Some concluding slides on LHCb and SHiP

- Two examples of intensity frontier -

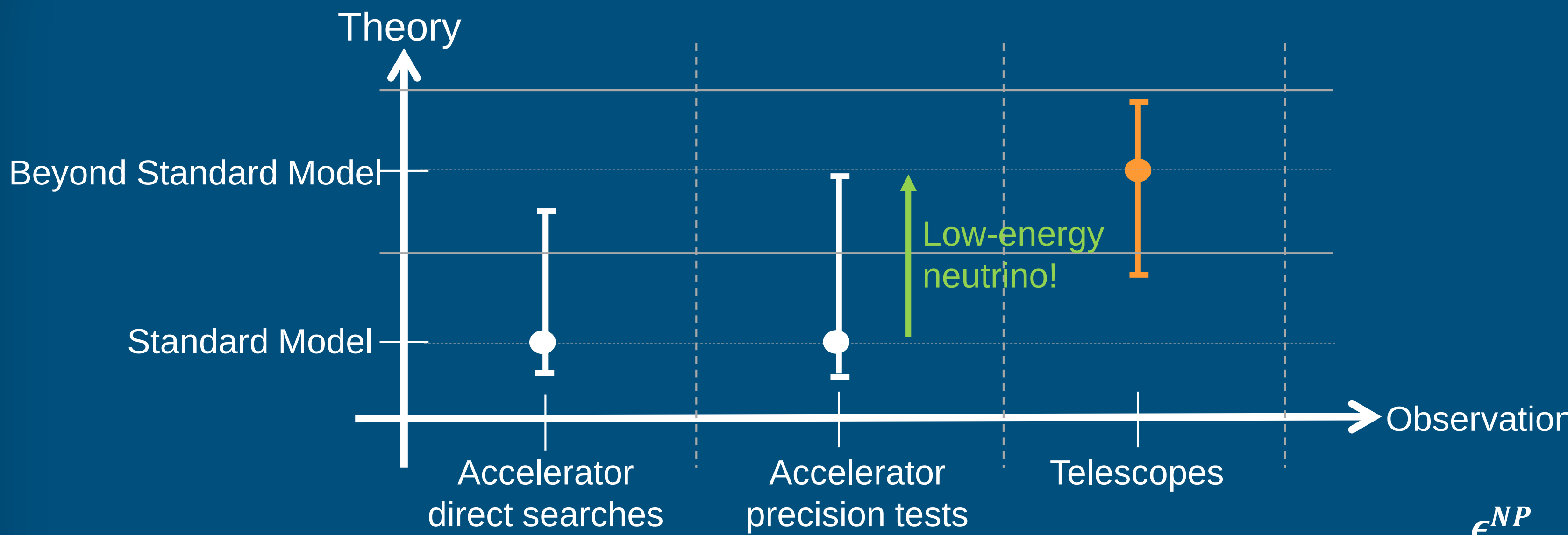
Richard Jacobsson

Note: Most of lecture on white board

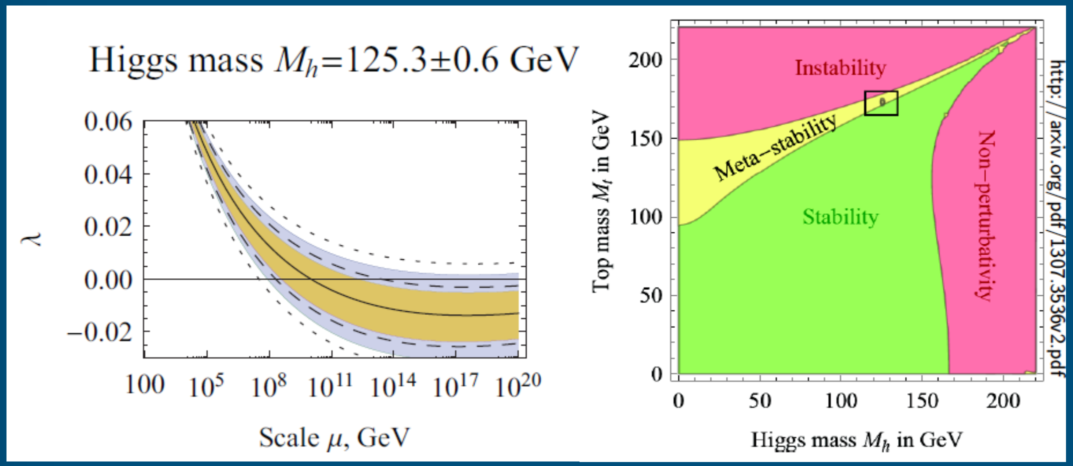
Big Bang symphony

$$
\begin{gathered}
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4} g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
\tfrac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - i g s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\tfrac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - \\
g M W^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \tfrac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \\
\phi^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + \\
i g s_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - i g \tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\tfrac{1}{4} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^-] - \tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) - \tfrac{1}{2} i g^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \tfrac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m_u^\lambda) u^\lambda_j - \\
\bar{d}^\lambda_j (\gamma\partial + m_d^\lambda) d^\lambda_j + i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] + \\
\tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3} s_w^2 - \\
1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s_w^2 - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) e^\lambda) + \\
(\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \\
\gamma^5) u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} \tfrac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1-\gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1+\gamma^5) \nu^\lambda)] - \\
\tfrac{g}{2} \tfrac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + \\
m_u^\lambda (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m_u^\kappa (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \\
\gamma^5) u^\kappa_j] - \tfrac{g}{2} \tfrac{m_u^\lambda}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m_d^\lambda}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m_u^\lambda}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \\
\tfrac{ig}{2} \tfrac{m_d^\lambda}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
\tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W^+_\mu (\partial_\mu \bar{Y} X^- - \\
\partial_\mu \bar{X}^+ Y) + i g c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \\
\partial_\mu \bar{Y} X^+) + i g c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H] + \\
\tfrac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \tfrac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \tfrac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{gathered}
$$

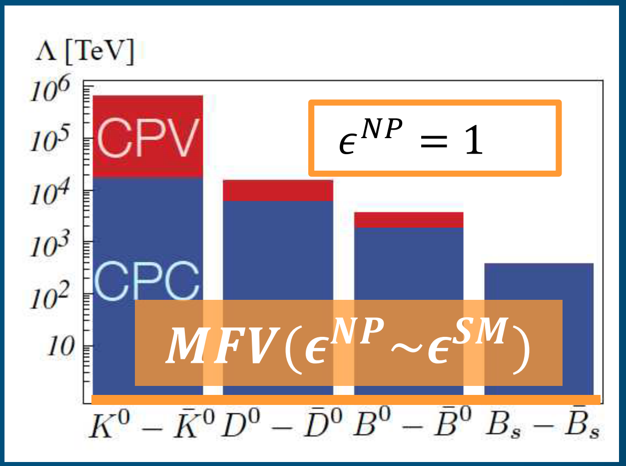
Physics Scenario after LHC Run 1



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \delta C[\frac{\epsilon^{NP}}{\Lambda^2_{NP}}]$$



arXiv:0906.0954



Physics Situation after LHC Run 1

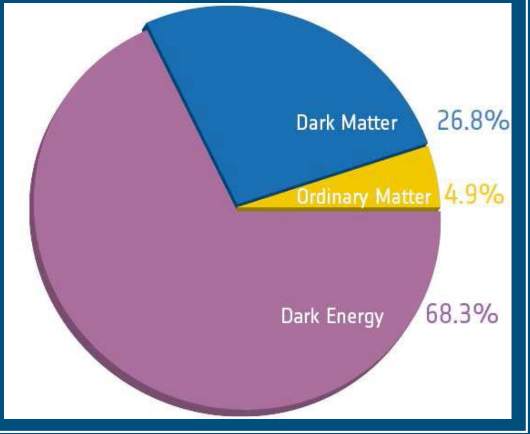
- *With a mass of the Higgs boson of 125 − 126 GeV, the Standard Model may be a self-consistent weakly coupled effective field theory up to very high scales (possibly up to the Planck scale) without adding new particles*
  - ➔ No *need* for new particles *up to* Planck scale!?

