Some ~~All~~ about Leptoquaks

Belle Analysis workshop 2024
Oct 19 – 23, 2024

Based on the coloration with Saunak Dutta, Anirban Karan, Rusa Mandal,
Snehashis Parashar, Avnish and Kirtiman Ghosh

EPJC 82 (2022) 10, 916, PRD 106 (2022) 9, 095040, EPJC 81 (2021) 4, 315,
NPB 971 (2021) 115524,EPJC 80 (2020) 6, 573, EPJC 78 (2018) 491, PRD 95 (2017) 3, 035007

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Belle II

Leptoquarks ?

- Leptoquarks are proposed particles with non-zero baryon number and lepton number
- Couple to quarks and leptons

- They are colour triplet bosons
- They emerge naturally in various BSM and unified gauge theories
- Different observed anomalies along with muon $g-2$ can be explained via these leptoquarks
- Loop Majorana mass can be generated for the neutrinos

Motivation

Leptoquarks

Theoretical

- Higher theories
- Vacuum Stability
- FOPT
- Loop Majorana neutrino mass
- Gets constrained from perturbative unitarity

Experimental

- Anomalies like $R_K, R_{K^*}, R_D, R_{D^*}$
- muon(g-2)

Scalar Leptoquarks

ϕ	Y_ϕ	T_3	Q_ϕ
Scalar leptoquarks			
S_1	2/3	0	1/3
$\tilde{S}_1$	8/3	0	4/3
R_2	7/3	1/2	5/3
		−1/2	2/3
$\tilde{R}_2$	1/3	1/2	2/3
		−1/2	−1/3
S_3	2/3	1	4/3
		0	1/3
		−1	−2/3

Different gauge charges

How to distinguish them

What about spin ?

Vector Leptoquarks

ϕ	Y_ϕ	T_3	Q_ϕ
Vector Leptoquarks			
$U_{1\mu}$	4/3	0	2/3
$\tilde{U}_{1\mu}$	10/3	0	5/3
$V_{2\mu}$	5/3	1/2	4/3
		−1/2	1/3
$\tilde{V}_{2\mu}$	−1/3	1/2	1/3
		−1/2	−2/3
$U_{3\mu}$	4/3	1	5/3
		0	2/3
		−1	−1/3

LQ mass limits from CMS

- Lower mass bounds For Leptoqurks is around 1.5-2.0 TeV

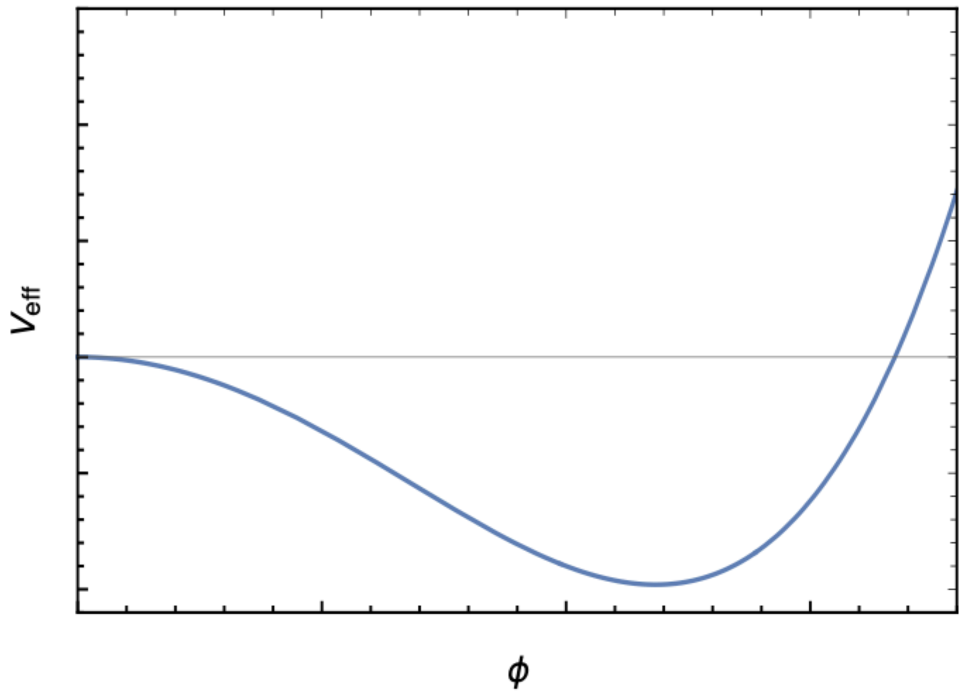
Slide is taken from Tanumoy's talk at PPC

Vacuum Stability

Stability of the potential

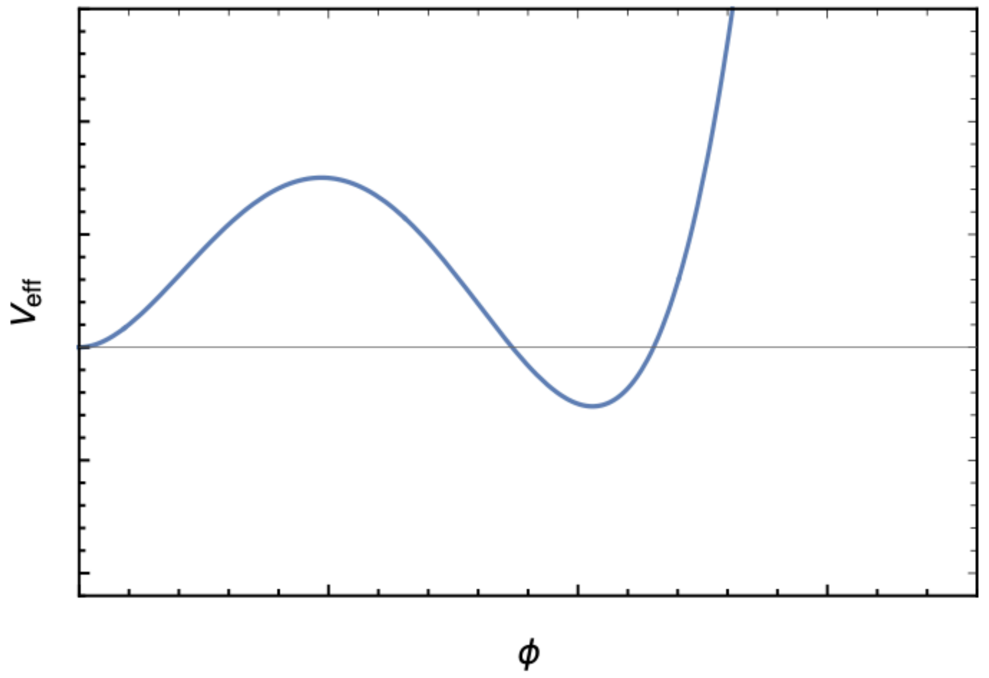
Stability

$$\lambda_{\text{eff}} > 0$$



Meta-stability

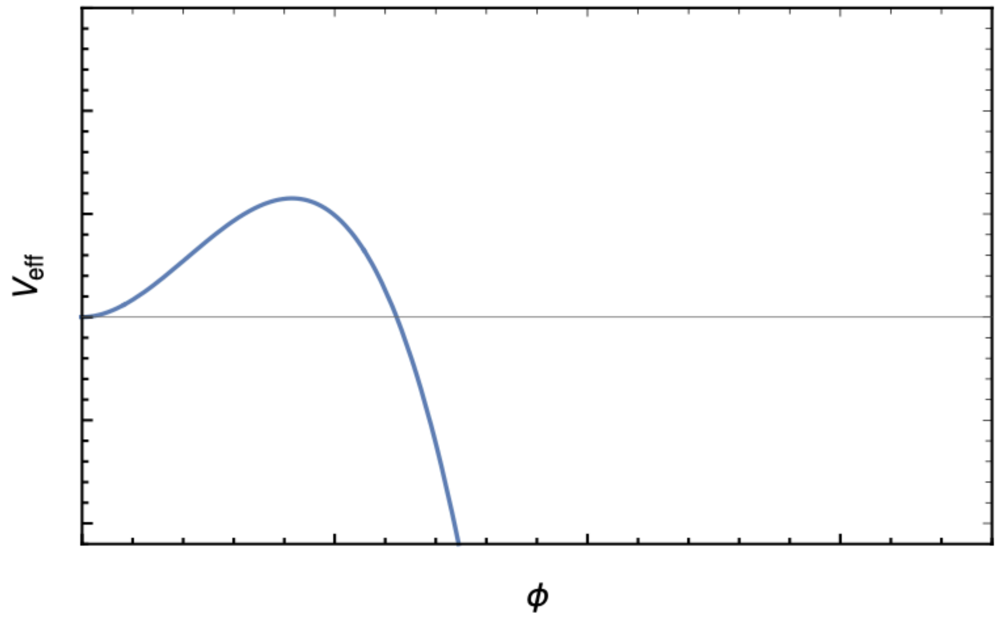
$$0 > \lambda_{\text{eff}}(\mu) \gtrsim \frac{-0.065}{1 - 0.01 \log\left(\frac{v}{\mu}\right)}$$

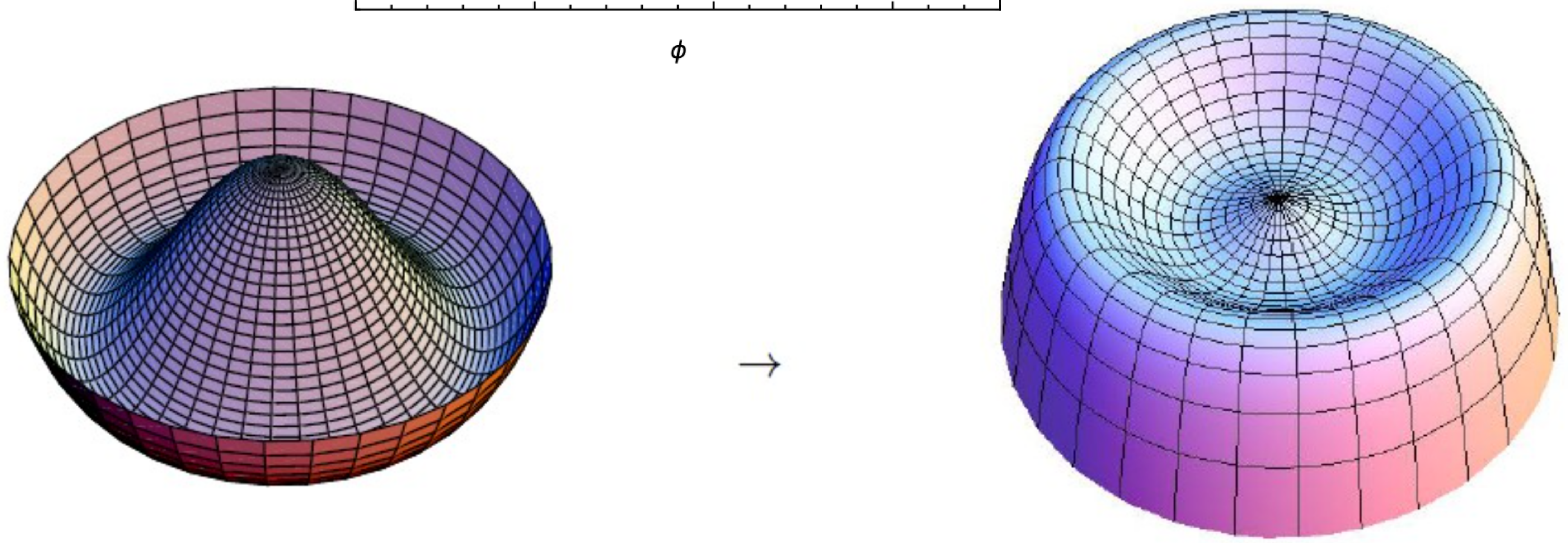


Instability

More negative λ_{eff}

G. Isidori et. al.: NPB 609 (2001) 387

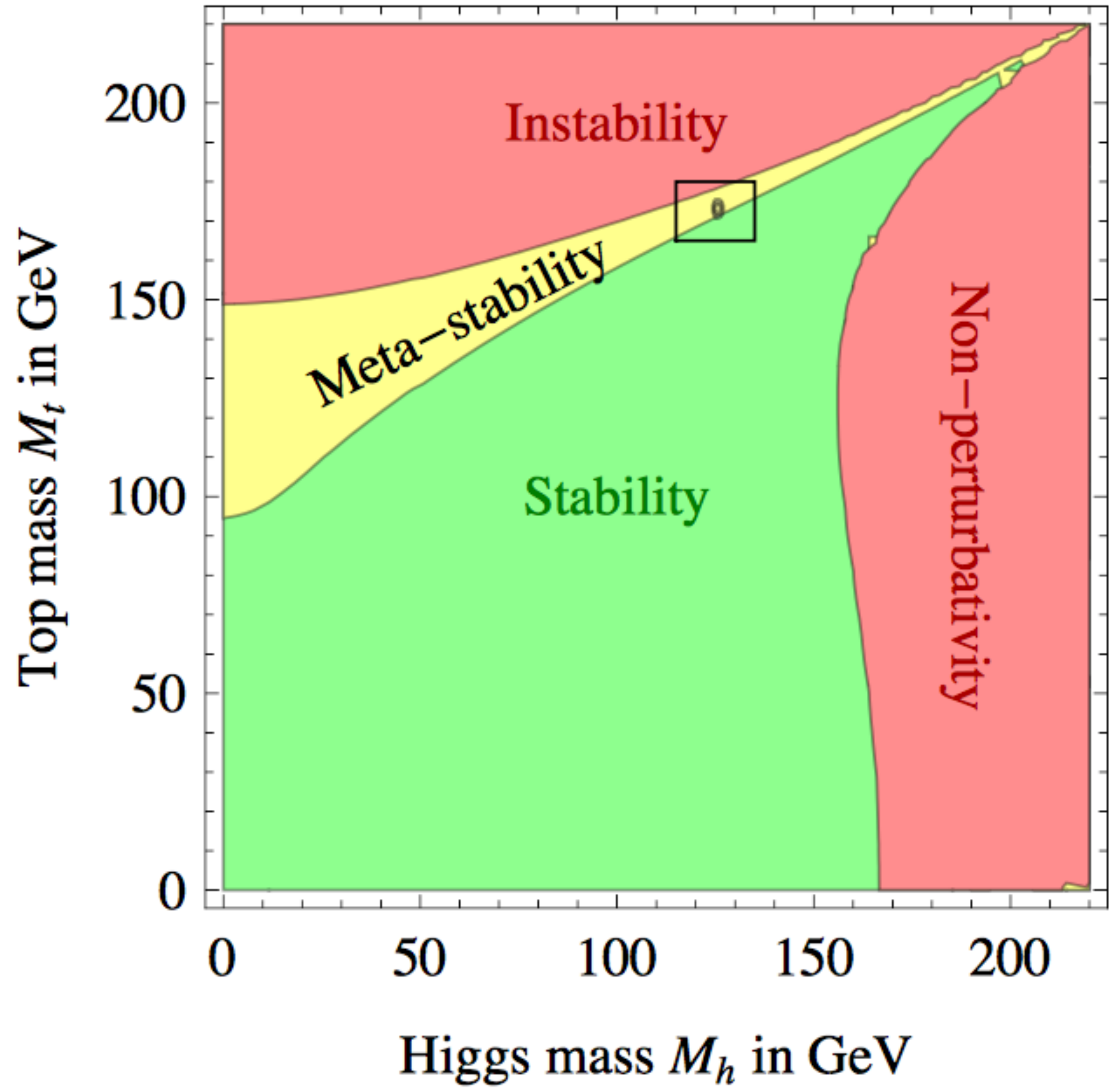


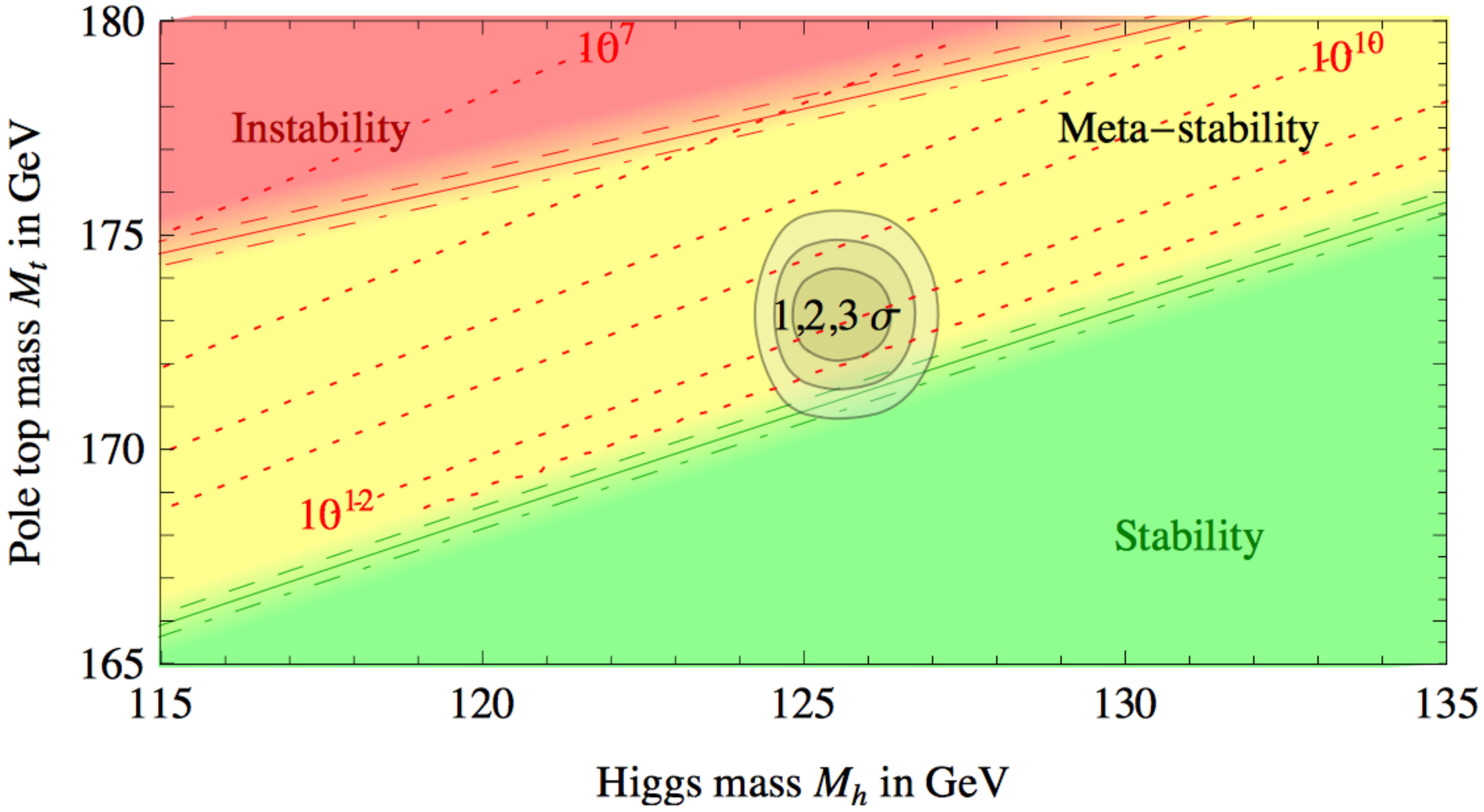


If your mexican hat turns out to be a dog bowl you have a problem...

from A. Strumia

Status of SM





Within the uncertainty of top mass we are in
a metastable vacuum

Degrassi et. al. :JHEP 1208, 098 (2012)

What is the rescue?

Addition of scalars

- Any scalar extension of SM will enhance the vacuum stability due to positive quantum correction to λ_{eff}
- We will only discuss scalar Leptoquark in stabilising the potential

Addition of scalar Leptoquark: $\phi(3,1,-1/3)$

- Here we extend Standard Model by a scalars Leptoquark: $\phi(3,1,-1/3)$

$$\mathcal{L}_\phi = (D_\mu\phi)^\dagger D^\mu\phi - m_\phi^2|\phi|^2 - g_{h\phi}|\Phi|^2|\phi|^2 + \bar{Q}^c Y^{\rm L} i\tau_2 L\phi^* + \bar{u}_R^c Y^{\rm R} e_R \phi^* + h.c.$$

Leptoquark Mass (m_ϕ^2) — Higgs-Leptoquark coupling ($g_{h\phi}$) — Leptoquark Yukawa couplings ($Y^{\rm L}$, $Y^{\rm R}$)

- The Leptoquark does not get vev due to colour symmetry
- Doesn't take part in electroweak symmetry breaking directly
- However, quantum corrections can be crucial in saving us from the metastability

PB, Rusa Mandal PRD 95 (2017) 3, 035007

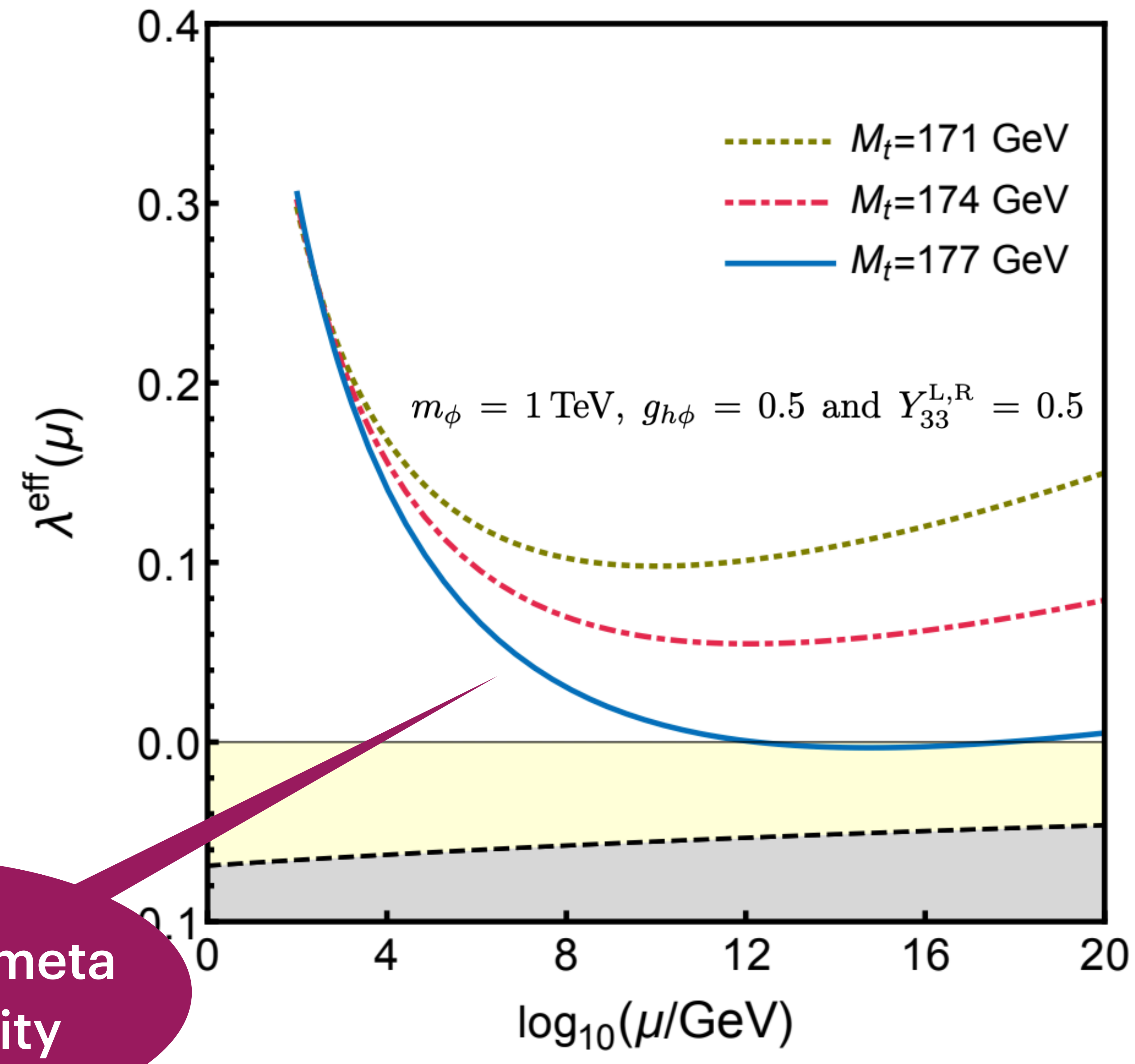
Addition of scalar Leptoquark: $\phi(3,1,-1/3)$

- The scalar Leptoquark ϕ contributes to the effective Higgs quartic coupling via $g_{h\phi}$

$$\lambda^{\rm eff}(h,\mu) \simeq e^{4\Gamma(\mu)}\Bigg\{\lambda(\mu) + \frac{1}{8\pi^2}\sum_{i=W,Z,h,G,t} N_i\kappa_i^2(\mu)\left[\ln\frac{\kappa_i(\mu)e^{2\Gamma(\mu)}h_c^2}{\mu^2} - C_i\right] + \frac{1}{8\pi^2}\frac{3g_{h\phi}^2(\mu)}{2}\left[\ln\frac{g_{h\phi}(\mu)e^{2\Gamma(\mu)}h_c^2}{2\mu^2} - \frac{3}{2}\right]\Bigg\},$$

- Where, κ_i represents the field dependent mass squared expressions

- Bounds obtained from stability along with perturbative unitarity



Saves from meta or instability

$$0.3 < g_{h\phi}(M_Z) \leq 0.65$$

$$g_{h\phi}(M_Z) \leq 0.55 \ \text{ and } \ Y_{ii}^{\rm L,R}(M_Z) \leq 0.55; \quad i \in \{1,2,3\}.$$

$$g_{h\phi}(M_Z) \leq 0.65 \ \text{ and } \ Y_{ii}^{\rm L,R}(M_Z) \leq 0.65; \quad i \in \{2,3\}$$

If vanishing $Y_{11}^{L,R}$ is assumed

PB, Rusa Mandal PRD 95 (2017) 3, 035007

Bounds from perturbativity

What happens when we have SU(2) doublet and triplet ?

- $\tilde{R}_2(3,2,1/6)$, $S_3(3,3,1/3)$, and $\tilde{R}_2 + S_3$ models are motivated by different anomalies and neutrino mass generation More
- As scalars, their addition can enhance the vacuum stability
- However, existence in the non-trivial gauge representations can be constrained as they may run the gauge coupling towards non-perturbativity

$$\beta(g_2)^{2-loop}_{SM} = -\frac{19}{6}\left(\frac{g_2^3}{16\pi^2}\right) + \frac{g_2^3}{(16\pi^2)^2}\left[\frac{9}{10}\,g_1^2 + \frac{35}{6}\,g_2^2 + 12\,g_3^2 - \frac{3}{2}\mathrm{Tr}\left(\frac{1}{3}\mathcal{X}_\ell + \mathcal{X}_u + \mathcal{X}_d\right)\right],$$

$$\beta(g_2)^{2-loop}_{\widetilde{R}_2,3-gen} = -\frac{5}{3}\left(\frac{g_2^3}{16\pi^2}\right) + \frac{g_2^3}{(16\pi^2)^2}\left[\frac{6}{5}\,g_1^2 + \frac{76}{3}\,g_2^2 + 36\,g_3^2 - \frac{3}{2}\mathrm{Tr}\left(\frac{1}{3}\mathcal{X}_\ell + \mathcal{X}_u + \mathcal{X}_d + \sum_{i=1}^{3}\mathcal{X}_{2,i}\right)\right]$$

Negative

$$\beta(g_2)^{2-loop}_{\vec{S}_3,3-gen} = \frac{17}{6}\left(\frac{g_2^3}{16\pi^2}\right) + \frac{g_2^3}{(16\pi^2)^2}\left[\frac{57}{10}\,g_1^2 + \frac{1043}{6}\,g_2^2 + 108\,g_3^2 - \frac{3}{2}\mathrm{Tr}\left(\frac{1}{3}\mathcal{X}_\ell + \mathcal{X}_u + \mathcal{X}_d + 3\sum_{i=1}^{3}\mathcal{X}_{3,i}\right)\right],$$

$$\beta(g_2)^{2-loop}_{\widetilde{R}_2+\vec{S}_3,3-gen} = \frac{13}{3}\left(\frac{g_2^3}{16\pi^2}\right) + \frac{g_2^3}{(16\pi^2)^2}\left[6\,g_1^2 + \frac{580}{3}\,g_2^2 + 132\,g_3^2 - \frac{3}{2}\mathrm{Tr}\left(\frac{1}{3}\mathcal{X}_\ell + \mathcal{X}_u + \mathcal{X}_d + \sum_{i=1}^{3}\mathcal{X}_{2,i} + 3\sum_{i=1}^{3}\mathcal{X}_{3,i}\right)\right].$$

