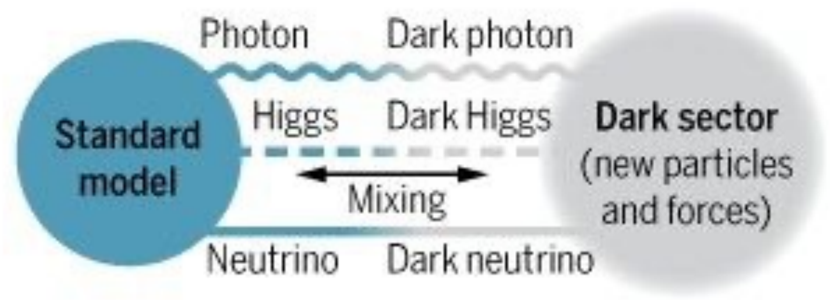
Paolo Valente – INFN Roma

Searching light dark matter particles in positrons annihilations

WE-Haraeus-Seminar - June 9th, 2021

Dark sector

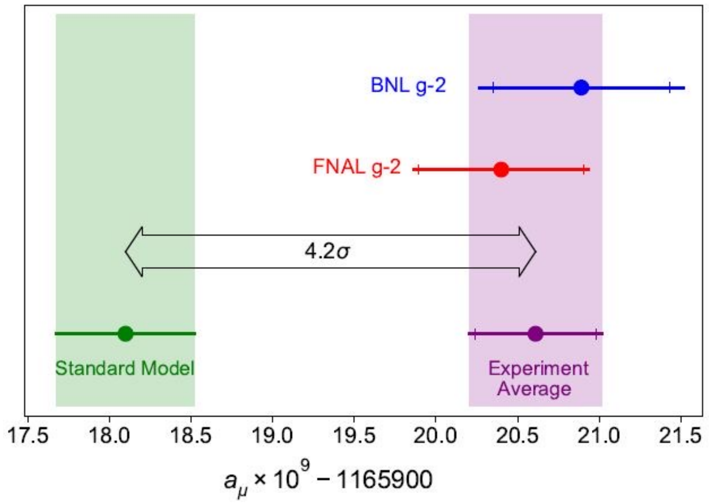


Lack of WIMPs + thermal DM = dark sector

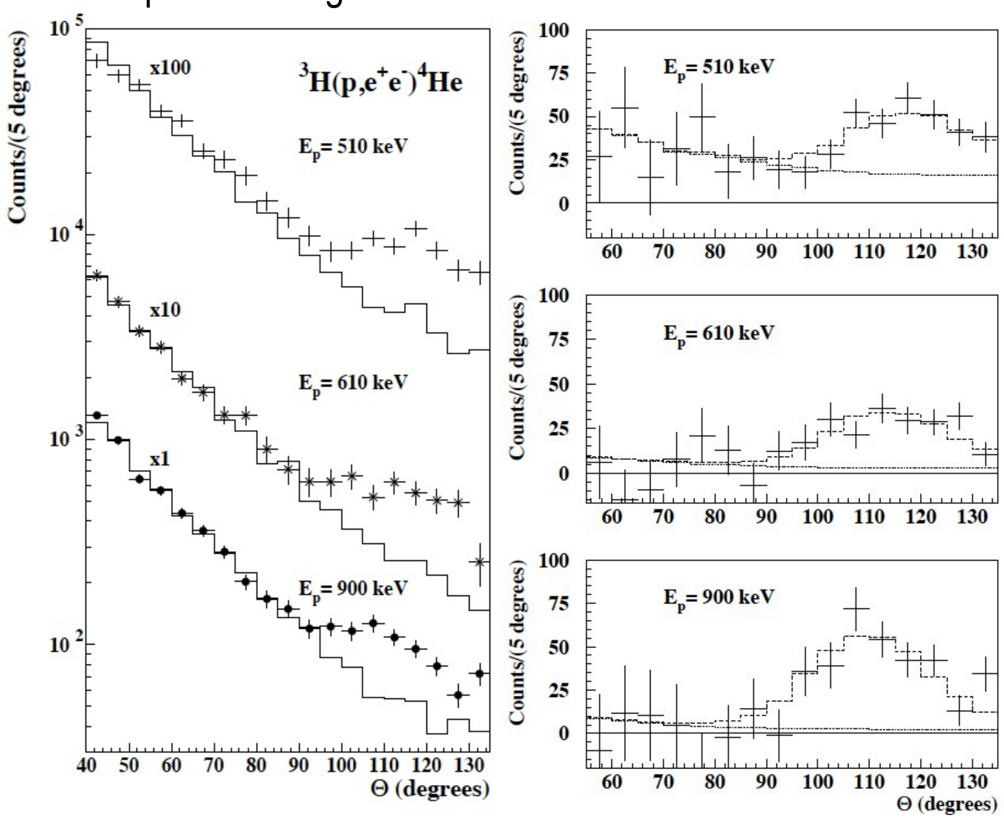
But **we also have anomalies in the MeV-GeV range**:

- g_μ-2 **recently confirmed to 4.2 σ**
- ^{8}Be and **now also ^{4}He**

Phys.Rev.Lett. 126 (2021) 14, 141801

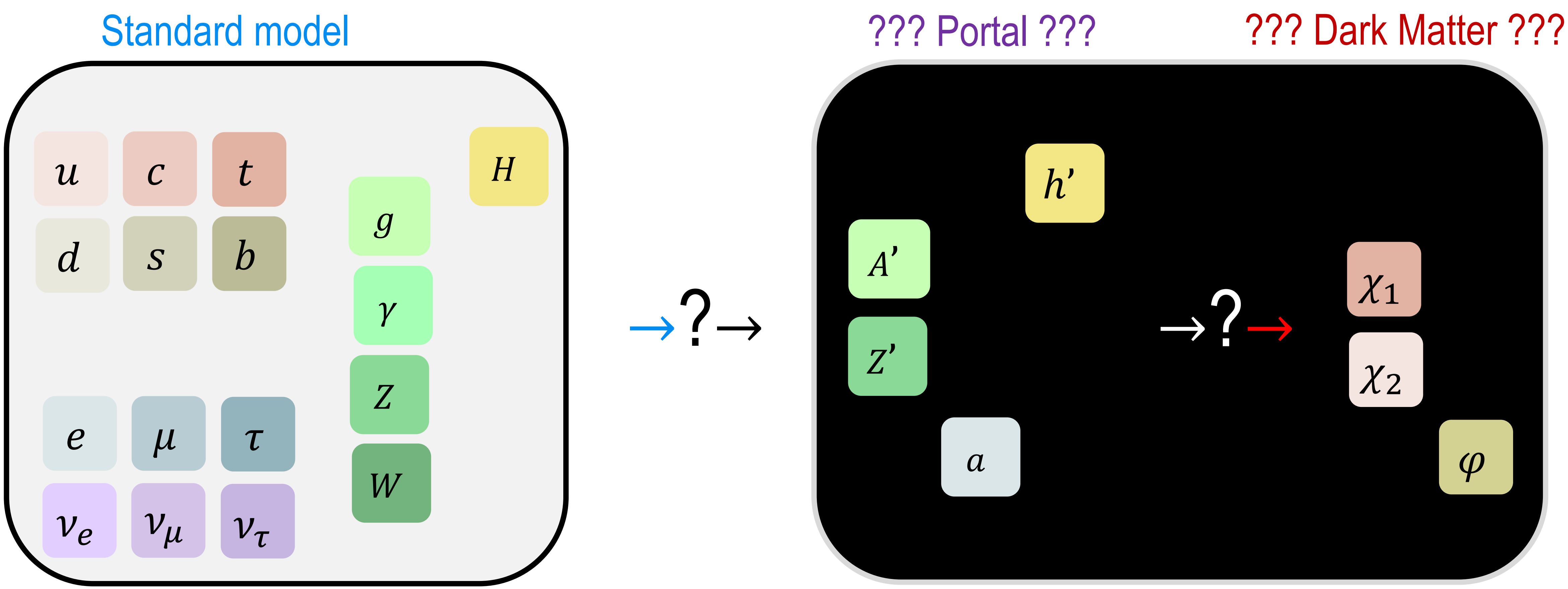


https://arxiv.org/abs/2104.10075v1



E_p (keV)	IPCC $\times 10^{-4}$	B_x $\times 10^{-6}$	Mass (MeV/c^2)	Confidence
510	2.5(3)	6.2(7)	17.01(12)	7.3σ
610	1.0(7)	4.1(6)	16.88(16)	6.6σ
900	1.1(11)	6.5(20)	16.68(30)	8.9σ
Averages		5.1(13)	16.94(12)	
^{8}Be values		6	16.70(35)	

What is a dark sector?



