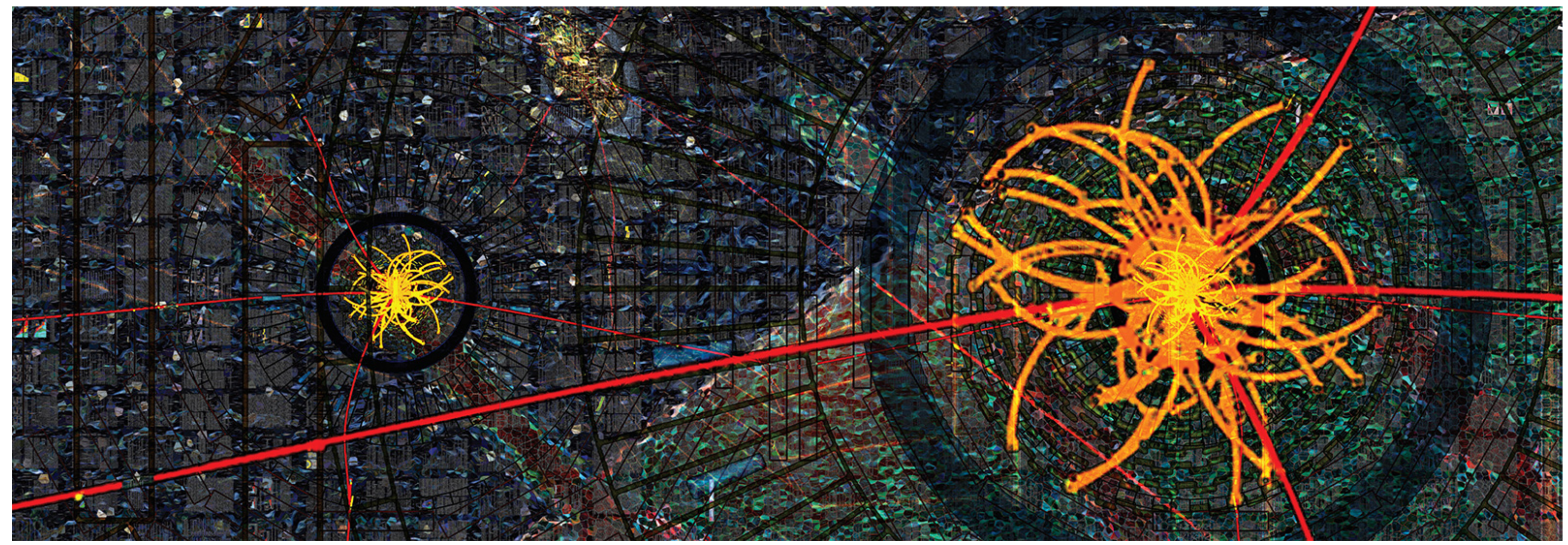
Particle Physics for the Future of Europe



Flavour &
Beyond Standard Model Physics

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Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	–1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	–1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	–1

Quarks spin = 1/2

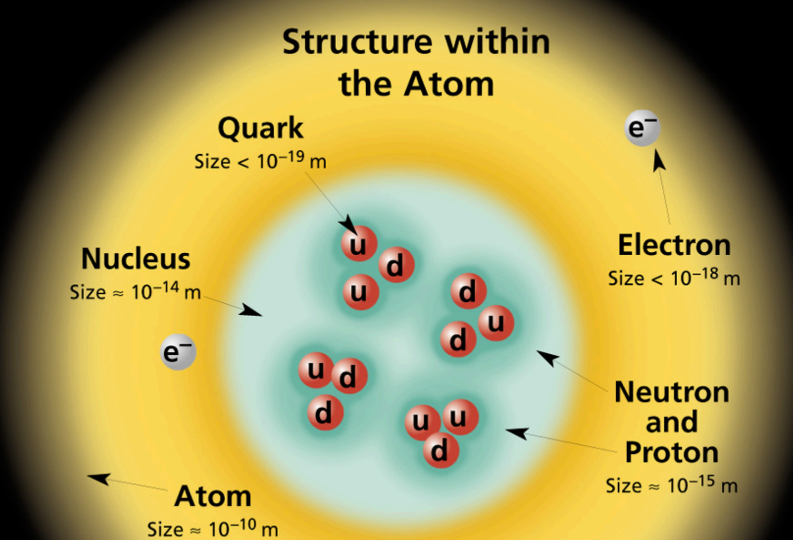
Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	175	2/3
b	bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

Structure within the Atom



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

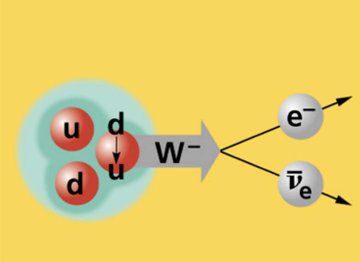
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

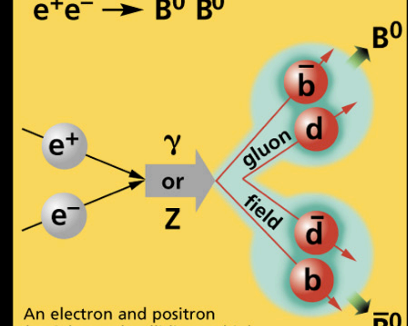
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



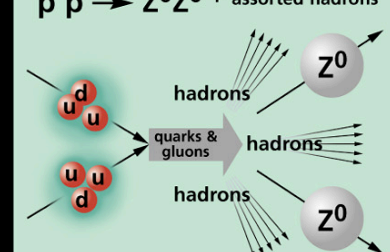
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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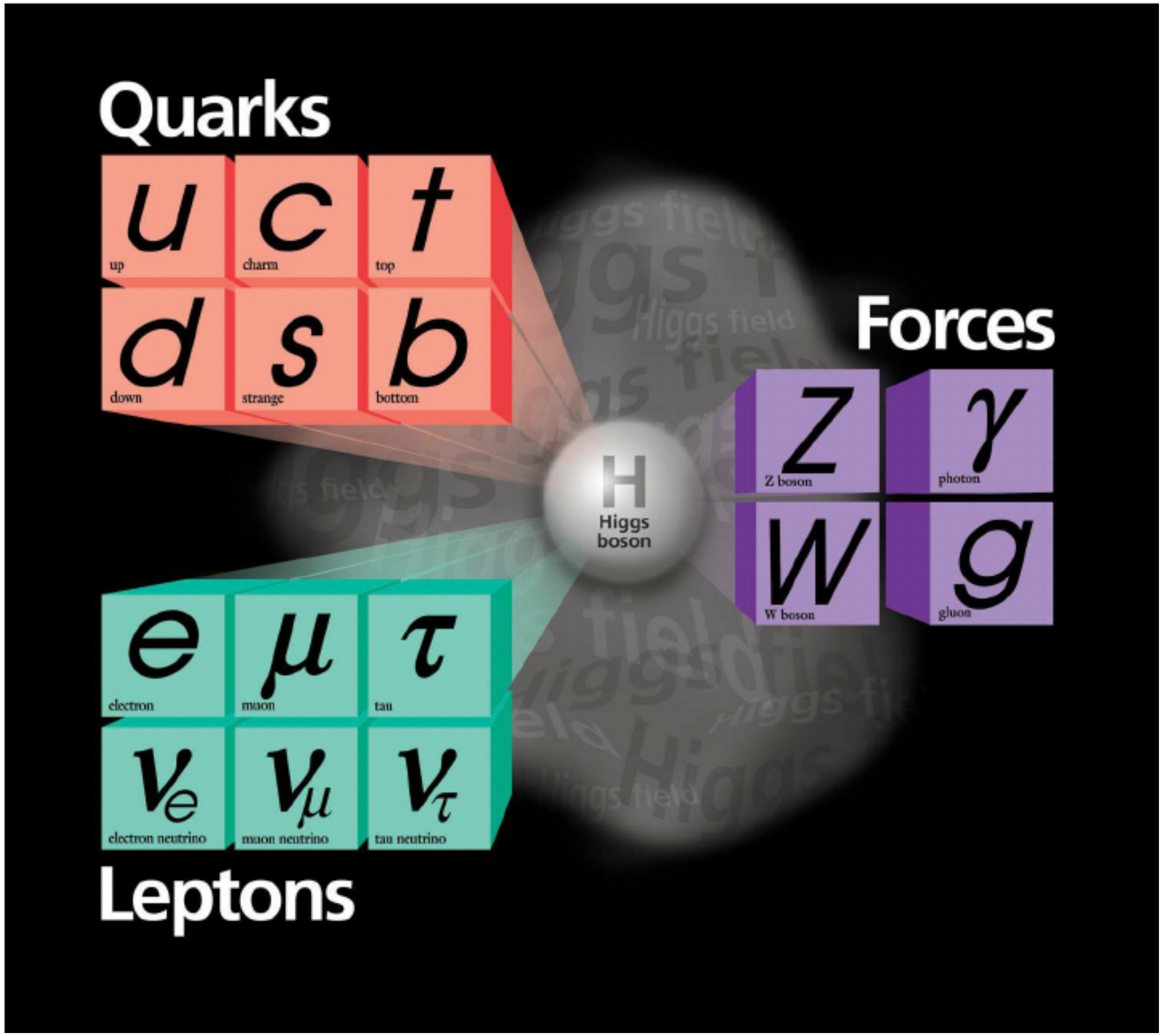
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://CPEPweb.org

Flavour Sector



Strong and

Electroweak

Sector

Flavour Sector

Higgs Sector

Quarks are not free in nature, they have fractional charges and always appear in bound states of integer charge (or zero charge) which are singlets of an SU(3) symmetry:

Mesons: combinations of one quark and one-anti-quark. For example:

pions: u, d quark and anti-quark

kaons: s (anti)-quark with u or d quark or anti-quark

D mesons: c (anti)-quark with u, d or s quark or anti-quark

B mesons: b (anti)-quark with u, d, s, c quark or anti-quark

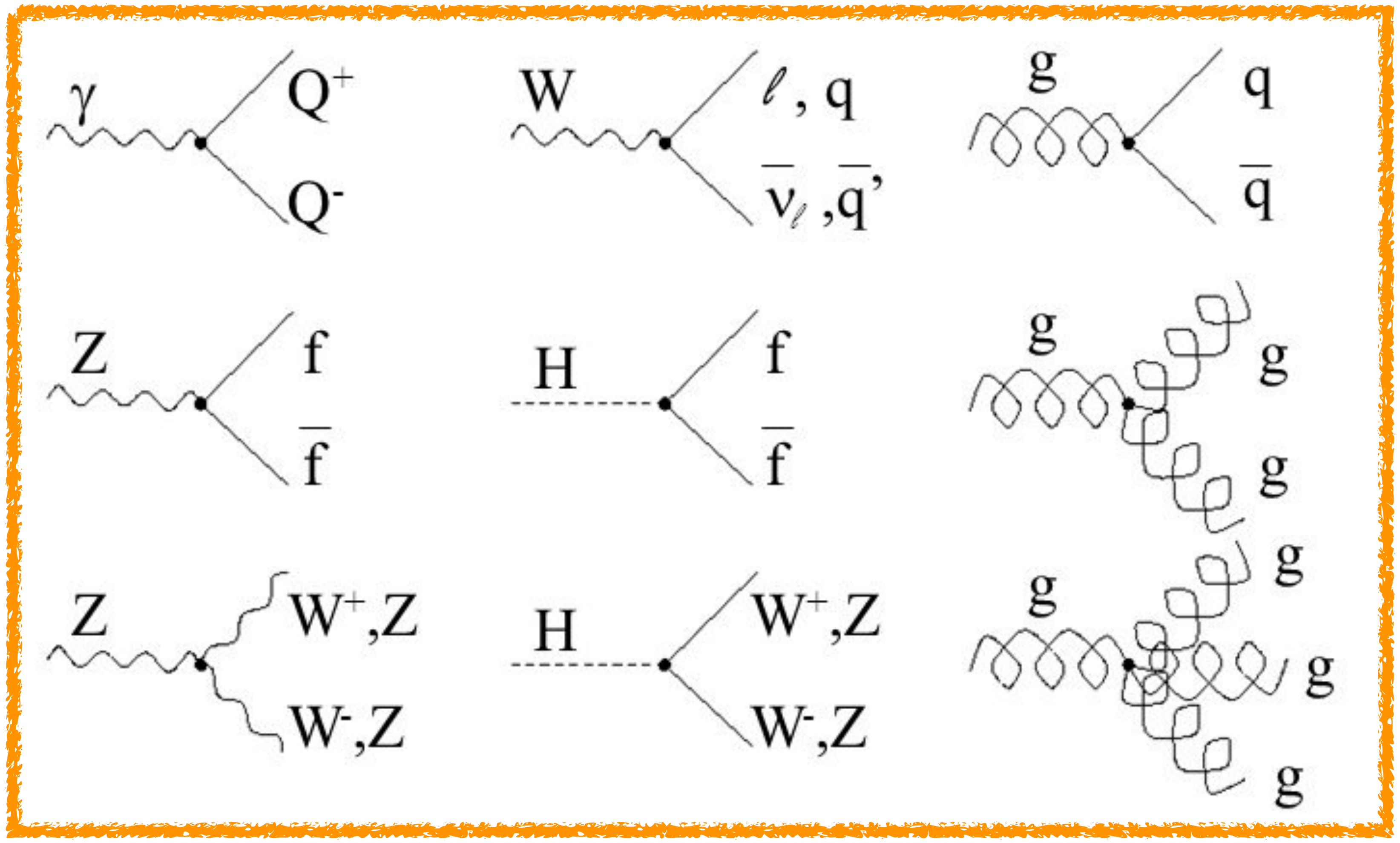
t quarks do not hadronise

Baryons: combinations of three quarks or three anti-quarks

e.g., **proton**: uud; **neutron**: udd

Exotics (not yet established): e.g. Pentaquarks

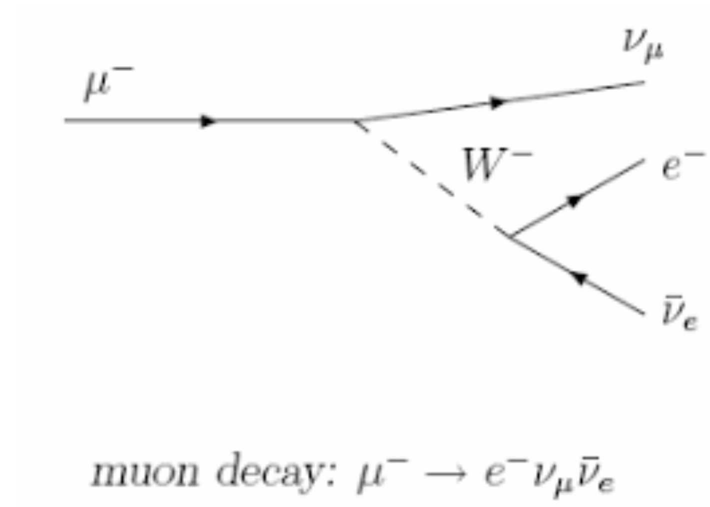
The Standard Model Vertices



Q means charged, f means fermion , ℓ means lepton , q means quark.

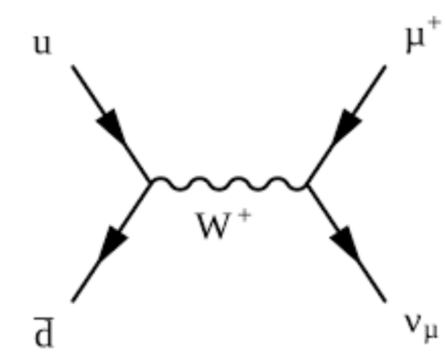
$$\mu^+ \rightarrow e^+ \ \nu_e \ \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \ \bar{\nu}_e \ \nu_\mu \, .$$



No FCNC in the SM!

