Search for New Light Bosons in Electron-Proton Collisions Using the JLab FEL

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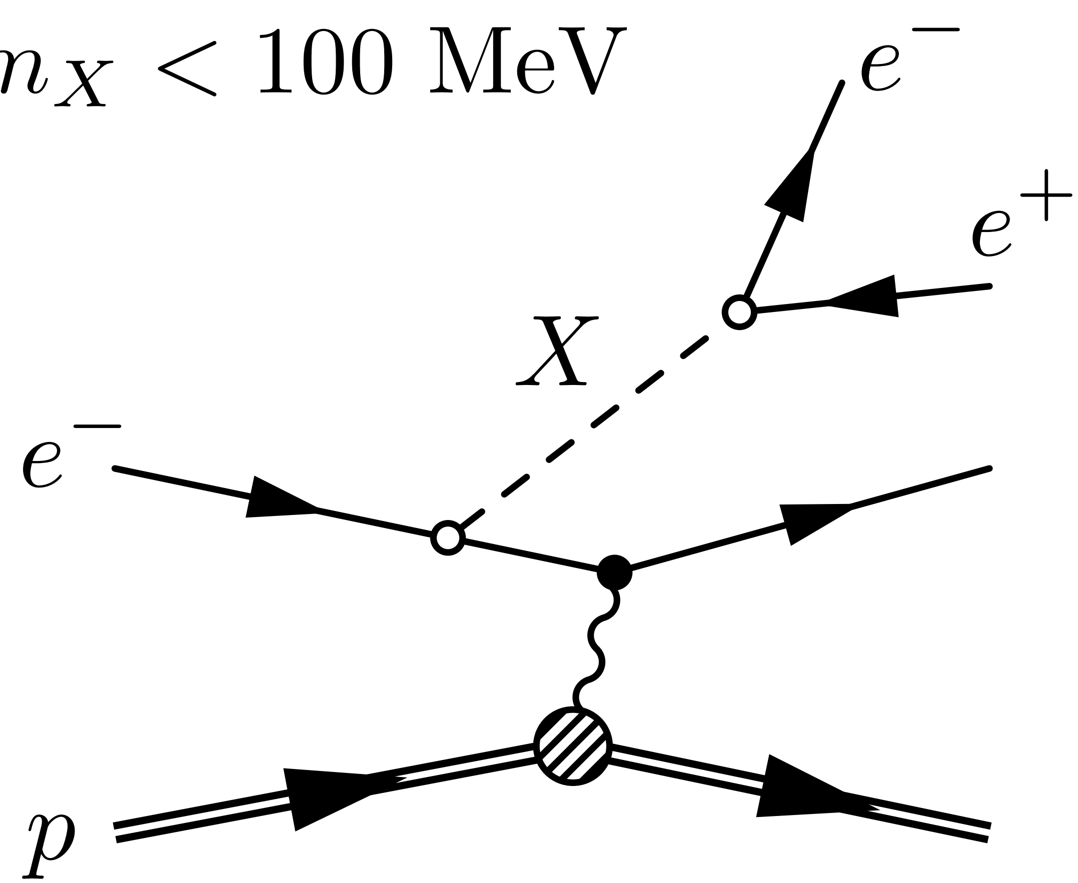
UC Berkeley — arXiv:0909.2862

Our Proposal

Electron-Proton Collisions Below the Pion Threshold

$$10 \text{ MeV} < m_X < 100 \text{ MeV}$$

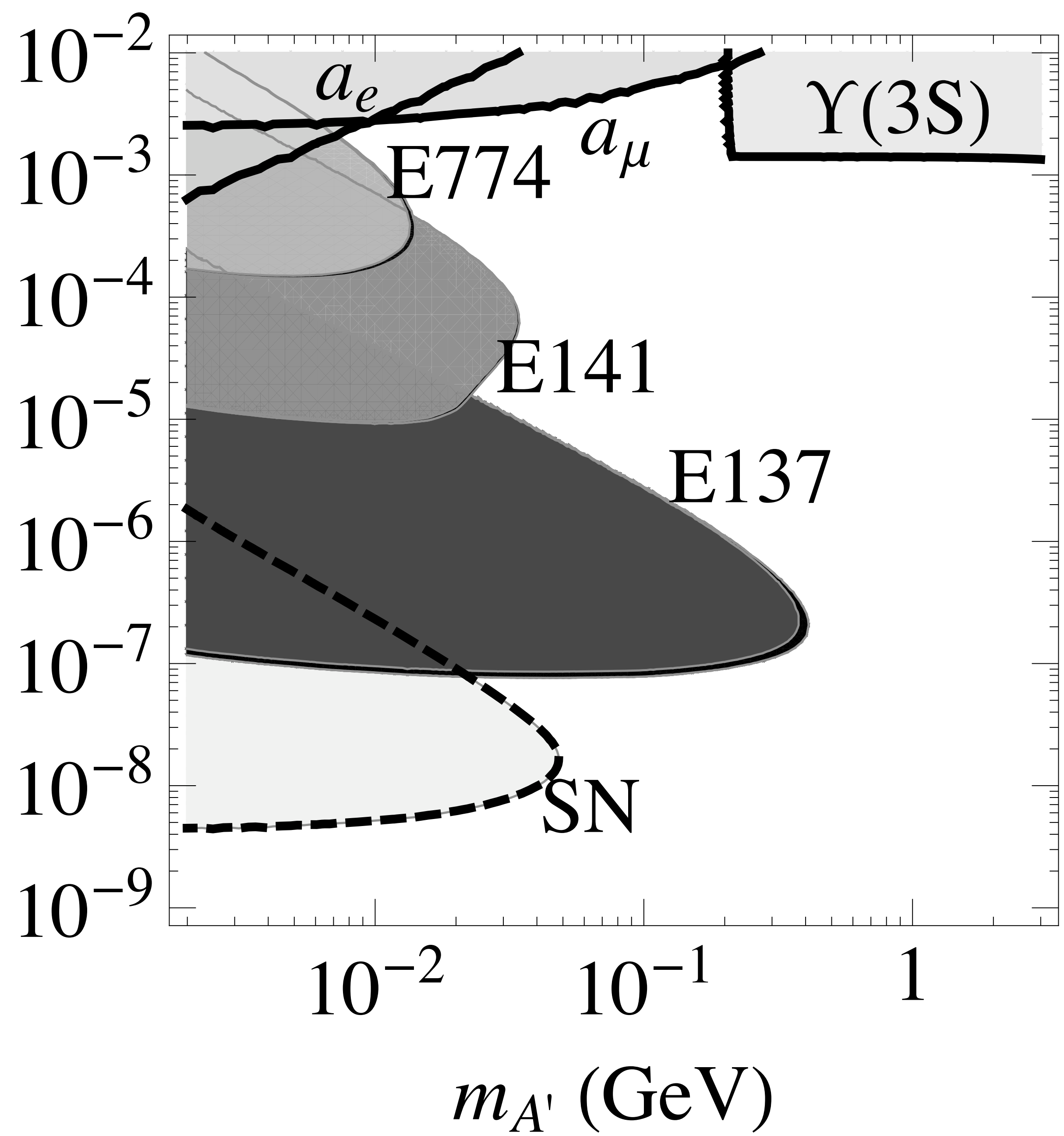
$$\alpha_X > 10^{-9}$$



High Intensity Electron Beam on Diffuse Hydrogen Gas Target

Luminosity: 1 ab^{-1} / month

Light Boson Scenarios

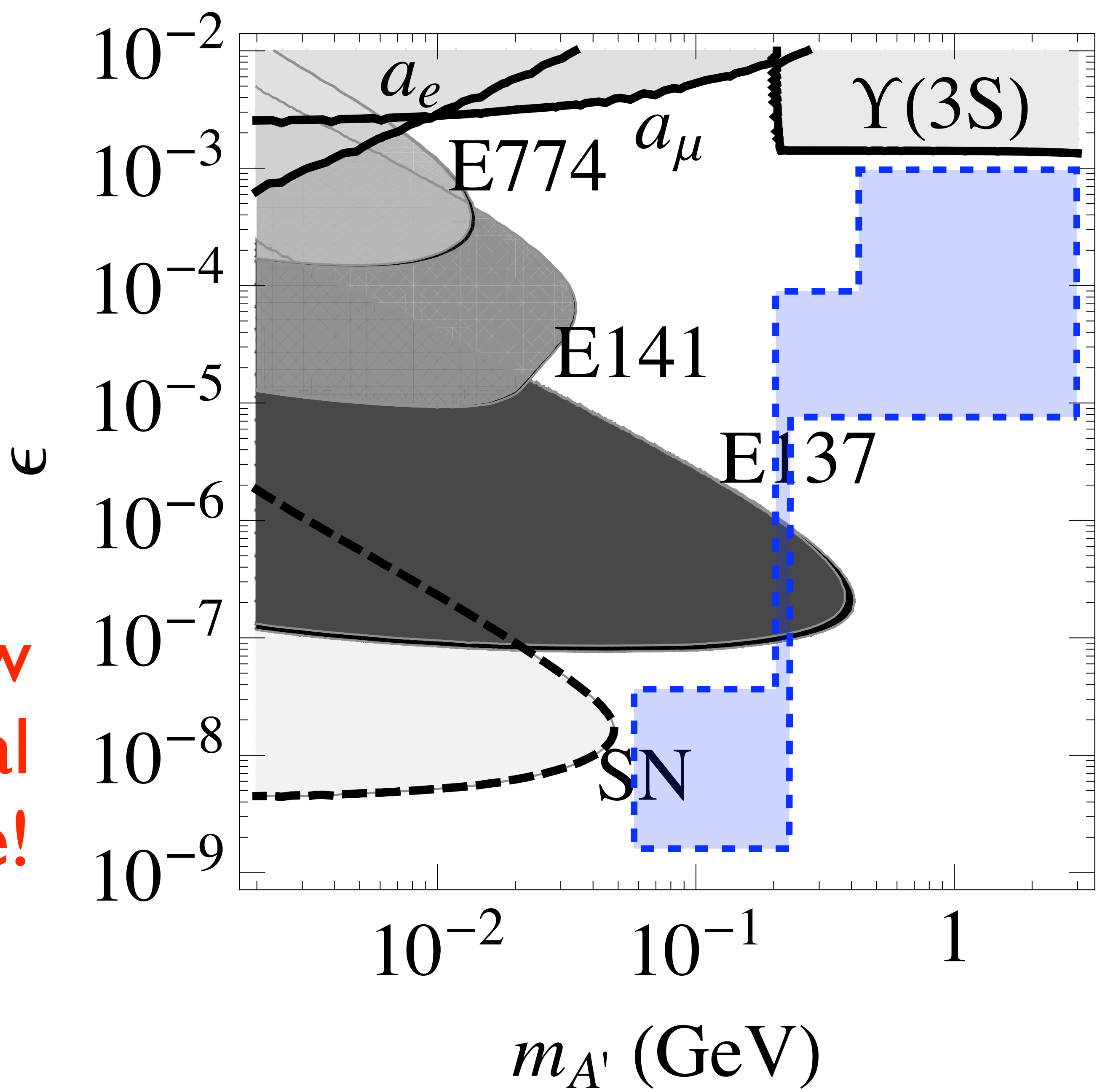


A New Dark Matter Paradigm?

