Leptoquark pair production at future hadron colliders

Maeve Madigan

B.C.Allanach, T. Corbett, MM: 1911.04455

UNIVERSITY OF CAMBRIDGE

3rd FCC Physics and Experiments Workshop
CERN, 16th January 2020

Motivation

How can the neutral current B anomalies motivate the FCC-hh?

If leptoquarks are responsible, could they be directly detected at future hadron colliders?

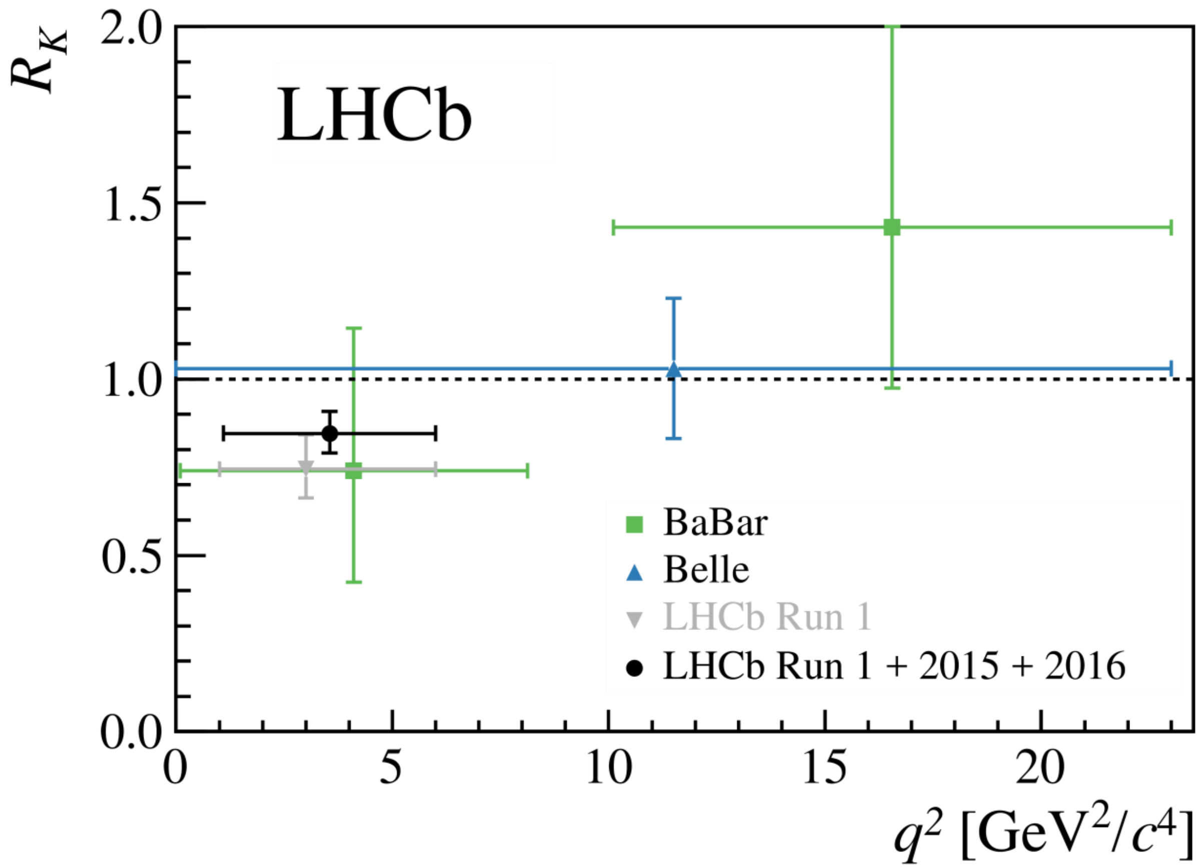
Future hadron colliders

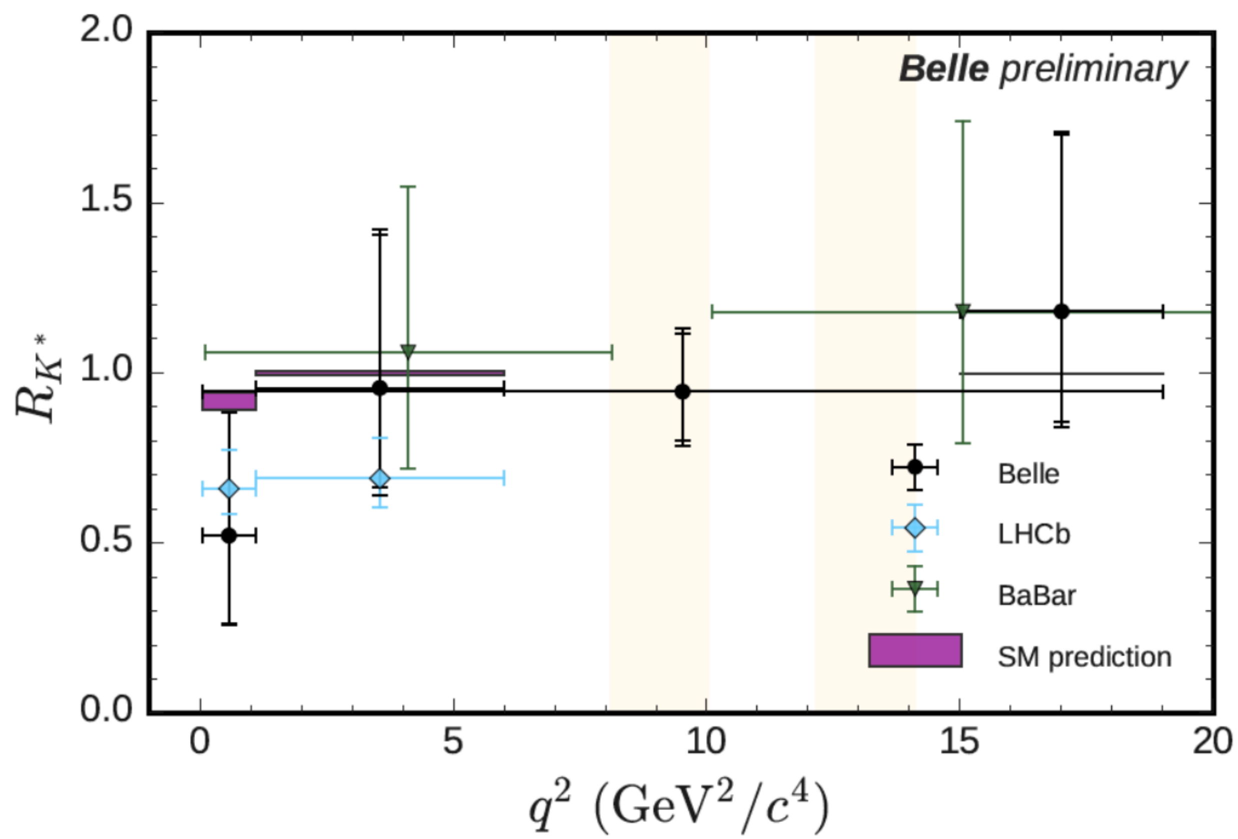
	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [ab^{-1}]
HL-LHC	14	3
HE-LHC	27	15
FCC-hh	100	20

Neutral current B anomalies

Discrepancies from the SM predictions in observables related to $b \to sll$ transitions including

$$P_5' \qquad \mathrm{BR}(B_s \to \phi\mu^+\mu^-) \qquad R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$





Neutral current B anomalies

Effective field theory description:

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i O_i + h.c.$$

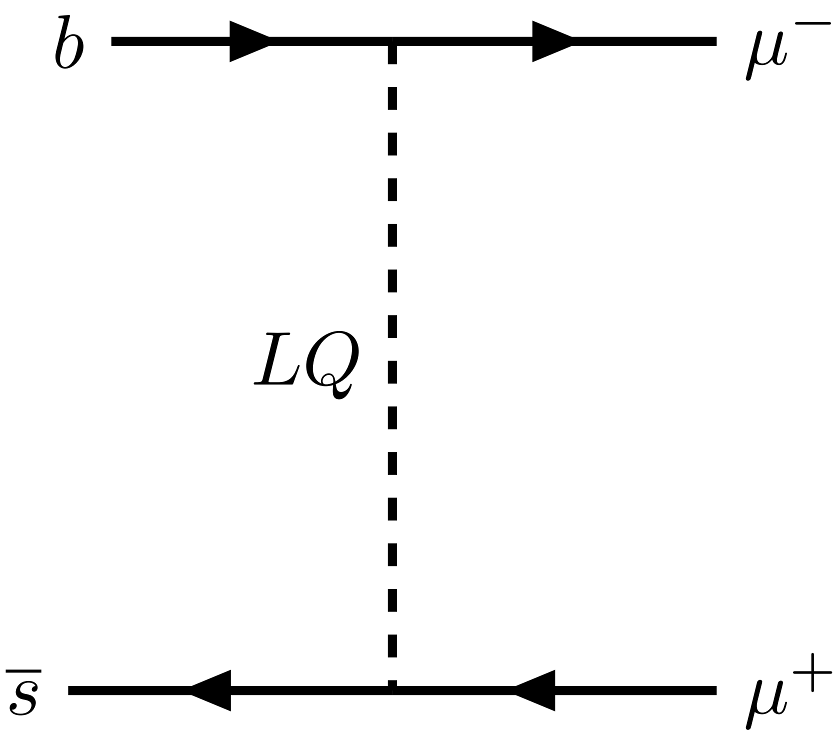
Aebischer, Altmannshofer, Guadagnoli, Reboud, Stangl, Straub 1903.10434:

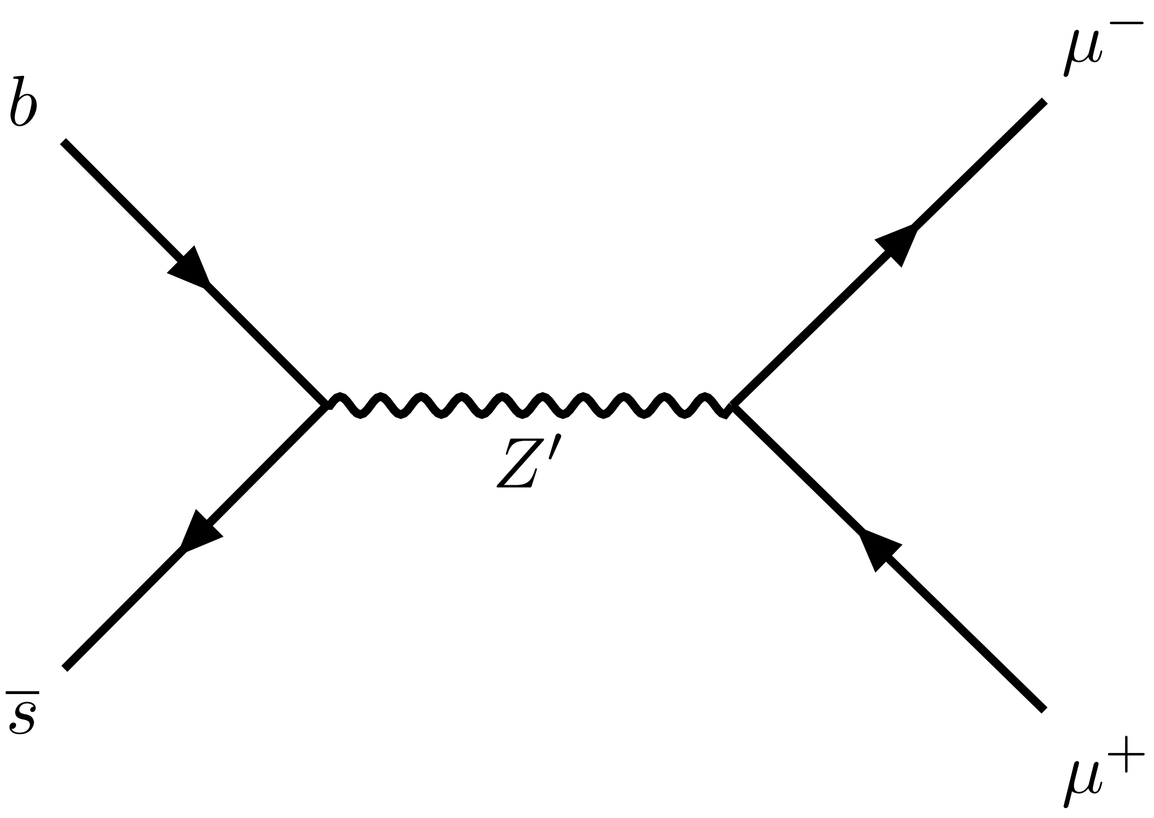
A single-coefficient fit to the flavour anomaly data prefers new physics in $C_9 = -C_{10}$ i.e.

$$\mathcal{O}_{LL} = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu P_L \mu) \qquad \text{with} \qquad C_{LL}^{\mathrm{NP}} = -0.53^{+0.08}_{-0.09}$$

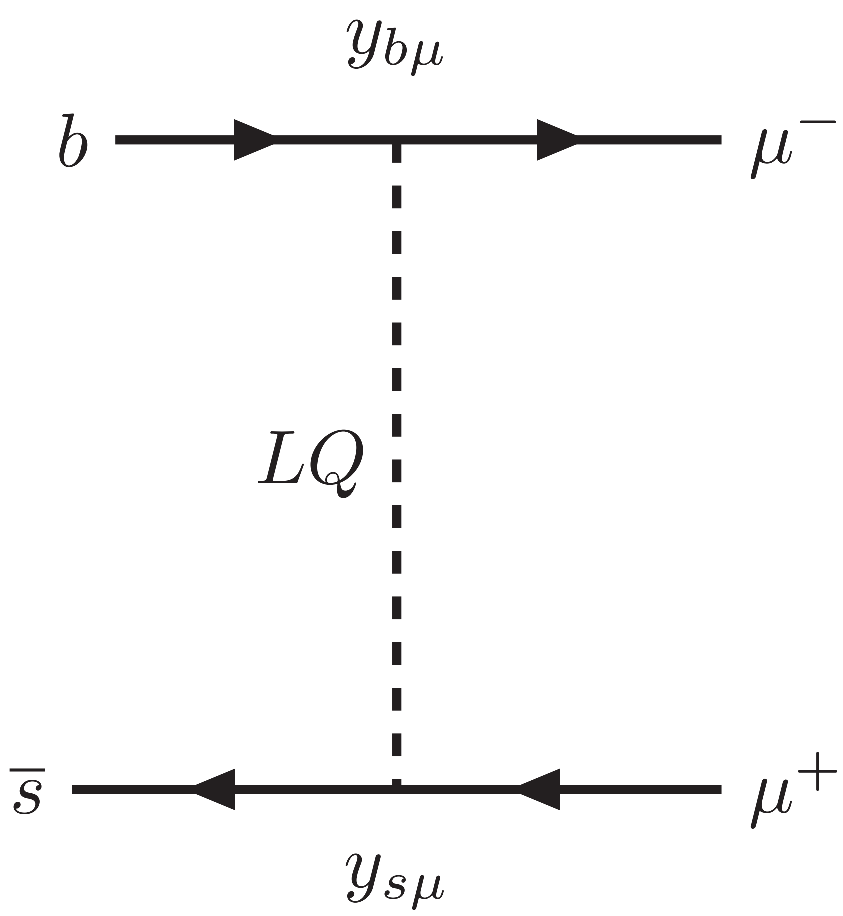
Other preferred options: $C_9, C_9 \;\&\; C_{10}$

Leptoquark solutions





Leptoquark solutions



$$S_3 : (\bar{3}, 3, \frac{1}{3})$$

under $SU(3) \times SU(2) \times U(1)$

$\rightarrow$ only $q_L l_L$ couplings

$\rightarrow$ scalar LQ

Leptoquark solutions

$$\mathcal{L} \supset y^{LL}_{3ij} \bar{Q}^{ci,a}_L \epsilon^{ab} (\tau^k S^k_3)^{bc} L^{j,c}_L$$

Rotate to the mass eigenbasis:

$$\begin{aligned} \to \mathcal{L} \supset & -\sqrt{2} y^{LL}_{3ij} \bar{d}^{ci}_L S^{\frac{4}{3}}_3 e^j_L \\ & - (y^{LL}_3 U)_{ij} \bar{d}^{ci} S^{\frac{1}{3}}_3 \nu^j_L \\ & - (V^T y^{LL}_3)_{ij} \bar{u}^{ci}_L S^{\frac{1}{3}}_3 e^j_L \\ & + \sqrt{2} (V^T y^{LL}_3 U)_{ij} \bar{u}^{ci}_L S^{-\frac{2}{3}}_3 \nu^j_L \end{aligned}$$

$y_{b\mu}, y_{s\mu}$

I. Doršner, S. Fajfer, A. Greljo, J.F. Kamenik, N. Košnik: 1603.04993

Leptoquark solutions

$$\mathcal{L} \supset y^{LL}_{3ij} \bar{Q}^{ci,a}_L \epsilon^{ab} (\tau^k S^k_3)^{bc} L^{j,c}_L$$

Rotate to the mass eigenbasis:

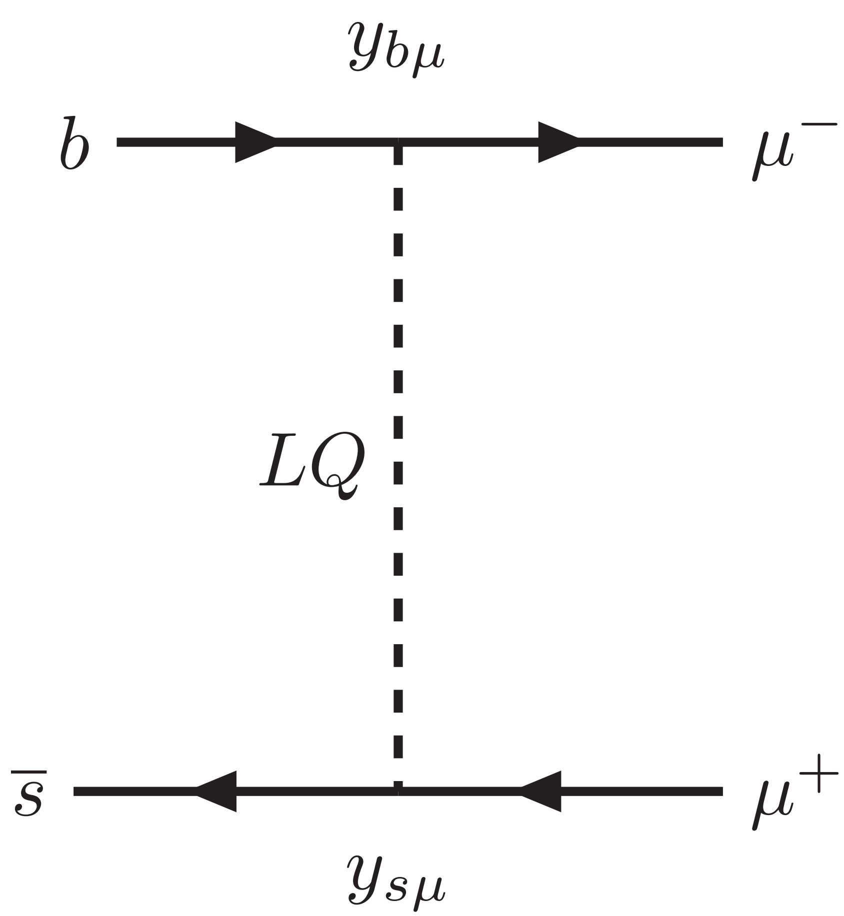
$$\begin{aligned} \to \mathcal{L} \supset &- \sqrt{2} y^{LL}_{3ij} \bar{d}^{ci}_L S^{\frac{4}{3}}_3 e^j_L \\ &- (y^{LL}_3 U)_{ij} \bar{d}^{ci} S^{\frac{1}{3}}_3 \nu^j_L \\ &- (V^T y^{LL}_3)_{ij} \bar{u}^{ci}_L S^{\frac{1}{3}}_3 e^j_L \\ &+ \sqrt{2} (V^T y^{LL}_3 U)_{ij} \bar{u}^{ci}_L S^{-\frac{2}{3}}_3 \nu^j_L \end{aligned}$$

$y_{b\mu}, y_{s\mu}$

I. Doršner, S. Fajfer, A. Greljo, J.F. Kamenik, N. Košnik: 1603.04993

We will work with $(y^{LL}_3)_{22} \propto y_{s\mu} \neq 0$, $(y^{LL}_3)_{32} \propto y_{b\mu} \neq 0$ and all other $(y^{LL}_3)_{ij} = 0$

Leptoquark solutions



$$y_{b\mu} y^*_{s\mu} = \frac{C^{\rm NP}_{LL} V_{tb} V^*_{ts} \alpha_{\rm EM}}{2\pi v^2} m^2_{\rm LQ}$$

