PROBING B-ANOMALIES VIA DIMUON TAILS AT A FUTURE COLLIDER

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in collaboration with Bradley Garland, Sebastian Jäger and Charanjit K. Khosa

based on arXiv:2112.05127

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INTRODUCTION

- B-anomalies:

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\bar{\mu}\mu)}{\mathrm{BR}(B \to K^{(*)}\bar{e}e)}$$

Observable	SM	Measurement	Experiment	
$BR(B_s \to \mu^+\mu^-)$	$(3.63 \pm 0.13) \times 10^{-9}$	$(2.8 \pm 0.3) \cdot 10^{-9}$	average [4] of ATLAS [5], CMS [6] and LHCb [7]	4.2σ
$R_K[1.1, 6]$ $R_K[1, 6]$	$1.0004^{+0.0008}_{-0.0007}$	0.85 ± 0.04 1.03 ± 0.28	LHCb [8] Belle [9]	3.1σ
$R_{K^*}[0.045, 1.1]$	$0.920^{+0.007}_{-0.006}$	0.66 ± 0.11 0.52 ± 0.37	LHCb [10] Belle [11]	2.2σ
$R_{K^*}[1.1, 6]$	0.996 ± 0.002	0.69 ± 0.12 0.96 ± 0.45	LHCb [10] Belle [11]	2.4σ

- Goal: model independent and conservative, focus on inclusive $pp \to \mu^+\mu^-$

2104.08921.

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- Described by BSM four-fermion contact interactions in the low-energy effective weak Hamiltonian involving muons only

$$\mathscr{L}^{\mathrm{BSM}}_{\mathrm{eff}} = -\mathscr{H}^{\mathrm{BSM}}_{\mathrm{eff}} = \frac{4G_F}{\sqrt{2}} V_{ts}V^*_{tb} \frac{e^2}{16\pi^2} \left\{ C_9^{\mathrm{NP}} \left(\bar{b}_L \gamma_\mu s_L\right)\left(\bar{\mu}\gamma^\mu \mu\right) + C_{10}^{\mathrm{NP}} \left(\bar{b}_L \gamma_\mu s_L\right)\left(\bar{\mu}\gamma^\mu \gamma^5 \mu\right) + \ldots \right\}$$

$$\equiv \frac{1}{\Lambda^2_{\mathrm{LL}}} \left(\bar{b}_L \gamma_\mu s_L\right)\left(\bar{\mu}_L \gamma^\mu \mu_L\right) + \frac{1}{\Lambda^2_{\mathrm{LR}}} \left(\bar{b}_L \gamma_\mu s_L\right)\left(\bar{\mu}_R \gamma^\mu \mu_R\right) + \ldots$$

- Excellent fit of $b \to s\ell^+\ell^-$ data obtained by LH muons only give $C_9^{\mathrm{NP}} = -C_{10}^{\mathrm{NP}} \equiv C_L \approx -0.40$, PhysRevD.104.035029, arXiv:2103.13370, arXiv:2104.08921

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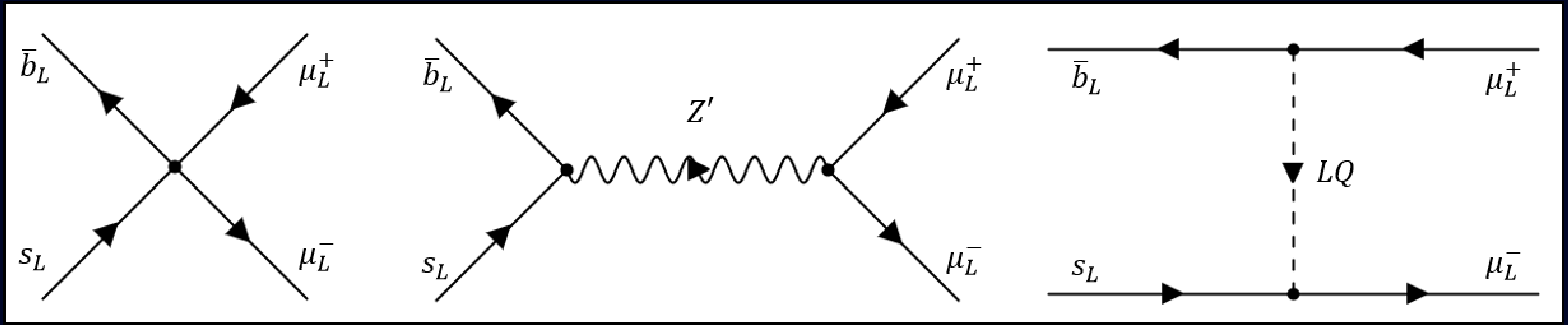

- Rare B decay dataset points to the presence of a left-handed contact interaction $\mathscr{L}_{\text{eff}} \supset \frac{1}{\Lambda^2}\mathcal{O}_{LL}$, where $\mathcal{O}_{LL} = \left(\bar{b}_L\gamma_\mu s_L\right)\left(\bar{\mu}_L\gamma^\mu\mu_L\right)$ and $\Lambda = (39 \pm 4)$ TeV

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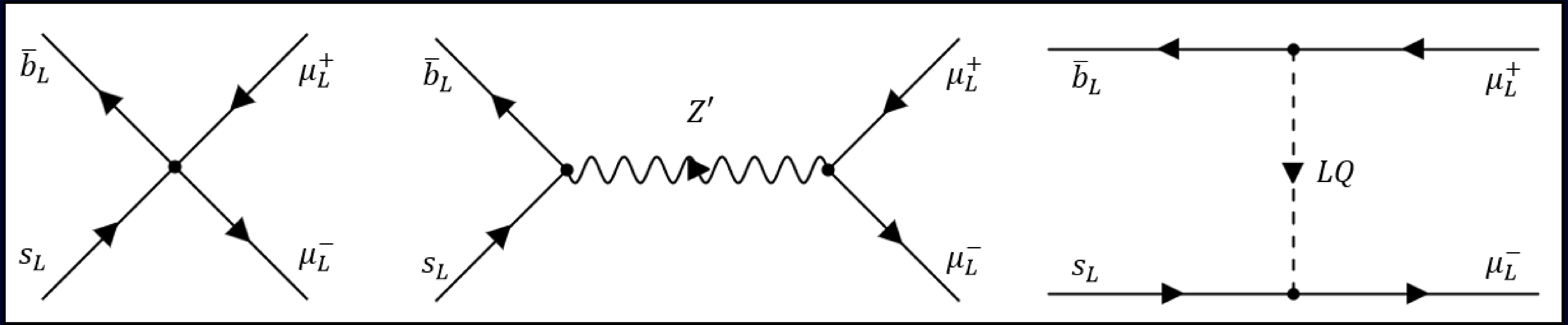

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- Low-energy effective description of SM extension, eg. Z' or (spin-1 or spin-0) leptoquark

- Perturbative unitarity allows, for $\Lambda = 39$ TeV, mediators as heavy as 105 TeV

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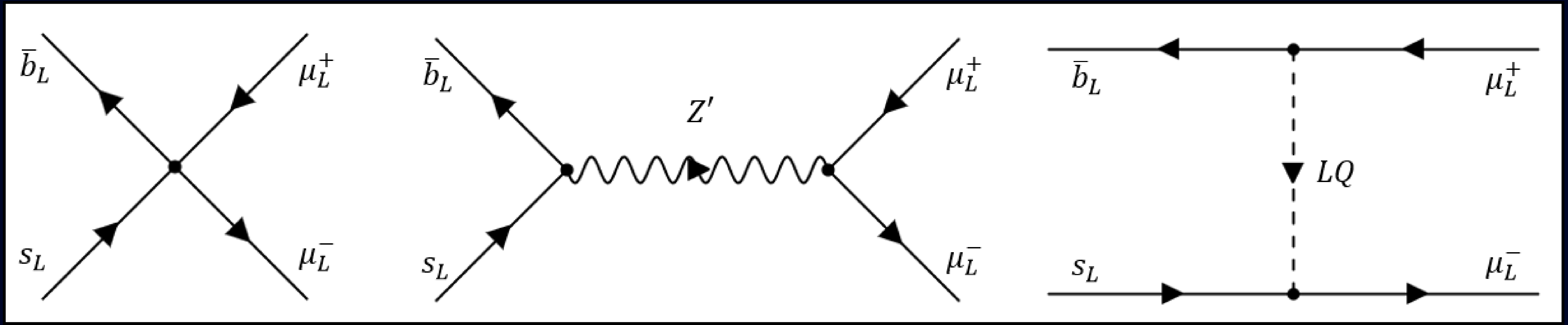

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- Low-energy effective description of SM extension, eg. Z' or (spin-1 or spin-0) leptoquark
- Perturbative unitarity allows, for $\Lambda = 39$ TeV, mediators as heavy as 105 TeV
- Look for effects of heavy NP in ``low-energy'' tails of $m_{\bar{\mu}\mu}$ within EFT
- To what extent does increased $\sqrt{s}$ improve the sensitivity to $bs\mu\mu$ contact interactions?

