Reinventing Muon Decay Channels, June 3 2021

Syd Kreitzman

What's coming down the beam pipe:

- Muon decay channels and TRIUMF's M9H:

- Finding Waldo (*viz* $\vec{P}_\mu \cdot \vec{p}_\mu = 0$) in $\pi \rightarrow \mu + \nu_\mu$:

  One might viscerally avoid (V-A); $M =< 0|J_V^\alpha + J_A^\alpha|\pi > [\overline{u}_\mu \gamma_\alpha (1-\gamma_5) u_\nu] = F(q^2) m_\mu [\overline{u}_\mu (1-\gamma_5) u_\nu]$

  and hence not find that $\vec{P}_\mu \cdot \vec{p}_\mu \propto \vec{P}_L = \eta \frac{1}{m_\mu p_0}\left[E_\mu p_\pi \cos\theta_{\pi\mu} - E_\pi p_\mu\right]\vec{n}_\mu$

  and therefore not realize if $\vec{P}_L = 0$ there is a unique $cos\theta_{\pi\mu}$

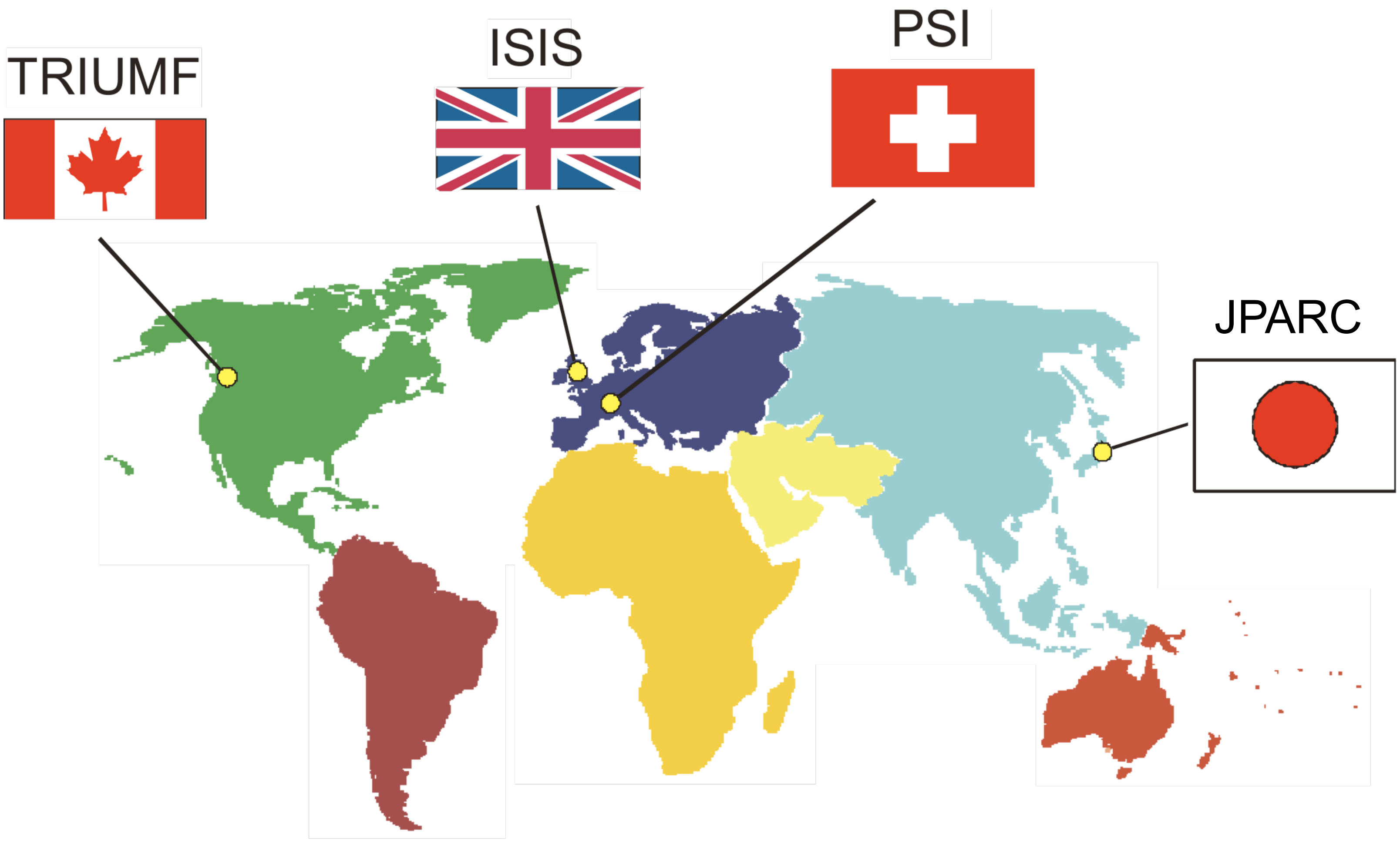
  so the fact that $\vec{P}_\mu \cdot \vec{p}_\mu$ is conserved in a solenoid didn't seem so important, **but it is!**

- Extracting the transverse polarization … a lopsided affair.

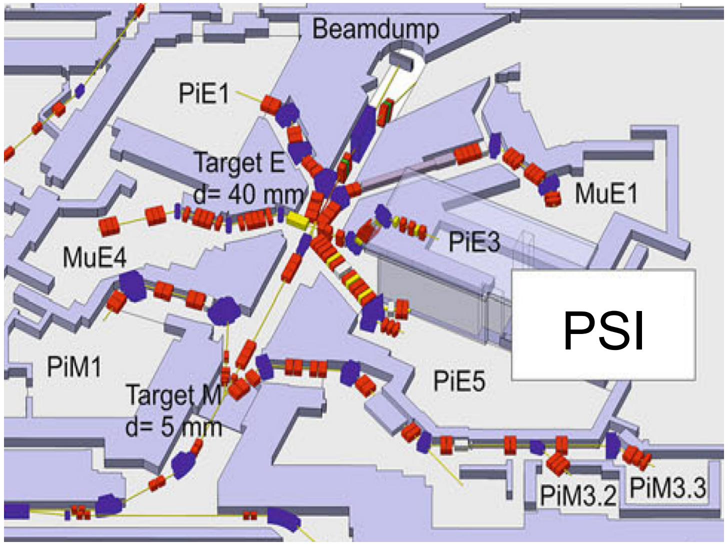
- Tuning a muon beamline … the tail should wag the dog.

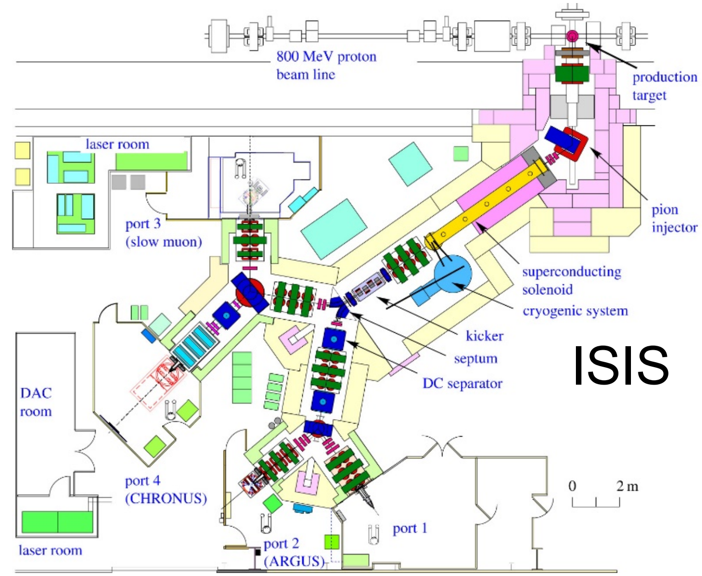
- A new science enabler:
  - Muon high TF spectroscopy in pressure controlled quantum phases
  - Efficient spin rotated ZF in contained environments
  - TF mu-SR and its corollaries

