Online Reconstruction on GPUs for J/Ψ TSSA Study at SpinQuest

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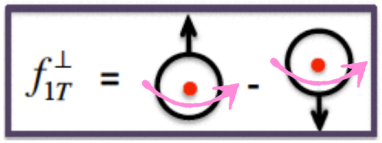
Outline

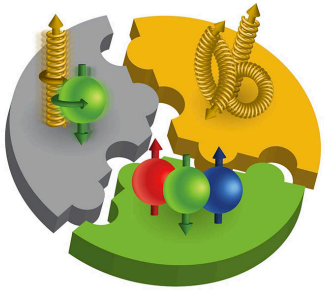
1. **The FNAL SpinQuest Experiment**
   - SpinQuest Motivation: Sivers Functions
   - Measurement of Transverse Single Spin Asymmetry (TSSA) via J/ψ Production
     - Anticipated Uncertainty for J/ψ TSSAs
   - The SpinQuest Spectrometer
2. **Online Reconstruction (OR) on GPUs at SpinQuest**
   - Overview and Status
3. **Summary**

SpinQuest Motivation: Sivers Functions

- Explore the **anti-quark** and **gluon Sivers functions,** $f_{1T}^{\perp}$:

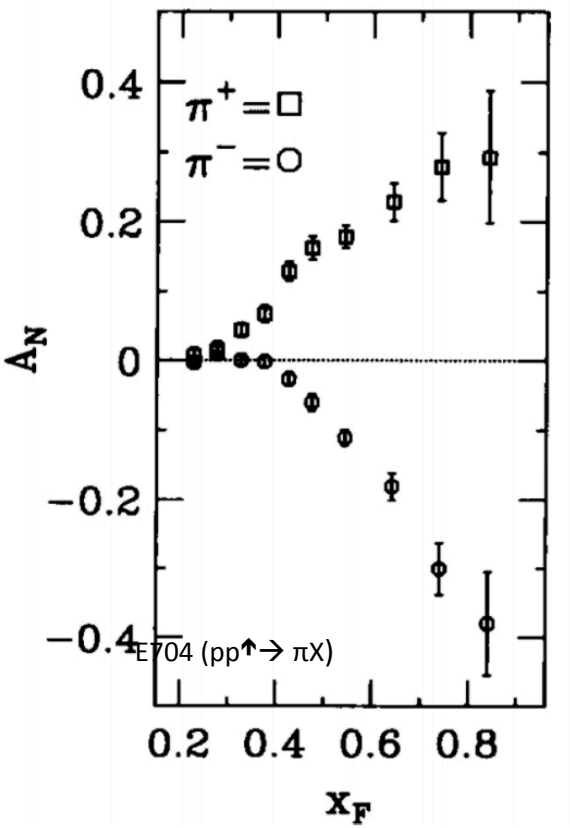


  - Large TSSAs and A_N ($\propto f_{1T}^{\perp}$) were observed in polarized pp-collisions
  - Study/constrain antiquark and gluon orbital angular momentum contributions to proton spin

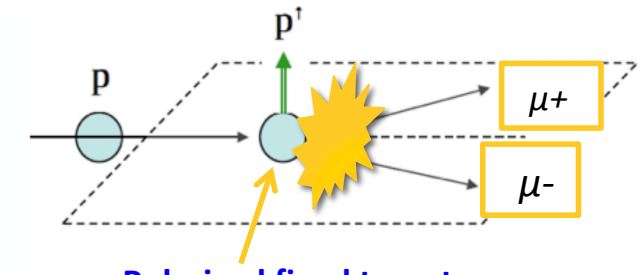


$$A_N = \frac{d\sigma^{\Uparrow} - d\sigma^{\Downarrow}}{d\sigma^{\Uparrow} + d\sigma^{\Downarrow}}$$

Phys. Lett. B 264, 462 (1991)



Sivers Functions at SpinQuest



Polarized fixed target

$x_{Bjorken} = x = p_{parton}/p_{proton}$
$x_2 = x_{target}$, $x_1 = x_{beam}$
$x_F = x_1 - x_2$

$N_{u\ (or\ d)}$ = # of dimuons for spin ↑(↓)
$L_{u\ (or\ d)}$ = live protons for spin ↑(↓)

i.e. The Drell-Yan Process

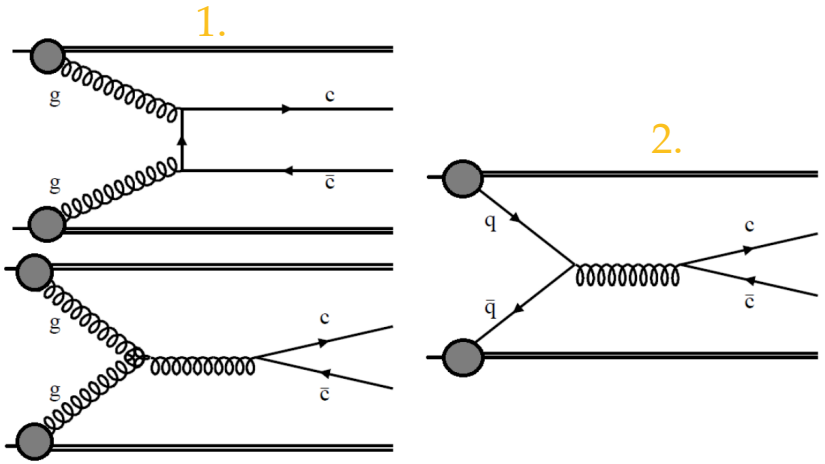
$$A_N = \frac{\frac{N_u}{L_u} - \frac{N_d}{L_d}}{\frac{N_u}{L_u} + \frac{N_d}{L_d}} \propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}$$

Small due to SpinQuest acceptance!