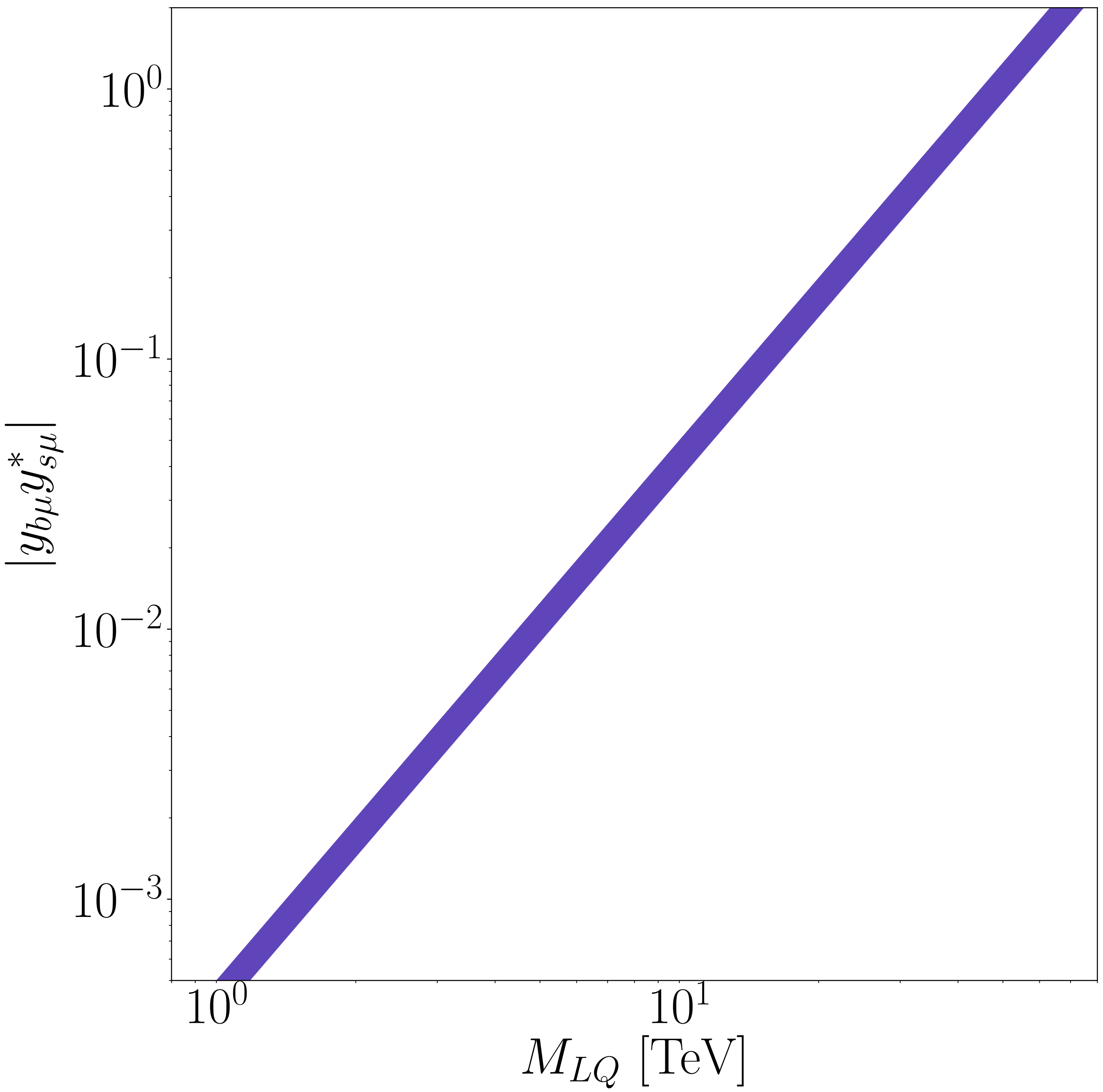
$$y_{b\mu} = y_{s\mu}$$

These couplings describe a narrow width leptoquark:

$$\Gamma = \frac{|y_{lq}|^2 m_{\rm LQ}}{16\pi} \qquad \Gamma / m_{\rm LQ} < 0.01$$

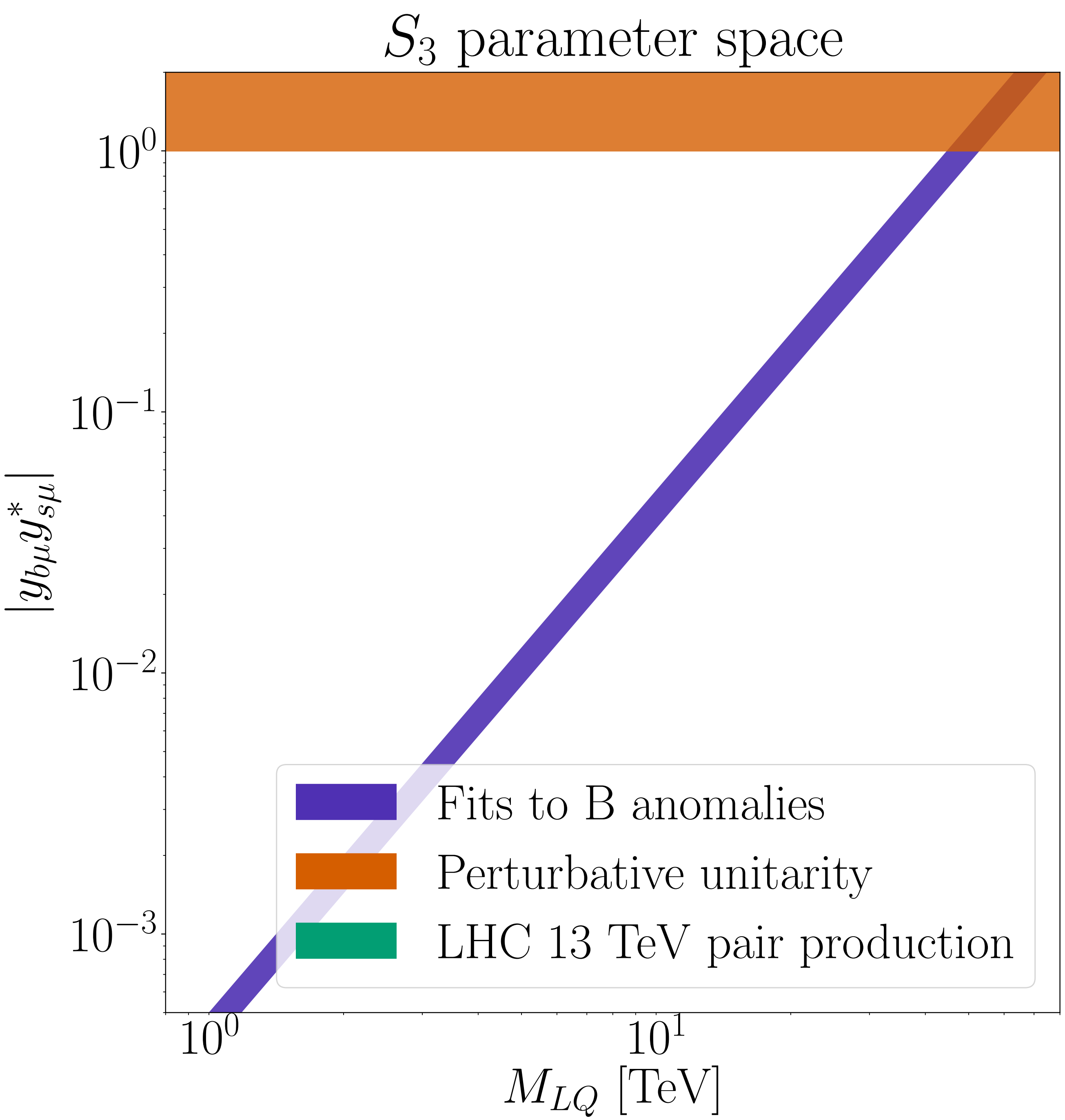
Plehn, Spiesberger, Spira, Zerwas: hep-ph/9703433

Leptoquark solutions



$$y_{b\mu}y^*_{s\mu} = \frac{C_{LL}V_{tb}V^*_{ts}\alpha_{\mathrm{EM}}}{2\pi v^2}m^2_{\mathrm{LQ}}$$

Leptoquark solutions



Constraints from:

LHC searches for LQ pair production

ATLAS:1906.08983 CMS:1808.05082 1605.06035

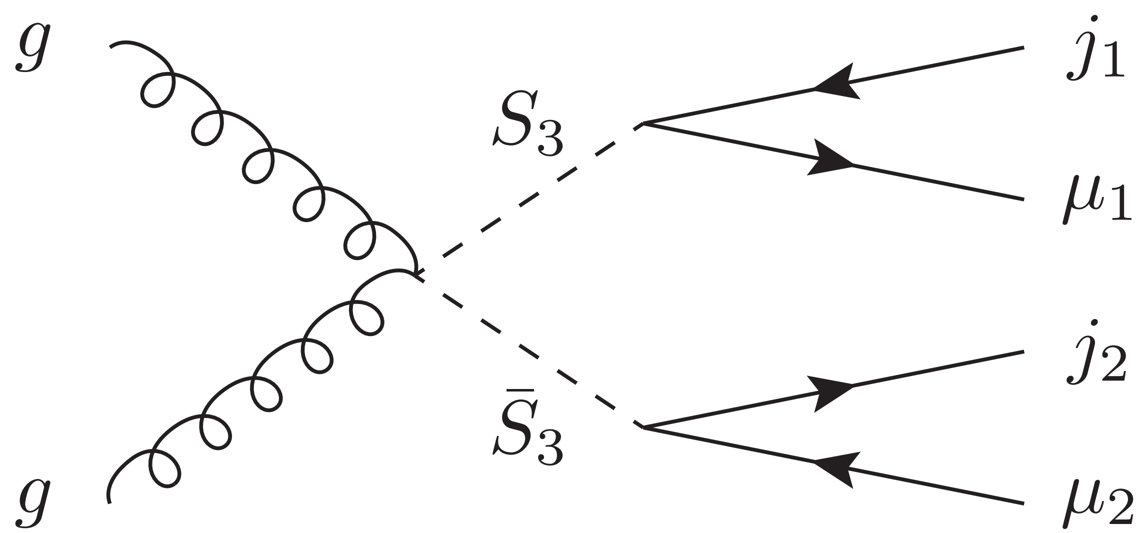
Perturbative unitarity

Neutral B meson mixing: $m_{\rm LQ} \lesssim 70$ TeV for LQ solutions to the B anomalies

