Requirement for slow extraction by future fixed target and beam dump experiments

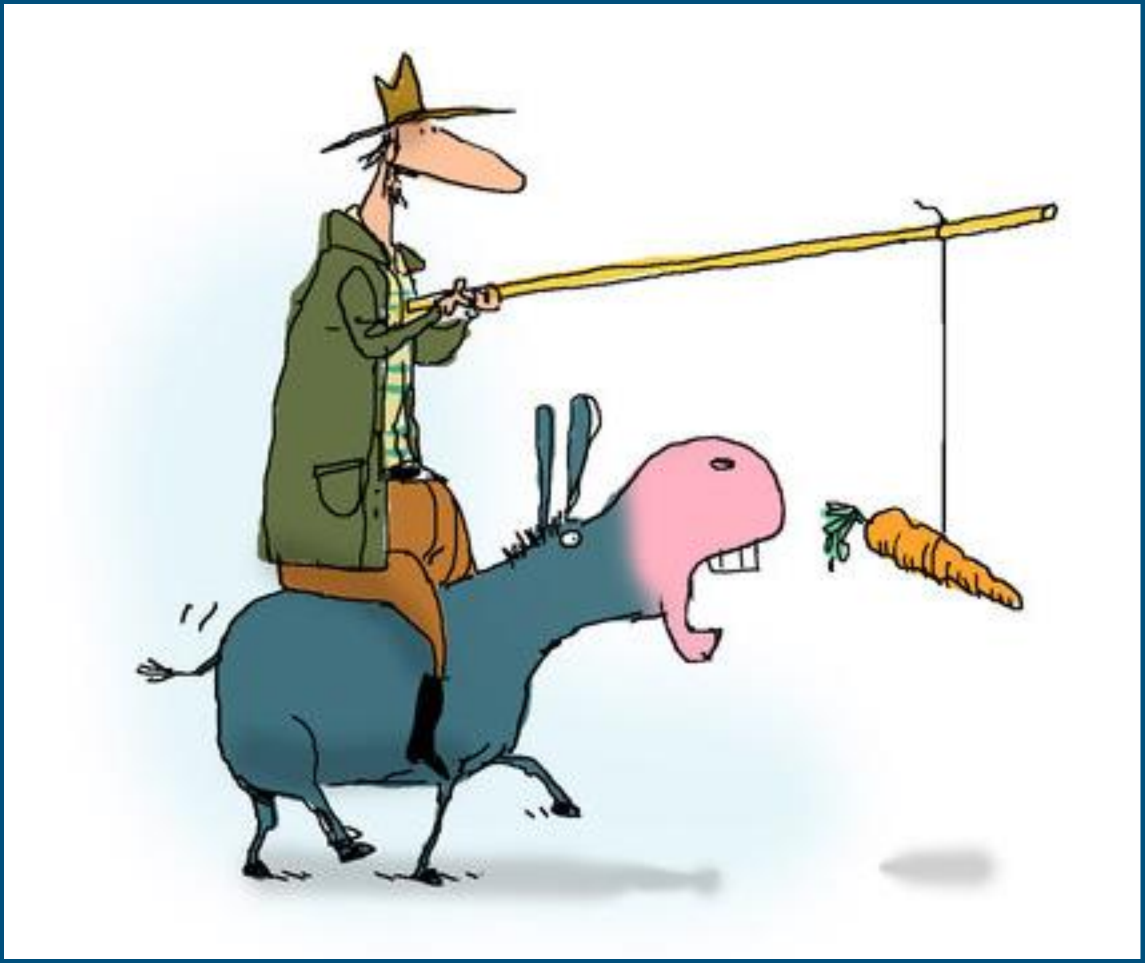
Richard Jacobsson

Fly over:

- Current physics landscape and the case for the intensity frontier
- The case for fixed target experiments
- Future objectives at the intensity frontier with fixed target and beam dump experiments
- Challenges and requirements
- Conclusions (more beam, more duty cycle, more spill stability!)

Apologies to all experiments which I do not mention!

The purpose of this talk



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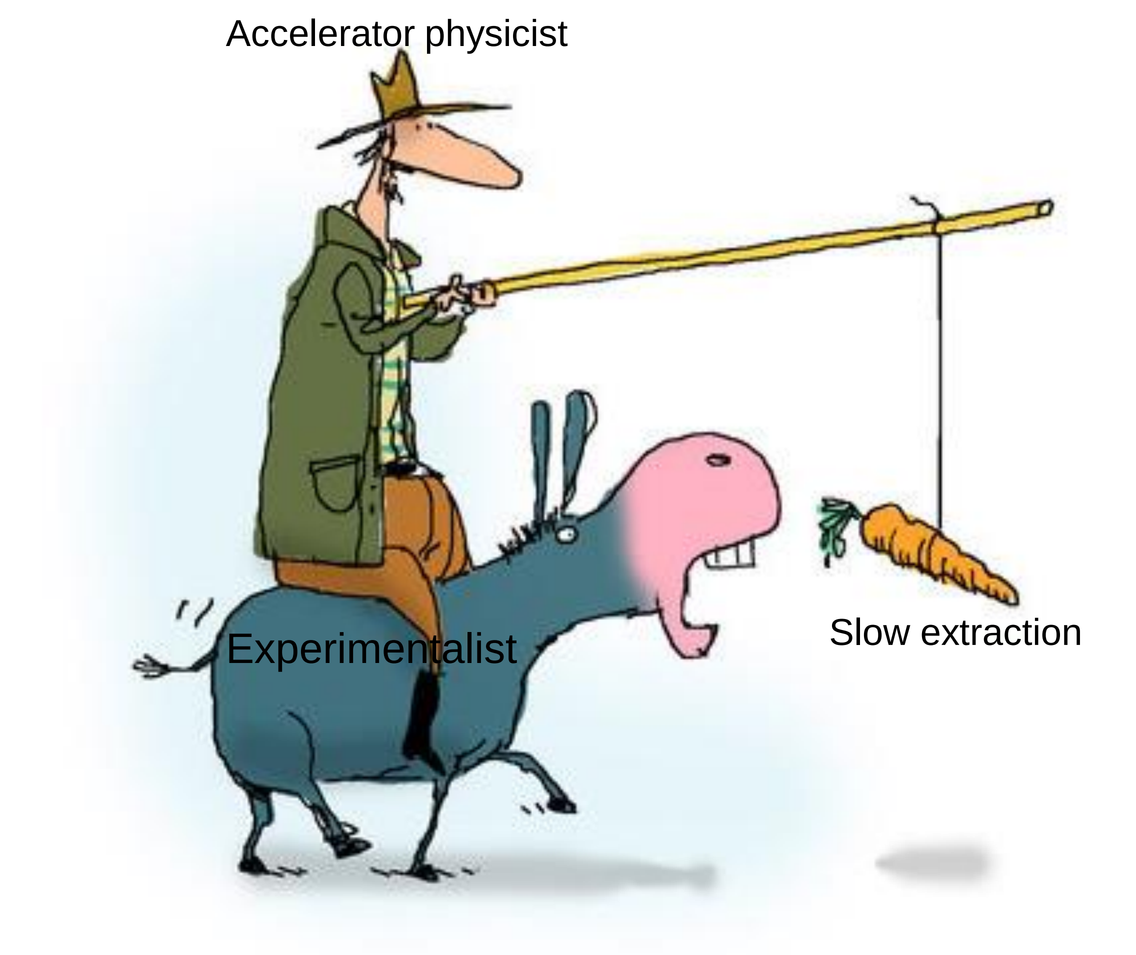


Fundamental questions = Evidence for New Physics

No significant deviations from SM, still…

Experimental evidence for New Physics

1. Neutrino masses and oscillations
2. Matter/antimatter asymmetry of the Universe
3. Dark Matter
4. Dark Energy

➔ *No prejudice on mass/energy scale of the "new physics" required to solve these!*