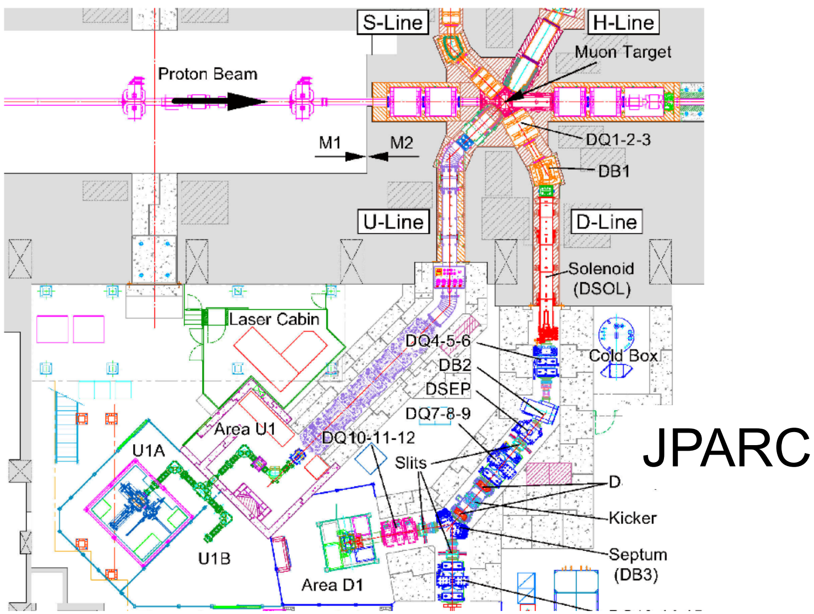
Muon Decay Channels around the World

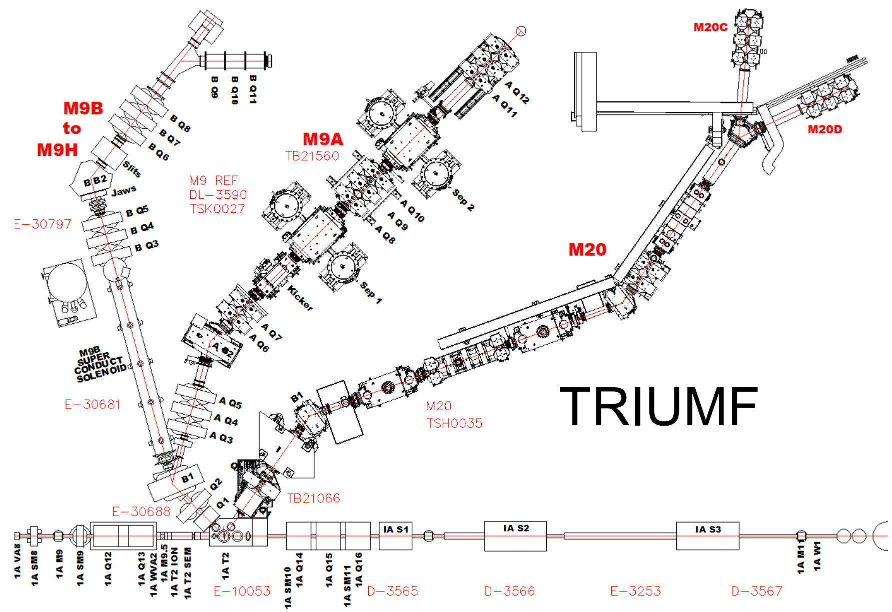


Muon Decay Channel Configurations









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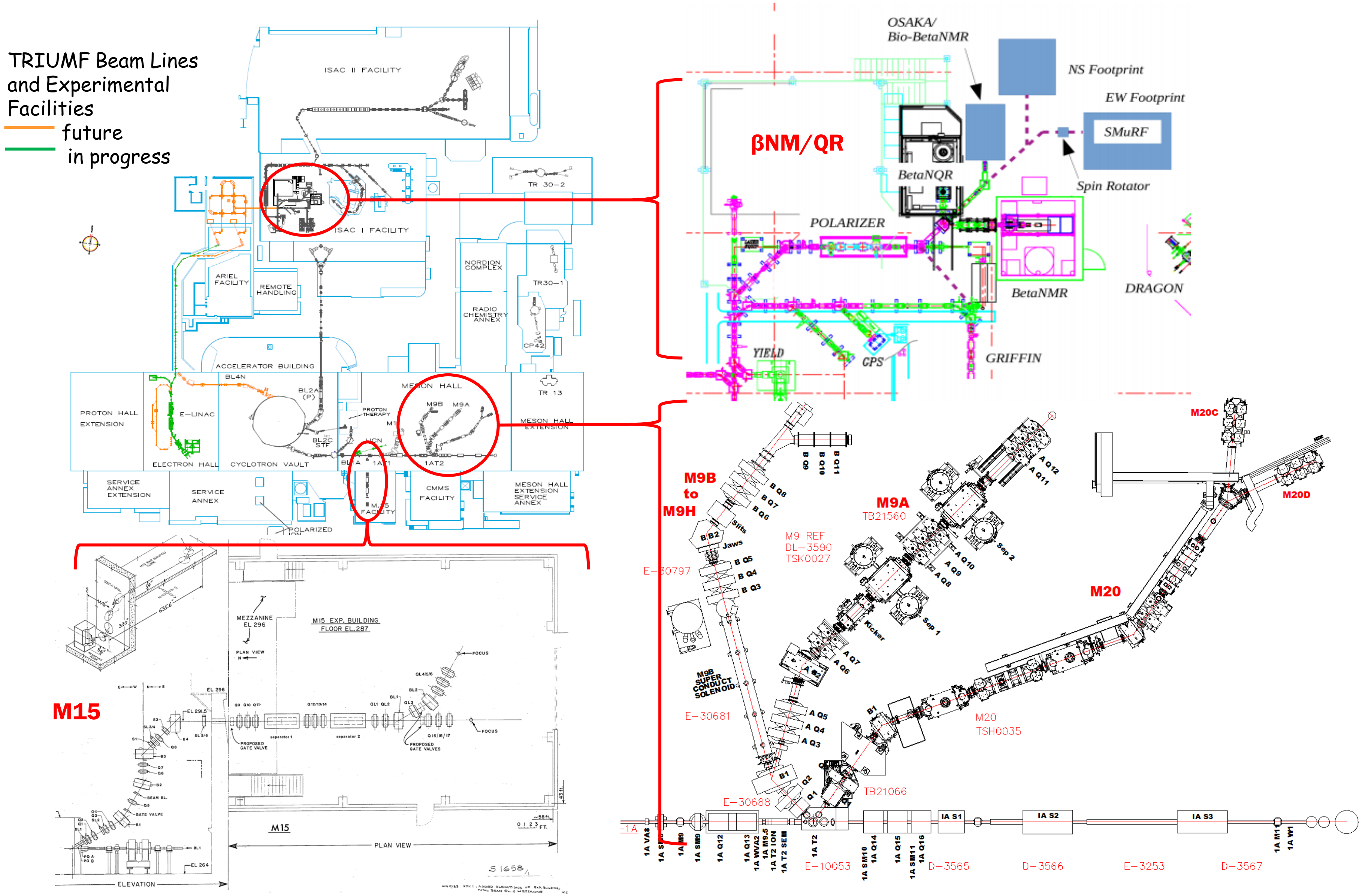
CMMS facilities (current & future?) within TRIUMF



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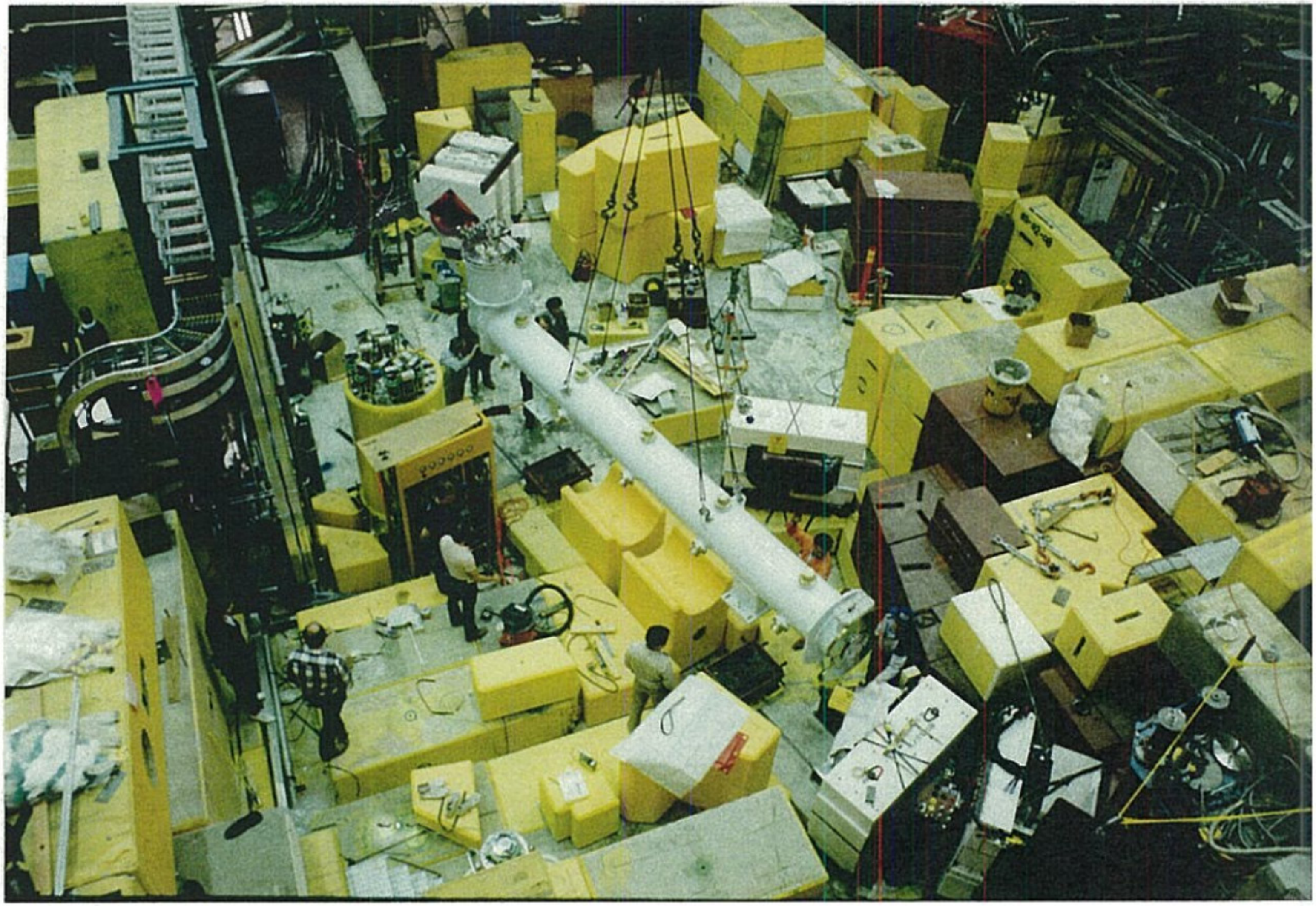
An Historical Perspective:



The M9B solenoid on its way in, circa 1986 … or, on its way out in 2022

The Project Community:

INNOVATION.CA
CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION

BC Knowledge Development Fund

Ontario Research Fund

Économie, Science et Innovation Québec

TRIUMF

SFU SIMON FRASER UNIVERSITY

UBC

McMaster University

Université de Montréal

Mount Allison UNIVERSITY

- PI: Jeff Sonier SFU (CFI lead)
- Co-applicants:

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○ Jess Brewer	UBC
○ Don Fleming	UBC
○ Khashayar Ghandi	Mt. Allison
○ Robert Kiefl	UBC
○ Graeme Luke	McMaster
○ William MacFarlane	UBC
○ Paul Percival	SFU
○ Jeffery Quilliam	U. Sherbrooke

TRIUMF

Project Leader: Syd Kreitzman

Project Sponsor: Jens Dilling

Project Engineer: Mahdiar Khosravi

Scientists: B. Hitti, D. Arseneau, S. Dunsiger, G. Morris, K. Kojima

Project Design Tech: John Langrish

Dept/Teams: CMMS / Proj. Management / Beamlines / Vacuum / Design Office / Electrical / Sci-Tech Dept. / Controls / Machine Shop / Accounting / Purchasing / Legal - wrt University Coordination

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CMMS

Summary of Project Objectives & Impacts

Objectives:

Beamline:

- 100 k$\mu^{+/-}$ /(sec-cm^2) @ 40-120 MeV/c; >80% longitudinal spin polarization.
- > 25 kμ^+ /(sec-cm^2) @ 70-120 MeV/c; >80% transverse spin polarization (|| X or Y in ZF).

