

Characterising Different Beyond the Standard Model Signatures at Present and Future Colliders

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Theories Beyond the Standard Model (BSM) to Address the Shortcomings of the Standard Model

Standard Model fails to provide any explanation for some crucial observations

- Neutrino Mass
- Dark Matter
- Baryon-Antibaryon ratio
- Anomalies in rare decays

Many BSM scenarios so far proposed to explain one or more such observations

- They often predict particles with different spins in similar Mass range
- Some of these particles may belong to different representations of Gauge Groups
- Biggest Challenge: HOW TO DISTINGUISH THEM?

The Leptoquarks

- Particles with color charge, possesses lepton and baryon numbers simultaneously
- May belong to spin-0 or 1 representations
- Accommodated in $SO(10)$ models and other GUT models with higher symmetry groups
- Scalar leptoquark enhances the vacuum stability
- Address some of the anomalies associated with rare decays

The Leptoquark Models

- $$\begin{cases} \mathcal{L}_{\phi_S} = (D^\mu \phi_S)^\dagger (D_\mu \phi_S) & + (Y_\phi \bar{Q}_{L,R} \phi_S \mathcal{L}_{L,R} + h.c.) \\ \mathcal{L}_{\phi_V} = -\frac{1}{2} \mathcal{G}_{\mu\nu}^\dagger \mathcal{G}^{\mu\nu} & + (Y_\phi \bar{Q}_{L,R} \gamma^\mu \phi_{V,\mu} \mathcal{L}_{L,R} + h.c.) \end{cases}$$

- Depending on $SU(2)$ representation, they are categorised as:

- $$\begin{cases} S_1 & (\bar{\mathbf{3}}, \mathbf{1}, \frac{2}{3}) \\ \tilde{S}_1 & (\bar{\mathbf{3}}, \mathbf{1}, \frac{8}{3}) \end{cases} \quad SU(2) \text{ singlet} \quad \begin{cases} U_{1\mu} & (\mathbf{3}, \mathbf{1}, \frac{4}{3}) \\ \tilde{U}_{1\mu} & (\mathbf{3}, \mathbf{1}, \frac{10}{3}) \end{cases}$$
- $$\begin{cases} R_2 & (\mathbf{3}, \mathbf{2}, \frac{7}{3}) \\ \tilde{R}_2 & (\mathbf{3}, \mathbf{2}, \frac{1}{3}) \end{cases} \quad SU(2) \text{ doublet} \quad \begin{cases} V_{2\mu} & (\bar{\mathbf{3}}, \mathbf{2}, \frac{5}{3}) \\ \tilde{V}_{2\mu} & (\bar{\mathbf{3}}, \mathbf{2}, -\frac{1}{3}) \end{cases}$$
- $$S_3 \quad (\bar{\mathbf{3}}, \mathbf{3}, \frac{2}{3}) \quad SU(2) \text{ triplet} \quad \begin{cases} U_{3\mu} & (\mathbf{3}, \mathbf{3}, \frac{4}{3}) \end{cases}$$

Leptoquark Probes at LHC [arXiv:2007.12997]

- Our analysis centres around the spin determination of BSM particles
- Our focus, signatures of Leptoquarks $\left\{ \begin{array}{l} \text{Spin-0 scalars} \\ \text{Spin-1 vectors} \end{array} \right.$

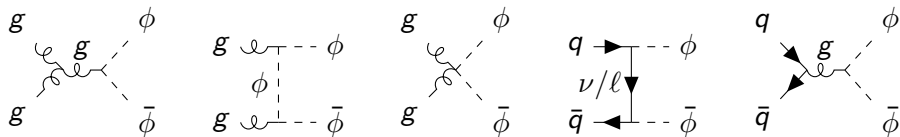
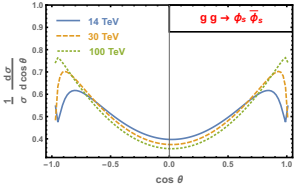


Figure: Feynman Diagrams for the Pair Production at LHC.

