Segregating BSM models at Present and Future Colliders based on Spin and Isospin

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Shortcomings of SM and Proposition of Different BSM Scenarios

- SM fails to Explain: 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?

Goal

- This work principally focuses on different strategies to address this challenge, mainly the Angular Distribution
- For most of our studies, we consider the BSM scenarios of the Leptoquarks
- However, the techniques are applicable to other BSM models as well

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
- May address some of the anomalies associated with rare decays

Their Isospin Representations

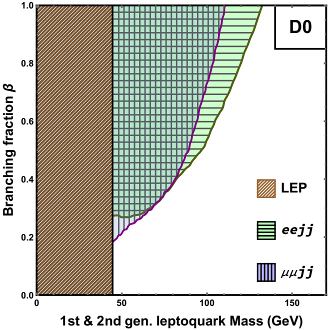
$$\left.\begin{array}{ll} S_1 & (\bar{\mathbf{3}},\ \mathbf{1},\ \tfrac{2}{3}) \\ \widetilde{S}_1 & (\bar{\mathbf{3}},\ \mathbf{1},\ \tfrac{8}{3}) \end{array}\right\} \quad SU(2)\text{ singlet} \quad \left\{\begin{array}{ll} U_{1\mu} & (\mathbf{3},\ \mathbf{1},\ \tfrac{4}{3}) \\ \widetilde{U}_{1\mu} & (\mathbf{3},\ \mathbf{1},\ \tfrac{10}{3}) \end{array}\right.$$

$$\left.\begin{array}{ll} R_2 & (\mathbf{3},\ \mathbf{2},\ \tfrac{7}{3}) \\ \widetilde{R}_2 & (\mathbf{3},\ \mathbf{2},\ \tfrac{1}{3}) \end{array}\right\} \quad SU(2)\text{ doublet} \quad \left\{\begin{array}{ll} V_{2\mu} & (\bar{\mathbf{3}},\ \mathbf{2},\ \tfrac{5}{3}) \\ \widetilde{V}_{2\mu} & (\bar{\mathbf{3}},\ \mathbf{2},\ -\tfrac{1}{3}) \end{array}\right.$$

$$\left.\begin{array}{ll} S_3 & (\bar{\mathbf{3}},\ \mathbf{3},\ \tfrac{2}{3}) \end{array}\right\} \quad SU(2)\text{ triplet} \quad \left\{\begin{array}{ll} U_{3\mu} & (\mathbf{3},\ \mathbf{3},\ \tfrac{4}{3}) \end{array}\right.$$

Leptoquark Probes at Particle Colliders

Light Leptoquarks



- Leptoquarks with mass ~ 70 GeV, with branching $\sim 25\%$ to first two generations of $\ell\ q$ allowed

Heavy Leptoquark Probes at Particle Colliders

- Scalar Leptoquarks:
  - For a 1^{st} generation leptoquark, $M_\phi > 1290$ GeV ($\phi_S \to e\ u/d$)
  - For a 2^{nd} generation leptoquark, $M_\phi > 1230$ GeV ($\phi_S \to \mu\ c/s$)
  - For a 3^{rd} generation leptoquark, $M_\phi > 800$ GeV ($\phi_S \to \tau/\nu_\tau\ b/t$)
- Vector Leptoquarks:
  - For a 1^{st} generation leptoquark, $M_\phi > 1270$ GeV ($\phi_V \to \nu_e\ u/d$)
  - For a 2^{nd} generation leptoquark, $M_\phi > 1285$ GeV ($\phi_V \to \nu_\mu\ c/s$)
  - For a 3^{rd} generation leptoquark, $M_\phi > 1115$ GeV ($\phi_V \to \nu_\tau t$)

Probes of Leptoquark Spins at LHC [arXiv:2007.12997 [hep-ph]]

(Bandyopadhyay, Karan, Jakkapu, SD)

