Comenius University Bratislava
Faculty of Mathematics, Physics and Informatics

Theory and Phenomenology

Dr. Tomáš Blažek (Comenius U.)

R-ECFA Meeting Bratislava 18 May 2018

Theoretical Physics and Particle Phenomenology in Slovakia have Long Tradition since 1950's

Over the past few years

Hadron Physics and Hadron Phenomenology

Physics Beyond Standard Model

- New Physics weakly coupled – Supersymmetry
  - Neutrino Sector
  - Flavour Changing Neutral Currents (FCNC)
    rare decays
  - (Charged) Lepton Flavor Violation
- New Physics coupled strongly
  - strong dynamics breaking electroweak symmetry

Quantum Mechanics in non-commutative space

Cosmology/Gravitation: Inflation mechanisms and CMB fluctuations in non-standard backgrounds

Theoretical Workshop and Summer School, each year in September over the past 12 years, typically 20 – 25 participants (MS and PhD students), one week long

Theoretical Physics Group,
Faculty of Mathematics, Physics and Informatics, Comenius University Bratislava

MODELS OF MODERN PHYSICS

Theoretical Physics Workshop and Summer School
Zuberec, Slovakia 9–15 Sep 2018

LHC and Particle Physics

- **Supersymmetry and Large Hadron Collider** (A.Sopczak, *Prague*)
- **Effective Potential Methods** (P. Maták, *Bratislava*)
- **Lessons from Standard Model in Search of New Physics** (different lecturers)

Slovenská fyzikálna spoločnosť

… *and more, for program details see web page*

https://indico.cern.ch/event/722090/

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Hadron Physics and Hadron Phenomenology

Department of Theoretical Physics, *Institute of Physics, Slovak Academy of Science, Bratislava*

five senior scientists (Dubnička, Adamuščin, Erik Bartoš, Liptaj, Nagy)

Department *of* Theoretical Physics and Didactics of Physics, *Comenius University, Bratislava*

one senior scientist (Dubničková)

- A solid analysis of existing data on S-wave isoscalar pi-pi scattering phase shift has been carried out and by means of our fully solvable mathematical scheme for the experimentally nonmeasurable scalar pion form factor, describing a structure of the resonance under consideration, an existence of long discussed (from 1974) existence of the lowest hadronic resonance so-called sigma -meson, or now named f_0(500) scalar meson, has been proven.

- In the framework of the covariant quark model investigating decay channels of the first discovered heavy quarkonia X(3872) we came to the conclusion that the latter can be interpretted as four quark state. By application of the same model to semileptonic and nonleptonic decays of heavy B_s and B_c mesons and comparing obtained results with existin experimental data correct incorporation of basic principles into the covariant quark model with infrared confinement has been proven.

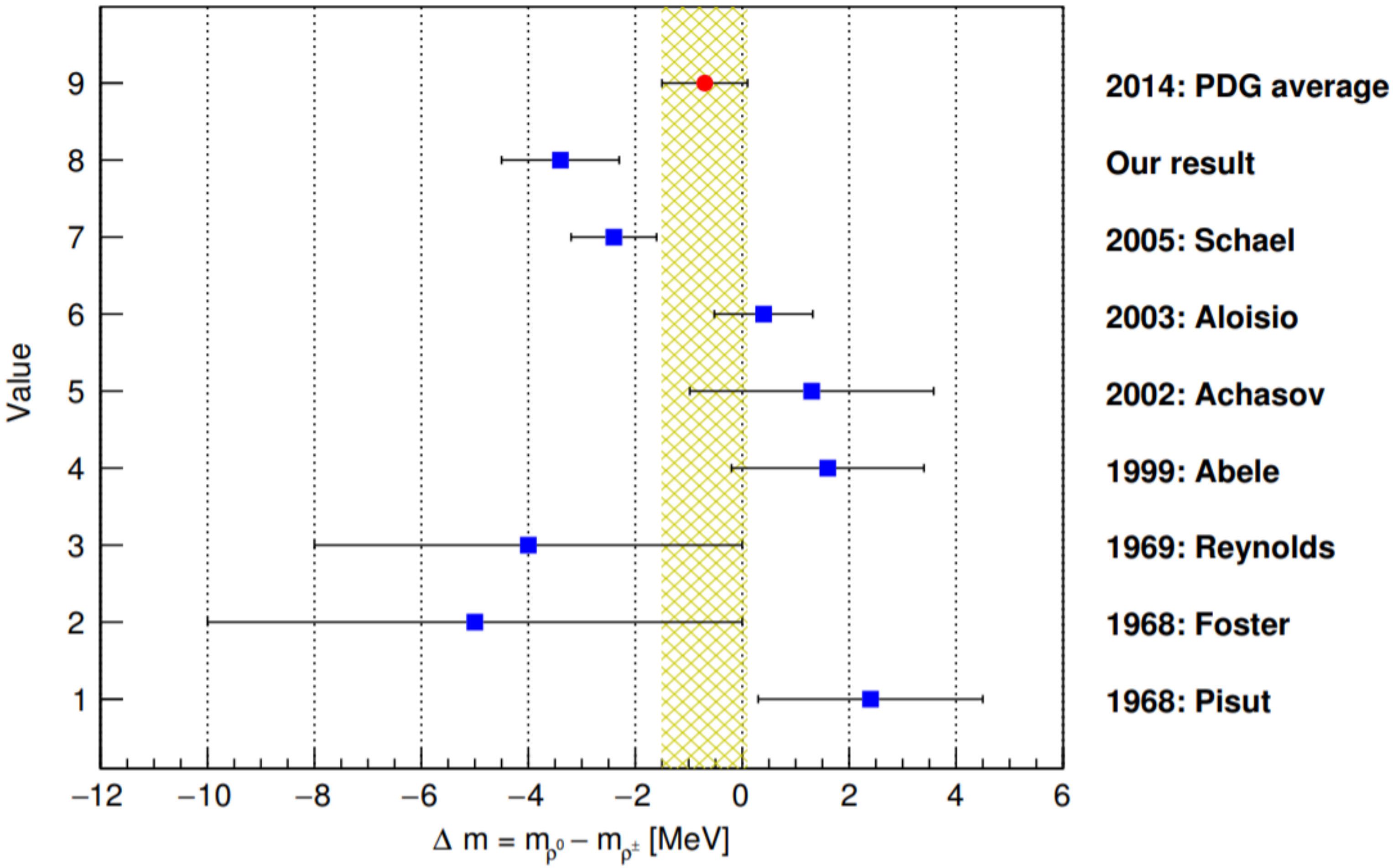
Hadron Physics and Hadron Phenomenology cont'd

- Unitary and Analytic models for the whole nonet of pseudoscalar mesons have been elaborated, an optimal description of all existing data on charged pios, charged and also neutral kaons and existing data on the transition form factors of all the rest neutral pseudoscalar mesons have been achieved by them. From the latter total cross sections of elektron-positron annihilation into meson-antimeson pairs have been calculated and contributions to g-2 muon anomaly evaluated with the lowest up to now error.

