EU Strategy for Particle Physics

Theory considerations about **Physics beyond the Standard Model**: opportunities at future experimental facilities

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Why BSM?

The SM: many unanswered questions:

- why 3 generations
- hierarchy among the fermion masses
- structure of the mixing matrices
- values of the parameters (fermion masses and mixings, gauge couplings, Higgs potential parameters…)

Present directions

the attempt to answer the questions + hints of deviations from SM (*anomalies, tensions*)
→ intense search for extensions of the SM (**BSM**) (new particles, new interactions)

ENERGY FRONTIER: direct searches at colliders

- New particles directly produced on-shell
- Identified through their decay modes

INTENSITY FRONTIER: through quantum effects

- New particles contribute as virtual states
- Deviations from SM predictions can emerge
- Might be sensitive to large mass scales (e.g. new massive mediators)

THEORY: keyword precision

- sharpen SM predictions
- a suitable BSM interpretation required

Which BSM?

Main lessons from LHC:

- The SM is correct up to energies of few TeV
  The Higgs boson has been found!

- Before LHC : find a single NP answering all the fundamental problems of the SM, e.g. susy
  No other particle has been found

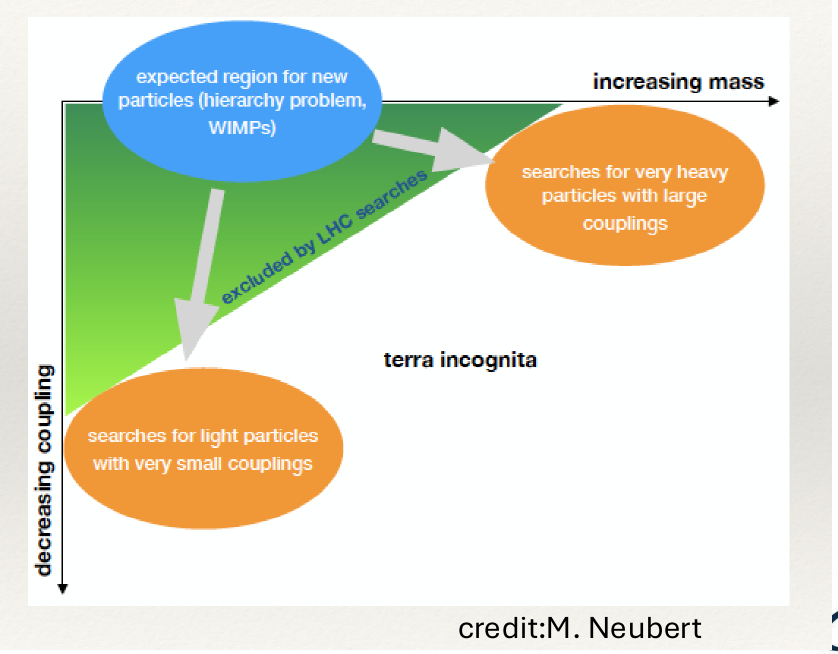
  - Many NP models in trouble

  - New attitude towards the search for BSM required

- Interplay among particle physics/astroparticle/cosmology

  → new particles not necessarily heavy but also weakly coupled
  → new experimental facilities required

  - scan different energy ranges
  - *precision* is as fundamental as *energy*
    - to identify New Physics
    - to sharpen our present knowlkedge



