This work was funded by:

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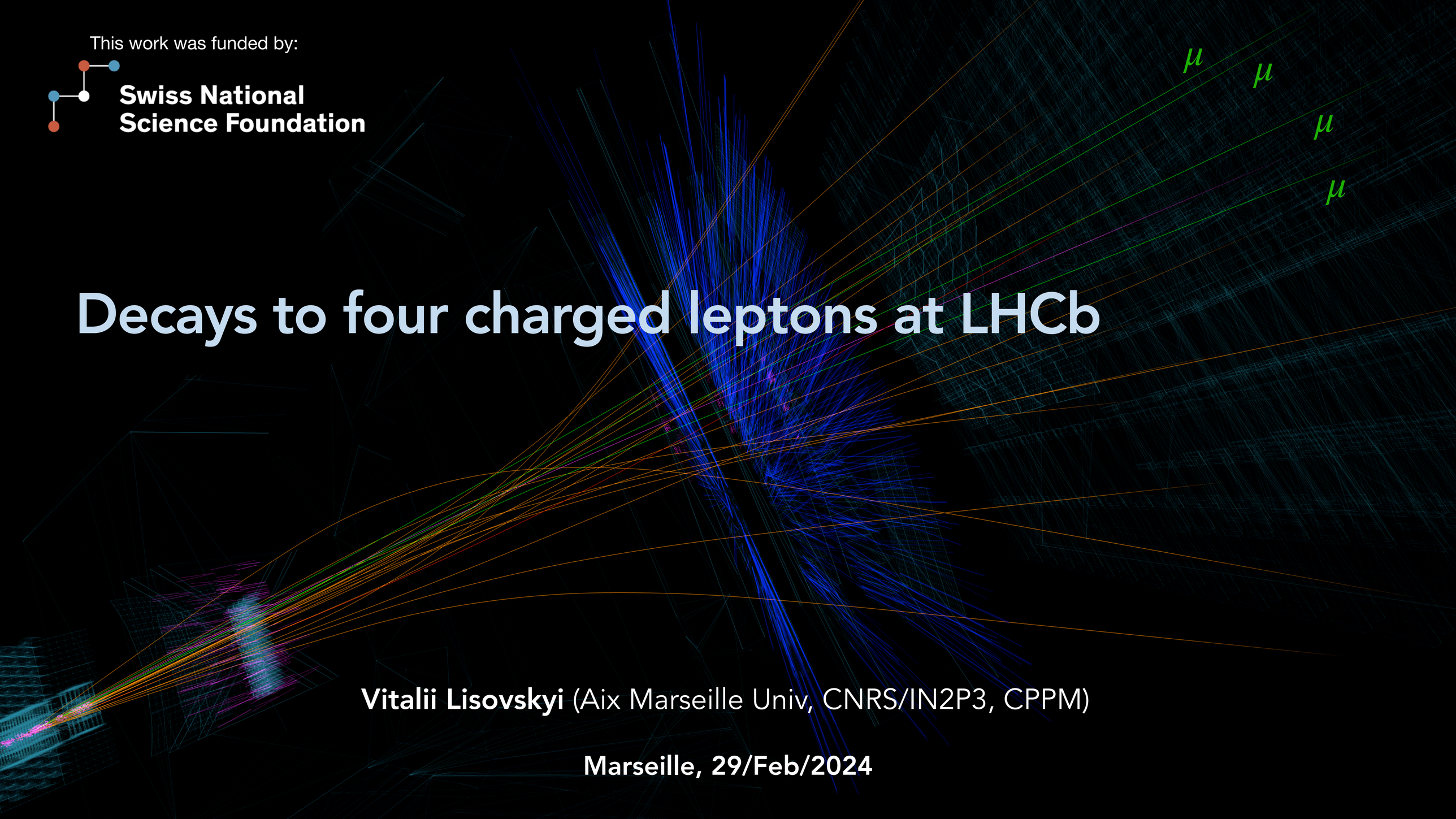


Decays to four charged leptons at LHCb

Vitalii Lisovskyi (Aix Marseille Univ, CNRS/IN2P3, CPPM)

Marseille, 29/Feb/2024

Impostor alert

- A Belle II person speaking about LHCb measurements :)
  - Some slides refurbished from Harry Cliff (thanks!)

Why multileptons?

