Searching for Leptoquarks at Future Circular Colliders

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Outline

- Introduction
  - Leptoquark (LQ) Models and Motivations
  - Future Circular Collider
- Z-boson decay at 1-loop via LQs
- Hadron-Hadron Collider Searches for LQs
- Conclusion

Introduction to Leptoquarks

Leptoquarks

- Leptoquarks (LQ) are Beyond the Standard Model (BSM) boson particles carrying both baryon and lepton quantum numbers
- The spin of LQ are either 0 (scalar LQ) or 1 (vector LQ)
- LQ carry colour, electric charge and weak charges
- LQ appear in many BSM models (Grand Unification / Supersymmetry / Composite fermion models etc.…)

Minimal Leptoquark Model (MLQ)

- Each model has one LQ in a single $SU(3)_C \times SU(2)_L \times U(1)_Y$ representation, coupling to only one SM lepton-quark fermion. One generation of fermions fields Q, U^C, D^C, L, E^C and we allow right-handed neutrino N^C:

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad u_R^C \qquad d_R^C \qquad L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad e_R^C \qquad (\nu_R)$$

- Taking Scalar LQ to couple in the following way: $S(\boldsymbol{QL})$

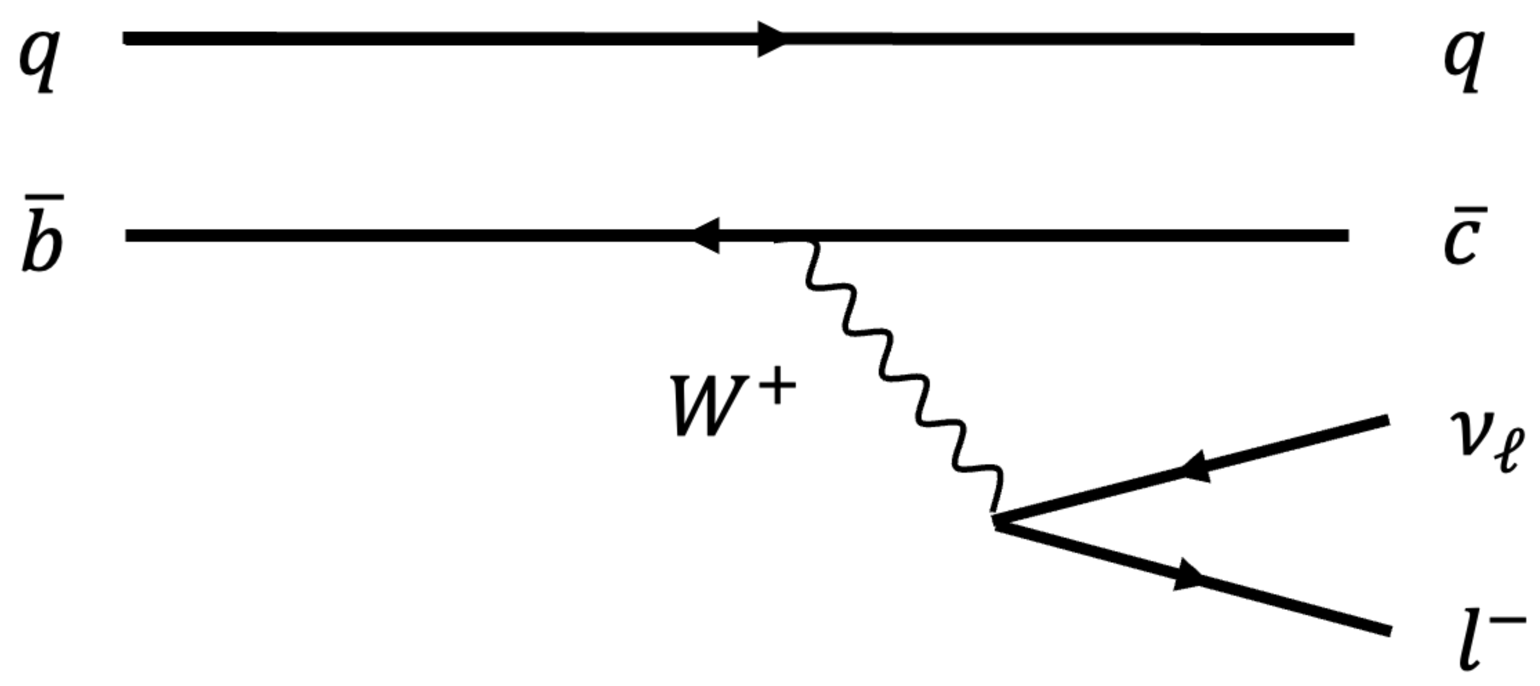
with $\boldsymbol{Q} \in Q, U^C, D^C$ and $\boldsymbol{L} \in L, E^C, N^C$

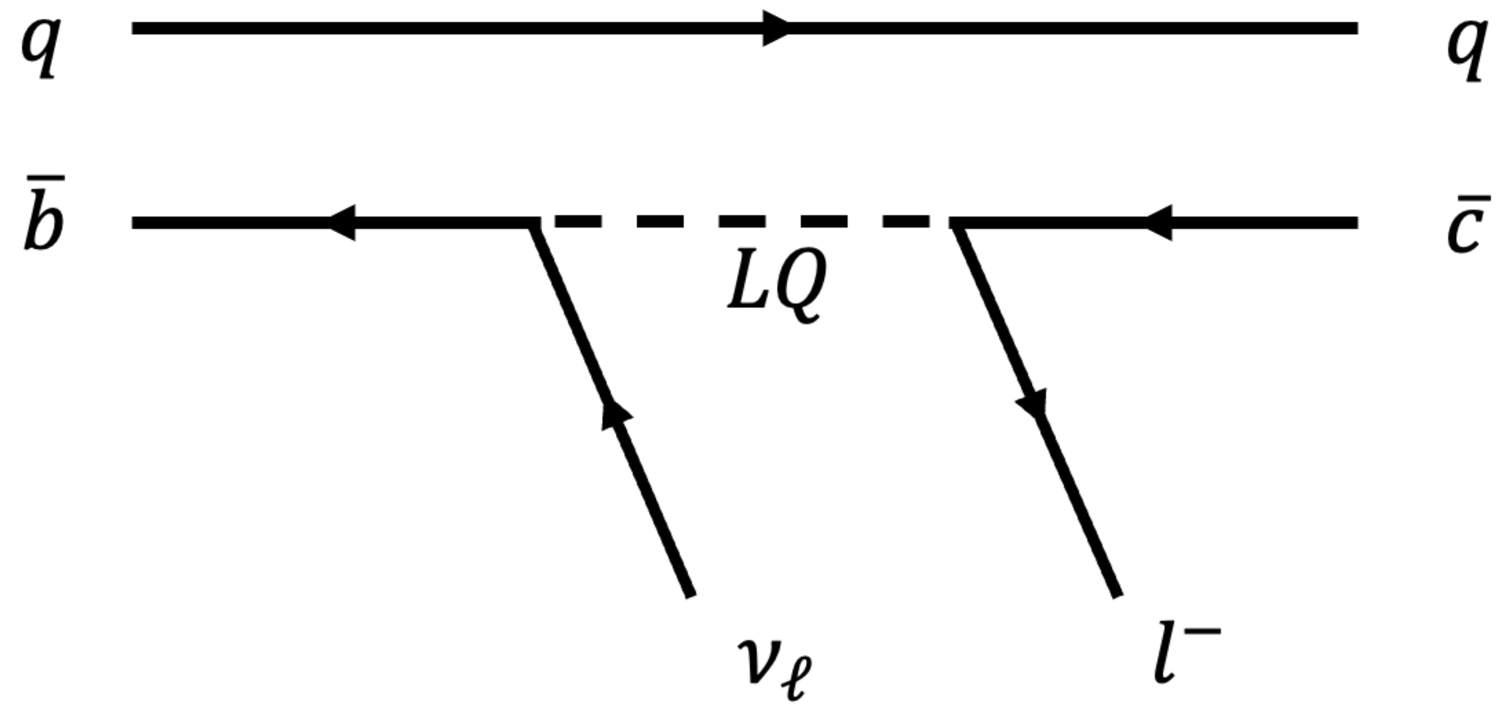
The Lagrangian describing LQ right-handed interaction is now: (*i* and *j* labelling the fermion generation)

$$L \supset \lambda_{ij} S_{ij} (E_i^C U_j^C)^*$$

Motivations for Leptoquark Searches

- LQ contribute for example to the following Flavour Physics process which have experimental tensions with the SM, namely: $b \to c\tau\nu$





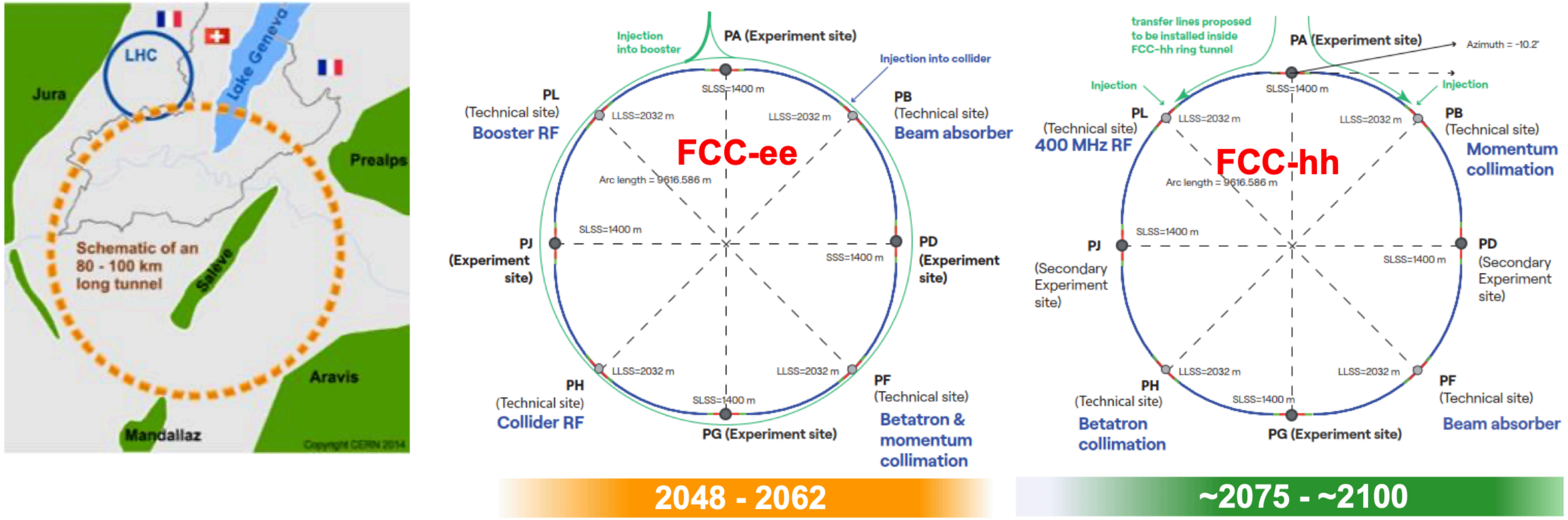
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\tau)} = 0.287 \pm 0.012; (\mathrm{SM} : 0.254 \pm 0.005)$$

10.1103/PhysRevD.110.075005
(Global Fit: BABAR, LHCb, Belle, and Belle II)

LQ interaction can enhance the rate of τ production

FCC-ee:
Z-boson decay
&
Leptoquark at 1-Loop

Future Circular Collider: ee-mode and hh-mode



- Future Circular Collider will run in 2 Stages: First as an electron-positron circular collider, and the Second Stage will consist of hadron-hadron collisions

- Feasibility Study has been completed, with next steps being the Project Approval by CERN council, Construction and finally Start of Operations in 2048 (FCC-ee) and 2075 (FCC-hh)

Future Circular Collider-ee as a Tera-Z factory

Operation Baseline for Future Circular Collider (electron-positron):

Working point	Z pole	WW thresh.	ZH
COM (GeV)	88, 91, 94	157, 163	240
Lumi/IP (10^{34} cm^{-2} s^{-1})	140	20	7.5
Lumi/year (ab^{-1})	68	9.6	3.6
Run time (year)	4	2	3
Integrated Lumi. (ab^{-1})	205	19.2	10.8
Number of events	6×10^{12} Z	2.4×10^{8} WW	2.2×10^{6} ZH

arXiv:2505.00272v1

- FCC-ee run at the Z pole offers unmatched sensitivity to indirect New Physics signals that could emerge from small deviations from the Standard Model

- FCC-ee can be used to measure small Loop corrections from heavy particles. Tera-Z will allow probes of heavy new physics up to 10s of TeV

Future Circular Collider-ee as a Tera-Z factory

Projected Uncertainty for Future Circular Collider (electron-positron):