A New Experimental Challenge!

[Bjorken, Essig, Schuster, Toro]

Light Boson Scenarios



A New Dark Matter Paradigm?

My Pet Theories
[Nomura, JDT; Mardon, Nomura, JDT]
(Axion Portal)

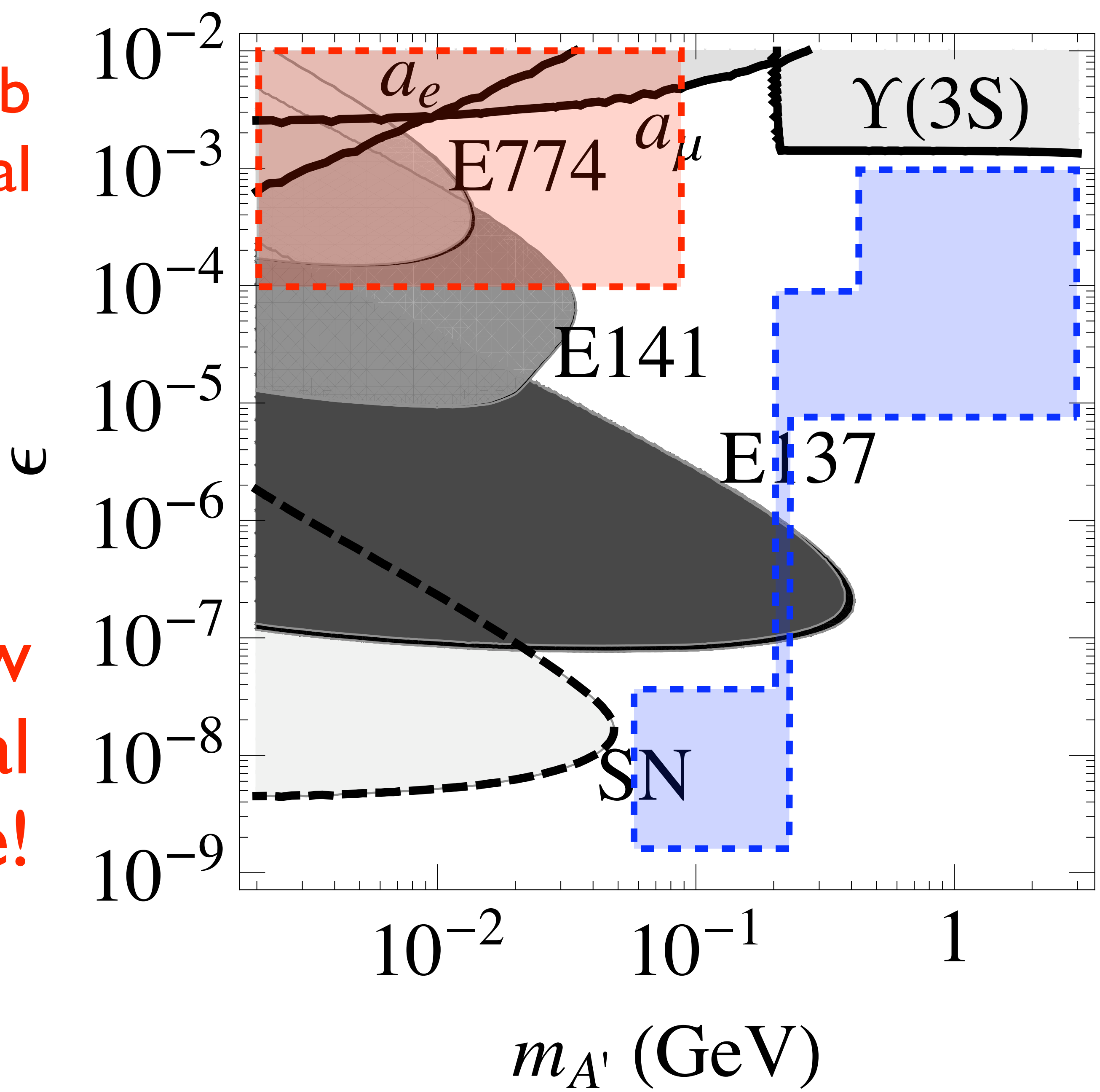
A New Experimental Challenge!

[Bjorken, Essig, Schuster, Toro]

Light Boson Scenarios

Focus of JLab
FEL Proposal

A New
Experimental
Challenge!



A New
Dark Matter
Paradigm?

My Pet Theories
[Nomura, JDT;
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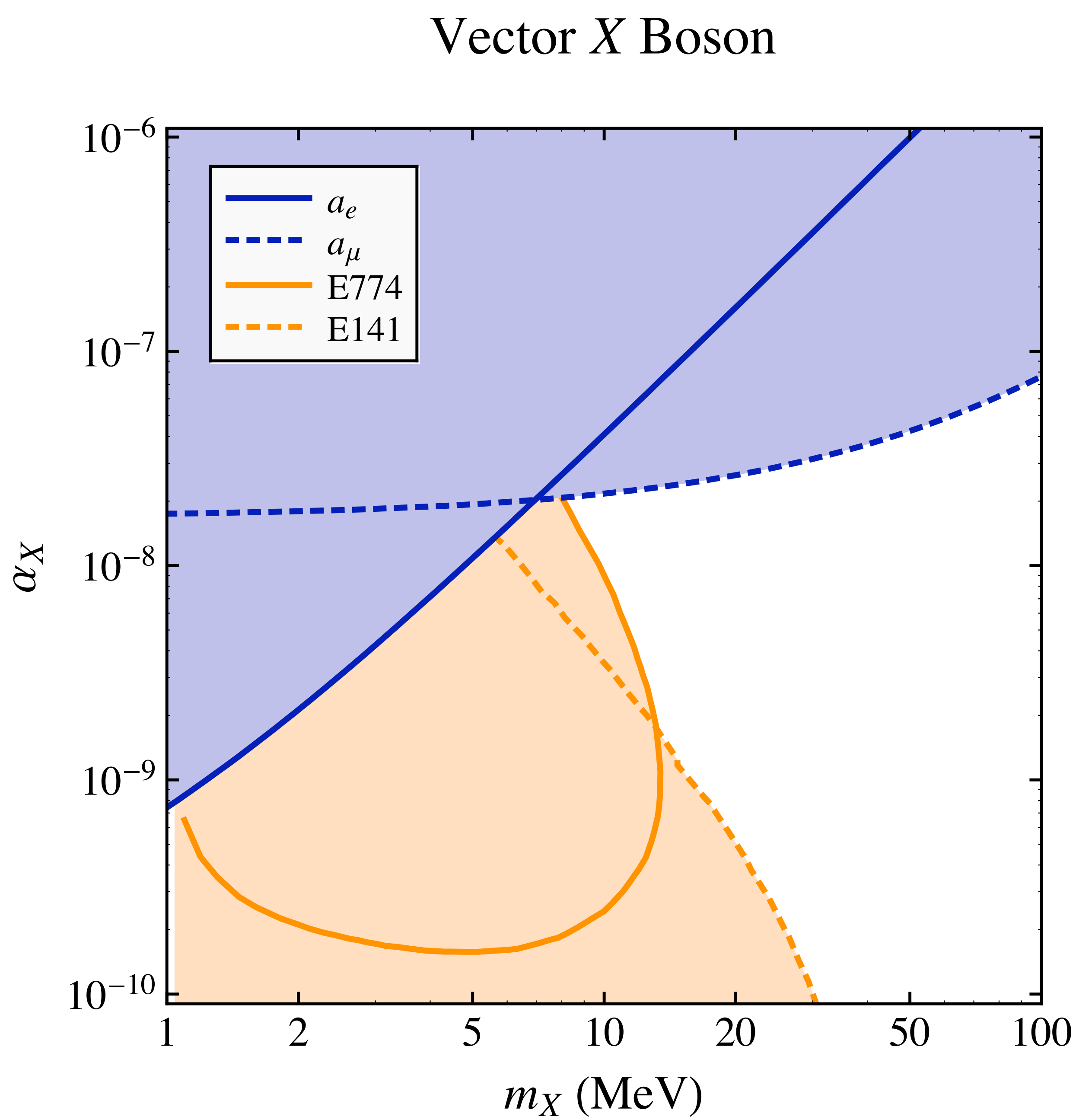
[Bjorken, Essig, Schuster, Toro]

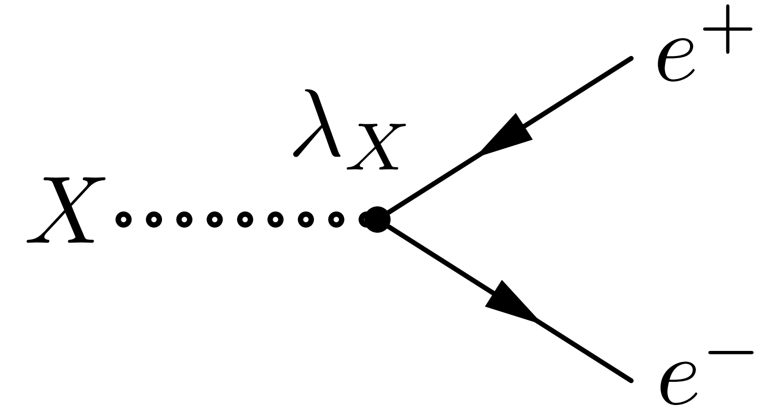
Below the Pion Threshold



$$\alpha_X \equiv \frac{\lambda_X^2}{4\pi}$$

[Freytsis, Ovanesyan, JDT]

What is best experiment to directly produce X boson?