π^+



Pion decay

Symmetries play a fundamental role in Particle Physics

The structure of the vertices presented in the previous slide is fixed by symmetries

Still: “There is a striking difference between the simplicity of the gauge sector, described by just three gauge couplings, and the complicated structure of the rest of the SM with over twenty **Higgs related parameters describing the SM flavour structure.** This suggests that **flavour physics is a unique portal** to a more fundamental organizing principle. “

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

arXiv:1910.11775

Some of the properties of the SM

- no **photon** mediated FCNC
- no **Z** mediated FCNC (which are possible in physics BSM)
- only one **Higgs** field (electrically neutral) (multi-Higgs may appear in physics BSM)
- no Higgs mediated FCNC (these are possible in physics BSM)
- **VCKM** (governs couplings of quarks to W) is a unitary matrix

(VCKM has "small" off-diagonal entries and has complex entries with physical meaning)

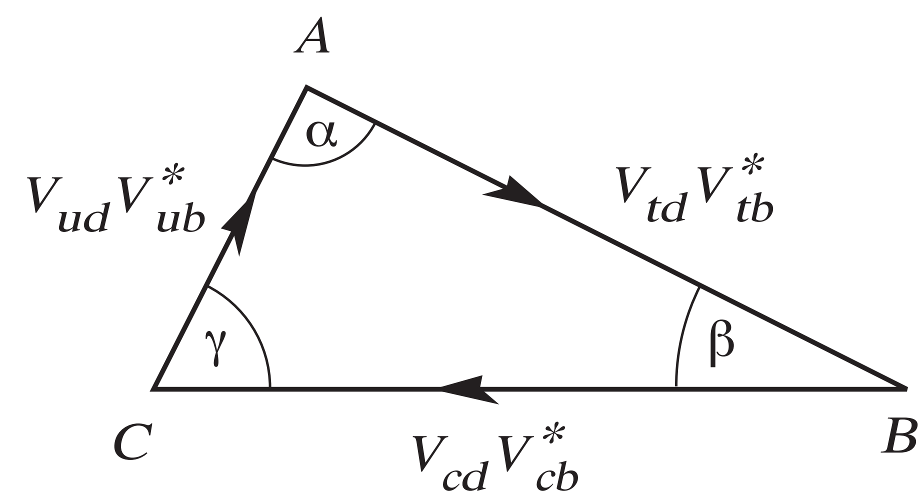
- **CP violation** in the quark sector
- neutrinos are strictly massless
- no leptonic mixing, i.e., the couplings of leptons to W are real diagonal, i.e. identity

VCKM plays a fundamental role in Flavour

$$\frac{-g}{\sqrt{2}}(\overline{u_L},\ \overline{c_L},\ \overline{t_L})\gamma^\mu W_\mu^+ V_{\text{CKM}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.} \qquad V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

most commonly used unitarity triangle $\quad V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$



$$J \equiv \text{Im}\, Q_{uscb} = \text{Im}\,(V_{us}V_{cb}V_{ub}^*V_{cs}^*)$$

$$J = (3.00^{+0.15}_{-0.09}) \times 10^{-5}$$

$$\text{Area} = \frac{|\text{Im}\, Q_{udcb}|}{2} = \frac{|J|}{2}$$

$$\begin{pmatrix} 0.97401 \pm 0.00011 & 0.22650 \pm 0.00048 & 0.00361^{+0.00011}_{-0.00009} \\ 0.22636 \pm 0.00048 & 0.97320 \pm 0.00011 & 0.04053^{+0.00083}_{-0.00061} \\ 0.00854^{+0.00023}_{-0.00016} & 0.03978^{+0.00082}_{-0.00060} & 0.999172^{+0.000024}_{-0.000035} \end{pmatrix}$$

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right),$$

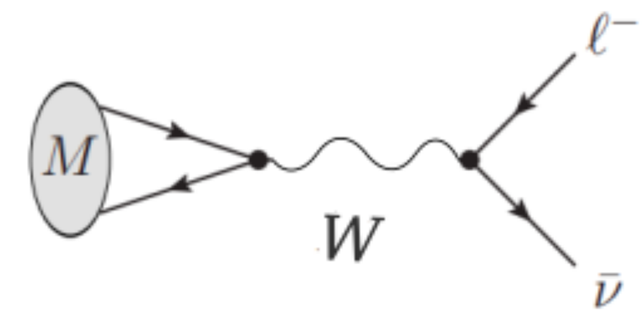
$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

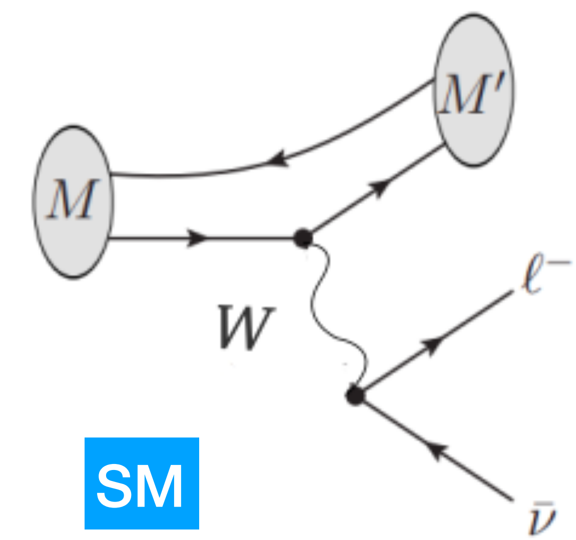
Why Physics Beyond the SM?

- The SM leaves many unanswered questions and cannot accommodate all data!
  - in the SM neutrinos are strictly massless
  - what is the nature of Dark Matter? No viable DM candidates in the SM
  - SM cannot account for the baryon asymmetry of the Universe
- Furthermore, there is the:
  - Electroweak hierarchy problem. Why is the Higgs so light?
  - Strong CP problem
  - Flavour puzzle: Origin of fermion masses, mixing and CP violation (Neutrino Physics is Physics Beyond the SM)

	SM Tree	SM Loop	Require Leptonic Mixing (BSM), Loop
$M \to \ell\overline{\nu}, M'\ell\overline{\nu}$	✓	✓	
$B^0 \to \ell_1^+\ell_2^-$		✓(1 =2)	✓(1 ≠ 2)
$M^0 \rightleftarrows \overline{M^0}$		✓	
$\ell_1^- \to \ell_2^-\ell_3^+\ell_4^-$			✓
$\ell_j \to \ell_i\gamma$			✓
$B \to X_s\gamma$ $(b \to s\ \gamma)$		✓	
$B \to K\ \ell^+\ell^-$ $(b \to s\ \ell^+\ell^-)$		✓	



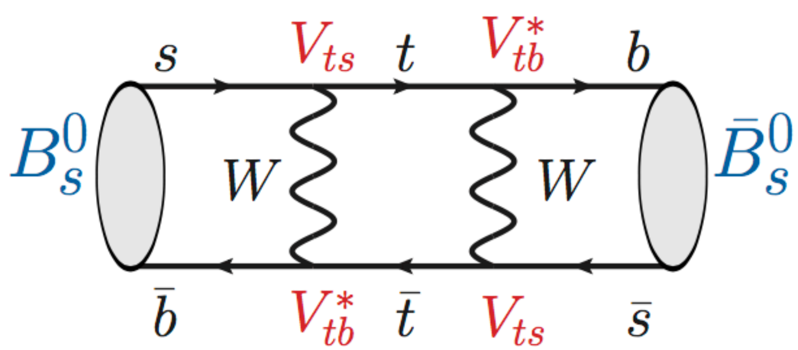
SM $M \to \ell\nu$



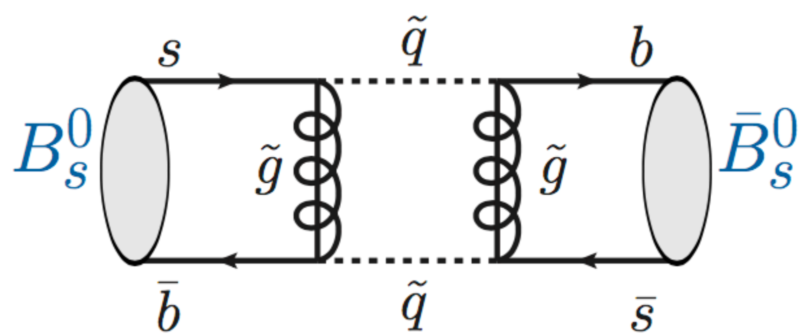
SM

$M \to M'\ell\nu$

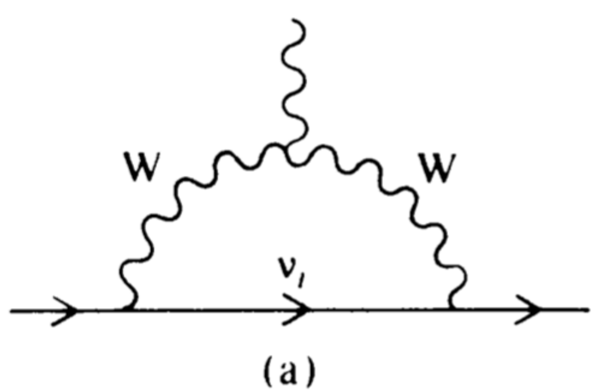
Examples



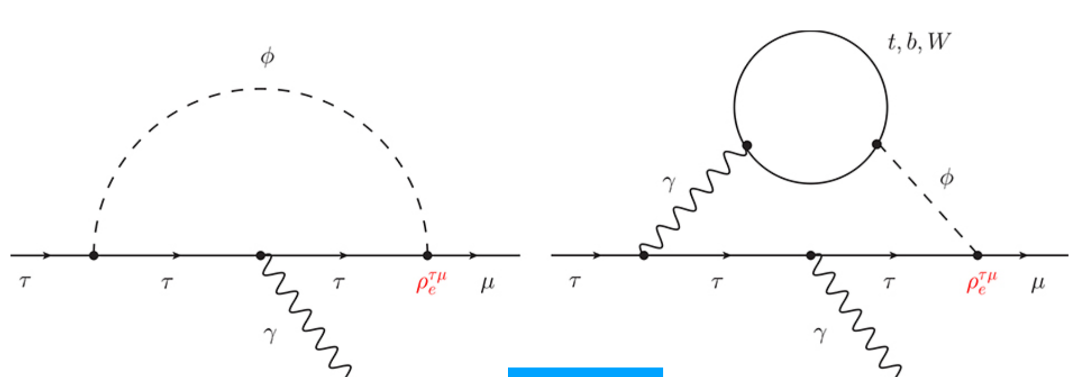
SM



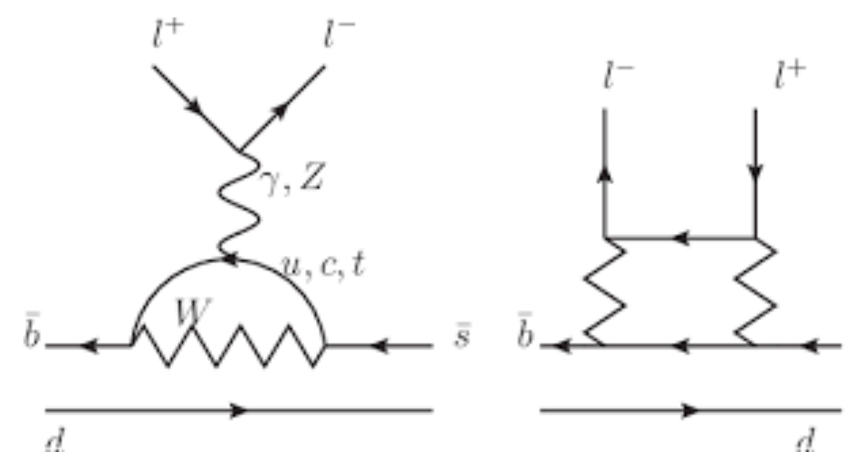
BSM



BSM



BSM

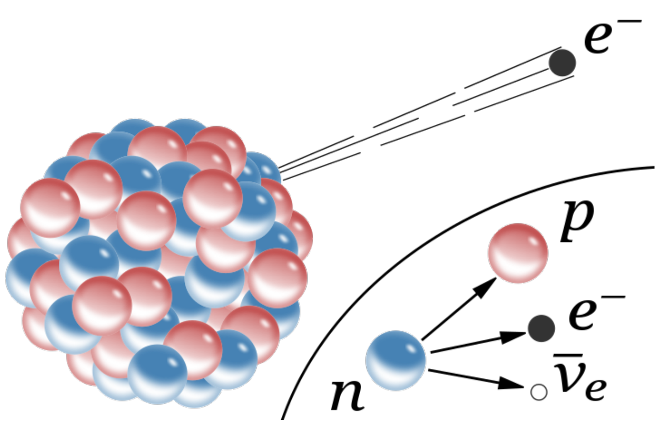


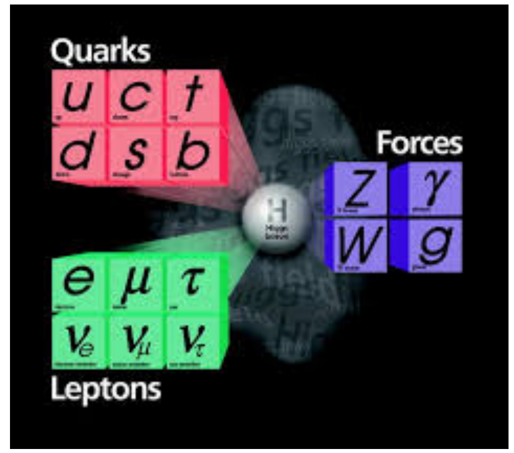
SM

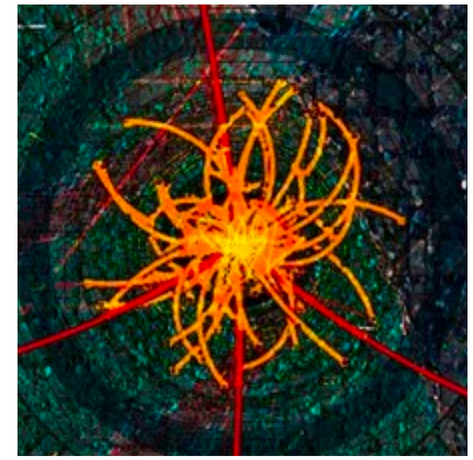
$B \to K\ \ell^+\ell^-$

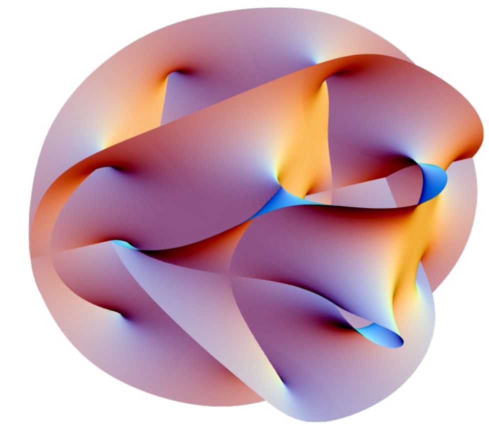
energy scale $m_{Z,W}$ m_H m_t Λ_{NP}

1930 . . . 1970 2012 2020 . . . future

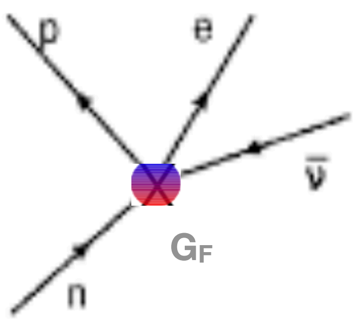


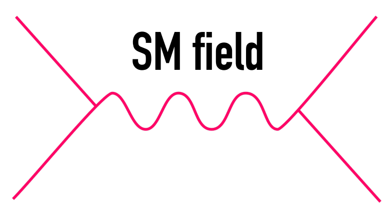


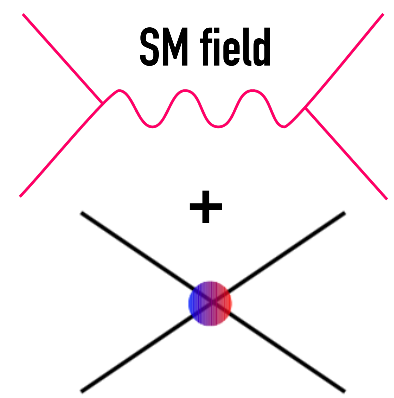


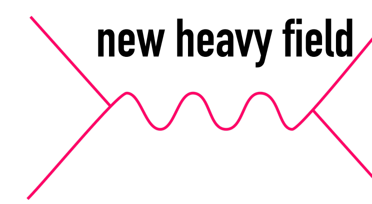


Fermi model	Standard Model	SM-EFT	UV theory









$$\mathcal{L}_{\mathrm{Fermi}} = -\frac{G_F}{\sqrt{2}} \bar{p}\gamma_\mu n\, \bar{e}\gamma^\mu \nu + \mathrm{h.c.}$$