<u>Experimental evidence for New Physics</u>

1. Neutrino oscillations: *tiny* masses and flavour mixing
   - → Requires new degrees of freedom in comparison to SM
2. Baryon asymmetry of the Universe
   - → Measurements from BBN and CMB $\eta = \left\langle\frac{n_B}{n_\gamma}\right\rangle_{T=3K} \sim \left\langle\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}}\right\rangle_{T\gtrsim 1\ GeV} \sim (6.3 \pm 0.3) \times 10^{-10}$
   - → Current measured CP violation in quark sector ➔ $\eta \sim 10^{-20}$!!
3. Dark Matter from indirect gravitational observations
   - → Non-baryonic, neutral and stable or long-lived
4. Dark Energy and Inflation

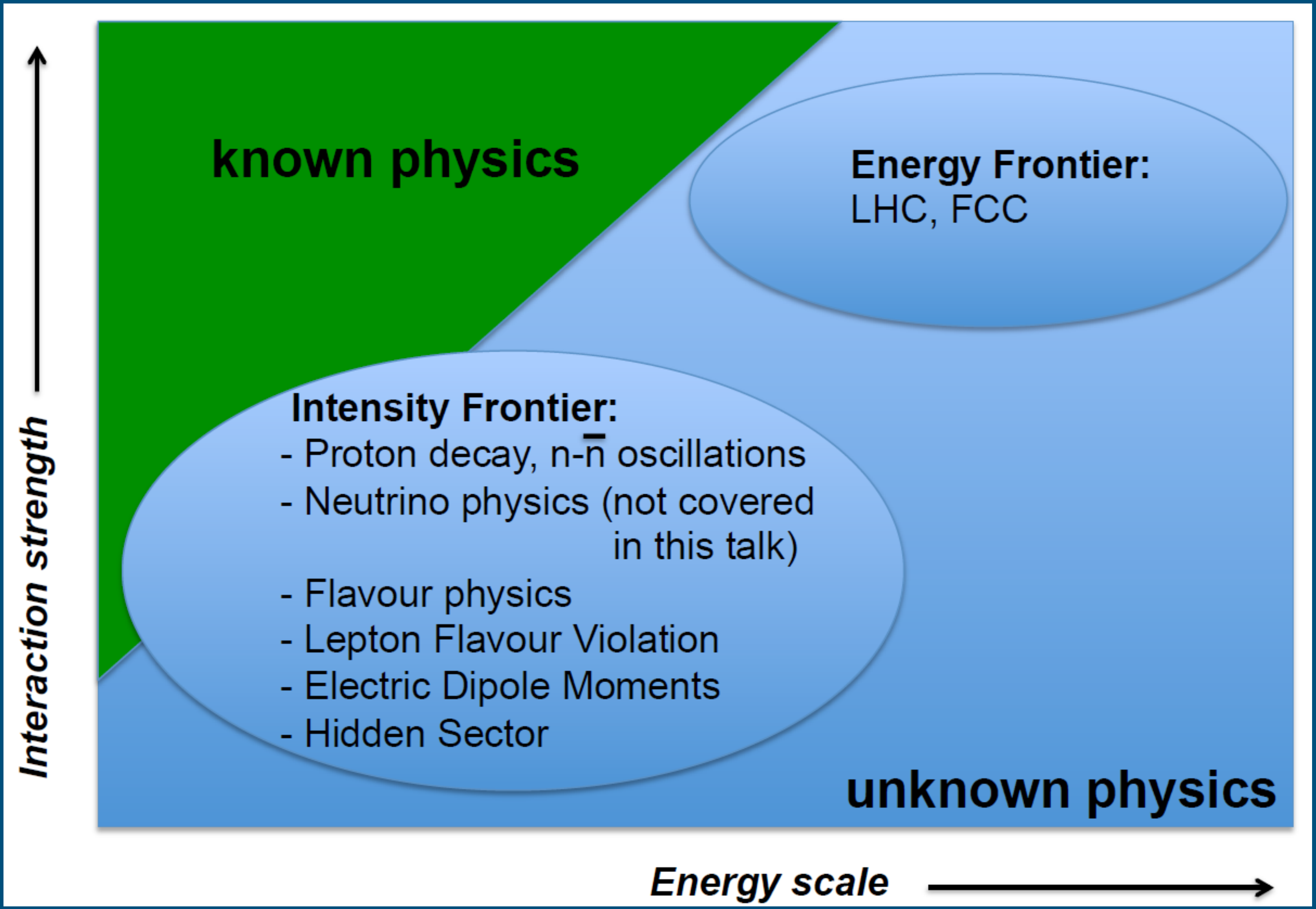
<u>Theoretical "evidence" for New Physics</u>

1. Hierarchy problem and stability of Higgs mass
2. SM flavour structure
3. Strong CP problem
4. Unification of coupling constants
5. Gravity
6. Inflation, etc



➔ *While we had unitarity bounds for the Higgs, no such indication on the next scale….*

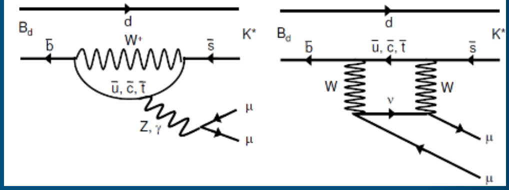
Energy – intensity frontier



In Praise of Precision Measurements

- Precision measurements likely to have the largest discovery potential for new physics
  - Higgs and top precision physics
  - Flavour precision physics
  - Complemented by direct searches at high scales AND low scales

➔ LHCb focus on measuring *indirect* effects of New Physics in CP violation and rare decays
  - Searching deviations from the SM
  - Virtual effects allow probing energies much higher than E_{cms} of the LHC

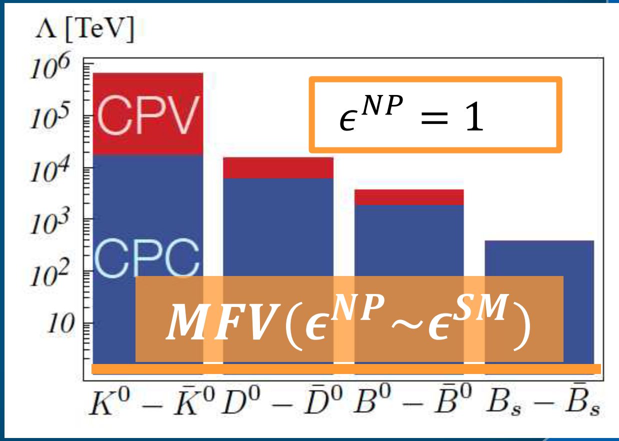


- b and c sector contains large repertoire of decays and topologies
  - New Physics may enter differently in boxes and in penguin contributions
  - ➔ Aim for access to "all" modes

