



Ultimi risultati per i decadimenti rari ed estremamente rari a LHCb

Gabriele Martelli

Università degli Studi di Perugia e INFN Perugia

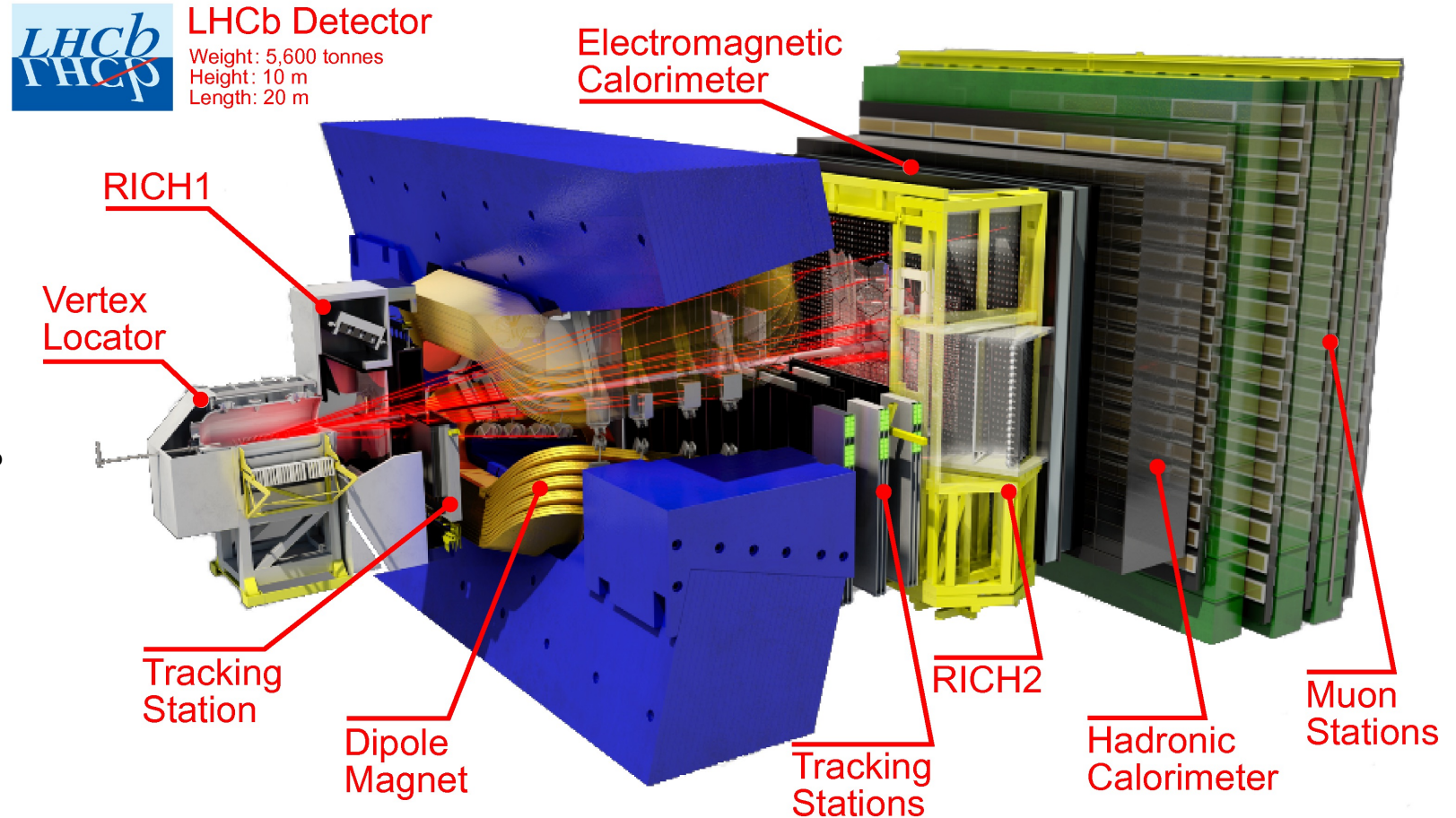
A nome della collaborazione LHCb

Firenze, 3 – 5 Aprile 2024

Incontri di Fisica delle Alte Energie

- *"Observation of the rare decay $J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ "*
 - Ad oggi la misura più precisa su $\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-)$
 - [LHCb-CONF-2024-001](#) - Articolo in preparazione
- *"Search for the $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ "*
 - Primo limite con la ricostruzione completa dello stato finale
 - [LHCb-PAPER-2023-045](#) - Articolo in preparazione
- *"Measurement of the branching fraction ratio $\mathcal{B}(\phi \rightarrow \mu^+ \mu^-)/\mathcal{B}(\phi \rightarrow e^+ e^-)$ with charm meson decays"*
 - Primo test di LFU nei decadimenti dei mesoni ϕ
 - [\[arXiv:2402.01336\]](#) - Sottomesso il 2 Febbraio 2024 alla rivista [JHEP](#)
- *"Comprehensive analysis of local and nonlocal amplitudes in the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay"*
 - Analisi d'ampiezza
 - Misura diretta dei coefficienti di Wilson
 - [LHCb-PAPER-2024-011](#) - Articolo in preparazione

- ▶ Spettrometro a singolo braccio in avanti
- ▶ Pseudorapidità coperta: $2 < \eta < 5$
- ▶ **Vertex Locator**
 - Ricostruzione dei vertici di decadimento
 - Risoluzione sul tempo di decadimento: 45 fs
 - Risoluzione sul punto di interazione: 20 μm
- ▶ **Dipole Magnet**
 - Forza di deflessione: 4 Tm
- ▶ **Stazioni di tracking TT e OT**
 - Risoluzione sul momento $\Delta p/p = 0.5\% - 1.0\%$
(5 GeV/c – 100 GeV/c)
- ▶ **Rivelatori RICH**
 - Efficienza di separazione $\varepsilon(K \rightarrow \pi) \sim 95\%$
mis-ID $\varepsilon(\pi \rightarrow K) \sim 5\%$
- ▶ **Calorimetri (ECAL, HCAL)**
 - Identificazione e misura energetica di e/γ
 - $\Delta E/E = 1\% \oplus 10\%/\sqrt{E}$ (GeV)
- ▶ **Stazioni muoniche**
 - Efficienza di identificazione $\varepsilon(\mu \rightarrow \mu) \sim 97\%$, mis-ID $\varepsilon(\pi \rightarrow \mu) \sim 1-3\%$



[JINST 3 (2008) S08005]

[IJMPA 30 (2015) 1530022]

- $J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ è un decadimento elettromagnetico raro
 - Stato finale radiativo (FSR) con emissione di γ^* da $J/\psi \rightarrow \mu^+ \mu^-$
 - Predizione del Modello Standard:
 $B(J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-) = (9.74 \pm 0.05) \times 10^{-7}$ [[Phys. Rev. D 104, 094023](#)]

- Interesse
 - Studio di processi elettromagnetici rari e QED
 - ✓ Larghezza di decadimento forte soppressa - **regola OZI**
 - Ricerca di Nuova Fisica nel processo FSR
 - ✓ $J/\psi \rightarrow XX \rightarrow \mu^+ \mu^- \mu^+ \mu^-$

➤ Stato dell'arte

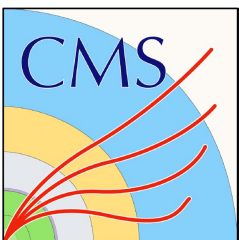


$$J/\psi \rightarrow e^+ e^- e^+ e^- \quad \checkmark$$

$$J/\psi \rightarrow e^+ e^- \mu^+ \mu^- \quad \checkmark$$

$$B(J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 16 \times 10^{-7} \quad \times$$

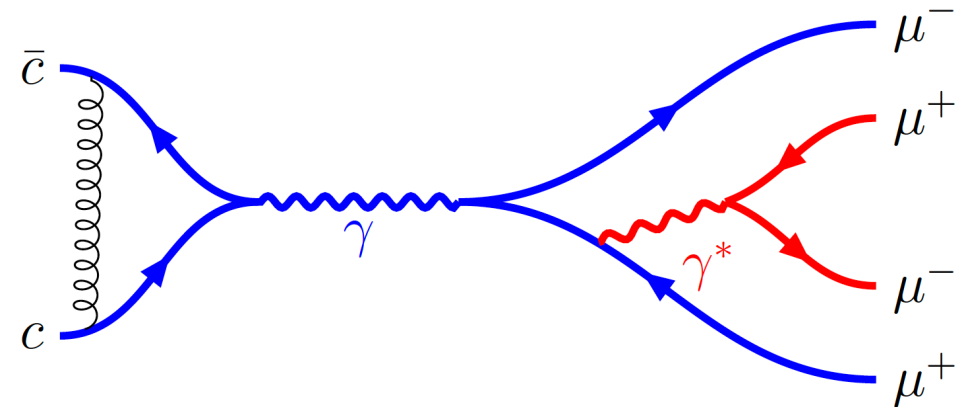
[[Phys. Rev. D 109, 052006](#)]



$$B(J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-) = (10.1_{-2.7}^{+3.3} \pm 0.4) \times 10^{-7} \quad \checkmark$$

[[arXiv:2403.11352](#)]

