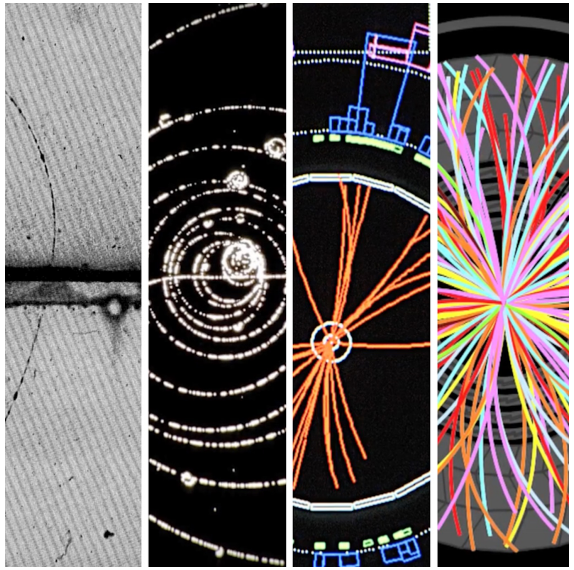
Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules

Développements technologiques et applications associés



GT01 Report: Particle Physics - the energy frontier

Marie-Hélène Genest

for the GT01 steering committee

LPSC GRENOBLE | MODANE

cnrs IN2P3 Les deux infinis

Organisation

- GT01 Seminar March 12-13 2020 (IP2I Lyon ; by video-conference)
  - Link to the contributions
- Steering committee:
  - Christophe Ochando (LLR)
  - Christopher Smith (CSI, LPSC)
  - Dirk Zerwas (IJCLab)
  - Francesco Polci (GDR InF, LPNHE)
  - Laurent Vacavant (IN2P3)
  - M-H.G. (LPSC)
- Topics covered by GT01:
  - *The Standard Model of particle physics and beyond*
  - *Mixing and CP violation in the quark sector*
  - *Precision tests of the fundamental interactions*
- The report can be found here

Since the last exercise (April 2012)

- Run-1 of the LHC (7 and 8 TeV)
  - Interesting excess at 125 GeV which will be confirmed a few months later with the Higgs boson discovery

  - BSM physics searches which already push the limits beyond those obtained at the Tevatron
    - in 2012: 50 physicists still working on D0, with around 210 working on ATLAS and CMS
    - today: around 180 CMS+ATLAS

  - HL-LHC foreseen, approved in 2016 ; future collider studies ongoing

- Consecration of the CKM model with the end of BaBar and Belle
  - Flavor physics switches more and more focus towards the measurement of processes which can be linked to BSM physics
    - in 2012: 40 physicists on LHCb, interest for SuperB
    - today: same amount of physicists on LHCb + a dozen on Belle II and SuperKEKb

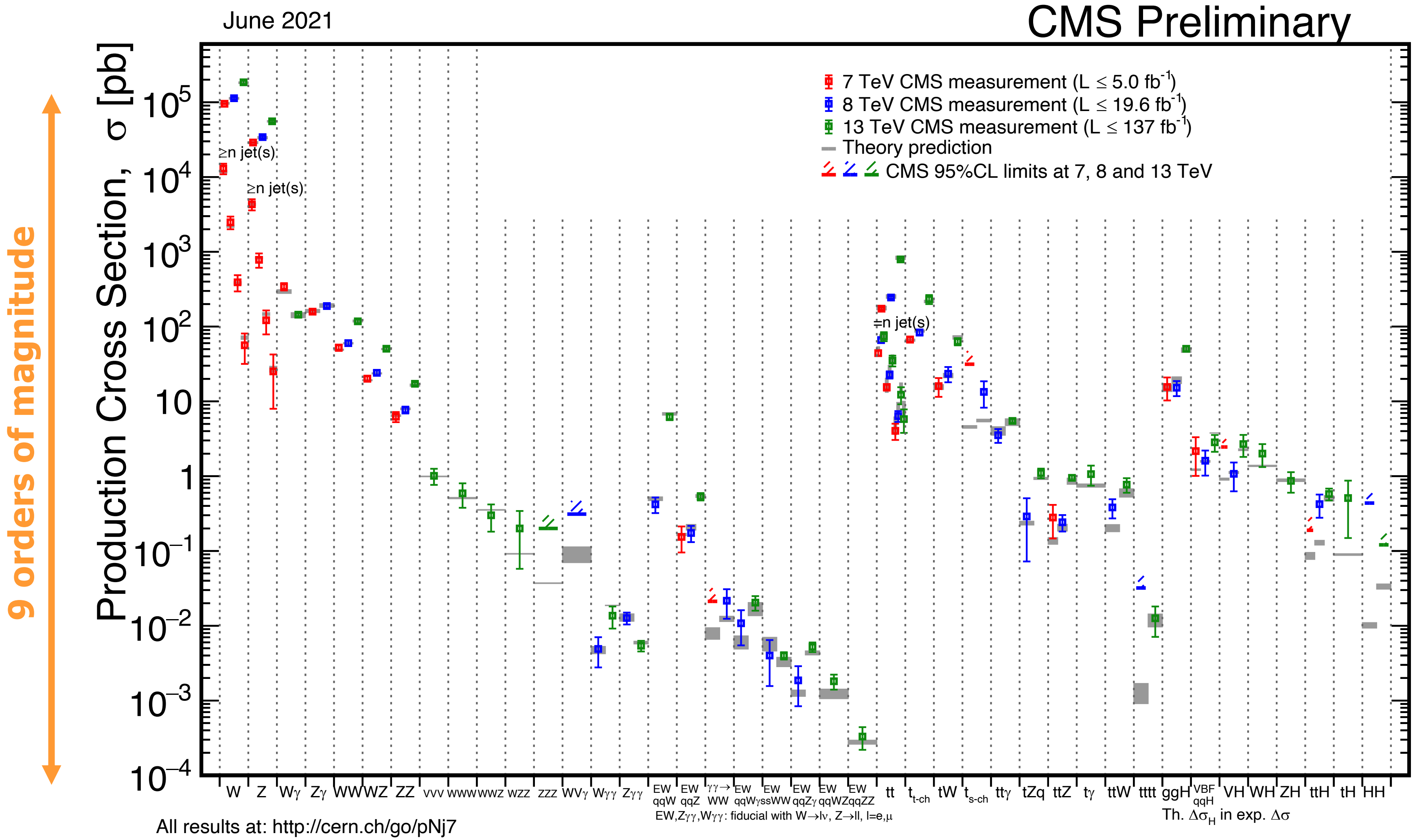
Beyond the Standard Model

- Despite the SM success, extensions are necessary if one wants to explain, for example:
  - the baryon asymmetry
  - dark matter
  - the parameters which look unnatural or accidental (hierarchy, absence of strong CP violation, mass hierarchy of the flavours / mixing)

- Around a hundred theorists involved in these studies, also connecting them to cosmological and astrophysical results
  - development of new avenues, phenomenology, studies of parameter coverage, precise computations, development of prediction tools and global fits, reinterpretation of results,...

- Even if BSM physics has not been discovered yet, the direct and indirect searches have permitted to constrain the models
  - A few tensions must also be followed, the muon anomalous magnetic moment and the anomalies in the B meson decays suggesting a possible lepton universality violation
  - The next decade should help us clarify these

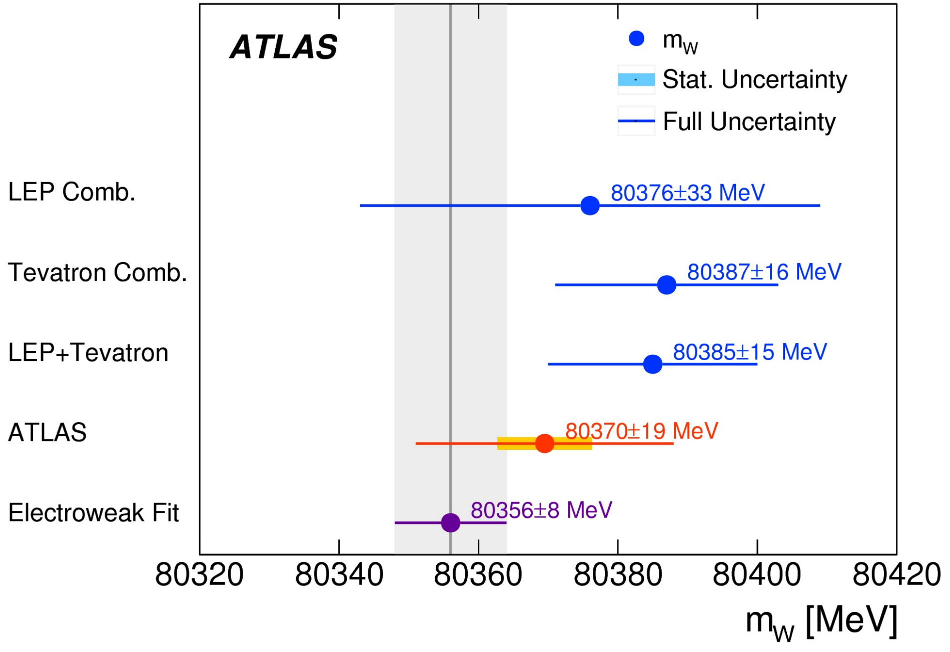
The Big Picture

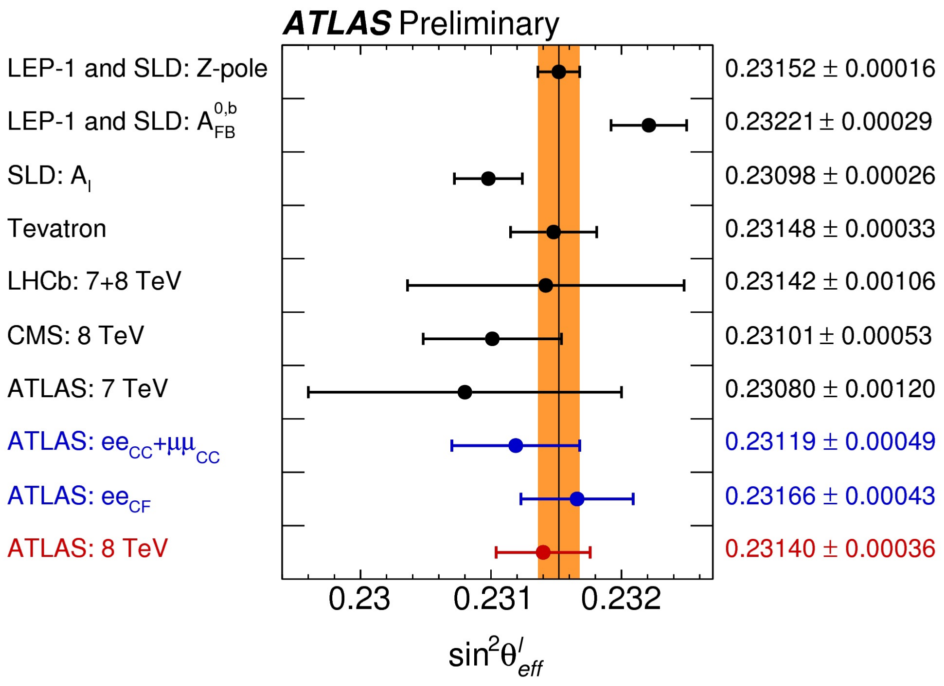


Electroweak **Top** **Higgs**

The Big Picture: electroweak

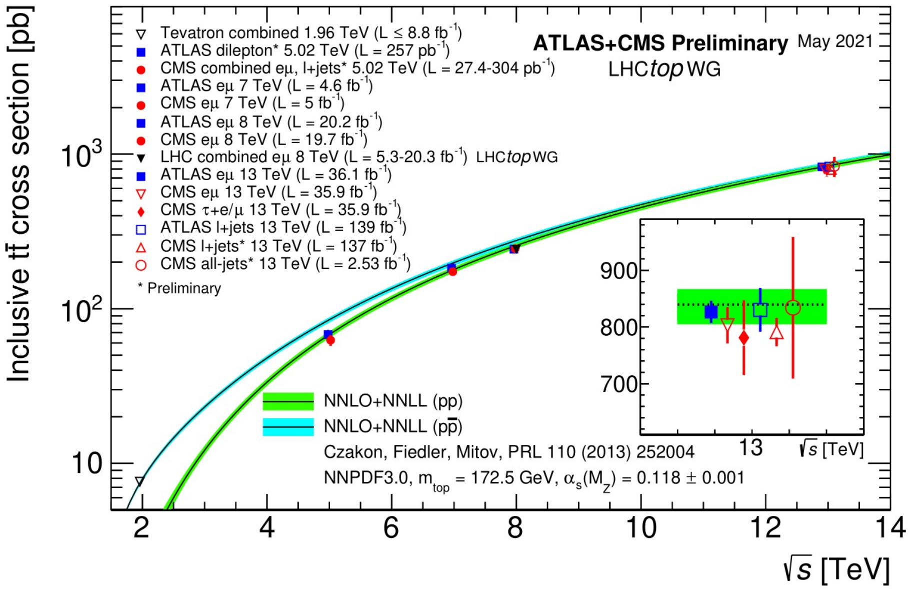
- EWK observables measured at percent precision (or better) at LEP, SLD, TeVatron, LHC,…

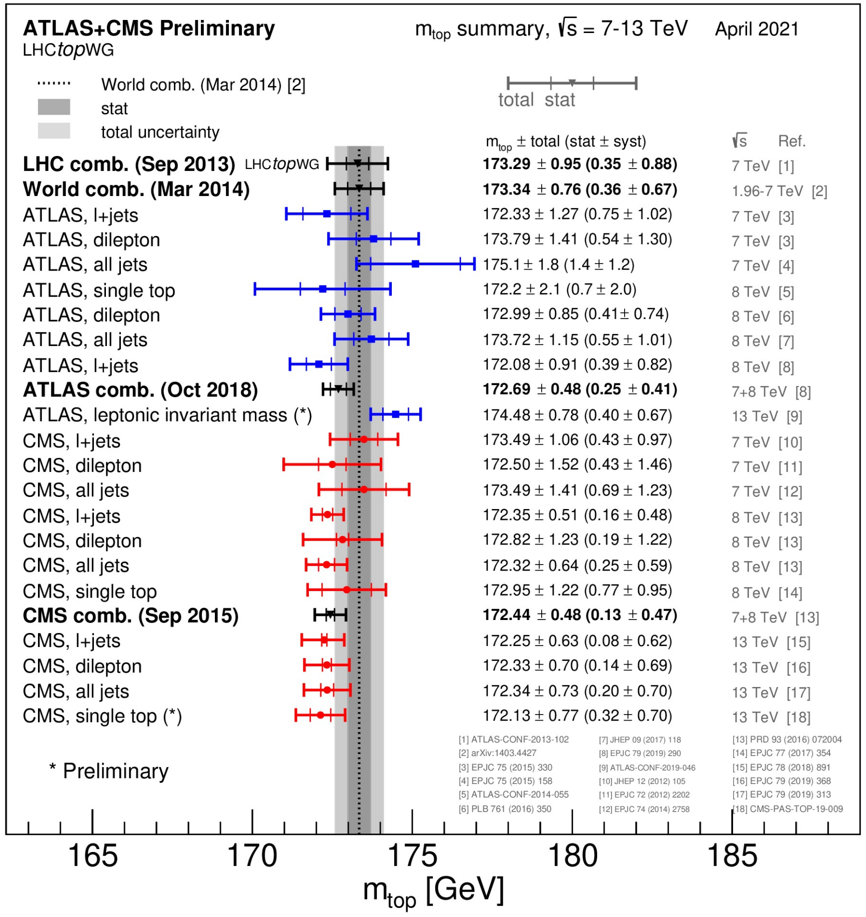




The Big Picture: top

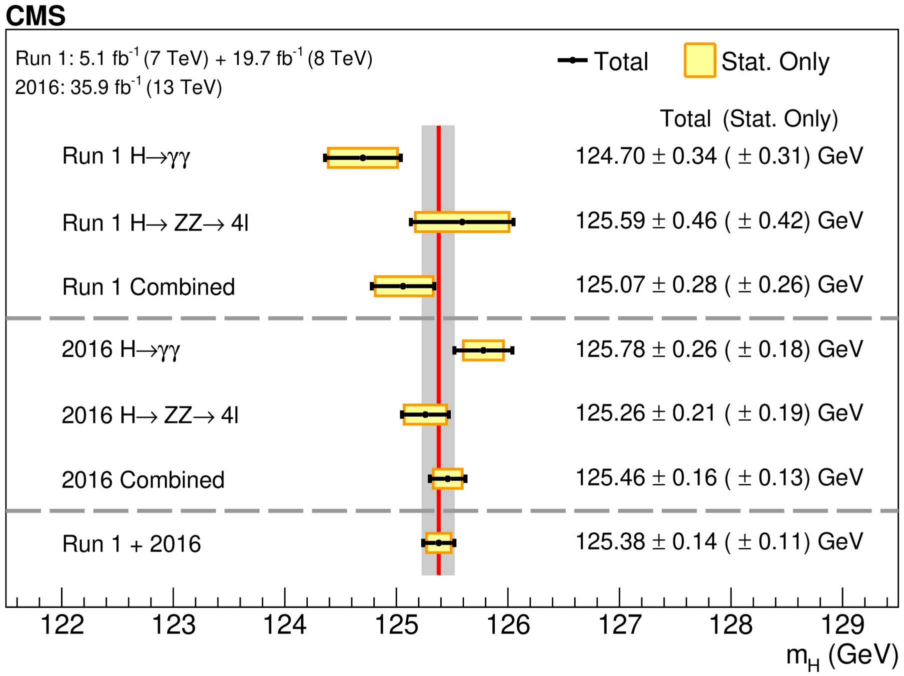
- Top quark: special role in electroweak symmetry breaking?
- m_t known to 500 MeV
- Knowledge of processes with top: limiting factor in many analyses