Observable	Value		Uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Leading Uncertainty
m_Z	91187600	$\pm$	200	**4**	100	Z line shape scan Beam Energy Calibration
Γ_Z	2495500	$\pm$	2300	**4**	12	Z line shape scan Beam Energy Calibration
$\sin^2\theta_W^{\text{eff}}(\times 10^6)$	231,480	$\pm$	160	**1.2**	1.2	From $A_{\text{FB}}^{\mu\mu}$ at Z peak

arXiv:2505.00272v1

Z-boson decay at 1-loop w/ Leptoquark

- New Physics contribution:

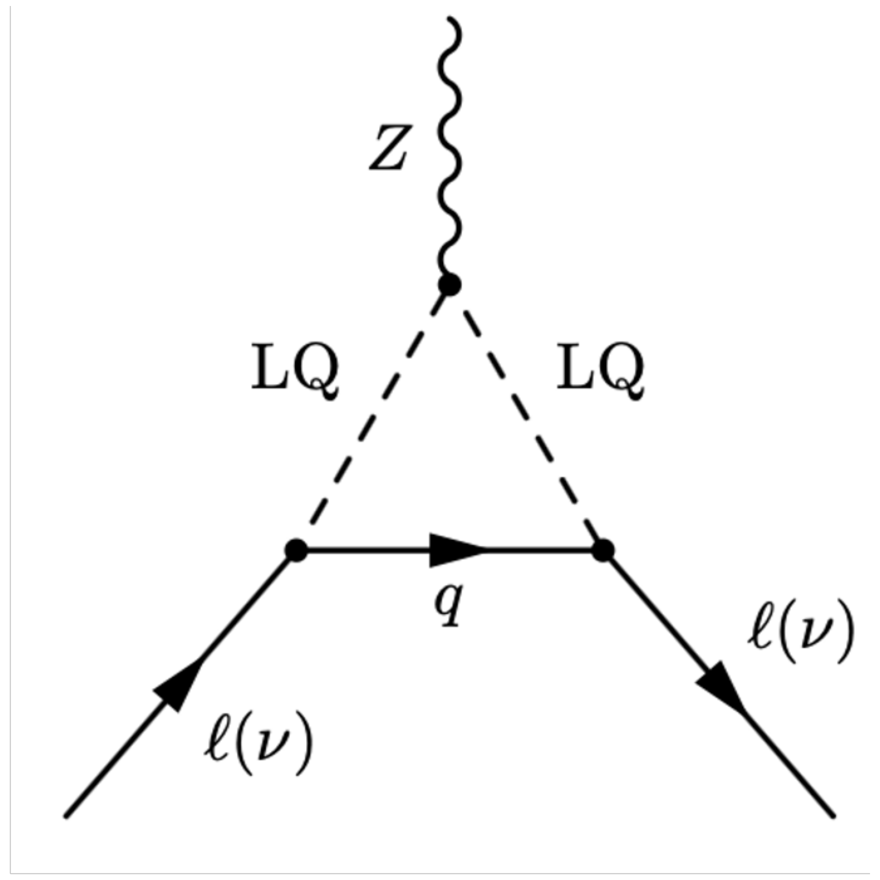
$$\delta g_Z \equiv \frac{(\Delta g_Z)}{g_Z^{SM}} \qquad \Delta g_Z \equiv g_Z - g_Z^{SM}$$

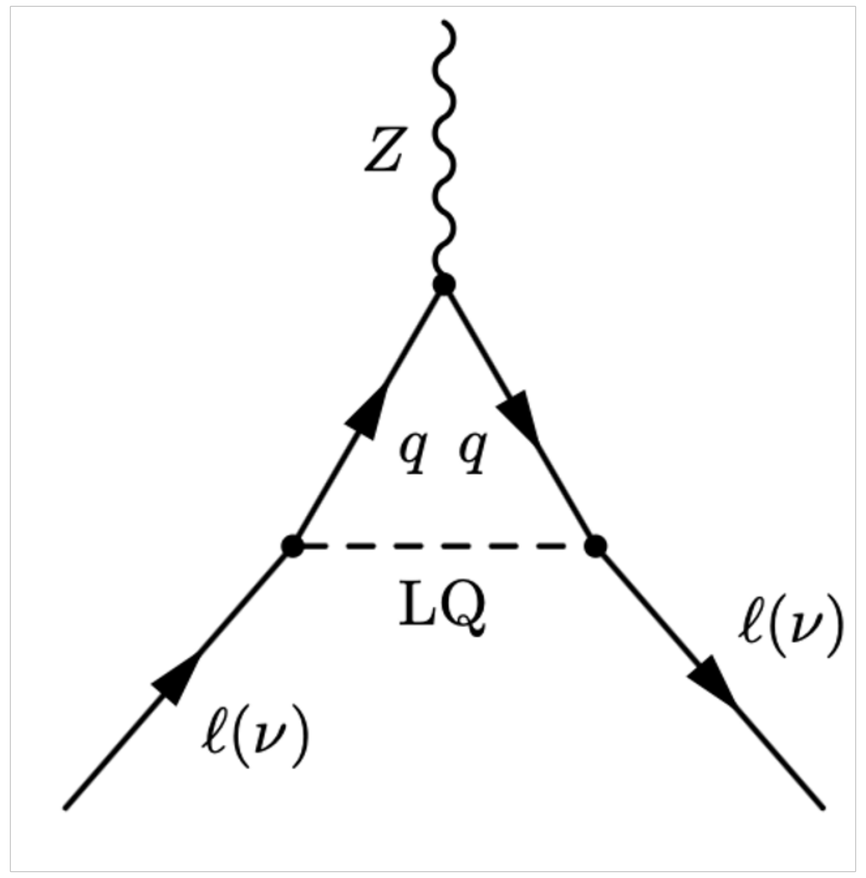
- Expansion is performed in the external momenta prior to integrating, and light quark masses are neglected

- Resulting equation takes into account corrections up to order $\mathcal{O}(\frac{m_Z^2}{m_\phi^2})$

$$[\delta g_Z^{ee}]_\phi = \frac{m_Z^2}{m_\phi^2} N_c \frac{\lambda_{ec}\lambda_{ec}^*}{48\pi^2}\left[-\frac{2}{3}s_W^2(\ln\frac{m_Z^2}{m_\phi^2} - i\pi - \frac{1}{6}) + \frac{s_W^2}{6}\right]$$

$$[\delta g_Z^{ee}]_\phi = N_c \frac{\lambda_{et}\lambda_{et}^*}{16\pi^2}\left[-\frac{1}{2}\frac{x_t(x_t - 1 - \log x_t)}{(x_t-1)^2} + \frac{m_Z^2}{12m_\phi^2}F_\phi(x_t)\right] \; ; \; \left(x_t = \frac{m_t^2}{m_\phi^2}\right)$$





Electroweak Precision Observables at FCC-ee

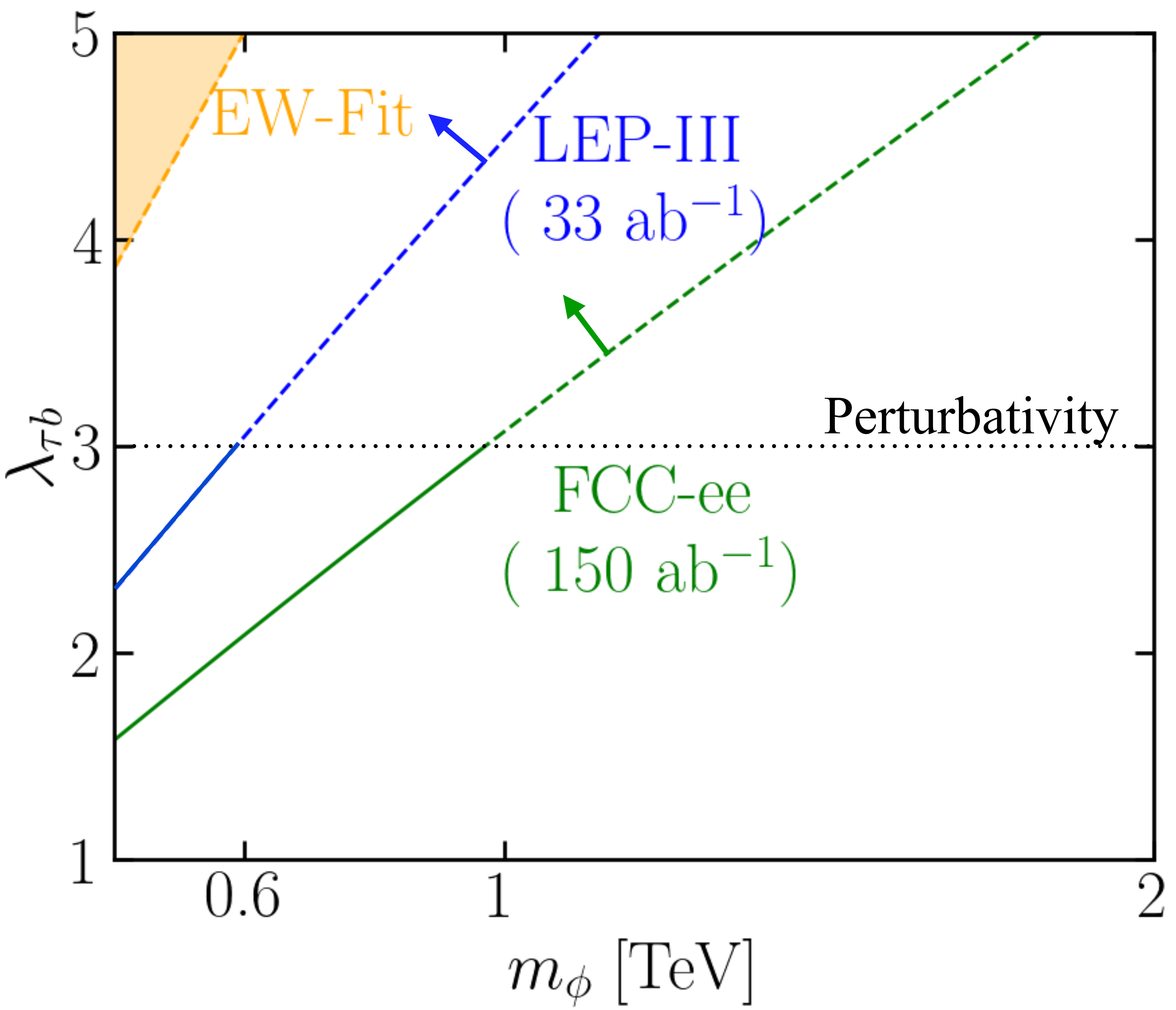
- Electroweak Precision Observables: Z-boson mass (m_Z), Z-decay width (Γ_Z), Left-Right Asymmetry (A_f) and Total Hadronic Cross section (σ^0_{had}) $e^+e^- \to Z \to$ hadrons

$$\Gamma_{Z\to e^+e^-} = \frac{\alpha M_Z}{6\sin^2\theta_w \cos^2\theta_w}\left(\left|g^{eff}_{Zee,\mathrm{L}}\right|^2 + \left|g^{eff}_{Zee,\mathrm{R}}\right|^2\right)$$

$$A_e = \frac{\left|g^{eff}_{Zee,\mathrm{L}}\right|^2 - \left|g^{eff}_{Zee,\mathrm{R}}\right|^2}{\left|g^{eff}_{Zee,\mathrm{L}}\right|^2 + \left|g^{eff}_{Zee,\mathrm{R}}\right|^2}$$

Mode	Z pole + WW + 240 GeV
$\delta g^e_{Z,R}$	0.0092%
$\delta g^\mu_{Z,R}$	0.0093%
$\delta g^\tau_{Z,R}$	0.0015%
$\delta g^u_{Z,R}$	0.084%
$\delta g^d_{Z,R}$	1.5%
$\delta g^b_{Z,R}$	0.16%

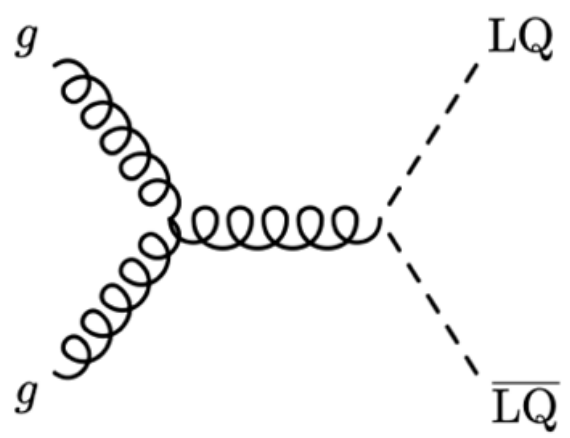
arXiv:2206.08326v5



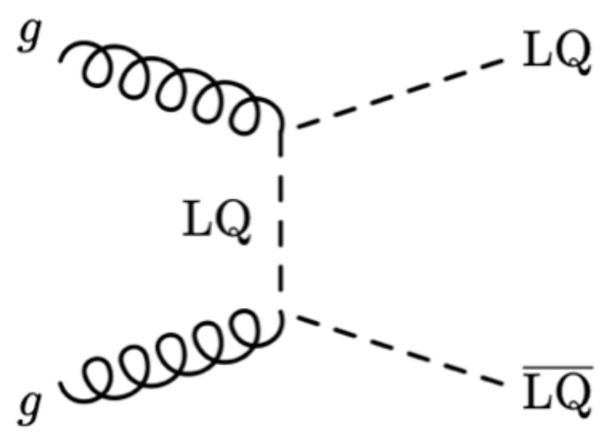
- Results including both LEP-III sensitivity, scaled from FCC-ee using Integrated Luminosity ratios, and including current EWPO fits