$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}} + \mathcal{L}_{\mathrm{higgs}}$$

$$\mathcal{L}_{\mathrm{SM\text{-}EFT}} = \mathcal{L}_{\mathrm{SM}} + \Sigma_i C_i O_i$$

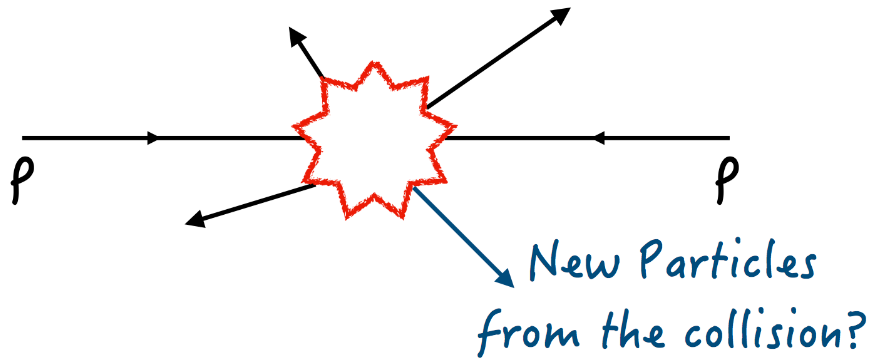
a predecessor of EWK theory

simple and elegant theory describing <u>*almost*</u> all microscopic phenomena

we're here!

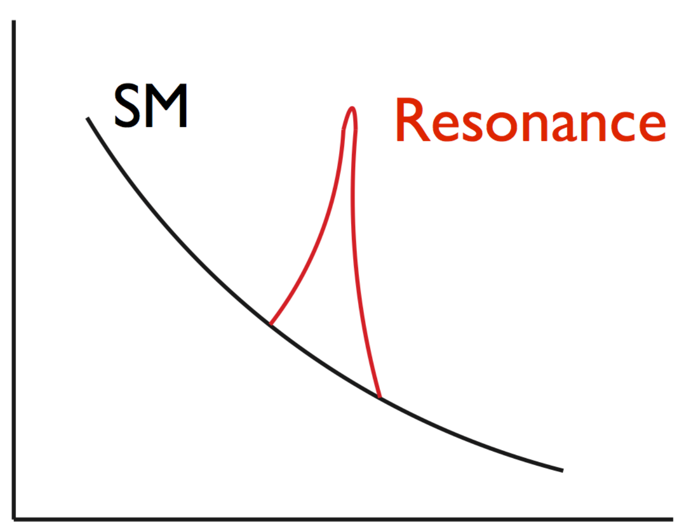
a more fundamental theory with new degrees of freedom

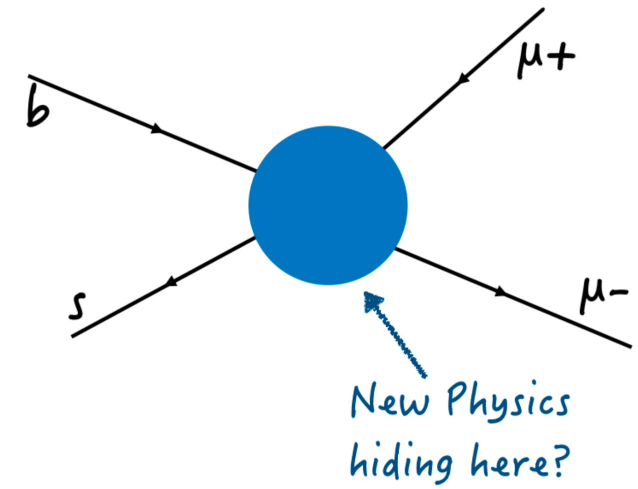
Searching for BSM



Direct

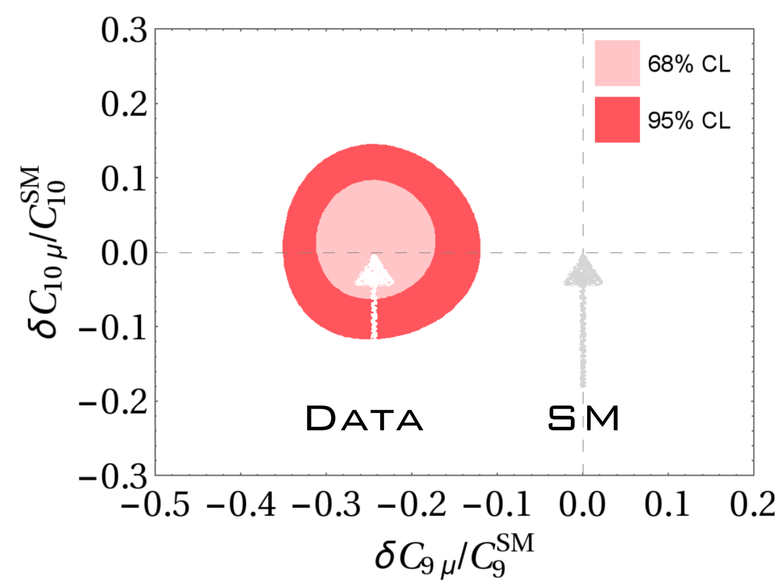
- searching for the decay products of NP particles produced in collision





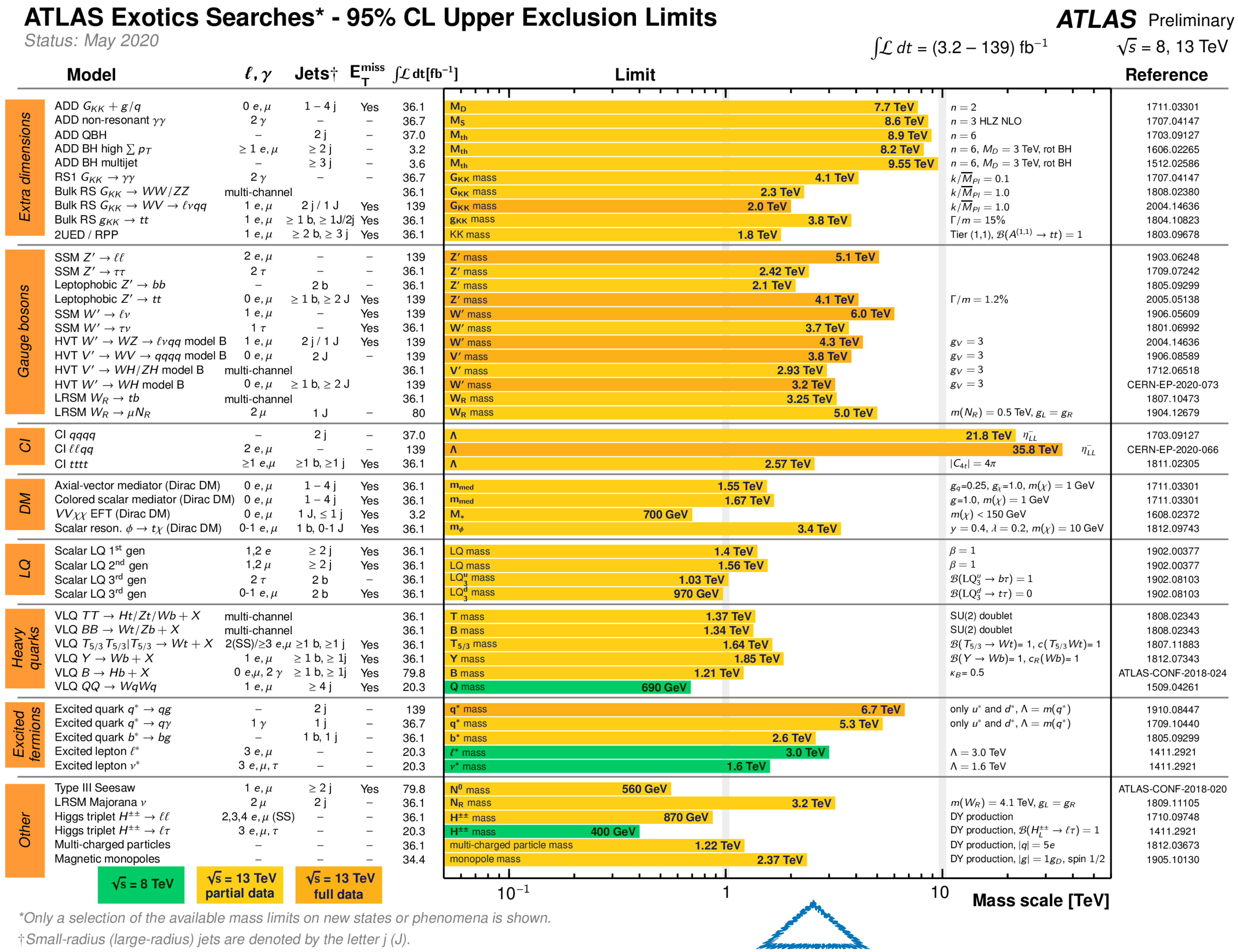
Indirect

- searching for effects of NP particles running in quantum loops (virtual)



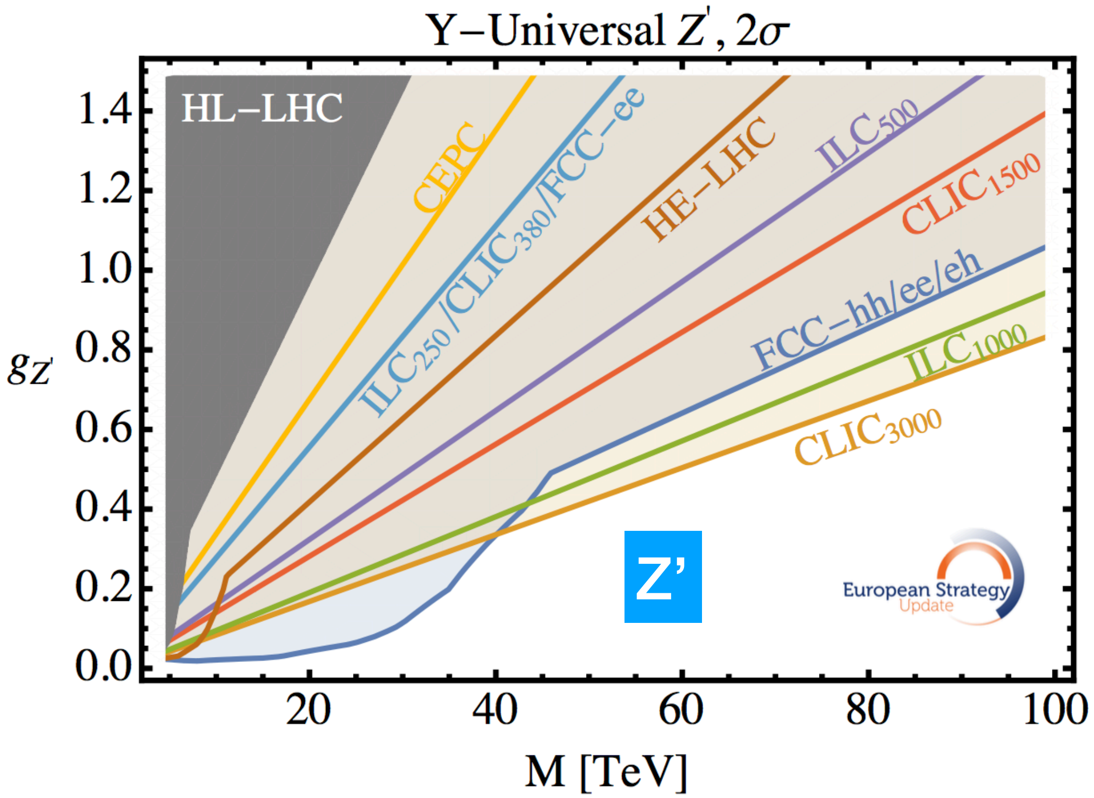
Precision
Rare
Forbidden

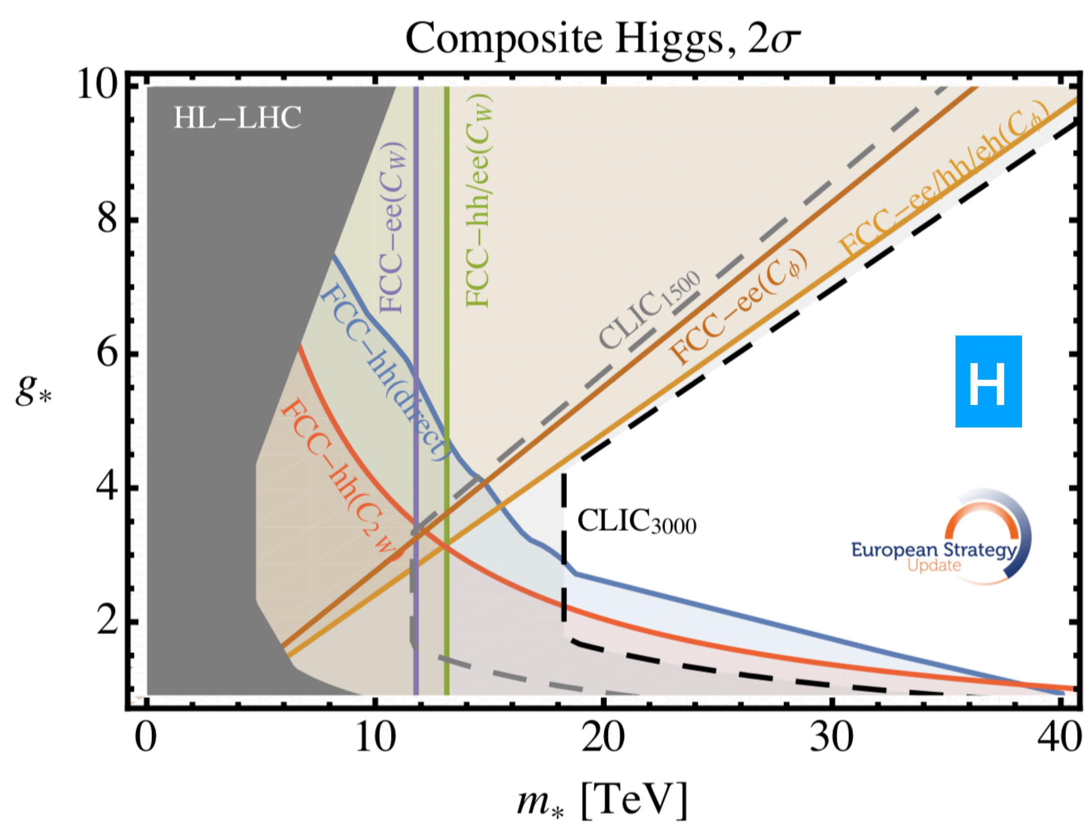
Direct searches: heavy NP particles



The LHC has granted us access to the TeV scale.
Current upper limits on NP mass scale: 1-10TeV

