Proposal to Search for a "Dark-Omega" Vector Boson in Direct Electroproduction Processes Using Intense High Energy Electron Beams

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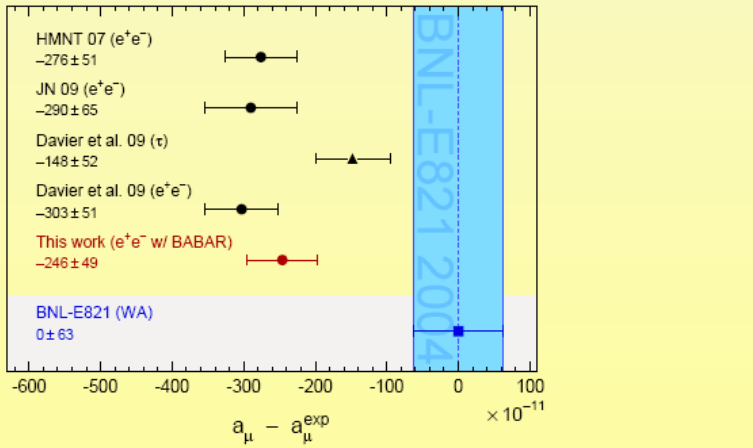
Outline

- Physics motivation, new GeV scale vector bosons
- Proposed experimental method
- Existing experimental apparatus to use
- Expected sensitivity of the proposed experiment
- Summary and outlook

Recent Motivations for New States (new forces below GeV)

- Theoretical motivations to look for an extra U(1) gauge group;
- New results from astrophysical observations (511 KeV line, PAMELA e^+ rise, …);
- More than a decade old discrepancy of the muon $(g\text{-}2)_\mu$
- Proton radius puzzle: ~8σ discrepancy of the muonic hydrogen Lamb shift;
- Long-standing puzzles in neutrino experiments (LSND, MiniBooNe, …)
- …



✱ Davier et al. arXiv:0906-5443

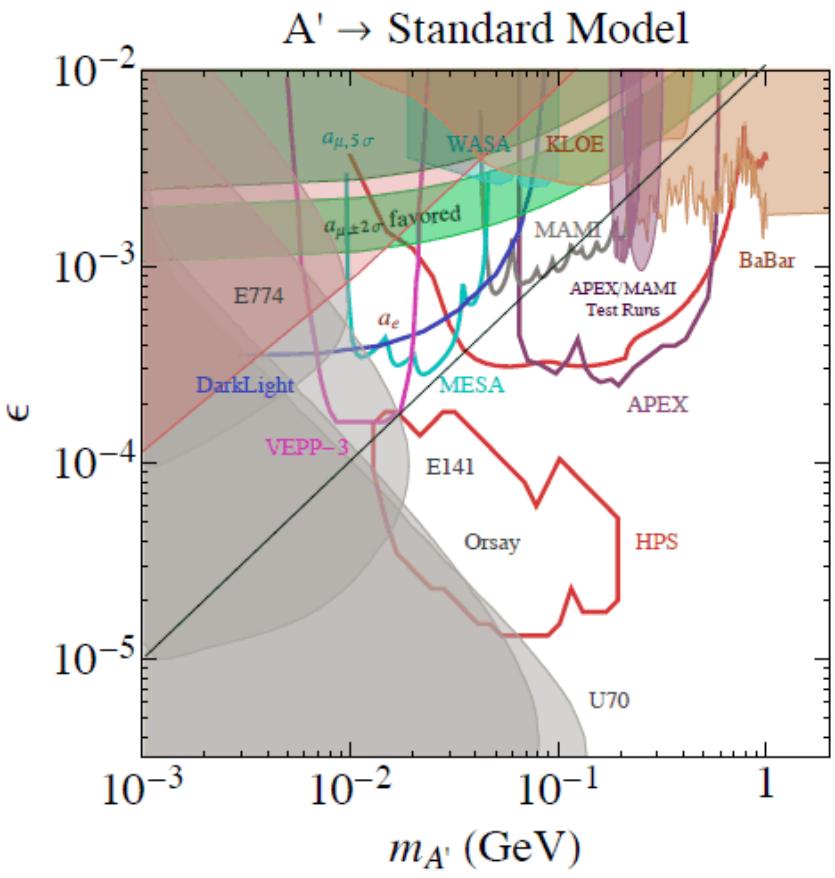
- ✓ More than 3σ discrepancy for most of the analyses
  - ➢ Possibly a sign of new physics; sub-GeV scale vector/scalars models (M. Pospelov, Krasnikov, Gninenko; Fayet, …)

Dark Photon Models (Search) with Mass Under 1 GeV (new gauge vector particle coupled with leptons)

- The “dark photon”, or A’ couples to SM via the kinetic mixing with the ordinary photon

$$\mathcal{L} = -\frac{1}{2}\varepsilon F^{\mu\nu} F'_{\mu\nu}.$$

ε is the kinetic mixing parameter



- A good opportunity for accelerator-based High-intensity experiments (MAINZ, MESA, HPS, APEX,…)

Baryonic Vector Models with Mass Under 1 GeV ("dark omega", V_B, …)

- New gauge field (B_μ) coupling primarily to baryon number (quarks):
  The interaction Lagrangian:

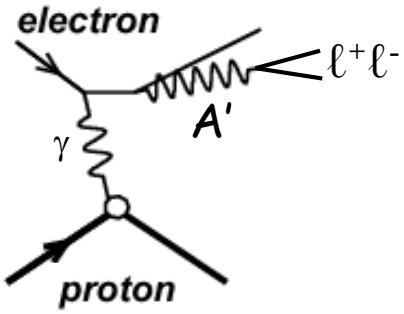
$$\frac{1}{3} g_B \bar{q} g^n q B_m$$

or in more general:

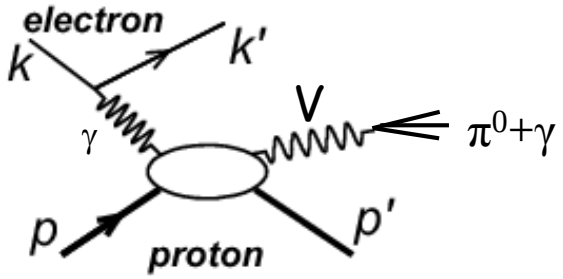
$$\mathcal{L}| = \mathcal{L}_\chi - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 - \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu} + g_B V_\mu J_B^\mu$$

$$J_B^\mu \equiv \tfrac{1}{3} \textstyle\sum_i \bar{q}_i \gamma^\mu q_i$$

- If mixing parameter (kappa) is small, this new vector state is an isospin singlet, like ordinary ω meson, "dark omega" with quantum numbers: $J^{PC} = 1^{--}$
  T.D. Lee and C.N. Yang, S. Tulin, M. Pospelov, …

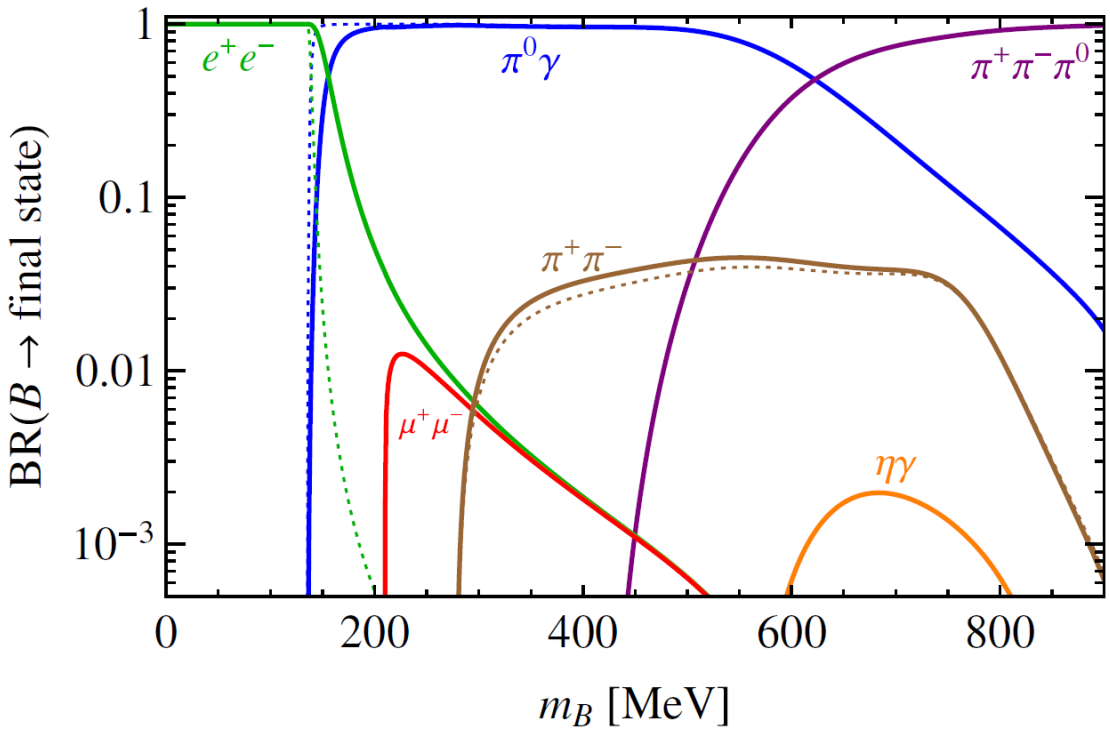


Dark Photon, A'



Dark Omega, V_B

Main Decay Modes of "Dark Omega"