credit:M. Neubert

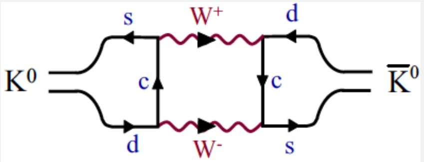
Keyword: precision

Precision is a discovery tool

Often (but not always…) theory has highlighted the path to discovery

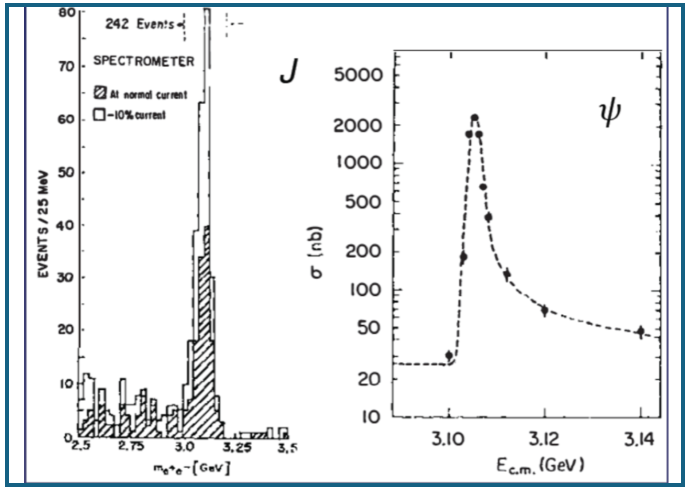
- 1974

M.K. Gaillard and B.W. Lee



studies of **rare** K decays and K^0-$\underline{K^0}$ mixing predict m_c

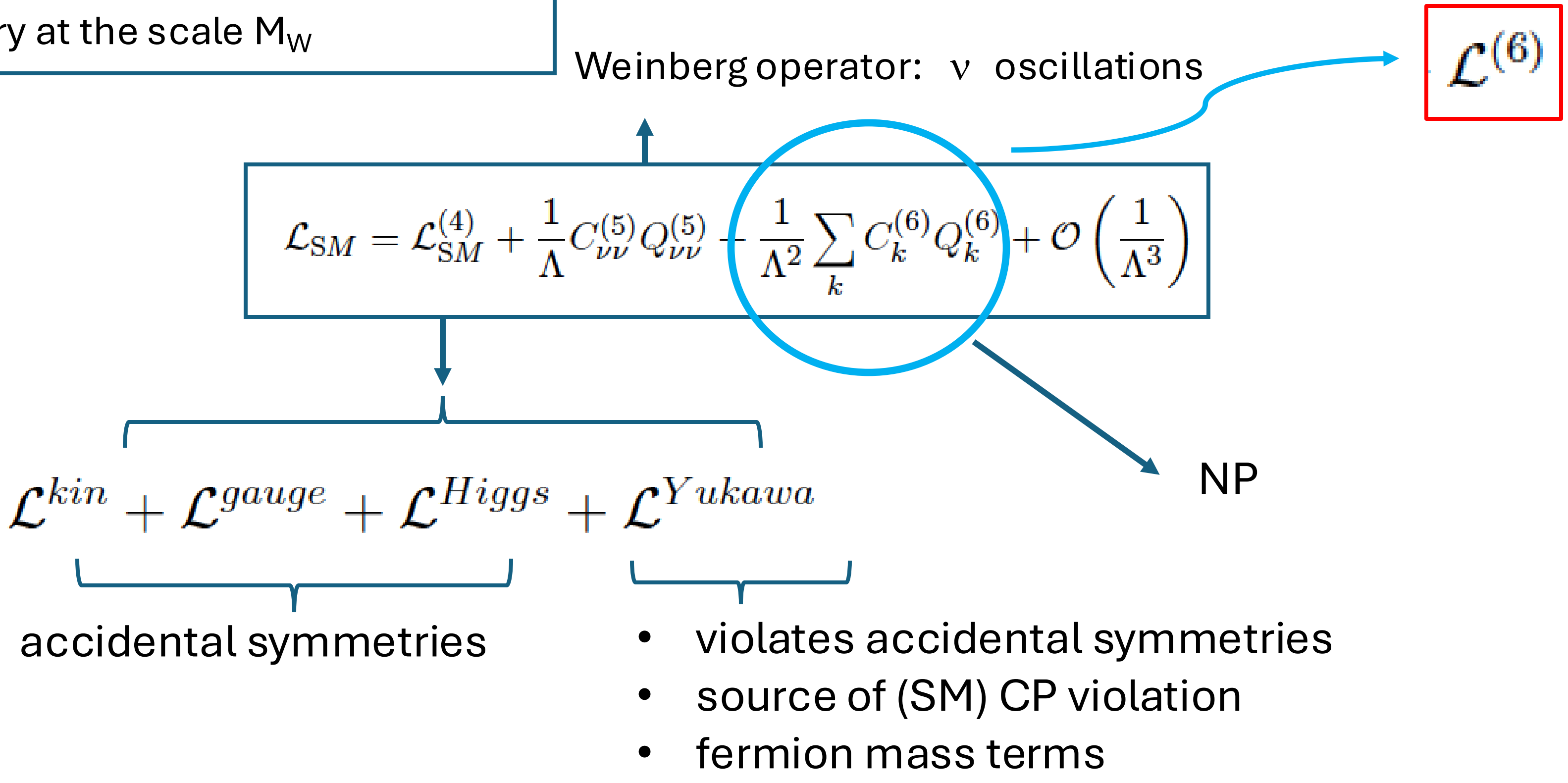
J/ψ discovery



Explore BSM effects: SMEFT ⟶ systematic extension of the SM

- NP exists at a high scale $\Lambda \gg M_W$
- NP gauge group contains the SM group
- SM gauge fields contained
- SM an effective theory at the scale M_W

Buchmuller et al,NPB 268 (1986) 621
Grzadkowski et al., JHEP 10 (2010) 085



Weinberg operator: ν oscillations

$\mathcal{L}^{(6)}$

$$\mathcal{L}_{\rm SM} = \mathcal{L}^{(4)}_{\rm SM} + \frac{1}{\Lambda} C^{(5)}_{\nu\nu} Q^{(5)}_{\nu\nu} + \frac{1}{\Lambda^2} \sum_k C^{(6)}_k Q^{(6)}_k + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

NP

$$\overbrace{\underbrace{\mathcal{L}^{kin} + \mathcal{L}^{gauge} + \mathcal{L}^{Higgs}}_{\text{accidental symmetries}} + \underbrace{\mathcal{L}^{Yukawa}}}$$

accidental symmetries

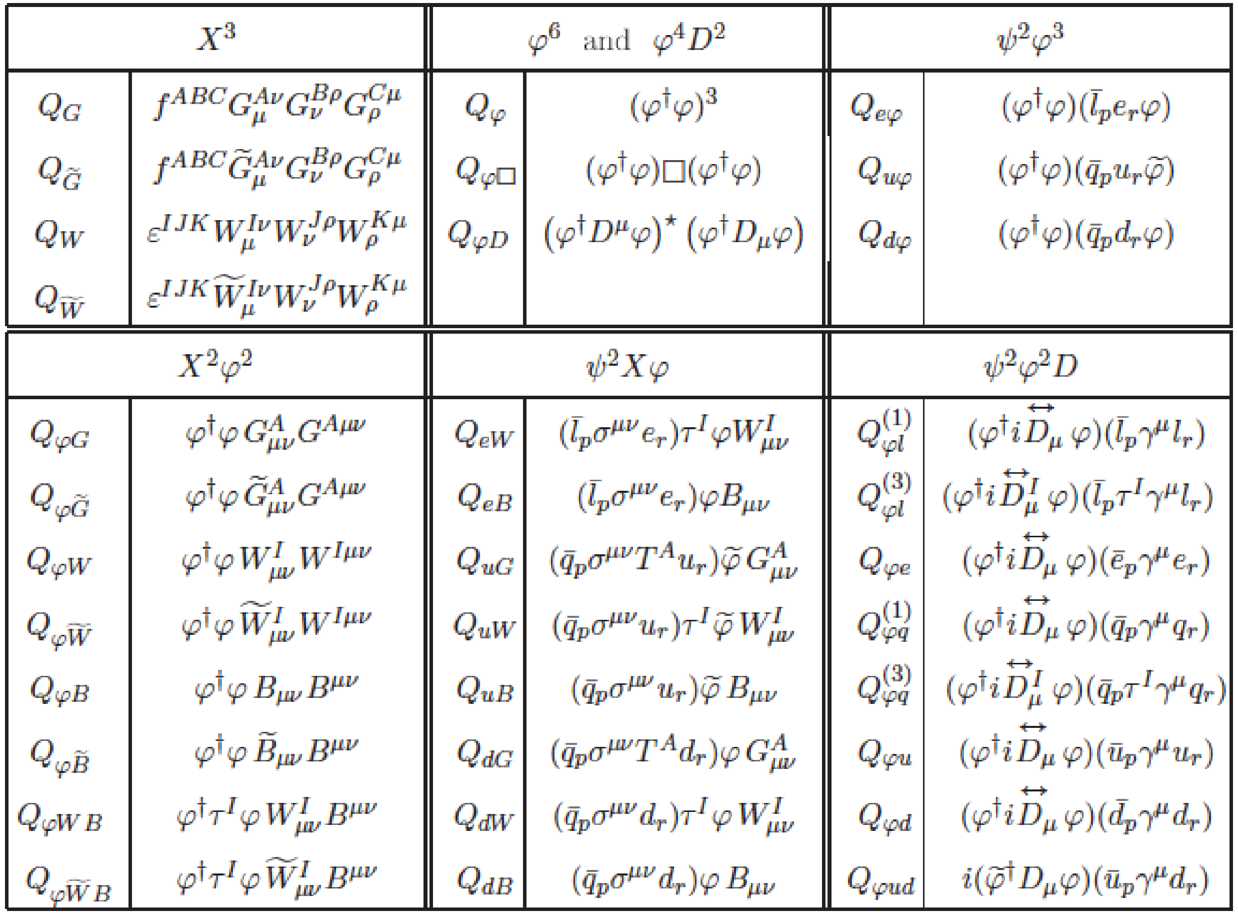
- violates accidental symmetries
- source of (SM) CP violation
- fermion mass terms

