SM TESTS WITH e^+ BEAM

I.Oceano on behalf of the PADME collaboration

OUTLINE

- PADME
- SM physics in e^+e^- collision
  - Final state with photons only
  - Final state with photon and leptons
  - Final state with leptons only

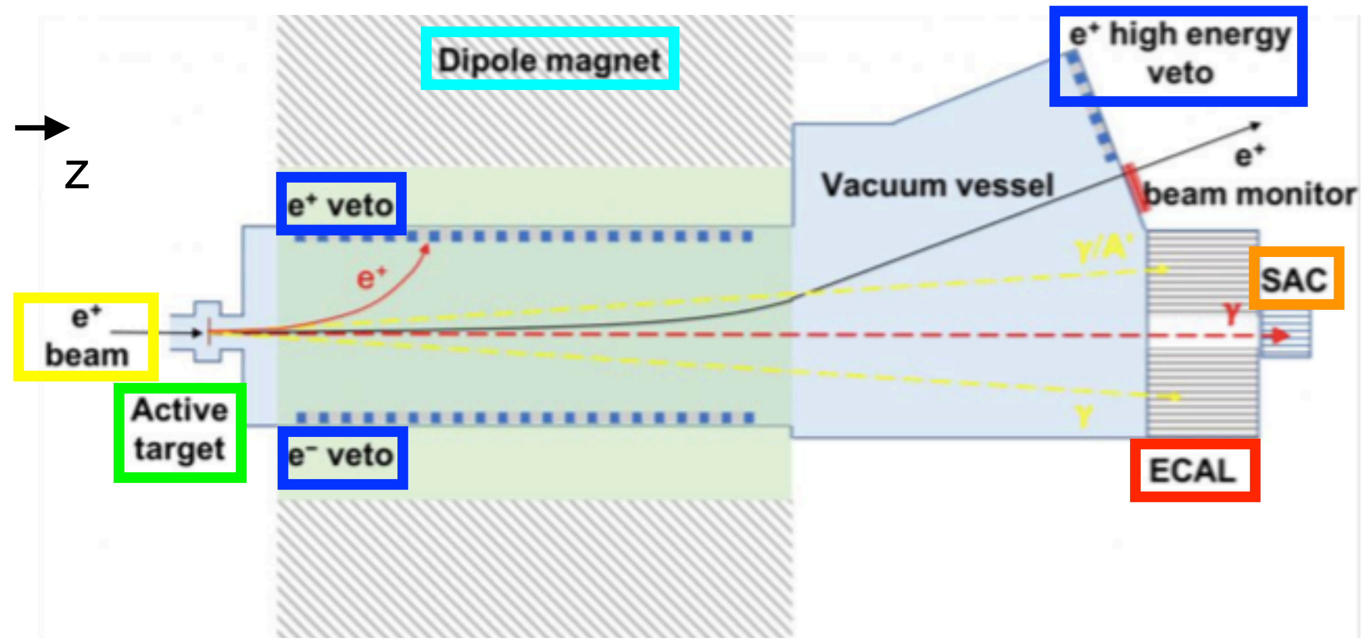
PADME INTERACTION

- e^+ beam impinging on diamond target
- Processes from e^+e^- interaction

- PADME beam
  - E beam = ~500 MeV
  - Bunch length ~300 ns
  - ~27k POT/bunch
  - 49 bunch/s

- PADME SM processes
  - Not many measurements of cross sections at this scale energy in literature
- PADME BSM processes
  - Primary goal: dark photon search
  - dark Higgs search
  - …

PADME scheme



- Detectors for charged and neutral particles
  - Electromagnetic calorimeters
    - SAC
    - ECAL, most upgraded detector
  - Veto for positrons and electrons
    - Can be used as spectrometers due to its segmentation and the presence of a stable magnetic field

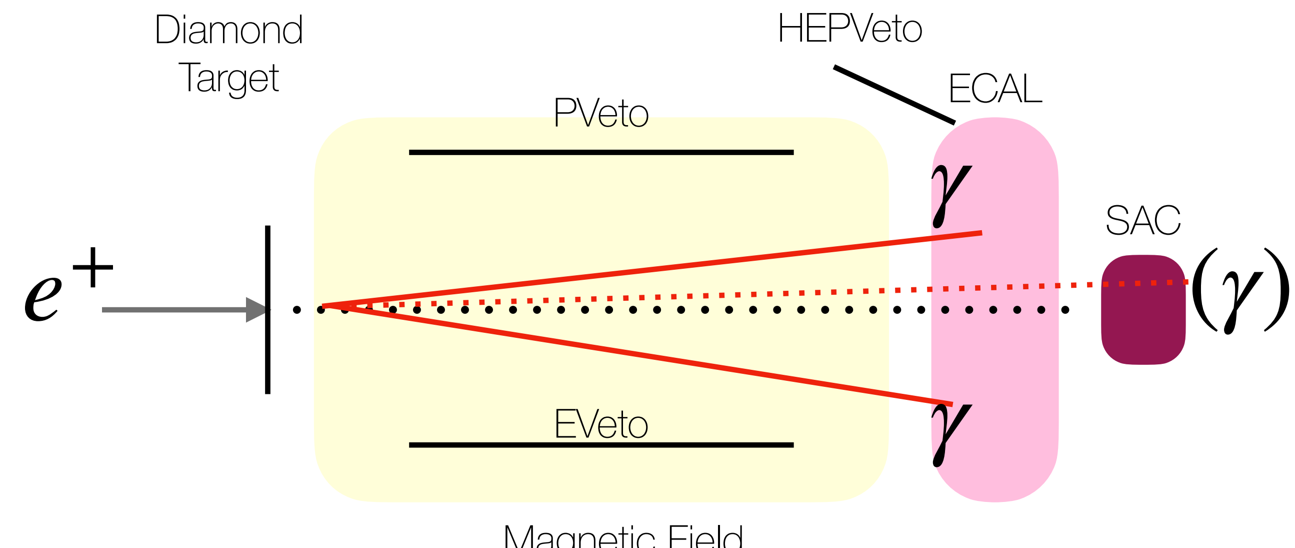
SM PHYSICS

- $e^+e^- \rightarrow$
  - Photons
  - Photon and charge particles
  - Leptons

MULTI PHOTON FINAL STATE

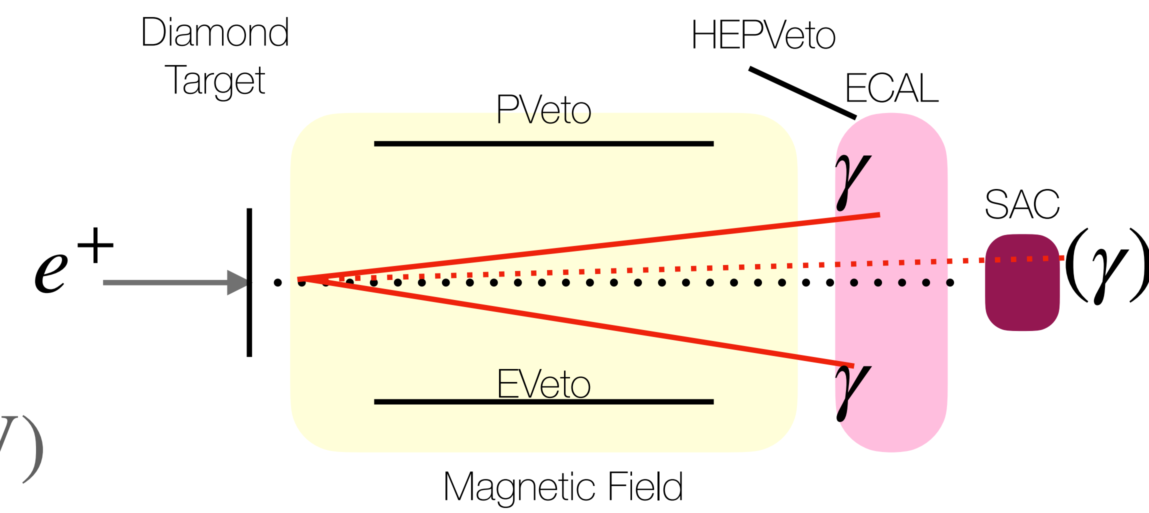
- $e^+e^- \to \gamma\gamma$
  - Tree level cross section
    - $$\sigma(E,Z) = \frac{Z\pi r_e^2}{\gamma+1} \times \left[\frac{\gamma^2+4\gamma+1}{\gamma^2-1} ln\left(\gamma+\sqrt{\gamma^2-1}\right) - \frac{\gamma+3}{\sqrt{\gamma^2-1}}\right]$$
    - Where
      - E is the positron energy
      - r_e I the classical electron radius
      - γ is the Lorentz factor of the beam particle