Presentato a
Moriond EW+U 2024



- $J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ è un decadimento elettromagnetico raro
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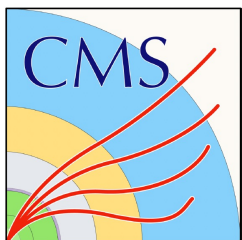


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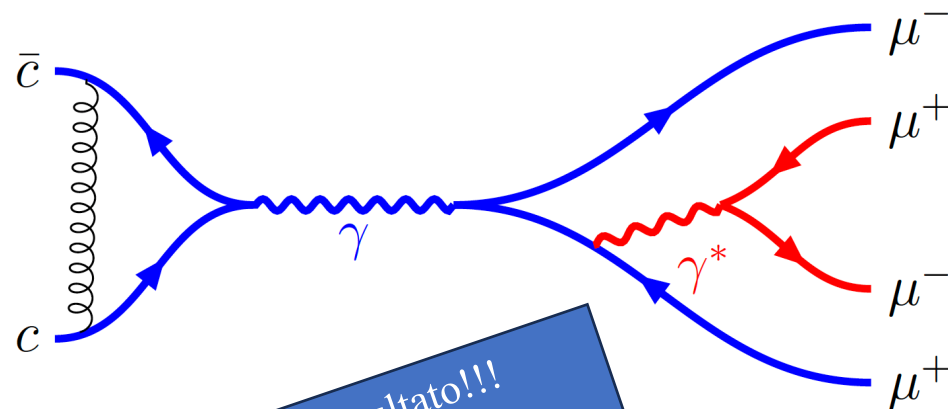
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[[arXiv:2403.11352](#)]

Presentato a
Moriond EW+U 2024



Nuovo risultato!!!
Presentato a
Moriond QCD 2024



- "Observation of the rare decay $J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ "
 - LHCb-CONF-2024-001 - Articolo in preparazione
 - $\sqrt{s} = 13 \text{ TeV}$, $\mathcal{L} = 5.4 \text{ fb}^{-1}$

- Strategia
 - Misura di $\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-)$
 - Analisi su campioni "prompt" e "secondari"
 - $J/\psi \rightarrow \mu^+ \mu^-$ come canale di normalizzazione

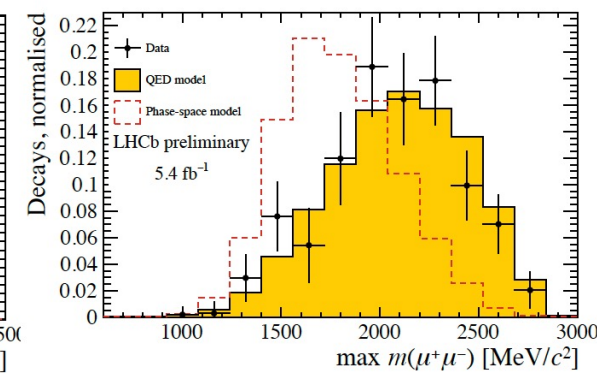
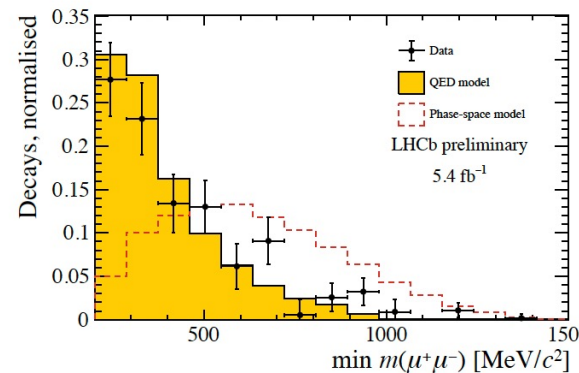
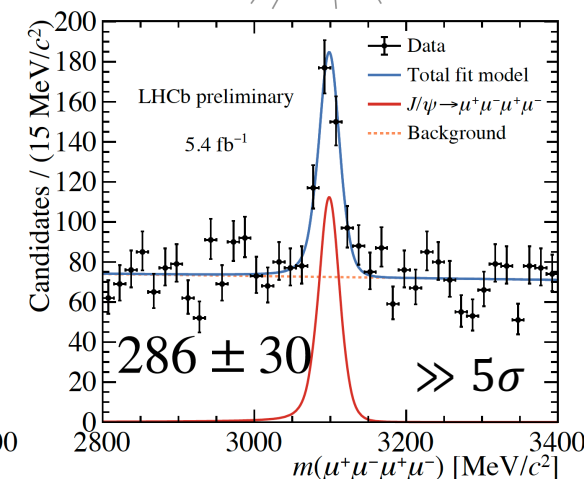
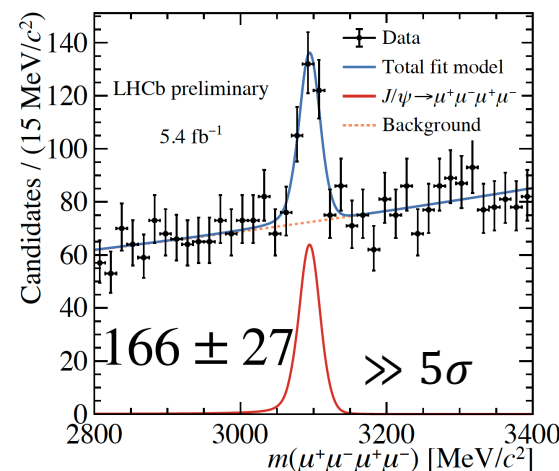
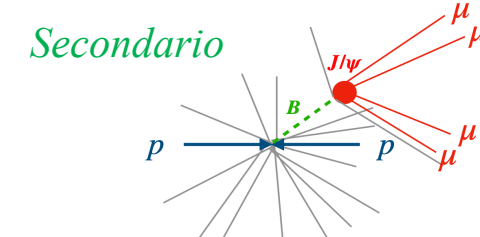
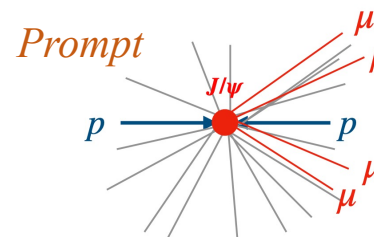
$$R_{BR} = \frac{\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-)}{\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)}$$

- Risultati

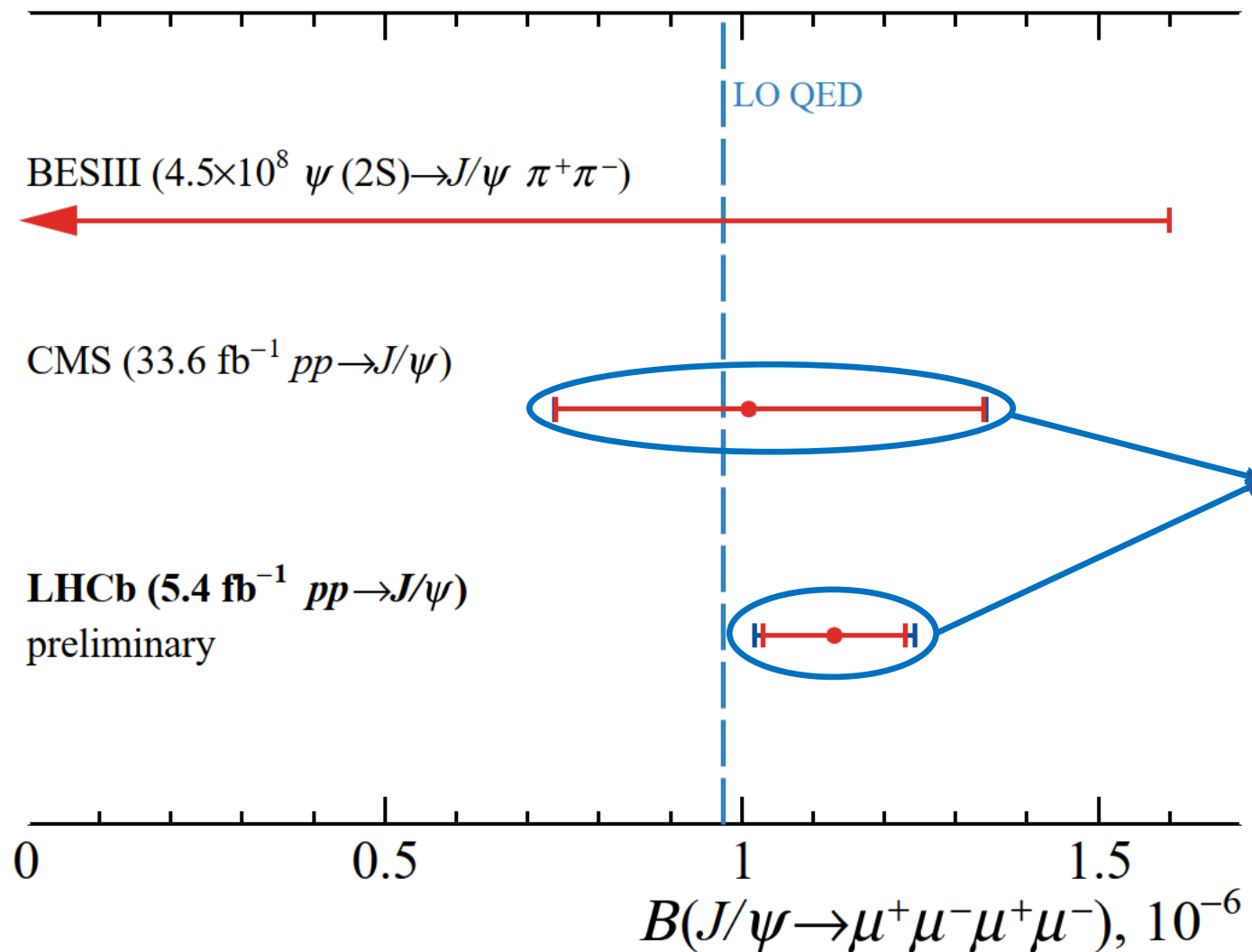
$$R_{BR} = (1.89 \pm 0.17_{stat.} \pm 0.08_{sist.}) \times 10^{-5}$$

$$\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-) = (1.13 \pm 0.10_{stat.} \pm 0.05_{sist.} \pm 0.01_{est.}) \times 10^{-6}$$

- Consistente con il Modello Standard entro $\sim 1.4\sigma$
 - ✓ Ad oggi la misura più precisa su $\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-)$
- Distribuzioni $m_{\mu^+ \mu^-}$ in accordo con i modelli QED
 - ✓ Nessuna struttura risonante osservata ...