Luzioa, Kirk, Lenz, Rauh: 1909.11087

Leptoquarks at future colliders

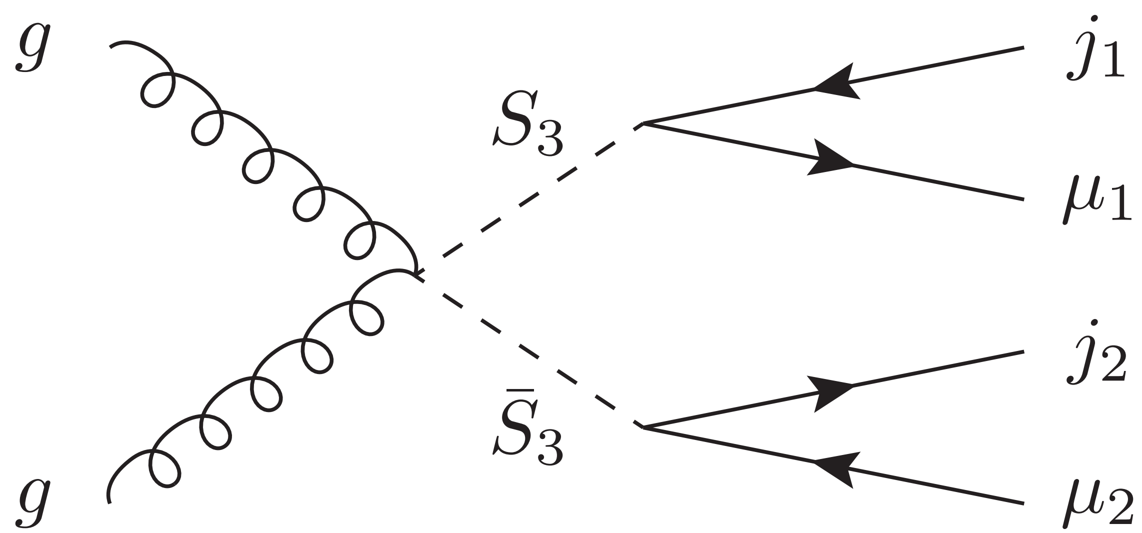
Simulate a search for the pair production of scalar LQs and decay into the dimuon dijet channel



We select events containing: 2 muons and $\geq$2 jets with no flavour tagging.

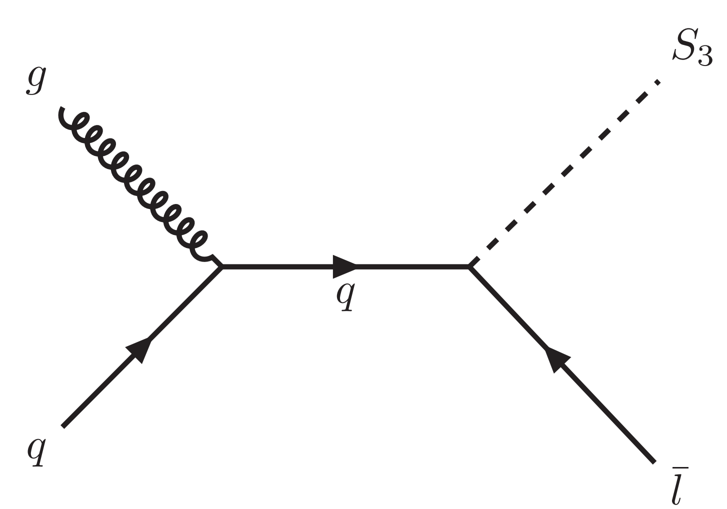
Leptoquarks at future colliders

Simulate a search for the pair production of scalar LQs and decay into the dimuon dijet channel



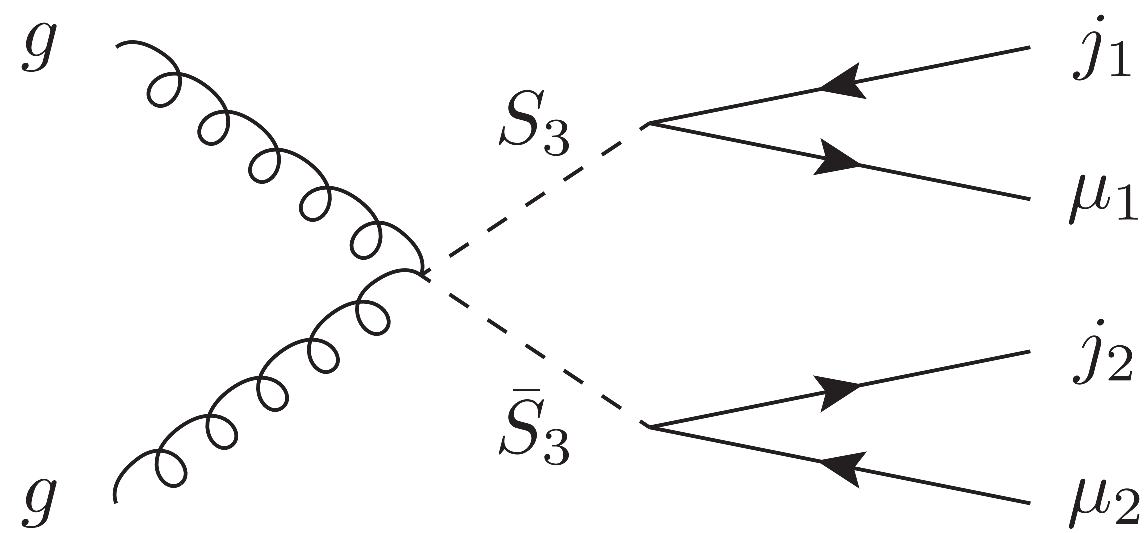
Pair production: dominant production mechanism for relevant couplings:

- independent of y_{lq}
- single production is always dependent on some y_{lq}



Leptoquarks at future colliders

Simulate a search for the pair production of scalar LQs and decay into the dimuon dijet channel

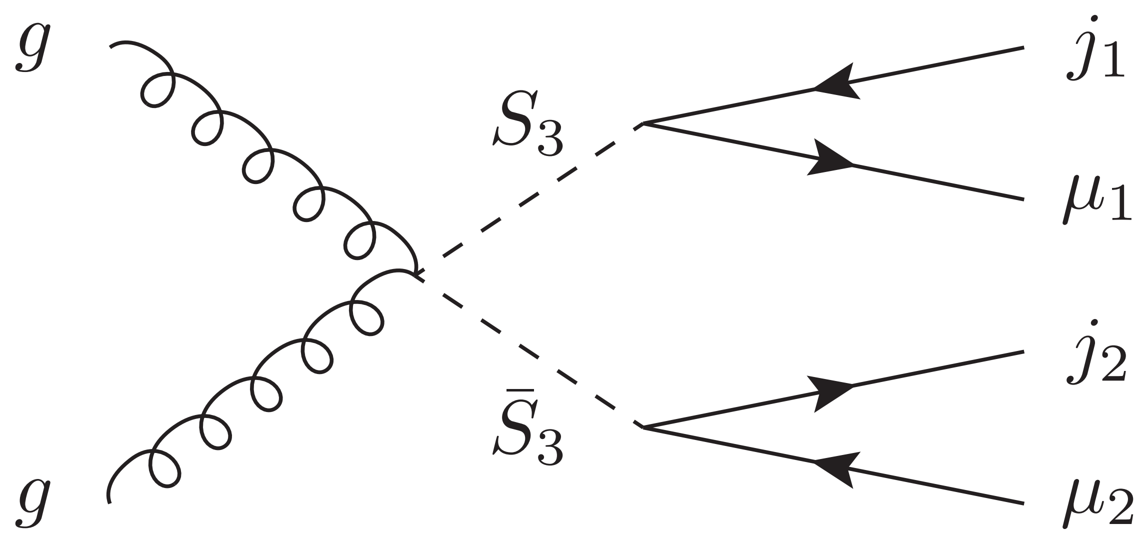


`

$\mu\mu jj$ channel: motivated by the couplings $y_{b\mu}, y_{s\mu}$ required by the neutral current B anomalies.

Leptoquarks at future colliders

Simulate a search for the pair production of scalar LQs and decay into the dimuon dijet channel



Direct search for a resonance in the invariant mass distribution, defined by:

Minimise $|m(\mu_1, j_1) - m(\mu_2, j_2)|$

Define: $m_{\min}(\mu, j) = \min[m(\mu_1, j_1), m(\mu_2, j_2)]$

Methodology

Simulate the standard model background in $m_{\min}(\mu, j)$ using

- Leading order **`Madgraph5`**
- **`Pythia8`** for parton showering
- **`Delphes3`** for detector simulation

Simulate the distribution of LQ events

UFO files from I. Doršner, A. Greljo, '*Leptoquark toolbox for precision collider studies*' 1801.07641

Statistical analysis using **`HistFactory`** via **`pyhf`**

Methodology

Signal region defined by cuts on $p_T^{\mu}, p_T^{j}, m_{\mu\mu}, |\eta_{\mu}|, |\eta_j|$ and
$S_T = p_T^{\mu_1} + p_T^{\mu_2} + p_T^{j_1} + p_T^{j_2}$

$$\left.\begin{array}{l} \text{Drell-Yan} + \text{jets} \\ t\bar{t} + \text{jets} \\ Wt + \text{jets} \\ W^+W^- + \text{jets} \end{array}\right\} \text{Match multijet samples with MLM matching}$$