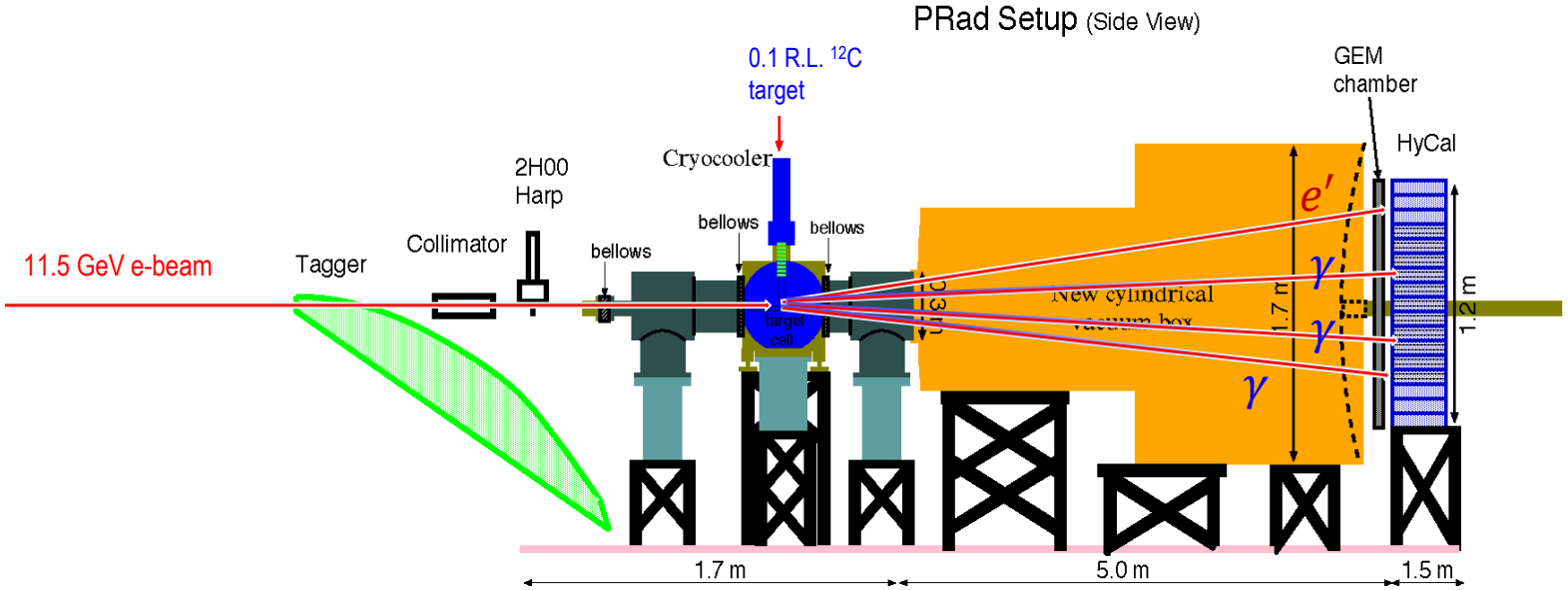
S. Tulin (2014)

- This new particle V_B will mix with existing vector mesons.
- below m_π the leading decay is $V_B \to e^+e^-$, like dark photon
- for $m_\pi < m_{VB} < 620$ MeV the leading decay is $V_B \to \pi^0+\gamma$
- for $620 < m_{VB} < 1000$ MeV, $V_B \to \pi^+ + \pi^- + \pi^0$

The Proposed Experiment:
Search for Hidden Sector V_B Boson in Direct Production Channels

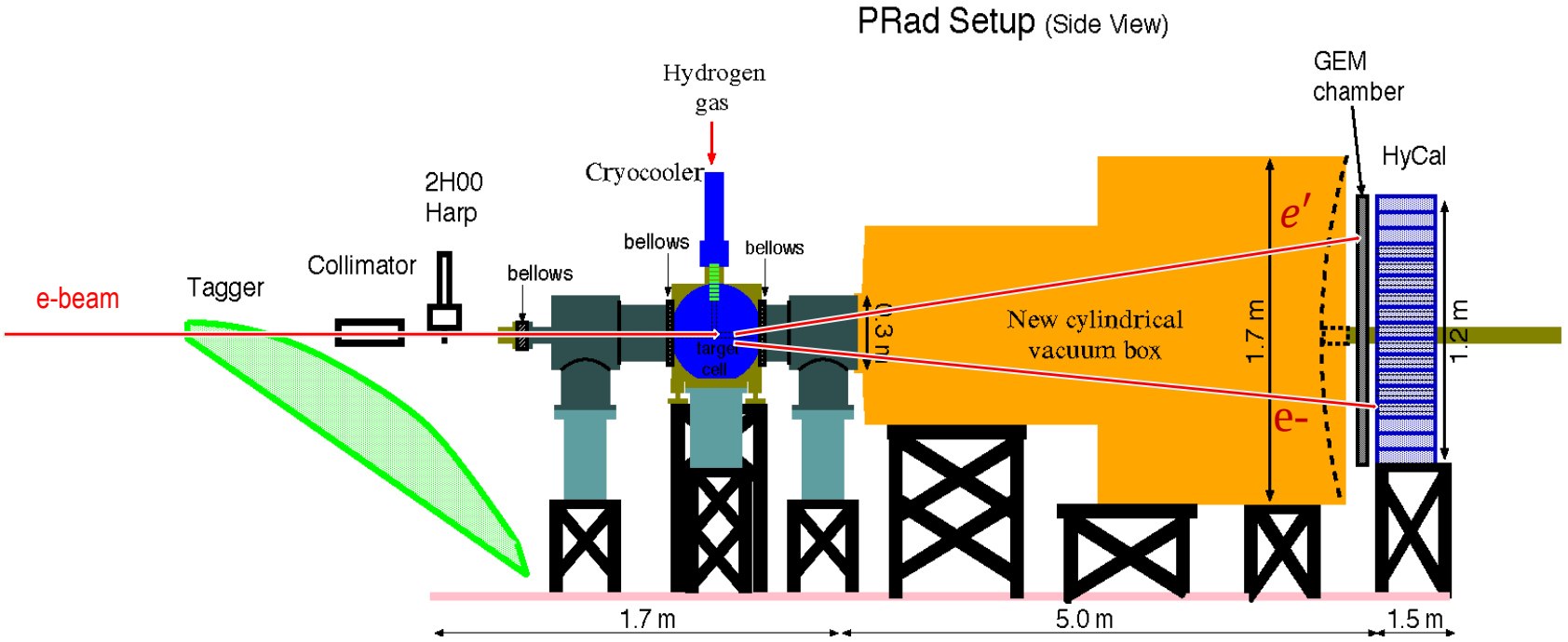
$$e^- + {}^{12}C \rightarrow V_B + X$$
$$\downarrow\rightarrow \pi^0 + \gamma \rightarrow \gamma + \gamma + \gamma$$

Beam: 11.5 GeV electron beam in Hall B at Jlab
Target: 0.1 - 0.3% R.L. ^{12}C



- It is suggested to run with the "π^0 Transition Form Factor Measurement at Very Low Q^2 Range, (PrimEx-IV)"
- Kind of a "by-product" experiment, (more chances to run!)

Proton Radius Experiment in Hall B at JLab (PRad)
(a very short update of the current status)



Basic advantages:

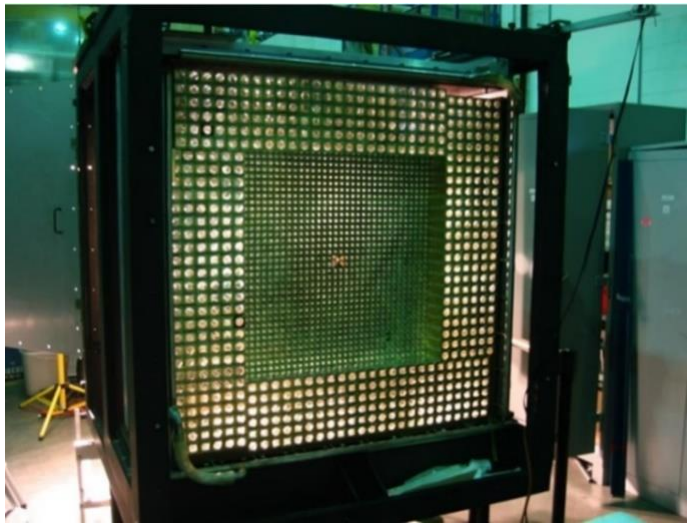
- ✓ non-magnetic (calorimetric) ep-scattering experiment;
- ✓ large acceptance GEM detectors for accurate position measurement;
- ✓ will reach to very low Q^2 range (2×10^{-4} – 3×10^{-2} $(GeV/c)^2$ for the first time;
- ✓ Windowless gas-flow H2 target to minimize the backgraond;
- ✓ Normalize ep-cross section to a well known QED process (Moller scat. on atomic e^-)

Current status of the PRad Apparatus: HyCal EM Calorimeter

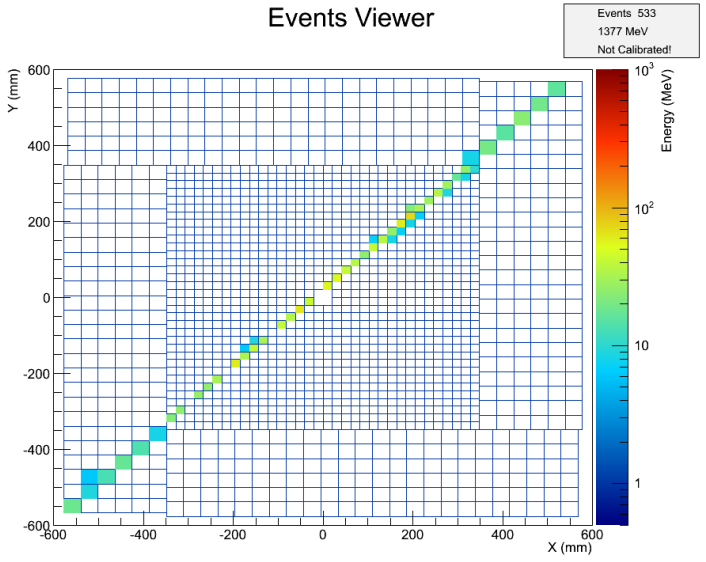
PrimEx HyCal EM calorimeter at JLab:

(118x118 cm^2 hybrid $PbWO_4$ + Pb-glass)

- ✓ refurbished and reinstalled in Hall B beam line.