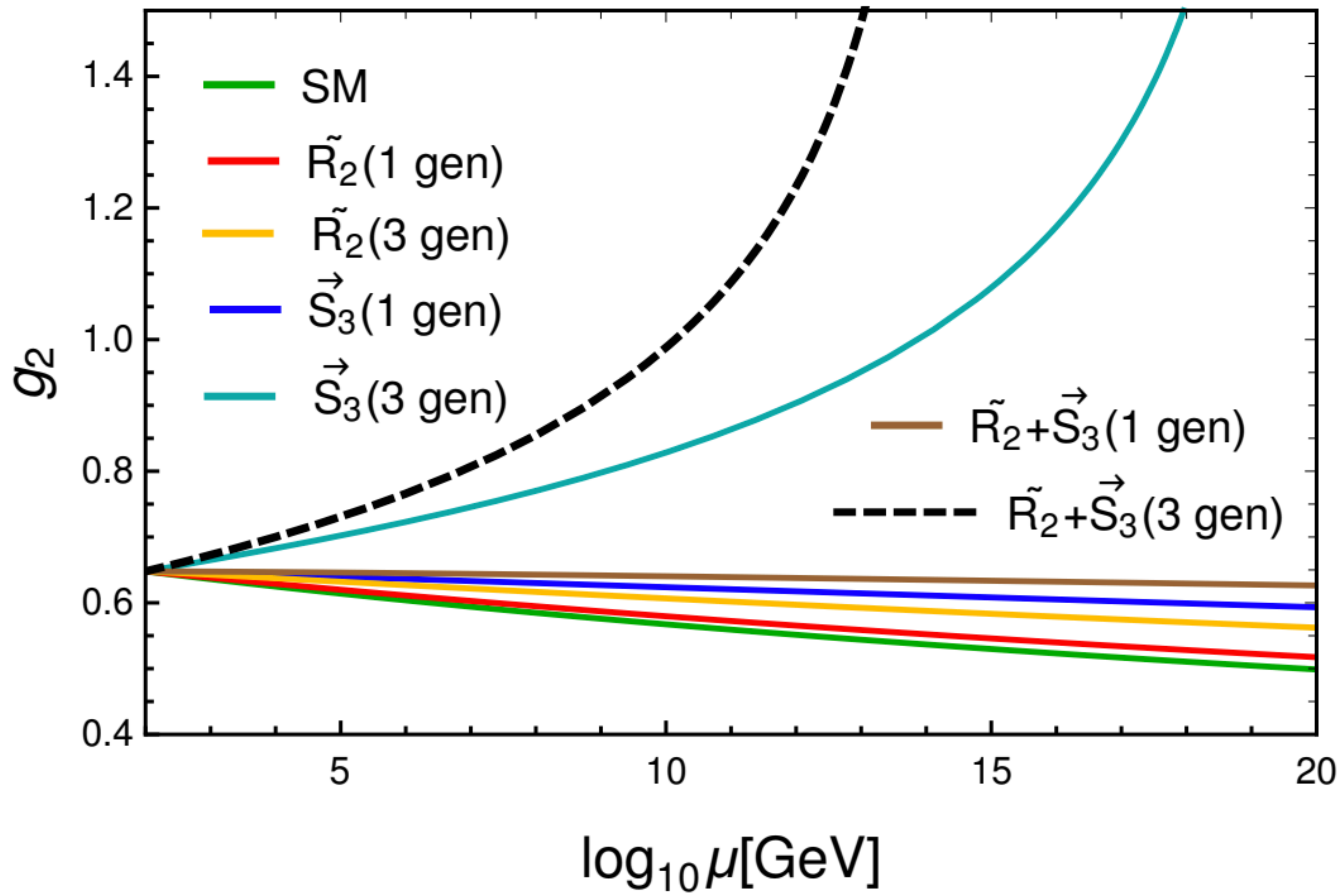
Positive

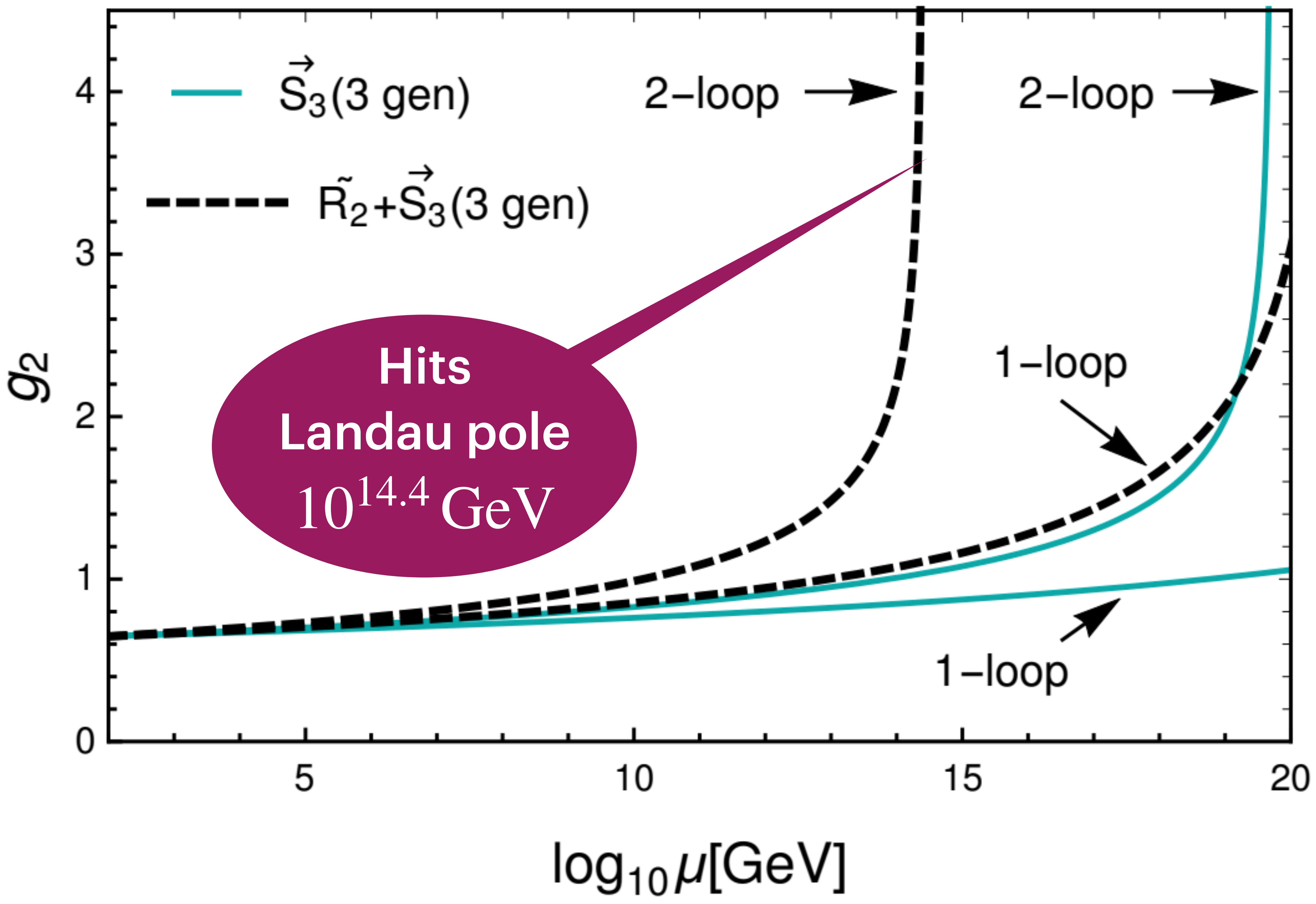
- $\mathrm{SM} \to \tilde{R}_2 \to S_3 \to \tilde{R}_2 + S_3$ get more

PB, Shilpa Jangid, Anirban Karan: EPJC 82 (2022) 6, 516

What happens when we have SU(2) doublet and triplet ?

- For three generations $S_3(3,3,1/3)$, and $\tilde{R}_2 + S_3$ cases, g_2 enhance with the scale due to additional positive contributions
- Planck scale Perturbativity is achieved for cases at oner-loop level
- However, at two-loop $\tilde{R}_2 + S_3$ runs into Landau pole around $10^{14.4}$ GeV





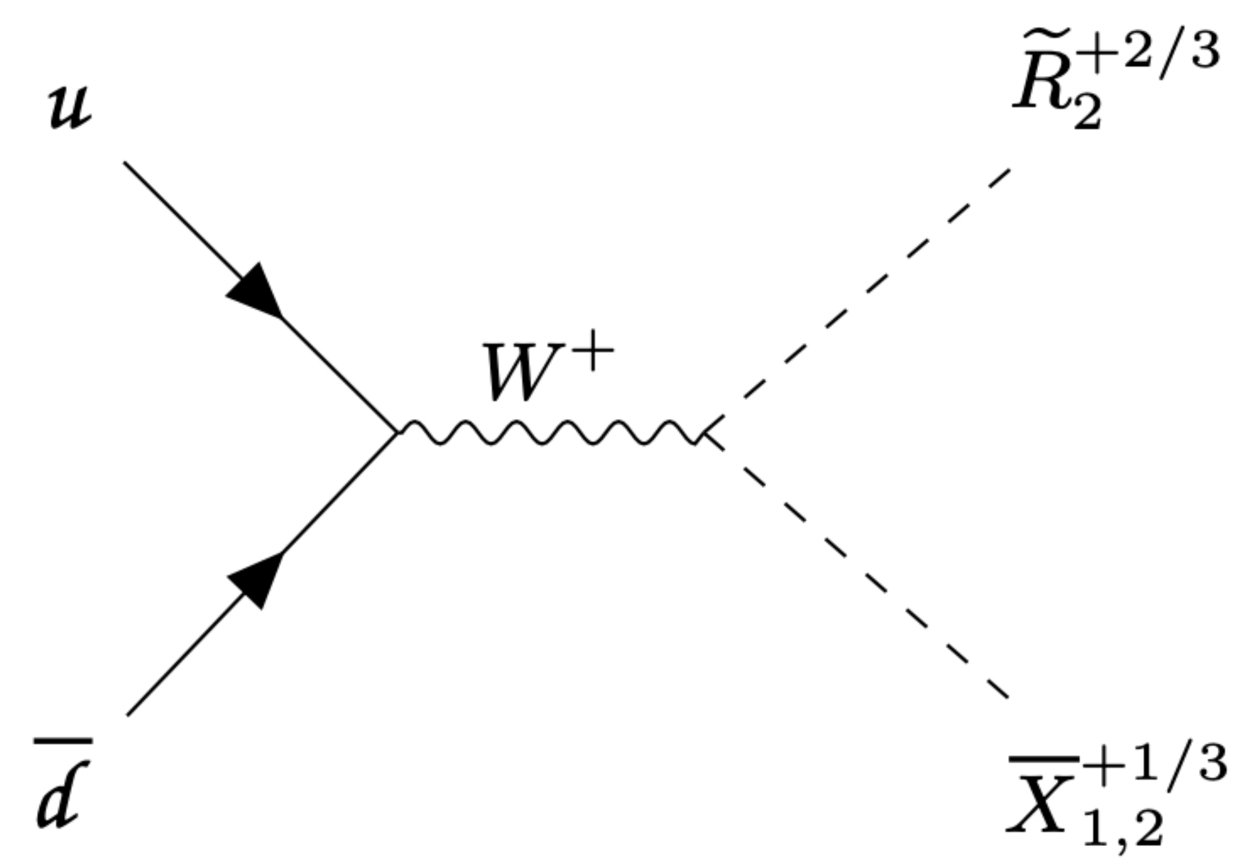
PB, Shilpa Jangid, Anirban Karan: EPJC 82 (2022) 6, 516

Explaining some experimental observations

muon(g-2) with $\tilde{R}_2$ and S_1 Leptoquarks

- $\tilde{R}_2$)3,2,1/6) $= (\tilde{T}_2^{2/3}, \tilde{R}_2^{-1/3})$ and $S_1^{1/3}$ Leptoquarks can explain muonn-(g-2_, rar leptonic decays and also generate Majoranna Neutrino mass

$$-\mathscr{L} \supset \left[\mathcal{Y}_1^L\, \overline{\boldsymbol{Q}}_L^c\, S_1\, (i\sigma_2)\, \boldsymbol{L}_L + \mathcal{Y}_1^R\, \overline{u}_R^c\, S_1\, \ell_R + \mathcal{Y}_2\, \overline{d}_R\, \widetilde{R}_2^T\, (i\sigma_2)\, \boldsymbol{L}_L + \kappa\, H^\dagger \widetilde{R}_2\, S_1 + h.c.\right]$$



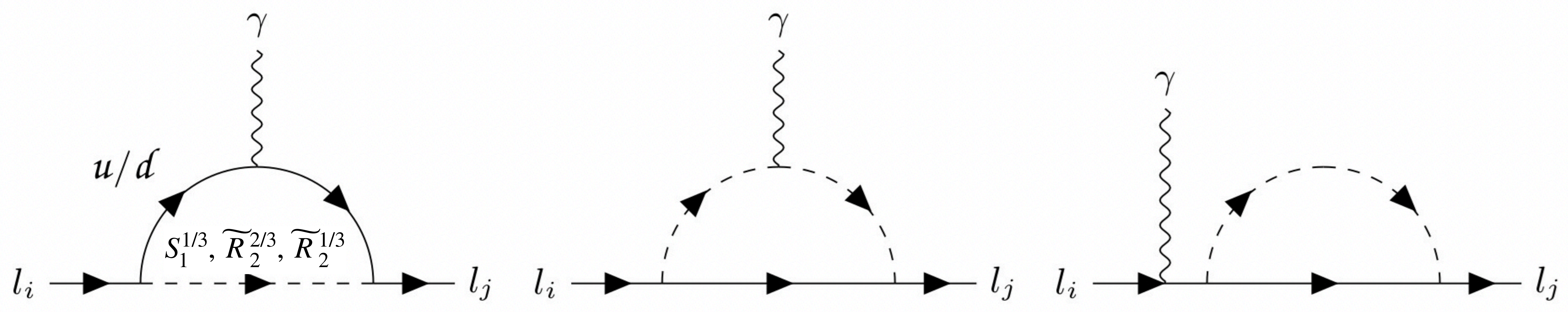
- Rare leptonic and hadronic decays can be satisfied
- Explains muon-(g-2)

- Lepton number violating
- Generates Majorana mass for neutrino
- Doublet and singlet Leptoquark mixes

- Asymmetric production can be prob the mixing at the LHC/FCC

Snehasis Parashar, Avnish, PB, Kirtiman Ghosh: PRD 106 (2022) 9, 095040

Muon $g-2$ with scalar LQs



- $a_\mu(\text{exp}) = \frac{(g-2)_\mu}{2} = 116592059(22) \times 10^{-11}$

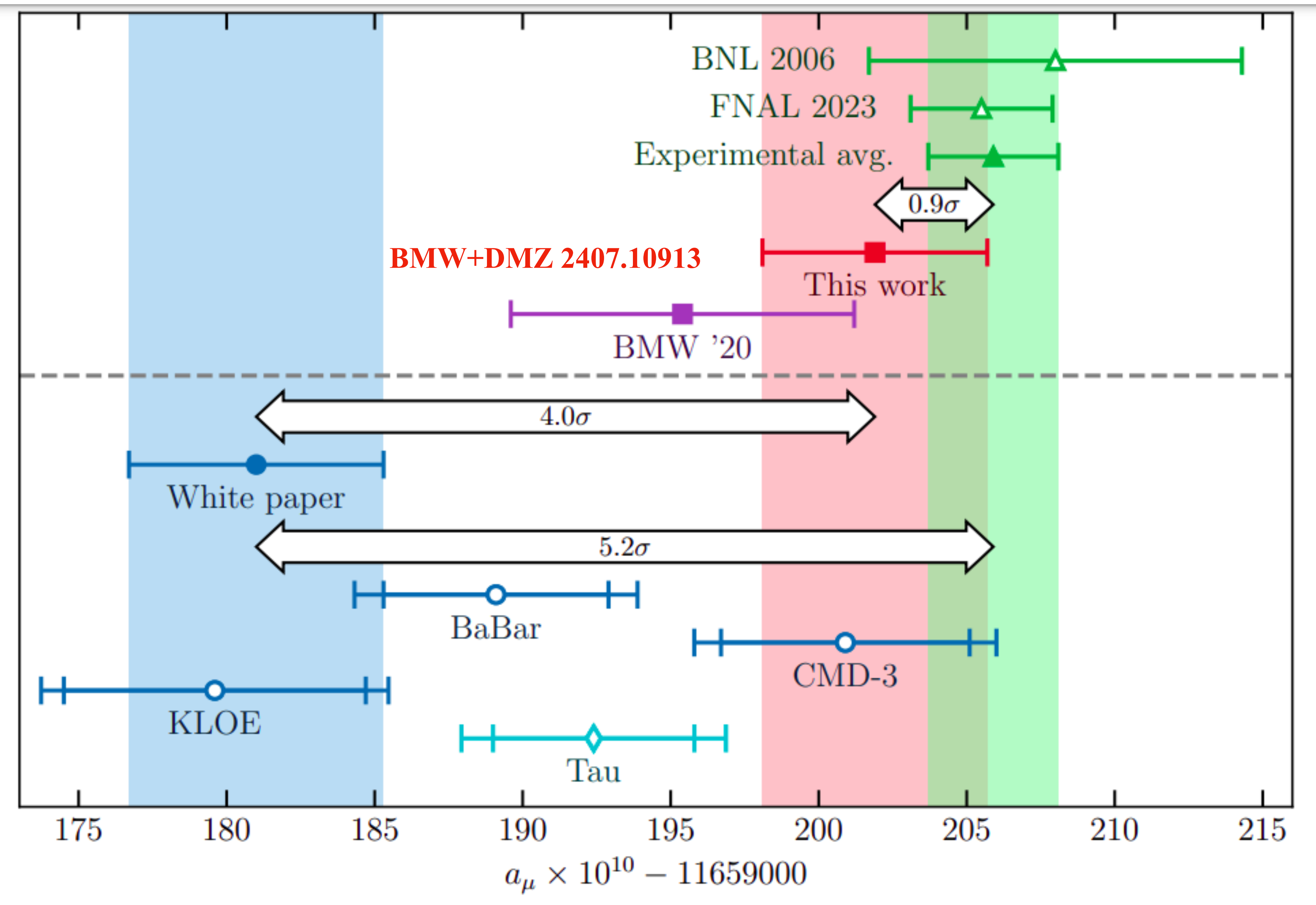
FNAL, PRL 131 (2023) 16, 161802

- LQ states in loops can enhance the muon $g-2$ to explain the experimental excess.

D. Zhang, JHEP 07 (2021) 069

- S_1 contribution is much larger than $\widetilde{R}_2$ due to top quark couplings of the singlet.
- Same diagrams can lead to charged lepton flavour violating decays like $\mu \to e\gamma$ with stringent bounds.

$BR_{\mu\to e\gamma} \leq 4.2 \times 10^{-3}$ MEG collaboration, Eur.Phys.J.C 76 (2016) 8, 434



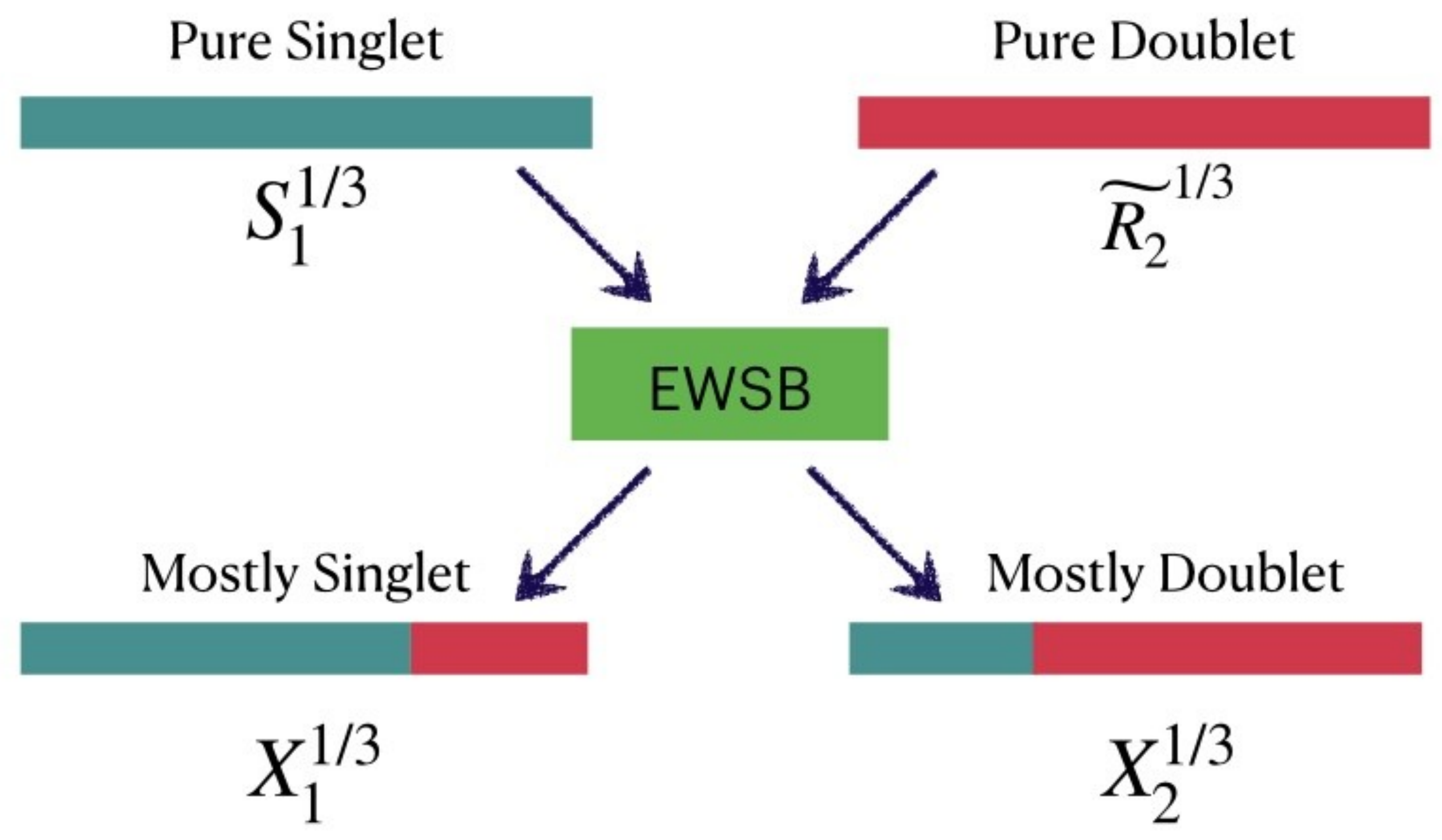
BMW+DMZ Lattice results and comparison from 2407.10913

Mixing of Leptoquarks

- The $\kappa H^\dagger \widetilde{R}_2 S_1$ term leads to mixing between the doublet and triplet LQs.
- After EWSB and mixing: mass eigenstates

Mixed states: $X_1^{1/3}, X_2^{1/3}$

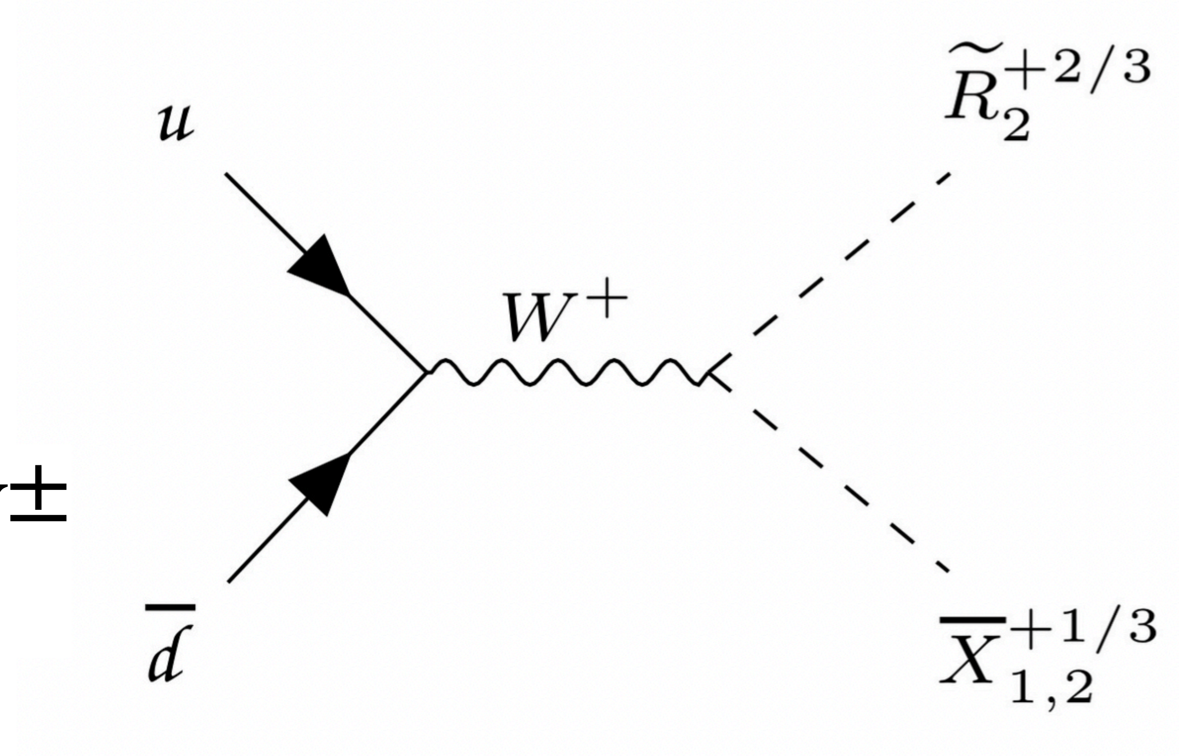
Pure doublet state: $\widetilde{R}_2^{2/3}$



- Mixing angle depends on κ and Higgs vev v:

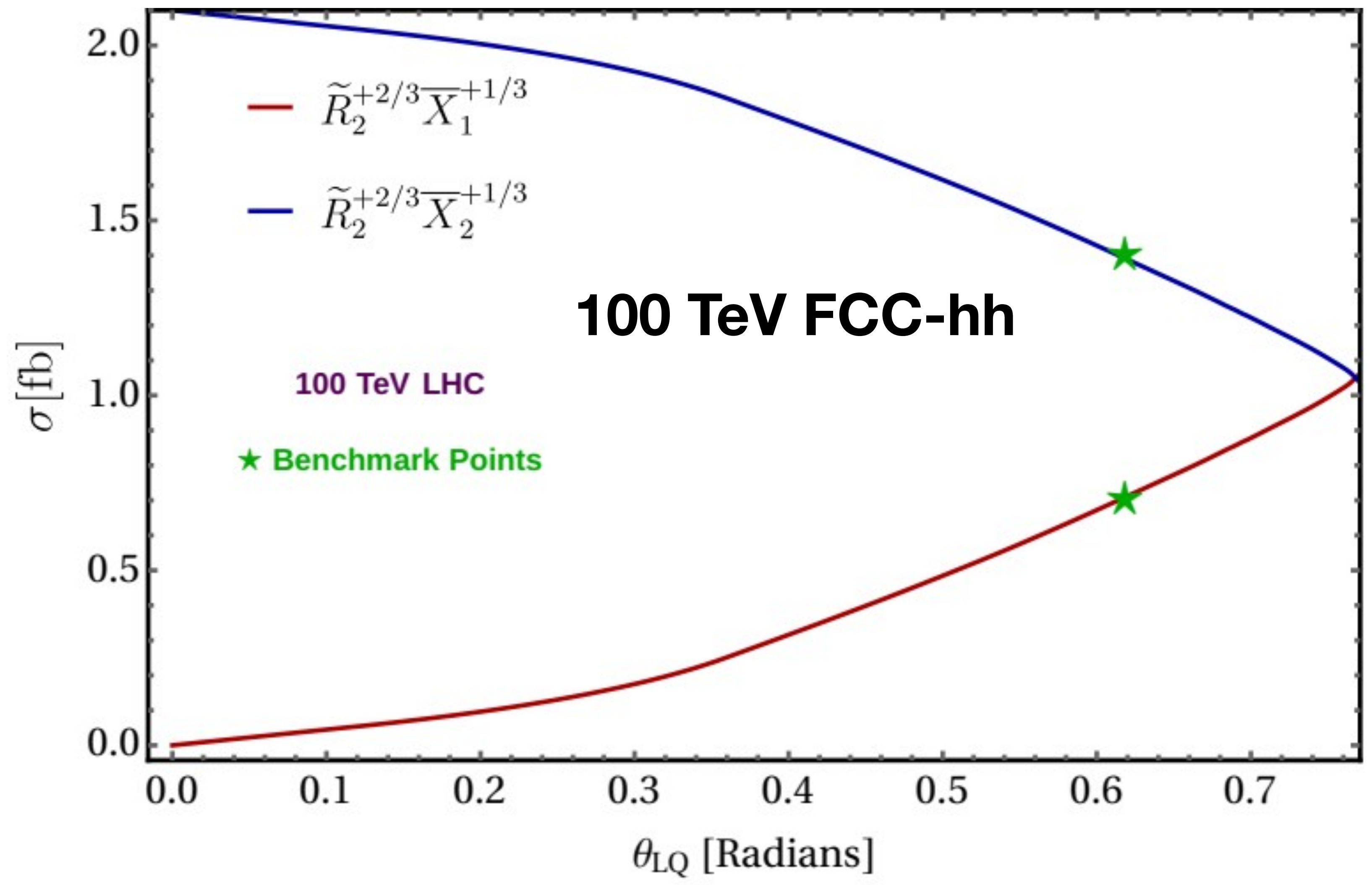
$$\tan 2\theta_{LQ} = \frac{-\sqrt{2}\kappa v}{m^2(S_1) - m^2(\widetilde{R}_2^{1/3})}$$

- Mixing angle can be probed via $W^\pm$-mediated asymmetric production.