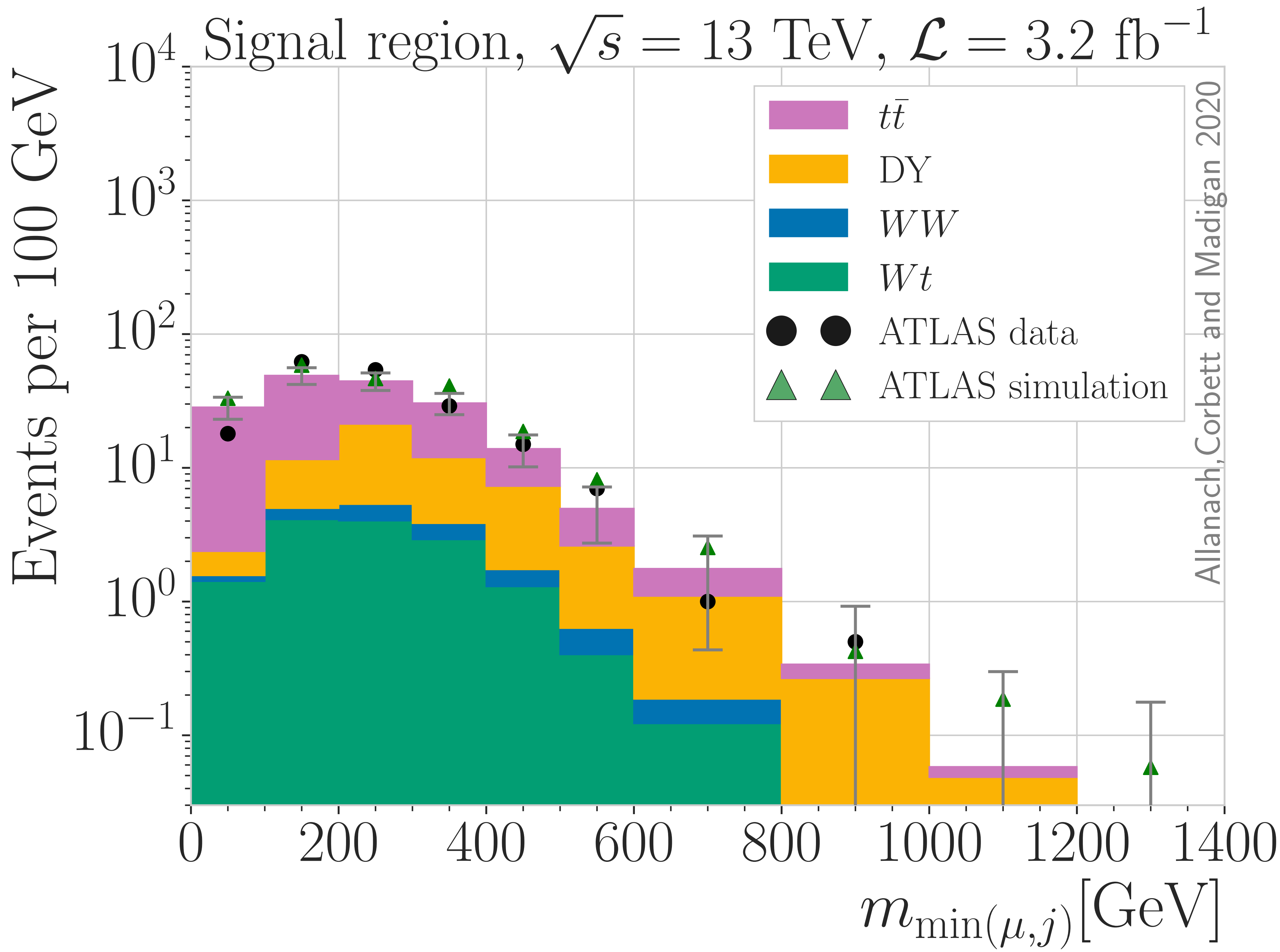
Methodology

- $DY, t\bar{t}, Wt$ in a 5-flavour scheme
- WW in a 4-flavour scheme to avoid interference between $W^+W^- + 2j,\ Wt + 1j$ and $t\bar{t}$
- Diagram removal method to remove interference between $Wt + 1j$ and $t\bar{t}$
- Bias the event generation to improve statistics in the tail regions.

Validation

Comparison with ATLAS search for scalar leptoquarks at $\sqrt{s}$=13 TeV, 3.2 fb^{-1}

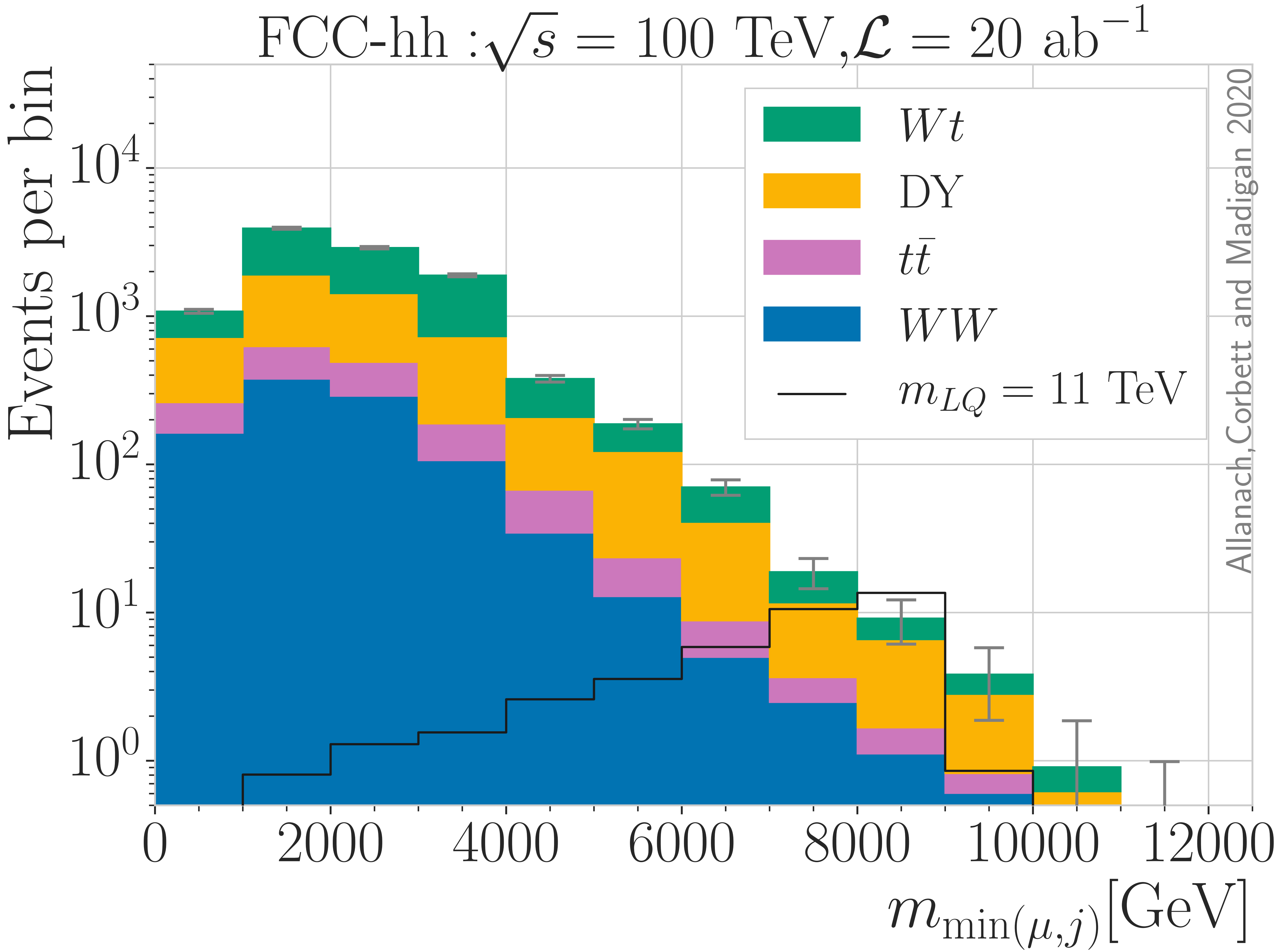
1605.06035



Future colliders

- Signal regions: scale up cuts on $p_T, M_{\mu\mu}, S_T$ by $\sqrt{s}/(13\ \mathrm{TeV})$
- Use the appropriate Delphes cards for each detector
- No selection on muon isolation is applied as the specific choice of parameters is found to have a significant impact on the SM background

following Helsens, Jamin, Mangano, Rizzo, Selvaggi: 1902.11217

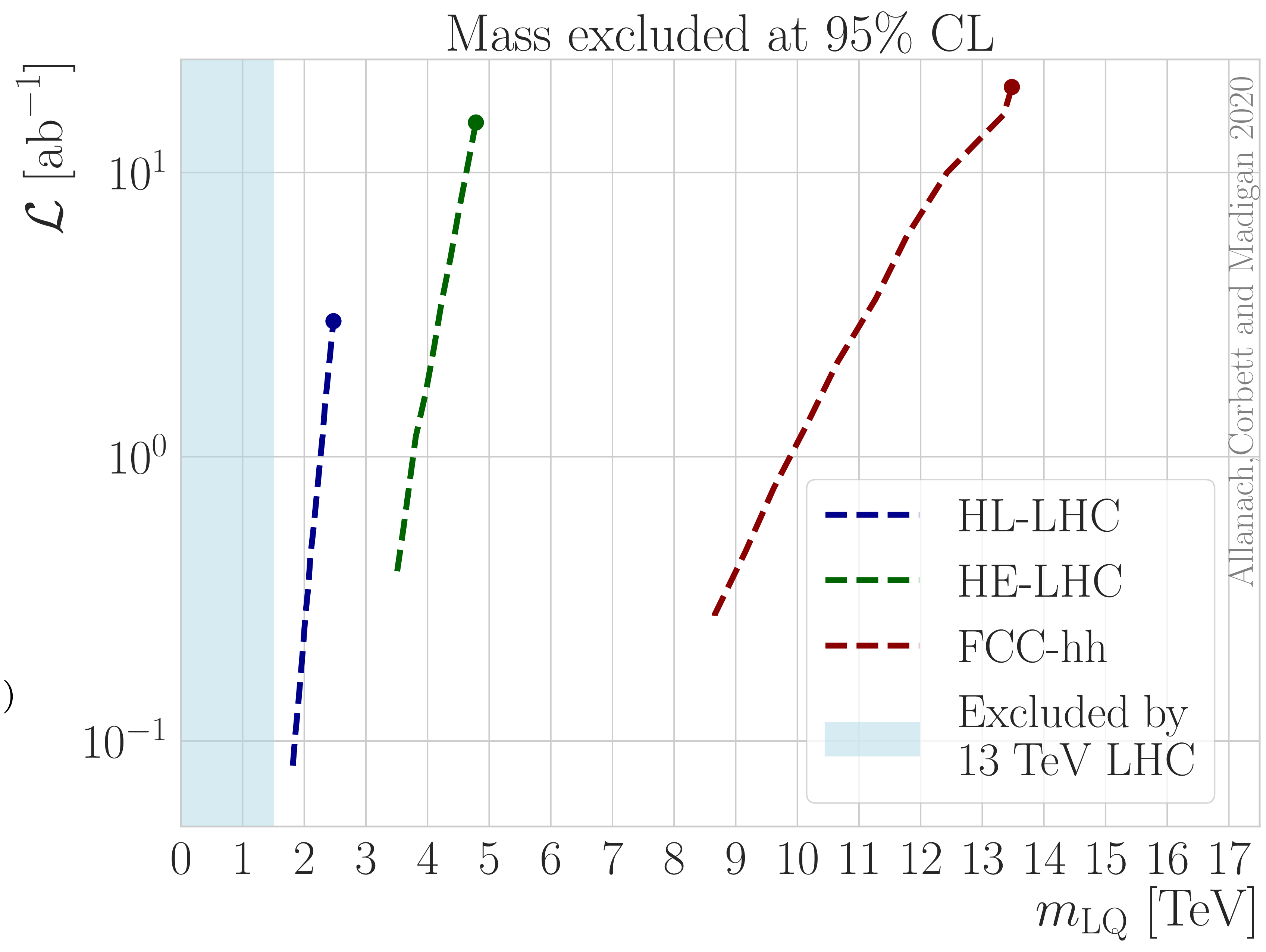


FCC-hh : $\sqrt{s}$ = 100 TeV, $\mathcal{L}$ = 20 ab^{-1}
Events per bin
10^4
10^3
10^2
10^1
10^0
0
2000
4000
6000
8000
10000
12000
$m_{\min(\mu,j)}$[GeV]
Wt
DY
$t\bar{t}$
WW
m_{LQ} = 11 TeV
Allanach, Corbett and Madigan 2020

Projections: exclusion limits

Integrated luminosity required to exclude masses up to m_{LQ} at 95% CL.