- Upgrade aim: reach experimental sensitivities ≤ theoretical uncertainties

$$\sigma_{stat+sys+th} < \delta C[\frac{\epsilon^{NP}}{\Lambda^2_{NP}}]$$

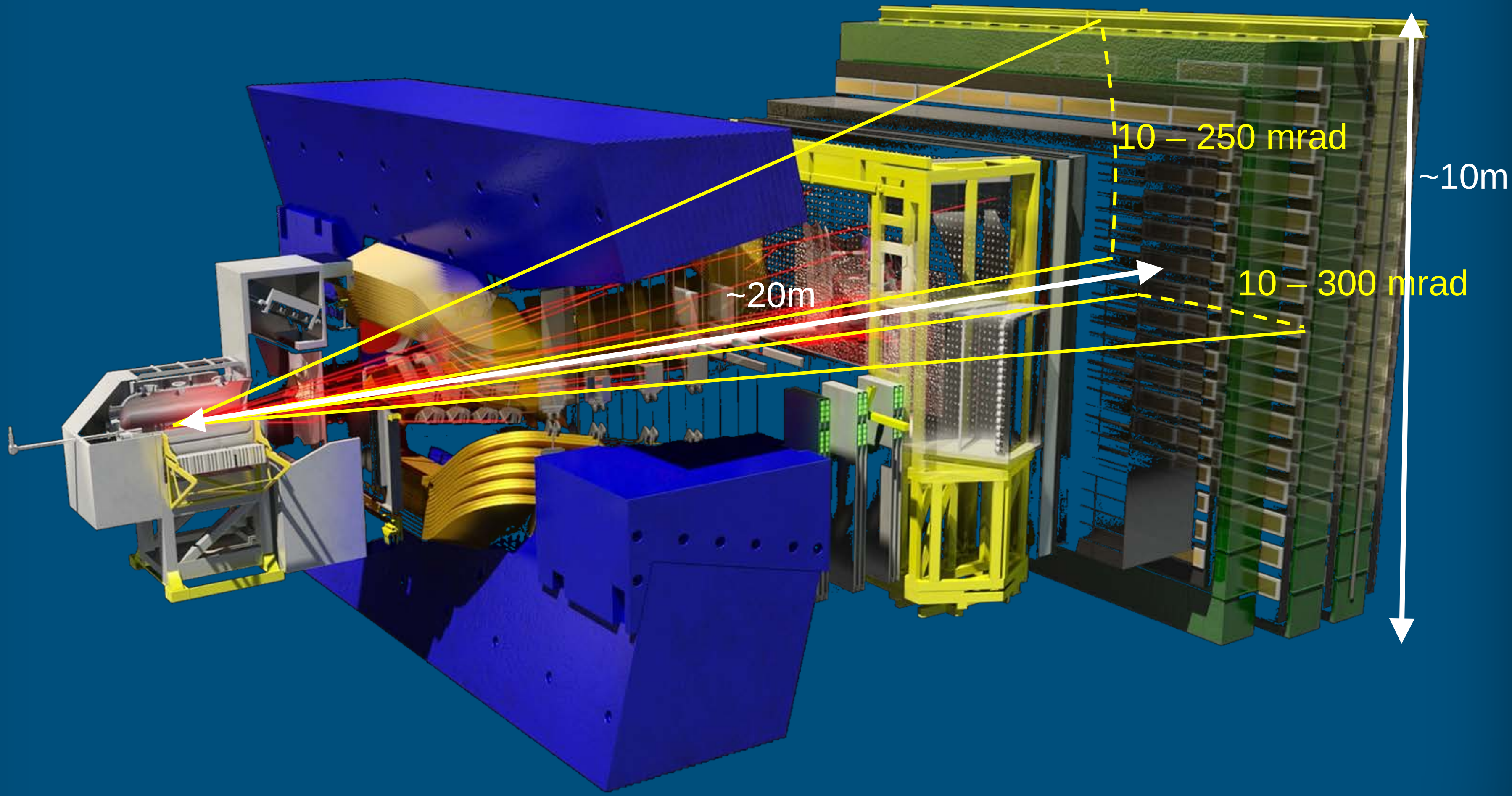
  - Not expected to be limited by systematics → often improves with increasing statistics
  - σ_{theory} often decrease with complementary measurements



Precision experiment: LHCb Detector

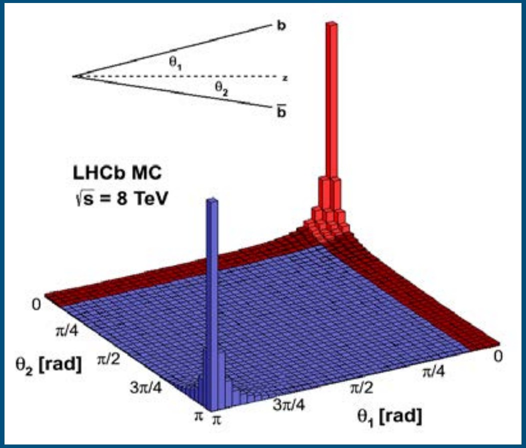
Covers ~4% of the solid angle, but captures ~40% of the heavy quark production cross-section

- Acceptance $2 < \eta < 5$ with entire detector



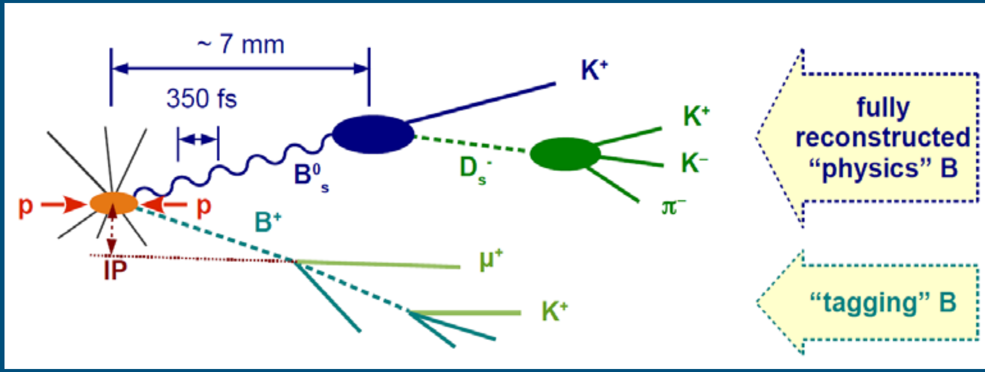
Key features of LHCb at LHC

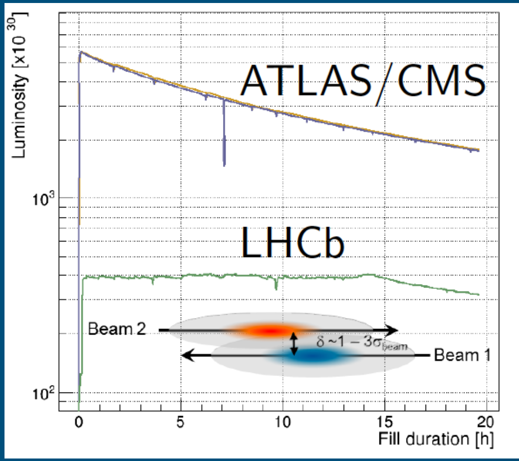
- **Large signal cross-sections**
  - >100 kHz → 1 MHz of $b\bar{b}$ pairs at LHCb interaction point
  - Access to all b-flavored hadrons B_u (~40%), B_d *(~40%)*, B_s (~10%), and B_c, and *B*-baryons Λ_b *(~10%)* , …
    (arXiv:1111.2357v2, arXiv:1301.5286)
  - $c\bar{c}$ production 20x more



- **The final state $b\bar{b}$ / $c\bar{c}$ pair are Lorentz boosted**
  - → The B / D hadrons appear in the same hemisphere
  - → Very good proper time resolution

- **Flavor tagging**
  - Same side, uses π or *K* emitted together with signal *B / D* hadron
  - Opposite side, detects flavor of partner *B / D* hadron from decay



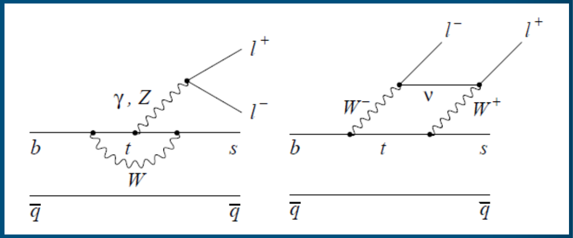


R. Jacobsson, Proc. IEEE NPSS-MIC 2012

- **Operating at a controllable levelled luminosity**
  - Control detector performance and systematics

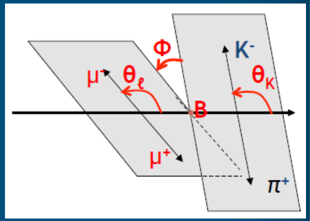
Example of prospects: $b \to sl^+l^-$

- Electroweak penguin/box diagram sensitive to NP ➔ Helicity structure
  - $B_d \to K^*\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$
  - 4-body angular analysis as a function of $q^2 = M^2(ll)$



