Spin Asymmetry Measurements from Quasi-Elastic dd Scattering at the SPD

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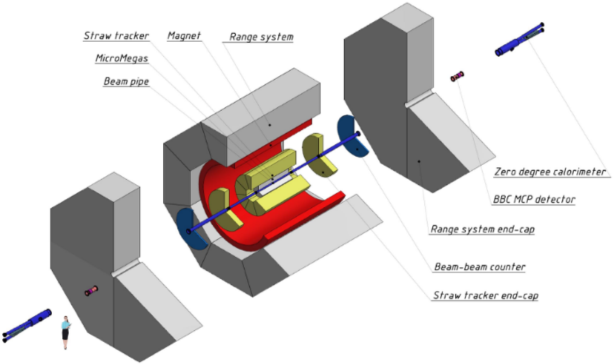
Sep 10, 2026

Outline

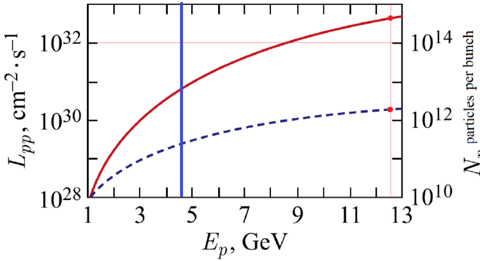
- NICA and SPD at the early stages
- Physics motivation
- Event generation
- Detctor response
- Signal and background estimates
- Summary

SPD in Stage 1

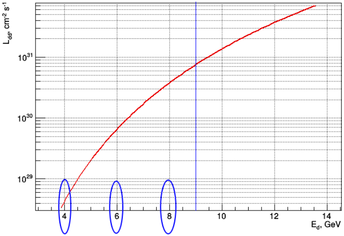


- Limited set of detectors : MicroMegas, Straw Tracker (charged particle momenta), Range System (muon detector), BBC, ZDC
- NICA performance at the early stages : $\sqrt{s_{NN}} \sim 10$ GeV with *pp* luminosity $\sim 10^{31} cm^{-2} s^{-1}$ and *dd* luminosity $\sim 10^{30} cm^{-2} s^{-1}$

NICA Energy and Luminosity Ranges



Luminosity range for *pp* collisions in stage 1



Luminosity range for *dd* collisions in stage 1

Blue lines represents corresponding maximum beam energies for stage 1

Physics Goals of the SPD at the Initial Stage

Possible studies at the first stage of the NICA collider operation with polarized and unpolarized proton and deuteron beams

V. V. Abramov[1], *A. Aleshko*[2], *V.A. Baskov*[3], *E. Boos*[2], *V. Bunichev*[2], *O.D. Dalkarov*[3], *R. El-Kholy*[4], *A. Galoyan*[5], *A.V. Guskov*[6], *V.T. Kim*[7,8], *E. Kokoulina*[5,9], *I.A. Koop*[10,11,12], *B.F. Kostenko*[13], *A.D. Kovalenko*[5], *V.P. Ladygin*[5], *A. B. Larionov*[14,15], *A.I. L'vov*[3], *A.I. Milstein*[10,11], *V.A. Nikitin*[5], *N. N. Nikolaev*[16,26], *A. S. Popov*[10], *V.V. Polyanskiy*[3], *J.-M. Richard*[17], *S. G. Salnikov*[10], *A.A. Shavrin*[18], *P.Yu. Shatunov*[10,11], *Yu.M. Shatunov*[10,11], *O.V. Selyugin*[14], *M. Strikman*[19], *E. Tomasi-Gustafsson*[20], *V.V. Uzhinsky*[13], *Yu.N. Uzikov*[6,21,22,*], *Qian Wang*[23], *Qiang Zhao*[24,25], *A.V. Zelenov*[7]

2. **Elastic pN, pd and dd scattering** [1]

The spin-dependent Glauber theory is applied to calculate spin observables of pd elastic scattering at 3-50 GeV/c using pp amplitudes available in the literature and parametrized within the Regge formalism. The calculated vector A_y^p, A_y^d and tensor A_{xx}, A_{yy} analyzing powers and the spin-correlation coefficients $C_{y,y}$, $C_{x,x}$, $C_{yy,y}$, $C_{xx,y}$ can be measured at SPD NICA and, thus, will provide a test of the used pN amplitudes.

