Strategieworkshop Bonn
May 2018

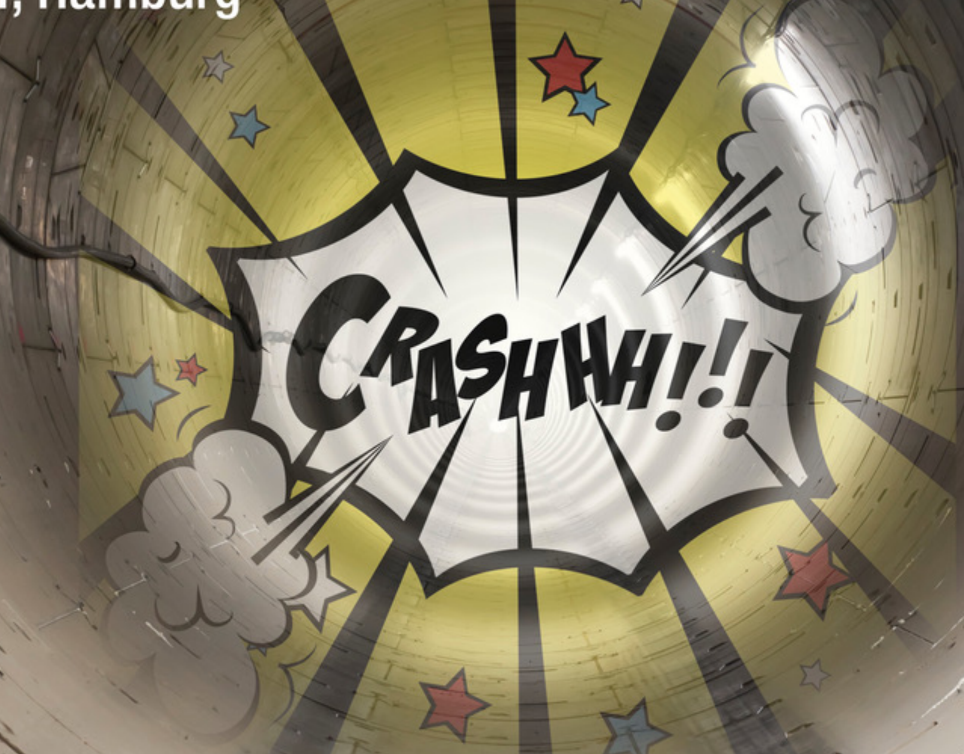
Physics opportunities for future high-energy proton colliders

Michael Krämer (RWTH Aachen University)

Workshop on

Future Hadron Colliders at the Energy Frontier

14-15 December 2017
DESY, Hamburg



The German committees for elementary particle physics (KET), astroparticle physics (KAT) and hadron & nuclear physics (KHuK) are jointly organising a workshop on future hadron colliders at the energy frontier.

Programme Committee:
Kerstin Borras (DESY, RWTH Aachen),
Volker Büscher (Mainz), Gregor Herten (Freiburg),
Frank Maas (Mainz), Silvia Masciocchi (GSI),
Joachim Mnich (DESY), Andre Schöning (Heidelberg),
Christian Weinheimer (Münster), Dieter Zeppenfeld (KIT)

Organizing Committee:
Manfred Fleischer, Michaela Grimm
Thomas Schörner, Anita Teufel

Contact:
hadron-collider-ws@desy.de

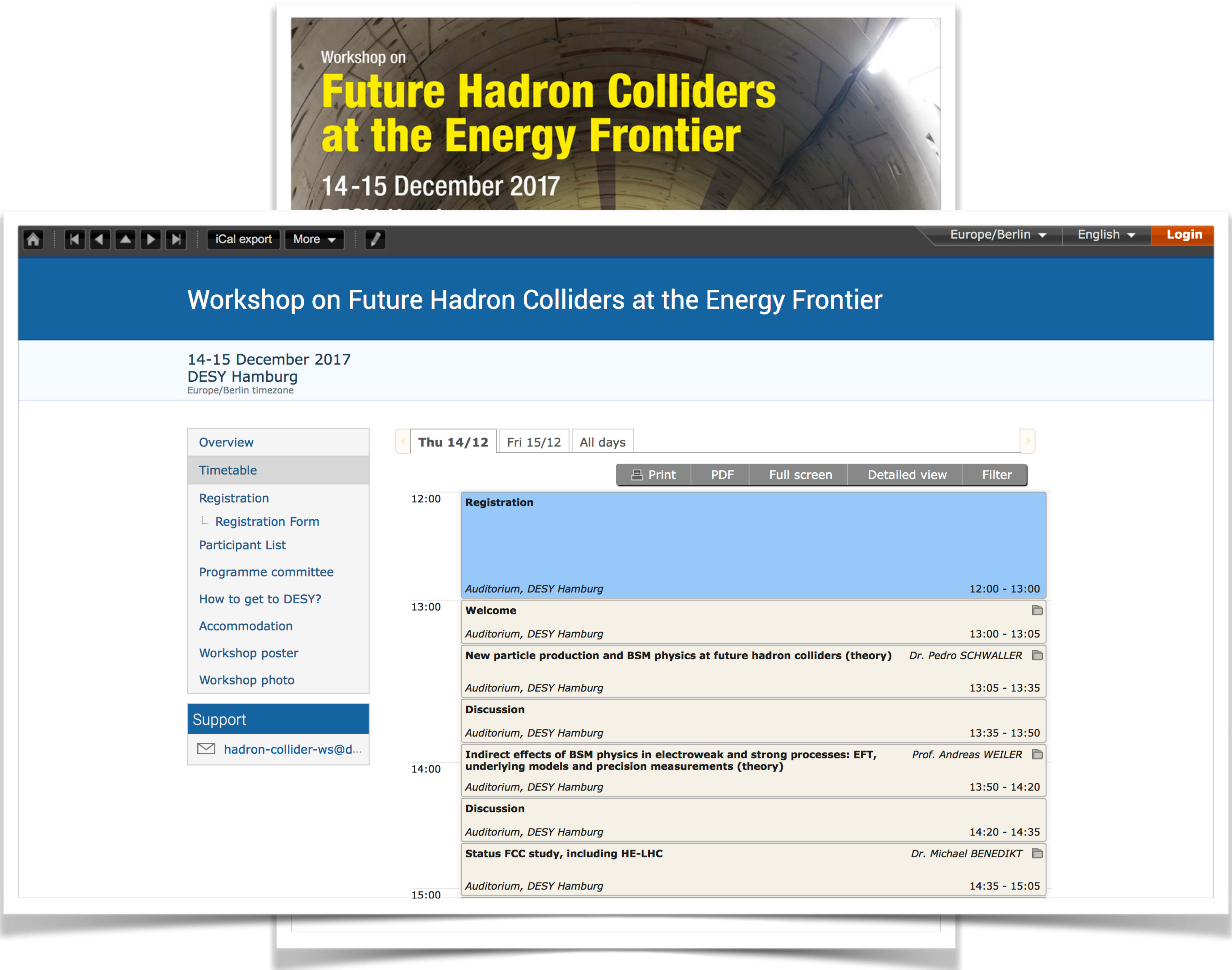
http://hadroncollisions.desy.de

KAT. Komitee für Astro. Teilchen. Physik

KET Komitee für Elementarteilchenphysik

KHUK

DESY


Workshop on
Future Hadron Colliders at the Energy Frontier
14-15 December 2017
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14-15 December 2017
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Programme committee
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hadron-collider-ws@d...
Thu 14/12
Fri 15/12
All days
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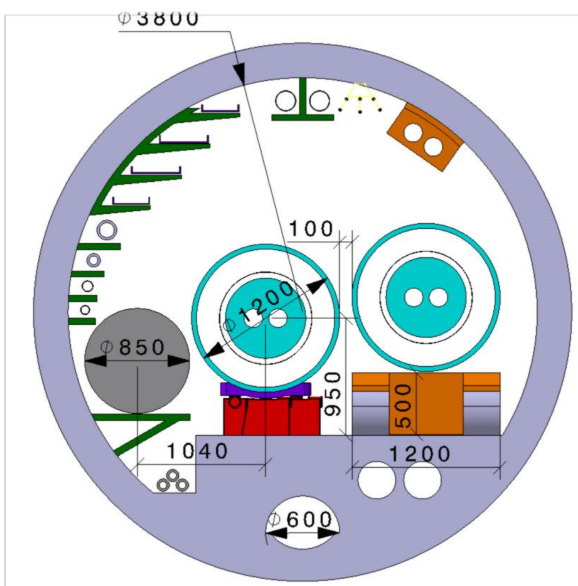
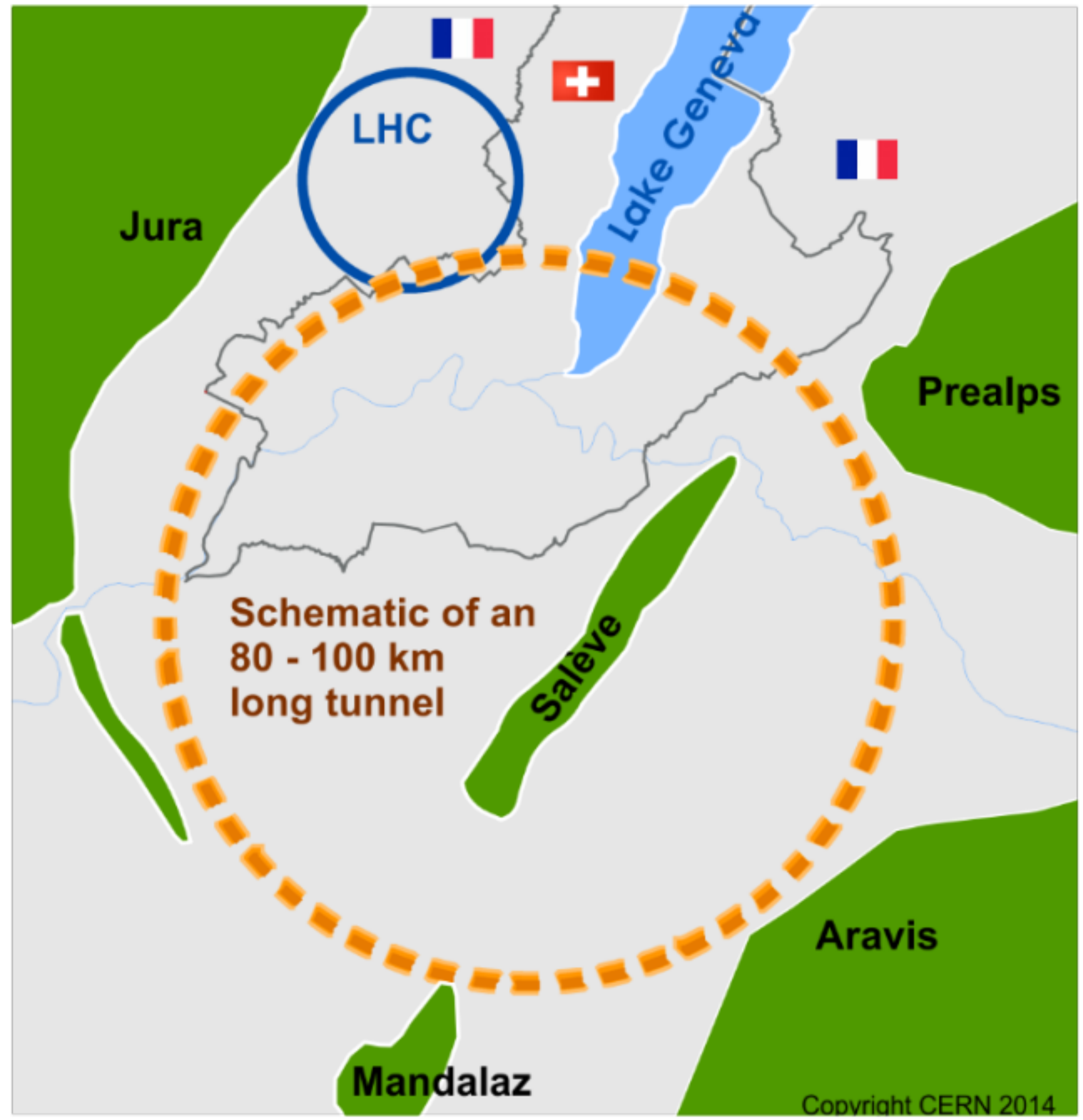
Registration
Auditorium, DESY Hamburg
12:00 - 13:00
13:00
Welcome
Auditorium, DESY Hamburg
13:00 - 13:05
New particle production and BSM physics at future hadron colliders (theory)
Dr. Pedro SCHWALLER
Auditorium, DESY Hamburg
13:05 - 13:35
Discussion
Auditorium, DESY Hamburg
13:35 - 13:50
14:00
Indirect effects of BSM physics in electroweak and strong processes: EFT, underlying models and precision measurements (theory)
Prof. Andreas WEILER
Auditorium, DESY Hamburg
13:50 - 14:20
Discussion
Auditorium, DESY Hamburg
14:20 - 14:35
Status FCC study, including HE-LHC
Dr. Michael BENEDIKT
Auditorium, DESY Hamburg
14:35 - 15:05
15:00