$W^\pm$ only couples to the doublet $\Longrightarrow$

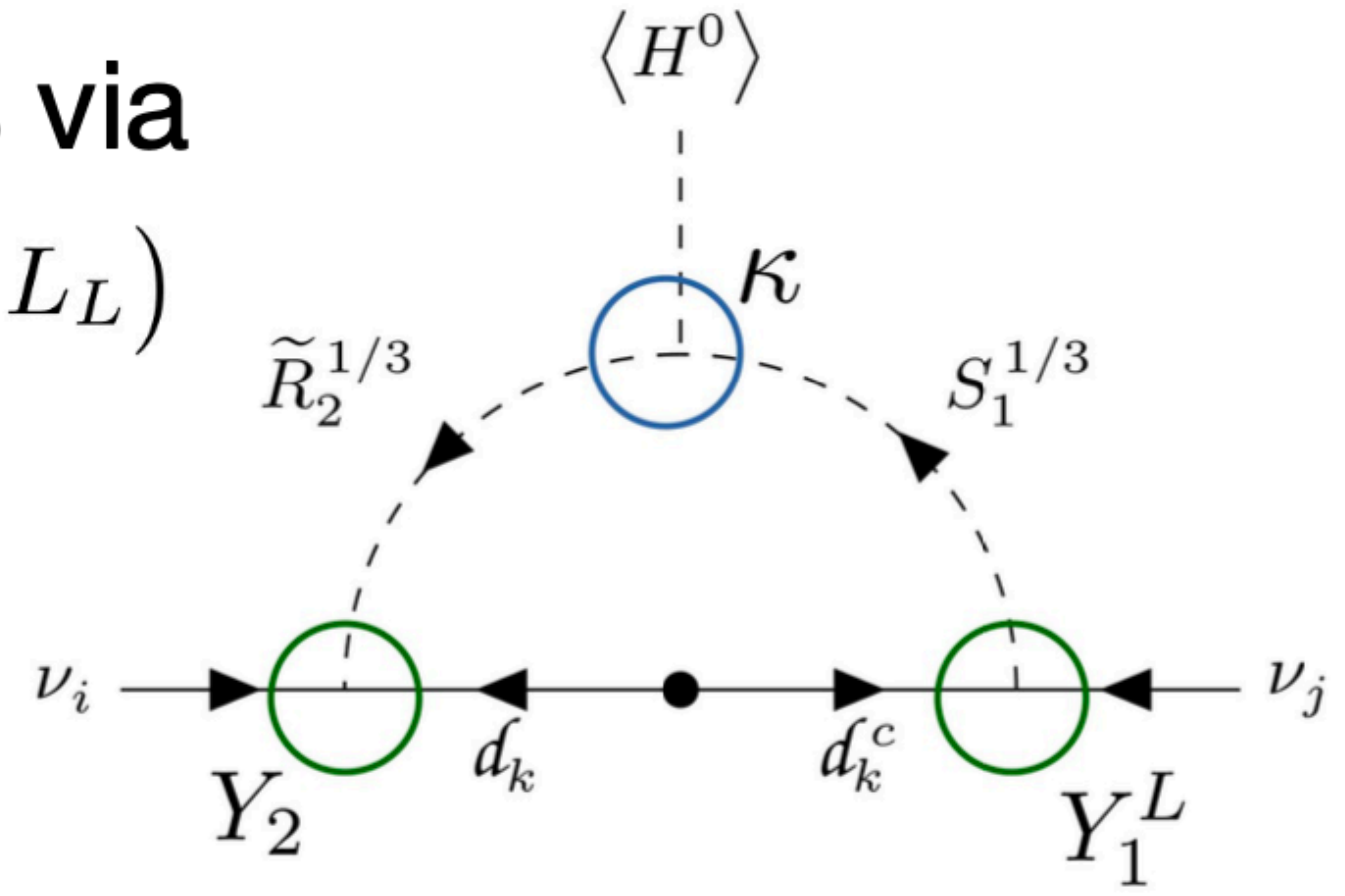
Final states from $X_2^{1/3}$ will have higher event rate



Snehasis Parashar, Avnish, PB, Kirtiman Ghosh: PRD 106 (2022) 9, 095040

loop Majorana neutrino mass generation

- One-loop Majorana mass of SM neutrinos via d=5 Weinberg operator $\mathcal{O}_5 = \frac{c}{\Lambda}\left(\overline{L_L^C}\tilde{H}^*\right)\left(\tilde{H}^\dagger L_L\right)$
  Bonnet et al, *JHEP 07 (2012) 153*
- Simultaneous presence of $\kappa,\, Y_1^L,\, Y_2$ violates lepton number.
- Light neutrino mass matrix:



$$M_\nu \simeq \frac{3\sin 2\theta_{LQ}}{32\pi^2} \ln\left(\frac{M_1^2}{M_2^2}\right)\left[Y_1^L\, m_d\, Y_2^T + Y_2\, m_d\, (Y_1^L)^T\right]$$

Babu et al, *JHEP 2003, 006 (2020)*

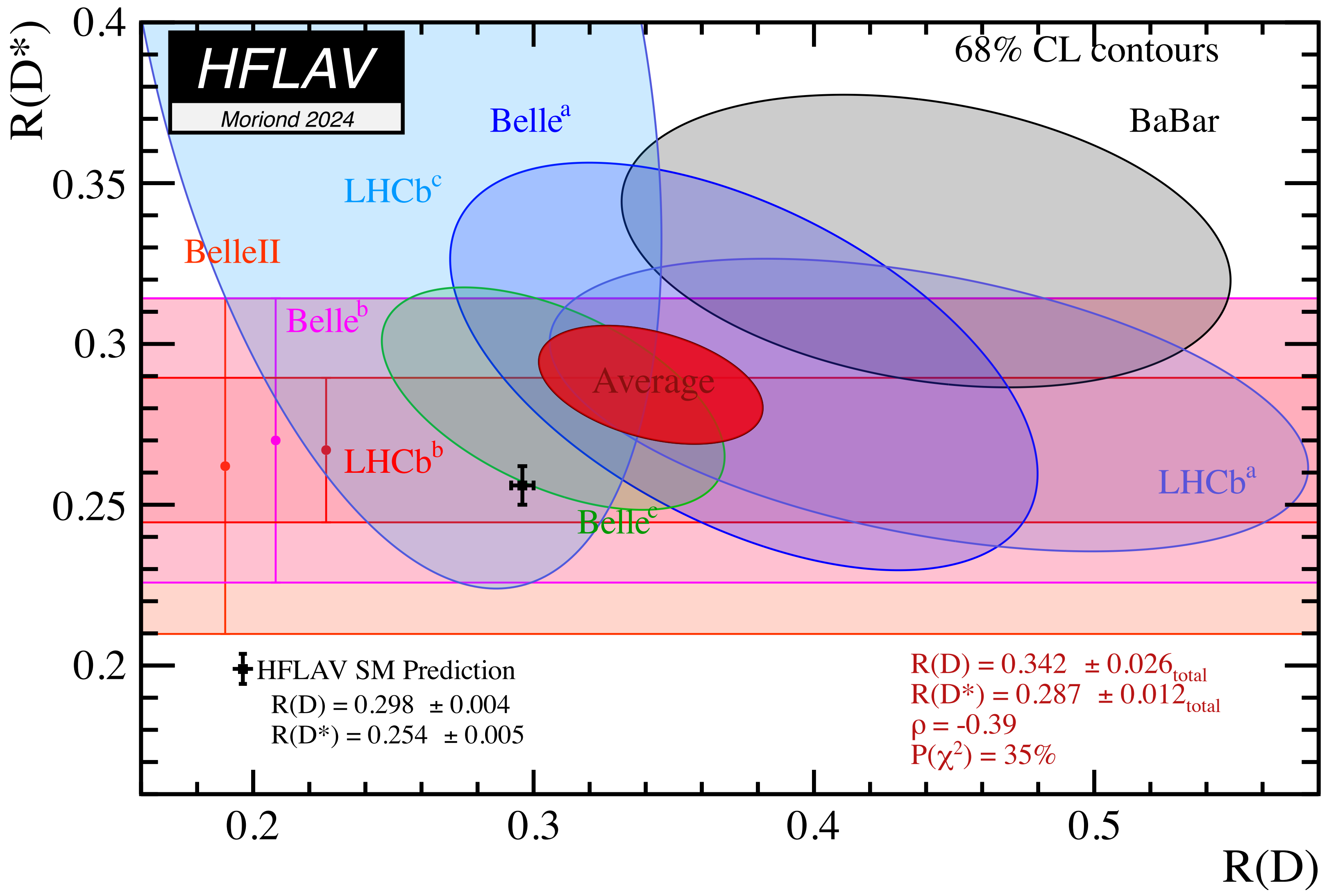
Snehasis Parashar, Aneesh, PB, Kirtiman Ghosh: PRD 106 (2022) 9, 095040

B-anomalies motivation: current status

- $R(D)/R(D^*)$: still persists!

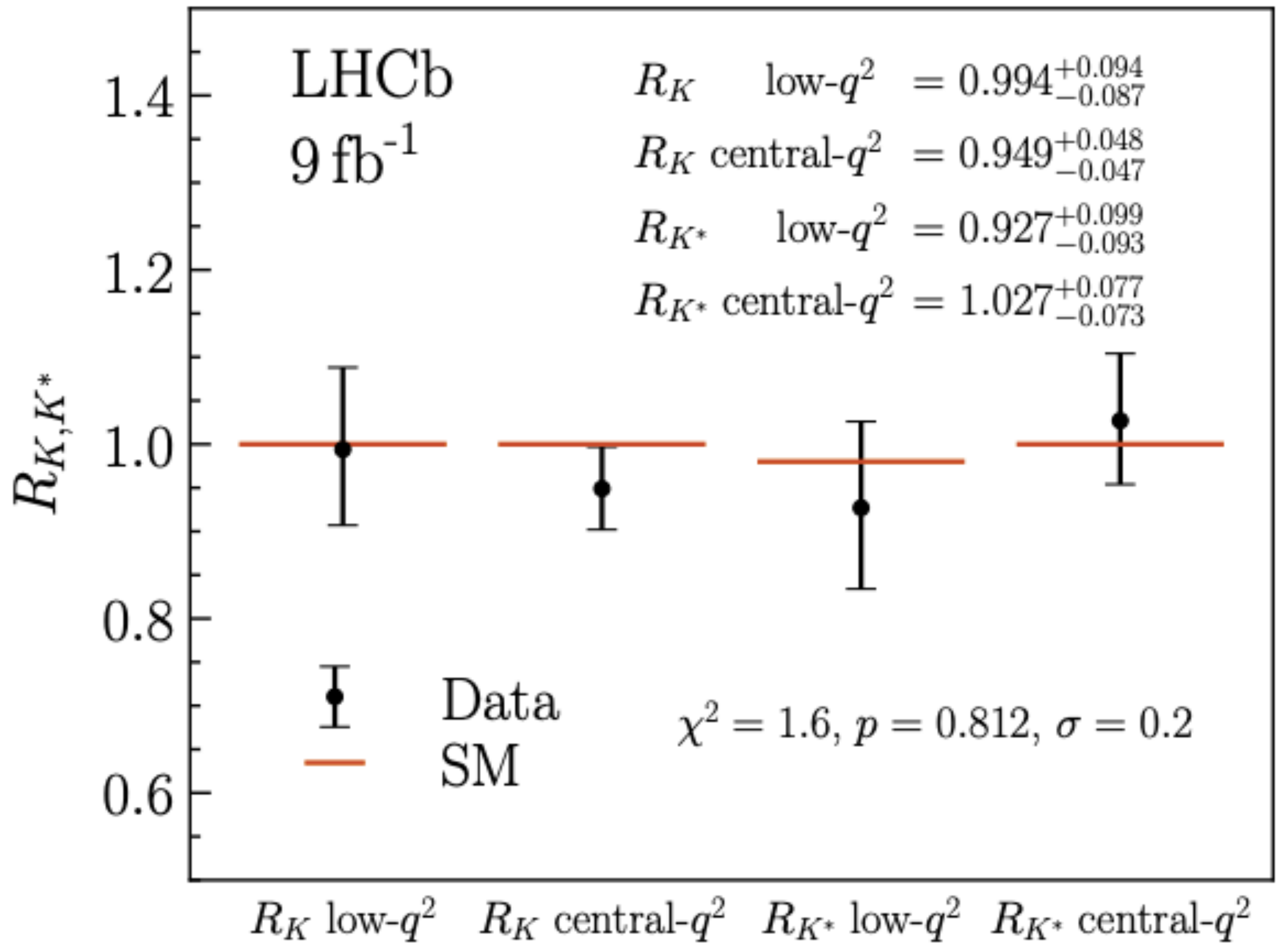
  HFLAV average from Moriond 2024:

  $R(D)_{SM} = 0.298 \pm 0.004, R(D^*)_{SM} = 0.254 \pm 0.005$
  $R(D)_{Exp} = 0.342 \pm 0.026, R(D^*)_{Exp} = 0.287 \pm 0.012$
  $\sim 3.3\sigma$ discrepancy!



- $R(K)/R(K^*)$: agrees with SM now.

  LHCb 2212.09153:
  $R(K)_{SM} = 0.9936 \pm 0.0003, R(K^*)_{SM} = 0.9832 \pm 0.0014$



$\mathcal{R}_{D/D^*}$ and $\mathcal{R}_{K/K^*}$

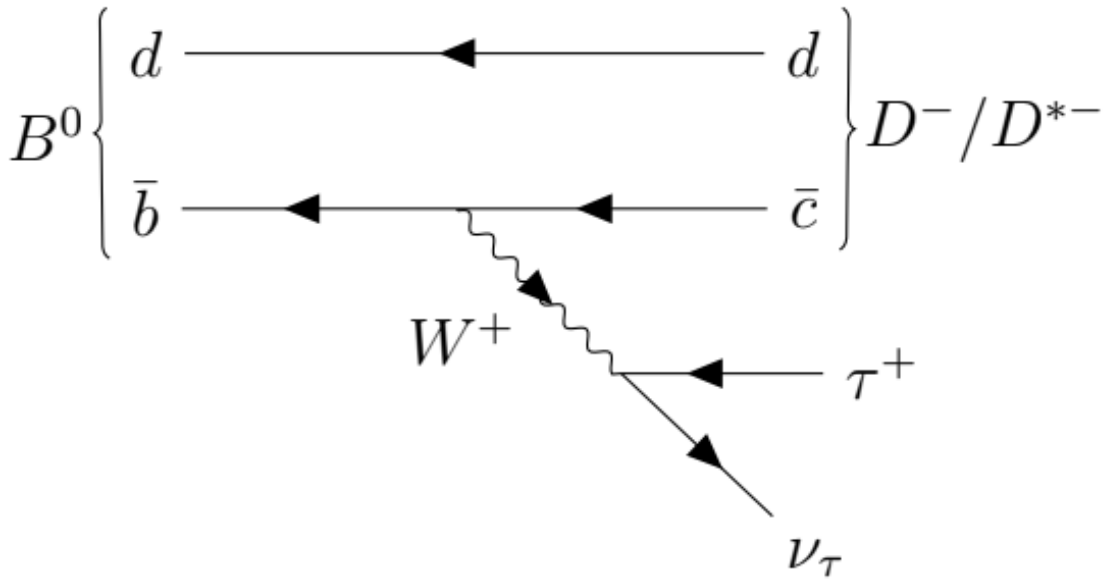
- Ratios of the decays:

$$\mathcal{R}_D = \mathcal{B}(B \to D\tau\nu_\tau)/\mathcal{B}(B \to D\ell\nu_\ell) \qquad \mathcal{R}_K = \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$$

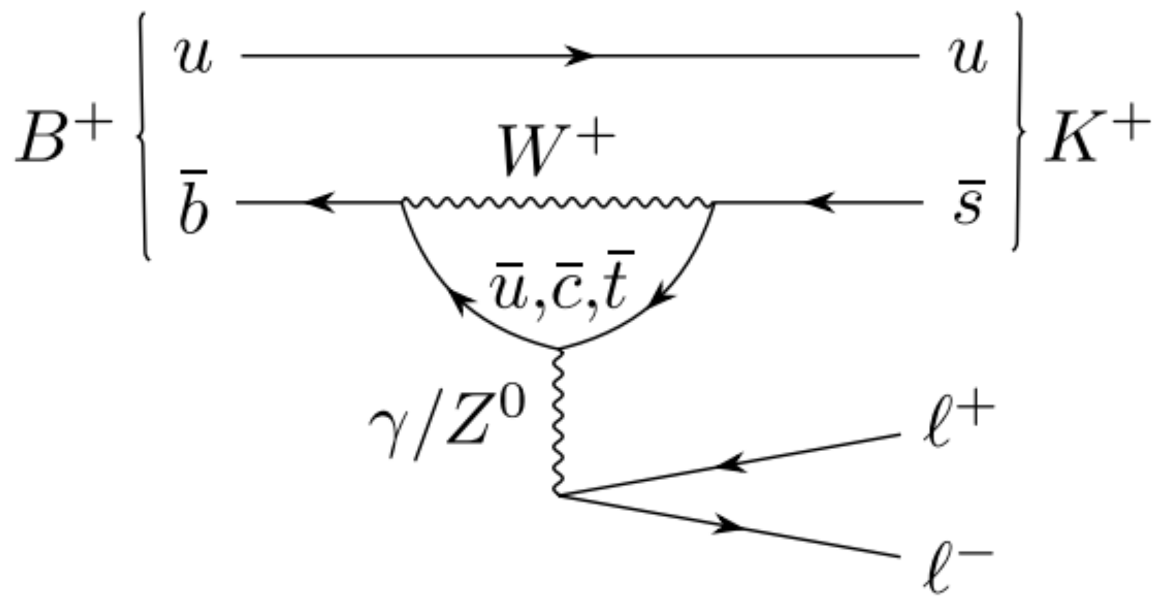
$$\mathcal{R}_{D^*} = \mathcal{B}(B \to D^*\tau\nu_\tau)/\mathcal{B}(B \to D^*\ell\nu_\ell) \qquad \mathcal{R}_{K^*} = \mathcal{B}(B^+ \to K^{*+}\mu^+\mu^-)/\mathcal{B}(B^+ \to K^{*+}e^+e^-)$$

- SM processes:

$\mathcal{R}_D^{\rm SM}$ at Tree-level



$\mathcal{R}_K^{\rm SM}$ at One-loop



- SM predicted values: $\mathcal{R}_D^{\rm SM} = 0.299 \pm 0.003, \quad \mathcal{R}_{D^*}^{\rm SM} = 0.258 \pm 0.005$

$$\mathcal{R}_K^{\rm SM} = 1.0003 \pm 0.0001, \quad \mathcal{R}_{K^*}^{\rm SM} = 1.00 \pm 0.01$$

- However, the expertmental values are different

R(D)_{Exp} = 0.342 ± 0.026, \, R(D^*)_{Exp} = 0.287 ± 0.012

- $R(D)/R(D^*)$ anomaly still exists

Leptoquarks model

- Leptoquarks with $S_3(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$ and $S_1(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ can explain the B-anomalies

- BSM Lagrangian components :

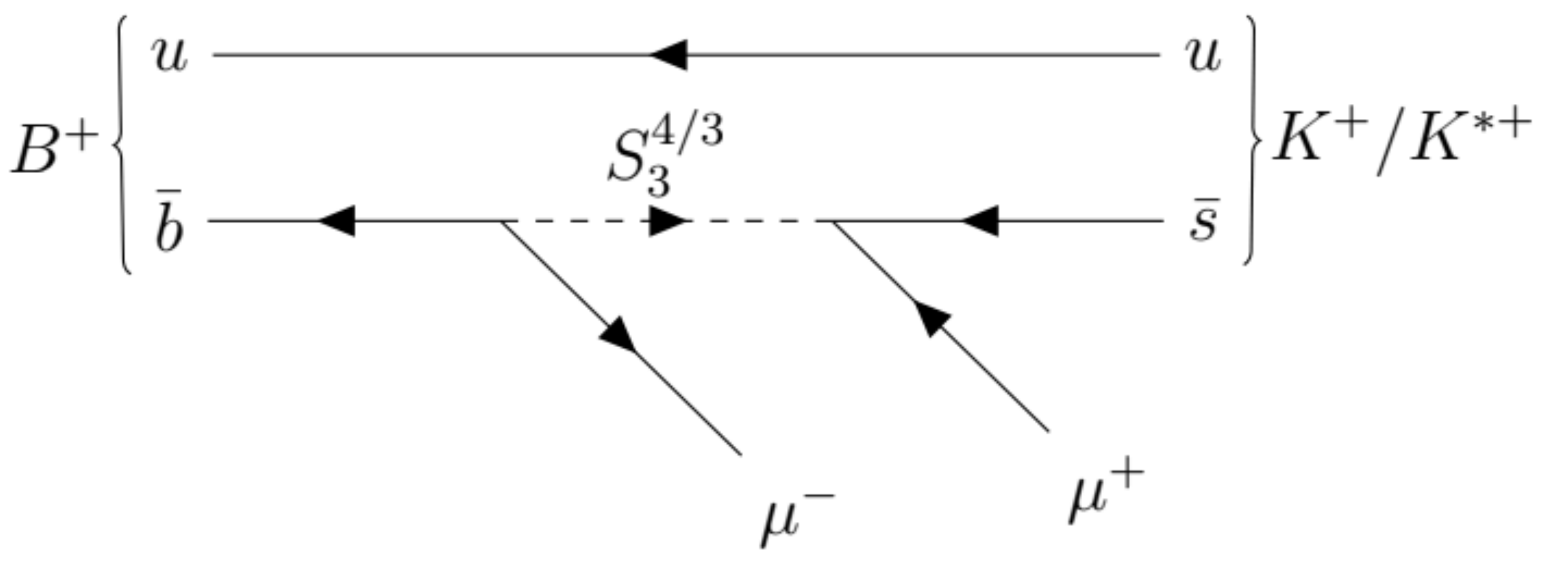
$$\mathcal{L}_{S_1} = \overline{Q^c} i\tau_2 Y^{i\alpha}_{S_1} L^\alpha S_1 + \overline{u^c_R} Z^{i\alpha}_{S_1} \ell^\alpha_R S_1 + h.c.$$

$$\mathcal{L}_{S_3} = \overline{Q^c} Y^{i\alpha}_{S_3} i\tau_2 \boldsymbol{\tau} \cdot \mathbf{S_3} L^\alpha + h.c.$$

- $Y^{i\alpha}_{S1}$, $Y^{i\alpha}_{S3}$ and $\mathrm{Z}^{i\alpha}_{\mathrm{S}_1}$ are corresponding Yukawa couplings

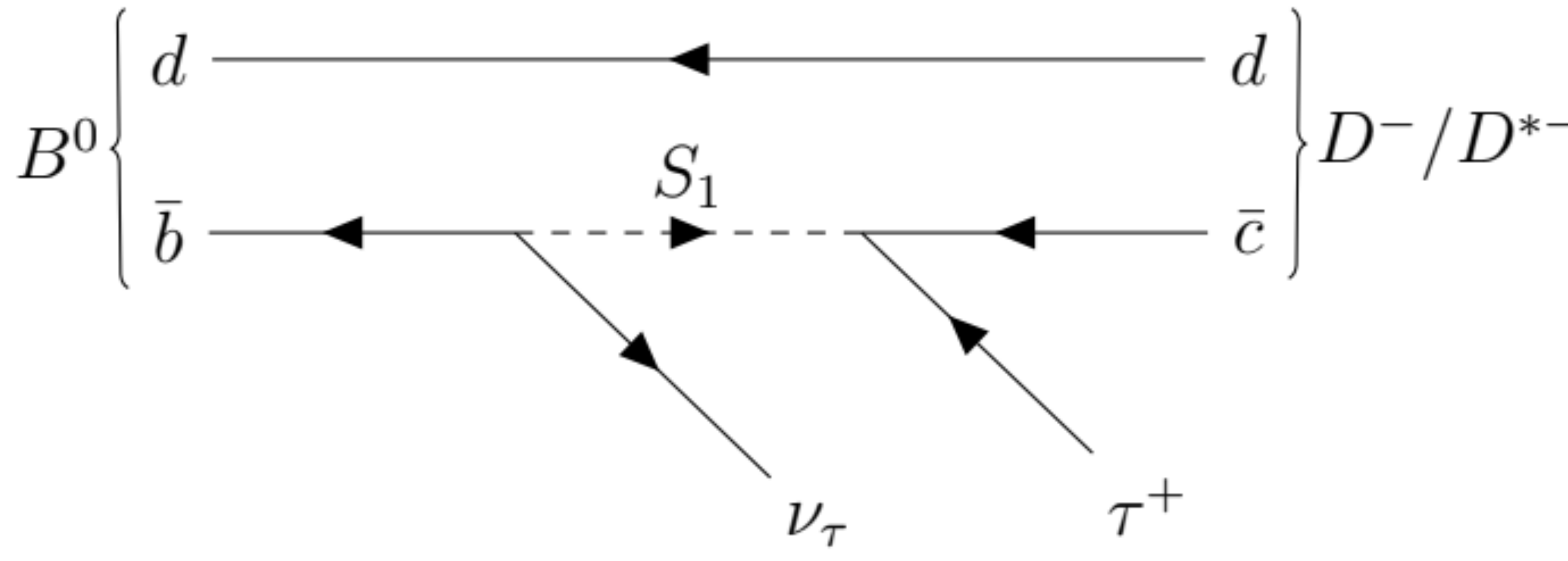
- Tree-level neutral current can explain $\mathcal{R}^{\mathrm{Exp}}_{K/K^*}$

$$\mathcal{H}^{\mathrm{NC}}_{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}} \frac{\alpha_{\mathrm{EM}}}{4\pi} V_{td} V^*_{ts} \left[C^{\mathrm{NP}}_9 (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu \mu) + C^{\mathrm{NP}}_{10} (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu \gamma_5 \mu)\right]$$



$$C^{\mathrm{NP}}_9 = -C^{\mathrm{NP}}_{10} = \frac{v^2}{M^2_{S_3}} \frac{\pi}{\alpha_{\mathrm{EM}} V_{tb} V^*_{ts}} Y^{*32}_{S_3} Y^{22}_{S_3}$$

- The charged current can explain $\mathcal{R}^{\mathrm{Exp}}_{D/D^*}$



$$\mathcal{H}^{\mathrm{CC}}_{\mathrm{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} \left[\mathcal{C}^S_L (\bar{c} P_L b)(\bar{\tau} P_L \nu) + \mathcal{C}^T_L (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu)\right]$$

$$\mathcal{C}^S_L(M_{S_1}) = -4\mathcal{C}^T_L(M_{S_1}) = -\frac{v^2}{4M^2_{S_1}} \frac{1}{V_{cb}} Y^{33}_{S_1} Z^{*23}_{S_1}$$

PB, Anirban KKaran,, Rusa Mandal, Snehasis Parashar: *Eur.Phys.J.C* 82 (2022) 10, 916

Mandal et al. JHEP 08 (2020) 022


Search Strategies
Leptoquarks
Scalar Leptoquarks
Spin zero
• SU(2) Singlet
• SU(2) doublet
• SU(3) Triplet
Vector Leptoquarks
Spin one
• SU(2) Singlet
• SU(2) doublet
• SU(3) Triplet
Gauge charge
Spin
Yukawa couplings
Angular Distribution
RAZ@ $e-\gamma, e-p$ collider
LHC
Single production @LHC
Pair production @muon collider

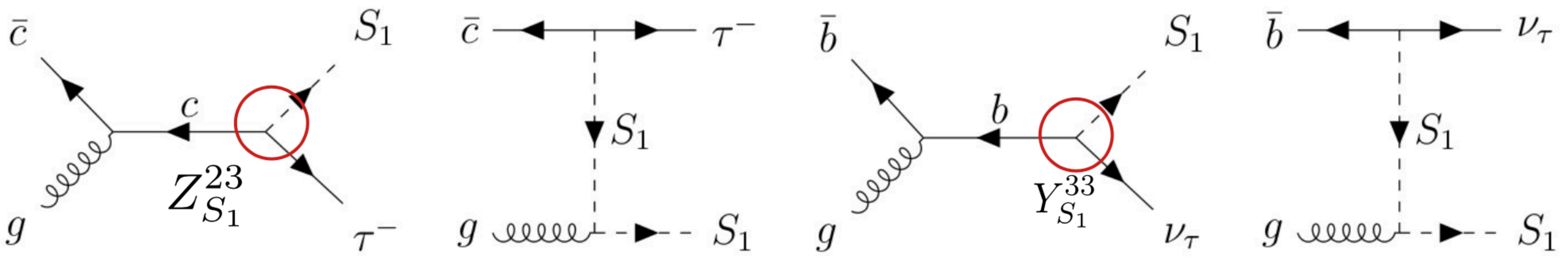
Is it possible to look for Yukawa couplings at the LHC?

Single Leptoquark production at the LHC!

Single Leptoquark(S_1): Motivation

$$\mathcal{L}_{S_1} \supset \overline{Q^c}^i \, i\tau_2 Y_{S_1}^{i\alpha} L^\alpha \, S_1 + \overline{u_R^c}^i Z_{S_1}^{i\alpha} \ell_R^\alpha \, S_1 + \text{h.c.}$$

- $Y_{S_1}^{33}, Z_{S_1}^{23}$ can explain the still existing $RD)/R(D)^*$ anomaly
- Which can be probed in single Leptoquarks production via quark-gluon fusion at the LHC



- Unlike pair production, here, both production and decays depend on the Yukawa couplings

PB, Anirban Karan, Rusa Mandal
Snehashis Parashar: EPJC 82 (2022) 10, 916

PB, Rusa Mandal EPC 78 (2018) 491

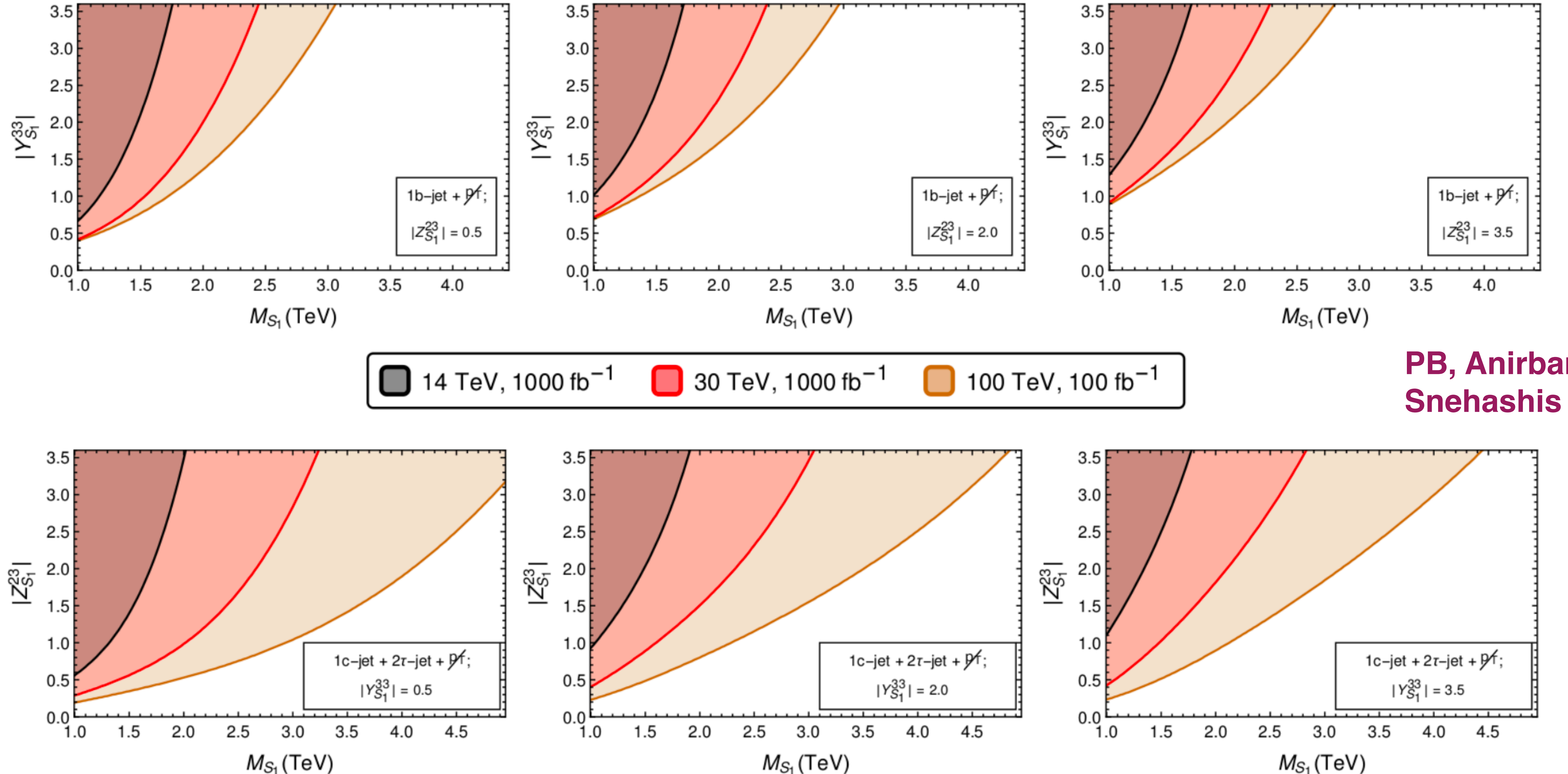
Single Leptoquark(S_1) at the LHC

- A few final states:

$$b - g \to S_1^{-1/3} \nu_\tau \to (b\nu_\tau) + \nu_\tau \to 1b\text{-jet} + \text{MET} \geq 500 \text{ GeV} \quad (Y_{S_1}^{33})$$

$$c - g \to S_1^{-1/3} \bar{\tau} \to (c\bar{\tau}) + \bar{\tau} \to 1c\text{-jet} + 2\tau\text{-jet} + \text{MET} \geq 200 \text{ GeV} \quad (Z_{S_1}^{23})$$

