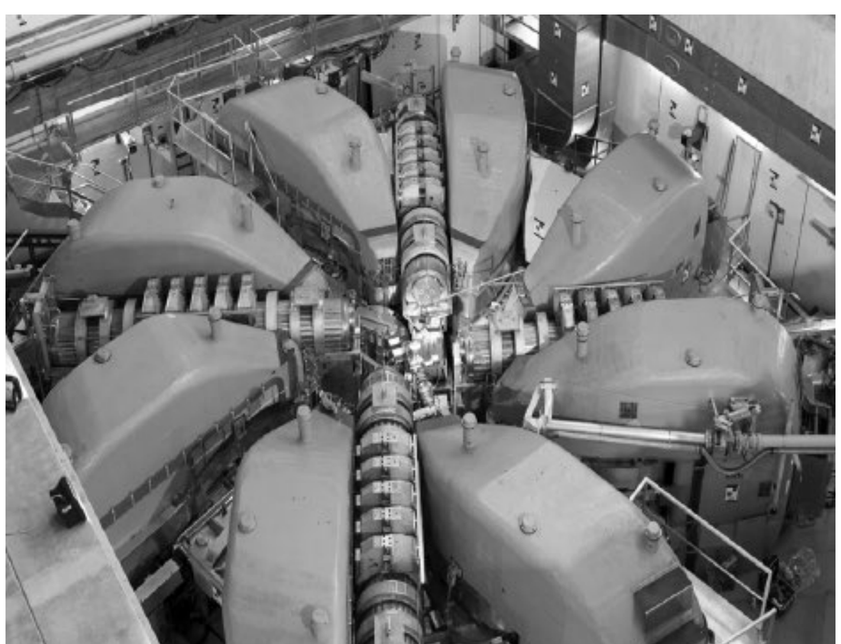
Muon physics and PSI muon beam lines & future developments

Angela Papa, Paul Scherrer Institut and University of Pisa/INFN On behalf of the HiMB and muCool group
Physics Opportunity with Gamma Factory (virtual meeting)
MITP Uni-Mainz 2020, Nov 30th - Dec 4th



Outline

- The role of low energy precision physics
- The High Intensity Muon Beam project at PSI (HiMB)
- Towards High-Brigthness low energy muon beams (muCool)
- Muon collider and Neutrino factory developments (in connection with low energy muon beam?)

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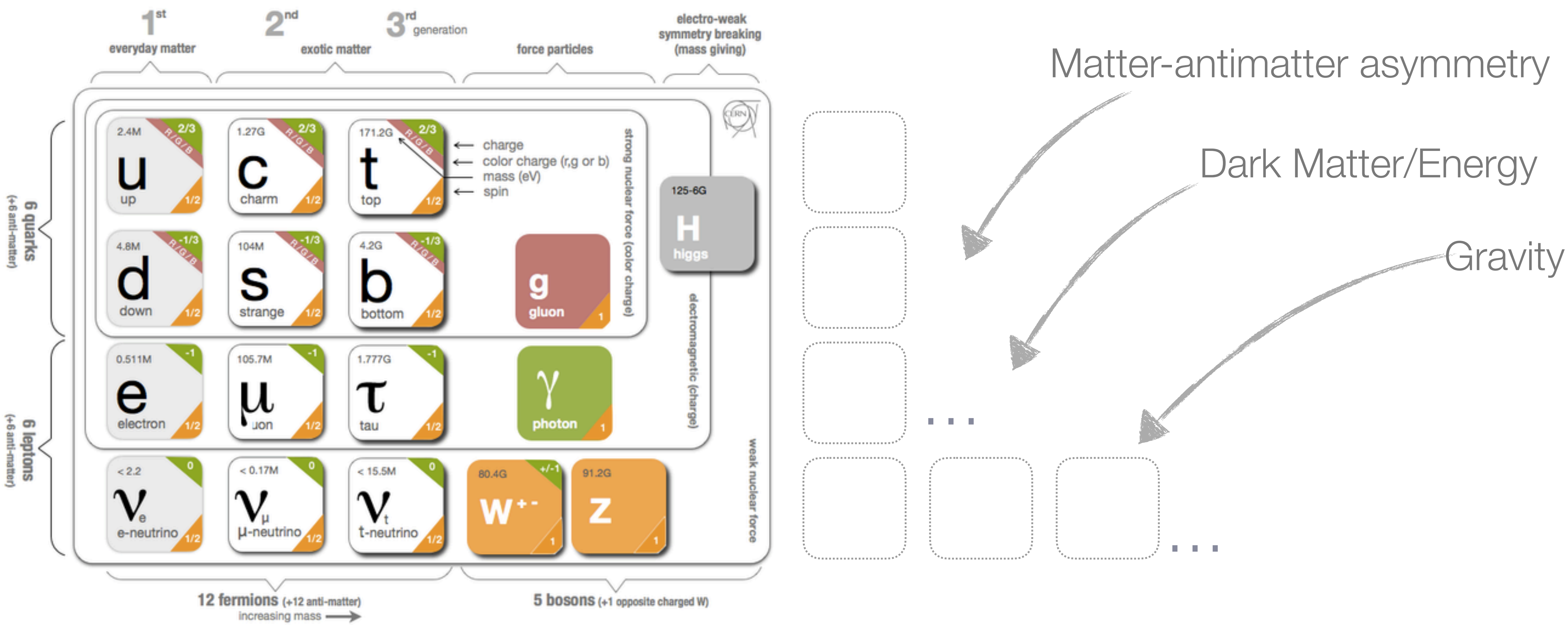
The role of the low energy precision physics

- The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory



- Low energy precision physics: Rare/forbidden decay searches, symmetry tests, precision measurements very sensitive tool for unveiling new physics and probing very high energy scale

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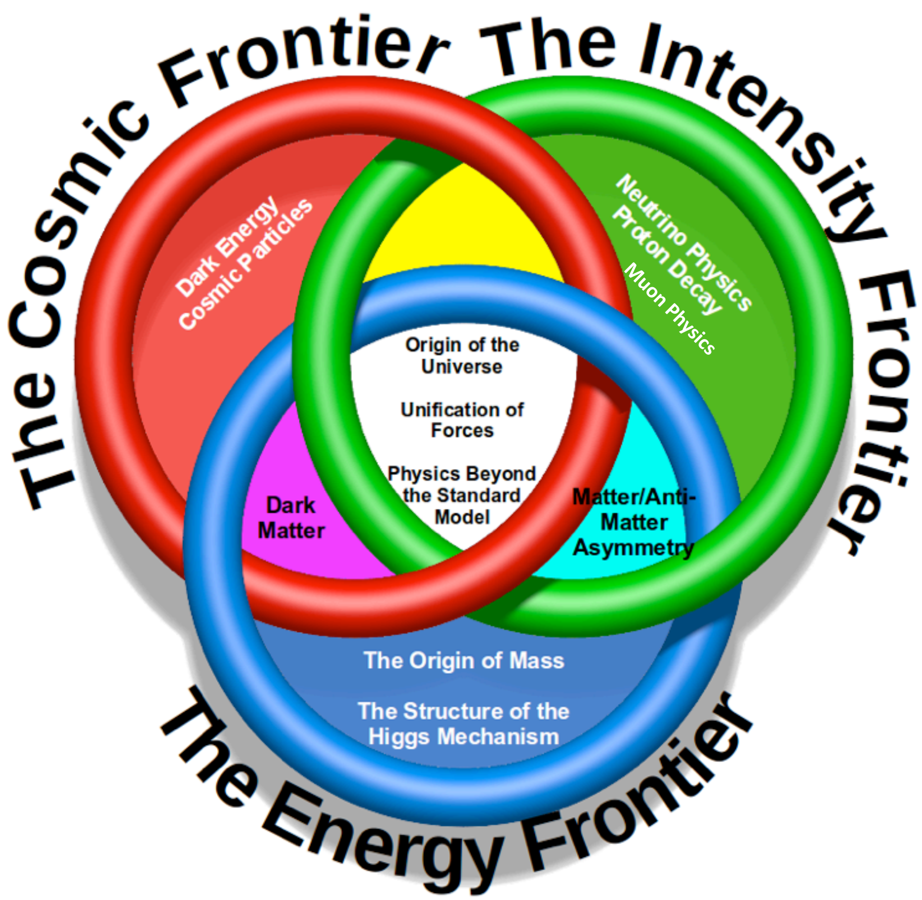

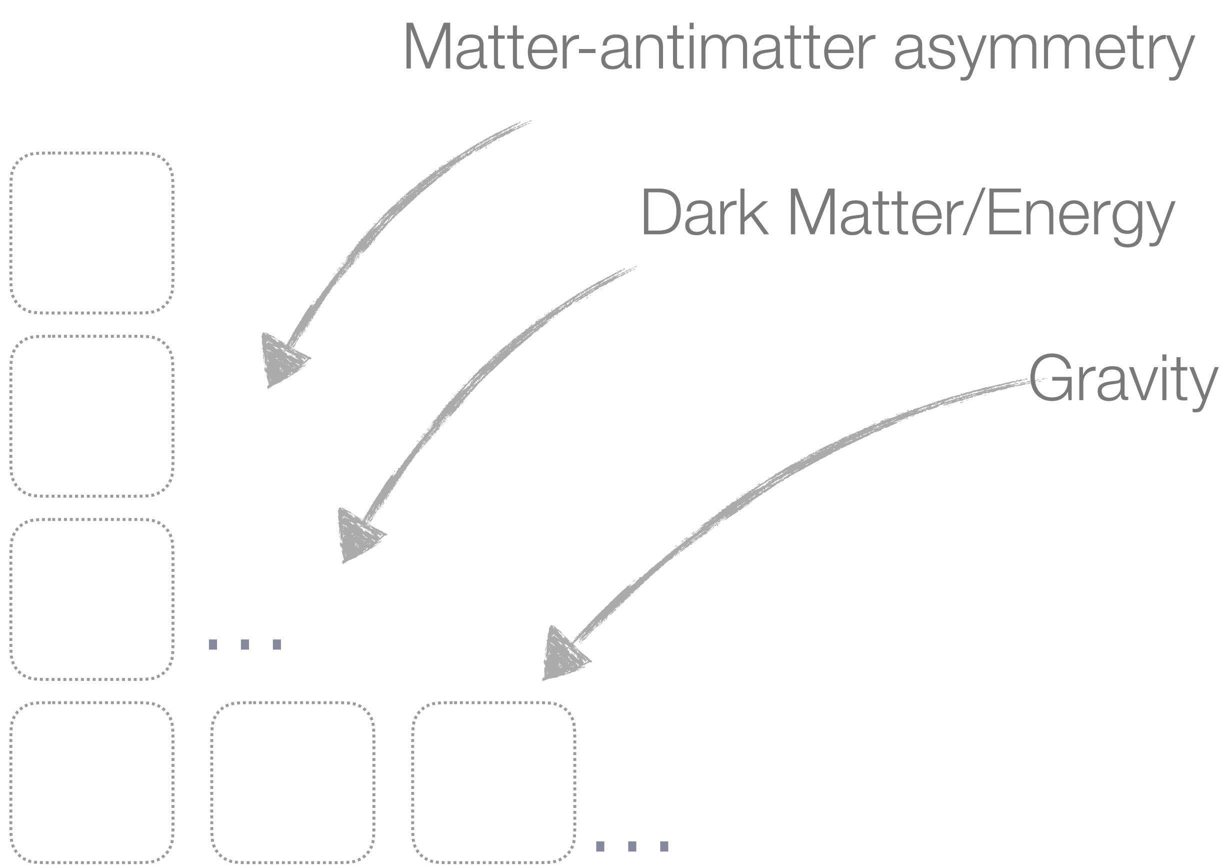

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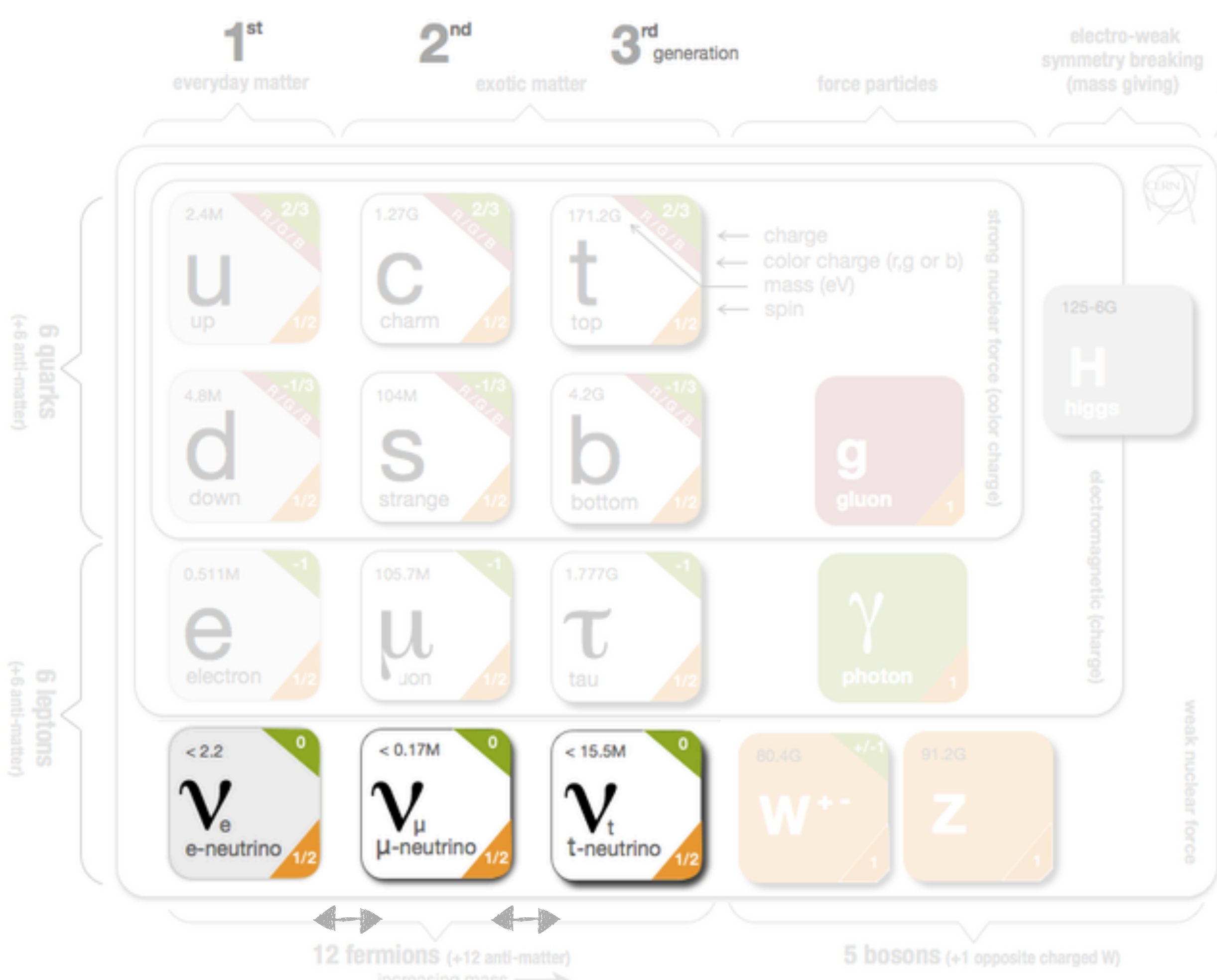
Charged lepton flavour violation

- Neutrino oscillations: Evidence of physics Behind Standard Model (BSM)
  Neutral lepton flavour violation



$\Delta N_i \neq 0$ with i = 1,2,3

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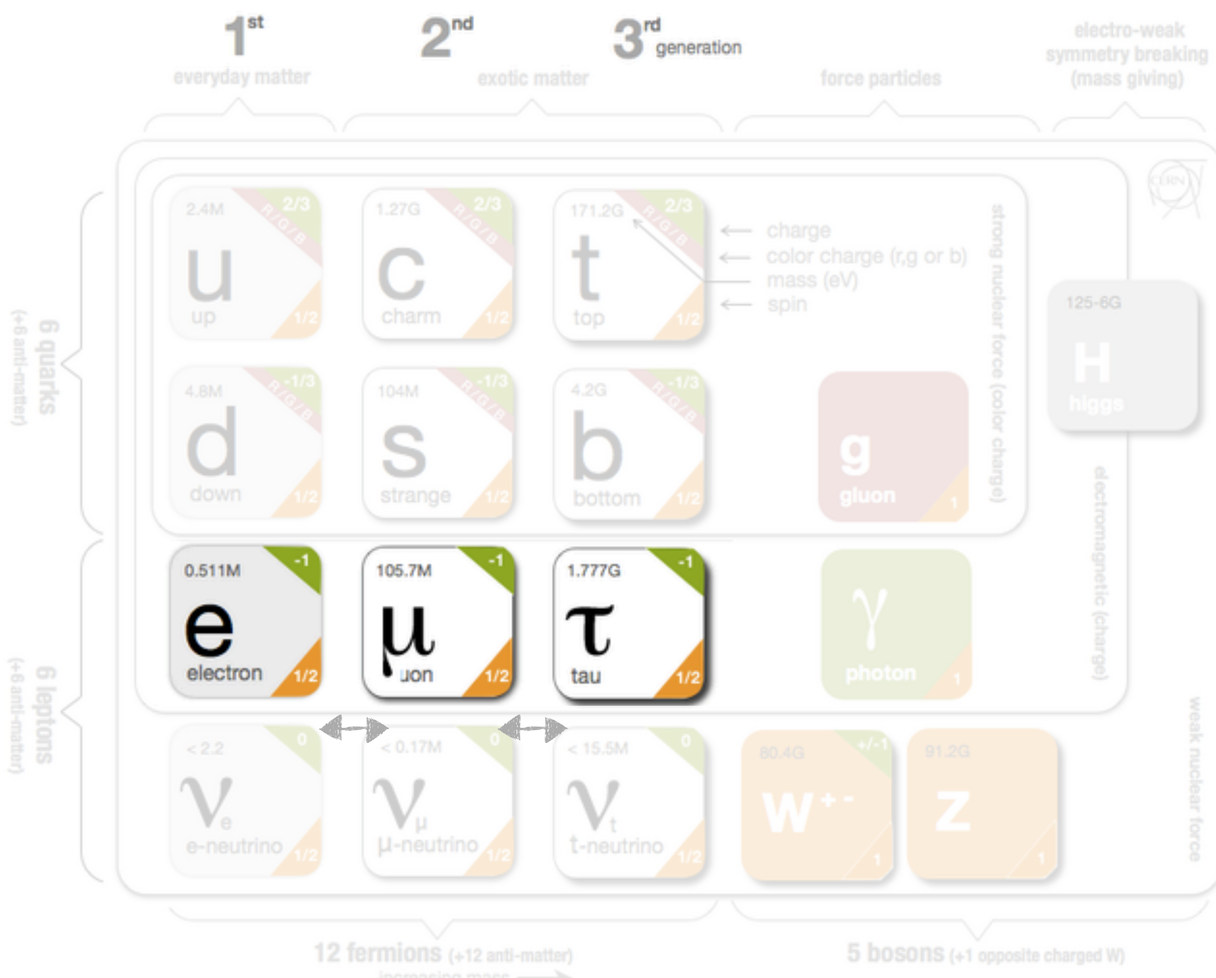


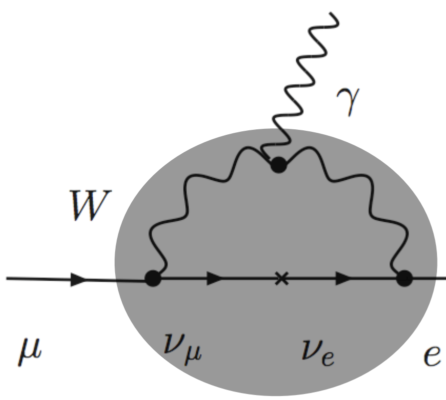
$$\Delta N_i \neq 0$$ with i = 1,2,3

- Charged lepton flavour violation: NOT yet observed

Charged lepton flavour violation search: Motivation

SM with massive neutrinos (Dirac)

$\mathcal{B}(\mu^+ \to e^+\gamma) \approx 10^{-54}$

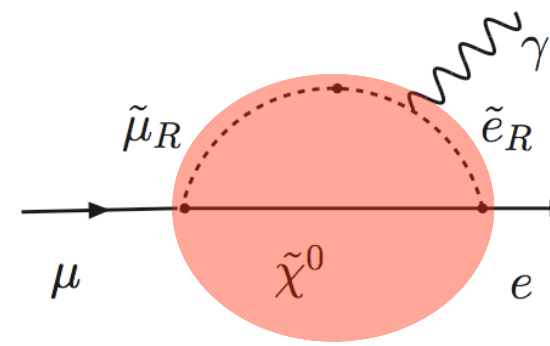


ν oscillations

too small to access experimentally

BSM

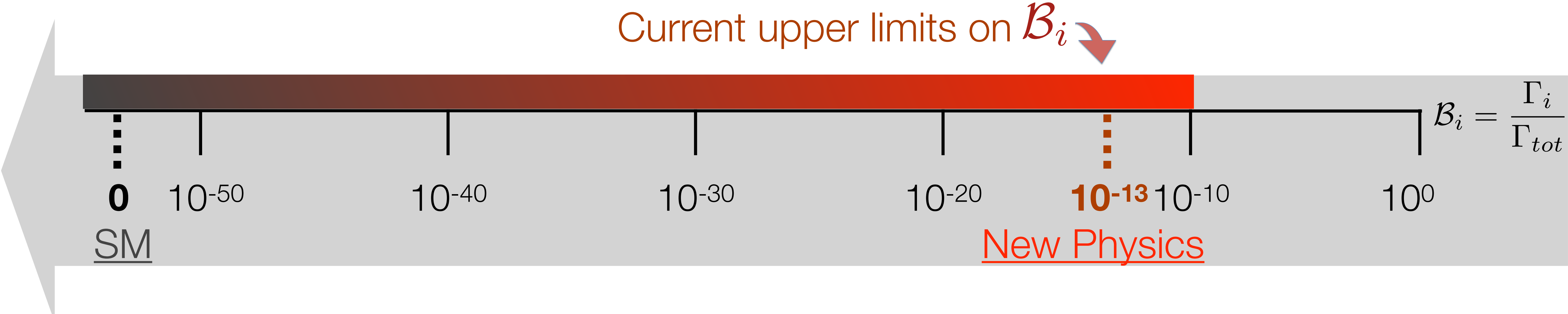
$\mathcal{B}(\mu^+ \to e^+\gamma) \gg 10^{-54}$



New particles

an experimental evidence:
a clear signature of New Physics NP
(SM background FREE)

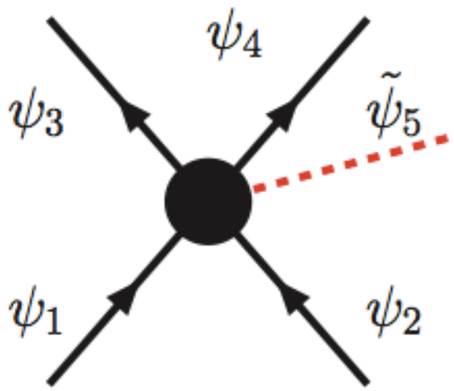
Current upper limits on $\mathcal{B}_i$



$\mathcal{B}_i = \frac{\Gamma_i}{\Gamma_{tot}}$

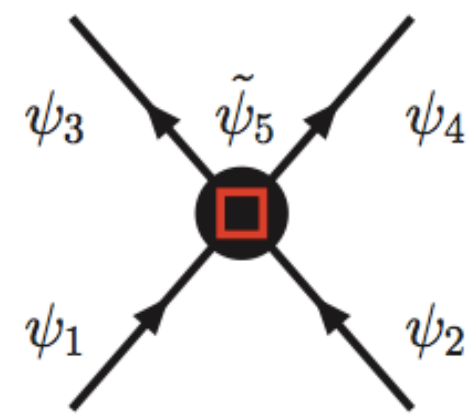
Complementary to “Energy Frontier”

