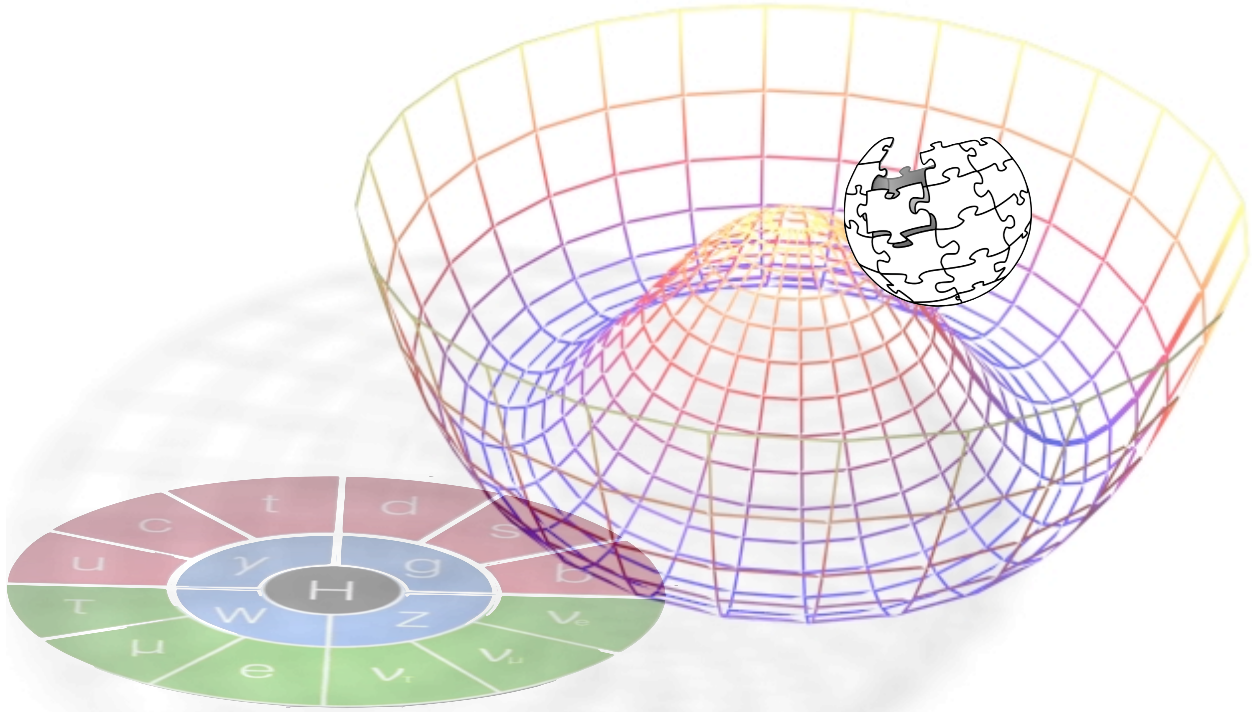
Implications of an Improved $n\bar{n}$ Oscillation Search for Baryogenesis

" Particle Physics with Neutrons at the ESS"

Nordita, Stockholm, Dec. 14, 2018



HELMHOLTZ GEMEINSCHAFT

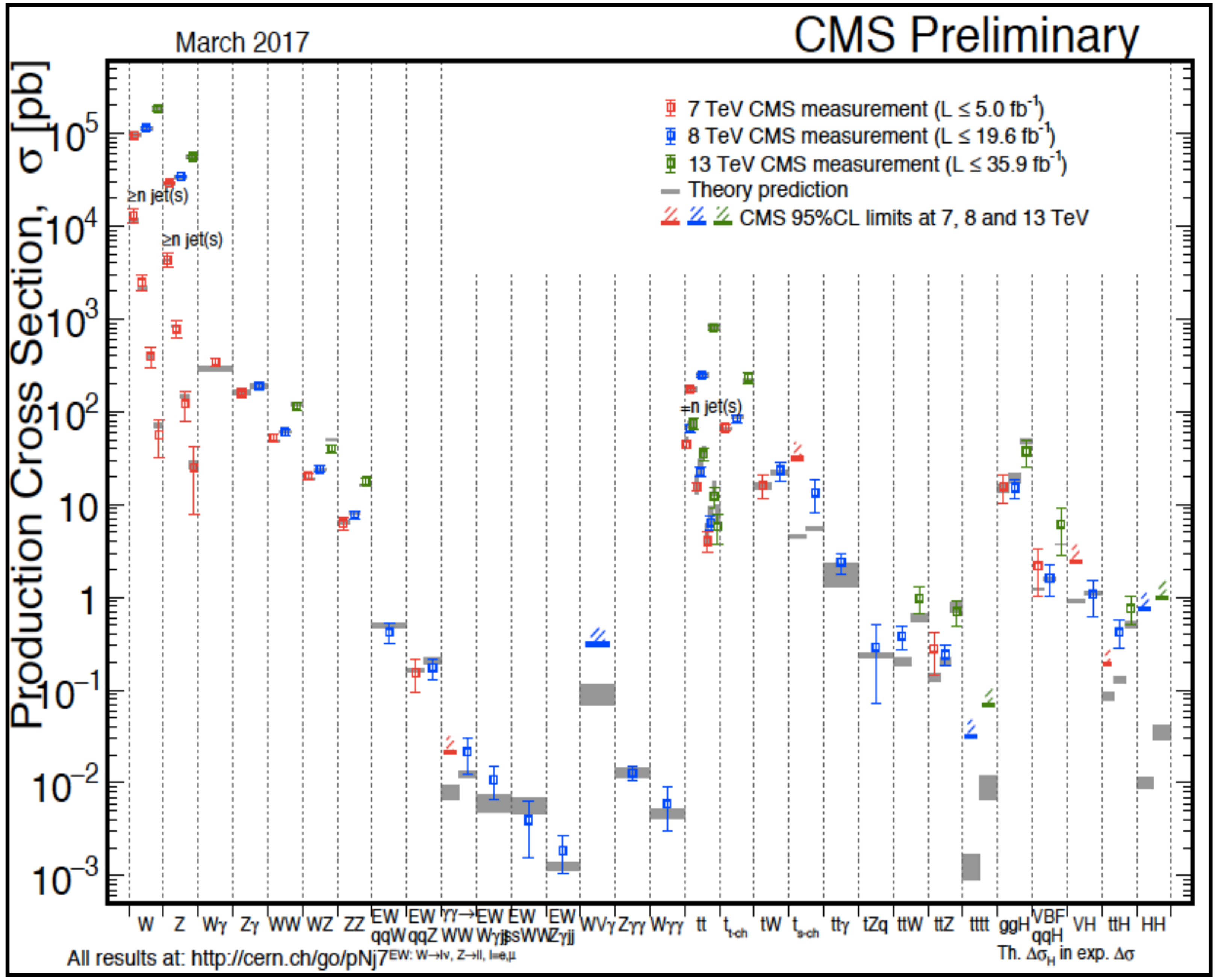
Christophe Grojean

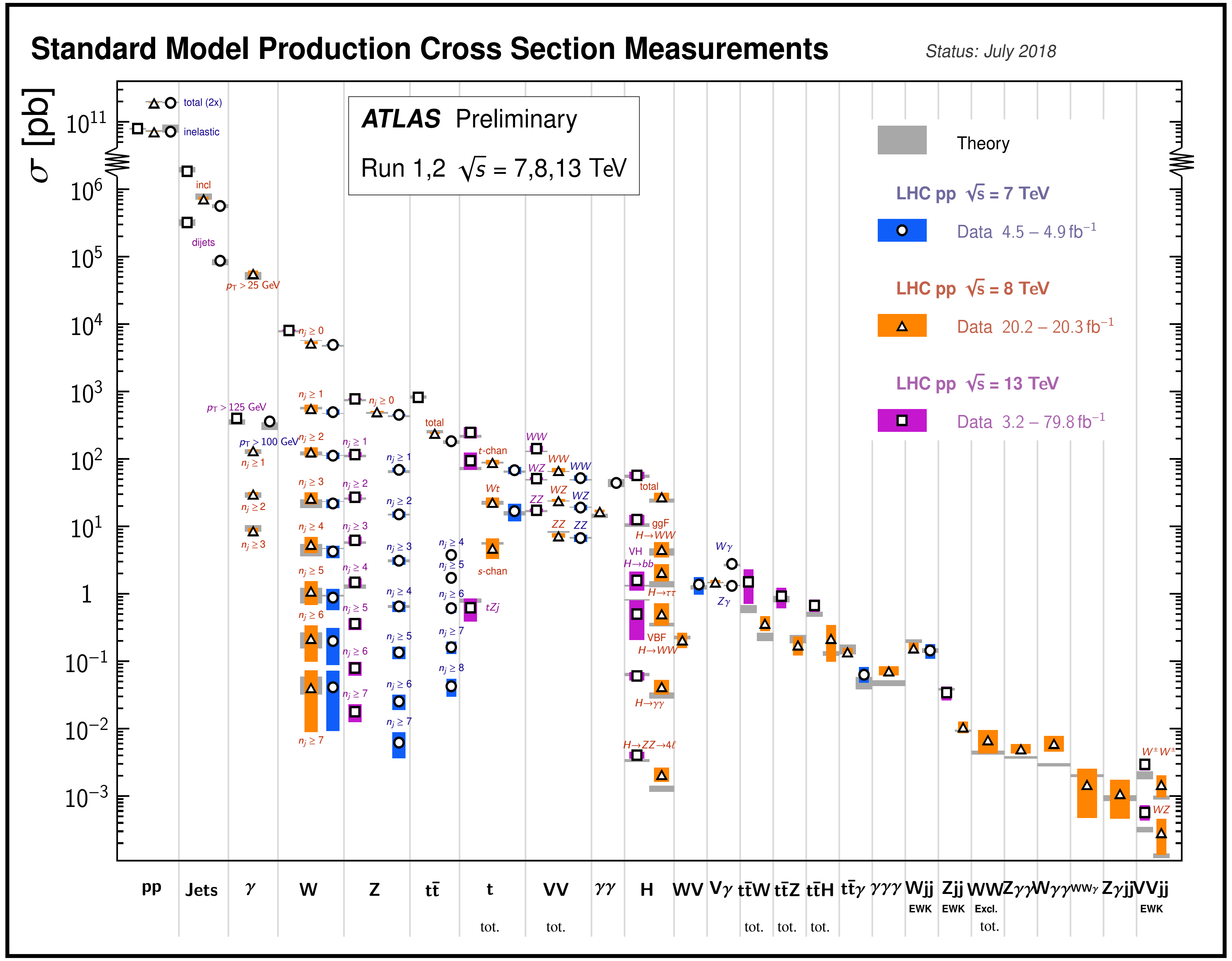
DESY (Hamburg)

Humboldt University (Berlin)

(christophe.grojean@desy.de)

