Leptoquarks from above and below

Matthew Kirk

27 Oct 2023

Intro to me

- PhD (2014 - 2018): Here in IPPP
  - With Alex Lenz

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  - Mostly working with Marco Nardecchia

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- La Sapienza, Rome (2018-2021)
  - Mostly working with Marco Nardecchia
- UB, Barcelona (2021-2023)
  - Mostly working with Federico Mescia

Interests

- PhD was mostly on B physics, particularly B meson mixing
  - Moved into some BSM via the $bs\ell\ell$ anomalies
- Generally interested in anomalies (e.g. CAA) and simple model building, global fits and computer tools

Now

- Working with Danny and Ery to carefully study $(\bar{b}s)(\bar{c}c)$ operators – can we properly disentangle QCD and NP?

Now let's talk physics

1) Using neutrino telescopes to search for LQs?

2) LQs without leptons for $bs\ell\ell$ anomalies?

1) Using neutrino telescopes to search for LQs?

(based on 2307.11152 with Keyun Wu and Shohei Okawa)

$\nu q \to \mathrm{LQ}$

- If LQs exist, they can be generated in an s-channel diagram from a neutrino-quark initial state
  - And on-shell if the centre-of-mass energy is large enough
- How large?

$\nu N \to \mathrm{LQ}$

- $\sqrt{s} = \sqrt{2 E_\nu m_N}$
- For $m_N \sim 1\,\mathrm{GeV}$, $\sqrt{s} \sim 1.4\,\mathrm{TeV}\sqrt{E_\nu / 10^6\,\mathrm{GeV}}$
- Where can I get a 1000 TeV neutrino source?

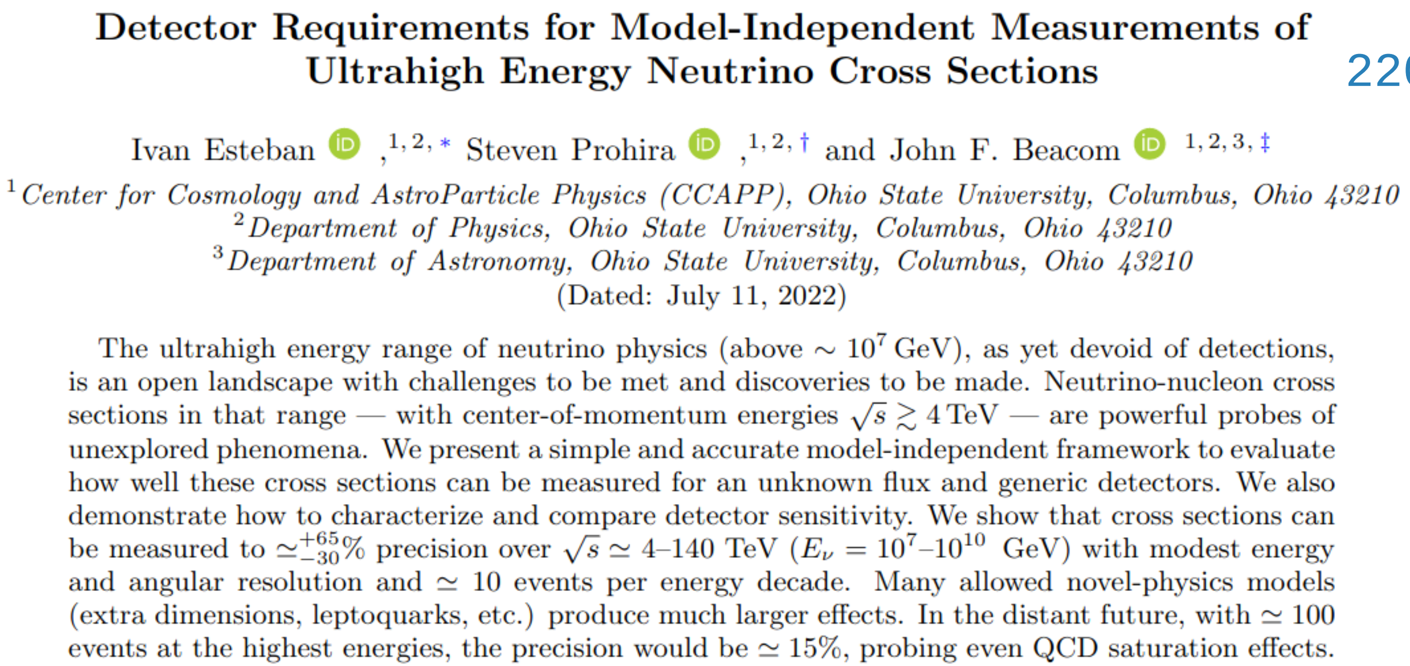
UHE neutrinos

- Astrophysical sources expected to generate neutrinos with energies up to at least 1 exa-electronvolt ($1\,\mathrm{EeV} = 10^{18}\,\mathrm{eV} = 10^{9}\,\mathrm{GeV}\,!$)
- Can we detect these?

UHE neutrino experiments

- Next generation neutrino telescopes will measure neutrino-nucleon cross-section (i.e. neutrino DIS) at ultra-high energies
  - GRAND, TAMBO, POEMMA, Trinity, …
- Enough to tell us anything about BSM?

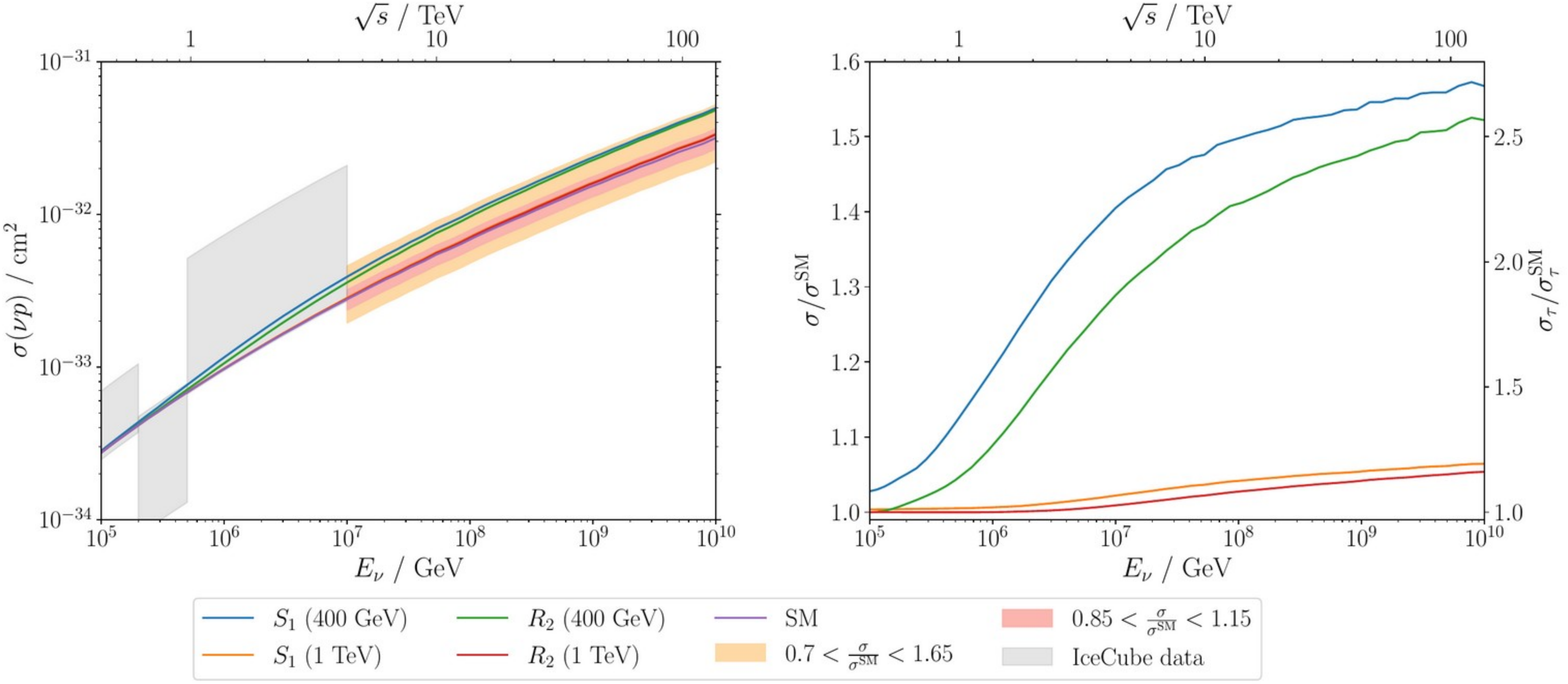
Measurements of $\sigma(\nu N)$



2205.09763

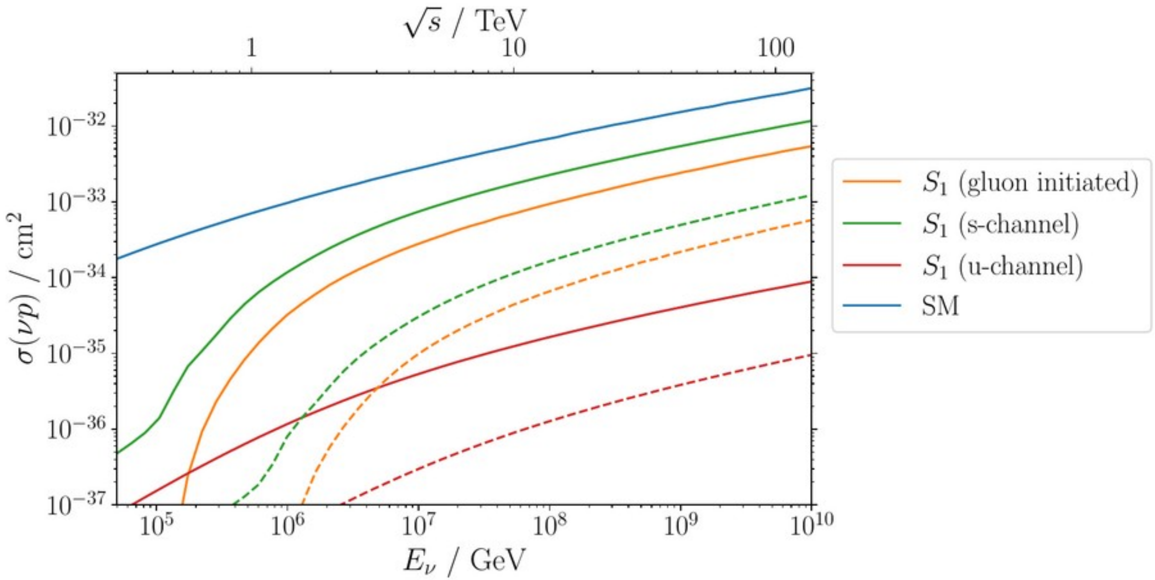
See also 2204.04237 and 2007.10334

Measurements of $\sigma(\nu N)$



Calculating $\sigma(\nu N)$

- Turns out not just s-channel is important, if looking at heavy quark couplings
  - Often true since 3rd gen BSM more motivated and collider bounds are weaker
- Gluon initial states also very relevant



