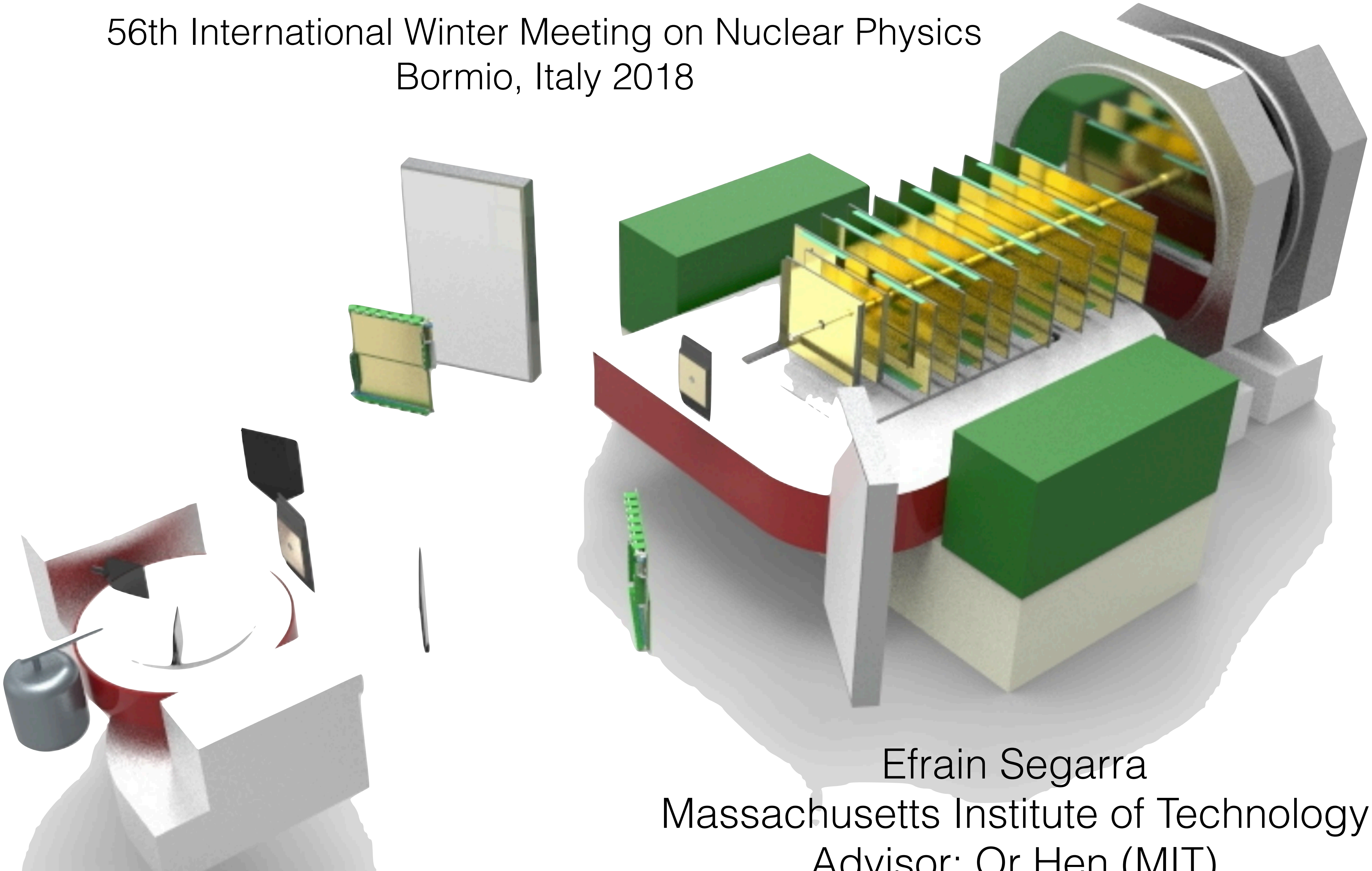
First Fully Exclusive Measurement of Short Range Correlation (SRC) Pairs at JINR

56th International Winter Meeting on Nuclear Physics
Bormio, Italy 2018



Efrain Segarra
Massachusetts Institute of Technology
Advisor: Or Hen (MIT)

Outline

Overview of Short Range Correlations

Motivation for SRC@JINR

Physics Extraction

Overview of SRC

How can we describe nucleons in a nucleus?

Overview of SRC

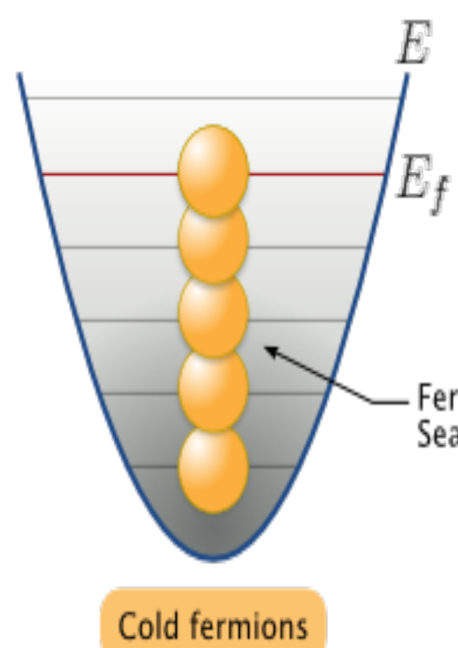
How can we describe nucleons in a nucleus?

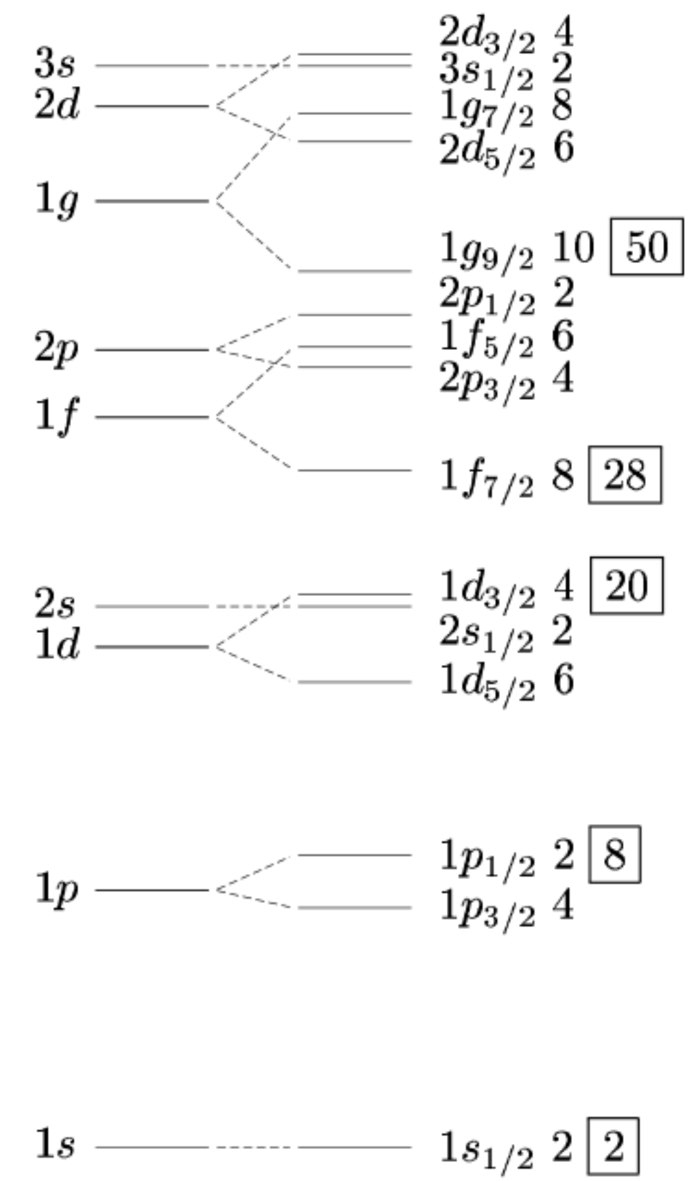
- Many-Body Hamiltonian:

$$H = \sum_{i=1}^{A} \frac{p^2}{2m_N} + \sum_{i<j=1}^{A} v_{2body}(i,j) + \cancel{\sum_{i<j<k=1}^{A} v_{3body}(i,j,k)} + \ldots$$

- Mean-Field Approximation:

$$H = \sum_{i=1}^{A} \frac{p^2}{2m_N} + \sum_{i=1}^{A} V(i)$$





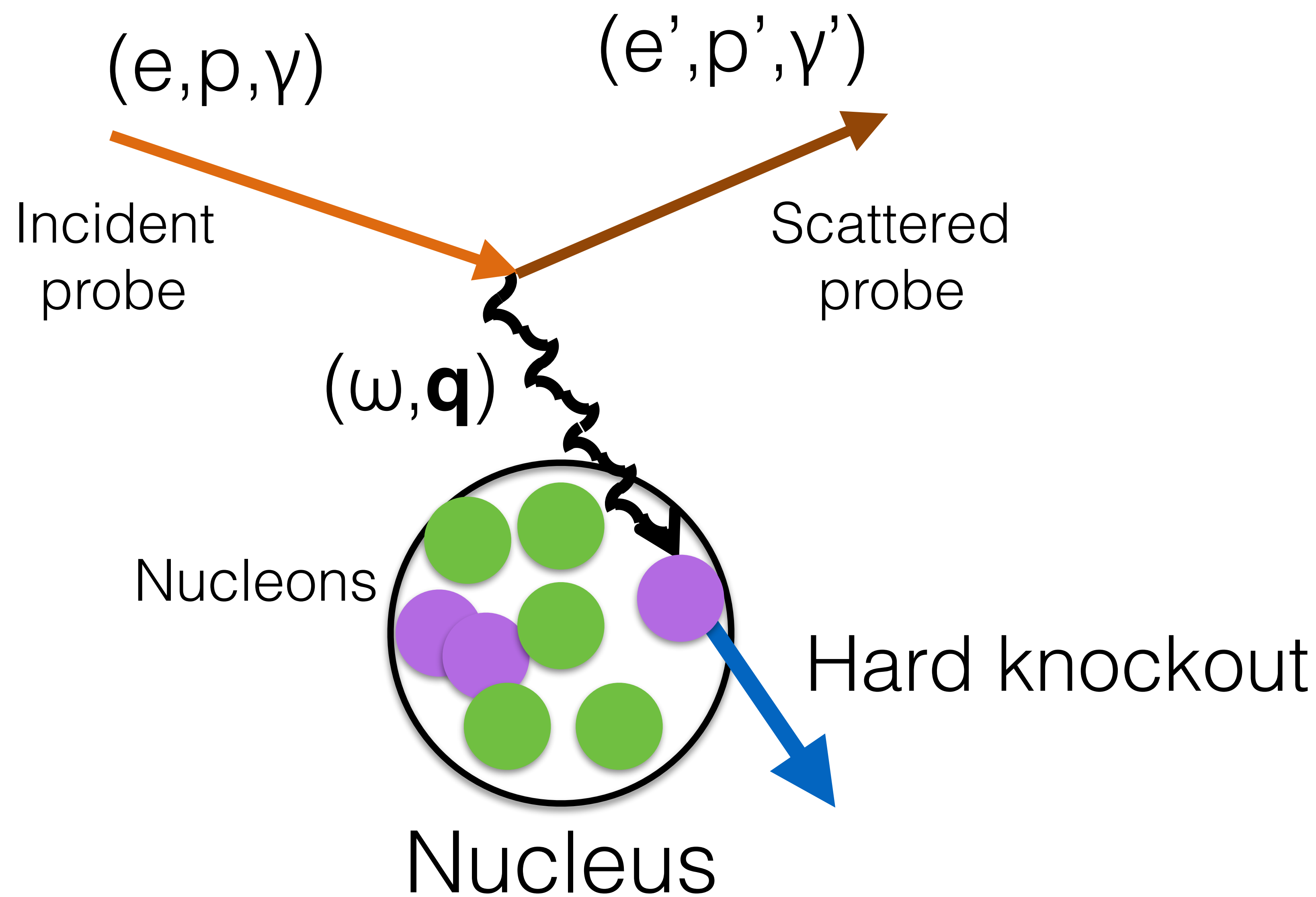
Nuclear Shell Model

Overview of SRC

How do we test our models?

Overview of SRC

How do we test our models? Quasi-Elastic Scattering



Overview of SRC

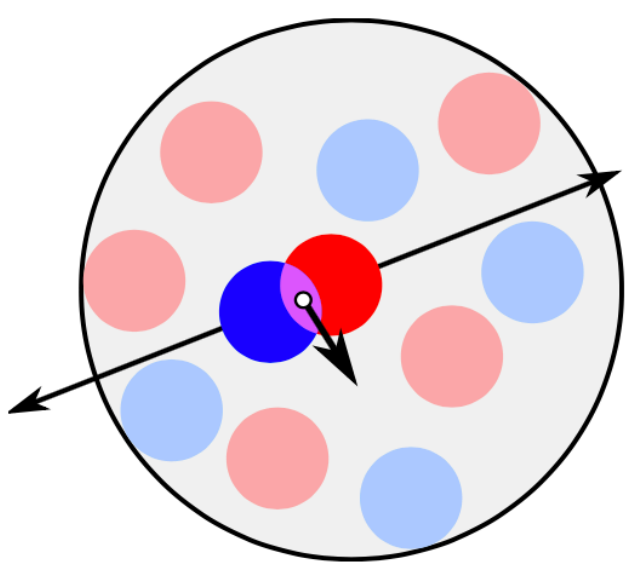
One way to test Mean-Field Model: QE spectroscopy

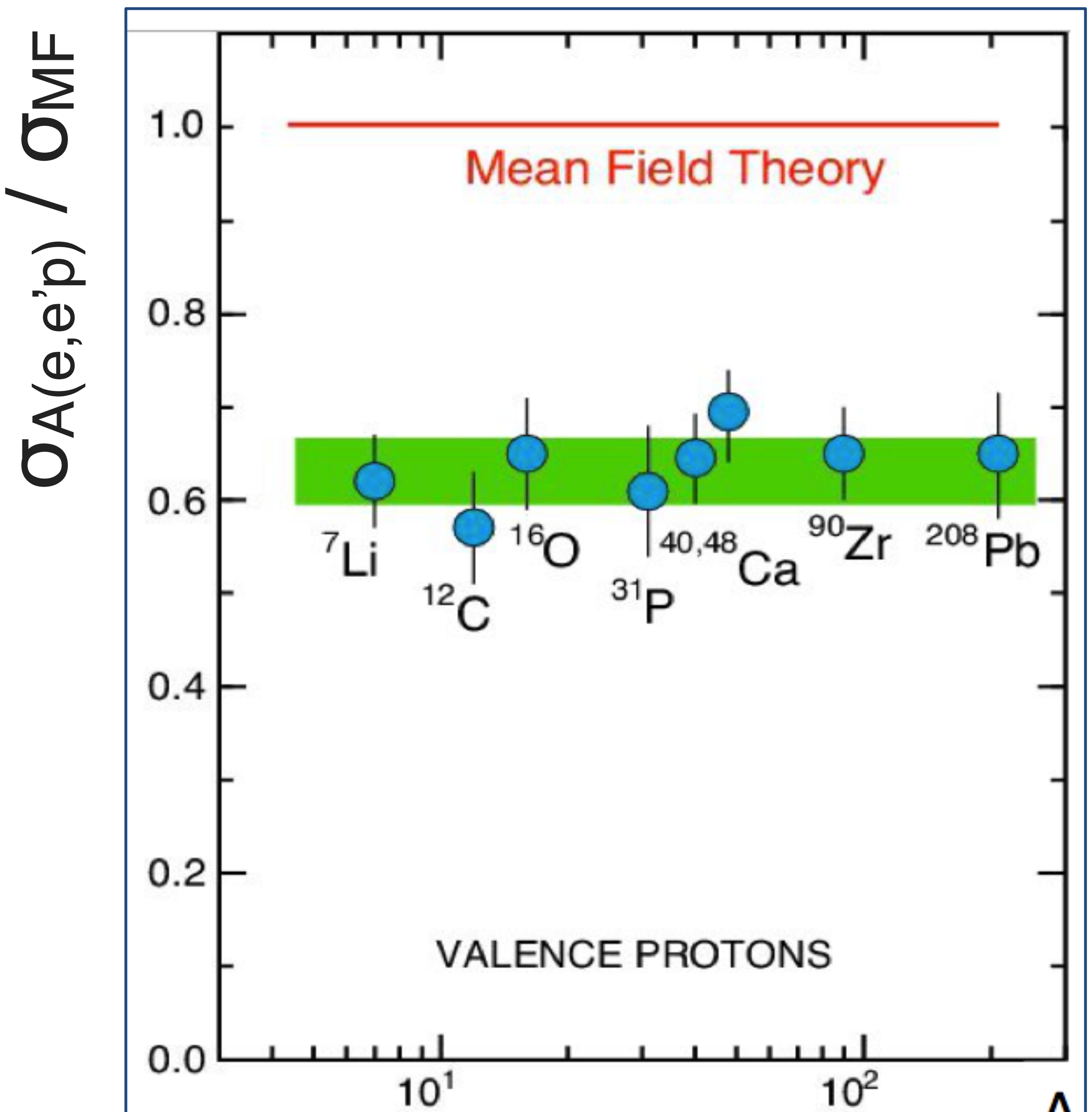
Overview of SRC

One way to test Mean-Field Model: QE spectroscopy

- Spectroscopic factors extracted from A(e,e'p) measurements demonstrated 30-40% less occupancy of valence protons than expected.

What's missing? Correlations!





L. Lapikas, Nucl. Phys. A **553** (1993) 297.

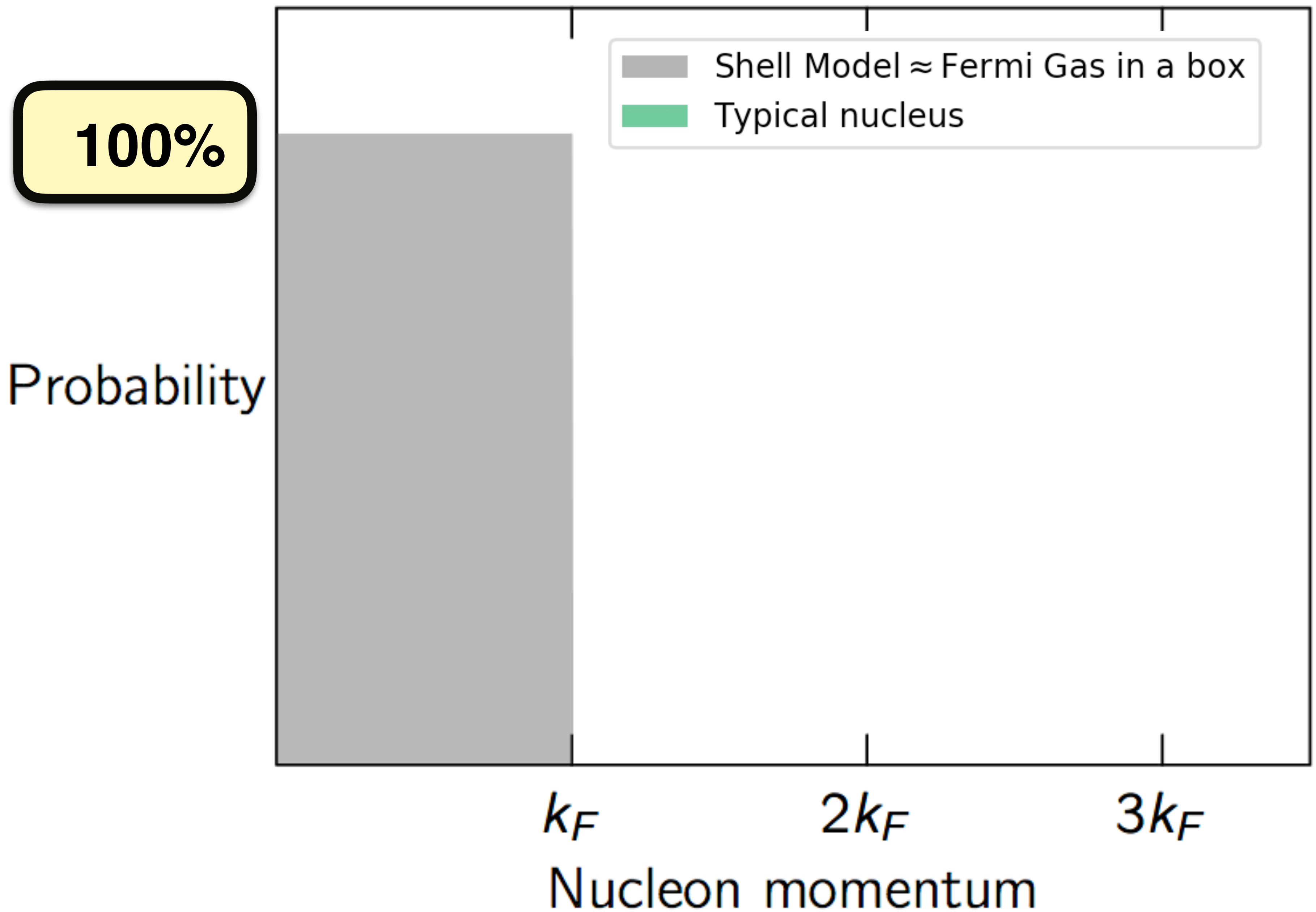
Overview of SRC

Global picture of SRC from inclusive & exclusive measurements

Overview of SRC

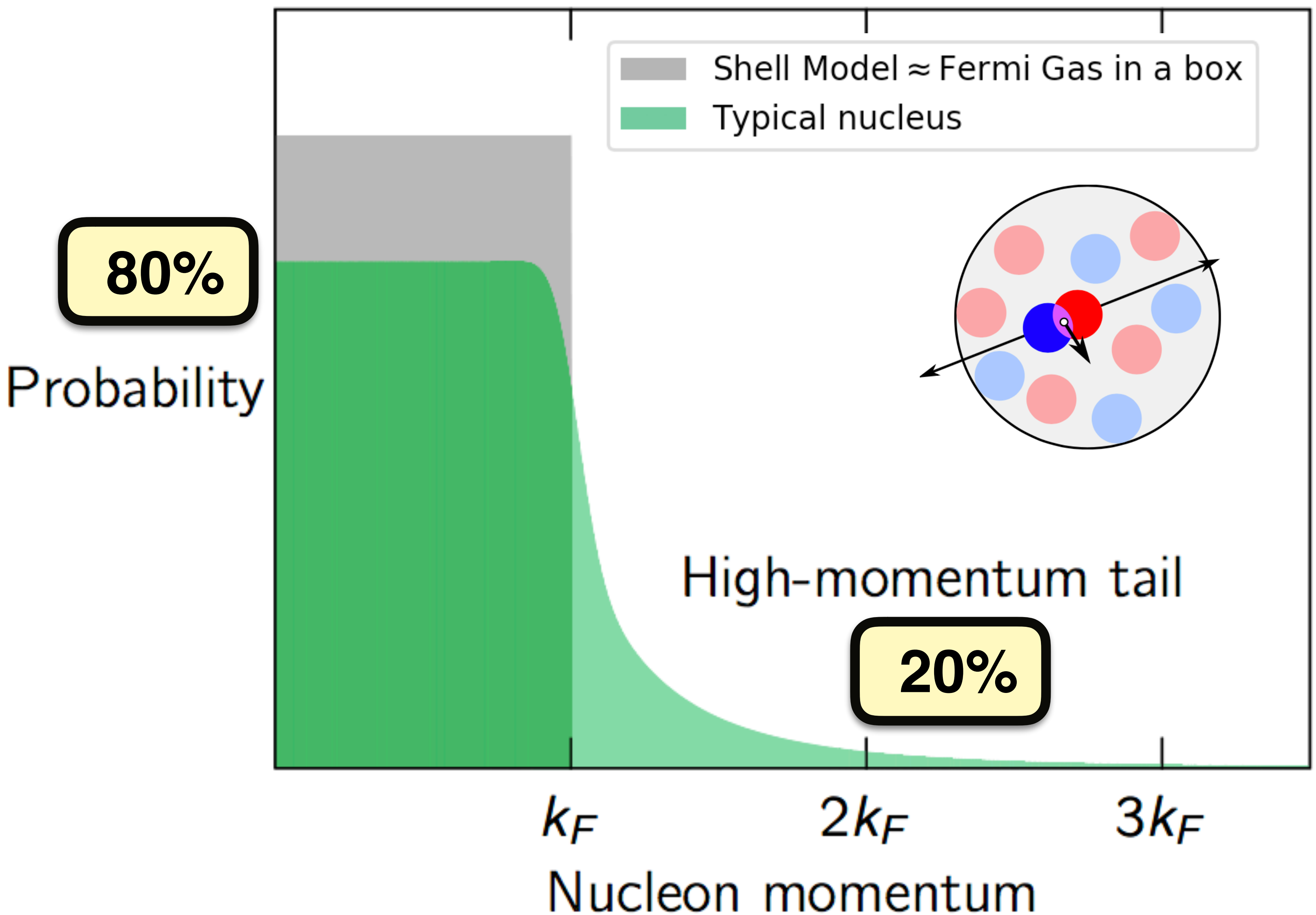
Global picture of SRC from inclusive & exclusive measurements

100%



Overview of SRC

Global picture of SRC from inclusive & exclusive measurements



Overview of SRC

If you don't follow anything else…

Short Range Correlations:

- 2 nucleons pairs that are close together in the nucleus (wave functions overlap)
- Momentum space: pairs with high relative momentum and low c.o.m momentum (with respect to k_F)
- 20% of nuclear wave function, np pairs dominate over pp/nn pairs

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Better understanding of the nucleon-nucleon interaction and the nucleon momentum distribution and the high-impact connections to other fields

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- SRC formation process and asymmetry dependence
- Proton dynamics in neutron rich nuclei
- Direct observation of 3N-SRC
- Mapping transition from Mean-Field to SRC (Migdal jump)

Overview of SRC

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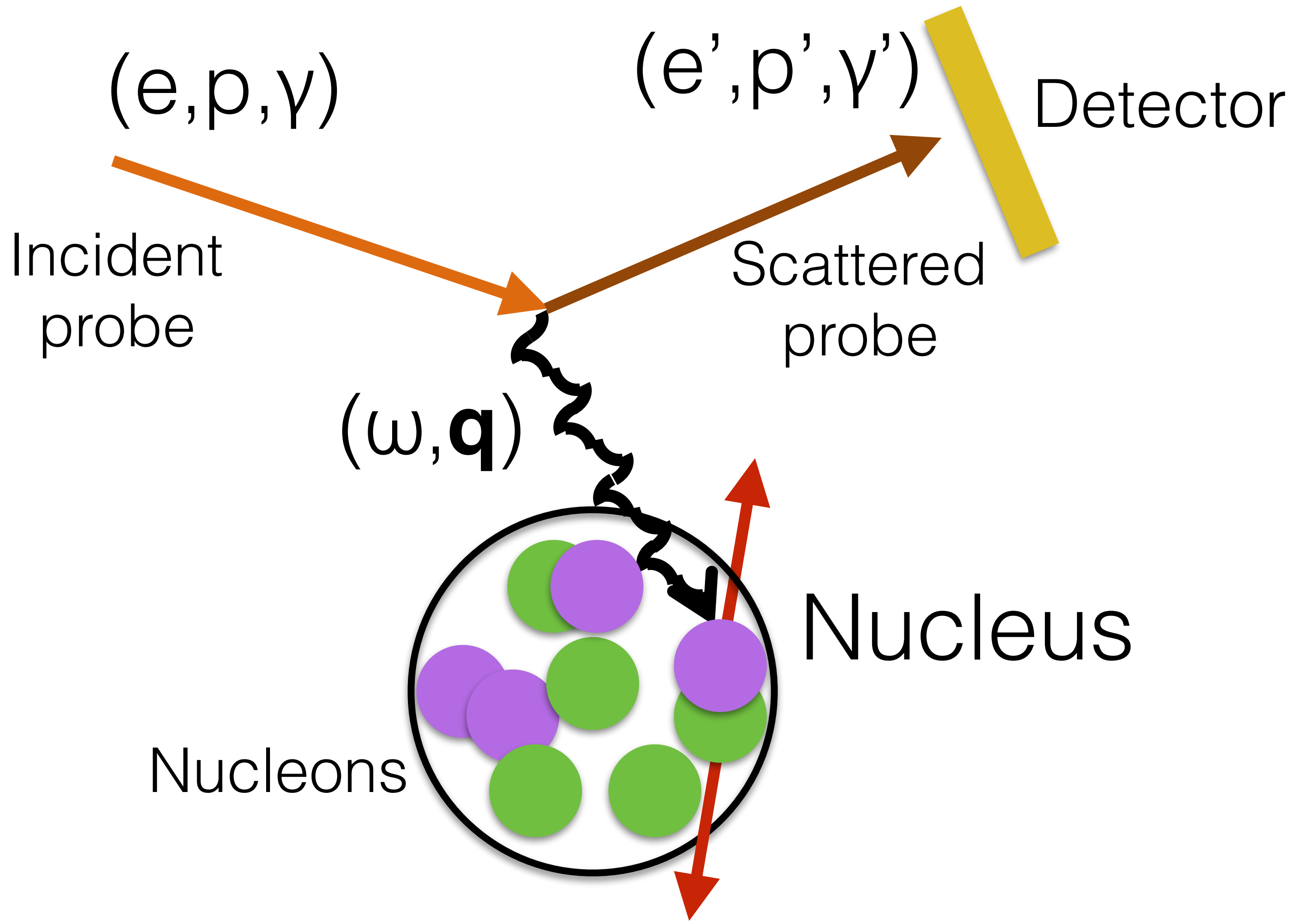
WHY YOU might care:

high-impact connections to other fields

- EMC effect (**future experiment @ JLab**)
- Neutrino-nucleus scattering
- Neutron stars
- Nuclear symmetry energy
- Energy sharing in imbalanced Fermi systems
- Contact interaction in universal fermi systems

Overview of SRC

How do we study SRC pairs?



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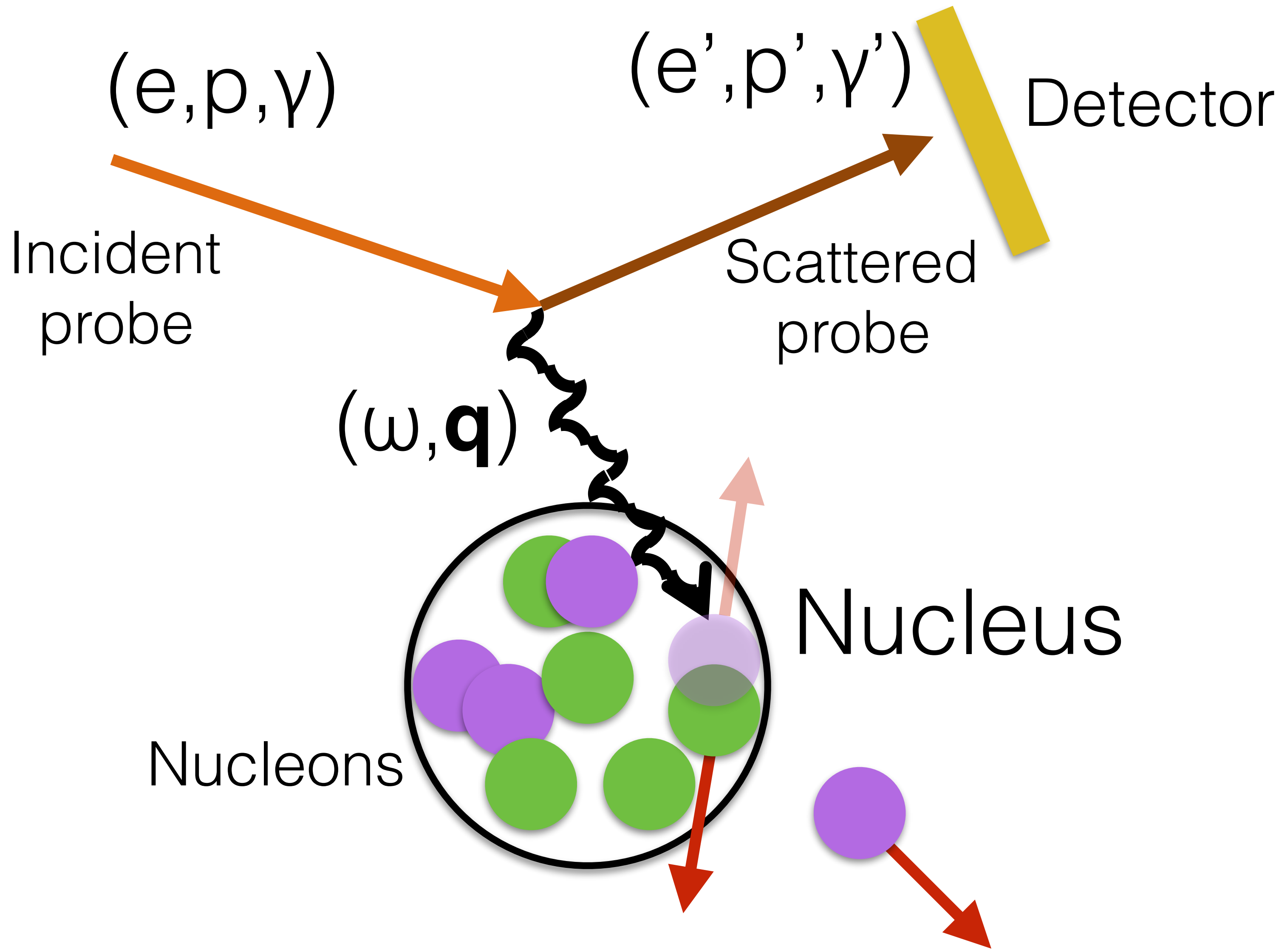

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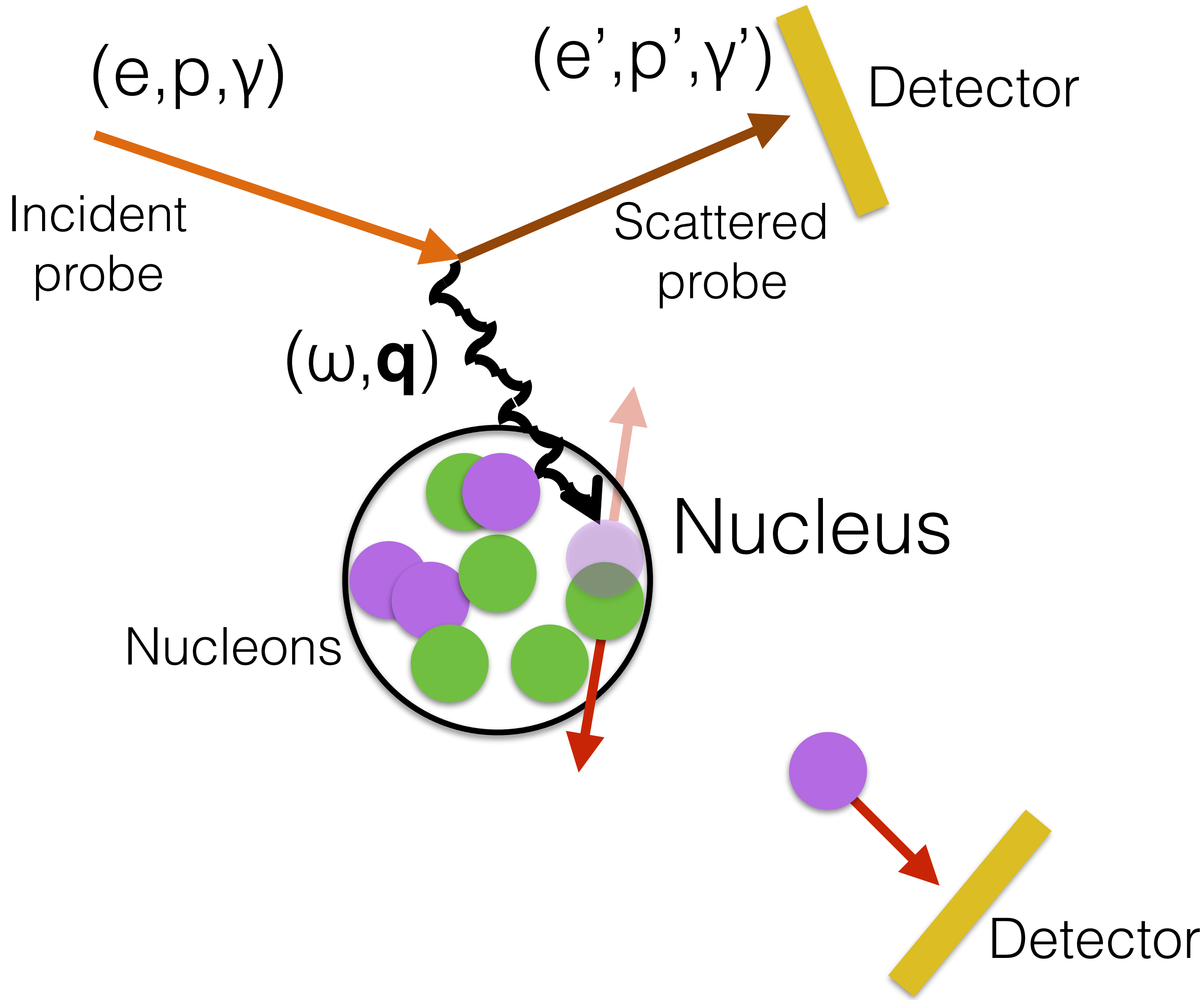

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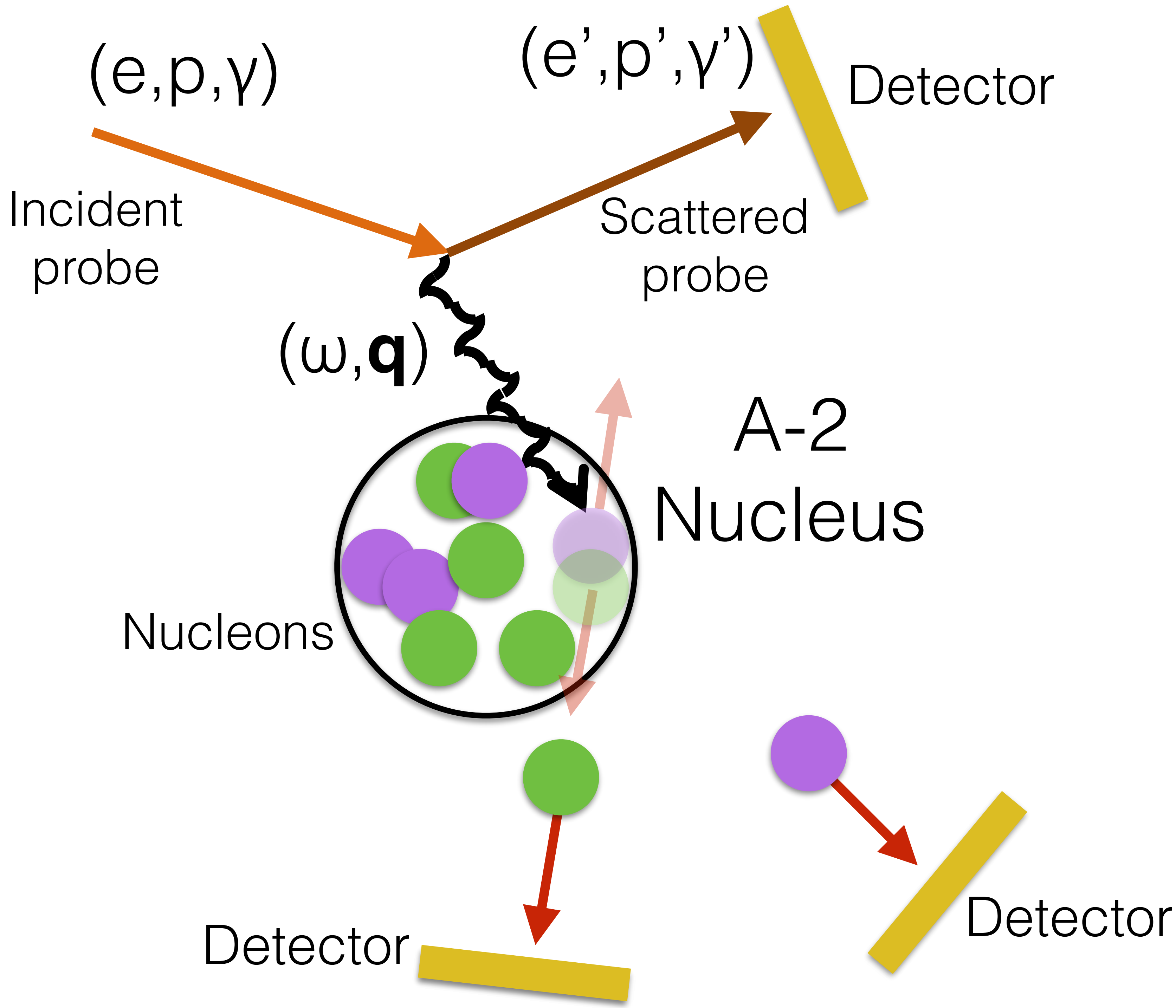
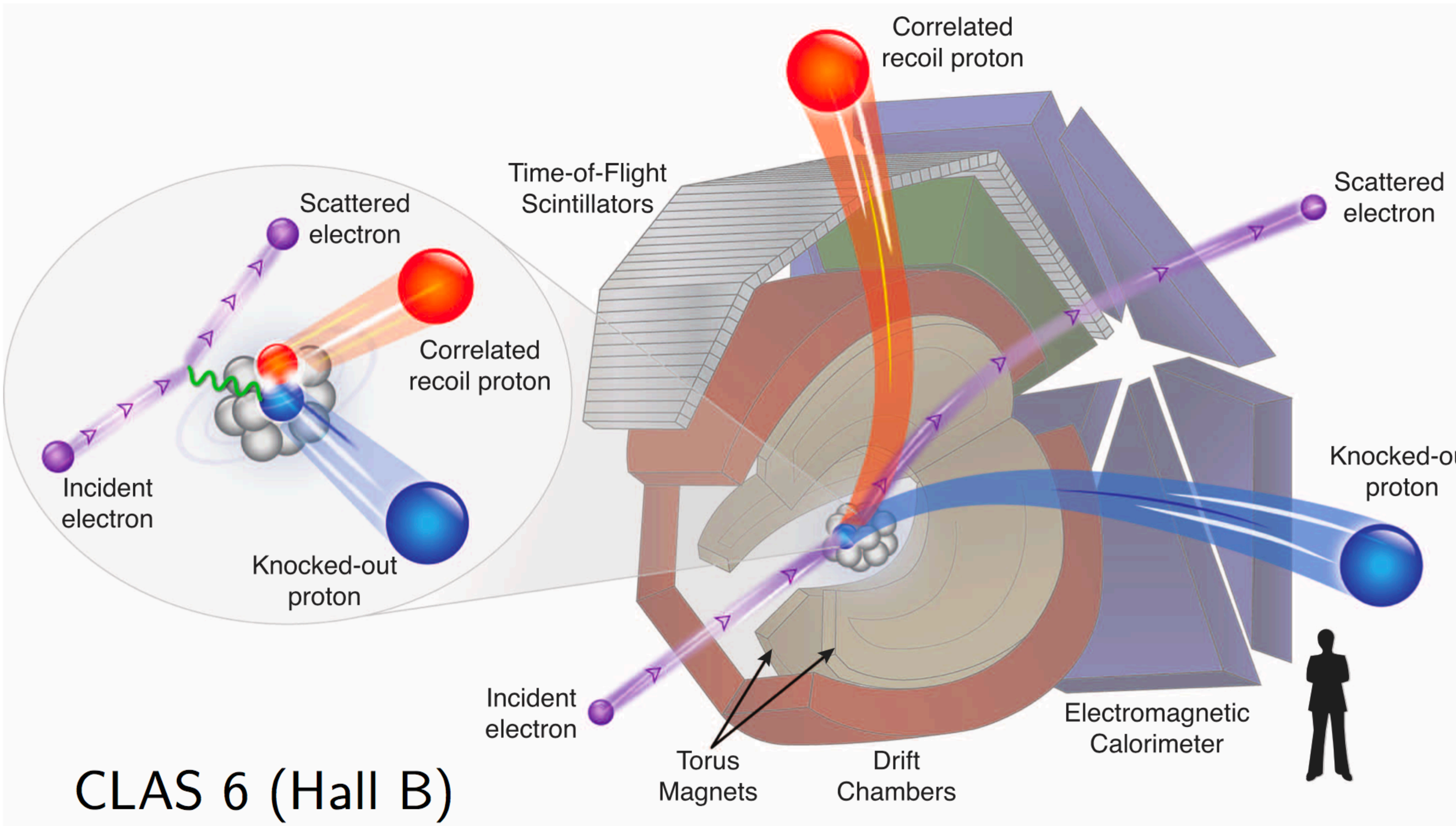


