Probing New Physics with Rare Hyperon Decays

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based on

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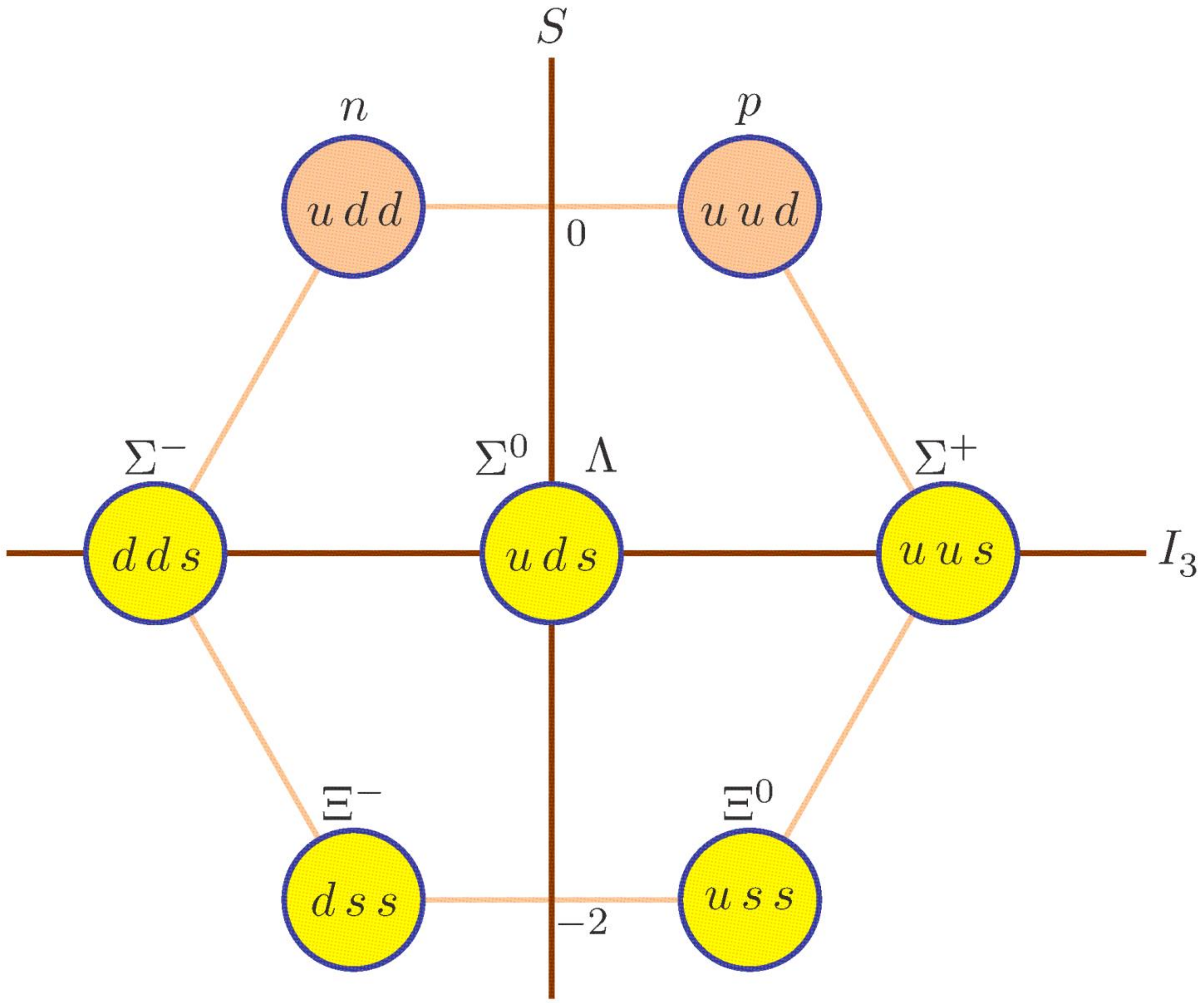
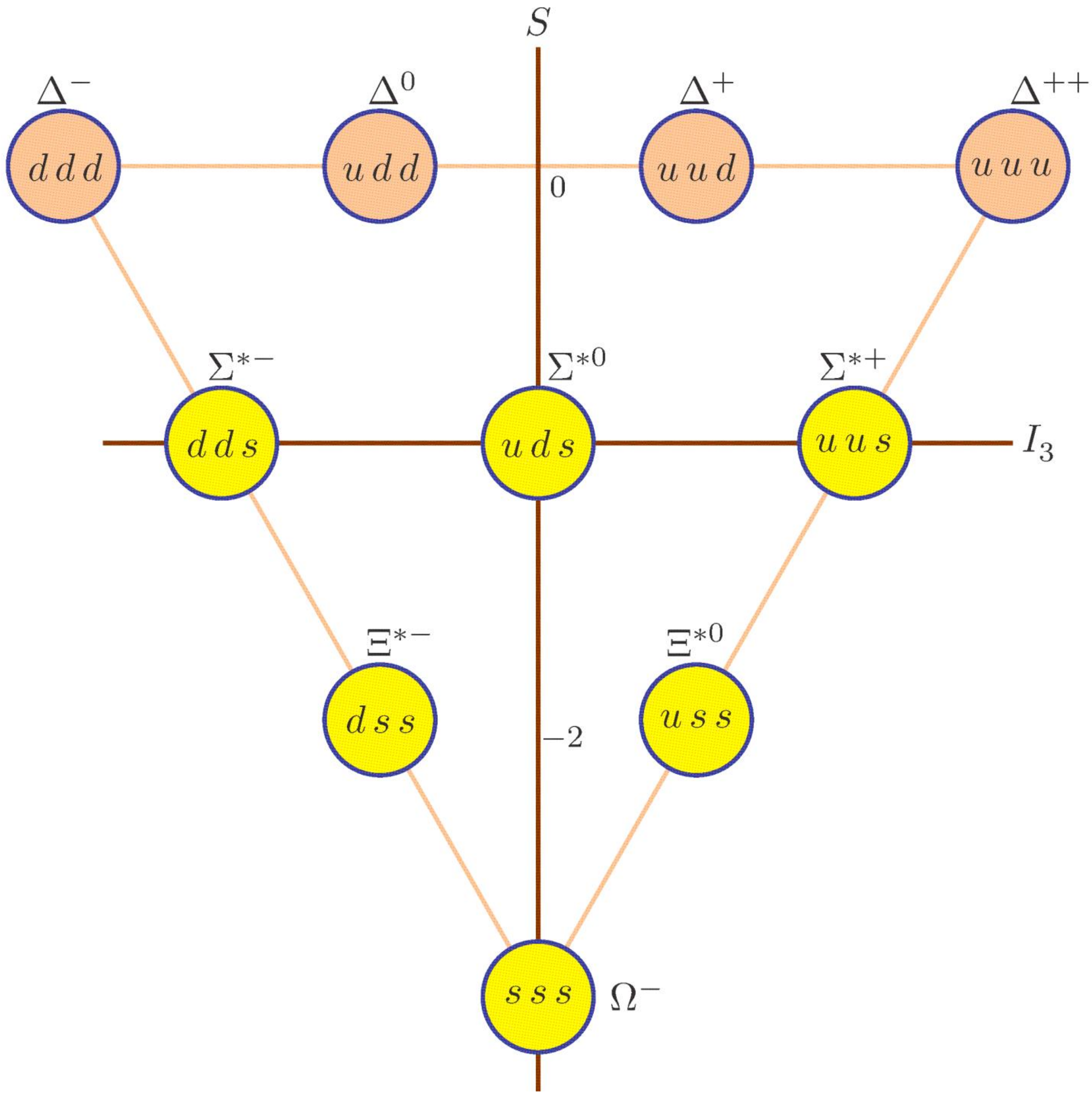
- Introduction
- $\Sigma^+ \to p\mu^+\mu^-$
  - Observables
  - SM predictions
  - Potential NP probes
- Other rare hyperon decays
- Conclusions

