First results from the PADME experiment

- getting ready for dark sector studies -

Isabella Oceano* on behalf of the PADME Collaboration

*Università del Salento, INFN Le

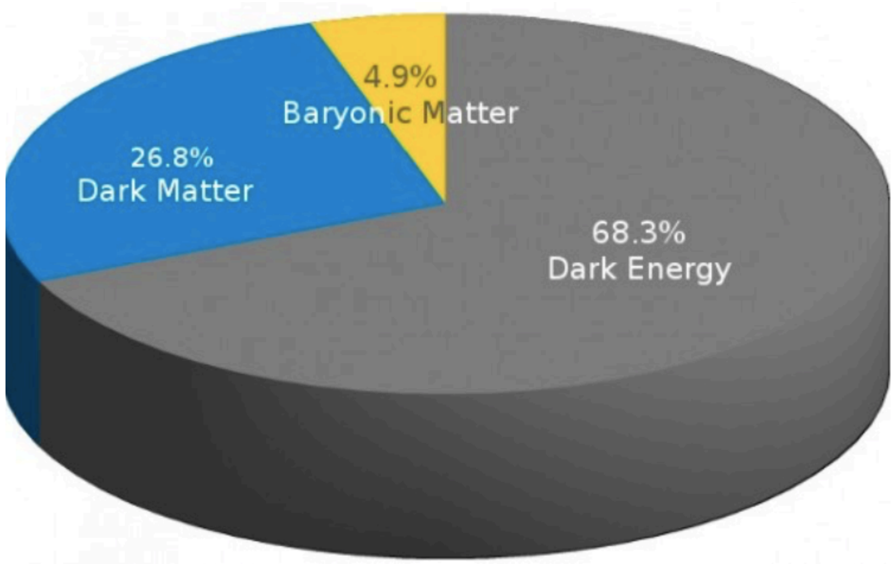
Rencontres de Moriond, Electroweak Interactions & Unified Theories

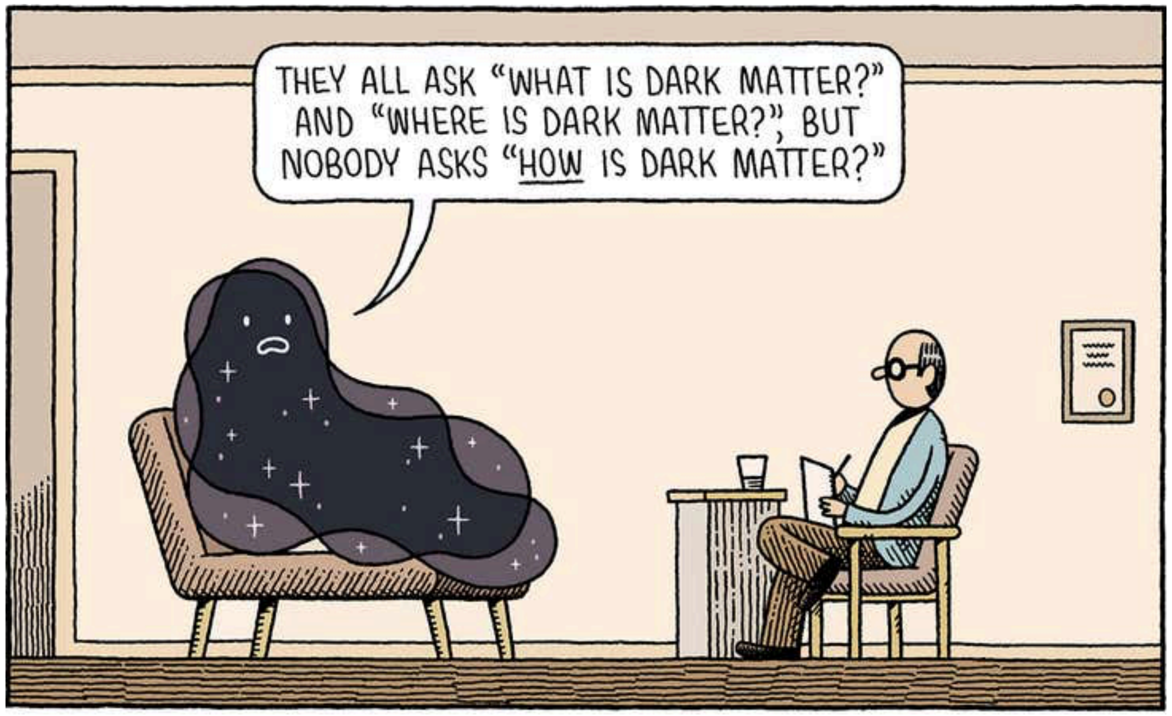
Outline

- PADME experiment
  - Testing the dark photon hypothesis
- Data taking
- $e^+e^- \to \gamma\gamma$ selection technique in PADME
- Annihilation cross section measurement
- Conclusions

Dark matter indications

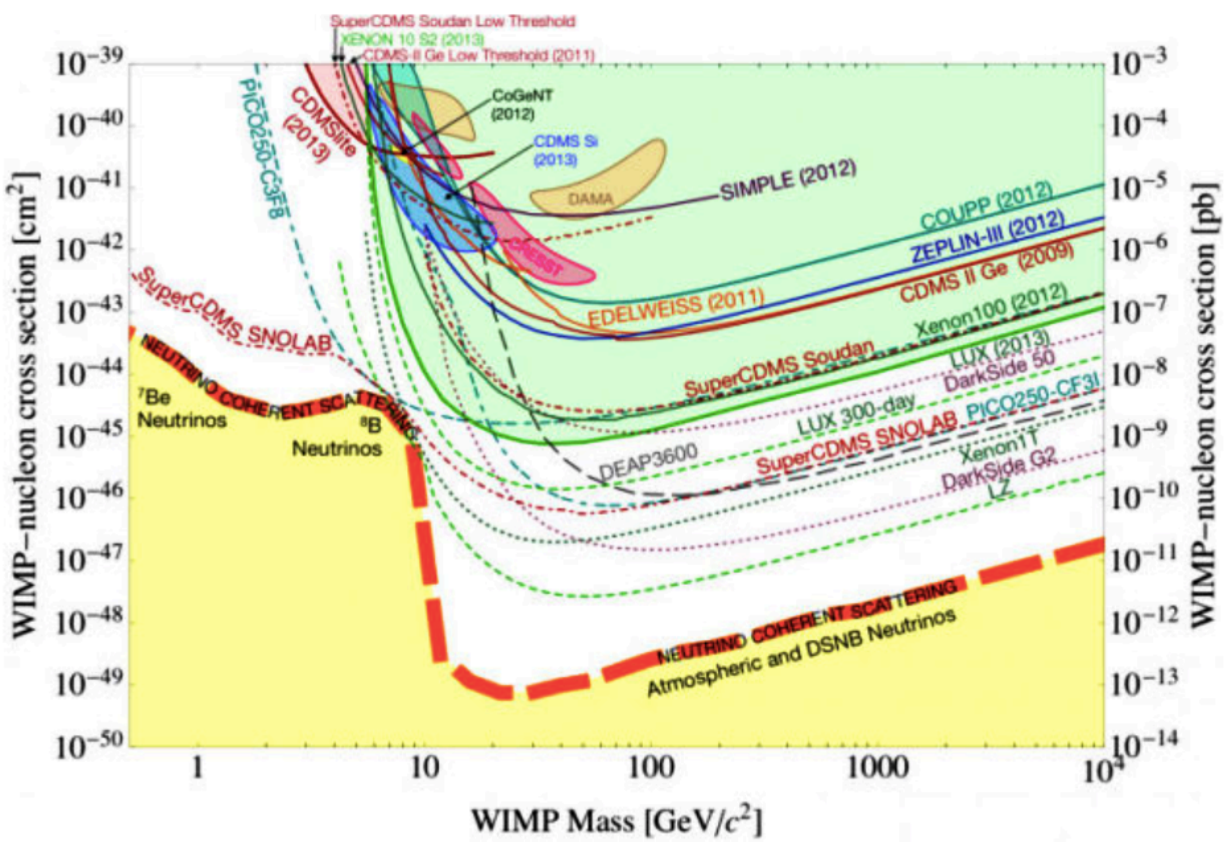
- Galactic rotation curves
- Galaxy clusters & GR lensing
- Bullet Cluster
- Velocity dispersions of galaxies
- Cosmic Microwave Background
- Baryon Acoustic Oscillations
- Type Ia supernovae distance measurements
- Big Bang Nucleosynthesis (BBN)
- Structure formation
- Several other hints





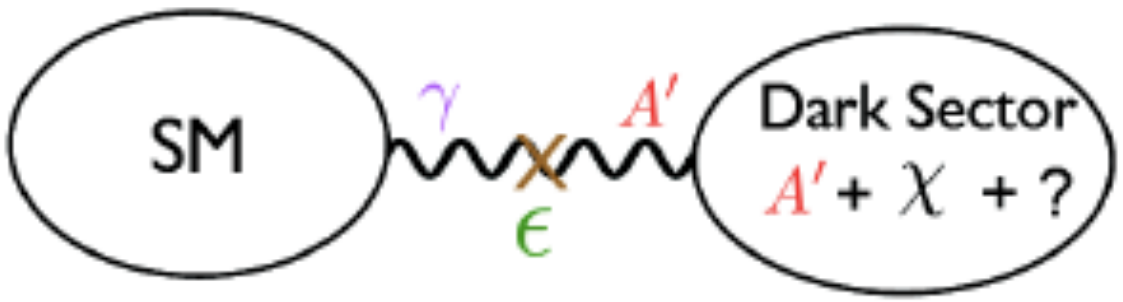
A new gauge boson

- Candidates challenged by LHC and direct detection experiments



- There are many possible ways to introduce the Dark Matter into the Standard Model
- A simple way to go beyond the SM
  - $SU(3) \times SU(2) \times U(1)_Y \times U(1)_D$
  - A new gauge symmetry $U(1)_D$ and a new photon: A'
    - Only dark matter charged under $U(1)_D$
  - Several mechanisms may be responsible for the A' mass (Higgs-like, Stuckelberg)

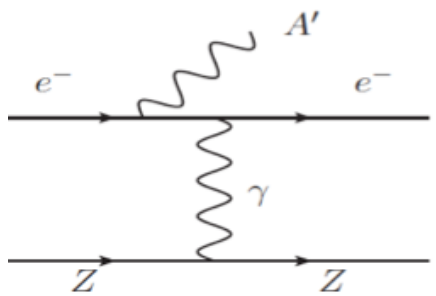
- Weak interaction with SM through ϵ
  - $L_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$



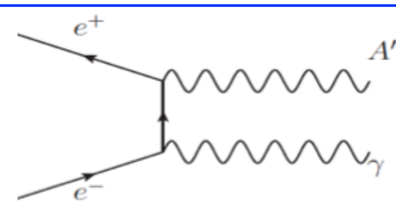
Kinetic mixing coefficient

A' production and decay channels

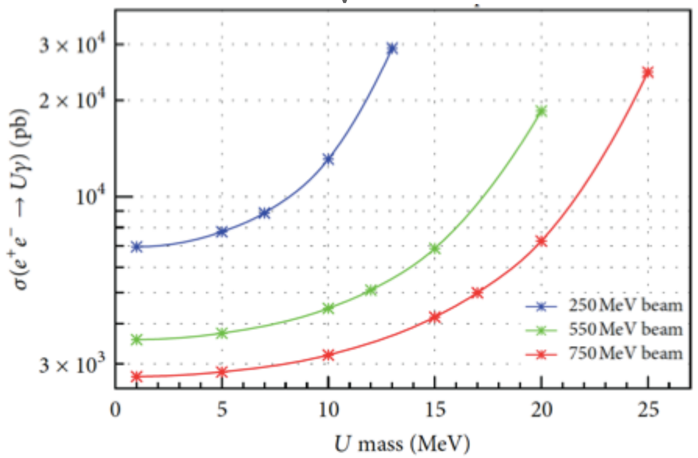
- Production mechanism allowed
  - A-strahlung
    - $\sigma \propto \frac{\alpha^3 \epsilon^2}{m^2_{A'}}$



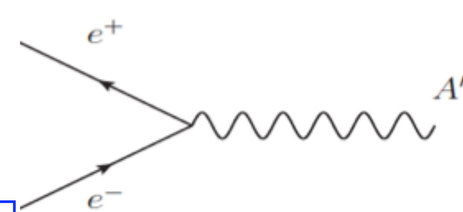
  - Associated production



    - If $m_{A'} << s$
      $\sigma \propto 2\epsilon^2 \sigma(e^+e^- \to \gamma\gamma)$
    - Limited range in mass
      $m_{A'} \leq \sqrt{2 m_e E_{beam}}$



  - Resonant annihilation

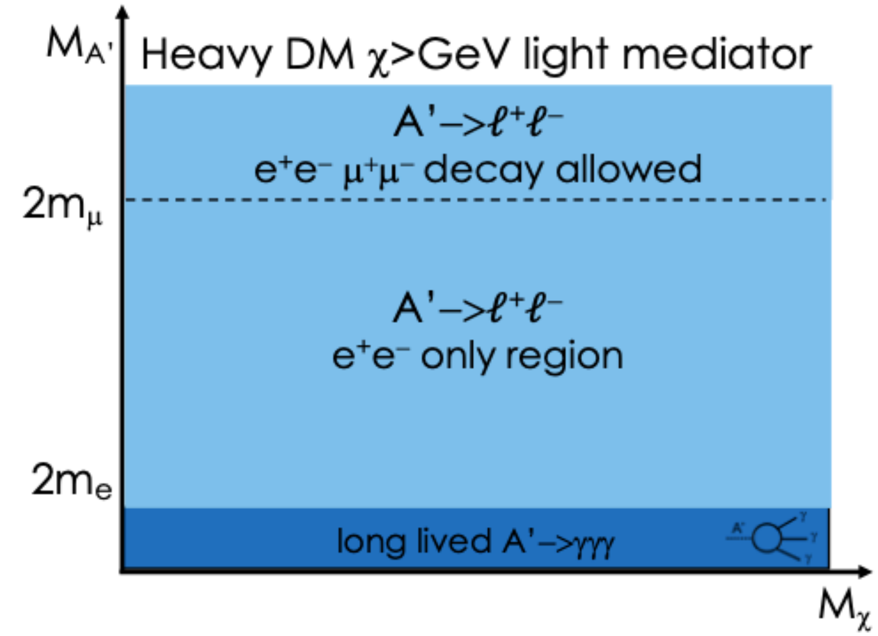


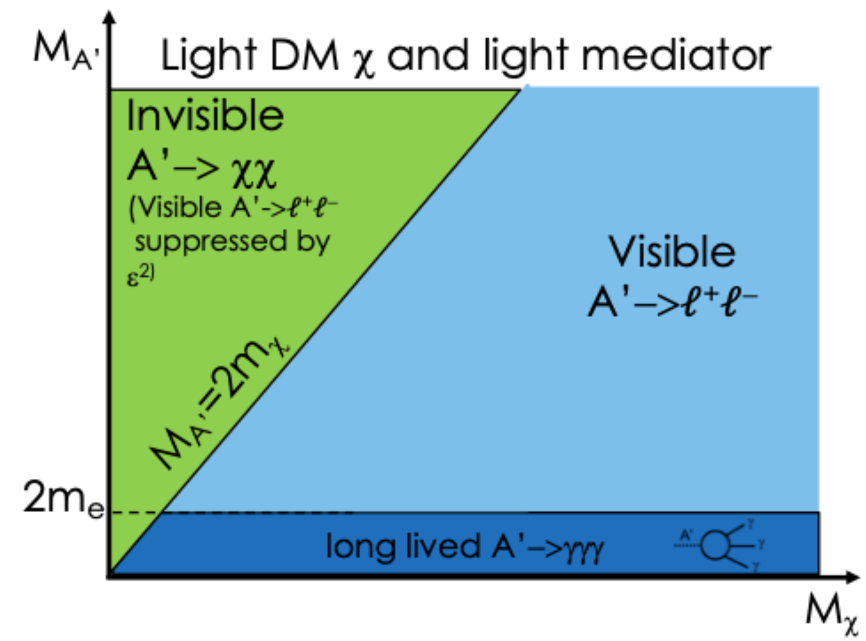
Allowed only with e^+ beam

Decays

– To SM particles if $2M_{DM} > M_{A'} > 2m_e$

– To DM (invisible) particles if $2M_{DM} < M_{A'}$



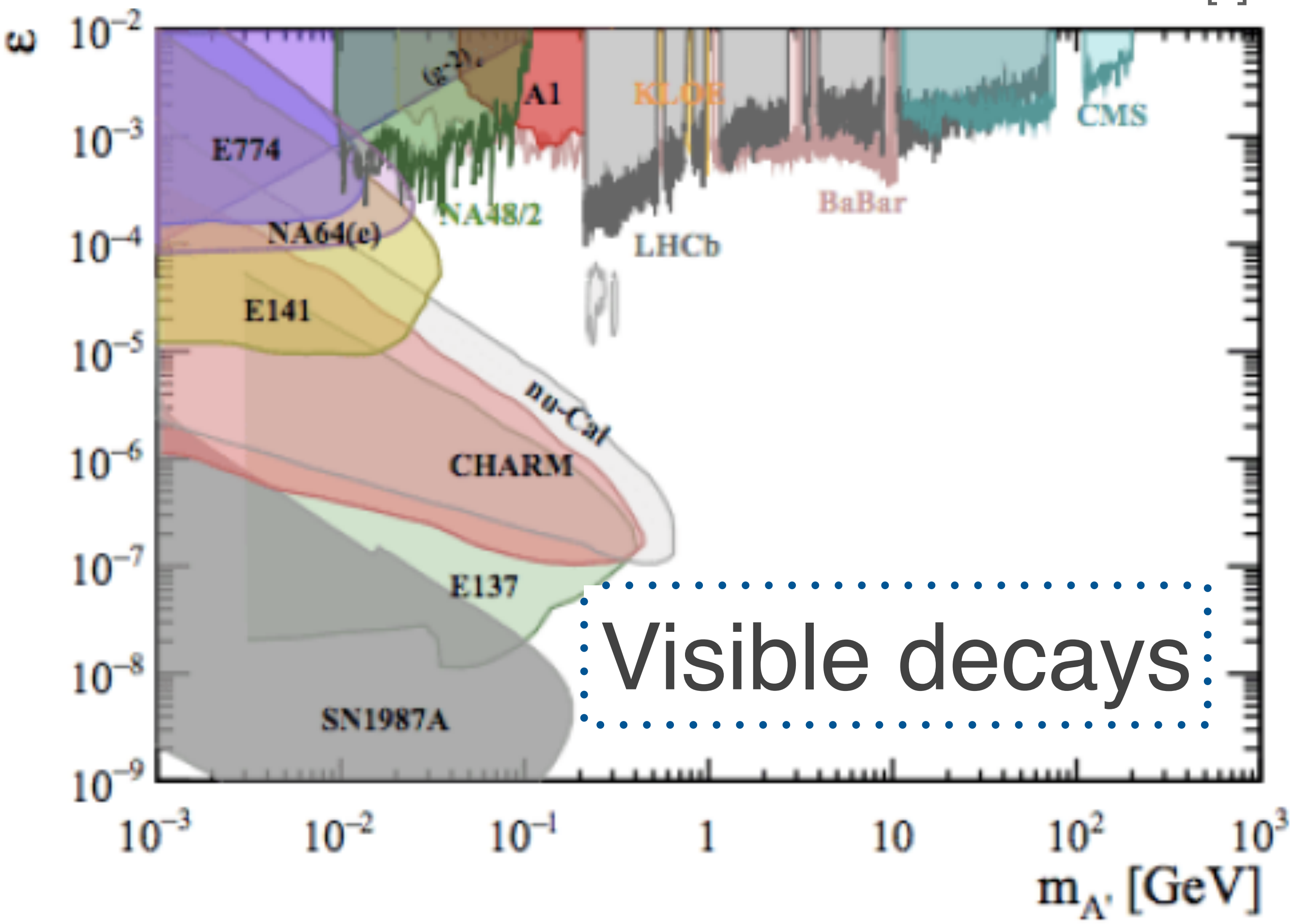


A' search
-visible decay
-invisible decay

Constraints from searches

[1]10.1007/978-3-030-62519-1

[1]



