Leptoquark pair production at future hadron colliders

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arXiv:1911.04455

with Ben Allanach and Tyler Corbett

Central question

If leptoquarks exist,
could we detect them at future hadron colliders?

Outline

- Motivation: Why future colliders?
  Why leptoquarks?

- Our strategy and methodology: simulation tools.

- Projections for future colliders: results.

Future colliders

How can we detect new physics beyond the standard model?

Higher precision

Higher energy

High luminosity (HL) LHC

140 fb^{-1} $\xrightarrow[\text{luminosity}]{\text{increase}}$ 3 ab^{-1}

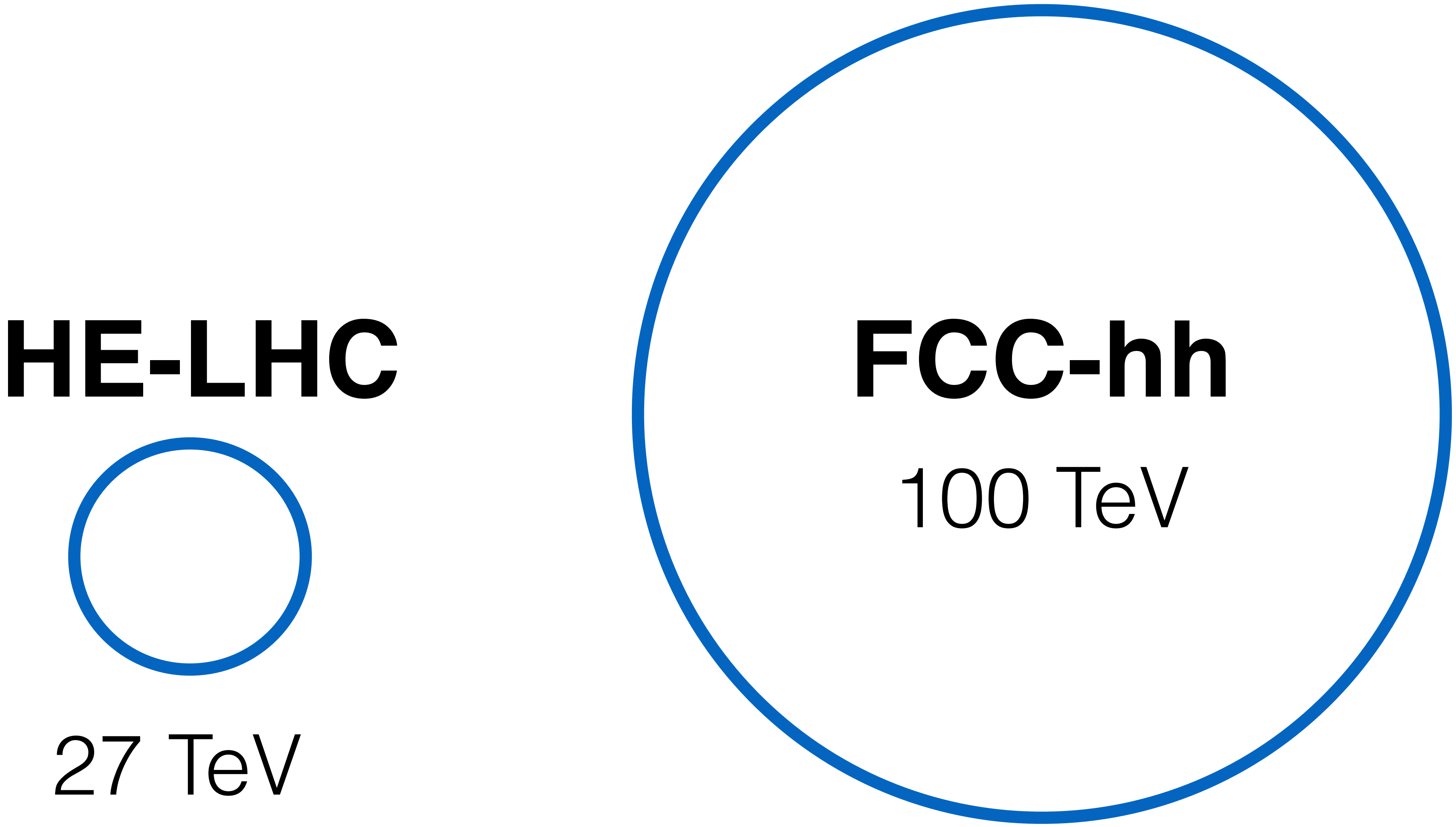
LHC

13 TeV

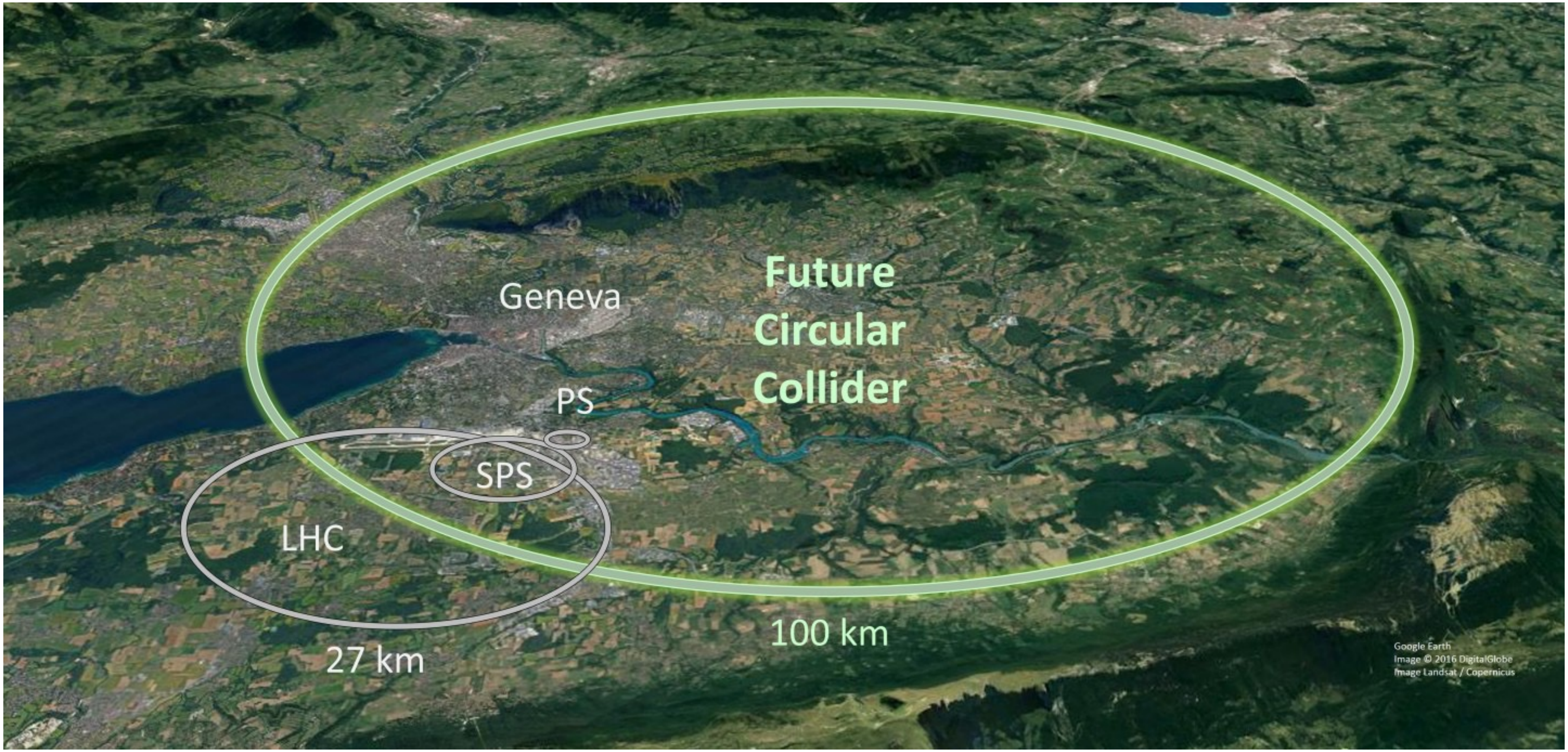
HL-LHC

14 TeV

High energy pp colliders



High energy pp colliders



High energy pp colliders

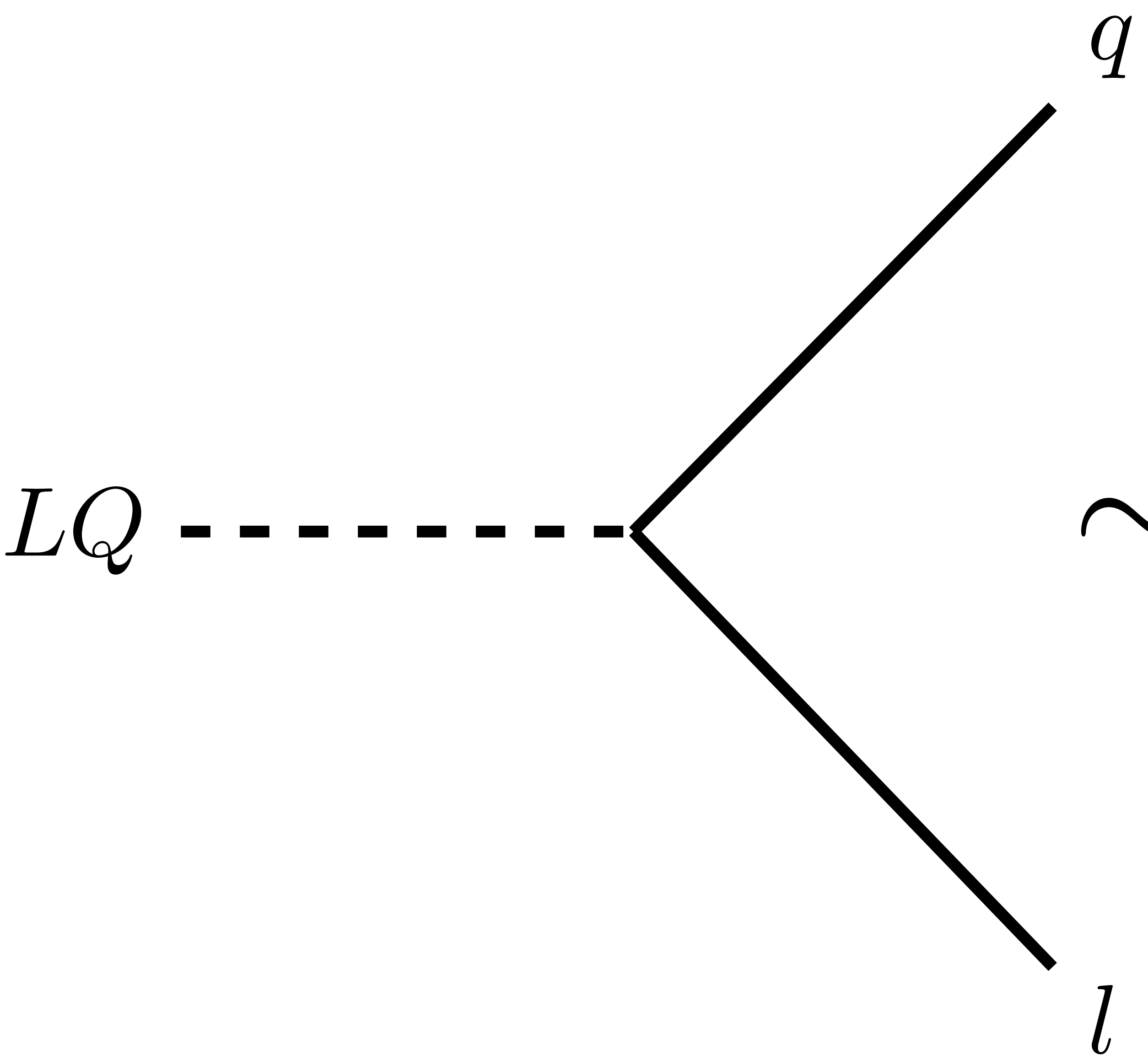
Proposals for ee colliders also exist e.g. FCC-ee.

These provide a much cleaner environment with reduced background noise, but do not have the same energy reach.

pp colliders have the potential to reach high centre of mass energies

- better prospects for direct detection of TeV scale new physics.

Leptoquarks



$$\sim y_{lq}$$

Leptoquarks as solutions to the neutral current B anomalies

LHCb, Belle, BaBar: measured discrepancies from the SM at the level of $2-3\sigma$ in observables including:

$$R_{K^{(*)}} \qquad P_5' \qquad \mathrm{BR}(B_s^0 \to \mu^+\mu^-)$$

Leptoquarks as solutions to the neutral current B anomalies

- Theoretical predictions have low uncertainties due to lepton flavour universality in the SM:

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

Leptoquarks as solutions to the neutral current B anomalies

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

- All observables are related to $b \to s\mu\mu$

Leptoquarks as solutions to the neutral current B anomalies

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

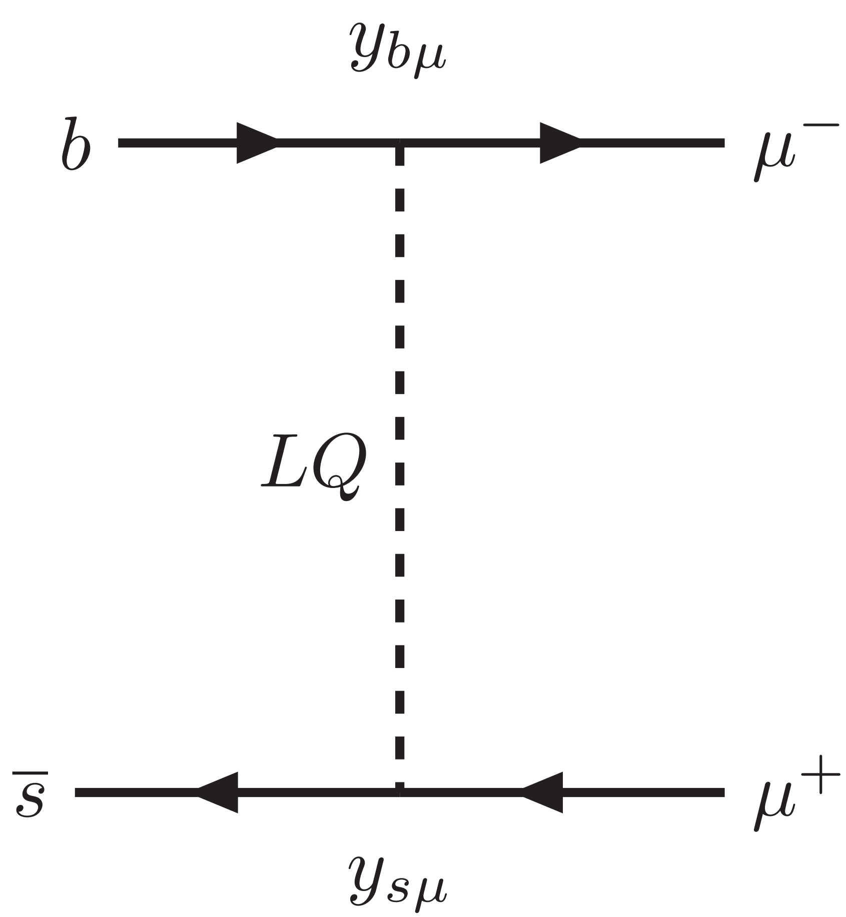
Fits to flavour anomaly data prefer new physics in

$$\mathcal{O}_{LL} = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu P_L \mu)$$

with $C_{LL} = -0.53^{+0.08}_{-0.09}$ $\rightarrow 6.5\sigma$ from the SM.

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

Leptoquarks as solutions to the neutral current B anomalies



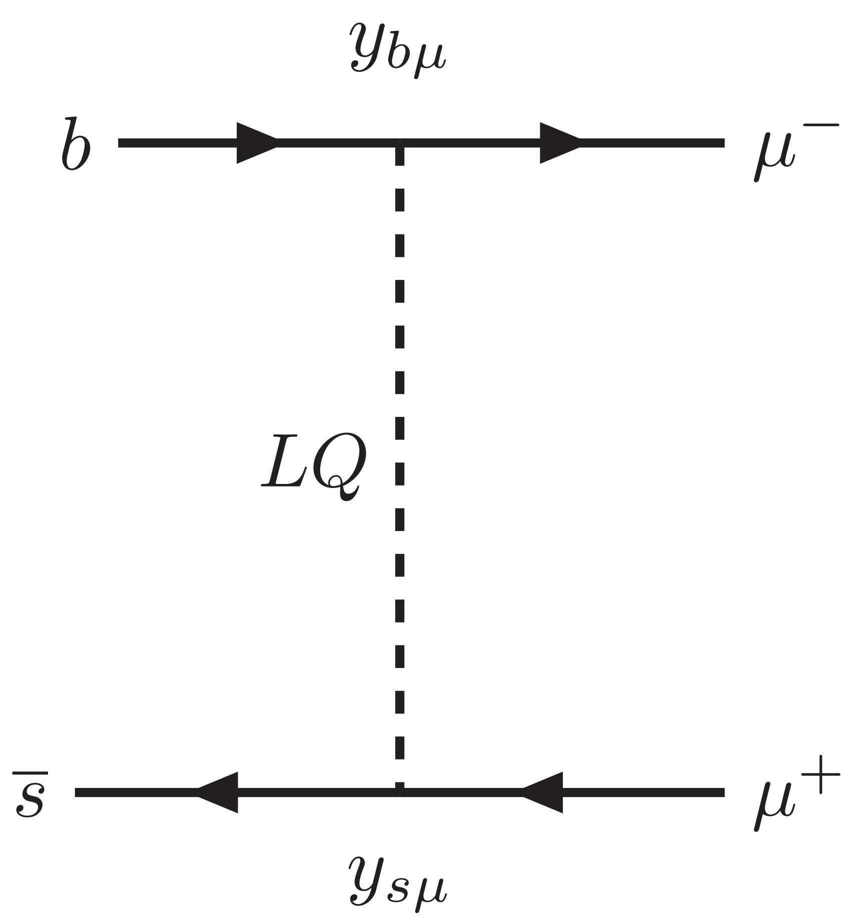
$$S_3 : (\bar{3}, 3, \frac{1}{3})$$

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

$\rightarrow$ only $q_L l_L$ couplings

$\rightarrow$ scalar LQ

Leptoquarks as solutions to the neutral current B anomalies



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

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

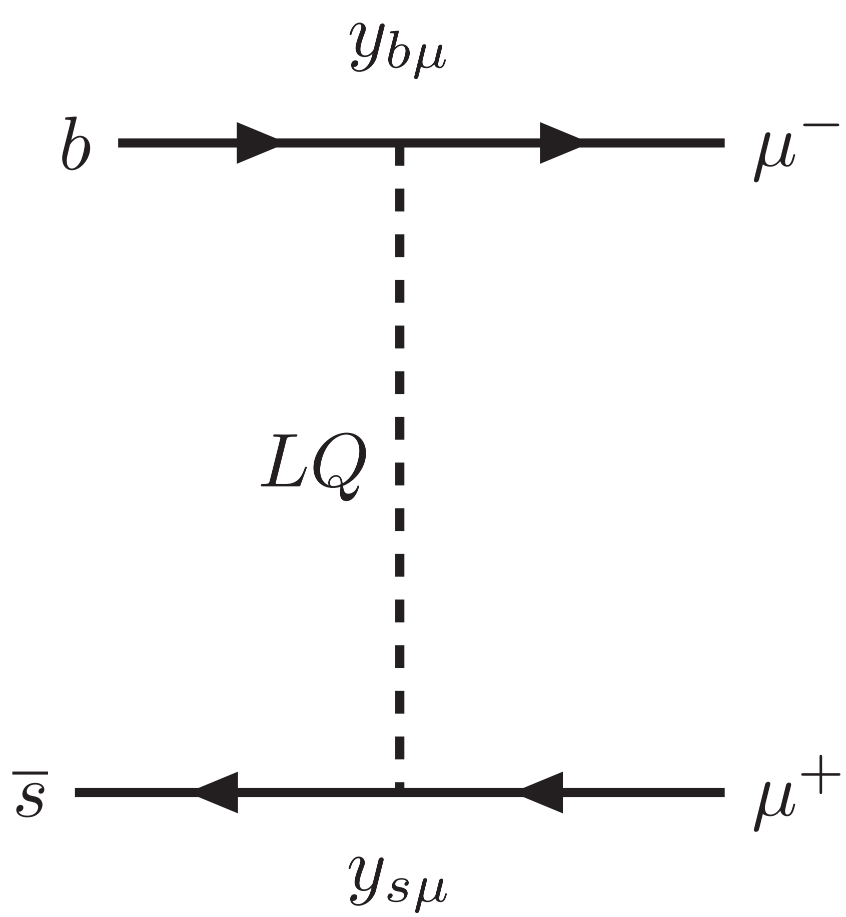
$\rightarrow$ only $q_L l_L$ couplings

$\rightarrow$ scalar LQ

$$\mathcal{L} = y_{lq} \bar{q}_L^c i\tau^2 \tau^a l_L S_3^a$$

$a = 1, 2, 3$
y_{lq} a 3×3 matrix
in flavour space.

Leptoquarks as solutions to the neutral current B anomalies

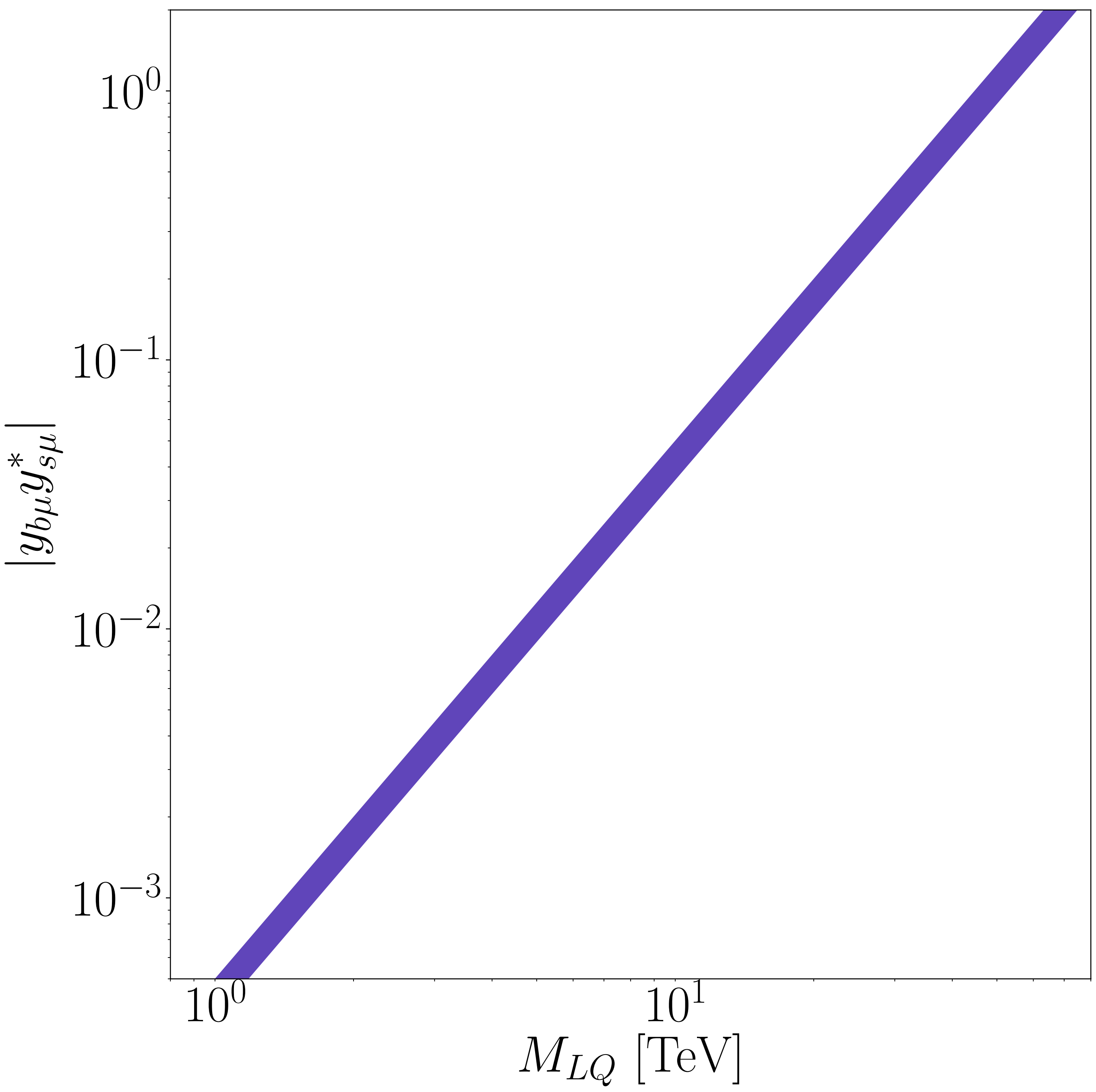


$$y_{b\mu} y^*_{s\mu} = \frac{C_{LL} V_{tb} V^*_{ts} \alpha_{\mathrm{EM}}}{2\pi v^2} m^2_{\mathrm{LQ}}$$

Central question

If LQs exist **and are responsible for these anomalies,** could we detect them at future hadron colliders?

