GPU Online Reconstruction in J/Ψ TSSA Study at SpinQuest

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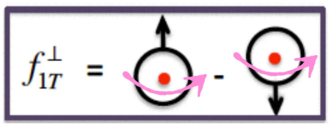
APS Topical Group on Hadronic Physics (GHP) Workshop

Overview

1. **The SpinQuest Experiment**
   - SpinQuest Motivation
   - Sivers Function at SpinQuest
   - J/ψ Production
   - J/ψ TSSAs (transverse single spin asymmetries)
   - Anticipated Accuracy for J/ψ TSSAs
   - The SpinQuest Spectrometer
2. **Online Reconstruction (OR) on GPUs at SpinQuest**
   - Tracking Framework
   - Improving Tracking and OR at SpinQuest
   - Features of GPU Tracking Framework
   - Status of OR Software
3. **Conclusion**

SpinQuest Motivation

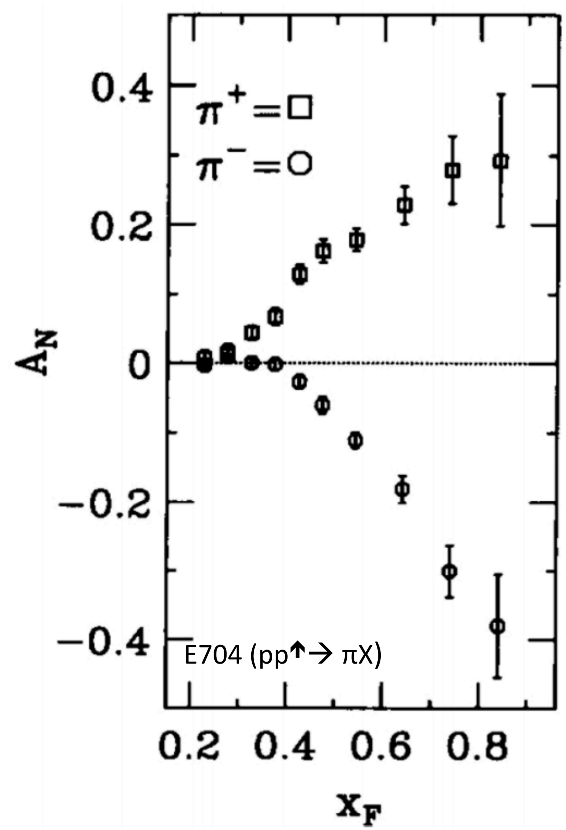
- Explore the **anti-quark** and **gluon Sivers functions**, $\boldsymbol{f_{1T}}^{\perp}$:

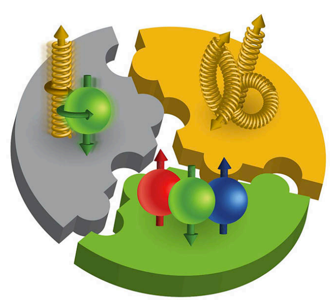


  - Large transverse single spin asymmetries (TSSAs), $A_N(\propto \boldsymbol{f_{1T}}^{\perp})$, observed in polarized pp-collisions
  - Study/constrain antiquark and gluon orbital angular momentum contributions to proton spin

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

Phys. Lett. B 264, 462 (1991)

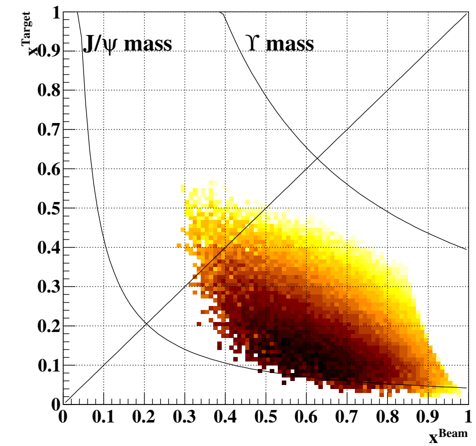


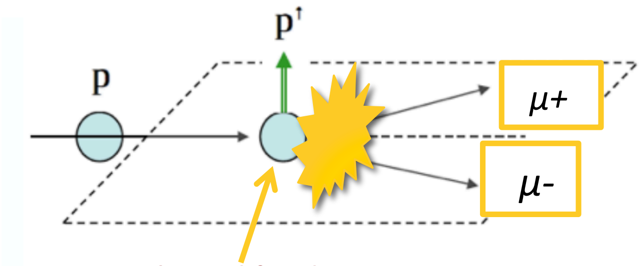


Details in previous talk by K. Nakano

Sivers Function at SpinQuest

SpinQuest Acceptance





i.e. The Drell-Yan Process: $p(q)p^{\uparrow}(\bar{q}) \rightarrow \mu^{+}\mu^{-}$

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

Small due to SpinQuest acceptance!

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

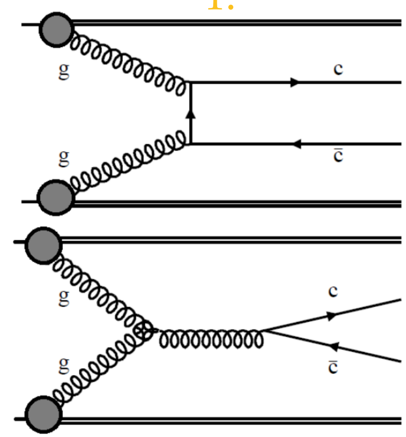
$x_{Bjorken} = x = p_{parton}/p_{proton}$
$x_2 = x_{target}$, $x_1 = x_{beam}$
$x_F = x_1 - x_2$

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

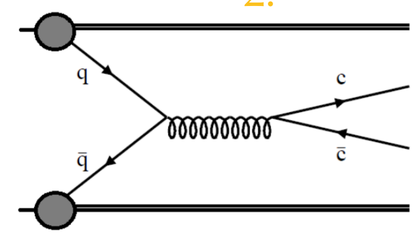
J/ψ Production

- The SpinQuest experiment can measure dimuons resulting from the decay of the J/ψ meson, a charm anti-charm bound state
- Two possible production mechanisms:
  1. gluon-gluon (g-g) fusion
  2. quark anti-quark annihilation

1.