Hadron-Hadron Colliders:
LHC Searches
&
FCC-hh Projections

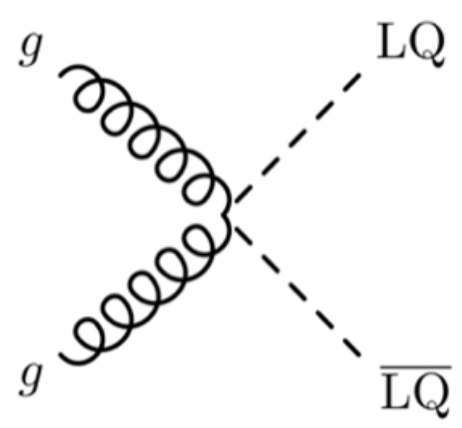
Leptoquark Production Channels at LHC/FCC



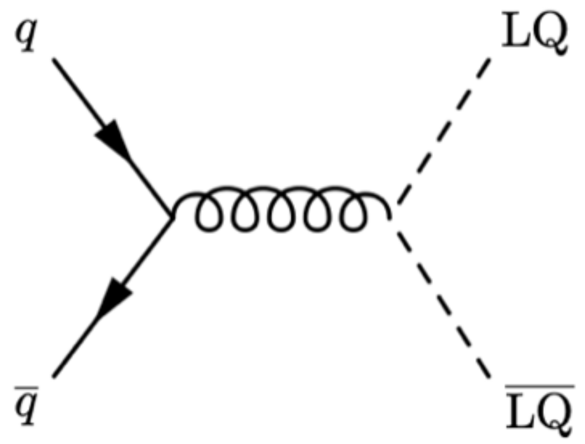
(PP-1)



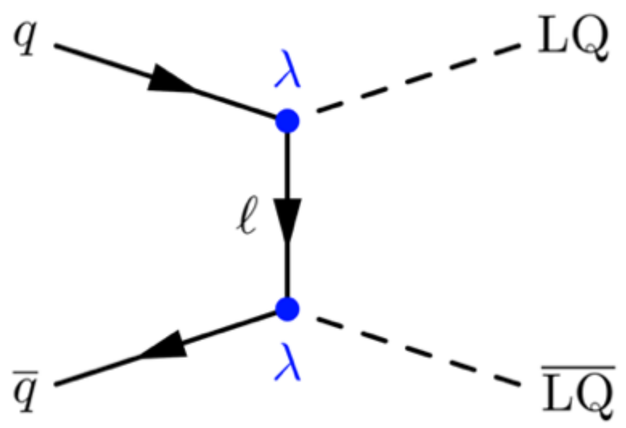
(PP-2)



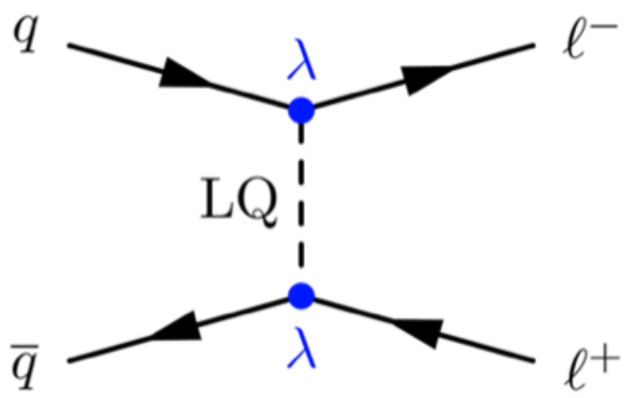
(PP-3)



(PP-4)



(PP-5)



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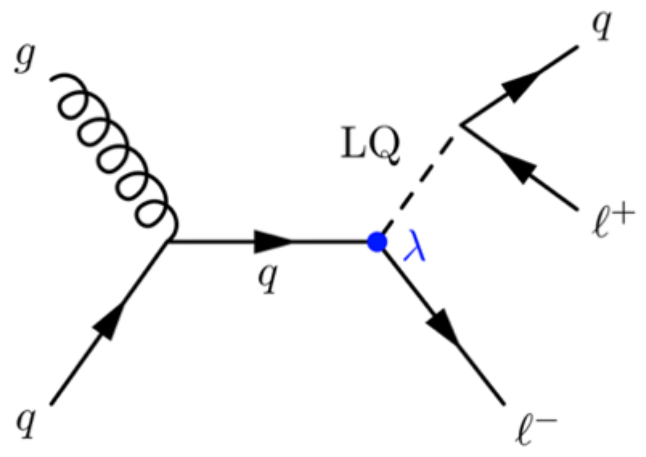
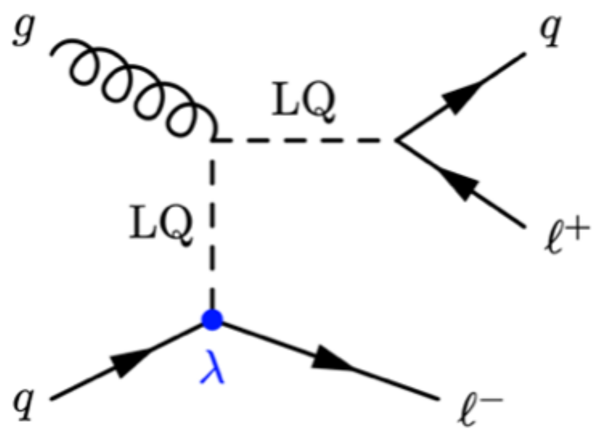
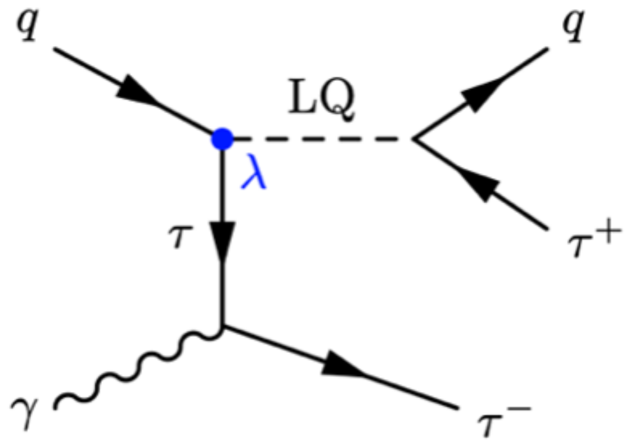


(SP-1)



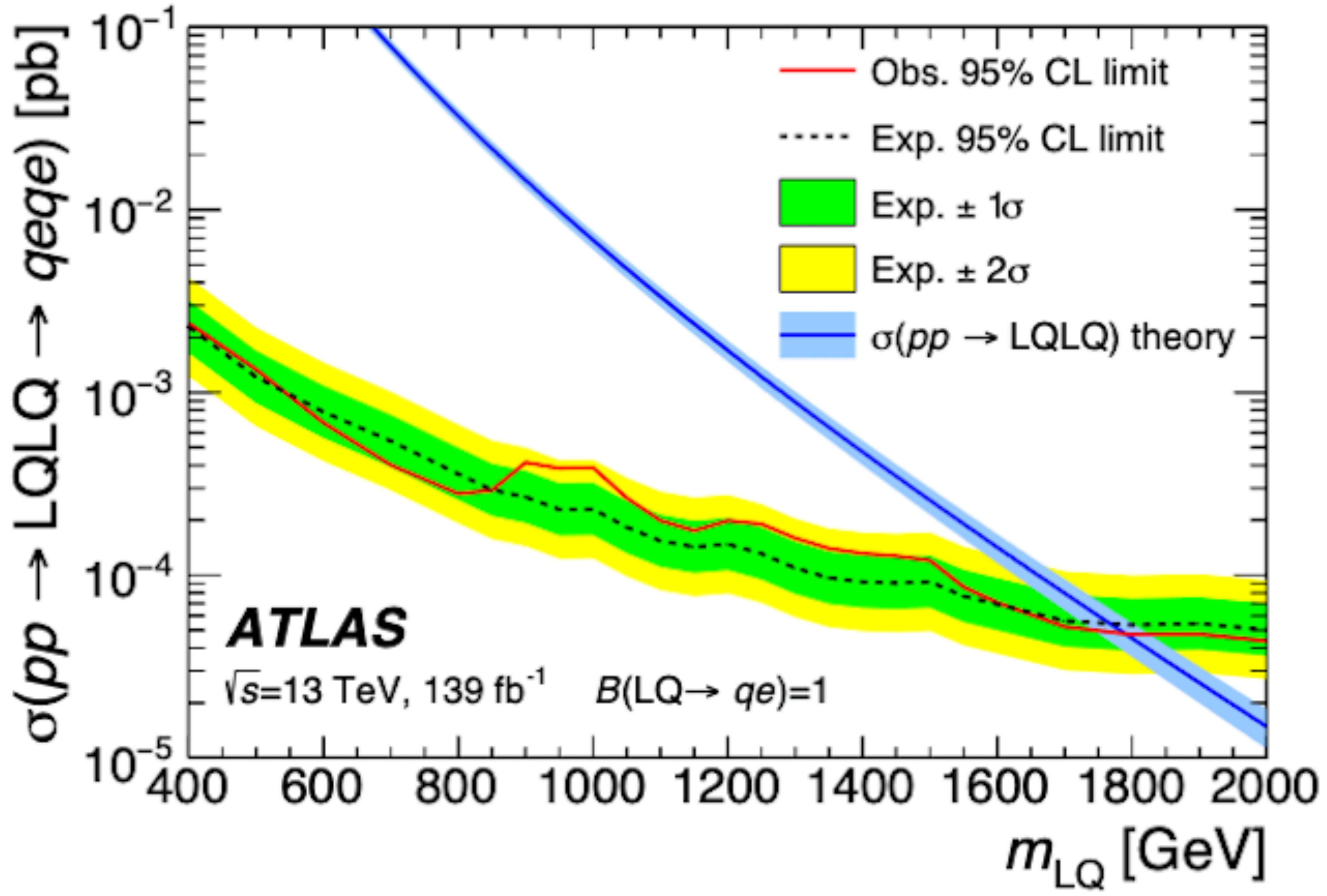
(SP-2)



(L-l)

Leptoquarks Pair Production (CMS/ATLAS)

- Pair production occurs at the LHC via gluon-gluon fusion and quark-antiquark annihilation
- The relevant kinematic distributions in the process are those related to $\ell\ell jj$, decay product of the LQ & anti-LQ final state
- We perform an extrapolation at Large Coupling using CMS and ATLAS results which assume negligible λ contribution in production cross section