1803.10112

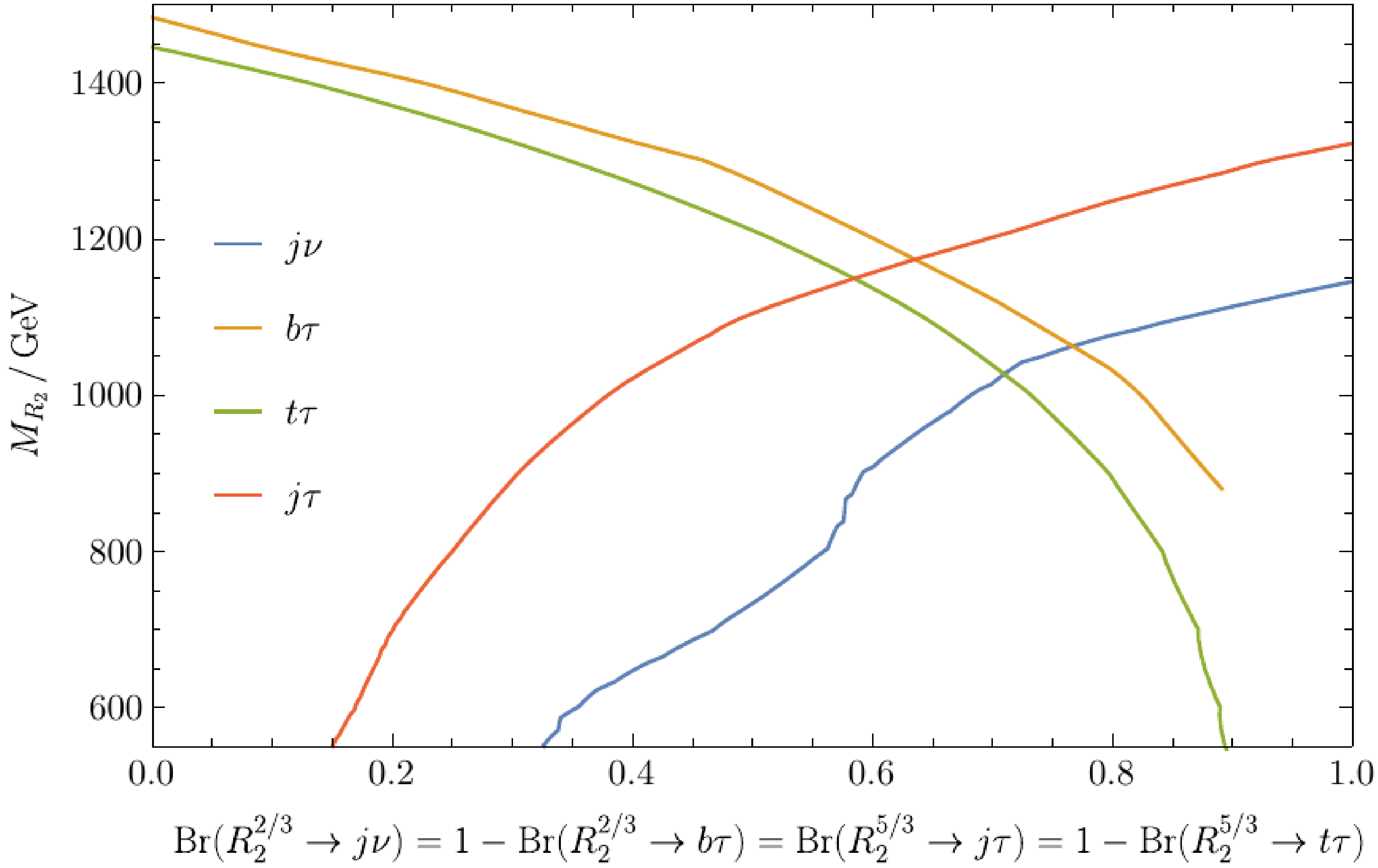
Theory uncertainties

- Primarily from PDFs
  - Around 5-10% from any particular PDF
  - Plus consider which PDF set to use
  - And what target: proton / proton+neutron average / Earth average
- We neglect these entirely

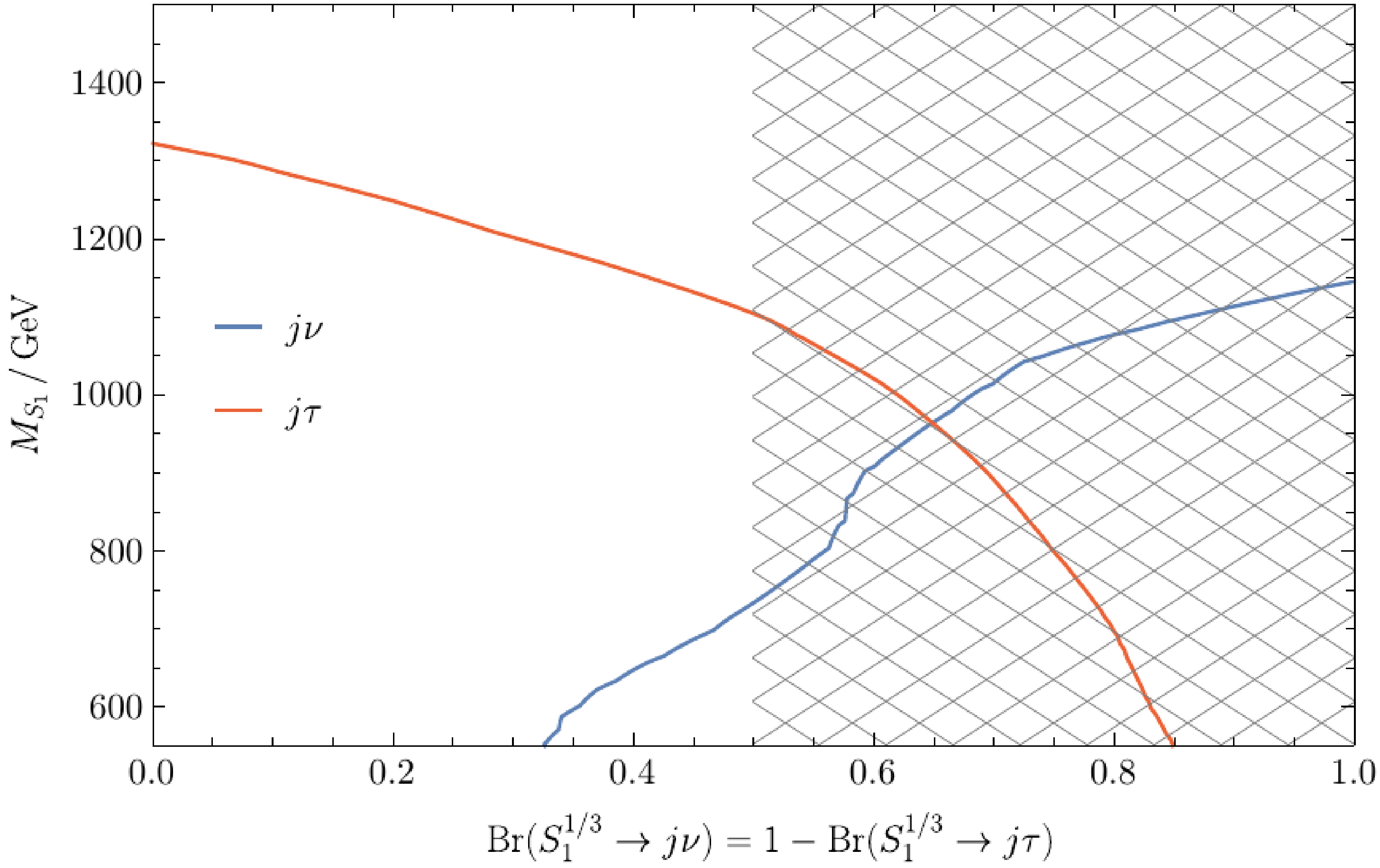
LQ models

- We study two LQ models:
  - $R_2 : (\mathbf{3}, \mathbf{2}, 7/6)$
    - Can explain $R(D), R(D^*)$ anomalies with large couplings, and has been previously looked at using IceCube data
  - $S_1 : (\mathbf{3}, \mathbf{1}, -1/3)$
    - Had recently (2021) been looked at using specific neutrino telescopes, where they showed potential!

LHC bounds – direct searches

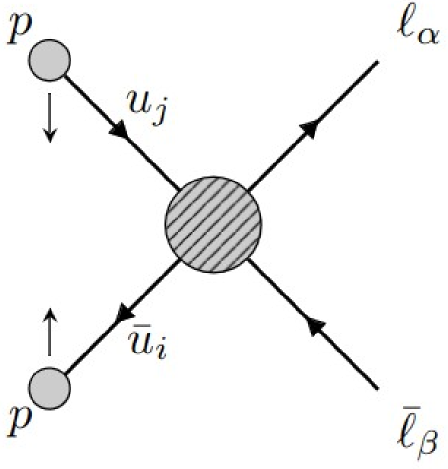


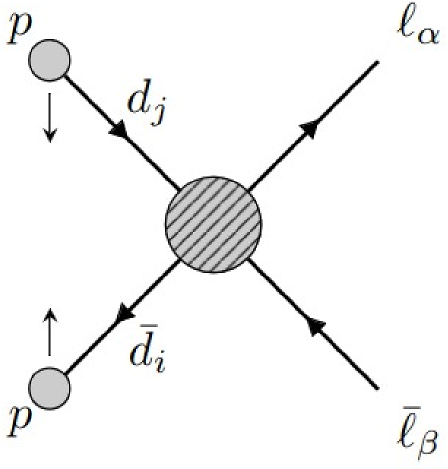
LHC bounds – direct searches

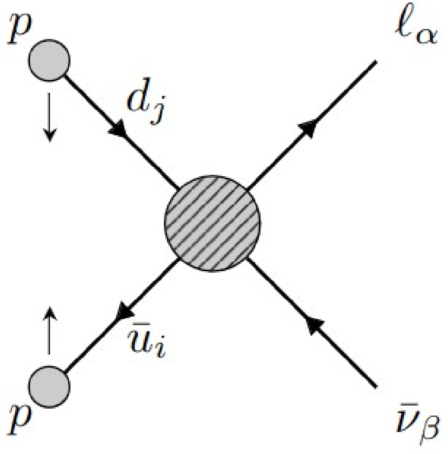


LHC bounds – high pT tails

- Four fermion EFT operators give energy enhanced contributions to the high pT tails at the LHC







LHC bounds – high pT tails

- There is now a software package HighPT which makes is straightforward to check LHC bounds on SMEFT operators with arbitrary flavour structures.

ZU-TH-29/22

HighPT

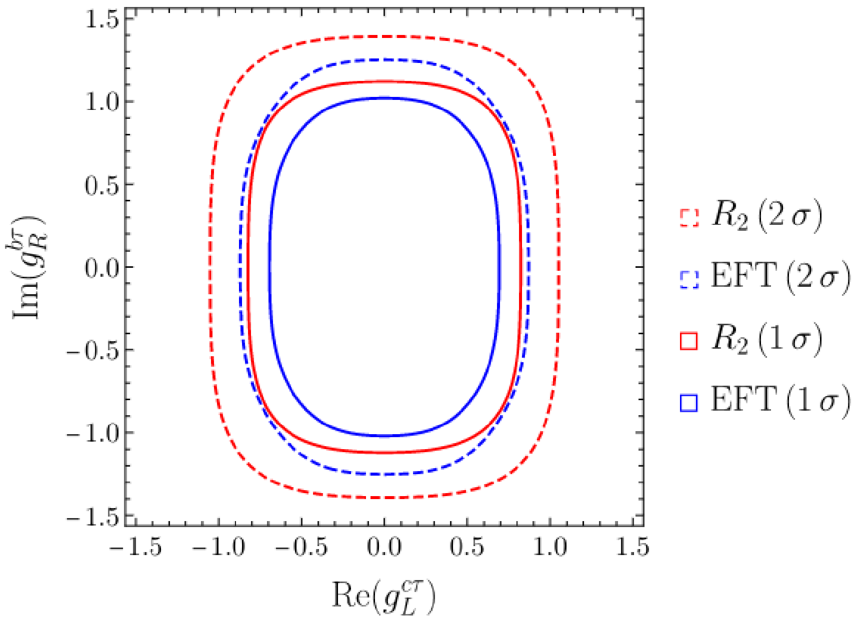
HighPT:

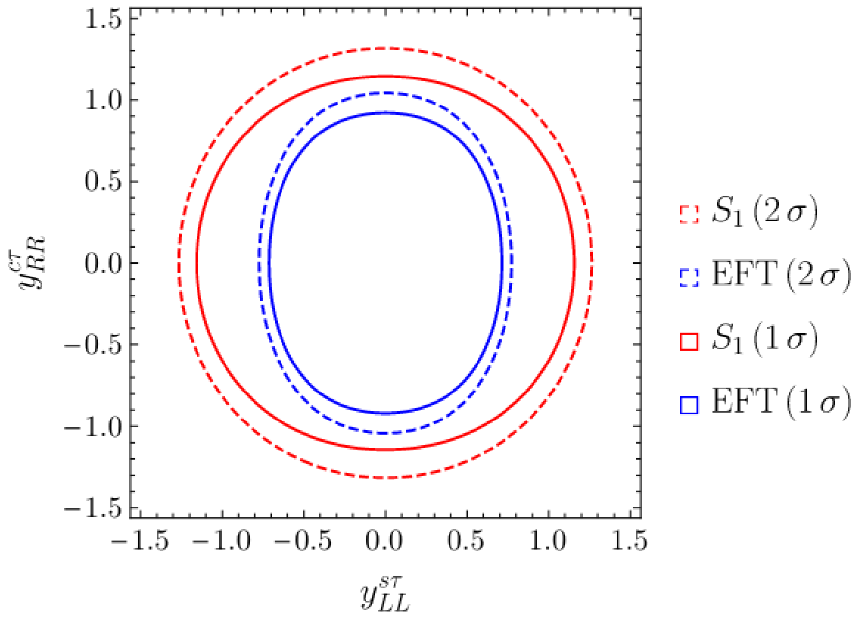
A Tool for high-p_T Drell-Yan Tails Beyond the Standard Model