Small Coupling...

$$\sigma_X \lesssim 10^{-4}\sigma_{\rm QED}$$

...but Short Lifetime

$$c\tau \simeq \frac{1}{\alpha_X m_X} \lesssim 10^{-2}\ {\rm cm}$$

(assume only coupling to electrons)

Experimental Design

Lepton Colliders?

$$e^+e^- \rightarrow \gamma + X$$
$$\quad\hookrightarrow e^+e^-$$

+ B-factories have ab^{-1} data sets
+ Full event reconstruction
– Photon conversion for m_X < 50 MeV

Beam Dumps?

$$e^-N \rightarrow e^-N' + X$$
$$\quad\hookrightarrow e^+e^-$$

+ Huge luminosity (ab^{-1}/day)
– No decay mode to penetrating muons
– No visible displaced vertex

Experimental Design

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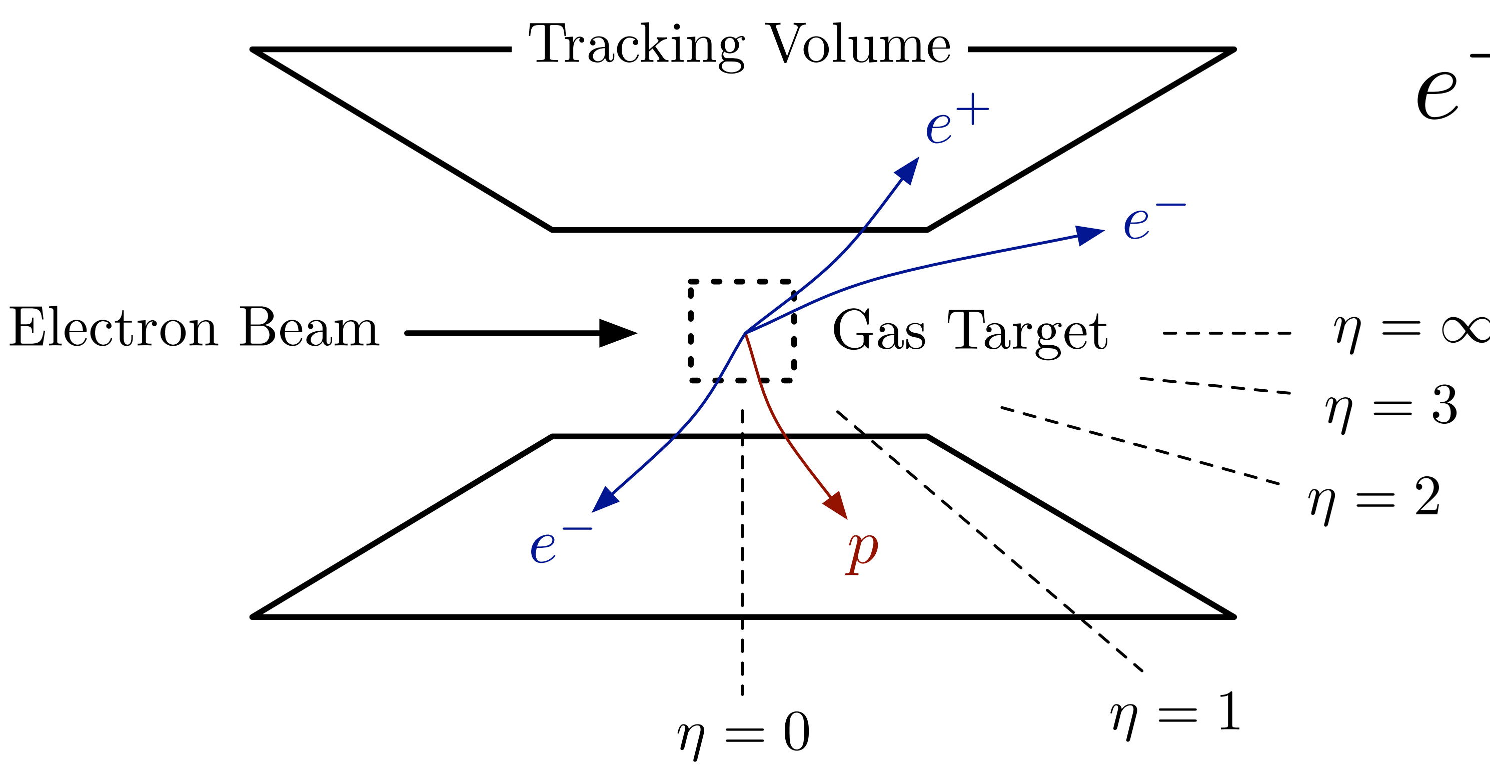
Ideal Experiment

Full Event Reconstruction (to control systematics, energy calibration)
High Luminosity (to beat QED with statistics)
Low Energy (to mitigate photon conversion, pion production)

See, e.g. [Heinemeyer, Kahn, Schmitt, Velasco]

Electron-Proton Collisions

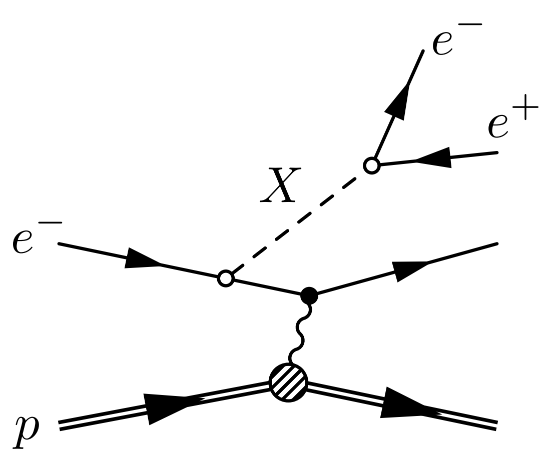


$$e^- p \to e^- p + X$$
$$\hookrightarrow e^+ e^-$$

$$E_{\text{beam}} \lesssim 140\ \text{MeV}$$

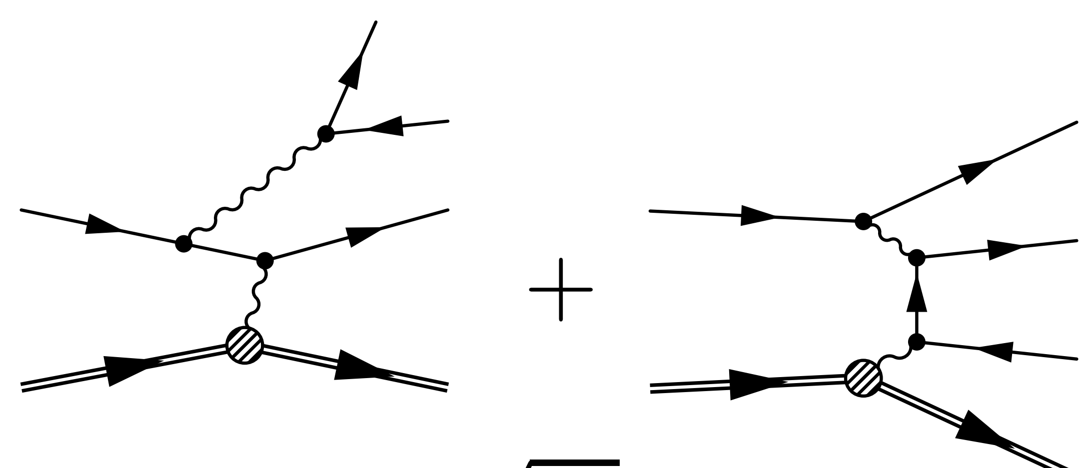
$$\text{ab}^{-1}/\text{month}$$

Narrow Resonance on Huge QED Background



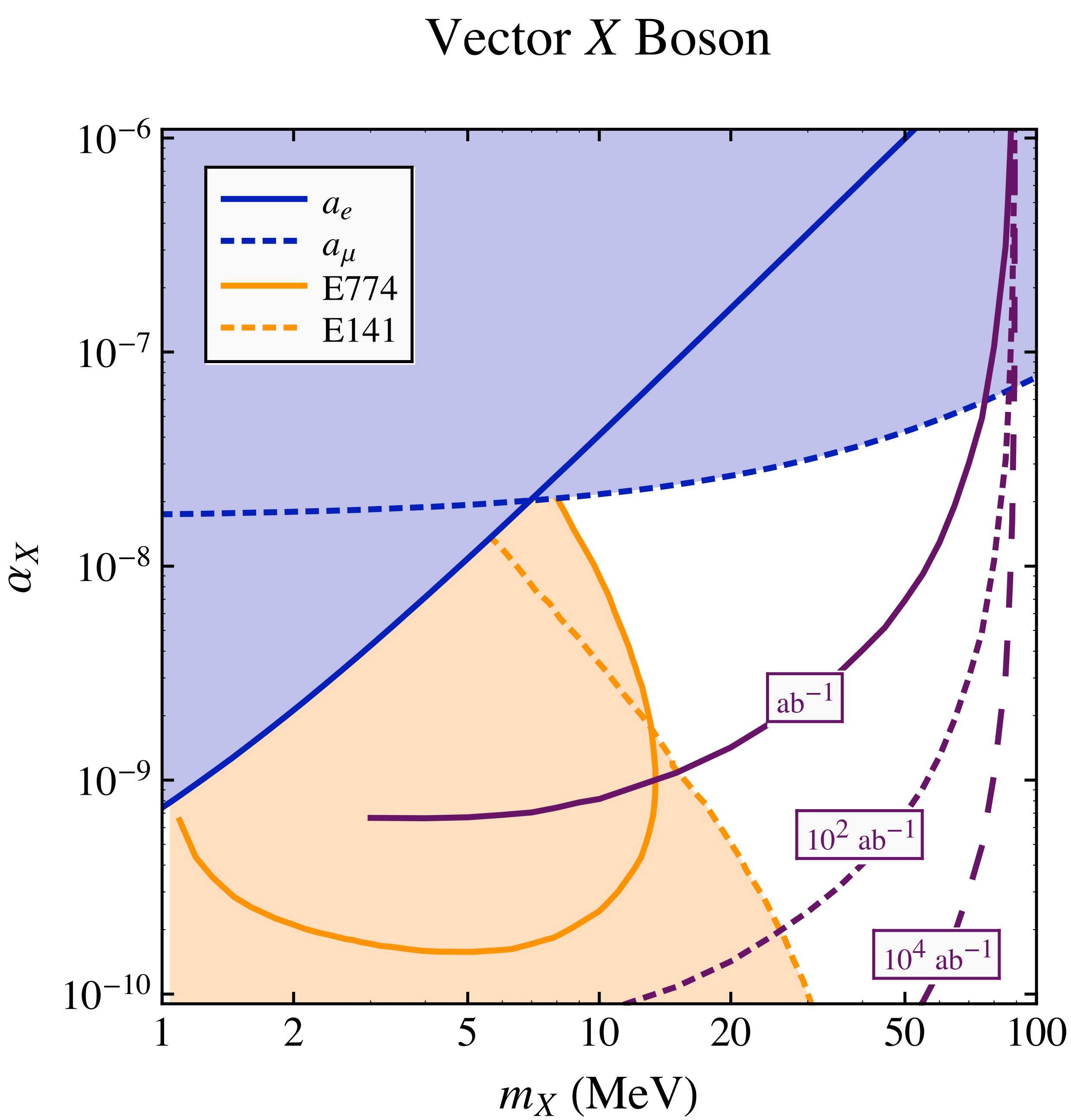
S

vs.