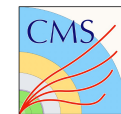


$J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ - Conclusioni



Principale differenza

- Modelli MC

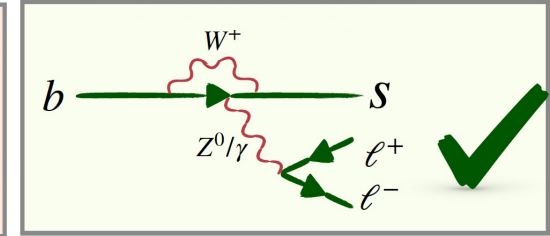
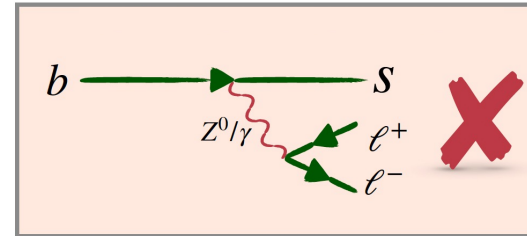


PHSP



Physics

$B_s^0 \rightarrow \mu^+ \mu^- \gamma$



- ▶ $b \rightarrow s \ell^+ \ell^-$ è soppressa al livello "albero"
 - Flavour Changing Neutral Current (FCNC)
 - Sensibile a contributi di Nuova Fisica

- ▶ Interesse
 - $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ è sensibile a molti operatori \mathcal{O}
 - ✓ $B_s^0 \rightarrow \mu^+ \mu^-$ sensibile solo a \mathcal{O}'_{10}
 - γ rimuove la soppressione chirale
 - ✓ $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma) \sim \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$

▶ Stato dell'arte



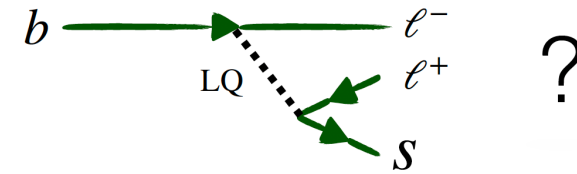
Prima ricerca

$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma) < 1.6 \times 10^{-7}$ ✗
[Phys. Rev. D 77 (2008) 011104]

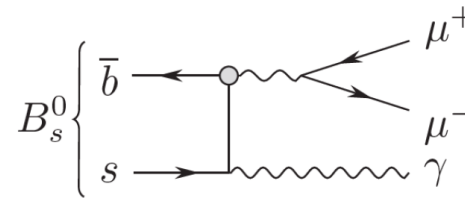


$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma) < 2.0 \times 10^{-9}$ ✗
[Phys. Rev. D105 (2022) 012010]

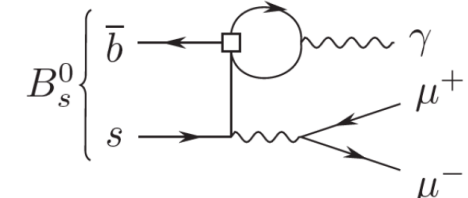
Parzialmente ricostruito
come fondo di $B_s^0 \rightarrow \mu^+ \mu^-$



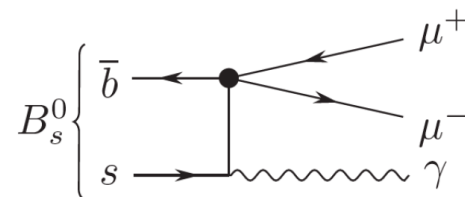
$\mathcal{O}_7^{(')}$ (a)



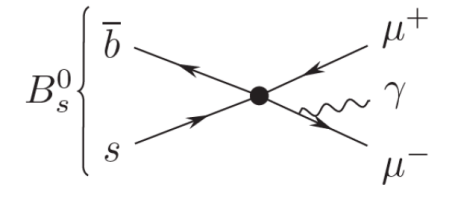
$\mathcal{O}_{1,2}$ (b)



$\mathcal{O}_{9,10}^{(')}$ (c)



$\mathcal{O}_{9,10}^{(')}$ (d)



"Search for the $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ "

- LHCb-PAPER-2023-045 - Articolo in preparazione
- $\sqrt{s} = 13 \text{ TeV}$, $\mathcal{L} = 5.4 \text{ fb}^{-1}$

Strategia

- Misura di $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma)$
 - ✓ Tre bin di q^2 (I, II, III)
- $B_s^0 \rightarrow J/\psi \eta$ come canale di normalizzazione
 - ✓ $J/\psi \rightarrow \mu^+ \mu^-$ e $\eta \rightarrow \gamma \gamma$

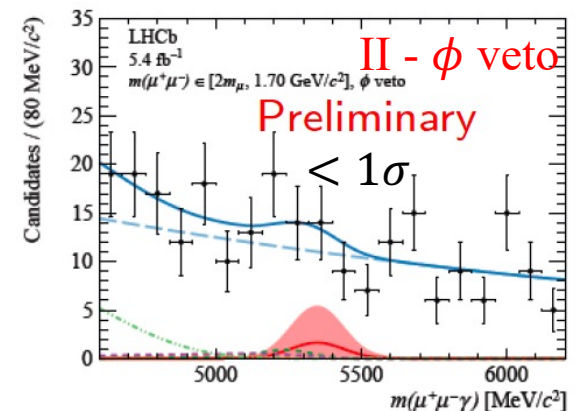
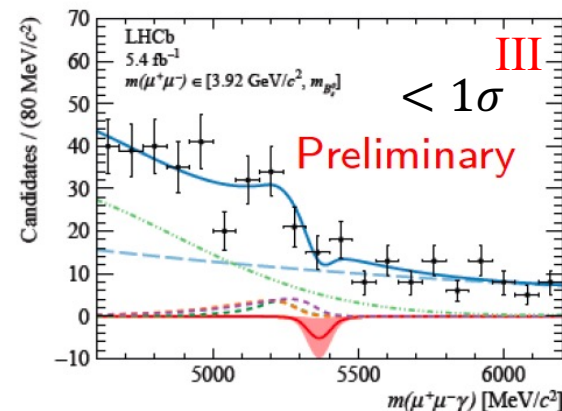
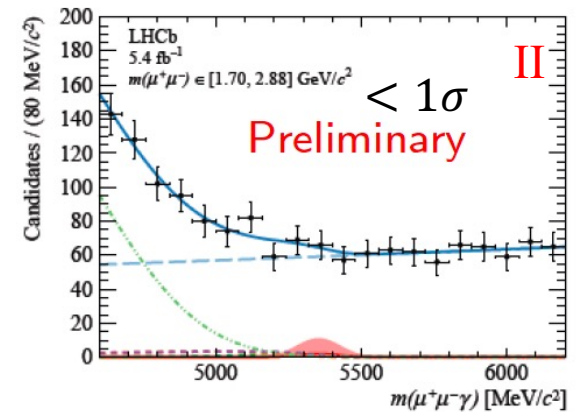
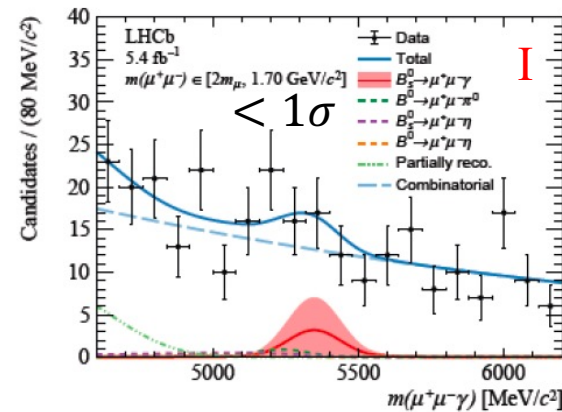
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma) = \frac{\mathcal{B}(B_s^0 \rightarrow J/\psi \eta)}{N_{B_s^0 \rightarrow J/\psi \eta}} \times \frac{\varepsilon_{B_s^0 \rightarrow J/\psi \eta}}{\varepsilon_{B_s^0 \rightarrow \mu^+ \mu^- \gamma}} \times N_{B_s^0 \rightarrow \mu^+ \mu^- \gamma}$$