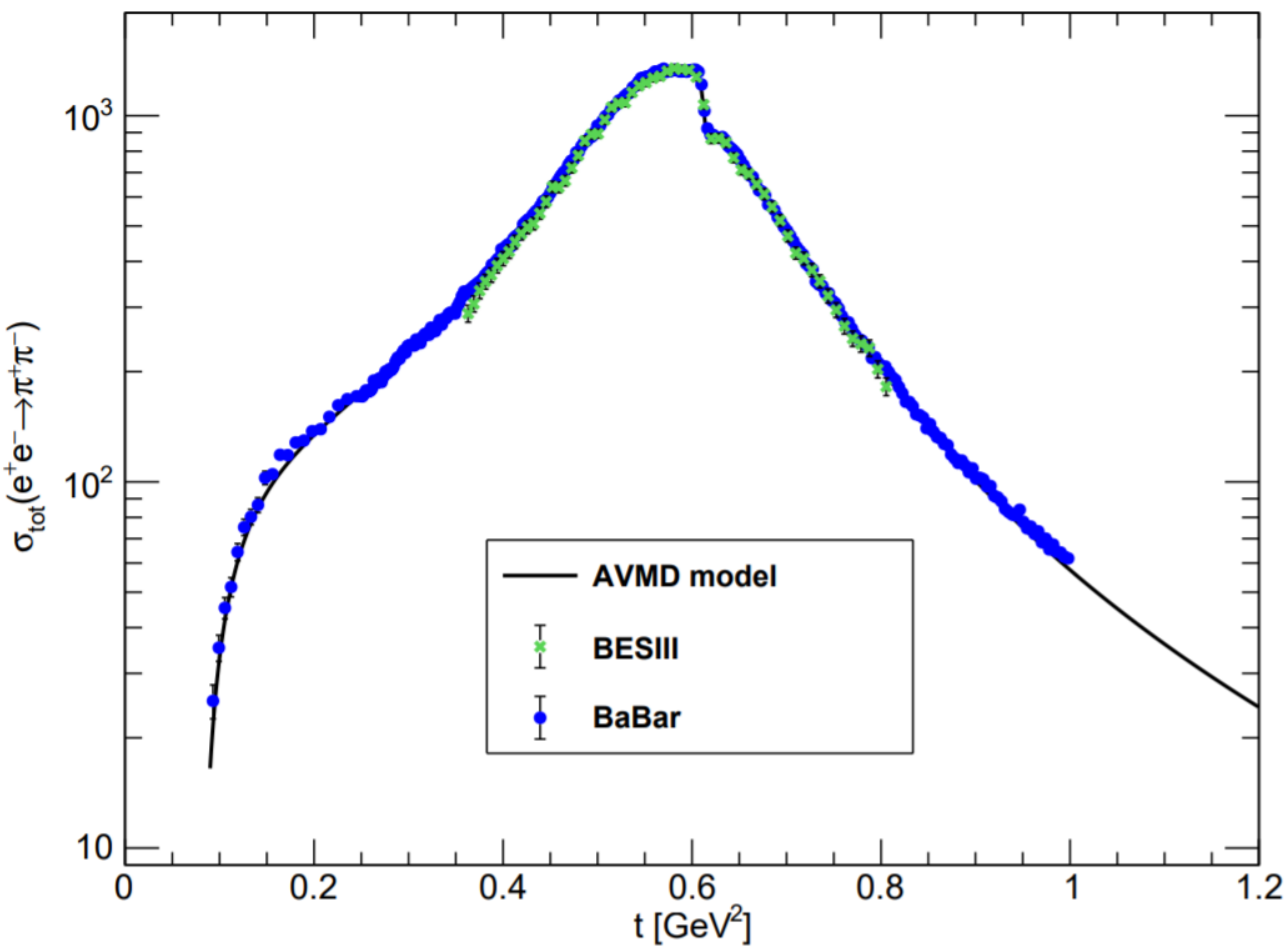
- The of the Gounaris-Sakurai pion electromagnetic form factor model at the elastic region, in which just the rho(770) resonance appears, wass investigated by the particular analysis of the most accurate P-wave isovector ππ scattering phase shift δ_1^1(t) data, obtained by the Garcia-Martin-Kamiński-Peláez-Yndurain approach, and by an application of the Unitary&Analytic pion electromagnetic structure model to a description of the newest precise data on the electron-positron annihilation process. Fig.2

- Unitary and Analytic models for the whole octet of baryons have been elaborated and from an optimal description of all existing nucleon data and SU(3) invariant Lagrangian of vector-meson baryon interaktions electromagnetic form factor behaviors of hyperons have been predicted.