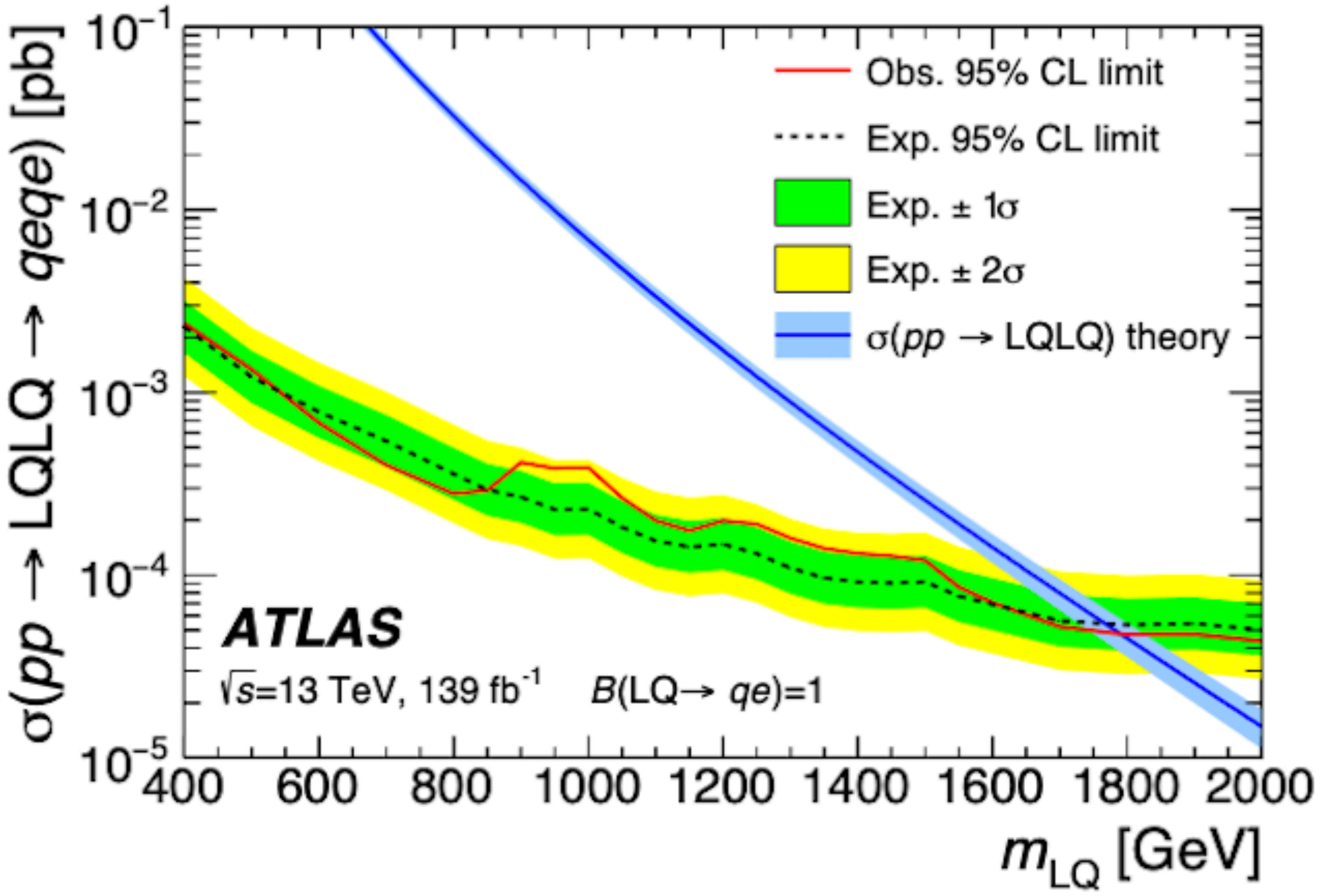


arXiv:2006.05872v2

Leptoquarks Pair Production (CMS/ATLAS)

- We simulate Pair-Production events using **MadGraph5** event generator at Tree-Level.

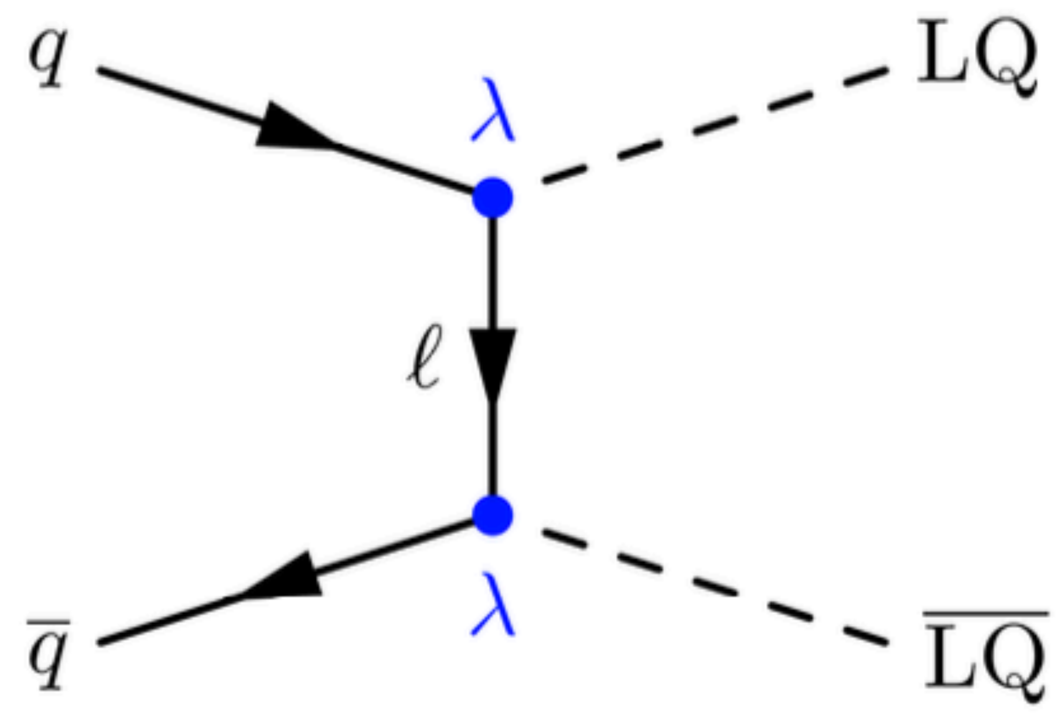
- Simulation cross section is attributed to each point in the $(\lambda - m_\phi)$ parameter space and matched to the experimental cross section



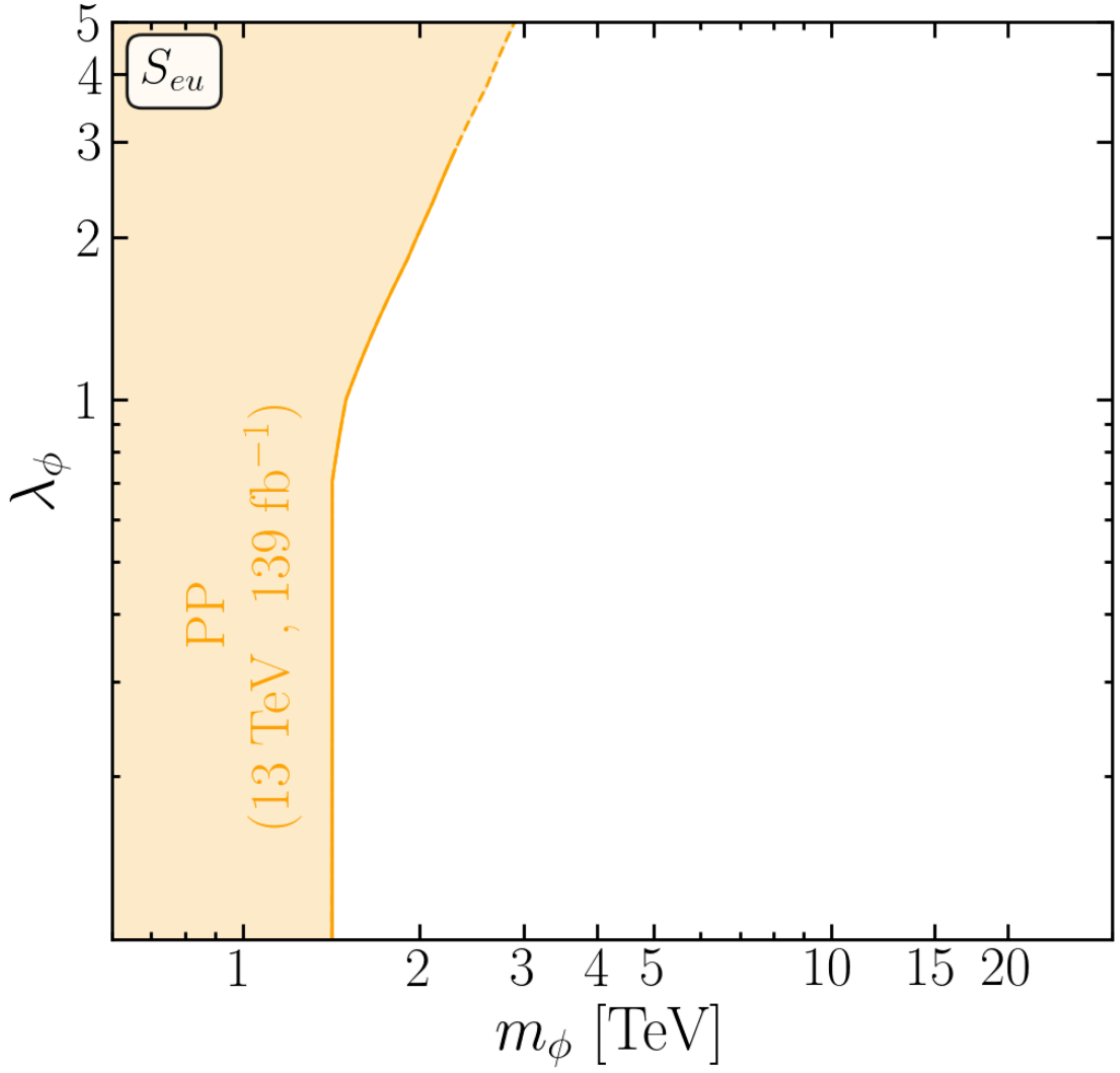
arXiv:2006.05872v2

Leptoquarks Pair Production (CMS/ATLAS)

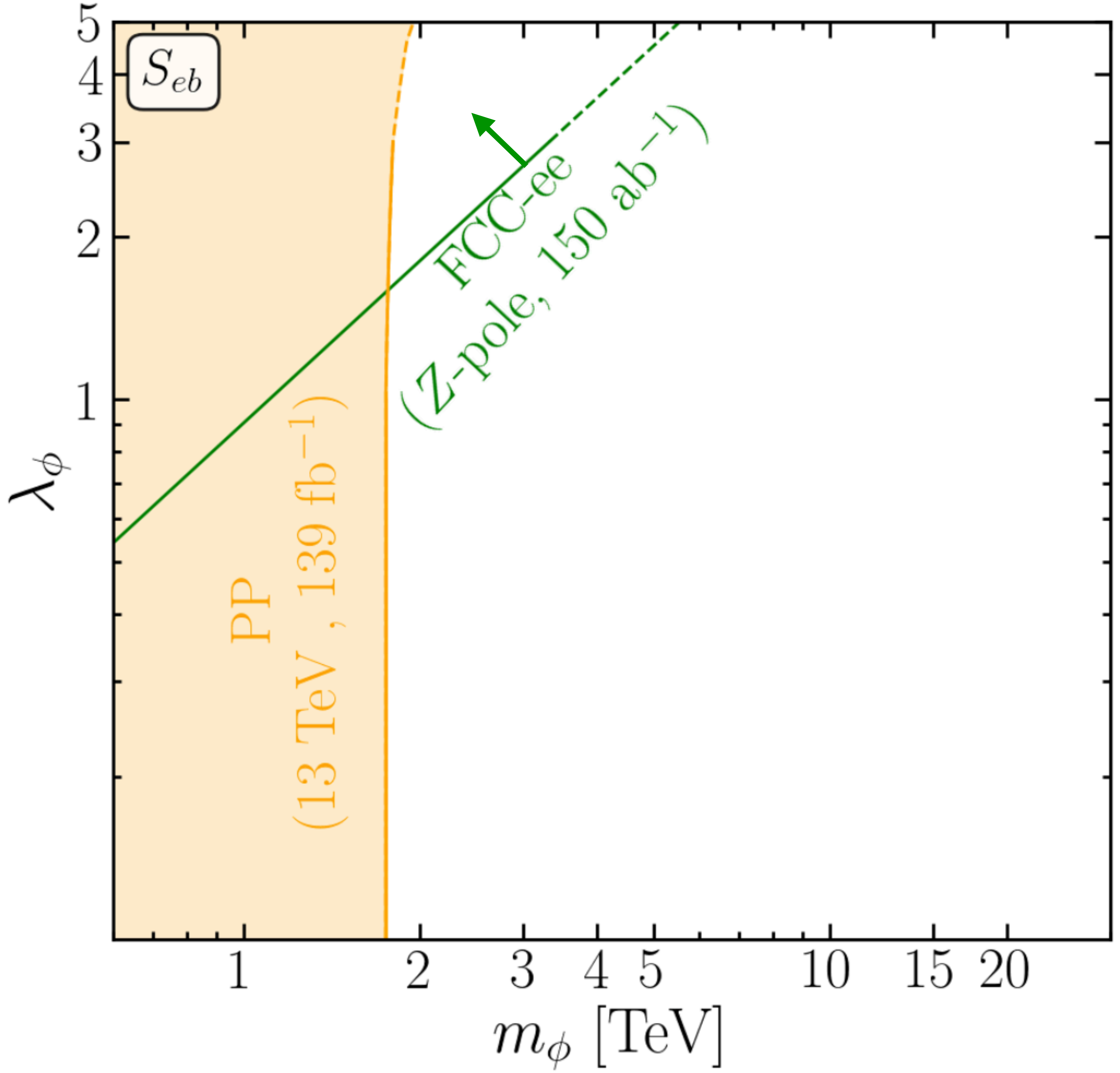
- Curvature in the bound ≡ PP-5 diagram (lepton exchange) starts to dominate. Effect is enhanced by the valence (u, d) quark content of the proton