Future high-energy hadron colliders

FCC
hh ee he

HE-LHC



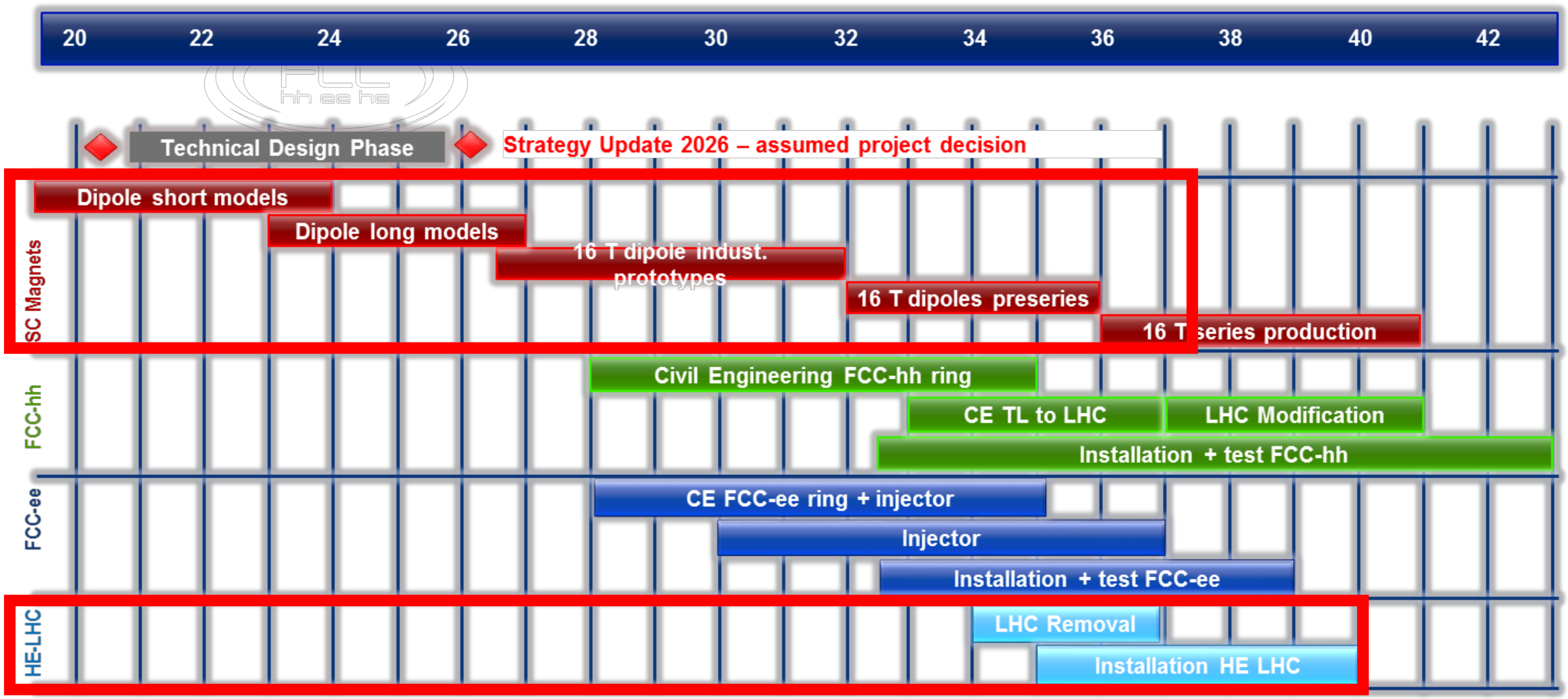


Future high-energy hadron colliders

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		**27**	14
dipole field [T]	16		**16**	8.3
circumference [km]	100		**27**	27
beam current [A]	0.5		**1.12**	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		**2.2**	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		**25 (12.5)**	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (2.2)		**2.5 (1.25)**	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	**0.25**	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	**25**	(5) 1
peak #events / bunch Xing	170	1000 (500)	**800** (400)	(135) 27
stored energy / beam [GJ]	8.4		**1.4**	(0.7) 0.36
SR power / beam [kW]	2400		**100**	(7.3) 3.6
transv. emit. damping time [h]	1.1		**3.6**	25.8
initial proton burn off time [h]	17.0	3.4	**3.0**	(15) 40

M. Benedikt

Future high-energy hadron colliders



technical schedule defined by magnets program and by CE
→ earliest possible physics starting dates:

- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop at LS5 / 2034)

HE-LHC

design & construction

M. Benedikt

References

CERN Yellow Report CERN-2017-003-M

https://arxiv.org/abs/1710.06353

- SM processes
- Higgs physics and EW symmetry breaking
- BSM phenomena
- Heavy Ion physics at FCC-hh
- Physics with the FCC-hh injectors

See also **FCC week 2018:** https://indico.cern.ch/event/656491/

Physics opportunities for high-energy colliders

- **Explore electroweak symmetry breaking**
- **Search for new particles**
- **Probe Standard Model dynamics**

Physics opportunities for high-energy colliders

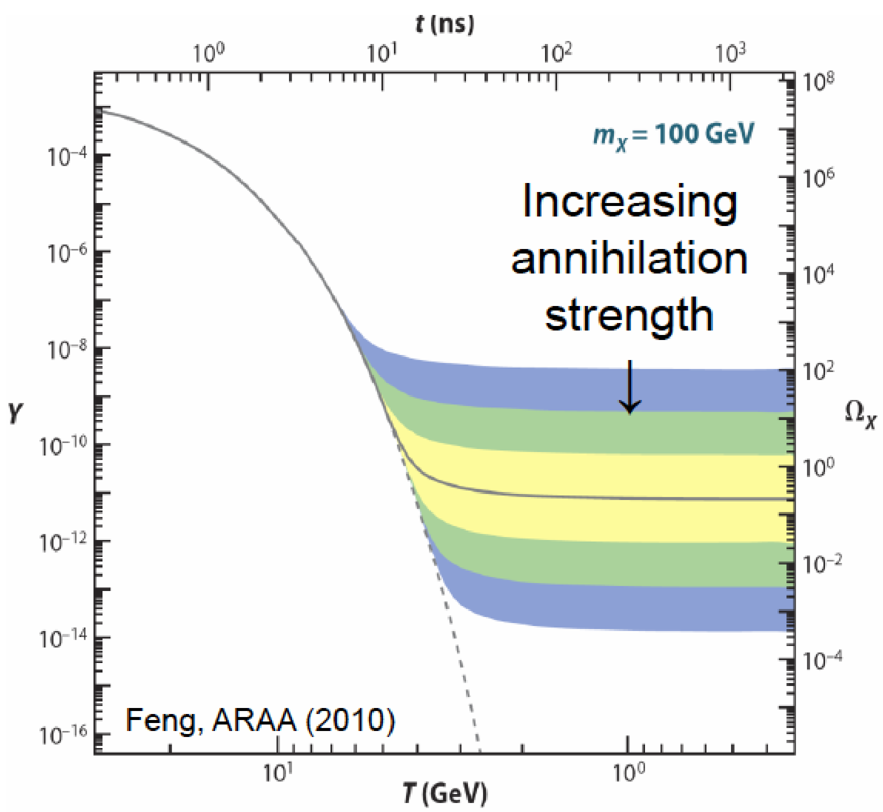
Explore electroweak symmetry breaking

$$\mathcal{L}_{\rm SM} \supset -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 - Y^{ij}\overline{\psi}^i_L H \psi^j_R$$

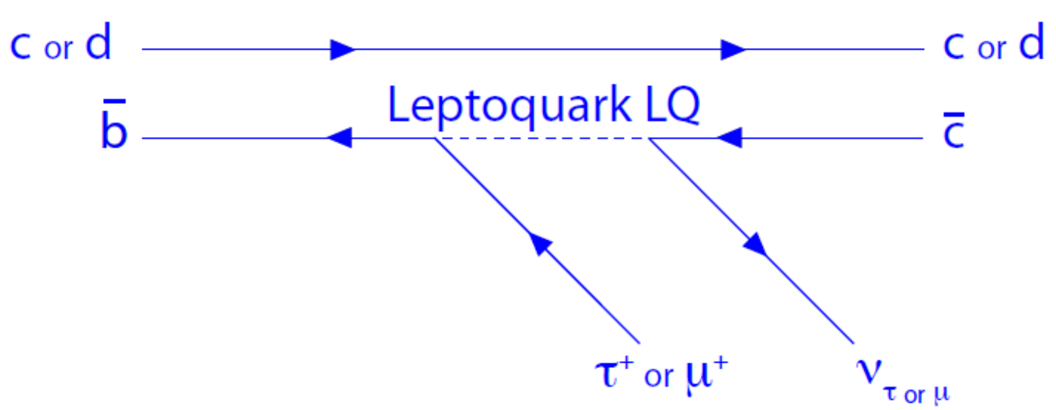
naturalness?	vacuum stability?	flavour structure?
portal to dark sector?	electroweak phase transition?	mass hierarchies?

Search for new particles

WIMP dark matter?

