GPU-based Online Reconstruction for J/ψ TSSA at the SpinQuest Experiment

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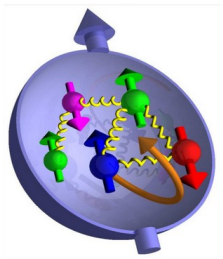
Outline

- **Motivation:**
  - The Nucleon Spin Puzzle and the Sivers Functions
  - The SpinQuest Experiment
- **SpinQuest Reconstruction with GPUs**
  - Motivations and Challenges
  - Features and Performances
- **Summary and Outlook**

Nucleon Spin Puzzle

Spin Sum Rule:

$$S_N = \tfrac{1}{2} = \tfrac{1}{2}\,\Delta\Sigma + \Delta G + L_q + L_g$$



$\Delta\Sigma$: spin of quarks and antiquarks

ΔG: spin of gluons

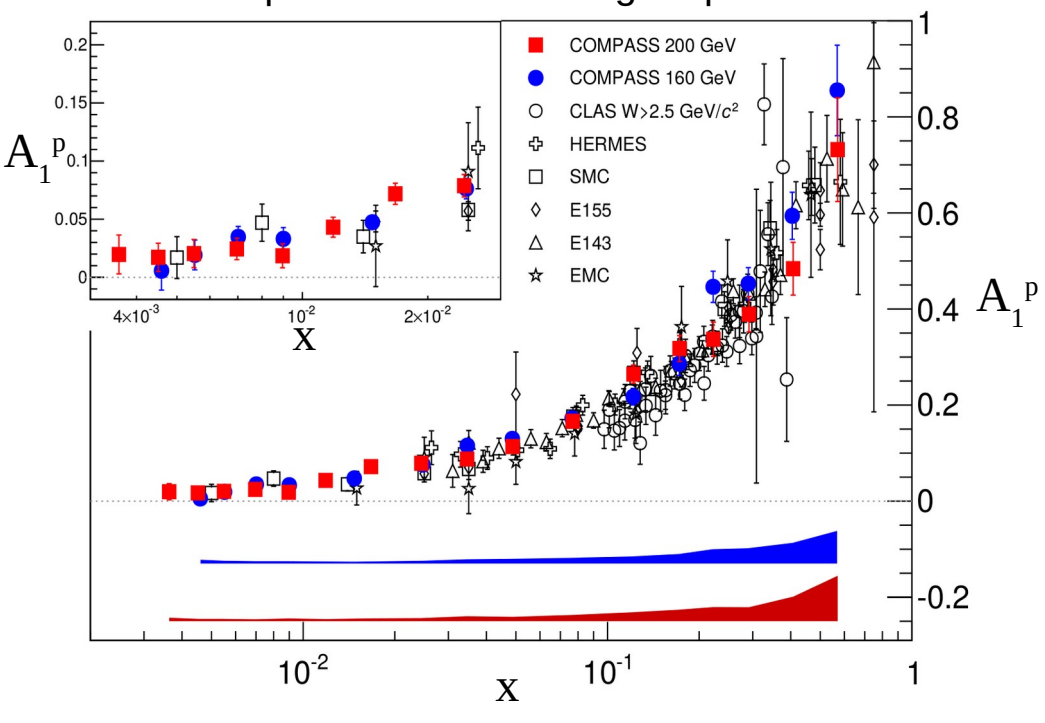
L_q: angular momentum of quarks and antiquarks;

L_g: angular momentum of gluons

Measurements of $\Delta\Sigma$:

- EMC: Nucl. Phys. B328, 1 (1989):
  $\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$,
- COMPASS: Phys. Lett. B753, 18 (2016):
  $0.26 < \Delta\Sigma < 0.36$

A_1^p: longitudinal Double Spin Asymmetry in Deep Inelastic Scattering on proton



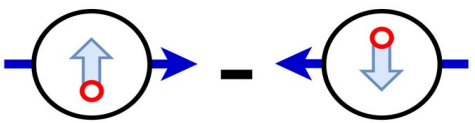
$\Delta G + L_q + L_g$ contributes to **more than half of the nucleon spin**

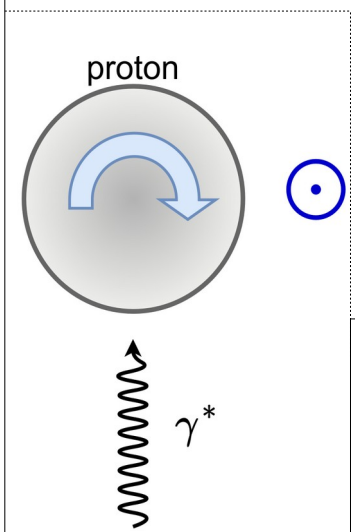
Sivers Function

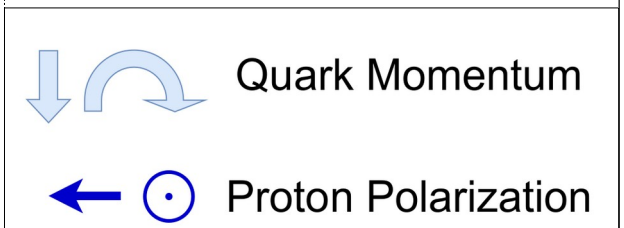
The Sivers function $f_T^{\perp q}$ provides information on the angular momentum of partons.

Sivers function accessed with Transverse Single Spin Asymmetries (TSSA) measurements on polarized Drell-Yan.

