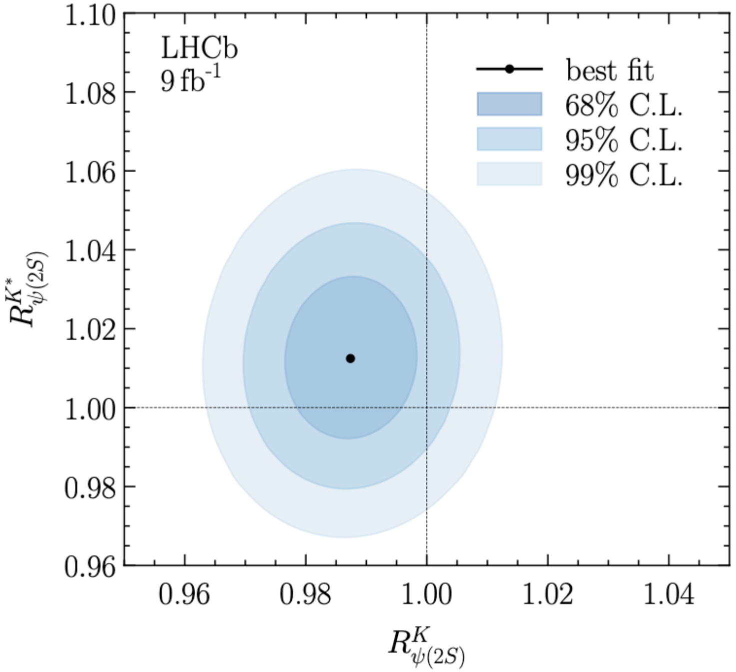


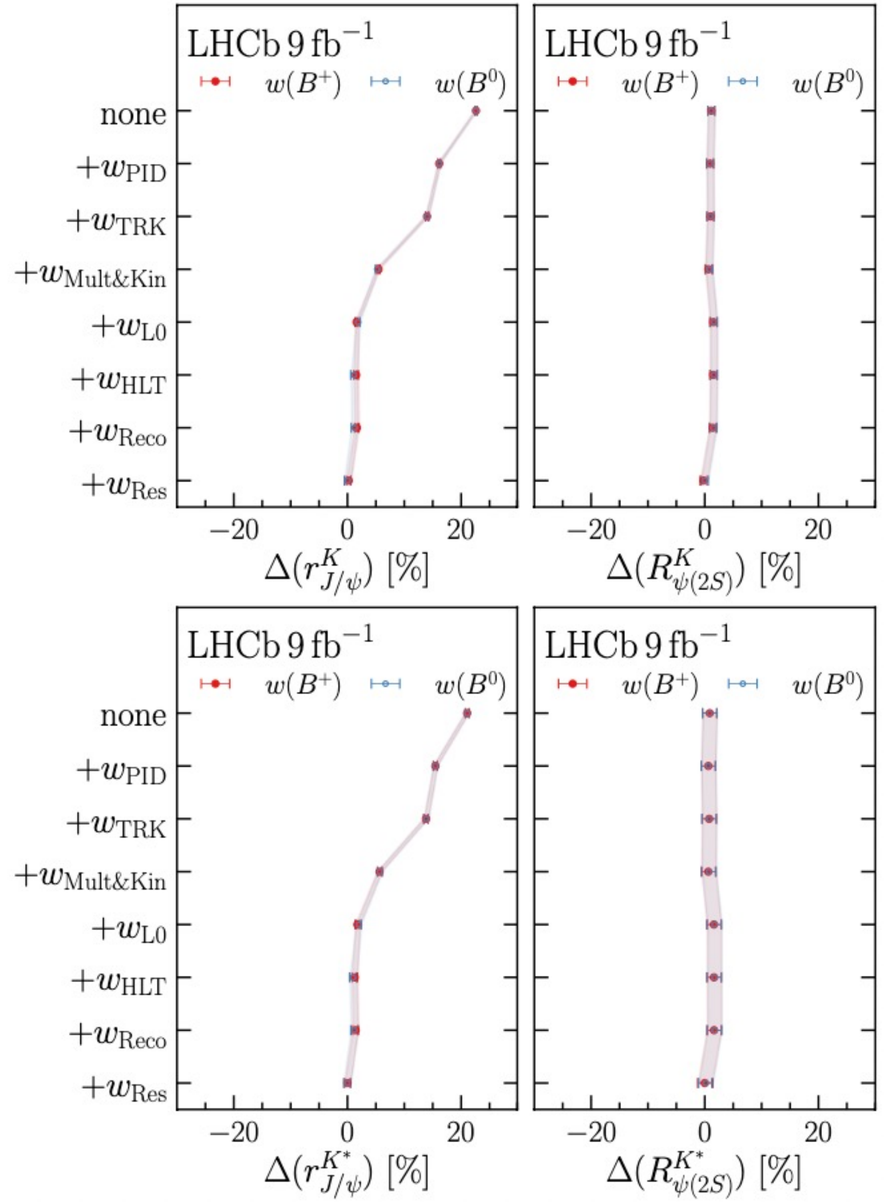
Hardware trigger: major differences in efficiency differences