beyond SM beyond LHC





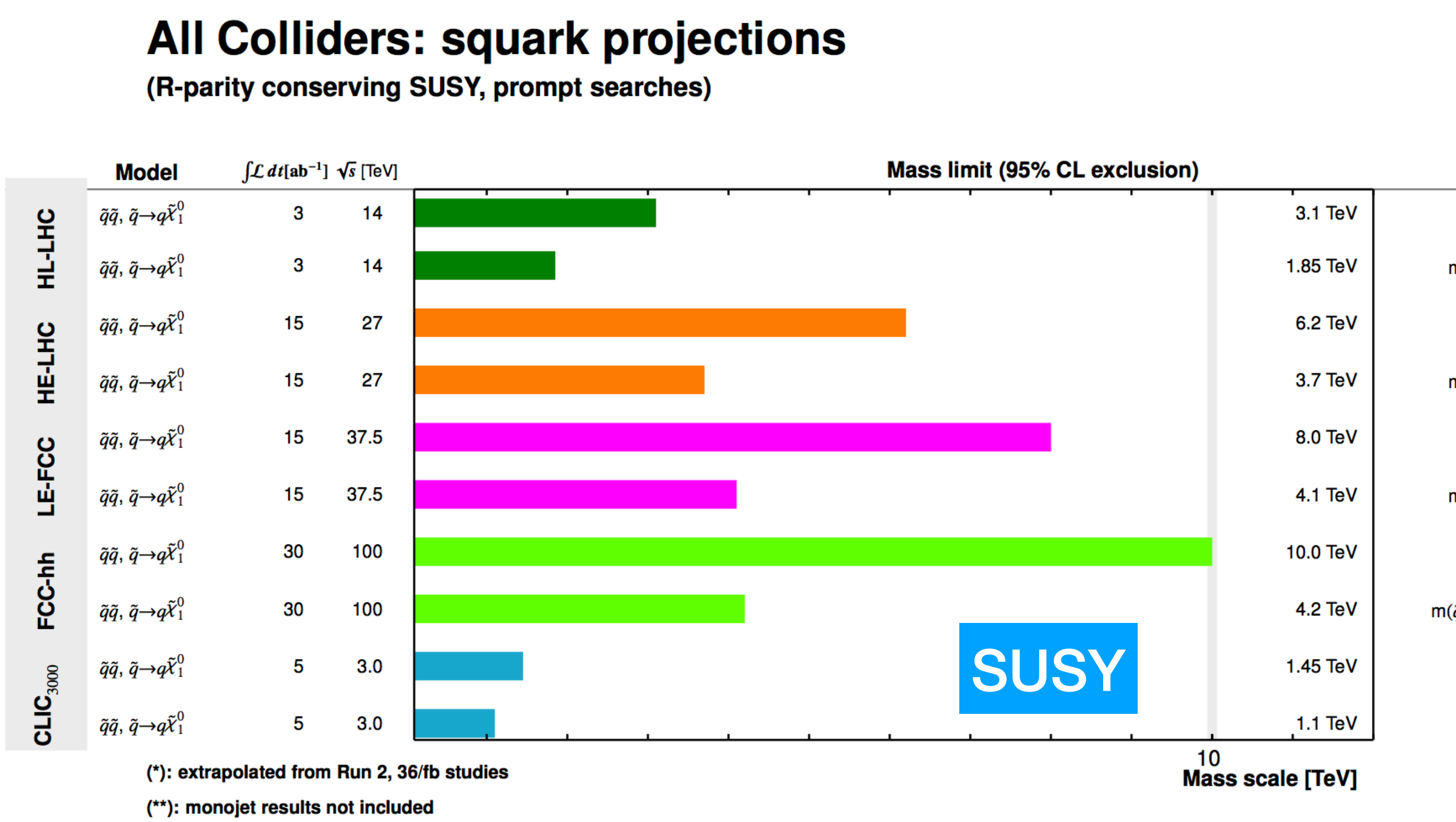
@HL-LHC

extend sensitivity by x2

- innovative analysis methods
- explore tails of distributions

@FC

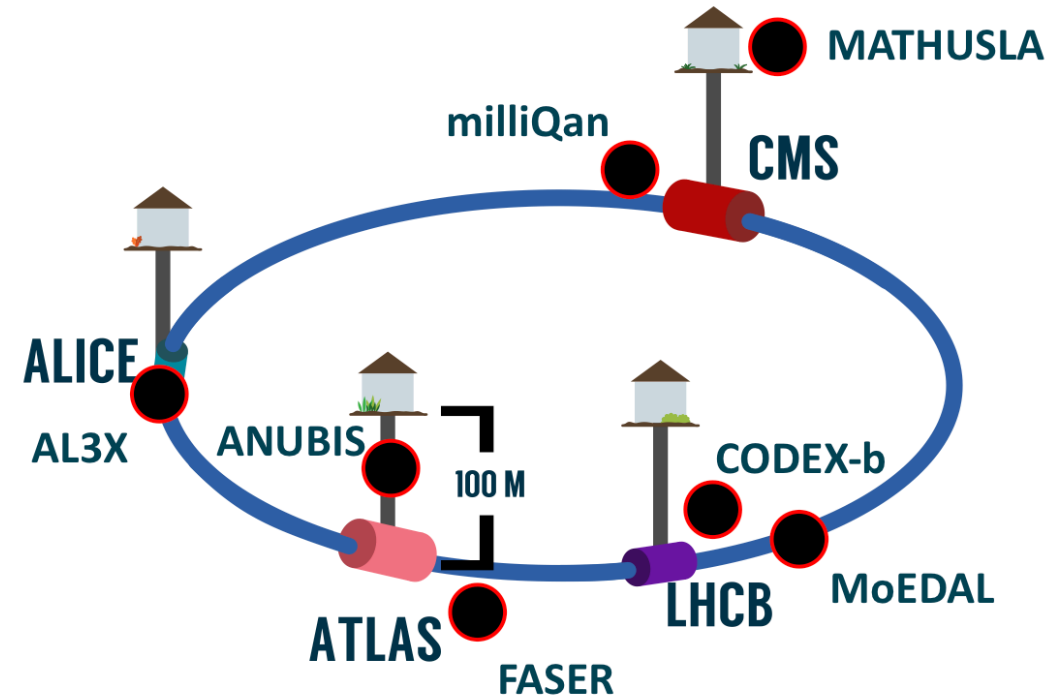
further large gains in sensitivity

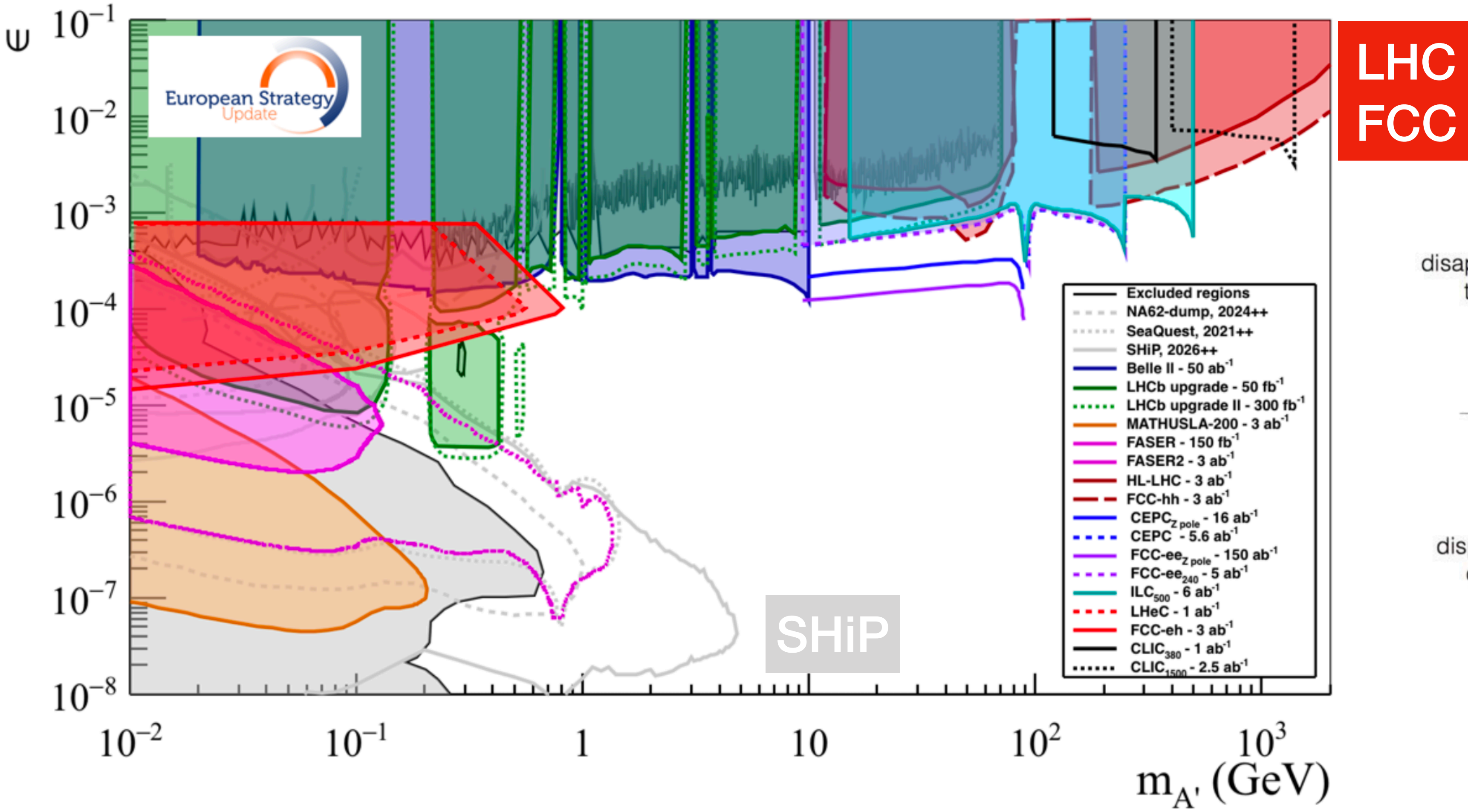


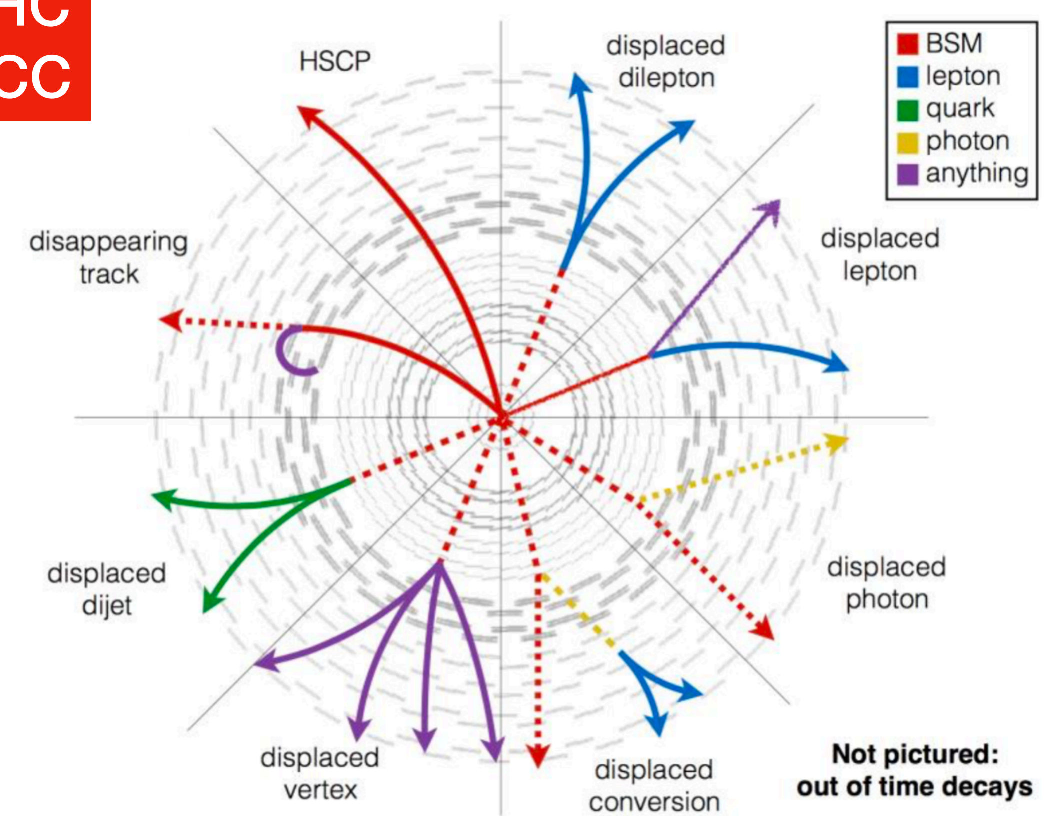
Feebly Interacting Particles

Explore the exotic & unconventional

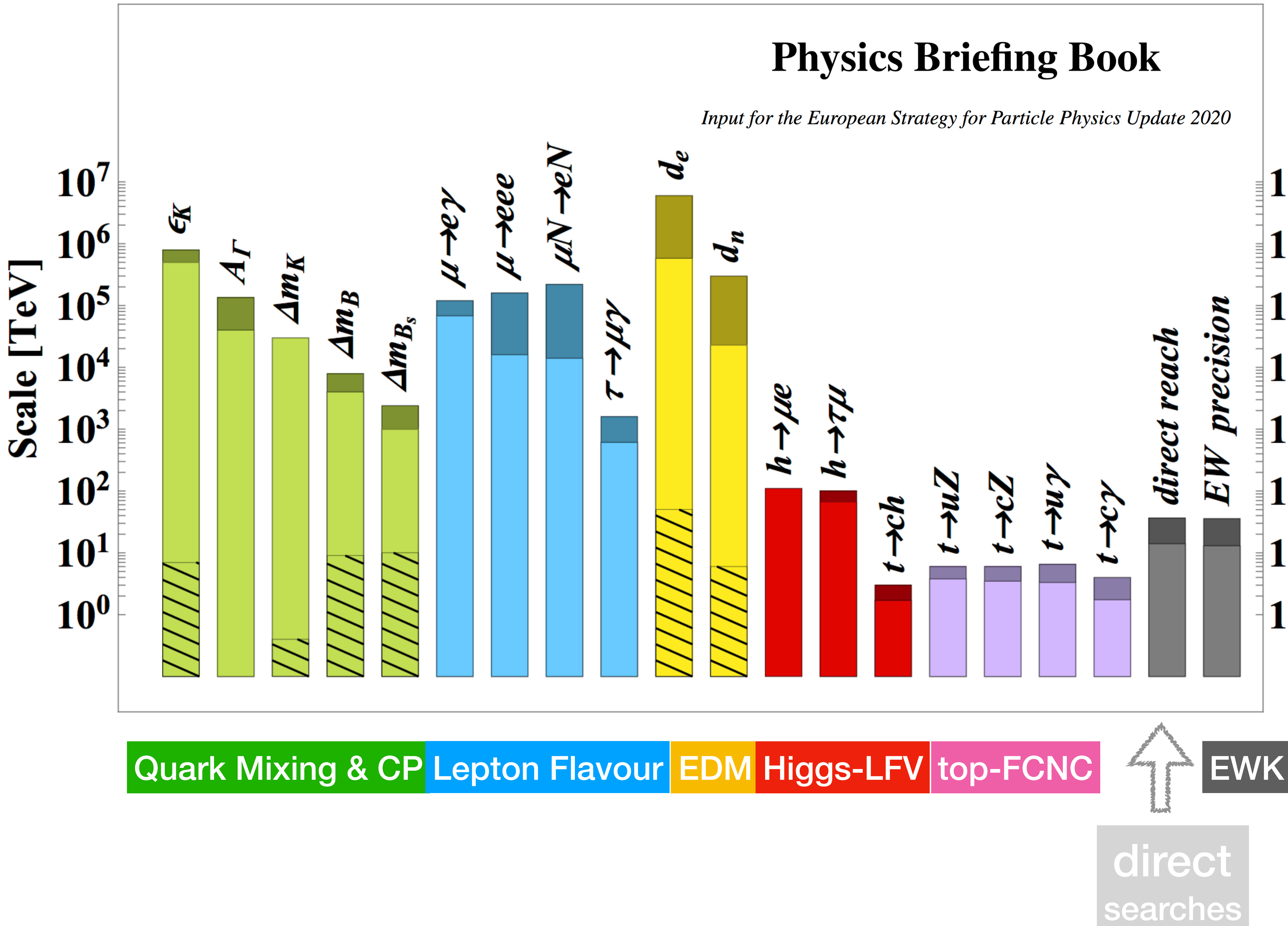
- New trigger strategies
- New experimental signatures
- New dedicated detectors
- At LHC and beyond