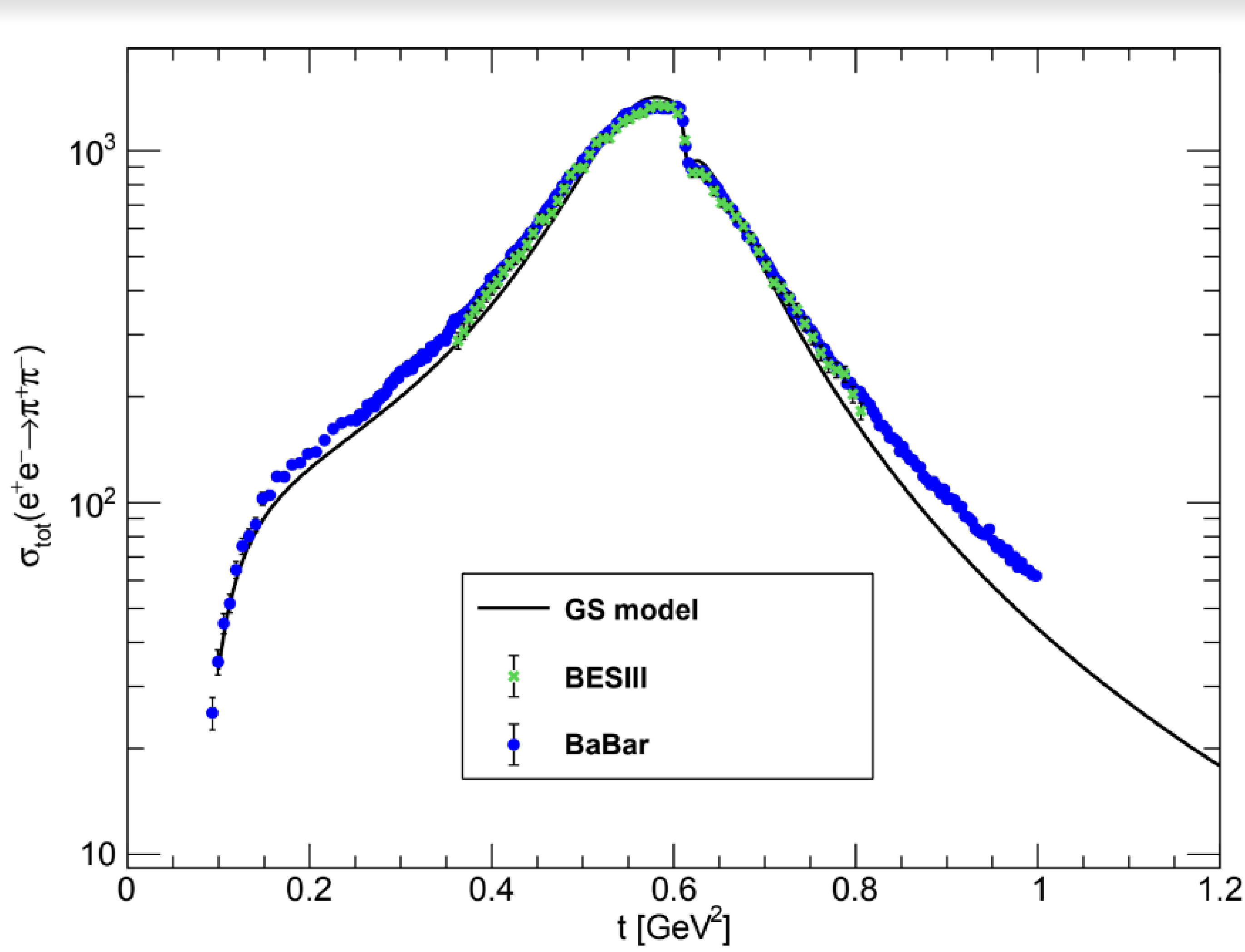
Hadron Physics and Hadron Phenomenology cont'd



Hadron Physics and Hadron Phenomenology cont'd



Hadron Physics and Hadron Phenomenology cont'd



Physics Beyond Standard Model

- New Physics weakly coupled – Supersymmetry
- Neutrino Sector
- Flavour Changing Neutral Currents (FCNC) rare decays
- (Charged) Lepton Flavor Violation

Supersymmetry (SUSY) $E \geq 100$ GeV

Many nice features we did not ask for:

* including the MSSM partners *improves* unification
* only possible extension of the space-time SM symmetry
* N=1 SUSY is automatically chiral

...

* Origin of the 100 GeV electroweak scale explained (potentially) as *induced by SUSY breaking*
* natural Dark Matter candidate
* ....

Indirect NEW PHYSICS Searches

Low Energy processes

$BR(B_s^0 \rightarrow \mu^+ \mu^-)$ with P.Maták, Intl. J. Phys. 2014, PhD Thesis 2015

$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

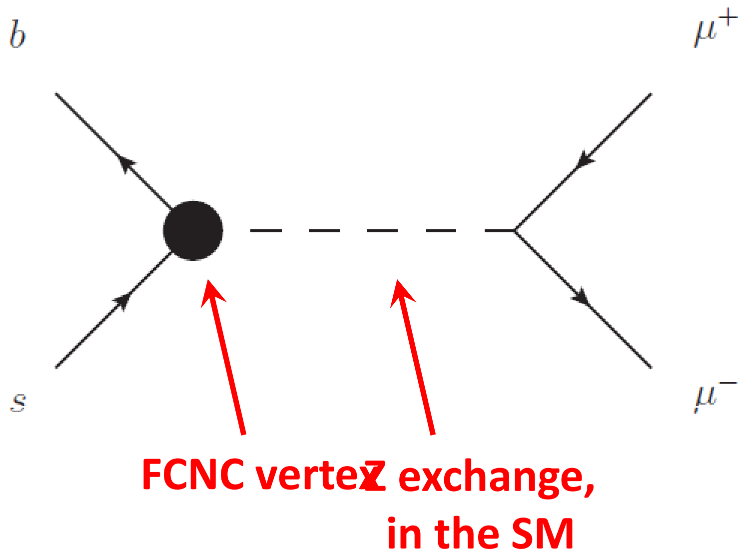
$R_K = \Gamma(K^+ \rightarrow e^+ \nu_e) / \Gamma(K^+ \rightarrow \mu^+ \nu_\mu)$ with P.Maták, Z.Kučerová and Z.Šinská, M.S. Thesis 2016