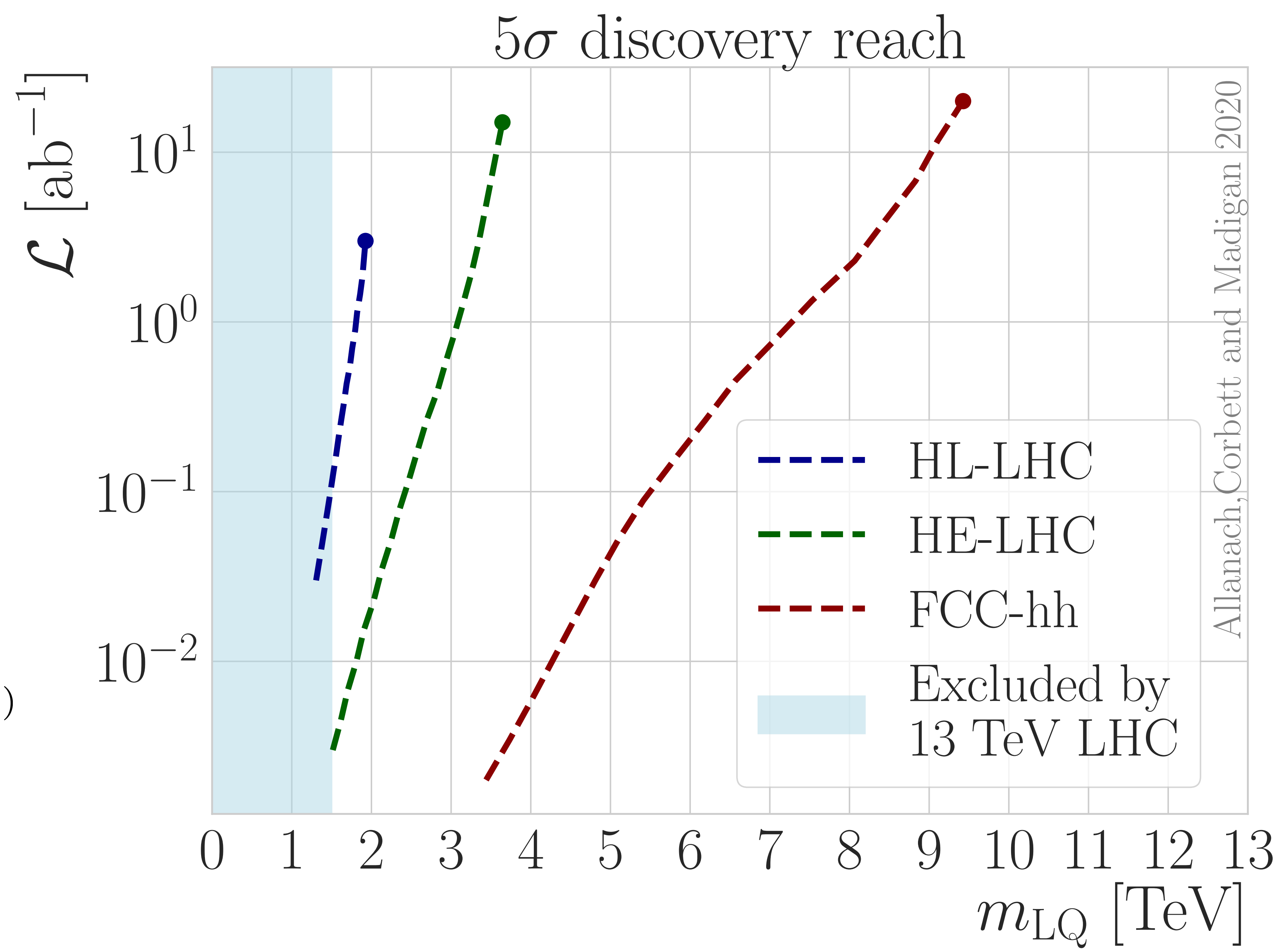
$$L = \prod_{\text{bins } i} \frac{(b_i + \mu s_i)^{n_i}}{n_i!} e^{-(b_i + \mu s_i)}$$



Projections: discovery potential

Integrated luminosity required to discover masses up to $m_{\rm LQ}$ with a significance of 5σ.

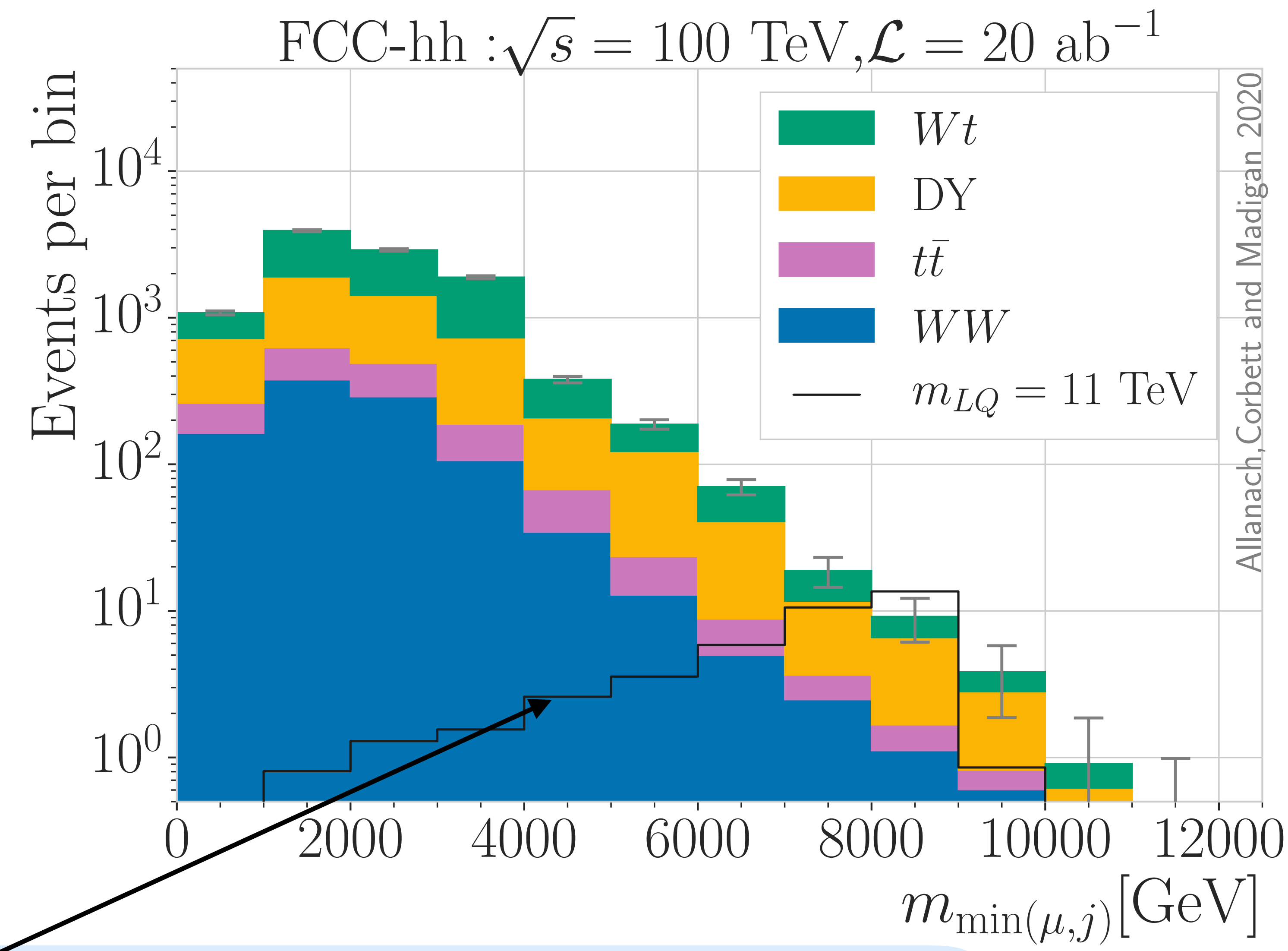
$$L = \prod_{\text{bins } i} \frac{(b_i + \mu s_i)^{n_i}}{n_i!} e^{-(b_i+\mu s_i)}$$