L. Allwicher•, D. A. Faroughy•, F. Jaffredo••, O. Sumensari••, F. Wilsch•*

LHC bounds – high pT tails

- They also include a mode with full model dependence for certain UV models and masses

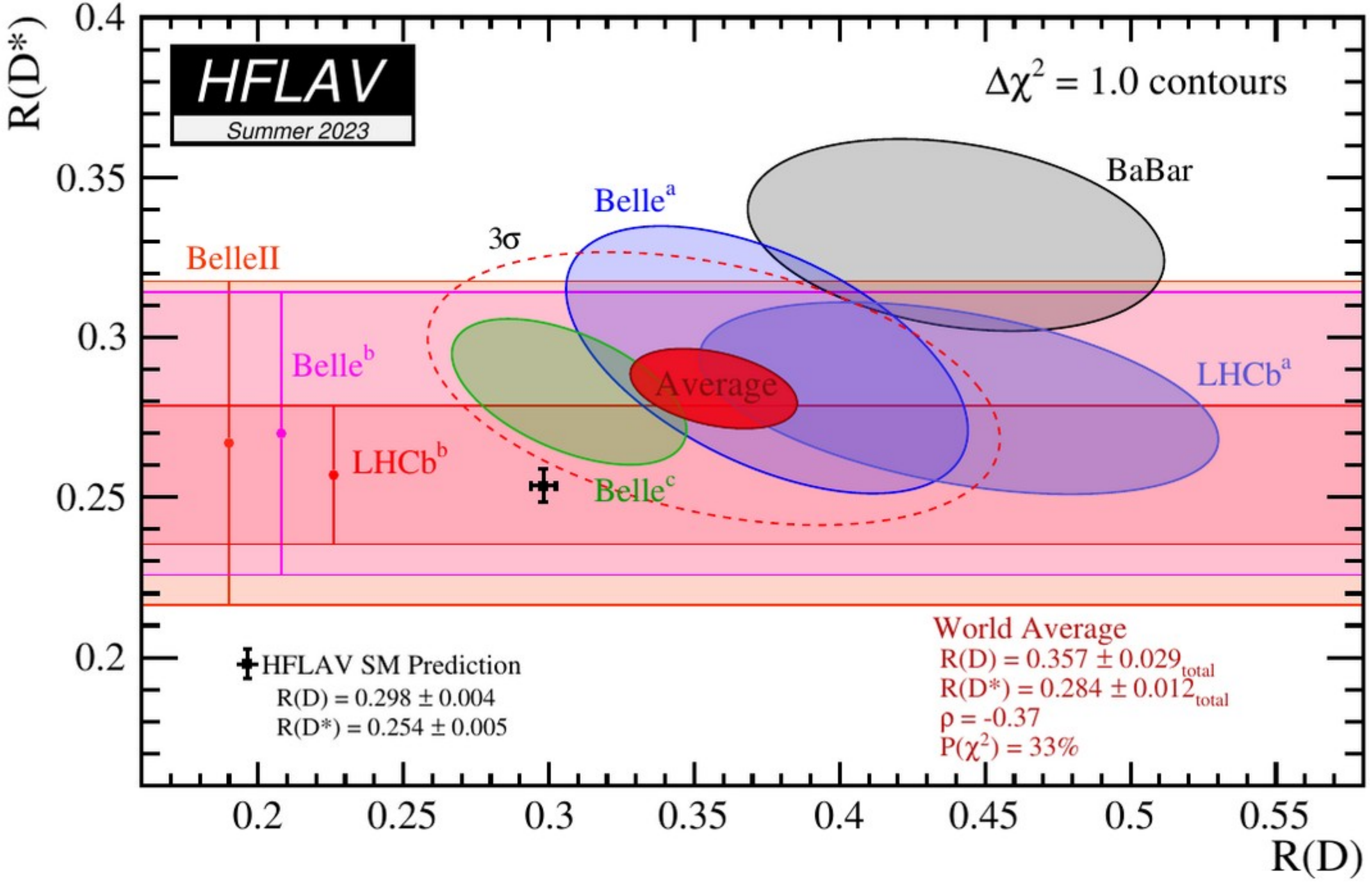




$R(D), R(D^*)$

- Anomaly in $b \to c\ell\nu$ decays

$R(D), R(D^*)$



HFLAV
Summer 2023
$\Delta\chi^2 = 1.0$ contours
BaBar
Belle[a]
3σ
BelleII
Belle[b]
Average
LHCb[a]
LHCb[b]
Belle[c]
HFLAV SM Prediction
R(D) = 0.298 ± 0.004
R(D*) = 0.254 ± 0.005
World Average
R(D) = 0.357 ± 0.029 total
R(D*) = 0.284 ± 0.012 total
ρ = -0.37
P(χ²) = 33%
R(D*)
R(D)
0.4
0.35
0.3
0.25
0.2
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55

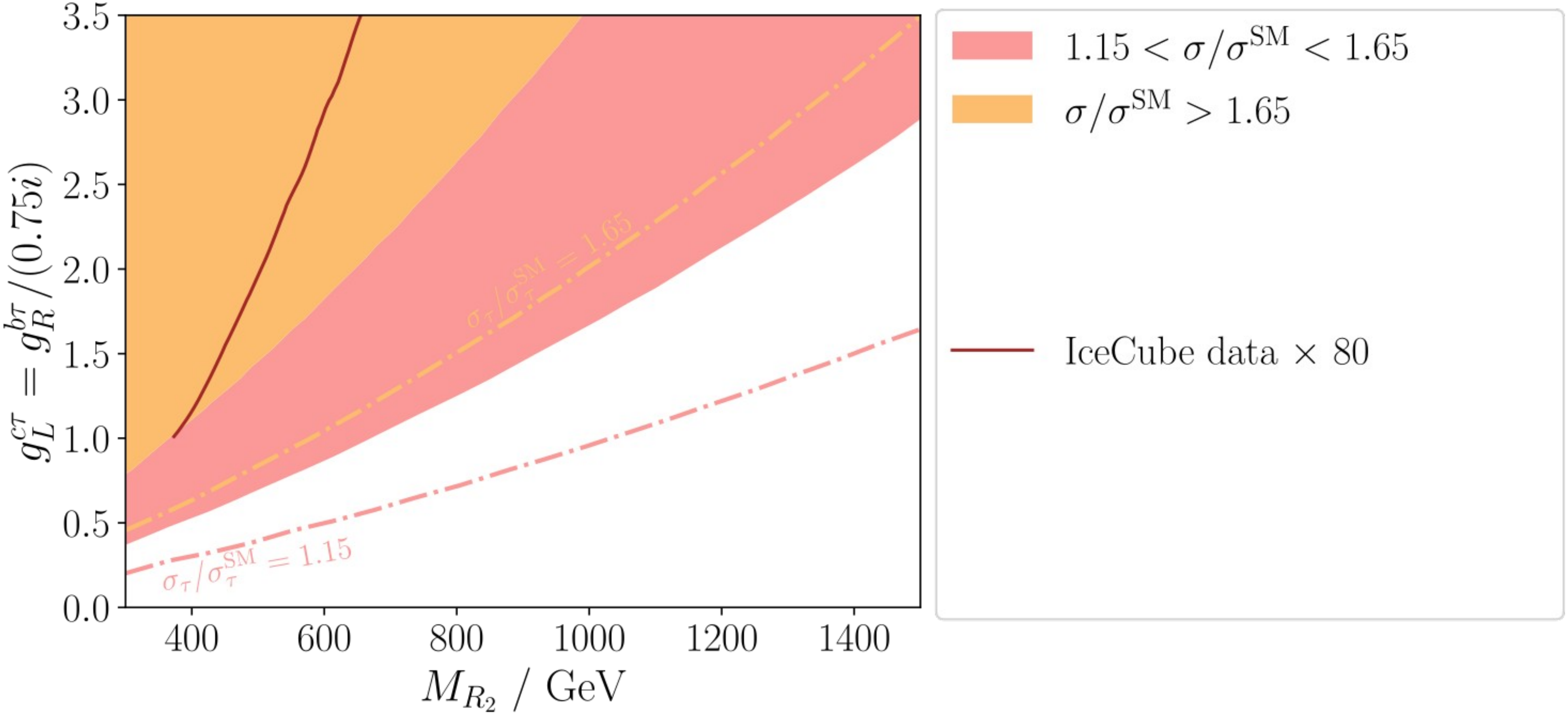
$R(D), R(D^*)$

- For R_2, choose two non zero couplings
  - $c\tau$ and $b\tau$
  - With one imaginary
- $\frac{|g_{c\tau}g_{b\tau}|}{M_{R_2}^2} \approx \frac{1}{(1.4\,\mathrm{TeV})^2}$ improves fit by $3.1\,\sigma$

Others

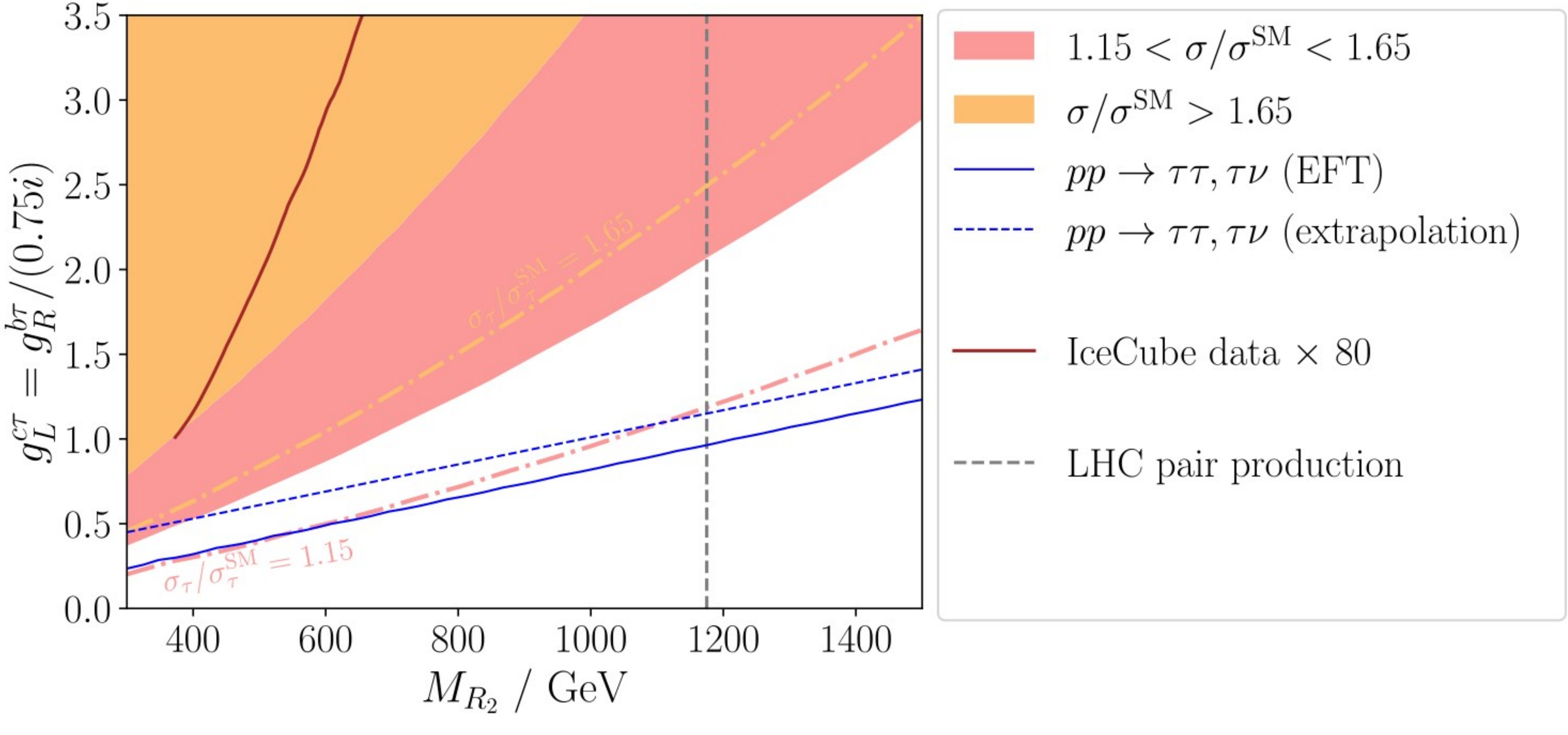
- S_1 mediates $\tau \to K\nu$, $D_s \to \tau\nu$
- R_2 with imaginary couplings gives quark EDMs
  - Neutron and mercury measurements
- At 1-loop, modified $Z \to \tau\tau$