- Previous talks (Pierre et al) motivated $B^{\pm} \to \ell^{\pm}\ell^{\mp}\ell^{\pm}\nu_{\ell}$ as hadron-collider-friendly siblings of $B^{\pm} \to \ell^{\pm}\nu_{\ell}$ and $B^{\pm} \to \ell^{\pm}\nu_{\ell}\gamma$

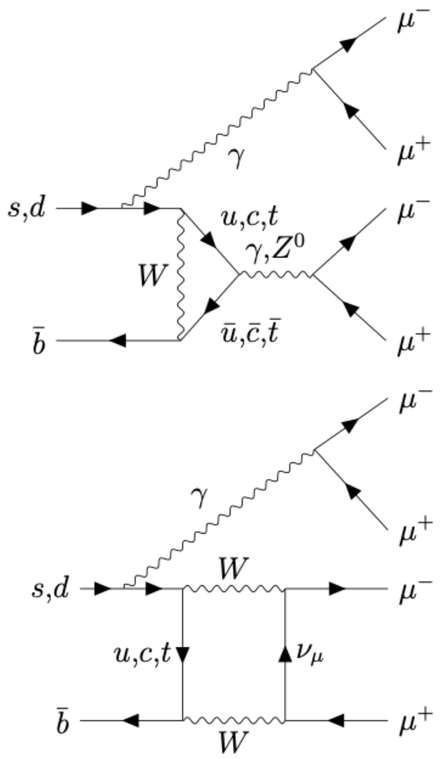
- **The same idea can be applied to (already friendly) decays without neutrinos:**
  - $B^0_{(s)} \to \mu^+\mu^-$ or $B^0_{(s)} \to \gamma\gamma$ are linked to $B^0_{(s)} \to \ell^+\ell^-\ell^+\ell^-$
    - Helicity-suppression (partially?) lifted → all lepton flavours are okay
    - Very rare nevertheless (loop and α^2)
  - Can also play the same trick on electromagnetic decays: $\psi \to \ell^+\ell^-\ell^+\ell^-$ to validate the experimental procedure, more on this later
    - Not so rare (tree but α^2), allows to see an actual signal peak

B to four leptons

- Several important SM contributions:

Each of those three contributions is treated separately in the analysis.

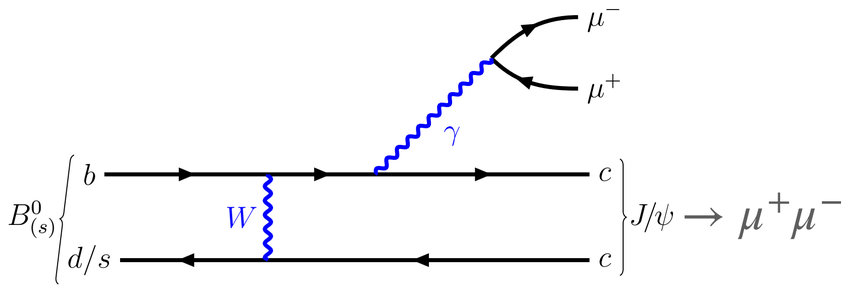
penguin+box ISR/FSR



rate $\sim 10^{-10}$ for B_s^0, 10^{-12} for B^0

[Danilina, Nikitin, Phys. Atom. Nuclei 81, 347–359 (2018)]

W exchange FSR/ISR

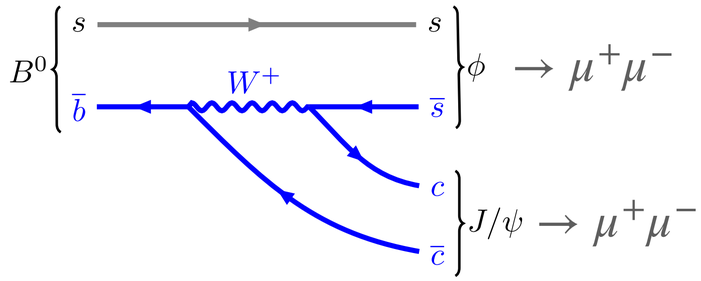


rate $\sim 10^{-10}$ for B_s^0 but mind $\mathcal{B}(J/\psi \to \mu\mu)$

[Nucl.Phys.B 577 (2000) 240-260]

Related to $B_s^0 \to J/\psi\gamma$ for which LHCb limit is <7.3e-6

Tree



"huge" compared to the rest:
effective BF~1.7e-8,
used as a normalisation mode

Other possible contributions e.g. $B_s^0 \to \phi(\mu\mu)\mu\mu$ or $B_s^0 \to \phi(\mu\mu)\phi(\mu\mu)$ are not considered, below experimental sensitivity

B to four leptons: BSM?

- Essence of the proposed BSM scenarios: $B \to a a^{(\prime)} \to 4\mu$
  - Several models on the market: some inspired by the $(g-2)_\mu$ or R_K which were superstars back 5 years ago; others are 
- A selection of models: (*don't ask me about it please*)
  - Light scalars and heavy vectors (Chala et al, Eur.Phys.J.C 79 (2019) 5, 431)
  - Hierarchical new physics with multiple scalars (Ramos et al, JHEP 11 (2022) 027)
  - Sglodstino pair production scalar+pseudoscalar (Demidov et al, Phys.Rev.D 85 (2012) 077701)
  - HyperCP anomaly...
  - *apologies for missing your favourite model here*
- Note: experimental signature is different if the BSM particle is long-lived: not covered by any published search yet.