The SM and… the LHC data so far





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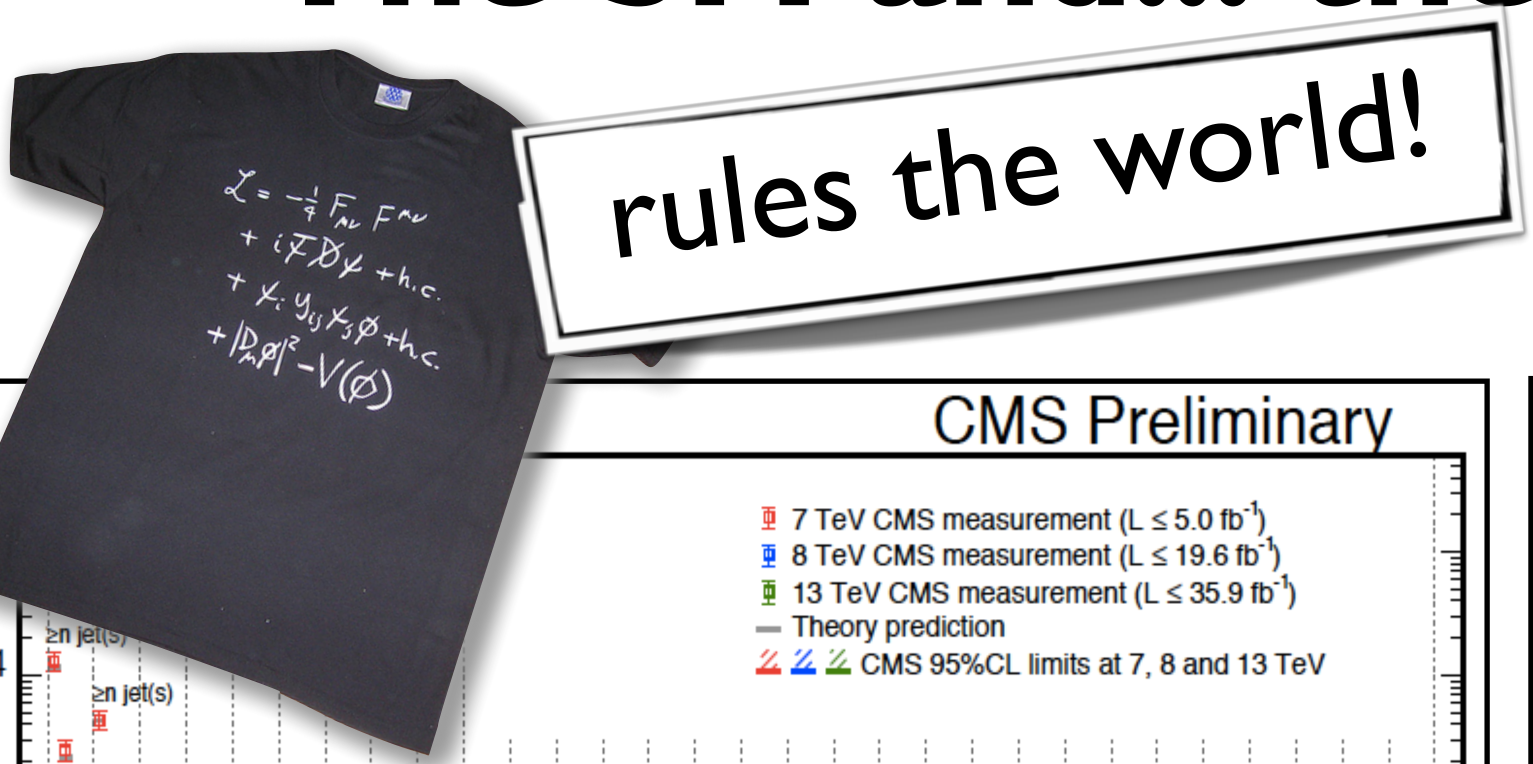
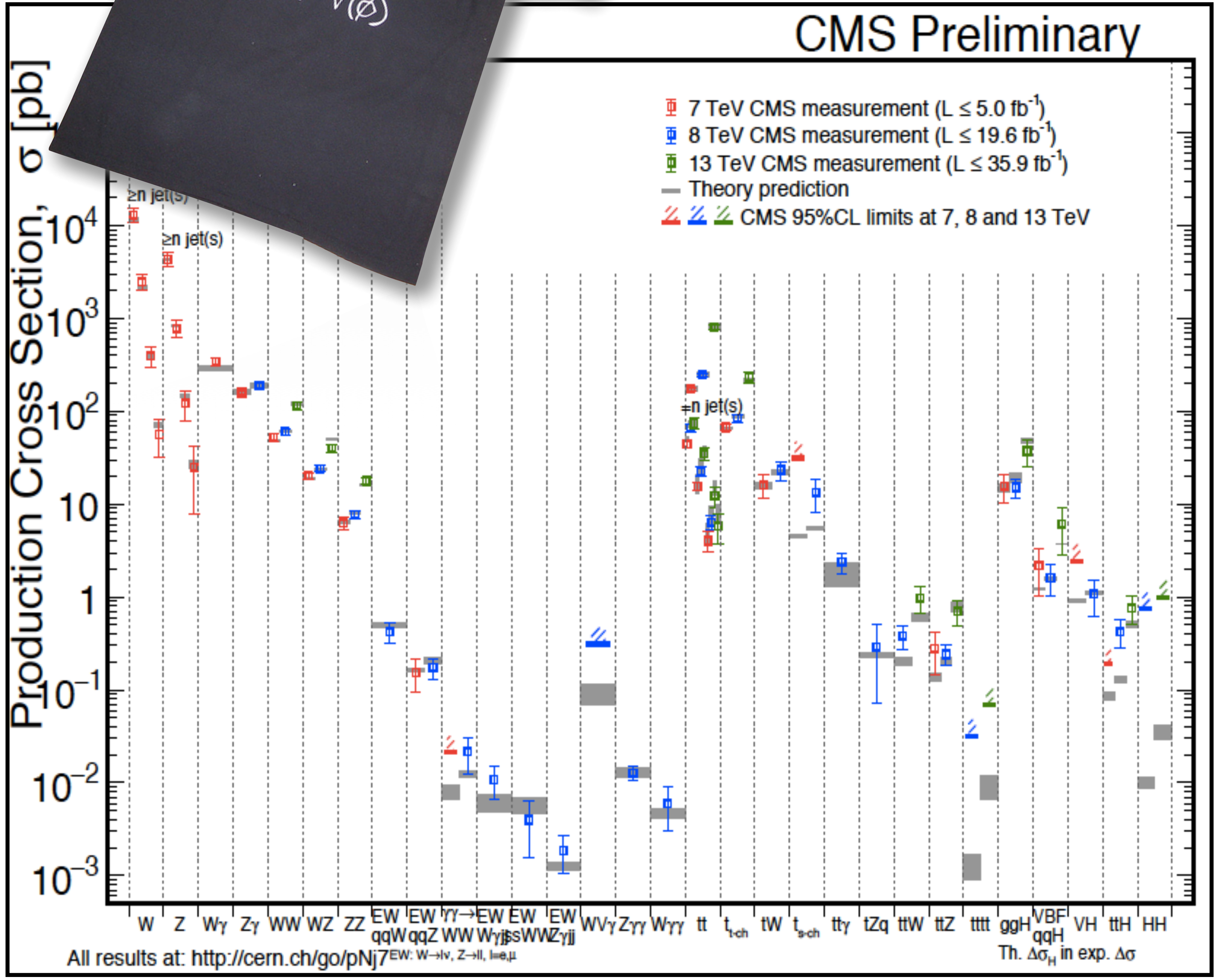
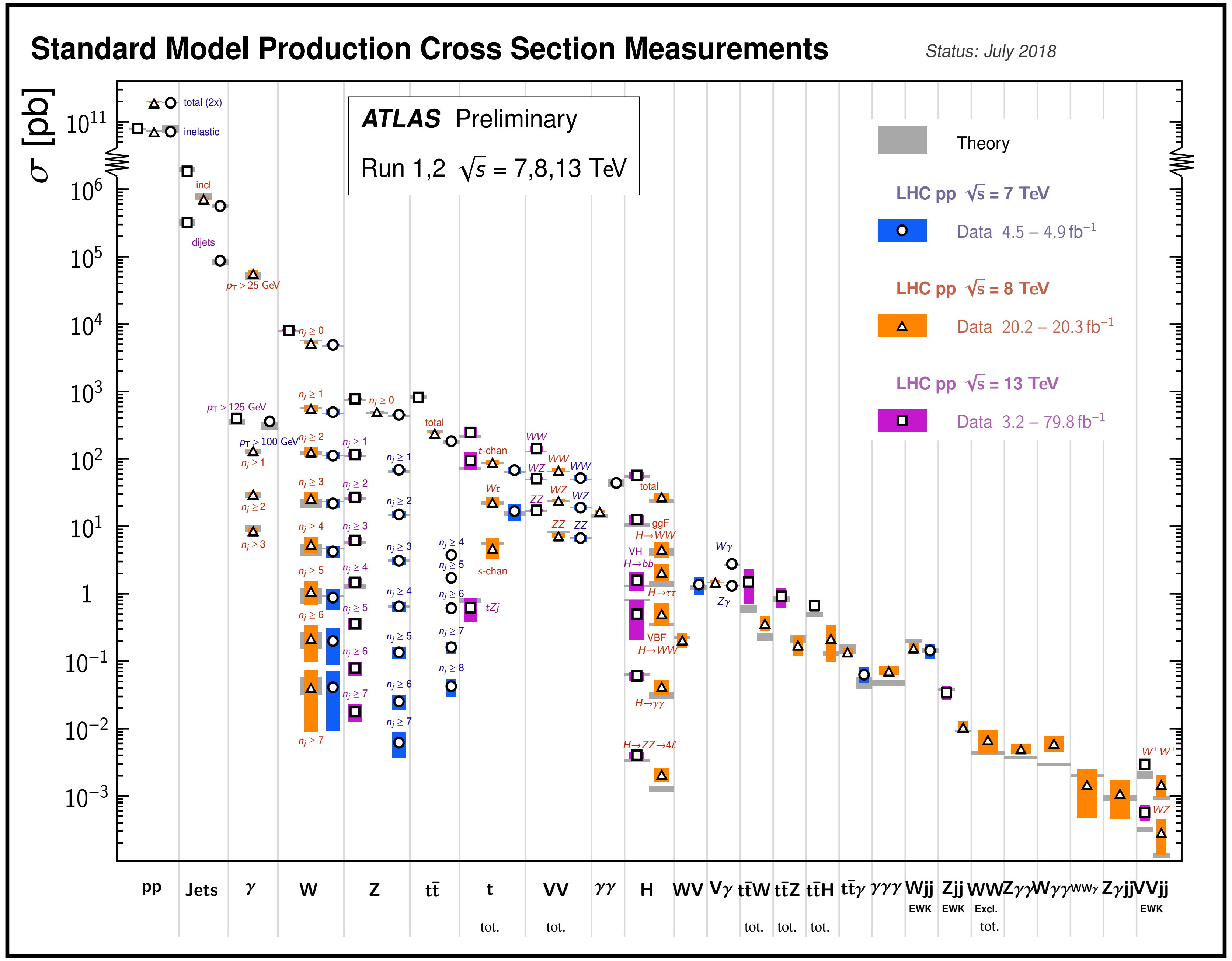