R_2



3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$g_L^{c\tau} = g_R^{b\tau}/(0.75i)$
400
600
800
1000
1200
1400
M_{R_2} / GeV
$\sigma_\tau/\sigma_\tau^{\mathrm{SM}} = 1.65$
$\sigma_\tau/\sigma_\tau^{\mathrm{SM}} = 1.15$
$1.15 < \sigma/\sigma^{\mathrm{SM}} < 1.65$
$\sigma/\sigma^{\mathrm{SM}} > 1.65$
IceCube data × 80

R_2



3.5
3.0
2.5
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1.5
1.0
0.5
0.0
400
600
800
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1200
1400
M_{R_2} / GeV
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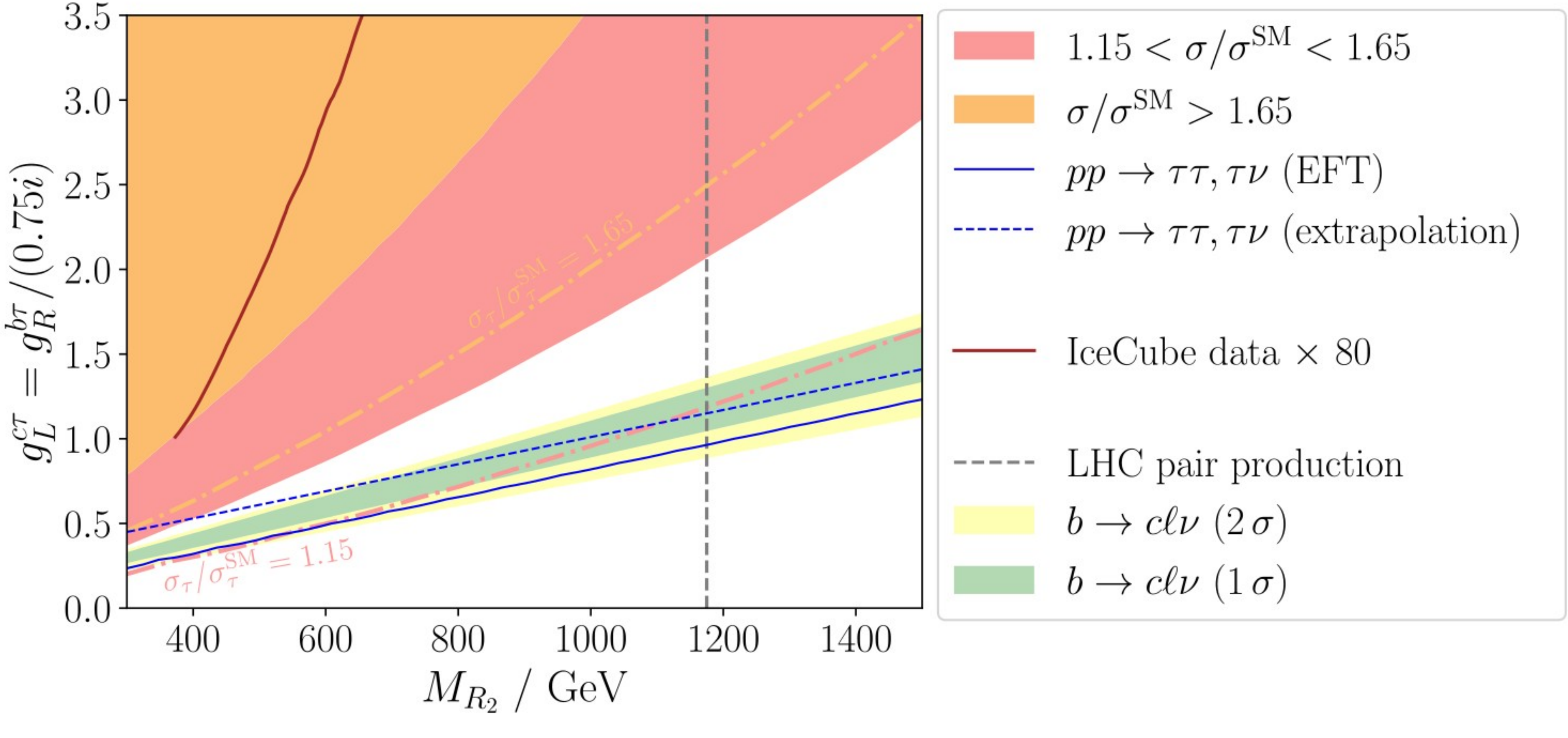
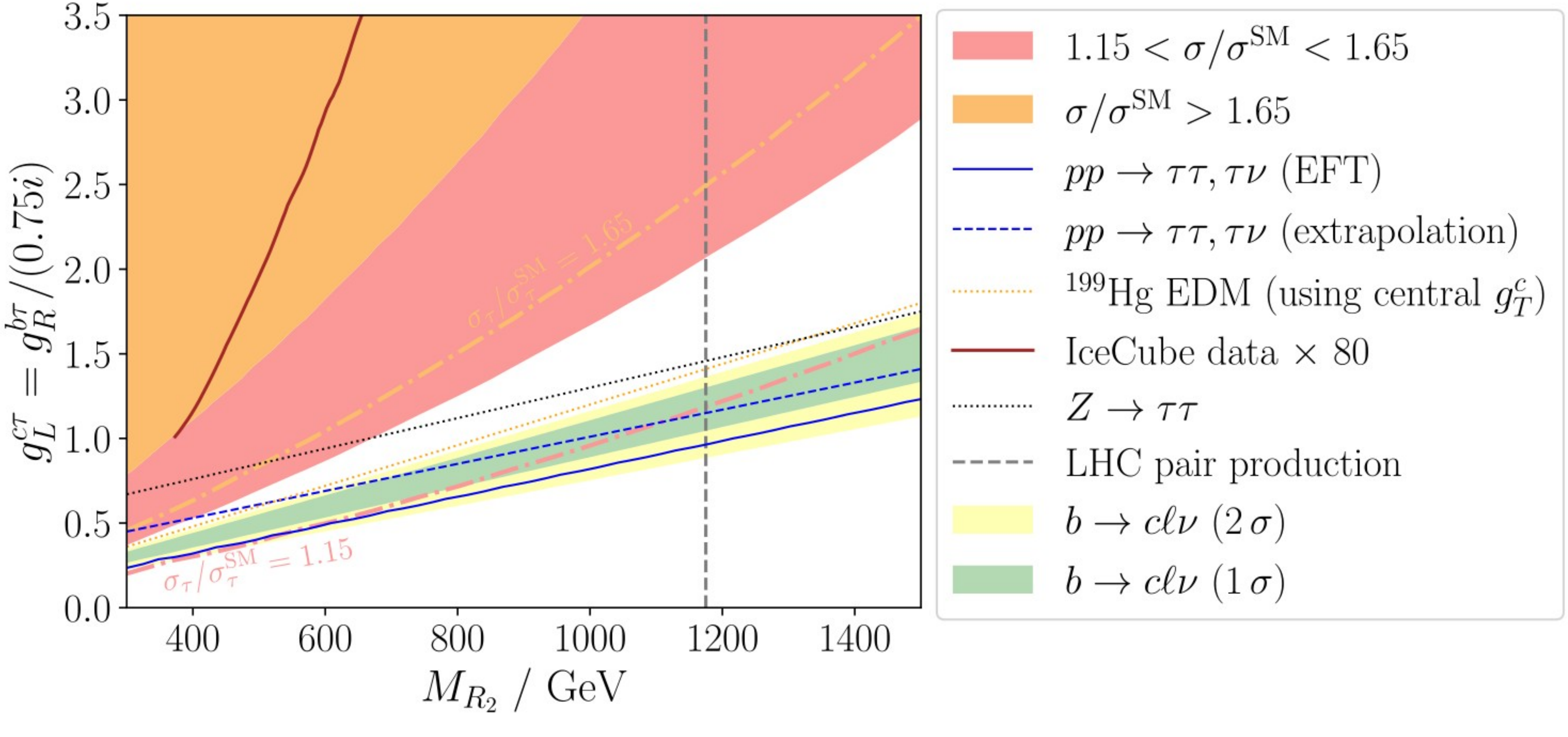
$\sigma_\tau/\sigma_\tau^{\rm SM} = 1.15$
$1.15 < \sigma/\sigma^{\rm SM} < 1.65$
$\sigma/\sigma^{\rm SM} > 1.65$
$pp \to \tau\tau, \tau\nu$ (EFT)
$pp \to \tau\tau, \tau\nu$ (extrapolation)
IceCube data × 80
LHC pair production

R_2



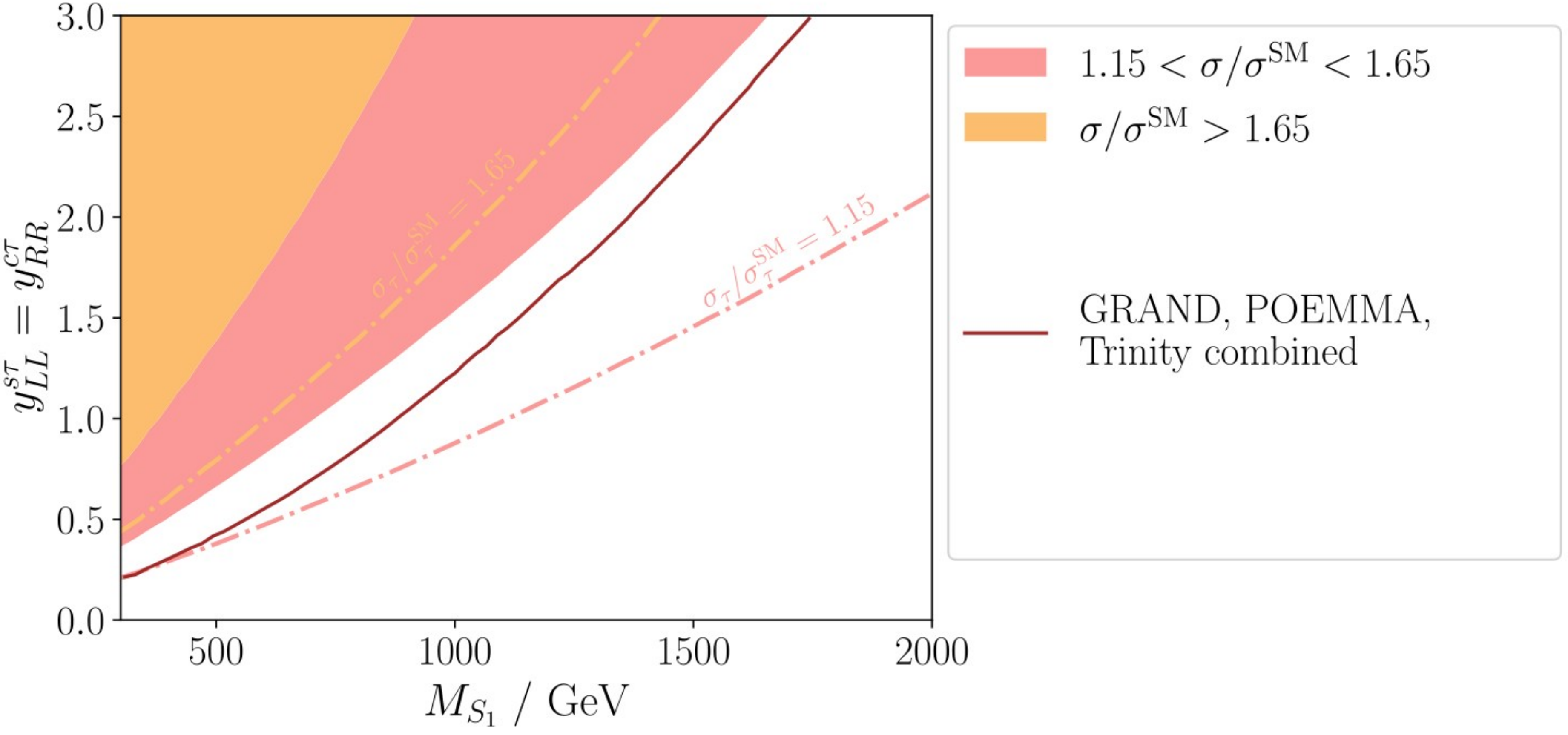
$1.15 < \sigma/\sigma^{SM} < 1.65$
$\sigma/\sigma^{SM} > 1.65$
$pp \to \tau\tau, \tau\nu$ (EFT)
$pp \to \tau\tau, \tau\nu$ (extrapolation)
IceCube data × 80
LHC pair production
$b \to c\ell\nu$ ($2\,\sigma$)
$b \to c\ell\nu$ ($1\,\sigma$)
$\sigma_\tau/\sigma_\tau^{SM} = 1.65$
$\sigma_\tau/\sigma_\tau^{SM} = 1.15$
$g_L^{c\tau} = g_R^{b\tau}/(0.75i)$
M_{R_2} / GeV
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
400
600
800
1000
1200
1400