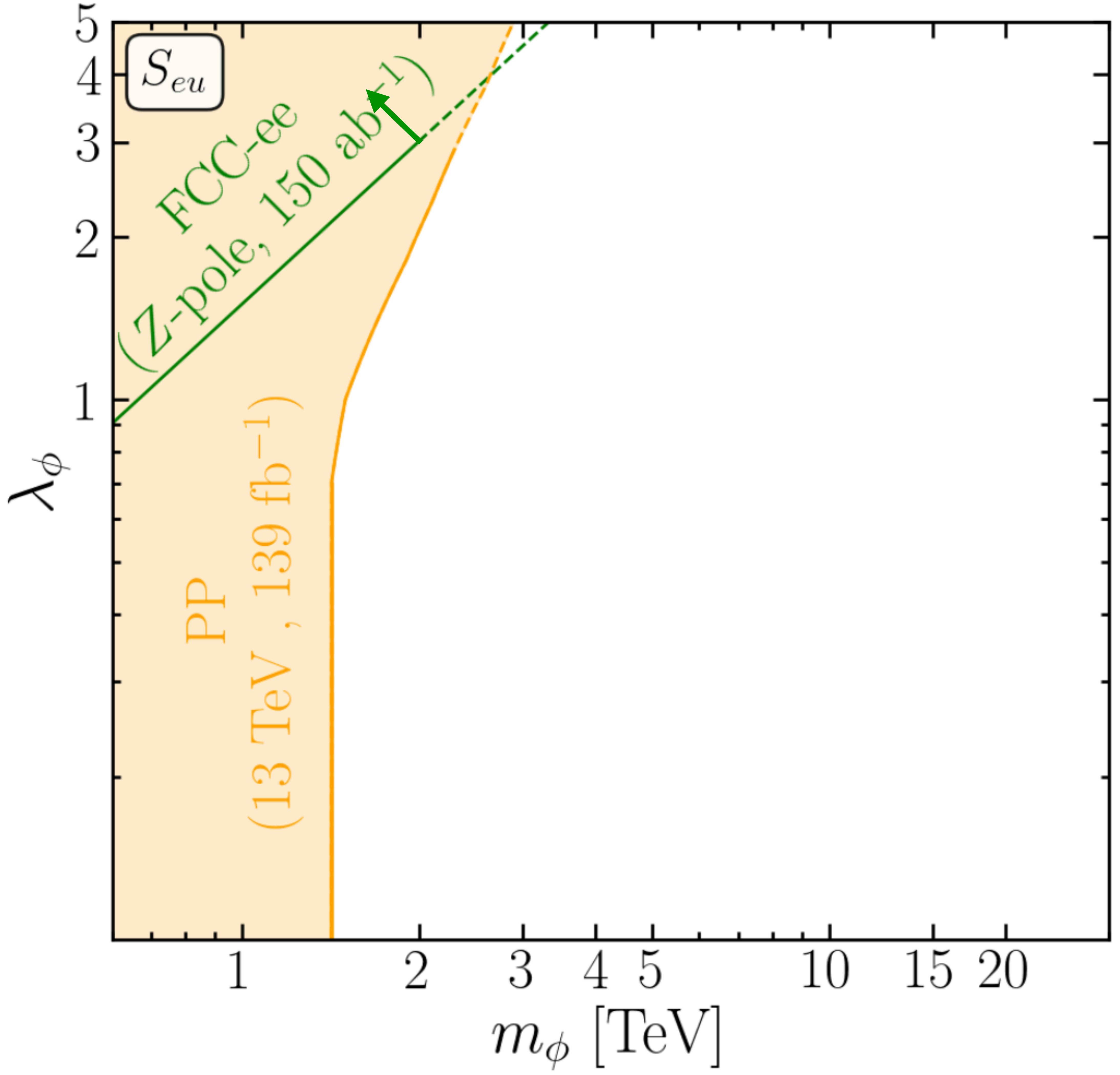


(PP-5)



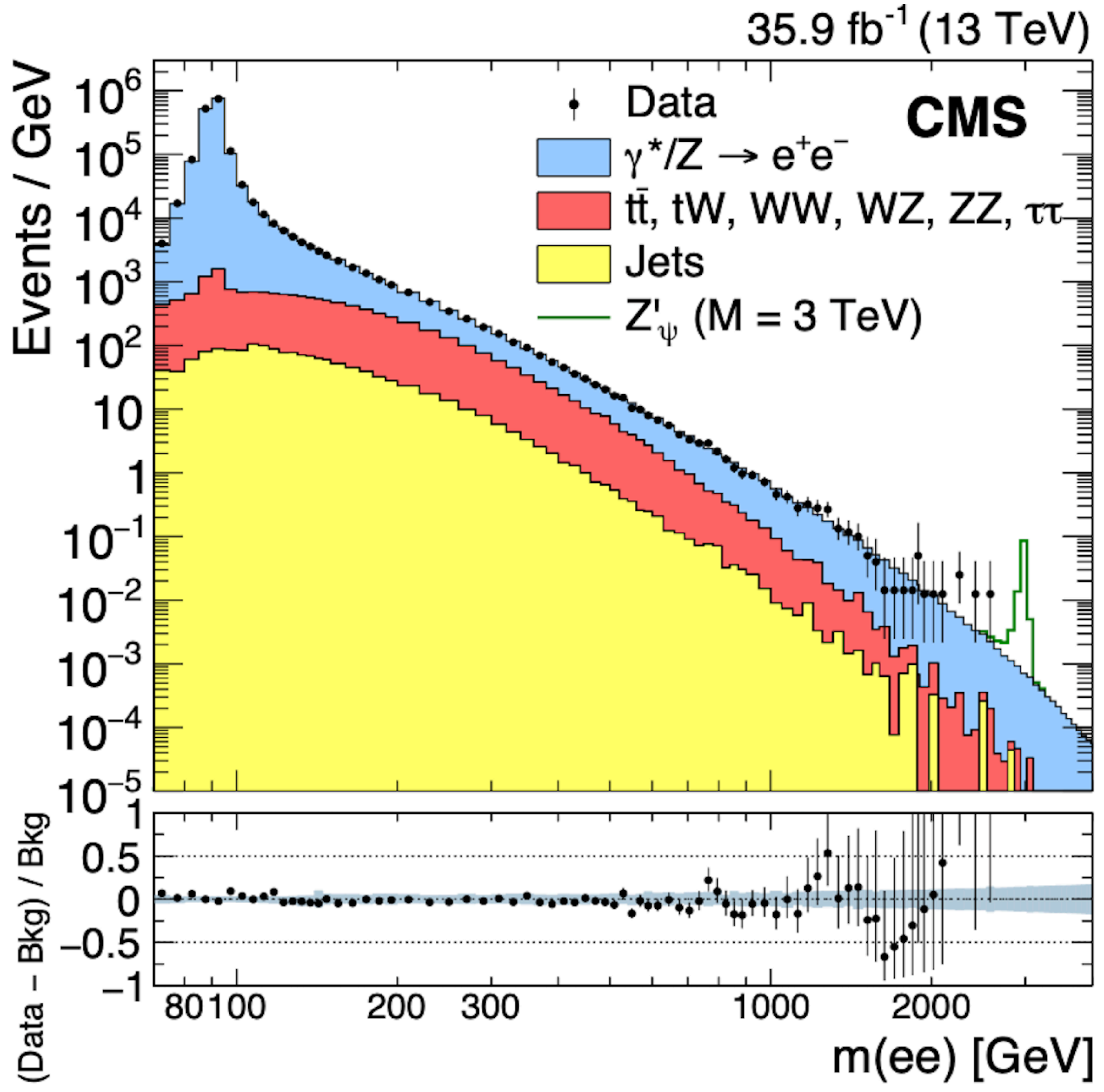
Leptoquarks Pair Production (CMS/ATLAS)





Drell-Yan t-channel Leptoquarks (CMS)

- Drell-Yan relevant kinematic quantity is the di-lepton invariant mass $m_{\ell^+\ell^-}$
- Non-resonant LQ signal is expected to contribute most in the high-$m_{\ell^+\ell^-}$ tail of the distribution
- A recast is performed from a Z' study
- Scans of the $(\lambda - m_\phi)$ parameter space are performed in **Madgraph5**. Kinematic distributions are compared to experimental distributions w/ "Cut and Count" analysis from Poisson Method



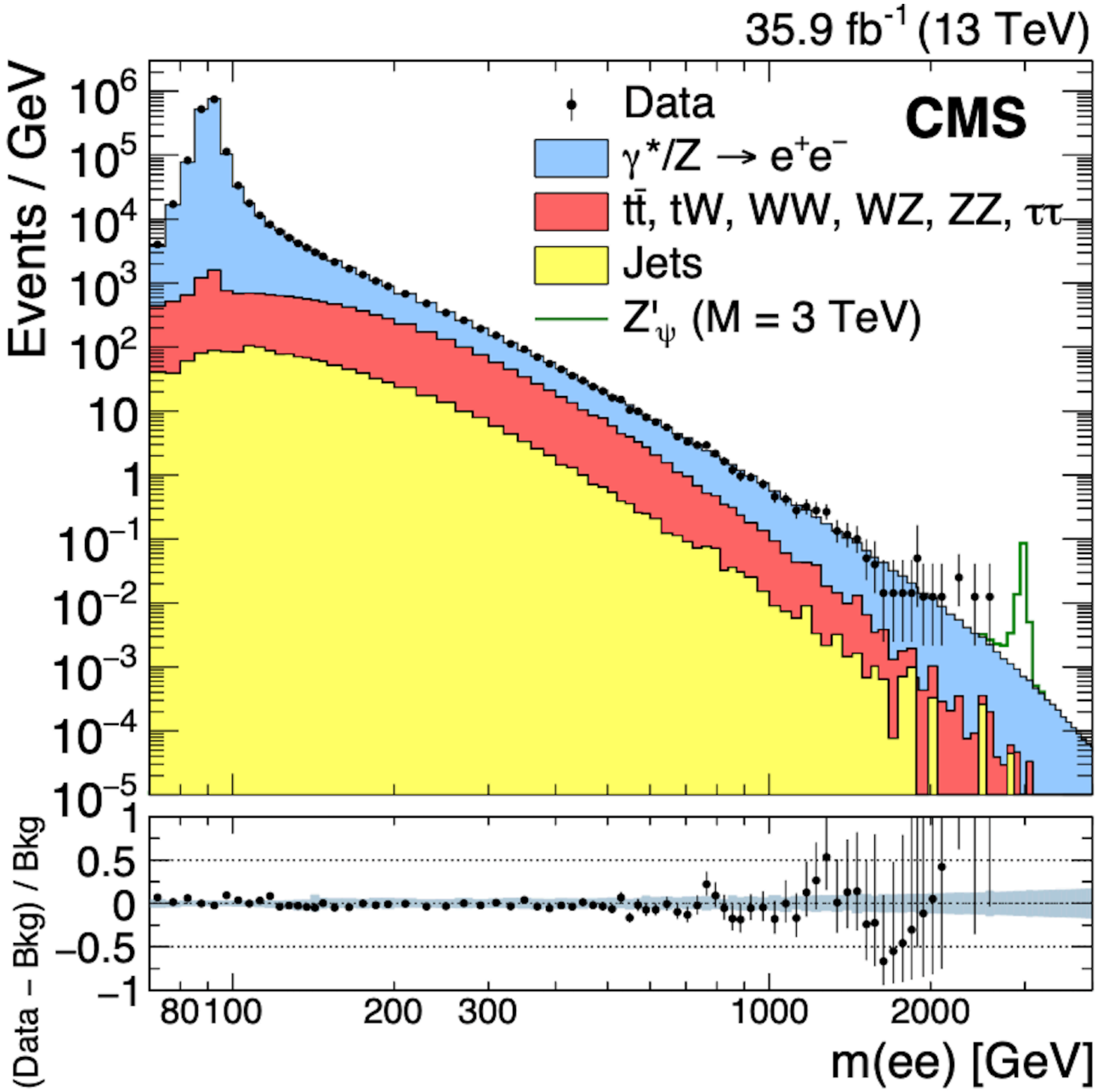
arXiv:1803.06292v2

Drell-Yan t-channel Leptoquarks (CMS)

- 95 % CL upper limit on signal number of events S_{limit}

$$P(n \leq n_{obs}|s+b) = \sum_{k=0}^{n_{obs}} \frac{e^{-(s+b)}(s+b)^k}{k!} = 0.05$$

