Uli Haisch, MPP Project Review 2020, 15.12.20

What’s beyond the Standard Model (BSM)?

Phenomenological explorations at low & high energies

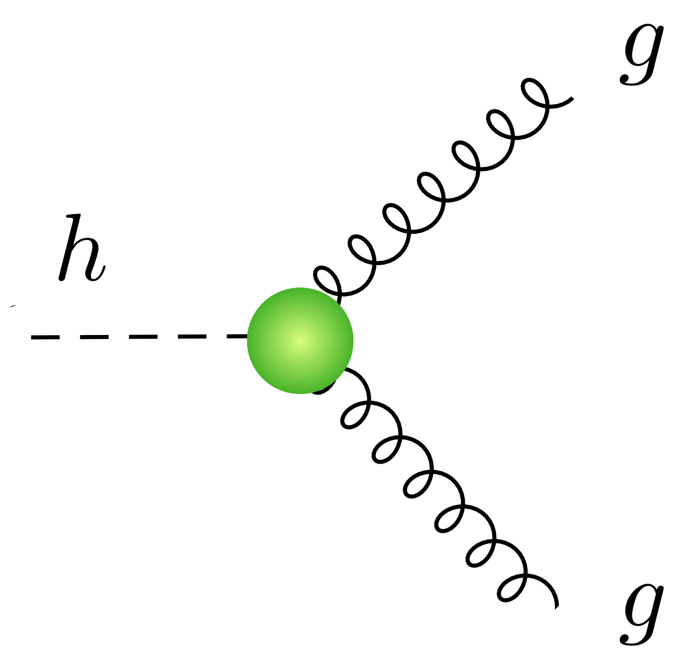
Research area: BSM phenomenology

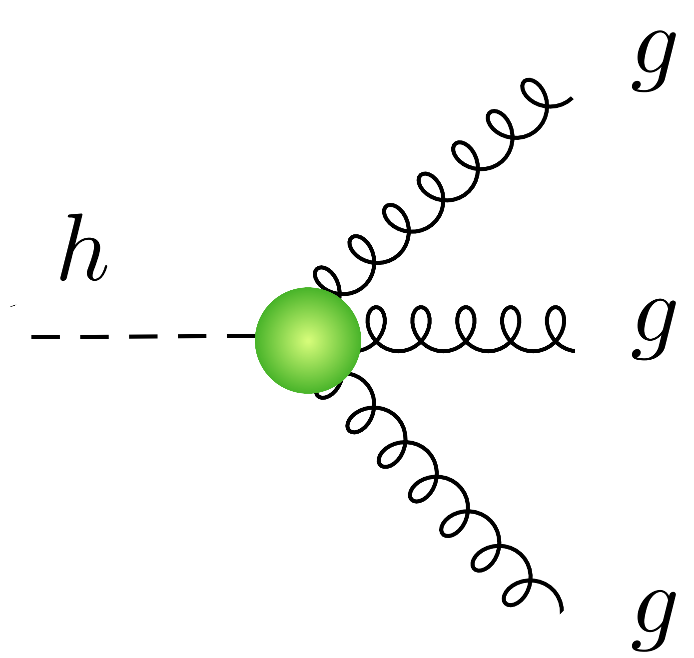
Theory group "BSM phenomenology" consists of three PhD students, i.e. Amando Hala, Gabriel Koole & Stefan Schulte & myself

This talk gives a brief summary of the finished & ongoing group activities

CP-violating Higgs couplings

$$\mathcal{L} = -g_s^2\,|H|^2\,\widetilde{G}^a_{\mu\nu}G^{a,\mu\nu}C_{H\widetilde{G}}$$

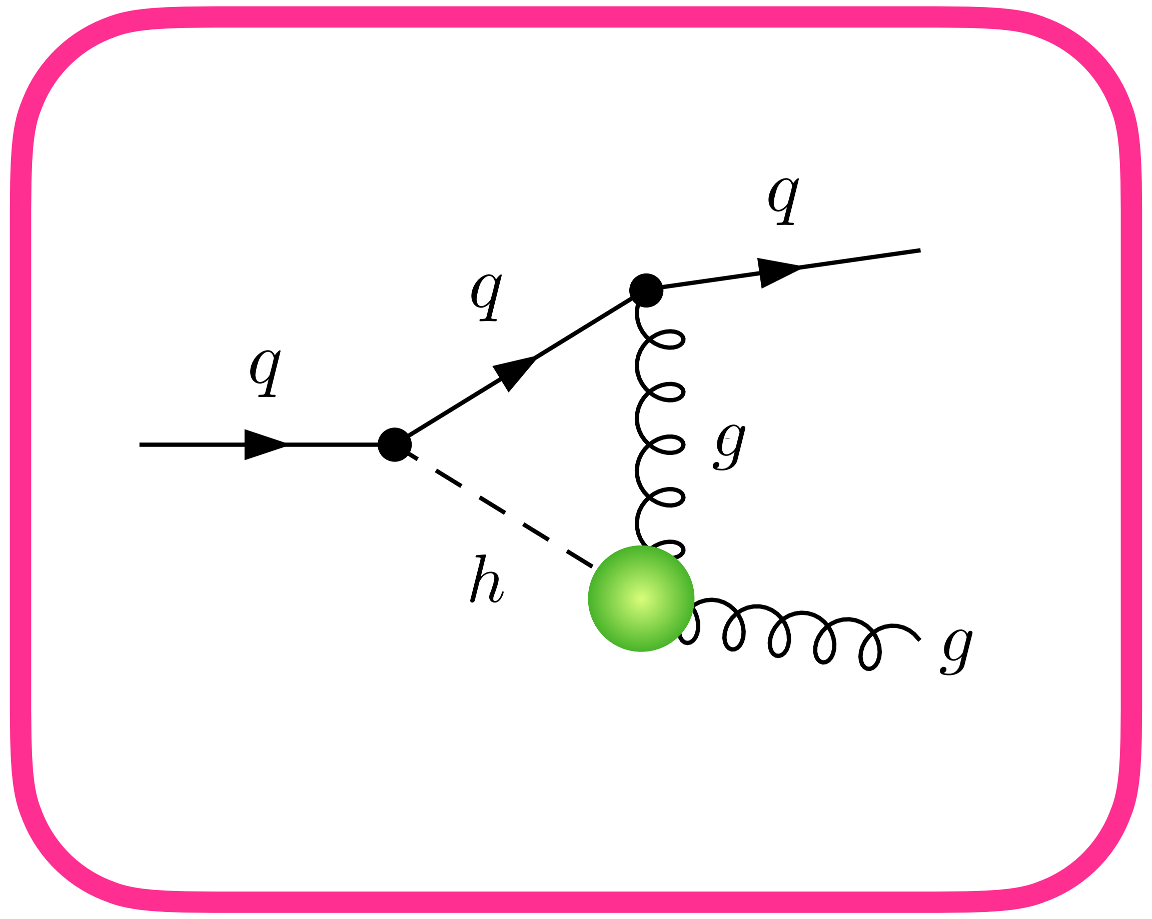




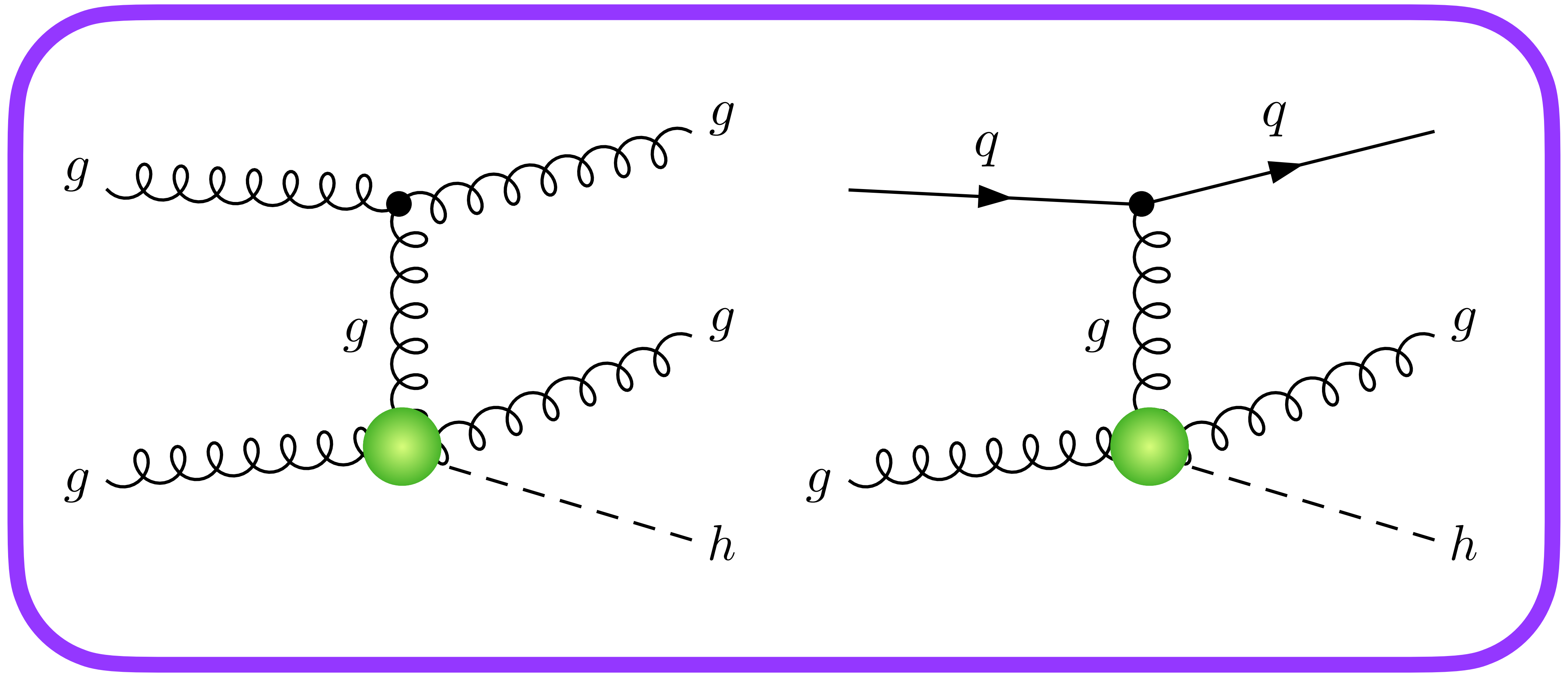
Standard Model effective field theory (SMEFT) contains one dimension-six CP-violating operators that couples a Higgs to gluons

[UH & Hala, JHEP 11 (2019) 117; JHEP 11 (2019) 154]

CP-violating Higgs couplings



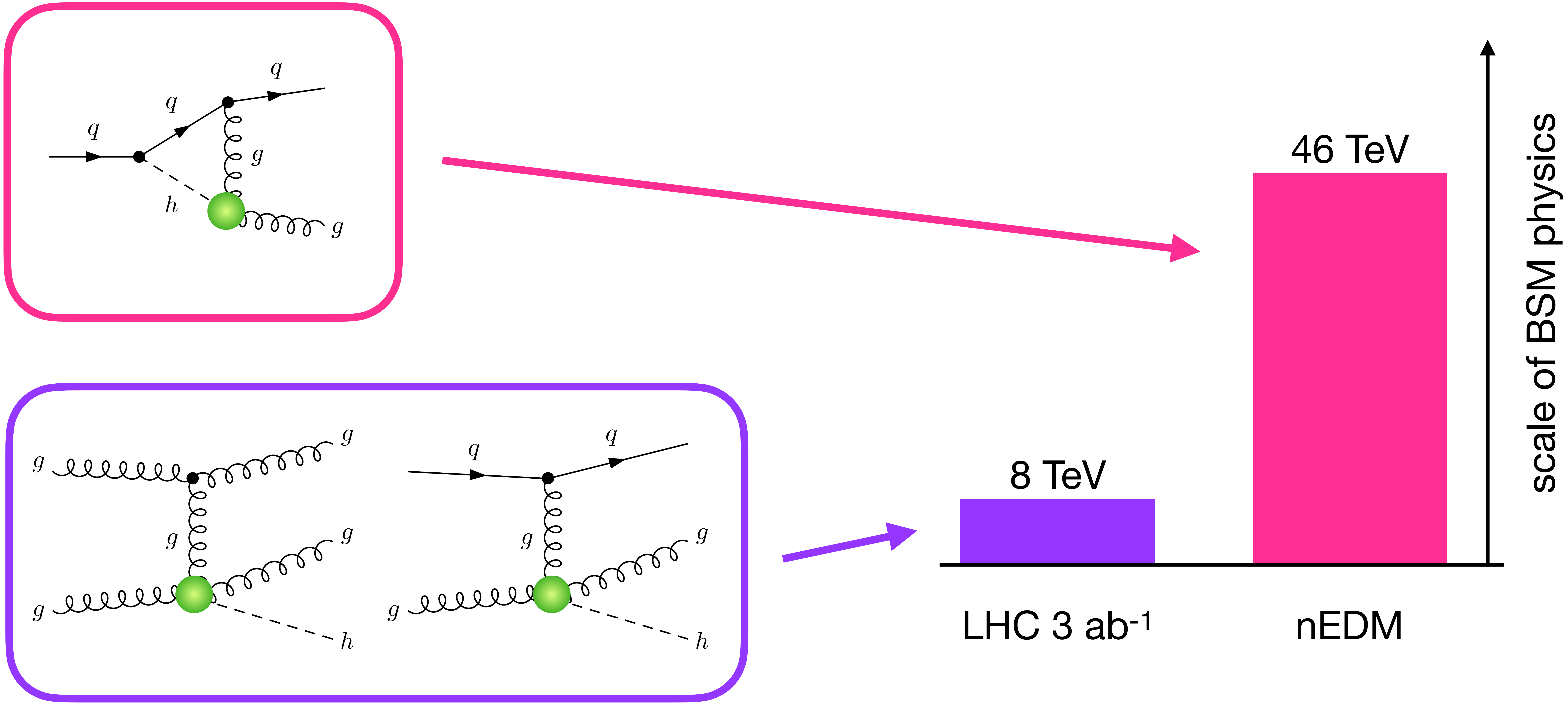
gives a contribution to the electric dipole moment of the neutron (nEDM)



leads to pp → h + 2 jets production @ the LHC

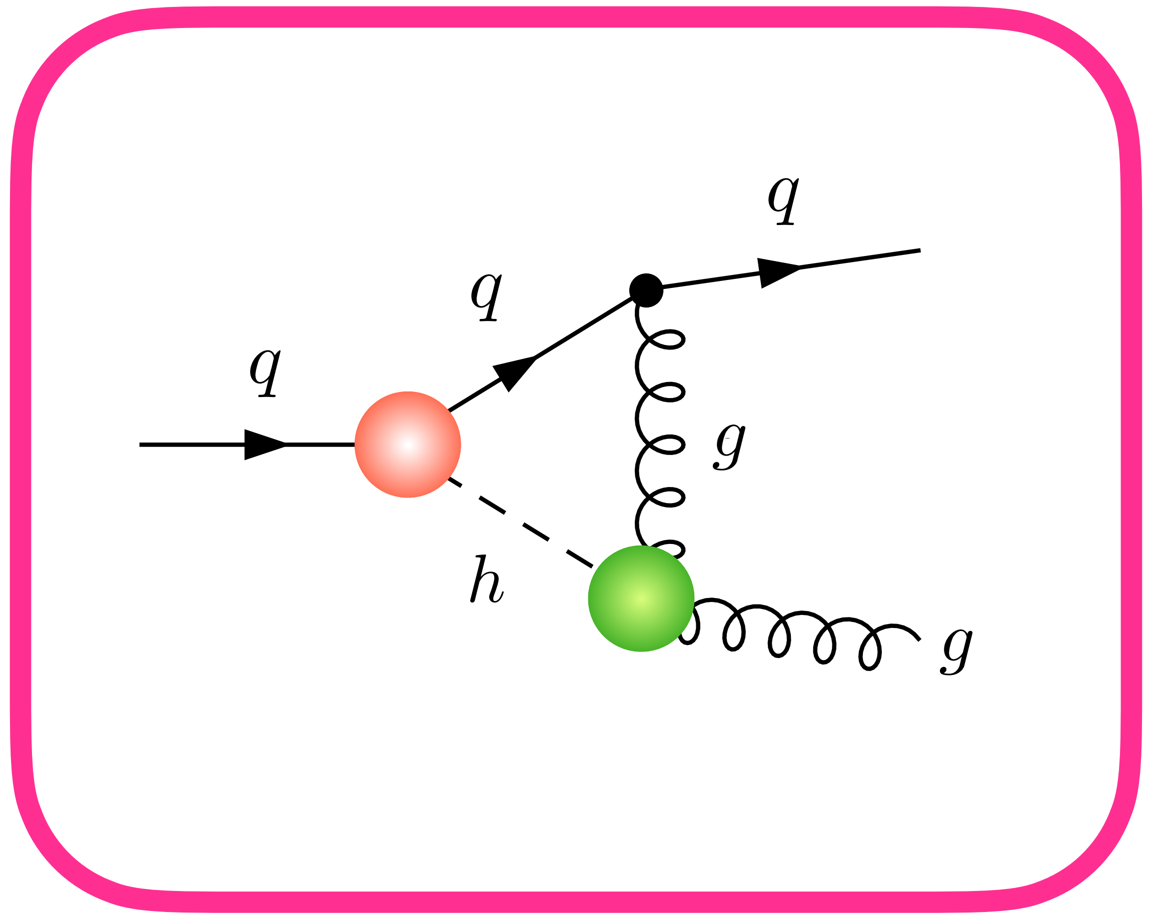
[UH & Hala, JHEP 11 (2019) 117; JHEP 11 (2019) 154]

CP-violating Higgs couplings

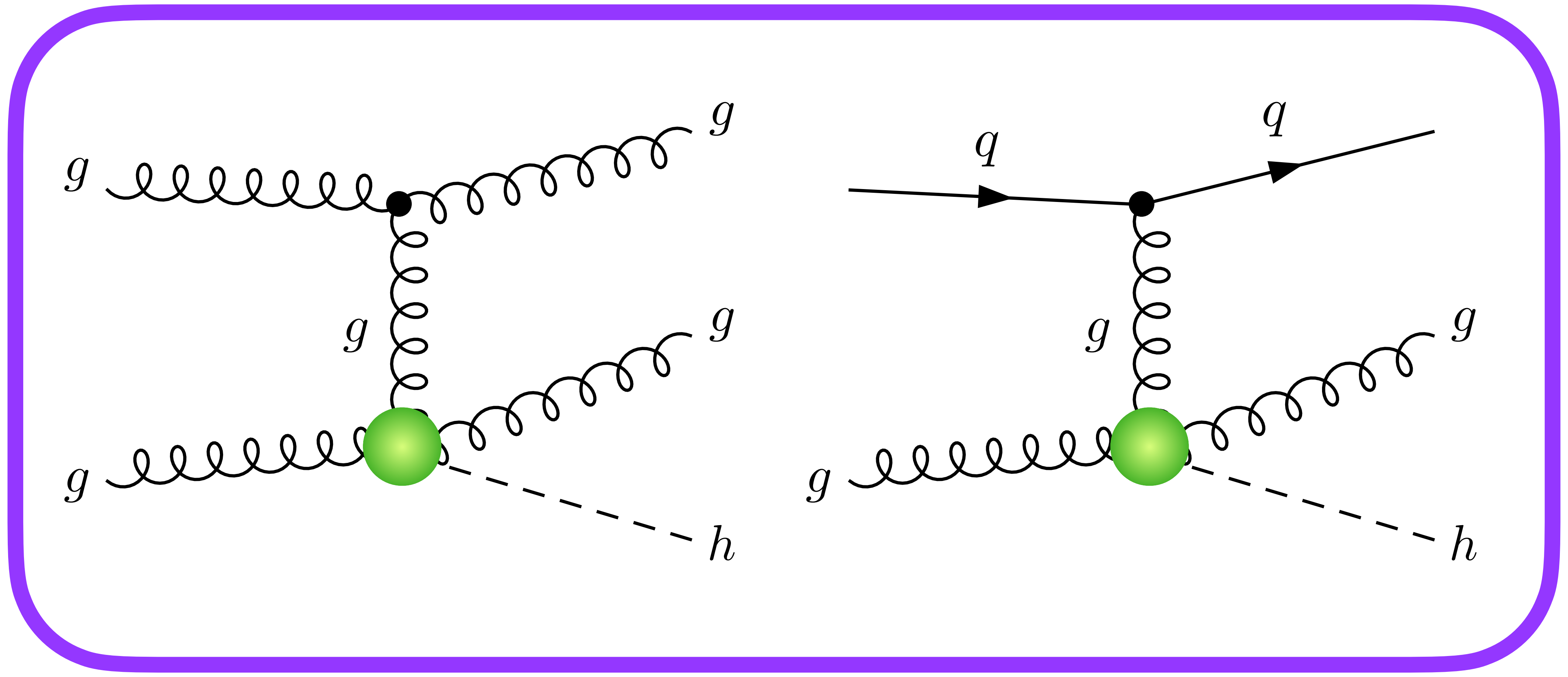


[UH & Hala, JHEP 11 (2019) 117; JHEP 11 (2019) 154]

CP-violating Higgs couplings

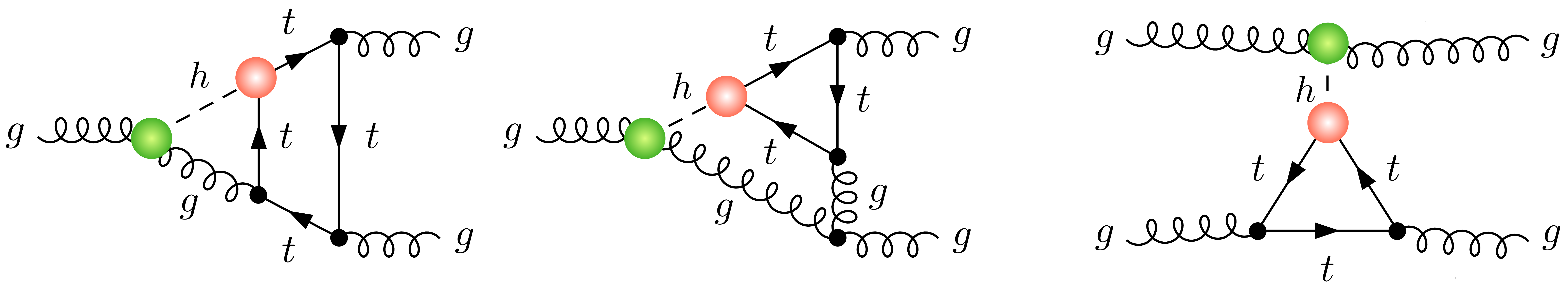


But nEDM bound assumes that Higgs couples with Standard Model (SM) strength to up & down quarks. How do the indirect limits change if this is not the case?



[UH & Hala, JHEP 11 (2019) 117; JHEP 11 (2019) 154]

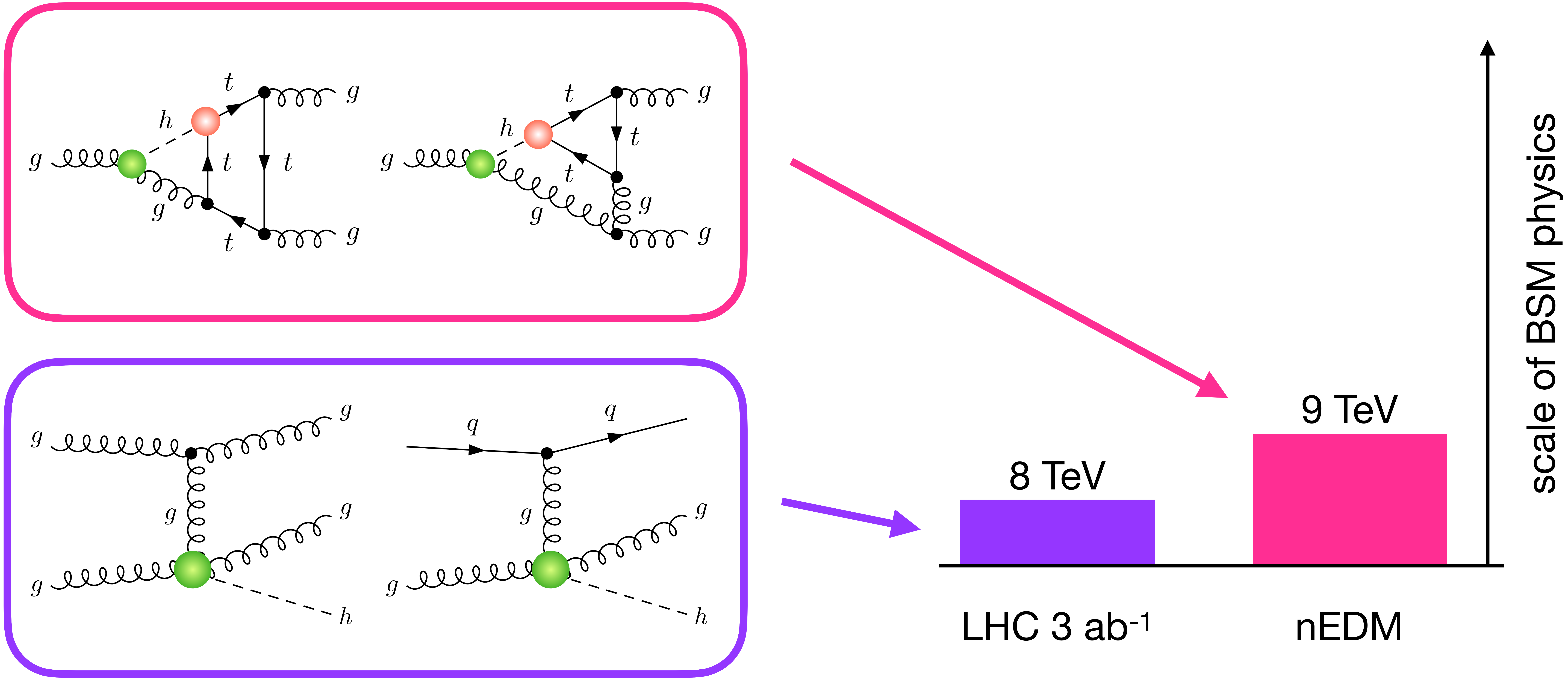
CP-violating Higgs couplings



LHC Higgs measurements tell us that 3rd generation quark Yukawa are SM-like. If 1st generation quark Yukawas are zero or strongly suppressed, dominant contribution to nEDM arises from loop diagrams involving tops

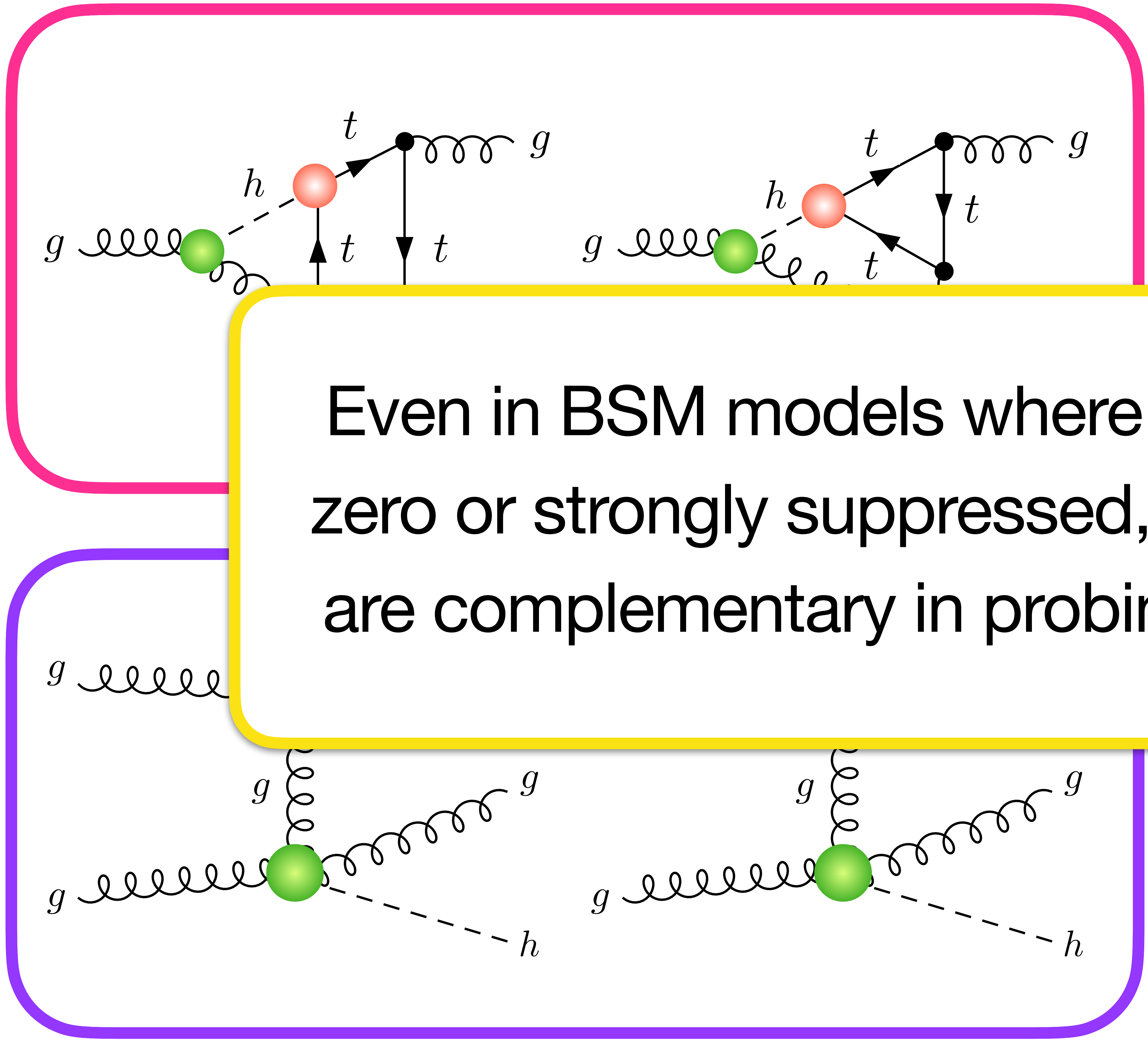
[UH & Hala, JHEP 11 (2019) 117; JHEP 11 (2019) 154]