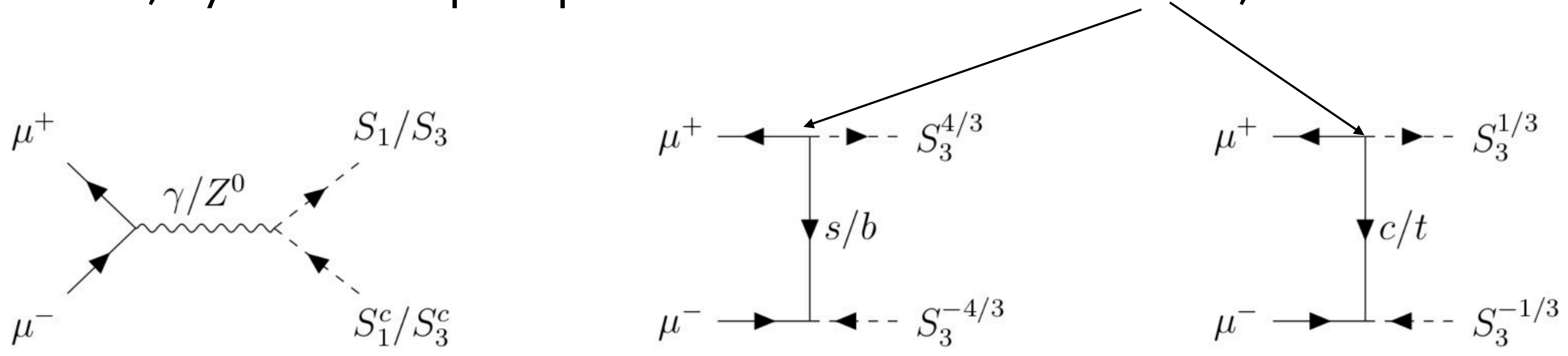
- LHC, HL-LHC, FCC reach plots can be given in terms of these Yukawa couplings



PB, Anirban Karan, Rusa Mandal Snehashis Parashar: EPJC 82 (2022) 10, 916

Leptoquarks at the muon Collider

- Muon collider is motivated due to no QCD radiation, less synchrotron radiation, collisions are in CM frame as fundamental particles collide
- It is going to be a precision machine
- But $\mu^+ \mu^-$ collision as the total charges zero single Leptoquarks production is not possible
- $S_{S_3}^{2/3}$ production via Yukawa is not possible
- However, symmetric pair production involves Yukawa, unlike LHC



PB, Anirban Karan, Rusa Mandal
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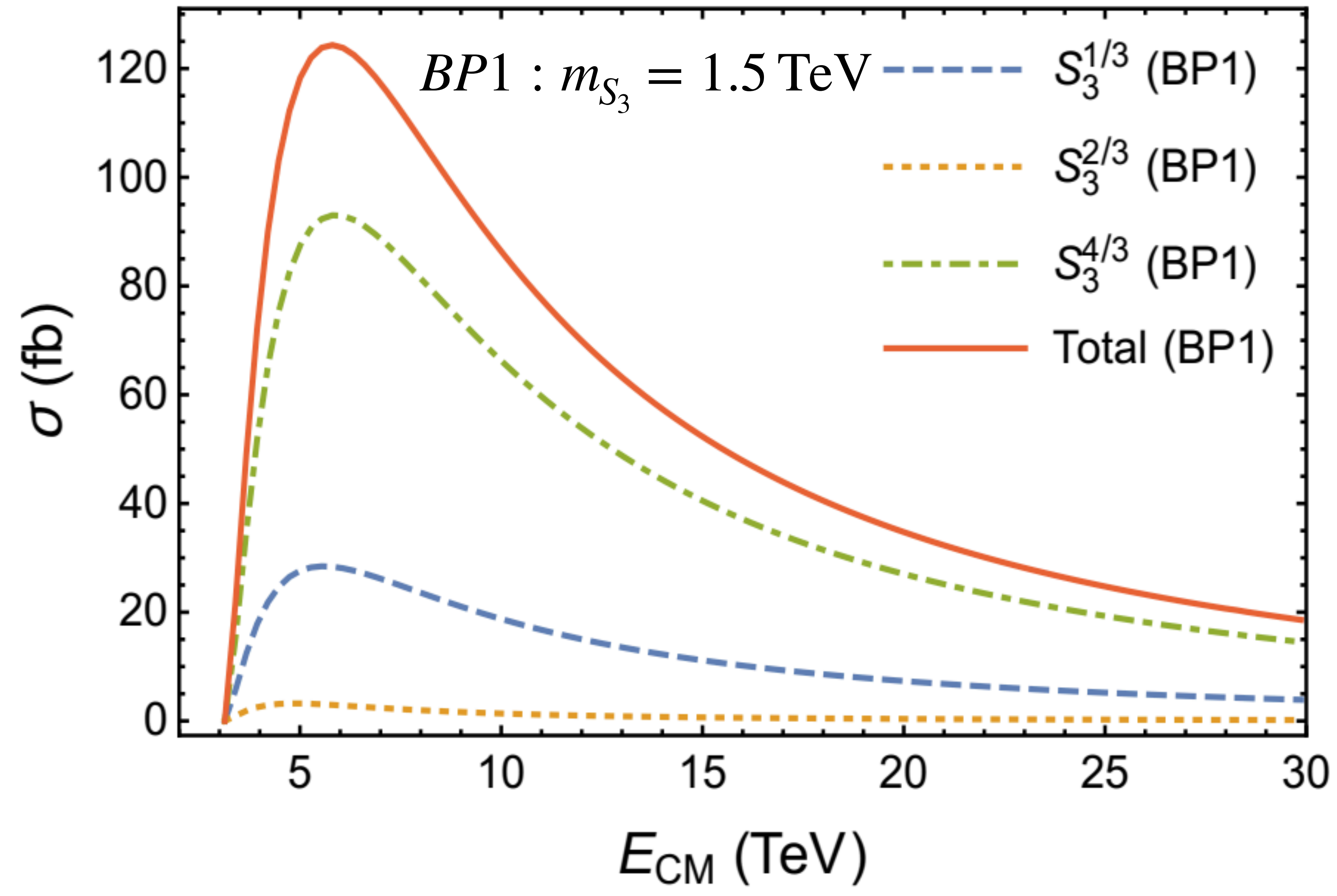
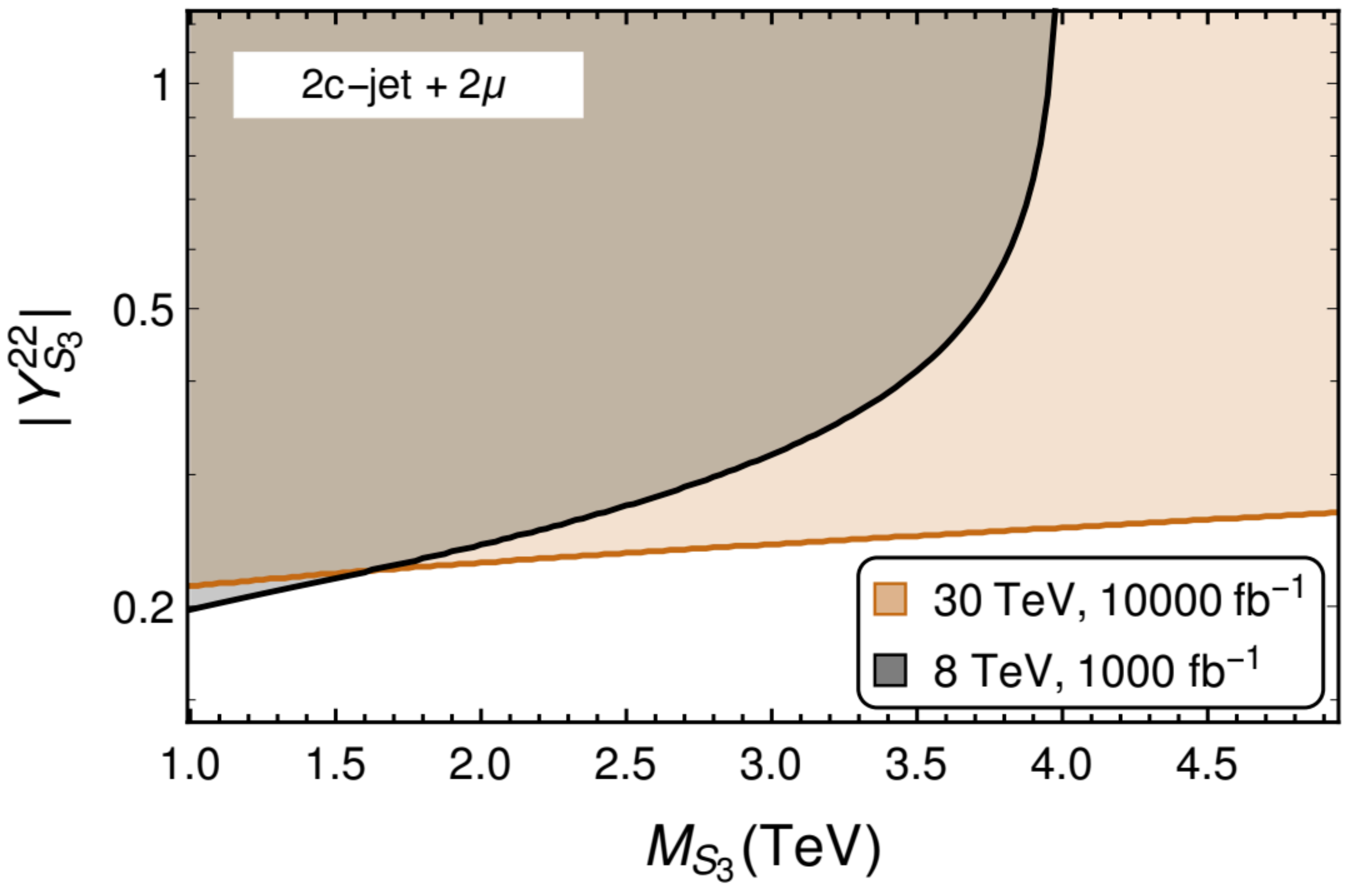
Leptoquarks at the muon Collider

- Unlike LHC, cross-sections donot always increase with CM energy
- Dependant on $Y^{22}_{S_3}, S^{32}_{S_3}$ one can have

$$\begin{aligned}\mu^+\mu^- &\to S_3^{1/3} S_3^{-1/3} \\ &\to (c\mu^-) + (\bar{c}\mu^+) \\ &\to 2c\text{-jet} + 2\mu\end{aligned}$$

- Projected reach can be seen for CM energies of 8 and 30 TeV





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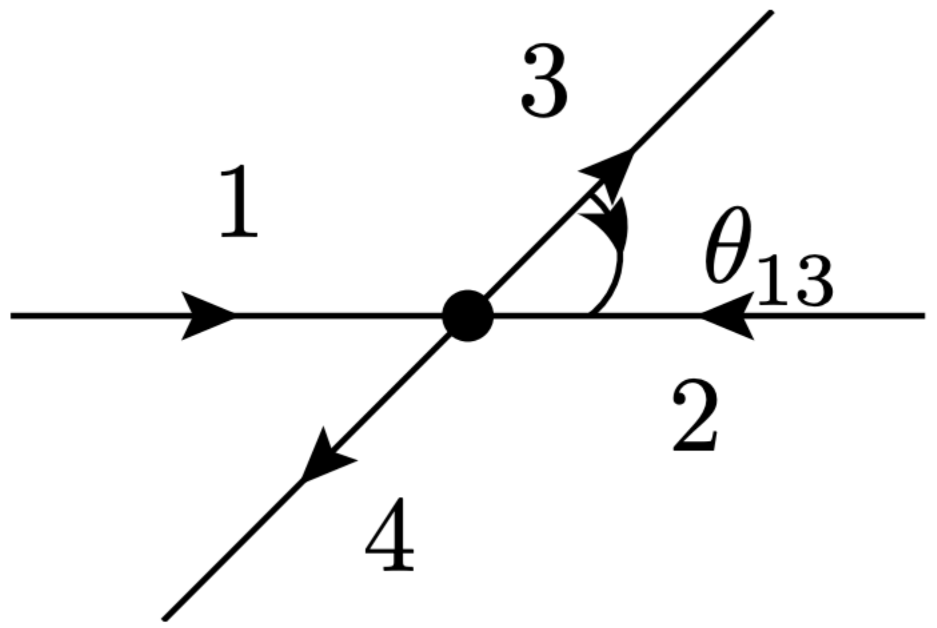
Can Angular distributions have some answers!

Why Angular distributions ? A little exercise!

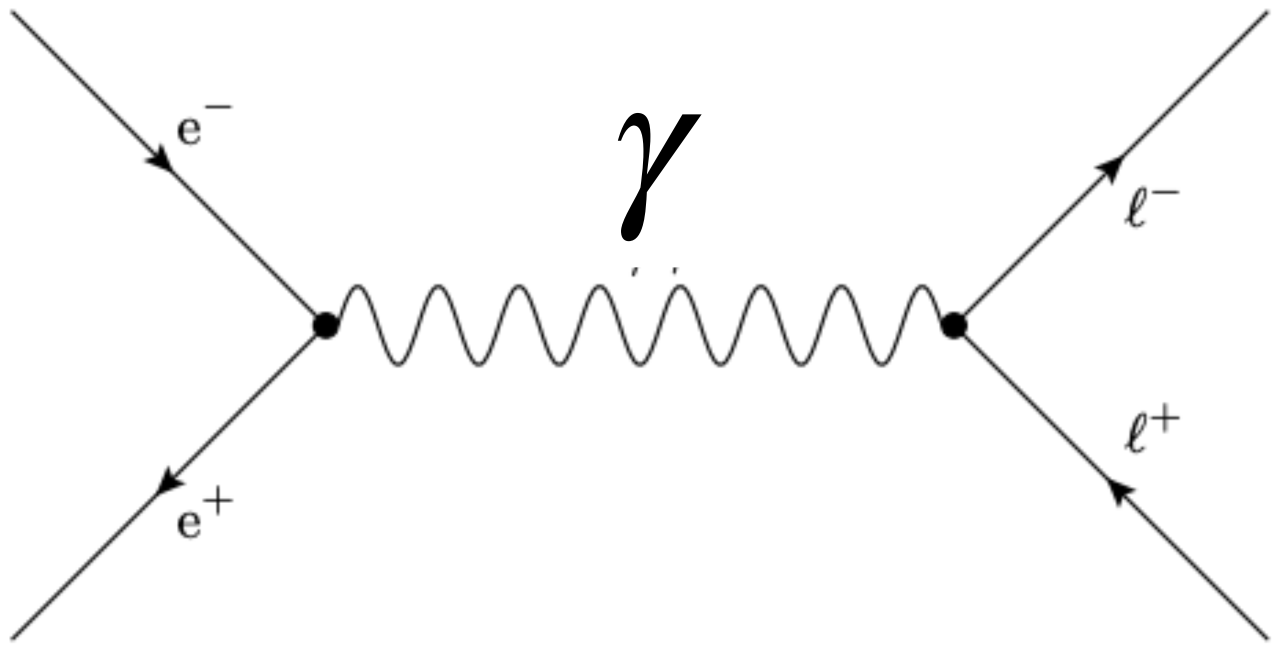
- Angular distributions in the Centre of Mass frame can decode the spin and gauge representations
- Consider normal Drell-Yan process $e^+e^- \to \ell^+\ell^-$

$$\frac{d\sigma}{d\cos\theta} \sim (1+\cos^2\theta)$$



- Similarly for scalar lepton pairs

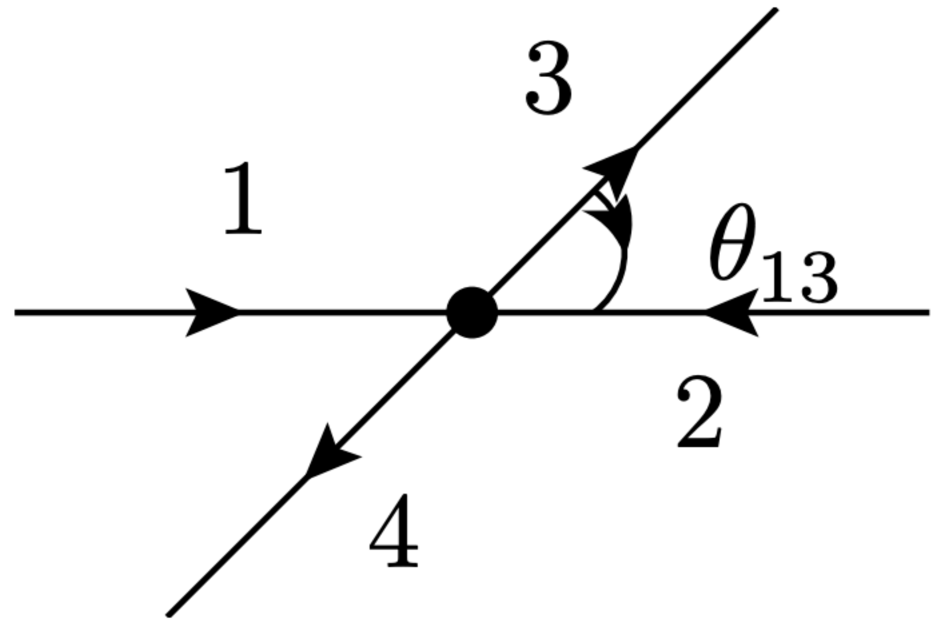
$$\frac{d\sigma}{d\cos\theta} \propto (1-\cos^2\theta)$$

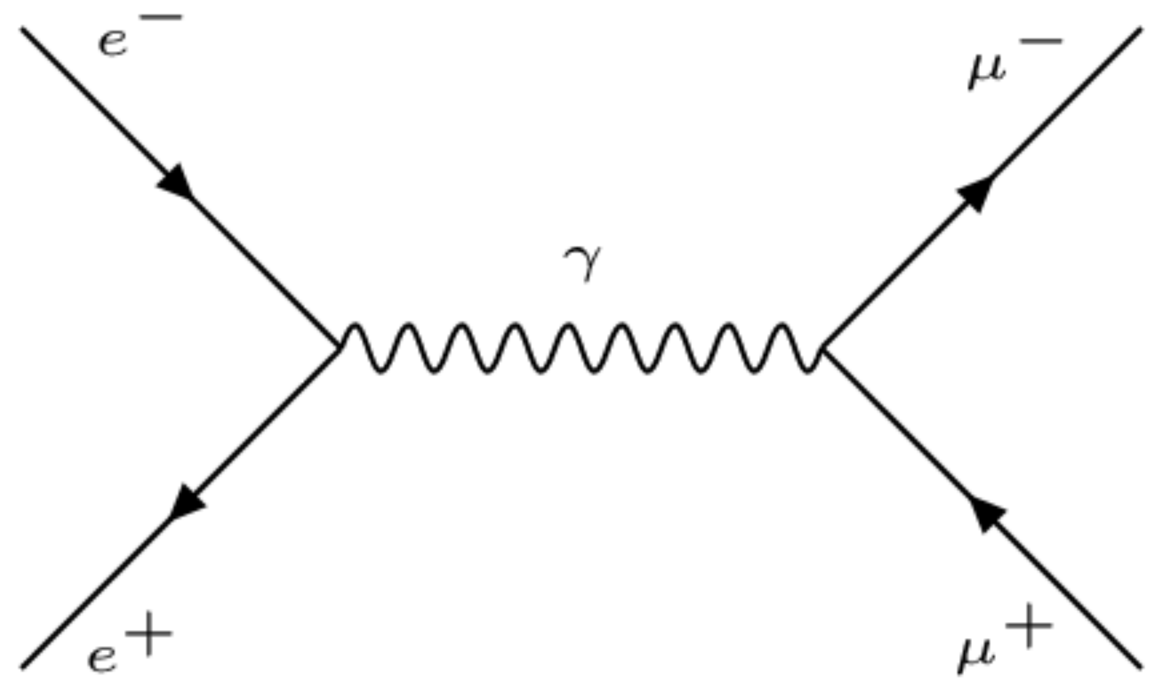


Datta et al. PRD 72 (2005) 119901, JHEP 07 (2005) 033

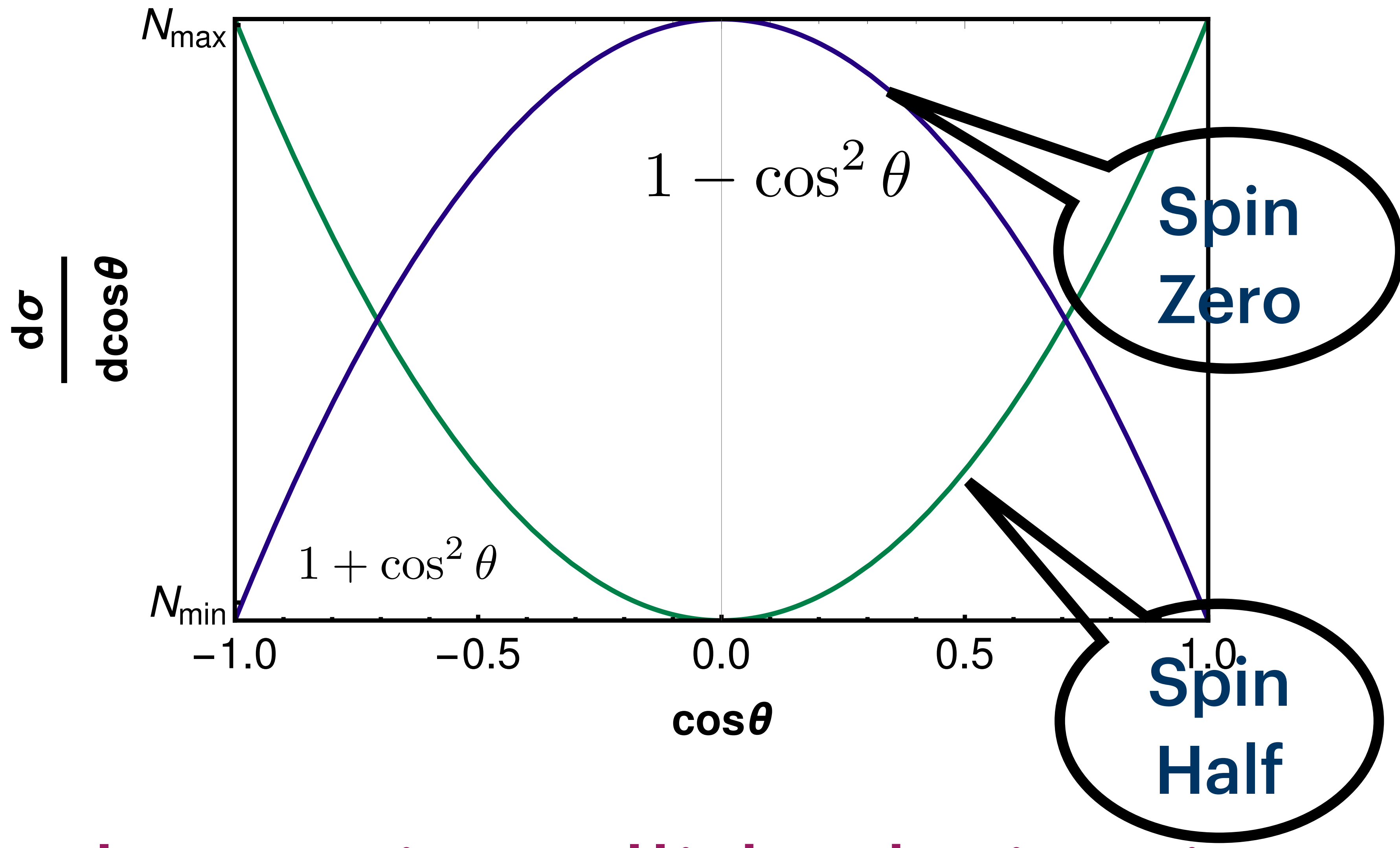
Spin Determination

- Spin information can be extracted via the angular distributions in CM frame





- For $e^+ e^- \to \mu^+ \mu^-$ via photon, $\frac{d\sigma}{d\cos\theta} \propto (1 + \cos^2\theta)$
- For the spin zero final states this is $\frac{d\sigma}{d\cos\theta} \propto (1 - \cos^2\theta)$
- Thus angular distribution can be instrumental in determining the spin of new particles
- Depending on the gauge structure of intermediate particles the distribution can change
- Knowing CM frame at LHC is challenging compared to leptonic collider being in CM frame



C. Sen, P. Bandyopadhyay, S. Dutta, A. KT, *EPJC* 82 (2022) 3, 230

Large Hadron Collider!
Can we determine spin of the Leptoquarks?

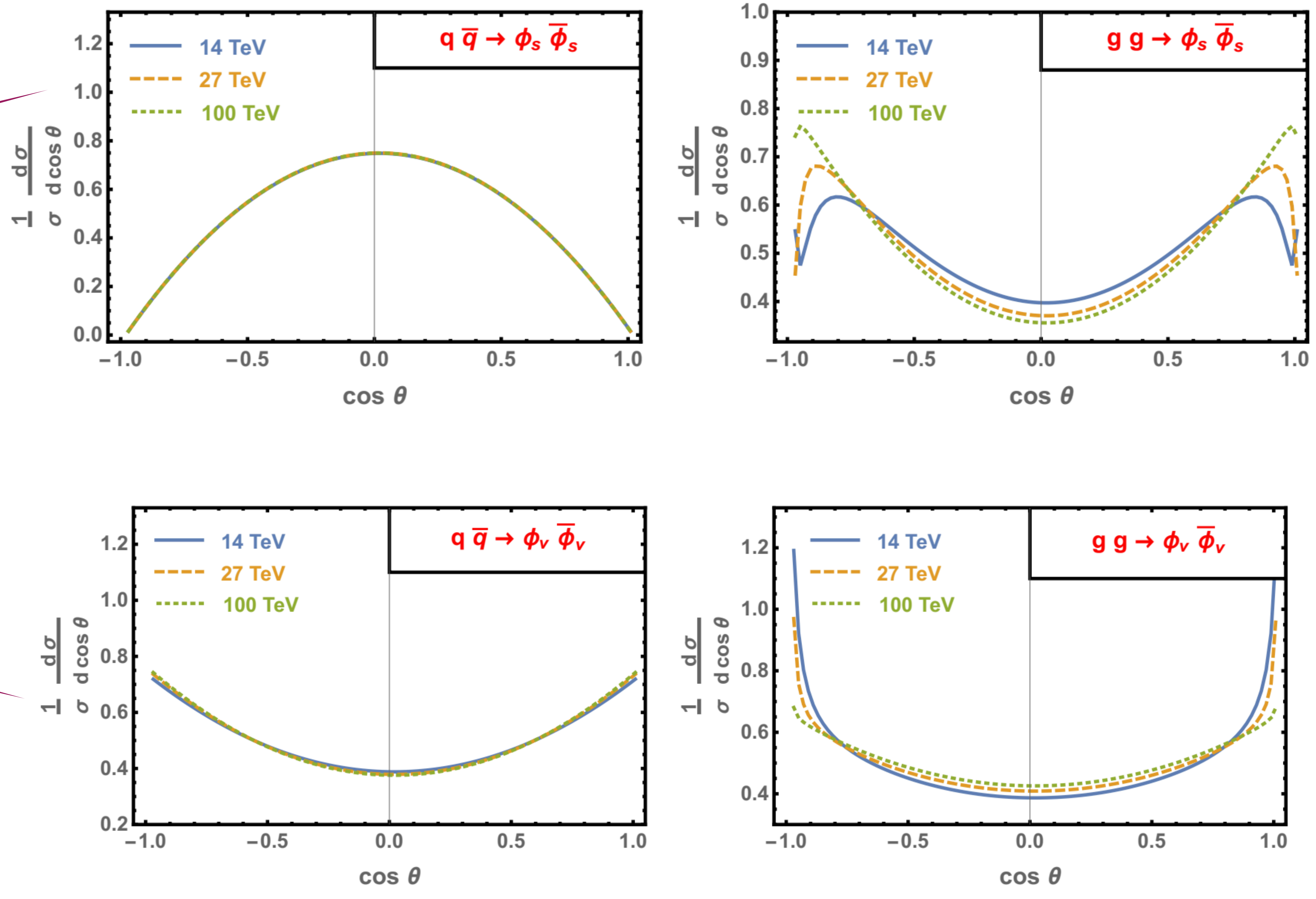
Determination of Spins of Leptoquarks@the LHC

- Leptoquark pair production at the LHC/FCC can decode their spin via the reconstruction of the angular distribution in the CM frame
- Parton level contributions look different

for scalar and vector leptoquarks

Scalar LQ

Vector LQ



P.Bandyopadhyay, Saunak Dutta, Mahesh Jakkapu, Anirban Karan, NPB 971 (2021) 115524

Determination of Spins of Leptoquarks@the LHC

- Fully visible final state is necessary to reconstruct to CM frame via boost-back

More

- Invariant mass reconstruction of LQ, is also necessary for the mass information
- At the LHC proton-proton scattering, the distributions still differs

(a) 14 TeV (b) 27 TeV (c) 100 TeV

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Radiation amplitude zero (RAZ)

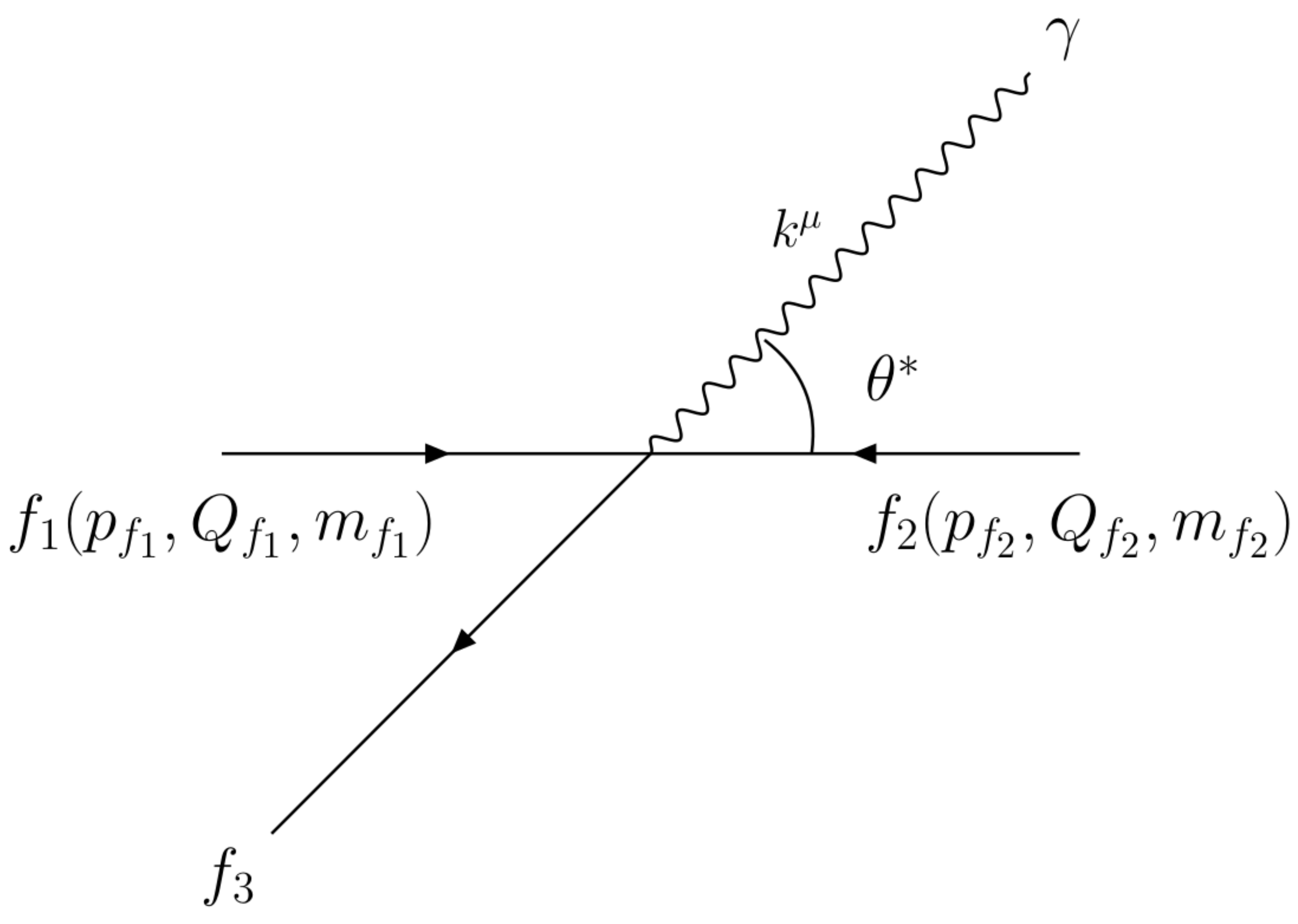
- There can be a minima (zeros) in the visible region of the angle (θ) in the differential distribution of the cross-section $\frac{d\sigma}{d\cos\theta}$, when a massless gauge boson is involved in the scattering
- The position of the zero depends on the charge of the final state and sometimes also on the masses of the finalstate particles, centre of mass energy
- The dependency on the charge makes it a convenient tool to probe differently charged Leptoquarks

RAZ@fermion-fermion collider

- The general criterion for the tree-level single photon amplitude to vanish is

$$\left(\frac{p_j \,.\, k}{Q_j}\right)$$

must be the same other than photon, where p_j^μ, Q_j are the four momentum and the charge of the j^{th} external particle and k^μ is the four momentum of the photon.