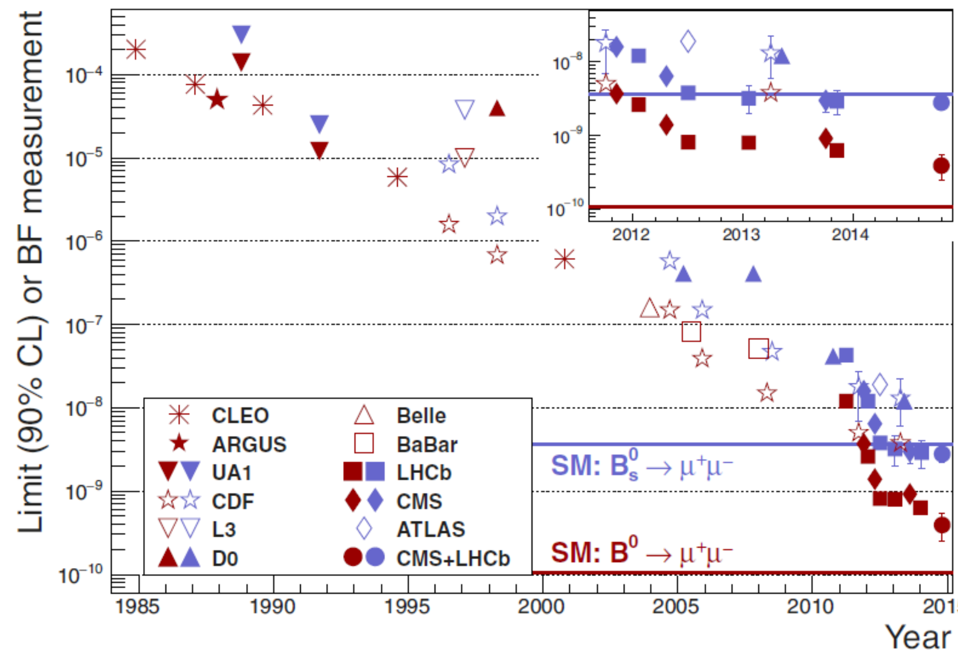
$BR(\tau \rightarrow e\gamma)$

$BR(H \rightarrow \tau \mu)$ with S.Beznák, M.S. Thesis 2017

considered SUSY each time

$B_s \longrightarrow \mu^+ \mu^-$

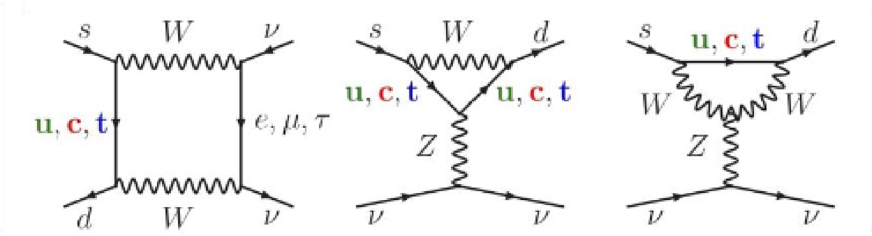




Standard Model: $Br\ (B_s \longrightarrow \mu^+ \mu^-) = 3.1 \pm 1.4 \times 10^{-9}$

$K^+ \rightarrow \pi^+$ ν vbar measured by NA62 Collaboration at CERN

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ is a FCNC process, very suppressed by CKM



in the Standard Model

Short distance contributions, dominated by t loop

Theoretical prediction [Buras et al. , JHEP 1511 (2015)]:

$$\mathrm{BR}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$$

Measured value [Phys. Rev. D 79, 092004 (2009)]:

$$\mathrm{BR}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$$

BNL Result

$K^+ \to \pi^+$ ν vbar in SM

$$\langle \pi^+ \nu\bar{\nu} | \bar{s}\gamma_\mu P_{L,R} d | K^+ \rangle \doteq \sqrt{2} \langle \pi^0 e^+ \nu_e | \bar{s}\gamma_\mu P_L u | K^+ \rangle$$

where, as far as the electron is treated massless, the effect of the leptonic current is the same for both decays. After the next-to-leading order (NLO) isospin breaking corrections are included, the hadronic matrix elements enter the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio through the parameter κ_+

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_c}{\lambda} (P_c + \delta P_{c,u}) + \frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X \right)^2 \right]$$

NNLO result[13]

$$P_c = (0.372 \pm 0.015) \times \left(\frac{0.2255}{\lambda} \right)$$

while long distance effects have been included in $\delta P_{c,u} = 0.04 \pm 0.02$.[3]

In our notation $X = X_L + X_R$ stands for the top quark and short distance contributions. In the SM $X_R^{\mathrm{SM}} = 0$ and $X_L^{\mathrm{SM}} \simeq X_0(x_t)$, where $x_t = m_t^2/M_W^2$. The loop function $X_0(x_t)$ represents the sum of the SM top quark diagrams and is equal to[14]

$$X_0(x_t) = \frac{x_t[x_t^2 + x_t - 2 + 3(x_t - 2)\ln x_t]}{8(1 - x_t)^2} .$$

Inclusion of NLO QCD corrections[5] and two-loop electroweak[15] corrections lead to $X(x_t) = 1.469 \pm 0.02$ and resulting branching fraction[15]

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})_{\mathrm{SM}} = (7.81^{+0.80}_{-0.71} \pm 0.29) \times 10^{-11}$$

$K^+ \to \pi^+ \nu \bar{\nu}$ in MSSM

In the super-CKM[b] basis, we assume the squark mass matrix

$$M_{\tilde{q}}^2 = \begin{pmatrix} M_{\tilde{q},LL}^2 & M_{\tilde{q},LR}^2 \\ M_{\tilde{q},LR}^{2\dagger} & M_{\tilde{q},RR}^2 \end{pmatrix}$$

with[c]

$$M_{\tilde{q},LL}^2 = V_{qL} \mathbf{m}_{\tilde{Q}}^2 V_{qL}^\dagger + \mathbf{m}_q^2 + \left(T_q^3 - Q_q s_W^2\right) M_Z^2 \cos 2\beta \mathbf{1} \,,$$