2.



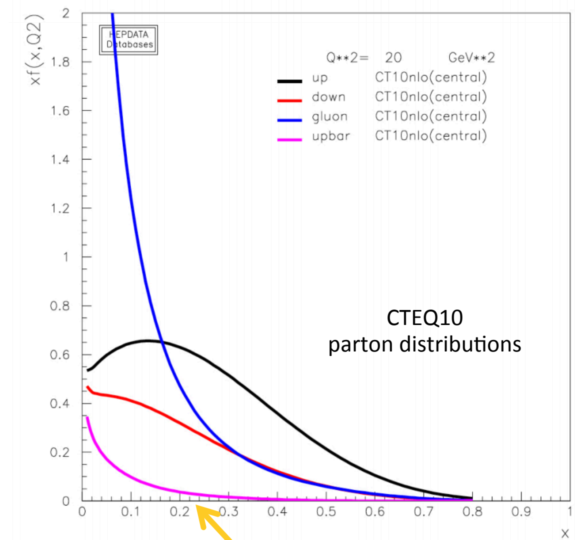
$$H_{beam,target}(x_{target}, x_{beam}; M^2) = \overbrace{g(x_{beam})g(x_{target})\sigma(gg \to c\bar{c}; M^2)}^{1.}$$

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

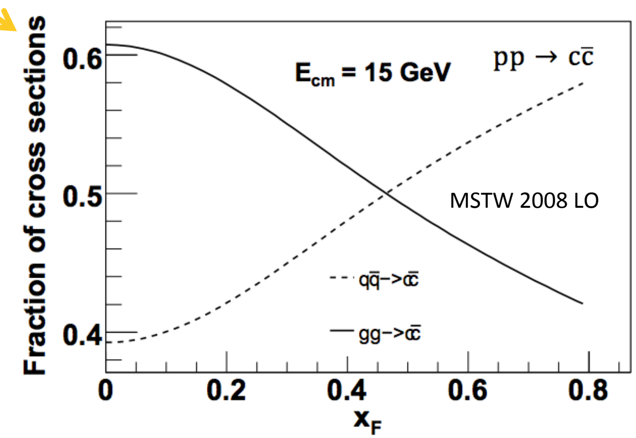
$$\frac{d^2\sigma}{d\tau dx_F} = \frac{2\tau}{\sqrt{{x_F}^2 + 4\tau^2}} H_{beam,target}(x_{target}, x_{beam}; x_{target}x_{beam}s)$$

J/ψ TSSAs

- 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- vs. g-g / Σ cross sections → gg mechanism dominant at SpinQuest's E_{cm} (=15GeV) for $x_F > 0.42$
- J/ψ TSSA to study gluon Sivers and QCD dynamics in hadron production with **improved statistics**!
  - Measurement by 120-GeV p + p is **unique**



Many gluons below 0.22!



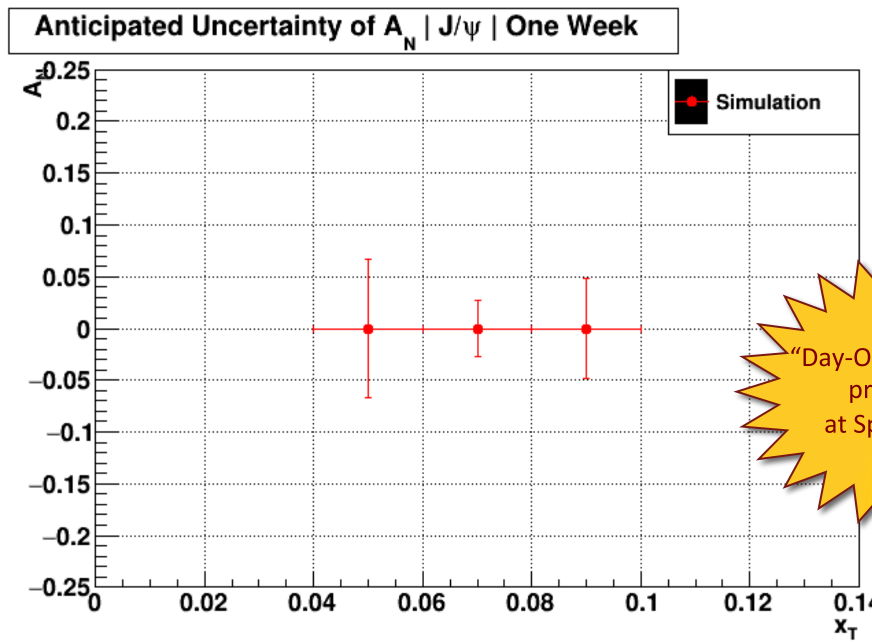
arXiv:1110.4268

Anticipated Uncertainty for J/ψ TSSAs

- Rate of in-acceptance dimuons estimated by GMC:
  - PYTHIA8 charmonium production
  - Geometric acceptance considered
  - Tracker reconstructed
- **One week** of dedicated data taking was assumed
  - Integrated luminosity: L_{1w} = 1.75e4 pb^{-1} & L_{sim} = 6567 pb^{-1}
  - Dilution factor: f = 0.176
  - Polarization: P = 0.8

Binning in (x_T, ϕ_{S_i})