Phys.Atom.Nucl. 85 (2022) 6, 1034-1044

- A variety of interesting ideas with compelling motivations proposed
- Feasibility study of one among them presented here, proposed by Yuriy N. Uzikov (see his presentation on Wednesday, 09/09/2026)

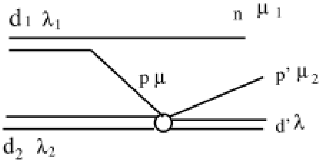
Motivation (briefly)

- Interpretation of spin-dependent hadron-nucleus or nucleus-nucleus processes requires spin amplitudes of *pp* and *pn* elastic scattering
- Only a limited range of data available (i.e. ANKE measurements in the range of $\sqrt{s} = 2.0$ - 2.9 GeV) - unique opportunity for SPD
- Ideally polarized *pd* elastic scattering is a perfect probe that consists of *p* interacting with the *p* or *n* in the deuteron
- Unfortunately, asymmetric collisions (i.e. *pd*) are, at present, unlikely at the NICA facility
- Polarized quasi-elastic dd scattering can be an excellent substitute under the Impulse Approximation where one of the deuterons splits with the *n* as a spectator ($dd \rightarrow npd$ process) and the rest is the intended polarized pd scattering

Interest in the Quasi-Elastic *dd* Process

- Intended measurements : asymmetries A_y (of p and d) with single beam vector pol., A_{yy} with single beam tensor pol., $C_{y,y}$ with both beams vector pol. and $C_{yy,y}$ with one tensor pol. beam and the other vector pol. beam
- It has been demonstrated (Phys.Part.Nucl.Lett. 22 (2025) 6, 1392-1397) by Y. N. Uzikov that the asymmetries for the (intended) *pd* scattering can be directly related to the counterpart quantities from the (quasi-elastic) *dd* scattering under the S-wave dominated impulse approximation
- For details : see Y. N. Uzikov's presentation on 09/09/2026

Relations Between Quantities Measured (dd) and Quantities Needed (pd) (Phys.Part.Nucl.Lett. 22 (2025) 6, 1392-1397)



$d_2^{\uparrow}$: Vector or tensor Polarized

$$A_Y^d(dd_2^{\uparrow} \to npd) = A_Y^d(pd^{\uparrow} \to pd),$$

$$A_{YY}(dd_2^{\uparrow} \to npd) = A_{YY}(pd^{\uparrow} \to pd)$$

$d_1^{\uparrow}$: Vector Polarized

$$A_Y^d(d_1^{\uparrow} d \to npd) = \frac{2}{3} A_Y^p(p^{\uparrow} d \to pd)$$

Both d_1 and d_2 deuterons are vector or tensor polarized:

$$C_{Y,Y}(d^{\uparrow} d^{\uparrow} \to npd) = \frac{2}{3} C_{y,y}(p^{\uparrow} d^{\uparrow} \to pd)$$

$$C_{Y,YY}(d^{\uparrow} d^{\uparrow} \to npd) = \frac{1}{3} C_{y,yy}(p^{\uparrow} d^{\uparrow} \to pd)$$

order to get the double spin correlation $C_{y,y}$, one needs four options for dd-collision: (i) $P_y = \frac{2}{3}$, $P_y^T = \frac{2}{3}$, (ii) $P_y = \frac{2}{3}$, $P_y^T = -\frac{2}{3}$, (iii) $P_y = -\frac{2}{3}$, $P_y^T = \frac{2}{3}$, (iv) $P_y = -\frac{2}{3}$, $P_y^T = -\frac{2}{3}$. The corresponding event counts are denoted as $N_{\uparrow\uparrow}$, $N_{\uparrow\downarrow}$, $N_{\downarrow\uparrow}$ and $N_{\downarrow\downarrow}$ for the first, second, third and fourth options, respectively. With these definitions the double spin correlation $C_{y,y}$ is derived from Eq. (15) as