R_2



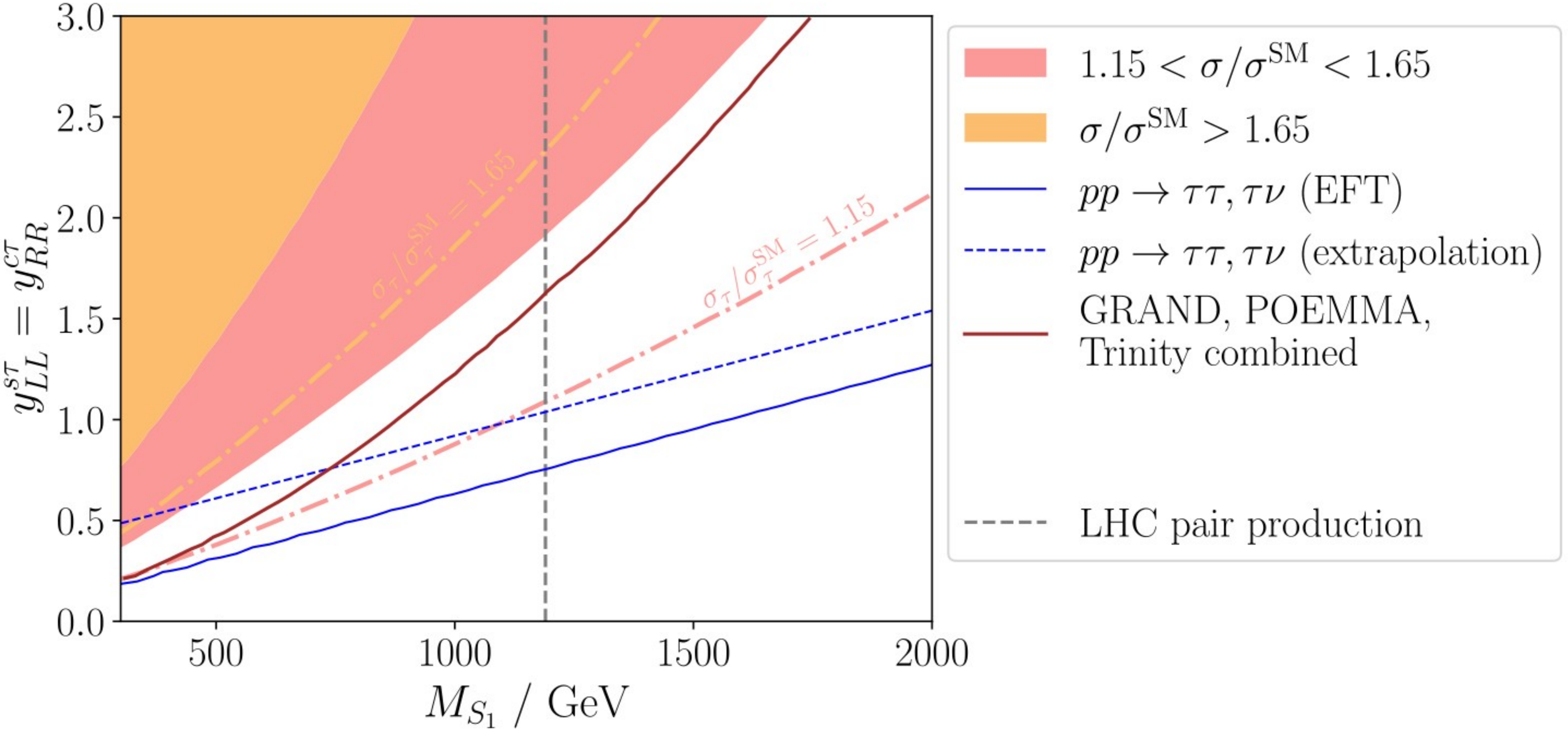
$g_L^{c\tau} = g_R^{b\tau}/(0.75i)$
M_{R_2} / GeV
$\sigma_\tau/\sigma_\tau^{SM} = 1.65$
$\sigma_\tau/\sigma_\tau^{SM} = 1.15$
$1.15 < \sigma/\sigma^{SM} < 1.65$
$\sigma/\sigma^{SM} > 1.65$
$pp \to \tau\tau, \tau\nu$ (EFT)
$pp \to \tau\tau, \tau\nu$ (extrapolation)
^{199}Hg EDM (using central g_T^c)
IceCube data × 80
$Z \to \tau\tau$
LHC pair production
$b \to c\ell\nu$ (2σ)
$b \to c\ell\nu$ (1σ)

S_1

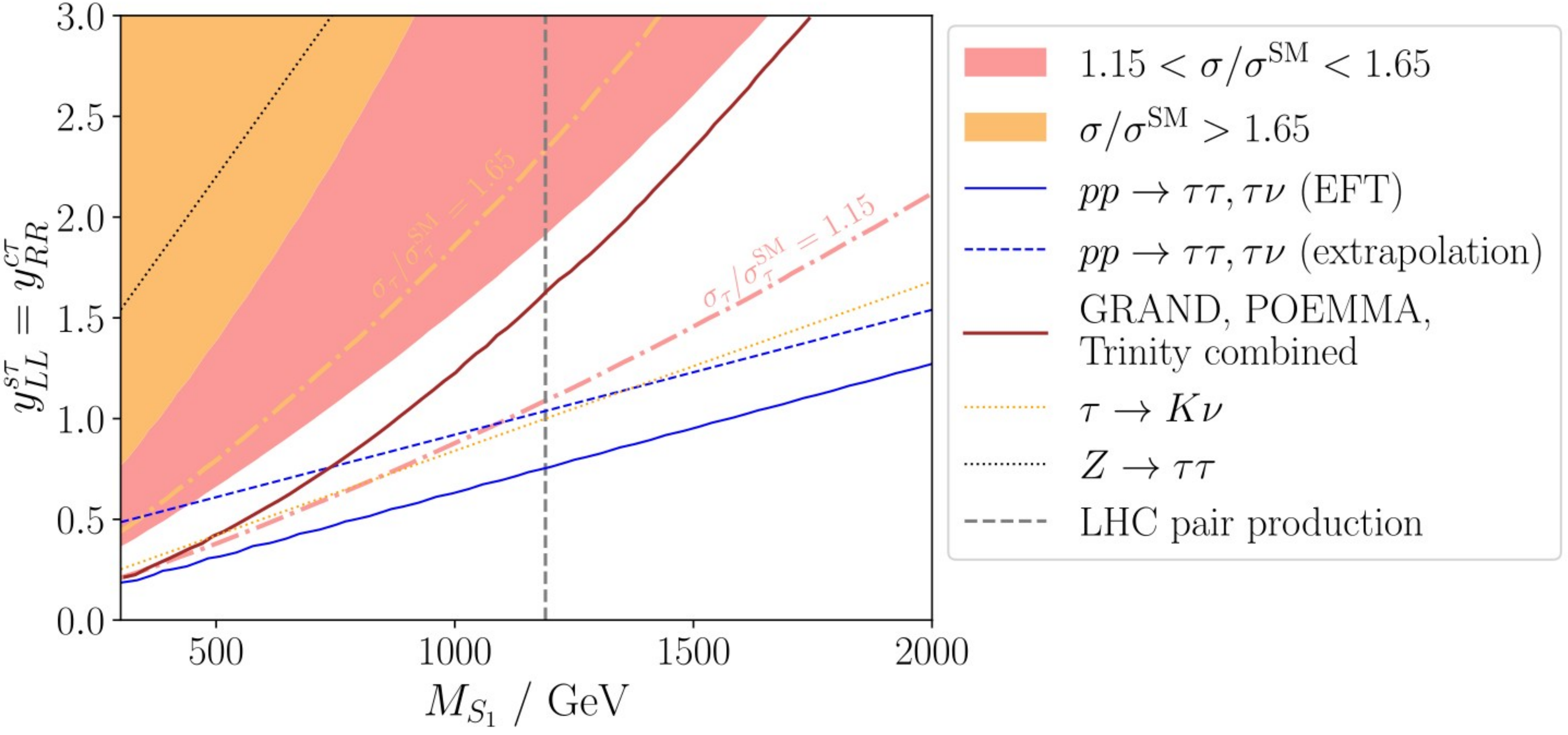


3.0
2.5
2.0
1.5
1.0
0.5
0.0
500
1000
1500
2000
M_{S_1} / GeV
$y^{s\tau}_{LL} = y^{c\tau}_{RR}$
$\sigma_\tau/\sigma_\tau^{SM} = 1.65$
$\sigma_\tau/\sigma_\tau^{SM} = 1.15$
$1.15 < \sigma/\sigma^{SM} < 1.65$
$\sigma/\sigma^{SM} > 1.65$
GRAND, POEMMA,
Trinity combined

S_1


3.0
2.5
2.0
1.5
1.0
0.5
0.0
$y_{LL}^{s\tau} = y_{RR}^{c\tau}$
500
1000
1500
2000
M_{S_1} / GeV
$\sigma_\tau/\sigma_\tau^{SM} = 1.65$
$\sigma_\tau/\sigma_\tau^{SM} = 1.15$
$1.15 < \sigma/\sigma^{SM} < 1.65$
$\sigma/\sigma^{SM} > 1.65$
$pp \to \tau\tau, \tau\nu$ (EFT)
$pp \to \tau\tau, \tau\nu$ (extrapolation)
GRAND, POEMMA, Trinity combined
LHC pair production

S_1



3.0
2.5
2.0
1.5
1.0
0.5
0.0
$y_{LL}^{s\tau} = y_{RR}^{c\tau}$
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1500
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M_{S_1} / GeV
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$\sigma/\sigma^{SM} > 1.65$
$pp \to \tau\tau, \tau\nu$ (EFT)
$pp \to \tau\tau, \tau\nu$ (extrapolation)
GRAND, POEMMA, Trinity combined
$\tau \to K\nu$
$Z \to \tau\tau$
LHC pair production

