

**CERN accelerator school on
Beam Dynamics and Technologies for Future Colliders
Zurich, Febr 21 - Mar 6, 2018**

High energy physics at future colliders

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What are we talking about when we're talking about CERN's future colliders ...



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pp @ 14 TeV, 3ab⁻¹

**✓ Approved
2026-37**

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e⁺e⁻ @ 380 GeV, 1.5 & ~3 TeV

**CDR 2012+
update '16**

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CDR (end '18)

100km tunnel

- **pp @ 100 TeV**
- **e⁺e⁻ @ 91, 160, 240, 365 GeV**
- **e_{60GeV} p_{50TeV} @ 3.5 TeV**

LHC tunnel: HE-LHC

- **pp @ 27 TeV, 15ab⁻¹**

and in the rest of the world:



e^+e^- @ 250, 350, 500 GeV

TDR 2012



CDR (Spring '18)

100km tunnel

- e^+e^- @ 91, 240 GeV (but possibly 160 & 350)
- Future possible pp @ ~ 70 TeV and $e_{60\text{GeV}} p_{35\text{TeV}}$

**Regardless of what I'll discuss,
whatever project you're working on
(LHC, ILC, CLIC, FCC, X-FEL, PSI, superKEKB, ...)
just be proud of it!!**

**Particle physicists can only be infinitely grateful to
accelerator physicists:**

without you, we'd be nowhere!

MLM, from talk given to Council, 2015, to justify HL-LHC

A “real” story from the past ...

Barcelona, 15 March 1493



Cristoforo Colombo:

Your Majesty, the fleet needs an **upgrade**, we need to go back to the Indies with **10 times** more ships

King Ferdinand and Queen Isabella:

You discovered the Indies, your theory is right, why do you need more?

Cristoforo Colombo:

Theorists* say these may not be the **standard Indies**. They calculated the Earth radius, and the standard Indies cannot be so close: these are likely to be **beyond the standard Indies** (*moving eastward ...*)

** If the King had listened to theorists to start with, he would have never authorized the mission: everyone would have died of starvation well before reaching the “standard” Indies ...*



**the discovery of the Higgs was not the end,
it was just the beginning ...**

The LHC experiments have been exploring a vast multitude of scenarios of physics beyond the Standard Model

In search of the origin of known departures from the SM

- Dark matter, long lived particles
- Neutrino masses
- Matter/antimatter asymmetry of the universe

To explore alternative extensions of the SM

- New gauge interactions (Z' , W') or extra Higgs bosons
- Additional fermionic partners of quarks and leptons, leptoquarks, ...
- Composite nature of quarks and leptons
- Supersymmetry, in a variety of twists (minimal, constrained, natural, RPV, ...)
- Extra dimensions
- New flavour phenomena
- unanticipated surprises ...

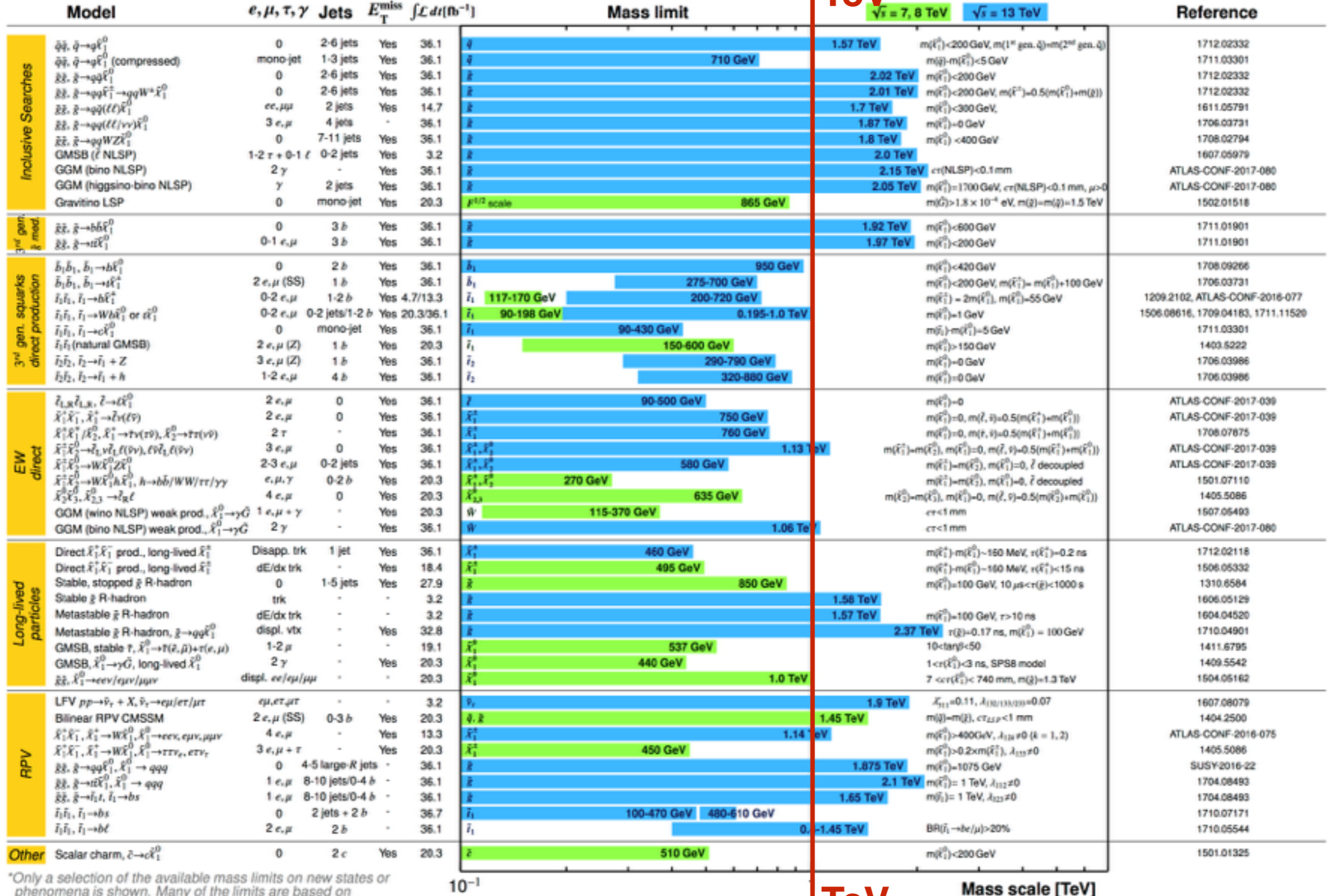
So far, no conclusive signal of physics beyond the SM

ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13 \text{ TeV}$



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10⁻¹

Mass scale [TeV]

TeV

however, notice the small print

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ATLAS SUSY Searches* - 95% CL Lower Limits

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Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} d\mathcal{L} (\text{fb}^{-1})$	Mass limit	Reference			
						$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$		
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\tilde{q} \rightarrow q\tilde{q}_1^0$	0	2-6 jets	Yes	36.1	\tilde{q}	1.57 TeV	$m(\tilde{q}_1^0) < 200 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q}) = m(2^{\text{nd}} \text{ gen. } \tilde{q})$	1712.02332
	$\tilde{q}\tilde{q}, \tilde{q}\tilde{q} \rightarrow q\tilde{q}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	\tilde{q}	710 GeV	$m(\tilde{q}) - m(\tilde{q}_1^0) < 5 \text{ GeV}$	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\tilde{q}_1^0$	0	2-6 jets	Yes	36.1	\tilde{g}	2.02 TeV	$m(\tilde{q}_1^0) < 200 \text{ GeV}$	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\tilde{q}_1^0 \rightarrow q\tilde{q}W^+\tilde{q}_1^0$	0	2-6 jets	Yes	36.1	\tilde{g}	2.01 TeV	$m(\tilde{q}_1^0) < 200 \text{ GeV}, m(\tilde{q}_1^0) = 0.5(m(\tilde{q}_1^0) + m(\tilde{g}))$	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{q}_1^0$	e, μ	2 jets	Yes	14.7	\tilde{g}	1.7 TeV	$m(\tilde{q}_1^0) < 300 \text{ GeV}$	1611.05791
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\tilde{q}(\ell\ell/\nu\nu)\tilde{q}_1^0$	$3 e, \mu$	4 jets	-	36.1	\tilde{g}	1.87 TeV	$m(\tilde{q}_1^0) = 0 \text{ GeV}$	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\tilde{q}WZ\tilde{q}_1^0$	0	7-11 jets	Yes	36.1	\tilde{g}	1.8 TeV	$m(\tilde{q}_1^0) < 400 \text{ GeV}$	1708.02794
	GMSB (\tilde{t} NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	3.2	\tilde{g}	2.0 TeV	$m(\tilde{q}_1^0) < 400 \text{ GeV}$	1607.05979
	GGM (bino NLSP)	2γ	-	Yes	36.1	\tilde{g}	2.15 TeV	$c\tau(\text{NLSP}) < 0.1 \text{ mm}$	ATLAS-CONF-2017-080
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	\tilde{g}	2.05 TeV	$m(\tilde{q}_1^0) = 1700 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu > 0$	ATLAS-CONF-2017-080
Gravitino LSP	0	mono-jet	Yes	20.3	\tilde{g}	865 GeV	$m(\tilde{g}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g}) = m(\tilde{q}) = 1.5 \text{ TeV}$	1502.01518	
3 rd gen. \tilde{g} mod.	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{q}_1^0$	0	3 b	Yes	36.1	\tilde{g}	1.92 TeV	$m(\tilde{q}_1^0) < 600 \text{ GeV}$	1711.01901
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow t\tilde{t}\tilde{q}_1^0$	0-1 e, μ	3 b	Yes	36.1	\tilde{g}	1.97 TeV	$m(\tilde{q}_1^0) < 200 \text{ GeV}$	1711.01901
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{q}_1^0$	0	2 b	Yes	36.1	\tilde{b}_1	950 GeV	$m(\tilde{q}_1^0) < 420 \text{ GeV}$	1708.09266
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{q}_1^0$	$2 e, \mu$ (SS)	1 b	Yes	36.1	\tilde{b}_1	275-700 GeV	$m(\tilde{q}_1^0) < 200 \text{ GeV}, m(\tilde{q}_1^0) = m(\tilde{q}_1^0) + 100 \text{ GeV}$	1706.03731
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{q}_1^0$	0-2 e, μ	1-2 b	Yes	4.7/13.3	\tilde{t}_1	117-170 GeV, 200-720 GeV	$m(\tilde{q}_1^0) = 2m(\tilde{q}_1^0), m(\tilde{q}_1^0) = 55 \text{ GeV}$	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{q}_1^0$ or $t\tilde{q}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1	\tilde{t}_1	90-198 GeV, 0.195-1.0 TeV	$m(\tilde{q}_1^0) = 1 \text{ GeV}$	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{q}_1^0$	0	mono-jet	Yes	36.1	\tilde{t}_1	90-430 GeV	$m(\tilde{q}_1^0) = 5 \text{ GeV}$	1711.03301
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	$2 e, \mu$ (Z)	1 b	Yes	20.3	\tilde{t}_1	150-600 GeV	$m(\tilde{q}_1^0) > 150 \text{ GeV}$	1403.6222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	$3 e, \mu$ (Z)	1 b	Yes	36.1	\tilde{t}_2	290-790 GeV	$m(\tilde{q}_1^0) = 0 \text{ GeV}$	1706.03986
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	\tilde{t}_2	320-880 GeV	$m(\tilde{q}_1^0) = 0 \text{ GeV}$	1706.03986
EW direct	$\tilde{\chi}_{1,2}^0\tilde{\chi}_{1,2}^0, \tilde{\chi} \rightarrow \tilde{\chi}\tilde{q}_1^0$	$2 e, \mu$	0	Yes	36.1	$\tilde{\chi}$	90-500 GeV	$m(\tilde{q}_1^0) = 0$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tilde{\chi}(\ell\nu)$	$2 e, \mu$	0	Yes	36.1	$\tilde{\chi}_1^\pm$	750 GeV	$m(\tilde{q}_1^0) = 0, m(\tilde{\chi}, \nu) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{q}_1^0))$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tilde{\chi}(\tau\nu), \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tilde{\chi}(\nu\nu)$	2τ	-	Yes	36.1	$\tilde{\chi}_1^\pm$	760 GeV	$m(\tilde{q}_1^0) = 0, m(\tilde{\chi}, \nu) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{q}_1^0))$	1708.07675
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0\nu\tilde{\chi}_1^0(\ell\nu\nu), \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0\nu\tilde{\chi}_1^0(\nu\nu)$	$3 e, \mu$	0	Yes	36.1	$\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$	1.13 TeV	$m(\tilde{q}_1^0) = m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\chi}, \nu) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{q}_1^0))$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow W\tilde{Z}\tilde{q}_1^0$	$2-3 e, \mu$	0-2 jets	Yes	36.1	$\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$	580 GeV	$m(\tilde{q}_1^0) = m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0) = 0, \tilde{\chi}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow W\tilde{Z}\tilde{h}\tilde{q}_1^0$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$	270 GeV	$m(\tilde{q}_1^0) = m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0) = 0, \tilde{\chi}$ decoupled	1501.07110
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tilde{g}\tilde{g}\tilde{q}_1^0$	$4 e, \mu$	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$	635 GeV	$m(\tilde{q}_1^0) = m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\chi}, \nu) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{q}_1^0))$	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	$1 e, \mu + \gamma$	-	Yes	20.3	\tilde{W}	115-370 GeV	$c\tau < 1 \text{ mm}$	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	2γ	-	Yes	36.1	\tilde{W}	1.06 TeV	$c\tau < 1 \text{ mm}$	ATLAS-CONF-2017-080
	Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^0$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$	460 GeV	$m(\tilde{q}_1^0) - m(\tilde{\chi}_1^0) = 160 \text{ MeV}, \tau(\tilde{\chi}_1^0) = 0.2 \text{ ns}$
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^0$		dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$	495 GeV	$m(\tilde{q}_1^0) - m(\tilde{\chi}_1^0) = 160 \text{ MeV}, \tau(\tilde{\chi}_1^0) < 15 \text{ ns}$	1506.05332
Stable, stopped \tilde{g} R-hadron		0	1-5 jets	Yes	27.9	\tilde{g}	850 GeV	$m(\tilde{q}_1^0) = 100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$	1310.6584
Stable \tilde{g} R-hadron		trk	-	-	3.2	\tilde{g}	1.58 TeV	-	1606.05129
Metastable \tilde{g} R-hadron		dE/dx trk	-	-	3.2	\tilde{g}	1.57 TeV	$m(\tilde{q}_1^0) = 100 \text{ GeV}, \tau > 10 \text{ ns}$	1604.04520
Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\tilde{q}_1^0$		displ. vtx	-	Yes	32.8	\tilde{g}	2.37 TeV	$\tau(\tilde{g}) = 0.17 \text{ ns}, m(\tilde{q}_1^0) = 100 \text{ GeV}$	1710.04901
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \mu) + \tau(\nu, \mu)$		1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	$10 < \tan\beta < 50$	1411.6795
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$		2γ	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV	$1 < c\tau(\tilde{\chi}_1^0) < 3 \text{ ns}, \text{SPS8 model}$	1409.5542
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow e\tilde{e}\nu/\mu\tilde{\nu}/\mu\tilde{\mu}\nu$		displ. $e\tilde{e}/\mu\tilde{\mu}$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$7 < c\tau(\tilde{\chi}_1^0) < 740 \text{ mm}, m(\tilde{g}) = 1.3 \text{ TeV}$	1504.05162
RPV	LFV $pp \rightarrow \tilde{\nu}_i + X, \tilde{\nu}_i \rightarrow e\mu/\tau\mu/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_i$	1.9 TeV	$\lambda_{111} = 0.11, \lambda_{110}/\lambda_{112}/\lambda_{113} = 0.07$	1607.08079
	Bilinear RPV CMSSM	$2 e, \mu$ (SS)	0-3 b	Yes	20.3	\tilde{q}, \tilde{g}	1.45 TeV	$m(\tilde{g}) = m(\tilde{q}), c\tau_{\tilde{LSP}} < 1 \text{ mm}$	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow W\tilde{Z}\tilde{q}_1^0, \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow e\tilde{e}\nu, \mu\tilde{\nu}, \mu\mu\nu$	$4 e, \mu$	-	Yes	13.3	$\tilde{\chi}_1^\pm$	1.14 TeV	$m(\tilde{q}_1^0) > 400 \text{ GeV}, \lambda_{112} \neq 0 (\lambda = 1, 2)$	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow W\tilde{Z}\tilde{q}_1^0, \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tau\tilde{\nu}_e, e\tilde{\nu}_\tau$	$3 e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$	450 GeV	$m(\tilde{q}_1^0) > 0.2m(\tilde{\chi}_1^\pm), \lambda_{113} \neq 0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\tilde{q}\tilde{q}_1^0, \tilde{q}_1^0 \rightarrow q\tilde{q}\tilde{q}$	0	4-5 large-R jets	-	36.1	\tilde{g}	1.875 TeV	$m(\tilde{q}_1^0) = 1075 \text{ GeV}$	SUSY-2016-22
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow t\tilde{t}\tilde{q}_1^0, \tilde{q}_1^0 \rightarrow q\tilde{q}\tilde{q}$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g}	2.1 TeV	$m(\tilde{q}_1^0) = 1 \text{ TeV}, \lambda_{112} \neq 0$	1704.08493
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g}	1.65 TeV	$m(\tilde{q}_1^0) = 1 \text{ TeV}, \lambda_{113} \neq 0$	1704.08493
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	0	2 jets + 2 b	-	36.7	\tilde{t}_1	100-470 GeV, 480-610 GeV	-	1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{t}$	$2 e, \mu$	2 b	-	36.1	\tilde{t}_1	0.1-1.45 TeV	$\text{BR}(\tilde{t}_1 \rightarrow b\tilde{e}/\mu) > 20\%$	1710.05544	
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{q}_1^0$	0	2 c	Yes	20.3	\tilde{c}	510 GeV	$m(\tilde{q}_1^0) < 200 \text{ GeV}$	1501.01325

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10⁻¹

TeV

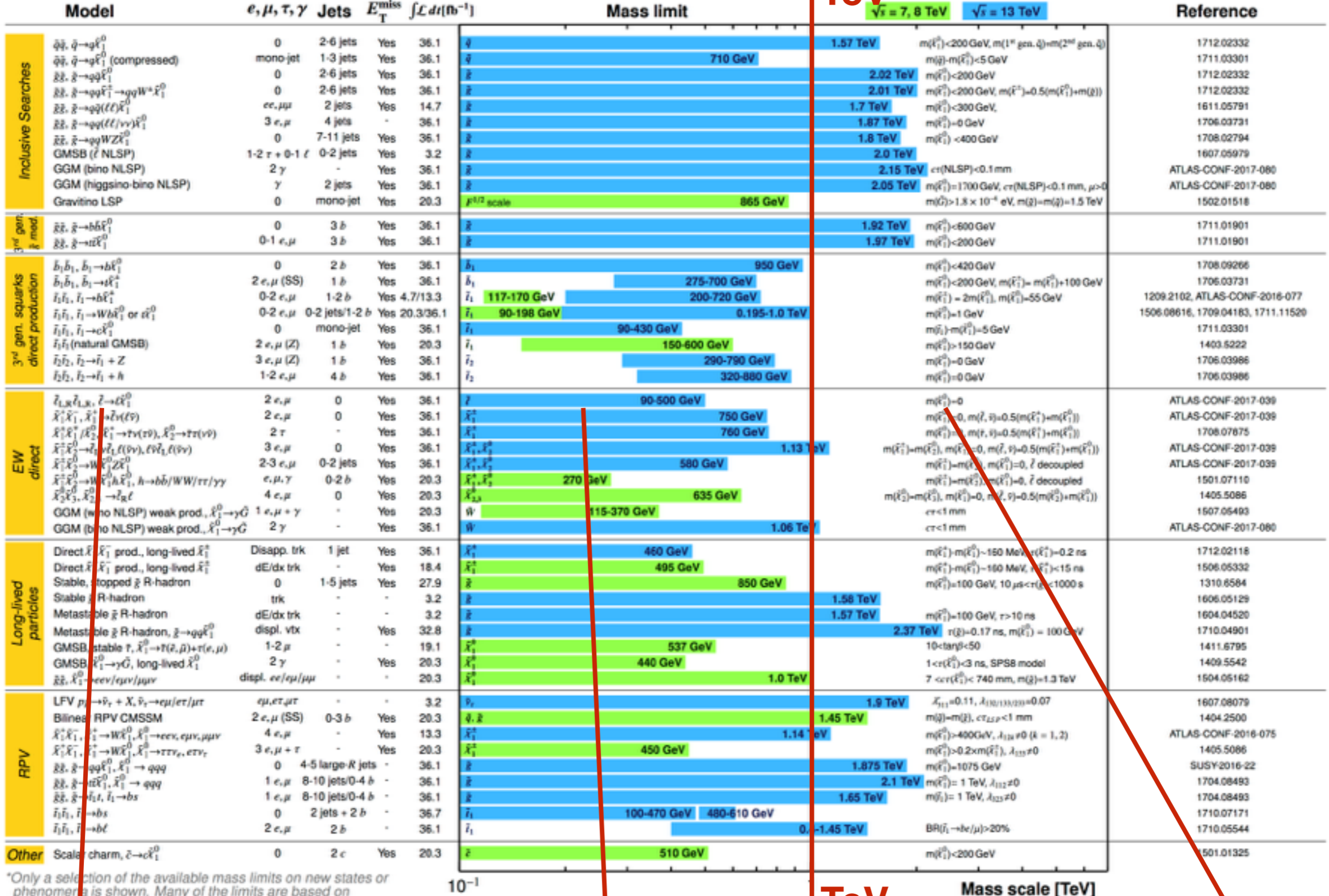
TeV

Mass scale [TeV]

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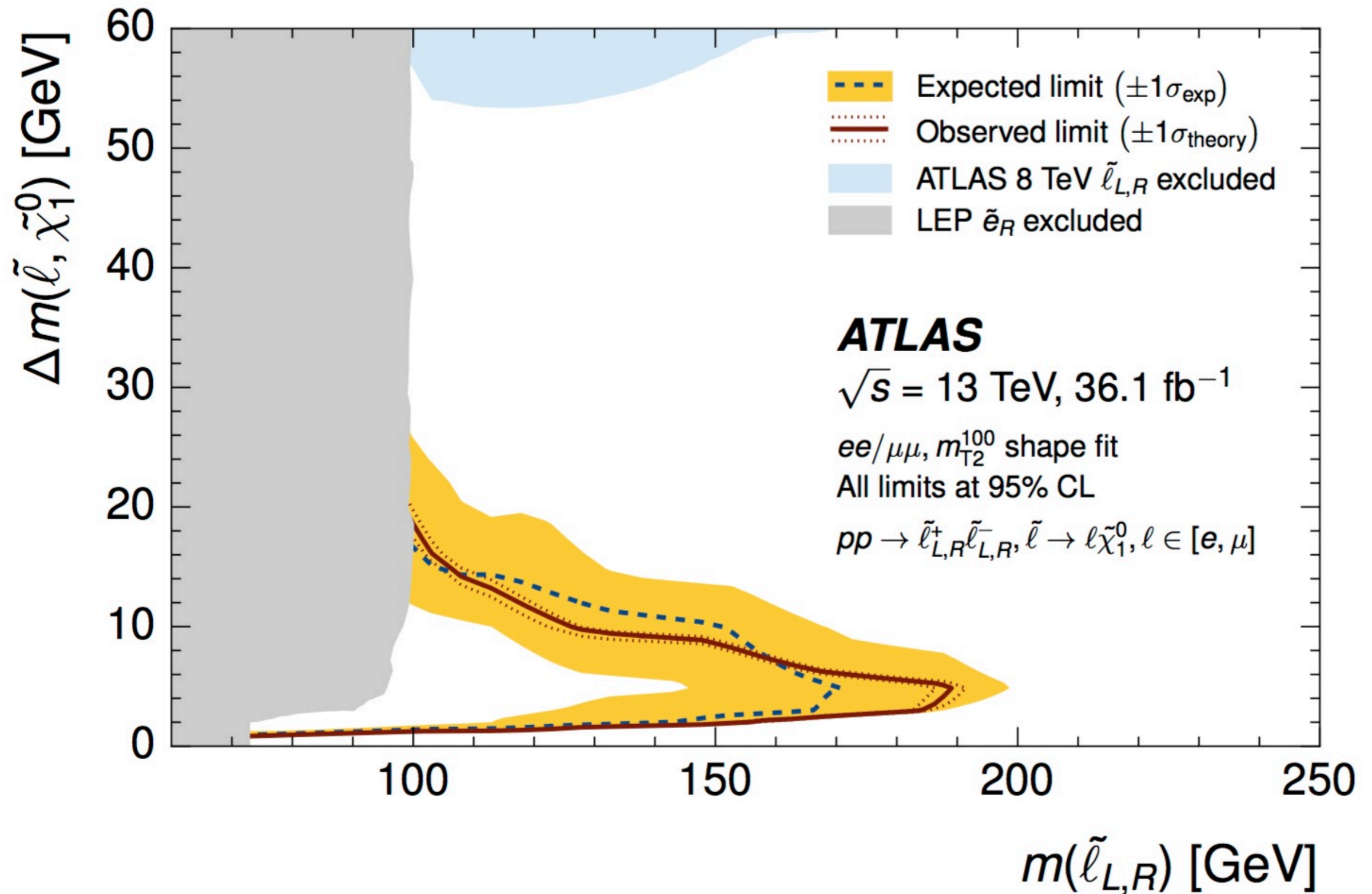
$\tilde{\ell}_{L,R} \tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$

$\tilde{\ell}$ 90-500 GeV

$m(\tilde{\chi}_1^0) = 0$

relaxing the $m(x^0)=0$ constraint ...