Explore BSM effects: SMEFT ⟶ systematic extension of the SM

$\mathcal{L}^{(6)}$

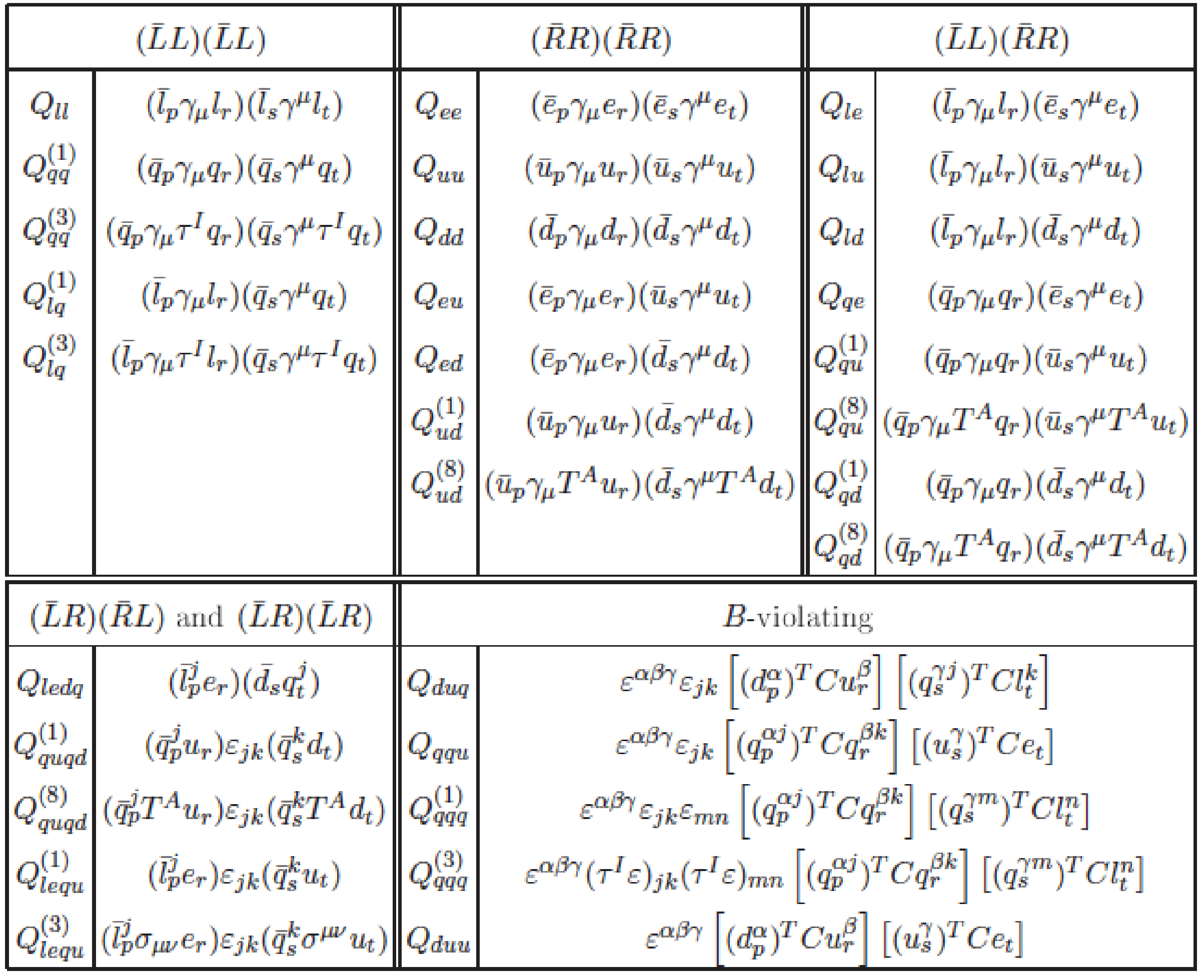
Warsaw basis

r,p=1,2,3
generation indices



X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$



$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Explore BSM effects: SMEFT ⟶ systematic extension of the SM

Huge work of de Blas et al. *JHEP* 03 (2018) 109

- 48 possible new particles generate previous operators
- Not all of them contribute to all operators

Recipe to identify NP once a deviation is found in a given process

1. figure out which NP operators can contribute to the process
2. determine experimentally the coefficients (bottom-up approach)
3. scrutinize which models predict the obtained values

Search for BSM at Future colliders

- Higgs Sector
- Flavour
- QCD

Search for BSM at Future colliders

- **Higgs Sector**
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EU Strategy 2020: ***An electron-positron Higgs factory is the highest-priority next collider***

Unique features

- The only interaction not described as a gauge theory related to a local symmetry
- No quantised charges
- Connected to space time vacuum structure

The discovery of the Higgs not an arrival point but a starting point

- Is it the SM Higgs? (needs e.g. measuring fermion Yukawas, H self-couplings)
- Is H an elementary particle? (Many composite models say no)
- A role in the big bang?
- Connection with other issues (DM, matter/antimatter asymmetry and CP violation...)

Future colliders (FCC will be an Higgs factory) can investigate these correlations

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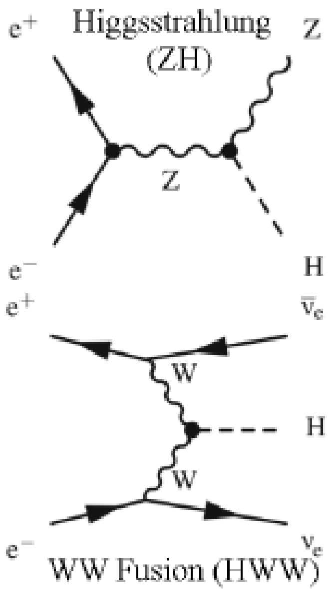
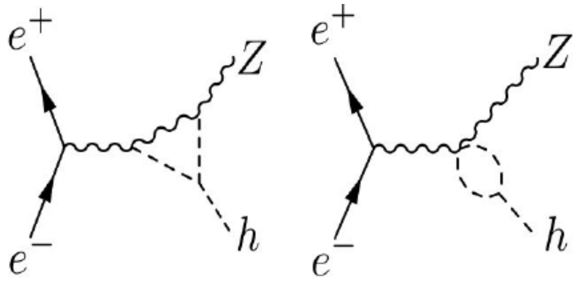
EU Strategy 2020: ***An electron-positron Higgs factory is the highest-priority next collider***

- Is it the SM Higgs?

- Production of H as s-channel resonance → direct access to e- Yukawa
- Check of Yukawas and self-couplings → ID card of H_{SM}
- Running at different energies: distinction between anomalous ZH coupling or H self coupling