$$C_{y,y} = \frac{(I_{\uparrow\uparrow} - I_{\uparrow\downarrow}) + (I_{\downarrow\downarrow} - I_{\downarrow\uparrow})}{(I_{\uparrow\uparrow} + I_{\uparrow\downarrow}) + (I_{\downarrow\downarrow} + I_{\downarrow\uparrow})}. \quad (17)$$

To get tenzor-vector dd-correlation $C_{yy,y}$ we use four options: $P_y = 0, P_{yy} = \pm 1$ for the deuteron d_1 and $P_y = \pm\frac{2}{3}, P_{yy} = 0$ for the deuteron d_2. Using this options one can find the coefficient $C_{yy,y}$ from Eq. (15) in the following form

$$C_{yy,y}(dd) = 3\frac{(I_{+\uparrow} - I_{+\downarrow}) + (I_{-\downarrow} - I_{-\uparrow})}{(I_{+\uparrow} + I_{+\downarrow}) + (I_{-\downarrow} + I_{-\uparrow})}, \quad (27)$$

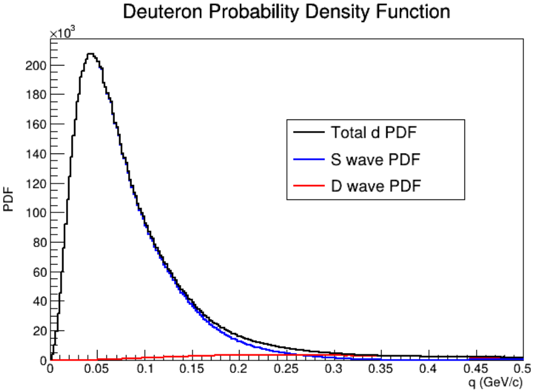
From an Experimentalist's POV

- Process of interest : $d + d \rightarrow n + p + d$
- Range of *dd* invariant energy : 8 - 18 GeV
- Event signature : only two (almost) back to back positive charged tracks (proton and deuteron), a spectator neutron at small angles
- Feasibility study : generate events, pass through detector simulation to study efficiency and resolutions, study possible background in *dd* minimimum bias events
- Three different collision energies (8, 12 and 16 GeV) studied, details for one (8 GeV) will be shown here

First Hardle : Event Generation

- No standard event generator for the purpose (no PYTHIA or similar software to make life easy for us)
- A custom event generator created
- Start from two d 4-momenta, assume d along $+$ve Z breaks up
- Probabilistically select n momenta (q) in the rest frame of mother d
- Deuteron S-wave function contributes $\sim 95\%$ at these energies, D-wave is neglected
- Spectator n 4-momenta in the lab. frame calculated

Deuteron Probability Density Function (PDF)



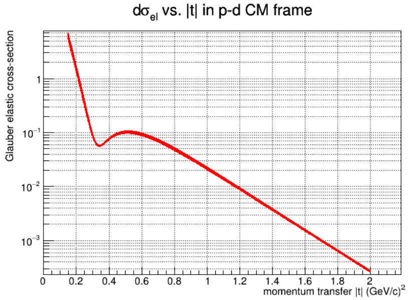
Deuteron probability density function in its rest frame as a function of neutron momentum q

For this study, only S-wave was used

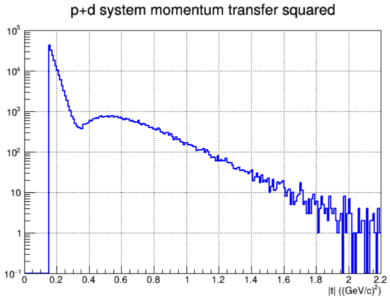
Event Generation (contd.)