Energy frontier



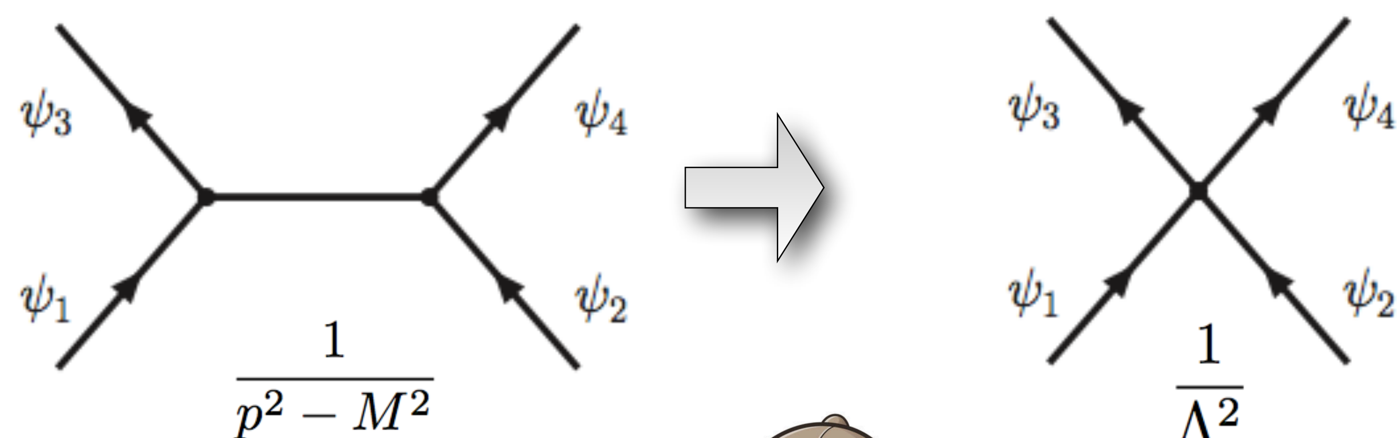
Real BSM particles

Precision and intensity frontier



Virtual BSM particles

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$



Unveil new physics

Probe energy scale otherwise unreachable

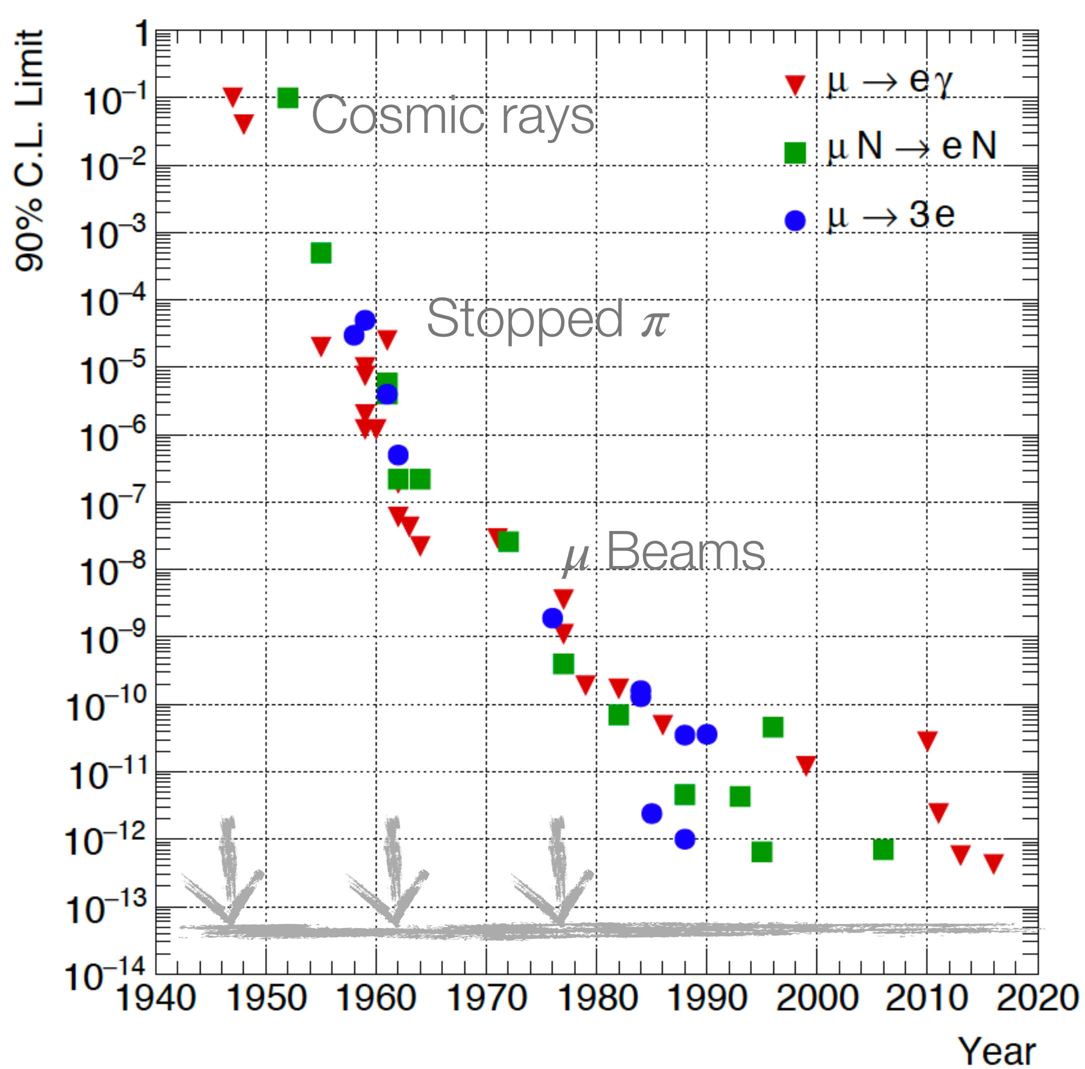
E > 1000 TeV

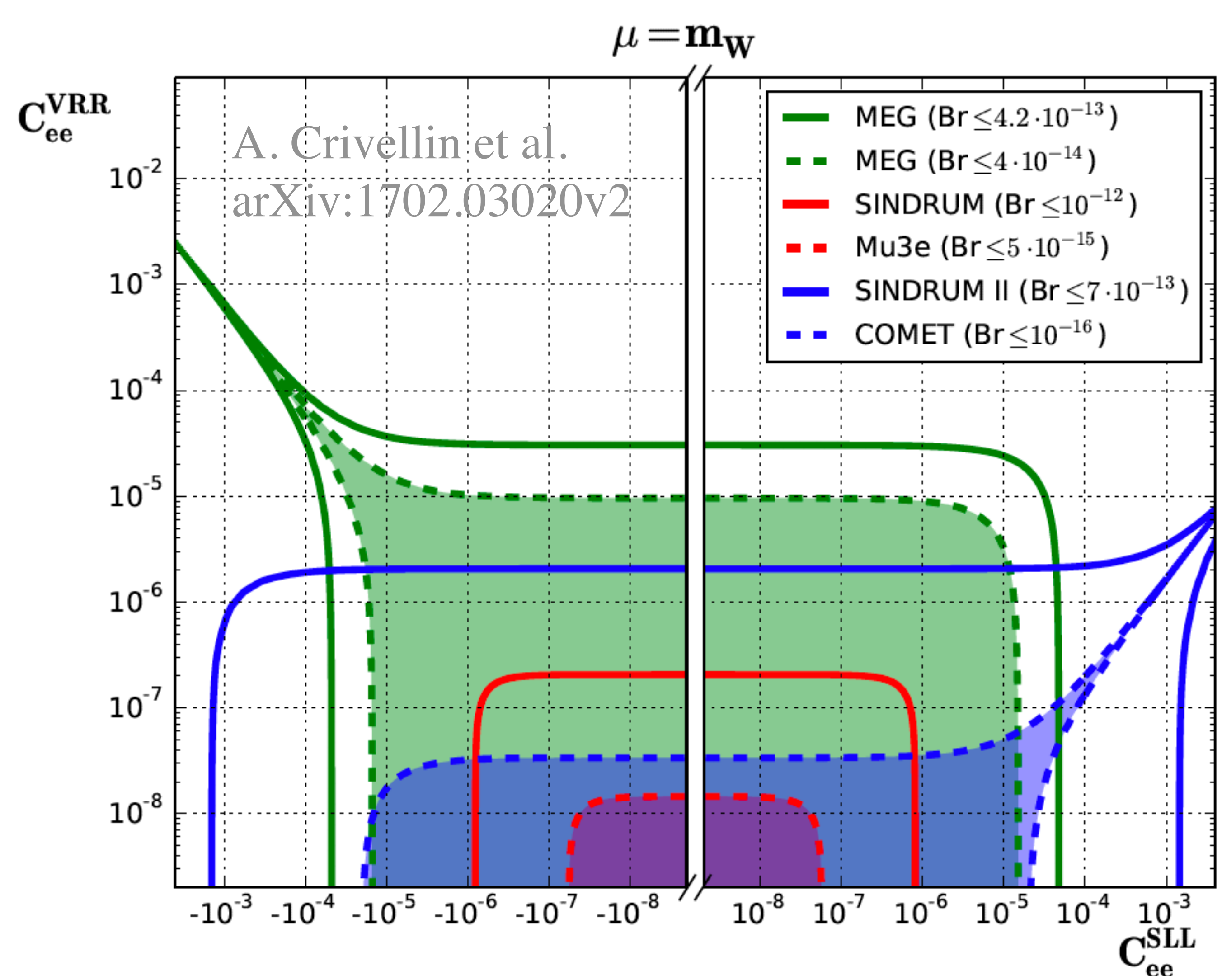
cLFV searches with muons: Status and prospects

- In the near future impressive sensitivities:

	Current upper limit	Future sensitivity
$\mu \to e\gamma$	4.2 x 10^{-13}	~ 4 x 10^{-14}
$\mu \to eee$	1.0 x 10^{-12}	~1.0 x 10^{-16}
$\mu N \to eN'$	7.0 x 10^{-13}	few x 10^{-17}

- Strong complementarities among channels: The only way to reveal the mechanism responsible for cLFV

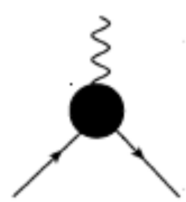
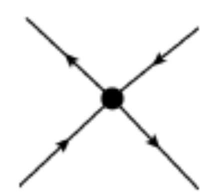


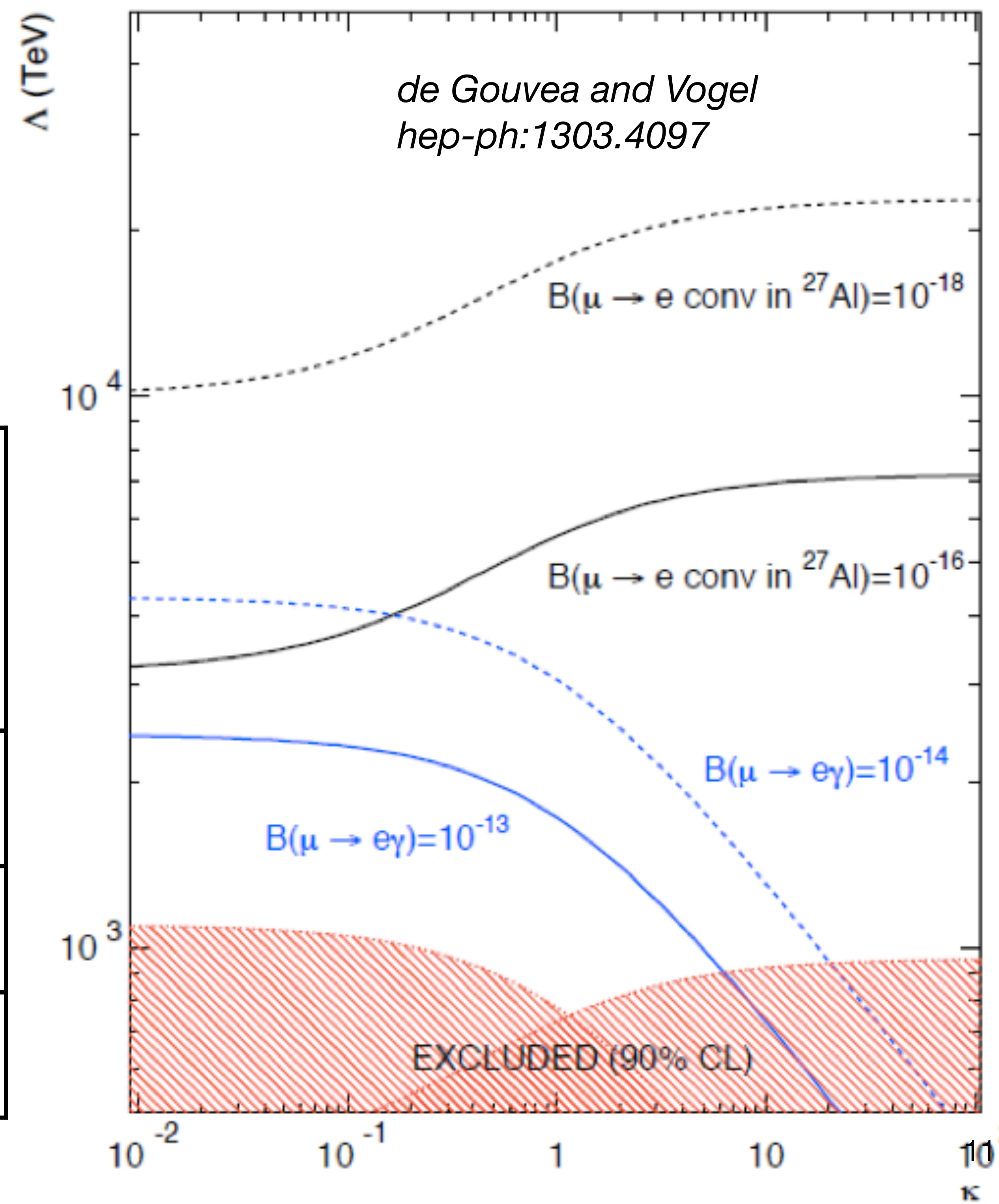


cLFV: “Effective” lagrangian with the k-parameter

- Due to the **extremely-low** accessible **branching ratios**, muon cLFV can strongly **constrain** new physics models and scales

Model independent lagrangian

$\frac{m_\mu}{(\kappa+1)\Lambda^2} \times$  $+$	$\frac{\kappa}{(\kappa+1)\Lambda^2} \times$ 
dipole term	contact term
$\mu \rightarrow e\gamma$	
$\mu \rightarrow eee$	
$\mu N \rightarrow eN$	



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HiMB motivations

- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Time schedule: **O(2025)**

- PSI delivers the highest intensity DC μ^+ beam: 5 x 10^8 μ^+/s

- Next generation cLFV experiments require higher muon rates
- New opportunities for future muon (particle physics) based experiments
- New opportunities for μSR experiments

- Different experiments demand for a variety of beam characteristics:
  - DC vs pulsed
  - Momentum depends on applications: stopped beams require low momenta

- Here focus on **DC low momenta muon beams**

- Maintain PSI leadership in DC low momentum high intensity muon beams

Fermilab $\rightarrow 5\times10^{10}\ \mu^-/s$

Mu2e: $R_{\mu e} = \mathcal{O}(10^{-17})$

J-PARC $\rightarrow 10^{10}\ \mu^-/s$

COMET: $R_{\mu e} = \mathcal{O}(10^{-17})$

Beam features vs experiment requirements

- Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world's highest beam intensities

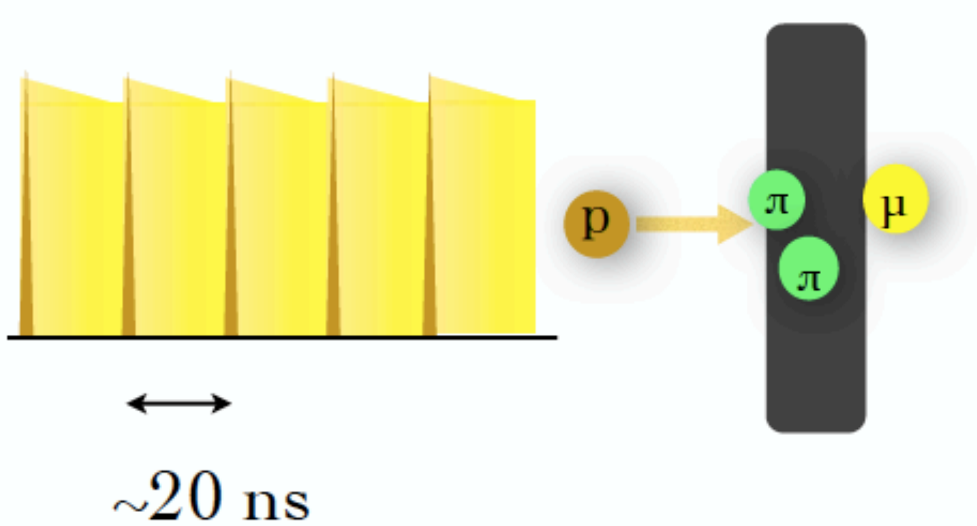
$I_{beam} \sim 10^8 - 10^{10}$ μ/s

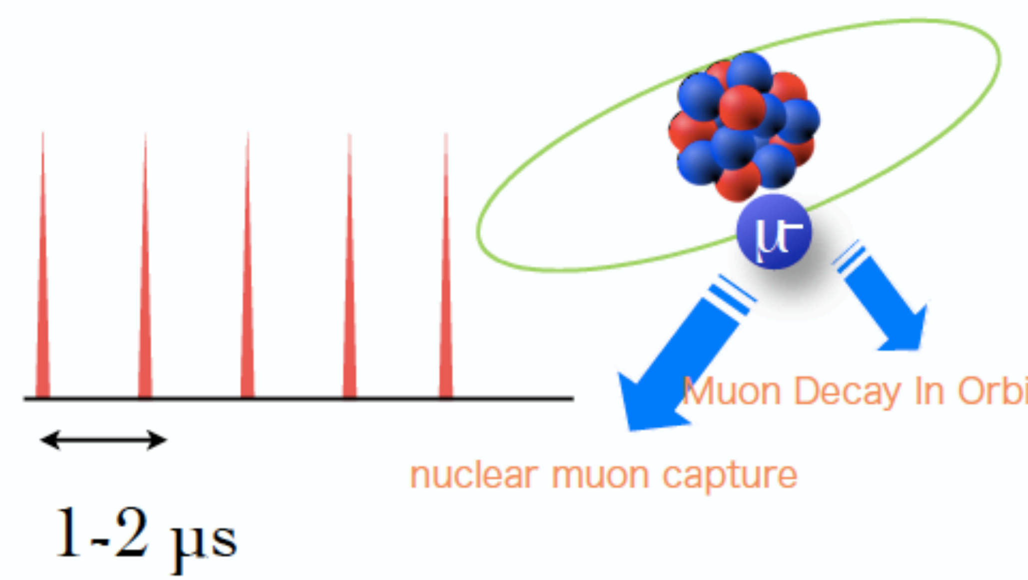
DC or Pulsed?

$I_{beam} \sim 10^{11}$ μ/s

- DC beam for coincidence experiments
  - $\mu \rightarrow e\gamma$, $\mu \rightarrow e e e$
- Pulse beam for non-coincidence experiments
  - μ-e conversion

@ PSI

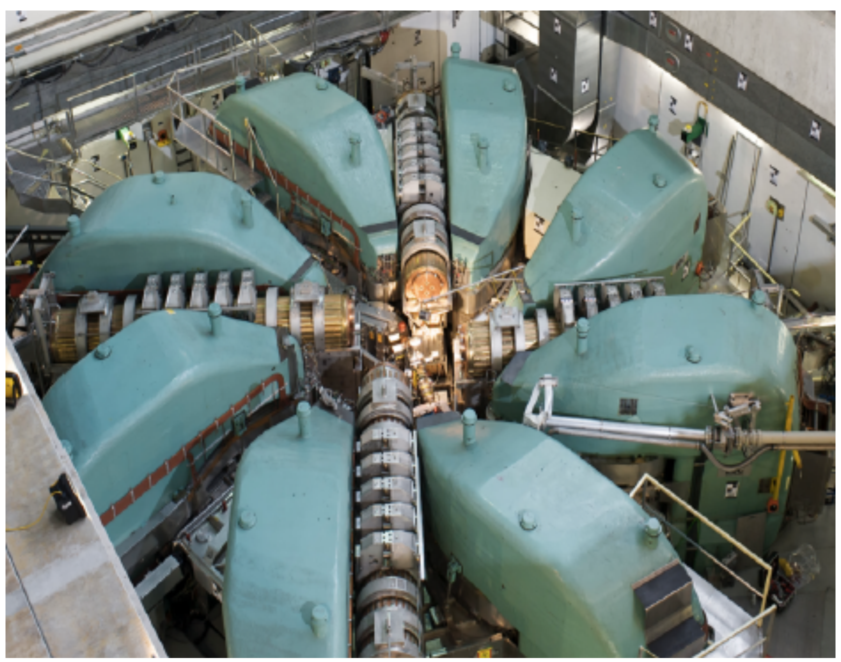




@ JPARC, FERMILAB

The world's most intense continuous muon beam

- PSI delivers the most intense continuous low momentum muon beam in the world (**Intensity Frontiers**)
    - Intensity = 5x 10^8 muon/s, low momentum p = 28 MeV/c

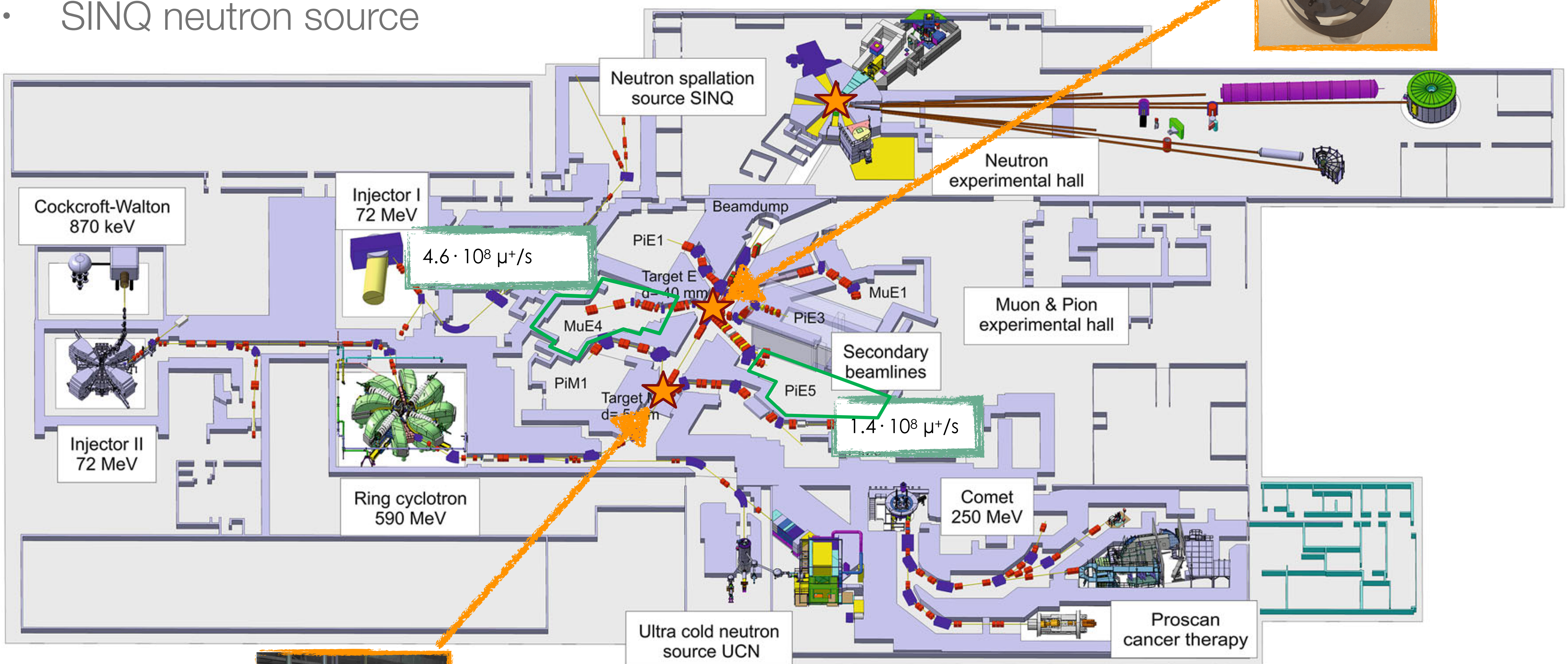


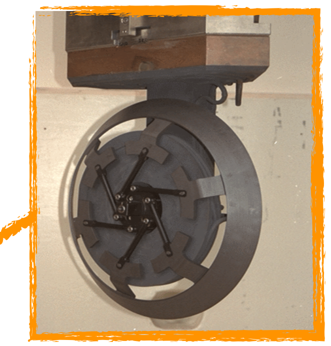
590 MeV proton ring cyclotron
Time structure: 50 MHz/20 ns
Power: 1.4 MW

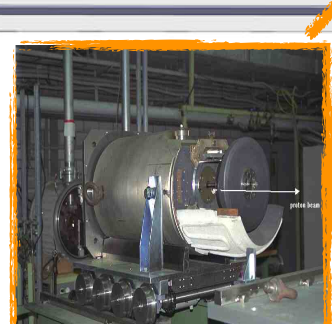
PSI landscape

The world's most intense continuous muon beam

- PSI High Intensity Proton Accelerator experimental areas
- Two production targets
- SINQ neutron source



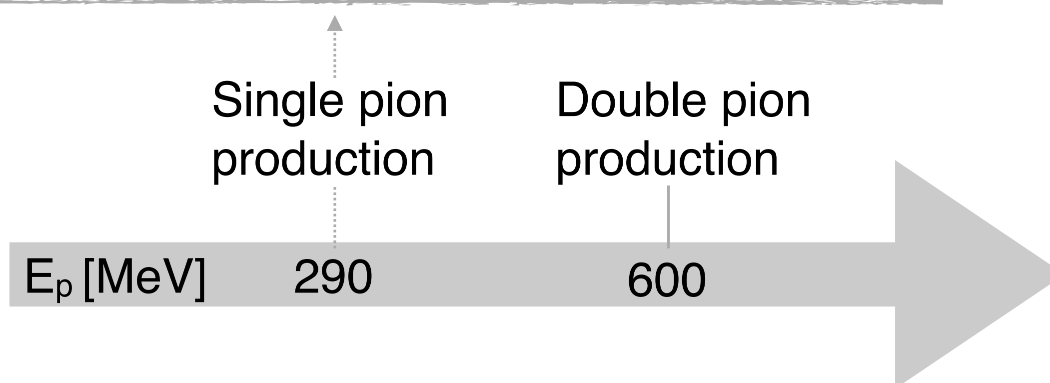


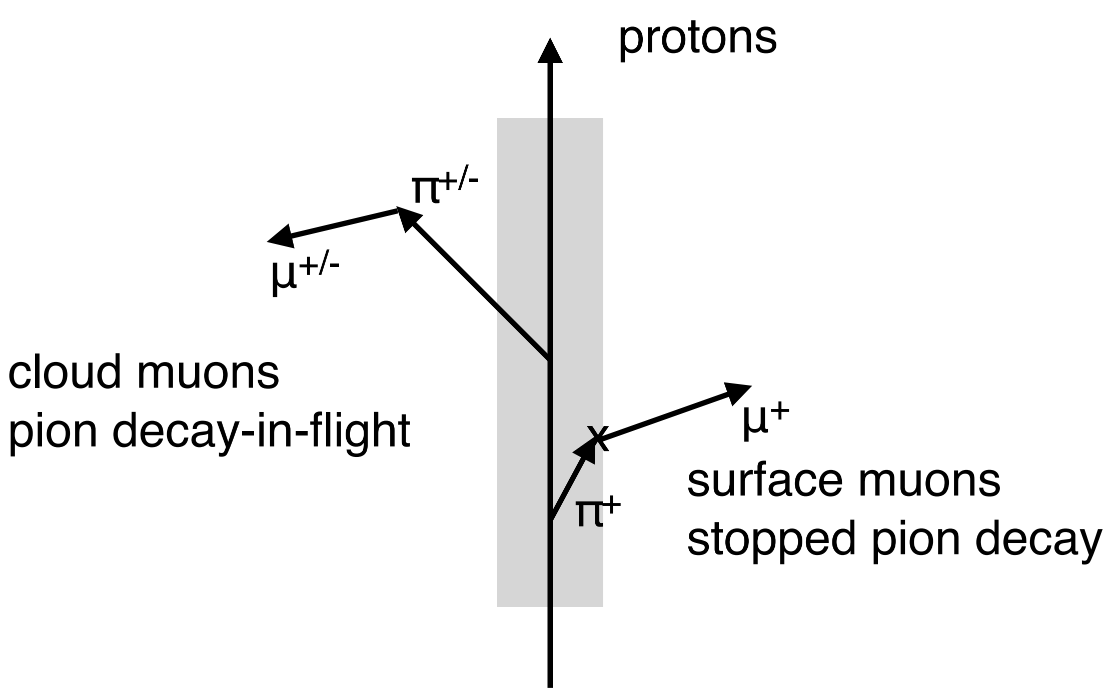


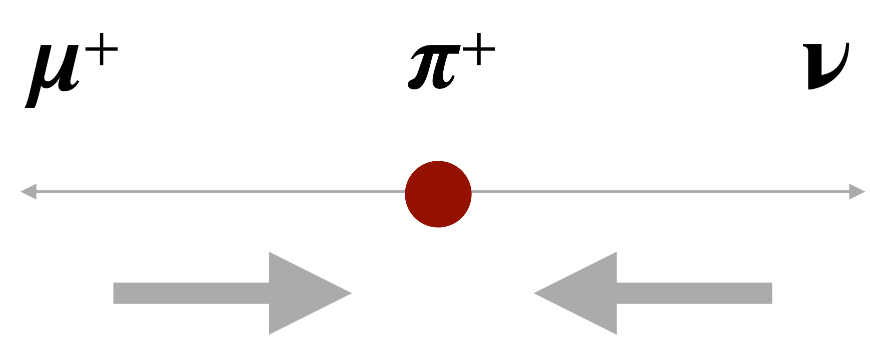
Muon production via pion decay

- Single pion production at 290 MeV proton energy (LAB)
- Low-energy muon beam lines typically tuned to surface-μ^+ at ~ 28 MeV/c
- Note: surface-μ —> polarized positively charged muons (spin antiparallel to the momentum)
- Contribution from cloud muons at similar momentum about 100x smaller
- Negative muons only available as cloud muons