Experimental Station:

- High pressure cells: 0.03 – 300 K, up to 2.5 GPa
- High Temperature environments: 273 – 900 K, up to 50 Mpa
- 4T Magic T superconducting magnet with SiPM based spectrometer
- DR /w sample changeover time < 5 hrs @ 0.1 K for Ø30 mm pressure cel

Impacts:

Quantum Materials:

- high-pressure (the tuning parameter) *m*SR studies of novel electronic and magnetic phases in qms
- i.e. superconductivity, low-dimensional and topological systems, quantum phase transitions

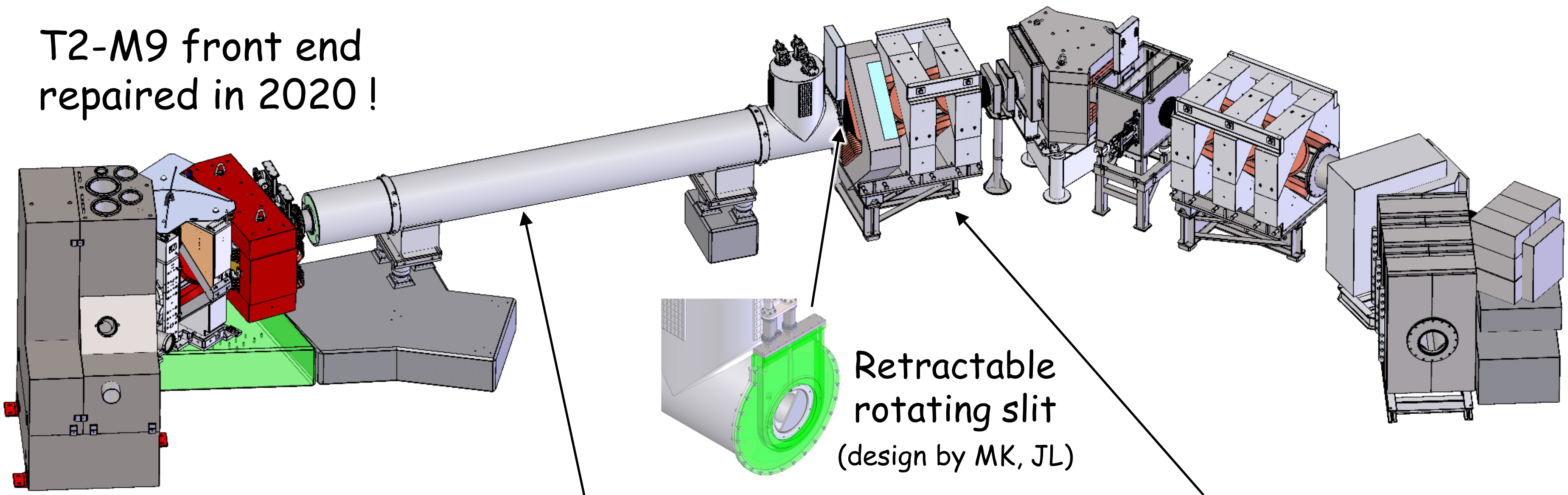
Environmental and Energy:

- Chemistry under extreme conditions, i.e. kinetics & radiolysis in pressurized-water nuclear reactors
- Green chemistry, i.e. ionic solutions and kinetics
- Hydrogen storage and Li battery lifetime research via μ- elemental analysis
- Muon Catalyzed Fusion (which was the impetus for the U. of Tokyo's original M9B beamline)

Cultural Object Analysis of important high-Z elements: Non-destructive μ-elemental analysis

Nuclear Physics: Nuclear hyperfine structure in heavy Muonic atoms

The Rising of the TRIUMF M9H Phoenix, with new chops



M9H Solenoid upgrades compared to previous M9B:

- 5T RT-bore solenoid, operates in persistent mode
- Increased bore diameter
- 70L recondensing system maintains SC state for 12 hrs., i.e. robust during total power loss or interruption
- Routine operations, semi-automated cool downs
- Awarded to Tesla Engineering, U.K

Post Solenoid Triplet:

- First "high pole field capable" quad placement very tight to solenoid exit

  Strong horizontal and vertical steering capabilities with all four poles independently driven.

- Subsequent quads in triplet also fitted with horizontal and vertical steering capabilities.

$\pi \rightarrow \mu + \nu_\mu$ in theory

Muon polarisation in the $\pi_{\mu 2}$ decay

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2.2 Angular distribution for the muon

Energy-momentum conservation:

$$\tilde{p}_\pi = \tilde{p}_\mu + \tilde{p}_\nu$$

leads to:

$$m_\pi^2 + m_\mu^2 - 2E_\pi E_\mu + 2\vec{p}_\pi \cdot \vec{p}_\mu = 0$$

and to the second degree equation ($ap_\mu^2 + 2b'p_\mu + c = 0$):

$$4p_\mu^2[E_\pi^2 - p_\pi^2 \cos^2\theta_{\pi\mu}] - 4p_\mu(m_\pi^2 + m_\mu^2)p_\pi \cos\theta_{\pi\mu} + 4m_\mu^2 p_\pi^2 - (m_\pi^2 - m_\mu^2)^2 = 0$$

with:

$$a = 4(E_\pi^2 - p_\pi^2 \cos^2\theta_{\pi\mu})$$

$$b' = -4m_\mu E_0 p_\pi \cos\theta_{\pi\mu}$$

$$c = 4m_\mu^2 p_\pi^2 - (m_\pi^2 - m_\mu^2)^2 = 4m_\mu^2(p_\pi^2 - p_0^2)$$

where:

$$p_0 = \frac{m_\pi^2 - m_\mu^2}{2m_\mu} = 39.35 \text{ MeV/c}$$

The determinant is:

$$\Delta' = 16m_\mu^2 E_\pi^2(p_0^2 - p_\pi^2 \sin^2\theta_{\pi\mu})$$

$\vec{p}_0$ is the transition momentum. The corresponding total energy is:

$$E_0 = \frac{m_\pi^2 + m_\mu^2}{2m_\mu} = 145.01 \text{ MeV}$$

and the corresponding kinetic energy:

$$T_0 = \frac{(m_\pi - m_\mu)^2}{2m_\mu} = 5.44 \text{ MeV}$$

- $p_\pi > p_0$

All muons are emitted forward ($\cos\theta_{\pi\mu}$ is always positive):

$$2E_\pi E_\mu - m_\pi^2 - m_\mu^2 > 2m_\pi \frac{(m_\pi^2 + m_\mu^2)}{2m_\mu} - (m_\pi^2 + m_\mu^2) = (m_\pi^2 + m_\mu^2)\left(\frac{m_\pi}{m_\mu} - 1\right) > 0$$

There is a limitation on the angle $\theta_{\pi\mu}$:

$$\sin\theta_{\pi\mu} < \frac{p_0}{p_\pi} \qquad \theta_{\pi\mu} < \theta_0$$

where:

$$\sin\theta_0 = \frac{p_0}{p_\pi}$$

There are two positive roots. Both have physical significance.

$$p_\mu = m_\mu \frac{E_0 p_\pi \cos\theta_{\pi\mu} \pm E_\pi \sqrt{p_0^2 - p_\pi^2 \sin^2\theta_{\pi\mu}}}{E_\pi^2 - p_\pi^2 \cos^2\theta_{\pi\mu}}$$

In V-A theory …. →

$$\vec{P}_L = \eta \frac{1}{m_\mu p_0}\Big[E_\mu p_\pi \cos\theta_{\pi\mu} - E_\pi p_\mu\Big]\vec{n}_\mu = \eta \frac{1}{m_\mu p_0}\Big[E_\mu p_\pi(\vec{n}_\pi \cdot \vec{n}_\mu) - E_\pi p_\mu\Big]\vec{n}_\mu$$

The longitudinal polarization is equal to zero if:

$$\cos\theta_{\pi\mu} = \frac{p_\mu}{E_\mu}\frac{E_\pi}{p_\pi} = \frac{v_\mu}{v_\pi}$$

The transverse polarization is:

$$\vec{P}_T = \eta \frac{p_\pi}{p_0}\Big[\vec{n}_\pi - (\vec{n}_\pi \cdot \vec{n}_\mu)\vec{n}_\mu\Big]$$

We also have:

$$P_T^2 = \frac{p_\pi^2}{p_0^2}\sin^2\theta_{\pi\mu}$$

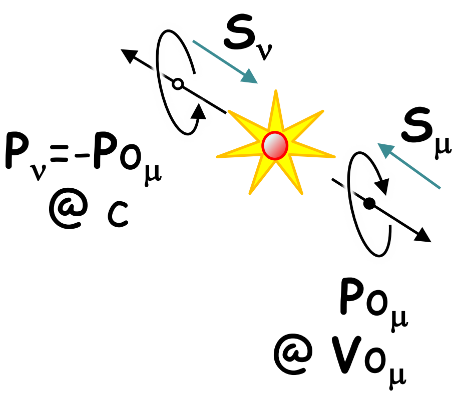
or:

$$P_T = \frac{\sin\theta_{\pi\mu}}{\sin\theta_0}$$

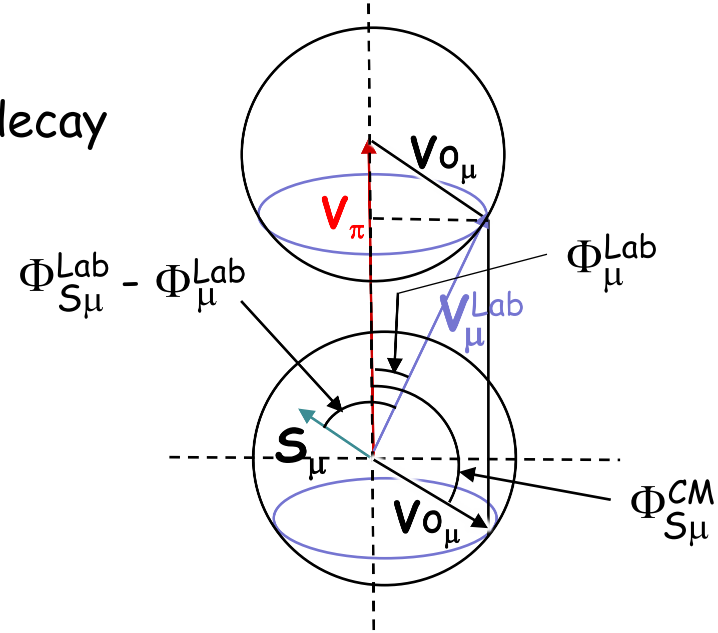
Simple non-relativistic picture of the TrS_μ p_μ p_π connection