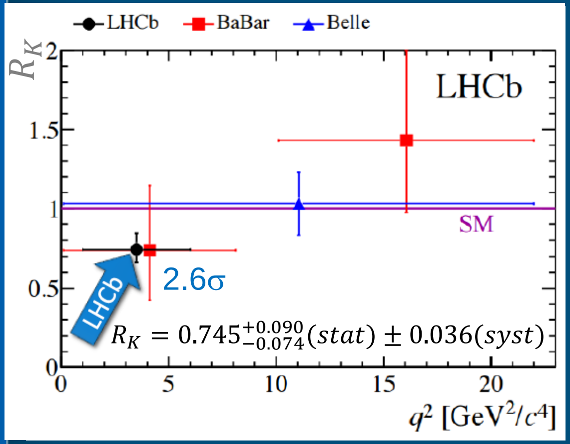
E.g. $A_{FB}(q^2) = \frac{\Gamma(\cos\theta_{Bl^+}>0)-\Gamma(\cos\theta_{Bl^+}<0)}{\Gamma(\cos\theta_{Bl^+}>0)+\Gamma(\cos\theta_{Bl^+}<0)}$, $A_{FB}(q^2) = 0$

E.g. $A_T^{(2)}(q^2) = \frac{|A_\perp(q^2)|^2-|A_\parallel(q^2)|^2}{|A_\perp(q^2)|^2+|A_\parallel(q^2)|^2}$

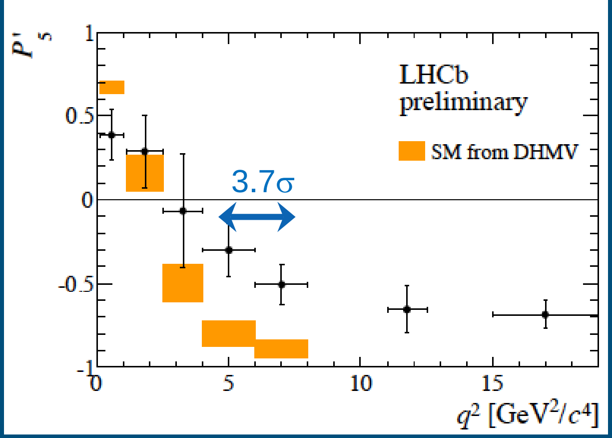


- Currently $b \to sl^+l^-$ only measurements with some interesting tensions
  - Lepton universality $R_K = \frac{Br(B^+\to K^+\mu^+\mu^-)}{Br(B^+\to K^+e^+e^-)}$ together with P_5' in the differential decay rate in $B_d \to K^*\mu^+\mu^-$

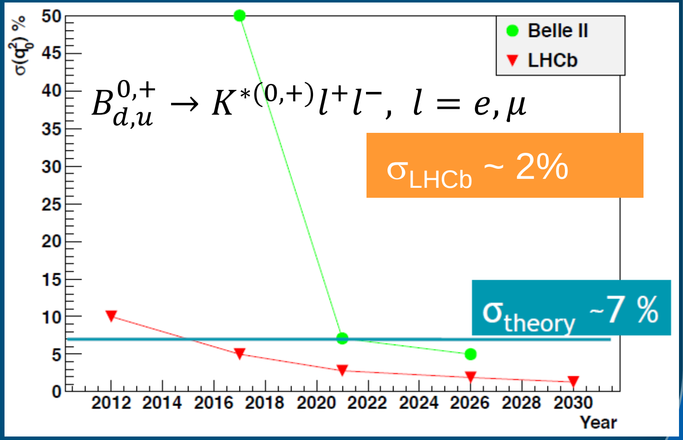
Expected future sensitivity on q_0^2 with 50 fb^{-1}



PRL 113 (2014) 151601



LHCb-CONF-2015-002



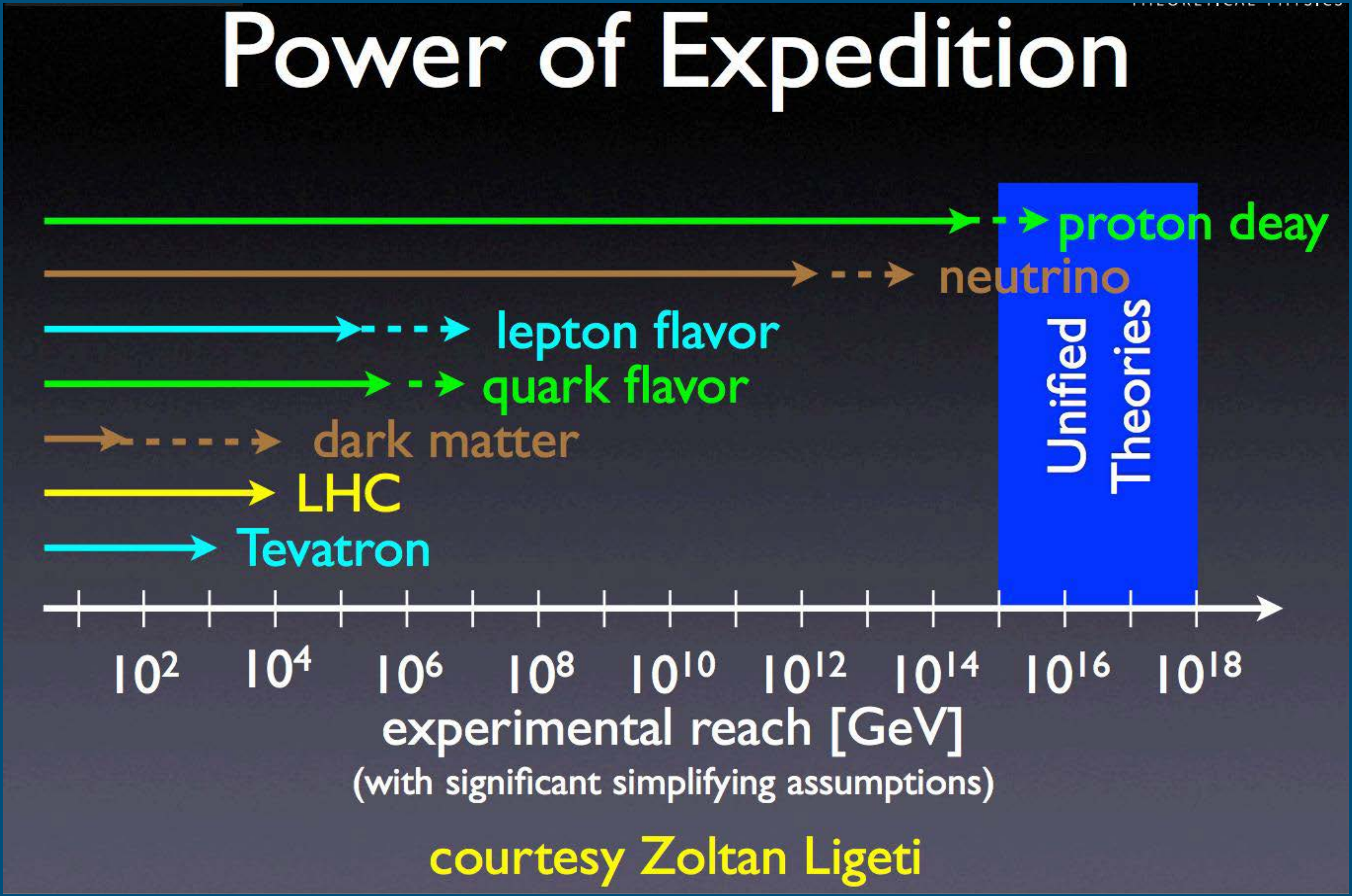
Upgrade Physics Prospects

Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade	Theory (SM)
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

+ a wealth of additional physics

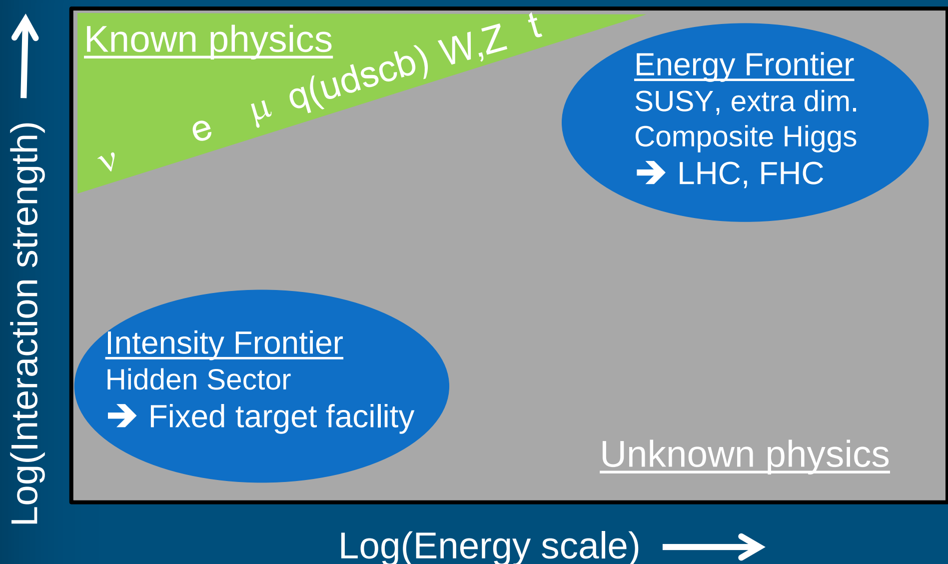
- ➔ Diversity and non-spectator effect of the B_c system, and baryons
- ➔ Lepton universality, lepton flavour violation, searches for long-lived "portals"
- Production measurements and spectroscopy, QCD, PDFs, and EW
- …and quarkonium and Z production in pA and possibly also AA collisions

Precision exploration



What if instead...?