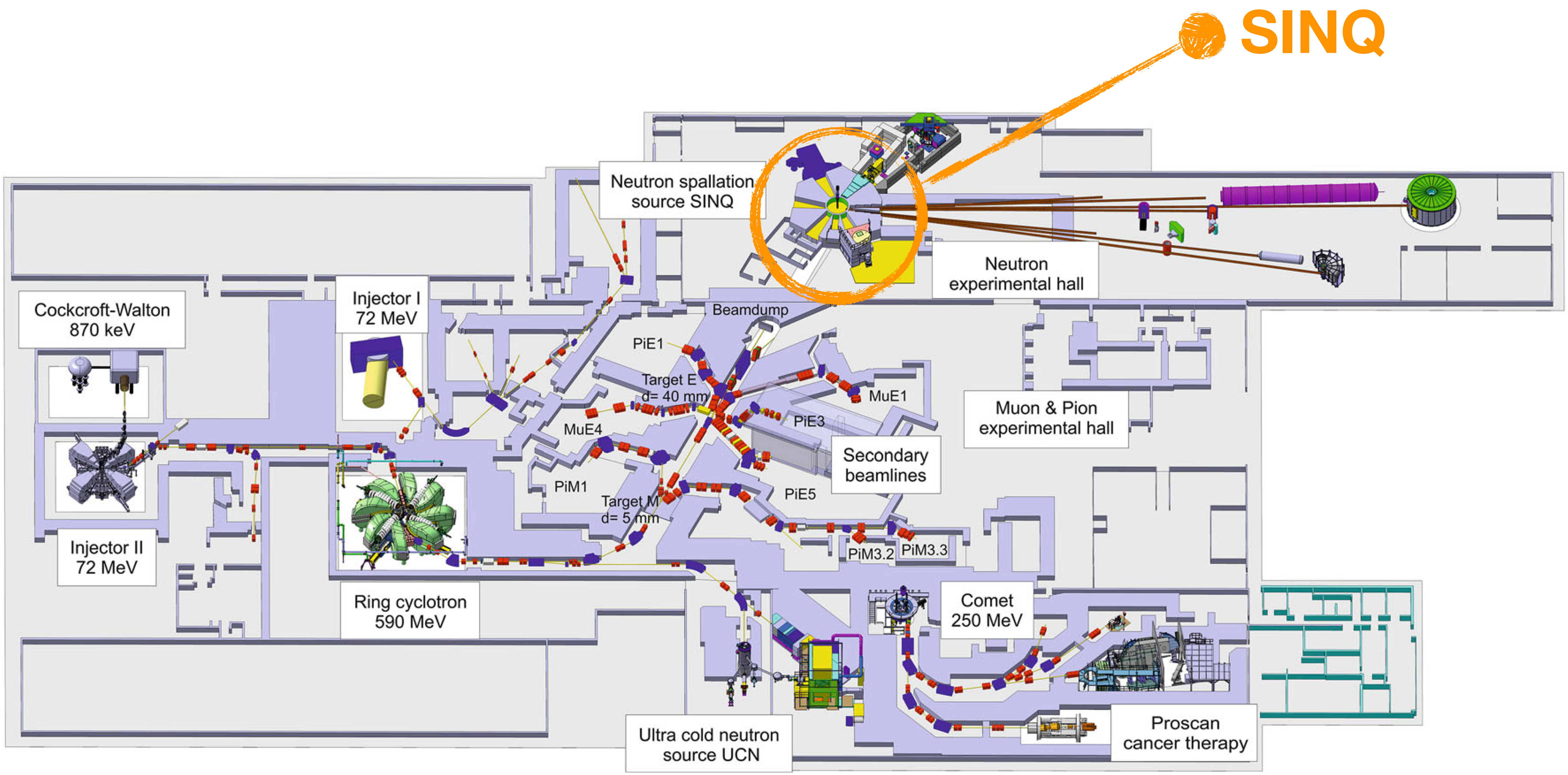
$$p + p \to p + n + \pi^+ \qquad p + n \to p + n + \pi^0$$
$$p + p \to p + p + \pi^0 \qquad p + n \to p + p + \pi^-$$
$$p + p \to d + \pi^+ \qquad p + n \to n + n + \pi^+$$







Initial HiMB concept: @SINQ



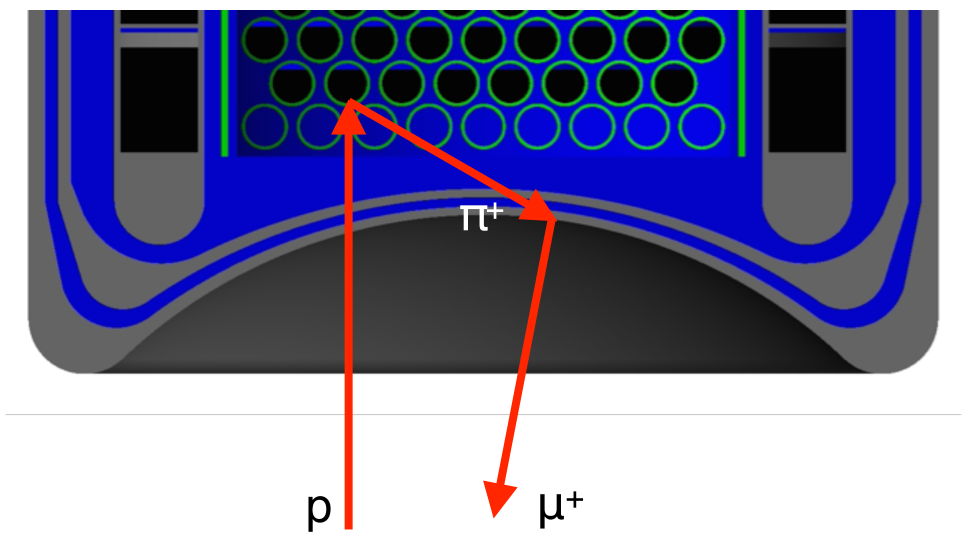
Initial HiMB concept: @SINQ

- Source simulation (below safety window):
  9 x 10^{10} surface-μ^+/s @ 1.7 mA I_p
- Profit from stopping of full beam
- Residual proton beam (~1 MW) dumped on SINQ

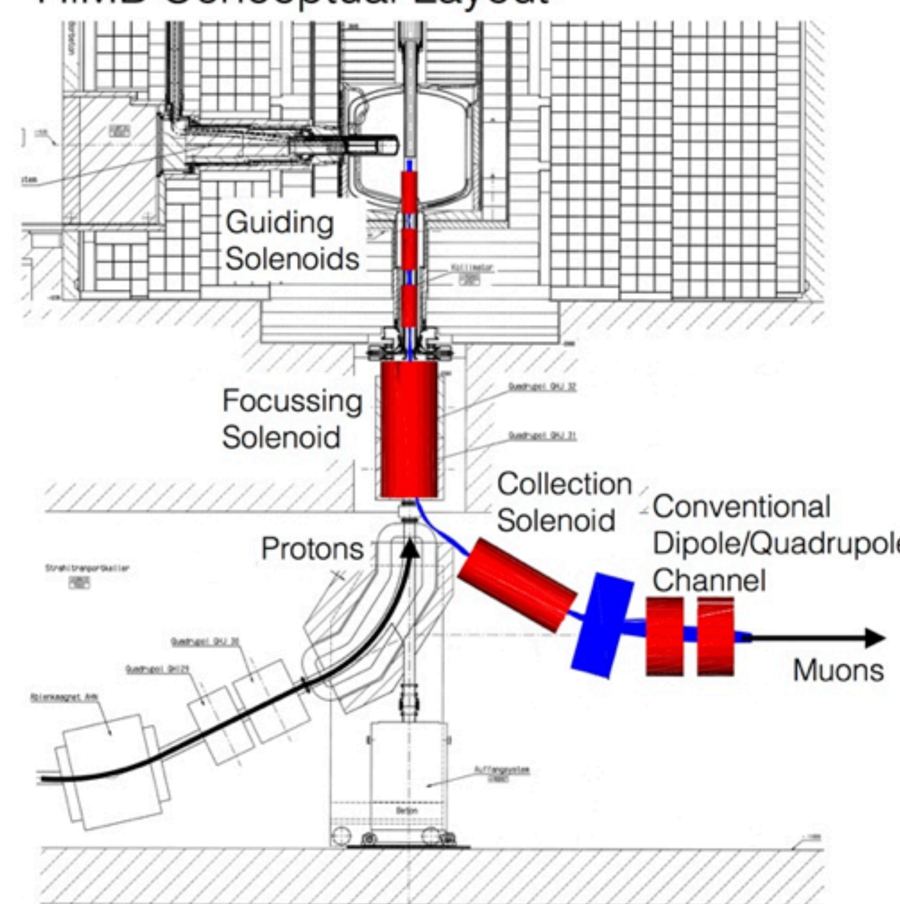
- Replace existing quadrupoles with solenoids:
  - Preserve proton beam footprint
  - Capture backward travelling surface muons
- Extract muons in Dipole fringe field
- Backward travelling pions stopped in beam window

- Capturing turned out to be difficult :
  - Large phase space (divergence & ‘source‘ extent)
  - Capture solenoid aperture needed to be increased, but constrained by moderator tank
- High radiation level close to target
- Due these constraints and after several iterations with different capturing elements:
  - **Not enough captures muons to make an high intensity beam**
  - **Alternative solution: HiMB @ EH**

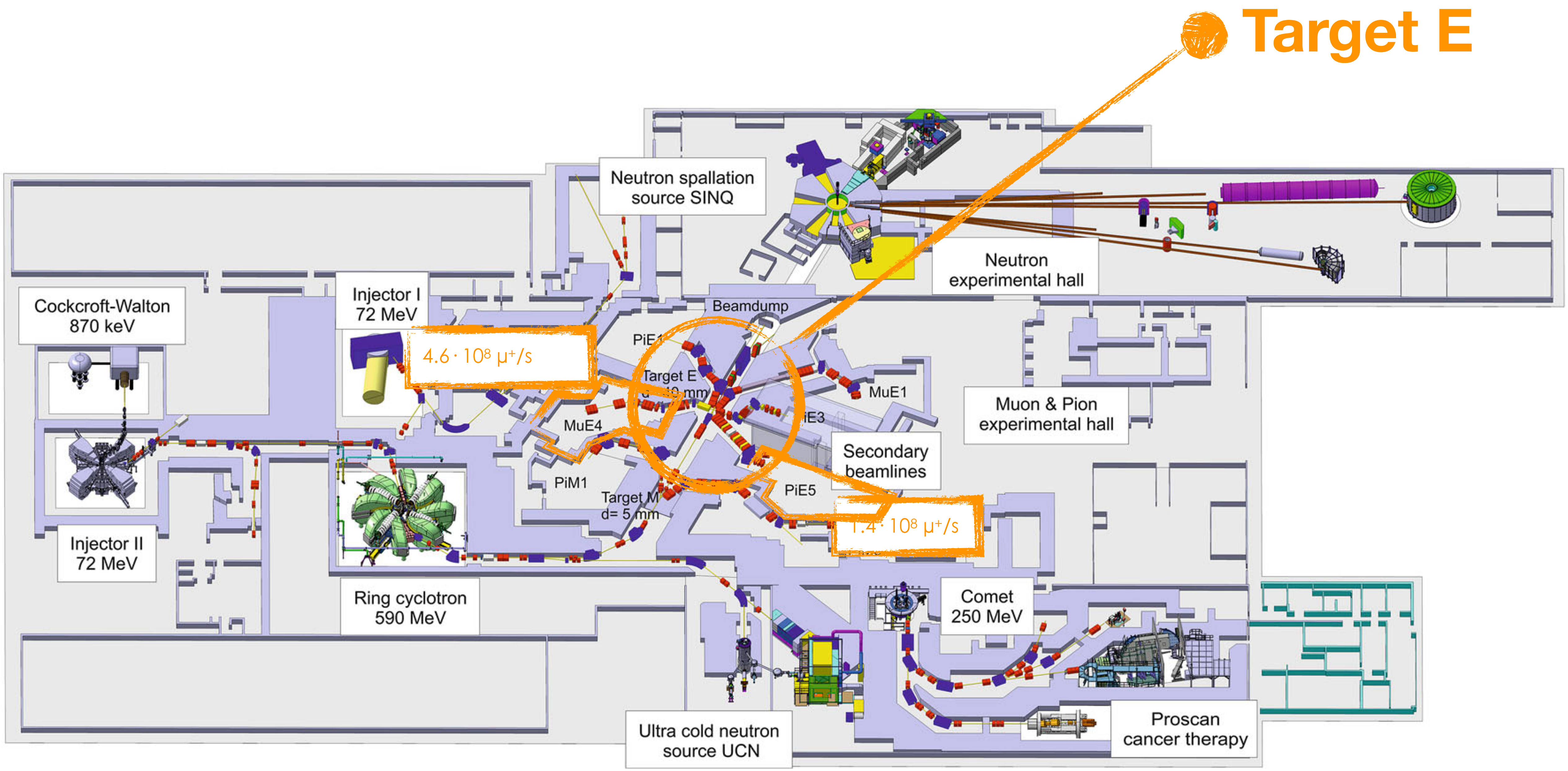
SINQ spallation target



HiMB Conceptual Layout

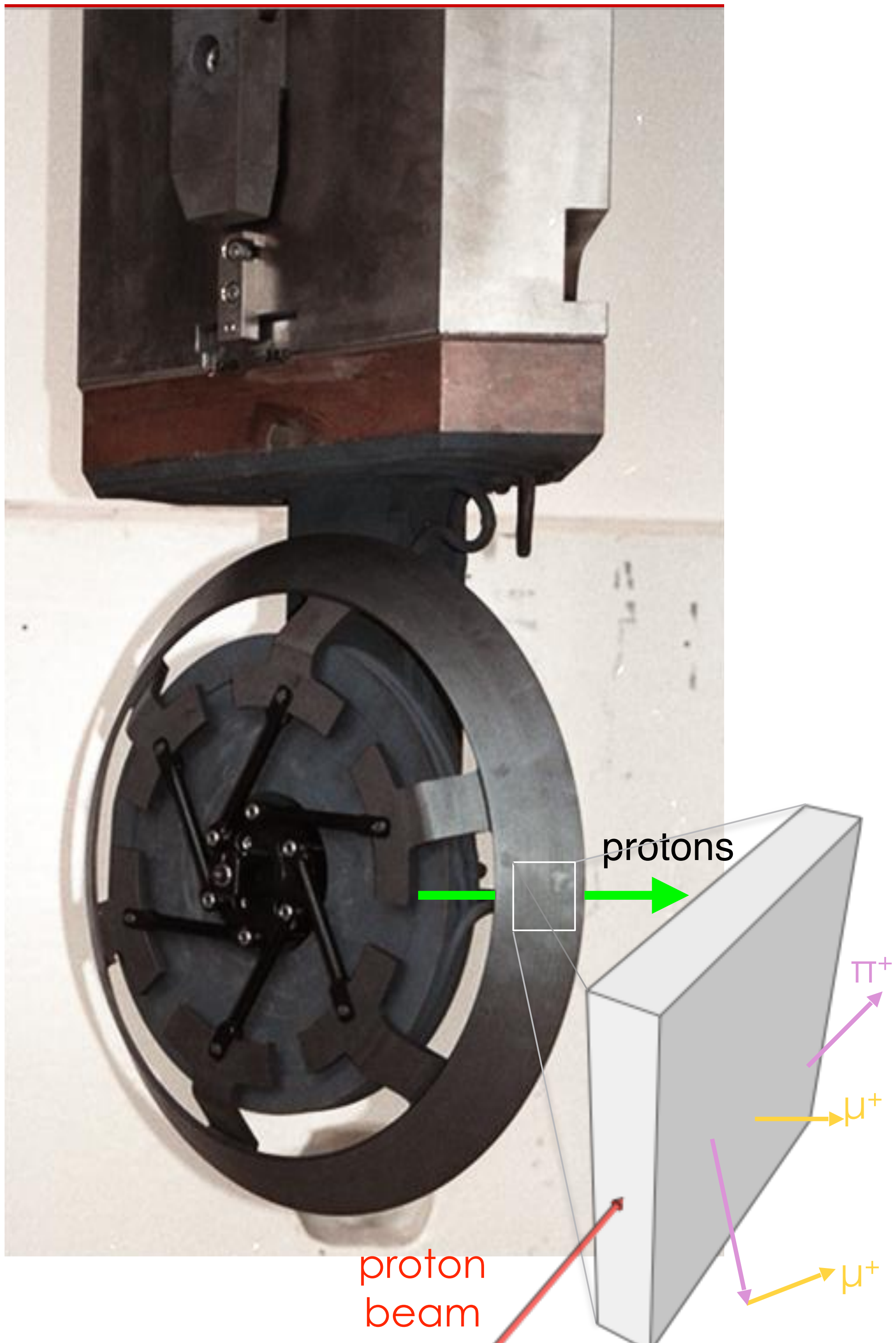


High Muon Beam Intensity: @Main Experimental Hall



Target E

- Rotating target (1 Hz)
- Polycrystalline graphite
- 40 mm length in beam direction
- 50 kW proton beam energy deposit
- 1700 K radiation cooled
- 30 % loss of protons
- Delivers world most intense surface muon beams

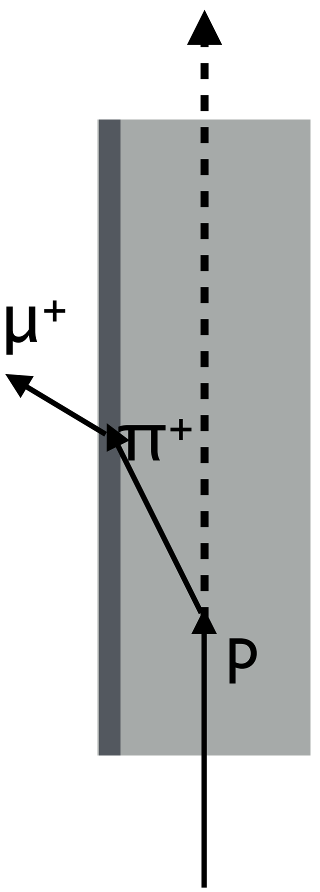


HiMB @ HE

- Back to standard target to exploit possible improvements towards high intensity beams:
  - Target
    - alternate materials
    - geometry
  - Beam line
    - high capture efficiency
    - large phase space acceptance transport channel

Optimization of standard production targets

- Back to standard target to exploit possible improvements towards high intensity beams
- **Target alternate materials**
    - Search for high pion yield materials -> higher muon yield
        - Several materials have pion yields > 2x Carbon
        - Relative muon yield favours low-Z materials, but difficult to construct as a target
        - B_4C and Be_2C show 10-15% gain

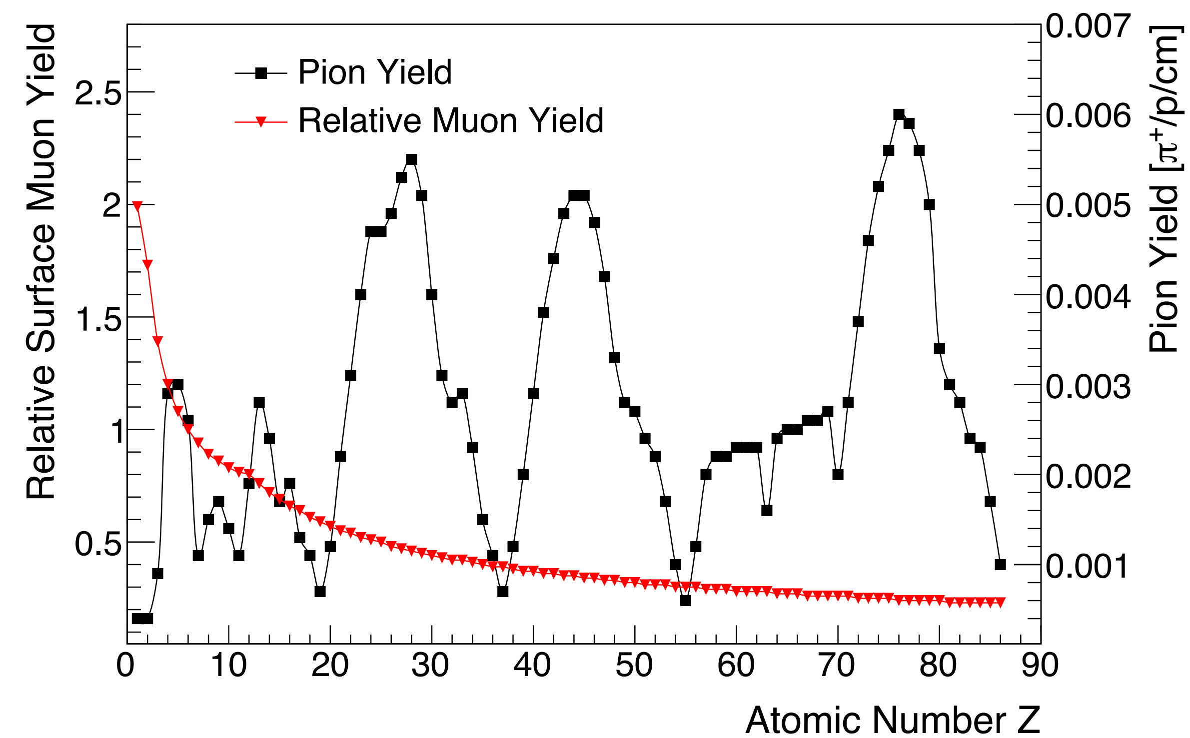


$$\textit{relative } \mu^+ \textit{yield} \propto \pi^+ \textit{stop density} \cdot \mu^+ \textit{Range} \cdot \textit{length}$$

$$\propto n \cdot \sigma_{\pi^+} \cdot SP_{\pi^+} \cdot \frac{1}{SP_{\mu^+}} \cdot \frac{\rho_C (6/12)_C}{\rho_x (Z/A)_x}$$

$$\propto Z^{1/3} \cdot Z \cdot \frac{1}{Z} \cdot \frac{1}{Z}$$

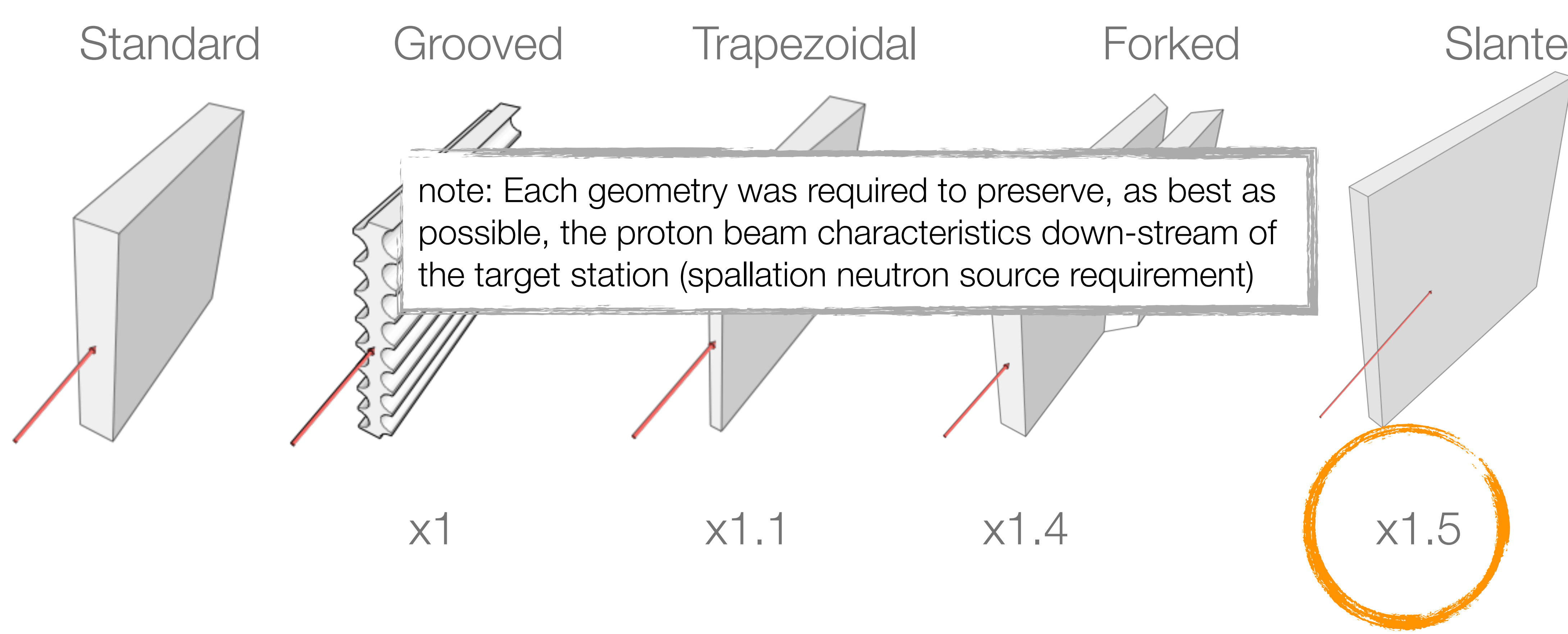
$$\propto \frac{1}{Z^{2/3}}$$



Optimization of standard production targets

- Strategy: either increasing the surface volume (surface area times acceptance depth) or the pion stop density near the surface

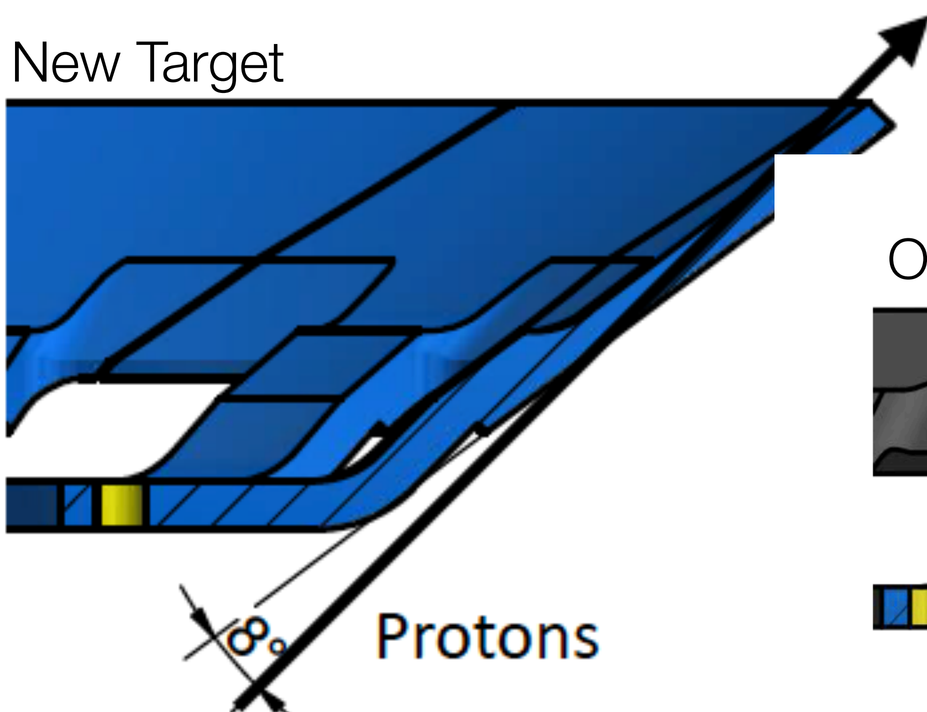
  - **Target geometry**
    - Comparison studies of different target geometries: **Different shapes and rotation angles**
    - Enhancements normalised to standard target



