Lepton PDFs and searches at future Muon Colliders

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2205.13552

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2303.xxxxx

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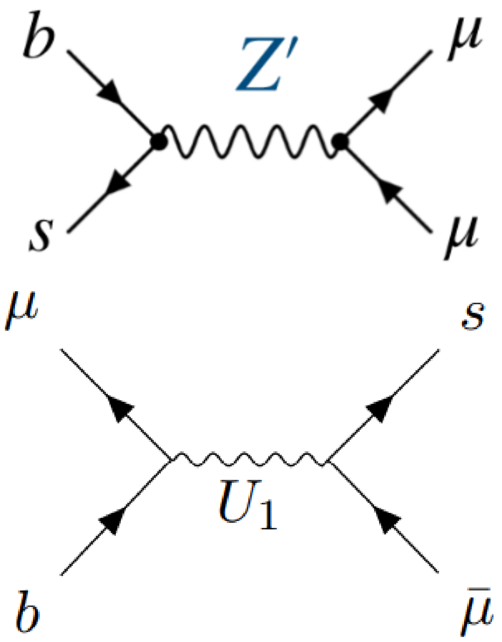
This talk before 20/12/22

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$



Approximately **4σ** deviation from the SM!

Which **future collider** would offer best sensitivity reach for **tree-level** heavy NP mediators?

FCC-hh or Muon Collider?

Outline

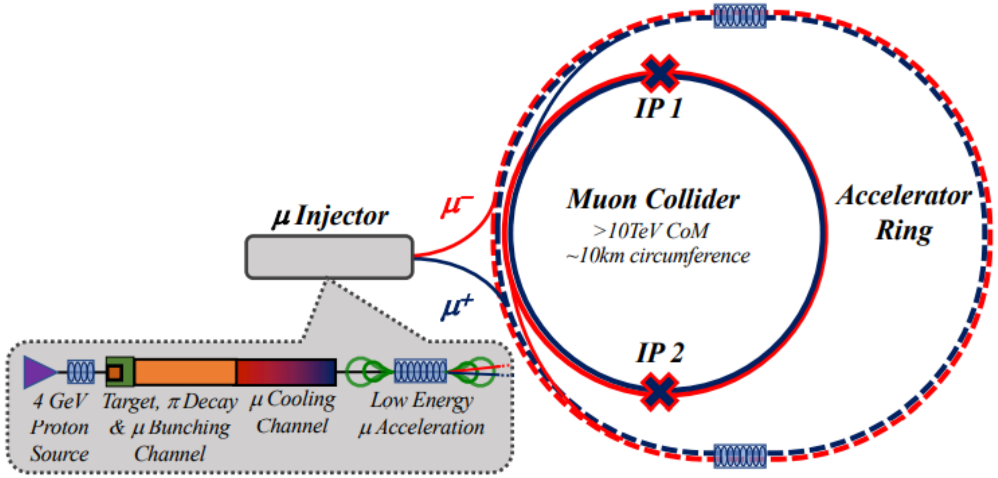
1) Introduction to MuC

2) Parton Distribution Functions for Leptonic Collisions

3) Application to Z'-Leptoquark searches at MuC

4) Conclusions

The Muon Collider (MuC)



- $\mu^+\mu^-$ circular collider
- Could start around **2045**
- Collider Rings:
  - **3 TeV ~ 4.5 km** circumference
  - **10 TeV ~10 km** circumference

[Reports] 2201.07895, 2203.08033, 2203.07224, 2203.07256, 2203.07261

See also GGI Tea Break on MuC: https://youtu.be/17JoTcuIs6k

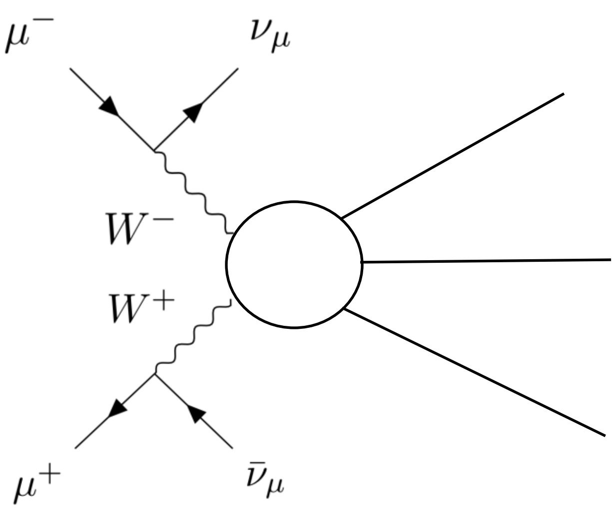
International MUON Collider Collaboration

Parton Model for Leptonic Collisions

The initial muon can emit **soft and collinear radiation**. Multiple splittings can be resummed leading to the **DGLAP equations** as in the parton model for the proton.

[T. Han et al.]
2007.14300, 2103.09844

$$\sigma_{\mu^+\mu^-\to X} = \sum_{i,j} \int_0^{\sqrt{s_0}} dm \frac{2m}{s_0} \mathcal{L}_{ij}\left(\frac{m^2}{s_0}\right) \sigma_{ij\to X}(m)$$



The total cross section of a process can be written in terms of **cross sections of the partonic processes** and their "probabilities" to occur, called **parton luminosities**.

$$\mathcal{L}_{ij}(\tau) = \int_\tau^1 \frac{dx}{x} f_i(x,m) f_j\left(\frac{\tau}{x}, m\right)$$