B to four leptons: experimentalist's approach

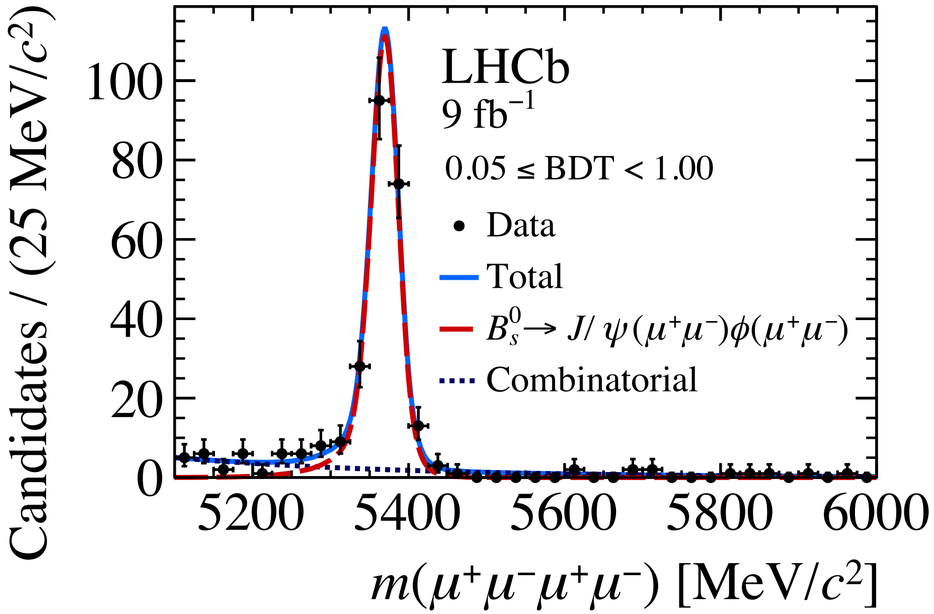
Tree-level

- Require one dimuon combination around the ϕ and one around the J/ψ
- The yield is quite small (~220 evts) due to low $\mathcal{B}(\phi \to \mu\mu)$

I will not bore you with selection details:
they are quite straightforward in this analysis.

Muon ID + a standard multivariate selection
against accidental combinations do all the job.

Important to know:
LHCb muon system requires $p > 3$ GeV for each muon!

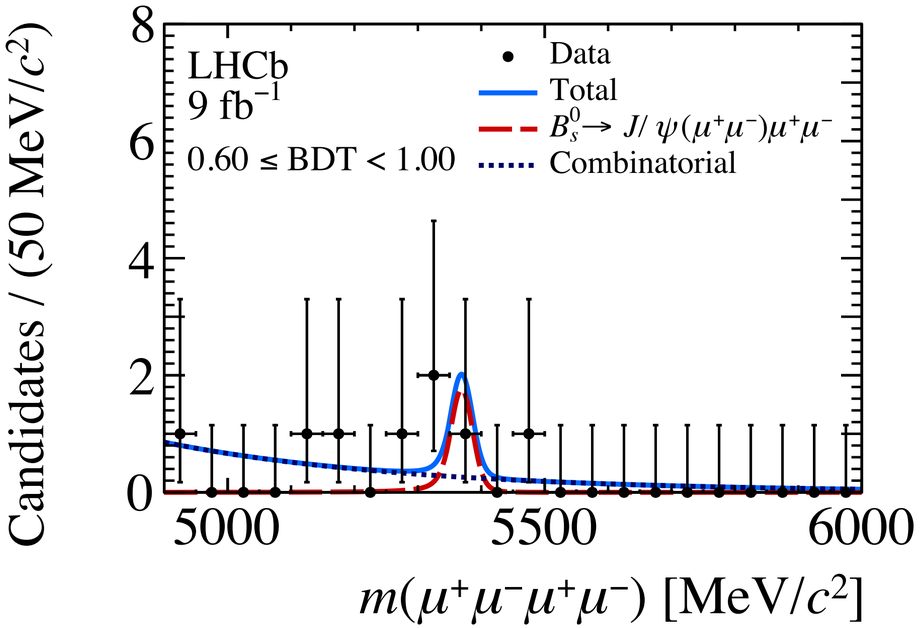


W exchange

- Require one dimuon combination around the J/ψ, veto the ϕ
- Misidentified $B \to J/\psi hh'$ could contribute: tight muon ID applied
- No significant signals, upper limits set at 95% CL:

$$\mathcal{B}(B_s^0 \to J/\psi(\mu^+\mu^-)\mu^+\mu^-) < 2.6 \times 10^{-9}$$
$$\mathcal{B}(B^0 \to J/\psi(\mu^+\mu^-)\mu^+\mu^-) < 1.0 \times 10^{-9}$$