Nonrelativistic picture, at the instant of pion decay

Pion Decay in
(Center of Mass)
Rest Frame



Boost to Lab
Frame with V=V_π



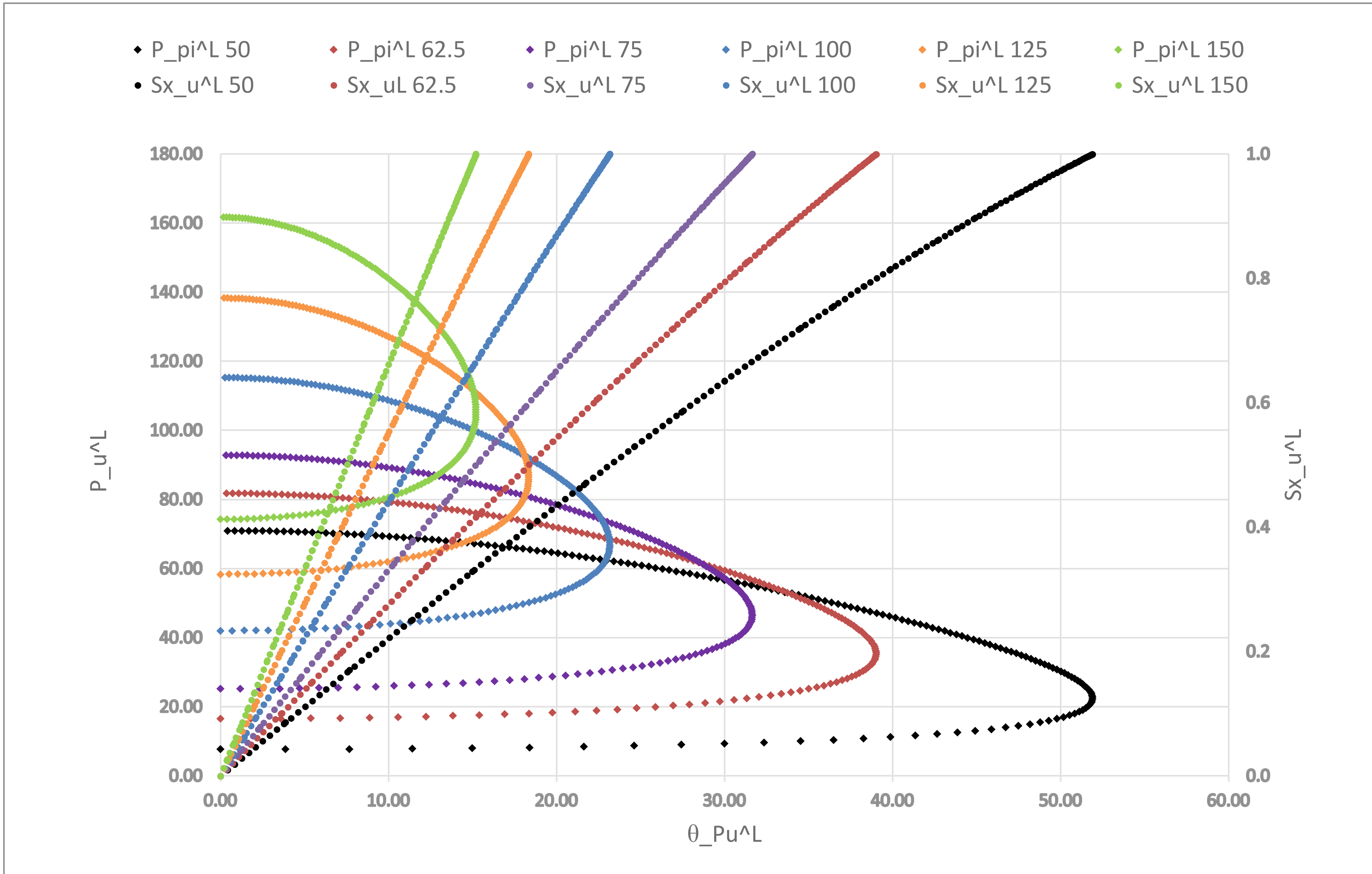
Note: when V^{Lab}_μ is tangent to the sphere defined by V_π + n*Vo_μ then V^{Lab}_μ is perpendicular to Vo_μ and S_μ

→ Transverse Spin Polarization occurs at the maximum allowed angle, Φ^{*Lab}_μ, between V^{Lab}_μ and V_π.

→ $\sin(\Phi^{*Lab}_\mu) = Vo_\mu / V_\pi \xrightarrow{rel} Po_\mu / P_\pi$

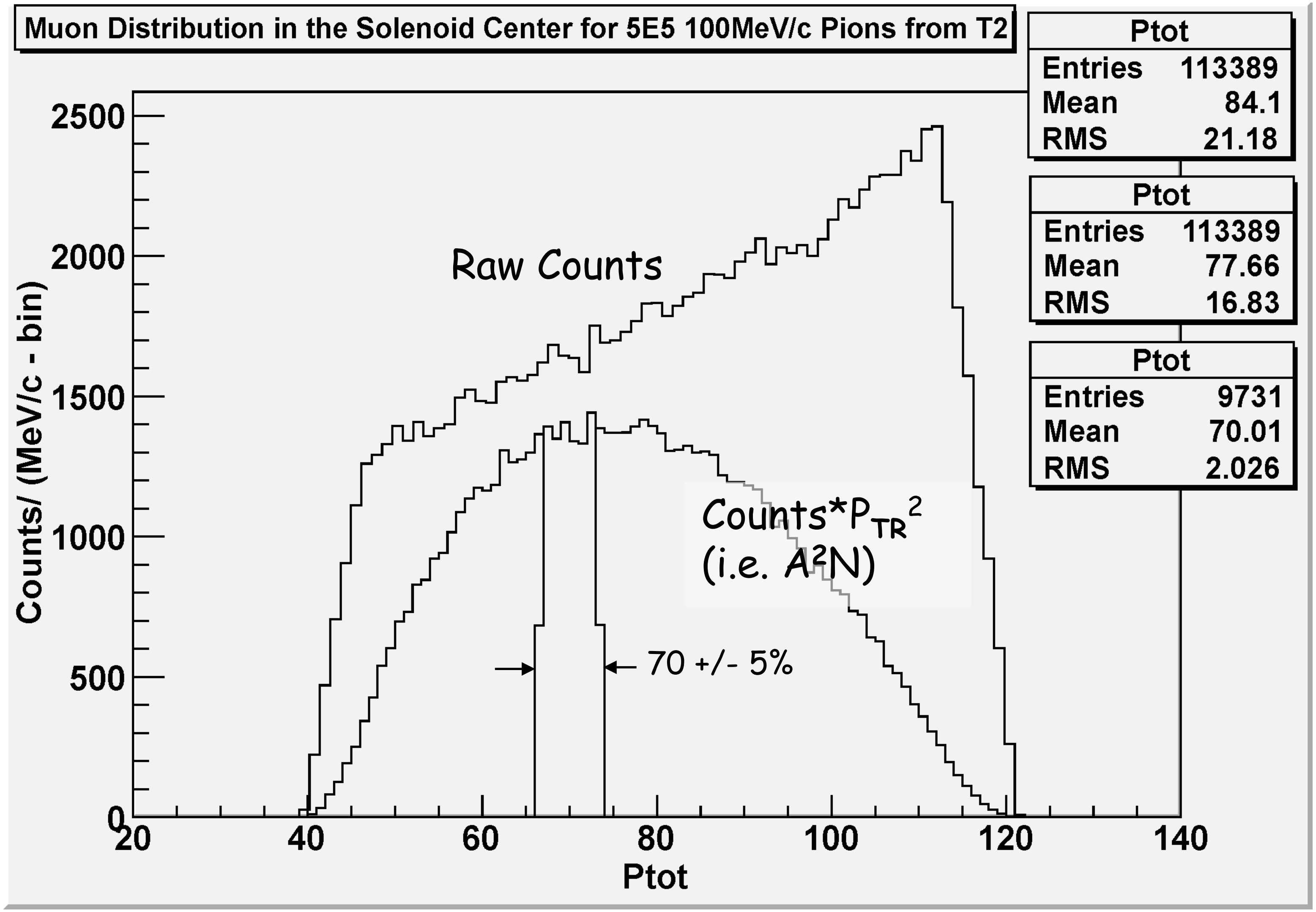
→ $V^{*Lab}_\mu = \cos(\Phi^{*Lab}_\mu) V_\pi$ rel OK!

