UNIVERSITÀ DEGLI STUDI DI PERUGIA

Summary of First Year Activity

By: Sehar Ajmal
Doctoral Student Cycle XXXVI

Thesis Topic:

Searches For New Physics With Direct Searches At LHC And Future Colliders as well as with Indirect Searches

Tutor:

Dr. Orlando Panella (University and INFN Perugia)

Brief Self Introduction

- Sehar Ajmal from Rawalpindi, Pakistan
- MS Physics (18 years of Education) from Comsats University, Islamabad, Pakistan
  - **Major Subjects**: Particle Physics 1, Particle Physics 2, Quantum Field Theory 1, Quantum Field Theory 2, Advance Quantum Mechanics.
  - **Thesis**: Study of Two Body Gluino Decays at One-Loop Level in MSSM
- Enrolled in University of Perugia in January 2021
- Physically Joined UniPG in July 2021

Educational Activities

Courses

- Introduction to Effective Field Theory (EFT), Dott. Dario Buttazzo, Prof. Pietro Govoni, Prof. Gen Tatara
- Nano systems and advanced materials, Prof. Maddalena Pedio, Prof. Paolo Postorino , Elena Garlati & Alessandro CHIESA
- Introduction To Atmospheric Physics, Climate And COPERNICUS DATA Store by Prof. Paolina Cerlini
- Physics at LHC, Prof. Michele Gallinaro
- Multimessenger Astrophysics (from em Multifrequency to gravitational waves), Prof. Gino Tosti, Prof. Stefano Germani, Prof. Michele Punturo

School

Advanced Vector Boson Scattering (VBS) Training School at Università di Milano Bicocca, which lasted 27 hours, from 29 August 2021 to 3 September 2021 (In person)

The program covered the frontier of current research in the electroweak symmetry breaking domain: polarised vector boson scattering, the connection between effective field theory and complete models, and the use of anomaly detection in the search for deviations from the standard model.

Educational Activities

- **Seminars/Workshop**
  - Lesson with laboratory of Dr. Giuseppe Greco - Gravitational waves course.
  - B-Physics Anomalies and the flavour problem, Gino Isidori
  - Present And Future Of Multi-messenger Astronomy Including Gravitational Wave, Marica Branchesi
  - Searching for life in the Universe, how where and why?, Amedeo Balbi
  - The black hole guide to the Quantum theories of gravity, Roberto Emparan
  - Neutrons for magnetism in Spin chain Materials, Béatrice Grenier
  - Theory Colloquium by Savas Dimopoulos (Stanford University) , with title "Particle Physics Circa 2021".
  - "Naturalness and the future of High Energy Physics" by Gian Giudice (CERN) & Riccardo Rattazzi (EPFL - École polytechnique fédérale de Lausanne)
  - Simulating EFT using MG5_aMC@NLO by Ken Mimasu King's College London

Research Activity

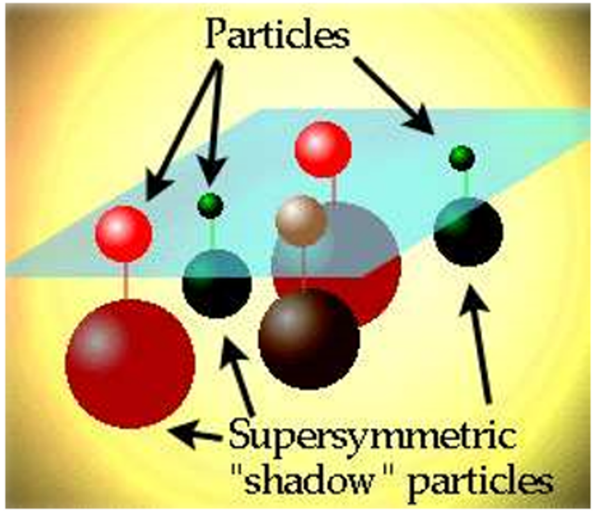
1. **Follow up article from the Masters Thesis (Under Review)**
   - Title: **Vacuum Stability Constraints on Flavour Mixing Parameters and Their Effect on Gluino Decays** [arXiv:2012.05832]
   - In Collaboration with **M. Rehman & F. Tahir** (Department of Physics, Comsats University Islamabad, Pakistan)
2. **Compositeness Effects in the $g_\mu - 2$**
   - Extension of the work "**Excited lepton triplet contribution to electroweak observables at one loop level** " [*Eur. Phys. J. C* 81, 392 (2021).]
   - In Collaboration with
     - **O. Panella** (INFN sezione di Perugia)
     - **M. E Gomez** (Departamento de Ciencias Integradas, Facultad de Ciencias Experimentales, Campus El Carmen, Universidad de Huelva, Spain)
     - **M. Rehman** (Department of Physics, Comsats University Islamabad, Pakistan)
3. **Composite Bosons Phenomenology at LHC**
   - Extension of the work "**Phenomenology at the LHC of composite particles from strongly interacting Standard Model fermions via four-fermion operators of NJL type**" [*Eur. Phys. J. C* 80, 309 (2020).]
   - In Collaboration with
     - **S. S. XUE** (ICRANet, Sapienza University Rome)
     - **O. Panella, R. Leonardi & M. Presilla** (INFN sezione di Perugia)
     - **F. Romeo, J. T. Gaglione & A. Gurrola** (Department of Physics and Astronomy, Vanderbilt University, Nashville, USA)
     - **H. Sun** (Institute of Theoretical Physics, School of Physics, Dalian University of Technology, People's Republic of China)