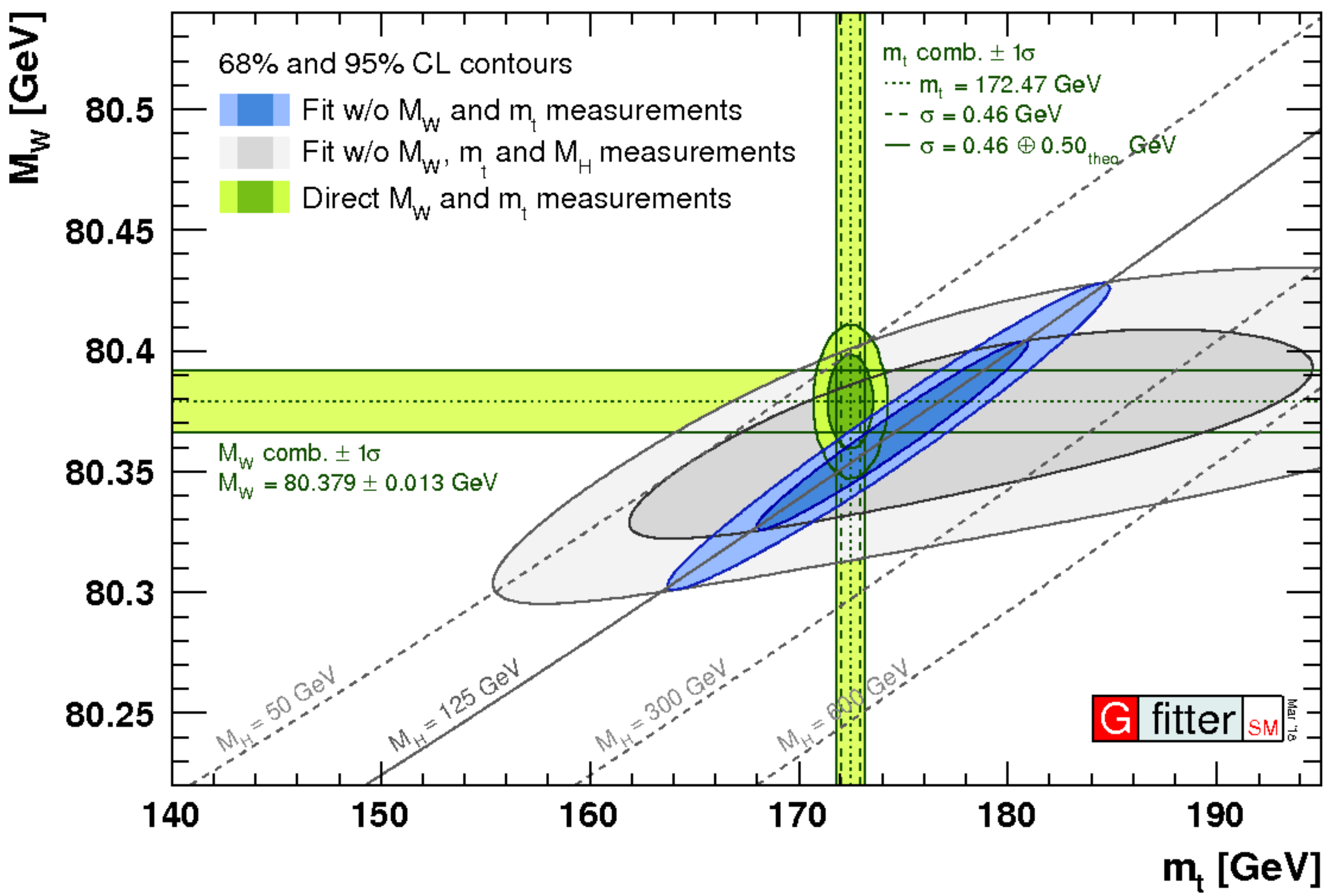


Flavour anomalies?



+ theoretically well motivated BSM scenarios such as supersymmetry, composite Higgs, …

Probe Standard Model dynamics



Physics opportunities for high-energy colliders

- **Explore electroweak symmetry breaking**
- **Search for new particles**
- **Probe Standard Model dynamics**

→ Precision (exp. & theory)

→ Energy/mass reach

→ Diverse searches (subtle and/or novel signatures)

Physics opportunities for high-energy colliders

Consider an EFT analysis of BSM physics

$$\mathcal{L}_{\mathrm{SMEFT}} \supset \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2} \sum_i \mathcal{O}_i \quad \Longrightarrow \quad \sigma = \sigma_{\mathrm{SM}} \left(1 + \mathcal{O}\left(\frac{E^2}{\Lambda^2} \right) + \ldots \right)$$

Physics opportunities for high-energy colliders

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Inclusive Higgs production:

$$\delta\sigma \sim \frac{m_H^2}{\Lambda^2} \approx 2\% \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 \quad \to \delta\sigma \approx 5\% \ \ \text{probes} \ \ \Lambda \approx 500\,\mathrm{GeV}$$

Physics opportunities for high-energy colliders

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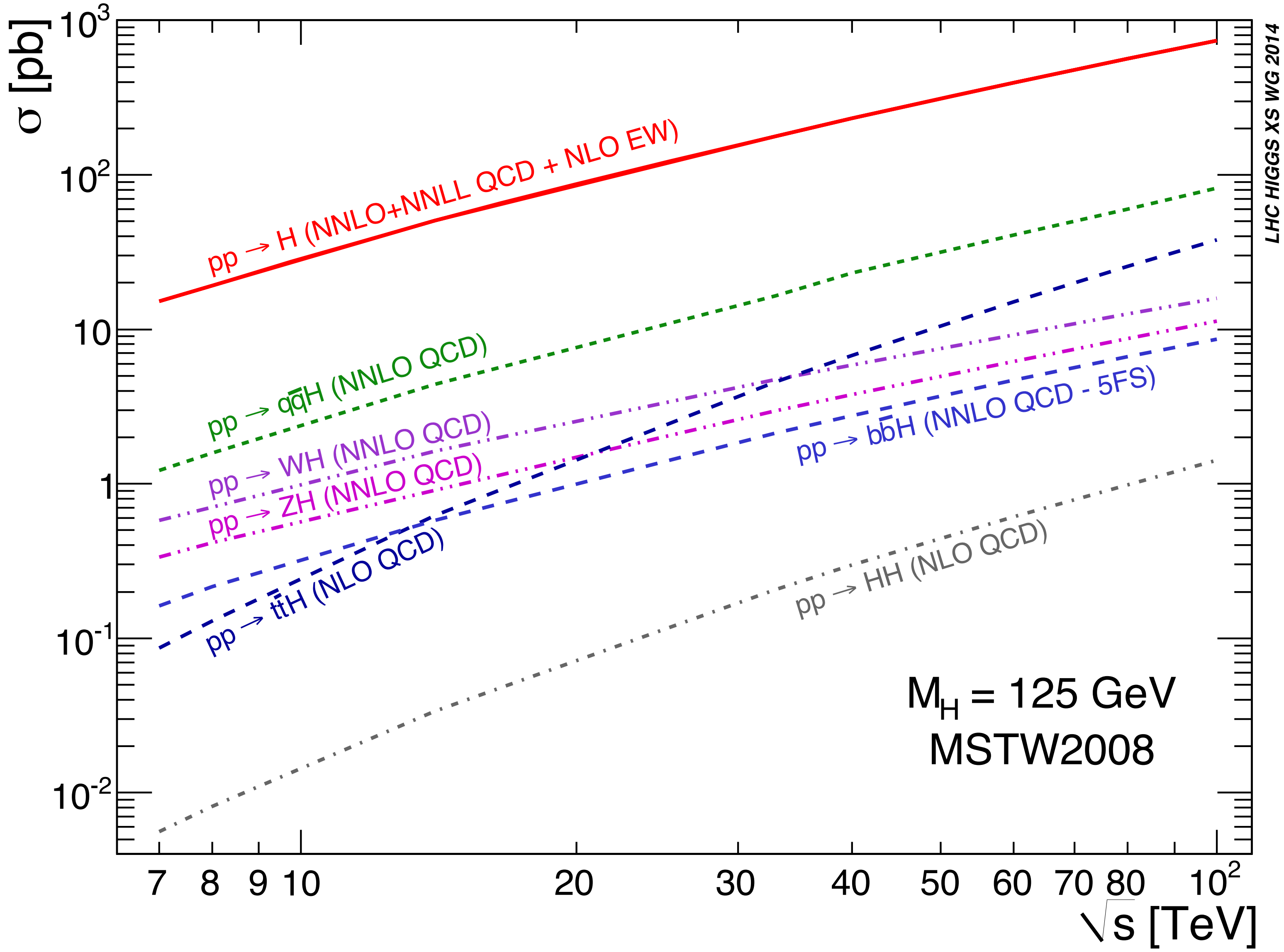
Production at large p⊥:

$$\delta\sigma \sim \frac{p_\perp^2}{\Lambda^2} \quad \to \delta\sigma \approx 20\% \;\; \text{and} \;\; p_\perp \approx 500\,\text{GeV probe} \;\; \Lambda \approx 1\,\text{TeV}$$