What we know

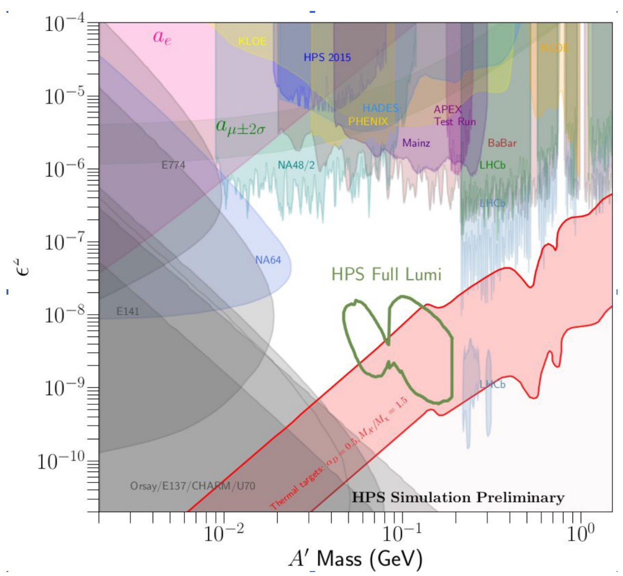
- Standard model only includes <20% of the matter in the Universe
- Dark matter interacts gravitationally

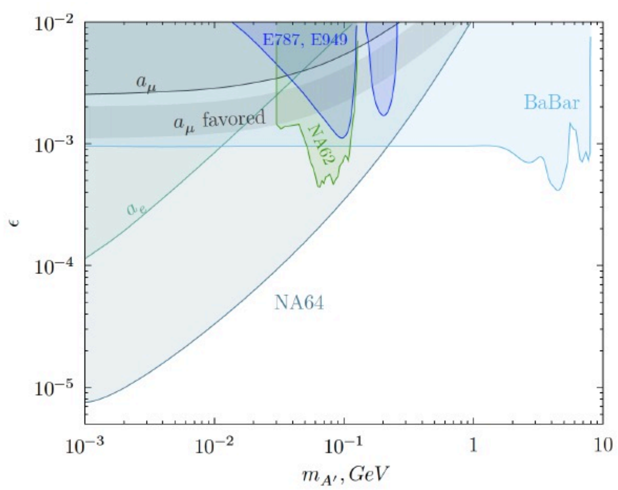
What we don't know

- What is **dark matter** made of?
- How dark matter interact, **if it does**, with SM particles?
- What's the **portal interaction** DM uses?
- Does one (or more) **new dark force** exist?
- **How complex is the dark sector spectrum**?