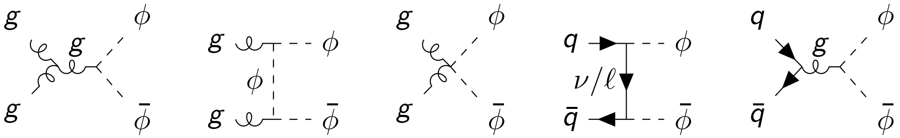
- Our analysis centres around the spin determination of BSM particles

- Consider Drell-Yan process, $e^+e^- \to \mu^+\mu^-$

$$\left.\frac{d\sigma}{d\cos\theta}\right|_{CM} \sim (1+\cos^2\theta) \qquad \text{(pair production of spin}\,\frac{1}{2}\text{ fermions)}$$

- Our focus, signatures of Leptoquarks $\begin{cases} \text{Spin-0 scalars} \\ \text{Spin-1 vectors} \end{cases}$

Pair-Productions

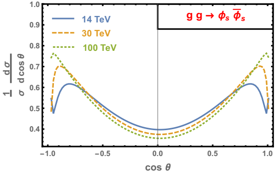


- $\frac{d\sigma}{d\cos\theta}\Big|_{CM}^{\phi s} \sim \begin{cases} \beta^3 \sin^2\theta & (qq) \\ \frac{(1-\beta^2)^2}{1-\beta^2\cos^2\theta} - \frac{25-34\beta^2+9\beta^4}{16(1-\beta^2\cos^2\theta)} + \frac{25+9\beta^2\cos^2\theta-18\beta^2}{32} & (gg) \end{cases}$
- $\frac{d\sigma}{d\cos\theta}\Big|_{CM}^{\phi v} \sim \begin{cases} (1+\sin^2\theta) + 3(1-\beta^2\sin^2\theta) & (qq) \\ \frac{1}{(1-\beta^2\cos^2\theta)^2} \quad (gg) & (approx) \end{cases}$
- $\beta = \sqrt{1 - 4M_\phi^2/s}$

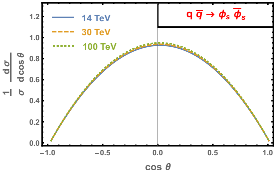
Z. Phys. C **76** (1997), 137-153

Parton-level Distributions

ϕ_S

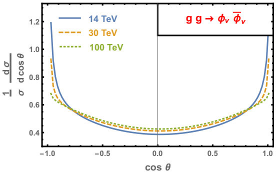


$gg \to \phi_S \bar{\phi}_S$

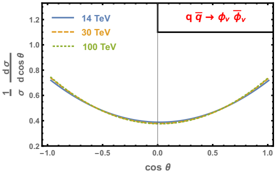


$q\bar{q} \to \phi_S \bar{\phi}_S$

ϕ_V



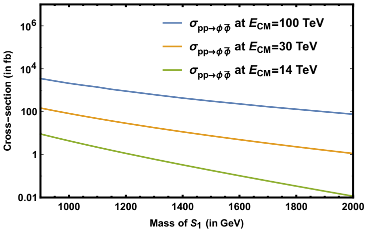
$gg \to \phi_V \bar{\phi}_V$

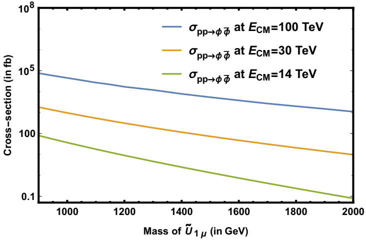


$q\bar{q} \to \phi_V \bar{\phi}_V$

Hard Scattering Cross-Sections

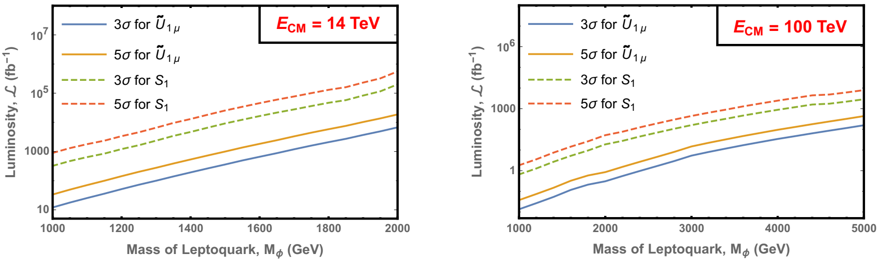
- ϕ_Vs have higher pair-production cross-section: 3 polarisation Degrees of Freedom