PDF

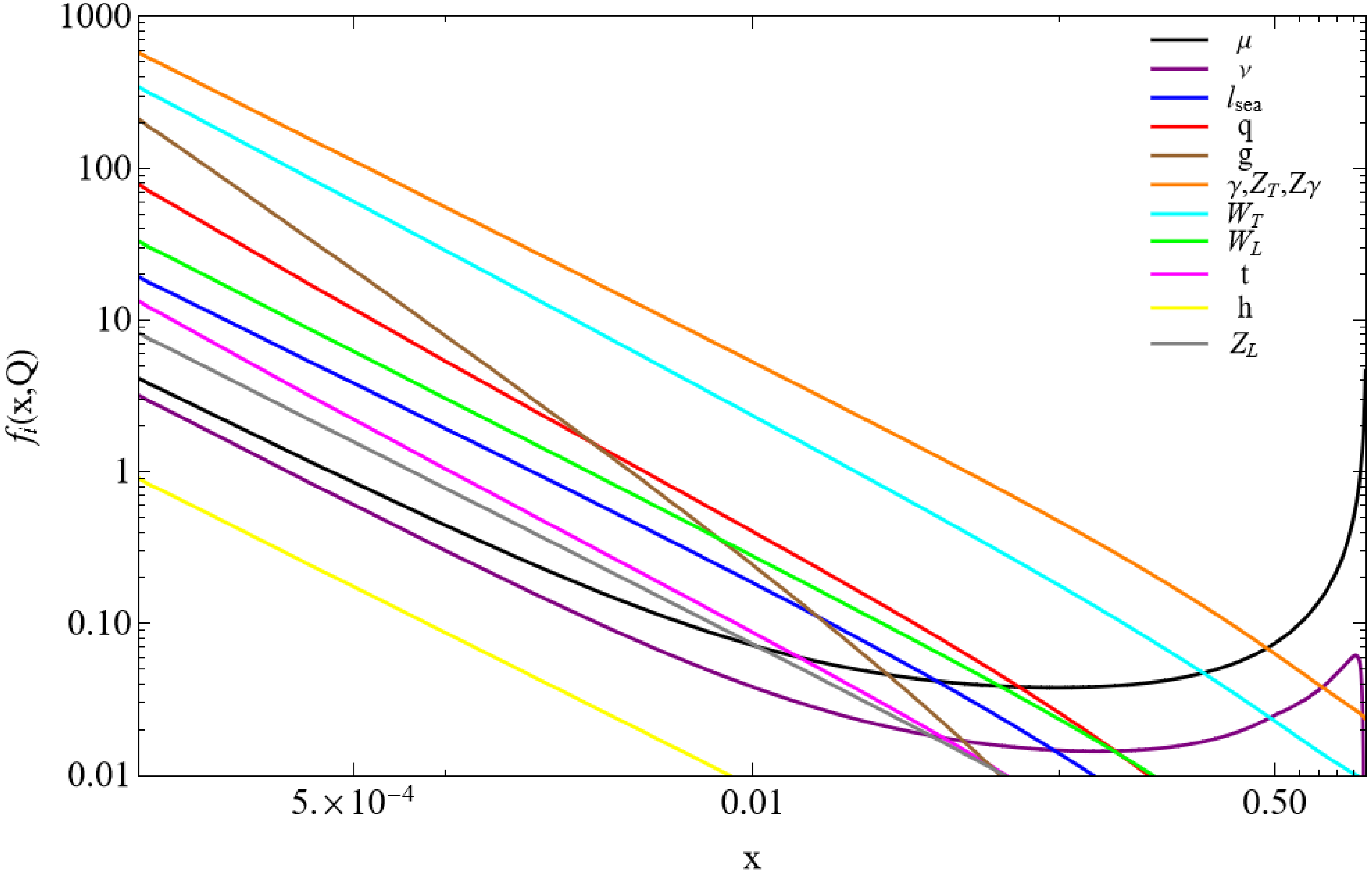
Our strategy

$$\frac{df_B(x,t)}{dt} = \sum_{A,C} \frac{\alpha_C}{2\pi} \int_x^1 \frac{dz}{z} P_{BA}^C\left(\frac{x}{z},t\right) f_A(z,t)$$

- Consider all the possible SM particles contributing, including chiralities and polarizations. With massless fermions, except for the top, we have **42 independent PDFs** to compute;
- Discretize the equations with a **grid in "x"**;
- Use the **rectangles method** to perform the integrals;
- Solve the coupled ODEs using a **Runge-Kutta algorithm**.

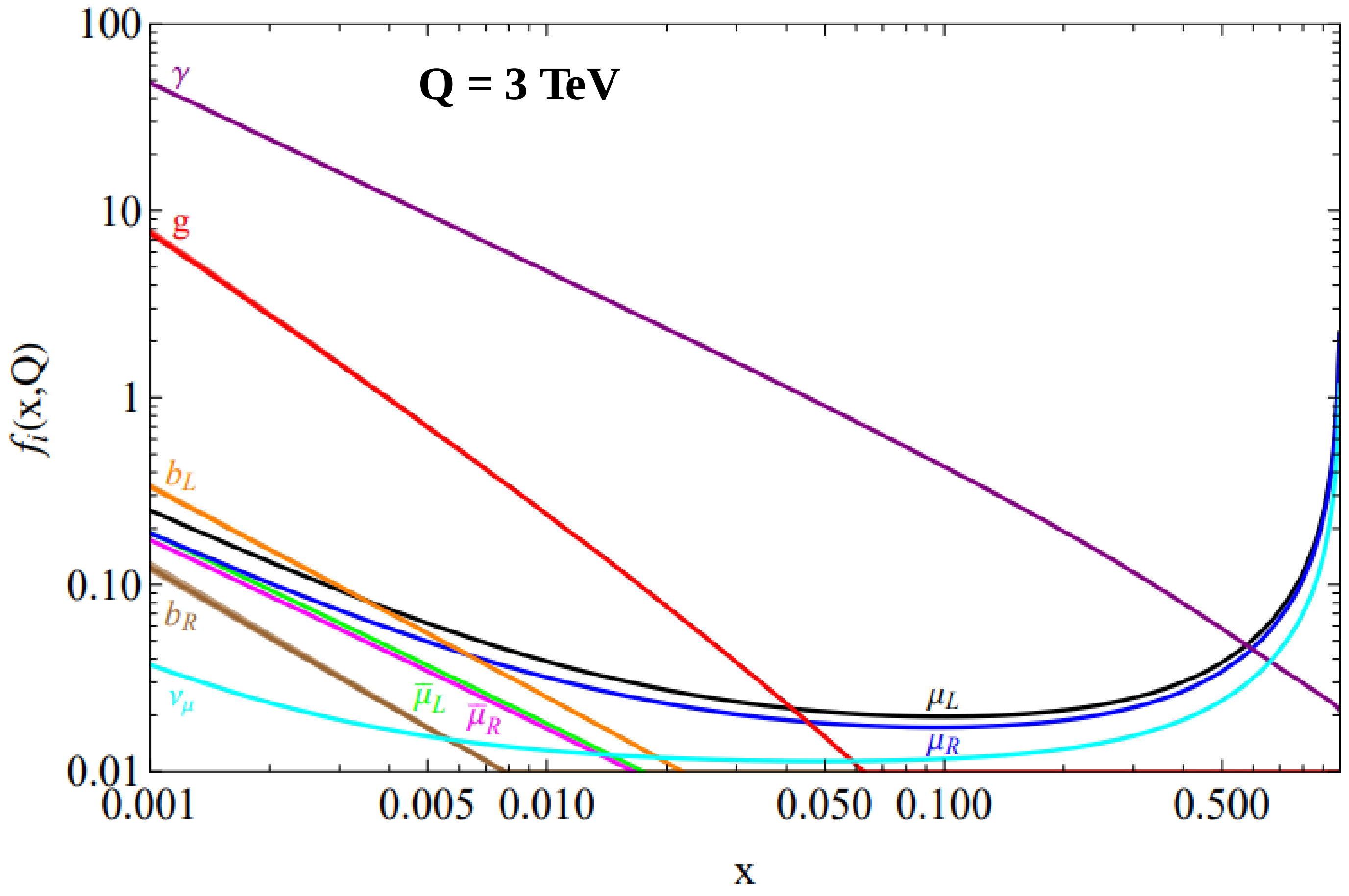
Leptons	μ_L	μ_R	e_L	e_R	ν_μ	ν_e	$\bar{\ell}_L$	$\bar{\ell}_R$	$\bar{\nu}_\ell$
Quarks	u_L	d_L	u_R	d_R	t_L	t_R	b_L	b_R	$+$ h.c.
Gauge Bosons	$\gamma_\pm$	$Z_\pm$	$Z\gamma_\pm$	$W^\pm_\pm$	$G_\pm$				
Scalars	h	Z_L	hZ_L	$W^\pm_L$					