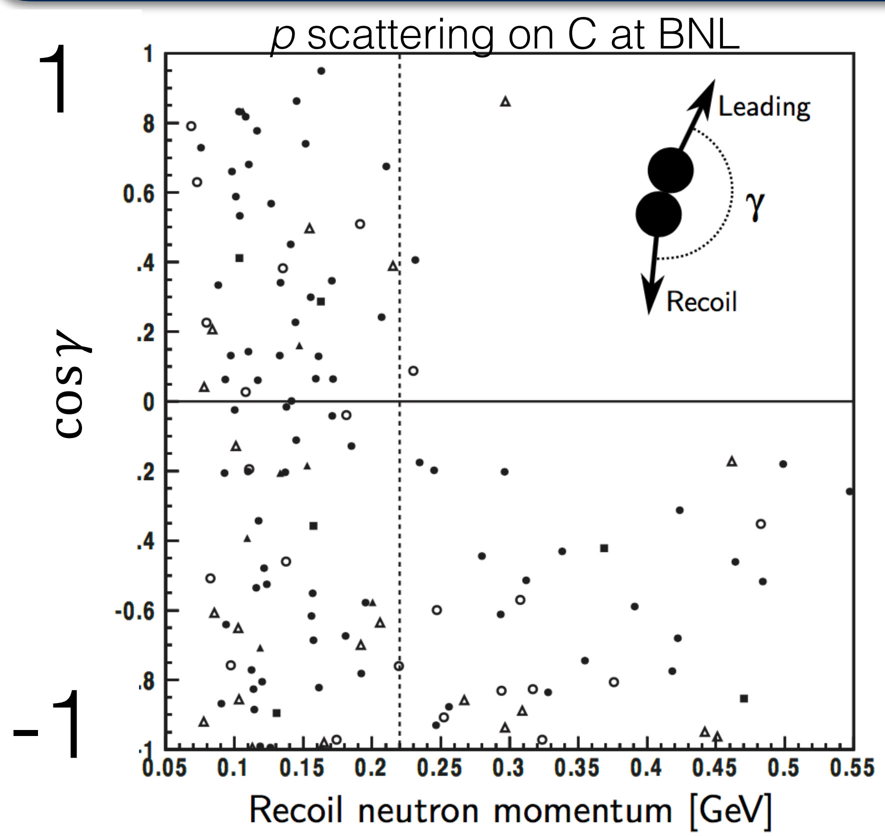
Overview of SRC

QE Exclusive Scattering



Overview of SRC

QE Exclusive Scattering Experimental Results



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Overview of SRC

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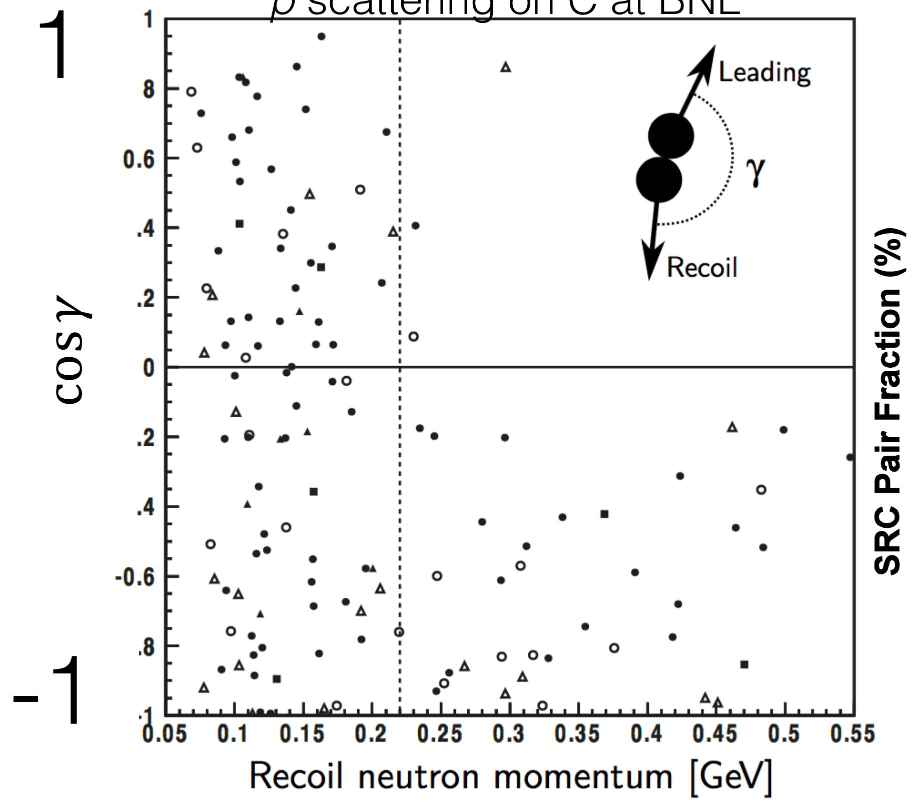
p scattering on C at BNL



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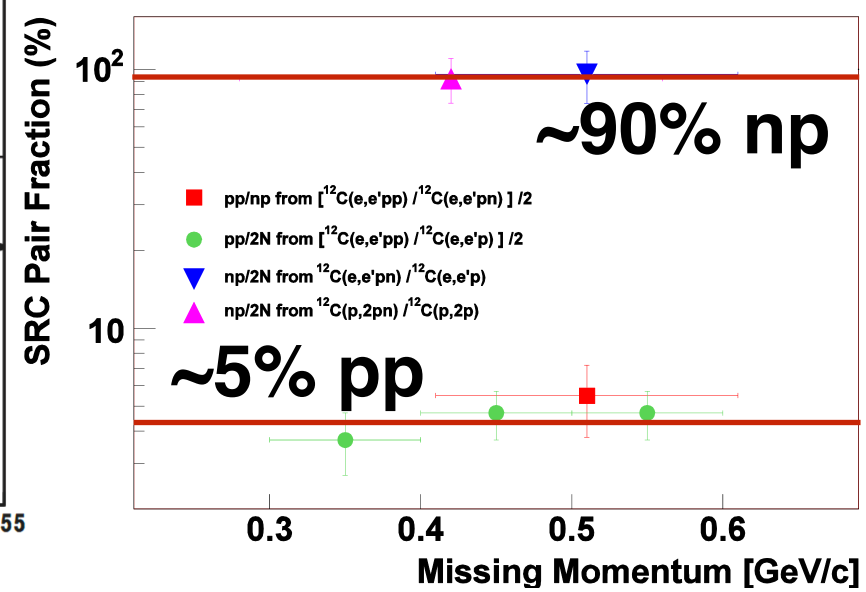

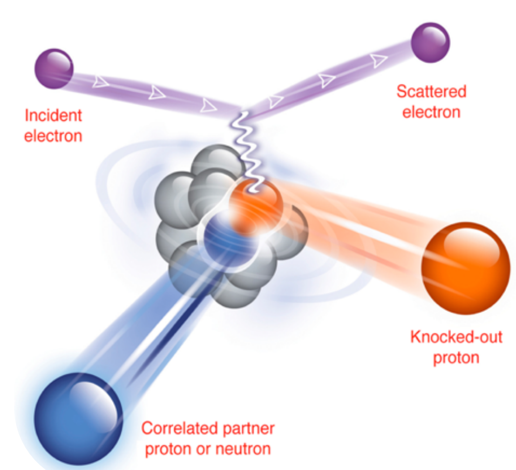

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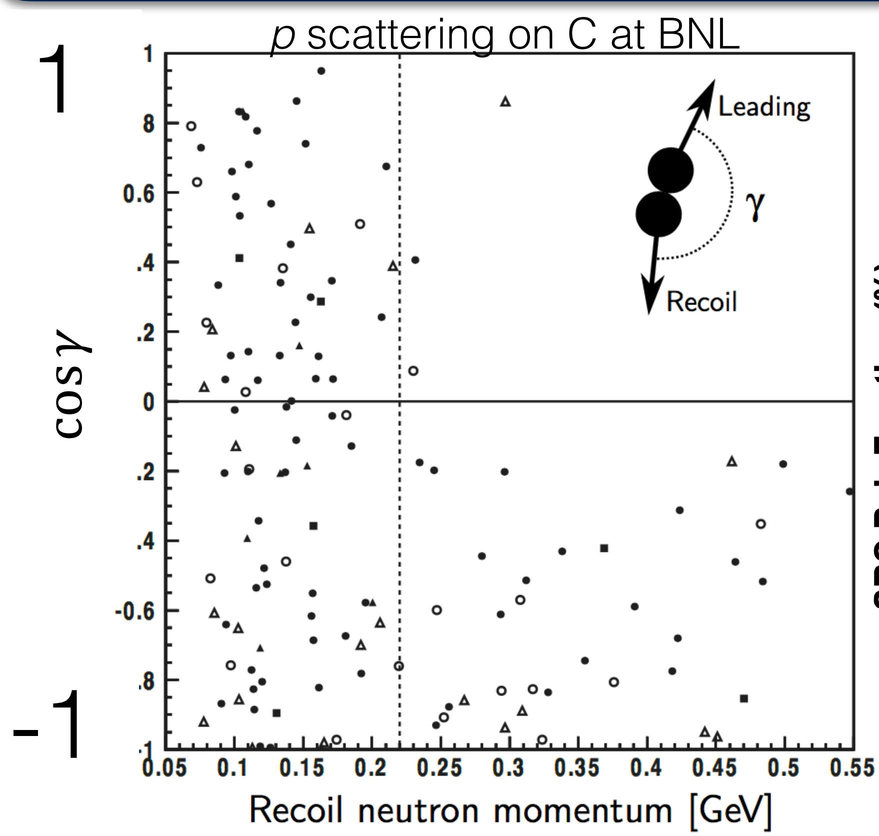

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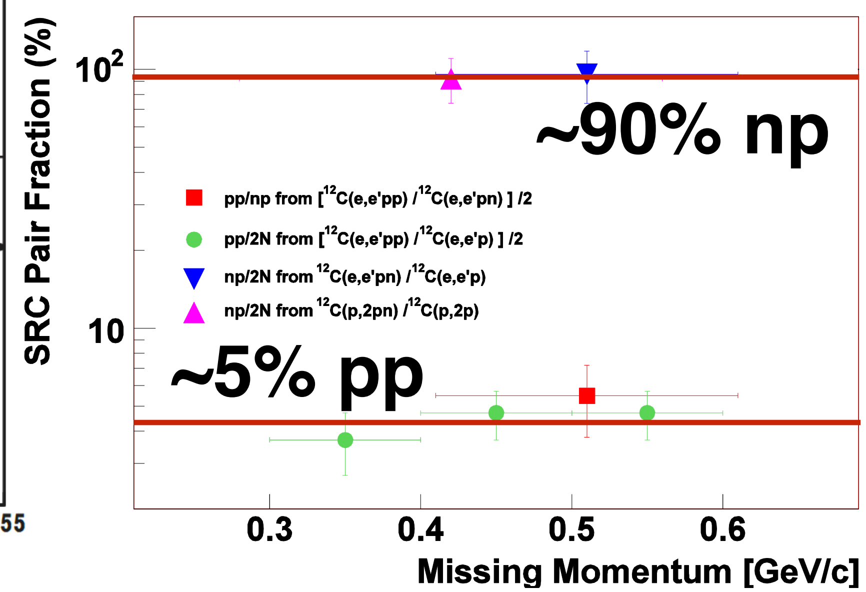

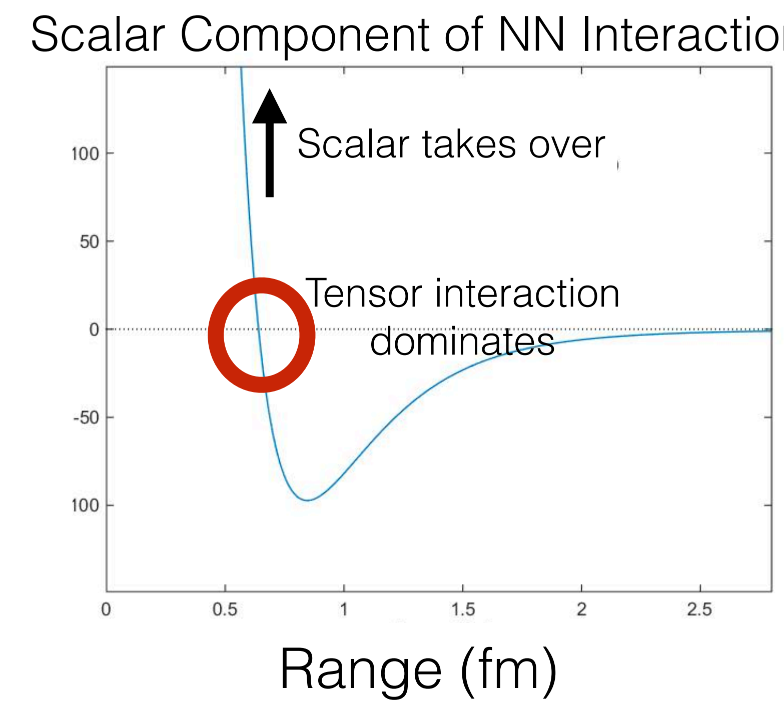

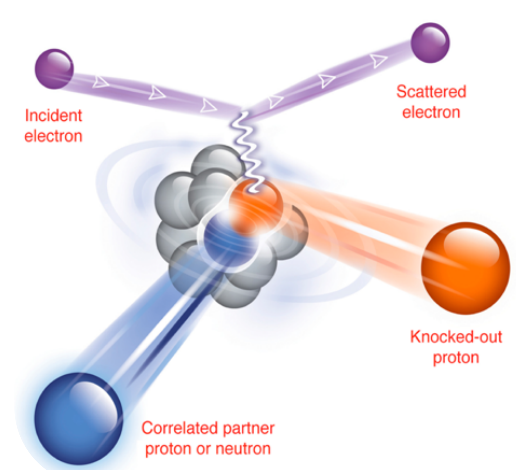

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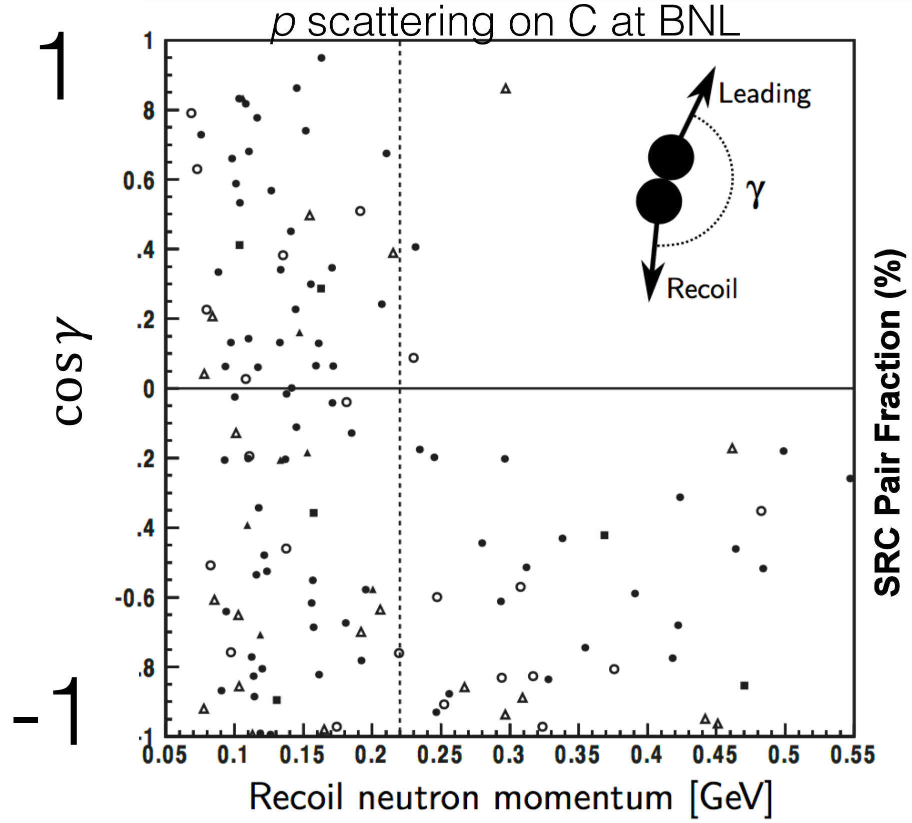

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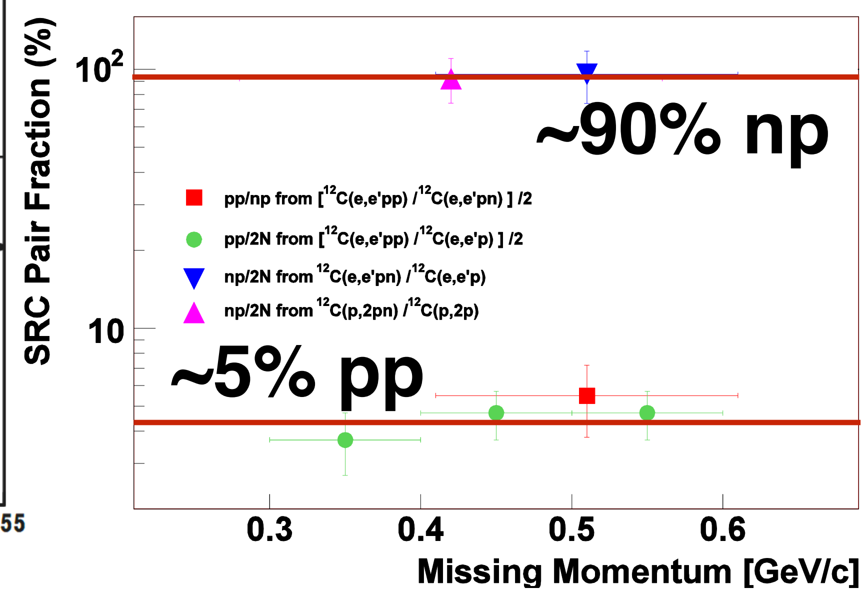
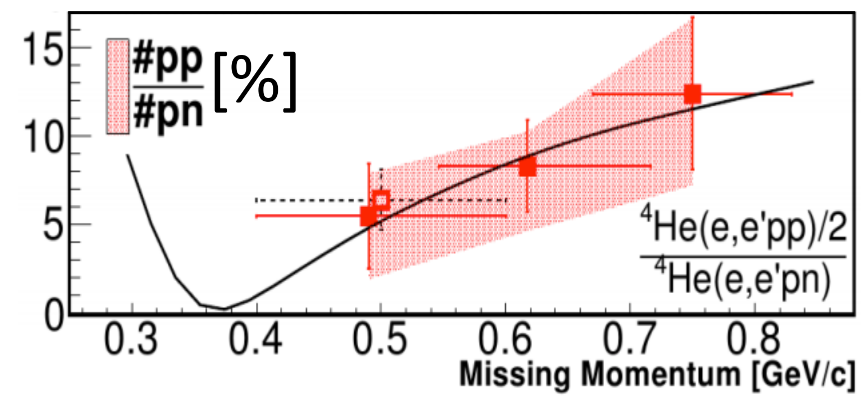
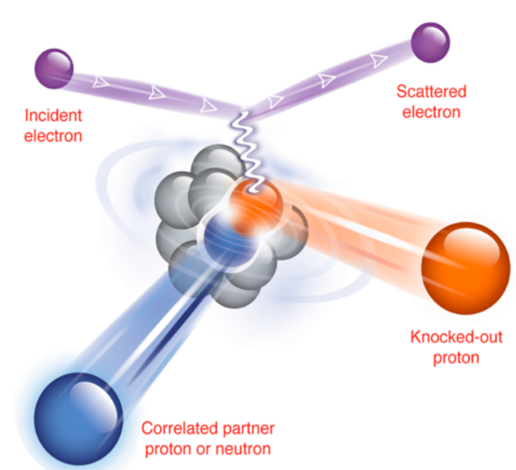




Korover, Navaphon and Hen et al., PRL 113 (2014) 022501



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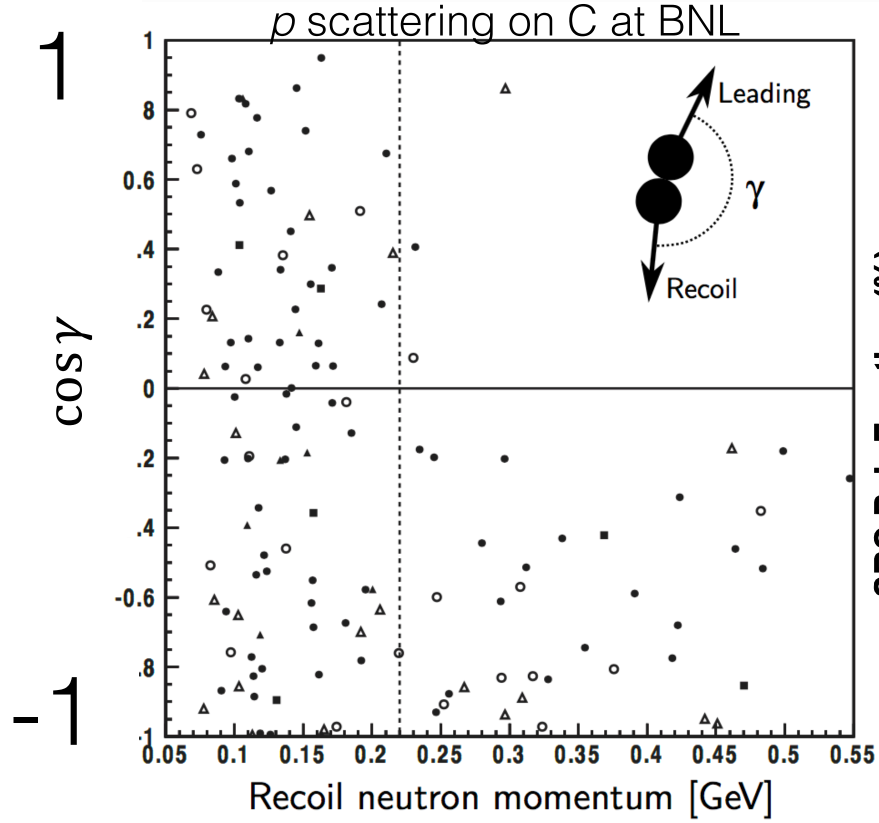

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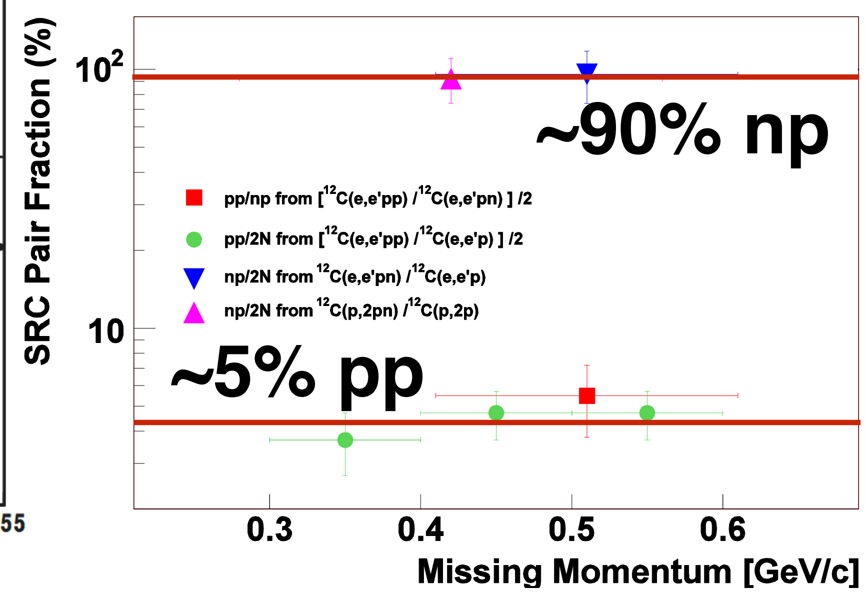

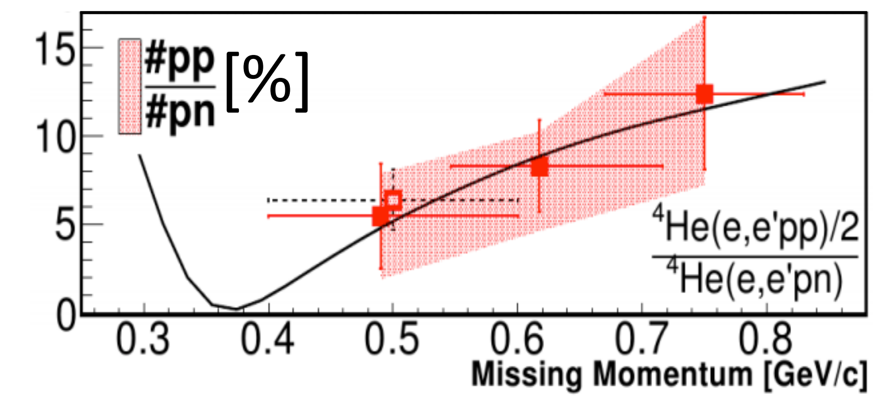

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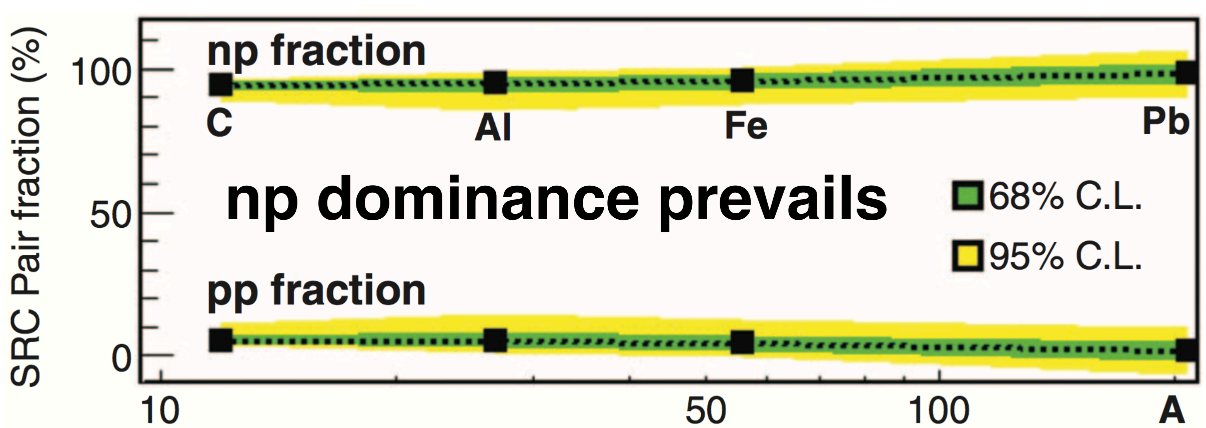
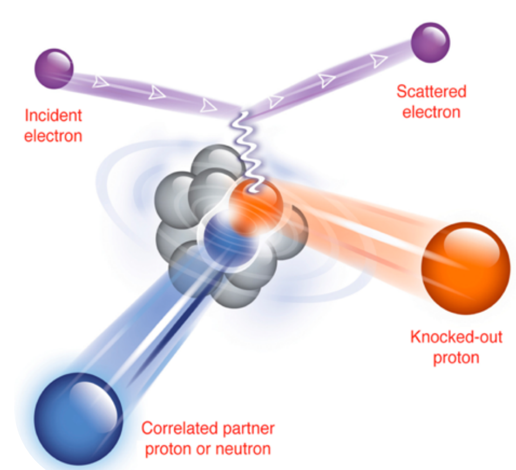


O. Hen et al, Science 346, 614 (2014)



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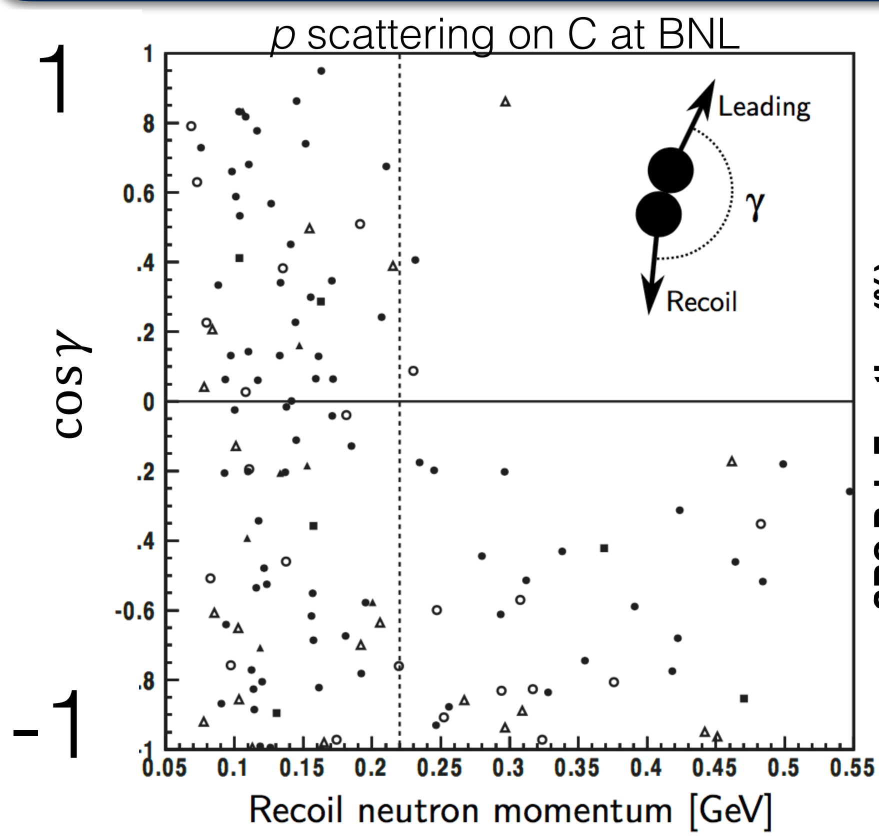

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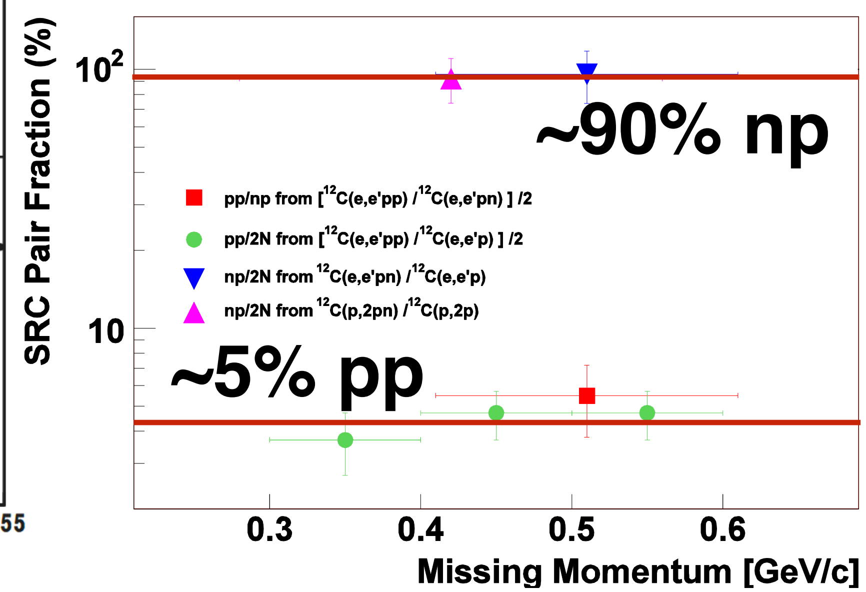

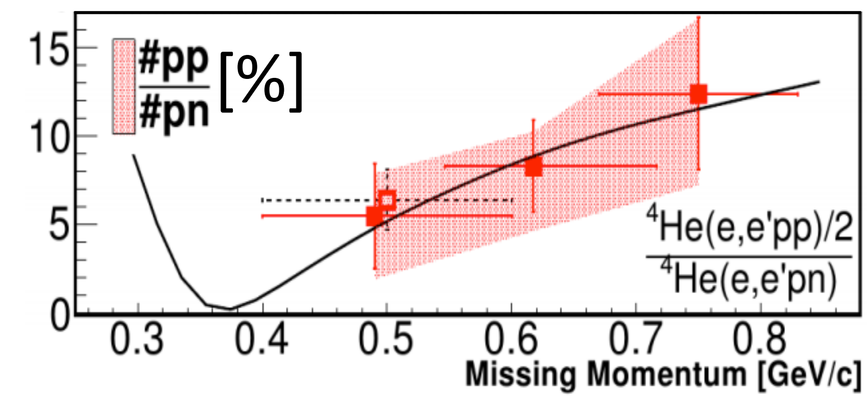

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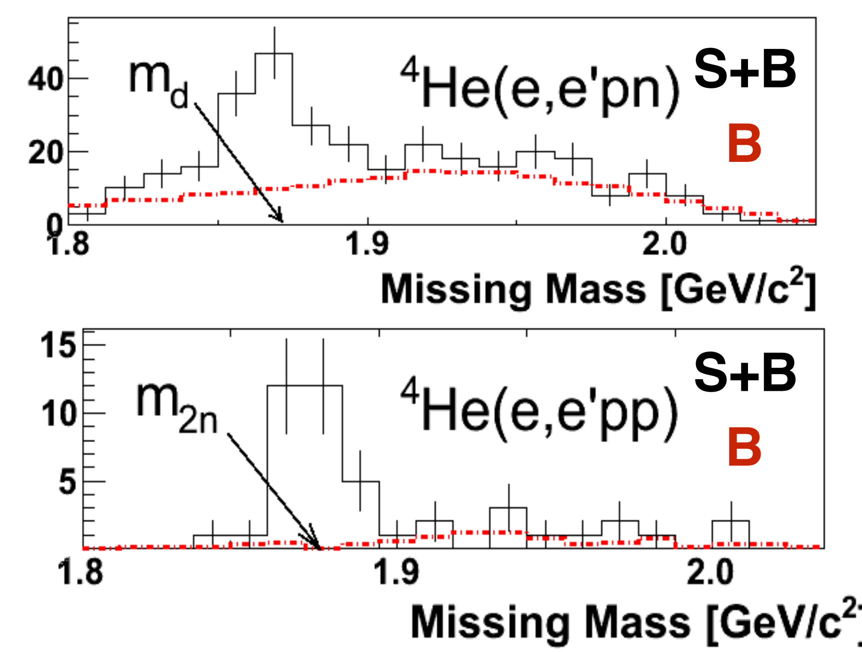

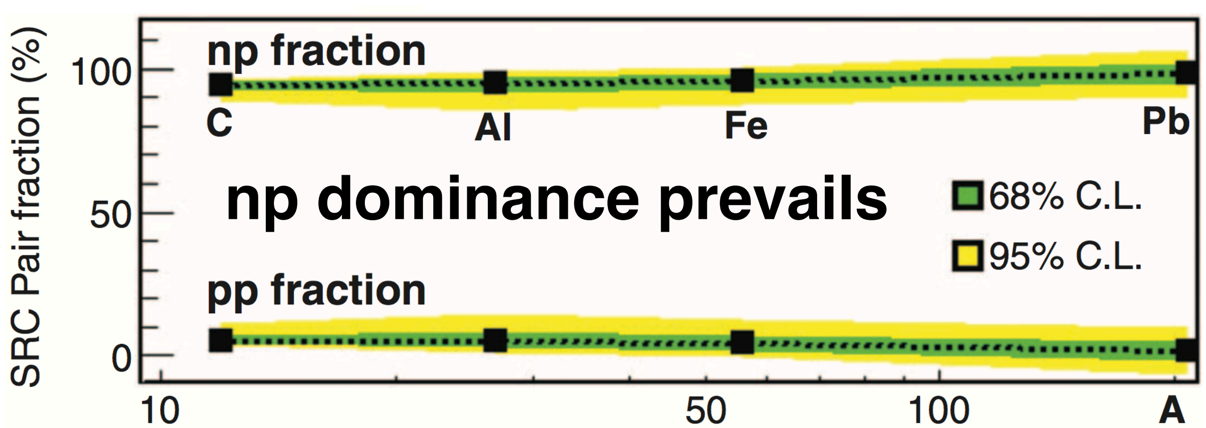

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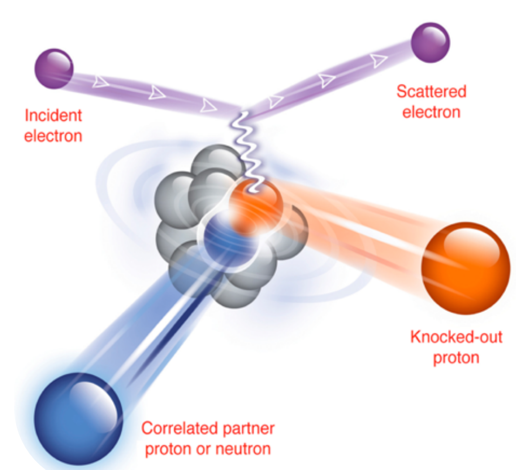

Outline

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Motivation for SRC@JINR

Physics Extraction

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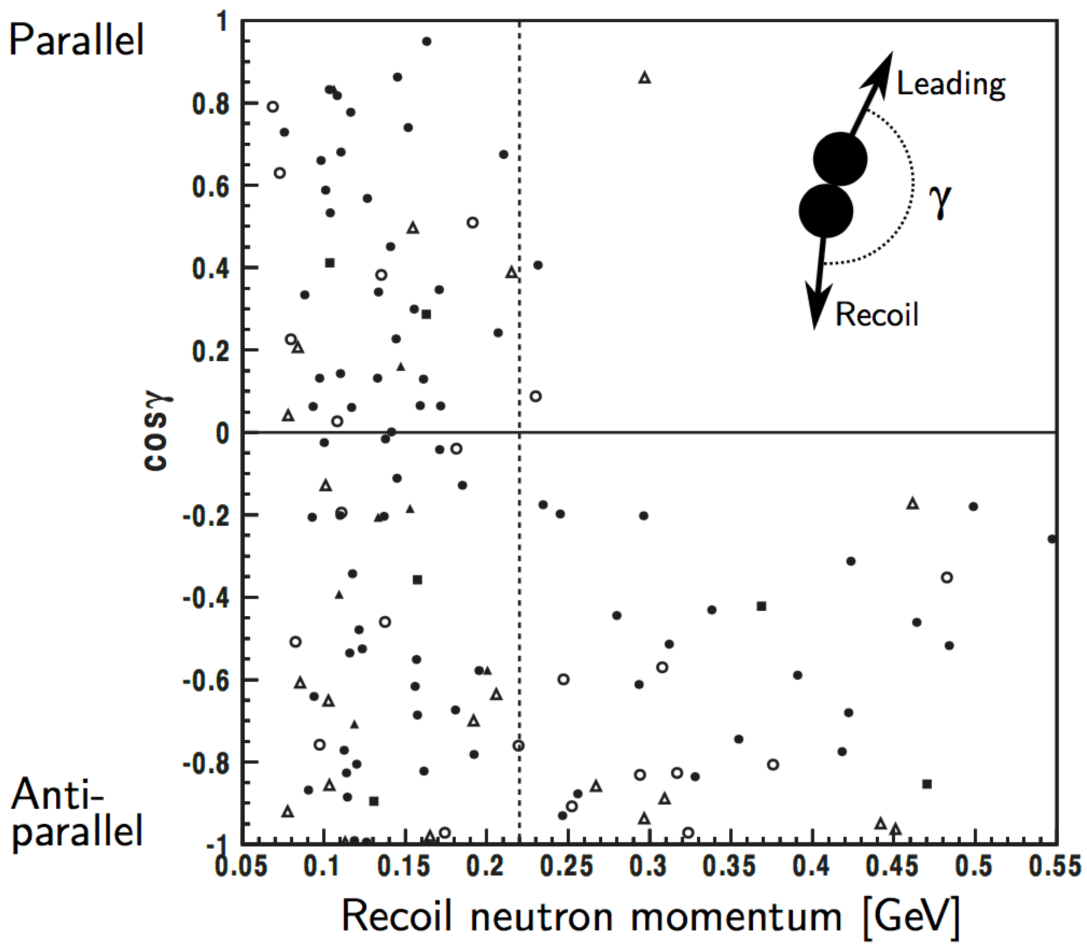
Current Limitation: Statistics

Experiment	pp Pairs	np Pairs	nn Pairs
E01-015/JLab	263	179	—
E07-006/JLab	50	223	—
CLAS/JLab	~400 / nucleus	—	—
Total	< 2000	< 450	0

Motivation for SRC@JINR

Current Limitation: Statistics



~30 events to 10,000 events?

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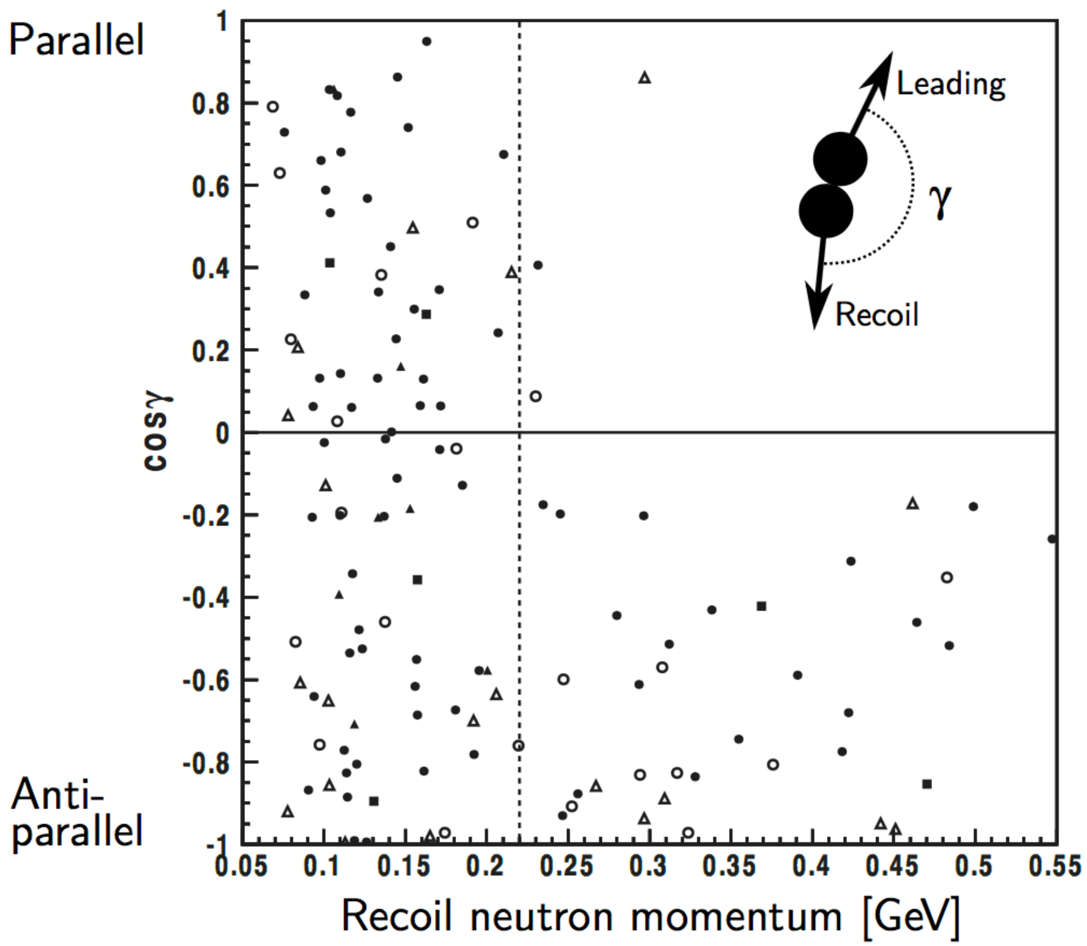

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Proton Probe - Selective Attention

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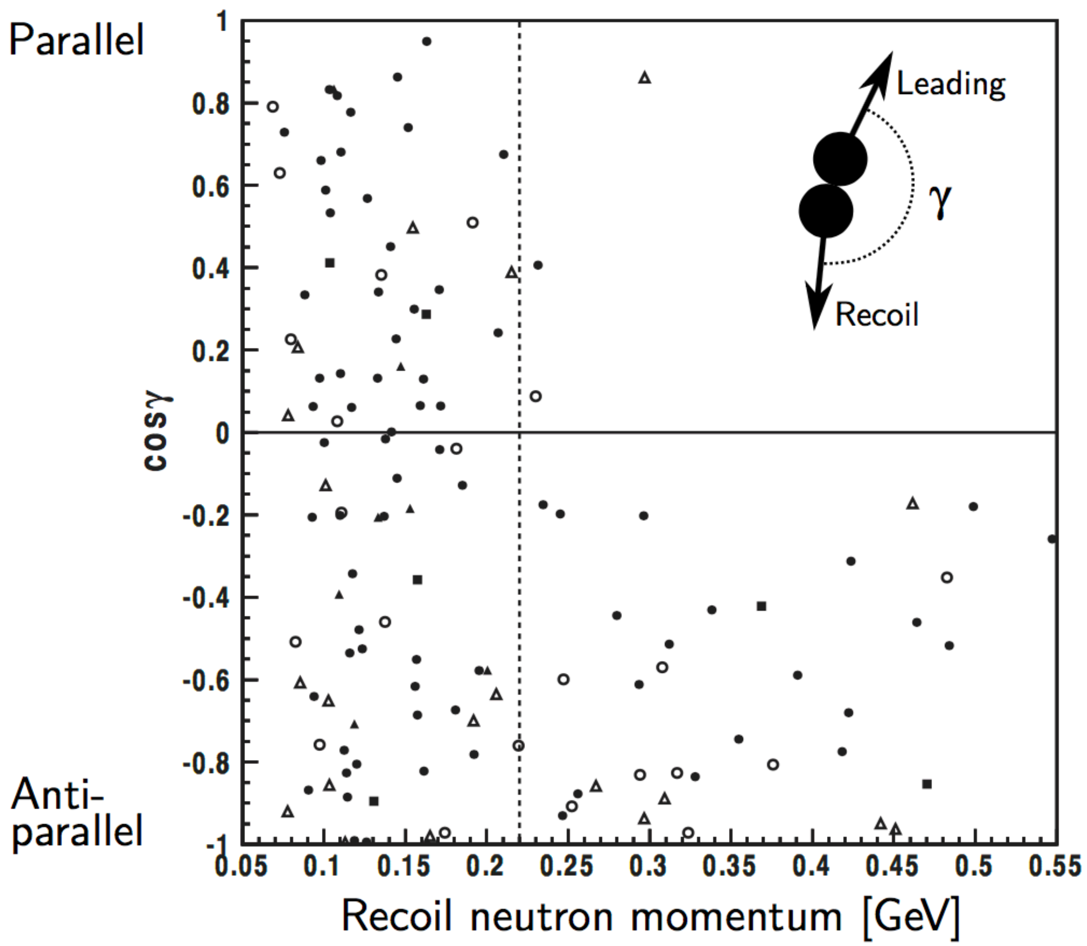

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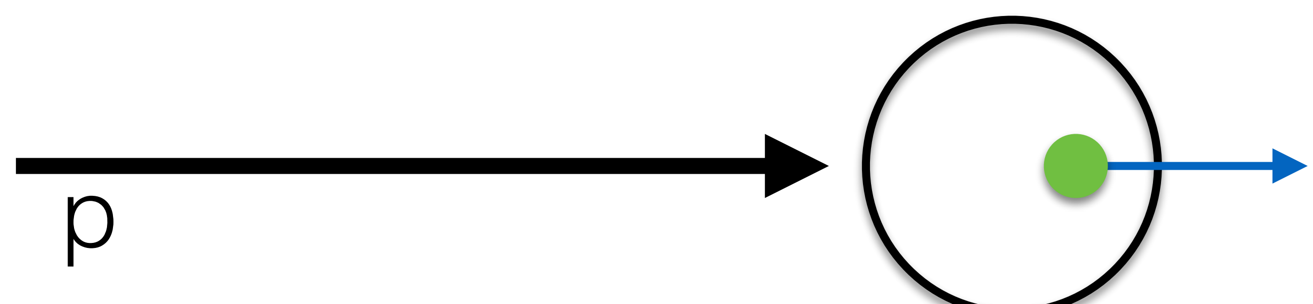
Proton Probe - Selective Attention

pp elastic scattering near 90 degrees c.m $\frac{d\sigma}{dt} \propto s^{-10}$



Statistics AND Remnant Nucleus?!