- Remaining p from the broken d with known 4-momenta now scatters elatically off the other d (moving toward -ve Z)
- In the COM frame of the $p + d$, events are generated according to unpolarized Glauber elastic cross-section
- Scattered p and d 4-momenta are calculated in the lab. frame
- Event generation completed with 4-momenta of all three final state particles (n,p,d) in the laboratory frame

Elastic Scattering of *pd*



Unpolarized Glauber elastic cross-section as function of $|t|$

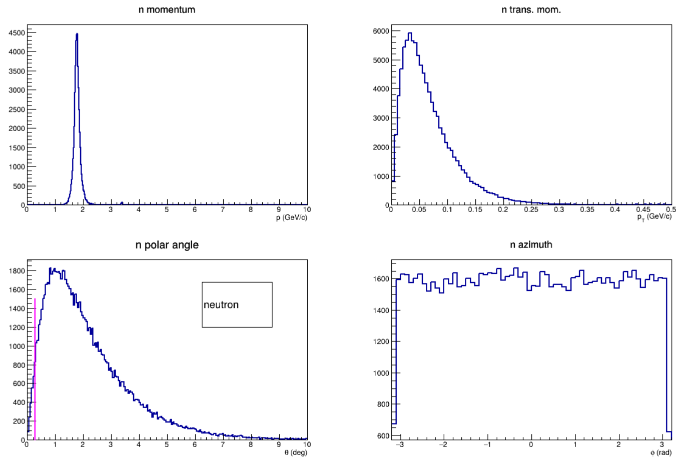


Distribution of momentum transfer-squared magnitude ($|t|$) for generated events

Detector Response Simulation

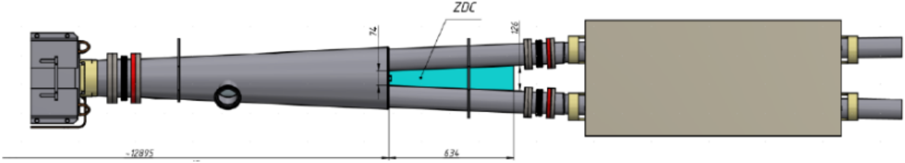
- SPD uses Geant4 description of the detectors in the CERN ROOT based framework (for data handling and reconstruction)
- Not to be too ingenuous - SPDRoot framework
- Generated events are passed through the SPDRoot for final reconstructed event data
- Relevant detectors : Micromegas based MVD, Straw Tracker and Zero Degree Calorimeter
- The first two helps rebuild scattered proton and deuteron tracks and reconstruct their 3-momenta
- The last (at VERY forward rapidity) helps to detect some of the spectator neutrons (unfortunately only a small fraction)

Generated Neutron Kinematics



Unfortunately, most of the spectator neutrons are beyond ZDC coverage

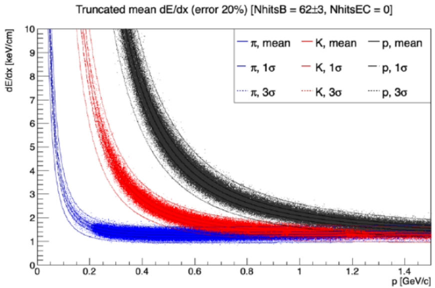
Zero Degree Calorimeter



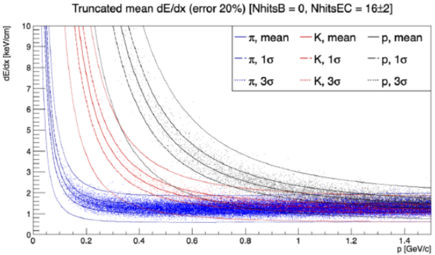
Zero Degree Calorimeter scmeatic

- ZDC is almost 13m from the nominal center of collisions
- Detects neutral particles
- Estimates their energies ($\frac{50-60\%}{\sqrt{E}} \oplus 8 - 10\%$)
- Covers a very small range of polar angle of ± 0.00466 rad ($\pm 0.27^0$)

