Exploring the Energy frontier with a Muon Collider

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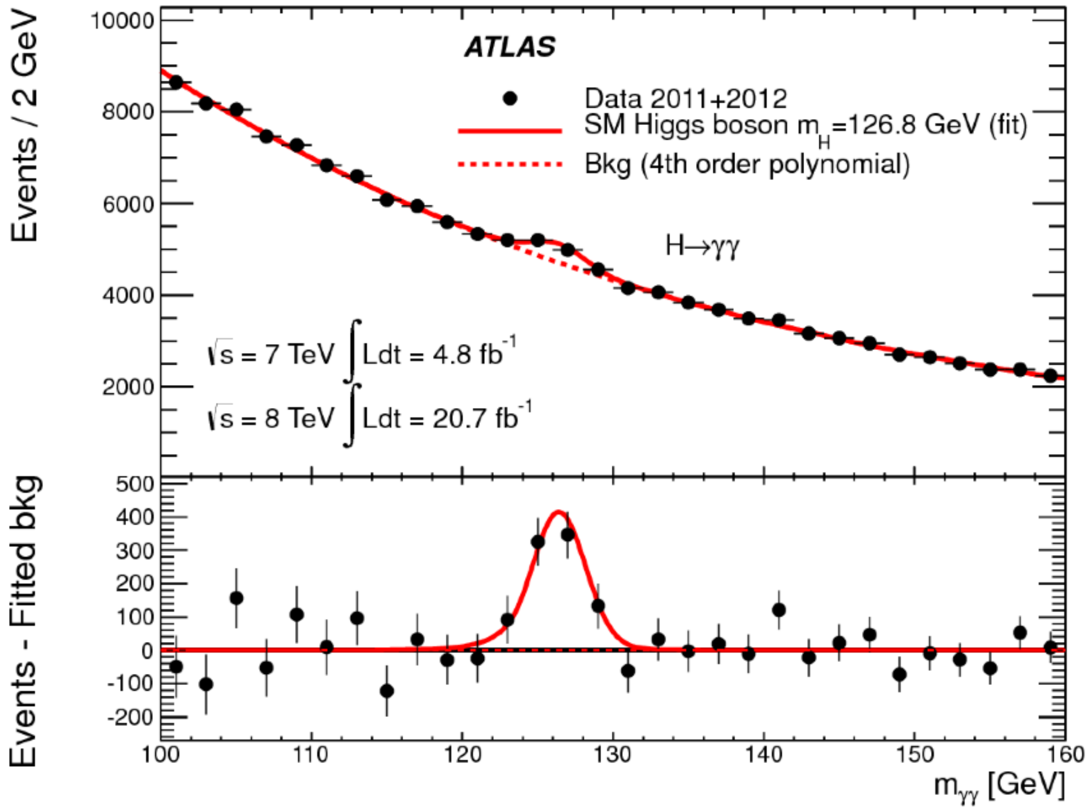
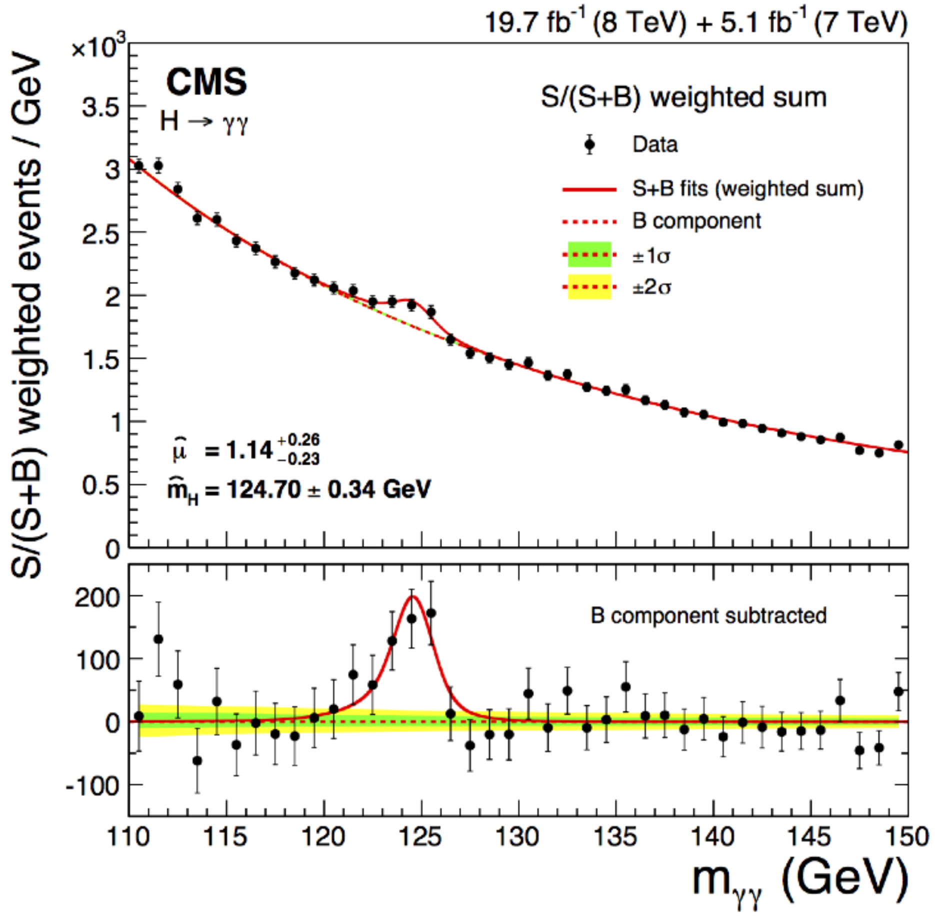
Thanks to Andrea Wulzer for his help and materials for the preparation of this talk

Muon Collider Workshop 2018
Padova, July 3, 2018

Particle Physics Today

- The LHC 2012: We finally found the Higgs…

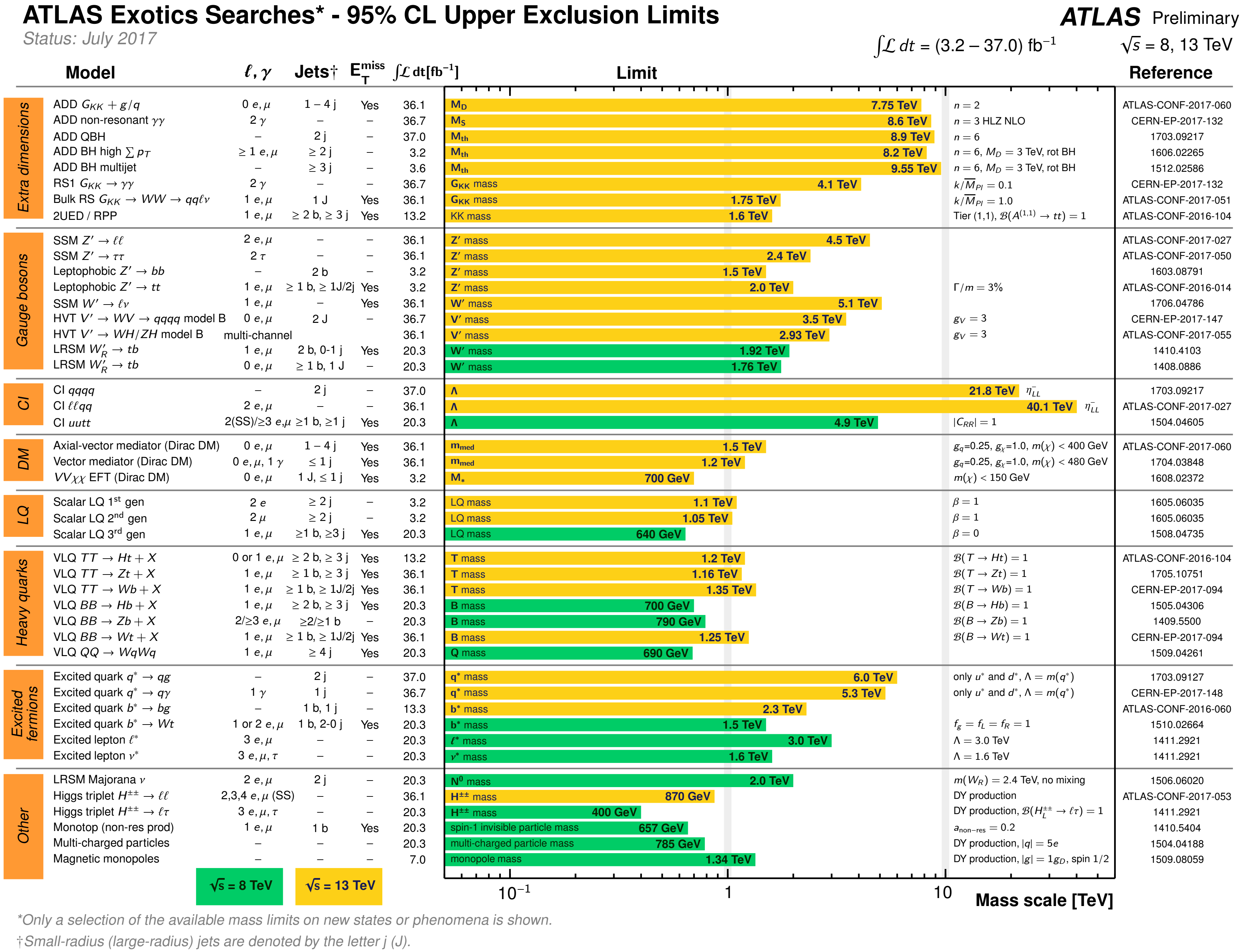




After chasing it for so long, all the "ingredients" of the SM were experimentally confirmed

Particle Physics Today

- But the Higgs is the only “new” physics we have found so far…



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 37.0)$ fb^{-1} $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK}+g/q$	0 e,μ	1 – 4 j	Yes	36.1	🟨 M_D 7.75 TeV	$n=2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	🟨 M_S 8.6 TeV	$n=3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	🟨 M_{th} 8.9 TeV	$n=6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e,μ	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n=6$, $M_D=3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n=6$, $M_D=3$ TeV, rot BH	1512.02586
	RS1 $G_{KK}\to\gamma\gamma$	2 γ	–	–	36.7	🟨 G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl}=0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK}\to WW\to qq\ell\nu$	1 e,μ	1 J	Yes	36.1	🟨 G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl}=1.0$	ATLAS-CONF-2017-051
	2UED / RPP	1 e,μ	≥ 2 b, ≥ 3 j	Yes	13.2	🟨 KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)}\to tt)=1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z'\to\ell\ell$	2 e,μ	–	–	36.1	🟨 Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z'\to\tau\tau$	2 τ	–	–	36.1	🟨 Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z'\to bb$	–	2 b	–	3.2	🟨 Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z'\to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	3.2	🟨 Z' mass 2.0 TeV	$\Gamma/m=3\%$	ATLAS-CONF-2016-014
	SSM $W'\to\ell\nu$	1 e,μ	–	Yes	36.1	🟨 W' mass 5.1 TeV		1706.04786
	HVT $V'\to WV\to qqqq$ model B	0 e,μ	2 J	–	36.7	🟨 V' mass 3.5 TeV	$g_V=3$	CERN-EP-2017-147
	HVT $V'\to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass 2.93 TeV	$g_V=3$	ATLAS-CONF-2017-055
	LRSM $W'_R\to tb$	1 e,μ	2 b, 0-1 j	Yes	20.3	🟩 W' mass 1.92 TeV		1410.4103
	LRSM $W'_R\to tb$	0 e,μ	≥ 1 b, 1 J	–	20.3	🟩 W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ 21.8 TeV	η_{LL}^-	1703.09217
	CI $\ell\ell qq$	2 e,μ	–	–	36.1	🟨 Λ 40.1 TeV	η_{LL}^-	ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	20.3	🟩 Λ 4.9 TeV	$\lvert C_{RR}\rvert=1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e,μ	1 – 4 j	Yes	36.1	🟨 m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi)<400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	0 e,μ, 1 γ	≤ 1 j	Yes	36.1	🟨 m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi)<480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	0 e,μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 700 GeV	$m(\chi)<150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta=1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta=1$	1605.06035
	Scalar LQ 3rd gen	1 e,μ	≥1 b, ≥3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta=0$	1508.04735
Heavy quarks	VLQ $TT\to Ht+X$	0 or 1 e,μ	≥ 2 b, ≥ 3 j	Yes	13.2	🟨 T mass 1.2 TeV	$\mathcal{B}(T\to Ht)=1$	ATLAS-CONF-2016-104
	VLQ $TT\to Zt+X$	1 e,μ	≥ 1 b, ≥ 3 j	Yes	36.1	🟨 T mass 1.16 TeV	$\mathcal{B}(T\to Zt)=1$	1705.10751
	VLQ $TT\to Wb+X$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 T mass 1.35 TeV	$\mathcal{B}(T\to Wb)=1$	CERN-EP-2017-094
	VLQ $BB\to Hb+X$	1 e,μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 B mass 700 GeV	$\mathcal{B}(B\to Hb)=1$	1505.04306
	VLQ $BB\to Zb+X$	2/≥3 e,μ	≥2/≥1 b	–	20.3	🟩 B mass 790 GeV	$\mathcal{B}(B\to Zb)=1$	1409.5500
	VLQ $BB\to Wt+X$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 B mass 1.25 TeV	$\mathcal{B}(B\to Wt)=1$	CERN-EP-2017-094
	VLQ $QQ\to WqWq$	1 e,μ	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^*\to qg$	–	2 j	–	37.0	🟨 q^* mass 6.0 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1703.09127
	Excited quark $q^*\to q\gamma$	1 γ	1 j	–	36.7	🟨 q^* mass 5.3 TeV	only u^* and d^*, $\Lambda=m(q^*)$	CERN-EP-2017-148
	Excited quark $b^*\to bg$	–	1 b, 1 j	–	13.3	🟨 b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^*\to Wt$	1 or 2 e,μ	1 b, 2-0 j	Yes	20.3	🟩 b^* mass 1.5 TeV	$f_g=f_L=f_R=1$	1510.02664
	Excited lepton ℓ^*	3 e,μ	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda=3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e,μ,τ	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda=1.6$ TeV	1411.2921
Other	LRSM Majorana ν	2 e,μ	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R)=2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm}\to\ell\ell$	2,3,4 e,μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm}\to\ell\tau$	3 e,μ,τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm}\to\ell\tau)=1$	1411.2921
	Monotop (non-res prod)	1 e,μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\mathrm{non-res}}=0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert=5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g\rvert=1g_D$, spin 1/2	1509.08059

