Flavor physics at a high energy Muon Collider

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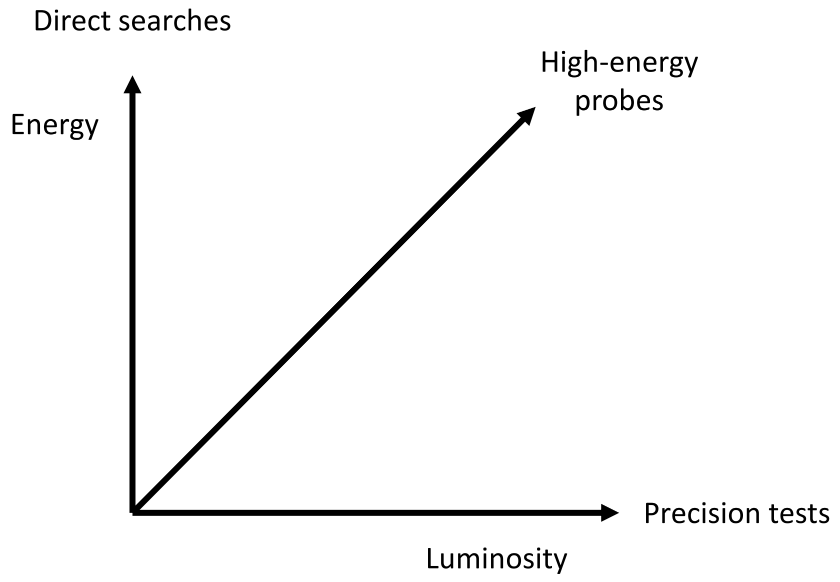
Chen, Glioti, Rattazzi, Ricci, Wulzer **2202.10509**
Glioti, Marzocca, Wulzer, **2509.08132**

High energy probes



Consider the SM as an **Effective Theory**

Standard Model

Possible deviations due to new **heavy** states

$$\mathcal{L} = \mathcal{L}^{d\leq 4} + \frac{1}{\Lambda}\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\mathcal{L}^{d=6} + \dots$$

By dimensional analysis, d=6 operators can give contribution that grow with the energy

$$\mathcal{A} = \mathcal{A}_{\rm SM} + \frac{E^2}{\Lambda^2}\mathcal{A}_{d=6} + \dots$$

Higher collider **energy** → Higher **reach** on new physics

High energy probes

Thanks to the energy growth, a muon collider can **indirectly** probe energies much higher than the collision energies

$$\frac{\Delta O_{\rm BSM}}{O_{\rm SM}} \sim \frac{E^2}{\Lambda^2}$$

$$\boxed{1\% \text{ at } E = 10 \text{ TeV} \implies \Lambda \sim 100 \text{ TeV}}$$

Similarly, for flavor violating processes, where the SM background is mainly coming from flavor mistags

$$\frac{\Delta O_{\rm BSM}}{O_{\rm SM}} \sim \frac{1}{\epsilon_{\rm flav}} \frac{E^4}{\Lambda^4}$$

Slower energy growth but smaller background. Still ~100 TeV reach

High energy probes

Caveat: achieving percent precision requires theoretical control of EW radiation

Exchange/emission of soft-collinear W/Z bosons is enhanced at energies much larger than the weak scale

In particular **Sudakov Double Logs**

$$C\frac{\alpha_w}{4\pi}\log^2\frac{E^2}{m_W^2} \sim C \cdot 0.25 \text{ at } 10 \text{ TeV}$$

Group theory factors

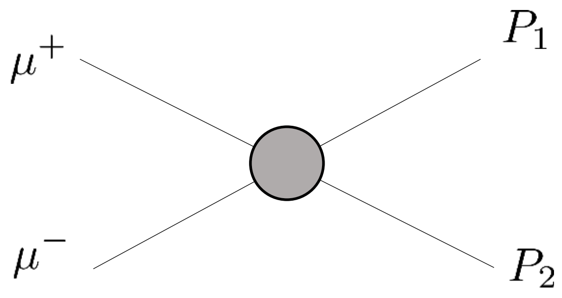
Several processes violate perturbation theory → Double logs require **resummation** in order to have any meaningful prediction at high energy

Which observables?

Chen, AG, Rattazzi, Ricci, Wulzer (2022)

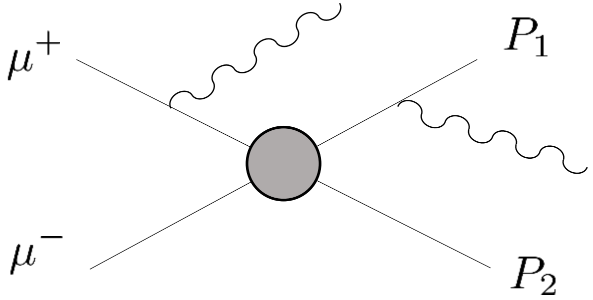
We consider **two representative observables** for which we know how to perform the DL resummation

Exclusive



- **Two hard** final particles with **definite** EW **color**
- **Veto** on soft/collinear EW **radiation**
- Inclusive on soft photons/gluons

Semi-Inclusive



- **Two hard** final particles with **definite** EW **color**
- All **radiation** is **allowed** (up to some hardness threshold)
- "**Semi**" since we don't **sum** over external legs colors

IREE strategy

Chen, AG, Rattazzi, Ricci, Wulzer (2022)

Our resummation strategy is based on an **InfraRed Evolution Equation** (IREE)

Fadin, Lipatov, Martin, Melles, 1999

$\lambda = E^2$ Born obs.

↓ IREE

$\lambda = m_W^2$ Resummed DL obs.