CP-violating Higgs couplings

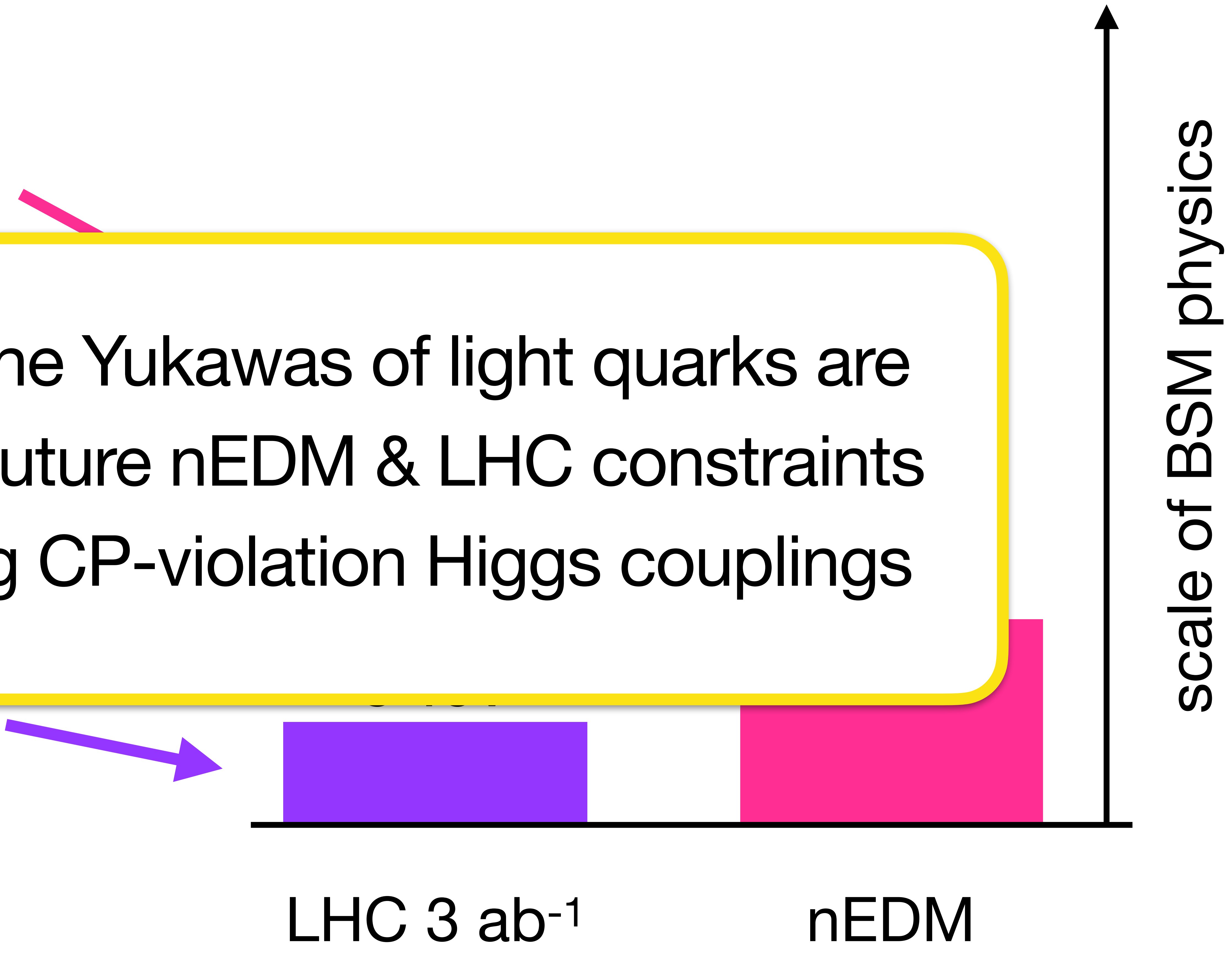


[UH & Hala, JHEP 11 (2019) 117; JHEP 11 (2019) 154]

CP-violating Higgs couplings

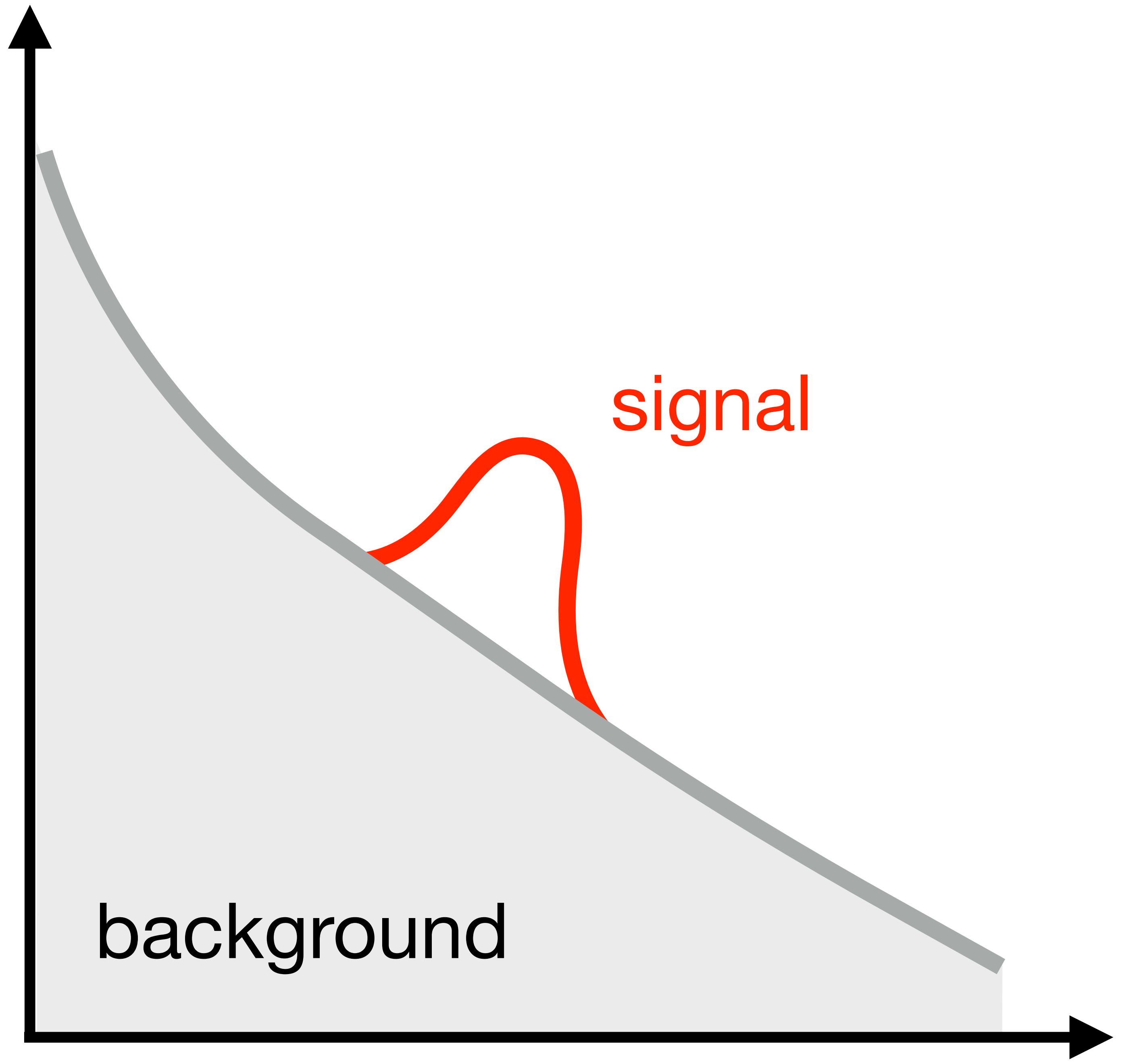


Even in BSM models where the Yukawas of light quarks are zero or strongly suppressed, future nEDM & LHC constraints are complementary in probing CP-violation Higgs couplings

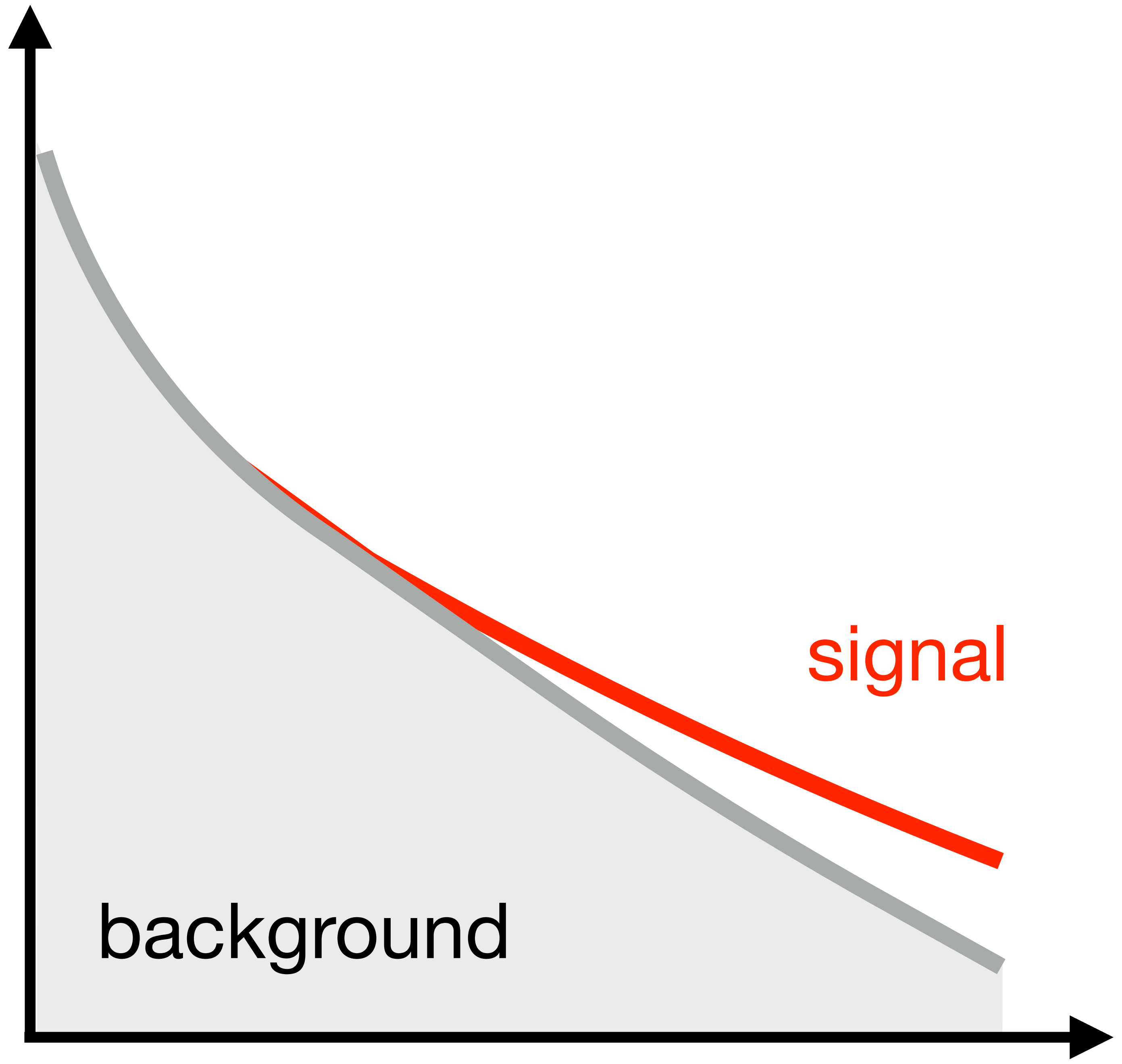


[UH & Hala, JHEP 11 (2019) 117; JHEP 11 (2019) 154]

Search strategies @ LHC

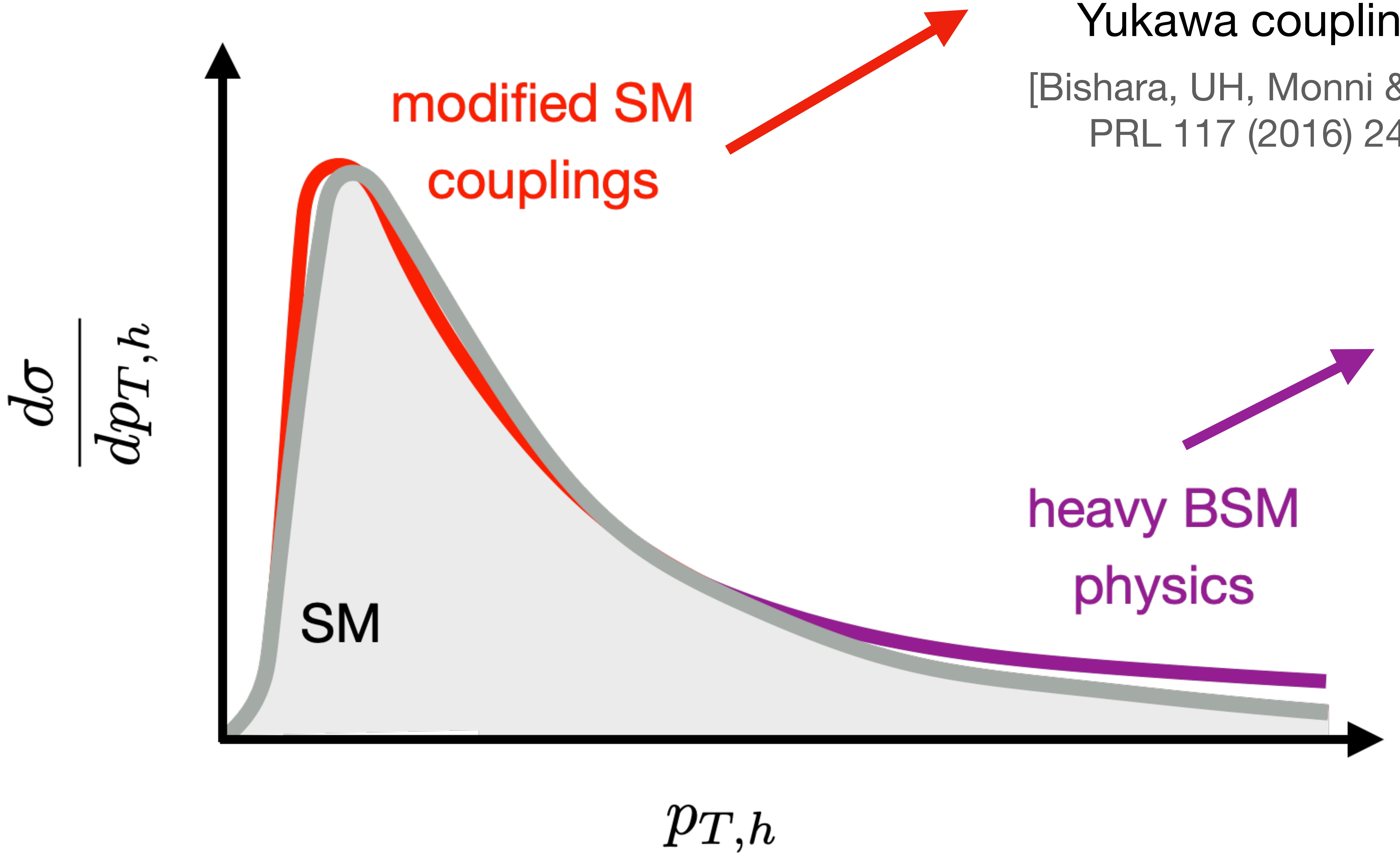


- Higgs ✓
- F(750), Σ(96) ✗
- Z′, G′ ✗
- …



- supersymmetry ✗
- leptoquarks (LQs) ✗
- dark matter (DM) ✗
- …

Higgs transverse momentum distribution



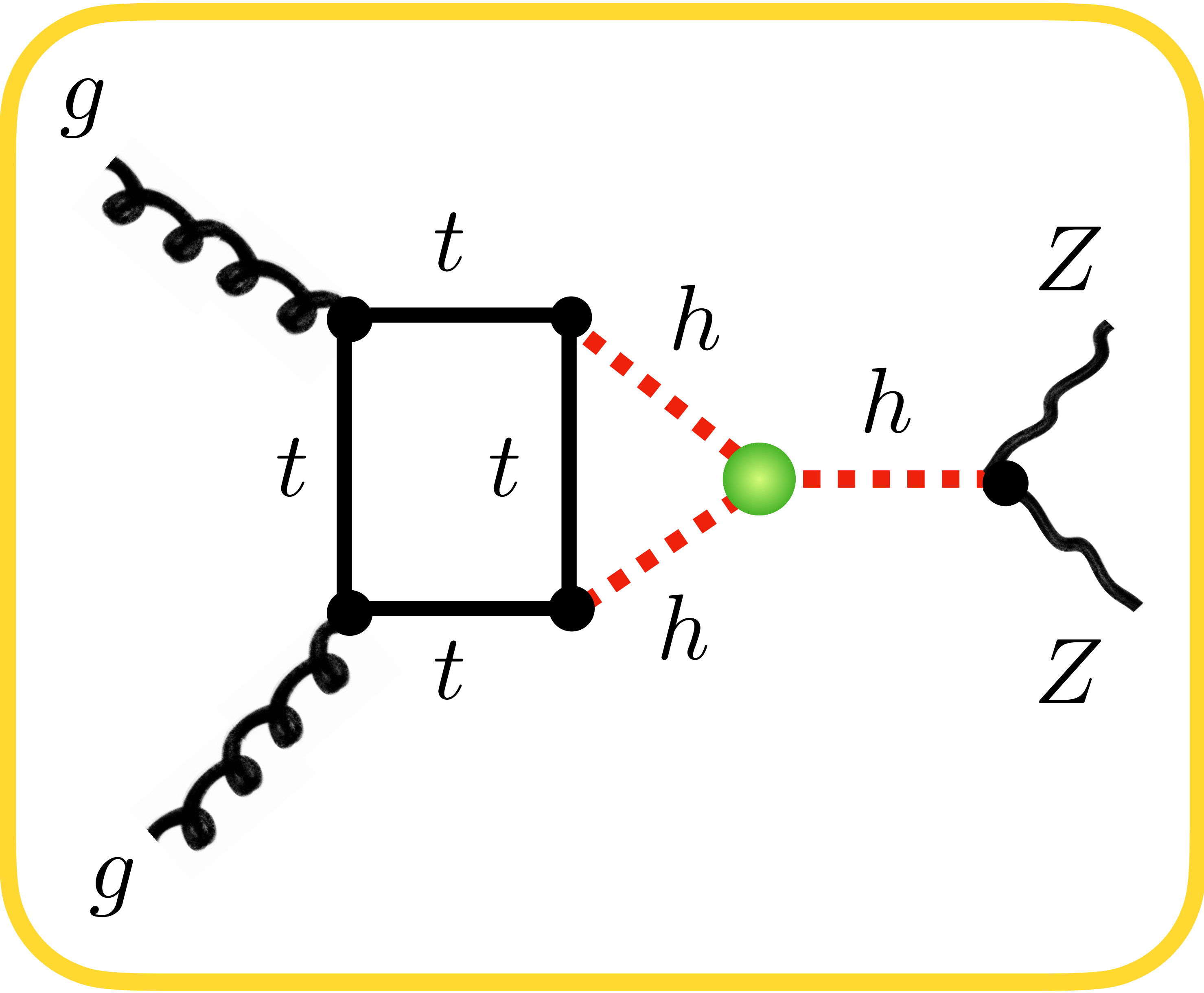
extraction of charm Yukawa coupling

[Bishara, UH, Monni & Re, PRL 117 (2016) 24]

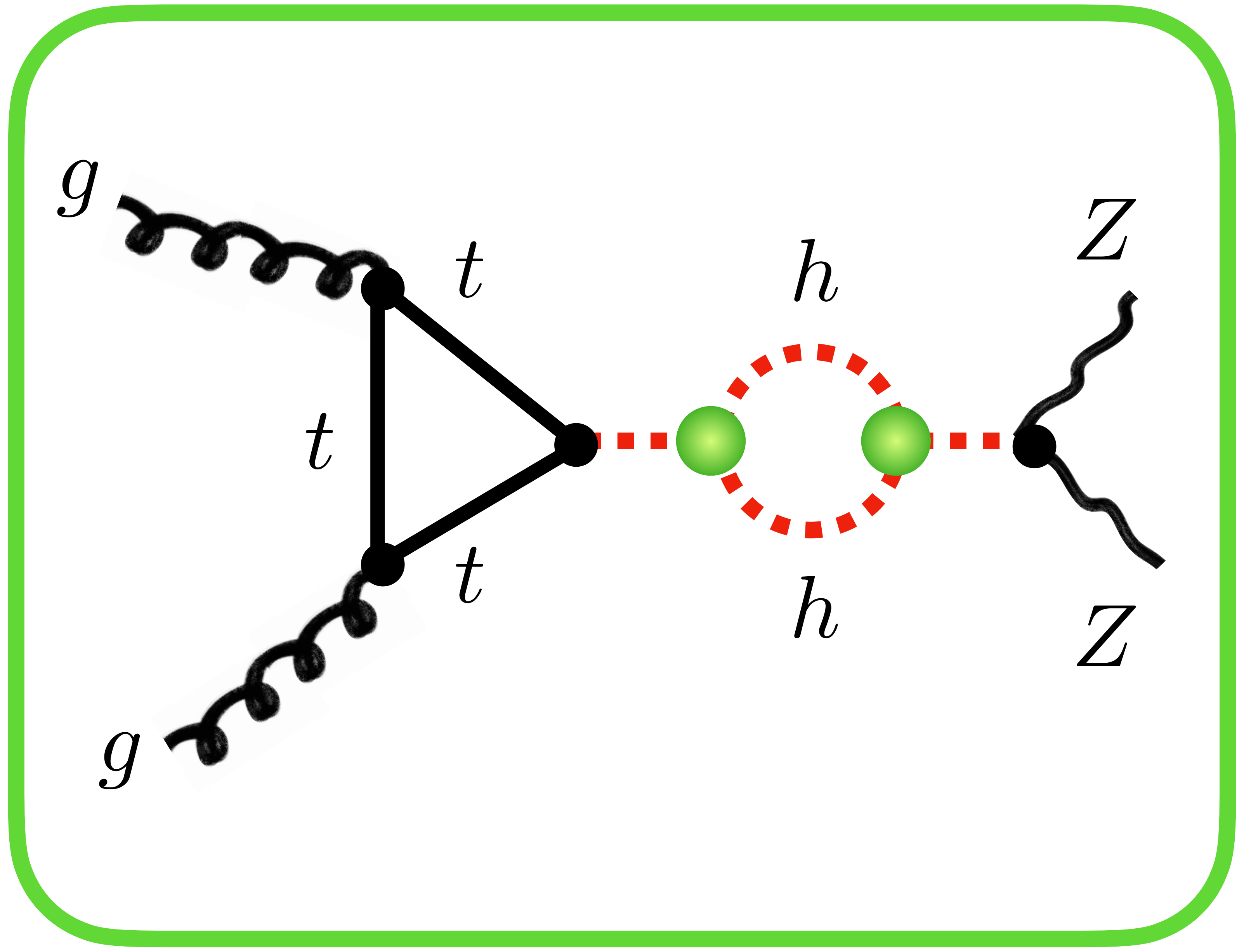
resolving effects from top Yukawa & gluon-Higgs coupling

[Wiesemann et al., JHEP 03 (2017) 115]

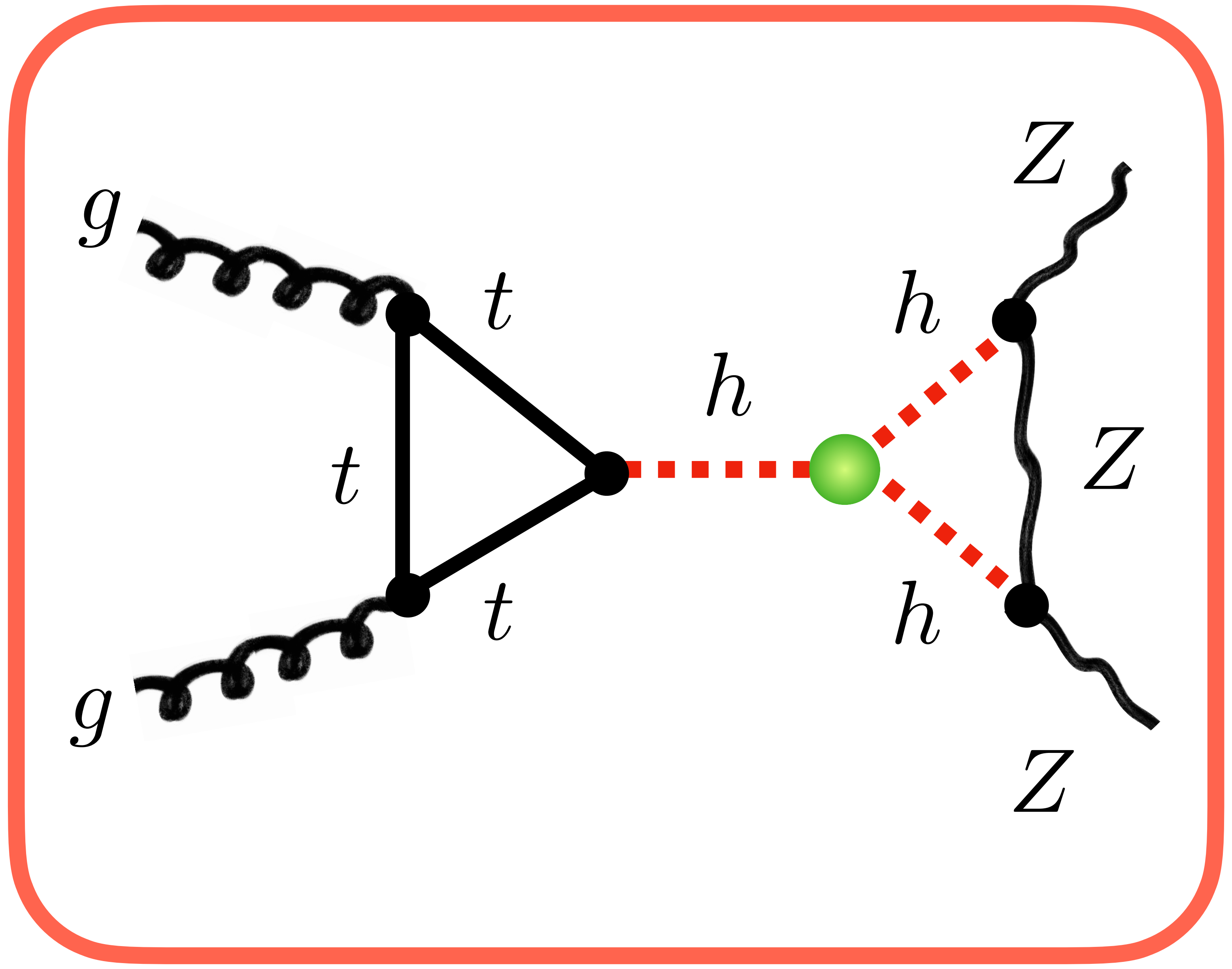
h^3 effects in off-shell Higgs production



Higgs production



Higgs propagator



Higgs decay

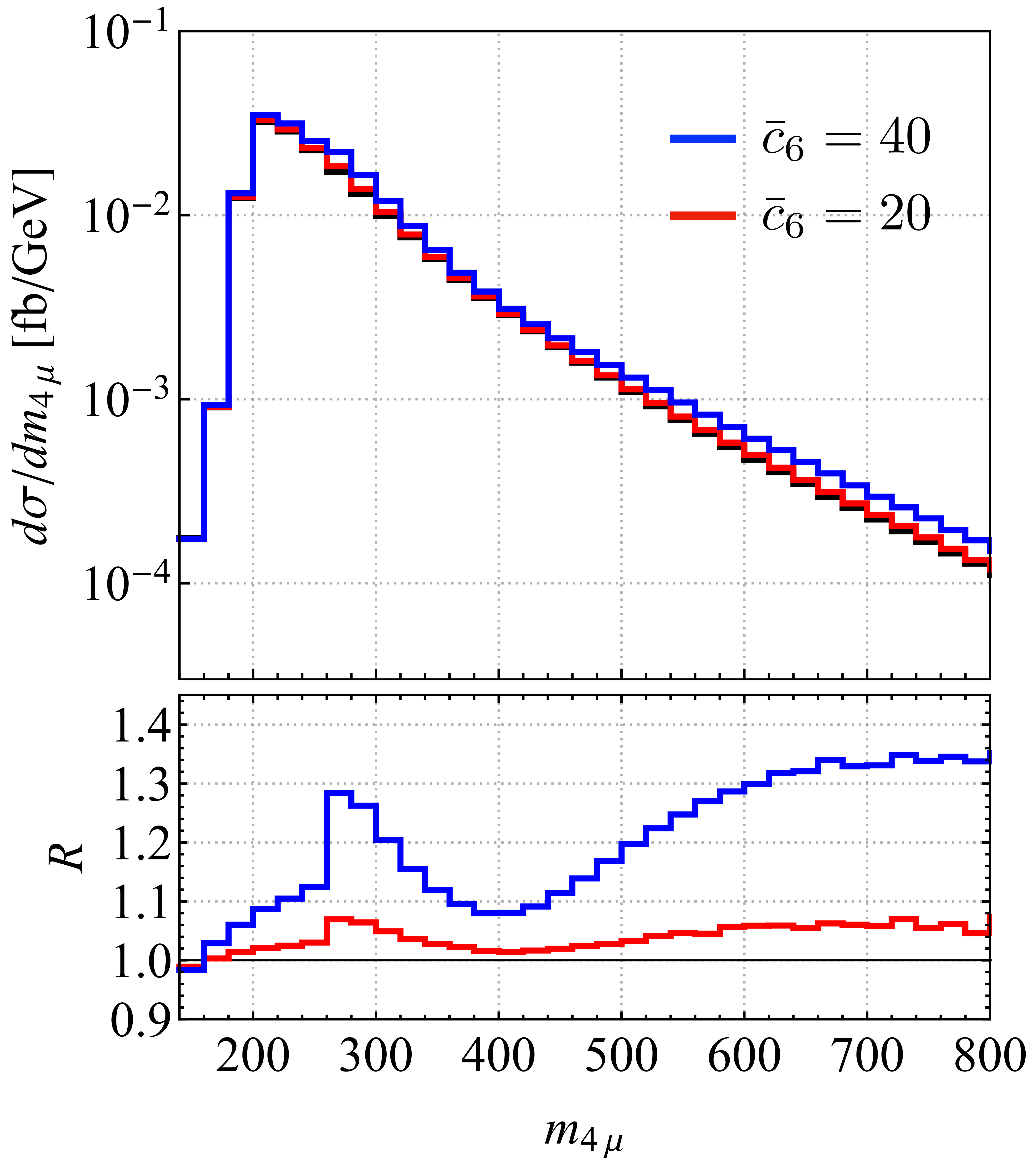
[Bizon, Gorbahn, UH, Zanderighi, JHEP 07 (2017) 083; Bizon, UH & Rottolli, JHEP 10 (2019) 267]