5. Anomaly in Lepton Universality?

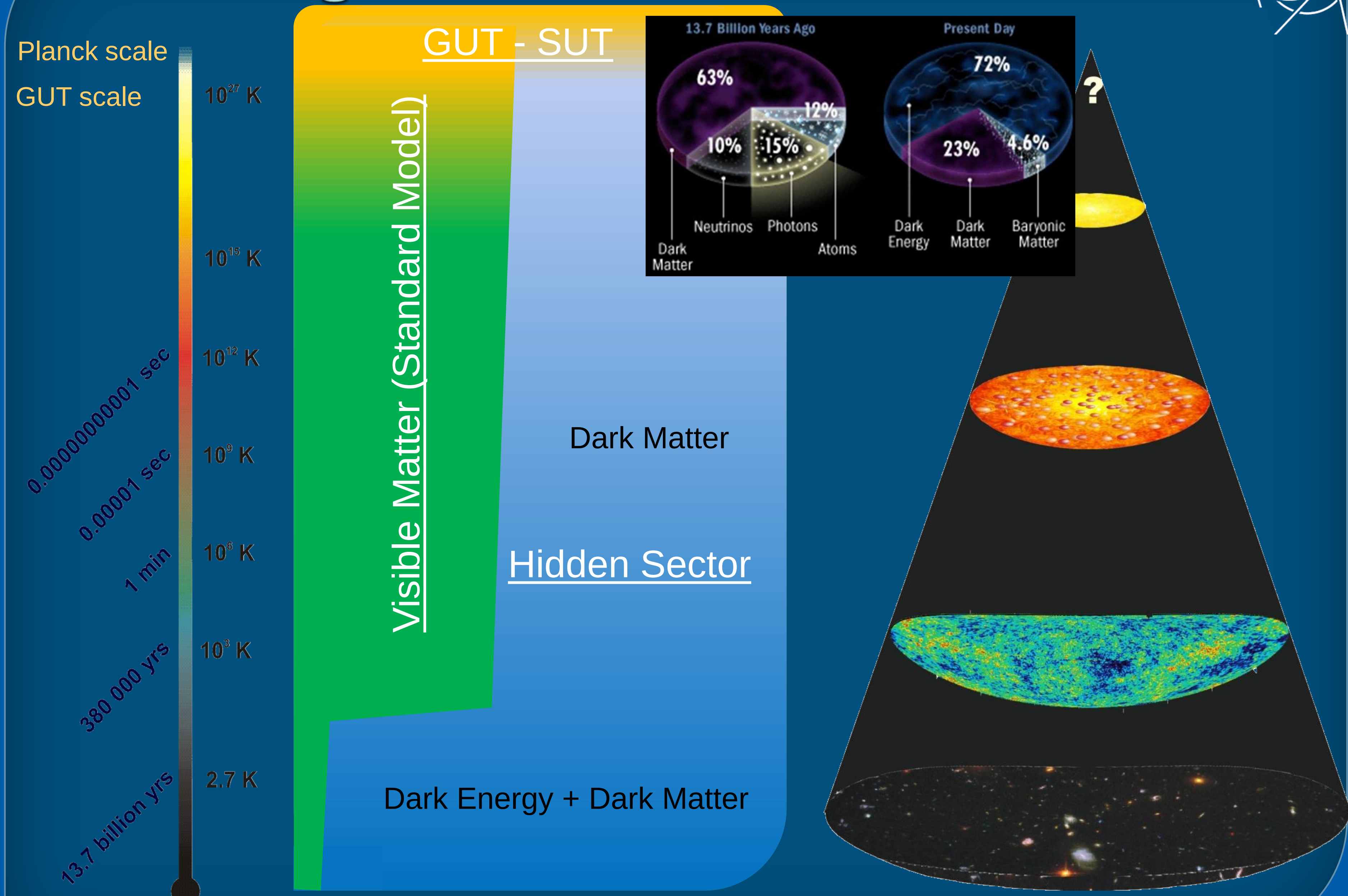
Theoretical "evidence" for New Physics

1. Hierarchy problem and stability of Higgs mass
2. Structure of Standard Model
3. Unification of interactions
4. Gravity
5. ….

➔ *Preference for high mass/energy scales….*

So far, most experimental efforts have been focusing on searching for particles with masses just above the electroweak scale and with sizeable couplings to SM particles = "Visible sector"

The Big Picture – Where are the answers?



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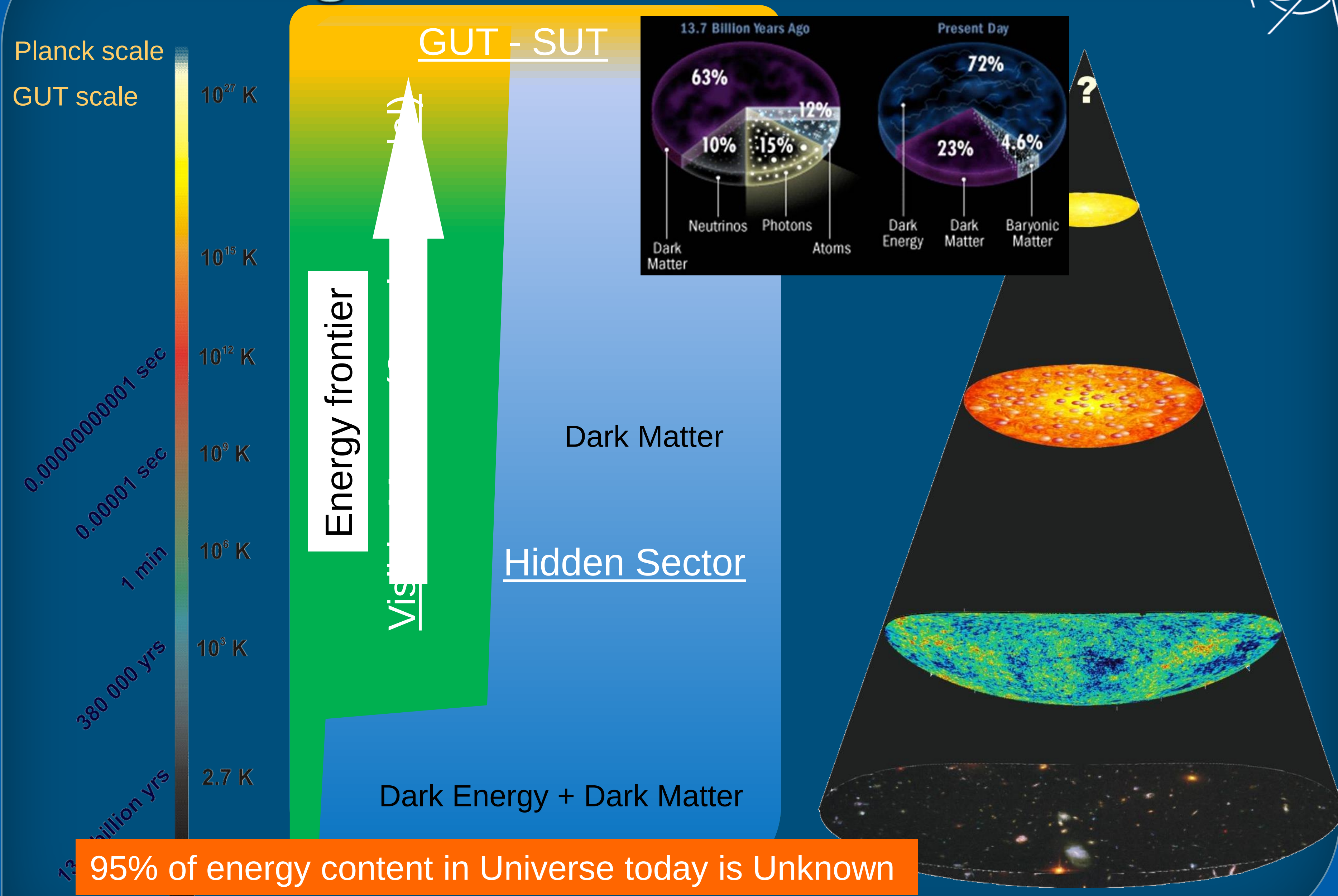