Conservative Background expectation: $b \to B' \equiv b - 2\delta b$



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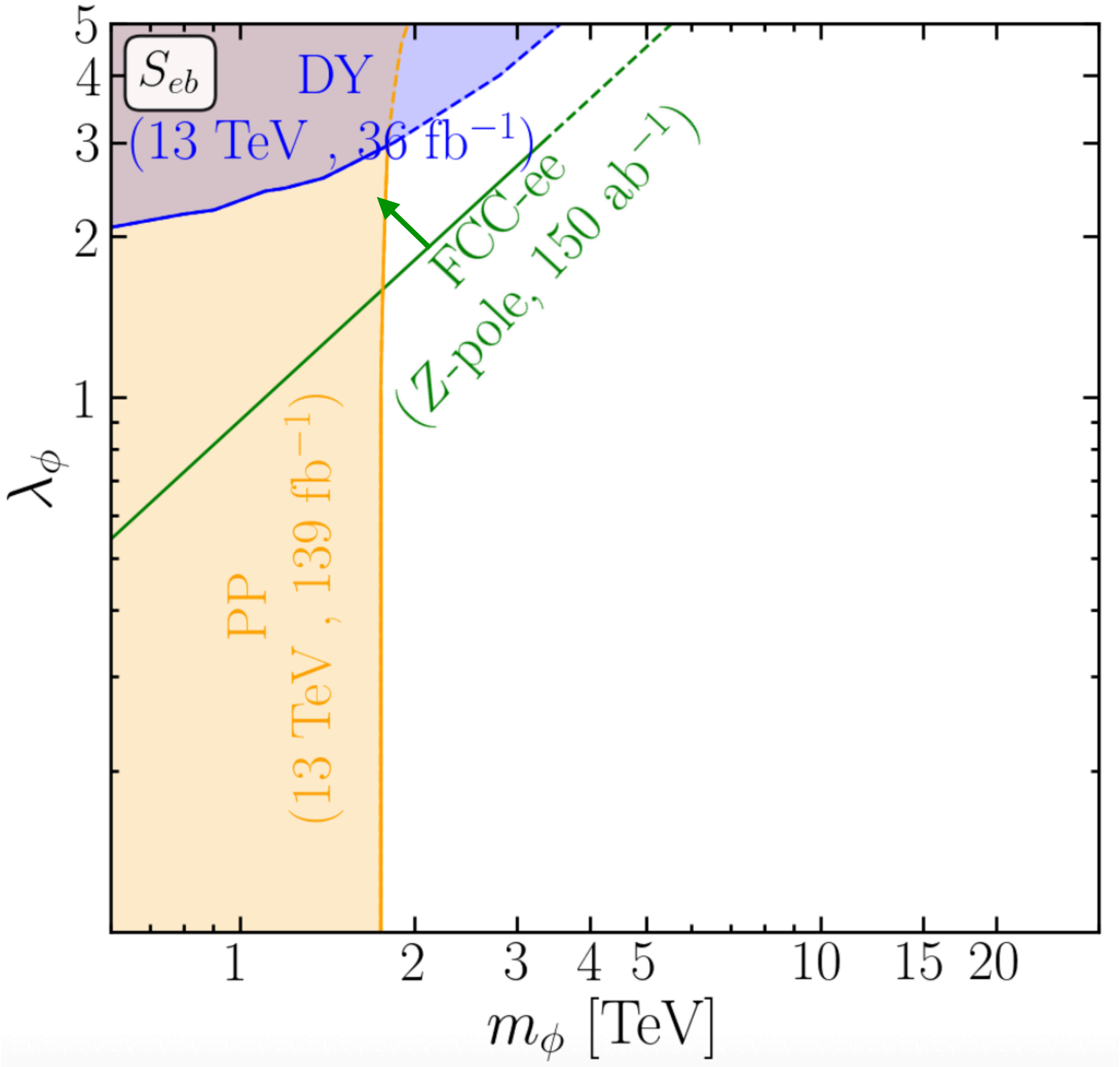
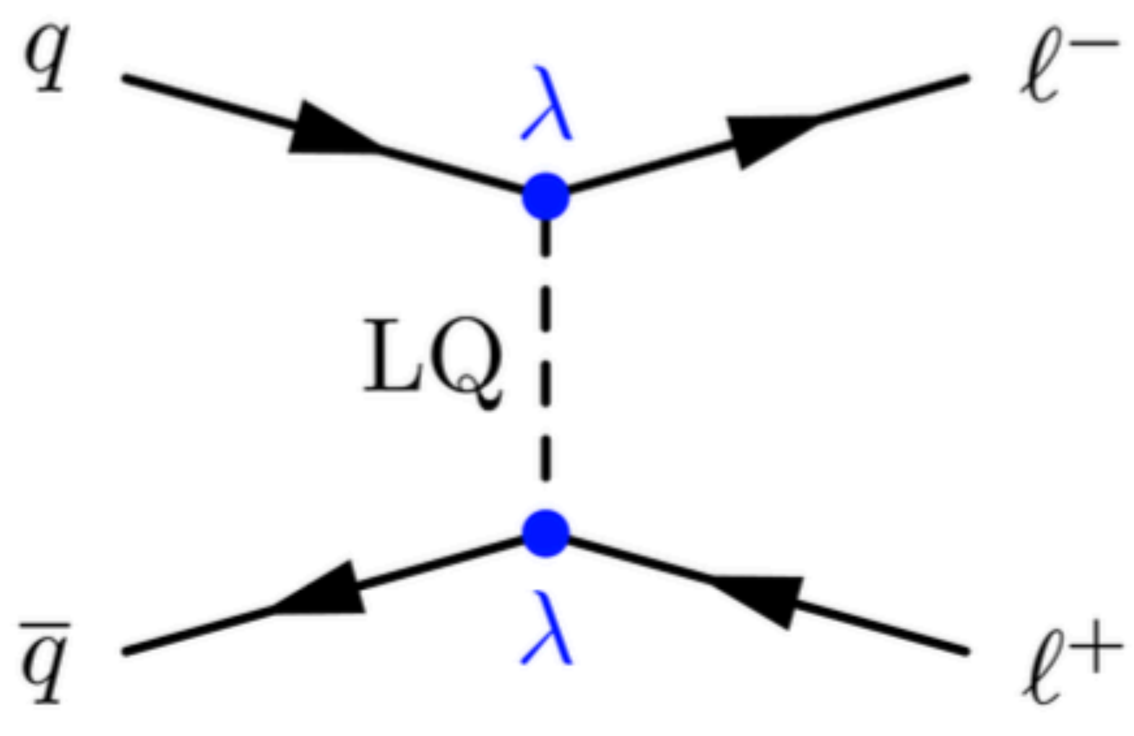
Drell-Yan t-channel Leptoquarks (CMS)



Drell-Yan t-channel Leptoquarks (CMS)

- A more recent CMS dedicated LQ study at higher luminosity, bins events in the same $m_{\ell^+\ell^-}$-distributions, in addition to rapidity $|y|$, results in stringent bounds



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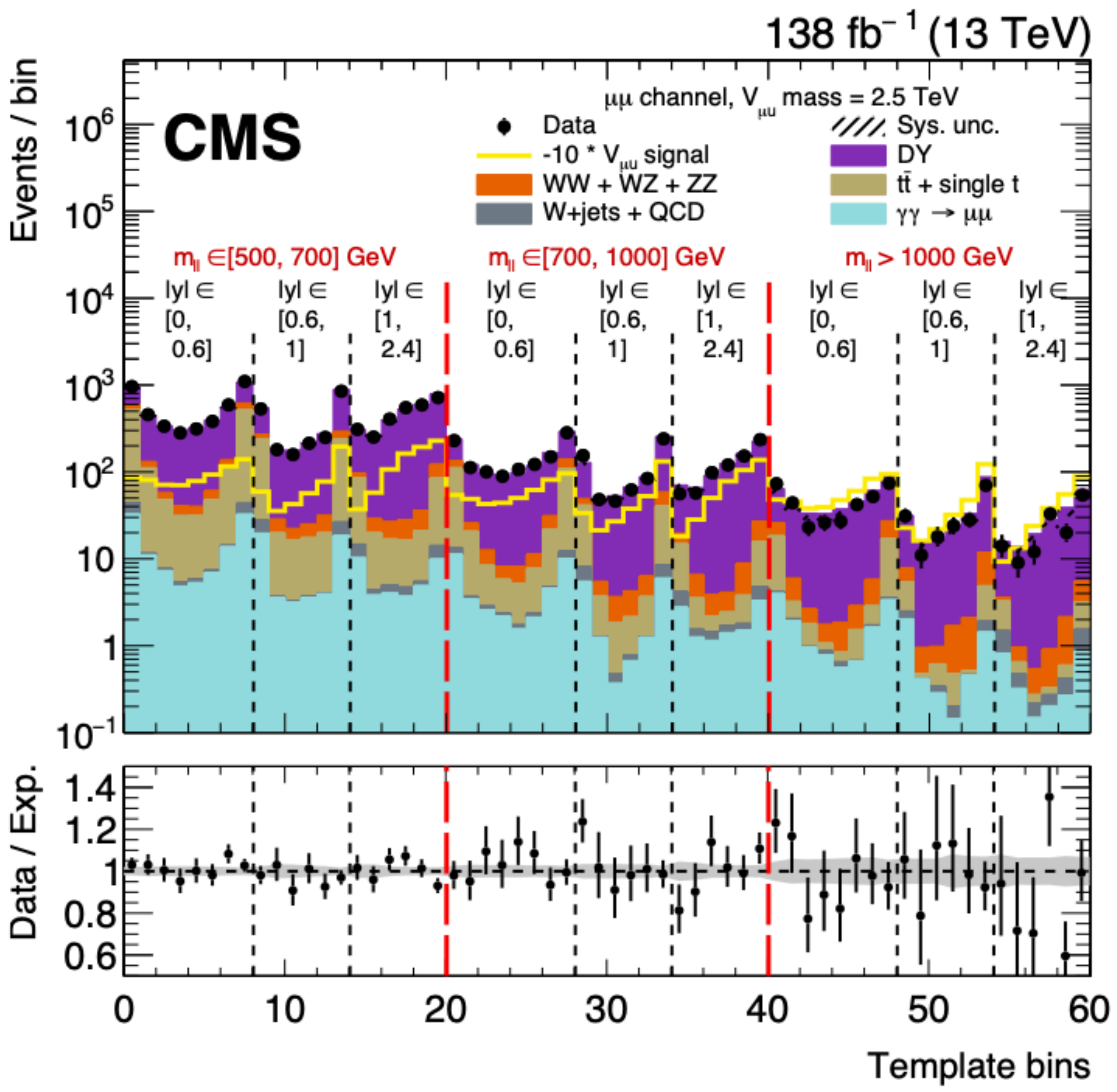
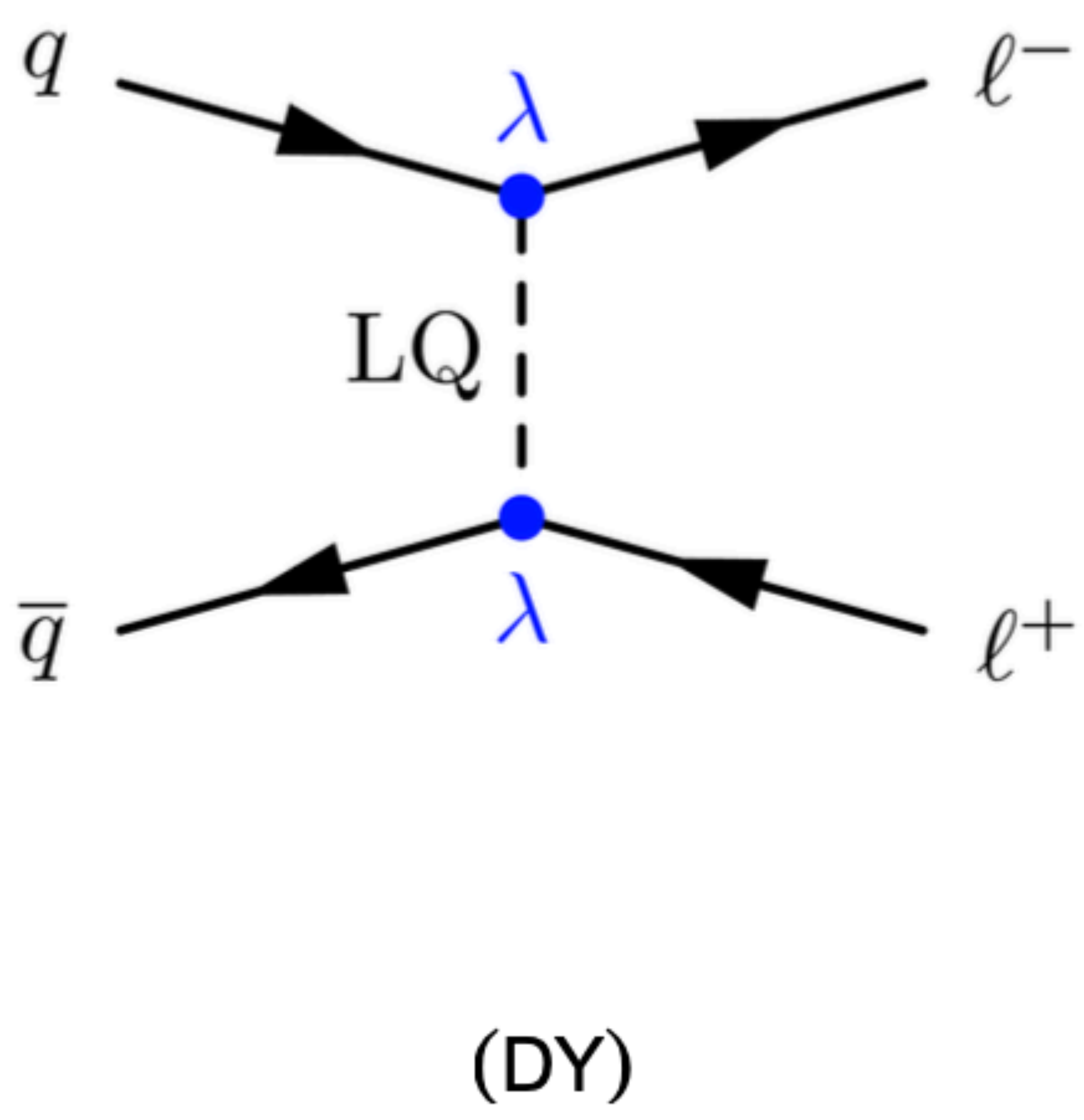
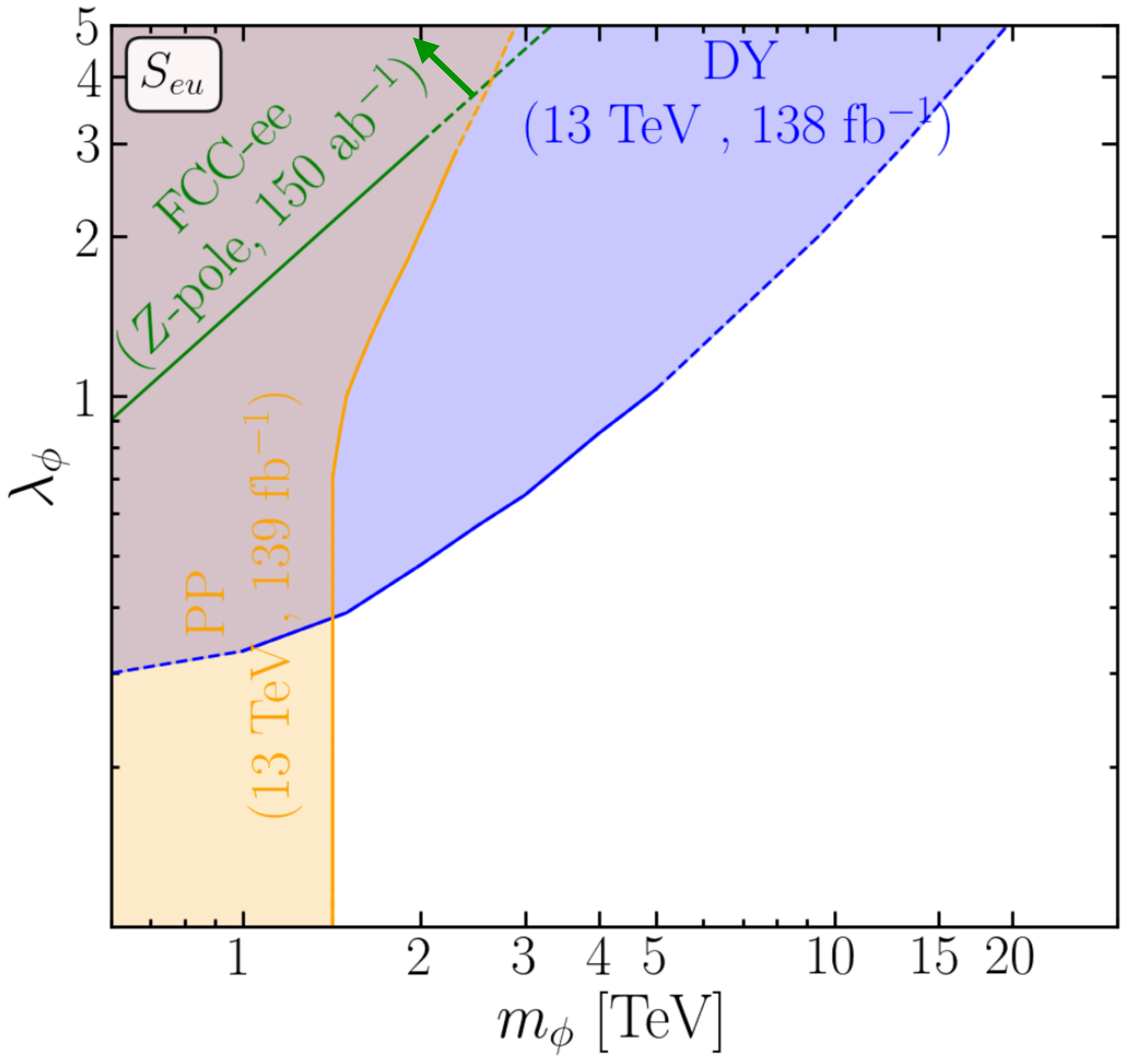