Physics opportunities for high-energy proton colliders

- **Higgs physics**
- **WIMP dark matter**
- **Flavour anomalies**

Higgs physics at high-energy proton colliders



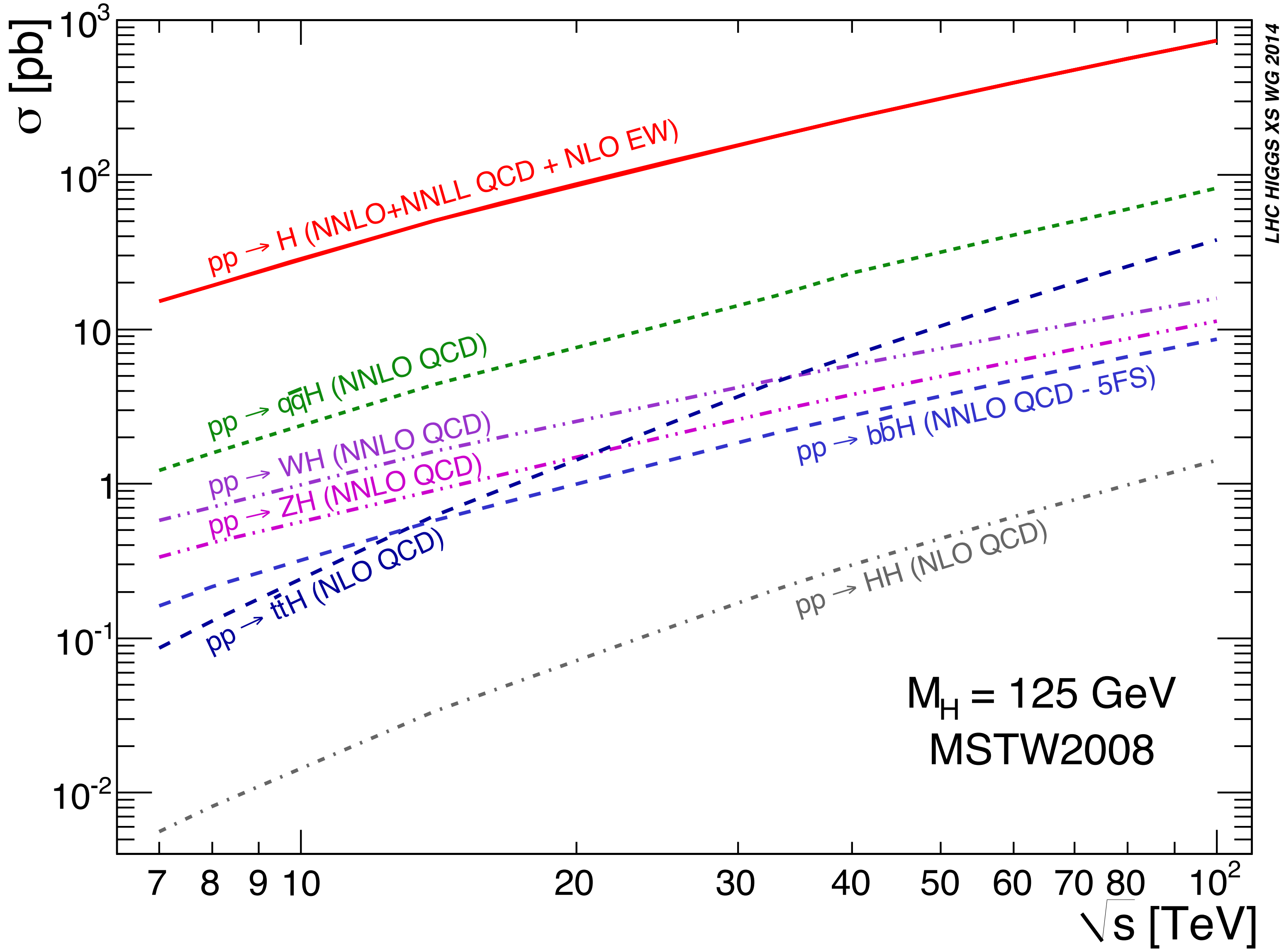
HE-LHC

15 ab^{-1} @ 27 TeV

$\sigma(H)/\sigma(H)_{LHC} \approx 2.5$

$\sigma(HH)/\sigma(HH)_{LHC} \approx 5$

Higgs physics at high-energy proton colliders



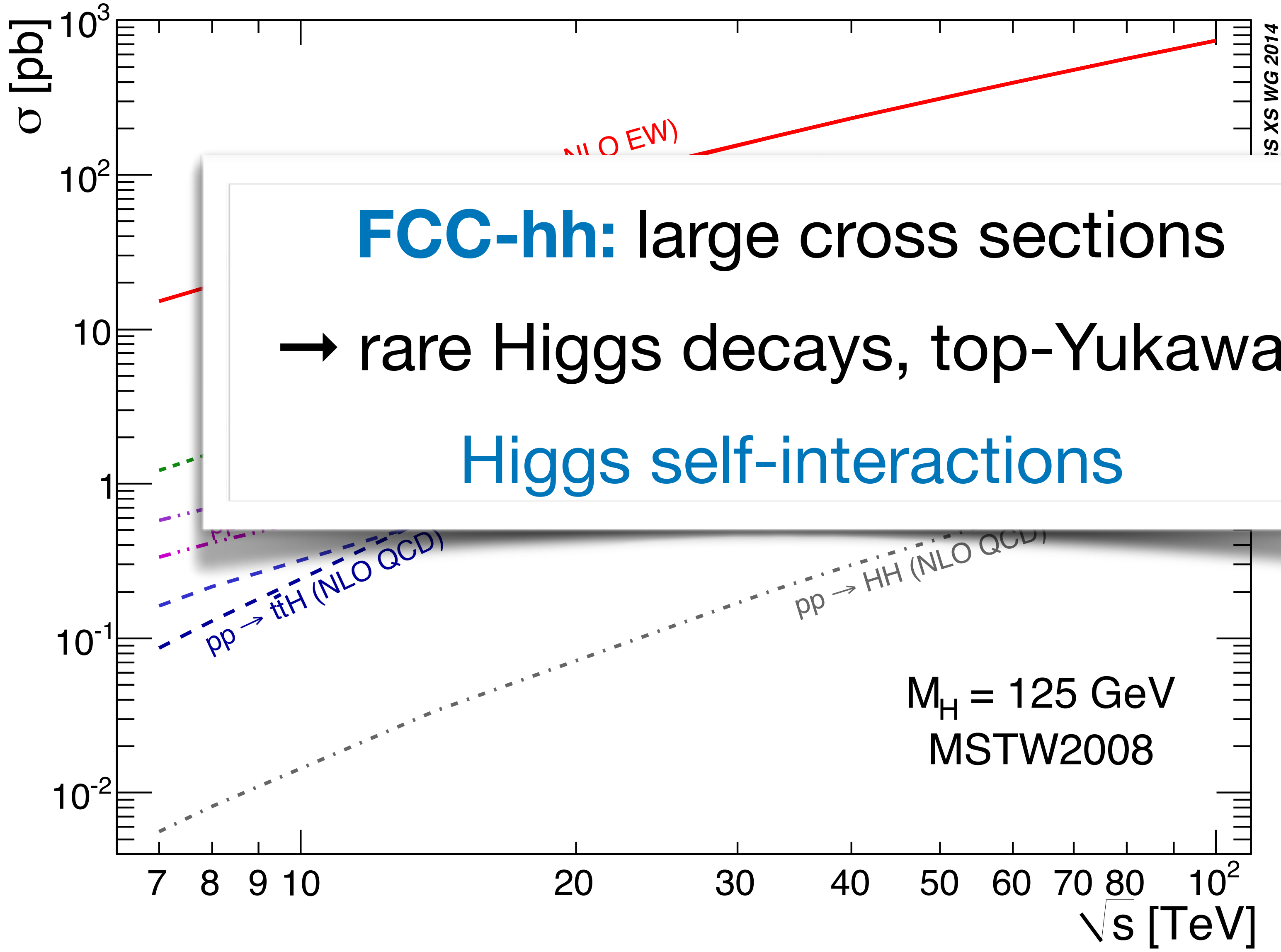
FCC-hh

30 ab^{-1} @ 100 TeV

$\sigma(H)/\sigma(H)_{LHC} \approx$ 10-50

$\sigma(HH)/\sigma(HH)_{LHC} \approx 40$

Higgs physics at high-energy proton colliders



FCC-hh: large cross sections

→ rare Higgs decays, top-Yukawa,

Higgs self-interactions

FCC-hh

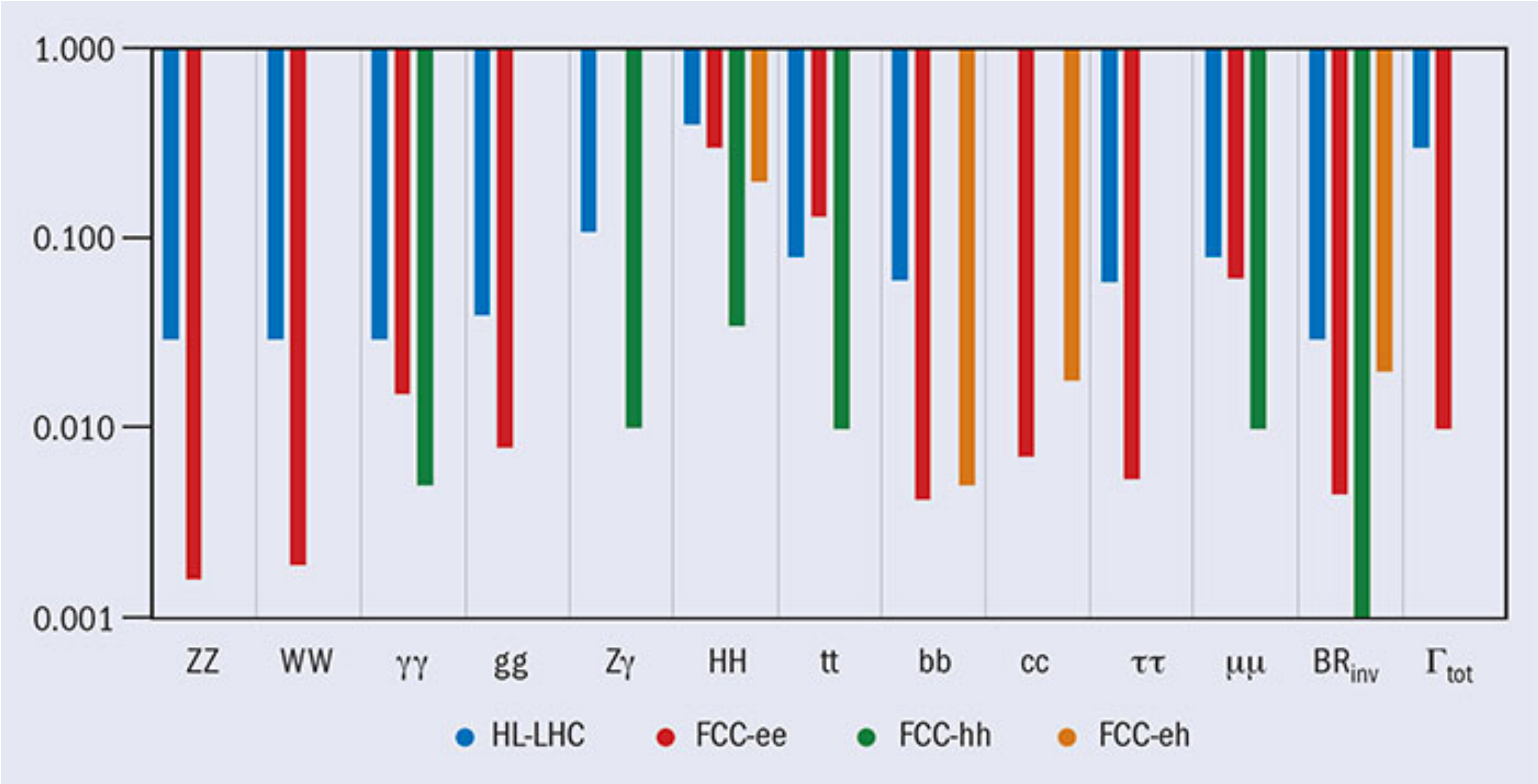
30 ab^{-1} @ 100 TeV

$\sigma(H)/\sigma(H)_{LHC} \approx 10\text{-}50$

$\sigma(HH)/\sigma(HH)_{LHC} \approx 40$

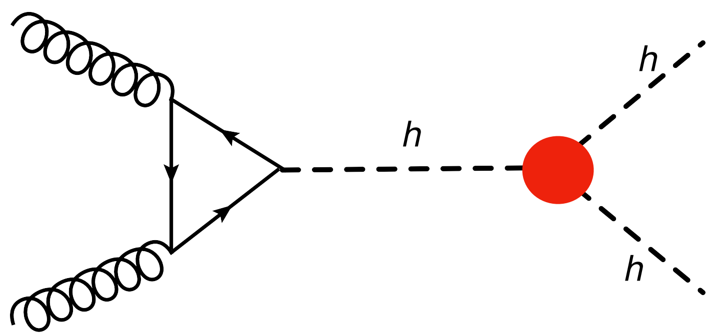
Higgs physics at high-energy proton colliders

Indicative precision in Higgs couplings



Mangano, Azzi, D'Onofrio, Mccullough

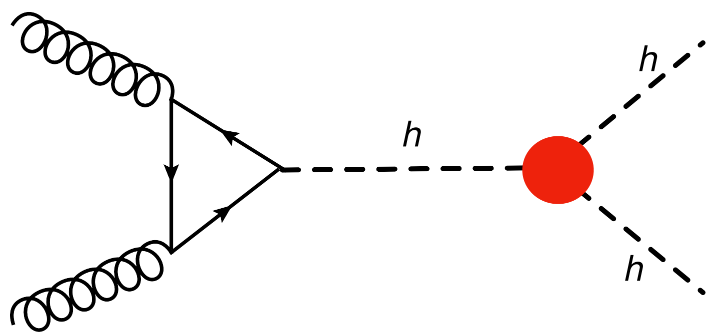
Higgs physics at high-energy proton colliders



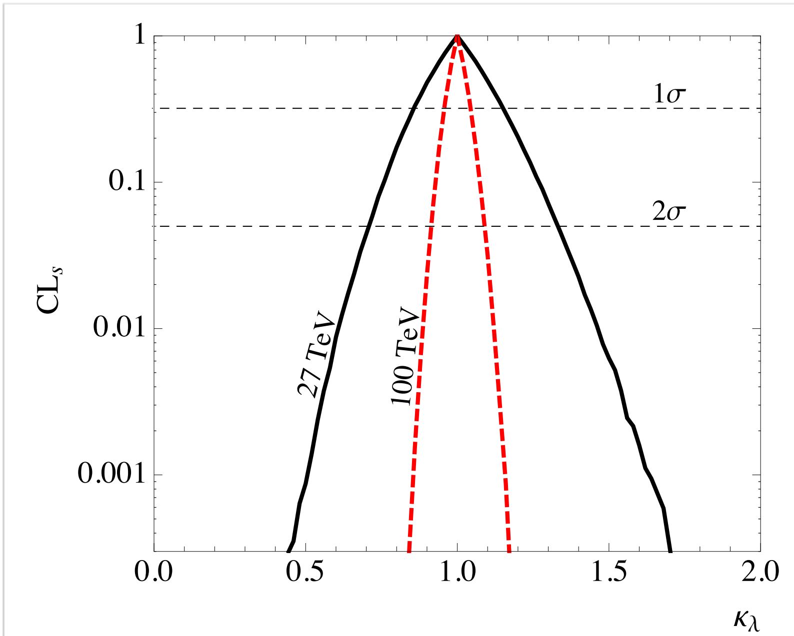
Statistical uncertainties only

process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

Higgs physics at high-energy proton colliders



arXiv:1802.04319 [hep-ph]