- Introduce an unphysical **IR cutoff** λ

$$\lambda < \min \left| \frac{(k_i \cdot q)(k_j \cdot q)}{(k_i \cdot k_j)} \right|$$

- Compute derivative of the observable wrt λ through **diagrammatic** techniques

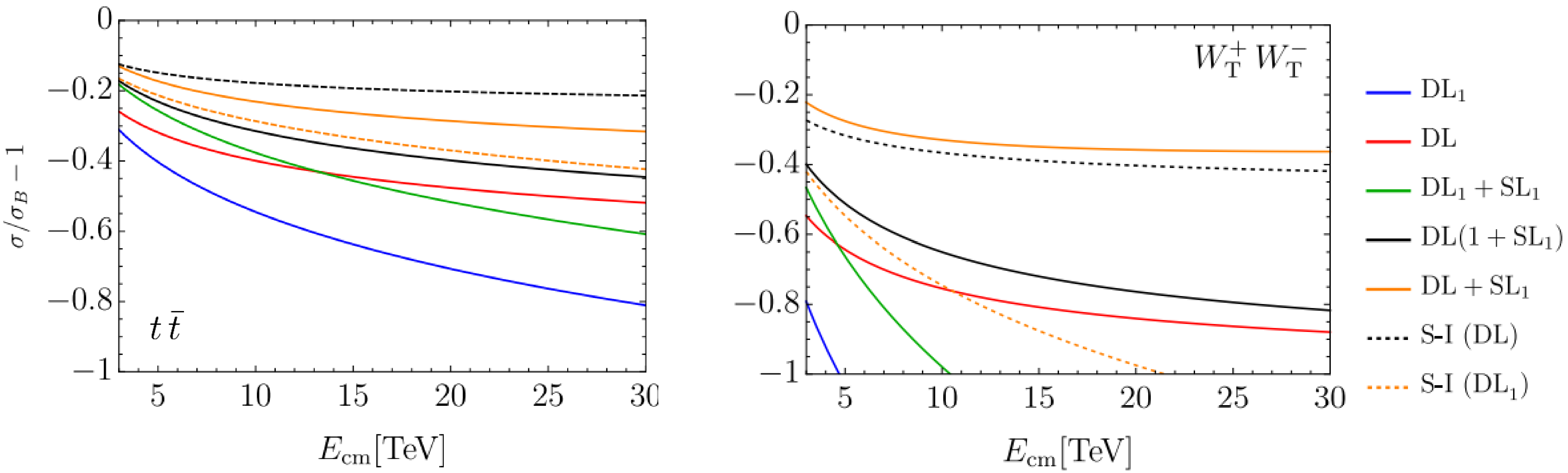
$$\frac{d}{d\lambda}\mathcal{O}^{\lambda} = \mathcal{K} \cdot \mathcal{O}^{\lambda}$$

- Solve the IREE with the **boundary condition**

$$\mathcal{O}^{\lambda=E^2} \equiv \mathcal{O}^{\text{Born}}$$

Effect of Double and Single Logs

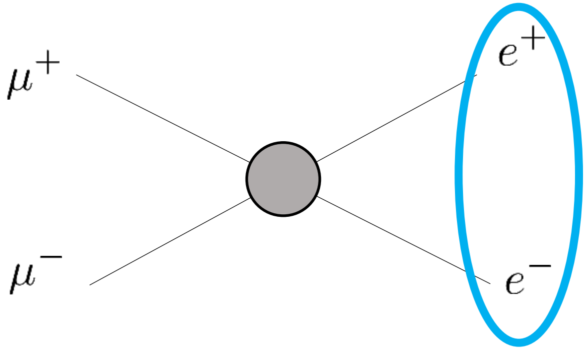
Chen, AG, Rattazzi, Ricci, Wulzer (2022)

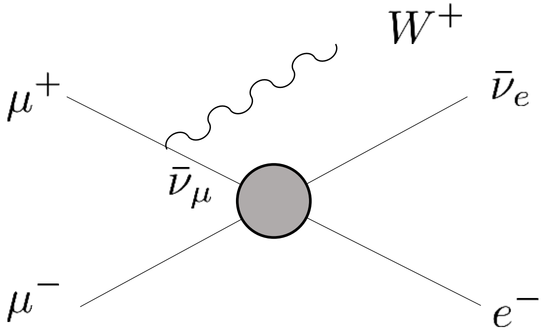


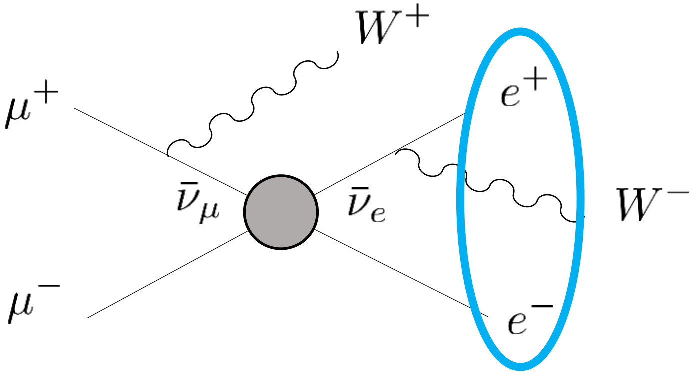
Single-Logs (virtual only) added at fixed-order from Denner, Pozzorini (2000)