Heitler formula



EXPECTED ANNIHILATION RATE IN PADME

- For a beam energy of 550 MeV tree level computing using CalcHEP[1]
  - $\sigma(e^+e^- \to \gamma\gamma) = 1.55\ \mathrm{mb}$
  - $\sigma(e^+e^- \to \gamma\gamma\gamma) = 0.16\ \mathrm{mb}\ (\mathrm{E}_\gamma > 1\ \mathrm{MeV})$



PADME today
- 27000 POT/bunch
- 49 bunch/s

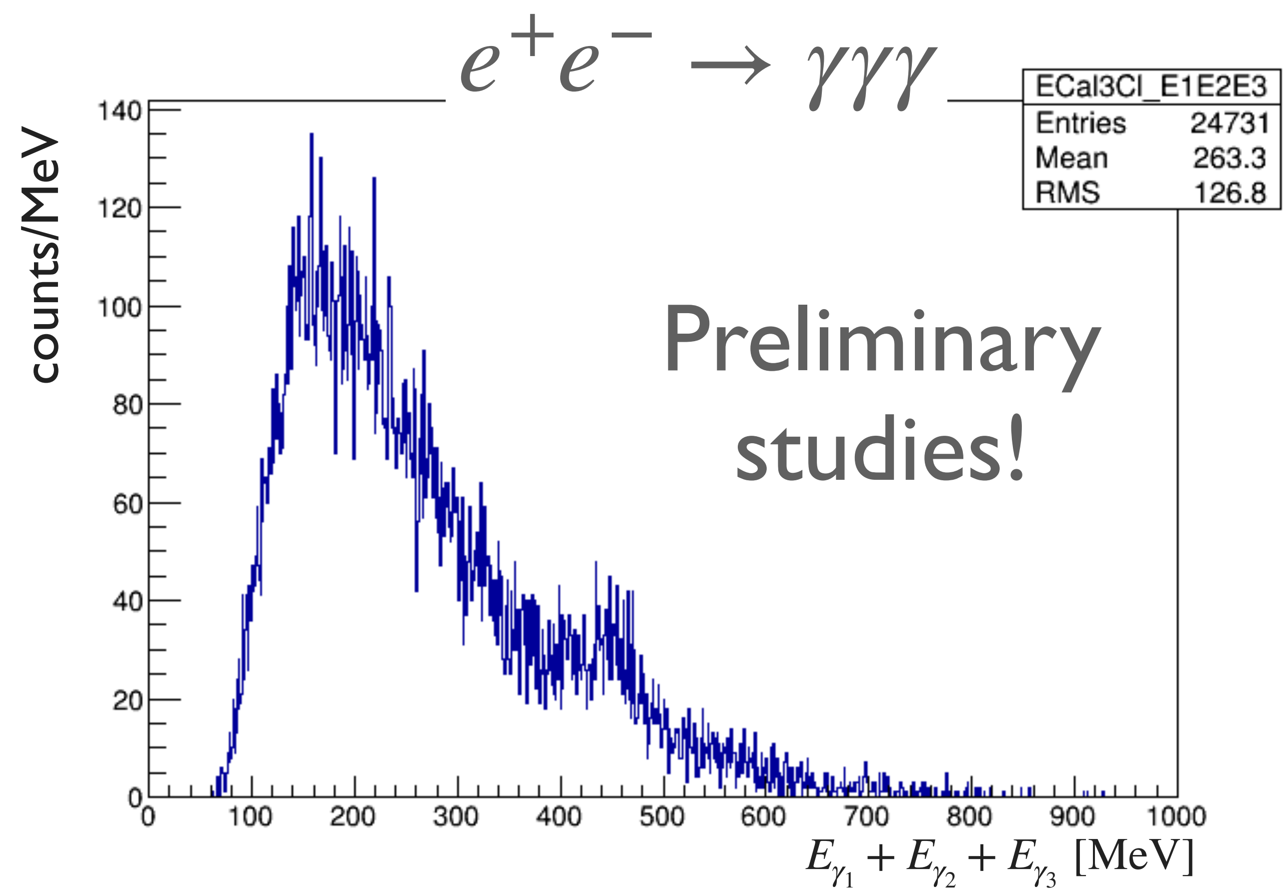
PROCESS	#EV/DAY	#EV/DAY X ACC
$e^+e^- \to \gamma\gamma$	1.8×10^6	1.3×10^5
$e^+e^- \to \gamma\gamma\gamma$	1.9×10^5	Not known

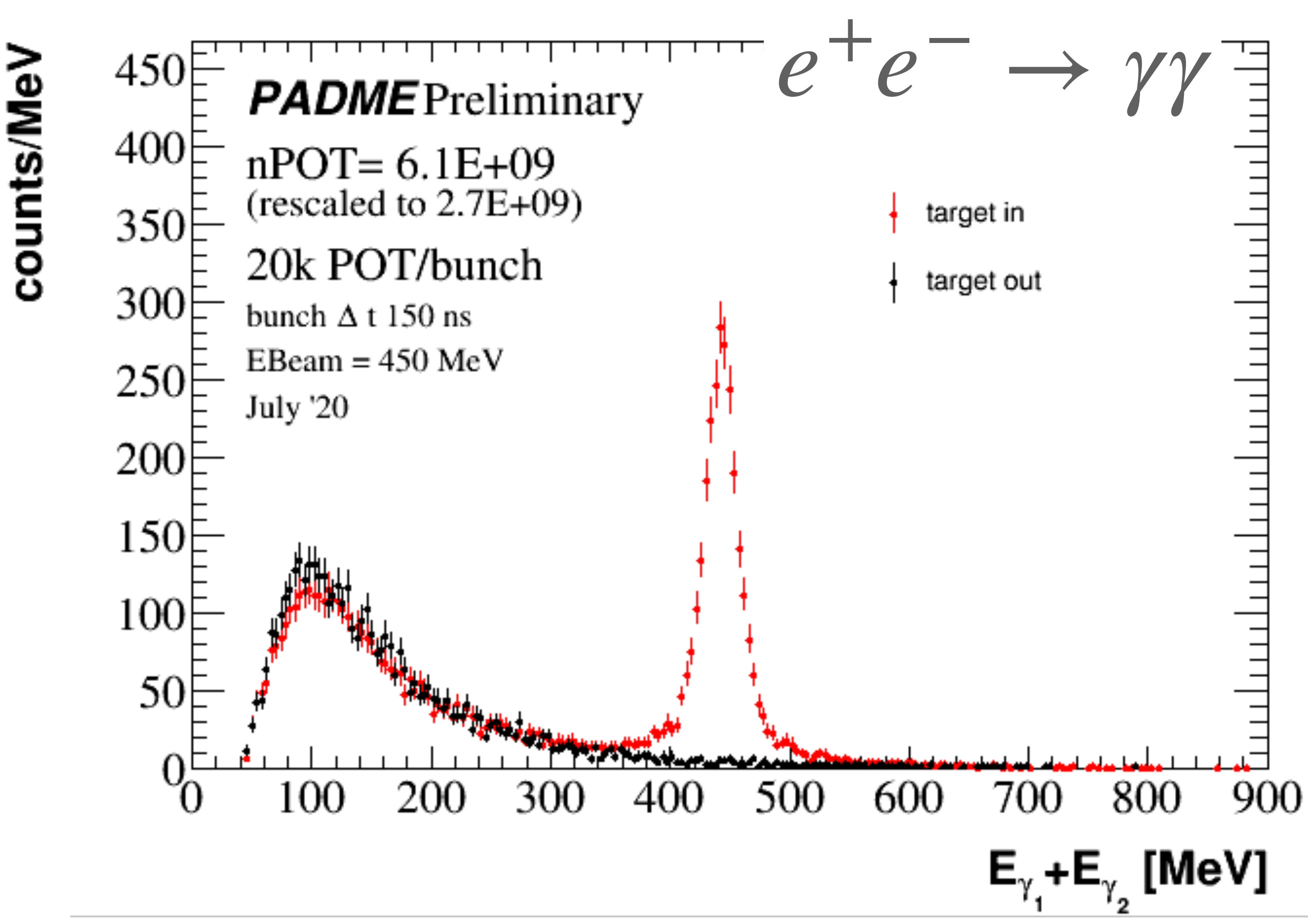
The acceptance for $e^+e^- \to \gamma\gamma$ in ECAL was extracted using CalcHEP tool.