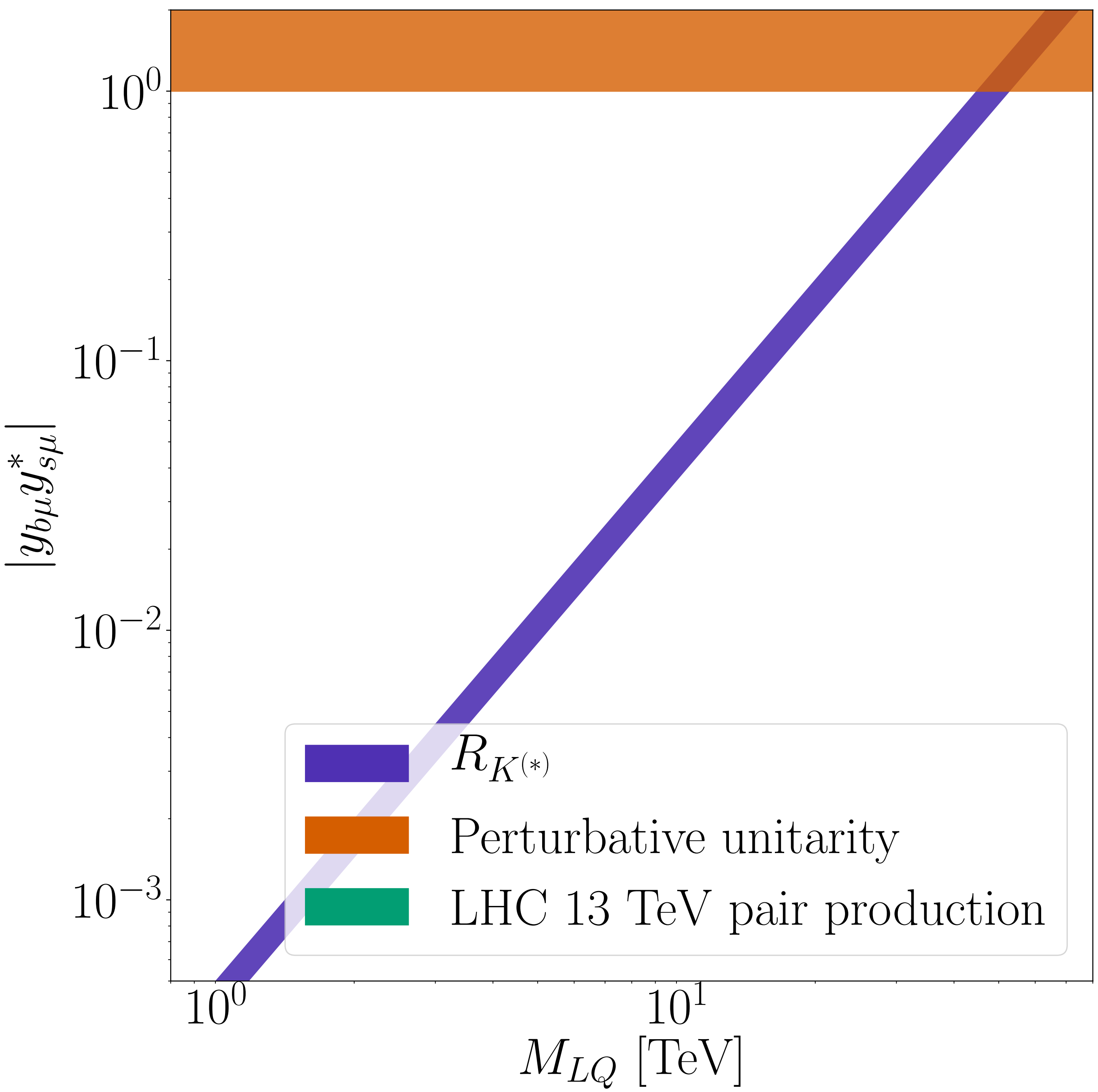
Leptoquark parameter space



Fits to the flavour anomalies require the couplings and mass to sit along this purple curve.

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

Constraints on leptoquarks



Constraints from:

LHC searches for LQ pair production

ATLAS:1906.08983 CMS:1808.05082

Perturbative unitarity

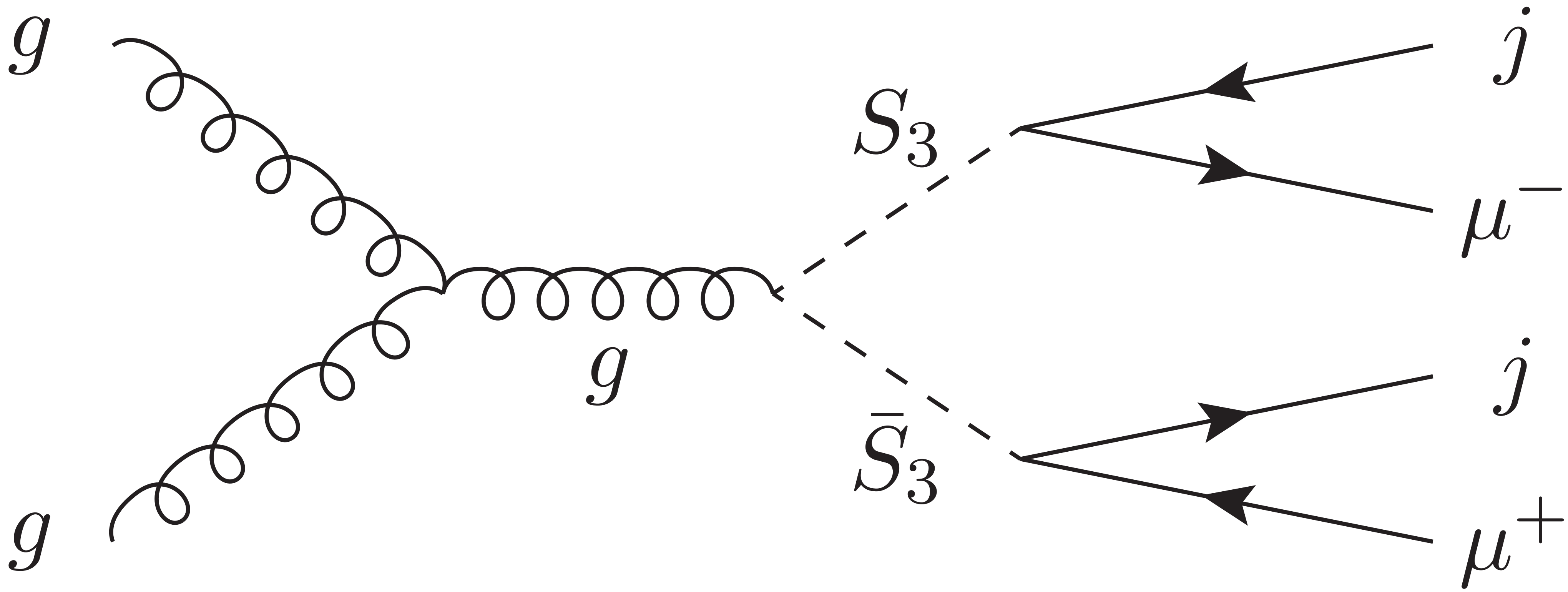
Neutral B meson mixing:

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

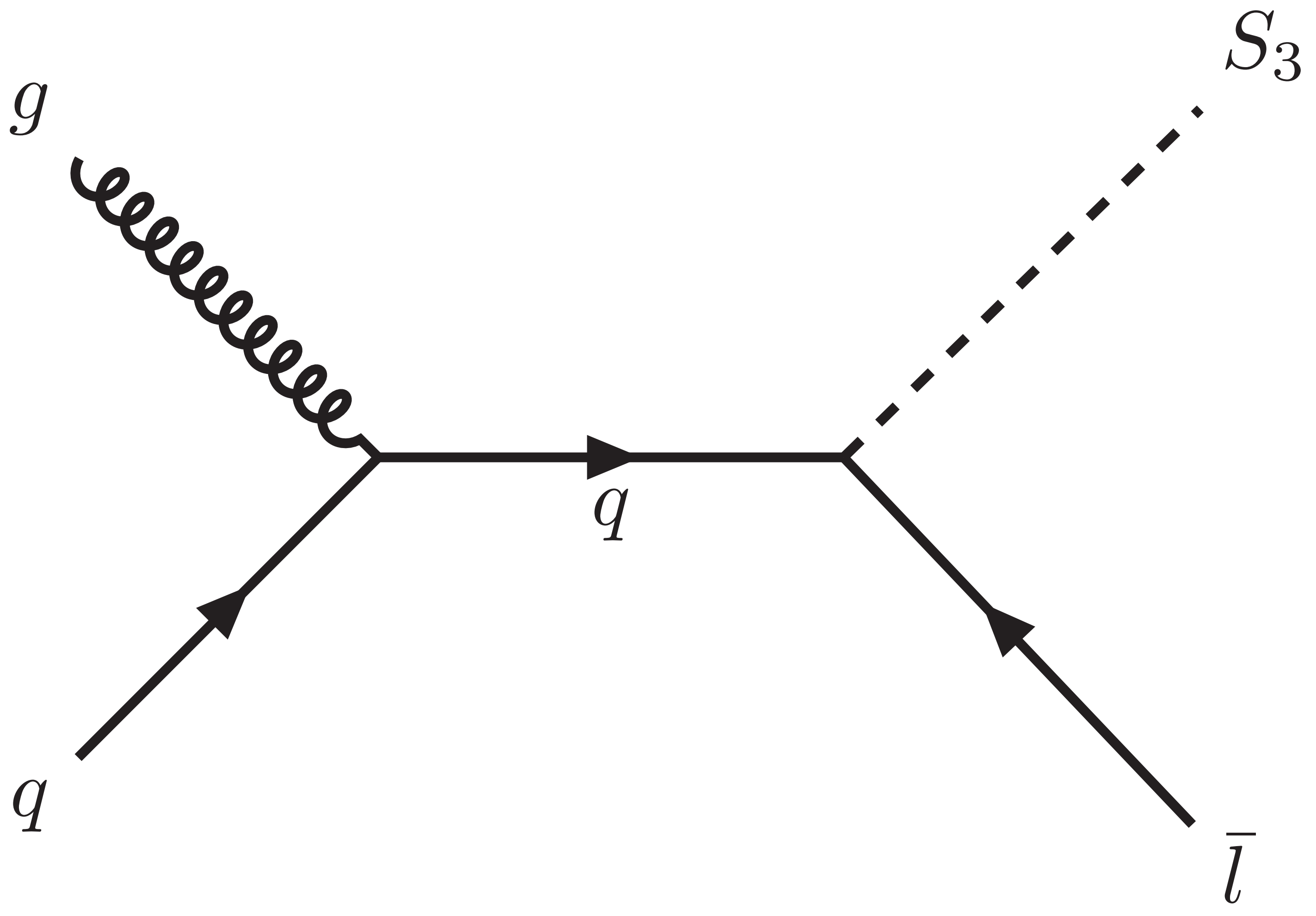
Luzioa, Kirk, Lenz, Rauh: 1909.11087

How far into this unconstrained parameter space can we expect future colliders to probe?

LQ search

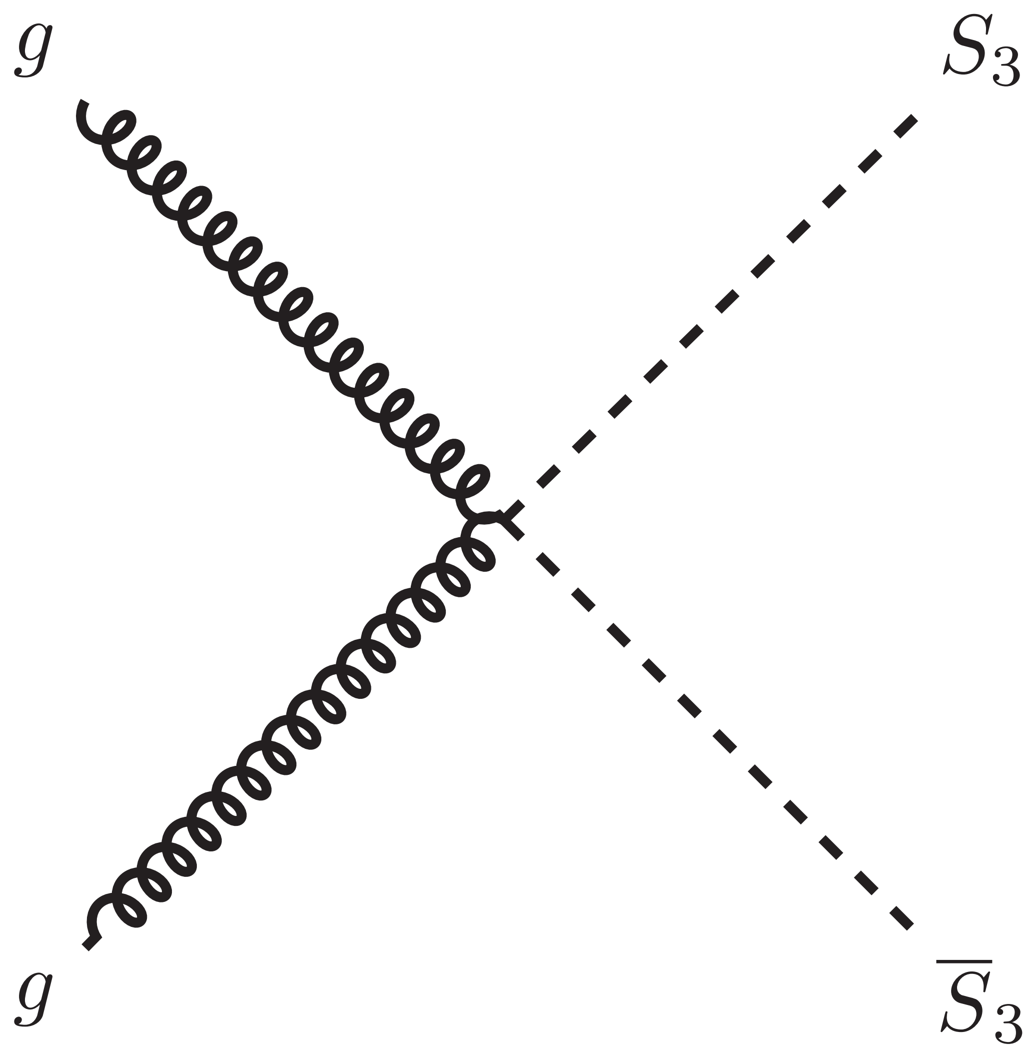


LQ production mechanisms



$$\sim y_{lq}$$

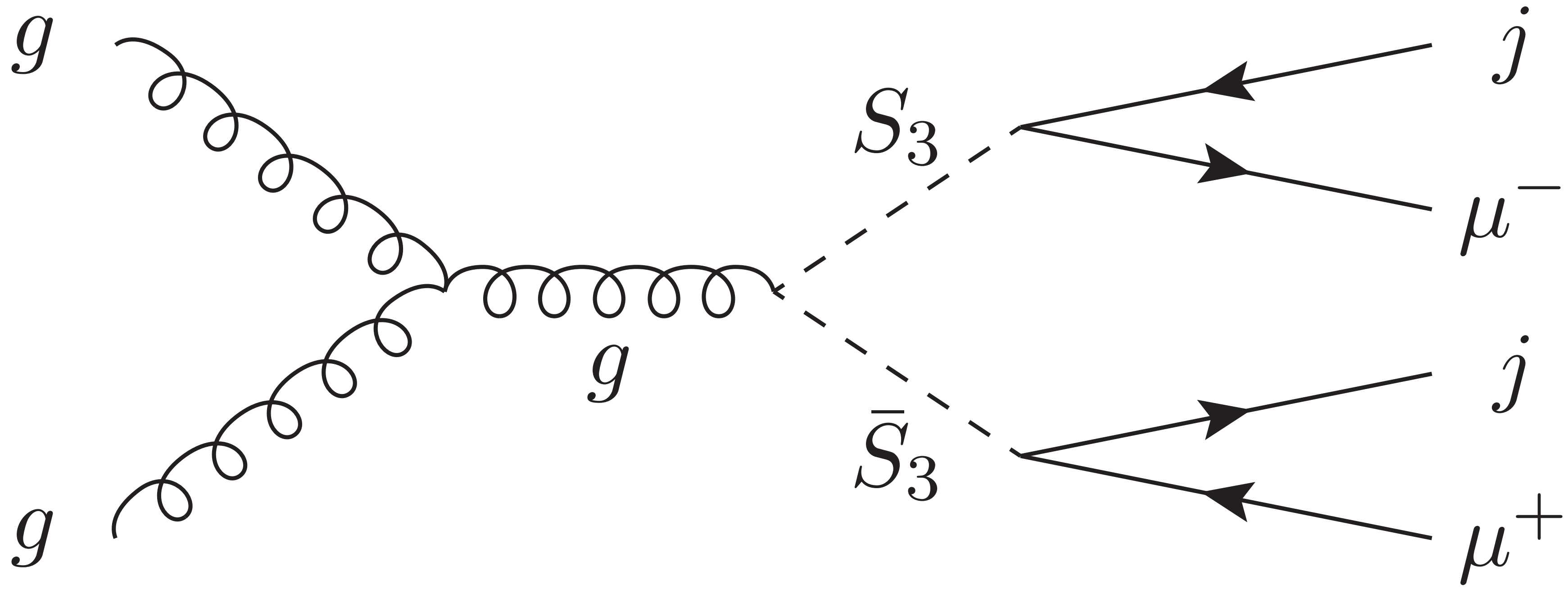
LQ production mechanisms



Independent of y_{lq}.

Dominant production mechanism for small couplings.

LQ decay channel



We select events containing: 2 muons

$\geq$ 2 jets

with no flavour tagging.

Methodology

Strategy

Sensitivity to a LQ signal is driven by the size of the SM background.

Strategy

Produce a detector-level simulation of the standard model background:

- `Madgraph5` at LO for matrix element event generation
- `Pythia8` for parton showering
- `Delphes3` for detector simulation

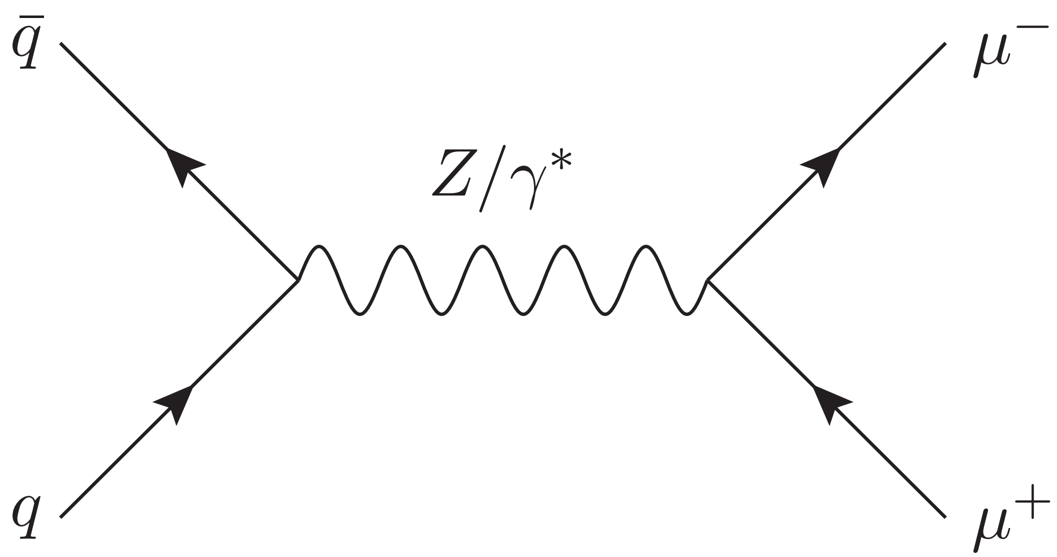
Compare with simulations of a leptoquark signal.

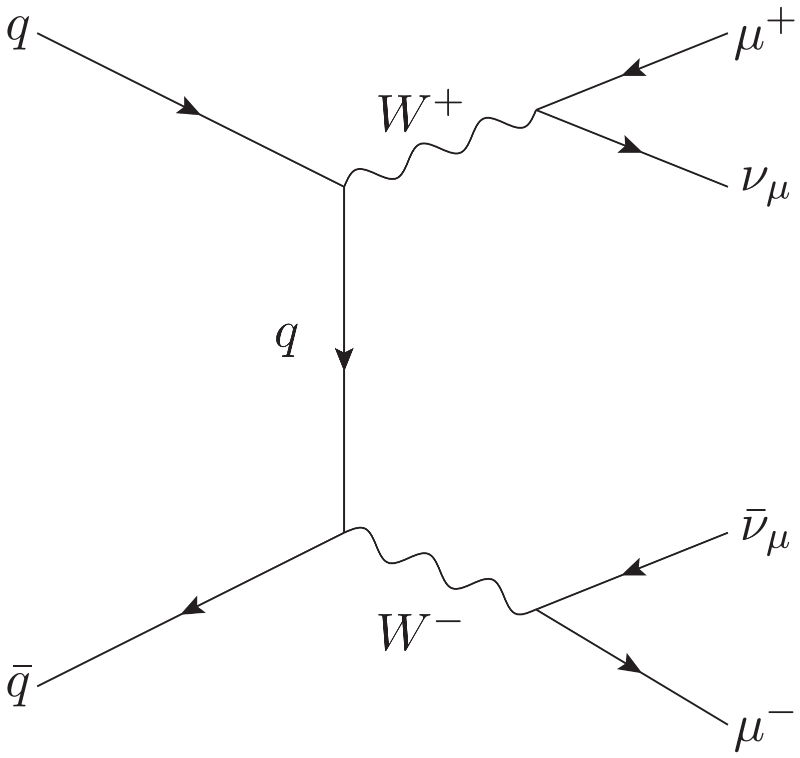
Determine the mass exclusion and the discovery potential.