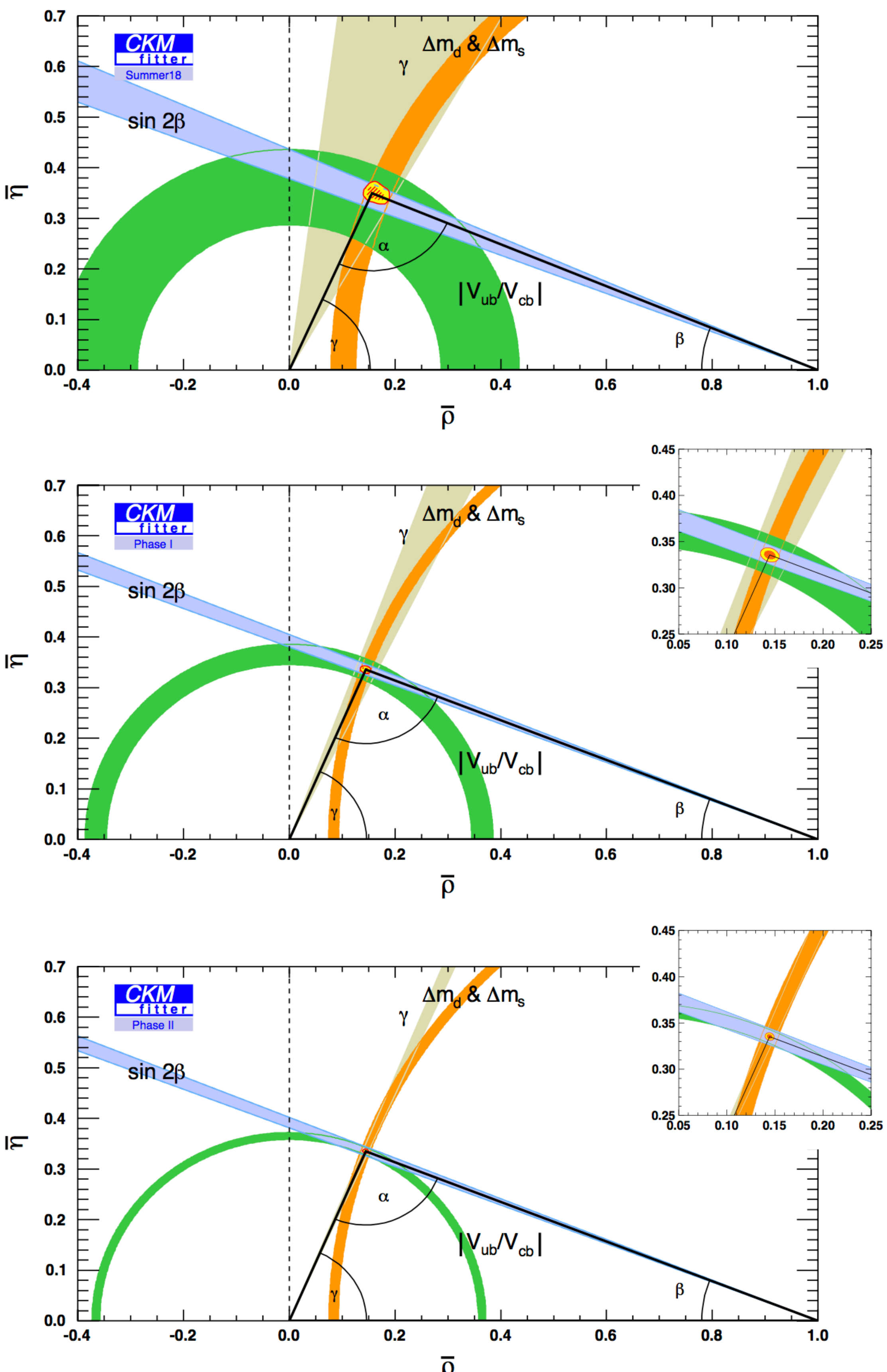


Indirect searches: fuelled by Quantum Mechanics

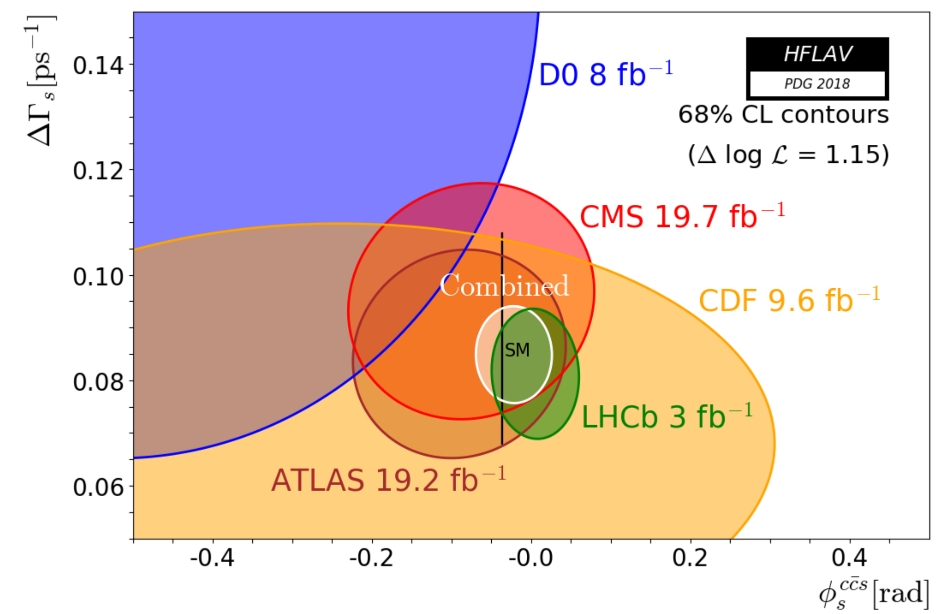


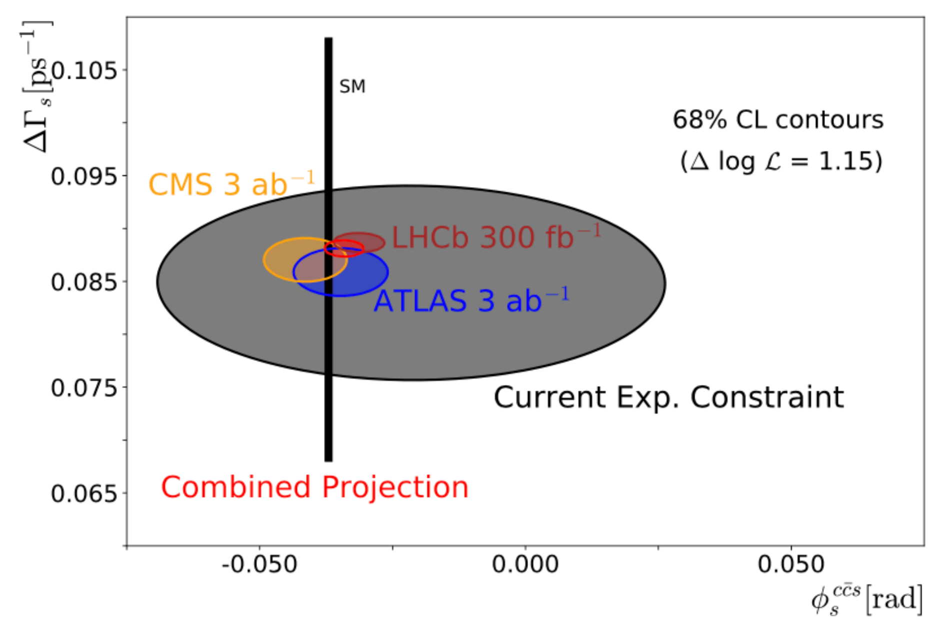
Heavy flavour

CKM ➡ ultra precision tests of SM flavour structure (⬅Higgs)

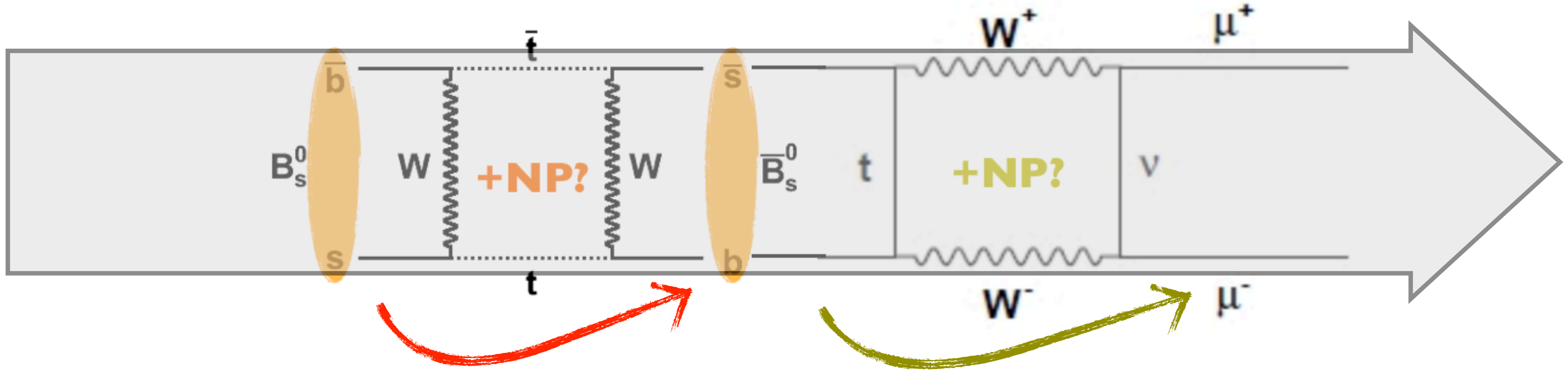


theory (lattice QCD) precision critical!





B $\mu\mu$

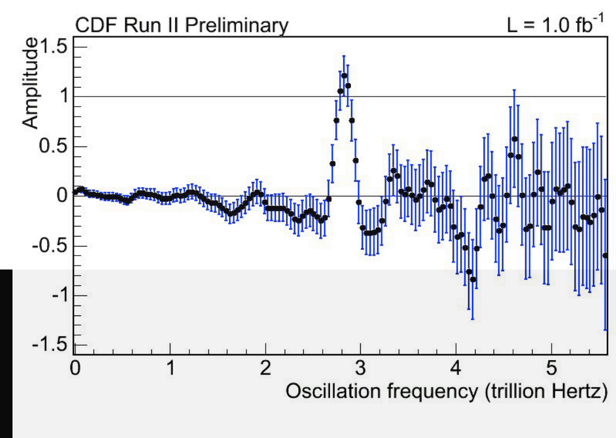


"fast and rare"

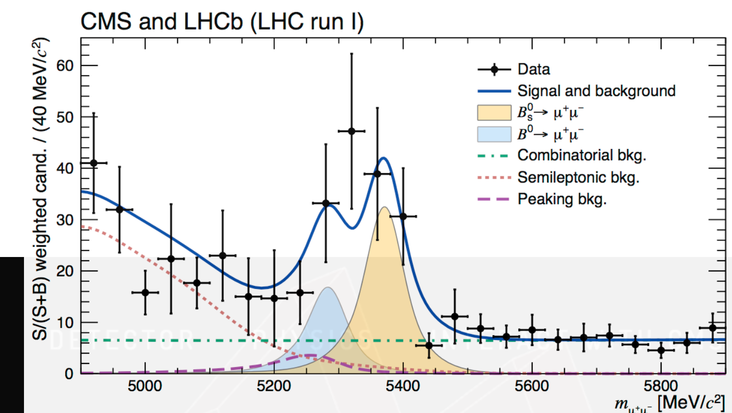
MIXING

DECAY

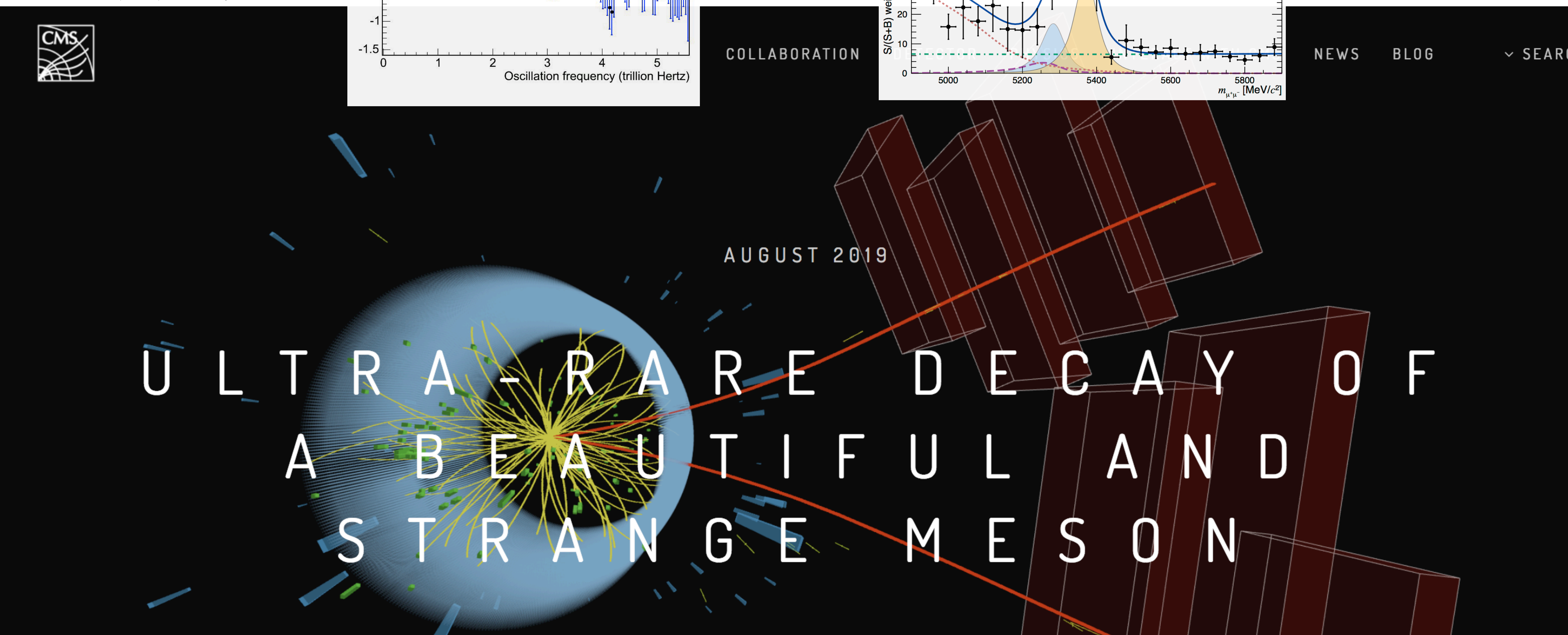
"doubly sensitive to NP"