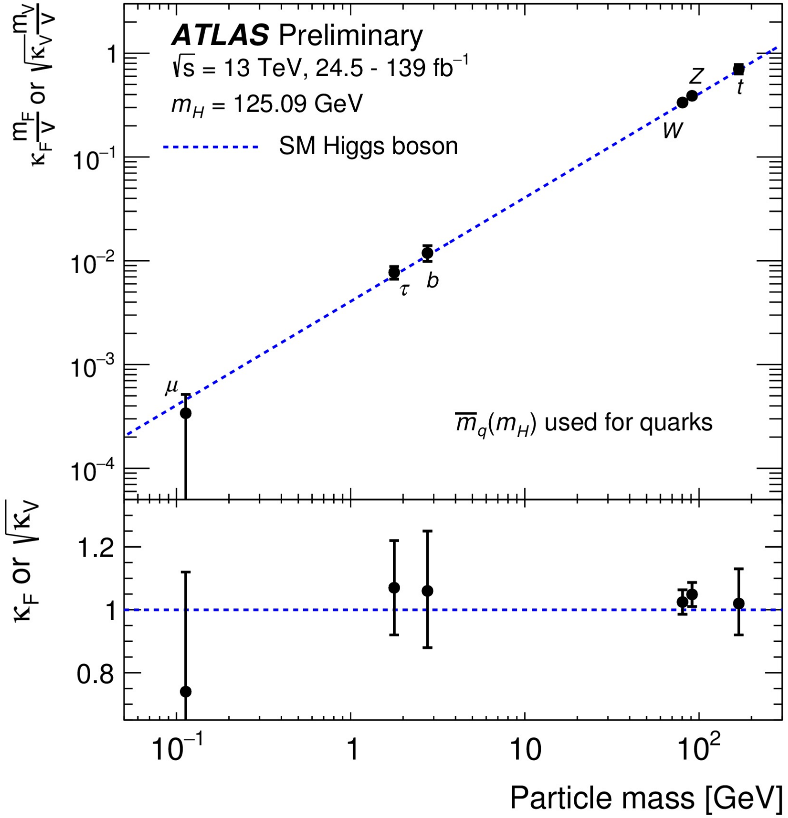




The Big Picture: Higgs

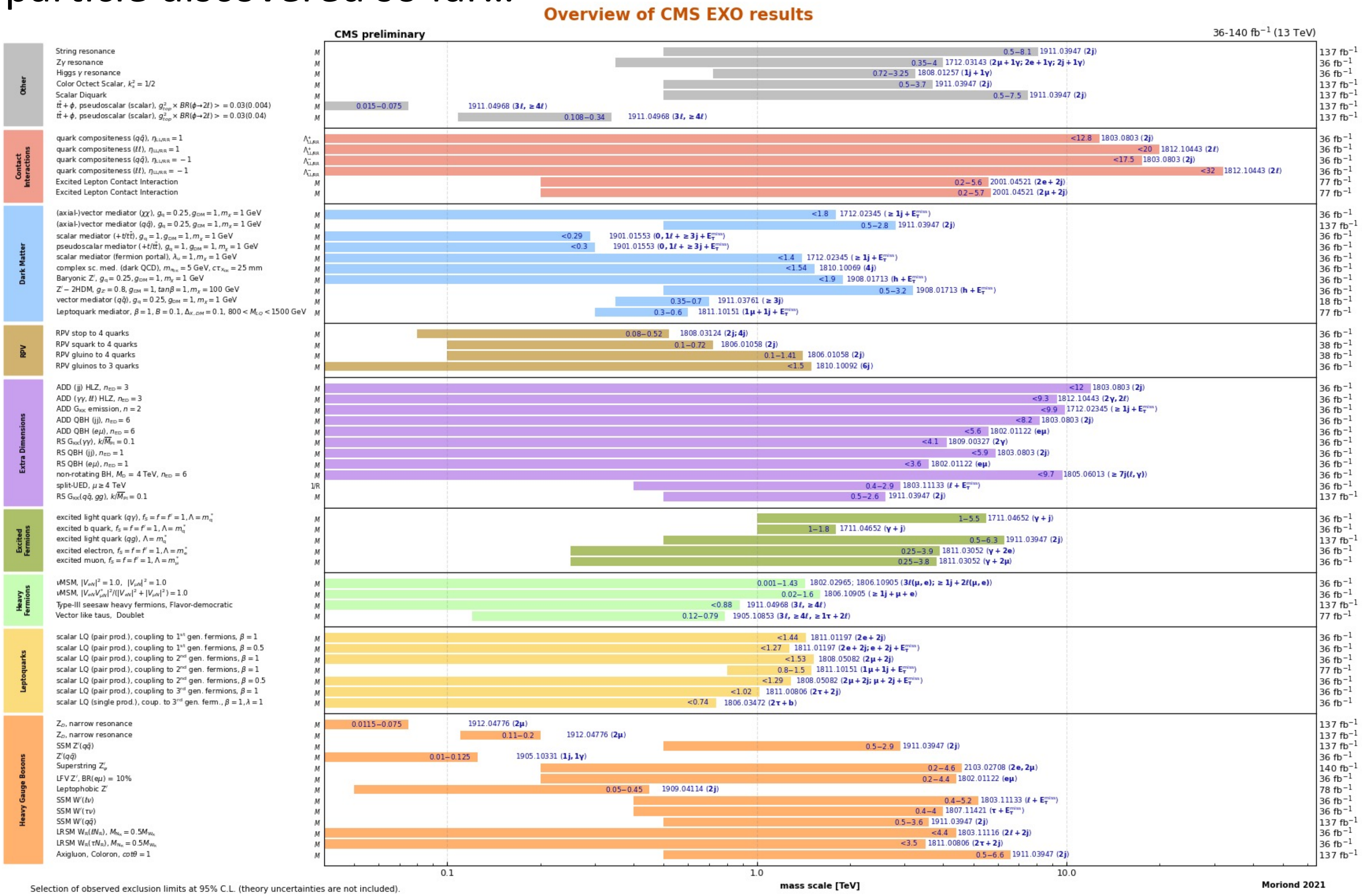
- Couplings to vector boson & 3rd generation fields known up to ~10%
- m_H=125.38 GeV with 0.11% precision & narrow width ($\Gamma_H = 3.2^{+2.8}_{-2.2}$ MeV)
- 0^+ state favoured over other J^{PC} hypothesis





The Big Picture: beyond the Standard Model

- No new particle discovered so far…

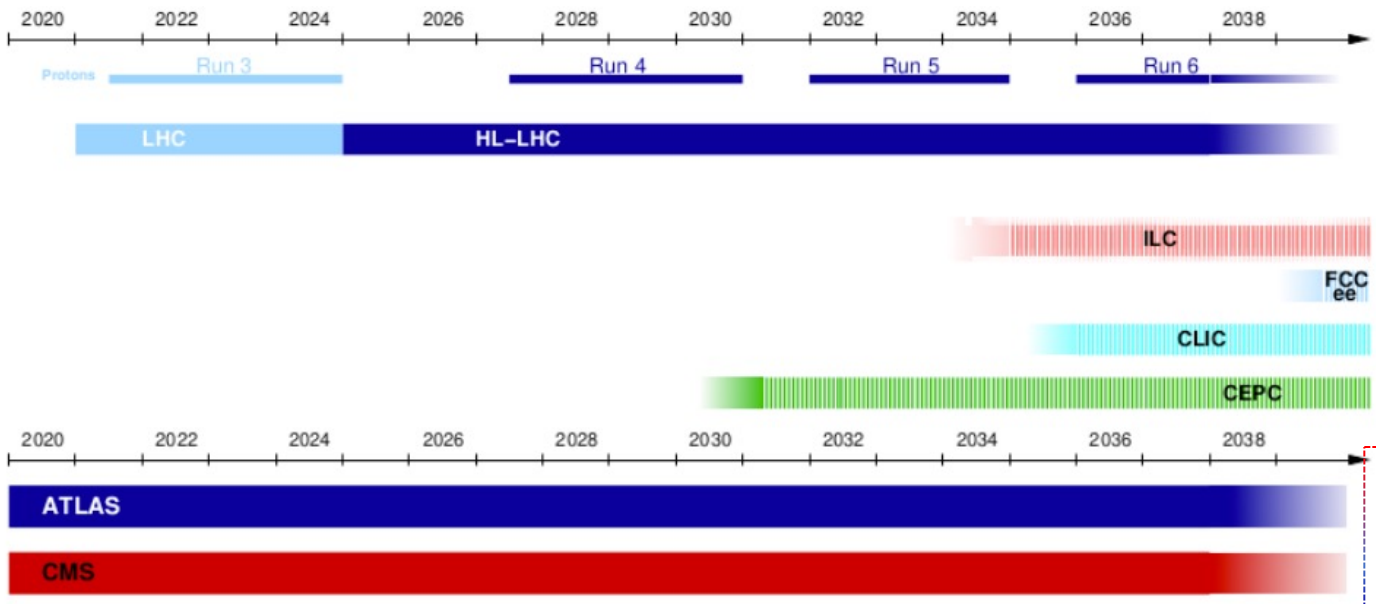


The identified science drivers

1. Characterize precisely the Higgs sector, is it standard or not ?
2. Measure precisely the particles carrying the imprint of the Higgs mechanism (electroweak bosons, top quark, ...).
3. Search directly for new particles which could solve open issues, such as the nature of dark matter or the hierarchy problem, covering as much parameter space as possible: low couplings, high masses, challenging signatures,...
4. Study of matter-antimatter asymmetry and flavor transitions in the quark sector.
5. Test lepton universality and search for charged lepton flavor violation.
6. Help resolve cosmological questions, especially those pointing towards new dynamics (inflation, modified gravity, baryogenesis,...) or new forms of matter.

Greyed SDs will be mostly discussed in the next talk by C. Smith

What tools do / could we have?



Future colliders:

linear e^+e^- @ at 250 GeV (up to 1 TeV), could start around 2035

circ. e^+e^- @ high lumi, after HL-LHC; could be followed by FCC-hh

linear e^+e^- @ around 380 GeV (up to 3 TeV)

like FCC-ee for construction time; no constraint from HL-LHC

Run-2 analyses + Run-3 preparation
Upgrade work (+ computing infrastructure) for a successful exploitation of HL-LHC (1000 fb^{-1} in 2030, 3000 fb^{-1} in 2039)

Other projects discussed within GT01 will be covered in the next talk by C. Smith

Link between projects and science drivers

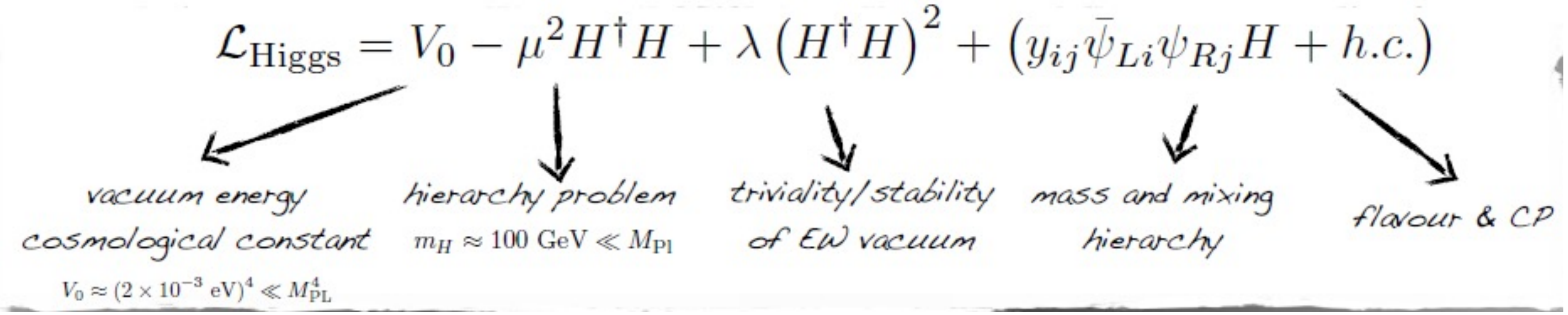
Project	project scale	interest in FR	SD1 Higgs sector	SD2 Higgs imprint	SD3 direct searches	SD4 quark flavors and CP	SD5 charged lepton flavors	SD6 cosmology
Energy frontier								
ATLAS&CMS@LHC/HL-LHC	€€€	★★⯪	***	***	***	*	*	-
ILC	€€	★★	***	***	*	-	-	*
CLIC	€€	★⯪	***	***	***	-	-	*
FCCee	€€	★★	***	**	*	***	***	*
CEPC	€€	★	***	**	*	***	***	*
High-energy pp	€€€	★★	***	***	***	**	**	-
Intensity frontier								
Belle-II	€	★	-	-	-	***	***	-
LHCb Ia	€€	★⯪	-	-	-	***	***	*
LHCb Ib	€	★⯪	-	-	-	***	***	*
LHCb II	€€	★⯪	*	-	-	***	***	*
Dedicated experiments								
n2EDM	€	★	-	-	-	***	-	-
COMET	€	★	-	-	-	-	***	-
OSQAR/VMB	<€	⯪	-	-	**	-	-	*
GBAR/AEgIS	<€	☆	-	-	-	-	-	**
CODEX-b	<€	⯪	-	-	**	-	-	*
SHiP	€	☆	-	-	**	-	-	*

Talk by Christopher Smith

Project scale: rough estimate of the material construction cost in O(10^n) M€
Interest in France: (or participation for ongoing ones): estimation in O(10^n) physicists

1. Higgs boson prospects

- The Higgs boson is a fundamental scalar particle and its theory is unlike anything else we have seen in nature.
- It is linked to several deep problems in High Energy Physics:



From C. Grojean

Getting (some) answers to the open questions and problems of the SM thus requires:

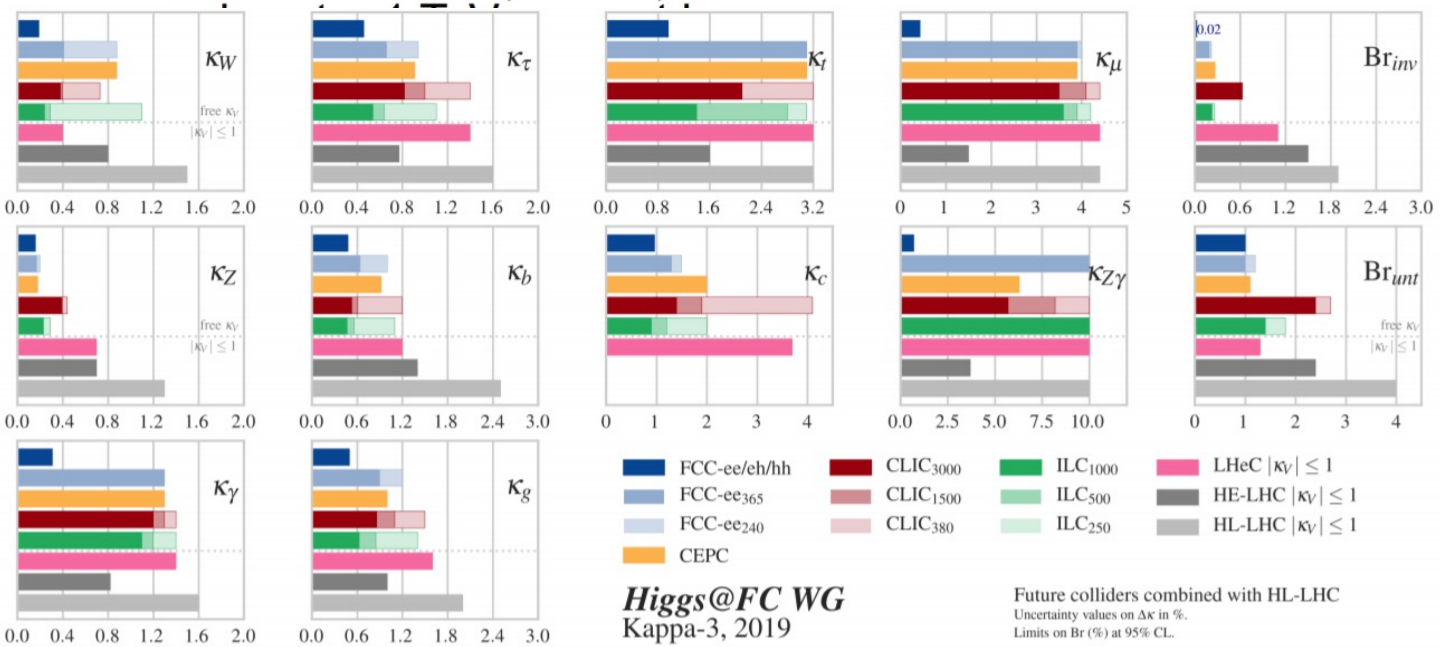
High Precision measurements (<=> deviation wrt minimal theory):
- In the Higgs sector…
- … but also in Top & EWK sectors

Continue direct searches
- Low mass/couplings (needs luminosity)
- Higher mass (needs energy)

1. Higgs boson prospects

Deviations of the Higgs coupling by New Physics: $\Delta \frac{g}{g_{SM}} < 5\% \left(\frac{1TeV}{\Lambda}\right)^2$

- **Is it THE Higgs from the SM?**
- Is it fundamental or composite?
- Does it couple to Dark Matter?
- Are there other Higgses?