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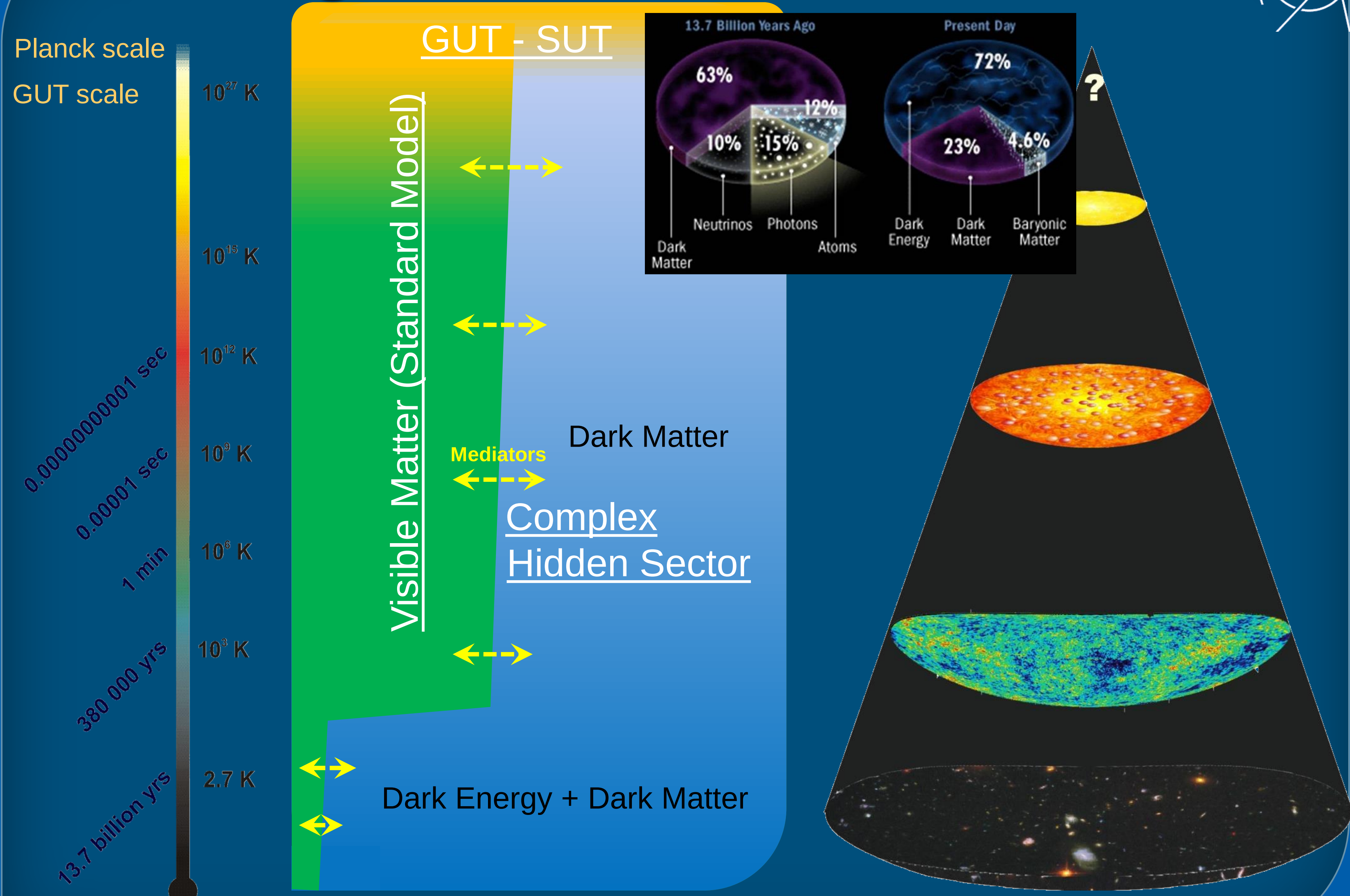
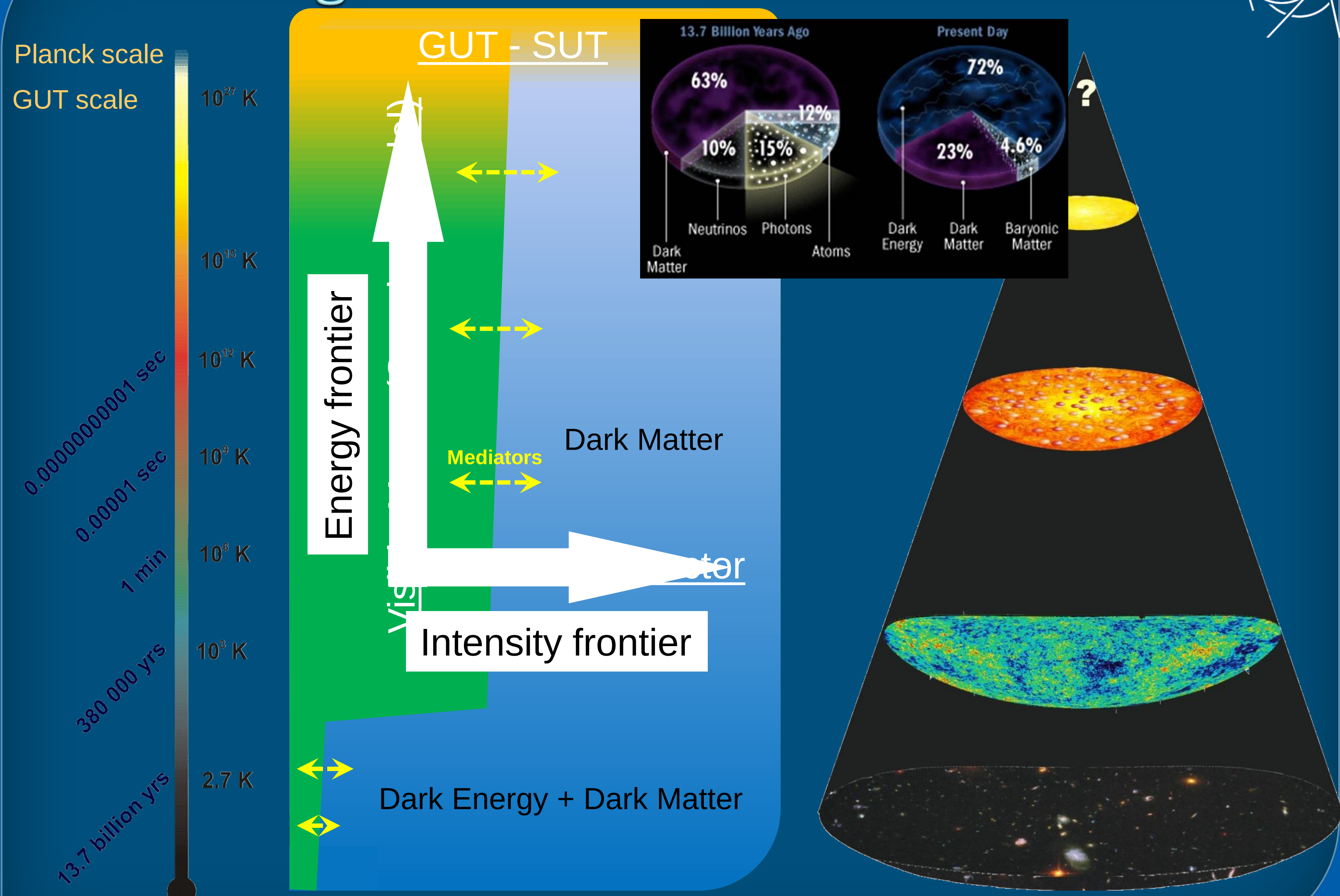
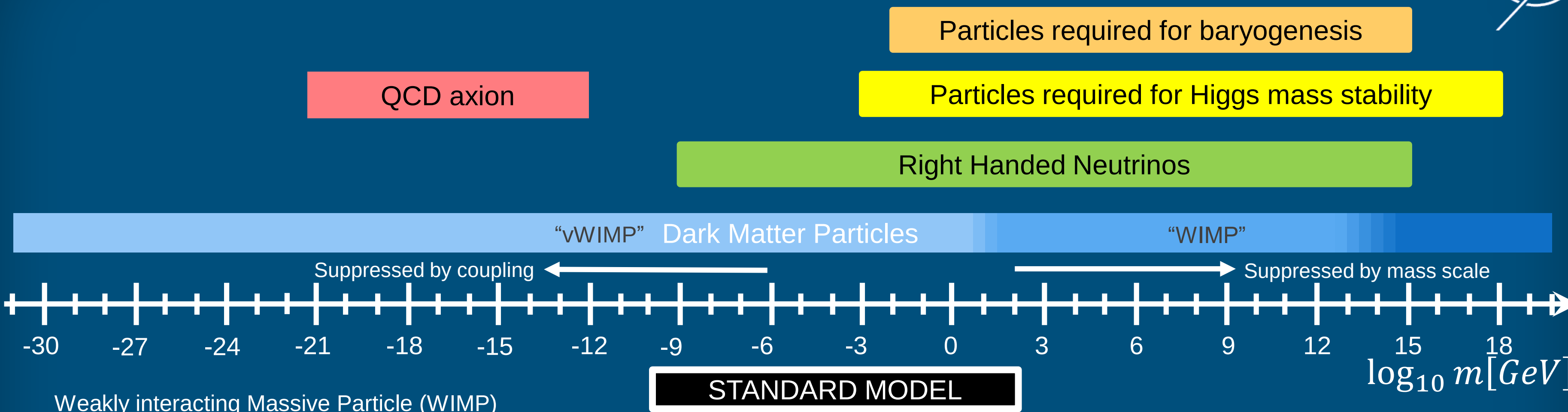


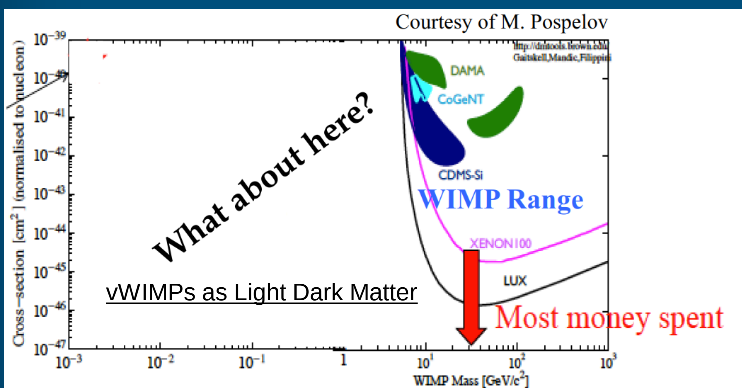
The Big Picture – Where are the answers?



Mass scales for New Physics…



Weakly interacting Massive Particle (WIMP)



➔ Look "everywhere"!

Absence of direct signal of Beyond Standard Model physics puts emphasis on precision measurements and models with very weak couplings:

- W, Z, Higgs,top precision measurements (ATLAS, CMS, CEPC, ILC, FCC-ee,…)
- Flavour physics (LHCb, Belle2, + FT)
- Light Dark Matter and complex Hidden Sectors (FT, + collider experiments)
- Neutrino physics

➔ **Intensity frontier (I.F.)**

I.F.: The case for fixed target experiments

Luminosity – boost – fiducial volume – secondary beams

Current SPS at 400 GeV/c ($4x10^{19}$ p.o.t./year)

- "Primary" FT luminosity for a long target (e.g. 1m++ Mo, ρ_N nucleon density)

$$\mathcal{L}_{int}[year^{-1}] = 10^6 s \times \int_0^{"\infty"} \Phi_0 \times \rho_N \times e^{-l/\lambda} dl = \Phi_0 \times \rho_N \times \lambda = \underline{3.6\text{x}10^{45}\ \text{cm}^{-2}}$$

+ production through cascade processes

- HL-LHC luminosity: $\mathcal{L}_{int}[year^{-1}] = 10^7 s \times 10^{35}\ s^{-1}cm^{-2} = \underline{10^{42}\ cm^{-2}}$

➔ Fixed target configuration ideal for studying low mass and/or long-lived final states

- E.g. LHC with 1 ab^{-1}, i.e. 3-4 years: ~ $2x10^{16}$ D's in 4π
- SPS@400 with $2x10^{20}$ p.o.t., i.e. ~5 years: ~ $2x10^{17}$ D's in forward acceptance

➔ Background is the key challenge

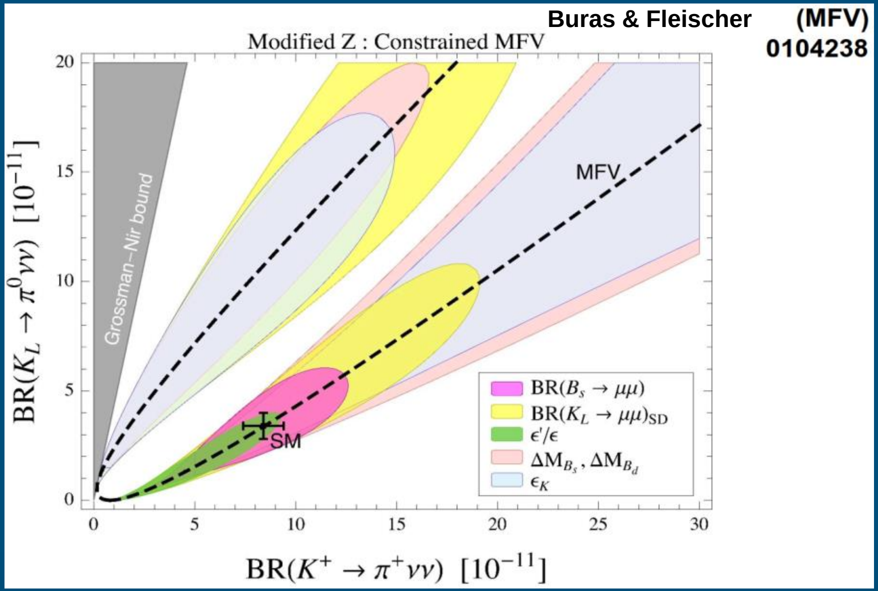
I.F.: Precision measurement in flavour physics

- Flavour physics offer highly sensitive probes up to mass scales of $\mathcal{O}(1000)$ TeV !