Dark sector candidates

Dark Photon

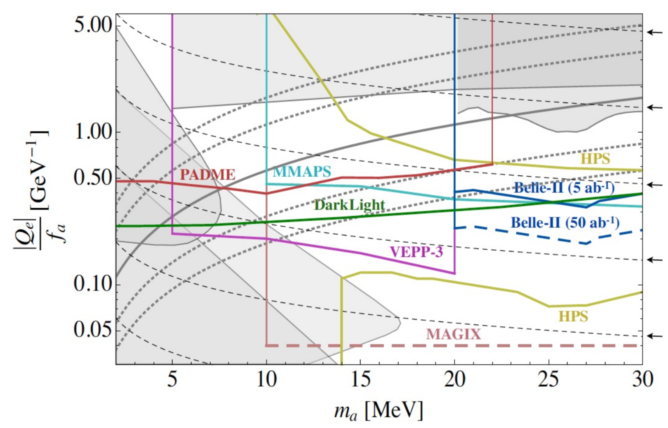


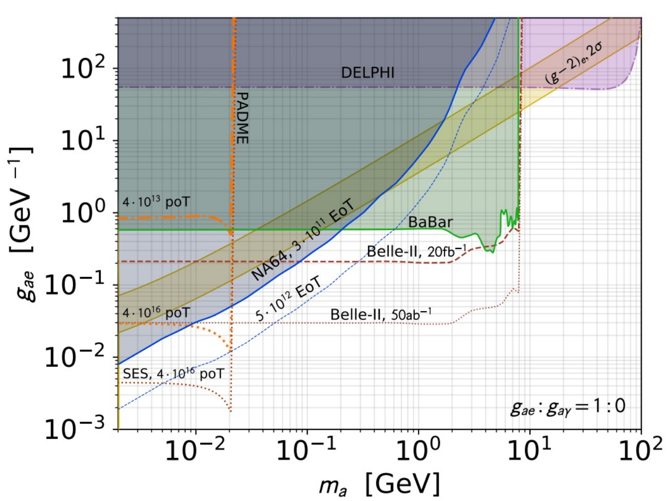


$e^+e^- \to \gamma A'$

Visible decays: $A' \to ee$
Invisible decays: $A' \to \chi\chi$

Axion Like Particles

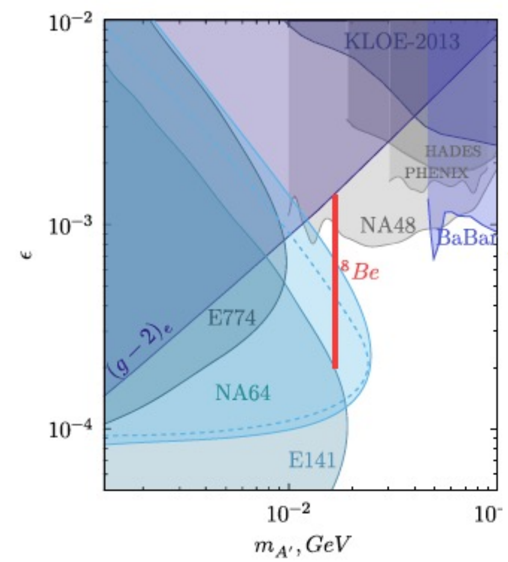


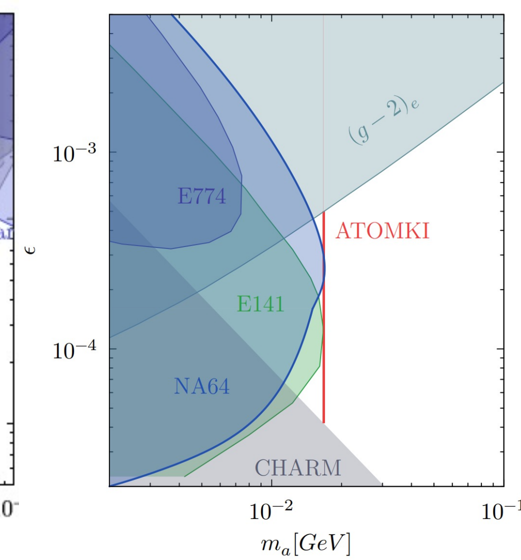


$e^+e^- \to \gamma a$

Visible final states: $a \to \gamma\gamma, ee$
invisible: $a \to \chi\chi$

^{8}Be anomaly – X17

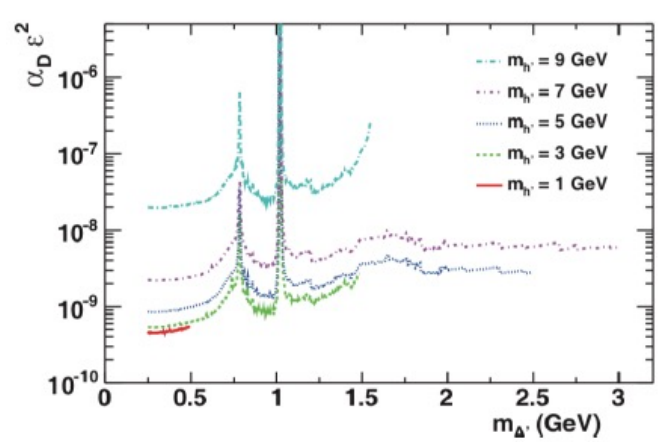




$e^+e^- \to [\gamma]X_{17}$

Final state $X_{17} \to ee$

Dark Higgs