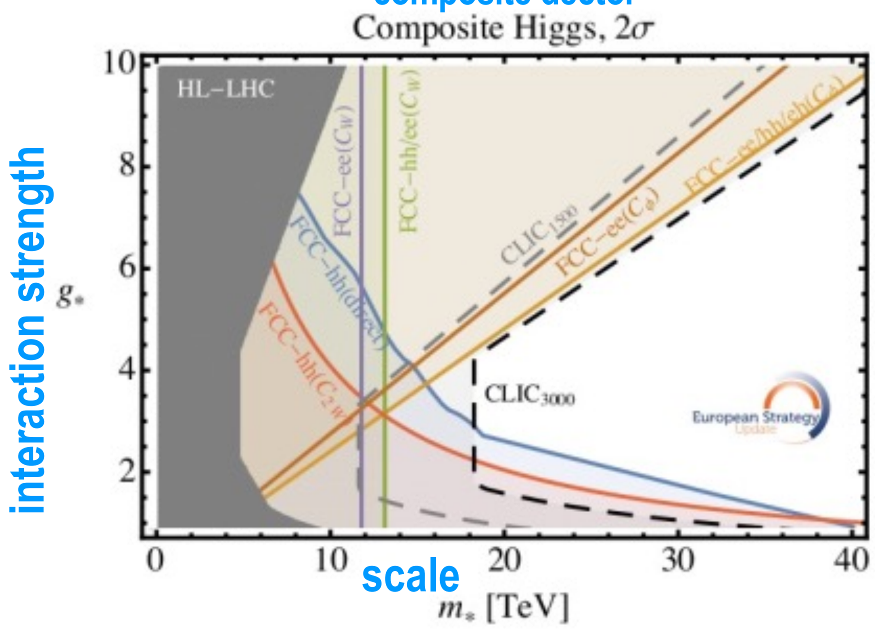
Need (sub-)percent precisions on couplings !

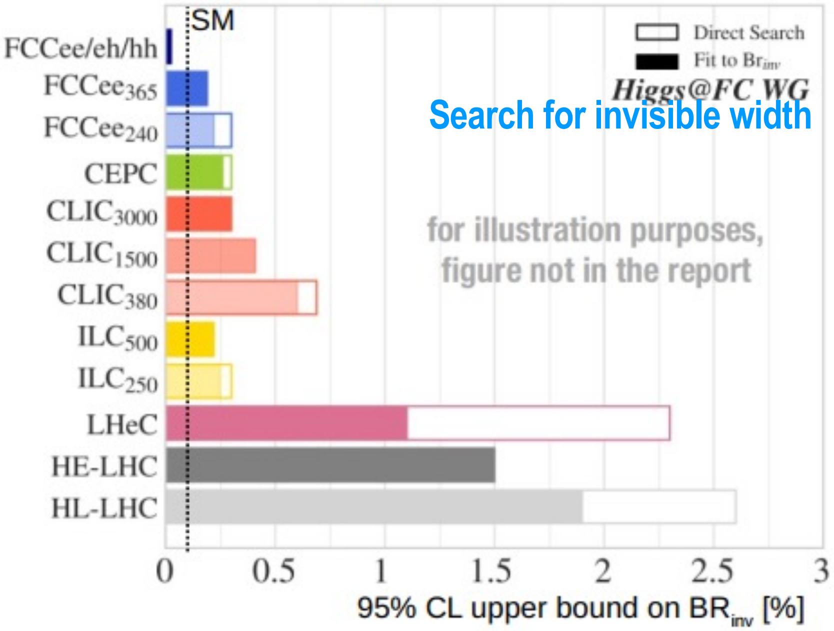
- 2nd generation already within observation reach
- 1st is probably unreachable in the next decades…
- **Also, need to look at rare (H→Zγ, H→Qγ, …), forbidden (H→eμ, …) decays**

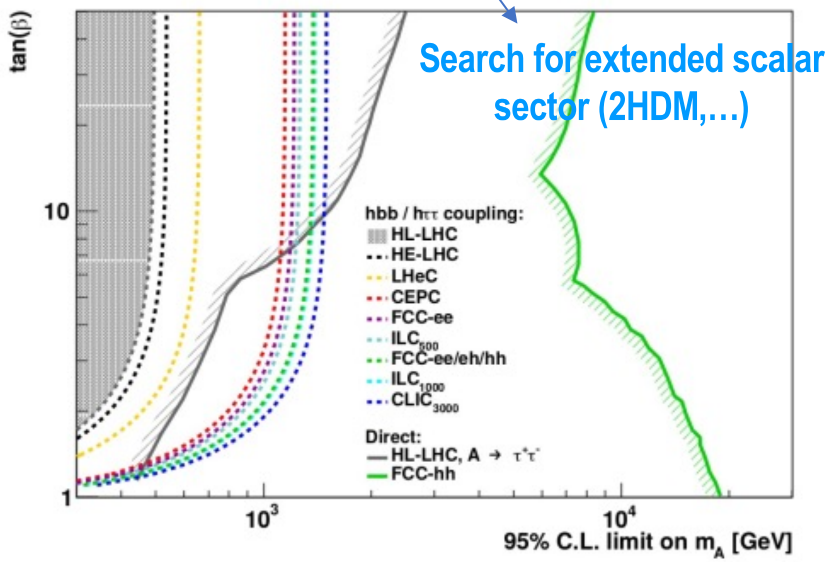
1. Higgs boson prospects

- Is it THE Higgs from the SM ?
- **Is it fundamental or composite ?**
- **Does it couple to Dark Matter?**
- **Are there other Higgses ?**

Higgs as a bound state of a new strongly-interacting confining composite dector



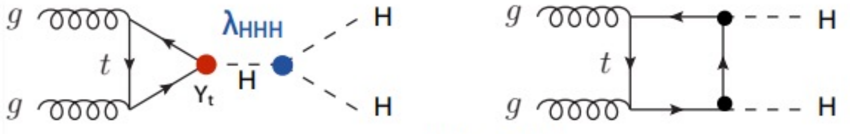




1. Higgs boson prospects

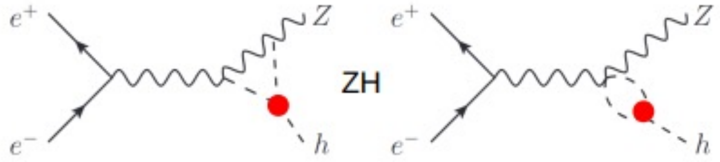
Probing Higgs-Self coupling (λ_{HHH}) is mandatory: dictates the dynamics of the electroweak phase transition

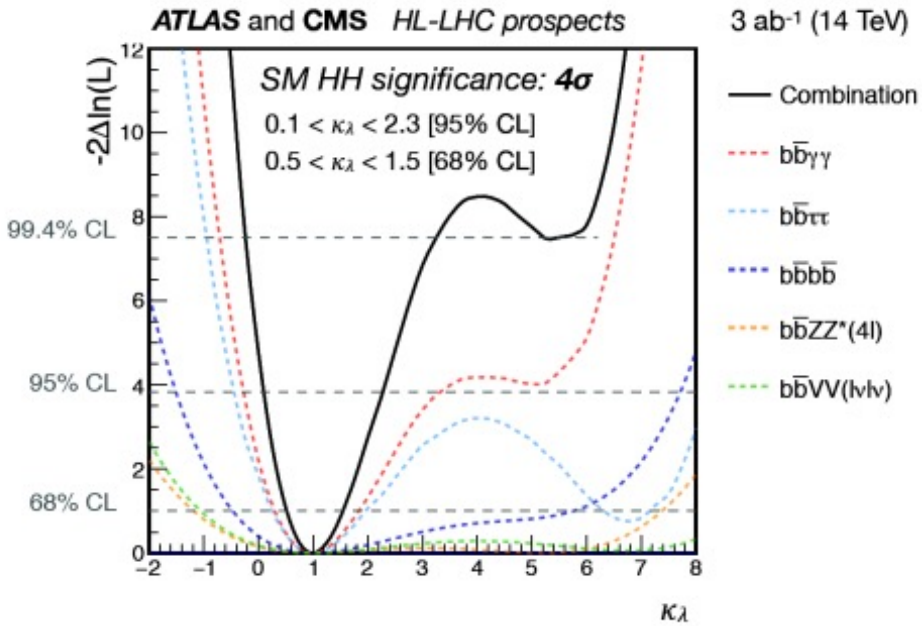
- Directly search via Di-Higgs production:

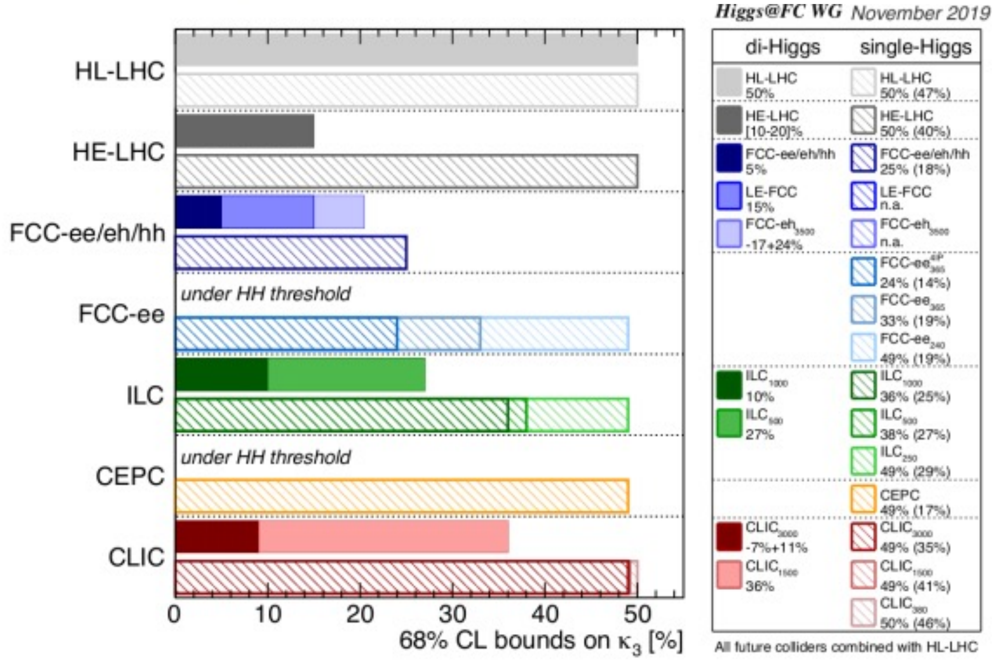


σ(gg→HH) = 33.5 fb
[@13 TeV, NNLO + NNLL with top mass effects]

- Indirectly, via single-H constraints:



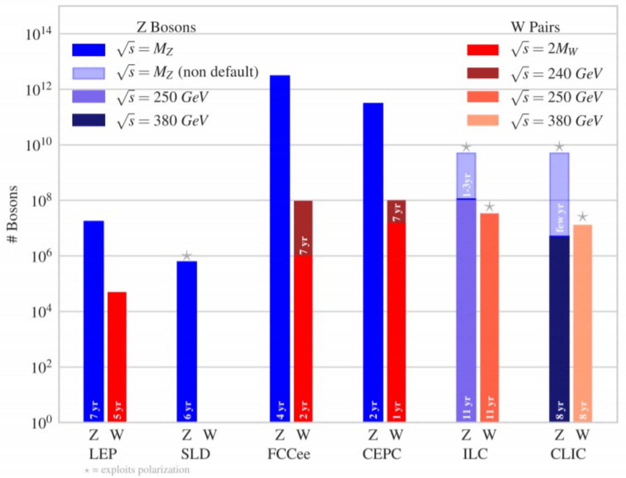




2. EWK Prospects

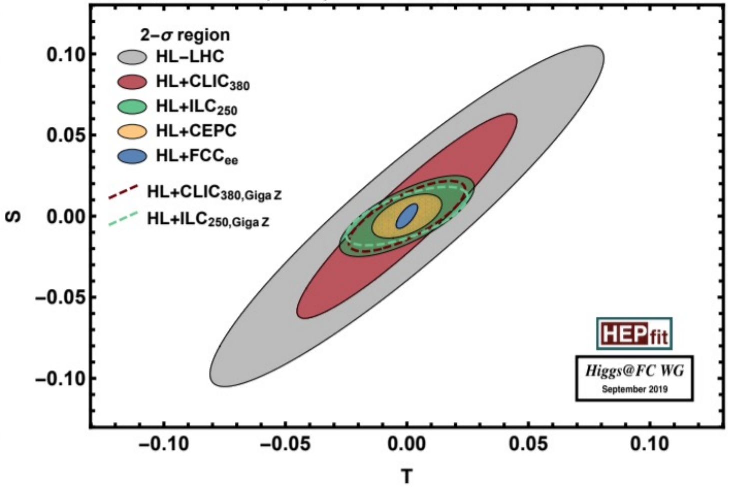
EWK Precision Observables are powerful tools to constraint New Physics: need unprecedented precision

Possible with W/Z factories

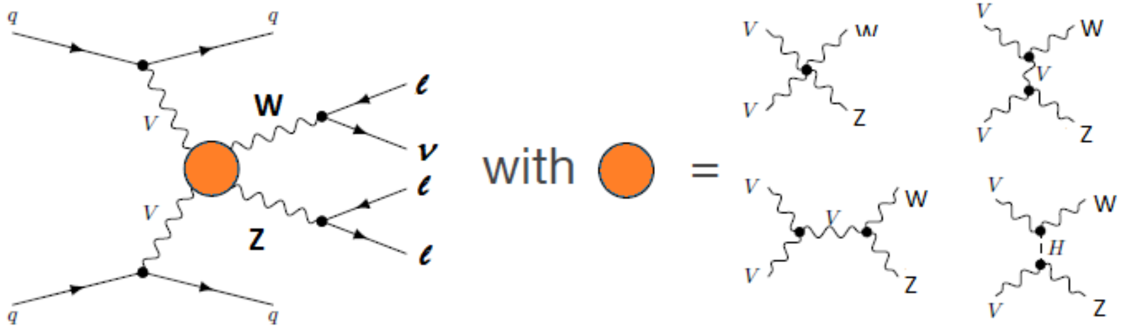


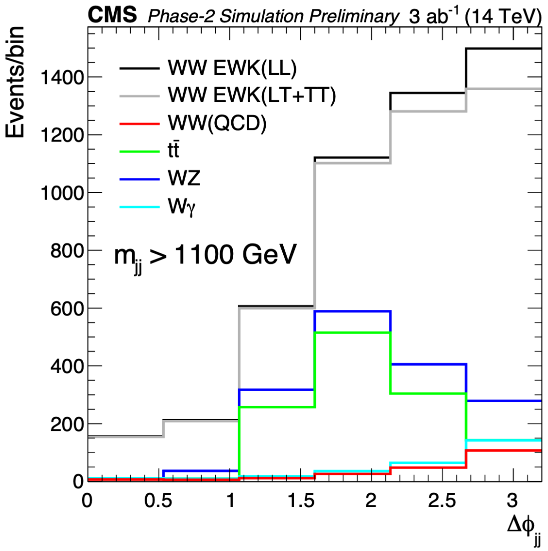
EWPO	Current	CEPC	FCC (ee)
M_Z [MeV]	2.1	0.5	0.1
Γ_Z [MeV]	2.1	0.5	0.1
N_ν [%]	1.7	0.05	0.03
M_W [MeV]	12	1	0.67
$A_{FB}^{0,b}$ [x10^4]	16	1	< 1
$\sin^2\theta_W^{\rm eff}$ [x10^5]	16	1	0.6
R_b^0 [x10^5]	66	4	2–6
R_μ^0 [x10^5]	2500	200	100

Constraints on oblique parameters
(T mainly depends m_W, S on $\sin^2\theta_W$)



➢ Also: mandatory to look for VBF/VBS





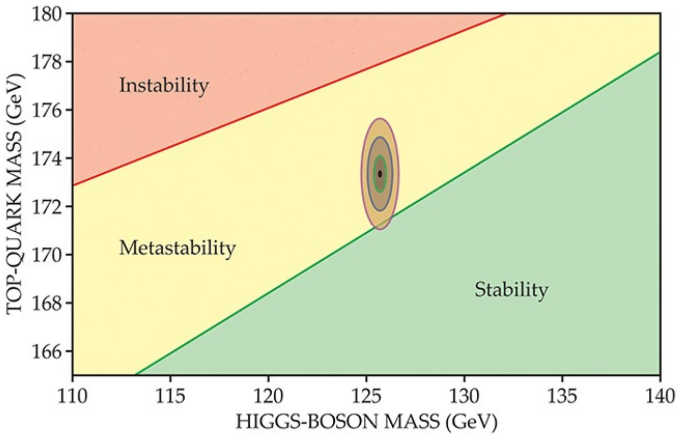
Gauge Structure (aTGC, aQGC) + EWSB mechanism