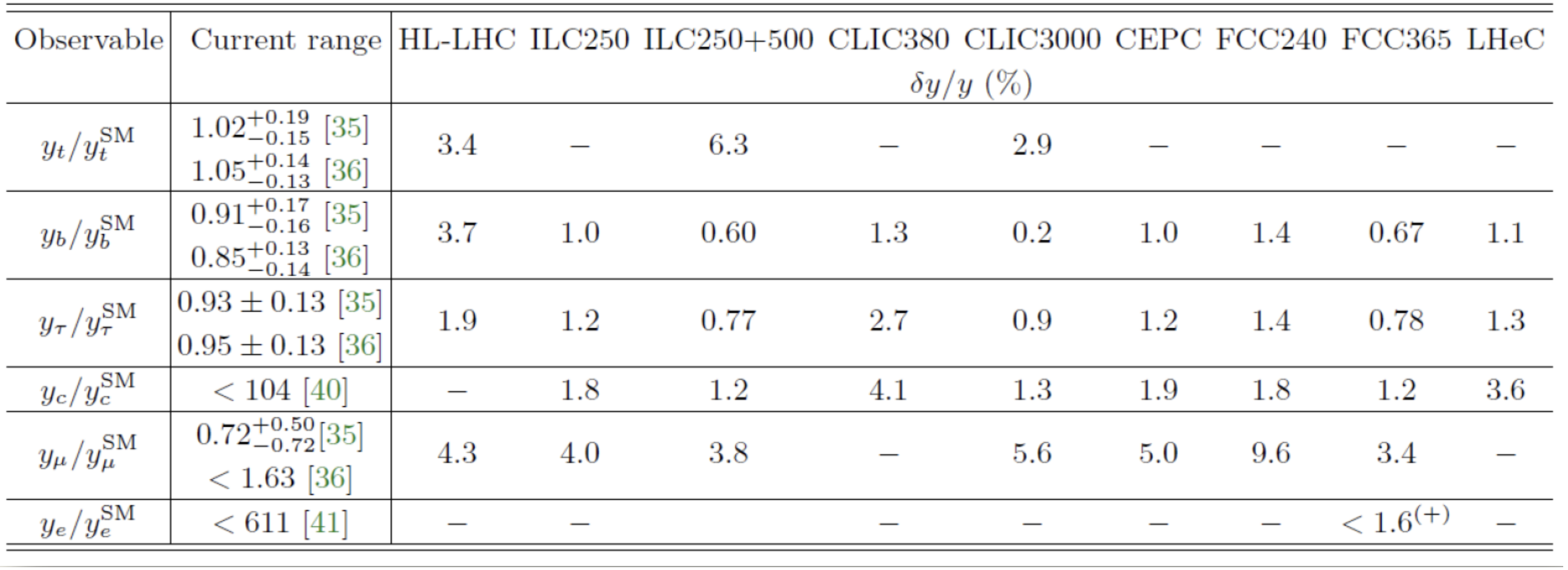




shape of the Higgs potential

Search for BSM at Future colliders

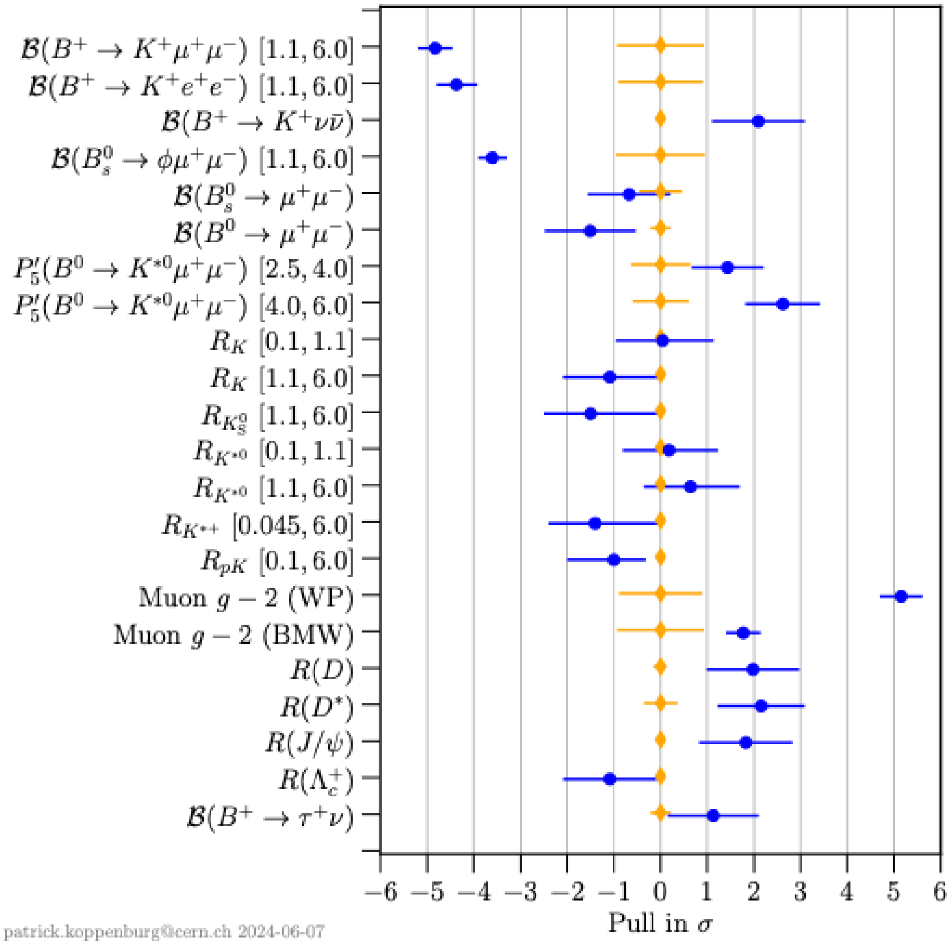
Heinemann and Nir



Observable	Current range	HL-LHC	ILC250	ILC250+500	CLIC380	CLIC3000	CEPC	FCC240	FCC365	LHeC
		$\delta y/y$ (%)								
y_t/y_t^{SM}	$1.02^{+0.19}_{-0.15}$ [35] $1.05^{+0.14}_{-0.13}$ [36]	3.4	–	6.3	–	2.9	–	–	–	–
y_b/y_b^{SM}	$0.91^{+0.17}_{-0.16}$ [35] $0.85^{+0.13}_{-0.14}$ [36]	3.7	1.0	0.60	1.3	0.2	1.0	1.4	0.67	1.1
$y_\tau/y_\tau^{\mathrm{SM}}$	0.93 ± 0.13 [35] 0.95 ± 0.13 [36]	1.9	1.2	0.77	2.7	0.9	1.2	1.4	0.78	1.3
y_c/y_c^{SM}	< 104 [40]	–	1.8	1.2	4.1	1.3	1.9	1.8	1.2	3.6
$y_\mu/y_\mu^{\mathrm{SM}}$	$0.72^{+0.50}_{-0.72}$[35] < 1.63 [36]	4.3	4.0	3.8	–	5.6	5.0	9.6	3.4	–
y_e/y_e^{SM}	< 611 [41]	–	–		–	–	–	–	$< 1.6^{(+)}$	–

Search for BSM at Future colliders

- ➢ Higgs Sector
- ➢ **Flavour**
- ➢ QCD



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FLAVOUR ANOMALIES

- in loop induced (rare decays)
- in tree level decays (R(D$^{(*)}$) - LFU violation?)

$$\mathcal{R}^0(D) = \frac{\mathcal{B}(\bar{B}^0 \to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^+\ell^-\bar{\nu}_\ell)}$$

$$\mathcal{R}^0(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell)}$$

CKM-related issues

- puzzle: tension in exclusive vs inclusive determinations of V_{cb} and V_{ub}
- Cabibbo anomaly: unitarity of CKM (first row)

CP violation

- ε'/ε
- Strong CP violation?

➢ correlated pattern of deviations from SM predictions?

➢ common origin of the anomalies?