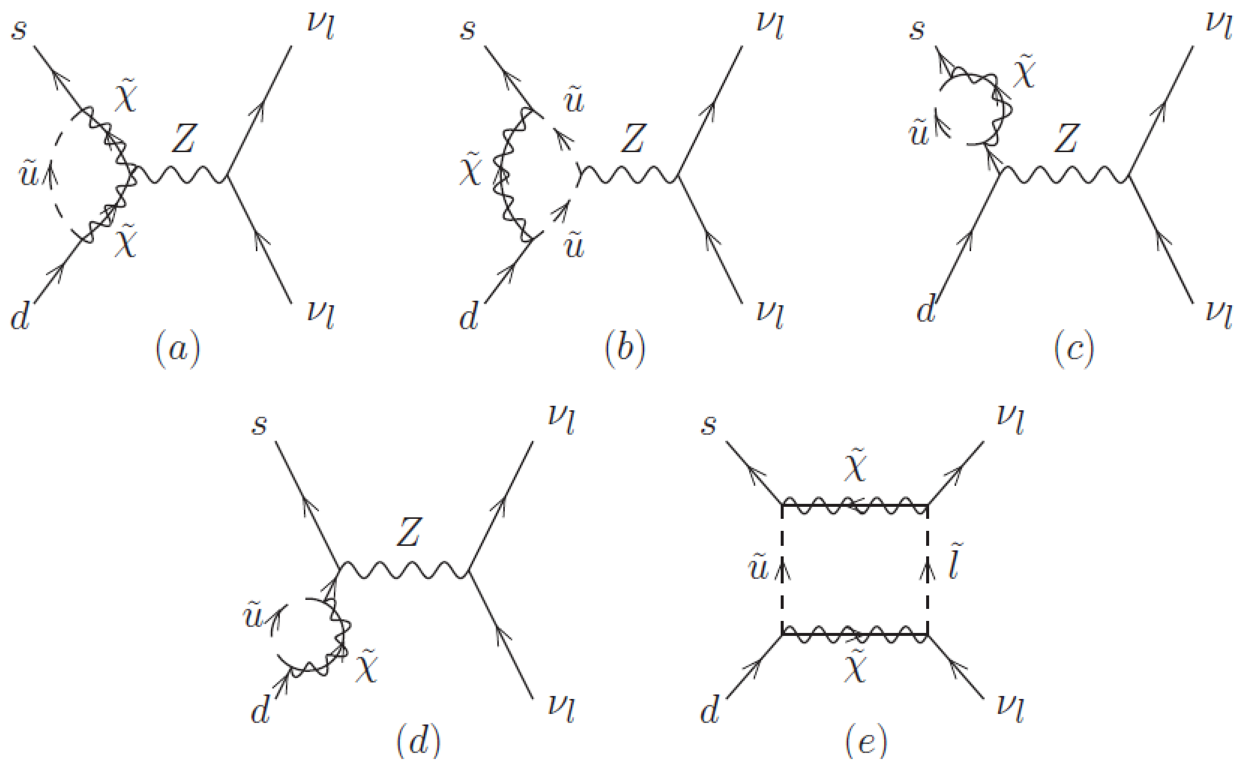
$$M_{\tilde{q},RR}^2 = V_{qR} \mathbf{m}_{\tilde{q}}^2 V_{qR}^\dagger + \mathbf{m}_q^2 + Q_q s_W^2 M_Z^2 \cos 2\beta \mathbf{1} \,,$$

$$M_{\tilde{q},LR}^2 = (\mathbf{A}_{\tilde{q}} - \mu^* \cot\beta) \mathbf{m}_q \,.$$

MSSM squark mass matrix: new sources of flavor violation *parametrized by*

$$\delta_{\tilde{q}XY}^{ij} = \frac{\left(M_{\tilde{q},XY}^2\right)^{ij}}{\sqrt{\left(M_{\tilde{q},XX}^2\right)^{ii} \left(M_{\tilde{q},YY}^2\right)^{jj}}} \,, \quad i \neq j$$

$K^+ \rightarrow \pi^+ \nu$ vbar in MSSM



MSSM chargino diagrams for the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$.

$K^+ \to \pi^+ \nu \bar{\nu}$ in MSSM

Numerical Results

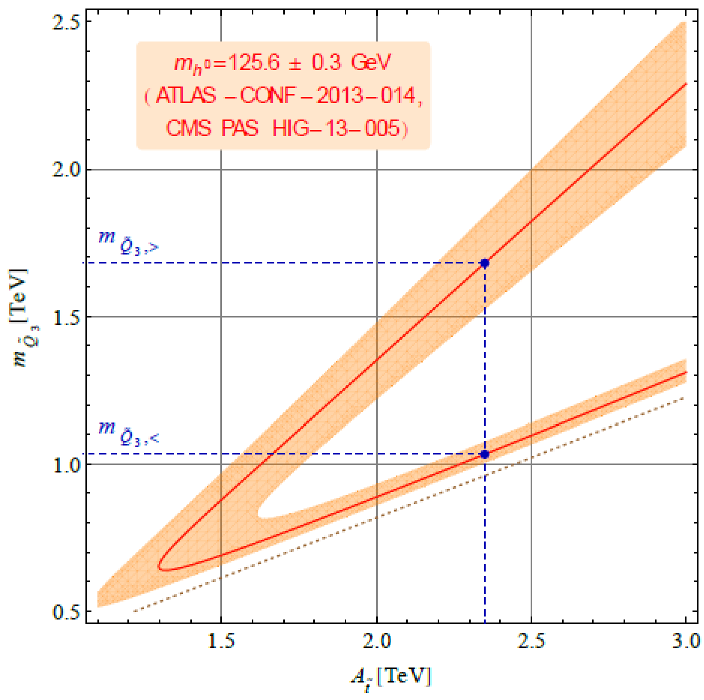


Figure 3: Allowed values of scalar mass and lef-right mixing corresponding to $\tan\beta = 50$ and average of Higgs mass measured by CMS [2] and ATLAS

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in MSSM

Numerical Results

Table 2: Used values of the MSSM parameters. All masses are in TeV.

M_2	μ	M_{A^0}	$\tan\beta$	$m_{\tilde{Q}_1}$	$m_{\tilde{u}_1,\tilde{d}_1}$	$m_{\tilde{u}_3,\tilde{d}_3}$
1.0	0.11	1.5	50	$1.2 \times m_{\tilde{Q}_3}$	$1.2 \times m_{\tilde{Q}_3}$	$m_{\tilde{Q}_3}$