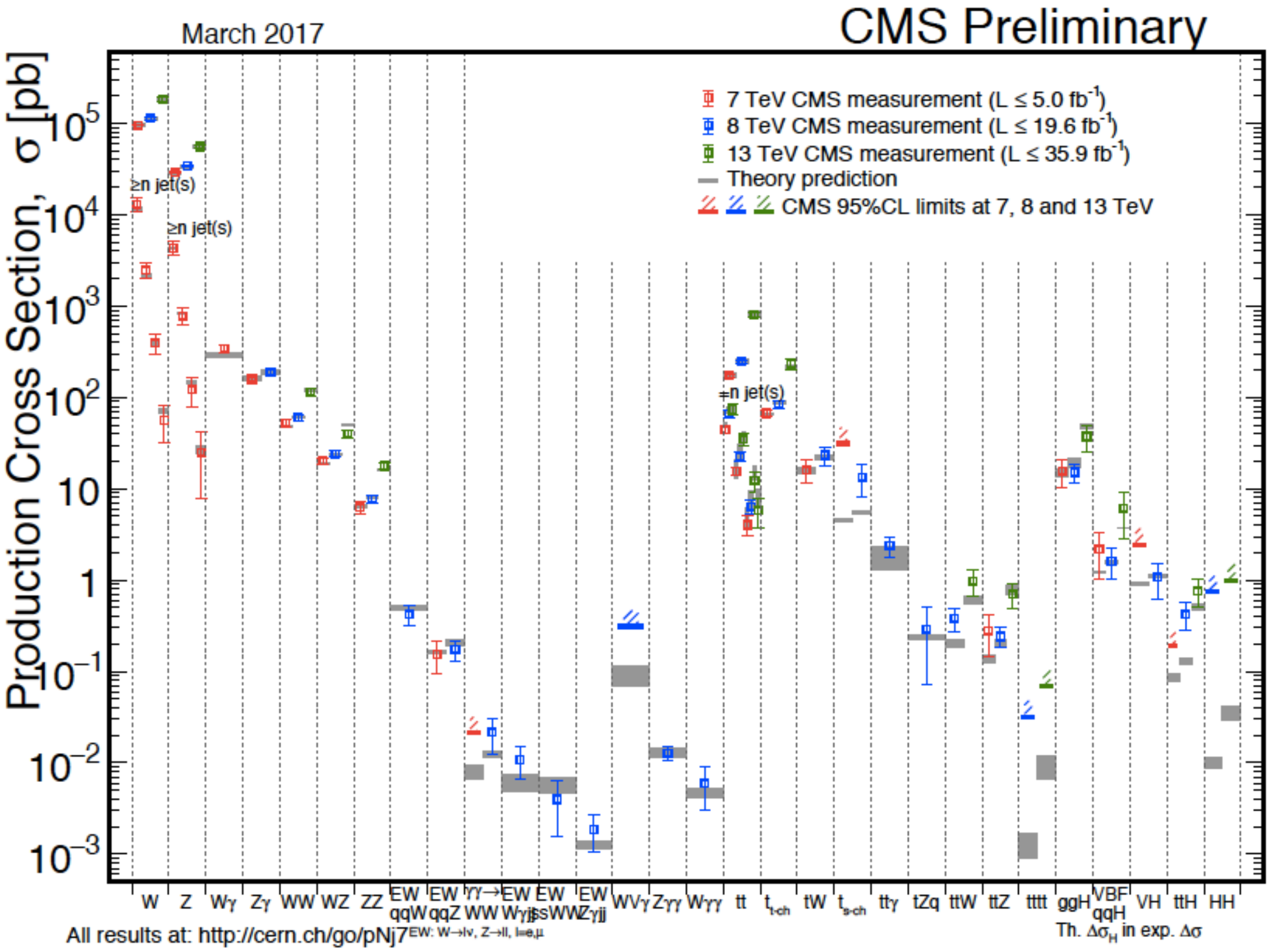
🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV

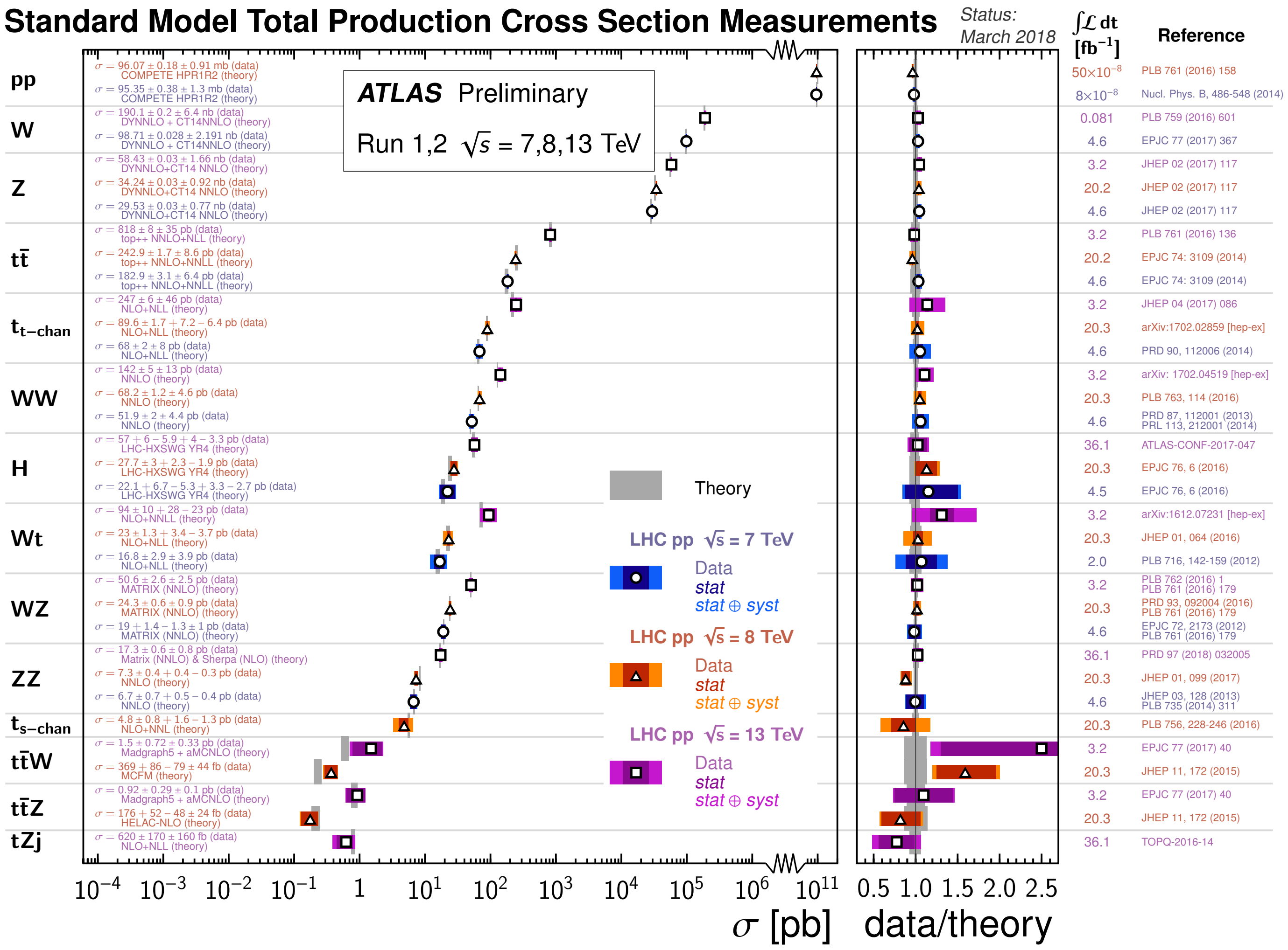
**Only a selection of the available mass limits on new states or phenomena is shown.*

†Small-radius (large-radius) jets are denoted by the letter j (J).

Particle Physics Today

- …and (almost) everything we have measured agrees well with the SM…





Particle Physics Today

- We know the SM cannot be the ultimate theory of fundamental physics…

Theoretical issues

It is “problematic”…

Hierarchy problem
Strong CP problem
Flavor problem

It is not very stable…

EW vacuum is metastable

Observational/Experimental issues

No Neutrino masses

No explanation of gravity

No Dark Matter/Dark Energy

Matter/Anti-Matter asymmetry?

…

Other questions

Why 3 families?

Do gauge couplings unify?

Aesthetical issues?

Too many parameters?

Particle Physics at Future Colliders

- But… what should we look for? The Higgs was “expected” within the SM, we knew what to search for…

…unless the LHC finds any hint of new physics, High Energy Physics at Future Colliders will be an exploration of the unknown…

No new discovery can be guaranteed

Naturalness
EW-B.Gen
D.M.
Dark Sectors
Flavour
ν-Mass
Strong CP
Quantum Gravity

?

The best Future Collider option is that which allows to explore many directions

Particle Physics at Future Colliders

The best Future Collider option is that allows to explore many directions

- Strengths of a Muon collider:
  - Muon Rare processes
  - Neutrino physics
  - Higgs factory ⇒ **See. A. Blondel's and M. Greco's talks**
  - **High Energy frontier** ⇒ **This talk**

- Can we define minimum energy/luminosity requirements for BSM exploration at High Energies?

Naturalness

- In the SM the Higgs mass/EW scale is very sensitive to any UV mass scales via quantum corrections

SM cut-off

$$m_H^2 = \int_0^\infty F(E;g) \approx \int_0^{\Lambda} F_{\rm SM}(E;g_{\rm SM}) + \int_\Lambda^\infty F(E;g)$$

$$\left(F(E;g) \xrightarrow[E \ll \Lambda]{} F_{\rm SM}(E;g_{\rm SM}) + \mathcal{O}(\tfrac{1}{\Lambda^n}) \right)$$

SM contrib. : $\delta m_H^2 = \frac{3y_t^2}{8\pi^2}\Lambda^2 + \ldots$

Must be cancelled by NP or fine tuning needed

- Fine tuning:

$$\Delta = \sqrt{\sum \left(\frac{\partial \log m_H^2}{\partial \log a_i}\right)^2}$$

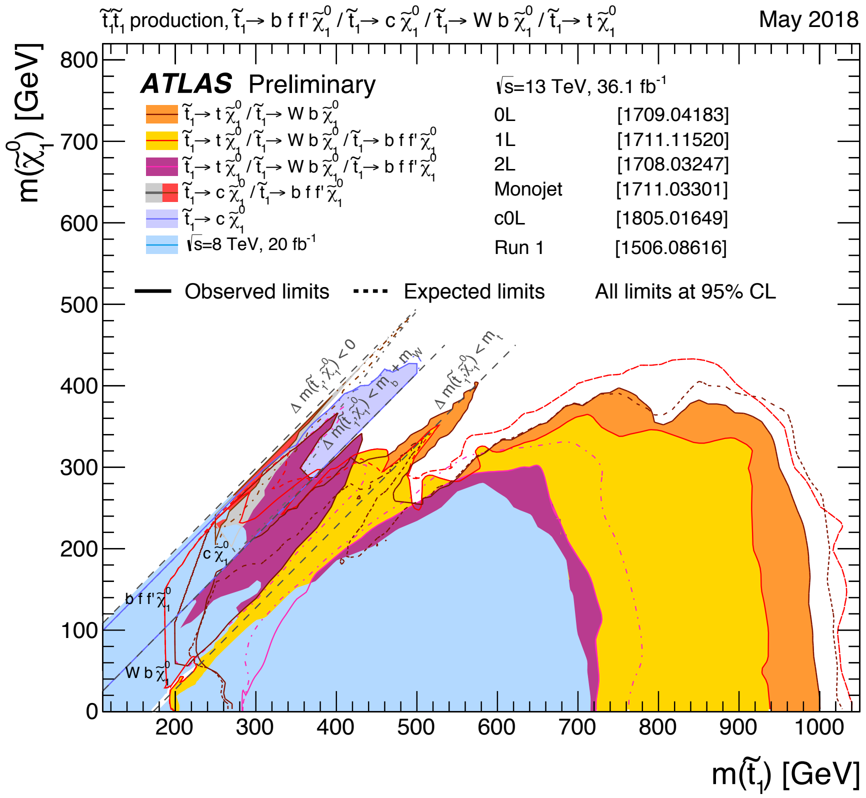
% variation in a_i → Δ% variation in m_H