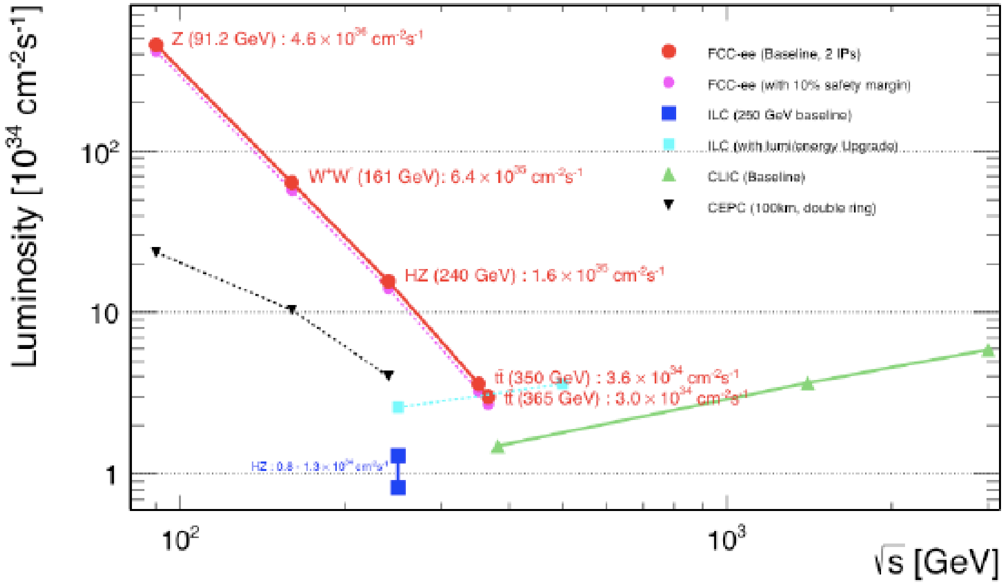
ex. V_{cb} , V_{ub} puzzles correlated with anomalies in tree-level modes?

☐ look for new modes/observables/correlations

☐ Null tests of the SM: LFV decays $\tau \to 3\mu$, $\mu \to e\,\gamma$ …

☐ Null tests of the SM: $D^0 \to \mu^+\mu^-$ (SM predicts BR ~10^{-21})

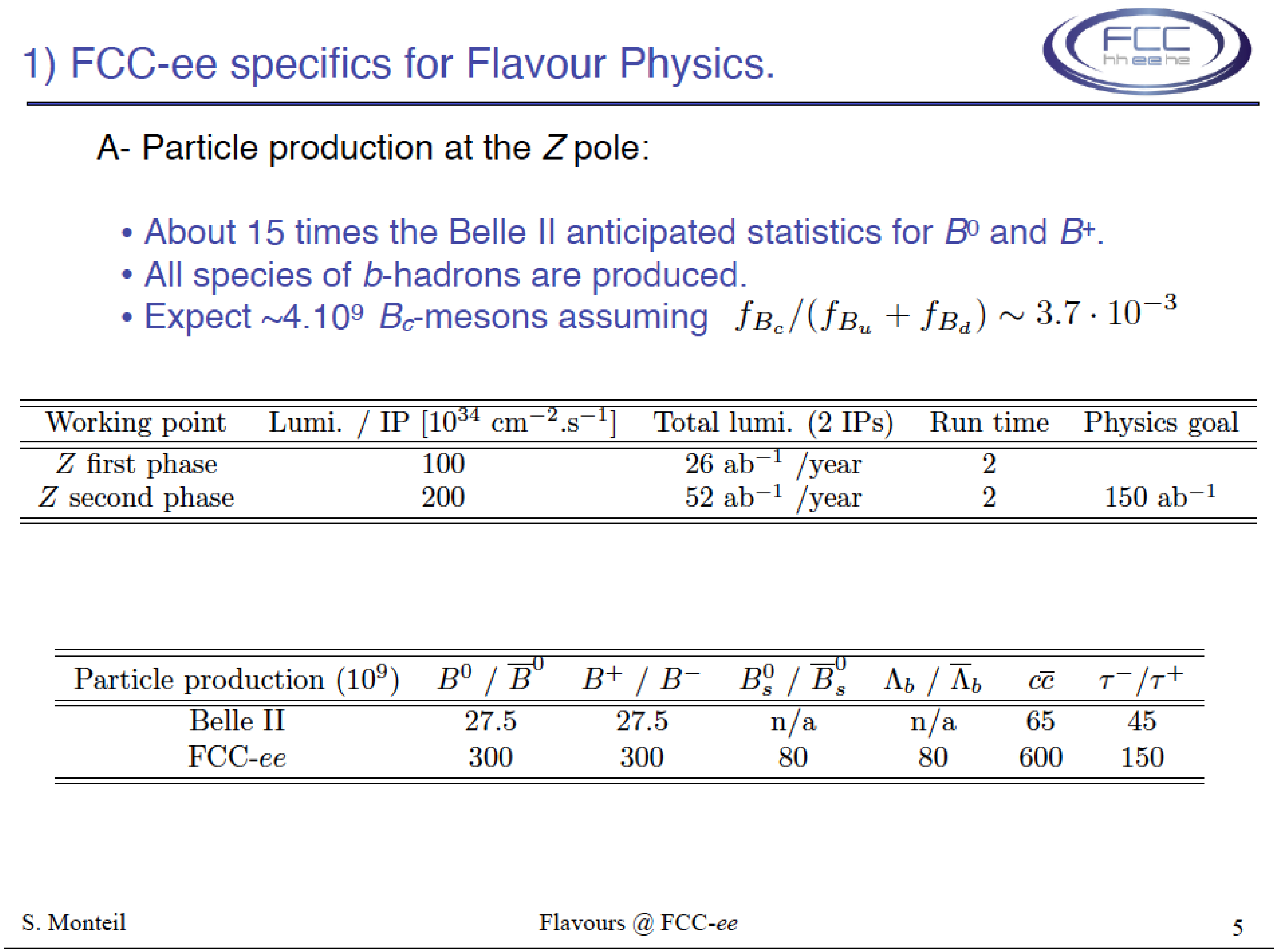
1) FCC-ee main features



- We‘re speaking of 10^5 *Z*/s , 10^4 *W*/h, 1.5 10^3 *H* and top /d, in a very clean environment: no pile-up, controlled beam backgrounds, *E* and *p* constraints, ~w/o trigger loss.

- In particular, you do the LEP in a minute!

Search for BSM at Future colliders



1) FCC-ee specifics for Flavour Physics.