... LHC has barely improved LEP2 limits ...



=> in principle there is still room for discoveries at CLIC even at its lowest energies!

Key question for the future developments of HEP:
Why don't we see the new physics we expected to be present around the TeV scale ?

- **Is the mass scale beyond the LHC reach ?**
- **Is the mass scale within LHC's reach, but final states are elusive to the direct search ?**

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:

- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

Remark

the discussion of the **future** in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can *guarantee discoveries* beyond the SM, and *answers* to the big questions of the field

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(1) the **guaranteed deliverables:**

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- target broad and well justified BSM scenarios ... *but guarantee sensitivity to more exotic options*
- exploit both direct (large Q^2) and indirect (precision) probes

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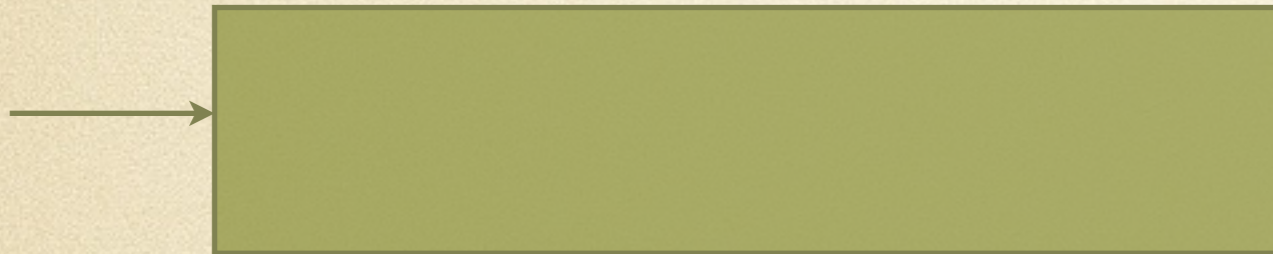
- target broad and well justified BSM scenarios ... *but guarantee sensitivity to more exotic options*
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(3) the potential to provide conclusive **yes/no answers** to relevant, broad questions.

**The guaranteed deliverable:
relevance of a continued precision study
of the Higgs boson**

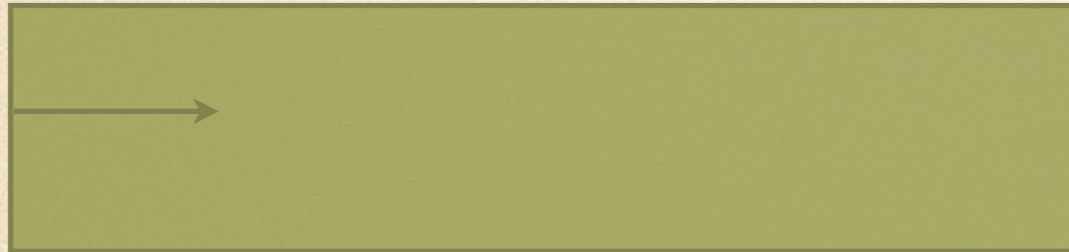
The Higgs and particles' masses

Light propagating in a medium is slowed down by its continuous interaction with the medium itself



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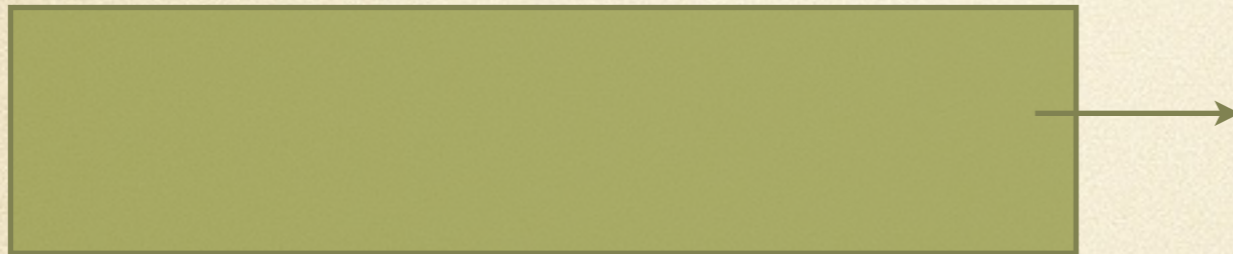
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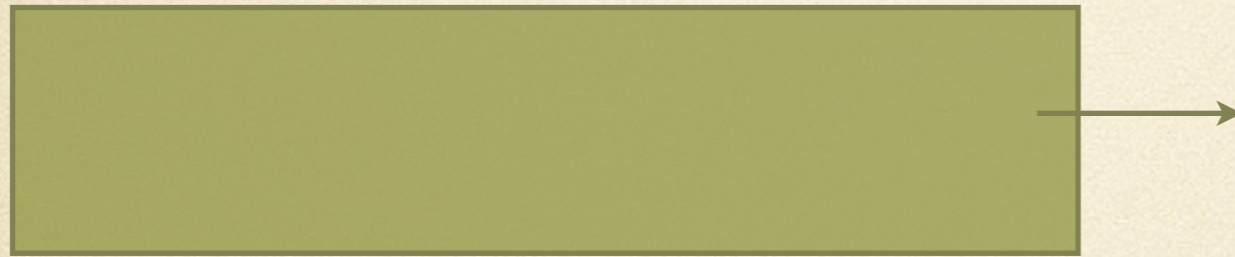


The time it takes to move across the medium is longer than if light were propagating in the vacuum,

$$\Rightarrow c_{\text{medium}} < c_{\text{vacuum}}$$

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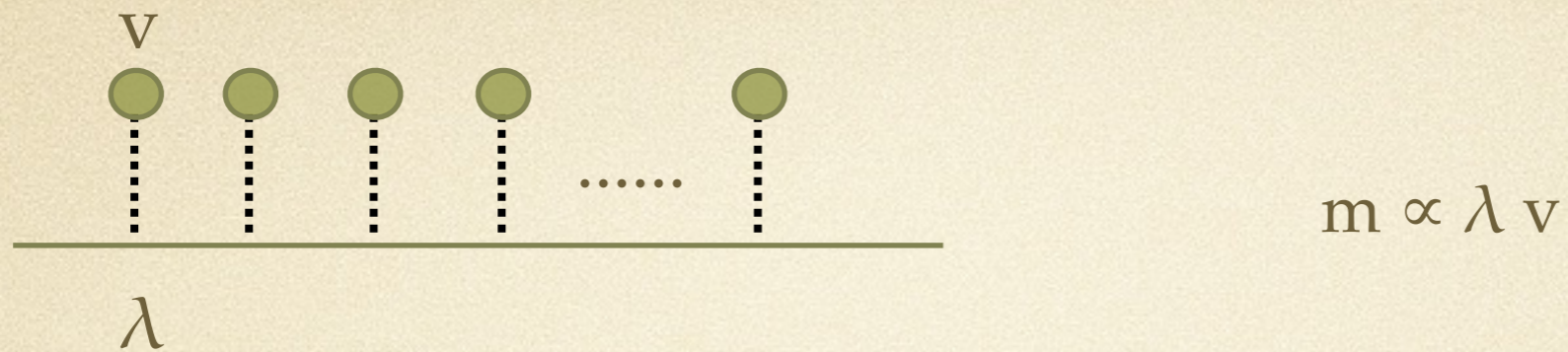
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$$\Rightarrow c_{\text{medium}} < c_{\text{vacuum}}$$

Think of the Higgs field as being a continuum medium embedding the whole Universe. Particles interacting with it will undergo a similar "slow-down" phenomenon. Rather than "slowing down", however, the interaction with the Higgs medium gives them "inertia" \Rightarrow mass



The number “ v ” is a universal property of the Higgs field background. The quantity “ λ ” is characteristic of the particle moving in the Higgs field. Particles which have large λ will have large mass, with $m \propto \lambda v$

Now the question of “why does a given particle has mass m ” is replaced by the question “why does a given particle couple with the Higgs field with strength $\lambda \propto m / v$ ”

However at least now we have a model to understand **how** particles acquire a mass.

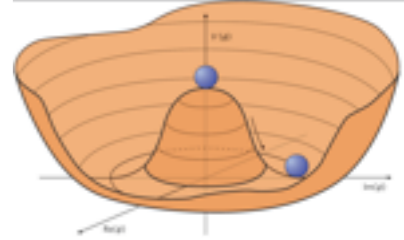
Detecting the Higgs boson

Like any other medium, the Higgs continuum background can be perturbed. Similarly to what happens if we bang on a table, creating sound waves, if we “bang” on the Higgs background (something achieved by concentrating a lot of energy in a small volume) we can stimulate “Higgs waves”. These waves manifest themselves as particles* , the so-called Higgs bosons

What is required is that the energy available be larger than the Higgs mass \Rightarrow LHC !!!

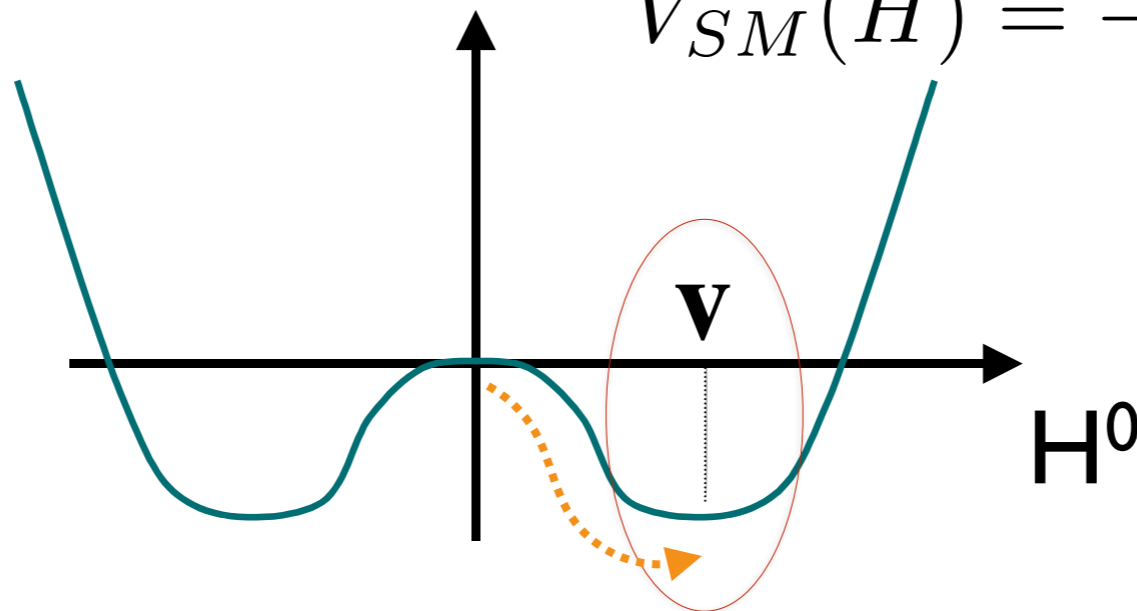
* Even the sound waves in a solid are sometimes identified with “quasi-particles”, called “phonons”

What gives the Higgs field its background value?



$$\mathbf{H} = \begin{pmatrix} H^0 \\ H^- \end{pmatrix}$$

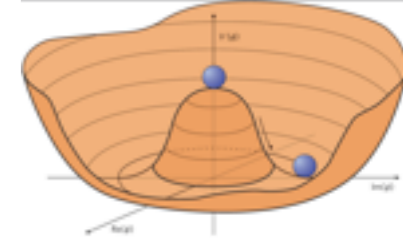
$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$



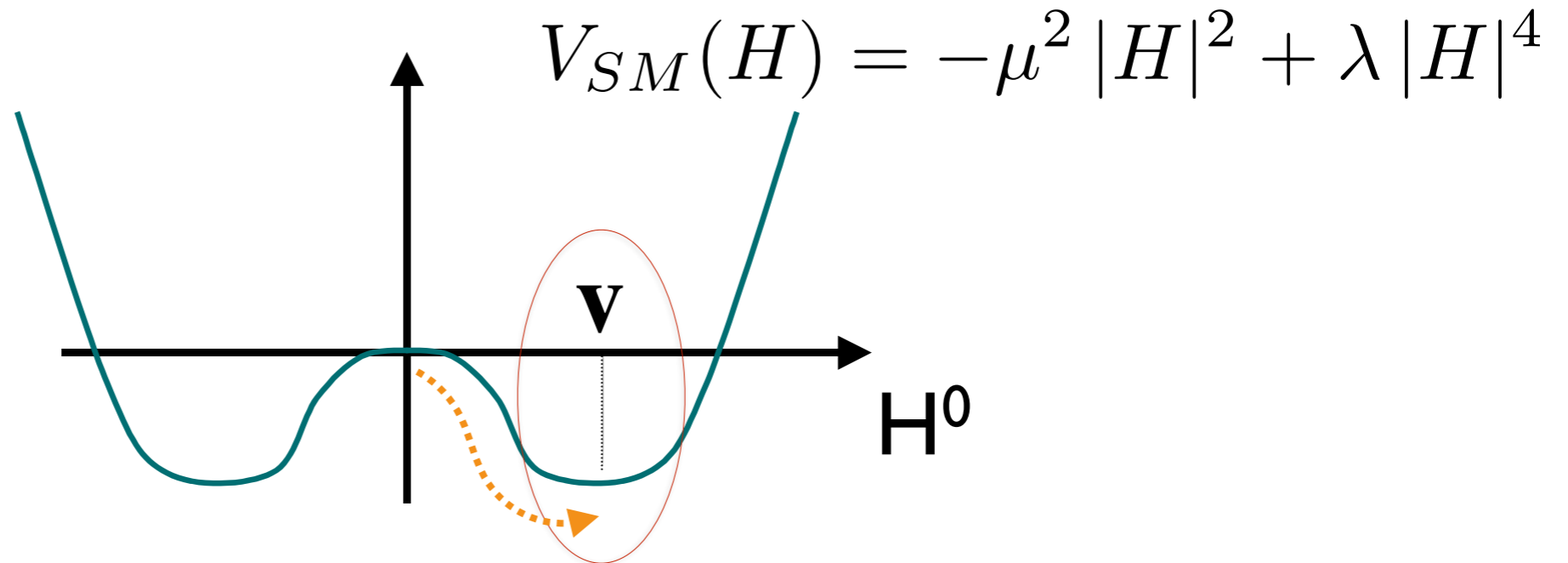
$$m \overline{\psi}_L \psi_R \rightarrow \lambda H \overline{\psi}_L \psi_R$$

Electroweak symmetry
breaking (EWSB)

What gives the Higgs field its background value?

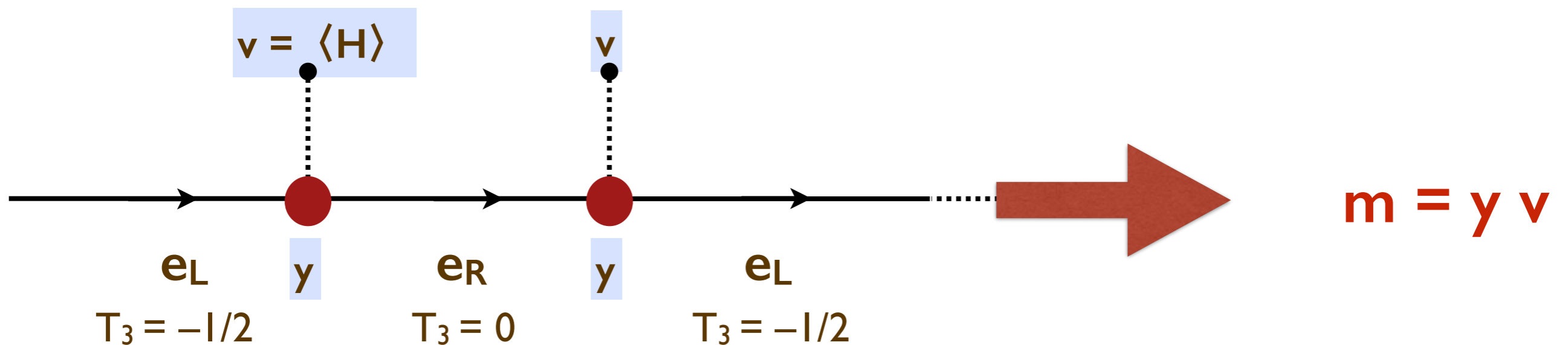


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Electroweak symmetry breaking (EWSB)



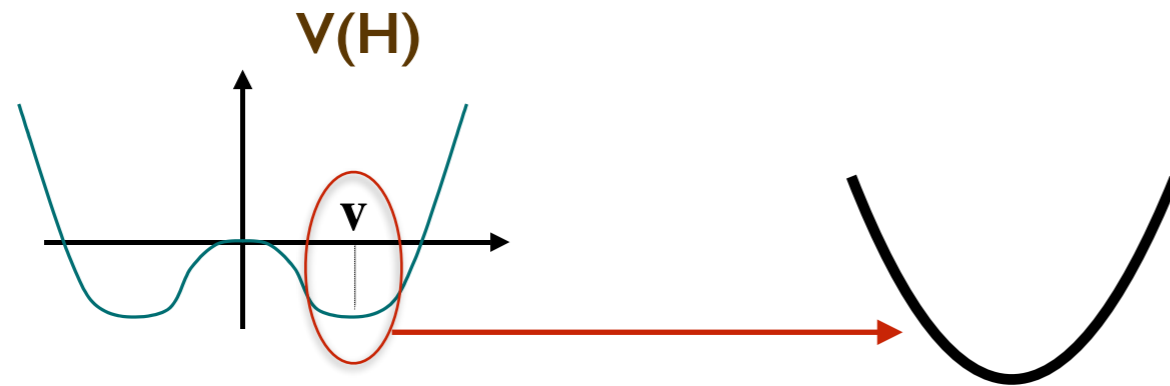
The transition between L and R states, and the absorption of the changes in weak charge, are ensured by the interaction with a background scalar field, H . Its “vacuum density” provides an infinite reservoir of weak charge.

First general consequences of this model

- Small oscillations around the minimum => a scalar particle (the “Higgs boson”)
- Couplings of H to SM particles proportional to their mass
- 3 out of 4 components of complex doublet field provide longitudinal degrees of freedom to weak gauge bosons $W^{+/-}$ and Z^0

How far have we tested the Higgs mechanism?

parameters of the potential

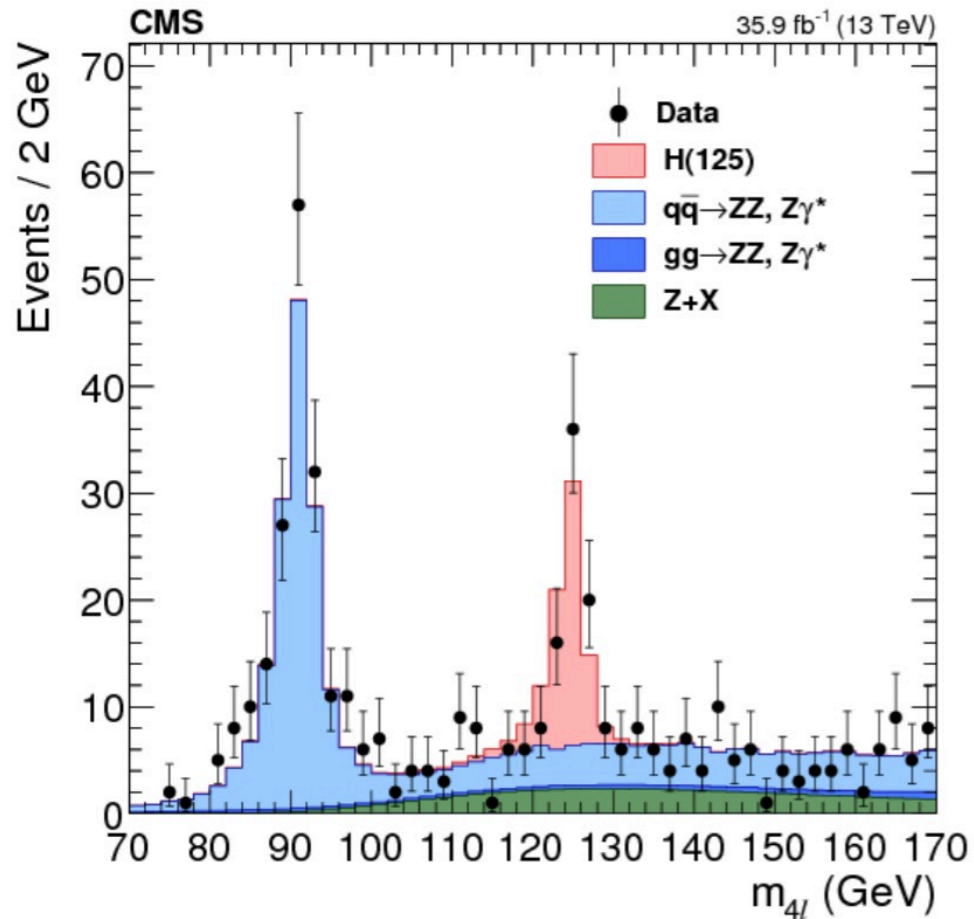


$$V(H) \sim m_H^2 (H - \mathbf{v})^2$$

$v=246$ GeV, from
weak decays

Higgs mass, 2017

CMS



[arXiv:1706.09936](https://arxiv.org/abs/1706.09936)