Future colliders

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

SM Background





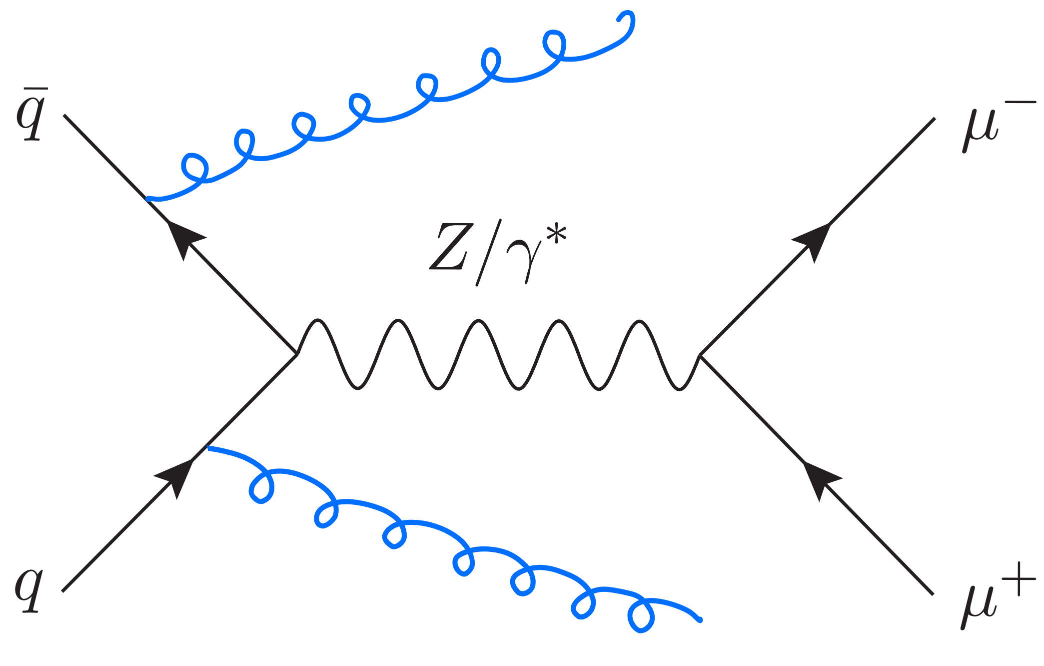
Drell-Yan

DY

Diboson

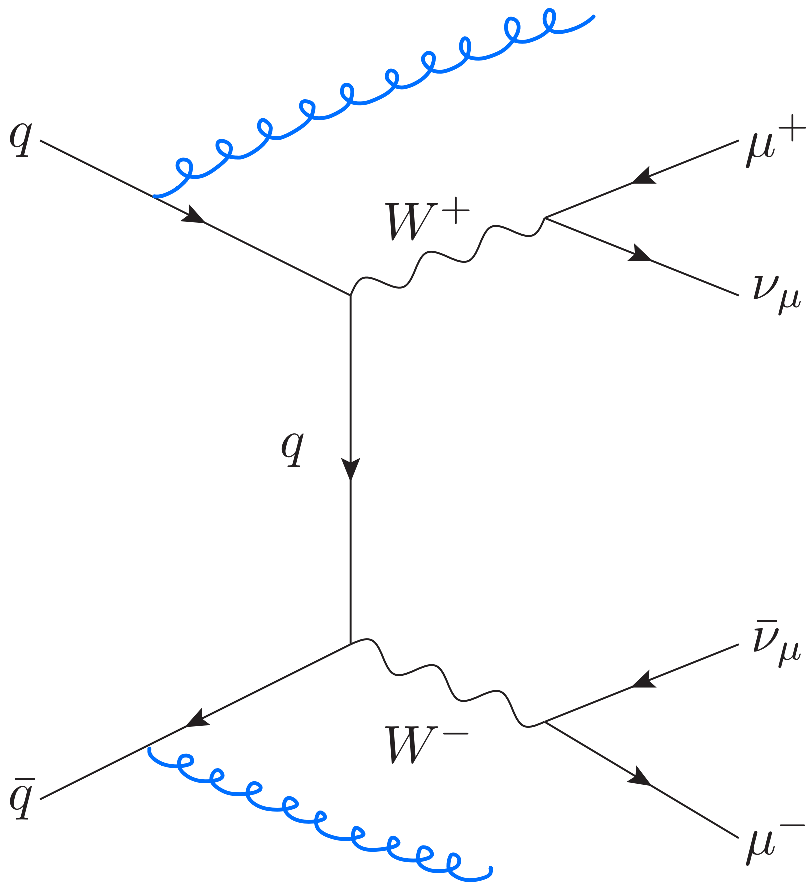
WW

SM Background



Drell-Yan + 2 jets

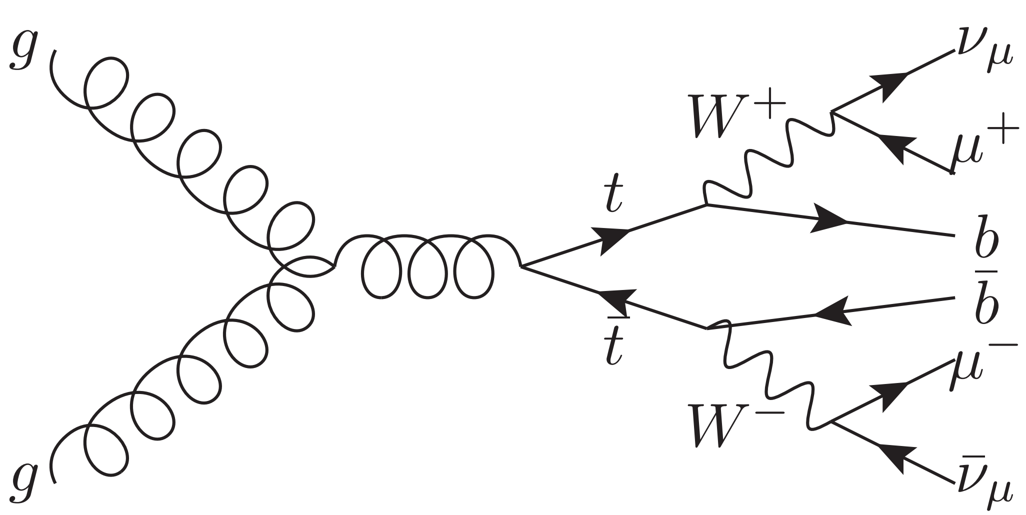
DY

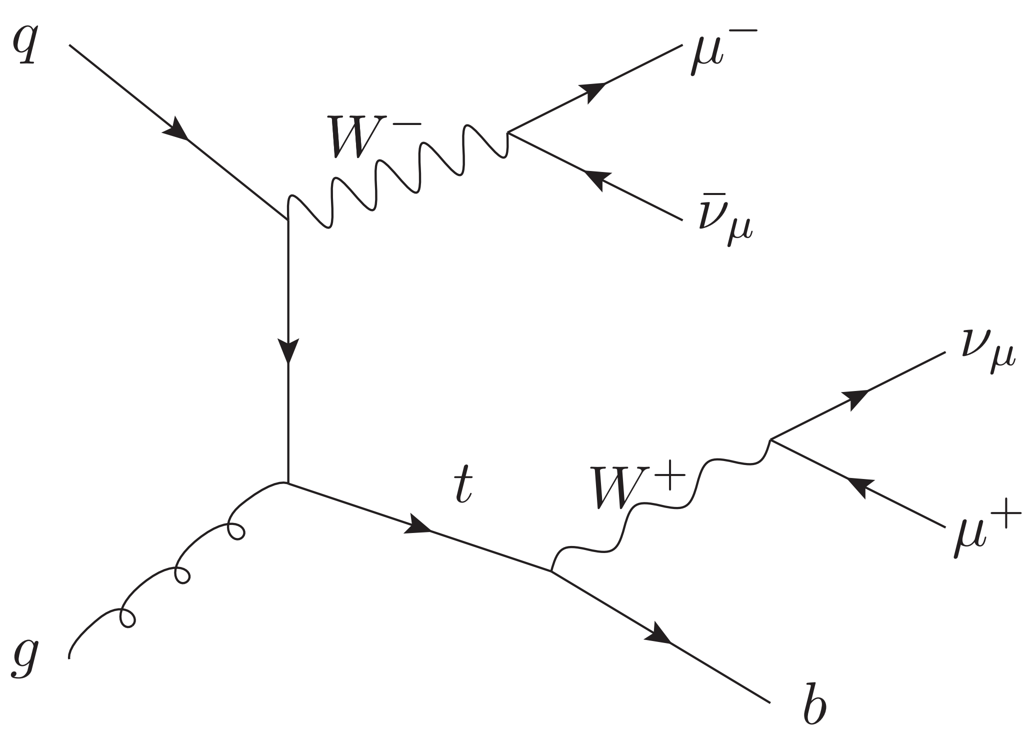


Diboson + 2 jets

WW

SM Background





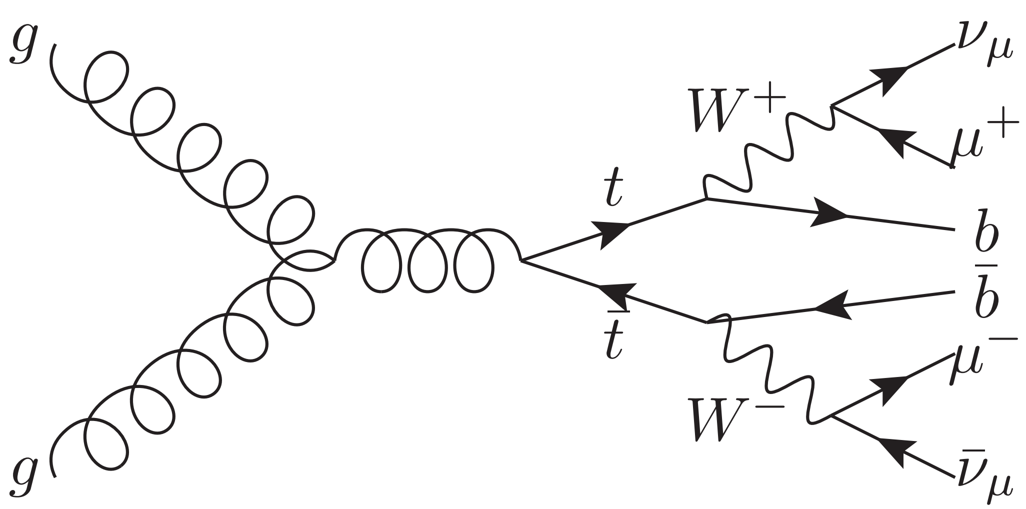
Top pair production

$t\bar{t}$

Single top

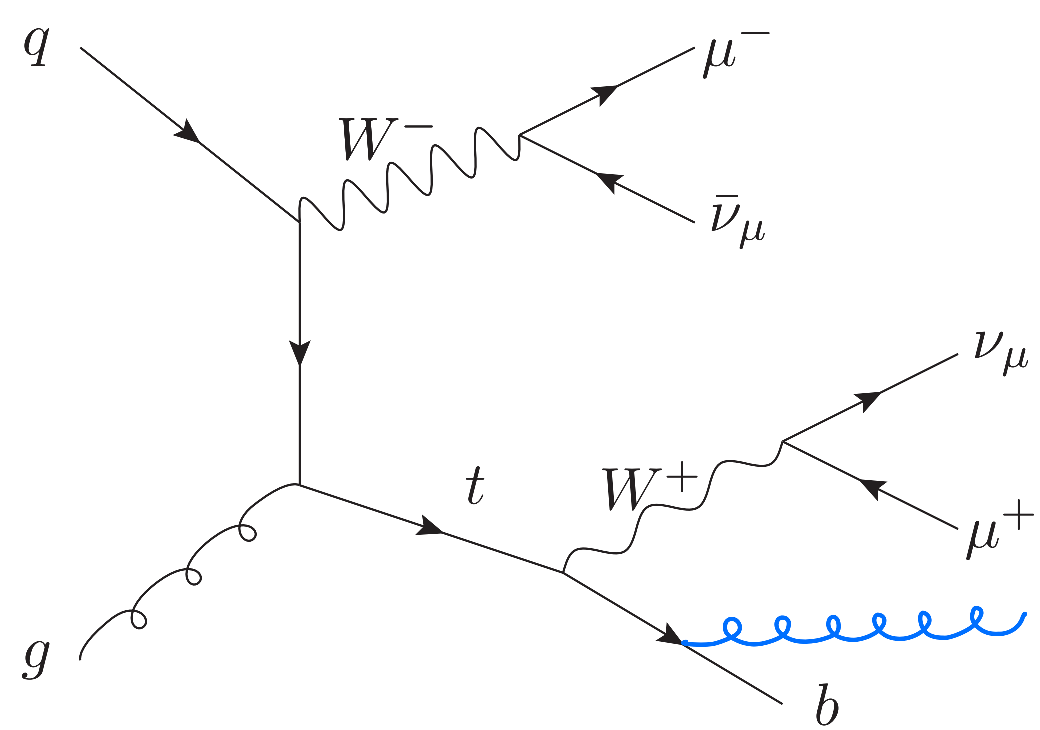
Wt

SM Background



Top pair production

$t\bar{t}$



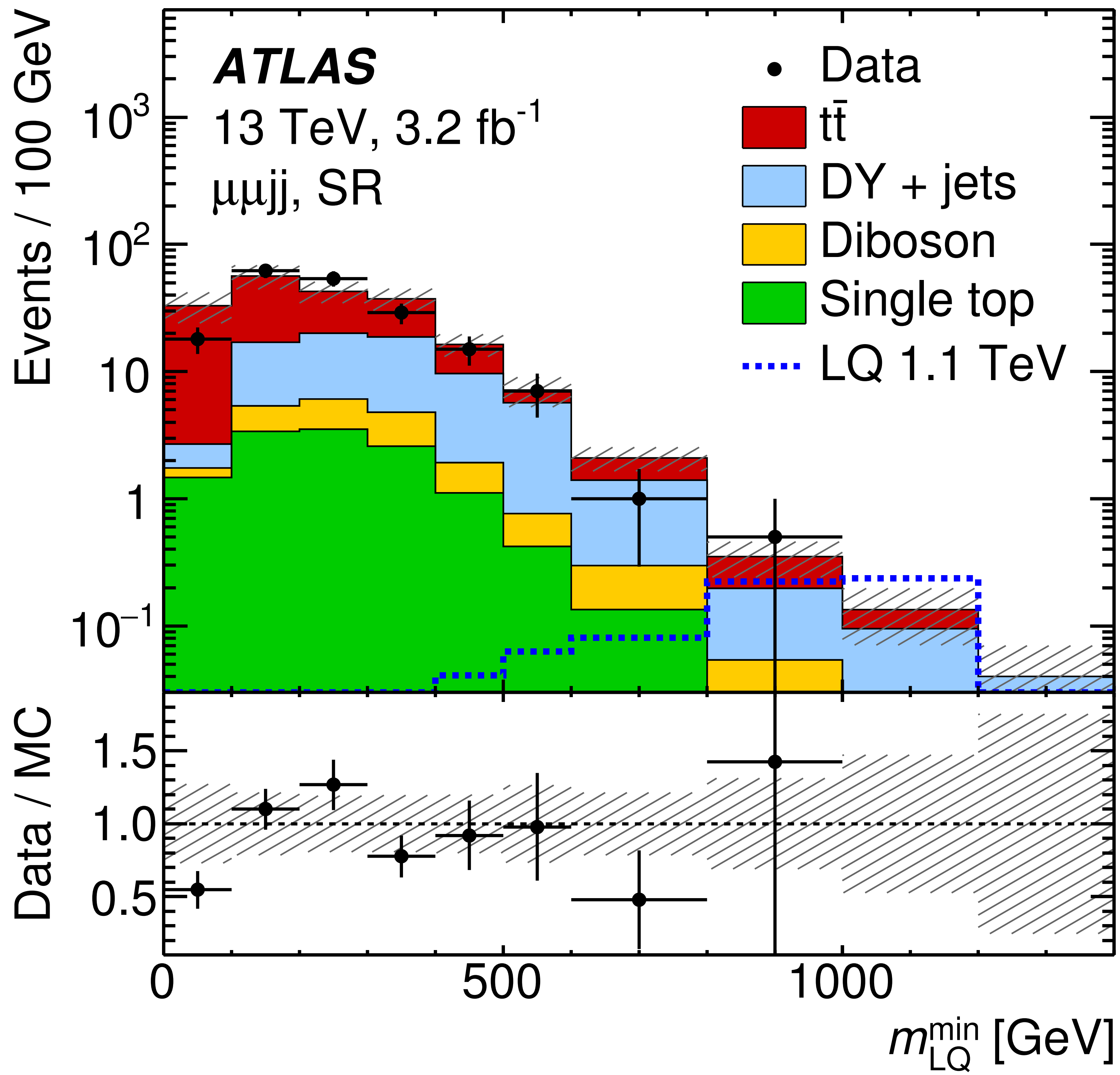
Single top + 1 jet

Wt

Simulations

ATLAS search for second generation leptoquarks.

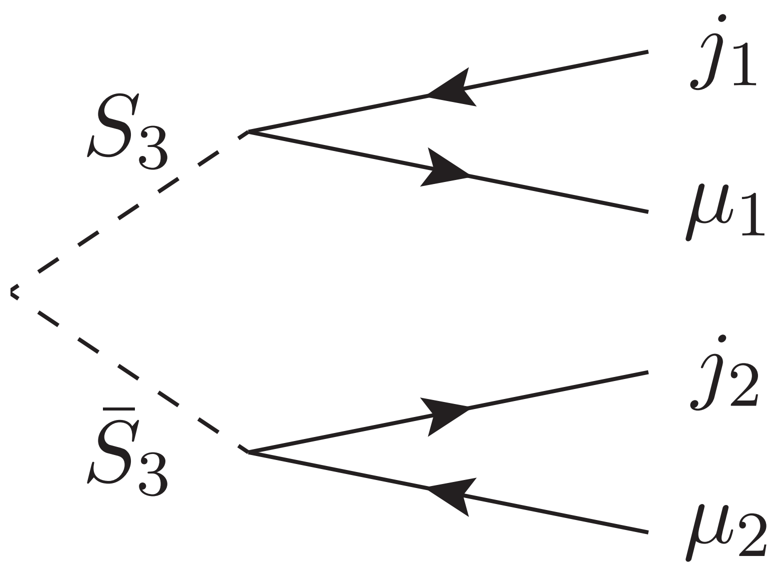
Use this to validate our simulation methods.



ATLAS Collaboration, M. Aaboud et. al., *Search for scalar leptoquarks in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS experiment*, New J. Phys. 18 (2016), no. 9 093016 [1605.06035]

LQ search

Model our search on ATLAS and CMS searches for 2nd generation leptoquarks.



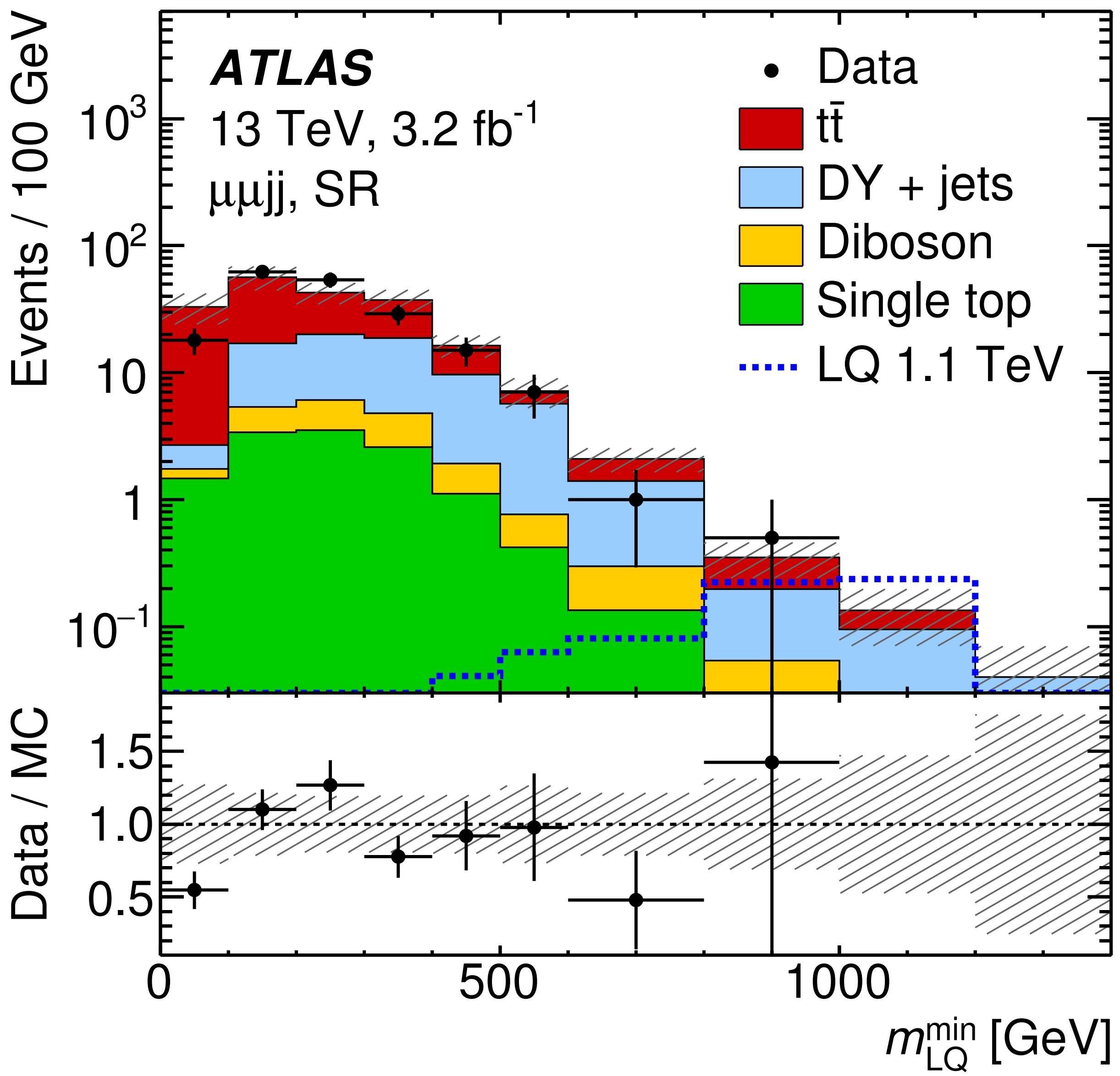
Minimise $|m(\mu_1, j_1) - m(\mu_2, j_2)|$

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

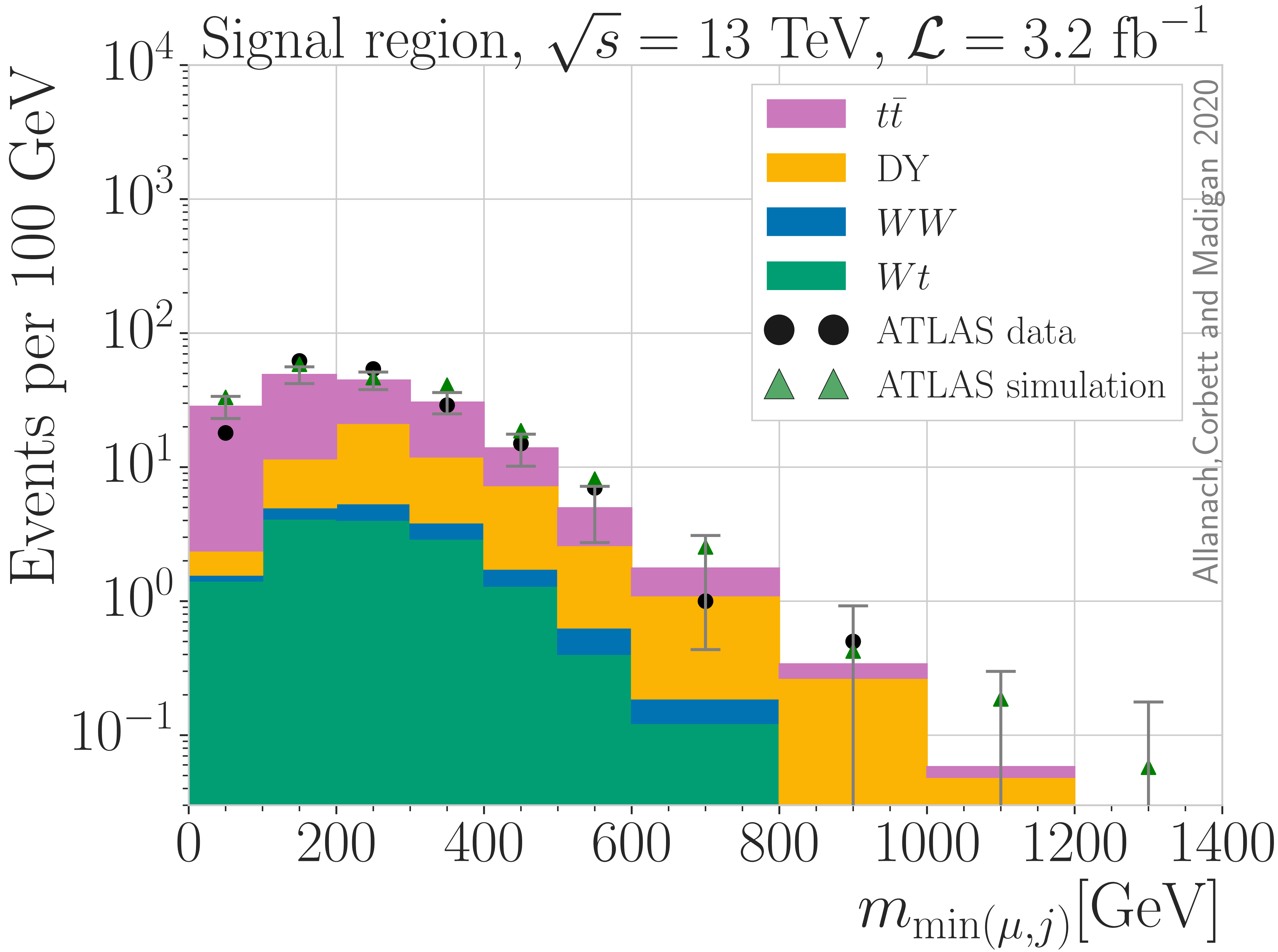
Search for a resonance in this LQ invariant mass distribution.