Four-lepton invariant mass distribution

$$\mathcal{L}_{\mathrm{SMEFT}} \supset -\frac{\lambda \bar{c}_6}{v^2} |\Phi|^6$$

after electroweak symmetry breaking

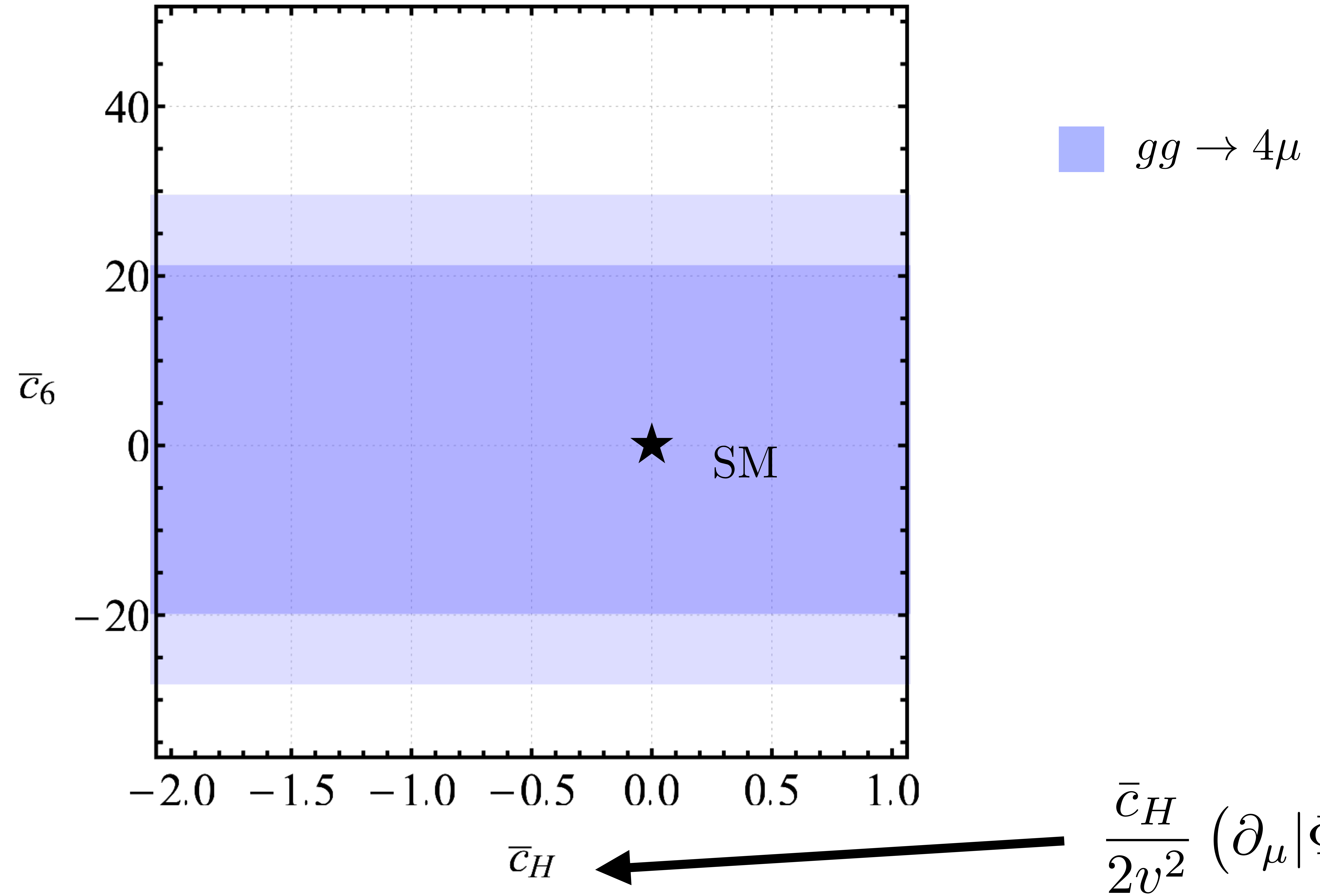
$$V_{\mathrm{SM}} \supset \lambda (1 + \bar{c}_6)\, v h^3$$



[ongoing work with Koole]

Constraints on SMEFT operators

$$-\frac{\lambda \bar{c}_6}{v^2} |\Phi|^6$$



$$\frac{\bar{c}_H}{2v^2} \left(\partial_\mu |\Phi|^2\right)^2$$

[ongoing work with Koole]

Constraints on SMEFT operators

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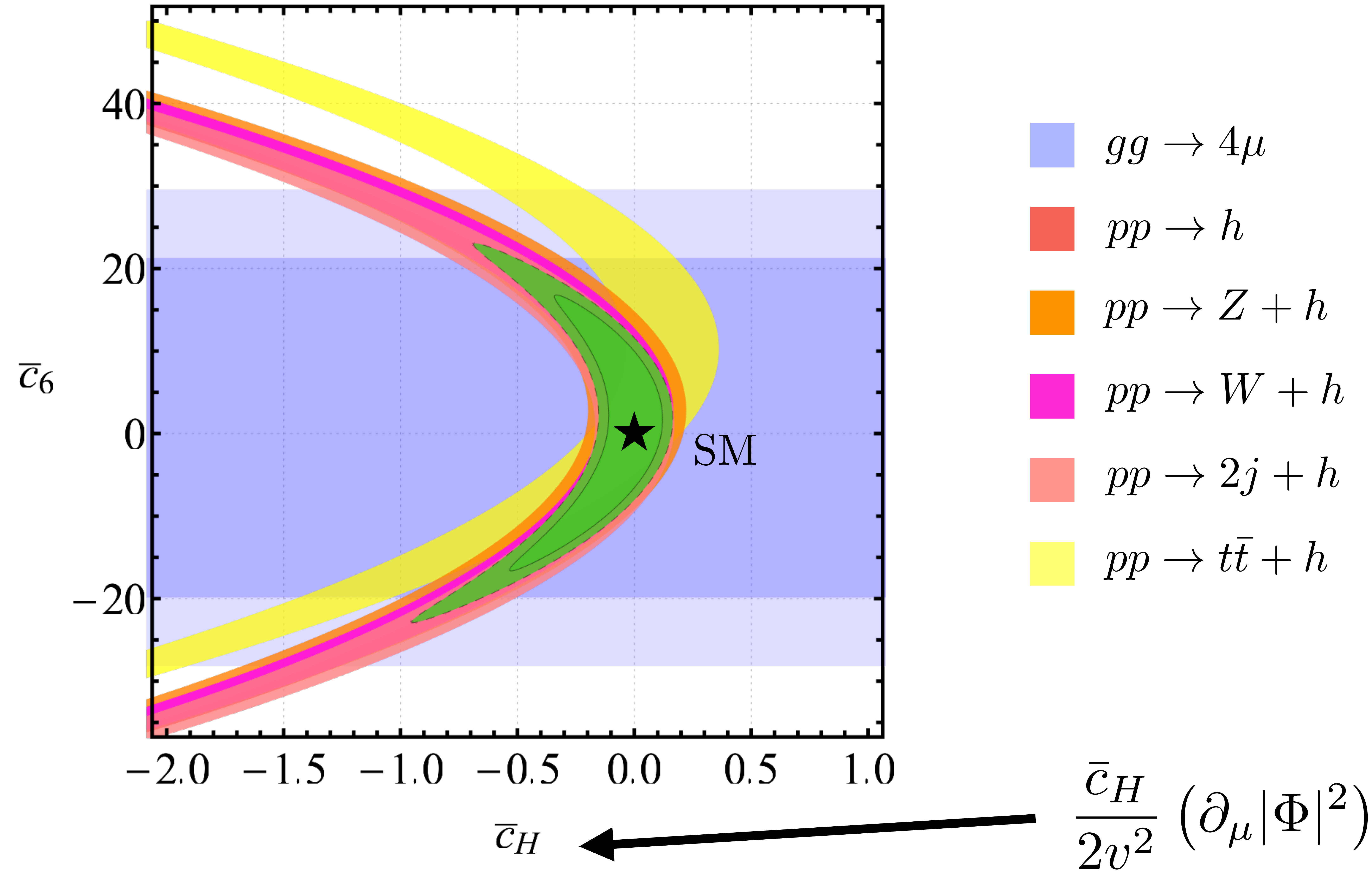

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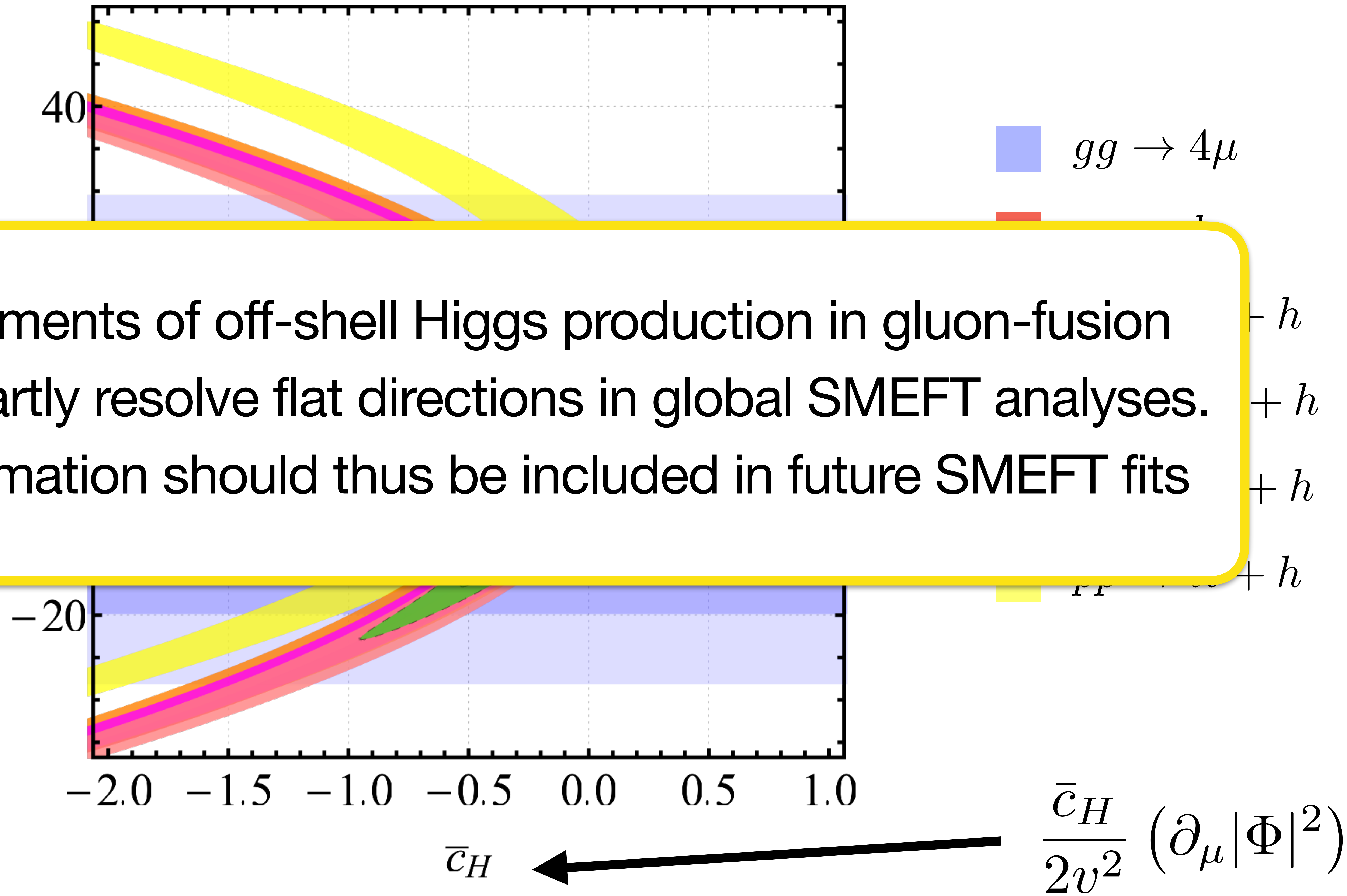
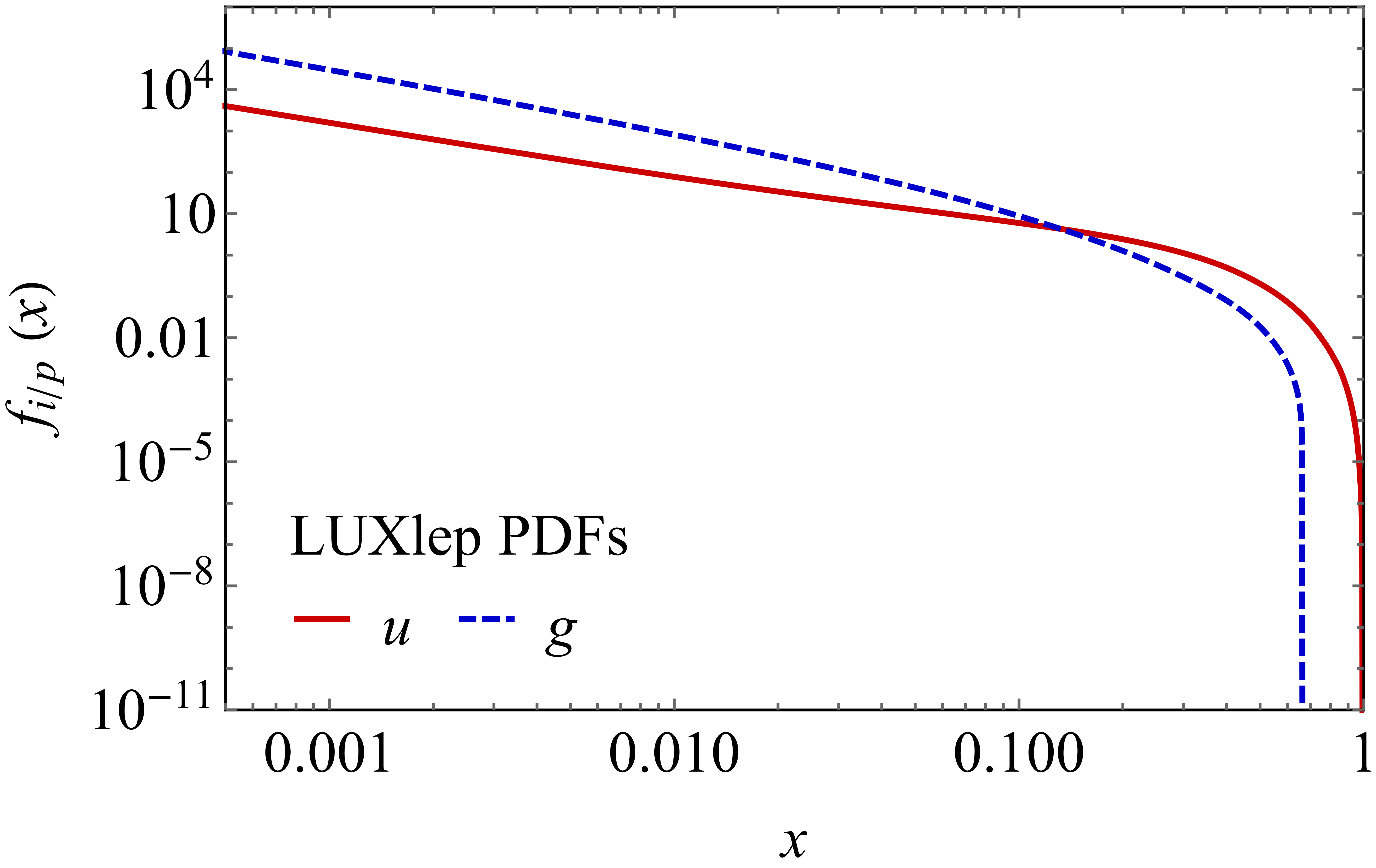


Measurements of off-shell Higgs production in gluon-fusion allow to partly resolve flat directions in global SMEFT analyses. This information should thus be included in future SMEFT fits

$\frac{\bar{c}_H}{2v^2}\left(\partial_\mu|\Phi|^2\right)^2$

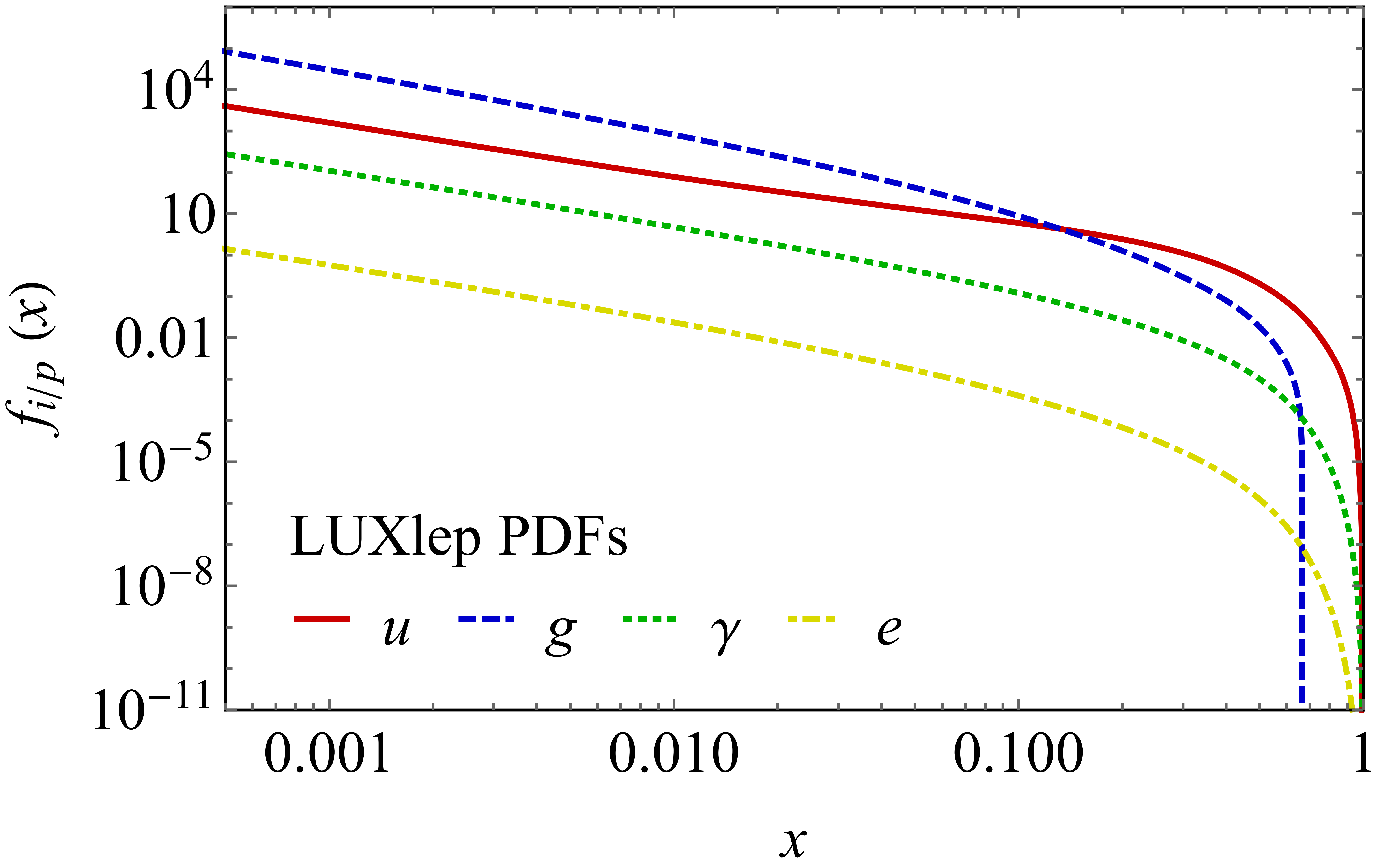
[ongoing work with Koole]

A proton consists of quarks, gluons, …



[Zanderighi et al., PRL 117 (2016) 24; JHEP 08 (2020) 08, 019]

… but also a little bit of photons & leptons



[Zanderighi et al., JHEP 08 (2020) 08, 019]

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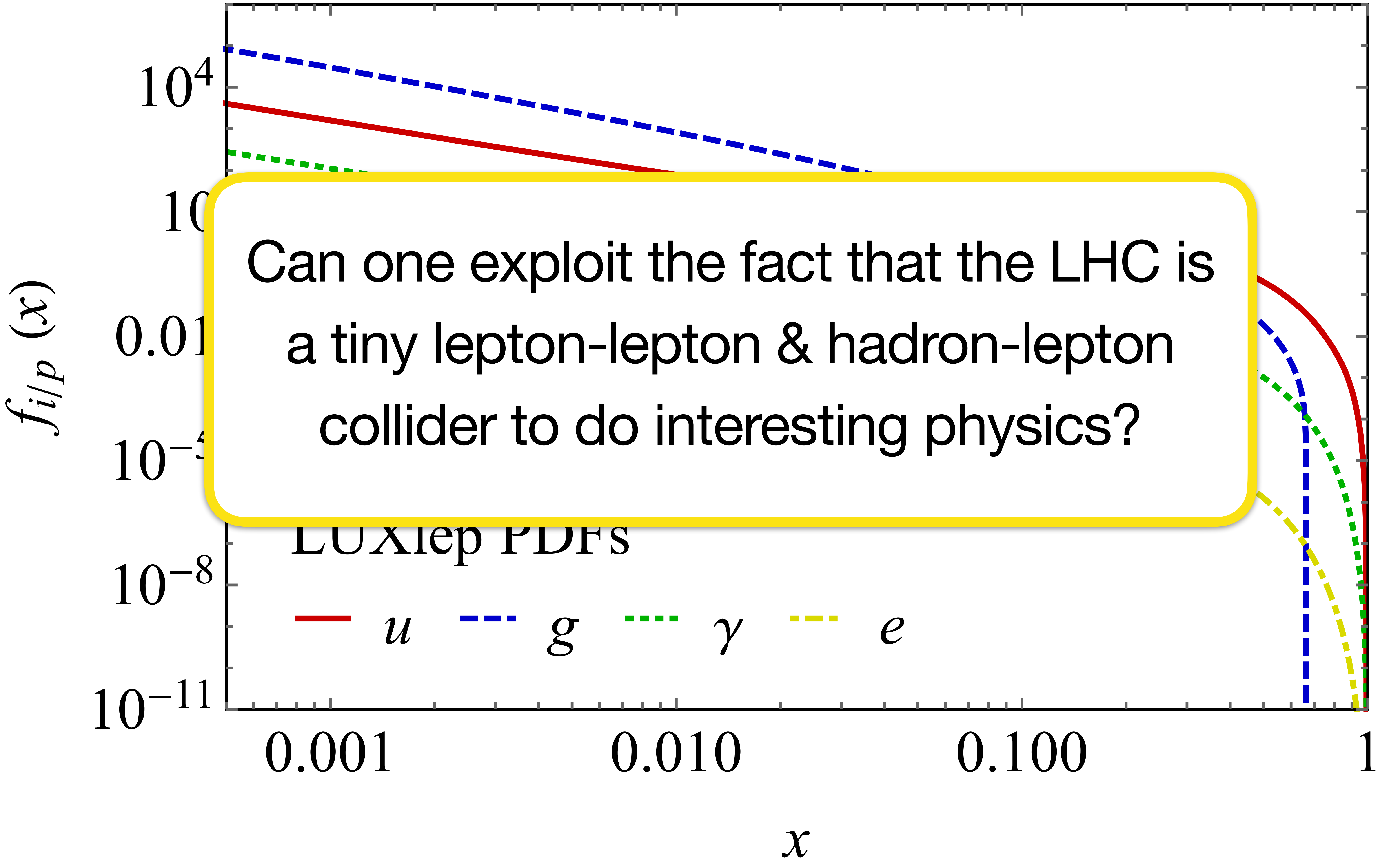
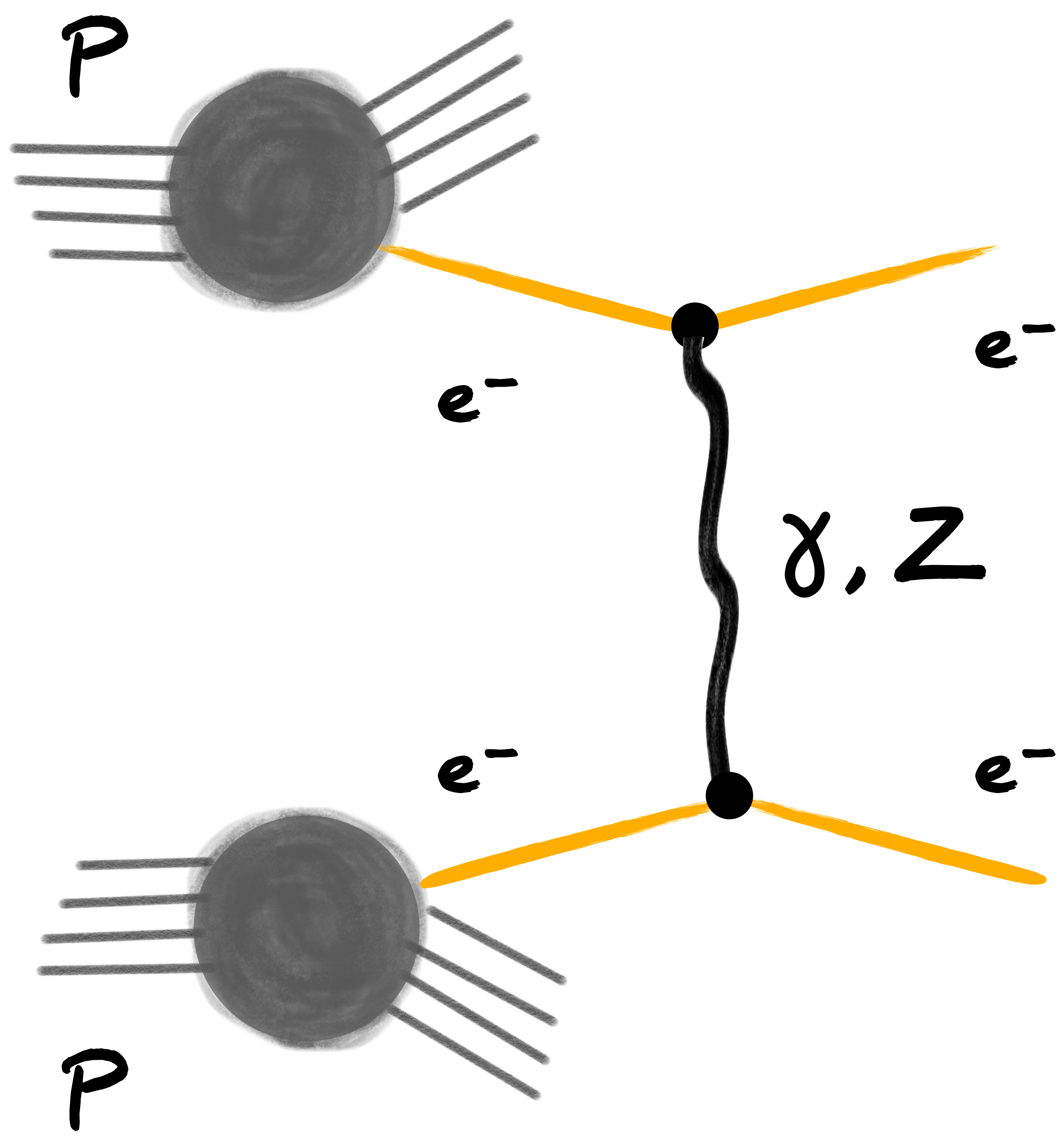


Can one exploit the fact that the LHC is a tiny lepton-lepton & hadron-lepton collider to do interesting physics?