- Measure azimuthal asymmetry, A_N, in:
  - DY dimuon production → study anti-quark Sivers
  - **J/ψ meson dimuon decay → study gluon Sivers**

Measurement of TSSA via J/ψ Production

- The SpinQuest experiment: access to dimuon decay of the J/ψ meson (charm, anti-charm bound state)
- Mechanisms:
  1. gluon-gluon (g-g) fusion
  2. quark anti-quark (q-q-) annihilation

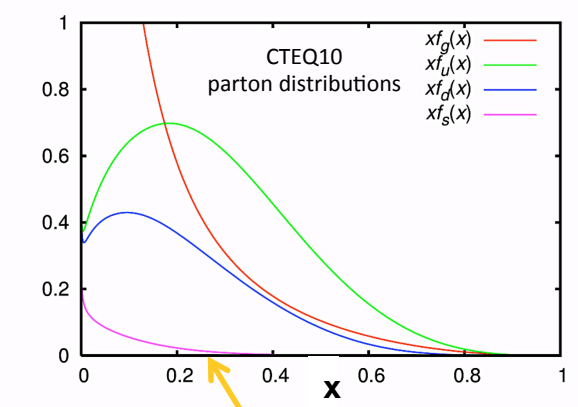


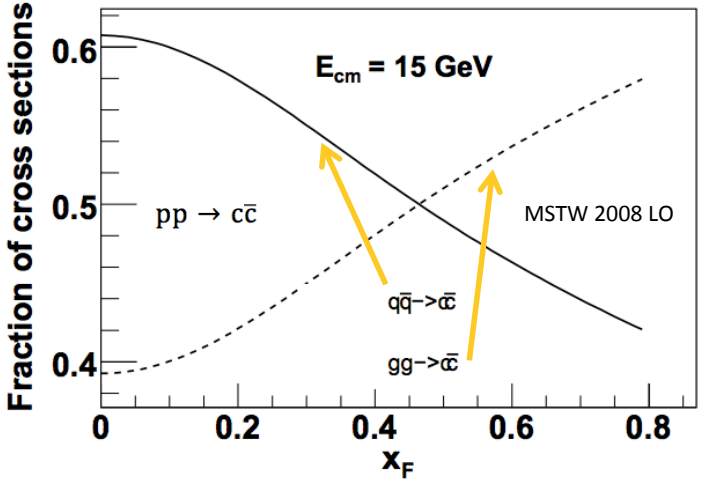
$$H_{beam,target}(x_{target}, x_{beam}; M^2) = g(x_{beam})g(x_{target})\sigma(gg \to c\bar{c}; M^2)$$
$$+ \sum_{i\in\{u,d,s,\ldots\}}^{n} [f_i(x_{beam})\bar{f}_i(x_{target}) + \bar{f}_i(x_{beam})f_i(x_{target})]\sigma(q\bar{q} \to c\bar{c}; M^2)$$

$$\frac{d^2\sigma}{d\tau dx_F} = \frac{2\tau}{\sqrt{{x_F}^2 + 4\tau^2}} H_{beam,target}(x_{target}, x_{beam}; x_{target}x_{beam}s)$$

Measurement of TSSA via J/ψ Production

- TSSAs (up to ~40%) observed in light hadron production in $0.1 < x < 0.5$
- **g-g fusion**: dominant mechanism for J/ψ production at SpinQuest
  - Acceptance $x_F \gg 0$ at J/ψ mass
  - q-q-bar vs. g-g / sum of cross sections → gg mechanism dominant at SpinQuest's E_{cm} (= 15 GeV) for $x_F > 0.42$
- J/ψ TSSA: study of gluon Sivers and QCD dynamics in hadron production with **improved statistics** in higher x_F region!





arXiv:1110.4268

Anticipated Uncertainty for J/ψ TSSAs

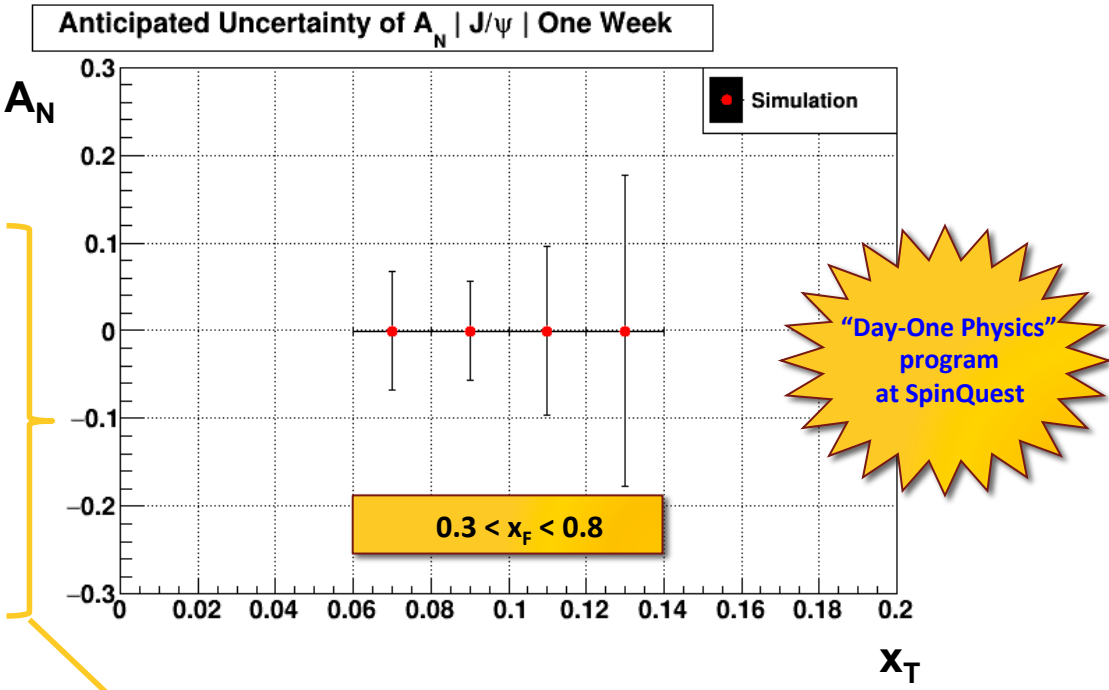
- Rate of dimuons estimated by Geant4 simulations
- **One week** of dedicated data taking was assumed
  - Integrated luminosity: L_{1w}= 7e4 pb^{-1} & L_{sim}= 8414.86 pb^{-1}
  - Dilution factor: f = 0.176
  - Polarization: P = 80%

Φ_S = azimuthal angle b/t target spin & hadron plane

x_T = Bjorken-x target

Binning in (x_T, ϕ_{S_i})