Motivation for BSM Physics

- SM does not incorporate neutrino masses and mixing, also there are too many parameters.
- No Dark Matter (DM) candidate present in the SM, does not accommodate gravity.
- Higgs mass Hierarchy problem. $\boldsymbol{\delta M_H^2(f) = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda^2 + \cdots]}$
- Generation puzzle and pattern with-in one generation
- Different Models can be used to solve these problems e.g., **Supersymmetry,**

  Left right symmetric Model, **Compositeness,** 331 Model, …etc.
- Effective Lagrangian approach-> At lower energies we may have an Effective Lagrangian which, in principle, can be derived from the fundamental high-energy Lagrangian. Effective Lagrangian contain higher-dimension operators (dimension 5, 6 and higher).

Vacuum Stability Constraints on Flavour Mixing Parameters and Their Effect on Gluino Decays
arXiv:2012.05832



Chiral Supermultiplets

Fields	*Bosonic*	*Fermionic*	$SU(3)_c \times SU(2)_L \times U(1)_Y$
$\hat{Q}_i$	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$(3, 2, \frac{1}{6})$
$\hat{U}_i$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{3}, 1, -\frac{2}{3})$
$\hat{D}_i$	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{3}, 1, -\frac{1}{3})$
$\hat{L}_i$	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)	$(1, 2, -\frac{1}{2})$
$\hat{E}_i$	$\tilde{e}_R^*$	$e_R^\dagger$	$(1, 1, 1)$
$\hat{H}_2$	(H_2^+, H_2^0)	$(\tilde{H}_2^+, \tilde{H}_2^0)$	$(1, 2, \frac{1}{2})$
$\hat{H}_1$	(H_1^0, H_1^-)	$(\tilde{H}_1^0, \tilde{H}_1^-)$	$(1, 2, -\frac{1}{2})$

Vector Supermultiplets

Fields	*Fermionic*	*Bosonic*	$SU(3)_c \times SU(2)_L \times U(1)_Y$
$\hat{G}^a$	$\tilde{g}$	g	$(8, 1, 0)$
$\hat{W}^i$	$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm, W^0$	$(1, 3, 0)$
$\hat{B}$	$\tilde{B}^0$	B^0	$(1, 1, 1)$

->Squarks, Sleptons, Higgsinos, Gluino, Wino, Bino

- In this article, we studied the two body Gluino decays $\tilde{g} \to \tilde{u}_i \bar{u}_g$, $\tilde{g} \to \tilde{d}_i \bar{d}_g$ with i = 1, 2, ...6 and g = 1, 2, 3 in the Minimal Supersymmetric Standard Model (MSSM) with quark flavour violation (QFV).