Risultati

$$\begin{aligned} \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma)_{\text{I}} &= (1.34 \pm 1.60 \pm 0.28) \times 10^{-8}, \\ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma)_{\text{II}} &= (0.76 \pm 3.55 \pm 0.30) \times 10^{-8}, \\ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma)_{\text{III}} &= (-2.55 \pm 2.25 \pm 0.41) \times 10^{-8}, \\ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma)_{\text{I, with } \phi \text{ veto}} &= (0.72 \pm 1.56 \pm 0.29) \times 10^{-8}. \end{aligned}$$

- Dominati dall'incertezza statistica

q^2 bin	I	II	III
q^2 [GeV ² /c ⁴]	$[4m_\mu^2, 2.89]$	$[2.89, 8.29]$	$[15.37, m_{B_s}^2]$
$m(\mu^+ \mu^-)$ [GeV/c ²]	$[2m_\mu, 1.70]$	$[1.70, 2.88]$	$[3.92, m_{B_s}^0]$
$10^{10} \times \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma)$ [8]	82 ± 15	2.54 ± 0.34	9.1 ± 1.1
Fraction of $B_s^0 \rightarrow \mu^+ \mu^- \gamma$	87%	2.7%	9.8%



"Search for the $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ "

- LHCb-PAPER-2023-045 - Articolo in preparazione
- $\sqrt{s} = 13 \text{ TeV}$, $\mathcal{L} = 5.4 \text{ fb}^{-1}$

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- Misura di $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma)$
 - ✓ Tre bin di q^2 (I, II, III)
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 - ✓ $J/\psi \rightarrow \mu^+ \mu^-$ e $\eta \rightarrow \gamma \gamma$

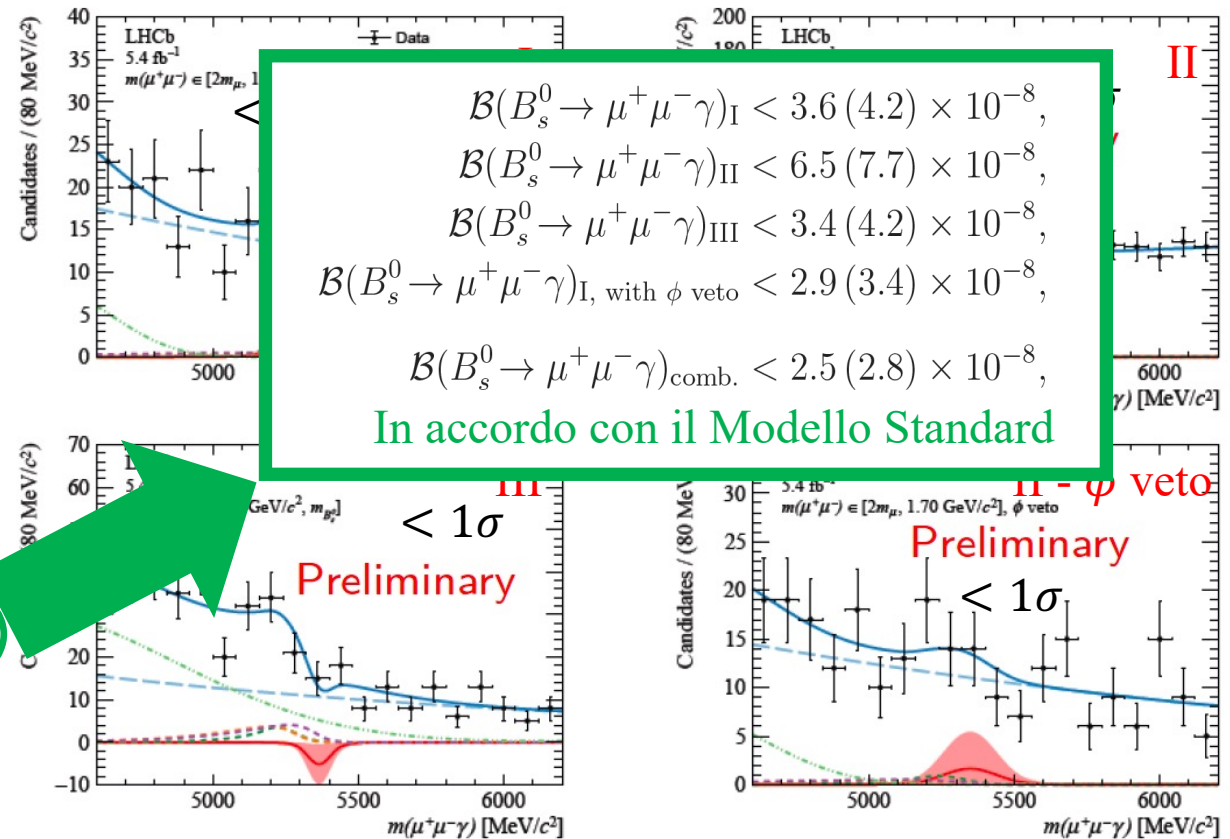
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma) = \frac{\mathcal{B}(B_s^0 \rightarrow J/\psi \eta)}{N_{B_s^0 \rightarrow J/\psi \eta}} \times \frac{\epsilon_{B_s^0 \rightarrow J/\psi \eta}}{\epsilon_{B_s^0 \rightarrow \mu^+ \mu^- \gamma}} \times N_{B_s^0 \rightarrow \mu^+ \mu^- \gamma}$$

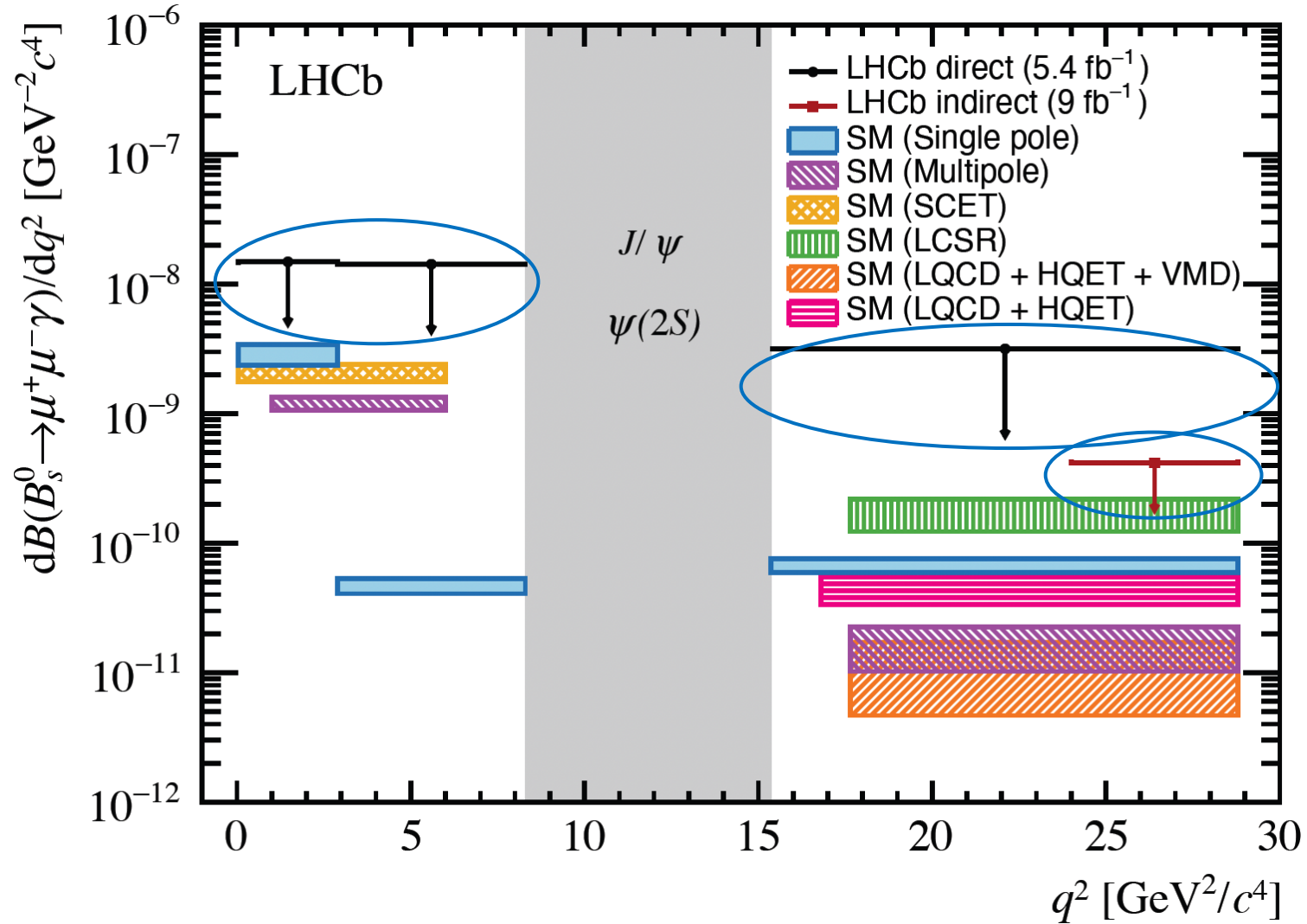
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- ▶ $b \rightarrow s \ell^+ \ell^-$ per indagare la Lepton Flavour Universality (LFU)
 - Simmetria accidentale del Modello Standard
 - Molto comune in estensioni di Nuova Fisica

▶ Analisi LFU a LHCb

"Test of lepton universality using $B^+ \rightarrow K^+ \ell^+ \ell^-$ decays"