Narrow width LQs

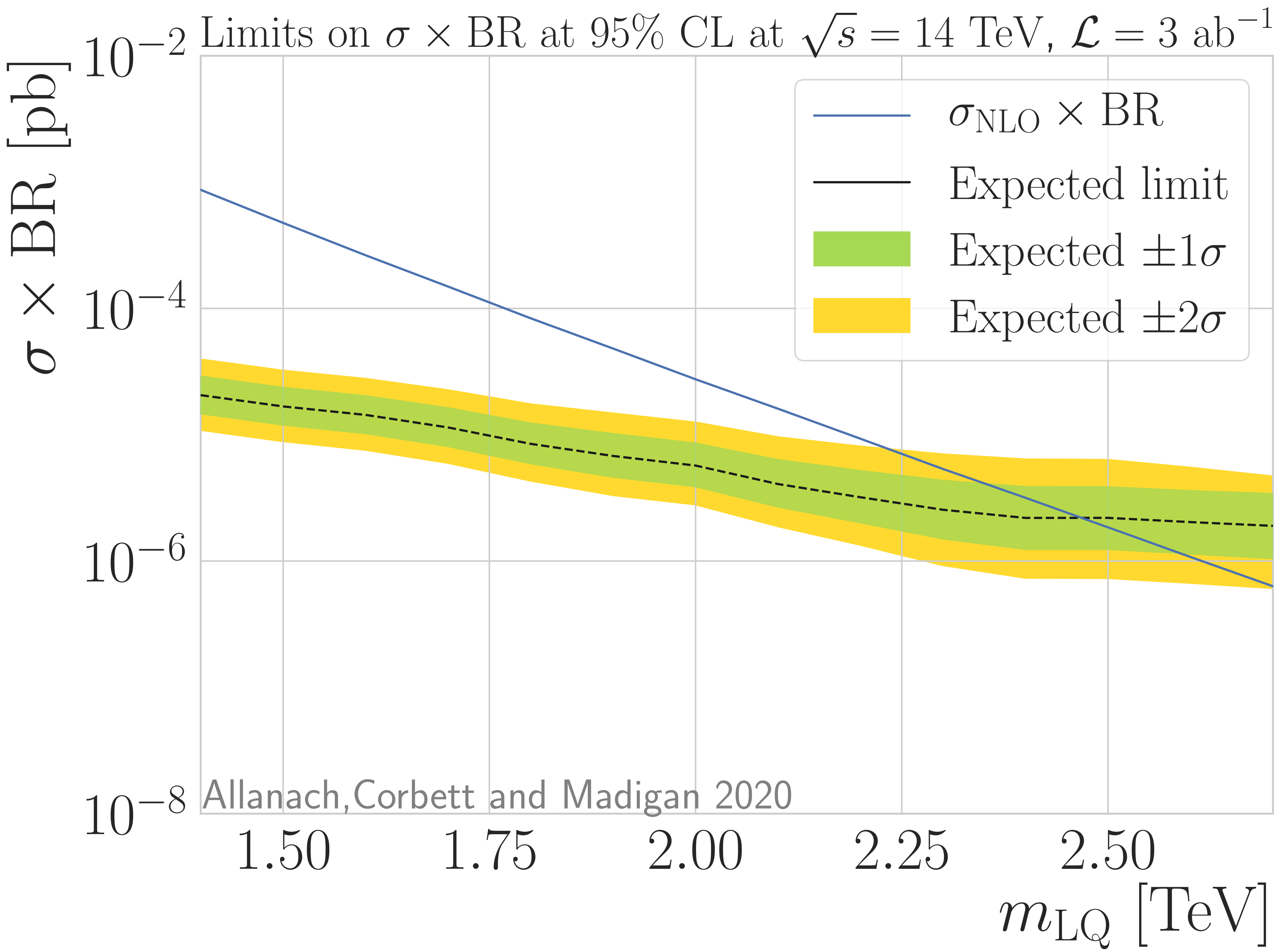
Spread of LQ events due to:

- momentum lost during parton showering
- smearing due to detector efficiency and mismeasurement
- definition of $m_{\min}(\mu, j)$

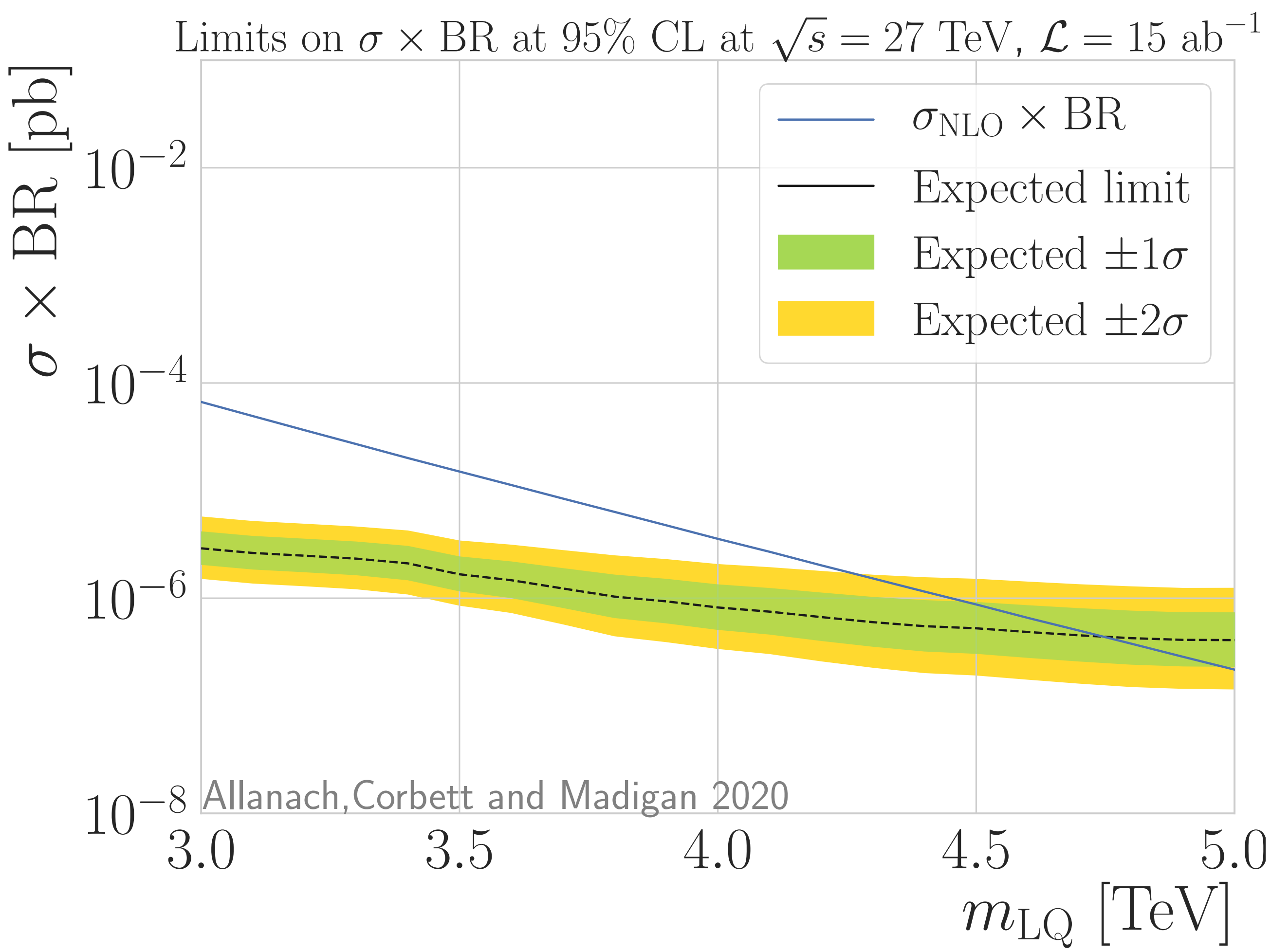


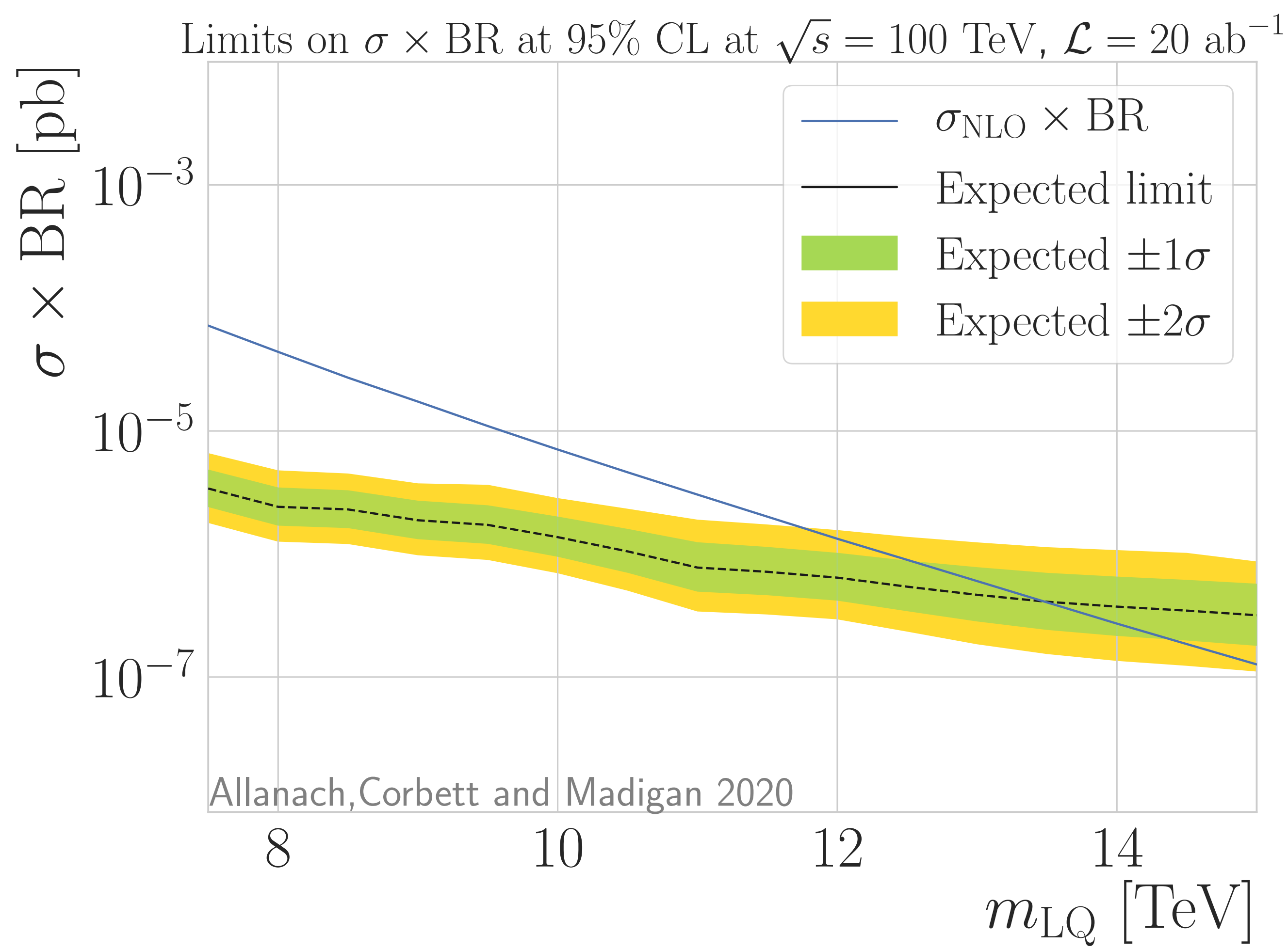
This shape is determined by the **experimental resolution**. Any narrow width scalar LQ should produce the same shape.