Proton Probe - Selective Attention

Motivation for SRC@JINR

Statistics AND Remnant Nucleus?!

Proton Probe - Selective Attention

Inverse Kinematics!

Motivation for SRC@JINR

Statistics AND Remnant Nucleus?!

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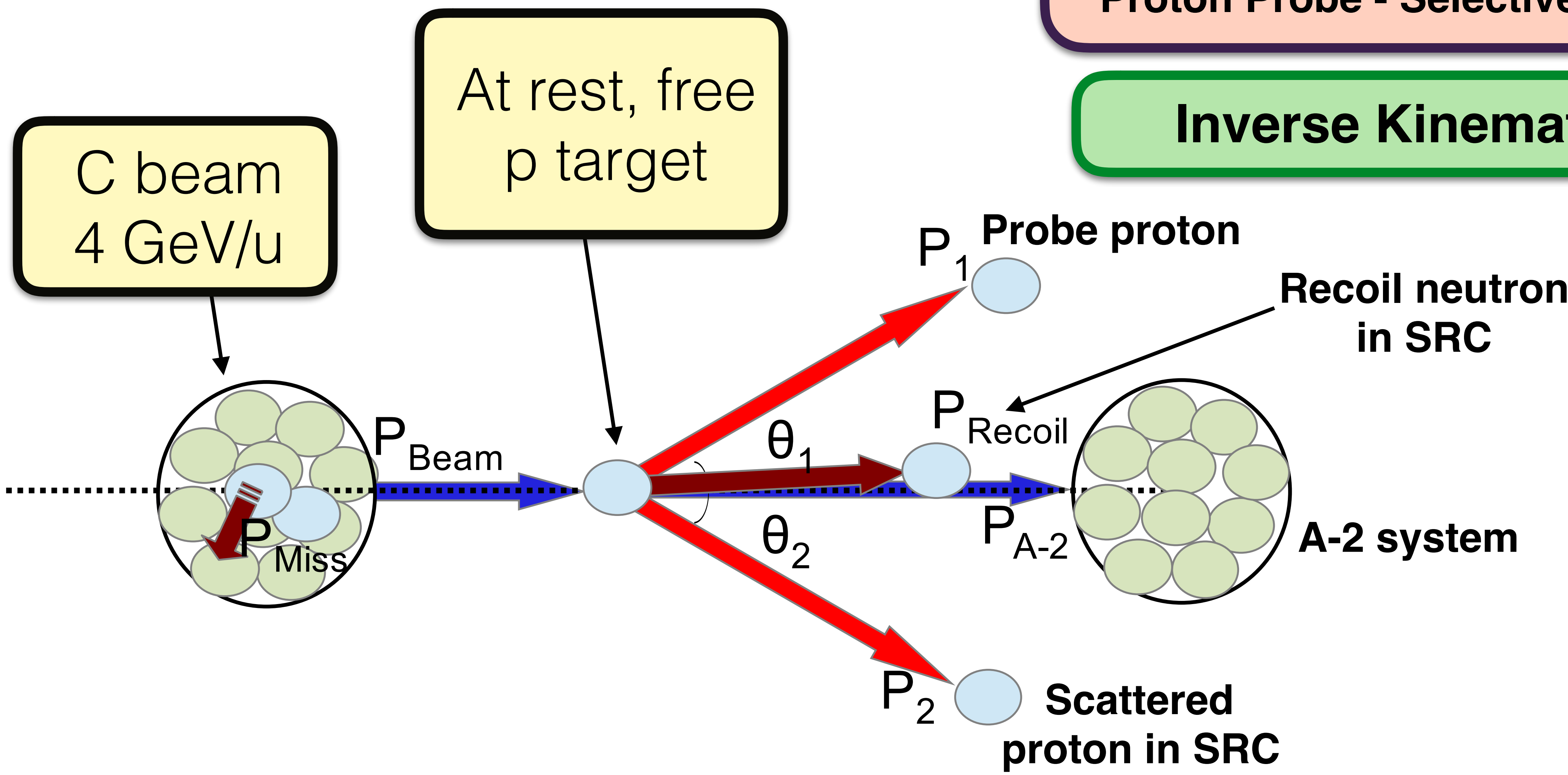

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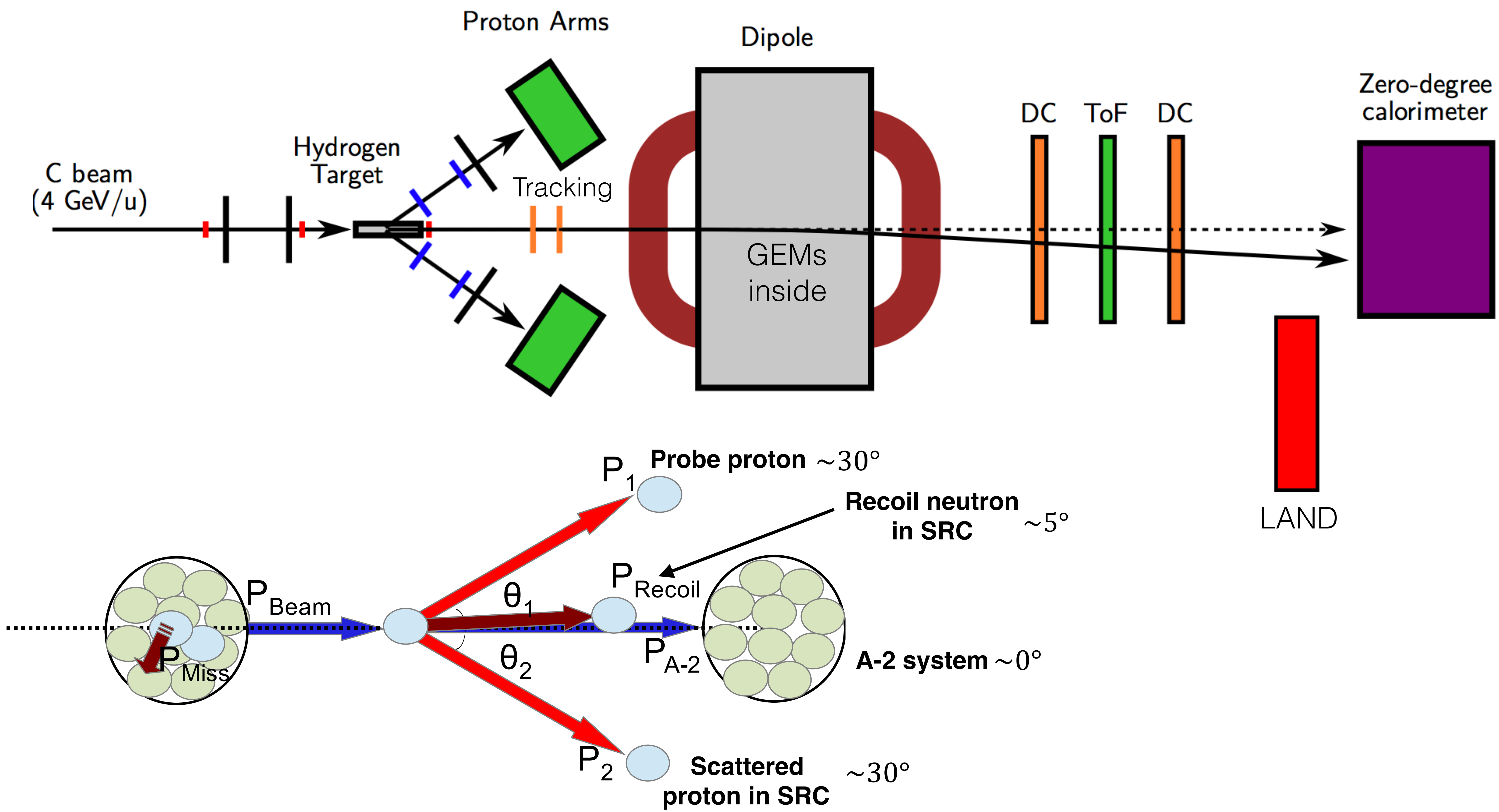

Motivation for SRC@JINR

Upcoming Experiment starting Feb 15th

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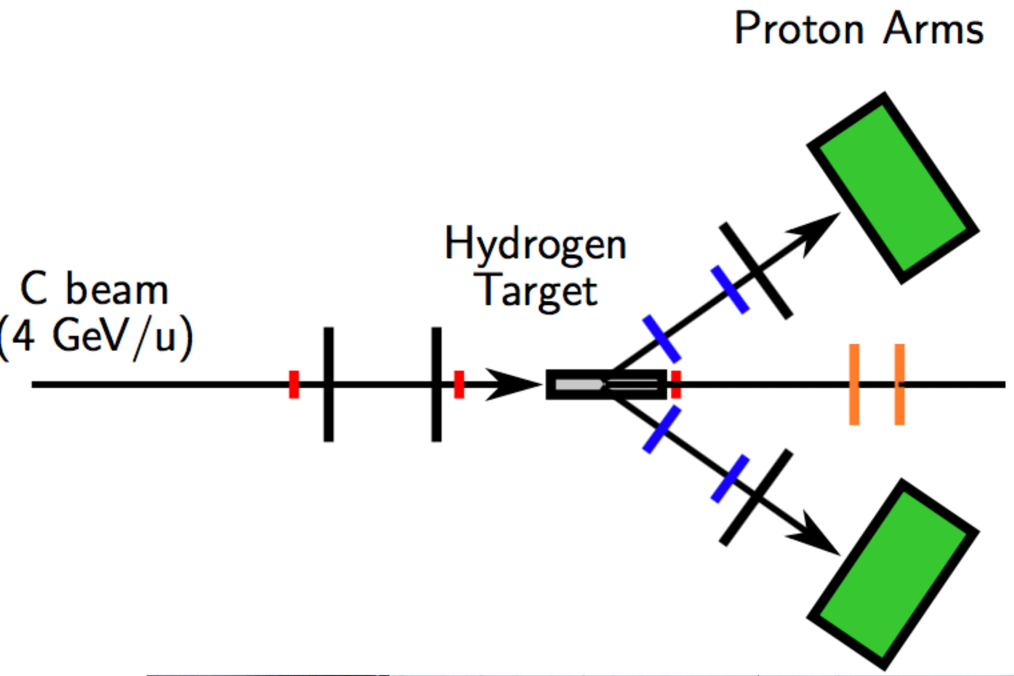
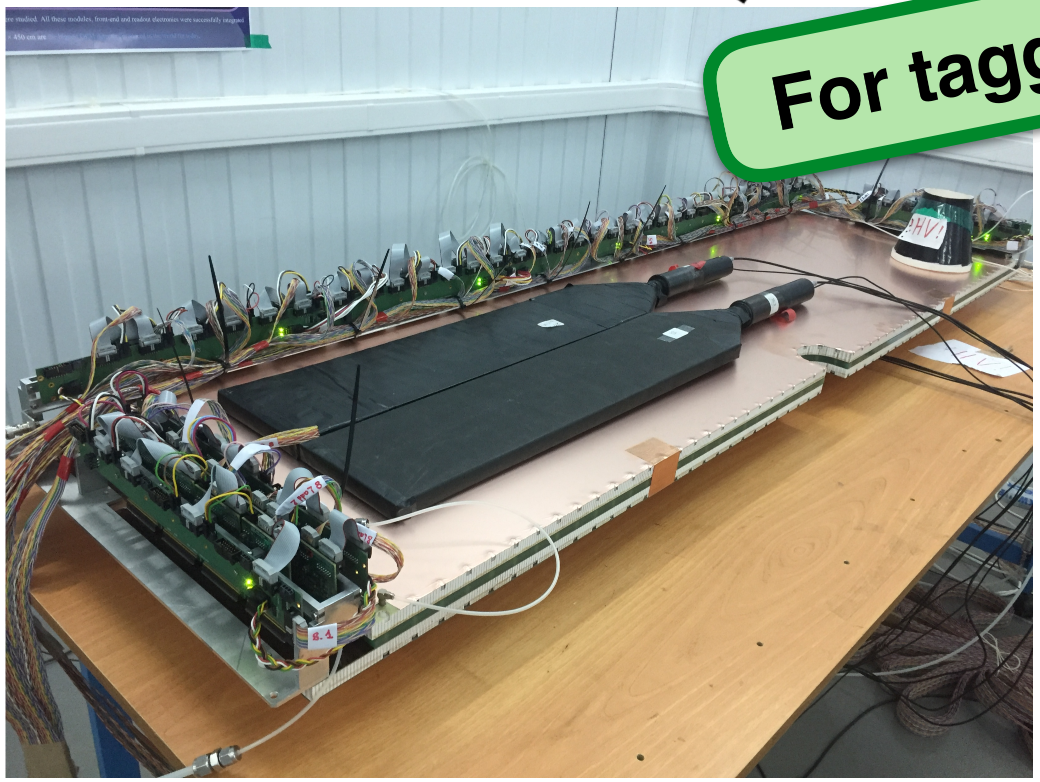
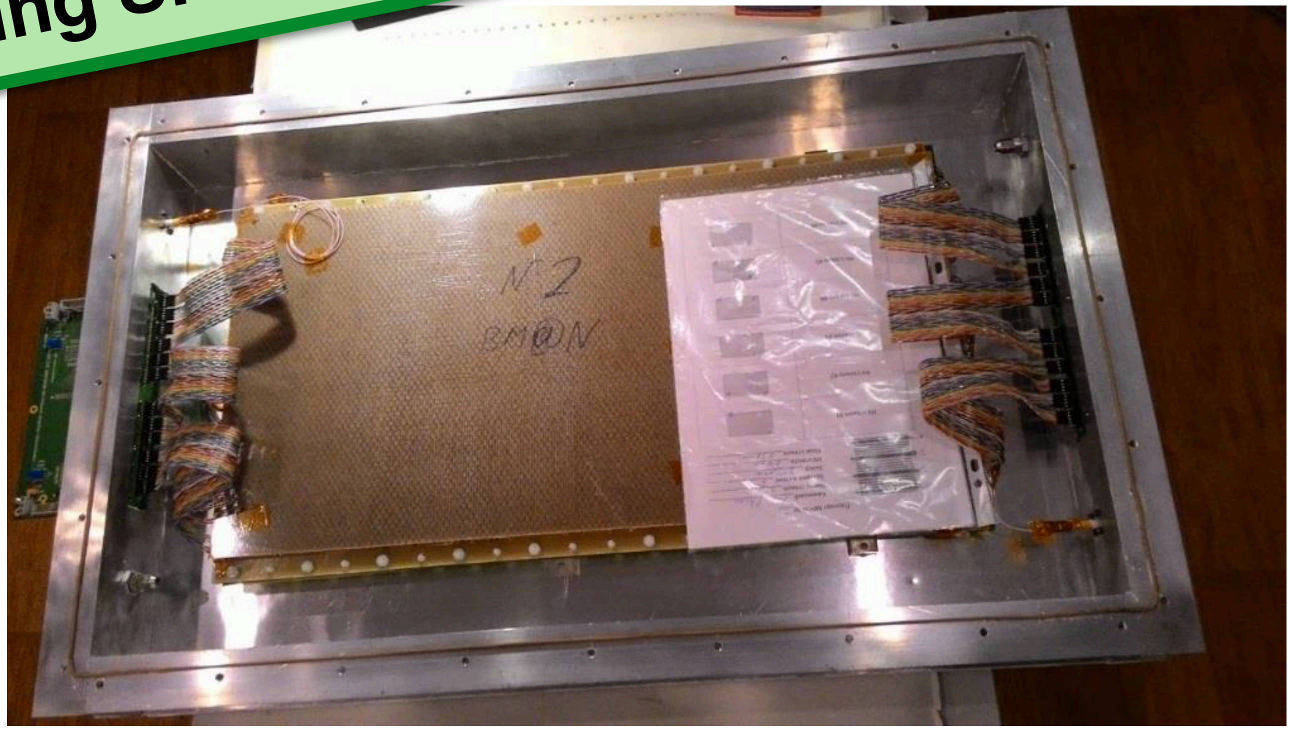


For tagging SRC events!





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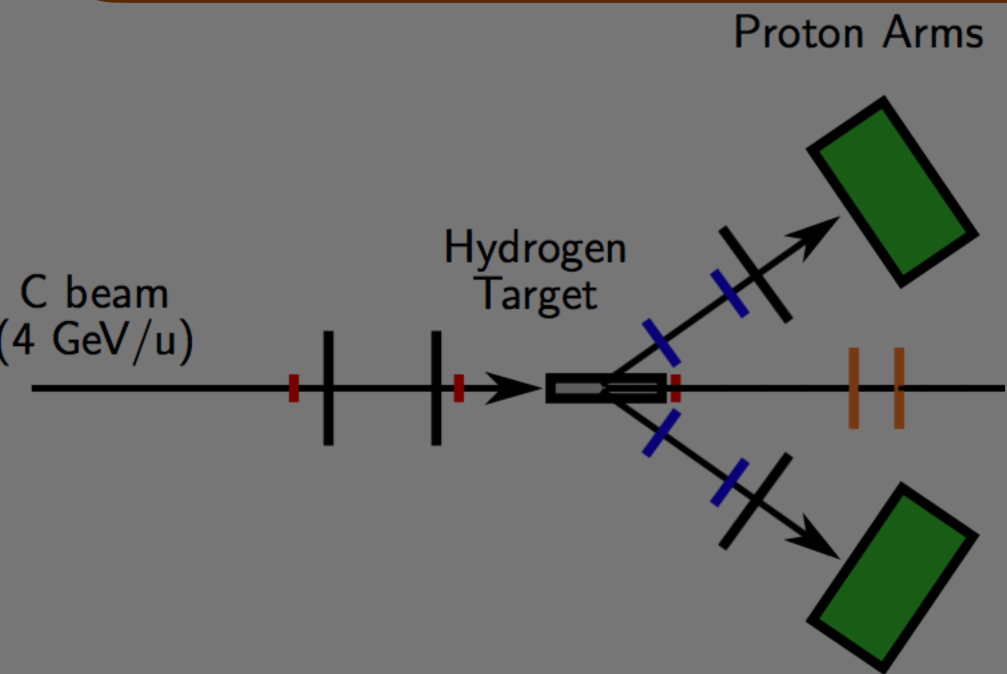

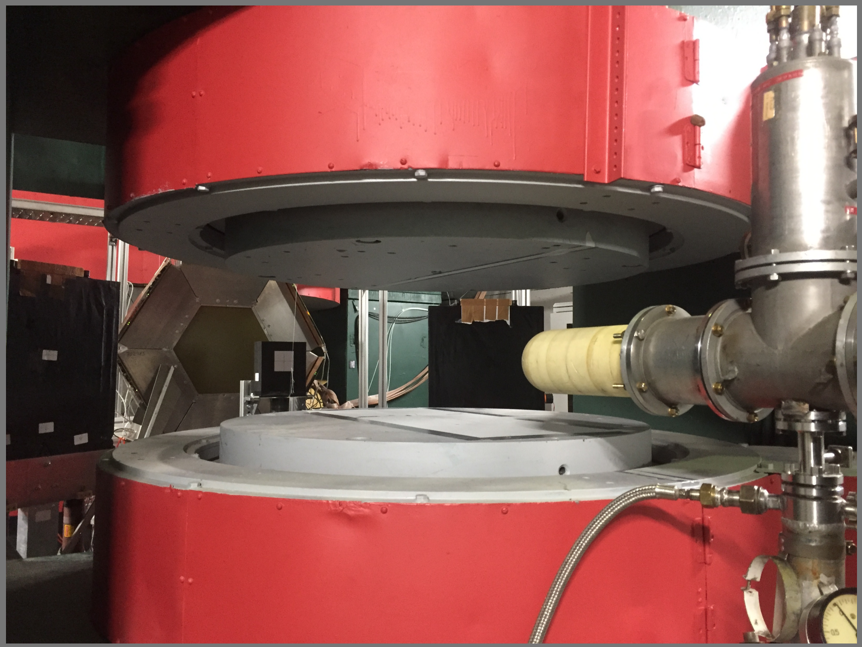

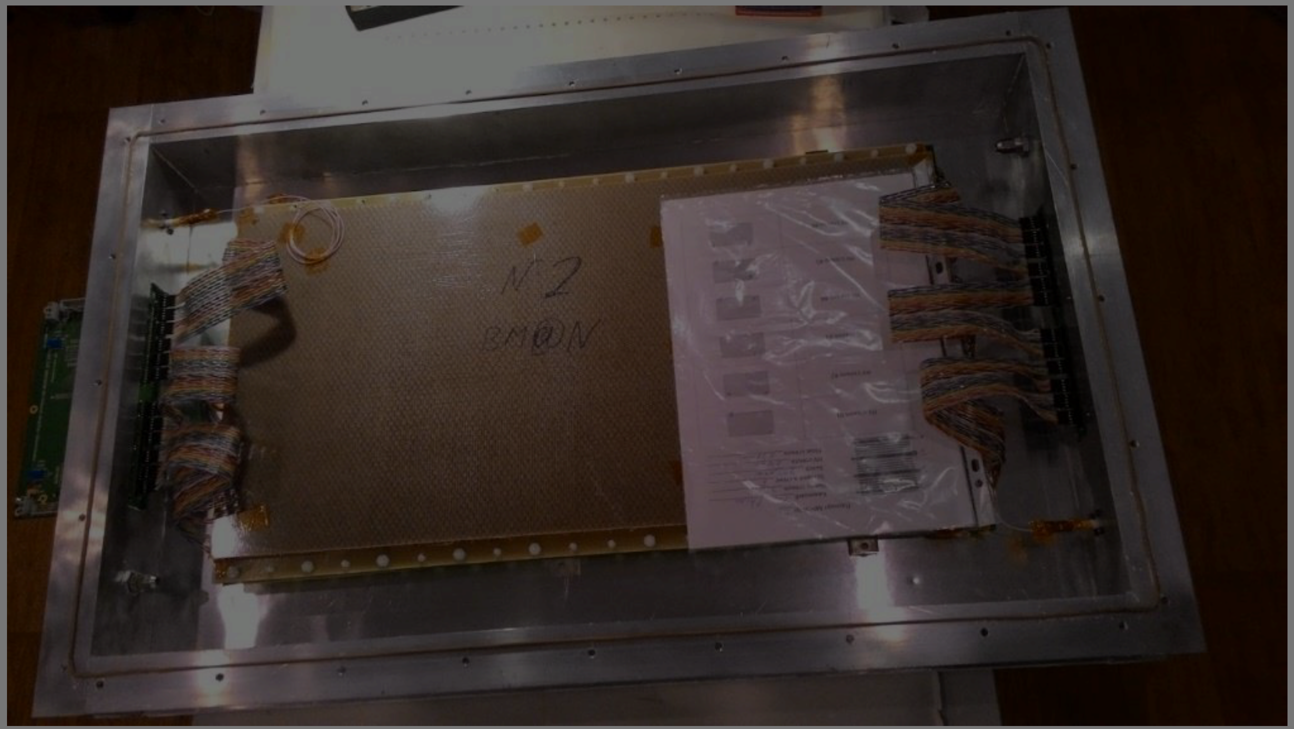

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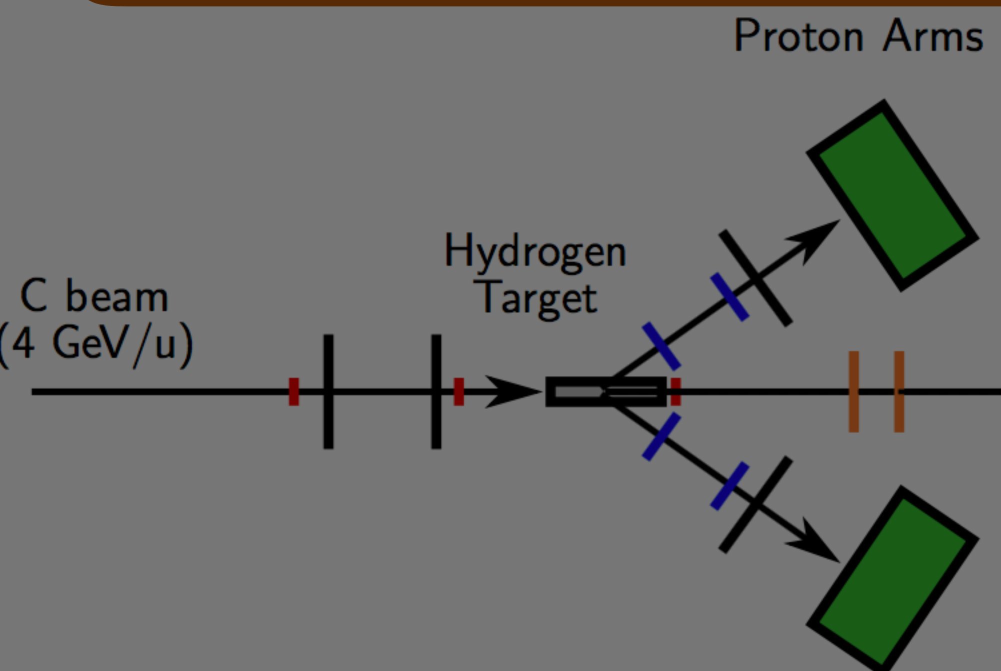
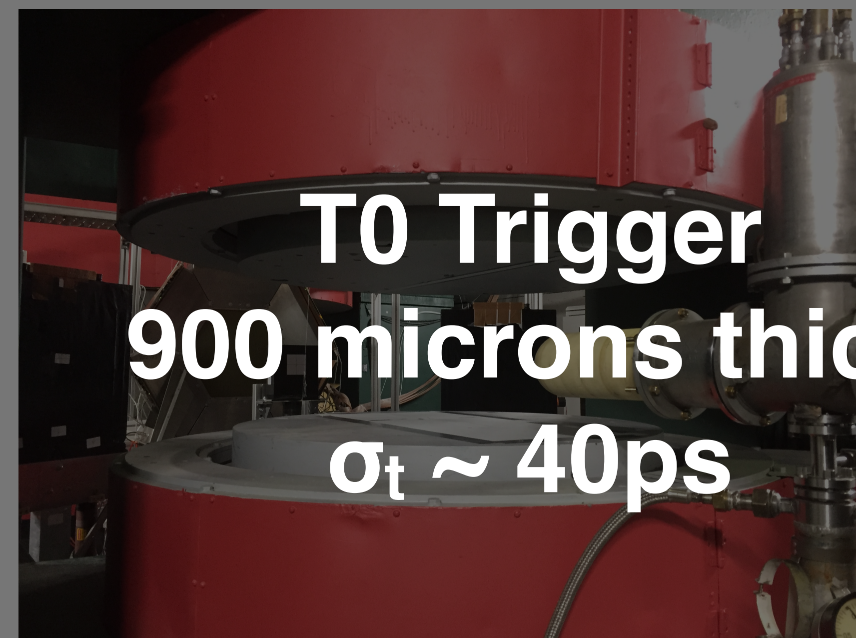
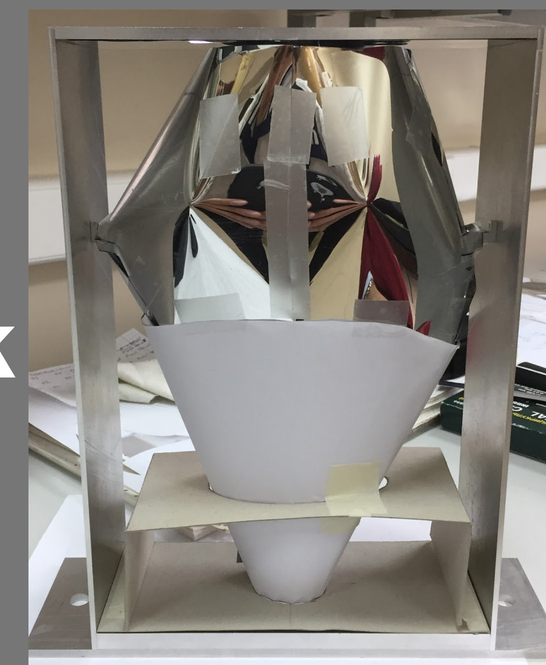
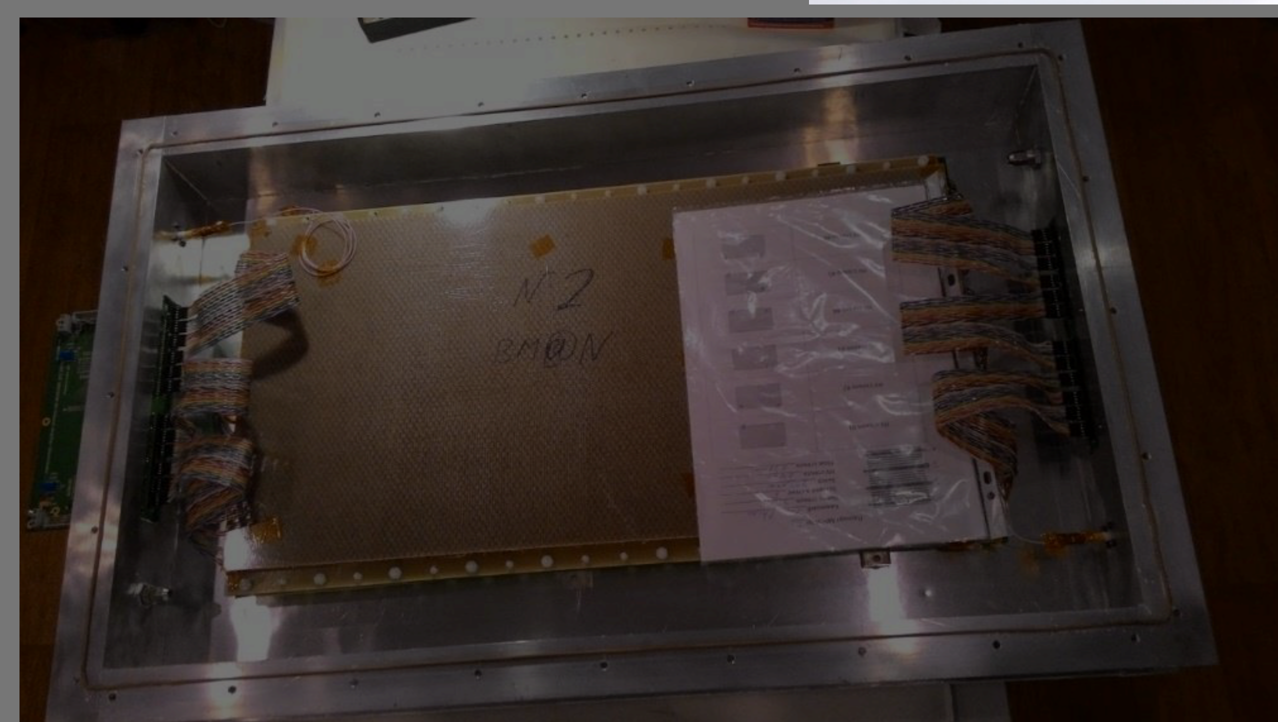




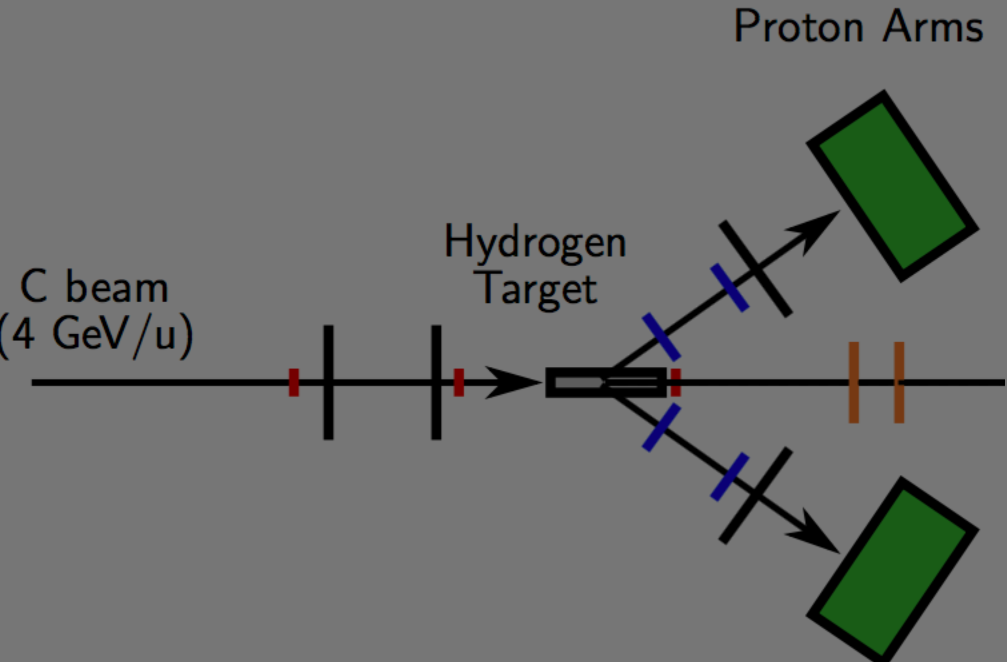
T0 Trigger
900 microns thick
$\sigma_t \sim 40$ps

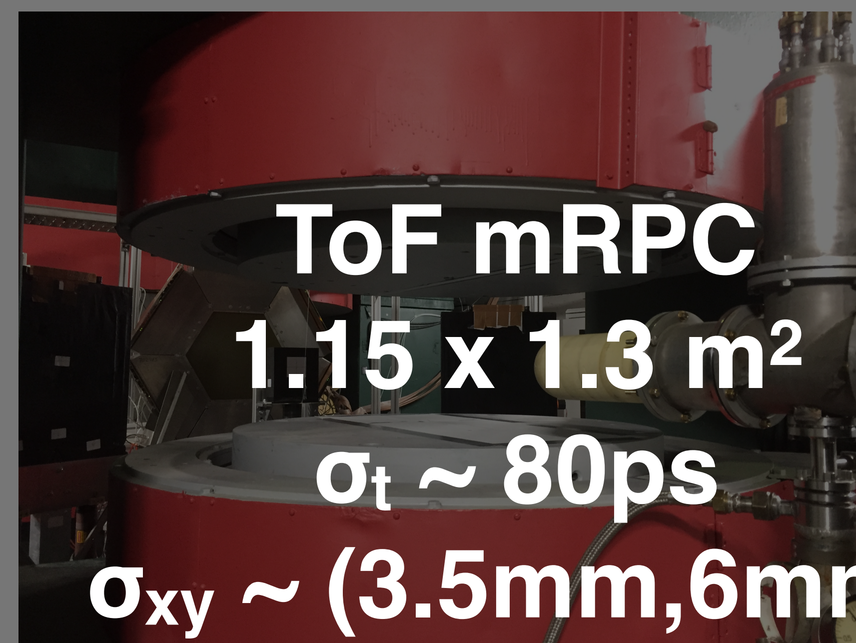




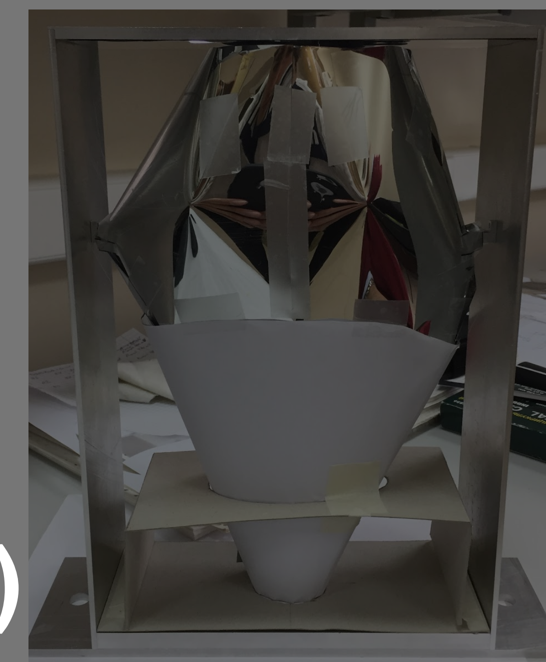
Motivation for SRC@JINR

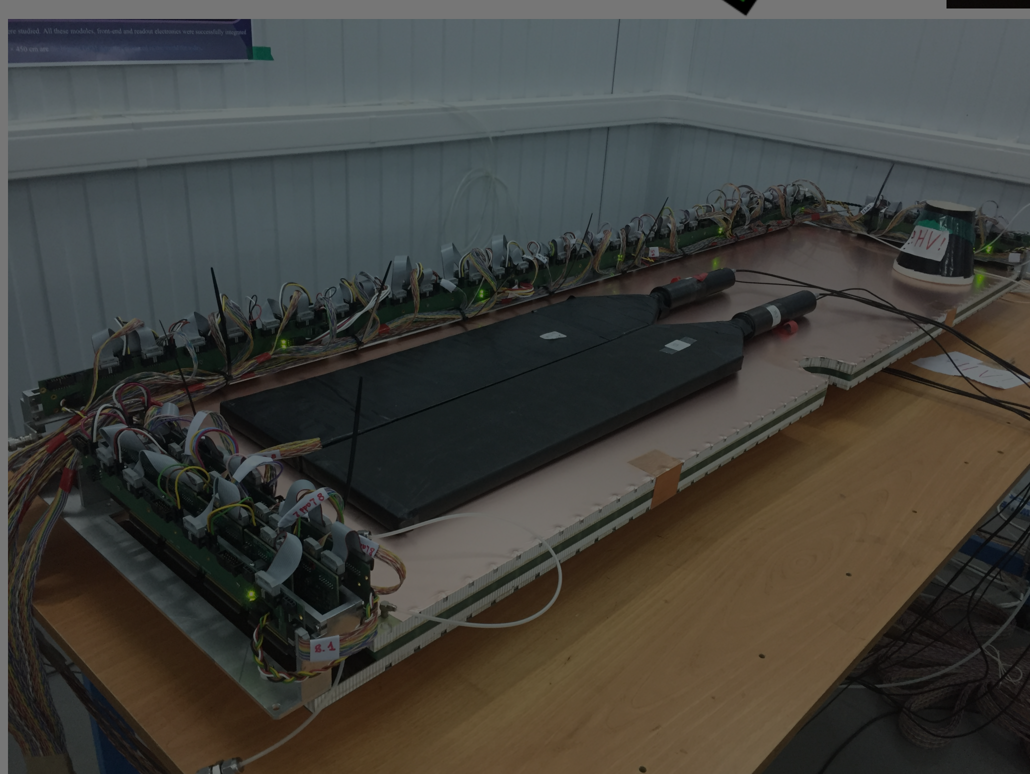
Upcoming Experiment starting Feb 15th

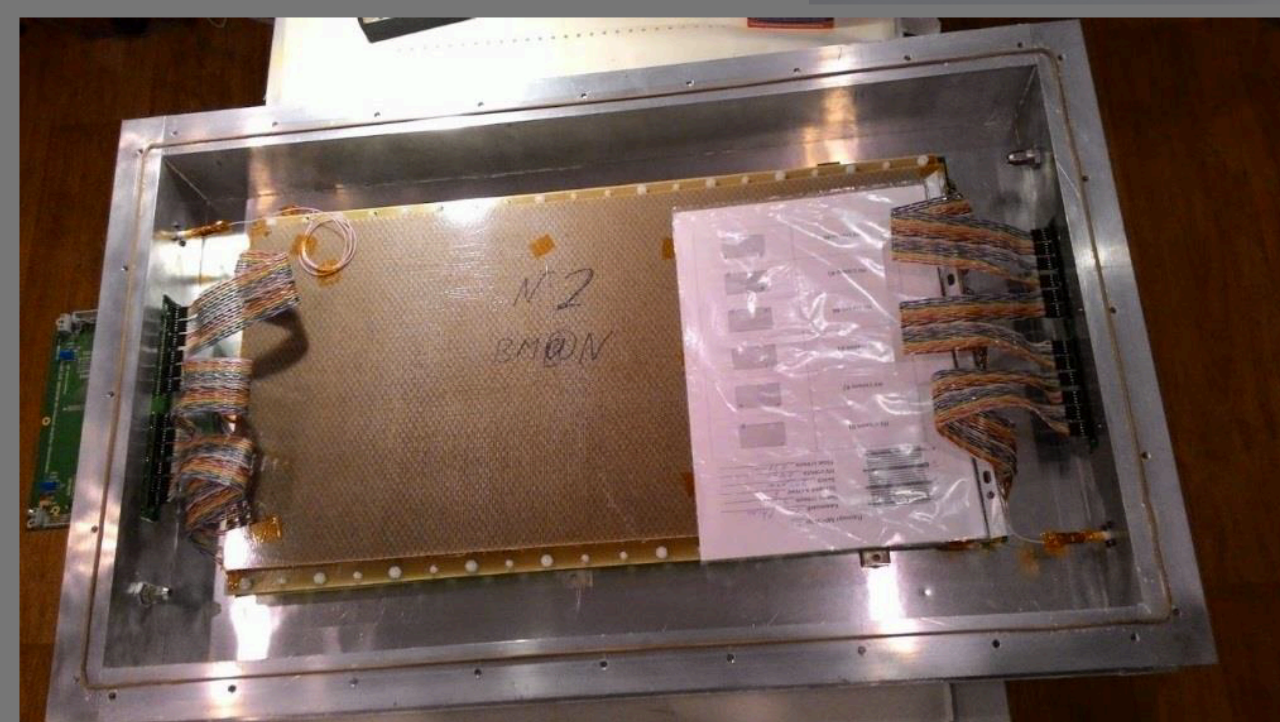




ToF mRPC
1.15 x 1.3 m²
$\sigma_t \sim 80$ps
$\sigma_{xy} \sim$ (3.5mm,6mm)