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in MSSM

T. Blažek & P. Maták

Numerical Results

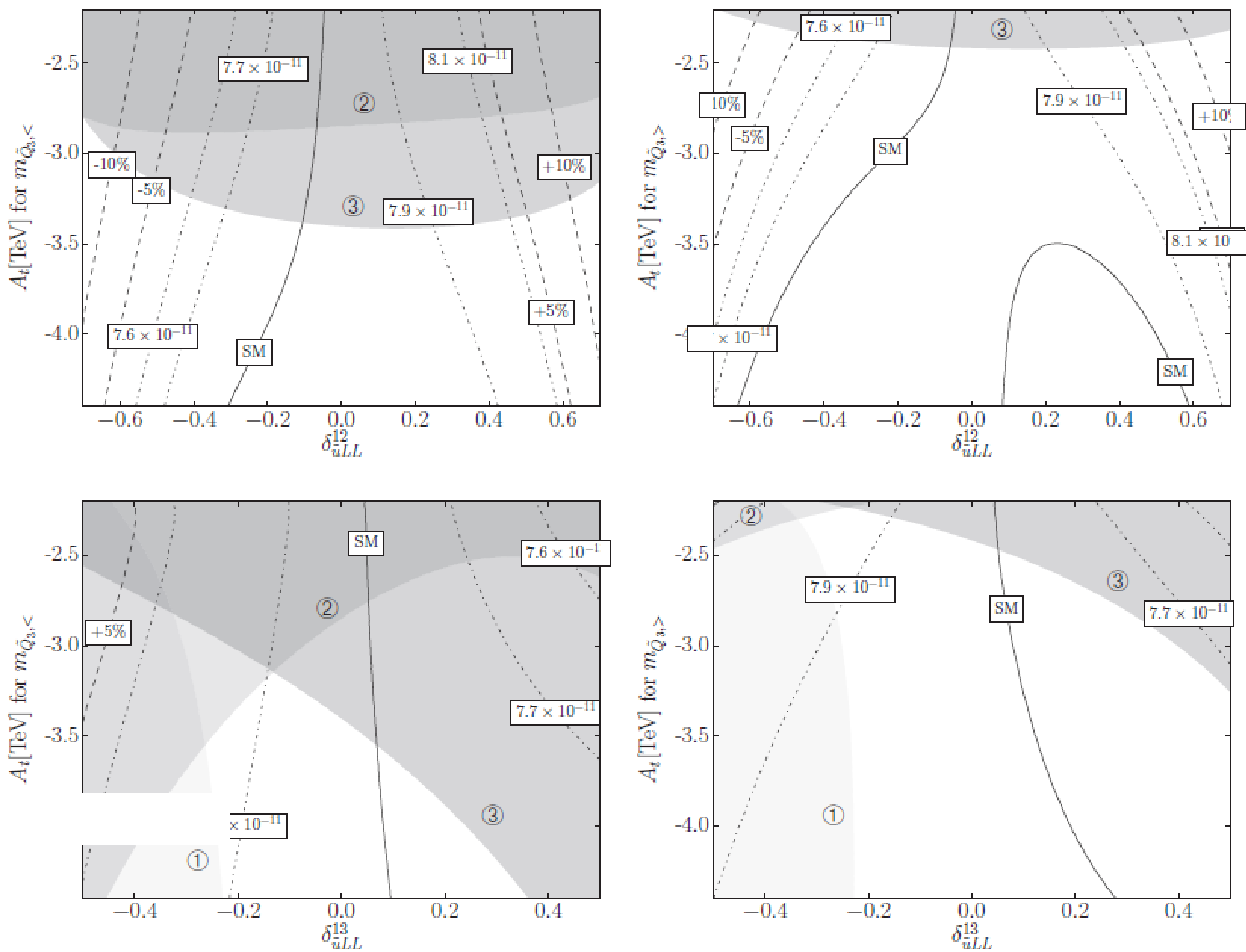


Fig. 4. The effect of $A_{\tilde{t}}$ and $\delta_{\tilde{u}LL}$ in the $K^+ \to \pi^+ \nu\bar{\nu}$ decay branching ratio.

$$R_K = \frac{\Gamma(K^+ \to e^+ \nu)}{\Gamma(K^+ \to \mu^+ \nu)}$$

$$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$$

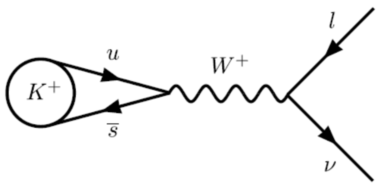
$$R_K^{exp} = (2.488 \pm 0.010) \times 10^{-5}$$

$$R_K = R_K^{SM}(1 + \Delta r), \qquad \Delta r \equiv \frac{R_K}{R_K^{SM}} - 1$$

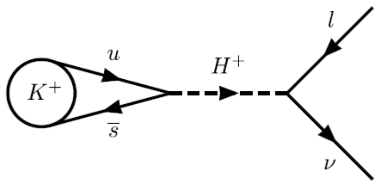
$$R_K = \frac{\Gamma(K^+ \to e^+ \nu)}{\Gamma(K^+ \to \mu^+ \nu)}$$

AT TREE LEVEL

SM



MSSM



$$i\mathcal{M}_{fi} = \langle 0| - i\frac{g_2}{\sqrt{2}} V^*_{us} \overline{v}_s \gamma^\mu P_L u_u |K^+\rangle \left(\frac{i}{M_W^2}\right) \left[-i\frac{g_2}{\sqrt{2}} \overline{u}_\nu \gamma_\mu P_L v_l\right] +$$
$$+ \langle 0| \, i \sin\beta y_s V^*_{us} \overline{v}_s P_L u_u |K^+\rangle \left(\frac{-i}{M_H^2}\right) [i \sin\beta y_e \overline{u}_\nu P_L v_l]$$

MSSM contrib. is Flavor Independent ... AT TREE LEVEL

SM **MSSM**

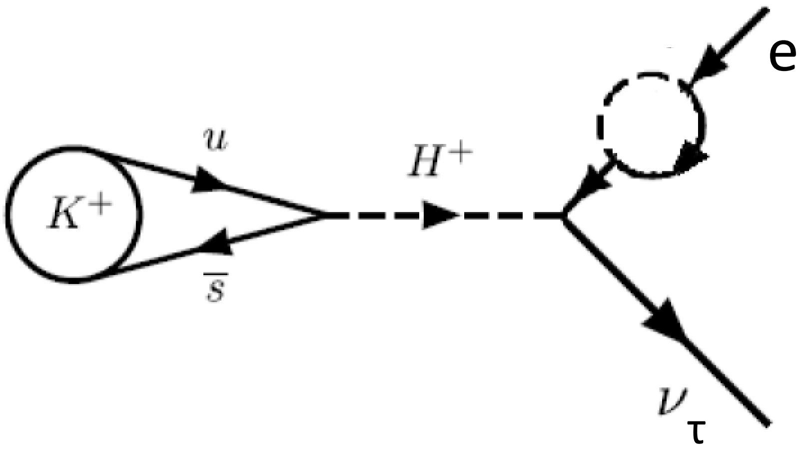
$$\Gamma\left(K^+ \to l^+ \nu\right) = \frac{1}{4\pi} [G_F F_0 V^*_{us} m_l]^2 \left[1 - \frac{m_K^2}{M_H^2} (\tan\beta)^2\right]^2 m_K \left(1 - \frac{m_l^2}{m_K^2}\right)^2$$

$$R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}$$

AT LOOP LEVEL

$$R_K = \frac{\Gamma(K \to e\nu_e) + \Gamma(K \to e\nu_\mu) + \Gamma(K \to e\nu_\tau)}{\Gamma(K \to \mu\nu_\mu) + \Gamma(K \to \mu\nu_e) + \Gamma(K \to \mu\nu_\tau)}$$