arXiv:2503.20023v3

Drell-Yan t-channel Leptoquarks (CMS)





Lepton-Induced Leptoquark (CMS)

- Lepton-Induced channel: $\gamma + q \to \tau^+\tau^- q$, with one large p_T final state tau lepton

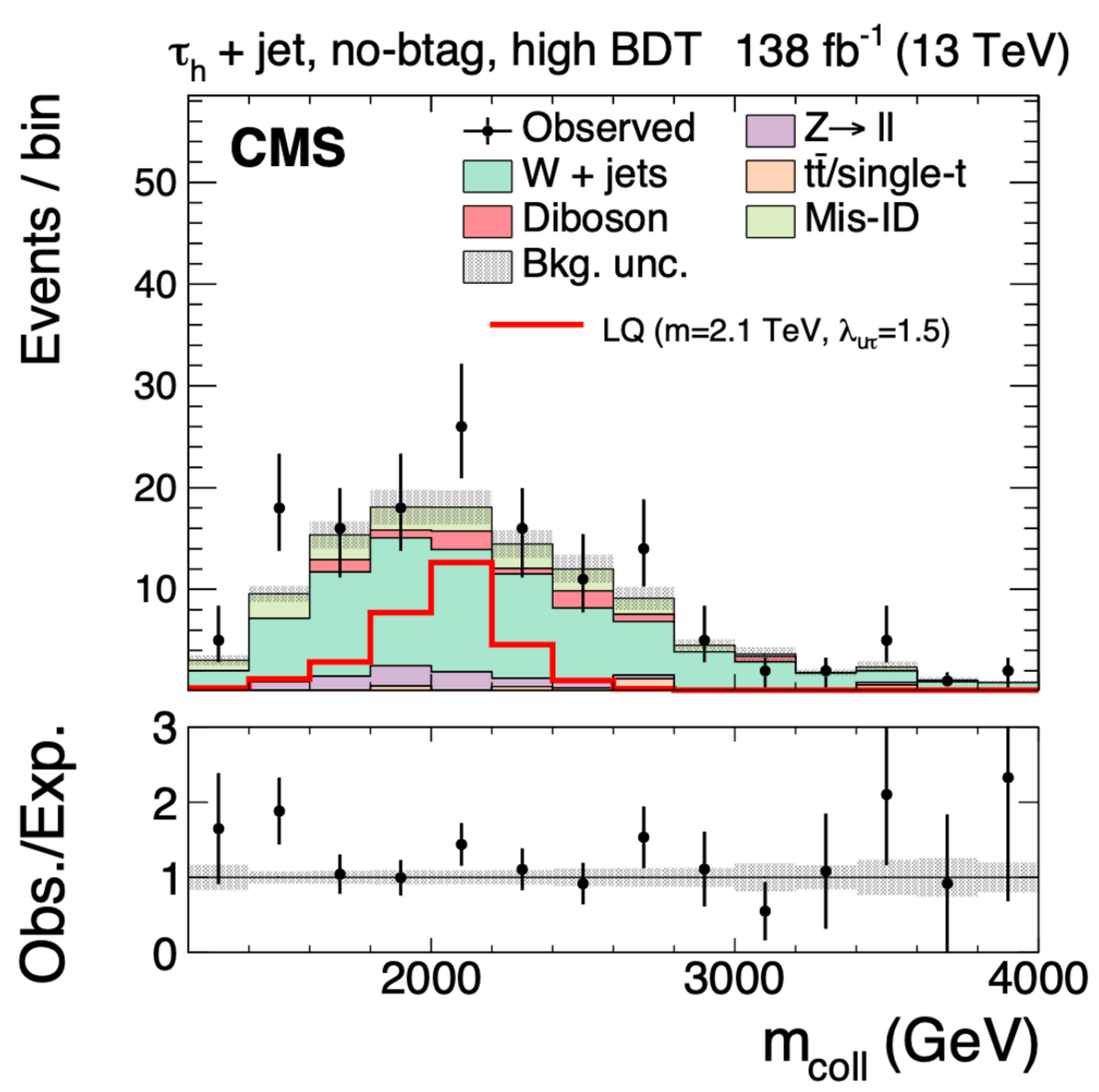
- The LQ mass is reconstructed via the decay product of the tau lepton

- Collinear approximation: both visible and invisible decay products are collinear + the only source of missing momentum arises from the neutrinos of the tau decay

$$m_{coll} = m_{vis}(\tau, j)/\sqrt{x_{vis}}$$

$$x_{vis} = p_T^{vis}(\tau)/\left(p_T^{vis}(\tau) + p_T^{invis}(\tau)\right)$$

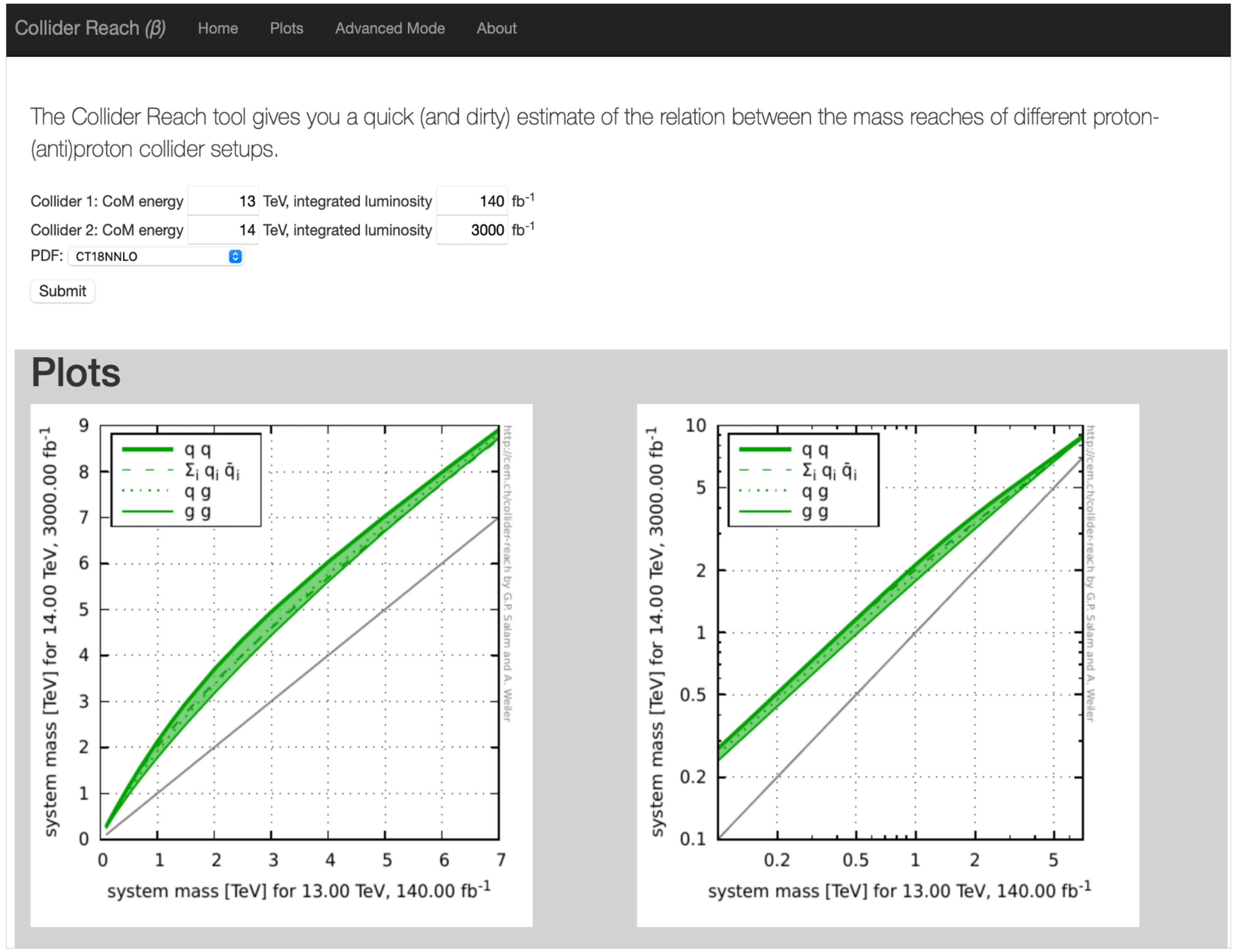
- Channel with identical final state as Single Production (SP), but SP has 2 large p_T final state tau leptons