PRL 97 (2006) 242003, NL thesis

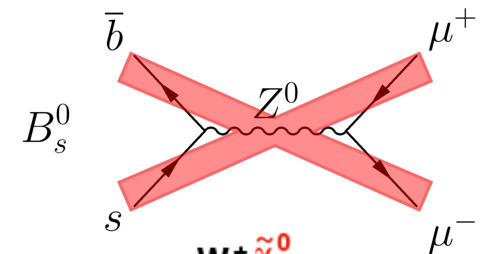


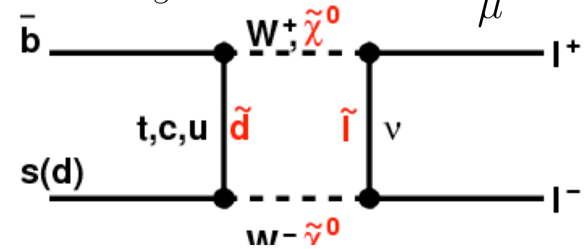
Nature 522 (2015) 68

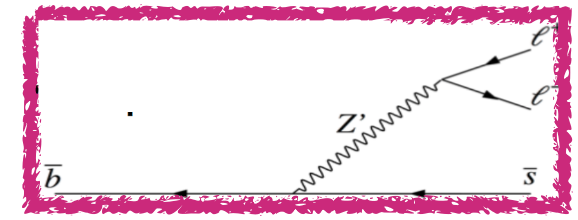


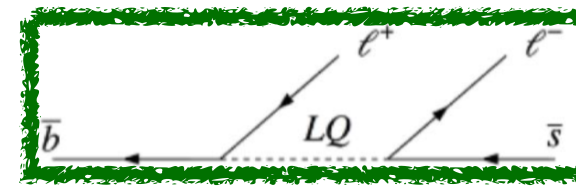
rare decay: b→sμμ

FCNC

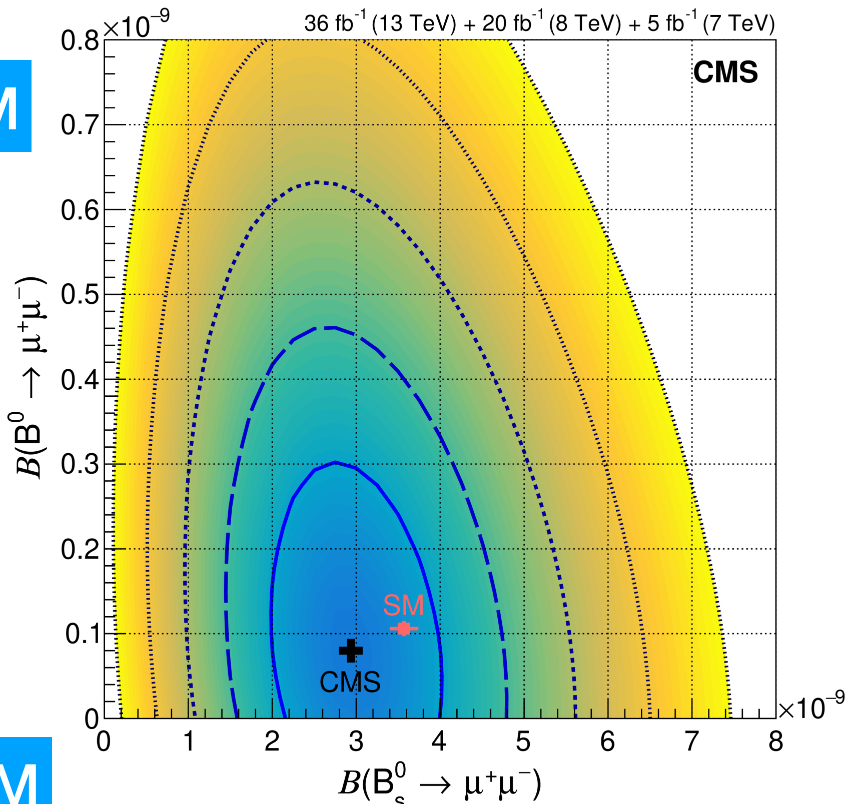




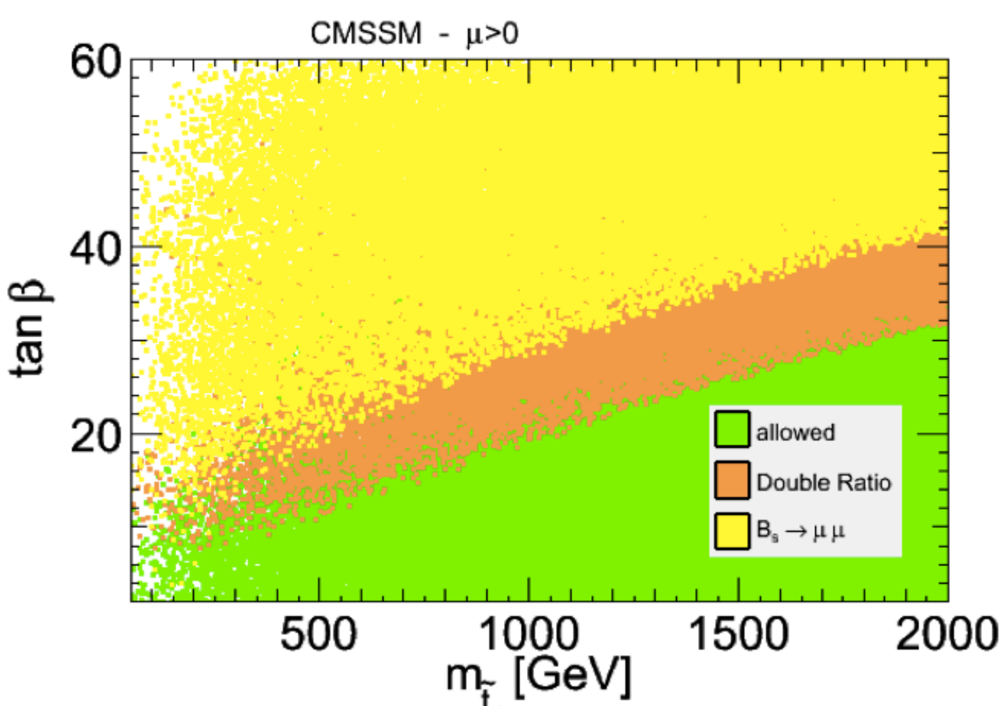




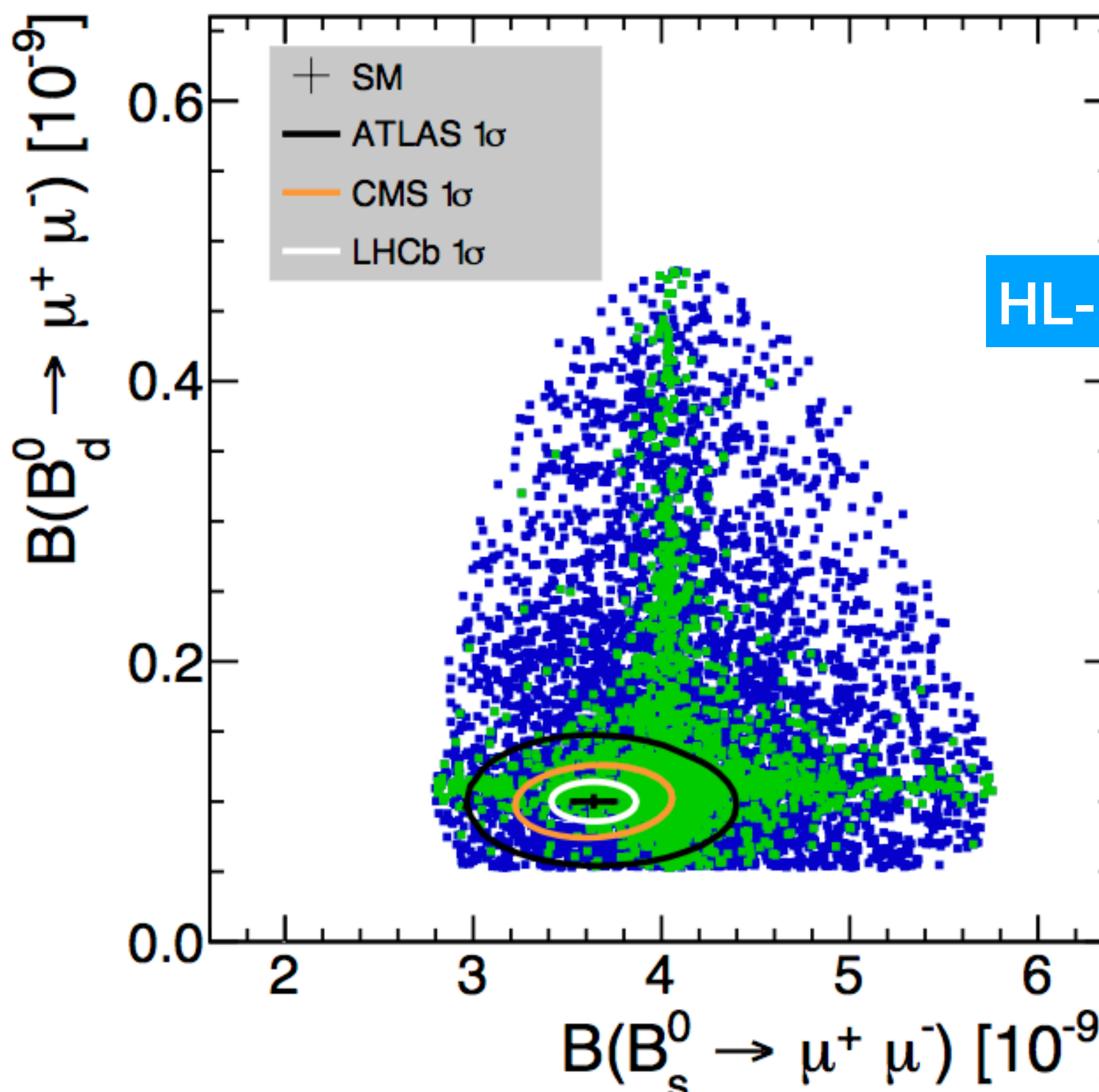