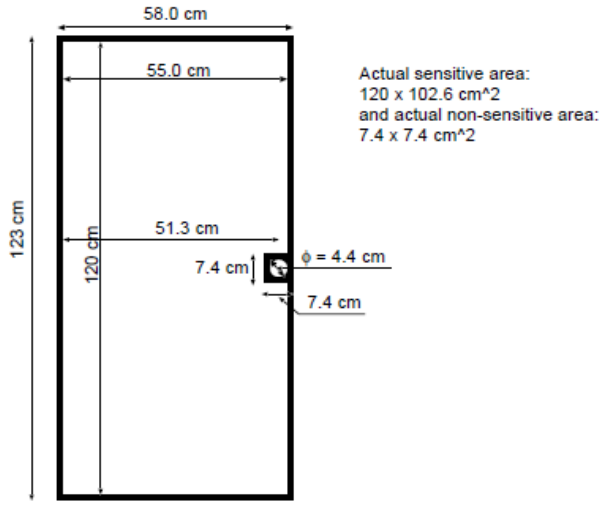


- ✓ Cosmic ray tests done in 2014

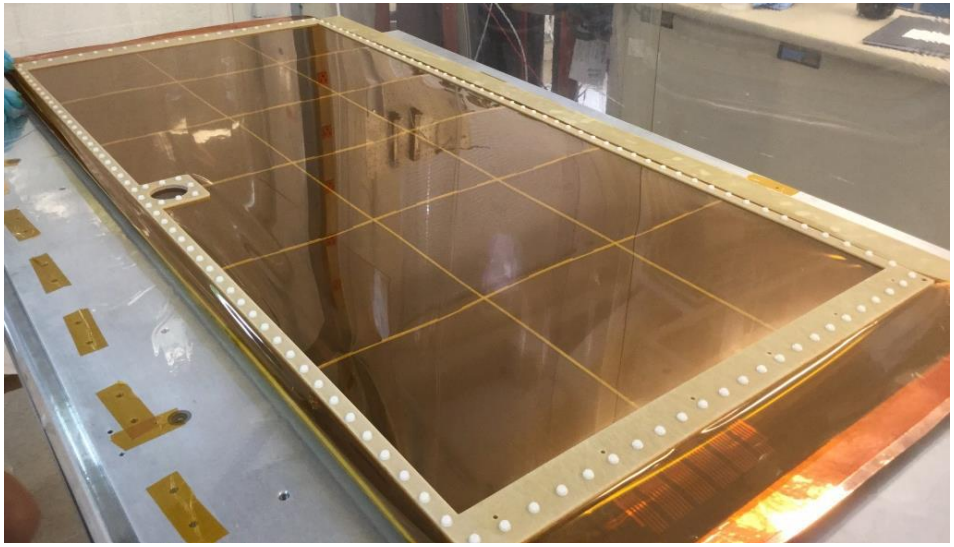


Current status of the PRad Apparatus: GEM Chambers

Desired Sensitive area: 116.4 x 116.4 cm^2
central hole: diameter 4.4 cm, including the frame max allowed
maximum allowable non-sensitive region 7.8 x 7.8 cm^2



Actual sensitive area:
120 x 102.6 cm^2
and actual non-sensitive area:
7.4 x 7.4 cm^2



- ✓ The first GEM chamber is completed at UVa
  - all post-construction tests are done
  - cosmic ray tests are underway
- ✓ The second chamber is planned for July/August

Current status of the PRad Apparatus: Target Chamber

- ✓ Windowless gas-flow H2 target (~10^{18} atoms/cm^2 at 25 K)
  - removes background from target windows (typical for all previous experiments);
  - has capability for solid targets (like ^{12}C, …)
- ✓ Ready for installation

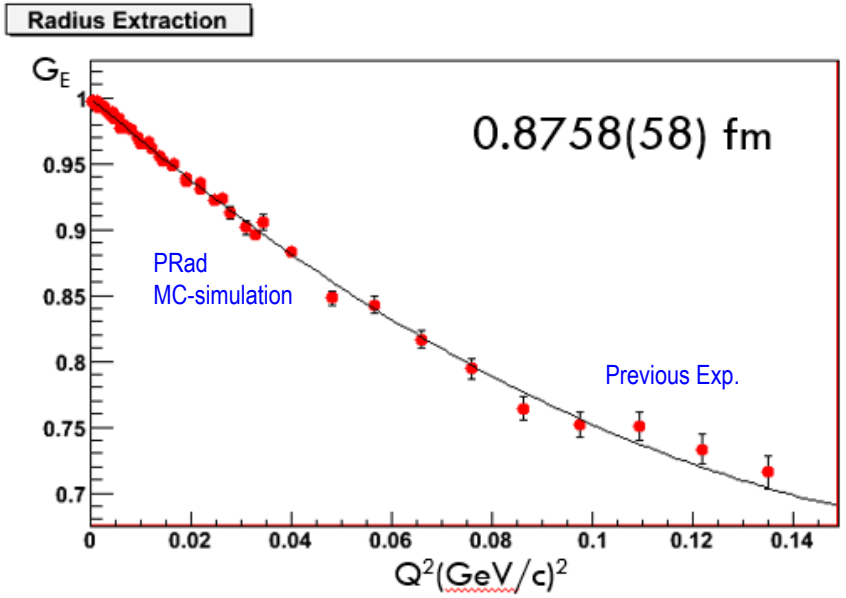
- ✓ Funded by NSF MRI award PHY-1229153

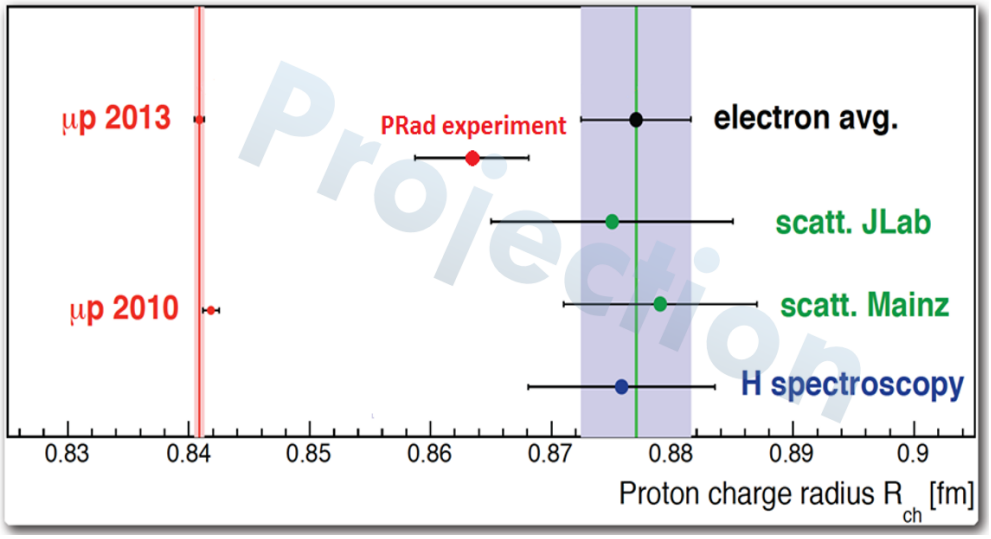
Current status of the PRad Apparatus: Vacuum Chamber

- ✓ Provides vacuum from the target to the detectors
  - less beam related background;
  - practically no re-scattering effects
- ✓ Completed, ready for installation