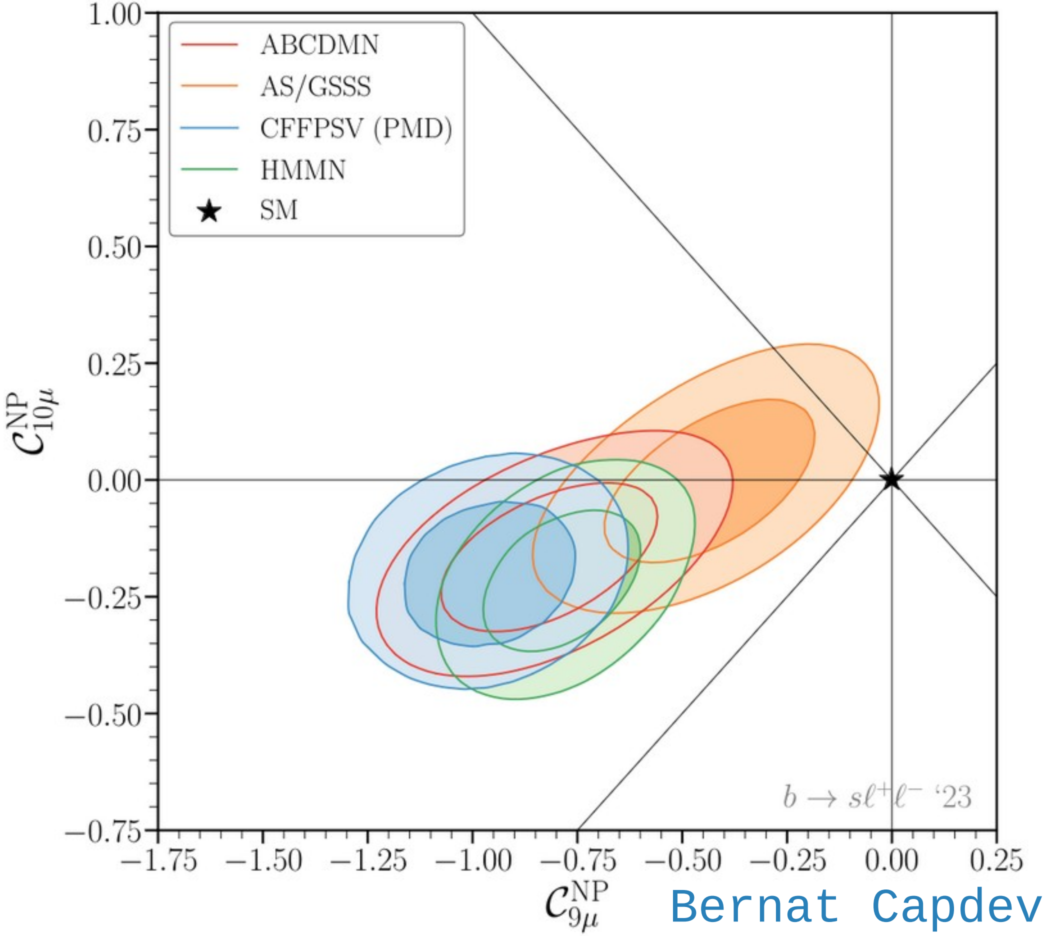
2) LQs without leptons for $bs\ell\ell$ anomalies?

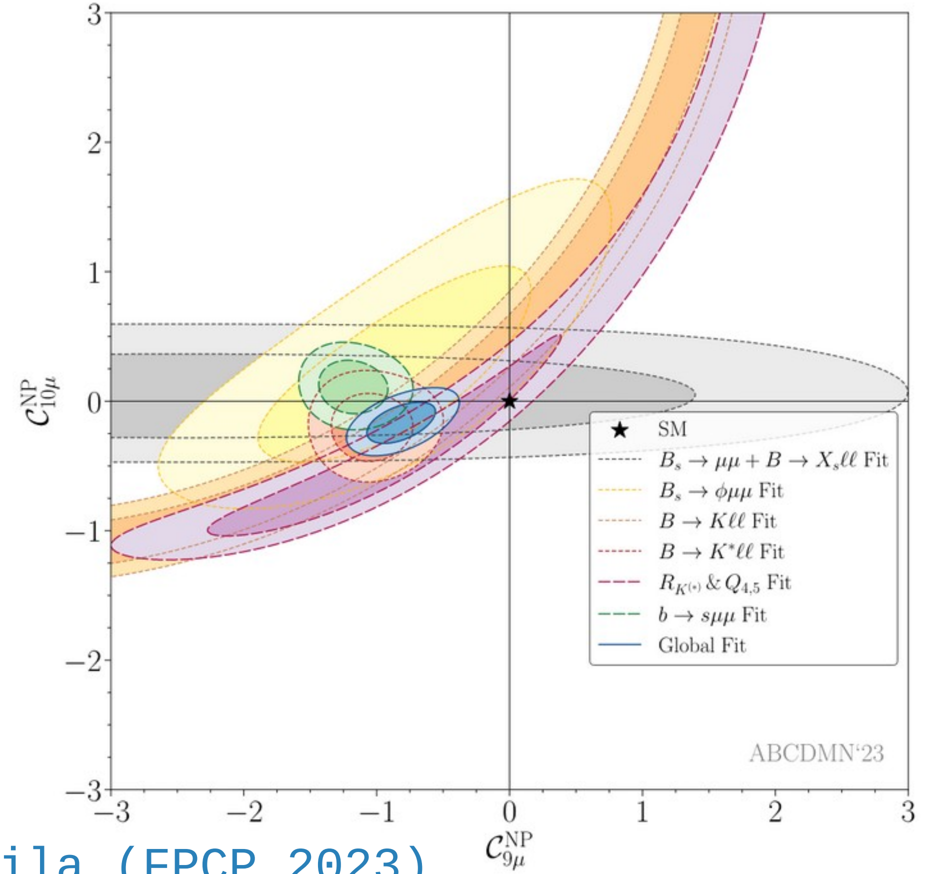
(based on `2309.07205` with Andreas Crivellin)

$bs\ell\ell$ anomalies

- Since 2013 there have been deviations in $b \to s\mu\mu$ decays
- For a while we thought these were muon specific, but since Dec 22 it appears not

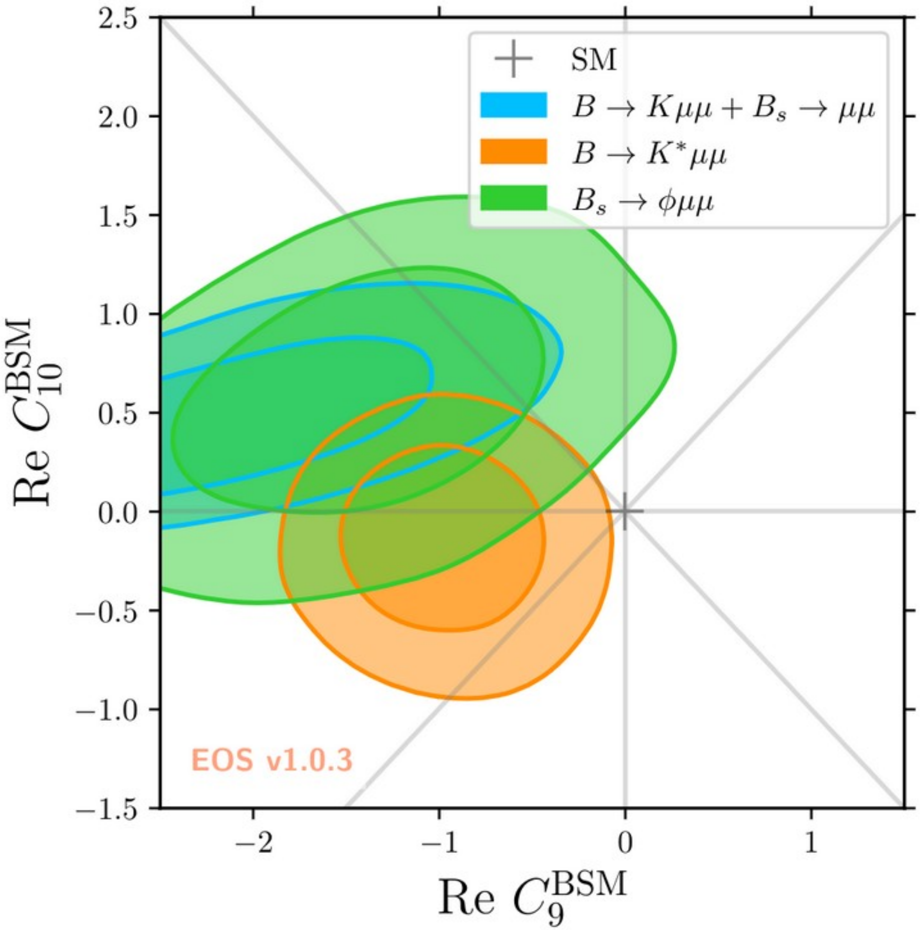
$bs\ell\ell$ anomalies





Bernat Capdevila (FPCP 2023)

$bs\ell\ell$ anomalies



Gubernari, Reboud, van Dyk, Virto (2206.03797)

$bs\ell\ell$ anomalies

- Since 2013 there have been deviations in $b \to s\mu\mu$ decays
- For a while we thought these were muon specific, but since Dec 22 it appears not
- So you need to keep universality in leptons

LQs for $bs\ell\ell$

- LQs are natural models for $bs\ell\ell$
  - But a LQ coupling to multiple lepton generations generally leads to LFV
- Old idea: NP in $bscc$?

JKLL 1701.09183
& 1910.12924

Charming new physics in b(eautiful) processes?

(based on 1701.09183)

Sebastian Jäger, Matthew Kirk, *Alex Lenz*, *Kirsten Leslie*

13th March 2017

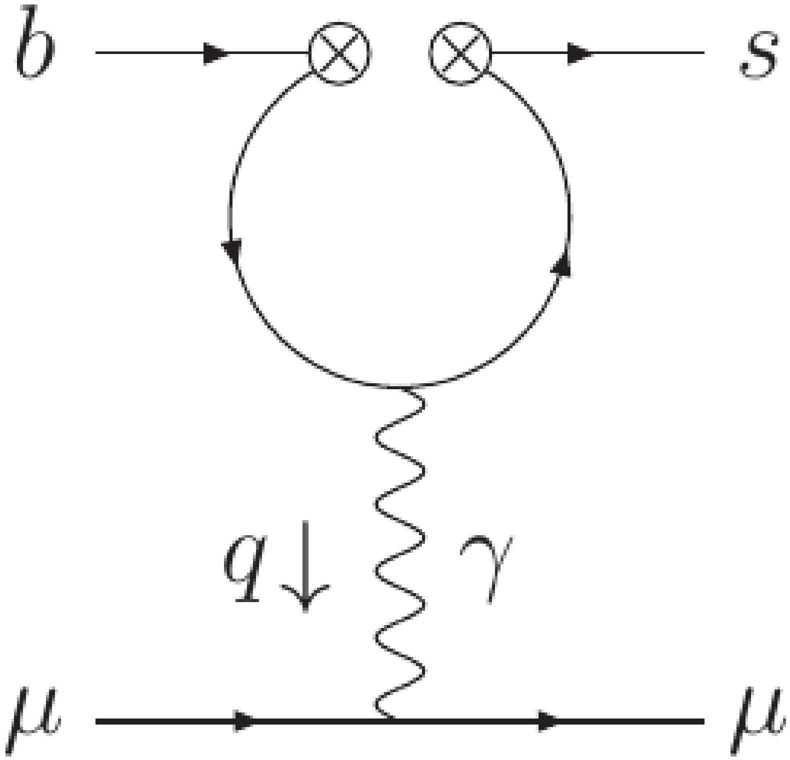
Durham University

IP3

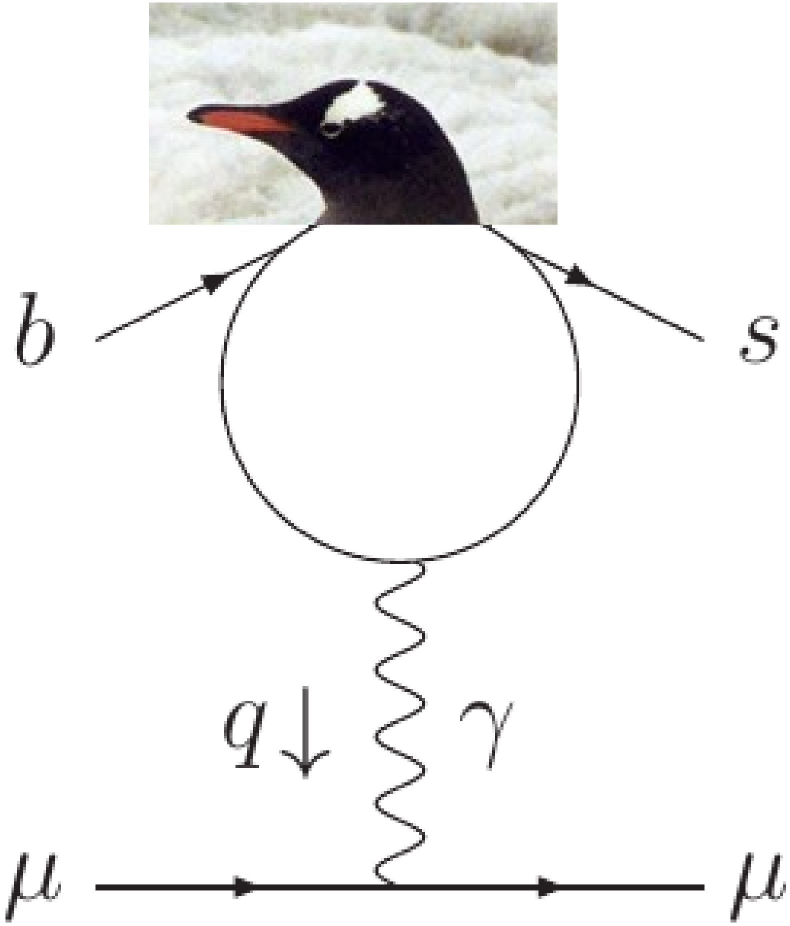
$bscc \to bs\ell\ell$

- In the SM, about half of the C_9 coefficient ($bs\ell\ell$ EFT operator) generated through charm loops

$$bscc \to bs\ell\ell$$



$$bscc \to bs\ell\ell$$



$bscc \to bs\ell\ell$

- In the SM, about half of the C_9 coefficient ($bs\ell\ell$ EFT operator) generated through charm loops
- What if some NP modified $bscc$ operators?
- Potential for large $bs\ell\ell$ effects, plus correlated effects in various precise B meson observables