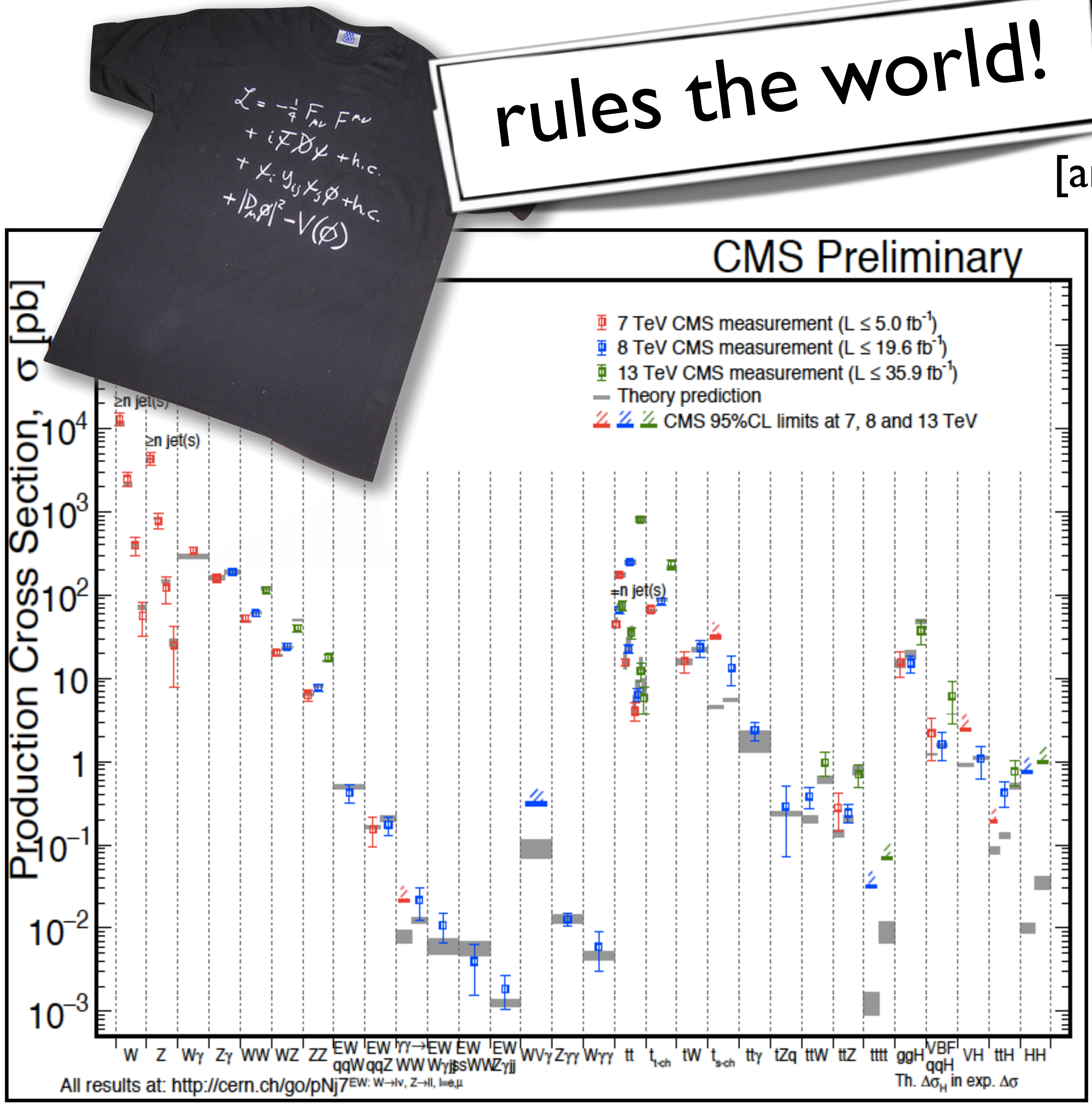


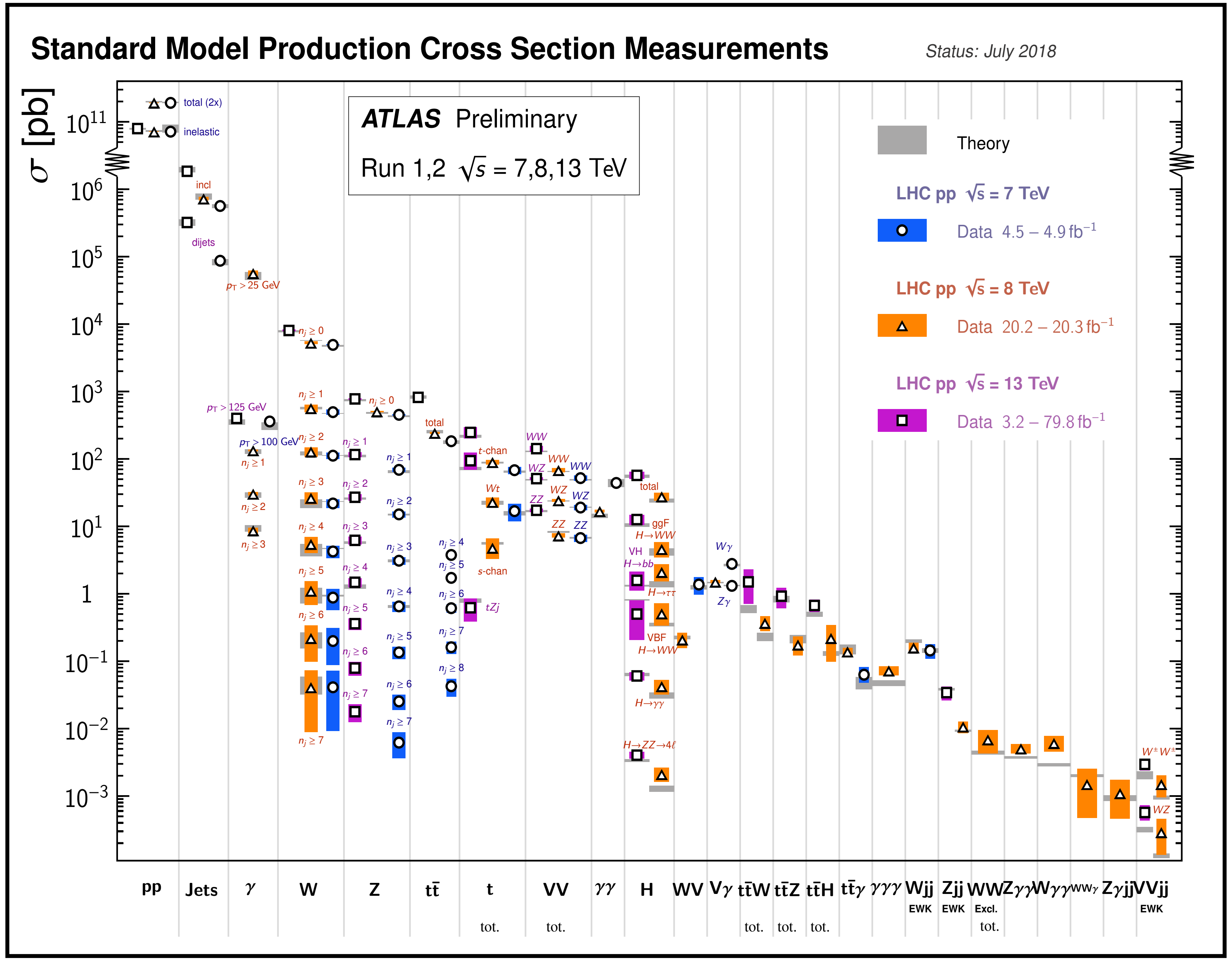


The SM and... the LHC data so far

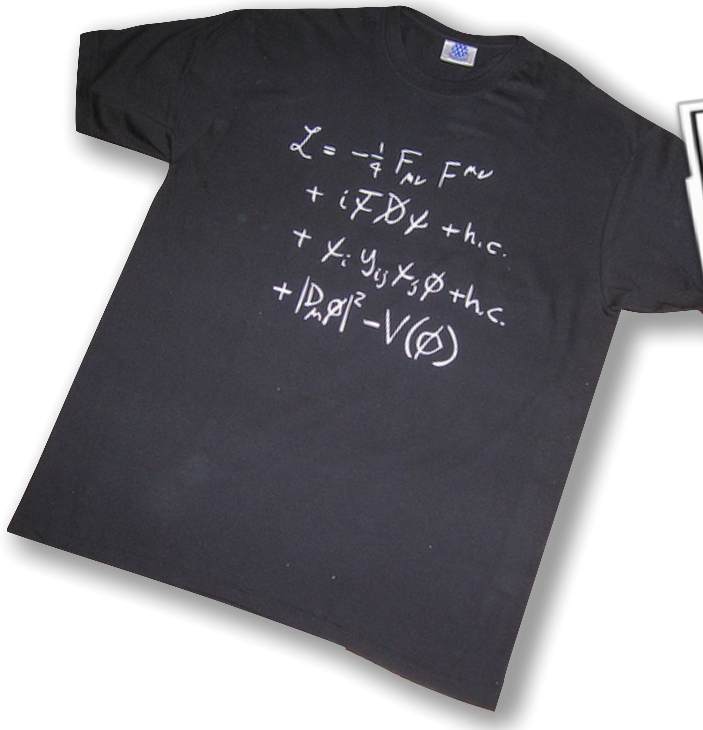
rules the world!

[and we, HEP practitioners, are all entitled for some royalties!]





The SM and... the rest of the Universe



is not enough

[and we all have to return our royalties!]

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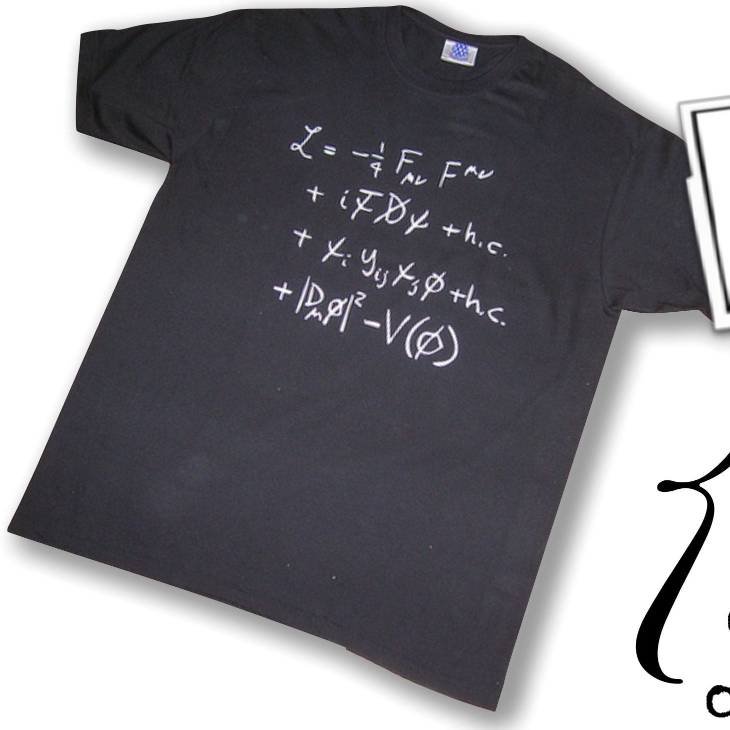

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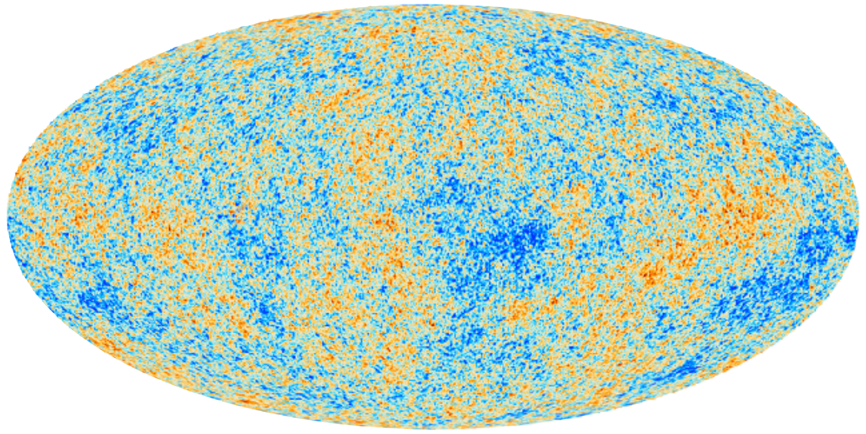
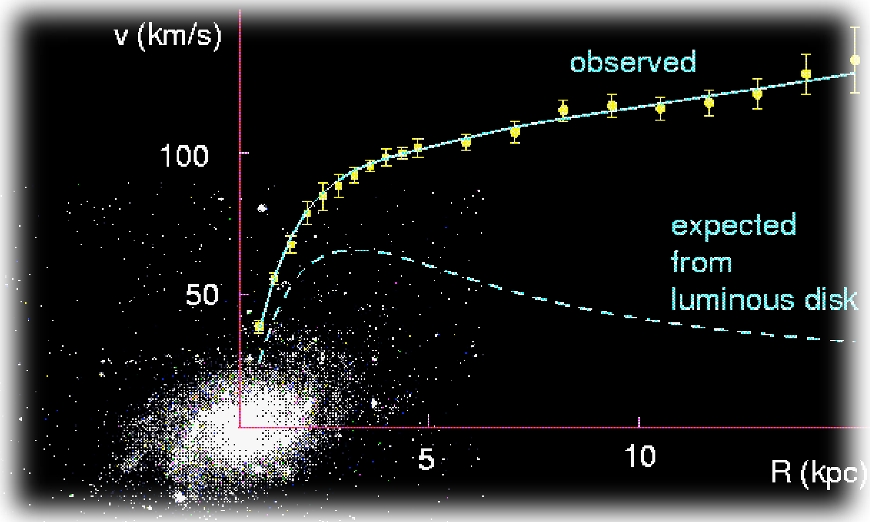
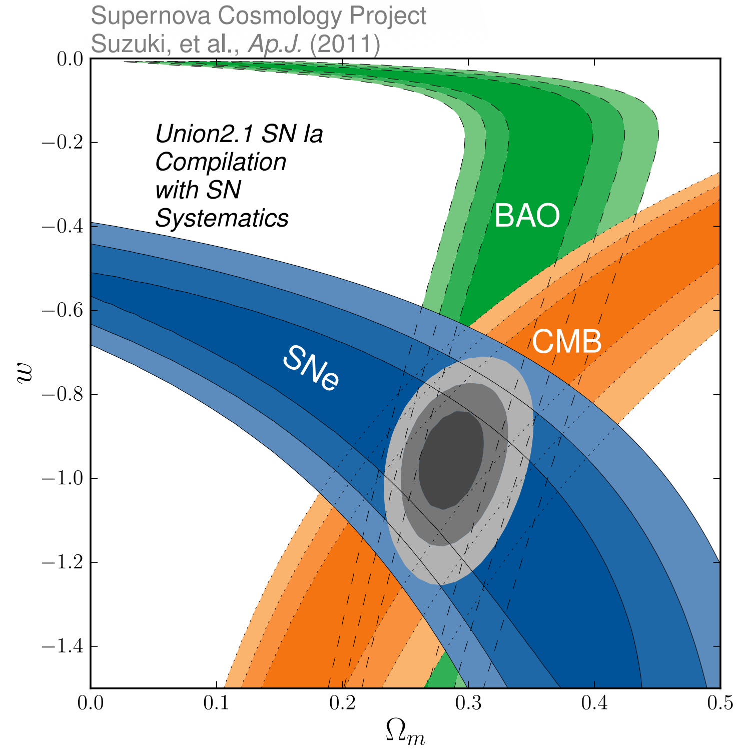
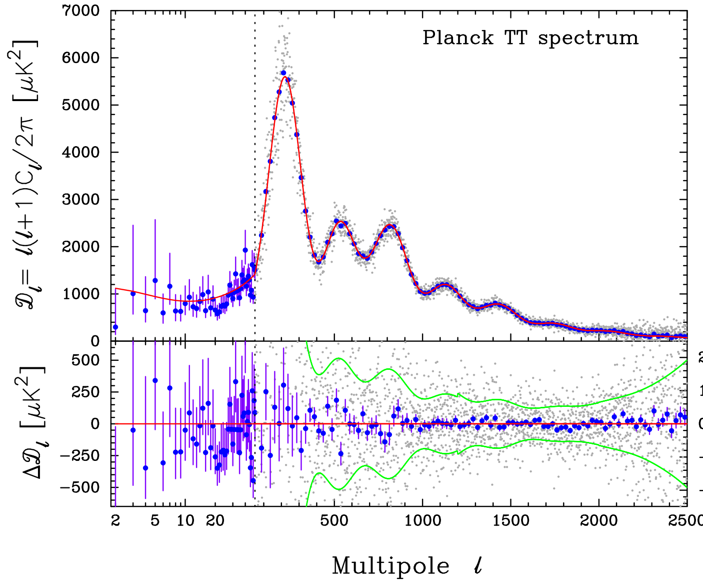
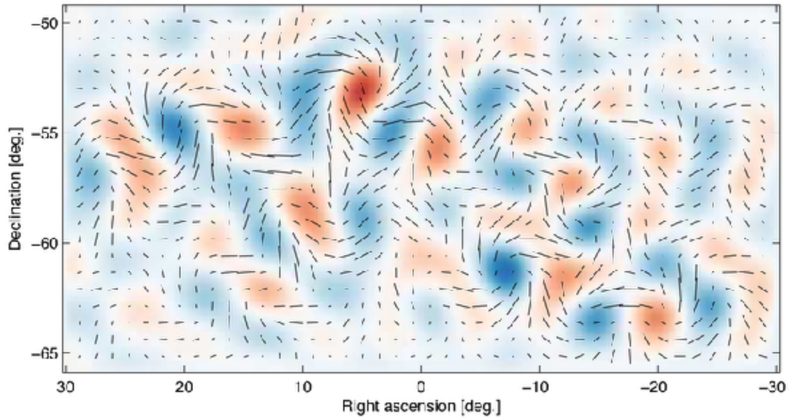
- Neutrino masses
- Matter-antimatter asymmetry
- Dark Matter
- Dark Energy
- Quantum gravity