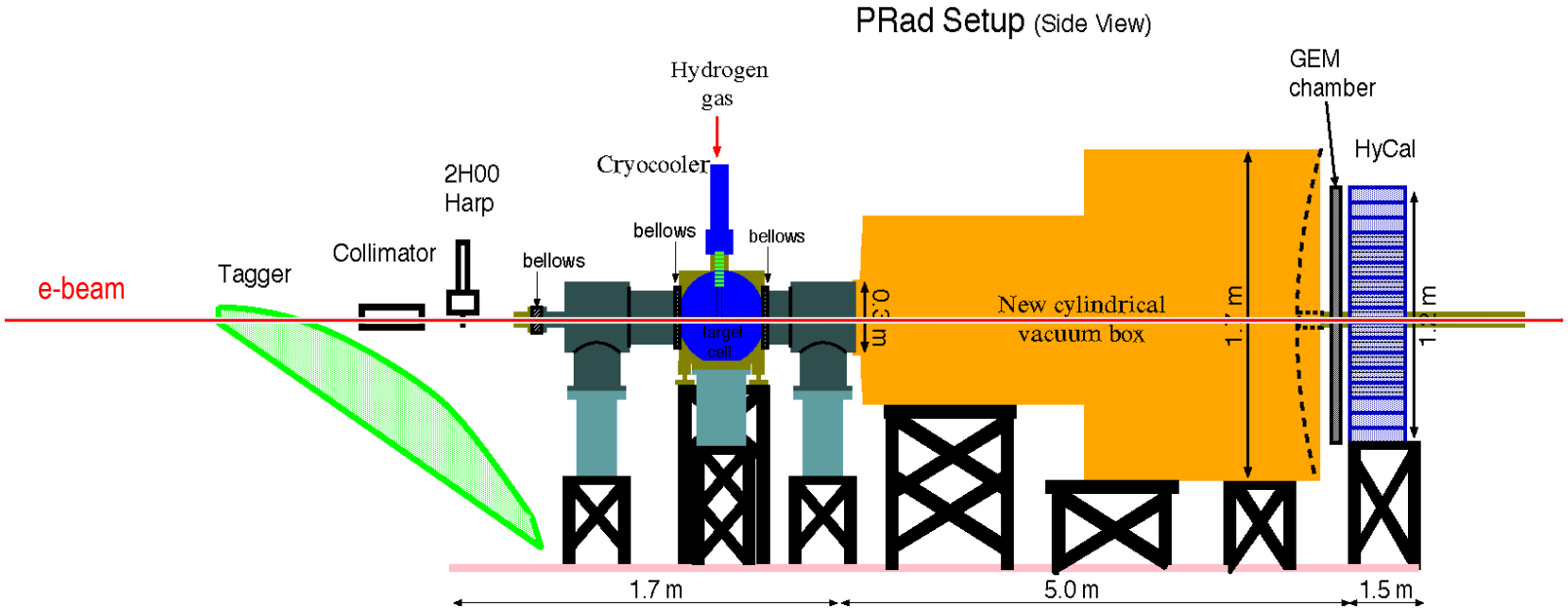
Expected Results from the PRad Experiment

- Critical input to the current "Proton Radius Puzzle"
- Also connected with the possible "… New Forces in Physics …"





Future Use of the PRad Experimental Setup (like the new V_B - search experiment)



Available capabilities:

- ✓ 11.5 GeV high intensity e-beam;
- ✓ high resolution, large acceptance EM calorimeter for multi - γ final states;
- ✓ Large acceptance GEM detectors for charge particles veto (e^-,e^+, μ^+,μ^-, …);
- ✓ High vacuum (~ 5 m long, 6×10^{-4} - 9×10^{-6} torr) from the target to the detectors to reduce the multiple scattering effects.

The Proposed Experiment:
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$\downarrow\rightarrow \pi^0 + \gamma \rightarrow \gamma + \gamma + \gamma$

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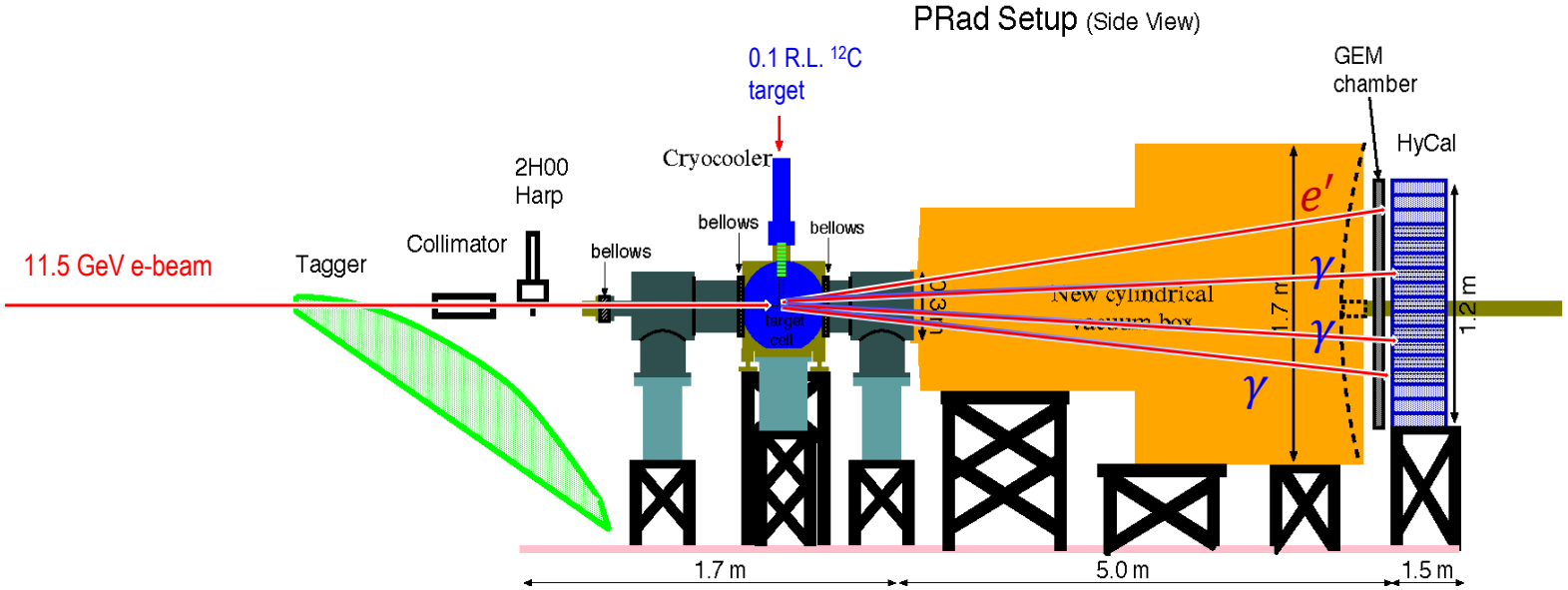
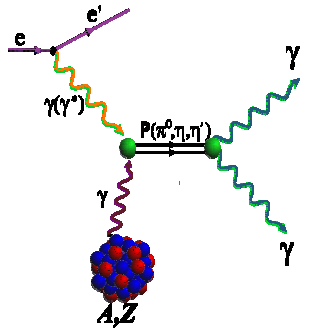


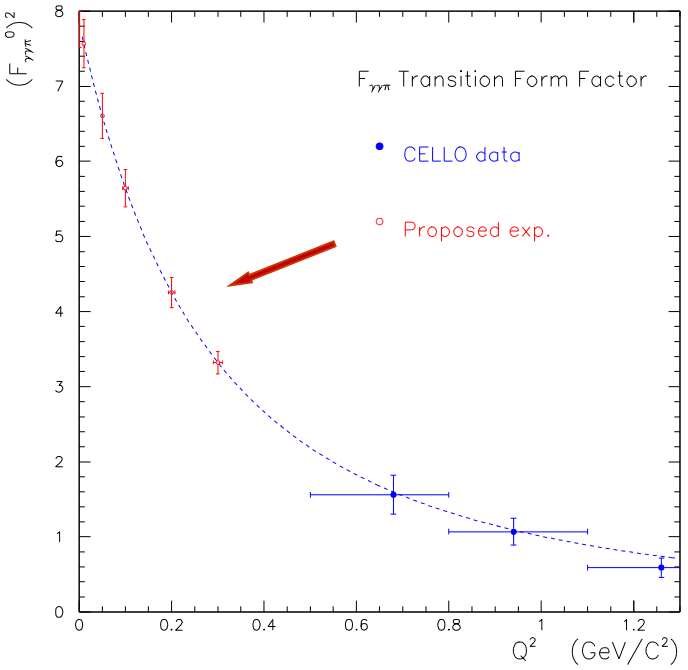
- It is suggested to run with the "π^0 Transition Form Factor measurement at very low Q^2 range, (PrimEx-IV)"
- a "by-product" experiment, (more chance to run)

π^0 Transition Form Factor at Low Q^2 Range
(upcoming PrimEx-IV proposal at JLab)



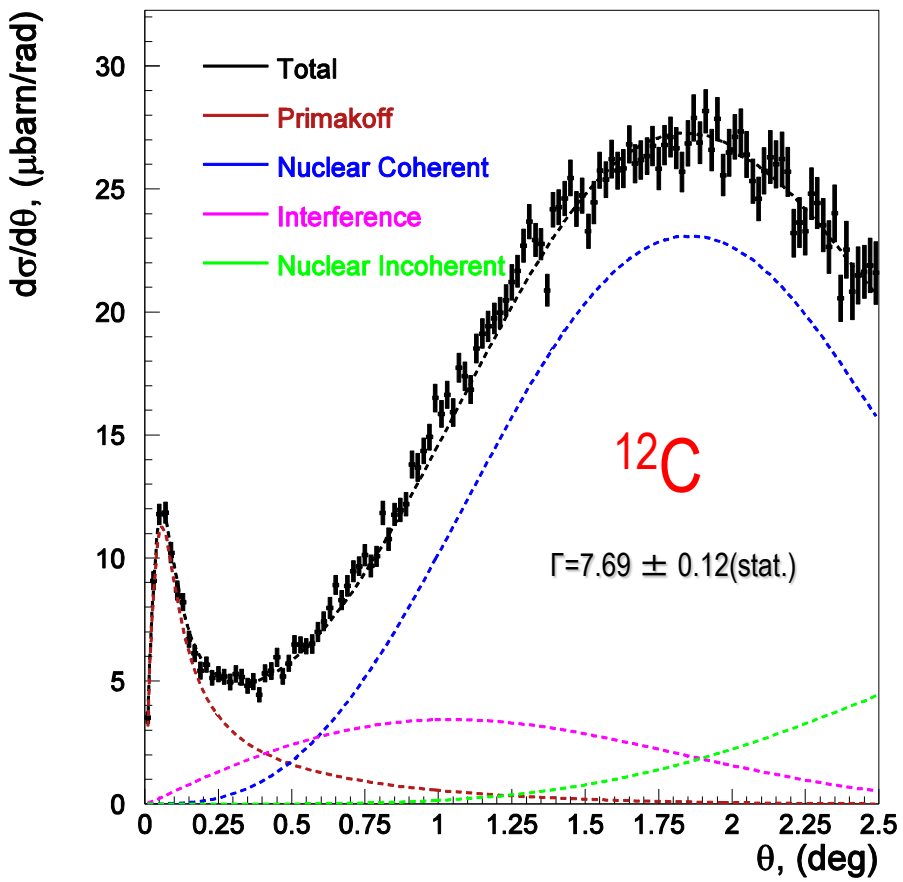
- Measure $F(\gamma\gamma^* \rightarrow \pi^0)$ at Q^2 = 0.001-0.5 (GeV/)^2
  - ✓ π^0 EM radius
  - ✓ input to g-2 crisis (light-by-light scattering effects)
  - ✓ test of Chiral symmetries and anomalies via the Primakoff effect