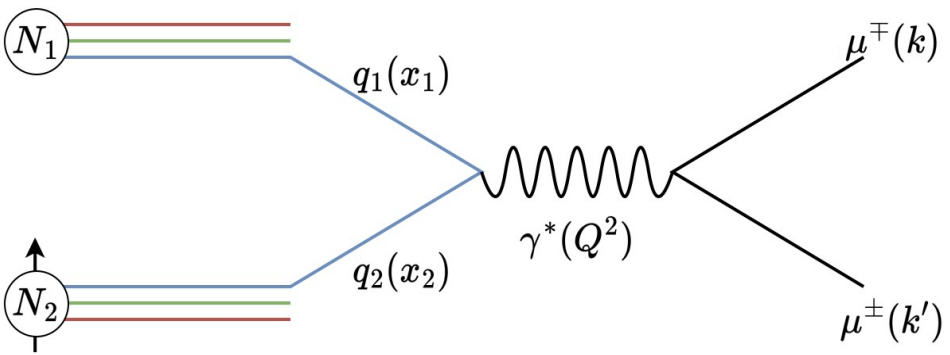
Sivers function







Drell-Yan



x_1: parton momentum fraction in the beam proton

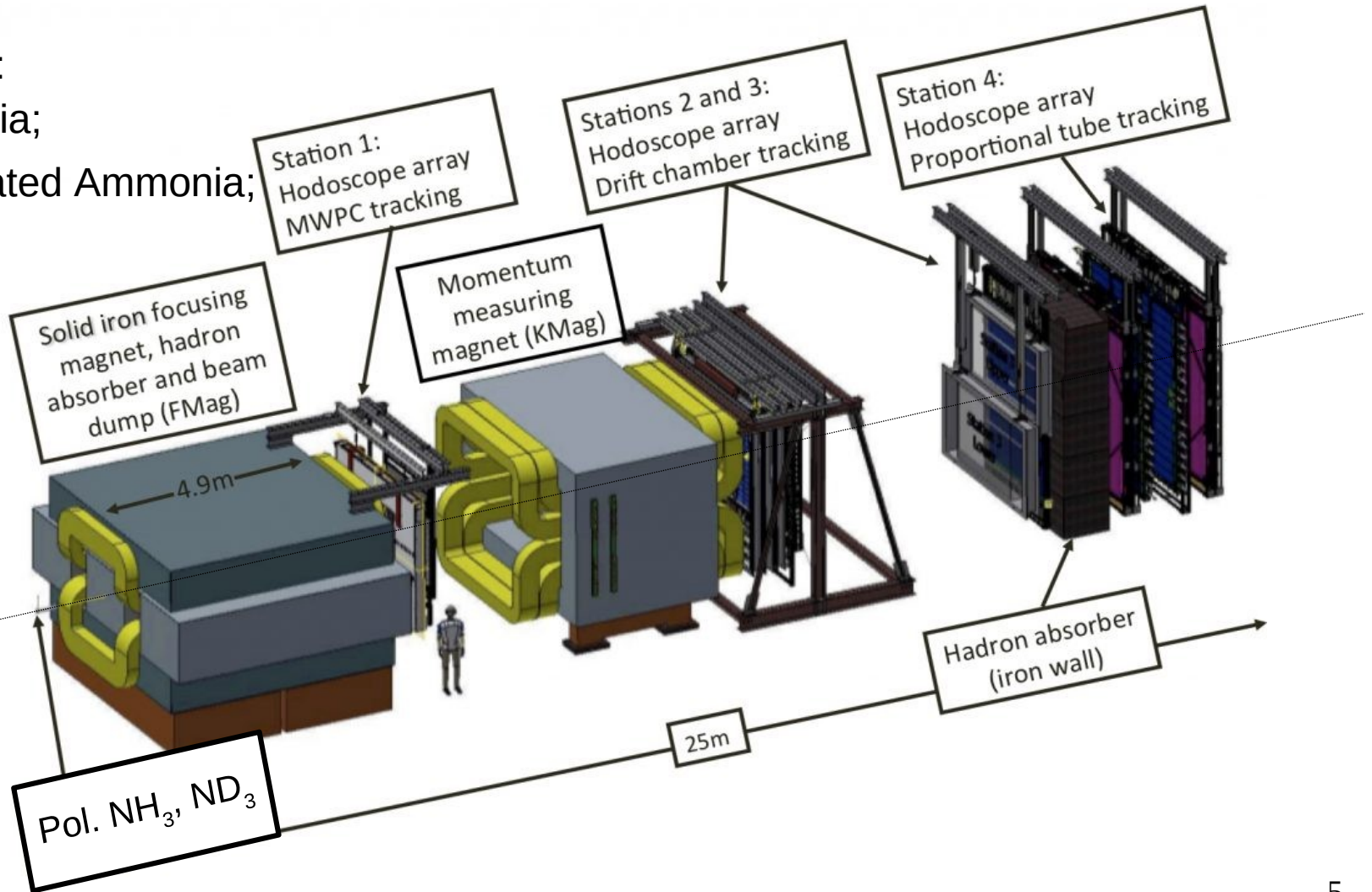
x_2: parton momentum fraction in the target nucleon

$x_F \equiv x_1 - x_2$: Feynman variable

The SpinQuest Experiment: Spectrometer

Polarized targets:

- NH_3: Ammonia;
- ND_3: Deuterated Ammonia;

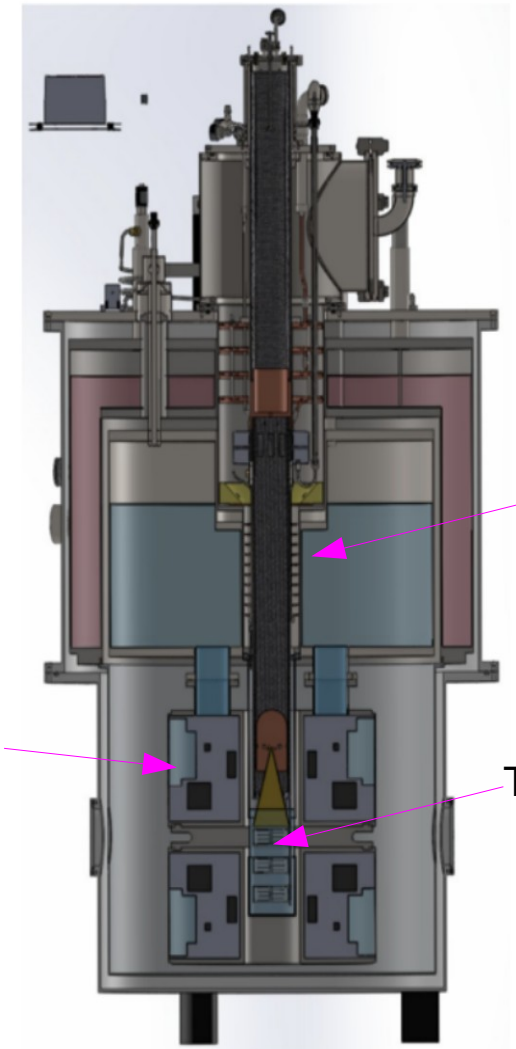


Beam delivered in 4-seconds long "spills" every 50 seconds

The SpinQuest Experiment: Polarized Target

Polarized targets:

- NH_3: Ammonia;
- ND_3: Deuterated Ammonia;
- **NH3 polarization: average 78% (maximum 93%)**
- **ND3 polarization: average 30% (maximum 50%)**
- Polarization flip every 8 hours.