- For a $2 \rightarrow 2$ scattering with photon in the final state the zero of the cross-section is given by

$$\cos\theta^* = \frac{Q_{f_2} - Q_{f_1}}{Q_{f_2} + Q_{f_1}},$$

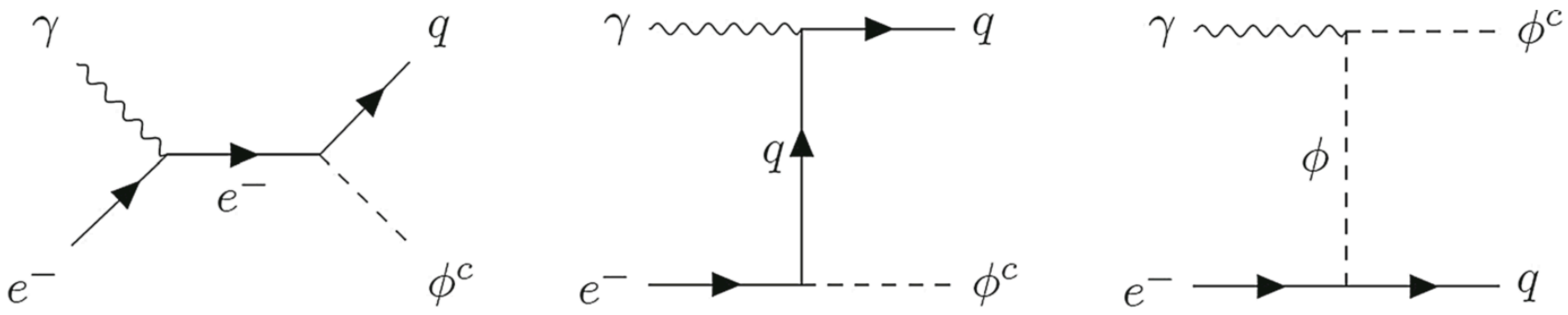
Where Q_{f_1}, Q_{f_2} are the charges of the incoming particles f_1,f_2 and θ^* is the angle between photon and f_1 in the CM frame

S.J. Brodsky et al. PRL 49, 966 (1982),
K.O. Mikaelian et al. PRL 43, 746 (1979)

$e - \gamma$ **collider**

RAZ@Lepton photon collider

- $e^- \gamma \to q\, \phi^c$:



- The general condition of the tree-level single photon amplitude to vanish (the zero of the cross-section) is given by

$$\frac{p_e \cdot p_\gamma}{-1} = \frac{p_q \cdot p_\gamma}{Q_q} = \frac{p_\phi \cdot p_\gamma}{Q_\phi} \ ,$$

where Q_ϕ is the charge of the Leptoquark in the unit of e, $Q_\phi = -(1+Q_q)$.

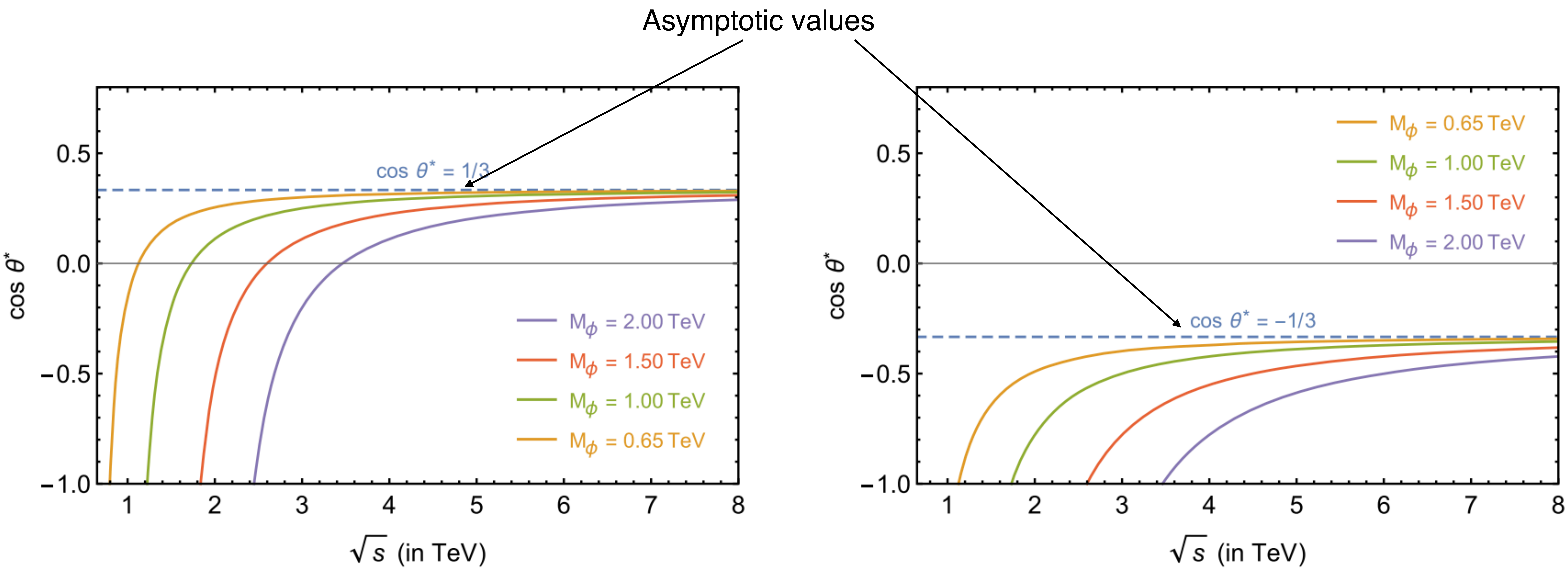
- The angle of the zero is given by

$$\cos\theta^* = 1 + \frac{2\,Q_q}{\left[1 - \left(M_\phi^2/s\right)\right]} = f\left(Q_q, M_\phi^2/s\right)$$

Function of mass and energy

where θ^* is the angle between the electron and the leptoquark or the photon and the quark

RAZ: dependency@$e - \gamma$ collider



Variation of $\cos\theta^*$ with respect to $\sqrt{s}$ for $Q_q = -1/3$ and $Q_{\bar{q}} = -2/3$, respectively, for different masses of leptoquark

Complementarity of the Leptoquarks

- Occurrence of RAZ in the different versions of Leptoquarks are independent of whether they are scalar or vector
- But mainly depends on the electromagnetic charges
- However, RAZ falling in the visible region of $\cos\theta^*$, may depends on the collider as well as charge, mass and the centre of mass energy
- It is interesting the $e-p$ and $\mathrm{e}-\gamma$ colliders can probe Leptoquarks which are complementary to each other
- The Leptoquarks models that can be probed in $e-p$, cannot be probed in $e-\gamma$ by means of RAZ and vice versa

Leptoquarks@$e-\gamma$ collider

- For vanishing amplitude within the visible region,

$$Q_q < 0 \quad \text{and} \quad \frac{M_\phi}{\sqrt{s}} \leq \sqrt{-Q_\phi}, \qquad -1 < Q_\phi < 0\,.$$

LQ	Y	Q_{em}	Interaction	Process	$\cos\theta^*$
Scalar leptoquarks					
S_1	2/3	1/3	$\overline{\Psi}^c_q\, P_L\, i\sigma_2 \Psi_l\, S_1,$	$\bar{u}\left(S_1^{+1/3}\right)^c$	$f(-2/3,\, M_\phi^2/s)$
			$\bar{q}^c_u\, P_R\, l_e\, S_1$		
$\widetilde{S}_1$	8/3	4/3	$\bar{q}^c_d\, P_R\, l_e\, \widetilde{S}_1$	$\bar{d}\left(\widetilde{S}_1^{+4/3}\right)^c$	–
$\mathbf{S}_3$	2/3	4/3	$\overline{\Psi}^c_q\, P_L\, (i\sigma_2\, S_3^{ad})\, \Psi_l$	$\bar{d}\left(S_3^{+4/3}\right)^c$	–
		1/3		$\bar{u}\left(S_3^{+1/3}\right)^c$	$f(-2/3,\, M_\phi^2/s)$
		−2/3		–	–
R_2	7/3	5/3	$\overline{\Psi}_q\, P_R\, R_2\, l_e,$	$u\left(R_2^{+5/3}\right)^c$	–
		2/3	$\bar{q}_u\, P_L\, (R_2^T\, i\sigma_2)\, \Psi_l$	$d\left(R_2^{+2/3}\right)^c$	$f(-1/3,\, M_\phi^2/s)$
$\widetilde{R}_2$	1/3	2/3	$\bar{q}_d\, P_L\, (\widetilde{R}_2^T\, i\sigma_2)\, \Psi_l$	$d\left(\widetilde{R}_2^{+2/3}\right)^c$	$f(-1/3,\, M_\phi^2/s)$
		−1/3		–	–

Back

P.Bandyopadhyay, Anirban Karan, Saunak Dutta EPJC 80 (2020) 6, 573

Leptoquarks@$e-\gamma$ collider

Visible region

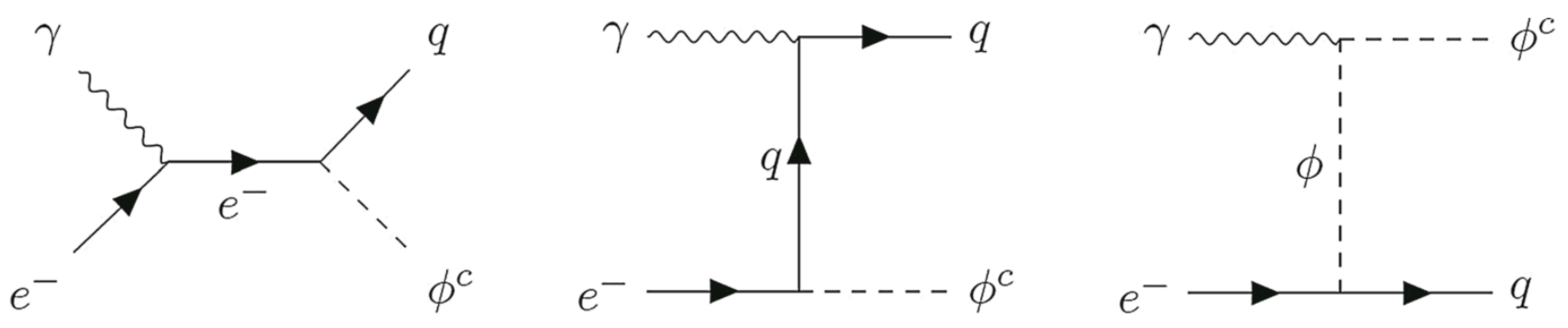
LQ	Y	Q_{em}	Interaction	Process	$\cos\theta^*$
Vector leptoquarks					
$V_{2\mu}$	$5/3$	$4/3$	$\overline{\Psi}^c_q\,\gamma^\mu P_R\,(i\sigma_2\,V_{2\mu})l_e$	$\bar{d}\left(V_{2\mu}^{+4/3}\right)^c$	–
		$1/3$	$\bar{q}^c_d\,\gamma^\mu P_L\,(V^T_{2\mu}\,i\sigma_2)\,\Psi_l$	$\bar{u}\left(V_{2\mu}^{+1/3}\right)^c$	$f(-2/3,\,M^2_\phi/s)$
$\widetilde{V}_{2\mu}$	$-1/3$	$1/3$	$\bar{q}^c_u\,\gamma^\mu P_L\,(\widetilde{V}^T_{2\mu}\,i\sigma_2)\,\Psi_l$	$\bar{u}\left(\widetilde{V}_{2\mu}^{+1/3}\right)^c$	$f(-2/3,\,M^2_\phi/s)$
		$-2/3$		–	–
$U_{1\mu}$	$4/3$	$2/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,\Psi_l\,U_{1\mu}$	$d\left(U_{1\mu}^{+2/3}\right)^c$	$f(-1/3,\,M^2_\phi/s)$
			$\bar{q}_d\,\gamma^\mu P_R\,l_e\,U_{1\mu}$		
$\widetilde{U}_{1\mu}$	$10/3$	$5/3$	$\bar{q}_u\,\gamma^\mu P_R\,l_e\,\widetilde{U}_{1\mu}$	$u\left(\widetilde{U}_{1\mu}^{+5/3}\right)^c$	–
$\mathbf{U}_{3\mu}$	$4/3$	$5/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,U^{ad}_{3\mu}\,\Psi_l$	$u\left(U_{3\mu}^{+5/3}\right)^c$	–
		$2/3$		$d\left(U_{3\mu}^{+2/3}\right)^c$	$f(-1/3,\,M^2_\phi/s)$
		$-1/3$		–	–

One example: scalar Leptoqurk $(S^{+1/3})^c$

Benchmark points	Values of $\cos\theta^*$ for zeros of $(d\sigma/d\cos\theta)$ at different $\sqrt{s}$		
	For $Q_{\bar{q}} = -2/3$ or $Q_\phi = -1/3$		
	0.2 TeV	2 TeV	3 TeV
BP1 (70 GeV)	−0.52	−0.33	−0.33
BP2 (650 GeV)	–	−0.49	−0.40
BP3 (1.5 TeV)	–	–	−0.78

Higher energy can access RAZ for higher mass

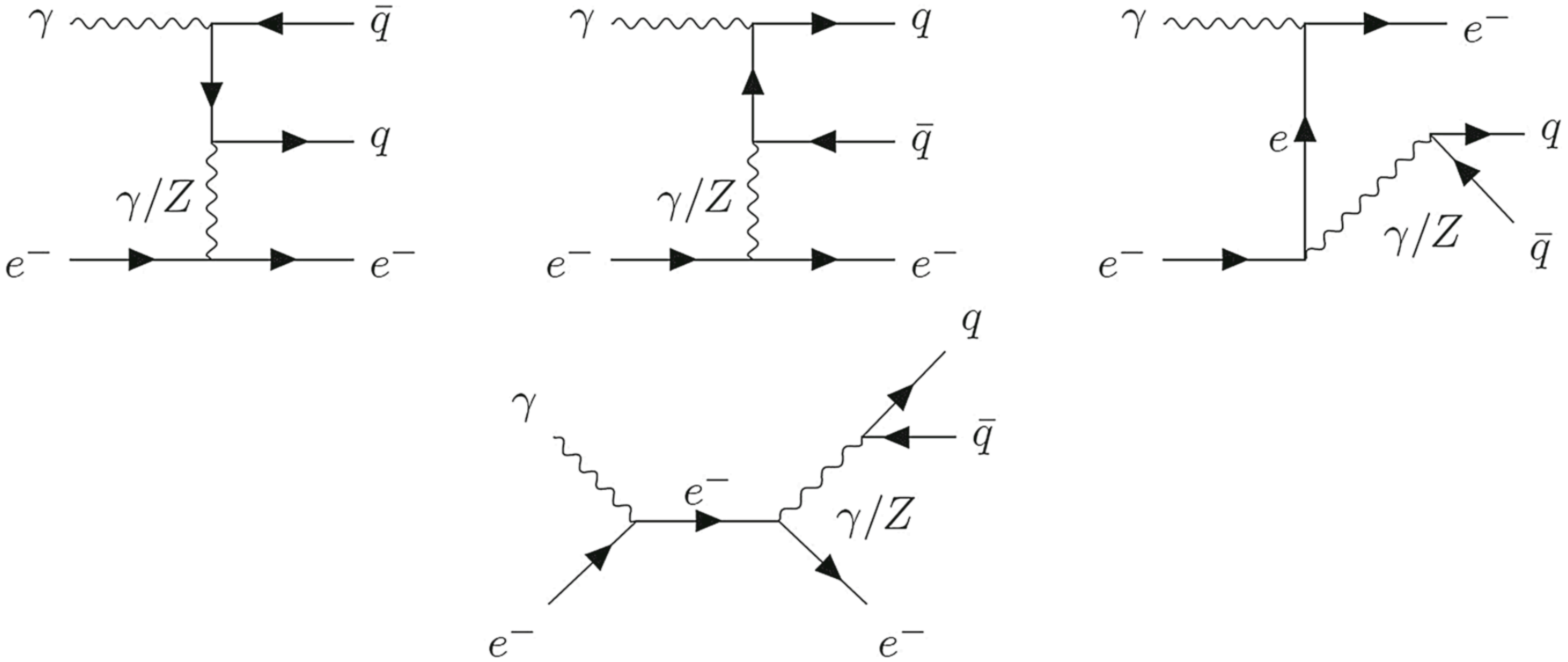
- Production process:



- Dominant decay mode is $q\,\ell \Longrightarrow \ell + 2jet$ final state

Backgrounds

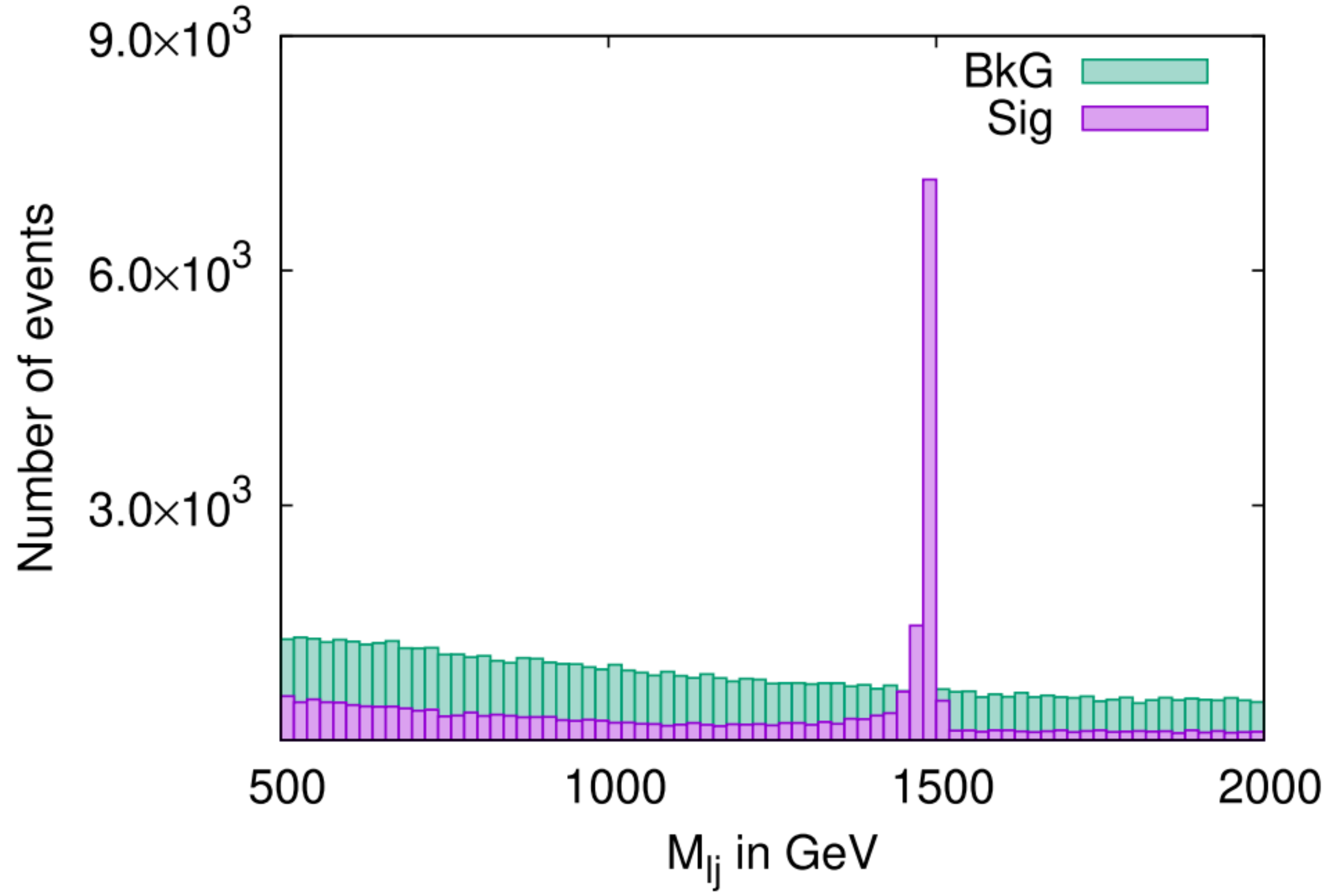
- There are SM processes that mimics $\ell + 2jet$ final state



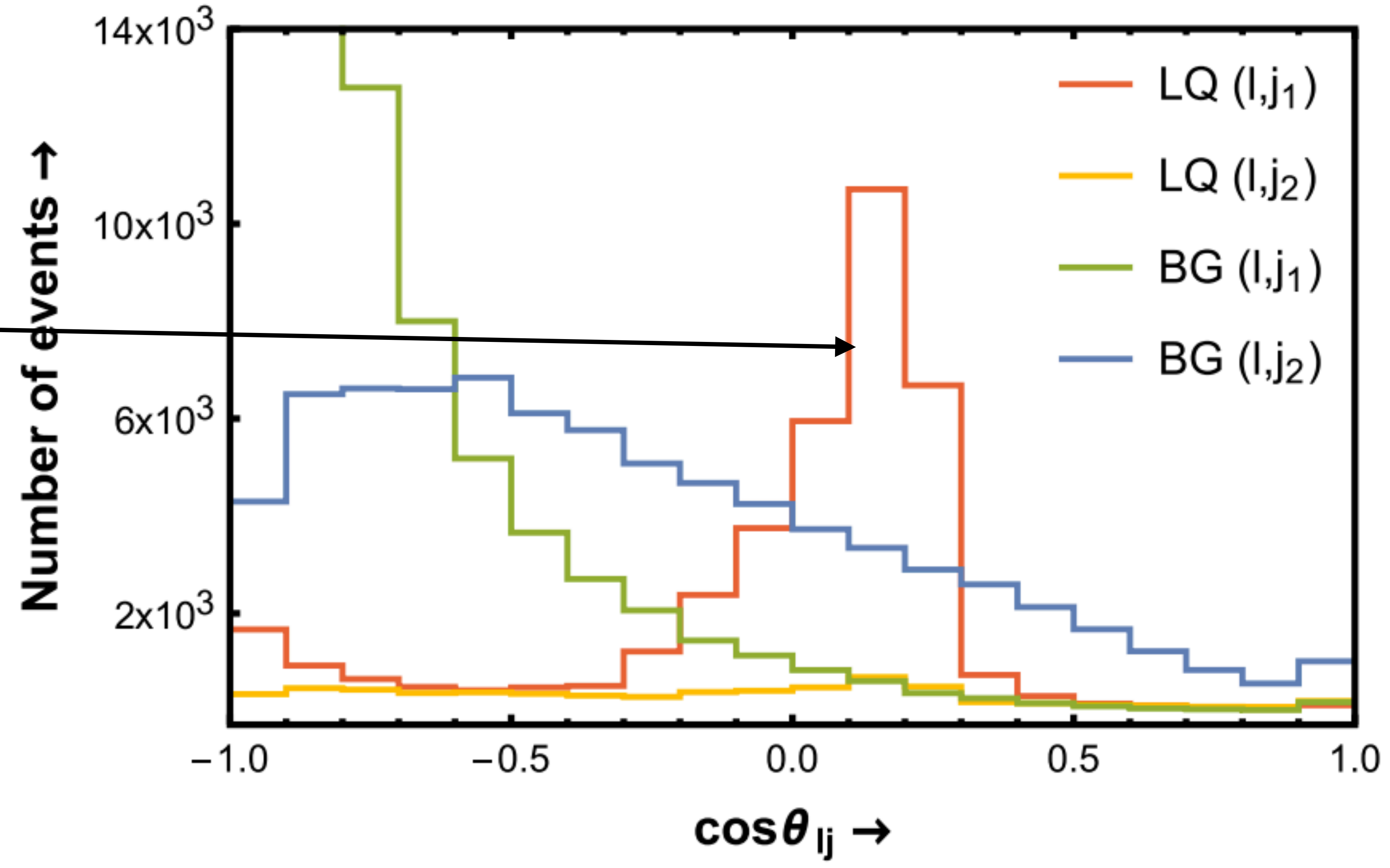
- Thus reconstruction of the Leptoquarks mass is crucial to eliminate such SM backgrounds

Reconstruction of the Leptoquarks mass

- Invariant mass distribution of ℓj can give us the Leptoquarks mass peak



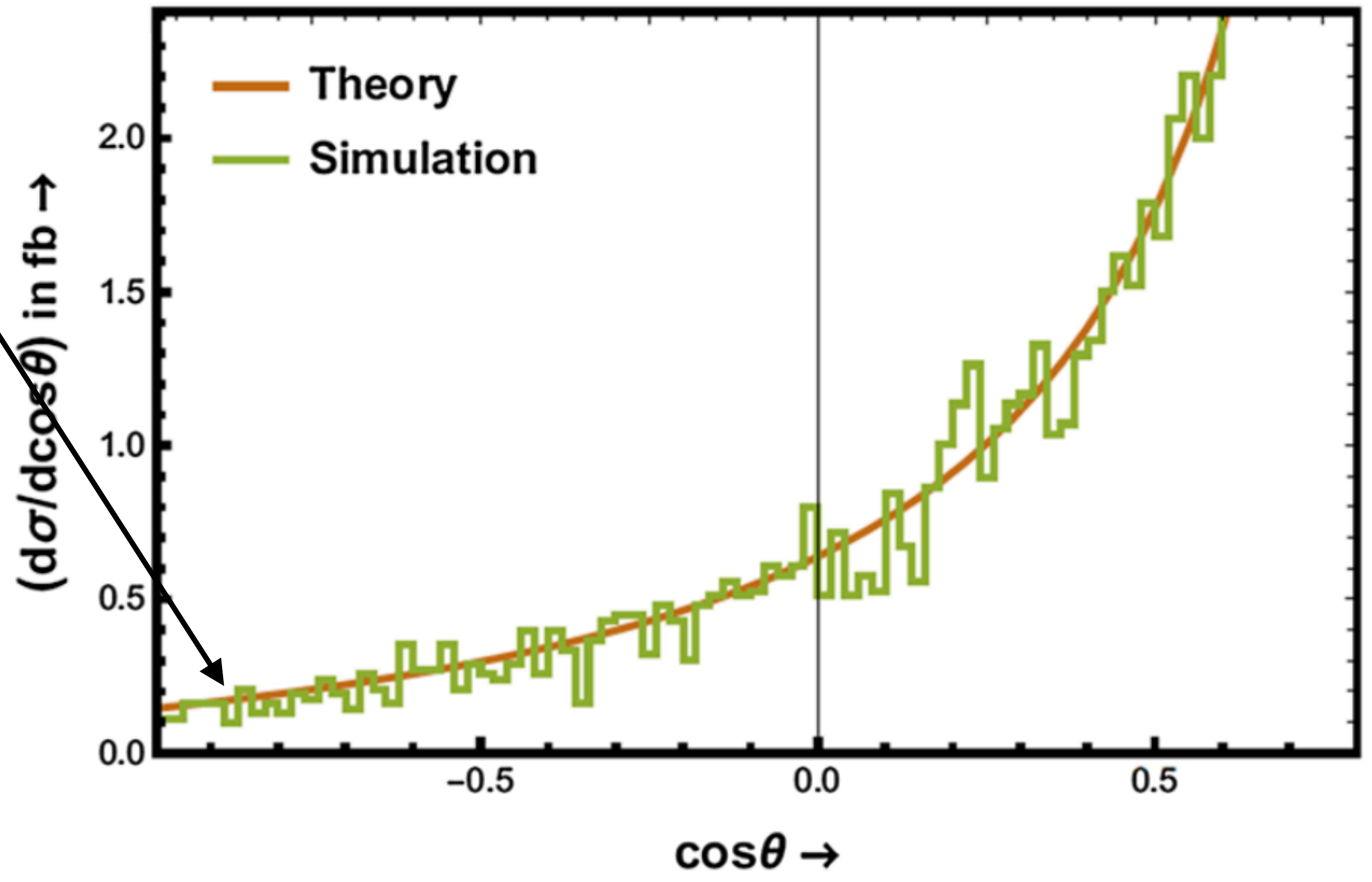
- Leptoquark decays to lepton and jet can be identified with the demand on $\cos\theta_{\ell j}$