Simulation methods

- Match multijet samples using MLM matching
- Bias event generation to understand the shape of the tail
- Remove interference between SM processes

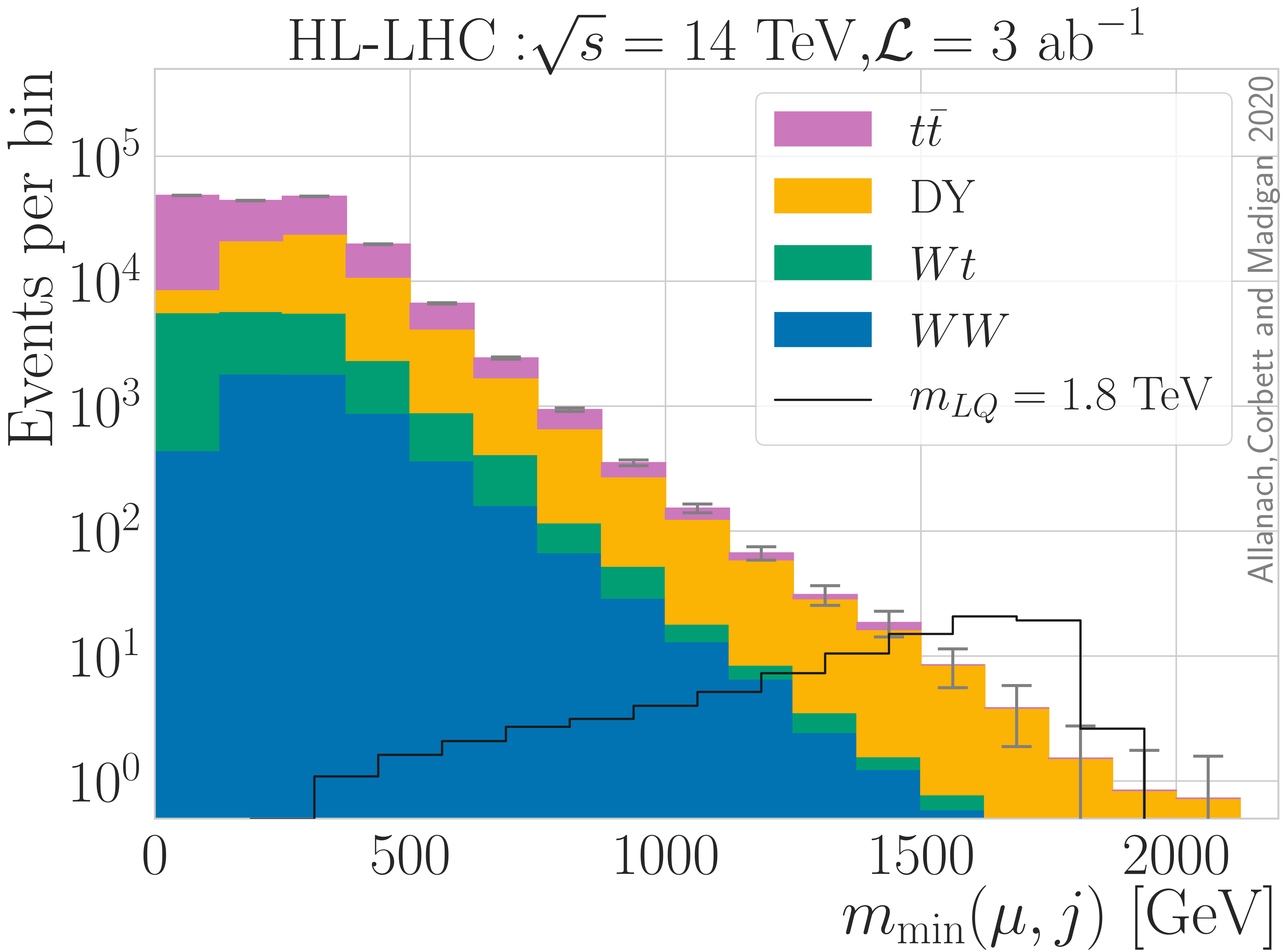


Validating simulation methods

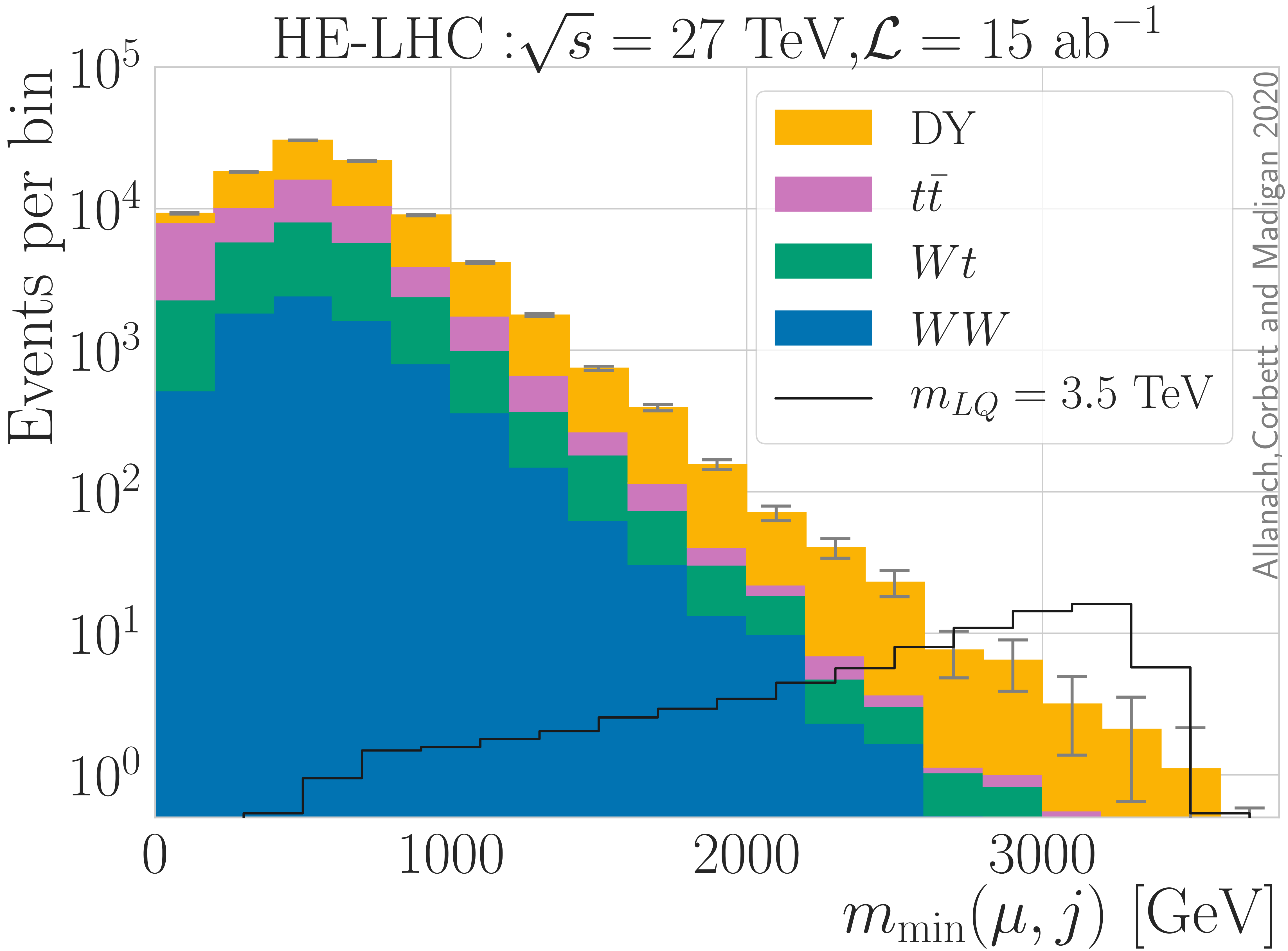


Future colliders

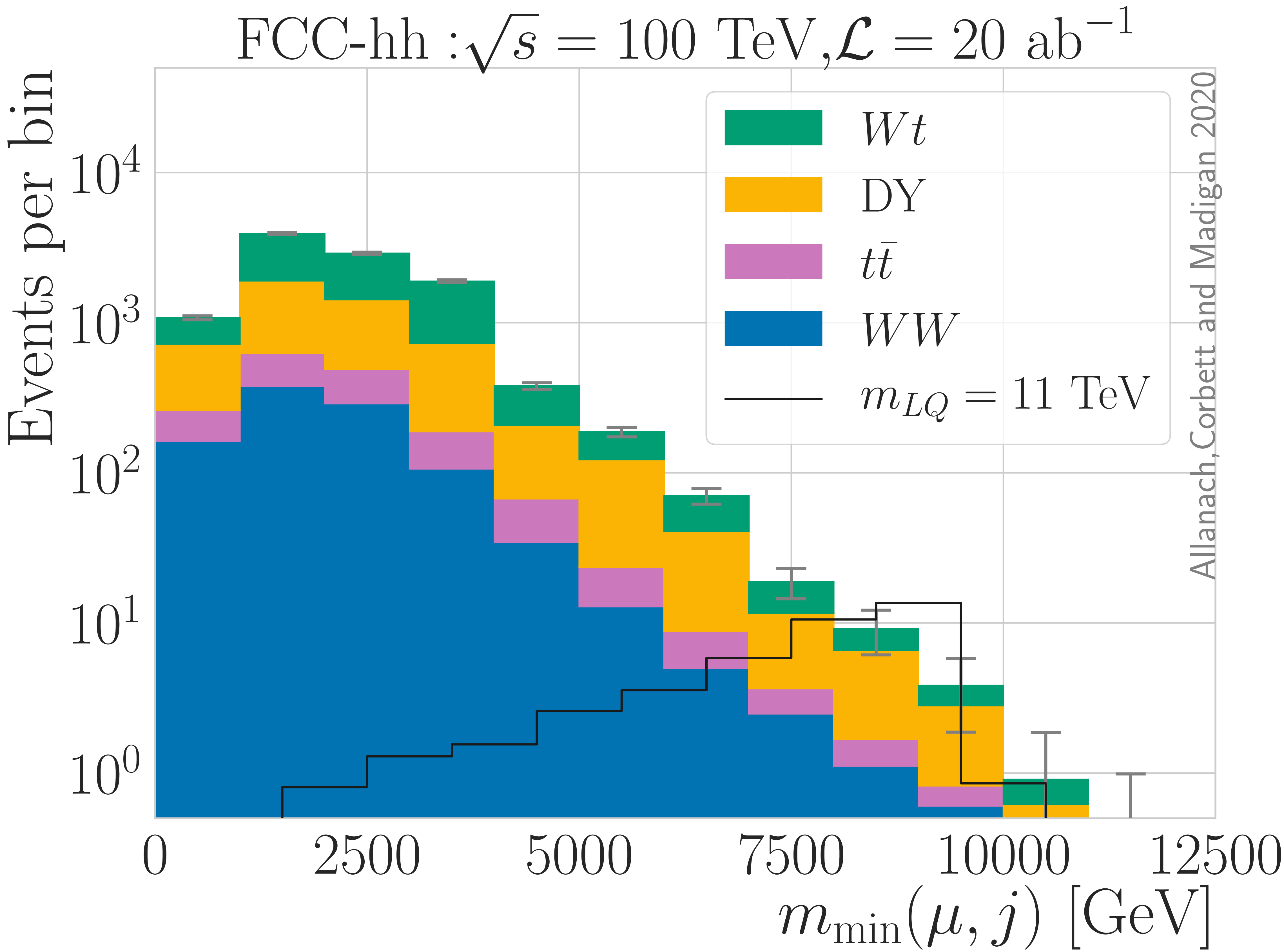
- Redefine the signal region:
  - scale up cuts on $p_T, M_{\mu\mu}, S_T$ by $\sqrt{s}/(13 \text{ TeV})$ to account for higher energies and heavier LQs.
  - modify cuts on $|\eta_j|, |\eta_\mu|$ at the HE-LHC and FCC-hh to account for differences in detectors.
- Redefine detector configuration in `Delphes3`.



HL-LHC : $\sqrt{s}$ = 14 TeV, $\mathcal{L}$ = 3 ab^{-1}
Events per bin
10^5
10^4
10^3
10^2
10^1
10^0
0
500
1000
1500
2000
$m_{\mathrm{min}}(\mu, j)$ [GeV]
$t\bar{t}$
DY
Wt
WW
m_{LQ} = 1.8 TeV
Allanach, Corbett and Madigan 2020



HE-LHC : $\sqrt{s}$ = 27 TeV, $\mathcal{L}$ = 15 ab^{-1}
Events per bin
10^5
10^4
10^3
10^2
10^1
10^0
DY
$t\bar{t}$
Wt
WW
m_{LQ} = 3.5 TeV
Allanach,Corbett and Madigan 2020
0
1000
2000
3000
$m_{\min}(\mu, j)$ [GeV]



FCC-hh : $\sqrt{s}$ = 100 TeV, $\mathcal{L}$ = 20 ab^{-1}
Events per bin
10^4
10^3
10^2
10^1
10^0
Wt
DY
$t\bar{t}$
WW
m_{LQ} = 11 TeV
Allanach, Corbett and Madigan 2020
0
2500
5000
7500
10000
12500
$m_{\min}(\mu, j)$ [GeV]

Signal simulations

Recall:

$$y_{b\mu} y^*_{s\mu} = \frac{C_{LL} V_{tb} V^*_{ts} \alpha_{\text{EM}}}{2\pi v^2} m^2_{\text{LQ}} \qquad C_{LL} = -0.53^{+0.08}_{-0.09}$$

We switch on $y_{b\mu} = y_{s\mu}$ and set all other couplings to zero.

Signal simulations

Recall:

$$y_{b\mu} y_{s\mu}^* = \frac{C_{LL} V_{tb} V_{ts}^* \alpha_{\rm EM}}{2\pi v^2} m_{\rm LQ}^2 \qquad C_{LL} = -0.53^{+0.08}_{-0.09}$$

We switch on $y_{b\mu} = y_{s\mu}$ and set all other couplings to zero.

Unequal $y_{b\mu}, y_{s\mu}$ will lead to a similar signatures as we are not b-tagging the jets.

Switching on other couplings will increase the possible decay channels and options for LQ discovery.

Sensitivity

Sensitivity

We quantify sensitivity of a future collider by asking two questions:

Exclusion limits

What LQ masses can we exclude?

$$95\% \text{ CL}$$

$$p = 0.05$$

Discovery potential

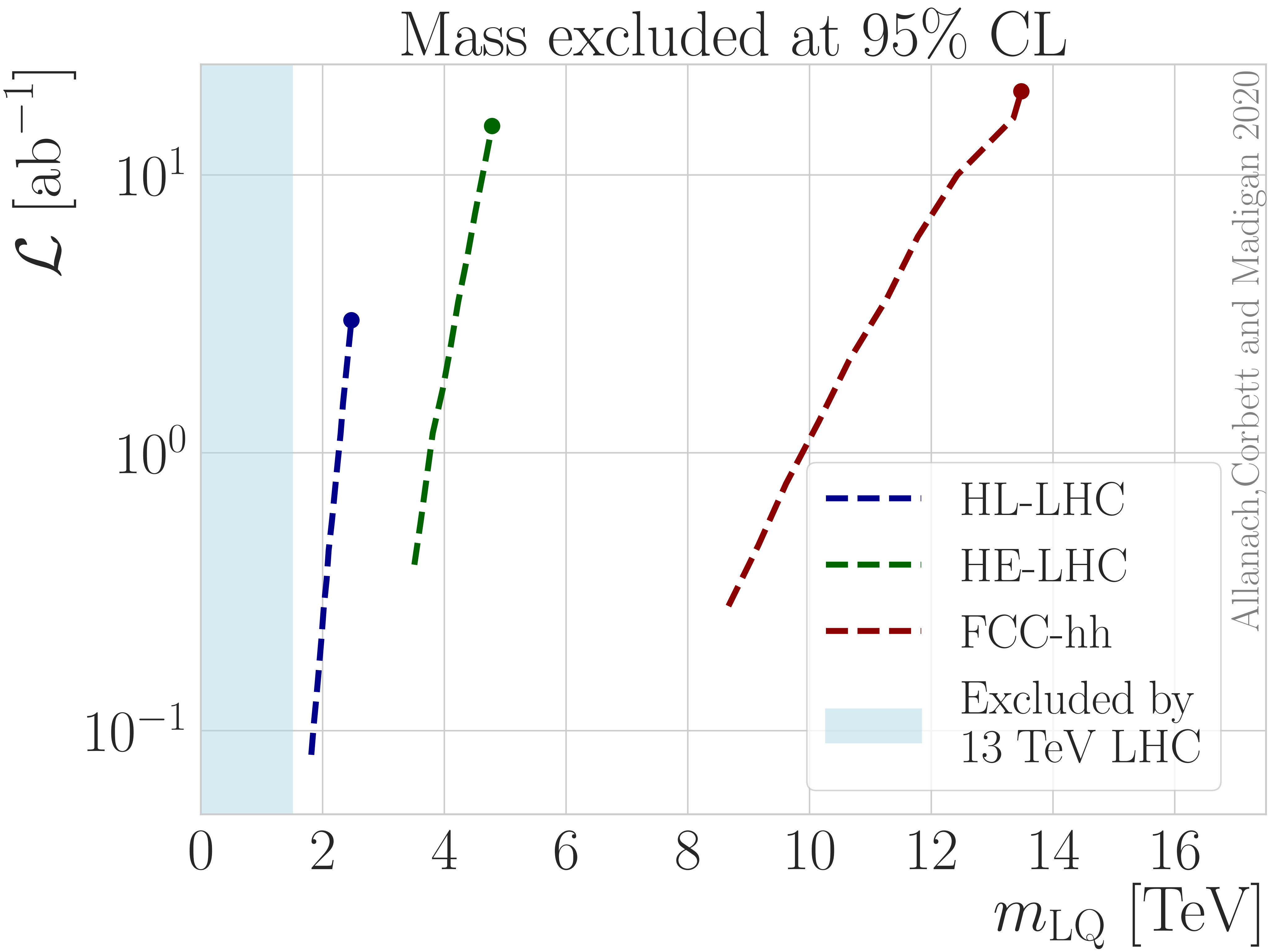
What LQ masses can we discover?