Lightest spin-1/2 baryons



Lightest spin-3/2 baryons



Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$

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We report the first evidence for the decay $\Sigma^+ \to p\mu^+\mu^-$ from data taken by the HyperCP (E871) experiment at Fermilab. Based on three observed events, the branching ratio is $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = [8.6^{+6.6}_{-5.4}(\mathrm{stat}) \pm 5.5(\mathrm{syst})] \times 10^{-8}$. The narrow range of dimuon masses may indicate that the decay proceeds via a neutral intermediate state, $\Sigma^+ \to pP^0, P^0 \to \mu^+\mu^-$ with a P^0 mass of $214.3 \pm 0.5\ \mathrm{MeV}/c^2$ and branching ratio $\mathcal{B}(\Sigma^+ \to pP^0, P^0 \to \mu^+\mu^-) = [3.1^{+2.4}_{-1.9}(\mathrm{stat}) \pm 1.5(\mathrm{syst})] \times 10^{-8}$.

Evidence for the Rare Decay $\Sigma^+ \to p\mu^+\mu^-$

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A search for the rare decay $\Sigma^+ \to p\mu^+\mu^-$ is performed using pp collision data recorded by the LHCb experiment at center-of-mass energies $\sqrt{s} = 7$ and 8 TeV, corresponding to an integrated luminosity of 3 fb^{-1}. An excess of events is observed with respect to the background expectation, with a signal significance of 4.1 standard deviations. No significant structure is observed in the dimuon invariant mass distribution, in contrast with a previous result from the HyperCP experiment. The measured $\Sigma^+ \to p\mu^+\mu^-$ branching fraction is $(2.2^{+1.8}_{-1.3}) \times 10^{-8}$, where statistical and systematic uncertainties are included, which is consistent with the standard model prediction.

A signal yield of $10.2^{+3.9}_{-3.5}$ is observed.

LHCb data

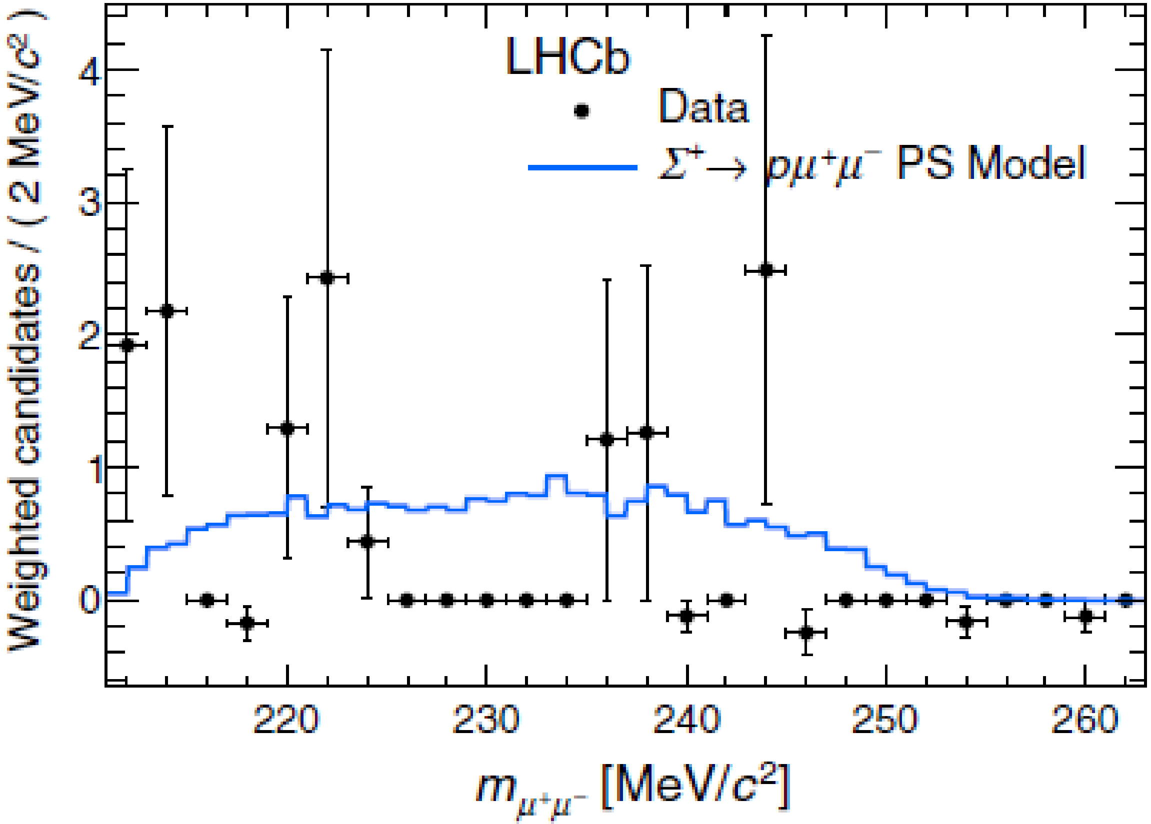
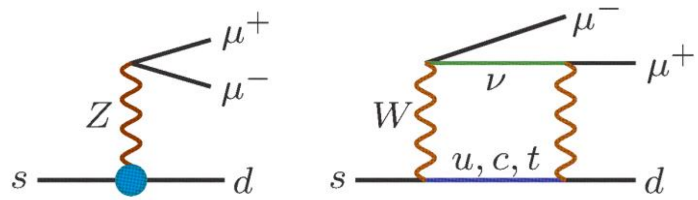
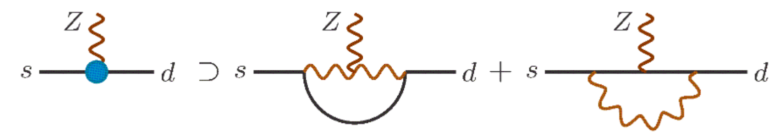