[1]"Background in the search for dark photon in e^+e^- annihilation"

MULTI PHOTON FINAL STATE IN PADME

- To detect $\gamma\gamma(\gamma)$ annihilation we only use ECal detector
- To increase the acceptance SAC calorimeter can be also used
  - Need reduced beam intensity





Annihilation in two photons yield : 7275
In standard PADME run conditions the signal correspond to one hour of data taking

ANNIHILATION PERSPECTIVES I

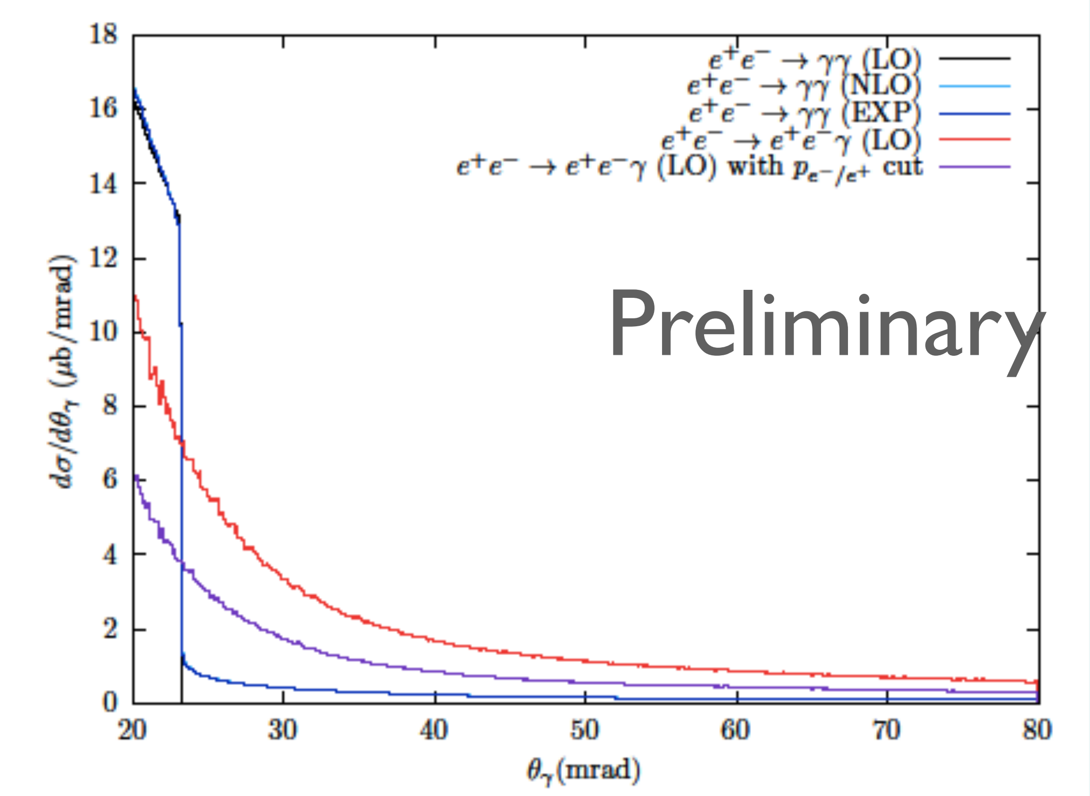
- The statistical error is always negligible
- Error in present PADME setup is dominated by the luminosity error (~few%), and reconstruction efficiency (~few%).
  - These systematics will be strongly reduced by reducing beam intensity.
- A continuum beam of positrons can improve the quality of the measurements
  - With a single positron/ns we have a strong reduction of pileup, with a consequent increase of reconstruction efficiency
  - Recover the central region in the acceptance
    - SAC calorimeter can also be used, no bremsstrahlung background
      - Possible improvements on SAC detector
        - Better energy resolution
        - Finer segmentation

ANNIHILATION PERSPECTIVES II

- At this energy scale there are no $\gamma\gamma$ nor $\gamma\gamma\gamma$ cross section measurements
  - PADME has a chance to first perform these cross sections measurement
- If we reach the 1-2% error we can aim to providing a meaningful comparison of cross section with an NLO calculation.
  - It is important to assess the background for new physics search and validate simulation

A calculation using BabaYaga generator shows a discrepancy of 22% between the LO and NLO cross section

- Single photon in ECAL (same signature as dark photon)
- $E_\gamma > 50$ MeV
- $\theta \in [20\ ,\ 80]$ mr



C.Carloni Calame, F.Giacchino, M.Pruna

SM PHYSICS

- $e^+e^- \to$
  - Photons
  - Photon and charged particles
  - Leptons

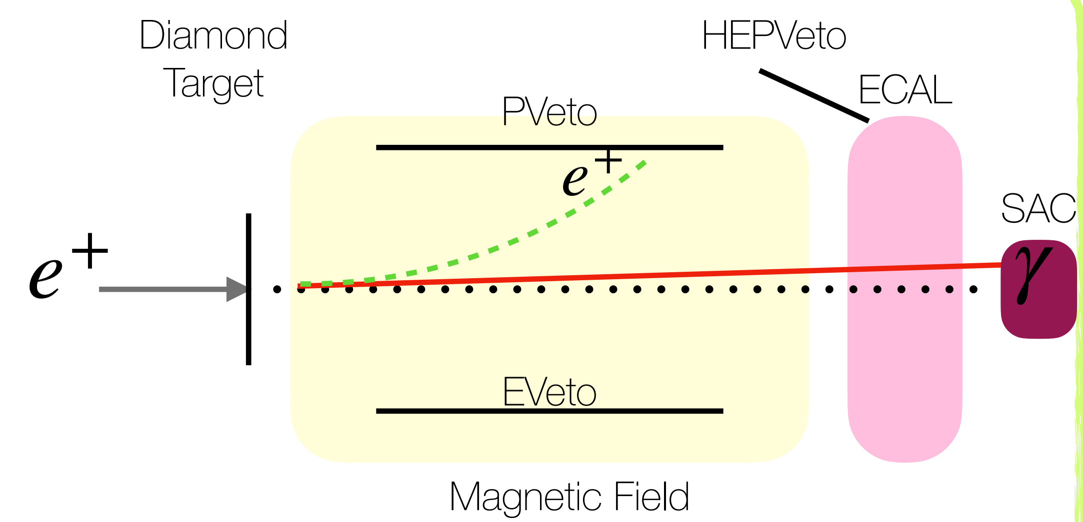
Charged and neutral particles in final state - bremsstrahlung

- Bremsstrahlung on nuclear magnetic field
- $e^+N \to e^+N\gamma$
- Cross section LO for carbon atom (from GEANT4)
  - $\sigma(e^+N \to e^+N\gamma) = 4000 \text{ mb } (\text{E}_\gamma > 1 \text{ MeV})$ [1]
  - $\propto z^2$ of material