Particle Identification in Stage 1



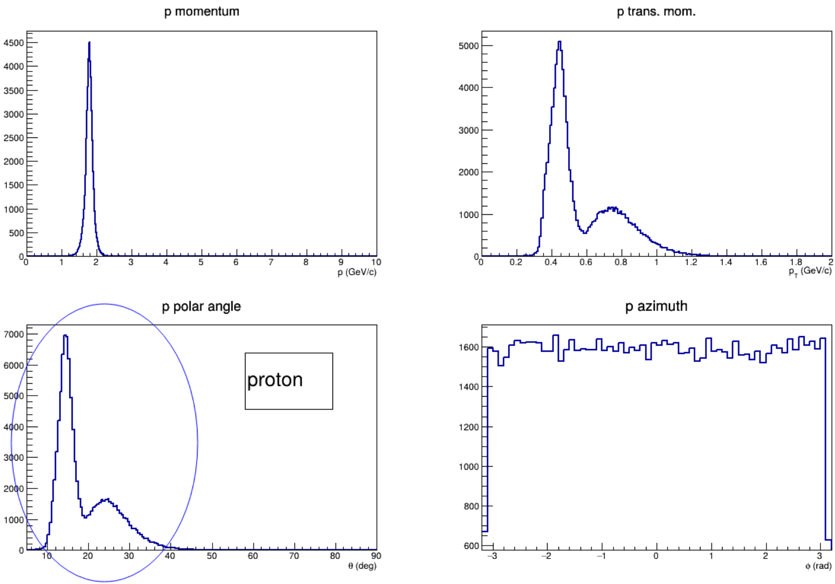
PID via energy deposition in ST barrel



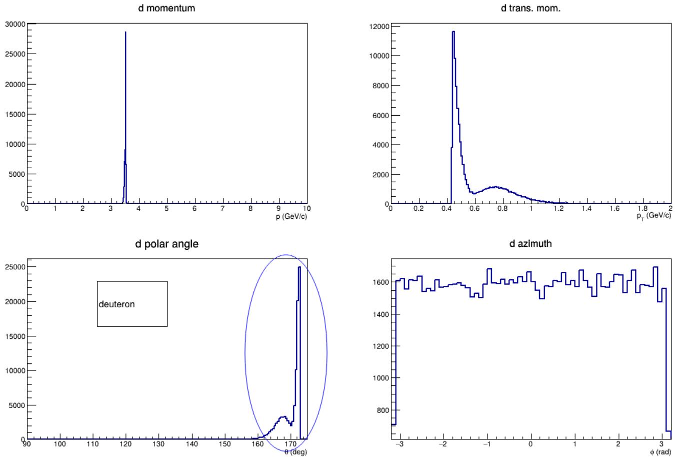
PID via energy deposition in ST end-cap

Limited momentum range for decent PID BUT the event kinematics dictates d will scatter at a smaller angle than p

Generated Proton Kinematics

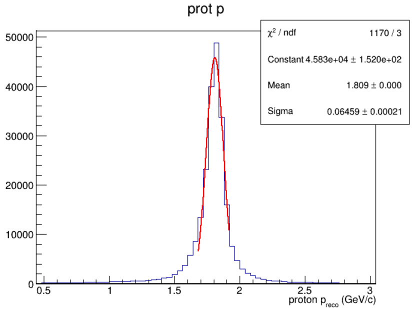


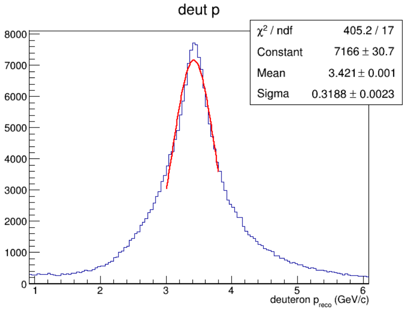
Generated Deuteron Kinematics



Protons in forward and deuterons in the backward direction (by assumption of this simulation), d at smaller angles