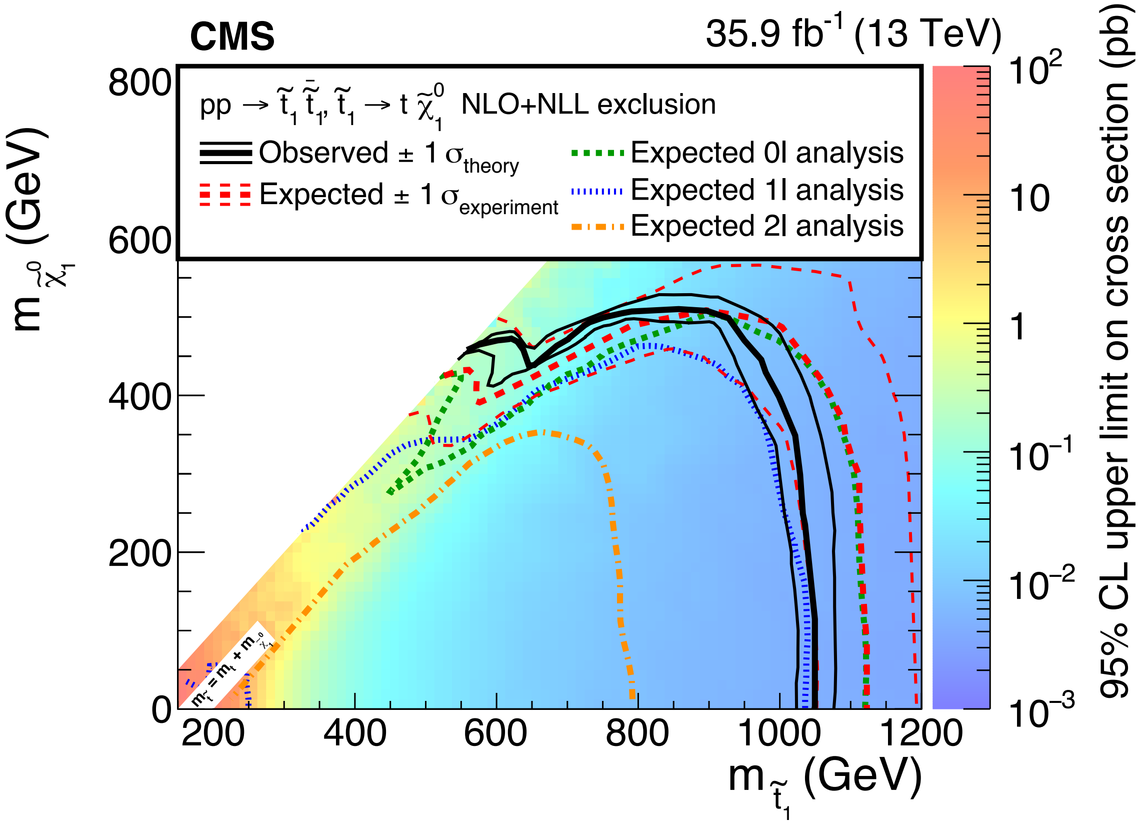
$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \approx \left(\frac{126\ \text{GeV}}{m_H}\right)^2 \left(\frac{\Lambda}{500\ \text{GeV}}\right)^2$$

Naturalness (Δ~1) ⇒ $\Lambda \lesssim 1$ TeV

Naturalness

- Current limits on conventional Natural models (colored Top partners)





Top partner masses ≳ 1 TeV

- HL-LHC may push

$$\Lambda \gtrsim 2~\text{TeV} \to \Delta \geq 10$$

Naturalness

- After the LHC:

$$\Lambda \gtrsim 2 \text{ TeV} \to \Delta \geq 10$$ **Typical natural scenarios**

- Naturalness could still be realized if δm_H^2 cancelled by QCD-uncolored particles

$\Rightarrow$ **Neutral naturalness**

Twin Higgs - Folded SUSY - Quirky Little Higgs - Hyperbolic Higgs

$$\Lambda \sim 1 \text{ TeV} \to \Delta \sim O(1)$$ **would survive the LHC search**

- Or it may just be that the EW scale is only "partially" unnatural

$$\Delta \sim O(100) \to \Lambda \sim 5 \text{ TeV}$$

Reasonable requirement based on (un)naturalness:
Reach of ~5 TeV for conventional Top partners

Dark Matter

- A future collider should be able to tell if Dark Matter is a WIMP:
  - "WIMP miracle": Weak mass and couplings reproduces relic abundance

$$M_\chi \sim v_{\mathrm{EW}}$$

  - Relic density can be satisfied for a larger range of masses and couplings

$$M_\chi \sim 10\ \ \mathrm{MeV} - 10\ \mathrm{TeV}$$

  - (Unitarity bounds $M_\chi < 100\ \mathrm{TeV}$)

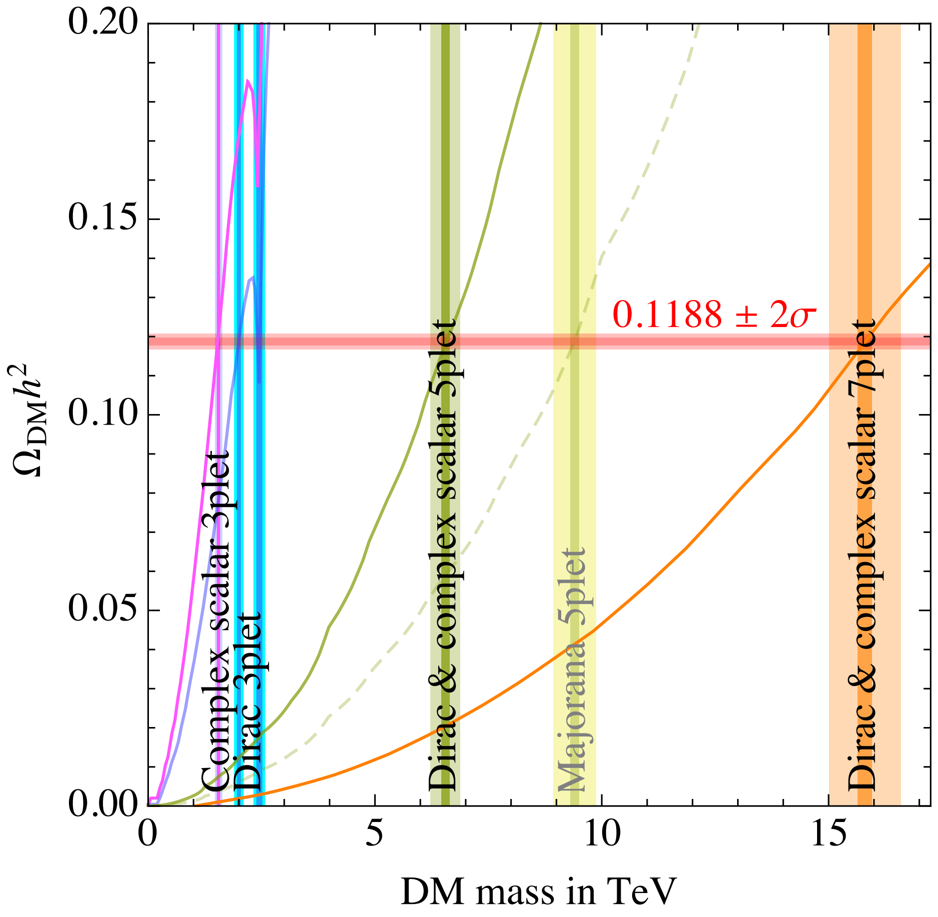
Minimal Models of DM

- **Accidental Dark Matter:** DM is stable due to accidental symmetries. Extensions to non-electric neutral DM can be stabilized via milicharges

Dark Matter

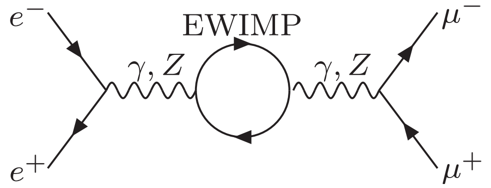
- **Accidental Dark Matter:** DM is stable due to accidental symmetries. Extensions to non-electric neutral DM can be stabilized via milicharges
  - n=3,5,7, … thermal prod. via gauge interactions (and suppressed Z couplings)
  - <u>Predictive:</u> mass fixed by relic density

χ	$M_\chi^{(\mathrm{DM})}$ [TeV]
$(1,3,\epsilon)_{\mathrm{CS}}$	1.5
$(1,3,\epsilon)_{\mathrm{DF}}$	2.0
$(1,3,0)_{\mathrm{MF}}$ *	3.0
$(1,5,\epsilon)_{\mathrm{CS,\,DF}}$	6.6
$(1,5,0)_{\mathrm{MF}}$ **	9.6
$(1,7,\epsilon)_{\mathrm{CS,\,DF}}$	16



Direct searches: mono-x, dissap. tracks…

Indirect searches also important

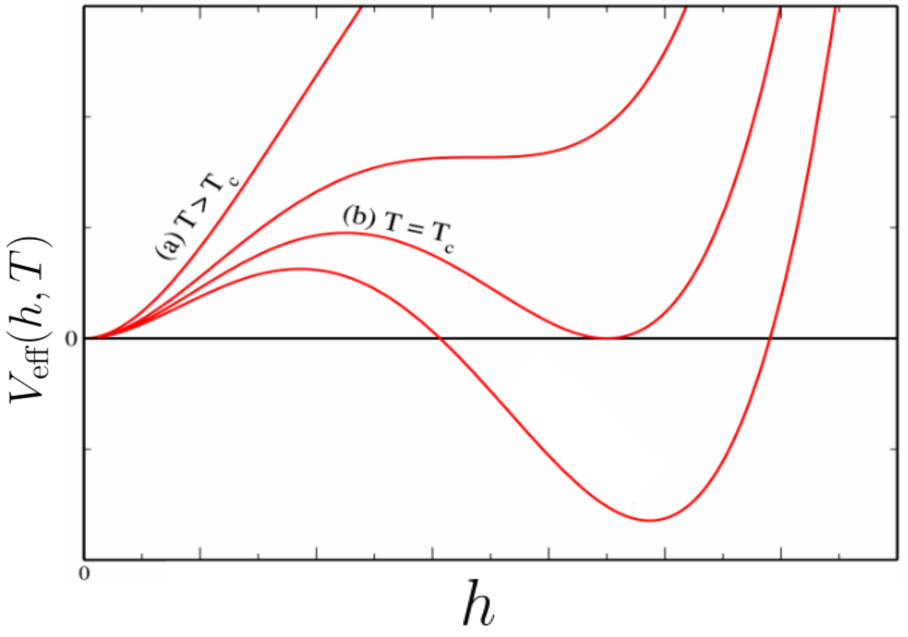


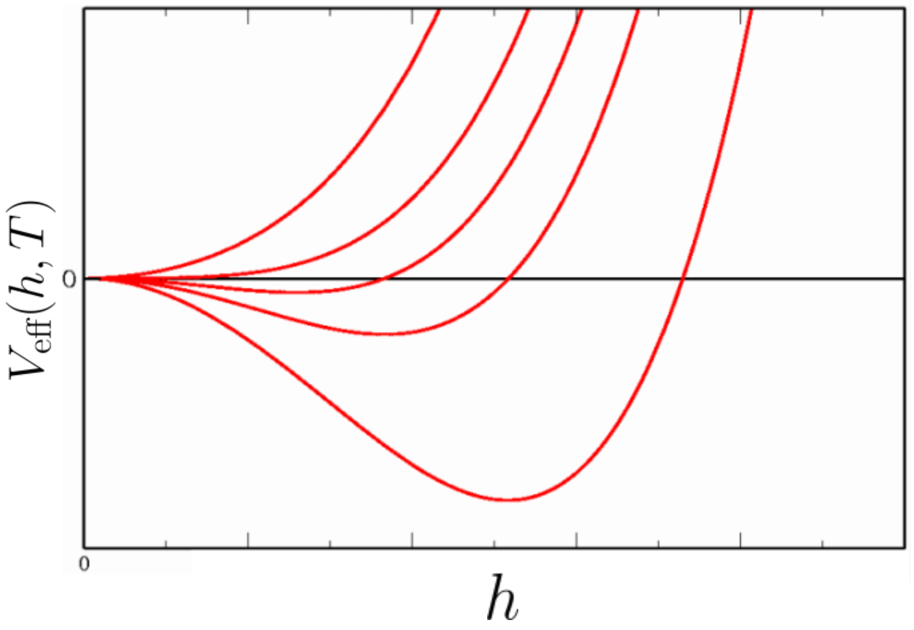
E. Del Nobile, M. Nardecchia, P. Panci, arXiv: 1512.05353 [hep-ph]