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



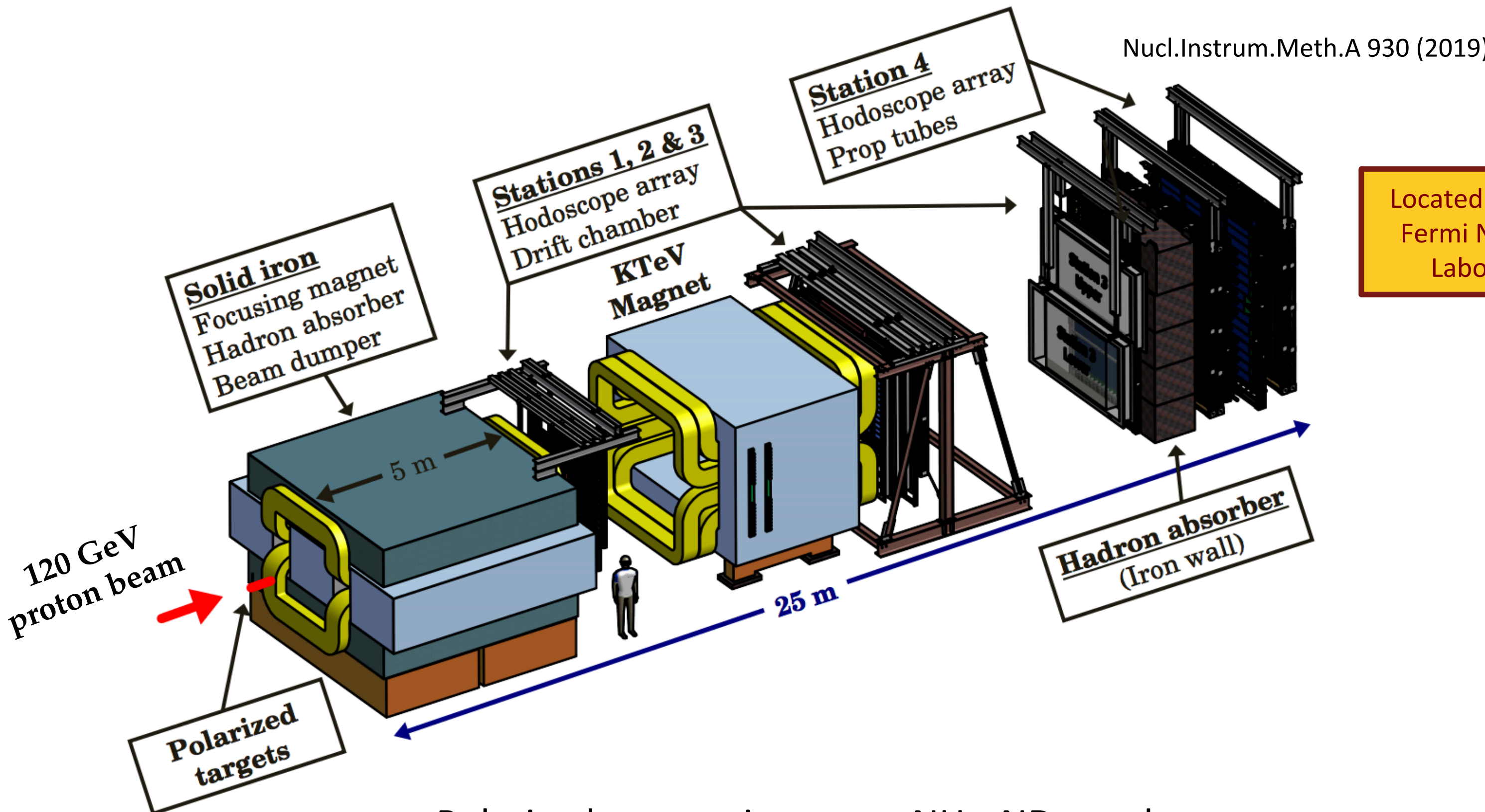
"Day-One Physics" program at SpinQuest

$$\delta_{AN}^{1w} = 1/f \cdot 1/P \cdot \delta_{AN}^{sim} \cdot \sqrt{L^{sim}/L^{1w}} = 3.3 \cdot \delta_{AN}^{sim}$$