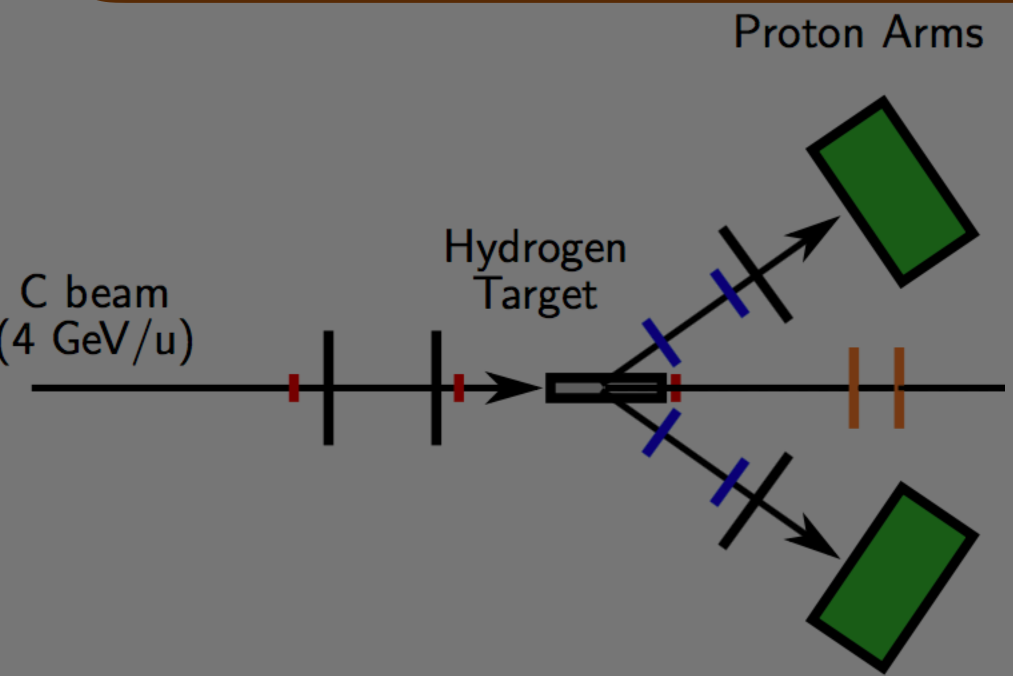


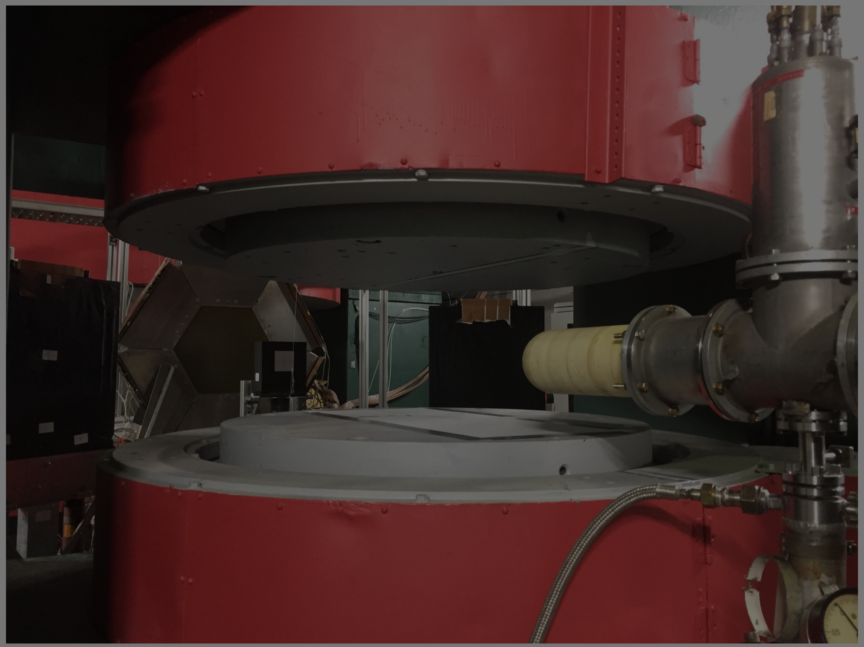


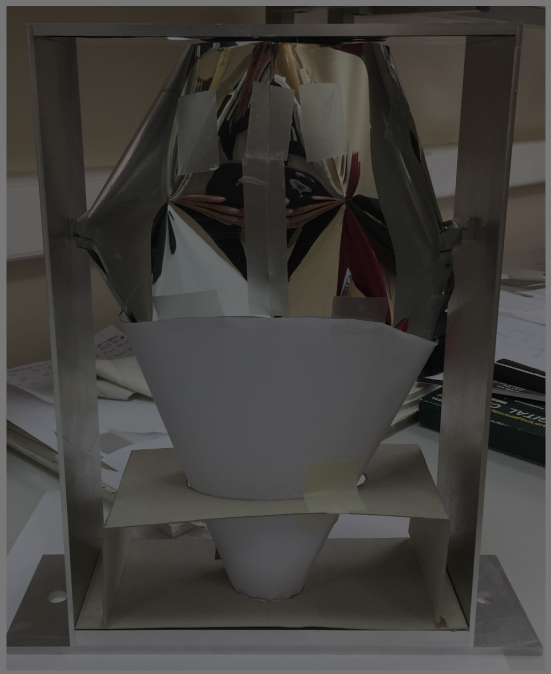


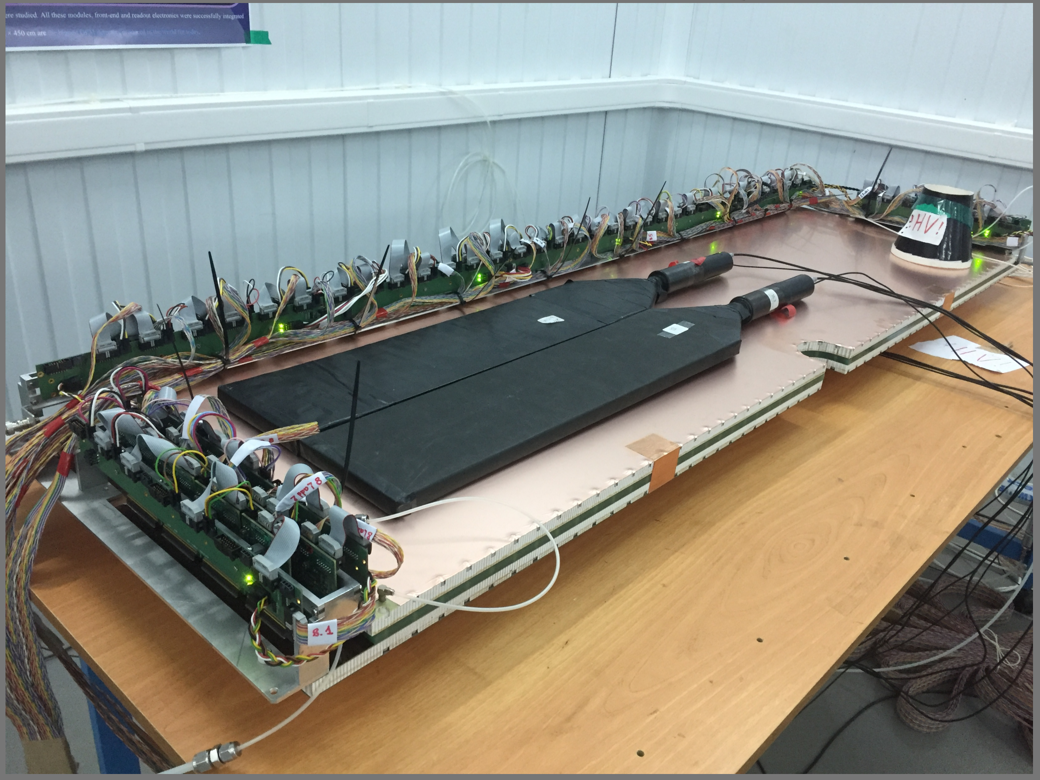
Motivation for SRC@JINR

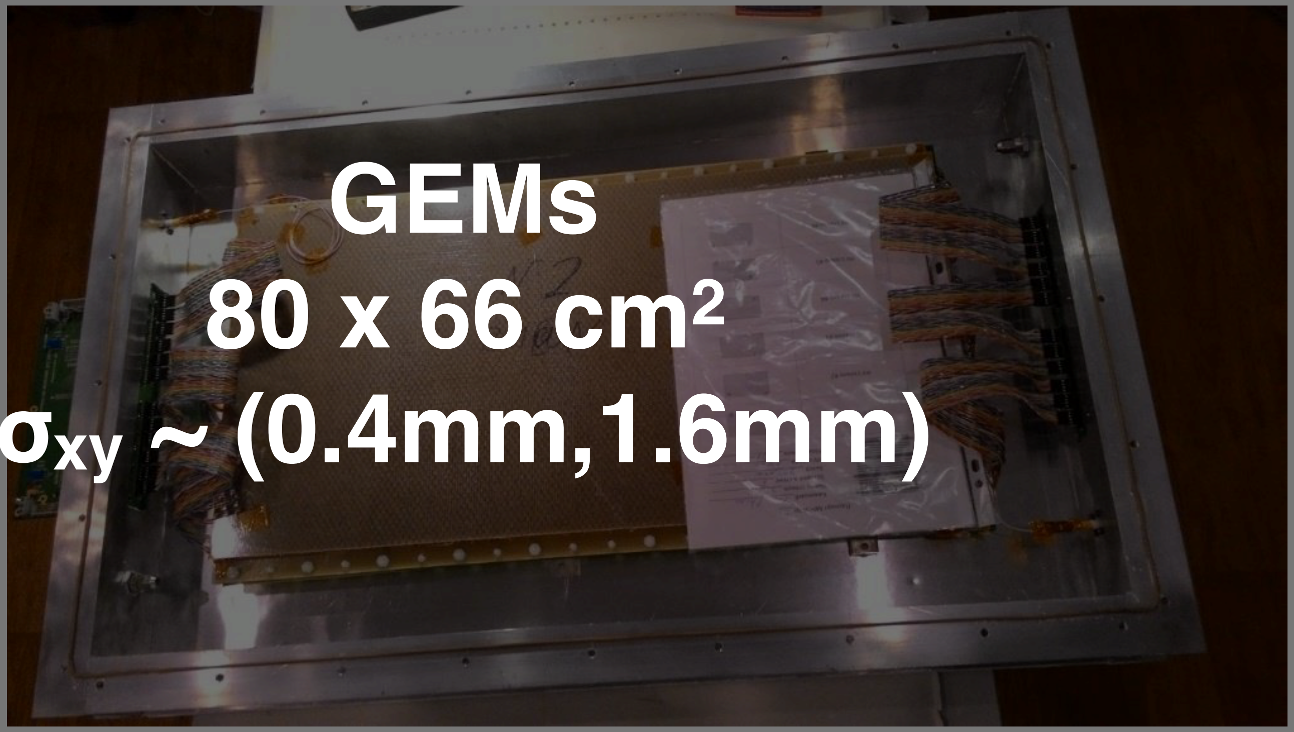
Upcoming Experiment starting Feb 15th





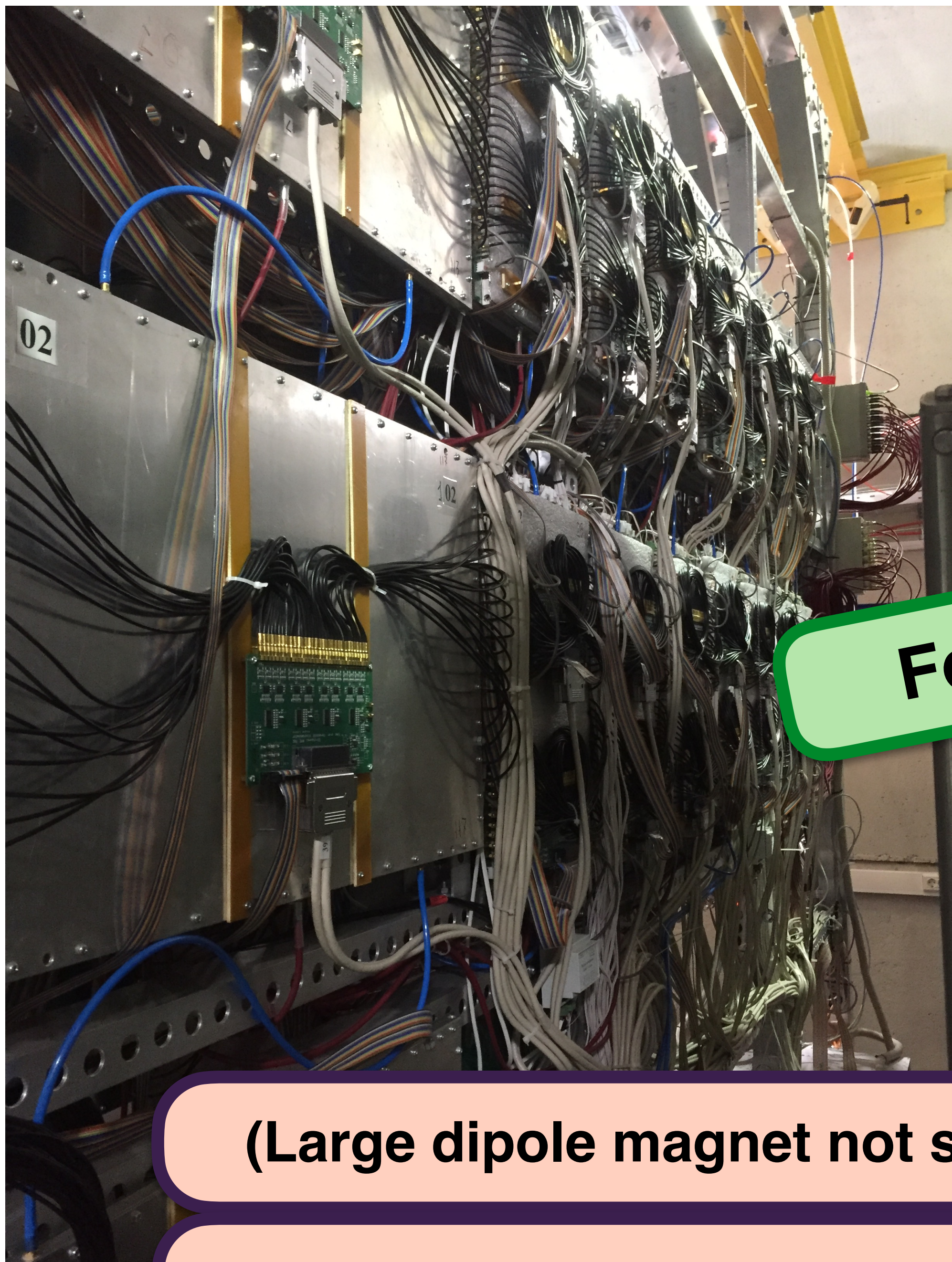


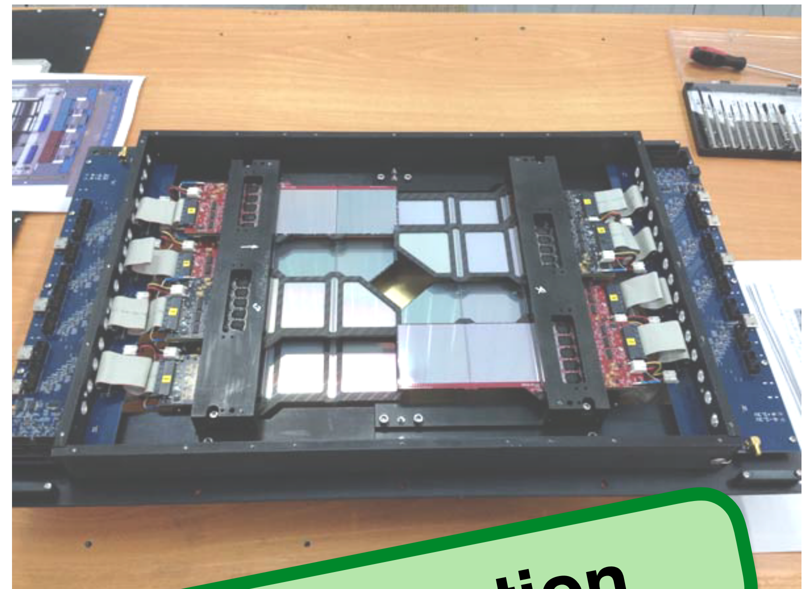


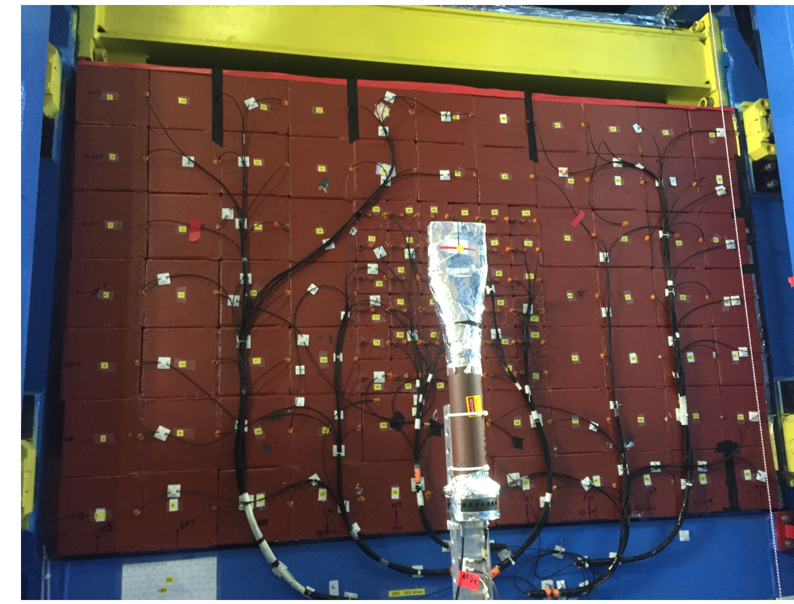


Motivation for SRC@JINR

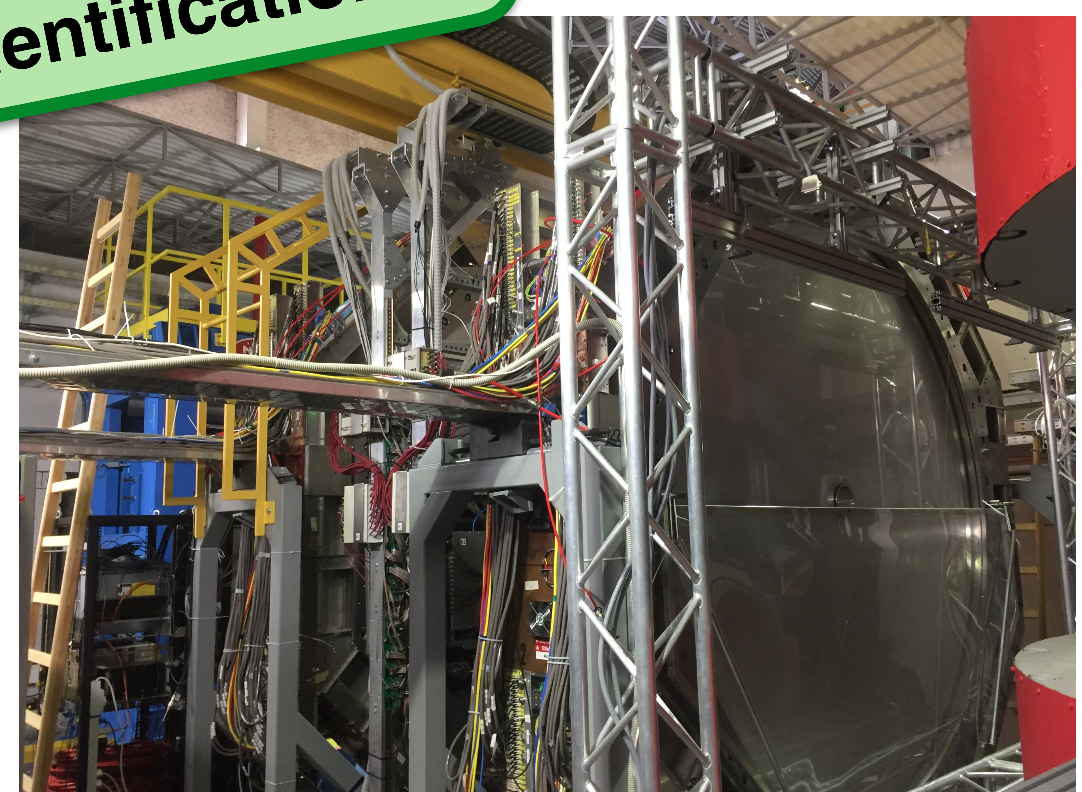
Upcoming Experiment starting Feb 15th







For A-2 identification

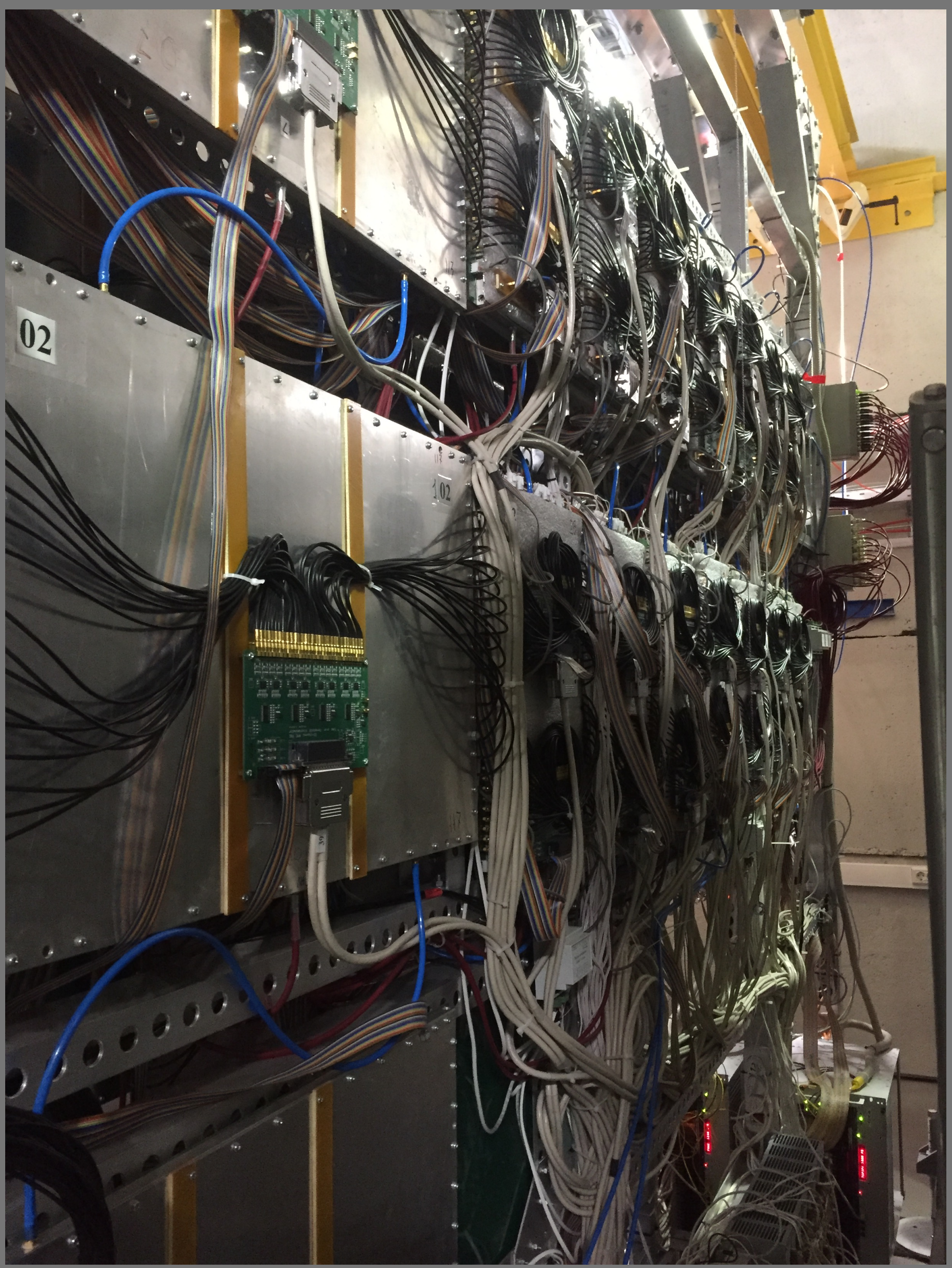


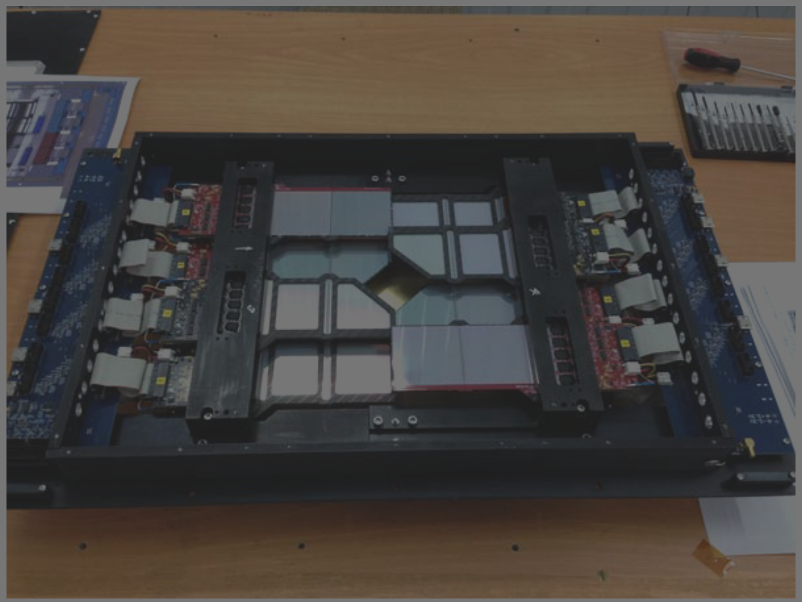
(Large dipole magnet not shown)

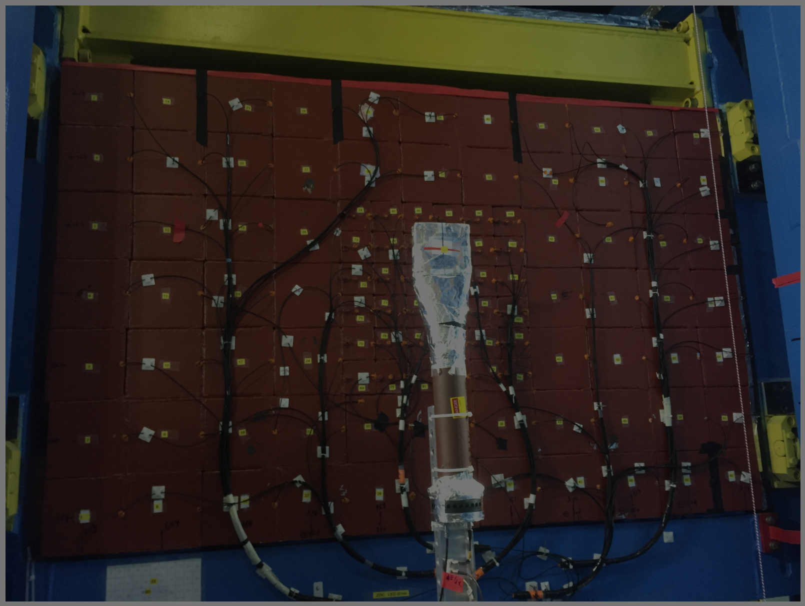
GEMs in large dipole magnet not shown

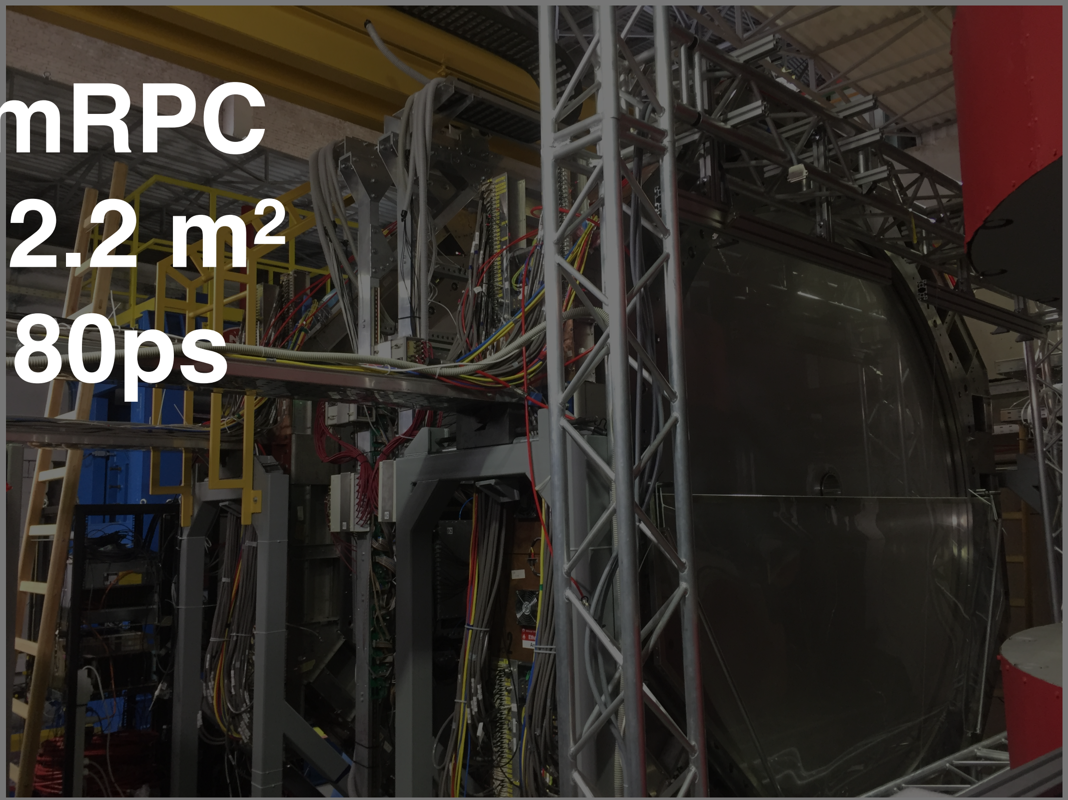
Motivation for SRC@JINR

Upcoming Experiment starting Feb 15th





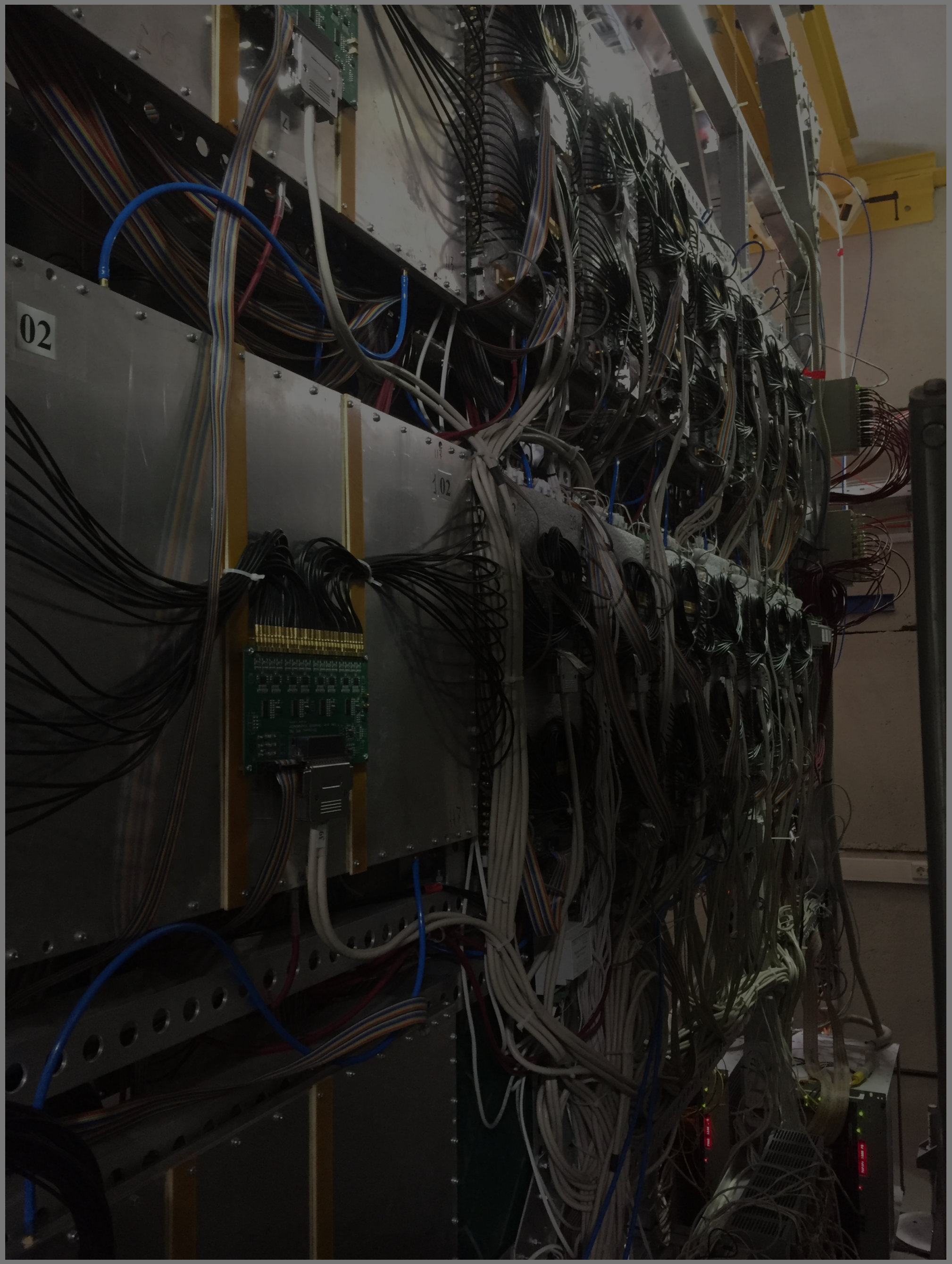


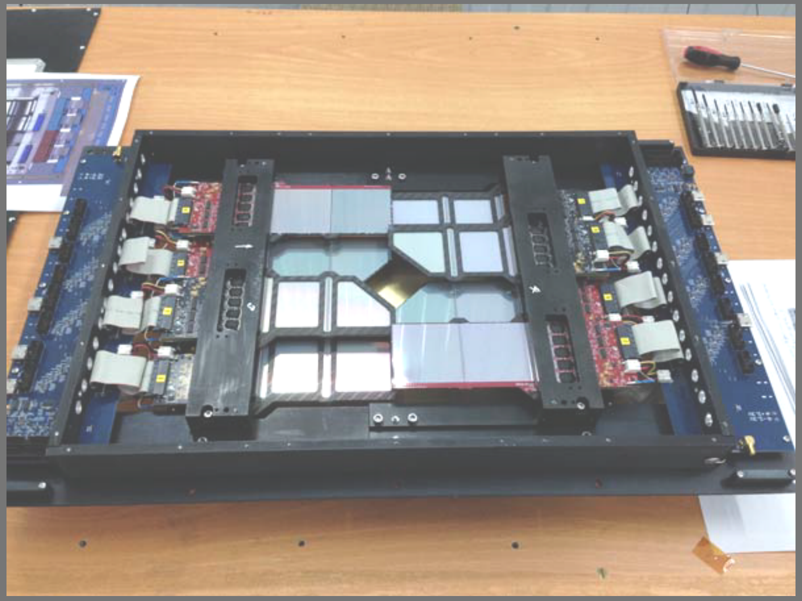


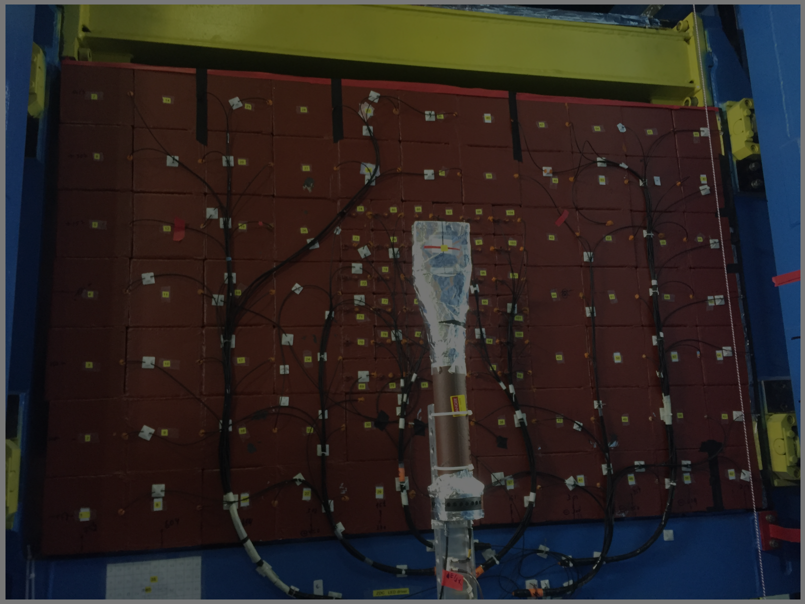
ToF mRPC
3.2 x 2.2 m^2
σ_t ~ 80ps

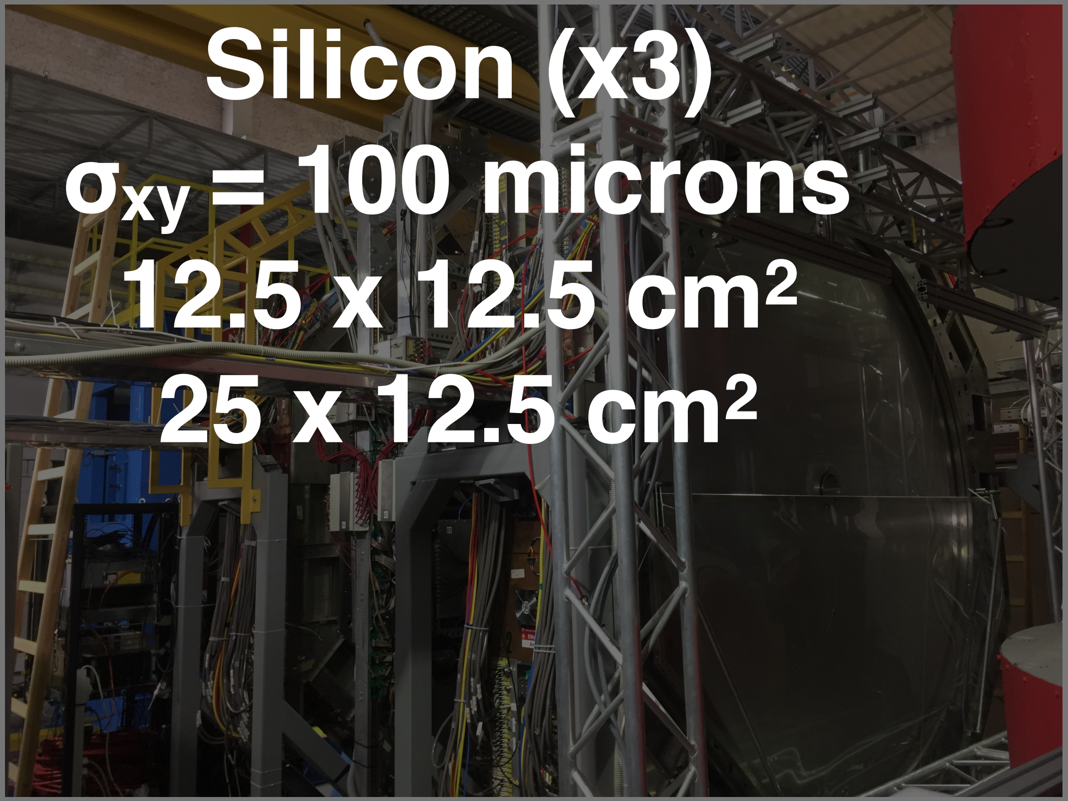
Motivation for SRC@JINR

Upcoming Experiment starting Feb 15th









Silicon (x3)