SMEFT

$$\mathscr{L}^{\text{SMEFT}} = \mathscr{L}^{\text{SM}} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} + \sum_j c_j^{(8)} \mathcal{O}_j^{(8)} + \cdots$$

SMEFT

$$\mathscr{L}^{\text{SMEFT}} = \mathscr{L}^{\text{SM}} + \Sigma_i c_i^{(6)} \mathcal{O}_i^{(6)} + \Sigma_j c_j^{(8)} \mathcal{O}_j^{(8)} + \cdots$$

- Choose a basis such that $b \to s\mu^+\mu^-$ governed by single Wilson coeff. C_{sb}^+

$$\mathscr{L}^{\text{SMEFT}} \supset C_{ij}^+ (\bar{d}_L^j \gamma_\rho\, d_L^i) \left(\bar{\mu}_L \gamma^\rho \mu_L\right) + C_{ij}^- (\bar{d}_L^j \gamma_\rho\, d_L^i) \left(\bar{\nu}_\mu \gamma^\rho \nu_\mu\right)$$

$$+ \Sigma_{k,l} V_{ki}^* C_{ij}^+ V_{lj} (\bar{u}_L^l \gamma_\rho u_L^k)(\bar{\nu}_\mu \gamma^\rho \nu_\mu) + \Sigma_{k,l} V_{ki}^* C_{ij}^- V_{lj} (\bar{u}_L^l \gamma_\rho u_L^k)(\bar{\mu}_L \gamma^\rho \mu_L)$$

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$$C^+ = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & C_{sb}^+ \\ 0 & {C_{sb}^+}^* & 0 \end{pmatrix}$$

- Consider minimal/conservative scenario

$$\mathscr{L}^{\text{SMEFT}} \supset C_{sb}^+ (\bar{b}_L \gamma_\rho s_L)\left(\bar{\mu}_L \gamma^\rho \mu_L\right) + \sum_{k,l} V_{ks}^* C_{sb}^+ V_{lb} (\bar{u}_L^l \gamma_\rho u_L^k)(\bar{\nu}_\mu \gamma^\rho \nu_\mu) + \text{h.c.}$$

$$C^- = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

where $C_{sb}^+ = \dfrac{1}{\Lambda^2}$

SET-UP

- Main SM contributions to $pp \to \mu^+\mu^-$:

  1. Drell–Yan via Z/γ^* exchange (~80-90%)
  2. diboson (ZZ, WZ and WW) production
  3. top-quark production ($\bar{t}t$ & tW)

- Use MadGraph5_aMC@NLO including fixed order NLO QCD and EW corrections for DY and LO for the rest

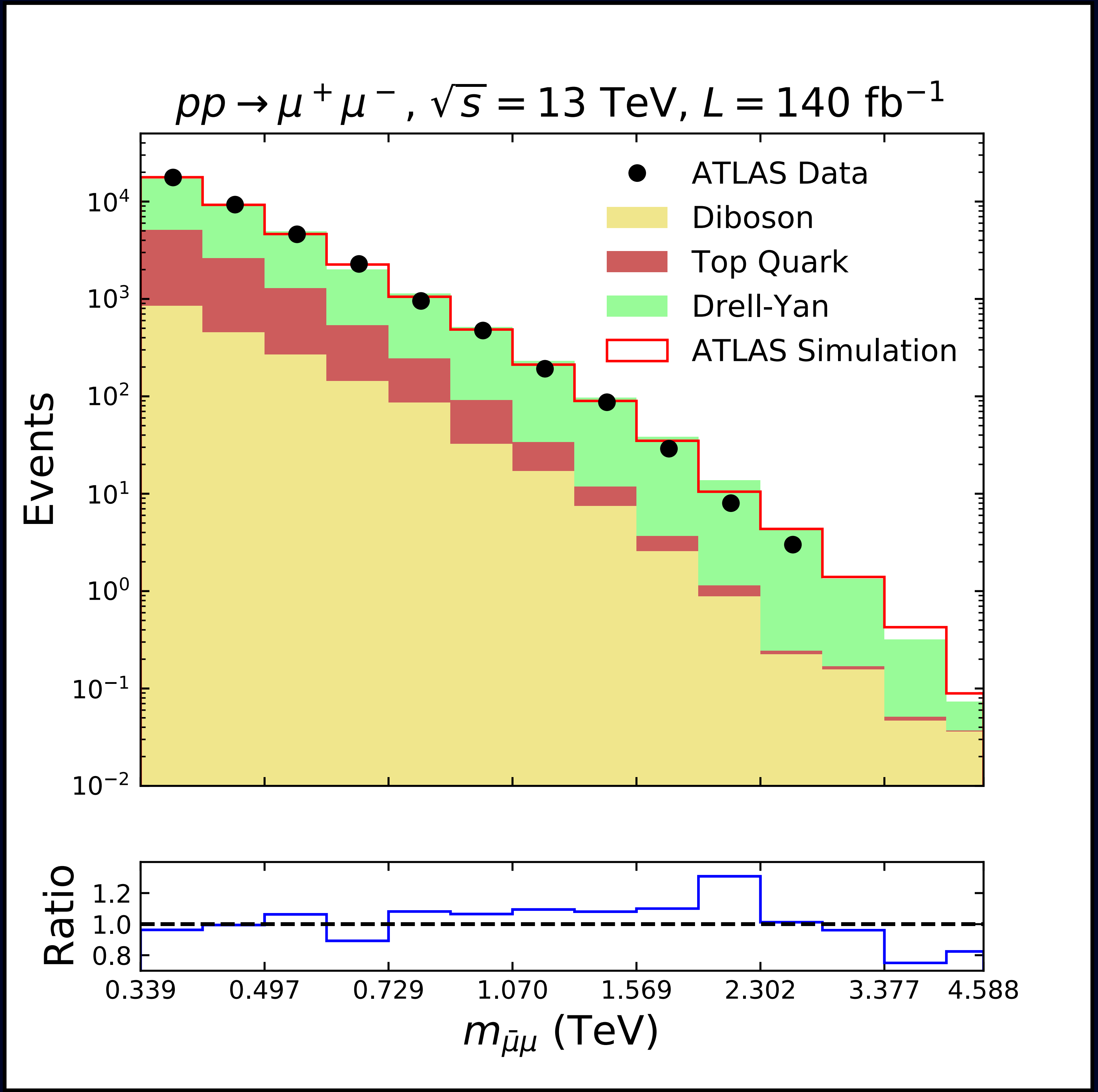
- NNPDF31_nlo_as_0118_luxqed 5 flavour

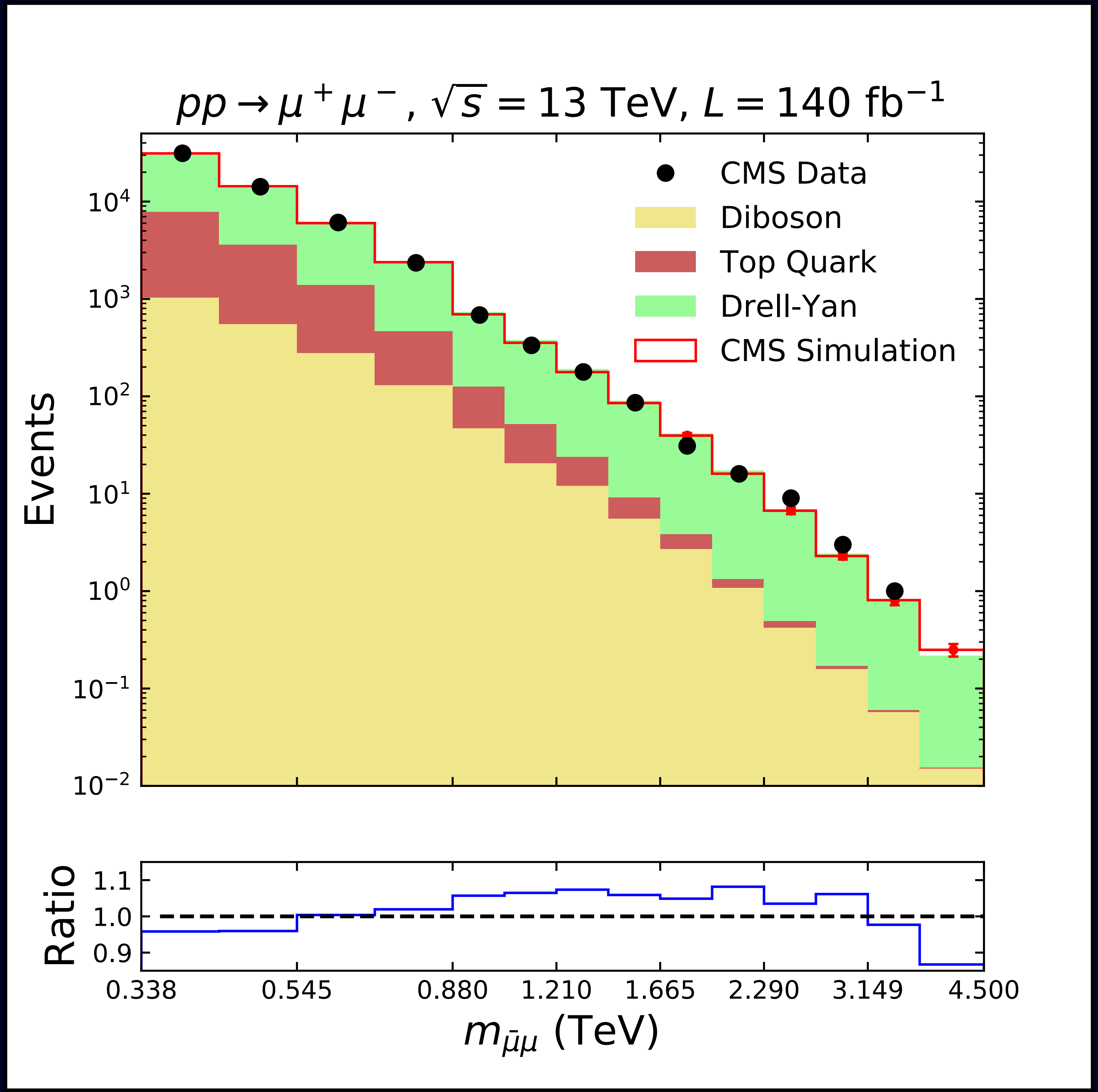
- Consider $\sqrt{s} = 13$ TeV LHC, $\sqrt{s} = 14$ TeV HL-LHC and FCC-hh with $\sqrt{s} = 100$ TeV