(this includes $\mathcal{B}(J/\psi \to \mu^+\mu^-)$)



Loop

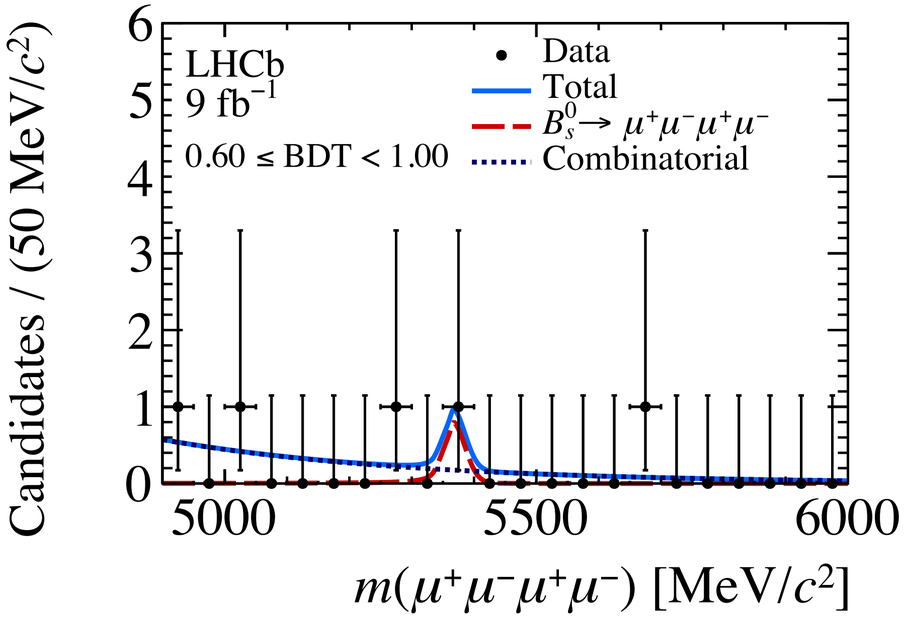
- Veto the ϕ, J/ψ, $\psi(2S)$ in any dimuon combination and consider all the rest

- No significant signals, either, upper limits set at 95% CL:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\mu^+\mu^-) < 8.6 \times 10^{-10}$$

factor <10 above the SM rate

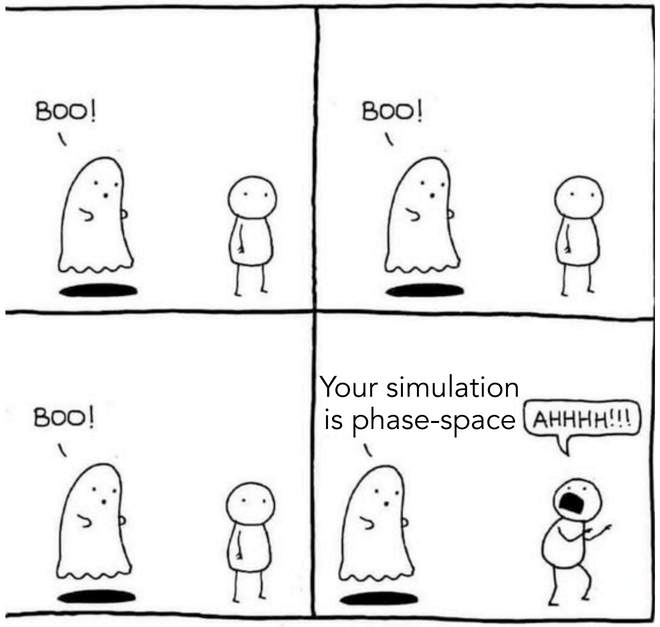
$$\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 1.8 \times 10^{-10}$$



- Upper limits also set on a specific NP model:
  a pair of 1-GeV scalar (otherwise does not pass the phi veto)
- See also the Run 1 paper JHEP 03 (2017) 001 for limits on sgoldstino scenarios

Decay model

- For the nonresonant $B_s^0 \to \mu^+\mu^-\mu^+\mu^-$ decays, the phase-space model is used
- But: muon reconstruction efficiencies depend on muon momenta
  - If there is a photon pole = more soft muons = lower efficiency!
- **20% systematic uncertainty** due to efficiency variations across the phase-space
  - Can actually be an important effect if we saw the signal, ok for an upper limit



- A theory+experiment initiative at TU Dortmund (Stamou, Wagner, Albrecht et al) to develop a reliable SM prediction and an EvtGen model targeting the Run3 analysis