What about solutions to (some/all) these questions *below Fermi scale* $E < G_F^{-1/2}$*?*

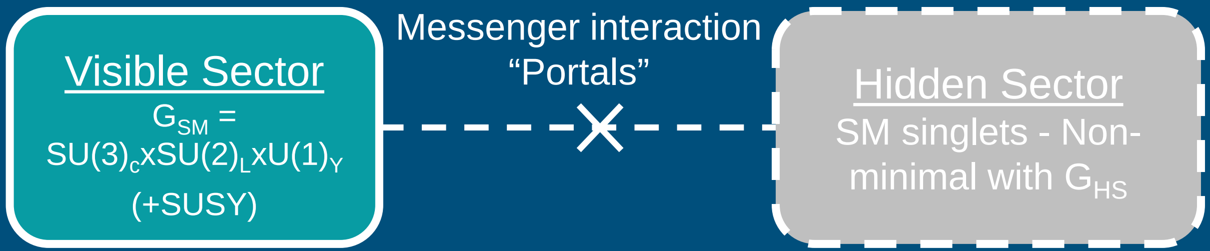


- Must have very weak couplings ➔ "*Light* Hidden Sector"
  - Not the first time! Neutrino is QED gauge singlet with SM Portal $(\bar{p}\gamma^{\mu}n)(\bar{e}\gamma_{\mu}\nu)$

- "Intensity Frontier" much less attention recently:
  - PS 191: early 1980s
  - CHARM: 1980s
  - NuTeV: 1990s
  - DONUT: late 1990s - early 2000

New Physics prospects in Hidden Sector

$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$



- New hidden particles are singlet under the SM gauge group
- Composite operators (hoping there is not just gravity…) $\mathcal{L}_{mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{HS}^{(k)} \mathcal{O}_{SM}^{(l)}}{\Lambda^n}$
  - ➔ Conventionally lowest dimension SM operator makes up "portals" between SM and Hidden Sector
  - No knowledge of hidden scale but hidden particles participating in portals may be light

➔ *Dynamics of Hidden Sector may drive dynamics and anomalies of Visible Sector!*

- ➔ *Dark Matter candidates comes for free – stable or unstable – and together with other cosmological observations impose powerful constraints*

- Two possibilities for Beyond Standard Model:
  1. SM + Hidden Sector with light messengers is all there is up to Planck scale – no new visible scale
  2. Wider theory exist at new energy scale (SUSY, extra dim.,etc) including *inherent* light messengers
  3. (or both…)

New Physics prospects in Hidden Sector

- Standard Model portals:
  - **D = 2: Vector portal**
    - Kinetic mixing with massive dark/secluded/paraphoton V : $\frac{1}{2}\varepsilon F^{SM}_{\mu\nu} F^{\mu\nu}_{HS}$

    ➔ Interaction with 'mirror world' constituting dark matter

  - **D = 2: Higgs portal**
    - Mass mixing with dark singlet scalar χ : $(\mu\chi + \lambda\chi^2)H^\dagger H$

    $$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\rho & -\sin\rho \\ \sin\rho & \cos\rho \end{pmatrix} \begin{pmatrix} \phi'_0 \\ S' \end{pmatrix}$$

    ➔ Mass to Higgs boson and right-handed neutrino, and function as inflaton in accordance with Planck and BICEP measurements

  - **D = 5/2: Neutrino portal**
    - Mixing with right-handed neutrino N (Heavy Neutral Lepton): $YH^\dagger \bar{N} L$

    ➔ Neutrino oscillation, baryon asymmetry, dark matter

  - **D = 4: Axion portal**
    - Mixing with Axion Like Particles, pseudo-scalars pNGB, axial vectors : $\frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi$, etc

    ➔ Solve strong CP problem, Inflaton

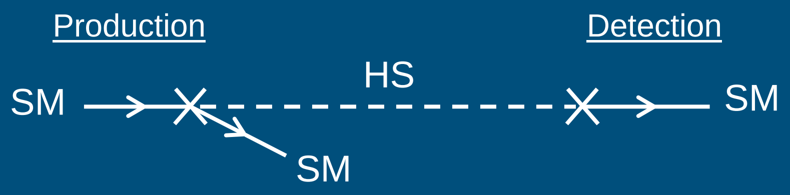
  - And possiby higher dimensional operator portals and **SUper-SYmmetric portals** (light neutralino, light sgoldstino,…)

    ➔ SUSY parameter space explored by LHC

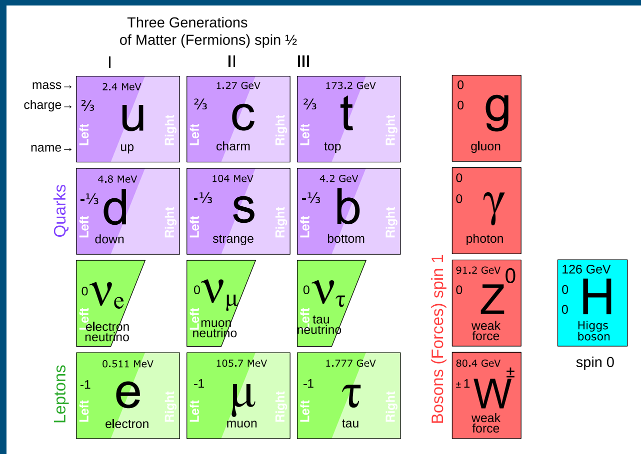
    ➔ Some of SUSY low-energy parameter space open to complementary searches

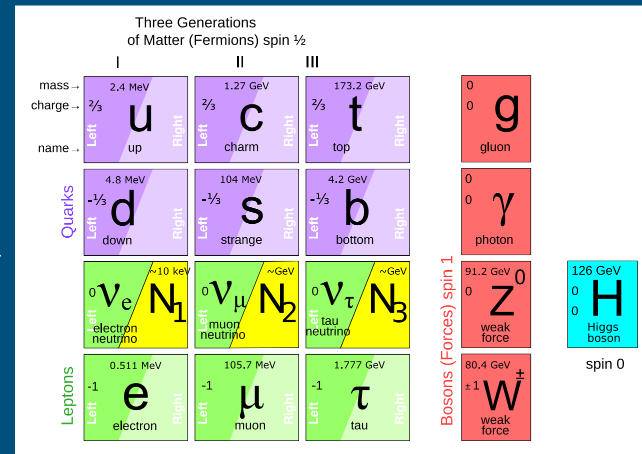
New Physics prospects in Hidden Sector

- Two search methods:
  1. "Indirect detection" through portals in (missing mass)
  2. "Direct detection" through both portals in and out