Electroweak phase transition

- We found the Higgs but still know little about the Higgs potential/EWSB

$$V_{\rm eff}(h,T) = V_0(h) + V_0^{\rm CW}(h) + V_T(h,T)$$


1st order


2nd order

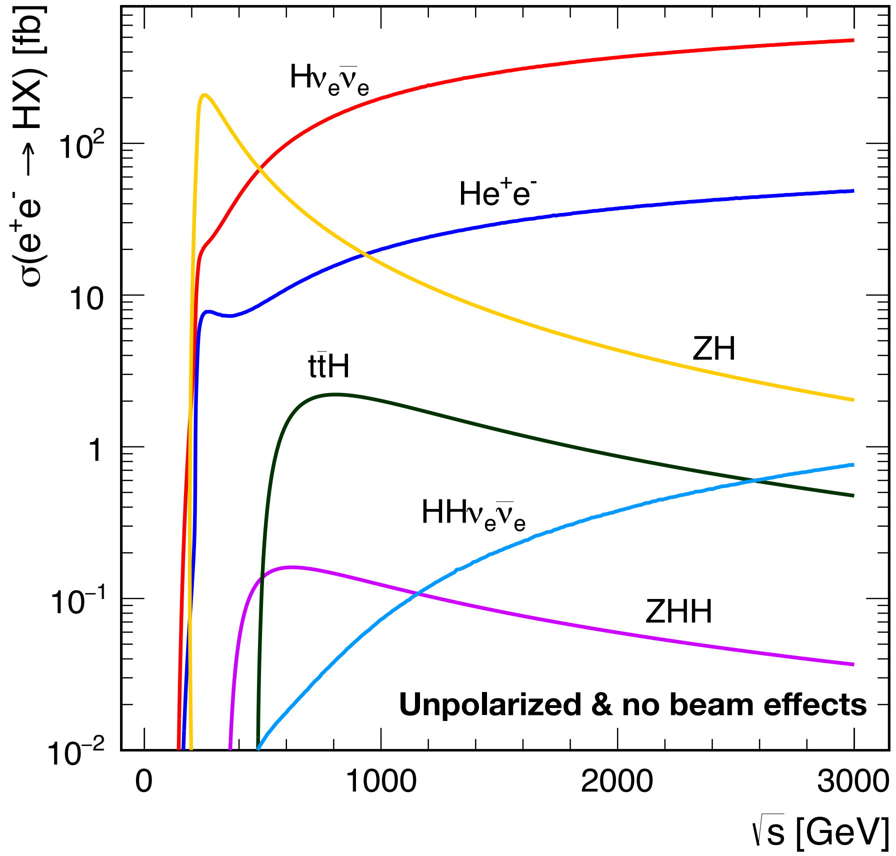
- A strong 1st order phase transition is one of the conditions to generate Baryon asymmetry (Baryogenesis)

Requires new physics modifying scalar potential

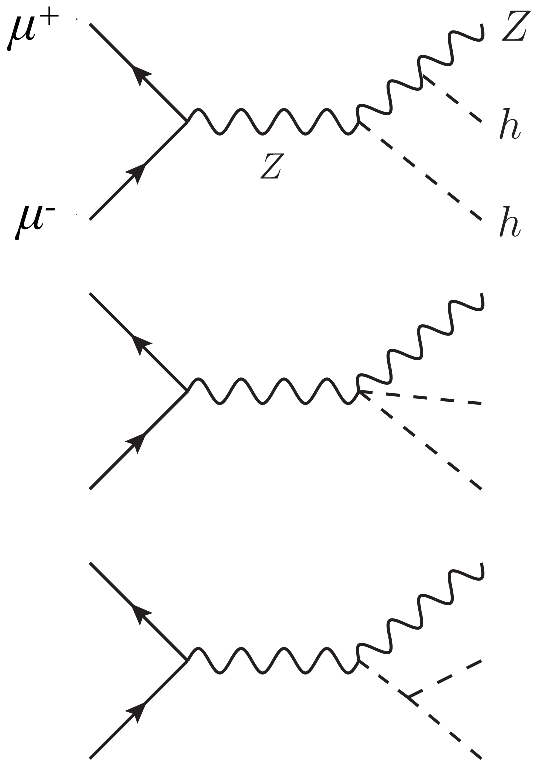
Can be tested via the trilinear Higgs coupling

Electroweak phase transition

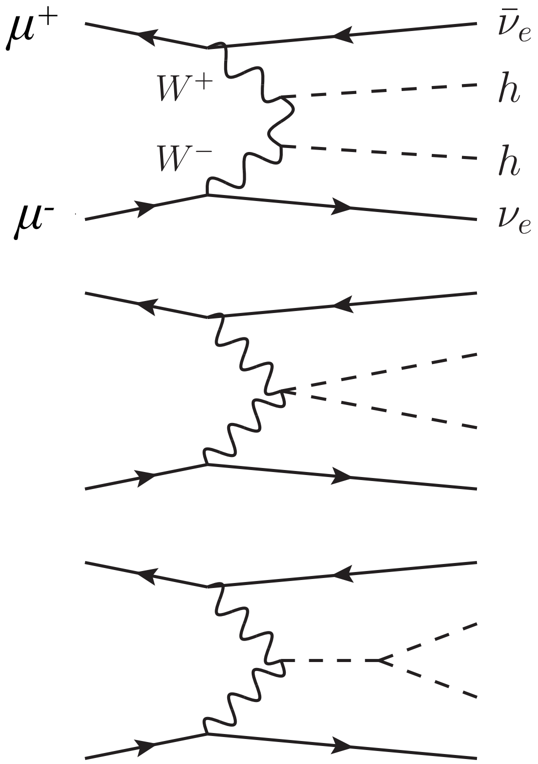
- Testing the Higgs scalar potential: Higgs cubic term



ZHH



WBF



Dominant at Multi-TeV lept. Coll

- Cross sections small (but somewhat larger than e^+e^- counterparts)

σ_{WBF}(3 TeV)= 0.9 fb σ_{WBF}(6 TeV)= 2.1 fb

- hWW must be well known for a precise extraction of hhh coupling

hWW~1% from single Higgs **hhh ~ O(20%)** **CLIC 3 TeV, 3 ab^{-1}**

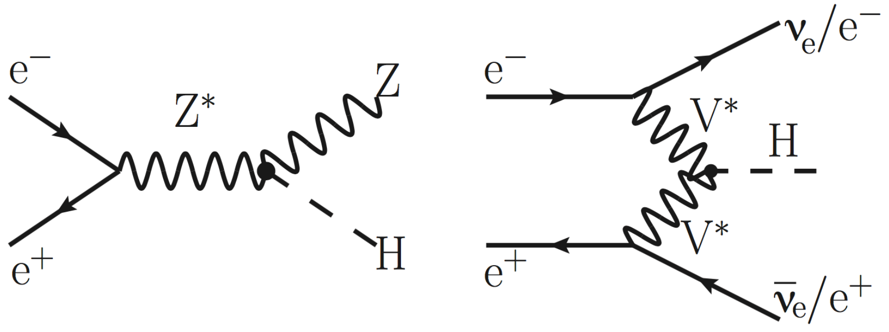
Electroweak phase transition

- New physics modifying scalar potential: Singlet extensions of the SM are the simplest scenario

Example: Direct reach at multi-TeV lepton coll. (CLIC 3 TeV)

Production via mixing γ with Higgs

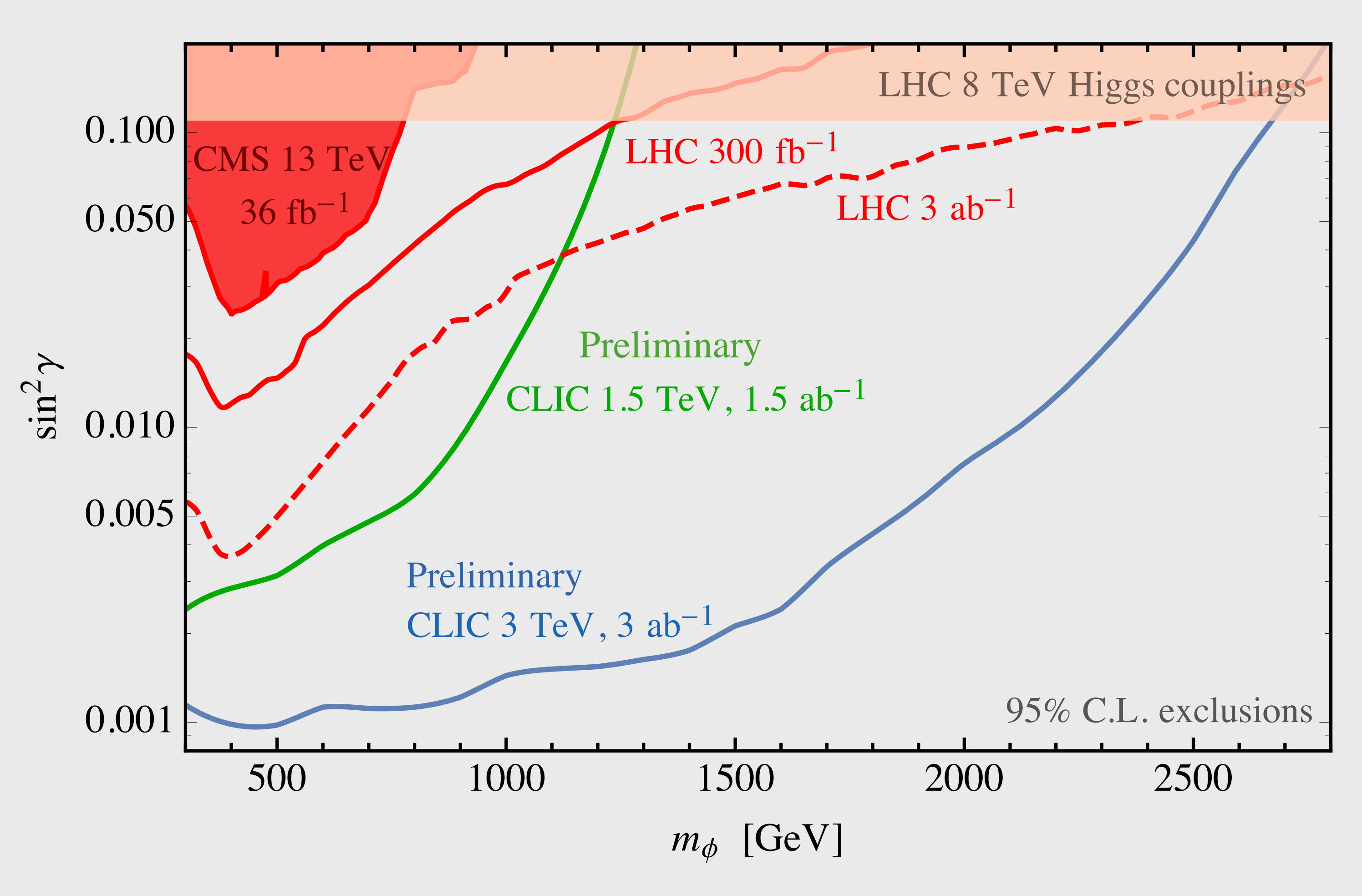
$e^+e^- \to \nu\nu\, S$



$\sigma \times \sin^2\gamma$

$S \to h\,h \to 4b$

Cleaner environment of lepton coll. allows to use most abundant hadronic final states (Backgr.: ννZZ, ννHH)



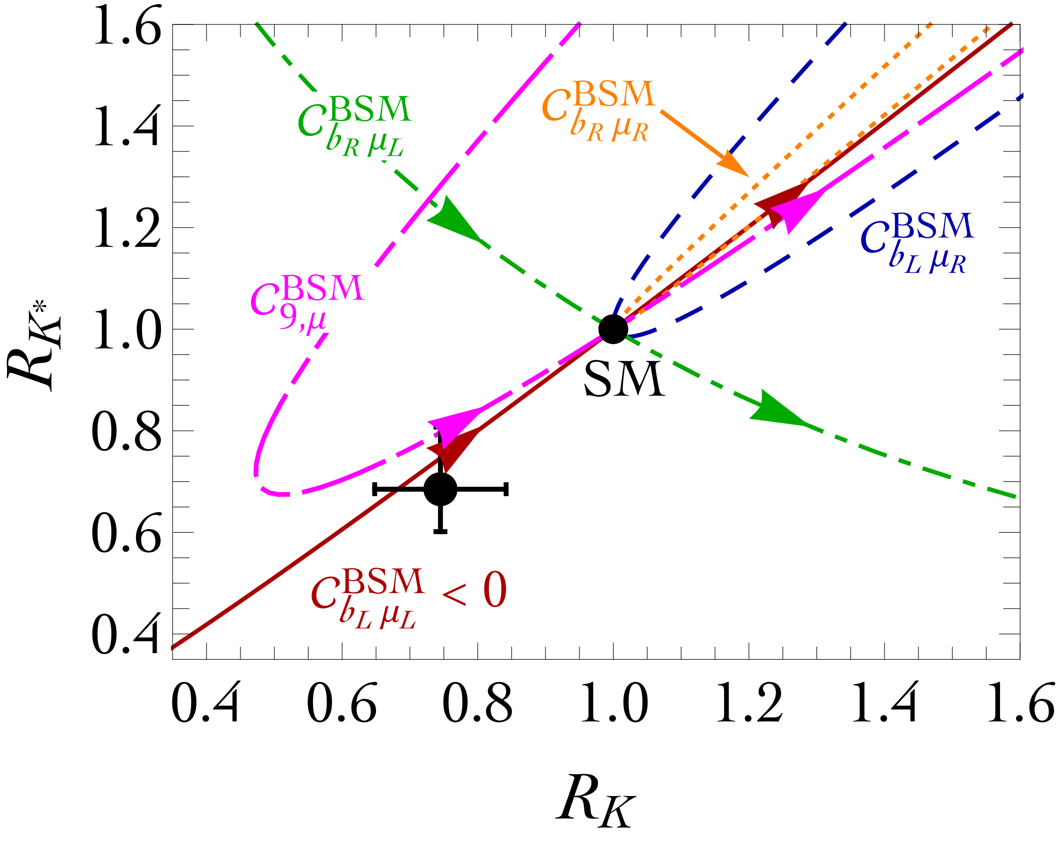
D. Butano, D. Redigolo, F. Sala, A. Tesi, CLIC Physics Potential Yellow Report, In preparation