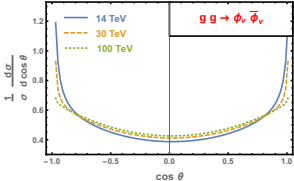
Parton-level Distributions

ϕ_s

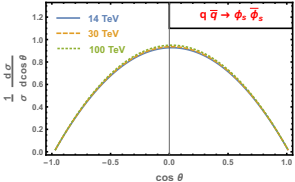


$gg \rightarrow \phi_s \bar{\phi}_s$

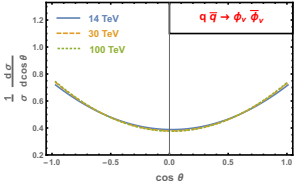
ϕ_V



$gg \rightarrow \phi_V \bar{\phi}_V$



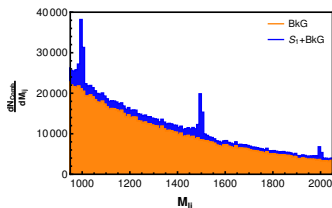
$q\bar{q} \rightarrow \phi_s \bar{\phi}_s$



$q\bar{q} \rightarrow \phi_V \bar{\phi}_V$

Event Reconstructions

- Simulation with PYTHIA at 14, 30 and 100 TeV Colliders
- All irreducible, dominant SM Backgrounds considered
- Optimising Signals over Background $\phi \rightarrow \mu c/s$ considered
- Reconstruction of leptoquarks crucial for reconstructing CM frame



Distinguishing Spins from Angular Distributions

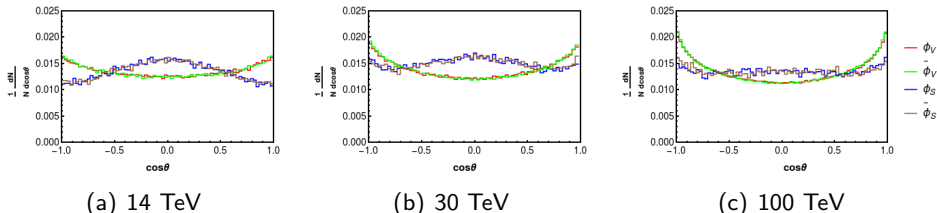


Figure: Distribution for 1.5 TeV Leptoquarks at different collision energies in CM frame

- Spins bear unique imprint on Angular distribution
- Angular distribution differs with collision energy and leptoquark mass
- The parton distribution function plays the key role

Another Example: Spin-1/2 Type-III Fermions

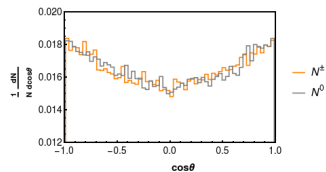
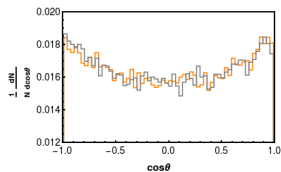
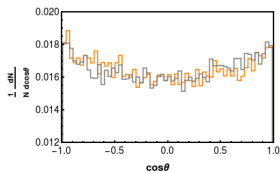
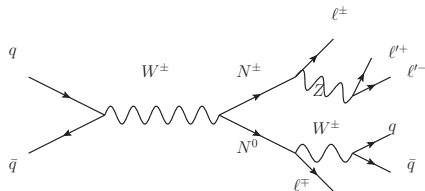
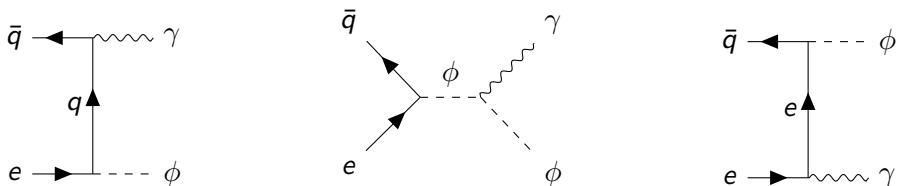


Figure: Distribution for 1.5 TeV Seesaw fermions at different collision energies in CM frame