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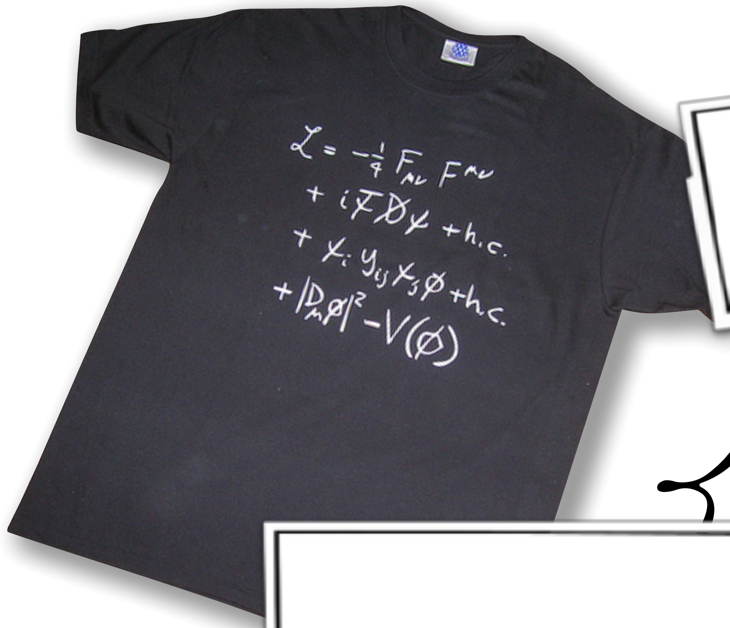

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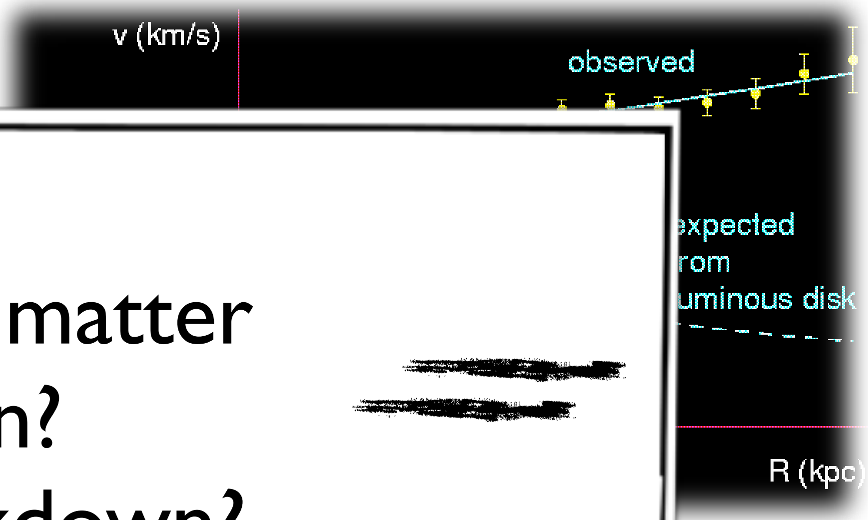
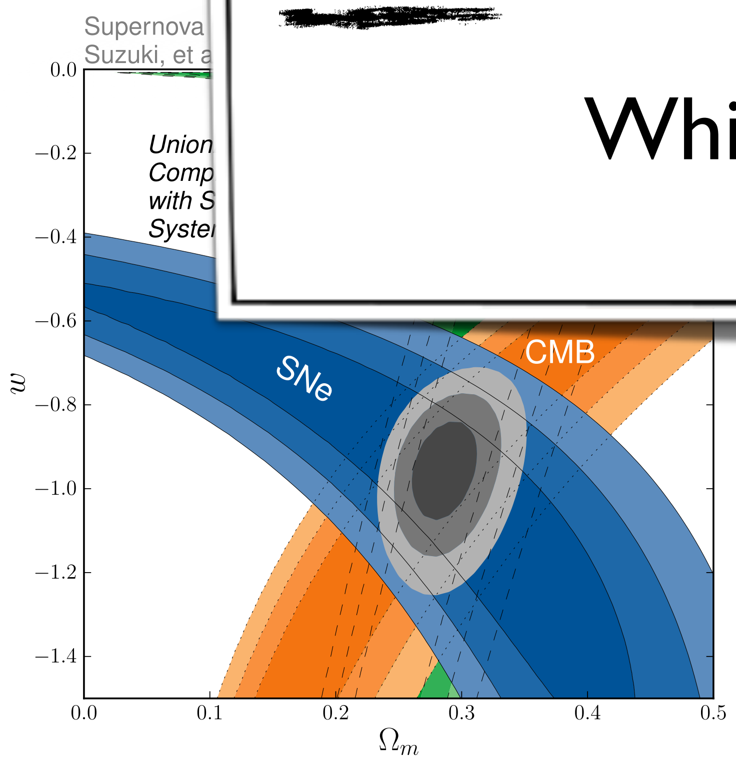
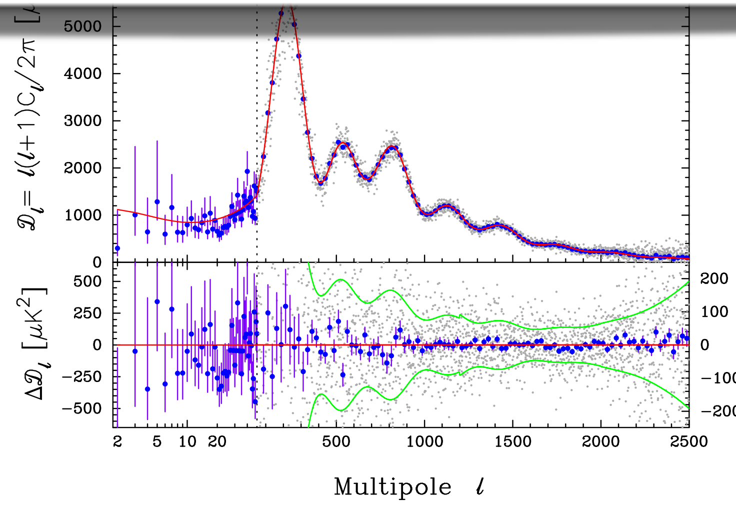
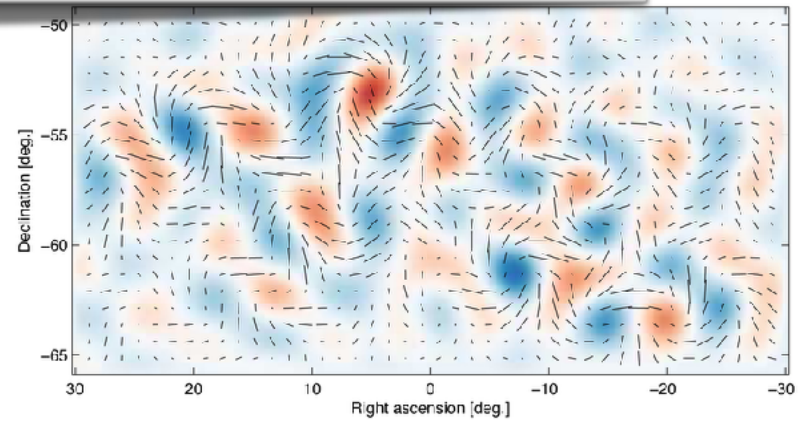


With Higgs boson, SM is self-consistent
but doesn't provide a complete description of matter
Where and how does the SM break down?
Which machine(s) will reveal (best) this breakdown?
Energy Frontier or Intensity Frontier?







Baryon number violation(s)

Why are we expecting B violation(s)?

1) Global symmetry are not consistent with quantum gravity

2) Need to generate matter-antimatter imbalance

3) Why not? Neutral meson oscillations, neutral lepton oscillations (very likely), why not neutral baryon oscillations?

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Selection rule

conservation of angular momentum ⇒ spin of nucleon should be transferred to another fermion

1) $\Delta B=\Delta L$ (nucleon → antilepton)
2) $\Delta B=-\Delta L$ (nucleon → lepton)
3) $\Delta L=\pm 2$ ($0\nu\beta\beta$)
4) $\Delta B=\pm 2$ (nn oscillations)

EW Baryogenesis?

Strong bounds on proton decay → BNV at high scale?

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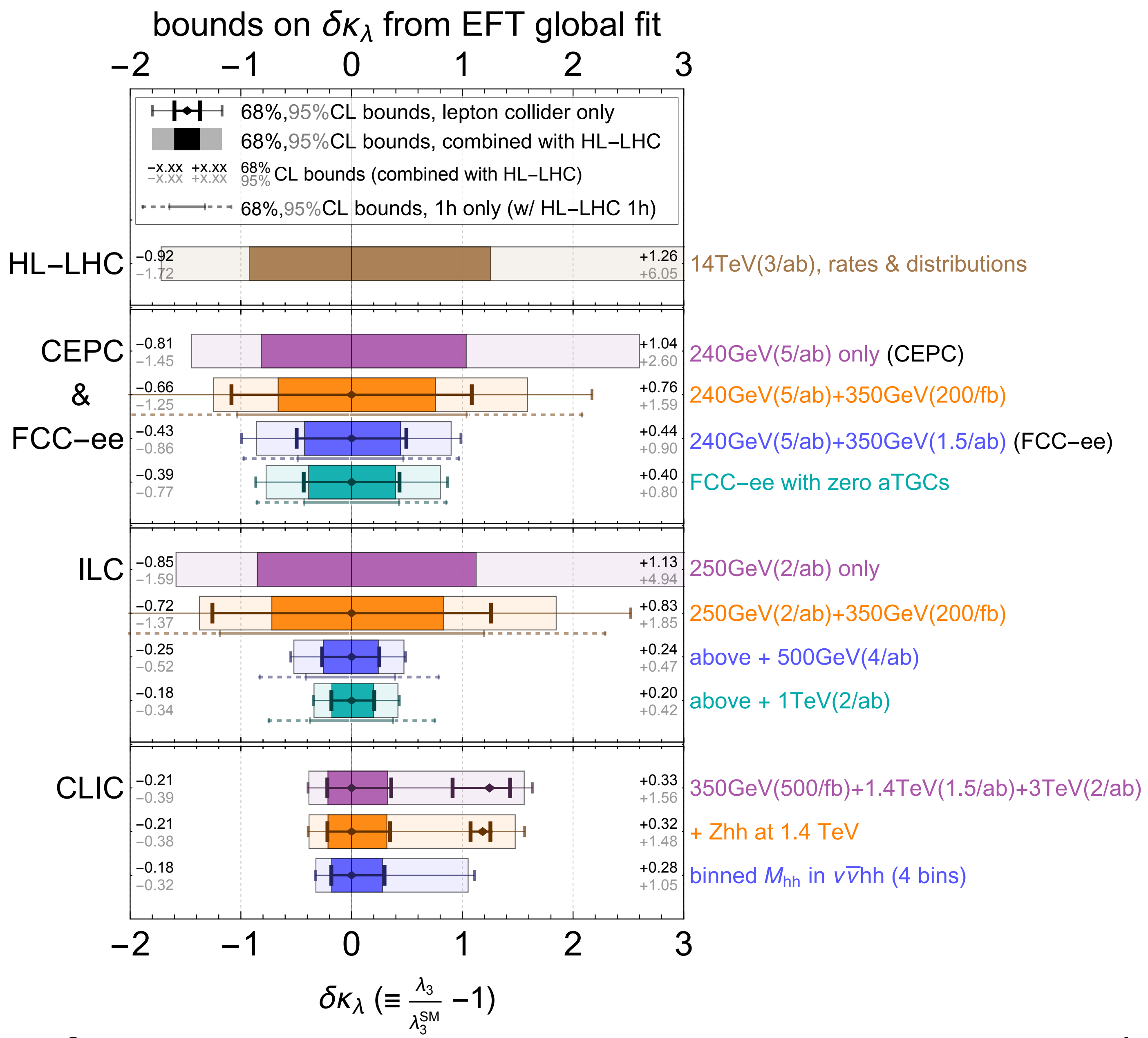