[\[Phys. Rev. Lett. 113 \(2014\) 151601\]](#)

"Test of lepton universality with $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ decays"

[\[JHEP 08 \(2017\) 055, arXiv:1705.05802\]](#)

"Search for lepton-universality violation $B^+ \rightarrow K^+ \ell^+ \ell^-$ decays"

[\[Phys. Rev. Lett. 122 \(2019\) 191801\]](#)

"Test of lepton universality in beauty-quark decays"

[\[Nature Physics 18 \(2022\) 277\]](#)

"Tests of lepton universality using $B^0 \rightarrow K_S^0 \ell^+ \ell^-$ and $B^+ \rightarrow K^{*+} \ell^+ \ell^-$ decays"

[\[Phys. Rev. Lett. 128 \(2022\) 191802\]](#)

"Test of lepton universality in $b \rightarrow s \ell^+ \ell^-$ decays"

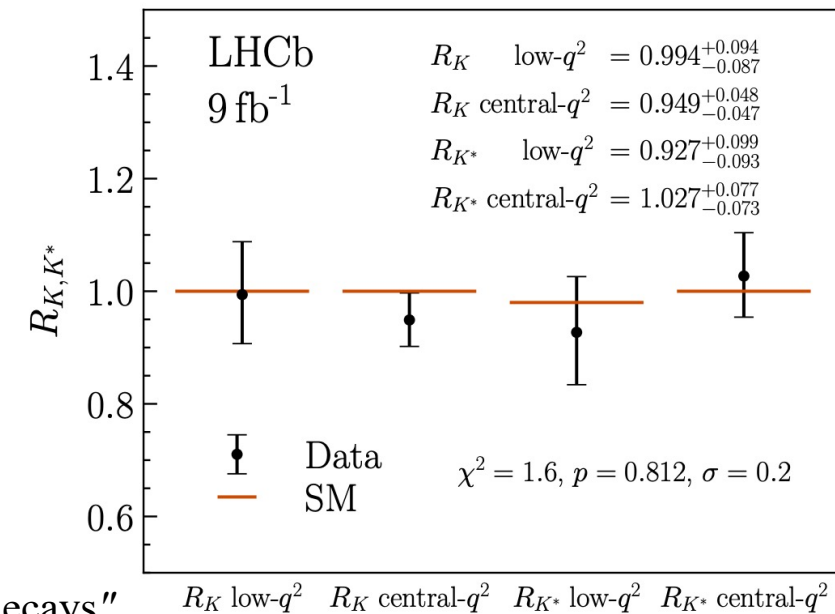
[\[Phys. Rev. Lett. 131 \(2023\) 051803\]](#)

"Measurement of lepton universality parameters in $B^+ \rightarrow K^+ \ell^+ \ell^-$ and $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ decays"

[\[Phys. Rev. D108 \(2023\) 032002\]](#)

~10 anni

$$R_{H_s} = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(H_b \rightarrow H_s \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(H_b \rightarrow H_s e^+ e^-)}{dq^2} dq^2}$$



► "Measurement of the branching fraction ratio $\mathcal{B}(\phi \rightarrow \mu^+ \mu^-) / \mathcal{B}(\phi \rightarrow e^+ e^-)$ with charm meson decays"

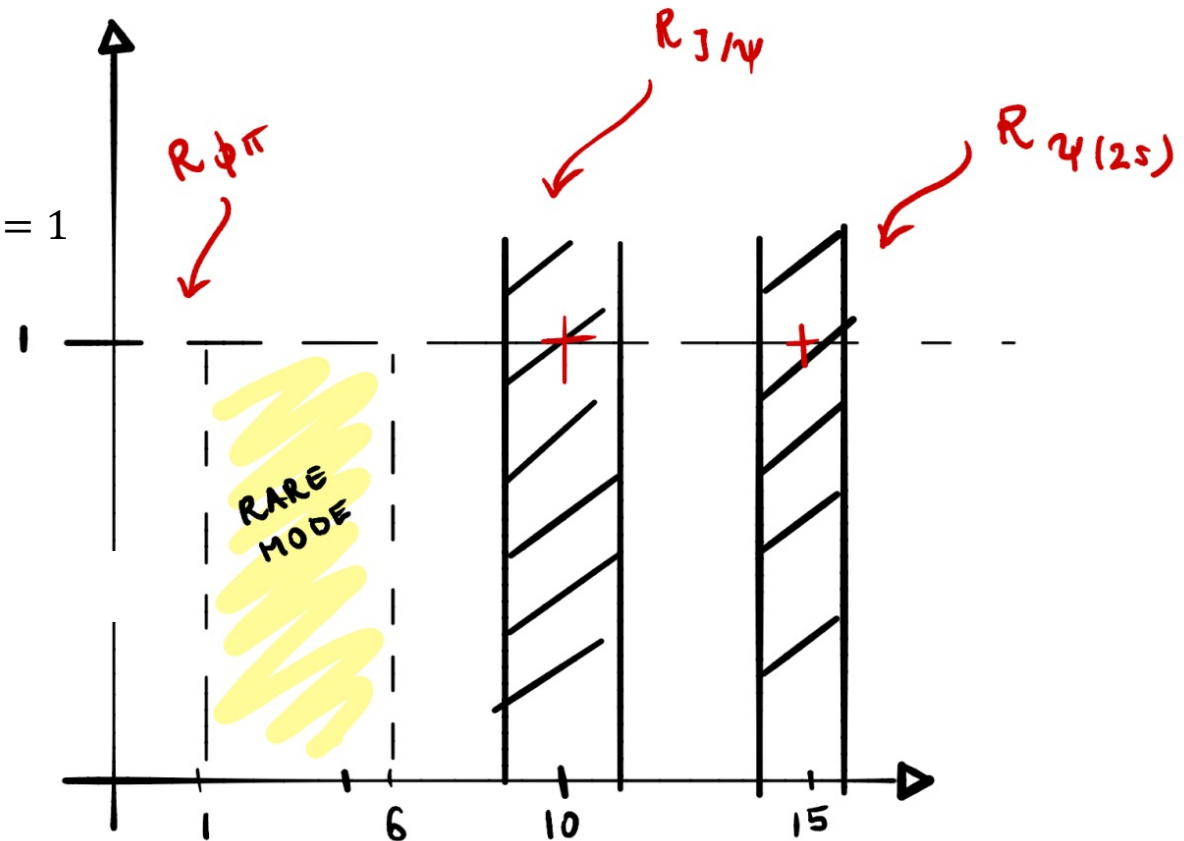
- [\[arXiv:2402.01336\]](https://arxiv.org/abs/2402.01336) sottomesso alla rivista JHEP
- $\sqrt{s} = 13 \text{ TeV}$, $\mathcal{L} = 5.4 \text{ fb}^{-1}$

► Strategia

- Test LFU con μe in transizione $b \rightarrow s \ell^+ \ell^-$

$$R_{\phi\pi}^{d(s)} = \beta \cdot \frac{\mathcal{B}(D_{(s)}^+ \rightarrow \phi(\mu^+ \mu^-) \pi^+)}{\mathcal{B}(D_{(s)}^+ \rightarrow \phi(e^+ e^-) \pi^+)} / \frac{\mathcal{B}(B^+ \rightarrow J/\psi(\mu^+ \mu^-) K^+)}{\mathcal{B}(B^+ \rightarrow J/\psi(\mu^+ \mu^-) K^+)} = 1$$

- $\phi \rightarrow \ell^+ \ell^-$ dal decadimento $D_{(s)}^+ \rightarrow \phi(\ell^+ \ell^-) \pi^+$
 - ✓ Controllo basse regioni di q^2
- $B^+ \rightarrow J/\psi(\ell^+ \ell^-) K^+$ come canale di normalizzazione



➤ "Measurement of the branching fraction ratio $\mathcal{B}(\phi \rightarrow \mu^+ \mu^-) / \mathcal{B}(\phi \rightarrow e^+ e^-)$ with charm meson decays"