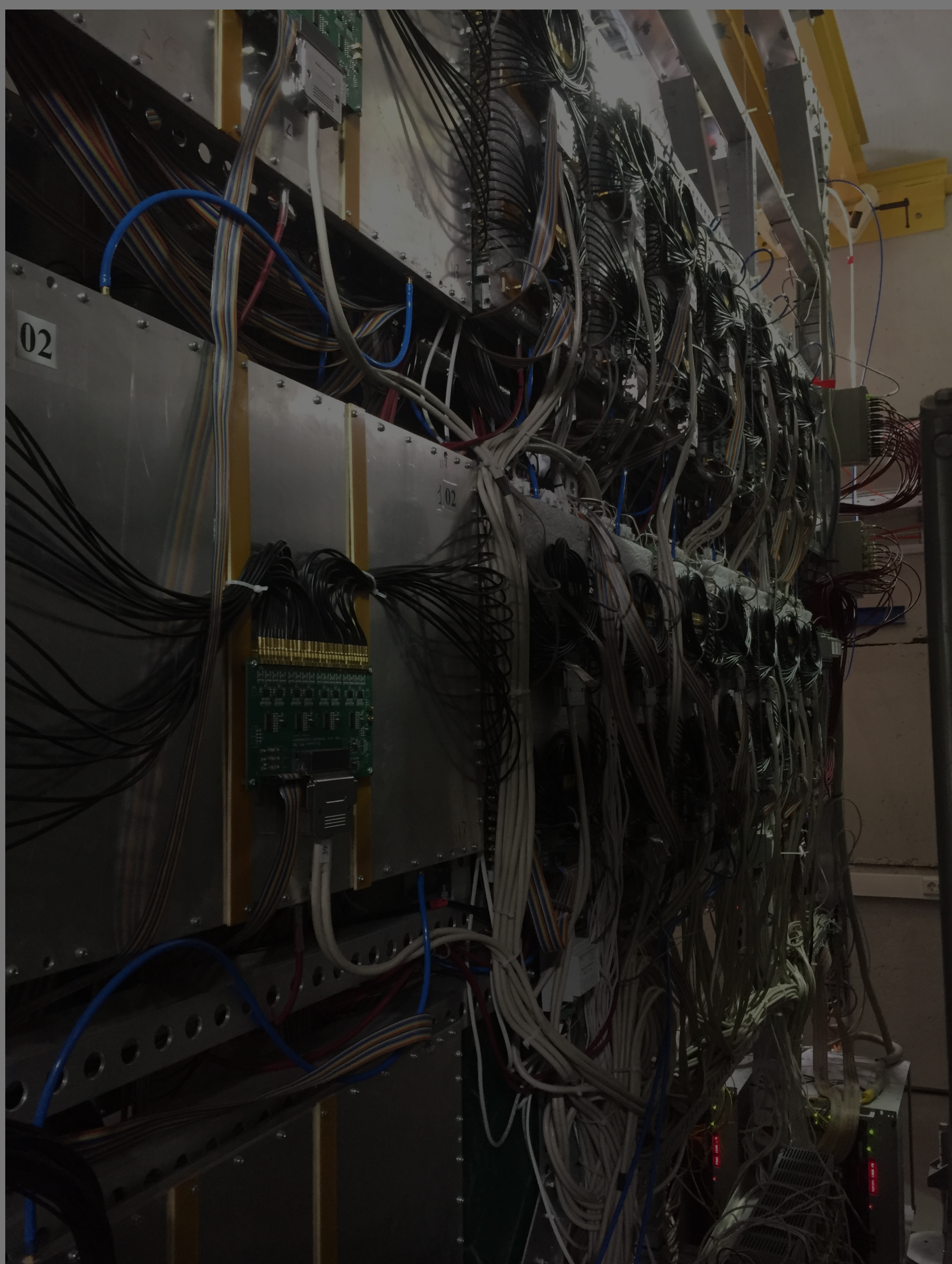
σ_{xy} = 100 microns

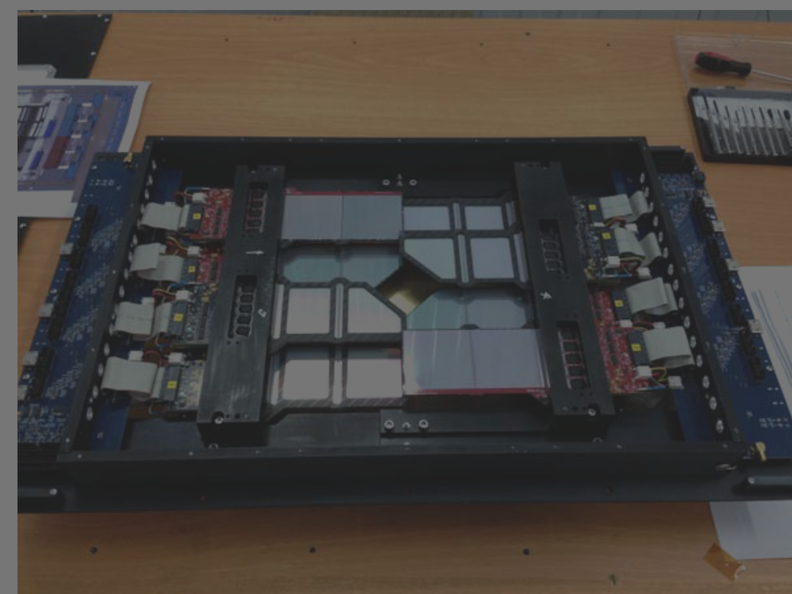
12.5 x 12.5 cm^2

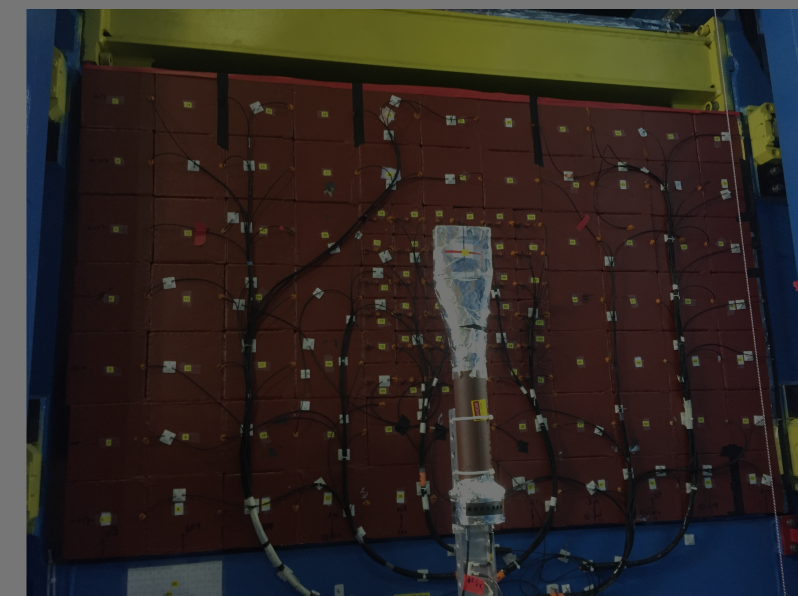
25 x 12.5 cm^2

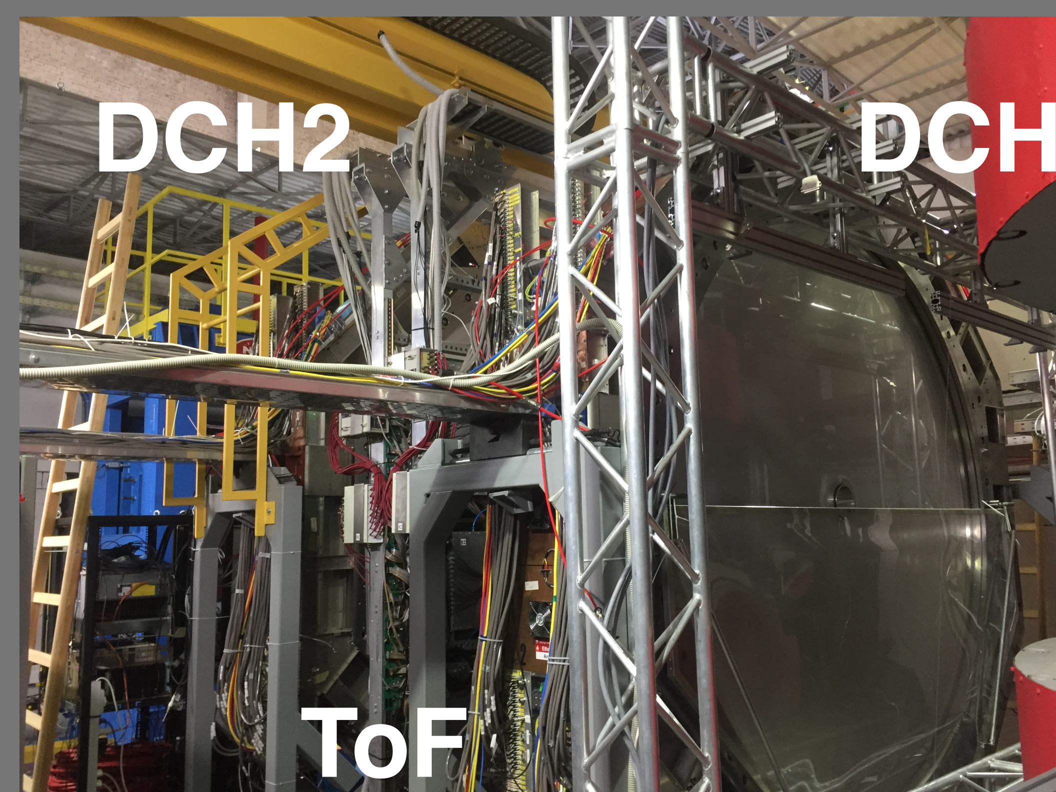
Motivation for SRC@JINR

Upcoming Experiment starting Feb 15th



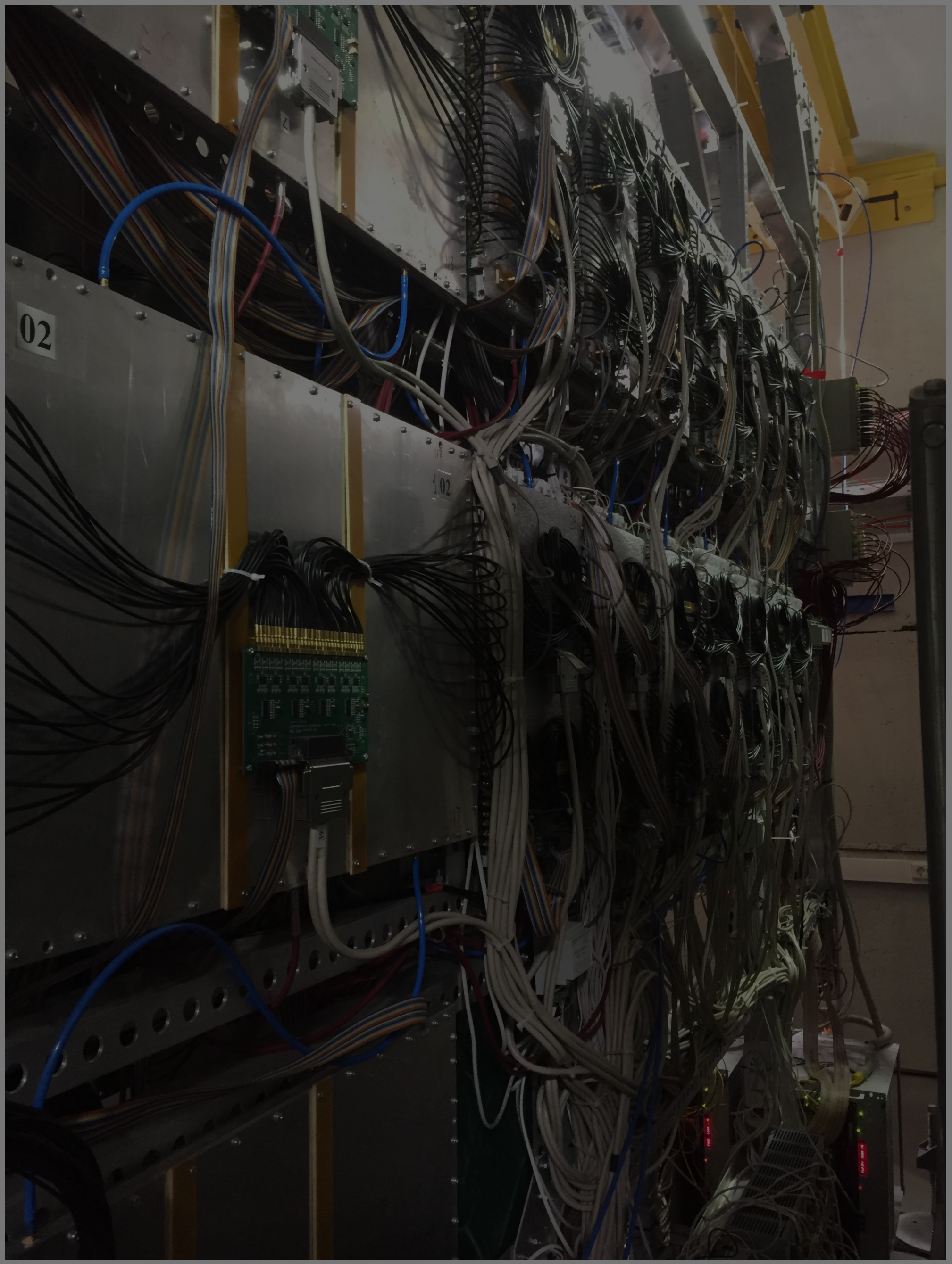


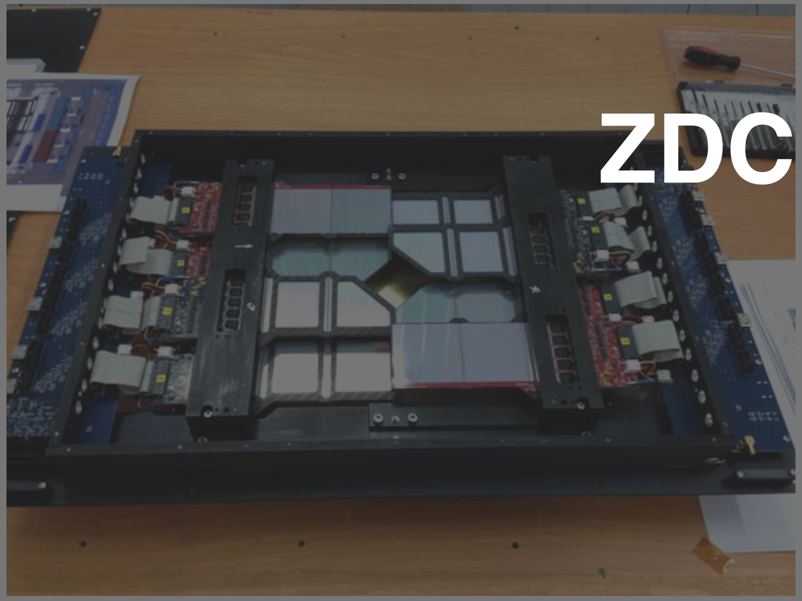


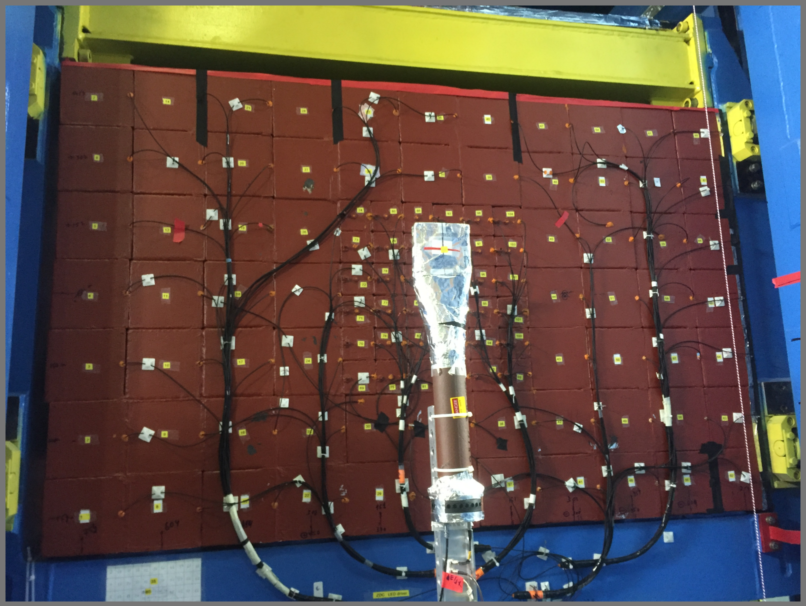


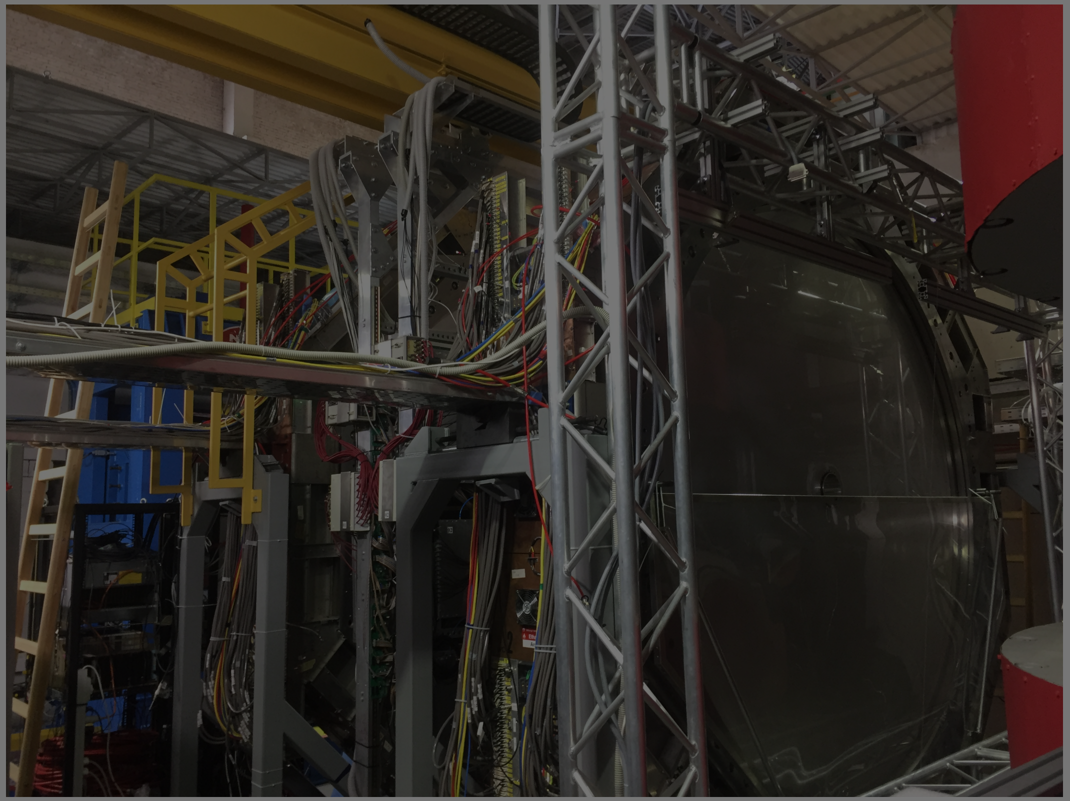
Motivation for SRC@JINR

Upcoming Experiment starting Feb 15th









Motivation for SRC@JINR

Upcoming Experiment starting Feb 15th

LAND (n detector)
~100% efficiency
σ_t ~ 300ps

For n in C(p,np A-2)X

Outline

Overview of Short Range Correlations

Motivation for SRC@JINR

Physics Extraction

Physics Extraction

Physics Reactions

Physics Extraction

Physics Reactions

$C + p \rightarrow B + pp$ — QE

$C + p \rightarrow B + pp + n$

$C + p \rightarrow B + pp + X$

np-SRC

$C + p \rightarrow Be + pp + p$

$C + p \rightarrow Be + pp + X$

pp-SRC

$np_{SRC} \,/ pp_{SRC}$

$np_{SRC} \,/ (p, 2p)$

$pp_{SRC} \,/ (p, 2p)$

Physics Extraction

Physics Reactions

$C + p \rightarrow B + pp$ QE

$C + p \rightarrow B + pp + n$

$C + p \rightarrow B + pp + X$

np-SRC

$C + p \rightarrow Be + pp + p$

$C + p \rightarrow Be + pp + X$

pp-SRC

$np_{SRC} \; / pp_{SRC}$

$np_{SRC} \; / (p, 2p)$

$pp_{SRC} \; / (p, 2p)$

More exotic channels?

$C + p \rightarrow 2\alpha + pp + X$

Physics Extraction

Physics Reactions

$C + p \rightarrow B + pp$ — QE

$C + p \rightarrow B + pp + n$

$C + p \rightarrow B + pp + X$

np-SRC

$C + p \rightarrow Be + pp + p$

$C + p \rightarrow Be + pp + X$

pp-SRC

$np_{SRC} \,/ pp_{SRC}$

$np_{SRC} \,/ (p, 2p)$

$pp_{SRC} \,/ (p, 2p)$

More exotic channels?

$C + p \rightarrow 2\alpha + pp + X$

Goal: Observe 2N-SRC and Identify A-2

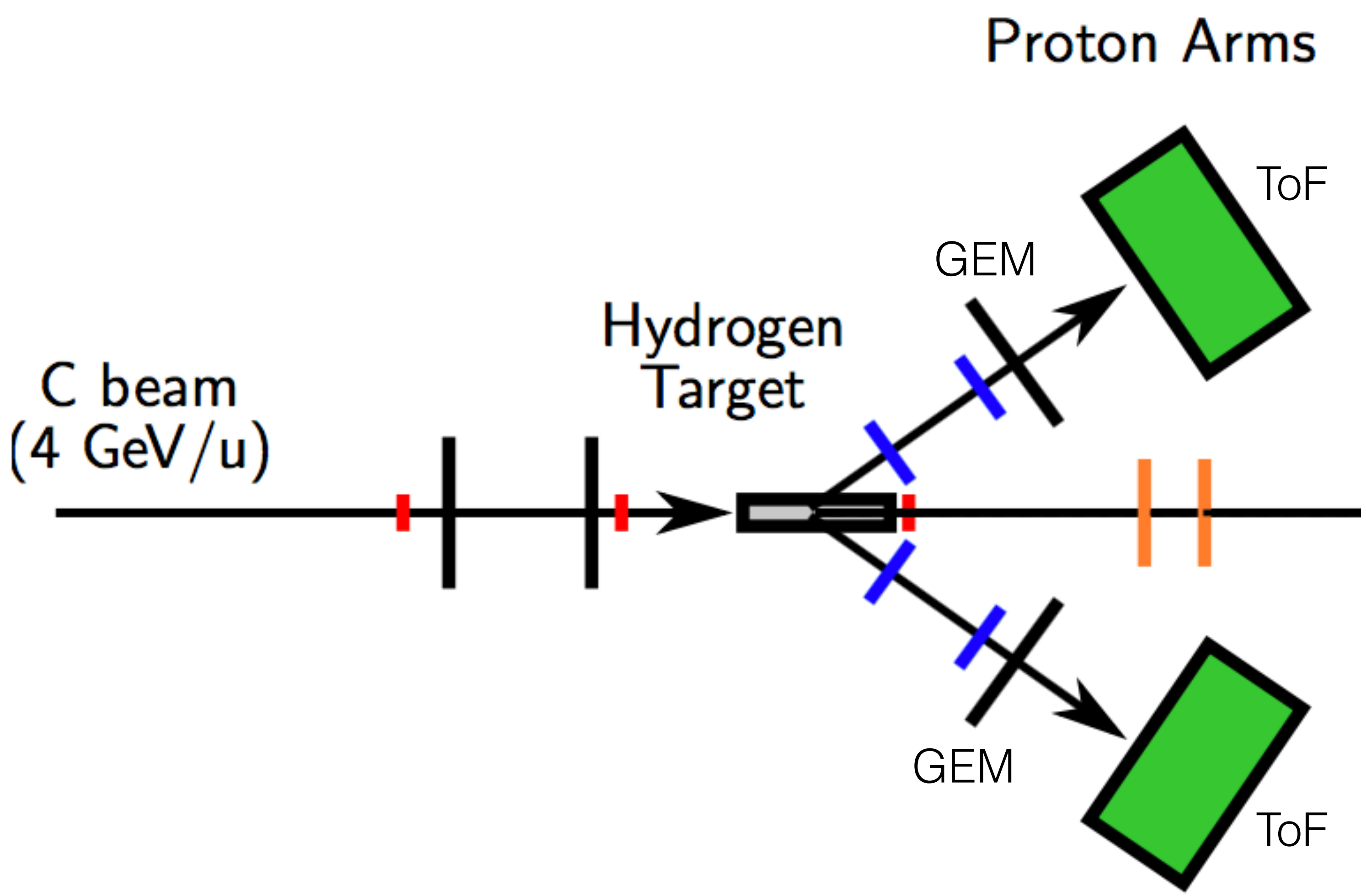
Physics Extraction

2N-SRC Identification

Physics Extraction

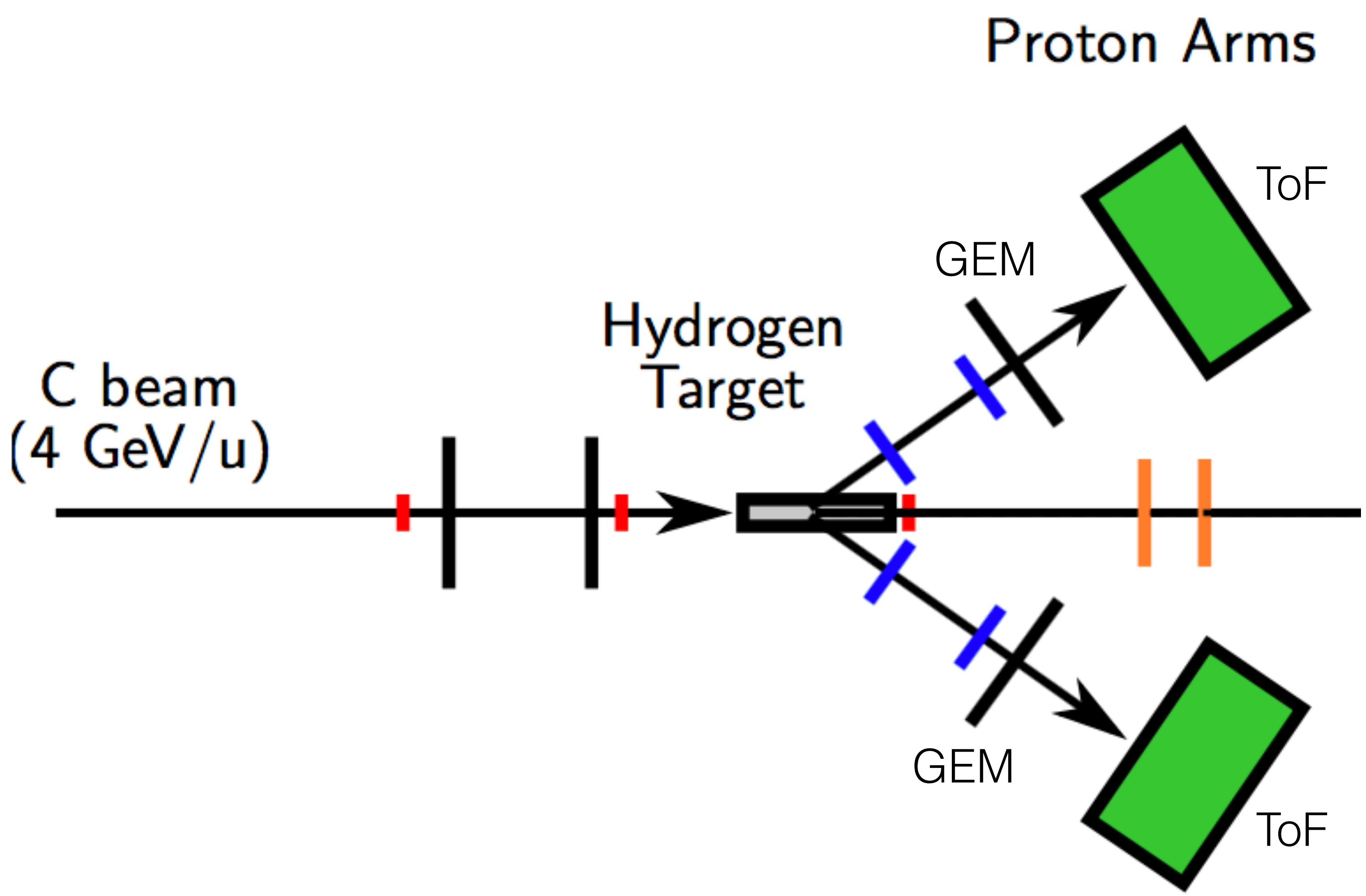
2N-SRC Identification

Trigger: Incoming nucleus, 2 out-going protons at 30°



Physics Extraction

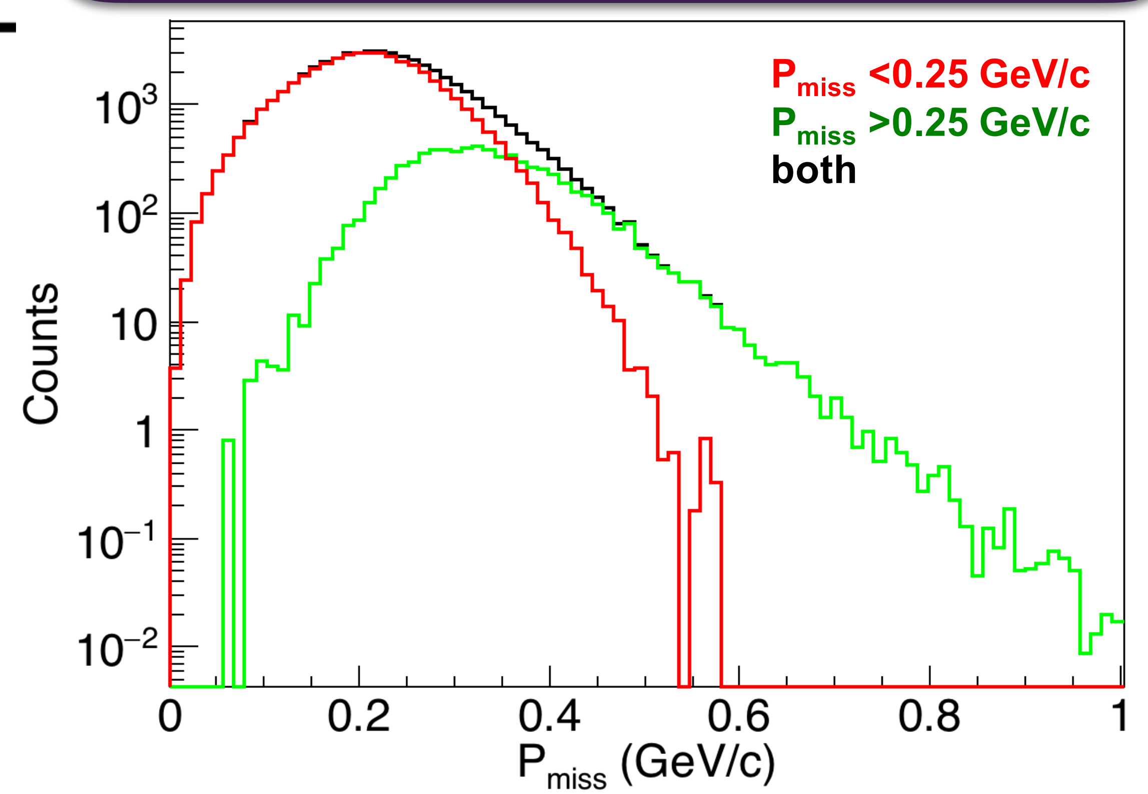
2N-SRC Identification



$$\vec{p}_{miss} = \vec{p}_p - \vec{q}$$

Trigger: Incoming nucleus, 2 out-going protons at 30°

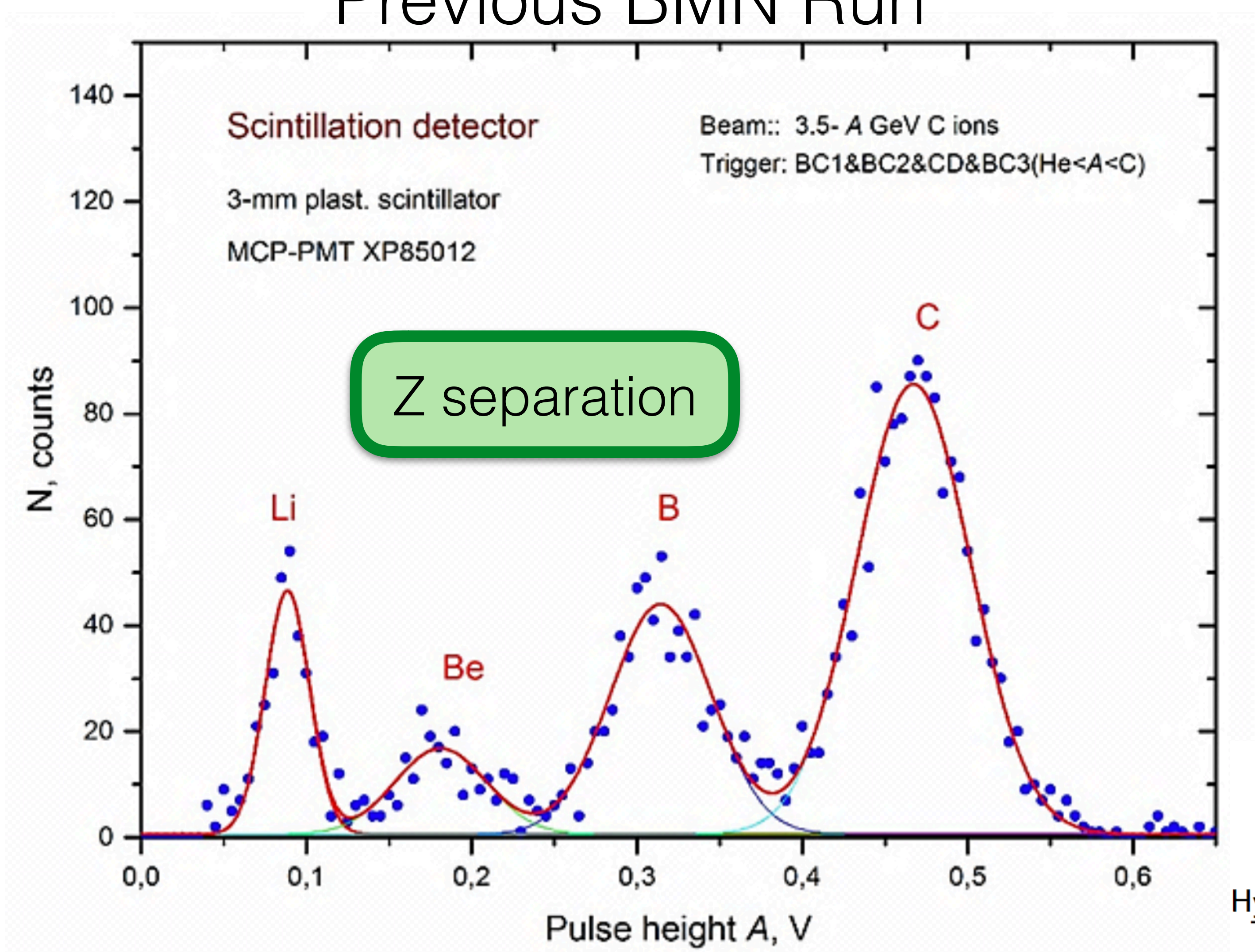
Reconstruct P_{miss} to tag SRCs

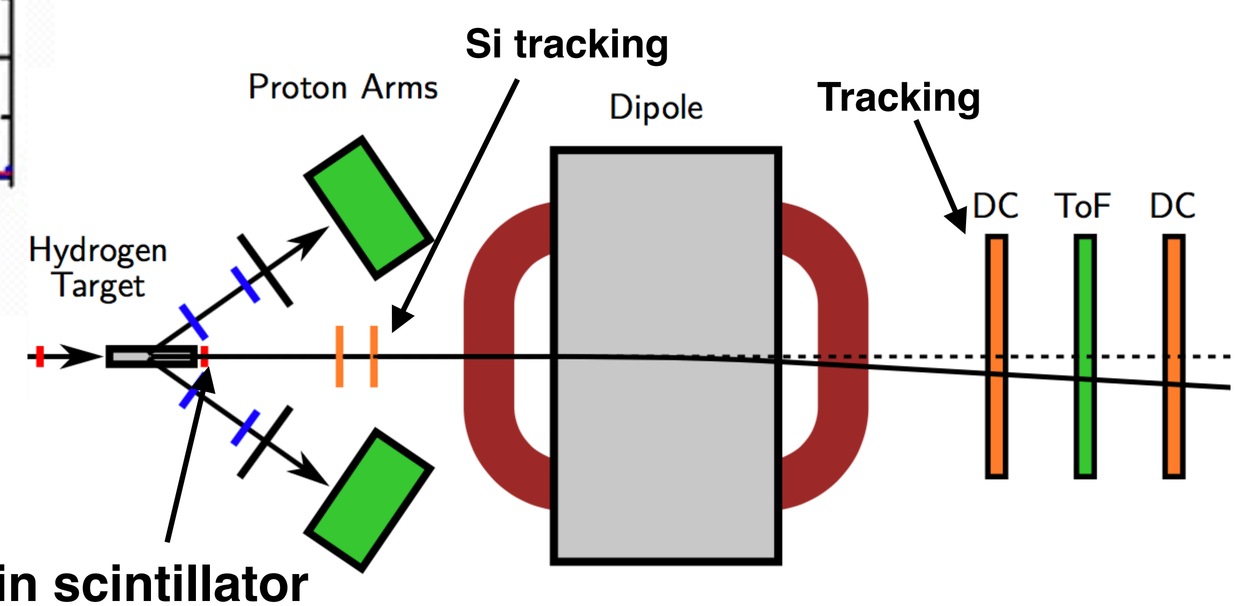


Physics Extraction

A-2 Identification

Previous BMN Run

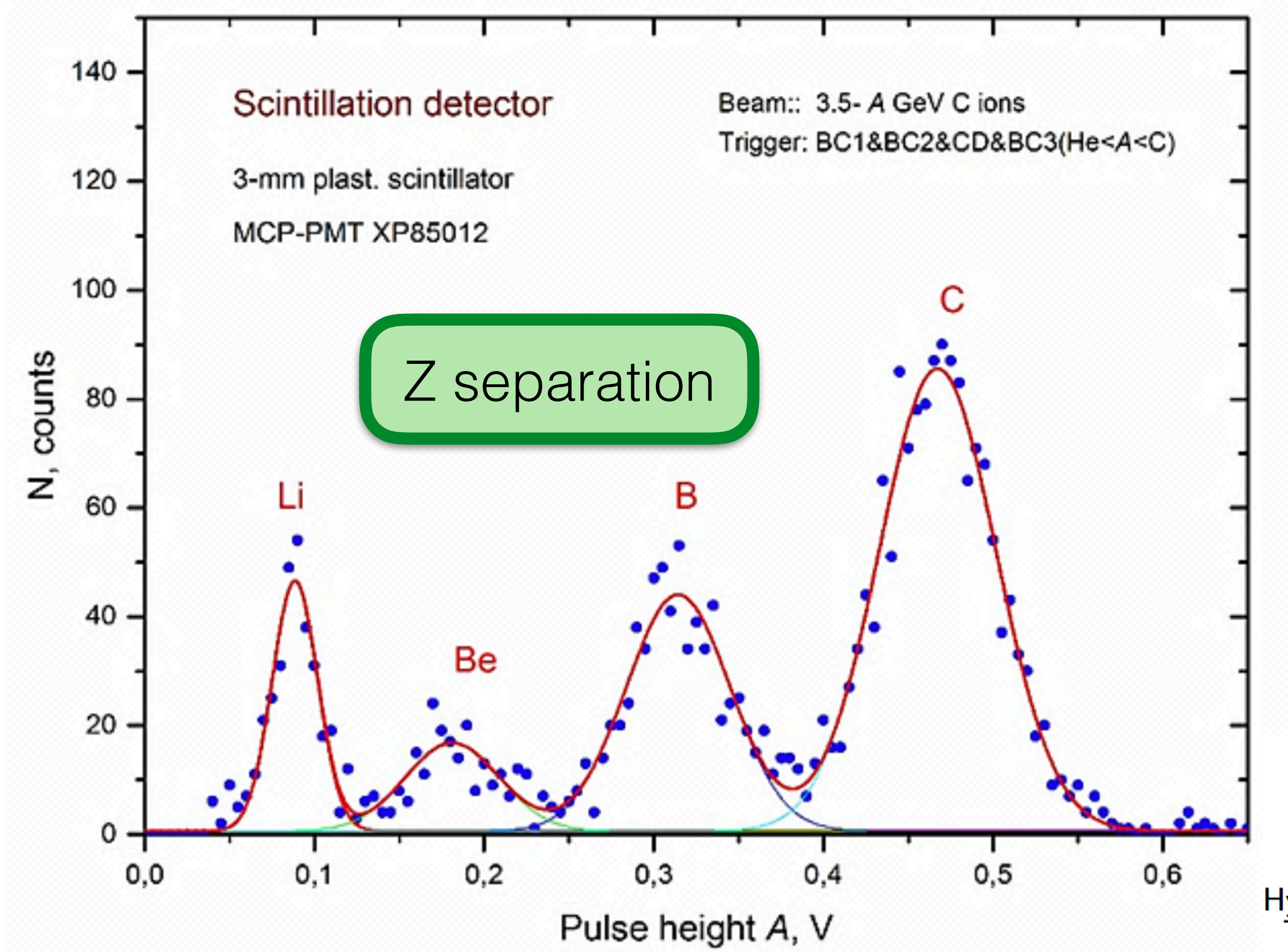


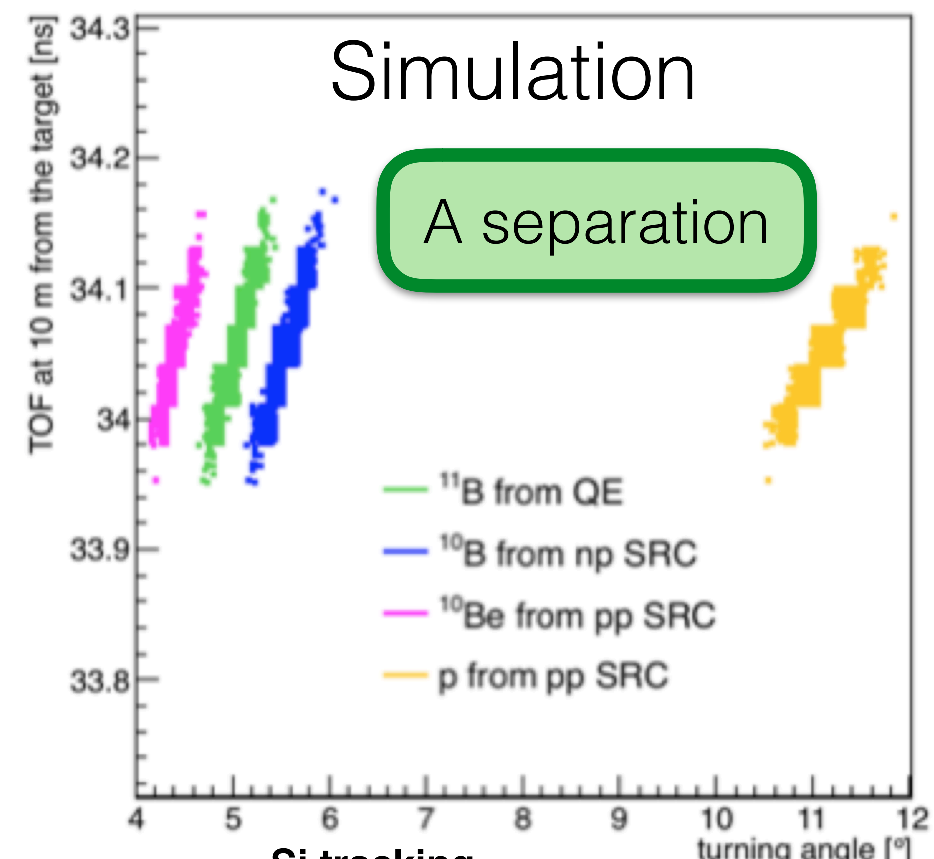


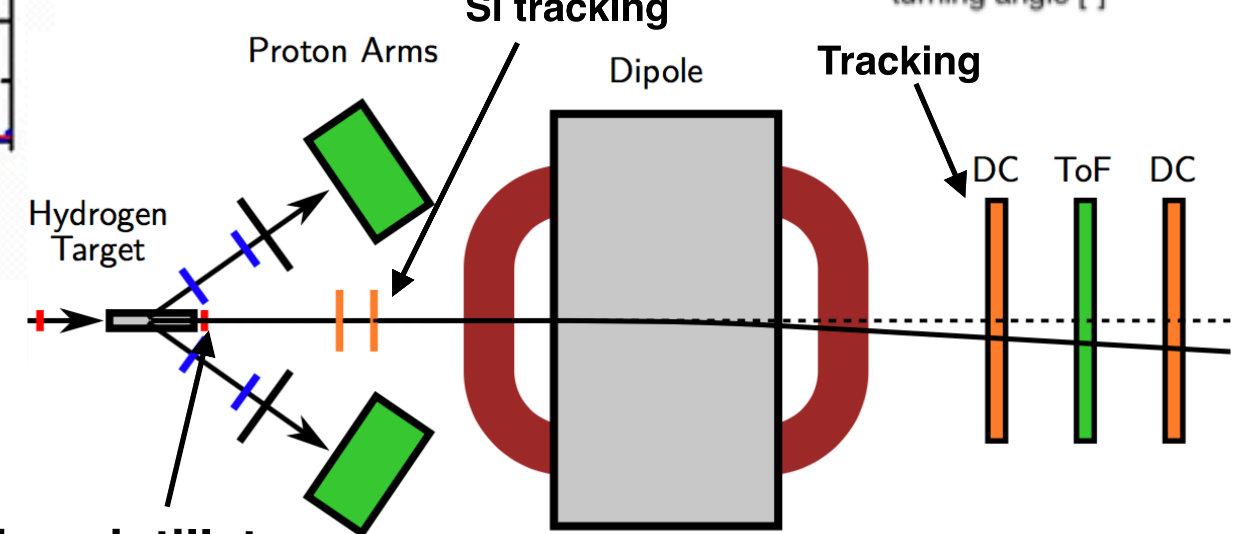
Physics Extraction

A-2 Identification

Previous BMN Run







Physics Extraction

NEXT MONTH: Initial Measurement

Parameters	Values
Length of LH2 target	30 cm
Target Thickness	1.2e24 protons/cm^2
Beam Time	**11 days**
Duty Cycle	20%
Flux	1e5 ions/s
n Detection Efficiency	~100%
Nuclear transparency	0.2

Cuts
$|s,t,u| > 2\ (\mathrm{GeV}/c)^2$
$P_{miss} > 0.25\ \mathrm{GeV}/c$

Physics Extraction

NEXT MONTH: Initial Measurement

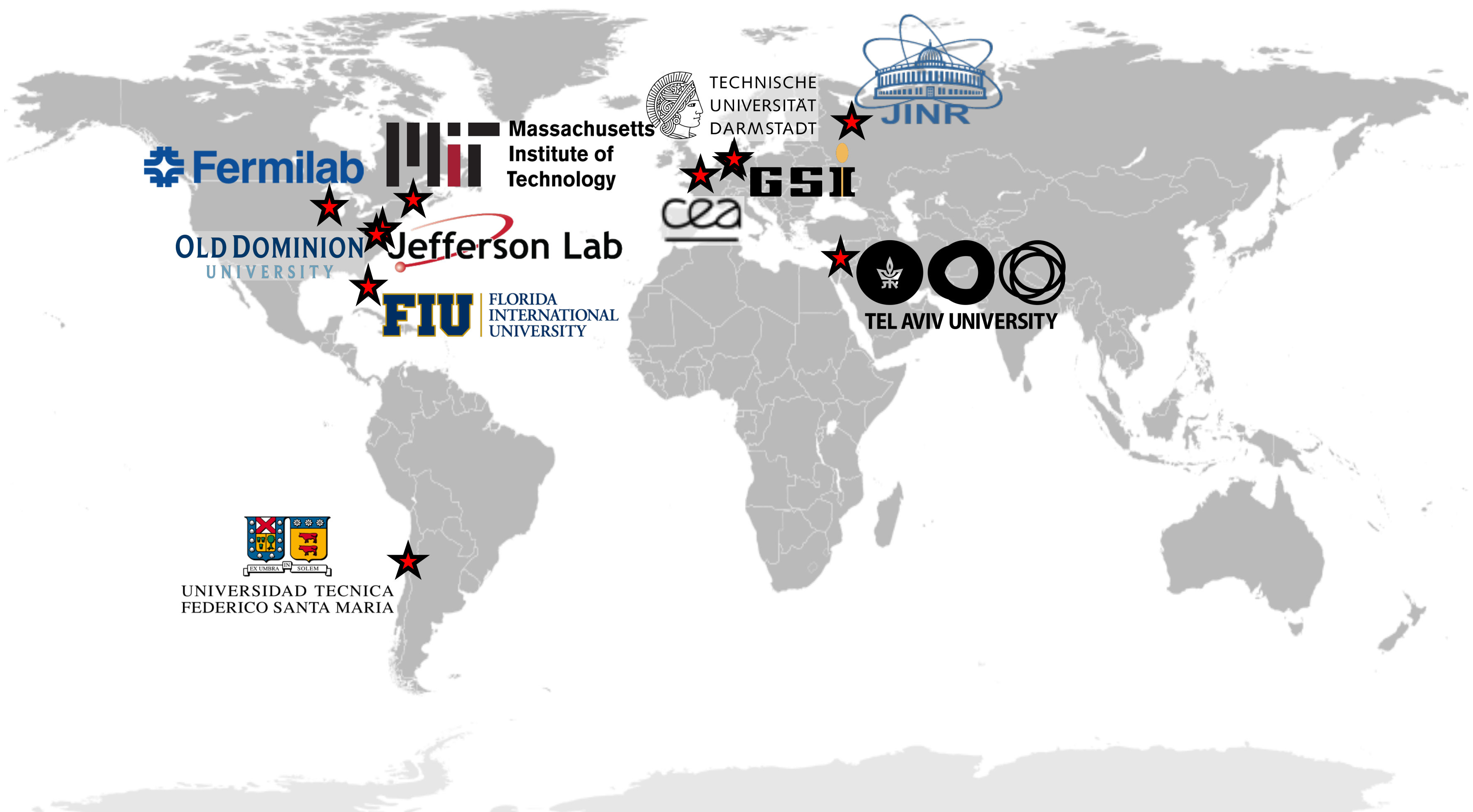
Reaction	Events
${}^{12}{}_{6}C + p \rightarrow {}^{10}{}_{5}B + pp$	4000
${}^{12}{}_{6}C + p \rightarrow {}^{10}{}_{5}B + pp + n$	350
${}^{12}{}_{6}C + p \rightarrow {}^{10}{}_{4}Be + pp$	200
${}^{12}{}_{6}C + p \rightarrow {}^{10}{}_{4}Be + pp + p$	100

Reaction	Signal:Background
$p({}^{12}C, 2p)N$	4:1
$p({}^{12}C, 2p, n)N$	18:1
$p({}^{12}C, 2p, n, A-2)N$	20:1

Thank You!

Collaboration

The World of SRC



+ Many Theory Collaborators: UW, Penn State, Huji, Gent, FIU, Perugia, …

Addition to the BM@N Physics Program: Probing Short-Range Correlations

Spokespersons:

Or Hen (MIT), Eli Piasetzky (TAU), Thomas Aumann (TUD, GSI), Mikhail Kapishin (JINR)

Coordinators:

Georgios Laskaris (MIT, TAU), Anatoly Litvinenko (JINR), Maria Patsyuk (MIT)

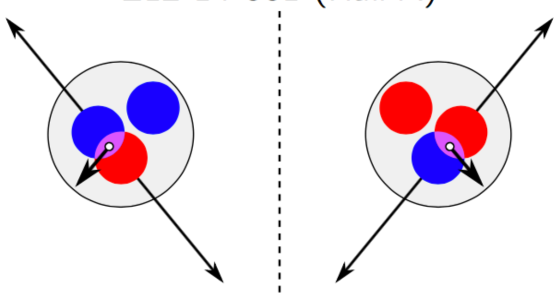
Special thanks to the JINR team for making our measurement possible

Thank You!

Future Experiments

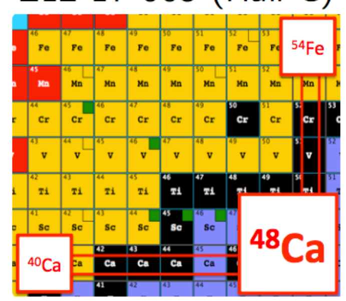
SRC @ Jefferson Lab

SRCs in ^{3}H, ^{3}He
E12-14-001 (Hall A)

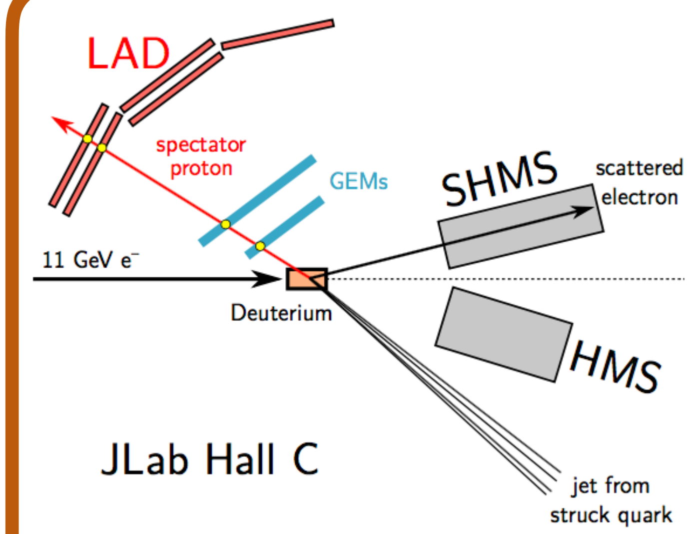


- Hall A tritium target
- Exploit isospin symmetry
- ^{3}H and ^{3}He are extremely asymmetric!