Flavour Anomalies

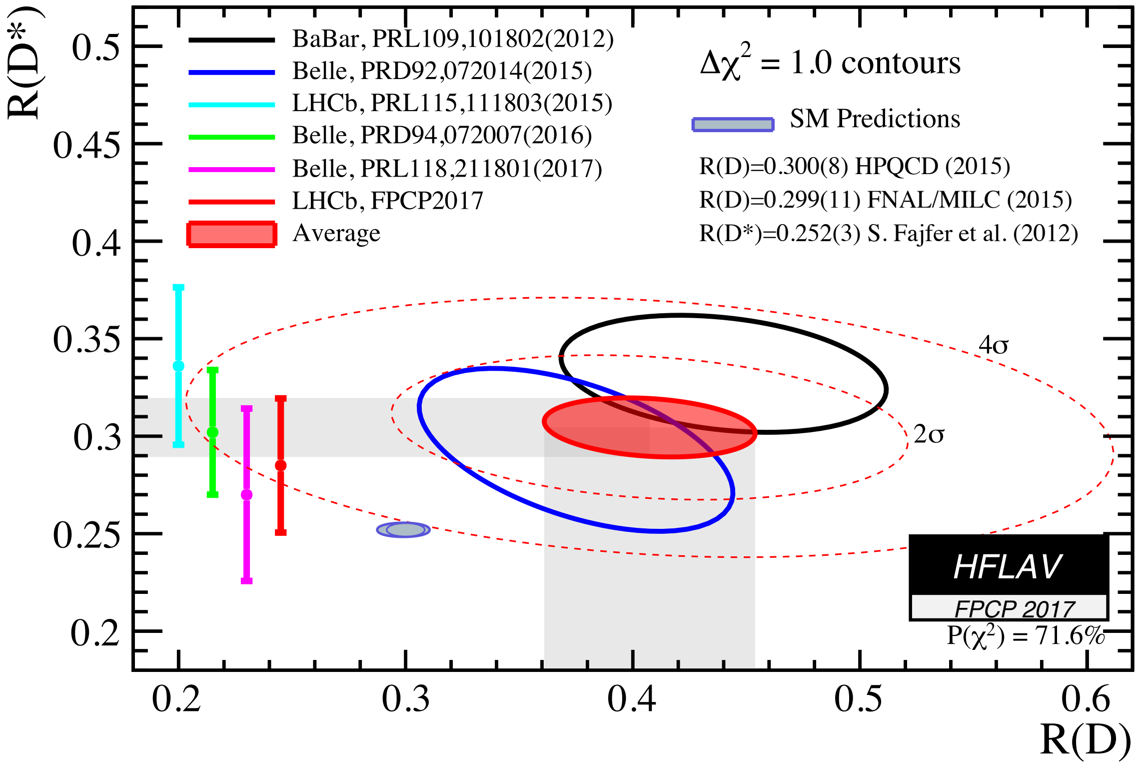
- Several anomalies in the B-sector (***b→sll, b→clv***) hint to additional BSM contributions

b→sll: $R_K = \frac{\mathrm{BR}\left(B^+ \to K^+\mu^+\mu^-\right)}{\mathrm{BR}\left(B^+ \to K^+e^+e^-\right)}$ $R_{K^*} = \frac{\mathrm{BR}(B \to K^*\mu^+\mu^-)}{\mathrm{BR}(B \to K^*e^+e^-)}$ $B_s \to \phi\mu^+\mu^-$ $P_5'\left(B \to K^*\mu^+\mu^-\right)$

b→clv: $R_D = \frac{\mathrm{BR}(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{\mathrm{BR}(\bar{B} \to D\ell^-\bar{\nu}_\ell)}$ $R_{D^*} = \frac{\mathrm{BR}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\mathrm{BR}(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)}$



G. D'Amico et al., arXiv: 1704.05438 [hep-ph]



HFLAV group

Flavour Anomalies

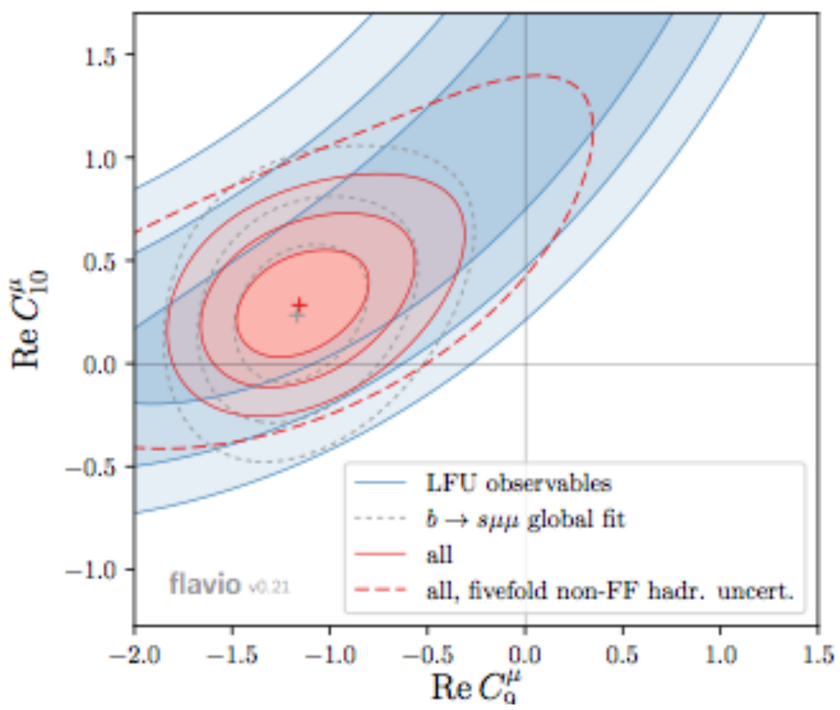
- ***b→sll*** : Consistent with NP contrib. to $\bar{b}s\mu^+\mu^-$ contact interactions
  - NP interaction scale < 80 TeV [unitarity] (< 9 TeV if common explanation for both ***b→sll*** and ***b→clν***)

L. Di Luzio, M. Nardecchia, arXiv: 1706.01868 [hep-ph]

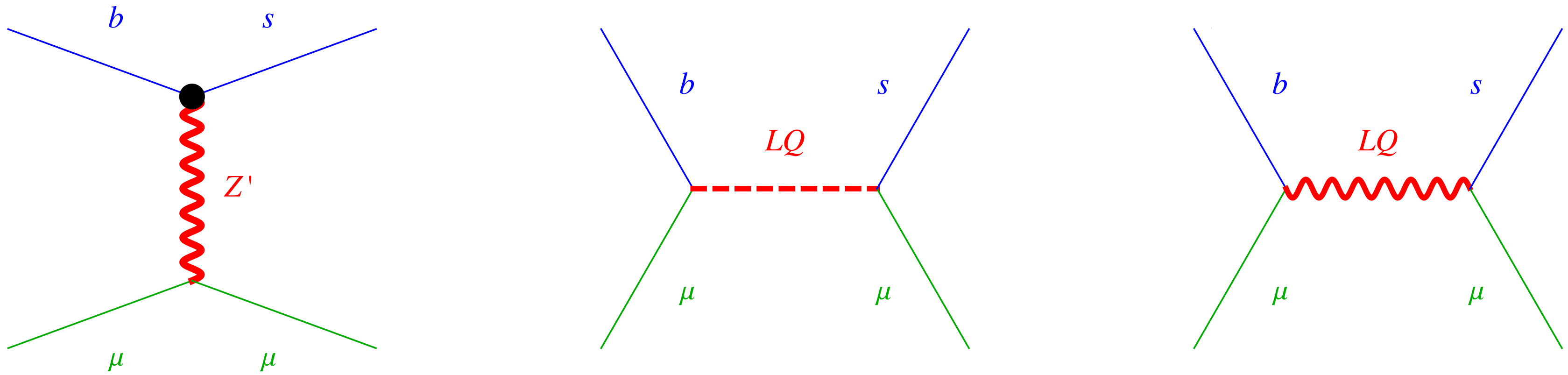
$$\mathcal{H}_{b\to s\mu\mu} \sim \bar{b}_L\gamma_\lambda s_L\bar{\mu}\left(C_9^{\mu\mu}\gamma^\lambda + C_{10}^{\mu\mu}\gamma^\lambda\gamma_5\right)\mu + \mathrm{h.c.}$$

$$\Delta C_9^{\mu\mu} = -\Delta C_{10}^{\mu\mu} = -0.63^{+0.16}_{-0.17}$$

W. Altmannshofer, P. Stangl, D.M. Straub, arXiv: 1704.05435 [hep-ph]



  - Candidates (Tree-level):



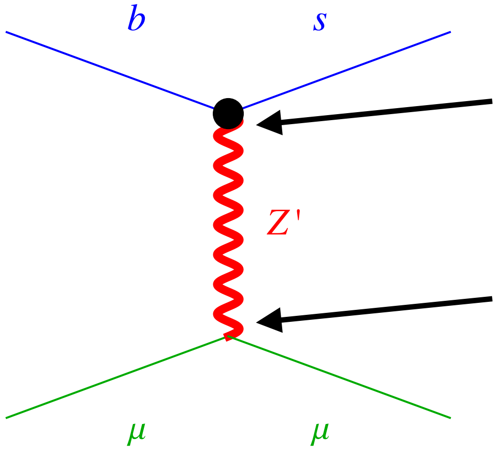
G. D'Amico et al., arXiv: 1704.05438 [hep-ph]

Sizable interactions with muons⇒ Good opportunities at a Muon Collider

Flavour Anomalies

- Candidates (Tree-level):

Sizable interactions with muons⇒ Better tested at a Muon Collider



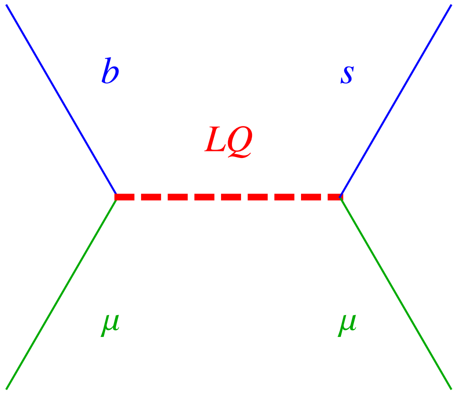
Very small (B_s mixing)

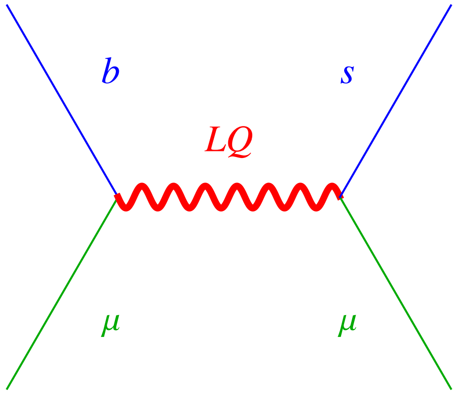
Sizable to explain anomalies

⇒

Better tested in $\mu^+ \mu^- \rightarrow \mu^+ \mu^-$

(s and t-channel exchange)

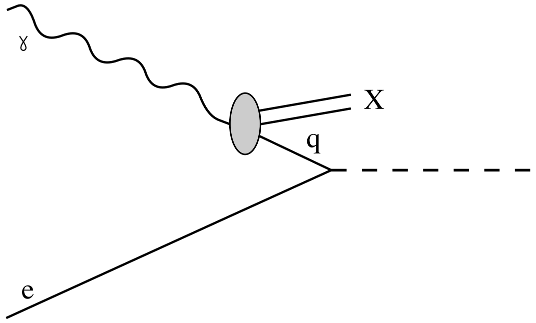




- Main effect via t-channel: $\mu^+ \mu^- \rightarrow bb, ss$

- Pair production

- Single prod. via



M.D. Doncheski, S. Godfrey, arXiv: hep-ph/9807290

Direct reach at Muon Colliders

Muon vs Hadron Colliders: High Energy Reach

- Hadron collider provide higher operating energies but cross sections affected by PDFs

Muon Coll. $\sqrt{s_L}$

$$\sigma_L(s_L) = \frac{1}{s_L}[\hat{s}\hat{\sigma}]_L$$

Hadron Coll. $\sqrt{s_H}$

$$\sigma_H(E, s_H) = \frac{1}{s_H}\int_{E^2/s_H}^{1} \frac{d\tau}{\tau}\frac{dL}{d\tau}[\hat{s}\hat{\sigma}]_H$$