Radiation for BSM

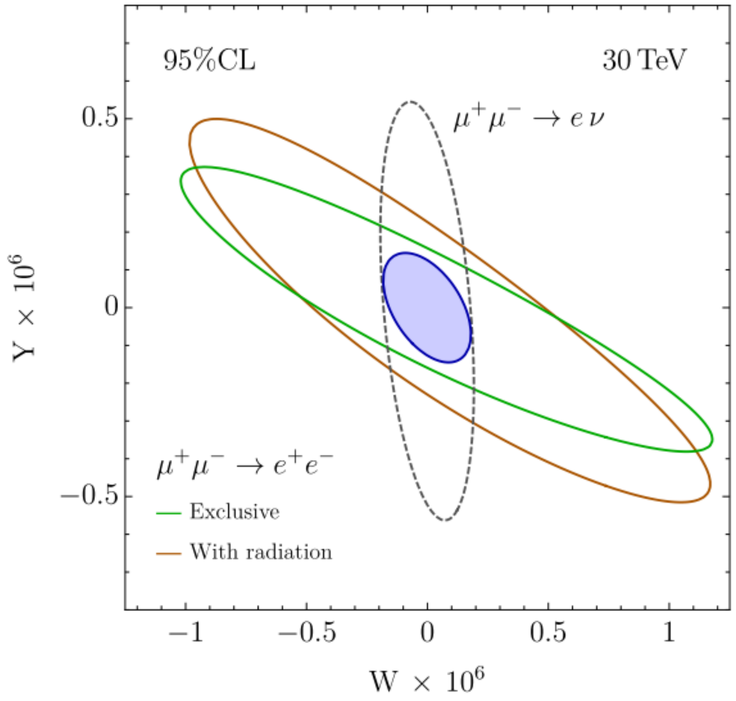
Thanks to the large double **logs processes with soft emission** become **as likely as** processes allowed at **tree-level**







Hard processes sensitive to **different combinations** of new physics parameters



Energy Growing effects

We studied all the following 2 → 2 processes

	Exclusive	Semi-Inclusive	Semi-Inclusive (charged)
Difermion	$\mu\mu \to l\bar{l}$ $\mu\mu \to q\bar{q}$	$\mu\mu \to l\bar{l} + X$ $\mu\mu \to q\bar{q} + X$	$\mu\mu \to l\nu + X$ $\mu\mu \to u\bar{d} + X$
Diboson	$\mu\mu \to Zh$ $\mu\mu \to WW$	$\mu\mu \to Zh + X$ $\mu\mu \to WW + X$	$\mu\mu \to Wh + X$ $\mu\mu \to WZ + X$

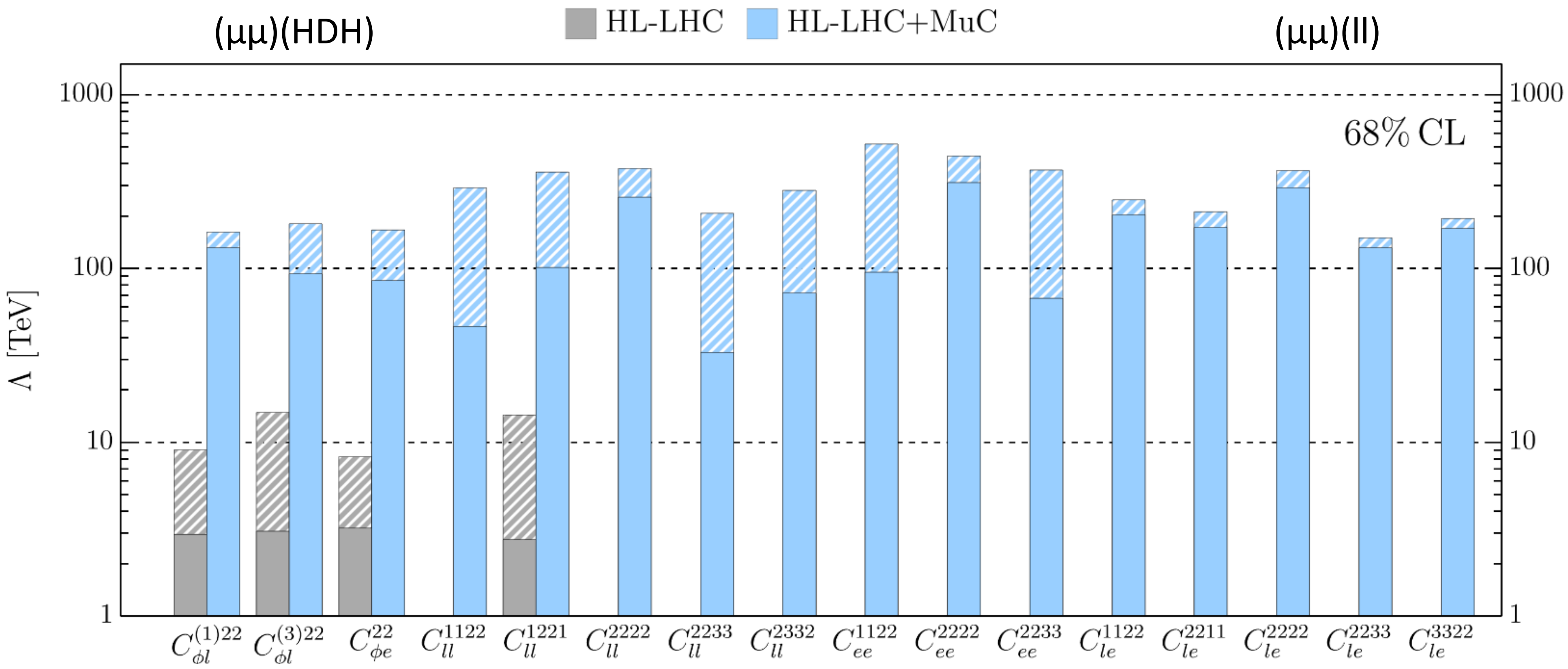
Including the energy growing contribution from dim=6 operators