S. Di Vita+ '17

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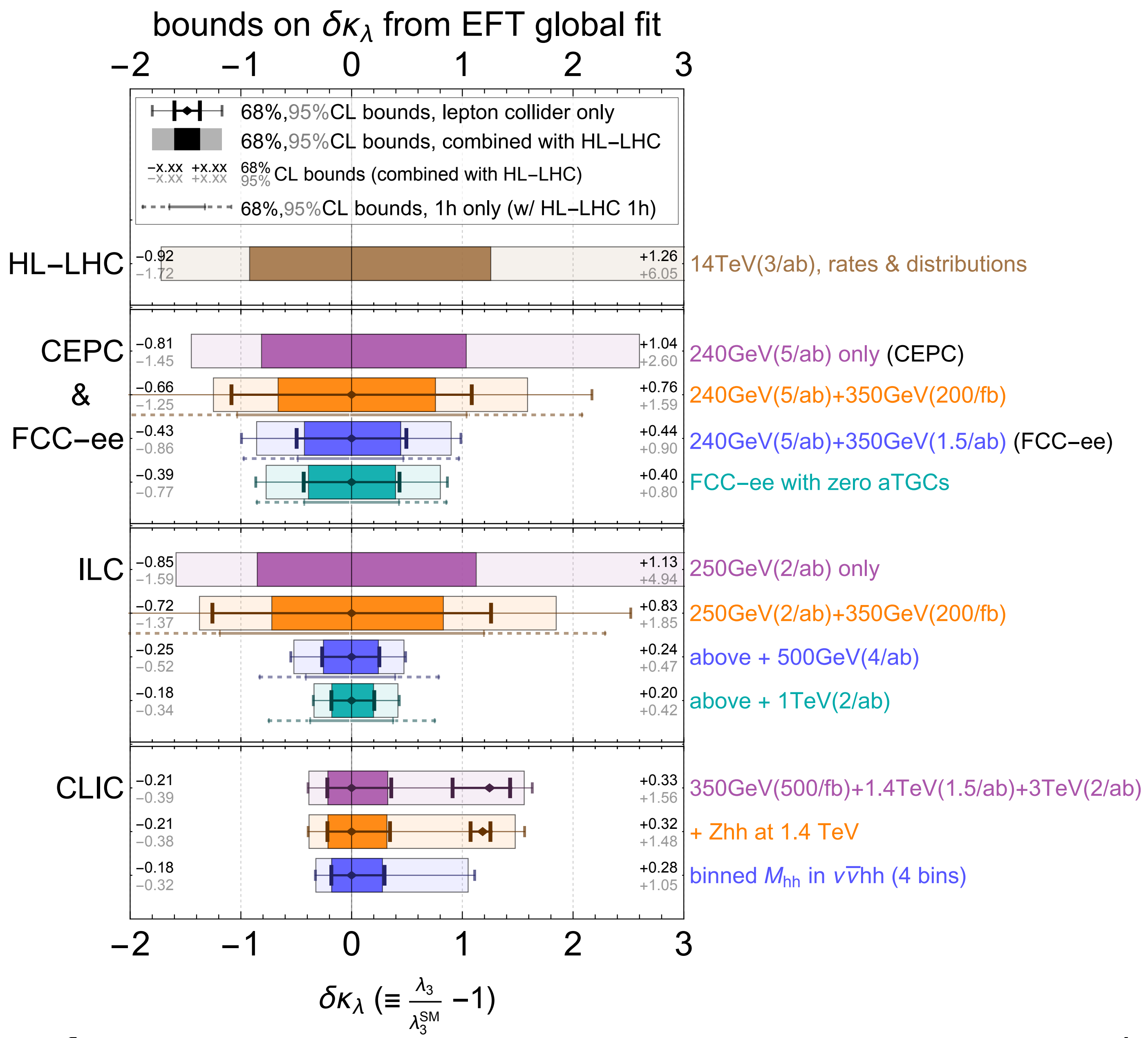
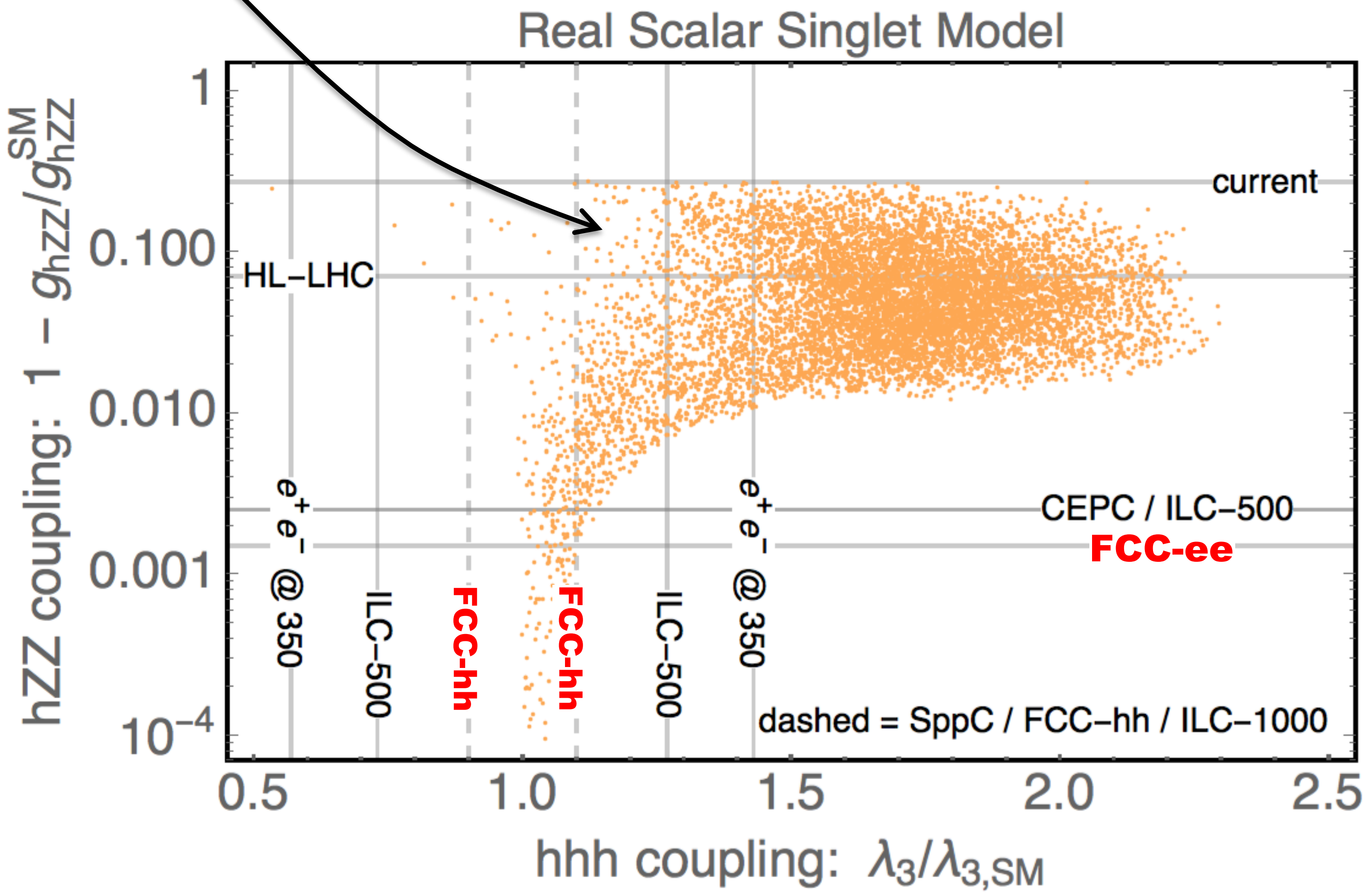


EWPT is 1st order giving rise to GW stochastic background



Huang, Long, Wang '16

(Flavourfull) EW Baryogenesis?

Electroweak baryogenesis requires:

- A strong first order phase transition
- Sufficient CP violation

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These negative results are tied to the fact that
Yukawa couplings during EW phase transition are identical the ones afterwards
What if they were larger?
E.g. flavor structure emerges during the EW transition

Berkooz, Nir, Volansky '04

Baldes, Konstandin, Servant '16

$$y_{ij} \bar{f}_L^i H f_R^j \quad \Rightarrow \quad y_{ij} \left(\frac{\chi}{M}\right)^{q_H+q_j-q_i} \bar{f}_L^i H f_R^j$$

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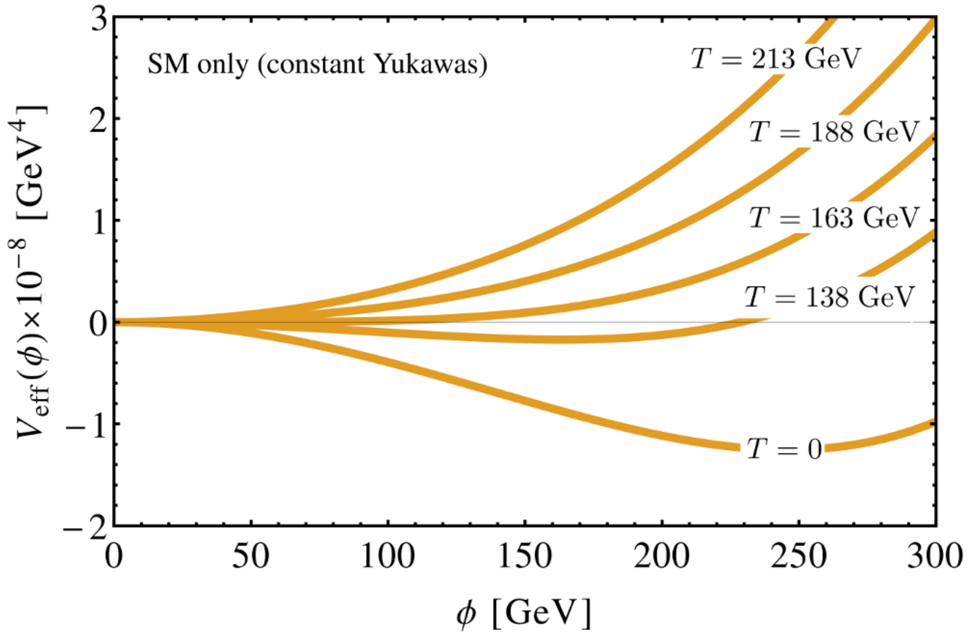
traditionally, M » v and χ is frozen during EWSB

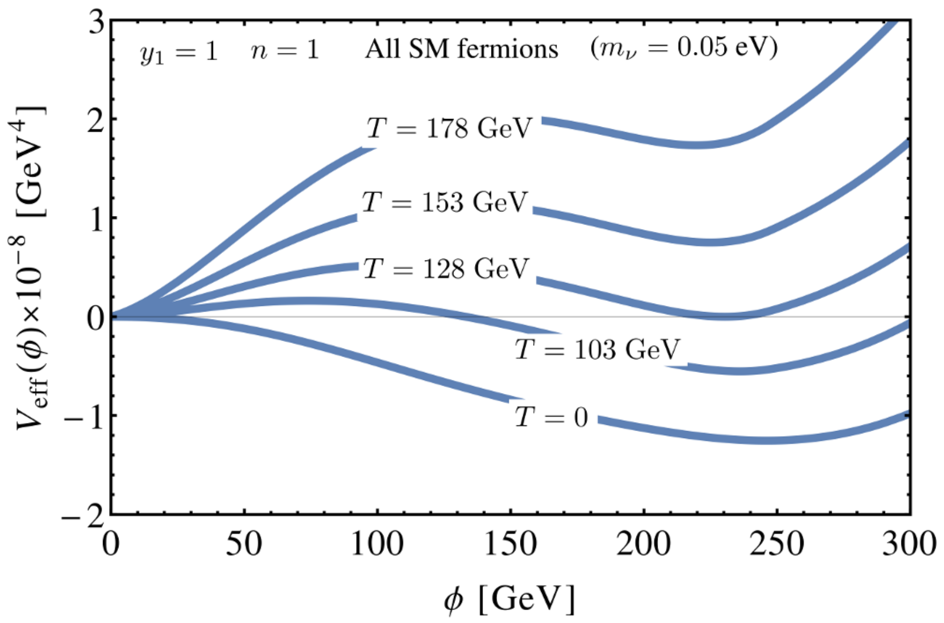
lowering M and allowing χ to vary leads to totally different phenomenology

EW scale flavons for EW baryogenesis

Baldes, Konstandin, Servant '16

$$y(\phi) = \begin{cases} y_1 \left(1 - \left[\frac{\phi}{v}\right]^n\right) + y_0 & \text{for} \quad \phi \le v, \\ y_0 & \text{for} \quad \phi \ge v. \end{cases}$$





The evolution of the effective potential with temperature in the SM (left) and with varying Yukawas (right) The varying Yukawa calculation includes all SM fermions with y1=1, n=1 and their respective y0, chosen to return the observed fermion masses today (the neutrinos are assumed to have a Dirac m=0.05eV).

In the varying Yukawa case, there is a first-order phase transition with ϕ_c=230GeV and T_C=128GeV (vs. second order transition at T_C=163GeV for the constant Yukawa case).