FIG. 3. Background-subtracted distribution of the dimuon invariant mass for $\Sigma^+ \to p\mu^+\mu^-$ candidates, superimposed with the distribution from the simulated phase-space (PS) model. Uncertainties on data points are calculated as the square root of the sum of squared weights.

- The decay amplitude consists of short-distance & long-distance parts.
- The SM short-distance contribution arises mainly from Z-penguin and box diagrams





- It's described by the effective Hamiltonian

$$\mathcal{H}_{\rm eff} = \frac{G_{\rm F}}{\sqrt{2}}\, \overline{d}\gamma^\kappa(1-\gamma_5)s\, \overline{\mu}\gamma_\kappa(\lambda_u z_{7V} - \lambda_t y_{7V} - \gamma_5\lambda_t y_{7A})\mu + \text{H.c.}$$

Buchalla *et. al*, 1996

with Wilson coefficients z_{7V} & $y_{7V,7A}$ and CKM factor $\lambda_q = V_{qd}^* V_{qs}$

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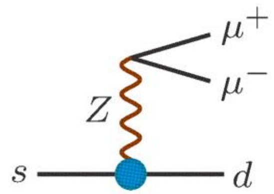

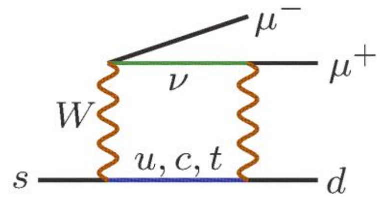

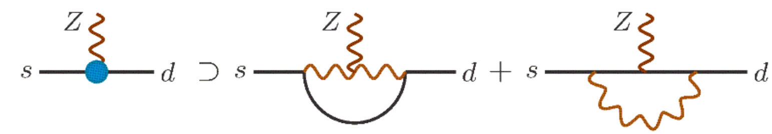

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Buchalla *et. al*, 1996

with Wilson coefficients z_{7V} & $y_{7V,7A}$ and CKM factor $\lambda_q = V_{qd}^* V_{qs}$

- Hadronic matrix elements

$$\langle p|\bar{d}\gamma^\kappa s|\Sigma^+\rangle = -\bar{u}_p\gamma^\kappa u_\Sigma\,,$$
$$\langle p|\bar{d}\gamma^\nu\gamma_5 s|\Sigma^+\rangle = (D-F)\left(\bar{u}_p\gamma^\nu\gamma_5 u_\Sigma + \frac{m_\Sigma + m_p}{q^2 - m_K^2}\,\bar{u}_p\gamma_5 u_\Sigma\, q^\nu\right)$$

- The SM SD contribution alone yields a branching fraction of order 10^{-12}
  - much smaller than the measured value, ~ 2 x 10^{-8}