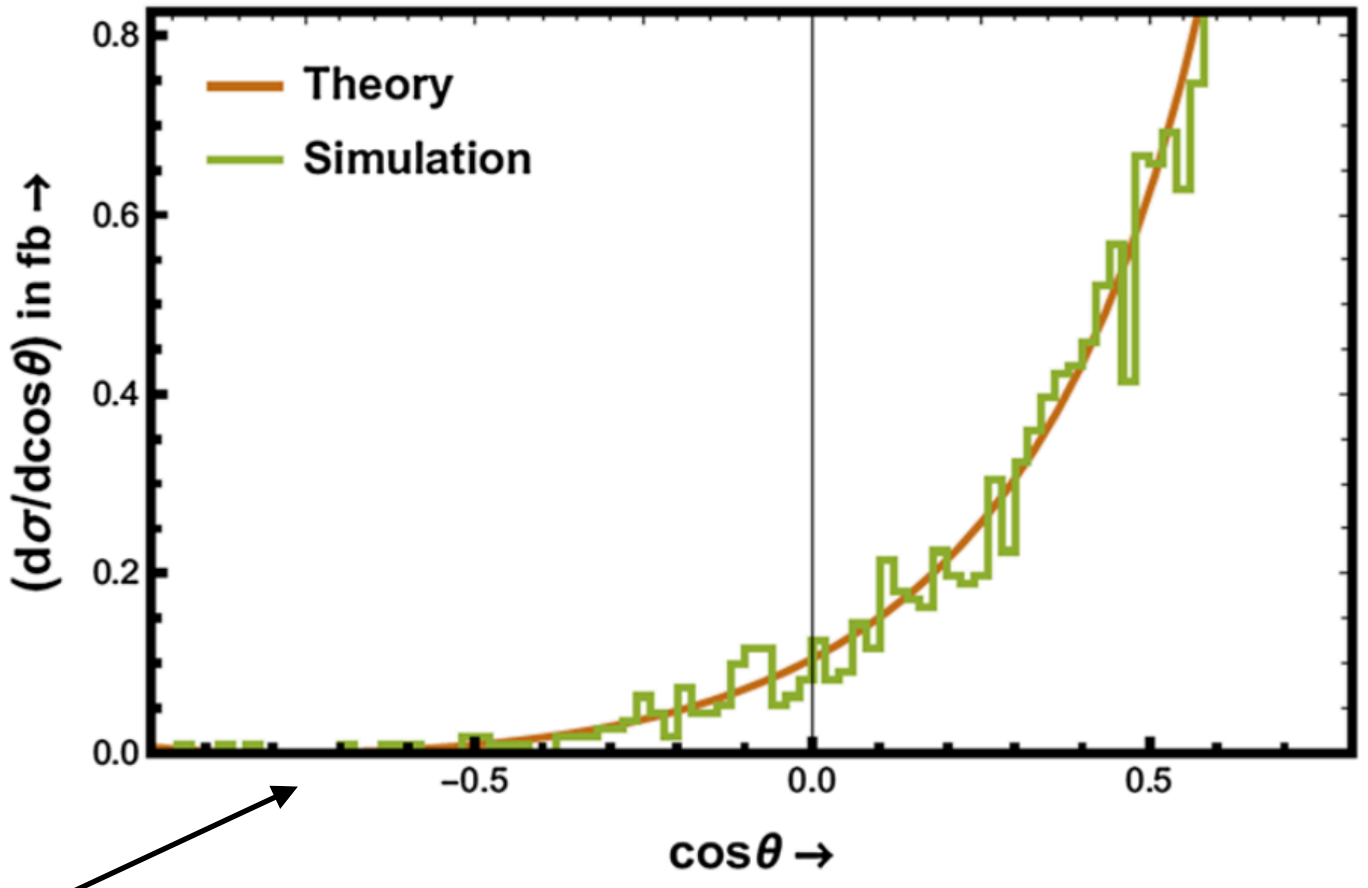
Zeros of cross-section

- For Ecm=2 TeV, BP3 does not have zero in the cross-section failing

$$Q_q < 0 \quad \text{and} \quad \frac{M_\phi}{\sqrt{s}} \leq \sqrt{-Q_\phi}, \qquad -1 < Q_\phi < 0\,.$$



Ecm=2 TeV



Ecm=3 TeV

- But such zero can be found out for Ecm=3 TeV at $\cos\theta^* = -0.78$

- Such minima or zeros can be probed via collecting asymmetric events around the minima and zeros

- A $\geq 5\sigma$ signal significance is possible at $100\,\text{fb}^{-1}$ integrated luminosity

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Event numbers for $(S^{+1/3})^c @ e - \gamma$ collider

Bench-mark points	$\sqrt{s}$ in TeV	Cut	Signal	Back-ground	Signi-ficance
BP3	2	$\lvert M_{lj} - M_{\phi}\rvert \leq 10$ GeV	280.8	1061.6	7.7
		cut1+$(-0.9) \leq \cos\theta_{\ell j} \leq 1$	199.8	391.5	8.2
	3	$\lvert M_{lj} - M_{\phi}\rvert \leq 10$ GeV	106.2	815.0	3.5
		cut1+$(-0.8) \leq \cos\theta_{\ell j} \leq 1$	101.6	254.7	5.4

Signal-background analysis for leptoquark $(S^{+1/3})^c$ with luminosity 100 fb^{-1} at e–γ collider

more

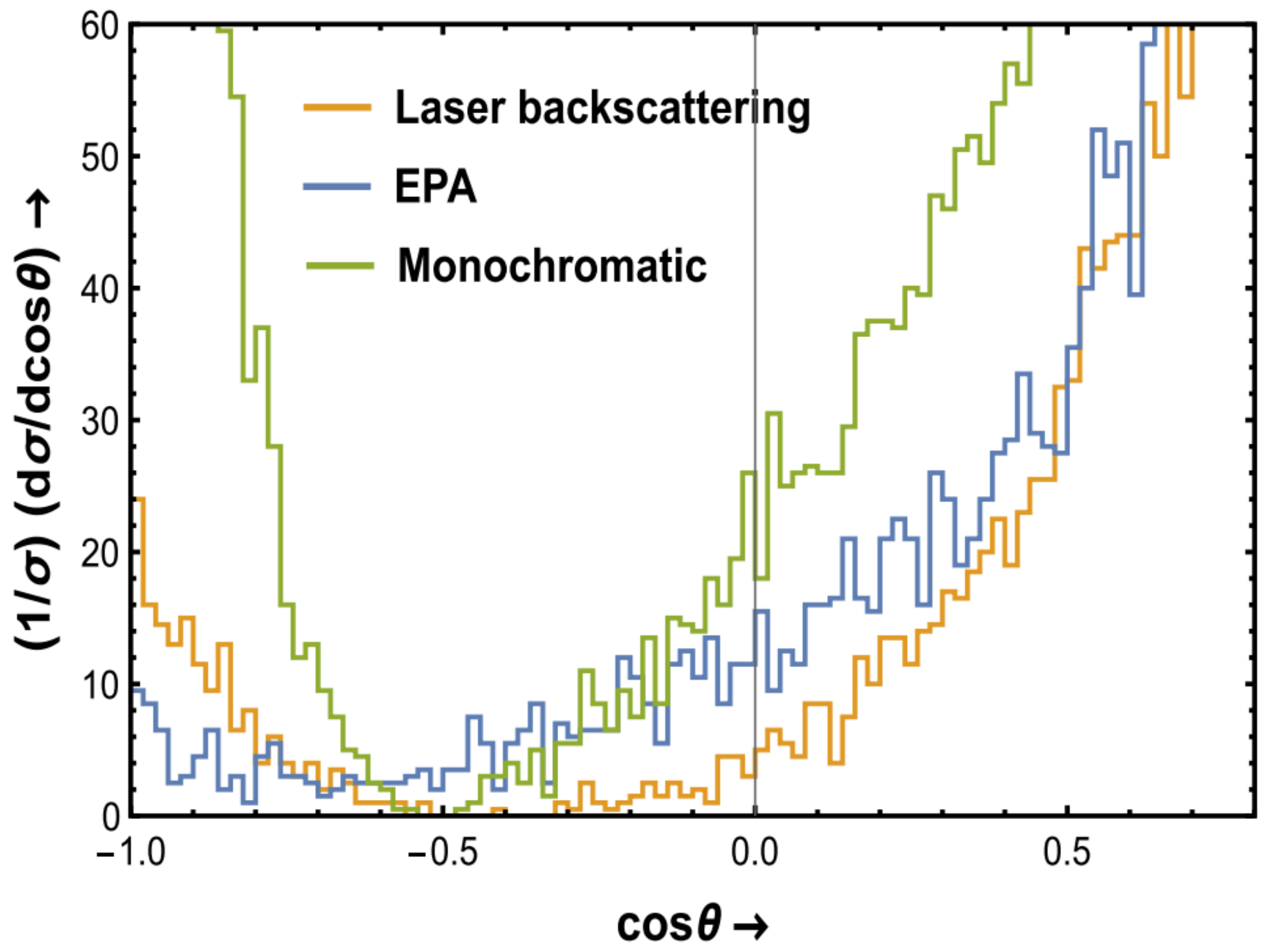
Effects of non-monochromatic photons

- The experimental collider technology cannot deal with monochromatic photons in the initial state at high energies
- There are two possible ways to produce them:

  a) Laser backscattering

  b) Equivalent photon approximation (EPA)

- In LB, the significance can be enhanced by 11-80%, but preserve the zeros, though little shifted.
- In EPA, the significance reduces by 27-90% and the zeros are smeared
- The effects on $(\tilde{V}_{2\mu}^{+1/3})^c$ are shown for three cases



More

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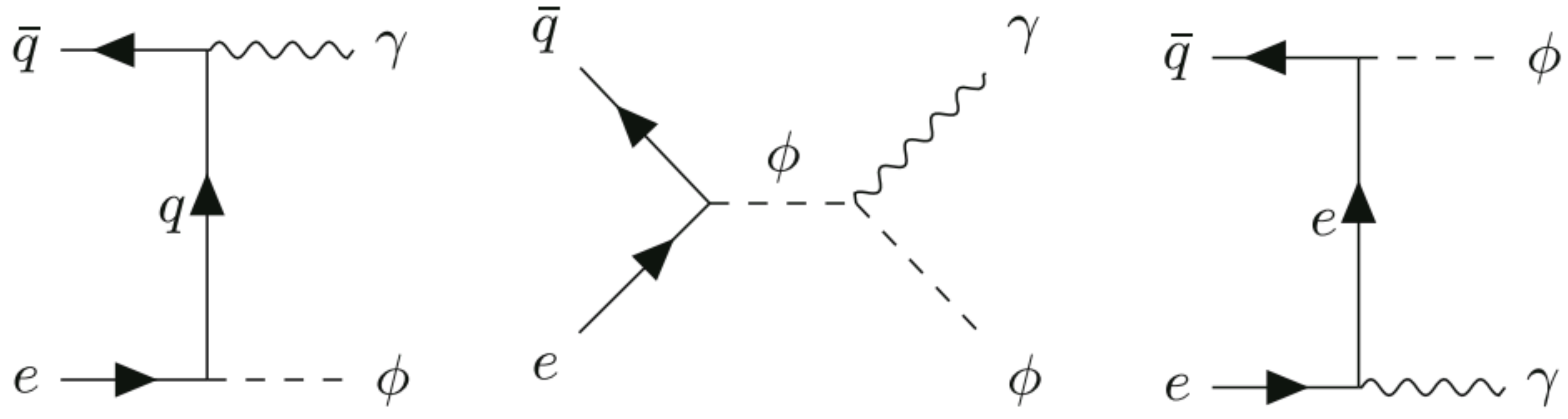
Electron-proton collider

Electron-proton collider

- In this case, the photon stays in the final state
- In the CM frame RAZ happens in the visible region for $\cos\theta^* = 1 + \frac{2}{Q_\phi}$ $\quad Q_\phi < -1.$



- Unlike $e-\gamma$, here the position of RAZ is independent of the mass of the final state particle as well as the centre of mass energy
- However, a complementarity is observed for the RAZ to be in the visible region as compared to the $e-\gamma$ collider
- The choice of μ, s in the final state, makes this SM background free

Positions of RAZs

Visible regions

ϕ	Y_ϕ	T_3	Q_ϕ	Production channel	$\cos\theta^*$
Scalar leptoquarks					
S_1	2/3	0	1/3	$e^- u \to \gamma\left(S_1^{+1/3}\right)^c$	–
$\widetilde{S}_1$	8/3	0	4/3	$e^- d \to \gamma\left(\widetilde{S}_1^{+4/3}\right)^c$	−1/2
R_2	7/3	1/2	5/3	$e^- \bar{u} \to \gamma\left(R_2^{+5/3}\right)^c$	−1/5
		−1/2	2/3	$e^- \bar{d} \to \gamma\left(R_2^{+2/3}\right)^c$	–
$\widetilde{R}_2$	1/3	1/2	2/3	$e^- \bar{d} \to \gamma\left(\widetilde{R}_2^{+2/3}\right)^c$	–
		−1/2	−1/3	–	–
S_3	2/3	1	4/3	$e^- d \to \gamma\left(S_3^{+4/3}\right)^c$	−1/2
		0	1/3	$e^- u \to \gamma\left(S_3^{+1/3}\right)^c$	–
		−1	−2/3	–	–

ϕ	Y_ϕ	T_3	Q_ϕ	Production channel	$\cos\theta^*$
Vector Leptoquarks					
$U_{1\mu}$	4/3	0	2/3	$e^- \bar{d} \to \gamma\left(U_{1\mu}^{+2/3}\right)^c$	–
$\widetilde{U}_{1\mu}$	10/3	0	5/3	$e^- \bar{u} \to \gamma\left(\widetilde{U}_{1\mu}^{+5/3}\right)^c$	−1/5
$V_{2\mu}$	5/3	1/2	4/3	$e^- d \to \gamma\left(V_{2\mu}^{+4/3}\right)^c$	−1/2
		−1/2	1/3	$e^- u \to \gamma\left(V_{2\mu}^{+1/3}\right)^c$	–
$\widetilde{V}_{2\mu}$	−1/3	1/2	1/3	$e^- u \to \gamma\left(\widetilde{V}_{2\mu}^{+1/3}\right)^c$	–
		−1/2	−2/3	–	–
$U_{3\mu}$	4/3	1	5/3	$e^- \bar{u} \to \gamma\left(U_{3\mu}^{+5/3}\right)^c$	−1/5
		0	2/3	$e^- \bar{d} \to \gamma\left(U_{3\mu}^{+2/3}\right)^c$	–
		−1	−1/3	–	–

More

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Different e-p colliders

- We chose four benchmark points with $M_\phi = 70, 900, 1500, 2000\,\text{GeV}$ for HERA, LHeC, FCC I, FCC II as BP1, BP2, BP3 and BP4 respectively

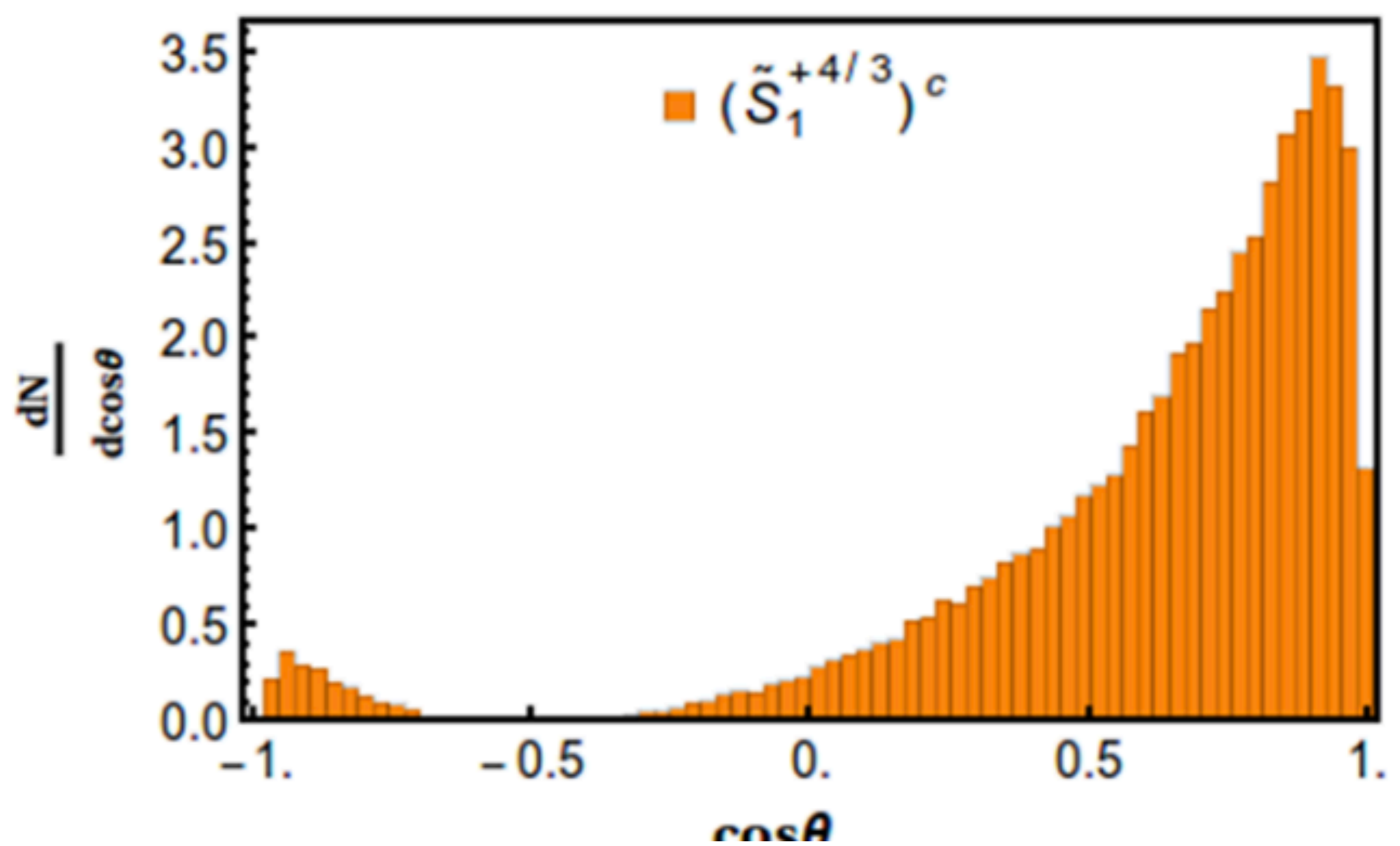
	E_p	E_{e^-}	$\sqrt{s}$	$\mathcal{L}_{int}$	$\mathcal{L}_{int}^{\text{projected}}$
HERA	920 GeV	27.5 GeV	318.1 GeV	400 pb^{-1}	100 fb^{-1}
LHeC	7 TeV	50 GeV	1.2 TeV		2000

	Stage	E_p (in TeV)	E_e (in GeV)	$\sqrt{s}$ (in GeV)	$\mathcal{L}_{int}^{\text{projected}}$ (in fb^{-1})
FCC	I	20	60	2190.2	2000
	II	50	60	3464.1	2000

An example: Scalar Leptoquark $(\tilde{S}_1^{+\frac{4}{3}})^c$

- The RAZ for $(\tilde{S}_1^{+\frac{4}{3}})^c$ is at $\cos\theta^* = -0.5$
- The decay $(\tilde{S}_1^{+\frac{4}{3}})^c$ in to $\mu\, s$ makes the final state SM background free

$$e\, p \to (\widetilde{S}_1^{+4/3})^c\, \gamma \to \mu\, s\, \gamma$$



- Numbers at HERA is promising

HERA

Cuts	Signal$(\widetilde{S}_1^{+4/3})^c$	Background
$\mathcal{B}(\widetilde{S}_1^c \to \mu\, s)$: BP1		
$\geqslant 1\mu + 1j + 1\gamma$	326.7	0.0
$\lvert M_{lj} - M_{\widetilde{S}_1}\rvert \leq 10$ GeV	267.9	0.0
$+1\gamma_{(p_T>20\mathrm{GeV})}$	263.5	0.0

- For LHeC, FCC I, II at 2000fb^{-1} for BP2, BP3 and BP4, the event numbers are still healthy

More

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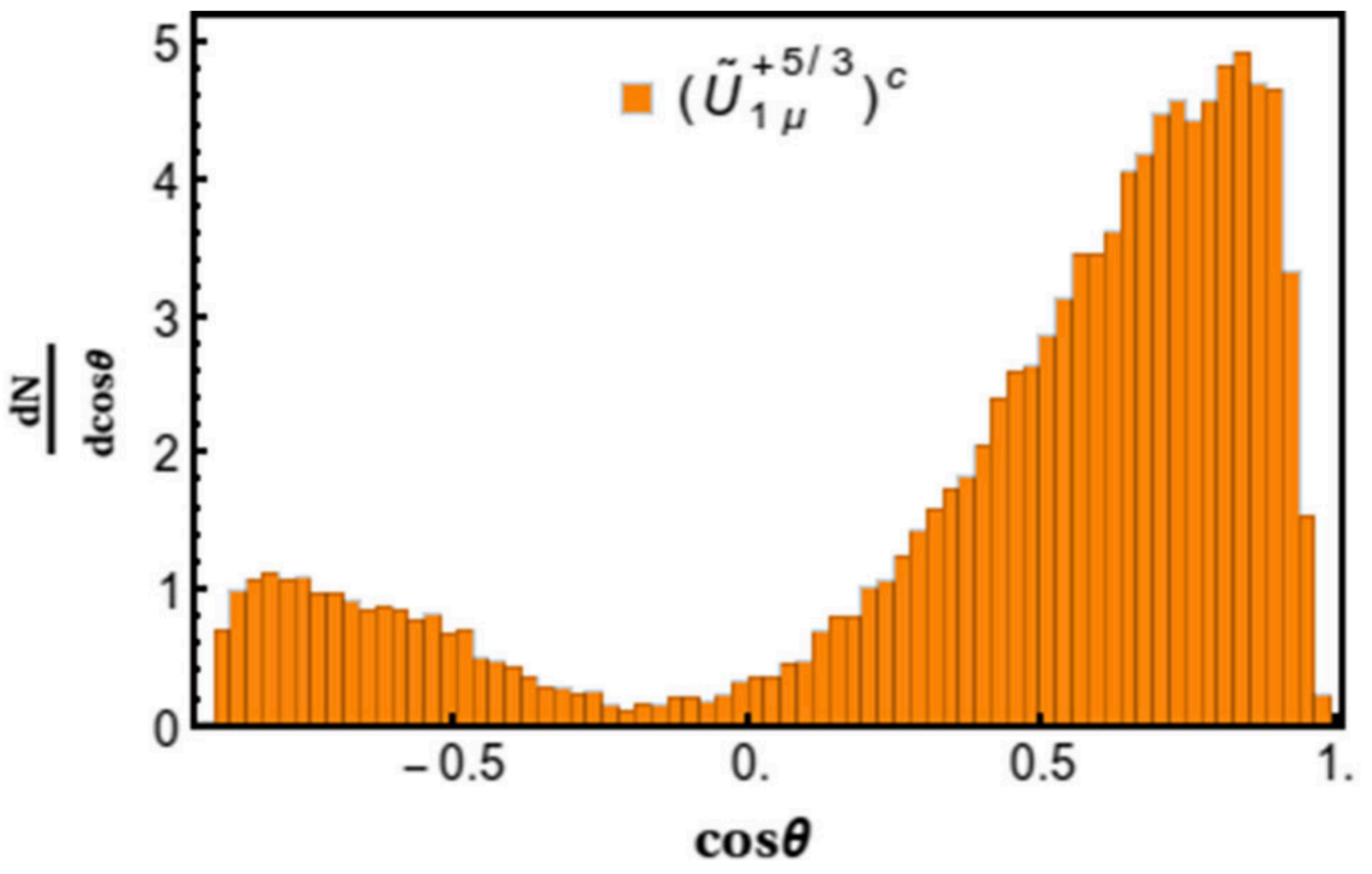
Another example: Vector Leptoquarks $(\widetilde{U}_{1\mu}^{+5/3})^c$

- It shows RAZ at $\cos\theta^* = -0.2$

- Focusing of the decay mode of $\mu\, c$ makes the final state background free $e\, p \to (\widetilde{U}_{1\mu}^{+5/3})^c\, \gamma \to \mu\, \bar{c}\, \gamma.$

- At HERA the numbers looks promising



Cuts	Signal$(\widetilde{U}_1^{+5/3})^c$	Background
$\mathcal{B}(\widetilde{U}_{1\mu}^c \to \mu^-\, \bar{c})$: BP1		
$\geqslant 1\mu + 1j + 1\gamma$	74.8	0.0
$\lvert M_{lj} - M_{\widetilde{U}_{1\mu}}\rvert \leq 10$ GeV	54.9	0.0
$+1\gamma_{(p_T > 20\text{ GeV})}$	54.2	0.0

- For BP2, BP3, BP4, the event numbers at LHeC, FCC I, II remains at the same order with 2000 fb^{-1}

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Leptoquarks with multiple components: Scalar triplet $S_3\,(\bar{\mathbf{3}}, \mathbf{3}, \frac{2}{3})$

$$-\mathfrak{L} \supset Y_L\, \bar{Q}_L^c \left(i\sigma^2\, S_3^{adj}\right) L_L + h.c.,$$

$$\text{where, } S_3^{adj} = \begin{pmatrix} \frac{S_3^{+1/3}}{\sqrt{2}} & S_3^{+4/3} \\ S_3^{-2/3} & -\frac{S_3^{+1/3}}{\sqrt{2}} \end{pmatrix}$$

$$e\,p \to (S_3^{+4/3})^c\,\gamma \to \mu\, s\, \gamma,$$
$$e\,p \to (S_3^{+1/3})^c\,\gamma \to \mu\, c\, \gamma.$$

ϕ	Y_ϕ	T_3	Q_ϕ	Production channel	$\cos\theta^*$
S_3	$2/3$	1	$4/3$	$e^- d \to \gamma \left(S_3^{+4/3}\right)^c$	$-1/2$
		0	$1/3$	$e^- u \to \gamma \left(S_3^{+1/3}\right)^c$	–
		-1	$-2/3$	–	–

RAZ

No production

No RAZs

Cuts	Signal $(S_3^{+4/3})^c$	SM + $(S_3^{+1/3})^c$
$\mathcal{B}(S_3^c \to \mu\, s/c)$: BP1		
$\geqslant 1\mu + 1j + 1\gamma$	328.5	520.2
$\lvert M_{\ell j} - M_{S_3}\rvert \leq 10\,\text{GeV}$ $+1\gamma_{p_T>20\text{GeV}}$	263.3	359.6
$Q_{Jet} < 0.0$	180.5	104.9
$\sigma_{Sig}(\mathcal{L}_{int} = 100\ \text{fb}^{-1})$	10.7	
$\sigma_{Sig}(\mathcal{L}_{int} = 400\ \text{pb}^{-1})$	0.67	
$\mathcal{L}_{5\sigma}(\text{ in fb}^{-1})$	21.8	

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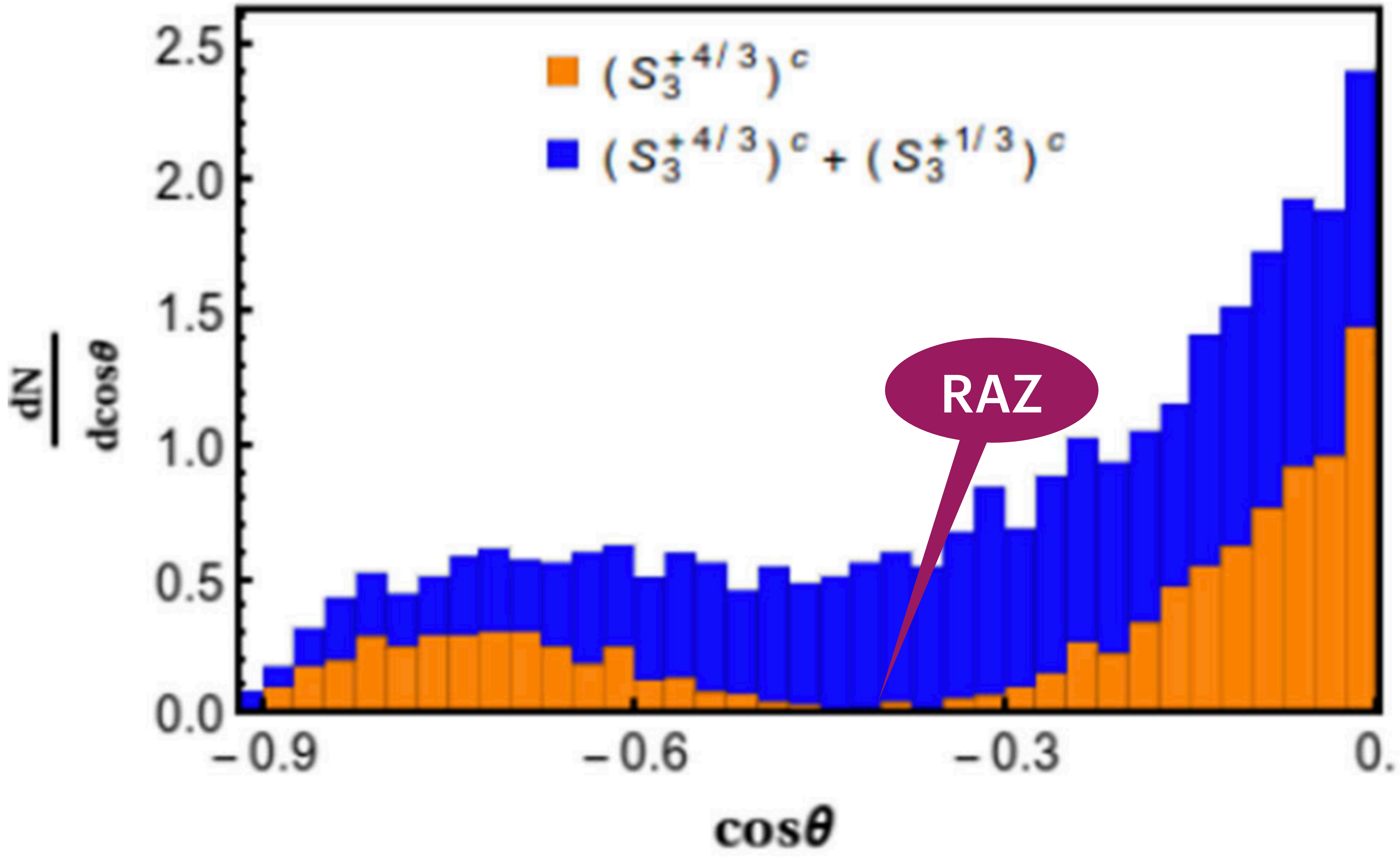


(c) Combined

Conclusions

- Leptoquarks models can enhance the stability of the electroweak vacuum
- However, constrained by the perturbative unitarity
- It can generate Majorana neutrino mass and explain muon-(g-2)
- Single Leptoquark at the LHC and pair production at Muon collider can probe the Leptoquark Yukawa
- Angular distributions can decode spin and gauge representation of different Leptoquarks
- RAZ can be crucial in a scattering involving photon and Leptoquarks
- $e-\gamma$ and $e-p$ colliders can be complementary in investigating RAZs
- Spin of Leptoquarks can be unraveled via the angular distributions in CM frame
- For LHC, construction of CM frame needs, fully visible final sates.
- Leptonic colliders have advantage over hadronic colliders in reconstructing the CM frame as well as measuring Yukawa coupling


THANK
YOU!