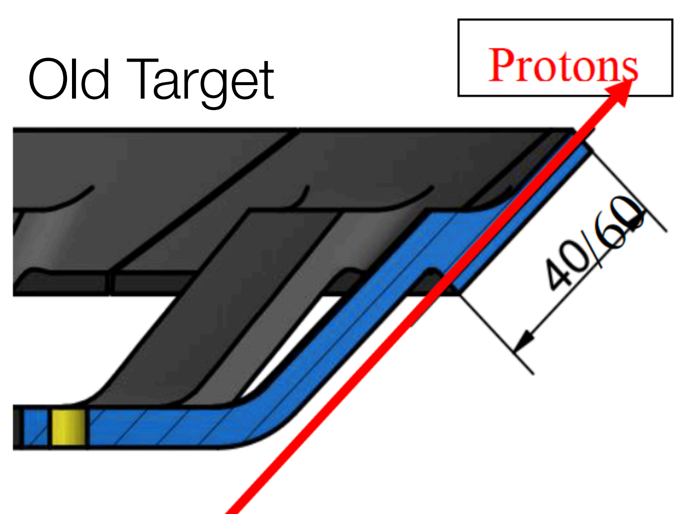
Slanted target: towards the test

- Upgrade existing graphite production target E 40 mm
  - 8° slanting angle: Measurement in forward / backward / sideways direction
  - Production and implementation feasible
  - Mechanical and thermal simulations completed and no show-stopper found
  - **Installed in week 48 (Nov. 25th, 2019)**
  - **Goals**
    - **Increase surface muon rates for all connected beam lines**
    - **Increase safety margin for "missing" target with the proton beam**

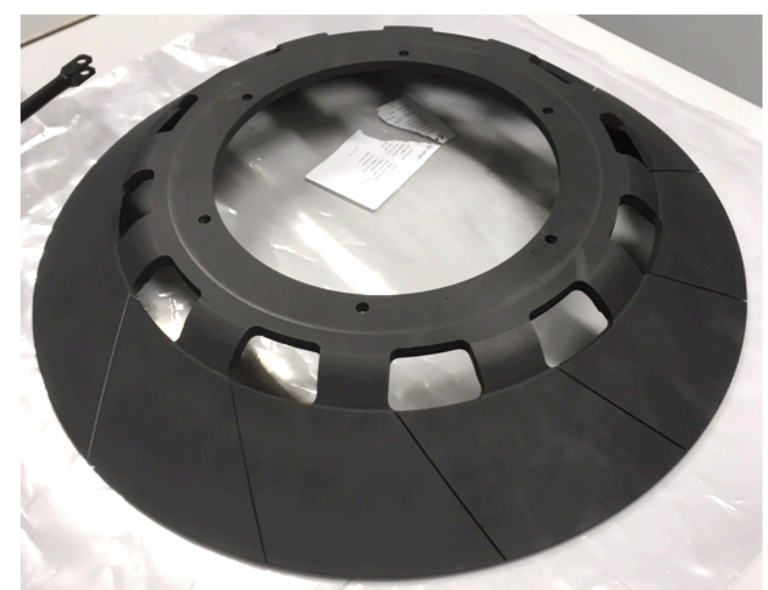
New Target



Old Target



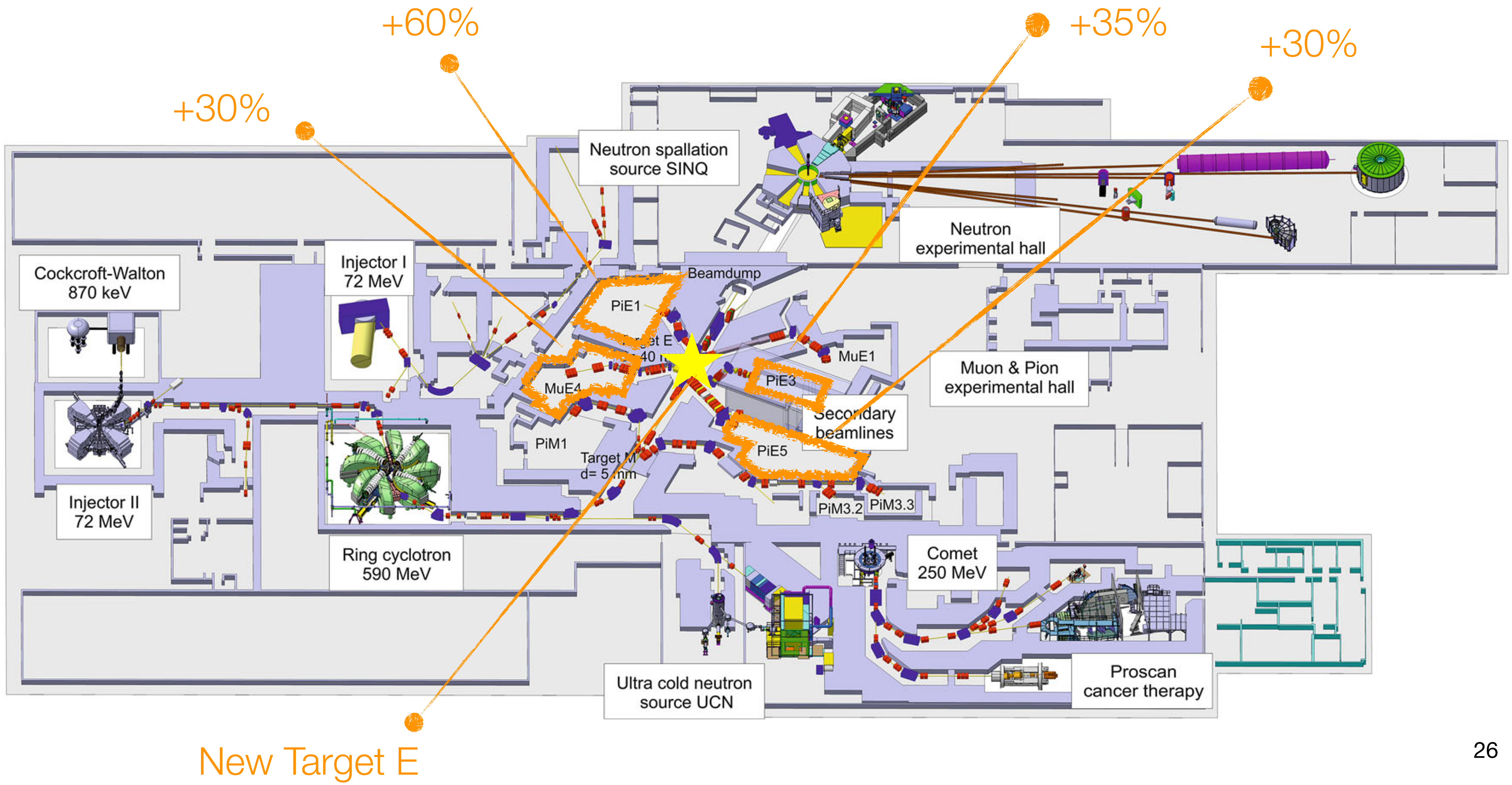
Prototype for the New Target E



New Target E

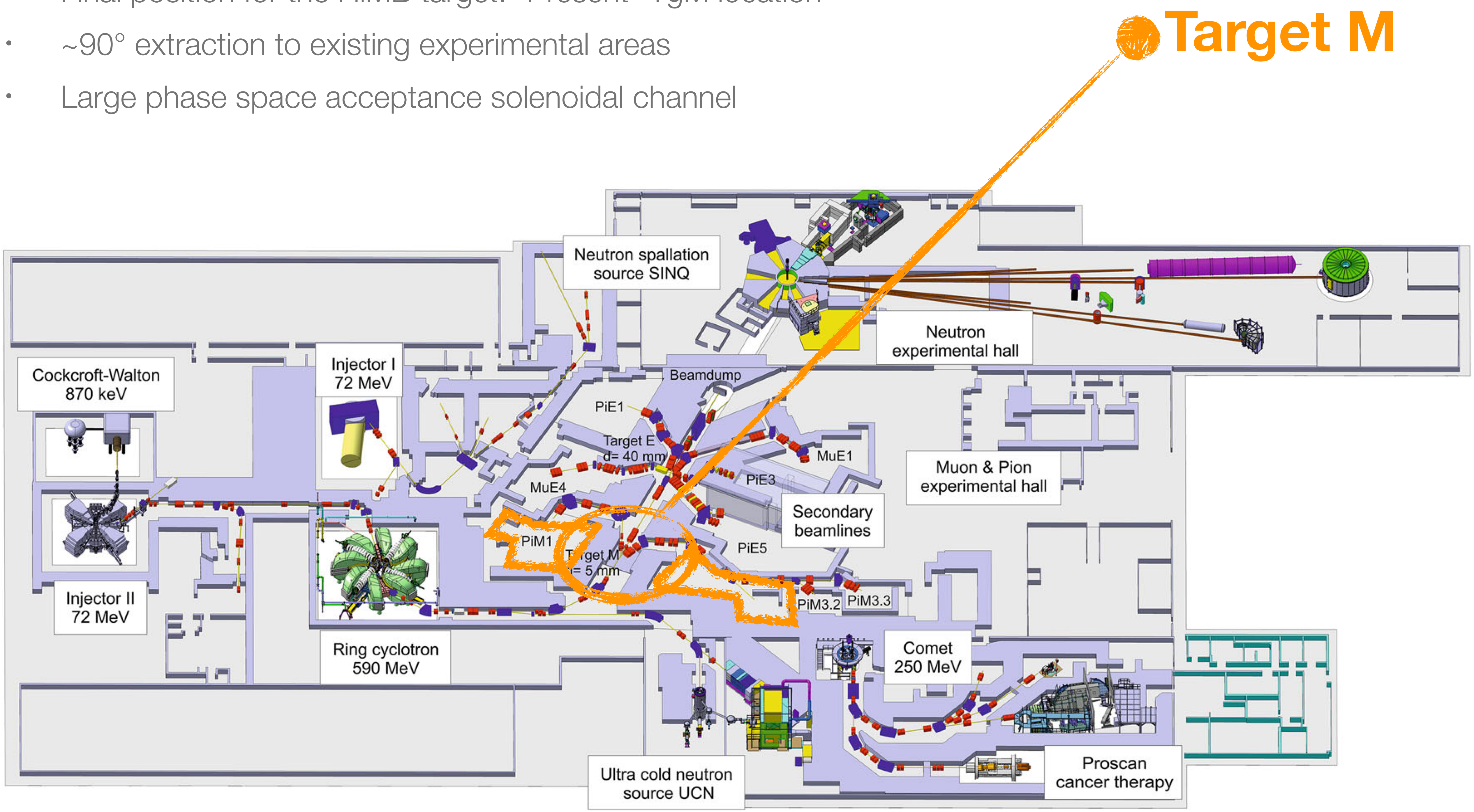
Slanted target: 2019 test Results

- Expect ~30-60 % enhancement
- Measurements successfully done in different experimental areas in fall 2019
- Analysis still undergoing: **increased muon yield CONFIRMED!**
- To be seen: **impact of higher thermal stress on long term stability of target wheel**



Towards the HiMB project @ PSI

- Final position for the HiMB target: “Present" TgM location
- ~90° extraction to existing experimental areas
- Large phase space acceptance solenoidal channel



Prospects

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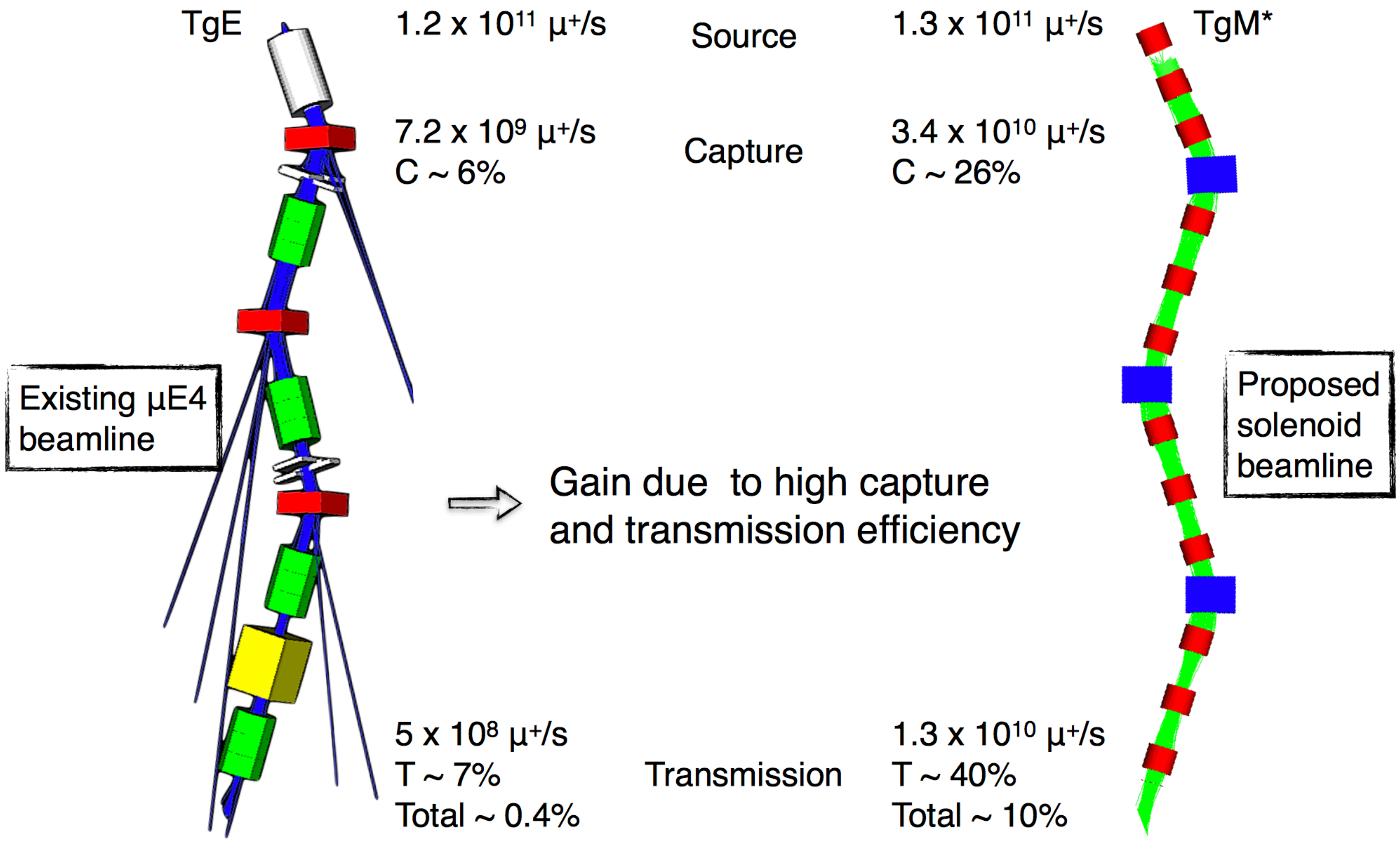
- Time schedule: **O(2025)**



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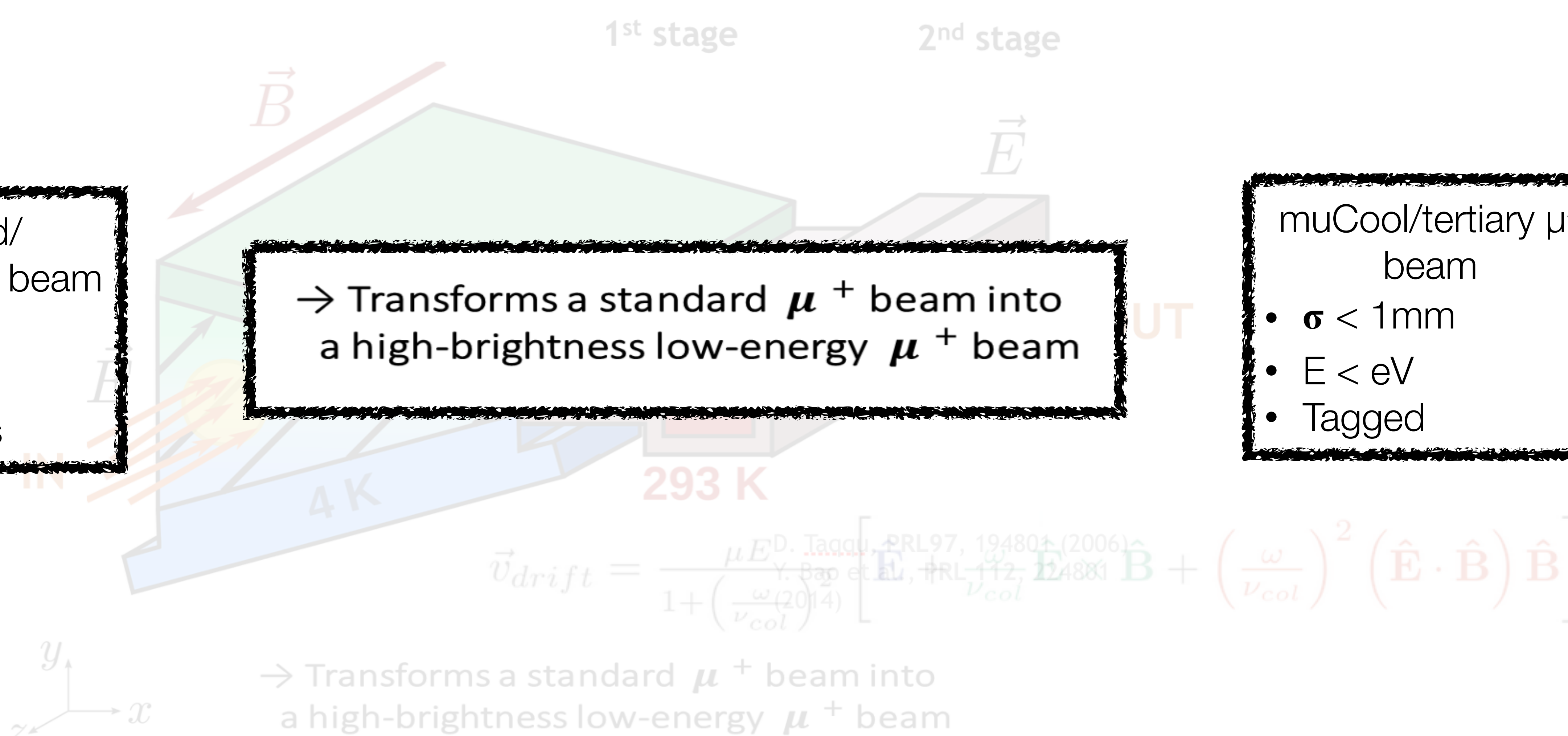
D. Taqqu, PRL 97 (2006) 194801
Y. Bao et al., PRL 112 (2014) 224801

The muCool project at PSI

- Aim: High-brightness low energy muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor $\mathbf{10^{10}}$ with an efficiency of $\mathbf{10^{-3}}$

for:
μSR (solid state physics)
muonium (spectroscopy, gravitational interaction...)
muon experiments (μEDM, g-2…)



Standard/ secondary μ+ beam
- σ = 10 mm
- E = 4 MeV
- Continuous

→ Transforms a standard μ^+ beam into a high-brightness low-energy μ^+ beam

muCool/tertiary μ+ beam
- σ < 1mm
- E < eV
- Tagged

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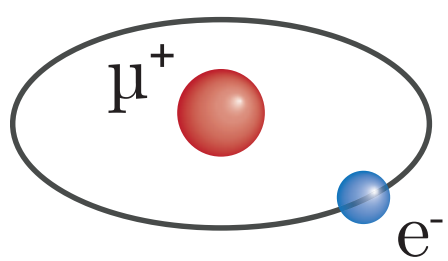
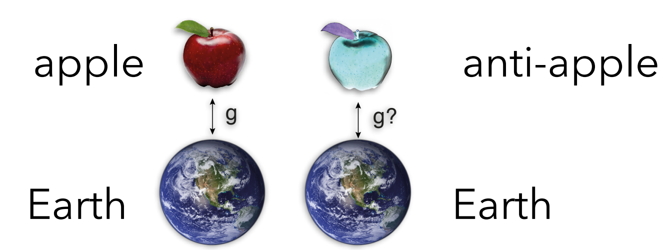


- hydrogen-like exotic atom
- pure leptonic system (1st and 2nd gen.)
- no finite size / nuclear effects
- … but, short lifetime ~ 2.2 us
- **Precision spectroscopy**: test of bound-state QED, fundamental constants: m_μ, R_∞, m_μ/m_p, q_μ/q_e ...

Muonium gravity experiment?



test of weak equivalence principle on μ^+ :
- **elementary** antiparticle
- second generation lepton

D. Taqqu, PRL 97 (2006) 194801
Y. Bao et al., PRL 112 (2014) 224801
I. Belosevic et al., EPJ C 79 (2019) 430

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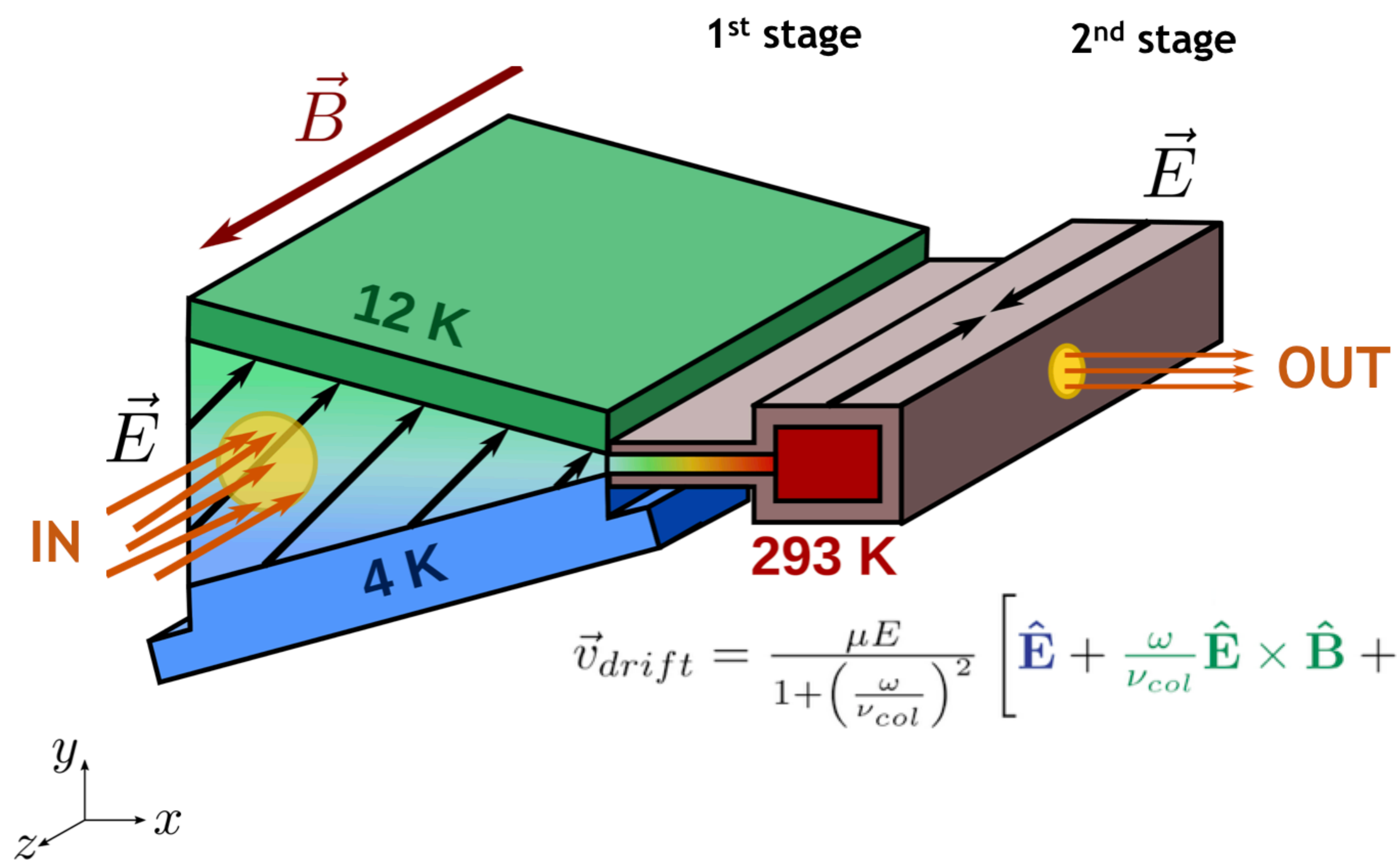
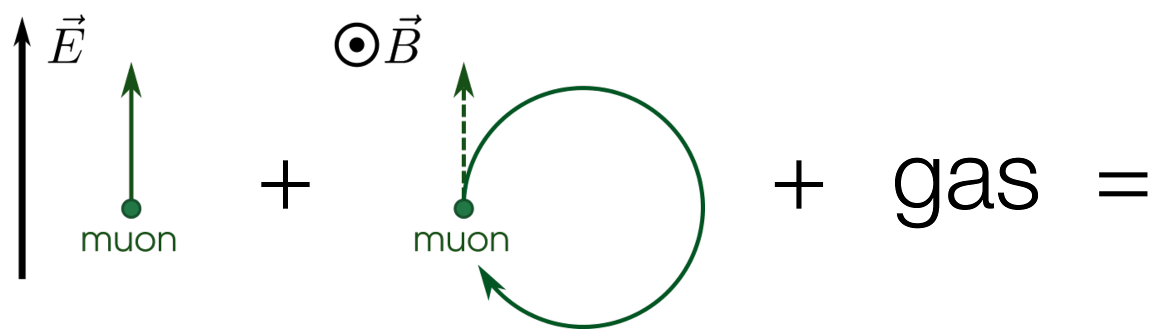
muon experiments (μEDM, g-2…)