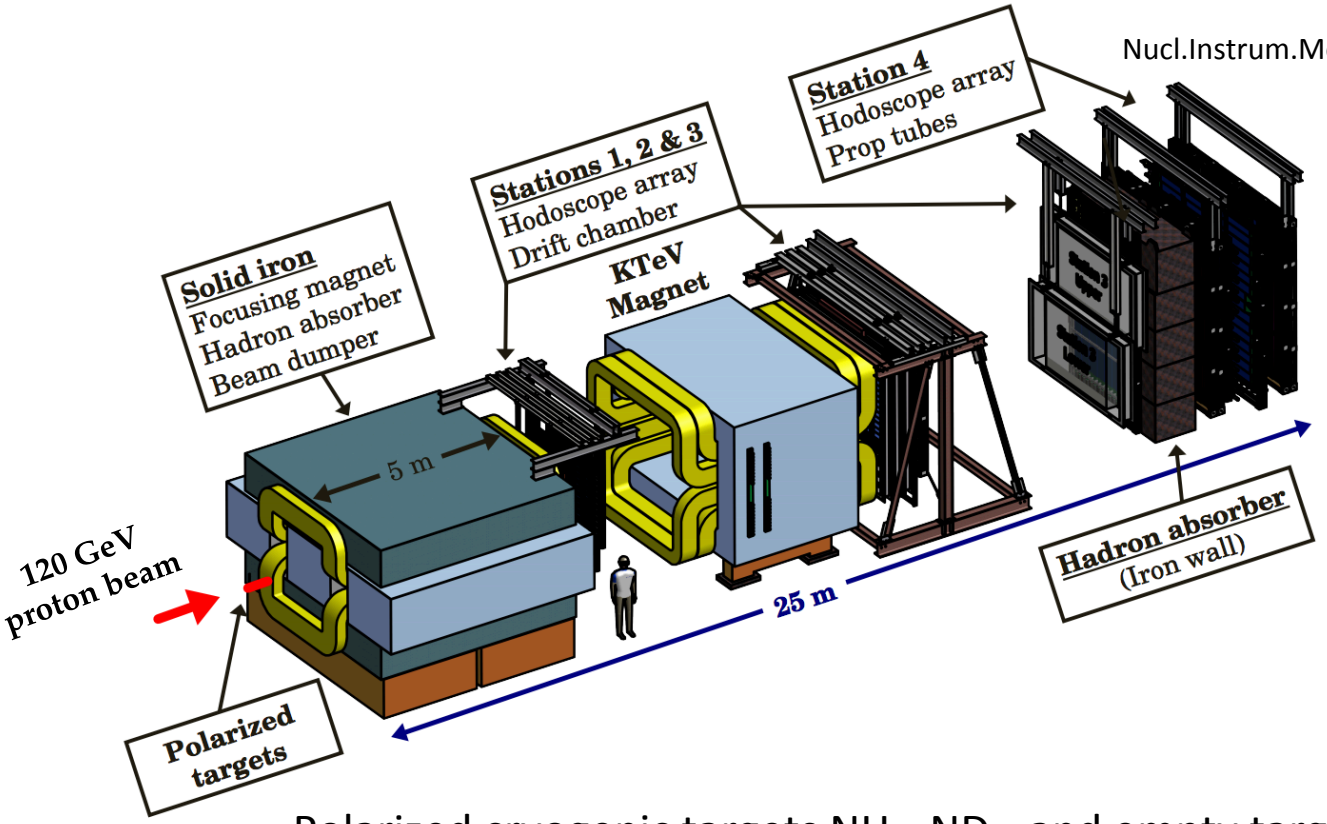
$$A_N = \frac{2}{f}\frac{\sum_i N(x_T,\phi_{S_i})\sin\phi_{S_i}}{\sum_i N(x_T,\phi_{S_i})}$$



$$\delta_{AN}^{1w} = 1/f \cdot 1/P \cdot \delta_{AN}^{sim} \cdot \sqrt{L^{sim}/L^{1w}}$$

$$\delta_{AN}^{sim} \sim 1/\sqrt{N_{measured}}$$

The SpinQuest Spectrometer

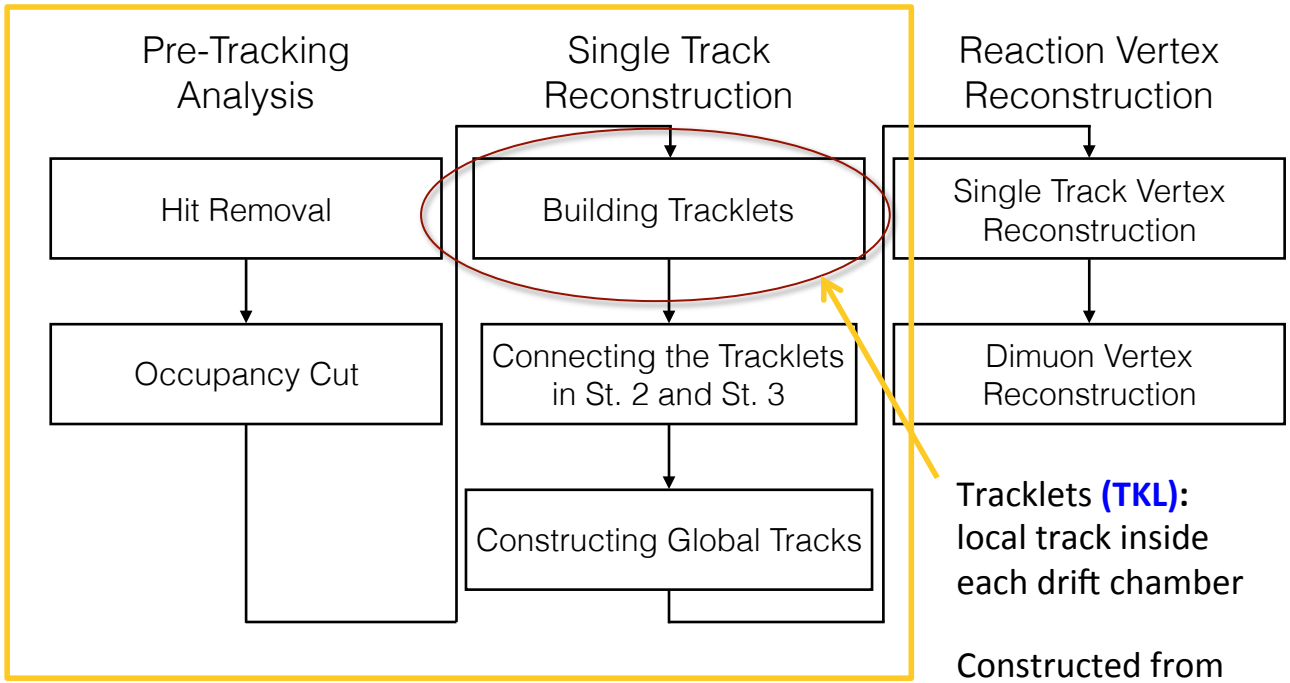


Nucl.Instrum.Meth.A 930 (2019)