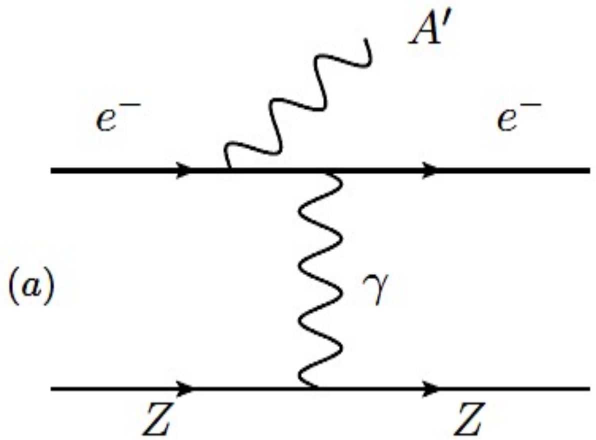
$e^+e^- \to h'A'; h' \to A'A', A' \to ee$

Final State: $A'A'A' \to e^+e^-e^+e^-e^+e^-$

Fixed-target positrons annihilations

With e+ beam 3 production mechanisms allowed:

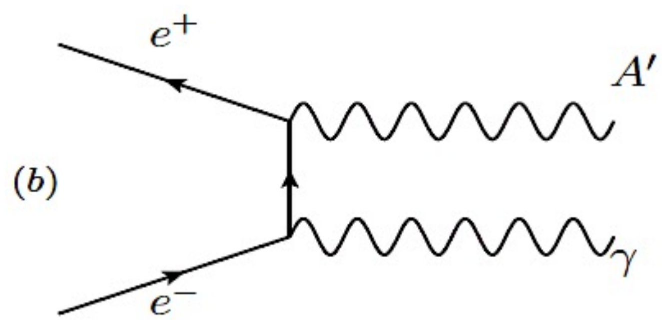
(a) A'-strahlung, **same as electrons**



Two additional mechanisms in e+ beams

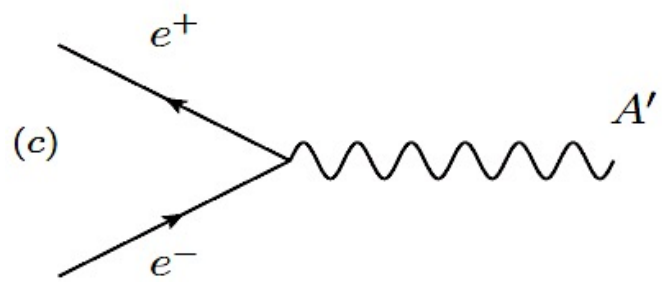
(b) Associated production O(α^2)

$$\sigma_{nr} = \frac{8\pi\alpha^2}{s}\left[\left(\frac{s-m_{A'}^2}{2s}+\frac{m_{A'}^2}{s-m_{A'}^2}\right)\log\frac{s}{m_e^2}-\frac{s-m_{A'}^2}{2s}\right]$$