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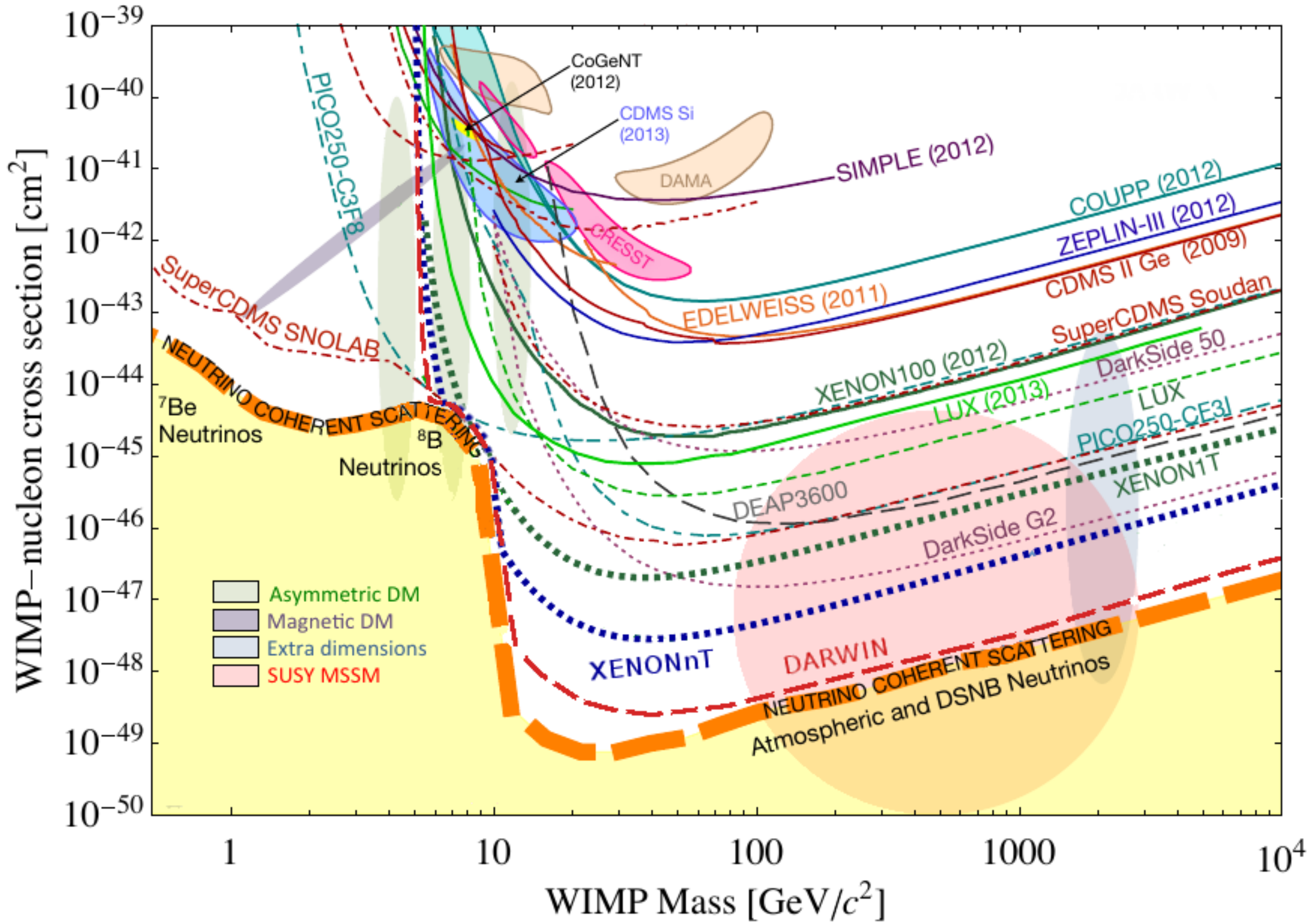
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

$$\delta\lambda_3 \approx \begin{cases} 30\% \text{ (HE-LHC)} \\ 10\% \text{ (FCC-hh)} \end{cases}$$

Dark matter

arXiv:1408.4371 [astro-ph.IM]



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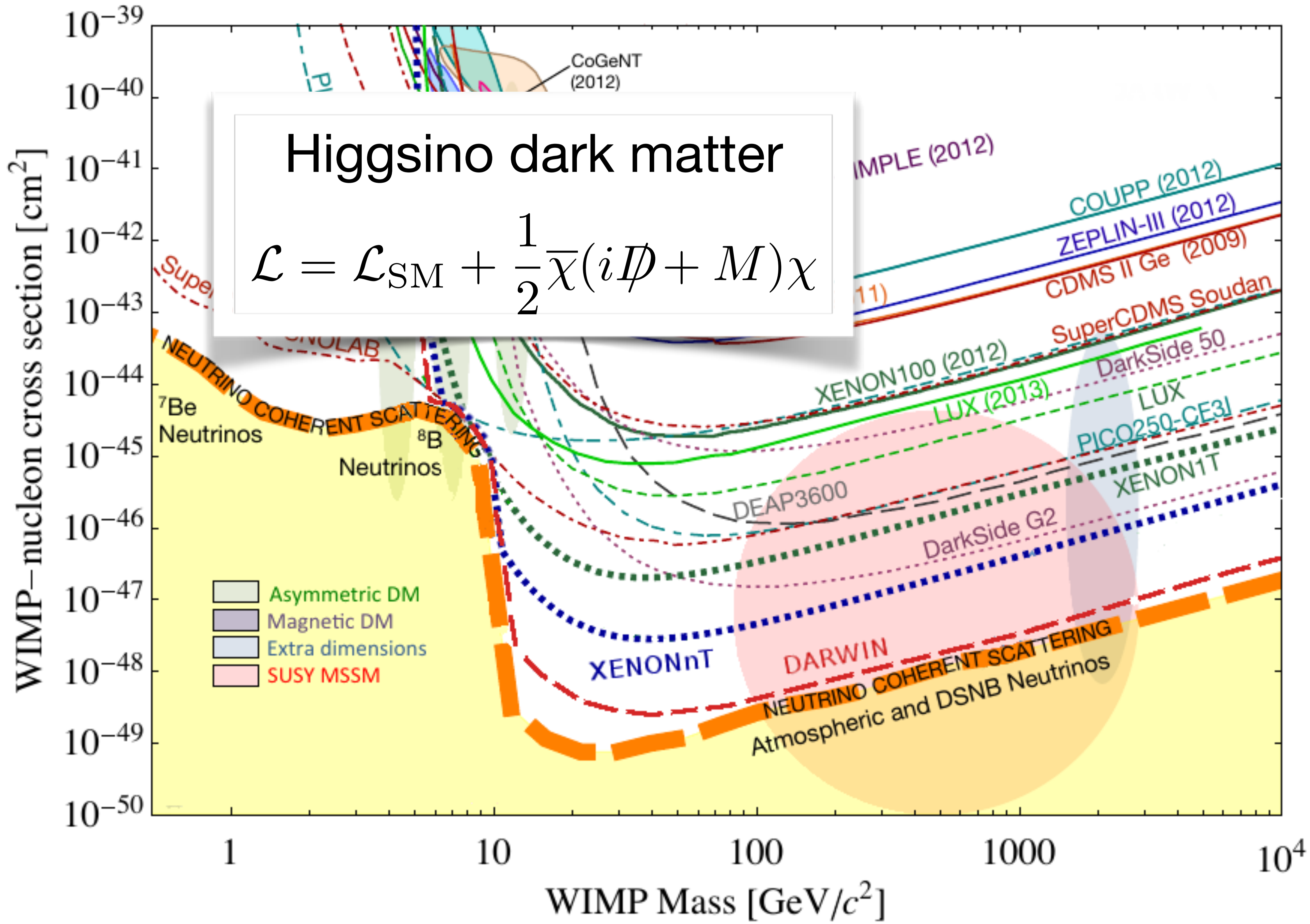
[arXiv:1408.4371](https://arxiv.org/abs/1408.4371) [astro-ph.IM]

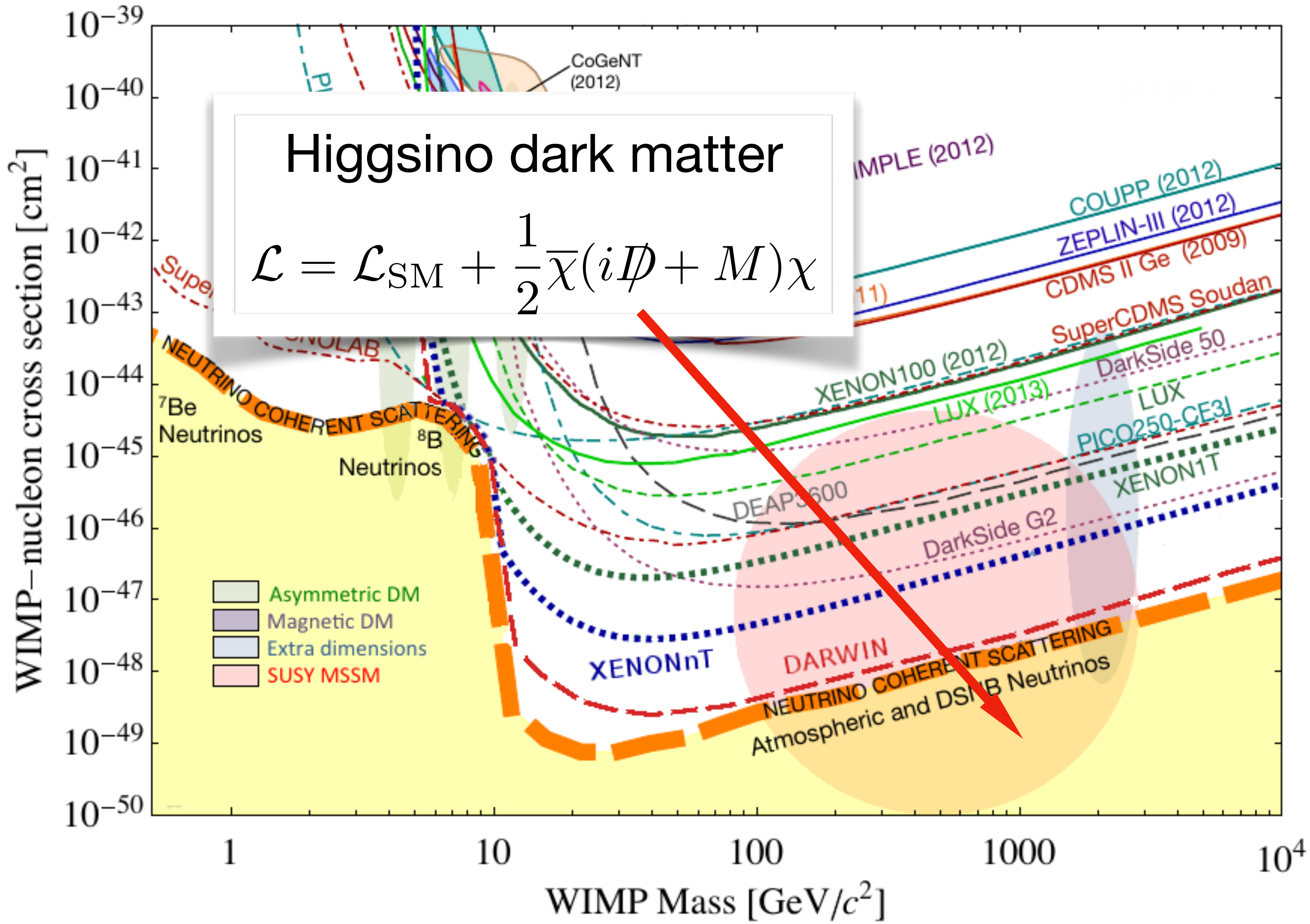


Higgsino dark matter

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\overline{\chi}(i\not{D} + M)\chi$$

Dark matter

arXiv:1408.4371 [astro-ph.IM]