3D likelihood fit (m_{4l}, ZZ bg, δm) ⇒

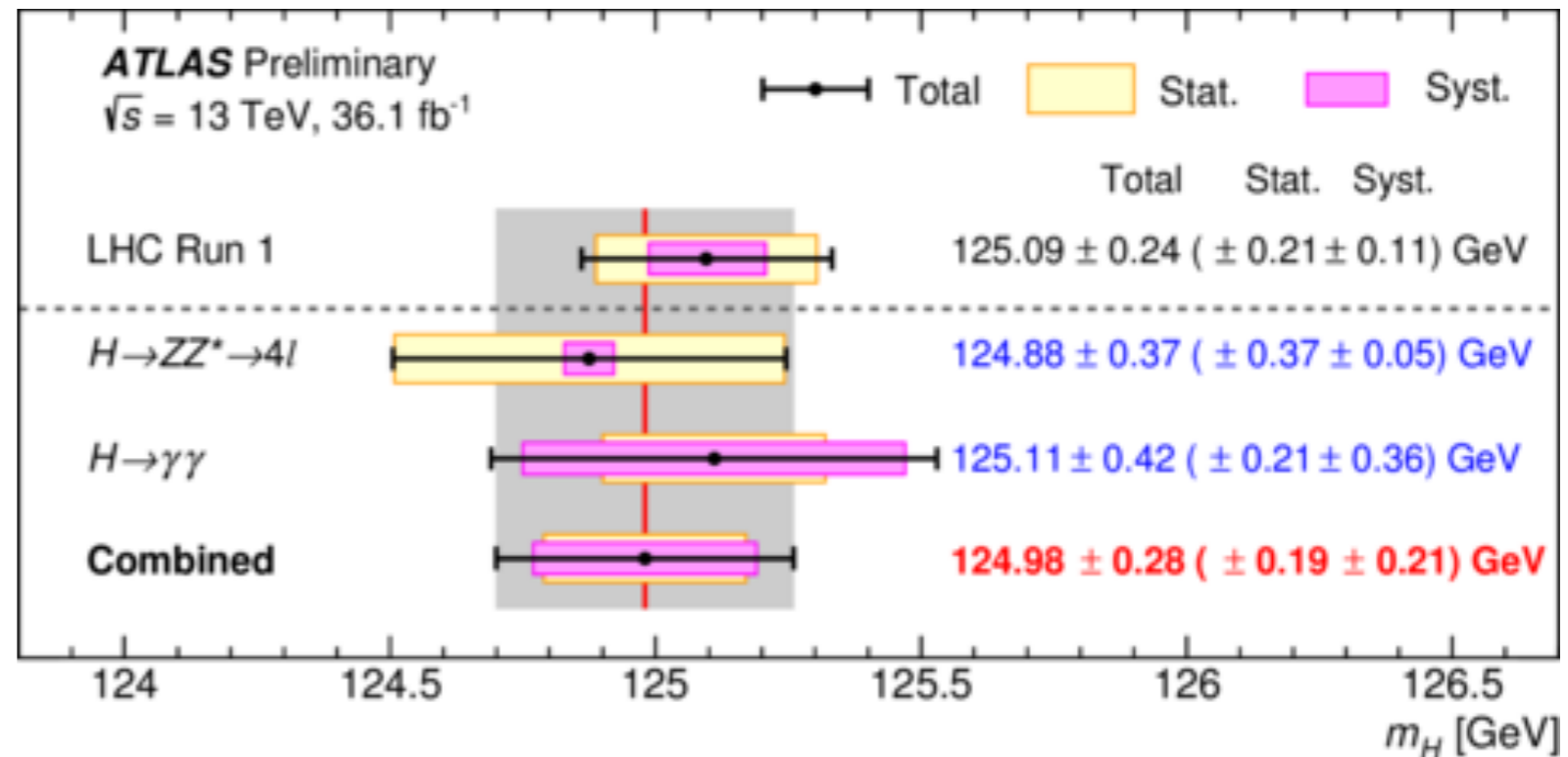
$$m_H = 125.26 \pm 0.20_{\text{stat}} \pm 0.08_{\text{syst}} \text{ GeV}$$

$$= 125.26 \pm 0.22 \text{ GeV}$$

⇒ 2 x 10⁻³ precision

it took over 6 years from 1983 discovery to get below 5 x 10⁻³ on m_z (1989: CDF, SLC, LEP) 23

ATLAS



[ATLAS-CONF-2017-046](https://atlas.conf.cern.ch/2017/046)

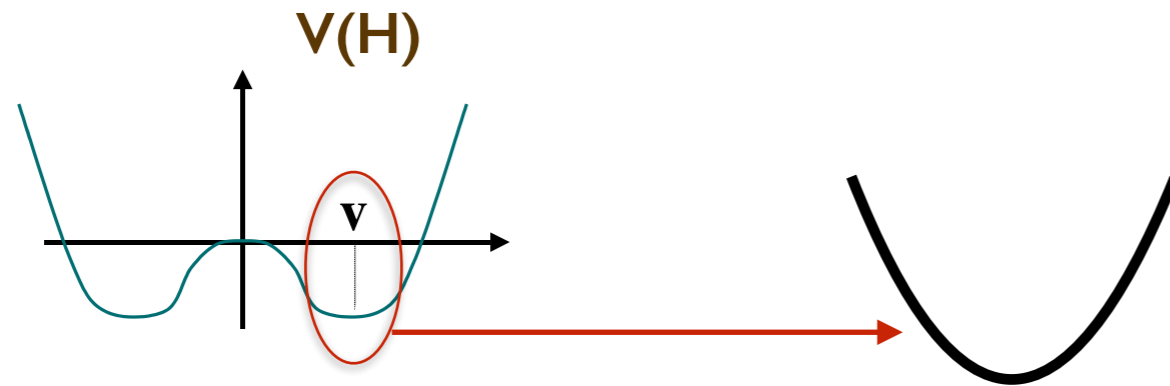
γγ and 4ℓ combination, run 1+2 ⇒

$$m_H = 124.98 \pm 0.19_{\text{stat}} \pm 0.21_{\text{syst}} \text{ GeV}$$

$$= 124.98 \pm 0.26 \text{ GeV}$$

How far have we tested the Higgs mechanism?

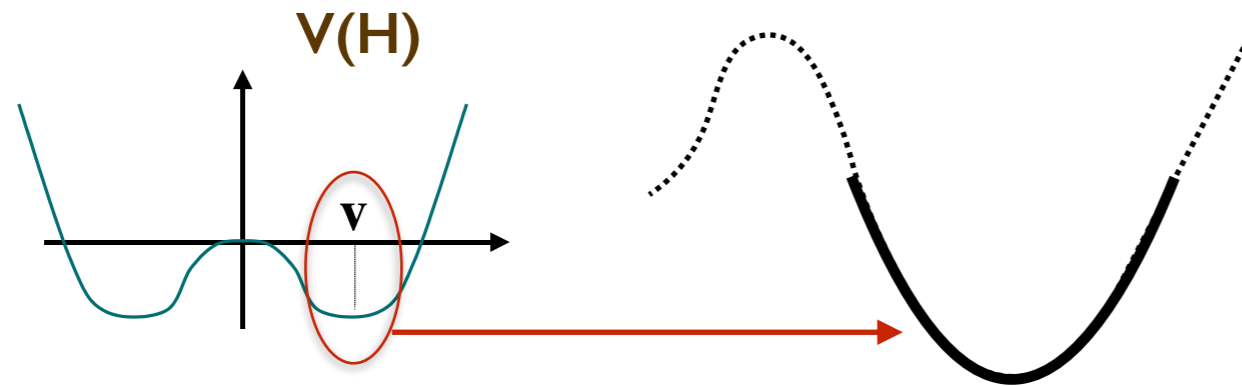
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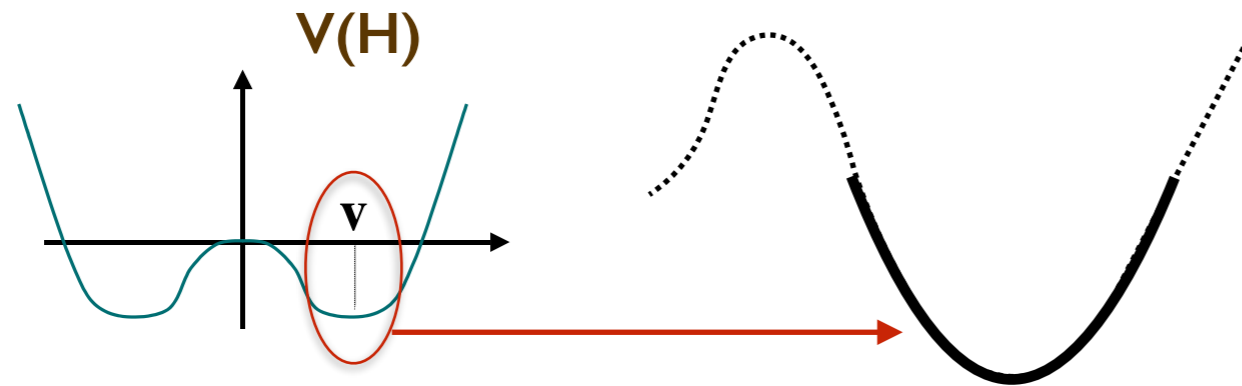
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$$V(H) \sim m_H^2 (H-v)^2 + ???$$

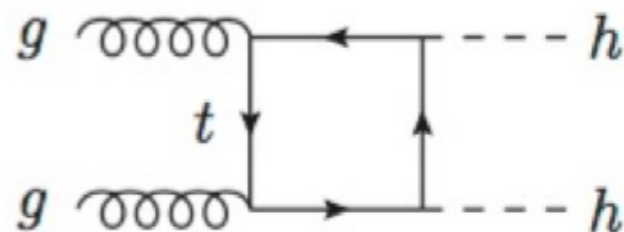
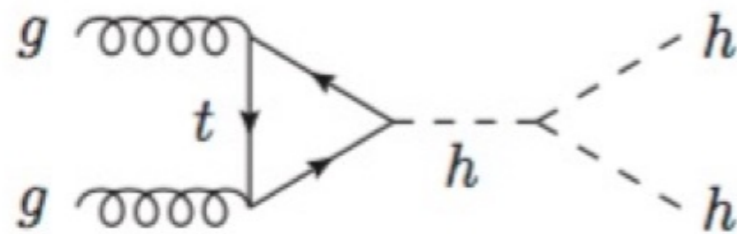
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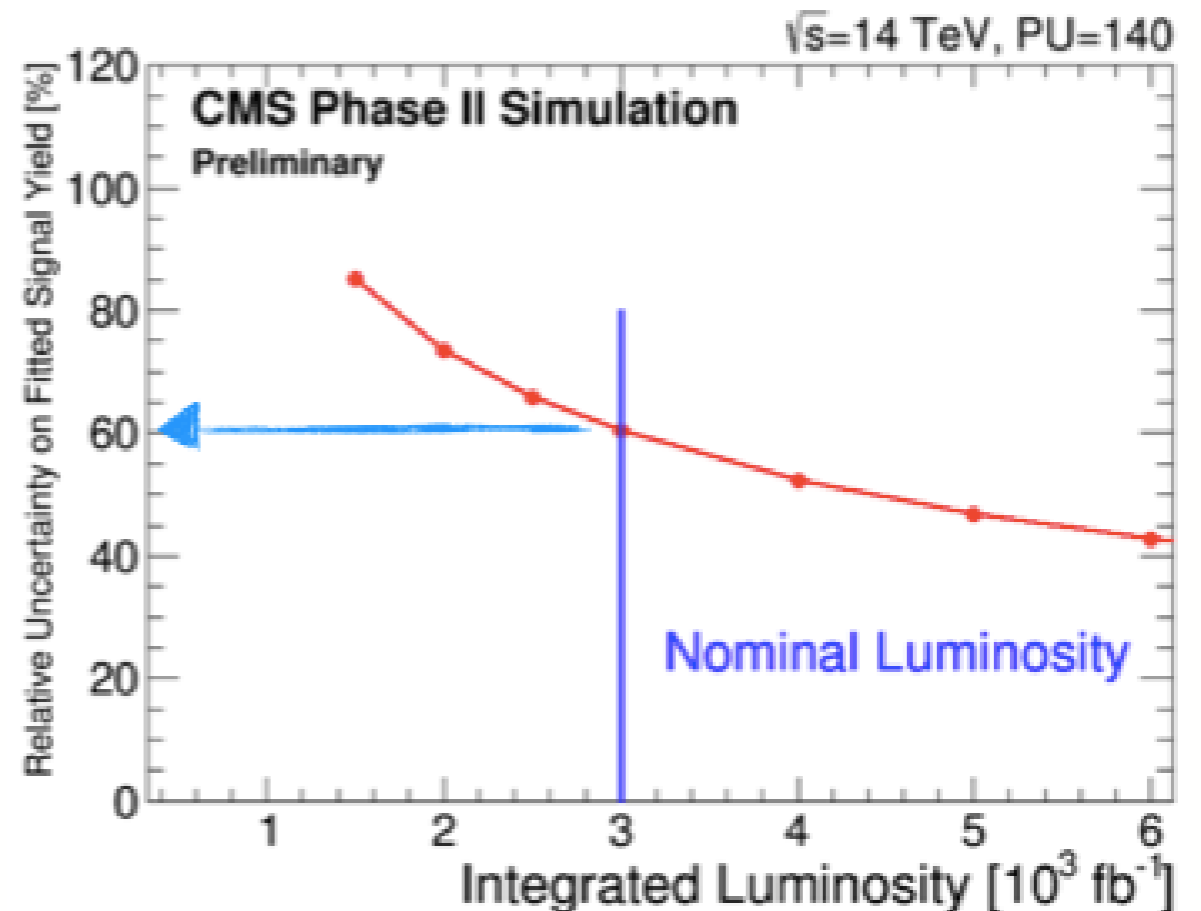


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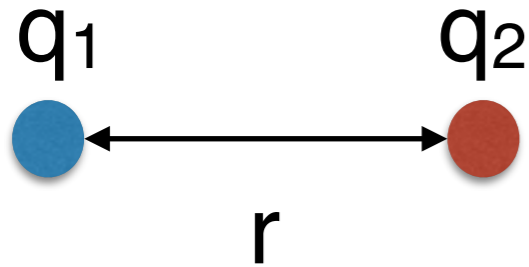
Probing the cubic term of the Higgs potential will require at least 100 x the current LHC statistics, and possibly more



Physics Performance for 2nd ECFA workshop

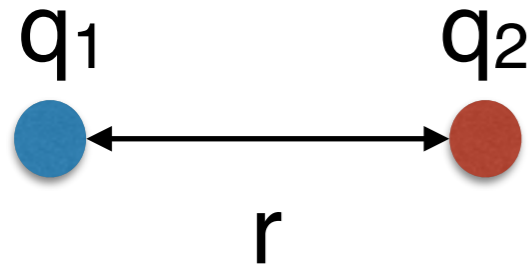


Electromagnetic vs Higgs dynamics



$$V(r) = + \frac{q_1 \times q_2}{r^1}$$

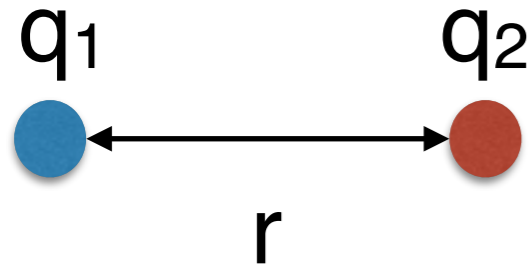
Electromagnetic vs Higgs dynamics



quantized,
in units of
fixed charge

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Electromagnetic vs Higgs dynamics



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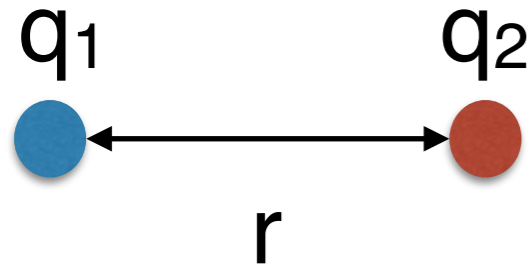
Annotations: The plus sign (+) is circled in blue. The product $q_1 \times q_2$ is circled in yellow. The denominator r^1 is circled in blue.

quantized,
in units of
fixed charge

sign fixed
by photon
spin

power determined by gauge
invariance/charge
conservation/Gauss theorem

Electromagnetic vs Higgs dynamics

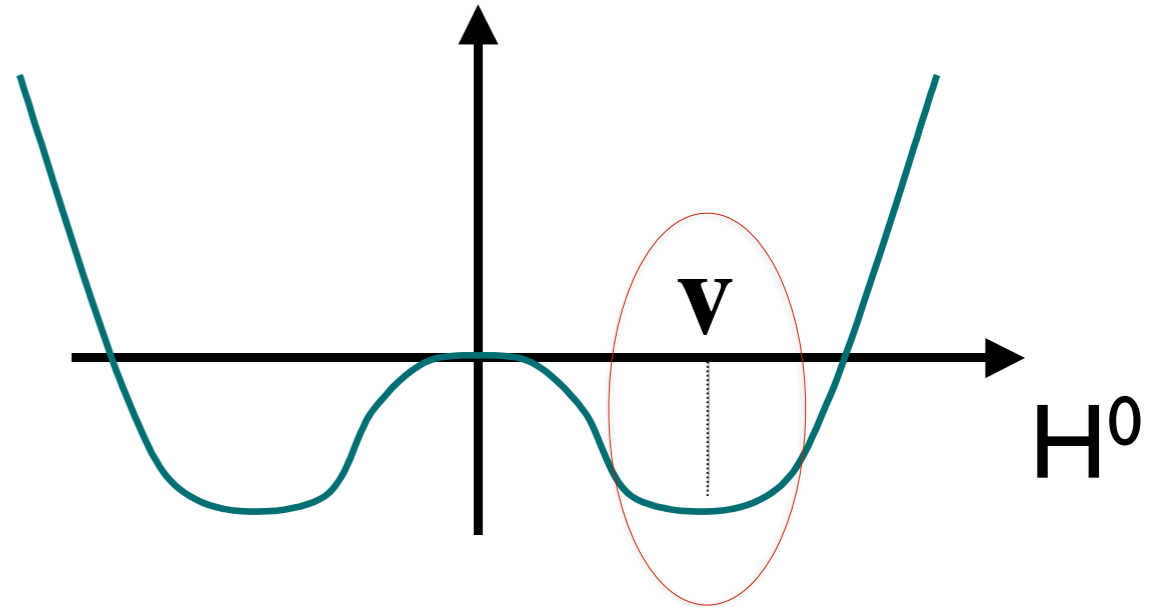


quantized,
in units of
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$$V(r) = \frac{q_1 \times q_2}{r^2}$$

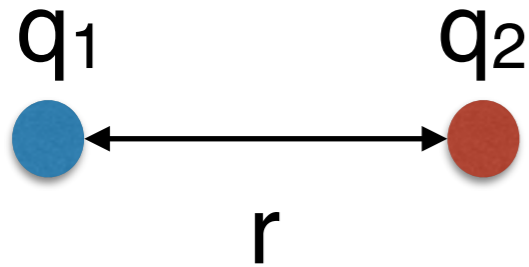
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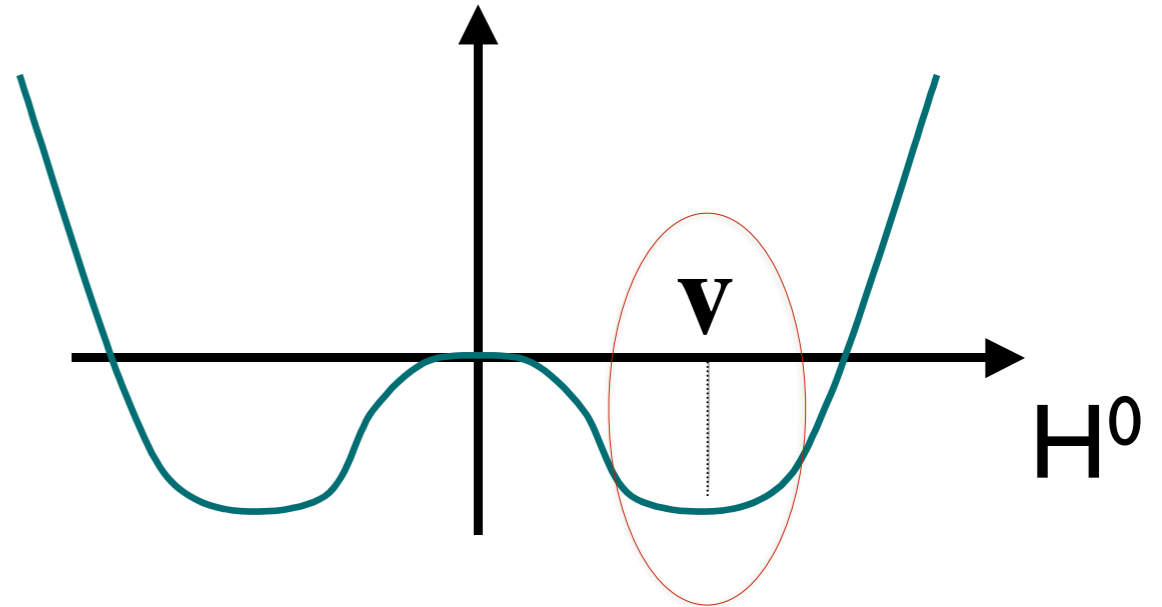


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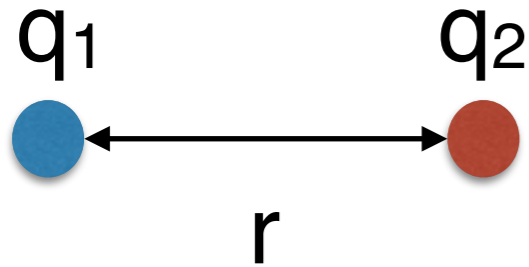


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both sign
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>0 to ensure
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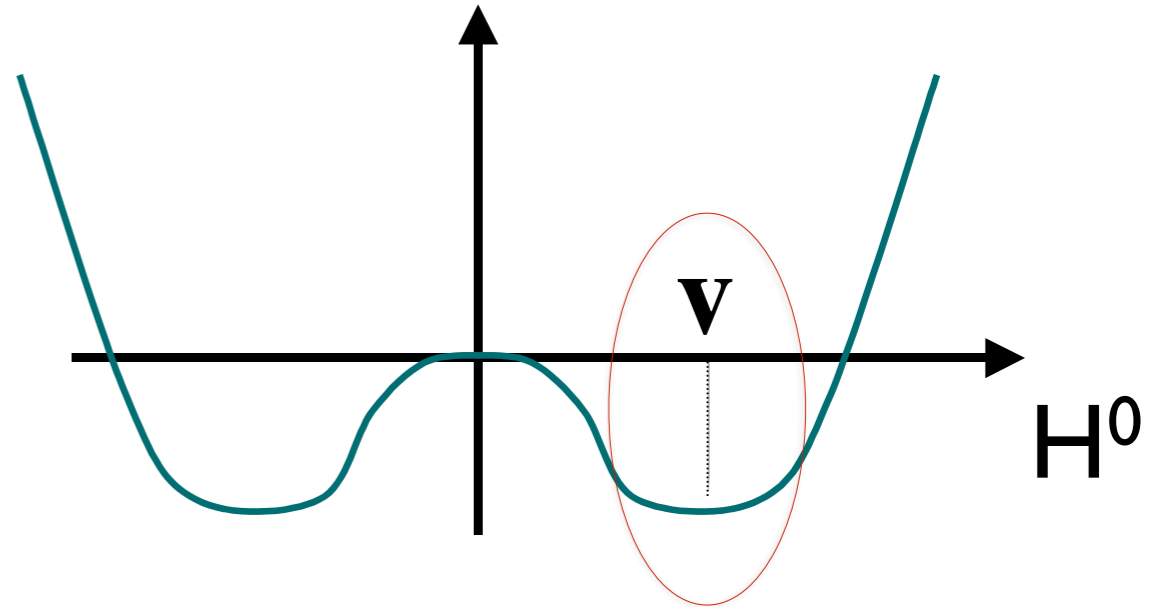


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any function of $|H|^2$ would be
ok wrt known symmetries

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

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a historical example: superconductivity