Located in NM4 enclosure at Fermi National Accelerator Laboratory (Fermilab)

- Polarized cryogenic targets NH_3, ND_3, and empty target
- Dynamic nuclear polarization (~ 80% target polarization at 4% uncertainty)
- Kept at 1K in 5T field, polarization flip every 8 hours

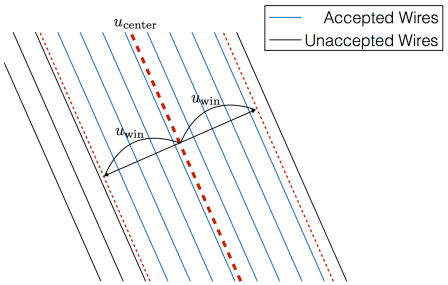
Tracking Framework Overview

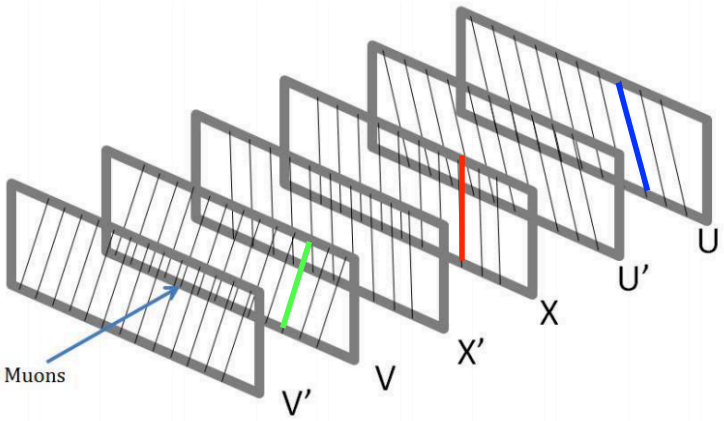


Online reconstruction (OR) framework will focus first on improved single track reconstruction

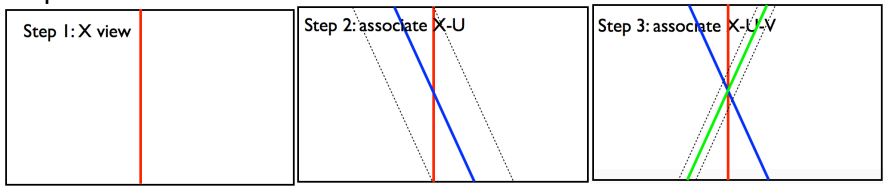
Tracklets **(TKL)**: local track inside each drift chamber