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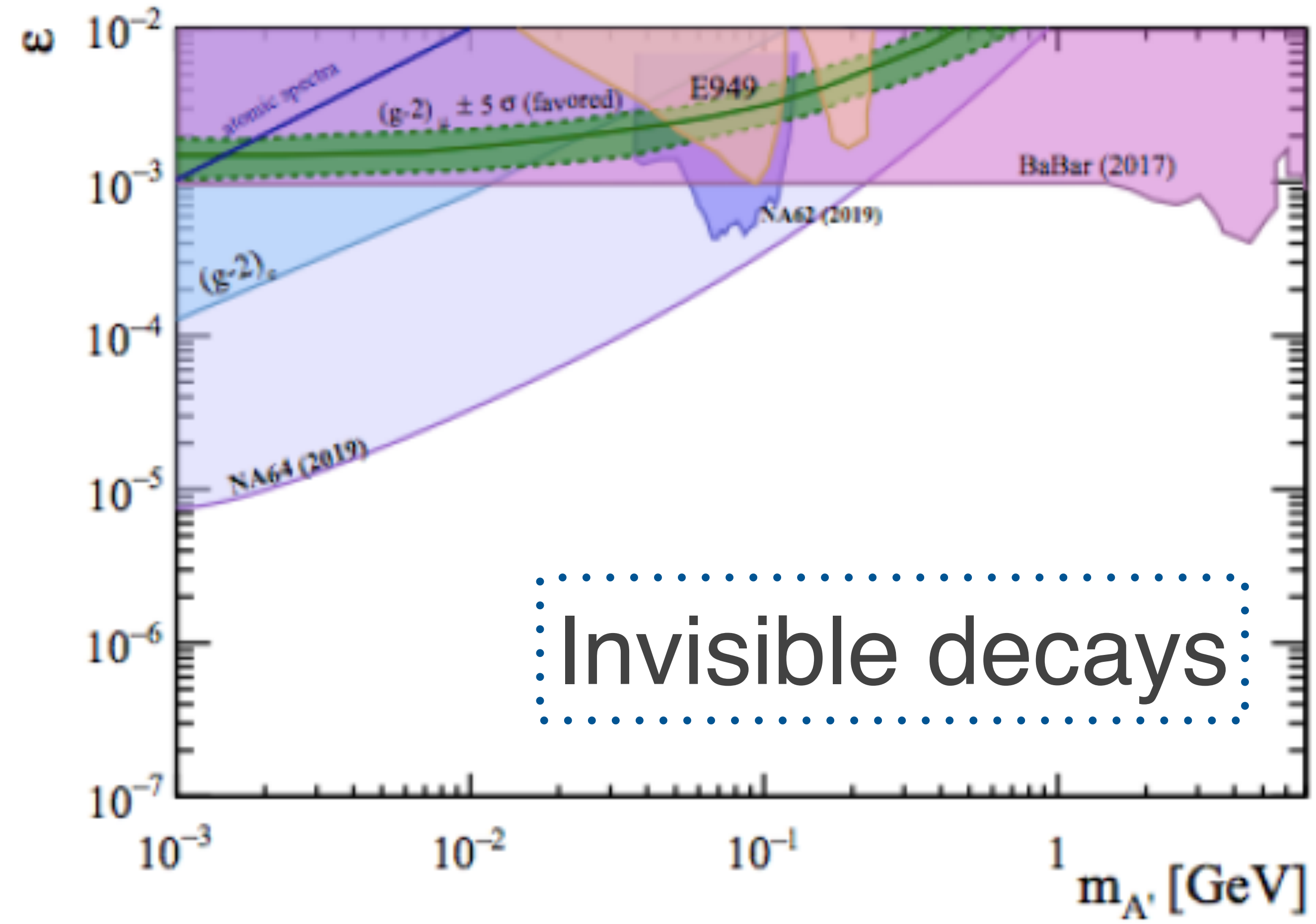

Visible search technique

- bump-hunting and/or detached vertexing
- fixed target experiments
- Beam dump experiments
- colliders

Invisible search technique

- missing mass
- missing momentum
- missing energy

Constraints from searches

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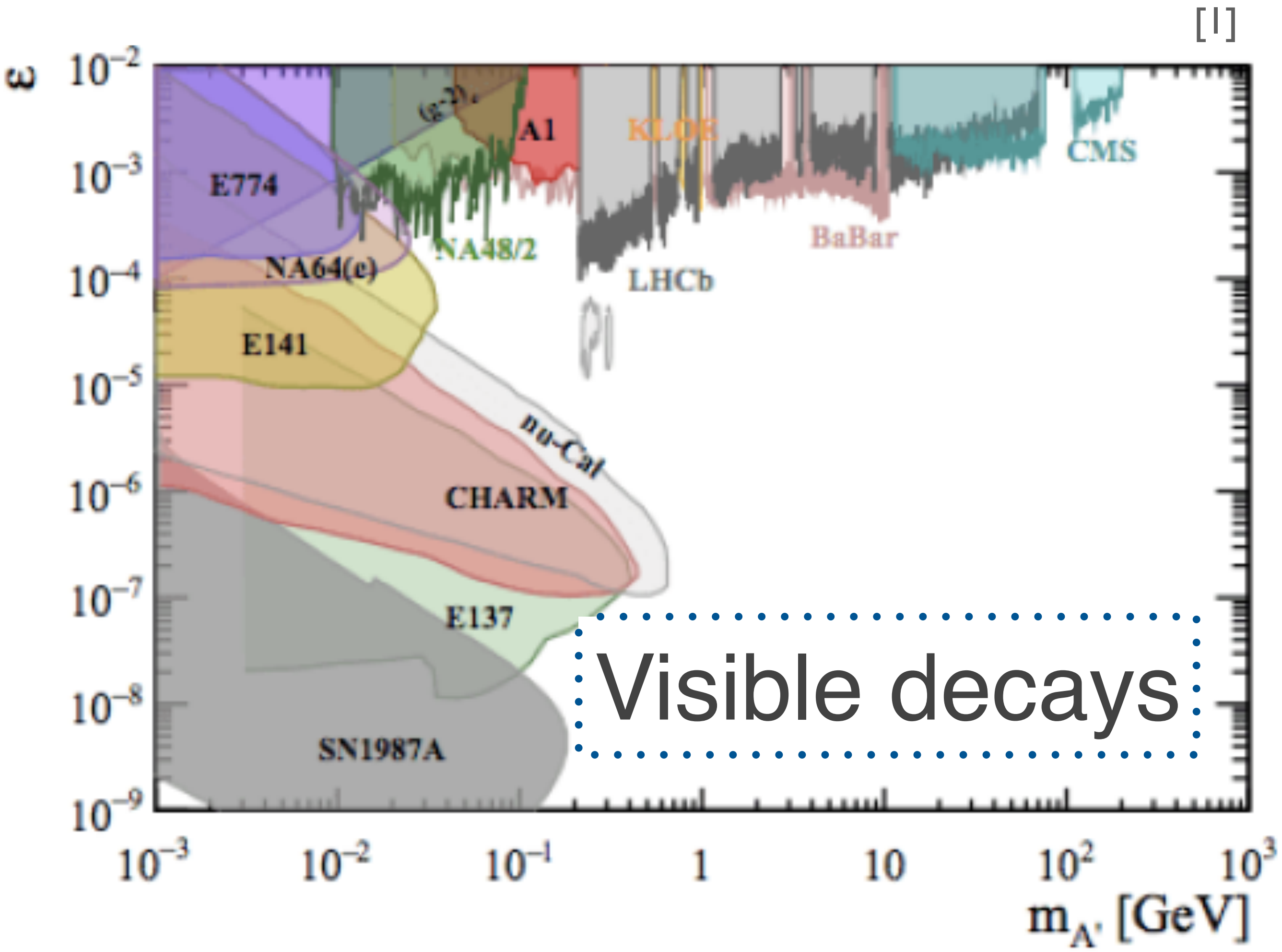
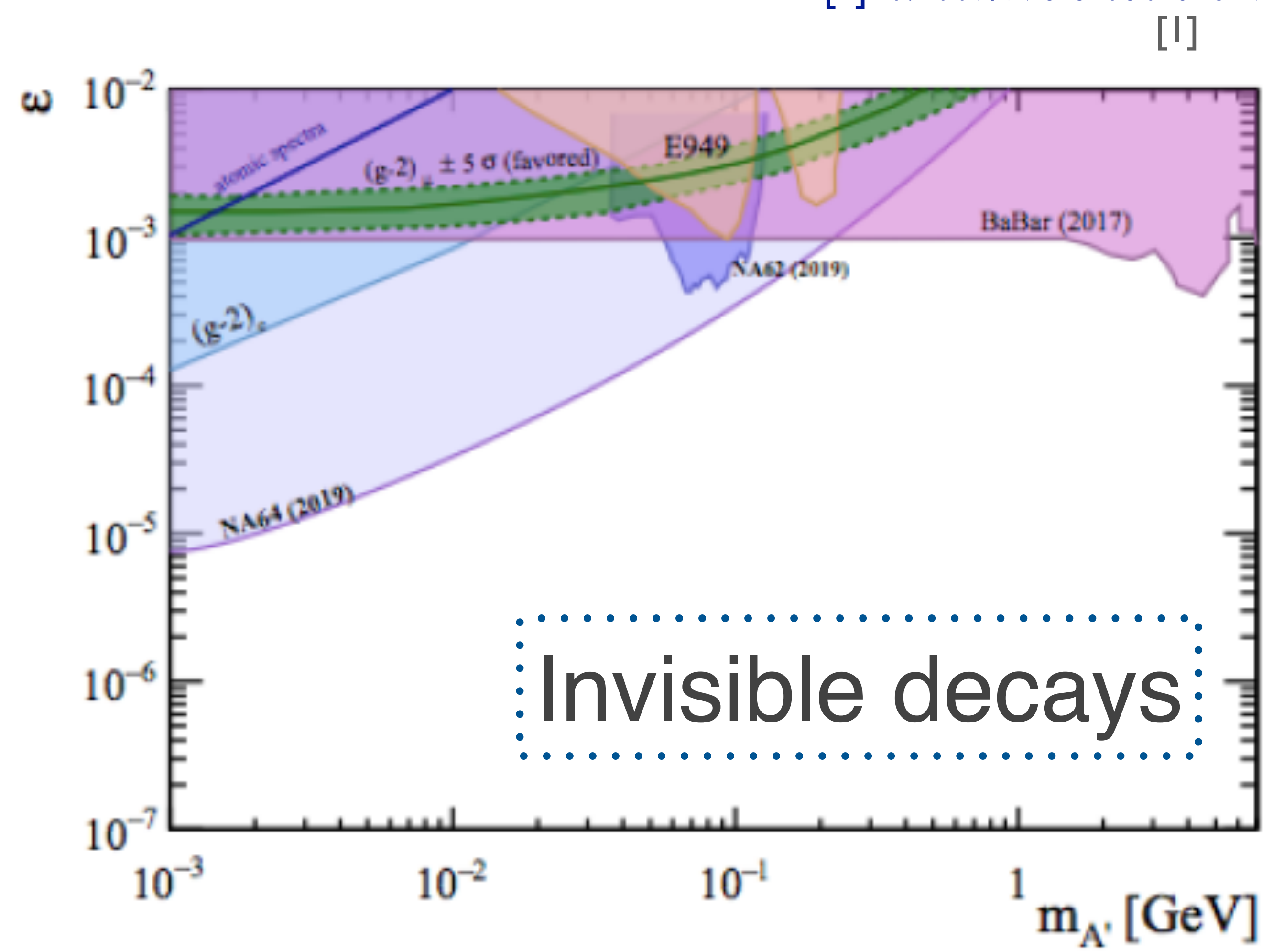




Visible search technique

- beam dump experiments
- fixed target experiments with bump-hunting
- fixed target experiments with detached vertexing
- colliders

Invisible search technique

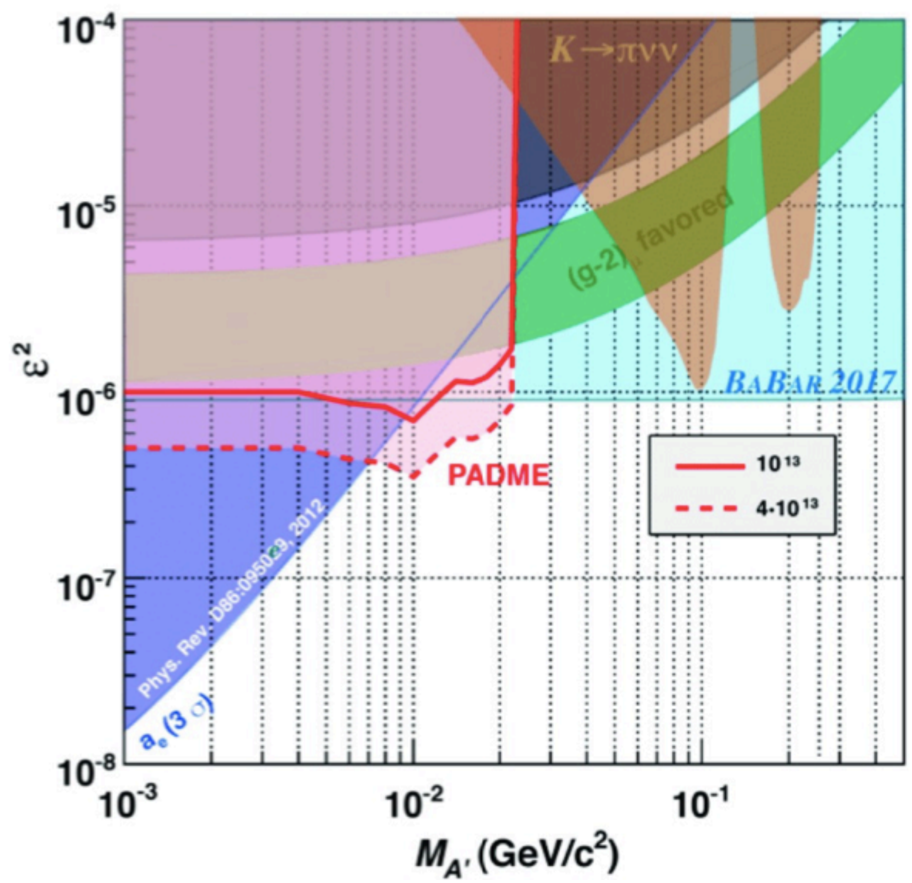
- **missing mass**
- missing momentum
- missing energy

Positron Annihilation into Dark Matter Experiment

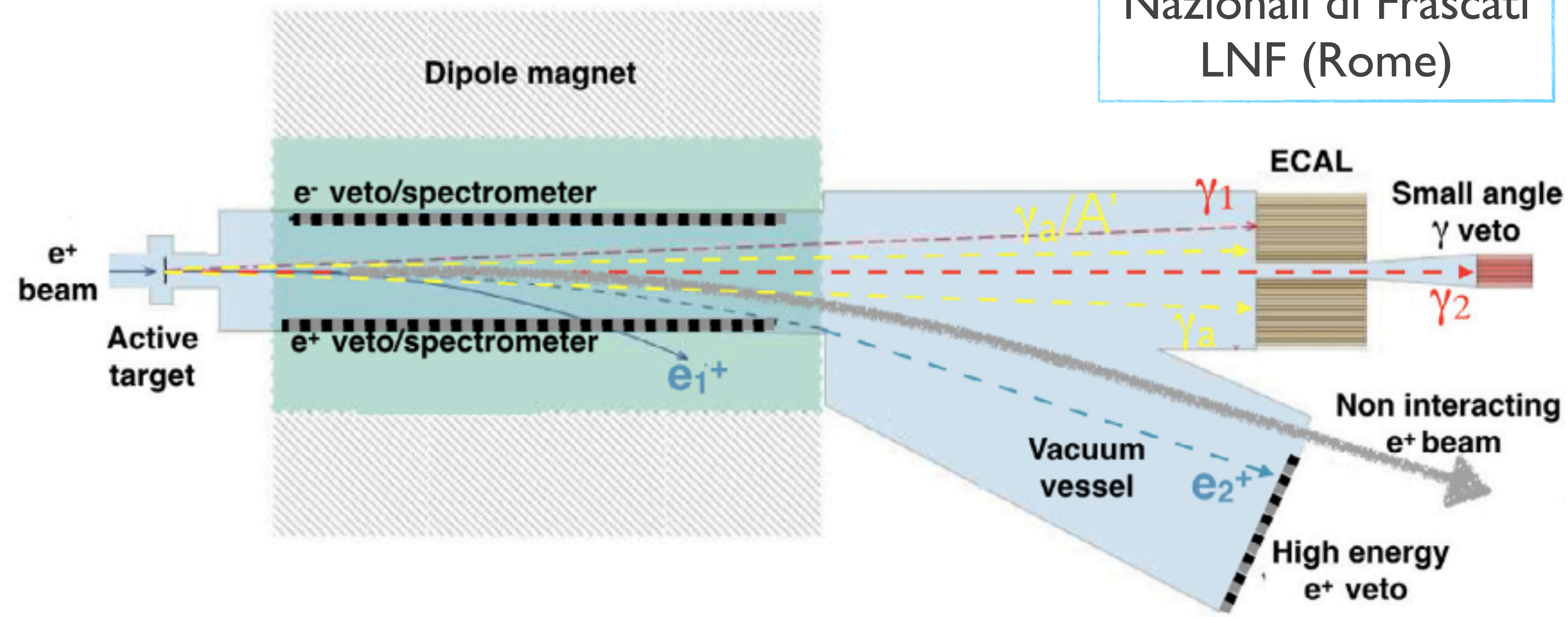
- e^+ fixed target experiment searching for dark photons with $M_{A'} \leq 23.7$ MeV

A' production and decay
- $e^+e^- \to \gamma A'$
- A' invisible decay

A' detection
- Missing mass technique used
  Goal: 4×10^{13} POT (Positrons On Target)