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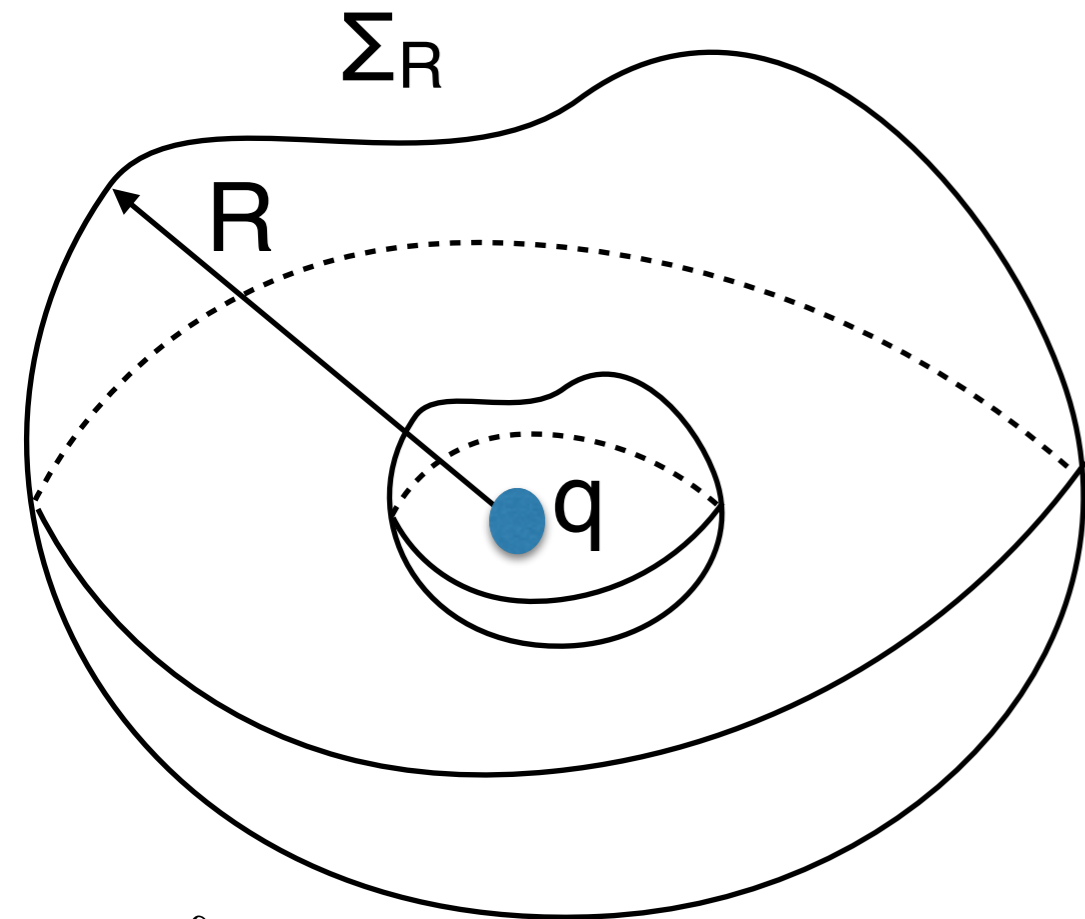
- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

a historical example: superconductivity

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- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

Decoupling of high-frequency modes

E&M

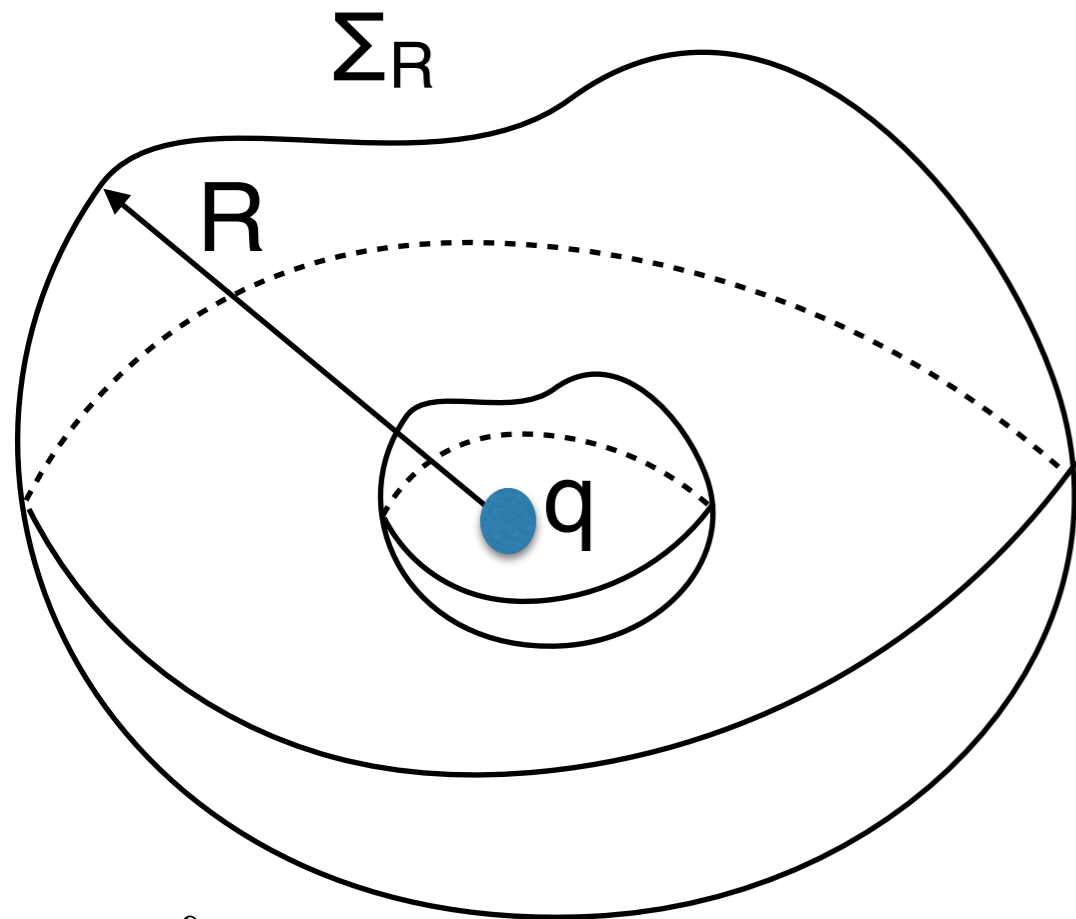


$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

short-scale physics does not alter
the charge seen at large scales

Decoupling of high-frequency modes

E&M



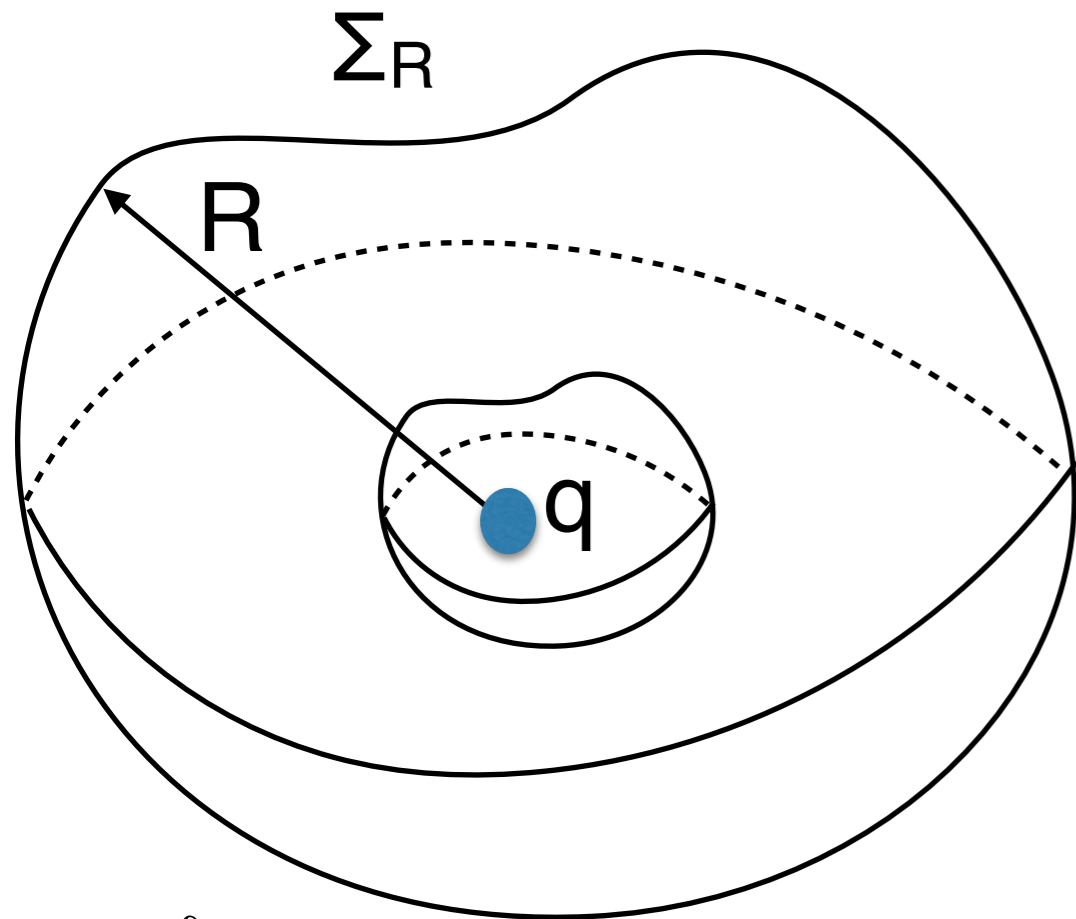
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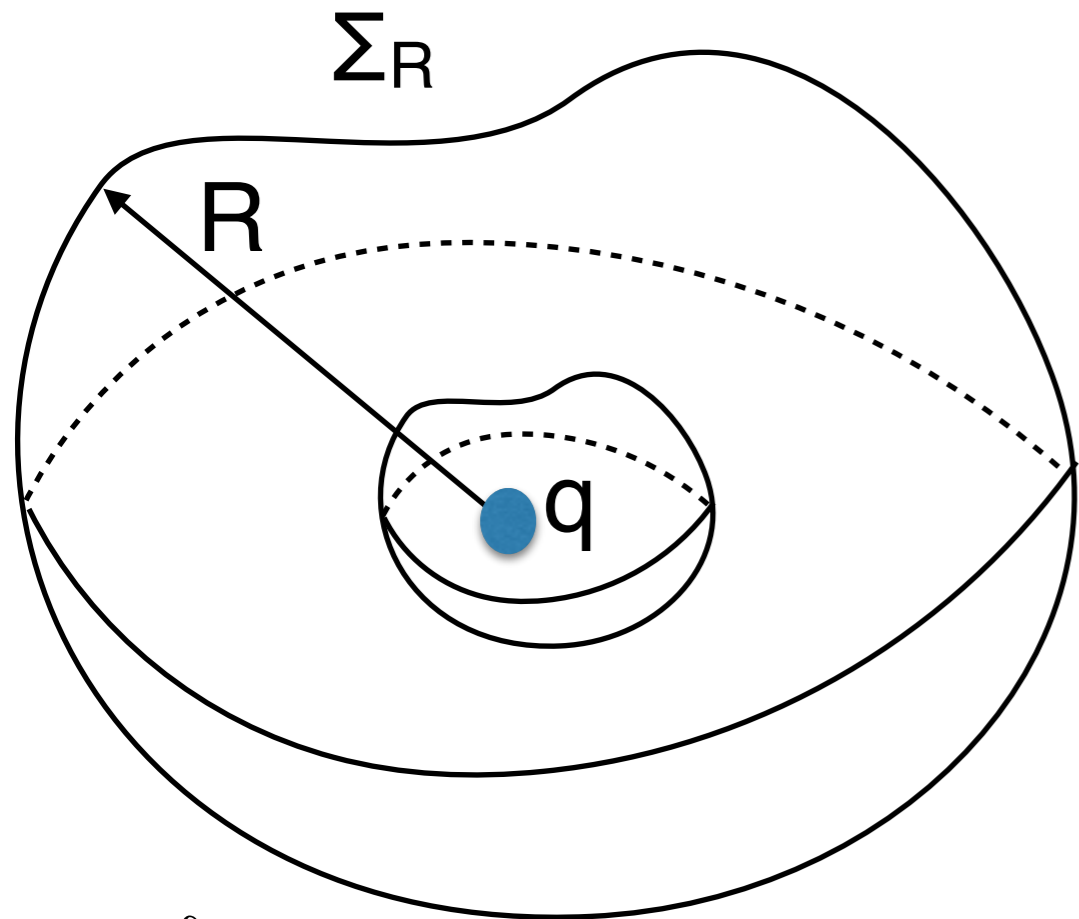
$$\mu^2_{\text{ren}} = \mu^2 + \frac{g^2}{16\pi^2} \ln \left(\frac{\Lambda}{\mu} \right) + \frac{y_t^2}{16\pi^2} \ln \left(\frac{\Lambda}{\mu} \right)$$

The diagram shows a Feynman diagram for the renormalization of the mass parameter μ^2 . It consists of a solid black dot on the left, followed by an equals sign, a dashed line, a plus sign, a dashed line with a dashed circle labeled 'W,H' in the middle, another plus sign, and a dashed line with a solid circle labeled 't' on the right. Below the first dot is μ^2_{ren} , below the middle dashed line is μ^2 , below the dashed circle is g^2 , and below the solid circle is $-y_t^2$.

$$\Delta\mu^2 \sim (c_W m_W^2 - c_t m_t^2) \times (\Lambda / v)^2$$

Decoupling of high-frequency modes

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$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

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$$\Delta\mu^2 \sim (c_W m_W^2 - c_t m_t^2) \times (\Lambda / v)^2$$

$$\lambda_{\text{ren}} = \lambda + \text{loop}(t, -y_t^4) + \text{loop}(h, \lambda^4)$$

$$\Rightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4 \propto a m_H^4 - b m_t^4$$

high-energy modes can change size and sign of both μ^2 and λ , dramatically altering the stability and dynamics

bottom line

- To predict the properties of EM at large scales, we don't need to know what happens at short scales
- The Higgs dynamics is sensitive to all that happens at any scale larger than the Higgs mass !!! A very **unnatural fine tuning** is required to protect the Higgs dynamics from the dynamics at high energy
- This issue goes under the name of **hierarchy problem**
- Solutions to the hierarchy problem require the introduction of new symmetries (typically leading to the existence of new particles), which decouple the high-energy modes and allow the Higgs and its dynamics to be defined at the “natural” scale defined by the measured parameters v and m_H

⇒ **naturalness**

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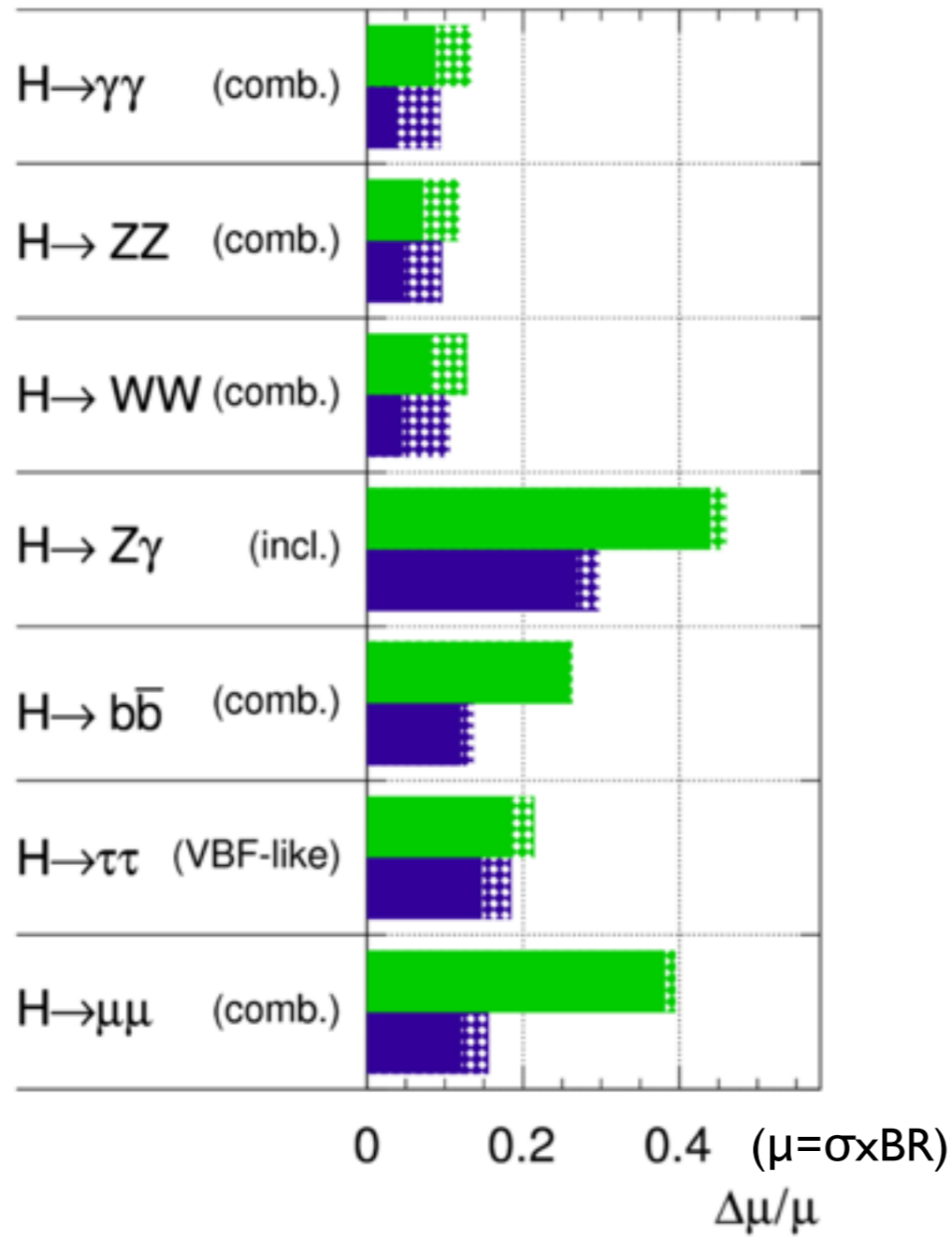
=> all this justifies the focus on the program of precision Higgs physics measurements

Projected precision on H couplings at HL-LHC

ATL-PHYS-PUB-2014-016

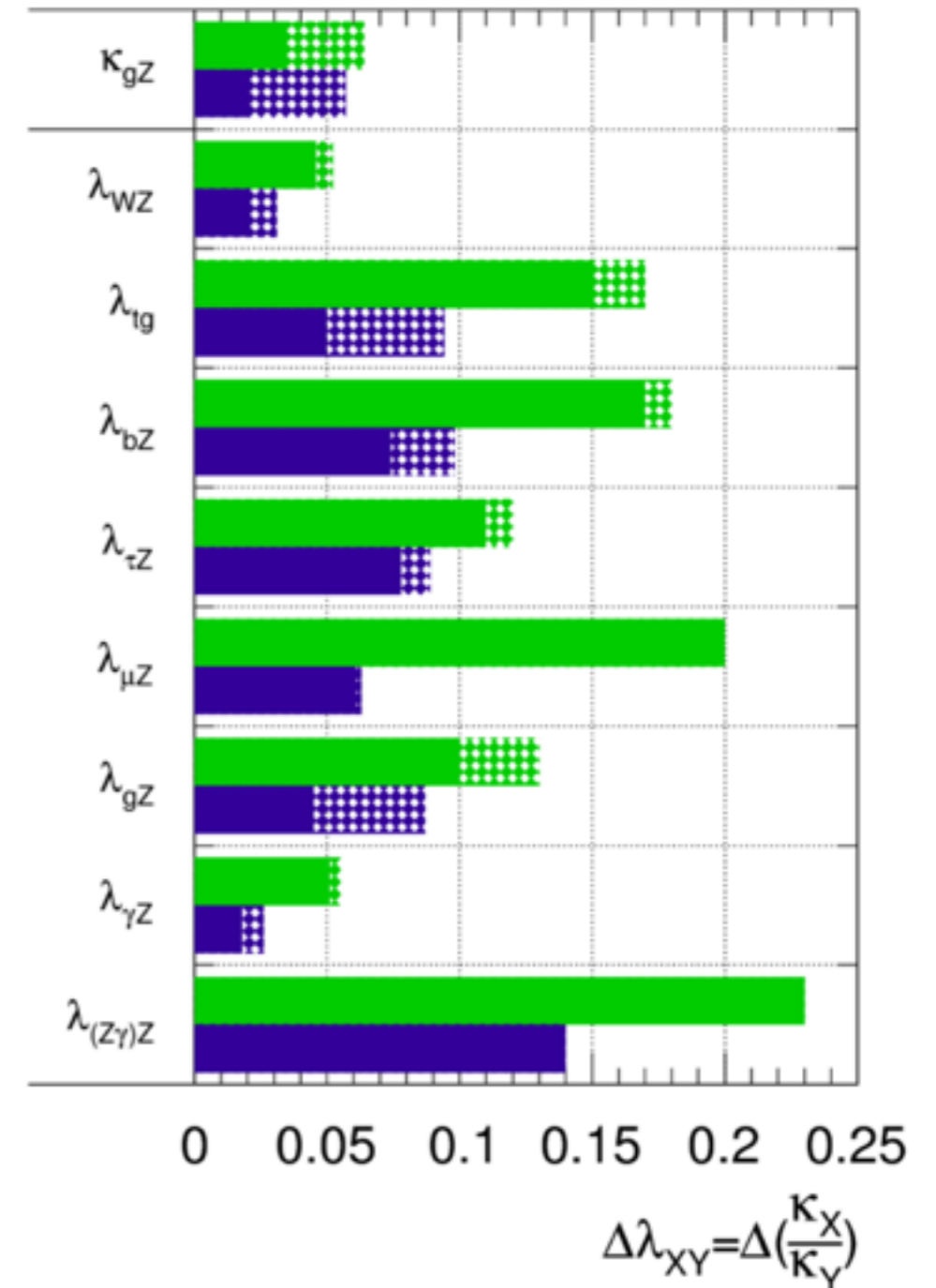
ATLAS Simulation Preliminary

$\sqrt{s} = 14 \text{ TeV}$: $\int L dt = 300 \text{ fb}^{-1}$; $\int L dt = 3000 \text{ fb}^{-1}$