Results



1000
100
10
1
0.10
0.01
$f_i(x,Q)$
$5.\times10^{-4}$
0.01
0.50
x
μ
ν
$l_{\rm sea}$
q
g
$\gamma, Z_T, Z\gamma$
W_T
W_L
t
h
Z_L

Results

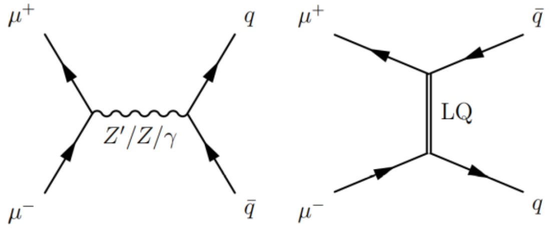


Q = 3 TeV
γ
g
b_L
b_R
ν_μ
$\bar{\mu}_L$
$\bar{\mu}_R$
μ_L
μ_R
$f_i(x,Q)$
x
100
10
1
0.10
0.01
0.001
0.005
0.010
0.050
0.100
0.500

Channels at MuC

- **Inverted Drell-Yan** (IDY)

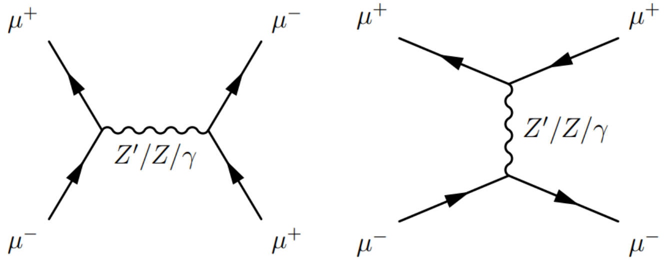
$$\mu^+\mu^- \to jj$$



Also charged current: $\nu_\mu \mu^+ \to jj$

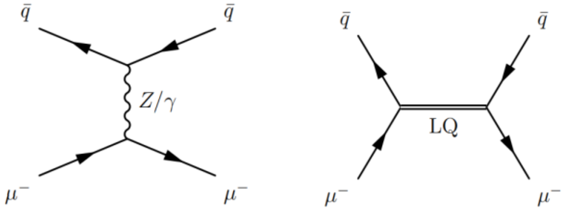
- **Di-lepton production (muons and taus)**

$$\mu^+\mu^- \to \mu^+\mu^-$$



- **Lepton plus jet**

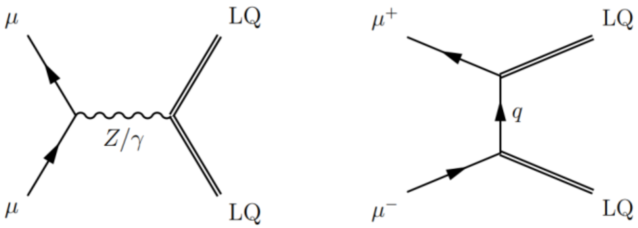
$$\mu q \to \mu j$$



Missed without partons!

- **LQ pair production**

$$\mu^+\mu^- \to \mathrm{LQ}\overline{\mathrm{LQ}}$$



Discovery and exclusion bounds

What can we say about New Physics?

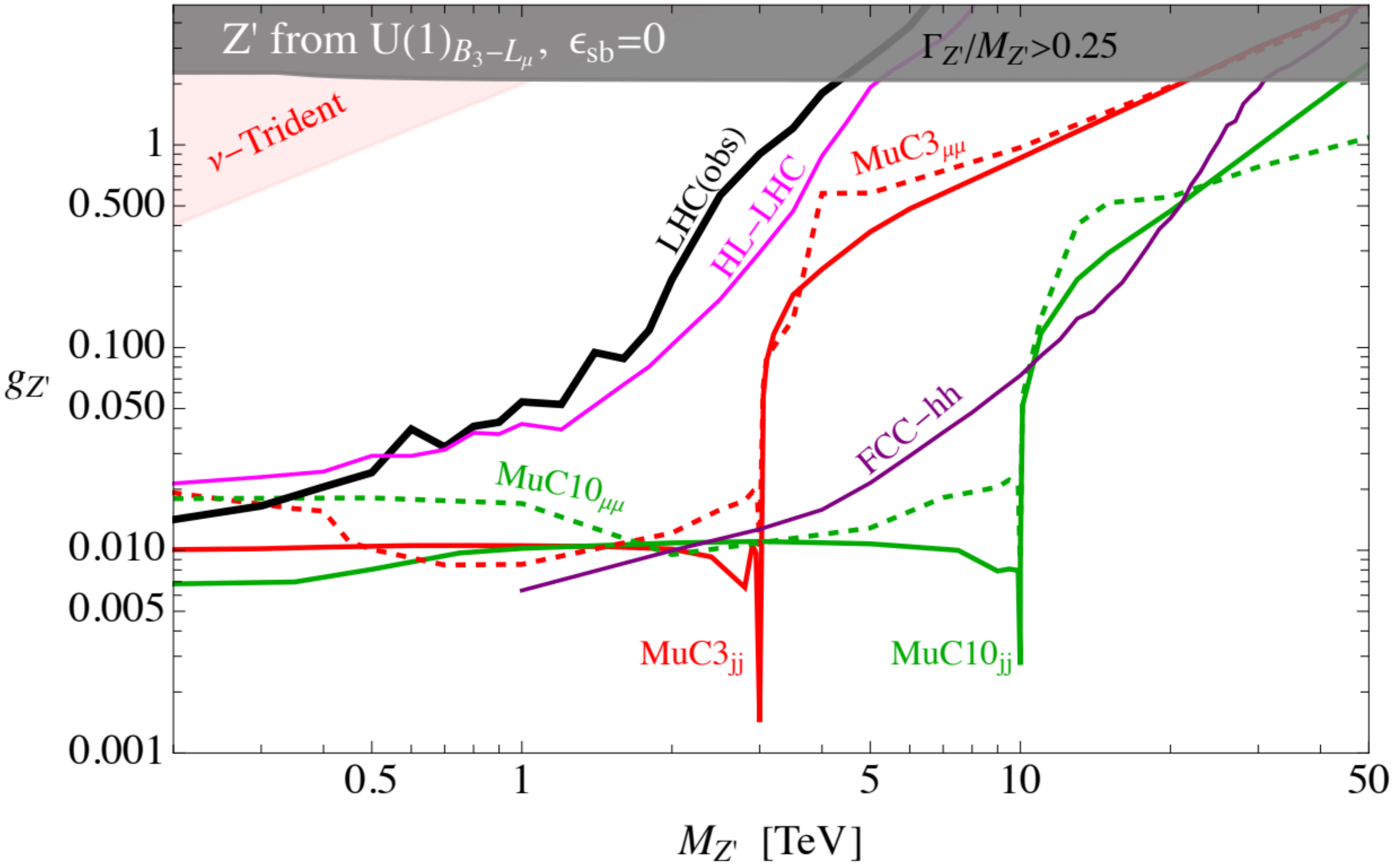
i. From the total cross sections we can compute the expected **number of events**, both in the SM and with NP.
ii. Build a **test statistics**:

$$\text{if } N_i^{\text{obs}} \geq 100 \;: \qquad -2\log L_i = \frac{(N_i - N_i^{\text{obs}})^2}{N_i + \epsilon^2 N_i^2}\,,$$

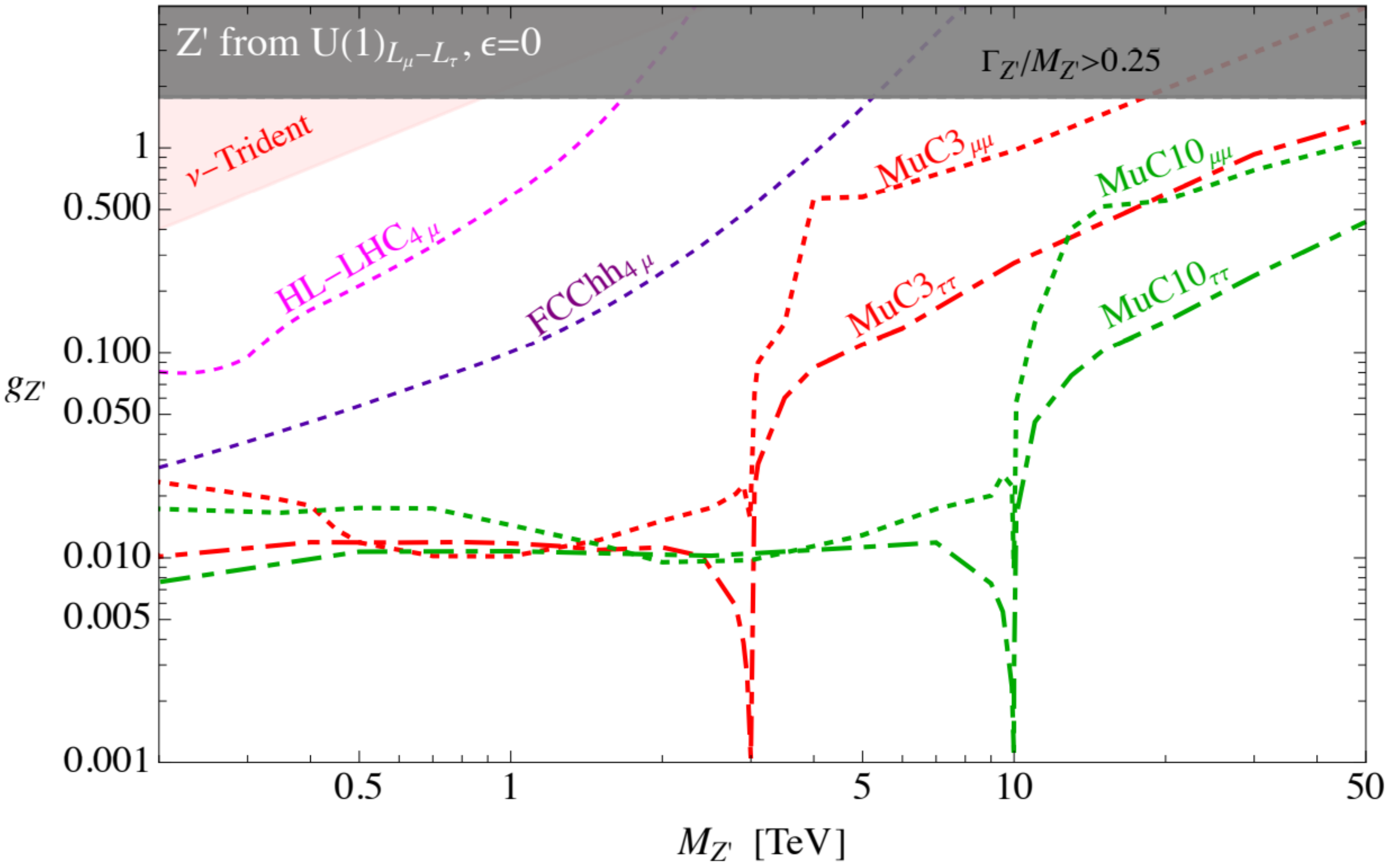
$$\text{if } N_i^{\text{obs}} < 100 \;: \qquad -2\log L_i = -2\log \frac{N_i^{N_i^{\text{obs}}} e^{-N_i}}{N_i^{\text{obs}}!}\,,$$

iii. Assuming a χ^2 distribution, derive the **exclusion** (observed = SM) and/or **discovery** (expected = SM) bounds.