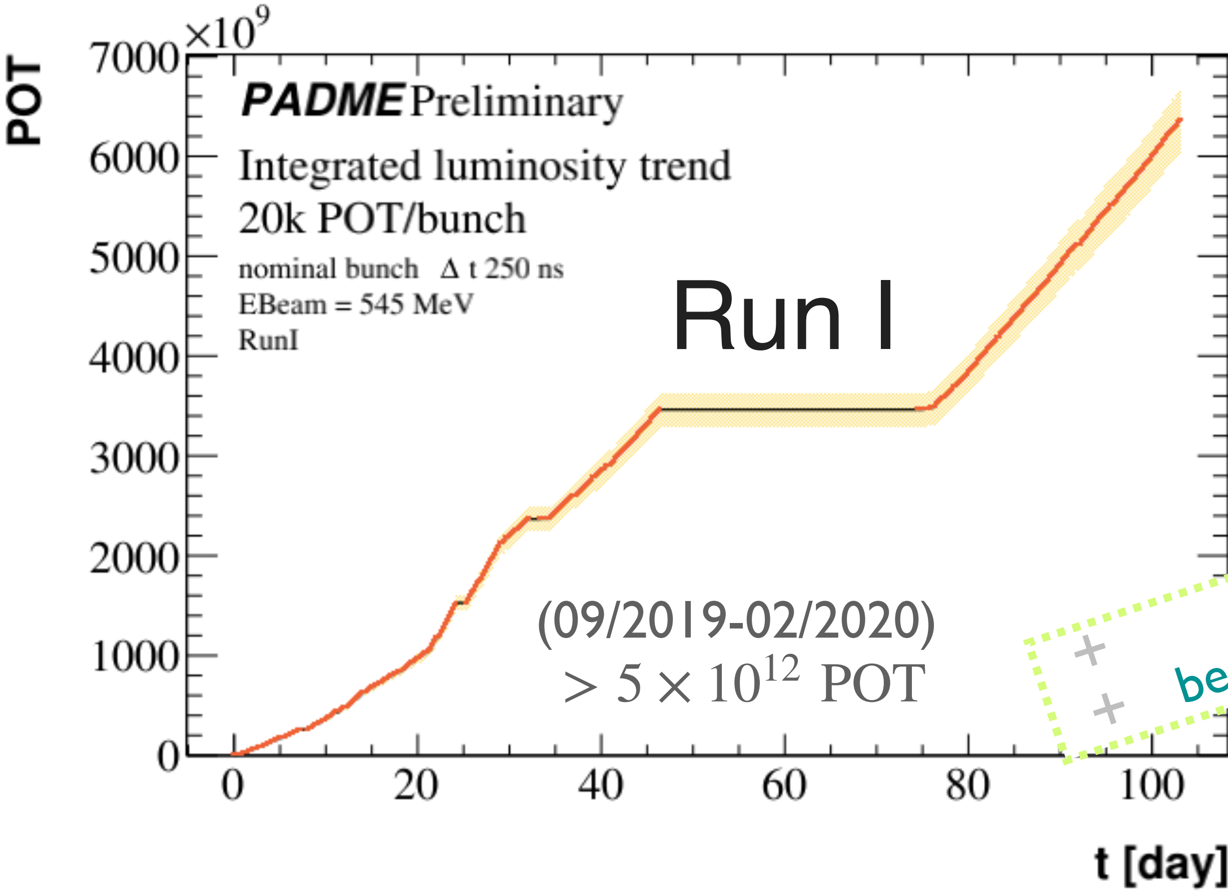


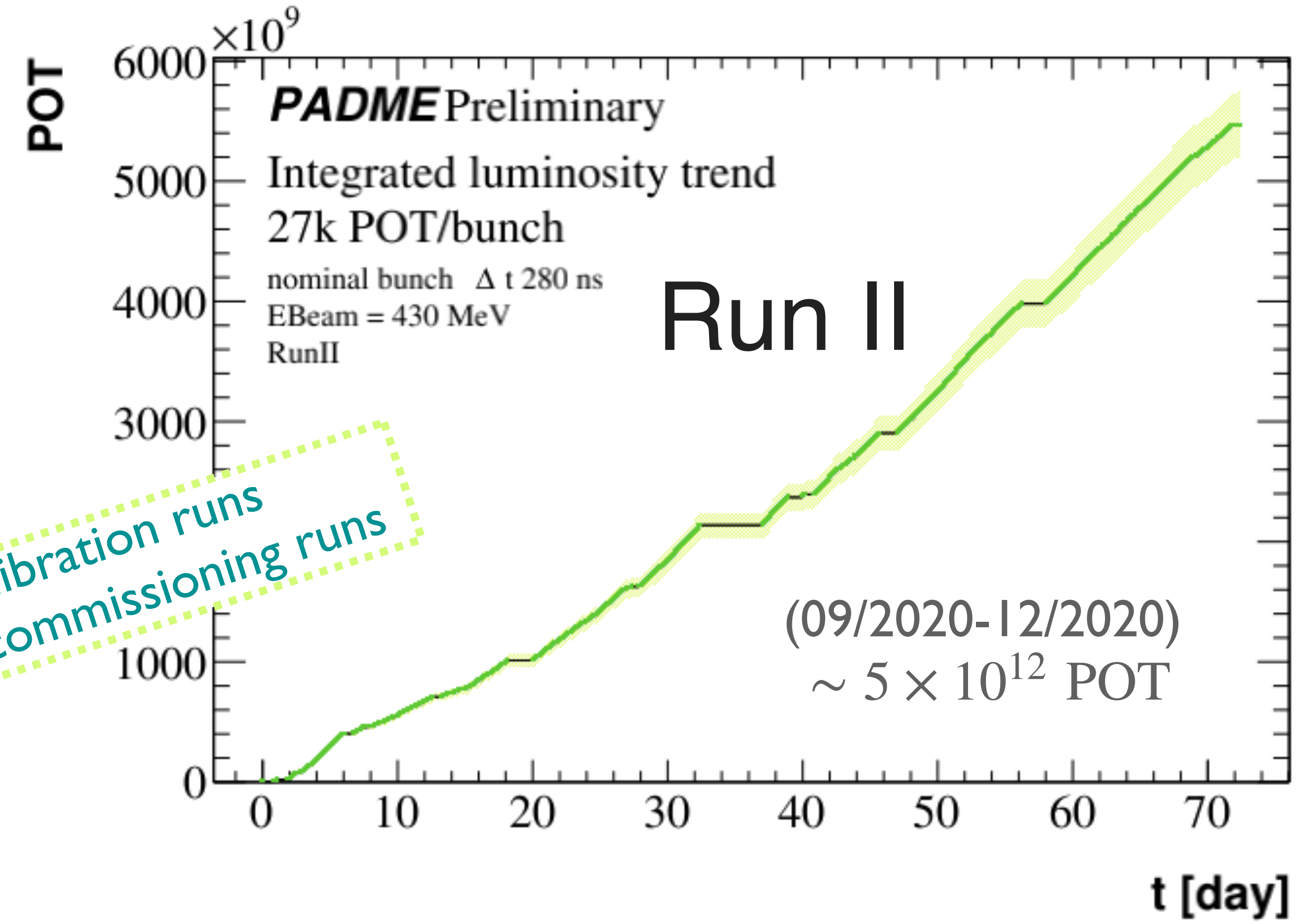
At Laboratori Nazionali di Frascati LNF (Rome)

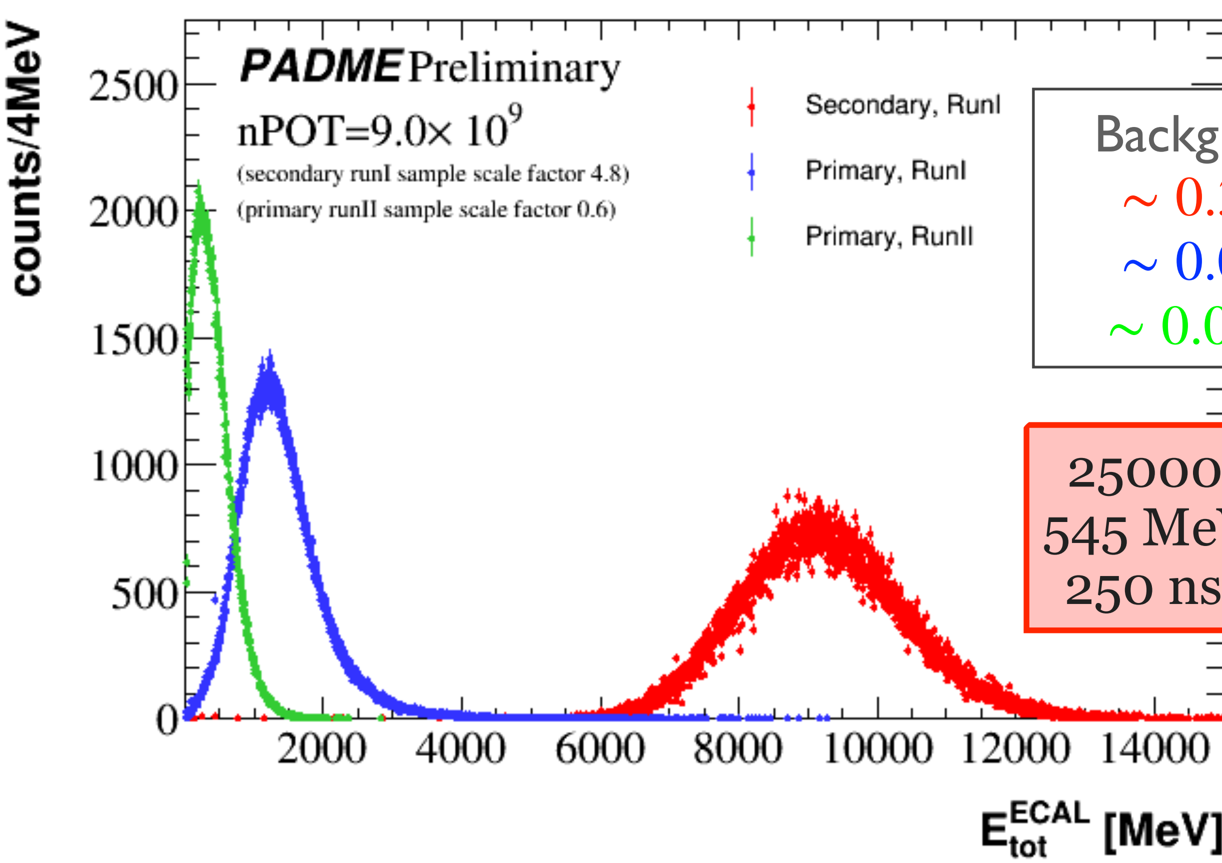


Experimental setup
- LINAC e^+ beam: energy ≤ 550 MeV
  - 50 Hz pulsed beam
  - 300 ns pulse maximum duration
  - ~10000 e+/pulse
- Diamond active Target: $2\text{ cm} \times 2\text{ cm} \times 100\ \mu\text{m}$
- Dipole magnet MBP-S: B ≤ 1.4 T
- Veto system: >200 plastic scintillator bars
- Main calorimeter ECAL: 616 BGO crystals
- Small Angle Calorimeter SAC: 25 PbF_2 crystals

PADME data taking







Background index:
~ 0.36 MeV/e$^+$
~ 0.03 MeV/e$^+$
~ 0.013 MeV/e$^+$

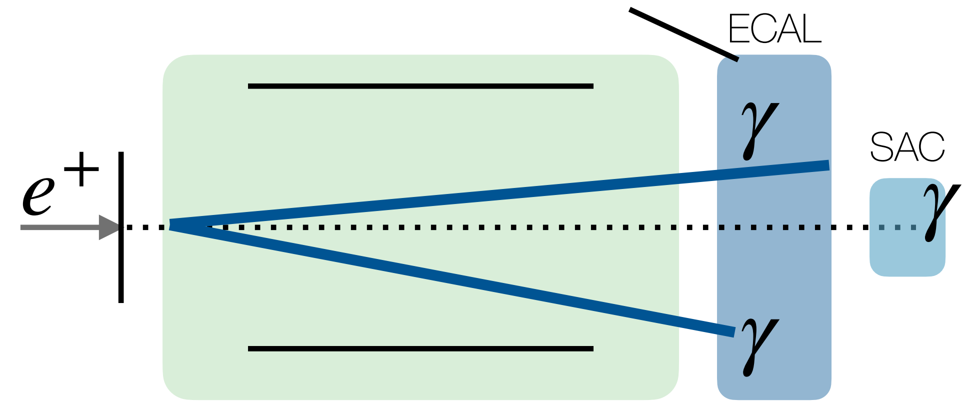
- Beam related background is observed
- Detailed beam line description in the MC used to investigate it
- Improving of the beam line → beam transportation

25000 kPOT/bunch
545 MeV beam energy
250 ns bunch length

25000 kPOT/bunch
490 MeV beam energy
250 ns bunch length

28000 kPOT/bunch
430 MeV beam energy
280 ns bunch length

Annihilation cross section measurement



A candle QED process:

➡ source of photons with energy in the range of interest for the signal

➡ $\sigma(e^+e^- \to \gamma A')$ proportional $\sigma(e^+e^- \to \gamma\gamma) \times \delta(M_{A'})$

➡ physics monitor / measurement of the number of POT

Why a measurement of the cross section ?

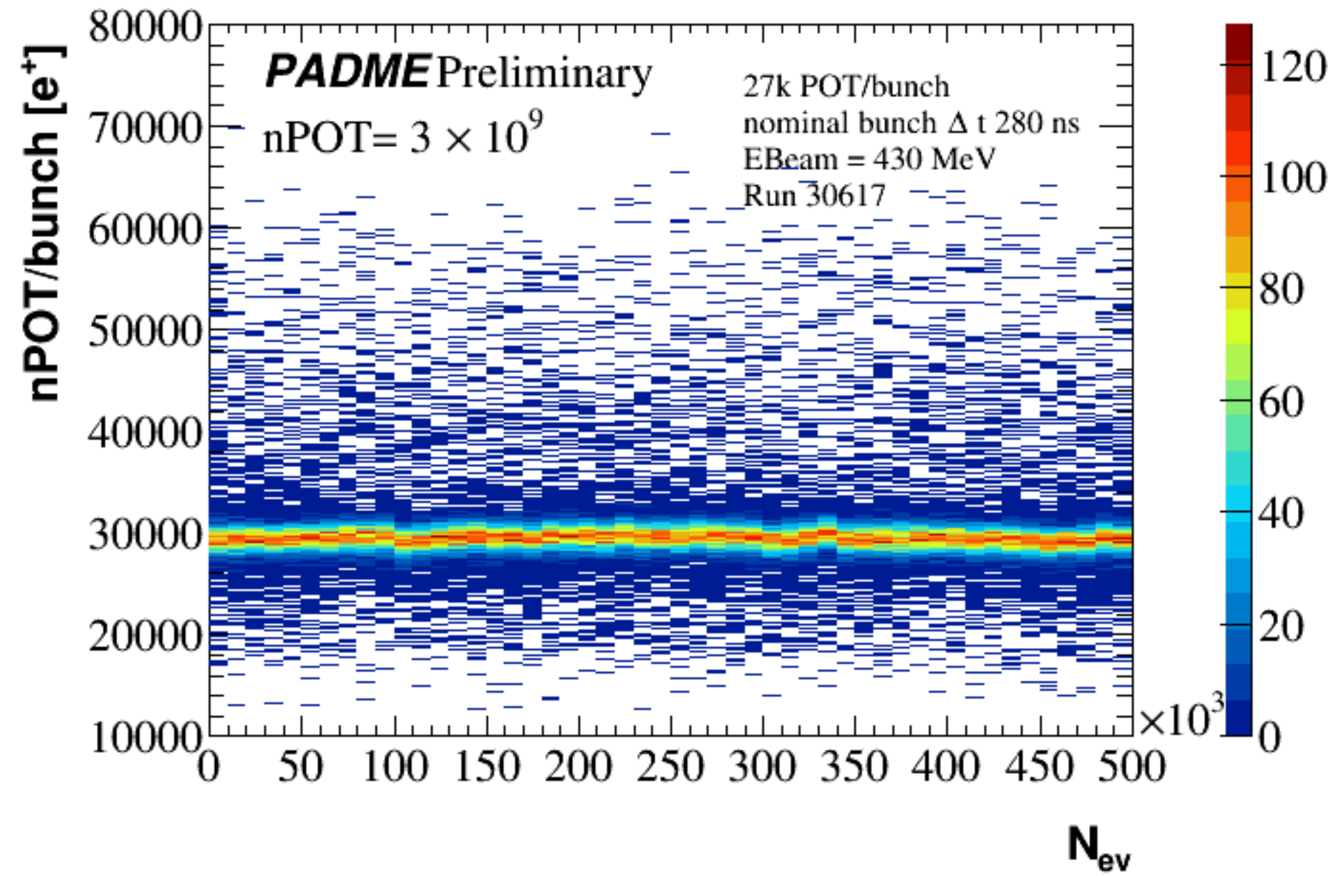
➡ To be sure we understand ECAL, the key PADME detector

➡ below 500 MeV only a set of measurements with 20% error

➡ Sensitive to extra contribution from new physics at sub-GeV scale (ALPs) **?**

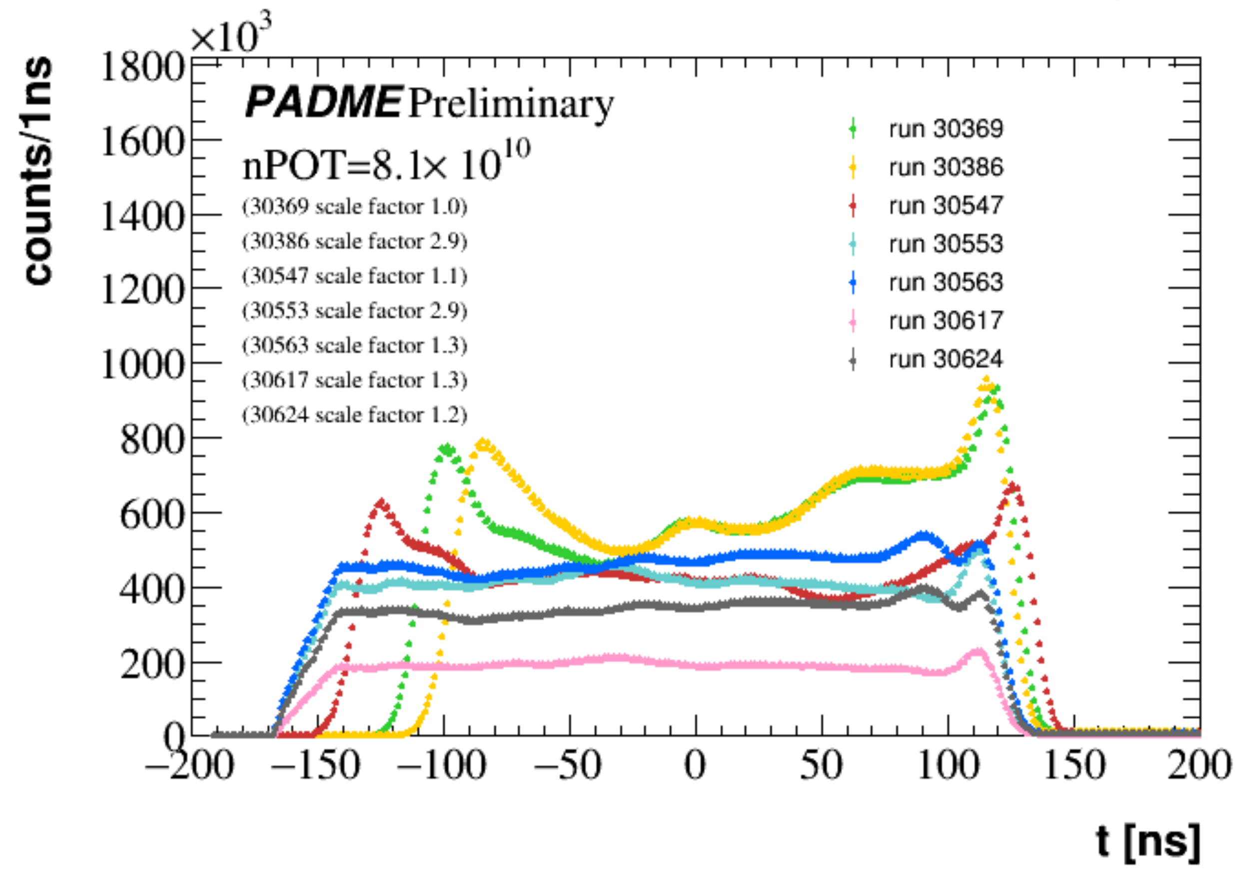
PADME dataset for annihilation cross section