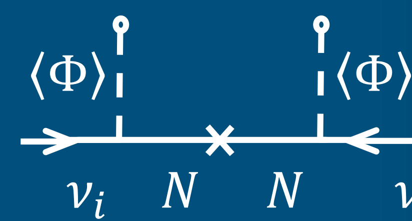


Neutrino portal

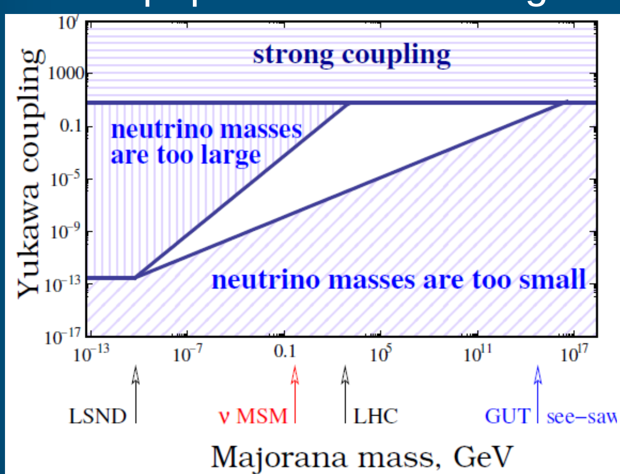




- $Y_{I\ell} H^\dagger \bar{N}_I L_\ell$ lepton flavour violating term results in mixing between N_I and SM active neutrinos when the Higgs SSB develops the $< VEV > = v \sim 246\ GeV$
  - ➔ Oscillations in the mass-basis and CP violation
  - ➔ Type I See-Saw with $m^R >> m_D (= Y_{I\ell} v)$



- Four "popular" N mass ranges:



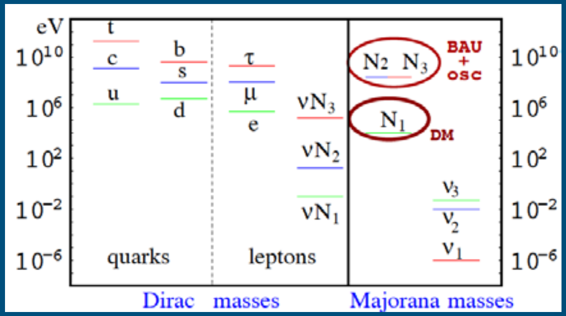
	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	direct search	experiment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

arXiv:1204.5379

Ex. : HNLs in νMSM (Asaka, Shaposhnikov)

Role of N_1 with a mass of $\mathcal{O}$(keV)
➔ Dark Matter

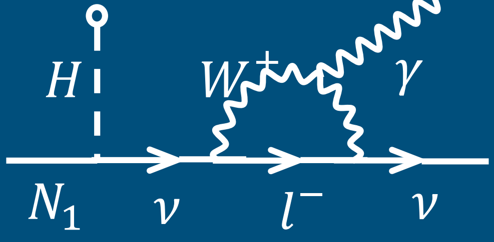
Role of N_2 and N_3 with a mass of $\mathcal{O}(m_q/m_{l^\pm})$ (100 MeV – GeV):
➔ Neutrino oscillations and mass, and BAU



➔ Assumption that N_I are $\mathcal{O}(m_q/m_l)$: <u>No new energy scale!</u>

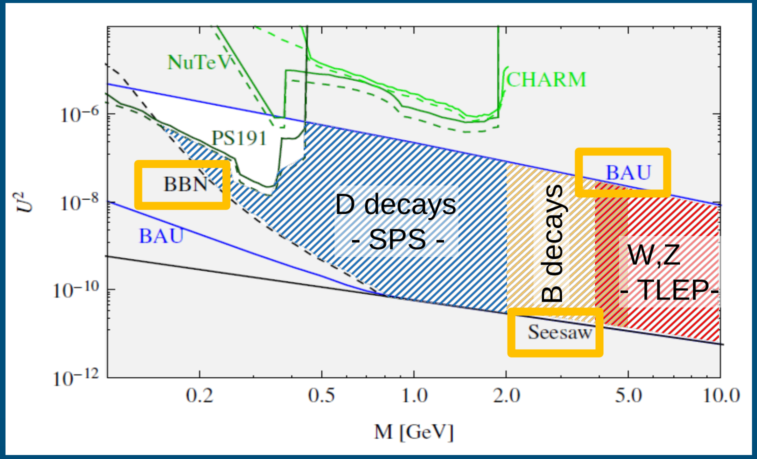
- $Y_{I\ell} = \mathcal{O}\left(\frac{\sqrt{m_{atm} m_I^R}}{v}\right) \sim 10^{-8} \quad (m^R = 1\,GeV, m_\nu = 0.05\,eV)$
- $\mathcal{U}^2 \sim 10^{-11}$ ➔ Intensity Frontier!

N_1 Subdominant radiative decay



$$E_\gamma = \frac{M_{N_1} c^2}{2}$$

Current limits on N_2 and N_3

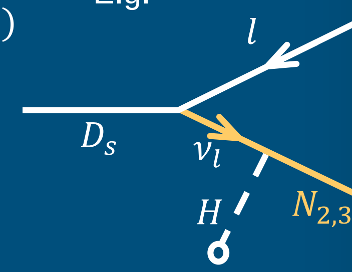


HNL production and decay

- Predominant production in mixing with active neutrino from leptonic/semi-leptonic weak decays of heavy mesons
  - $D_s \rightarrow lN,\ (\tau \rightarrow X\nu_\tau)$ $U^2_{e,\mu,\tau}$ and $N_N \leq M(D_s) - m_l,\ (N_N \leq M(\tau) - M(X))$
  - $D \rightarrow lKN$ $U^2_{e,\mu}$ and $N_N \leq M(D_s) - m_l$
  - $B_{(s)} \rightarrow D_{(s)}lN$ $U^2_{e,\mu,\tau}$ and $N_N \leq M\big(B_{(s)}\big) - M(D_{(s)}) - m_l$
  - $B \rightarrow lN \ \ (B \rightarrow l\pi N)$ $U^2_{e,\mu,\tau}$ and $N_N \leq M(B) - m_l$ $, Br \propto V^2_{ub}/V^2_{cb}$

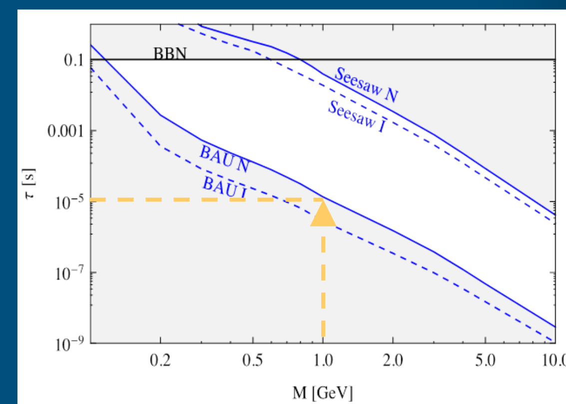
  ➔ Branching ratios $\mathcal{O}(10^{-7} - 10^{-8})$

E.g.



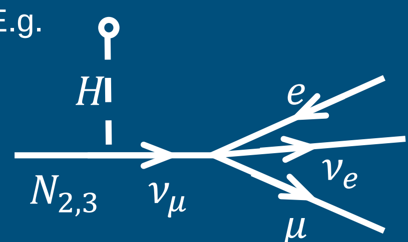
- Very weak HNL-active neutrino mixing → $N_{2,3}$ much longer lived than SM particles

  ➔ Typical lifetimes > 10 μs for $M_{N_{2,3}} \sim 1\ GeV$ → Decay distance $\mathcal{O}(km)$



- Decay modes
  - $N \rightarrow h^0\nu,\ with\ h^0 = \pi^0, \rho^0, \eta \ \ , \eta'$
  - $N \rightarrow h^\pm l^\mp,\ with\ h^\pm = \pi^\pm, \rho^\pm$
  - $N \rightarrow 3\nu$
  - $N \rightarrow l^\pm l^\mp \nu$

E.g.