Relation between $A^{\tilde{f}}_{ij}$ and δ^{FAB}_{ij}

- In order to get true ground state, one has to satisfy

$$\left|A^{\tilde{u}}_{ij}\right|^2 \leq \lambda^2_{u_k}\left(m^2_{\tilde{u}_{L_i}} + m^2_{\tilde{u}_{R_j}} + m^2_2\right),$$

k= Max(i, j)

$$\left|A^{\tilde{d}}_{ij}\right|^2 \leq \lambda^2_{d_k}\left(m^2_{\tilde{d}_{L_i}} + m^2_{\tilde{d}_{R_j}} + m^2_1\right)$$

- Flavor violating deltas are related to trilinear couplings as

$$\delta^{\mathrm{ULR}}_{\mathrm{ij}} = \left(\frac{v_2}{\sqrt{2}}\right)\frac{A^{\tilde{u}}_{ij}}{\sqrt{M^2_{\tilde{U}_{ii}} M^2_{\tilde{Q}_{jj}}}}, \qquad \delta^{\mathrm{DLR}}_{\mathrm{ij}} = \left(\frac{v_1}{\sqrt{2}}\right)\frac{A^{\tilde{d}}_{ij}}{\sqrt{M^2_{\tilde{D}_{ii}} M^2_{\tilde{Q}_{jj}}}}$$

- Charge and Color Breaking (CCB) and Unbounded from Below (UFB) bound directly effect the Left right mixing. The partial decay width of Gluino depends upon these parameters.

- Furthermore, we have calculated the constraints on $\delta_{23}^{URL}, \delta_{23}^{ULR}, \delta_{23}^{DRL}, \delta_{23}^{DLR}$, using for a specific set of MSSM parameters using charge and colour breaking minima (CCB) and unbounded from below minima (UFB) conditions.

		CCB Bounds	UFB Bounds
δ_{23}^{ULR}	S1	-0.12:0.12	-0.12:0.12
	S2	-0.12:0.12	-0.13:0.13
	S3	-0.12:0.12	-0.13:0.13
	S4	-0.09:0.09	-0.09:0.09
	S5	-0.19:0.19	-0.22:0.22
δ_{23}^{DLR}	S1	-0.003:0.003	-0.003:0.003
	S2	-0.003:0.003	-0.003:0.003
	S3	-0.003:0.003	-0.003:0.003
	S4	-0.002:0.002	-0.002:0.002
	S5	-0.006:0.006	-0.005:0.005

Constraints from B-physics

δ_{23}^{ULR}	S1	(-0.27:0.27)
	S2	(-0.27:0.27)
	S3	(-0.27:0.27)
	S4	(-0.22:0.22)
	S5	excluded
δ_{23}^{DLR}	S1	(-0.0069:0.014) (0.12:0.13)
	S2	(-0.0069:0.014) (0.11:0.13)
	S3	(-0.0069:0.014) (0.11:0.13)
	S4	(-0.014:0.021) (0.17:0.19)
	S5	(0.076:0.12) (0.26:0.30)

- These constraints are more stringent compared to the constraints coming from B-physics observables (BPO), that are already available in literature [Phys. Rev. D, 90(7):075003, 2014.].

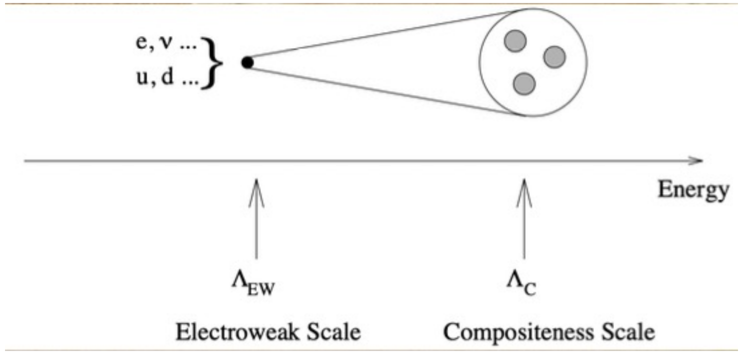
- In the second step, we re-calculate the partial decay widths of $\tilde{g} \to \tilde{u}_i \bar{u}_g$, $\tilde{g} \to \tilde{d}_i \bar{d}_g$ for the allowed range of QFV parameters.