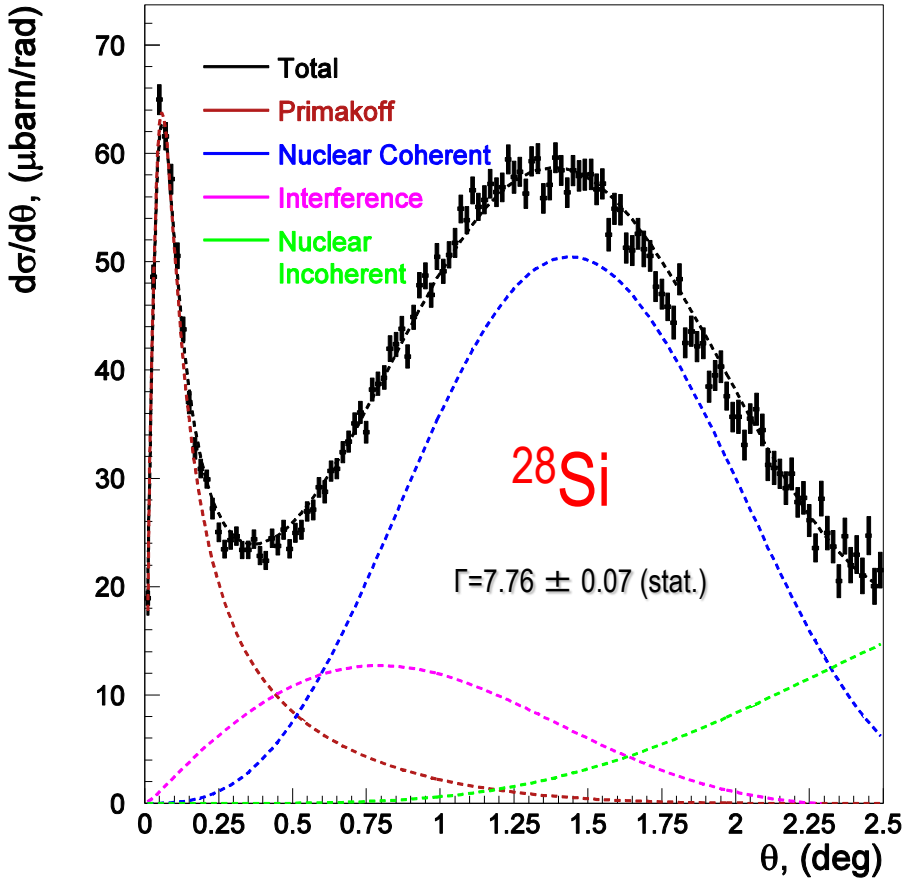
- Experimental Features:
  - ✓ use 11.5 GeV e-beam
  - ✓ 0.1 – 0.3 % R.L. ^{12}C target
  - ✓ e^- ,γ, γ in final state (detected in HyCal and GEM)
  - ✓ Trigger:
    - Total energy in HyCal > 8. GeV
    - 3 clusters in HyCal with $E_{clust.}$ > 0.3 GeV
    - One charged particle in GEM



An Example of Experimental Primakoff Cross Section

(Eγ = 5.0 GeV)





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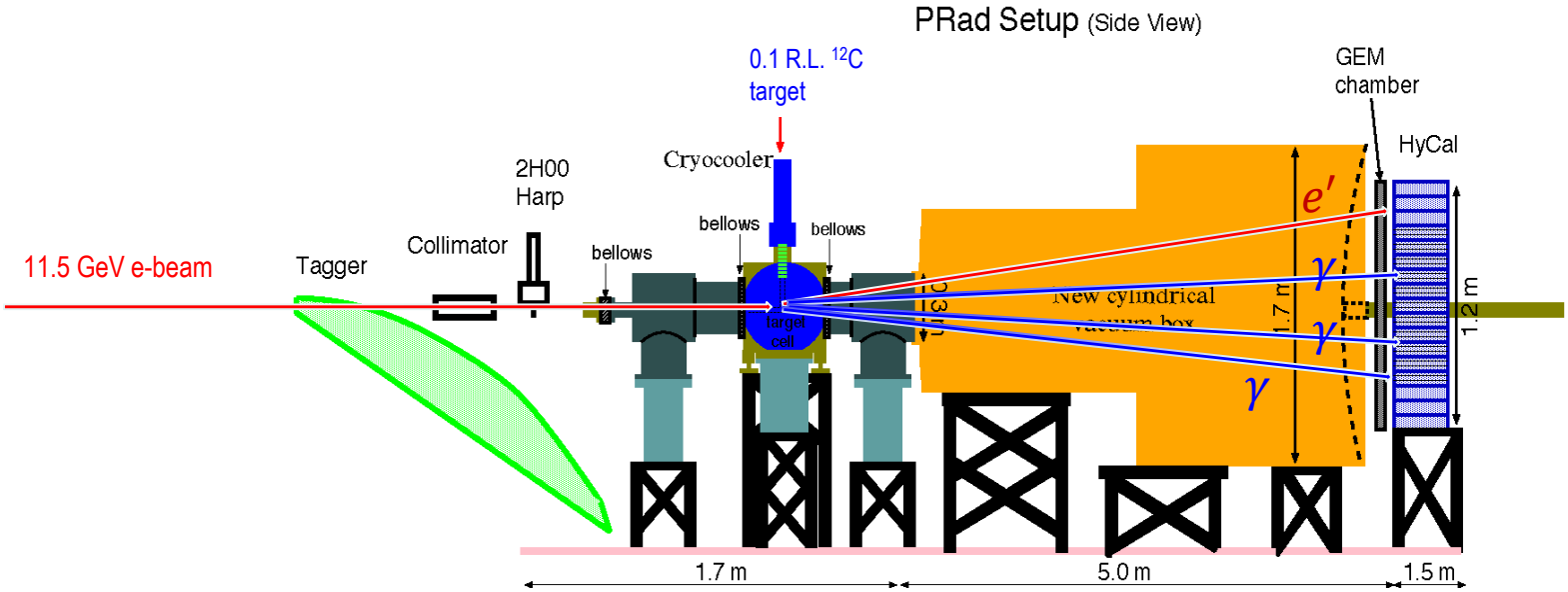
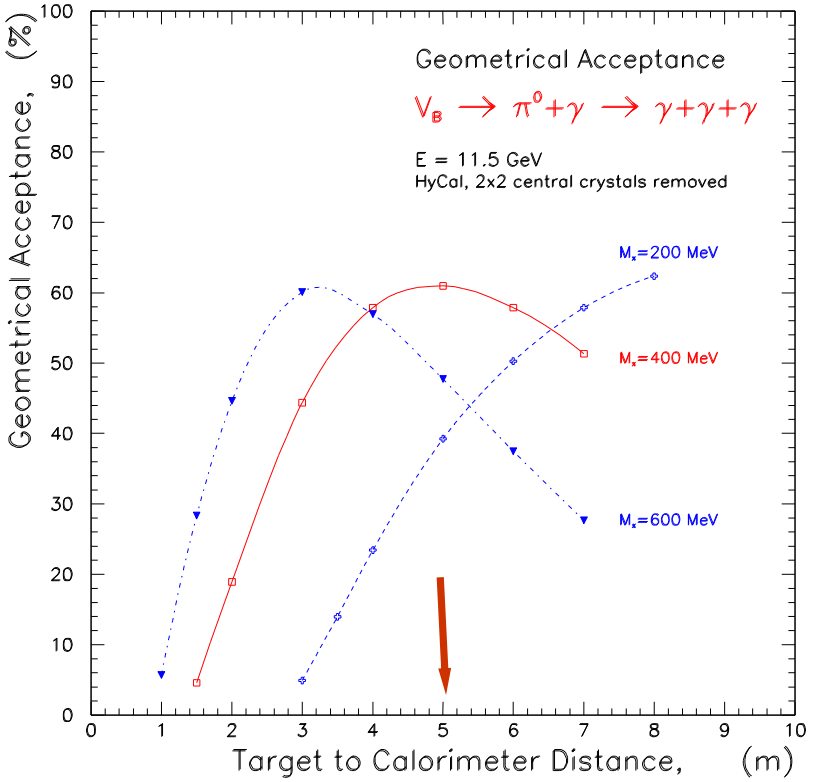