$\sqrt{B}$

Experimental Target



[Freytsis, Ovanesyan, JDT]

$$E_{\text{beam}} = 100 \text{ MeV}$$

Fiducial Cuts

$$-2 < \eta < 2 \quad (15.4^\circ \text{ to beamline})$$

$$\text{KE}_{e^\pm} > 5 \text{ MeV}$$

$$\text{KE}_p > 0.5 \text{ MeV}$$

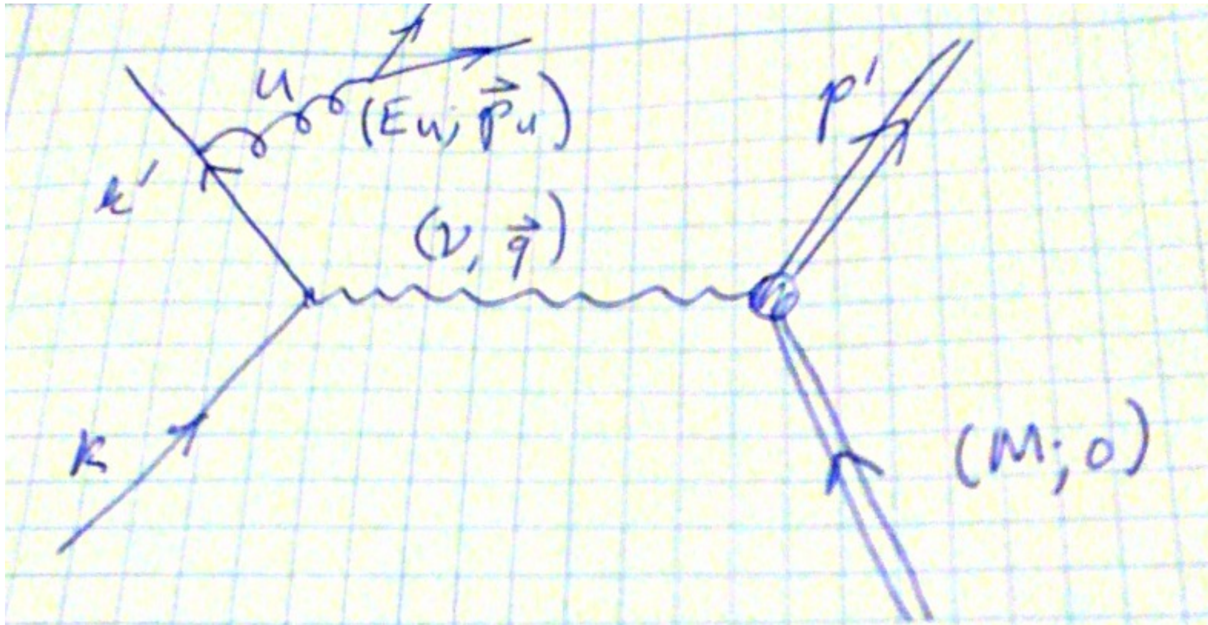
Fiducial Resolution

$$\Delta m(e^+e^-) = 1 \text{ MeV}$$

(Can gain factor of 3 in reach by using Matrix Element Method)

Boson production

U→ e+e- or γ+γ



$$\nu = T_{p'} + E_u$$

$$\vec{q} = \vec{p}\,' + \vec{p}_u$$

$$T_{p'} = \frac{|\vec{p}\,'|^2}{2M} = \frac{|\vec{q} - \vec{p}_u|^2}{2M}$$

Kinematics

- E_0 = 100 MeV, E' ~ 50 MeV, E_U ~ 50 MeV
- Elastic scattering at θ=90^o => Q^2= 0.02$(GeV/c)^2$
- **k**, **k'**, **q** define the electron scattering plane
- $T_{p'}$ ~ 50 x 50 MeV^2 ÷ 2000 MeV ~ 1 MeV

Measurement of energy and direction non-trivial!

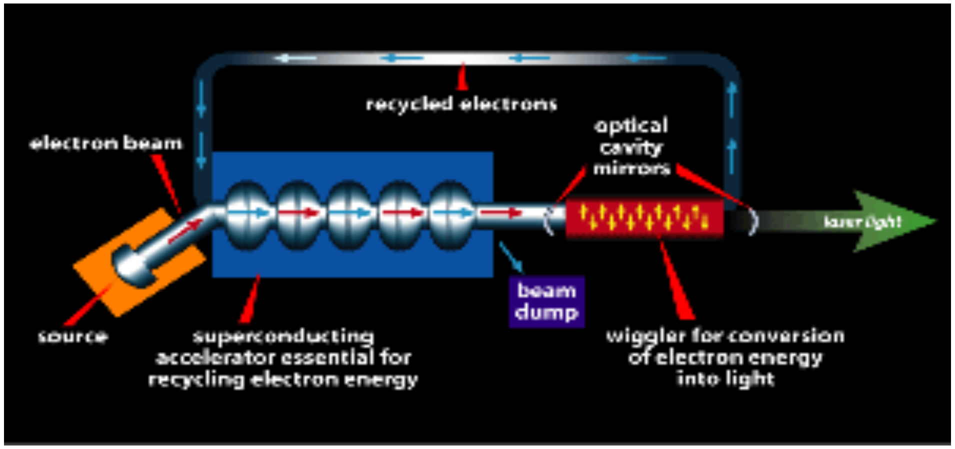
- **q=p'+p$_U$** => out of scattering plane components of **p'** and **p$_U$** must cancel => detection of ~ 1MeV recoil proton track gives direction of U production
- U decays to dileptons or two photons with E_e ~ E_γ ~ 10-20 MeV
- U may have lifetime of up to 0.1 mm so vertex reconstruction may help
- Would also trigger on invisible final states

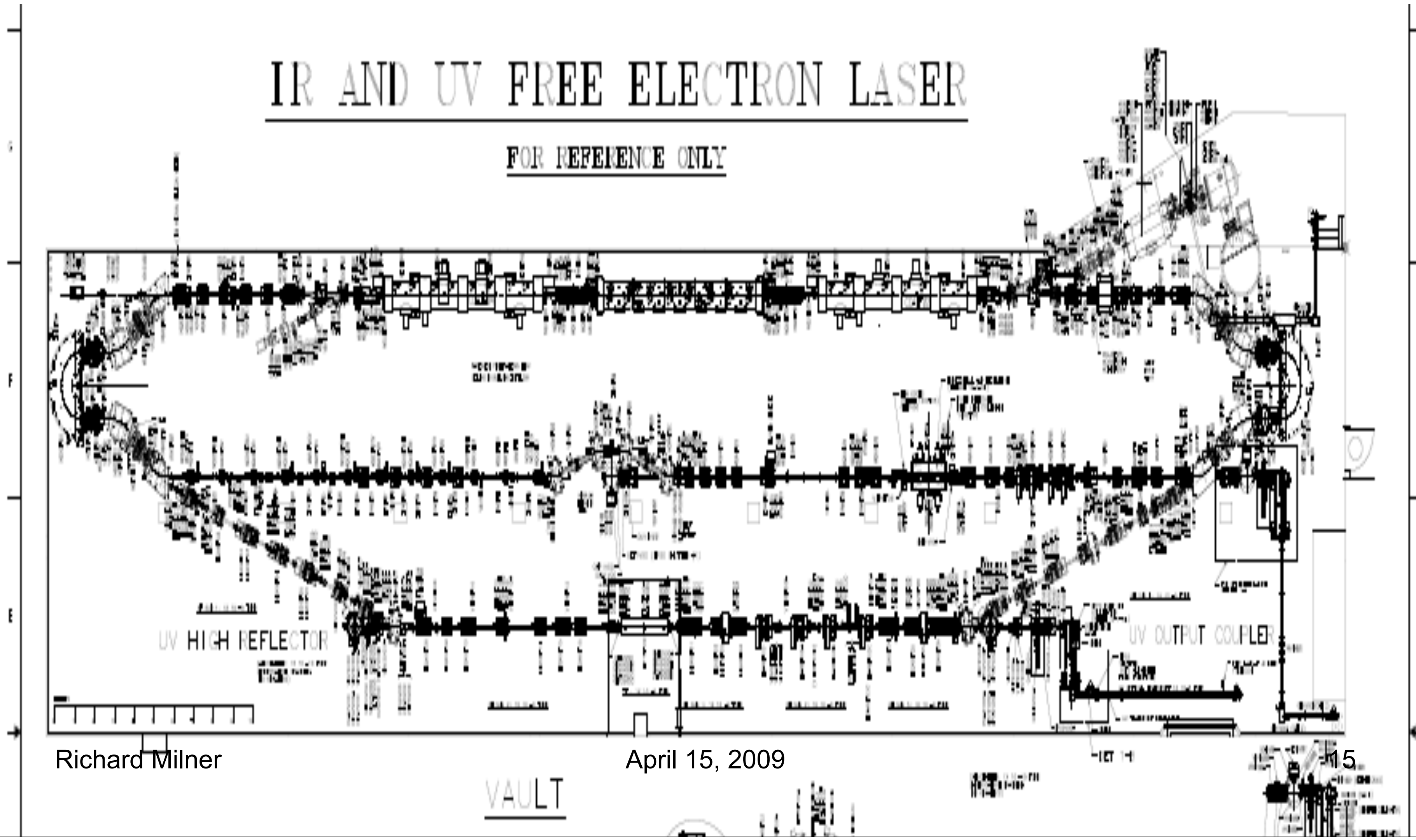
Jefferson Lab FEL Specifications

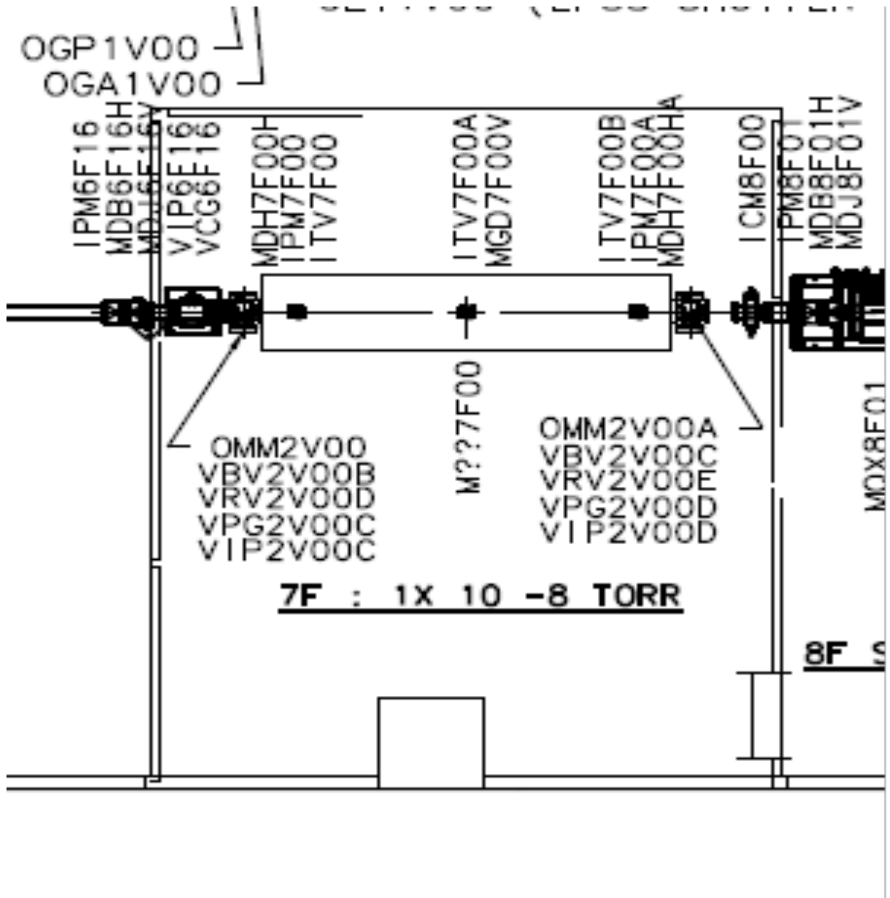
1 MW in beam!