- Signal generated by adding dim 6 ops. to default SM UFO file and including R_2 terms by hand to yield gauge-invariant results

VALIDATION

- Check that our background simulation is in agreement with CMS and ATLAS
- $p_T > 30$ GeV and $|\eta| < 2.5$ for ATLAS
- $p_T > 53$ GeV and $|\eta| < 2.4$ for CMS

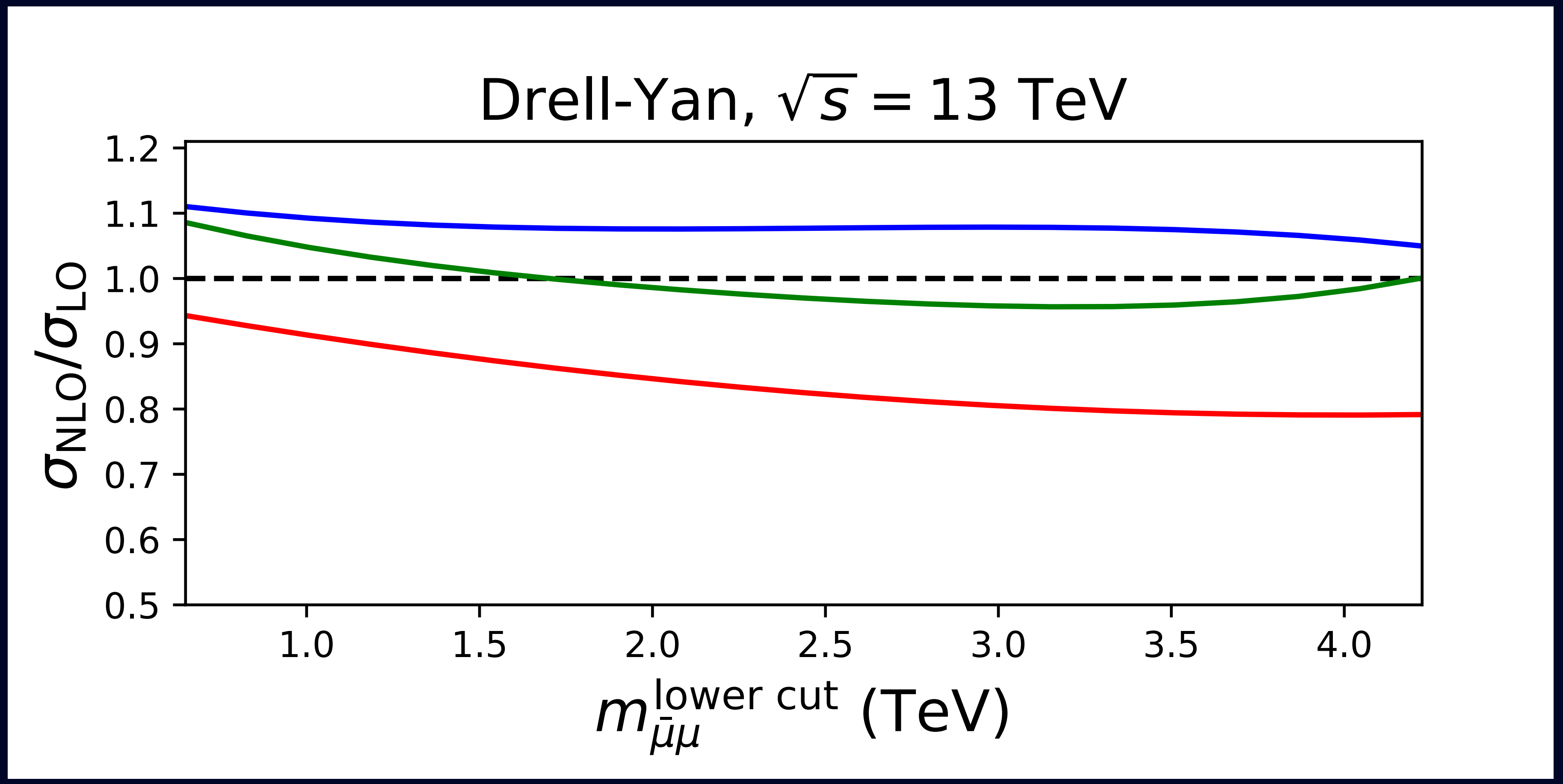


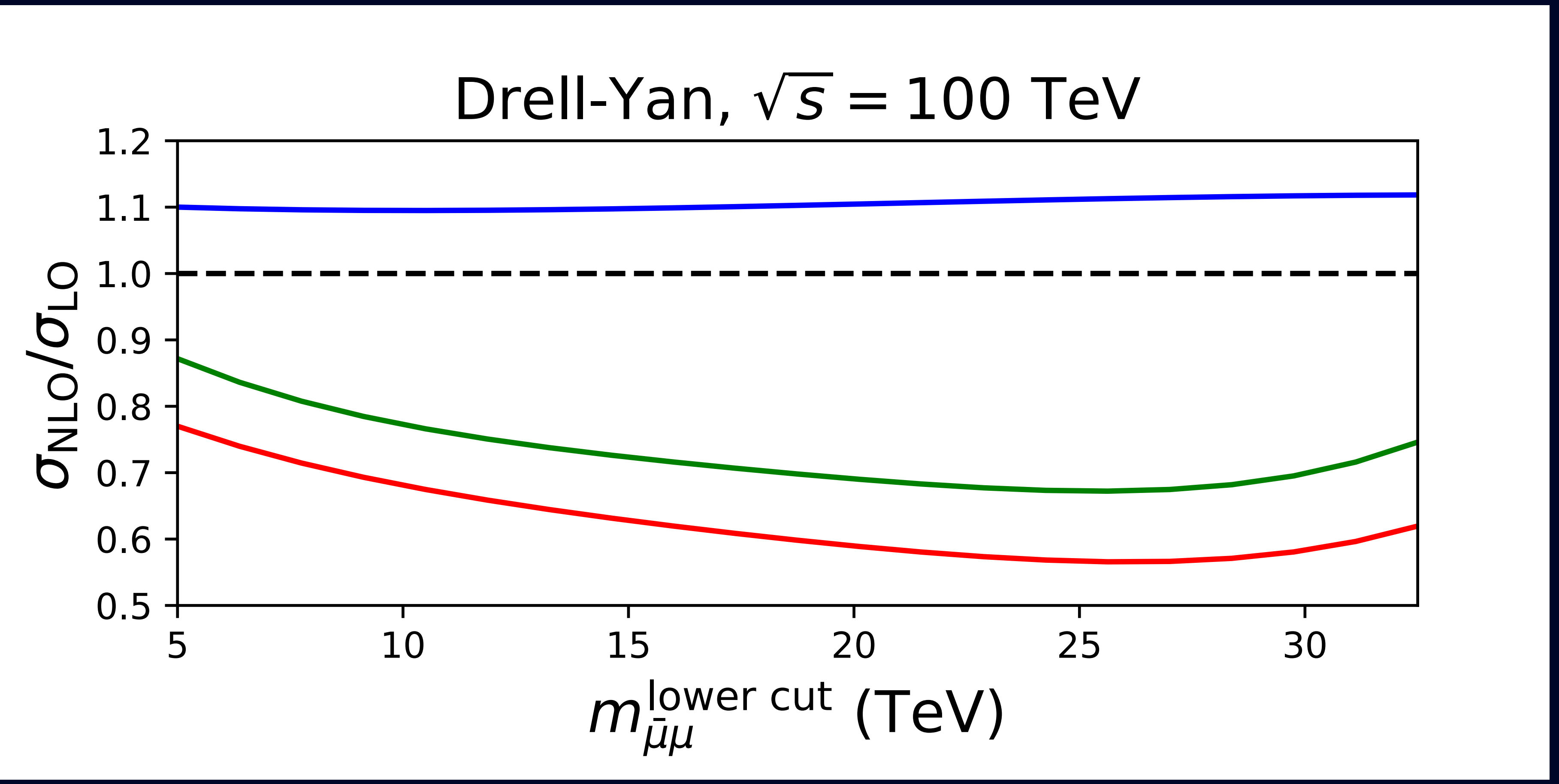


- Our background is in excellent agreement with CMS (within ~10%), slightly worse for ATLAS due to more complicated selection criteria
- CMS JHEP07 (2021) 208, ATLAS JHEP11 (2020) 006

INCLUSION OF NLO

- DY process receives large EW corrections in the high $m_{\bar{\mu}\mu}$ region
- NLO-EW corrections contain large negative Sudakov double logarithms that reduce $d\sigma/dm_{\bar{\mu}\mu}$ of the inclusive DY process at large values of $m_{\bar{\mu}\mu}$





Blue: NLO-QCD

Red: NLO-EW

Green: NLO QCD&EW

EFT VALIDITY

- $m_{\bar{\mu}\mu}^{\text{max}}$ cannot be taken to be arbitrarily large
- Tree-level unitarity implies upper bound for $m_{\bar{\mu}\mu} < \Lambda_*$
- Model dependent bound from UV mediator mass, e.g. $m_{\bar{\mu}\mu} < m_{Z'}$ or $m_{\bar{\mu}\mu} < m_{\text{LQ}}$