PADME today
- 27000 POT/bunch
- 49 bunch/s

PROCESS	#EV/DAY (E>1MEV)	#EV/DAY X ACC (E>1MEV)
$e^+N \to e^+N\gamma$	4.7×10^9	expected $\sim 10^9$

With the default luminosity/bunch, SAC is overwhelmed by bremsstrahlung photons! A new beam configuration can help to reduce pileup

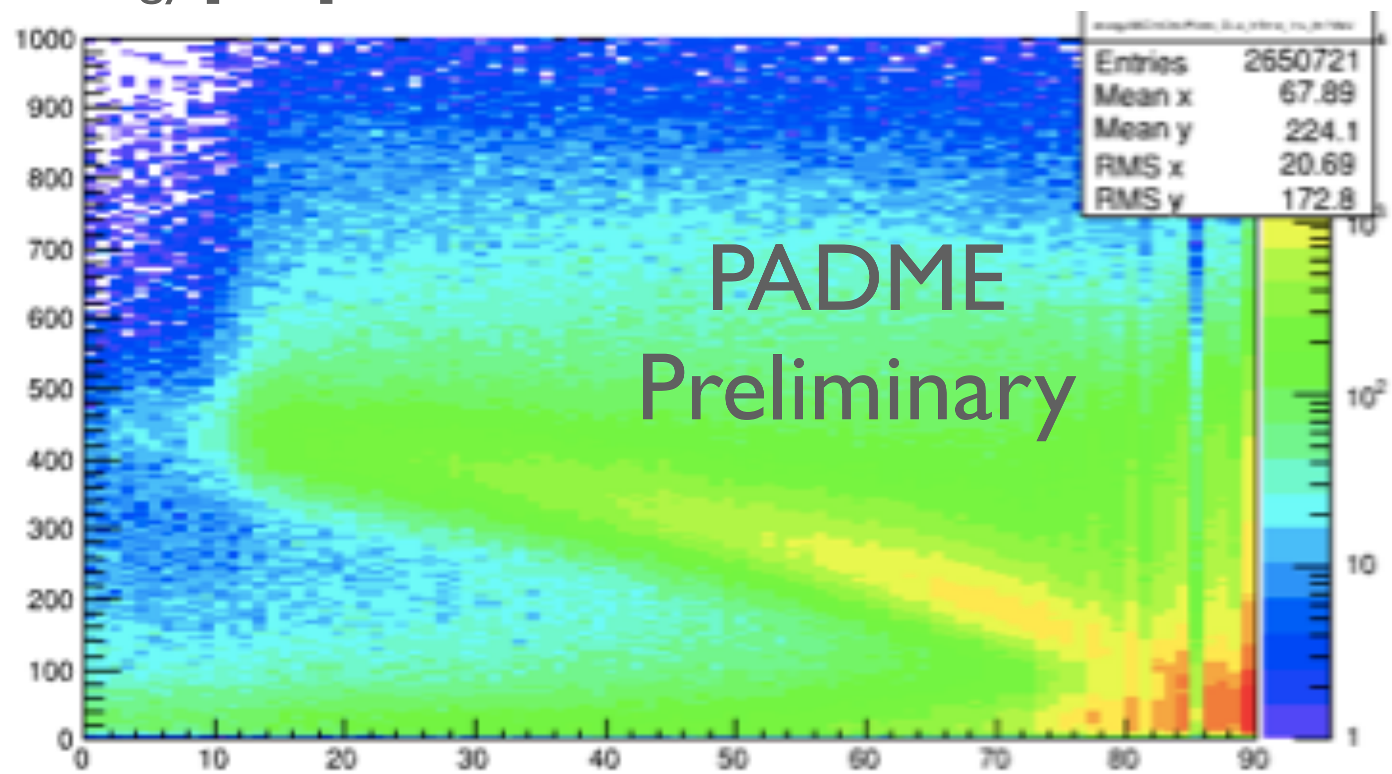


- Two detectors are used to define the signature:
  - A photon in the electromagnetic calorimeters
  - A track in the veto for positrons (PVeto)
- The bremsstrahlung can also be observed from the pVeto occupancy spectrum after the background subtraction
- If the two methods gives the same result we can validate the differential cross section

[1]"Background in the search for dark photon in e^+e^- annihilation"

Charged and neutral particles in final state - bremsstrahlung in PADME

SAC ClEnergy [MeV]



PVeto channel ID

- Luminosity extraction:
  - Once calibrated, bremsstrahlung process can give a measurement of luminosity to be compared with the same measurement extracted using other detectors (diamond target and TimePix), the precision on luminosity measurement can be better.

Bremsstrahlung events are the main background for the dark photon search. A good knowledge of this process is mandatory to achieve a good efficiency on A' search

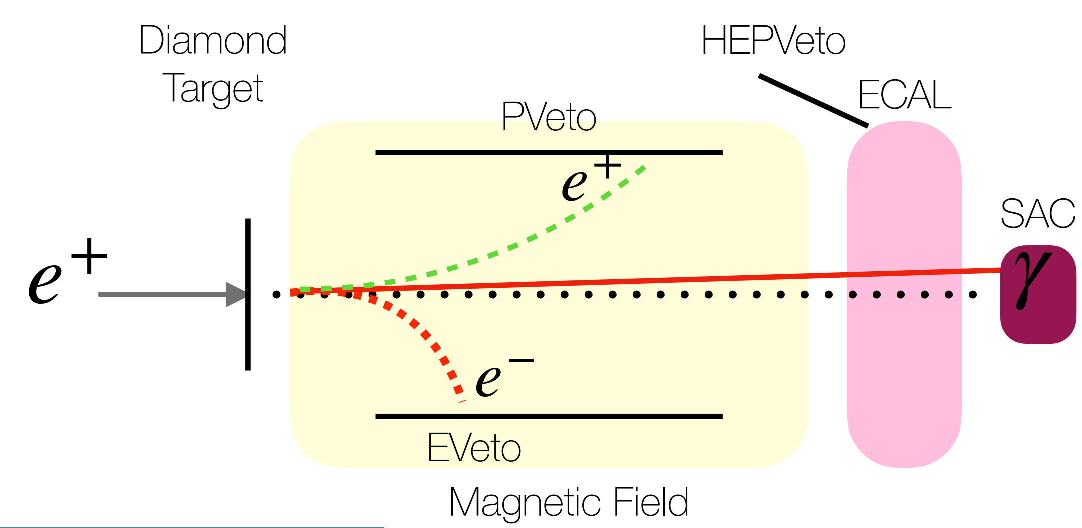
- In the electromagnetic calorimeter the bremsstrahlung signature is the same of the dark photon one

CHARGED AND NEUTRAL PARTICLES IN FINAL STATE - RADIATIVE BHABHA

- Radiative Bhabha
  - $e^+e^- \to e^+e^-\gamma$
- LO cross section (550 MeV beam energy) extracted using CalcHEP
  - $\sigma(e^+e^- \to e^+e^-\gamma) = 180\ \mathrm{mb}\ (\mathrm{E}_\gamma > \ 1\ \mathrm{MeV})$ [1]

It decreases a lot with few cuts:
$E_\gamma > 50$ MeV and photon in
ECal acceptance →
$\sigma(e^+e^- \to e^+e^-\gamma) = 0.123$ mb
No request for e+,e-

PADME today
- 27000 POT/bunch
- 49 bunch/s



PROCESS	#EV/DAY (E>1MEV)	#EV/DAYXACC'
$e^+e^- \to e^+e^-\gamma$	2.2×10^8	1.5×10^5

[1]"Background in the search for dark photon in e^+e^- annihilation"

CHARGED AND NEUTRAL PARTICLES IN FINAL STATE- BHABHA RADIATIVE PROSPECT

- The radiative Bhabha can be also studied in different targets (in PADME can be used diamond and silicon)
  - Useful to study the electron velocity effect (?)