Constructed from plane hit triplets

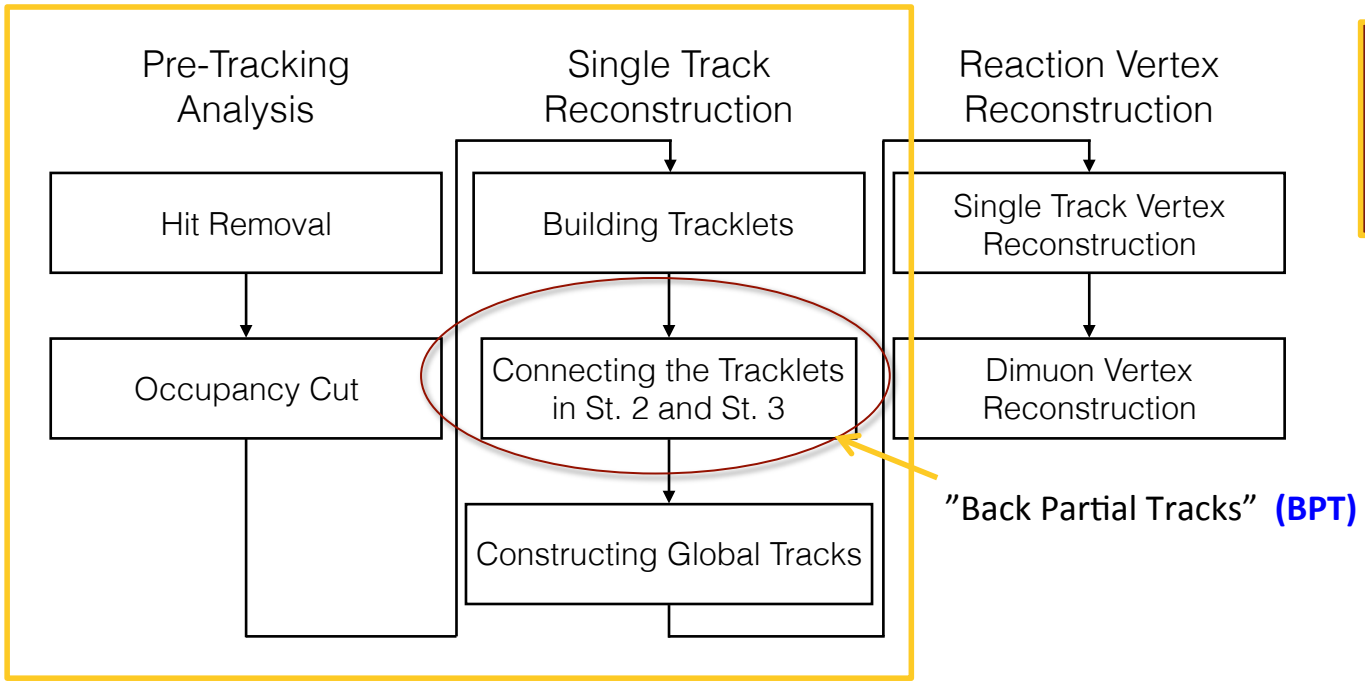




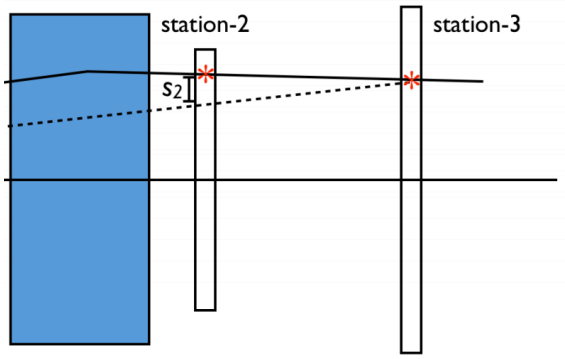
Triplet search window

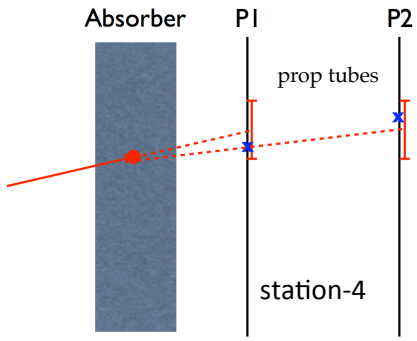


Tracking Framework Overview



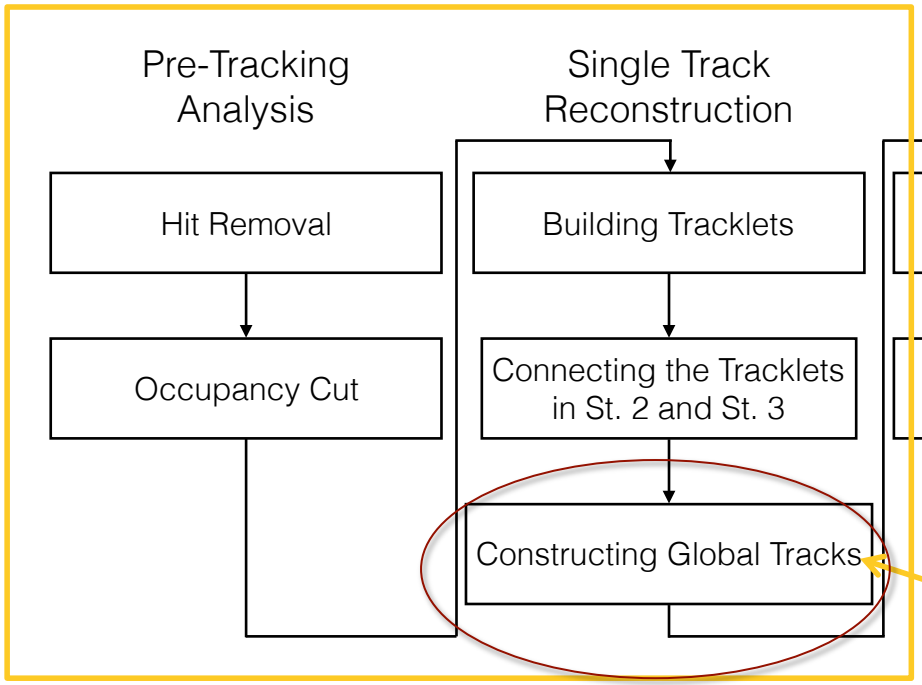
Online reconstruction (OR) framework will focus first on improved single track reconstruction





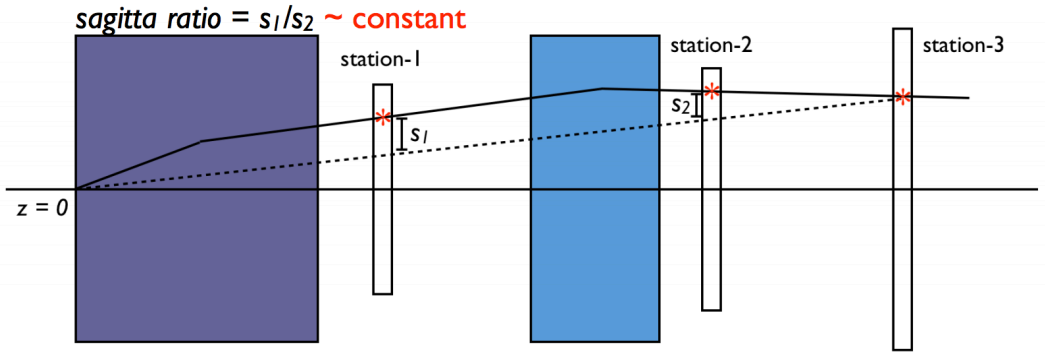
TKLs from St. 2 an 3 only matched if X hits point to valid prop tube in St.4

Tracking Framework Overview



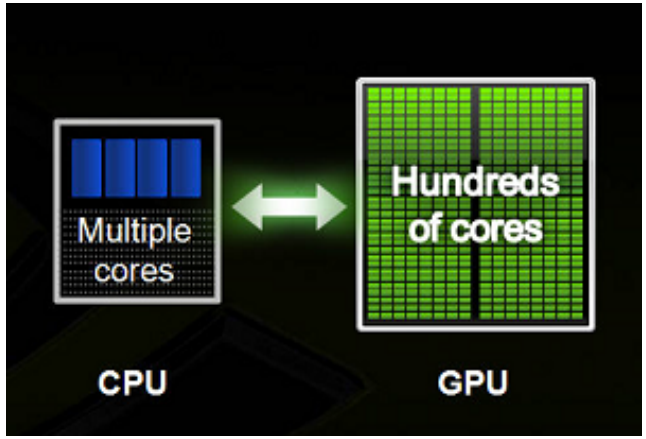
Online reconstruction (OR) framework will focus first on improved single track reconstruction

Tracklets in St.1 + Back partial Tracks = Global Tracks **(GT)**

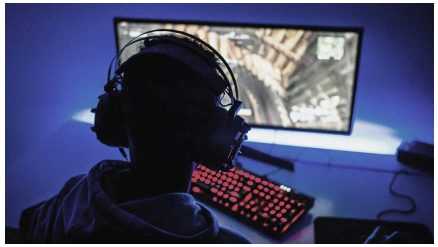


GPU OR Motivation

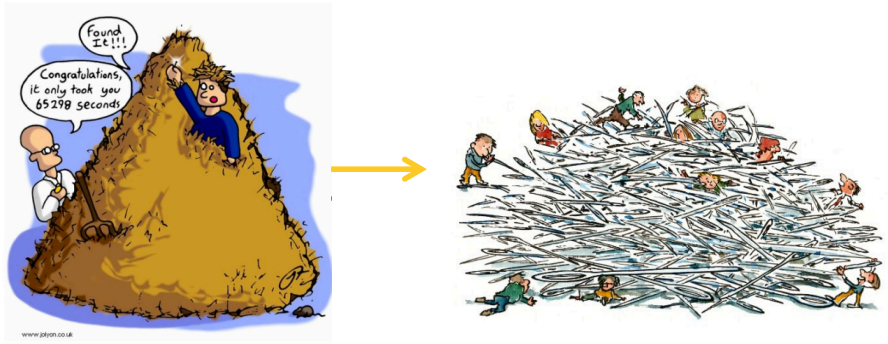
- Use multi-threaded application to:
  - Improve performance of event reduction and track reconstruction
  - Test using SeaQuest data and Monte Carlo simulations
- Implement in CUDA with Nvidia GPUs
- Other GPU applications: gaming, driverless cars, AI training…