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

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

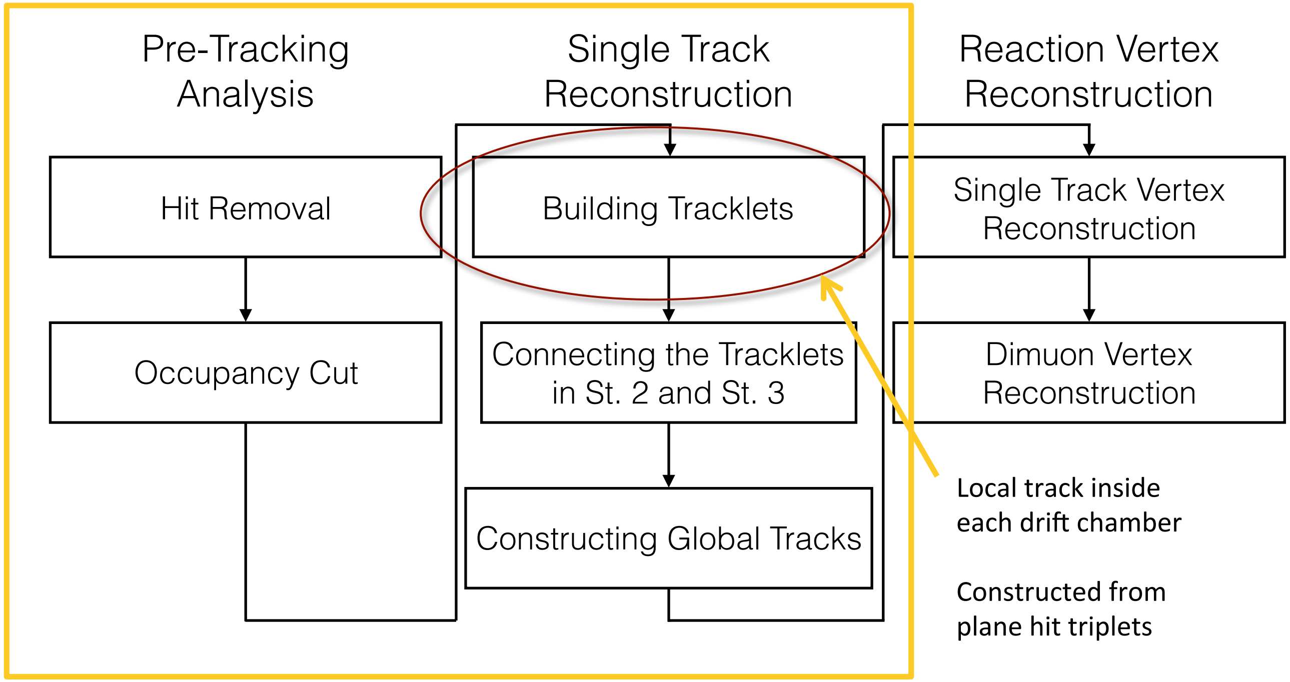
The SpinQuest Spectrometer



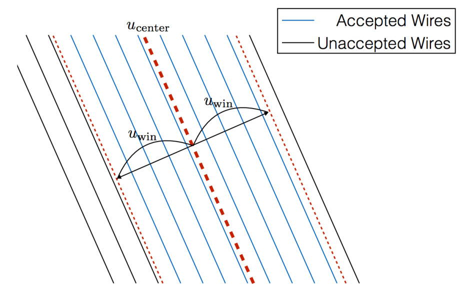
Located in NM4 enclosure at Fermi National Accelerator Laboratory (Fermilab)

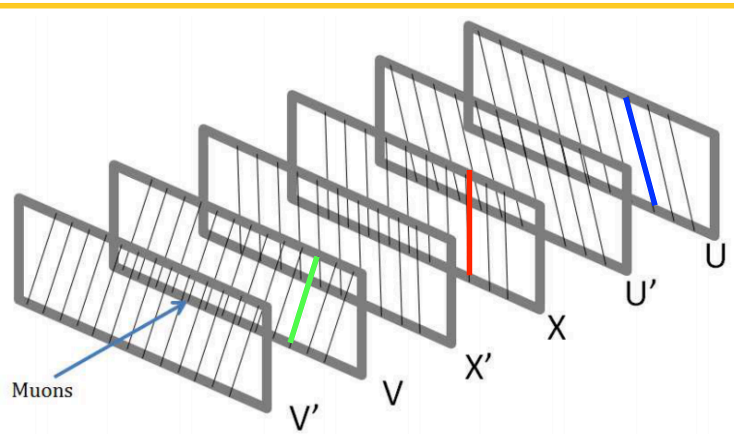
- Polarized cryogenic targets NH_3, ND_3, and empty target
- Dynamic nuclear polarization (~ 80% target polarization at 4% uncertainty)
- Kept at 1K in 5 T field, polarization flip every 8 hours

Tracking Framework

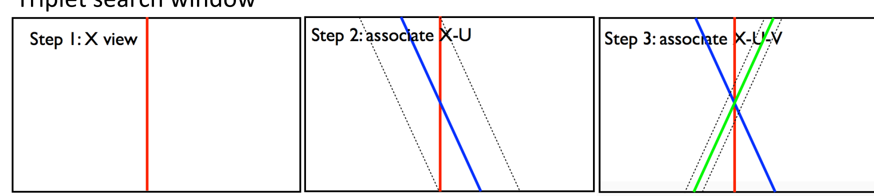


Online reconstruction (OR) framework will focus first on improved single track reconstruction

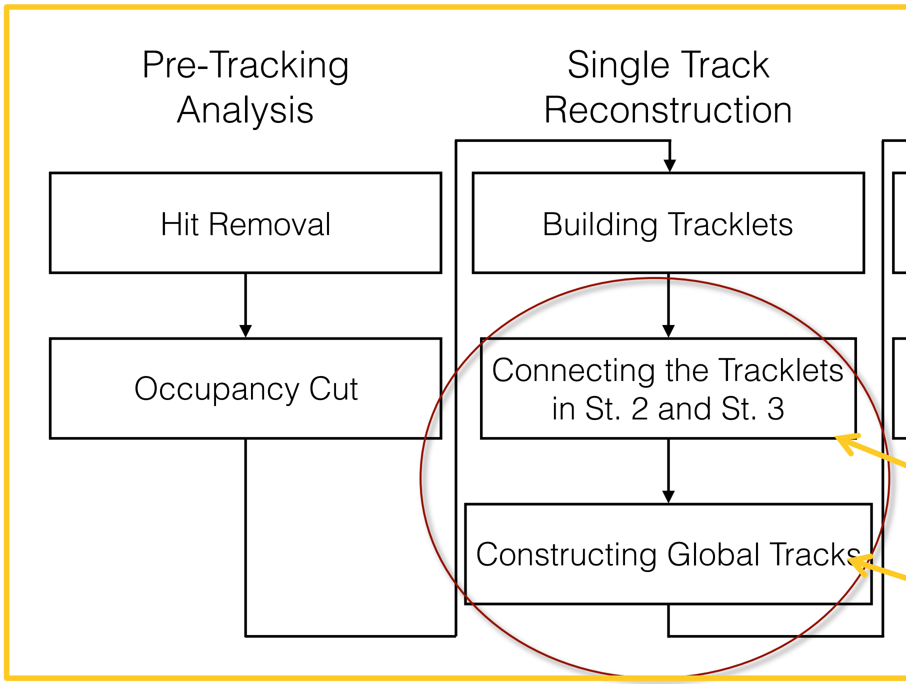




Triplet search window



Tracking Framework



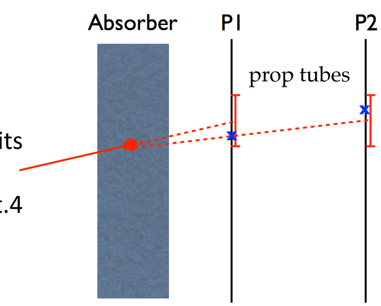
Online reconstruction (OR) framework will focus first on improved single track reconstruction

"Back Partial Tracks"