- 7 runs from RunII representative of full statistics
  - N_{POT} stable in time
  - Total of 4×10^{11} POT
    - Few percent of the full data sample
  - $E_{beam} = 430$ MeV



- N_{POT} between $19k$ and $36k$ e^+/bunch
- Bunch length ~280 ns, different time profile from run to run

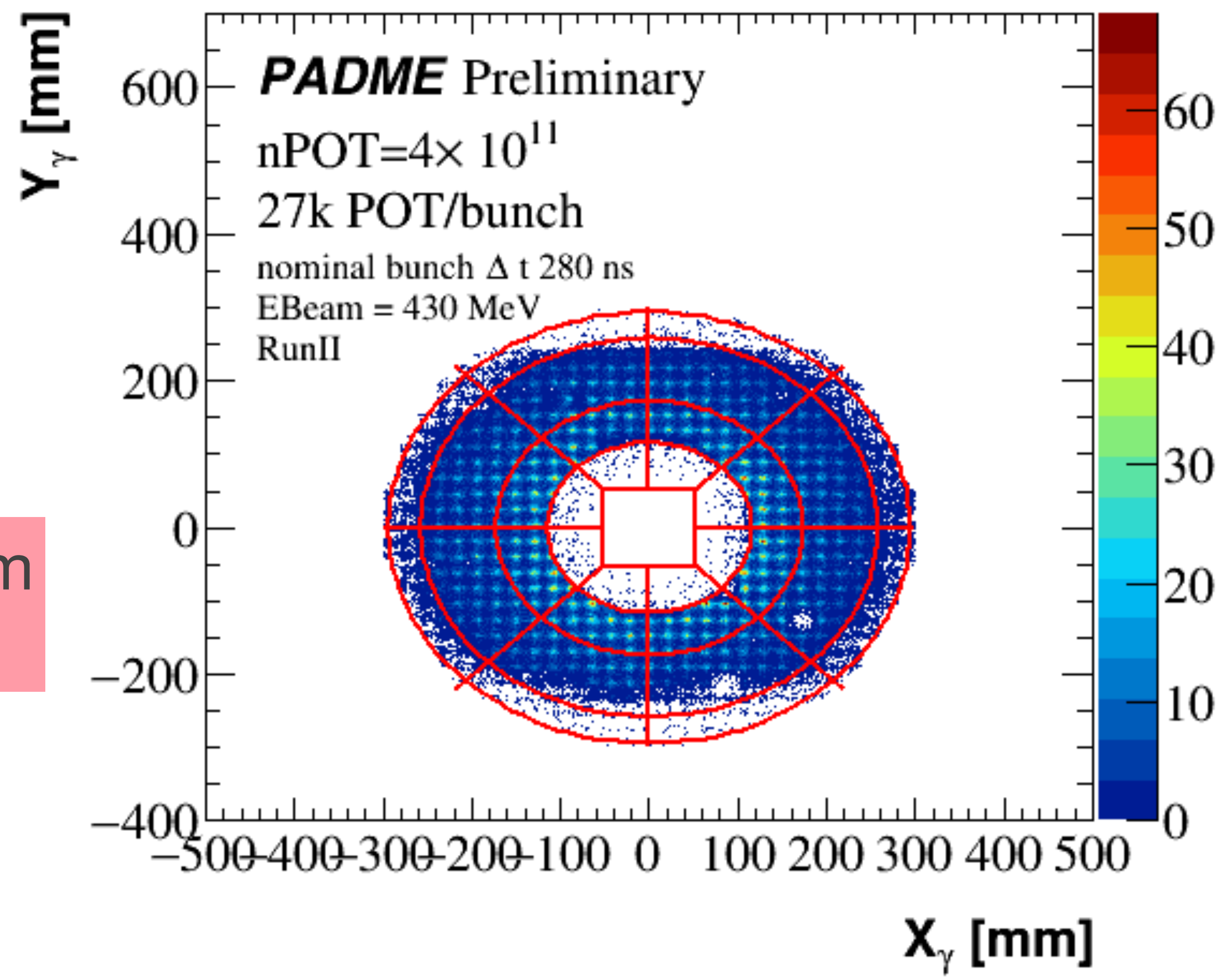
- + 2 background runs [target out of the beam line] for beam background subtraction

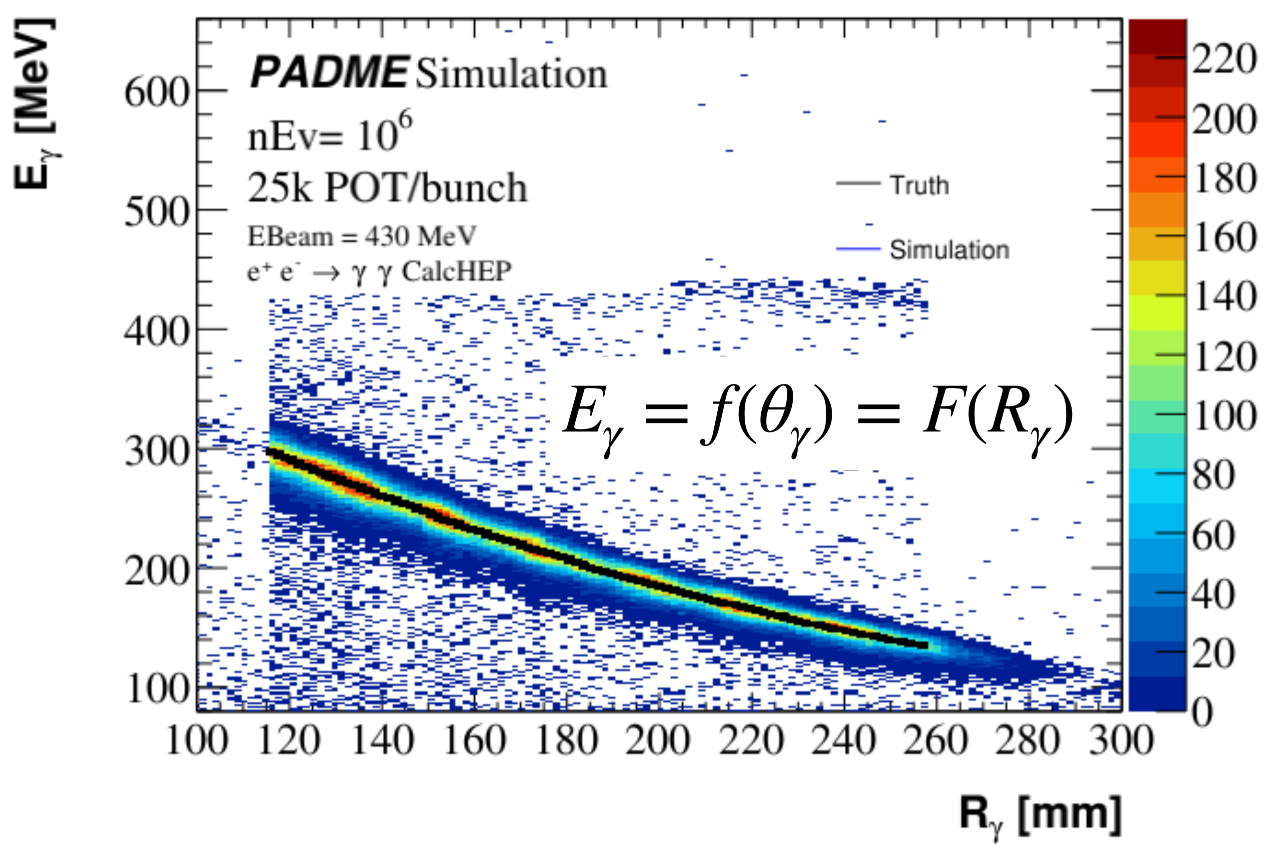


Annihilation $\gamma\gamma$ signature and selection

- Signature
- Two photons in the ECAL detector
  - Energy / momentum conservation: $E_{\gamma_1} + E_{\gamma_2} = E_{Beam}$
  - $E_\gamma = f(\theta_\gamma)$ for each photon
  - Back to back in the transverse plane

Fiducial region: 115.8 < R < 285 mm
~6% acceptance

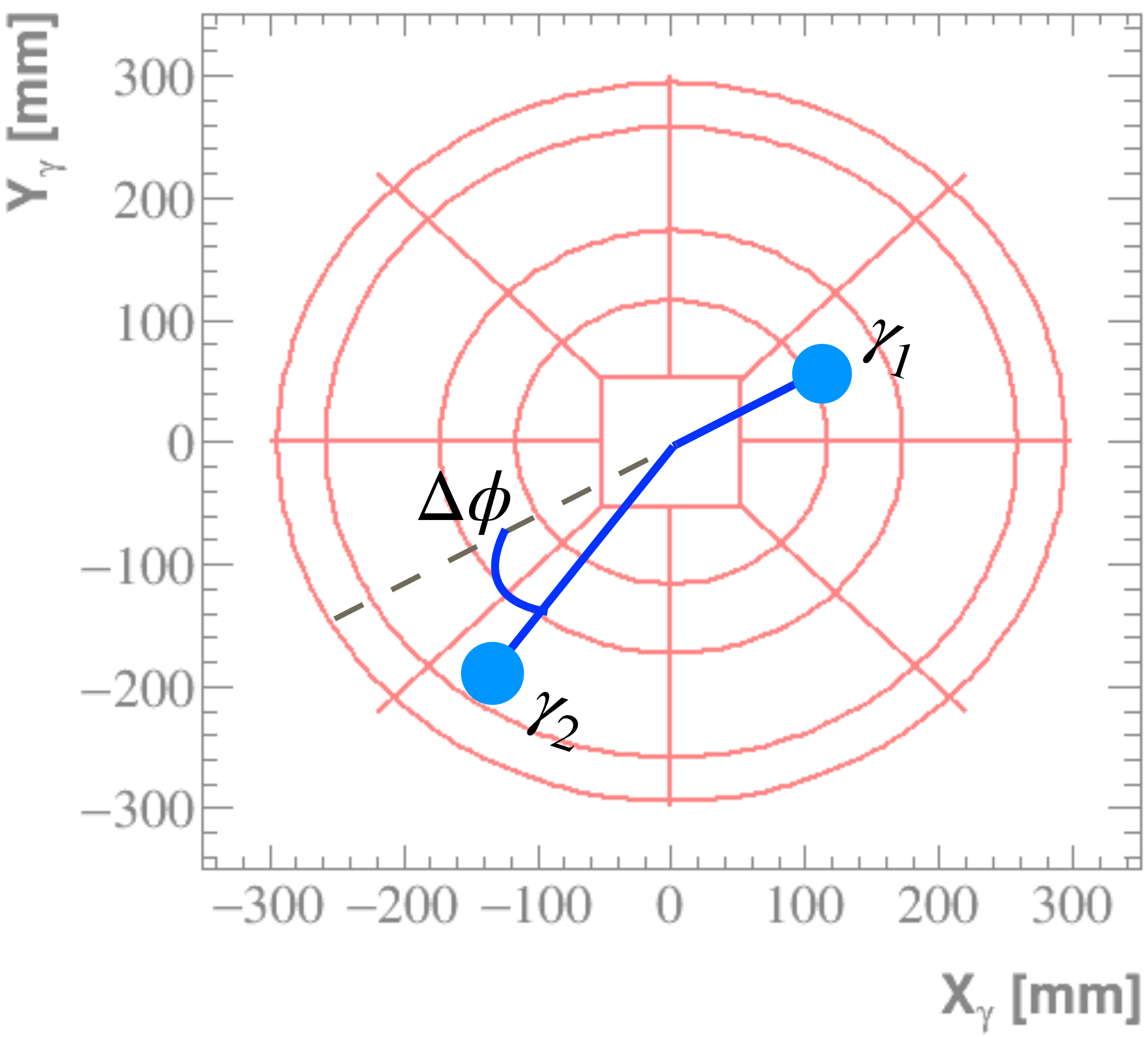




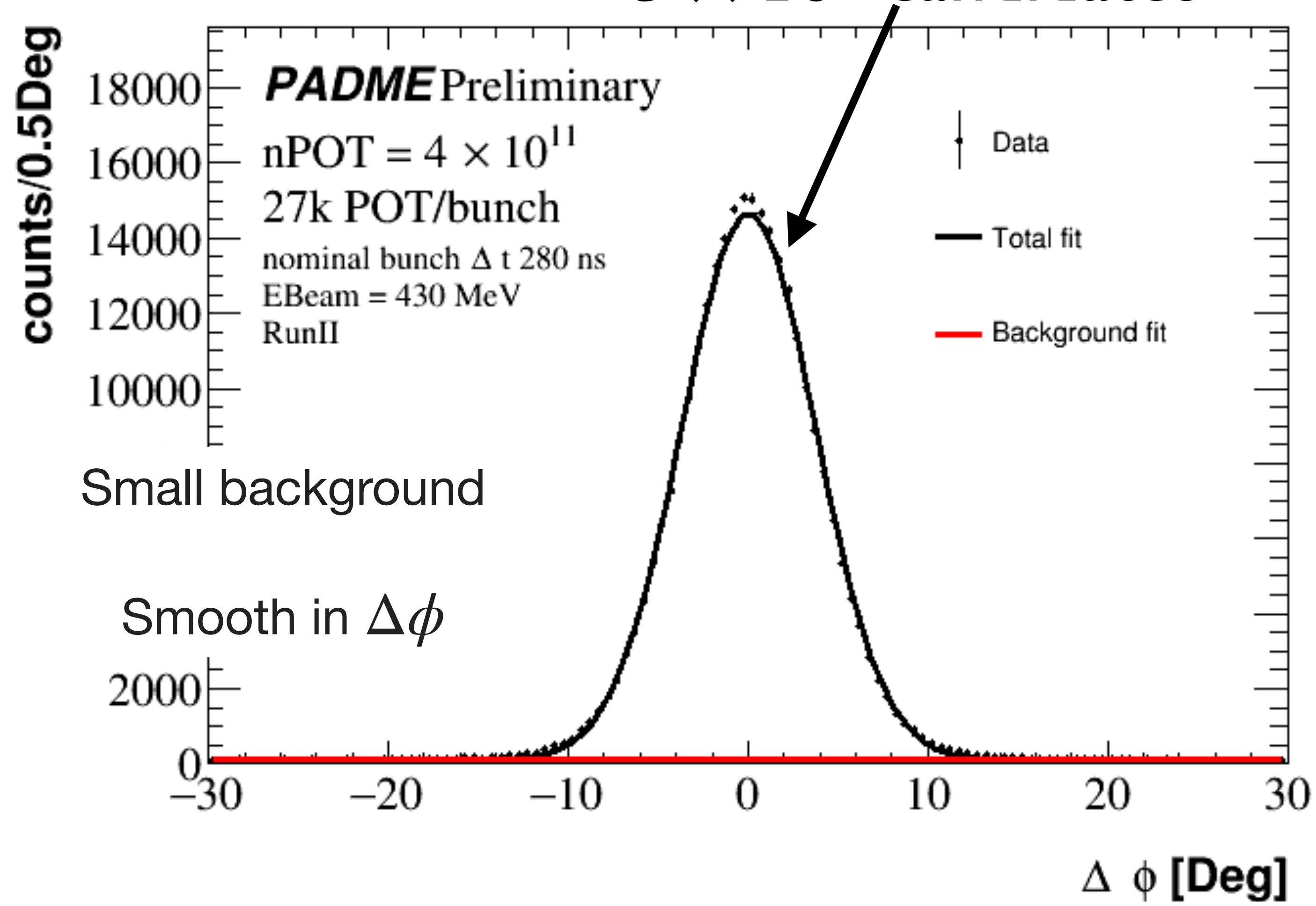
Each photon $\Delta E = E_\gamma - f(\theta_\gamma) \sim 0$ MeV

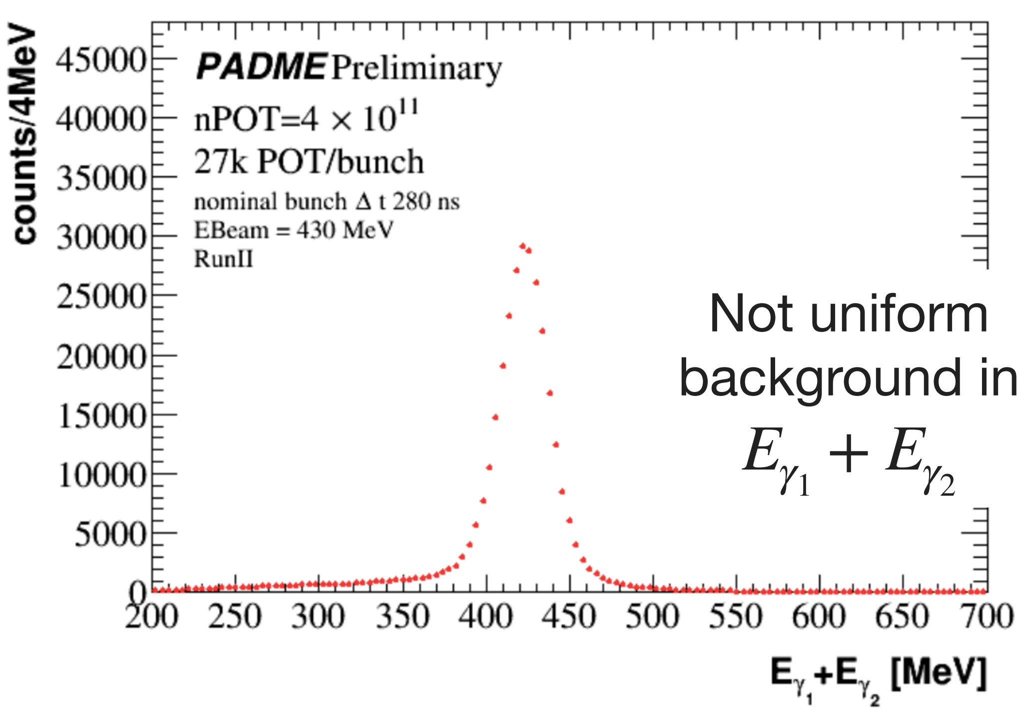
- Two ***good quality*** ECAL clusters
  - $|\Delta t| < 10$ ns
  - $E_{\gamma_1} > 90$ MeV and $E_{\gamma_2} > 90$ MeV
  - $|\Delta E(\theta_1)| < 100$ MeV and $|\Delta E(\theta_2)| < 100$ MeV
  - For the leading photon $R_{\gamma_1} \in FR$