[Zanderighi et al., PRL 117 (2016) 24; JHEP 08 (2020) 08, 019]

Same sign lepton-pair production @ LHC



Signal events after cuts:

$N_{HL\text{-}LHC}(e^-e^-) \simeq 700,$

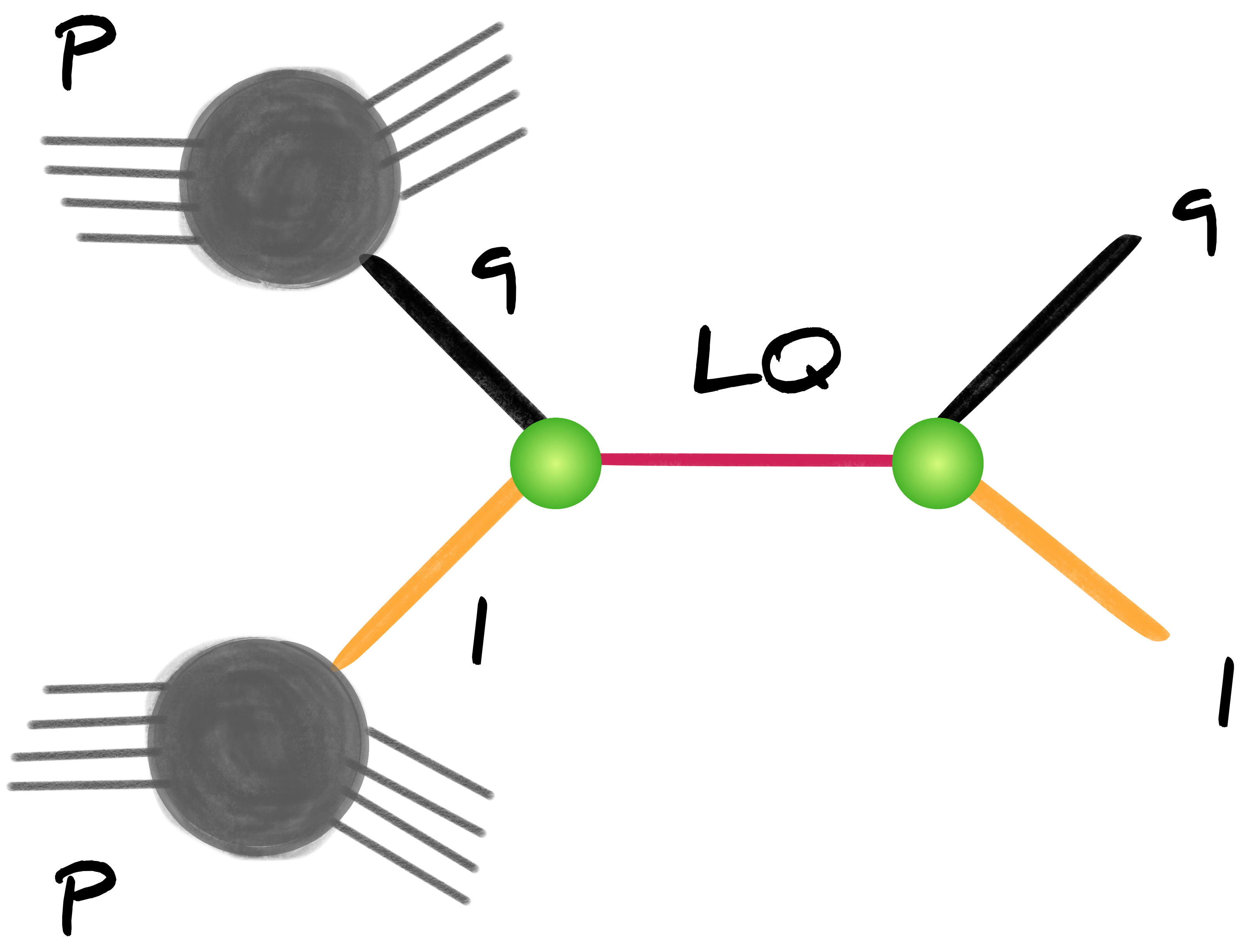
$N_{HL\text{-}LHC}(\mu^-\mu^-) \simeq 550,$

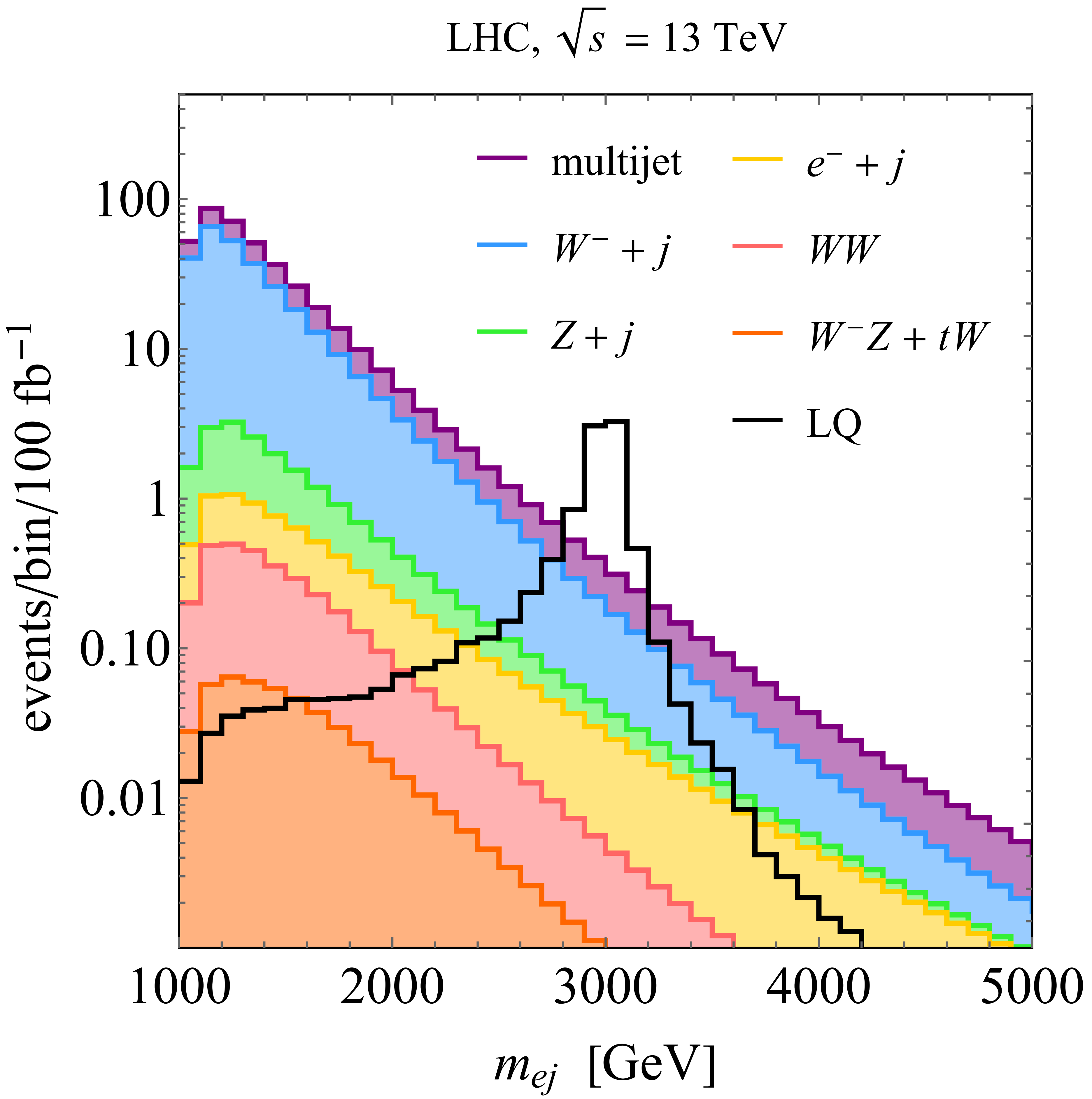
$N_{HL\text{-}LHC}(\tau^-\tau^-) \simeq 250$

Dominant SM background from W^-W^- production after same cuts close to 0

[Zanderighi et al., JHEP 08 (2020) 08, 019; ATLAS analysis ongoing]

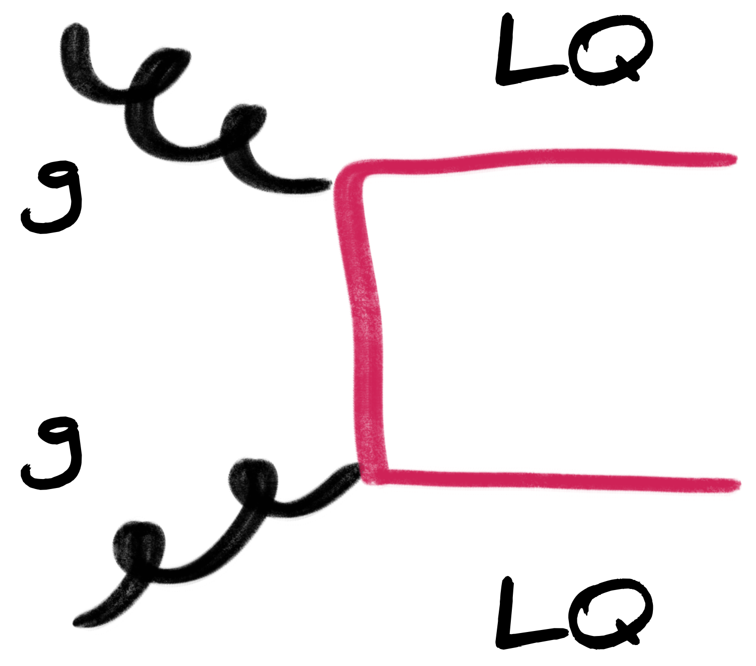
Resonant LQs @ the LHC



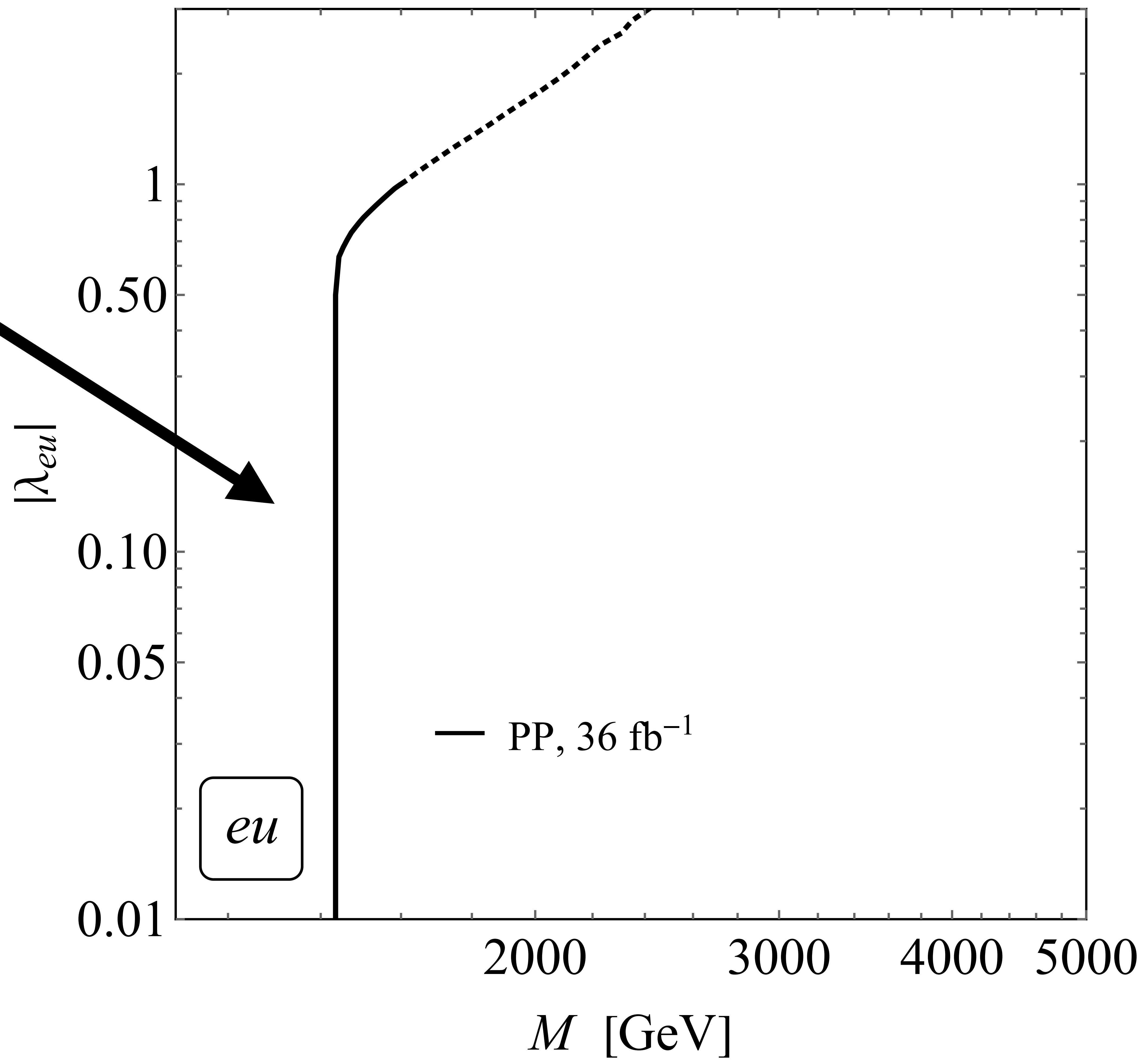


[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

LHC limits on 1st & 2nd generation LQs



LQ pair production (PP)



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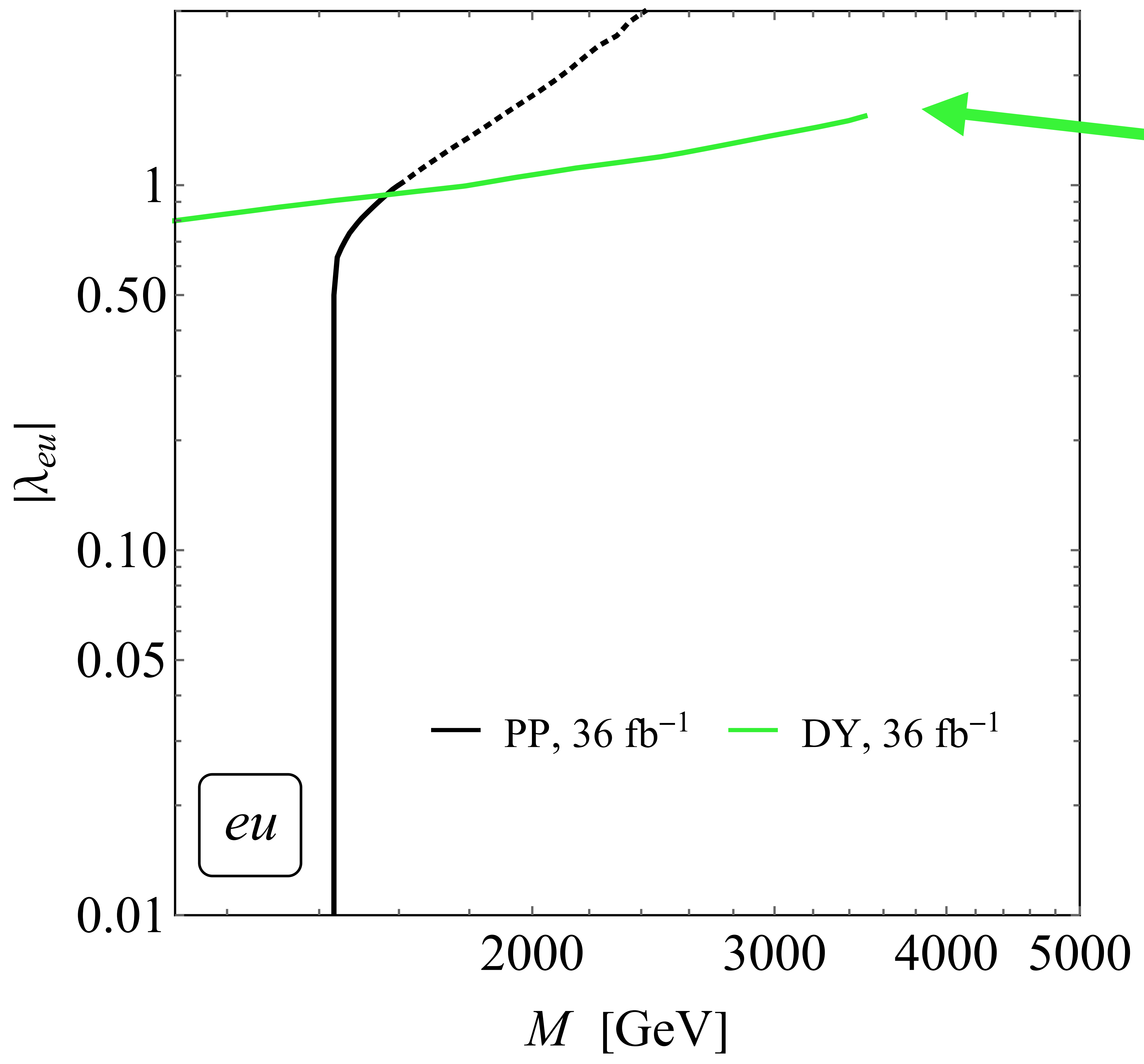
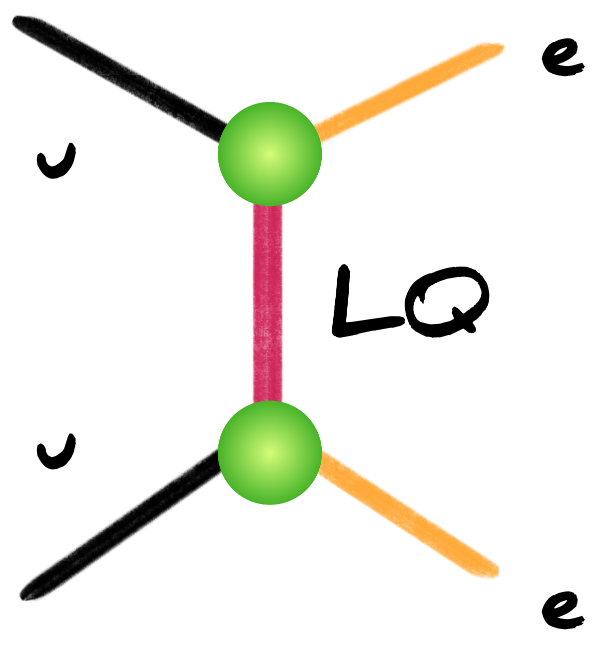
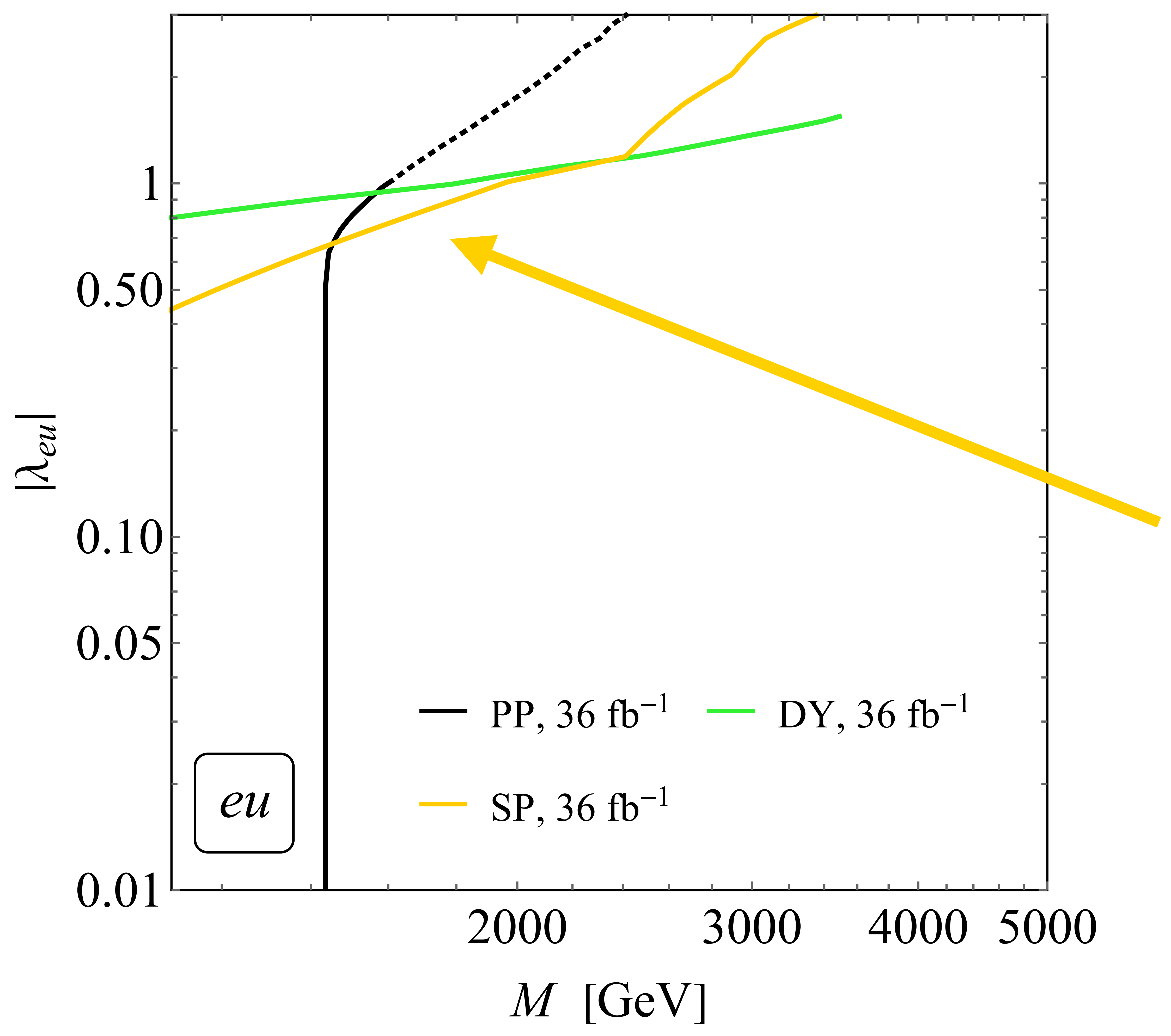


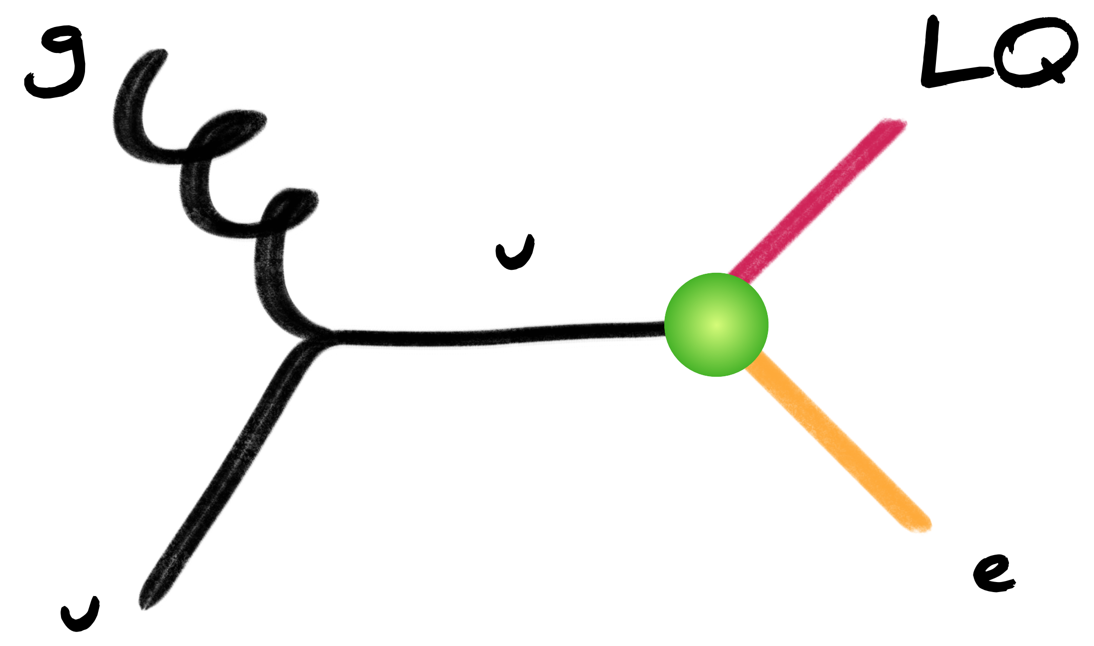


t-channel Drell-Yan (DY)

[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

LHC limits on 1st & 2nd generation LQs

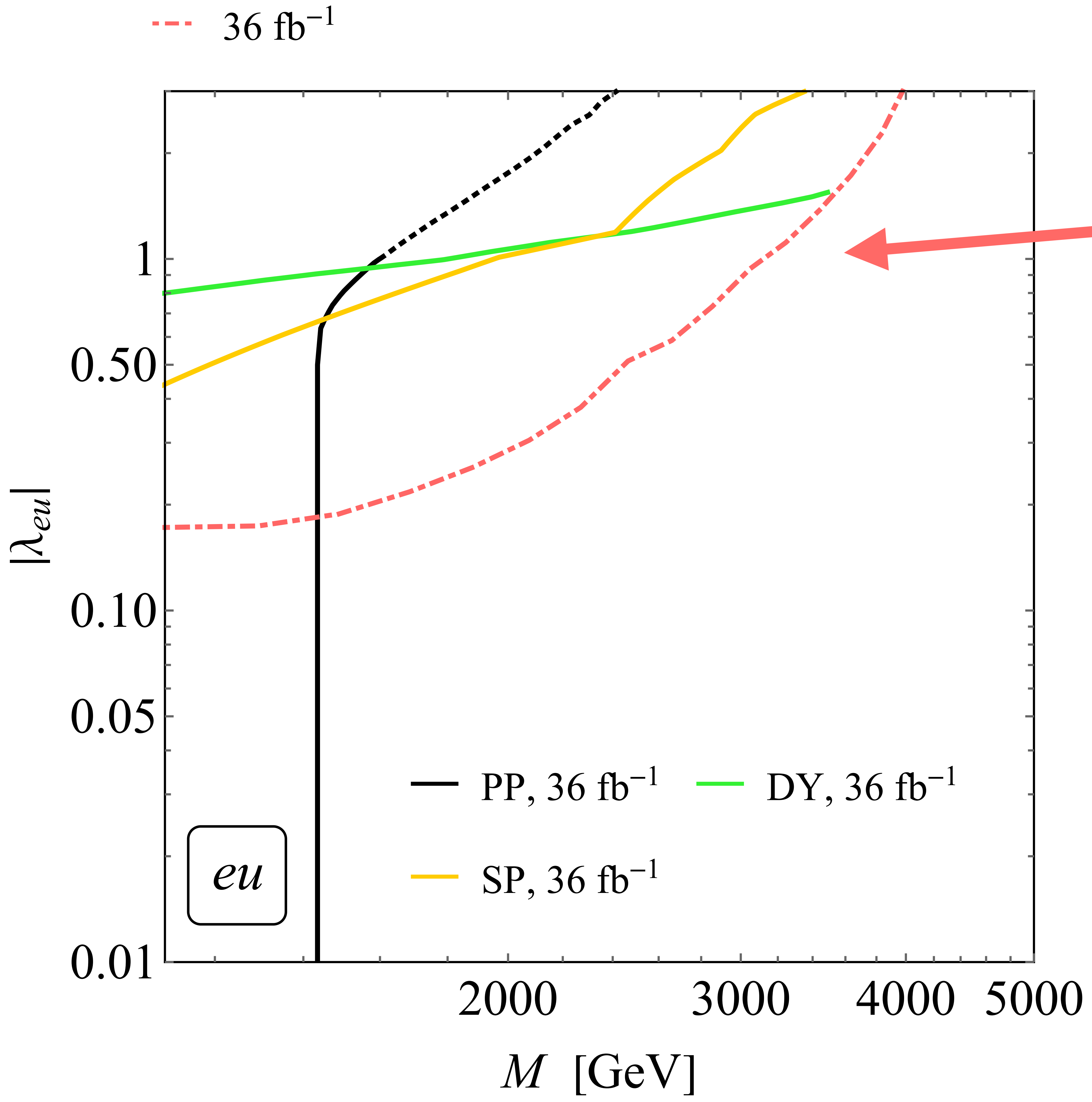


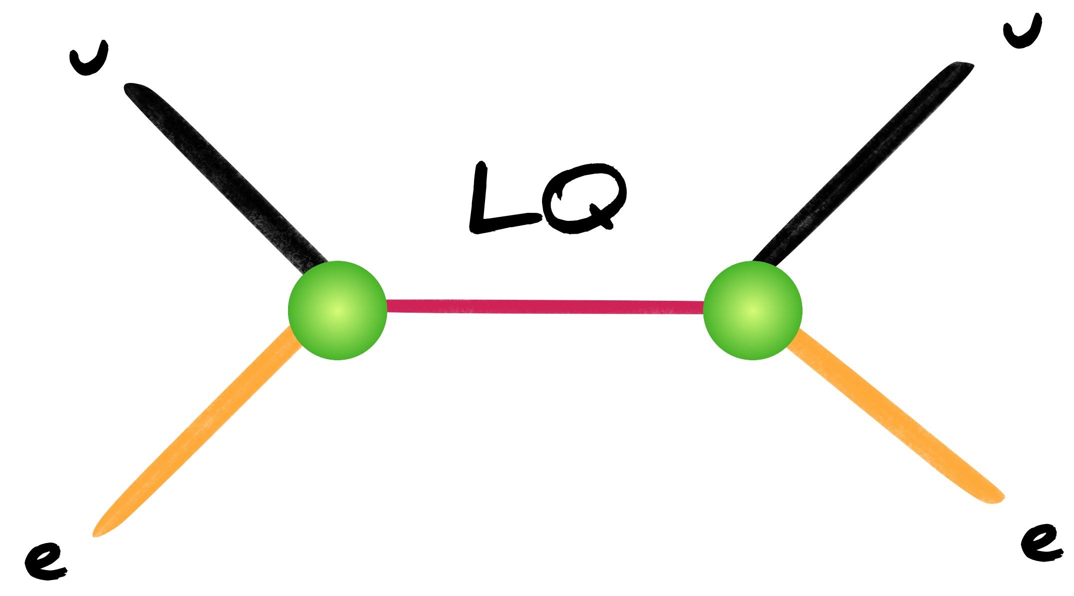


single LQ production (SP)