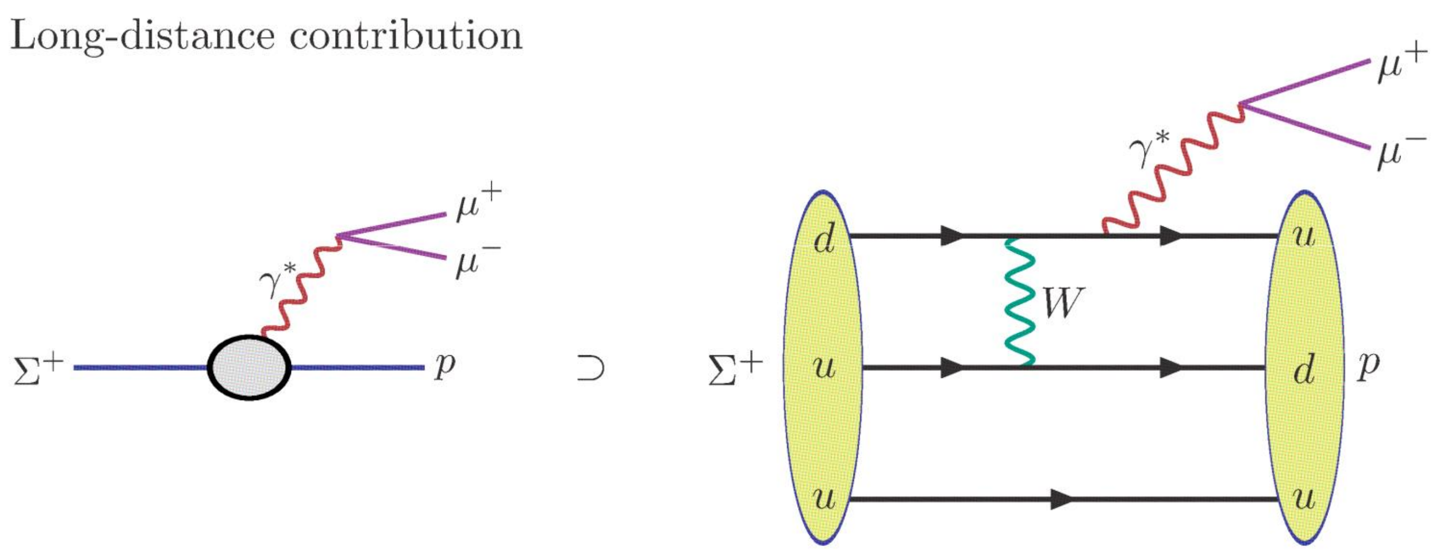
He, JT, Valencia, 2005

- Long-distance contribution mainly from $\Sigma^+ \to p\gamma^* \to p\mu^+\mu^-$

$$\mathcal{M}_{\rm SM}^{\rm LD} = \frac{-ie^2 G_{\rm F}}{q^2}\, \bar{u}_p (a + \gamma_5 b) \sigma_{\kappa\nu} q^\kappa u_\Sigma\, \bar{u}_\mu \gamma^\nu v_{\bar{\mu}} - e^2 G_{\rm F}\, \bar{u}_p \gamma_\kappa (c + \gamma_5 d) u_\Sigma\, \bar{u}_\mu \gamma^\kappa v_{\bar{\mu}}$$

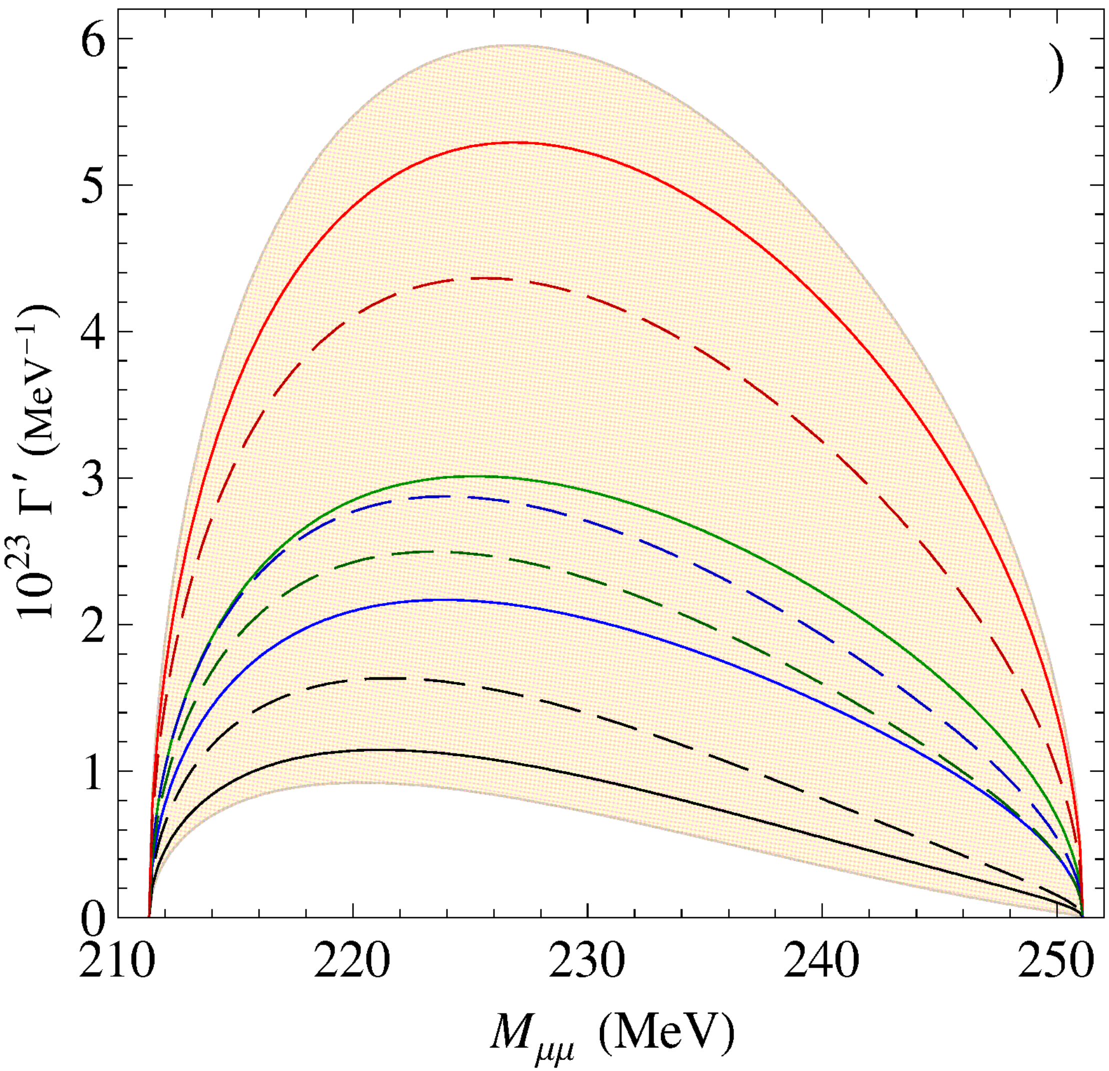
a, b, c, d are form factors depending on $q^2 = M_{\mu\mu}^2$

Lyagin & Ginzburg, 1962
Bergstrom, Safadi, Singer, 1988
He, JT, Valencia, 2005



- The LD contribution leads to significant uncertainties in the predicted rate.