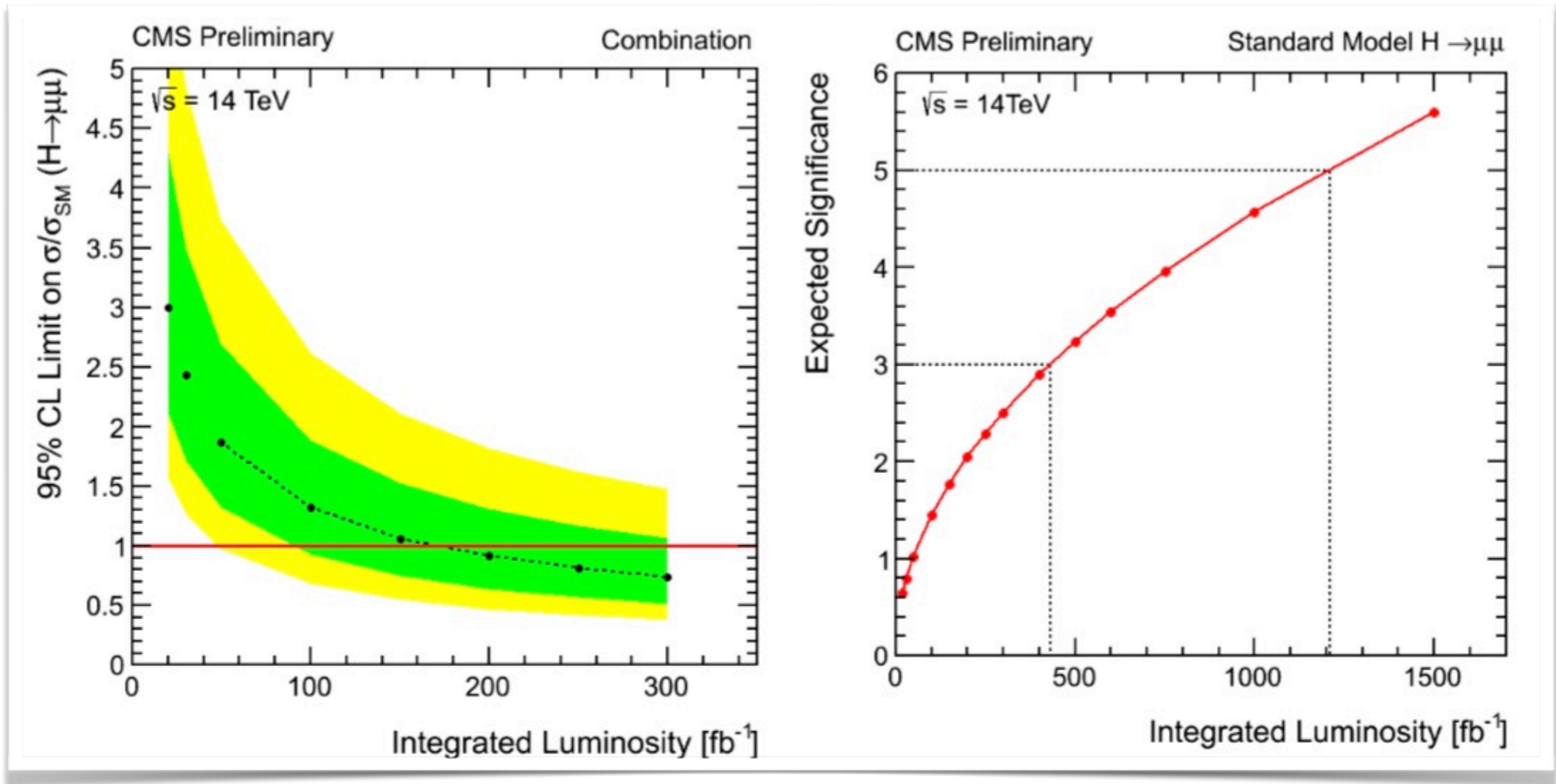
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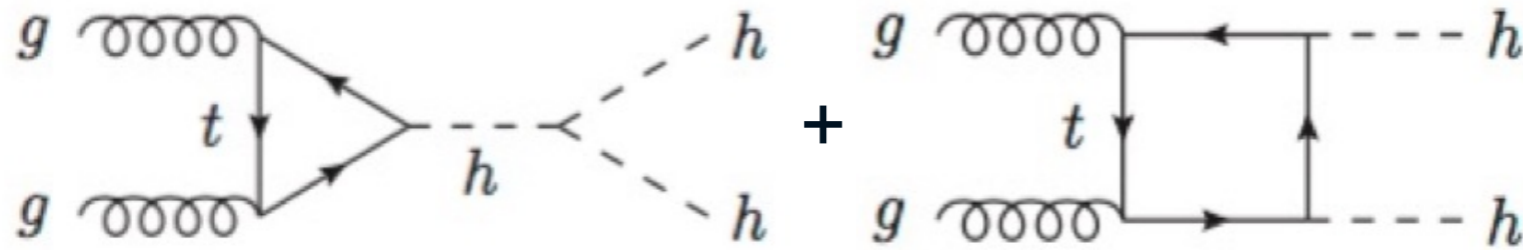


solid areas: no TH systematics
shaded areas: with TH systematics

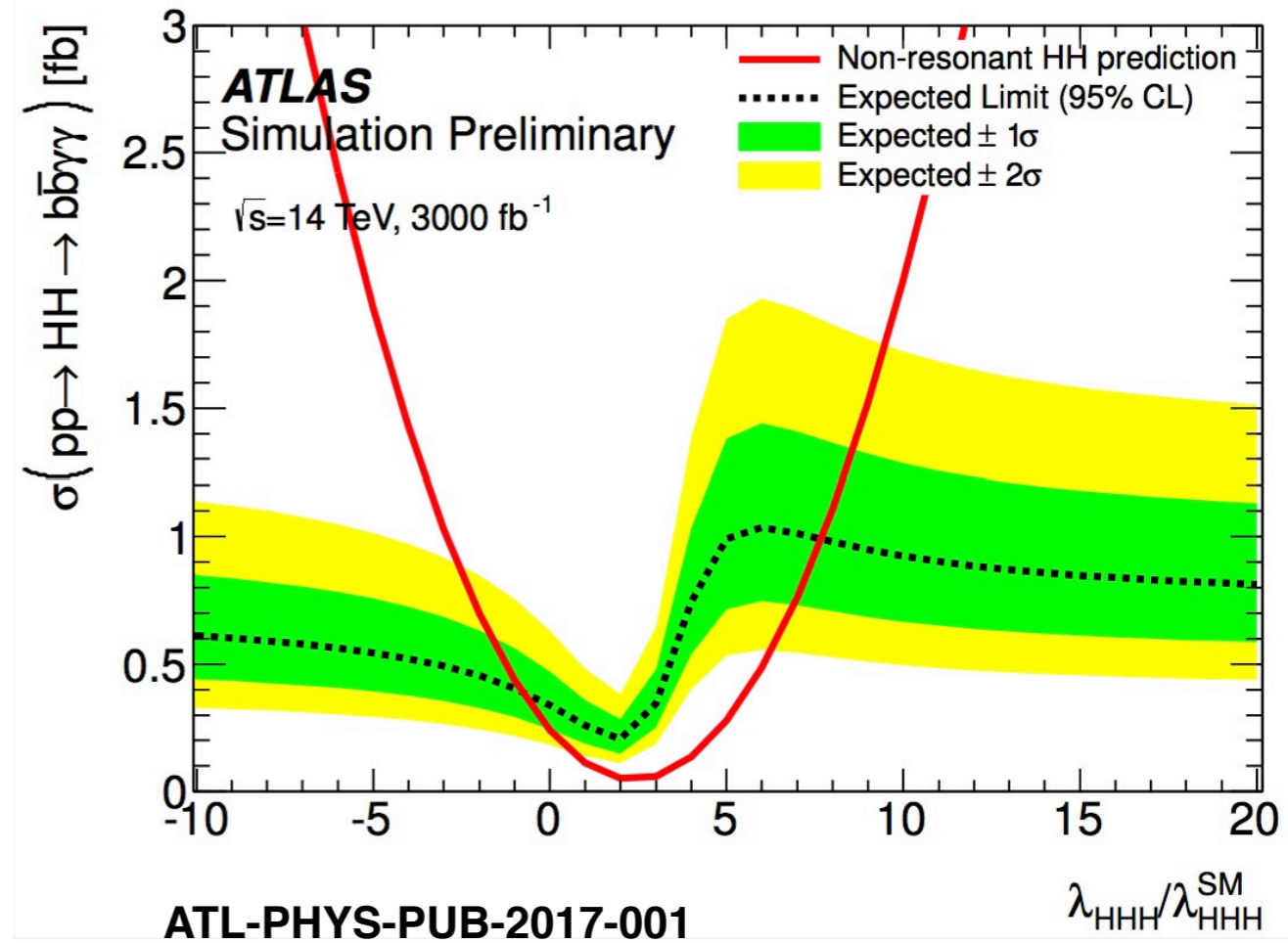
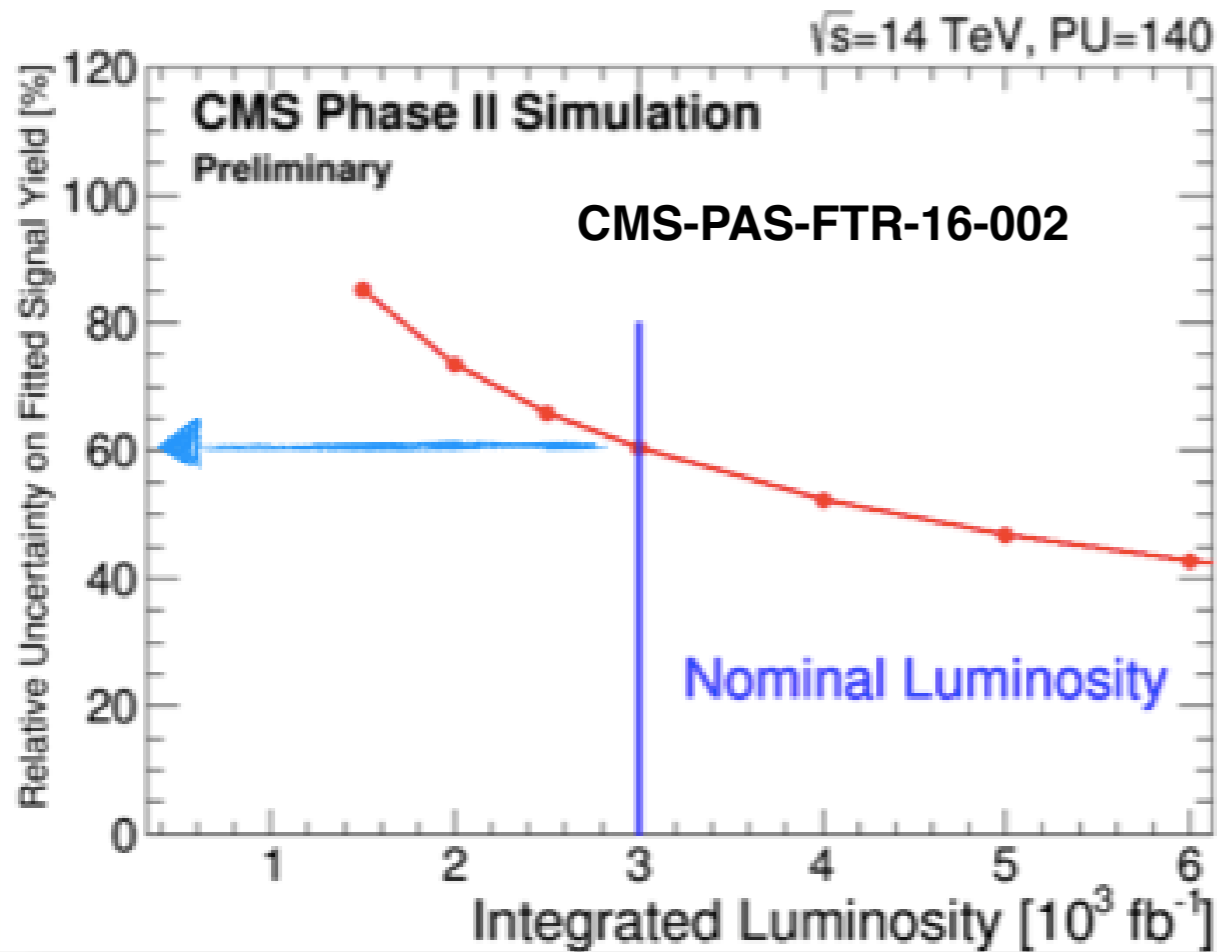
H couplings to 2nd generation: the role of HL-LHC



What will HL-LHC tells us about the Higgs potential?



- Strong negative interference between the two diagrams near threshold
- Selfcoupling diagram suppressed well above threshold, due to I/S behaviour
- => it's hard!!



Barely 1- 2σ evidence for Higgs pair production, but no quantitatively significant determination of λ : $-0.8 < \lambda/\lambda_{\text{SM}} < 7.7$ @95%CL

$-0.2 < \lambda/\lambda_{\text{SM}} < 2.6$
w. kinematical analysis

Higgs couplings @ FCC

g_{HXY}	ee [240+350 (4IP)]	pp [100 TeV] 30ab ⁻¹	ep [60GeV/50TeV], 1ab ⁻¹
ZZ	0.15%	<1%	
WW	0.19%		
bb	0.42%		0.2%
cc	0.71%		1.8%
gg	0.80%		
ττ	0.54%		
μμ	6.2%	<1%	
γγ	1.5%	<0.5%	
Zγ		<1%	
tt	~13%	1%	
HH	~30%	3.5%	under study
uu,dd	H->ργ, under study		
ss	H->φγ, under study		
BR _{inv}	< 0.45%	few 10 ⁻⁴	
Γ _{tot}	1%		

**What other open questions arise
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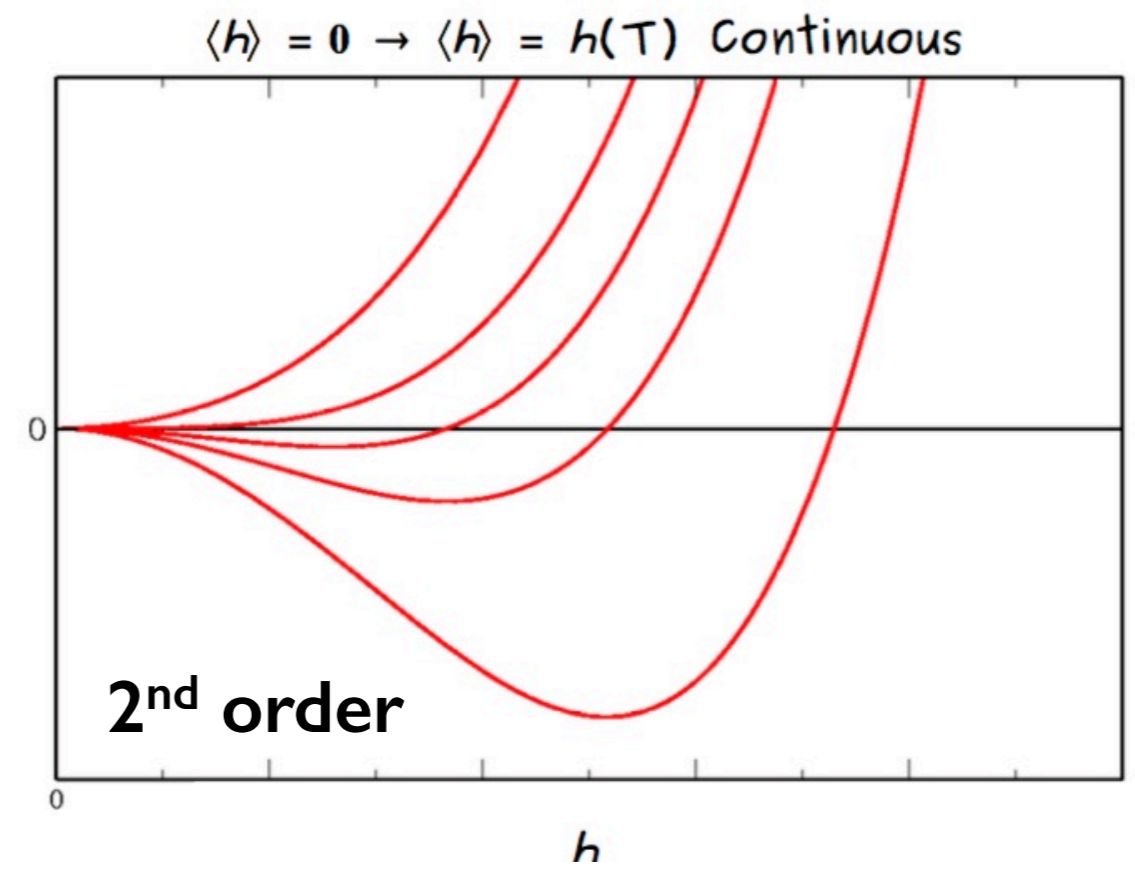
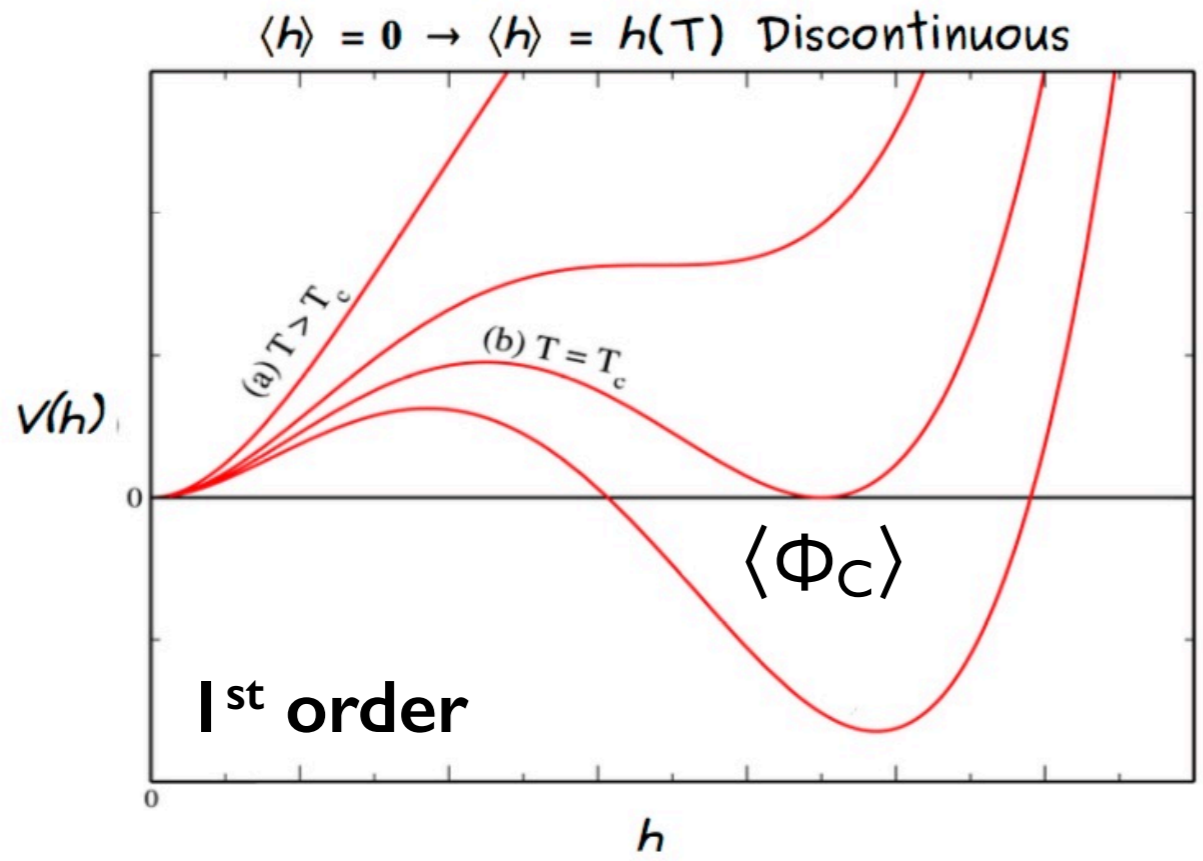
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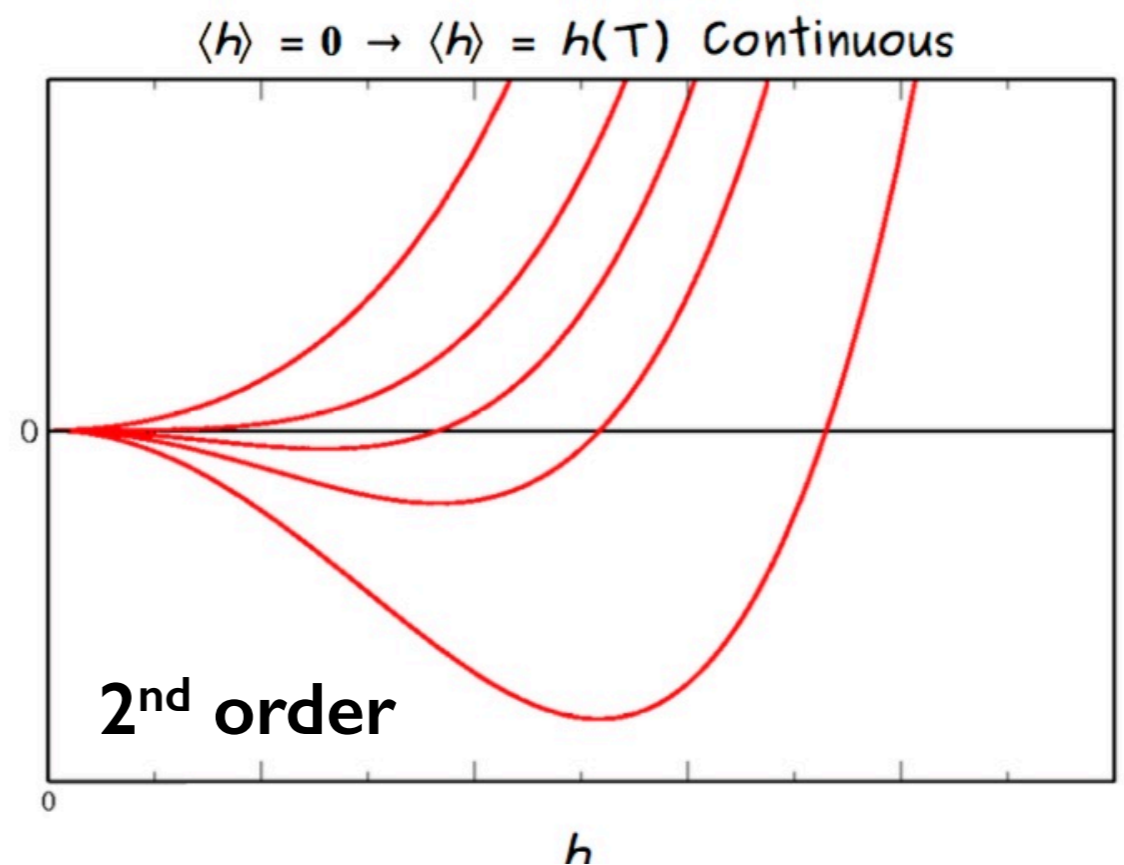
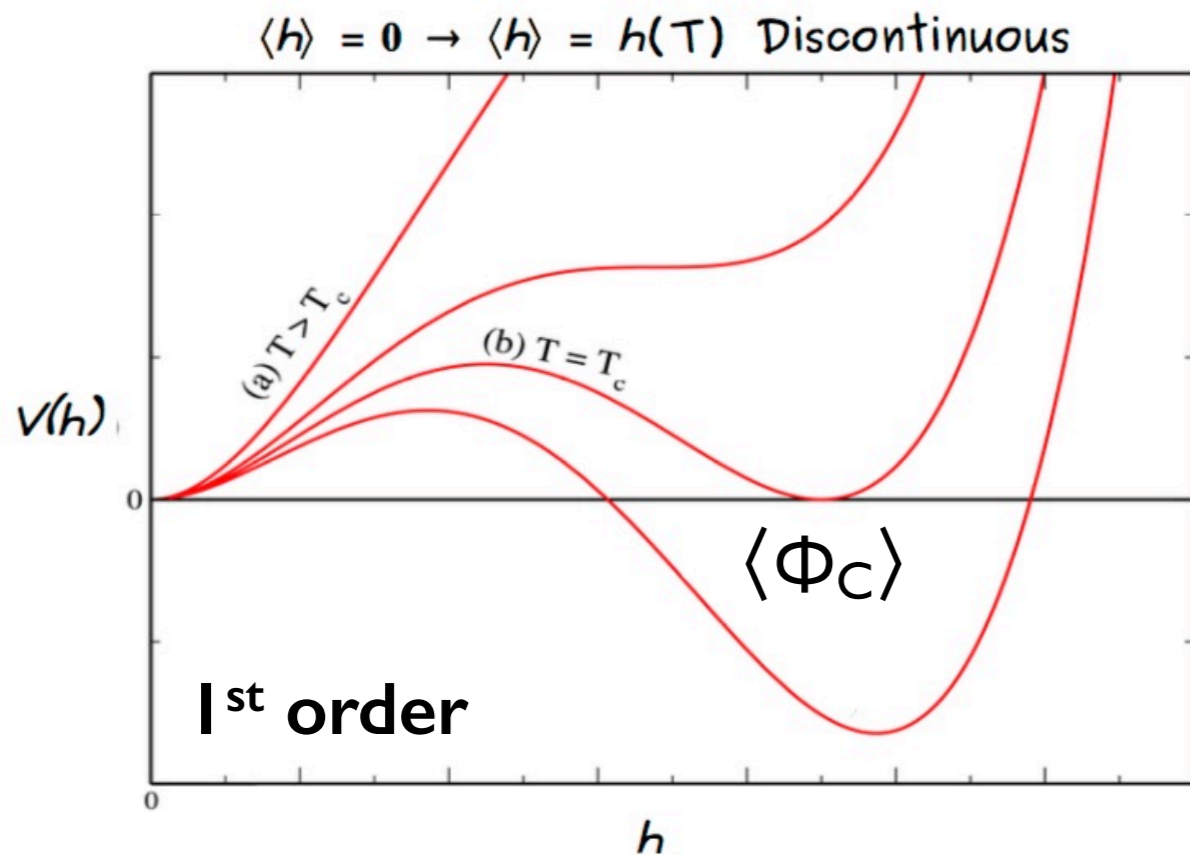
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- Is there a deep reason for the apparent metastability of the Higgs vacuum?