[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

LHC limits on 1st & 2nd generation LQs

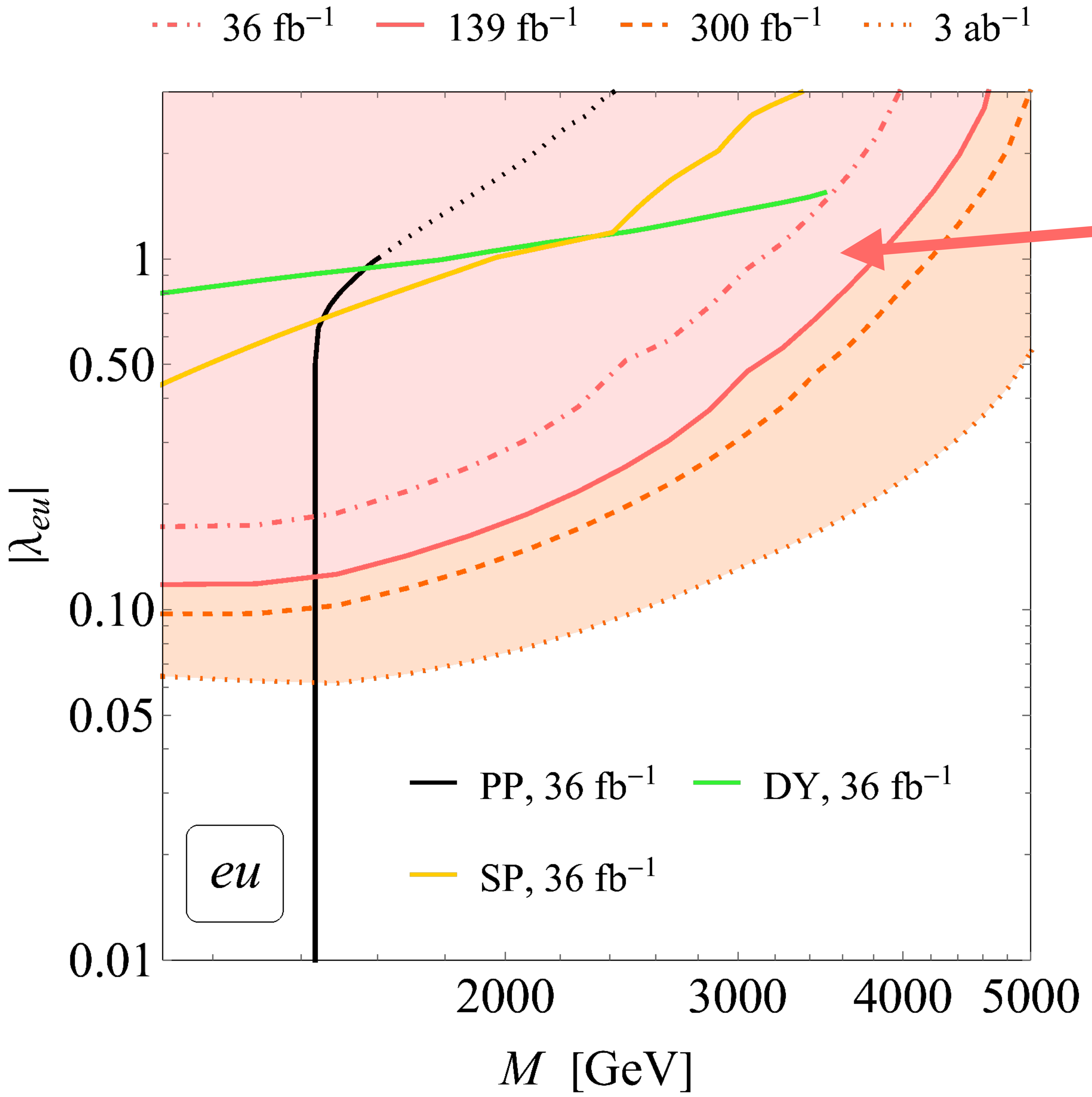


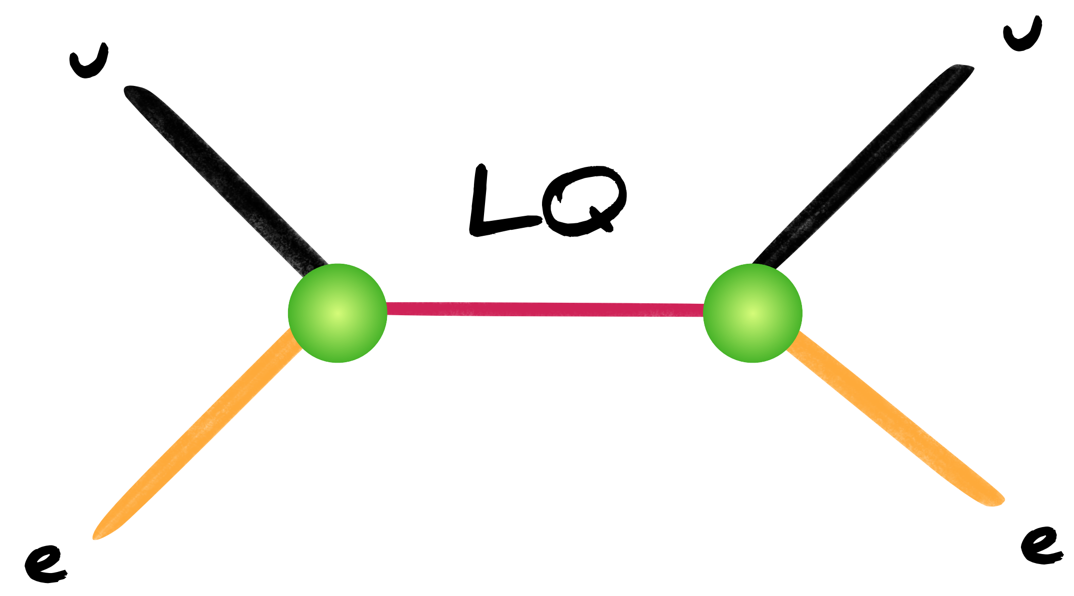


resonant LQ production

[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

LHC limits on 1st & 2nd generation LQs





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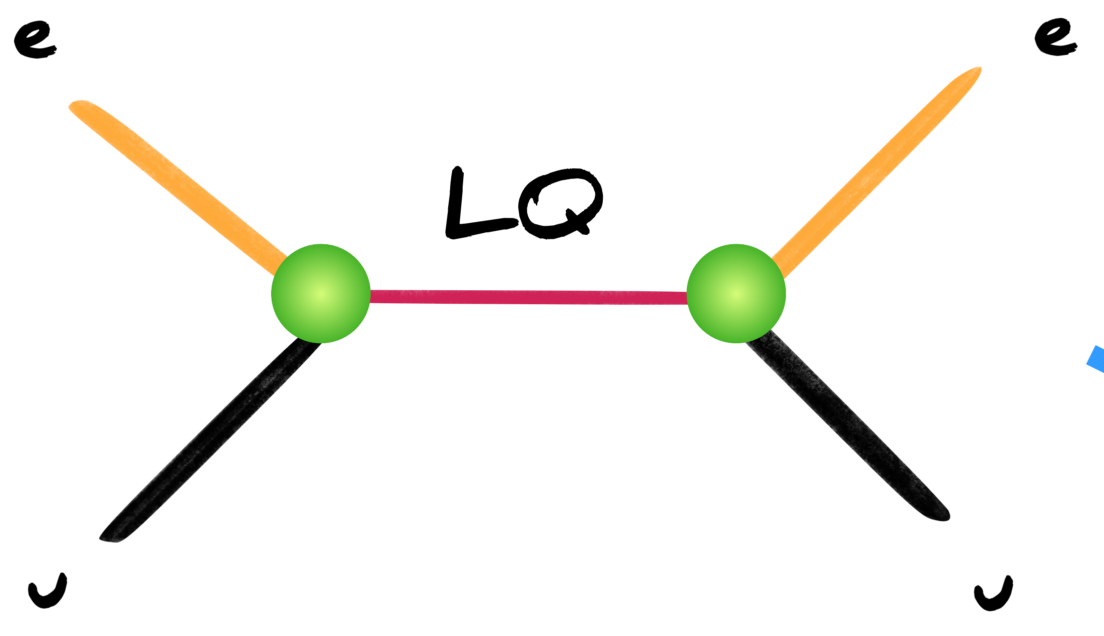
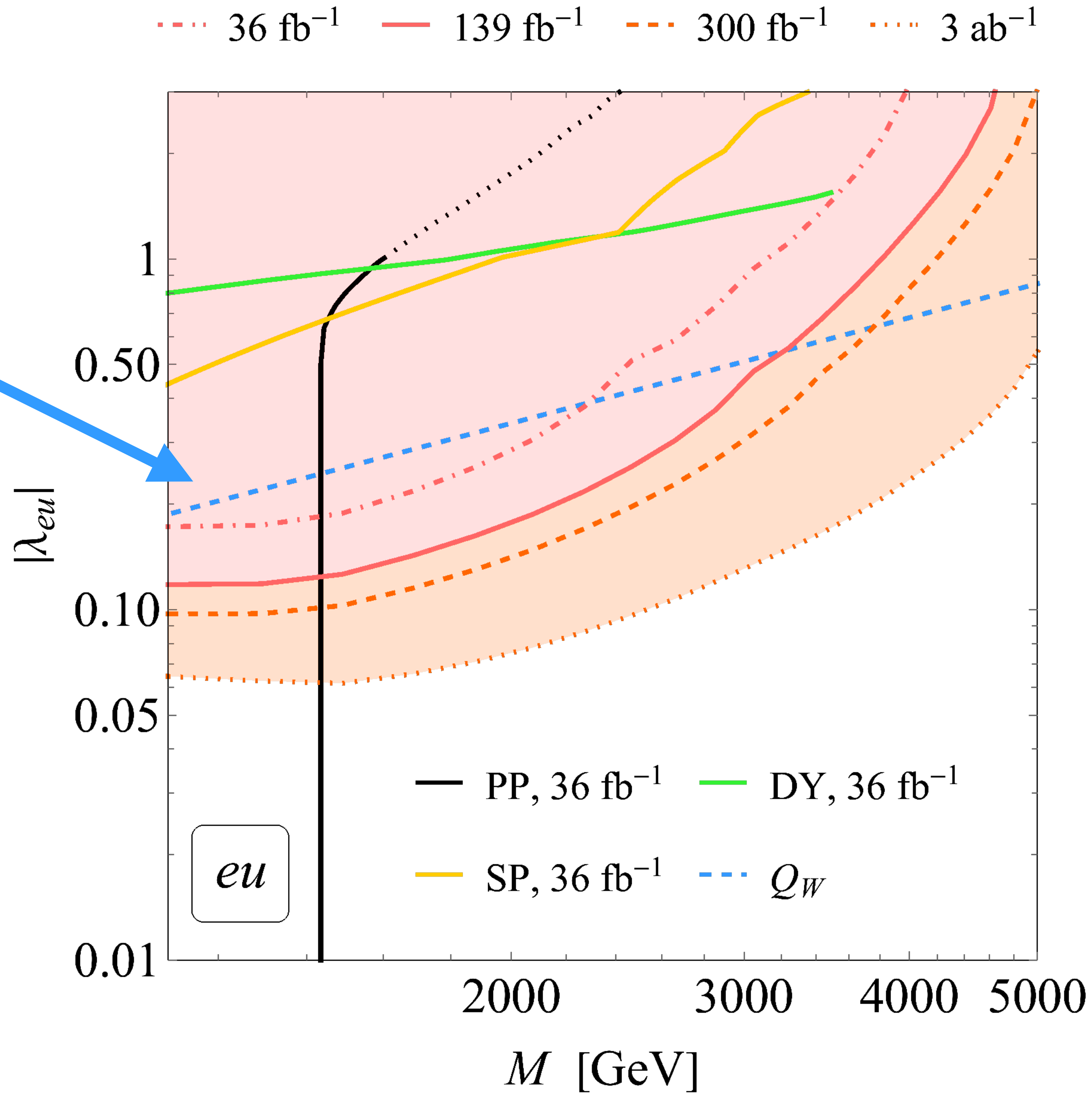
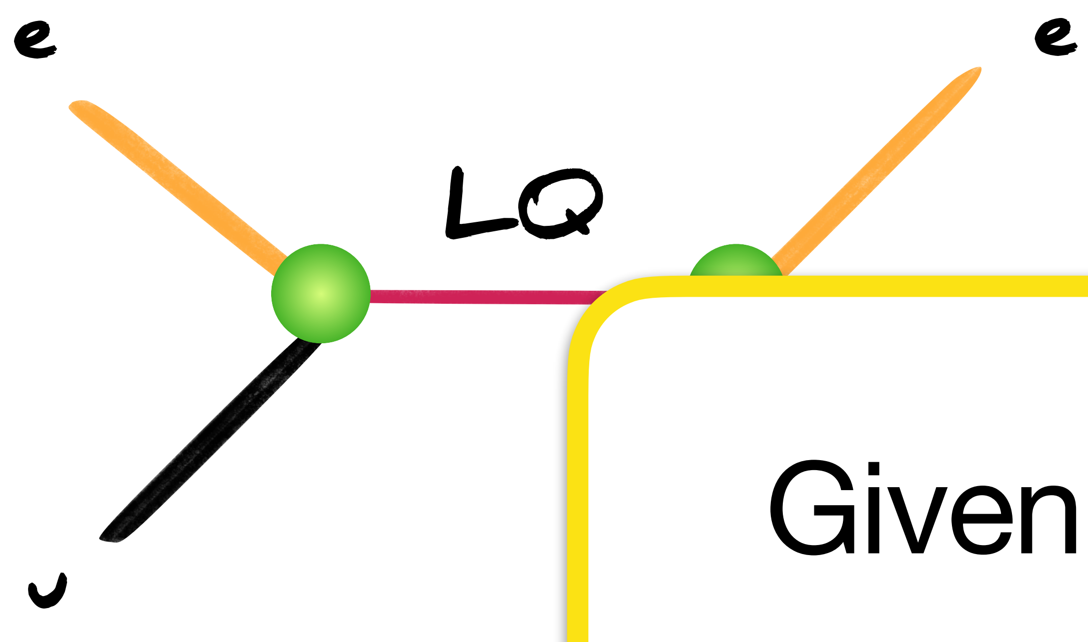


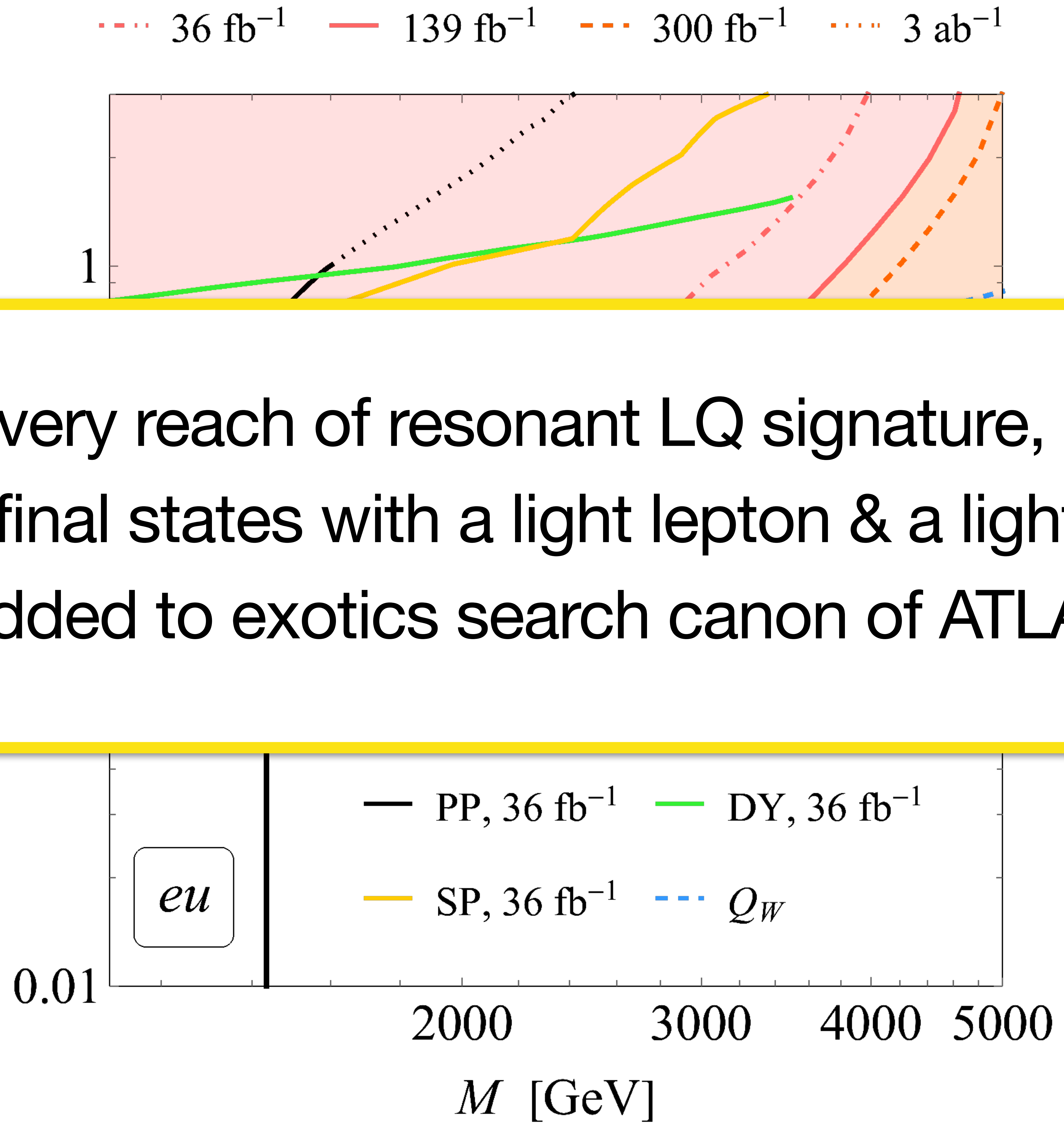
weak charge
measurements (Q_W)



[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

LHC limits on 1st & 2nd generation LQs





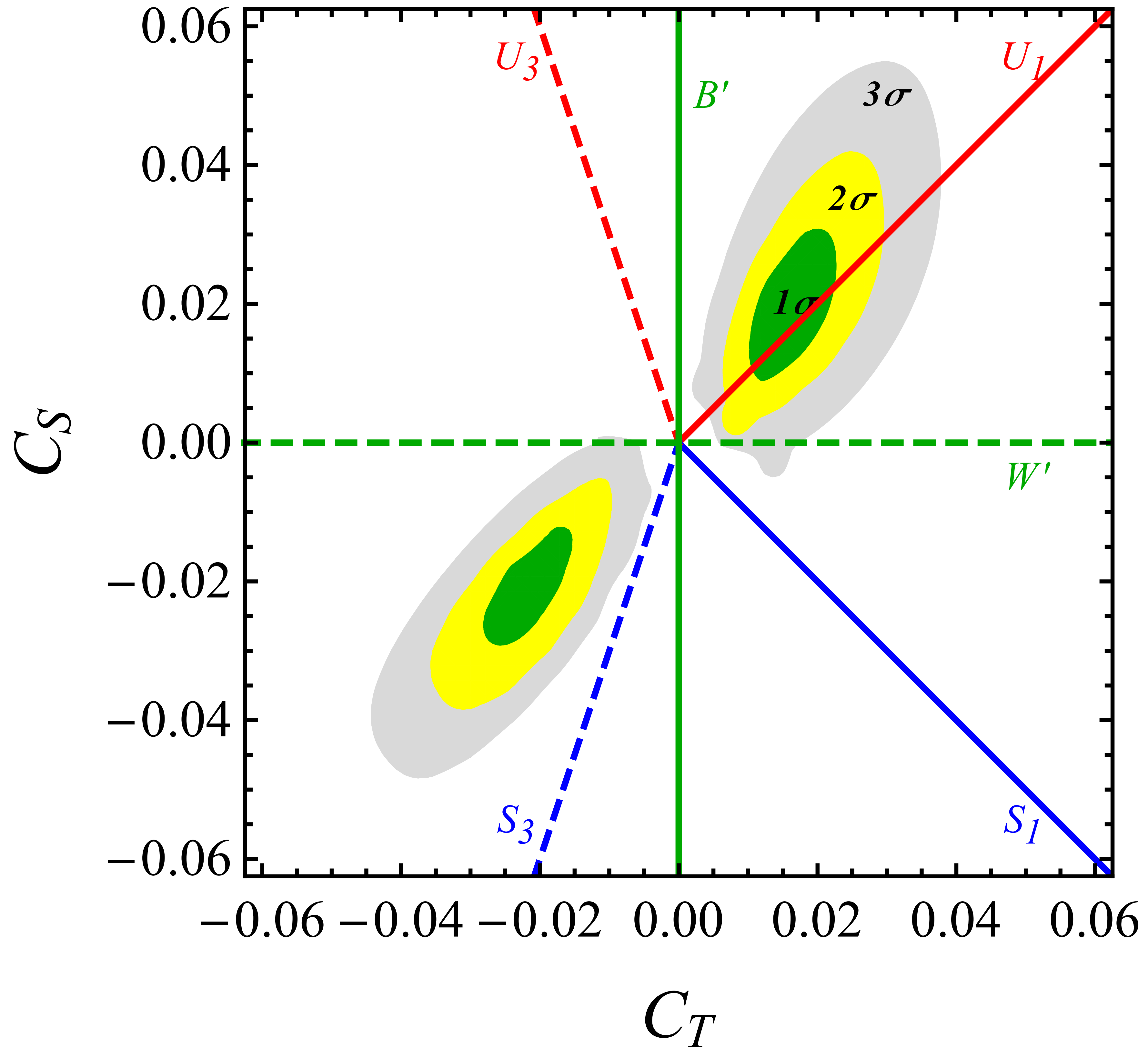
weak c
measurem

Given discovery reach of resonant LQ signature, dedicated searches for final states with a light lepton & a light-flavour jet should be added to exotics search canon of ATLAS & CMS

[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

Simplified models for B anomalies

$$\lambda^q_{ij}\lambda^l_{\alpha\beta}\left(C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)+C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right)$$



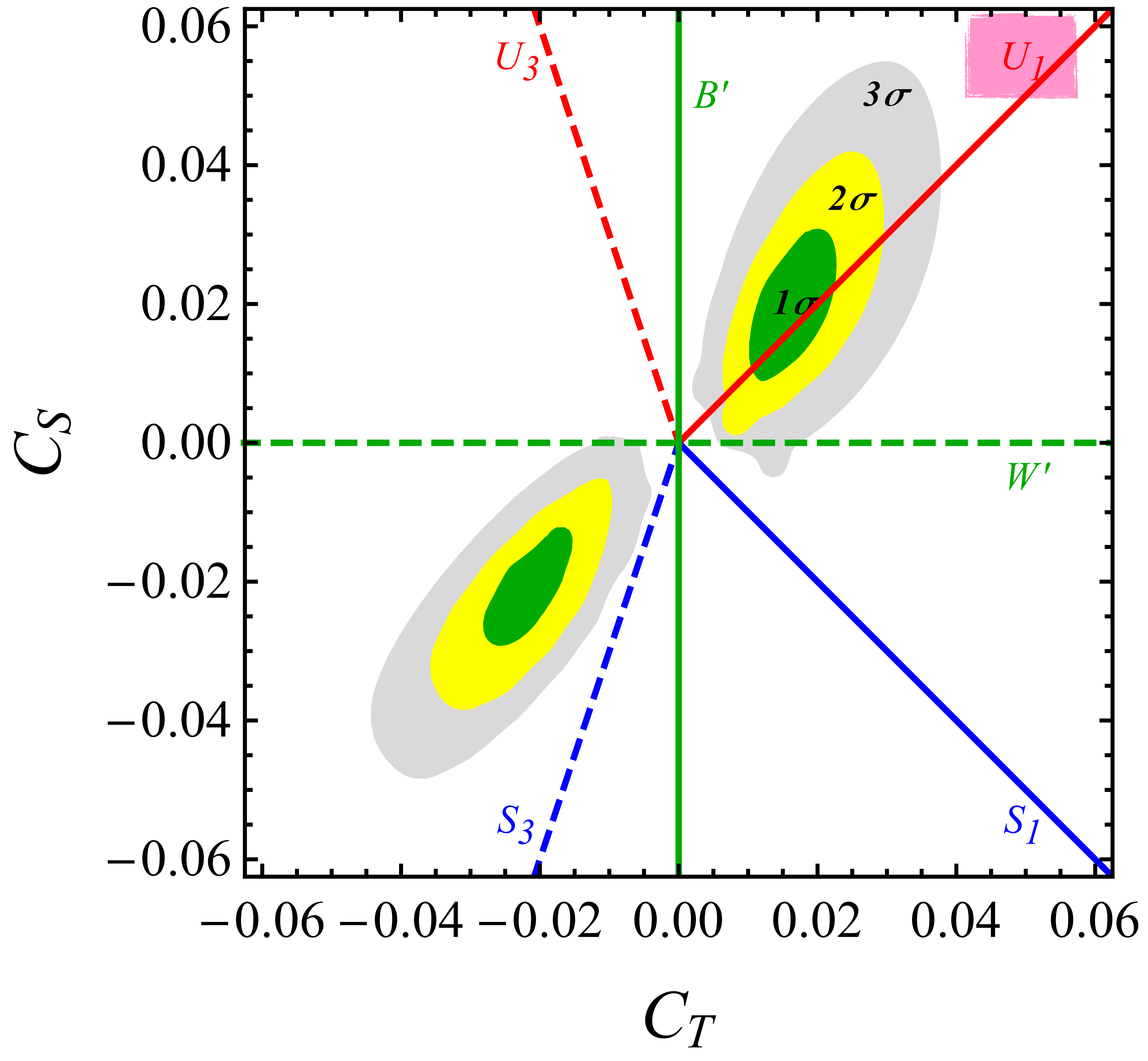
Model	Mediator	$b \to s$	$b \to c$
Colorless vectors	$B' = (1,1,0)$	✓	✗
	$W' = (1,3,0)$	✗	✓
Scalar leptoquarks	$S_1 = (\bar{3},1,1/3)$	✗	✓
	$S_3 = (\bar{3},3,1/3)$	✓	✗
Vector leptoquarks	$U_1 = (3,1,2/3)$	✓	✓
	$U_3 = (3,3,2/3)$	✓	✗

b → s (b → c) anomalies alone can be explained by several simple single-mediator models

[see for instance Buttazzo et al., JHEP 11 (2017) 044]

Simplified models for B anomalies

$$\lambda^q_{ij}\lambda^l_{\alpha\beta}\left(C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right)$$



Model	Mediator	$b \to s$	$b \to c$
Colorless vectors	$B' = (1,1,0)$	✓	✗
	$W' = (1,3,0)$	✗	✓
Scalar leptoquarks	$S_1 = (\bar{3},1,1/3)$	✗	✓
	$S_3 = (\bar{3},3,1/3)$	✓	✗
Vector leptoquarks	$U_1 = (3,1,2/3)$	✓	✓
	$U_3 = (3,3,2/3)$	✓	✗

U_1 vector LQ is the only single-mediator model that can explain both sets of anomalies

[see for instance Buttazzo et al., JHEP 11 (2017) 044]

Vector LQ models for B anomalies

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} \left[\beta_L^{ij} \, \bar{Q}_L^{i,a} \gamma_\mu L_L^j + \beta_R^{ij} \, \bar{d}_R^{i,a} \gamma_\mu \ell_R^j \right] U^{\mu,a} + \text{h.c.} \,, \qquad |\beta_L^{22}| \lesssim |\beta_L^{32}| \ll |\beta_L^{23}| \lesssim |\beta_L^{33}| = \mathcal{O}(1)$$

Parameters		Branching ratios			
β_L^{33}	β_L^{23}	$\text{BR}(U \to b\tau^+)$	$\text{BR}(U \to t\bar{\nu}_\tau)$	$\text{BR}(U \to s\tau^+)$	$\text{BR}(U \to c\bar{\nu}_\tau)$
1	0	51%	49%	0%	0%
1	1	25%	22%	25%	27%

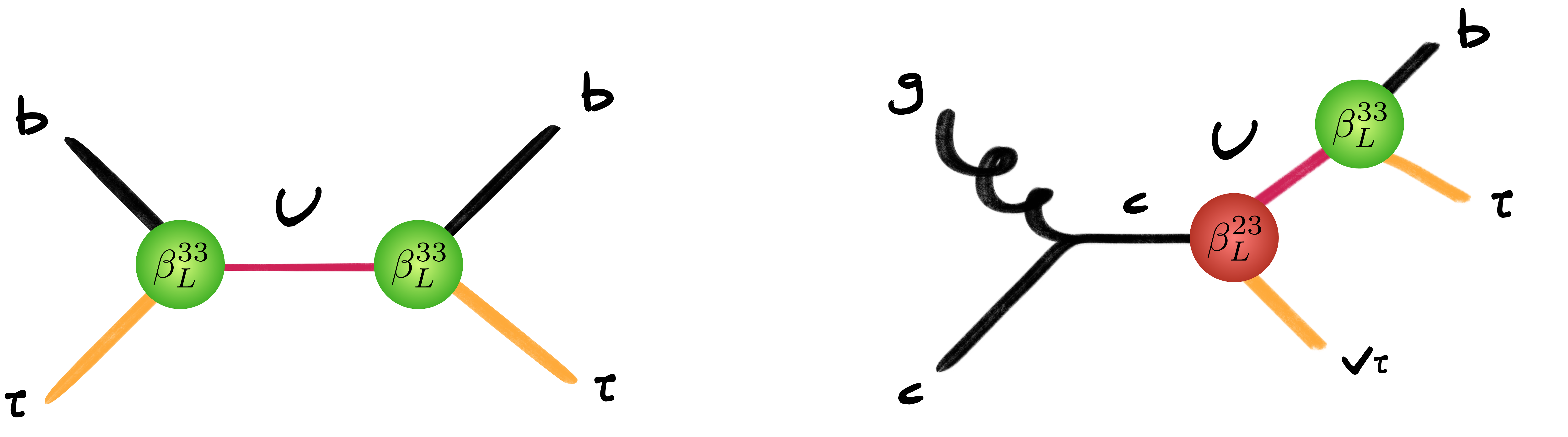
b + τ signature

mono-top signature

mono-jet signature

[ongoing work with Polesello]