- $\Gamma' = d\Gamma(\Sigma^+ \to p\mu^+\mu^-)/dq^2$



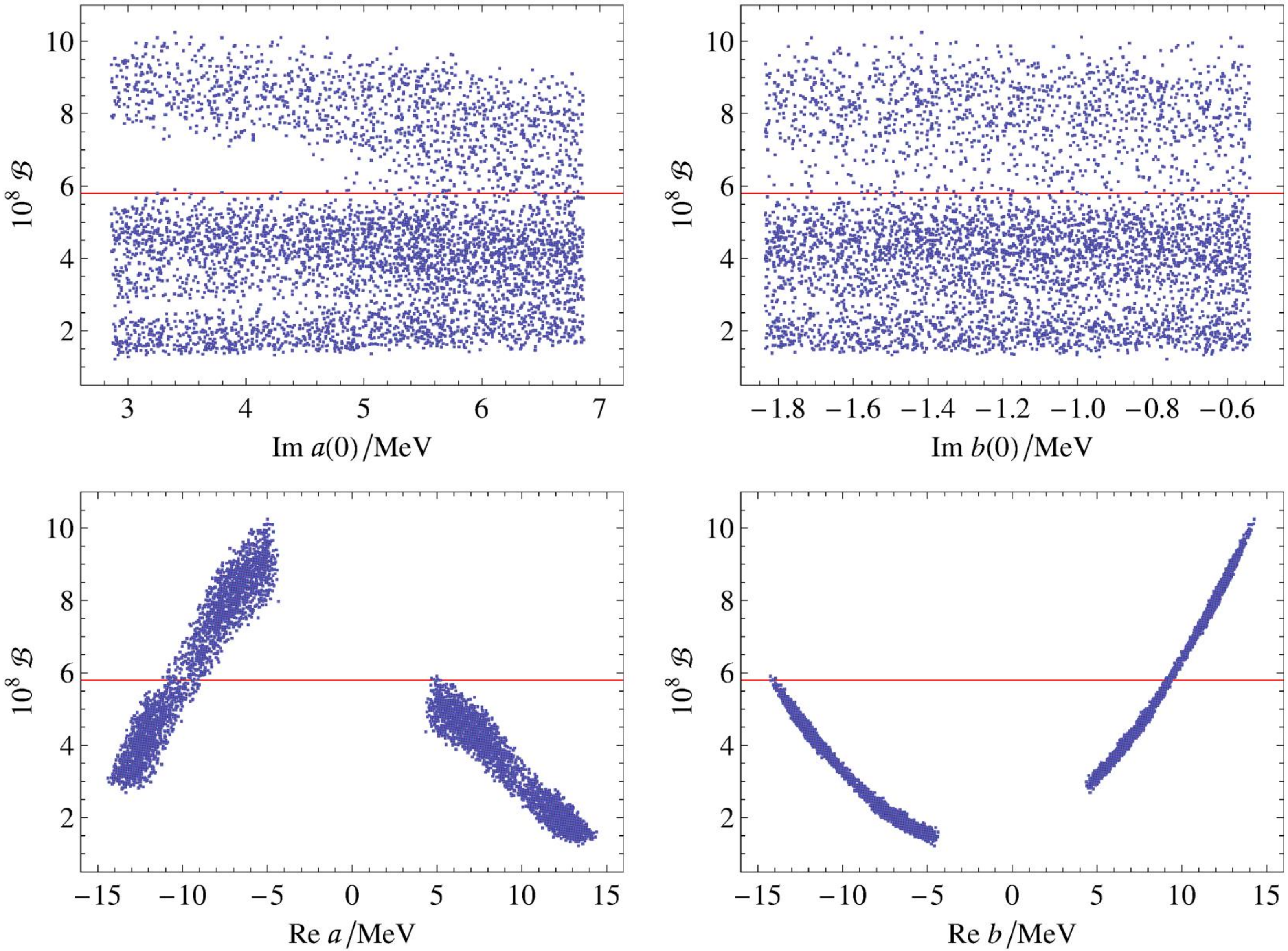


FIG. 1: Sample points of $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) \times 10^8$ in relation to the preferred ranges of $\mathrm{Im}(a,b)$ at $q^2 = 0$ and of $\mathrm{Re}(a,b)$, as explained in the text. Each horizontal red line marks the 2σ upper-limit of the LHCb measurement [2].

- Amplitude accommodating SM and potential NP contributions

$$\mathcal{M} = \bar{u}_p\big[iq_\kappa(\tilde{\mathrm{A}} + \gamma_5\tilde{\mathrm{B}})\sigma^{\nu\kappa} - \gamma^\nu(\tilde{\mathrm{C}} + \gamma_5\tilde{\mathrm{D}})\big]u_\Sigma\,\bar{u}_\mu\gamma_\nu v_{\bar{\mu}} + \bar{u}_p\gamma^\nu(\tilde{\mathrm{E}} + \gamma_5\tilde{\mathrm{F}})u_\Sigma\,\bar{u}_\mu\gamma_\nu\gamma_5 v_{\bar{\mu}}$$
$$+ \bar{u}_p(\tilde{\mathrm{G}} + \gamma_5\tilde{\mathrm{H}})u_\Sigma\,\bar{u}_\mu v_{\bar{\mu}} + \bar{u}_p(\tilde{\mathrm{J}} + \gamma_5\tilde{\mathrm{K}})u_\Sigma\,\bar{u}_\mu\gamma_5 v_{\bar{\mu}}$$

$\tilde{\mathrm{A}}, \tilde{\mathrm{B}}, \ldots, \tilde{\mathrm{K}}$ are complex coefficients

- SM contributions

$$\tilde{\mathrm{A}} = \frac{e^2 G_\mathrm{F}\, a}{q^2}\,, \qquad \tilde{\mathrm{B}} = \frac{e^2 G_\mathrm{F}\, b}{q^2}\,,$$

$$\tilde{\mathrm{C}} = e^2 G_\mathrm{F}\, c + G_\mathrm{F}\frac{\lambda_u z_{7V} - \lambda_t y_{7V}}{\sqrt{2}}\,, \qquad \tilde{\mathrm{D}} = e^2 G_\mathrm{F}\, d + \frac{D-F}{\sqrt{2}}G_\mathrm{F}(\lambda_u z_{7V} - \lambda_t y_{7V})$$

$$\tilde{\mathrm{E}} = \frac{G_\mathrm{F}}{\sqrt{2}}\lambda_t y_{7A}\,, \qquad \tilde{\mathrm{F}} = \frac{D-F}{\sqrt{2}}G_\mathrm{F}\,\lambda_t y_{7A}\,,$$

$$\tilde{\mathrm{K}} = \frac{m_\Sigma + m_p}{q^2 - m_K^2}\sqrt{2}\,(D-F)G_\mathrm{F}\,\lambda_t y_{7A} m_\mu$$

- Observables may be constructed which are sensitive to terms in the amplitude not dominated by LD contributions
  - Such observables are then sensitive to SD effects beyond the SM.