- θ : Angle between e^- and γ
- $\left. \frac{d\sigma}{d\cos\theta} \right|_{CM} \sim 0$ at $\cos\theta \equiv \cos\theta^* = 1 + \frac{2}{Q_\phi}$
- $\cos\theta^*$ independant of leptoquark mass and interaction energy
- Signals obtained in the **visible region**, $|\cos\theta^*| \leq 1$ for $\tilde{S}_1^{-4/3}$, $R_2^{-5/3}$, $S_3^{-4/3}$ and $\tilde{U}_{1\mu}^{-5/3}$, $V_{2\mu}^{-4/3}$, $U_{3\mu}^{-5/3}$ with $|Q_\phi| > 1$

Benchmark Points and Collision Energies

M_ϕ	E_e	E_p
70 GeV	27.5 GeV	920 GeV
900 GeV	50 GeV	7 TeV
1500 GeV	60 GeV	20 TeV
2000 GeV	60 GeV	50 TeV

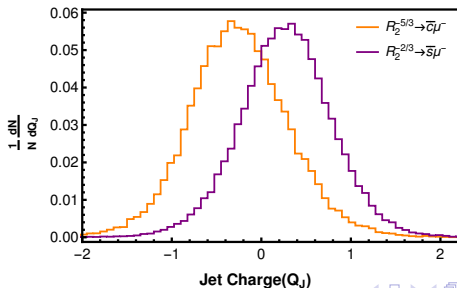
- Decay to only 2nd generation fermions eliminates SM Background
- Model Background persists

Distinguishing Leptoquarks from Jet Charge

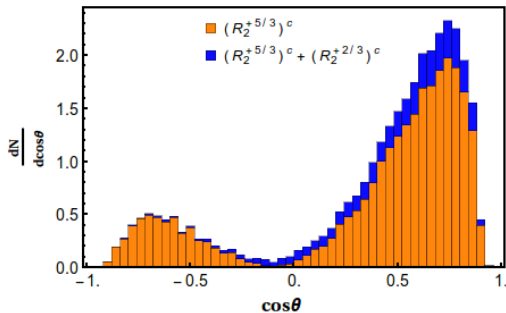
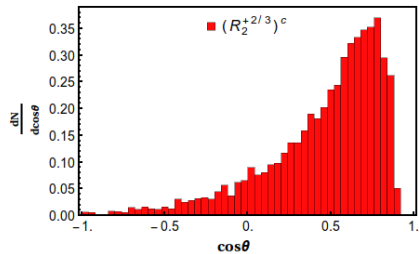
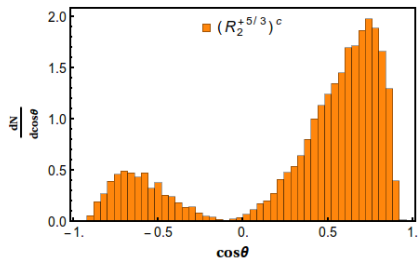
- Leptoquark decay to quarks of different electromagnetic charges of the same generation

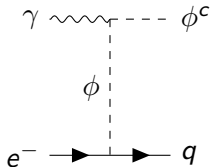
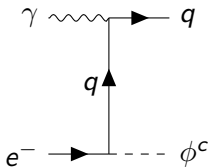
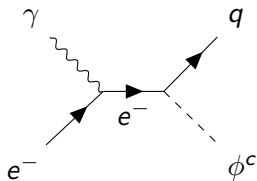
- $$\left\{ \begin{array}{l} R_2^{-5/3} \rightarrow \bar{c} \mu^- \\ R_2^{-2/3} \rightarrow \bar{s} \mu^- \end{array} \right.$$

- $$Q_J = \sum_{i \in J} \left(\frac{E_i}{E_J} \right)^{0.2} Q_i \left\{ \begin{array}{l} Q_J, E_J : \text{jet charge(energy)} \\ Q_i, E_i : \text{charge(energy) of } i^{\text{th}} \text{ constituent} \end{array} \right.$$



Amplitude Zero in ep Collision





- θ : Angle between e^- and ϕ
- Zeros in the visible region, $|\cos\theta^*| \leq 1$ displayed by $S_1^{-1/3}$, $R_2^{-2/3}$, $S_3^{-1/3}$ and $U_{1\mu}^{-2/3}$, $V_{2\mu}^{-1/3}$, $U_{3\mu}^{-2/3}$ with $|Q_\phi| < 1$
- They form the set complementary to those exhibiting zeros at ep collisions