➔ Measurement of strongly suppressed decays and phenomena well suited for fixed target, e.g.:

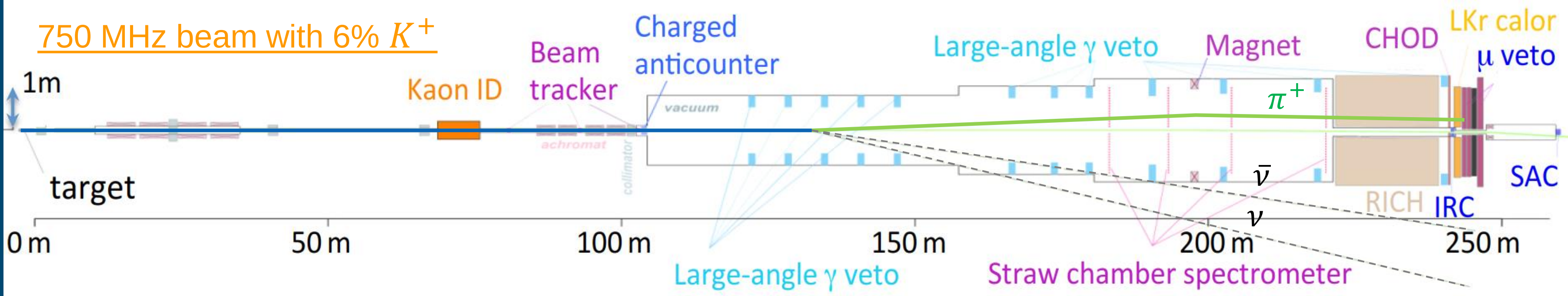
- FCNC $K^+ \to \pi^+ \nu\bar{\nu}$ (BR_{SM}: ~8×10^{-11}) - NA62@CERN
- FCNC $K_L \to \pi^0 \nu\bar{\nu}$ (BR_{SM}: ~3×10^{-11}) – KOTO@JPARC, K_LEVER@CERN
- FCNC $K_S, K_L \to \nu\bar{\nu}$ (BR_{SM}: ~10^{-10}) – NA64@CERN
- cLFV $\mu - e$ ($\mu N \to eN$) conversion (BR_{SM}: ~10^{-19}) - Mu2e@FNAL
- cLFV $\mu \to eee$ (BR_{SM}: immeasurably small) – Mu3e@PSI
- cFLV $\tau \to \mu\mu\mu$ (BR_{SM}: immeasurably small) – SHiP@CERN
- LUV $R_K = \Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$ - NA62@CERN
- $\nu_\tau/\bar{\nu}_\tau$ studies – SHiP@CERN
- …

➔ Difficult and weak signatures



I.F.: Flavour physics challenges

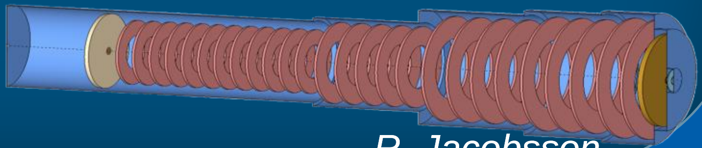
- NA62 (BR($K^+ \to \pi^+ \nu\bar{\nu}$)) to 10%) 10^{12} p.o.t./s with ~3.5s SPS 400 GeV spills: 10^{18}/year
  - Signature: π^+ + missing energy (expect 100 signal events)
  - Most difficult backgrounds: $K^+ \to \pi^+\pi^0(\gamma),\quad \mu^+\nu(\gamma)$
  - ➔ Rejection by kinematics, identification, photon veto, timing (association!)



➔ Sensitivity not limited by proton yield ➔ duty cycle

NA62 also:
- LFV and LNV with from 10^{13} K+ and 10^{11} π^0 decays
- Hidden Sector searches

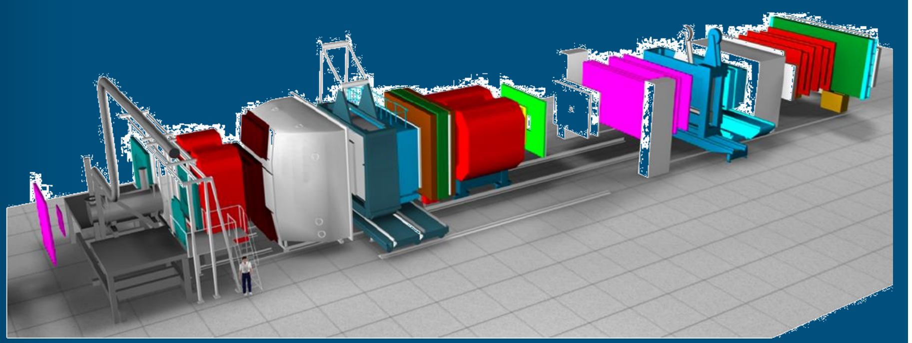
- NA62 ➔ K_LEVER (BR($K_L \to \pi^0 \nu\bar{\nu}$)) 7x$10^{12}$ p.o.t./s with ~3.5s SPS 400 GeV spills: 10^{19}/year
  - Signature: 2 γ from π^0 with unbalanced transverse momentum and ($m(\gamma\gamma) = m_{\pi^0}$) + nothing else!
  - 3×10^{13} K_L for $\mathcal{O}(100)$ signal events
  - All other K_L decays have ≥2 extra photons or ≥2 tracks to veto
  - Most difficult background: $K_L \to \pi^0\pi^0$ with lost photons, $\Lambda \to \pi^0 n,\ n + N \to X\pi^0,\ X\eta$
  - 280 MHz of K_L, 230 MHz of photons (>5 GeV), 3 GHz of neutrons (>1 GeV)
  - Rejection by transverse momentum, photon veto, timing
  - ➔ Similar layout to NA62

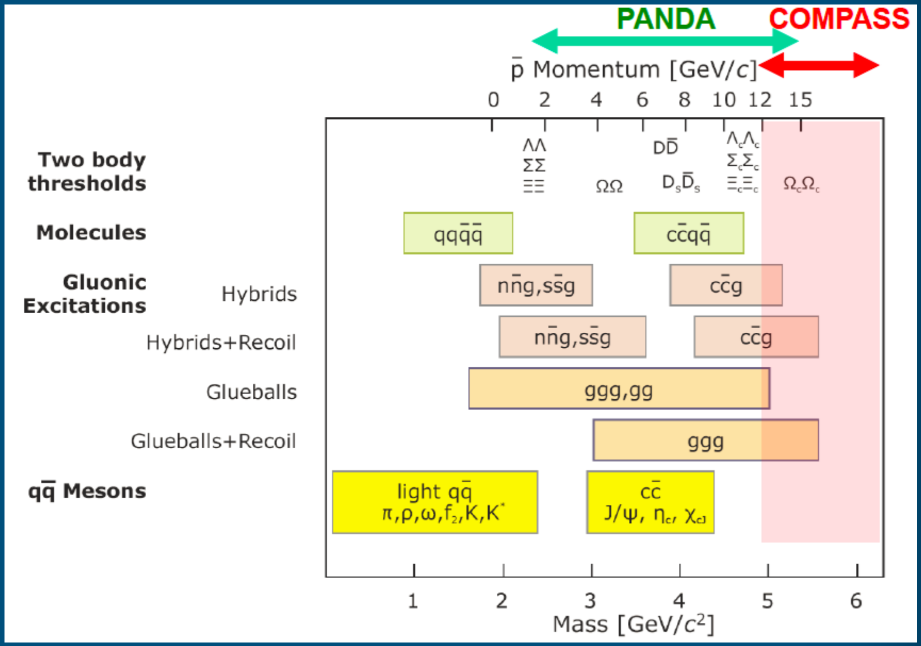


I.F.: QCD studies

- COMPASS, a Universal Facility for Hadron Structure and Spectroscopy studies

- Beyond 2025:
  - *RF separated antiproton and kaon beams with $4x10^{13}$ p.o.t. over 10s*
    - *3 x 10^7 antiprotons per second (50x yield of previous experiments)*
    - *8 x 10^7 kaon per second at ~100 GeV(80x yield of previous experiments)*
  - ➔ High statistics strange meson spectroscopy
  - ➔ Exotic charmonium like states spectroscopy complementary to LHCb/PANDA
  - ➔ Kaon and antiproton structure
  - ➔ …