$$Z = 5\sigma$$

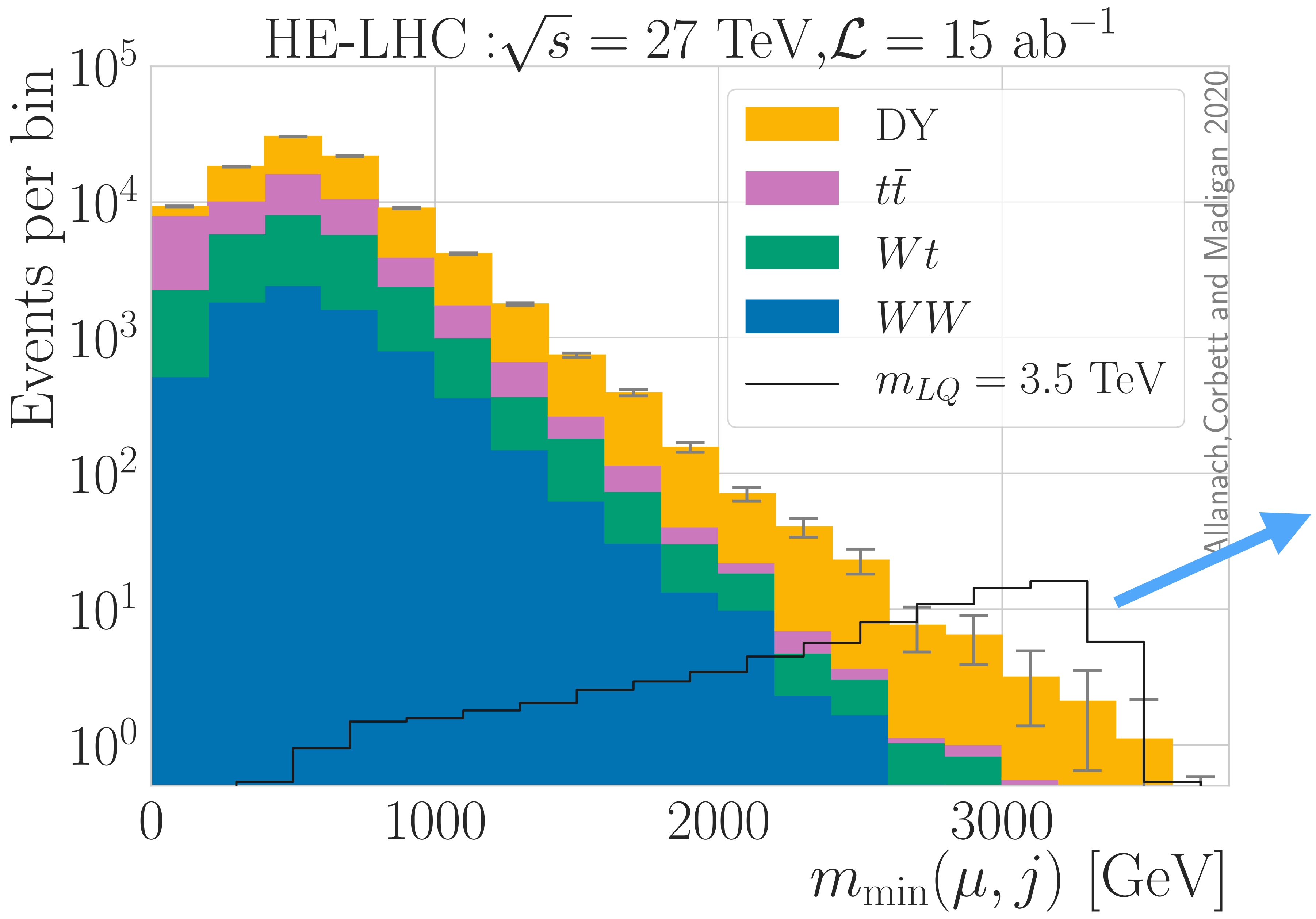
$$p = 2.9 \times 10^{-7}$$

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

Exclusion limits: combined projections

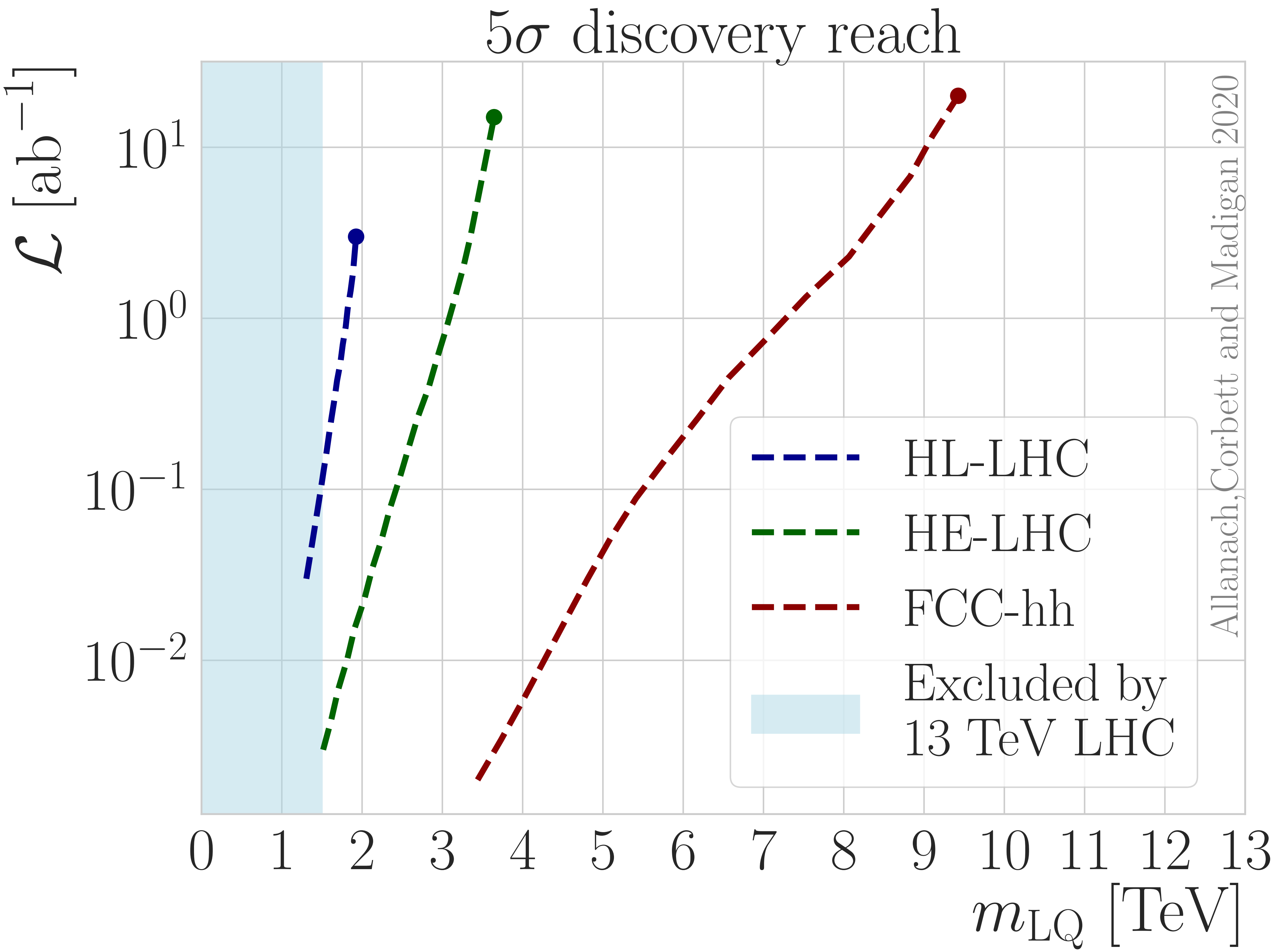


Discovery potential

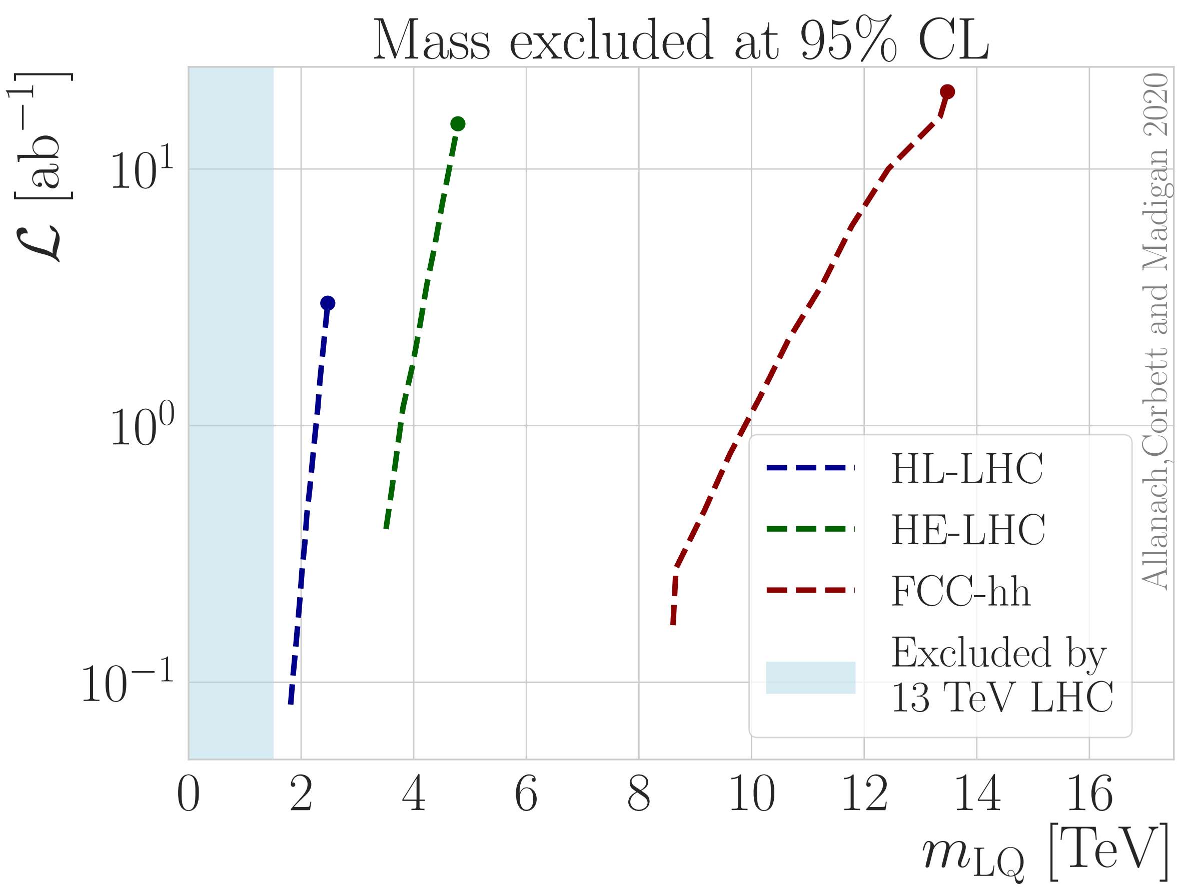


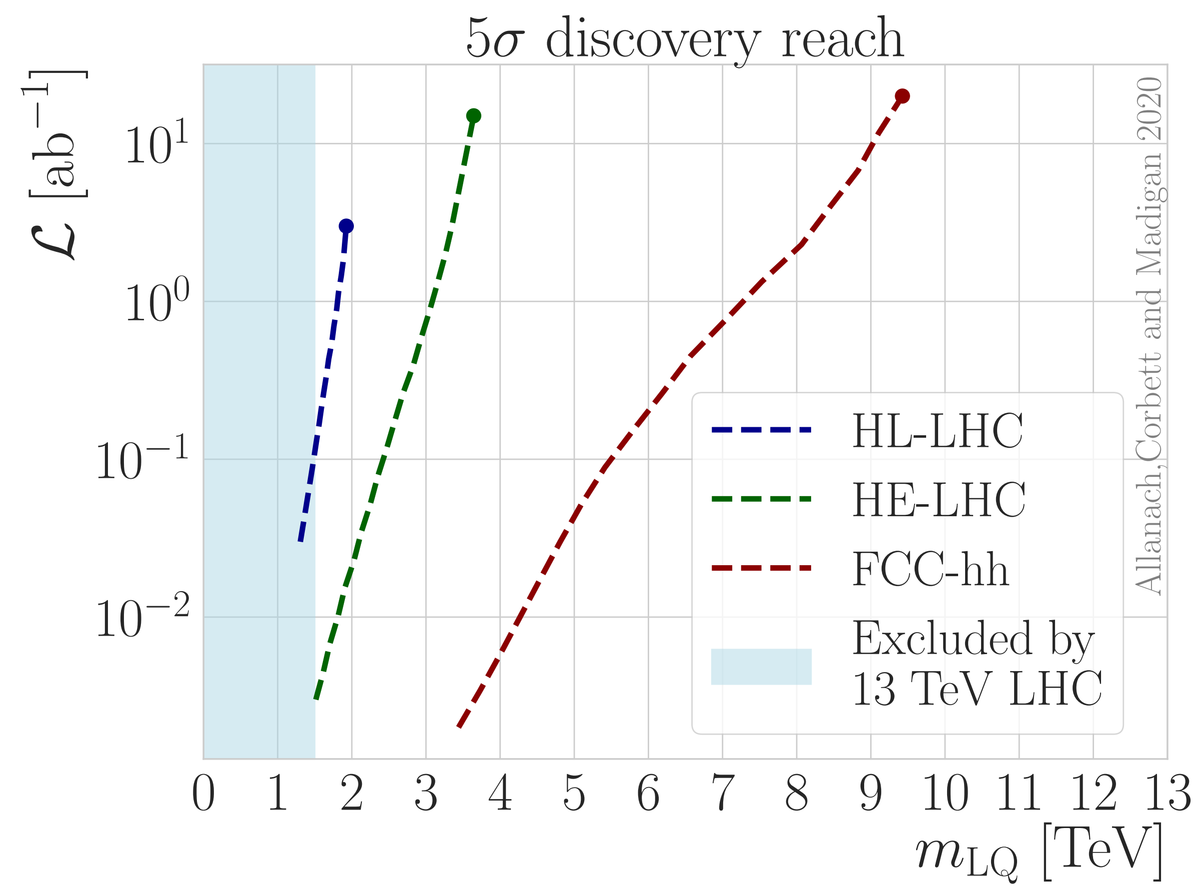
At the HE-LHC, a LQ of mass $m_{\rm LQ} = 3.5$ TeV produces a signal with a significance of 6σ

Discovery potential: combined



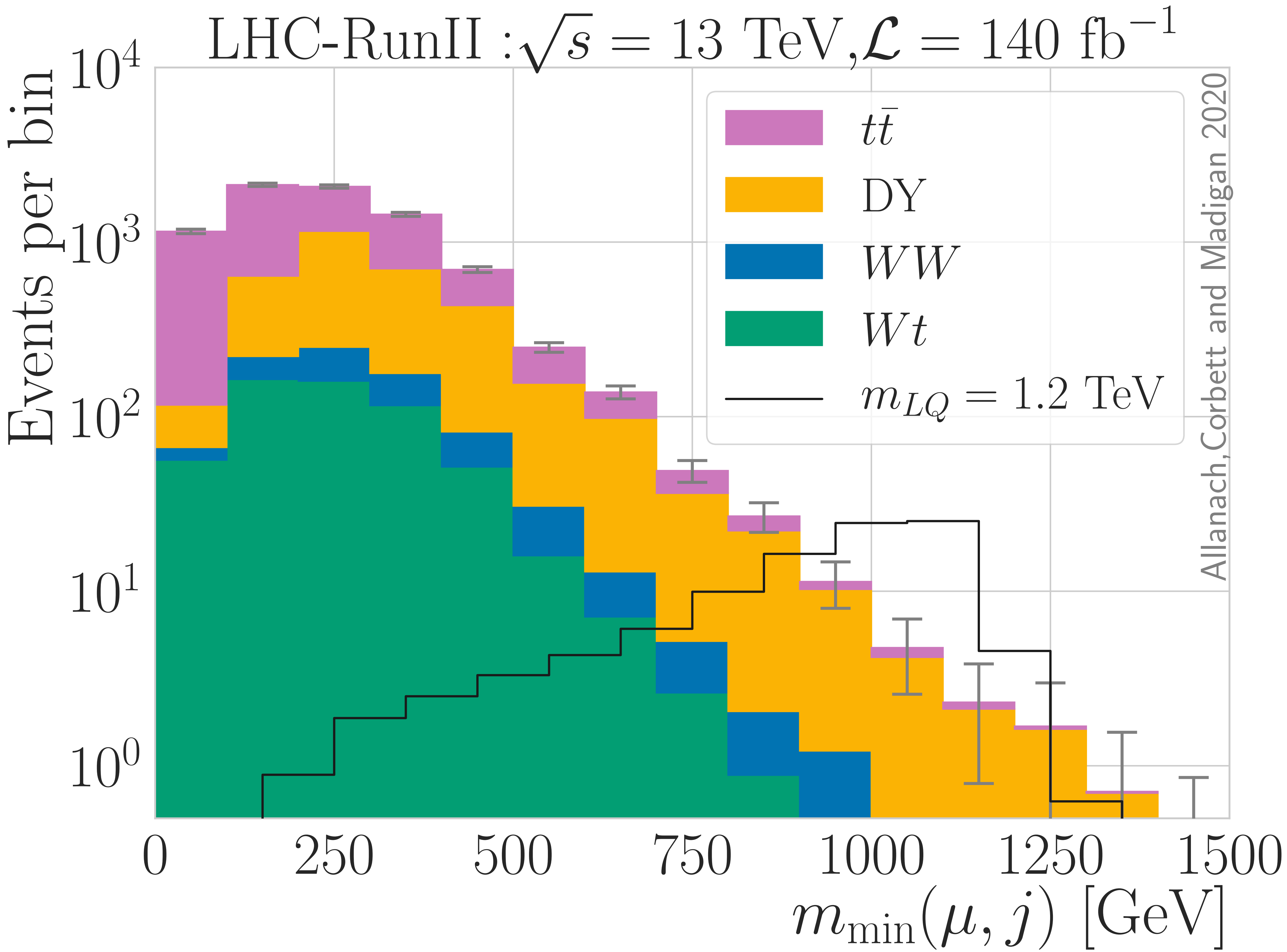
Conclusions





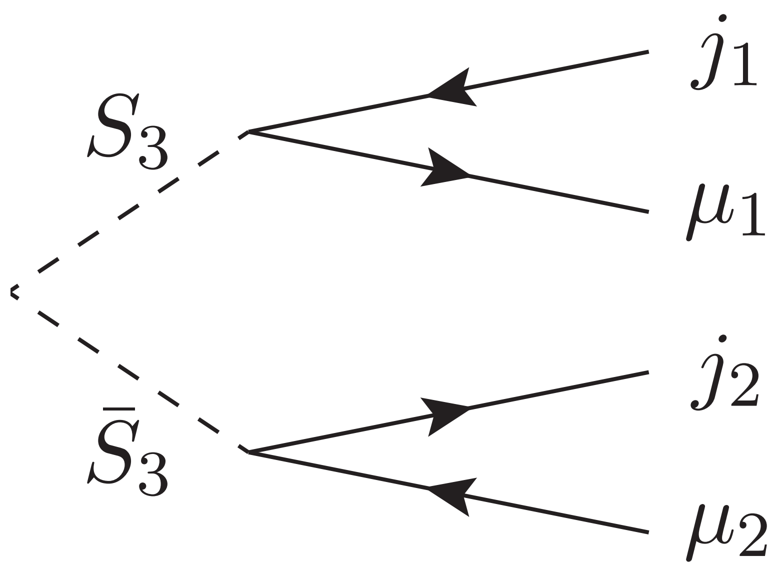
- Estimated the sensitivity of future colliders to LQ solutions to the neutral current B anomalies.

Backup slides


LHC-RunII : $\sqrt{s}$ = 13 TeV, $\mathcal{L}$ = 140 fb^{-1}
Events per bin
10^4
10^3
10^2
10^1
10^0
$t\bar{t}$
DY
WW
Wt
m_{LQ} = 1.2 TeV
Allanach, Corbett and Madigan 2020
0
250
500
750
1000
1250
1500
$m_{\min}(\mu, j)$ [GeV]

LQ search

Model our search on ATLAS and CMS searches for 2nd generation leptoquarks.



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

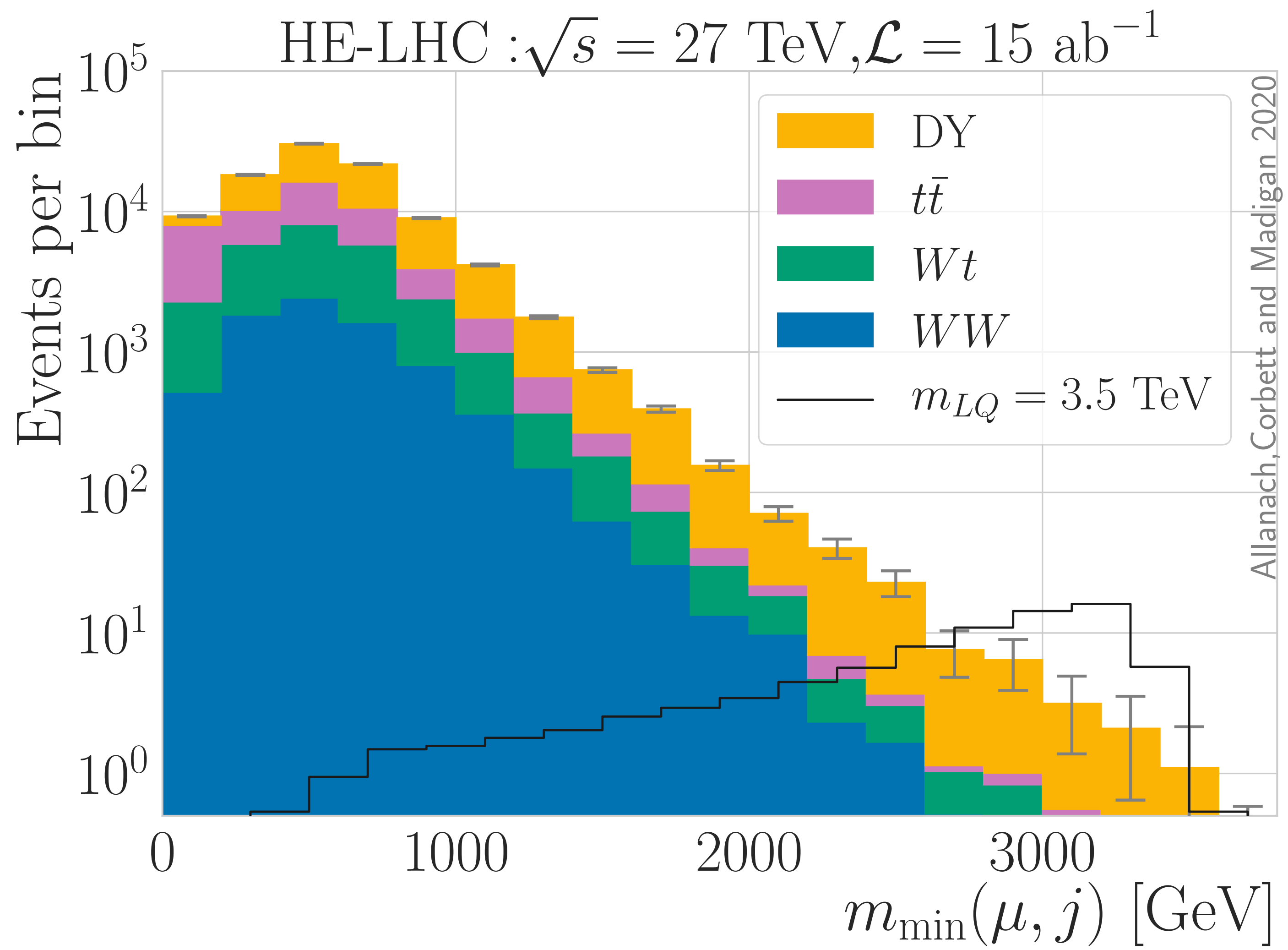
Define: $m_{\min}(\mu, j) = \min[m(\mu_1, j_1), m(\mu_2, j_2)]$

Search for a resonance in this LQ invariant mass distribution.

Signal simulations

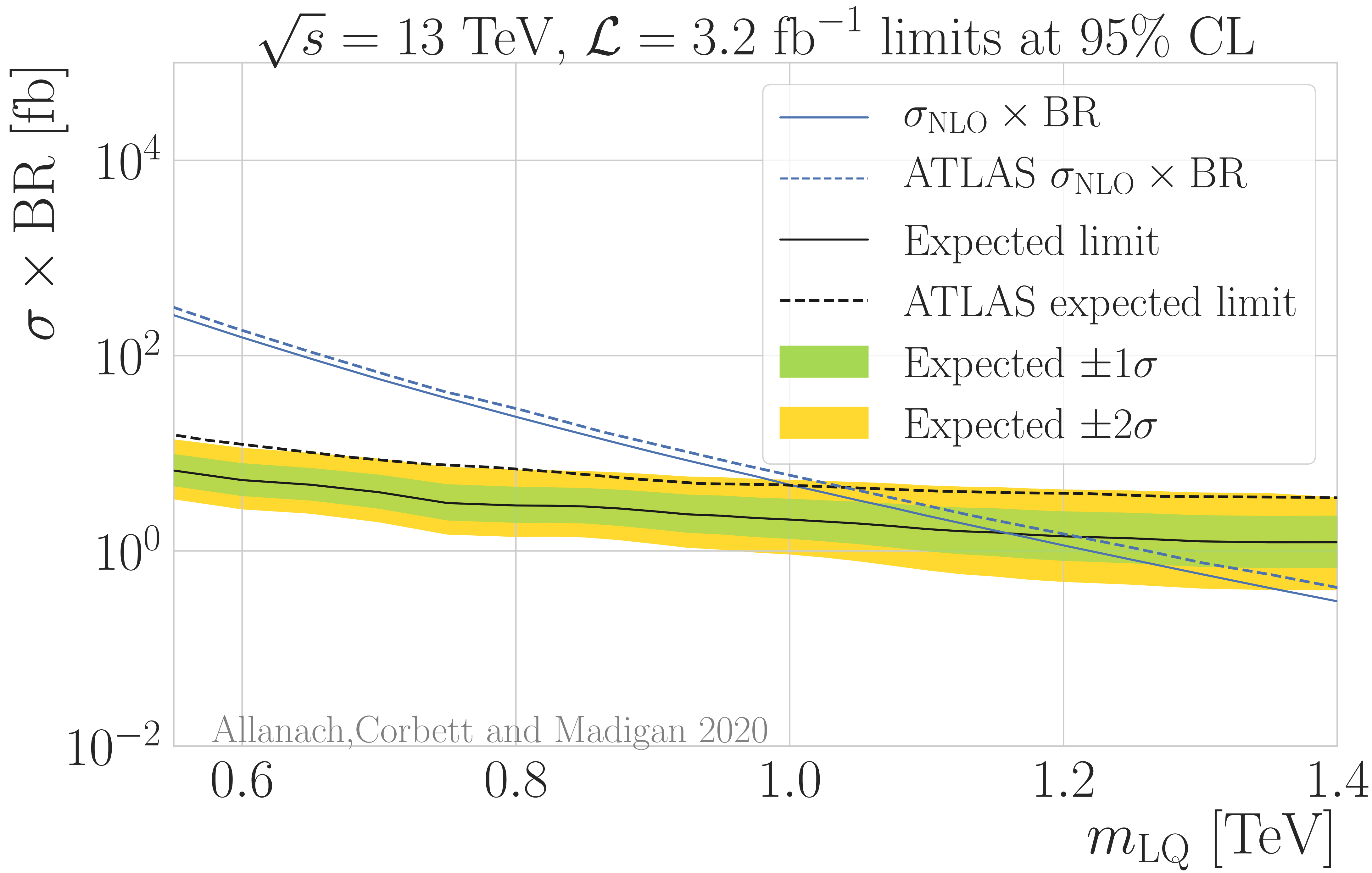
Spread of LQ events is due to:

- momentum lost during parton showering
- smearing due to detector efficiency and mismeasurement



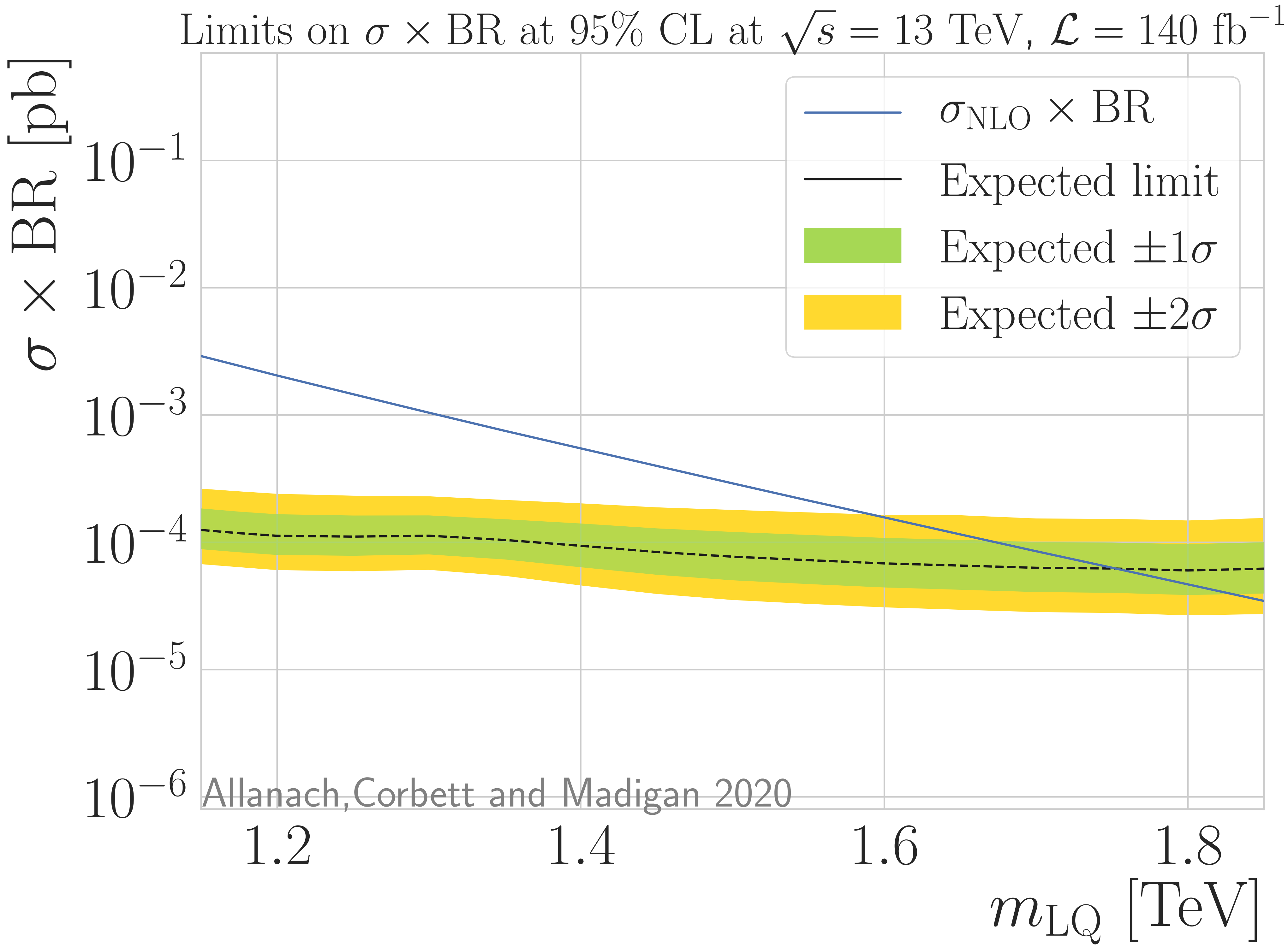
This shape is determined by the **resolution**. Any narrow width LQ would produce the same shape.