The nature of the EW phase transition



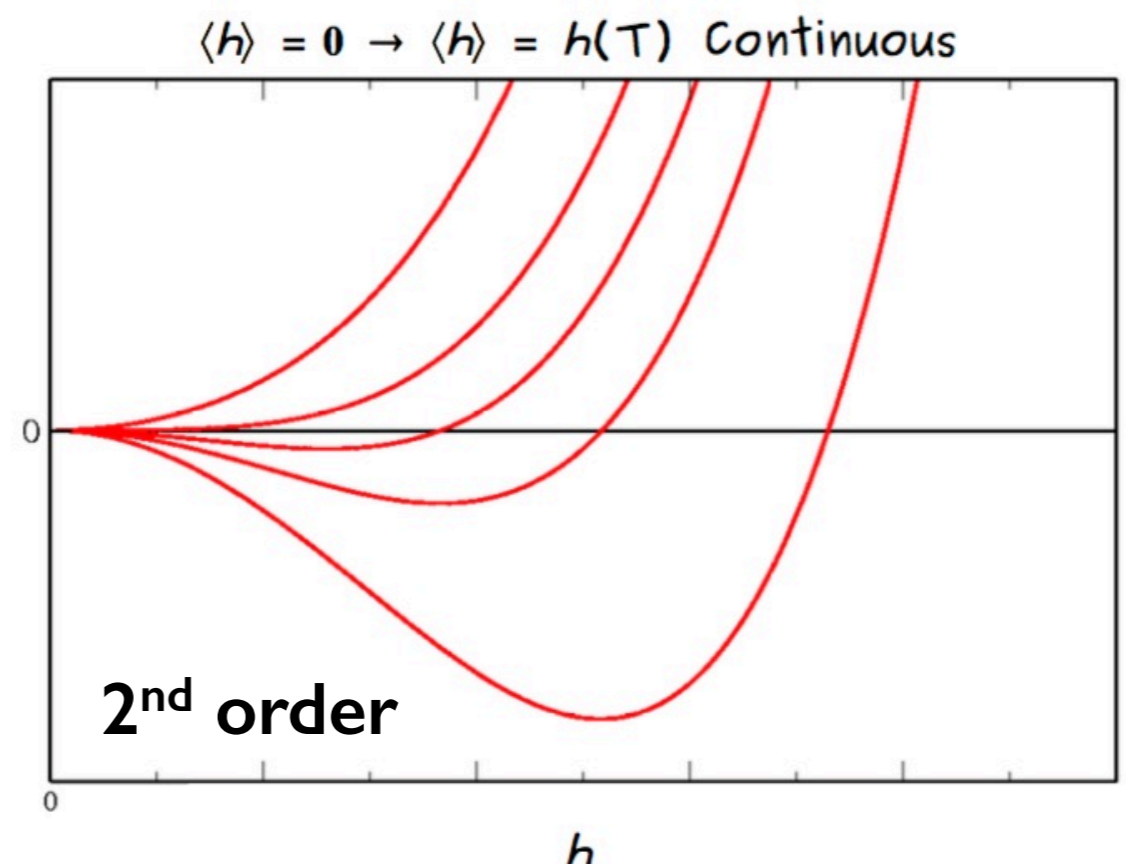
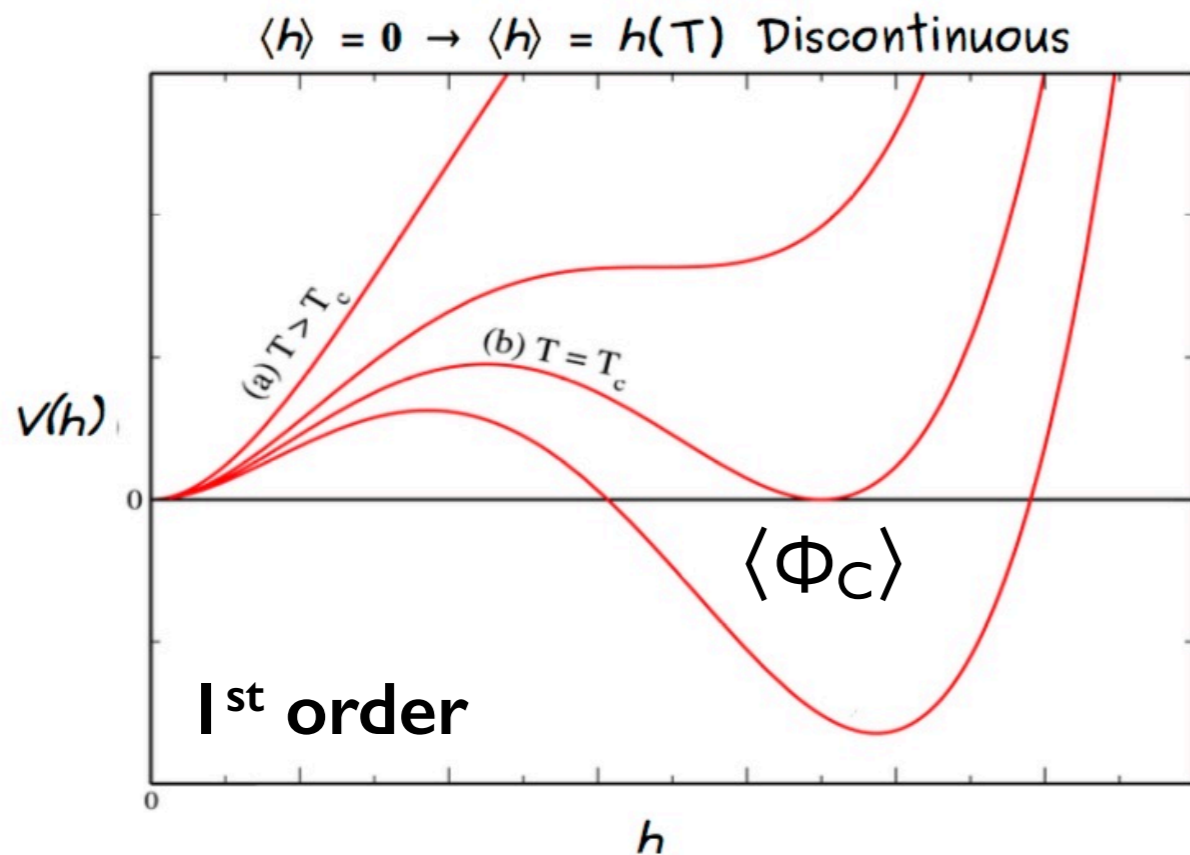
The nature of the EW phase transition



Strong 1^{st} order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

Strong 1^{st} order phase transition $\Rightarrow \langle \Phi_C \rangle > T_C$

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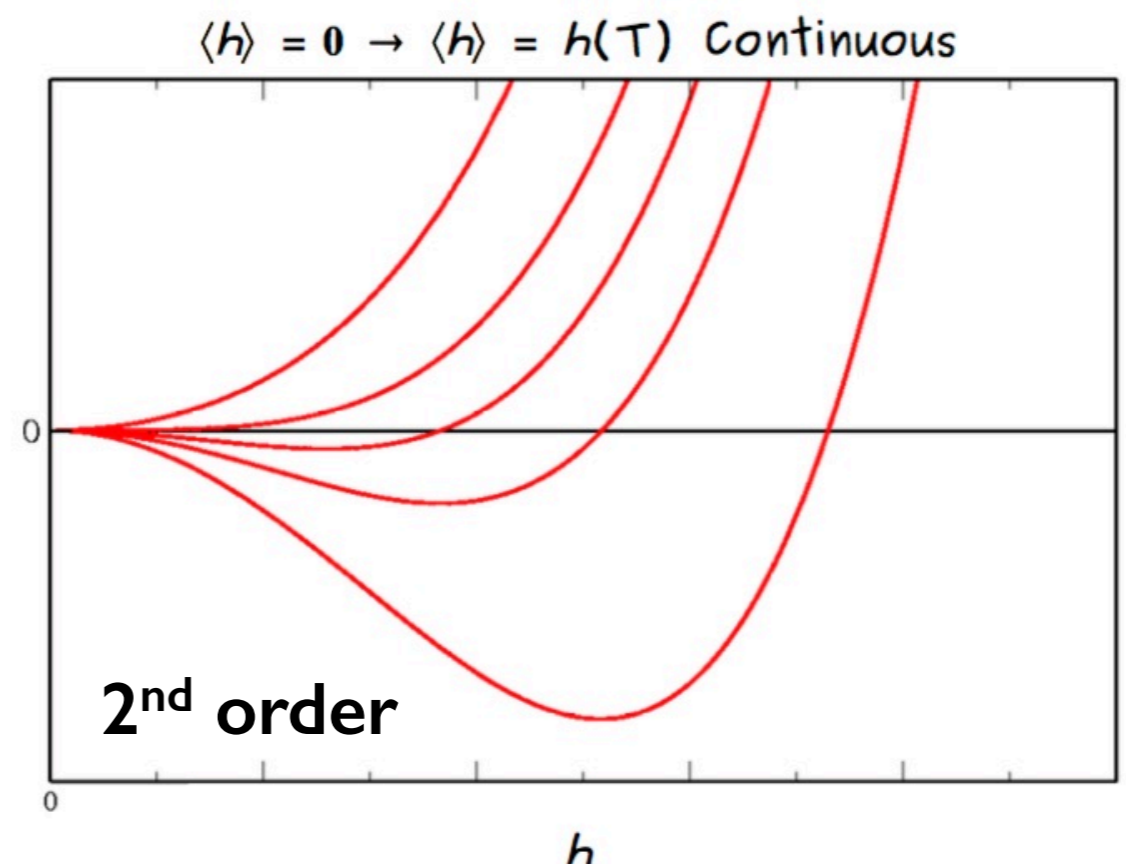
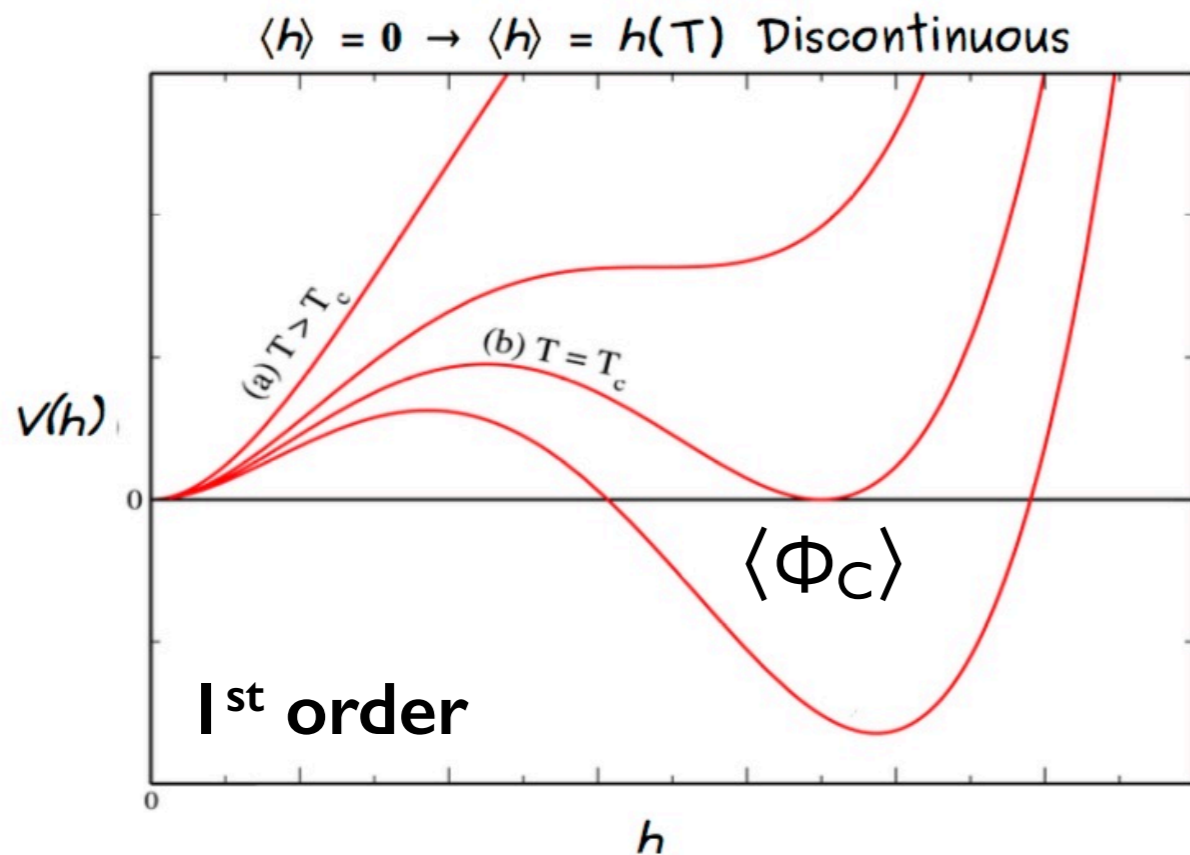
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In the SM this requires $m_H \lesssim 80$ GeV, else transition is a smooth crossover.

Since $m_H = 125$ GeV, **new physics**, coupling to the Higgs and effective at **scales $O(\text{TeV})$** , must modify the Higgs potential to make this possible

The nature of the EW phase transition

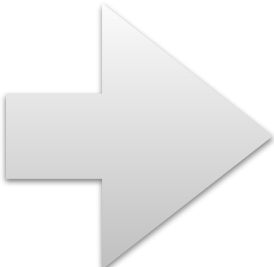


Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

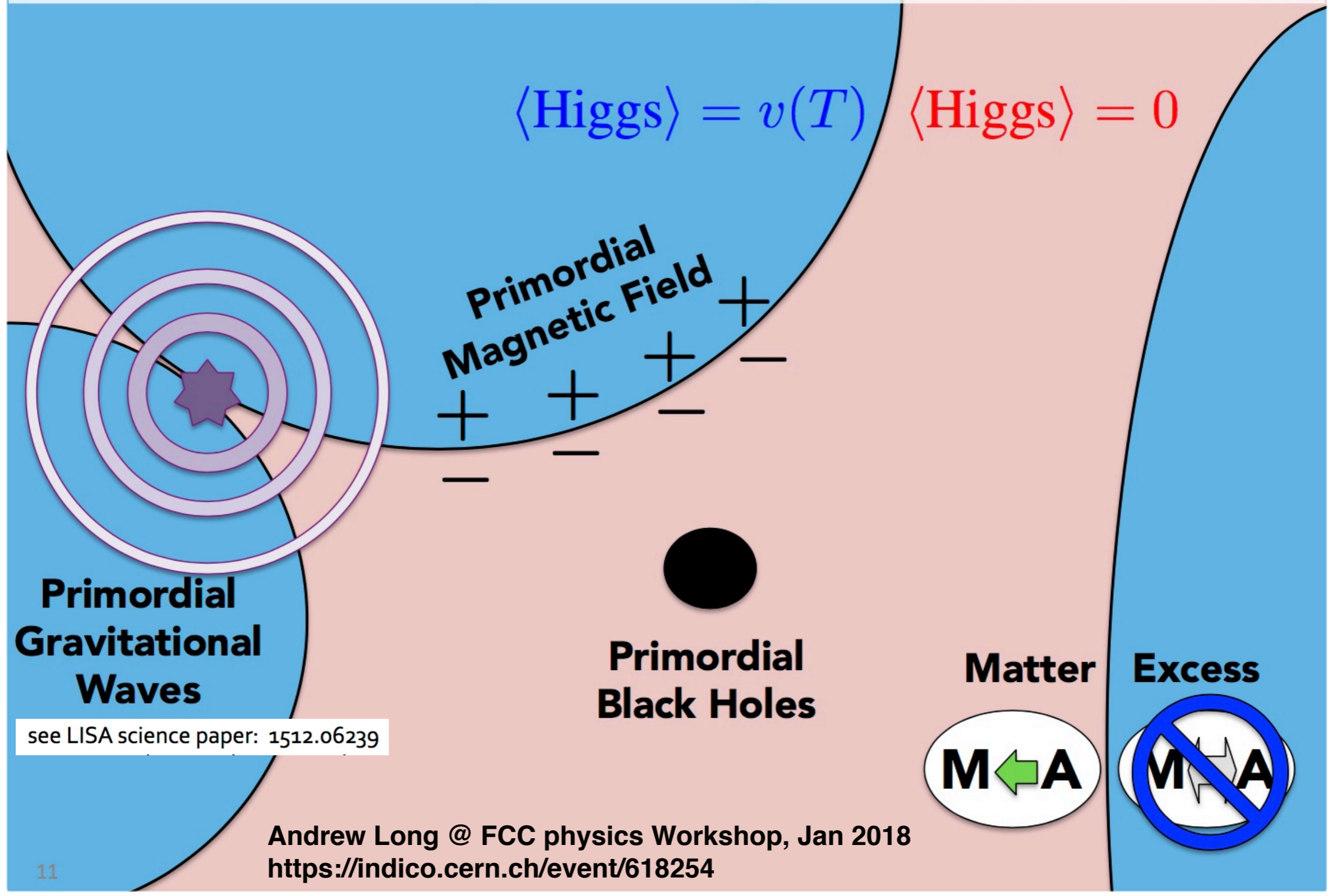
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- 
- Probe higher-order terms of the Higgs potential (selfcouplings)
 - Probe the existence of other particles coupled to the Higgs

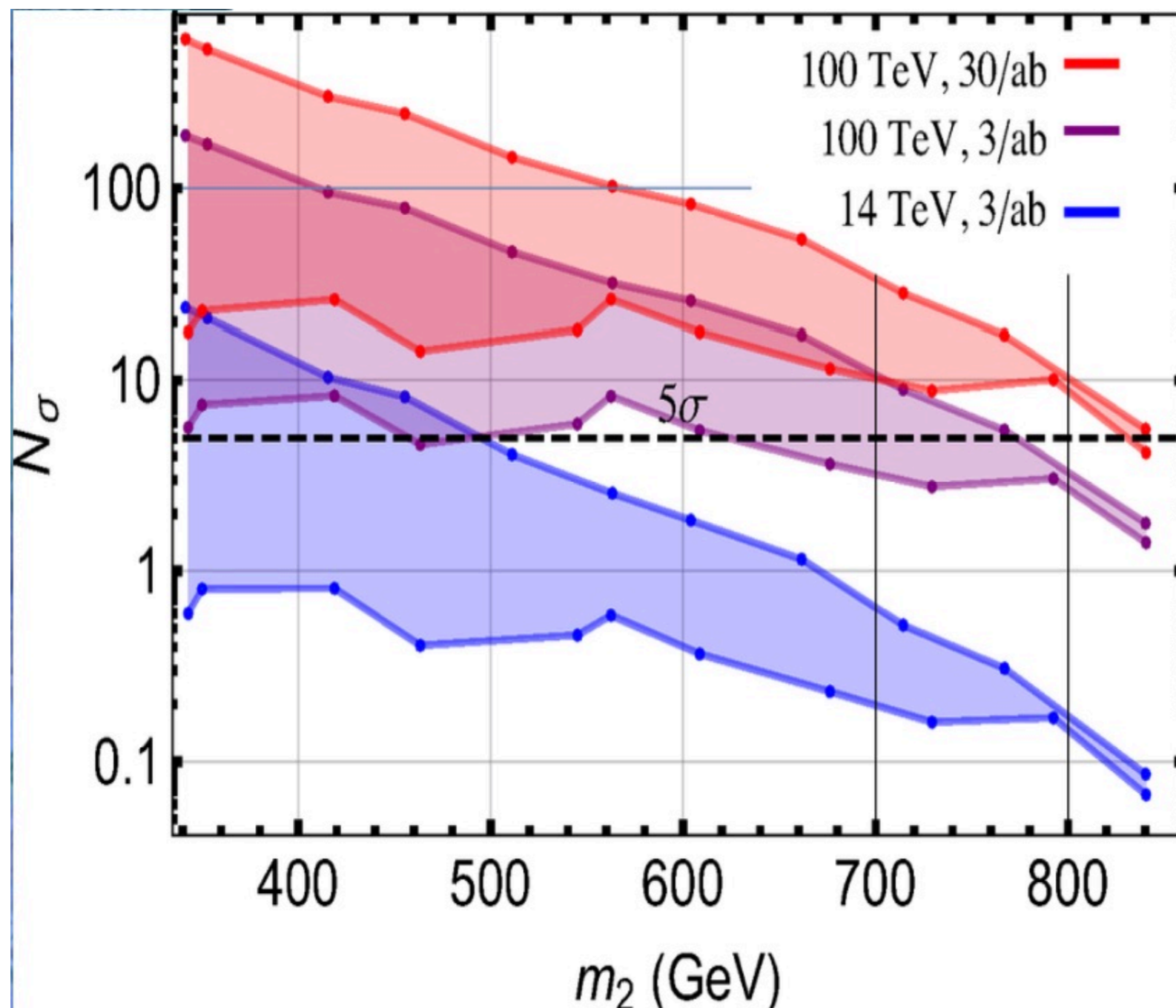
1st Order EWPT has profound implications for cosmology



Andrew Long @ FCC physics Workshop, Jan 2018
<https://indico.cern.ch/event/618254>

Sensitivity to extra Higgs bosons enabling a 1st order EWPT

$$h_2 \rightarrow h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$$



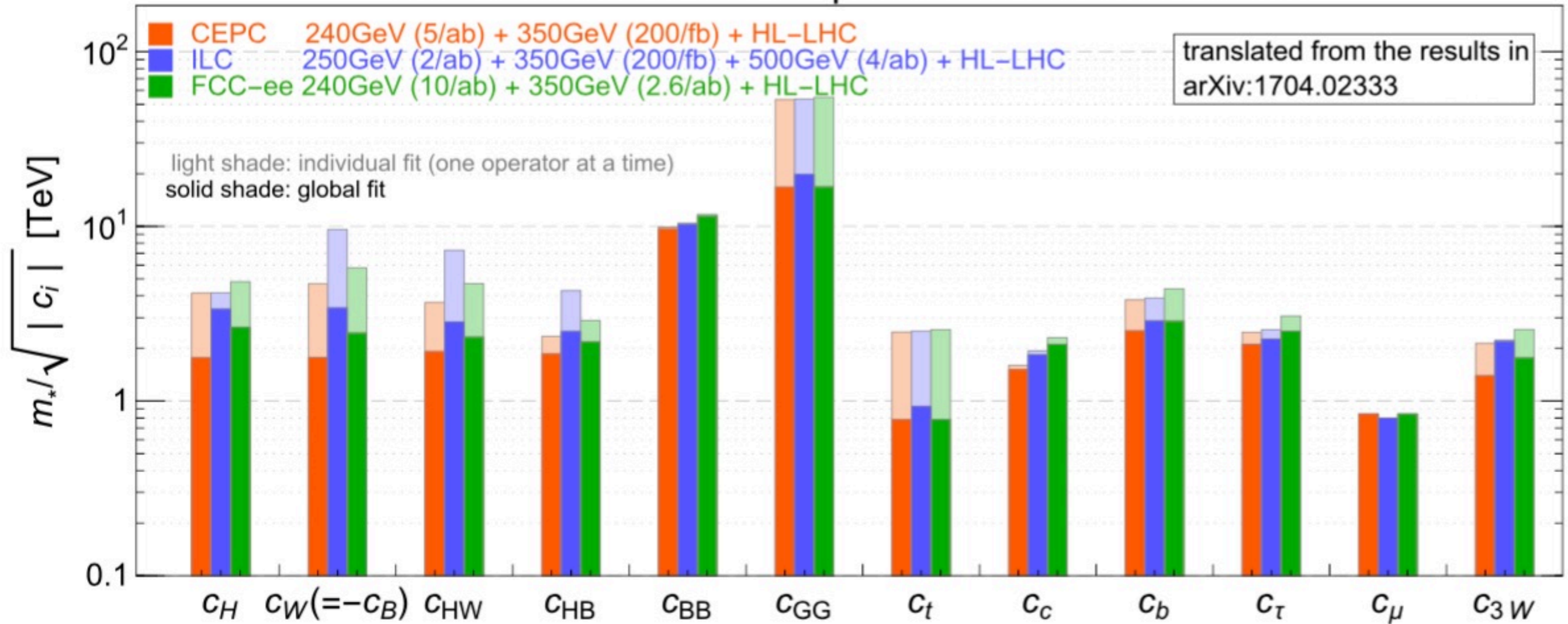
**Notice role of
energy and of
luminosity**