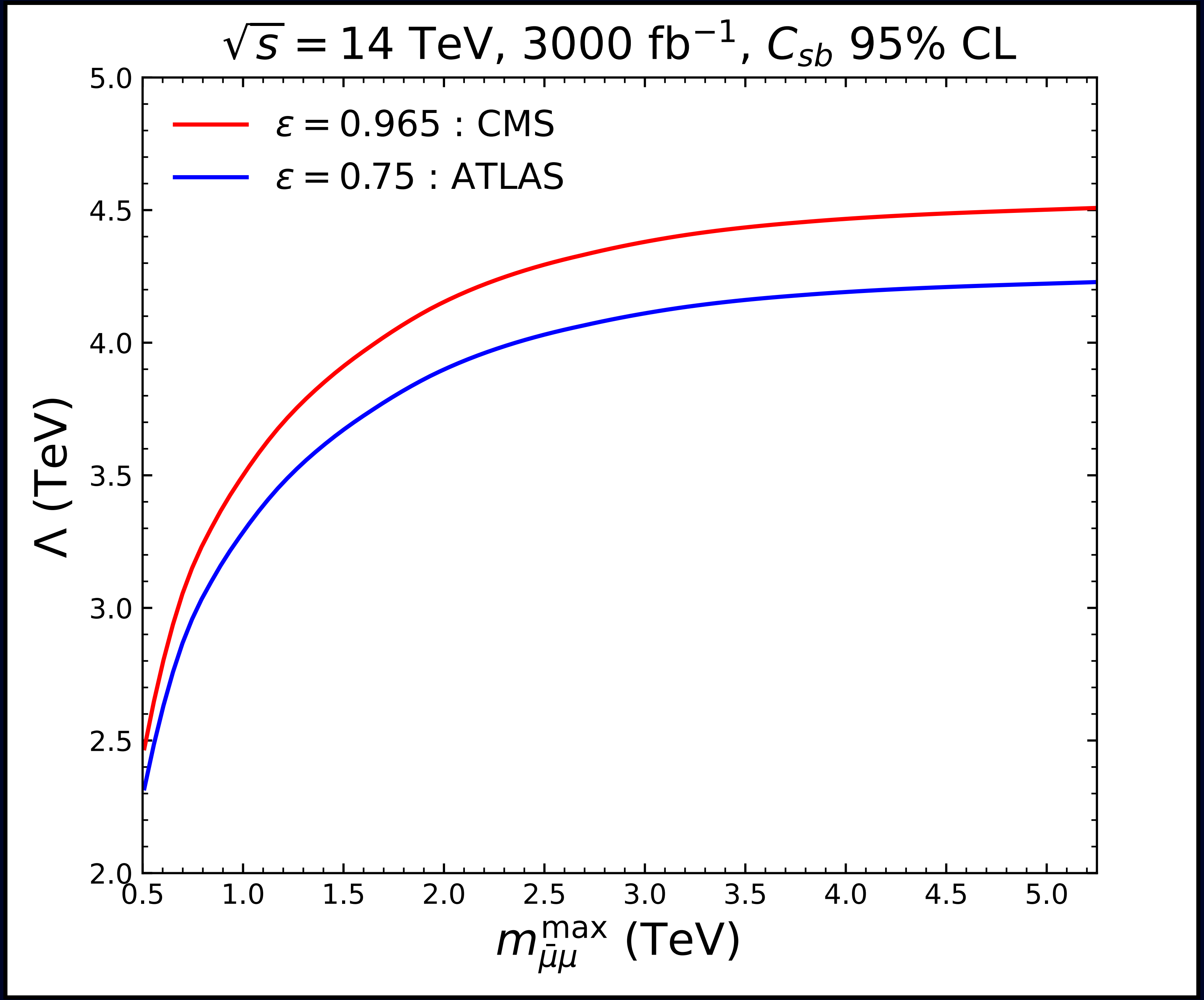
RESULTS

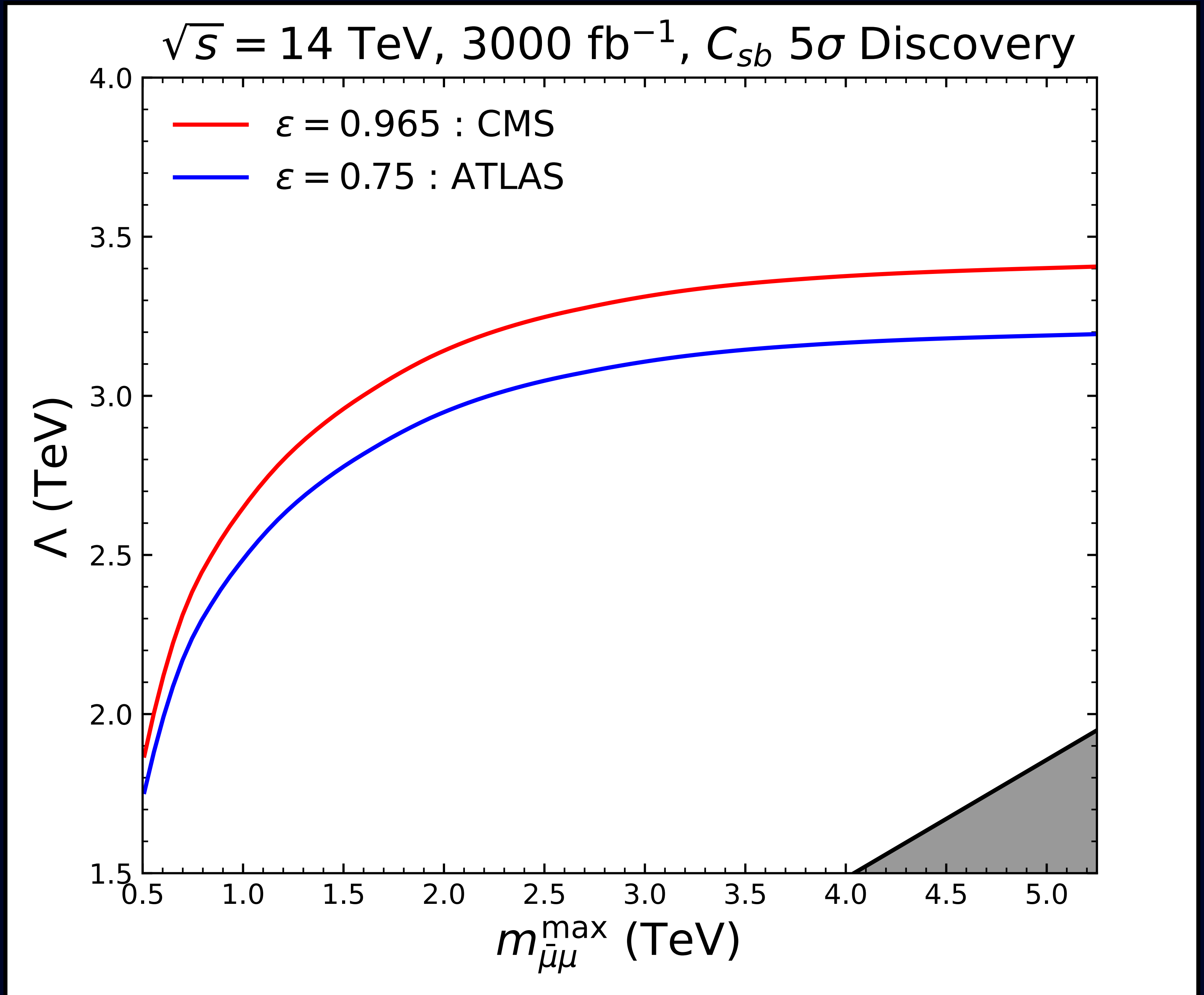
LHC & HL-LHC SENSITIVITY

- Collider recast based on JHEP10 (2017) 182 using 36 fb^{-1} ATLAS search and in agreement with literature arXiv:1704.09015 and including NLO

	95% Exclusion				5σ Discovery			
$\sqrt{s}$ (TeV)	13			14	13			14
L (fb^{-1})	36	139	3000	3000	36	139	3000	3000
Λ (TeV) ($\epsilon = 0.75$)	2.3	2.7	4.1	4.2	1.7	2.1	3.1	3.2
Λ (TeV) ($\epsilon = 0.965$)	2.4	2.9	4.3	4.5	1.8	2.2	3.2	3.4

- ε - ATLAS/CMS muon identification efficiency
- $m_{\bar{\mu}\mu}^{\max} = \{4.5, 5.25\}$ TeV
- Exclude and discover areas of parameter space for a given NP model without the need for a direct search