Backups

Stability bounds

- Higgs couples to fermions via Yukawa couplings $\mathcal{L}_Y = Y_t \bar{Q} \phi t_R$
- At low field values the top quark contribution is important $\mu \frac{d\lambda}{d\mu} \simeq -\frac{3}{8\pi^2} Y_t^4$
- The solution takes a form, $\lambda(\mu) = \lambda - \frac{3}{8\pi^2} \lambda_t^4 \ln \frac{\mu}{v}$, where at some point we hit $\lambda(\mu) < 0$, leading instability to Higgs potential

$$m_h^2 > \frac{3 m_t^2}{\pi^2 v^2} \ln \frac{\Lambda}{v}$$

- In the Coleman-Weinberg's effective potential approach the RG-improved potential can be written as

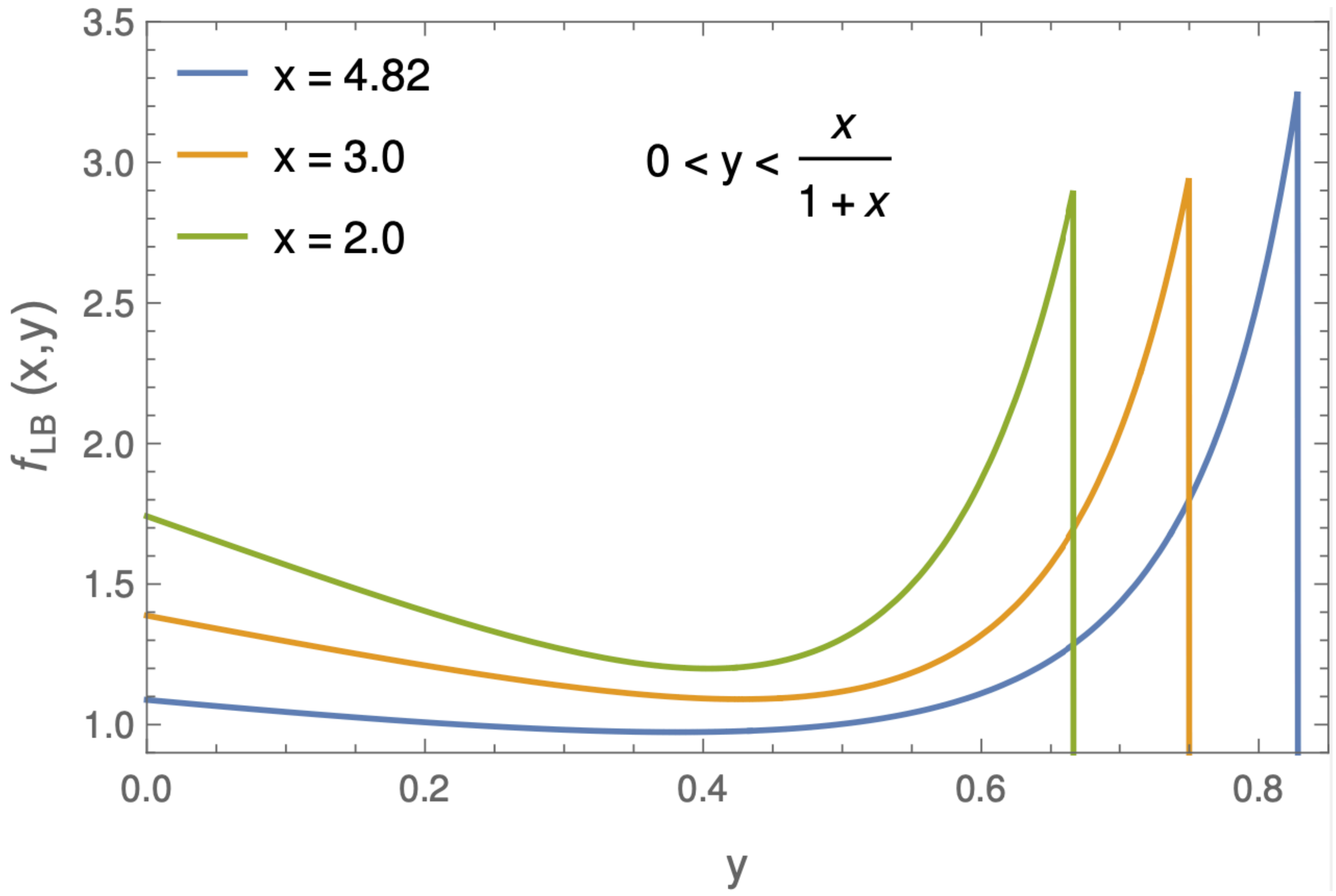
$$V_{\text{eff}}(h,\mu) \simeq \lambda_{\text{eff}}(h,\mu) \frac{h^4}{4}, \quad \text{with } h \gg v\,,$$

- Where λ_{eff} assimilates the loop effects

$$\lambda_{\text{eff}}(h,\mu) \simeq \underbrace{\lambda_h(\mu)}_{\text{tree-level}} + \underbrace{\frac{1}{16\pi^2} \sum_{\substack{i=W^\pm,Z,t,\\ h,G^\pm,G^0}} n_i \kappa_i^2 \left[\log \frac{\kappa_i h^2}{\mu^2} - c_i\right]}_{\text{Contribution from SM}}$$

Non-monochromatic photon: LBA, EPA

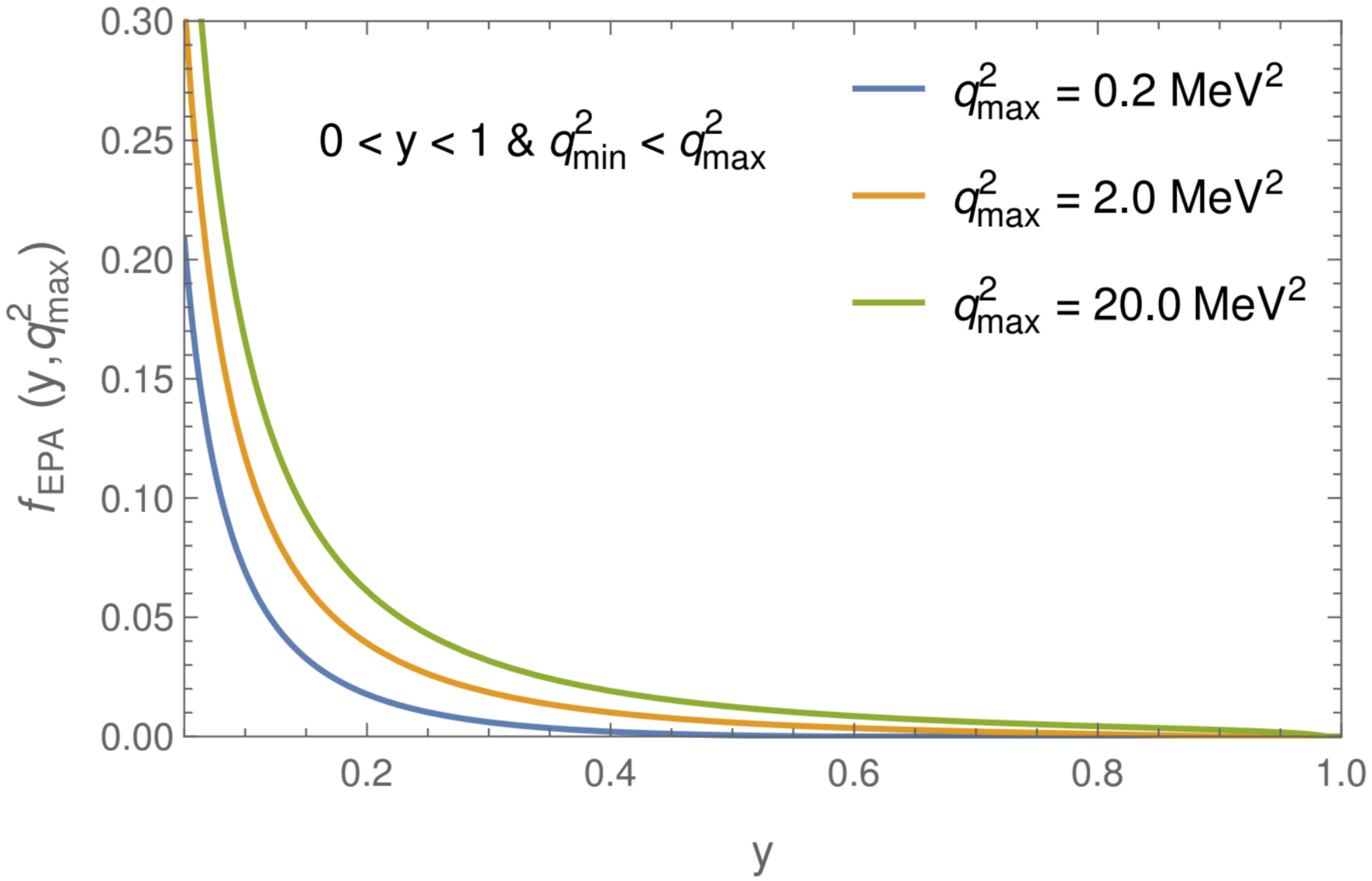
Laser back scattering



$$\frac{1}{\sigma_c}\frac{d\sigma_c}{dy} = f(x, y) = \frac{2\sigma_0}{x\,\sigma_c}\left[1 - y + \frac{1}{1-y} - \frac{4y}{x(1-y)} + \frac{4y^2}{x^2(1-y)^2}\right]$$

for $0 < y < y_{max}$

Equivalent photon approximation



$$f(y, q^2_{max}) = \frac{\alpha}{\pi}\left[\left(\frac{1}{y} - 1 + \frac{y}{2}\right)\ln\left(\frac{q^2_{max}}{q^2_{min}}\right) + \left(1 - \frac{1}{y}\right)\left(1 - \frac{q^2_{min}}{q^2_{max}}\right)\right]$$

for $0 < y < 1$

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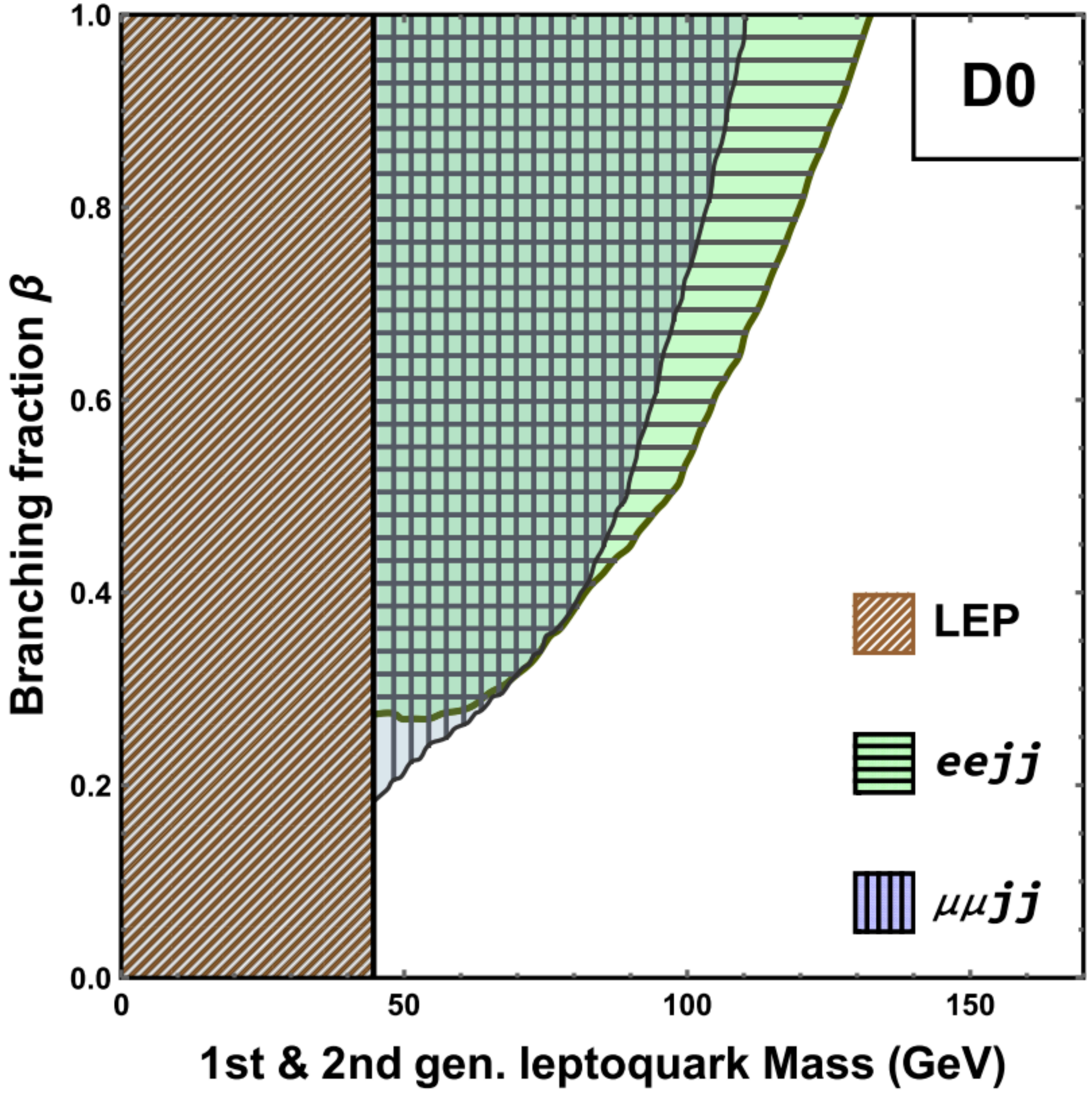
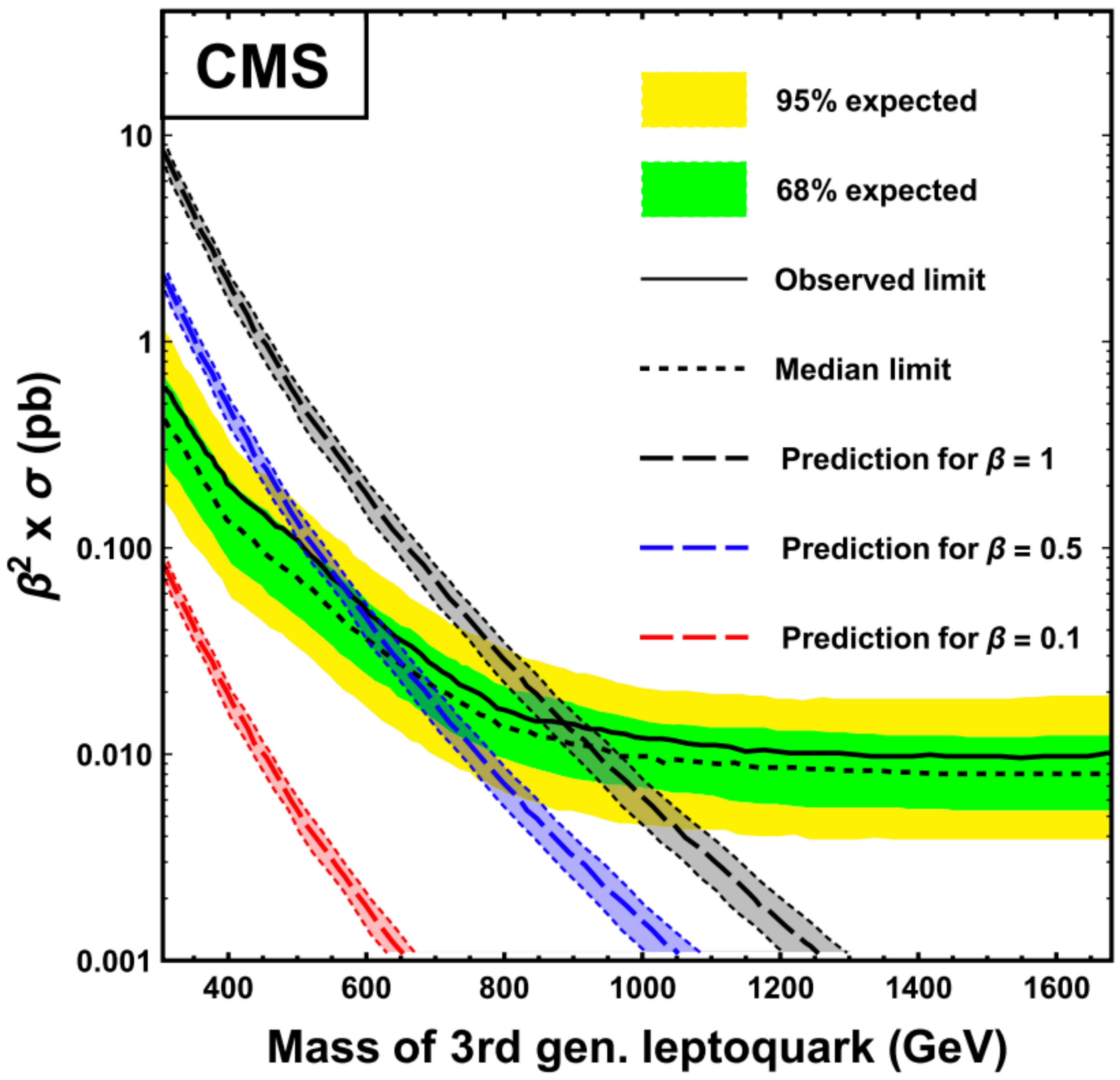
Benchmarking Leptoquark masses





- A light leptoquark can still be possibility

Setup for collider analysis

- A PYTHIA8 based simulation was performed
- Models were implemented in SARAH and events were generated via CalcHEP
- Fastjet with CA algorithm with $R = 0.5$ was used
- Minimum transeverse momentum of each jet: $p_{T,\min}^{\text{jet}} = 20$ GeV
- Leptons($\ell = e, \mu$) are selected with $p_{T,\min}^{\ell} = 10$ GeV
- Jet-lepton isolation: $\Delta R_{j\ell} > 0.4$ and lepton-lepton isolation: $\Delta R_{\ell\ell} > 0.2$ are demanded
- $p_{T,\min}^{\gamma} \geq 10\text{GeV},\ \Delta\text{R}_{\gamma\ell} = \Delta\text{R}_{\gamma\text{j}} > 0.2$ chosen for the final state with photons

Loop Majorana Mass

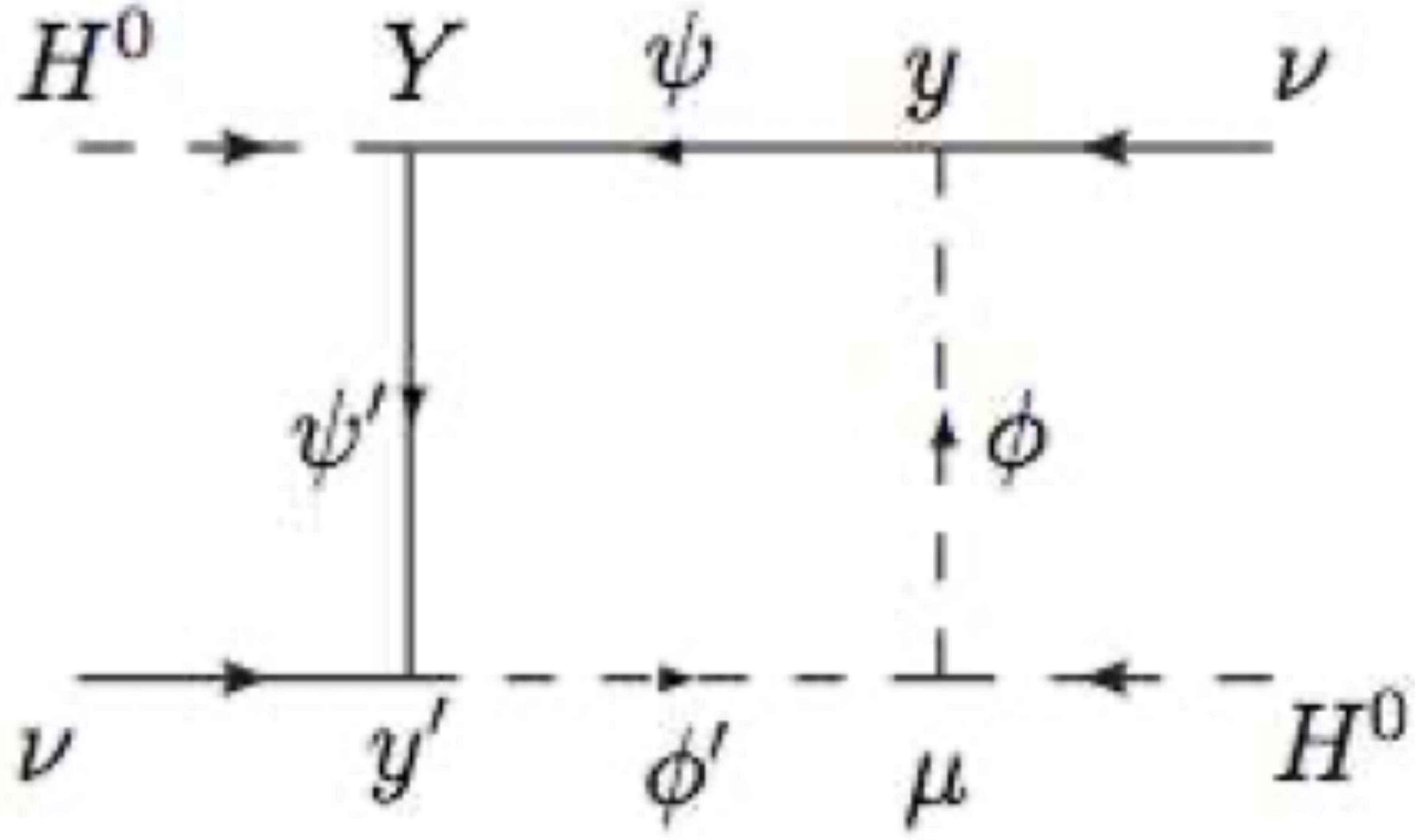
- $\tilde{R}_2(3,2,1/6)$, $S_3(3,3,1/3)$, and $\tilde{R}_2 + S_3$

$$\mathscr{L}_2 \supset (D^\mu \widetilde{R}_2)^\dagger (D_\mu \widetilde{R}_2) - (m_2^2 + \lambda_2 H^\dagger H)(\widetilde{R}_2^\dagger \widetilde{R}_2) - \widetilde{\lambda}_2 H^\dagger \widetilde{R}_2\, \widetilde{R}_2^\dagger H - [Y_2\, \overline{d}_R\, (\widetilde{R}_2^T i\sigma_2)\, \boldsymbol{L}_L + h.c.]\ ,$$

$$\mathscr{L}_3 \supset \mathrm{Tr}[(D^\mu S_3^{ad})^\dagger (D_\mu S_3^{ad})] - \widetilde{\lambda}_3\, H^\dagger S_3^{ad}\, (S_3^{ad})^\dagger H - (m_3^2 + \lambda_3\, H^\dagger H)\, \mathrm{Tr}[(S_3^{ad})^\dagger\, S_3^{ad}] + [Y_3\, \overline{\boldsymbol{Q}}{}_L^c\, (i\sigma_2\, S_3^{ad})\, \boldsymbol{L}_L + h.c.]\ ,$$

$$\mathscr{L}_{23} = \mathscr{L}_2 + \mathscr{L}_3 - [\kappa_h H^\dagger S_3^{ad} \widetilde{R}_2 + h.c.]$$

Loop Majorana mass generation



ψ	ϕ	ϕ'	ψ'
2^F_α	$3^S_{1+\alpha}$	2^S_α	$1^F_{1+\alpha}$

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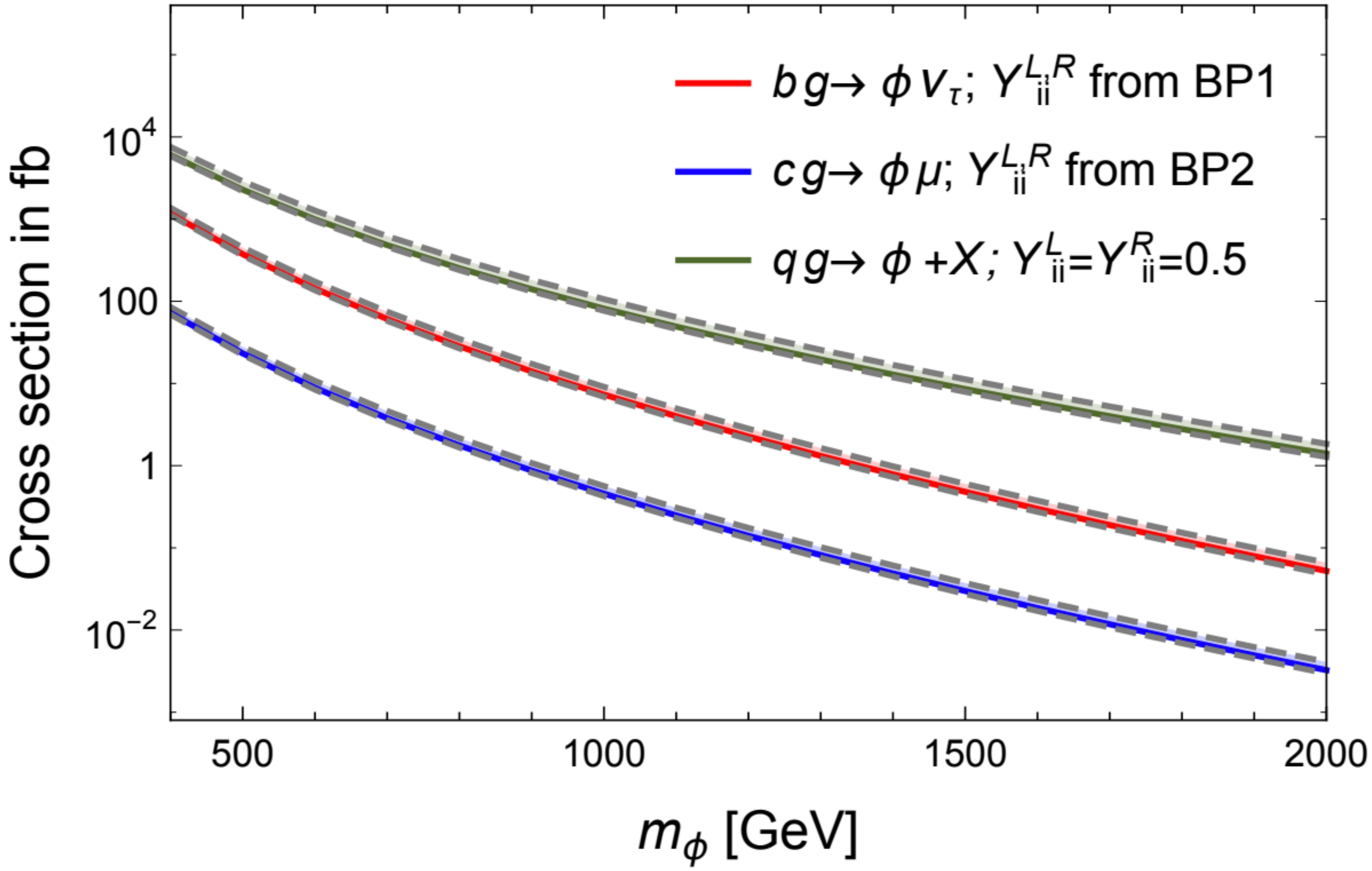
Single ϕ production at the LHC

- Quark gluon fusion can give rise to single Leptoquarks productions
- They depend on the Yukawa couplings
- Bounds can be drawn to these Leptoquark

Yukawa via single production



For an updated study at the LHC and muon collider, please look into Snehashis' talk (EPJC 82(2022) 10, 916)

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$$\text{Laboratory} \leftrightarrow \text{Rest Frame of Interaction}: \begin{cases} p_{3x} = p_{3x}^{CM} & p_{4x} = p_{4x}^{CM} \\ p_{3y} = p_{3y}^{CM} & p_{4y} = p_{4y}^{CM} \\ p_{3z}^{CM} = -p_{4z}^{CM} \end{cases}$$

$$\begin{aligned} p_{3z} &= \gamma(p_{3z}^{CM} - \beta E_3^{CM}), & p_{4z} &= \gamma(p_{4z}^{CM} - \beta E_4^{CM}), \\ E_3 &= \gamma(E_3^{CM} - \beta p_{3z}^{CM}), & E_4 &= \gamma(E_4^{CM} - \beta p_{4z}^{CM}). \end{aligned}$$

Therefore we have,

$$\begin{aligned} \frac{p_{3z} - p_{4z}}{2\gamma} &= p_{3z}^{CM} \\ \frac{E_3 + E_4}{2\gamma} &= E_3^{CM}, \end{aligned}$$

where

$$\beta = \frac{E_3 - E_4}{p_{3z} - p_{4z}} = \frac{(E_3)^2 - (E_4)^2}{(p_{4z} - p_{3z})(E_3 + E_4)} = -\frac{p_{3z} + p_{4z}}{E_3 + E_4}; \qquad |\beta| < 1,$$

and $\gamma = \frac{1}{\sqrt{1-\beta^2}}$. We can calculate the energy of the finalstate particles by

$$\begin{aligned} E_3 &= \left((p_{3x})^2 + (p_{3y})^2 + (p_{3z})^2 + (M_3)^2\right)^{\frac{1}{2}}, \\ E_4 &= \left((p_{4x})^2 + (p_{4y})^2 + (p_{4z})^2 + (M_4)^2\right)^{\frac{1}{2}}. \end{aligned}$$

We need mass information for the energy and to calculate boost

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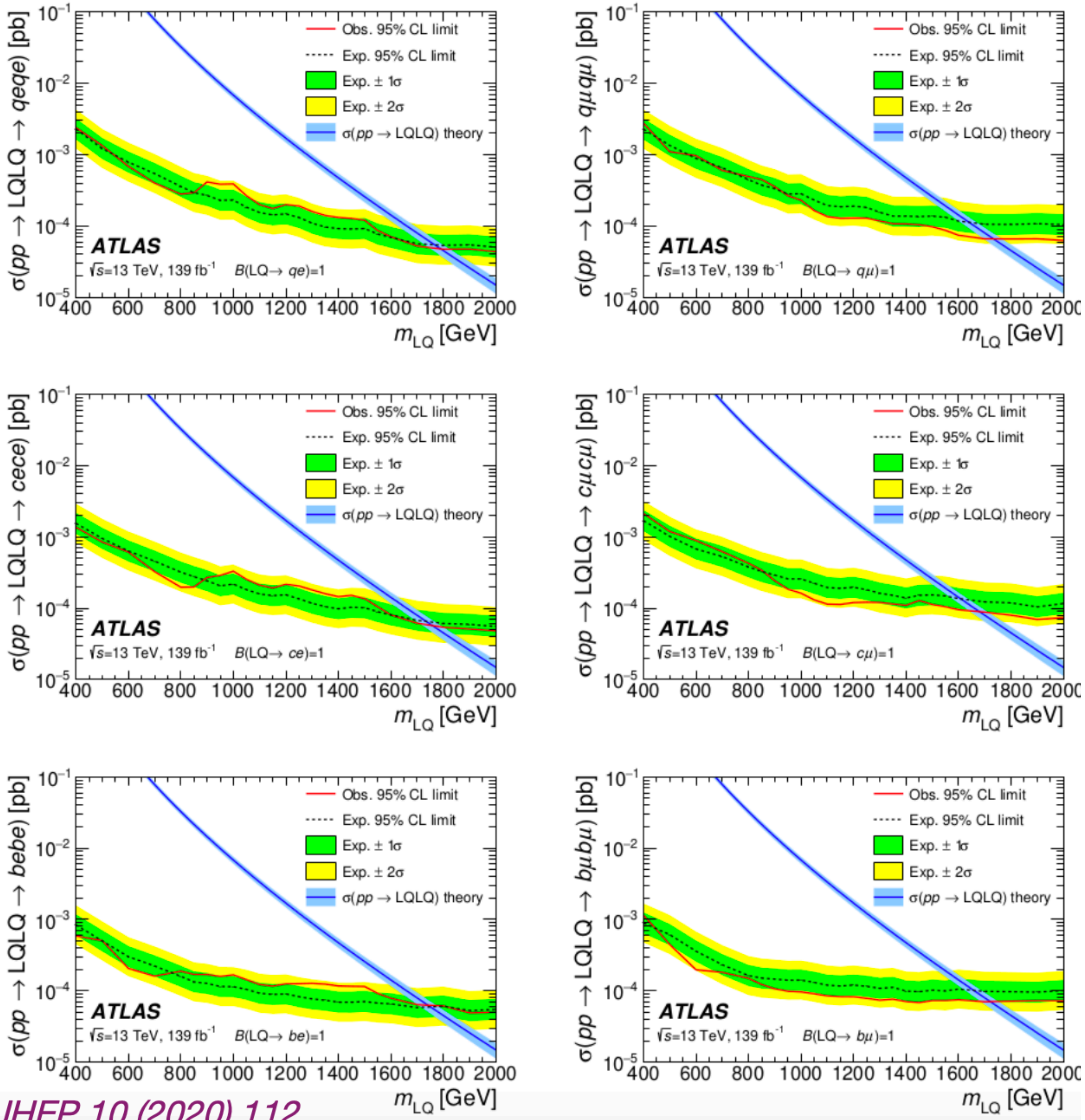
Current status: Pair production