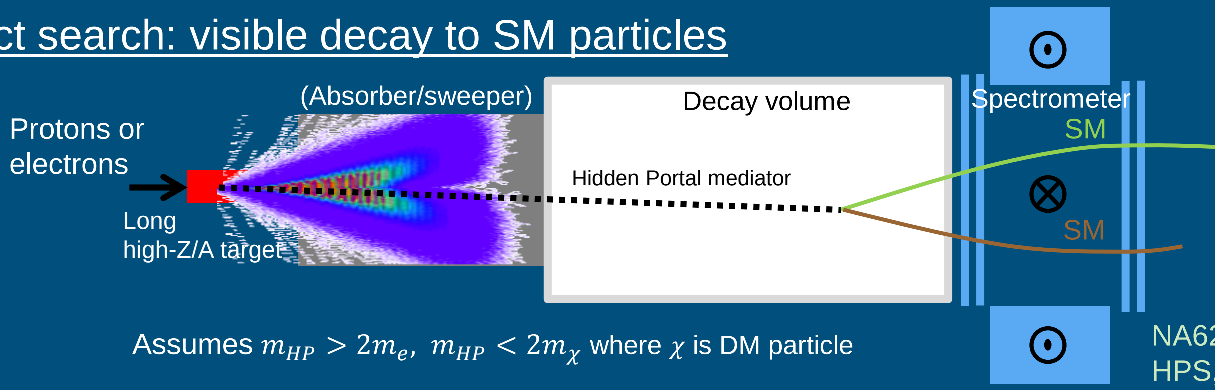




I.F. : Searches for low mass and long-lived

BR: <10^{-10}

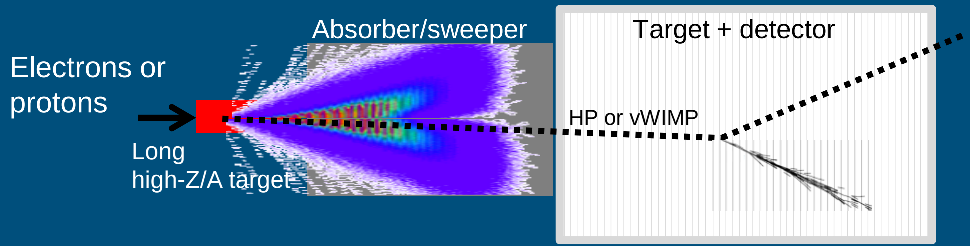
- ## Direct search: visible decay to SM particles



Assumes $m_{HP} > 2m_e,\ m_{HP} < 2m_\chi$ where χ is DM particle

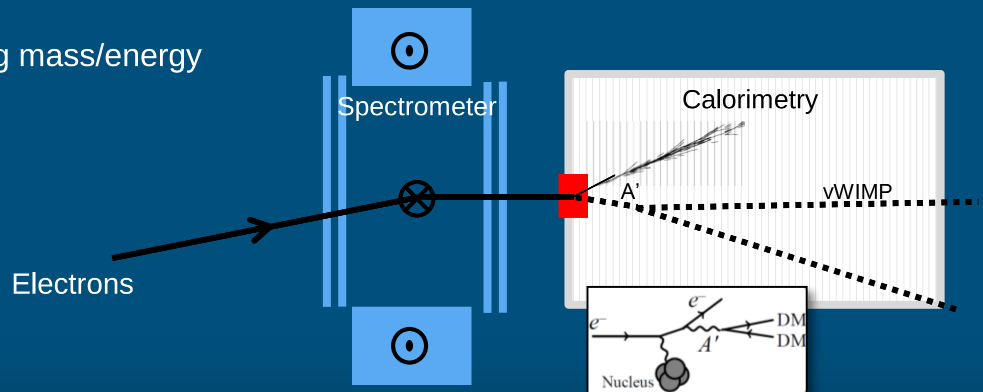
NA62++@CERN (p@400, 10^{18})
HPS, APEX, DarkLight@JLAB (e@1-10)
SHiP@CERN (p@400, 2×10^{20}),
SeaQuest@FNAL (p@120, 10^{18}–10^{20})
(LBNF@FNAL)

- ## Indirect search (Assumes interaction with matter via dark photon mediator)
  - ➔ Scattering off atomic electrons and nuclei



BDX@JLAB (e@11, 10^{22}),
MiniBooNE@FNAL (p@8.9, 10^{20}),
SHiP@CERN (p@400, 2×10^{20})
(interest for BDX-like experiments at LNF, Mainz (MESA), SLAC, Cornell…)

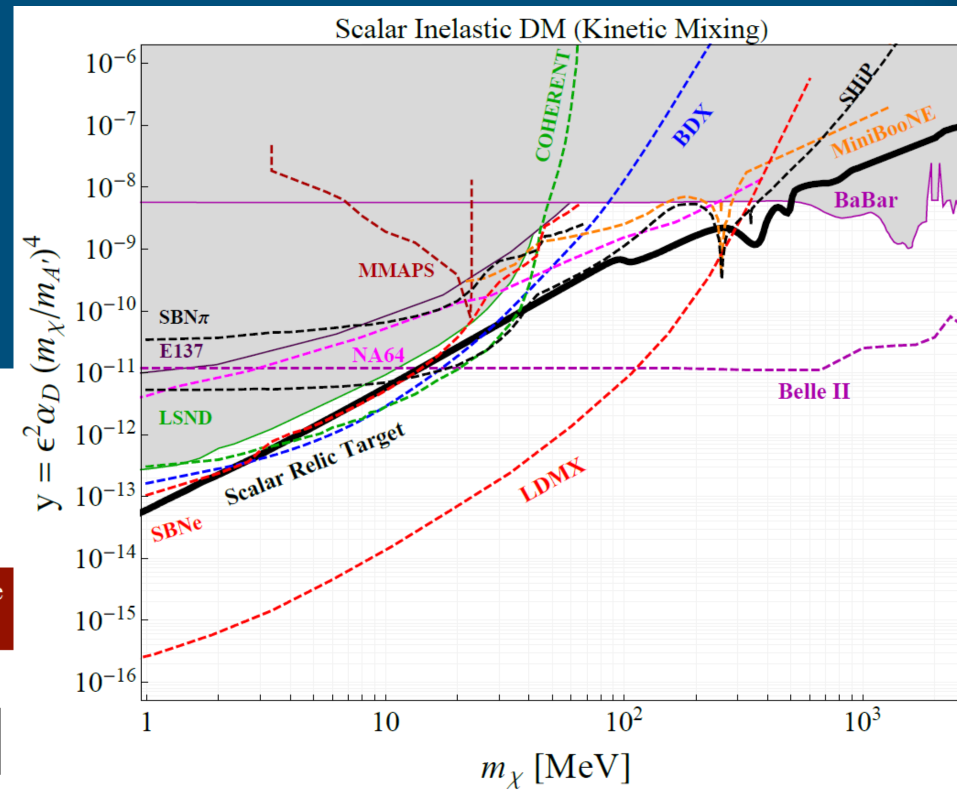
  - ➔ Missing mass/energy



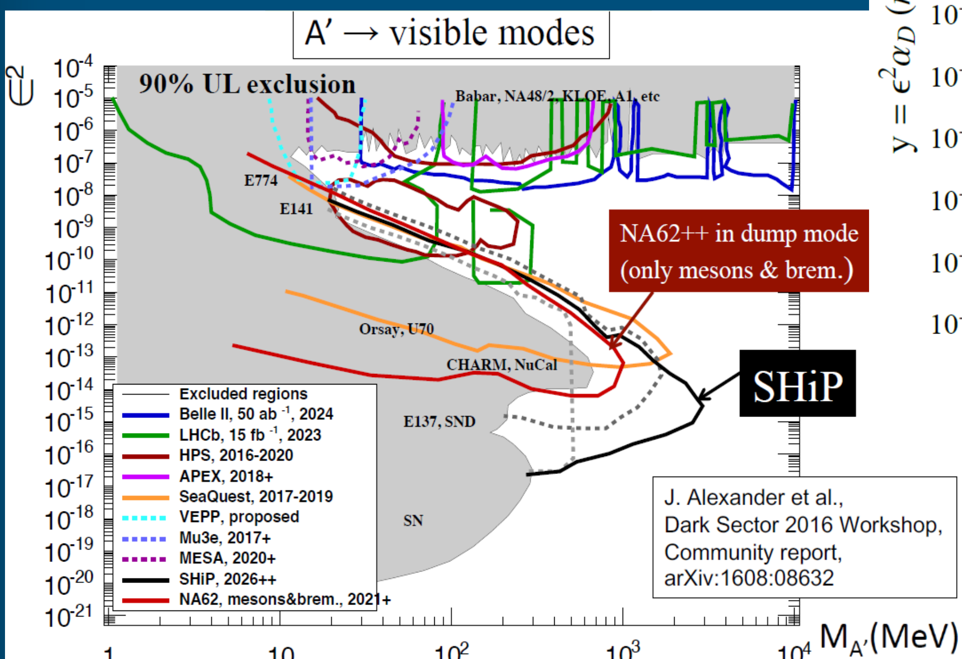
NA64@CERN (e@100, 10^{12}),
LDMX@SLAC (e@10, 10^{16})

The hunting team is growing!