Energy (MeV)	80-200	200
Charge per bunch (pC)	135	135
Average current (mA)	10	5
Peak Current (A)	270	270
Beam Power (kW)	2000	1000
Energy Spread (%)	0.50%	0.13%
Norm.emittance (mm-mrad)	<30	<11

JLab FEL


recycled electrons
electron beam
optical
cavity
mirrors
laser light
beam
dump
source
superconducting
accelerator essential for
recycling electron energy
wiggler for conversion
of electron energy
into light


IR AND UV FREE ELECTRON LASER
FOR REFERENCE ONLY
UV HIGH REFLECTOR
UV OUTPUT COUPLER
VAULT



OGP1V00
OGA1V00
IPM6F16
MDB6F16H
MDJ6F16V
VIP6F16
VCG6F16
MDH7F00H
IPM7F00
ITV7F00
ITV7F00A
MGD7F00V
ITV7F00B
IPM7F00A
MDH7F00HA
ICM8F00
IPM8F01
MDB8F01H
MDJ8F01V
OMM2V00
VBV2V00B
VRV2V00D
VPG2V00C
VIP2V00C
M??7F00
OMM2V00A
VBV2V00C
VRV2V00E
VPG2V00D
VIP2V00D
MQX8F01
7F : 1X 10 -8 TORR

SUPERSONIC GAS JET TARGET FOR GENERATION OF RELATIVISTIC ELECTRONS WITH 12TW-50fs LASER PULSE

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K. Nakajima, KEK, Tsukuba, Ibaraki, 305-0801 Japan
M. Kando, H. Kotaki, JAERI Kansai, 8-1Umemidai Kizu, Souraku, Kyoto, 619-0215 Japan

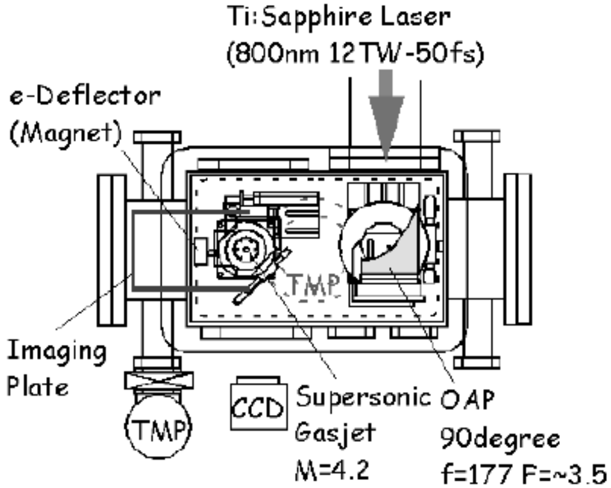

Figure 4: Experimental setup for electron generation with the supersonic gas jet and ultra-short laser pulse.

4 SUMMARY

We have designed the supersonic, rapidly expanding conical *Laval* nozzle using the method of characteristics to make a well-defined gas jet target for the relativistic electron generation experiment. The ultra-short laser pulse was focused on the supersonic helium jet in the gas density range from 7×10^{18} to 3×10^{19} cm^{-3} with the relativistic intensity of approximately 1.5×10^{19} W/cm^2. The energetic electron beams (up to 40MeV) were observed in the forward direction.

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North-Holland Publishing Company

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A SUPERSONIC JET GAS TARGET FOR γ-RAY SPECTROSCOPY MEASUREMENTS *

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Received 10 December 1981

A five-stage differentially pumped and recirculating gas target system of the supersonic jet type has been developed for γ-ray spectroscopy measurements. The features of this jet system are described.

Thickness ~ 3 x 10^{17} atoms/cm^2

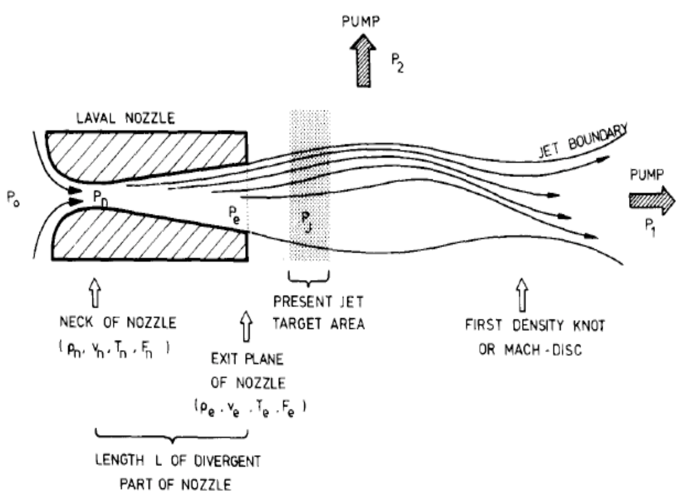
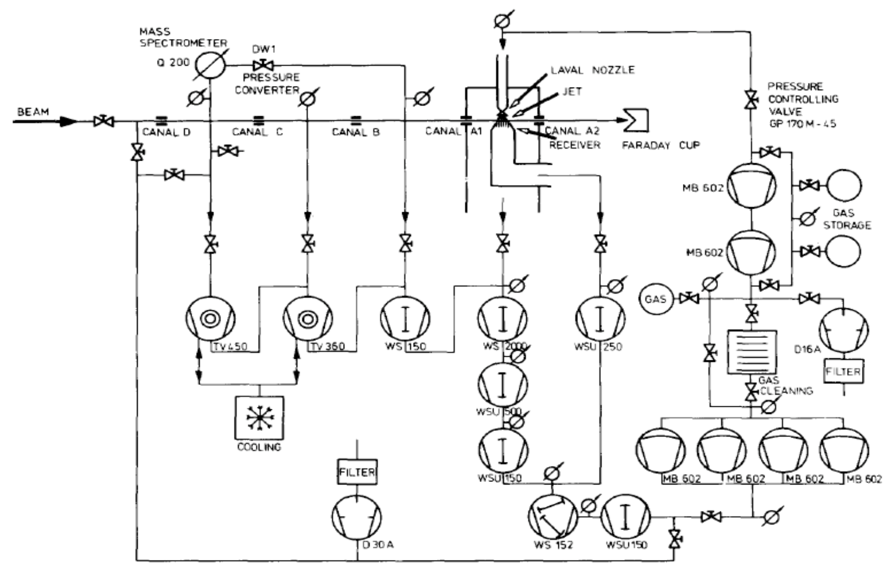
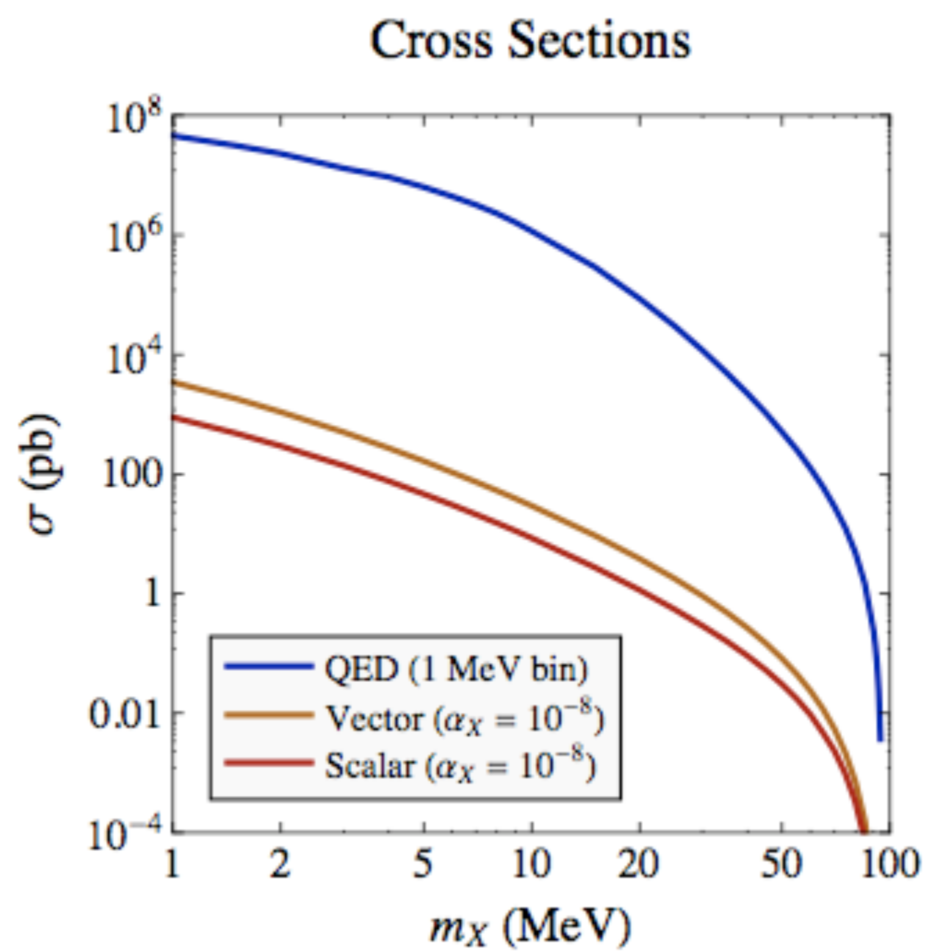


Fig. 1. Schematic presentation of streamlines of an underexpanded axisymmetric free-jet flow produced by a Laval nozzle [4–15]. The gas pressure at various locations in and near the nozzle are labelled with the letter P. Gas dynamical parameters (density ρ, flow velocity v, gas temperature T and cross-section area F) at the neck and exit plane of the nozzle characterize to a large extent the jet properties. In the present work the free-jet zone near the exit of the nozzle has been chosen as the target area.



17 pumps, 2.1 tons!