Analytic expressions for the cross sections and Mathematica notebook for DL Resummation available

https://github.com/aglioti/muColSudakov

Results on effective operators

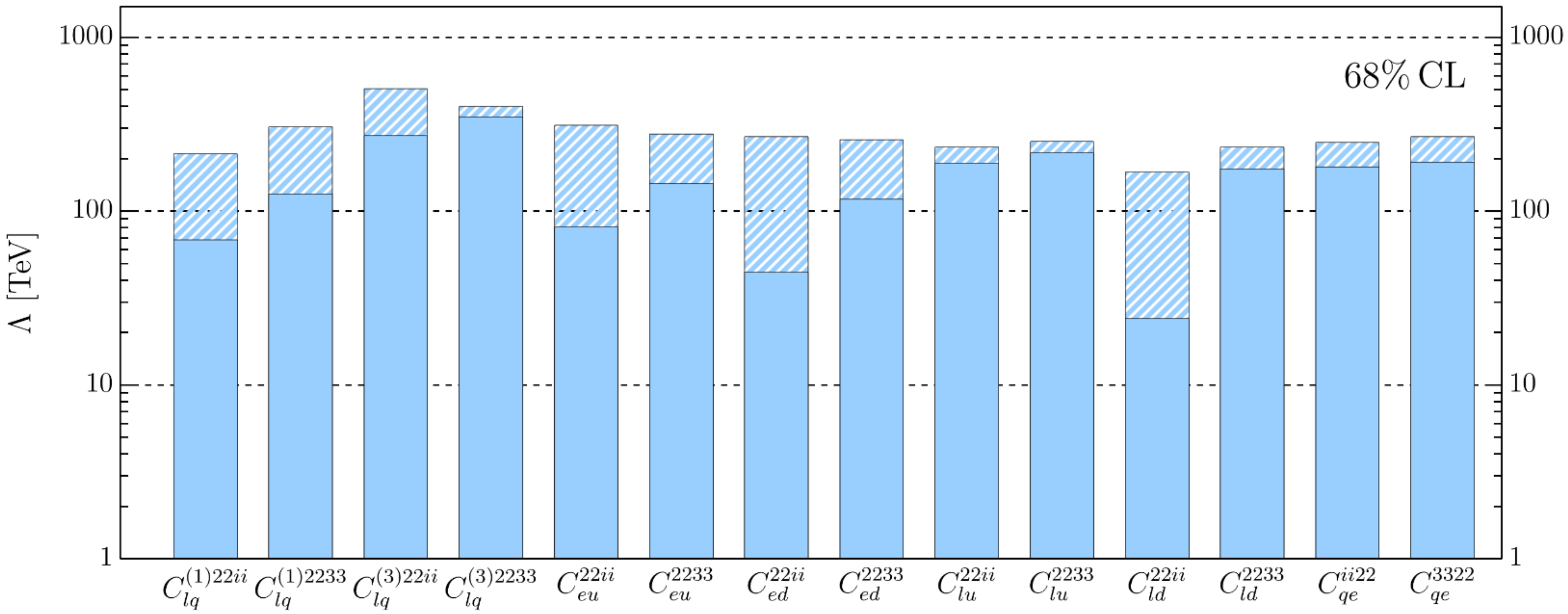
Diboson & Dilepton



Results on effective operators

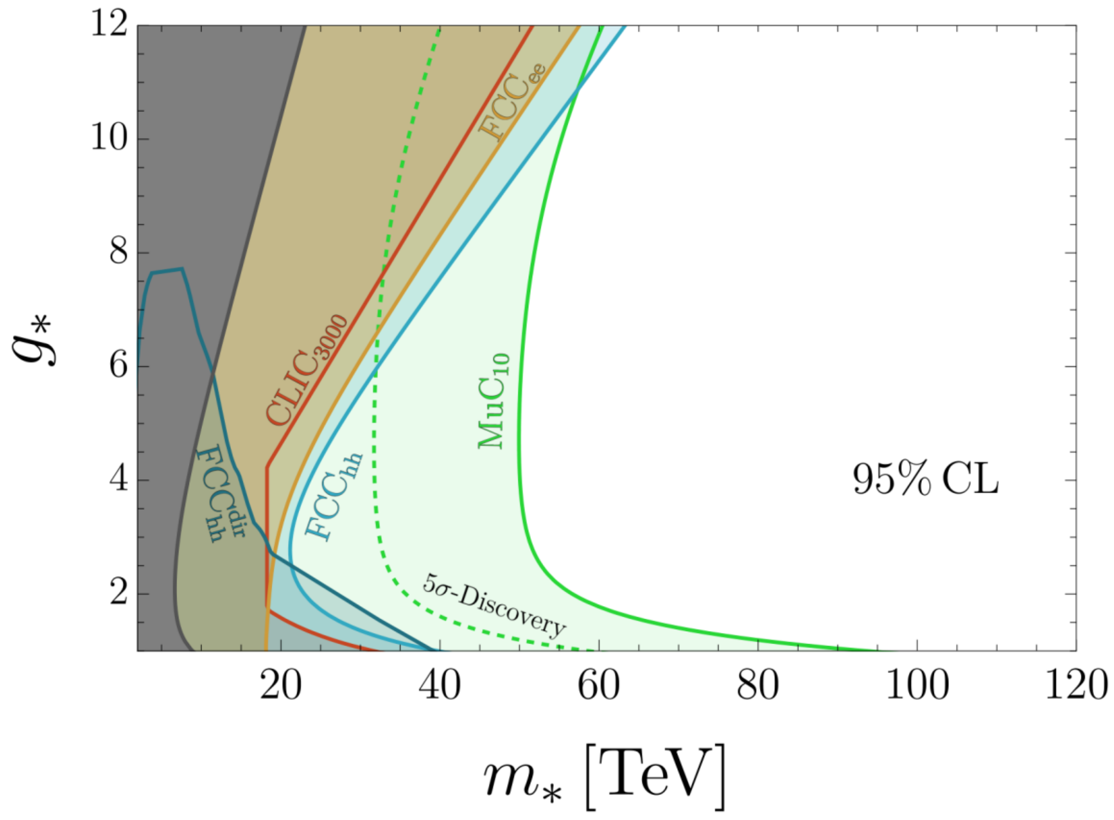
Diquark

(μμ)(qq)