Counting annihilation events - 2 γ selection



$\sim 3 \times 10^5$ candidates





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  - $|\Delta E(\theta_1)| < 100$ MeV and $|\Delta E(\theta_2)| < 100$ MeV
  - For the leading photon $R_{\gamma_1} \in FR$

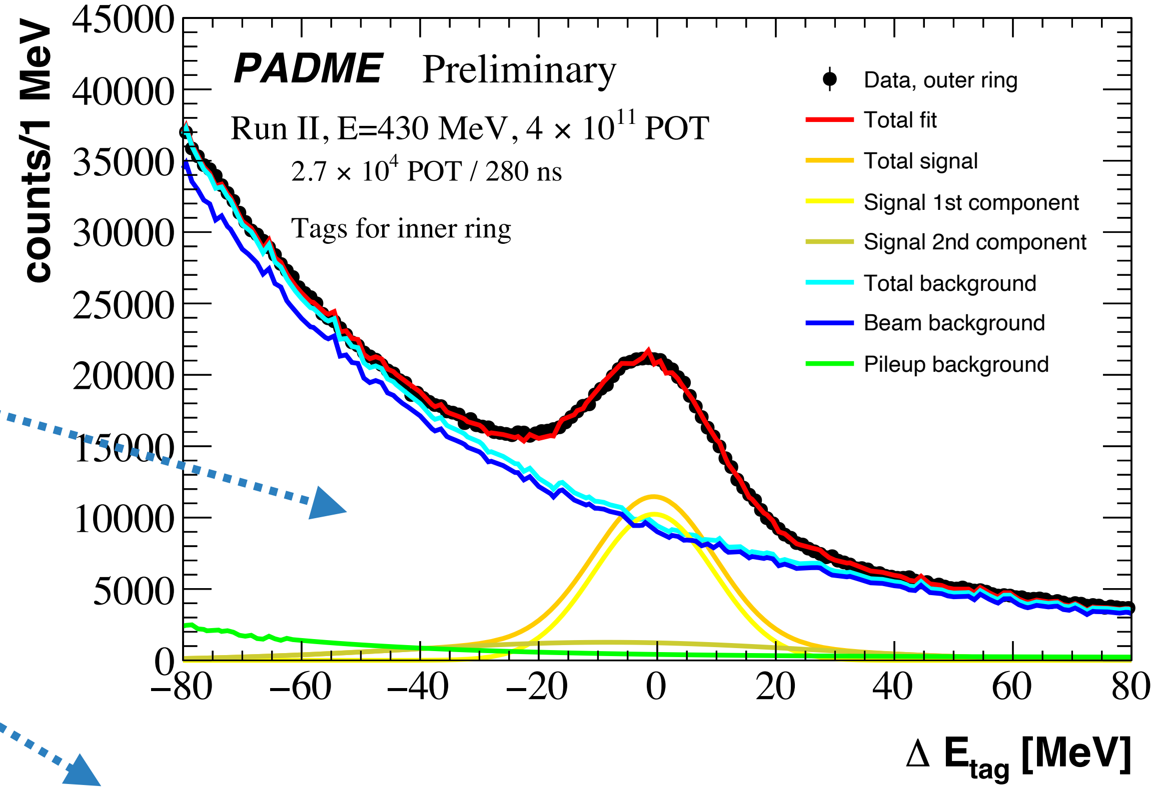
Photon selection efficiency

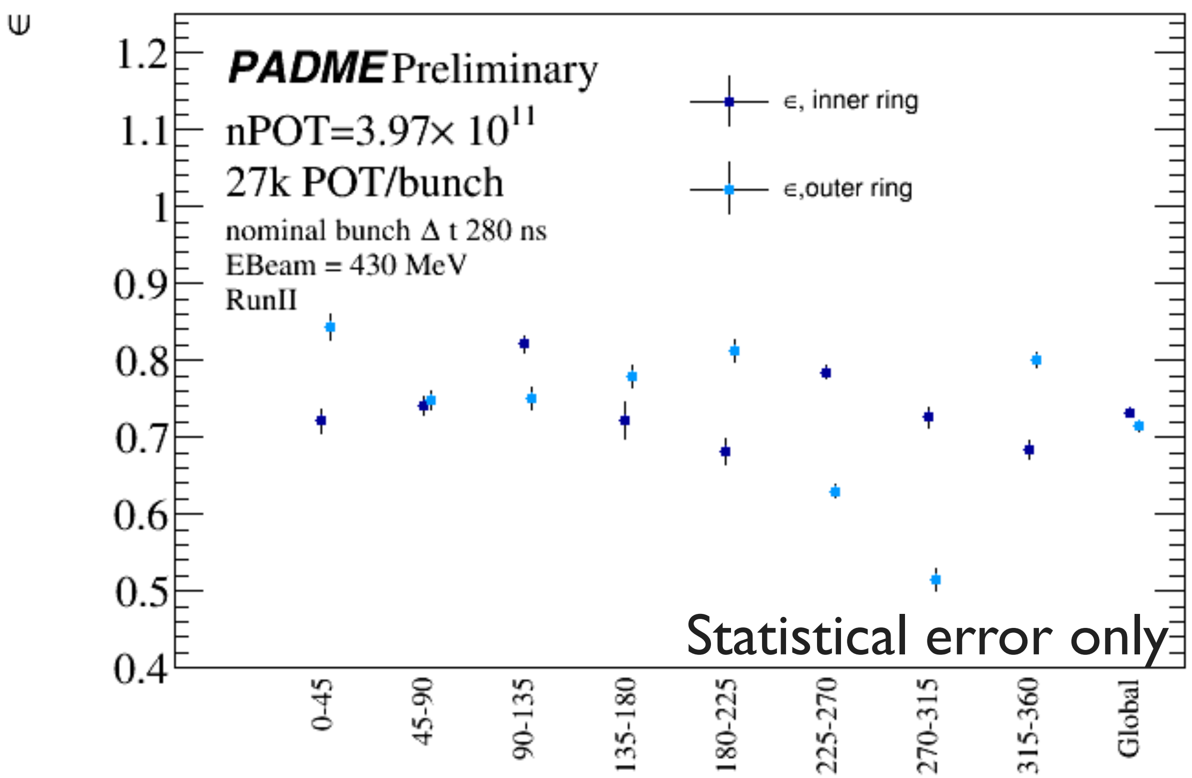
Each annihilation photon $\Delta E = E_\gamma - f(\theta_\gamma) \sim 0$ MeV

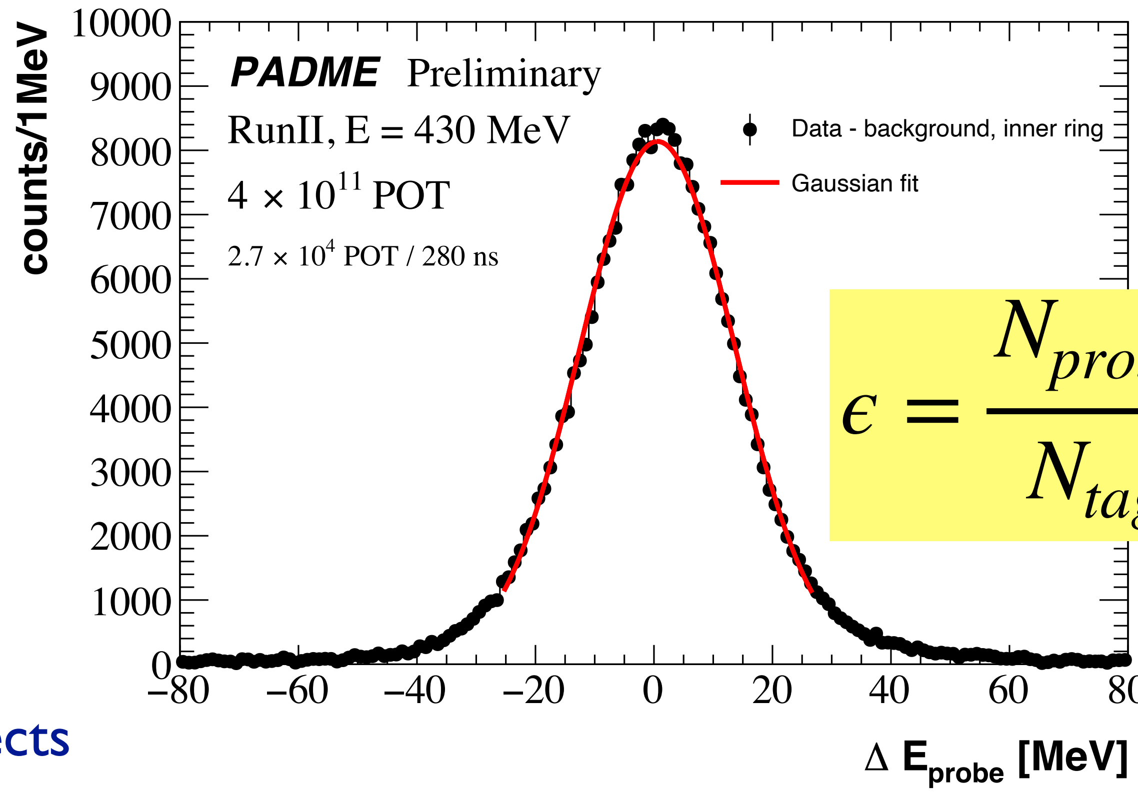
A measurement in data:

a photon with $\Delta E = E_\gamma - f(\theta_\gamma) \sim 0$ MeV
in one of the 8 ϕ sectors and in the inner (outer) ring
-> ***count tagging photons***

implies a photon in the opposite sector in the outer (inner) ring
-> look for selected photons matching the hypothesis







$$\epsilon = \frac{N_{probe}}{N_{tag}}$$

Trend matching asymmetric detector acceptance / local defects

Counting annihilation events - 1 γ selection

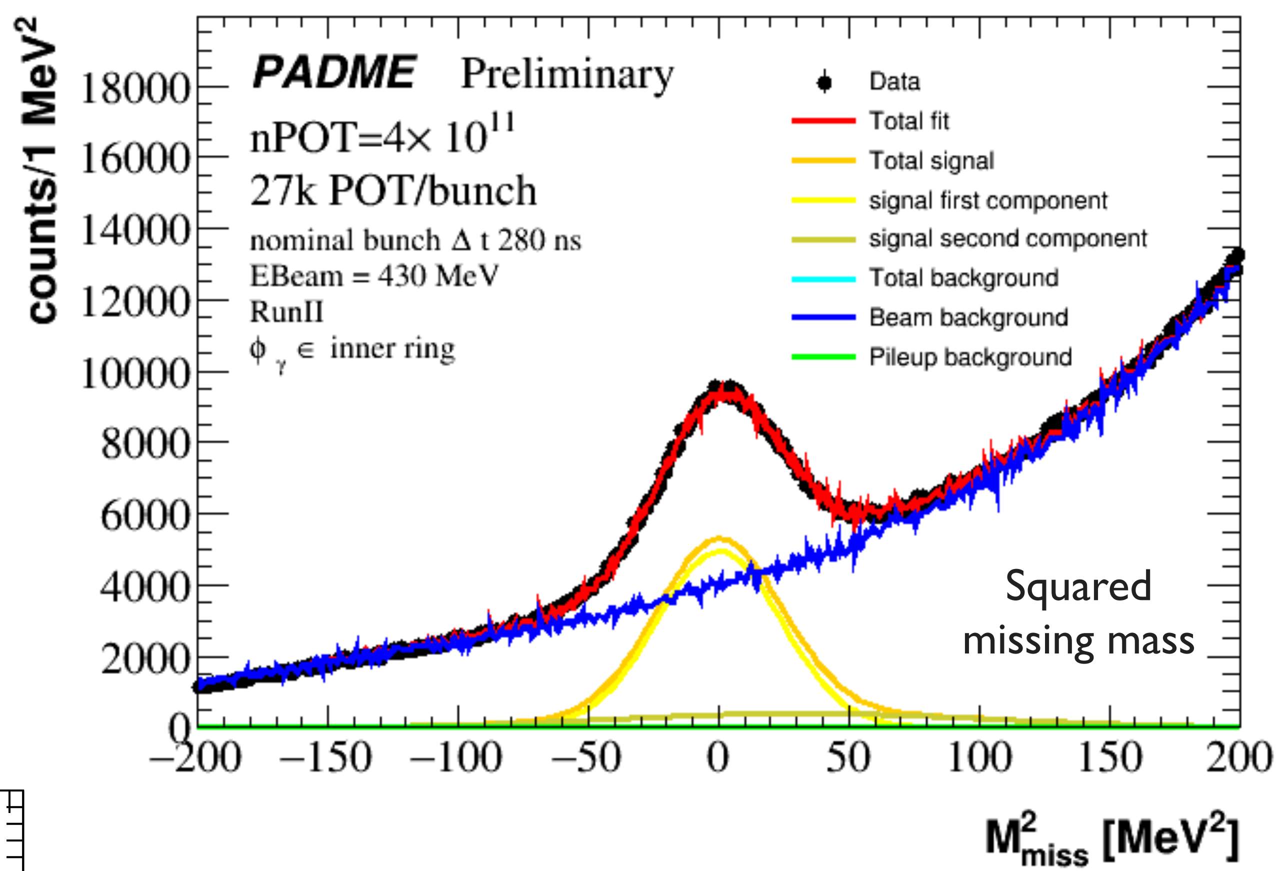
With a single photon selection:

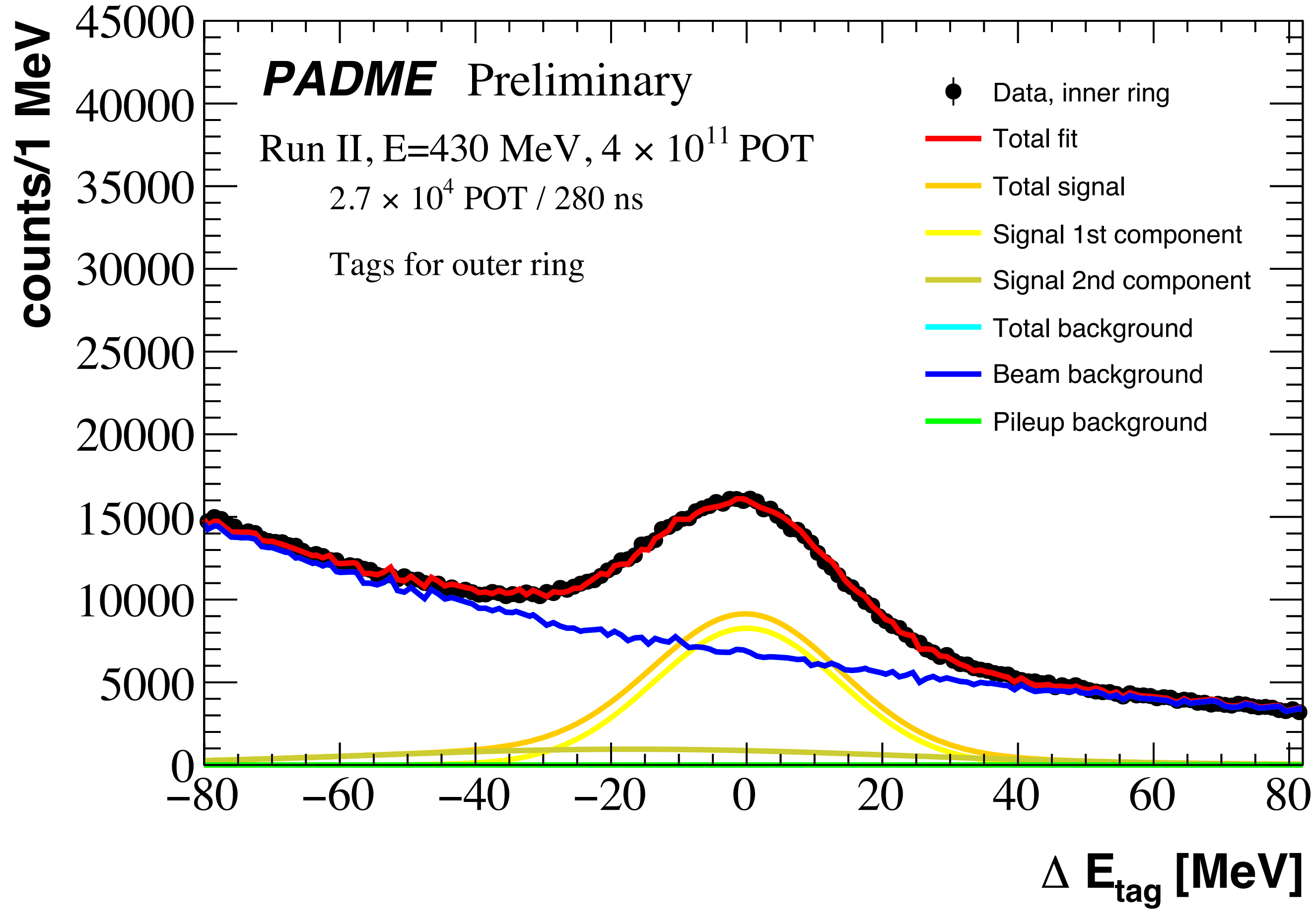
(either in the inner or outer ring)

Exploiting

1) $\Delta E = E_\gamma - f(\theta_\gamma) \sim 0$ MeV

2) $M^2_{missing} \sim 0$ MeV^2





- Large background to be subtracted,
  - Templates for beam related background from no-target data
  - Templates for pileup from MC
  - Different shapes in ΔE and M^2_{miss} useful for systematics assessment