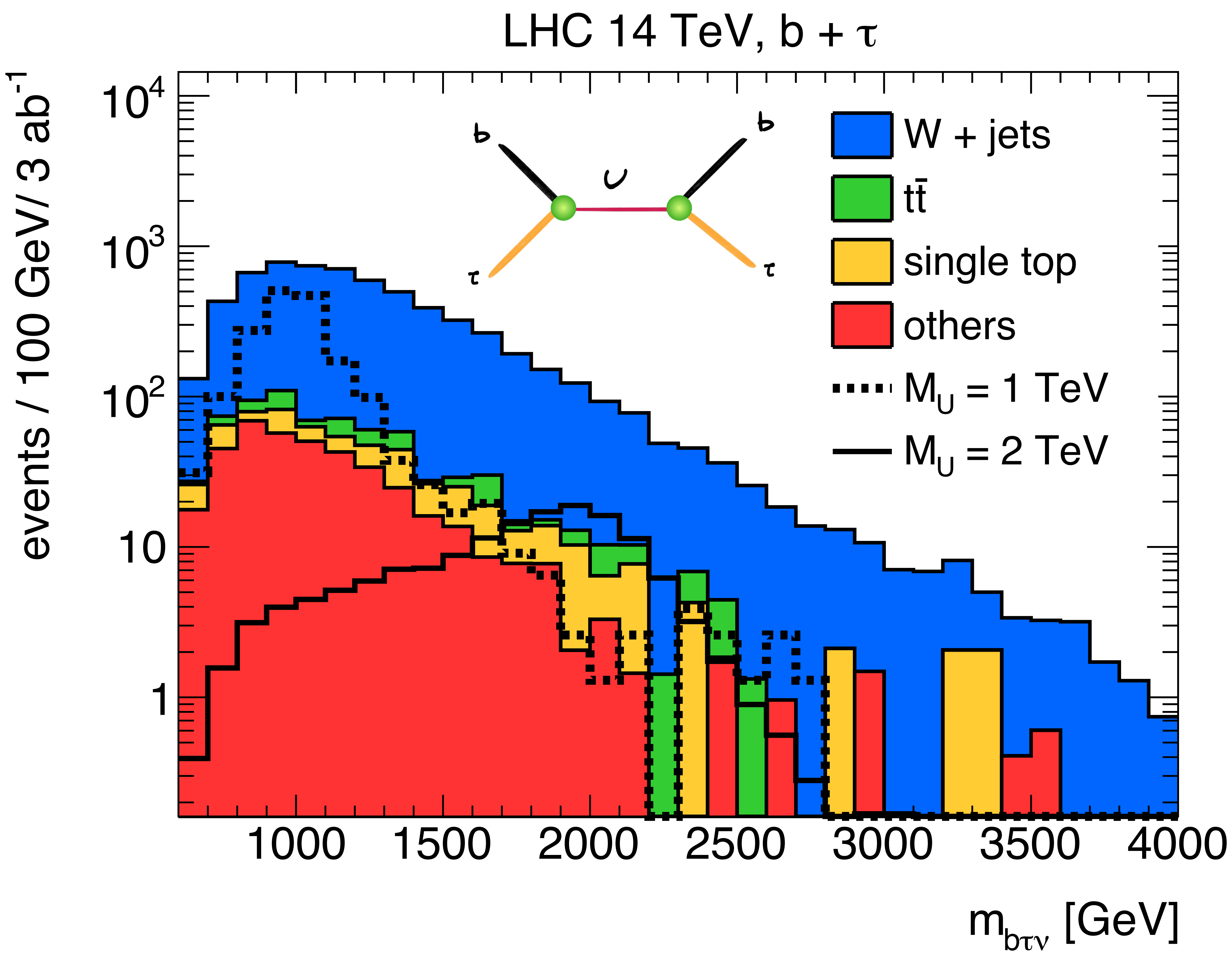
LQ contributions to b + τ signature

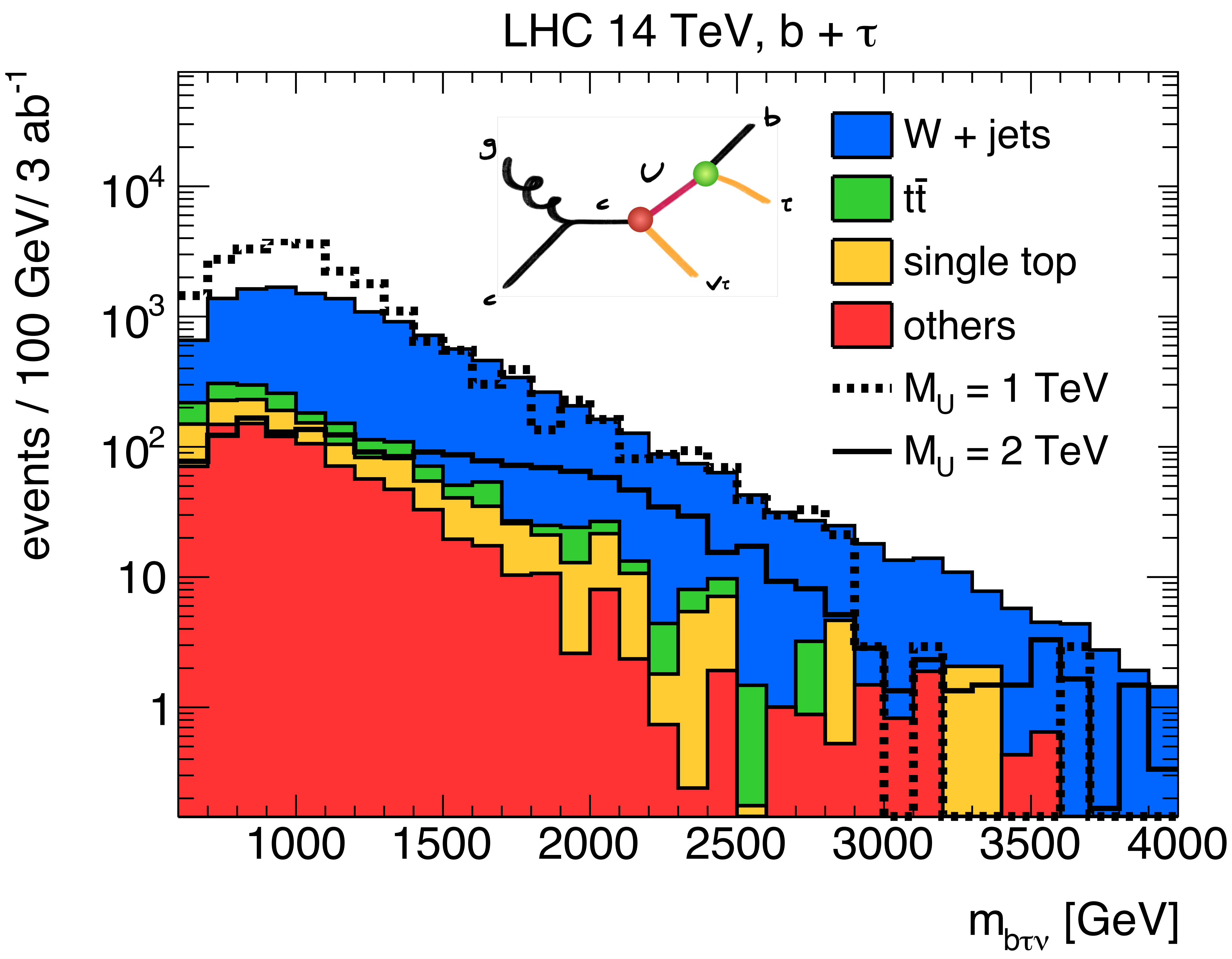


For $\beta_L^{23} = 0$, b + τ signal arises only from 2 → 2 process, while for $\beta_L^{23} \neq 0$ also 2 → 3 scattering is relevant. Since two topologies lead to final states with very different kinematic features, it is essential to develop two separate search strategies for them

[ongoing work with Polesello]

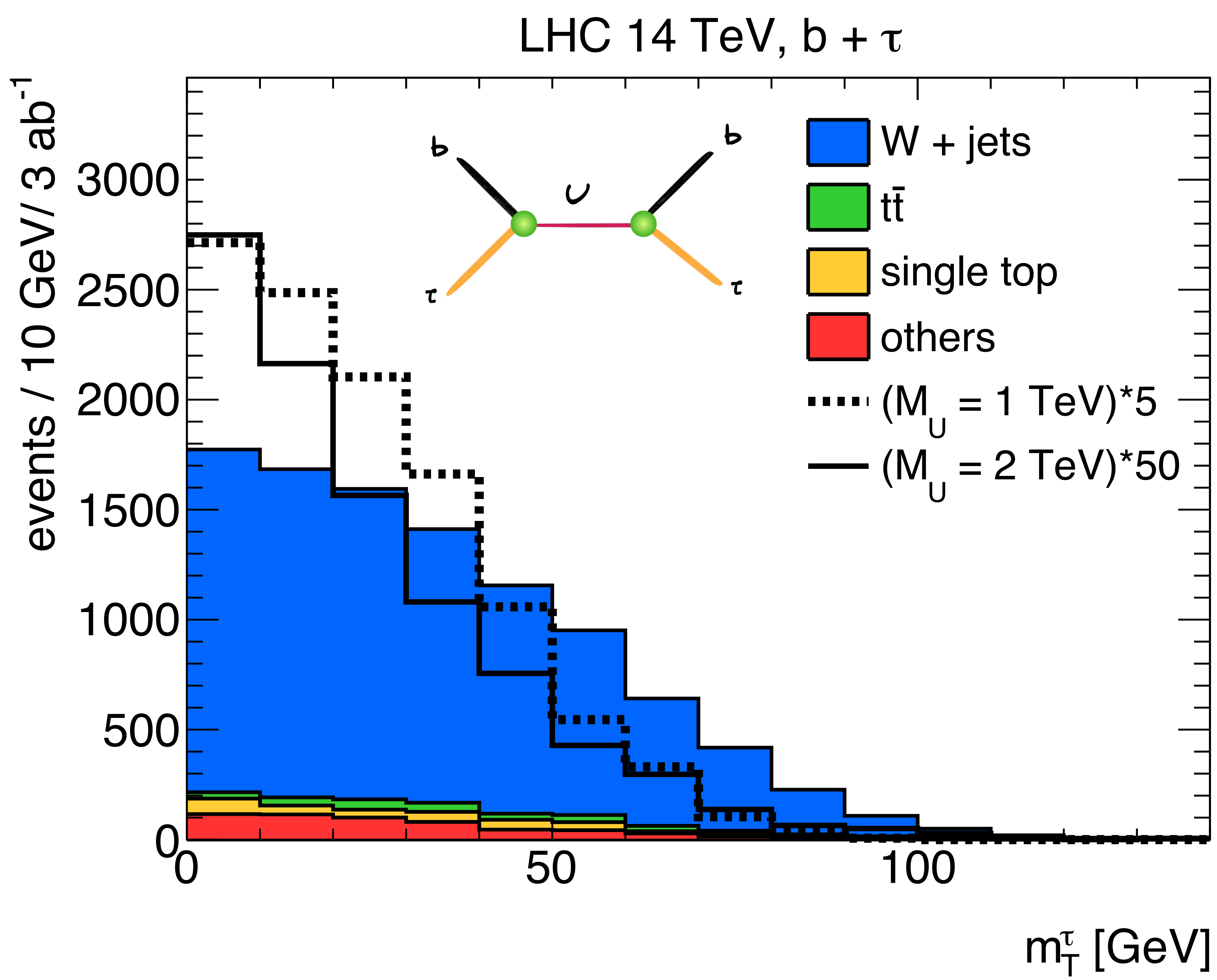
Kinematic distributions of b + τ signal

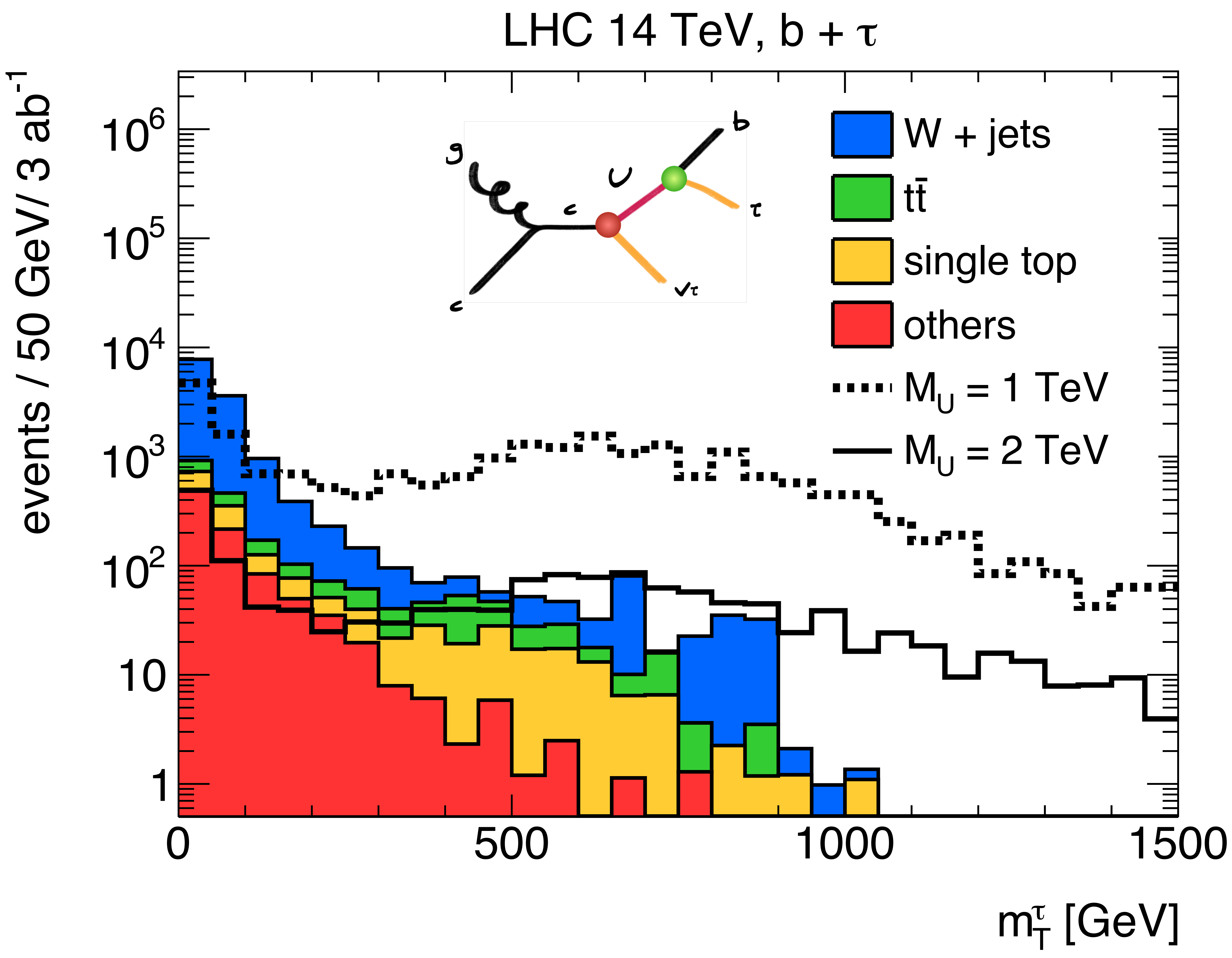




[ongoing work with Polesello]

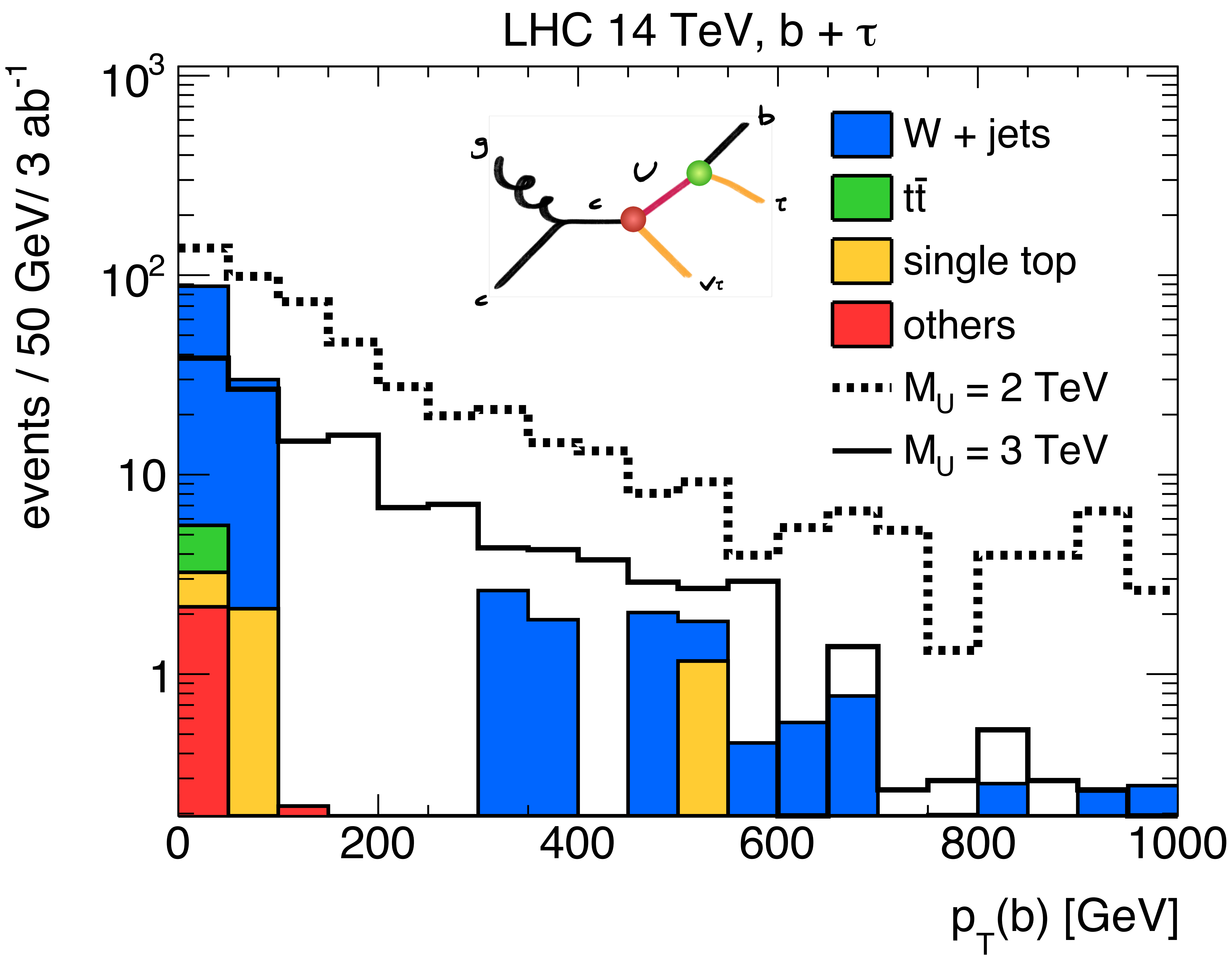
Kinematic distributions of b + τ signal

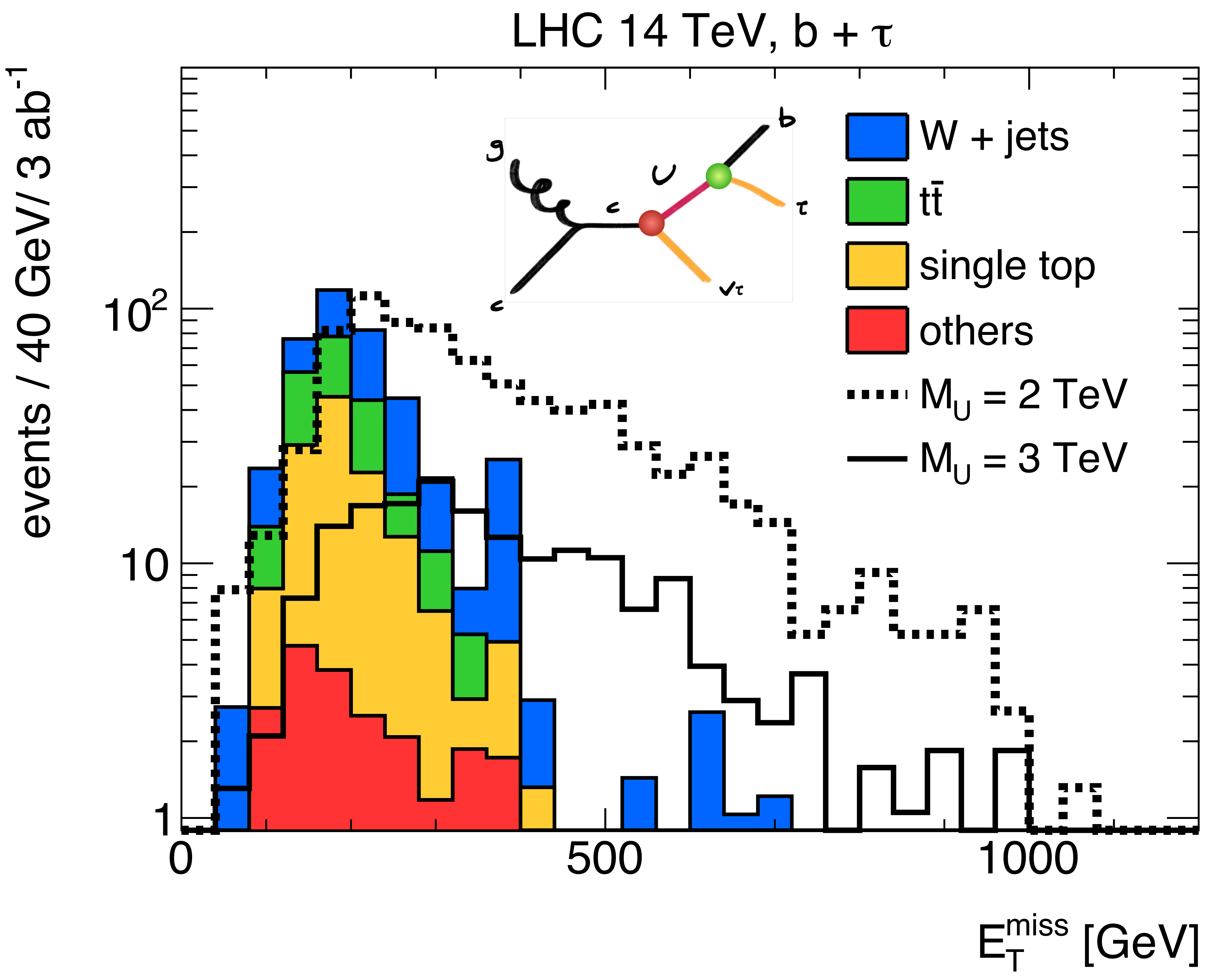




[ongoing work with Polesello]

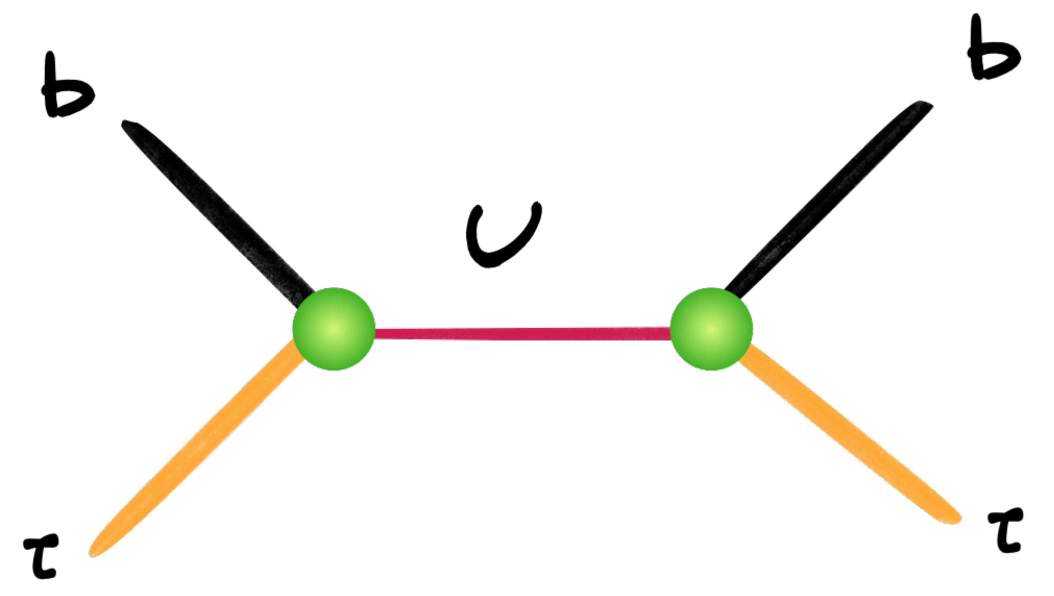
Kinematic distributions of b + τ signal

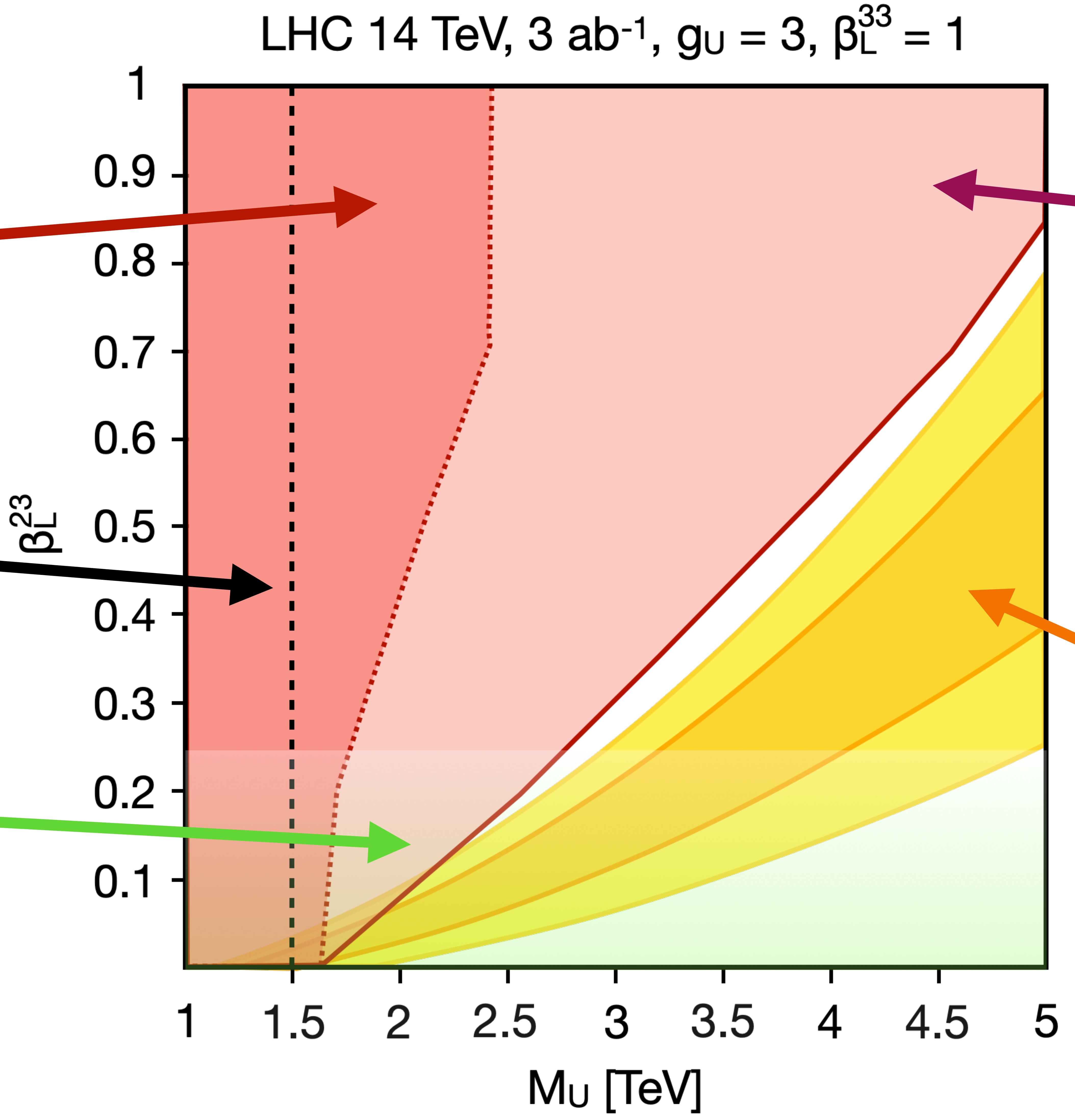


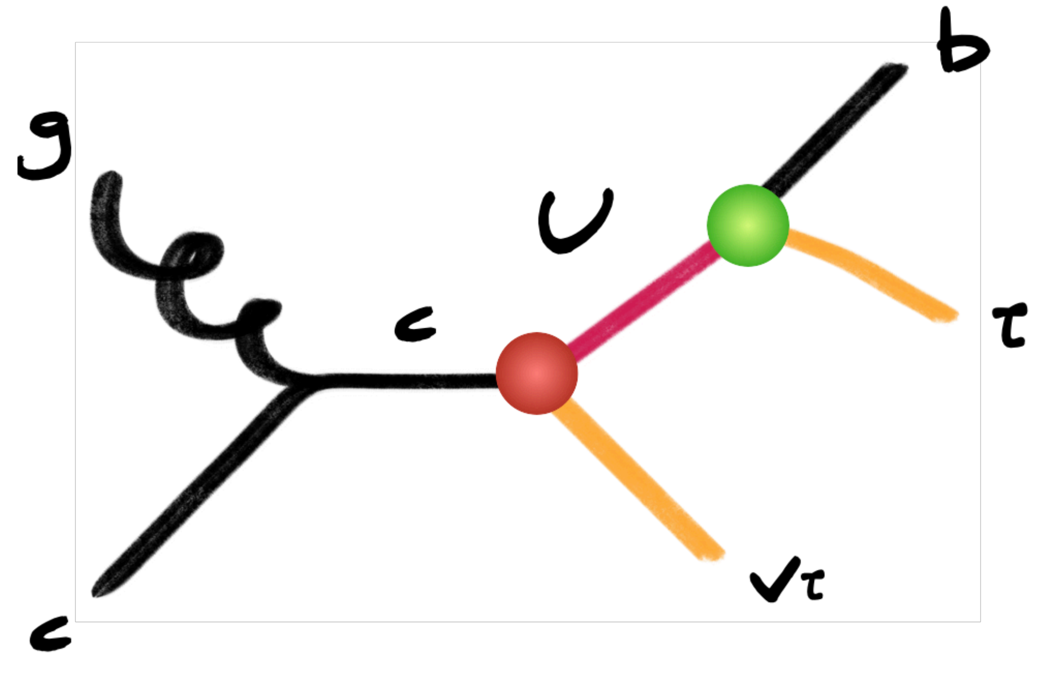


[ongoing work with Polesello]