**Direct and indirect sensitivity to
the largest mass scales:
examples**

Indirect sensitivity to new mass scales via Higgs and EW precision measurements in e^+e^-

[arXiv:1709.06103] J. Gu, H. Li, Z. Liu, S. Su, W. Su

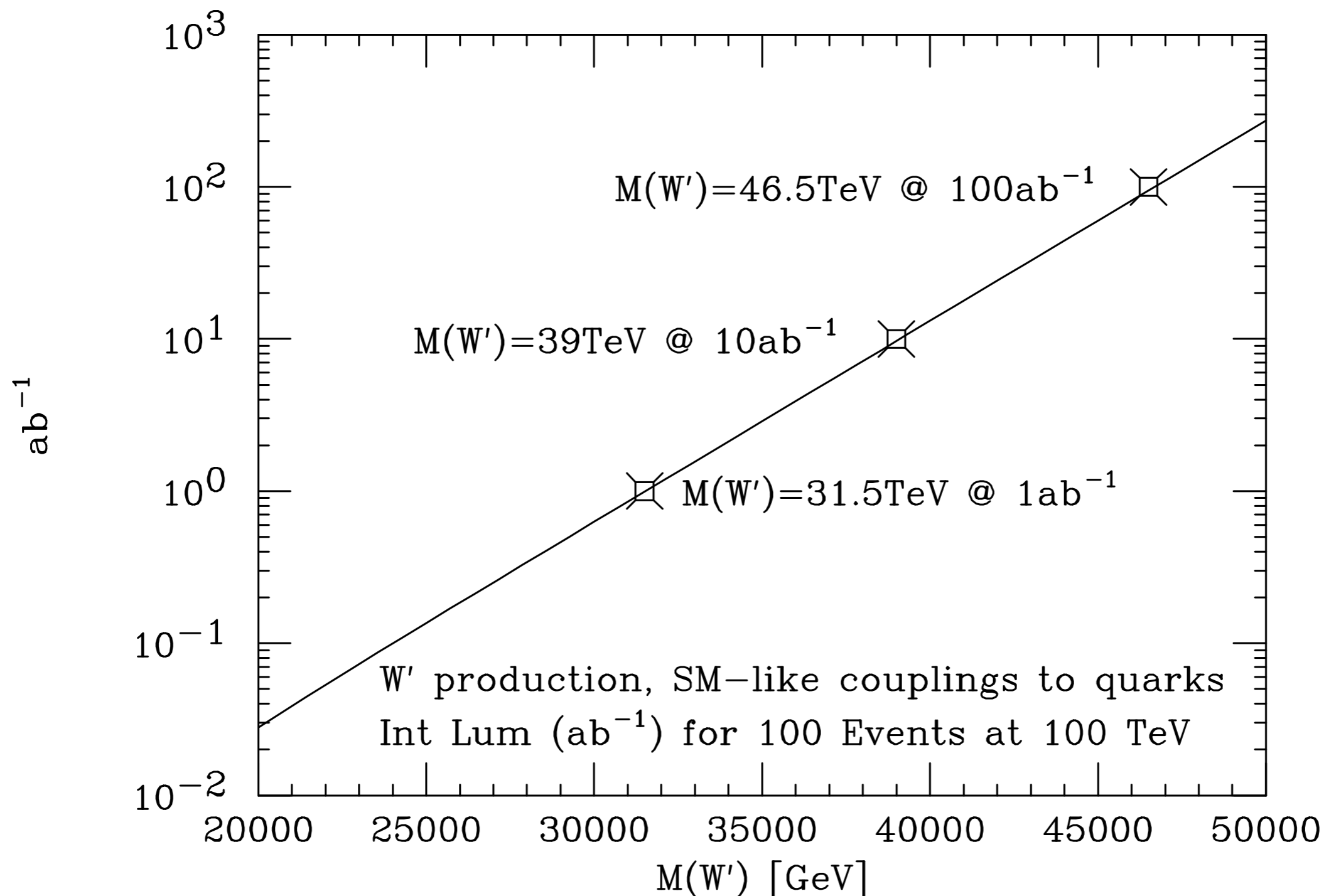
95%CL bound of the 12-parameter fit in SILH' basis



New gauge bosons discovery reach

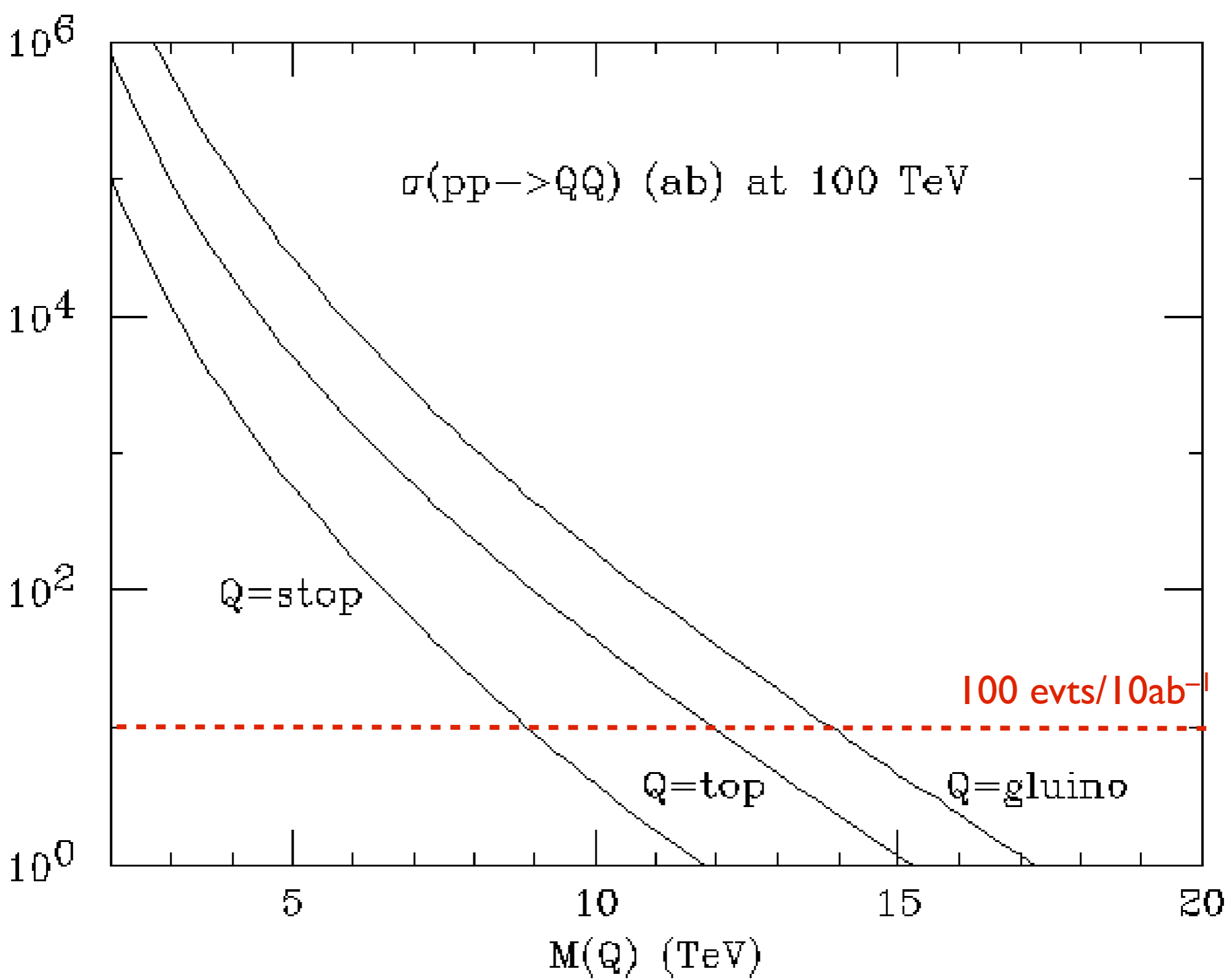
Example: W' with SM-like couplings

NB For SM-like Z' , $\sigma_{Z'} BR_{lept} \sim 0.1 \times \sigma_{W'} BR_{lept}$, \Rightarrow rescale lum by ~ 10

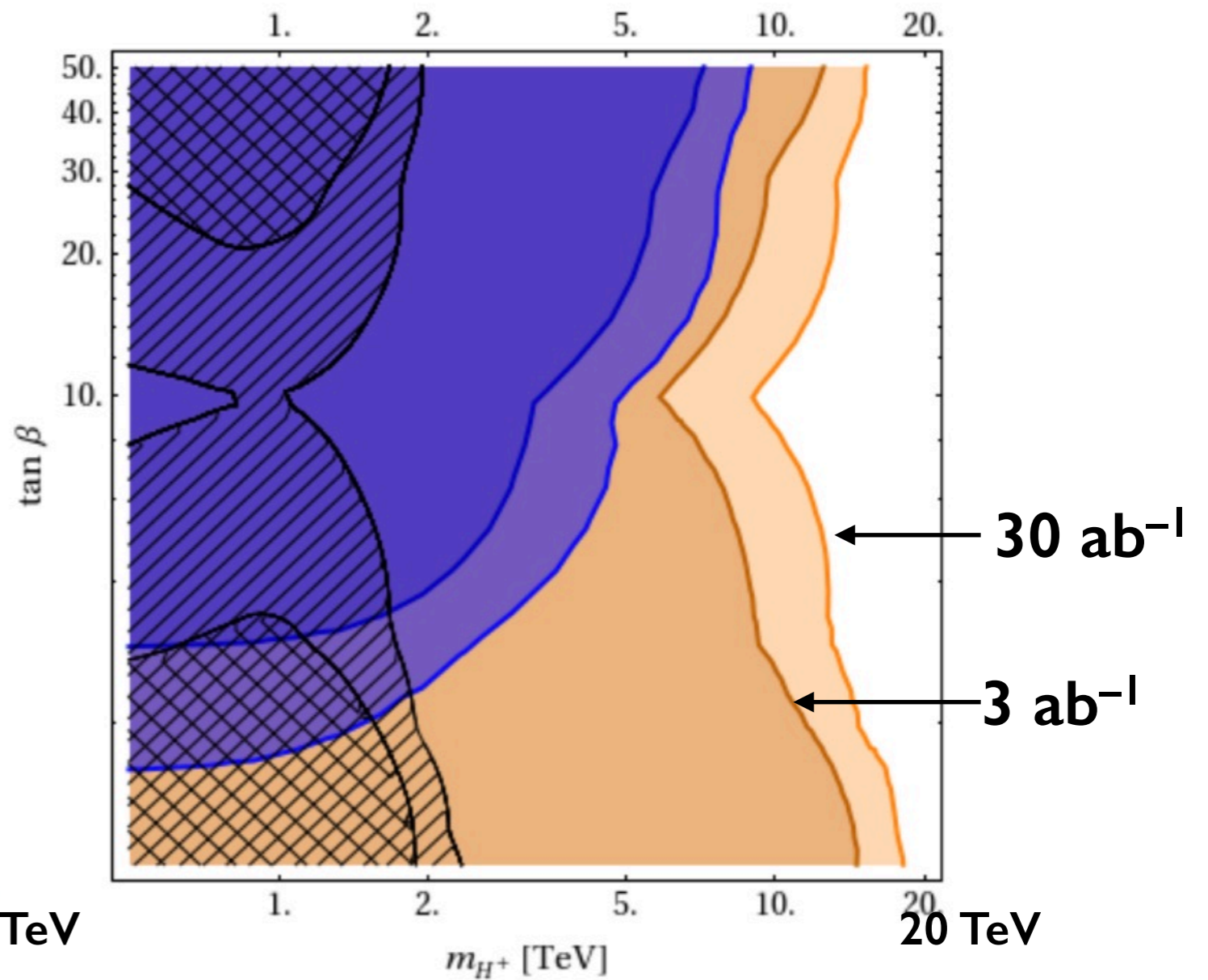
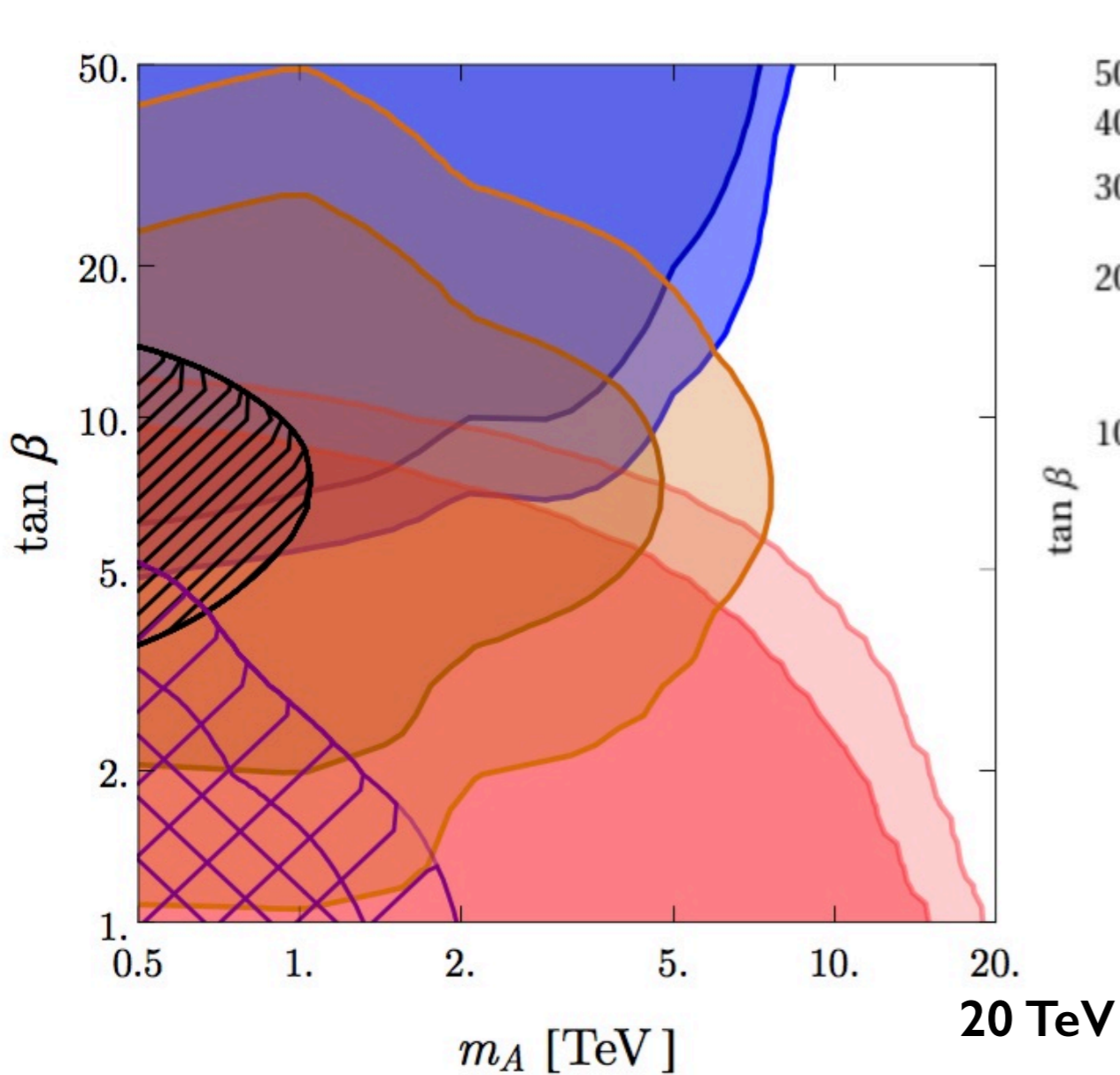
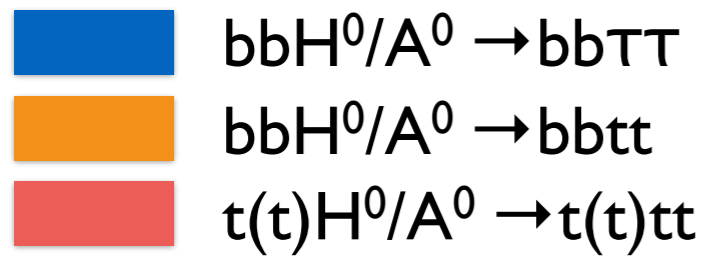


At $L=O(ab^{-1})$, Lum $\times 10 \Rightarrow \sim M + 7 \text{ TeV}$

Discovery reach for pair production of strongly-interacting particles



MSSM Higgs @ 100 TeV



N. Craig, J. Hajer, Y.-Y. Li, T. Liu, H. Zhang,
arXiv:1605.08744

J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu,
arXiv:1504.07617

Bottom line

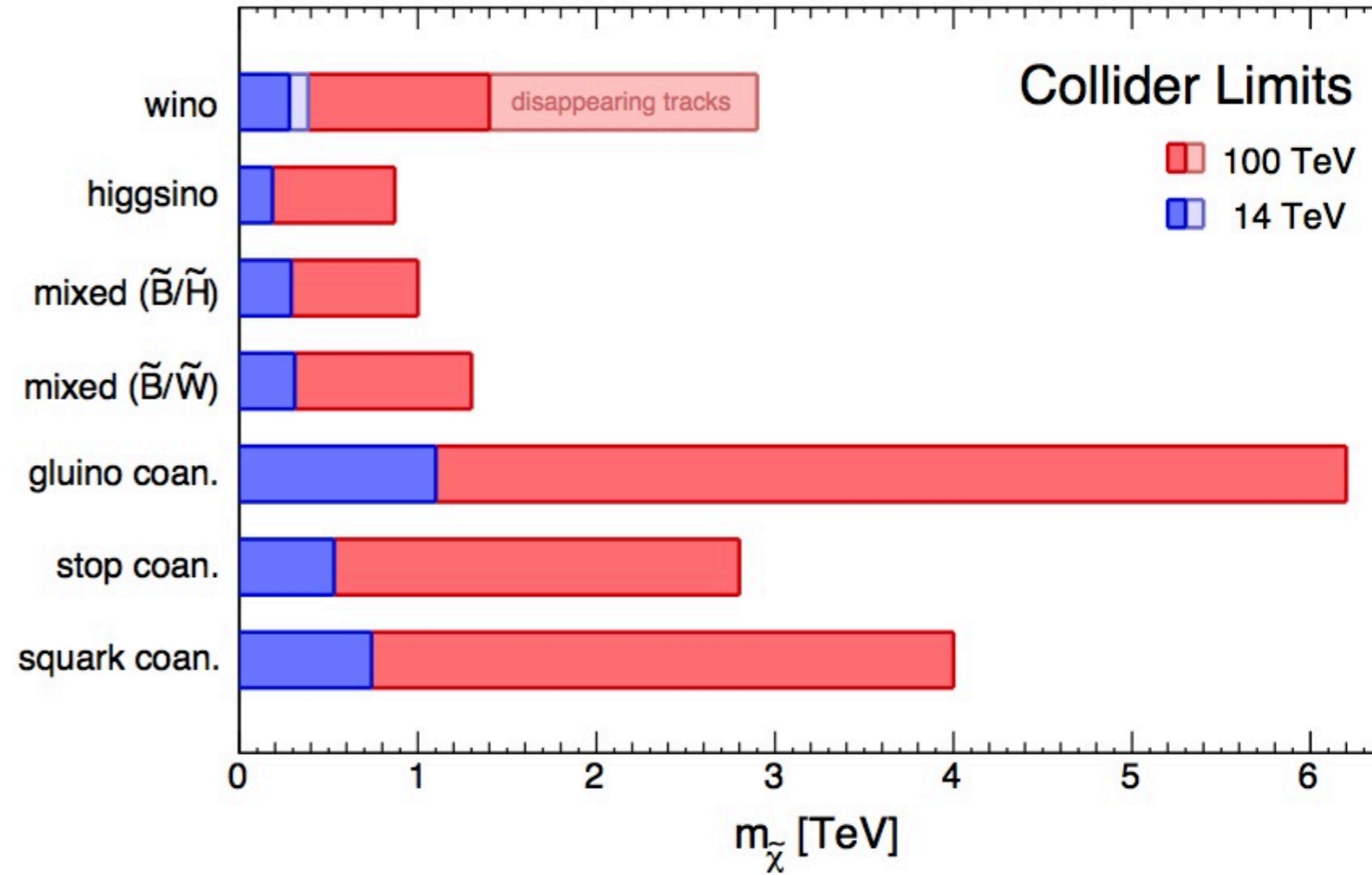
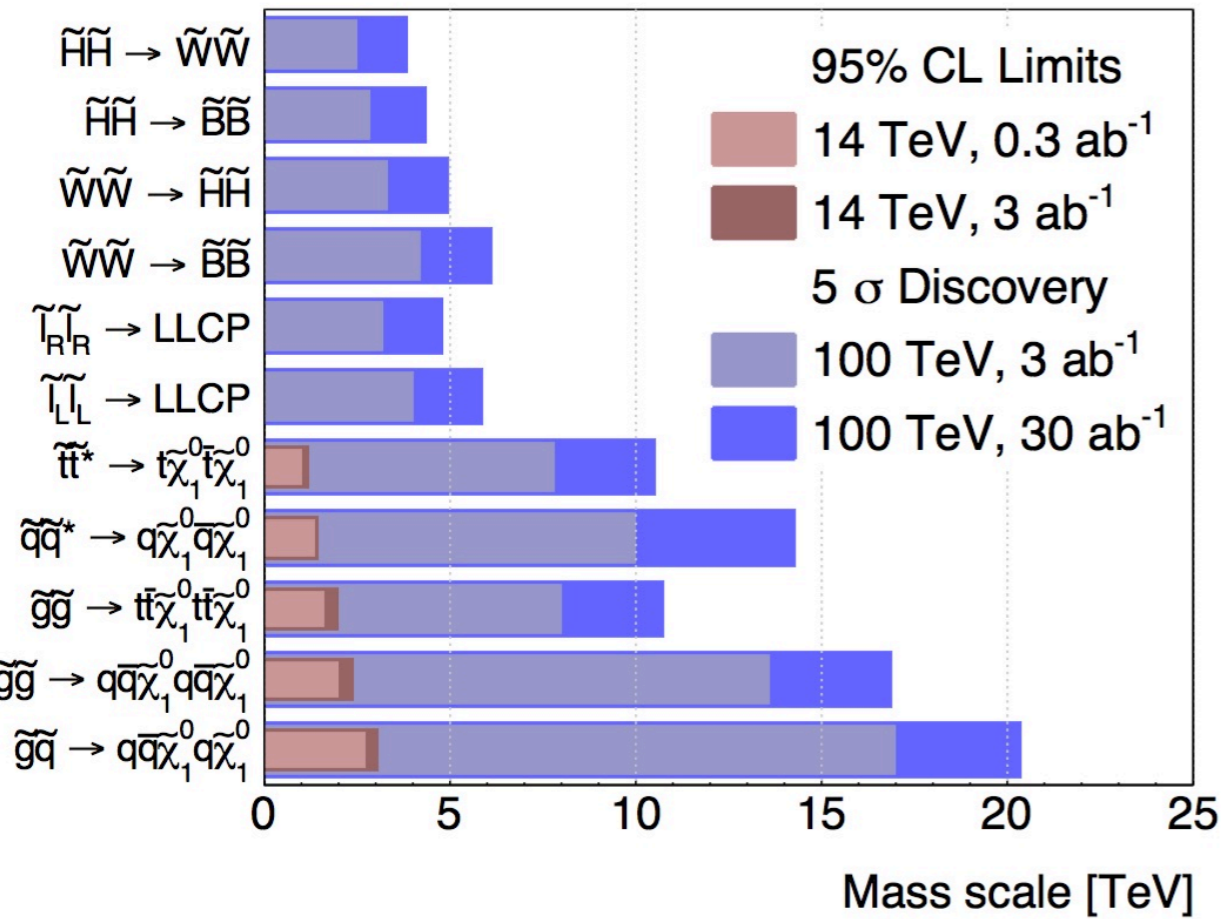
- energy and luminosities of the ee&pp components of the FCC programme are well matched, to synergistically cover similar mass scales in complementary ways

Examples: conclusive yes/no answers

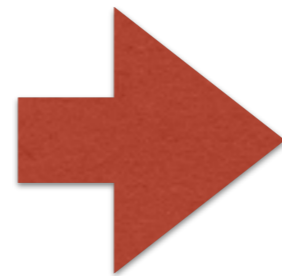
Dark Matter

- DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).
- More in general, no experiment can guarantee an answer to the question "what is DM?"
- Scenarios in which DM is a WIMP are however compelling and theoretically justified
- **We would like to understand whether a future collider can answer more specific questions, such as:**
 - do WIMPS contribute to DM?
 - can WIMPS, detectable in direct and indirect (DM annihilation) experiments, be discovered at future colliders? Is there sensitivity to the explicit detection of DM-SM mediators?
 - what are the opportunities w.r.t. new DM scenarios (e.g. interacting DM, asymmetric DM,)?