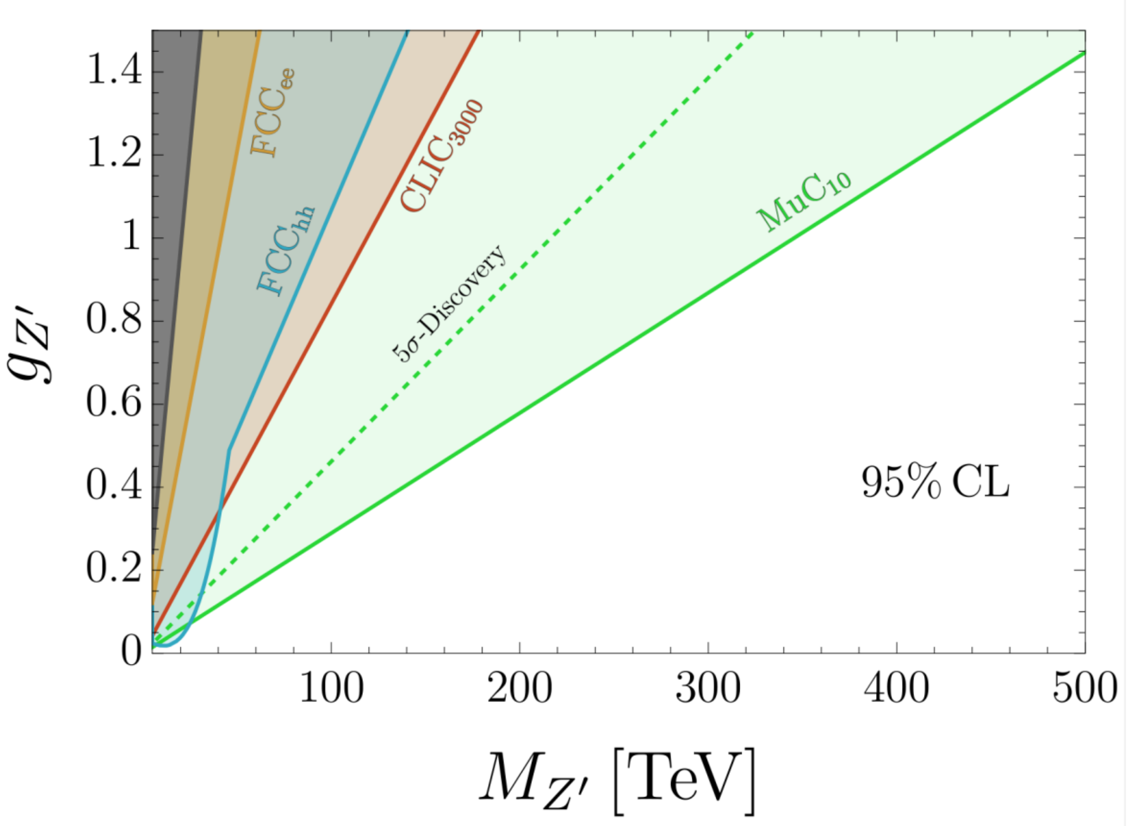


Reach on BSM models

Composite Higgs



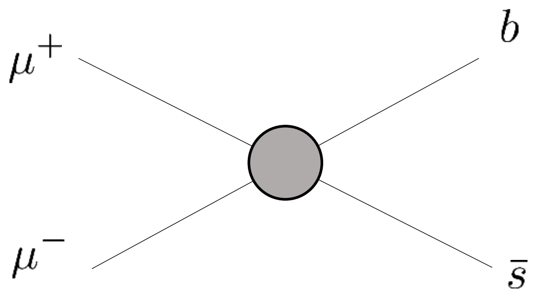
Y-universal Z’