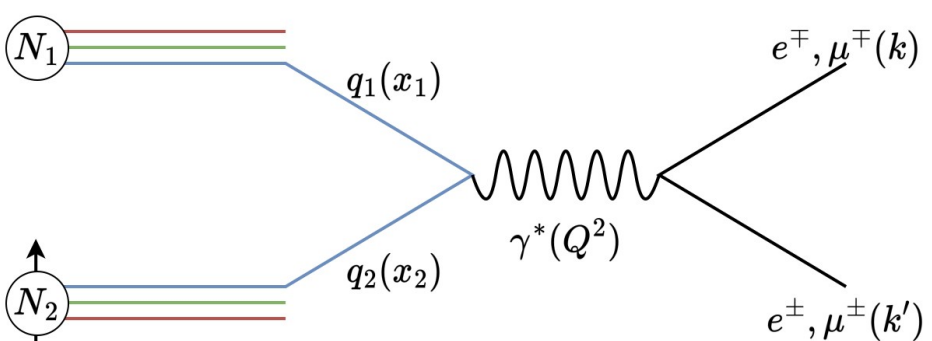
The SpinQuest Experiment: Drell-Yan measurement

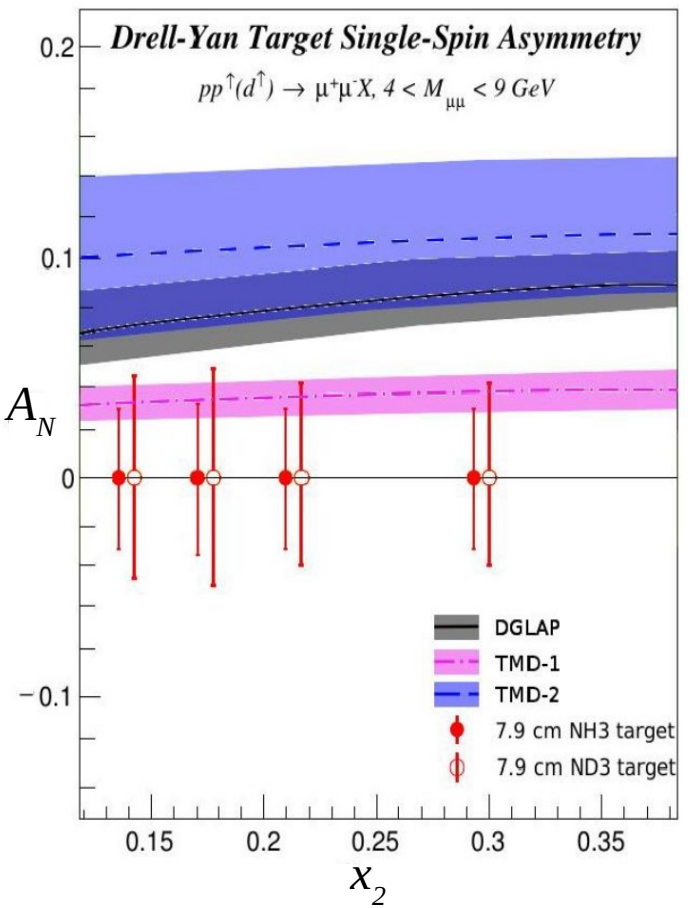
Measurement of the antiquark Sivers function $f_T^{\perp q}$ on proton (NH3) and neutron (ND3).

Contributions of the beam Sivers function suppressed by acceptance.

Acceptance suppressed

$$A_n = \frac{\frac{N_u}{L_u} - \frac{N_d}{L_d}}{\frac{N_u}{L_u} + \frac{N_d}{L_d}} \propto \frac{\sum_{q \in u,d,s} e_q^2 \left[f^q(x_1) f_T^{\perp,\bar{q}}(x_2) + f^q(x_2) f_T^{\perp,\bar{q}}(x_1) \right]}{\sum_{q \in u,d,s} e_q^2 \left[f^q(x_1) f^{\bar{q}}(x_2) + f^q(x_2) f^{\bar{q}}(x_1) \right]}$$