vs SM



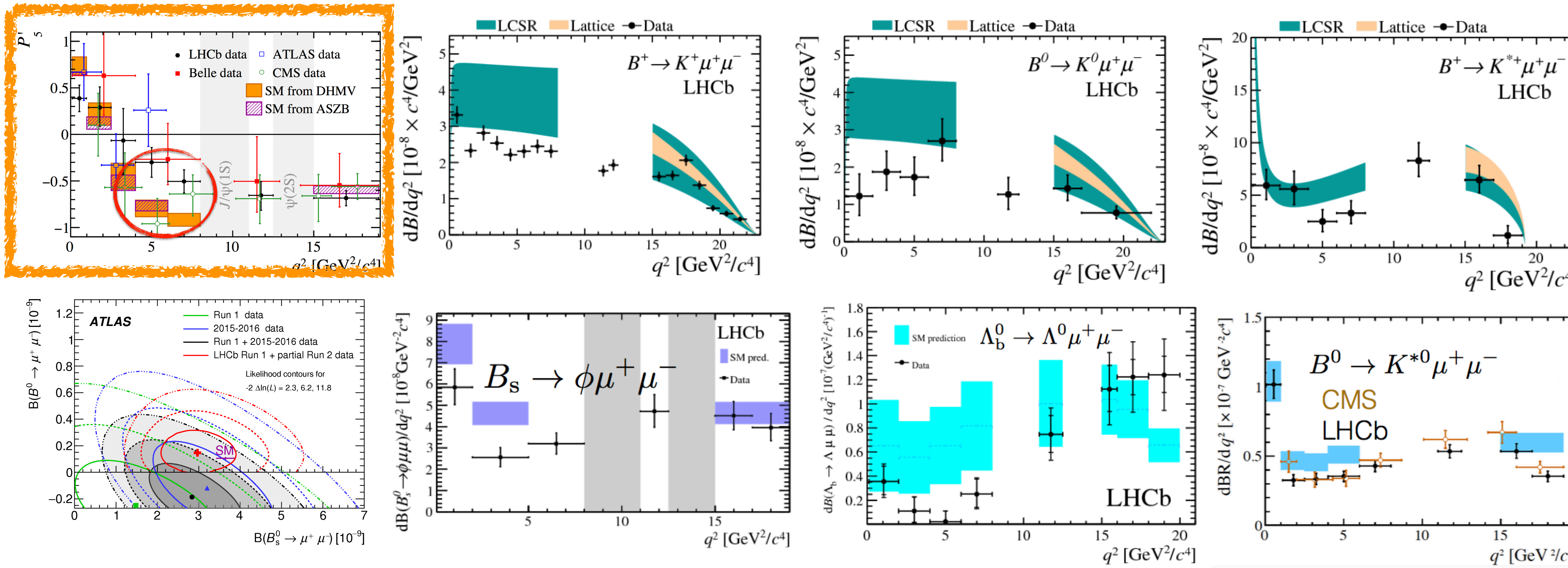
vs BSM



HL-LHC



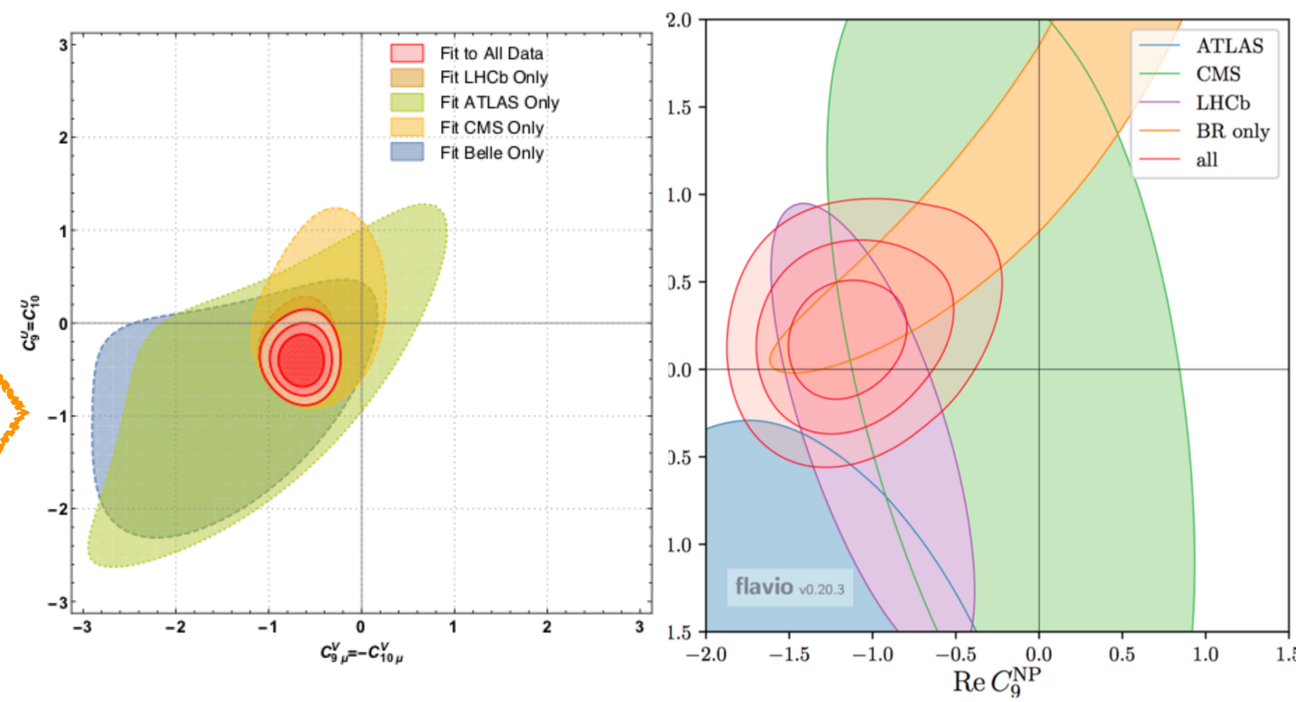
b→sμμ | global fits



Experimental measurements

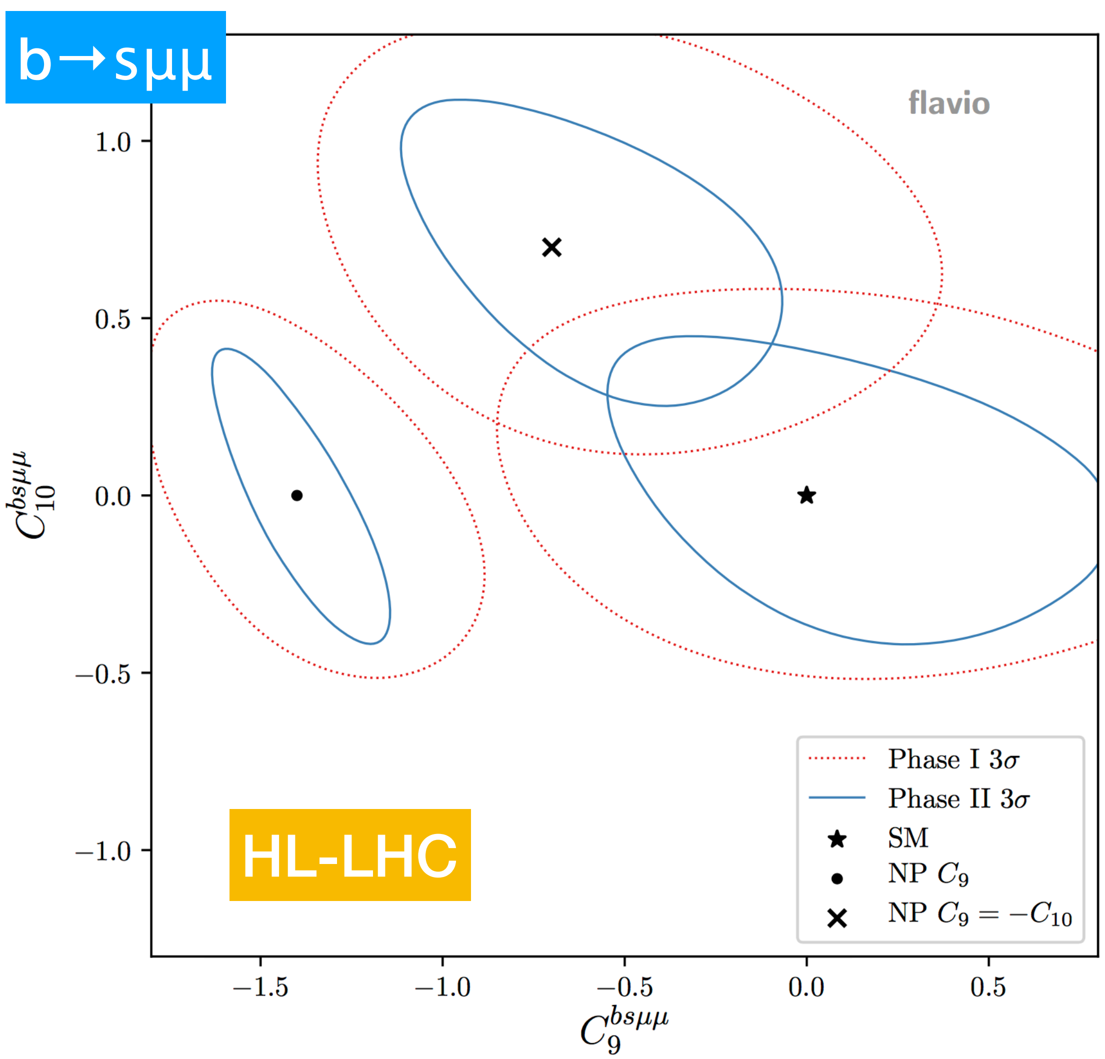
SM - **E**ffective **F**ield **T**heory

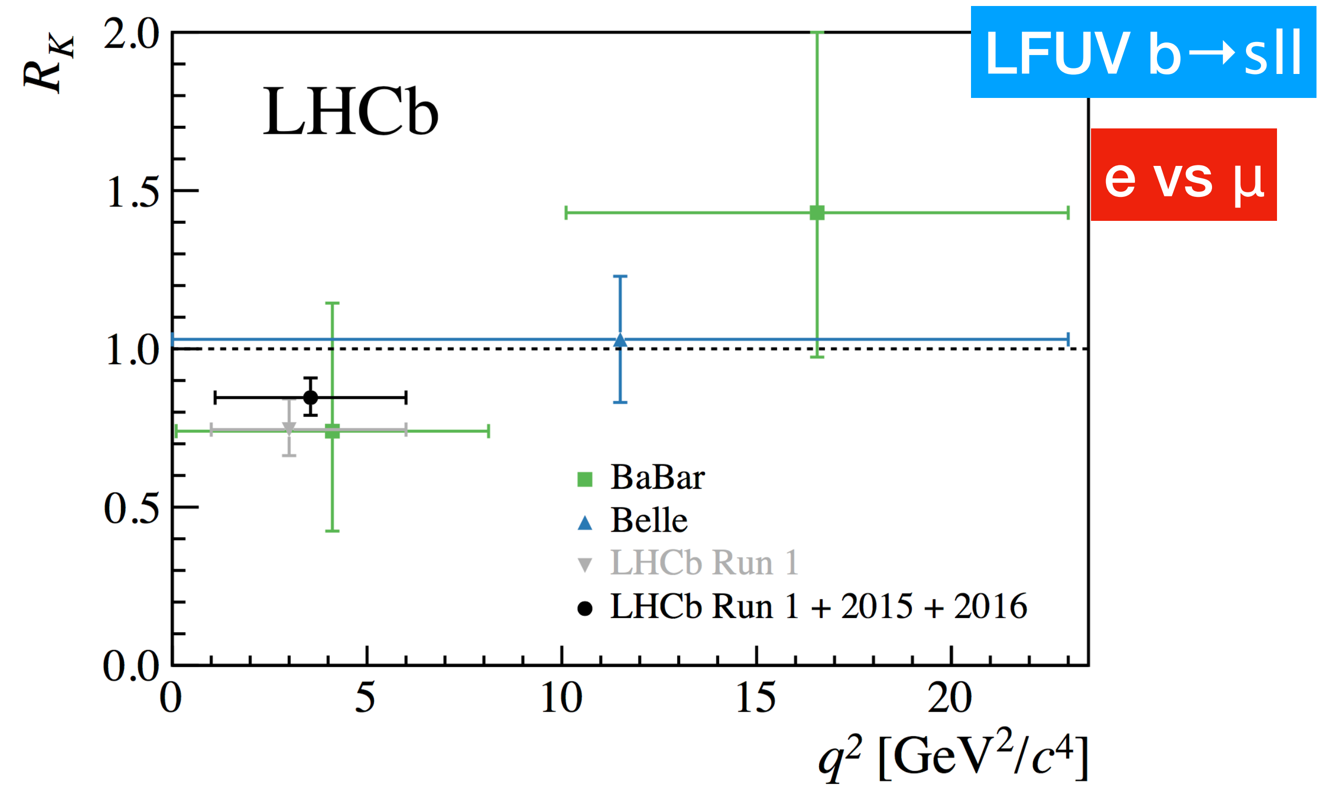
$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{SM}} + \Sigma_i C_i O_i$$