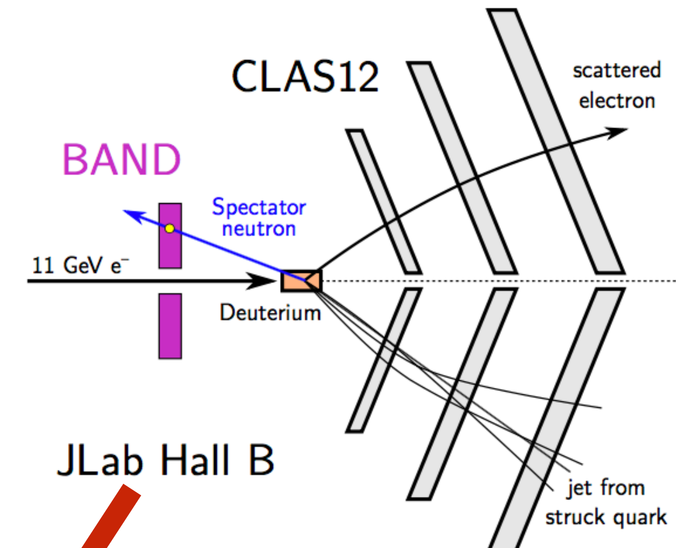
The CaFe Experiment
E12-17-005 (Hall C)



- Disentangle asymmetry and mass number dependence
- ^{40}Ca $\rightarrow$ ^{48}Ca $\rightarrow$ ^{54}Fe
- Pairing from different orbitals

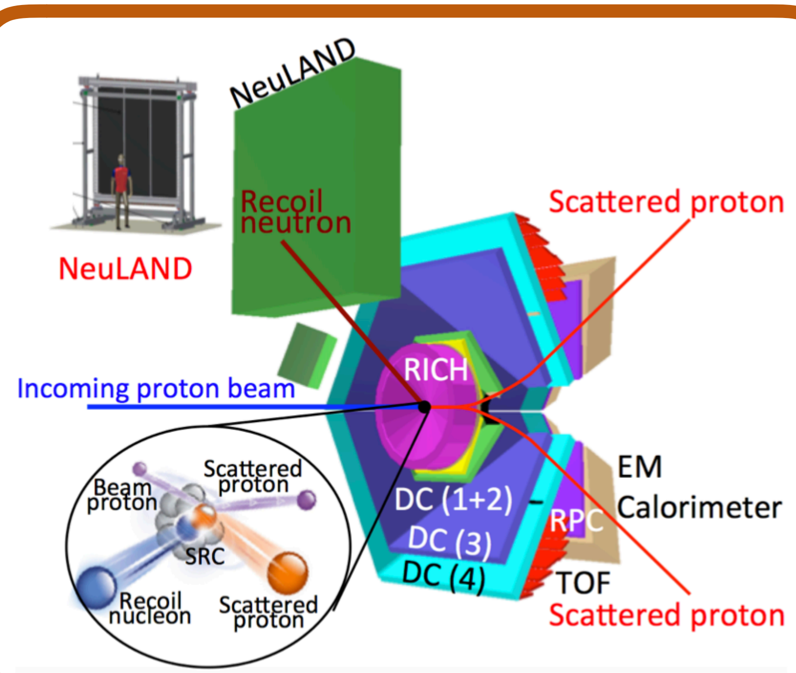


E12-11-003A



E12-11-107

BAND: EMC Effect in Highly-Virtual Nucleons
See my poster & come talk to me!



SRC@GSI

Thank You!

Questions?

If you don't follow anything else…

Short Range Correlations:

- 2 nucleons pairs that are close together in the nucleus (wave functions overlap)
- Momentum space: pairs with high relative momentum and low c.o.m momentum (with respect to k_F)
- 20% of nuclear wave function, np pairs dominate over pp/nn pairs

WHY YOU might care:

General knowledge…

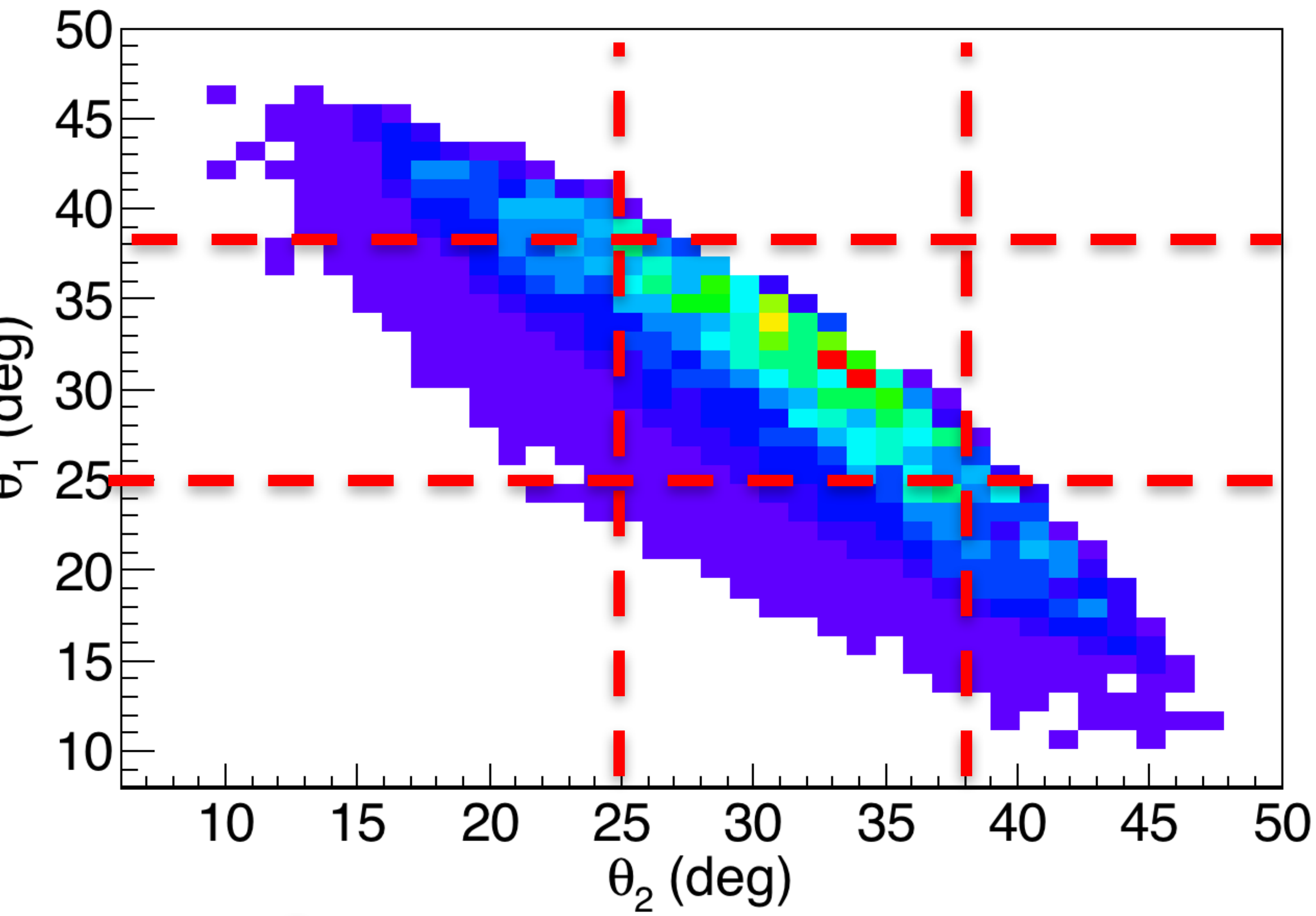
- EMC effect (**future experiment @ JLab**)
- Neutrino-nucleus scattering
- Neutron stars
- Nuclear symmetry energy
- Energy sharing in imbalanced Fermi systems
- Contact interaction in universal fermi systems

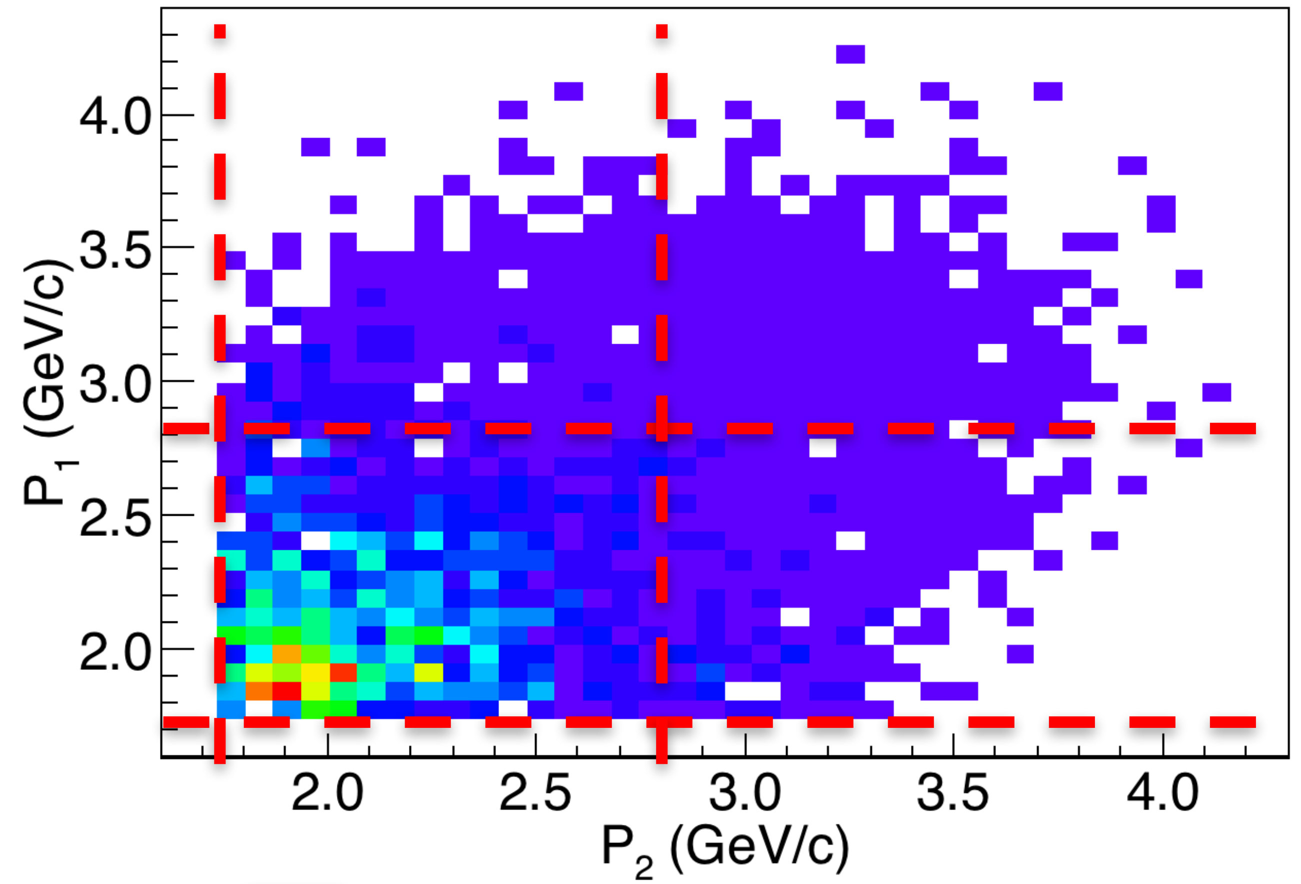
First fully exclusive measurement at JINR to study A-2 system and 2N-SRC with higher statistics

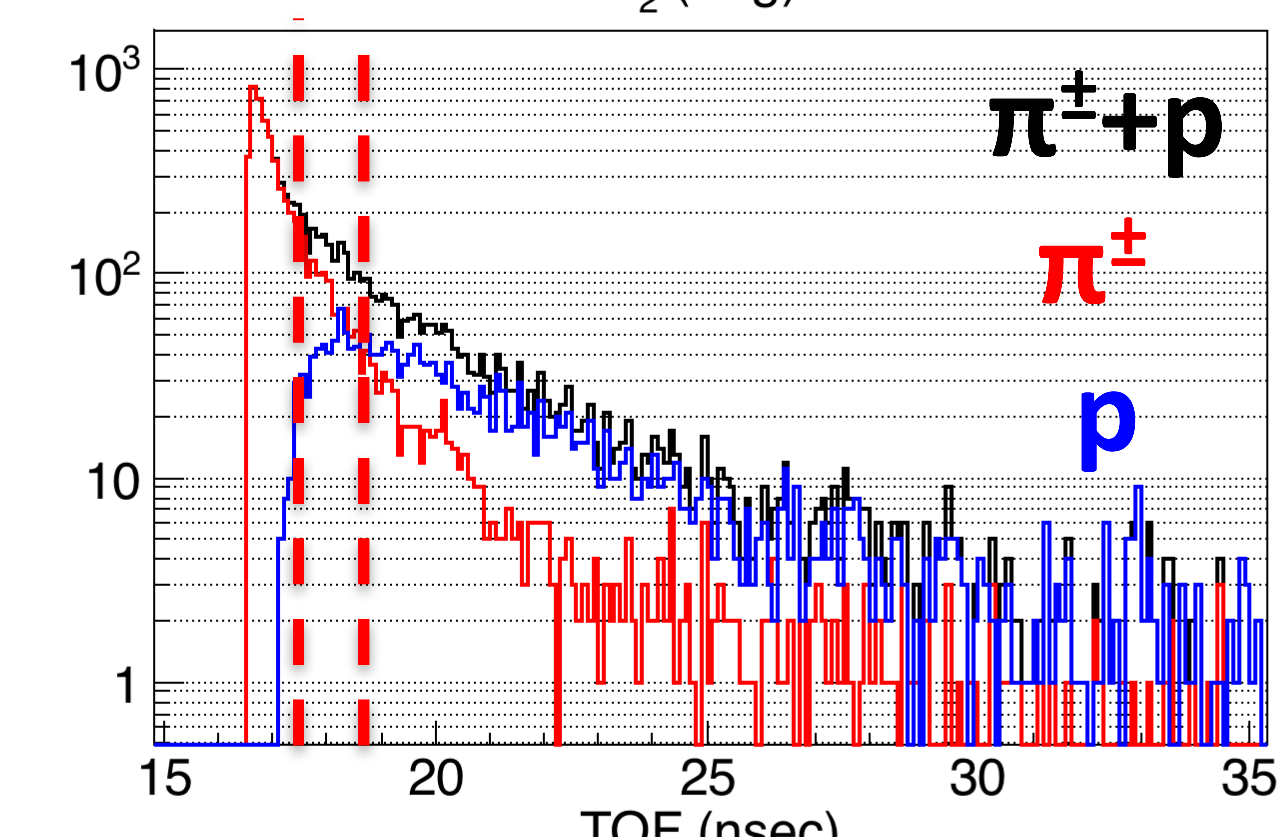
BACK UP SLIDES:

FS Kinematic Distributions
Inclusive QE scattering
Old diagrams + pics of hall layout
Detector breakdowns
Resolutions
Electronics
Calibrations
Timeline
How SRC connects to other things

Cuts for Background reduction



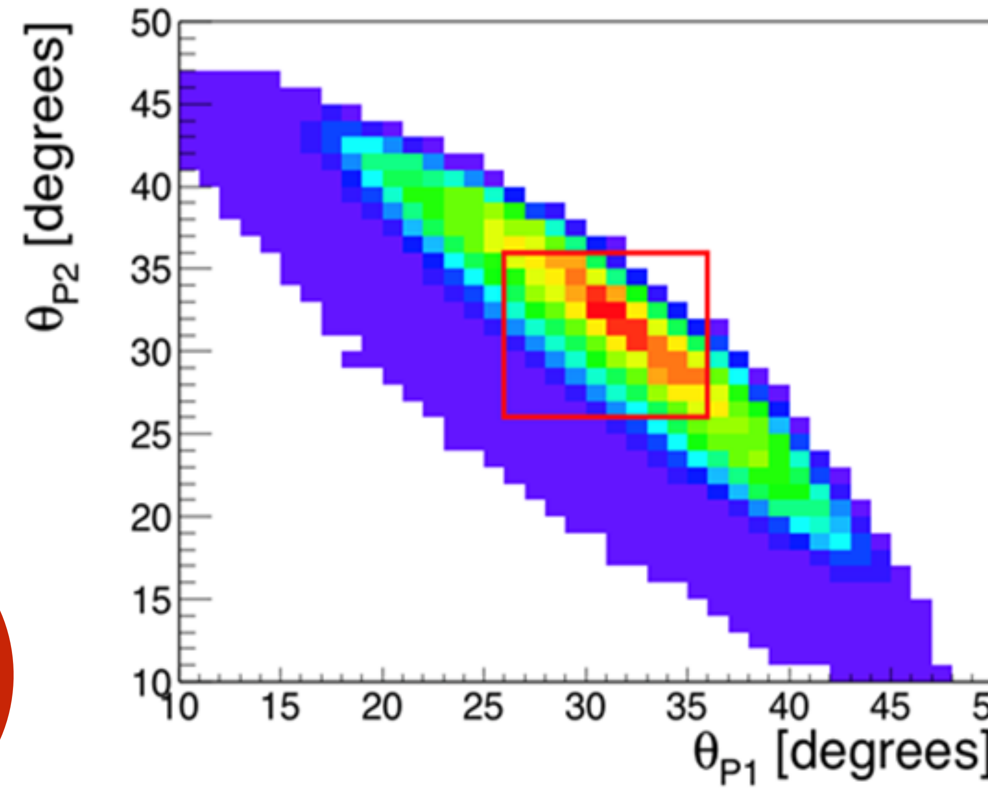


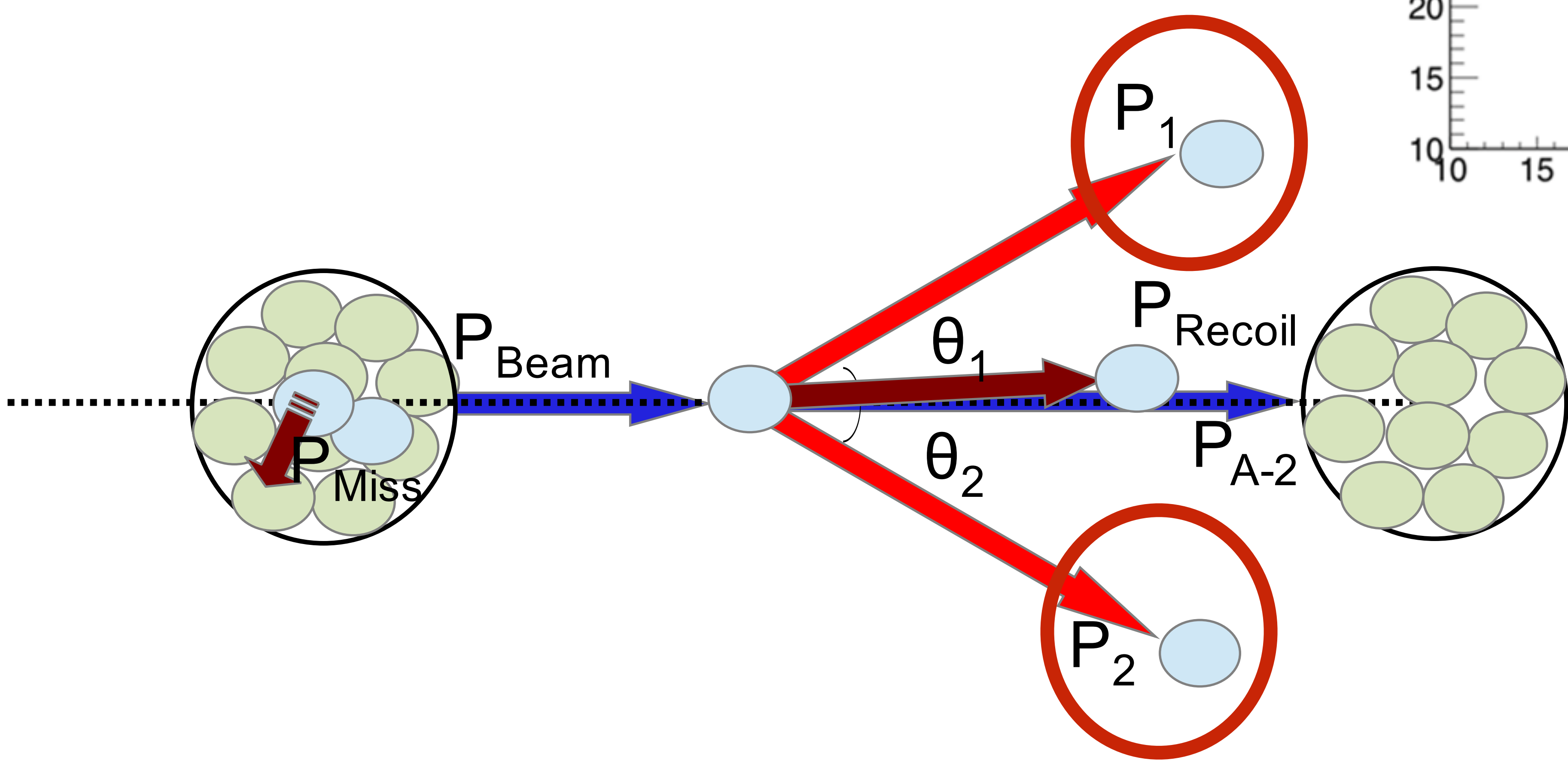


Trigger cuts
$25^\circ \leq \theta_{1,2} \leq 38^\circ$
$\lvert\phi_1\rvert < 7.5^o$
$\lvert\lvert\phi_2\rvert - 180.5^o\rvert < 7.5^o$
17.4 (2.8 GeV/c)$<tof_{1,2}<$18.7 (1.75 GeV/c)

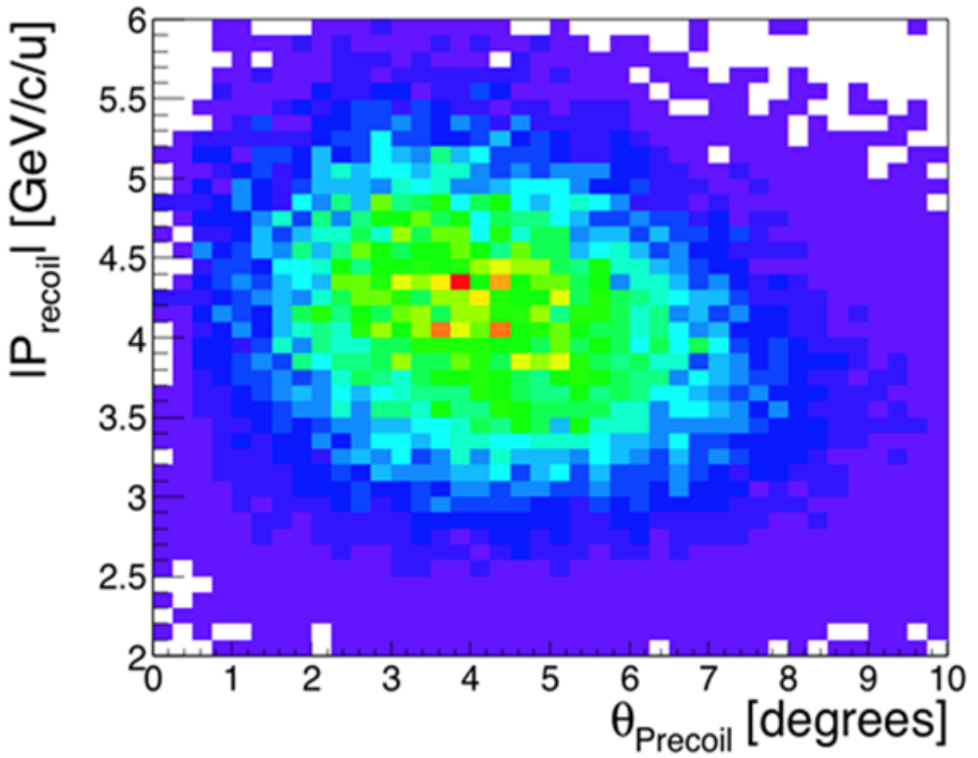
Motivation for SRC@JINR

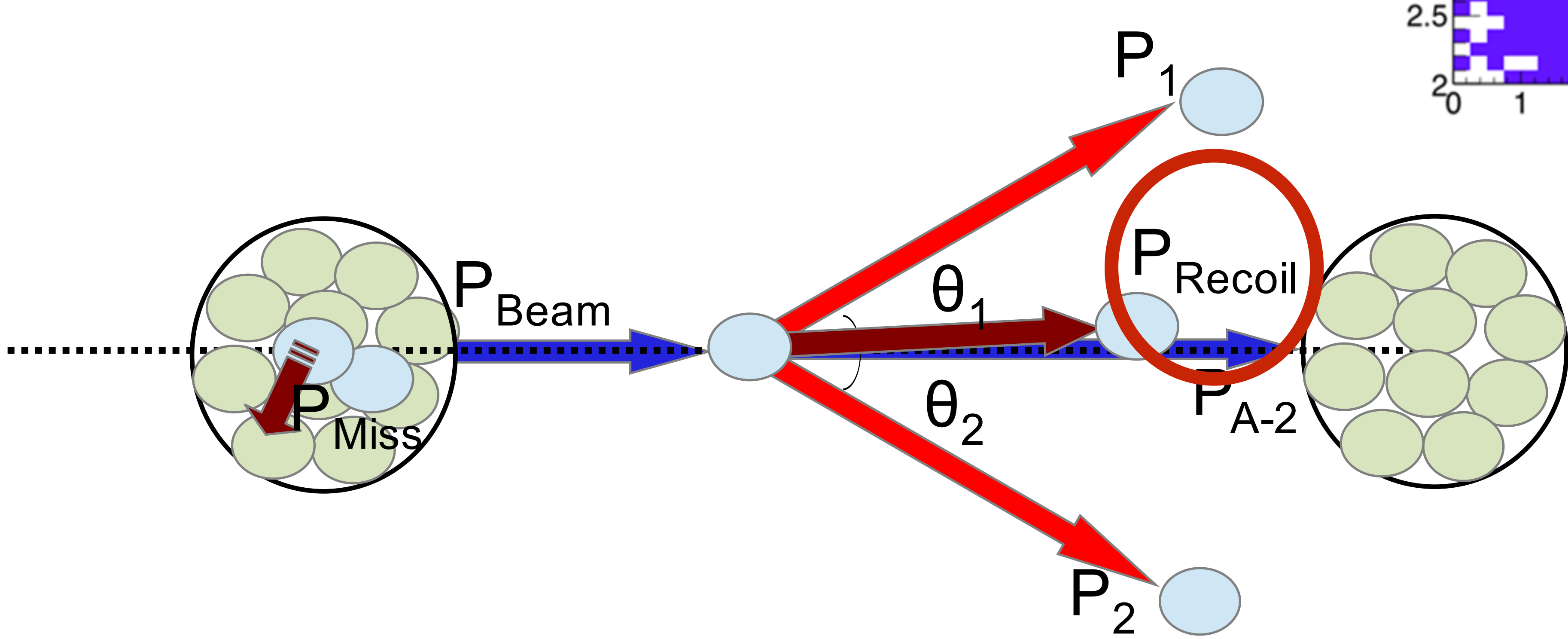
Final-State Angular Distributions for inverse kinematics [4GeV/c/u C beam]





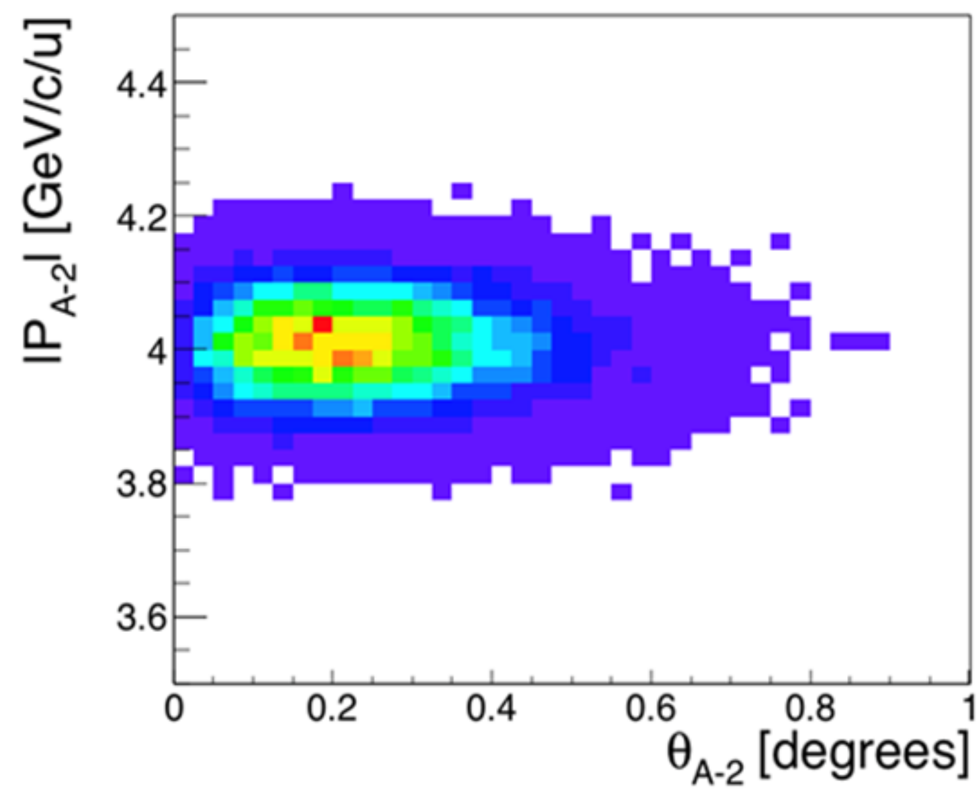
Final-State Angular Distributions for inverse kinematics [4GeV/c/u C beam]

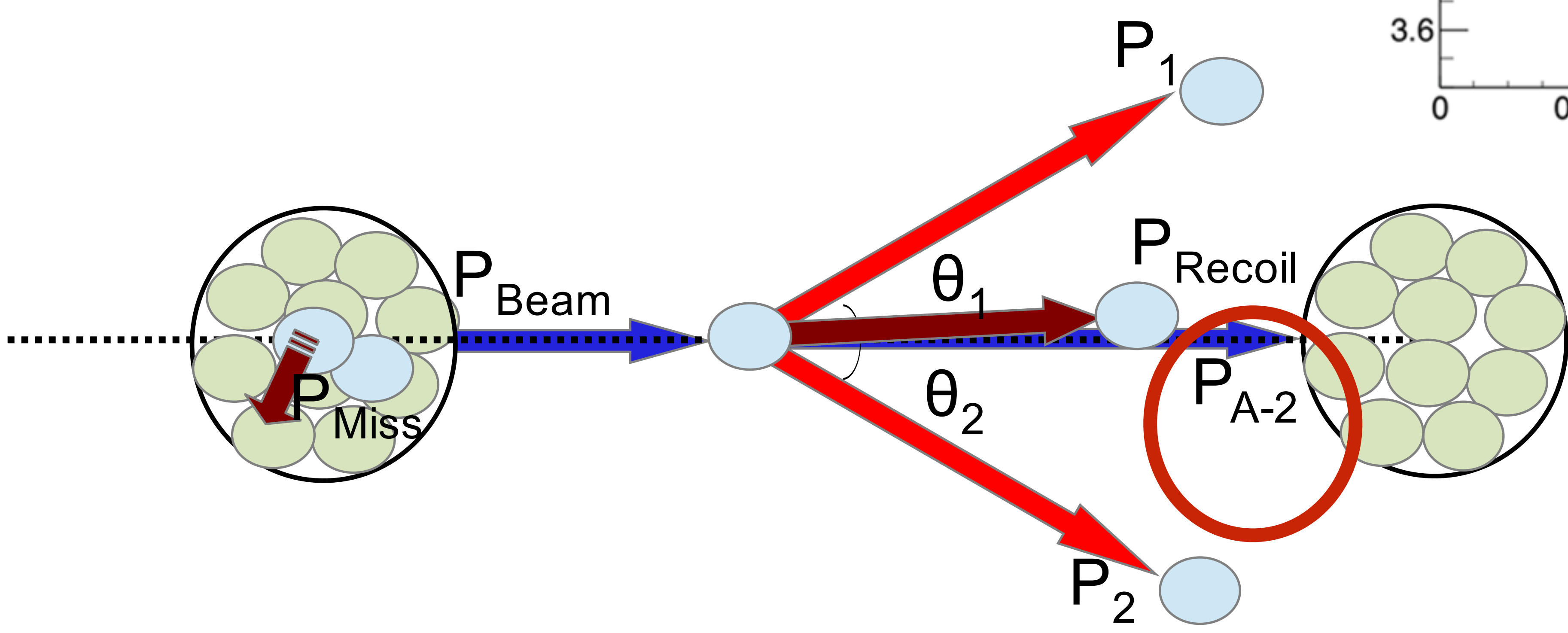




Motivation for SRC@JINR

Final-State Angular Distributions for inverse kinematics [4GeV/c/u C beam]

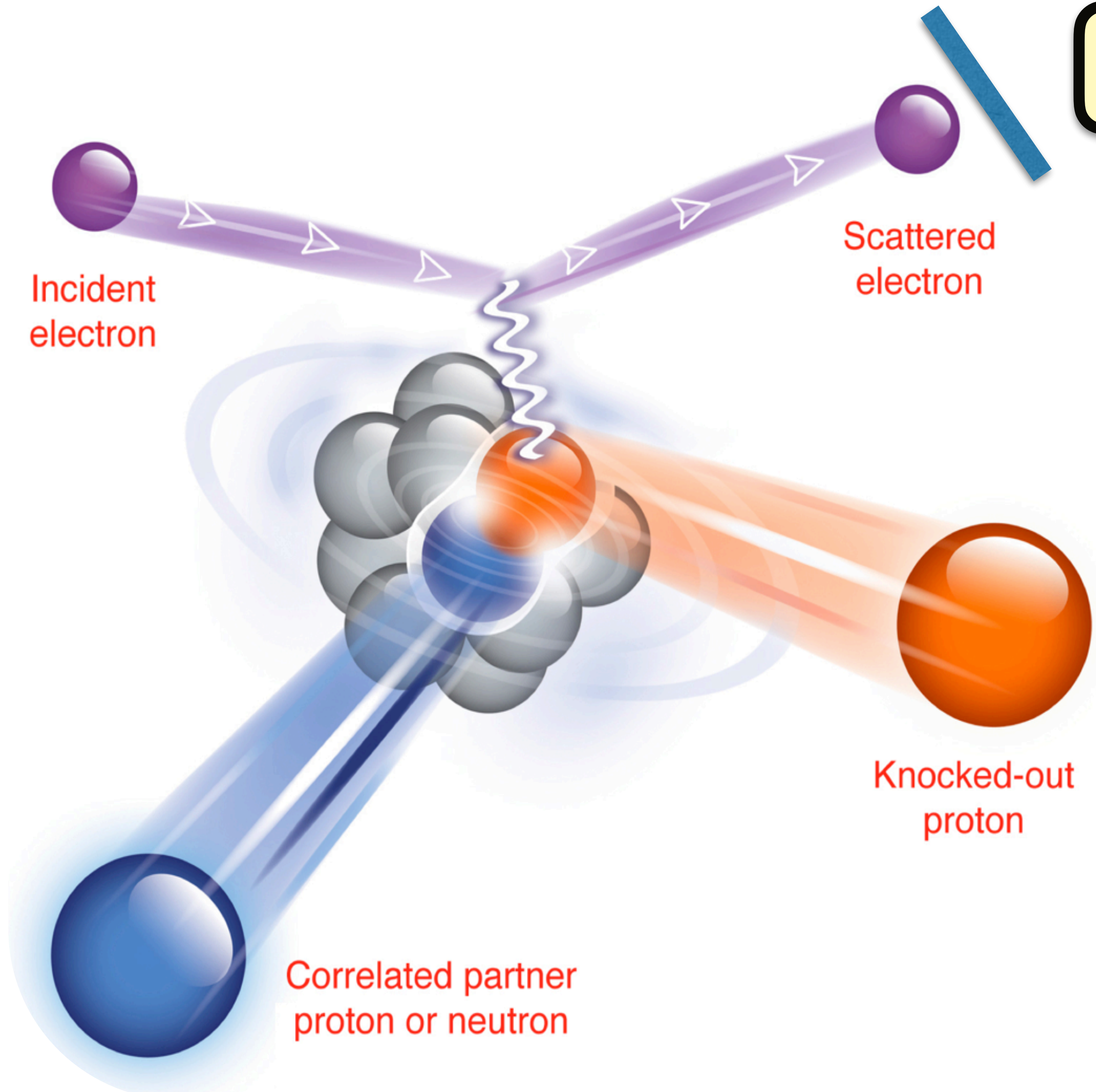




Overview of SRC

How do we study SRC pairs? Inclusive vs Exclusive

Inclusive

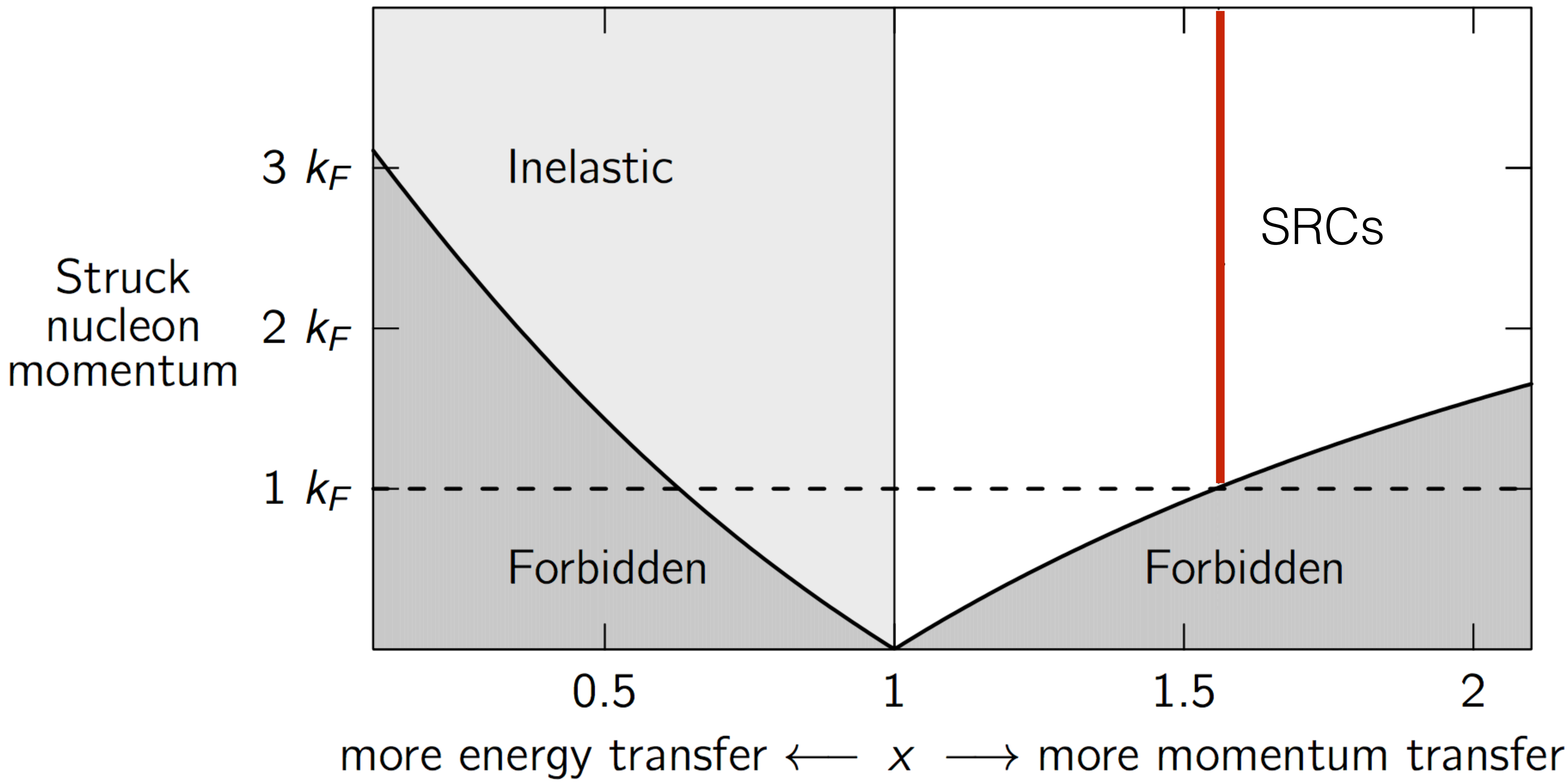


Overview of SRC

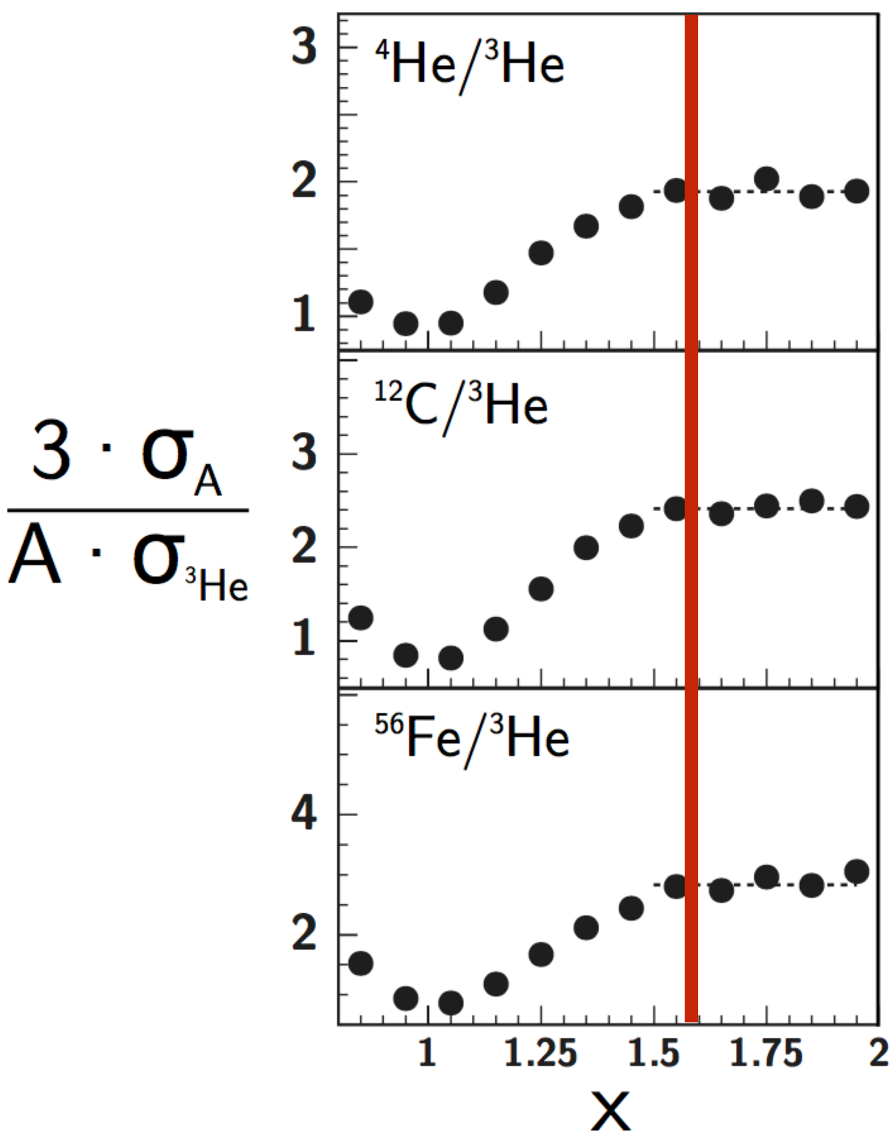
QE Inclusive Scattering Experimental Results