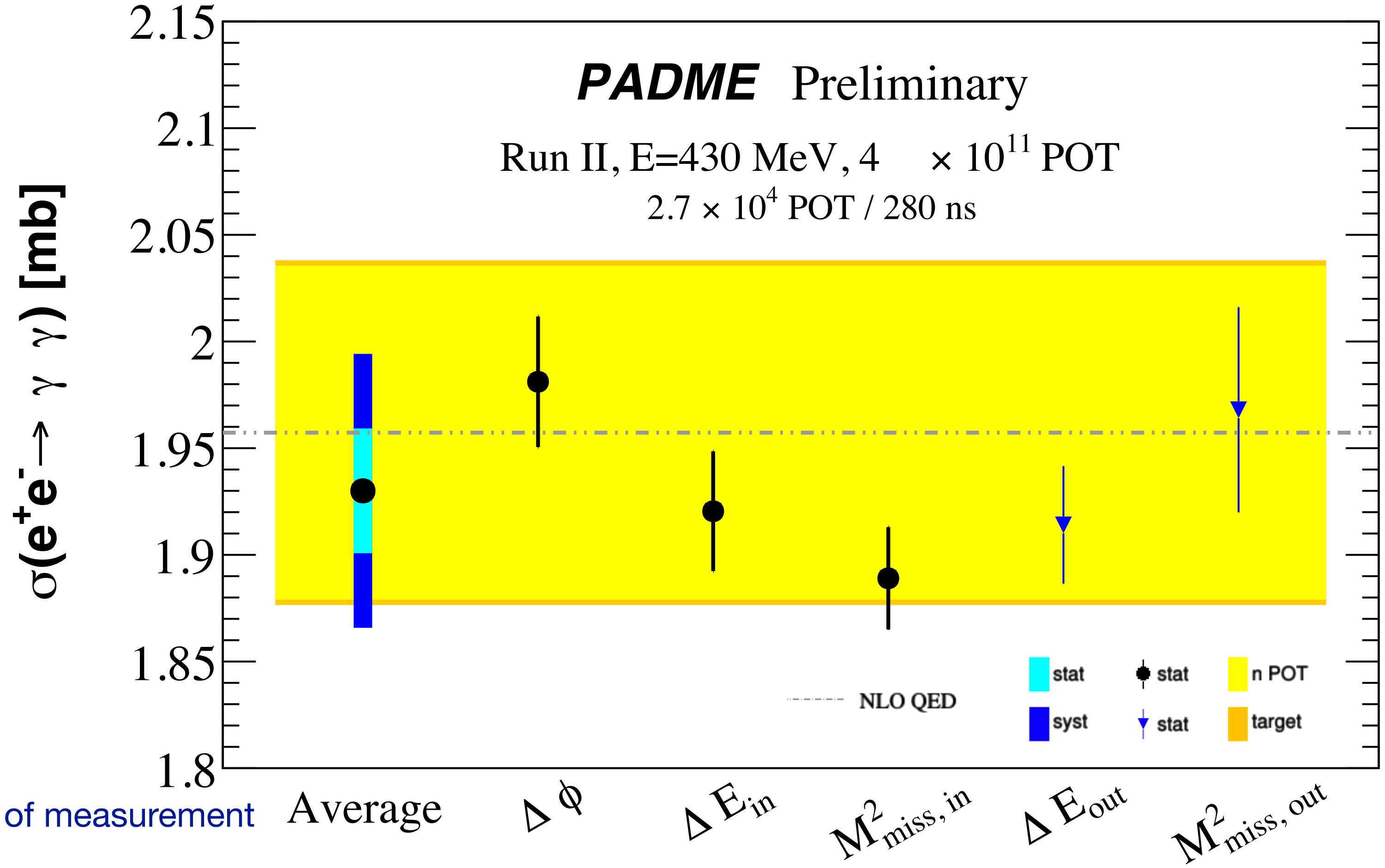
Cross section measurement

$E_{beam} = 430$ MeV

- PADME absolute measurement of $e^+e^- \to \gamma\gamma$ process

$$\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.930 \pm 0.029 \text{ (stat)} \pm 0.057 \text{ (syst)} \pm 0.020 \text{ (target)} \pm 0.079 \text{ (lumi) mb}$$

- QED @NLO $\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.9573 \pm 0.0005 \text{ (stat)} \pm 0.0020 \text{ (syst) mb}$



Band = error on # POT

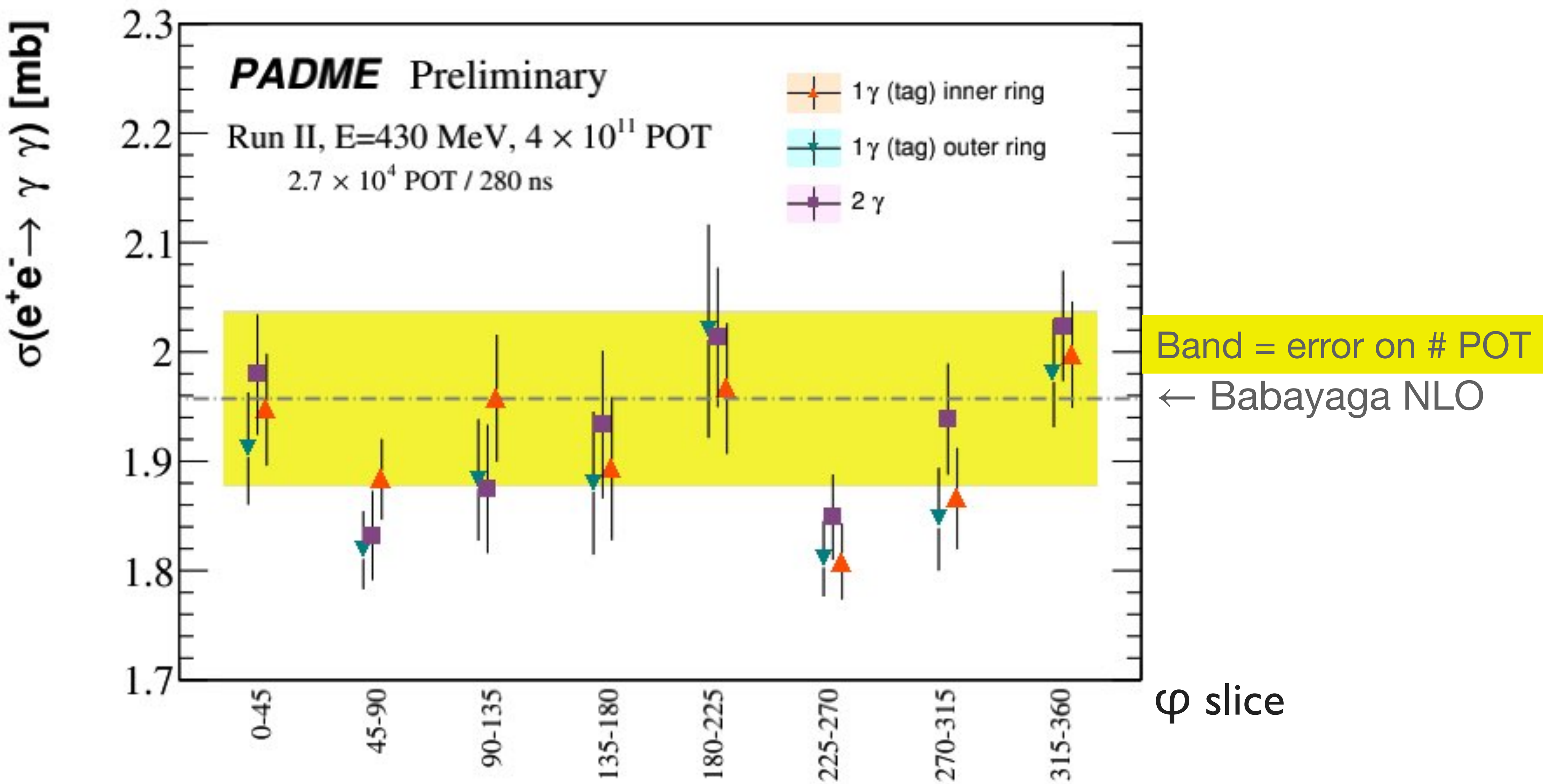
← Babayaga QED @NLO
arXiv:0801.3360

- Average of measurement variants

Detector defects	0.020 mb
Background modelling	0.047 mb
Acceptance	0.025 mb
Number of POT	0.079 mb
Target electron surface density	0.020 mb

- Detector defects → How good is the efficiency determination vs ϕ ? Check xsec stability
- Background modelling → How good is background subtraction? Check xsec from Δϕ, ΔE, MM
- Acceptance → How well do we know fiducial region boundaries ?
- Number of POT → From active target absolute and relative calibration
- Target electron surface density → 1 μm uncertainty on target thickness

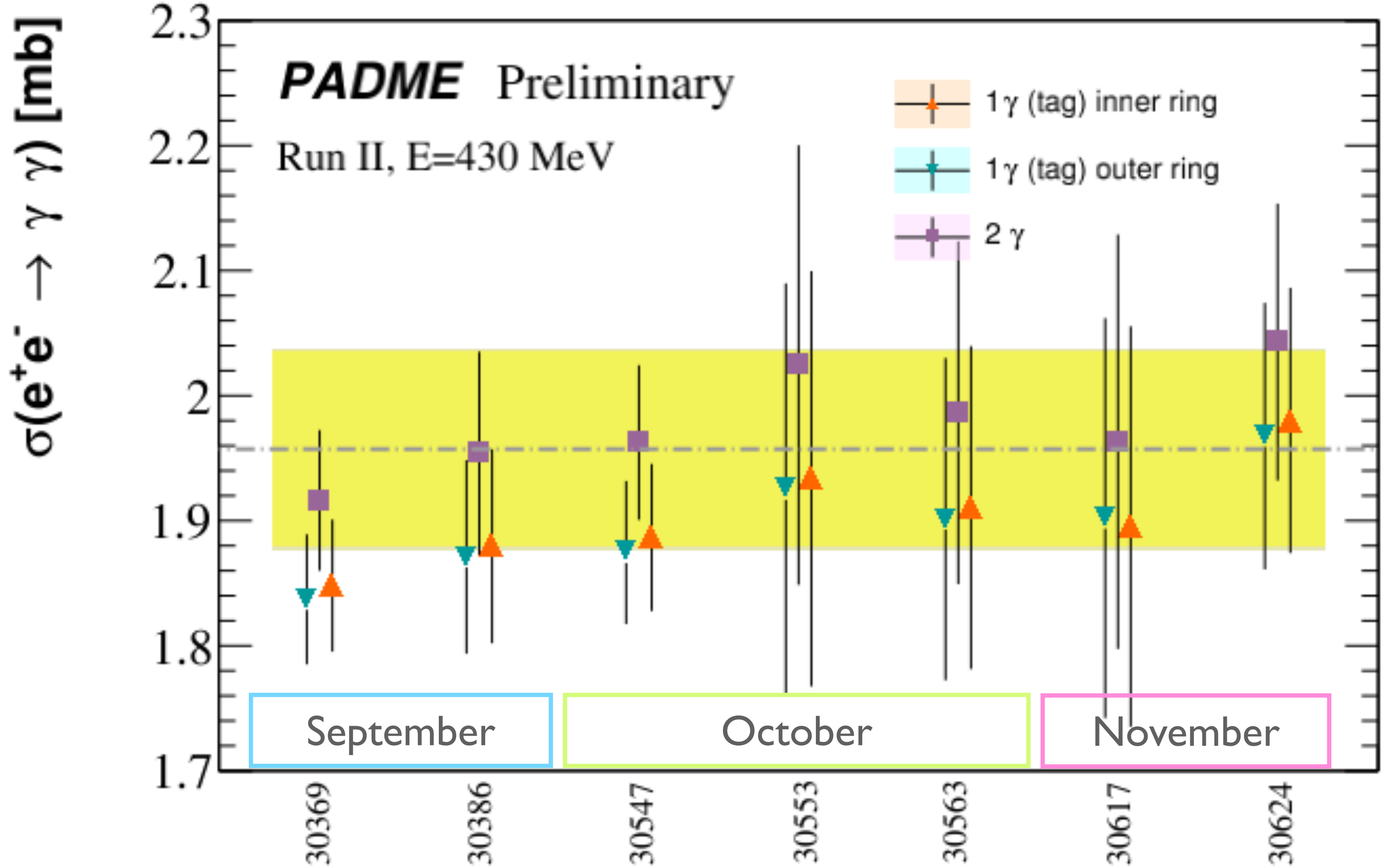
Measurement stability vs φ sector



Rather uniform cross section measurement
in spite of sector-dependent yield and photon selection efficiency

Residual differences, above statistical fluctuations, used to quote a systematic uncertainty arising from "detector defects"

Measurement stability vs beam setting



Band = error on # POT

← Babayaga NLO

No emerging systematic effects

Not-unif, typical # POT/bunch

Not-unif, Low # POT/bunch

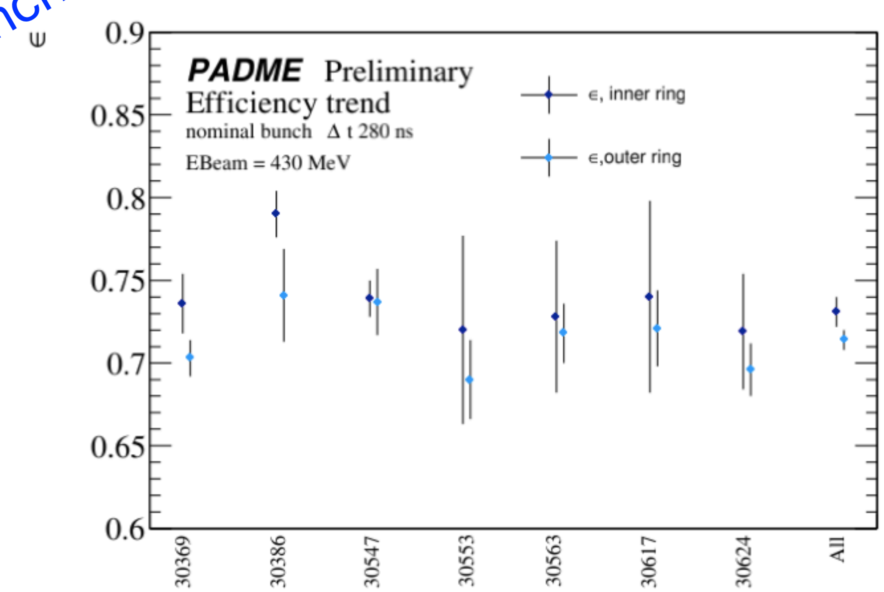
~ unif, High # POT/bunch

Unif, Very high # POT/bunch

Unif, Typical # POT/bunch

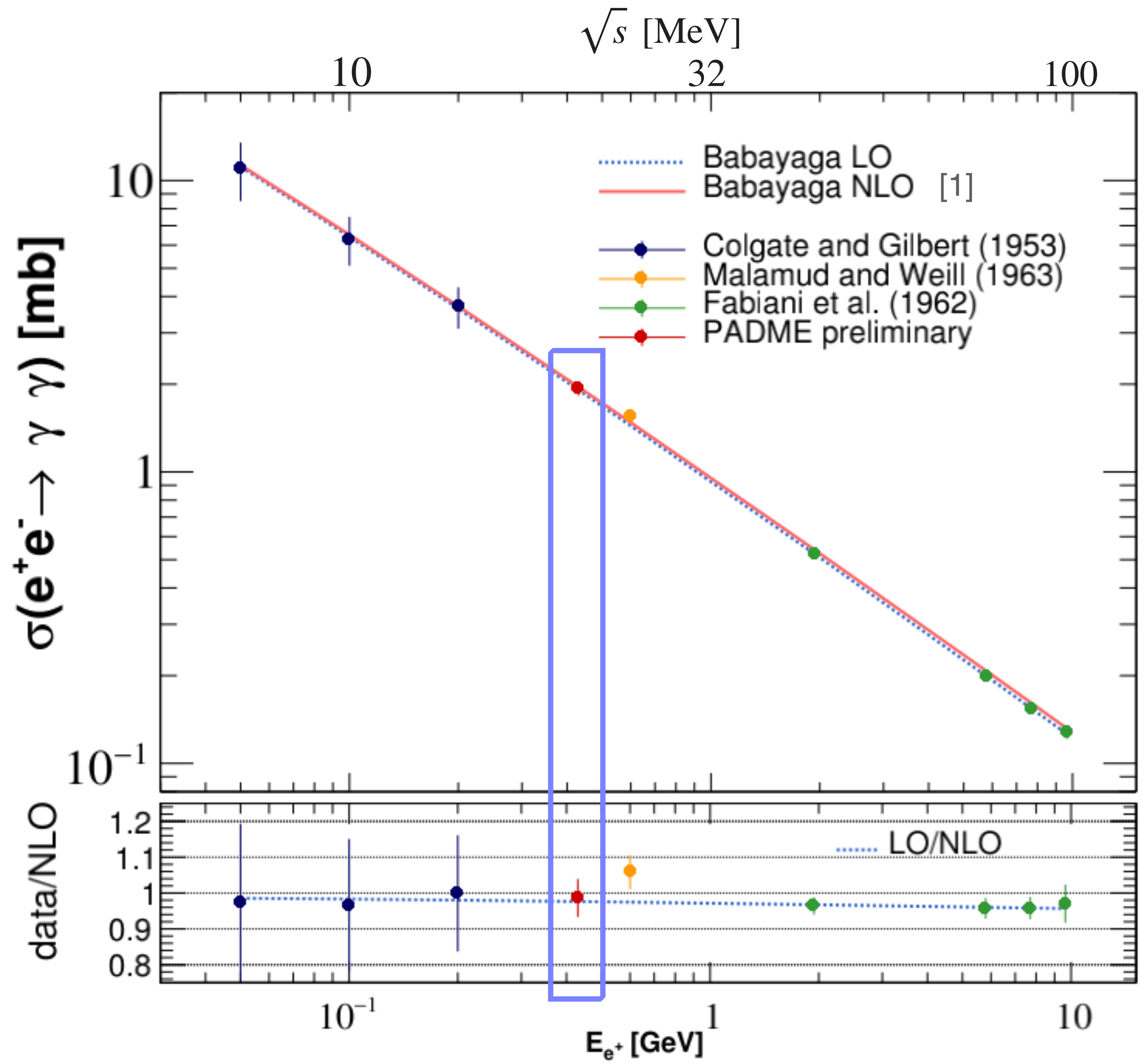
Unif, Very high # POT/bunch

Unif, Typical # POT/bunch



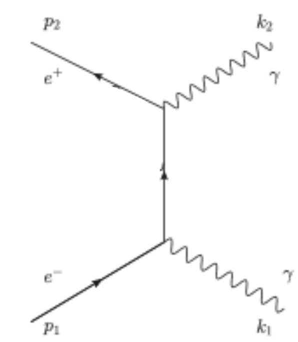
State of the art for annihilation in flight

[1] arXiv:0801.3360

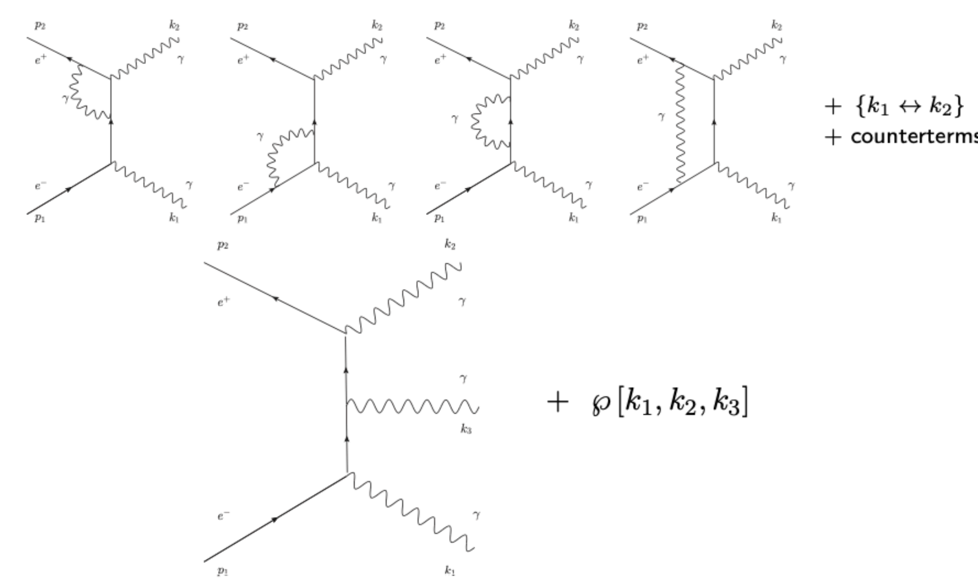


PADME measurement beam energy @ 430 MeV

Babayaga at LO



Babayaga at NLO



PADME is the only experiment capable to measure the cross-section of $e^+e^- \to \gamma\gamma$ with a total error of ~5% at $\sqrt{s} \sim 21$ MeV.