DOMINANT MSSM LOOP LEVEL CONTRIBUTION



$$R_K = \frac{\Gamma(K^+ \to e^+ \nu)}{\Gamma(K^+ \to \mu^+ \nu)}$$

AT LOOP LEVEL

$$\Gamma\left(K^+ \to l^+ \nu\right) = \Gamma^{SM,tree}\left(K^+ \to l^+ \nu\right) \times$$

$$\times \left[\overset{\text{ŠM}}{1} - \underbrace{\frac{m_K^2}{M_H^2}(\tan\beta)^2}_{a} \,{}^{\text{MSSM-tree}} + \frac{m_K^2}{M_H^2}(\tan\beta)^2 \, \underbrace{\frac{i}{m_l} m_A F\left(C_\tau^R C_\tau^{L*} + N_\tau^R N_\tau^{L*}\right)}_{b(l)} \,{}^{\text{MSSM-1-loop}} \right]^2$$

$$R_K = \frac{\Gamma\left(K^+ \to e^+ \nu\right)}{\Gamma\left(K^+ \to \mu^+ \nu\right)} = R_K^{SM} \frac{|1 - a + ab(e)|^2}{|1 - a + ab(\mu)|^2}$$

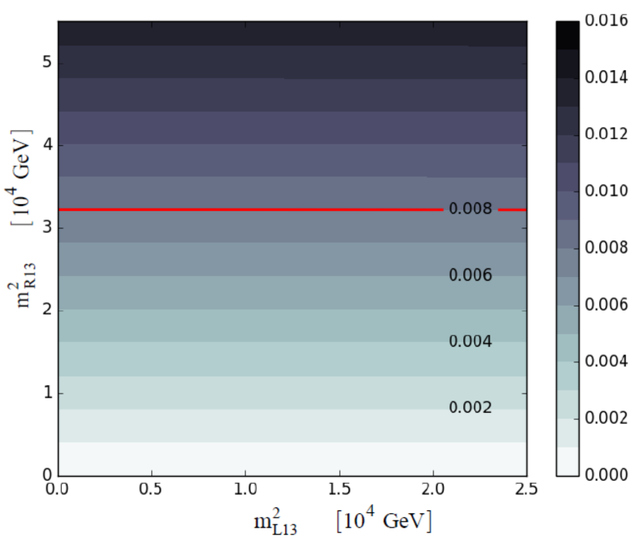
$$\Delta r = \frac{R_K}{R_K^{SM}} - 1 = \frac{|1 - a + ab(e)|^2}{|1 - a + ab(\mu)|^2} - 1$$

R.M.Fonseca et al, Eur.Phys.J. C72 (2012)

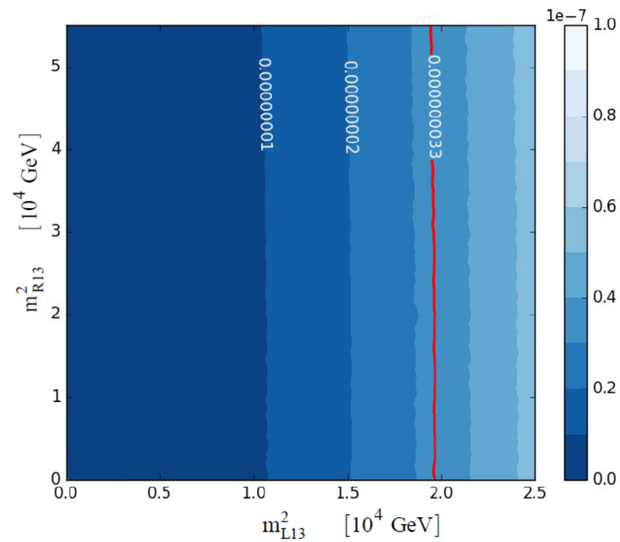
$$R_K = \frac{\Gamma(K^+ \to e^+ \nu)}{\Gamma(K^+ \to \mu^+ \nu)}$$

$\mu = 300$ GeV
$m^2_{L33} = 225000$ GeV, $m^2_{R33} = 210000$ GeV
fixované: $m^2_{L23} = 0$ GeV, $m^2_{R23} = 0$ GeV

(4.4.1) Δr



(4.4.2) BR_e



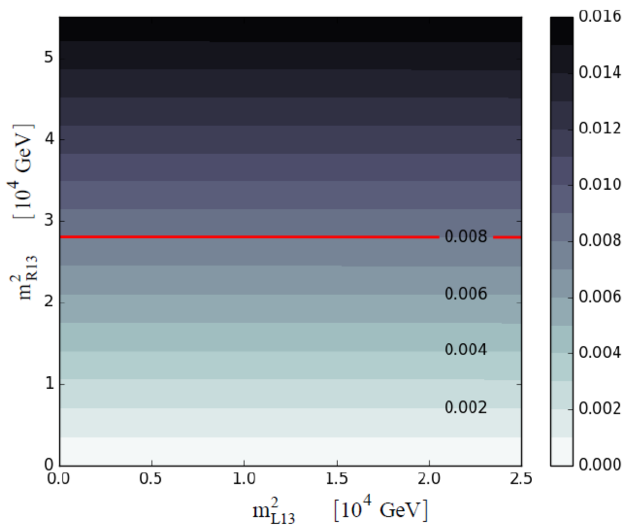
$$R_K = \frac{\Gamma(K^+ \to e^+ \nu)}{\Gamma(K^+ \to \mu^+ \nu)}$$