RX: measurements of $r_{J/\psi}$ and $R_{\psi(2S)}$





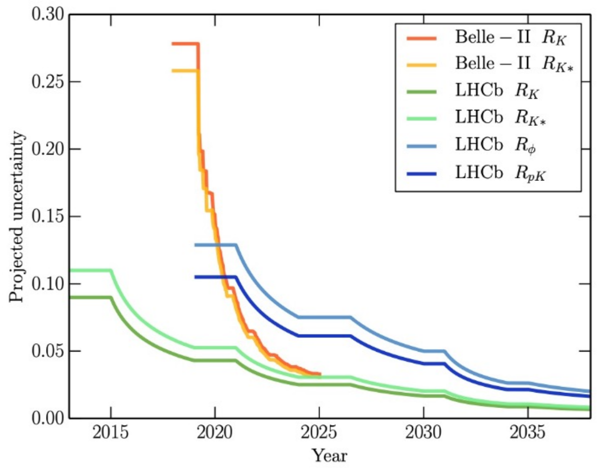


Comparison of Belle II with LHCb

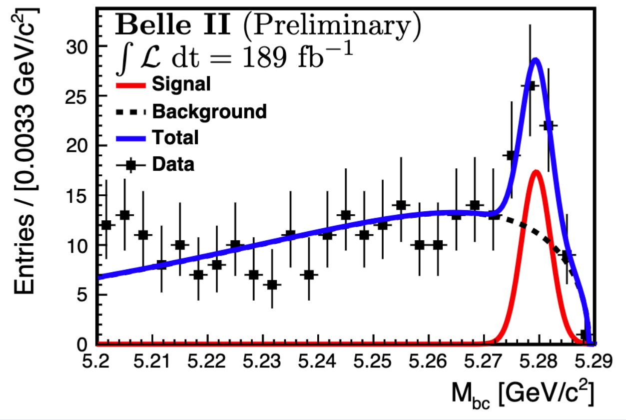
- Belle II experiment: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- Complementarity with LHCb: excellent reconstruction of neutral particles

The Belle II Physics Book [PTEP 2019 (2019) 12, 123C01]

Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
R_K ([1.0, 6.0] GeV^2)	28%	11%	3.6%
R_K (>14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ([1.0, 6.0] GeV^2)	26%	10%	3.2%
R_{K^*} (>14.4 GeV^2)	24%	9.2%	2.8%



$B^0 \to K^* l^+ l^-$: 40 events



- 2022: Belle II sample $\sim$**0.5**× Belle.
- Very similar distributions for $B^0 \to K^*\mu^+\mu^-$ and $B^0 \to K^*e^+e^-$