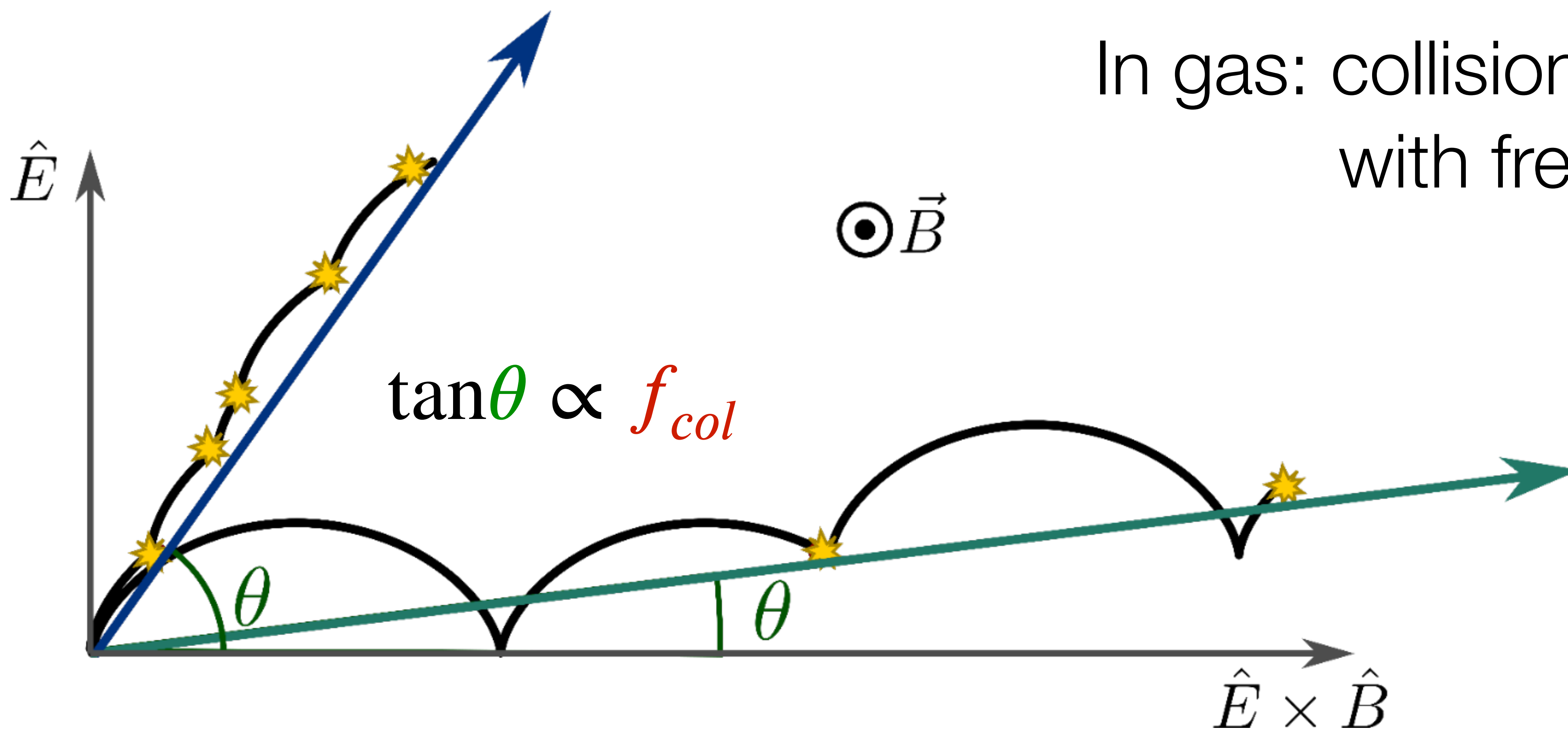


$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

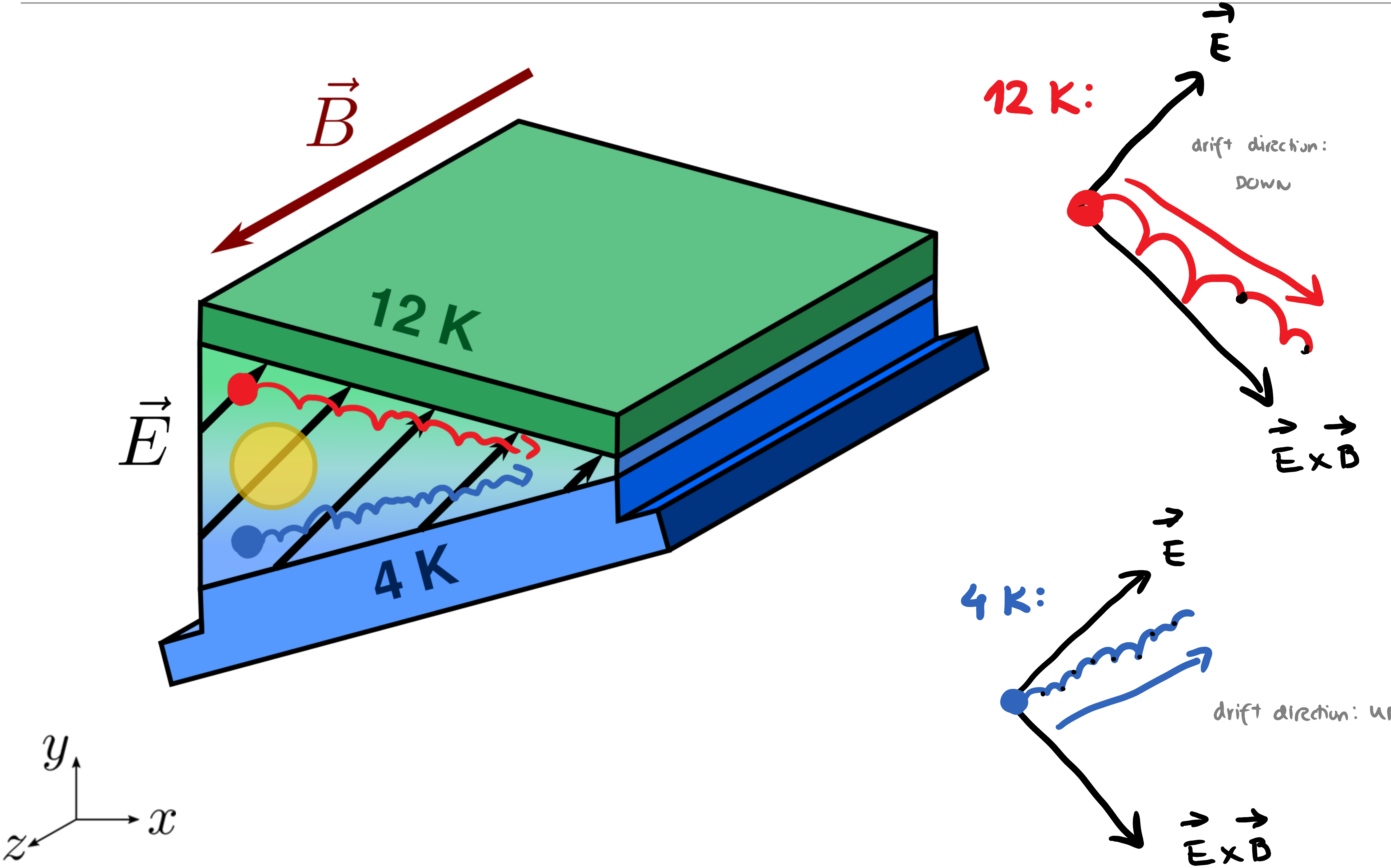
Trajectories in E and B field + gas



In gas: collisions ☆
with frequency f_{col}

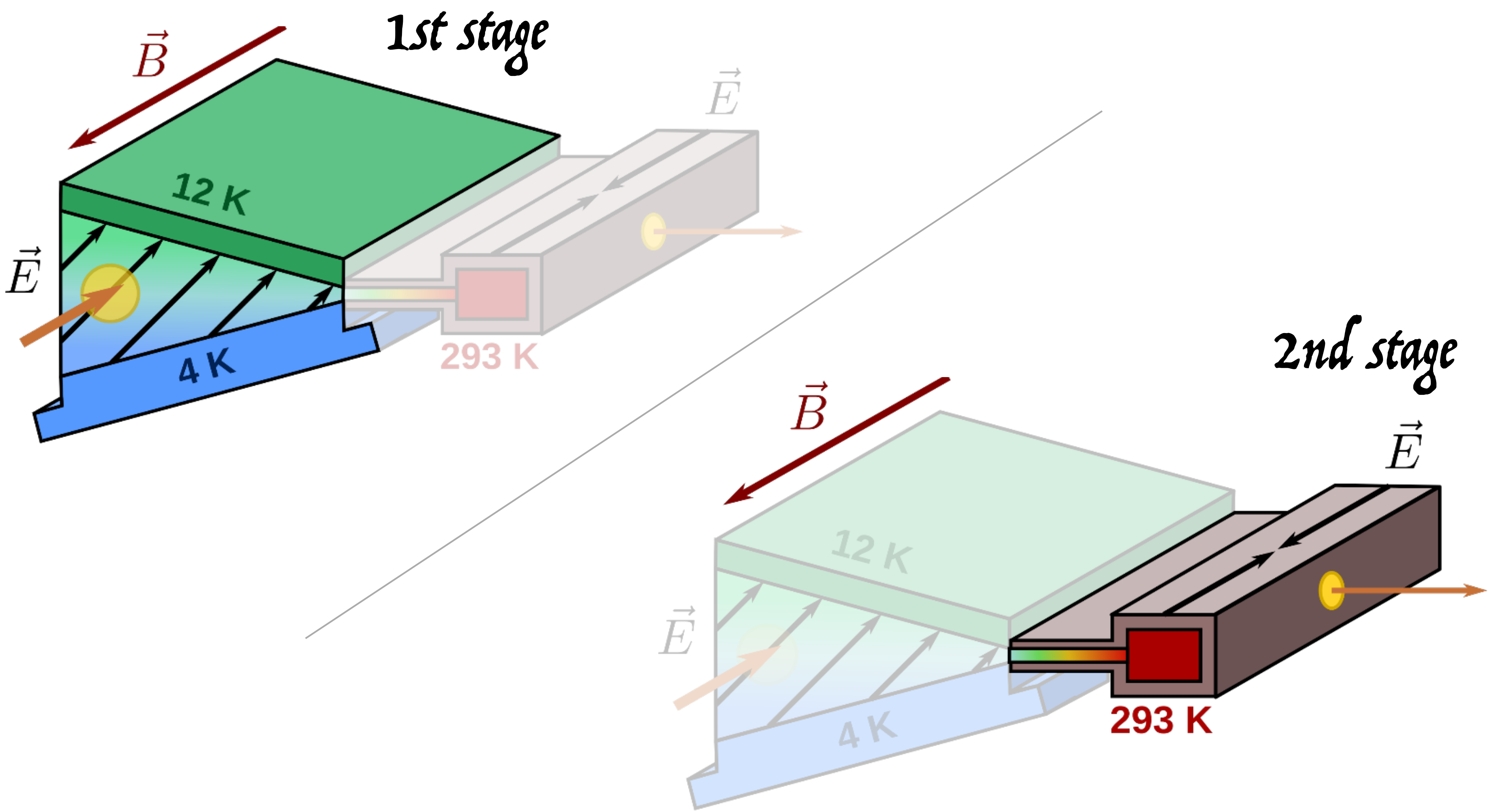


Working principle: 1st Stage

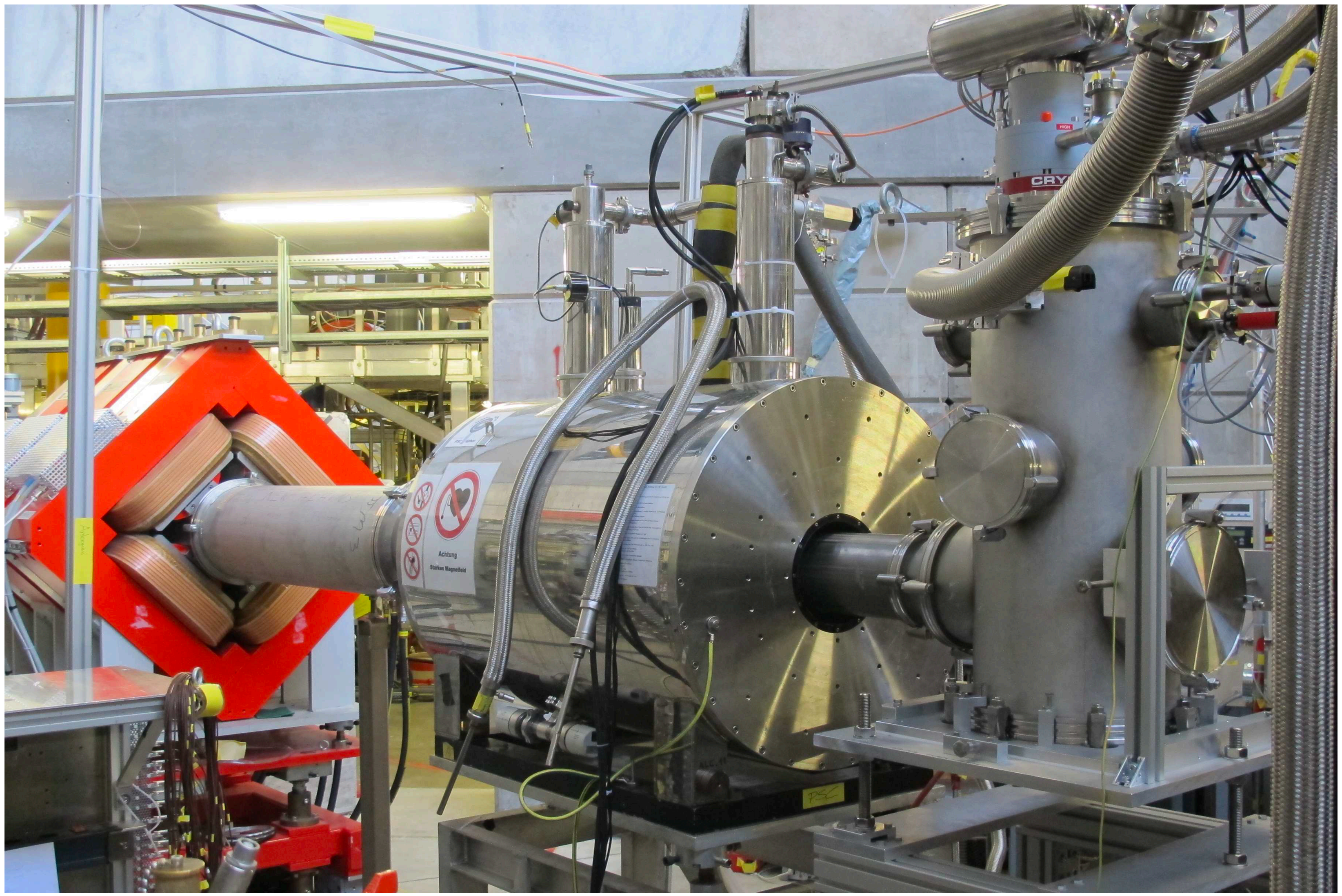


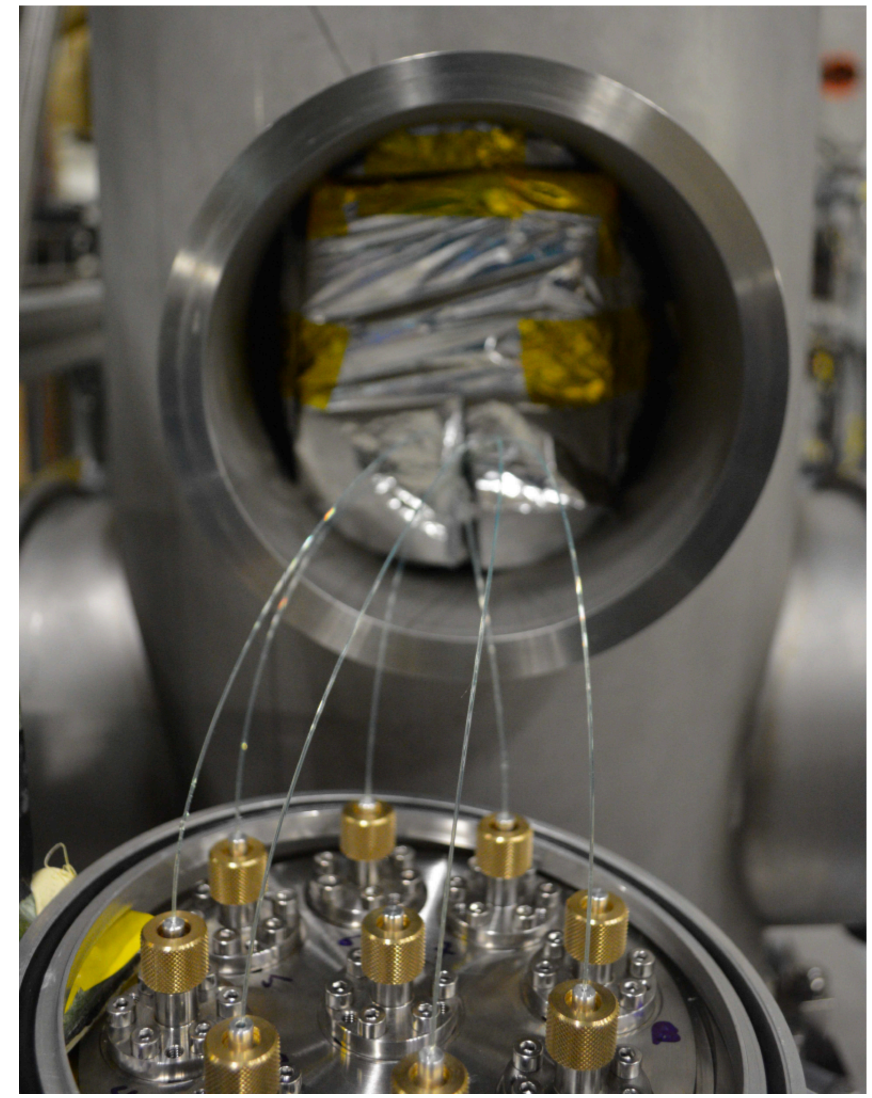
Experimental setup and results: 1st stage and 2 stage

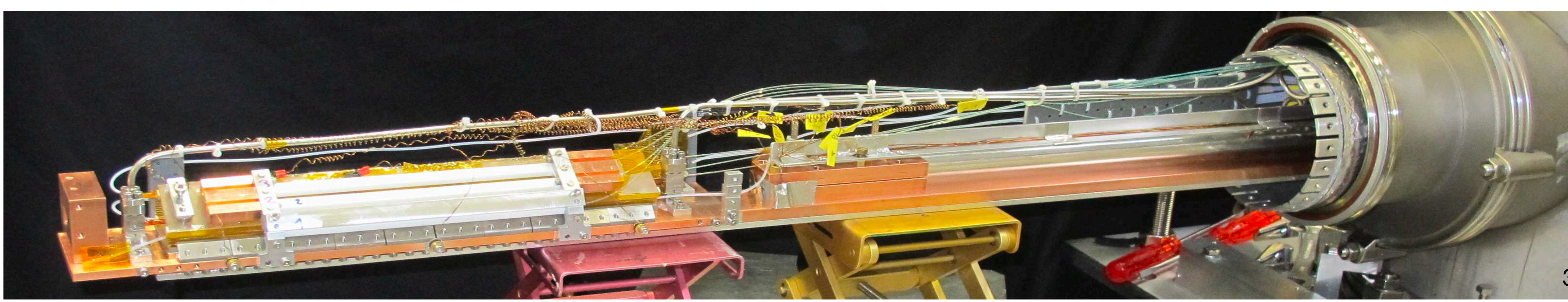
- Separately longitudinal and transverse compression: **PROVED**
- **Very good agreement between data and simulations**



Experimental setup and results: 1st stage

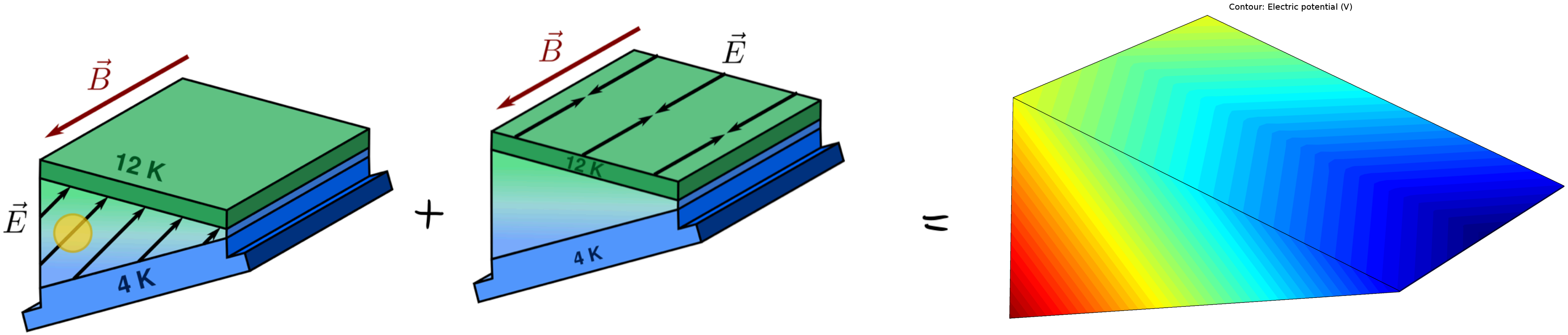


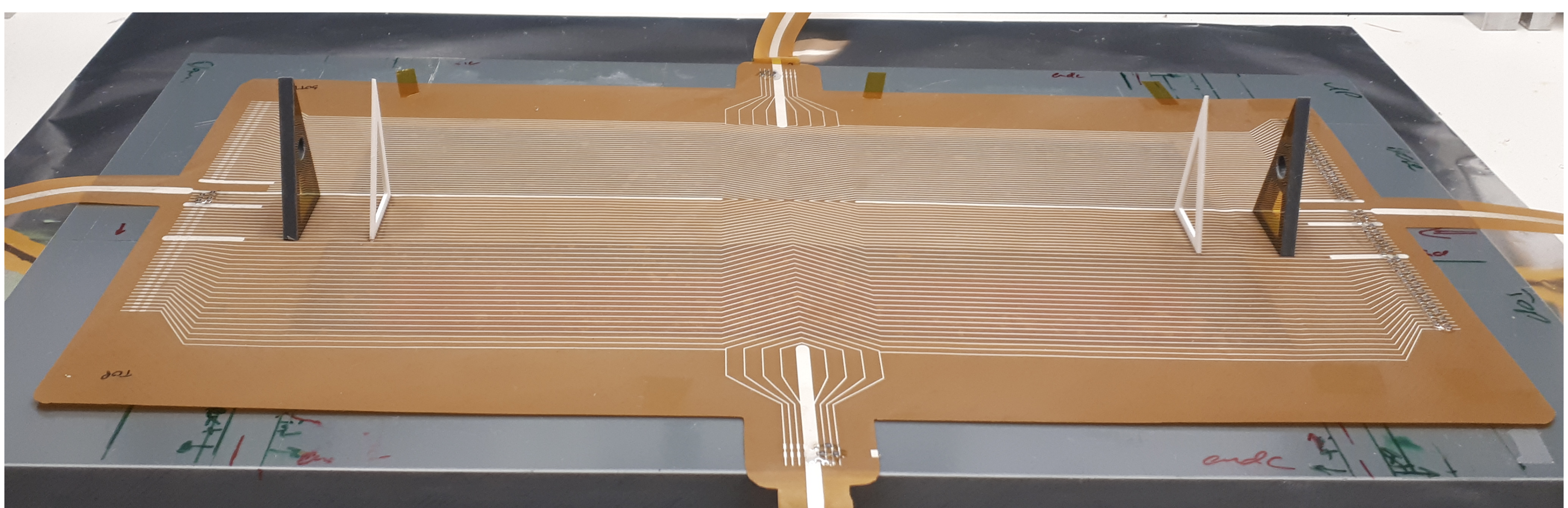




The muCool project at PSI: Status

- 1st stage + 2nd stage
- **Next Step**: Extraction into vacuum



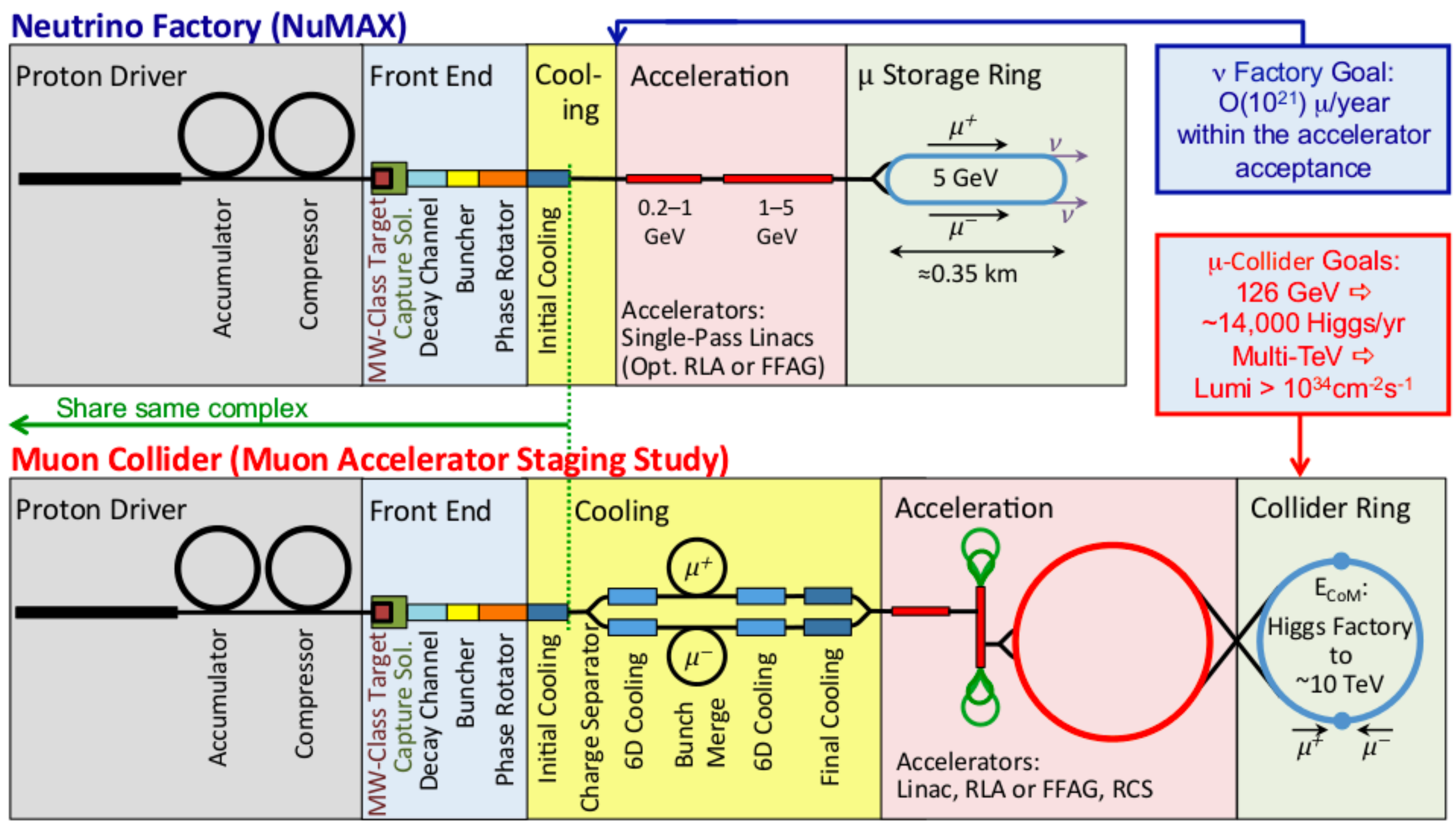


Outline

- The role of low energy precision physics
- The High Intensity Muon Beam project at PSI (HiMB)
- Towards High-Brigthness low energy muon beams (muCool)
- **Muon collider and Neutrino factory developments (in connection with low energy muon beam?)**

Muon Collider & Neutrino Factory (very short intro!)