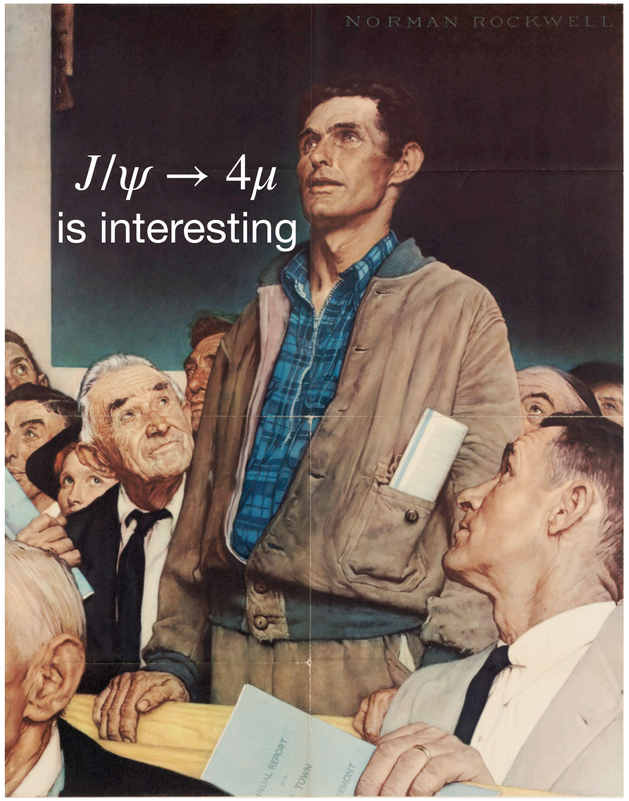
B to four leptons: what next?

- Run 3 data can actually help to reach the SM sensitivity goalpost for $B_s^0 \to \mu\mu\mu\mu$!
  - Reliable SM predictions can be useful ;)

- Straightforward next steps (planned/ongoing at LHCb):
  - $B_s^0 \to \mu\mu ee$: interesting interplay with the $B_s^0 \to \mu\mu\gamma$ at very low q^2 (+ photon conversions in the material).
  - $B^+ \to K^+\mu\mu\mu\mu$: larger B^+ production rate helps
  - $B \to \mu\mu\mu\mu(K)$ with long-lived intermediate particles decaying to dimuons
  - Six muons, anyone? [see Phys.Rev.D 100 (2019) 11, 115015]

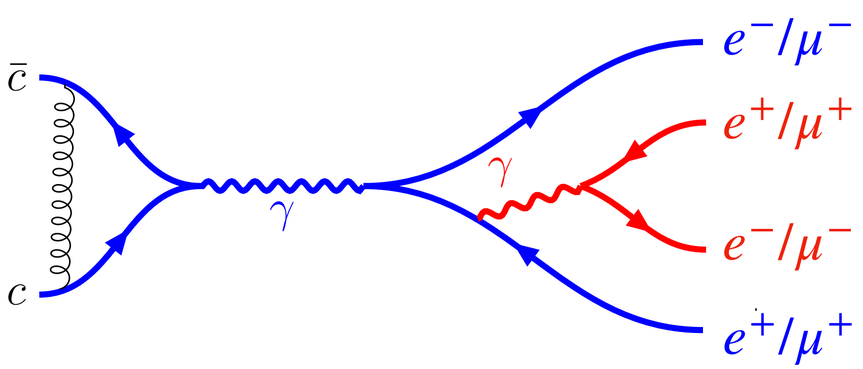
An experimentalist's digression

- I mentioned $B^+ \to K^+\mu\mu\mu\mu$.
- What kind of resonant contributions does one expect here?
  - $B^+ \to K^+ J/\psi(\mu\mu)\mu\mu$ with all the possible $B^+ \to K^+(\chi_c \to J/\psi(\mu\mu)\mu\mu)$, $B^+ \to K^+ J/\psi(\mu\mu)V(\mu\mu)$ etc
  - $B^+ \to K^+ J/\psi(\mu\mu\mu\mu)$
- At this point we realised that the decay $J/\psi \to \mu\mu\mu\mu$ was not seen yet!
- **Let's talk about it.**



J/ψ decays to four leptons

- Final-state radiation of a virtual photon from the $J/\psi \to \mu^+\mu^-$ or $J/\psi \to e^+e^-$