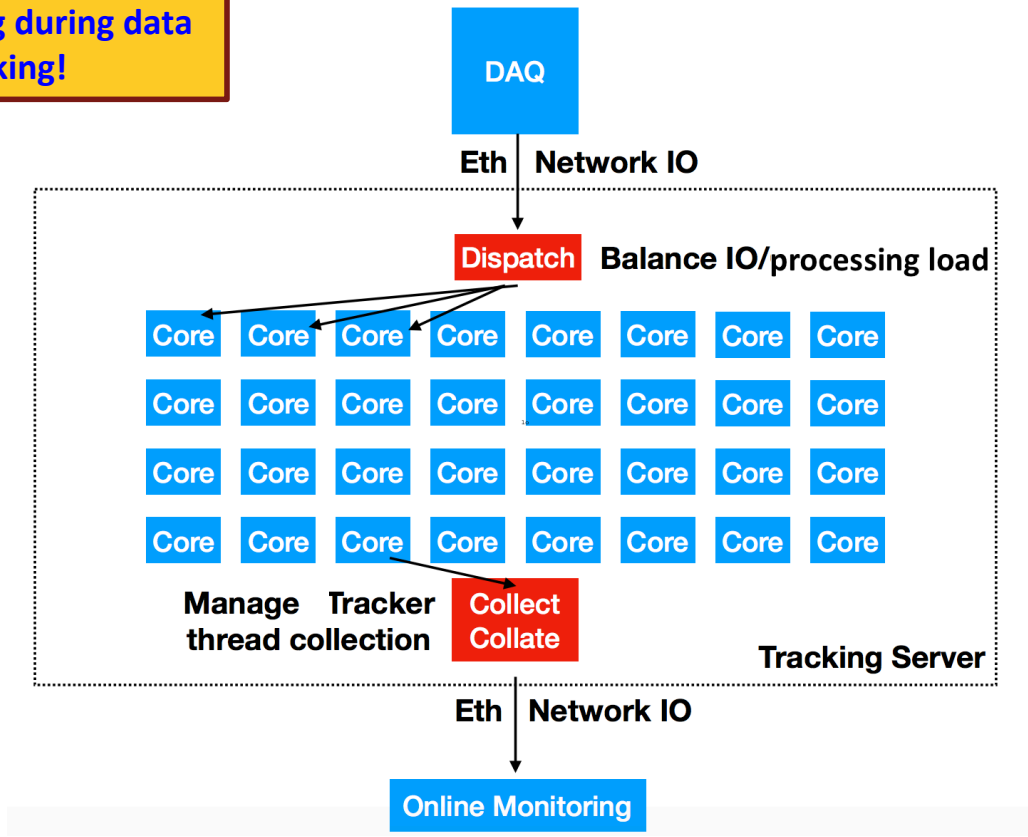
$349, 1920 cores



OR Schema

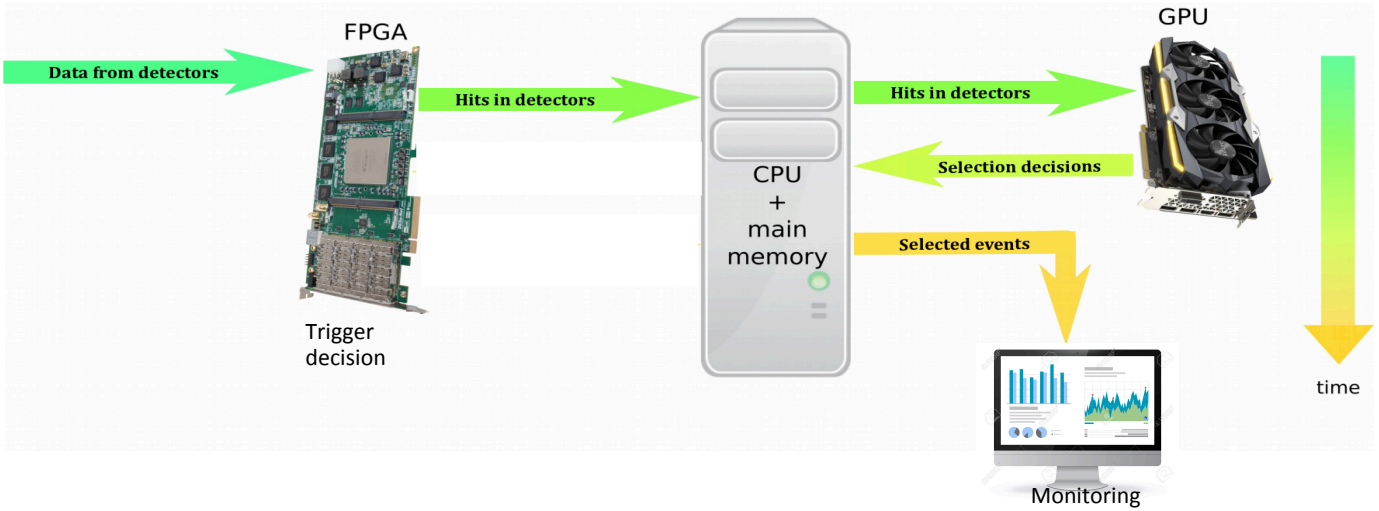


Fast and efficient online monitoring during data taking!