- $\frac{d\sigma}{d\cos\theta} \Big|_{CM} \sim 0$ at $\cos\theta \equiv \cos\theta^* = 1 + \frac{2Q_q}{1-M_\phi^2/s} \sim f(M_\phi, \sqrt{s})$

Benchmark Points and Collision energies

M_ϕ	\sqrt{s}	γ Source
70 GeV	200 GeV	Monochromatic
650 GeV	2 TeV	Laser Backscattering
1500 GeV	3 TeV	Effective Photon Approximation

Amplitude Zero with monochromatic photons: Scalar

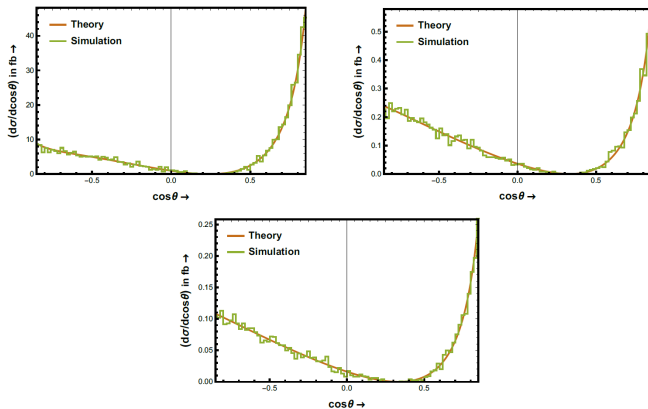


Figure: Probe for 70 GeV $\tilde{R}_2^{-2/3}$ at three different collision energies

Amplitude Zero with monochromatic photons: Vector

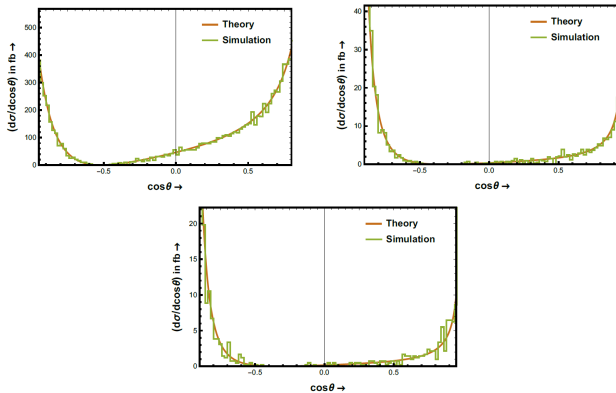
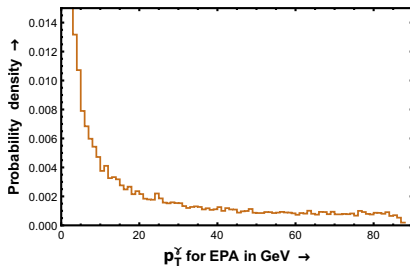
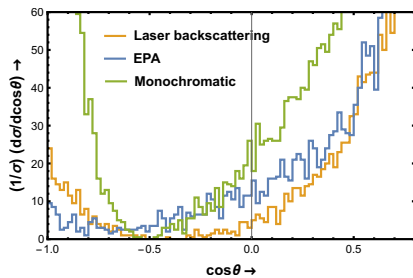


Figure: Probe for 70 GeV $\tilde{V}_{2\mu}^{-1/3}$ at three different collision energies

Effect of Non-monochromatic Photons



In a Nutshell...

pp Collision	ep Collision	$e\gamma$ Collision
<ul style="list-style-type: none">● Pair Production	Associated Production	Associated Production
<ul style="list-style-type: none">● QCD dominated	Involves γ in final state	Involves γ in initial state
<ul style="list-style-type: none">● Determines Spin	Determines Q_ϕ	Determines Q_ϕ
<ul style="list-style-type: none">● Analysis for spin-1/2, 3/2 possible	Determines $SU(2)$ Representation	Determines $SU(2)$ Representation
<ul style="list-style-type: none">● Necessitates Boost Back	Necessitates Boost Back	Interactions at CM frame