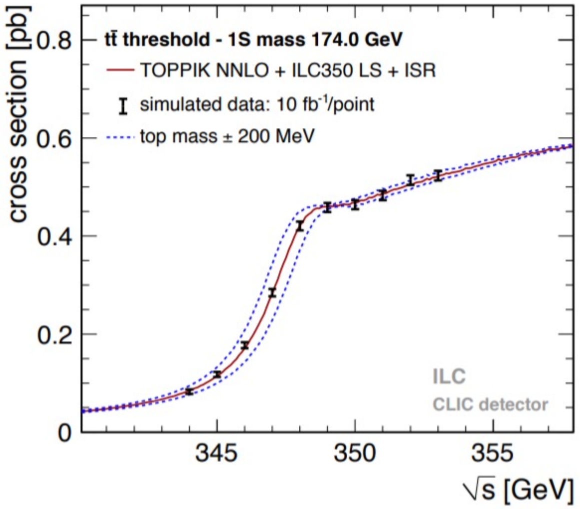
$V_L V_L$ only a few% of total VBS cross-section…

2. Top Prospects

Another avenue to challenge the SM and probe NP: explore deeper the top quark sector

- Top mass related to stability of EWK-vacuum:





100 MeV doable at e+e- colliders with threshold scans techniques

- Searches/Measurement of rare processes:

- $t\bar{t}$: 832 pb — **QCD production** discussed earlier

- t-channel: 217 pb
- tW: 72 pb
- s-channel: 10 pb

EW production, probe Wtb vertex (V_{tb}, dipoles), PDFs, but also m_t – arXiv:1710.10699

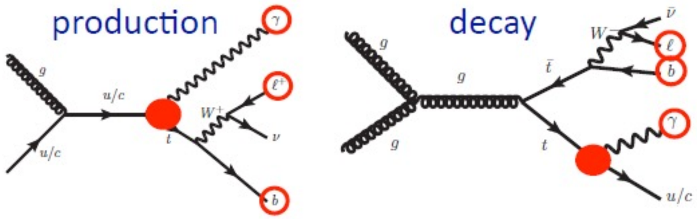
- $t\bar{t}Z$: 0.8 pb
- $t\bar{t}W$: 0.6 pb
- $t\bar{t}\gamma$: $\sim$ 0.5 pb
- $t\bar{t}H$: 0.6 pb
- $t\gamma q$: 0.6 pb
- tZq: 0.6 pb

Few 100's fb: rare processes. Low couplings and/or high mass final-state. probes $Zt\bar{t}$, $\gamma t\bar{t}$, FCNC, ... first observation of tZq: 2018

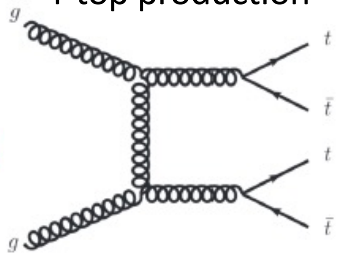
- tHq: 75 fb
- $t\bar{t}t\bar{t}$: 12 fb
- $t\bar{t}tX$: 1.6 fb

Few 10's fb and below: very rare processes, not observed yet. Sensitive to C_{4t}, sign(y_t), ...

FCNC (forbidden at tree level, suppressed @NLO)



4-top production

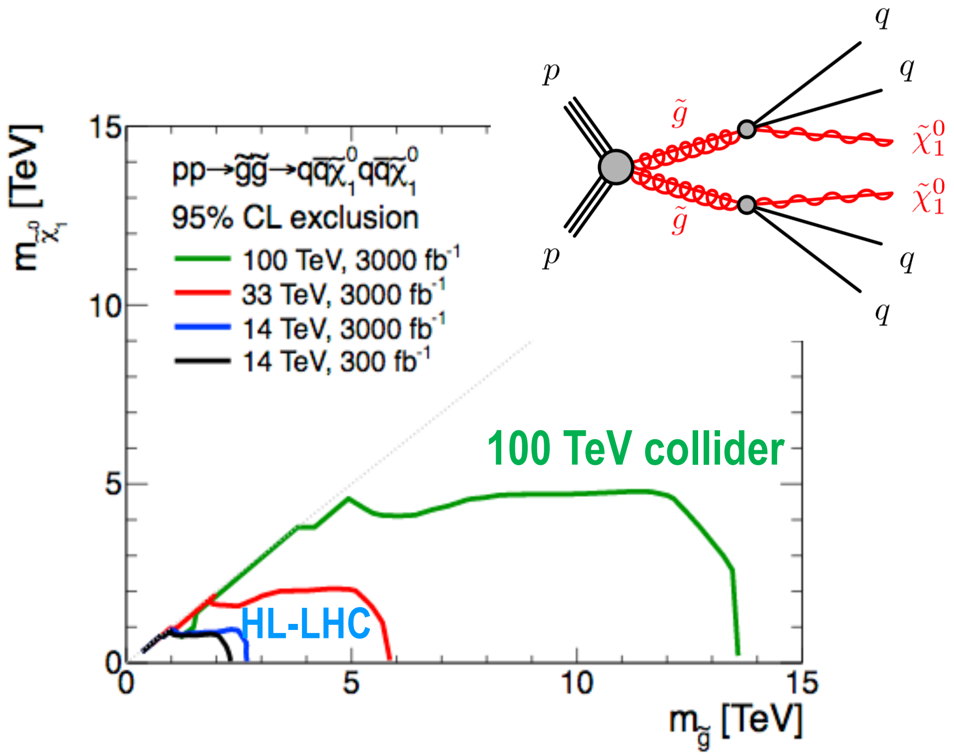


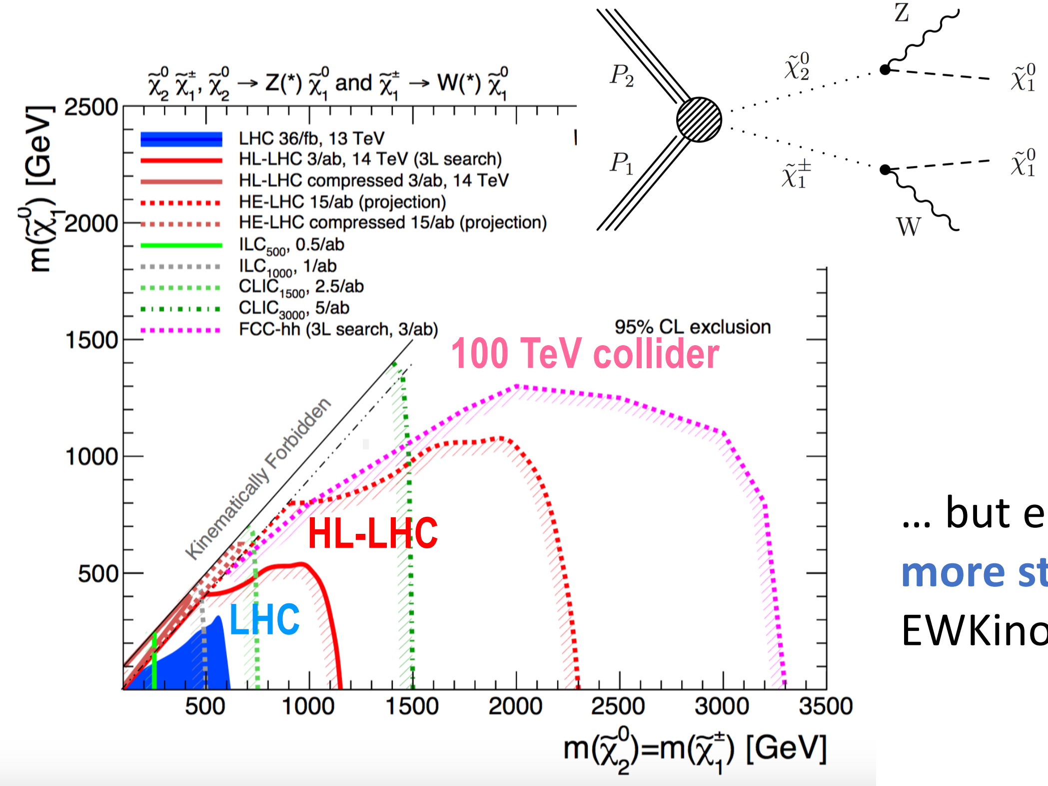
3. BSM prospects

Are there new interactions or new particles around or above the EWK scale ?

- Direct searches continues, with broad number of candidates
  - SUSY (squarks, gluinos,…), W', Z', excited leptons, …

Going to **higher energy** is a must for several signatures…

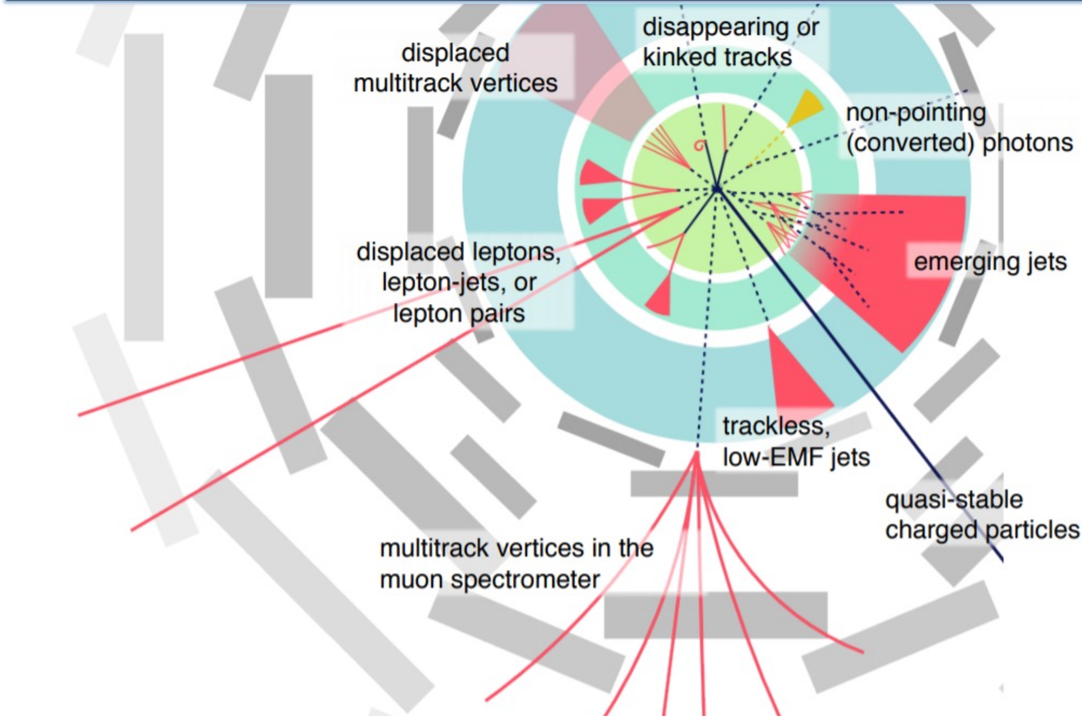


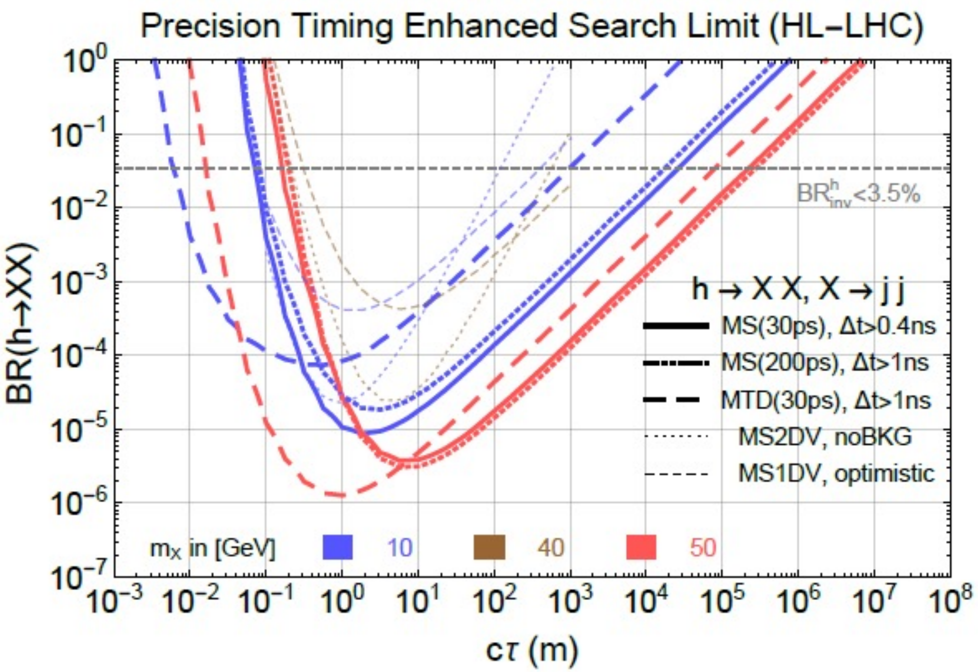


… but emphasis will also shift to **modes requiring more statistics** to be effectively probed (stop, EWKino, …)

3. BSM prospects

- A wide range of BSM models introduce long-lived and/or weakly coupled particles (R-parity violating / Gauge mediated /… SUSY, asymmetric / composite DM, …)
  - Growing interest
  - Need dedicated and complex reconstruction algorithms
  - Will benefit from new techniques and upgraded detectors (fast-timing)





Theoretical aspects

- Ultimate precision cannot be achieved without important progress on theoretical calculations
- Examples for ee colliders:

More theory work needed to match EXP uncertainties

	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
ΔM_Z[MeV]	2.1	0.5	0.1			
$\Delta\Gamma_Z$[MeV]	2.3	1	0.1	0.4	$\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$	0.15
$\Delta \sin^2\theta^\ell_{eff}[10^{-5}]$	23	1.3	0.6	4.5	$\alpha^3, \alpha^2\alpha_s$	1.5
$\Delta R_b[10^{-5}]$	66	14	6	11	$\alpha^3, \alpha^2\alpha_s$	5
$\Delta R_\ell[10^{-3}]$	25	3	1	6	$\alpha^3, \alpha^2\alpha_s$	1.5

The greatest challenges: (+ many more very demanding tasks)

- Z:
  - ◇ full EW 2-loop calculation for off-shell $e^+e^- \to f\bar{f}$ + theoretically sound concept of pseudo-obervables
  - ◇ massive 3-loop calculations for $1 \to 2$ decays and μ decay
- WW:
  - ◇ NNLO threshold EFT calculation for $e^+e^- \to WW$
- Higgs:
  - ◇ full EW 2-loop calculation for off-shell $e^+e^- \to ZH$
  - ◇ massless 4-/5-loop QCD calculations for $1 \to 2$ decays

- Similar for hadron colliders: need better precision for PDFs, α_s, …

Theoretical aspects

- Interpretations of measurements will require closer and closer theory-experiments links

SMEFT: $\mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d$

SM particles & symm.

NP decouples for $\Lambda \to \infty$

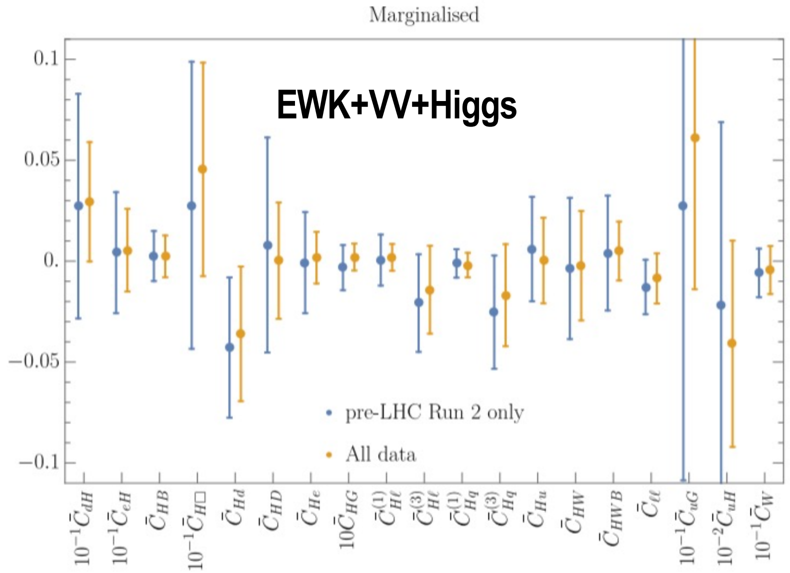
$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i$$

$$= \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

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

Observ. Effects $q = v, E < \Lambda$

Interpretations with Effective Field Theory, constraining 6-dim or 8-dim operators



Towards global fits with Higgs, EWK & Top..