A- Particle production at the *Z* pole:

- About 15 times the Belle II anticipated statistics for B^0 and B^+.
- All species of *b*-hadrons are produced.
- Expect ~4.10⁹ B_c-mesons assuming $f_{B_c}/(f_{B_u} + f_{B_d}) \sim 3.7 \cdot 10^{-3}$

Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

Search for BSM at Future colliders

- Higgs Sector
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FCC-ee @Zpole

- large improvement in the statistics in particular $b\bar{b}$ and $\tau\bar{\tau}$ pairs
- heavily boosted → possible topological reconstruction of modes with missing energy

  - b-hadrons at BELLE II modest boost - almost at rest
  - τ decays: missing energy modes difficult at LHCb
  - recent anomaly in $B \rightarrow K \nu \bar{\nu}$ - missing energy mode

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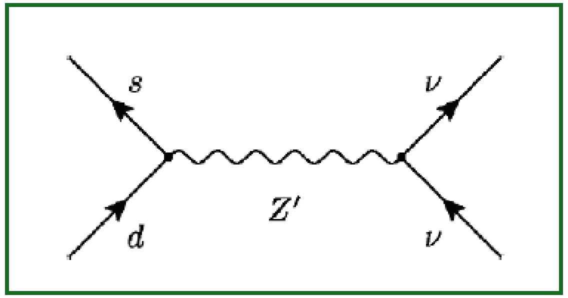


- Anomalies: in b→ s $\mu^+ \mu^-$ high luminosity : b→ s $\tau^+ \tau^-$ (out of the reach of LHCb, BelleII)

- Anomalies: R(D), R(D*)→ Lepton Flavour Universality (LFU) violation
  - modes not accessible/difficult to measure
    - observables sensitive to baryon polarization (Λ_b)
    - LFU violation in baryon decays
    - $B_c \rightarrow \tau \bar{\nu}_\tau$ (out of the reach of LHCb and Belle II)

  SPIF- BA involved

  - new heavy mediators e.g. Z' coupling differently to the 3 generations

  SPIF- BA involved

  - determination of G_F from tau decays

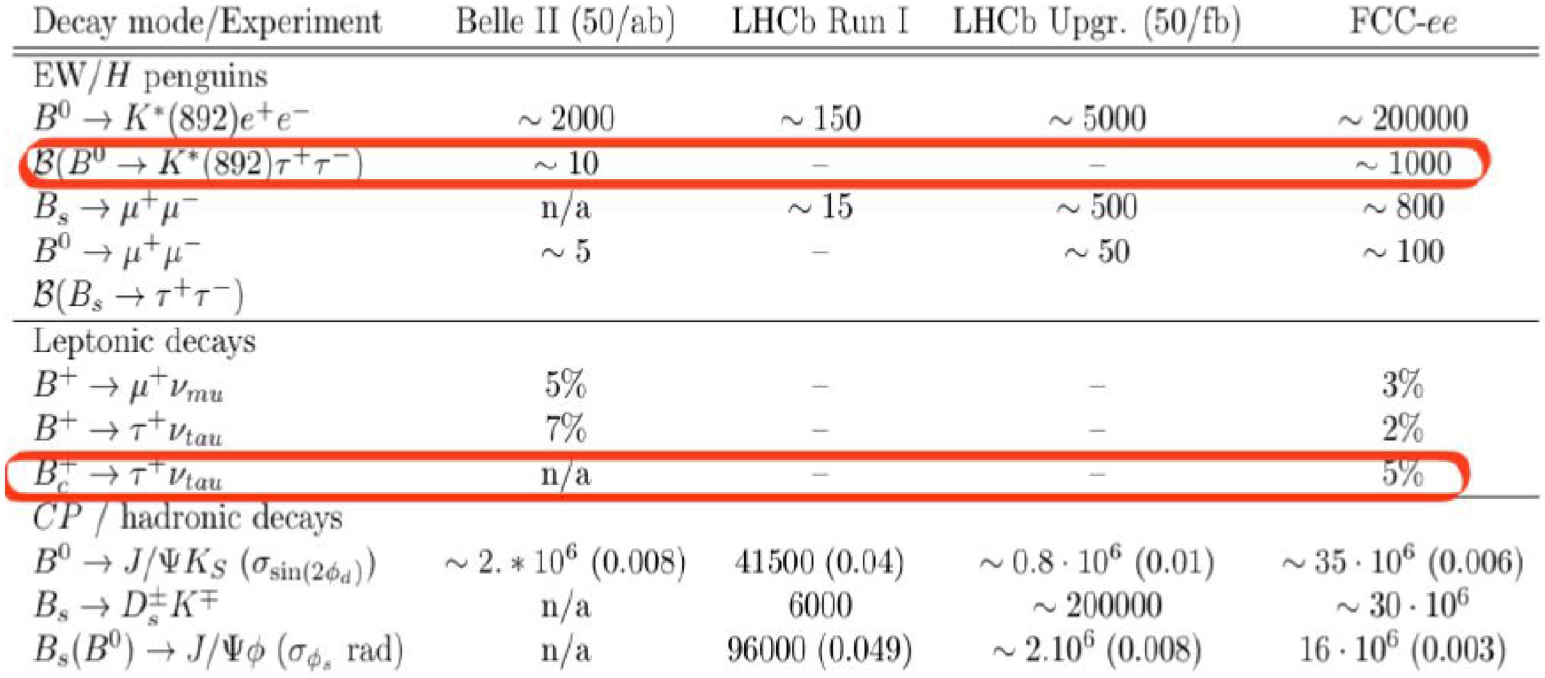
- Lepton Flavour Violation (LFV)
  - $B(\tau \rightarrow 3\mu) < 2 \times 10^{-8}$ (Belle)
    $< 3 \times 10^{-10}$ (Belle II)
    $< 10^{-11}$ (FCC-ee)

  CMS-Bari + SPIF BA involved

  - LFV in B decays $B_s \rightarrow \mu\tau$, $B \rightarrow K^* \mu\tau$

  SPIF- BA involved

Search for BSM at Future colliders



Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu_{mu}$	5%	–	–	3%
$B^+ \to \tau^+\nu_{tau}$	7%	–	–	2%
$B_c^+ \to \tau^+\nu_{tau}$	n/a	–	–	5%
CP / hadronic decays				
$B^0 \to J/\Psi K_S$ $(\sigma_{\sin(2\phi_d)})$	$\sim 2.*10^6$ (0.008)	41500 (0.04)	$\sim 0.8 \cdot 10^6$ (0.01)	$\sim 35 \cdot 10^6$ (0.006)
$B_s \to D_s^\pm K^\mp$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \to J/\Psi\phi$ (σ_{ϕ_s} rad)	n/a	96000 (0.049)	$\sim 2.10^6$ (0.008)	$16 \cdot 10^6$ (0.003)

Grojean 2024

Search for BSM at Future colliders

- **Higgs Sector**
- **Flavour**
- QCD

- Anomalies: $(g\text{-}2)_\mu$ → $(g\text{-}2)_\tau$

SPIF- BA involved

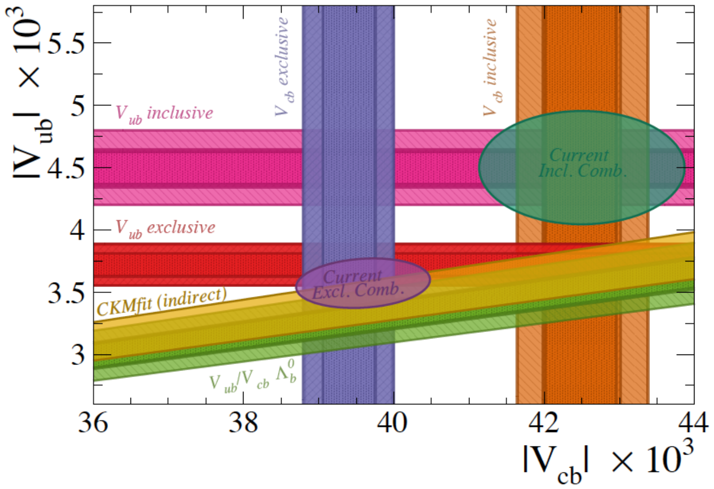
- $(g\text{-}2)_\mu$ implies enhancement of $H \rightarrow \mu^+ \mu^-$ → look at the τ case
- LFV in H,Z decays : $H \rightarrow \mu e$, $Z \rightarrow \mu e$ (in the SM with lepton mixing $<10^{-50}$)