- Total rate depend on $\mathcal{U}^2 = \sum_{\substack{I=2,3 \\ \ell=e,\mu,\tau}} |\mathcal{U}_{\ell I}|^2$

  ➔ Relation between $\mathcal{U}_e{}^2, \mathcal{U}_\mu{}^2$ and $\mathcal{U}_\tau{}^2$ depends on flavour mixing

Decay mode	Branching ratio
$N_{2,3} \rightarrow \mu/e + \pi$	*0.1 - 50 %*
$N_{2,3} \rightarrow \mu^-/e^- + \rho^+$	*0.5 - 20 %*
$N_{2,3} \rightarrow \nu + \mu + e$	*1 - 10 %*

HS common experimental features

- Cosmologically interesting and experimentally accessible $m_{HS} \sim \mathcal{O}(MeV - GeV)$
  - ➔ Hidden particle production through hadron decays (π, K, D, B), proton bremsstrahlung,…
  - ➔ Hidden particle decays

Models	Final states
Neutrino portal, SUSY neutralino	$\ell^\pm\pi^\mp, \ell^\pm K^\mp, \ell^\pm\rho^\mp, \quad \rho^\pm \to \pi^\pm\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^+\ell^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+\pi^-, K^+K^-$
Neutrino portal ,SUSY neutralino, axino	$\ell^+\ell^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\pi^0$

  - ➔ Full reconstruction and particle ID aim at maximizing the model independence

- Production and decay rates are very suppressed relative to SM
  - Production branching ratios $\mathcal{O}(10^{-10})$
  - Long-lived objects
  - Travel unperturbed through *ordinary* matter
  - ➔ Challenge is background suppression➔ requires extremely careful estimation

➔ Fixed-target ("beam-dump") experiment with large decay volume

- ➔ Side benefit: Optimizing for heavy meson decays also optimizes facility for $\nu_\tau(\nu_e, \nu_\mu)$ physics
  - $Br(D_s \to \tau + \nu_\tau) \sim$ 5.6% : 10^{15}

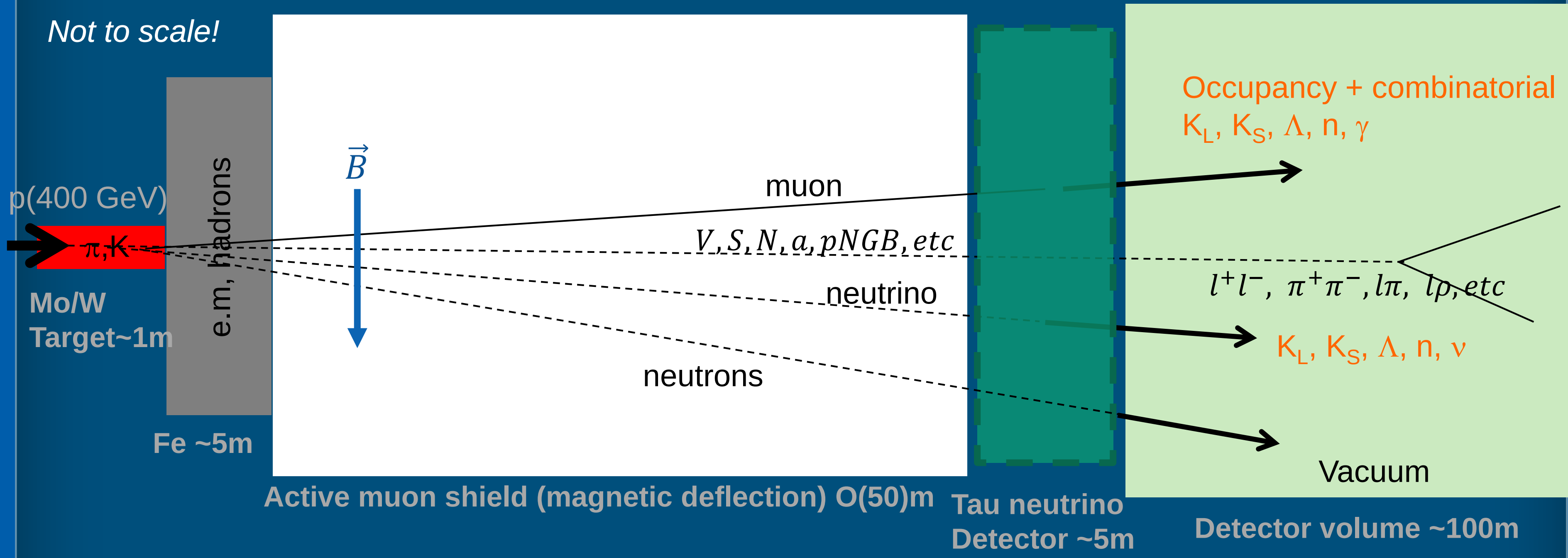
SHiP: Experimental Requirements

Proposal: ***fixed-target (beam dump like) experiment at the SPS***

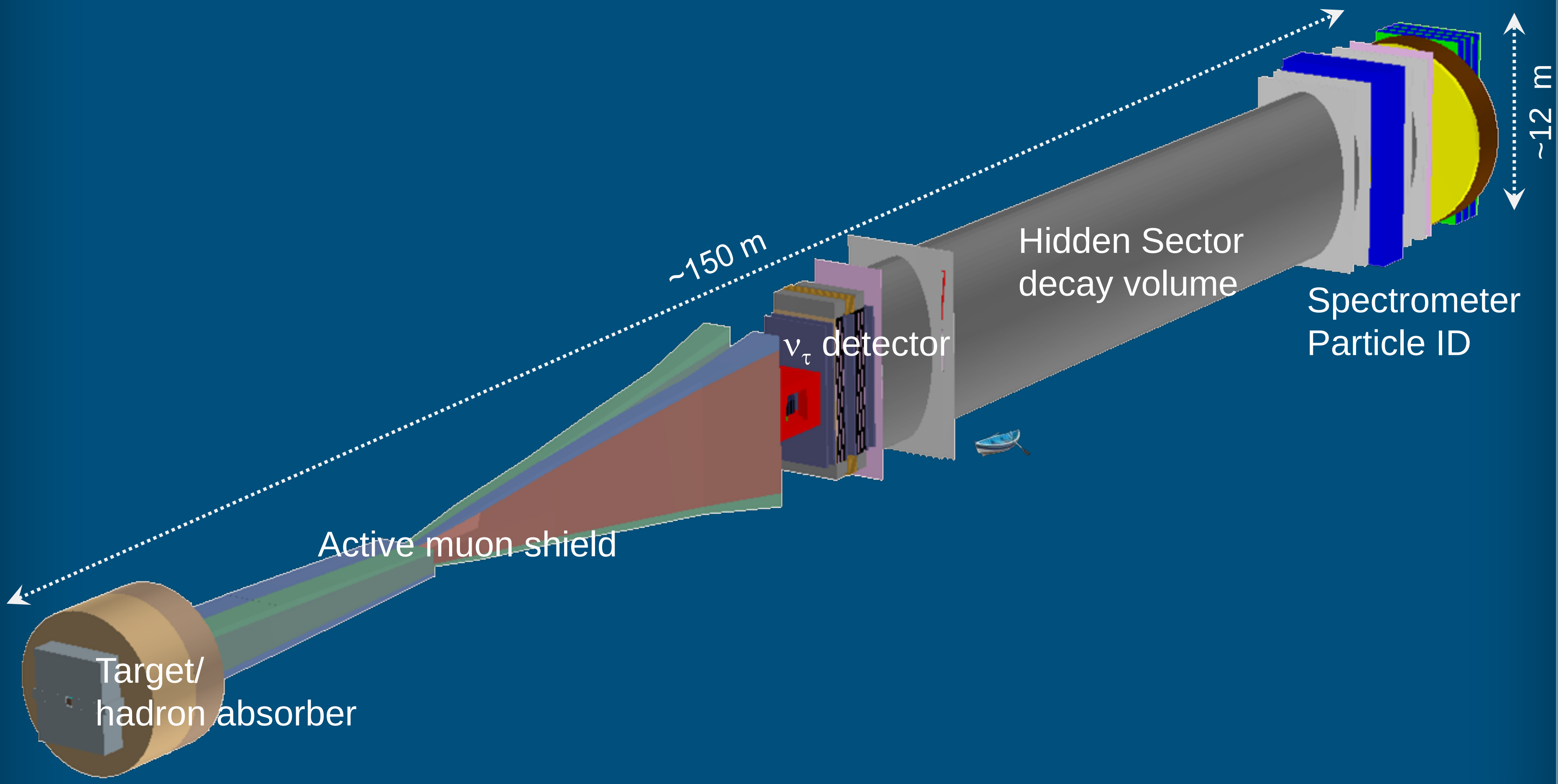
1. Superweakly interacting new particles → Number of protons on target
   ➔ SPS: 4×10^{13} / 7s @ 400 GeV = 500 kW → 2×10^{20} in 5 years
2. Preference for slow beam extraction of $1s$ to reduce detector occupancy
3. Heavy material target
4. Muon shield to range out flux of muons
5. Away from walls and minimize surrounding structures
7. Vacuum in particle decay volume
8. Detector as close as possible to target to maximize acceptance