Light Dark Matter

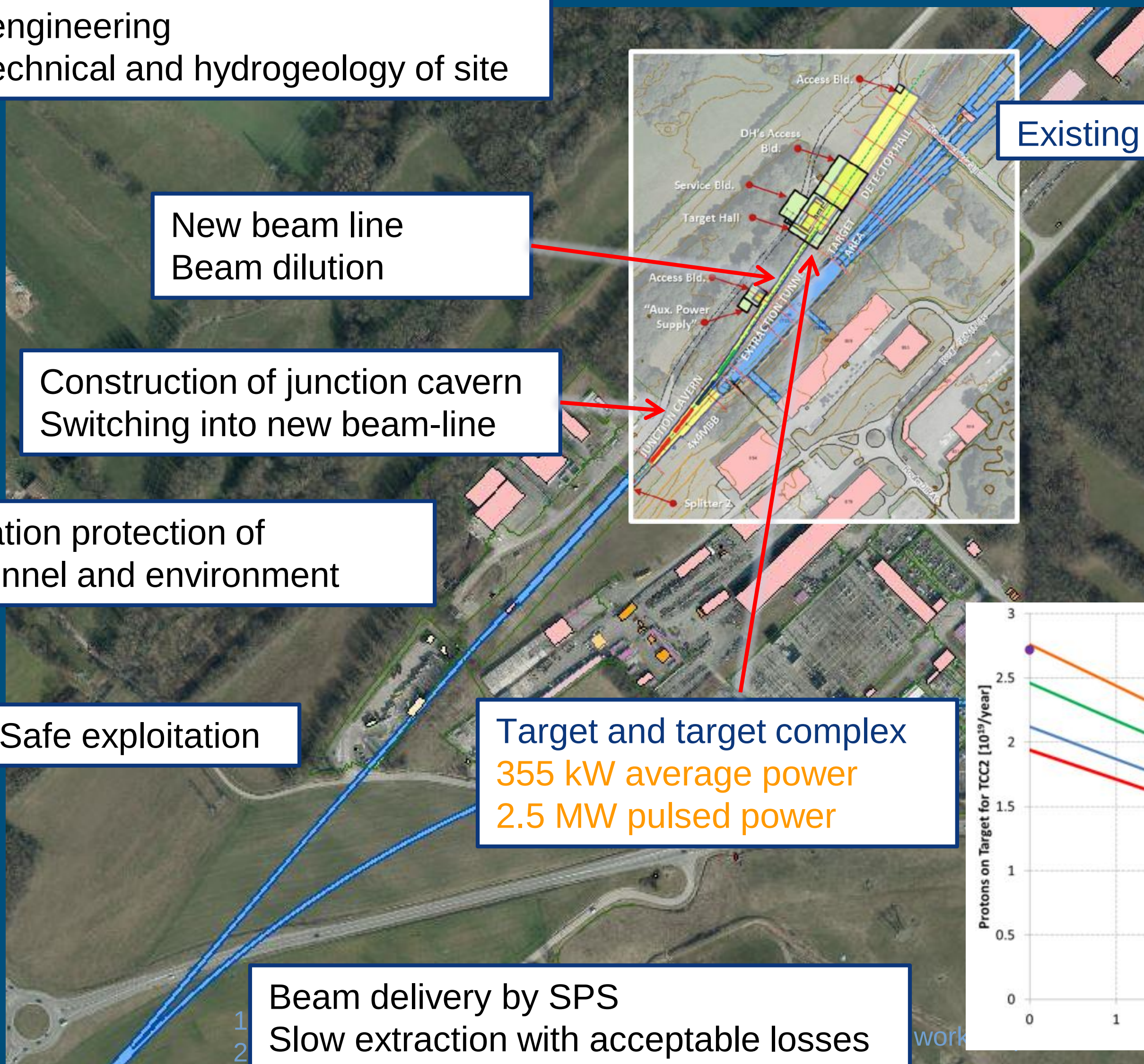


Hidden Photon



SHiP Beam Dump Facility at the SPS

➔ Goal: 4×10^{13} protons at 400 GeV with 1s uniform spill down to 100ps resolution



Civil engineering
Geotechnical and hydrogeology of site

Existing users

New beam line
Beam dilution

Construction of junction cavern
Switching into new beam-line

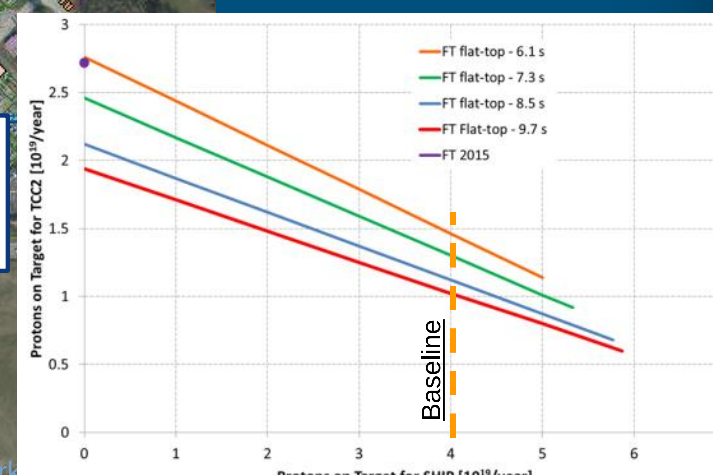
Radiation protection of personnel and environment

Safe exploitation

Target and target complex
355 kW average power
2.5 MW pulsed power

Beam delivery by SPS
Slow extraction with acceptable losses

Preliminary studies of beam sharing

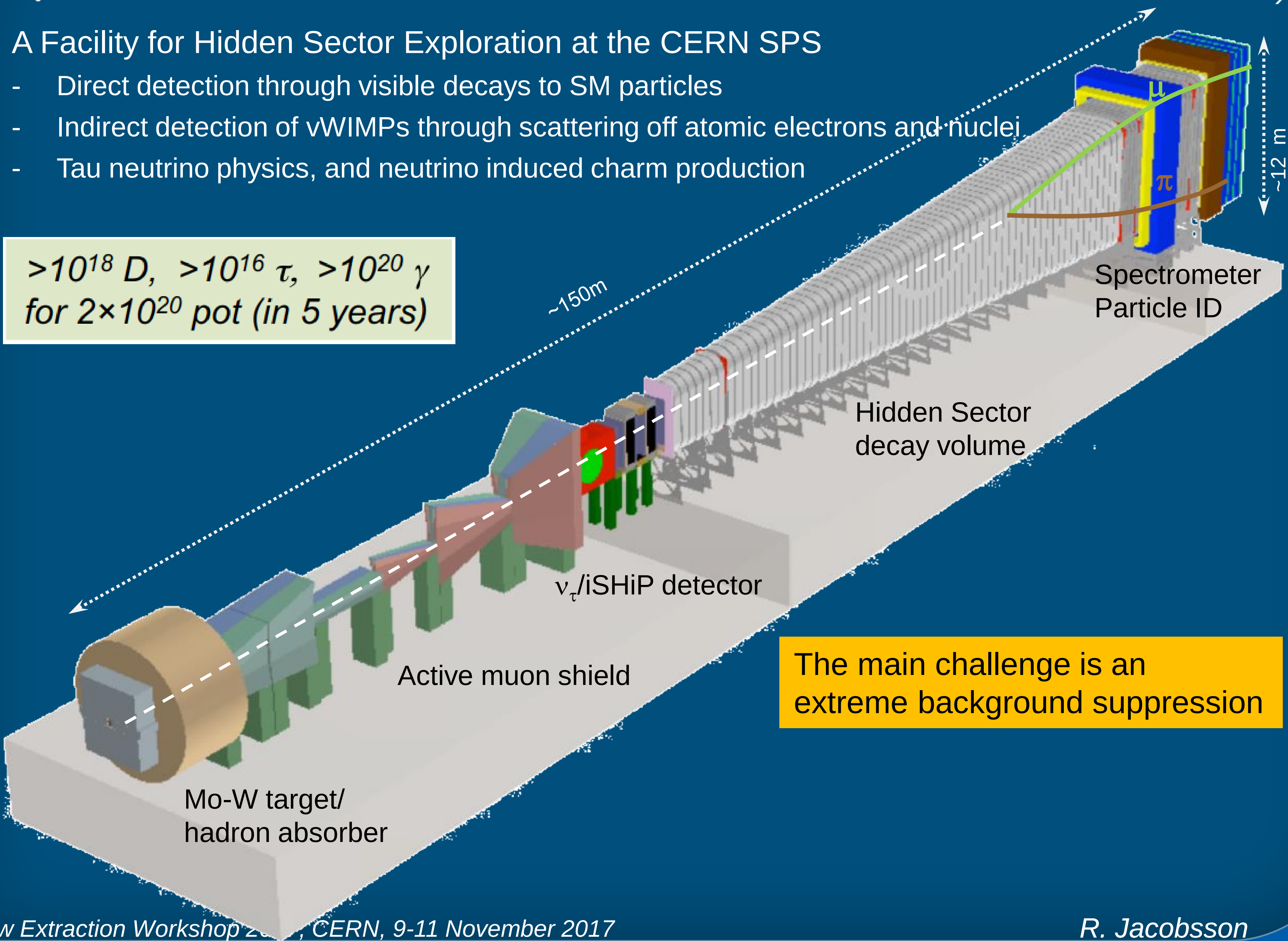


Ultimate beam dump: SHiP experiment

A Facility for Hidden Sector Exploration at the CERN SPS

- Direct detection through visible decays to SM particles
- Indirect detection of νWIMPs through scattering off atomic electrons and nuclei
- Tau neutrino physics, and neutrino induced charm production

$>10^{18}$ D, $>10^{16}$ τ, $>10^{20}$ γ for 2×10^{20} pot (in 5 years)

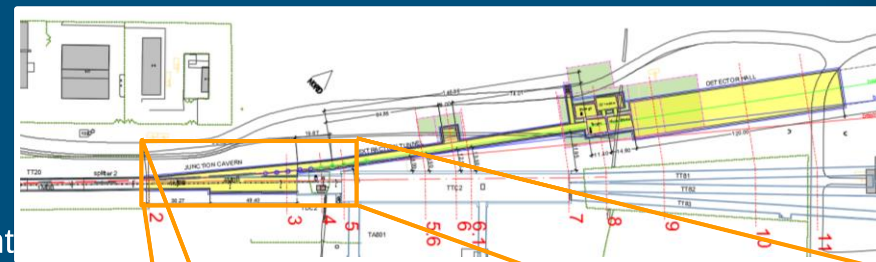


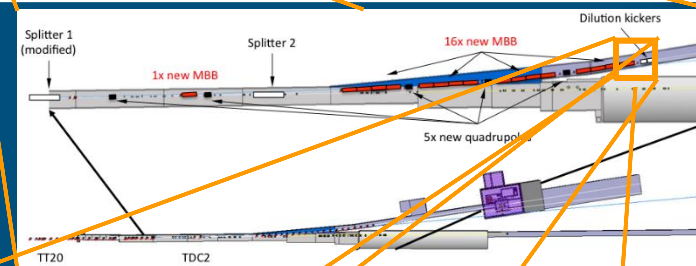
The main challenge is an extreme background suppression