After Reconstruction





Protons : $\sigma_p \sim 65$ MeV/c

Deuterons : $\sigma_p > 320$ MeV/c

Momentum resolution for small angle d is not ideal

Constrained kinematic fit is performed for precise knowledge of track momenta and momentum transfer-squared $|t|$ i.e. FUMILI fit

Enumerating results

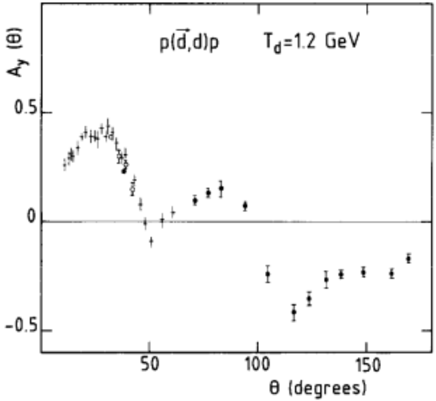
- Process of interest : $d + d \longrightarrow n + p + d$
- Event signature : two (almost) back to back positive charged tracks (proton and deuteron), a spectator neutron at small angles
- Signal cross-section from custom event generator at $\sqrt{s_{dd}} = 8$ GeV : $\sigma_{dd}^{sig} \sim 45.6\ \mu$b,
- Corresponding $\mathcal{L}_{dd} \sim 4.5 \times 10^{28}$ cm^{-2} s^{-1}, $\epsilon_{det} \sim 5\%$
- Data recording period : 1 month (as a reference point)
- Estimated signal counts : ~ 18000
- Background process studied : $\sqrt{s_{dd}} = 8$ GeV : $\sigma_{dd}^{inel} \sim 160$mb
- Upper limit (none observed in study) : 1 in 20M events, estimated background counts : ~ 3000

Required Polarization States of Deuteron beams

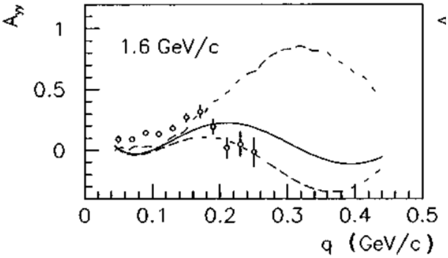
	p_y^{d1}	p_{yy}^{d1}	p_y^{d2}	p_{yy}^{d2}
1	$\frac{2}{3}$	0	$\frac{2}{3}$	0
2	$\frac{2}{3}$	0	$-\frac{2}{3}$	0
3	$-\frac{2}{3}$	0	$\frac{2}{3}$	0
4	$-\frac{2}{3}$	0	$-\frac{2}{3}$	0
5	$\frac{1}{3}$	1	unpol	unpol
6	$-\frac{1}{3}$	1	unpol	unpol
7	$\frac{1}{3}$	-1	unpol	unpol
8	$-\frac{1}{3}$	-1	unpol	unpol
9	$\frac{2}{3}$	0	0	1
10	$\frac{2}{3}$	0	0	-1
11	$-\frac{2}{3}$	0	0	1
12	$-\frac{2}{3}$	0	0	-1

- Based on pol. states used in : Nuch. Phys. A431, 613-636
- states 1,2,3,4 will provide single beam and both beams vector polarized asymmetries A_y and $C_{y,y}$
- states 5,6,7,8 provide single beam tensor polarized asymmetry A_{yy}
- states 9,10,11,12 provide vector-tensor polarization asymmetry $C_{yy,y}$
- POSSIBLE to measure the above mentioned quantities from other spin combinations these exact combinations are not available

Expected Asymmetry Values (Ref : Nuch. Phys. A431, 613-636)