CKM studies:

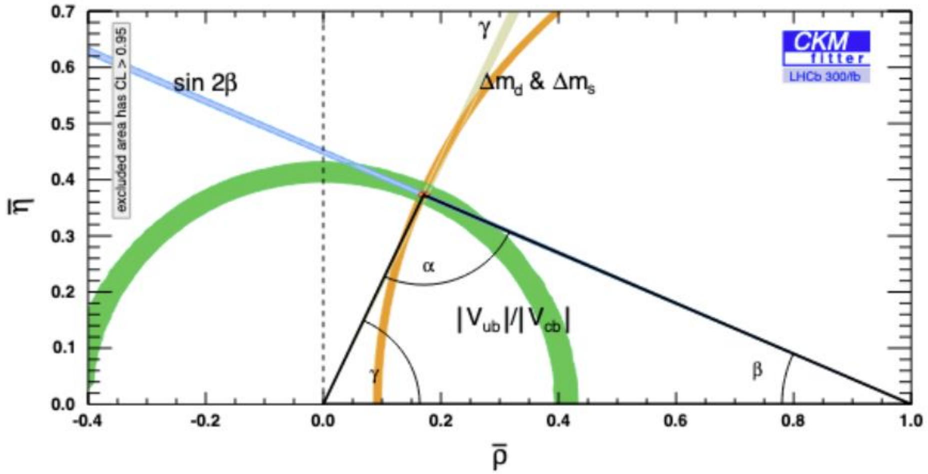
inclusive decays: V_{cb}, V_{ub}

UT triangle → improved determination of α

credit:
M. Kenzie



SPIF- BA involved



Search for BSM at Future colliders

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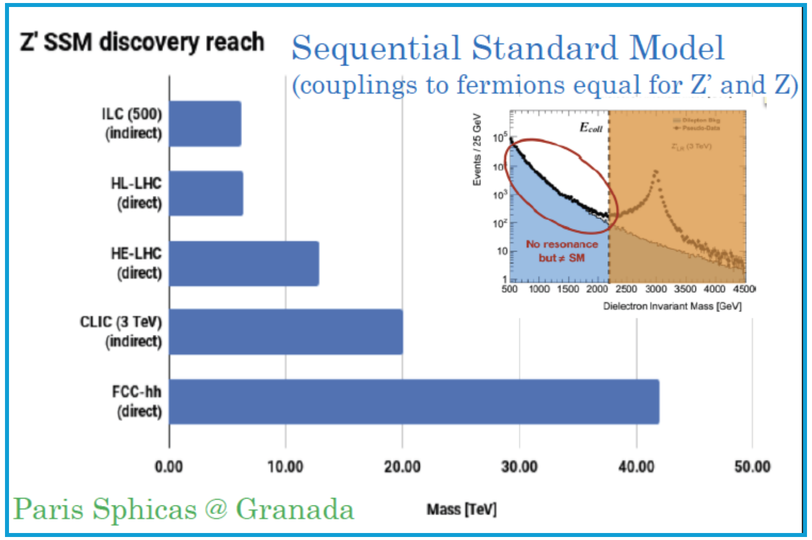
energy frontier:
discovery reach for new mediators

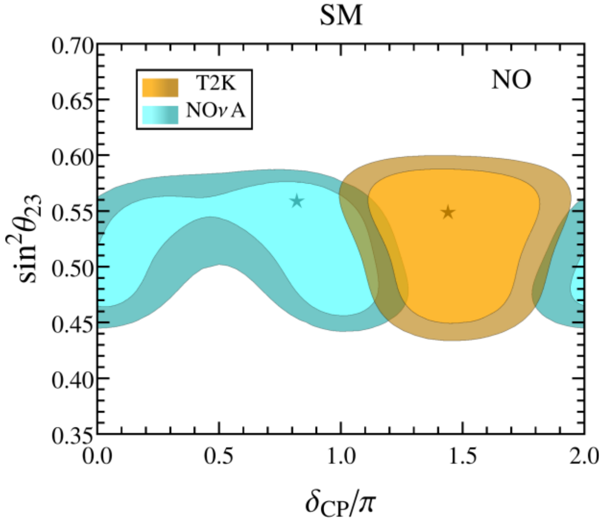


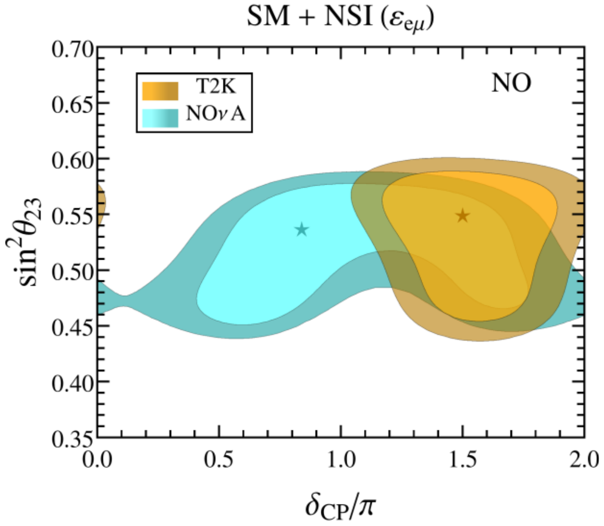
Sequential Standard Model
(couplings to fermions equal for Z' and Z)

Paris Sphicas @ Granada

SPIF- BA
involved

interplay with anomalies in ν physics





- fixing ν oscillation parameters
- tension between T2K and NOvA (long baseline ν exp)
- possible solution: flavor changing non-standard ν interactions
- hint of Z'?