$V_B \rightarrow \pi^0 + \gamma \rightarrow \gamma + \gamma + \gamma$ Detection Acceptance

- HyCal calorimeter is defining the acceptance:
  - ✓ 118 x 118 cm^2 cross sectional area:
  - ✓ 35 x 35 cm^2 $PbWO_4$ crystals in central part;
  - ✓ 2 x 2 $PbWO_4$ crystals are removed for the beam (4 x 4 cm^2).
- GEM detector covers entire HyCal
- E_{clust} > 0.5 GeV cut is included



- Z = 5 m distance will provide 30 ÷ 60% detection acceptance for the [150 ÷ 650 MeV] mass range

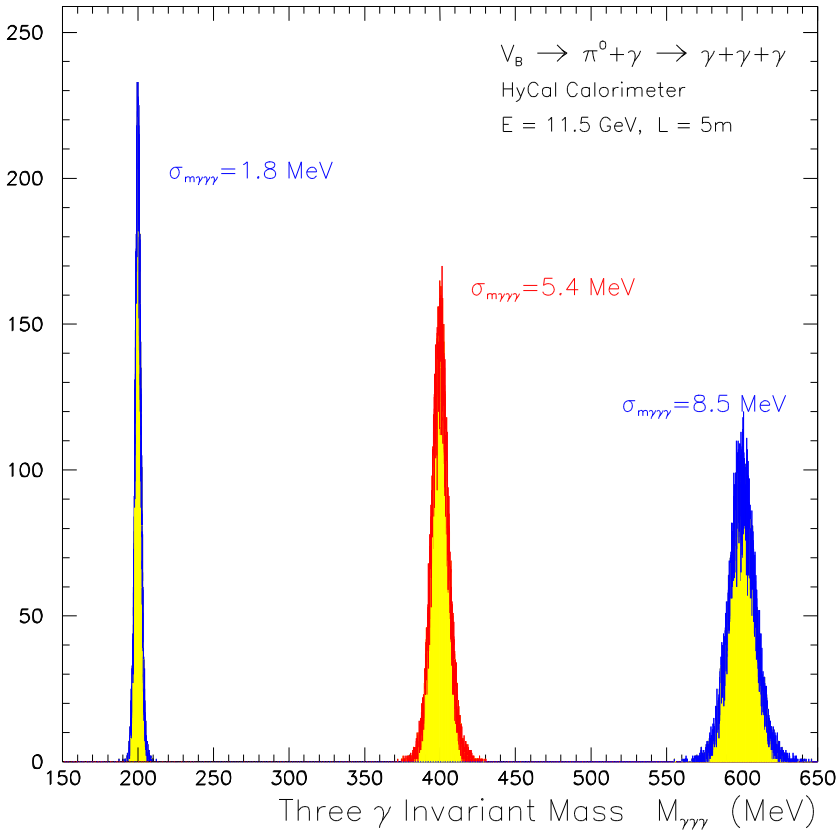
$V_B \rightarrow \pi^0 + \gamma \rightarrow \gamma + \gamma + \gamma$ Invariant Mass Reconstruction

- HyCal position and energy resolutions are defining the $M_{\gamma\gamma\gamma}$ resolution:
  - ✓ Pb-glass part:

$$\sigma_E/E = 5.6\%/\sqrt{E}\ ,$$
$$\sigma_{x,y} = 5.4\frac{mm}{\sqrt{E}}$$

  - ✓ $PbWO_4$ crystal part;

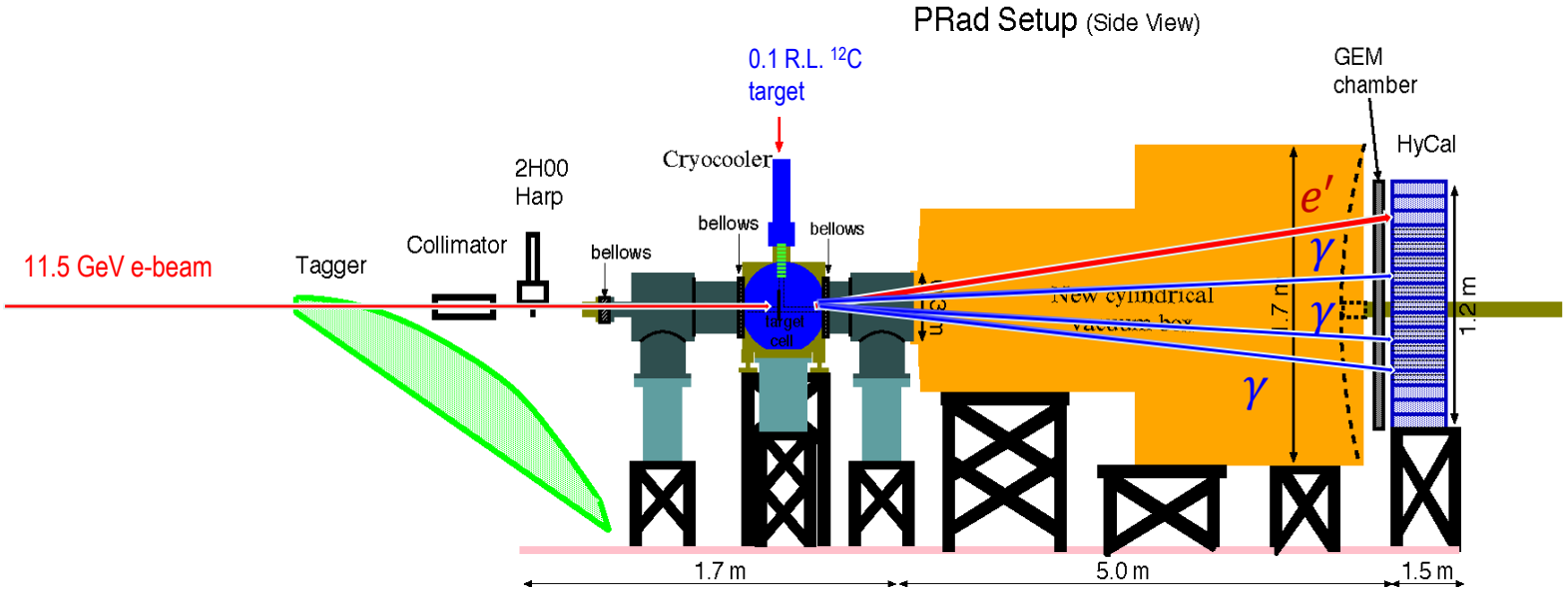
$$\sigma_E/E = 2.6\%/\sqrt{E}$$
$$\sigma_{x,y} = 2.5\frac{mm}{\sqrt{E}}$$



- Good $M_{\gamma\gamma\gamma}$ resolution is expecting in this experiment [1.8 ÷ 8.5] MeV
- Critically important for the signal identification over the background

$V_B \rightarrow \pi^0 + \gamma$ Displaced Vertex Reconstruction

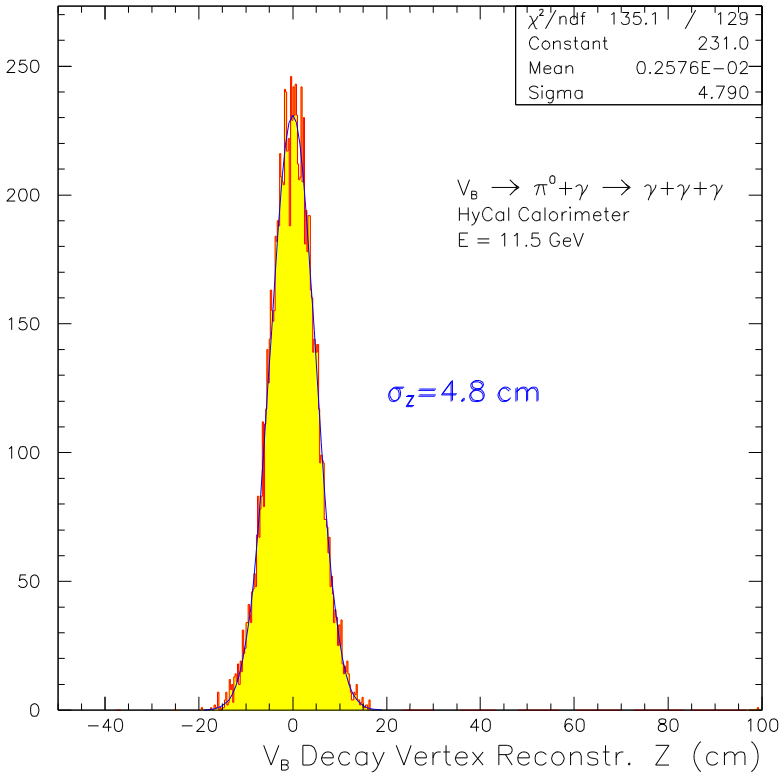
- $\pi^0 \rightarrow \gamma + \gamma$ defines the decay vertex of V_B boson, assuming the $M_{\gamma\gamma}$ is known.