**Hadron Coll.
operating energy $\sqrt{s_H}$
to give same
BSM cross section
at E= $\sqrt{s_L}$
as Muon collider**

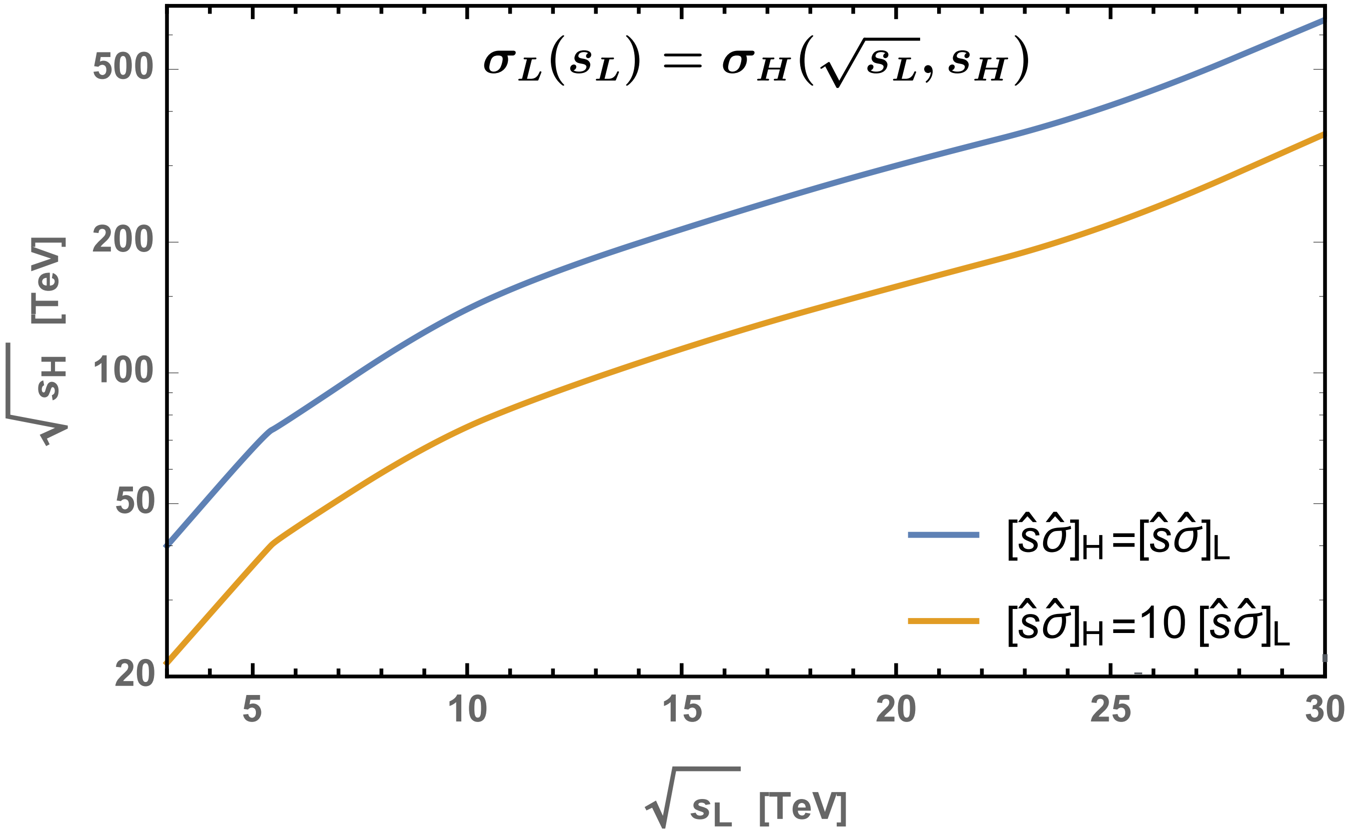


Fig. by A. Wulzer

Illustrative for

QCD-Neutral BSM

QCD-Colored BSM

Direct reach at Muon Colliders

Muon vs Hadron Colliders: High Energy Reach

- Hadron collider provide higher operating energies but cross sections affected by PDFs

Muon Coll. $\sqrt{s_L}$

$$\sigma_L(s_L) = \frac{1}{s_L}[\hat{s}\hat{\sigma}]_L$$

Hadron Coll. $\sqrt{s_H}$

$$\sigma_H(E, s_H) = \frac{1}{s_H}\int_{E^2/s_H}^{1}\frac{d\tau}{\tau}\frac{dL}{d\tau}[\hat{s}\hat{\sigma}]_H$$

Hadron Coll. operating energy $\sqrt{s_H}$ to give same BSM cross section at E= $\sqrt{s_L}$ as Muon collider

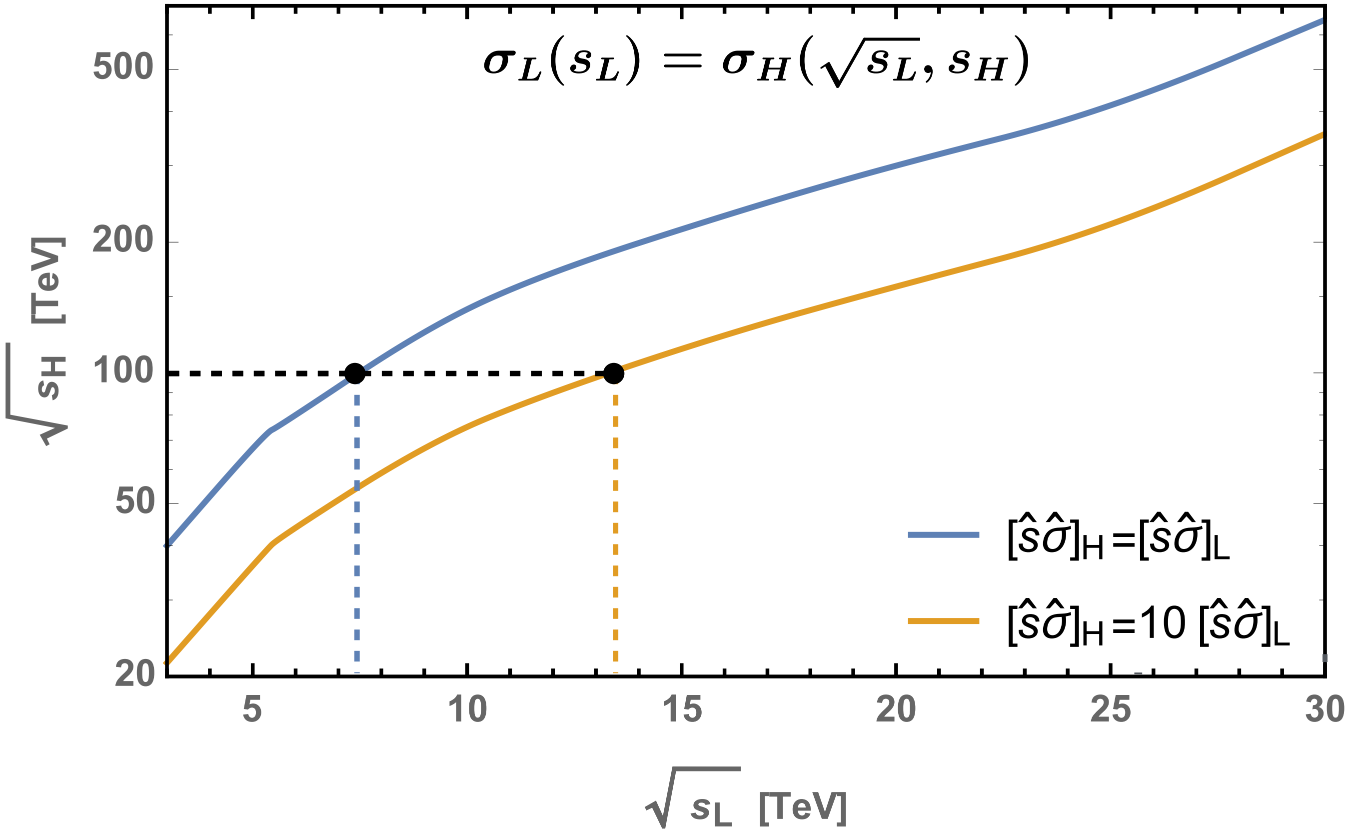


Fig. by A. Wulzer

~10 TeV Muon colliders comparable to ~100 TeV Hadron colliders

Illustrative for	$\sqrt{s_L}$ equiv. to $\sqrt{s_H}$ =100 TeV
QCD-Neutral BSM	~7-8 TeV
QCD-Colored BSM	~13-14 TeV