- Neutrino factory is also a muon factory and viceversa
- In both facilities:
  - High power protons
  - Target → pions
  - Capture → **muons**
  - **Cooling**
  - Rapid acceleration
  - Storage ring

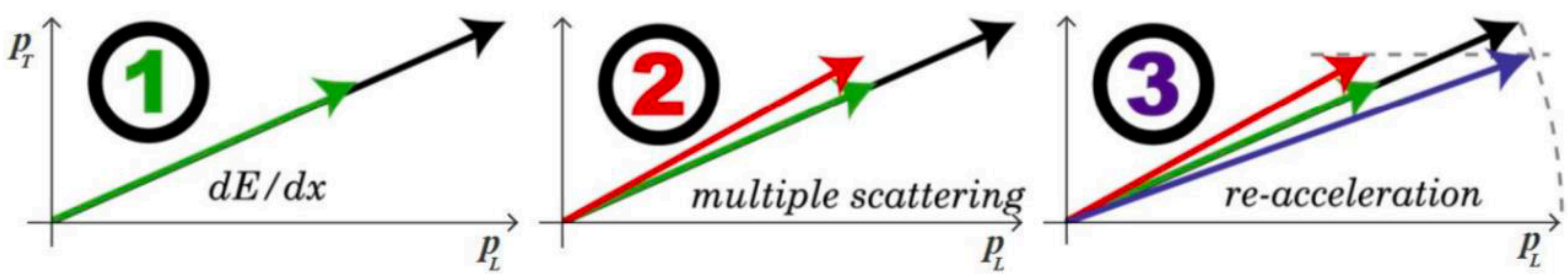


- **Challenges:**
  - Muon beam: **tertiary** (p→ π → μ) and **unstable** (muon life time ~ 2.2 μs)
    - Use high power proton driver
    - Use fast cooling (ionisation cooling → MICE)
    - Develop rapid accelerators

Credits: J. Pasternak, ICHEP2020

What is Muon Ionization cooling? (MICE)

- Energy loss in the absorbers reduces p_L and p_T
- Scattering **heats** the beam
- RF cavity restore p_L only
- The net effect is the reduction of the beam emittance: **cooling**
  - Strong focusing, low-Z absorber material and high RF cavity are required



$$\frac{d\epsilon_n}{ds} \sim -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp(0.014\mathrm{GeV})^2}{2E_\mu m_\mu L_R}$$

Cooling — Heating

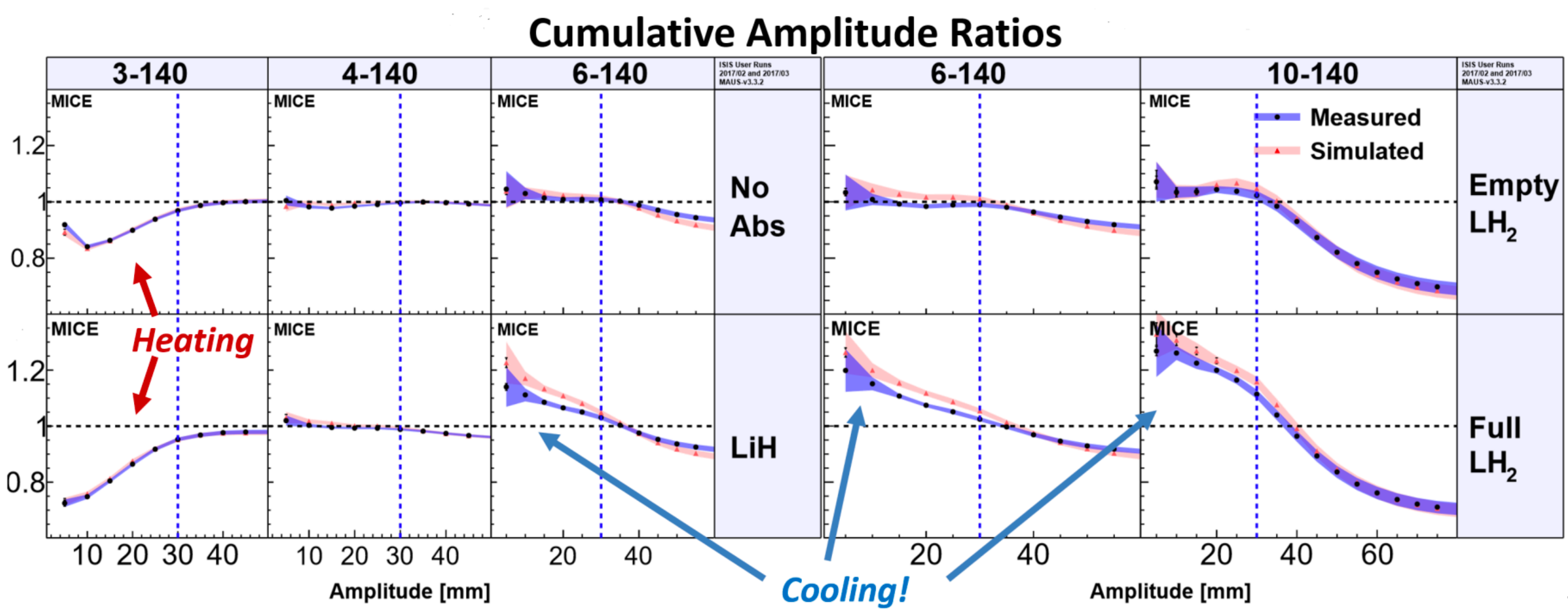
$d\varepsilon_n/ds$ is the rate of change of normalised-emittance within the absorber;
β, **E_μ** and **m_μ** the muon velocity, energy, and mass, respectively;
$\beta_\perp$ is the lattice betatron function at the absorber;
L_R is the radiation length of the absorber material.

Credits: J. Pasternak, ICHEP2020

Nature volume 578, pages 53–59 (2020)

MICE results

- Muon cooling is last “in principle” challenge for muon collider and neutrino factory R&D.
- MICE:
  - measured the underlying physics processes that govern cooling
  - made an unprecedented single particle measurement of the particle trajectories in an accelerator lattice
  - first observation of ionisation cooling

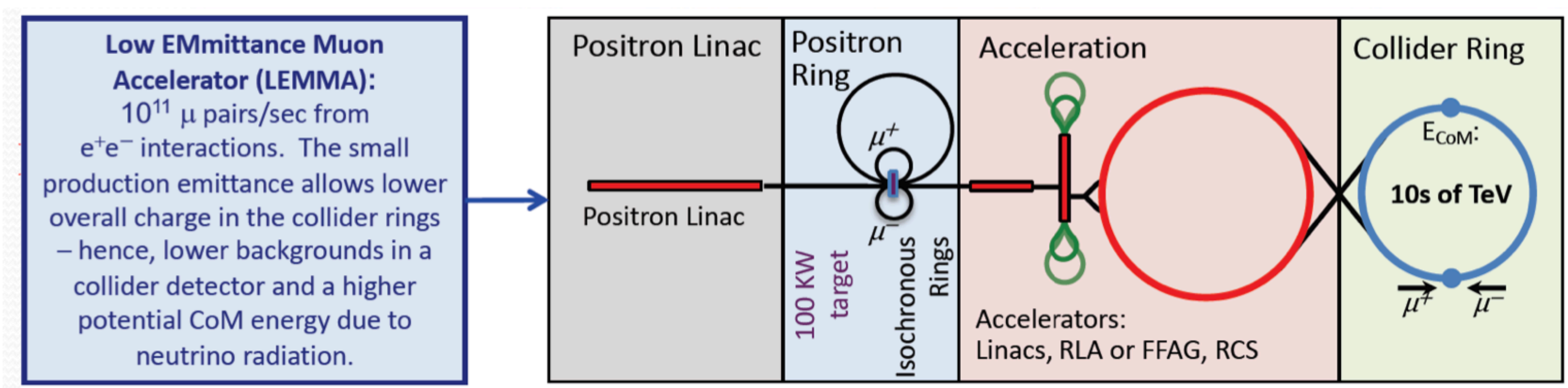


Credits: M. Boscolo, N. Pastrone, EPS-HEP2019

arXiv:1905.05747

LEMMA concept

- LEMMA: Low EMmittance Muon Accelerator
- Positron driver muon source
- Muons produced from $e^- e^+ \rightarrow \mu^- \mu^+$
  - 45 GeV positron beam impinging on a target (e^- at rest)
  - $\mu^- \mu^+$ produced @ ~22 GeV with low transverse emittance with $\gamma(\mu) \approx$ **200** and μ laboratory **lifetime** of about **500** μ**s**
  - Aimed at obtaining high luminosity with relatively small $\mu^\pm$ fluxes thus reducing background rates and activation problems due to high energy $\mu^\pm$ decays



Credits: D. Schulte, ICHEP2020

European Strategy

From the deliberation document of the European Strategy Update:

High-priority future initiatives
[..]In addition to the high field magnets the accelerator R&D roadmap could contain:

[..] an international design study for a muon collider, as it represents a unique opportunity to achieve a multi-TeV energy domain beyond the reach of e+e--colliders, and potentially within a more compact circular tunnel than for a hadron collider. The biggest challenge remains to produce an intense beam of cooled muons, **but novel ideas are being explored**;

For the European Strategy the Laboratory Directors Group (LDG) established a muon collider working group to provide input on the muon collider

- LDG represents: CERN, DESY, INFN, STFC, IRFU (CEA), CIEMAT, NIKHEF, LNGS, IJCLab(CNRS), PSI
- Proposed to the European Strategy Process to form an international collaboration to study the muon collider

Open questions - We have asked ourself about (discussion just started):

Can muCool&HiMB contribute on this program?
Can a low energy high-brightness negative muon beam be produced?
What about a muon collider/accelerator concept based on low energy high-brightness muon beams subsequently re-accelerated?

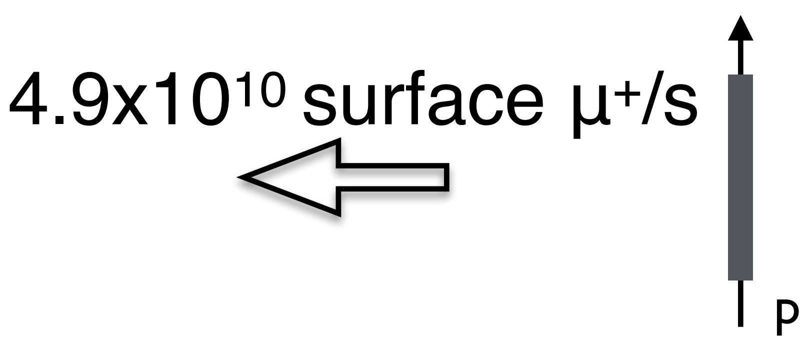
Outlook

- Precision physics is a very sensitive tool to explore and unveil new physics
- HiMB aims at surface high intensity muon beam **O(10^{10} muon/s)**
  - Initial simulations show that such rates are feasible; Target optimisation test: successfully done. Increase muon rate as expected. Beam optics and investigations on proton beam modifications underway
  - Put into perspective the target optimisation only, corresponding to **50%** of muon beam intensity gain, would corresponds to effectively raising the proton beam power at PSI by **650 kW**, equivalent to a beam power of almost **2 MW.** If the same exercise is repeated put into perspective the beam line optimisation the equivalent beam power would be of the order of **several tens of MW**
- muCool aims at low energy high-brightness muon beam
  - Increase in brightness by a factor **10^{10}** with an efficiency of **10^{-3}**
  - First two stages demonstrated independently. Measurements and simulations agree. Current development: combining two stages and extraction into the vacuum
- Future accelerator concepts based on muons are part of the European Strategy recommendations
- Ongoing efforts (Muon collider&Neutrino Factory&New Ideas) open the doors for high energy muon accelerators as a probe of fundamental physics

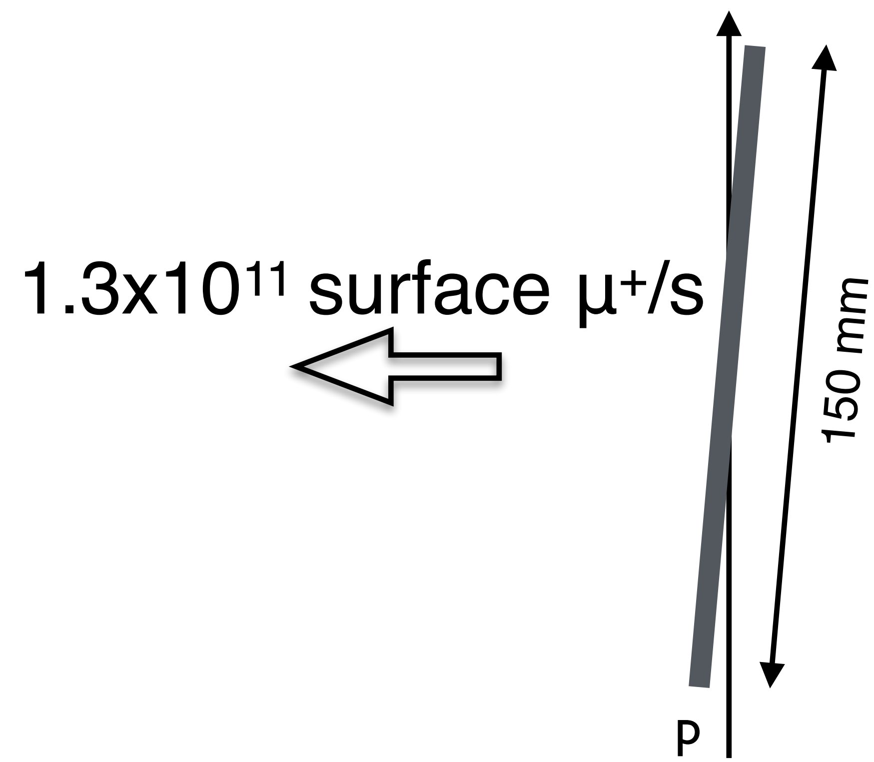
IPA ETH zürich PAUL SCHERRER INSTITUT PSI

Target geometry for new target M*

- Change current 5 mm TgM for 20 mm TgM*
- 20 mm rotated slab target as efficient as Target E



20 mm target

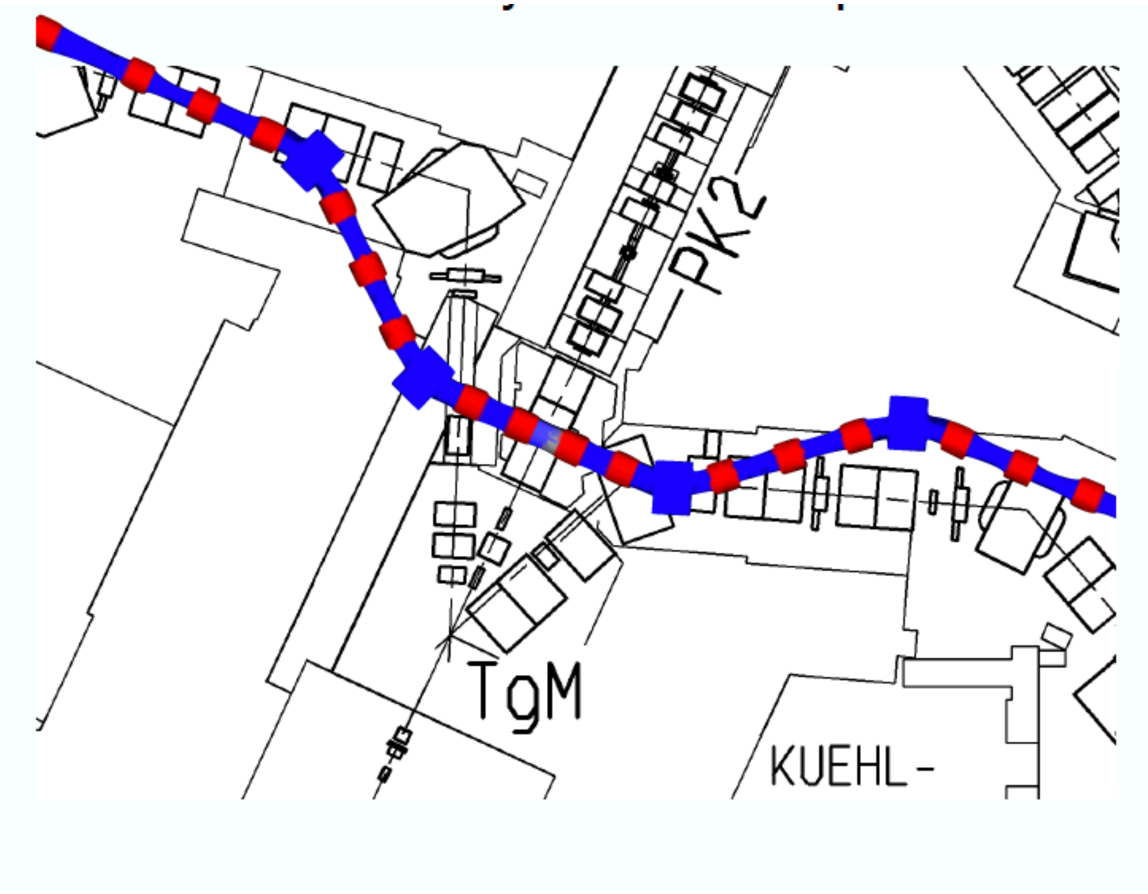


20 mm effective length
5° rotated slab

ToDo

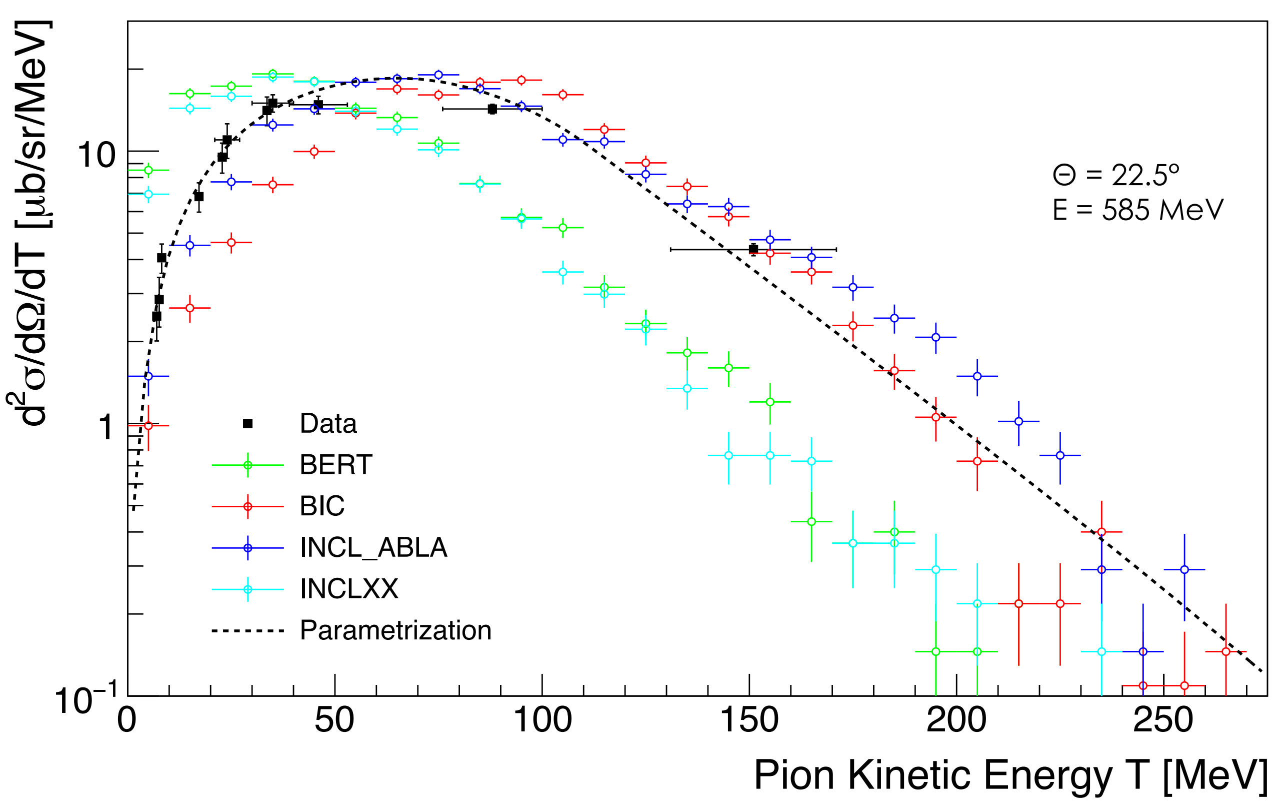
- Optimization of capturing
- Optimize final focussing
- Iterative Beam line optimization and implementation of beam monitoring and particle separator locations with max. transmission
- Minimize shielding modifications
- Particle separation
- Investigate impact on proton beam properties
- Study extraction angle
- Determine new target location
- Disposal of highly radioactive waste
- Study Mu3e setup phase space acceptance and optimize final focus properties
- Find solution with current users of Target M

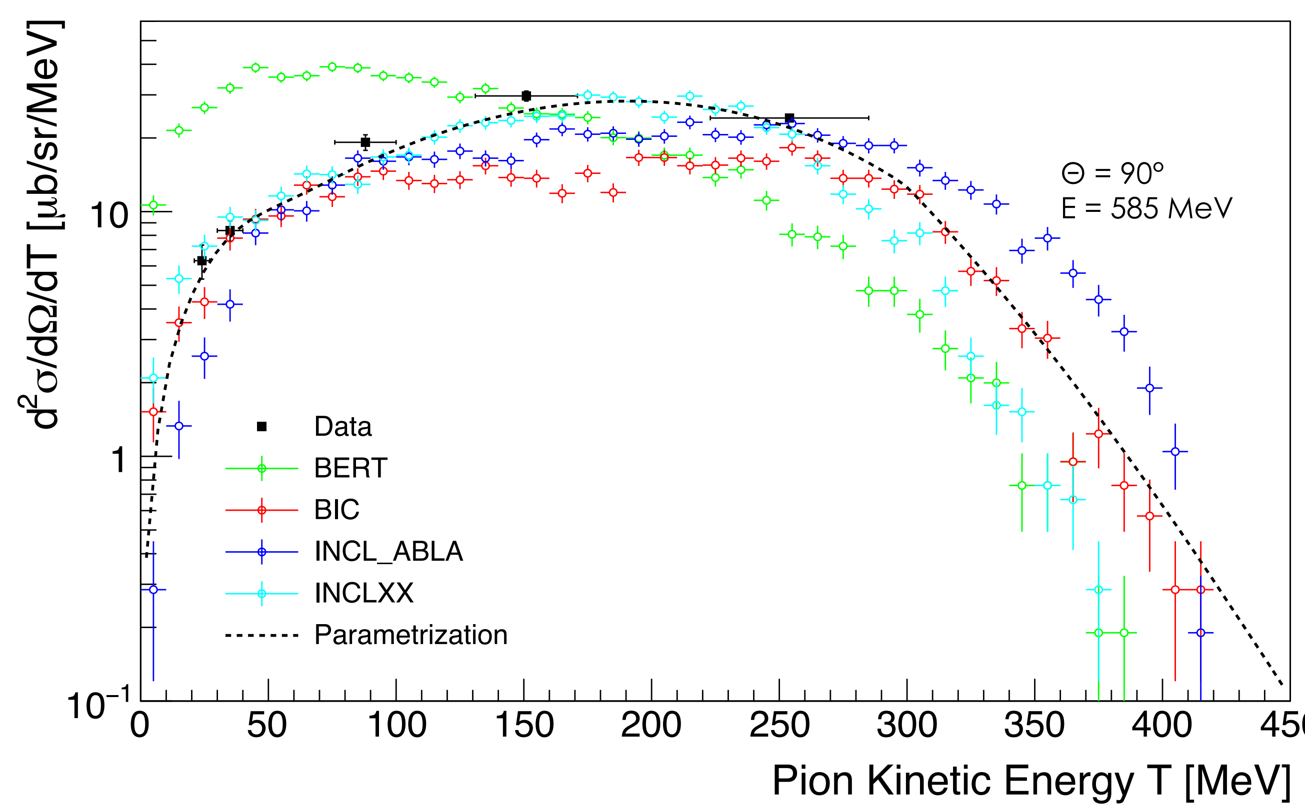
Schematic of the layout in the experimental hall



HiMB Simulation

- Geant4 pion production cross sections not optimised for low energies
- Implemented our own pion production cross section into Geant4/G4beamline based on measured data and two available parametrizations (**HiMB model**)
- Valid for all pion energies, proton energies < 1000 MeV, all angles and all materials
- Reliable results at 10% level