1st order phase transition + enhanced source of CP

Composite Higgs EW baryogenesis

Bruggisser, von Harling, Matsedonskyi, Servant ’18

$$V^0[h] \,=\, \alpha^0 \sin^2\left(\frac{h}{f}\right) \,+\, \beta^0 \sin^4\left(\frac{h}{f}\right)$$

$v \ll f$ → tuning: $\alpha_0 = (v^2/f^2)\beta_0$

exp. data: $v^2/f^2 \lesssim 0.1$

NEW: We promote f to a dynamical field χ (the dilaton);

<χ>=f today

⬇

$$\alpha[\chi] = c_\alpha \frac{3y^2[\chi]g_*^2}{(4\pi)^2} f^4, \quad \beta[\chi] = c_\beta \frac{3y^2[\chi]g_*^2}{(4\pi)^2} f^4 \left(\frac{y[\chi]}{g_*}\right)^{p_\beta}$$

⬇

Non-trivial Higgs-dilaton interplay

To be probed at **Energy Frontier** (LHC, ILC, FCC…)

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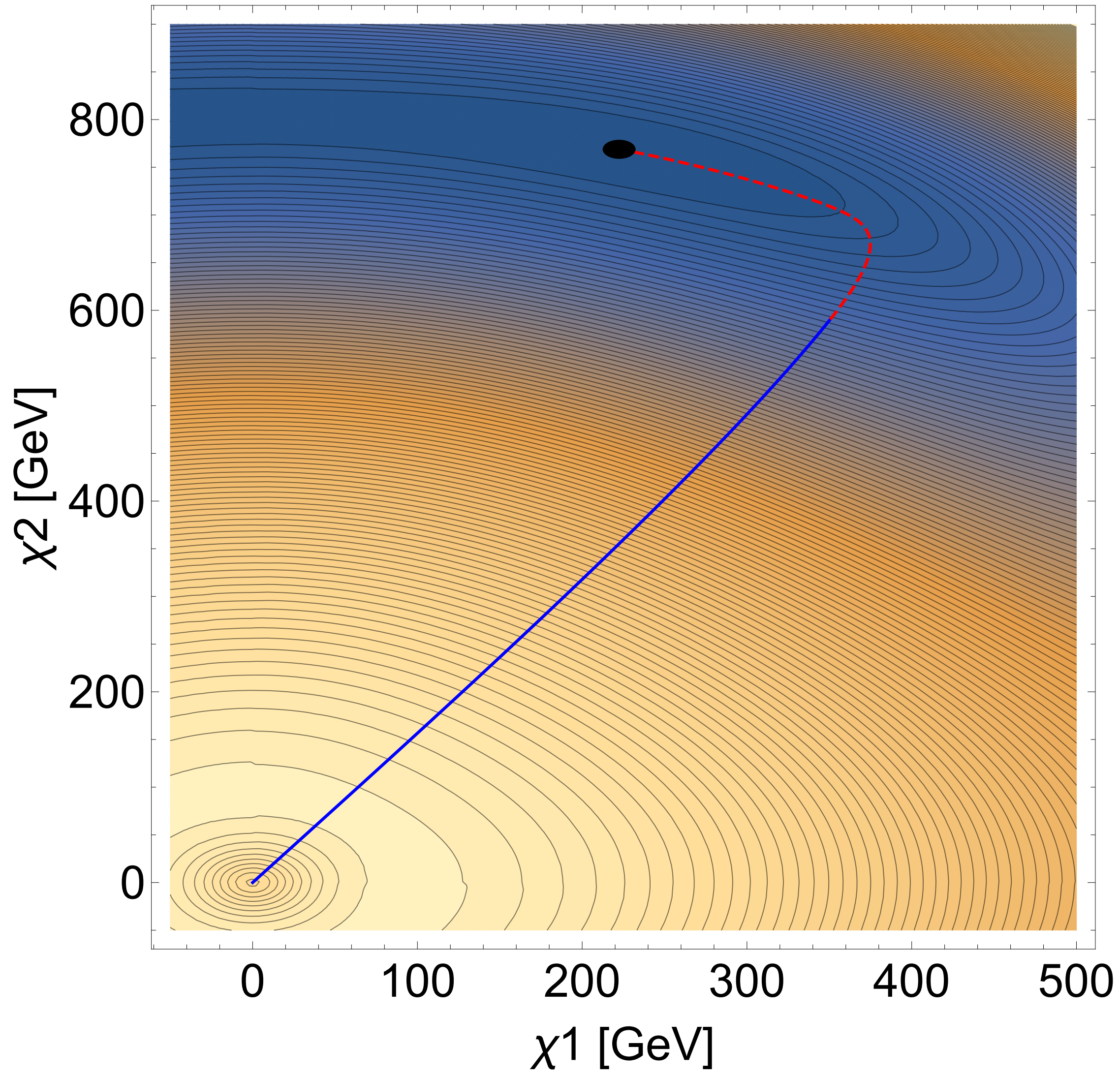

$$\chi_1 = \chi \sin\left(\frac{h}{\chi}\right)$$

$$\chi_2 = \chi \cos\left(\frac{h}{\chi}\right)$$

tunneling

rolling

To be probed at **Energy Frontier** (LHC, ILC, FCC…)

CP violation for EW baryogenesis

In addition to out-of-equilibrium dynamics, extra sources of **CP-violation** beyond CKM are needed, e.g.

To be searched for at **Energy Frontier**
(LHC, ILC, FCC…)

- Charginos/neutralinos/sfermions (MSSM)

Cline et al,
Carena et al,
Chung et al…

- **Varying phase in effective Top quark Yukawa:**

SM+singlet (Fromme-Huber)

Composite Higgs (Espinosa, Gripaios, Konstandin, Riva)

2-Higgs doublet model (Konstandin et al, Cline et al)

- Two recent alternatives:

strong CP QCD axion (Servant '15)
CP in DM sector (e.g. Cline'17)

High Scale Baryogenesis?

In high-scale baryogenesis scenarios, B-L is likely to be broken
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	Mode	Partial mean life (10^{30} years)	Confidence level
	Antilepton + meson		
τ_1	$N \to e^+\pi$	> 2000 (n), > 8200 (p)	90%
τ_2	$N \to \mu^+\pi$	> 1000 (n), > 6600 (p)	90%
τ_3	$N \to \nu\pi$	> 1100 (n), > 390 (p)	90%
τ_4	$p \to e^+\eta$	> 4200	90%
τ_5	$p \to \mu^+\eta$	> 1300	90%
τ_6	$n \to \nu\eta$	> 158	90%
τ_7	$N \to e^+\rho$	> 217 (n), > 710 (p)	90%
τ_8	$N \to \mu^+\rho$	> 228 (n), > 160 (p)	90%
τ_9	$N \to \nu\rho$	> 19 (n), > 162 (p)	90%
τ_{10}	$p \to e^+\omega$	> 320	90%
τ_{11}	$p \to \mu^+\omega$	> 780	90%
τ_{12}	$n \to \nu\omega$	> 108	90%
τ_{13}	$N \to e^+K$	> 17 (n), > 1000 (p)	90%
τ_{14}	$p \to e^+K^0_S$		
τ_{15}	$p \to e^+K^0_L$		
τ_{16}	$N \to \mu^+K$	> 26 (n), > 1600 (p)	90%
τ_{17}	$p \to \mu^+K^0_S$		
τ_{18}	$p \to \mu^+K^0_L$		
τ_{19}	$N \to \nu K$	> 86 (n), > 5900 (p)	90%
τ_{20}	$n \to \nu K^0_S$	> 260	90%
τ_{21}	$p \to e^+K^*(892)^0$	> 84	90%
τ_{22}	$N \to \nu K^*(892)$	> 78 (n), > 51 (p)	90%
	Antilepton + mesons		
τ_{23}	$p \to e^+\pi^+\pi^-$	> 82	90%
τ_{24}	$p \to e^+\pi^0\pi^0$	> 147	90%
τ_{25}	$n \to e^+\pi^-\pi^0$	> 52	90%
τ_{26}	$p \to \mu^+\pi^+\pi^-$	> 133	90%
τ_{27}	$p \to \mu^+\pi^0\pi^0$	> 101	90%
τ_{28}	$n \to \mu^+\pi^-\pi^0$	> 74	90%
τ_{29}	$n \to e^+K^0\pi^-$	> 18	90%

ΔB=ΔL=1 decay bounds

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τ_{30}	$n \to e^-\pi^+$	> 65	90%
τ_{31}	$n \to \mu^-\pi^+$	> 49	90%
τ_{32}	$n \to e^-\rho^+$	> 62	90%
τ_{33}	$n \to \mu^-\rho^+$	> 7	90%
τ_{34}	$n \to e^-K^+$	> 32	90%
τ_{35}	$n \to \mu^-K^+$	> 57	90%
	Lepton + mesons		
τ_{36}	$p \to e^-\pi^+\pi^+$	> 30	90%
τ_{37}	$n \to e^-\pi^+\pi^0$	> 29	90%
τ_{38}	$p \to \mu^-\pi^+\pi^+$	> 17	90%
τ_{39}	$n \to \mu^-\pi^+\pi^0$	> 34	90%
τ_{40}	$p \to e^-\pi^+K^+$	> 75	90%
τ_{41}	$p \to \mu^-\pi^+K^+$	> 245	90%

ΔB=-ΔL=1 decay bounds

	Mode	Partial mean life (10^{30} years)	Confidence level
τ_{66}	$pp \to \pi^+\pi^+$	> 72.2	90%
τ_{67}	$pn \to \pi^+\pi^0$	> 170	90%
τ_{68}	$nn \to \pi^+\pi^-$	> 0.7	90%
τ_{69}	$nn \to \pi^0\pi^0$	> 404	90%
τ_{70}	$pp \to K^+K^+$	> 170	90%
τ_{71}	$pp \to e^+e^+$	> 5.8	90%
τ_{72}	$pp \to e^+\mu^+$	> 3.6	90%
τ_{73}	$pp \to \mu^+\mu^+$	> 1.7	90%
τ_{74}	$pn \to e^+\overline{\nu}$	> 260	90%
τ_{75}	$pn \to \mu^+\overline{\nu}$	> 200	90%
τ_{76}	$pn \to \tau^+\overline{\nu}_\tau$	> 29	90%
τ_{77}	$nn \to \nu_e\overline{\nu}_e$	> 1.4	90%
τ_{78}	$nn \to \nu_\mu\overline{\nu}_\mu$	> 1.4	90%
τ_{79}	$pn \to$ invisible	$> 2.1 \times 10^{-5}$	90%
τ_{80}	$pp \to$ invisible	$> 5 \times 10^{-5}$	90%

ΔB=2/ΔL=0 decay bounds*

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τ_{78}	$nn \to \nu_\mu\overline{\nu}_\mu$	> 1.4	90%
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τ_{80}	$pp \to$ invisible	$> 5 \times 10^{-5}$	90%

ΔB=2/ΔL=0 decay bounds*

*For flavour universal models, $n\bar{n}$ gives the strongest constraints. For other flavour setups (e.g. MFV-RPV susy), dinucleon decays might win

High Scale Baryogenesis?

In high-scale baryogenesis scenarios, B-L is likely to be broken
Otherwise any B asymmetry created above EWSB scale is wiped out by active EW sphalerons

No opportunities, new signatures
Colliders are not necessarily the best probes anymore

	Mode	Partial mean life (10^{30} years)	Confidence level
	Antilepton + meson		
τ_1	$N \to e^+\pi$	$> 2000\ (n),\ > 8200\ (p)$	90%
τ_2	$N \to \mu^+\pi$	$> 1000\ (n),\ > 6600\ (p)$	90%
τ_3	$N \to \nu\pi$	$> 1100\ (n),\ > 390\ (p)$	90%
τ_4	$p \to e^+\eta$	> 4200	90%
τ_5	$p \to \mu^+\eta$	> 1300	90%
τ_6	$n \to \nu\eta$	> 158	90%
τ_7	$N \to e^+\rho$	$> 217\ (n),\ > 710\ (p)$	90%
τ_8	$N \to \mu^+\rho$	$> 228\ (n),\ > 160\ (p)$	90%
τ_9	$N \to \nu\rho$	$> 19\ (n),\ > 162\ (p)$	90%
τ_{10}	$p \to e^+\omega$	> 320	90%
τ_{11}	$p \to \mu^+\omega$	> 780	90%
τ_{12}	$n \to \nu\omega$	> 108	90%
τ_{13}	$N \to e^+K$	$> 17\ (n),\ > 1000\ (p)$	90%
τ_{14}	$p \to e^+K^0_S$		
τ_{15}	$p \to e^+K^0_L$		
τ_{16}	$N \to \mu^+K$	$> 26\ (n),\ > 1600\ (p)$	90%
τ_{17}	$p \to \mu^+K^0_S$		
τ_{18}	$p \to \mu^+K^0_L$		
τ_{19}	$N \to \nu K$	$> 86\ (n),\ > 5900\ (p)$	90%
τ_{20}	$n \to \nu K^0_S$	> 260	90%
τ_{21}	$p \to e^+K^*(892)^0$	> 84	90%
τ_{22}	$N \to \nu K^*(892)$	$> 78\ (n),\ > 51\ (p)$	90%
	Antilepton + mesons		
τ_{23}	$p \to e^+\pi^+\pi^-$	> 82	90%
τ_{24}	$p \to e^+\pi^0\pi^0$	> 147	90%
τ_{25}	$n \to e^+\pi^-\pi^0$	> 52	90%
τ_{26}	$p \to \mu^+\pi^+\pi^-$	> 133	90%
τ_{27}	$p \to \mu^+\pi^0\pi^0$	> 101	90%
τ_{28}	$n \to \mu^+\pi^-\pi^0$	> 74	90%
τ_{29}	$n \to e^+K^0\pi^-$	> 18	90%

ΔB=ΔL=1 decay bounds

	Mode	Partial mean life (10^{30} years)	Confidence level
	Lepton + meson		
τ_{30}	$n \to e^-\pi^+$	> 65	90%
τ_{31}	$n \to \mu^-\pi^+$	> 49	90%
τ_{32}	$n \to e^-\rho^+$	> 62	90%
τ_{33}	$n \to \mu^-\rho^+$	> 7	90%
τ_{34}	$n \to e^-K^+$	> 32	90%
τ_{35}	$n \to \mu^-K^+$	> 57	90%
	Lepton + mesons		
τ_{36}	$p \to e^-\pi^+\pi^+$	> 30	90%
τ_{37}	$n \to e^-\pi^+\pi^0$	> 29	90%
τ_{38}	$p \to \mu^-\pi^+\pi^+$	> 17	90%
τ_{39}	$n \to \mu^-\pi^+\pi^0$	> 34	90%
τ_{40}	$p \to e^-\pi^+K^+$	> 75	90%
τ_{41}	$p \to \mu^-\pi^+K^+$	> 245	90%