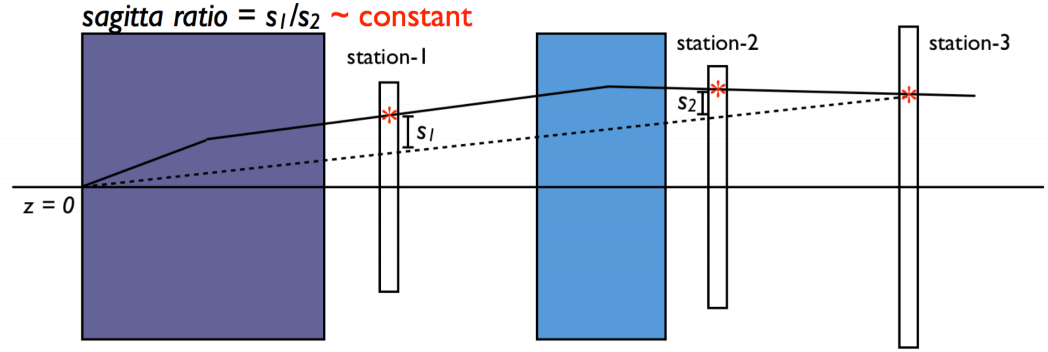
Tracklets in St.1 + Back partial Tracks = Global Tracks

station-4

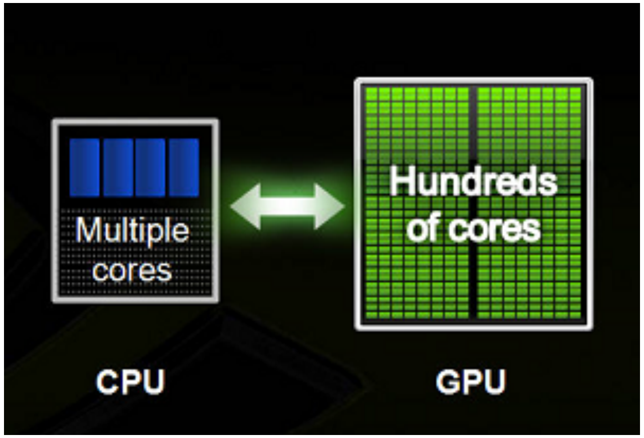
Tracklets from St. 2 an 3 only matched if X hits point to valid prop tube in St.4



sagitta ratio = s_1/s_2 ~ constant

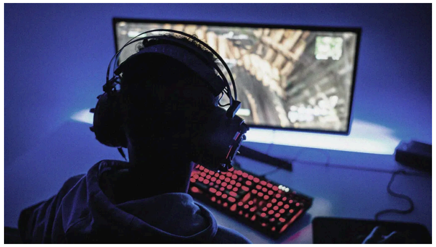


Improving Tracking and OR at SpinQuest



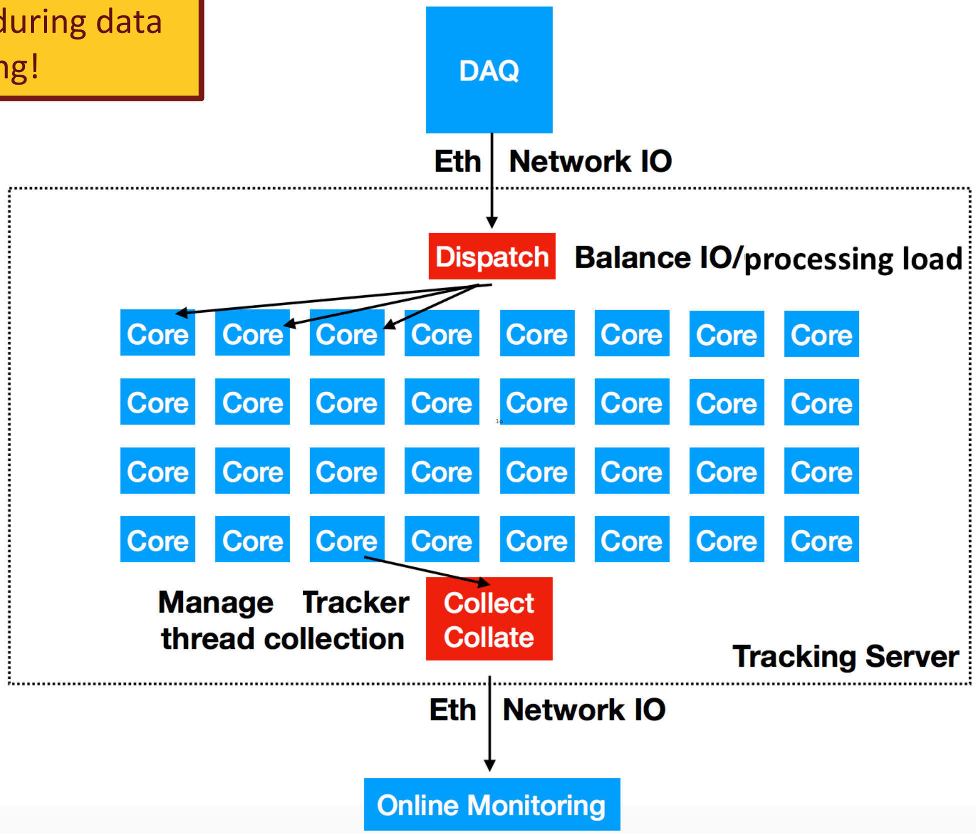
- Use multi-threaded application to:
  - Improve performance/speed of event "cleaning" and single track reconstruction
  - Test using data files from SeaQuest
- Implement in **CUDA** with Nvidia GPUs
- Other GPU applications: gaming, driverless cars, AI training…