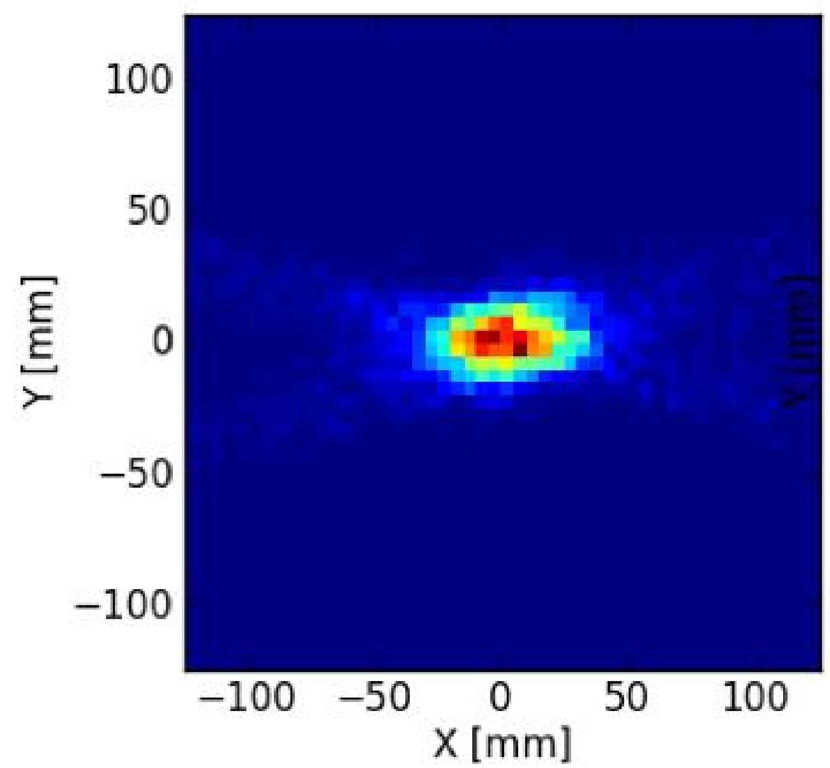


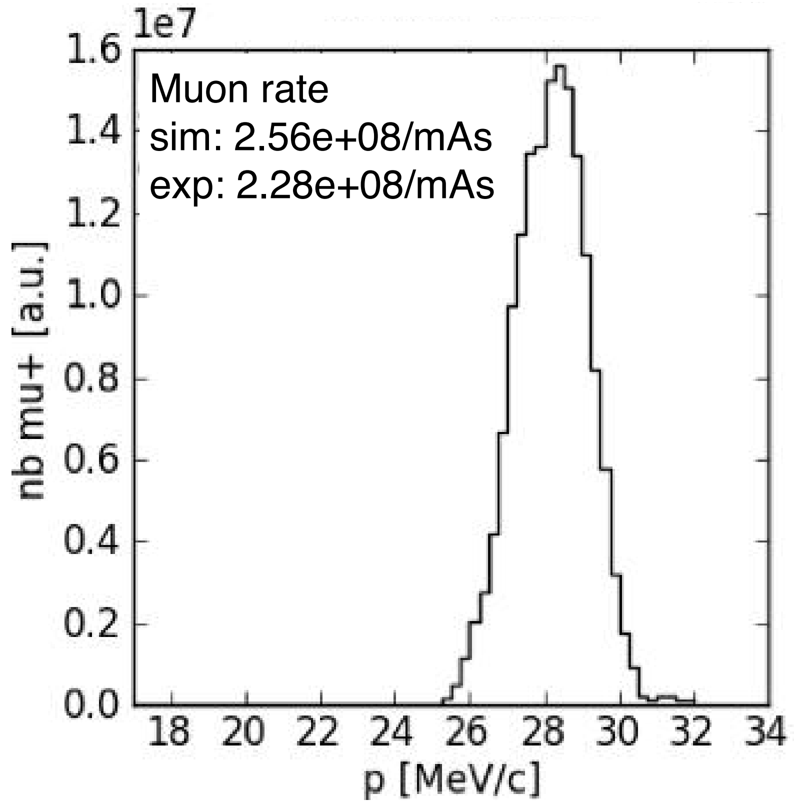


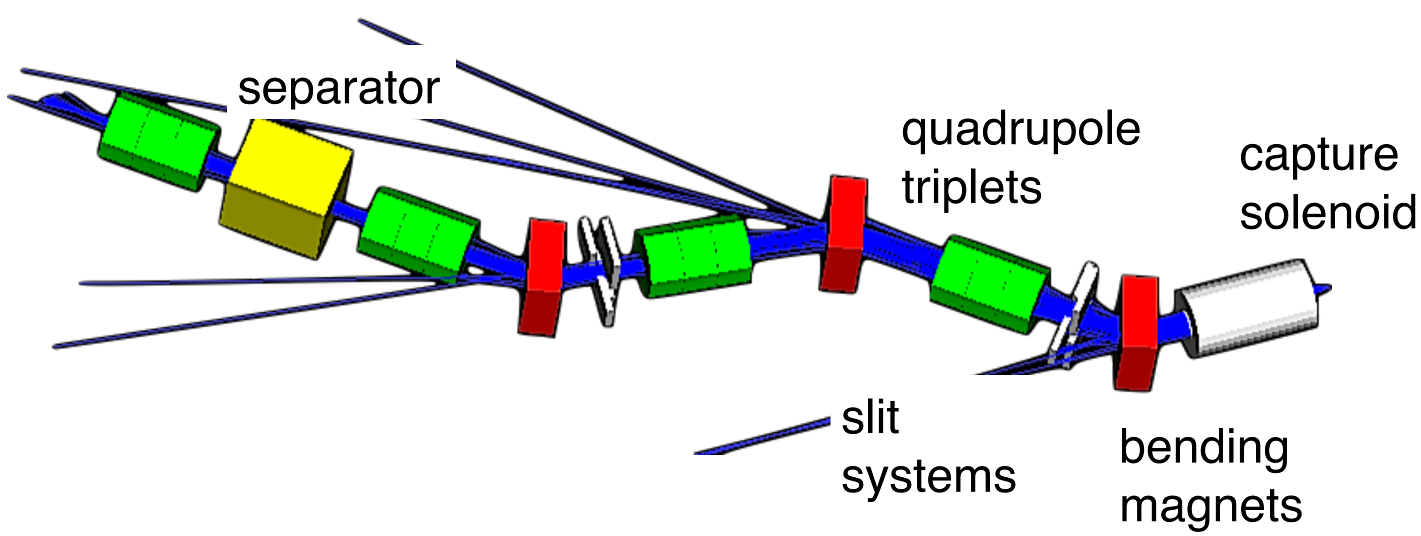
R. L. Burman and E. S. Smith, Los Alamos Tech. Report LA-11502-MS (1989)
R. Frosch, J. Löffler, and C. WIgger, PSI Tech. Report TM-11-92-01 (1992)
F. Berg et al., Phys. Rev. Accel. Beams **19**, 024701 (2016)

HiMB model validation

- Full simulation of μE4 and piE5 beam lines starting from proton beam
- Detailed field maps available for all elements
- Very good agreement between simulation and measurements







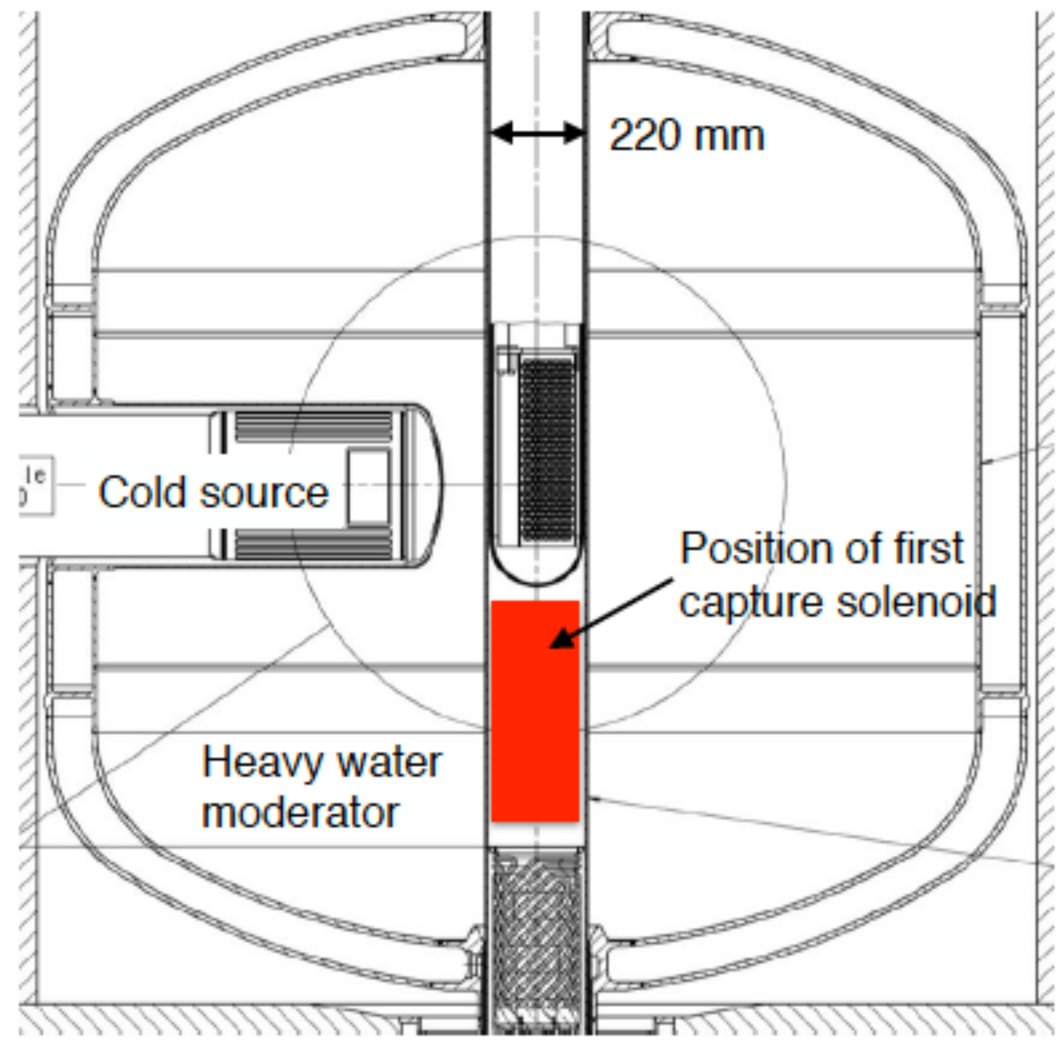
Initial HiMB concept: @SINQ

- Source simulation (below safety window):
  9×10^{10} surface-μ^+/s @ 1.7 mA I_p
- Profit from stopping of full beam
- Residual proton beam (~1 MW) dumped on SINQ

- Replace existing quadrupoles with solenoids:
  - Preserve proton beam footprint
  - Capture backward travelling surface muons
- Extract muons in Dipole fringe field
- Backward travelling pions stopped in beam window

- Capturing turned out to be difficult :
  - Large phase space (divergence & ‘source‘ extent)
  - Capture solenoid aperture needed to be increased, but constrained by moderator tank
- High radiation level close to target

- Due these constraints and after several iterations with different capturing elements:
  - **Not enough captures muons to make an high intensity beam**
  - **Alternative solution: HiMB @ EH**



Optimization of standard production targets

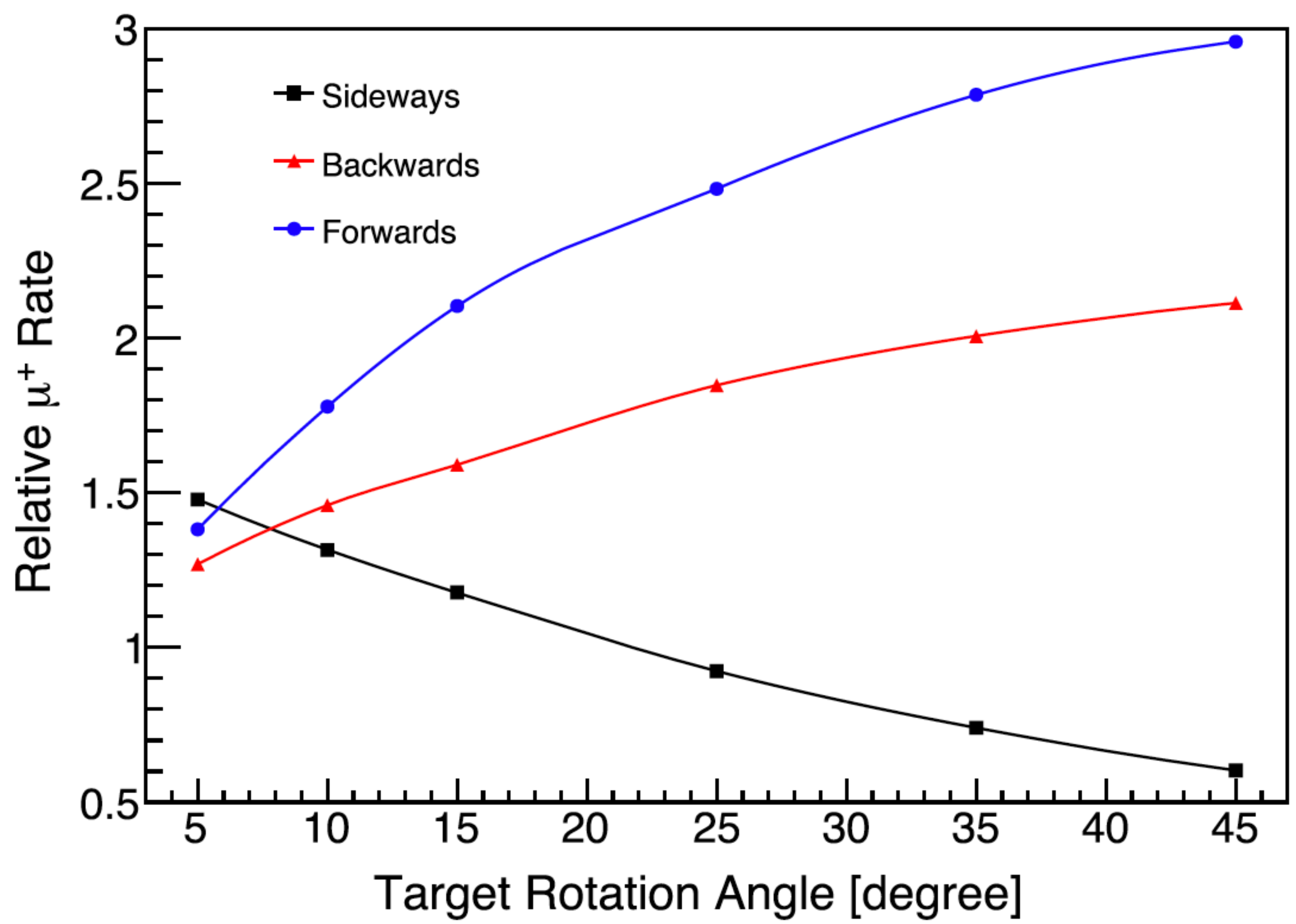
- Strategy: either increasing the surface volume (surface area times acceptance depth) or the pion stop density near the surface
  - **Target geometry**
    - Comparison studies of different target geometries: **TgE for different lengths**

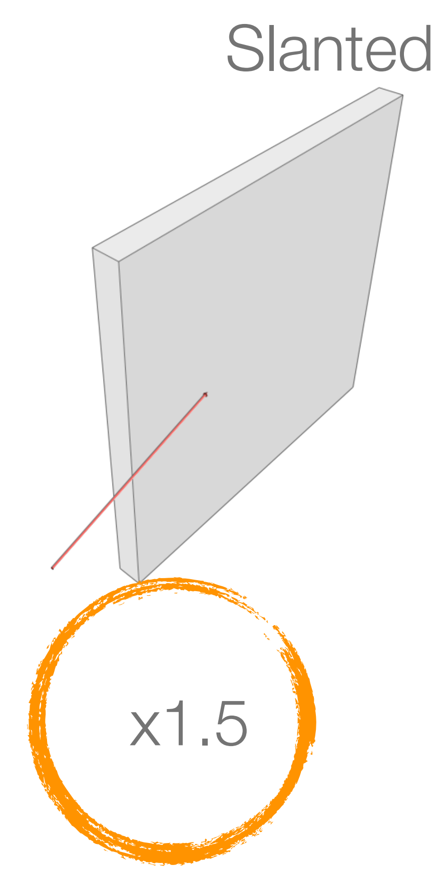
Surface muon rate

Length [mm]	Upstream	Downstream	Side
10	1.4×10^{10}	9.0×10^{9}	1.8×10^{10}
20	1.6×10^{10}	1.2×10^{10}	5.1×10^{10}
30	1.9×10^{10}	1.1×10^{10}	8.5×10^{10}
40	1.8×10^{10}	1.1×10^{10}	1.2×10^{11}
60	1.8×10^{10}	1.2×10^{10}	2.1×10^{11}

Optimization of standard production targets

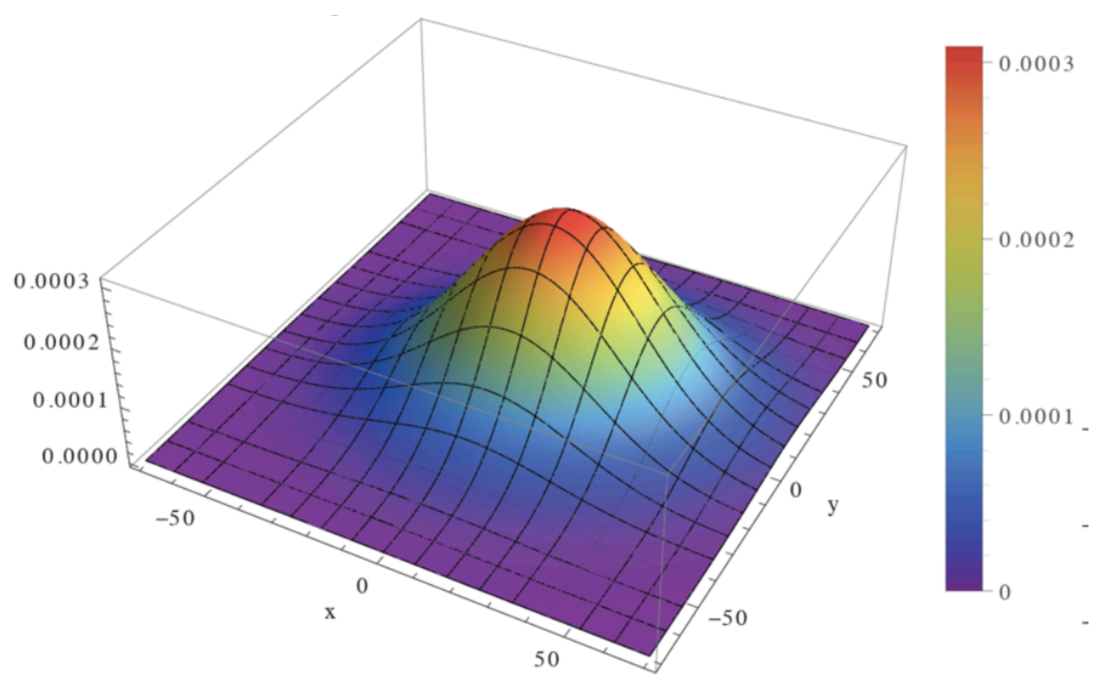
- Strategy: either increasing the surface volume (surface area times acceptance depth) or the pion stop density near the surface
  - **Target geometry**
    - Comparison studies of different target geometries: **Different rotation angles**
    - Enhancements normalised to standard target

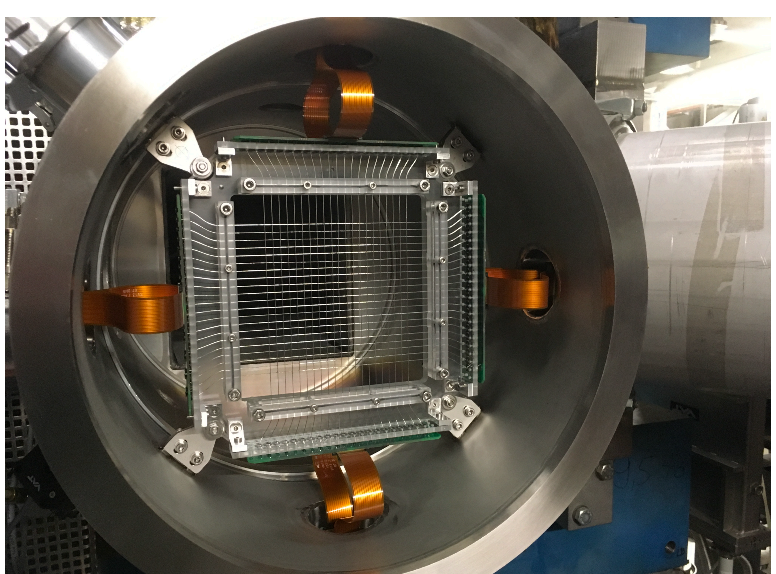


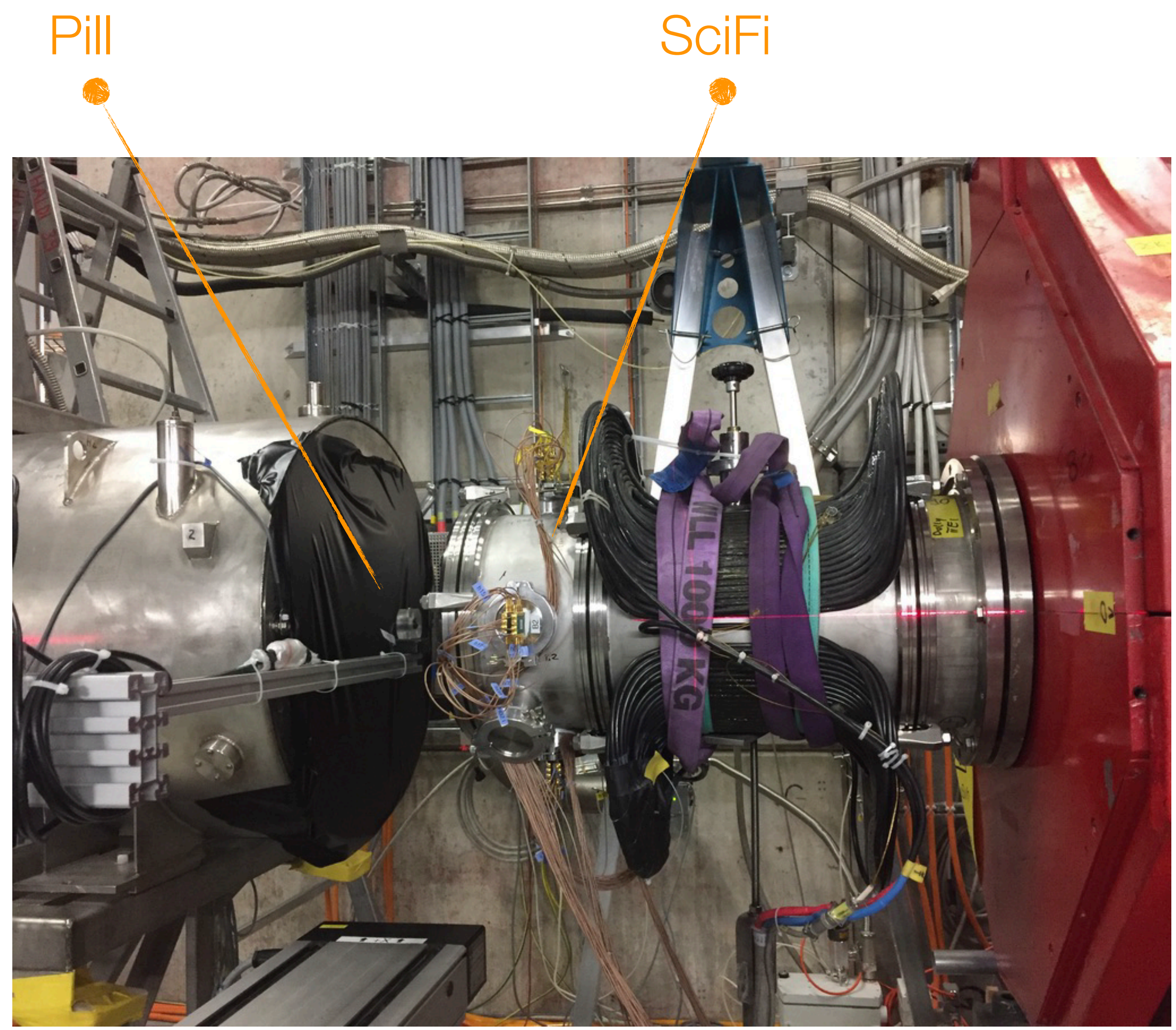


Slanted target: 2019 test Results

- Two independent detectors
  - SciFi: 0.5x0.5 mm2 scintillating fibers coupled to SiPMs to form a grid
  - Pill: (diam.) 2 mm x (length) 2 mm scintillator coupled to Hamamatsu R9880U-110 photomultiplier



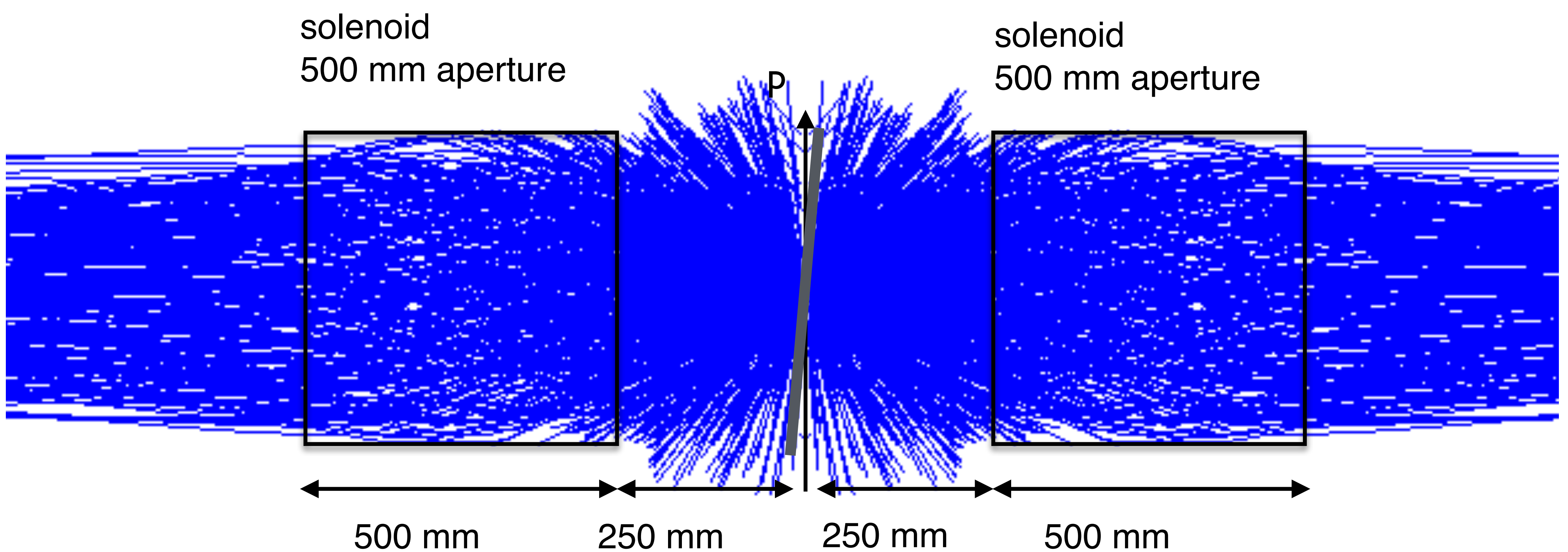




Split capture solenoids

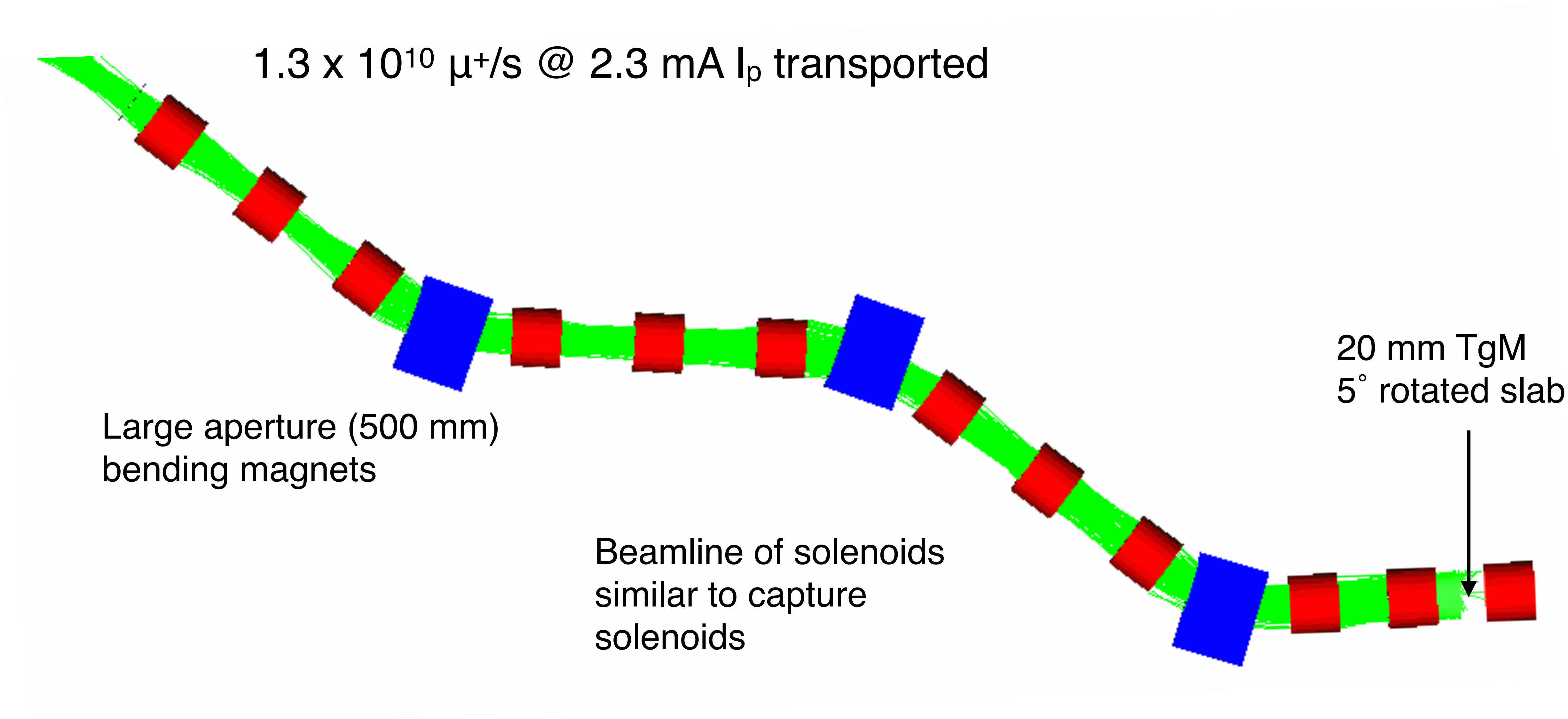
- Two normal-conducting, radiation-hard solenoids close to target to capture surface muons