$\pi \rightarrow \mu + \nu_\mu$ in a graph, TSP μ have high DOS

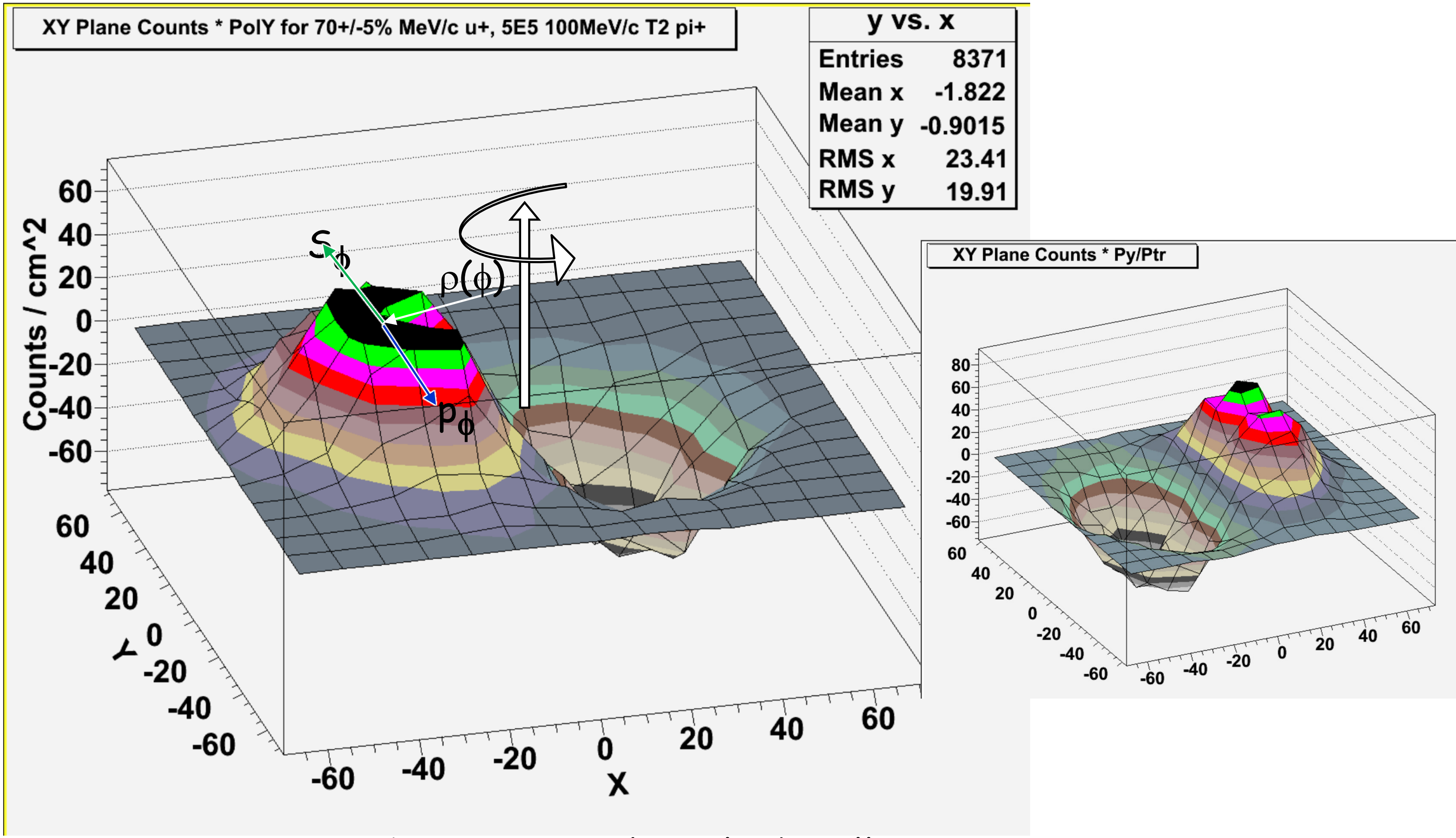


The relationship in the lab frame between TrSμ, p_μ for fixed p_π

How many TSP muons are there? Actually quite a few !

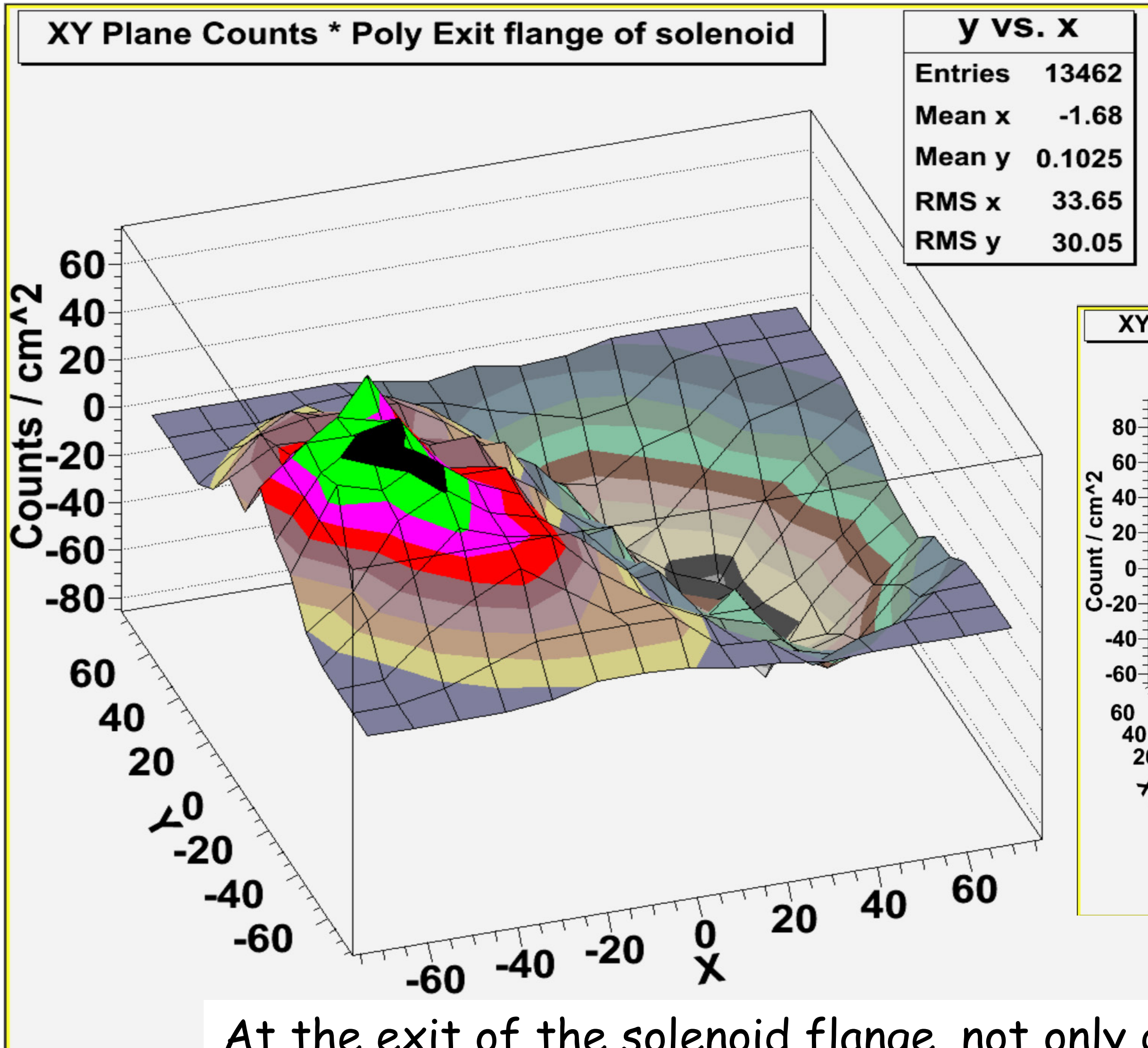


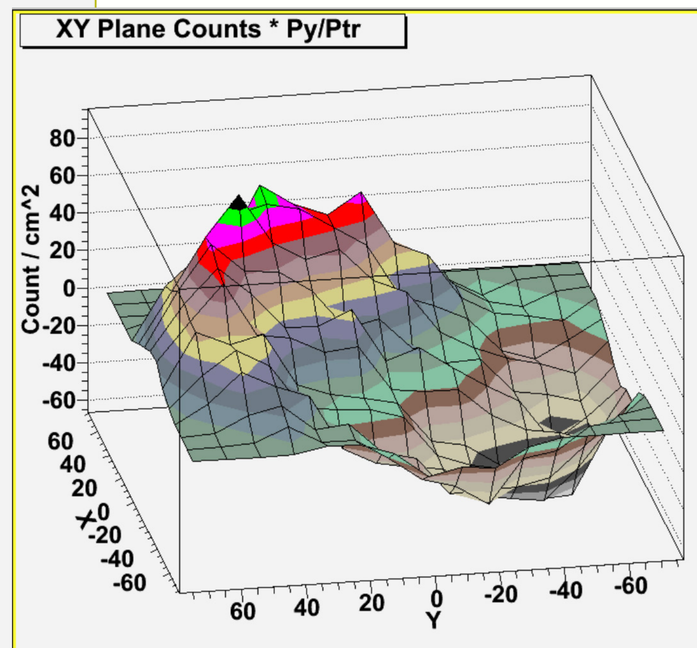
They are off axis & asymmetrically distributed in the solenoid



Rotating about z gives the cylindrically symmetric azimuthal correlations between $\rho(\phi)$, $S_\phi(\rho)$ and $p_\phi(\rho)$

… and when they emerge, Sμ p_{μ} ρ correlations become complex

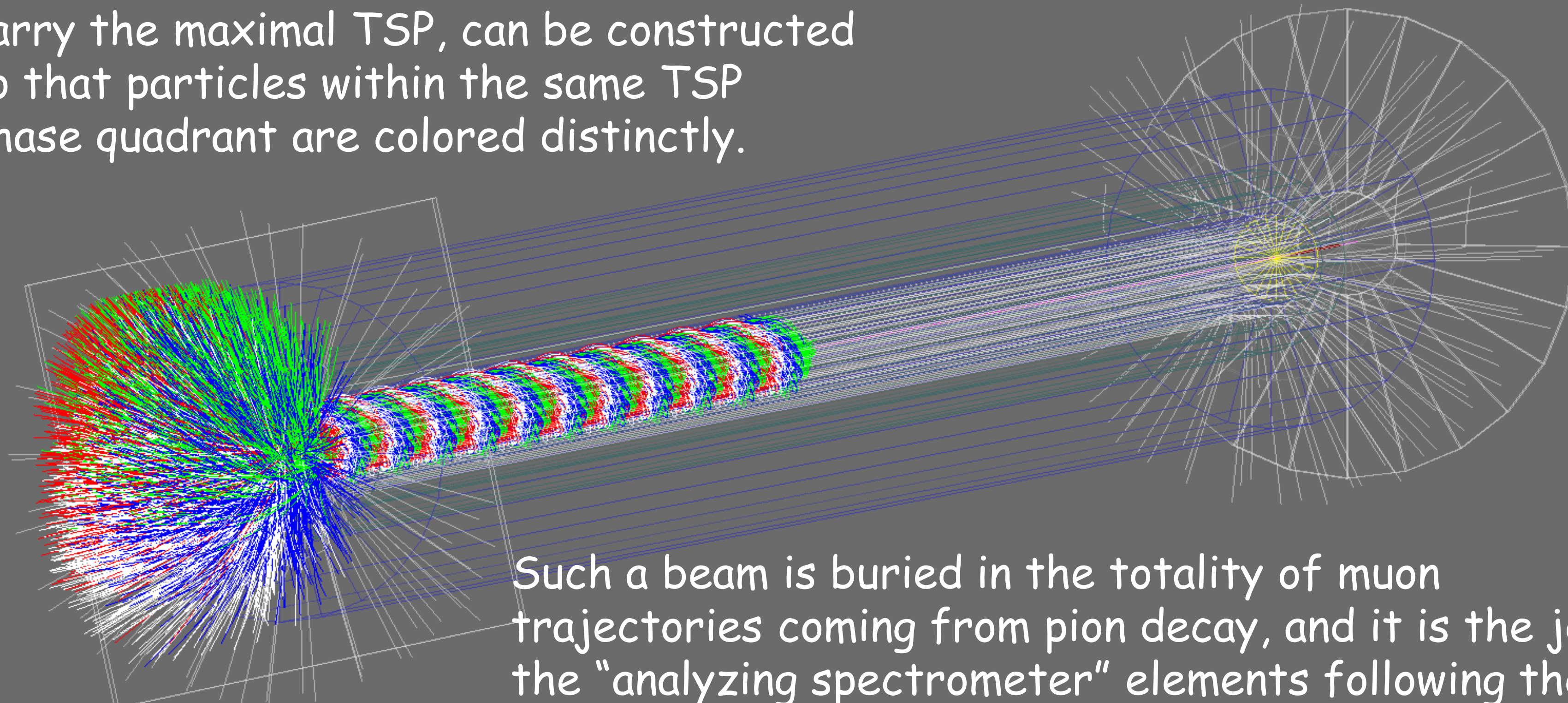




At the exit of the solenoid flange, not only does the TSP beam "annulus" expand, the correlations seen within the solenoid diverge.