$349, 1920 cores



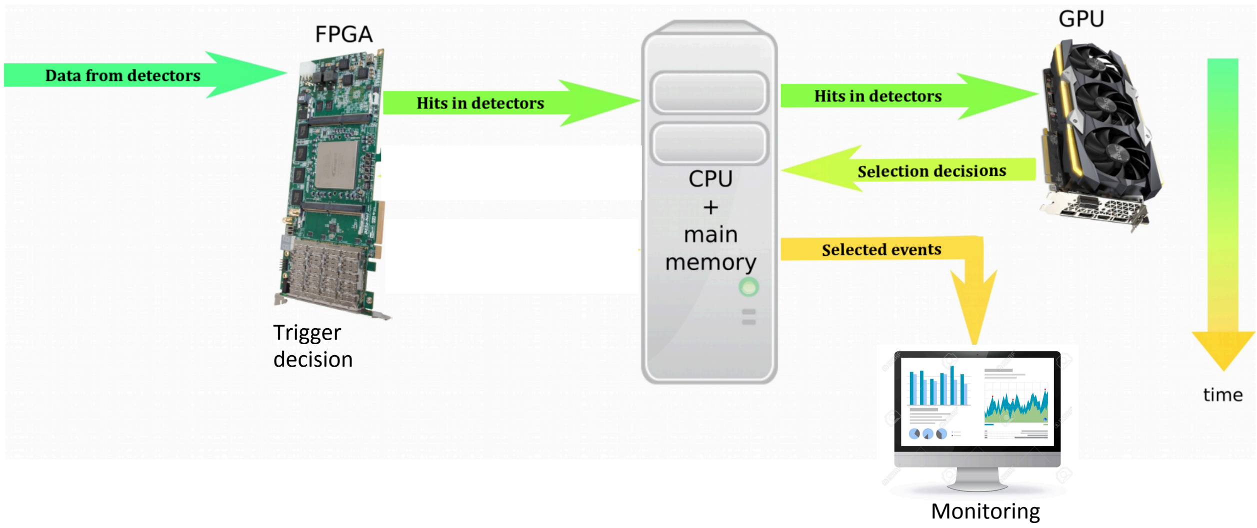
Eventually…

Fast and efficient online monitoring during data taking!

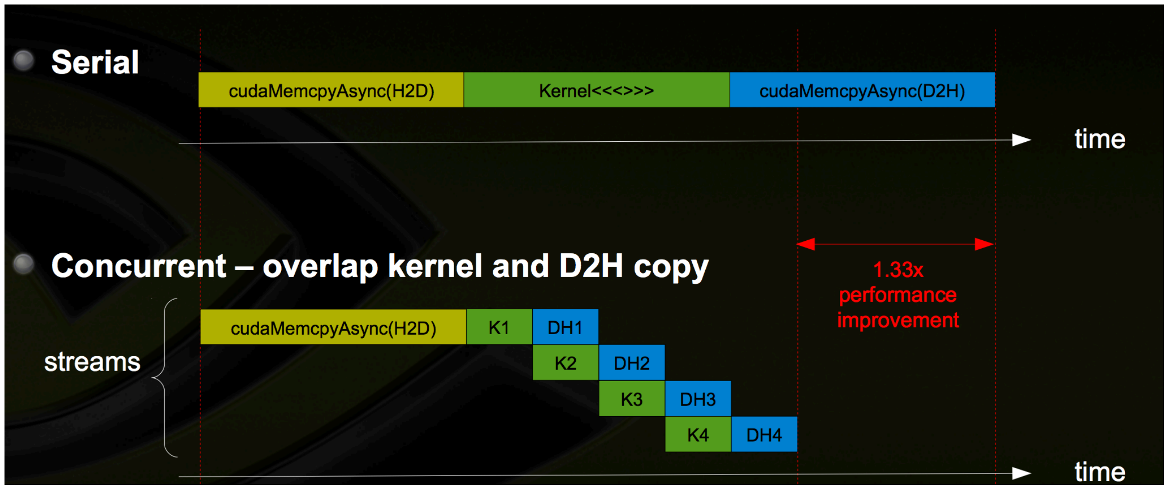


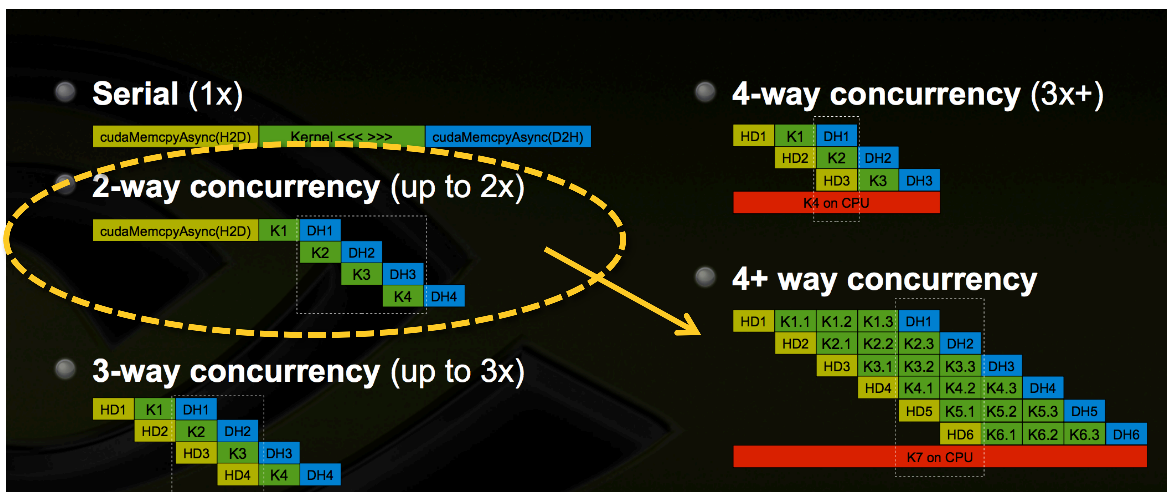
Features of GPU Tracking Framework

- Framework structure motivated by *The Allen project* at LHCb
- 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 Tracking Framework





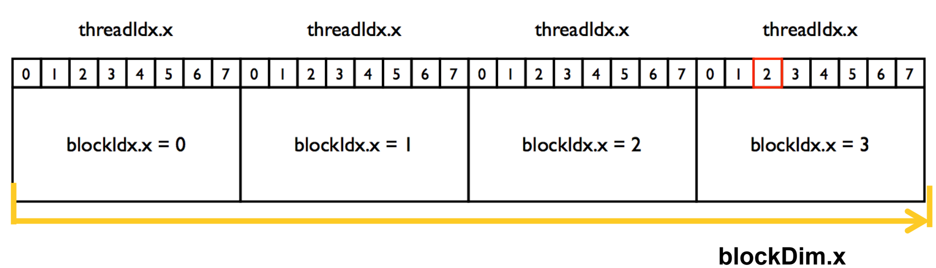
Features of GPU Tracking Framework

- **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 and for each fitting subroutine

```
__global__ void cuda_calculate_chi_squares(
    REAL * chi_squares,
    int * states,
    REAL const * data,
    REAL const * values,
    REAL const * weights,
    int const n_points,
    int const n_fits,
    int const estimator_id,
    int const * finished,
    int const n_fits_per_block,
    char * user_info,
    std::size_t const user_info_size)
{
```

From GPUfit library github repo

```
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;
```



Status of OR Software

- GPU parallelization of event reducer (pre-tracking event cleaning)

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!