$bscc \to bs\ell\ell$

- Potential for large $bs\ell\ell$ effects, plus correlated effects in various precise B meson observables
  - B_s meson mixing ($\Delta\Gamma_s$)
  - B meson lifetimes ($\tau(B_s)/\tau(B_d)$)
  - $B \to X_s\gamma$

UV $\rightarrow bscc$

- What kind of NP can generate $bscc$ after being integrated out?
  - Size of anomaly suggests tree level effect
- If tree level b and s interactions, need to avoid tree level B_s mixing (known at O(3%) precision)
  - Big problem for Z's, or heavy gluon type field

UV $\to bscc$

- Charged Higgs is one option
- Has been re-examined recently

Kumar 2212.07233
& Iguro 2302.08935

- But parameter space is quite constrained ($M_{H^+} \leq 200 - 250\,\mathrm{GeV}$)

S_1

- Consider the $S_1 : (\mathbf{3}, \mathbf{1}, -1/3)$
- In addition to lepton-quark interactions, can write down quark-quark interactions
- Only get $u - d - S_1$ terms, not $d - d - S_1$ or $u - u - S_1$, so safe from meson mixing

S_1 LQ without leptons

- In general, having both lepton-quark and quark-quark couplings leads to tree level proton decay
- So often people drop the diquark term
- But instead we drop the lepton-quark term

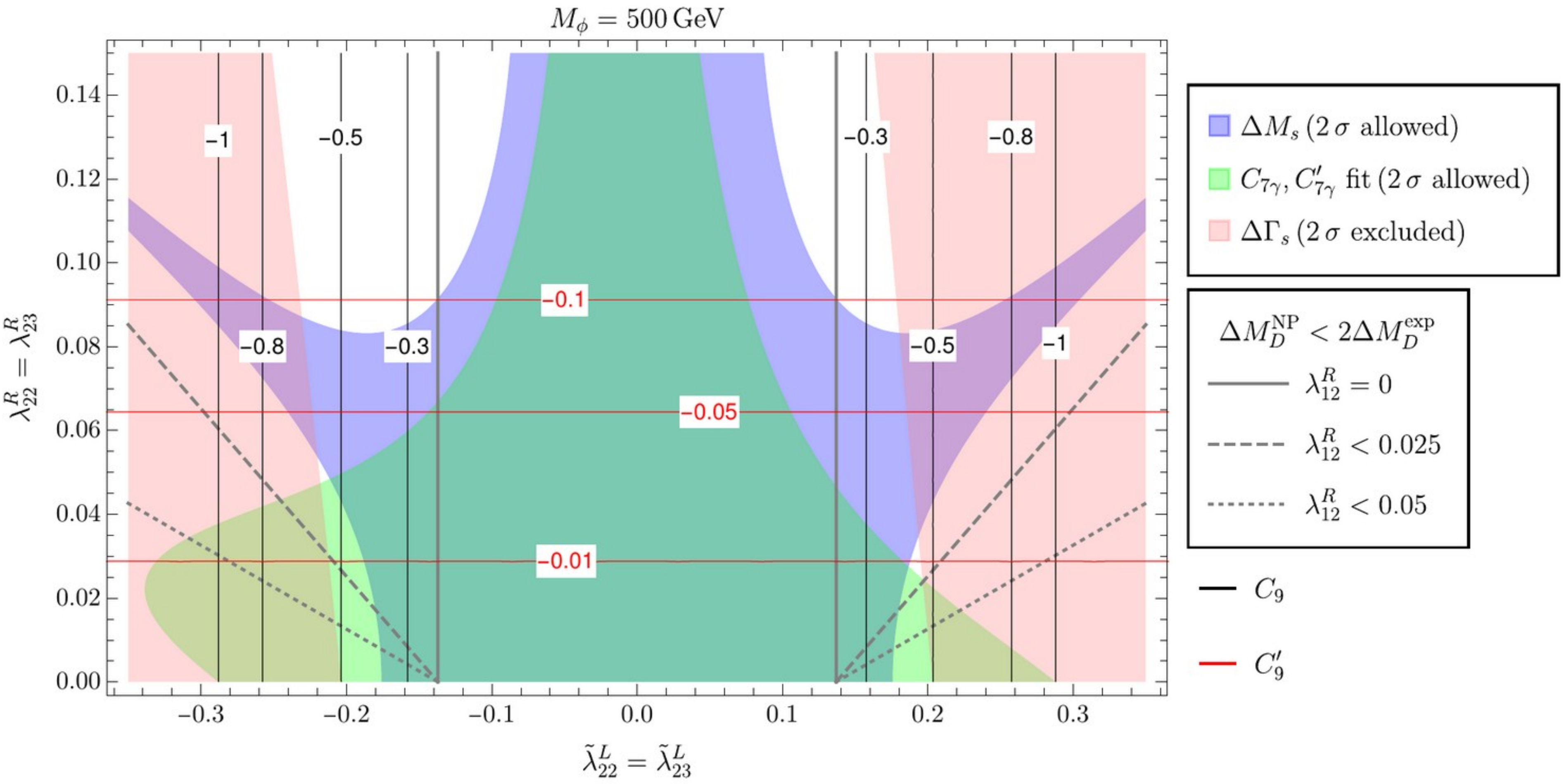
S_1 diquark

- $(\lambda_L \bar{Q}^c Q + \lambda_R \bar{u}^c d) S_1$
- $\to \bar{u}^c (\lambda_L P_L + \lambda_R P_R) d \, S_1$

S_1 diquark

- It will turn out that we need the S_1 to be quite light – $M_{S_1} \sim 500\,\mathrm{GeV}$
- Integrate it out along with top/Z/W
- Loop calculations give (extra) constraints from B_s mixing, $B \to X_s\gamma$, D mixing

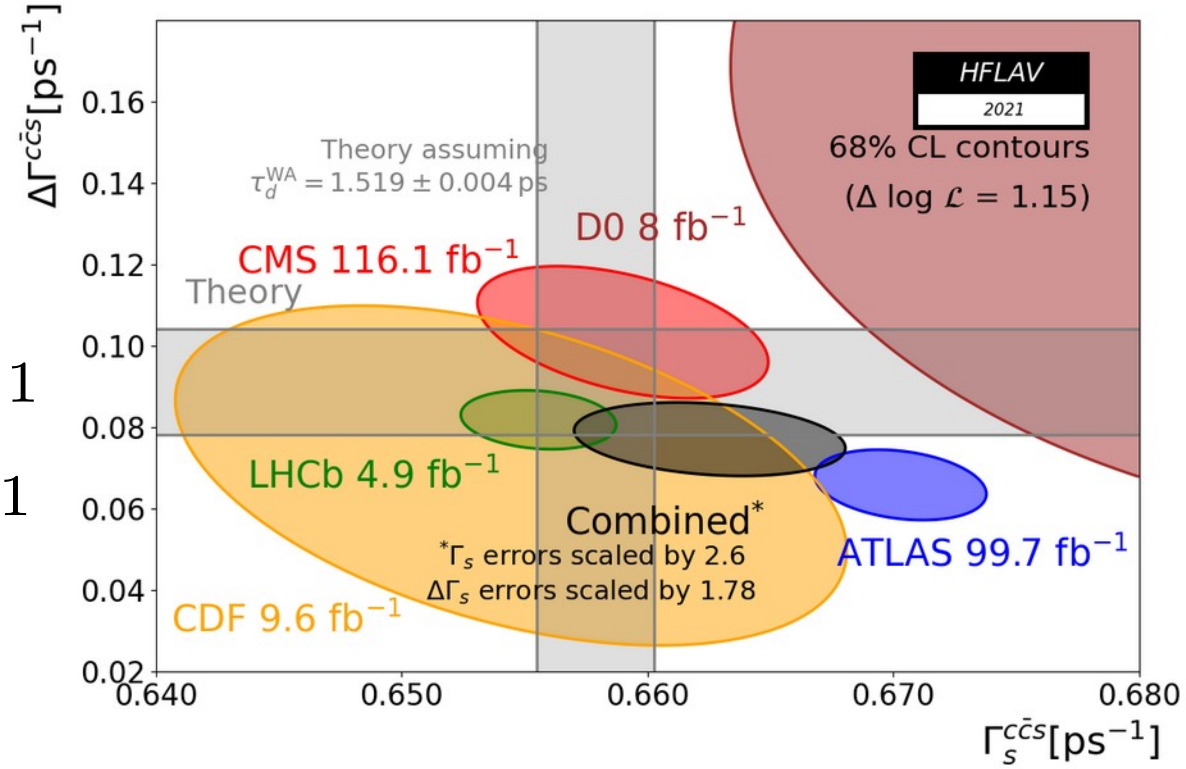
Results



$M_\phi = 500\,\mathrm{GeV}$
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
$\lambda^R_{22} = \lambda^R_{23}$
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
$\tilde{\lambda}^L_{22} = \tilde{\lambda}^L_{23}$
−1
−0.5
−0.3
−0.8
−0.8
−0.3
−0.5
−1
−0.1
−0.05
−0.01
ΔM_s ($2\,\sigma$ allowed)
$C_{7\gamma}, C'_{7\gamma}$ fit ($2\,\sigma$ allowed)
$\Delta\Gamma_s$ ($2\,\sigma$ excluded)
$\Delta M_D^{\mathrm{NP}} < 2\Delta M_D^{\mathrm{exp}}$
$\lambda^R_{12} = 0$
$\lambda^R_{12} < 0.025$
$\lambda^R_{12} < 0.05$
C_9
C'_9

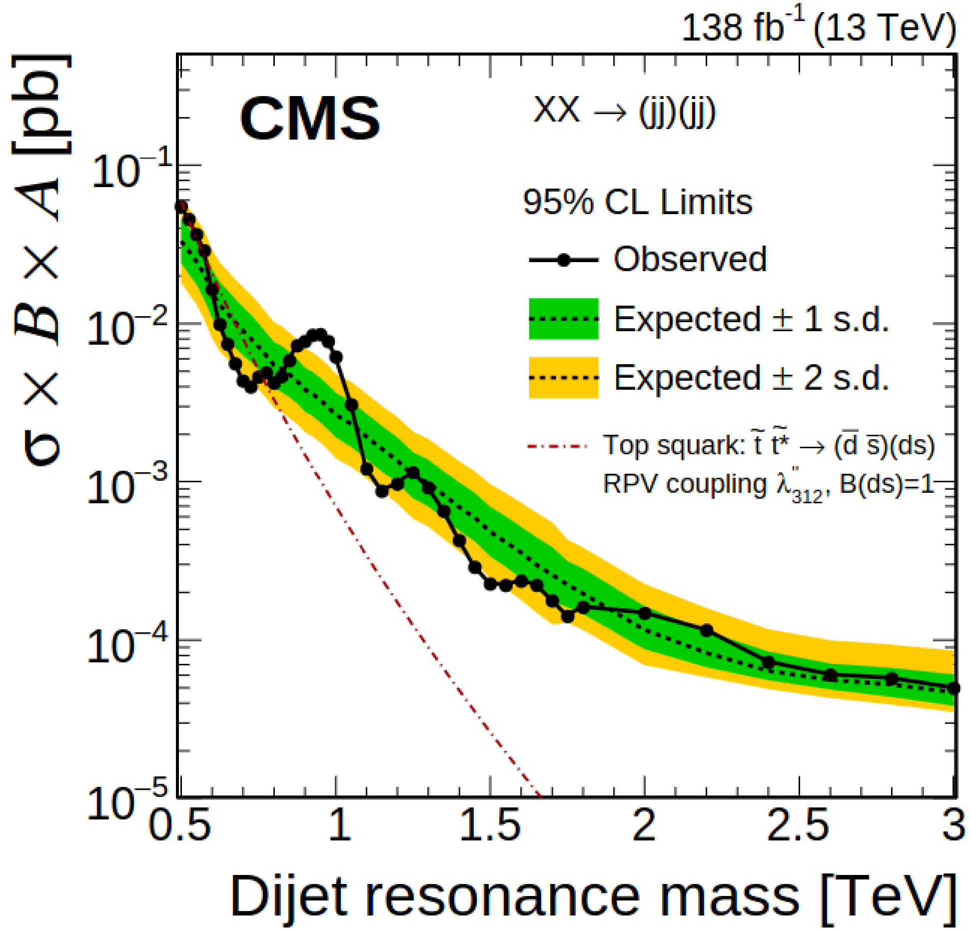
Results

- Interestingly, we predict an increase to $\Delta\Gamma_s$
- From $90 \times 10^{-3}\,\mathrm{ps}^{-1}$ $\rightarrow 110 \times 10^{-3}\,\mathrm{ps}^{-1}$



Results

- CMS di-di-jet analysis (2206.09997)
  - Hints for 500 GeV scalar?