… the beam carrying the TSP explodes out of the solenoid

An artificial test muon beam, which would carry the maximal TSP, can be constructed so that particles within the same TSP phase quadrant are colored distinctly.



Such a beam is buried in the totality of muon trajectories coming from pion decay, and it is the job the “analyzing spectrometer” elements following the solenoid to extract the majority of one such quadrant.

The propagation of Coherent TSP Phase quadrants down the solenoid is an effect of the “collective” off-centre muon corkscrew orbits. These are ~2x the diameter, but with same pitch, of the individual muon trajectories in the field.

Challenges and Solutions to Capturing useable TSP

Challenges:

1. Assign a name to the concept of a coherent TSP phase quadrant = CTSPPQ (I'm very open to suggestions)
2. CTSPPQs exit the solenoid with large divergent momentum components from a significantly off-axis source.
3. Unconstrained, CTSPPQs with the same $P\mu$ will average to zero.

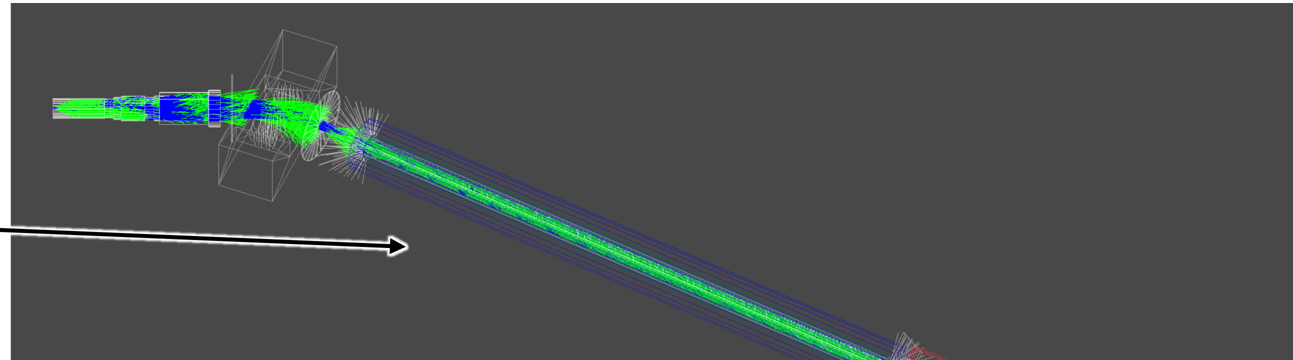
Solutions:

1. Practice saying "KitsPiks" (better than KitsPeaQues?)?
2. Place the first quad following the solenoid as close as possible to it exit, and include strong steering components.
3. a: CTSPPQs change sign across the center plane → put a rotatable half-aperture slit at the solenoid exit.

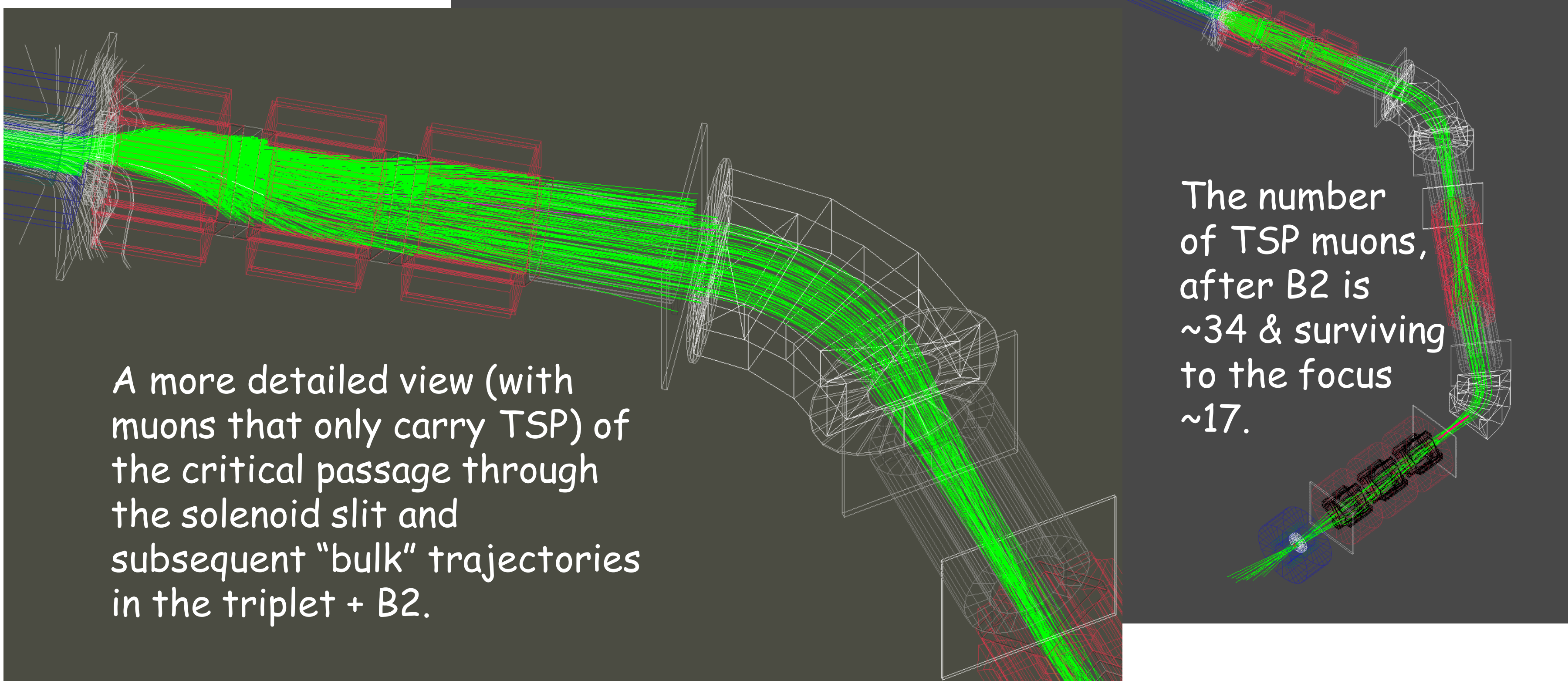
   b: Find a tuning method to use the steering elements immediately downstream of the solenoid as an "angle resolving spectrometer".

M9H TSP Optical Design Characteristics

A fully optimized simulation of TSP 70MeV/c muon beam tune, with 83% final TSP, starting from 10,000 100MeV/c (~ideal Pπ) pions from T2.

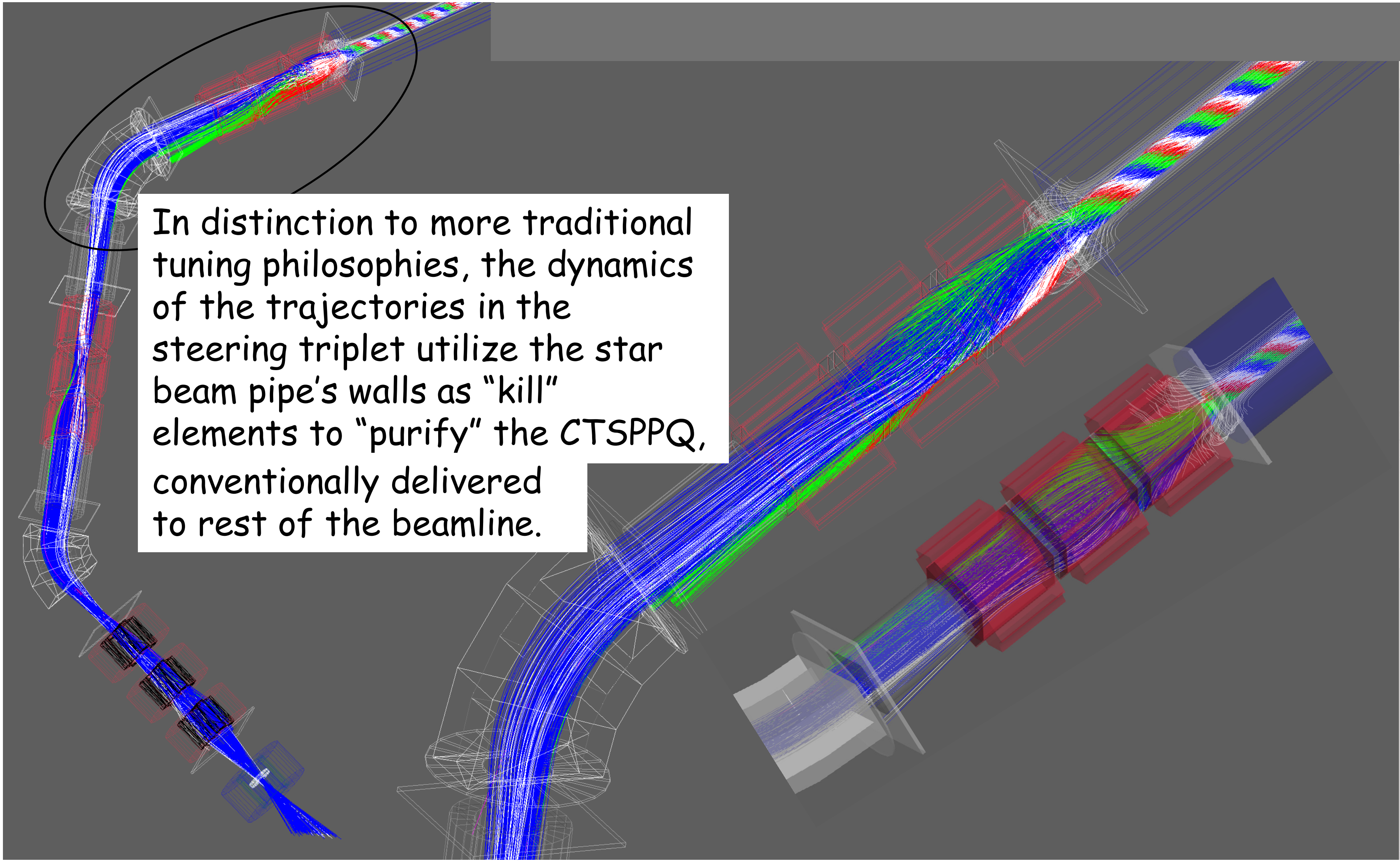


The number of TSP muons, after B2 is ~34 & surviving to the focus ~17.