$\tilde{g} \to \bar{c}\tilde{u}_1$				
Point	No FV	δ_{23}^{QLL}	δ_{23}^{ULR}	δ_{23}^{URR}
$S1$	0	0	1.117	80.2
$S2$	0	0	1.17	80.2
$S3$	0	0	1.17	78.57
$S4$	0	0	11.6	116.68
$\tilde{g} \to \bar{t}\tilde{u}_1$				
Point	No FV	δ_{23}^{QLL}	δ_{23}^{ULR}	δ_{23}^{URR}
$S1$	0	0	0	83.9
$S2$	0	0	0	83.9
$S3$	0	0	0	82.3
$S4$	36.9	0	28.06	119

$\tilde{g} \to \bar{s}\tilde{d}_1$				
Point	No FV	δ_{23}^{QLL}	δ_{23}^{DLR}	δ_{23}^{DRR}
$S1$	0	6.39	0.61×10^{-3}	75.6
$S2$	0	4.3	0.61×10^{-3}	75.6
$S3$	0	1.16	0.61×10^{-3}	75.6
$S4$	0	19.18	2.06	113.6
$\tilde{g} \to \bar{b}\tilde{d}_1$				
Point	No FV	δ_{23}^{QLL}	δ_{23}^{DLR}	δ_{23}^{DRR}
$S1$	0	6.35	0.16×10^{-2}	75.61
$S2$	0	4.32	0.10×10^{-1}	75.61
$S3$	0	1.22	0.50×10^{-1}	75.61
$S4$	22.29	19.21	20.29	113.7

- The QFV in the LR/RL sector is usually ignored due to stringent CCB and UFB constraints. However, our analysis reveals that this mixing can contribute to Partial decay width up to ≈ 12 GeV for some parameter points and should not be ignored.

Composite Models



- The idea is that at some high energy scale Λ a further level of compositeness of the "elementary" particles will show up. It goes back quite some time.
- P.A.M Dirac, Sci. Am. 208,45 (1963); Terazawa et al., PRD 15, 480 (1977); Eichten, Lane, Peskin, PRL 50, 811 (1983); Cabibbo, Maiani, Srivastava, PLB 139, 459 (1984);
- Y. Nambu, G. Jona-Lasinio, Phys. Rev. **122**, 345 (1961)
- Models uses Effective Field Theoretical approach, So Standard Model should be seen as the low energy limit of a more fundamental theory
- Most basic Structure can be
  - Excited states L^*, Q^* with mass M^* appears
  - Contact Interactions between Leptons and Quarks as well as between Excited states and SM fermions.
  - Also encountered with higher dimension (dim-5 or dim-6) operators e.g. $(\bar{u}_{Lb} d_{Rb})(\bar{d}^a_R u_{La})$
- Currently working with two different scenarios
  - Composite Models with effective four fermions operators of NJL type
  - Composite model of Preons where the couplings of the excited leptons are described by an effective $SU(2)\times U(1)$ invariant Lagrangian.

Compositeness effects in the $g_\mu - 2$

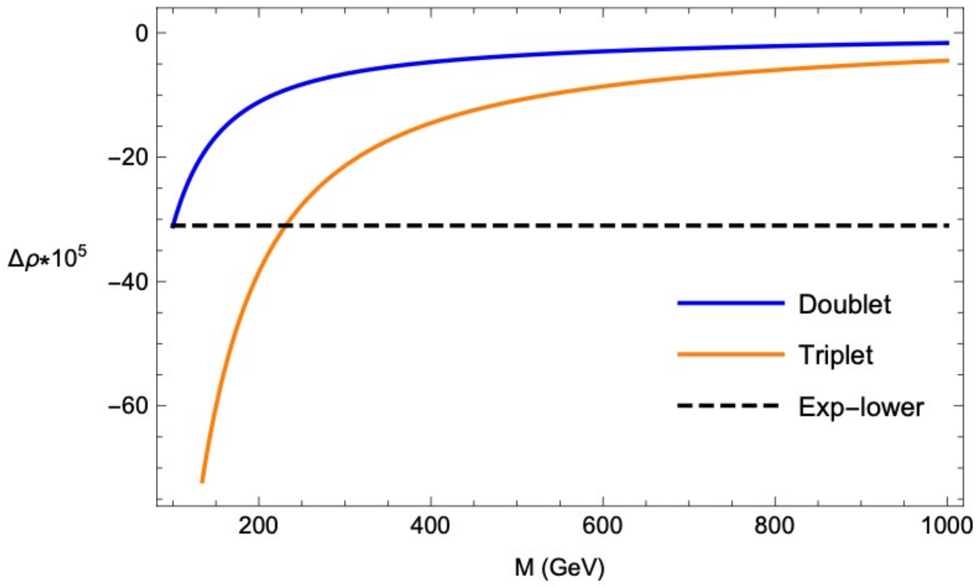
- Model independent phenomenologocal analysis where one can apply the Effective Lagrangian techniques to describe the physics of the excited states below the compositeness scale.
- Previously , production of excited states members of multiplets of isospin $I_W = 0, ½$ was discussed.
- However, higher isopin multiplets are also allowed, $I_W = 1, \frac{3}{2}$ [Pancheri-Srivastava, Phys.Lett. 146B (1984) 87-94]