Status of OR Software

- Performance comparisons to CPU at χ^2 analysis tracklet stage completed
- GPU χ^2 analysis at back partial and global track stage underway
- Testing GPU track reconstruction on live cosmic ray data
- Comparison with multithreaded CPU framework underway

Processor	Time (s)	Fits/s
CPU	21.905	~ 19,730
GPU	0.765	~ 564,946
Tracklets analyzed: 432,184, Station 2		

Time performance gain for fits on GPU/CPU = 28.63!

Conclusion

- 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:
  - Allow for efficient monitoring of data quality
  - Improve reconstruction speed and performance
  - Lay groundwork for next tracking stage: vertex reconstruction
  - Help pave the way for robust analyses at SpinQuest

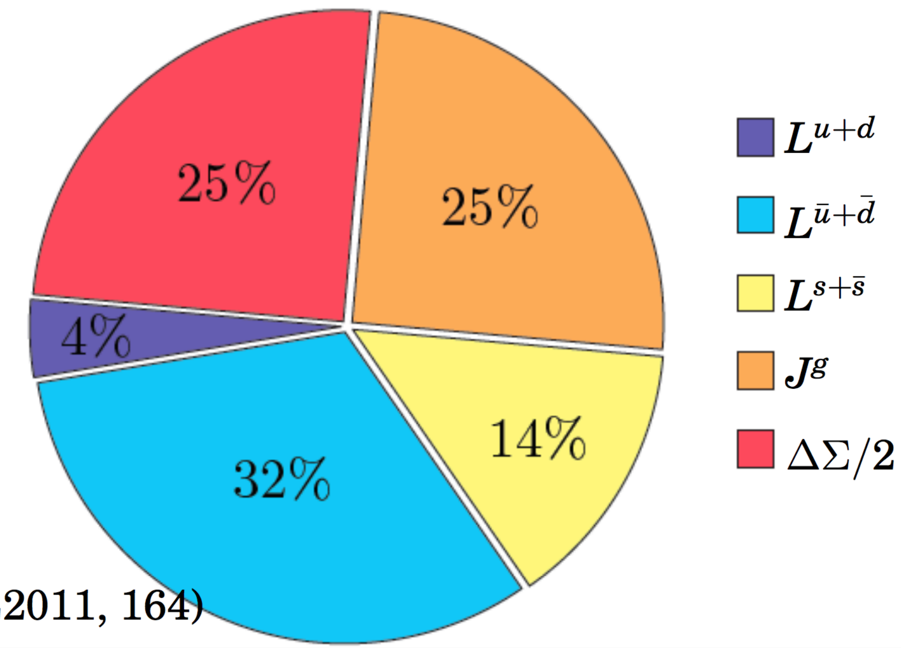
This work is supported in part by the US DOE contract # DE-FG02-07ER41528

Backup Slides

Importance of Gluons and Seaquarks

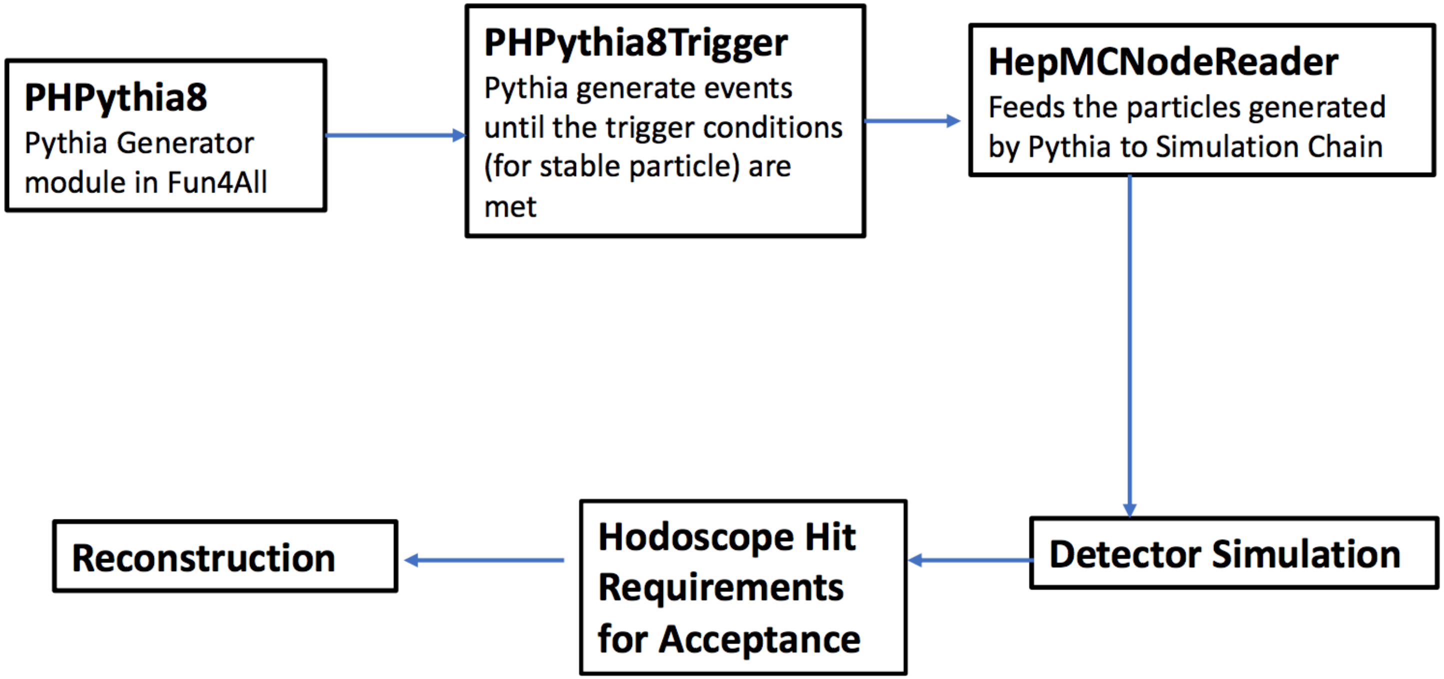
- Proton spin puzzle:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + J_G + L_q + L_{\bar{q}}$$