- Cross section measurement
  - High efficiency with a no pileup beam
  - The acceptance of the process in PADME has to be estimated
  - Comparison between numerical calculation and measured value

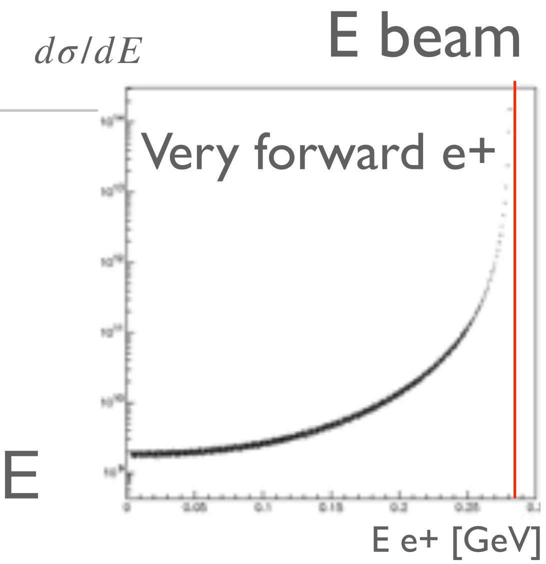
- Same final state in visible A' decay coupled with the SM photon
  - Search for X17
  - PADME is not able to extract the resonance mass from the charged particles, but the photon can give the mass of e^+e^- as for the missing mass case!

All process are not statistically limited!

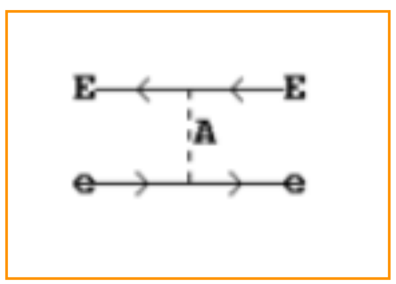
SM PHYSICS

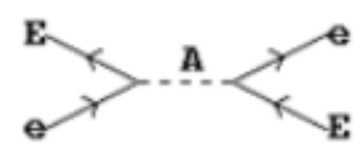
- $e^+e^- \rightarrow$
  - Photons
  - Photon and charge particles
  - Leptons
    - $e^+e^- \rightarrow e^+e^-$
    - $e^+e^- \rightarrow e^+e^-e^+e^-$
    - $e^+e^- \rightarrow e^+e^-e^+e^-e^+e^-$

$e^+e^- \rightarrow e^+e^-$



- Bhabha scattering final state
  - A positron -> detected using pVeto
  - An electron-> mainly with low energy -> not detected in PADME





From CalcHEP $\sigma(e^+e^- \rightarrow e^+e^-) \sim 0.5$ b

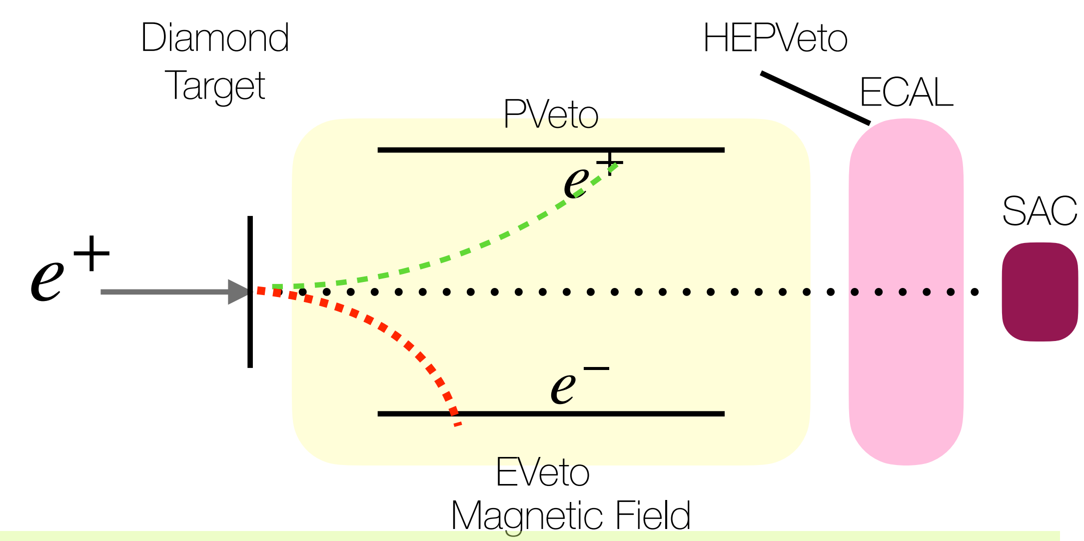
$\sigma(e^+e^- \rightarrow e^+e^-) \sim 3.3 \times 10^{-3}$ b if $E_{e+/-} > 50$ MeV

PROCESS	#EV/DAY	#EV/DAY X ACC
$e^+e^- \rightarrow e^+e^-$	6×10^8	4×10^6

PADME today
- 27000 POT/bunch
- 49 bunch/s

Visible with reduced intensity

Most of the experiments extract the luminosity from Bhabha



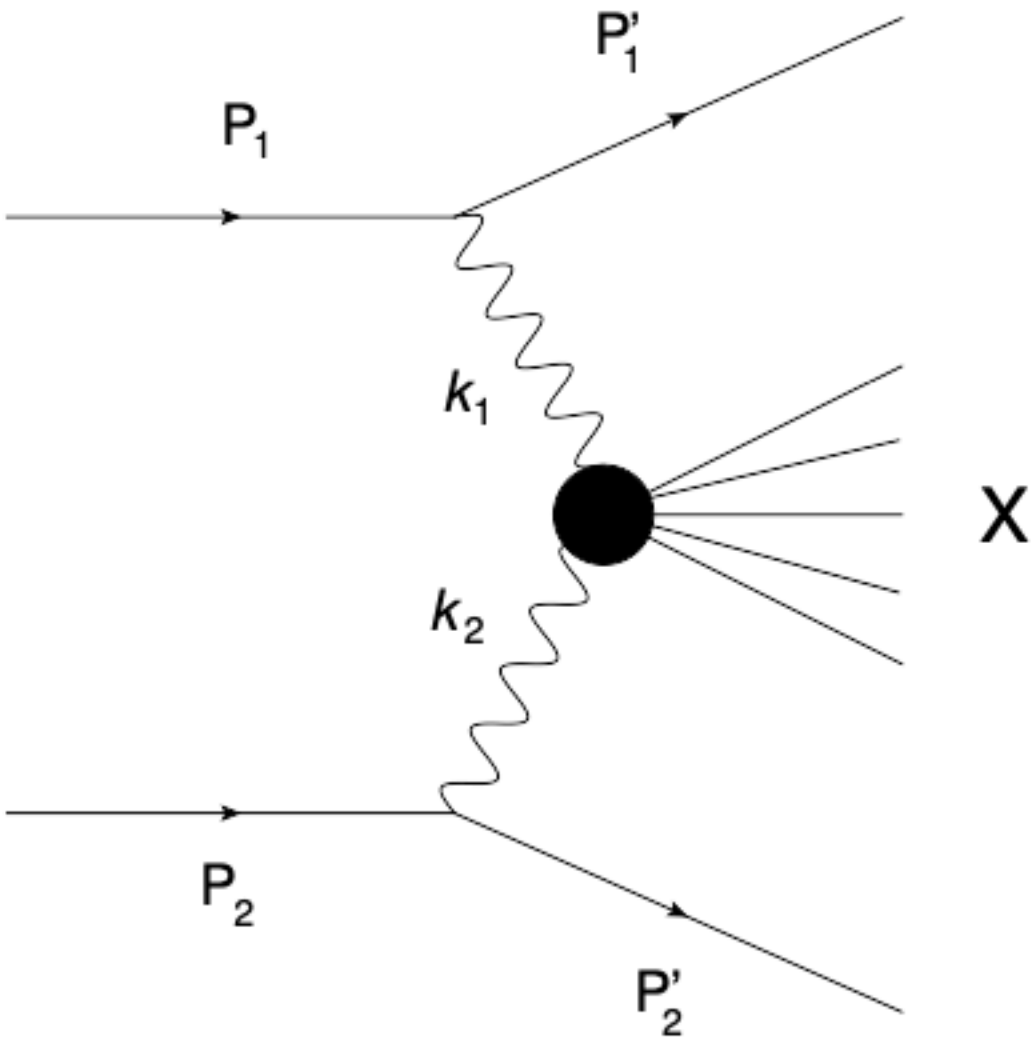
Visible decay of the dark photon is $A' \rightarrow e^+e^-$
- Charged particles should be ~symmetrical in energy
- Possible channel to verify in resonance production X_{17}