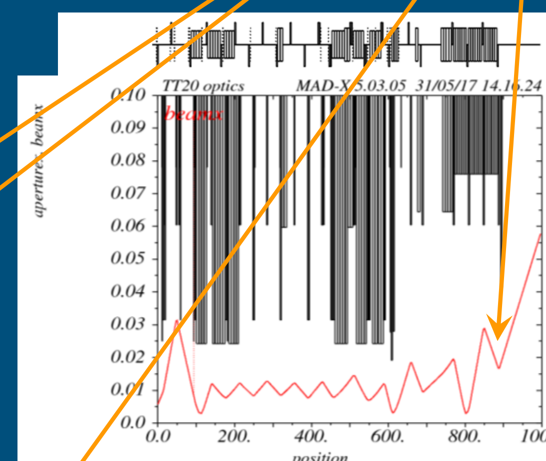
"τSHiP"

Opportunity for LFV $\tau \rightarrow 3\mu$

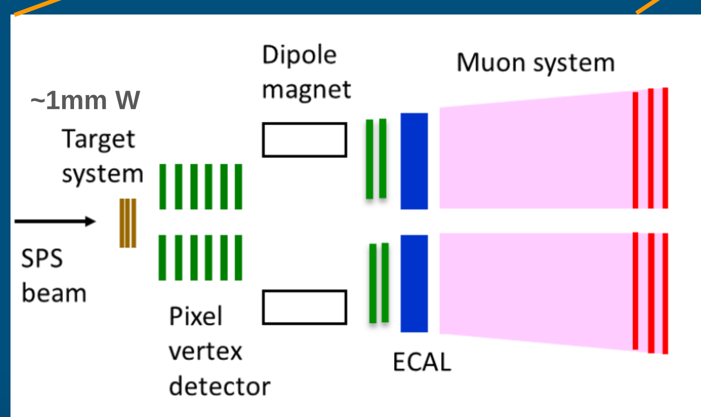
- With $5\text{x}10^{13}$ τ, U.L. on BR($\tau \rightarrow 3\mu$) ~ 10^{-10} or better
- Challenges
  - Parallel operation with iSHiP and dSHiP most efficient
  - Radiological aspects 1% beam loss ($4\text{x}10^{12}$ p/spill…)
  - Entire Facility to be moved downstream by 20-30m
  - Main background: $D_s \rightarrow \eta(\mu^+\mu^-\gamma)\mu^-\nu_\mu$ and combinatorial background from muons produced in η, ρ, ω decays
  - ➔ Very interesting and challenging technologically





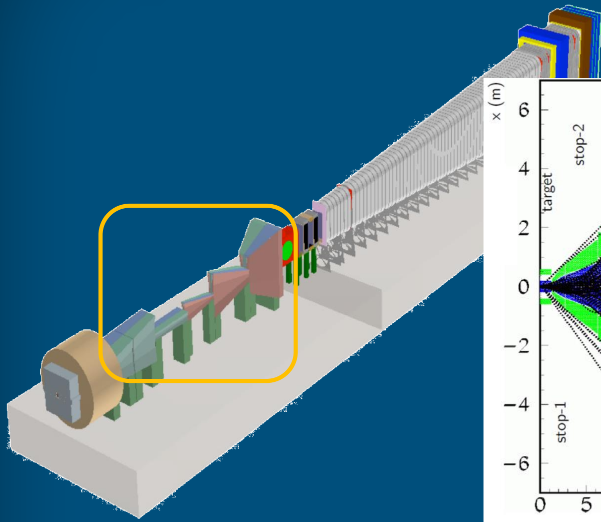


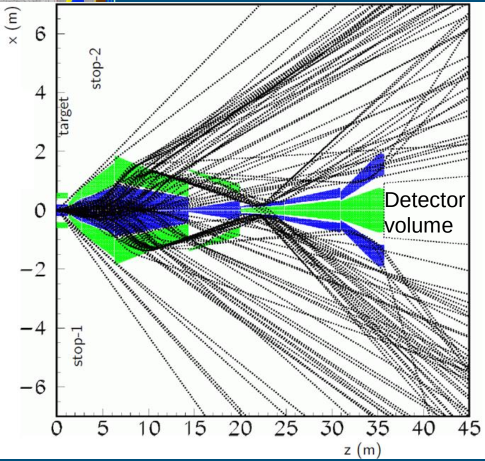
6σ beam envelope incl. 5 mm orbit deviation and 10% beta beating ➔ RMS 3mm

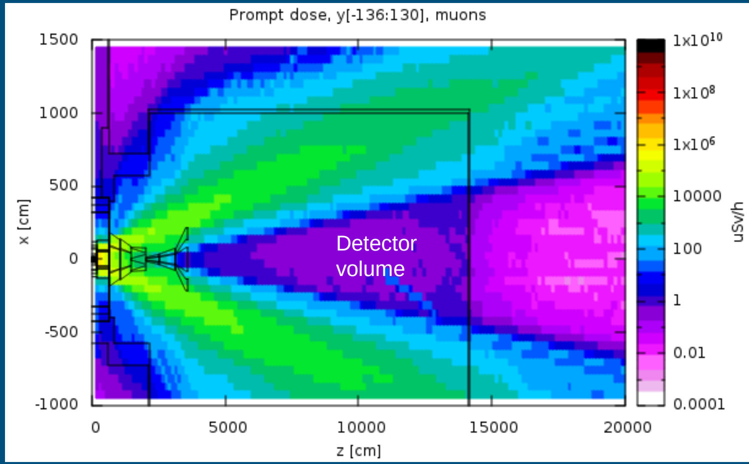


Background suppression

SHiP muon shield

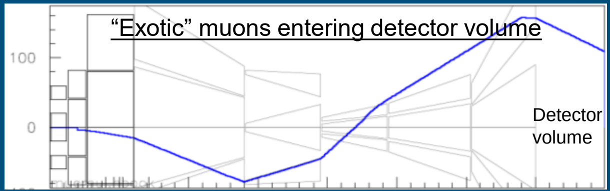






M. Casolino

- Challenge: Studying background from random combinations of residual muons with SHiP muon shield ("combinatorial background")



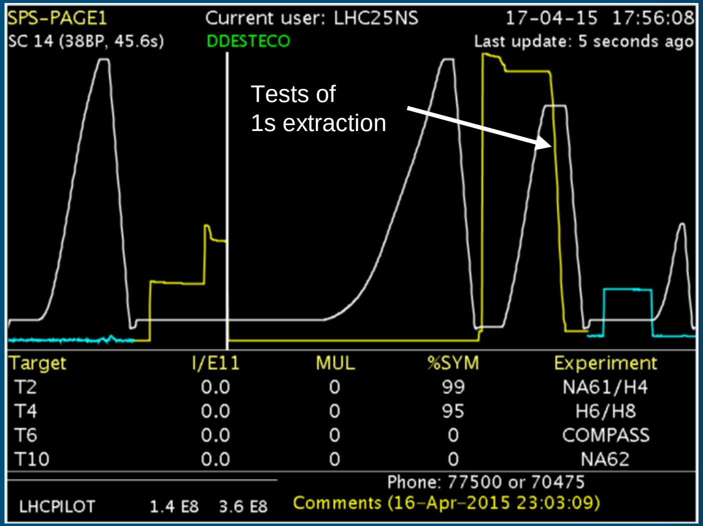
- $4x10^{13}$ pot/spill, $4x10^{19}$ p/year
  - Objective is 0 background in $2x10^{20}$ pot
  - $5x10^{10}$ Hz of muons leaving target despite being designed to suppress pion and kaon decays
- Simulation: 25ms/proton…
  - $2x10^{10}$ protons: ~2month on a very large cluster… (1/2000 of a single spill…)
  - 5 kHz of muons entering detector volume
  - Statistics of muons fully reconstructed by spectrometer: $\mathcal{O}(10)$….
  - ➔ Use special techniques to boost "dangerous" muon spectrum
  - ➔ Main rejection criteria: coincidence at the level of <100 ps

The case for slow extraction (or continuous)

Four coupled parameters: proton yield % proton rate % duty cycle % spill structure

The double-edged sword of high intensity: “Beam induced background”

- Consequences:
  1. Target longevity
  2. Detector trips
  3. Data acquisition/trigger bandwidths
  4. Occupancy – track/momentum reconstruction and association with calorimetry and particle identification
  5. VETO
  6. Combinatorial background



- Mitigations:
  - ➔ Trivial: Reduce instantaneous rate of primary beam!
  - ➔ *(in addition for some experiments: RF separated beams to reduce beam rate)*
  - ➔ *Pushing detector technology (space and time resolution)*

Spill instabilities:

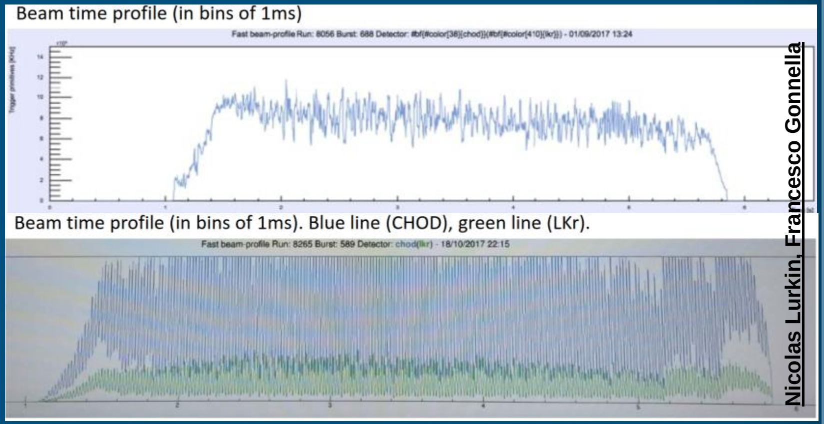
- Initial spike, results mainly in inefficiency by affecting #2, #3 ➔ rejected data
  - Other problems are hidden behind this