I_W	Multiplet	Q	Y	Couple to	Couple through
0	(E^-)	-1	-2	e_R	B^μ
$\frac{1}{2}$	$\begin{pmatrix} E^0 \\ E^- \end{pmatrix}$	0 1	-1	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	B^μ, W^μ
1	$\begin{pmatrix} E^0 \\ E^- \\ E^{--} \end{pmatrix}$	0 -1 -2	-2	e_R	W^μ
$\frac{3}{2}$	$\begin{pmatrix} E^+ \\ E^0 \\ E^- \\ E^{--} \end{pmatrix}$	$+1$ 0 -1 -2	-1	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	W^μ

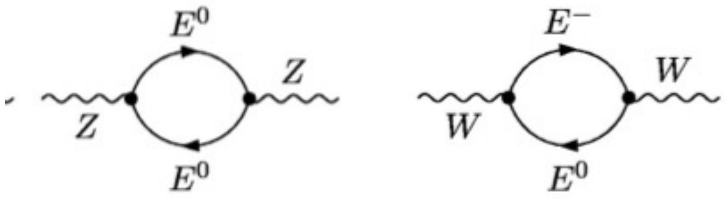
Constraining the Parameter Space

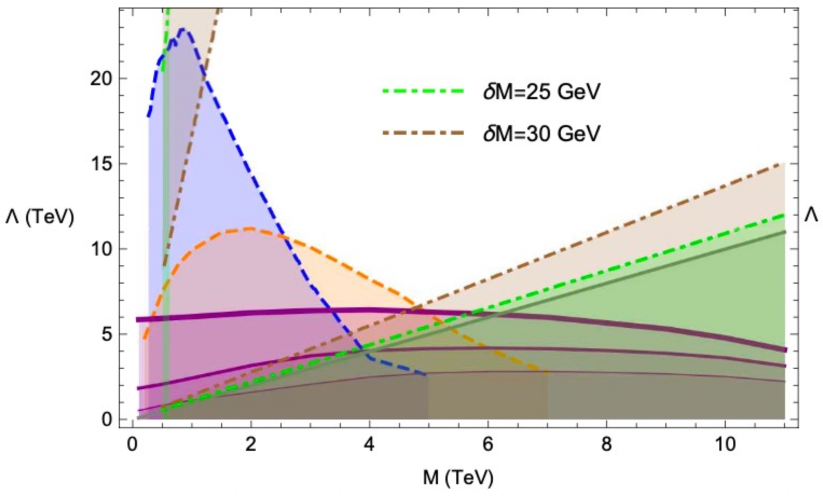
- Parameter space $[\Lambda, M]$
- Excited leptons triplet contribution to electroweak observables at one loop level [*Eur. Phys. J. C* 81, 392 (2021)]
- The electroweak ρ-parameter is a measure of the relative strengths of neutral and charged-current interactions

$$\boldsymbol{\rho} = \frac{\boldsymbol{G_{NC}}}{\boldsymbol{G_{CC}}} \quad \rightarrow \Delta\rho = \frac{\Sigma_Z^1(0)}{M_Z^2} - \frac{\Sigma_W^{(1)}(0)}{M_W^2}$$