SM PHYSICS

- $e^+e^- \rightarrow$
  - Photons
  - Photon and charge particles
  - Leptons
    - $e^+e^- \rightarrow e^+e^-$
    - $e^+e^- \rightarrow e^+e^-e^+e^-$
    - $e^+e^- \rightarrow e^+e^-e^+e^-e^+e^-$

4LEPTONS AND 6LEPTONS PROBLEM

- $e^+e^- \to e^+e^-X$ or $\gamma\gamma \to X$ (gamma gamma scattering)
- For this studies we consider
  - $X \to e^+e^-$
  - $X \to e^+e^-e^+e^-$
- Processes hard to calculate even at tree level
  - Huge number of Feynman diagrams
  - For 6l decay
    - six-body phase space
    - No tree level analytical or numerical calculation



$e^+e^- \rightarrow e^+e^-e^+e^-$

- No exact analytic expression for the QED tree level cross section. However it is extracted using some approximations [2] [3]
- Equivalent Photon Approximation (EPA) at leading log
  - $\sigma(e^+e^- \rightarrow e^+e^-e^+e^-) \approx \frac{28\alpha^4}{27\pi m_e^2}\left(log\frac{s}{m_e^2}\right)^3$
  - Complete analytical calculation
  - $\sigma(e^+e^- \rightarrow e^+e^-e^+e^-) \approx \frac{28\alpha^4}{27\pi m_e^2}\left[\left(log\frac{s}{m_e^2}\right)^3 - A\left(log\frac{s}{m_e^2}\right)^2 + B\left(log\frac{s}{m_e^2}\right) + C\right] + O\left(\frac{1}{s}\right)$
  - $A = 178/28 \sim 6.36$
  - $B \sim -11$
  - $C \sim 100$

S center of mass energy
fixed target experiment
$s \sim 2E_{beam}m_e$

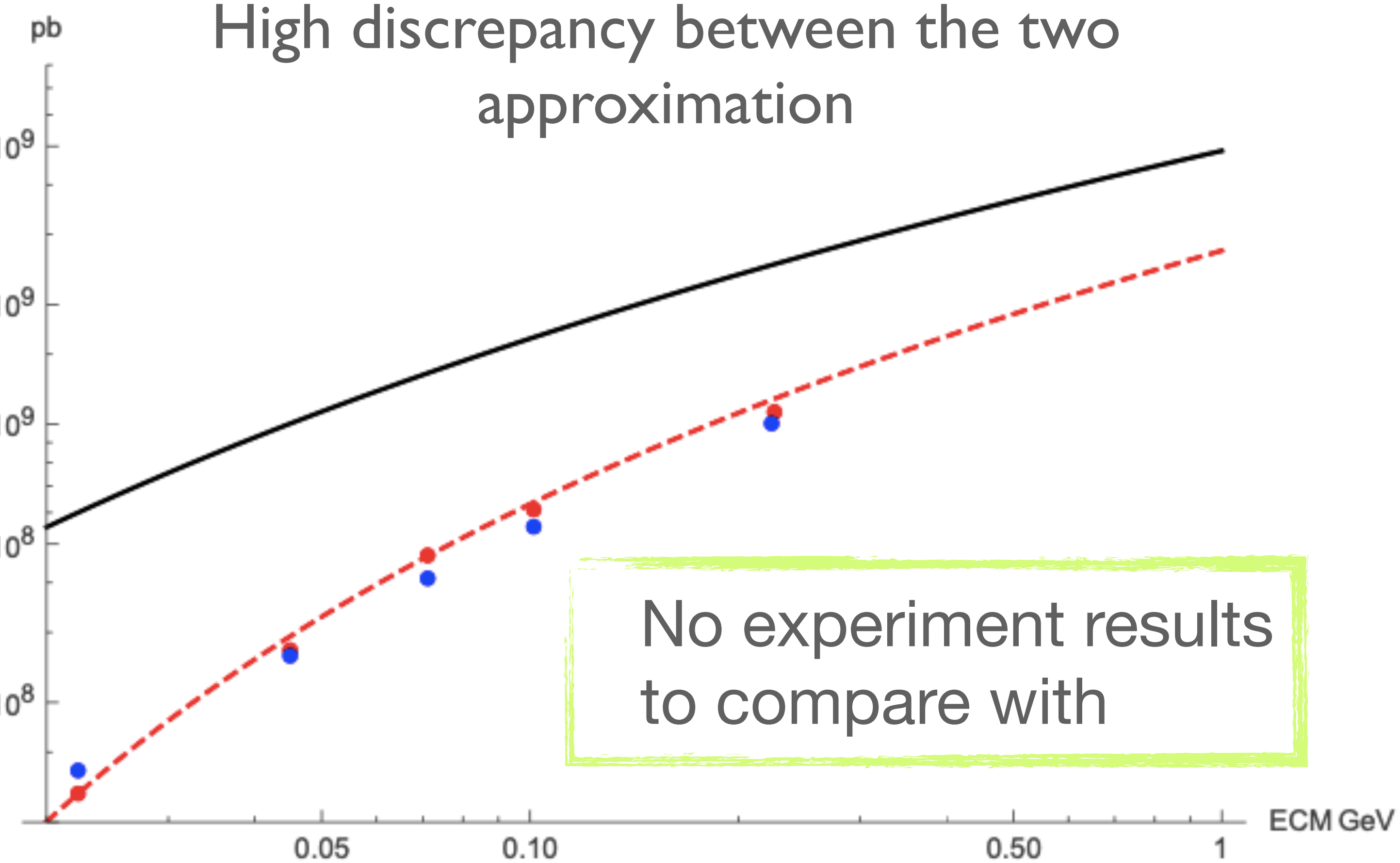
Cancellation of the cross section logarithmic terms. Measurement of the constant one.

- Tree level numerical calculation using CalcHEP tool
- Approximate analytic expression

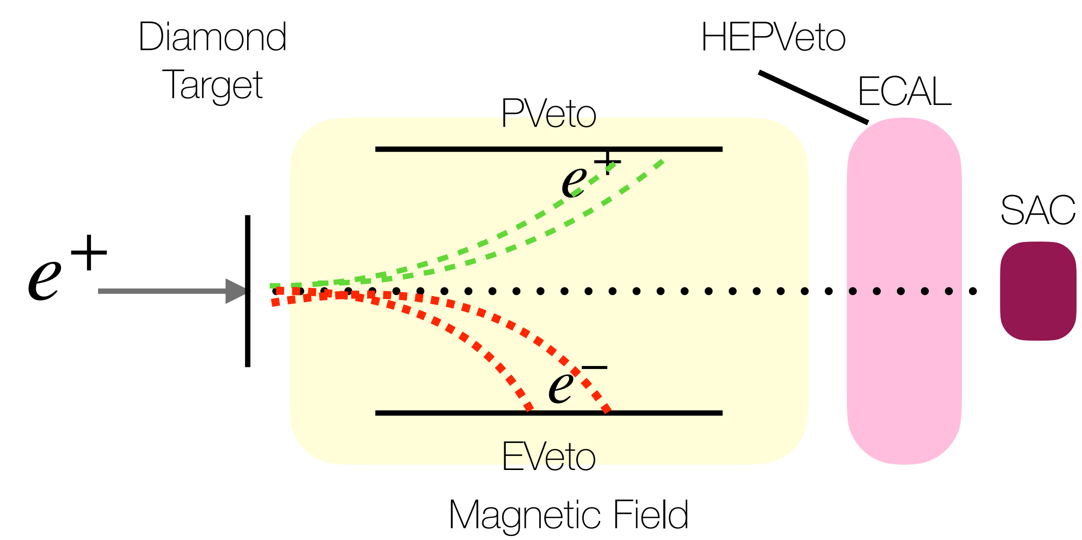
$e^+e^- \to e^+e^-e^+e^-$

[2]