- Forward-backward asymmetry

$$\mathcal{A}_{\rm FB} = \frac{\int_{-1}^{1} dc_\theta\, {\rm sgn}(c_\theta)\, \Gamma''}{\int_{-1}^{1} dc_\theta\, \Gamma''}\,, \qquad \Gamma'' = \frac{d^2\Gamma(\Sigma^+ \to p\mu^+\mu^-)}{dq^2\, dc_\theta}\,, \quad c_\theta = \cos\theta$$

θ angle between μ^- and p directions in dimuon's rest frame

$$\mathcal{A}_{\rm FB} = \frac{\beta^2\bar\lambda}{64\pi^3\,\Gamma'\, m_\Sigma^3}\,{\rm Re}\Big\{\big[{\tt M}_+\tilde{\bf A}^*\tilde{\rm F} - {\tt M}_-\tilde{\bf B}^*\tilde{\rm E} - \big(\tilde{\bf A}^*\tilde{\rm G} + \tilde{\bf B}^*\tilde{\rm H}\big)m_\mu + \tilde{\bf C}^*\tilde{\rm F} + \tilde{\bf D}^*\tilde{\rm E}\big]q^2 - \big({\tt M}_+\tilde{\bf C}^*\tilde{\rm G} - {\tt M}_-\tilde{\bf D}^*\tilde{\rm H}\big)m_\mu\Big\}$$

with $\beta = \sqrt{1 - 4m_\mu^2/q^2}\,, \quad \bar\lambda = \hat m_-^2\,\hat m_+^2\,, \quad \hat m_\pm^2 = {\tt M}_\pm^2 - q^2\,, \quad {\tt M}_\pm = m_\Sigma \pm m_p$

- Integrated forward-backward asymmetry

$$\tilde A_{\rm FB} = \frac{1}{\Gamma(\Sigma^+ \to p\mu^+\mu^-)}\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \int_{-1}^{1} dc_\theta\, {\rm sgn}(c_\theta)\, \Gamma''$$

$q^2_{\rm min} = 4m_\mu^2\,, \qquad q^2_{\rm max} = \left(m_\Sigma - m_p\right)^2$

- It's the main observable that could provide a window into NP modifying part of the SM amplitude not dominated by LD effects.

⋆ Polarization asymmetries of the muons

$$\frac{d\Gamma^-(\varsigma_x^-,\varsigma_y^-,\varsigma_z^-)}{dq^2} = \frac{\Gamma'}{2}\left(1 + \mathcal{P}_T^-\varsigma_x^- + \mathcal{P}_N^-\varsigma_y^- + \mathcal{P}_L^-\varsigma_z^-\right)$$

$$\hat{z} = \frac{p_\mu}{|p_\mu|}, \qquad \hat{y} = \frac{p_p \times p_\mu}{|p_p \times p_\mu|}, \qquad \hat{x} = \hat{y}\times\hat{z}\ , \qquad (\varsigma_x^-)^2 + (\varsigma_y^-)^2 + (\varsigma_z^-)^2 = 1$$

$$\begin{aligned}\mathcal{P}_L^- = \frac{\beta^2\sqrt{\bar\lambda}}{192\pi^3\,\Gamma'\,m_\Sigma^3}\,\mathrm{Re}\Big\{&\big[-3\big(2\mathrm{M}_+\tilde{\mathrm{A}}^*\tilde{\mathrm{E}} + \tilde{\mathrm{H}}^*\tilde{\mathrm{K}}\big)q^2 - 2\big(\hat{m}_+^2 + 3q^2\big)\tilde{\mathrm{C}}^*\tilde{\mathrm{E}} + 6m_\mu\mathrm{M}_+\tilde{\mathrm{F}}^*\tilde{\mathrm{H}}\big]\hat{m}_-^2 \\ &+ \big[3\big(2\mathrm{M}_-\tilde{\mathrm{B}}^*\tilde{\mathrm{F}} - \tilde{\mathrm{G}}^*\tilde{\mathrm{J}}\big)q^2 - 2\big(\hat{m}_-^2 + 3q^2\big)\tilde{\mathrm{D}}^*\tilde{\mathrm{F}} - 6m_\mu\mathrm{M}_-\tilde{\mathrm{E}}^*\tilde{\mathrm{G}}\big]\hat{m}_+^2\Big\}\end{aligned}$$

$$\begin{aligned}\mathcal{P}_N^- = \frac{\beta^2\bar\lambda\sqrt{q^2}}{256\pi^2\,\Gamma'\,m_\Sigma^3}\,\mathrm{Im}\Big\{&2\big[(\mathrm{M}_+\tilde{\mathrm{A}} + \tilde{\mathrm{C}})^*\tilde{\mathrm{F}} + (\tilde{\mathrm{D}} - \mathrm{M}_-\tilde{\mathrm{B}})^*\tilde{\mathrm{E}}\big]m_\mu - \big(\tilde{\mathrm{A}}^*\tilde{\mathrm{G}} + \tilde{\mathrm{B}}^*\tilde{\mathrm{H}}\big)q^2 \\ &- \big(\tilde{\mathrm{C}}^*\tilde{\mathrm{G}} - \tilde{\mathrm{E}}^*\tilde{\mathrm{J}}\big)\mathrm{M}_+ + \big(\tilde{\mathrm{D}}^*\tilde{\mathrm{H}} - \tilde{\mathrm{F}}^*\tilde{\mathrm{K}}\big)\mathrm{M}_-\Big\}\end{aligned}$$