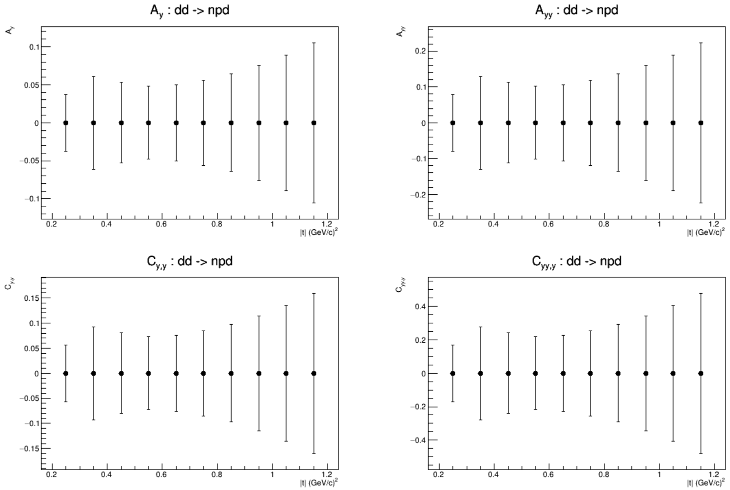
Vector analyzing power



Tensor analyzing power

Quantities shown here were measured at fixed target experiments at Saclay. But if somewhat similar asymmetries are expected at SPD enegies, then $5-10$ % precison should be good enough

Estimated Statistical Uncertainties



Projected statistical uncertainties of various asymmetries

Summary

- Expected 'clean' measurement with signal to background ratio ~ 6
- Dilution of asymmetry due to background was not taken into account
- Statistical uncertainties $\sim 5 - 15\%$ for the first three asymmetries and for the vector-tensor combination, up to 40%
- Asymmetries in different energy ranges measured in other experiments show a 10% precision is good enough
- This study is a sample of ONLY 4 different asymmetries. Ideally, many more asymmetries with other vector and tensor polarization combinations are possible and desirable. If possible, longer period can be dedicated to measure other asymmetries
- Study shown here used close to lower limit of d energy at stage 1, using the higher end of the range can increase statistics by almost an order of magnitude but will probe higher $|t|$ range

Thank You

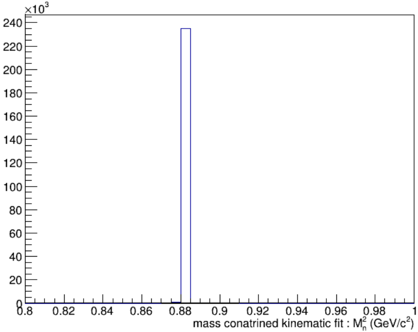
Backup Slides

Estimates of Signal

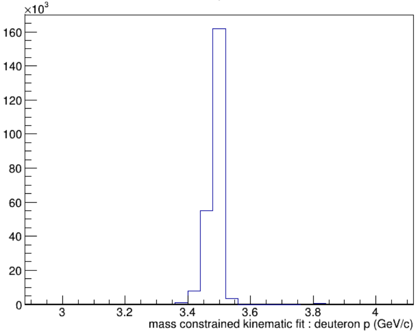
Event count for 1 month of 'data recording' (2σ mass window, one deuteron break up) :

- 8 GeV d+d : $\sigma_{dd}^{sig} \sim 45.6\ \mu$b, $\mathcal{L}_{dd} \sim 4.5 \times 10^{28}$ cm^{-2} s^{-1}, $\epsilon_{det} \sim 5\%$, $\epsilon_{gen} \sim 0.2$
- Estimated signal count : $\boxed{18000}$
- 16 GeV d+d : $\sigma_{dd}^{sig} \sim 0.94\ \mu$b, $\mathcal{L}_{dd} \sim 3.8 \times 10^{30}$ cm^{-2} s^{-1}, $\epsilon_{det} \sim 10\%$, $\epsilon_{gen} \sim 0.4$
- Estimated signal count : $\boxed{125\ 000}$

Constrained Kinematic FUMILI Fit



Neutron mass-squared from fit of detected p and d



Precise deuteron momenta from fit