High discrepancy between the two approximation



- LLEPA
- FullEPA
- CalcHEP
- Numerical EPA



PADME $E_{beam} = 500$ MeV, fullEPA gives [2]

$$\sigma(e^+e^- \to e^+e^-e^+e^-) \sim (6.0 - 5.0 - 1.16 + 1.4) \times 10^8 = 1.2 \times 10^8 \text{ pb}$$

PROCESS	#EV/DAY	#EV/DAYXACC
$e^+e^- \to e^+e^-e^+e^-$	2.4×10^5	Not known

PADME today

- 27000 POT/bunch
- 49 bunch/s

SM PHYSICS

- $e^+e^- \rightarrow$
  - Photons
  - Photon and charge particles
  - Leptons
    - $e^+e^- \rightarrow e^+e^-$
    - $e^+e^- \rightarrow e^+e^-e^+e^-$
    - $e^+e^- \rightarrow e^+e^-e^+e^-e^+e^-$

$e^+e^- \rightarrow e^+e^-e^+e^-e^+e^-$

- Cross section very hard to calculate due to the high number of particles in the final state producing several thousand of Feynman diagrams which contribute to the amplitude [2]
- Leading log EPA approximation
  - $$\sigma(e^+e^- \rightarrow e^+e^-e^+e^-e^+e^-) = \frac{\alpha^2}{6\pi^2}\sigma(\gamma\gamma \rightarrow e^+e^-e^+e^-)\left(log\frac{s}{m_e^2}\right)^4$$
- in the present literature there is no full analytic expression nor numerical calculation for the 6l case. Numerical EPA approximation better estimates the tree level cross section
  - $$\sigma(e^+e^- \rightarrow e^+e^-e^+e^-e^+e^-) = \frac{28\alpha^2}{6\pi}\sigma(\gamma\gamma \rightarrow e^+e^-e^+e^-)\left[\left(log\frac{s}{m_e^2}\right)^4 + A\left(log\frac{s}{m_e^2}\right)^3 + B\left(log\frac{s}{m_e^2}\right)^2 + C\left(log\frac{s}{m_e^2}\right) + D\right]$$
    - Where
    - $A \sim -11.9$
    - $B \sim 22.62$
    - $C \sim 143.5$
    - $D \sim -521.1$

Cancellation of the cross section logarithmic terms. Measurement of constant one.

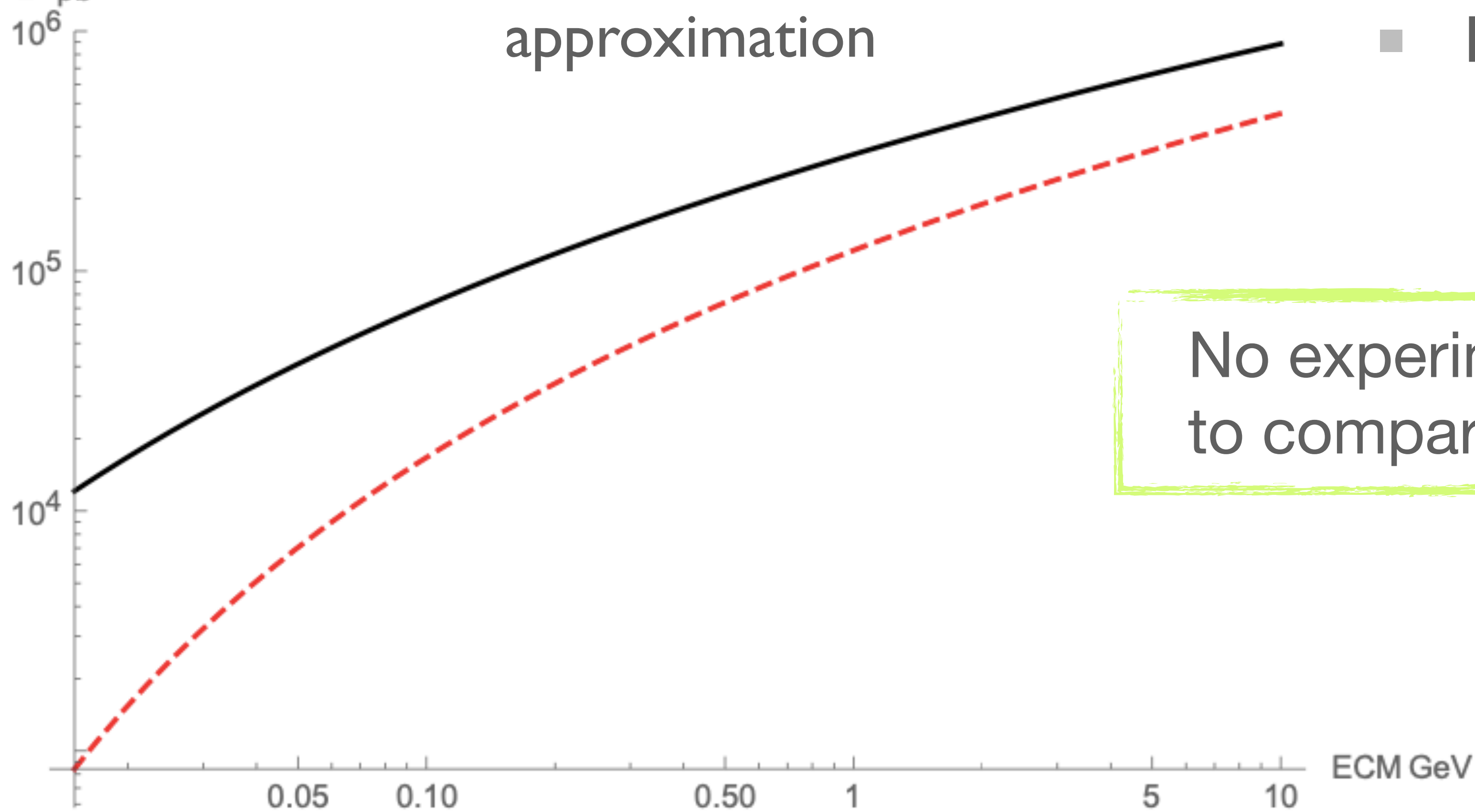
- a numerical result for the cross section using both CalcHEP and MadGraph tools failed

[2] "Searching for dark sectors in multi lepton final state in e+ e- collisions"

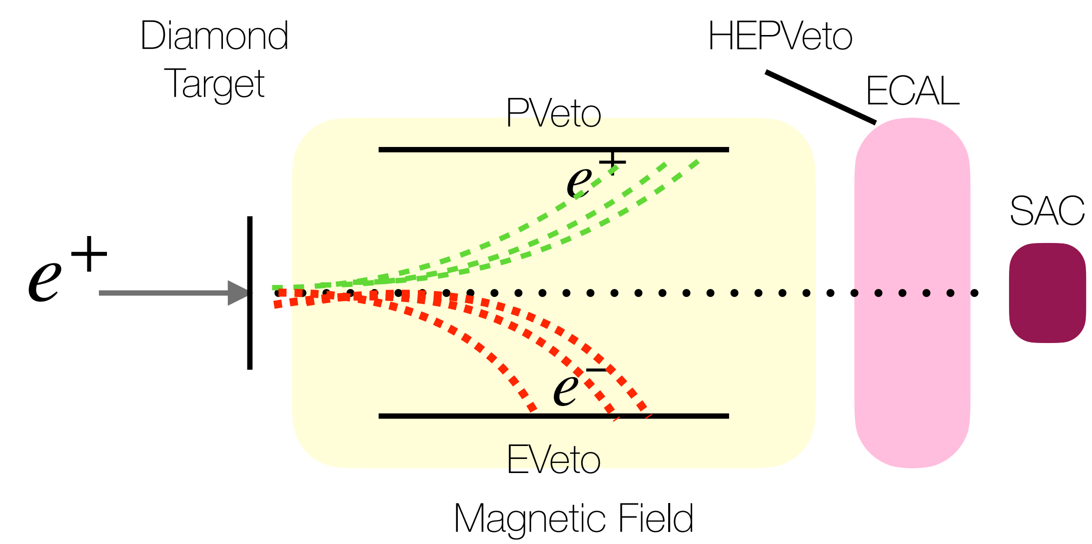
$e^+e^- \to e^+e^-e^+e^-e^+e^-$

[2]