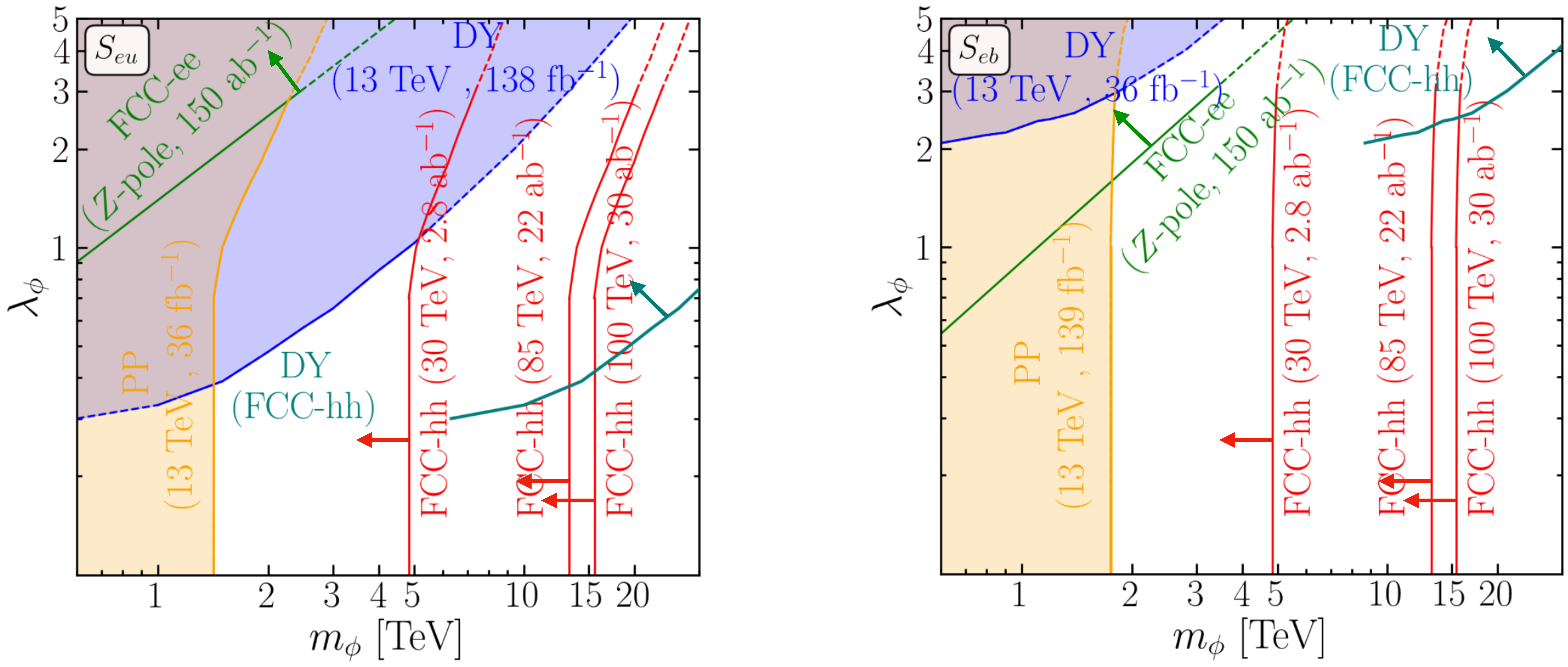
arXiv:2308.06143v2

Collider Reach Tool and FCC-hh projections

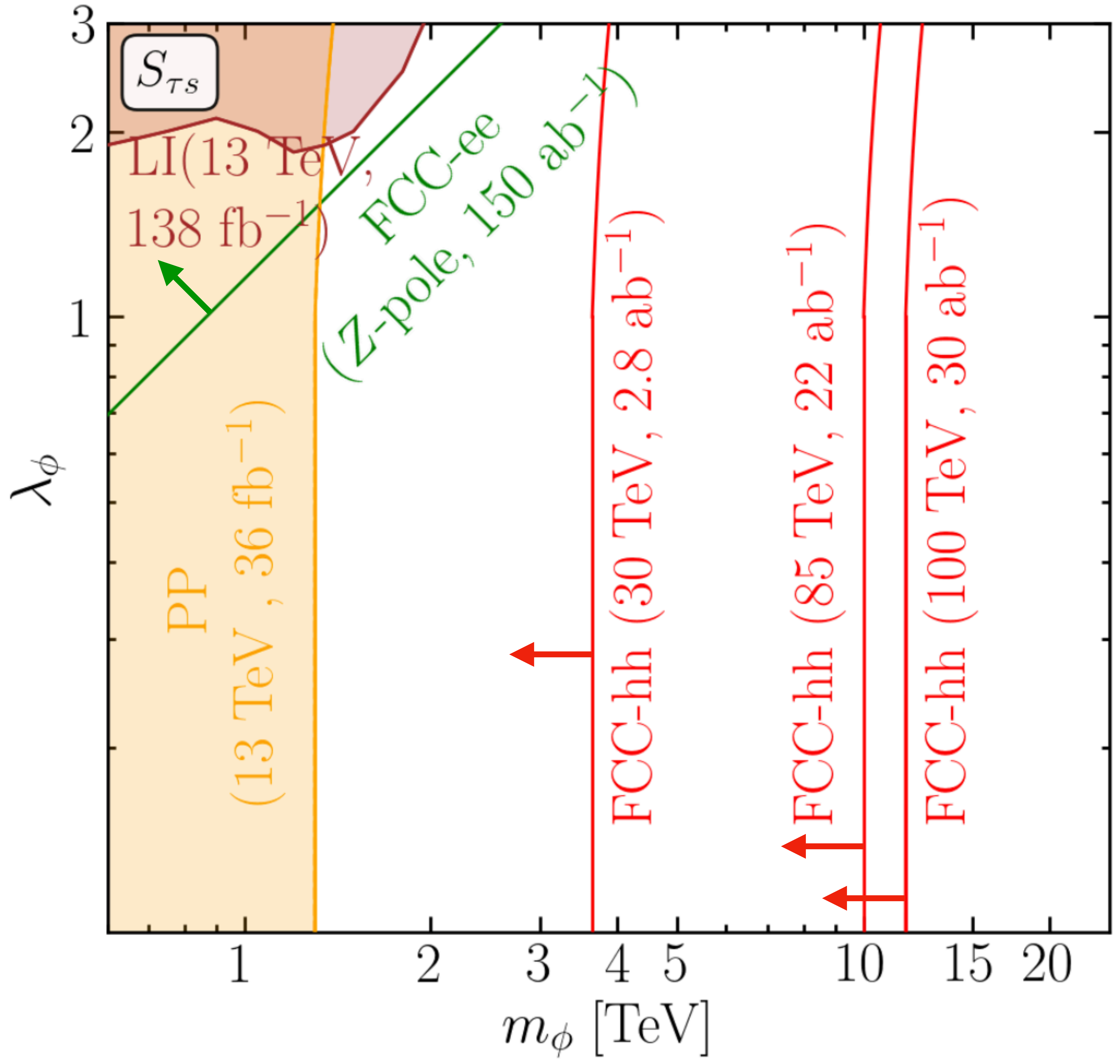
- Collider Reach Tool provides a mass estimate of the mass reach for FCC-hh
- Input: $\sqrt{s}$ energy, L Integrated Luminosity and PDF Parton Distribution Function for both LHC and FCC-hh
- This tool takes the cross section as scaling with the inverse squared mass of the system

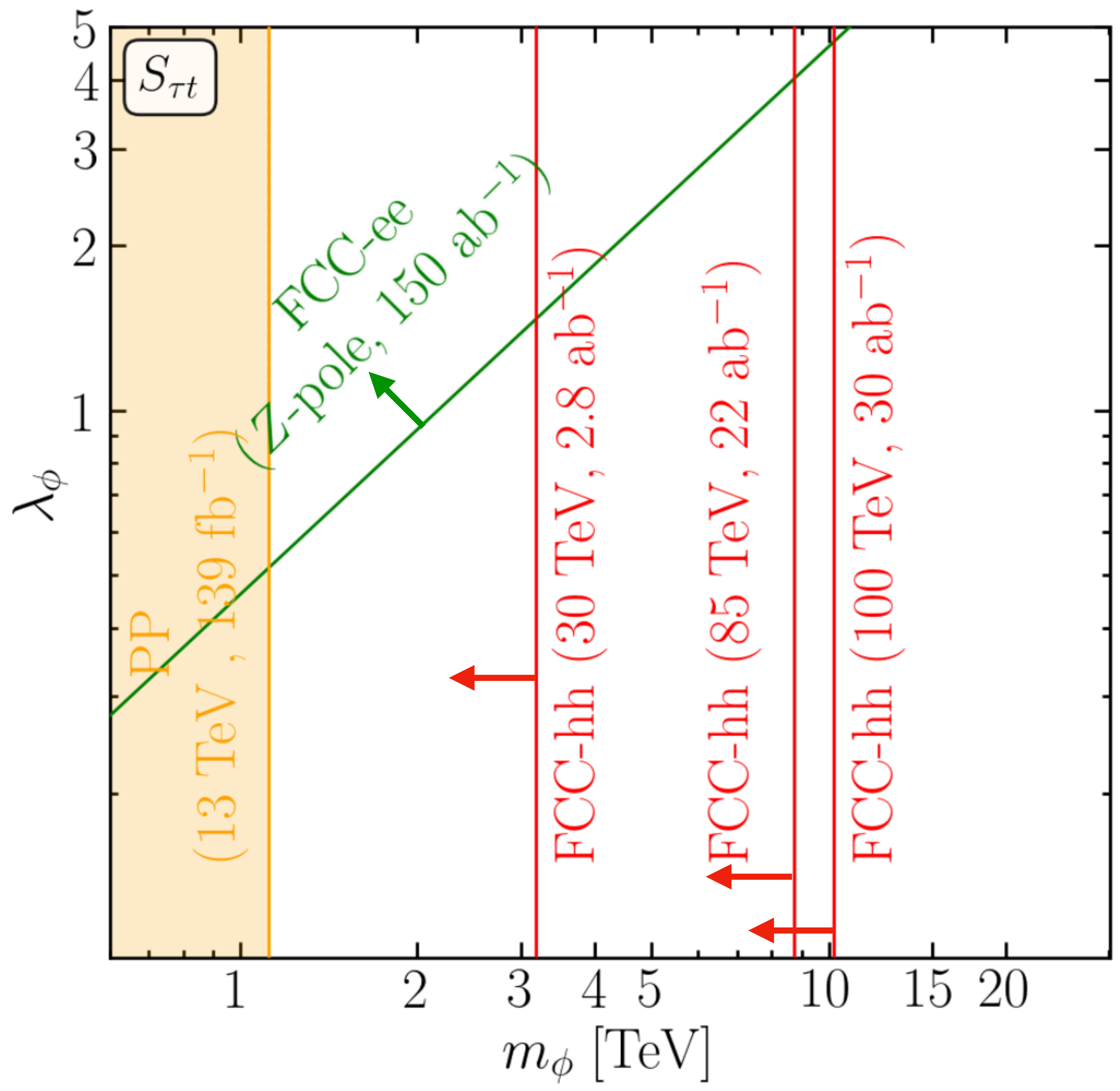


Combined results: FCC-ee & FCC-hh



Combined results: FCC-ee & FCC-hh





Summary

- LQ searches are well motivated by BSM models and anomalies of the SM. Combining the various production channels of LQ allows CMS and ATLAS to constraint the $(\lambda - m_\phi)$ parameter space of LQ.

- FCC-ee will provide us with a Tera-Z factory, allowing unprecedented precision test at the Z-pole. Loop level effects are induced by LQ. By combining analytical work with precision numerical work we motivated the search for LQ at FCC-ee.

- FCC-hh will push the boundary of reachable Energies, allowing to probe the entirety of the parameter space of interest for LQ. In the context of LQ that carry color, it is more than reasonable to think that FCC-hh will outperform FCC-ee.

- The entirety of the different SM sectors will face a precision test at FCC-hh and FCC-ee.