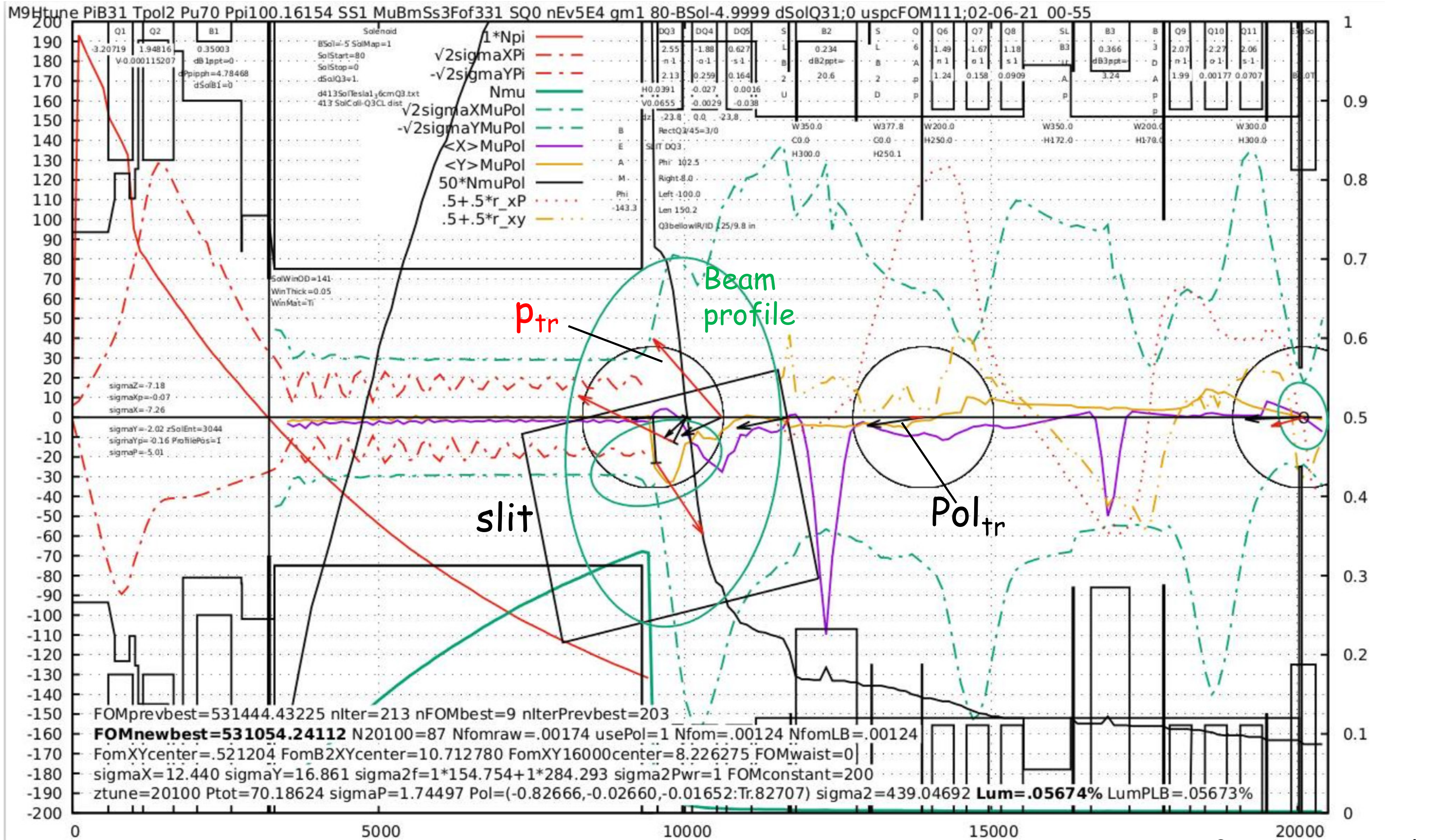
A more detailed view (with muons that only carry TSP) of the critical passage through the solenoid slit and subsequent "bulk" trajectories in the triplet + B2.

M9H Optical Design: CTSPPQ evolution down the beamline



In distinction to more traditional tuning philosophies, the dynamics of the trajectories in the steering triplet utilize the star beam pipe's walls as "kill" elements to "purify" the CTSPPQ, conventionally delivered to rest of the beamline.

M9H Optical Design: A 70MeV/c PolX tune, via G4Beamline/Gminuit



The tuning procedure uses a figure of merit which is dominated by $(A_{tr}^2 N/\text{sigma})^{-1}$, i.e. beam luminosity^{-1}, at the focus … and driven by Minuit simplex minimization.

Losses in Q3, Q4 and entering B2 enhance the TSP

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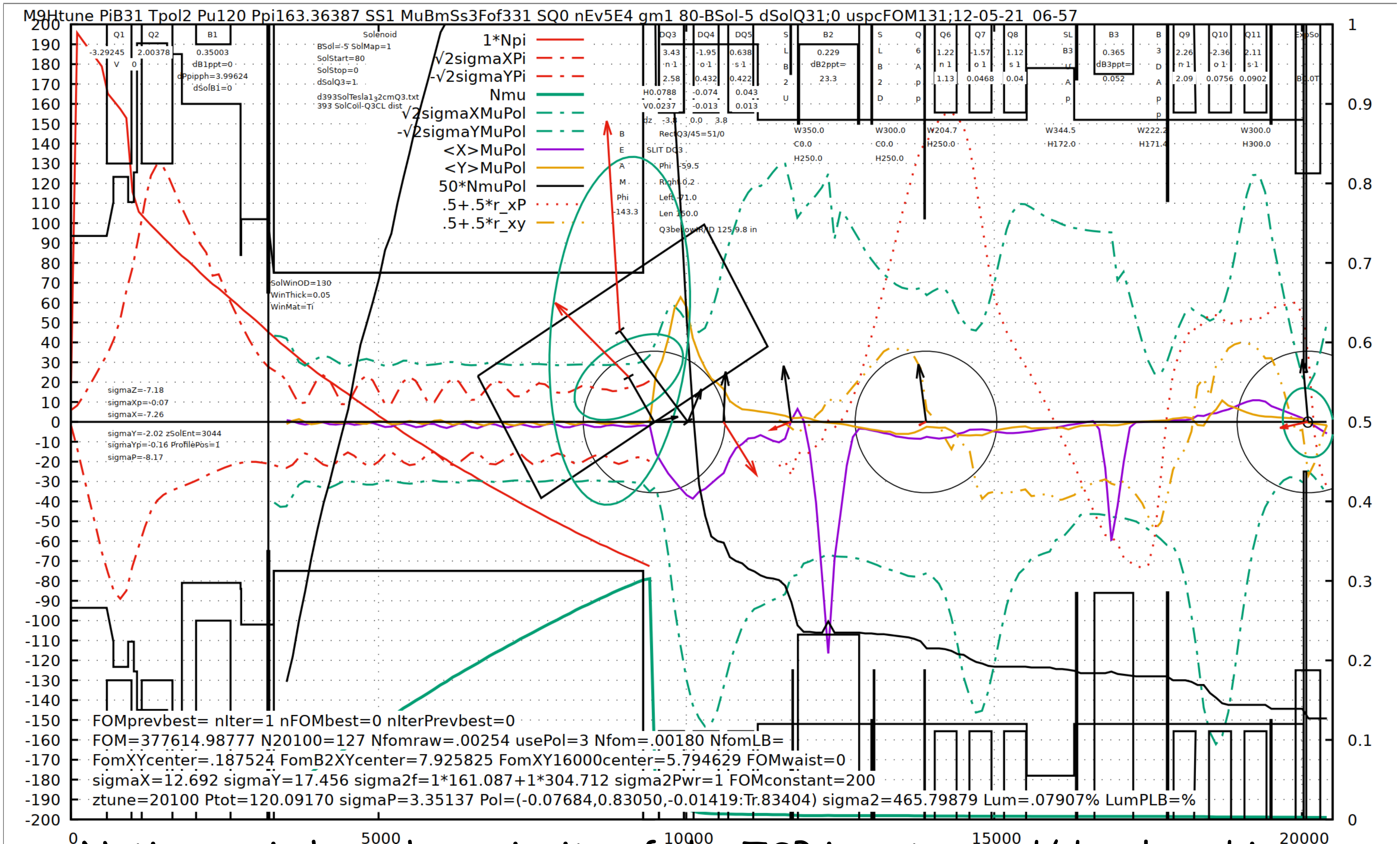
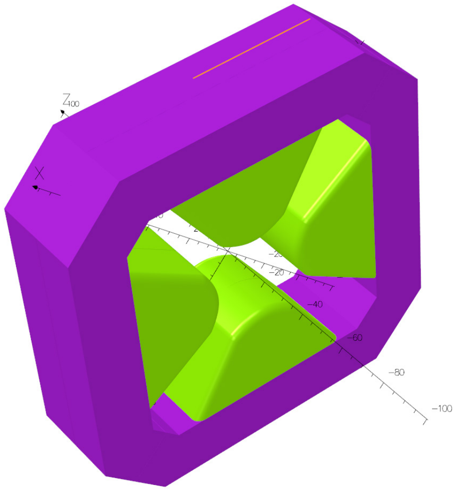
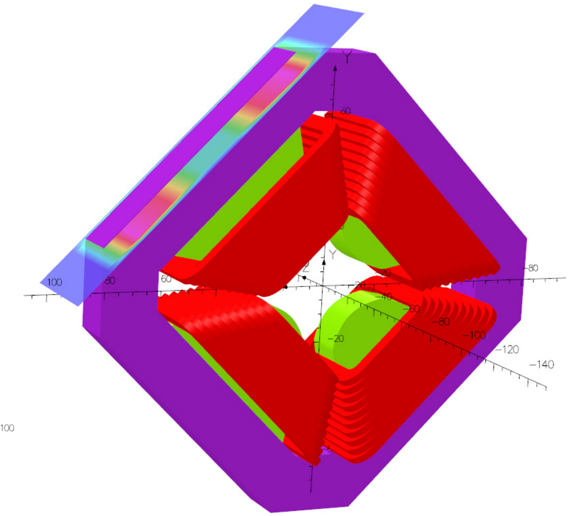
M9H Optical Design: A 120MeV/c PolY tune