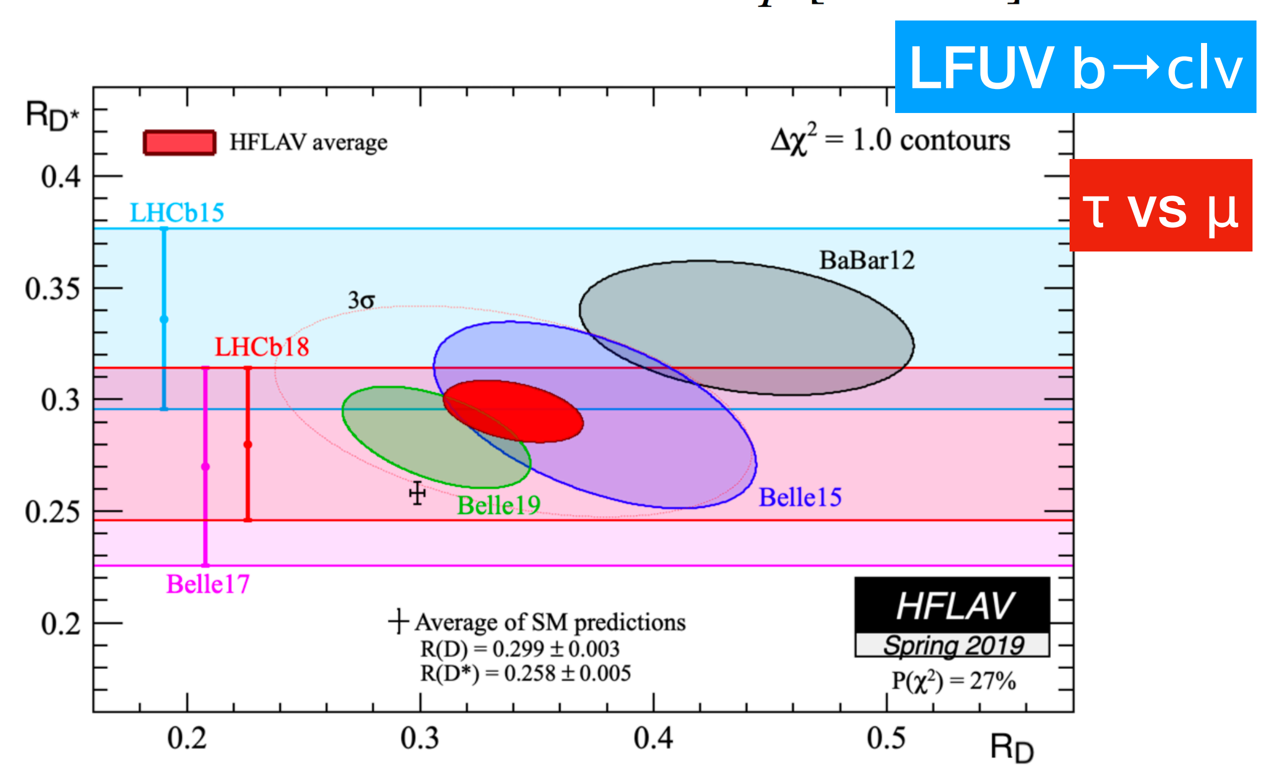


Theory space

Flavour Anomalies



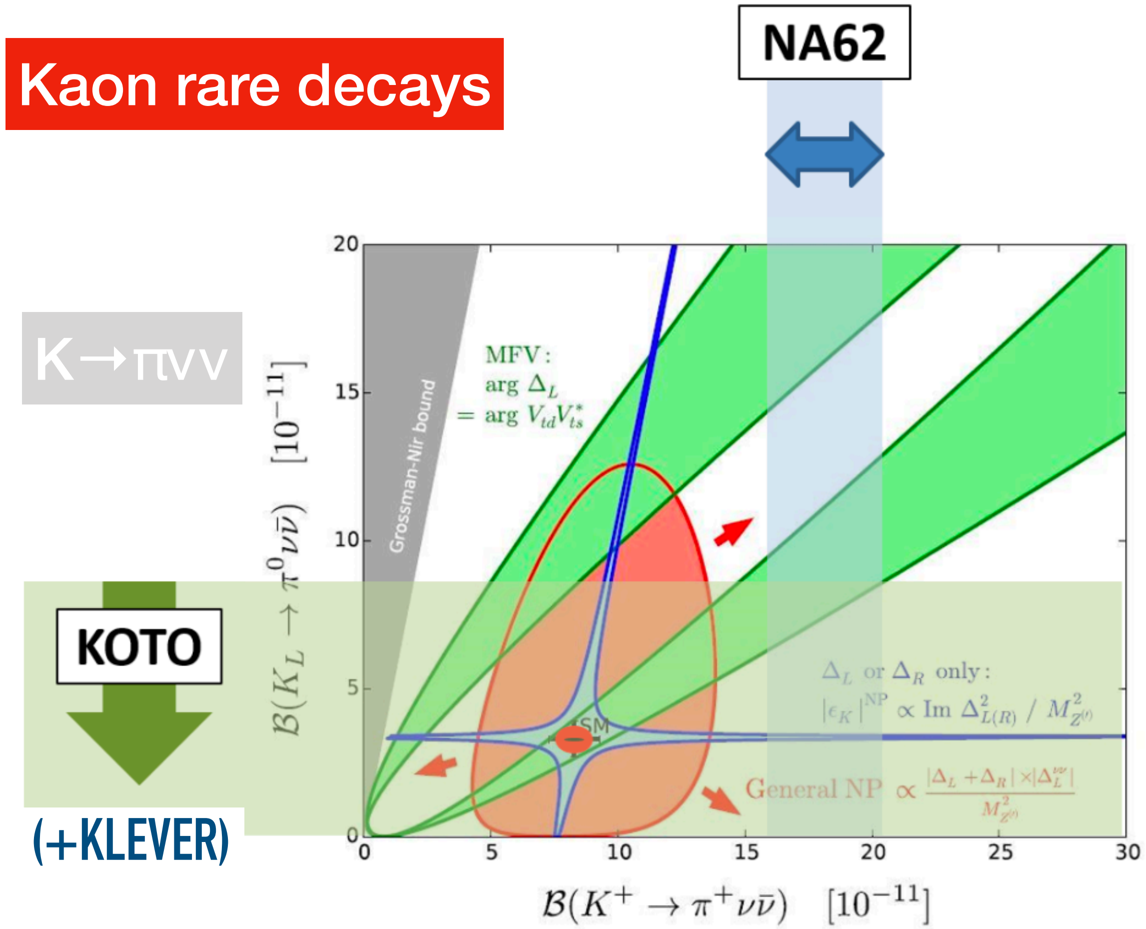




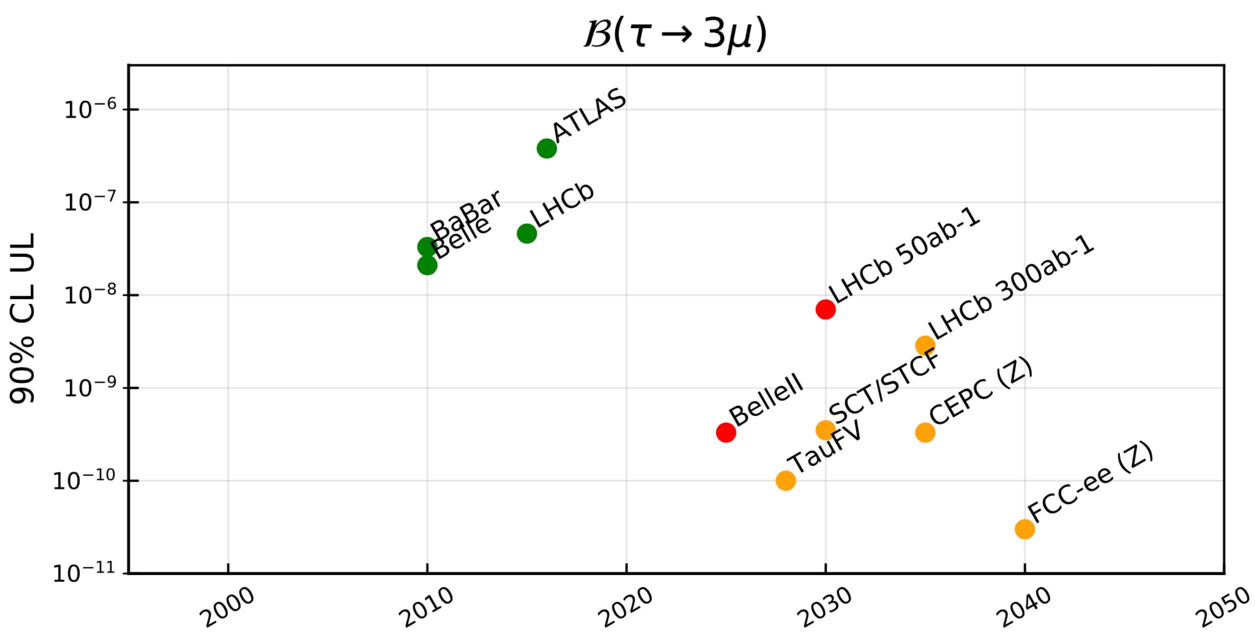
Clarification being actively pursued experimentally by LHCb,ATLAS,CMS, and BelleII + theory calculations and model building

Light flavour sector

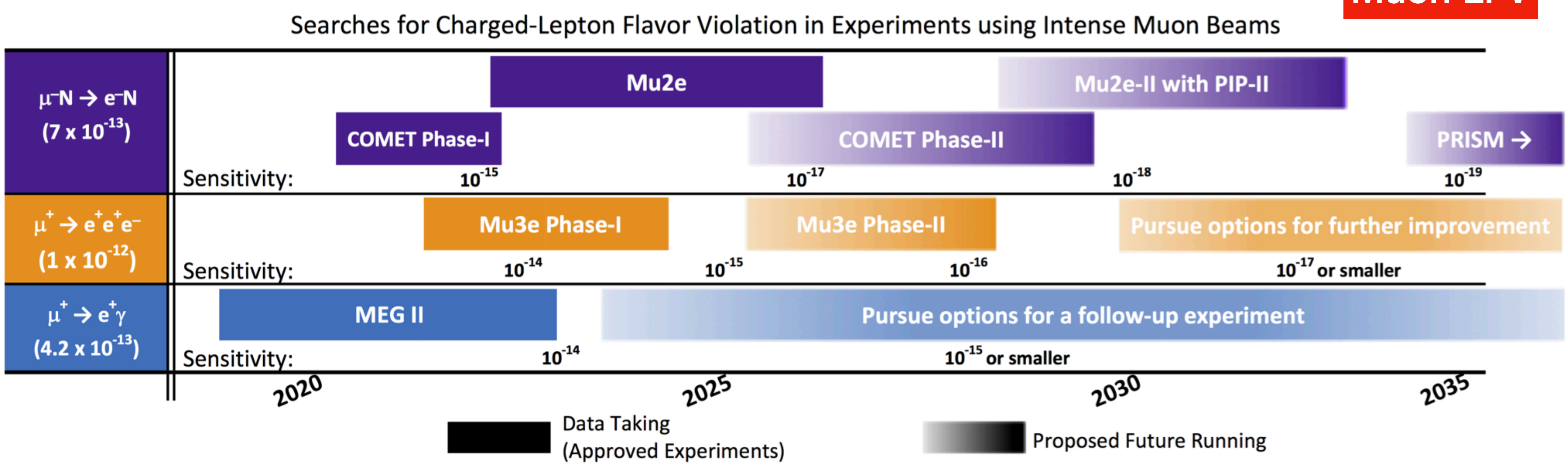
Kaon rare decays



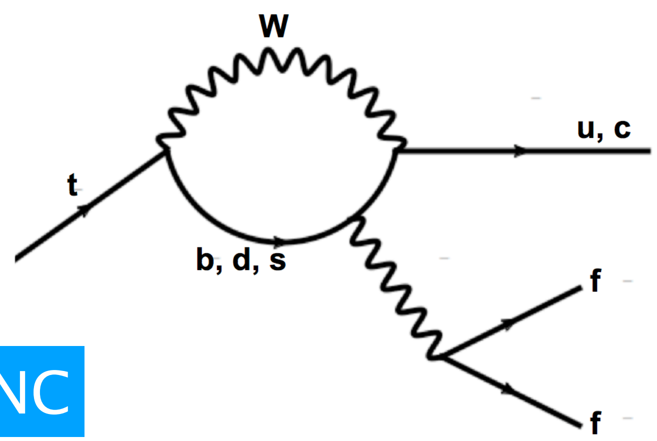
Tau LFV



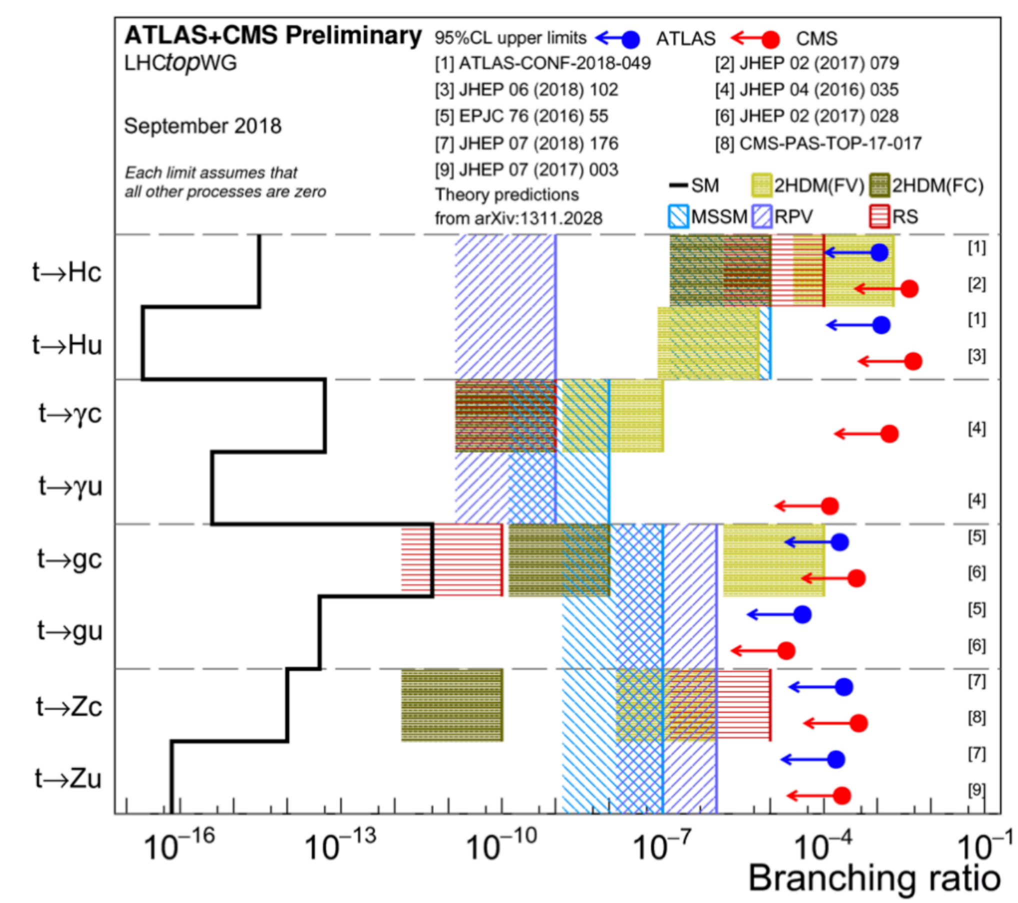
Muon LFV



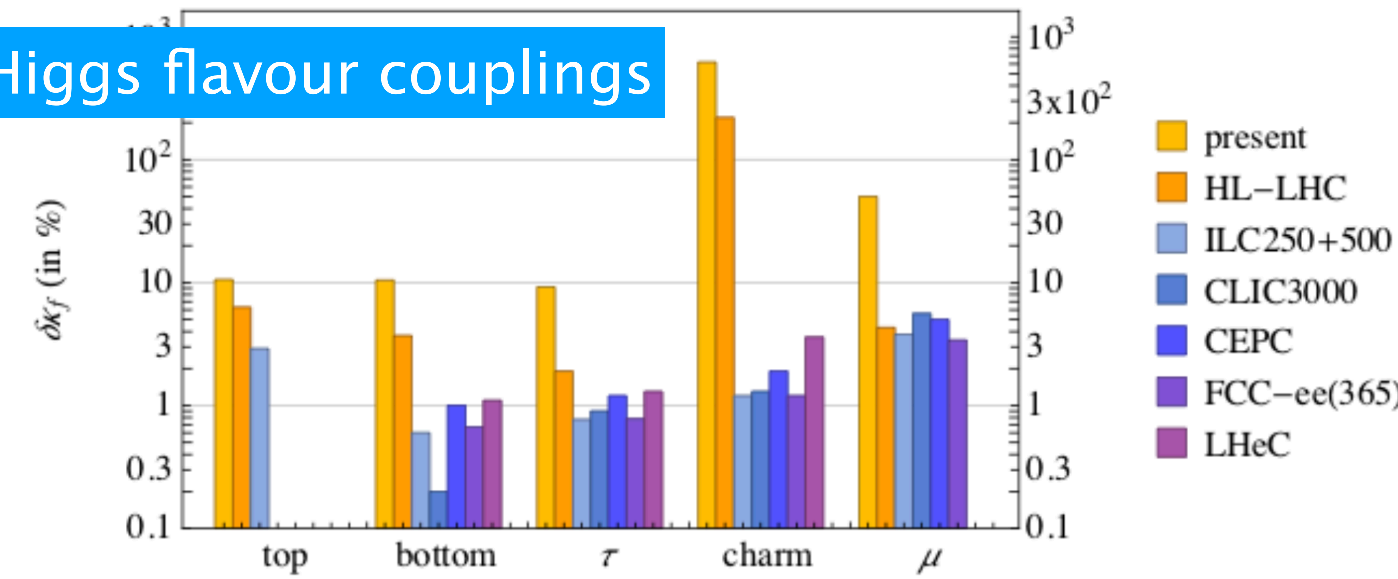
top & Higgs FCNC



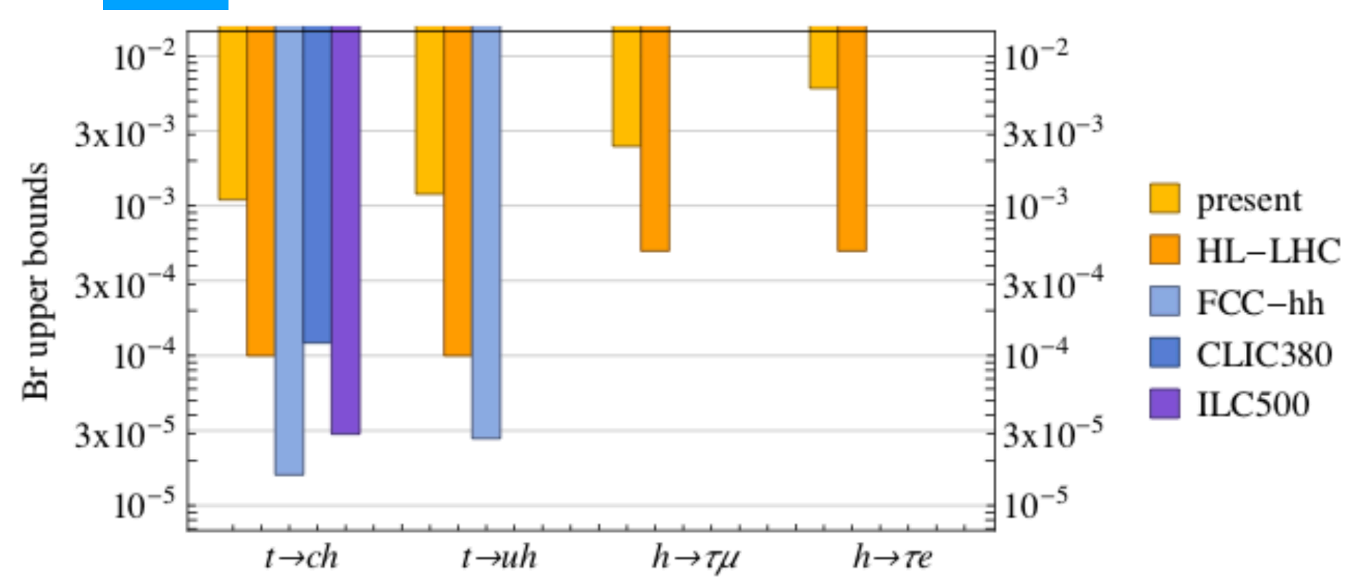
top FCNC



Higgs flavour couplings



LFV



Summary

- BSM physics is actively searched at LHC & beyond
  - Direct searches: novel trigger/analysis strategies, unconventional signatures
  - Precision measurements: flavour mixing & CPV, particle properties/couplings
  - Indirect searches: rare and forbidden decays, FCNC, LFV, LFUV
- Flavour provides sensitivity to BSM well beyond collision energy
  - light quarks — heavy quarks — leptons
- Perspectives are bright
  - HL-LHC and other mid-term new projects (@CERN and elsewhere) shall facilitate large increases in sensitivity to New Physics
  - Also through exploration of new ideas and novel approaches
  - Europe, and Portugal, well positioned to (continue to) play leading role

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