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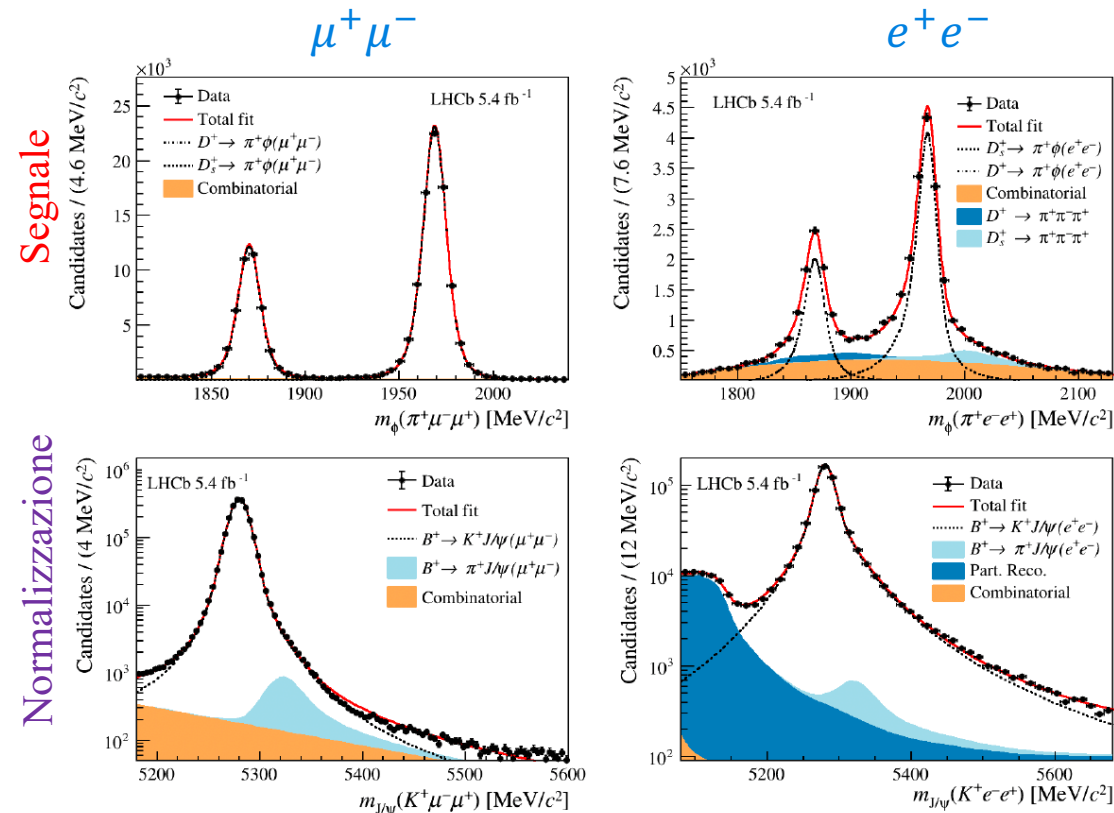
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 - ✓ Controllo basse regioni di q^2
- $B^+ \rightarrow J/\psi(\ell^+ \ell^-) K^+$ come canale di normalizzazione

➤ Risultati

$$R_{\phi\pi}^{d(s)} = 1.022 \pm 0.012_{stat.} \pm 0.048_{sist.}$$

$$\mathcal{B}(\phi \rightarrow \mu^+ \mu^-) = (3.045 \pm 0.049_{stat.} \pm 0.148_{sist.}) \times 10^{-4}$$

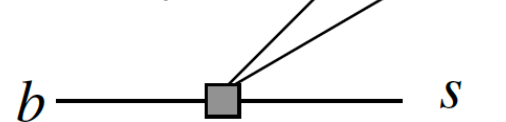
- Primo test di LFU nei decadimenti di mesoni ϕ
- Ad oggi la misura più precisa su $\mathcal{B}(\phi \rightarrow \mu^+ \mu^-)$



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

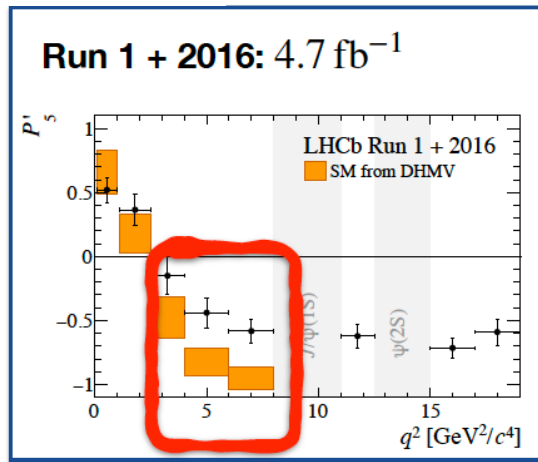
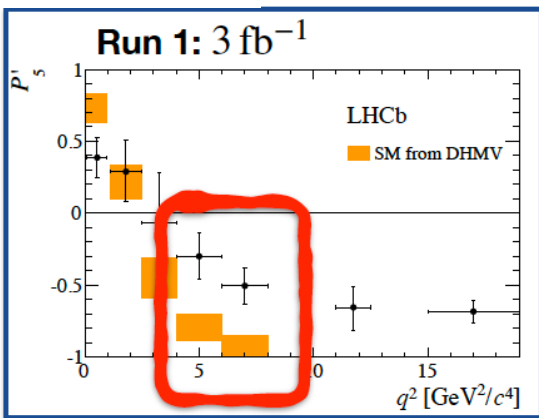
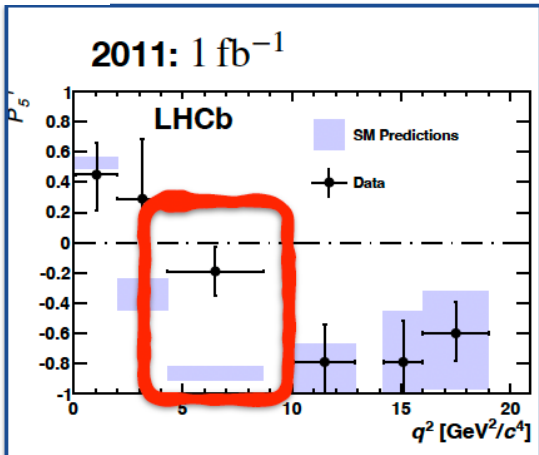
- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ è una transizione $b \rightarrow s \ell^+ \ell^-$
 - Descrizione EFT con diversi coefficienti di Wilson \mathcal{C}

$$\mathcal{L} \propto \sum_i C_i \mathcal{O}_i$$



- Electromagnetic $C_7^{(\prime)}$
- Vector $C_9^{(\prime)}$
- Axial vector $C_{10}^{(\prime)}$

Dubbi e perplessità negli ultimi 10 anni

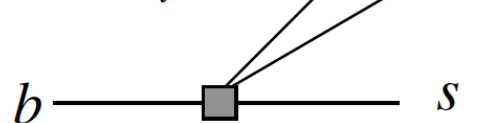


- Stato dell'arte
 - Deviazioni dal Modello Standard $\sim 3.0\sigma$

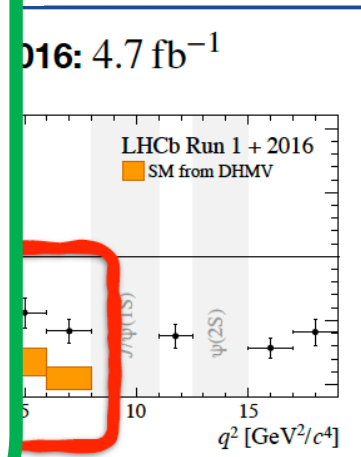
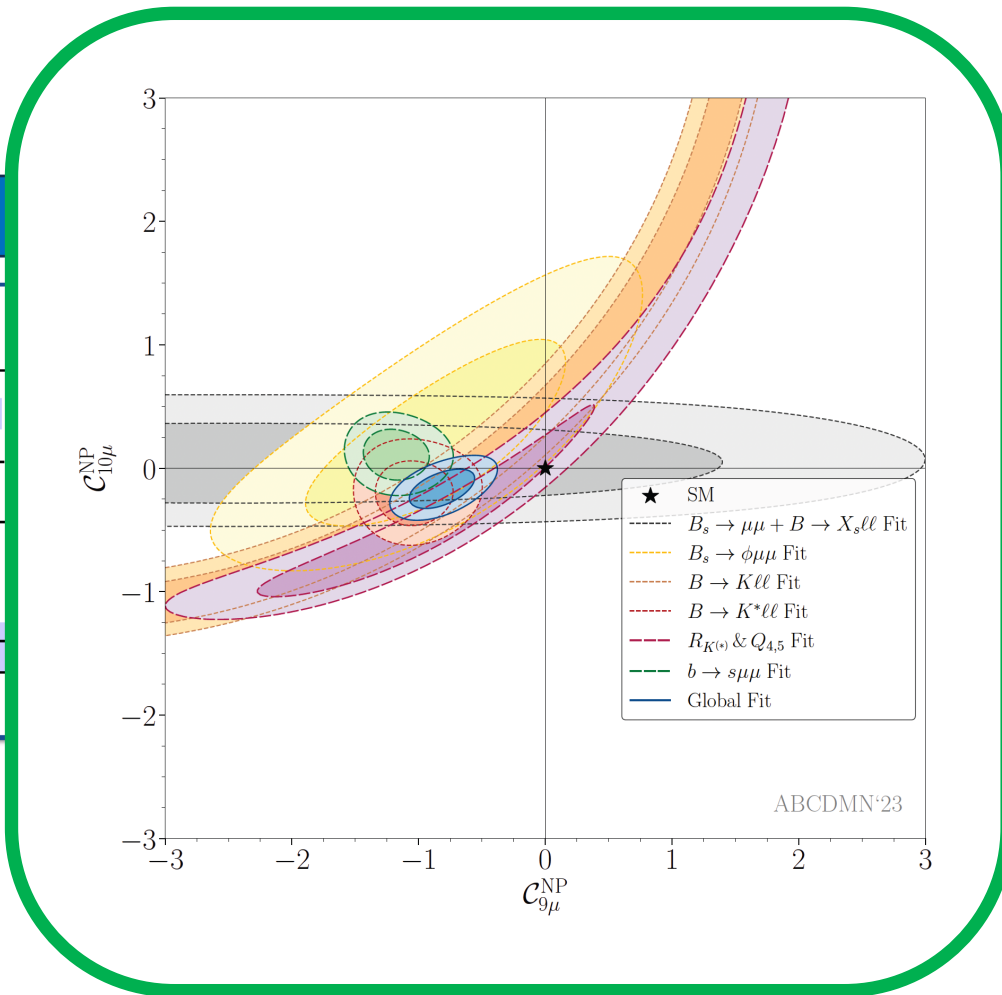
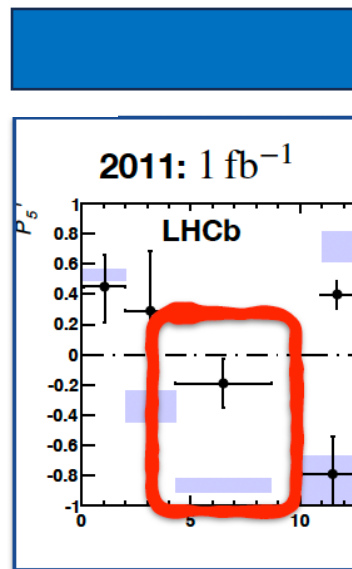
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ è una transizione $b \rightarrow s \ell^+ \ell^-$
 - Descrizione EFT con diversi coefficienti di Wilson \mathcal{C}

$$\mathcal{L} \propto \sum_i C_i \mathcal{O}_i$$



- Electromagnetic $C_7^{(\prime)}$
- Vector $C_9^{(\prime)}$
- Axial vector $C_{10}^{(\prime)}$