Lattice QCD
(PoS LATTICE2011, 164)

Generating J/ψ's for Uncertainty Study



Four X hodoscopes must be fired by a muon track.

SpinQuest Kinematics

Input: Muon's momentum in the Lab. Frame,
initial hadron, Spin Vector $S = (0,1,0,0)$

$E_\mu = \sqrt{\vec{p}^2 + m^2}$ (Muon Energy)

Muon's 4-Vector

Boost to the CM frame of the initial hadron

$$x_F = \frac{P_l}{P_{l,max}} = x_1 - x_2$$

$$p_{l,\max} = \sqrt{s}/2\,(1 - M^2/s).$$

$$y = 0.5\ \ln\left[(E + p_l)/(E - p_l)\right].$$

$$\tau = M^2/s = x_1 x_2$$

$$x_1 = \tfrac{1}{2}[(x_F^2 + 4\tau)^{1/2} + x_F]$$

$$x_2 = \tfrac{1}{2}[(x_F^2 + 4\tau)^{1/2} - x_F].$$

$x_F, x_1, x_2 = x$ Fermi, Beam, Target
P_l = Dimuon longitudinal mom.
M = Dimuon invariant mass
E = Dimuon Energy
y = Rapidity

SpinQuest Kinematics

What is ϕ_S ? The spin vector angle in what reference?

From SpinQuest Proposal:

When studying the angular dependence of the proton induced Drell-Yan process, $pp^{\uparrow} \rightarrow \mu^+\mu^-$, three angles are of relevance: the azimuthal angle ϕ_S of the transverse spin orientation $\mathbf{S}_T$ of the target (determined in the target rest frame) and the polar and azimuthal angles θ and ϕ of the dimuon pair (determined in the Collins-Soper frame [29], i.e. the dimuon center-of-mass system).

From the reference paper:

mixed up when switching between both frames. Since an experimental setup and also the parton model approximation have a closer connection to the cm-frame than to the CS-frame it is preferable to work with cm-frame components of the hadron spin vectors.

PHYSICAL REVIEW D **79**, 034005 (2009)

Dilepton production from polarized hadron hadron collisions

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(Received 24 November 2008; published 6 February 2009)

In this paper we present a comprehensive formalism for dilepton production from the collision of two polarized spin-$\frac{1}{2}$ hadrons by identifying the general angular distribution of the cross section in combination with a complete set of structure functions. The various structure functions are computed in the parton model approximation where we mainly consider the case when the transverse momentum of the dilepton pair is much smaller than its invariant mass. In this kinematical region dilepton production can be described in terms of transverse momentum dependent parton distributions.

SpinQuest Kinematics

the dilution factor f, which describes the ratio of polarizable nucleons over the total number of nucleons, and integrating over the virtual photon transverse momentum p_T and the lepton pair angle Θ we can write the number of events in a x_b and x_T bin as :

$$\begin{aligned}\frac{dN(x_b,x_T,\phi,\phi_S)}{d\phi d\phi_S} &= N(x_b,x_T)\Big\{\Big(1+\tfrac{1}{2}A_{UU}^{\cos 2\phi}\cos 2\phi\Big)\\ &+ fS_L\tfrac{1}{2}A_{UL}^{\sin 2\phi}\sin 2\phi\\ &+ f|S_T|\Big[A_{UT}^{\sin\phi_S}\sin\phi_S+\tfrac{1}{2}\Big(A_{UT}^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S)\\ &+ A_{UT}^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\Big)\Big]\Big\}\end{aligned}$$

The Sivers mechanism manifests itself in a $\sin\phi_S$ (1 + cos2θ) modulation in the cross section

Using the Fourier projection on the $\sin\phi_S$ modulation finally gives

$$A_{UT}^{\sin\phi_S}=\frac{2}{f|S_T|}\frac{\int d\phi_S d\phi\frac{dN(x_b,x_T,\phi,\phi_S)}{d\phi_S d\phi}\sin\phi_S}{N(x_b,x_T)}.$$

Anticipated Uncertainty Study for J/ψ TSSAs

- The geometric acceptance of the hodoscope planes was considered
- No trigger acceptance, detector efficiency nor tracking efficiency
- No beam/detector down time was considered
- Non-zero asymmetry was generated and reconstructed

x_T bin	Yields
0.05	7702
0.07	38,878
0.09	8,684

Pre-tracking Event Cleaning

- Types of hit clusters

Size	Type	Characteristics
2	Edge Hit	A muon hits the edge of cell and produces a signal on the neighboring wire. If the drift distance of one of the two hits is larger than 90% of cell size and that of the other is larger than 40%, the cluster is regarded as “Edge hit”.
	Electronic Noise	The difference of the drift times is less than 8 ns. It appears only on St. 3+ drift chamber in Run II data.
≥ 3	Electronic Noise	Average of the differences of drift times of neighboring wire hits is less than 10 ns.
	Delta Ray	These clusters are arise from delta rays created by muons. Average of the differences of drift times of neighboring wires is 10 ns or larger.