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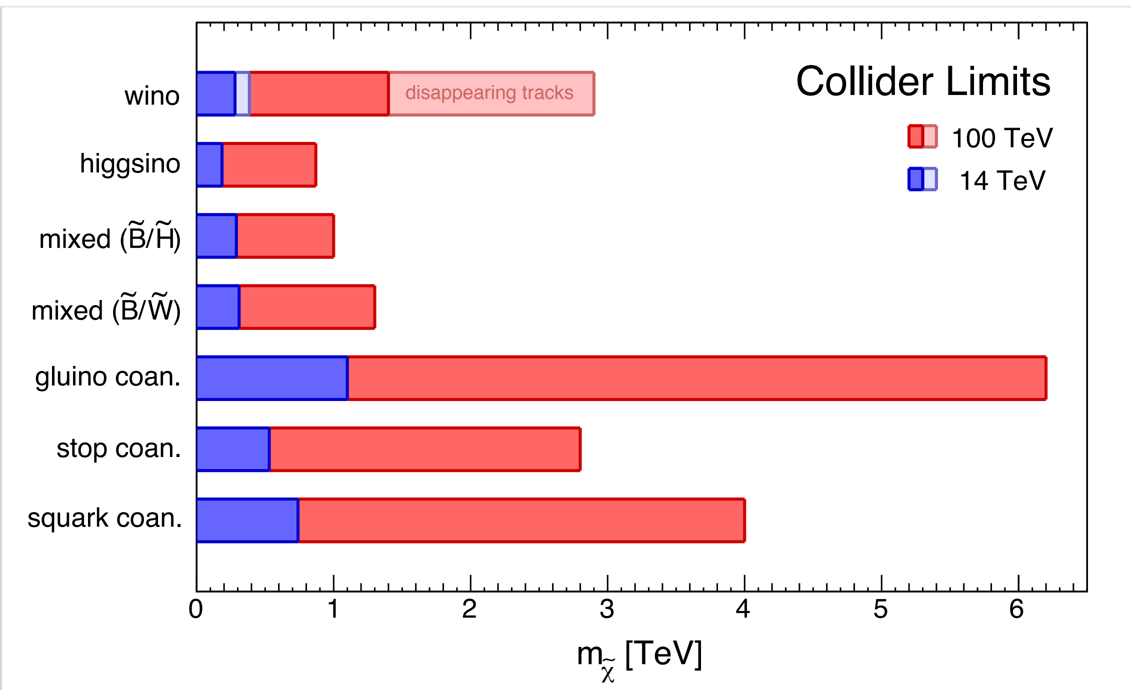
arXiv:1404.0682 [hep-ph]



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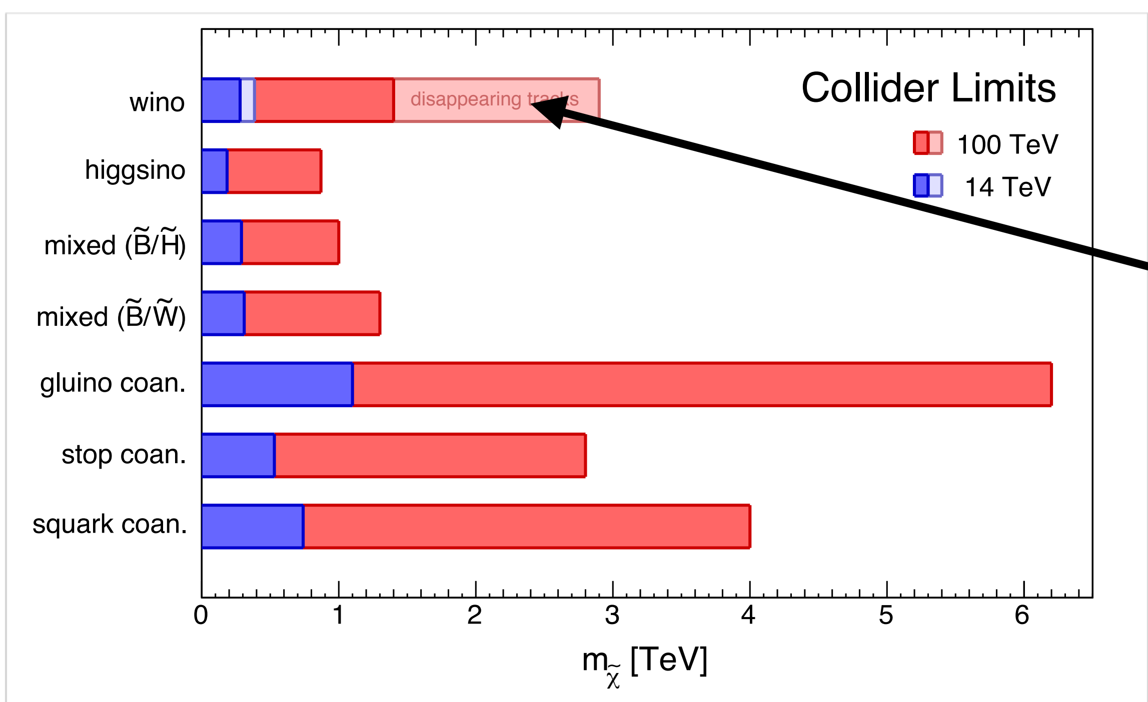
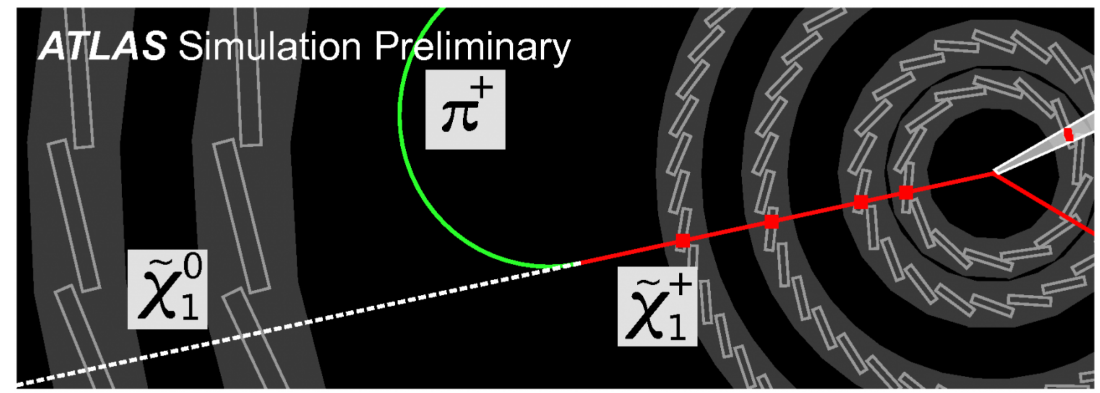


Disappearing track searches crucial



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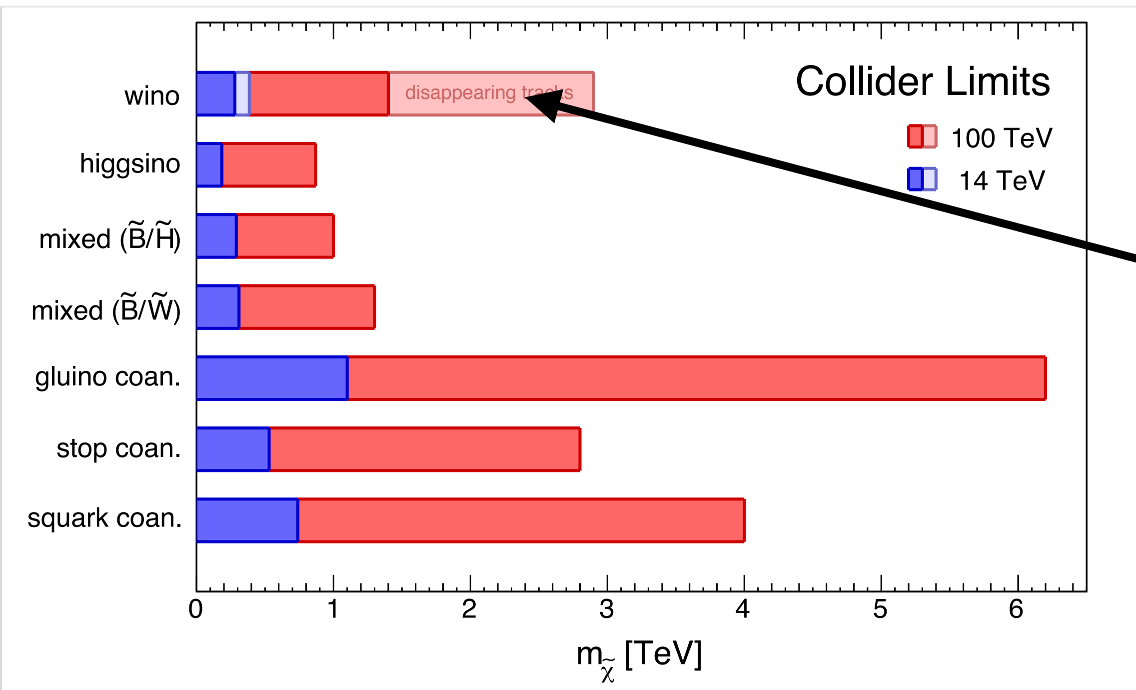

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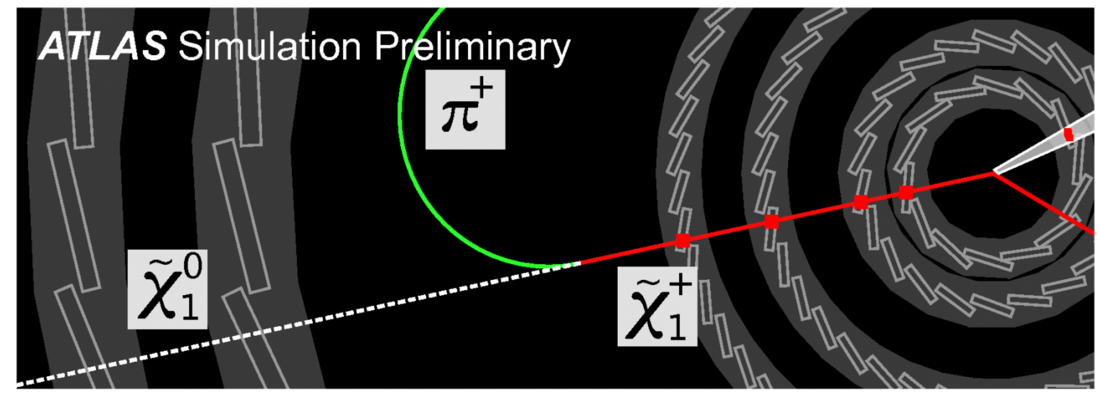
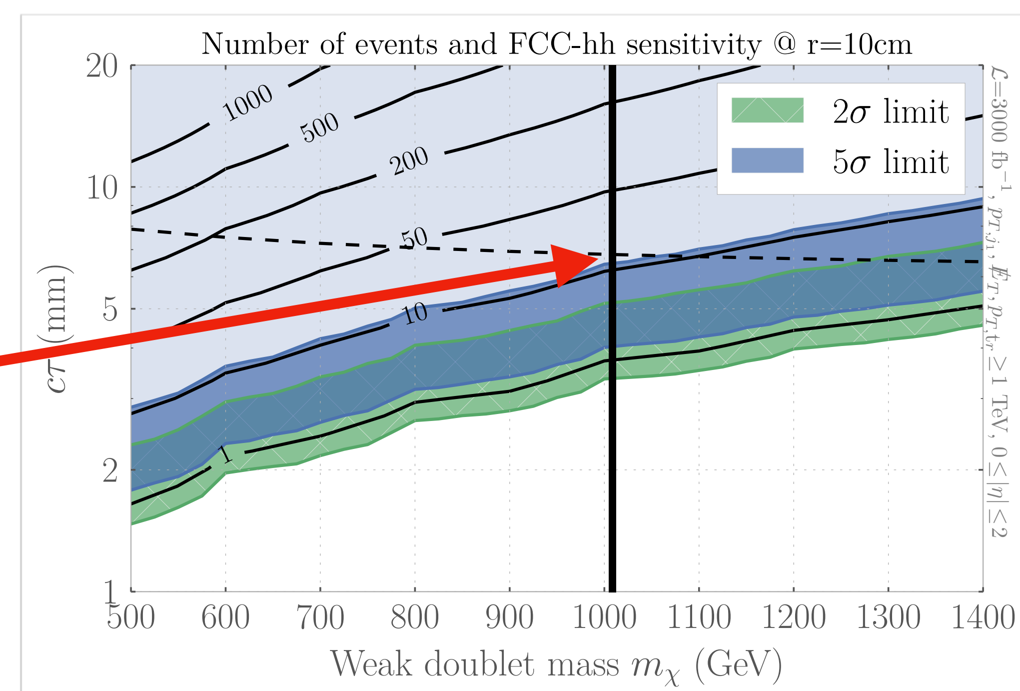


arXiv:1703.05327 [hep-ph]