Conclusion

- PADME in run II collected 6×10^{12} POT, about half of the planned statistics, with an improved beam configuration.
- The candle QED process $e^+e^- \to \gamma\gamma$ has been studied with 4×10^{11} POT

$$\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.930 \pm 0.029 \text{ (stat)} \pm 0.099 \text{ (syst) mb}$$

- The inclusive cross section measurement agrees with the QED prediction at NLO within ~5% total error

$$\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.9573 \pm 0.0005 \text{ (stat)} \pm 0.0020 \text{ (syst) mb}$$

  - The uncertainty is dominated by the systematics on the number of POTs
  - Data show that a compelling task is the control of beam related background
  - The result gives confidence on a detailed understanding of the key detectors.
  - Assuming no new physics contributions, the annihilation process measures the luminosity with ~3% precision, more than enough for the search of an invisible A'

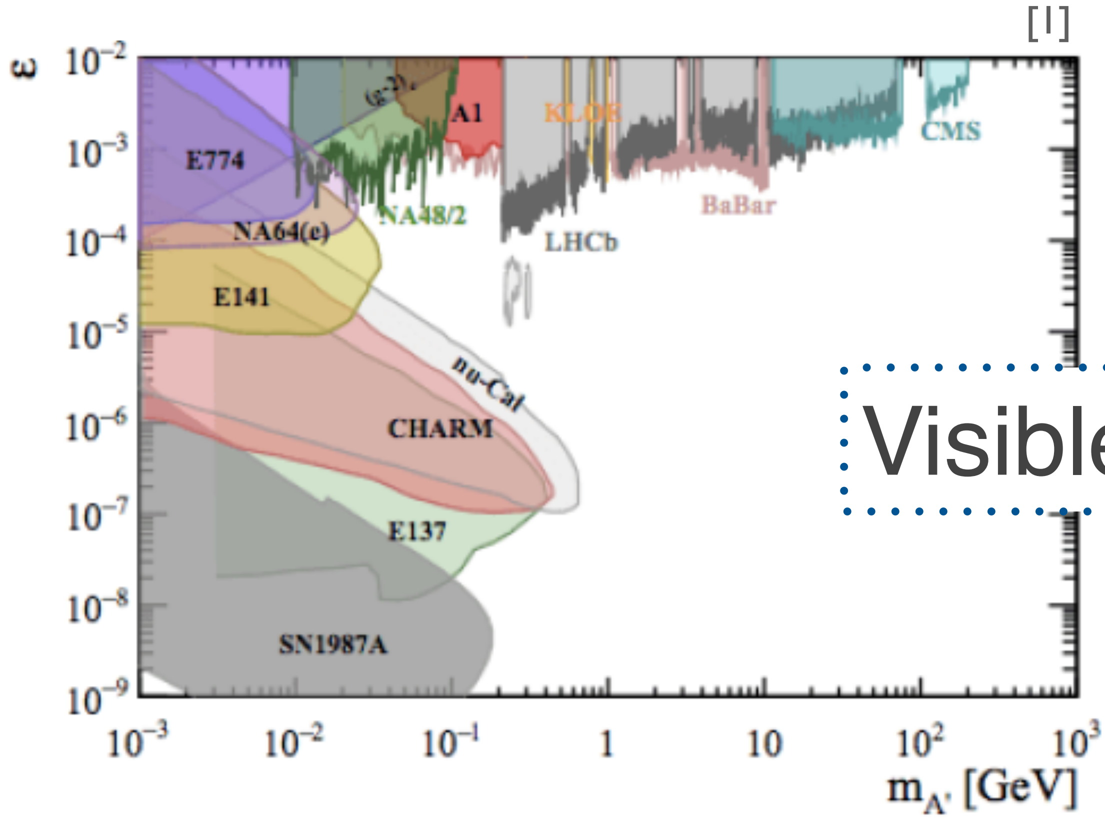
- ***Ready for dark photon searches! Stay tuned***

BACKUP

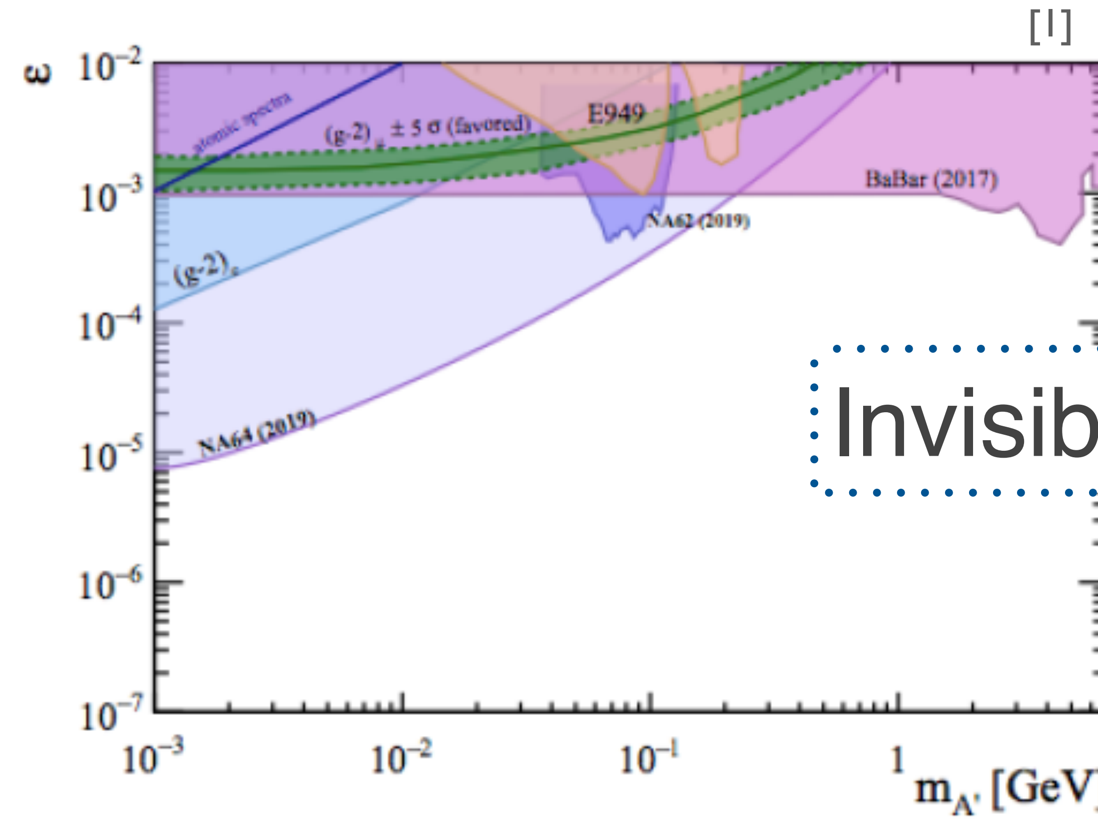
Visible and invisible limits

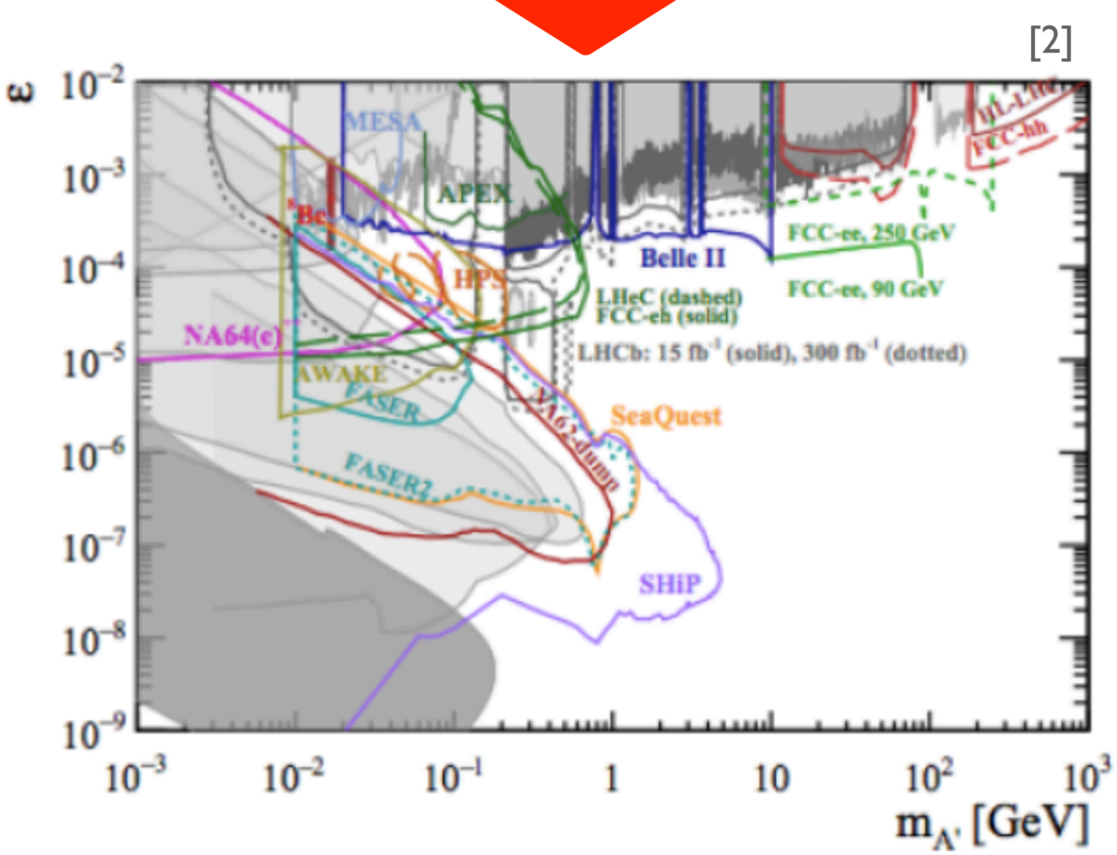
[1]10.1007/978-3-030-62519-1
[2]10.1088/1361-6471/ab4cd2

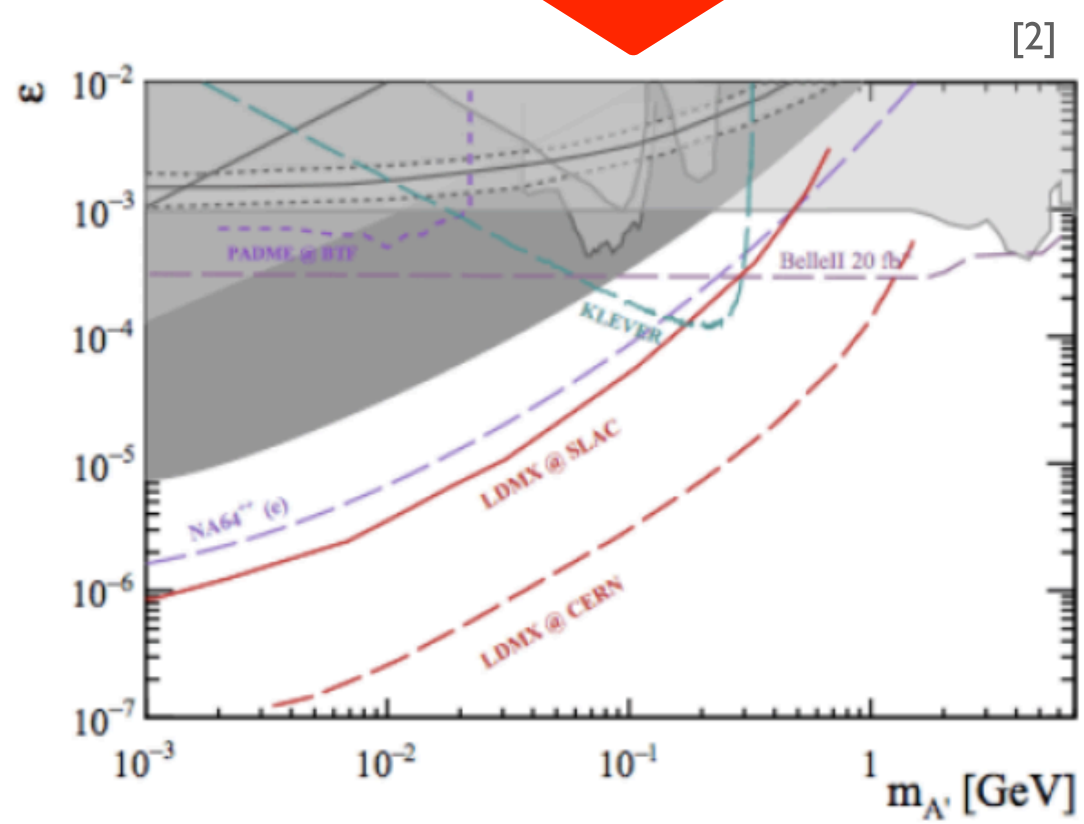
Visible



Invisible

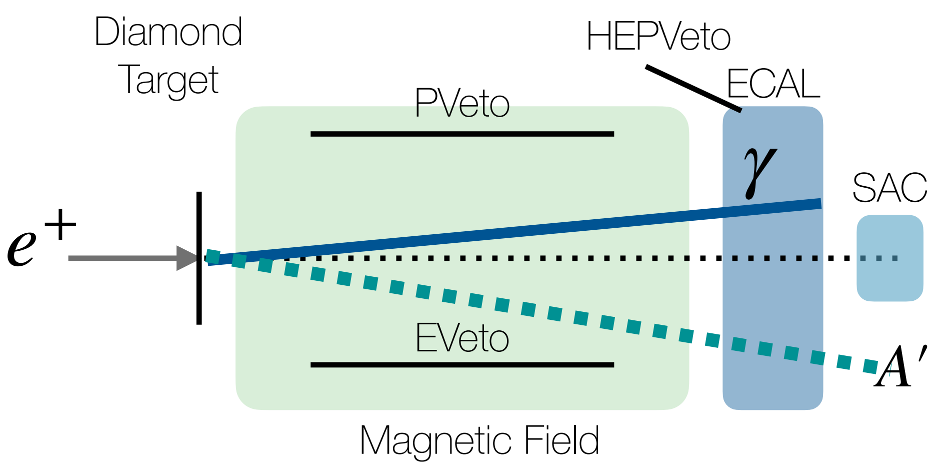


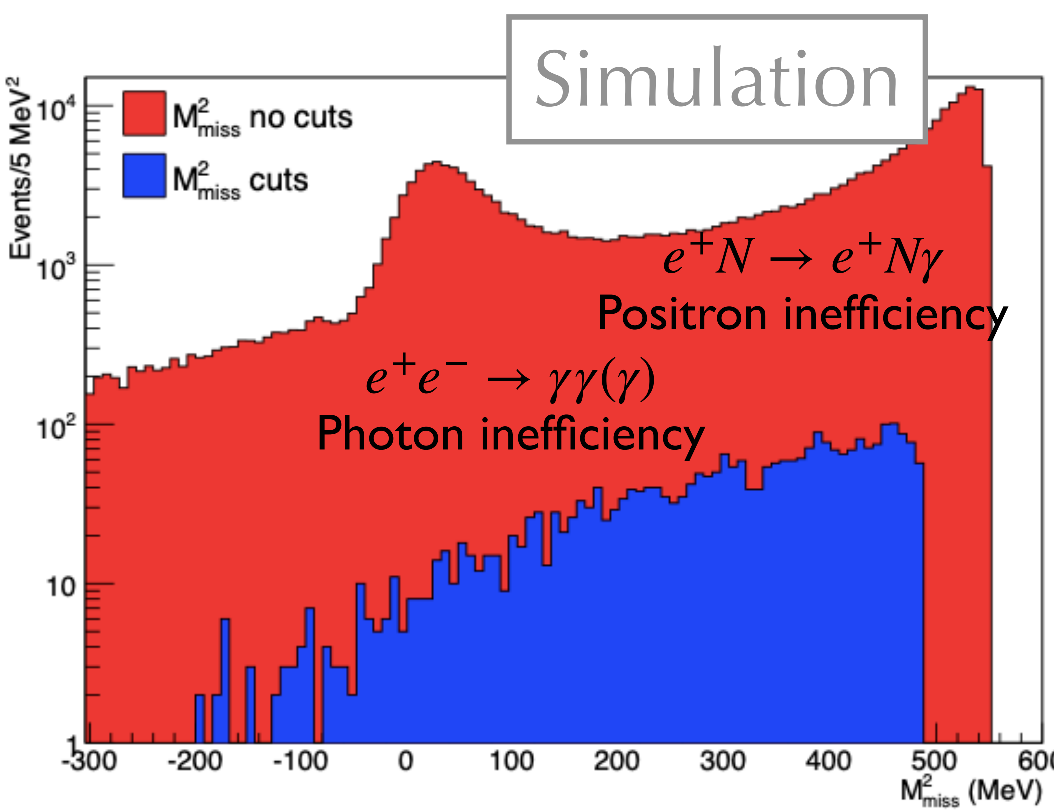




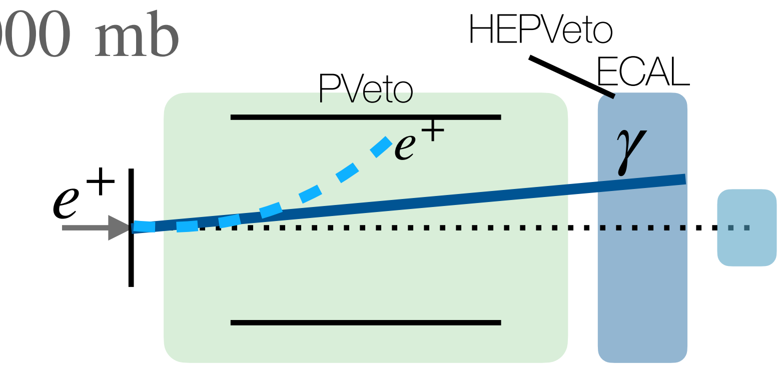
Missing mass signature

- **Signal**
  - One photon in ECAL

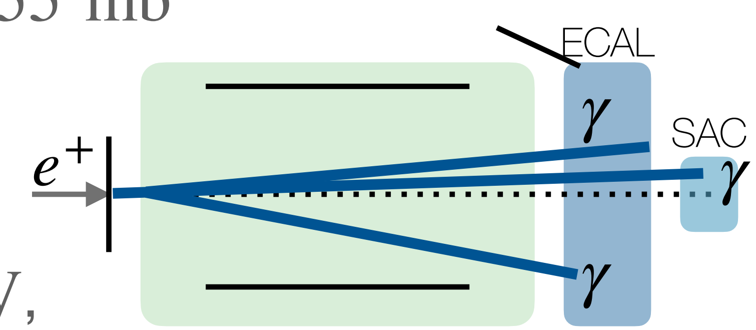




- **SM backgrounds**
  - Bremsstrahlung
    - One photon in ECAL + one positron in PVeto
    - If $E_\gamma > 1$ MeV and $E_{beam} = 550$ MeV, $\sigma(e^+N \to e^+N\gamma) = 4000$ mb