- Stato dell'arte
 - Deviazioni dal Modello Standard $\sim 3.0\sigma$

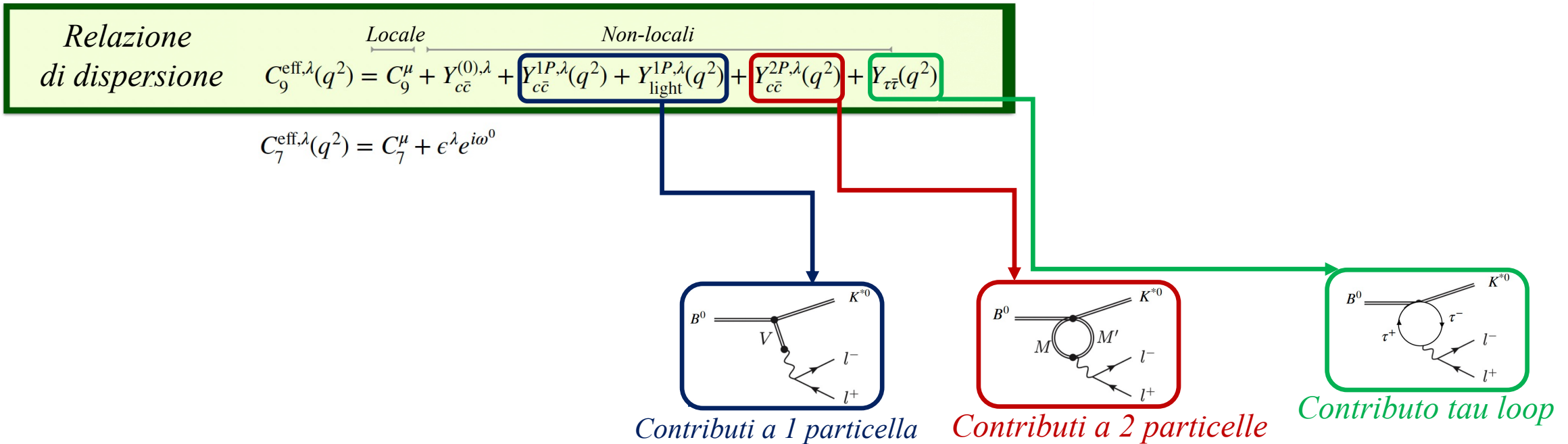
Possibile contributo anomalo vettoriale?

► "Comprehensive analysis of local and nonlocal amplitudes in the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay"

- LHCb-PAPER-2024-011 - Articolo in preparazione
- $\sqrt{s} = 7, 8, 13$ TeV, $\mathcal{L} = 8.4 \text{ fb}^{-1}$

► Strategia:

- Analisi "unbinned" e "model-dependent"



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➤ Strategia:

- Analisi "unbinned" e "model-dependent"

Relazione di dispersione

$$C_9^{\text{eff},\lambda}(q^2) = C_9^\mu + Y_{c\bar{c}}^{(0),\lambda} + \underbrace{Y_{c\bar{c}}^{1P,\lambda}(q^2)}_{\text{Locale}} + \underbrace{Y_{\text{light}}^{1P,\lambda}(q^2)}_{\text{Non-locali}} + \underbrace{Y_{c\bar{c}}^{2P,\lambda}(q^2)}_{\text{Non-locali}} + \underbrace{Y_{\tau\bar{\tau}}(q^2)}_{\text{Non-locali}}$$

$$C_7^{\text{eff},\lambda}(q^2) = C_7^\mu + \epsilon^\lambda e^{i\omega^0}$$

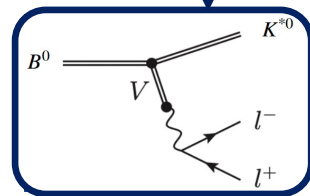
$$\frac{d^4 \bar{\Gamma}(B^0 \rightarrow K^+ \pi^- \mu^+ \mu^-)}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi} \sum_i \bar{J}_i(q^2) f_i(\cos \theta_\ell, \cos \theta_K, \phi) G_i,$$

- Fit simultaneo in 5 dimensioni

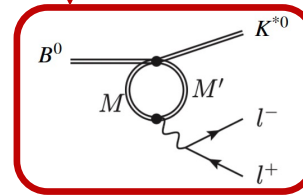
- ✓ $\cos\vartheta_\ell, \cos\vartheta_K, \phi, q^2, m_B$
- ✓ $1.0 < q^2 < 18.0 \text{ GeV}^2/c^4$

- Estrapolazione dei coefficienti di Wilson

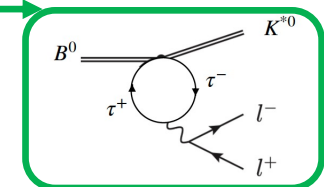
- ✓ Analisi contributi locali e non-locali