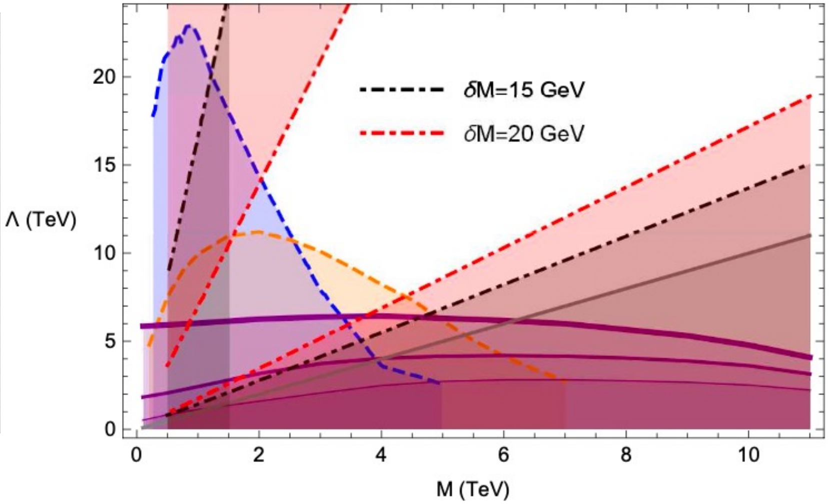


- For triplet we have Feynman diagrams





Excited Lepton doublet.



Excited Lepton triplet

The triplet contribution to the anamoulos magnetic moment of leptons.

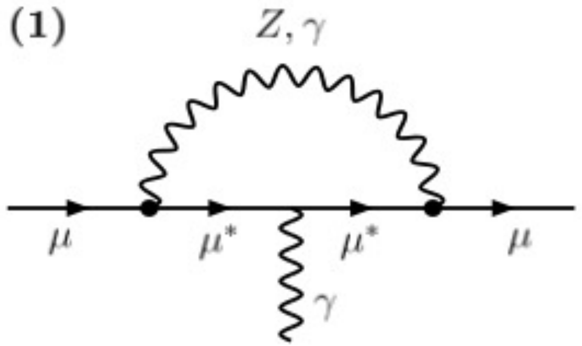
- In recent studies $a_\mu(Exp) = 116592061(41)\times10^{-11}$[*Phys. Rev. Lett.*, vol. 126, p. 141801, Apr 2021]
- $a_\mu(Exp) - a_\mu(SM) = (251 \pm 59)\times10^{-11}$ with significance of 4.2σ
- These results will motivate the development

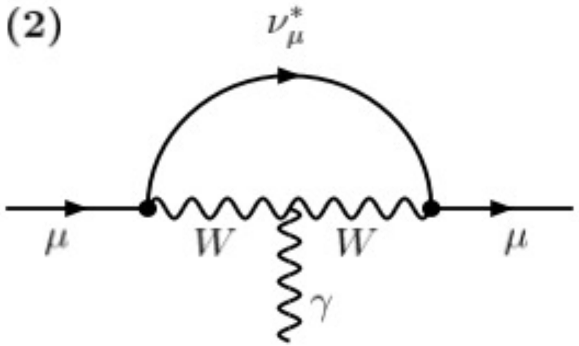
of SM extensions and helps one to constraint the parameter space.

- As a first step we are calculating the contribution of

excited states with $I_W = 0, ½$ to the $g_\mu - 2$ [Physics Letters B 389 (1996) 707-712].

- Main Goal is to calculate the triplet and quadruplets contributions to the $g_\mu - 2$





Composite Bosons Phenomenology at LHC

- Based on the Composite NJL Model [*J. High Energy. Phys.* **2016,** 72 (2016)]**,** The model explains the hierarchy spectrum of SM fermion masses.
- Four fermion operators

$$G\left[\left(\overline{l_L^i}e_R\right)\left(\overline{d_R^a}\psi_{Lia}\right)+(\overline{l_L^i}\nu_R)(\overline{u_R^a}\psi_{Lia})\right]+h.c$$

$$G\left[\left(\overline{\psi_L^{bi}}d_{Rb}\right)\left(\overline{d_R^a}\psi_{Lia}\right)+(\overline{l_L^i}\nu_R)(\overline{u_R^a}\psi_{Lia})\right]+h.c$$

- In the previous work phenomenology of composite fermion is considered [*Eur. Phys. J. C* 80, 309 (2020)]
- In the extended work we are studying Phenomenology of **Composite Bosons** which arises from four fermion operators

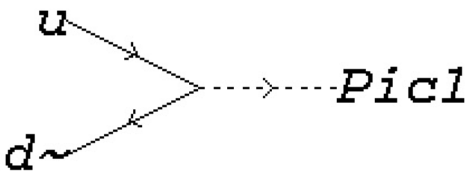
Composite bosons Π	Constituents
Π^+	$(\bar{d}_R^a u_{La})$
Π^-	$(\bar{u}_R^a d_{La})$
Π_d^0	$(\bar{d}_R^a d_{La})$
Π_u^0	$(\bar{u}_R^a u_{La})$