Energy Frontier: recommendations

For the **high energy frontier** the group's recommendations are:

1. Exploit the current LHC data collected by ATLAS and CMS in Run–2, ensure the successful upgrade of the detectors for Run–3 and HL-LHC and exploit the data that will be collected in these phases. Support for theory and phenomenology is mandatory for the success of the HL-LHC.

2. Support the construction of an e^+e^- collider running at the Higgs production resonance upgradable to higher energies. Support the theoretical effort to reach the expected precision of the measurements as well as the phenomenological studies.

3. Support the studies of the physics potential and performance requirements for a future high energy proton–proton machine.

Links to other GTs

Transverse to all experiments **technological developments** are recommended:

1. Support developments in detectors, accelerators, computing and algorithms (e.g., Machine Learning, data flow etc), as they are common challenges for multiple projects. A strong connection between physicists and engineers of several working groups (GT07, GT08, GT09) is necessary.

GT
- 07: Accélérateurs et instrumentation associée
- 08: Détecteurs et instrumentation associée
- 09: Calcul, algorithmes et données

Interdisciplinary

In order to reach the physics goals it is necessary to collaborate **beyond the boundaries of GT01**, e.g., GT03, GT04, GT06:

1. Putting together the results from different experiments and exploring alternative routes to test the SM and search for New Phenomena necessitate a close collaboration between experimentalists and theorists which are addressed in the GDR/IRNs. The work of and in the GDR/IRNs should be supported.

IRN and GDRs:

- Terascale
- Intensity Frontier
- QCD
- Neutrino

GT connections:

- 05: Physique de l'inflation et énergie noire
- 06: Physique des neutrinos et matière noire
- 03: Physique hadronique
- 04: Physique des astroparticules

20 octobre 2021

Exercice de prospective nationale en physique nucléaire, physique des particules et astroparticules

Développements technologiques et applications associés

GT01: Physique des Particules

A Tale of Two Frontiers: Energy & Intensity

Part II : Intensity Frontier and Dedicated experiments

Based on the talks and contributions received
https://indico.in2p3.fr/event/19802/overview

M-H. Genest, C. Ochando, F. Polci, *C. Smith*, L. Vacavant, D. Zerwas.

Why aim at the intensity frontier?

Fully exploit the peculiarities of the Standard Model flavor sector

The flavor sector is the least constrained (2/3 free SM parameters)

Yet, there are many (mostly unexplained) patterns, hierarchies, accidents

→ Many processes happen to be suppressed/forbidden in the SM

Quark flavor transitions & CP violation are small,
and always proceed through the weak interactions,

Lepton flavor transitions are forbidden (for massless neutrinos)

Baryon & lepton numbers are conserved

Since New Physics need not share the same properties, a powerful strategy is:

To use the long-lived/stable states (μ, τ, K, D, B, n, p, ...) for

Flavor experiments — Precision measurements of small observables,

Dedicated experiments — Search for (quasi) forbidden effects.

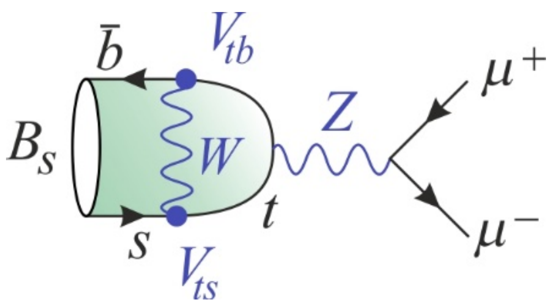
I. Flavor Experiments

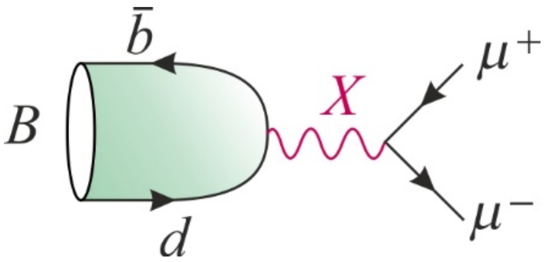
Flavor experiments : How far can they go to test the SM?

An example: The Z penguin flavor changing neutral current

The sensitivity of rare decays to New Physics:

$$B_s \to \mu^+ \mu^-$$





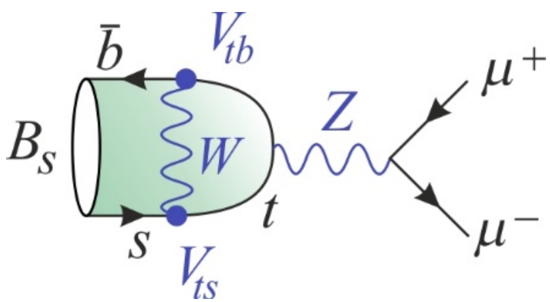
Flavor experiments : How far can they go to test the SM?

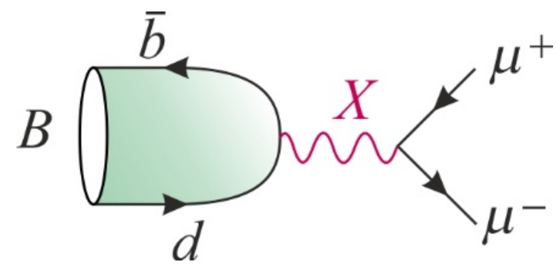
An example: The Z penguin flavor changing neutral current

The sensitivity of rare decays to New Physics:

$$B_s \to \mu^+\mu^- \quad \sim \frac{g^2}{4\pi^2}\frac{g^2}{M_W^2}(V_{tb}^{\dagger}V_{ts}) \leftrightarrow \frac{1}{M_X^2} \quad \Rightarrow M_X > 10\,TeV$$

$V_{tb}^{\dagger}V_{ts}$: 0.04

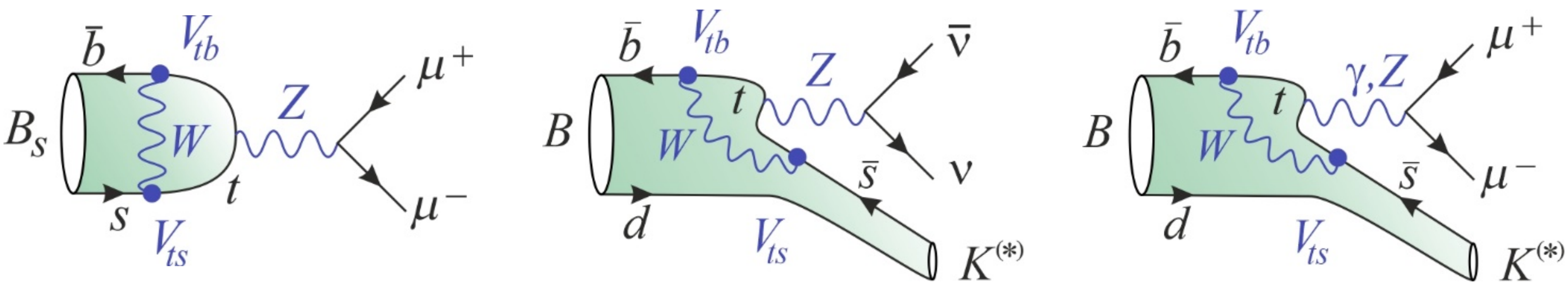




Flavor experiments : How far can they go to test the SM?

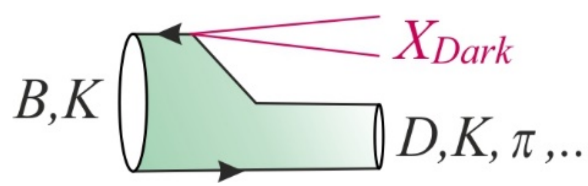
An example: The Z penguin flavor changing neutral current

$B_s \to \mu^+\mu^-, \phi\ell^+\ell^-, \phi\nu\bar{\nu}, \ldots$	$\lvert V_{tb}^\dagger V_{ts} \rvert \sim 0.04$	$\Rightarrow M_X > 10\,TeV$
$B \to \mu^+\mu^-, K\ell^+\ell^-, K\nu\bar{\nu}, \ldots$	$\lvert V_{tb}^\dagger V_{td} \rvert \sim 0.008$	$\Rightarrow M_X > 20\,TeV$
$K \to \pi\nu\bar{\nu}$	$\lvert V_{ts}^\dagger V_{td} \rvert \sim 0.0003$	$\Rightarrow M_X > 100\,TeV$



Probe new physics in the TeV range, but also at the opposite frontier:

$$\frac{g^2}{4\pi}\frac{g^2}{M_W^2}(V_{ij}^\dagger V_{ik}) \leftrightarrow \frac{g_{Dark}}{M_{B,K}^2}$$



Flavor experiments : How far can they go to test the SM?

An example: The Z penguin flavor changing neutral current

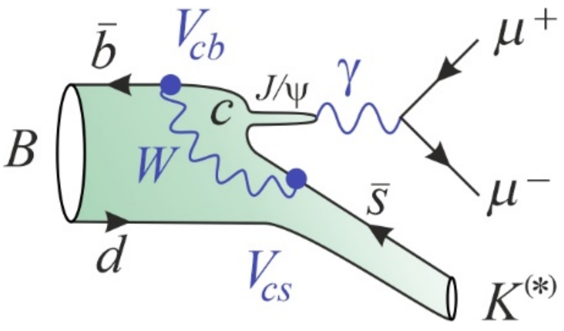
$B_s \to \mu^+\mu^-, \phi\ell^+\ell^-, \phi\nu\bar{\nu}, \ldots$	$\lvert V_{tb}^\dagger V_{ts} \rvert \sim 0.04$	$\Rightarrow M_X > 10\, TeV$
$B \to \mu^+\mu^-, K\ell^+\ell^-, K\nu\bar{\nu}, \ldots$	$\lvert V_{tb}^\dagger V_{td} \rvert \sim 0.008$	$\Rightarrow M_X > 20\, TeV$
$K \to \pi\nu\bar{\nu}$	$\lvert V_{ts}^\dagger V_{td} \rvert \sim 0.0003$	$\Rightarrow M_X > 100\, TeV$

To effectively use these modes to test the SM:

Precision calculations to predict the SM contributions

Very challenging at the hadronic scale

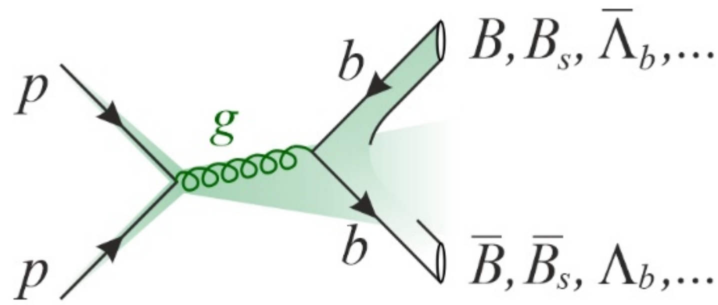
→ decay constants, form factors, charm contributions



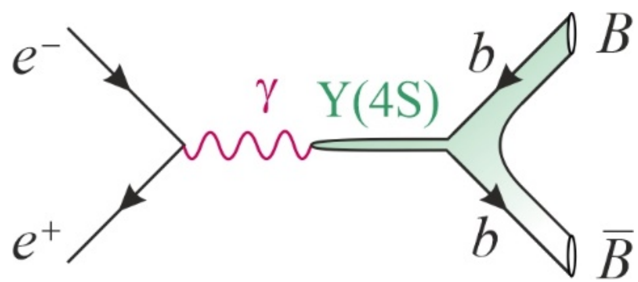
High intensity to measure these very small SM rates.

Flavor experiments : Projects and timescale

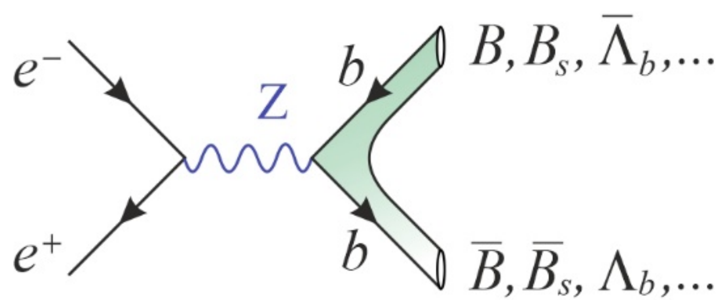
Current and planned B physics experiments



All b hadrons
Large production rate



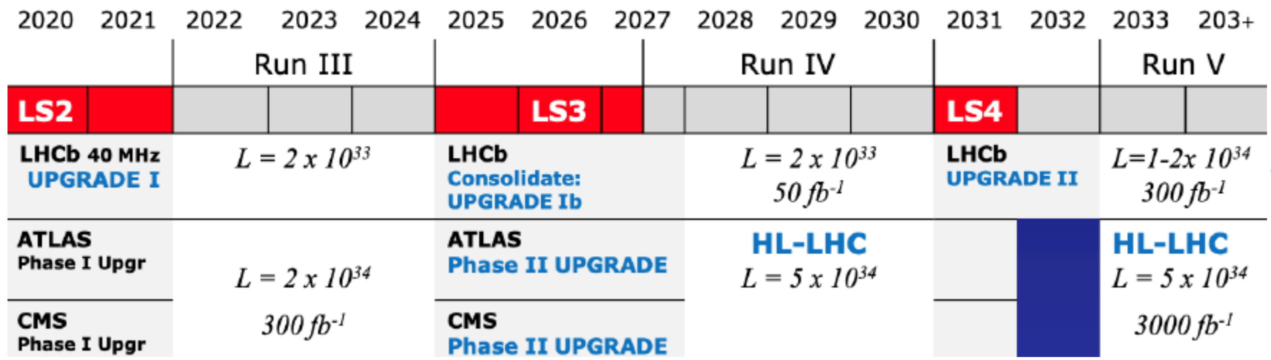
Clean environment
Entanglement
Neutral decay products
Hermiticity (neutrinos)
τ factory

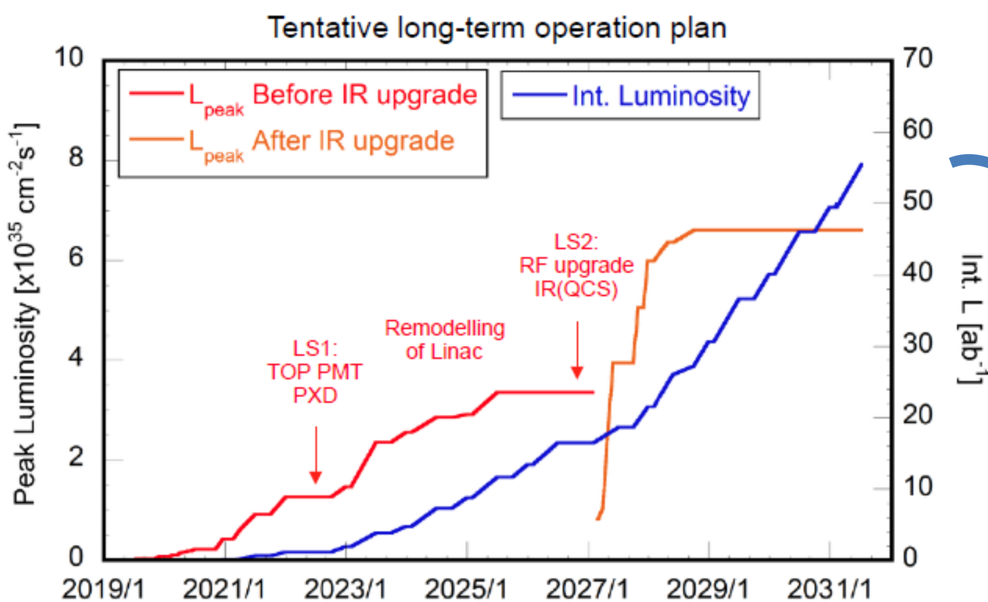


Many of the advantages of LHCb and Belle II

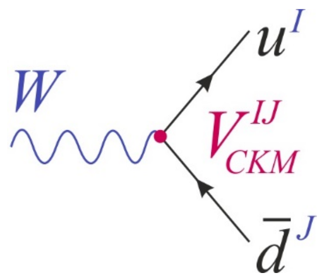
Flavor experiments : Projects and timescale

Timescale of the upgrades





Flavor experiments : The CKM picture

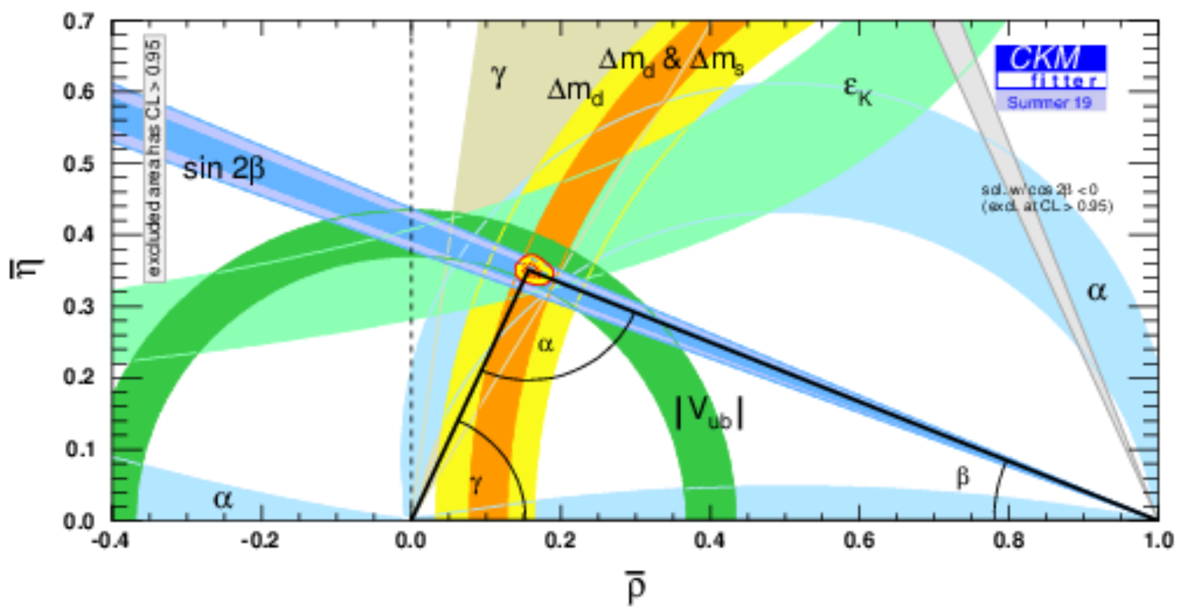


$$V_{CKM}^{IJ} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

In the SM: Only 4 free parameters

Imposes some correlations among observables, fantastically confirmed:

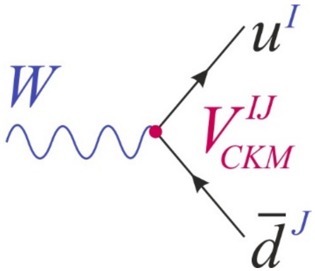
(mostly past experiments: BaBar, Belle)



Hidden in these fits are many B decay modes (+ a few others)

As well as many theory inputs, especially lattice calculations.