Direct reach at Muon Colliders

Muon vs Hadron Colliders: High Energy Reach

- Example: Fermionic Top partners in Composite Higgs

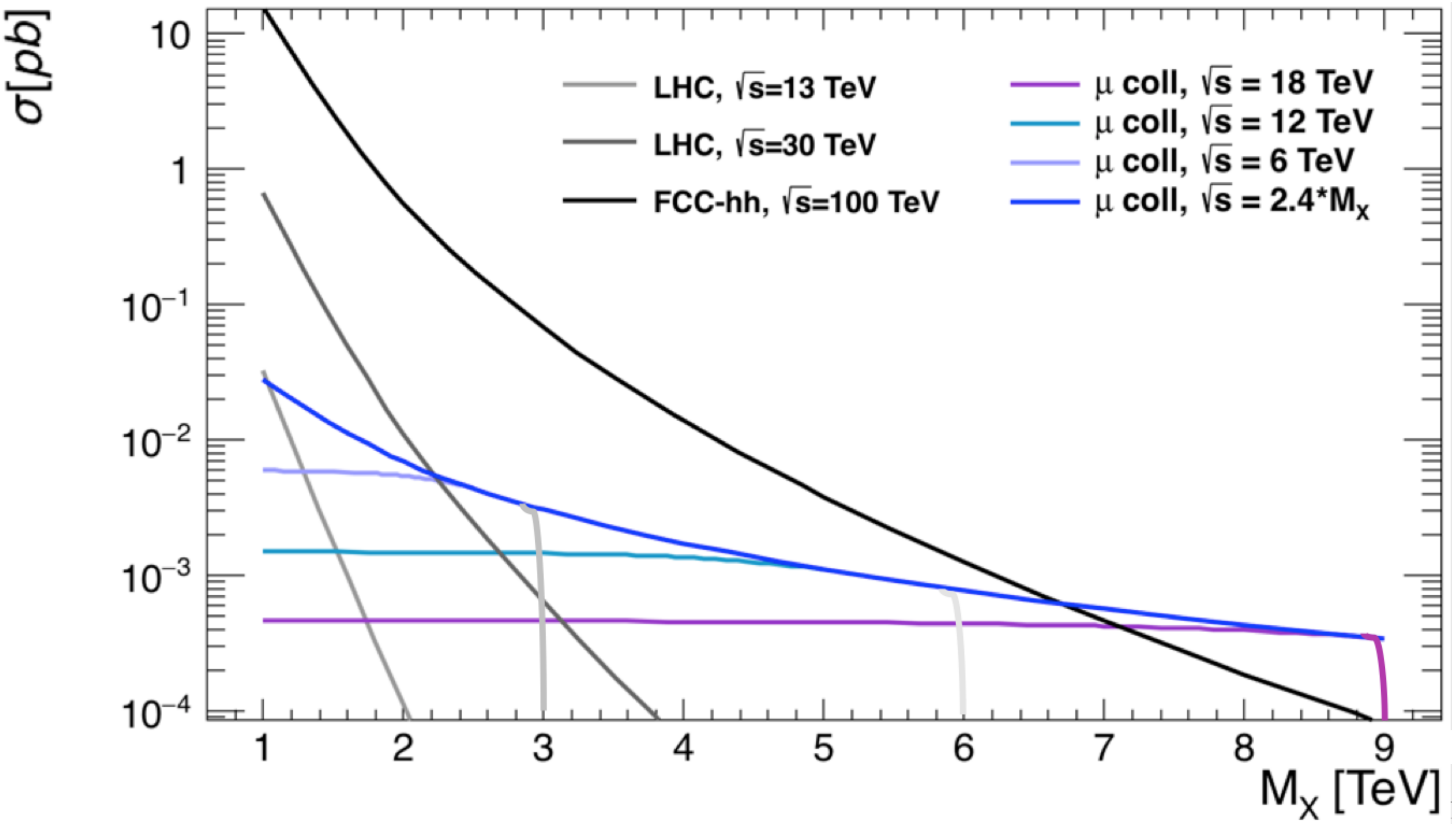


Fig. by A. Wulzer

Similar results/conclusions for SUSY sTops

Direct reach at Muon Colliders

Muon Colliders: Requirements for Direct searches

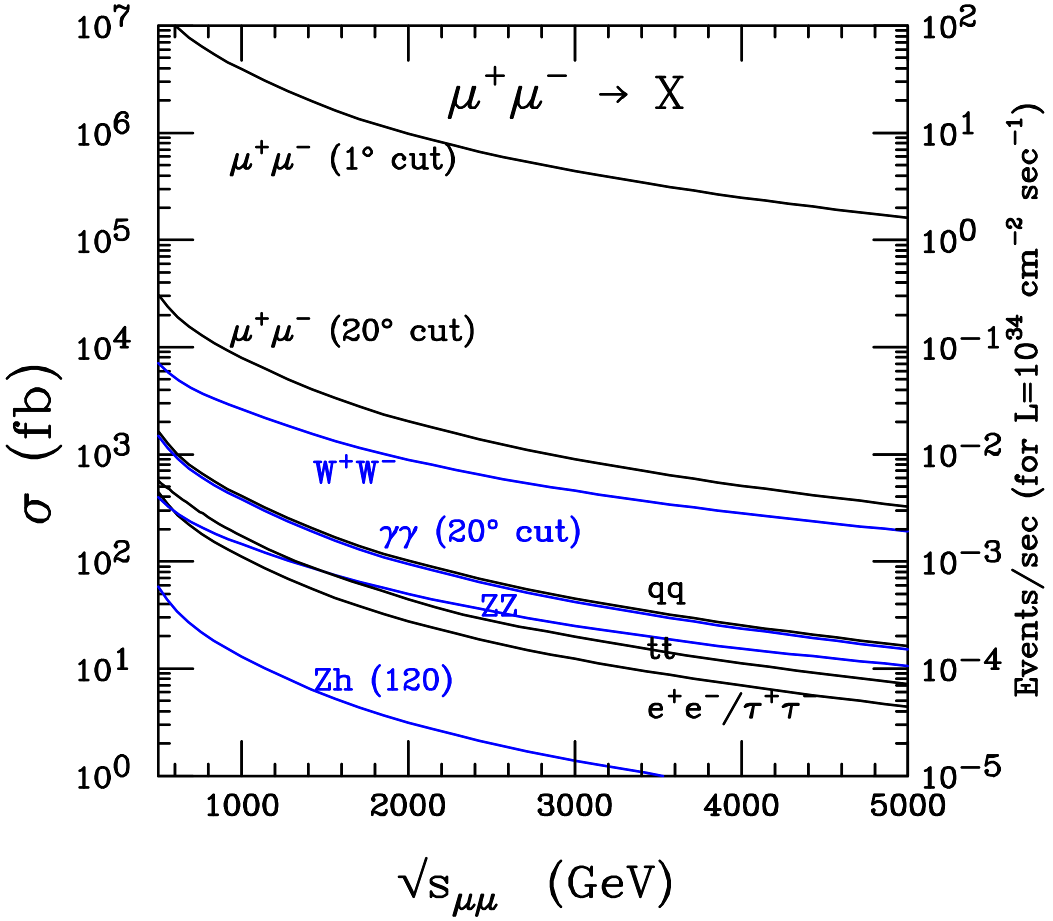
- Energy enough to pair-produce ~5 TeV BSM (naturalness, conventional Top partners)
- Run for a reasonable time (e.g. 3 x LHC) → 900 fb^{-1}
- Probe easy decay modes of BSM: Pair-produce > 100 EW particles

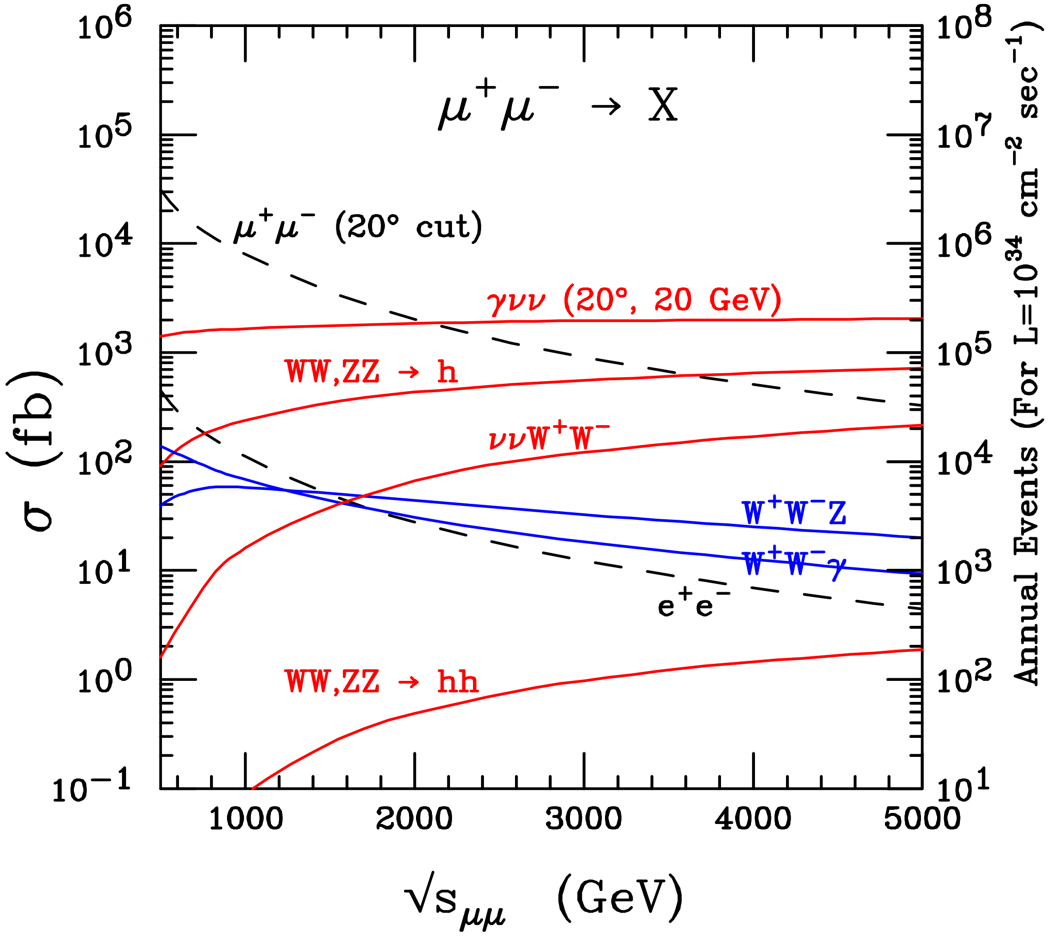
$$N = 1300 \left(\frac{10\ \mathrm{TeV}}{\sqrt{s}}\right)^2 \left(\frac{L}{10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}}\right) \quad \Rightarrow \quad L > \frac{1}{13}\left(\frac{\sqrt{s}}{10\ \mathrm{TeV}}\right)^2 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

e.g. Top partners/Stops

Indirect tests: Energy and Accuracy

- A future collider must be also able to provide accurate measurements of SM processes to perform precision tests of new physics





- Such precision tests can also benefit from High Energies…

Indirect tests: Energy and Accuracy

- Even if new physics is beyond direct reach, high energy measurements can improve greatly the indirect sensitivity to virtual new physics effects

EFT description of BSM effects

$$\mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

$$q = v, E < \Lambda$$

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E-const effects

$$\left.\frac{\Delta O}{O}\right|_{\mathcal{L}_6} \sim \frac{v^2}{\Lambda^2}$$

Sensitivity benefits from:
Accuracy (L, low sys., low th. unc.)

E-growing effects

$$\left.\frac{\Delta O}{O}\right|_{\mathcal{L}_6} \sim \frac{E^2}{\Lambda^2}$$

Sensitivity benefits from:
Accuracy and High Energy

High E can compensate less accuracy ⇒ Precision Tests at High E colliders

Indirect tests: Energy and Accuracy

- Example: Indirect reach for universal NP effects via Drell-Yan

Oblique W & Y parameters

$$\mathcal{L}_{W,Y} = -\frac{Y}{4M_W^2}(\partial_\rho B_{\mu\nu})^2 - \frac{W}{4M_W^2}(D_\rho W^a_{\mu\nu})^2 = \underline{-\frac{Y g'^{\,2}}{2M_W^2}(J_Y^\mu)^2 - \frac{W g^2}{2M_W^2}(J_L^{a\mu})^2} + \ldots$$

Induce 4-fermion operators:

Contribution to cross section for 2→2 fermion processes $\sim \frac{E^2}{\Lambda^2}$

		LEP	ATLAS 8	CMS 8	LHC 13		100 TeV	ILC	TLEP	CEPC	ILC 500 GeV
	luminosity	$2\times10^7\,Z$	$19.7\,\mathrm{fb}^{-1}$	$20.3\,\mathrm{fb}^{-1}$	$0.3\,\mathrm{ab}^{-1}$	$3\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$10^9\,Z$	$10^{12}\,Z$	$10^{10}\,Z$	$3\,\mathrm{ab}^{-1}$
NC	$\mathrm{W}\times10^4$	$[-19,3]$	$[-3,15]$	$[-5,22]$	±1.5	±0.8	±0.04	±4.2	±1.2	±3.6	±0.3
	$\mathrm{Y}\times10^4$	$[-17,4]$	$[-4,24]$	$[-7,41]$	±2.3	±1.2	±0.06	±1.8	±1.5	±3.1	±0.2
CC	$\mathrm{W}\times10^4$	—	±3.9		±0.7	±0.45	±0.02	—	—	—	—

M. Farina, G. Panico, D. Pappadopulo, J. T. Rudermann, R. Torre, A. Wulzer, arXiv: 1609.08157 [hep-ph]

Only CLIC at 3 TeV (3 ab^{-1}) could be competitive with 100 TeV Hadron Collider

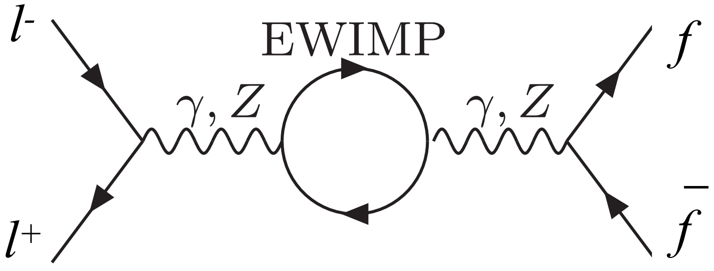
A High(er) Energy muon collider could do better with less Lumi

$$\int dt L \geq 3\frac{(3\ \mathrm{TeV})^2}{s}\mathrm{ab}^{-1}$$

Indirect tests: Energy and Accuracy

- Example: Indirect reach for universal NP effects via Drell-Yan

Application to Accidental DM scenarios



EFT limit

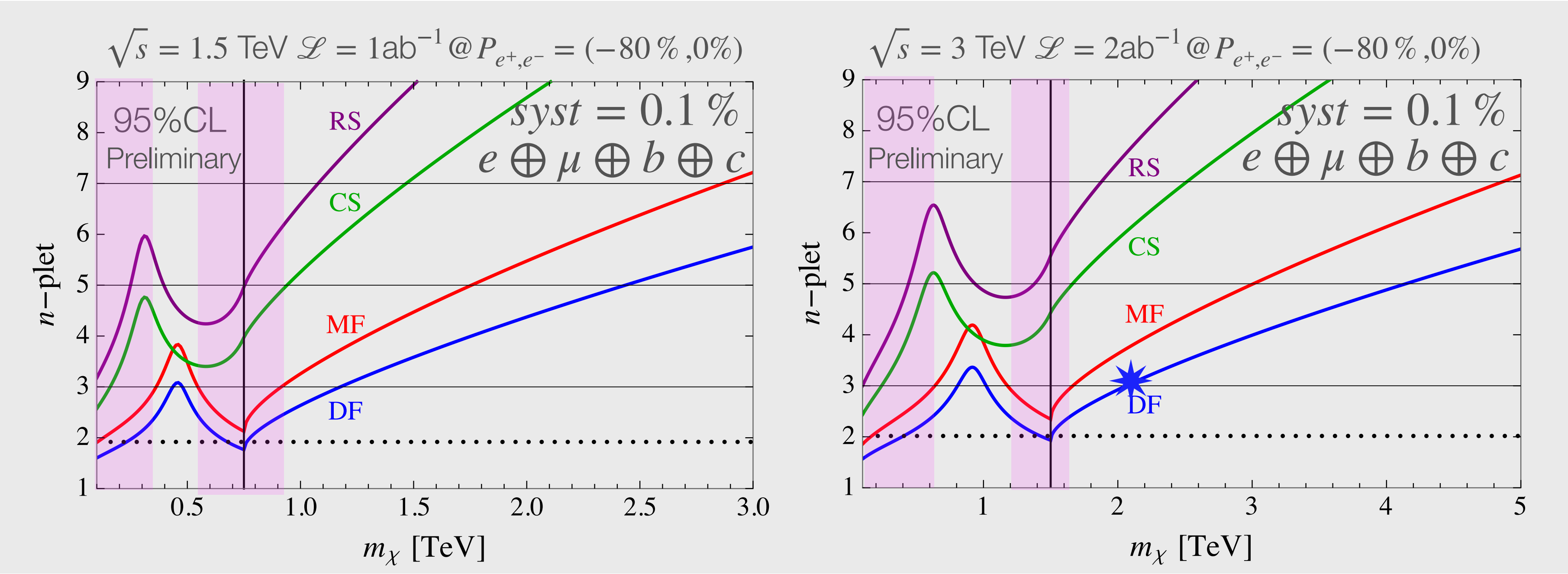
$$W = \frac{g^2 C^{\rm eff}_{WW}}{960\pi^2}\frac{m_W^2}{m_\chi^2} \qquad Y = \frac{g'^2 C^{\rm eff}_{BB}}{960\pi^2}\frac{m_W^2}{m_\chi^2}$$

$$C^{\rm eff}_{WW} = \kappa(n^3-n)/6,\; C^{\rm eff}_{BB} = \kappa 2nY^2$$

$$\kappa = \frac{1}{2},1,4,8 \text{ for RS,CS,MF,DF}$$

χ	$M_\chi^{(\rm DM)}$ [TeV]
$(1,3,\epsilon)_{\rm CS}$	1.5
$(1,3,\epsilon)_{\rm DF}$	2.0
$(1,3,0)_{\rm MF}$ *	3.0
$(1,5,\epsilon)_{\rm CS,\,DF}$	6.6
$(1,5,0)_{\rm MF}$ **	9.6
$(1,7,\epsilon)_{\rm CS,\,DF}$	16

Example: Indirect reach at Multi-TeV lepton coll. (CLIC 3 TeV)



Suppressed indirect effects
Reach still larger than Direct for DF Triplet

L. Di Luzio, R. Grober, G. Panico, CLIC Physics Potential Yellow Report, In preparation

Conclusions

- Theoretical motivation for a high-energy muon collider is clear in several directions of BSM exploration

- BSM physics at a Multi-TeV muon collider:
  - Possible to define minimum interesting energy/luminosity requirements
  - **Pros:** Clean environment, Lumi increases with energy, reach comparable to Hadron Collider operating at much higher energies
  - **Challenges:** Neutrino radiation, background, technology has to be demonstrated

- A high-energy muon collider can also perform precision tests of NP (Important both in presence or absence of a new discovery)

Backup Slides

Sterile Heavy Neutrinos

- Neutrino oscillations prove that neutrinos have mass.