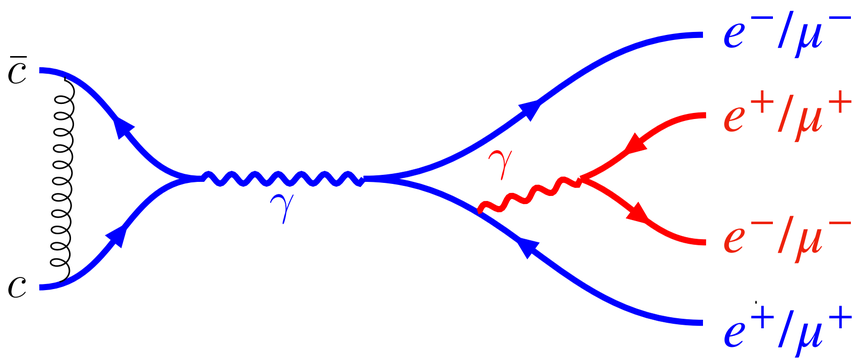


- Initial-state radiation process suppressed by C parity: $J/\psi \to \gamma\gamma$ is forbidden
  - strictly 0 for on-shell photons (Landau-Yang theorem)
  - *is this still true for virtual photons?*
- No significant contribution from intermediate vector resonances: $J/\psi \to VV \to 4\mu$ violates C parity
- A clean FSR process with future applications and sensitivity to possible BSM $J/\psi \to XX \to 4\mu$ scenarios

Observing the $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ signal would allow to validate the simulated description of the $\gamma^* \to \mu^+\mu^-$.

J/ψ decays to four leptons

- Final-state radiation of a virtual photon from the $J/\psi \to \mu^+\mu^-$ or $J/\psi \to e^+e^-$



- Ratio of decay rates to **4 leptons** / 2 leptons can be predicted in QED

- Predicted LO-QED decay rates [Chen et al., PRD 104 (2021) 9, 094023]:

Decay	$\mathcal{B}(4\ell)/\mathcal{B}(2\ell)$	$\mathcal{B}(4\ell)$
$J/\psi \to e^+e^-e^+e^-$	8.85×10^{-4}	5.288×10^{-5}
$J/\psi \to e^+e^-\mu^+\mu^-$	6.31×10^{-4}	3.763×10^{-5}
$J/\psi \to \mu^+\mu^-\mu^+\mu^-$	0.163×10^{-4}	0.0974×10^{-5}

size of QED/QCD uncertainties unclear

- Virtual photon → decay rates falls with $\sim 1/m^2_{\ell^+\ell^-}$
- Rate larger for e^+e^- modes: enhancement at low $m_{e^+e^-}$ (below the dimuon threshold)
- Identical leptons create interference

Can we trust these predictions?

The BES III saga

- The BES III experiment studied four-lepton Jpsi decays [arXiv:2111.13881]
- Original arXiv submission (late 2021) claimed a discrepancy with the SM

> Using a data sample of 4.481×10^8 $\psi(3686)$ events collected with the BESIII detector, we report the first observation of the four-lepton-decays $J/\psi \to e^+e^-e^+e^-$ and $J/\psi \to e^+e^-\mu^+\mu^-$ utilizing the process $\psi(3686) \to \pi^+\pi^- J/\psi$. The branching fractions are determined to be $[4.32 \pm 0.26\ (\text{stat}) \pm 0.19\ (\text{syst})] \times 10^{-5}$ and $[2.45\ \pm 0.21\ (\text{stat}) \pm 0.10\ (\text{syst})] \times 10^{-5}$, respectively. The results deviate from theoretical predictions, by 2.8 and 5.2 σ, respectively. No significant signal is observed for $J/\psi \to \mu^+\mu^-\mu^+\mu^-$, and an upper limit on the branching fraction is set at 1.6×10^{-6} at the 90% confidence level. A CP asymmetry observable is constructed for the first two channels, which is measured to be $(-0.019 \pm 0.067 \pm 0.025)$ and $(-0.016 \pm 0.081 \pm 0.003)$, respectively. No evidence for CP violation is observed in this process.

  - This version has never been published in a journal

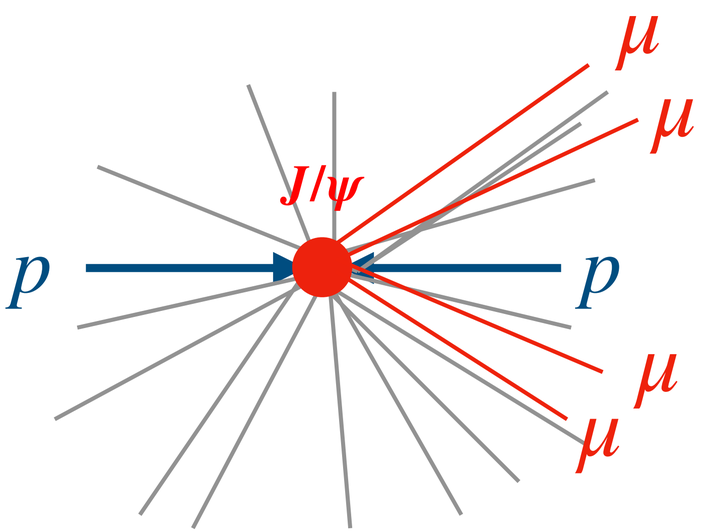
- A corrected version (Sept 2023, v3 on arXiv): good agreement with the SM