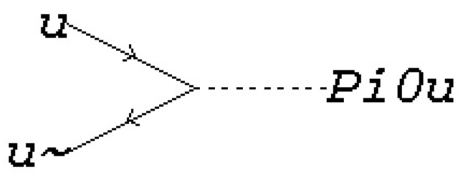
Composite bosons Π	constituents
$\Pi_a^{+5/3}$	$(\bar{e}_R u_{La})$
$\Pi_a^{-1/3}$	$(\bar{\nu}_R^e d_{La})$
$\Pi_{u_a}^{2/3}$	$(\bar{\nu}_R^e u_{La})$
$\Pi_{d_a}^{2/3}$	$(\bar{e}_R d_{La})$

Current Progress

- Production and Decay of $\Pi^{0,\pm}$
  - Full decay chain is

$$pp \to \ \Pi \to qq'$$
$$pp \to \Pi \to \tilde{G}\tilde{G}'$$





- Partonic cross section

$$\widehat{\sigma_\Pi}(\hat{s}, m_\Pi) = \frac{\pi}{12}\left(\frac{F_\Pi}{\Lambda}\right)^4 \delta\left(\hat{s} - m_\Pi^2\right)$$

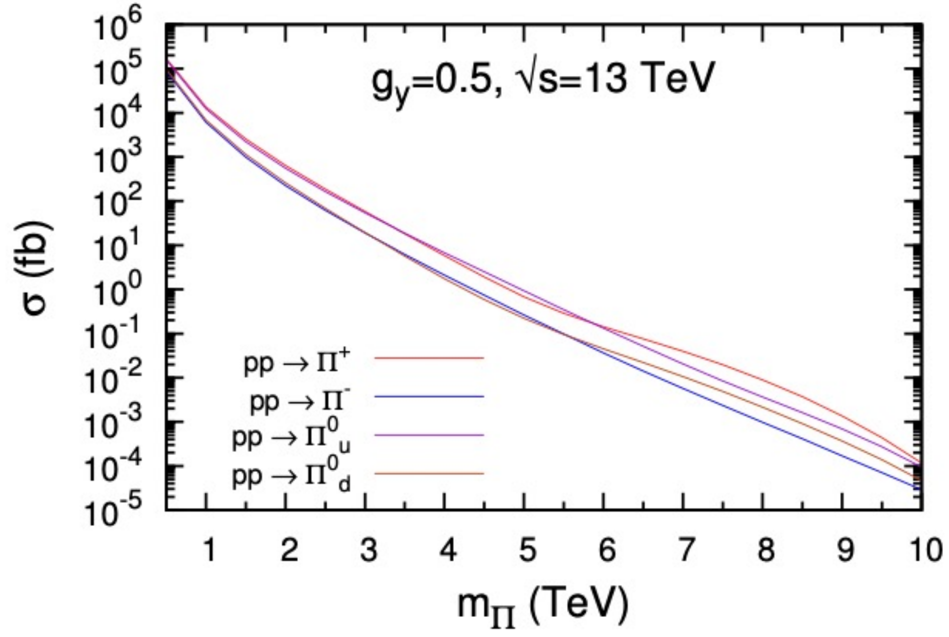
- Hadronic cross section

$$\sigma_\Pi = \sum_{ij} \int_{\frac{m_\Pi^2}{s}}^{1} d\tau \int_\tau^1 \frac{dx}{x} f_i(x, \widehat{Q^2})\, \hat{\sigma}(\tau s, m_\Pi)$$

- Decay width

$$\Gamma(\Pi \to qq') = \frac{3}{16\pi}\left(\frac{F_\Pi}{\Lambda}\right)^4 m_\Pi$$

- Parameter space $[(\Lambda, m_F, F_\Pi, m_\Pi) \to (\frac{m_F}{\Lambda}, \frac{F_\Pi}{m_\Pi}, \frac{m_\Pi}{m_F})]$



- I have validated and reproduced the Decay width and partonic cross section.
- Mainly i'm focusing on the implementation of the model in the Madgraph.
- MadGraph is a Monte Carlo event generator for collider studies, nowadays widely used to simulate events at the LHC. We want to do numerical analysis with Madgraph in order to get closer to the experimental predictions.