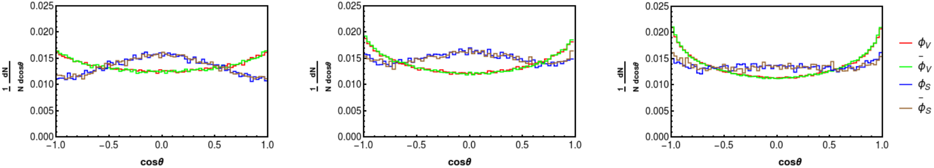
[arXiv:2007.12997 [hep-ph]]

Leptoquark Reaches at LHC/FCC



[arXiv:2007.12997 [hep-ph]]

Distinguishing Spins from Angular Distributions

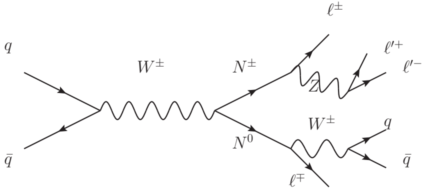


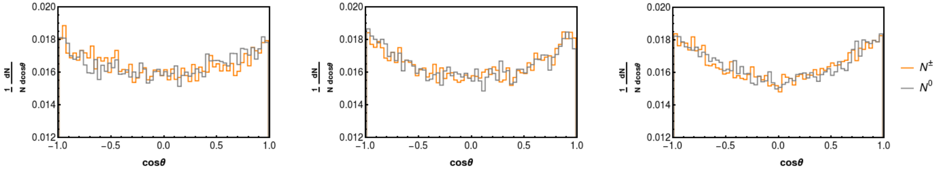
(e) 14 TeV (f) 30 TeV (g) 100 TeV

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



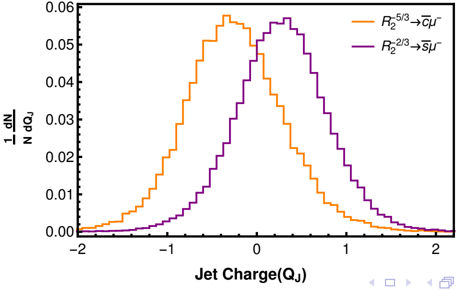


(a) 14 TeV (b) 30 TeV (c) 100 TeV

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

Distinguishing Leptoquarks from Jet Charge

- Leptoquark decay to quarks of different electromagnetic charges of the same generation
- $\begin{cases} R_2^{-5/3} \to \bar{c}\ \mu^- \\ R_2^{-2/3} \to \bar{s}\ \mu^- \end{cases}$
- $\mathcal{Q}_J = \sum_{i \in J} \left(\frac{E_i}{E_J}\right)^{0.2} \mathcal{Q}_i \quad \begin{cases} \mathcal{Q}_J, E_J : \text{ jet charge(energy)} \\ \mathcal{Q}_i, E_i : \text{ charge(energy) of } i^{th}\text{constituent} \end{cases}$

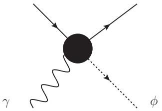


Radiation Amplitude Zeros

- Scattering amplitude for n-particles, with charge Q_i and 4-momenta p_i, involving a photon, of 4-momentum k vanishes at certain kinematical zones, characterised by identical $\frac{Q_i}{p_i \cdot k}$ ratios

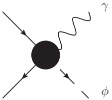
  Our Focus: $2 \to 2$ scattering producing a massive particle with

  - γ in the initial state



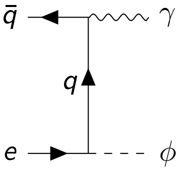
(See Anirban Karan's Talk)