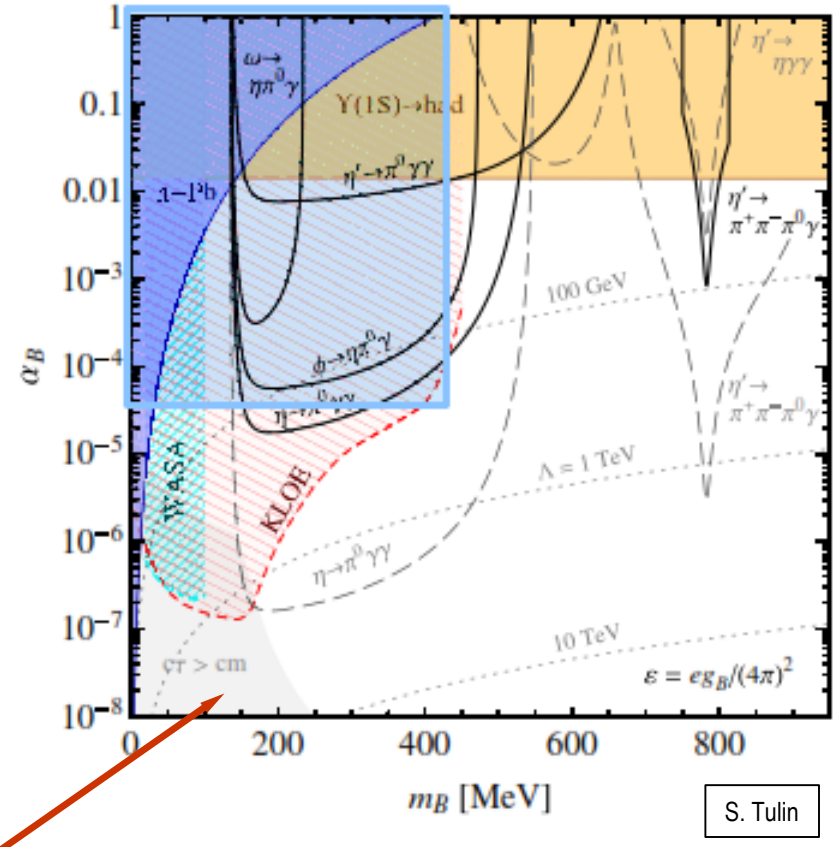


- An important tool to filter the signal from the background events.

$V_B \rightarrow \pi^0 + \gamma$ Displaced Vertex Reconstruction: Resolution

- $\pi^0 \rightarrow \gamma+\gamma$ defines the decay vertex, assuming the $M_{\gamma\gamma}$ is known



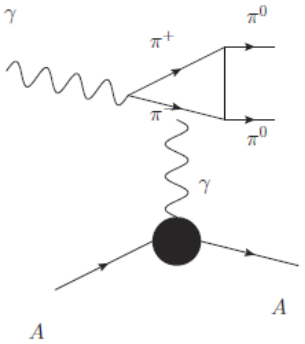


- Decay Length: $Z \cong (E_{VB}/M_{VB}) \times c\tau \approx$ 10 x cτ for this experiment
- Has a good potential to play a good role in this search experiment

Physics Background: *Forward Production of* Two π^0 *Mesons*

- $\gamma^* + {}^{12}C \rightarrow \pi^0 + \pi^0 + X$

  $\downarrow \rightarrow \gamma + \gamma \rightarrow \gamma + \gamma + \gamma$



$$\frac{d\sigma}{d\Omega dM} = \frac{\alpha}{\pi^2}\frac{\beta^2 k^4 sin^2\theta}{Q^4}\frac{1}{M}\sigma(\gamma\gamma)F^2(M,Q^2)$$

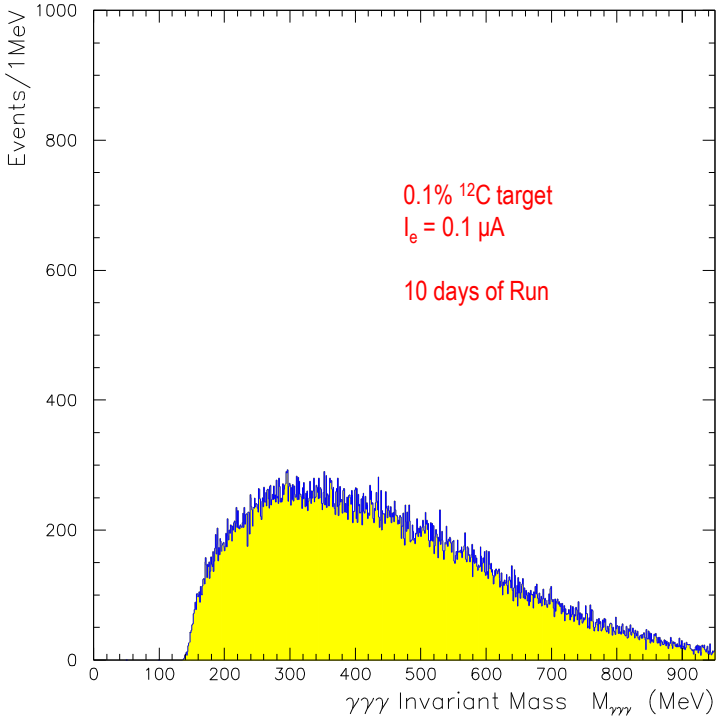
S. Gevorkyan, in publication

for E_γ = 11 GeV, ΔE=1.GeV, ΔM=0.4 GeV

$\Delta\sigma(\gamma* + P \rightarrow \pi^0 + \pi^0 + P) \approx 0.008$ μb

then:

$\Delta\sigma(\gamma* + {}^{12}C \rightarrow \pi^0 + \pi^0 + X) \approx 0.1$ μb



- Selection rule:
  - ✓ any combination of 3γ was treated as $V_B \rightarrow \pi^0 + \gamma$ event

Physics Background: *Electro-production of ρ Mesons*

- $\gamma^* + {}^{12}C \rightarrow \rho + 12C$

  $\downarrow\rightarrow \pi^0 + \gamma \rightarrow \gamma + \gamma + \gamma$

  Branching ratio: 6×10^{-4}

  M_ρ = *775.26, Full width: Γ= 149.1 MeV*

- *VDM model predicts:*

  $\Delta\sigma(\gamma^* + P \rightarrow \rho + P) \approx 10 \times \Delta\sigma(\gamma^* + P \rightarrow \omega + P)$

- *from experiment:*

  $\Delta\sigma(\gamma^* + P \rightarrow \omega + P) \approx 0.23\ \mu b$

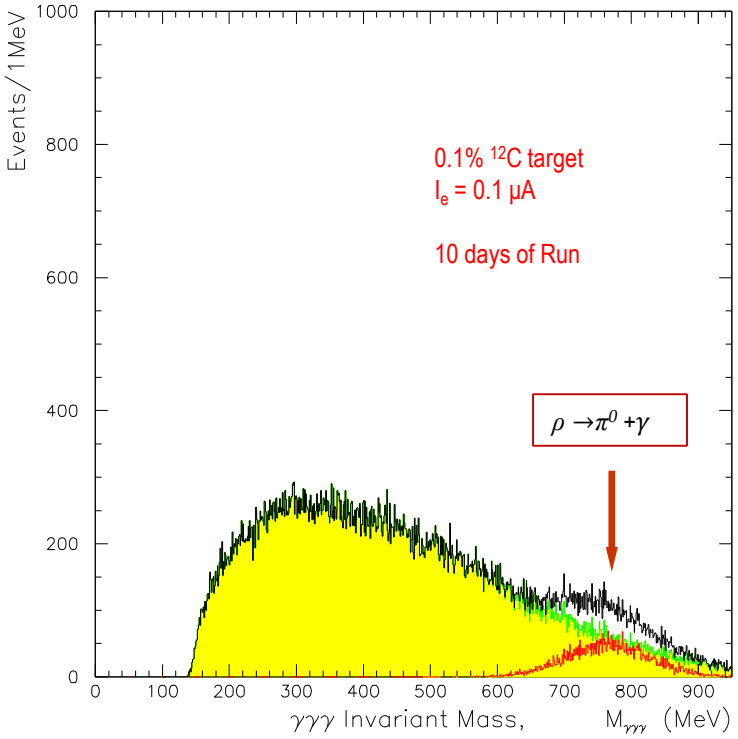
  and:

  $\Delta\sigma(\gamma^* + A \rightarrow \omega + A) \approx (A)^{1.5}\ \Delta\sigma(\gamma^* + P \rightarrow \omega + P)$

  then:

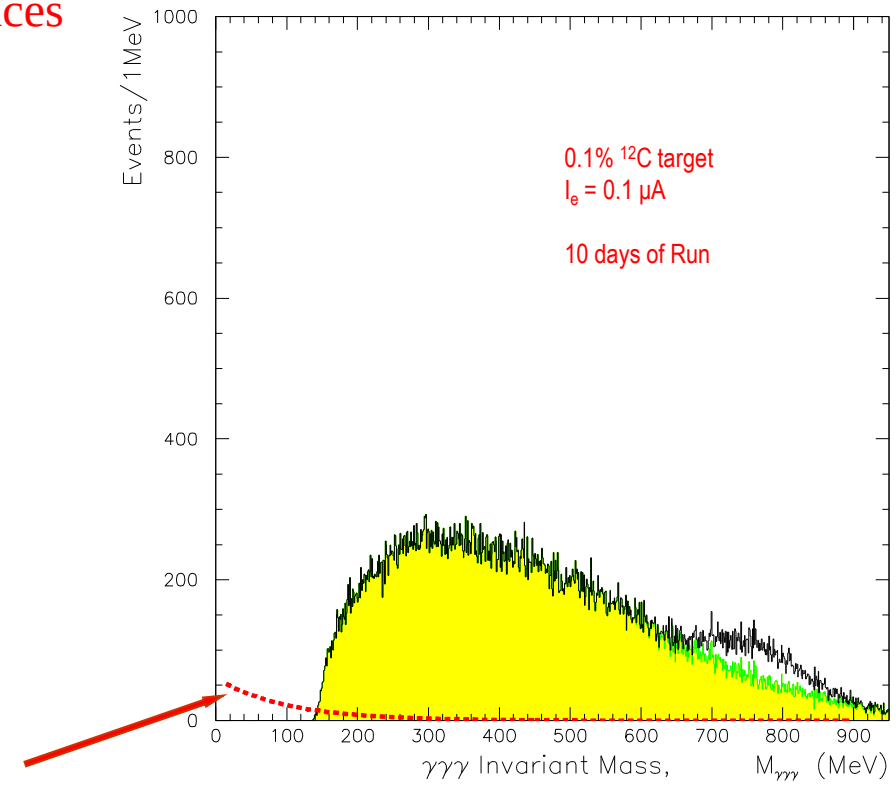
  $\Delta\sigma(\gamma^* + {}^{12}C \rightarrow \rho + {}^{12}C) \approx 10.\ \mu b$

- Selection rule:
  - ✓ $\rho \rightarrow \pi^0 + \gamma$ events generated with different mass according to *Γ= 149.1 MeV*.