Flavor experiments : The CKM picture



$$= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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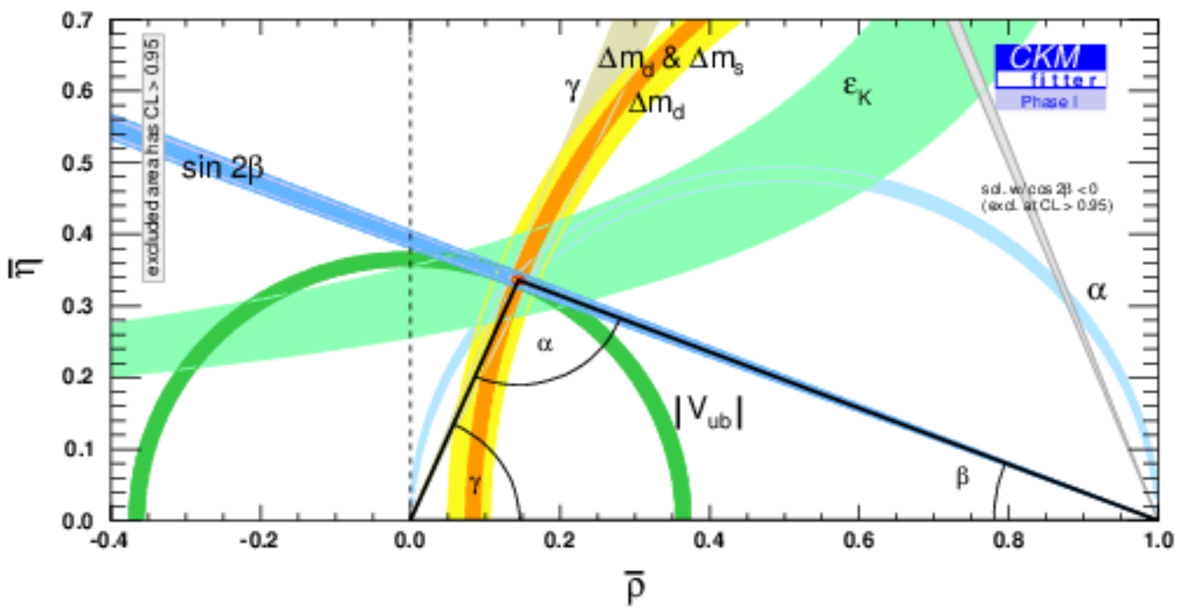
Prospects at Belle II @ 50 ab^{-1} and LHCb @ 23fm^{-1}:



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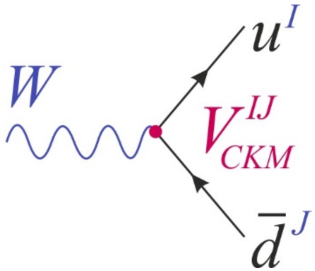
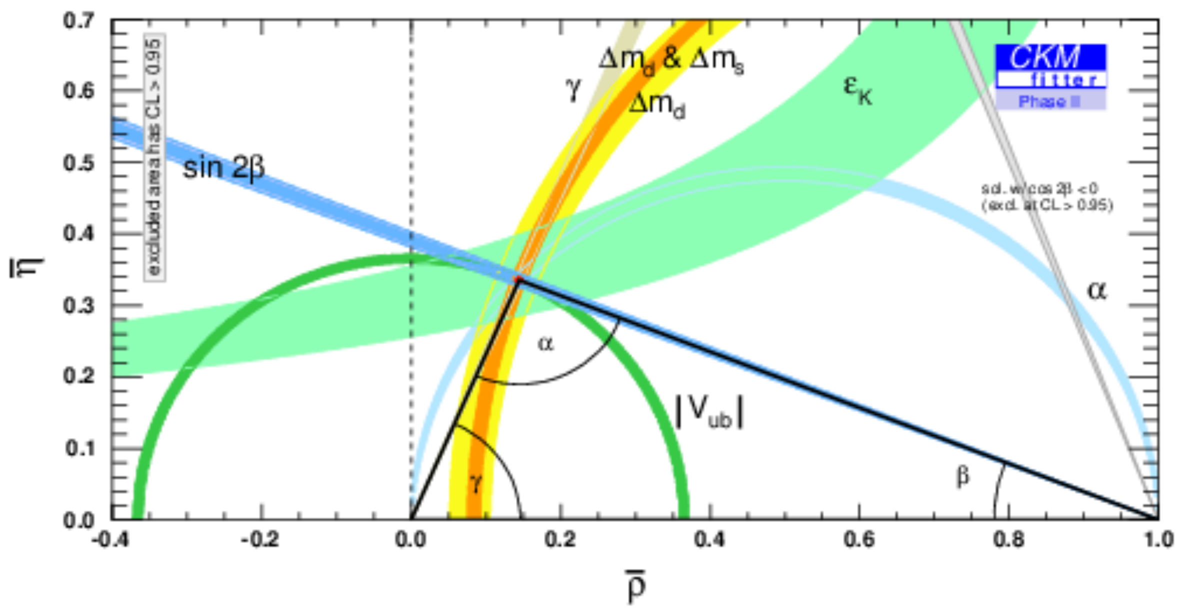


$$V^{IJ}_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

In the SM: Only 4 free parameters

Imposes some correlations among observables, fantastically confirmed:

Prospects at Belle II @ 50 ab^{-1} and LHCb @ 300fm^{-1}:



Hidden in these fits are many B decay modes (+ a few others)

As well as many theory inputs, especially lattice calculations.

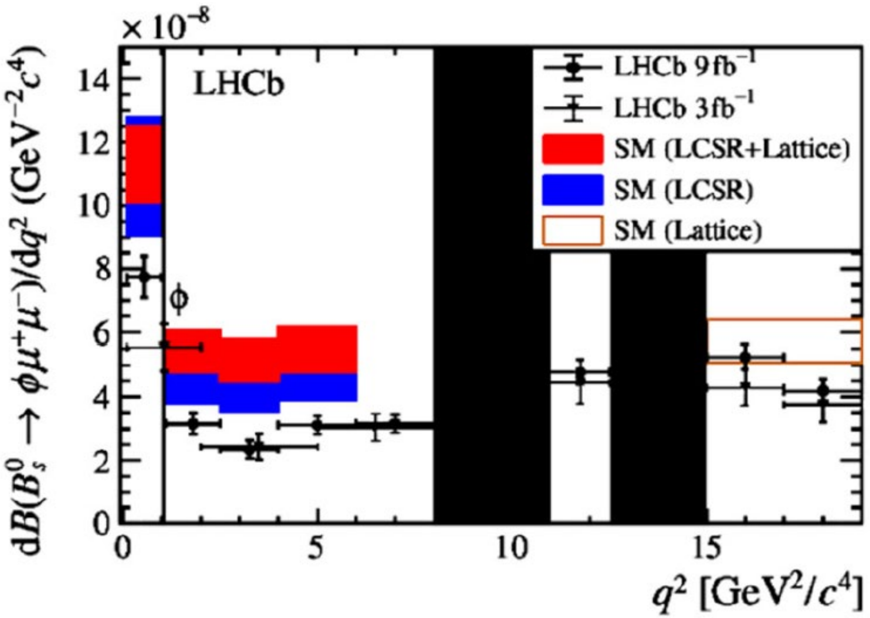
Flavor experiments : The B physics anomalies

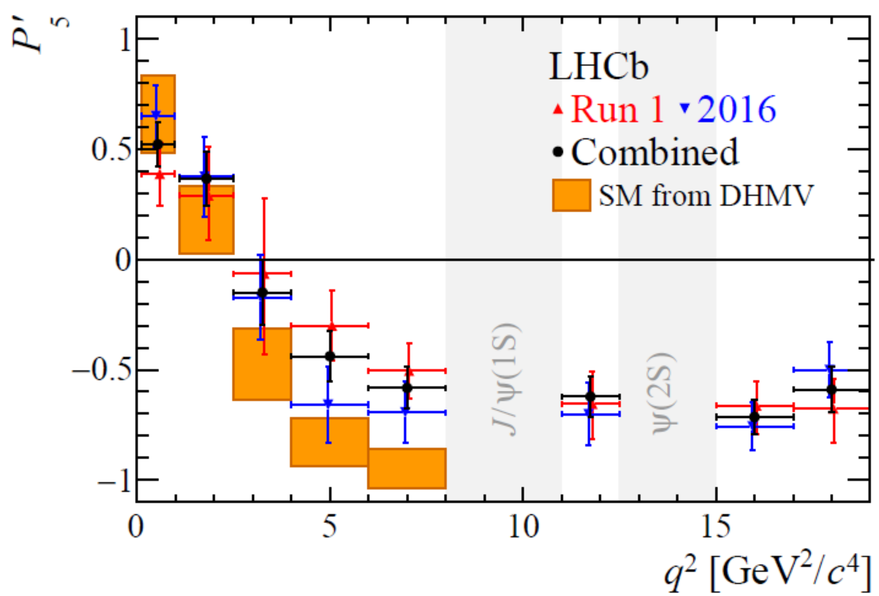
What has been seen so far?

Neutral current, b to s transitions:

Differential rates fall short at small q^2, angular distributions disagree for

$$B \to K\mu^+\mu^-, \Lambda_b \to \Lambda\mu^+\mu^-, B \to K^*\mu^+\mu^-, B_s \to \phi\mu^+\mu^-$$





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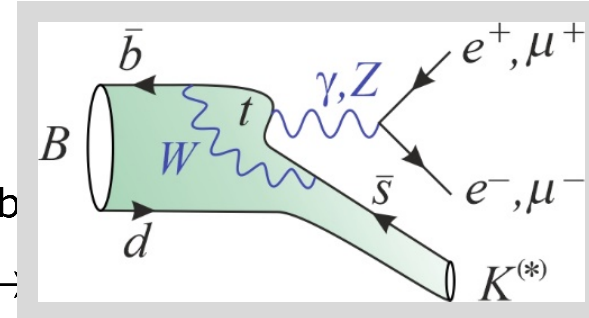
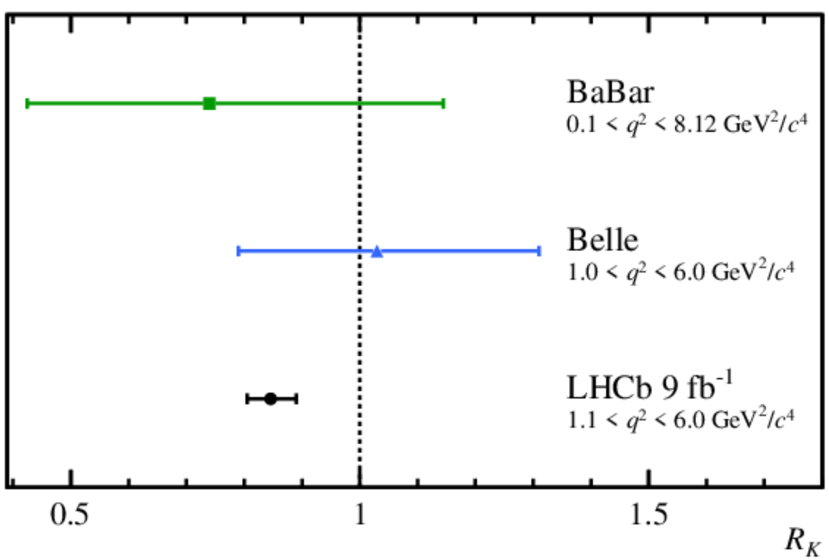
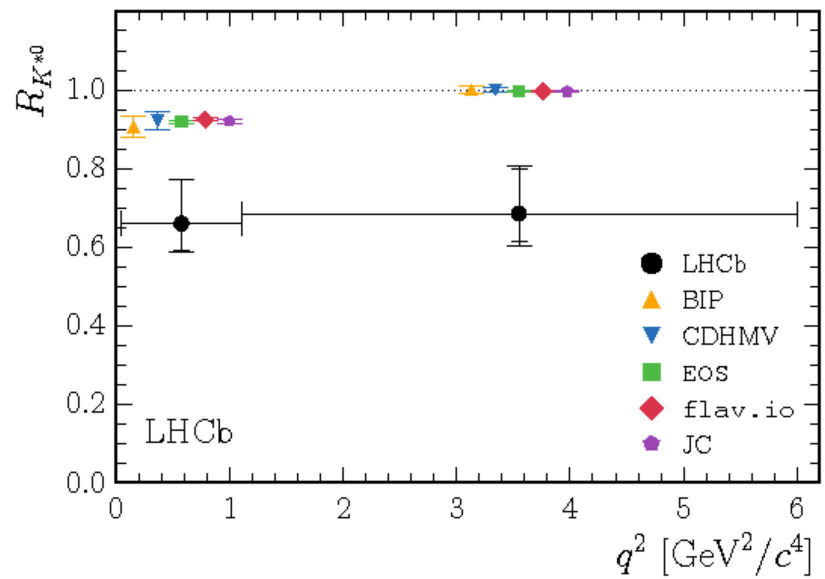


Differential rates fall short at small q^2, angular distrib

$$B \to K\mu^+\mu^-, \Lambda_b \to \Lambda\mu^+\mu^-, B \to K^*\mu^+\mu^-, B_s \to$$

Lepton universality looks broken $R_{K^{(*)}} \equiv \dfrac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)}$.





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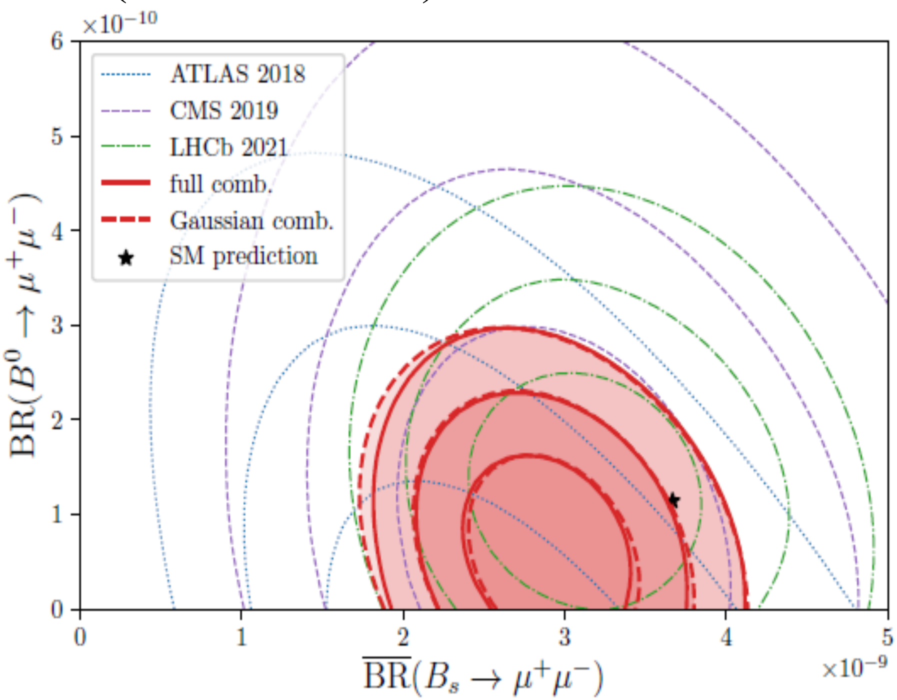
Yet $B_{s,d} \to \mu^+\mu^-$ are still roughly ok.