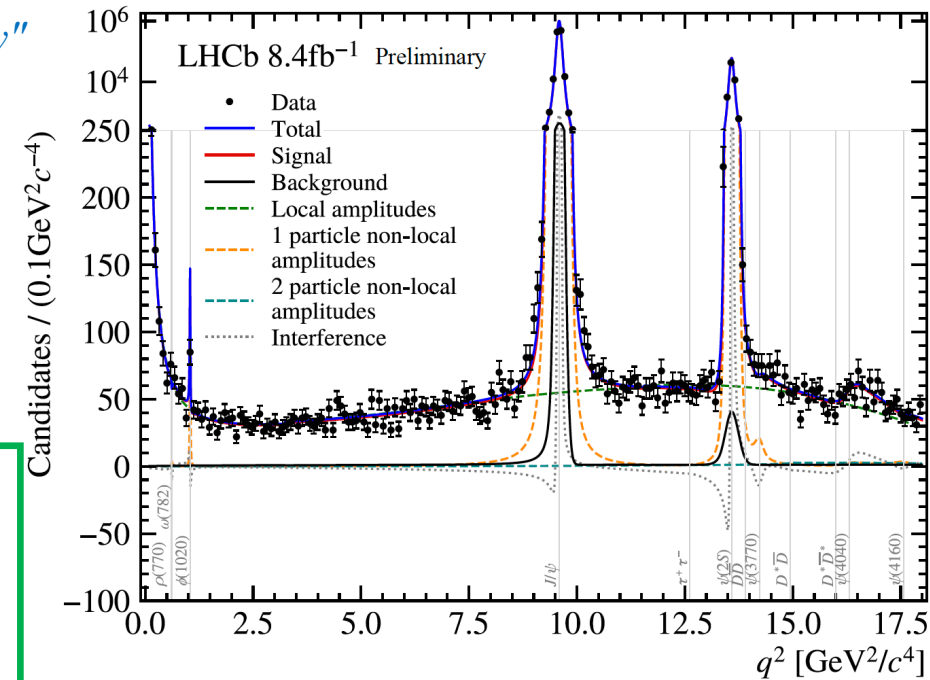
Contributi a 1 particella



Contributi a 2 particelle



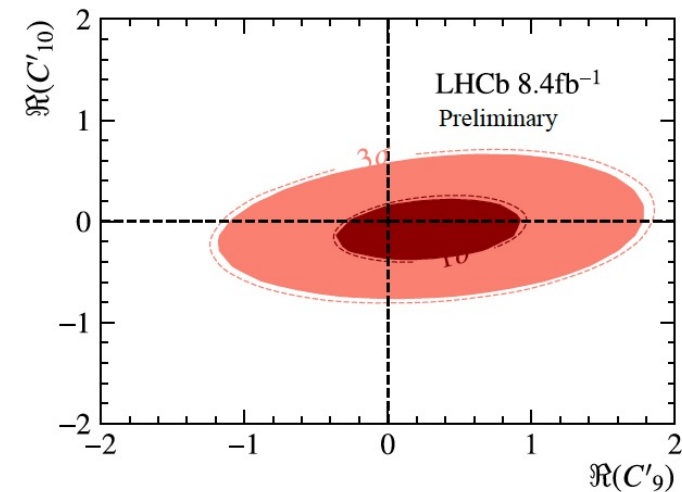
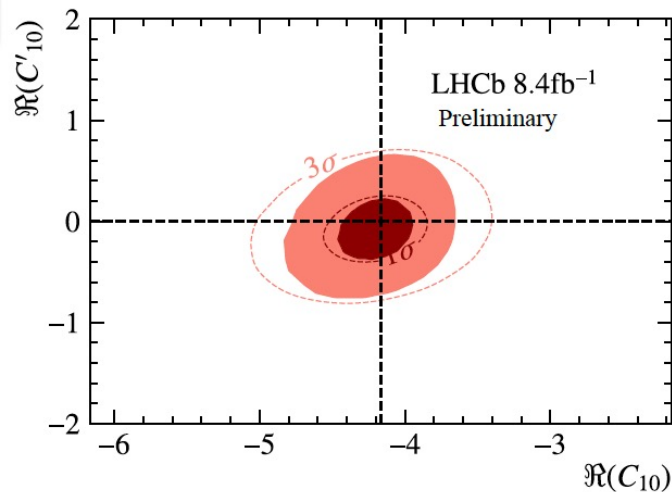
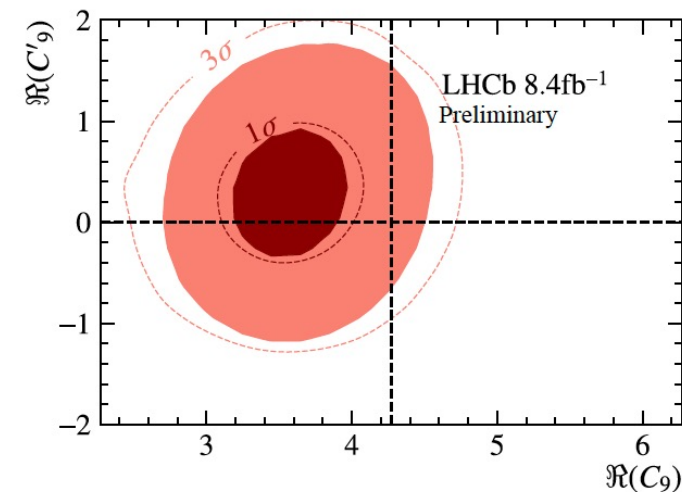
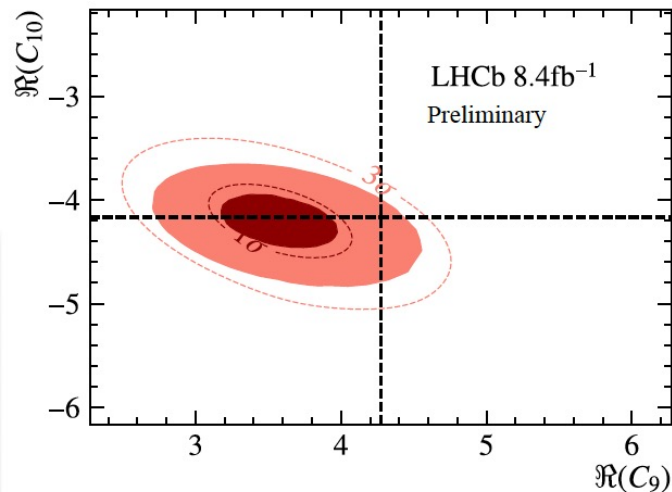
Contributo tau loop



Misure dei coefficienti di Wilson

C_9	$3.56 \pm 0.28 \pm 0.18$	2.1σ
C_{10}	$-4.02 \pm 0.18 \pm 0.16$	0.6σ
C'_9	$0.28 \pm 0.41 \pm 0.12$	0.7σ
C'_{10}	$-0.09 \pm 0.21 \pm 0.06$	0.4σ
C_9^τ	$-116 \pm 264 \pm 98$	0.4σ

- Deviazione **globale** dal Modello Standard $\sim 1.5\sigma$
 - ✓ In accordo con le precedenti analisi
- Deviazione per $C_9 \sim 2.1\sigma$
 - ✓ $\Delta C_9^{NP} = -0.71$
- Prima misura di C_9^τ



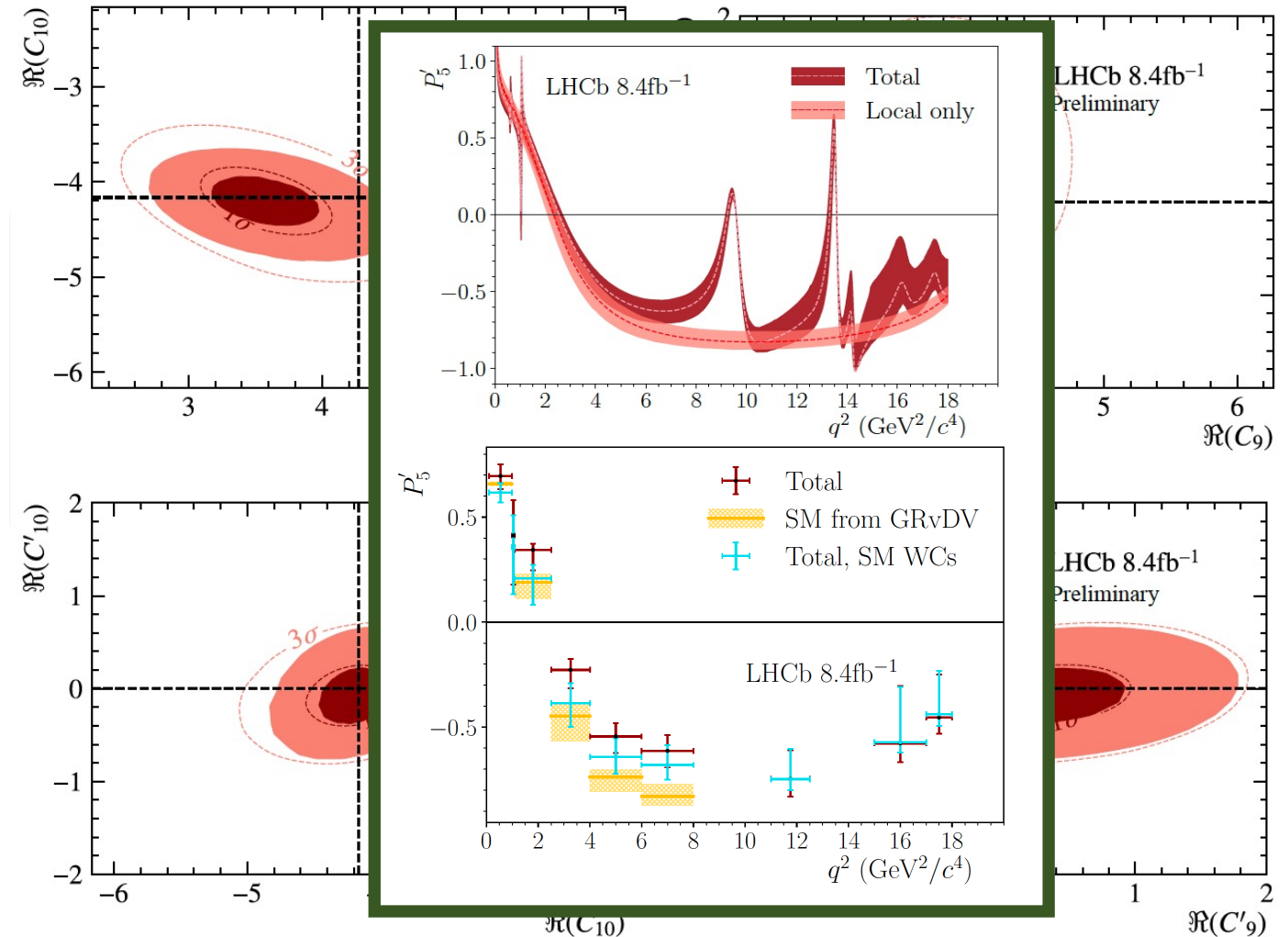
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► Ampiezze non-locali

- Influenza dei contributi sulle misure angolari ...
- ... **non dominante**



► Sono stati presentati risultati recenti per i decadimenti rari ed estremamente rari a LHCb

- $J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ - Ad oggi la misura più precisa su $\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-)$

$$\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-) = (1.13 \pm 0.10_{stat.} \pm 0.05_{sist.} \pm 0.01_{est.}) \times 10^{-6}$$

- $B_s^0 \rightarrow \mu^+ \mu^- \gamma$ - Primo limite con ricostruzione completa dello stato finale

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma)_{comb.} < 2.5 (2.8) \times 10^{-8}$$

- $\mathcal{B}(\phi \rightarrow \mu^+ \mu^-) / \mathcal{B}(\phi \rightarrow e^+ e^-)$ - Primo test di LFU nei decadimenti di mesoni ϕ

$$R_{\phi\pi} = 1.022 \pm 0.012_{stat.} \pm 0.048_{sist.}$$

$$\mathcal{B}(\phi \rightarrow \mu^+ \mu^-) = (3.045 \pm 0.049_{stat.} \pm 0.148_{sist.}) \times 10^{-4}$$

- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ - Analisi angolare con misura dei coefficienti di Wilson

\mathcal{C}_9	$3.56 \pm 0.28 \pm 0.18$	2.1σ
\mathcal{C}_{10}	$-4.02 \pm 0.18 \pm 0.16$	0.6σ
\mathcal{C}'_9	$0.28 \pm 0.41 \pm 0.12$	0.7σ
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A nome della collaborazione LHCb
vi ringrazio per la vostra attenzione