Exclusion limits: validating our methods

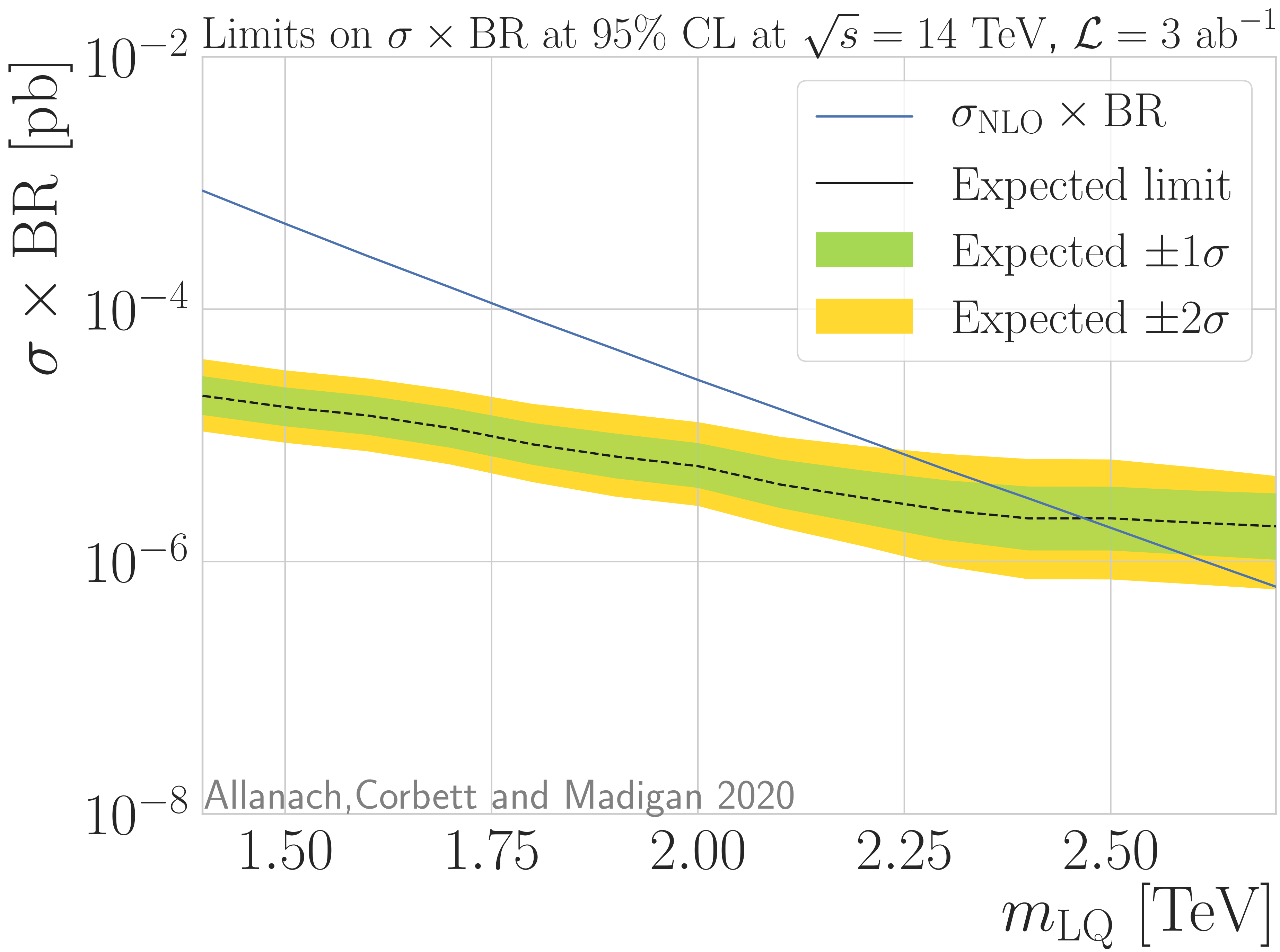


Excludes LQ masses up to $m_{\mathrm{LQ}} \approx 1.15$ TeV

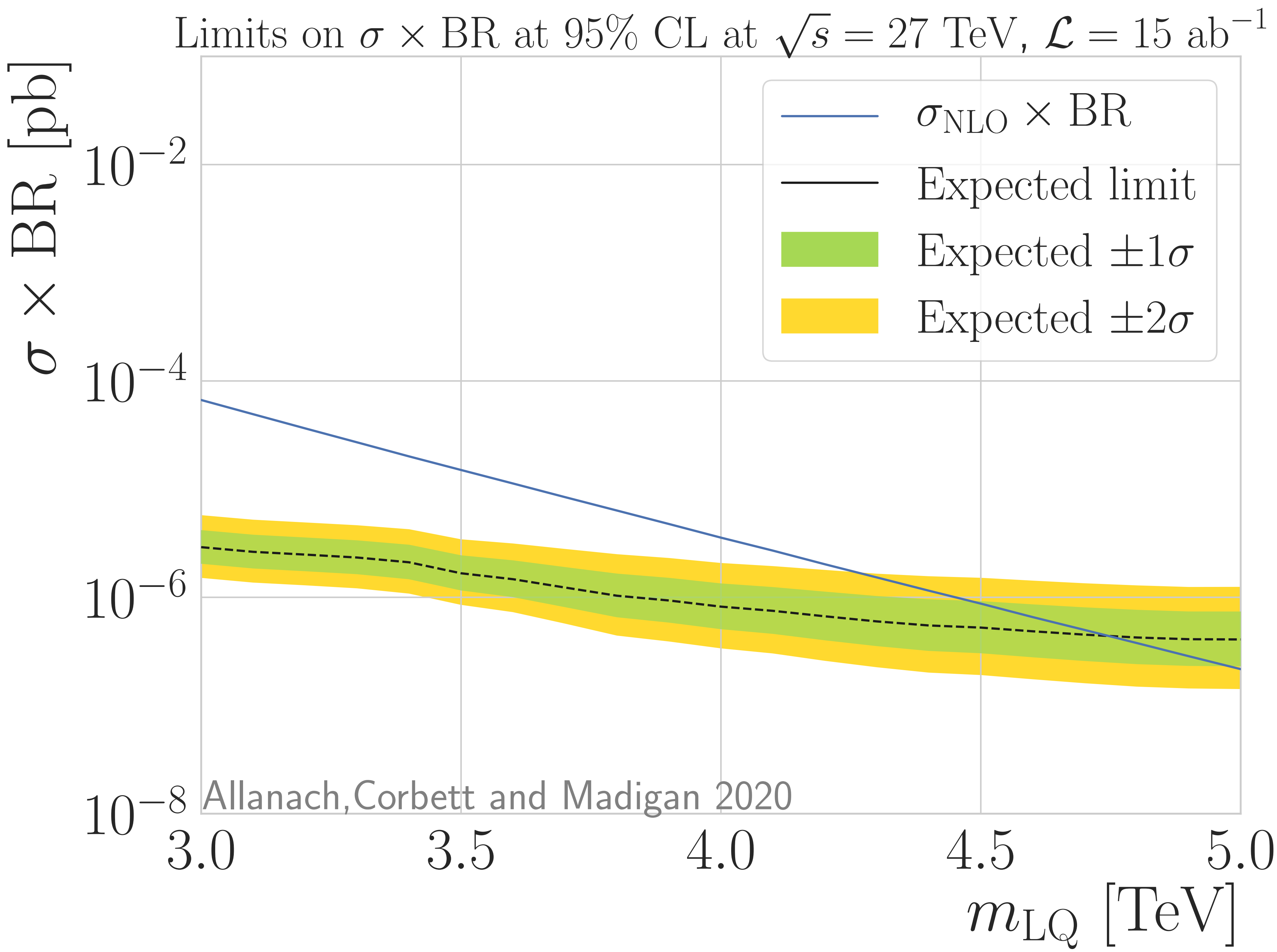
Exclusion limits: Projections for LHC Run II



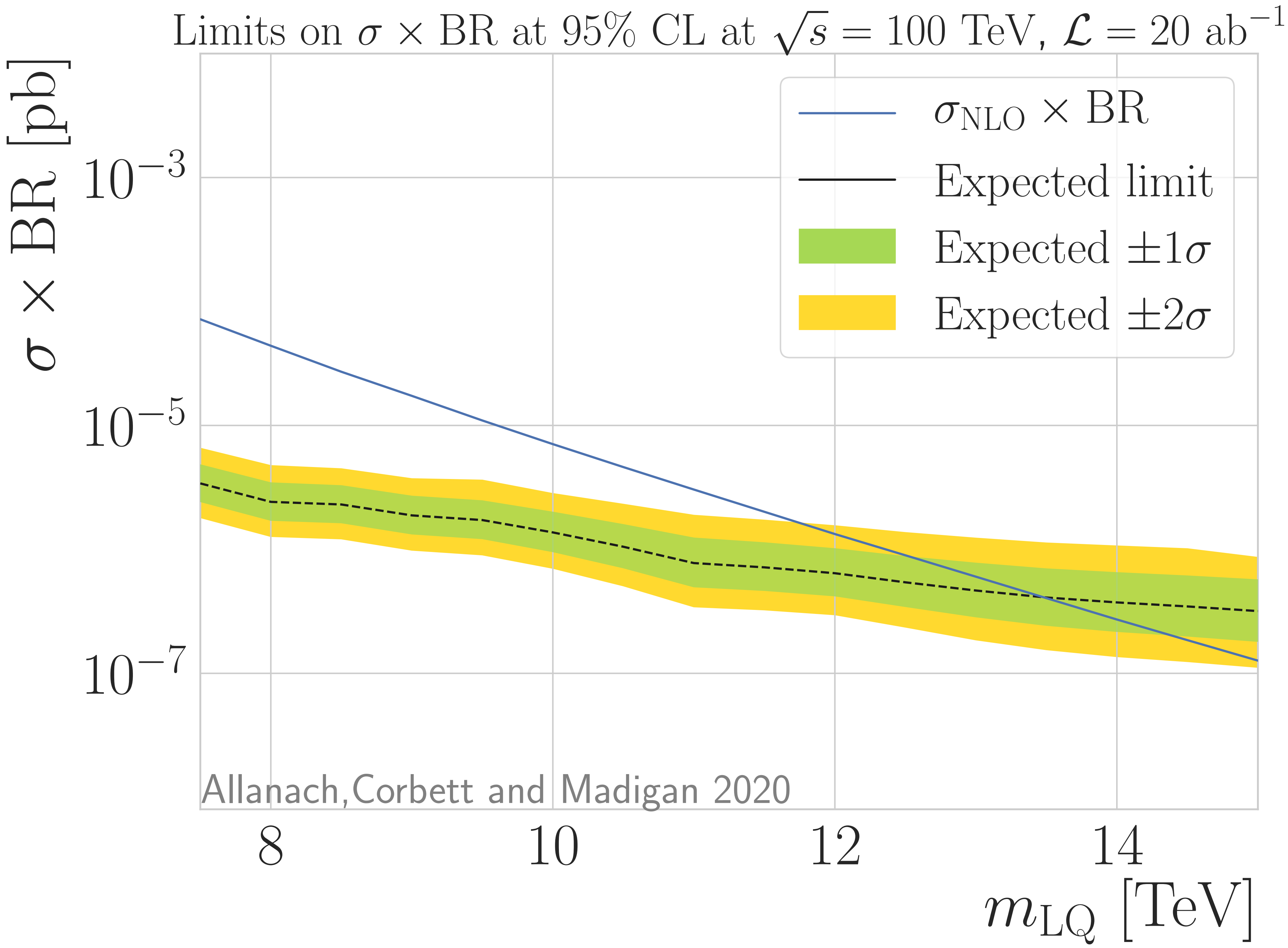
Exclusion limits: Projections for HL-LHC



Exclusion limits: Projections for HE-LHC



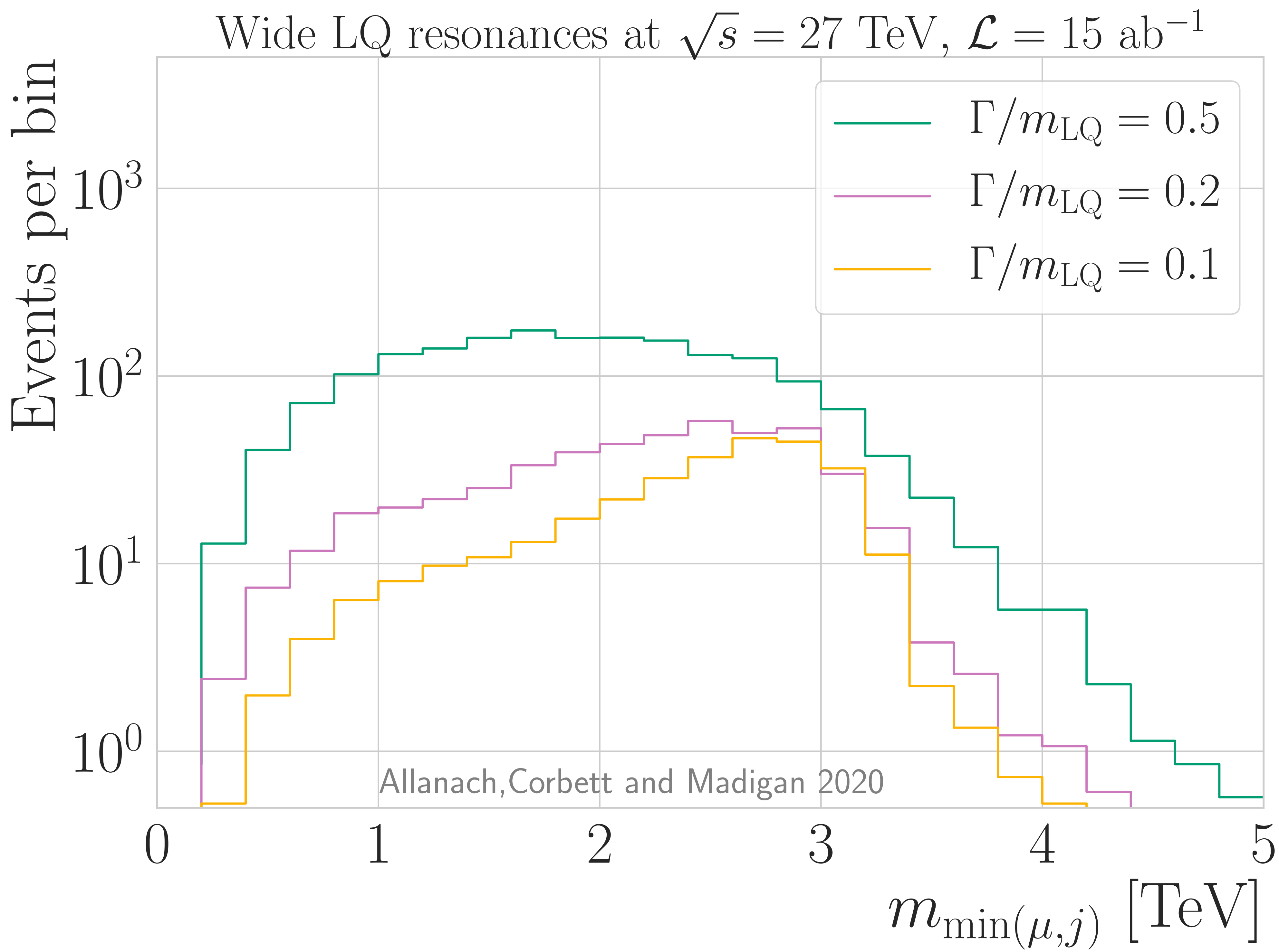
Exclusion limits: Projections for FCC-hh



Wide LQs

- We can apply our limits to other narrow LQ scenarios with $\Gamma/m_{\mathrm{LQ}} < 0.01$
- What about wide LQs?

Wide LQs



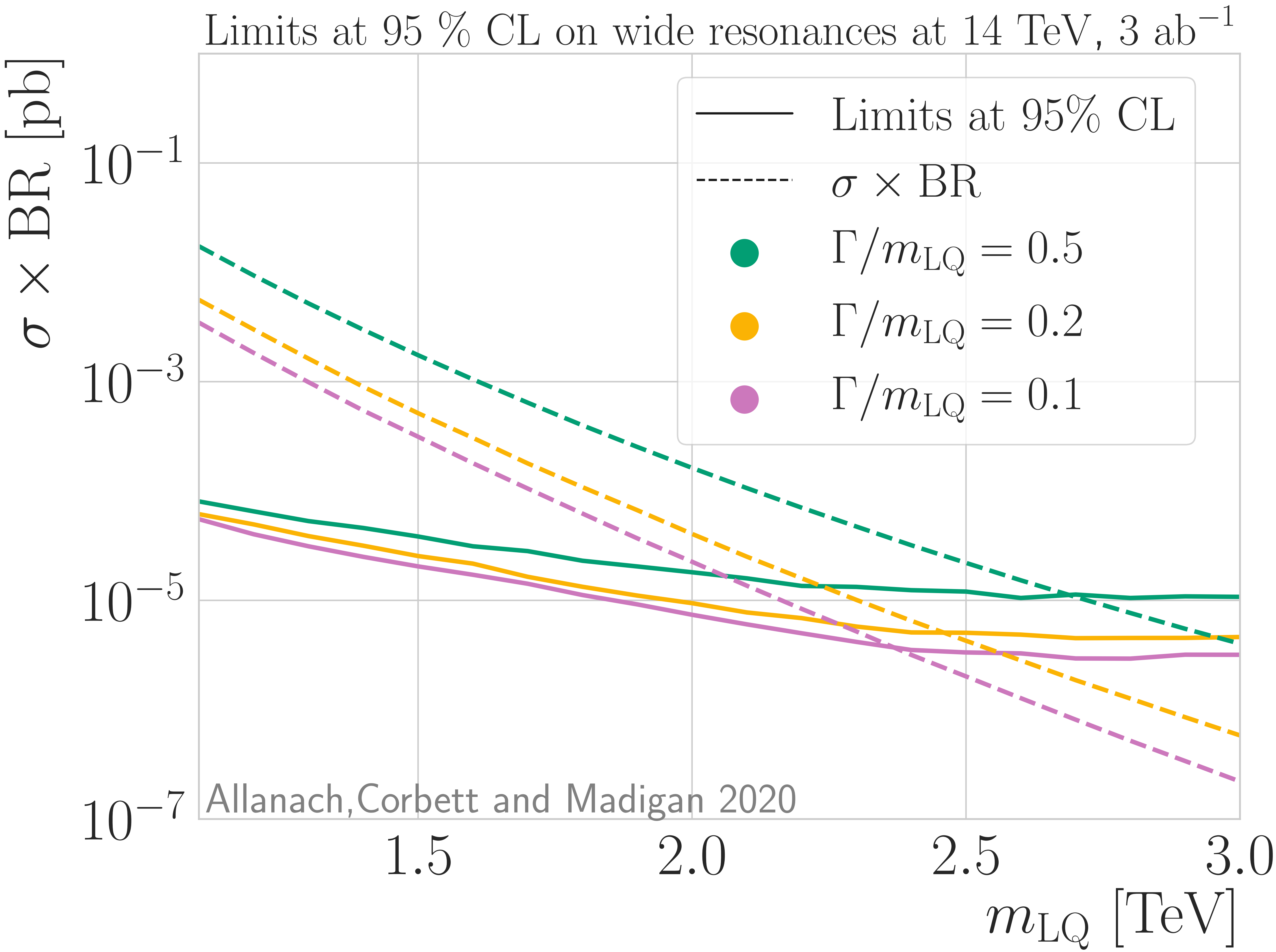
Wide LQ resonances at $\sqrt{s} = 27$ TeV, $\mathcal{L} = 15$ ab^{-1}
Events per bin
10^3
10^2
10^1
10^0
$\Gamma/m_{\mathrm{LQ}} = 0.5$
$\Gamma/m_{\mathrm{LQ}} = 0.2$
$\Gamma/m_{\mathrm{LQ}} = 0.1$
Allanach,Corbett and Madigan 2020
0
1
2
3
4
5
$m_{\min(\mu,j)}$ [TeV]

Wide LQs

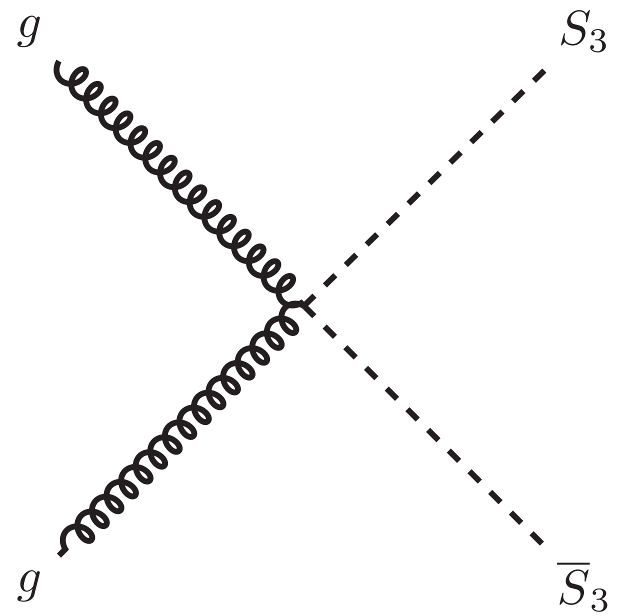
Recall: $$\Gamma = \frac{|y_{lq}|^2 m_{\rm LQ}}{16\pi}$$

For wide LQs we take $y_{b\mu} = y_{s\mu}$ as before, scaling them up to reach

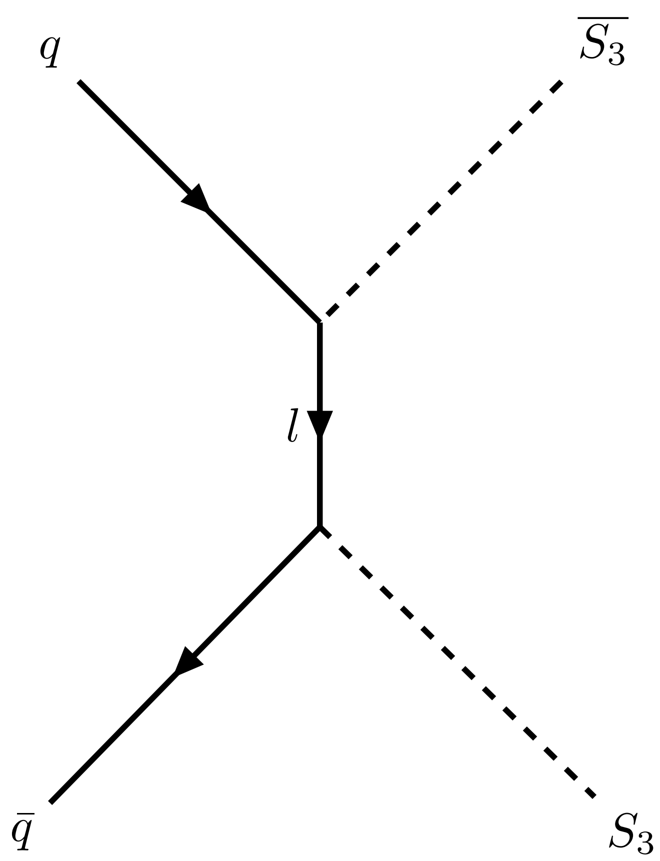
$$\Gamma/m_{\rm LQ} = 0.1, 0.2, 0.5$$


Limits at 95 % CL on wide resonances at 14 TeV, 3 ab^{-1}
Limits at 95% CL
$\sigma \times \mathrm{BR}$
$\Gamma/m_{\mathrm{LQ}} = 0.5$
$\Gamma/m_{\mathrm{LQ}} = 0.2$
$\Gamma/m_{\mathrm{LQ}} = 0.1$
$\sigma \times \mathrm{BR}$ [pb]
10^{-1}
10^{-3}
10^{-5}
10^{-7}
1.5
2.0
2.5
3.0
m_{LQ} [TeV]
Allanach,Corbett and Madigan 2020