$$\begin{aligned}\mathcal{P}_T^- = \frac{\beta\bar\lambda\sqrt{q^2}}{256\pi^2\,\Gamma'\,m_\Sigma^3}\,\mathrm{Re}\Big\{&2\big[2\big(\mathrm{M}_+\tilde{\mathrm{A}} + \tilde{\mathrm{C}}\big)^*\big(\tilde{\mathrm{D}} - \mathrm{M}_-\tilde{\mathrm{B}}\big) - \mathrm{M}_-\tilde{\mathrm{A}}^*\tilde{\mathrm{E}} + \mathrm{M}_+\tilde{\mathrm{B}}^*\tilde{\mathrm{F}}\big]m_\mu \\ &- \mathrm{M}_+\tilde{\mathrm{C}}^*\tilde{\mathrm{J}} + \mathrm{M}_-\tilde{\mathrm{D}}^*\tilde{\mathrm{K}} + \beta^2\big(\mathrm{M}_+\tilde{\mathrm{E}}^*\tilde{\mathrm{G}} - \mathrm{M}_-\tilde{\mathrm{F}}^*\tilde{\mathrm{H}}\big)\Big\} \\ &- \frac{\beta\bar\lambda\,\mathrm{Re}\Big[\big(\tilde{\mathrm{A}}^*\tilde{\mathrm{J}} + \tilde{\mathrm{B}}^*\tilde{\mathrm{K}}\big)q^4 + 2\big(\tilde{\mathrm{C}}^*\tilde{\mathrm{E}} + \tilde{\mathrm{D}}^*\tilde{\mathrm{F}}\big)\mathrm{M}_+\mathrm{M}_-m_\mu\Big]}{256\pi^2\,\Gamma'\,m_\Sigma^3\sqrt{q^2}}\end{aligned}$$

⋆ Integrated polarization asymmetries $\quad \tilde{P}_{L,N,T}^- = \dfrac{1}{\Gamma(\Sigma^+ \to p\mu^+\mu^-)}\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2\,\Gamma'\,\mathcal{P}_{L,N,T}^-$

- LD contributions dominate $\mathcal{P}_\mathrm{T}$

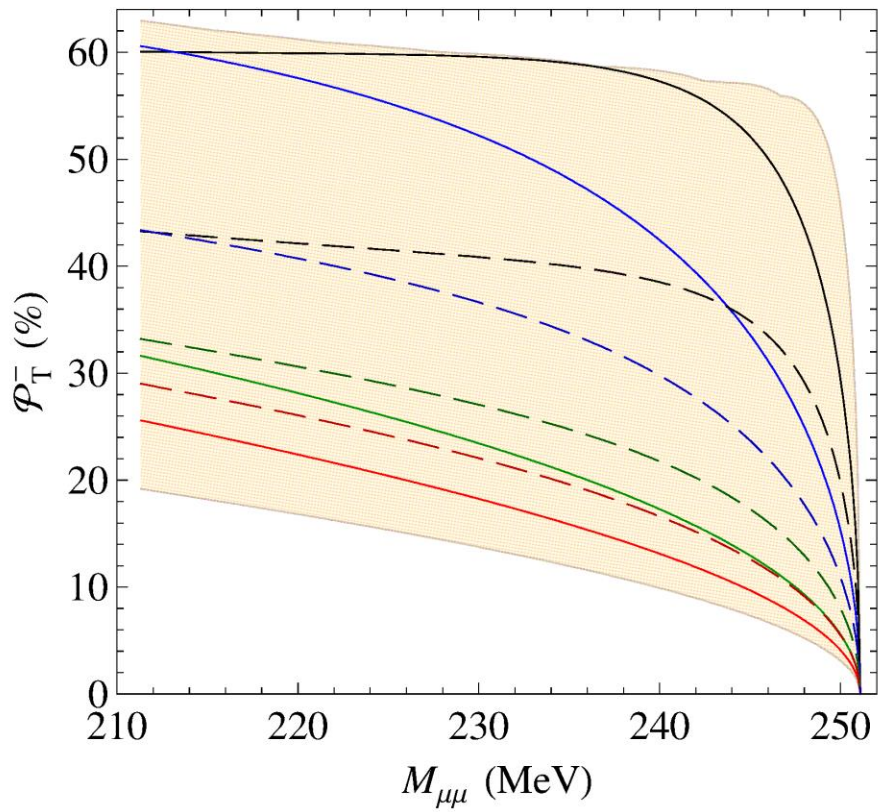


FIG. 3: The μ^- transverse-polarization asymmetry $\mathcal{P}_\mathrm{T}^-$ in $\Sigma^+ \to p\mu^+\mu^-$ versus $M_{\mu\mu}$ in the SM.

Branching fraction & asymmetries of $\Sigma^+ \to p\mu^+\mu^-$ in SM

$\frac{\mathrm{Re}\,a}{\mathrm{MeV}}$	$\frac{\mathrm{Re}\,b}{\mathrm{MeV}}$	$10^8\,\mathcal{B}$	$10^5\,\tilde{A}_{\mathrm{FB}}$	$10^5\,\tilde{P}_{\mathrm{L}}^-$	$10^6\,\tilde{P}_{\mathrm{N}}^-$	$\tilde{P}_{\mathrm{T}}^-$ (%)
13.3	−6.0	1.6	3.7	−7.0	−0.2	59
−13.3	6.0	3.5	−1.4	4.5	−9.6	50
6.0	−13.3	5.1	0.9	−5.1	−1.1	23
−6.0	13.3	9.1	−0.3	3.3	−3.1	17
11.0	−7.4	2.4	2.7	−5.7	−7.3	41
−11.0	7.4	4.7	−0.7	4.1	−10	36
7.4	−11.0	4.0	1.4	−5.2	−5.0	26
−7.4	11.0	7.4	−0.3	3.6	−6.0	21

TABLE I: Sample values of the branching fraction $\mathcal{B}$ of $\Sigma^+ \to p\mu^+\mu^-$ and the corresponding integrated asymmetries $\tilde{A}_{\mathrm{FB}}$ and $\tilde{P}_{\mathrm{L,N,T}}^-$ computed within the SM including the SD and LD contributions. In the evaluation of the $\mathcal{B}$, $\tilde{A}_{\mathrm{FB}}$, and $\tilde{P}_{\mathrm{L,N,T}}^-$ entries in the first [last] four rows, the relativistic [heavy baryon] expressions for $\mathrm{Im}(a,b,c,d)$ have been used, as explained in the text.