➔ For #4, #5, #6 overall spill uniformity plays a crucial role

- ➔ Characteristic time scale is different for the different aspects (and varies between experiments)

Spill structure

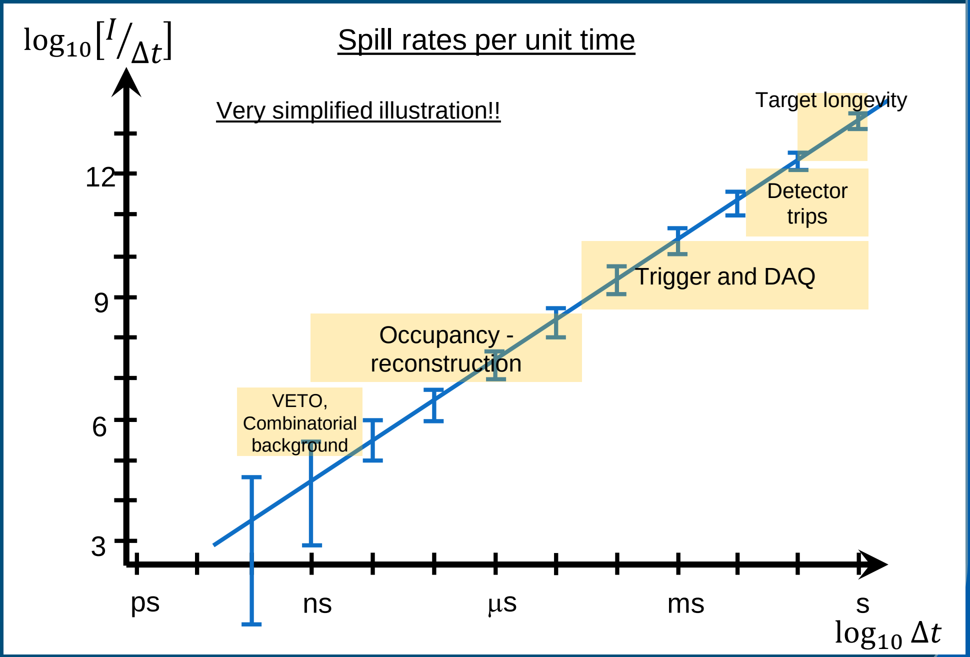
- Sensitivity to spill structure = fluctuation of intensity per unit time
  - Depends on characteristic time resolution of detector (drift time, single hit resolution, time resolution)



- E.g. techniques to reject combinatorial background
  - Topological criteria (kinematics
  - VETO counters
  - PID
  - <u>Timing!</u>
  - ➔ Detector designed with the average rate in mind

- Probability of combinatorial background:
  - Convolution of the distribution of fluctuations of the proton rate at the time resolution of the detector

➔ Need to have the full envelope of spread of fluctuations and the detailed distributions of beam rates for specific time scales



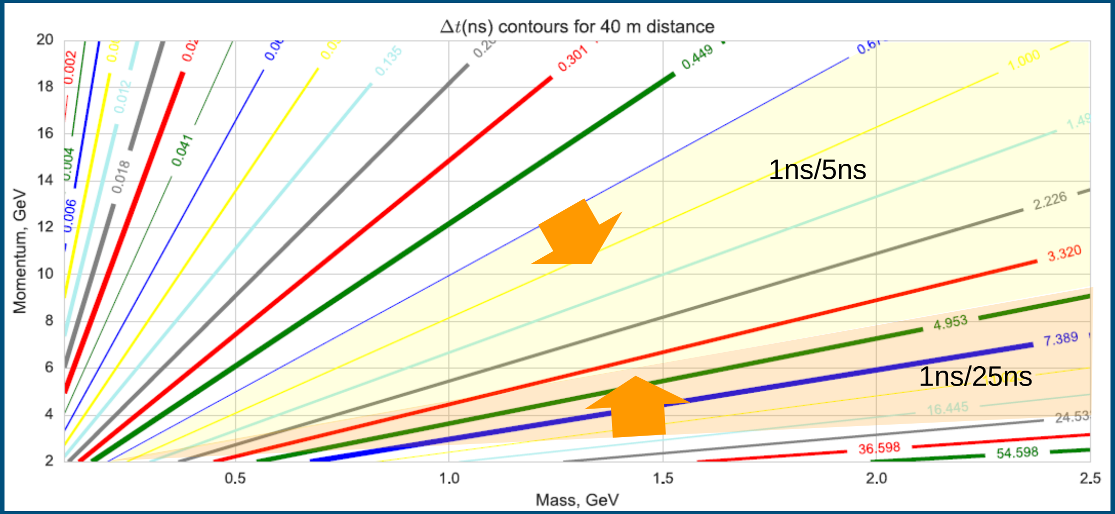
Further improving background rejection

- Ordinary neutrinos is the main background challenge in hidden sector search through electron/nuclei scattering

- Suppressing neutrino background
  - Avoid production → Target with short interaction length
  - Avoid interaction → sensitive volume under vacuum
  - Different angular spectrum → Off-axis detector
  - Different time-of-flight → Bunched beam

→ Slow extraction with bunched beam, i.e. short bunch length and $^{I_{bunch}}/_{I_{gap}} \rightarrow \infty$! (Mu2e)

Assume 1ns bunch length and 40m distance to detector target:

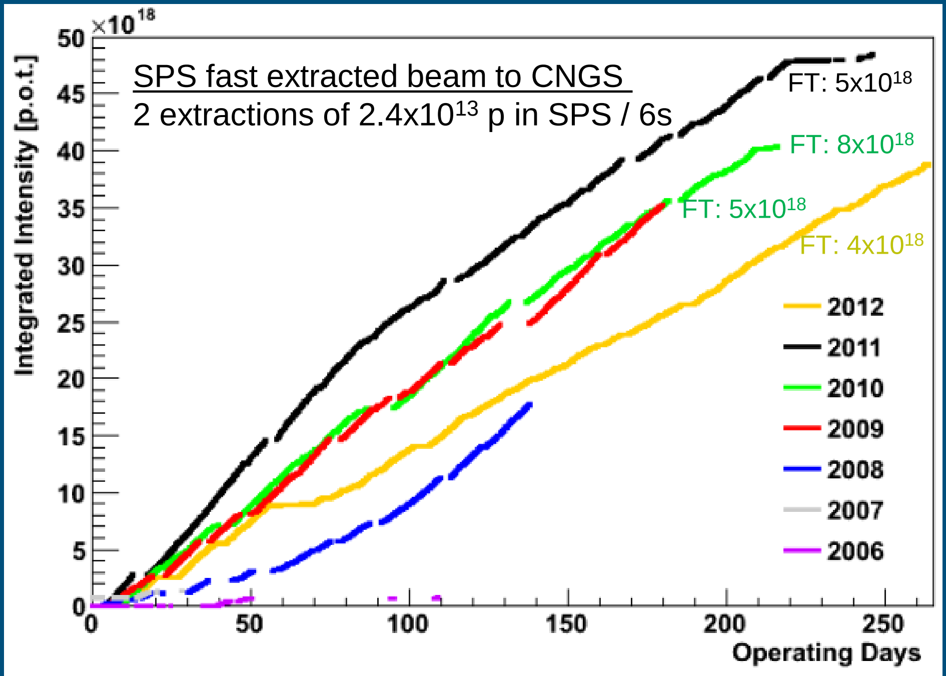


→ E.g. bunch length/spacing=1ns/5ns allows significant discrimination 1<m<2.6 GeV/c^2 at p=10 GeV/c

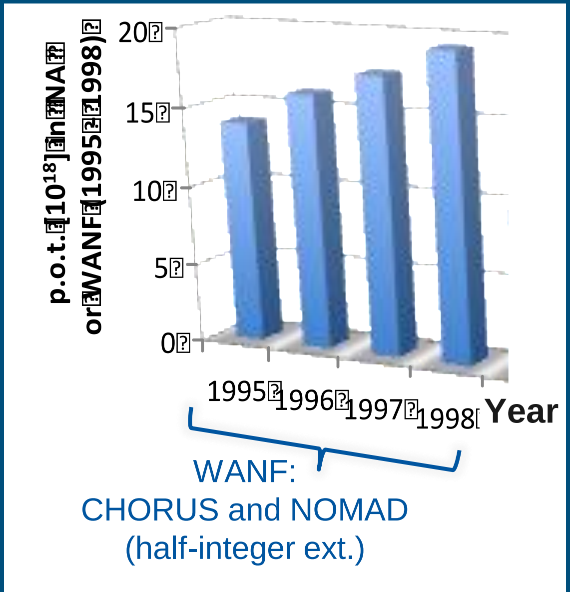
→ E.g. bunch length/spacing=1ns/25ns: 1<m<5.9 GeV/c^2 at p=10 GeV/c or 0.5<m<2.9 GeV/c^2 at p=5 GeV/c

The slow extraction challenge at the SPS

5×10^{19} p.o.t./year @ 400 GeV are available at the SPS!



Gschwendtner et al, IPAC2013



Matthew Fraser

➔ The protons are there, the physics case is there, the experiments are (almost) there

Can we get the beam there nice and clean?

Conclusions

Wish you a VERY fruitful workshop!

Thanks for the extremely good collaboration between accelerators and experiments!