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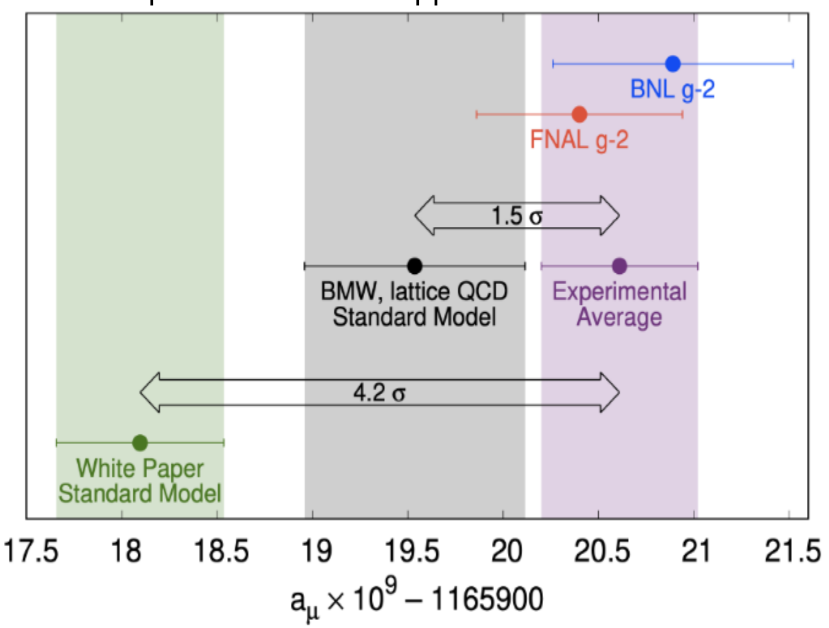
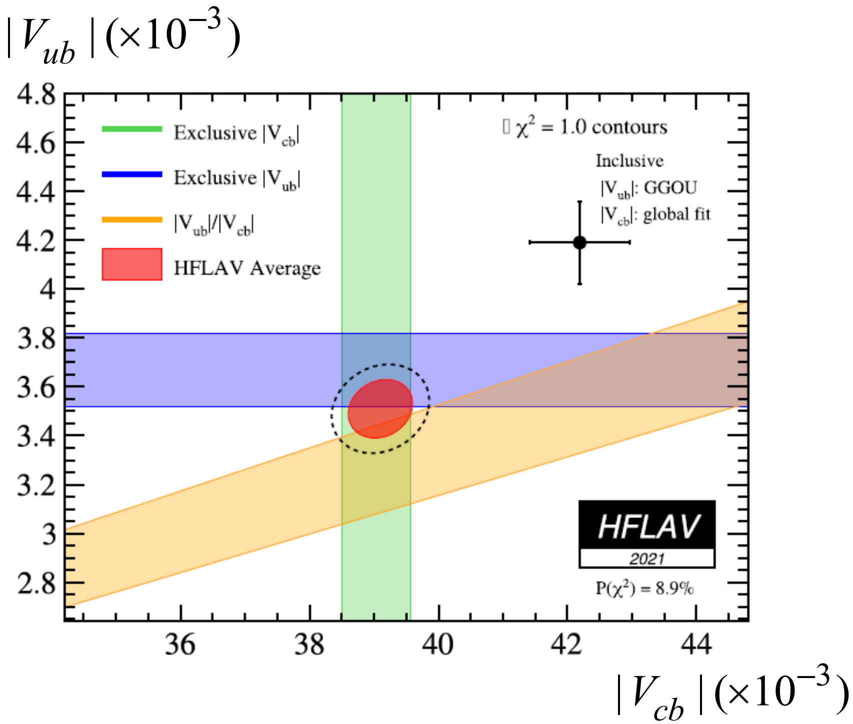
And the situation for $(g-2)_\mu$ is...

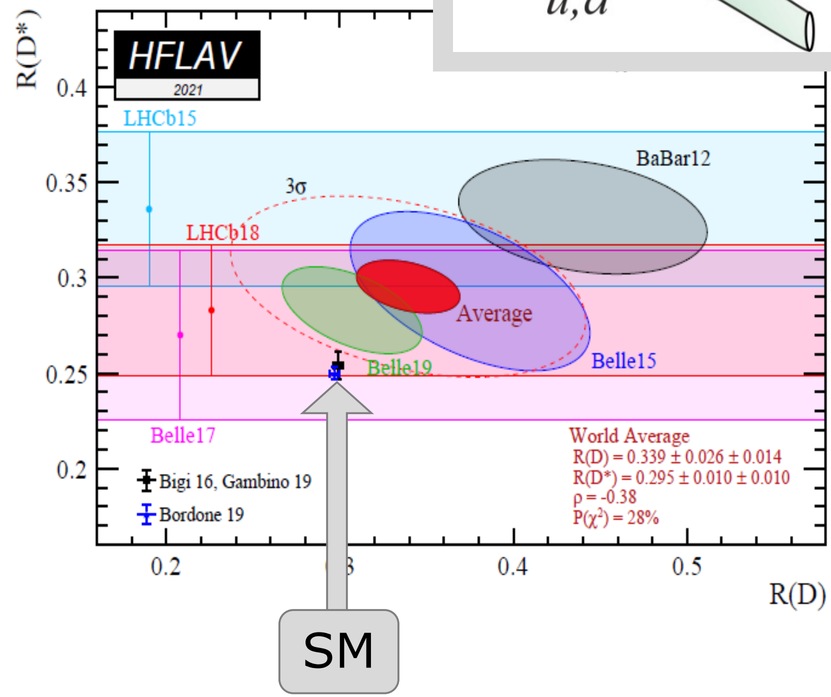
Budapest-Marseille-Wuppertal collaboration 2021

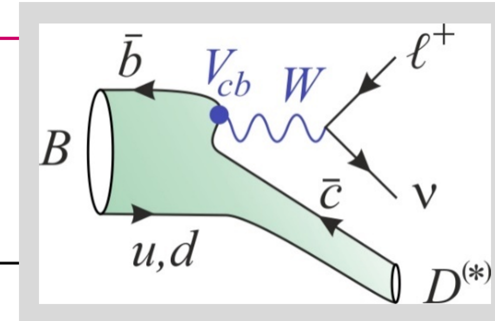


Flavor experiments : The B physics anomalies

What has been seen so far?







Charged current, b to c transitions:

Long-standing V_{cb} discrepancy between $\Gamma(B \to D\ell\nu)$ and $\Gamma(B \to X_c\ell\nu)$,

More recently, lepton universality discrepancy in $R_{D^{(*)}} \equiv \dfrac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$.

Flavor experiments : The B physics anomalies

What has been seen so far?

Neutral current, b to s transitions:

Less clean

[Di]fferential rates fall short at small q^2, angular distributions disagree for

Clean

$$B \to K\mu^+\mu^-, \Lambda_b \to \Lambda\mu^+\mu^-, B \to K^*\mu^+\mu^-, B_s \to \phi\mu^+\mu^-$$

Lepton universality looks broken $R_{K^{(*)}} \equiv \dfrac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)}$ Clean

Yet $B_{s,d} \to \mu^+\mu^-$ are still roughly ok Clean

And the situation for $(g-2)_\mu$ is Complicated

Charged current, b to c transitions:

Complicated

Long-standing V_{cb} discrepancy between $\Gamma(B \to D\ell\nu)$ and $\Gamma(B \to X_c\ell\nu)$,

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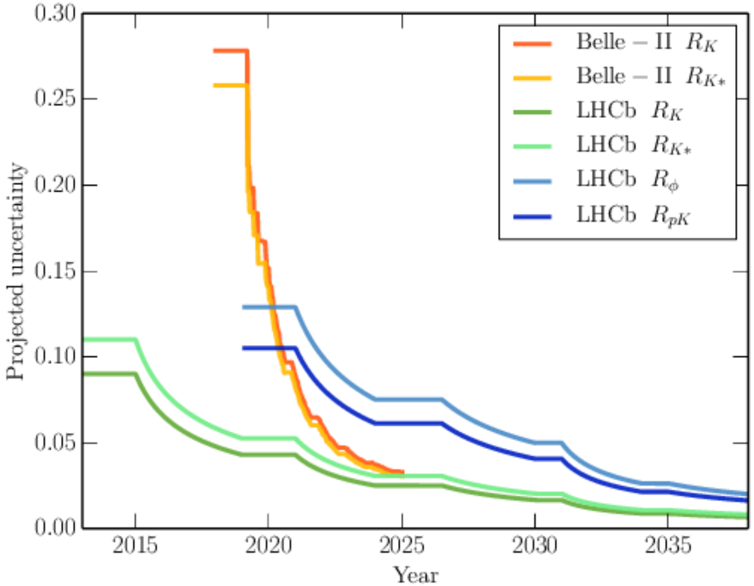
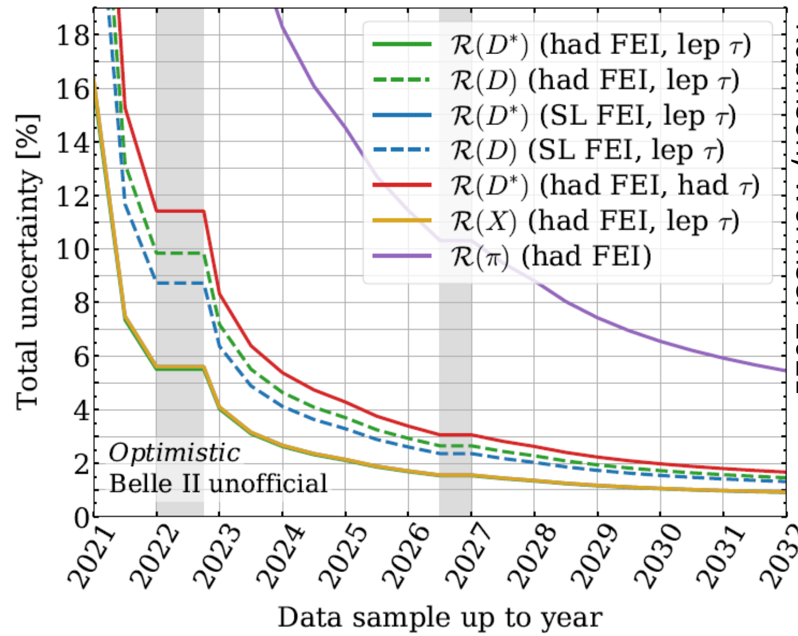
Flavor experiments : The B physics anomalies

Should we believe in those anomalies? Experimental perspective

LHCb will further study these modes, and Belle II is coming up



Bifani,Descotes-Genon, Romero,Vidal,Schune 2018



Bernlochner, Sevilla, Robinson, Wormser 2021

+ Anomalies must occur in other b hadron semileptonic $\mu^+\mu^- / e^+e^-$ decays

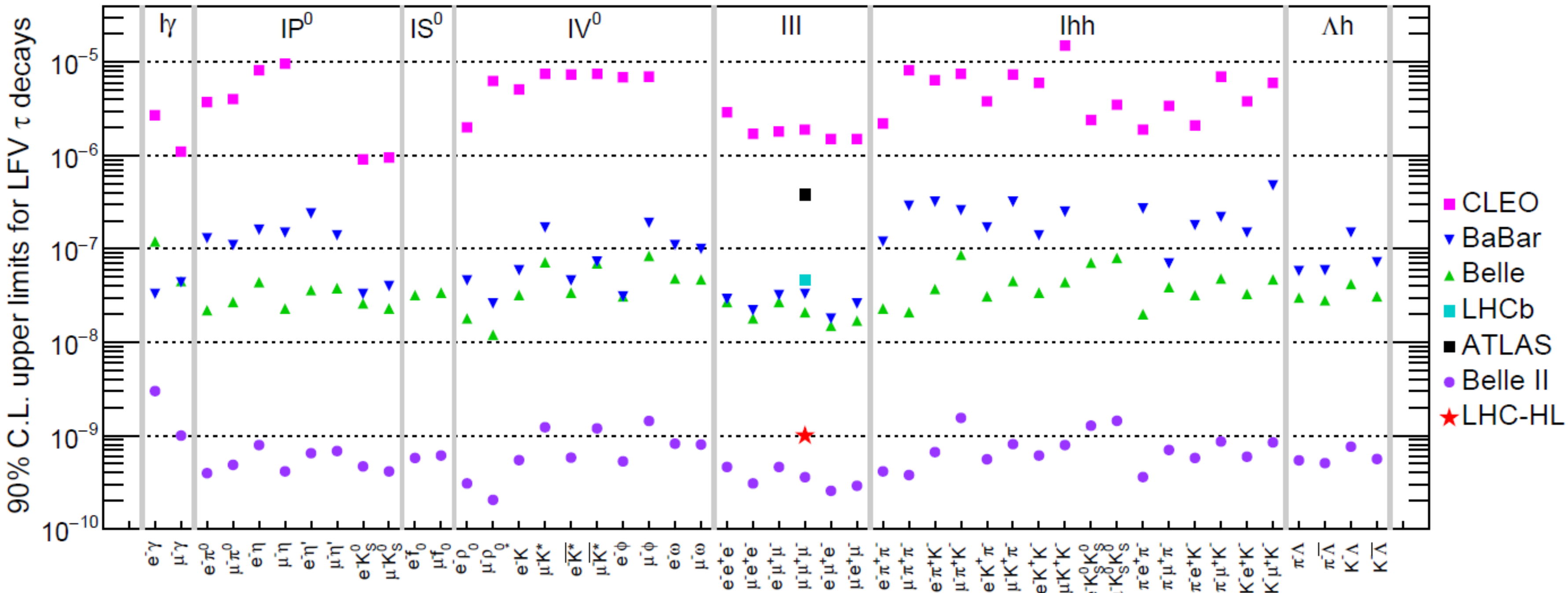
+ Anomalies expected in modes like $B \to K^* \nu\bar{\nu}$ (Belle II with a few ab^{-1})

+ Anomalies may occur in modes like $B \to K\tau^+\tau^-$ (not much known yet)

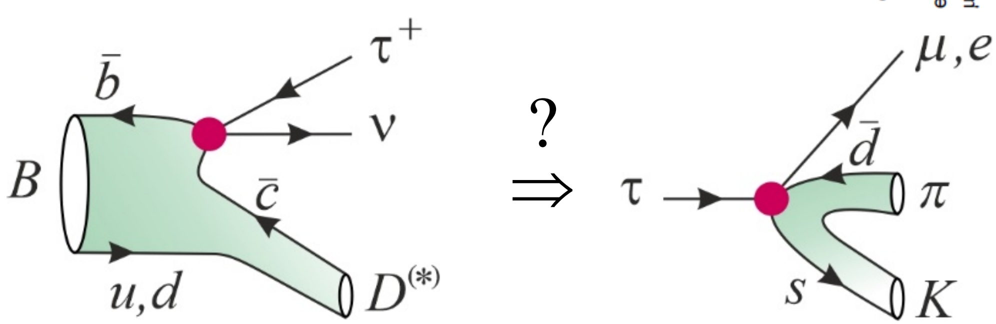
+ τ lepton may have LFV decay modes (especially hadronic)

Flavor experiments : The B physics anomalies

Should we believe in those anomalies? Experimental perspective



arxiv:1812.07638



+ τ lepton may have LFV decay modes (especially hadronic)

Flavor experiments : The B physics anomalies

Should we believe in those anomalies? Theoretical perspective

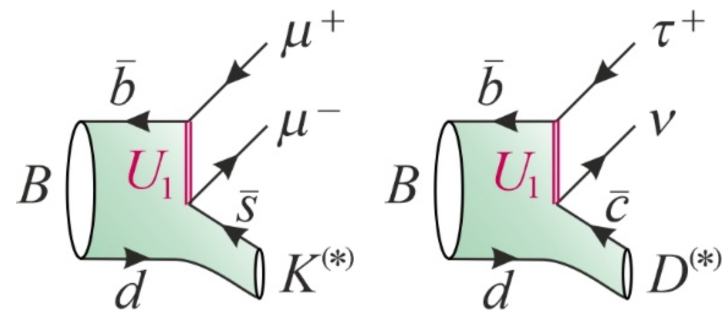
What could explain them but preserve the CKM fit and pass LHC constraints?

Leptoquarks, with non-trivial flavorfull couplings

	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Spin 0	S_3 $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
Spin 0	S_1 $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
Spin 0	R_2 $(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓	✗
Spin 1	U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
Spin 1	U_3 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

Angelescua , Becirevic, Faroughy, Sumensari, 2018

Many models (SUSY, ED, TC,…)



$$SU(4) \otimes SU(2)_L \otimes SU(2)_R$$

GUT origin?