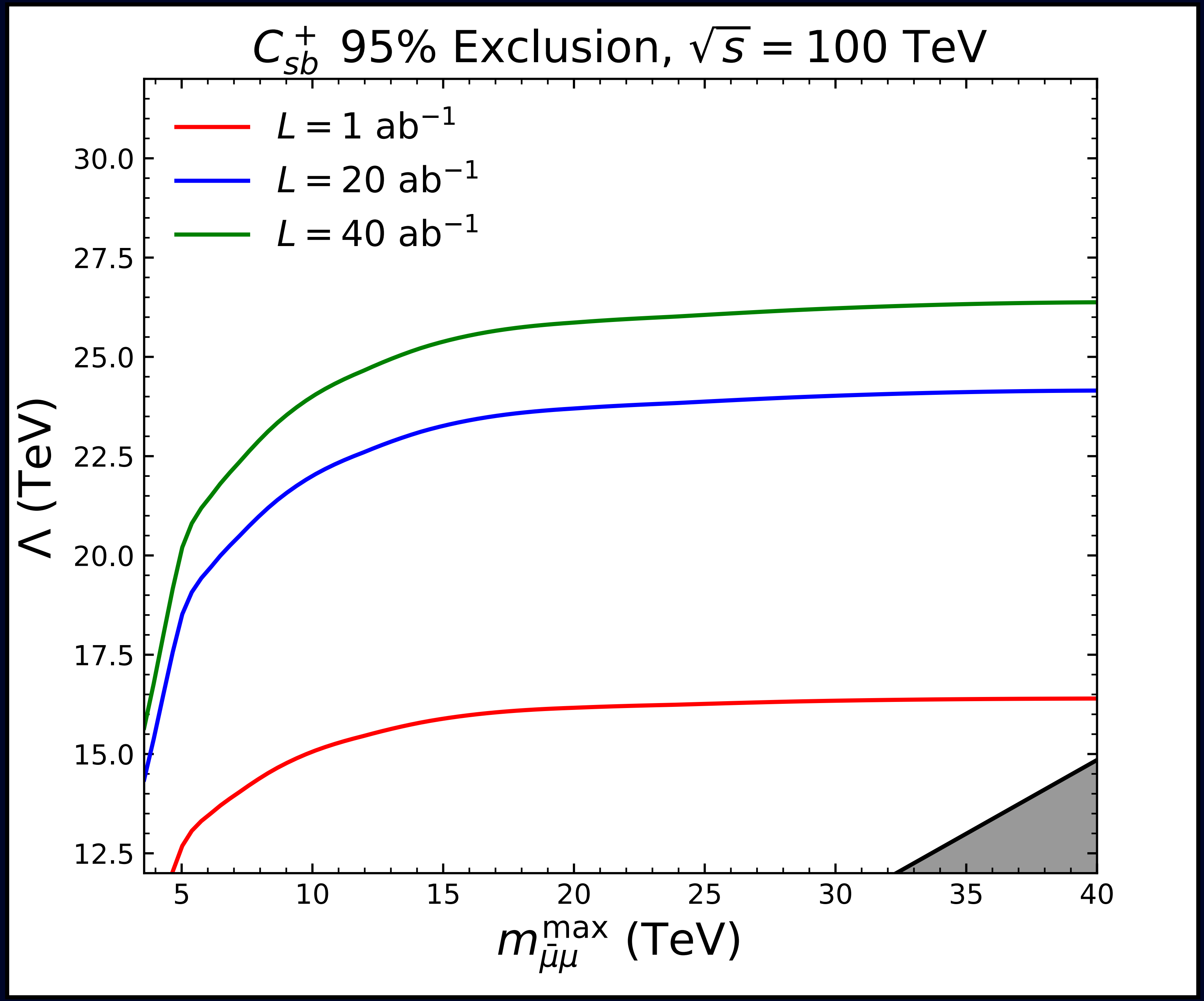


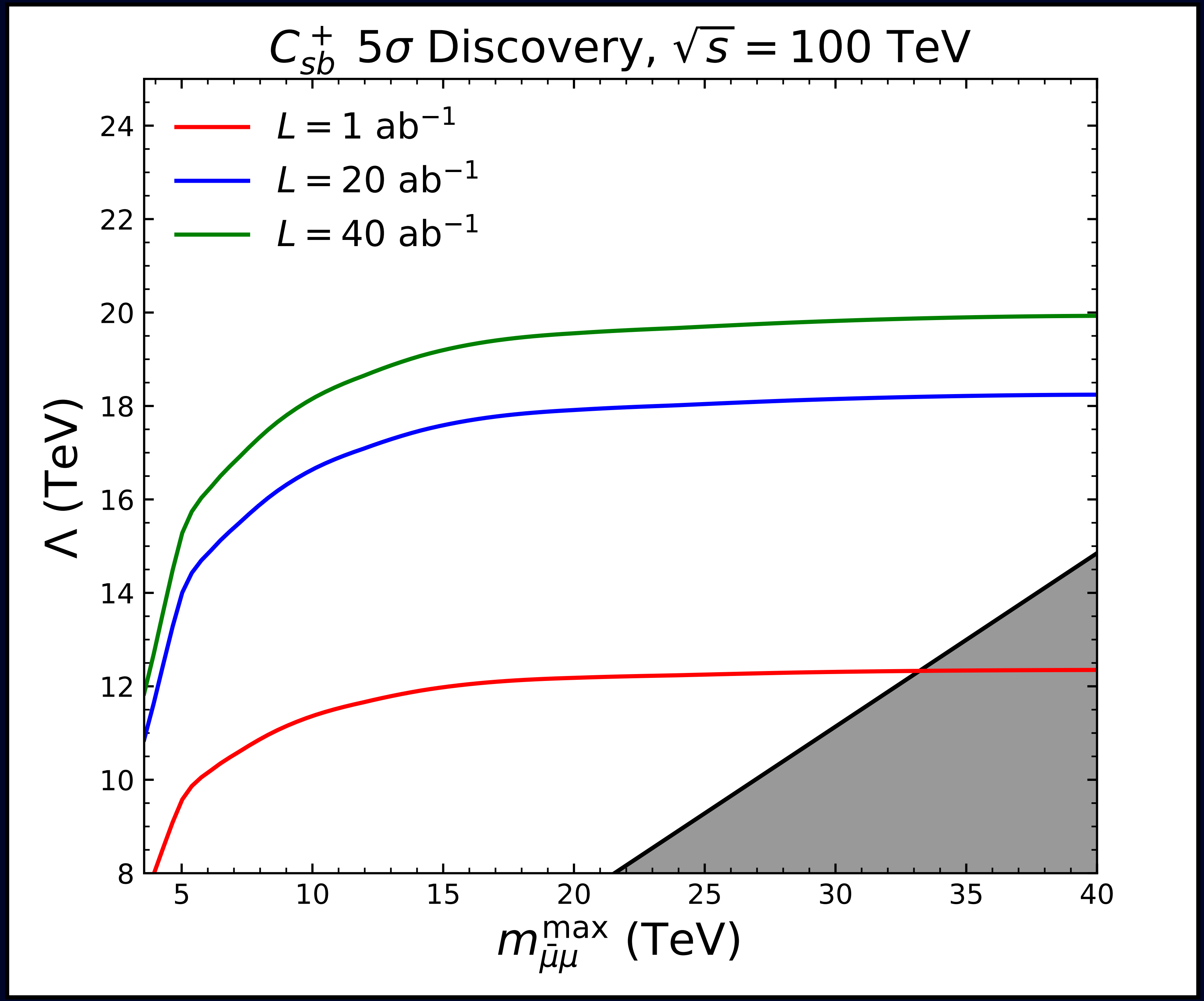
SENSITIVITY AT FCC-HH

- $m_{\bar{\mu}\mu}^{\text{max}} = \{15, 40, 30\}$ TeV

	95% Exclusion			5σ Discovery		
L (ab^{-1})	1	20	40	1	20	40
Λ (TeV)	15.8	24.1	26.4	12.0	18.1	19.8

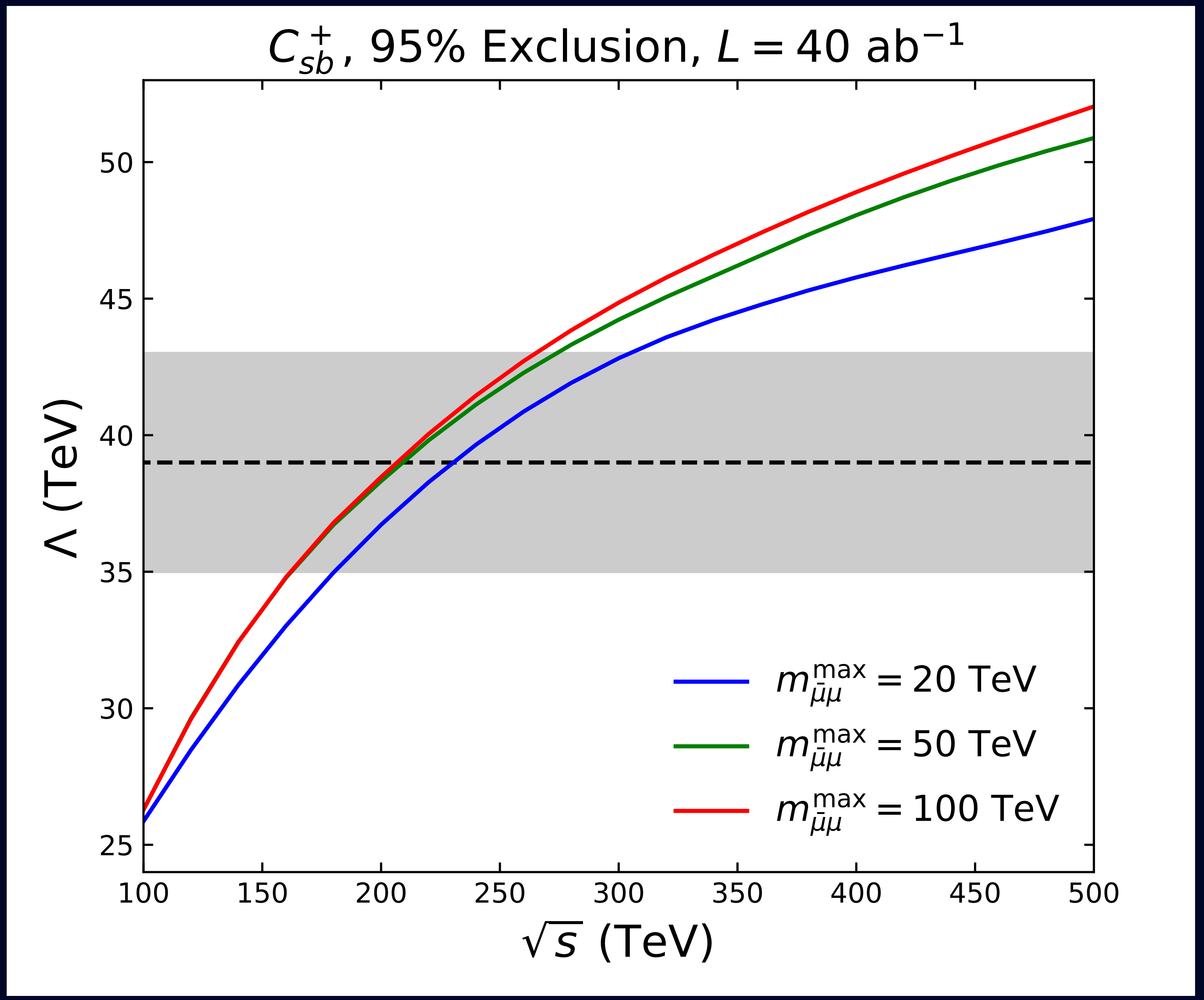
- Unitary bound is more relevant at low luminosities
- Improved sensitivity at FCC-hh by ~5 times
- Need ~2 times more luminosity to exclude $\Lambda \approx 30$ TeV
- Need ~20 times more luminosity to exclude $\Lambda \approx 40$ TeV