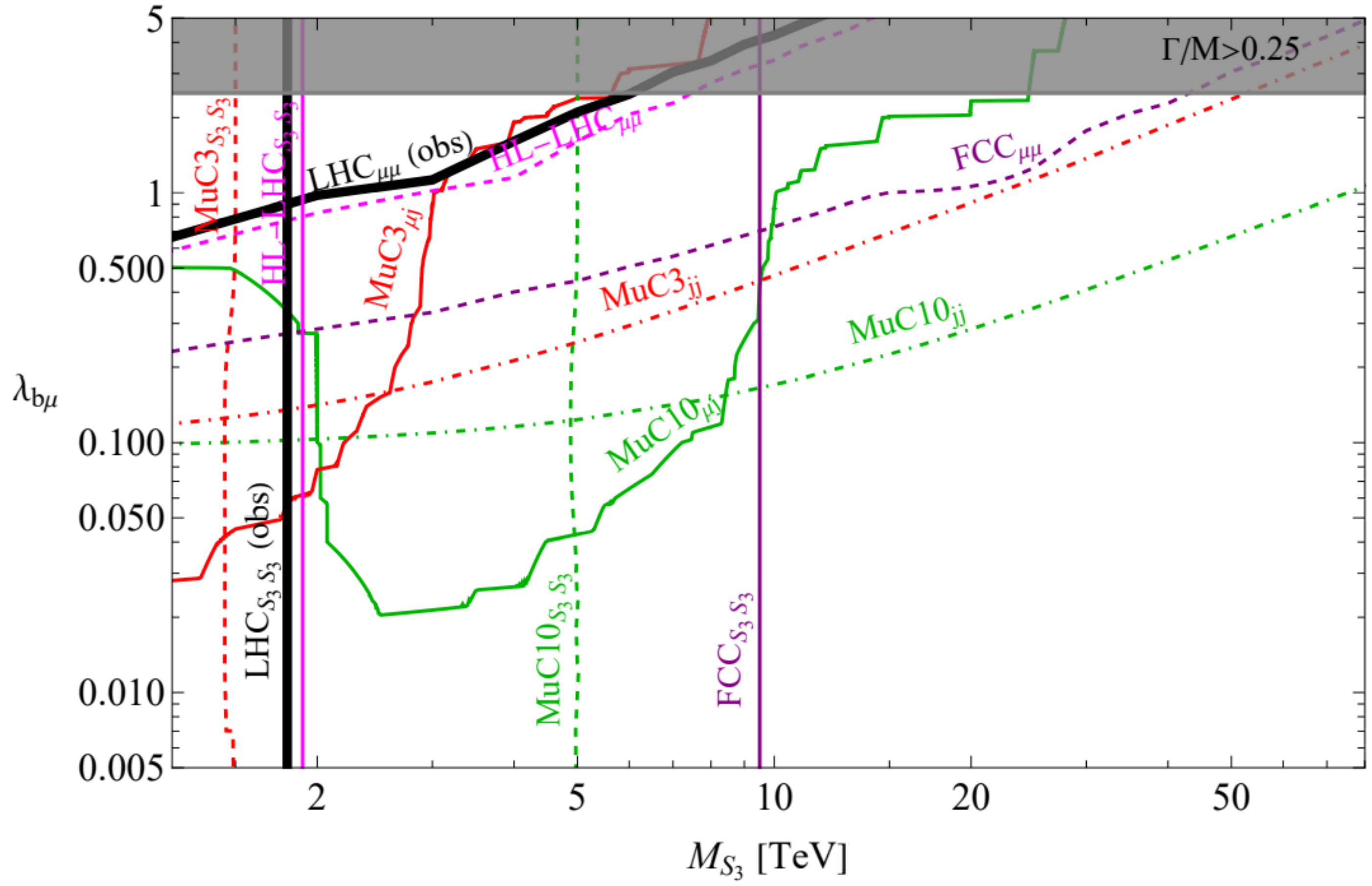
Discovery reach for Z'



Discovery reach for Z'



Discovery reach for S3 leptoquark



$$S_3 \sim \left(\bar{\mathbf{3}}, \mathbf{3}, \frac{1}{3}\right)$$

Conclusions and outlooks

- With the formalism of **PDFs** we are able to compute cross sections at high energy lepton colliders taking into account the soft and collinear radiation.

- The PDFs we computed can be used to study how future lepton colliders, like **MuC**, can perform in specific NP searches.

- Since the long-term future of particle physics crucially depends on the decisions we make today about the **next generation of high-energy colliders**, it is important to compare different machines (e.g. MuC vs. **FCC-hh**) on a broad set of NP hypothesis.

- Even though the most promising B anomalies disappeared, these machines will be able to scrutinize ***Z'* and leptoquark models** with mediator masses of O(10-100 TeV).

- We can use PDFs for other studies at future MuC: vector boson fusion at high precision, dark matter searches and many others.

THANKS FOR YOUR ATTENTION!

Backup Slides

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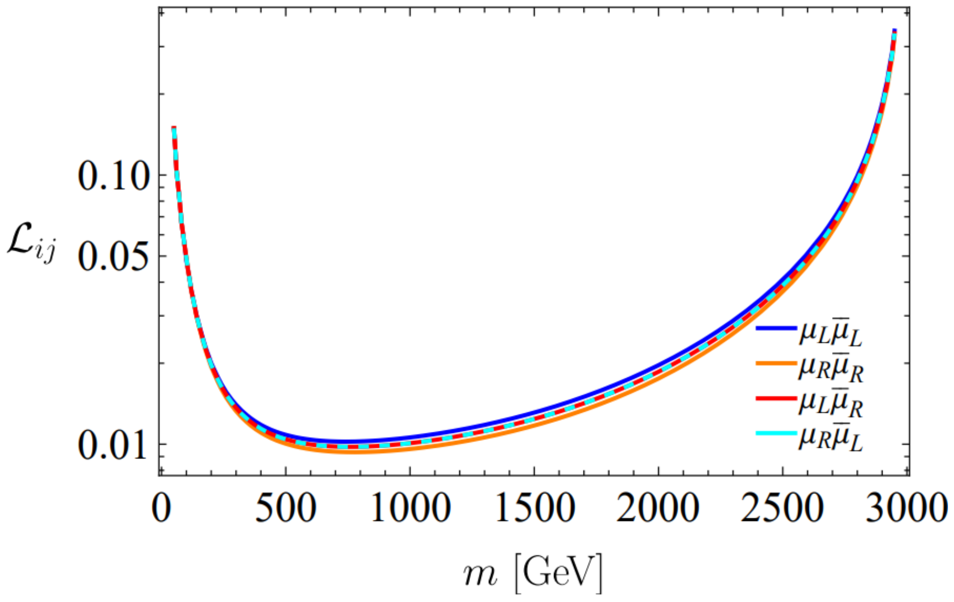
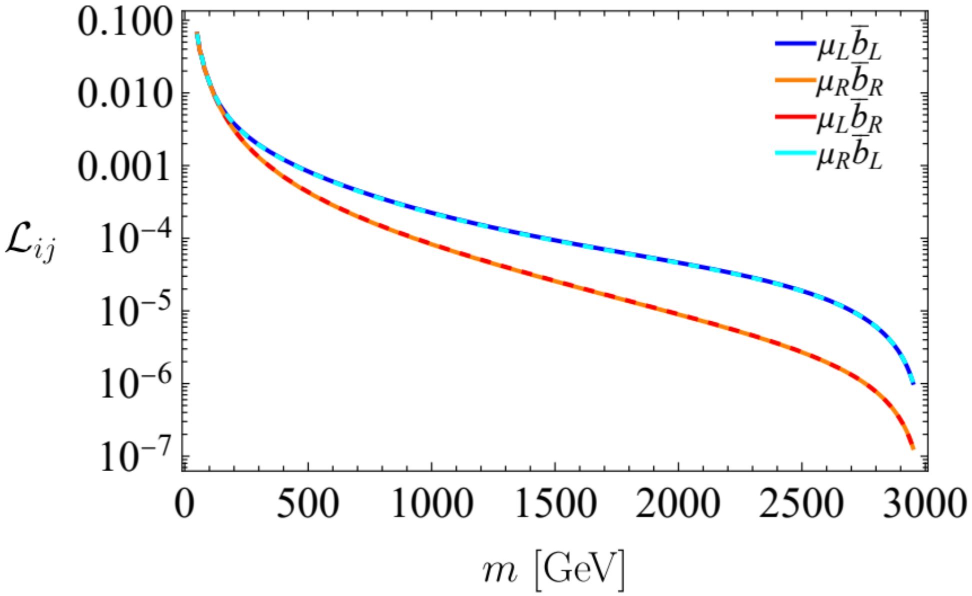
Parton Luminosities