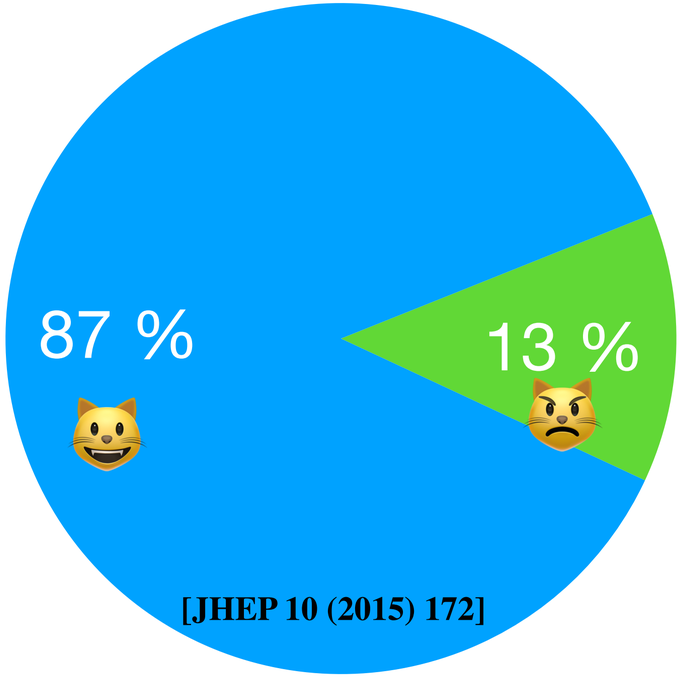
> Using a data sample of 4.481×10^8 $\psi(3686)$ events collected with the BESIII detector, we report the first observation of the four-lepton-decays $J/\psi \to e^+e^-e^+e^-$ and $J/\psi \to e^+e^-\mu^+\mu^-$ utilizing the process $\psi(3686) \to \pi^+\pi^- J/\psi$. The branching fractions are determined to be $[5.48 \pm 0.31\ (\text{stat}) \pm 0.45\ (\text{syst})] \times 10^{-5}$ and $[3.53\ \pm 0.22\ (\text{stat}) \pm 0.13\ (\text{syst})] \times 10^{-5}$, respectively. The results are consistent with theoretical predictions. No significant signal is observed for $J/\psi \to \mu^+\mu^-\mu^+\mu^-$, and an upper limit on the branching fraction is set at 1.6×10^{-6} at the 90% confidence level. A CP asymmetry observable is constructed for the first two channels, which is measured to be $(-0.012 \pm 0.054 \pm 0.010)$ and $(0.062 \pm 0.059 \pm 0.006)$, respectively. No evidence for CP violation is observed in this process.

An LHCb measurement of $J/\psi \to \mu^+\mu^-\mu^+\mu^-$ would help to complete the puzzle