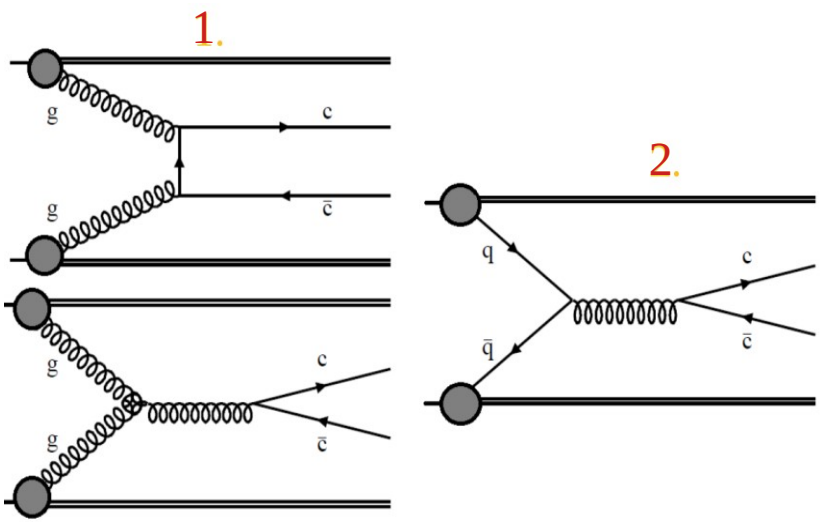




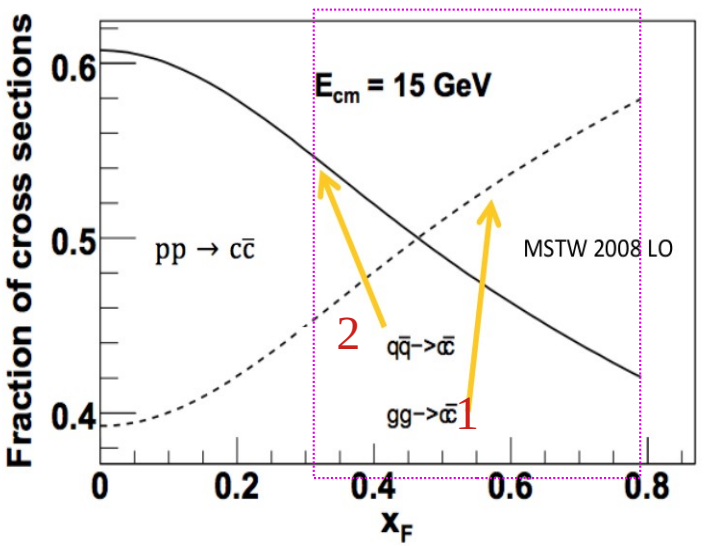
The SpinQuest Experiment: J/ψ measurement

J/ψ TSSA is dominated by gluon fusion in the SpinQuest kinematical coverage:

- gluon Sivers function;
- **gluon angular momentum (L_g).**



SpinQuest kinematical coverage



$x_F \equiv x_1 - x_2$

The SpinQuest Experiment: J/ψ measurement

J/ψ TSSA is dominated by gluon fusion in the SpinQuest kinematical coverage:

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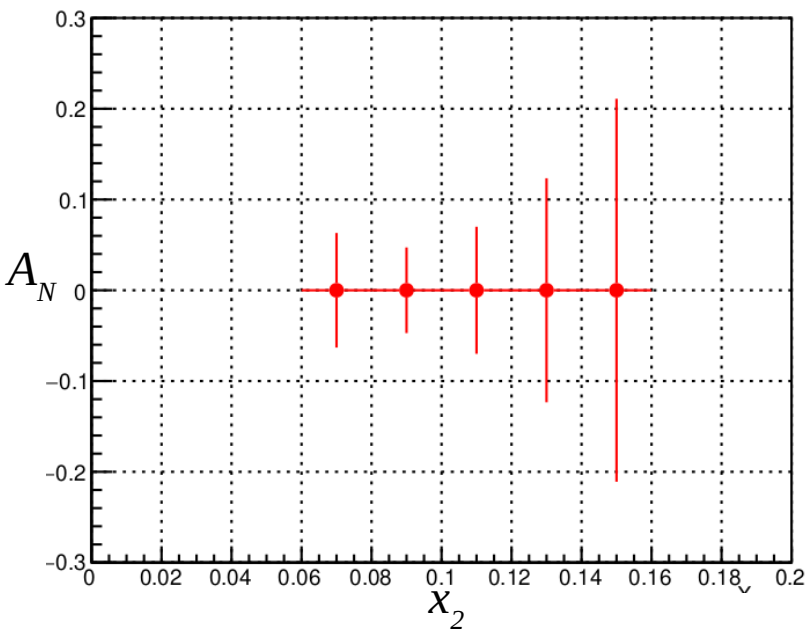
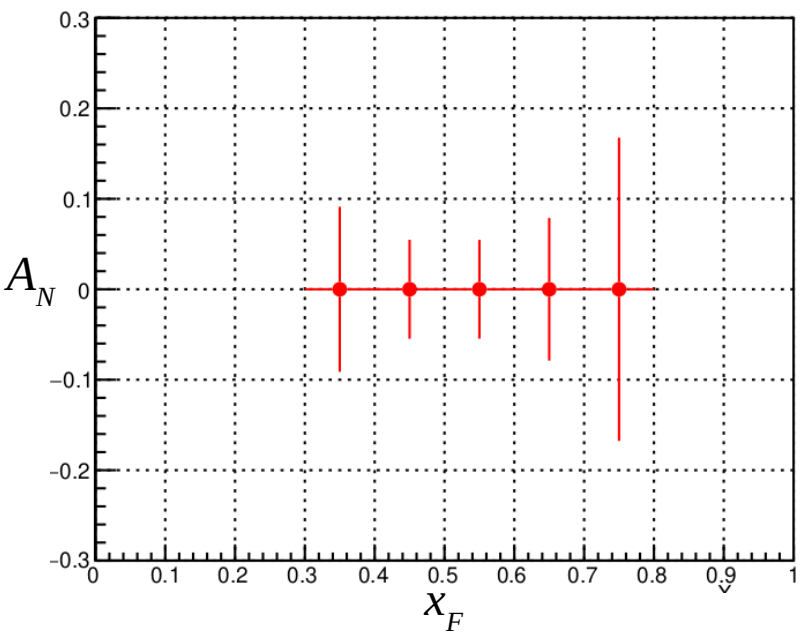
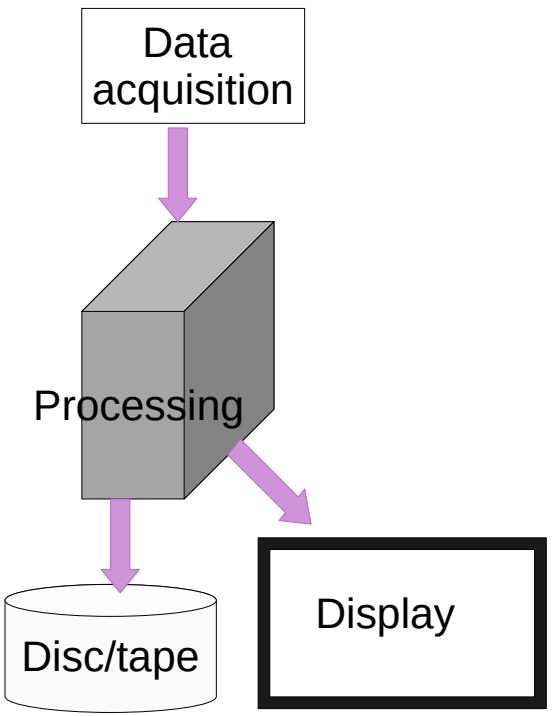
TSSA statistical uncertainties for **one week of J/ψ data for the first SpinQuest publication.**