High discrepancy between the two approximation



No experiment results to compare with



PADME $E_{beam} = 500$ MeV, fullEPA gives [2]

$\sigma(e^+e^- \to e^+e^-e^+e^-e^+e^-) \sim 1500$ pb

PROCESS	#EV/DAY	#EV/DAYXACC
$e^+e^- \to e^+e^-e^+e^-e^+e^-$	2	Not known

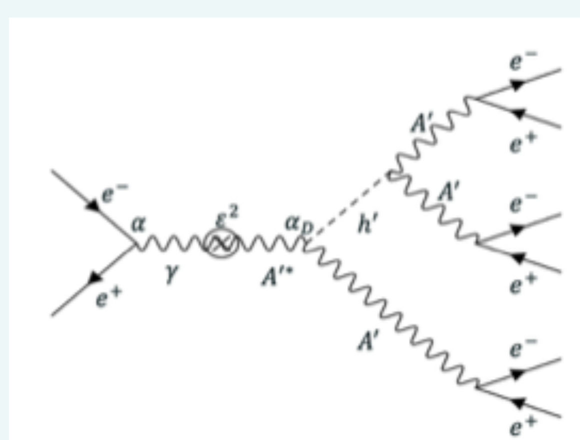
PADME today

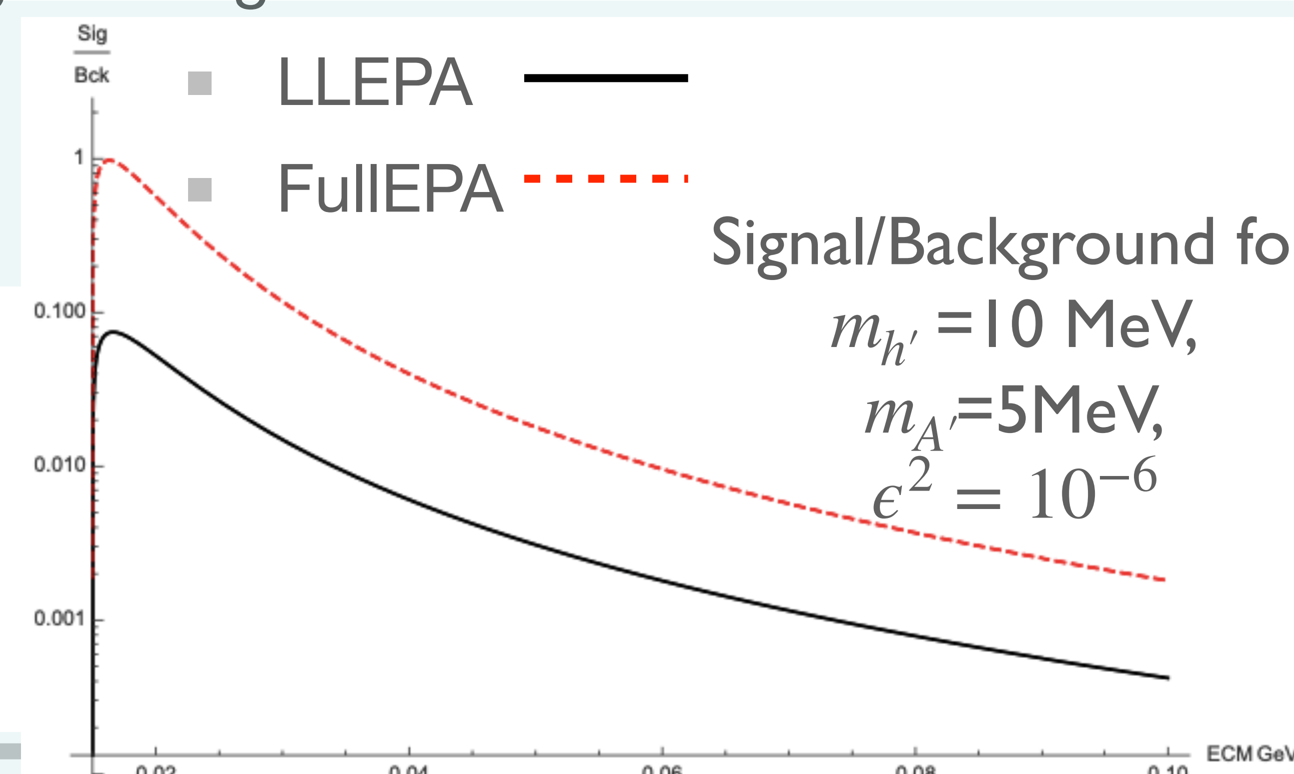
- 27000 POT/bunch
- 49 bunch/s

SIX LEPTON FINAL STATE IN PADME

- PADME can measure annihilation in six leptons cross section
  - No high background pileup in standard run condition (27 kPOT/bunch)
  - The time coincidence of six leptons in Veto suppresses the backgrounds
  - If the veto is used as spectrometer , requiring that the sum of all momentums is comparable with beam energy would increase the S/B ratio
  - The PADME charged particle vetos detect $e^{+/-}$ with E>50 MeV
    - The acceptance is expected to be very low in the present run condition. But can be increased by reducing the magnetic field

- Dark contribution can have sizeable impact on the total cross section





CONCLUSIONS

- PADME can investigate several SM processes in a short data taking time. The cross sections can be measured for the first time with a beam energy of ~500 MeV
- If a continuum beam is used, with a single positron/ns, the pileup will be negligible-> low systematics
  - $\mathrm{POT/day} \sim 10^{14}\mathrm{POT}$ -> the processes yield should increase of three orders of magnitude
  - Negligible pileup allows recovering acceptance at low angle
  - The limited time required for the data taking to have enough statistic allow us to choose a specific run condition for each process

$\boxed{\mathrm{POT/day} = 1.11 \times 10^{11}}$

PROCESS	#EV/DAY	$\#\mathrm{ev/day} \times \mathrm{acc}$	PADME NOW
$e^+e^- \to \gamma\gamma$	1.8×10^6	1.3×10^5	Precision (5-10)%
$e^+e^- \to \gamma\gamma\gamma$	1.9×10^5	Not known	Precision (5-10)%
$e^+N \to e^+N\gamma$	4.7×10^9	Not known	✓
$e^+e^- \to e^+e^-\gamma$	2.2×10^8	1.5×10^5	✓
$e^+e^- \to e^+e^-e^+e^-$	2.4×10^5	Not known	Few events
$e^+e^- \to e^+e^-e^+e^-e^+e^-$	2	Not known	✗

REFERENCES

- [1] V. Kozhuharov , “Background in the search for dark photon in e^+e^- annihilation”, DOI: 10.1051/epjconf/201714201018
- [2] P.Ciafaloni, G.Martelli, M.Raggi, “Searching for dark sectors in multi lepton final state in e+ e- collisions”, arXiv:2012.04754
- [3]V. M. Budnev, I. F. Ginzburg, G. V. Meledin and V. G. Serbo, “The Two photon particle production mechanism. Physical problems. Applications. Equivalent photon approximation”, DOI: 10.1016/0370-1573(75)90009-5