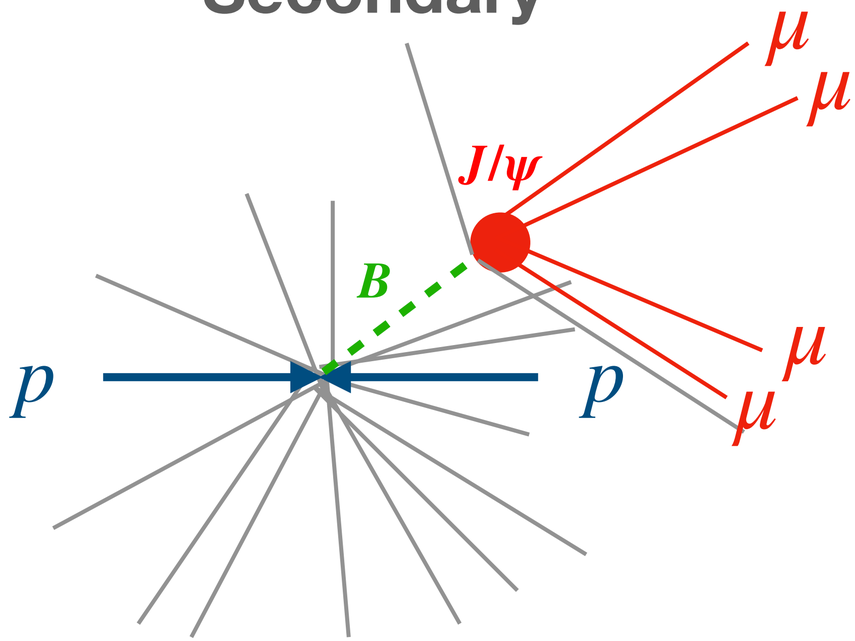
Production of J/ψ mesons at LHCb

Prompt





Secondary



High background 😾

Tight trigger selection 😾

Displacement: lower background 😺

Profit from B-physics triggers 😺

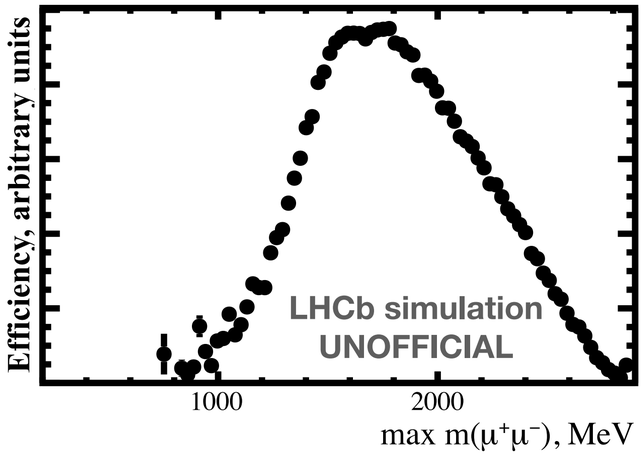
The two methods provide a valuable cross-check of experimental procedure.

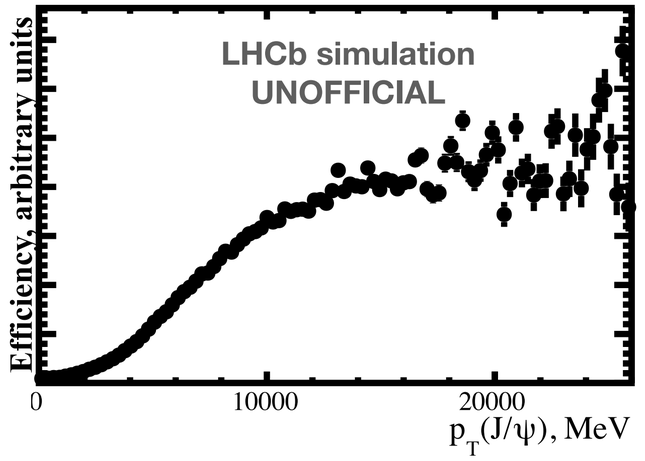
Efficiency dependence

Even more important
for $J/\psi \to e^+e^-\mu^+\mu^-$
(photon pole)

The LHCb reconstruction+preselection efficiency as a function of kinematics:
(The *total* efficiency trend will be even more complicated)

Prompt





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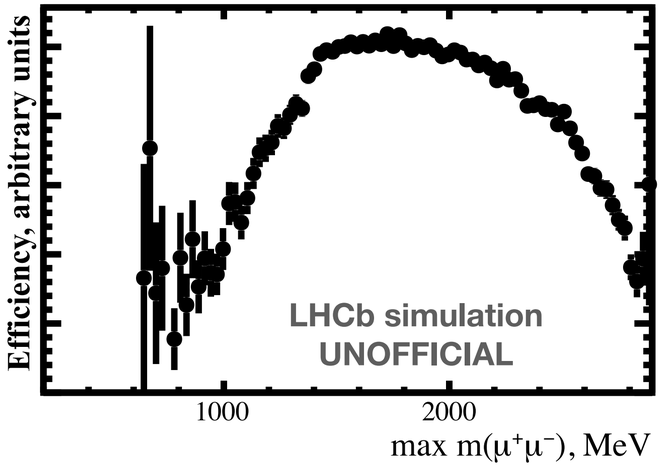

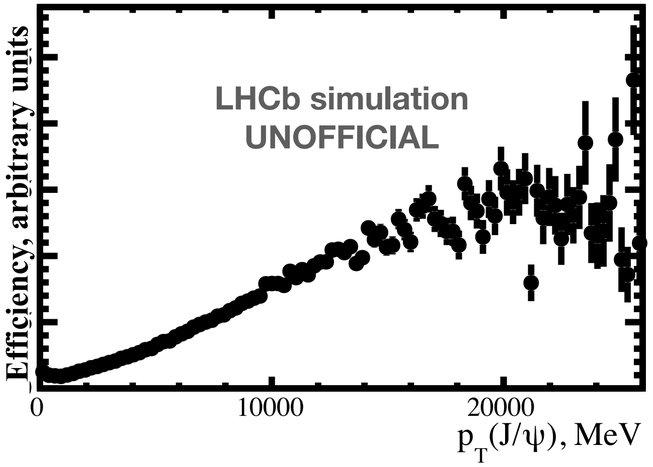

Highlights importance of having the correct decay model in simulation!

Discusion item: model-independent presentation of results?

Summary

- Multilepton decays await to be explored, many possible surprises
- LHCb Run3 data would be interesting, as well as data from other experiments
  - I did not talk about: recent CMS result on $\eta \to 4\mu$ (two-photon diagram = not FSR), similar BES results...
- Theory guidance would be helpful
  - **Reliable simulation models (EvtGen) are crucial**, large biases possible otherwise!
  - Measured BF values depend on the theory assumptions in LHCb simulation

https://www.smbc-comics.com/?id=2088