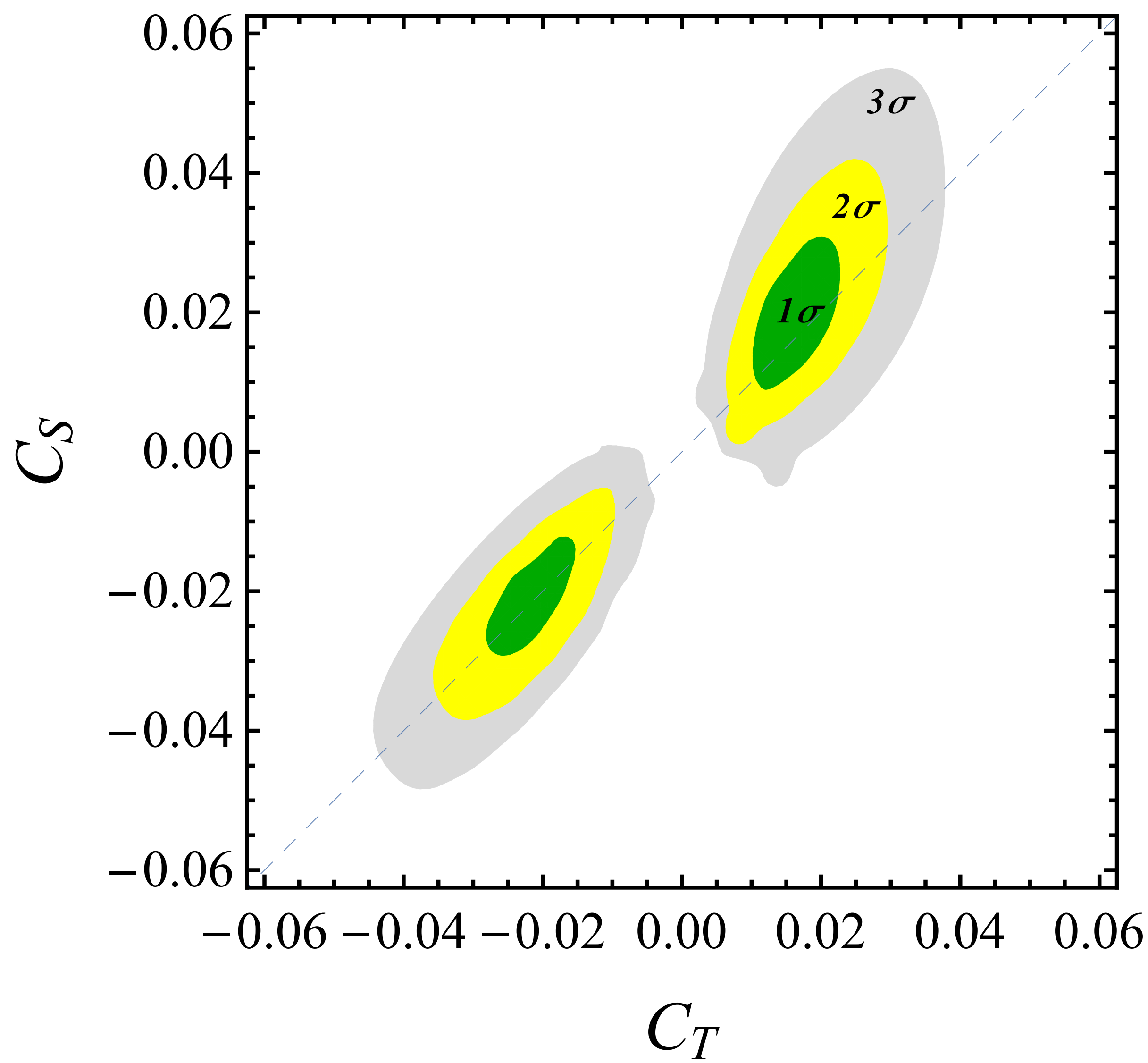


Thermal Higgsino

Flavour anomalies

B physics anomalies $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$

arXiv:1706.07808 [hep-ph]



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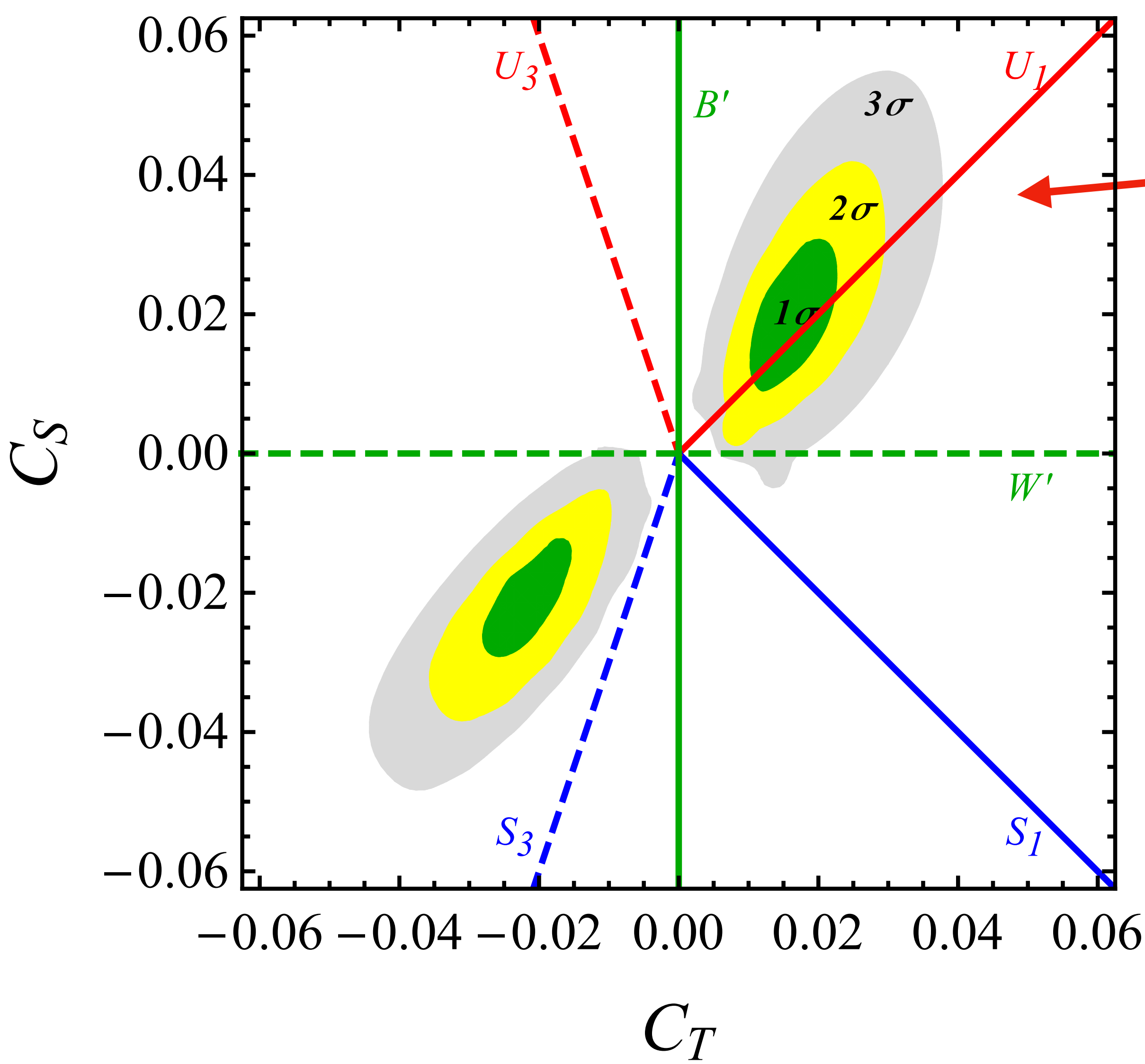

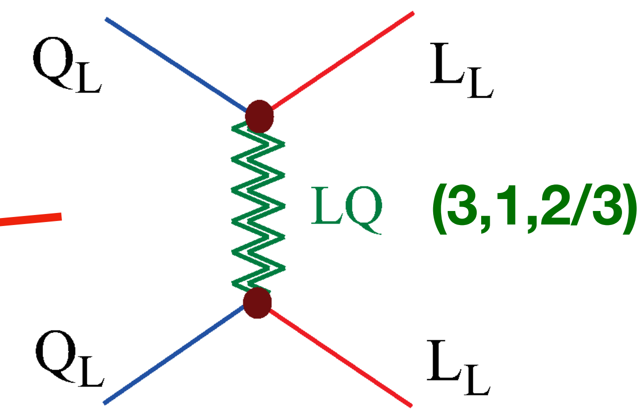

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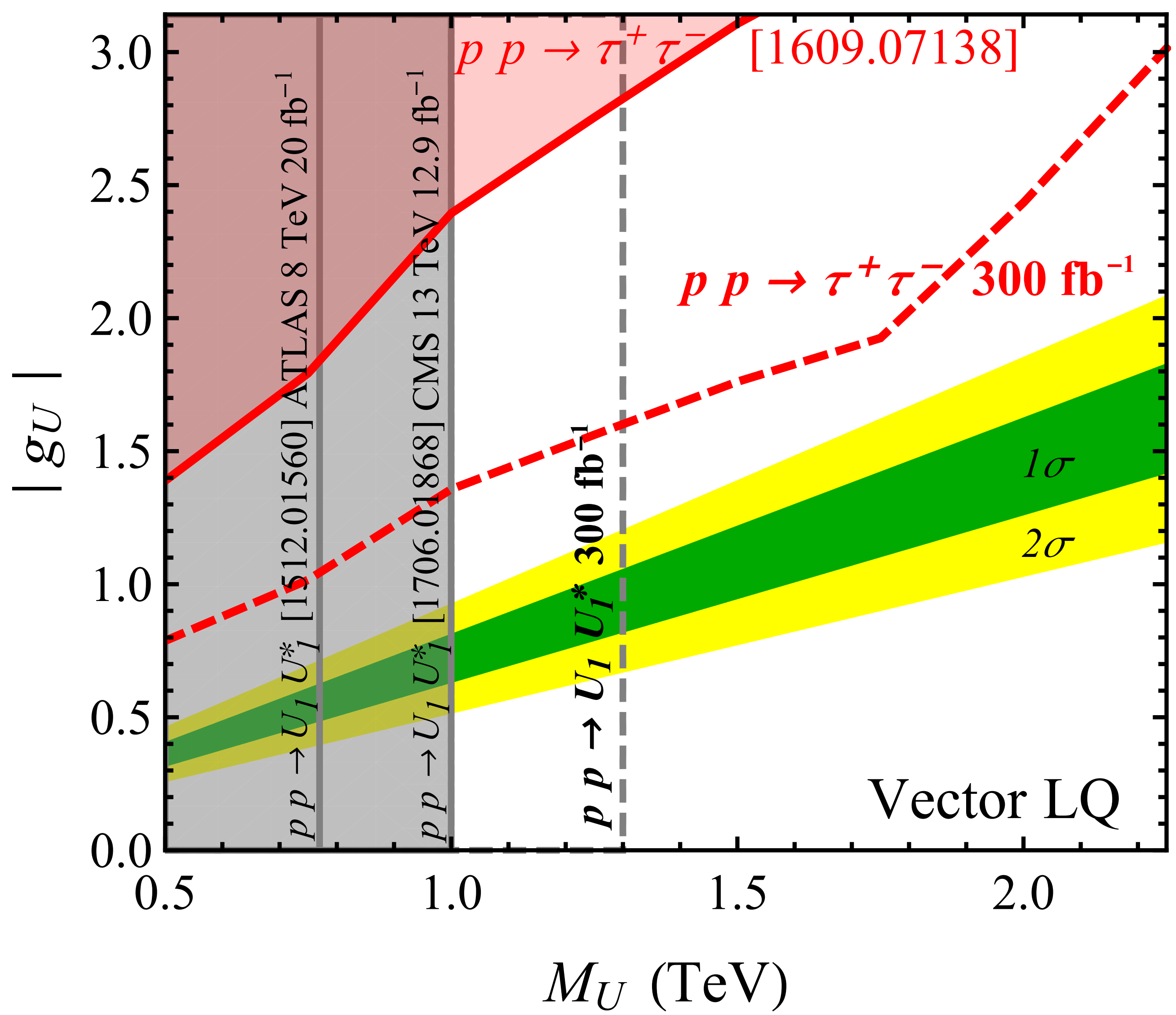