ΔB=-ΔL=1 decay bounds

	Mode	Partial mean life (10^{30} years)	Confidence level
τ_{66}	$pp \to \pi^+\pi^+$	> 72.2	90%
τ_{67}	$pn \to \pi^+\pi^0$	> 170	90%
τ_{68}	$nn \to \pi^+\pi^-$	> 0.7	90%
τ_{69}	$nn \to \pi^0\pi^0$	> 404	90%
τ_{70}	$pp \to K^+K^+$	> 170	90%
τ_{71}	$pp \to e^+e^+$	> 5.8	90%
τ_{72}	$pp \to e^+\mu^+$	> 3.6	90%
τ_{73}	$pp \to \mu^+\mu^+$	> 1.7	90%
τ_{74}	$pn \to e^+\overline{\nu}$	> 260	90%
τ_{75}	$pn \to \mu^+\overline{\nu}$	> 200	90%
τ_{76}	$pn \to \tau^+\overline{\nu}_\tau$	> 29	90%
τ_{77}	$nn \to \nu_e\overline{\nu}_e$	> 1.4	90%
τ_{78}	$nn \to \nu_\mu\overline{\nu}_\mu$	> 1.4	90%
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ΔB=2/ΔL=0 decay bounds*

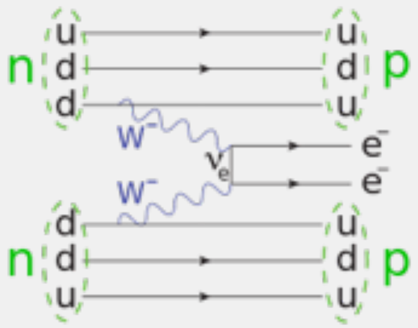
*For flavour universal models, $n\bar{n}$ gives the strongest constraints. For other flavour setups (e.g. MFV-RPV susy), dinucleon decays might win

Pattern of B violation in SM(EFT)

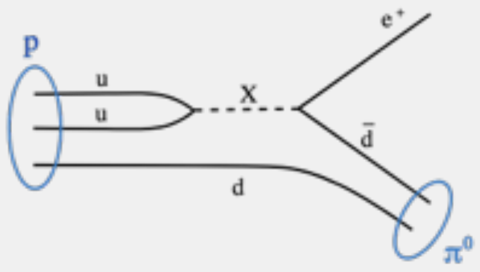
A. Kobach '16

$\mathcal{L}$ =	$\mathcal{L}_{SM}$	+ dim-5	+ dim-6	+ dim-7	+ dim-8	+ dim-9 + …
allowed (ΔB, ΔL)	(0, 0)	**(0, 2)**	(0, 0), **(1, 1)**	(0, 2), (1, -1)	(0, 0), (1, 1)	**(2, 0)**, (1, -1), (0, 2), (1, 3)

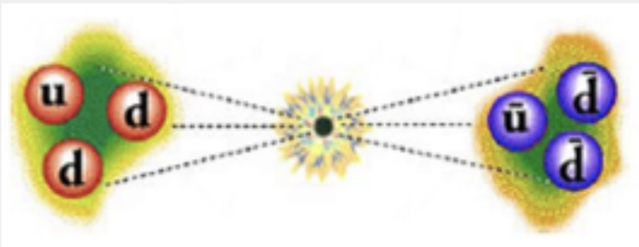
$0\nu\beta\beta$ decay



proton decays



neutron-antineutron oscillation



Slide stolen to Z. Zhang @ Pascos'18

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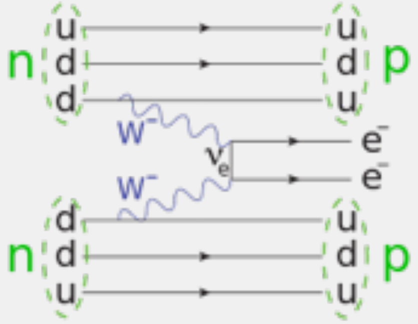

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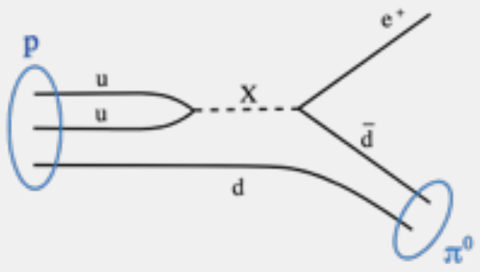

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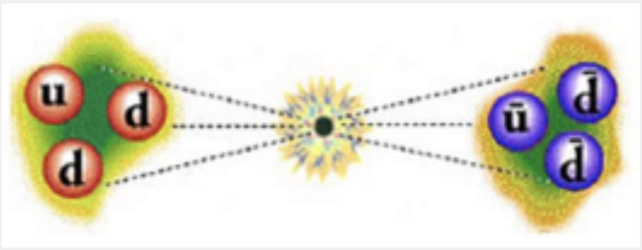

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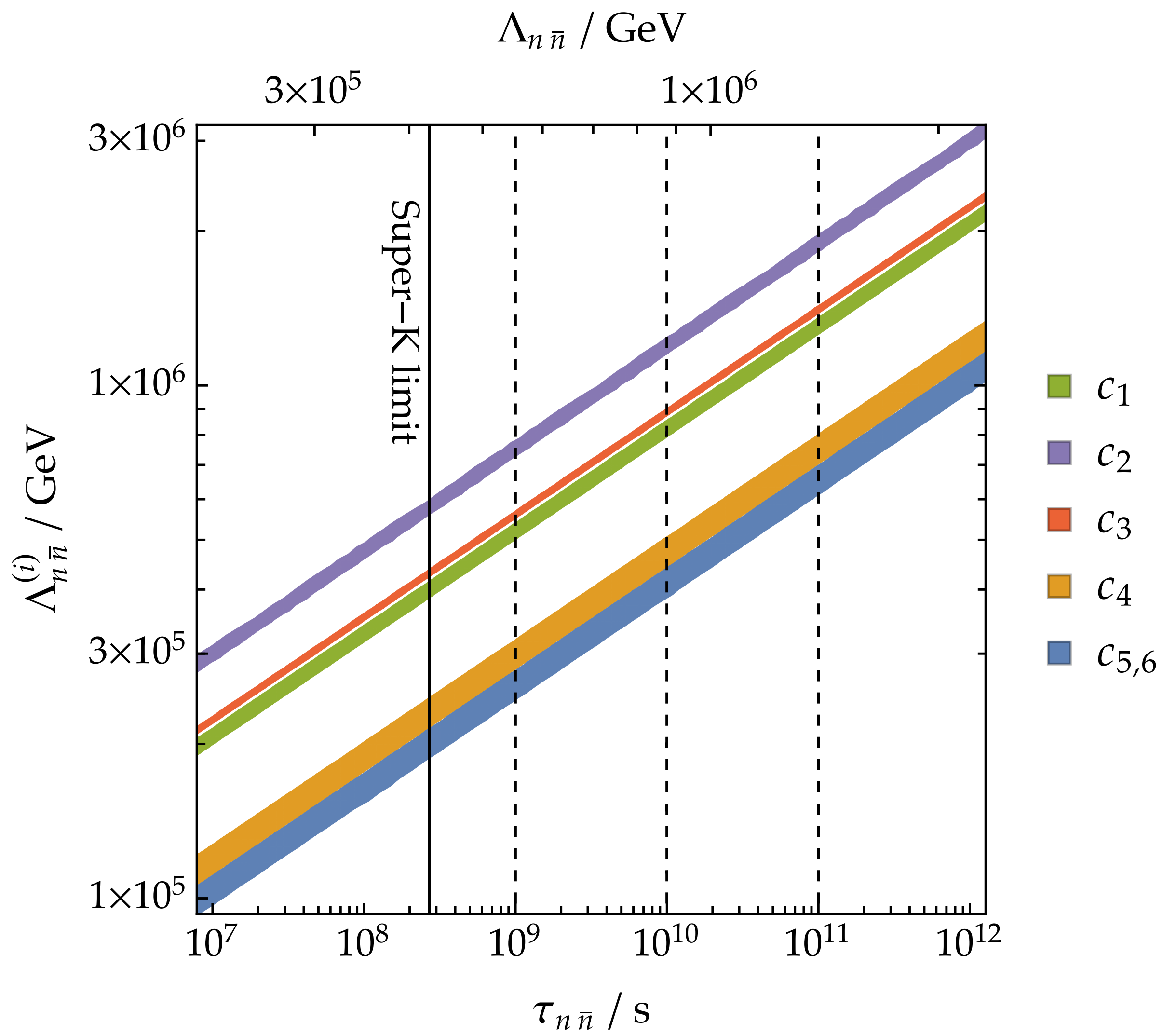
12 operators (of the type 'uudddd')

$$\tau_{n\bar{n}}^{-1} = \left|\langle \bar{n} | \mathcal{H}_{\rm eff} | n \rangle\right|$$

SuperK/ESS, DUNE is/will probe scales 10^5-10^6 GeV

$\Lambda \sim \tau^{-1/5}$: 1 order of magnitude improvement on $\tau \leftrightarrow$ mere 1.5 improvement on Λ

Width of bands:
current lattice calculation uncertainty
(including syst. effects of excited states)
[Rinaldi et al '18]

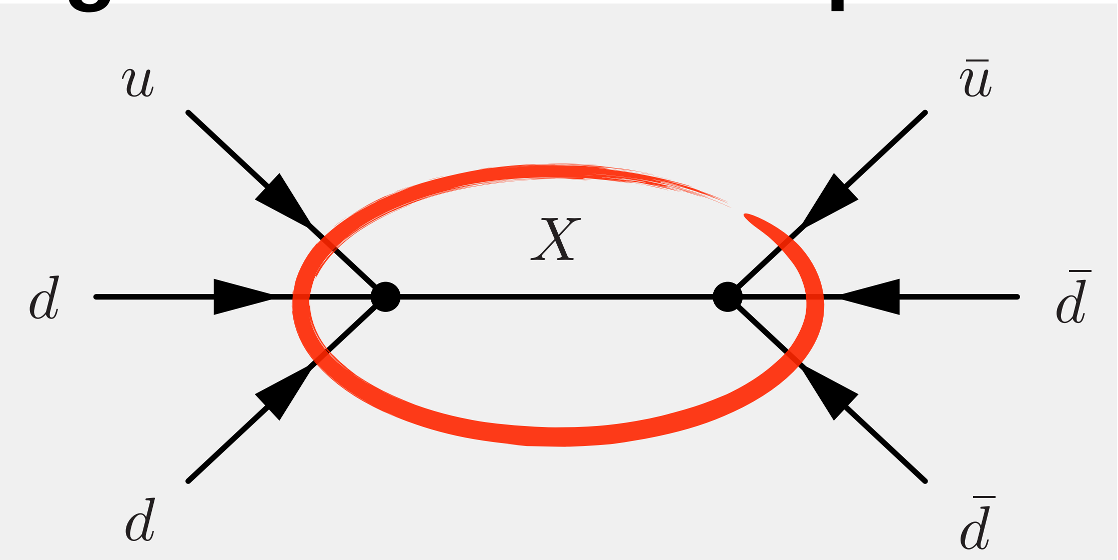


Grojean, Shakya, Wells, Zhang '18

$n\bar{n}$ Oscillations and Baryogenesis

Grojean, Shakya, Wells, Zhang '18

Origin of dim-9 BNV operator?