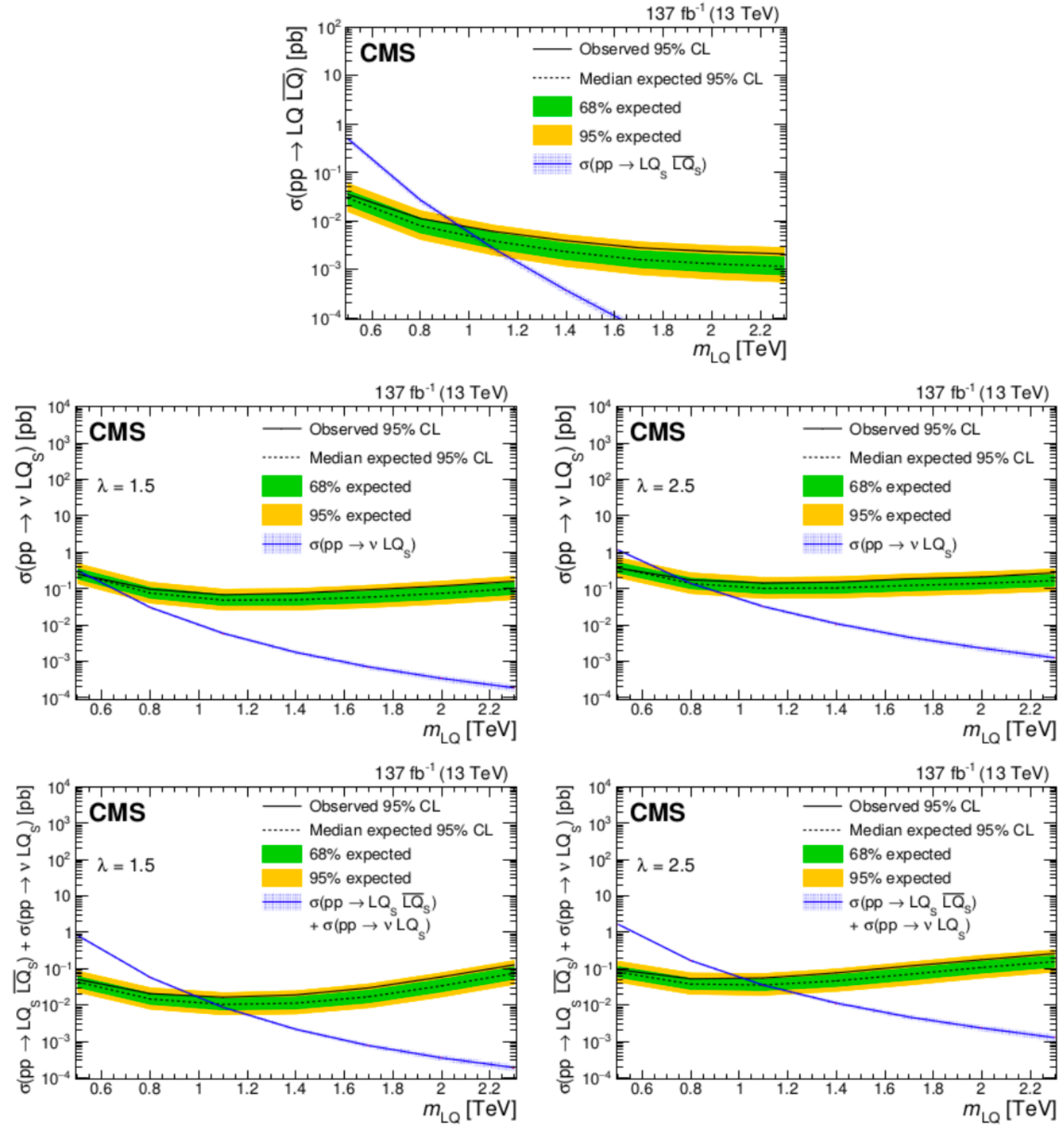
- Leptoquarks decay into a quark and a lepton, leading often to a 2-lepton + 2-jet final state if they are pair produced.
- Current LHC searches are for such symmetric final states from pair production.
- Assuming 100% BR to each channel, they exclude LQ with mass upto ~1.5 TeV.
- These bounds can be recast according to our models, adjusted with the BR. See e.g. A. Bhaskar et al, Phys.Rev.D 104 (2021) 3, 035016 Phys.Rev.D 106 (2022) 11, 11



ATLAS collaboration, *JHEP 10 (2020) 112*

Current status: Single production

- Single production of leptoquarks decaying into third-generation leptons and quarks.
- Motivated by the $B-$anomalies.
- Excludes LQ masses below ~1 TeV for third-generation decay modes.
- Leaves scope for cross-generation final state searches.

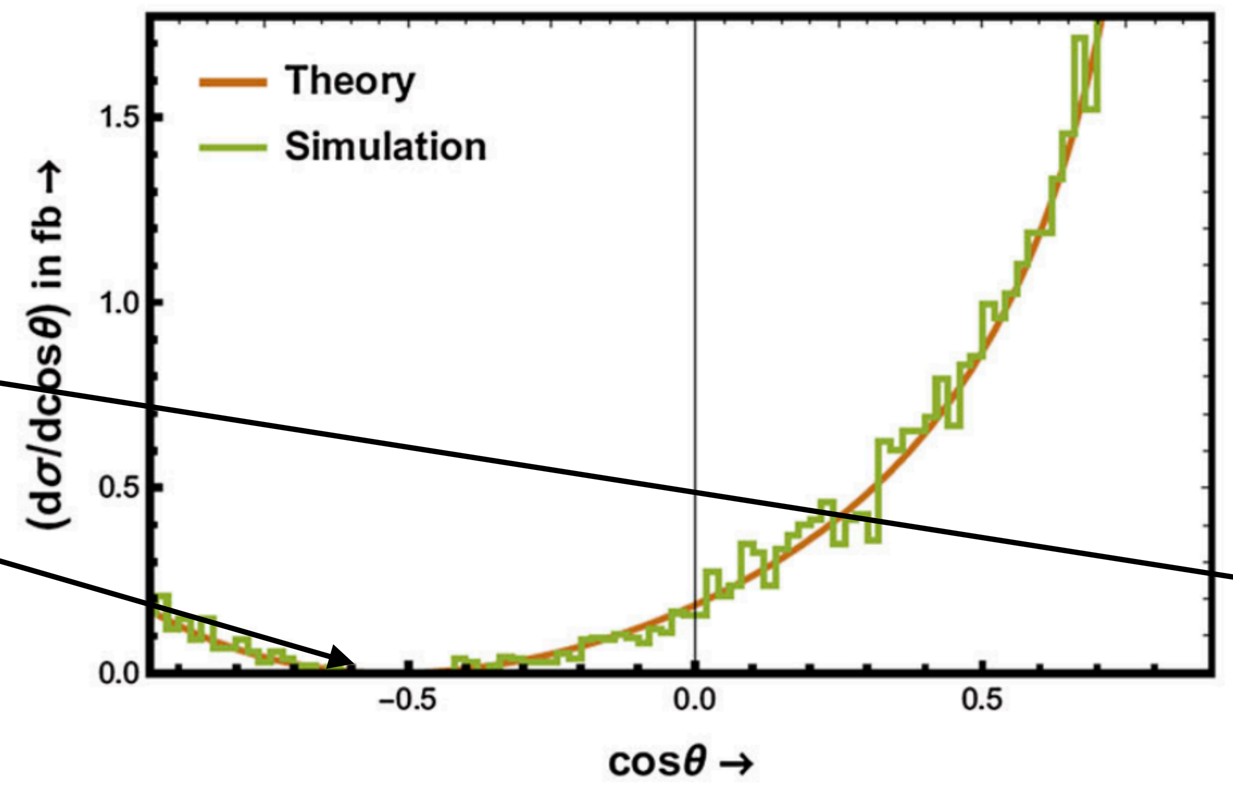


CMS collaboration,
Phys.Lett.B 819 (2021) 136446

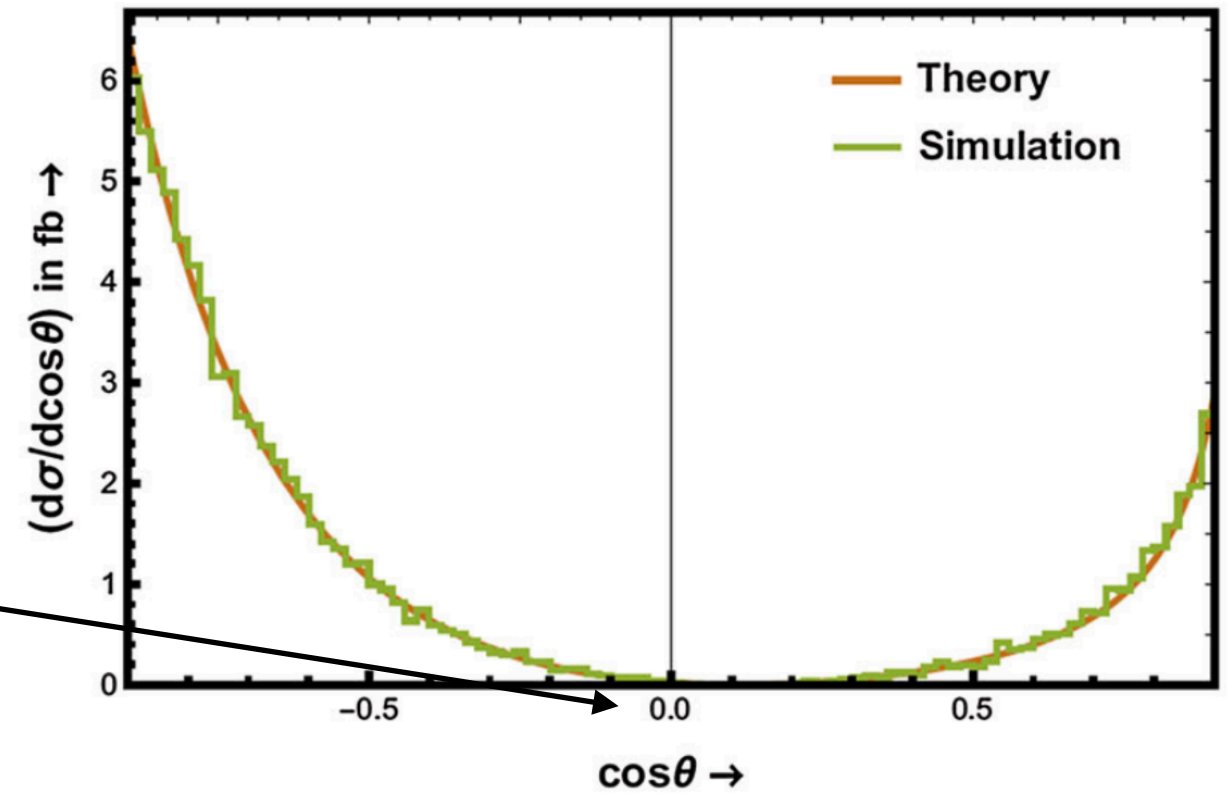
Another example: Vector Leptoquark $((U_\mu^{2/3})^c)$

- In this case, zeros can be found out

for Ecm=2, 3 TeV at $\cos\theta^* = -0.52, 0.11$



Ecm=2 TeV



Ecm=3 TeV

Bench-mark points	$\sqrt{s}$ in TeV	Cut	Signal	Back-ground	Signi-ficance
BP3	2	$\lvert M_{lj} - M_\phi \rvert \leq 10$ GeV	144.4	1061.6	4.2
		cut1+$(-0.9) \leq \cos\theta_{\ell j} \leq 1$	102.2	391.5	4.6
	3	$\lvert M_{lj} - M_\phi \rvert \leq 10$ GeV	63.9	815.0	2.2
		cut1+$(-0.8) \leq \cos\theta_{\ell j} \leq 1$	60.7	254.7	3.4

Signal-background analysis for $(U_{1\mu}^{+2/3})^c$ with luminosity 100 fb^{-1} at e–γ collider

- Singal significance is above 3σ at 100fb^{-1} luminosity

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Leptoquarks with multiple components: Doublet

- Other excitation can contaminate the desired ones

ϕ	Y_ϕ	T_3	Q_ϕ	Production channel	$\cos\theta^*$
R_2	$7/3$	$1/2$	$5/3$	$e^- \bar{u} \to \gamma \left(R_2^{+5/3}\right)^c$	$-1/5$
		$-1/2$	$2/3$	$e^- \bar{d} \to \gamma \left(R_2^{+2/3}\right)^c$	$-$

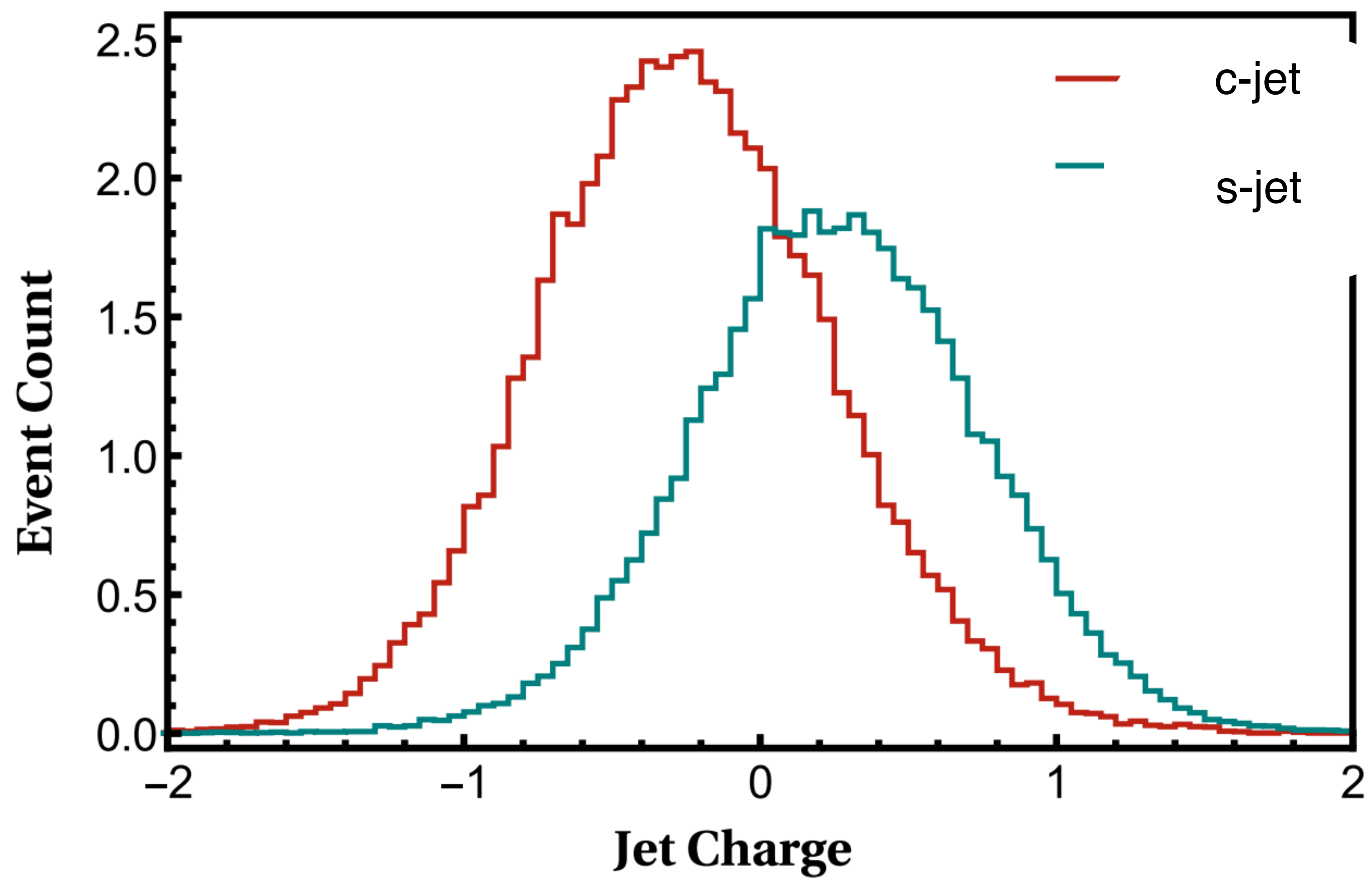
RAZ exists

No RAZ exists but can contaminate the other one

- Identifying the two components $R_2^{+5/3}, R_2^{+2/3}$ is important
- Their decay patters are different:

$$e\,\bar{u} \to (R_2^{+5/3})^c\,\gamma \to \mu\,\bar{c}\,\gamma,$$
$$e\,\bar{d} \to (R_2^{+2/3})^c\,\gamma \to \mu\,\bar{s}\,\gamma$$

- Determination of the charge of the jets (c/s) is instrumental in distinguishing these modes



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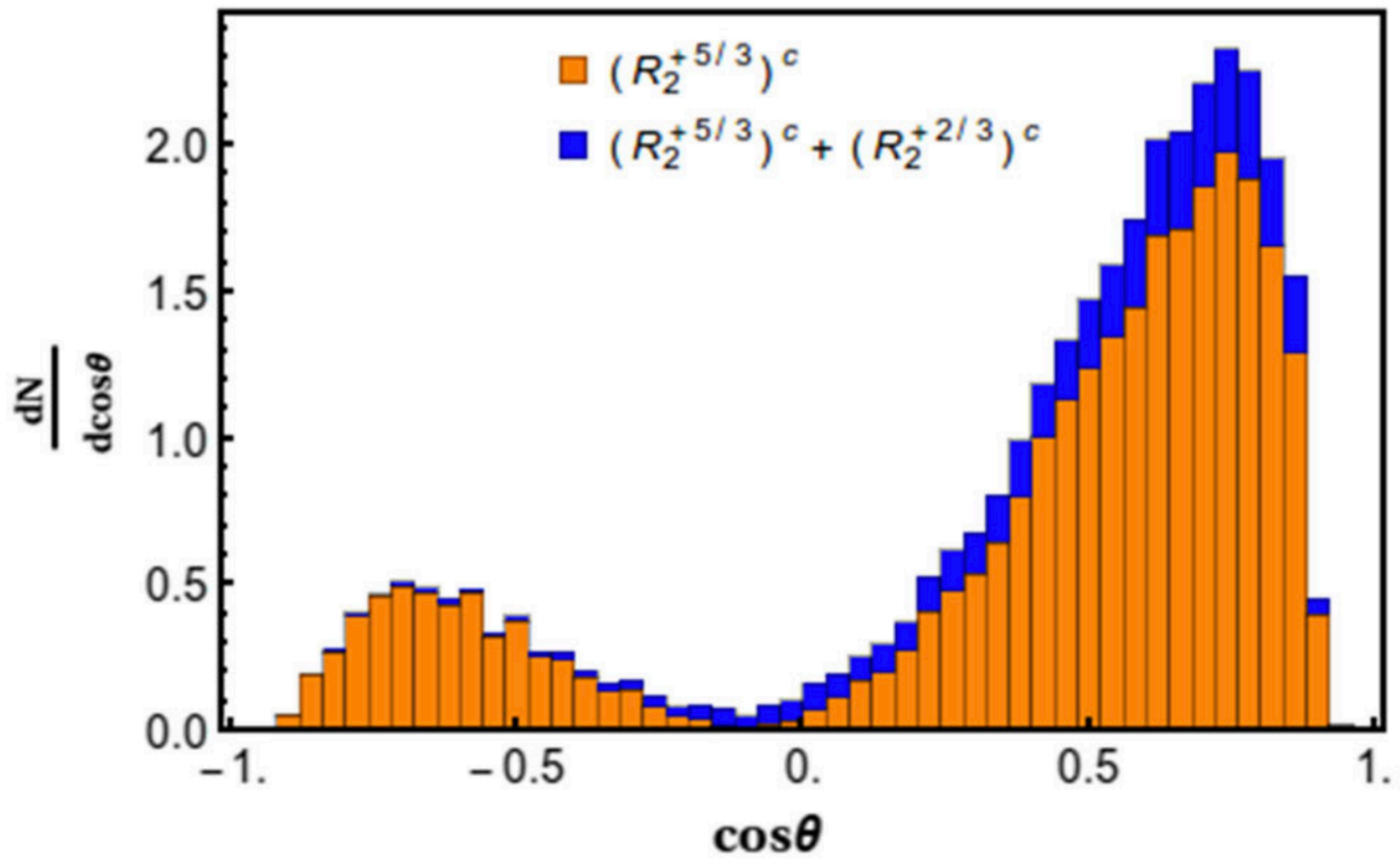
Leptoquarks with multiple components: Doublet

- The RAZ for $(R_2^{+5/3})^c$ is contaminated by $(R_2^{+2/3})^c$
- The model background has to be taken into consideration for the signal significance



@HERA

Cuts	Signal $(R_2^{+5/3})^c$	SM + $(R_2^{+2/3})^c$
$\mathcal{B}(R_2^c \to \mu\, \bar{c}/\bar{s})$: BP1		
$\geqslant 1\mu + 1j + 1\gamma$	77.2	58.5
$\lvert M_{\ell j} - M_{R_2}\rvert \leq 10$ GeV $+1\gamma_{p_T > 20\mathrm{GeV}}$	59.2	44.7
$Q_{Jet} < -0.3$	27.7	5.3
$\sigma_{Sig}(\mathcal{L}_{int} = 100\ \mathrm{fb}^{-1})$	4.8	
$\sigma_{Sig}(\mathcal{L}_{int} = 400\ \mathrm{pb}^{-1})$	0.3	
$\mathcal{L}_{5\sigma}$ (in fb^{-1})	108.5	

- For BP2, BP3 and BP4 at the LHeC, FCC I, II, the signal significances are 2.2, 2.9 and 6.1 σ, respectively at 2000 fb^{-1} of integrated luminosity
- Similar results can be obtained for other multi-component leptoquarks (triplet)

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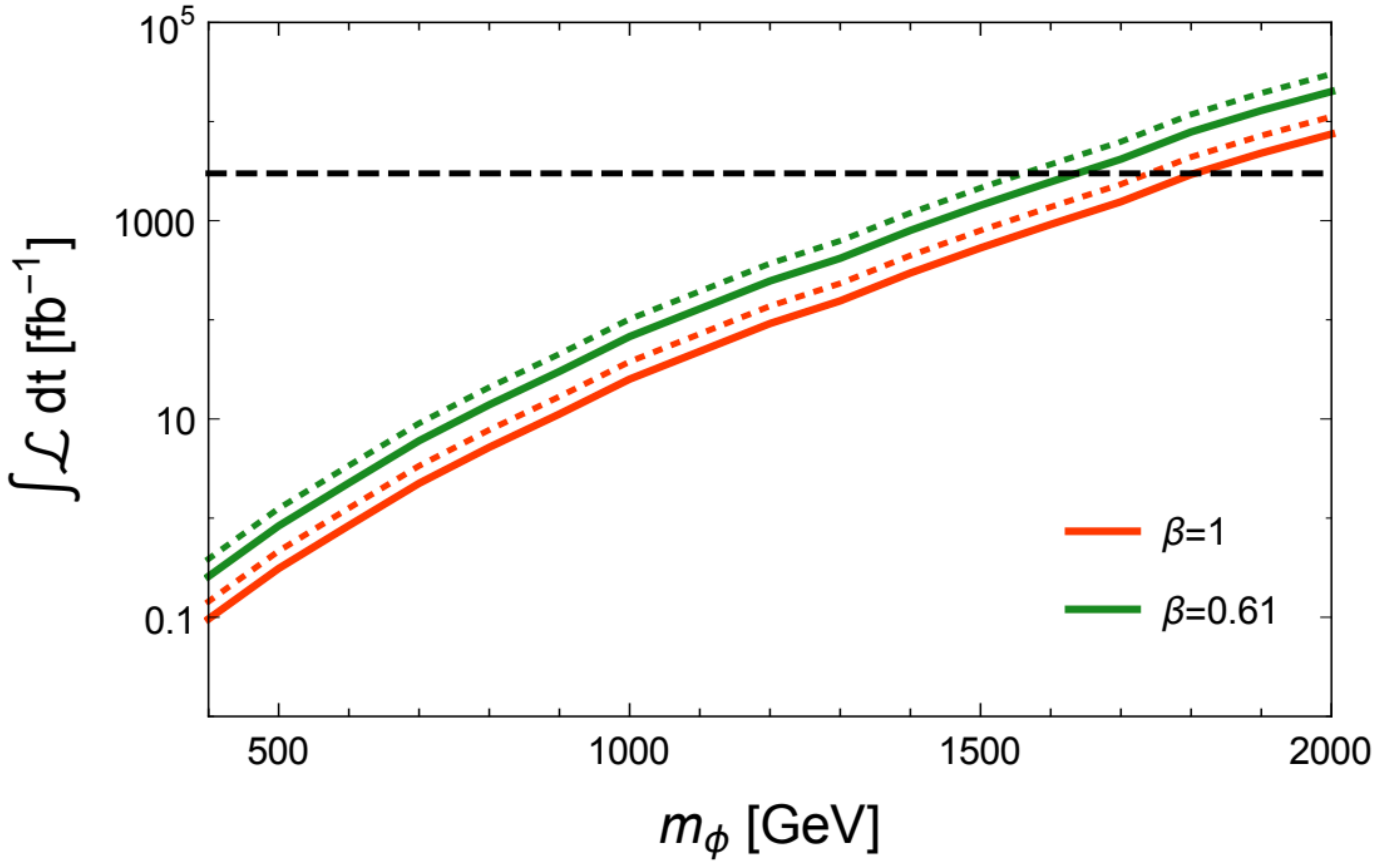
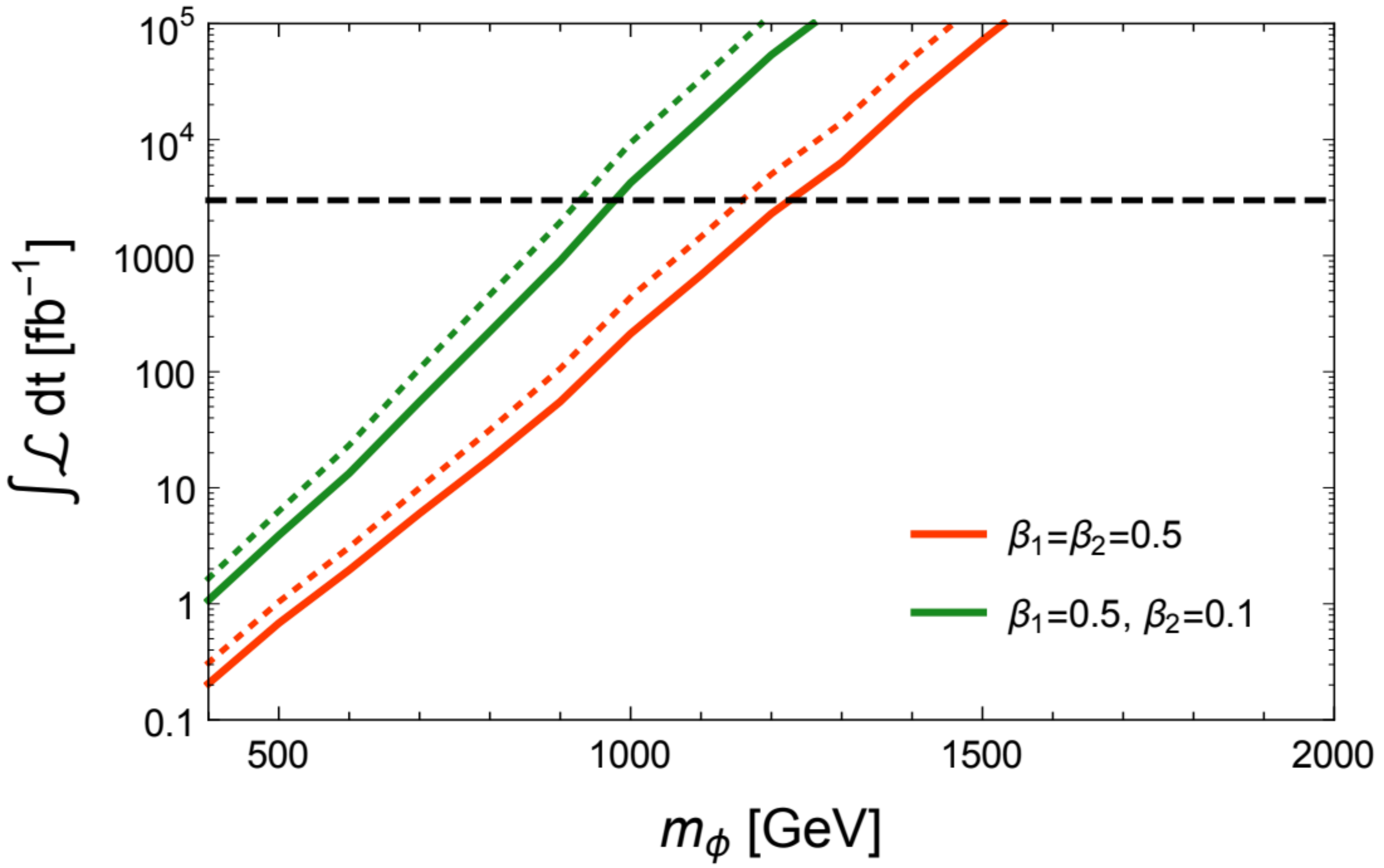
Pair production of $\phi(3,1,-1/3)$ at the LHC

- Most of the collider searches was based on first two generation decays

- We focused on the third generation decays with $\mathscr{B}_1 = \mathscr{B}(\phi \to \bar{t}, \tau^+)$





- A pair production with $2b + 2\tau + 4j$ final state can be sensitive to LHC reach for TeV mass scale Leptoquark

- Considering both thirdly and second generation decay with $\beta_2 = \mathscr{B}(\phi \to \bar{c}\mu^+)$, we also find the reach for $1b + 1\tau + 1\ell + 1\mu + 1j$ final state

For the phenomenology $\tilde{R}_2 + S_1$ at the LHC and their plausible mixings, please look into Snehashis' talk (PRD 106(2022) 9, 095040)

More

Snehashis Parashar, Avnish, PB, Kiritiman Ghosh:PRD 106 (2022) 9, 095040

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