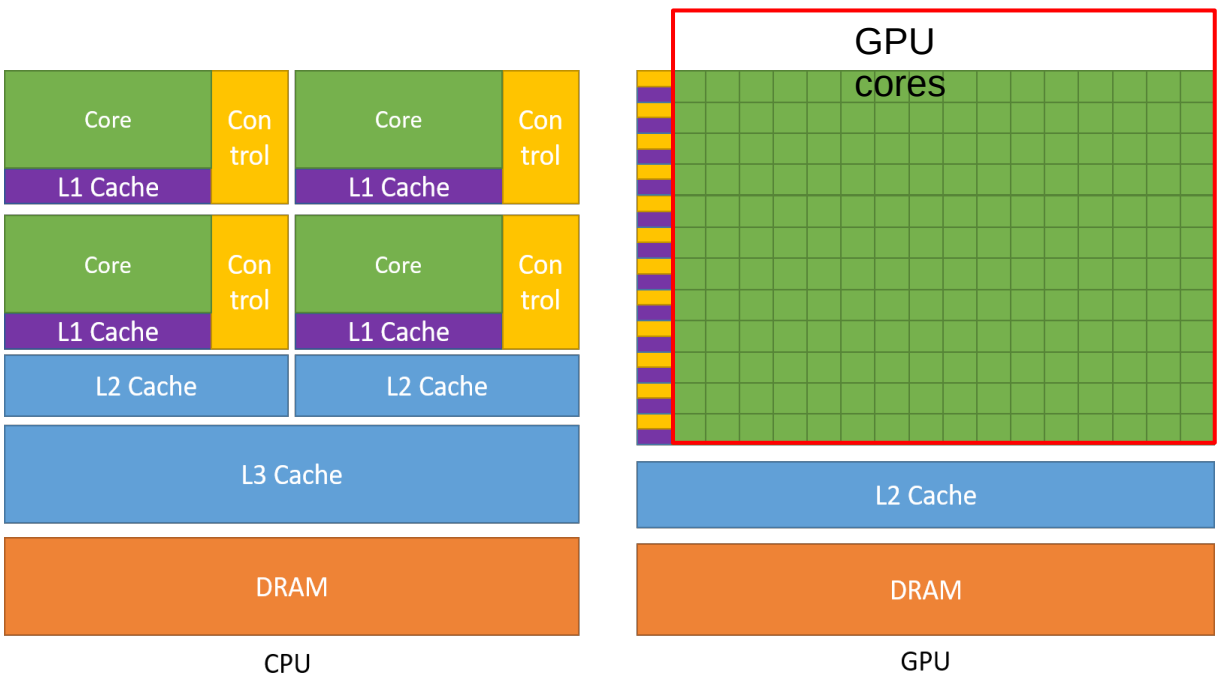




GPU-based Online Reconstruction Program

Scope of the project: monitor SpinQuest data *in real-time* with an ultra-fast analysis program using Graphics Processing Units (GPUs) instead of Computer Processing Units (CPUs).

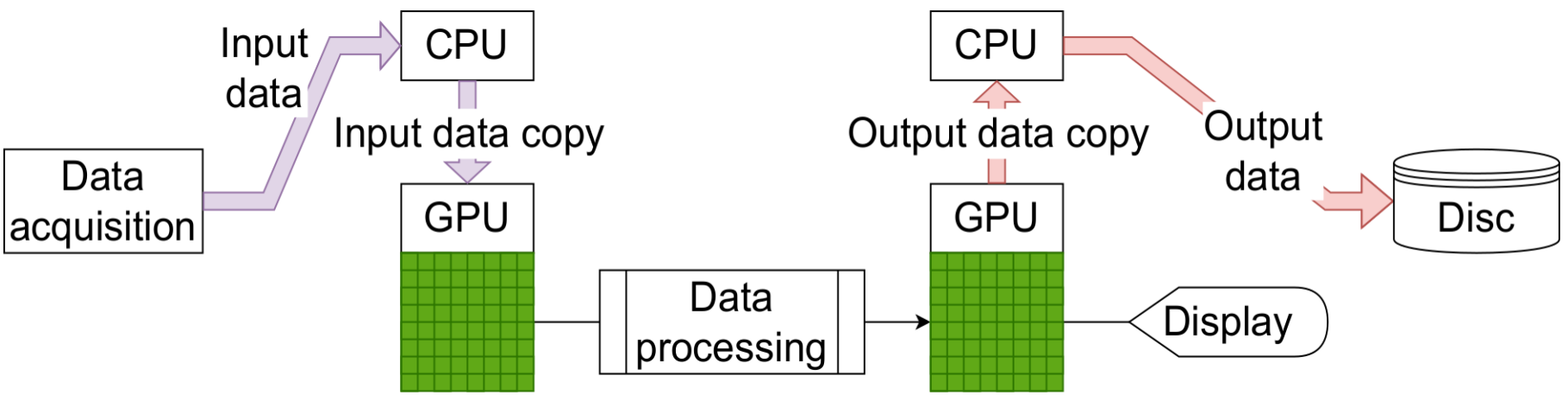




GPU Programming Challenges

Memory management much more “rigid” on GPUs than on CPU:

- Memory *must be pre-allocated* on GPUs (input**+**output);
- Input data copied from CPU to GPU;
- data processed on GPUs;
- output data copied back to CPU to save the output of the data processing on disk.