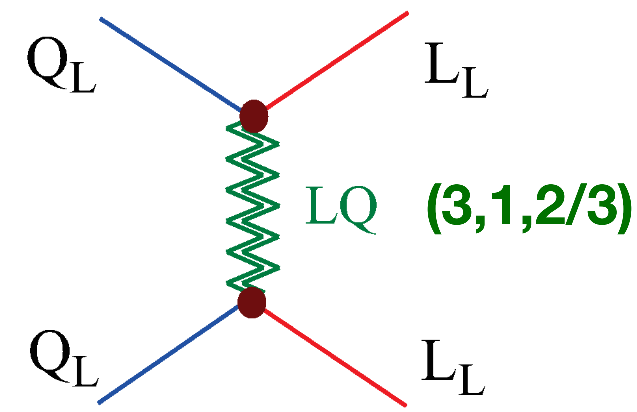

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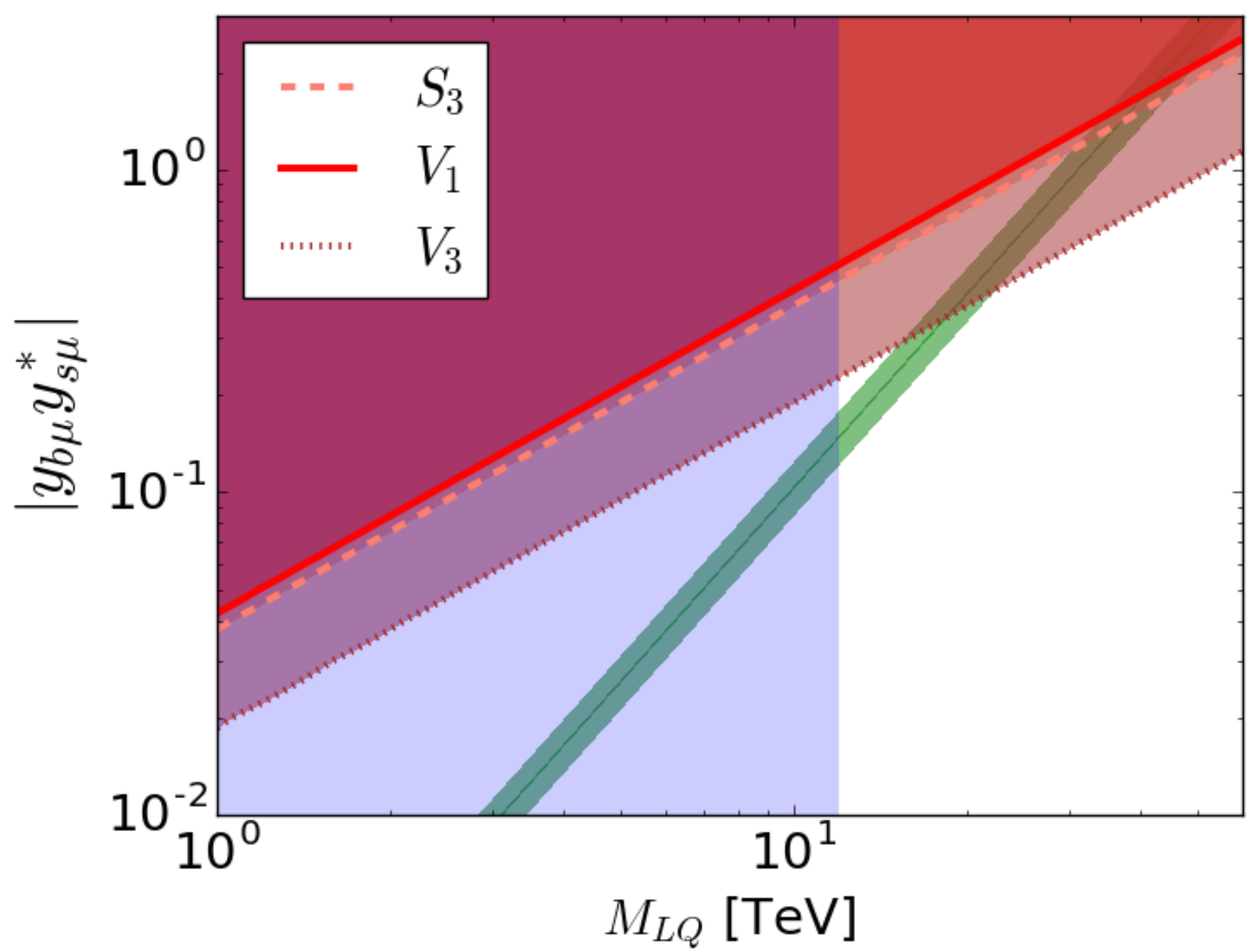
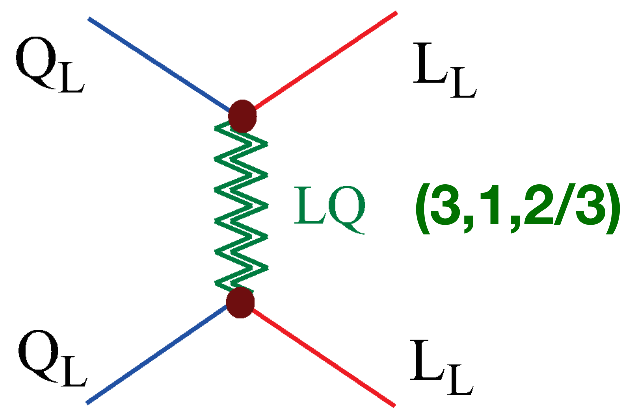
arXiv:1710.06363 [hep-ph]





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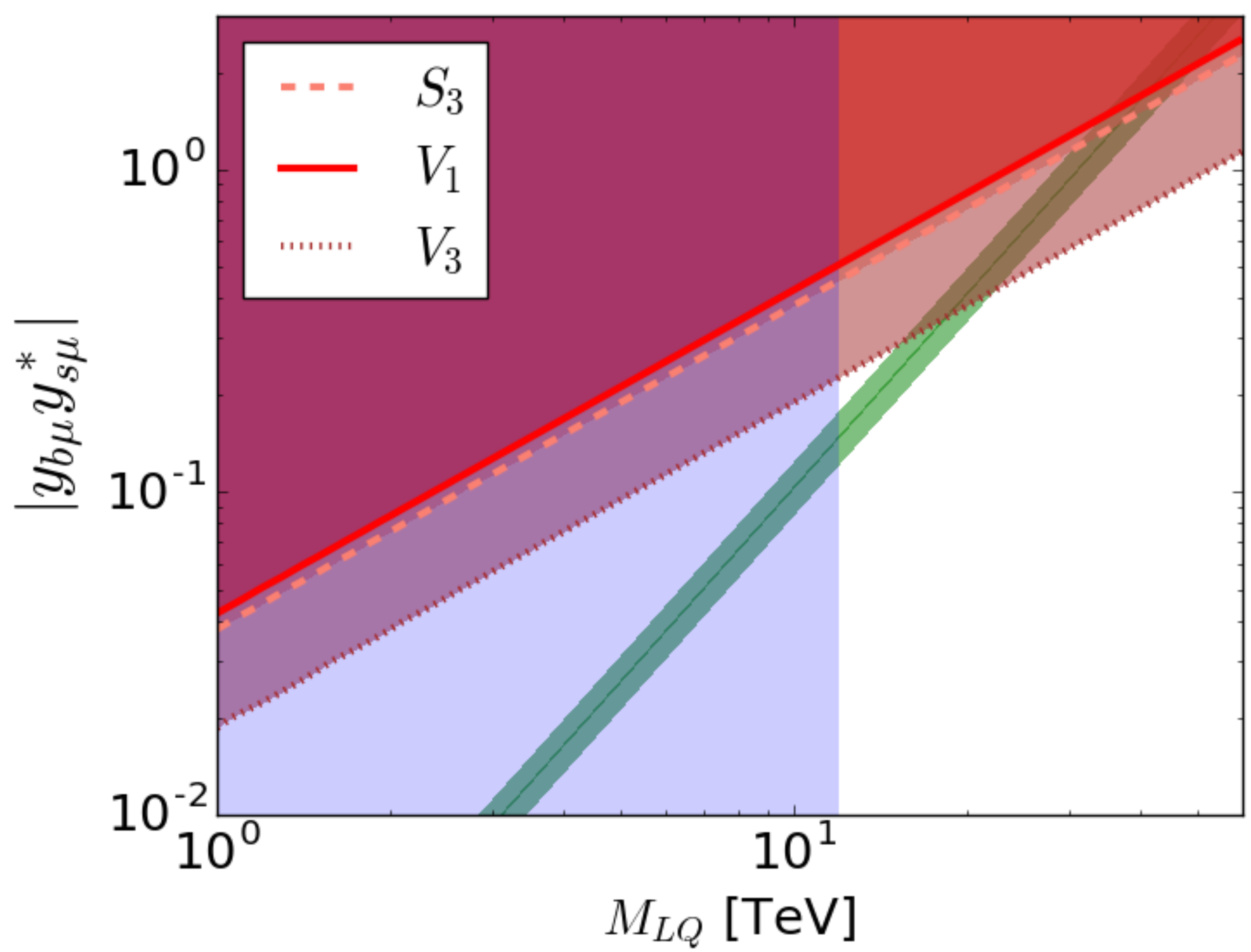
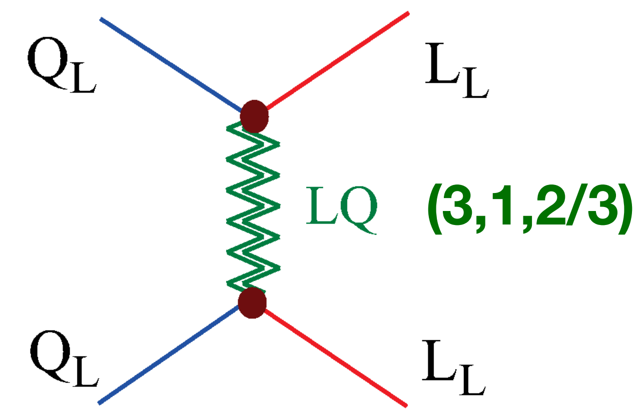
arXiv:1710.06363 [hep-ph]





Z' explanations of the flavour anomalies can be covered completely at an FCC-hh

Physics opportunities for high-energy colliders

The physics programme of a future high-energy proton collider should not be considered an extension of the LHC programme.

Physics opportunities for high-energy colliders

The physics programme of a future high-energy proton collider should not be considered an extension of the LHC programme.

A 100 TeV proton collider would journey into uncharted waters, exploring nature in the laboratory at unprecedented energies.

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	Neutral Currents -> Z,W
AGS BNL (1960)	π N interactions	Two kinds of neutrinos Time reversal non-symmetry charm quark
FNAL Batavia (1970)	Neutrino Physics	bottom quark top quark
SLAC Spear (1970)	ep, QED	Partons, charm quark tau lepton
ISR CERN (1980)	pp	Increasing pp cross section
PETRA DESY (1980)	top quark	Gluon
Super Kamiokande (2000)	Proton Decay	Neutrino oscillations
Telescopes (2000)	SN Cosmology	Curvature of the universe Dark energy

Slide by Shipsey/Ting

Physics opportunities for high-energy colliders

The physics programme of a future high-energy proton collider should not be considered an extension of the LHC programme.

A 100 TeV proton collider would journey into uncharted waters, exploring nature in the laboratory at unprecedented energies.

There is no guarantee for a discovery.

However, there is a tremendous potential to **explore** some of the most fundamental questions in physics (science), such as the **origin of electroweak symmetry breaking**, the **nature of dark matter**, the origin of the **matter-antimatter asymmetry,** the structure of **space-time symmetries**, and many more.