- Central field of solenoids ~0.35 T
- Field at target ~0.1 T



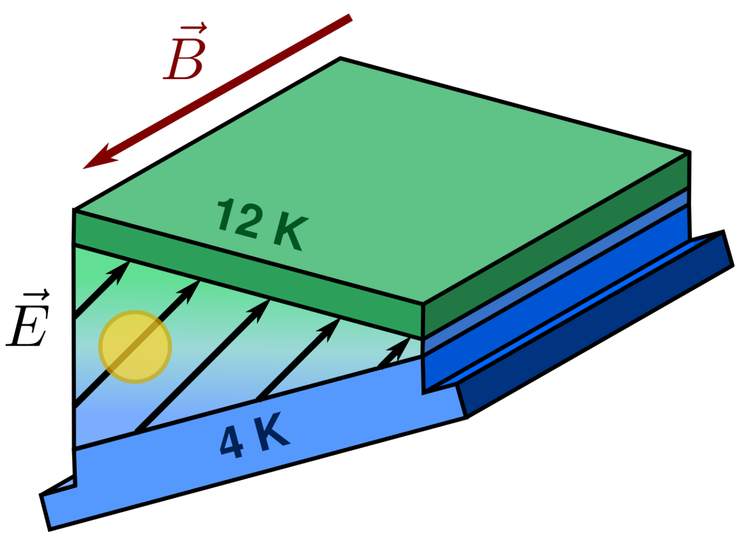
Solenoid beam line

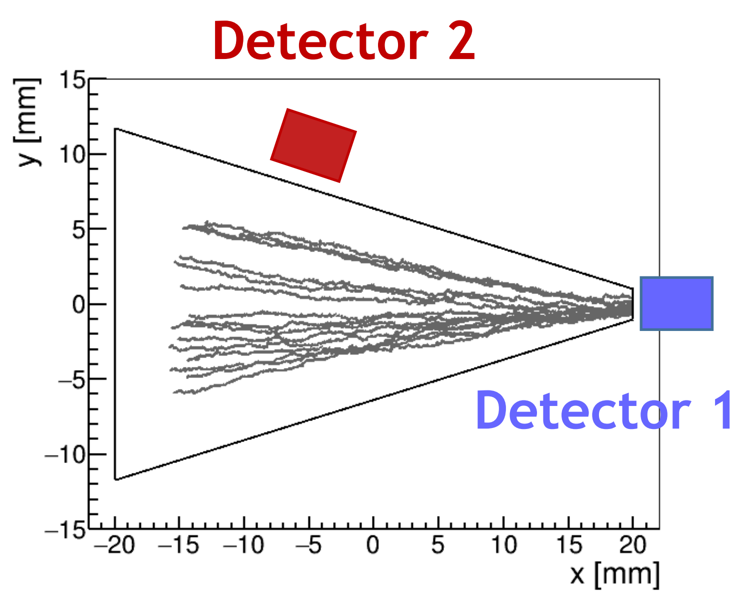
- First version of beam optics showing that large number of muons can be transported.
- Almost parallel beam, no focus, no separator, …
- Final beam optics under development

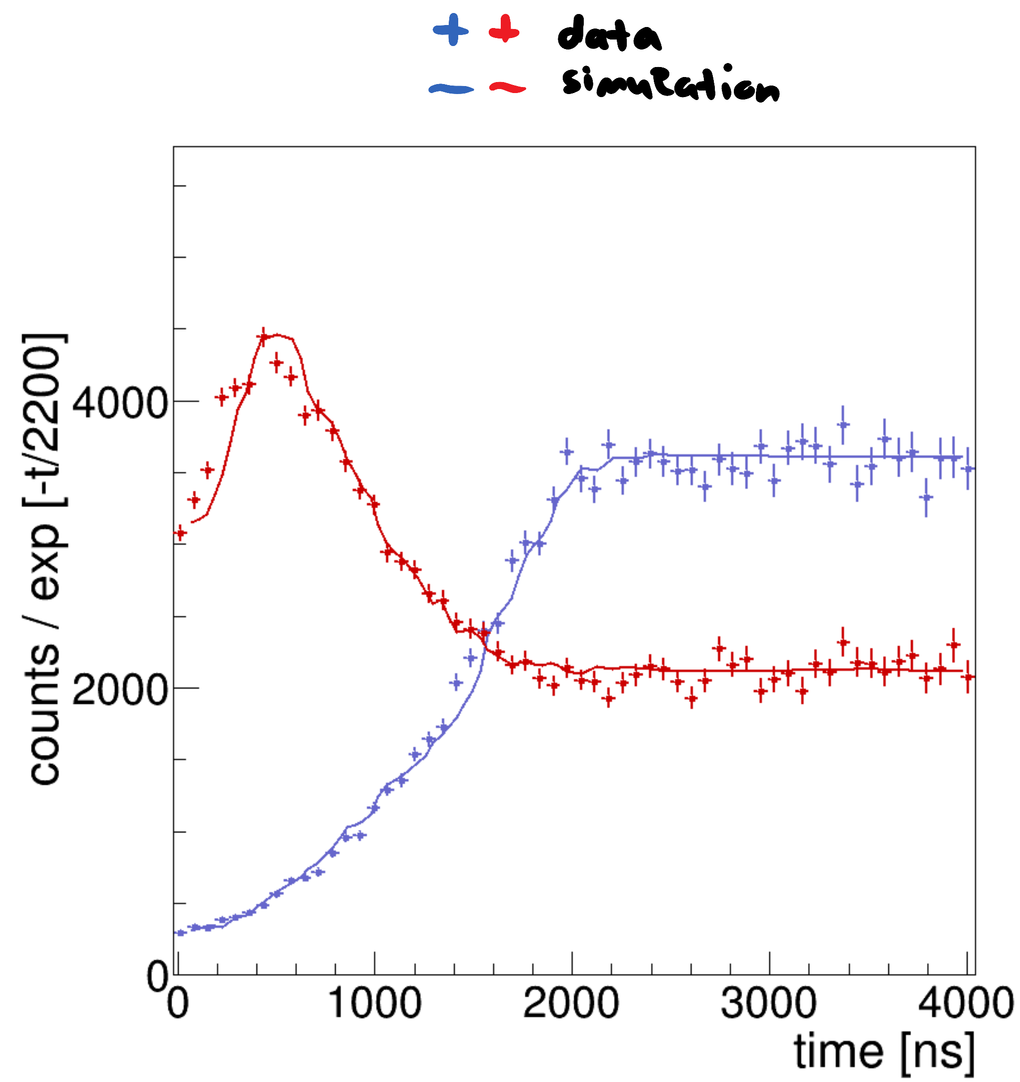


Experimental setup and results: 1st stage

- Separately longitudinal and transverse compression: **PROVED**
- **Very good agreement between data and simulations**

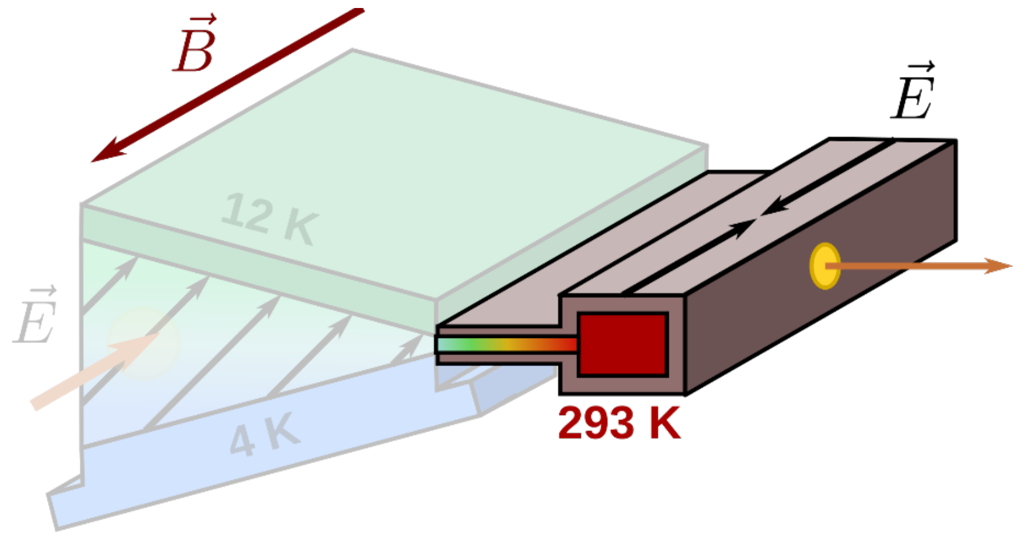


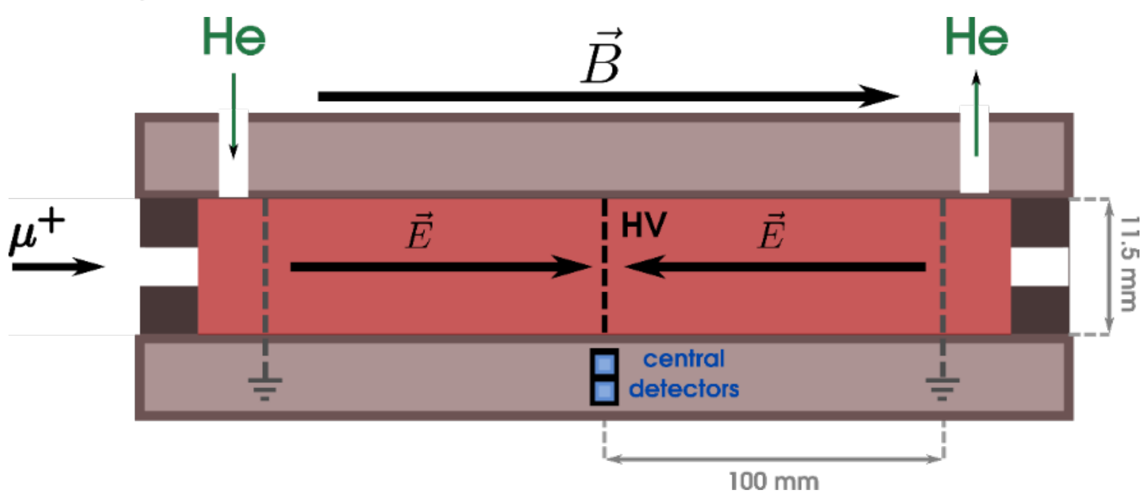


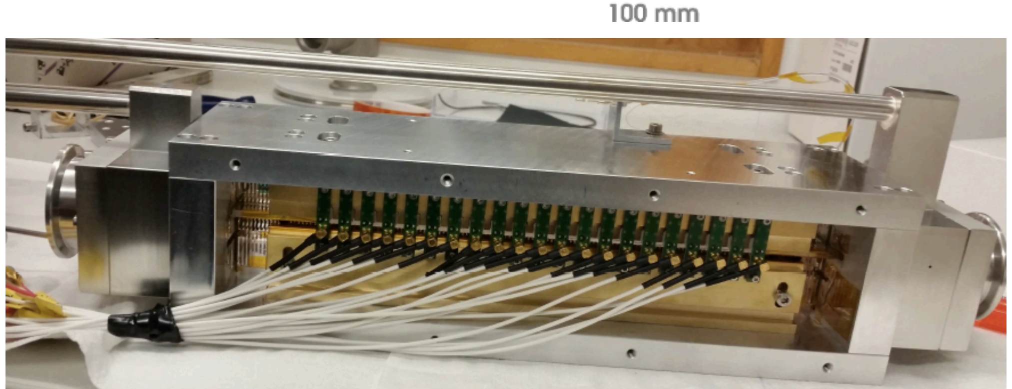


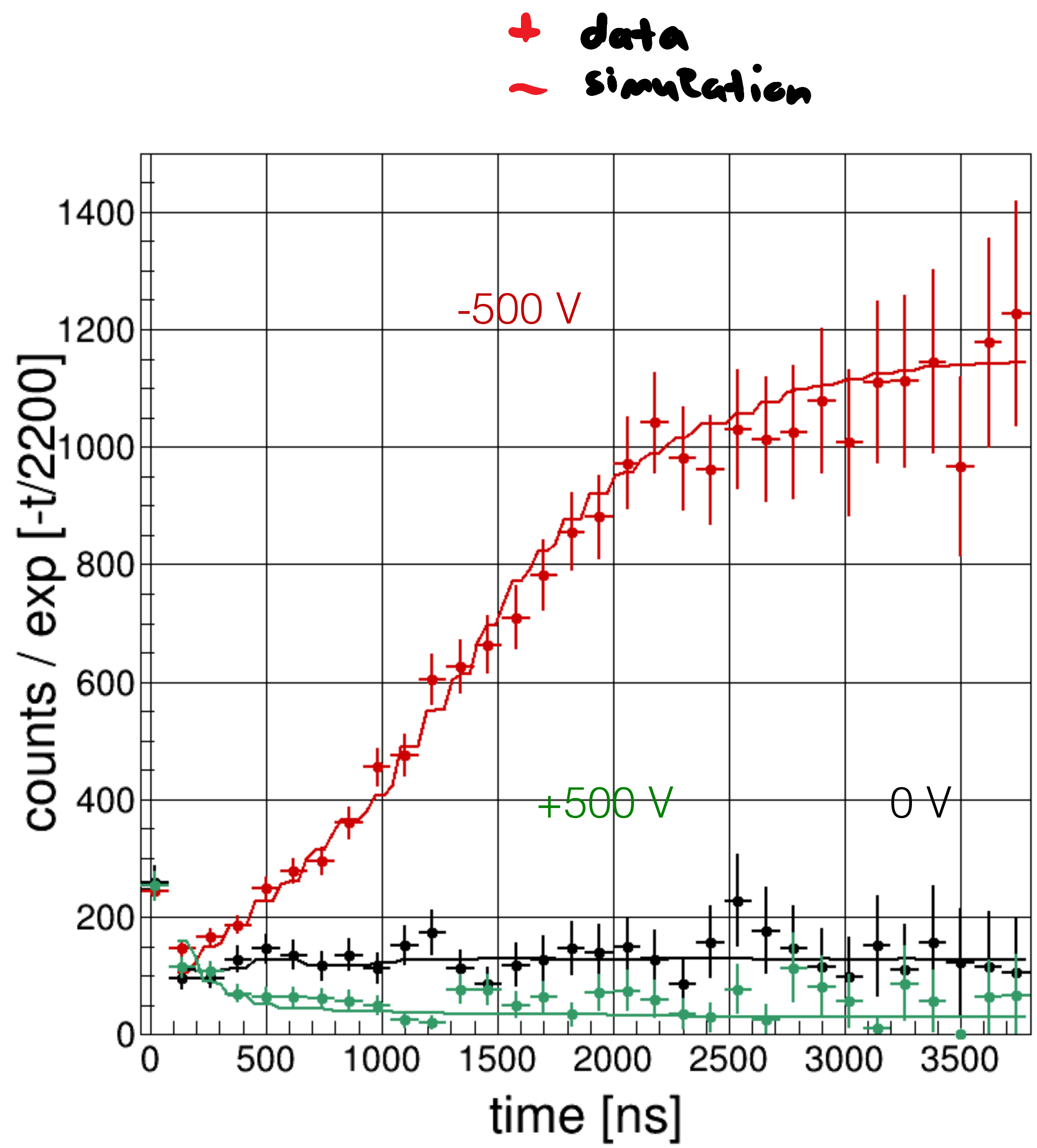
Experimental setup and results: 2nd stage

- Separately longitudinal and transverse compression: **PROVED**
- **Very good agreement between data and simulations**



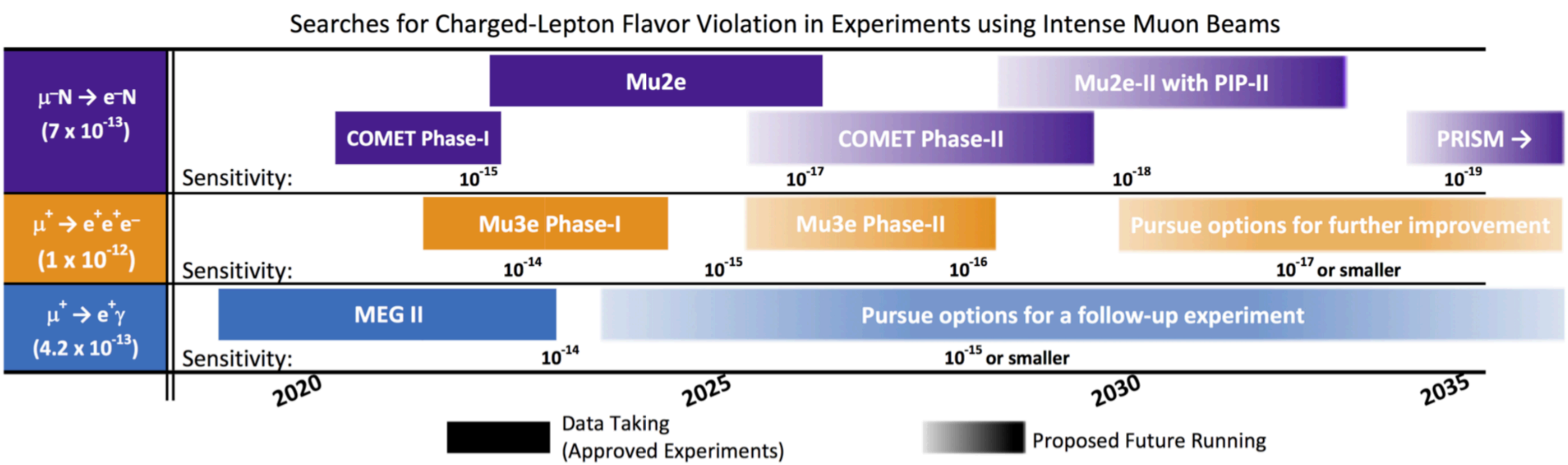






Final remarks

- Astonishing sensitivities in muon cLFV channels are foreseen for the incoming future
- **cLFV remains one of the most exciting place where to search for new physics**
- Submitted inputs to the European Strategy Committee

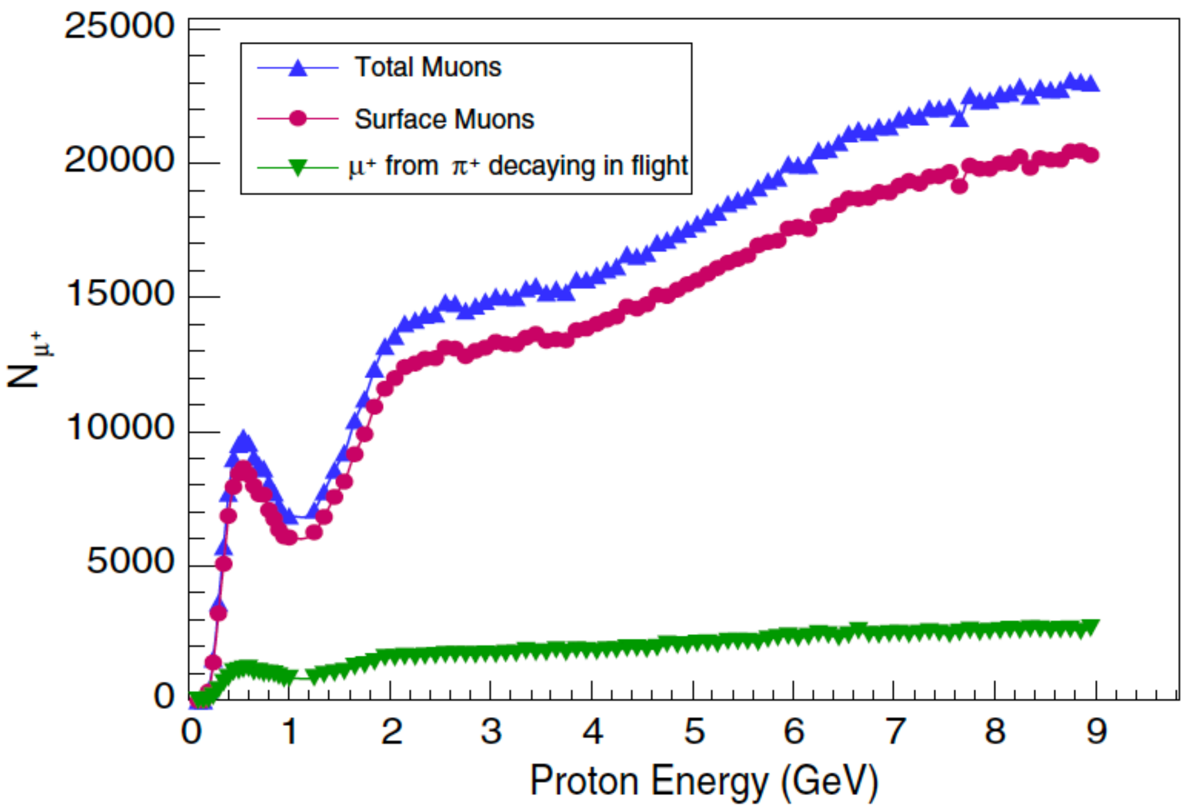


Thanks for your attention!

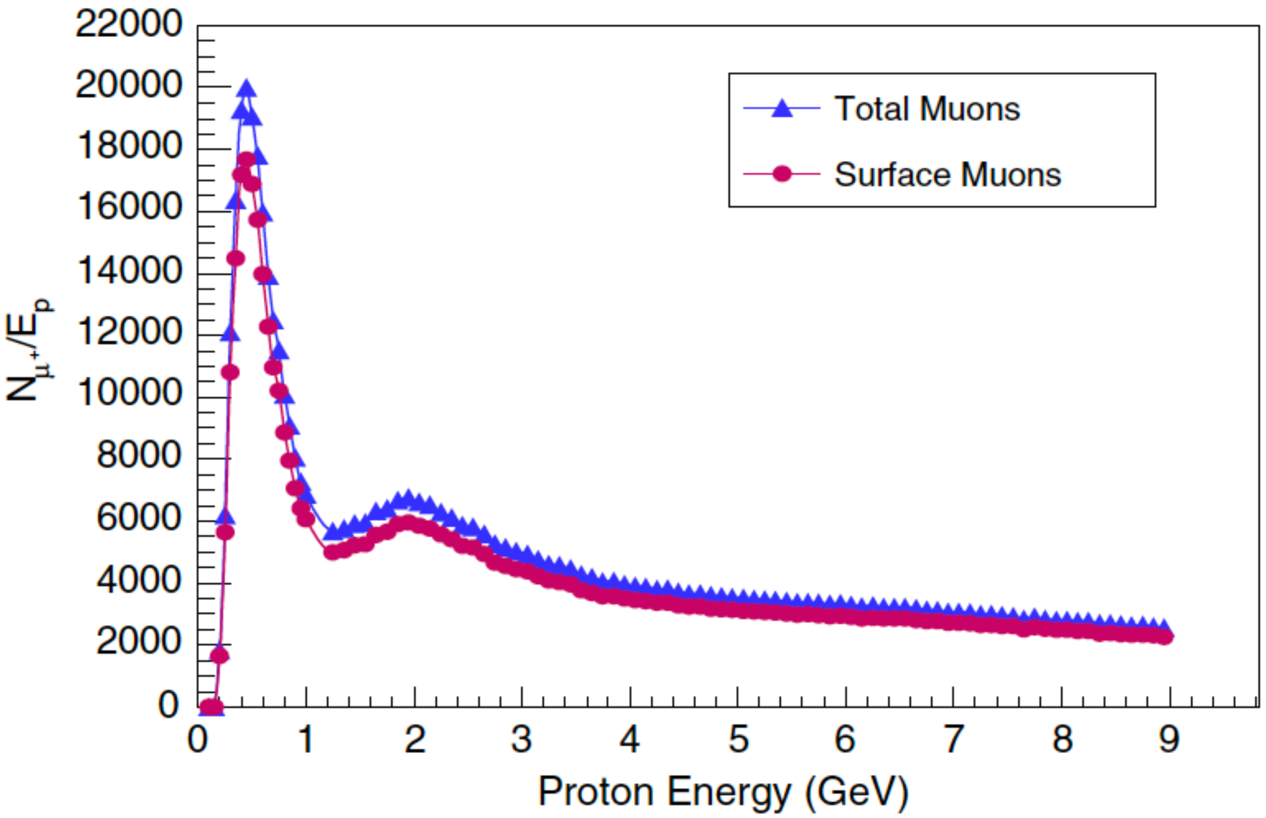
Optimal surface muon production

- **BUNGAU** et al., Phys. Rev. ST Accel. BEAMS **16**, 014701 (2013)
- Target: graphite
- Simulation validation: ISIS data
- For standalone muon facility: 500 MeV proton energy is the optimal energy

Variation of muon yield with proton energy at higher energies



Normalization of the muon yield to the proton energy



Muon production via pion decay

- Single pion production at 290 MeV proton energy (LAB)
- Low-energy muon beam lines typically tuned to surface-μ^+ at ~ 28 MeV/c
- Note: surface -μ —> polarized positively charged muons (spin antiparallel to the momentum)
- Contribution from cloud muons at similar momentum about 100x smaller
- Negative muons only available as cloud muons