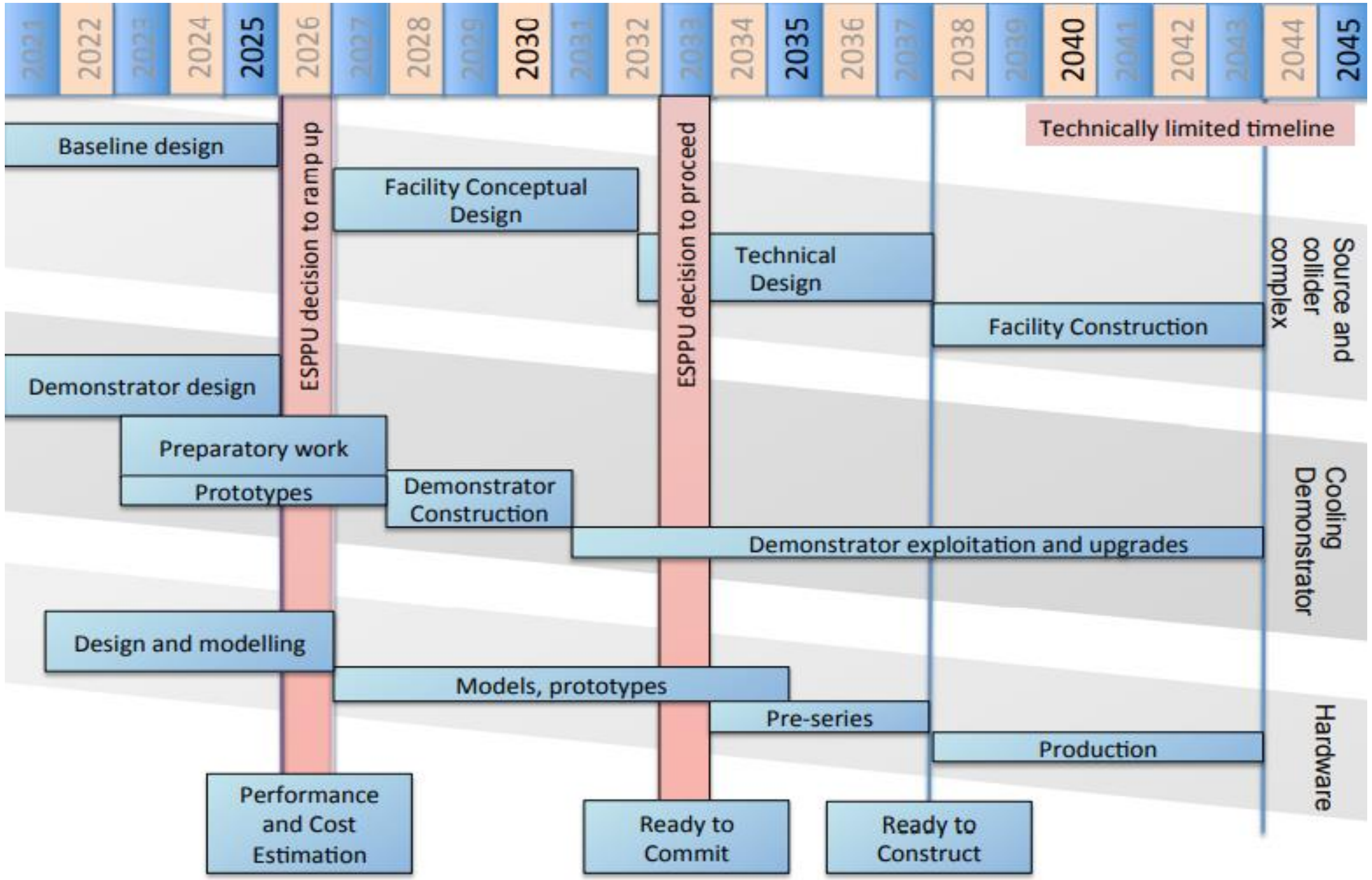
The peculiar behaviour of the **$\mu^+\mu^-$ luminosity** (valence partons), growing for invariant mass approaching zero and the collider energy, with a minimum inbetween, allows to look for NP both in the shape of the cross-section (resonance or t-channel exchange) and in its precise measurement in the highest invariant mass bin.

The colliders we considered

Which future collider would offer best sensitivity reach for **tree-level** heavy NP mediators?

Collider	C.o.m. Energy	Luminosity	Label
LHC Run-2	13 TeV	140 fb^{-1}	LHC
HL-LHC	14 TeV	6 ab^{-1}	HL-LHC
FCC-hh	100 TeV	30 ab^{-1}	FCC-hh
Muon Collider	3 TeV	1 ab^{-1}	MuC3
Muon Collider	10 TeV	10 ab^{-1}	MuC10
Muon Collider	14 TeV	20 ab^{-1}	MuC14

MuC aspirational timeline



2201.07895

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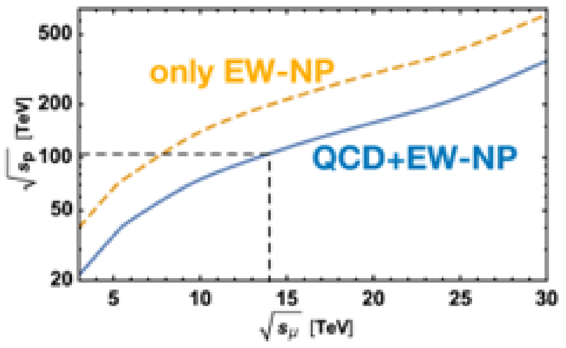
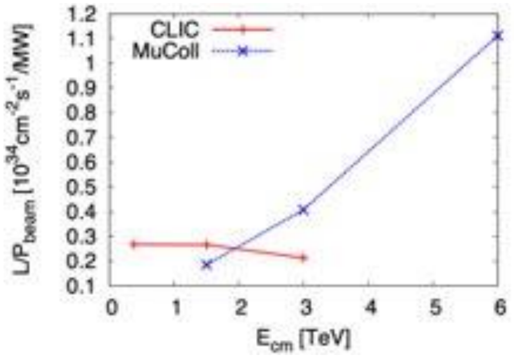
Why Muon Colliders?