Constraints from b + τ search







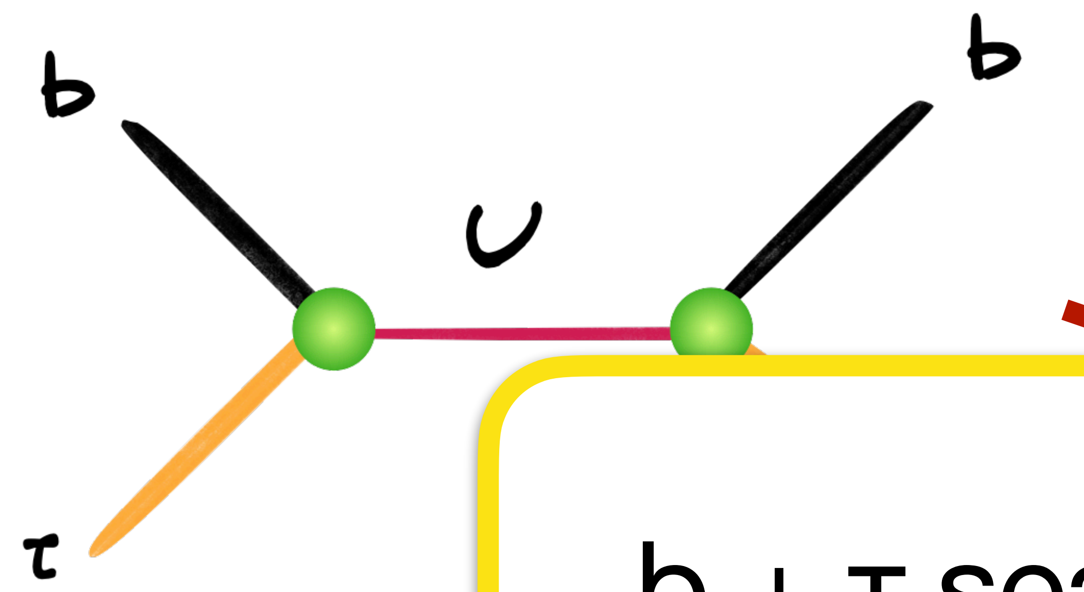
LQ pair production @ LHC Run II

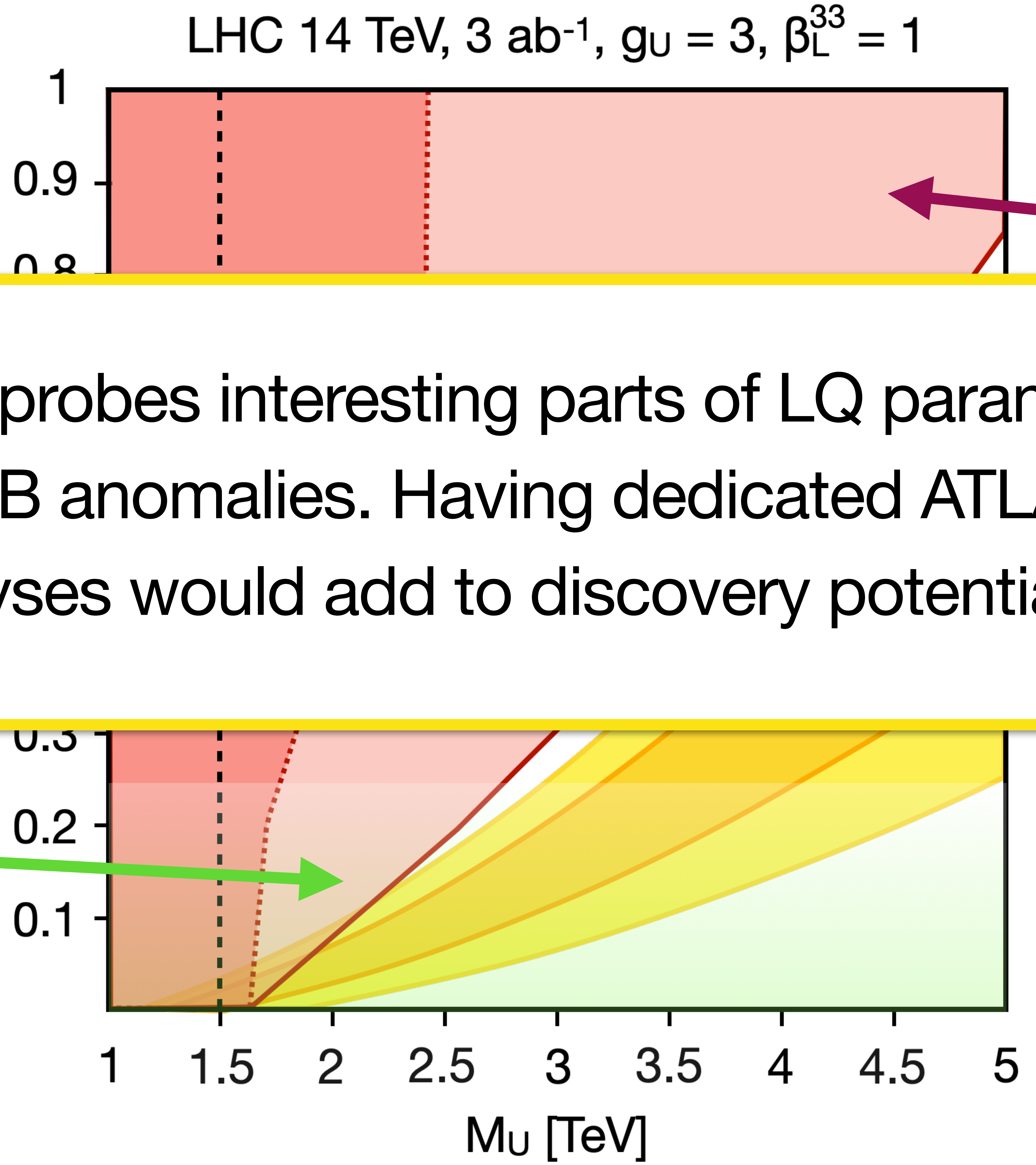
natural parameter space of $U(2)_Q$ flavour models

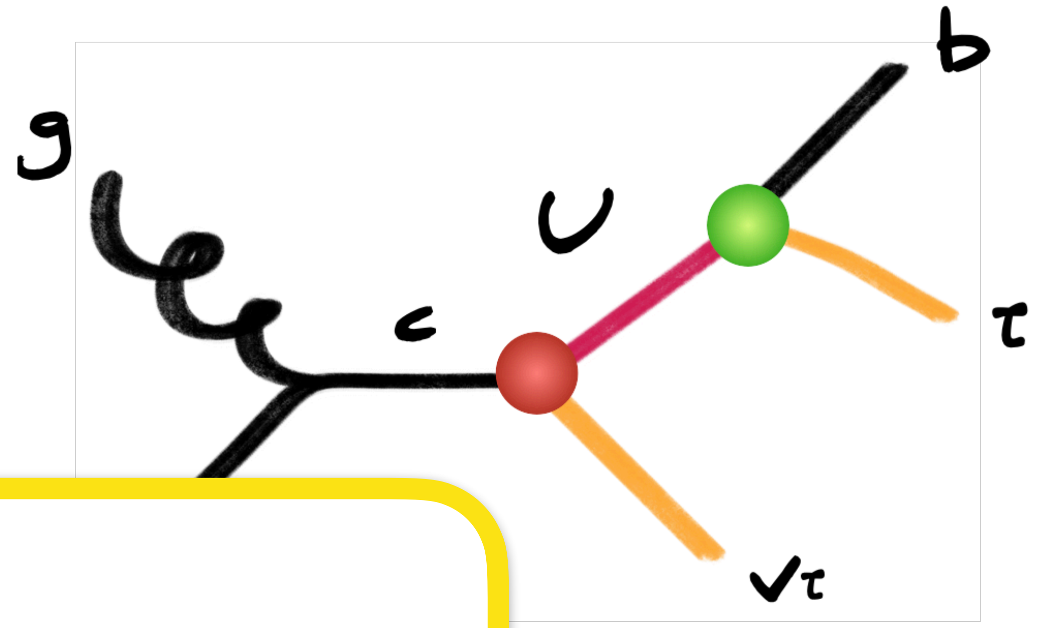
68% CL (95% CL) region favoured by b → c anomalies

[ongoing work with Polesello]

Constraints from b + τ search







b + τ search probes interesting parts of LQ parameter space addressing B anomalies. Having dedicated ATLAS & CMS b + τ analyses would add to discovery potential of LHC

LQ
produc
LHC F

natural parameter space of $U(2)_Q$ flavour models

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[ongoing work with Polesello]

Pseudo Nambu-Goldstone boson (PNGB) DM

Higgs doublet

real singlet scalar
acting as DM

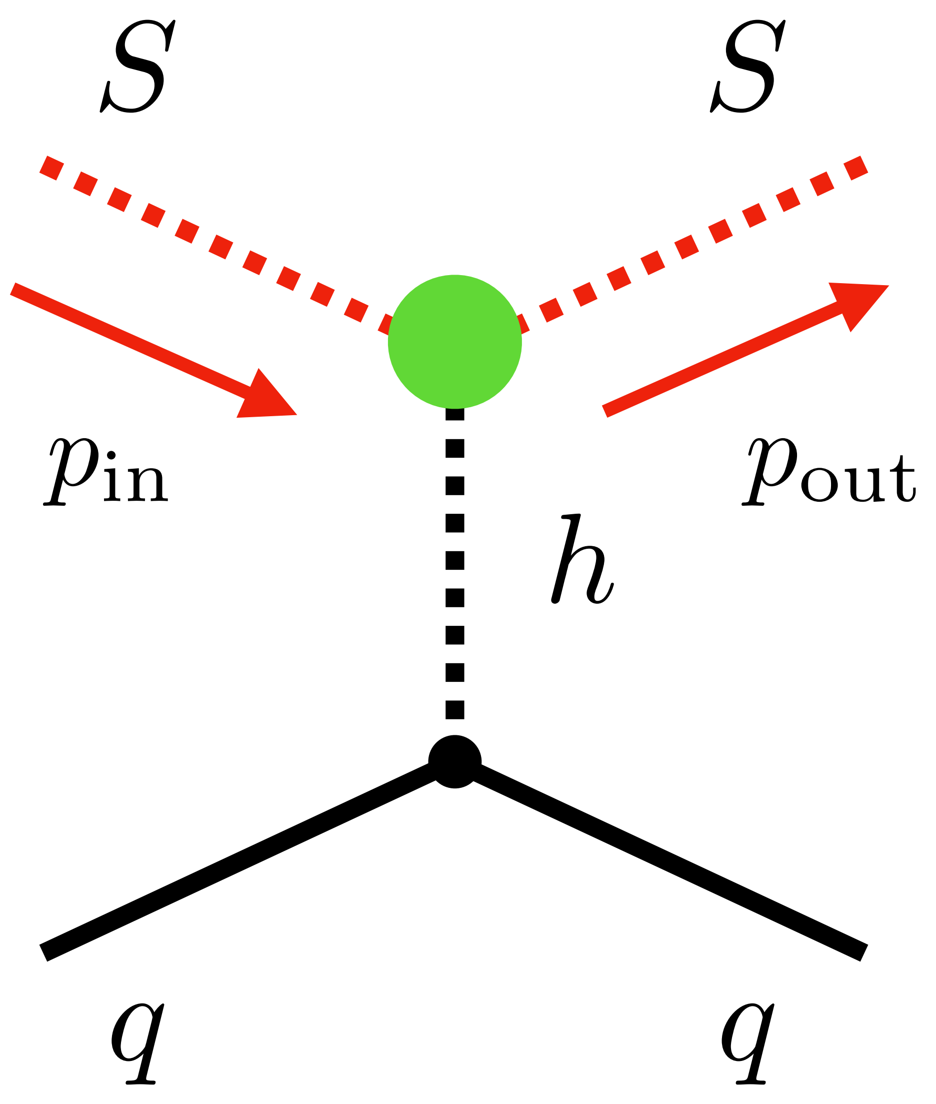
$$\mathcal{L} \supset \frac{1}{2f^2} \partial_\mu |\Phi|^2 \partial^\mu S^2$$

appears as low-energy EFT of
SM with an additional complex
scalar & heavy radial mode

in PNGB DM models, f is scale
where global symmetry is broken

[see for instance Ruhdorfer, Salvioni & Weiler, SciPost Phys. 8 (2020) 027]

Direct detection in PNGB DM models

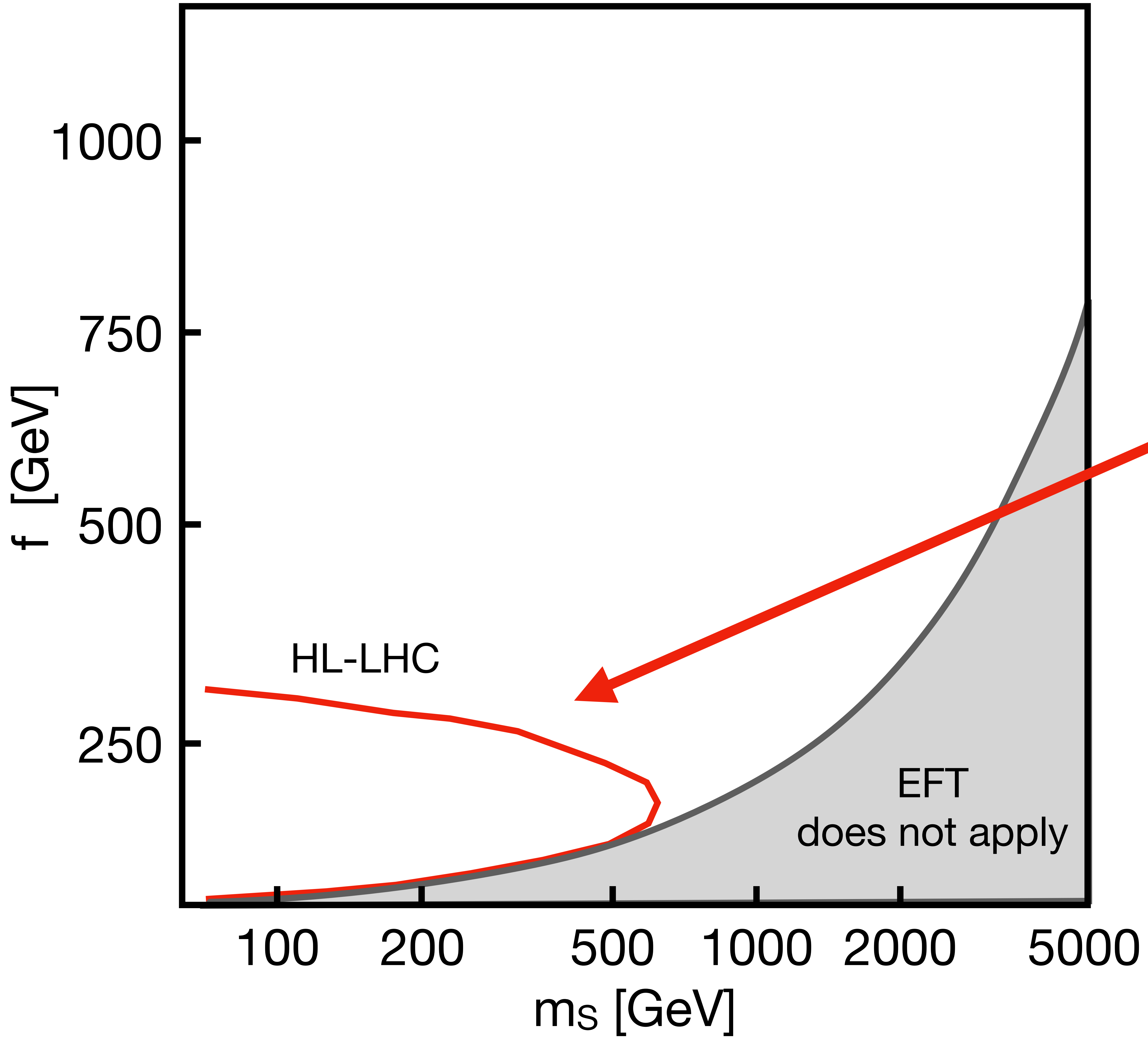


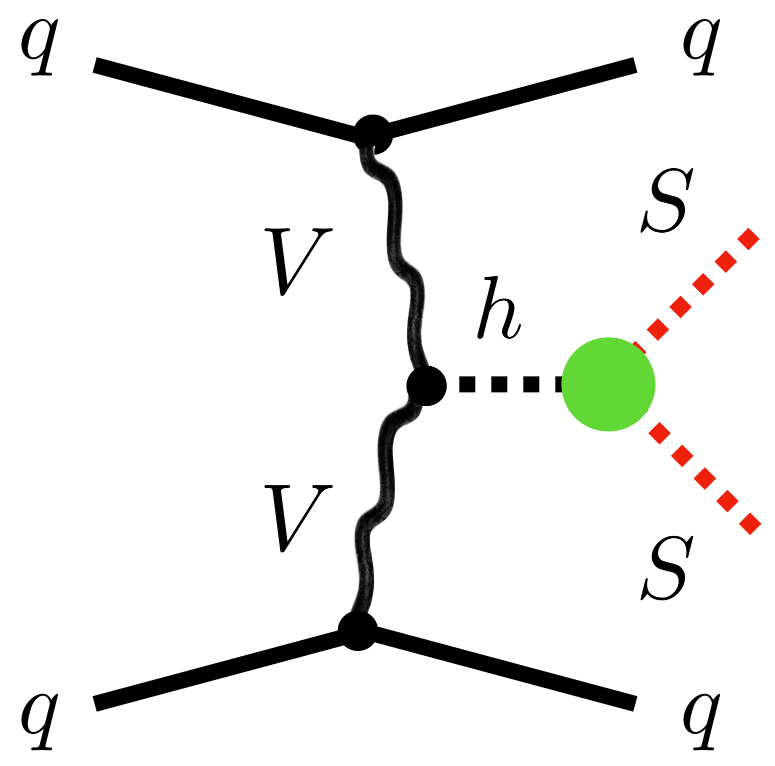
$$\propto \frac{(p_{\rm in} - p_{\rm out})^2}{f^2} \lesssim \frac{(100\,\mathrm{MeV})^2}{(1\,\mathrm{TeV})^2}$$

due to momentum suppression
direct detection limits easily avoided

[see for instance Ruhdorfer, Salvioni & Weiler, SciPost Phys. 8 (2020) 027]

Collider constraints on PNGB DM models

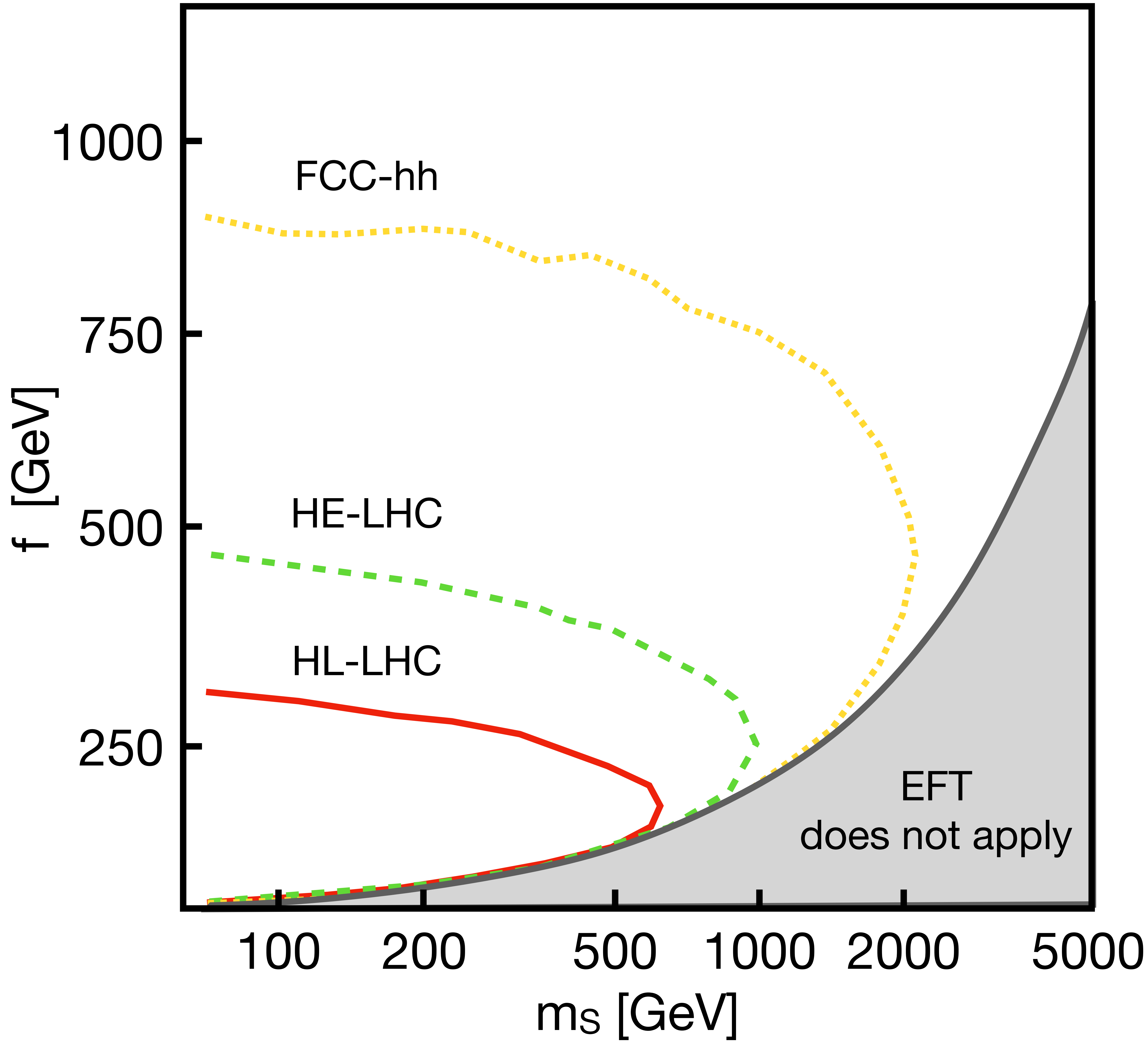




off-shell Higgs boson production in vector-boson fusion channel

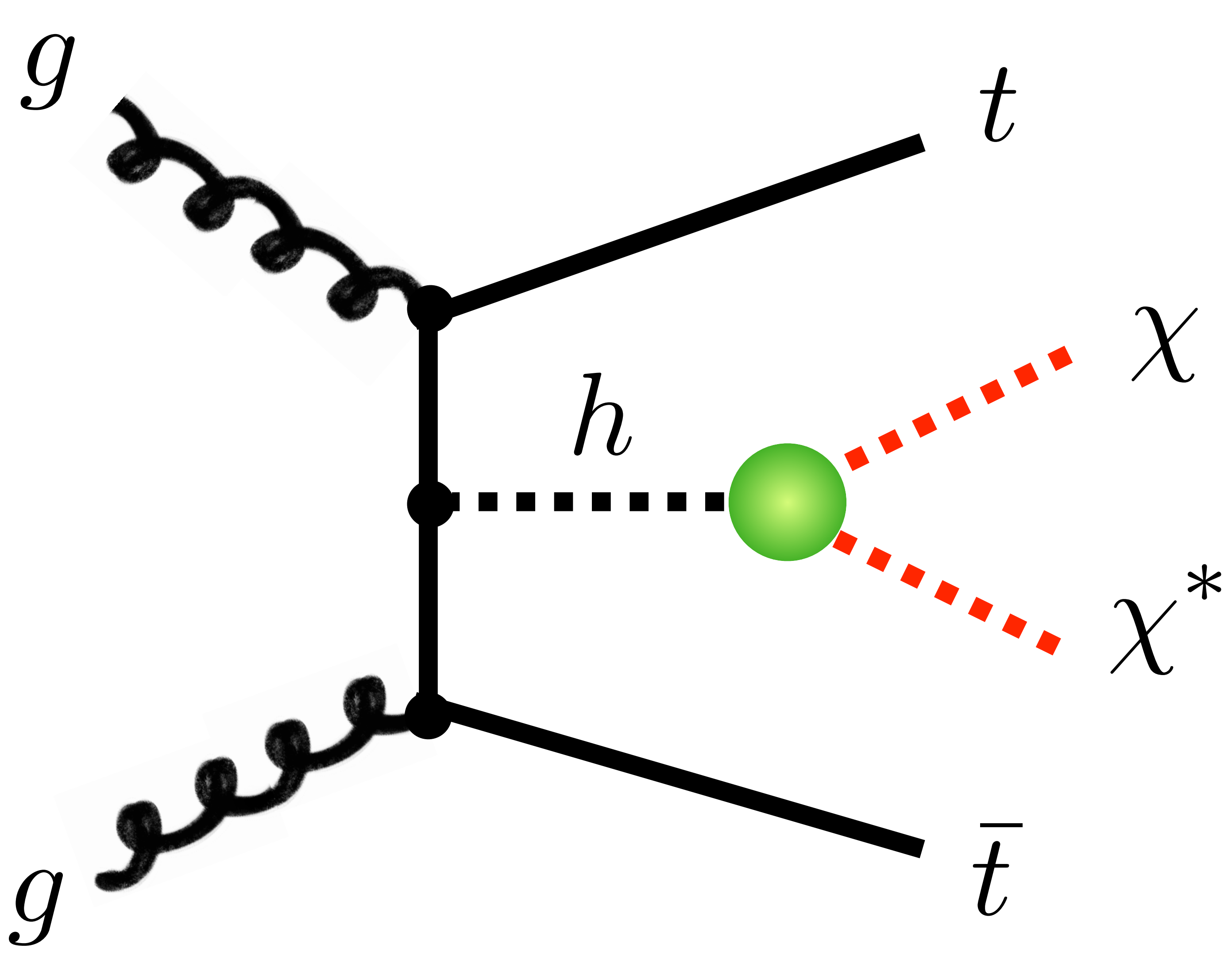
[Ruhdorfer, Salvioni & Weiler, SciPost Phys. 8 (2020) 027]

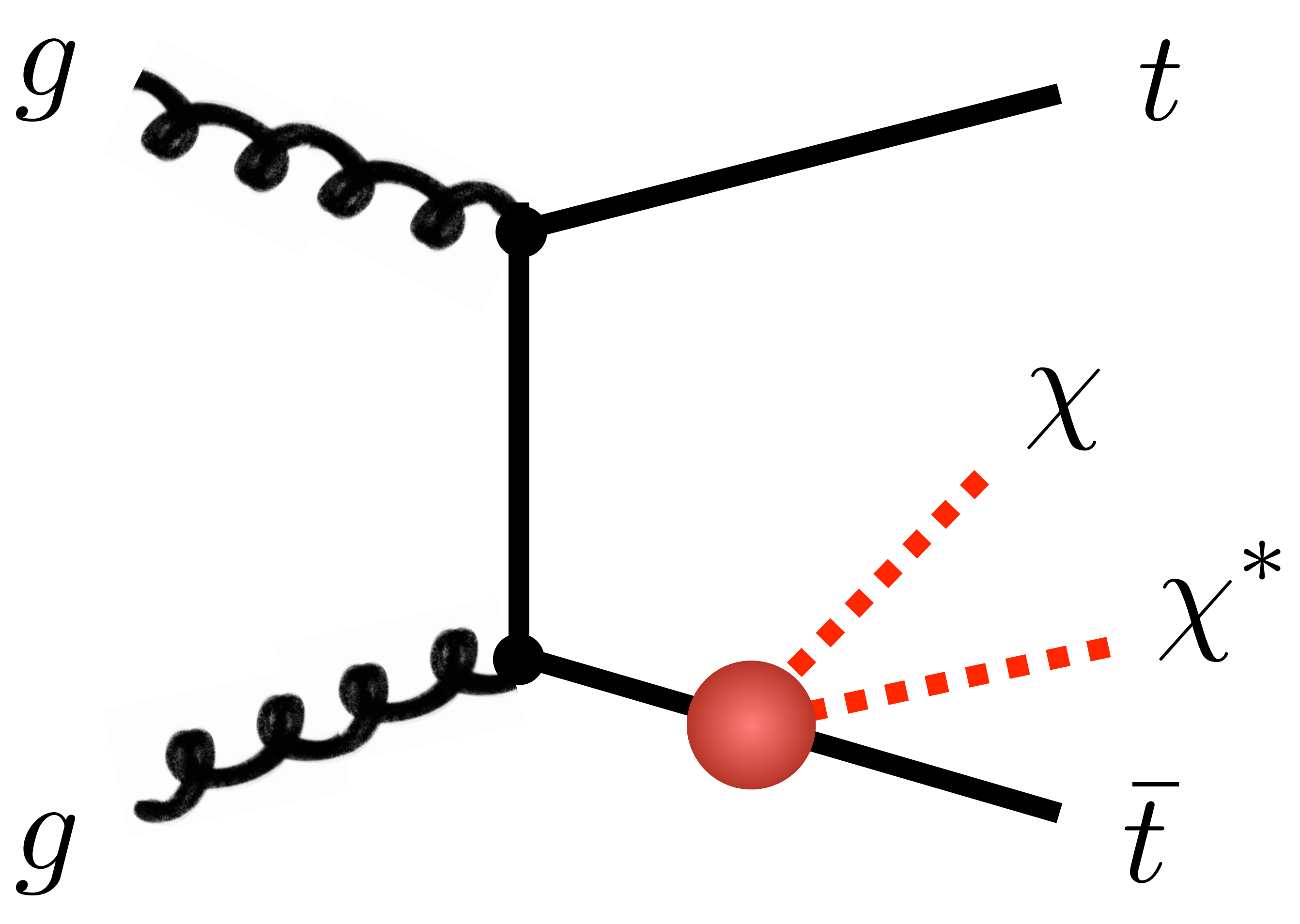
Collider constraints on PNGB DM models



[Ruhdorfer, Salvioni & Weiler, SciPost Phys. 8 (2020) 027]

Effects of PNGB DM in $t\bar{t} + E_T^{miss}$ final states





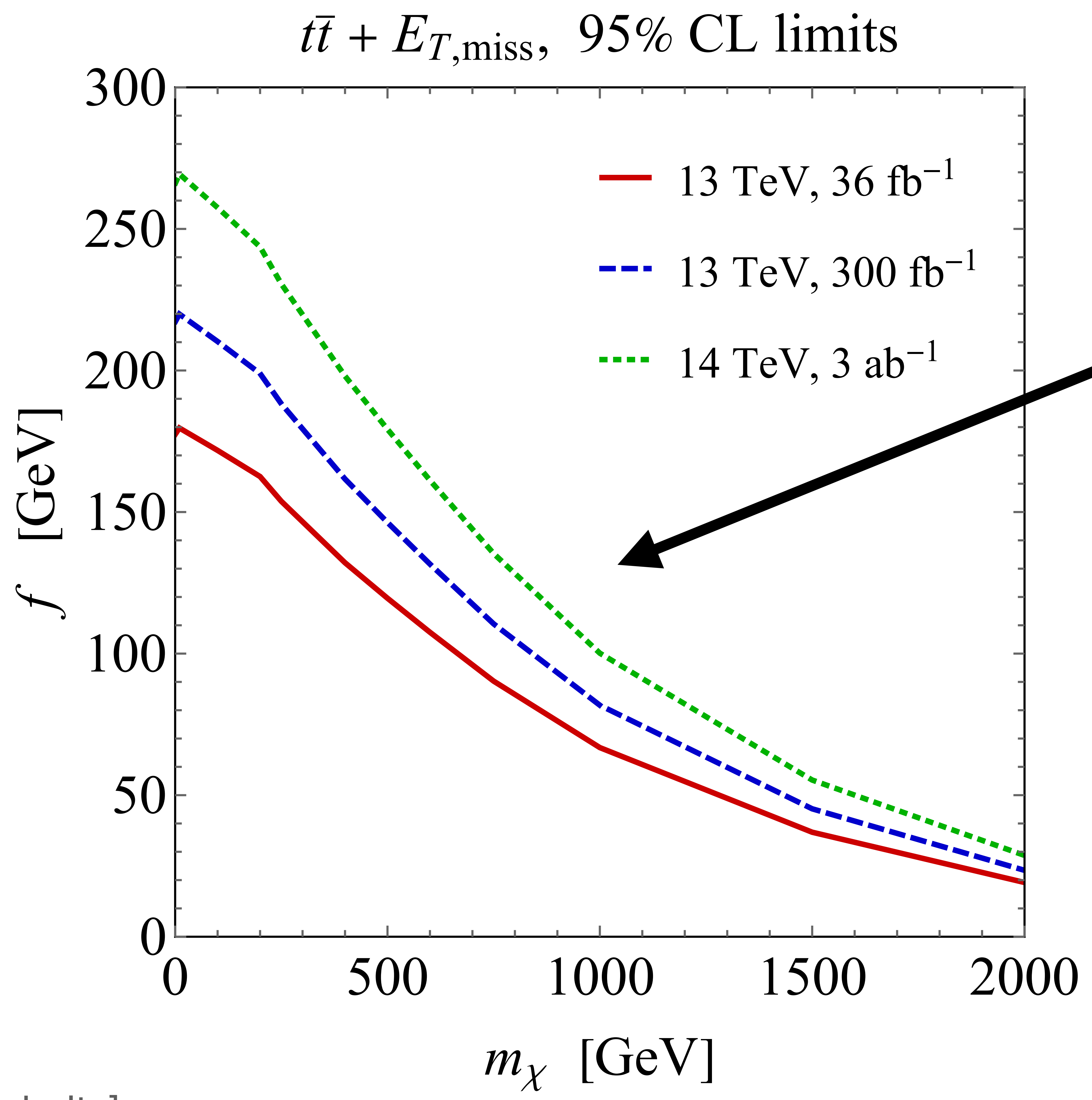
$\partial_\mu |\chi|^2 \partial^\mu |\Phi|^2 \,, \ldots$