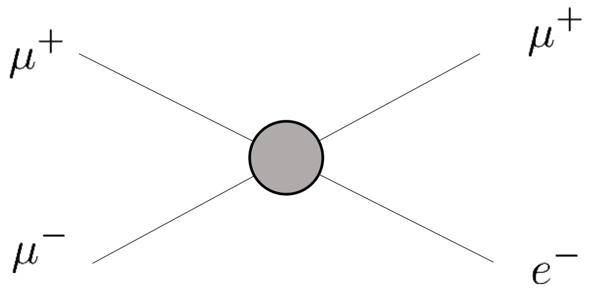
Flavor at MuCol

The Muon Collider can also probe flavor violating 4-fermion contact interactions

For **example**



bsμμ



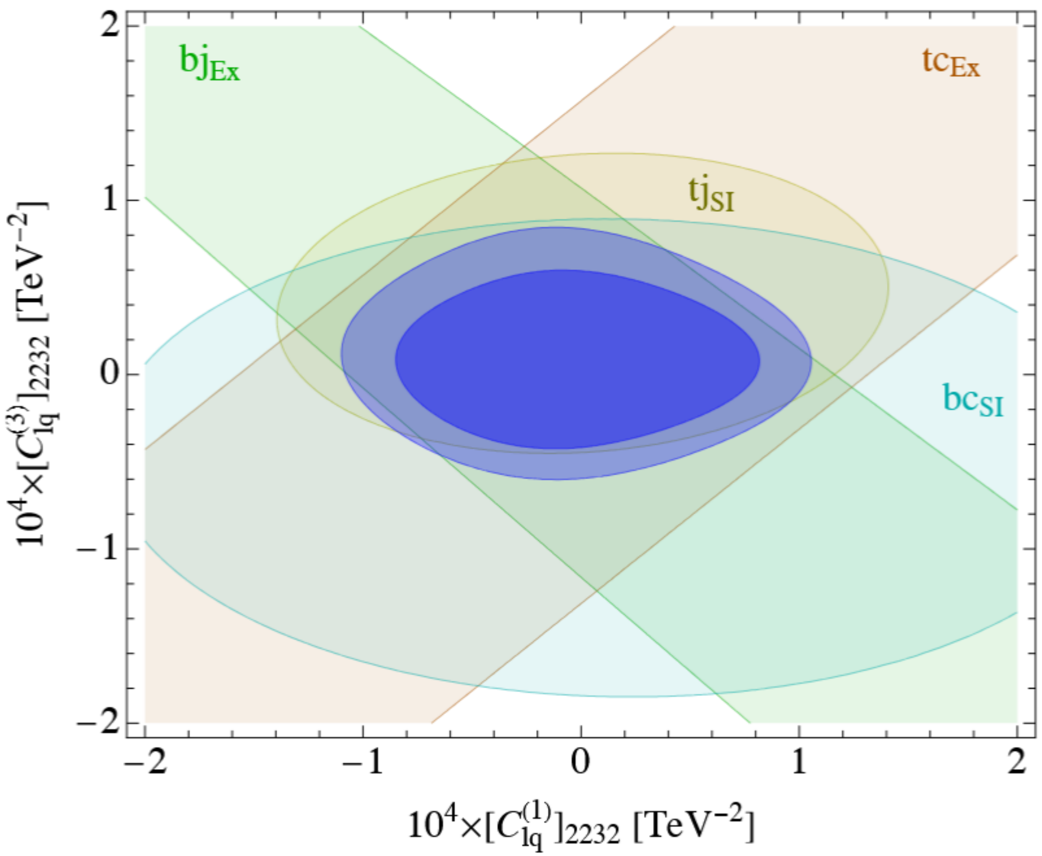
LFV

Even in this case we can exploit the **energy growth** to probe higher new physics scales

NP reach is comparable/better with low energy dedicated precision measurements

The MuCol is also a flavor machine!

Flavor at MuCol



The MuCol offers a variety of different final states probe the BSM parameter space in different directions

- Different **flavors** in the final state, eg t vs b
- Different level of **inclusiveness** in EW radiation (Exclusive vs Semi-inclusive observables)
- **Charged final states** (with W soft radiation) enhanced by Sudakov Logs

This gives many independent probes that can be used together to constrain new physics

Flavor at MuCol

We studied all diquark and dilepton events, including flavor violating processes

$$2b, \quad 2c, \quad 2j, \quad b+j, \quad c+j, \quad b+c, \quad 2t^{\mathcal{B}}, \quad t^{\mathcal{B}}+b, \quad t^{\mathcal{B}}+c, \quad t^{\mathcal{B}}+j$$

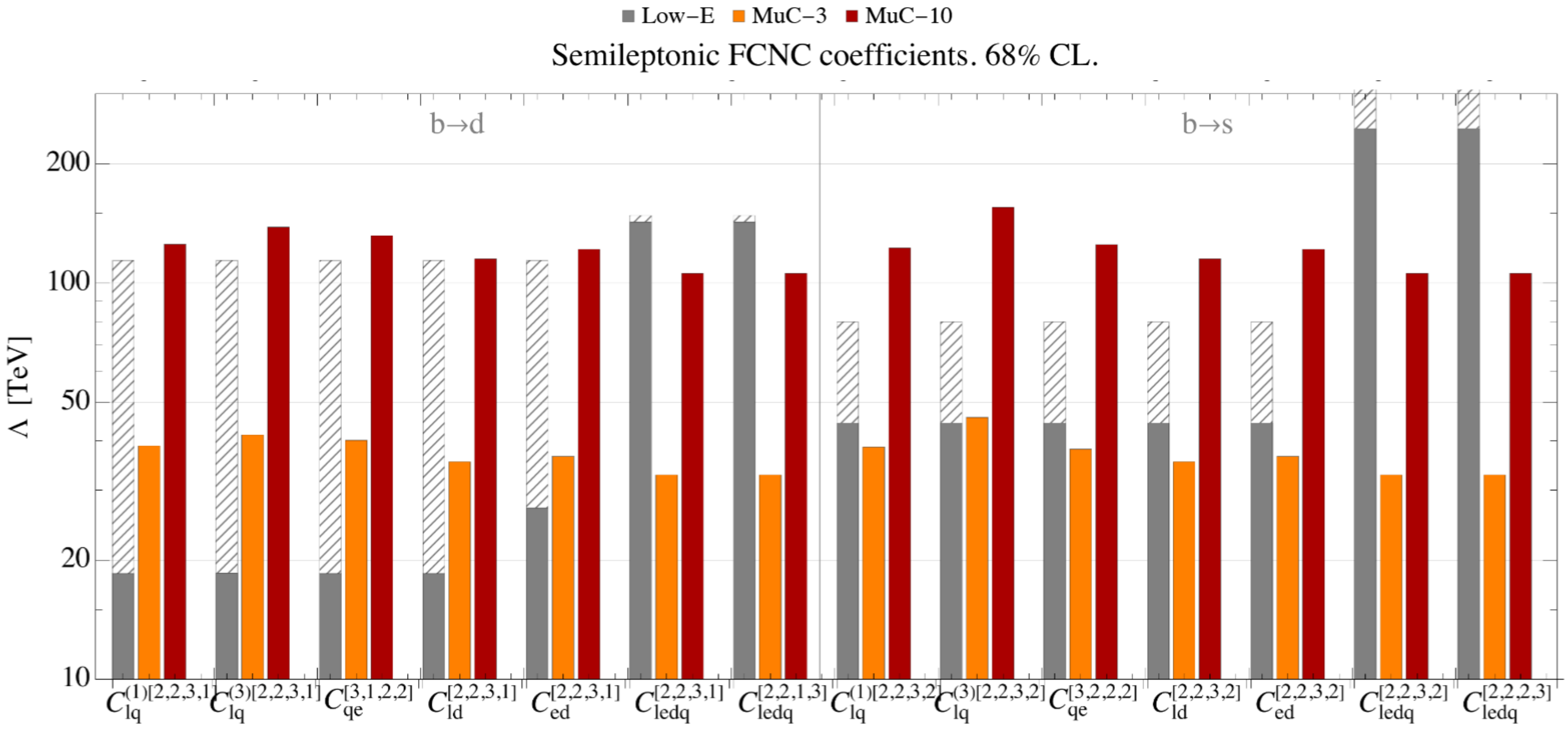
Boosted top

$$\mu^-\mu^+, \quad e^-e^+, \quad \tau^-\tau^+, \quad e^{\mp}\mu^{\pm}, \quad \tau^{\mp}\mu^{\pm}, \quad e^{\mp}\tau^{\pm}$$