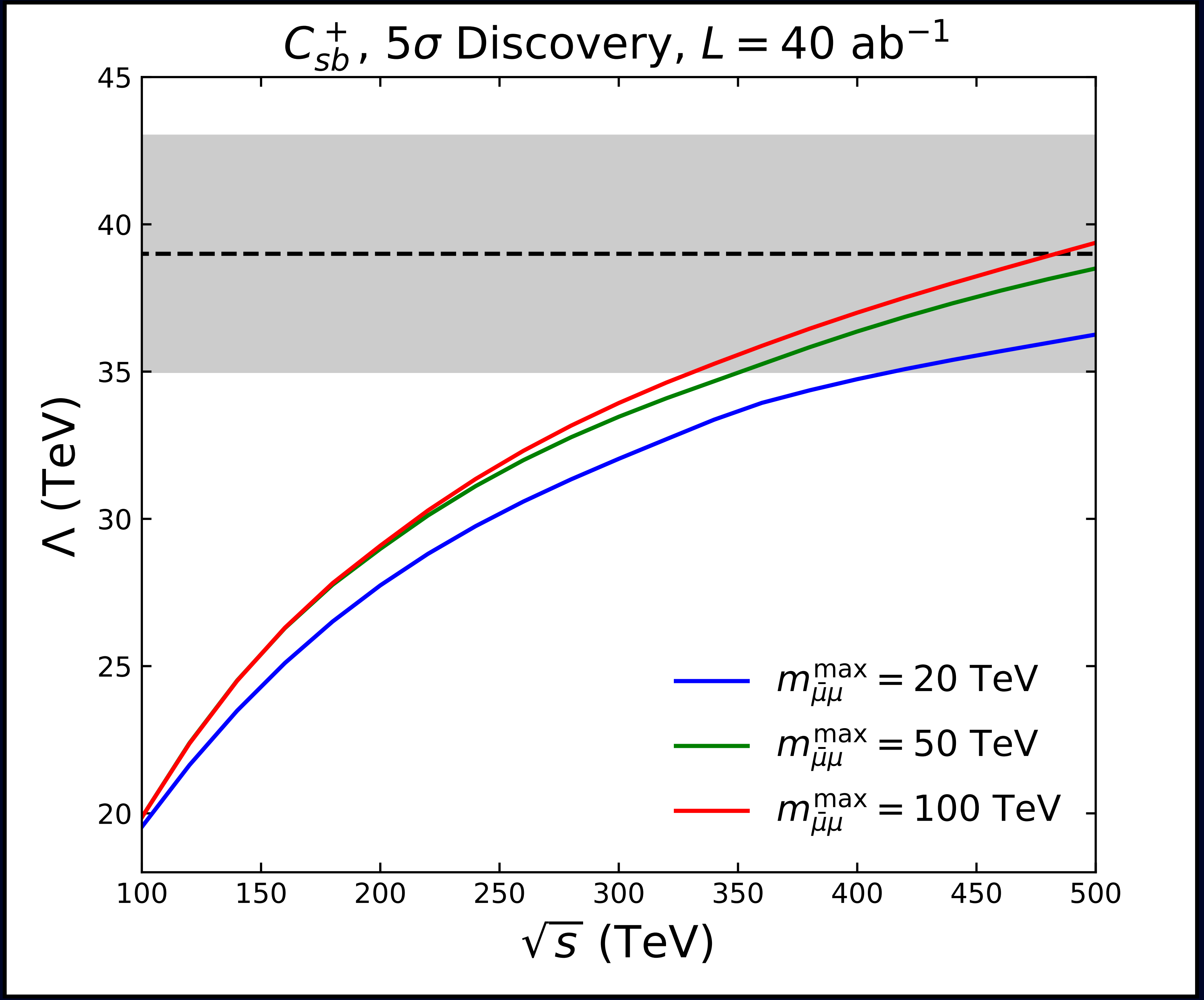




BEYOND FCC-HH

- Consider FCC-hh with increased c.o.m energy, i. e. $\sqrt{s} > 100$ TeV and $L = 40$ ab^{-1}
- As c.o.m energy increases the DY process and the EFT signal is suppressed by increasingly larger negative Sudakov Double Logarithms
- Diboson process dominates the background around $\sqrt{s} = 300$ TeV
- $m_{\bar{\mu}\mu}^{\text{min}} = 3$ TeV gives the optimised sensitivity in the region of $\sqrt{s} = [100, 500]$ TeV





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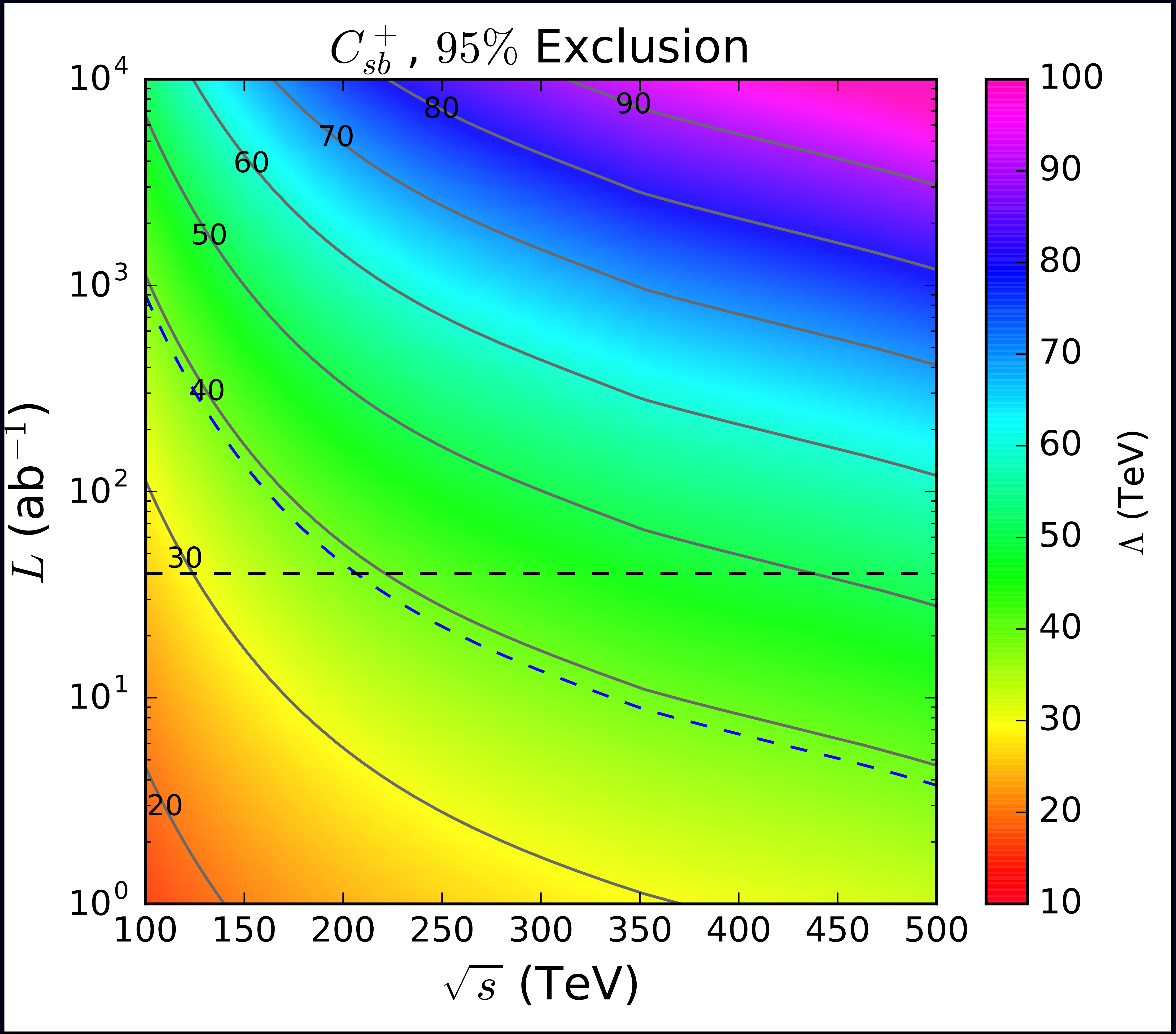