- The asymmetries expected to be tiny in the SM can serve as probes of NP effects
  - These asymmetries are (approximate) null tests of the SM.

Enhanced asymmetries in of $\Sigma^+ \to p\mu^+\mu^-$ due to new physics

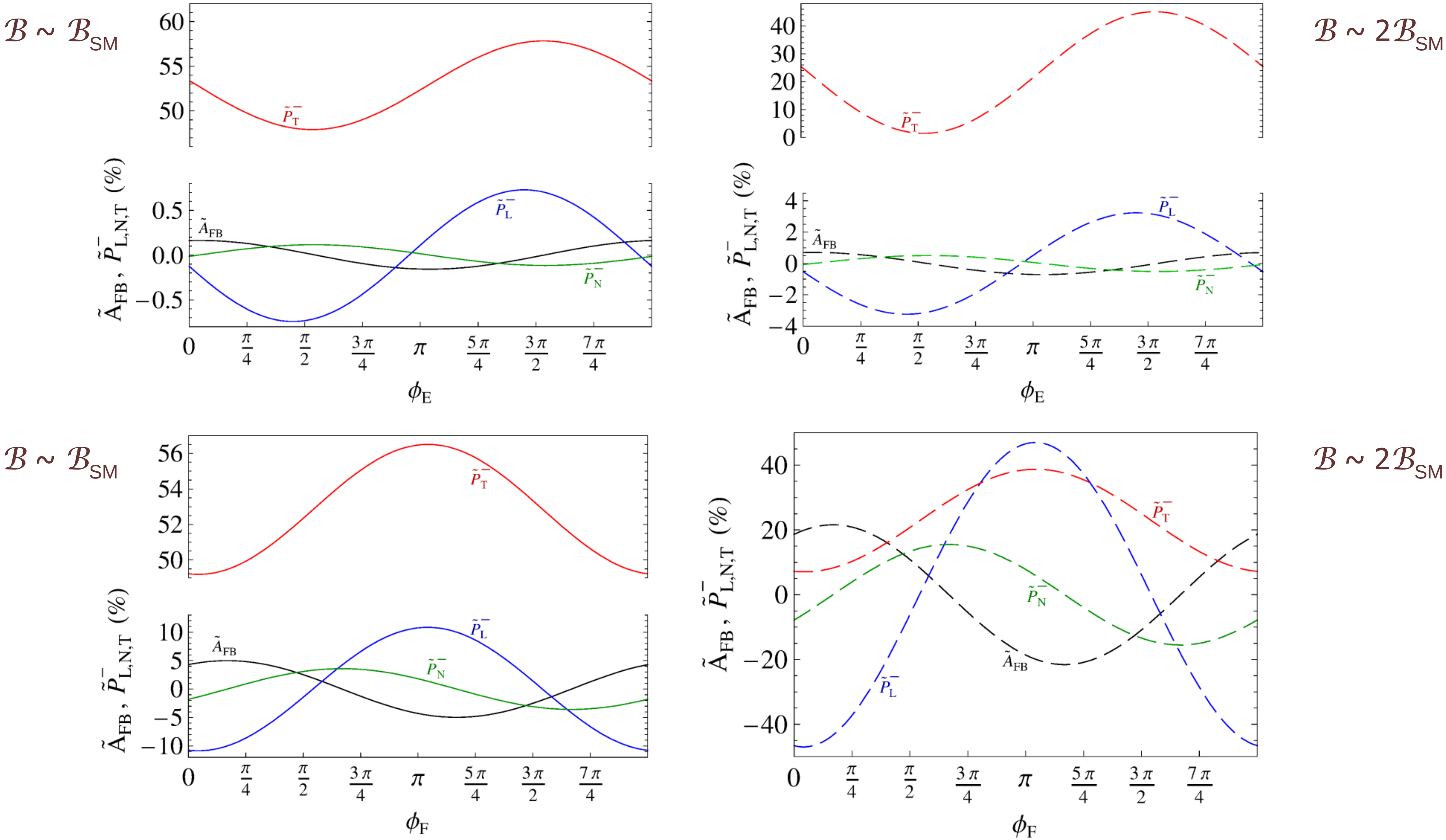


FIG. 4: The integrated asymmetries $\tilde{A}_{FB}$ and $\tilde{P}^-_{L,N,T}$ of the muon in $\Sigma^+ \to p\mu^+\mu^-$ versus the phases $\phi_{E,F}$ of the NP contributions to the coefficients $\tilde{E}$ (top plots) and $\tilde{F}$ (bottom plots), respectively, in the decay amplitude. For the top plots, only $\tilde{E}$ has the NP term with magnitude $g_E = 7 \times 10^{-9}\,\text{GeV}^{-2}$ (left) and $7 \times 10^{-8}\,\text{GeV}^{-2}$ (right). For the bottom plots, only $\tilde{F}$ has the NP term with magnitude $g_F = 1 \times 10^{-8}\,\text{GeV}^{-2}$ (left) and $1 \times 10^{-7}\,\text{GeV}^{-2}$ (right).

- Lepton-flavor-violating decays
  - $\Sigma^+ \to p e^\pm \mu^\mp$
  - $\Omega^- \to \Xi^- p e^\pm \mu^\mp$
  - . . .

- Decays with missing energy
  - $\Sigma^+ \to p \chi(\chi)$
  - $\Omega^- \to \Xi^- \chi(\chi)$
  - . . .

- Rare hyperon decays can serve as potentially sensitive probes of physics beyond the SM.
- These decays can offer useful information on new physics which is complementary to that from the kaon sector.
- For $\Sigma^+ \to p\mu^+\mu^-$, although the observables in the SM involve significant uncertainties, some of the muon asymmetries are predicted to be tiny in the SM and therefore can be sensitive to BSM physics, which may be testable at LHCb.