$\mu = 300$ GeV

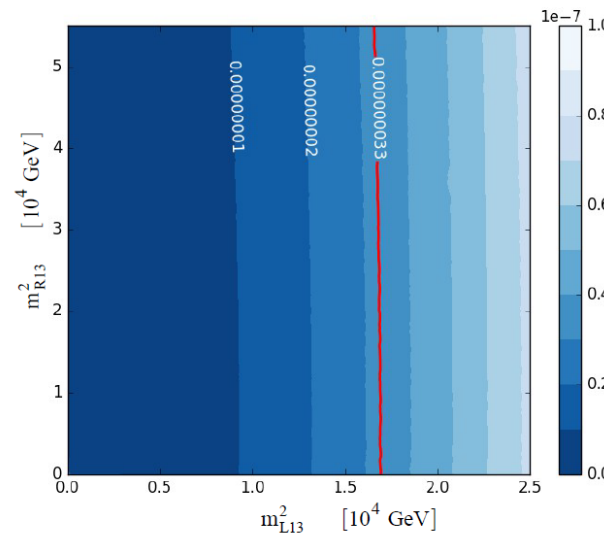
$m^2_{L33} = 180000$ GeV , $m^2_{R33} = 160000$ GeV

fixované : $m^2_{L23} = 0$ GeV , $m^2_{R23} = 0$ GeV

(4.6.1) Δr



(4.6.2) BR_e



New Physics coupled strongly

- strong dynamics breaking electroweak symmetry

2017

1. *M. Gintner, J. Juran:*
   The LHC mass limits for the SU $(2)_{L+R}$ vector resonance triplet of a strong extension of the Standard model (pdf)
   Acta Physica Polonica B, Vol. 48, No. 8 (2017), p. 1383.
   ISSN 0587-4254, ADC.
   arXiv: **1705.04806 [hep-ph]**

2. *M. Gintner, J. Juran:*
   The current LHC limis for the tBESS Lagrangian (pdf)
   Communications : scientific letters of the University of Zilina, Vol. 19, No. 1 (2017), p. 71.
   ISSN 1335-4205, ADF.

3. *M. Gintner:*
   Physics in the engineering education: focus on the essential (pdf)
   Proceedings of the 9th International Conference PTEE 2017 "Physics teaching in engineering education", Zilina, Slovakia, May 18 -- 19, 2017, AFD

2016

4. *M. Gintner, J. Juran:*
   The limits on the strong Higgs sector parameters in the presence of new vector resonances (pdf)
   Eur.Phys.J. C76 (2016) 651
   DOI: 10.1140/epjc/s10052-016-4484-z ISSN: 1434-6052 (online), 1434-6044 (print), ADC
   Copyright 2016 by Springer
   arXiv: **1608.00463 [hep-ph]**

5. *M. Gintner, J. Juran:*
   The LHC limits for the Higgs sector of the tBESS Lagrangian (pdf)
   Proceedings of the 22th Conference of Slovak Physicists, Kosice, Slovakia, Sep 5-8, 2016, AFD

New Physics coupled strongly

- strong dynamics breaking electroweak symmetry

2015

6. *M. Gintner:*
The effective field theory approach to Higgs physics beyond the standard model (pdf)
Proceedings of the 21th Conference of Slovak Physicists, Nitra, Slovakia, Sep 7-10, 2015, AFD

7. *M. Gintner, J. Juran:*
The top-BESS vector resonance triplet confronted with the LHC measurements (pdf)
published in Proceedings, 18th Conference of Czech and Slovak Physicists, with participation of Hungarian and Polish Physical Societies : Olomouc, Czech Republic, September 16-19, 2014 AFD
ISBN: 9788024447254 (CD), 9788024447261 (online)

2014

8. *M. Gintner, J. Juran:*
Hiding the vector resonance signal (pdf)
Communications : scientific letters of the University of Zilina, Vol. 16, No. 1 (2014), p. 50.
ISSN 1335-4205, ADF.

9. *M. Gintner, J. Juran:*
Phenomenology of the new strong vector resonance (pdf)
Proceedings of the **20th Conference of Slovak Physicists**, Bratislava, Slovakia, Sep 2 -- 5, 2013, AFD

2013

10. *M. Gintner, J. Juran:*
The vector resonance triplet with the direct coupling to the third quark generation (pdf)
Eur.Phys.J. C73 (2013) 2577
DOI: 10.1140/epjc/s10052-013-2577-5 ISSN: 1434-6052 (online), 1434-6044 (print), ADC
Copyright 2013 by Springer
arXiv: **1309.6597 [hep-ph]**

11. *M. Gintner:*
LHC and strongly-interacting extensions of the Standard Model (pdf)
Proceedings of the 19th Conference of Slovak Physicists, Presov, Slovakia, Sep 3 -- 6, 2012, AFD
arXiv: **hep-ph/1301.4348**

12. *M. Gintner, J. Juran:*
A 125 GeV scalar improves the low-energy data support for the top-BESS model
arXiv: **hep-ph/1301.2124**

Quantum Mechanics in non-commutative space

1) Laplace-Runge-Lenz vector in quantum mechanics in noncommutative space
Galikova, Veronika; Kovacik, Samuel; Presnajder, Peter
JOURNAL OF MATHEMATICAL PHYSICS , impakt faktor 1.176
Volume: 54 Issue: 12 Article Number: 122106 Published: DEC 2013, cit. 7

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2) The velocity operator in quantum mechanics in noncommutative space
Kovacik, S ; Presnajder, P
JOURNAL OF MATHEMATICAL PHYSICS, impakt faktor 1.176
Volume: 54 Issue: 10 Article Number: 102103 Published: OCT 2013, cit. 2

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3) Coulomb problem in non-commutative quantum mechanics
Galikova, V; Presnajder, P
JOURNAL OF MATHEMATICAL PHYSICS, impakt faktor 1.176
Volume: 54 Issue: 5 Article Number: 052102 DOI: 10.1063/1.4803457 Published: MAY 2013, cit. 2

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4) Hydrogen atom in fuzzy spaces - Exact solution
Galikova, V ; Presnajder, P
7TH INTERNATIONAL CONFERENCE ON QUANTUM THEORY AND SYMMETRIES (QTS7)
Book Series: Journal of Physics Conference Series Volume: 343 Article Number: 012096
Published: 2012, cit. 9

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5) Quantum field theory on quantized Bergman domain
Grosse, H.; Presnajder, P.; Wang, Zhituo
JOURNAL OF MATHEMATICAL PHYSICS, impakt faktor 1.176
Volume: 53 Issue: 1 Article Number: 013508 Published: JAN 2012 , cit. 7