Madgraph Implementation

- We are implementing the Model in the Madgraph
  - Aim is to create UFO files
  - Feynrules source file -> Export in Mathematica -> Extract the Feynman rules
  - UFO models can be imported in Monte Carlo generators, for the simulations of LHC events

```
MG5_aMC>import model SheSheng_UFO
INFO: Change particles name to pass to MG5 convention
Kept definitions of multiparticles p / j / l+ / l- / vl / vl~ unchanged
Defined multiparticle all = g u c d s u~ c~ d~ s~ a ve vm vt e- ve~ vm~ vt~ e+ t b t~ b~ z w+ h al01+ al02+ al03+ anc1
+ anc2+ anc3+ alc1 alc2 alc3 an01 an02 an03 pic1+ pi0u pi0d w- al01~ al02~ al03~ anc1~ anc2~ anc3~ pic1~ mu- ta- e0 mu
0 tau0 nc1 nc2 nc3 ec muc tauc n01 n02 n03 mu+ ta+ e0~ mu0~ tau0~ nc1~ nc2~ nc3~ ec~ muc~ tauc~ n01~ n02~ n03~
MG5_aMC>
```

```
MG5_aMC>generate p p > e0 e+/pic1+
INFO: Checking for minimal orders which gives processes.
INFO: Please specify coupling orders to bypass this step.
INFO: Trying coupling order WEIGHTED<=2: WEIGTHED IS NP+QCD+2*QED
INFO: Trying process: u d~ > e0 e+ WEIGHTED<=2 / pic1+ @1
INFO: Process has 1 diagrams
INFO: Trying process: u s~ > e0 e+ WEIGHTED<=2 / pic1+ @1
INFO: Trying process: c d~ > e0 e+ WEIGHTED<=2 / pic1+ @1
INFO: Trying process: c s~ > e0 e+ WEIGHTED<=2 / pic1+ @1
INFO: Process d~ u > e0 e+ added to mirror process u d~ > e0 e+
1 processes with 1 diagrams generated in 0.022 s
Total: 1 processes with 1 diagrams
MG5_aMC>
```

Madgraph Implementation

```
Block frblock
    1 6.250000e+02 # lc
    2 5.000000e+02 # MUU
    3 1.000000e+03 # MPi
    4 5.000000e+03 # FPi
    5 2.277360e-01 # cabi2
```

Edit parameters in the param_card.dat

$m_F/\Lambda = 0.8$

```
Cross-section :   543.6 +- 1.771 pb
Nb of events :  10000
```

```
INFO: Running Systematics computation
WARNING: impossible to download all the pdfsets. Bypass systematics
store_events
INFO: Storing parton level results
INFO: End Parton
reweight -from_cards
decay_events -from_cards
INFO: storing files of previous run
INFO: Done
quit
INFO:
more information in /Users/seharajmal/MG5_aMC_v3_1_0/bin/M1/index.html
```

- Results are generated via built-in PDF's but we are aiming to use NNPDF30.

Recap

- **Up till now**
  - Learned many new things by interacting with the Professors, Collaborators and colleagues
  - Gained knowledge specific for research field and hoping to enhance it in future.
  - Gaining experiences in conferences' world
- **Looking Forward**
  - To avail every opportunity which helps in improving my scientific skills.
  - Possible collaboration with the Internal CMS group of Perugia i.e**. Production Of Monte Carlo Simulated Samples For The Vector Boson Scattering Data Analysis** (currently ongoing within the PG group)
  - Plan to go the GGI school "**GGI Lectures on the Theory of Fundamental Interactions 2022**"
  - Carry on the research work for the PhD thesis.

Thank You!

Effective Field Theories

$$\mathcal{L}_{EFT} = \sum_i \frac{C_i}{\Lambda^{\delta_i - 4}} O_i$$

- C_i is the Wilson coefficient which is simply a coupling which depends upon the scale at which it is probed.
- O_i is the effective operator, it contains all the low energy interactions that are physically accessible at the EFT scale.
- There is also dependence of cutoff scale below which the EFT is effective and δ_i is the dimension.
- We can factorize information about possibly-but not unknown UV physics from low energy physics.
- UV information lives in Wilson coefficient, IR information lives in operators.
- The UV physics that we factorize into the Wilson coefficients need not to be known.