➔ Defines the list of critical parameters and layout of the experiment

Schematic Principle of Experimental Setup

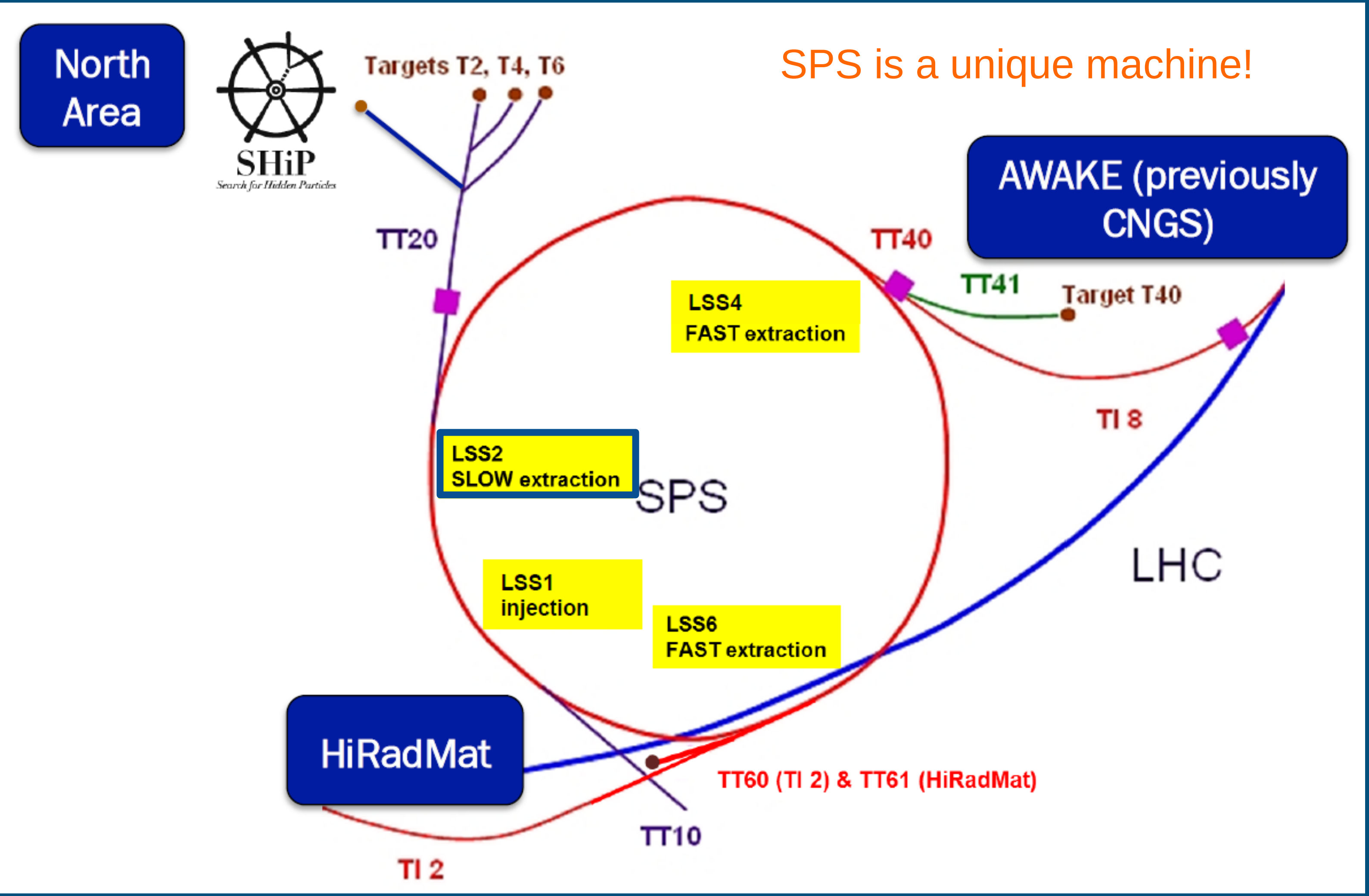


A reality view of SHiP

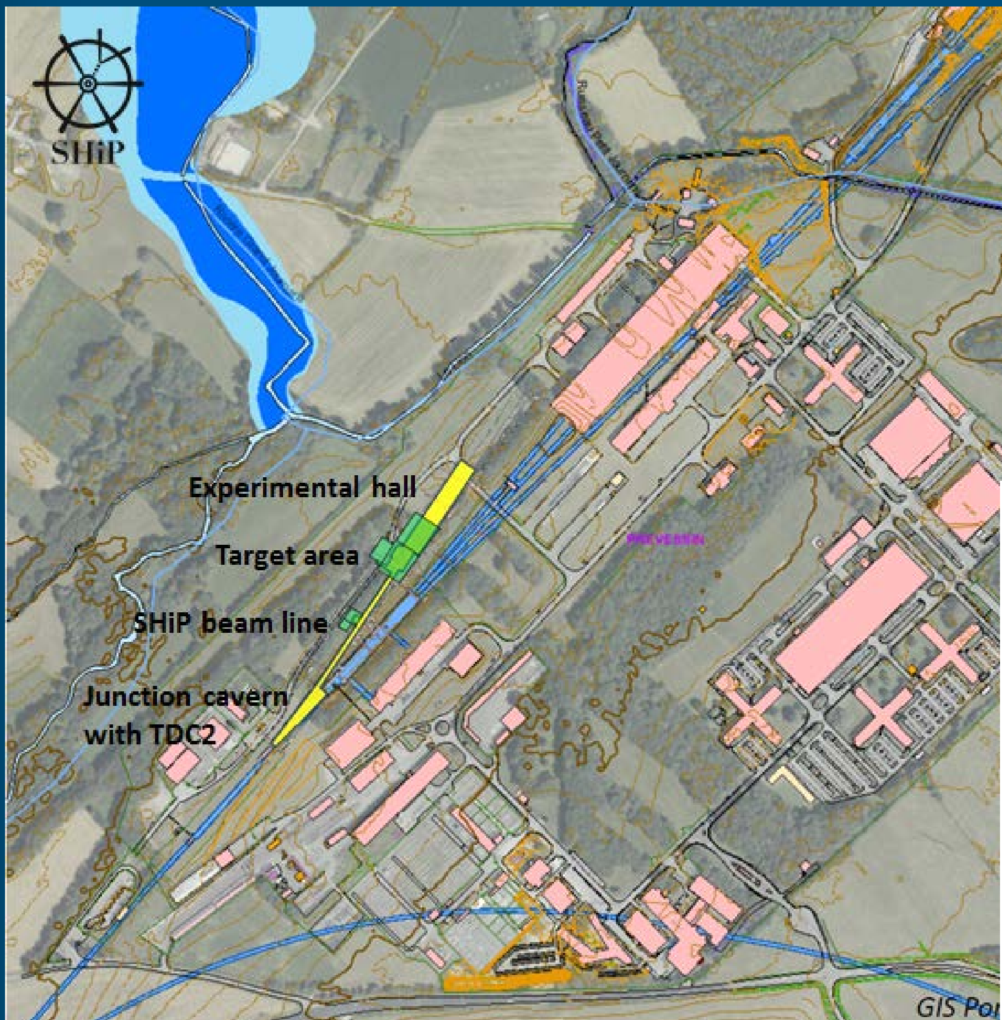


SHiP Location

- Proposed location by CERN beams and support departments



SHiP Facility at Prevessin North Area



- Civil engineering close to existing infrastructures
  - ~5 years in total