SUSY and DM reach at 100 TeV

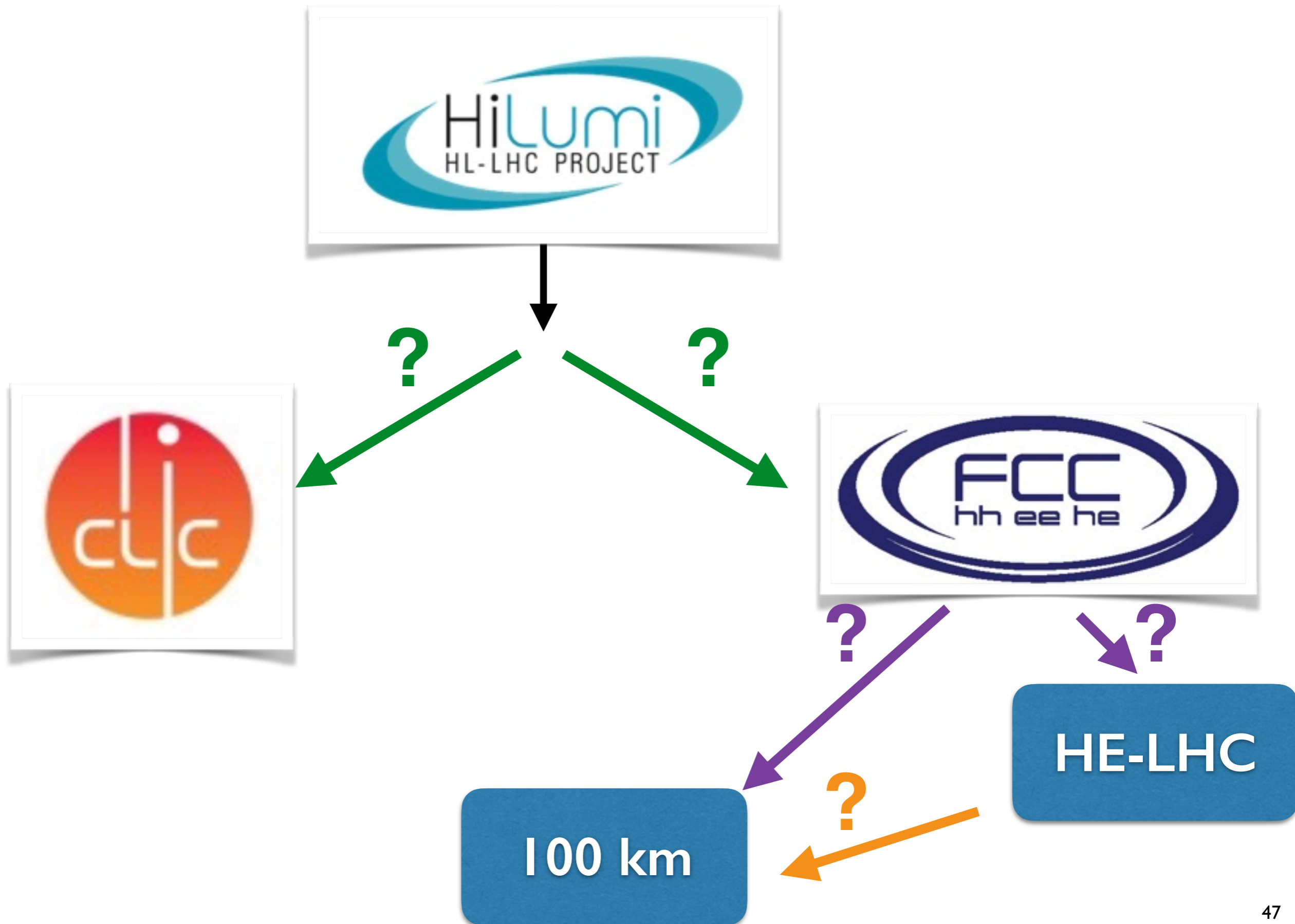


$$M_{\text{WIMP}} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3} \right)$$

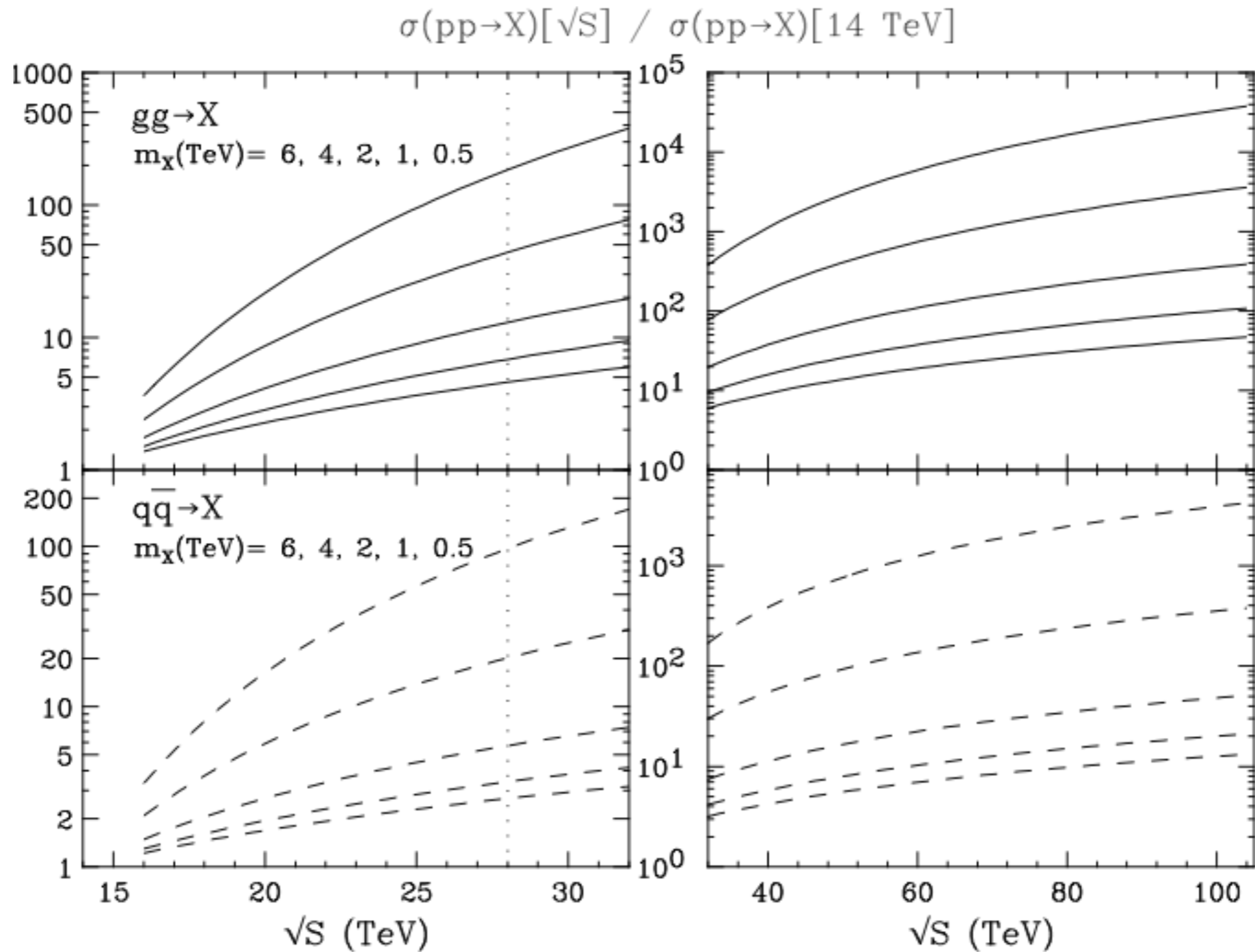


possibility to find (or rule out) thermal WIMP DM candidates

Possible paths for CERN



Evolution, with beam energy, of scenarios with the discovery of a new particle at the LHC



Possible questions/options

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Possible questions/options

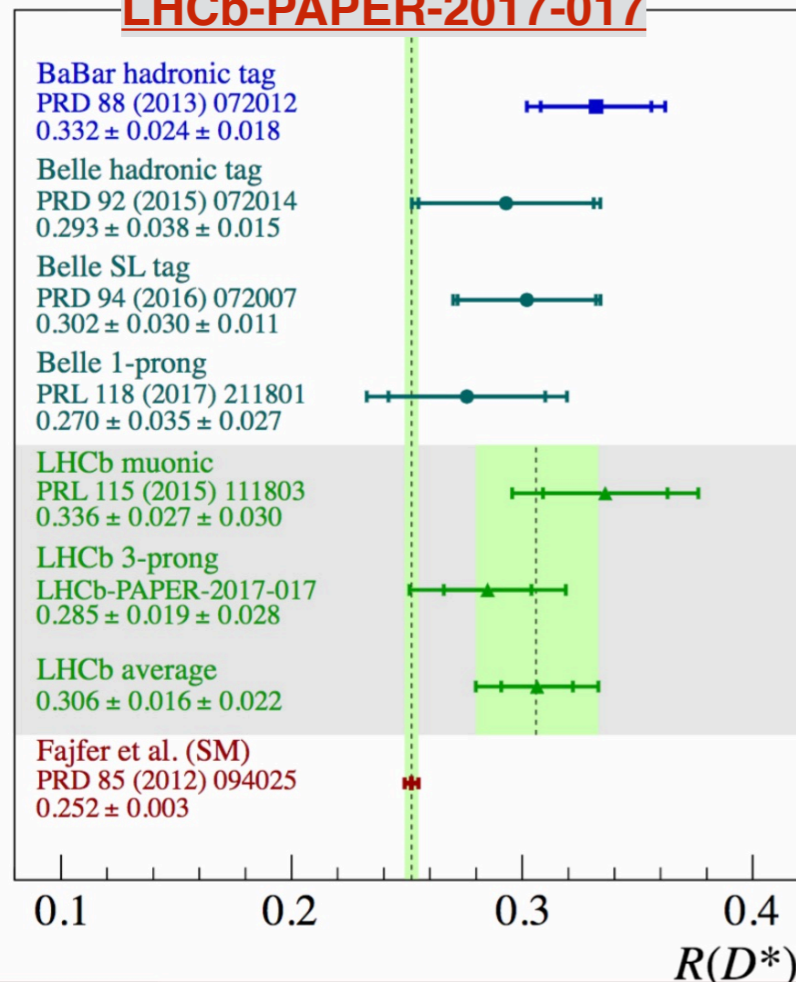
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- etc.etc.

Flavour anomalies at LHC & Bfact's

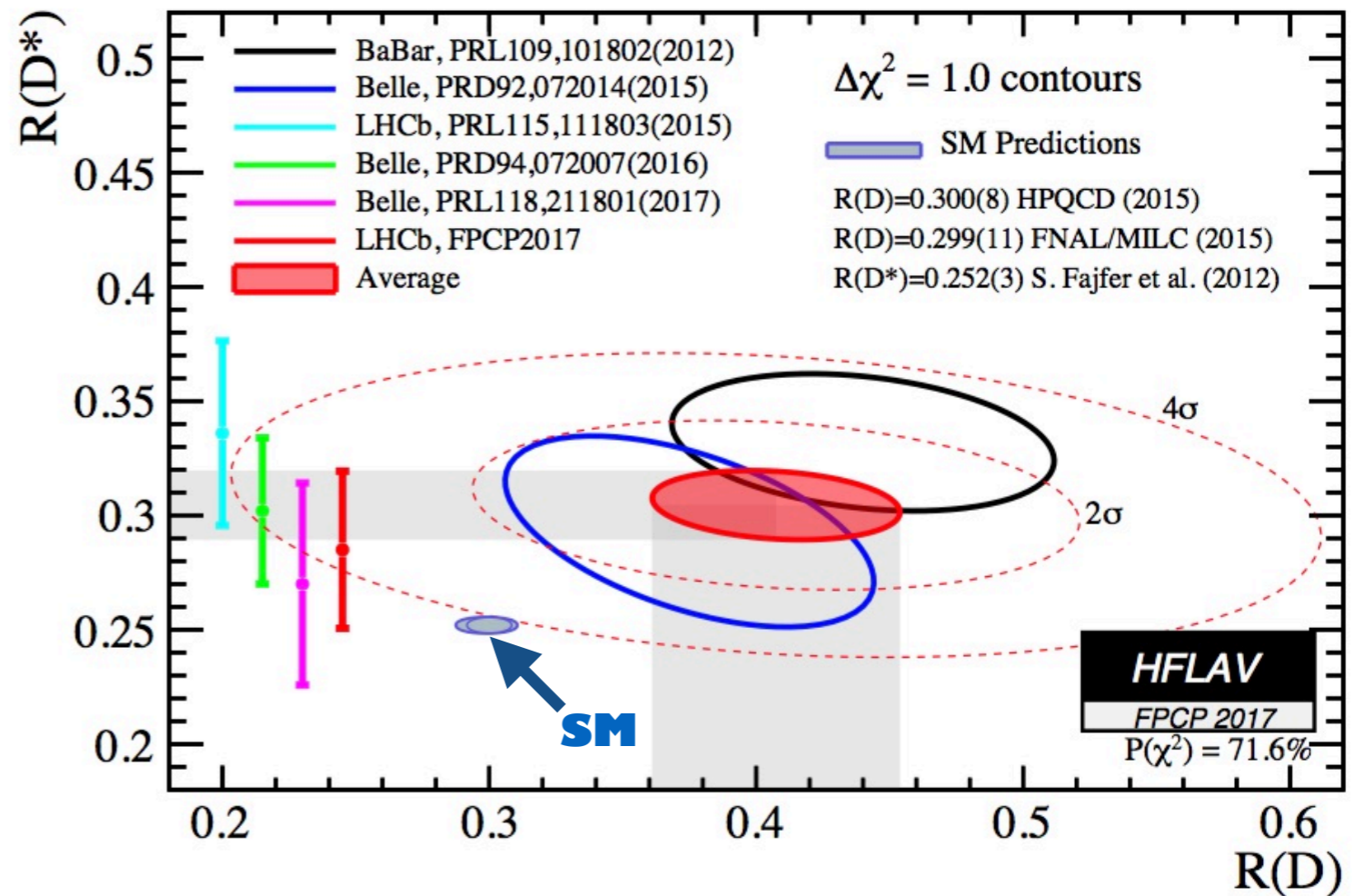
$b \rightarrow c \ell \nu$

$$R(D^{(*)}) = \frac{BR(B \rightarrow D^{(*)} \tau \nu)}{BR(B \rightarrow D^{(*)} \mu \nu)}$$

LHCb-PAPER-2017-017



Overall combination of R(D) and R(D*) is 4.1σ from SM



$b \rightarrow s \ell \ell$

$$R_{K^{(*)}} = \frac{BR(B \rightarrow K^{(*)} \mu \mu)}{BR(B \rightarrow K^{(*)} e e)}$$

$m_{\mu\mu}$ [mass range]	SM	Exp.
R_K [1-6]	1.00 ± 0.01	$0.745_{-0.074}^{+0.090} \pm 0.036$
R_{K^*} [1.1-6]	1.00 ± 0.01	$0.685_{-0.069}^{+0.113} \pm 0.047$
R_{K^*} [0.045,1.1]	0.91 ± 0.03	$0.660_{-0.070}^{+0.110} \pm 0.024$

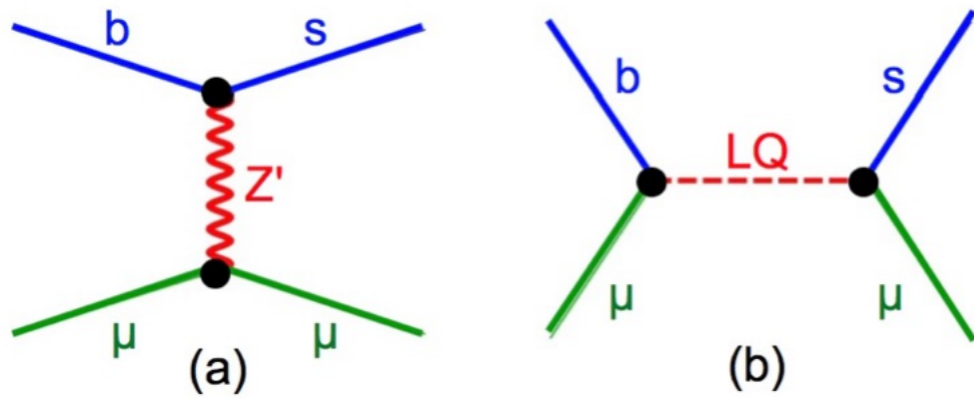
LHCb, PRL 113 (2014) 151601, arXiv:1705.05802

Example of EFT interpretation of R_K

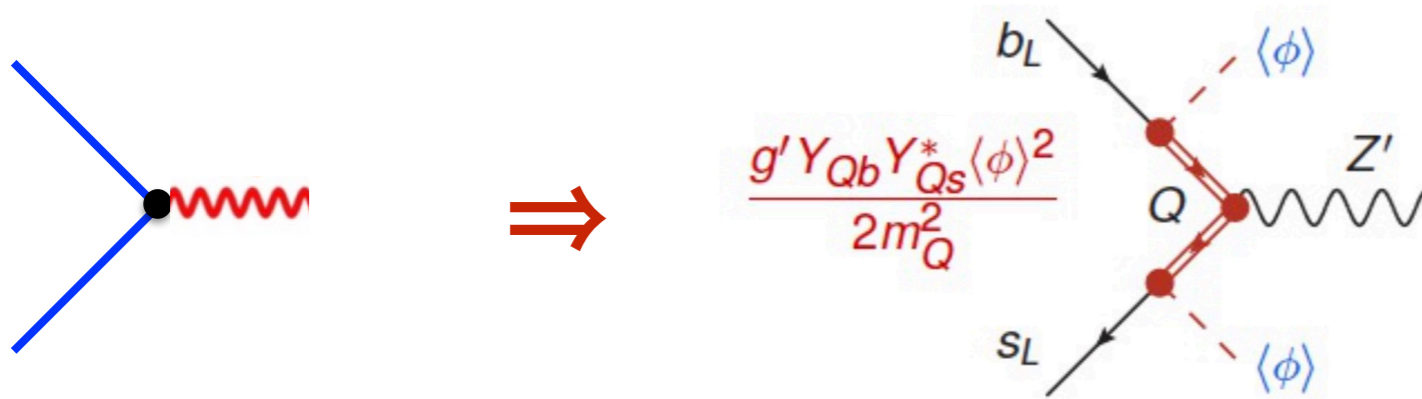
$$O_9^l = (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l),$$

$$O_{10}^l = (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu \gamma_5 l)$$

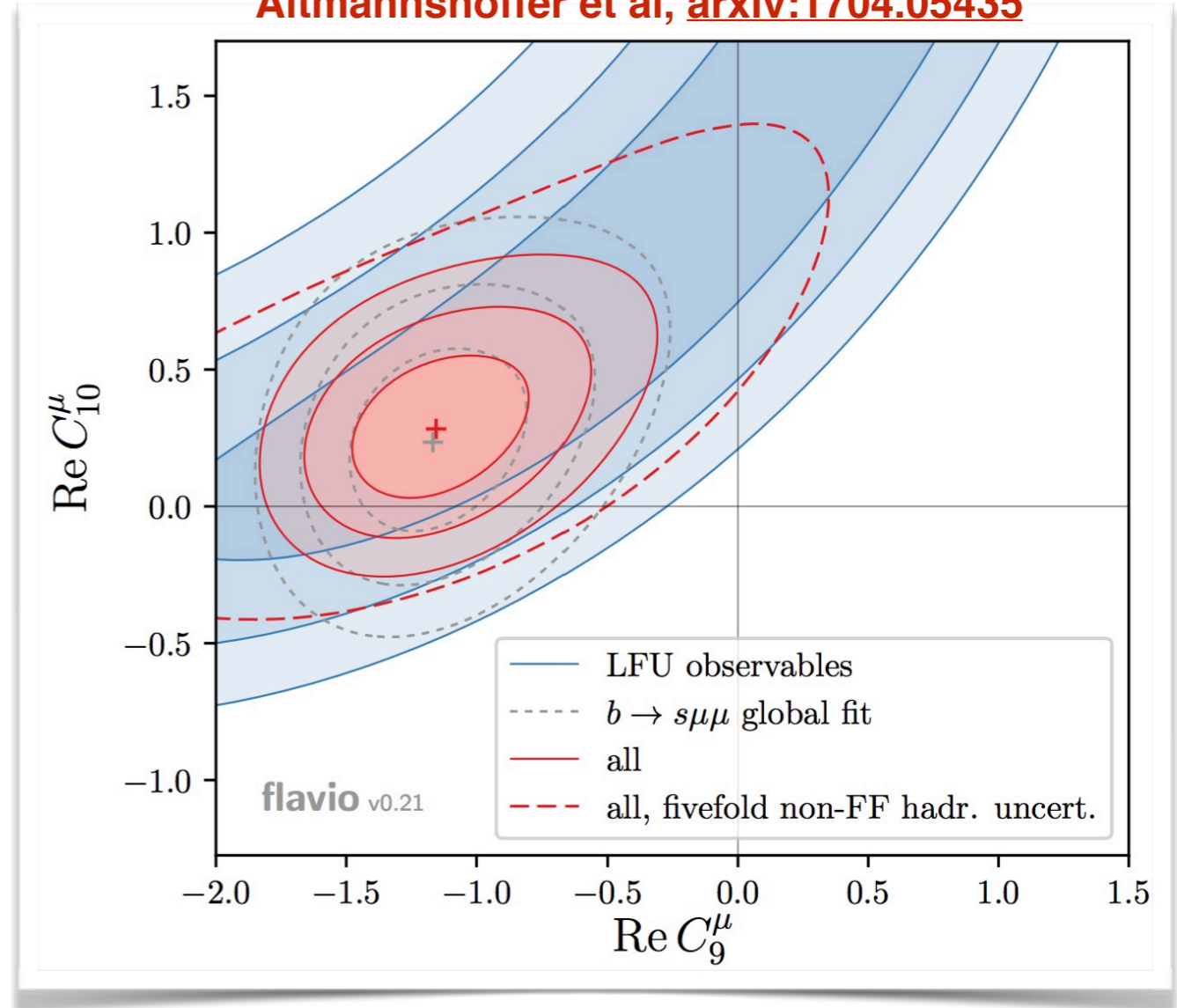
Possible explicit realizations:



where, e.g.,



Altmannshofer et al, arxiv:1704.05435



Upper limits on Z' and Leptoquark masses are model-dependent, and constrained also by other low-energy flavour phenomenology, but typically lie in the range of $1 \rightarrow O(10)$ TeV

\Rightarrow if anomalies confirmed, we may want a no-lose theorem to identify the next facility! 5 |

Final remarks

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- The physics case of a 100 TeV collider is very clear as a long-term goal for the field, simply because no other proposed or foreseeable project can have direct sensitivity to such large mass scales.
- Nevertheless, the precise route followed to get there (via CLIC? via HE-LHC? via FCC-ee? ...) must take account of the fuller picture, to emerge from the LHC as well as other current and future experiments in areas ranging from flavour physics to dark matter searches. The right time scale for this assessment is probably ~8-10 yrs from now