Exclusion limits: Projections for HL-LHC



Exclusion limits: Projections for HE-LHC and FCC-hh



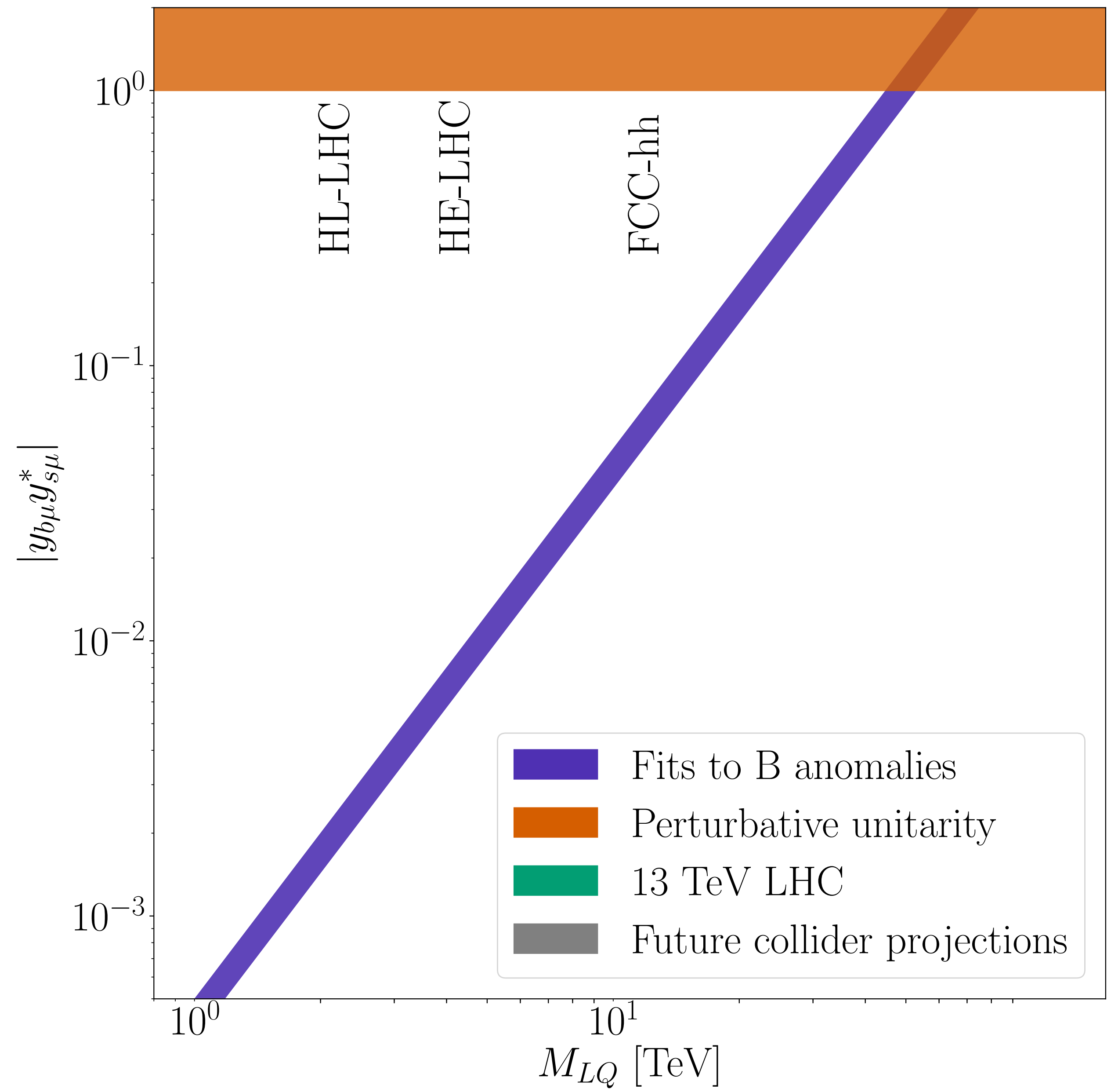


Conclusions

Neutral current B anomalies are good motivators for future hadron colliders, if they remain.

For similar work on Z' solutions to the neutral current B anomalies:

B. C. Allanach, B. Gripaios, T. You: 1710.06363
B. C. Allanach, T. Corbett, M. J. Dolan, T.You: 1810.02166
B. C. Allanach, J. M. Butterworth, T. Corbett: 1904.10954



Backup

LO Madgraph5 vs MG5_aMC@NLO

Model our definition of signal region on the ATLAS search:

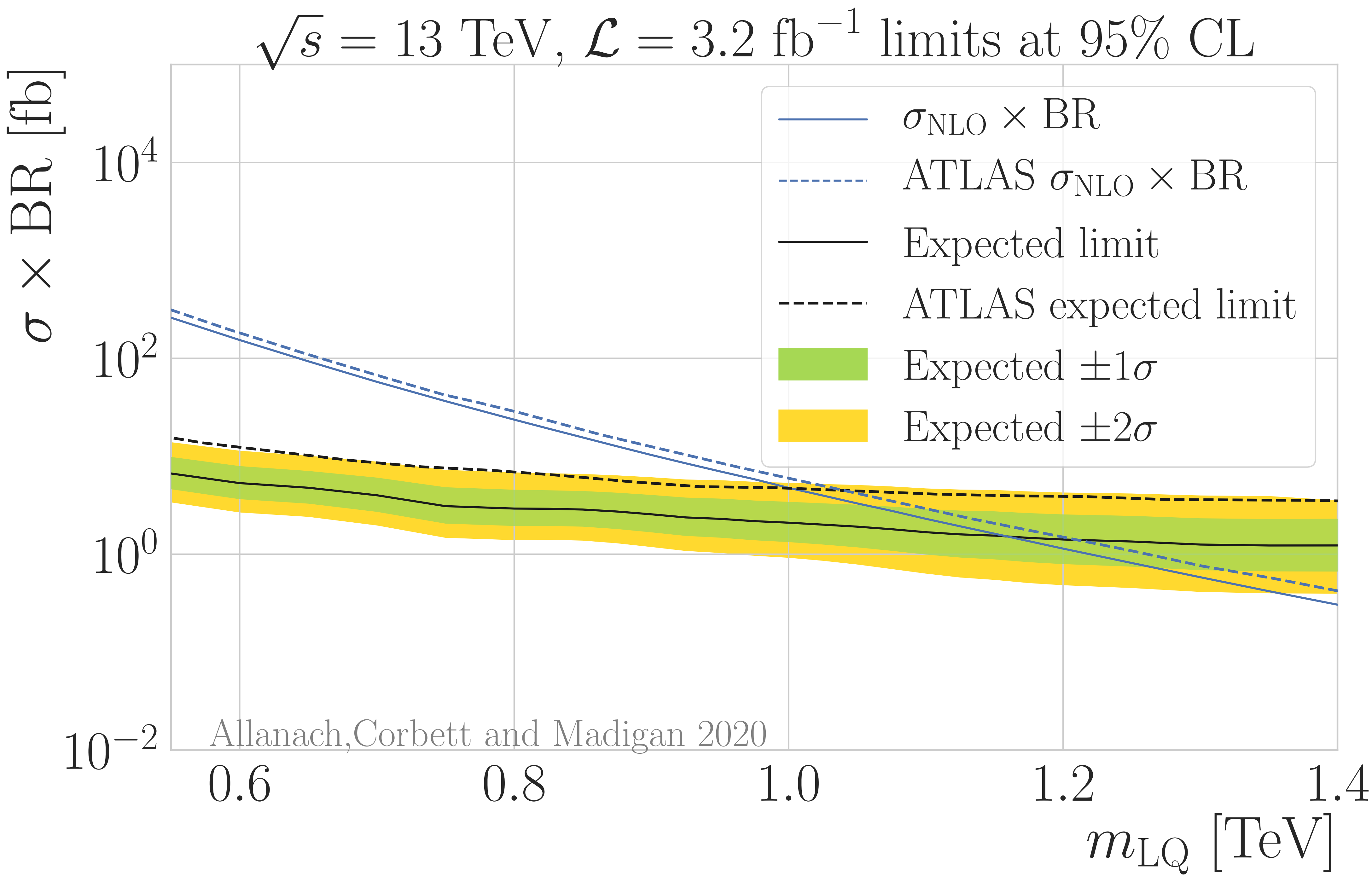
p_T^j (GeV)	p_T^μ (GeV)	$M_{\mu\mu}$ (GeV)	S_T (GeV)
> 50	> 40	> 130	> 600

$\Delta R_{\mu j}$	$\Delta R_{\mu\mu}$	$\lvert\eta_\mu\rvert$	$\lvert\eta_j\rvert$
> 0.4	> 0.3	< 2.5	< 2.8

For efficiency we need to place cuts on the final state particles at parton level while generating events in Madgraph.

This was not efficient enough in MG5_aMC@NLO + MadSpin.

Validation by comparison with ATLAS: 1605.06035



Use of ATLAS data

We model our search and validate our simulations against arXiv:1605.06035

Search for scalar leptoquarks in pp collisions at $\sqrt{s}=13$ TeV with the ATLAS experiment (at 3.2 fb^{-1})

This has the advantage of following a simple cut-based analysis which is easily reproducible.

Other searches from ATLAS & CMS exist which are more constraining:

- CMS:1808.05082 search at $\sqrt{s}=13$ TeV and 35.9 fb^{-1}
  - uses a 3-dimensional optimisation to optimise signal-to-background separation (using Punzi significance).
- ATLAS: 1906.08983 search at $\sqrt{s}=13$ TeV and 36.1 fb^{-1}
  - uses boosted decision trees to discriminate signal from background.

Charged current anomalies and vector leptoquarks

We ignore charged current anomalies associated with $b \to c\tau\bar{\nu}$ transitions.

The scale of new physics required is $\sim \mathcal{O}(1 \text{ TeV})$ compared to $\sim \mathcal{O}(10 \text{ TeV})$ for the charged current anomalies

$\longrightarrow$ this new physics should be more easily discoverable

The vector LQ U_1 can accommodate both anomalies

see e.g. A. Angelescu, D. Becirevic, D.A. Faroughy, O. Sumensari 1808.08179
C. Cornella, J. Fuentes-Martin, G. Isidori 1903.11517