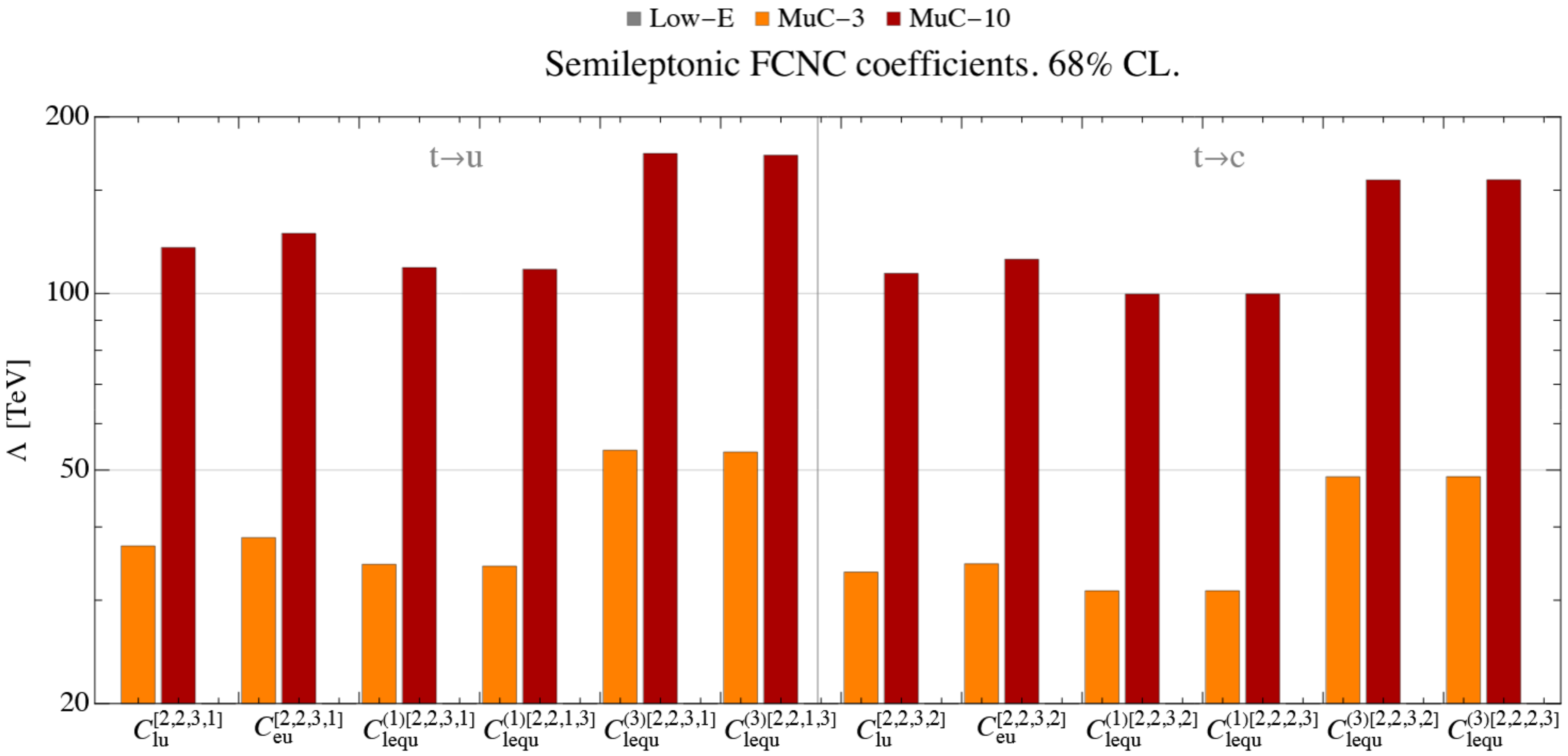
Since **flavor tagging** is crucial for this analysis, we did a complete study including estimates for the **flavor tag and mistag probabilities** at the MuCol

We then compared our sensitivity projections for a **3TeV** and **10TeV** Muon Collider to the current and projected (after HL-LHC) sensitivity from **low energy** flavor measurements