Beam Background: *Electromagnetic Background*

- $e^- + {}^{12}C \rightarrow$ anything in calorimeter
- GEANT simulation of accidental coincidences *within 50 ns time window.*
  Using:
  - ✓ *e^- beam with I_e = 0.1 μA*
  - ✓ *1.0% ^{12}C target*
- Selection rule:
  - ✓ Any $\gamma+\gamma+\gamma$ events treated like $V_B \rightarrow \pi^0 + \gamma$ event
- Requirement of $\gamma+\gamma+\gamma$ with:
  $E_\gamma > 0.3$ GeV and
  $\Sigma E_\gamma > 8.$ GeV
  makes this background not dominating



$V_B \rightarrow \pi^0 + \gamma$ Signal Events

- Theoretical activities are in progress to estimate $\Delta\sigma(e^- + A \rightarrow V_B + X)$ based on realistic models.
  (S. Tulin, M. Pospelov, …)

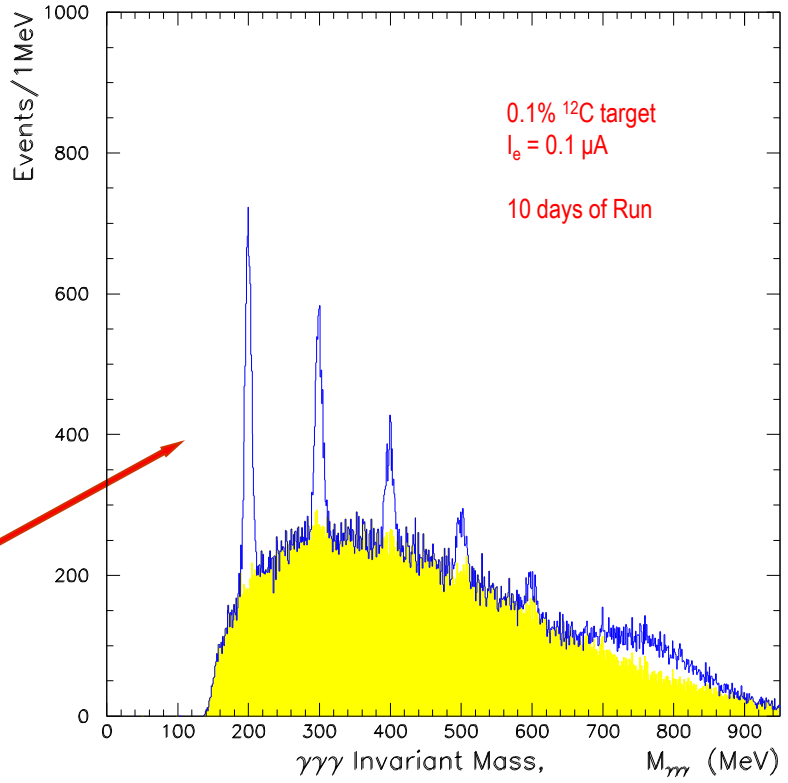
- At this stage it is assumed:

$\sigma(e^- P \rightarrow V_B) \sim$
$\sim (\alpha_{em}/\pi)\,(\alpha_B/\alpha_{em})\,(M_\omega/M_B)^2\,\sigma(\gamma P \rightarrow \text{hadrons})$

(M. Pospelov, private communication)

For estimation purposes, take $\sigma(\gamma P) \sim 1$ μb
Then:

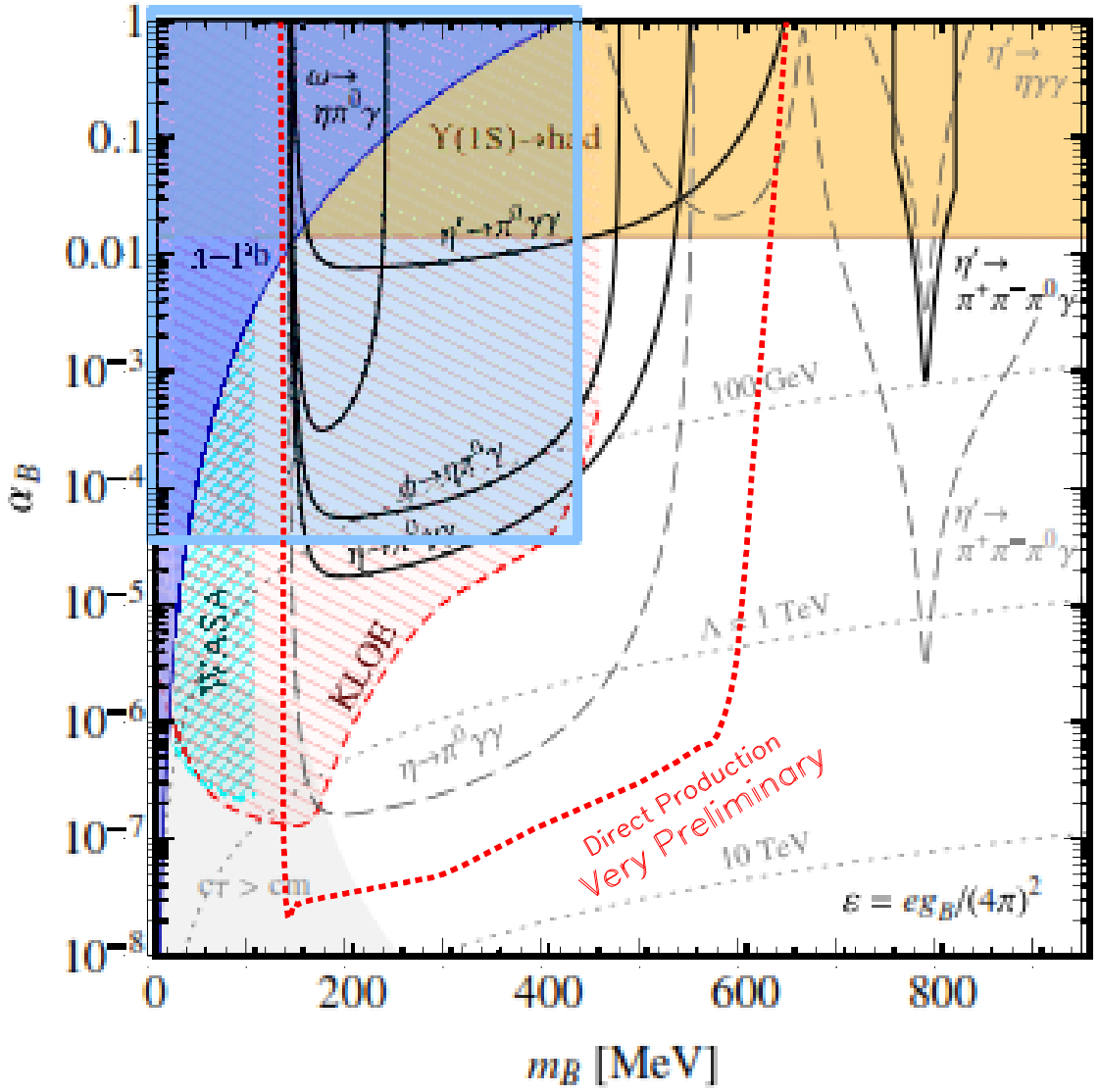
$\sigma(V_B) \sim 1$ pb at $\alpha_B = 10^{-8}$
for ^{12}C target and $M_B = 200$ MeV



- (Signal)/sqrt(backgr.) = 750/sqrt(6084) = 9.6
  for M_B = 600 MeV

Sensitivity of the Proposed Experiment
(Physics Reach)

- With assumption that:
  $\sigma(V_B) \sim 1$ pb at $\alpha_B = 10^{-8}$
- Needs more input from theory part



Summary and Outlook

- Experiments with intense medium energy electron beams represent a “window of opportunity” to search for new particles in the GeV mass range.

- Recently predicted new vector boson with $V_B \rightarrow \pi^0 + \gamma$ decay mode is well suited to be searched with an existing experimental setups at JLab:
  - ✓ Vertex detection capability
  - ✓ large invariant mass ranges with good resolutions
  - ✓ high detection efficiencies
  - ✓ controllable experimental backgrounds

- Theoretical contributions are highly required to identify all production channels.

- More work is needed to finalize the background level in the experiment

- Complimentary to other search experimental projects (like the meson decays).

Physics Motivation
(Search for Hidden-Sector (Pseudo-)Scalars)