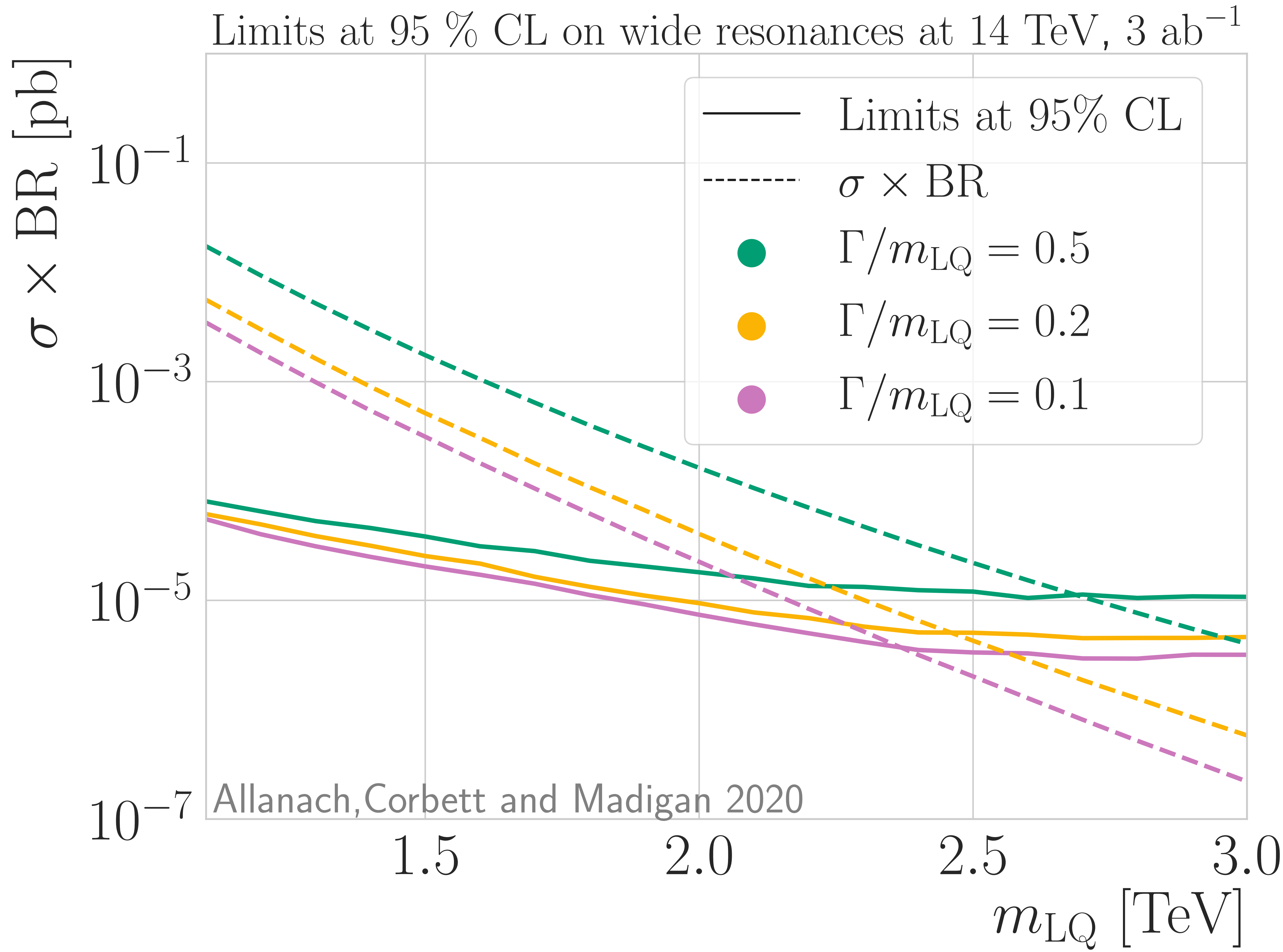
Wide LQs



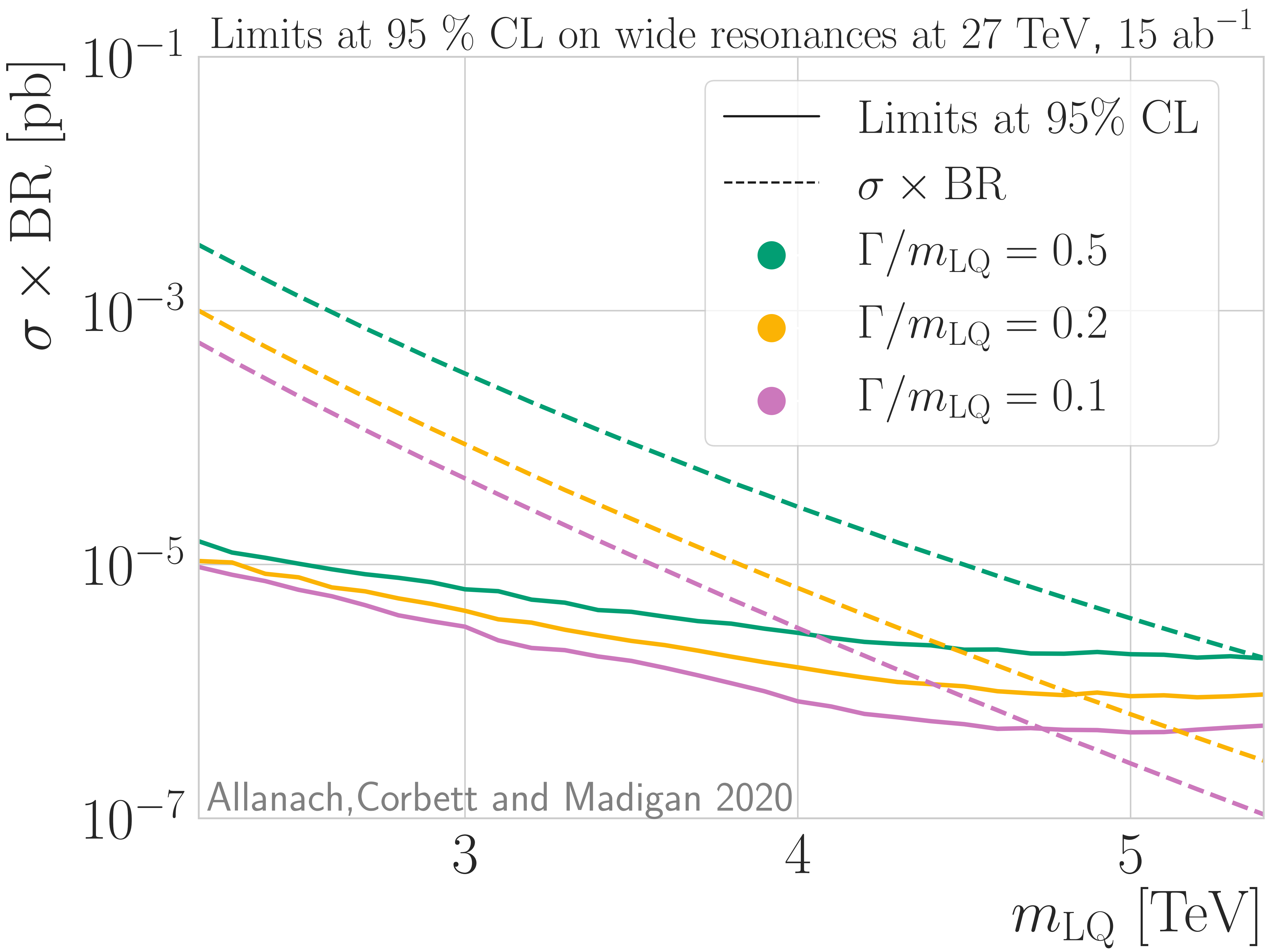
Pair production is no longer dominated by y_{lq} independent diagrams



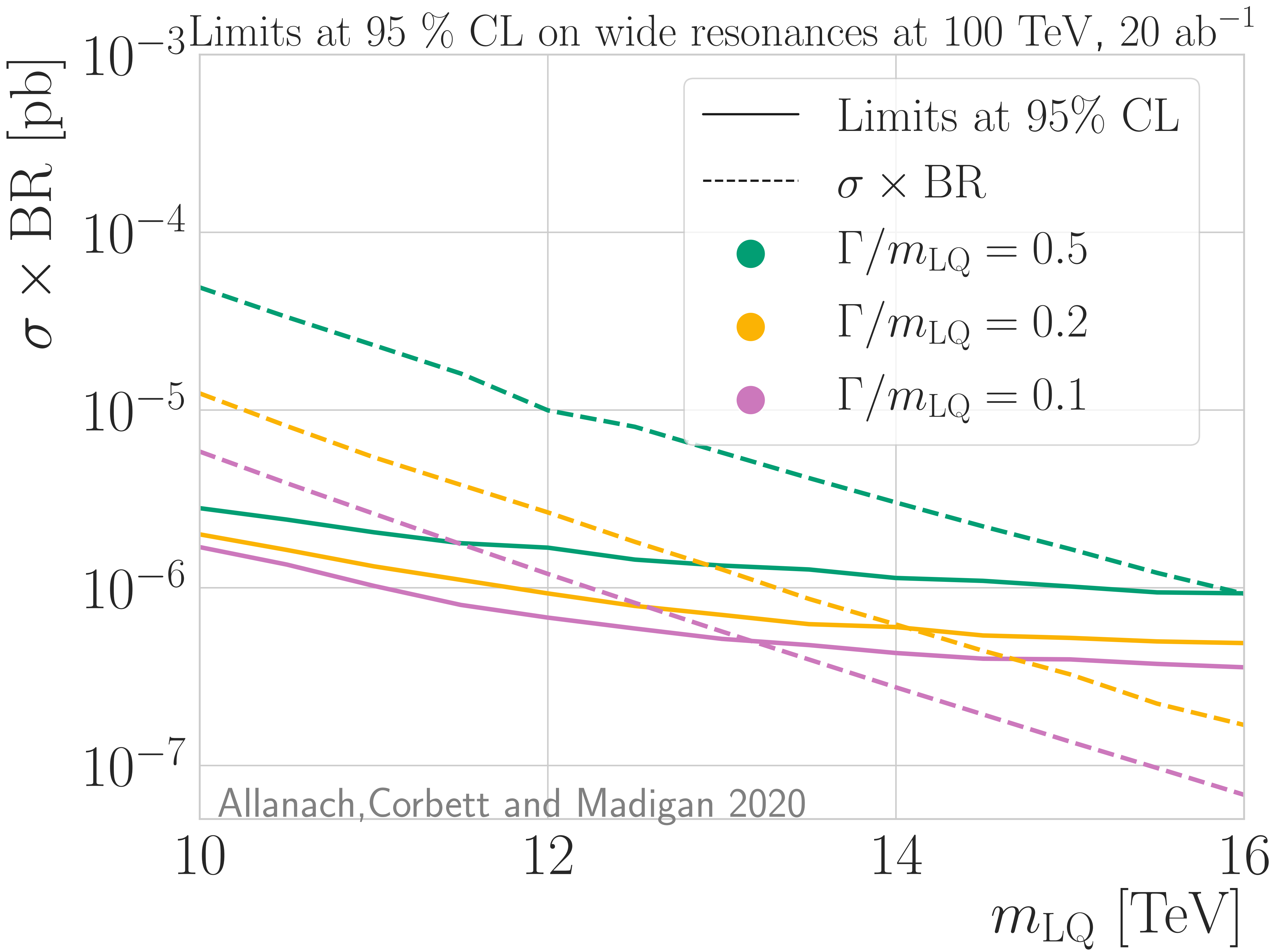
$\sigma \times \mathrm{BR}$ is increased by contributions from y_{lq} dependent diagrams



Limits at 95 % CL on wide resonances at 14 TeV, 3 ab^{-1}
$\sigma \times$ BR [pb]
10^{-1}
10^{-3}
10^{-5}
10^{-7}
Limits at 95% CL
$\sigma \times$ BR
$\Gamma/m_{LQ} = 0.5$
$\Gamma/m_{LQ} = 0.2$
$\Gamma/m_{LQ} = 0.1$
Allanach,Corbett and Madigan 2020
1.5
2.0
2.5
3.0
m_{LQ} [TeV]

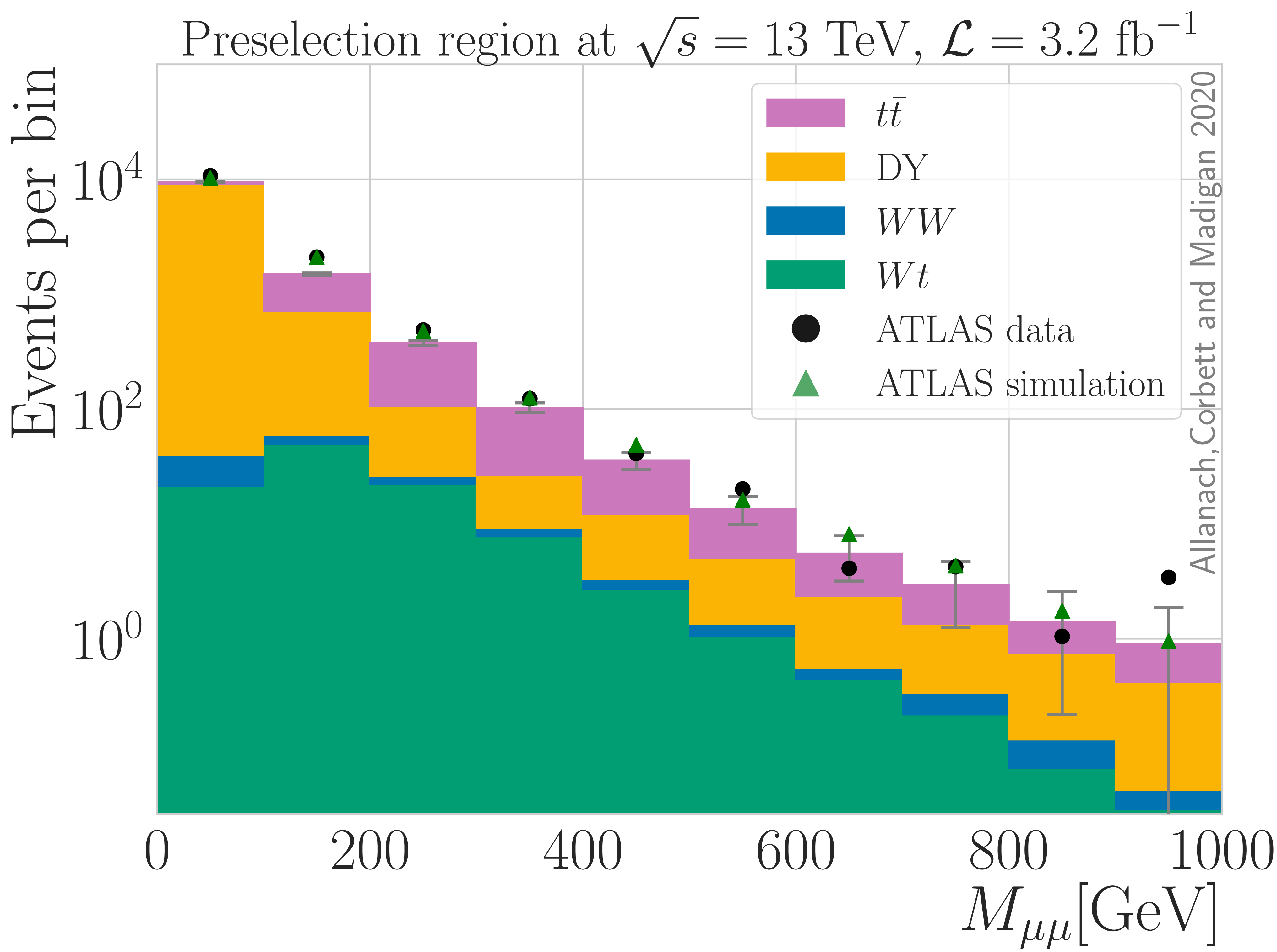


Limits at 95 % CL on wide resonances at 27 TeV, 15 ab^{-1}
$\sigma \times$ BR [pb]
10^{-1}
10^{-3}
10^{-5}
10^{-7}
Limits at 95% CL
$\sigma \times$ BR
$\Gamma/m_{LQ} = 0.5$
$\Gamma/m_{LQ} = 0.2$
$\Gamma/m_{LQ} = 0.1$
Allanach,Corbett and Madigan 2020
3
4
5
m_{LQ} [TeV]



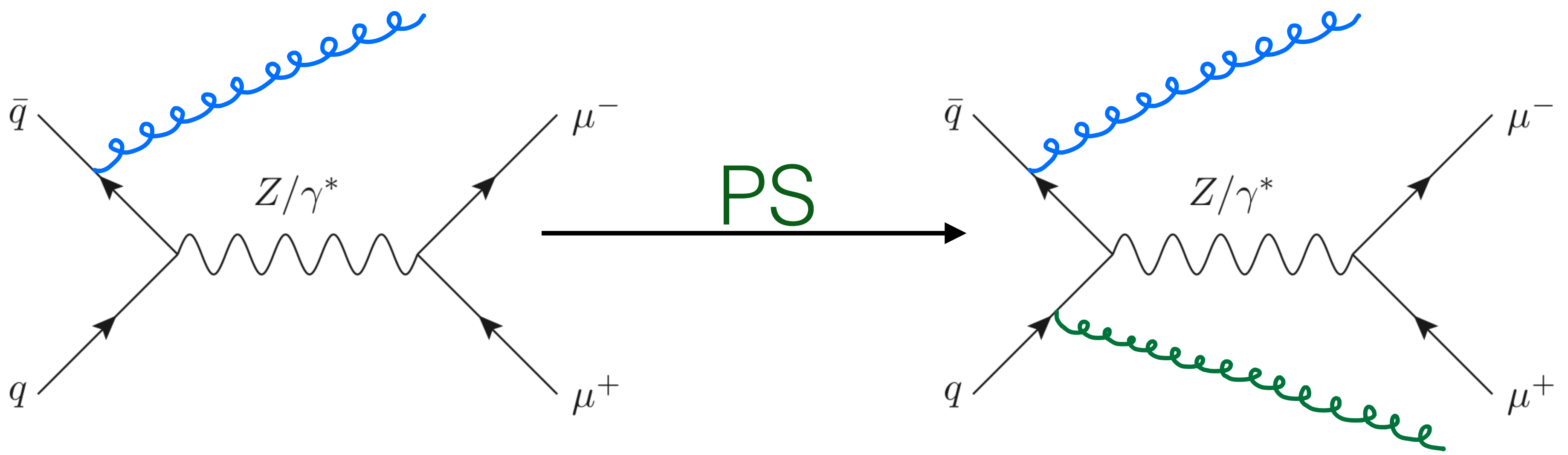
Limits at 95 % CL on wide resonances at 100 TeV, 20 ab^{-1}
$\sigma \times$ BR [pb]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Limits at 95% CL
$\sigma \times$ BR
$\Gamma/m_{\mathrm{LQ}} = 0.5$
$\Gamma/m_{\mathrm{LQ}} = 0.2$
$\Gamma/m_{\mathrm{LQ}} = 0.1$
Allanach,Corbett and Madigan 2020
10
12
14
16
m_{LQ} [TeV]

Simulations - validation



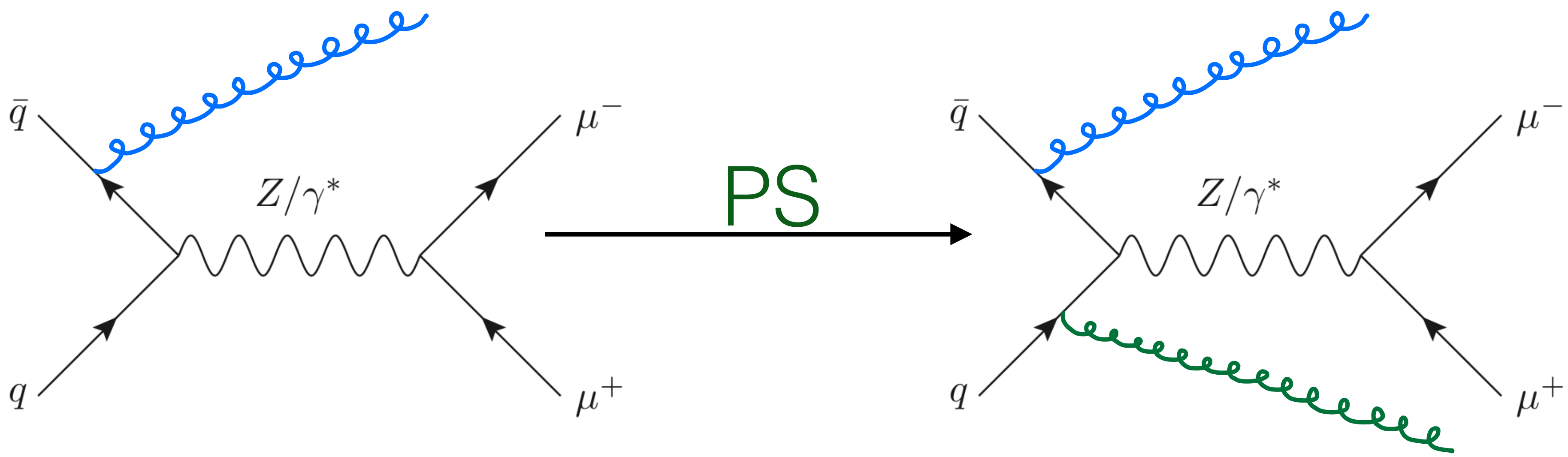
Overcounting

DY + 1 jet

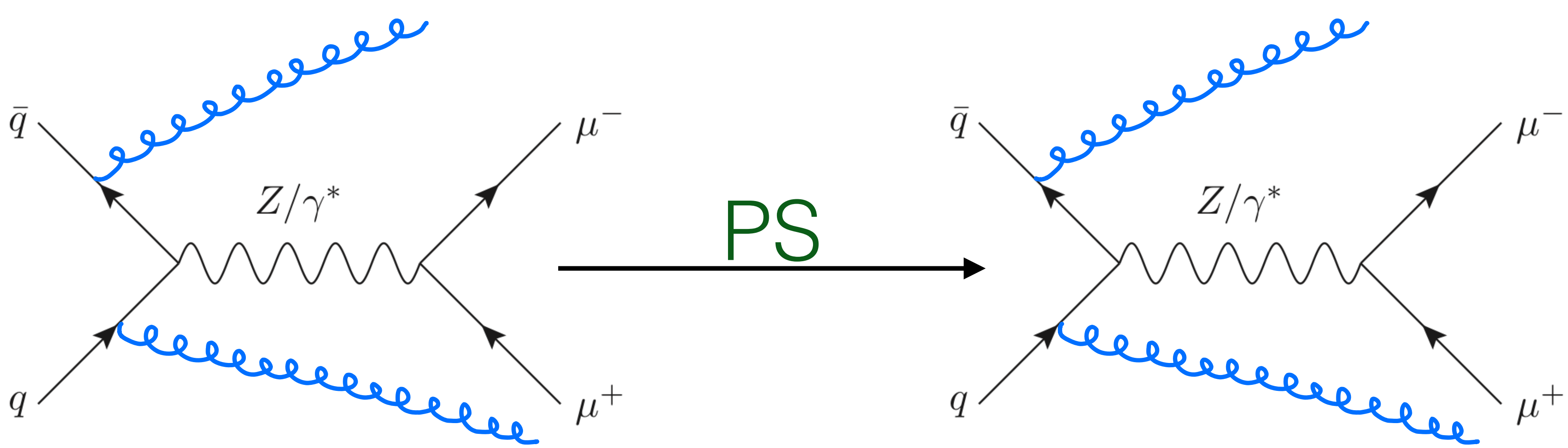


Overcounting

DY + 1 jet



DY + 2 jets



Overcounting

MLM matching used to combine samples of different jet multiplicity.

Depends on input parameters: $xqcut, Q_{cut}$

- different for each process and each signal region.

- these are cuts on jets,quarks and gluons with dimensions of energy.