Main messages: Reasonable models can still explain the anomalies,

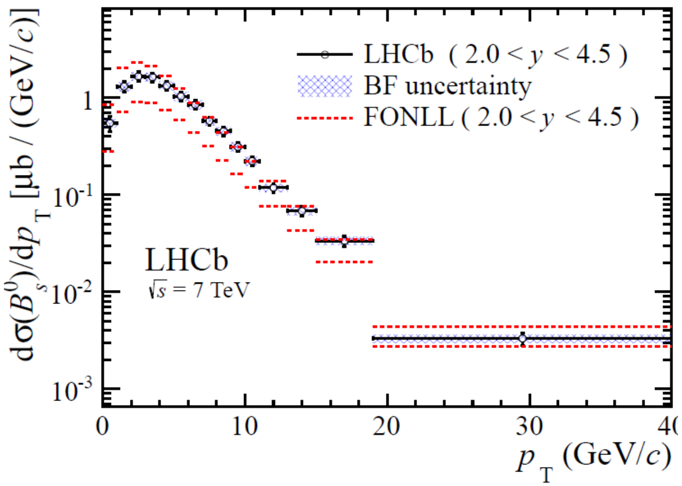
But no other compelling reason for these models yet (DM, CP,…).

First signs of a rich phenomenology above the TeV?

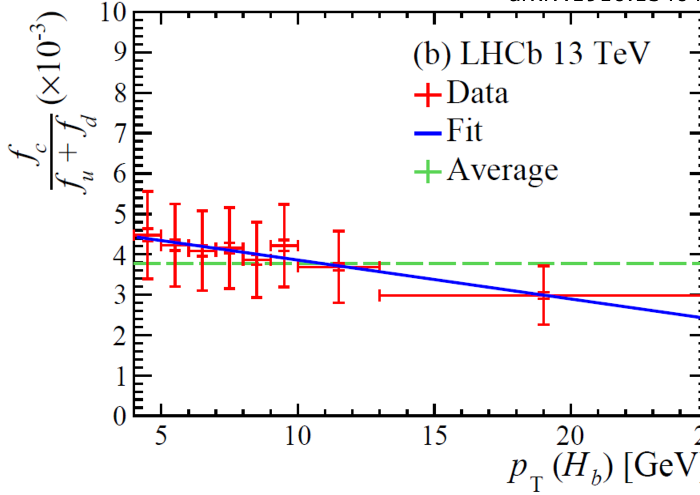
Flavor experiments : Exotics

Heavy flavor production, Decay constants

arxiv:1306.3663

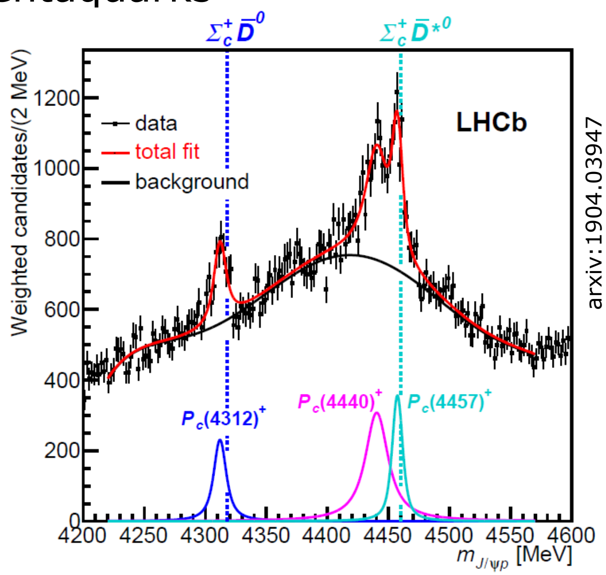


arxiv:1910.13404



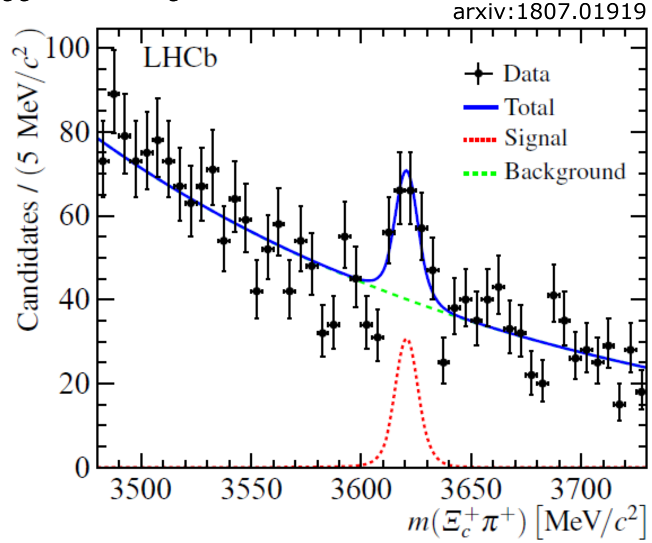
Spectroscopy, Exotics and Doubly-heavy

Pentaquarks



$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

arxiv:1807.01919



Powerful tests of lattice QCD, and connection with heavy ion/perturbative QCD → GT03

II. Dedicated experiments

Dedicated experiments : Null test targets

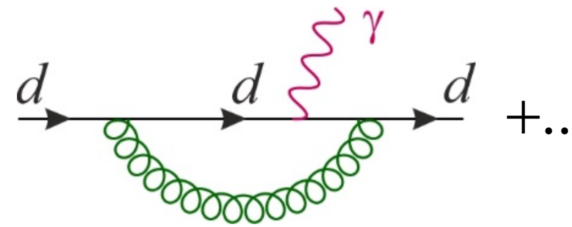
Electric dipole moments:

- n2EDM at PSI aims at the neutron EDM
- Holds the best limit, to be improved by 10 to 100.

In the SM:

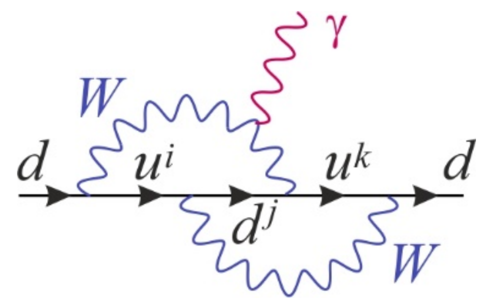
- Strong contribution is way too large!

→ To be killed by the axion → GT06



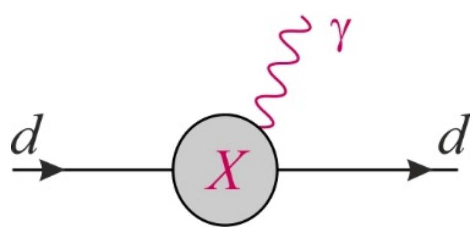
- Weak contribution is totally negligible

→ Null test for the SM



Beyond the SM:

- New flavored and unflavored contributions



$$\Rightarrow M_X > 15000\,TeV$$

Dedicated experiments : Null test targets

Electric dipole moments:

$\Rightarrow M_X > 15000\,TeV$

- n2EDM at PSI aims at the neutron EDM
- Holds the best limit, to be improved by 10 to 100.
- Related to axion searches → GT06

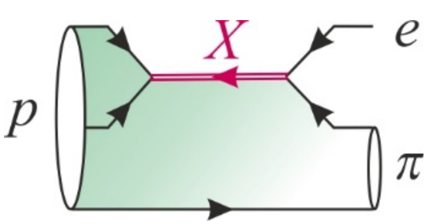
Baryon & lepton numbers:

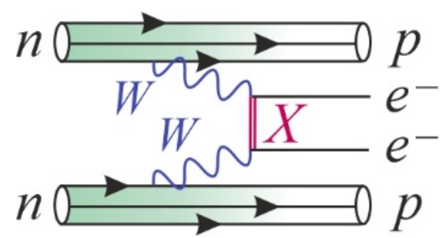
- Conserved for the SM, but not for baryogenesis → GT05
- $0\nu\beta\beta$ searches → neutrino mass → GT06

Nucleon decay
Δbaryon, Δlepton = 1

$0\nu\beta\beta$
Δlepton = 2

Neutron oscillations
Δbaryon = 2





$\Rightarrow M_X > 10^{11}\,TeV$

$\Rightarrow M_X > 1\,TeV$

$\Rightarrow M_X > (1-10^5)\,TeV$

(very model-dependent)

Dedicated experiments : Null test targets

Electric dipole moments:
$\Rightarrow M_X > 15000\, TeV$

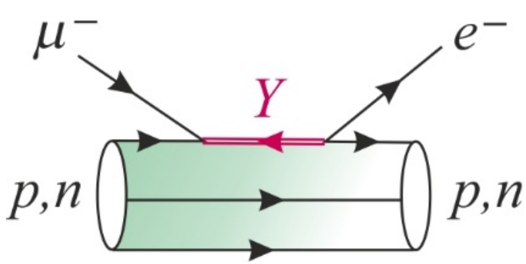
- n2EDM at PSI aims at the neutron EDM
- Holds the best limit, to be improved by 10 to 100.
- Related to axion searches → GT06

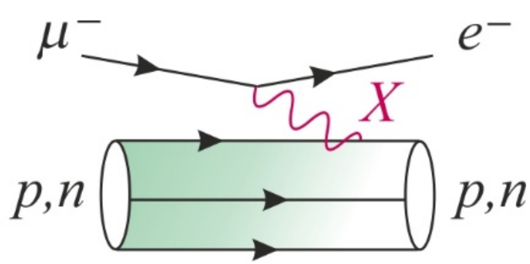
Baryon & lepton numbers:
$\Rightarrow$ up to $M_X > 10^{11}\, TeV$

- Conserved for the SM, but not for baryogenesis → GT05
- $0\nu\beta\beta$ searches → neutrino mass → GT06

Lepton Flavor Violation:

- B decays & τ decays at LHCb/Belle II
- COMET (J-Parc) search for μ-e conversion
- Factor 100 (Phase I) to 10000 (Phase II) improvement
- Related to neutrino mass models → GT06





$\Rightarrow M_X > 1000\, TeV$

Dedicated experiments : Null test targets

Electric dipole moments:
$\Rightarrow M_X > 15000\, TeV$

- n2EDM at PSI aims at the neutron EDM
- Holds the best limit, to be improved by 10 to 100.
- Related to axion searches → GT06

Baryon & lepton numbers:
$\Rightarrow$ up to $M_X > 10^{11}\, TeV$

- Conserved for the SM, but not for baryogenesis → GT05
- $0\nu\beta\beta$ searches → neutrino mass → GT06

Lepton Flavor Violation:
$\Rightarrow M_X > 1000\, TeV$

- B decays & τ decays at LHCb/Belle II
- COMET (J-Parc) search for μ-e conversion
- Factor 100 (Phase I) to 10000 (Phase II) improvement
- Related to neutrino mass models → GT06

Exotic & unexpected:

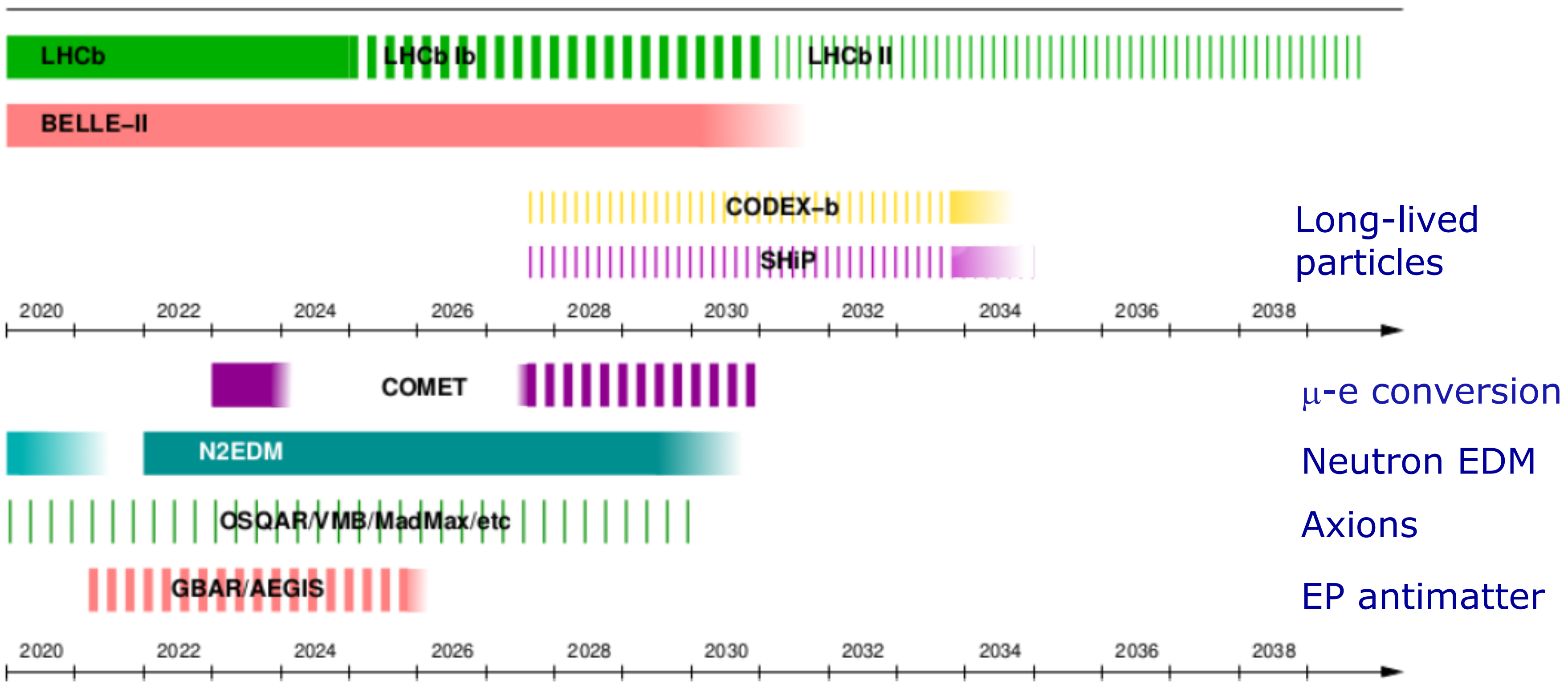
- Photon mass, Equivalence principle, Lorentz invariance, …

⇩

- AEgIS, GBAR at CERN: First test for antimatter → GT05

Dedicated experiments : Null test targets

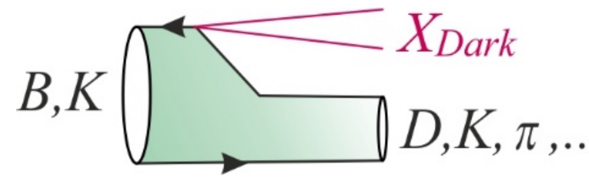
Timescale of the dedicated experiments:



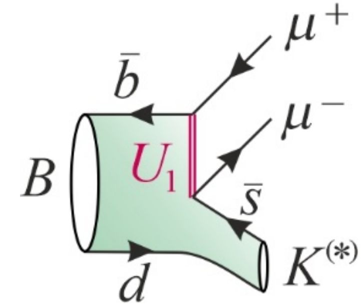
Drivers and Recommendations

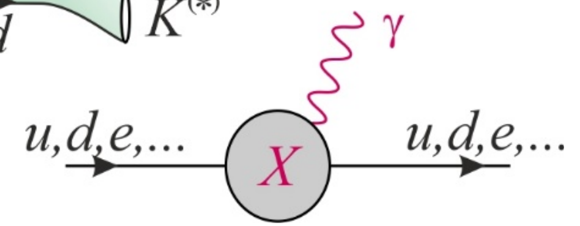
Conclusion – Science Drivers

3. Search directly for new particles which could solve open issues, such as the nature of dark matter or the hierarchy problem, covering as much parameter space as possible: low couplings, high masses, challenging signatures,...

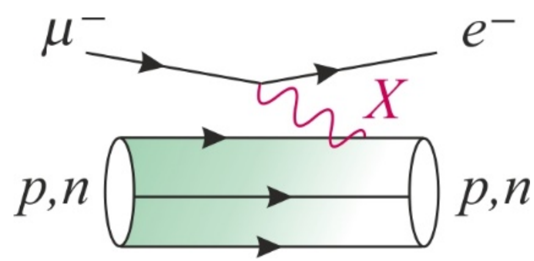


4. Study of matter-antimatter asymmetry and flavor transitions in the quark sector.

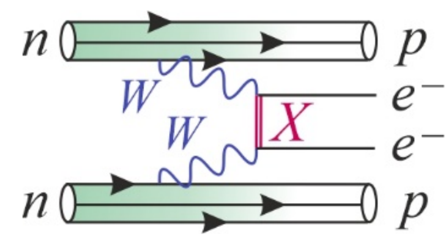




5. Test lepton universality and search for charged lepton flavor violation.



6. Help resolve cosmological questions, especially those pointing towards new dynamics (inflation, modified gravity, baryogenesis,...) or new forms of matter.



Conclusion – Recommendations

French community (EXP & TH) already heavily involved in tackling these science drivers:

Intensity Frontier:

1. Exploit LHCb and Belle-II, study the current flavor anomalies, and support the related theoretical efforts, e.g., lattice calculations.
2. Pursue a long-term flavor physics program, via LHCb and/or Belle-II upgrades, or the FCC-ee running at the Z pole. Theoretical support is crucial.

Dedicated Experiments:

1. Support experiments dedicated to specific fundamental observables, like Electric Dipole Moments and Lepton Flavour Violation.
2. Support the searches for new long-lived particles at colliders and in dedicated experiments.

Transverse:

1. Necessity for GT01, GT03, GT04, GT05, GT06 collaborations.
2. Support for GDR/IRNs where experimentalists and theorists can exchange ideas and find new paths to test the SM and discover New Physics.