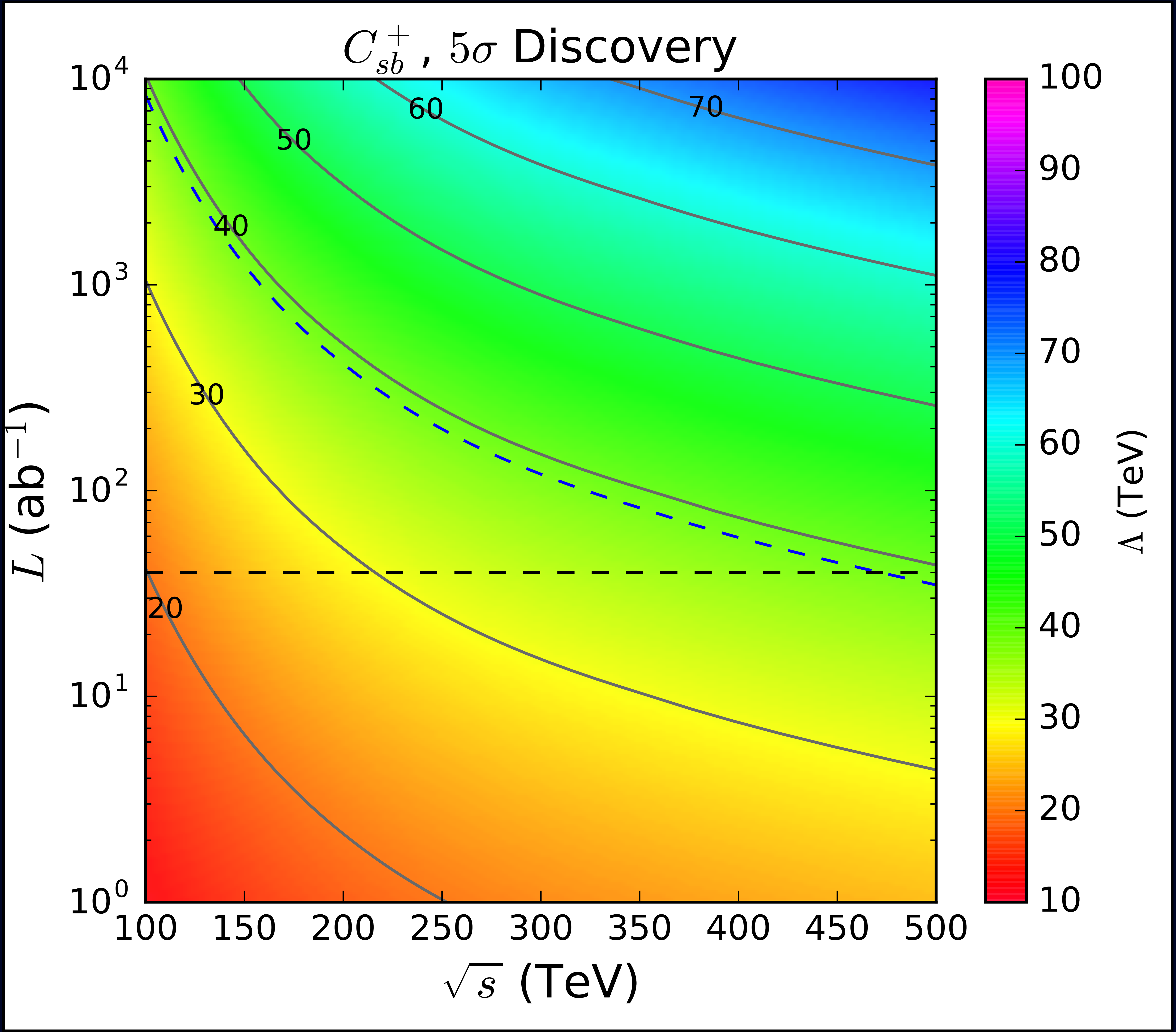

CONCLUSION

- Model-independent and most conservative analysis
- Probing a value of $\Lambda \approx 39$ TeV as suggested by the B-anomalies would be possible with a machine with higher energy and/or luminosity than the FCC-hh
- A comprehensive case would combine contact interaction searches (for heavy mediators) with direct searches (for lighter mediators)
- Could improve sensitivity by considering a more complex final state with a reduced SM background, eg. exclusive $\mu^+\mu^-b$ search JHEP08 (2018) 056
- Muon collider offers encouraging results PhysRevD.105.015013

BACK-UP

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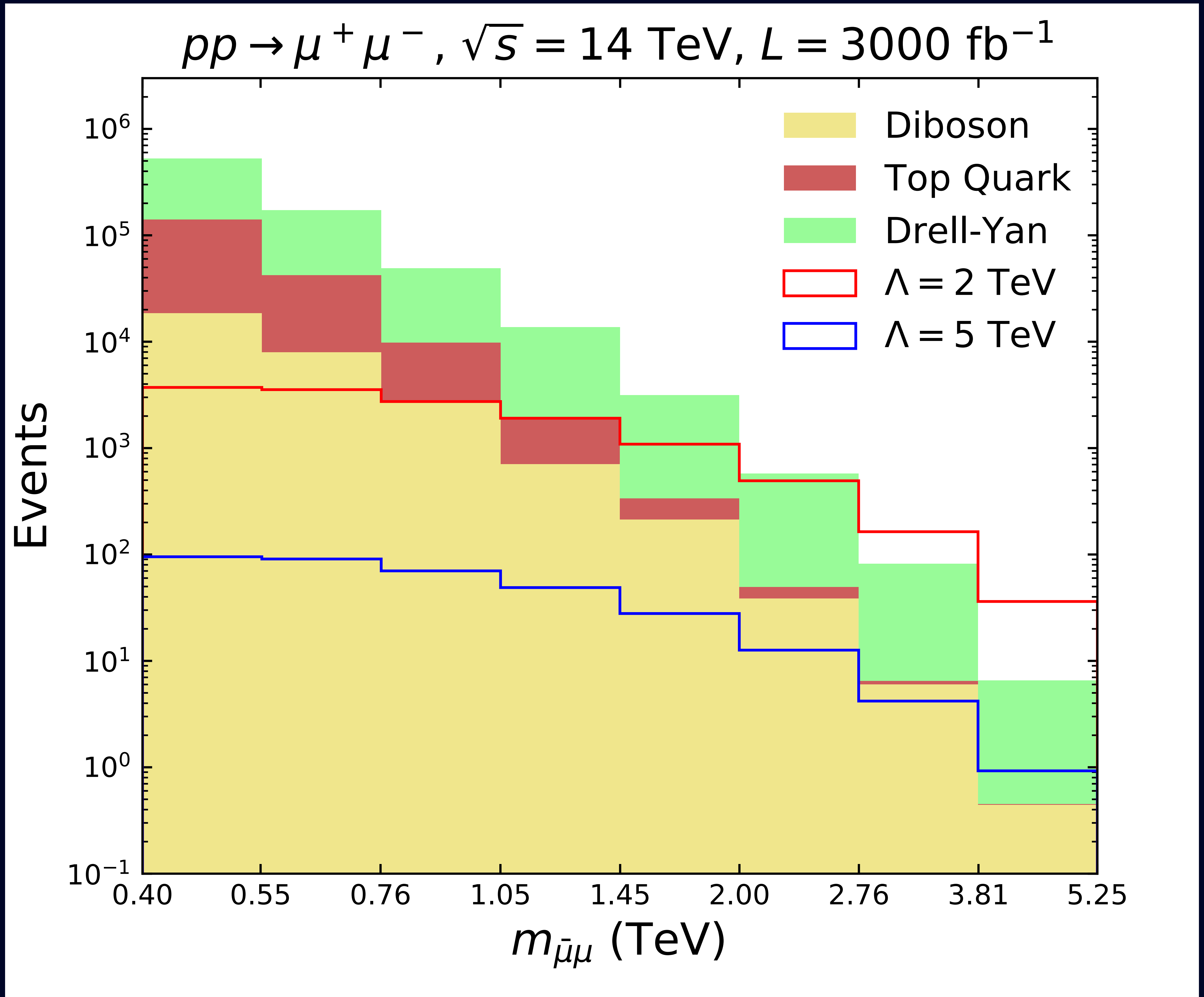
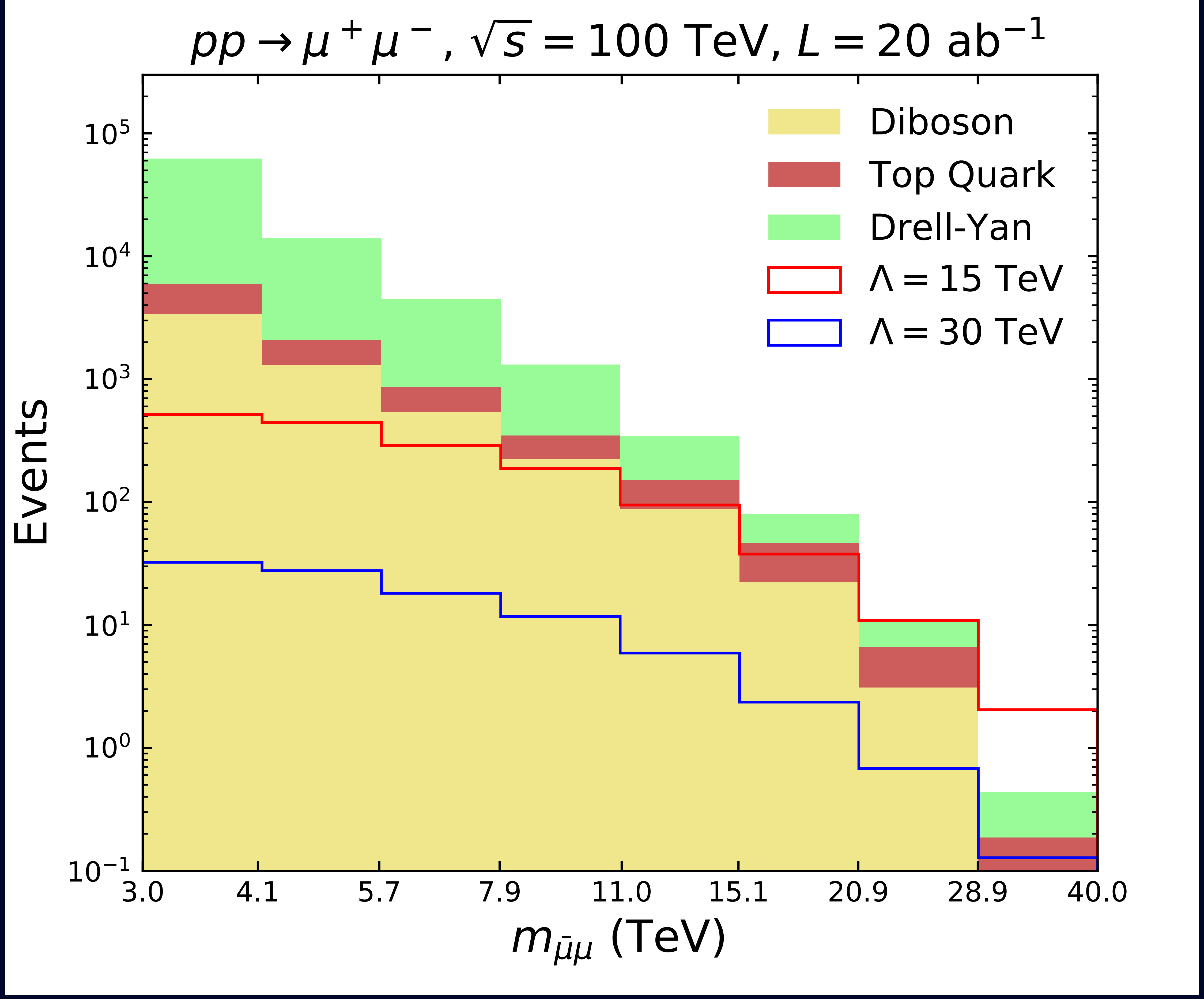