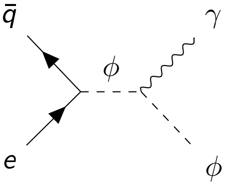
  - γ in the final state

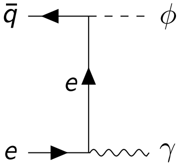


Leptoquark Probes at *ep* Collider (Eur. Phys. J. C **81** (2021) no.4, 315)

(Bandyopadhyay, Karan, SD)







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

Scalar and Vector Leptoquarks with $|\cos\theta^\star| \leq 1$

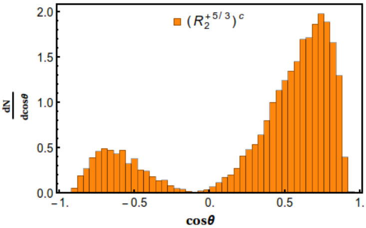
ϕ_S	Representation	$\cos\theta^\star$	ϕ_V	Representation	$\cos\theta^\star$
$\widetilde{S}_1^{4/3}$	$(\bar{\mathbf{3}},\ \mathbf{1},\ \frac{\mathbf{8}}{\mathbf{3}})$	-0.5	$\widetilde{U}_{1\mu}^{5/3}$	$(\mathbf{3},\ \mathbf{1},\ \frac{\mathbf{10}}{\mathbf{3}})$	-0.2
$R_2^{5/3}$	$(\mathbf{3},\ \mathbf{2},\ \frac{\mathbf{7}}{\mathbf{3}})$	-0.2	$V_{2\mu}^{4/3}$	$(\bar{\mathbf{3}},\ \mathbf{2},\ \frac{\mathbf{5}}{\mathbf{3}})$	-0.5
$S_3^{4/3}$	$(\bar{\mathbf{3}},\ \mathbf{3},\ \frac{\mathbf{2}}{\mathbf{3}})$	-0.5	$\widetilde{U}_{3\mu}^{5/3}$	$(\mathbf{3},\ \mathbf{1},\ \frac{\mathbf{4}}{\mathbf{3}})$	-0.2

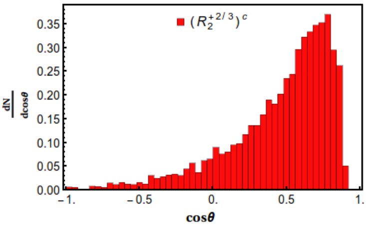
Benchmark Points and Collision Energies

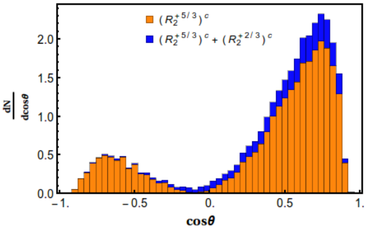
M_ϕ	E_e	E_p
70 GeV	27.5 GeV	920 GeV
900 GeV	50 GeV	7 TeV
1500 GeV	60 GeV	20 TeV
2000 GeV	60 GeV	50 TeV

- Decay to only 2^{nd} generation fermions eliminates SM Backround
- Model Background persists

Amplitude Zero in *ep* Collision







Eur. Phys. J. C **81** (2021) no.4, 315

Conclusion

- Angular Distributions are instrumental in determining spins and gauge representations
- Strategies prescribed in our work are generic and applicable in other scenarios
- Reconstruction of CM frame at *pp* collisions can determine spins
- For 5σ significance in 100 TeV collisions
  - 1.5 TeV Leptoquark probes require $\sim 10\ \text{fb}^{-1}$
  - 1.5 TeV Type-III Seesaw probes requires $\sim 370\ \text{fb}^{-1}$

Conclusion

- Studies at *ep* and $e\gamma$ collisions are complementary

- At *ep* collisions
  - Signal significance for $V_{2\mu}$ is greater than that for $U_{3\mu}$
  - Signal significance for S_3 is greater than that for R_2

  - At FCC-II all the candidates can be determined with $> 5\sigma$


Thank you!