TASP- BA
involved

Flavour Physics in SMEFT: a few examples

Semileptonic b→U ℓ ν U=u,c decays in SMEFT

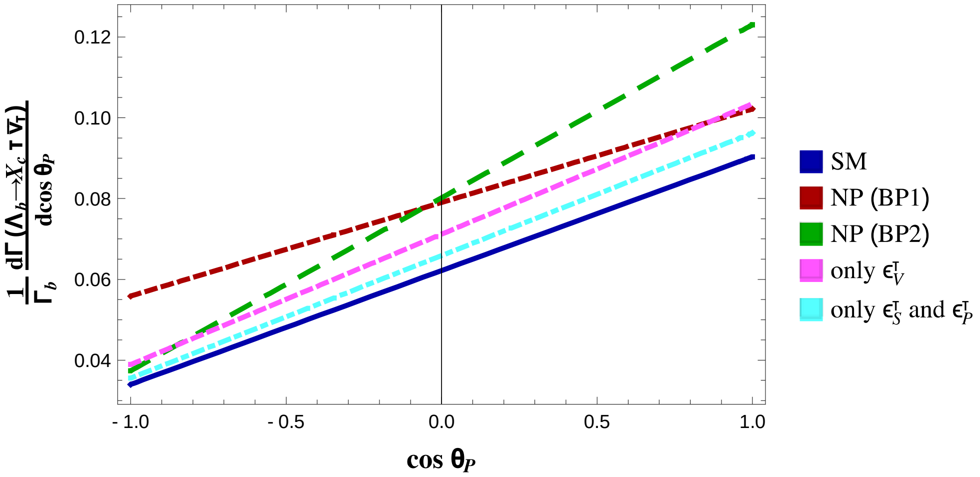
SM

$$
\begin{aligned}
H_{\rm eff}^{b\to U\ell\nu} = \frac{G_F}{\sqrt{2}} V_{Ub}\,\Big[& (1+\epsilon_V^\ell)\,(\bar U\gamma_\mu(1-\gamma_5)b)\,(\bar\ell\gamma^\mu(1-\gamma_5)\nu_\ell) \\
& + \epsilon_S^\ell\,(\bar U b)\,(\bar\ell(1-\gamma_5)\nu_\ell) + \epsilon_P^\ell\,(\bar U\gamma_5 b)\,(\bar\ell(1-\gamma_5)\nu_\ell) \\
& + \epsilon_T^\ell\,(\bar U\sigma_{\mu\nu}(1-\gamma_5)b)\,(\bar\ell\sigma^{\mu\nu}(1-\gamma_5)\nu_\ell) \\
& + \epsilon_R^\ell\,(\bar U\gamma_\mu(1+\gamma_5)b)\,(\bar\ell\gamma^\mu(1-\gamma_5)\nu_\ell)\Big] + h.c.\ .
\end{aligned}
$$

determining which of the SMEFT coefficients contribute

=

selecting viable NP candidates



new operators contribute to different processes

	ϵ_V^ℓ	ϵ_S^ℓ	ϵ_P^ℓ	ϵ_T^ℓ
$B^- \to \ell^-\bar\nu_\ell$	✓		✓	
$\bar B \to \pi\ell^-\bar\nu_\ell$	✓	✓		✓
$B \to \rho\ell\bar\nu_\ell$	✓		✓	✓
$B \to a_1\ell\bar\nu_\ell$	✓	✓		✓

Flavour Physics in SMEFT: a few examples

Semileptonic b→U ℓ ν U=u,c decays in SMEFT

determining which of the SMEFT coefficients contribute

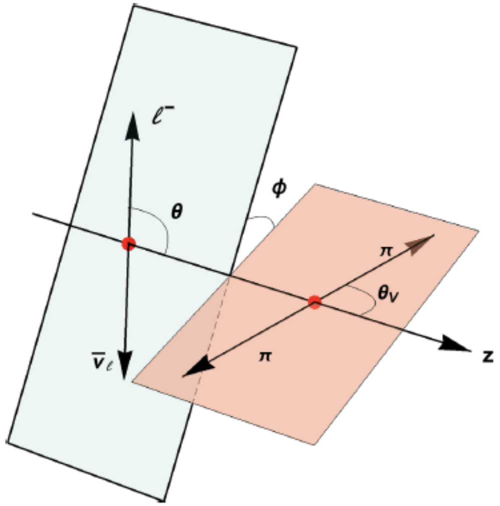
=

selecting viable NP candidates

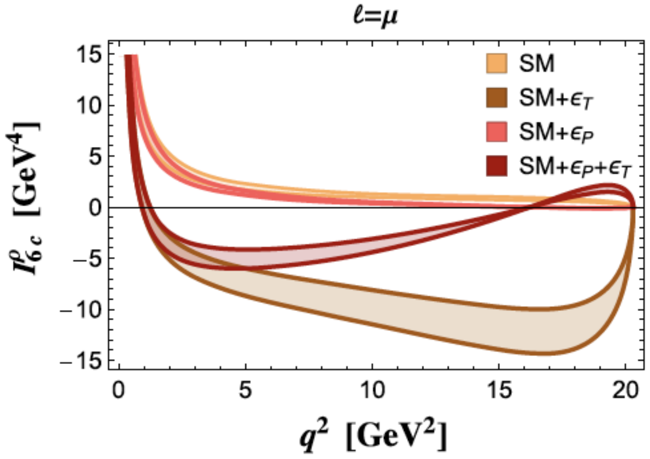
high statistics required

SM

$$H_{\rm eff}^{b\to U\ell\nu}=\frac{G_F}{\sqrt{2}}V_{Ub}\Big[(1+\epsilon_V^\ell)(\bar{U}\gamma_\mu(1-\gamma_5)b)\,(\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell)$$
$$+\epsilon_S^\ell(\bar{U}b)\,(\bar{\ell}(1-\gamma_5)\nu_\ell)+\epsilon_P^\ell(\bar{U}\gamma_5 b)\,(\bar{\ell}(1-\gamma_5)\nu_\ell)$$
$$+\epsilon_T^\ell(\bar{U}\sigma_{\mu\nu}(1-\gamma_5)b)\,\,(\bar{\ell}\sigma^{\mu\nu}(1-\gamma_5)\nu_\ell)$$
$$+\epsilon_R^\ell(\bar{U}\gamma_\mu(1+\gamma_5)b)\,(\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell)\Big]+h.c.\ \ .$$



$$\frac{d^4\Gamma(\bar{B}\to V(P_1P_2)\ell^-\bar{\nu}_\ell)}{dq^2\,d\cos\theta d\phi d\cos\theta_V}$$
$$=\mathcal{C}|\vec{p}_V|\left(1-\frac{m_\ell^2}{q^2}\right)^2\{I_{1s}\sin^2\theta_V+I_{1c}\cos^2\theta_V$$
$$+(I_{2s}\sin^2\theta_V+I_{2c}\cos^2\theta_V)\cos 2\theta$$
$$+I_3\sin^2\theta_V\sin^2\theta\cos 2\phi+I_4\sin 2\theta_V\sin 2\theta\cos\phi$$
$$+I_5\sin 2\theta_V\sin\theta\cos\phi$$
$$+(I_{6s}\sin^2\theta_V+I_{6c}\cos^2\theta_V)\cos\theta$$
$$+I_7\sin 2\theta_V\sin\theta\sin\phi+I_8\sin 2\theta_V\sin 2\theta\sin\phi$$
$$+I_9\sin^2\theta_V\sin^2\theta\sin 2\phi\},$$



Search for BSM at Future colliders

- Higgs Sector
- Flavour
- **QCD**

Foreseen directions

- Hadron spectroscopy — SPIF- BA involved
- Parton distribution functions
- QCD phase diagram — SPIF- BA involved

Huge theoretical efforts required:

- multiloop calculations
- understanding non-perturbative dynamics: prerequisite for most of flavour analyses

Thank you