$pp \to \mu^+\mu^-$, $\sqrt{s} = 14$ TeV, $L = 3000$ fb^{-1}
Diboson
Top Quark
Drell-Yan
$\Lambda = 2$ TeV
$\Lambda = 5$ TeV
Events
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
0.40
0.55
0.76
1.05
1.45
2.00
2.76
3.81
5.25
$m_{\bar{\mu}\mu}$ (TeV)



$pp \to \mu^+\mu^-$, $\sqrt{s} = 100$ TeV, $L = 20$ ab^{-1}
Diboson
Top Quark
Drell-Yan
$\Lambda = 15$ TeV
$\Lambda = 30$ TeV
Events
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
3.0
4.1
5.7
7.9
11.0
15.1
20.9
28.9
40.0
$m_{\bar{\mu}\mu}$ (TeV)

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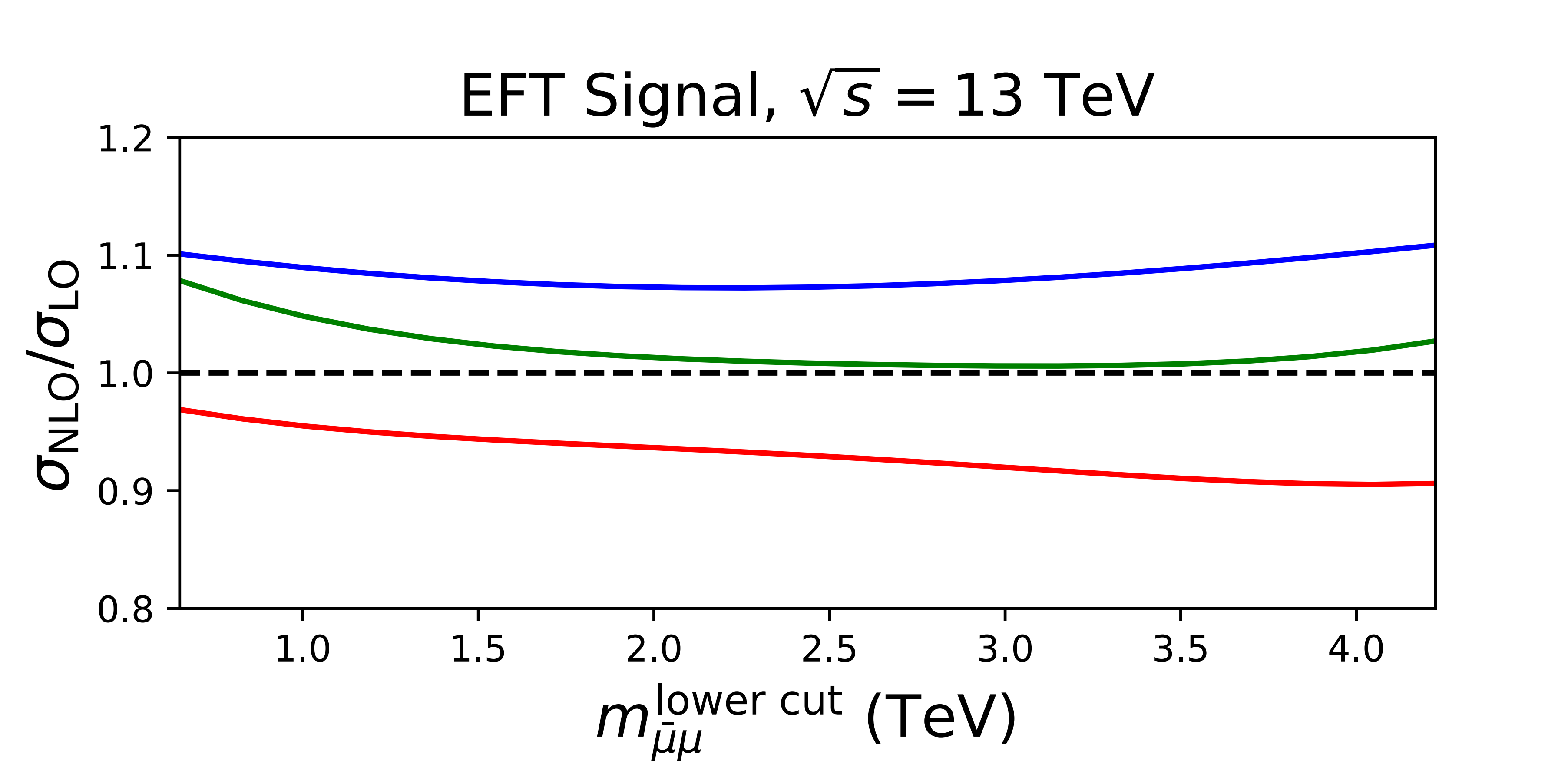

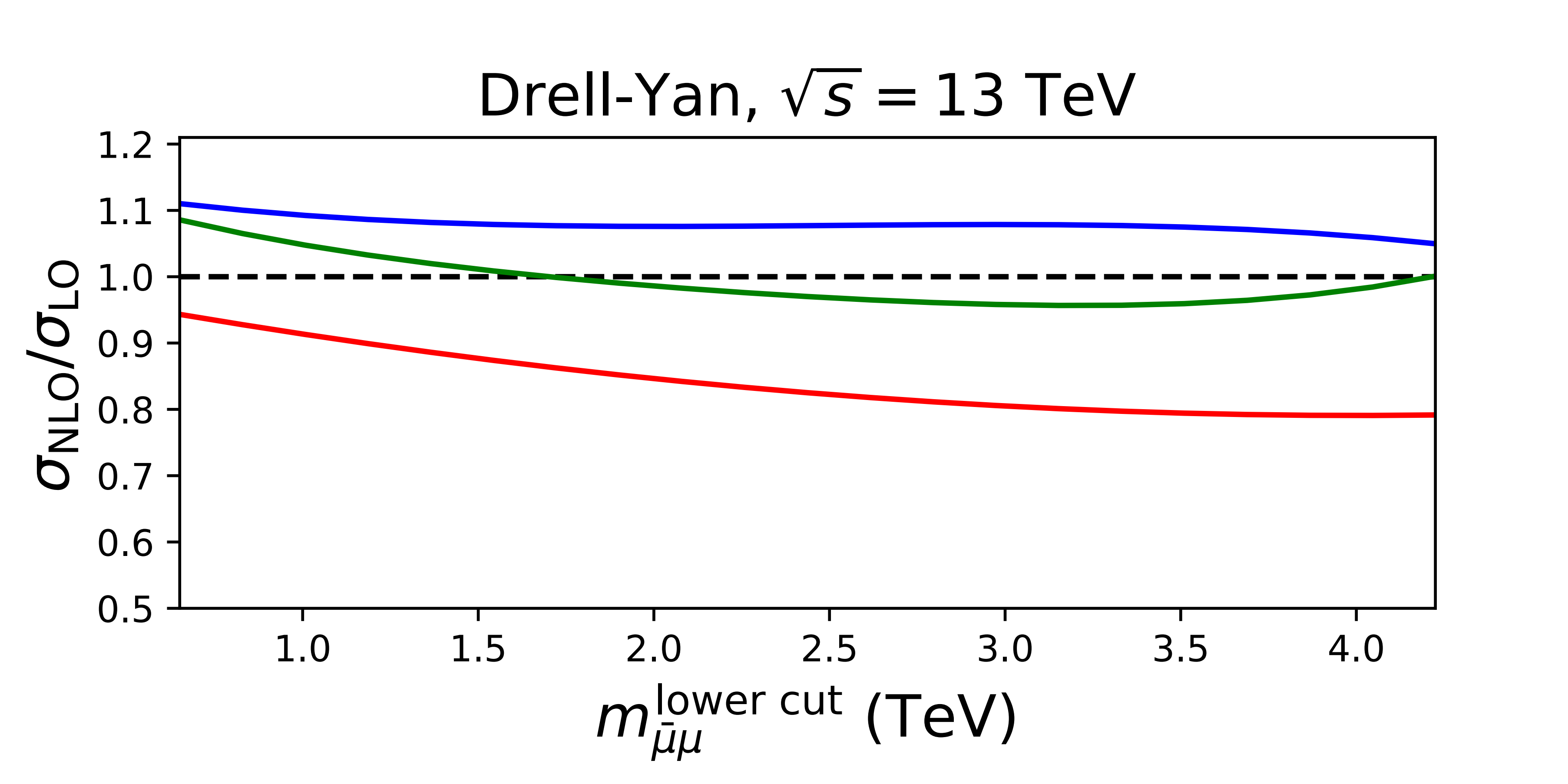

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