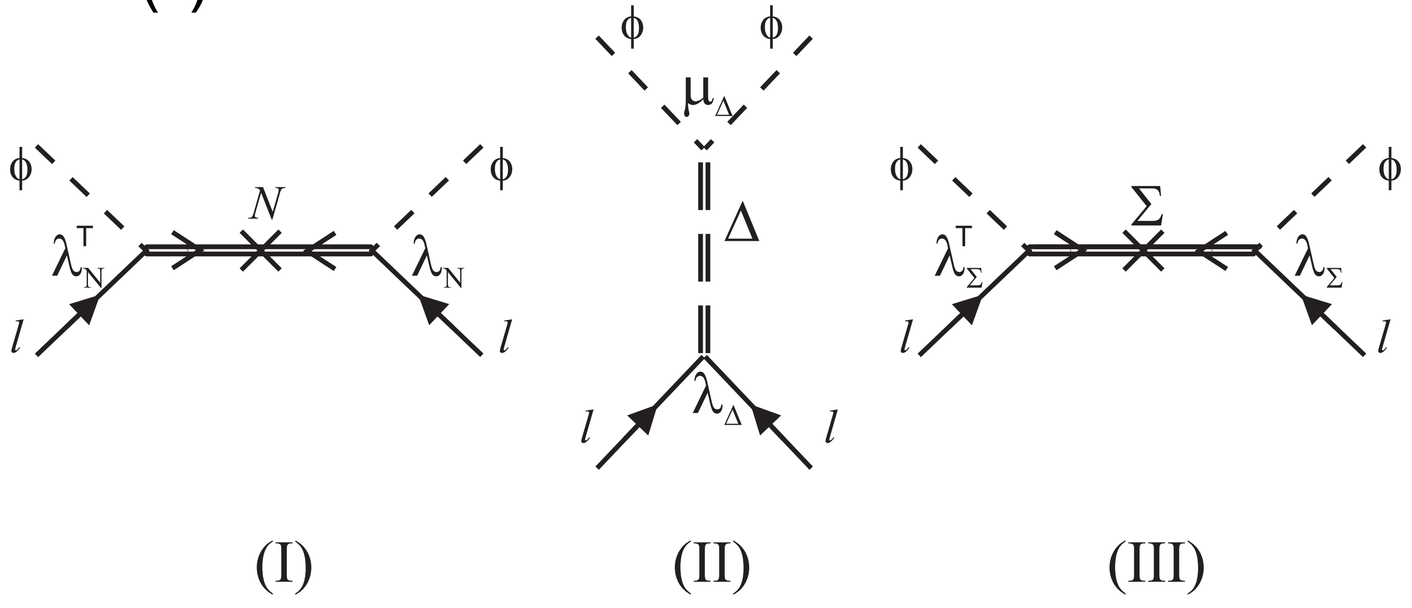
SM: Neutrinos are massless ⇒ BSM physics

- Majorana neutrino mass can only be generated in the SM via higher-dimensional operators

Weinberg operator
(Dim 5, LNV)

$$(\mathcal{O}_5)_{ij} = \overline{(l_L^i)^c}\tilde{\phi}^*\tilde{\phi}^\dagger l_L^j \to \frac{v^2}{2}\overline{(\nu^i)^c}\nu^j$$

- Seesaw mechanism(s):

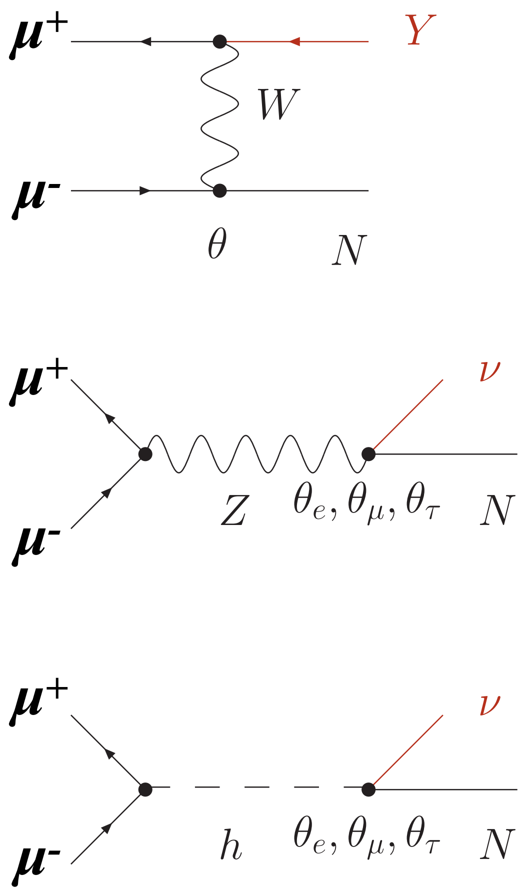


Neutrino singlet **Scalar triplet** **Lepton triplet**

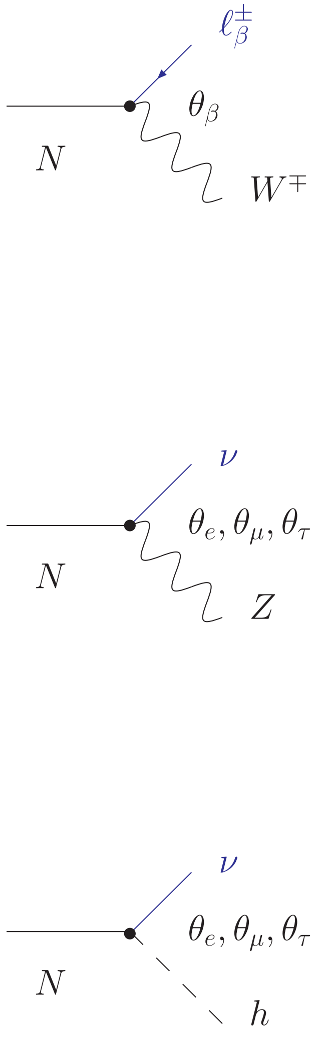
Sterile Heavy Neutrinos

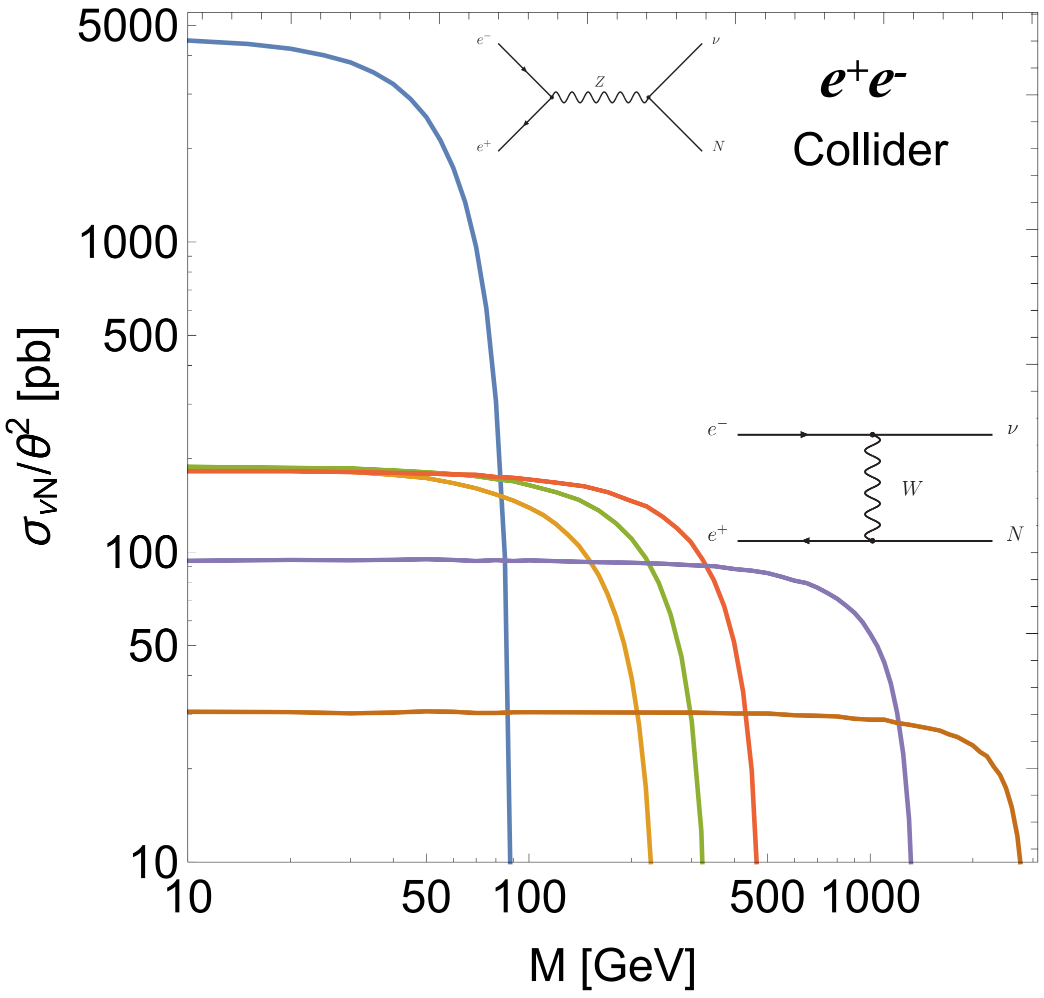
- Present in minimal neutrino mass models (seesaw mechanism type 1)
- Interactions with SM via mixing with active neutrinos $\theta_\alpha = \frac{y^*_{\nu_\alpha}}{\sqrt{2}} \frac{v_{\mathrm{EW}}}{M}$

Production



Decay





S. Antusch, E. Cazzato, O. Fischer, arXiv: 1612.02728 [hep-ph]

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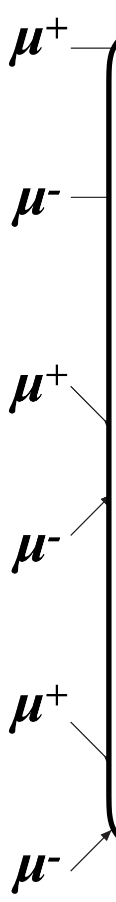
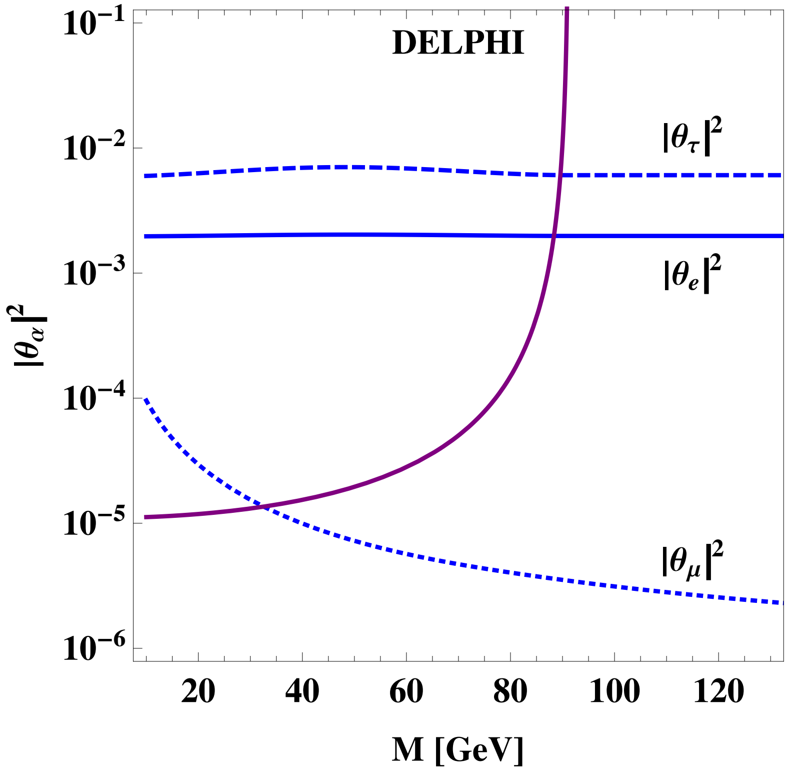
Production **Decay**



Neutrino prod. at Muon Collider

Larger Energy reach than Linear Colliders

But current (indirect) constraints are stronger for mixing with 2nd family for minimal seesaw models with EW-scale neutrinos…



S. Antusch, E. Cazzato, O. Fischer, arXiv: 1612.02728 [hep-ph]