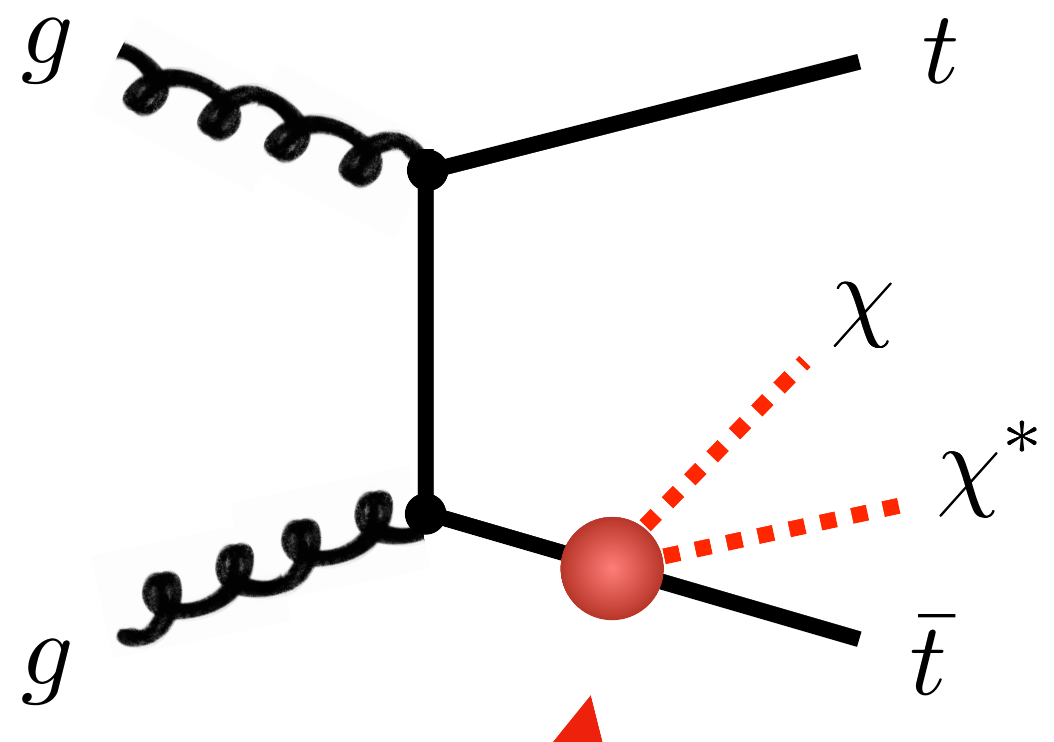
$|\chi|^2 \left(y_t \bar{q}_L \tilde{\Phi} t_R + \text{h.c.} \right) \,,$

$i \chi^* \overleftrightarrow{\partial}_\mu \chi \, \bar{t}_R \gamma^\mu t_R \,, \ldots$

[ongoing work with Schulte]

Effects of PNGB DM in $t\bar{t} + E_T^{miss}$ final states

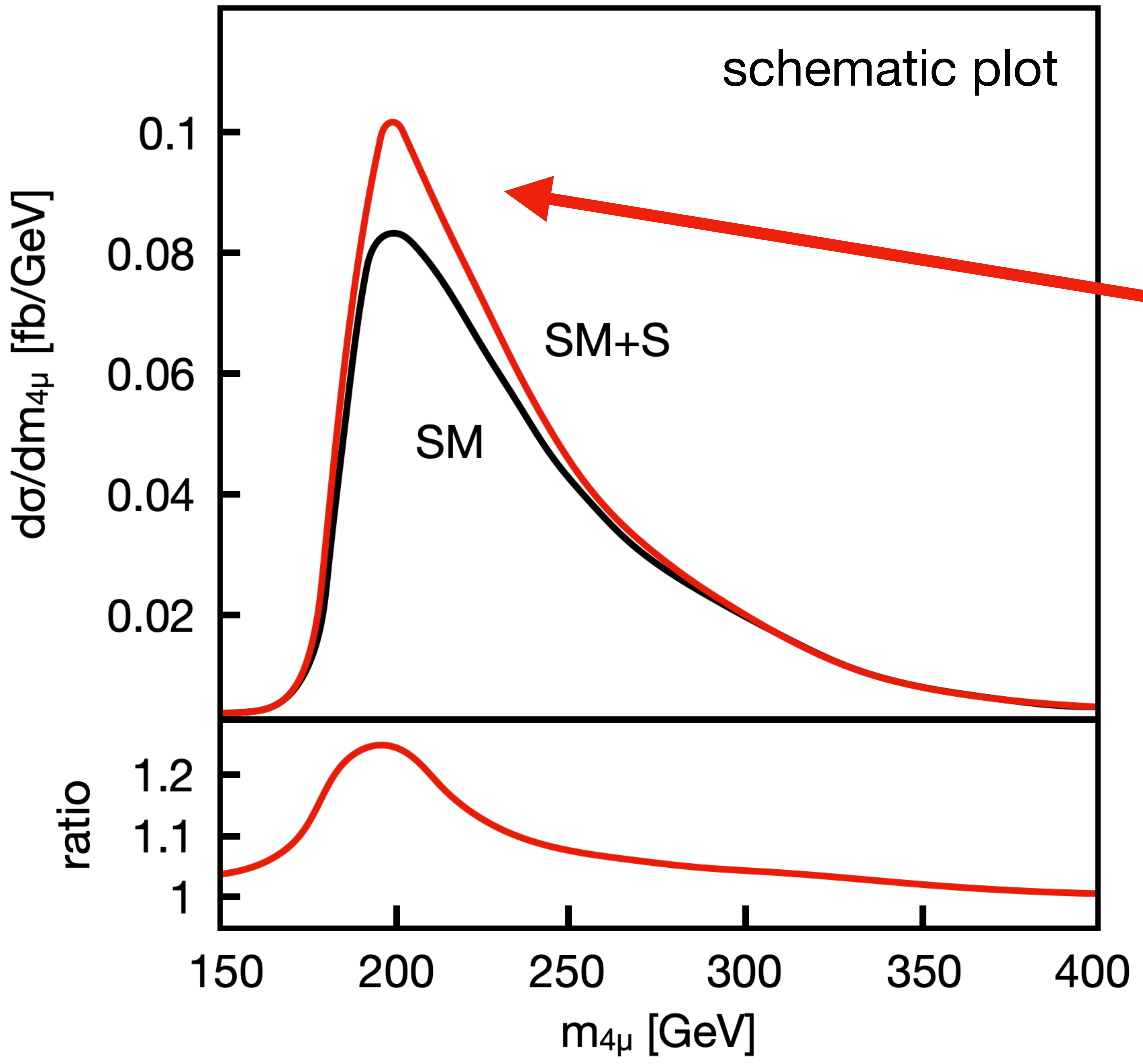


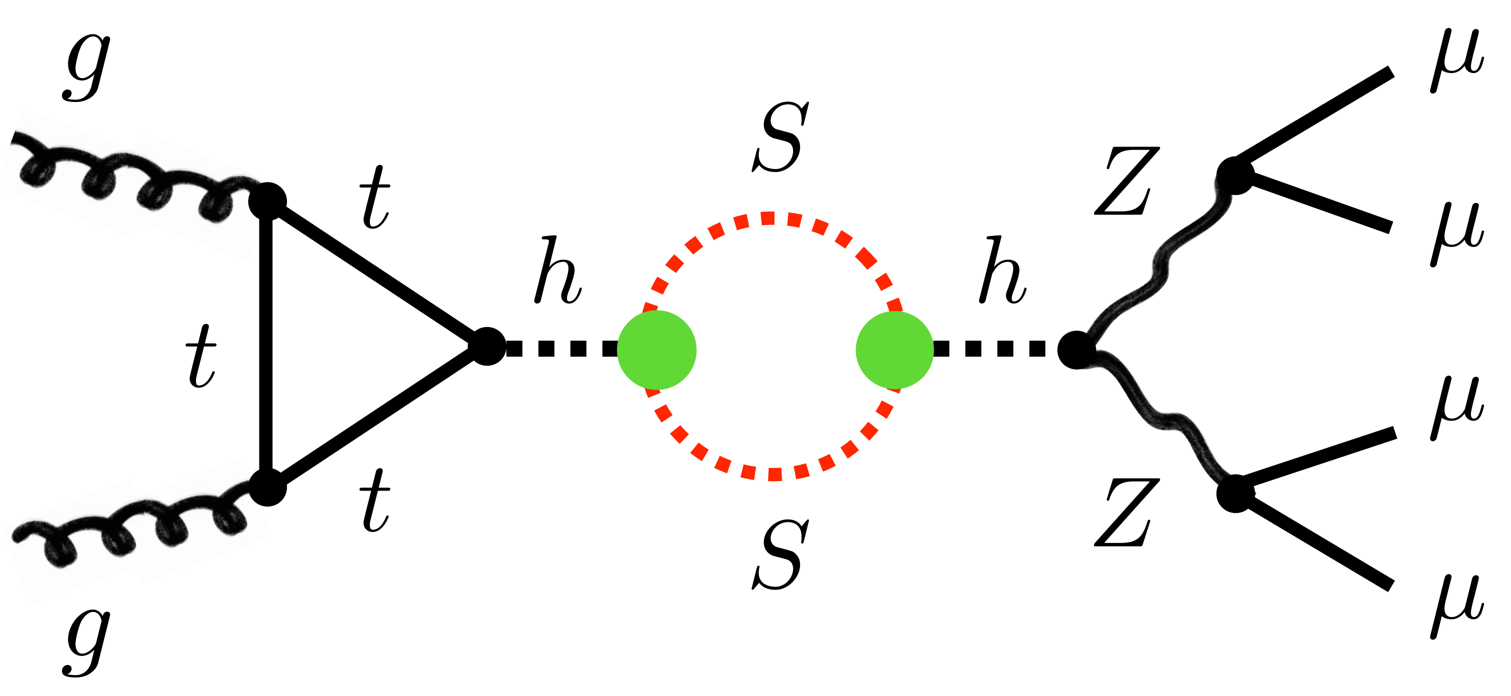


$$\frac{i}{f^2}\chi^* \overleftrightarrow{\partial}_\mu \chi \, \bar{t}_R \gamma^\mu t_R$$

[ongoing work with Schulte]

Probing PNGB DM in Higgs physics

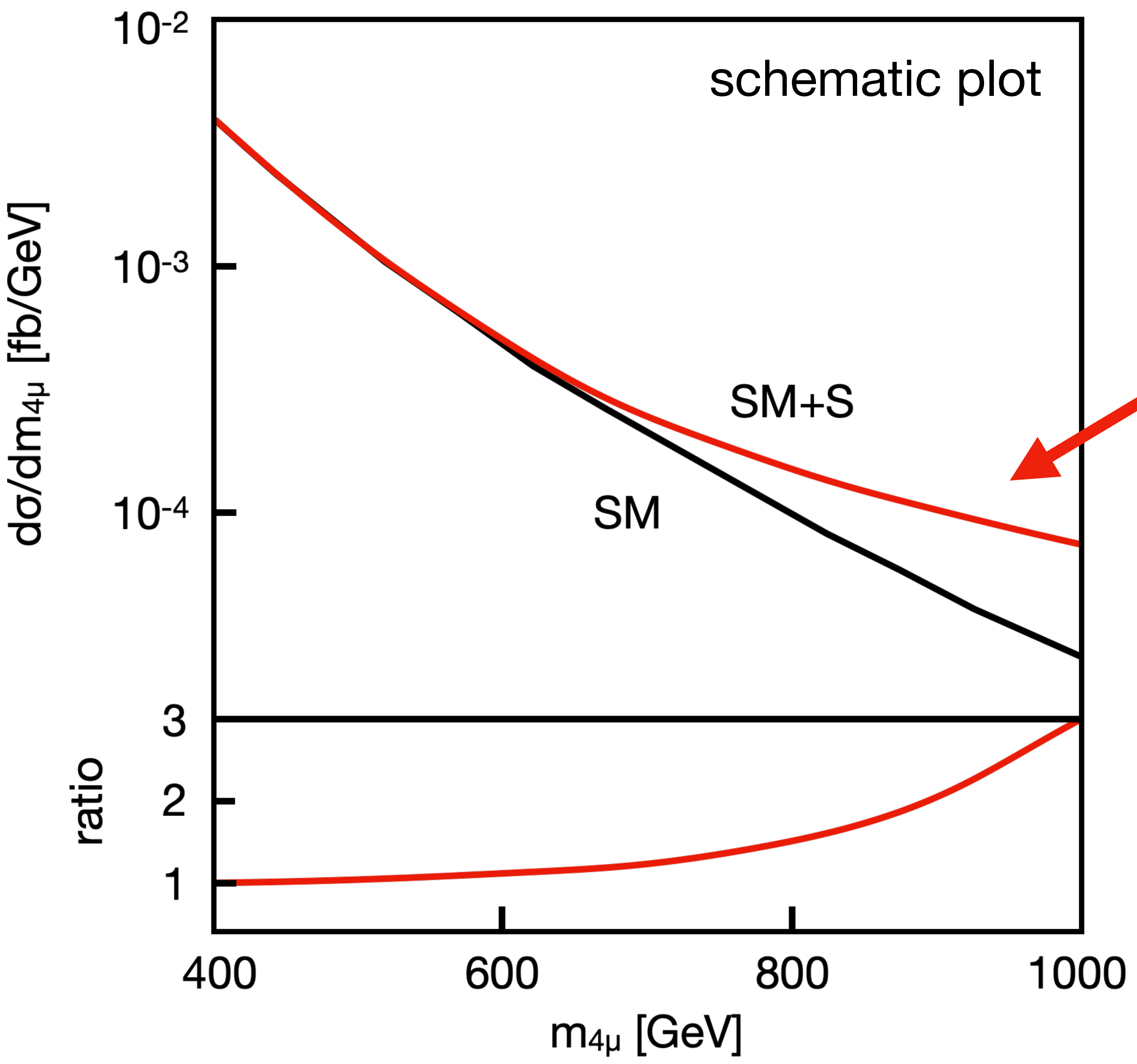




bump-like kinematic feature in $m_{4\mu}$ distribution of $gg \to 4\mu$ due to “on-shell” S loops

[ongoing work with Ruhdorfer, Salvioni, Venturini & Weiler]

Probing PNGB DM in Higgs physics

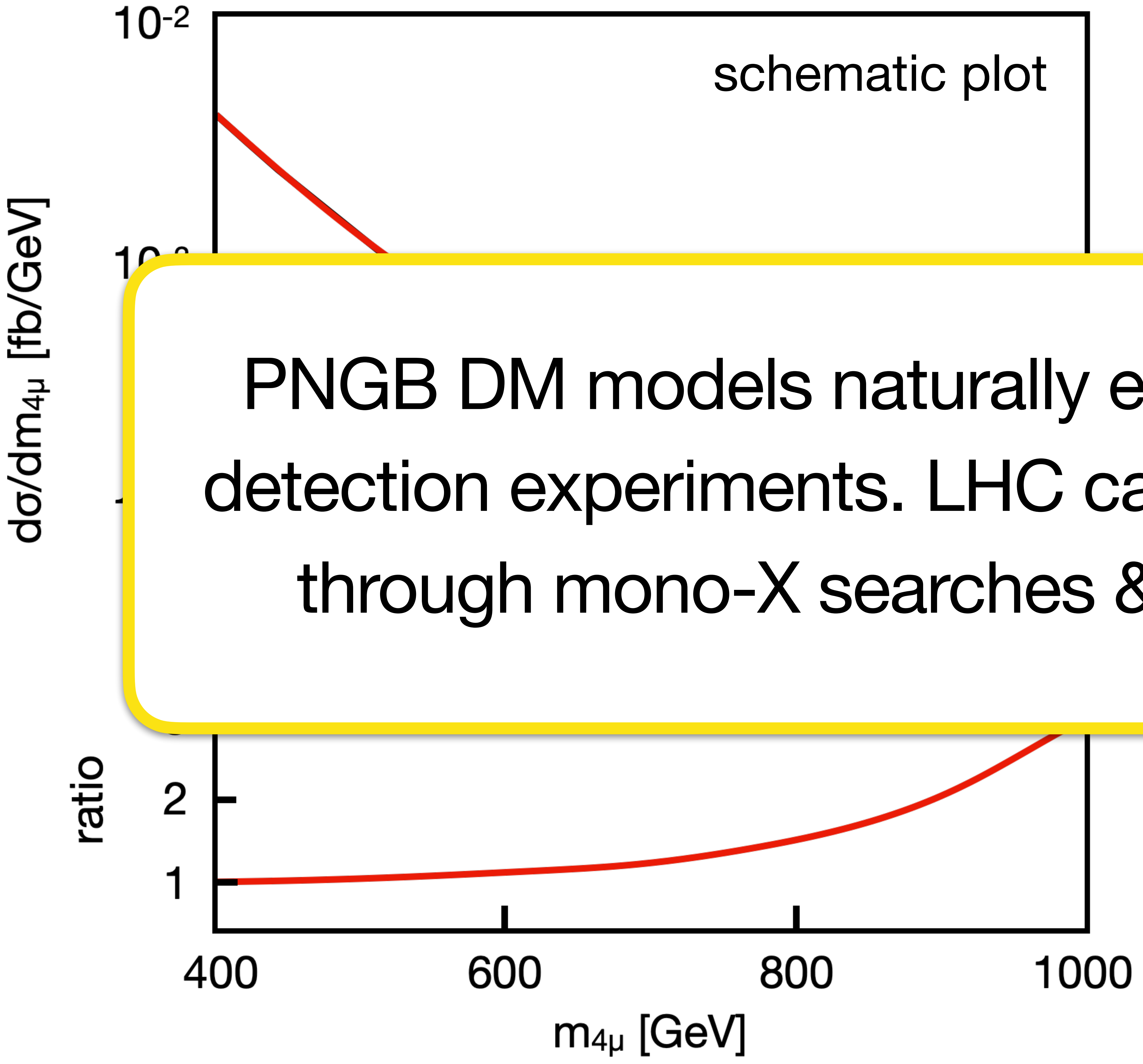


$$|\Phi|^2\Box|\Phi|^2, (\Box|\Phi|^2)^2, \ldots$$

SMEFT operators that arise together with portal interactions after integrating out heavy degrees of freedom modify tail of $m_{4\mu}$ spectrum in $gg \to 4\mu$

[ongoing work with Ruhdorfer, Salvioni, Venturini & Weiler]

Probing PNGB DM in Higgs physics



$|\Phi|^2\Box|\Phi|^2, \; (\Box|\Phi|^2)^2, \; \dots$

PNGB DM models naturally explain null results of (in)direct detection experiments. LHC can probe these models directly through mono-X searches & indirectly in Higgs physics

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[ongoing work with Ruhdorfer, Salvioni, Venturini & Weiler]

Summary

…

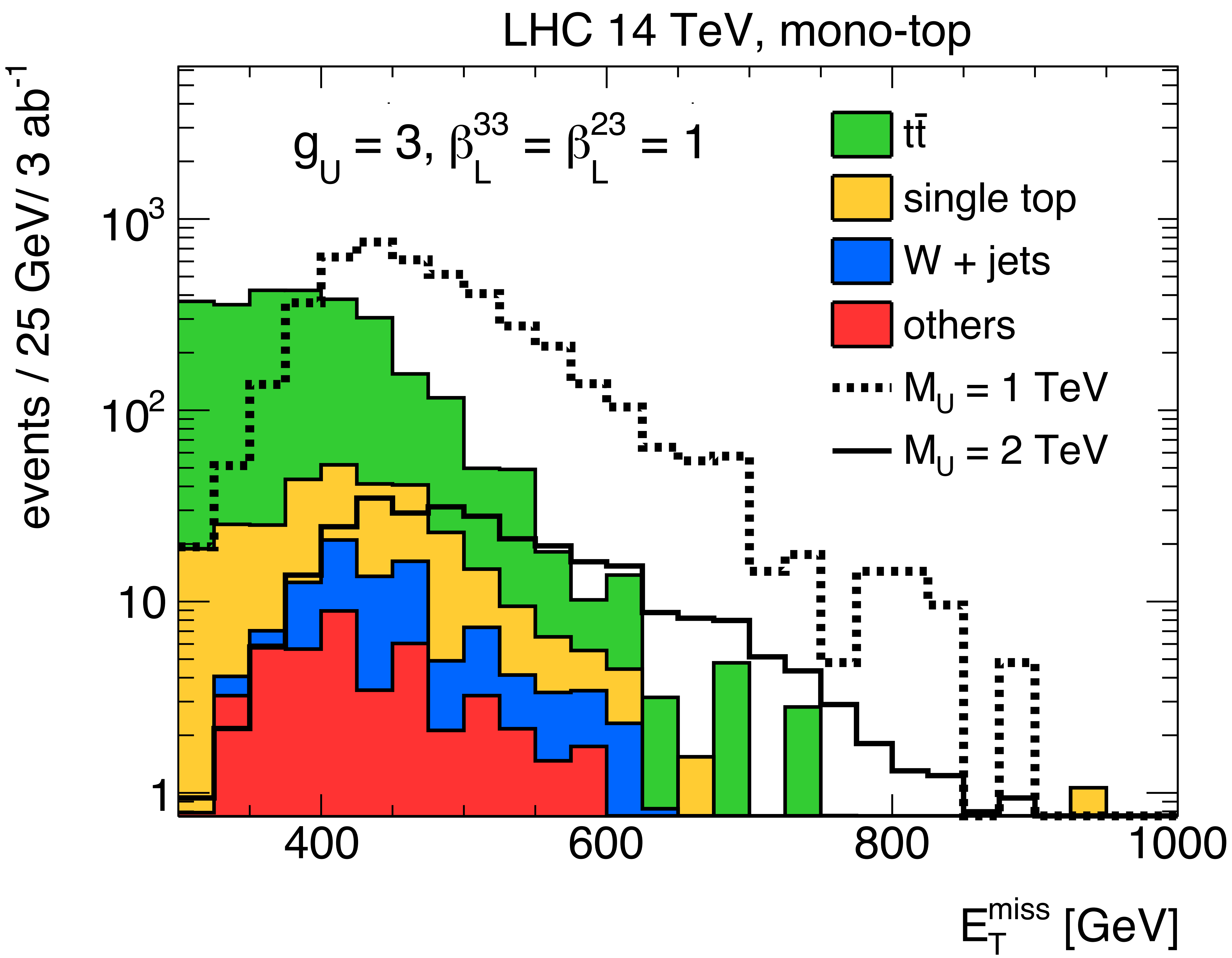
The time is gone, the song is over.

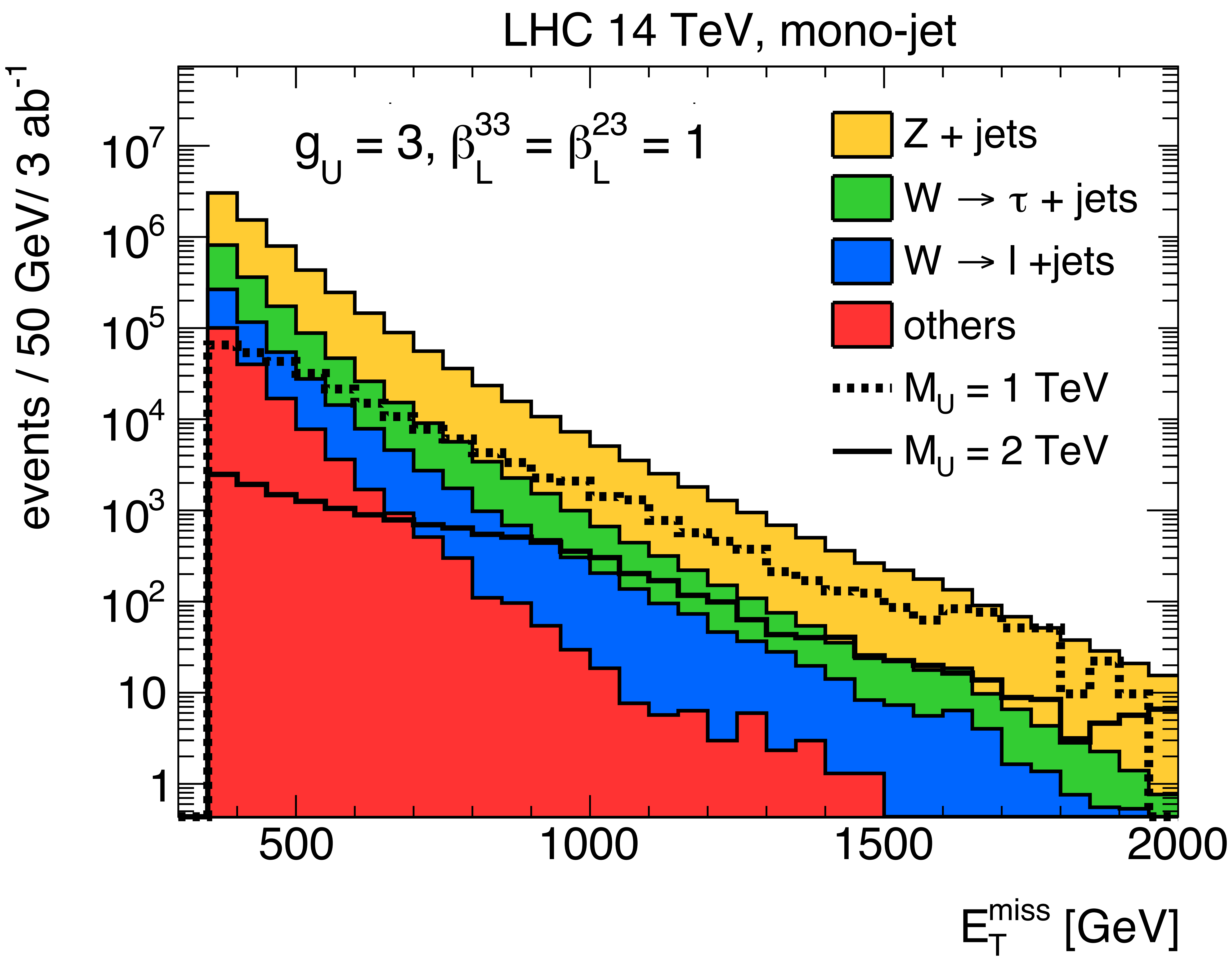
Thought I'd something more to say.

…

Time, Pink Floyd

Mono-top & mono-jet distributions





[ongoing work with Polesello]

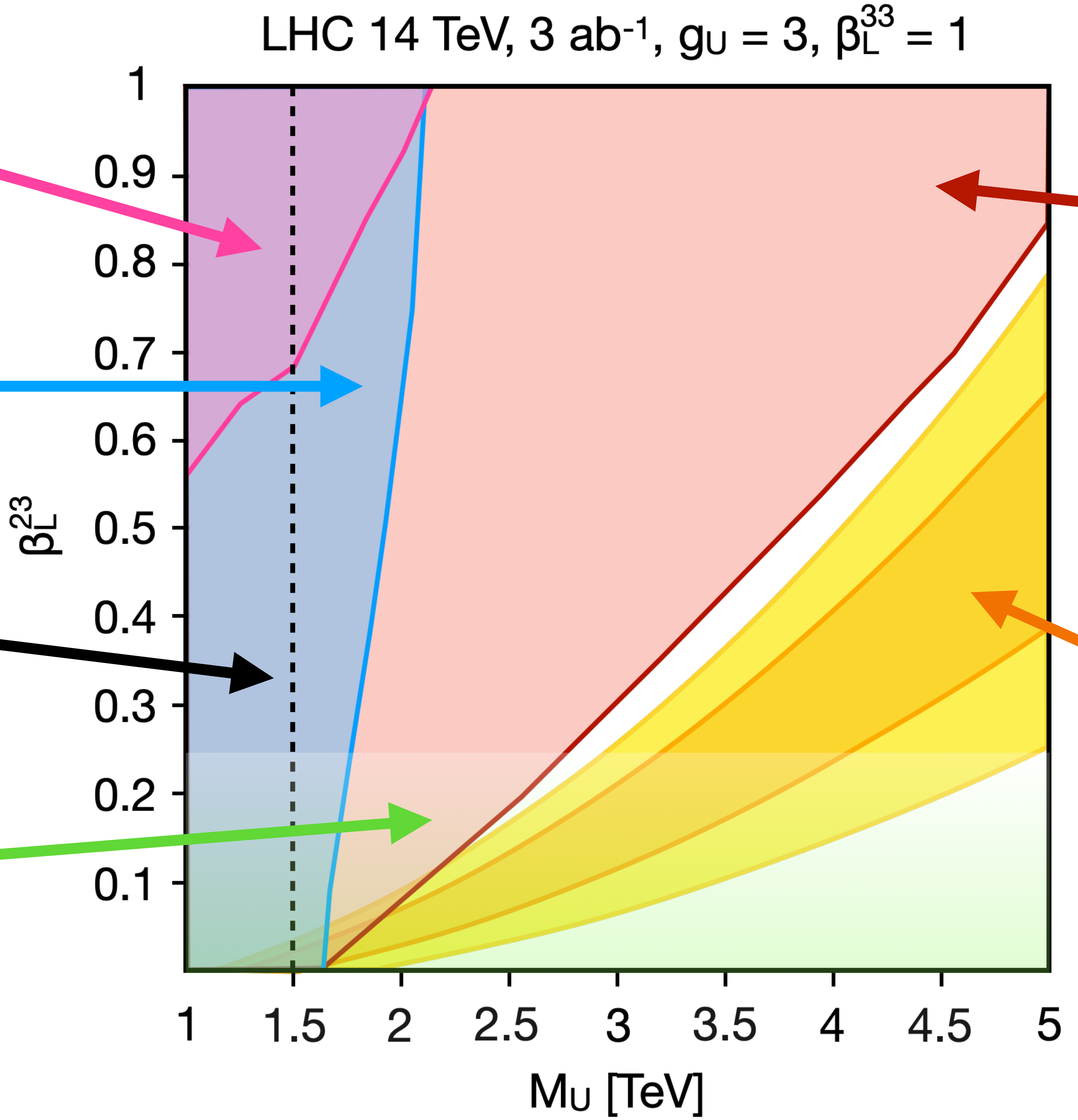
Resonant third-generation LQ constraints

mono-jet search

mono-top search

LQ pair production @ LHC Run II

natural parameter space of $U(2)_Q$ flavour models



b + τ search

68% CL (95% CL) region favoured by b → c anomalies

[ongoing work with Polesello]