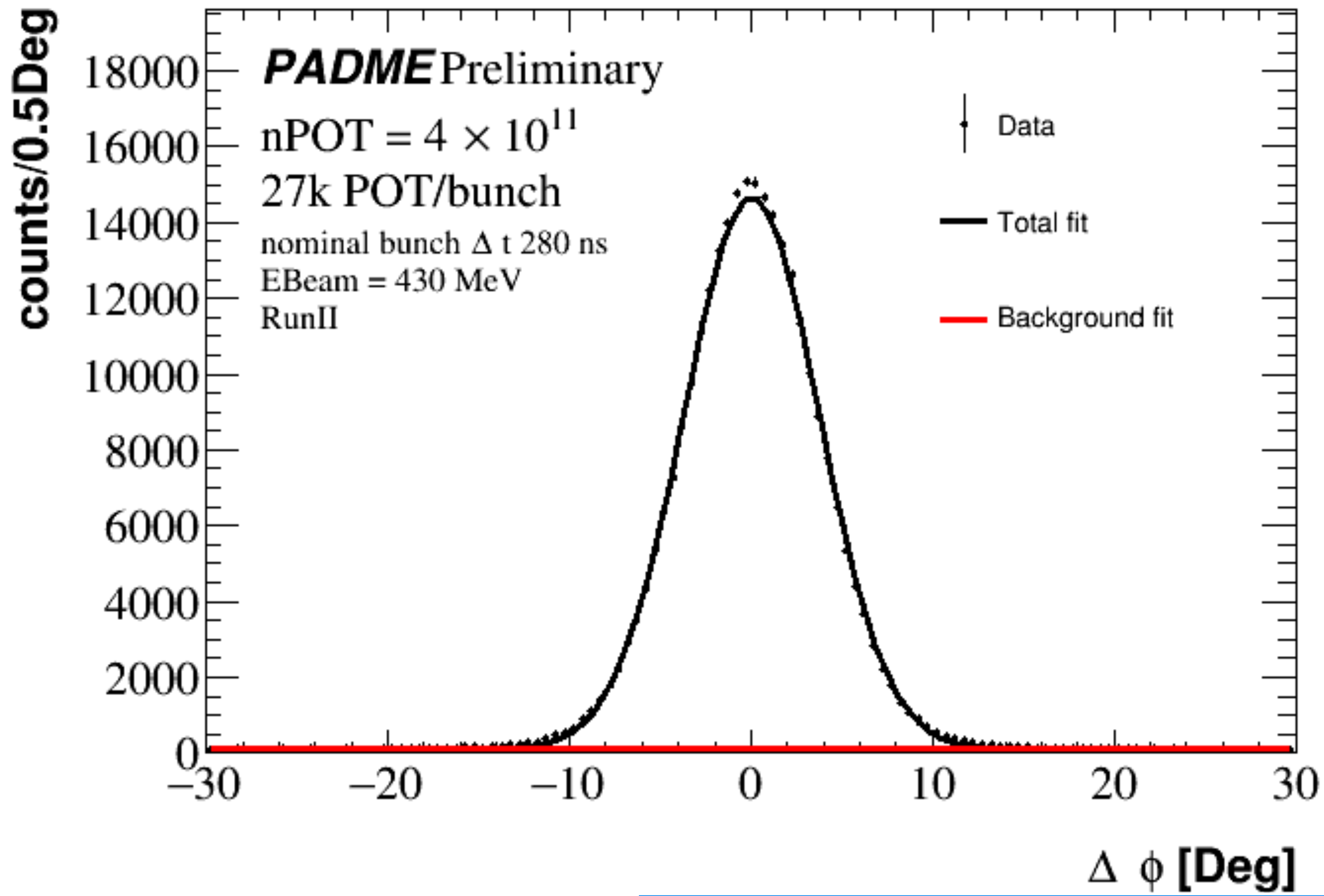


  - Annihilation
    - $e^+e^- \to \gamma\gamma$
      - Two symmetric photons in ECAL with correlated energy and polar angle
      - If $E_{beam} = 550$ MeV, $\sigma(e^+e^- \to \gamma\gamma) = 1.55$ mb
    - $e^+e^- \to \gamma\gamma\gamma$
      - Symmetry lost
      - If $E_{beam} = 550$ MeV, $\sigma(e^+e^- \to \gamma\gamma\gamma) = 7.5 \times 10^{-2}$ mb

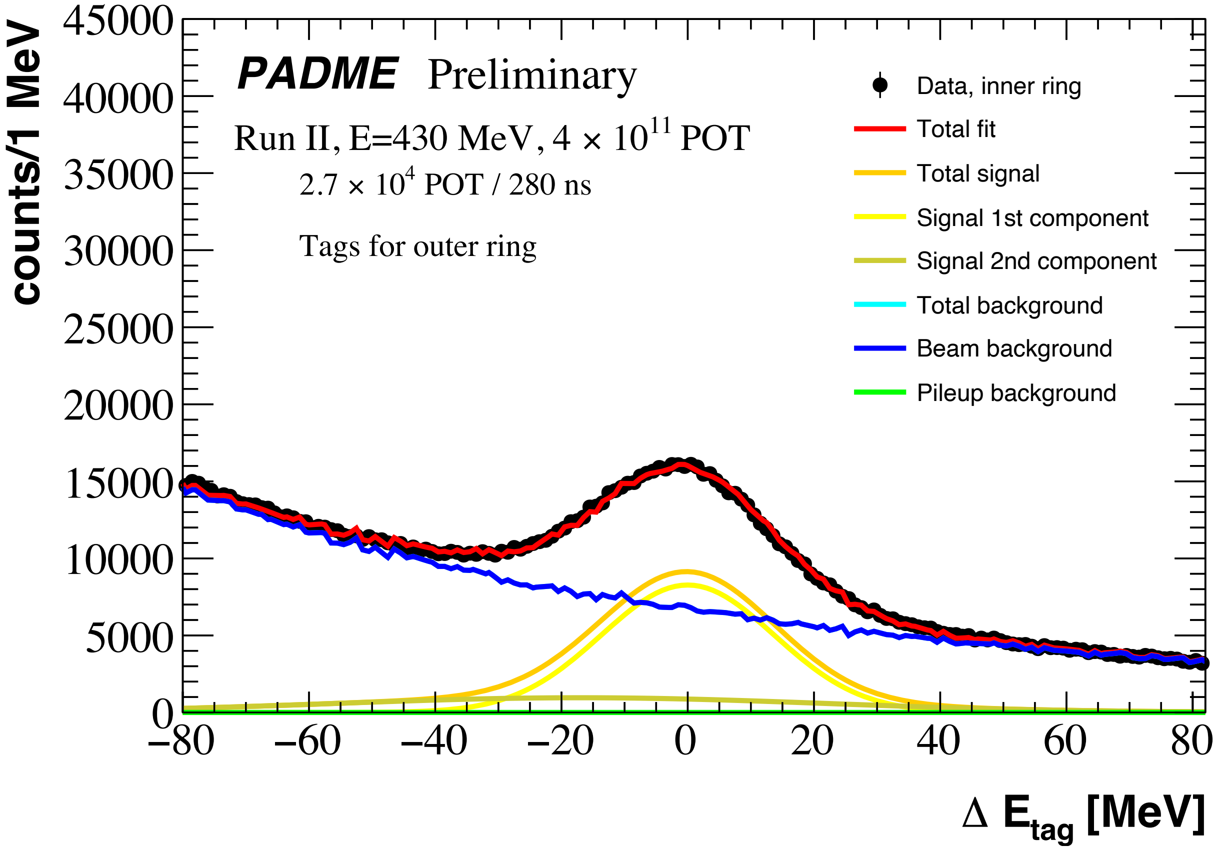


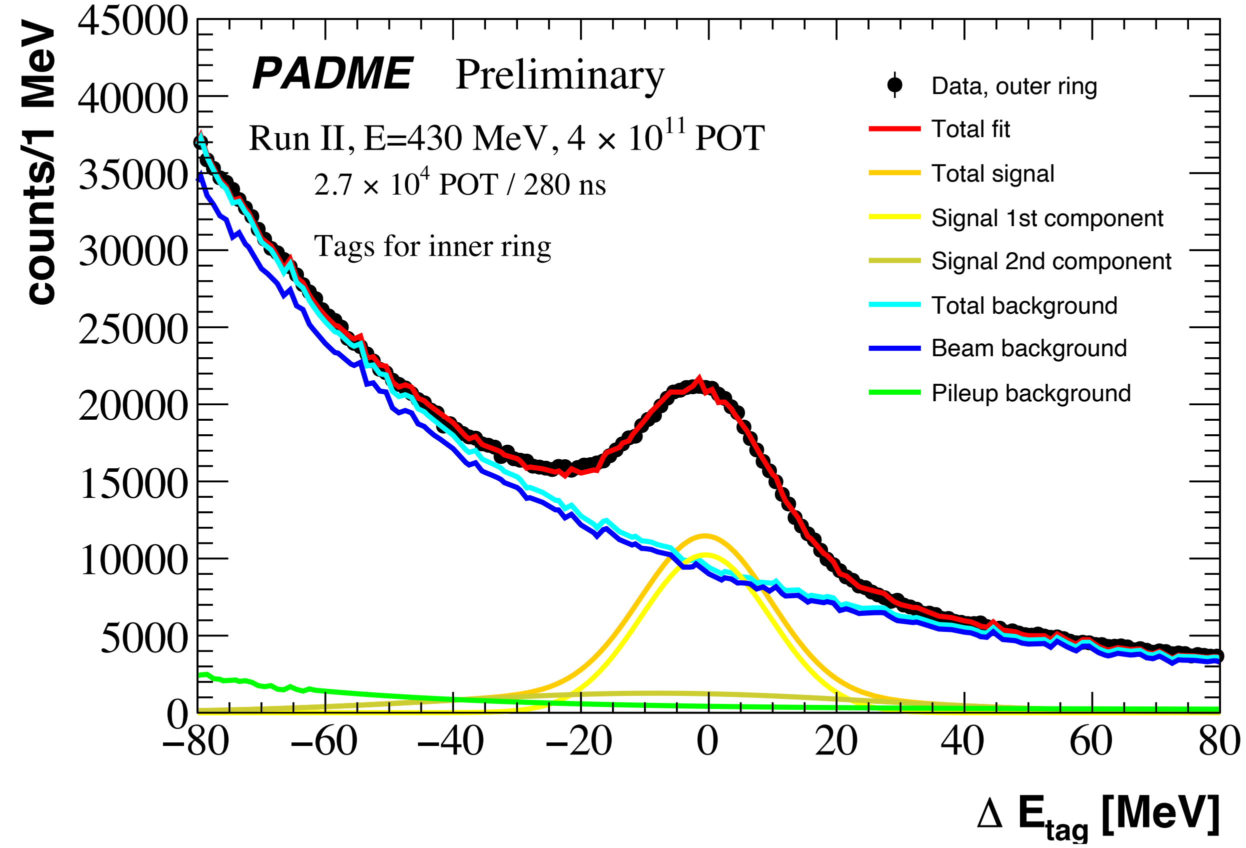
Annihilation cross section measurement

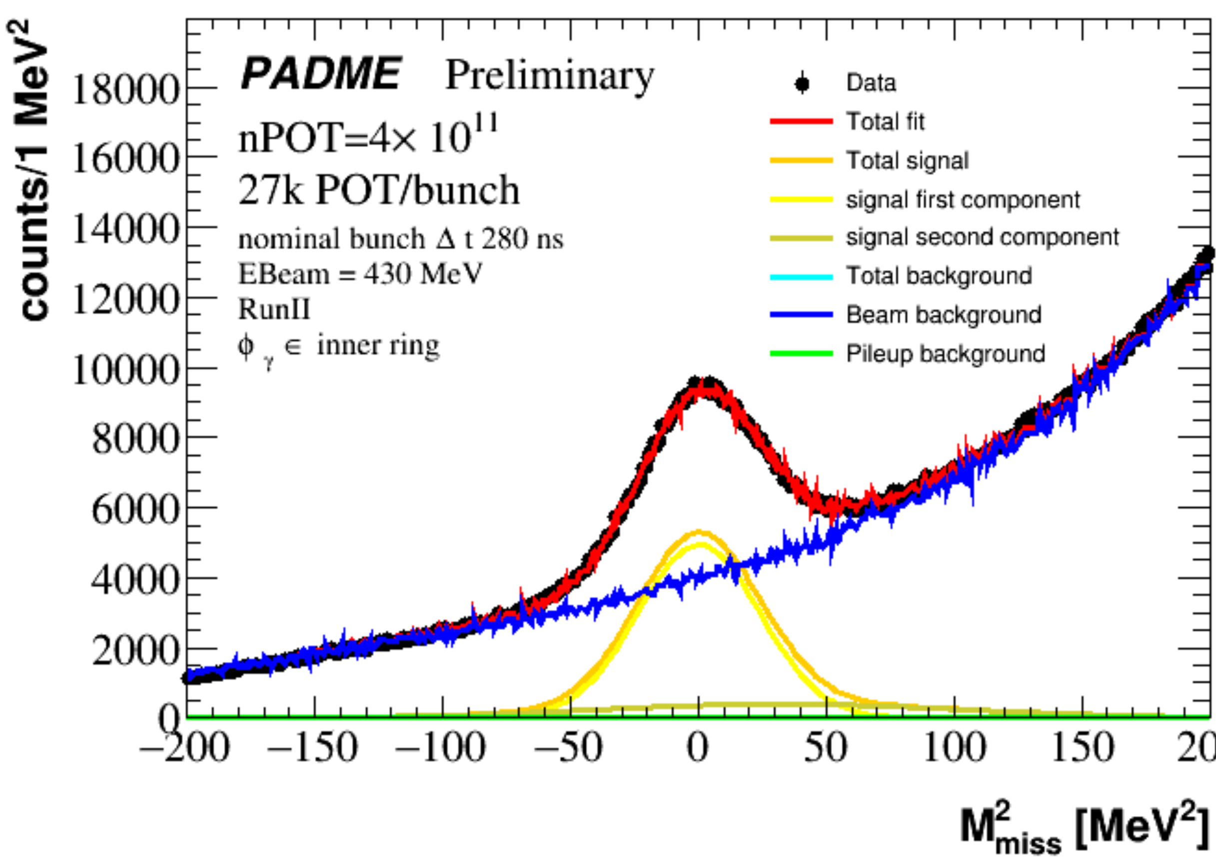
Method	Yield	cross section [mb]
$\Delta\phi$	276700 ± 530	1.981 ± 0.031
ΔE_{in}	375600 ± 3000	1.921 ± 0.028
ΔE_{out}	365700 ± 4300	1.914 ± 0.028
$M^2_{miss,\ in}$	369400 ± 1100	1.889 ± 0.027
$M^2_{miss,\ out}$	365200 ± 8500	1.912 ± 0.048

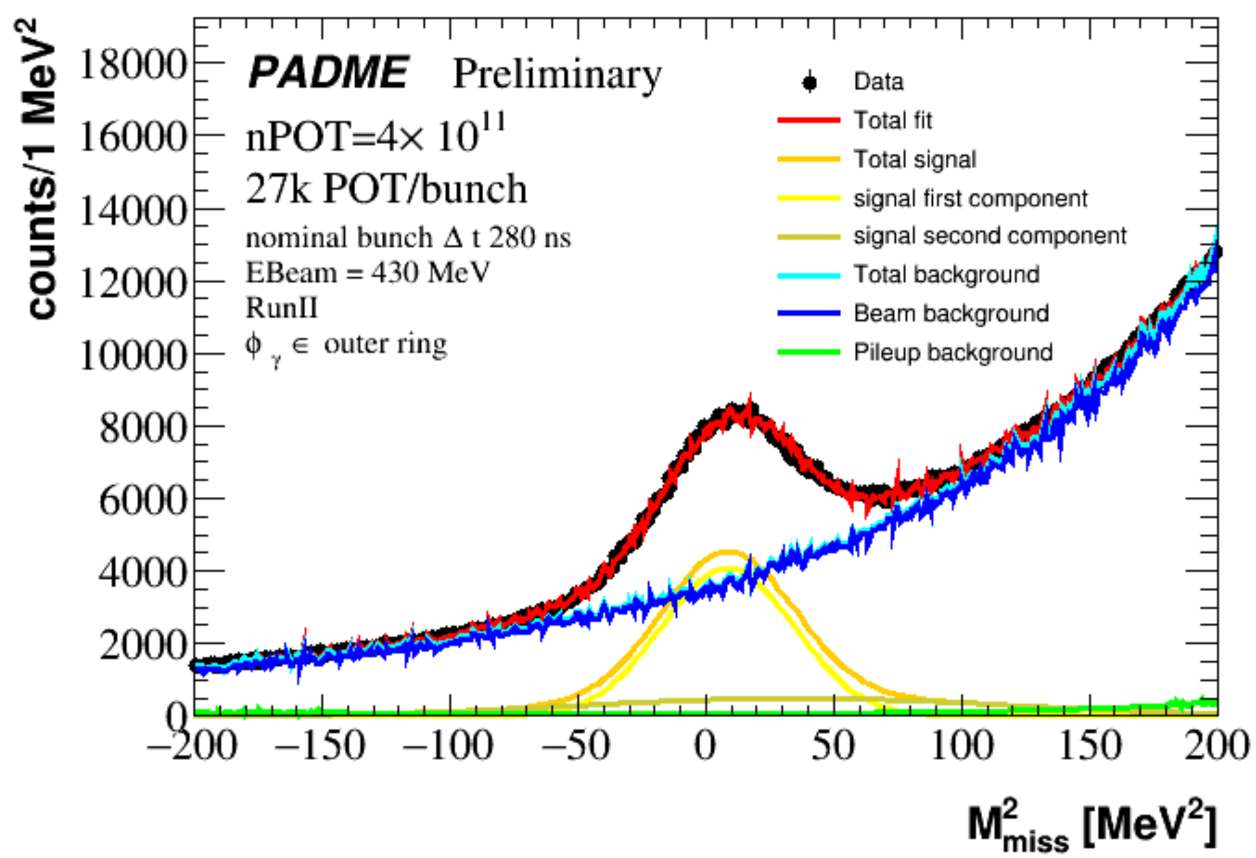


Annihilation cross section measurement I









Annihilation cross section measurement

Fiducial region: 115.8 < R < 285 mm

Method	Yield	cross section [mb]
$\Delta\phi$	276700 ± 530	1.981 ± 0.031
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Selection acceptance obtained from generator level photons preprocessed to merge particles unresolved due to calorimeter granularity + clusterisation algorithm

Extrapolating to full phase
With NLO QED generator

Correcting for photon selection efficiency
From tag-and-probe

inner ring efficiency	0.731 ± 0.009
outer ring efficiency	0.714 ± 0.006
acceptance	0.06424 ± 0.00025
N_{POT}	4×10^{11}
$N_{e/S}$	$0.0105b^{-1}$

Measuring total number of POT
With the active diamond target

Calibrated with a calorimeter with high precision