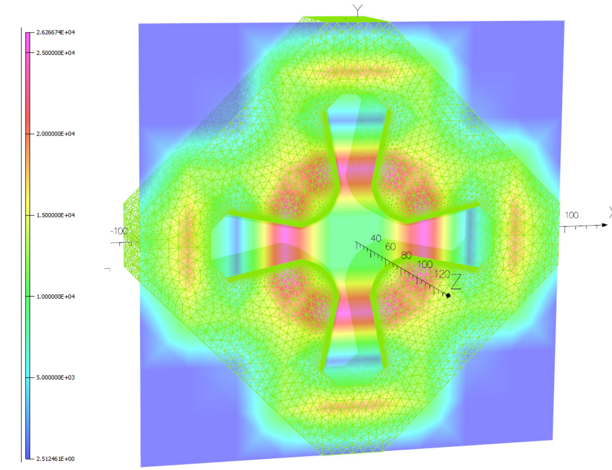


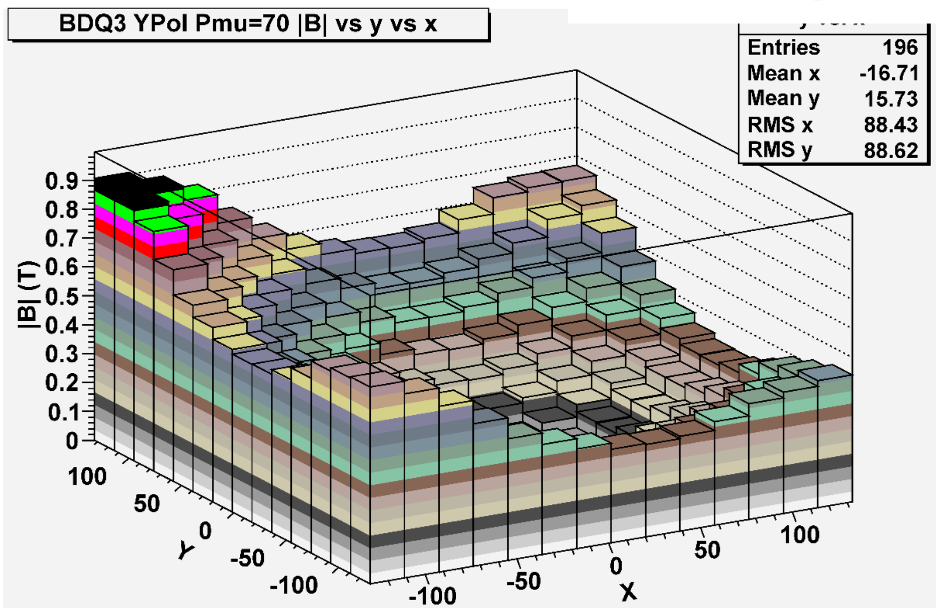
Notice again how the majority of the TSP is extracted/developed in the triplet. Also the strengths and steering of Q3 is very different wrt the PolX tune above.

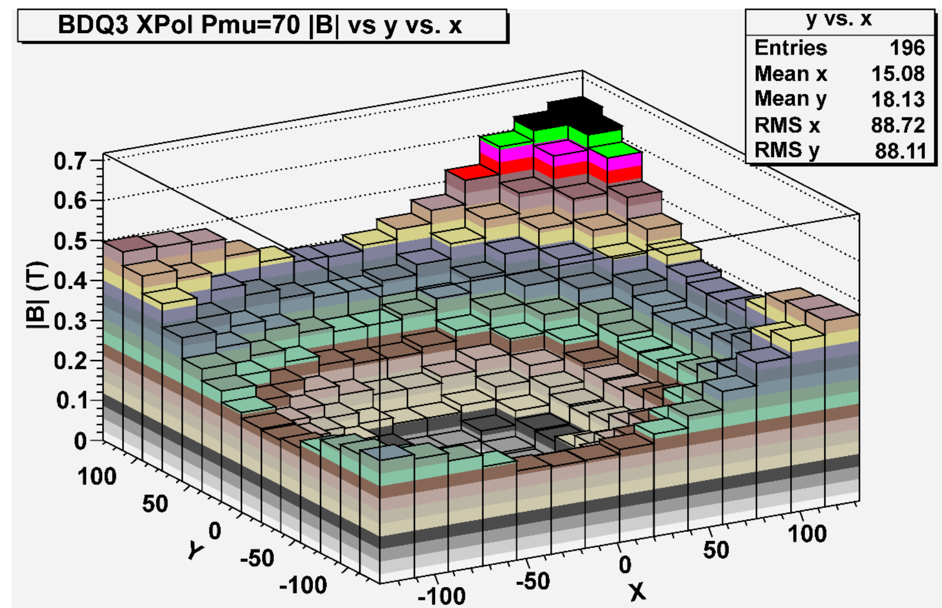
New Q3 design – accommodates large asymmetric fields











Typical field asymmetries within Q3 when tuning for PolX and PolY

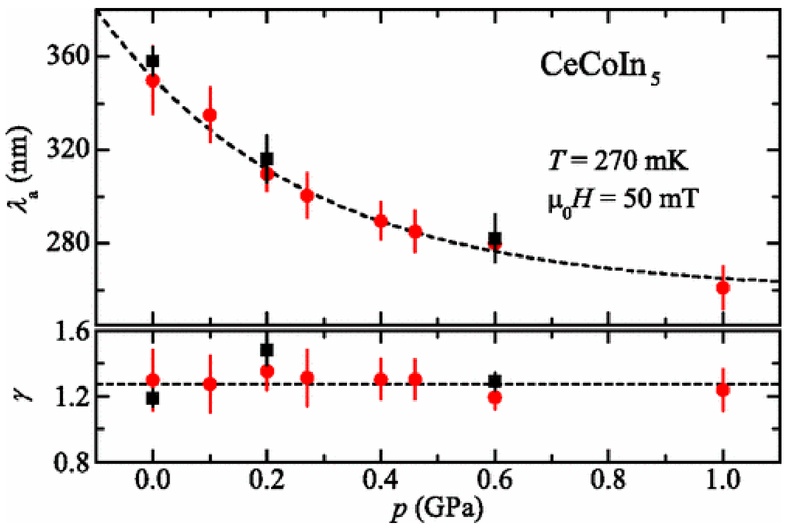
Science opportunities using TSP decay beams

TF-μSR Measurements of Superconducting Response under Pressure

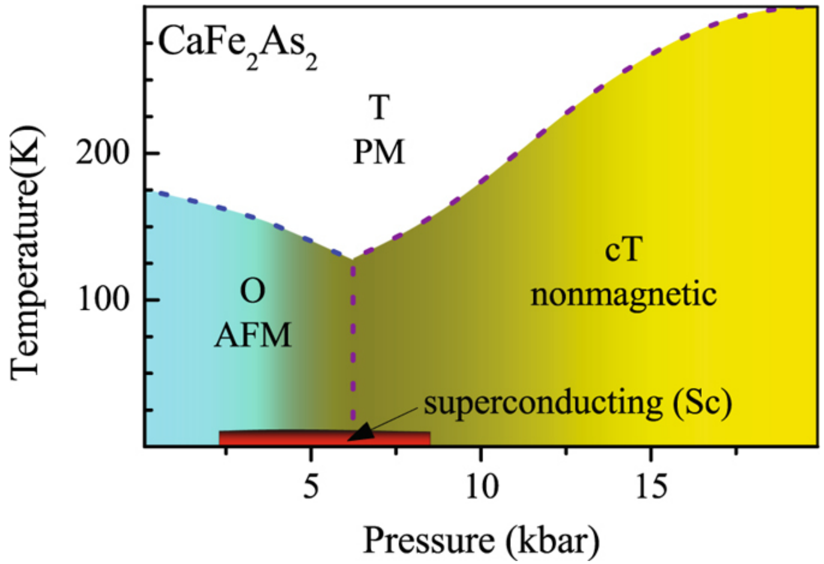
T and *H* dependences of the *magnetic penetration depth* (λ)

- determine superfluid density
- identify pairing symmetry
- identify multi-band superconductivity

Pressure **dependence** **or** pressure used to **induce** superconductivity



L. Howald *et al.*, *Phys. Rev. Lett.* **110**, 017005 (2013)



M. Torikachvili *et al.*, *Phys. Rev. Lett.* **101**, 057006 (2008)

(via, the good offices of Jeff Sonier)

Science opportunities using TSP decay beams, … from the veterans, who have been waiting patiently?

- The F+ and F- hyperfine states of muonic atoms with nonzero nuclear spin; opens up an enormous range of alternatives to the usual mu-C & mu-O probes.
- Beating the "muon depolarization" in muonic atoms by triggering on different muonic X-rays: e.g. if you only start the clock for muons that go straight to the ground state, emitting an X-ray with the full binding energy, they should be essentially fully polarized, giving at least a factor of 16 rate advantage (also JS.)

- Renew neutral-muonic He ("heavy H") since it was just getting started on its reaction with CH_4 when M9B went down. A unique contribution, wrt Mu, of isotopic mass effects, applicable to a host of other quantum systems.
- Use forward decay μ^+, with opposite helicity wrt more usual backward variety, which could bear on experiments exploring whether Mu formation (and muoniated radicals) might depend on molecular chirality.

- Frequency or muonic atom Knight shift measurements as a function of pressure are a very interesting and unique field.
- μ-SR measurements for magnetically ordered materials are very difficult in a pulsed muon facility due to a loss of the information in an early time domain. Thus, with decent counting rates, TRIUMF would become a good place for mu-SR (inspired by Alex A.)

TRIUMF

Thank You !

Merci !

Discovery, accelerated