These are unphysical parameters:

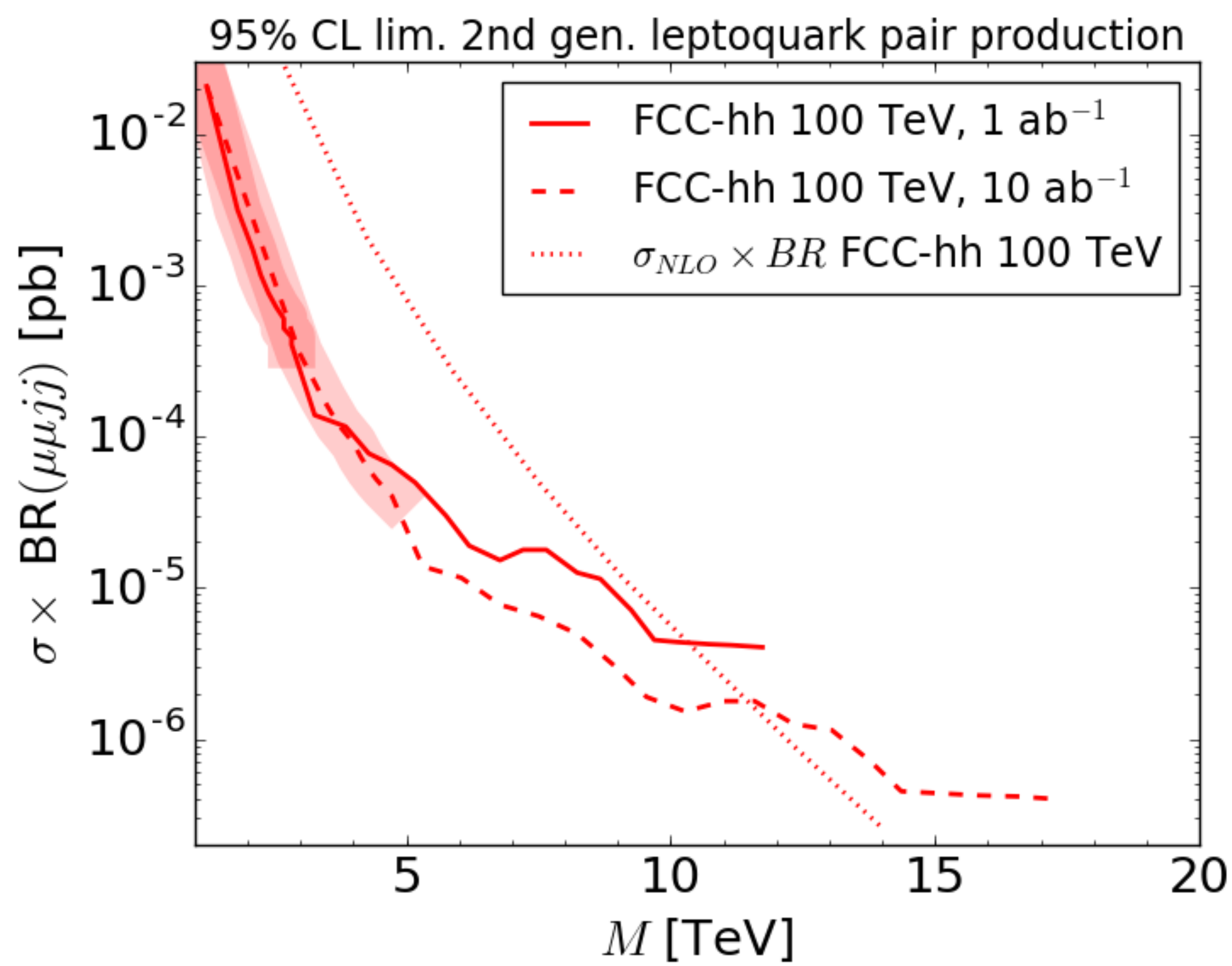
- confirm that observables do not depend on $xqcut, Q_{cut}$

Previous work:

Allanach, Gripaios, You: 1710.06363

- Sensitivity to **leptoquarks** is driven by the size of the standard model background.
- Extrapolate from 13 TeV LHC performance to future colliders, assuming no changes to detector performance

i.e. **acceptance and efficiency remain the same.**



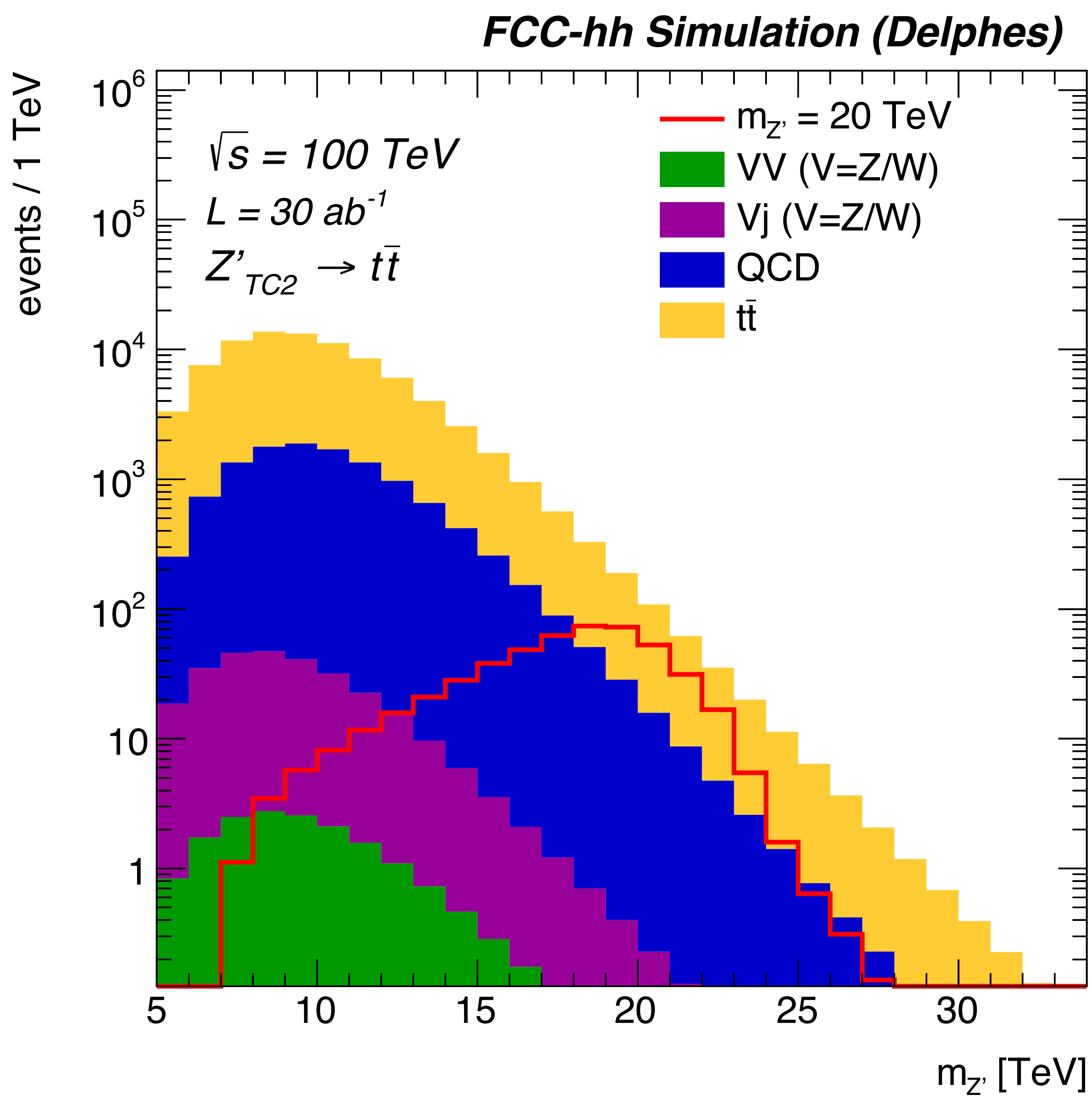
Find the FCC-hh at $100\ \mathrm{TeV}, 10\ \mathrm{ab}^{-1}$

is sensitive to $m_{\mathrm{LQ}} < 12\ \mathrm{TeV}$

Previous work:

Helsens, Jamin, Mangano, Rizzo, Selvaggi: 1902.11217

- Sensitivity to **new physics** is driven by the size of the standard model background.
- Produce a detailed understanding of the standard model background using Monte Carlo simulations.
- Account for differences in current and future detectors using `Delphes` for detector simulation.

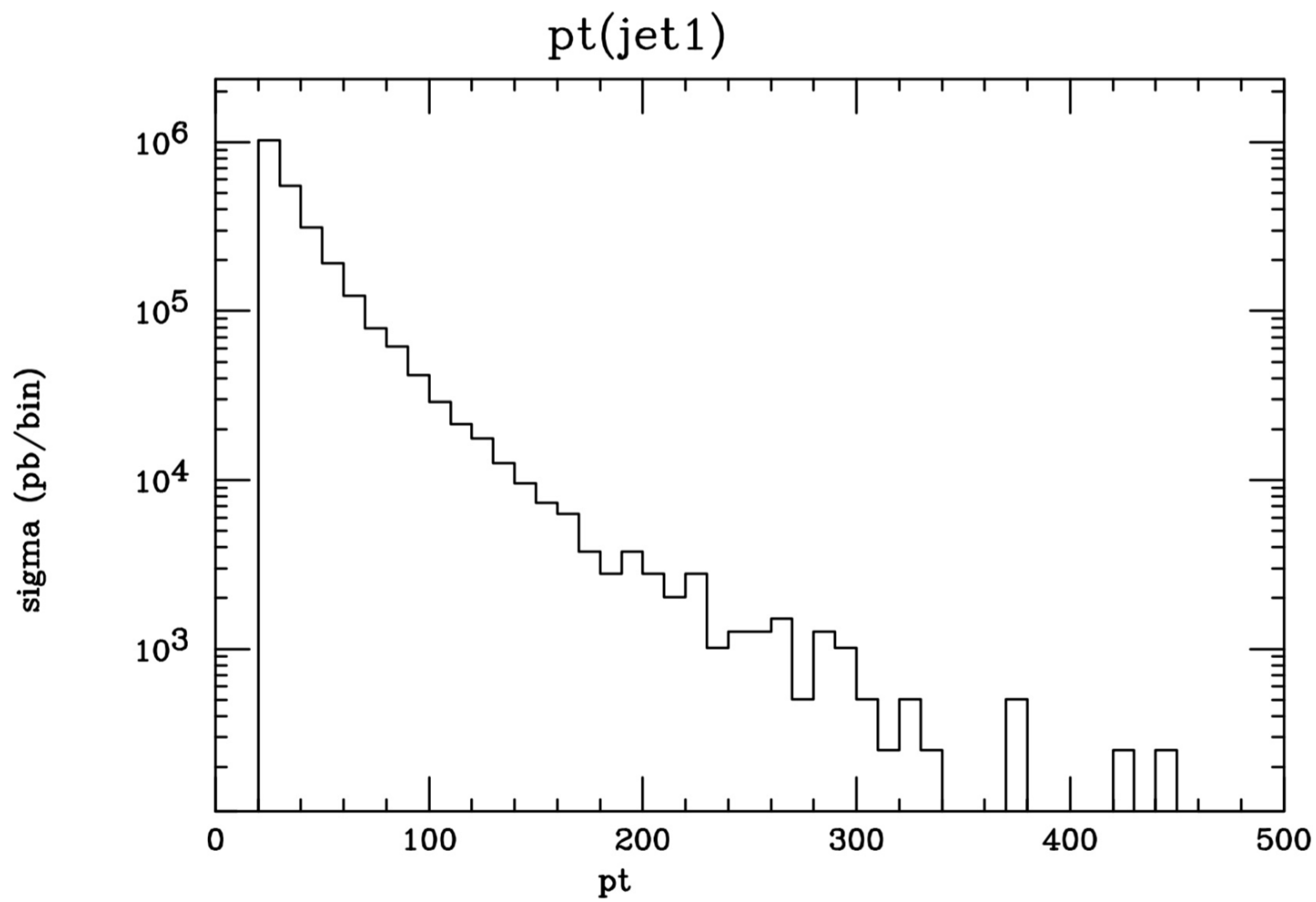


Biasing event generation

By default Madgraph generates **unweighted events.**

All events have the same weight.

The number of events in a region of phase space is proportional to the probability in this region.



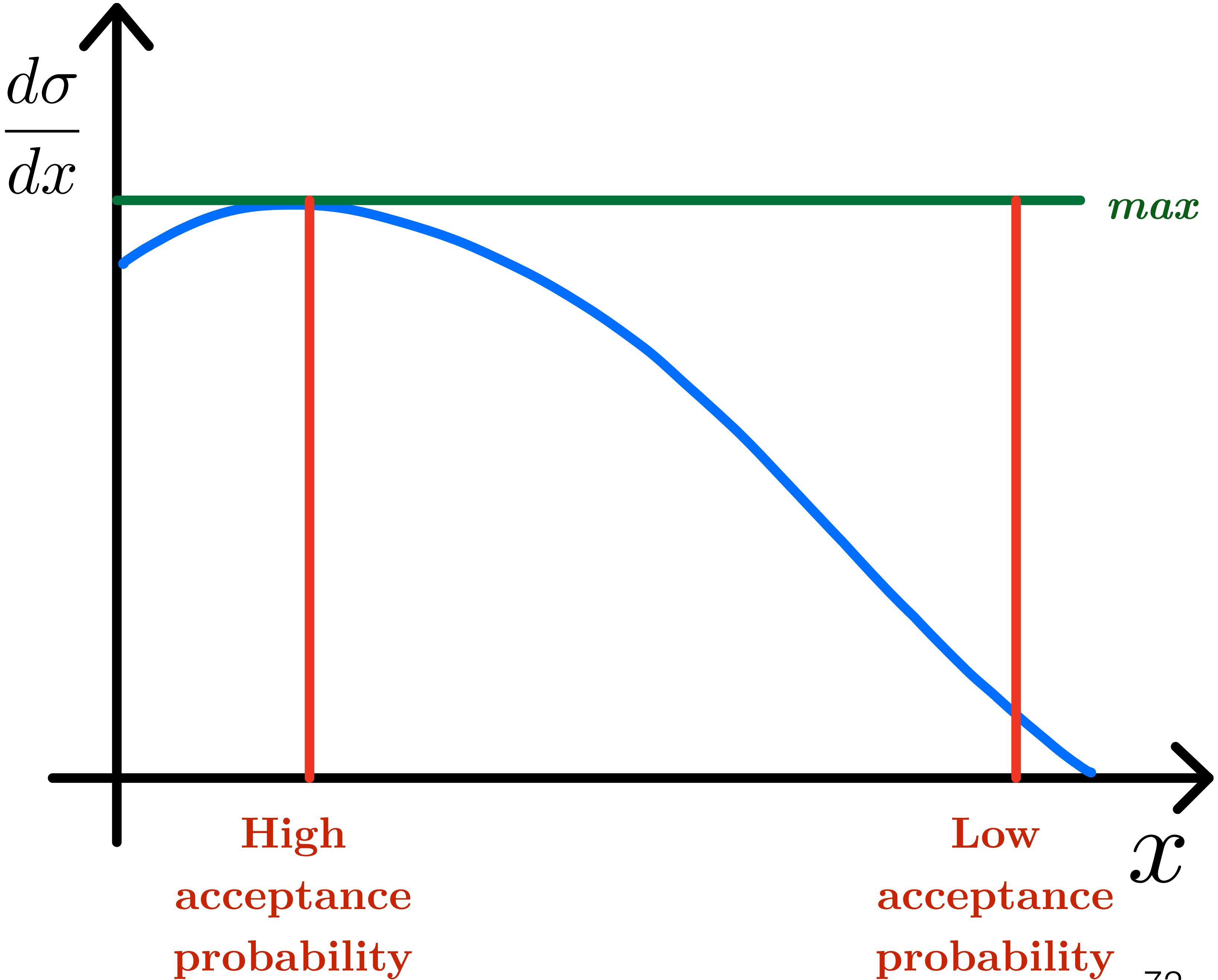
From Madgraph5 online tutorial *LOEventGenerationBias*

Biasing event generation

Generating unweighted events:

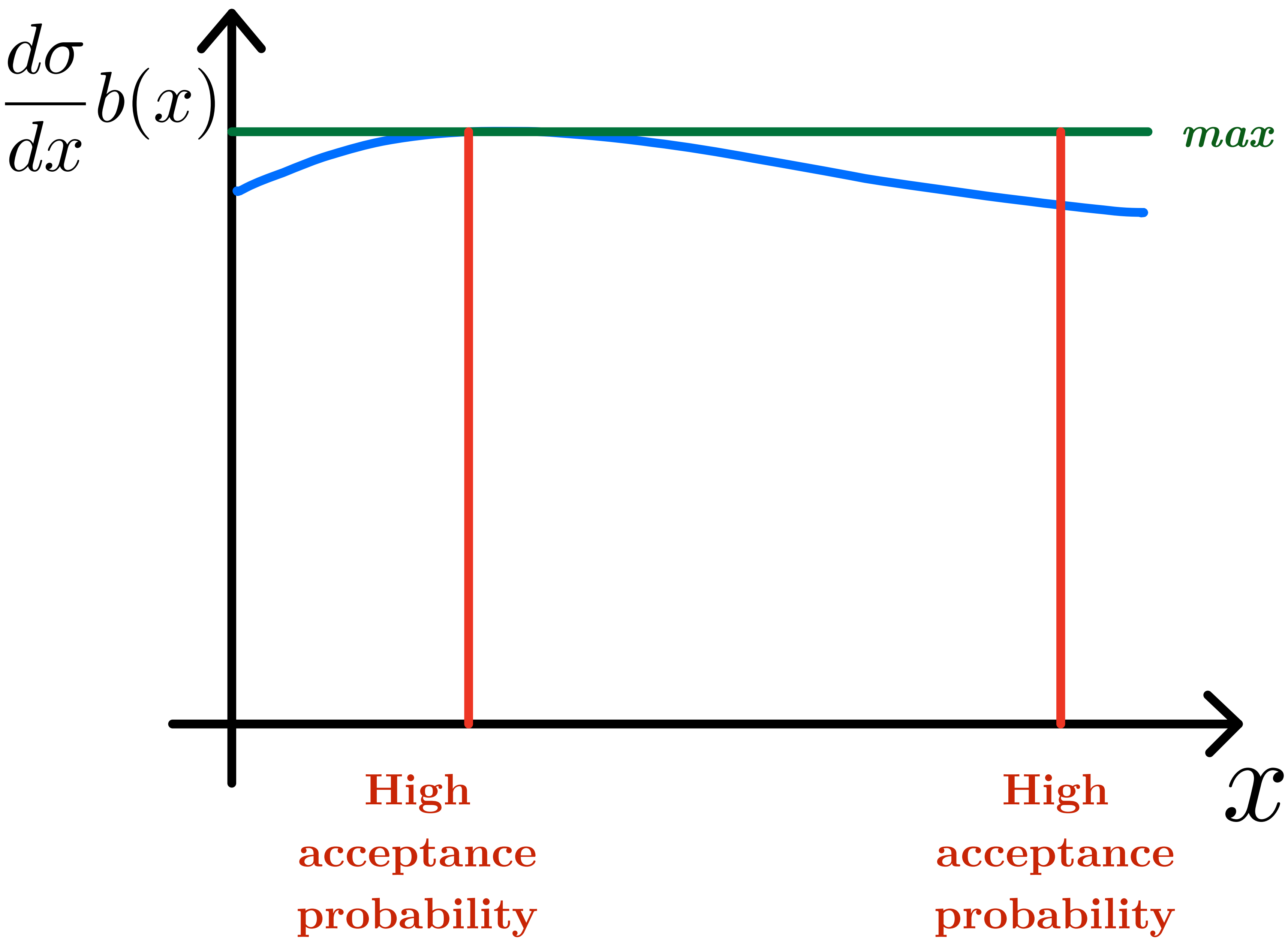
Accept a phase space point x and generate the event with probability

$$\frac{d\sigma/dx}{(d\sigma/dx)_{max}}$$



Biasing event generation

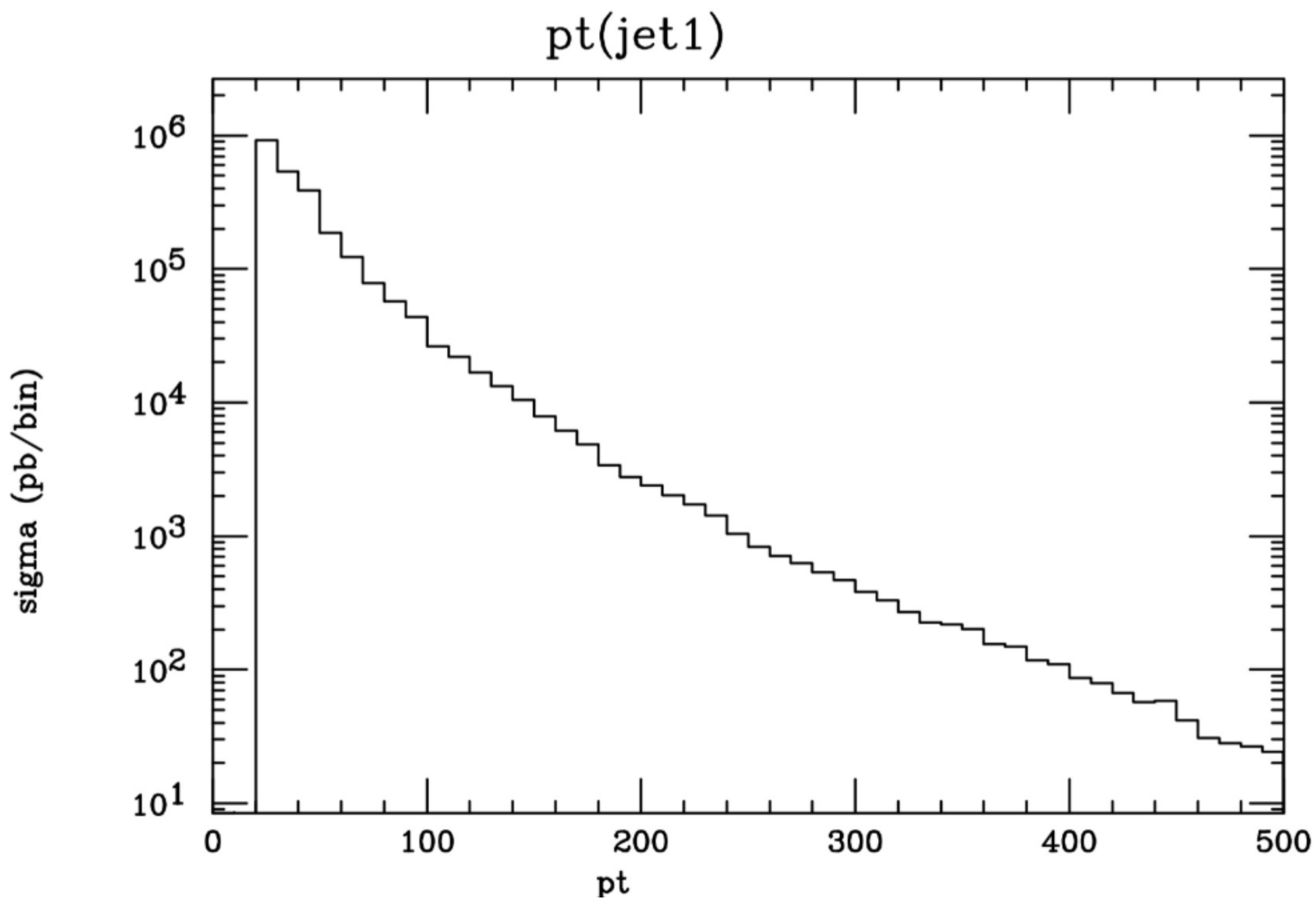
Introduce a bias function $b(x)$ and accept/reject with probability $\dfrac{\frac{d\sigma}{dx}b(x)}{(\frac{d\sigma}{dx}b(x))_{max}}$



Biasing event generation

We must reweight each event using the bias to reproduce the physical distribution.

Then the overall shape or values of physical observables are not modified.



From Madgraph5 online tutorial *LOEventGenerationBias*

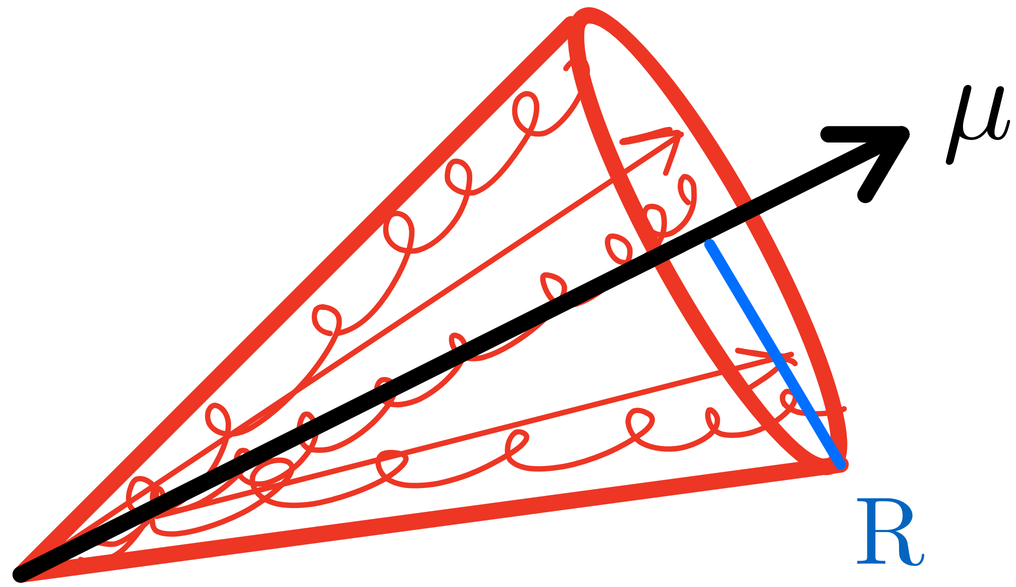
Biasing event generation

We define our bias function as $b(x) \propto P^5$ where

DY+0,1,2,3j	$P^2 = (p_{\mu_1} + p_{\mu_2})^2$
tt + 0,1j	$= (p_{\mu_1} + p_{\mu_2} + p_{j_1} + p_{j_2})^2$
Wt + 0, 2j	$= (p_{\mu_1} + p_{\mu_2} + p_{j_1})^2$
WW + 0,1,2j	$= (p_{\mu_1} + p_{\mu_2})^2$

Muon isolation

- We use the `Delphes3` detector configurations for ATLAS, HL-LHC, HE-LHC and FCC-hh, only modifying muon isolation:



Isolated if $\sum_{cone} p_T < p_T^{max}$

Muon isolation

We completely remove the requirement of muon isolation at the HE-LHC and FCC-hh.

This results in overestimating the SM background.

Muon isolation

We completely remove the requirement of muon isolation at the HE-LHC and FCC-hh.

This results in overestimating the SM background.

Why? Following the same reasoning as Helsens, Jamin, Mangano, Rizzo, Selvaggi: 1902.11217

The selection efficiency is found to be highly dependent on the muon isolation parameters, in particular $t\bar{t}$ production.