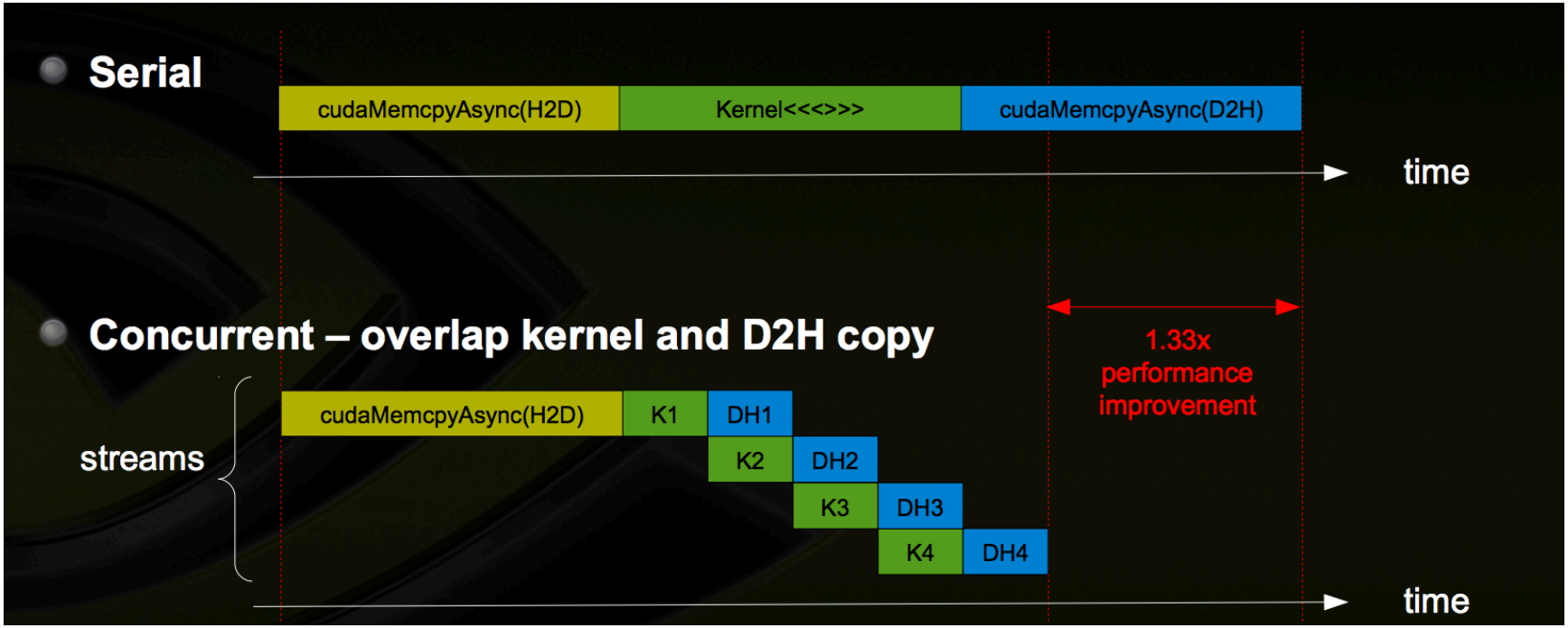


Features of GPU OR Framework

- Multithreading and multistreaming
- Cross-platform compatibility with CPU architectures
- Single transfer of data to GPU device
- No dynamic memory allocation
- Pass through events that will not finish in time via scheduling



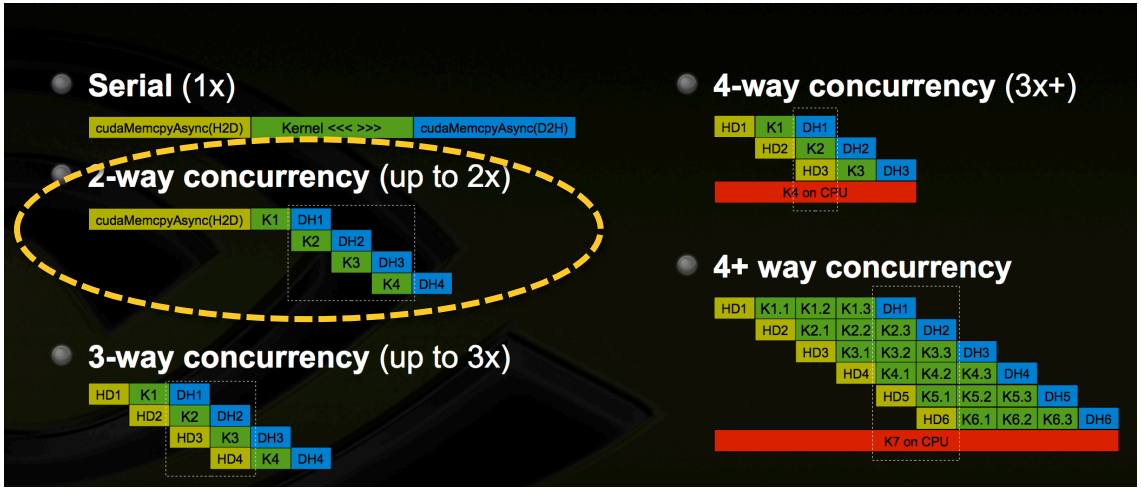
Features of GPU OR Framework



Features of GPU OR Framework

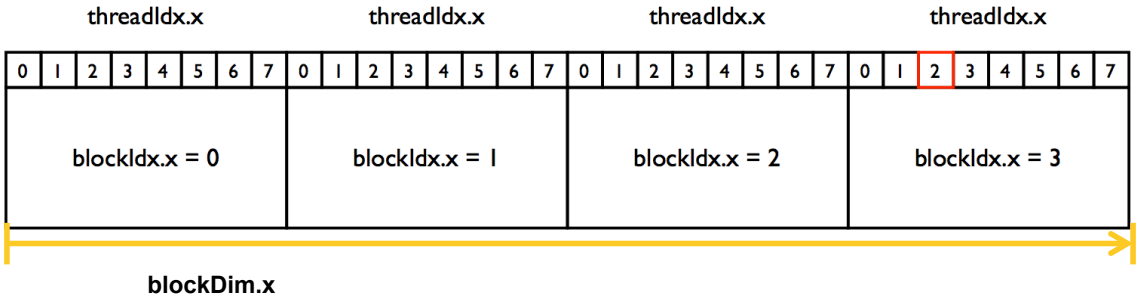
```
cudaMalloc ( &dev1, size ) ;
double* host1 = (double*) malloc ( &host1, size ) ;
…

cudaMemcpy ( dev1, host1, size, H2D ) ;
kernel2 <<< grid, block >>> ( …, dev2, … ) ;
some_CPU_method ();
kernel3 <<< grid, block >>> ( …, dev3, … ) ;
cudaMemcpy ( host4, dev4, size, D2H ) ;
...
```