Overview of SRC

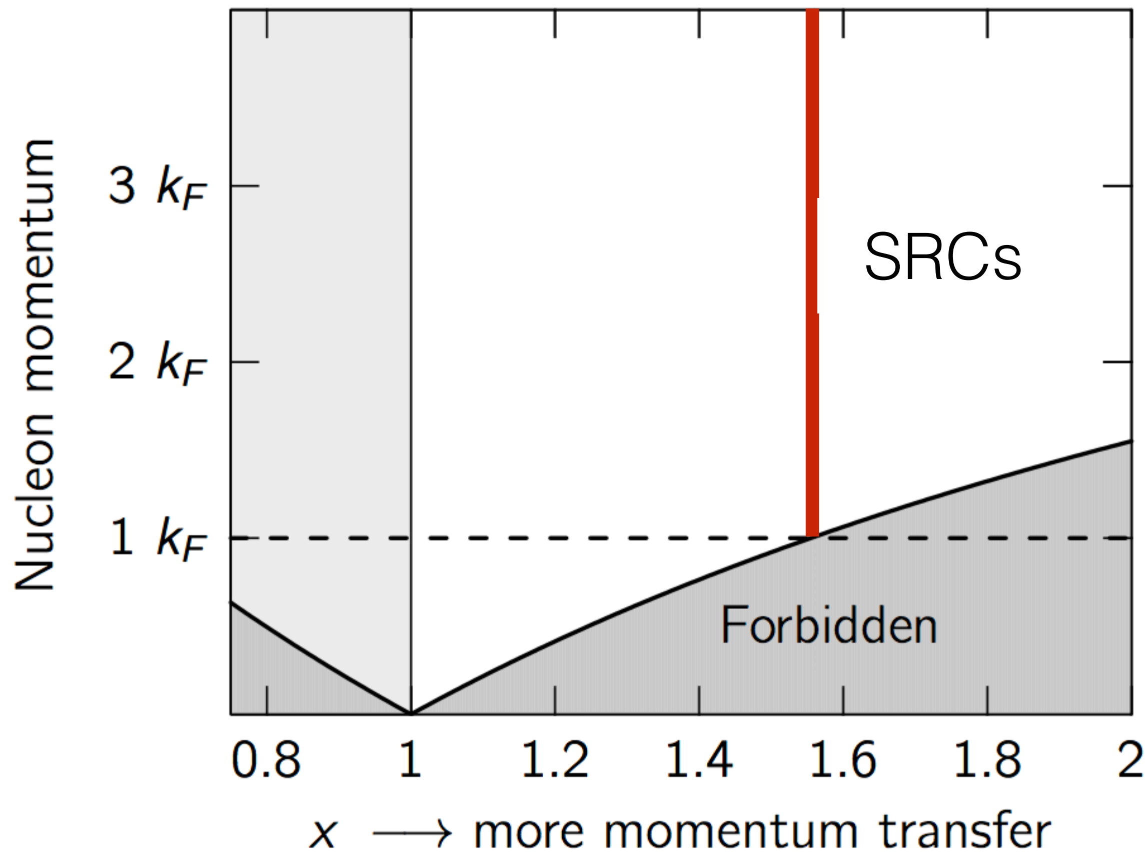
QE Inclusive Scattering Experimental Results



QE Inclusive Scattering Experimental Results



K.S. Egiyan et al. PRL 96, 082501(2006)

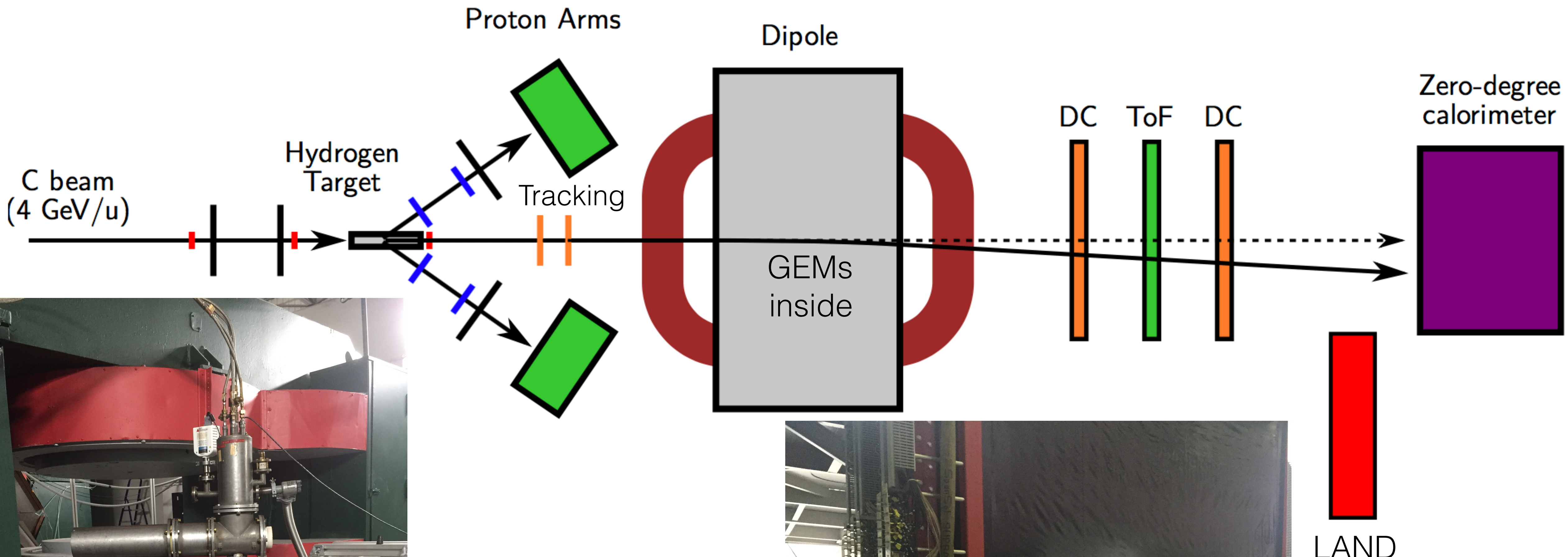


Scaling constant a_2:

$$\sigma_A = \mathbf{a}_2 \times \frac{A}{2}\sigma_d$$

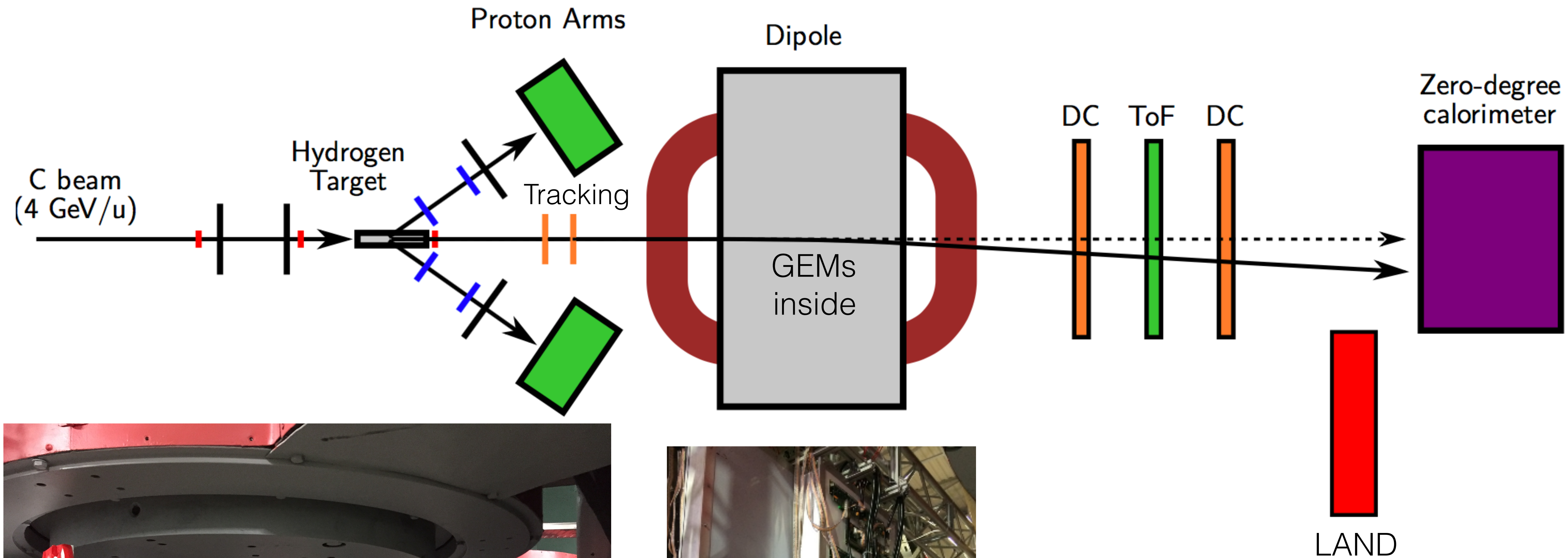
Motivation for SRC@JINR

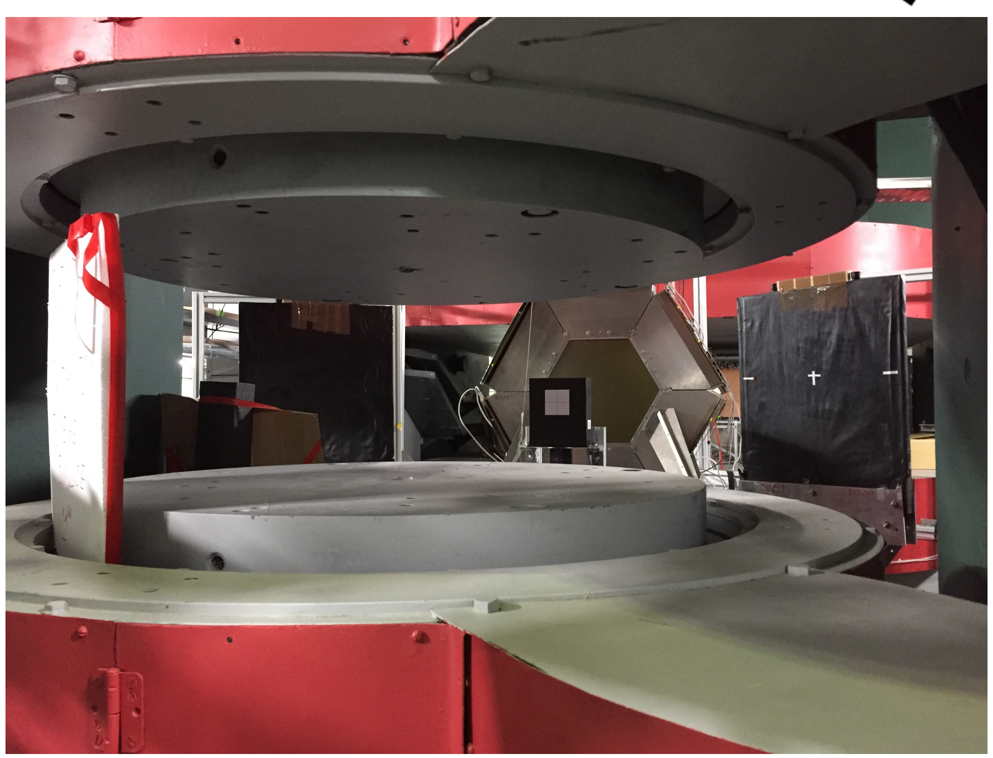
First <u>Fully</u> Exclusive Measurement of SRC Pairs at JINR

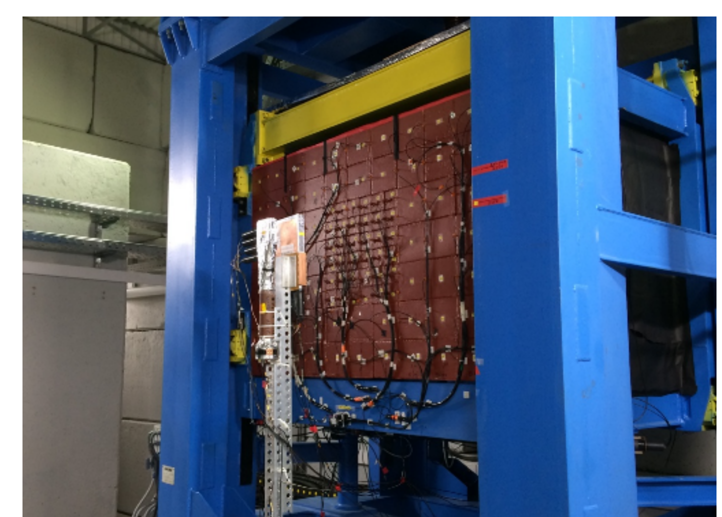


Motivation for SRC@JINR

First Fully Exclusive Measurement of SRC Pairs at JINR

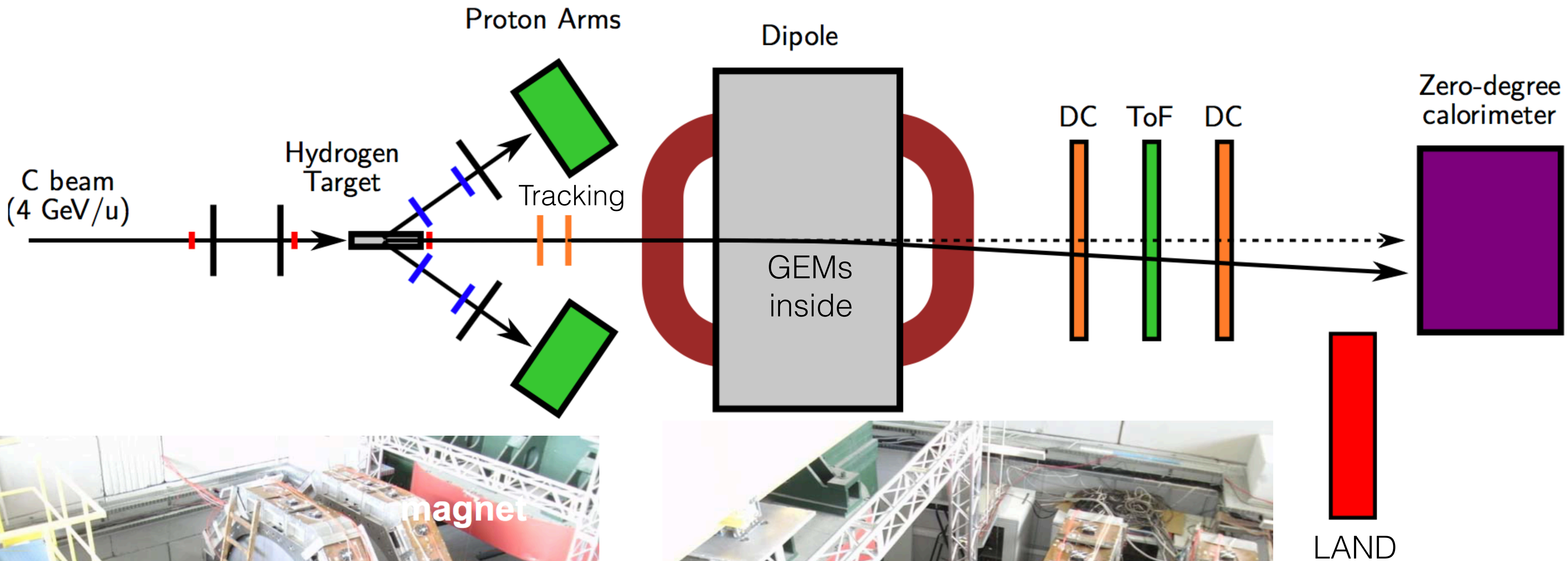


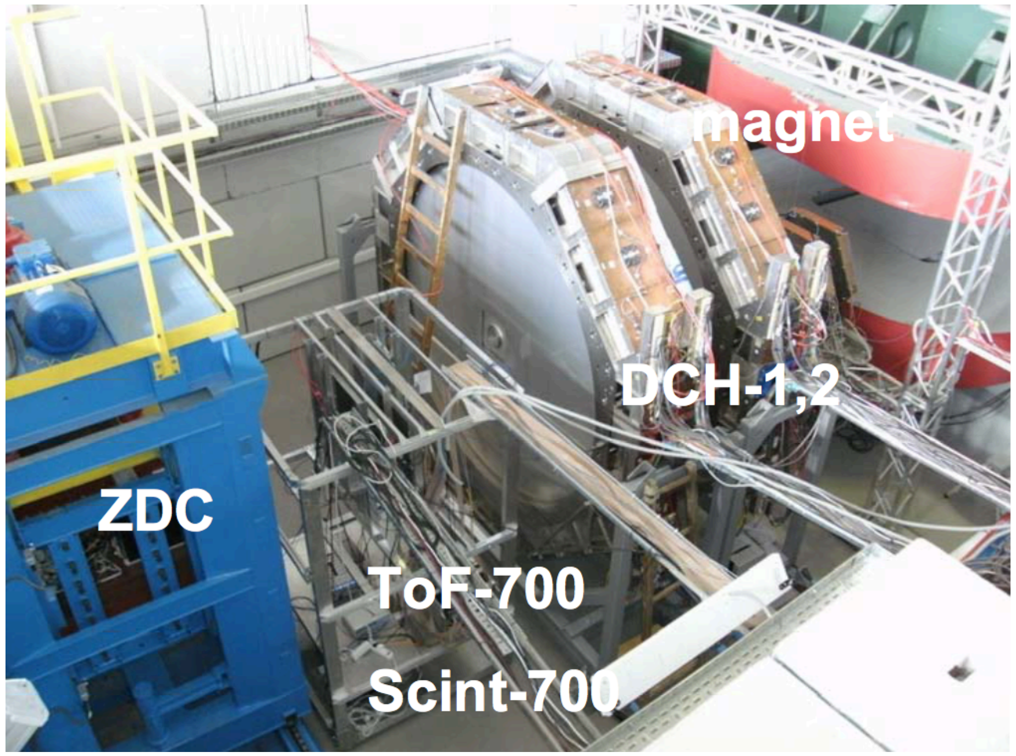


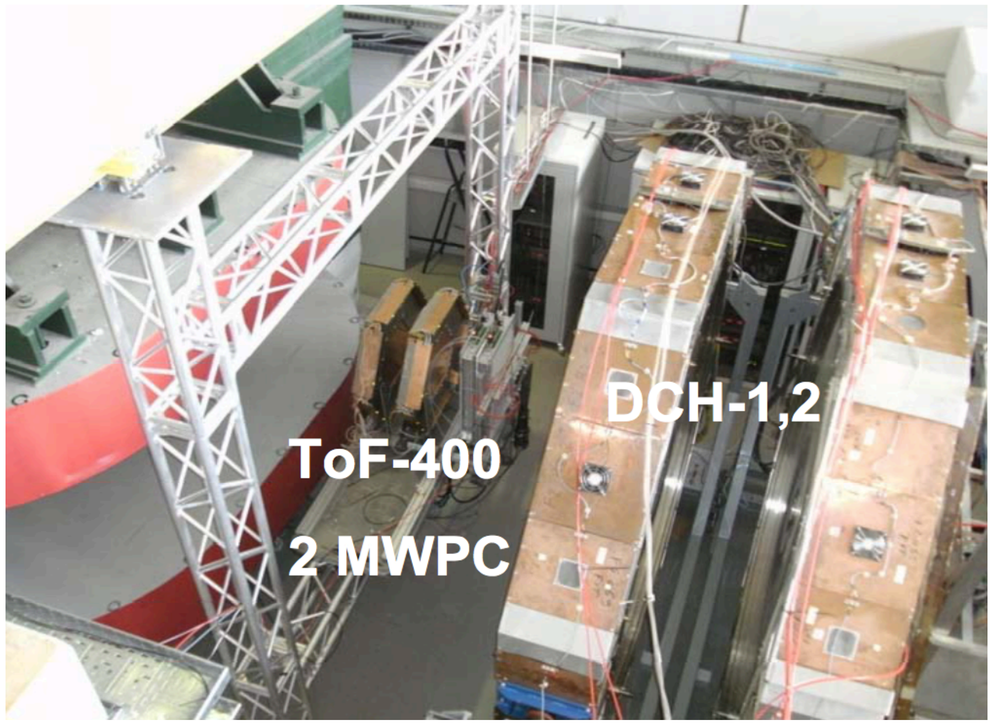


Motivation for SRC@JINR

First <u>Fully</u> Exclusive Measurement of SRC Pairs at JINR





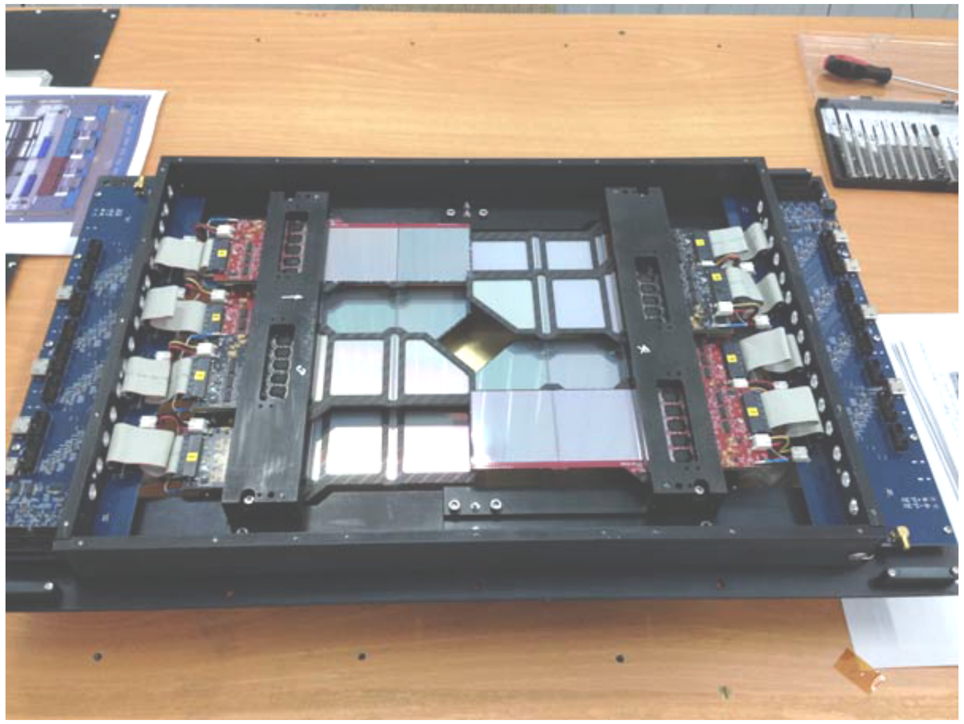


Trigger Detectors

Name	Location / function	Scintillator dimensions, cm^3	PMTs
BC1	Beam Telescope	15 x 15 x 0.3	XP 2020
BC2	T0	3.8 x 3.8 (actually 7.4, tilted by 45º) x 0.091	MCP-PMT PP03656 (Photonics)
BC3	Charge separation	10 x 10 x 0.29	XP 2020
Veto	Veto	15 x 15 x 0.3 with a hole 4.5 cm in diameter	XP 2020

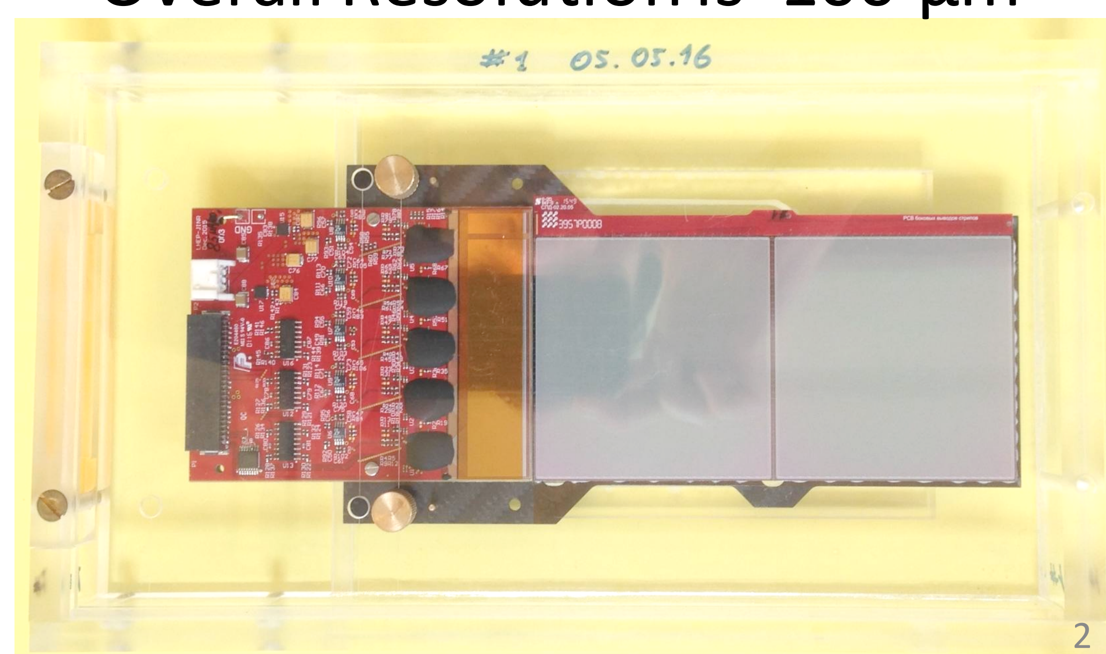
Trigger counters	Location	Scintillator dimensions, cm^3	PMTs
X, two planes	Inside SP-57	30 x 15 x 1, two optically isolated halves each read out by 1 PMT	Hamamatsu 7724
Y, two planes	Behind SP-57	50 x 50 x 2, read out by 2 (4) PMTs	ET9954KB

Silicon



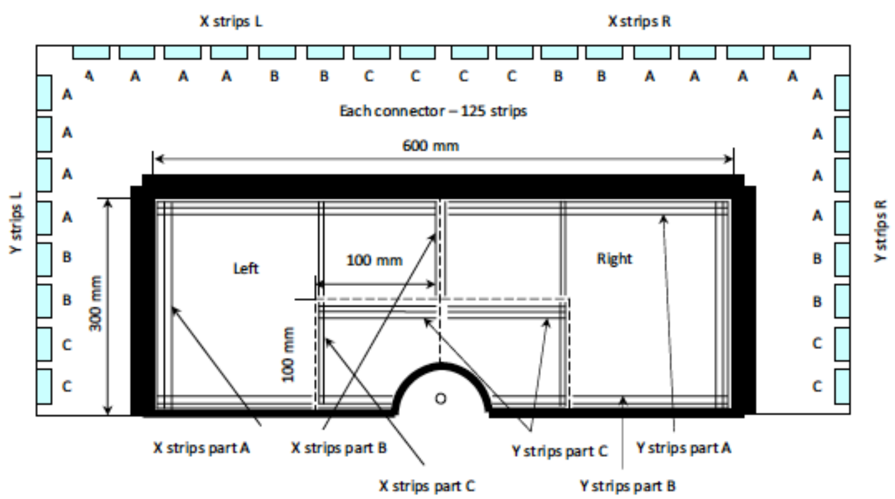
- 8 silicon modules
- 2 square shape silicon microstrip detector
- Dimensions of each module: 6.1 cm x 6.1 cm
- Thickness: 300 µm
- 1280 strips per silicon module

Overall Resolution is 100 µm

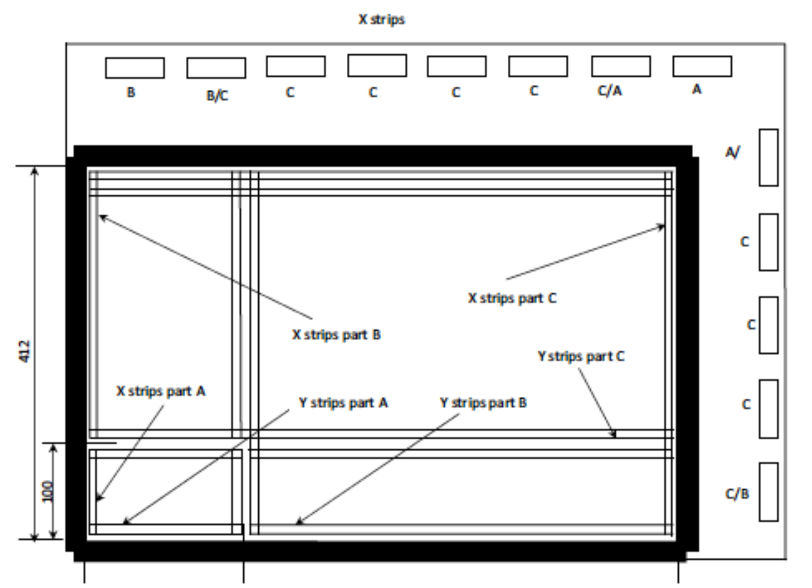


GEMs

a)

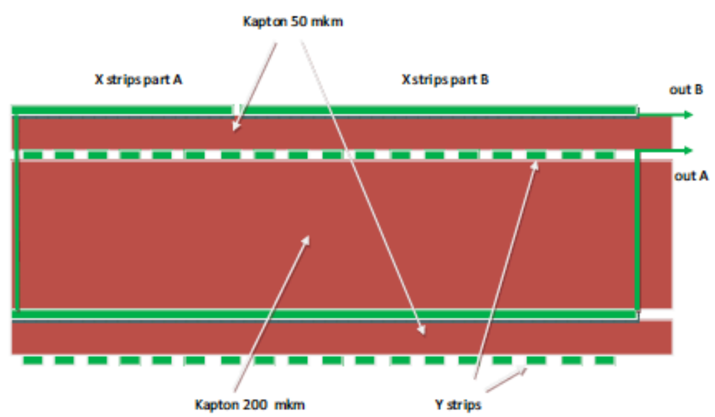


b)



Resolution:
(0.4mm, 1.6mm)

c)



d)

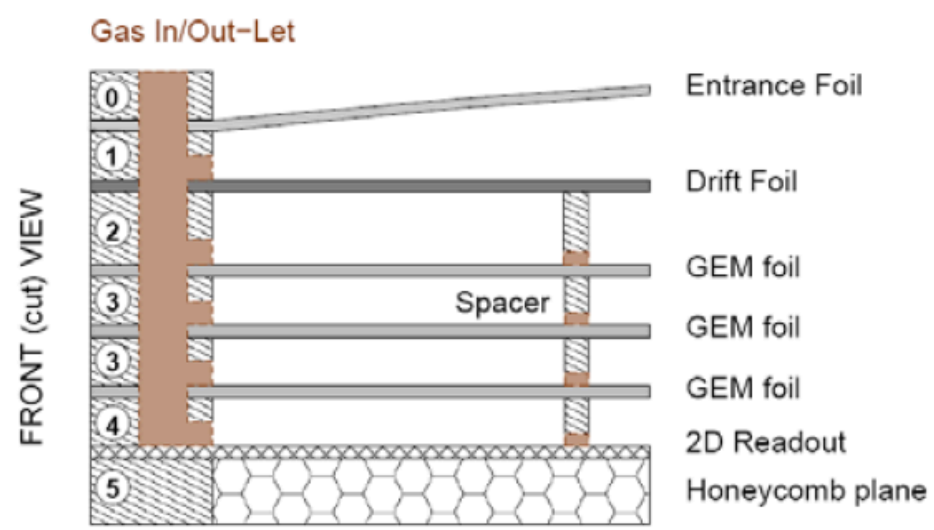
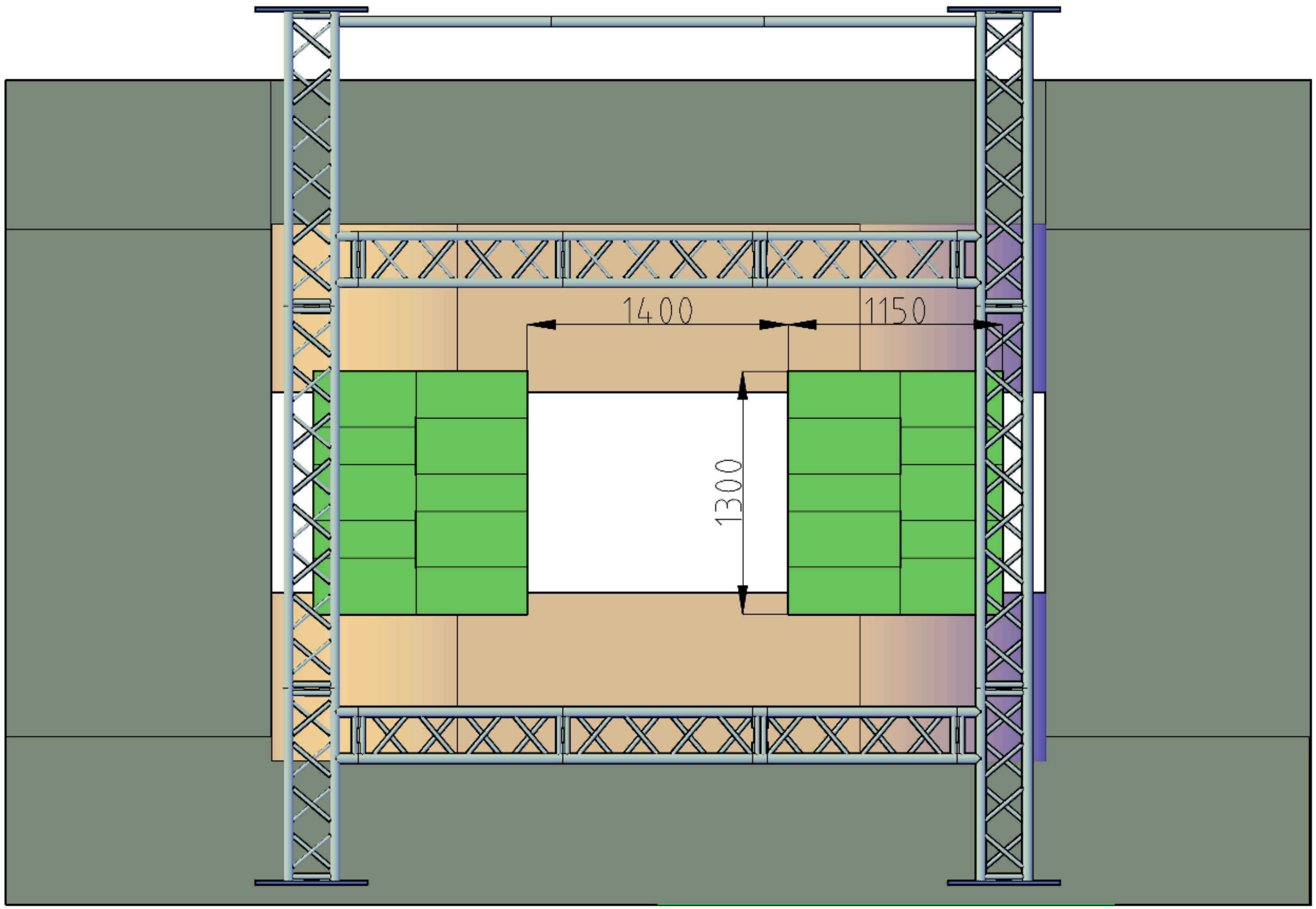


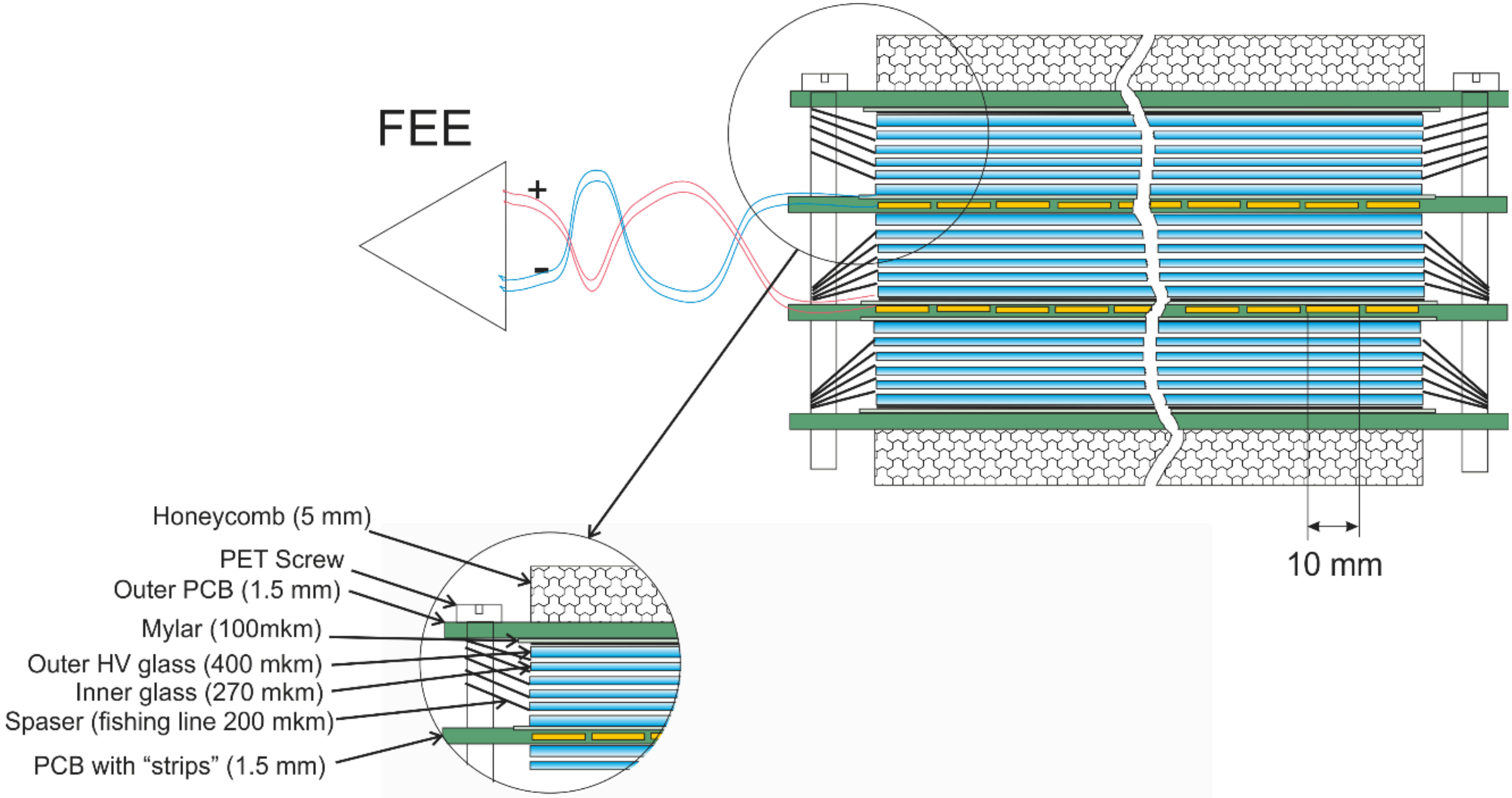
Figure 2: a) Schematic view of the first GEM half-plane with the readout strips split into zones. b) Schematic view of the GEM middle 1/4 plane with the readout strips split into zones. c) Layout of the strip readout from different zones. d) Schematic transverse structure of the triple GEM detector.

TOF400

mRPC: multi-gap resistive plate chamber

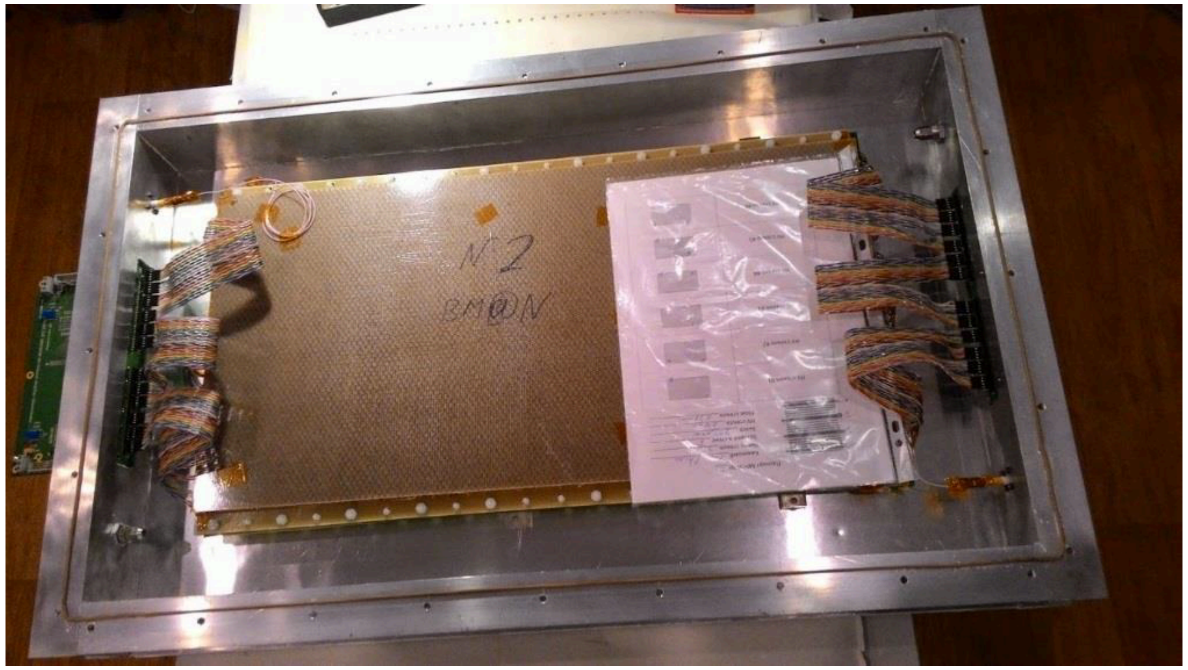


TOF400


FEE
+
-
Honeycomb (5 mm)
PET Screw
Outer PCB (1.5 mm)
Mylar (100mkm)
Outer HV glass (400 mkm)
Inner glass (270 mkm)
Spaser (fishing line 200 mkm)
PCB with “strips” (1.5 mm)
10 mm

TOF400

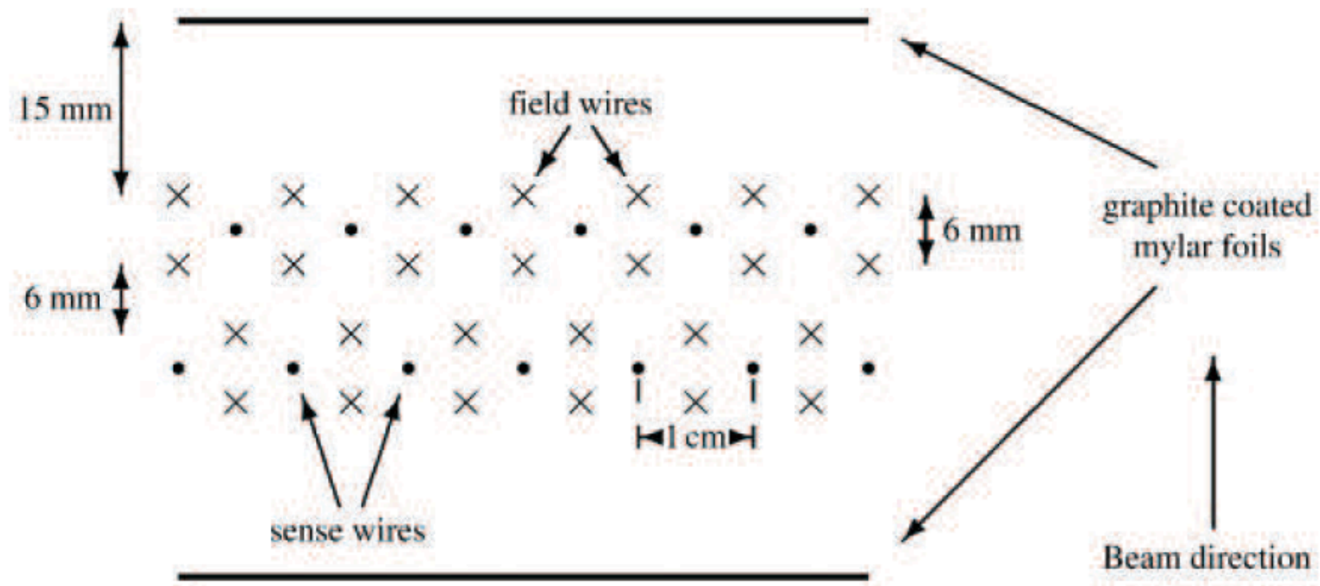
- Glass – 280 µm
- Gap width – 200 µm
- Number of gaps – 15
- Active area – 300*600 mm^2
- Strip size – 10*600 mm^2
- Strip impedance – 50 Ohm
- 24 strips, 48 ch FFE.