Muon colliders combine the advantages of both proton-proton (high-energy) and electron-positron colliders (precision):

- high energy reach (not limited by synchroton radiation)
- high precision measurements (low QCD background & clean initial state)
- Luminosity / Beam power increases with energy.
- all beam energy available in $\mu+\mu-$ collisions.



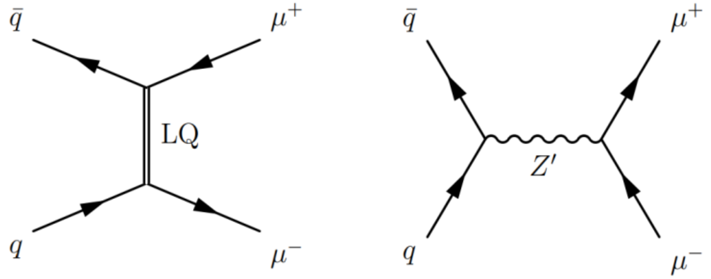


[Daniel Shulte, GGI talk]

Channels at FCC-hh

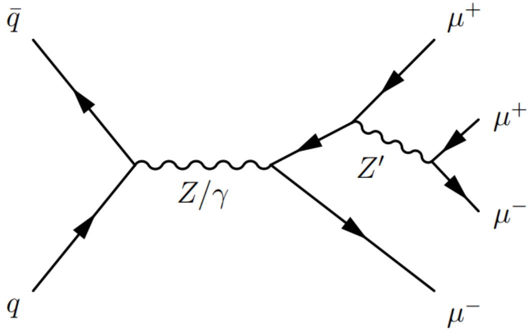
- **Drell-Yan** (DY):

$$q\bar{q} \to \mu^+\mu^-$$



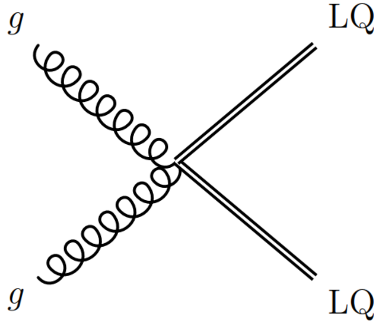
- **Multilepton:**

$$q\bar{q} \to 4\mu$$



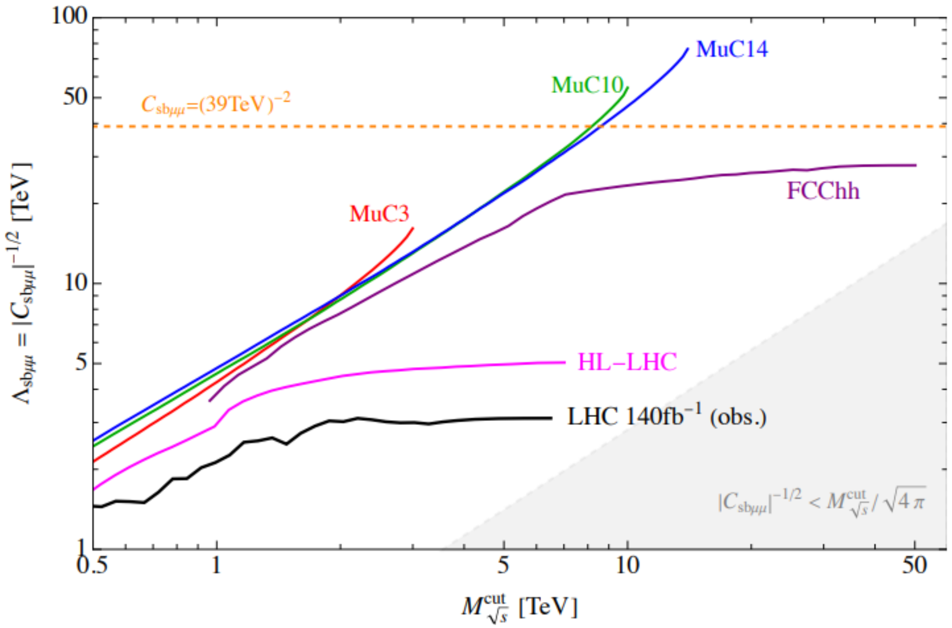
- **LQ pair production:**

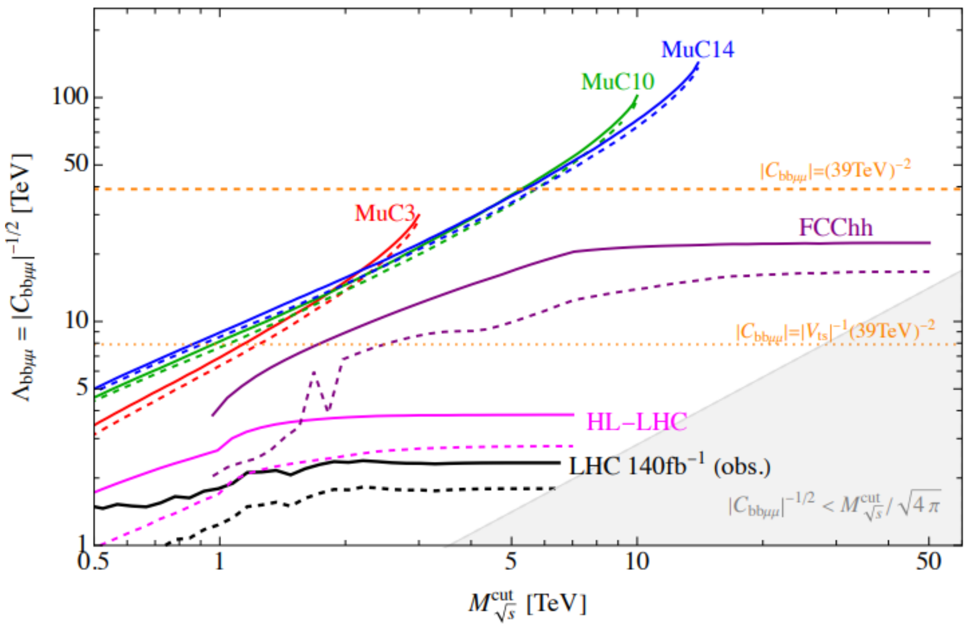
$$gg \to \mathrm{LQ}\overline{\mathrm{LQ}}$$



Contact interactions

Pessimistic scenario: NP too heavy, cannot be produced on-shell. Need to look for effects in the SMEFT operators.