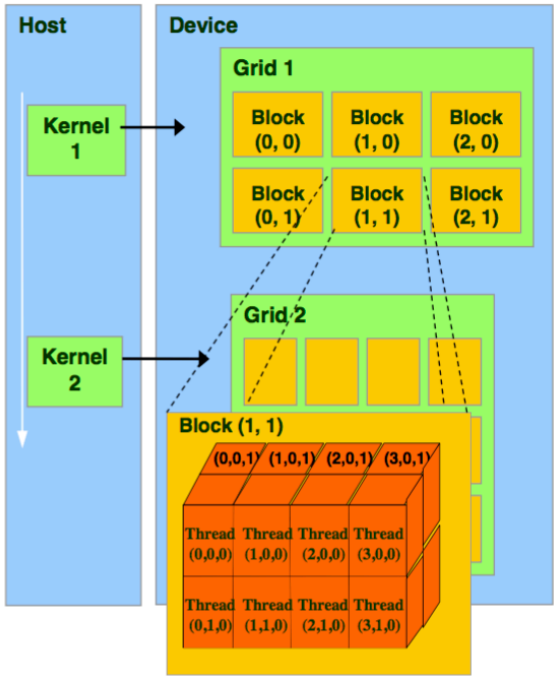
potentially overlapped



Features of GPU OR Framework

- **Parallelization schema**: defined at each stage
  - Pre-tracking and triplet hit construction→ simple, fixed parallelization schema (1 thread per event)
  - Tracklet/track χ^2 analysis → tailored to fitting needs, for each fitting subroutine

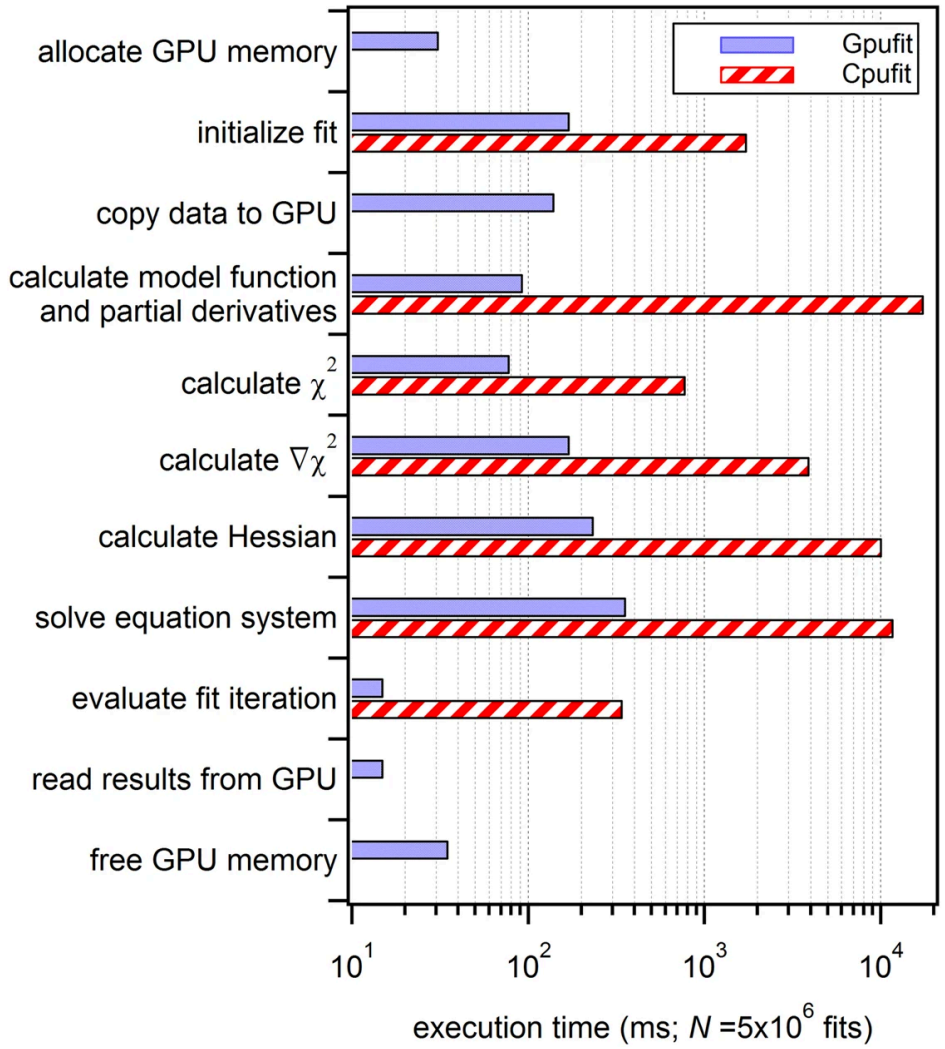





```
int const shared_size = blockDim.x / n_fits_per_block;
int const fit_in_block = threadIdx.x / shared_size;
int const fit_piece = blockIdx.x / n_fits;
int const fit_index = blockIdx.x * n_fits_per_block + fit_in_block - fit_piece * n_fits;
int const point_index = threadIdx.x - fit_in_block * shared_size + fit_piece * shared_size;
int const first_point = fit_index * n_points;
```

Performance Metrics

- From Gpufit library--Przybylski, A., J. et al. Gpufit: An open-source toolkit for GPU-accelerated curve fitting (2017)
  - github.com/gpufit/Gpufit
- **Plot**: comparison of execution times for each section of the Cpufit and Gpufit programs
  - 2D Gaussian fits
- All sections of the fit algorithm required less time when executed on the GPU



Performance Metrics

Process	Time (s)
Read and prepare events from loaded file (CPU)	1.92
Copying data (host to device)	0.44
Event reducer (GPU)	**0.81**
GPU parameters: 20 blocks, 512 threads per block, 10240 threads (9607 events processed, 114MB)	

Compared to ~ **6 minute** processing time on CPU!

Processor/Process	Time (s)	# of Fits
CPU/**TKL**	21.905	564,946
GPU/**TKL**	0.765	564,946
CPU/**BPT**	98.67	345,378
GPU/**BPT**	4.561	345,378
CPU/**GT**	253.891	302,734
GPU/**GT**	17.876	302,734

×30

×20

×15

Summary

- Polarized DY and J/ψ data at SpinQuest will help constrain important anti-quark and gluon Sivers functions
  - First J/ψ TSSA measurement will be available quickly and with good statistical precision
- Track reconstruction software on GPUs will:
  - Lay groundwork for next tracking stage: vertex reconstruction
  - Allow for efficient monitoring of data quality
  - Improve reconstruction speed and performance
  - Help pave the way for robust analyses at SpinQuest

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Back up

Anticipated Uncertainty for J/ψ TSSAs