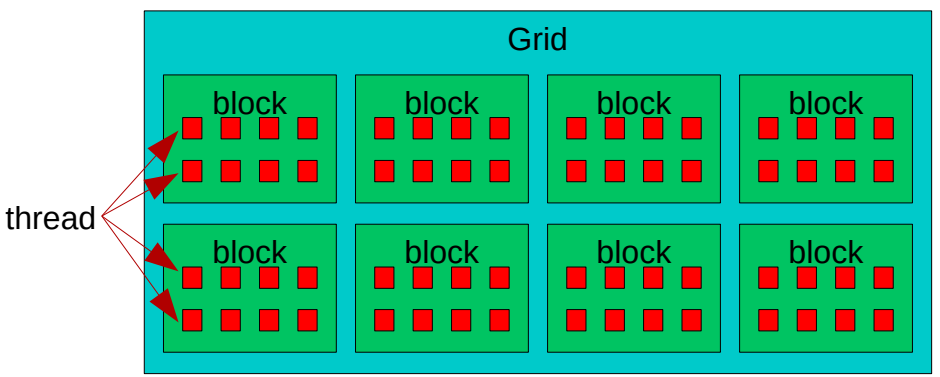
GPUs Speed Optimization: Per-Event Multithreading

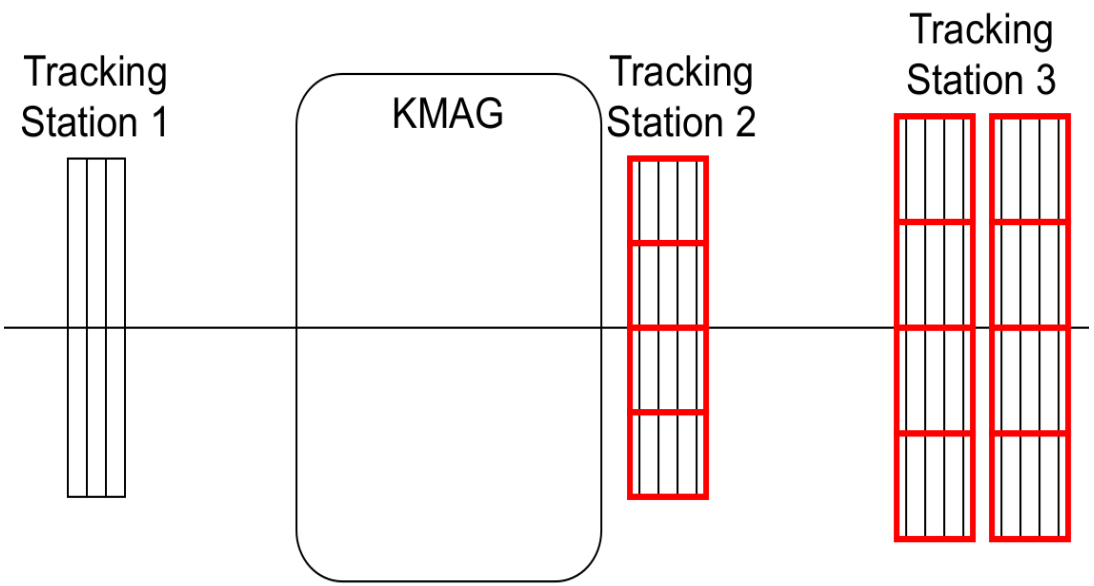
Multithreading is pivotal to achieve the required processing speed:

- Search of tracks candidates on a definite portion of the acceptance for each thread (32 threads total);
- Track candidates spread evenly over the existing threads to optimize GPU resources.

GPU workload:

- Grid dimension - Events under execution
- Block dimension - Intra-event parallelism

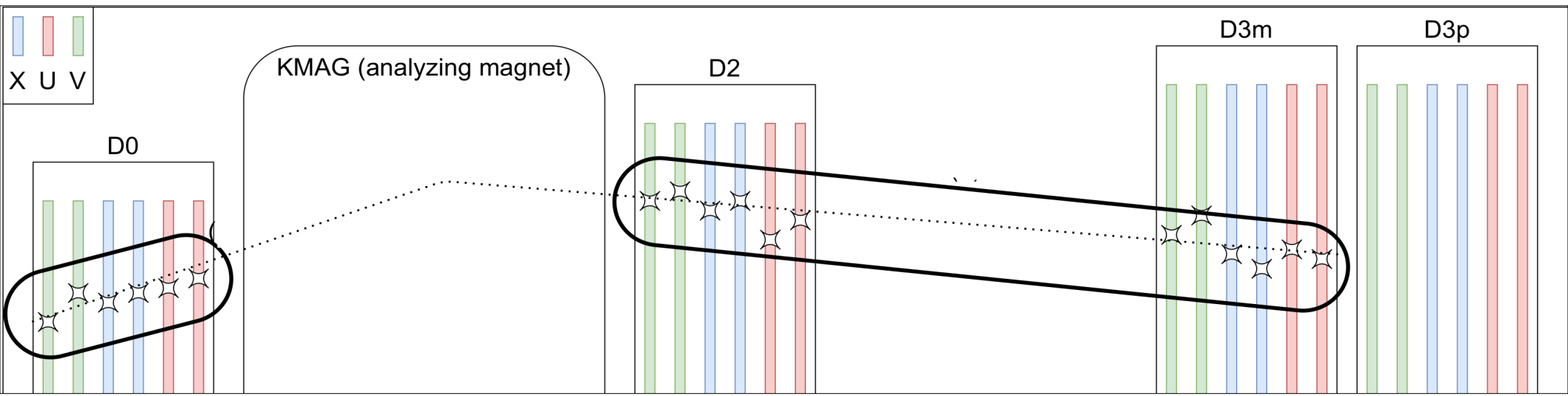




Track Reconstruction for SpinQuest

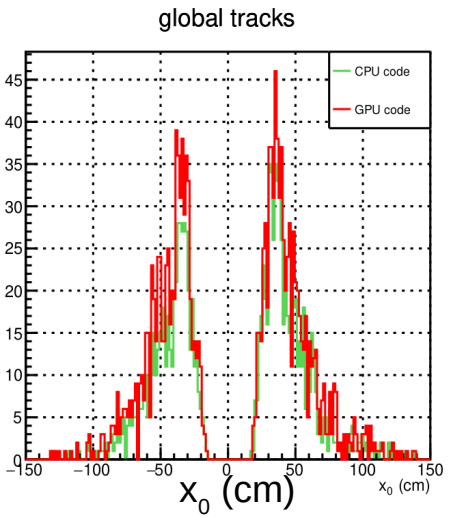
Main steps:

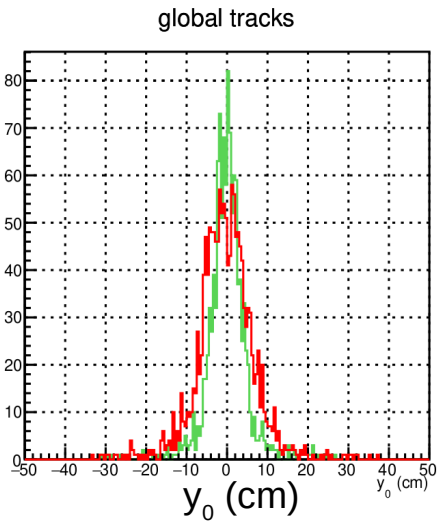
- reconstruct straight tracks from station 2 (D2) to station 3 (D3p/D3m);
- associate hits with station 1 (D0) to straight tracks;
- combining station 2-station 3 track and station 1 track segments => momentum.

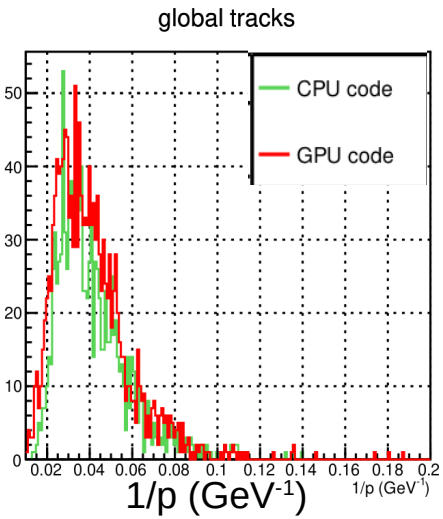


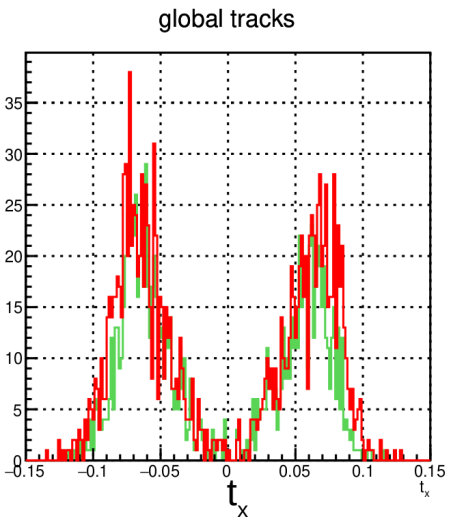
X: vertical wires
U: wires at +14 degrees with respect to x wires
V: wires at -14 degrees with respect to x wires

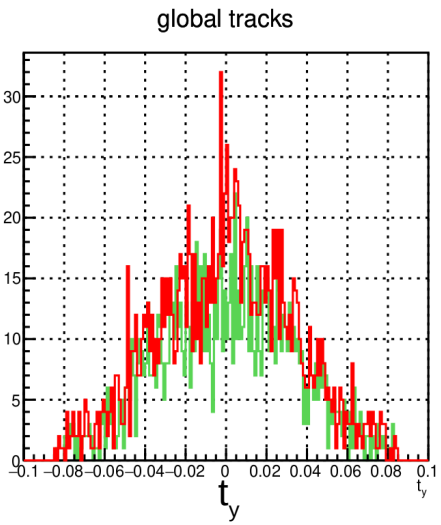
Tracking Comparison: GPU vs. CPU











Pure Monte Carlo dimuons:

Green: analysis made with CPU track reconstruction

Red: analysis made with GPU track reconstruction

x_0, y_0: track position at origin

t_x, t_y: track slope

p: momentum

GPU Online Reconstruction Performance

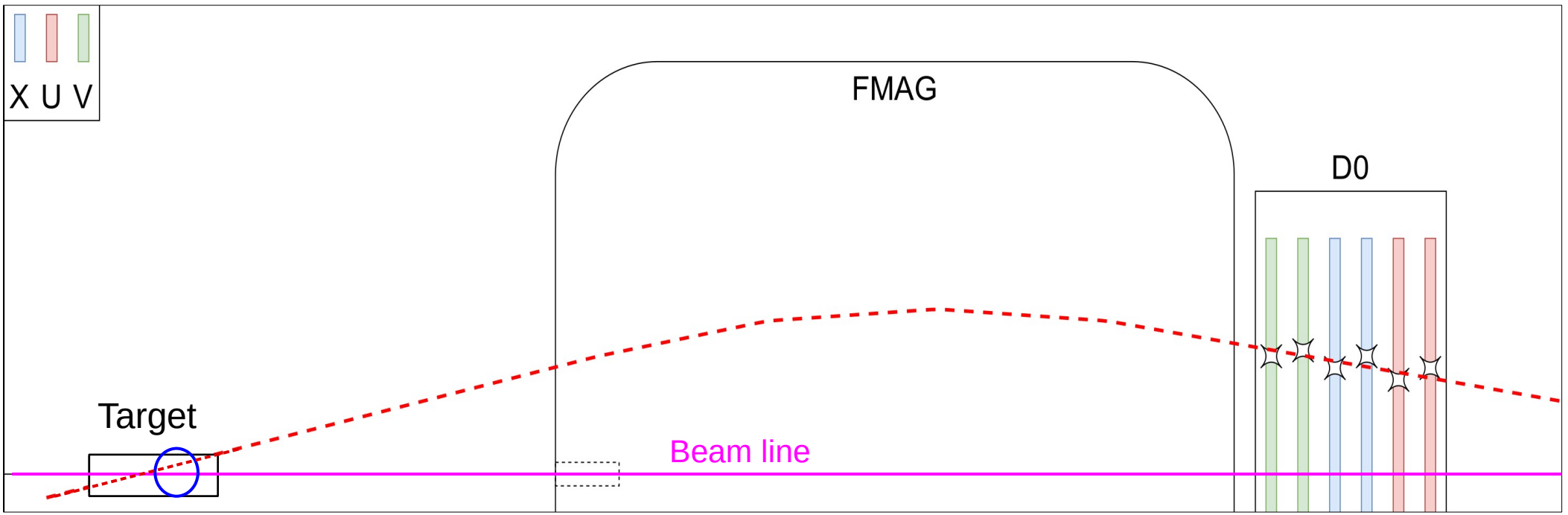
Processing of 12000 data events:

- with NVidia GTX1070 Max-Q design (2048 cores, 8GB) **35 seconds**
- *15 times faster than multi-threaded CPU program;* (CPUs not fast enough)
- further improvements expected with newest hardware (NVidia RTX4090, 16384 cores, 24GB).

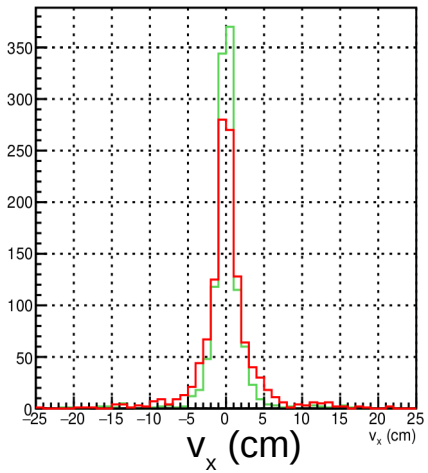
Vertex Reconstruction for SpinQuest

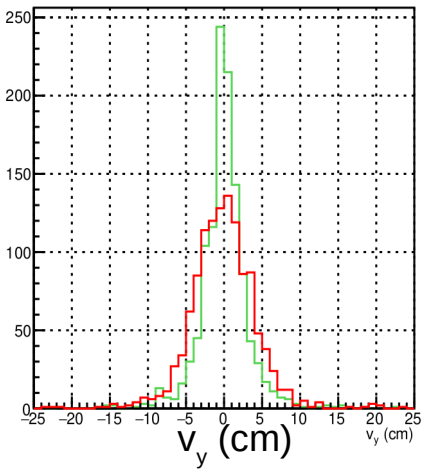
Main steps:

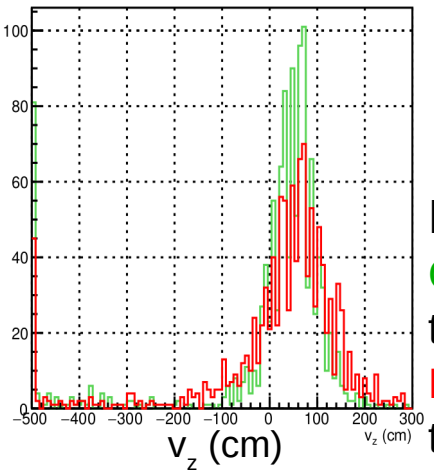
- propagate the track through the Focusing magnet;
- extrapolate the track to the target;
- distance of closest approach from beam line => vertex.



Vertex Comparison: GPU vs. CPU







Pure Monte Carlo dimuons:
Green: analysis made with CPU track reconstruction
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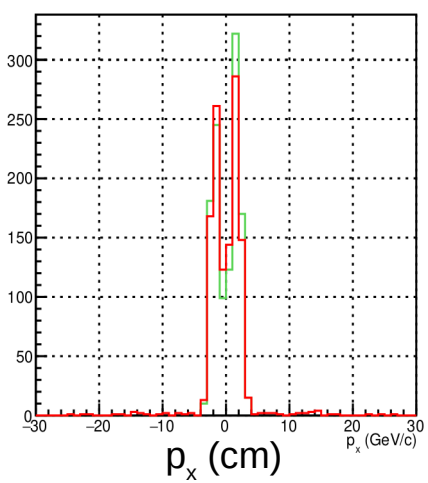

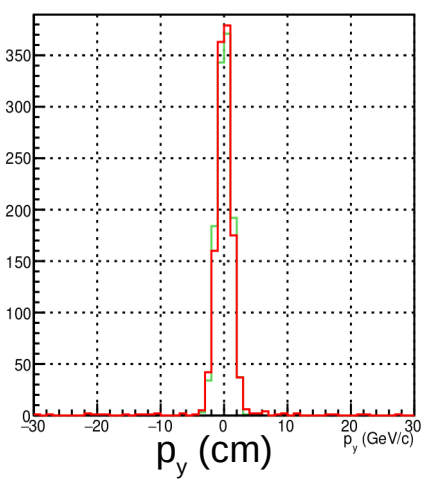

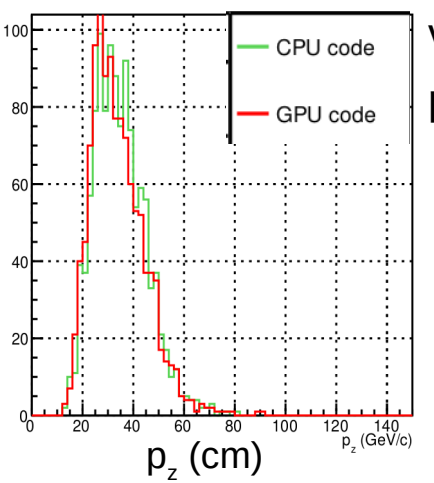

v_x, v_y, v_z: vertex position

p_x, p_y, p_z:momentum at vertex

Summary and Outlook

The Spinquest experiment will provide great insight on the question of the nucleon spin puzzle:

- Drell-Yan on the proton and the neutron => antiquark Sivers function;
- J/ψ => Gluon Sivers function!

GPU online reconstruction program close to completion

- GPU offers significant performance improvement compared to CPUs;
- Tracking and vertexing results compare reasonably well with CPU analysis;
- Next steps:
  - Optimization of the code for real data processing (ongoing);
  - online display.

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