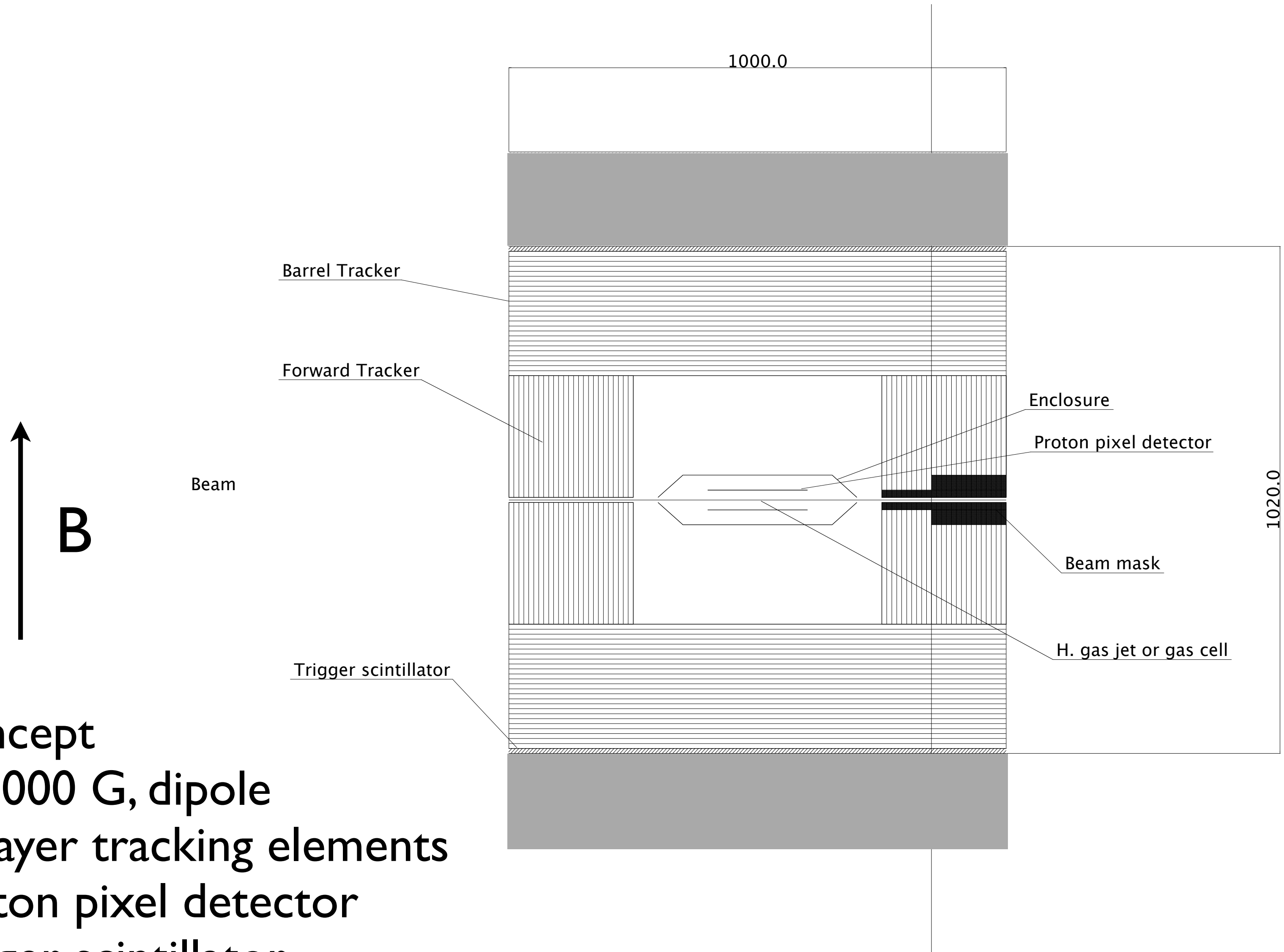
Cross Sections
10^8
10^6
10^4
100
1
0.01
10^{-4}
σ (pb)
1
2
5
10
20
50
100
m_X (MeV)
QED (1 MeV bin)
Vector ($\alpha_X = 10^{-8}$)
Scalar ($\alpha_X = 10^{-8}$)

Possible experiment concept

- FEL beam produces 6 x 10^{16} electrons/sec at 100 MeV onto 10^{19} /cm^2 target:

  luminosity of 6 x 10^{35} $cm^{-2}s^{-1}$
- Rate $\sigma \sim 10^4$ pb => 6 kHz (QED background for m_γ=50 MeV)

  $\sigma \sim 10^{-2}$ pb => 5,200 counts/day (signal for m_U=50 MeV)
- Gas jet target provides pointlike electron-proton interaction
- Target embedded in dipole magnetic field
- Recoil proton detector in same vacuum as target?
- FEL beam traverses both field and target
- Coincident detection of scattered electron and recoil proton as well as dilepton/diphoton final state



Concept
B=3000 G, dipole
25 layer tracking elements
Proton pixel detector
Trigger scintillator
Gas jet target $10^{19}/cm^2$

Tracking

Want $\Delta m \sim 0.1$ MeV ➛ $\sigma_p/p \sim 0.001$:

Single wire resolution of 150 μ

B=3kG

25 cm lever arm

25 samples

Multiple scattering from wires:

25 μ wires on a pitch of 5 mm gives 0.005 per wire

25 wires gives 0.12 for large scattering prob. per lepton

32% of events will contain a lepton that hits a wire

Multiple scattering from gas:

Helium based gas at 1 bar gives 400 μ at E=10 MeV

40 μ at E=100 MeV

Proton detector

Single layer 100 μ pixel detector 5 cm from target

Proton ID:

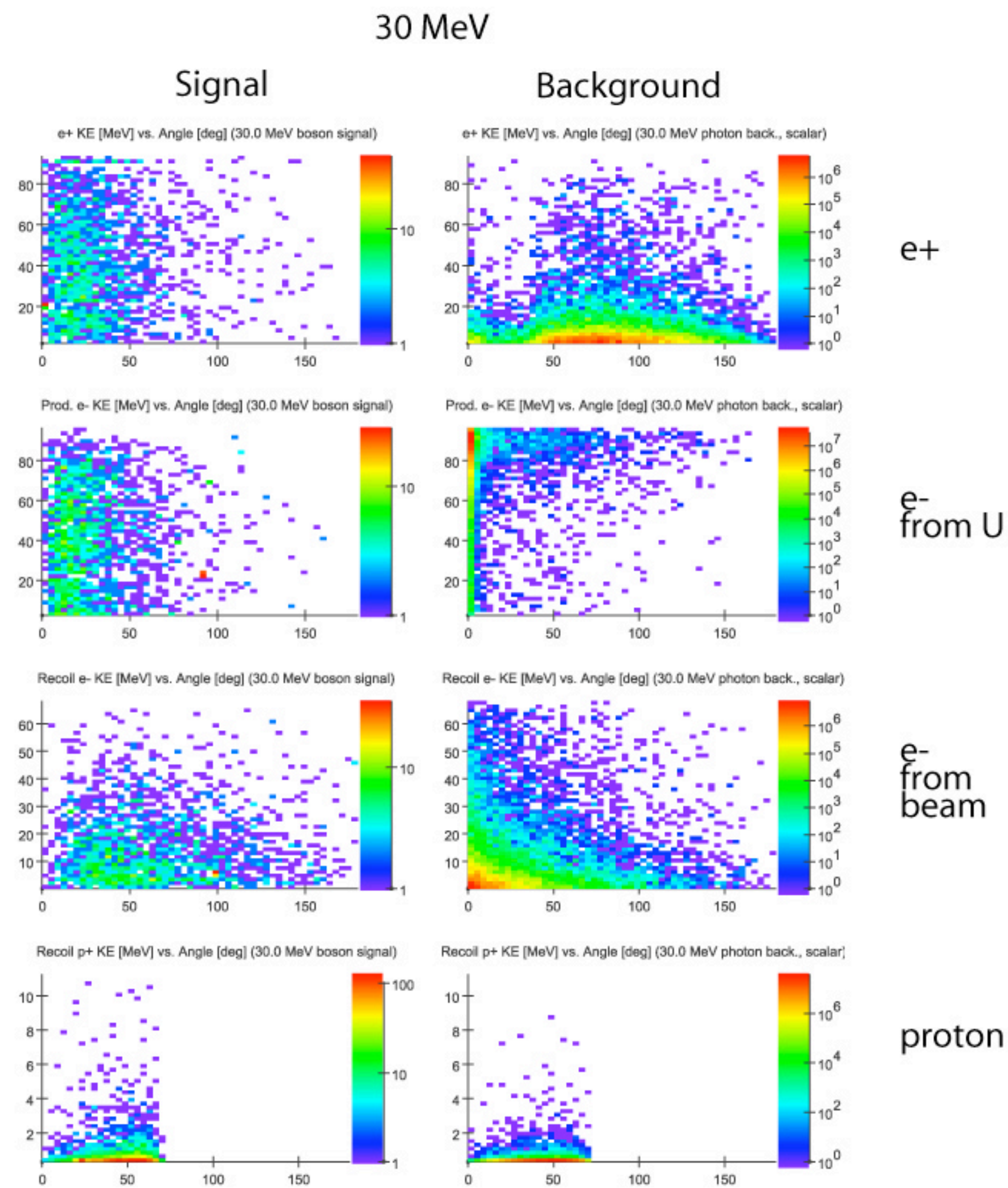
few MeV electron is minimum ionizating, leaving a few keV in the detector