Only ***bsμμ*** ***bsμμ + bbμμ*** (more realistic)

Z' models

There are **two different scenarios**:

i. $g_{sb} \ll g_{bb} \sim g_{\mu\mu}$ realizable gauging $U(1)_{B_3-L_\mu}$

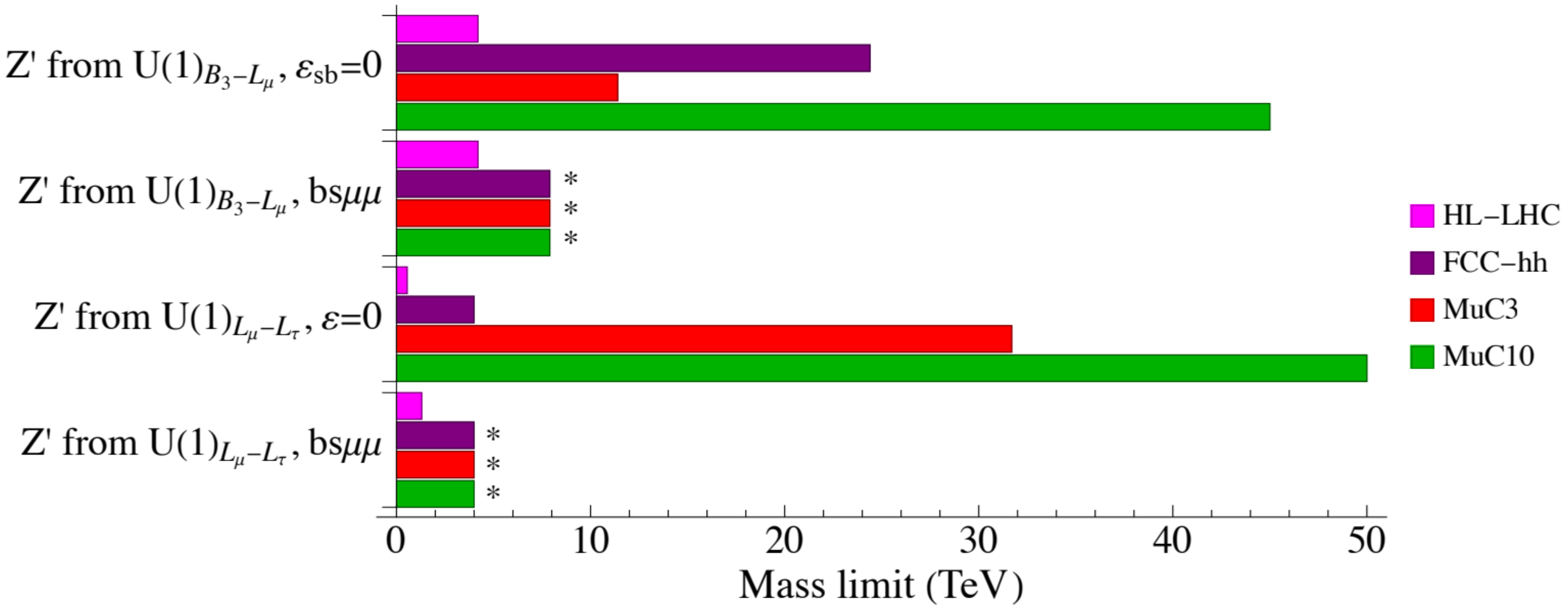
$$\mathcal{L}^{\text{int}}_{Z'_{B_3-L_\mu}} = -\, g_{Z'} Z'_\alpha \Big[\frac{1}{3}\bar{Q}^3_L \gamma^\alpha Q^3_L + \frac{1}{3}\bar{b}_R \gamma^\alpha b_R + \frac{1}{3}\bar{t}_R \gamma^\alpha t_R - \bar{L}^2_L \gamma^\alpha L^2_L - \bar{\mu}_R \gamma^\alpha \mu_R + \\ + \left(\frac{1}{3}\epsilon_{sb} \bar{Q}^2_L \gamma^\alpha Q^3_L + \text{h.c.} \right) + \mathcal{O}(\epsilon^2_{sb}) \Big]$$

Approximate ***U*(2)³** in the quark sector

ii. $g_{sb} \sim g_{bb} \ll g_{\mu\mu}$ by gauging $U(1)_{L_\mu - L_\tau}$

$$\mathcal{L}^{\text{int}}_{Z'_{L_\mu-L_\tau}} = -\, g_{Z'} Z'_\alpha \left[\bar{L}^2_L \gamma^\alpha L^2_L + \bar{\mu}_R \gamma^\alpha \mu_R - \bar{L}^3_L \gamma^\alpha L^3_L - \bar{\tau}_R \gamma^\alpha \tau_R + \\ + |\epsilon_b|^2 \bar{Q}^3_L \gamma^\alpha Q^3_L + |\epsilon_s|^2 \bar{Q}^2_L \gamma^\alpha Q^2_L + (\epsilon_b \epsilon^*_s \bar{Q}^2_L \gamma^\alpha Q^3_L + \text{h.c.}) + \ldots \right]$$

Z' prospects



Z' from $U(1)_{B_3-L_\mu}$, $\varepsilon_{sb}=0$
Z' from $U(1)_{B_3-L_\mu}$, $bs\mu\mu$
Z' from $U(1)_{L_\mu-L_\tau}$, $\varepsilon=0$
Z' from $U(1)_{L_\mu-L_\tau}$, $bs\mu\mu$
*
*
*
*
*
*
0
10
20
30
40
50
Mass limit (TeV)
HL−LHC
FCC−hh
MuC3
MuC10

Leptoquarks: general setup

There are **two possibilities**:

i. Scalar LQ, $\mathbf{S_3}$

$$\mathcal{L}^{\rm int}_{S_3} = -\lambda_{i\mu} S_3^{(1/3)} (V^*_{ji} \overline{u^{j\,c}_L} \mu_L + \overline{d^{i\,c}_L} \nu_\mu) + \sqrt{2}\lambda_{i\mu} \left(V^*_{ji} S_3^{(-2/3)} \overline{u^{j\,c}_L} \nu_\mu - S_3^{(4/3)} \overline{d^{i\,c}_L} \mu_L \right) + \text{h.c.}$$

ii. Vector LQ, $\mathbf{U_1}$

$$\mathcal{L}^{\rm int}_{U_1} = \lambda_{i\mu} \overline{Q_L}^i \gamma_\alpha L^2_L U_1^\alpha + \text{h.c.} = \lambda_{i\mu} U_1^\alpha \left(V_{ji} \bar{u}^j_L \gamma_\alpha \nu_\mu + \bar{d}^i_L \gamma_\alpha \mu_L \right) + \text{h.c.}$$

Anomaly fixed by

$$\lambda_{b\mu}\lambda_{s\mu} = -8.4 \times 10^{-4} \left(\frac{M_{S_3}}{\text{TeV}} \right)^2 \left(\frac{\Delta C_9^\mu}{-0.39} \right)$$

Leptoquarks prospects