X=Majorana fermion, e.g. RPV bino
(here SM neutral)

Mediator X

X **decays** cannot generate a baryon asymmetry at leading order in the B violating coupling (Nanopoulos-Weinberg theorem '1979)

2→2 **scattering** doesn't work either

($\mathcal{M}_{uX\to d\bar{d}} = \mathcal{M}_{\bar{u}X\to dd}$)

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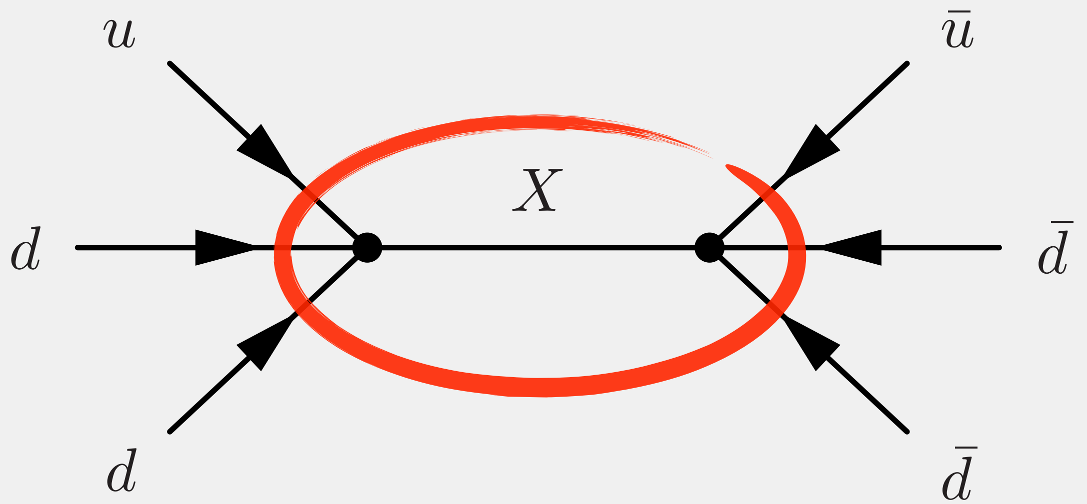

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$$\left(\mathcal{M}_{uX\to d\bar{d}} = \mathcal{M}_{\bar{u}X\to dd} \right)$$

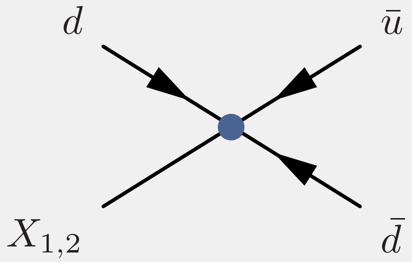
Two mediators X_1, X_2 (M_{X1}<M_{X2})

e.g. RPV bino & gluino

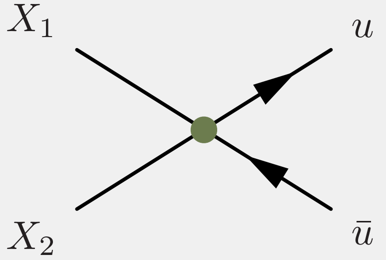
$$\mathcal{L} \supset \eta_{X_1}\, \epsilon^{ijk} (\bar{u}^c_i P_R d_j)(\bar{d}^c_k P_R X_1) + \eta_{X_2}\, \epsilon^{ijk} (\bar{u}^c_i P_R d_j)(\bar{d}^c_k P_R X_2) + \eta_c\, (\bar{u}^i P_L X_1)(\bar{X}_2 P_R u_i) + \text{h.c.}$$

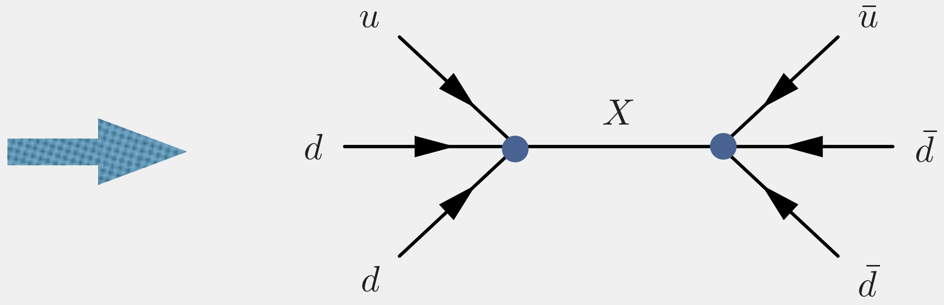
$$|\eta_{X_1}| \equiv \Lambda_{X_1}^{-2}\,,\ |\eta_{X_2}| \equiv \Lambda_{X_2}^{-2}\,,\ |\eta_c| \equiv \Lambda_c^{-2}\,.$$

- 2 *B-violating* operators



- 1 *B-conserving* operator





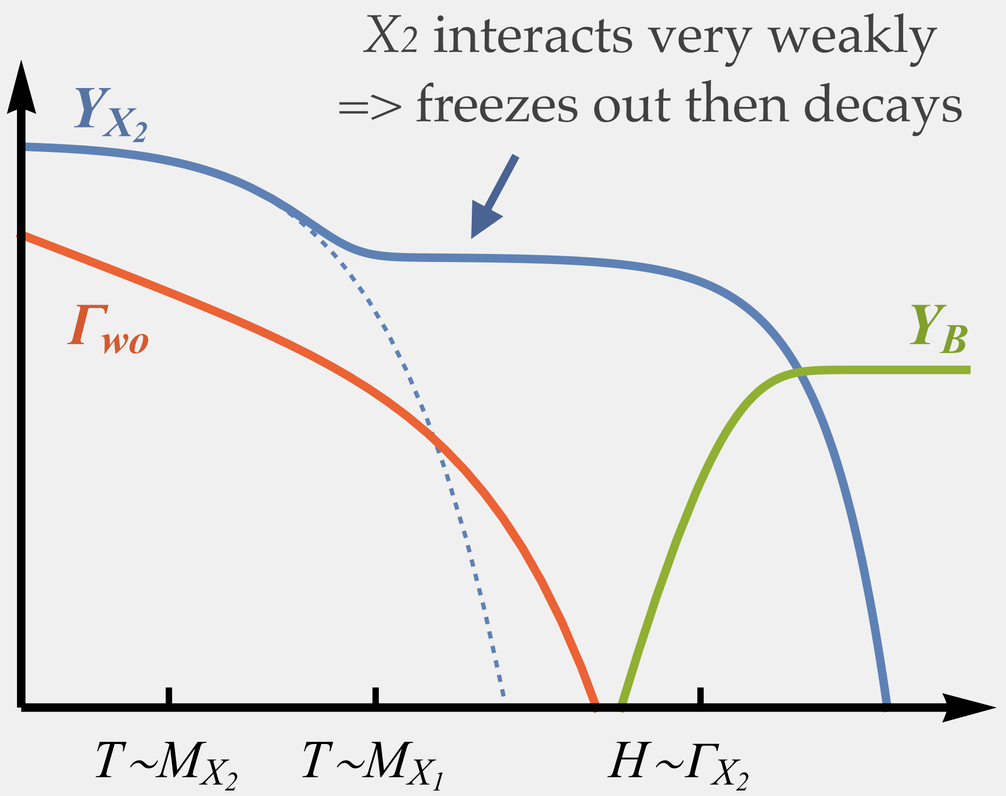
$$c_1 = \frac{1}{\left(\Lambda^{(1)}_{n\bar{n}}\right)^5} = \frac{1}{M_{X_1}\Lambda^4_{X_1}} + \frac{1}{M_{X_2}\Lambda^4_{X_2}}$$

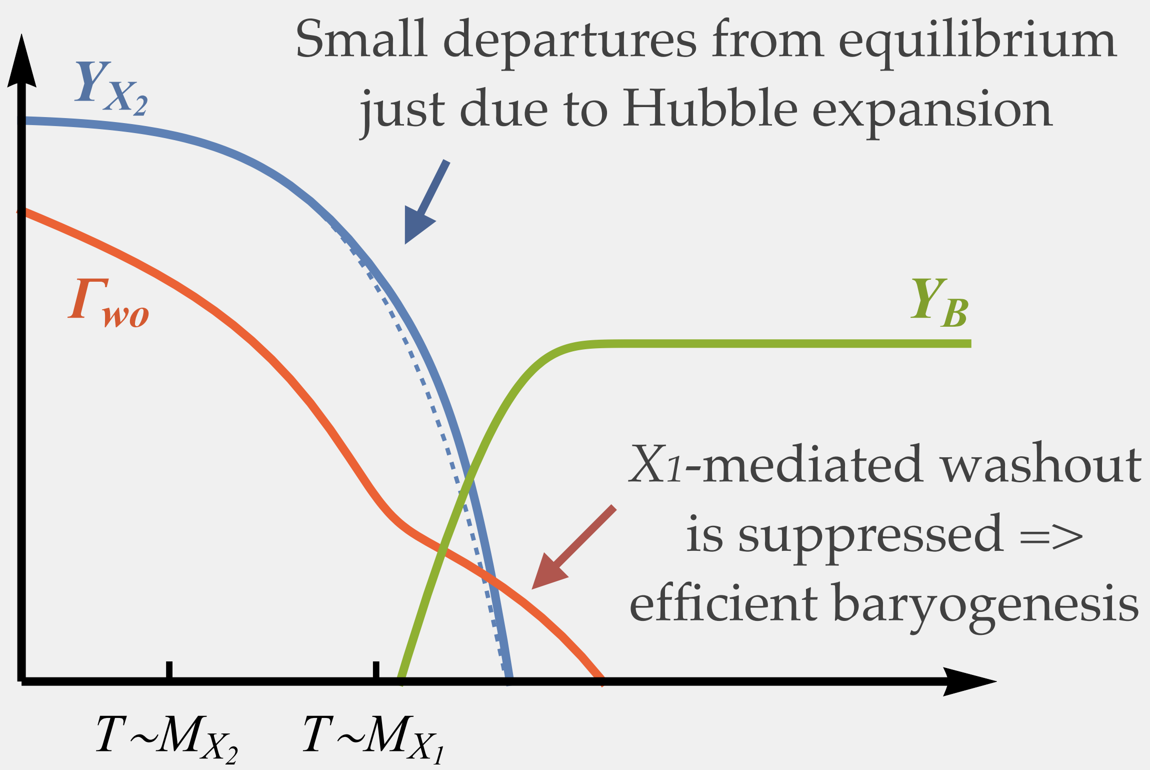
Baryogenesis

Grojean, Shakya, Wells, Zhang '18

Single scale: either too strong (insufficient departure from eq.) or too weak (insuffisant CP violation)

Late decay scenario	Early decay scenario
$\Lambda_{X_2} \sim \Lambda_c \gg \Lambda_{X_1}$	$\Lambda_{X_1} \gg \Lambda_{X_2} \gtrsim \Lambda_c$





nn oscillations dominated by X_1 exchange
X_2 has weaker interactions & freezes-out with larger abundance
X_2 is long-lived and decays after washout

nn oscillations dominated by X_2 exchange
X_2 is short-lived and its abundance is close to eq.
Washout dominated by X_2 becomes inefficient below M_{X2}

Baryogenesis

Grojean, Shakya, Wells, Zhang '18

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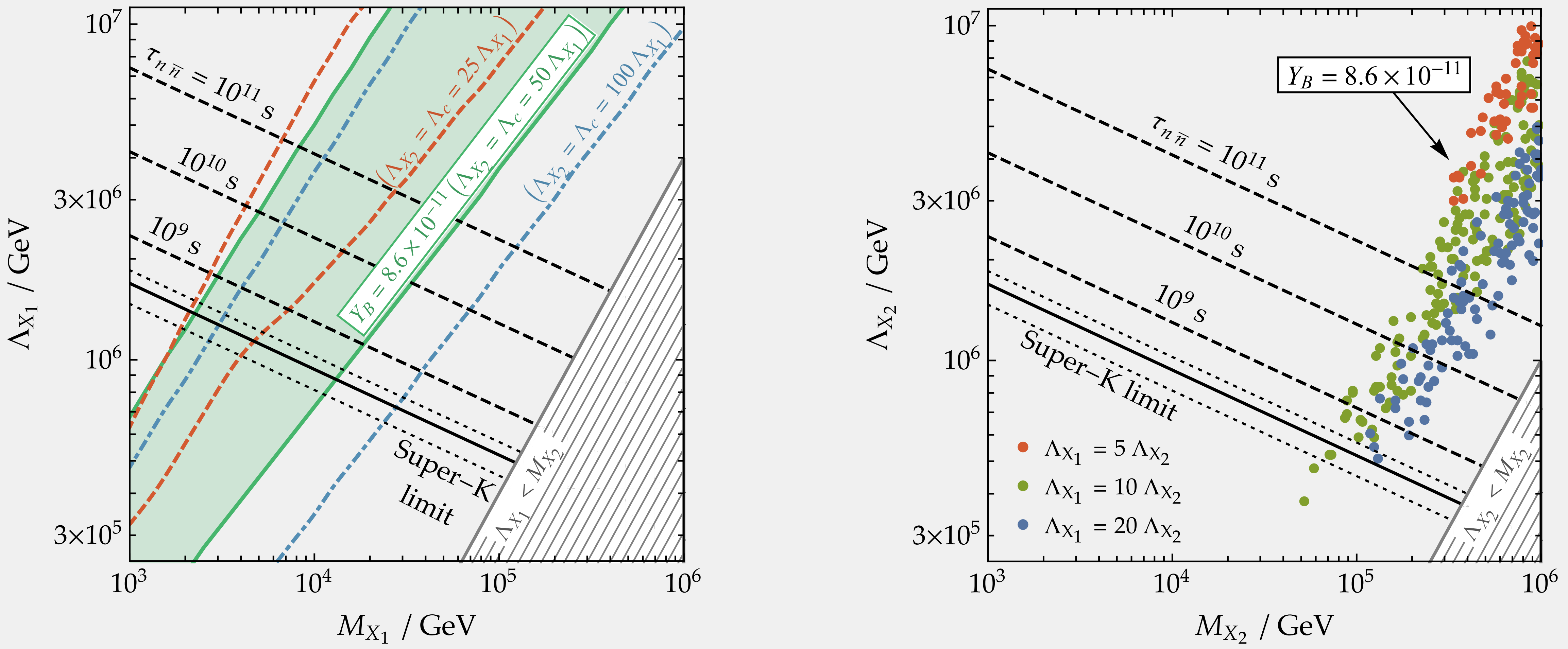

Explicit realisation of late decay scenario: RPV SUSY with late decays of the bino in presence of a wino/gluino
[F.Rompineve, 1310.0840] [Y.Cui, 1309.2952] [G.Arcadi, L.Covi, M.Nardecchia, 1507.05584]

Conclusions

The discovery of the Higgs boson and the absence of new physics at the TeV scale (so far)
are leaving many important questions answers,
starting with puzzling fact that matter took over antimatter.

The answer might come from the observation of susy/composite Higgs at FCC in 2060…
But Nature might have also chosen a different path.
And the matter imbalance might not be related to EW symmetry breaking.

Looking for the neutron oscillations might give answer that powerful colliders would miss.
The exploration of the Intensity Frontier can also teach us about the Energy Frontier.