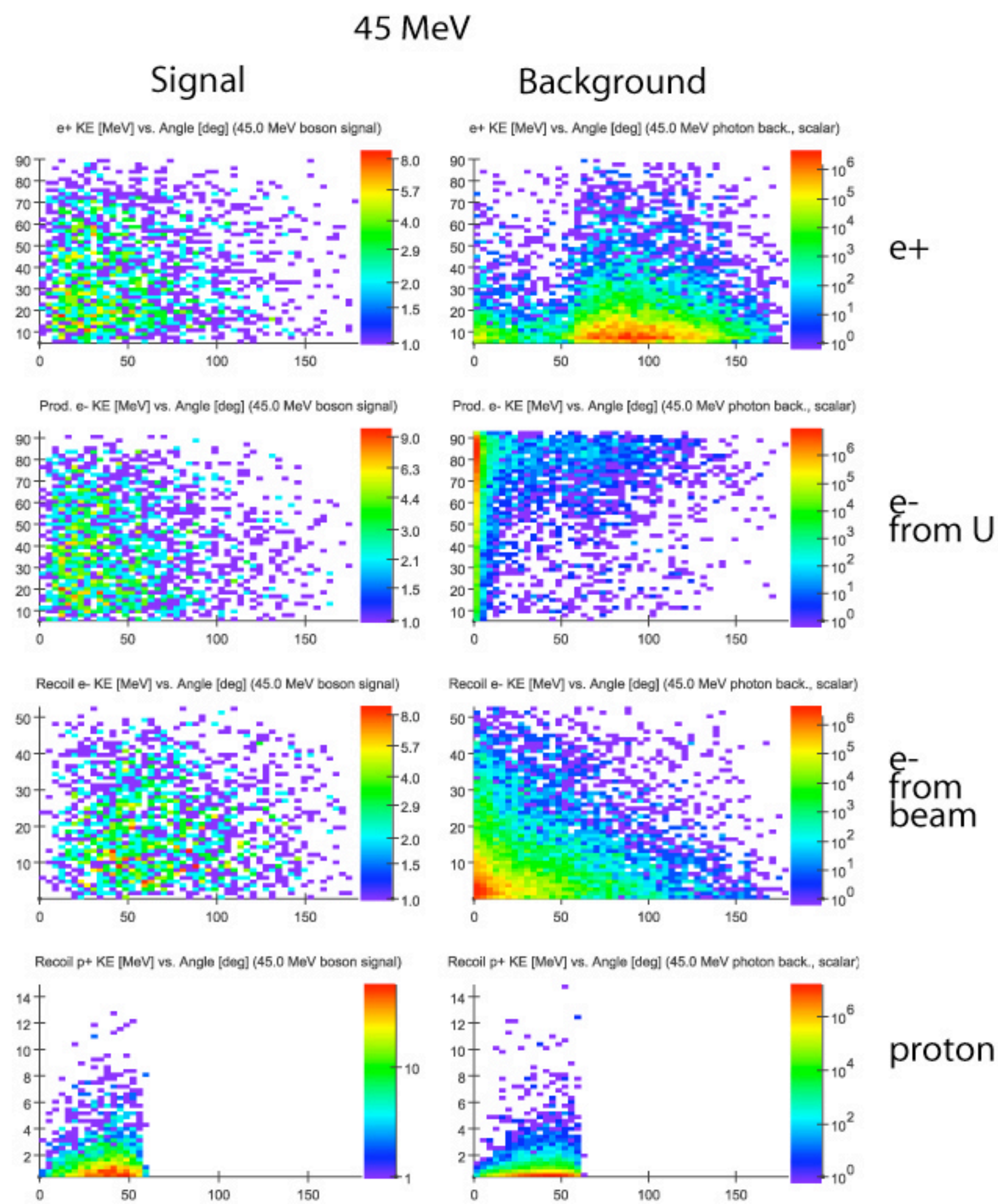
Proton is 0.5-2 MeV, loses all energy in detector

Track measurement:

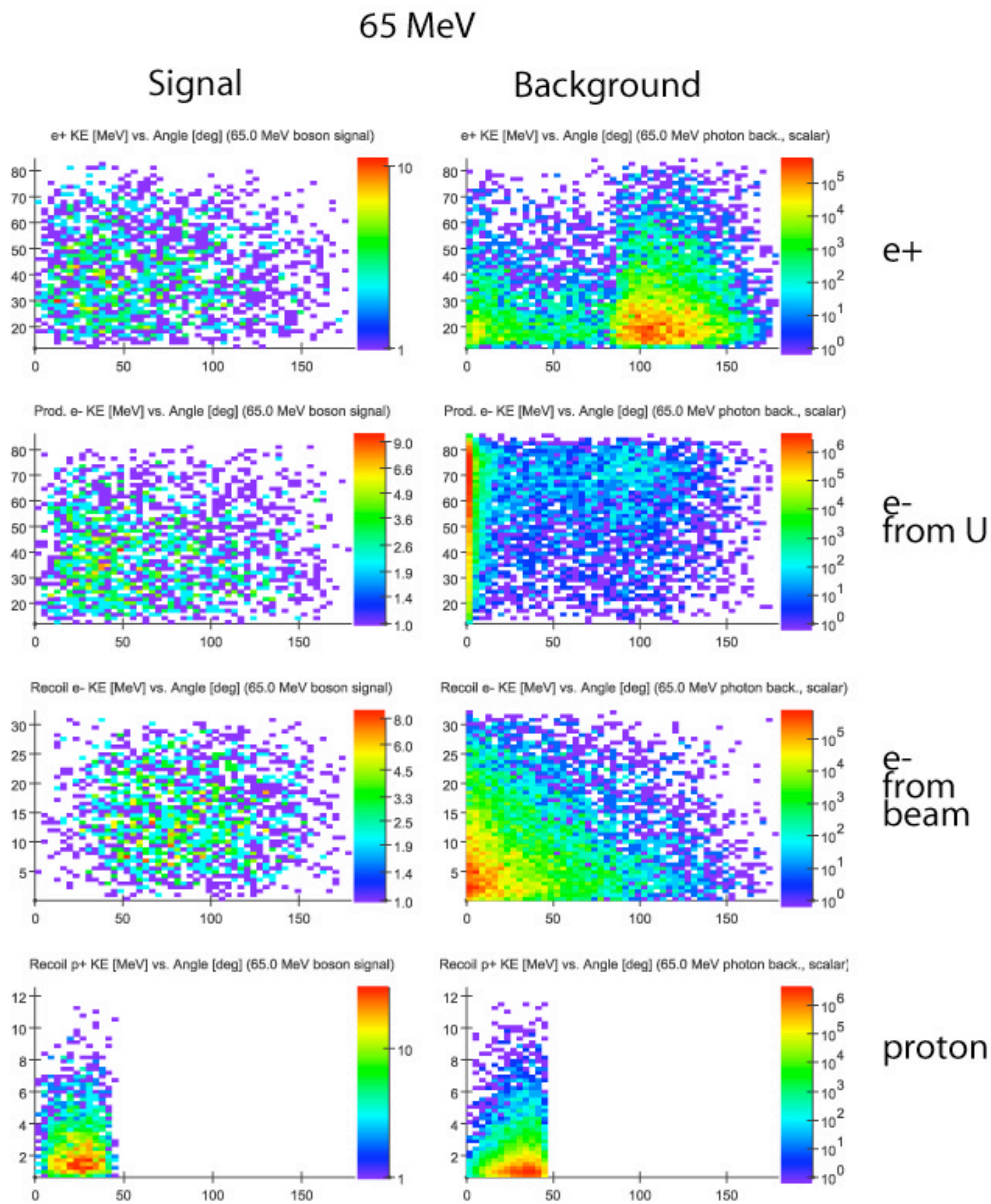
Vertexing using extrapolation of leptons
Connect vertex to pixel cluster
Use measured energy to get momentum three vector

Can it survive in 5 cm from a 1 MW beam and at supersonic gas jet?

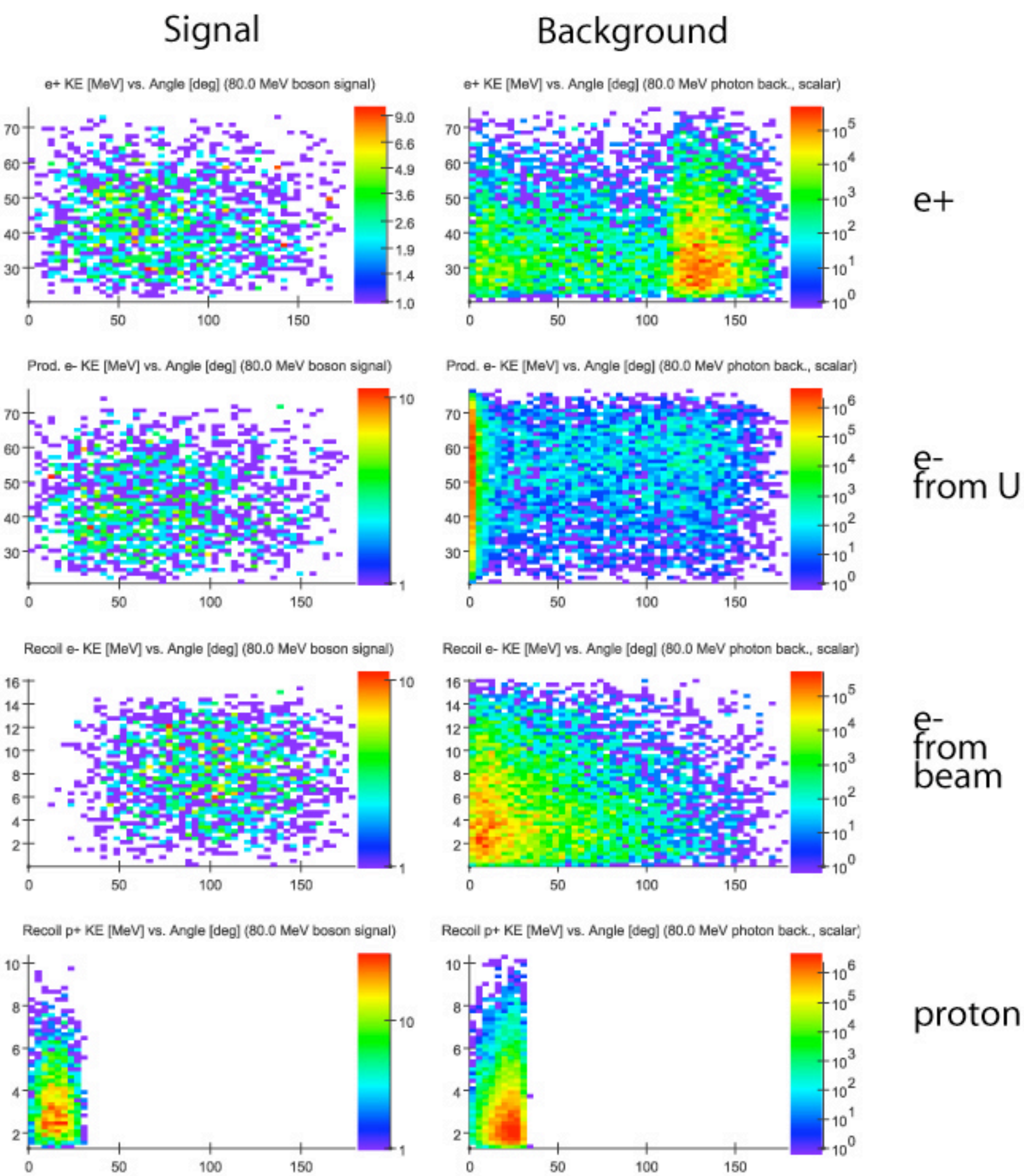

30 MeV
Signal
Background
e+ KE [MeV] vs. Angle [deg] (30.0 MeV boson signal)
e+ KE [MeV] vs. Angle [deg] (30.0 MeV photon back., scalar)
e+
Prod. e- KE [MeV] vs. Angle [deg] (30.0 MeV boson signal)
Prod. e- KE [MeV] vs. Angle [deg] (30.0 MeV photon back., scalar)
e-
from U
Recoil e- KE [MeV] vs. Angle [deg] (30.0 MeV boson signal)
Recoil e- KE [MeV] vs. Angle [deg] (30.0 MeV photon back., scalar)
e-
from
beam
Recoil p+ KE [MeV] vs. Angle [deg] (30.0 MeV boson signal)
Recoil p+ KE [MeV] vs. Angle [deg] (30.0 MeV photon back., scalar)
proton