Resolution:
(0.34mm,
6mm)
80ps

DCHs

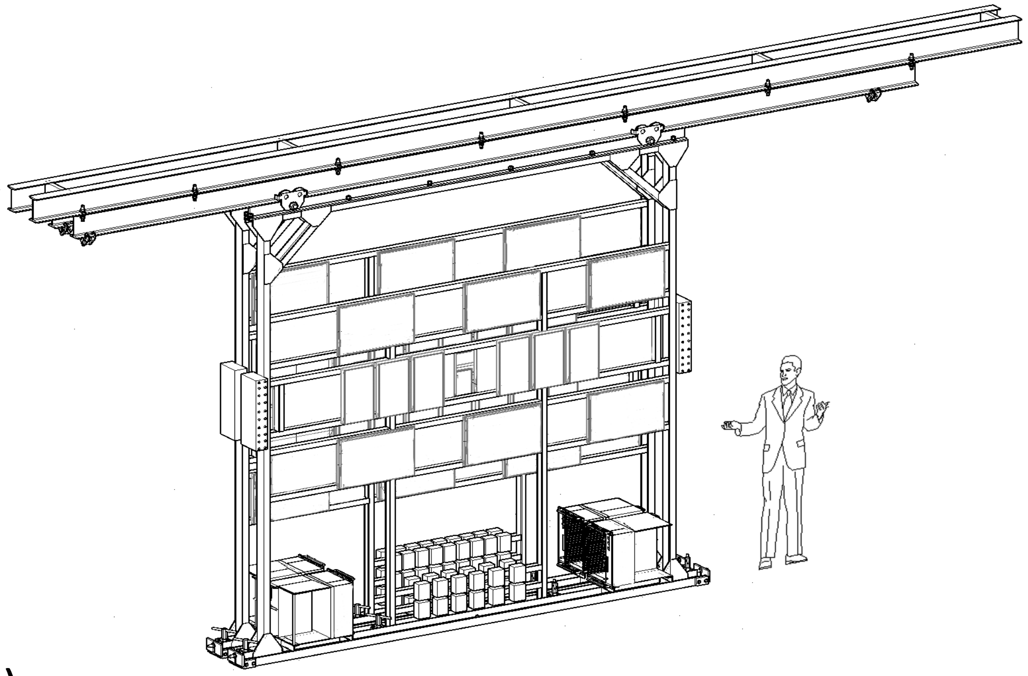
- wire inclination angles of 0, 90, ±45°
- outer dimensions of the sensitive area of Y_{out} ± 1.2 m, X_{out} ± 1.2 m
- 256 wires per coordinate plane
- 2048 wires per chamber



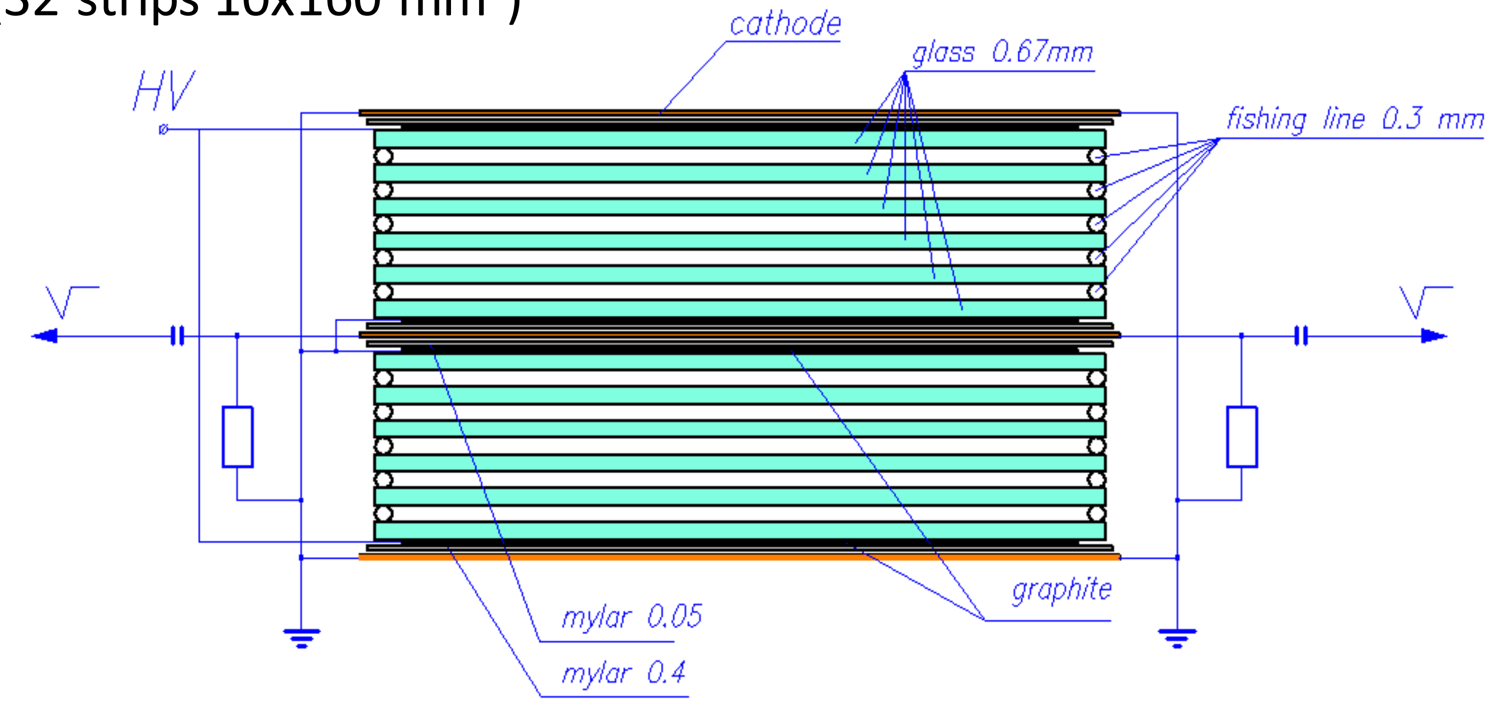
TOF700

32 Hot and 40 Cold Regions of mRPC

~80ps resolution



- Hot regions: 30.3x56 cm^2 (16 strips 18x560 mm^2)
- Cold regions: 16x35.1 cm^2 (32 strips 10x160 mm^2)



Resolutions

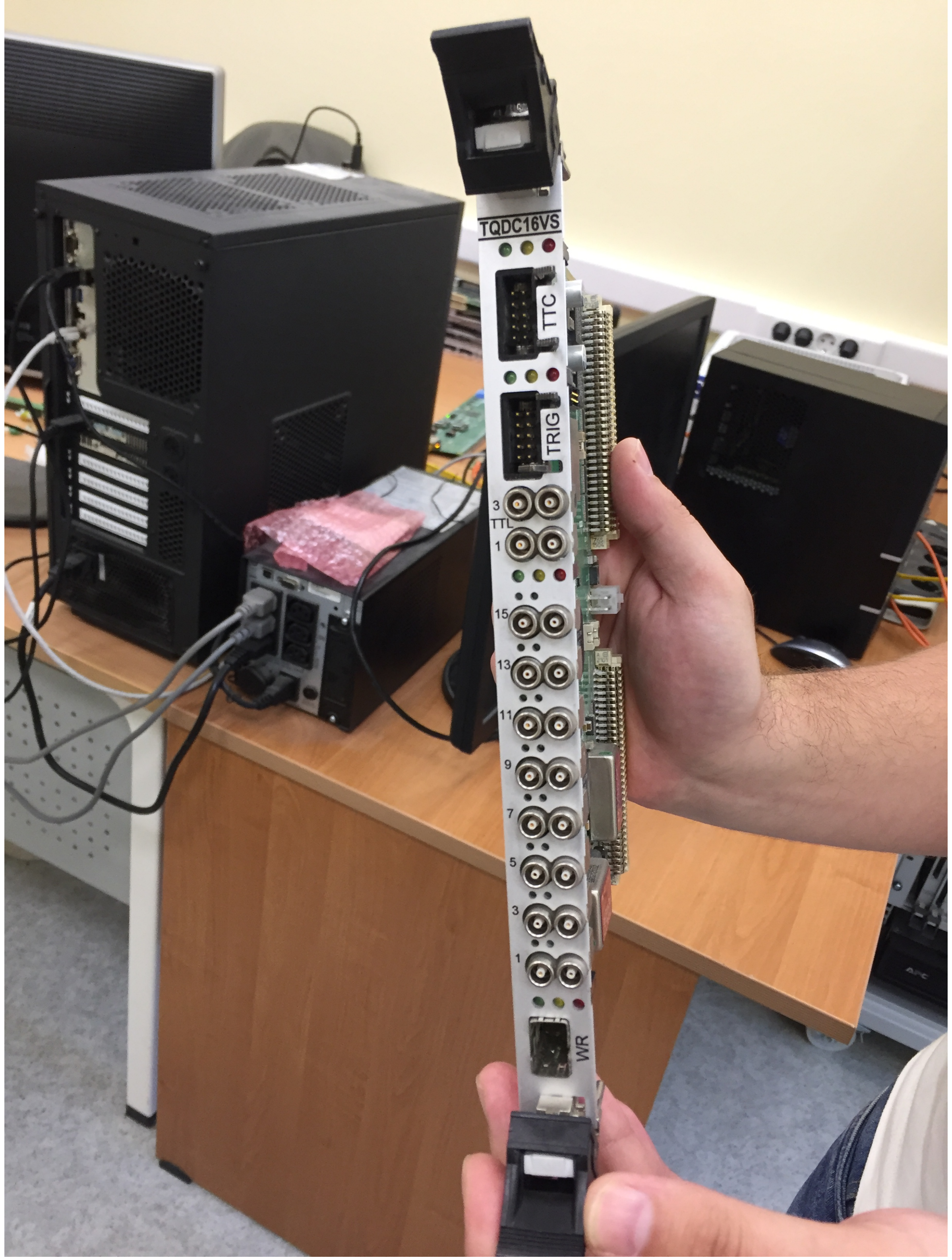
Detectors	Value
Beam Momentum resolution	0.3%
Beam Angular Resolution	0.04^o
TOF-400 time resolution	80 psec
Leading protons polar resolution	0.06^o
Leading protons azimuthal	0.13^o
LAND time resolution	300 psec
LAND polar resolution	0.06^o
LAND azimuthal resolution	0.06^o
Momentum resolution for A-2	0.6%
Polar resolution for A-2	0.02^o
Azimuthal resolution for A-2	0.03^o

TQDC Module

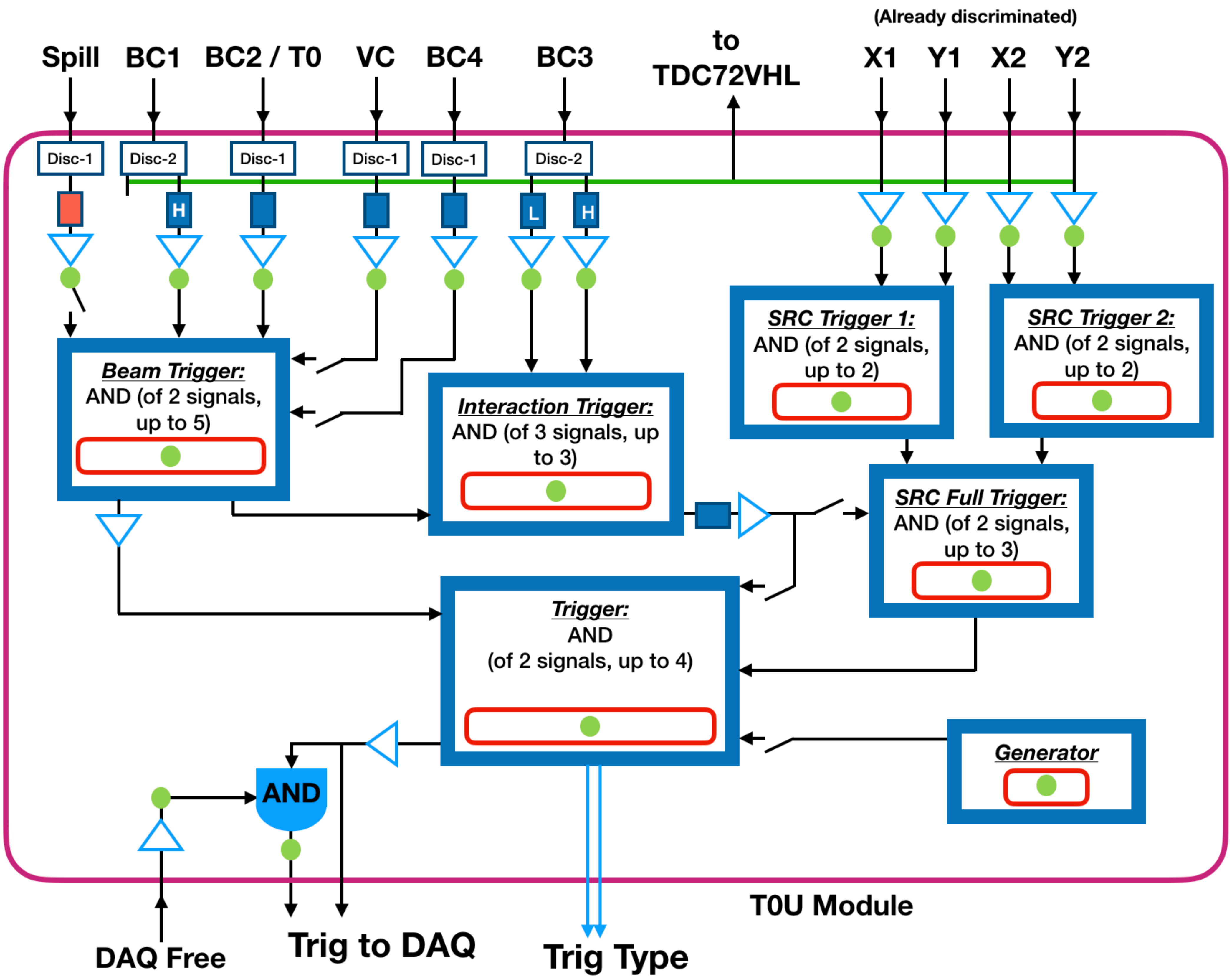
<u>Specify</u>:

Latency
Search Window
ADC Window

125 MS/s
14 bit resolution
25ps resolution

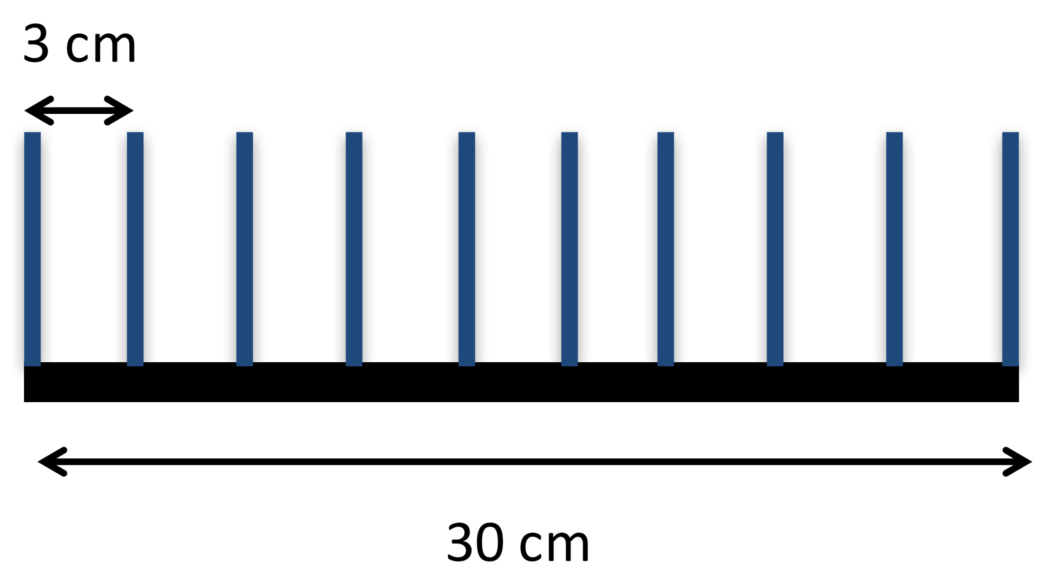


Trigger Module

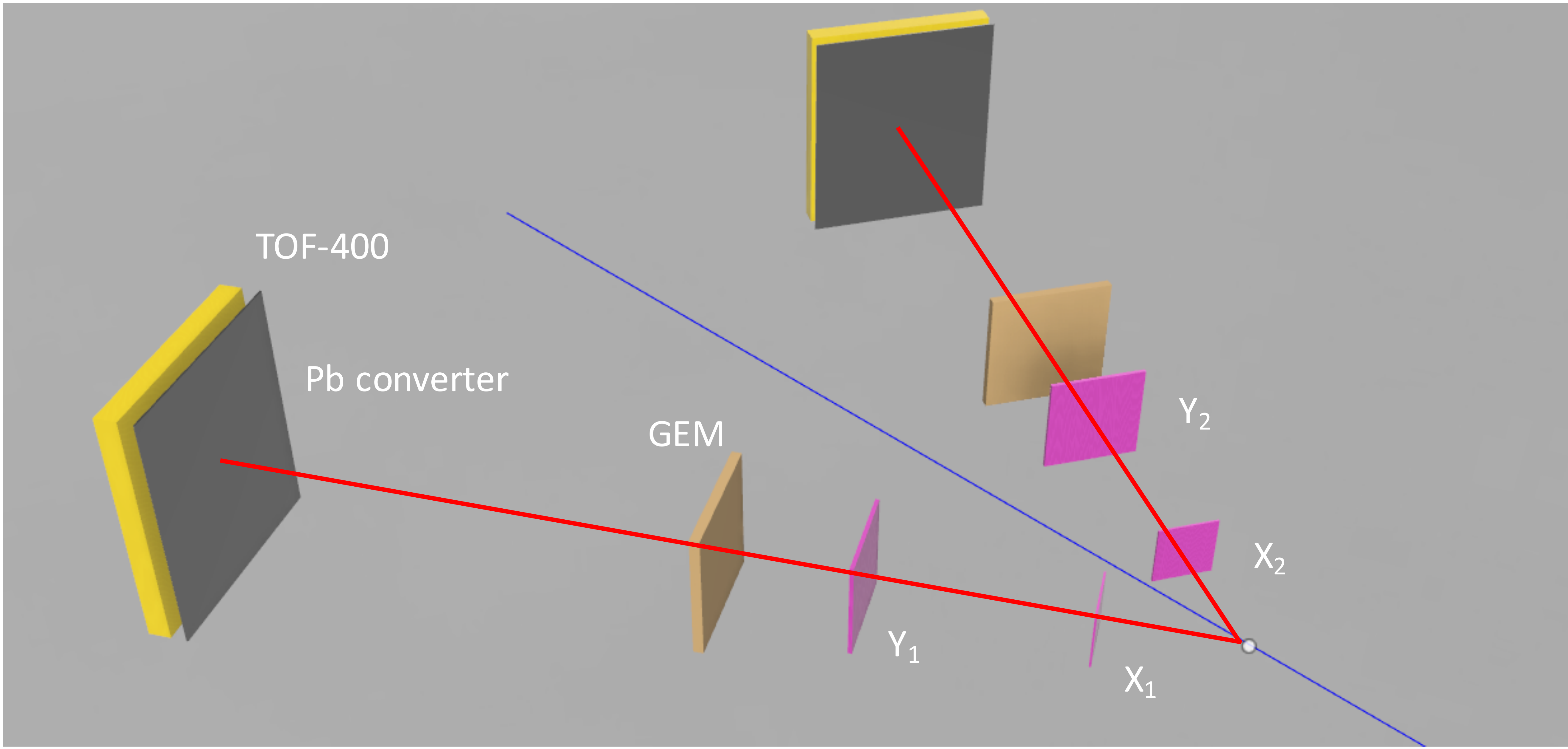


Optics Calibration

- Use a 2-5% NIP Pb target (e.g. 2.5 mm Pb target corresponds to 2.8% NIP)
- Foils @ MIT Hen Lab are 250 μm thick
- 10 scattering centers along the 30 cm long H_2 target region



TOF Calibration



Current Status & Timeline

Timeline

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Dates	Events
Feb 6	Accelerator Starts
Feb 10	BMN Running
Mar 6 - 12	SRC Commissioning
Mar 13 - 23	SRC Running

Current Status & Timeline

Timeline

Dates	Events
Feb 6	Accelerator Starts
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Electronics setup & testing ✓
Quality control software ✓
Prelim online analysis ✓

Sensitivity to SRCs

<u>Assuming scattering off 2N-SRC pairs:</u>

- (e,e'p) is sensitive to *np* and *pp* pairs
- (e,e'pp) is sensitive to *pp* pairs alone

=> (e,e'pp)/(e,e'p) ratio is sensitive to the *np*/*pp* ratio

$$A(e,e'pp) \propto \#\, pp_A \cdot 2\sigma_p$$

$$A(e,e'p) \propto \#\, pp_A \cdot 2\sigma_p + \#\, pn_A \cdot \sigma_p$$

$$= \#\, pp_A \cdot 2\sigma_p \left[1 + \frac{1}{2} \frac{\#\, pn_A}{\#\, pp_A} \right]$$

$$\Rightarrow \frac{\#\, np_A}{\#\, pp_A} = 2 \cdot \left[\frac{A(e,e'p)}{A(e,e'pp)} - 1 \right]$$

Assuming No FSI

Sensitivity to SRCs

<u>Assuming scattering off 2N-SRC pairs:</u>

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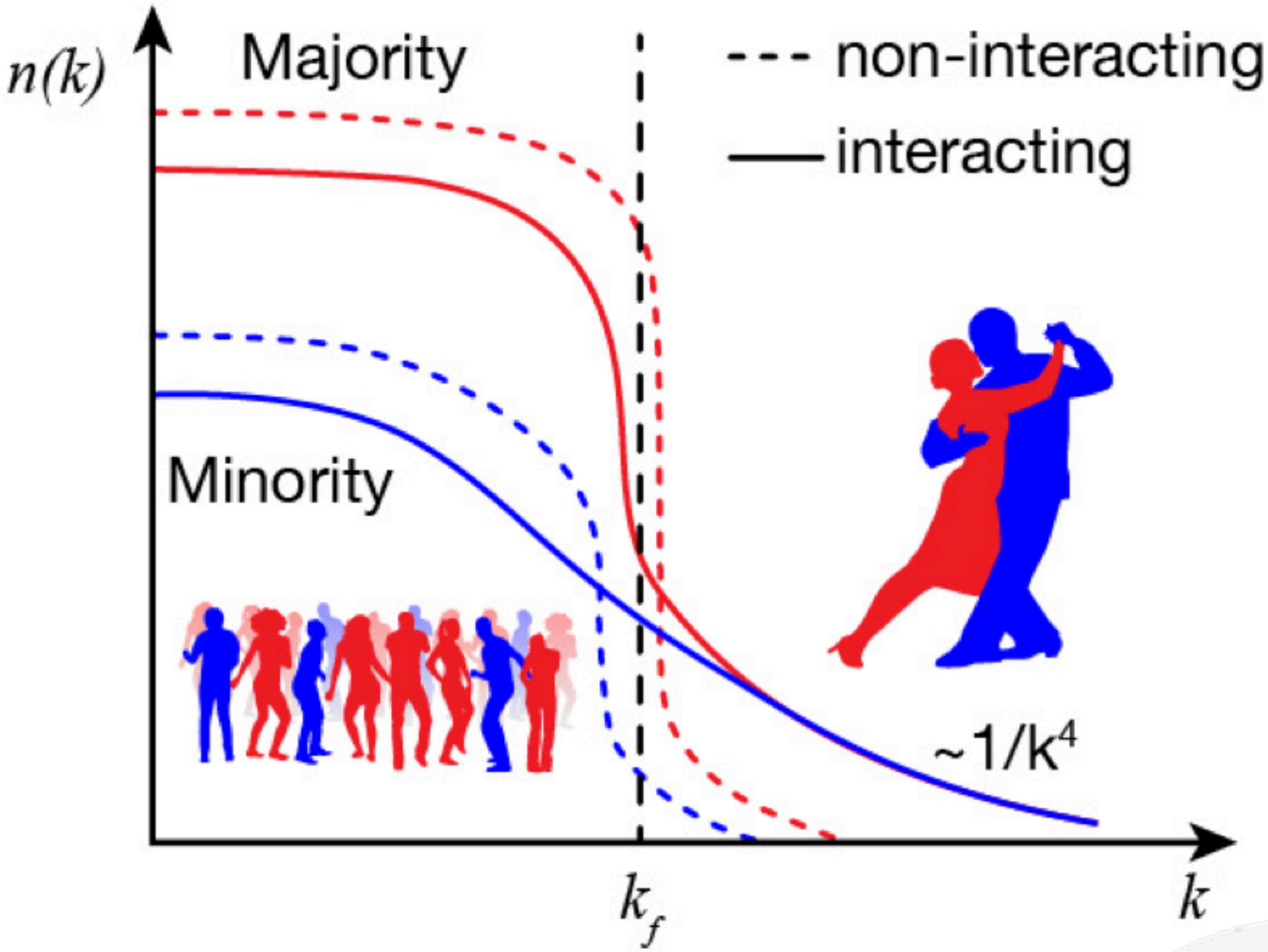
$$= \# pp_A \cdot 2\sigma_p \left[1 + \frac{1}{2} \frac{\# pn_A}{\# pp_A} \right]$$

$$\Rightarrow \frac{\# np_A}{\# pp_A} = 2 \cdot \left[\frac{A(e,e'p)}{A(e,e'pp)} - 1 \right]$$

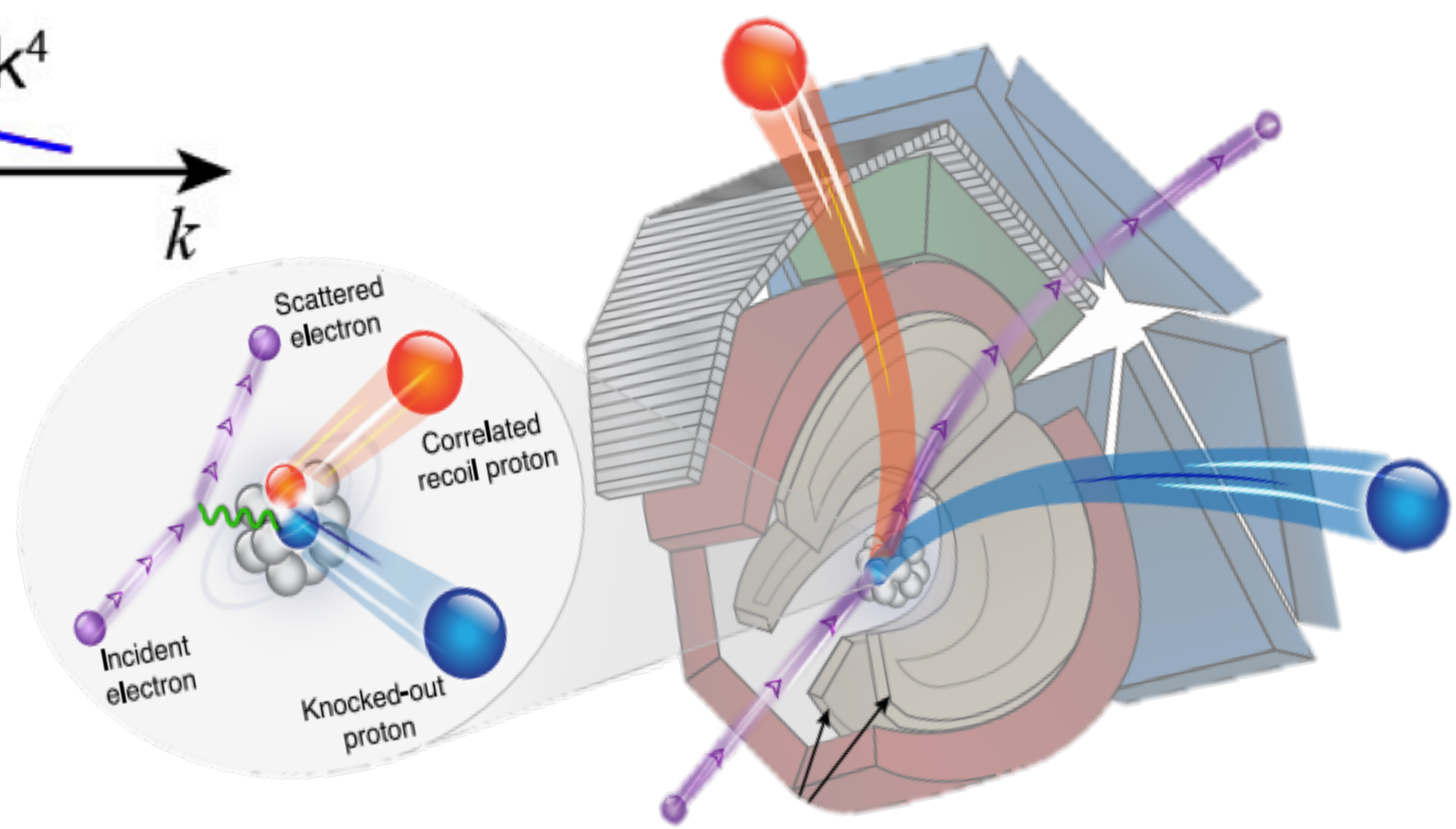
Corrected for Final-State Interactions (FSI) on the outgoing nucleon

(Attenuation and Single-Charge Exchange.)

Kinetic Energy Sharing



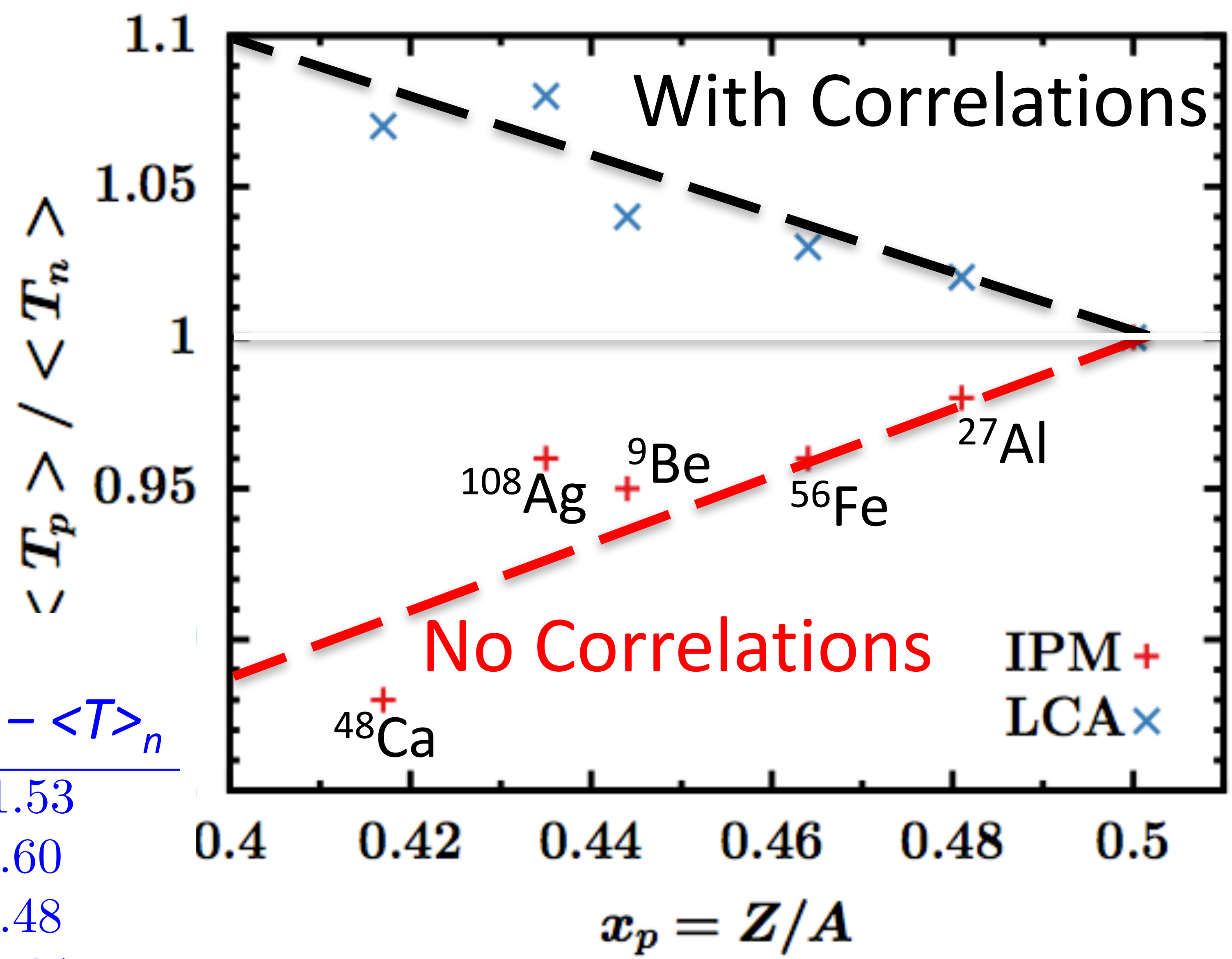
Momentum distribution of an imbalanced two-component Fermi system



O. Hen et al. (CLAS Collaboration), Science 346, 614 (2014)

Calculations *Predict* Correlations wins

$\langle T \rangle_{Minority} \geq \langle T \rangle_{Majority}$



Light Nuclei (A<12)

	$\frac{\lvert N-Z \rvert}{A}$	$\langle T \rangle_p$	$\langle T \rangle_n$	$\langle T \rangle_p - \langle T \rangle_n$
^{8}He	0.50	30.13	18.60	11.53
^{6}He	0.33	27.66	19.06	8.60
^{9}Li	0.33	31.39	24.91	6.48
^{3}He	0.33	14.71	19.35	-4.64
^{3}H	0.33	19.61	14.96	4.65
^{8}Li	0.25	28.95	23.98	4.97
^{10}Be	0.2	30.20	25.95	4.25
^{7}Li	0.14	26.88	24.54	2.34
^{9}Be	0.11	29.82	27.09	2.73
^{11}B	0.09	33.40	31.75	1.65

<u>Heavy Nuclei (27<A<108):</u>
M. Vanhalst, W. Cosyn, and J. Ryckebusch, arXiv: 1405.3814.

<u>VMC Calculations:</u> R. Wiringa et al., Phys. Rev. C **89**, 024305 (2013)

The Contact and Universal Relations

A concept developed for a ***dilute*** two-component Fermi systems with a short-range interaction.

Scattering length

$$\text{dilute} \equiv r_{eff} << a, d$$

Distance between fermions

These systems have a high-momentum tail:

$$n(k) = C / k^4 \quad \text{for} \quad k > k_F$$

C is the contact term

Tan's Contact term:

1. Measures the number of SRC different fermion pairs.
2. Determines the thermodynamics through a series of universal relations.

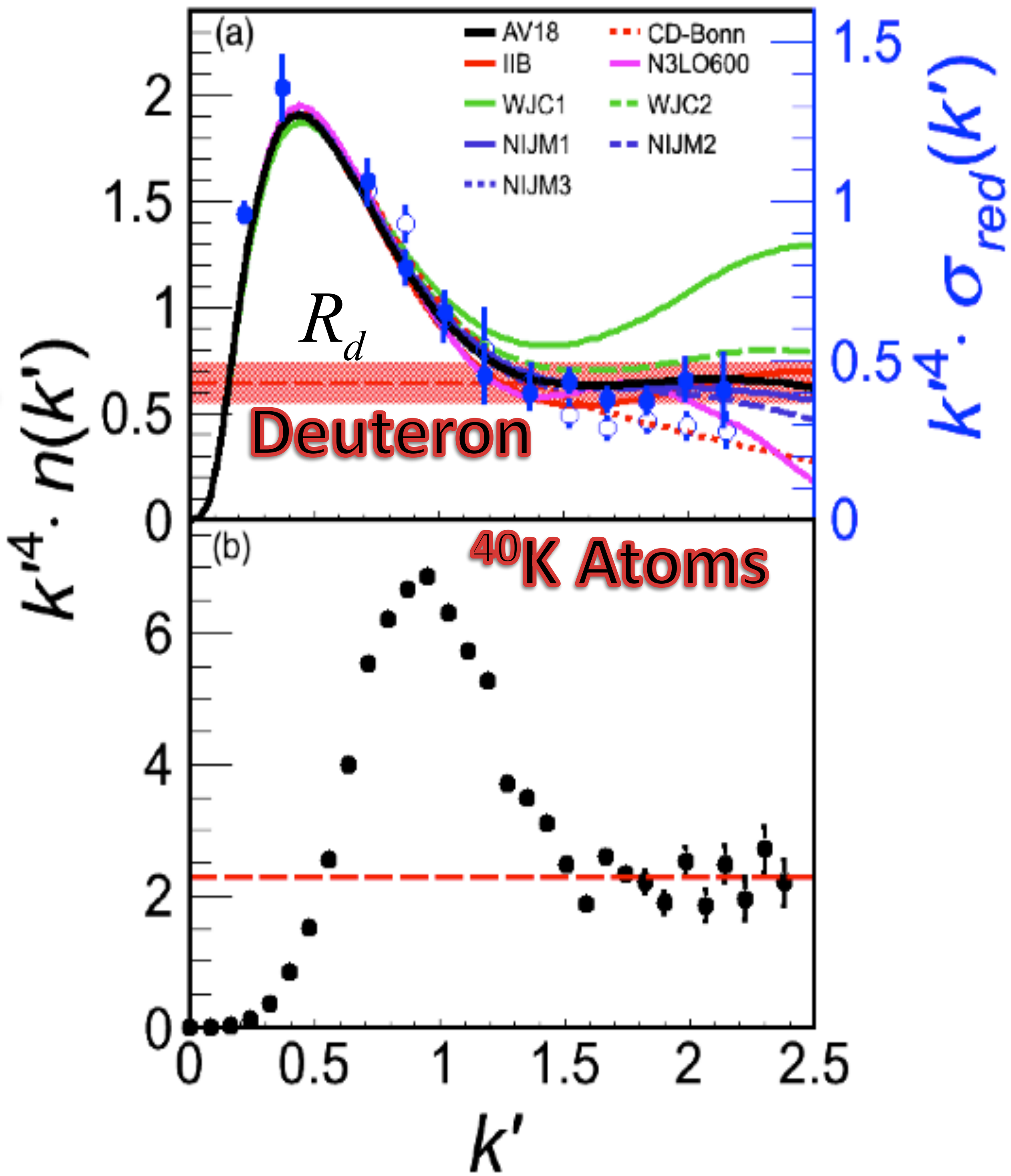
S. Tan Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987

A Nuclear Contact?

Is there $1/k^4$ scaling regardless? <u>YES!</u>

$$1.5k_F < k < 3k_F$$

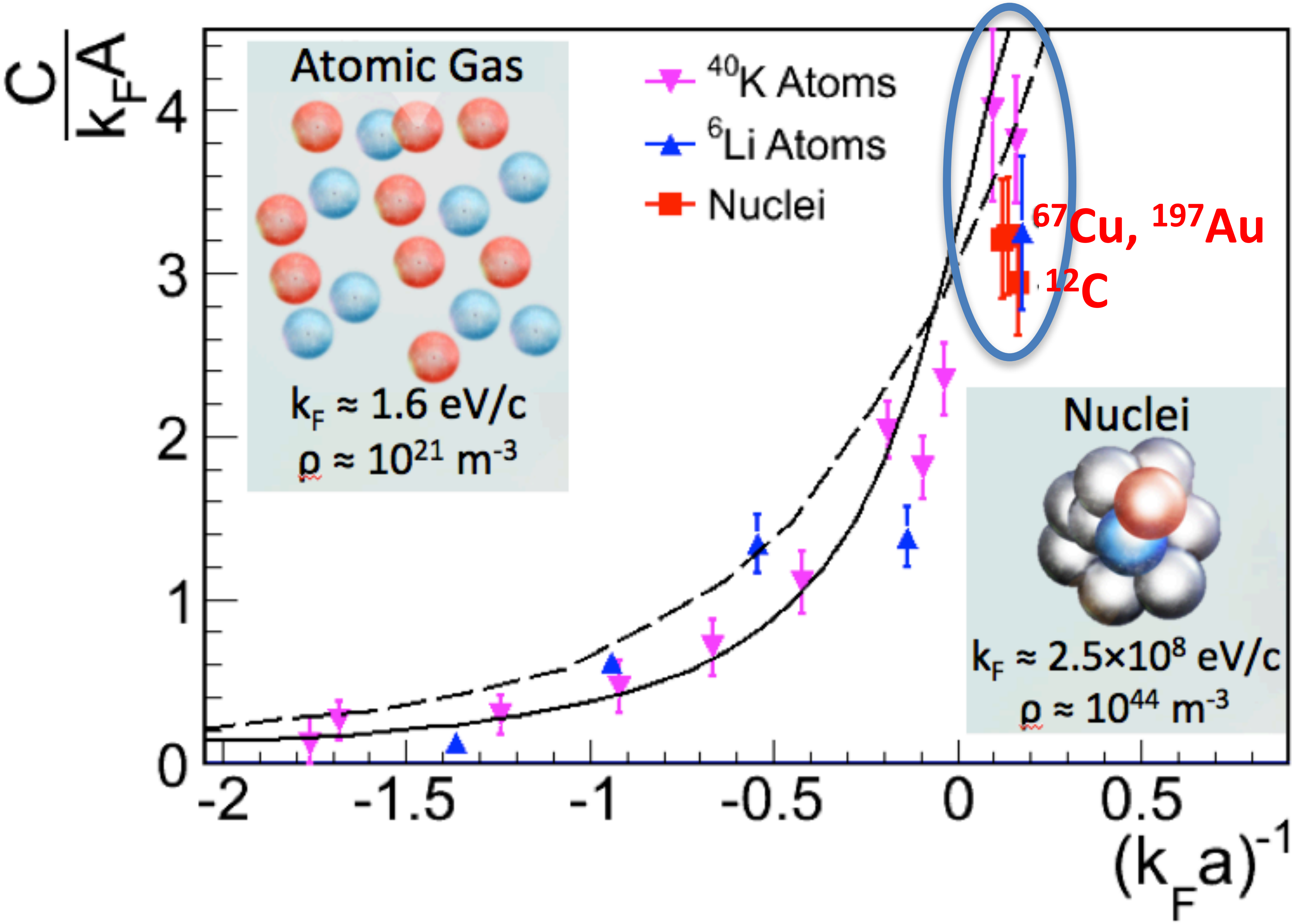
$$n_A(k) = a_2(A/d) \cdot n_d(k)$$



O. Hen et al. Phys. Rev. C **92**, 045205 (2015)

Comparing with atomic systems

Equal contacts for equal interactions strength!



For Nuclei:

$k_F \approx 1.27\ \text{fm}^{-1}$

$a \approx 5.4\ \text{fm}$

=> $(k_F a)^{-1} \approx 0.15$

Nucleus	$\frac{C}{k_F A}$
^{12}C	3.04 ± 0.49
^{56}Fe	3.33 ± 0.54
^{197}Au	3.30 ± 0.53

$$\frac{C}{k_F \cdot A} = a_2(A) \cdot R_d$$

O. Hen et al. Phys. Rev. C **92**, 045205 (2015)
Stewart et al. Phys. Rev. Lett. **104**, 235301 (2010)
Kuhnle et al. Phys. Rev. Lett. **105**, 070402 (2010)

Nuclear Symmetry Energy

Energy of *asymmetric* nuclear matter:

$$E(\rho_n, \rho_p) = E_0(\rho_n = \rho_p) \quad E_{sym}(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + O(\delta^4)$$

symmetry energy

$$E_{sym}(\rho) \approx E(\rho)_{\mathrm{PNM}} - E(\rho)_{\mathrm{SNM}}$$

Relates to the energy change when replacing n with p

- equation-of-state of neutron stars
- heavy-ion collisions
- r-process nucleosynthesis
- core-collapse supernovae
- more…

Constraining the Symmetry Energy

[With SRCs]

Adding np-SRCs breaks the Fermi-Gas picture

=> Need a correlated Fermi-Gas Model

$$E_{sym}(\rho) = \underbrace{E_{sym}^{kin}(\rho_0)\left(\frac{\rho}{\rho_0}\right)^{\alpha}}_{} + E_{sym}^{pot}(\rho_0)\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

Fermi-Gas Model + Correlations

$$E_{sym}^{kin}(\rho) = \frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3} + \Delta_{SRC}(\rho)$$

~~Only unknown is γ_i probed in HI collision measurements and neutron stars observations~~

☑ $\alpha = \cancel{2/3}$

☑ $E_{sym}^{kin}(\rho_0) = \cancel{12.5}\ \text{MeV}$

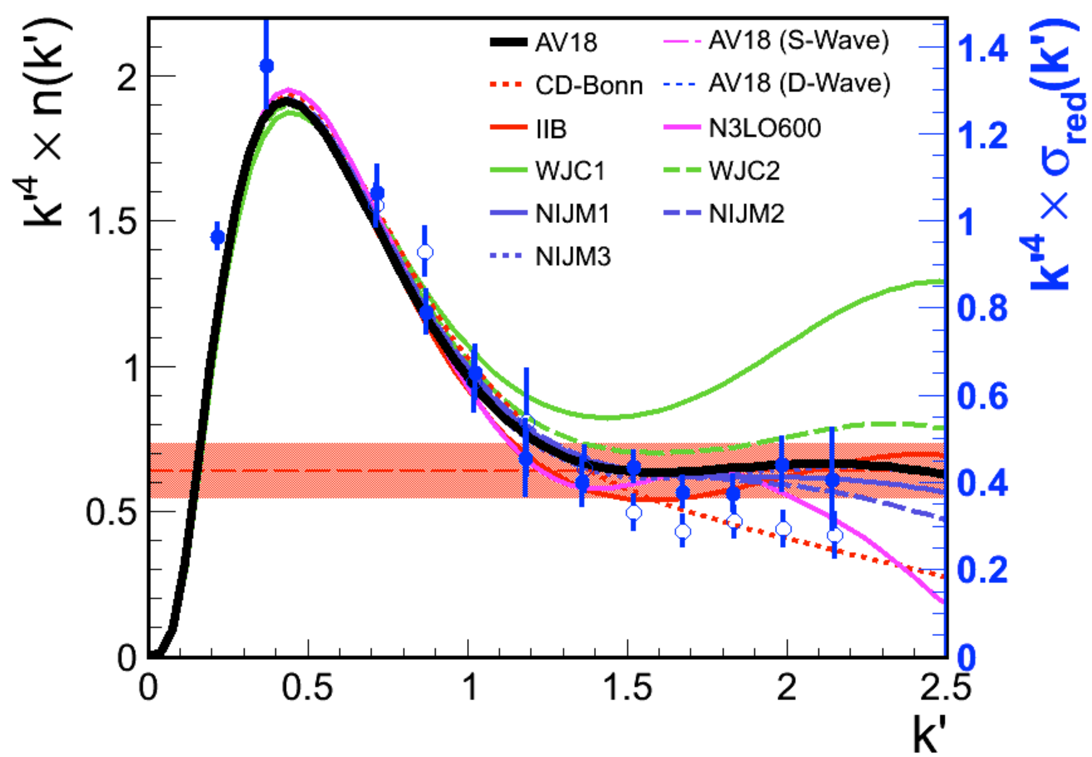
☑ $E_{sym}^{pot}(\rho_0) = E_{sym}(\rho_0) - E_{sym}^{kin}(\rho_0) \approx \cancel{18.5}\ \text{MeV}$

Correlated Fermi-Gas Model (CFG)

[Fermi-Gas with an SRC tail]

$$
\begin{array}{lcc}
 & \text{SNM} & \text{PNM} & \\
n_{CFG}(k) = & \left\{ \begin{array}{ccc} A_0 & , \; A_1 & k < k_F \\ C_\infty / k^4 & , \; 0 & k_F < k < \lambda k_F^0 \\ 0 & , \; 0 & 0k > \lambda k_F^0 \end{array} \right.
\end{array}
$$

C/k^4 is a good parameterization of the high-momentum tail:



O. Hen et al., Phys. Rev. C 91, 025803 (2015).

Next Step – Incorporating CFG model into:

- neutron stars equation-of-state fits
- Transport models for HI collision analysis