Flavor: high vs low energy

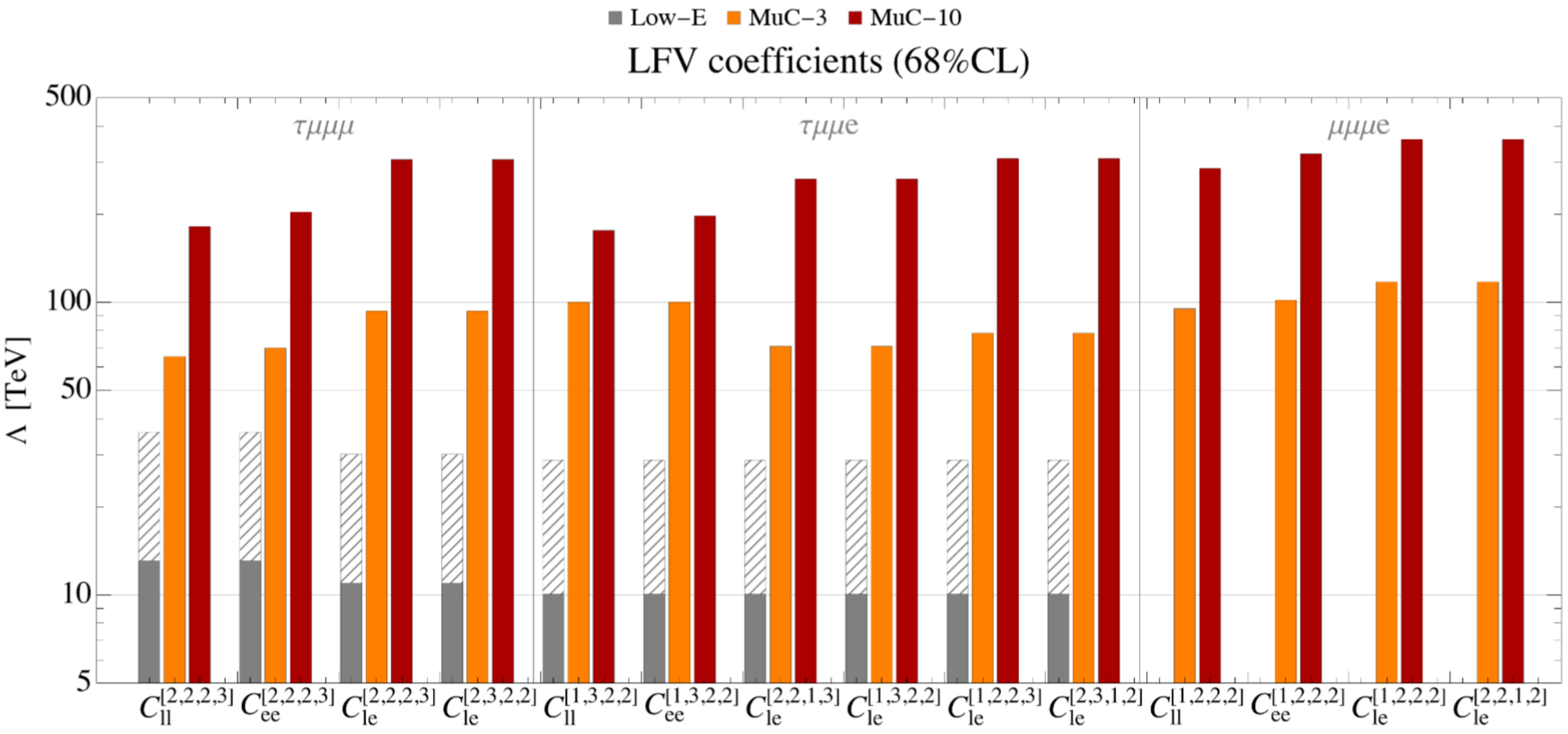


Flavor: high vs low energy

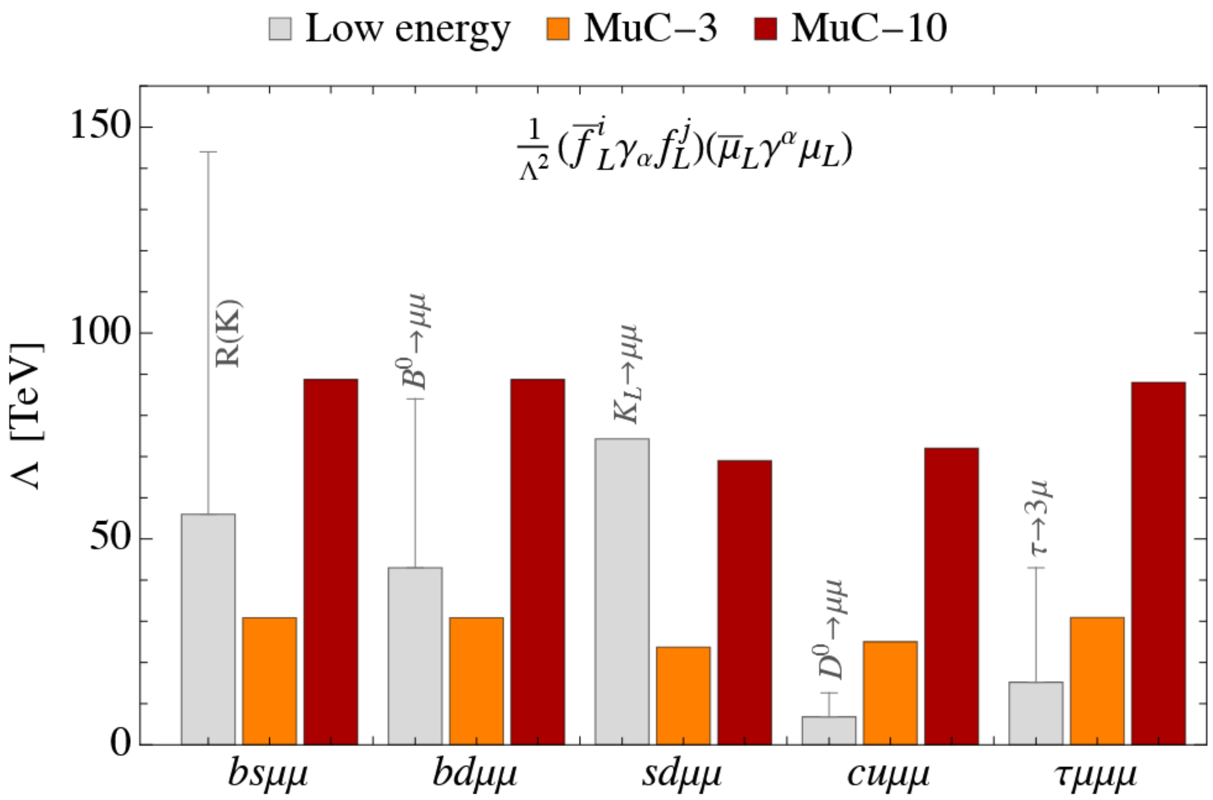


MuCol can study flavor violating top quark transition
Negligible bounds from LHC from top quark decays

Flavor: high vs low energy



Flavor: high vs low energy



Conclusions

- A **10 TeV Muon Collider** can indirectly probe New Physics up to **100+ TeV**
- Large radiation effect allows to **probe New Physics** in a **richer way** compared to tree-level prediction
- This also extends to **flavor violating observables**, where the Muon Collider is competitive with other specific experiments
- Furthermore, the study of EW radiation is an amazing playground of fundamental QFT questions