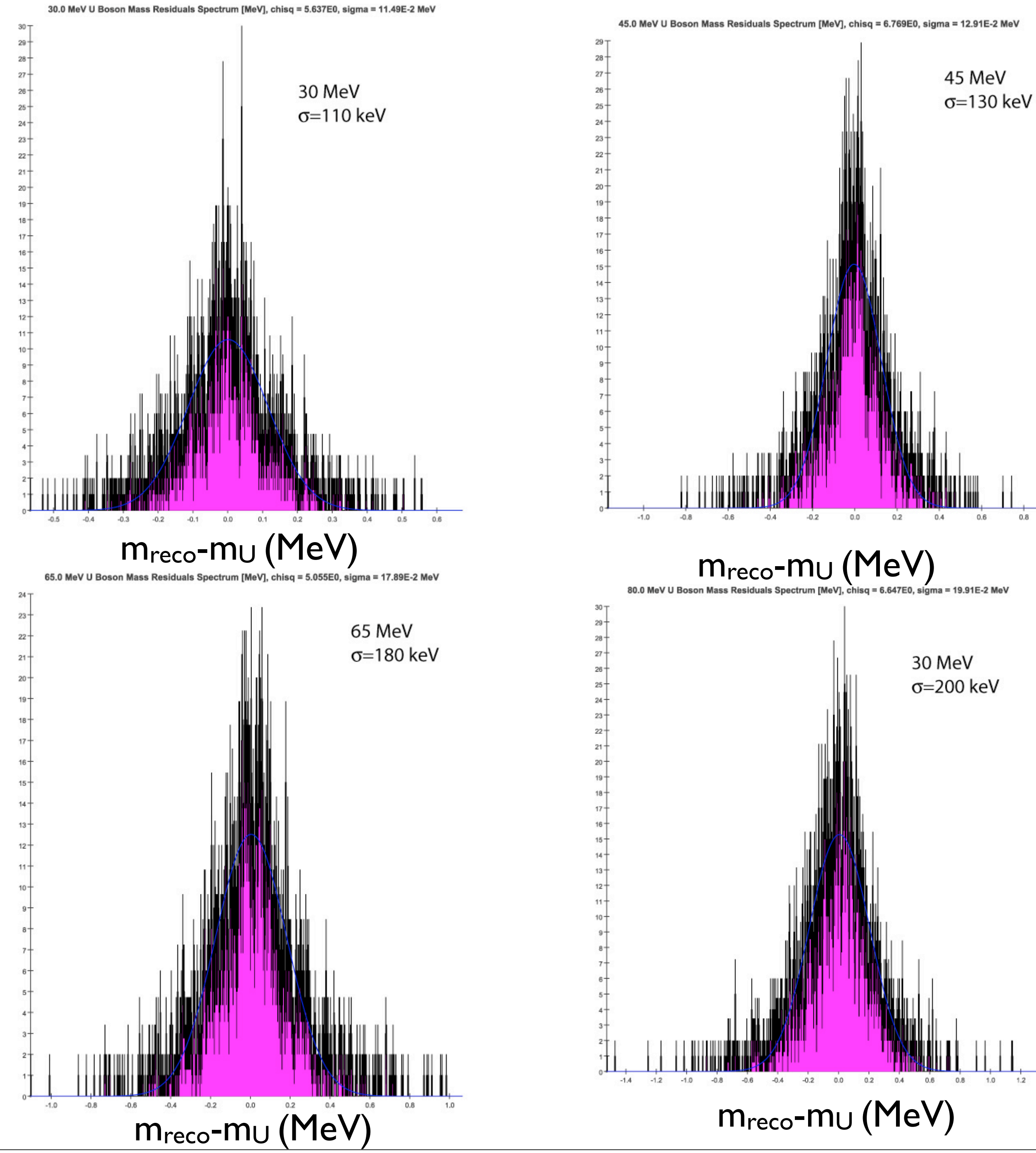


45 MeV
Signal
Background
e+ KE [MeV] vs. Angle [deg] (45.0 MeV boson signal)
e+ KE [MeV] vs. Angle [deg] (45.0 MeV photon back., scalar)
e+
Prod. e- KE [MeV] vs. Angle [deg] (45.0 MeV boson signal)
Prod. e- KE [MeV] vs. Angle [deg] (45.0 MeV photon back., scalar)
e-
from U
Recoil e- KE [MeV] vs. Angle [deg] (45.0 MeV boson signal)
Recoil e- KE [MeV] vs. Angle [deg] (45.0 MeV photon back., scalar)
e-
from
beam
Recoil p+ KE [MeV] vs. Angle [deg] (45.0 MeV boson signal)
Recoil p+ KE [MeV] vs. Angle [deg] (45.0 MeV photon back., scalar)
proton


65 MeV
Signal
Background
e+ KE [MeV] vs. Angle [deg] (65.0 MeV boson signal)
e+ KE [MeV] vs. Angle [deg] (65.0 MeV photon back., scalar)
e+
Prod. e- KE [MeV] vs. Angle [deg] (65.0 MeV boson signal)
Prod. e- KE [MeV] vs. Angle [deg] (65.0 MeV photon back., scalar)
e-
from U
Recoil e- KE [MeV] vs. Angle [deg] (65.0 MeV boson signal)
Recoil e- KE [MeV] vs. Angle [deg] (65.0 MeV photon back., scalar)
e-
from
beam
Recoil p+ KE [MeV] vs. Angle [deg] (65.0 MeV boson signal)
Recoil p+ KE [MeV] vs. Angle [deg] (65.0 MeV photon back., scalar)
proton

80 MeV


Signal
Background
e+ KE [MeV] vs. Angle [deg] (80.0 MeV boson signal)
e+ KE [MeV] vs. Angle [deg] (80.0 MeV photon back., scalar)
e+
Prod. e- KE [MeV] vs. Angle [deg] (80.0 MeV boson signal)
Prod. e- KE [MeV] vs. Angle [deg] (80.0 MeV photon back., scalar)
e-
from U
Recoil e- KE [MeV] vs. Angle [deg] (80.0 MeV boson signal)
Recoil e- KE [MeV] vs. Angle [deg] (80.0 MeV photon back., scalar)
e-
from
beam
Recoil p+ KE [MeV] vs. Angle [deg] (80.0 MeV boson signal)
Recoil p+ KE [MeV] vs. Angle [deg] (80.0 MeV photon back., scalar)
proton


30.0 MeV U Boson Mass Residuals Spectrum [MeV], chisq = 5.637E0, sigma = 11.49E-2 MeV
30 MeV
σ=110 keV
m_reco-m_U (MeV)
45.0 MeV U Boson Mass Residuals Spectrum [MeV], chisq = 6.769E0, sigma = 12.91E-2 MeV
45 MeV
σ=130 keV
m_reco-m_U (MeV)
65.0 MeV U Boson Mass Residuals Spectrum [MeV], chisq = 5.055E0, sigma = 17.89E-2 MeV
65 MeV
σ=180 keV
m_reco-m_U (MeV)
80.0 MeV U Boson Mass Residuals Spectrum [MeV], chisq = 6.647E0, sigma = 19.91E-2 MeV
30 MeV
σ=200 keV
m_reco-m_U (MeV)

Efficiency

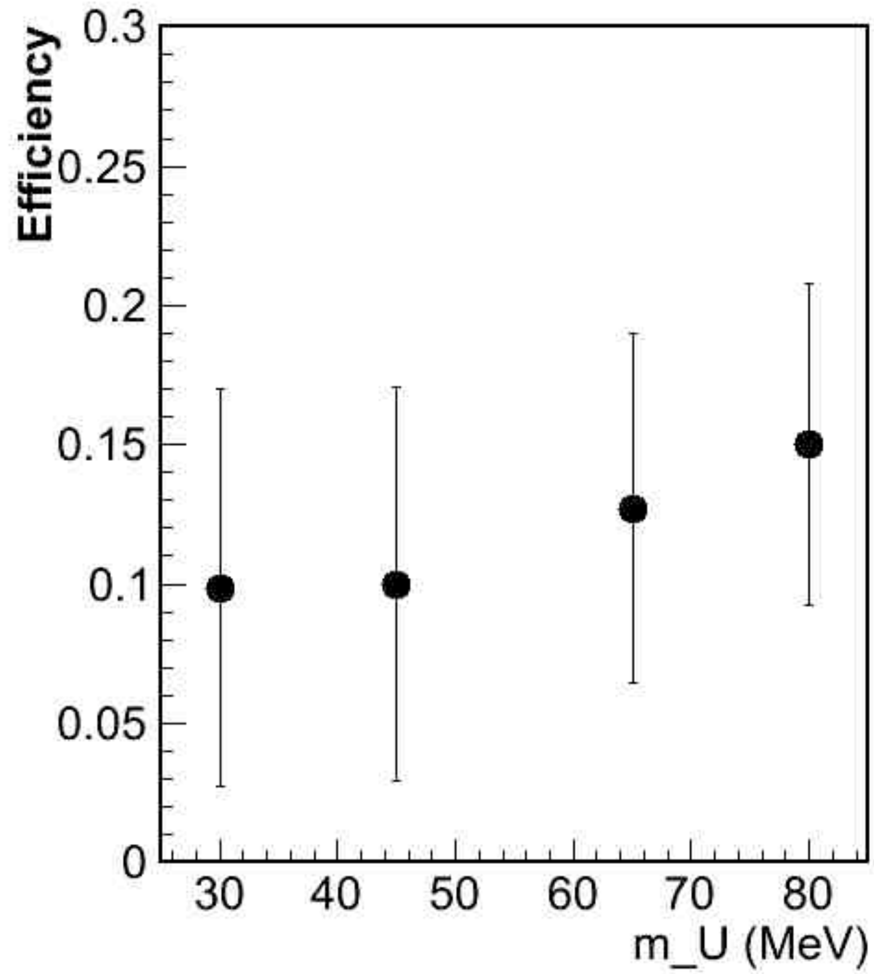
Cuts to reduce background by 10^4

Proton energy 0.9-4 MeV

Proton in acceptance

Leptons in acceptance, KE>0.5 MeV

Signal efficiency 10-15%



Questions

HUGE rate from QED scattering!

Survivability of everything in 1 MW beam?

Is proton detector sufficient to fully reconstruct event?

Is calorimetry needed for particle ID?

Track measurement:
- Drift velocity in a very high rate environment (pileup)
- Multiple scattering in gas enclosure and support elements

Status

We have made an initial presentation to JLab

We are planning to submit a more detailed LOI to JLab in the coming months

We are developing a full detector design