Results

hep-ph/0011258

- Missing charm puzzle?
  - Inclusive $b \to c\bar{c}s$ rate

Some comments on the missing charm puzzle

Alexander Lenz
Universität Regensburg, D-93040 Regensburg, Germany
E-mail: alexander.lenz@physik.uni-regensburg.de

Abstract. In this talk we summarize the status of theoretical predictions for the average number of charm quarks in a B-hadron decay.

New physics in inclusive decays? II

Motivation for a re-analysis of inclusive decays:

- Old analyses at least 15 years old - input parameters ($m_b, m_c, V_{CKM}, ...$) are now much better known
  Missing charm puzzle; semileptonic branching fraction, e.g.
  Bigi et al '94; Bagan et al. '94; Falk, Wise, Dunietz '95, Buchalla et al '95; Neubert '97; Kagan '97,'98,... A.L. ,hep-ph/0011258
- Theory is now much more reliable! e.g. $b \to c\bar{c}s$
- Many rare decays were neglected, e.g. $b \to sg, b \to u\bar{u}s, ...$
- Some NLO-QCD contributions are still missing
- Experimental improvements - latest number from BaBar; hep-ex/0606026
- This gives model and even decay channel independent bounds

Thanks!

BACKUP

UHE neutrino source

Introduction

Ivan Esteban, Ohio State University, esteban.6@osu.edu

See arXiv:2205.09763, with S. Prohira and J. F. Beacom!

What about neutrinos?

The idea is simple:

Ultra-high energy proton flux ⇒ **Ultra-High Energy neutrino flux**

$$p + \gamma_{\mathrm{bkg}} \Rightarrow \Delta^+ \Rightarrow n + \pi^+$$

$$n \Rightarrow p + e^- + \bar{\nu}_e$$

$$\pi^+ \Rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \Rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

Greisen–Zatsepin–Kuzmin, 1966

For $E_p \gtrsim 10^9\,\mathrm{GeV}$, we **expect** this flux at $E_\nu \sim 10^7$–$10^{10}\,\mathrm{GeV}$

$$\phi_\nu \sim 1\text{–}100\,\nu/\mathrm{km}^2/\mathrm{year}$$

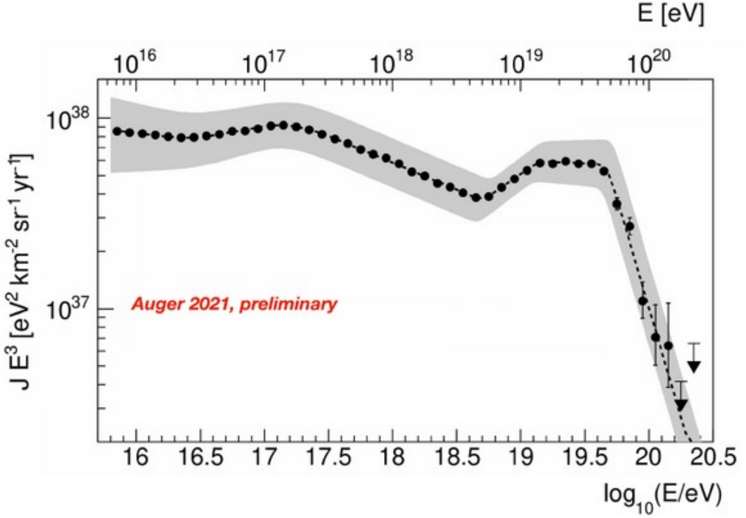
UHE neutrino source

Introduction

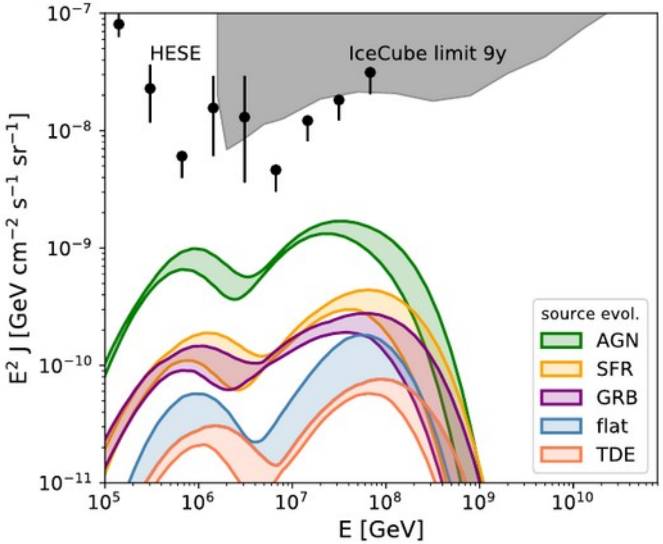
Ivan Esteban, Ohio State University, esteban.6@osu.edu
See arXiv:2205.09763, with S. Prohira and J. F. Beacom!

6 / 22 **What about neutrinos?**

Ultra-high energy proton flux ⇒ **Ultra-High Energy neutrino flux**



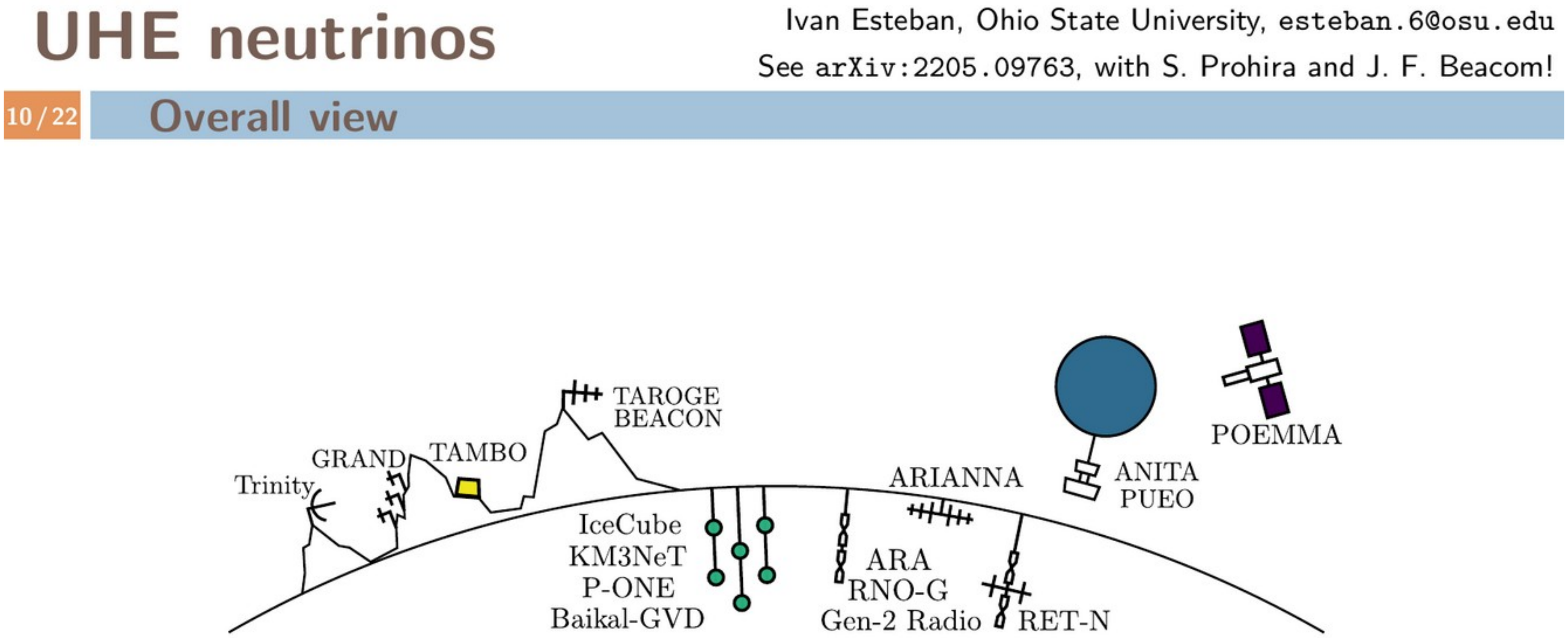
Auger, ICRC2021



Heinze et al, 1901.03338

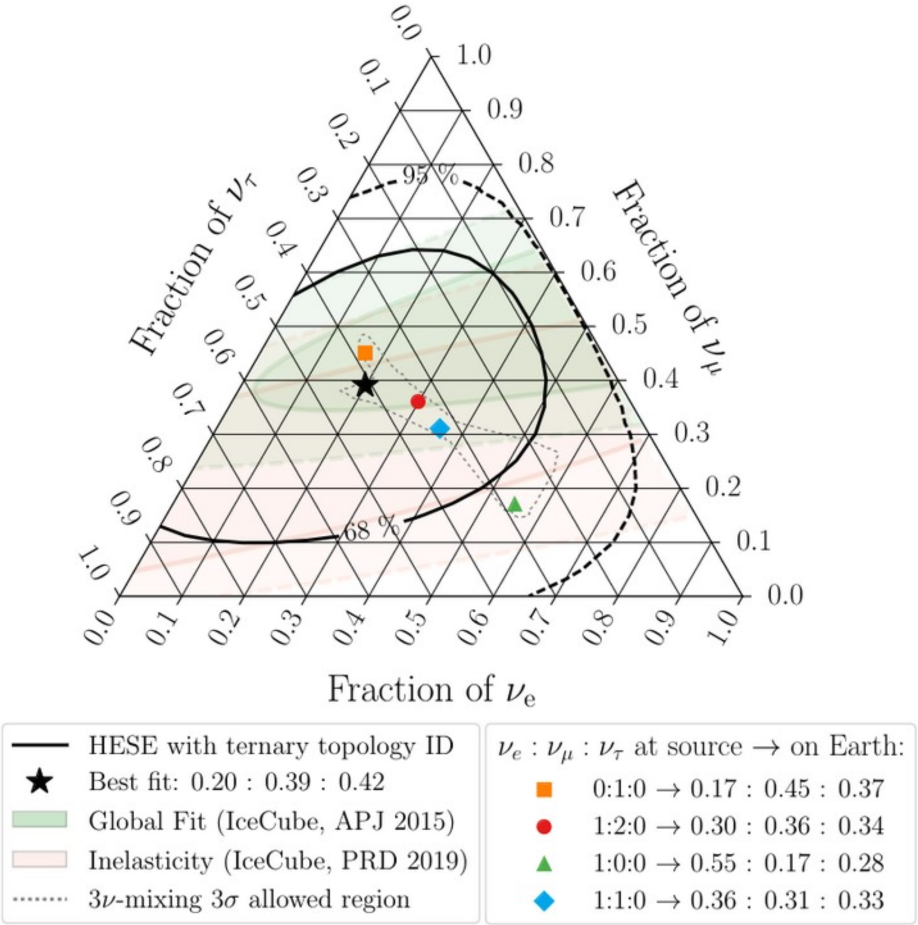
(Of course, sources could also directly produce neutrinos)

UHE neutrino experiments

- 

Flavour composition of neutrinos

- 2011.03561



ATLAS di-jet

- 1804.03496