(c) Resonant annihilation O(α)

$$\sigma_{\rm res}(E_e) = \sigma_{\rm peak}\frac{\Gamma_{A'}^2/4}{(\sqrt{s}-m_{A'})^2+\Gamma_{A'}^2/4}$$

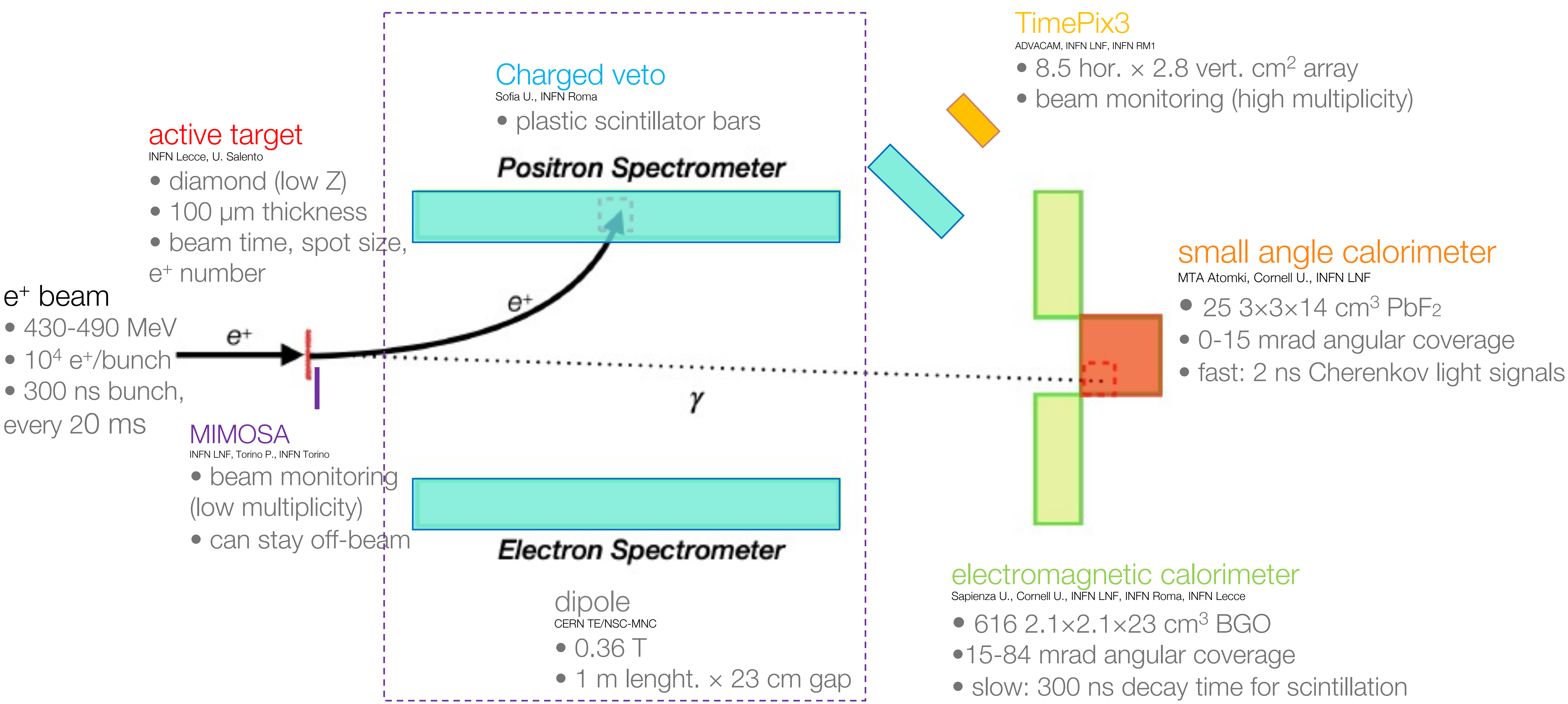


$$\sigma_{\rm peak} = 12\pi/m_{A'}^2$$

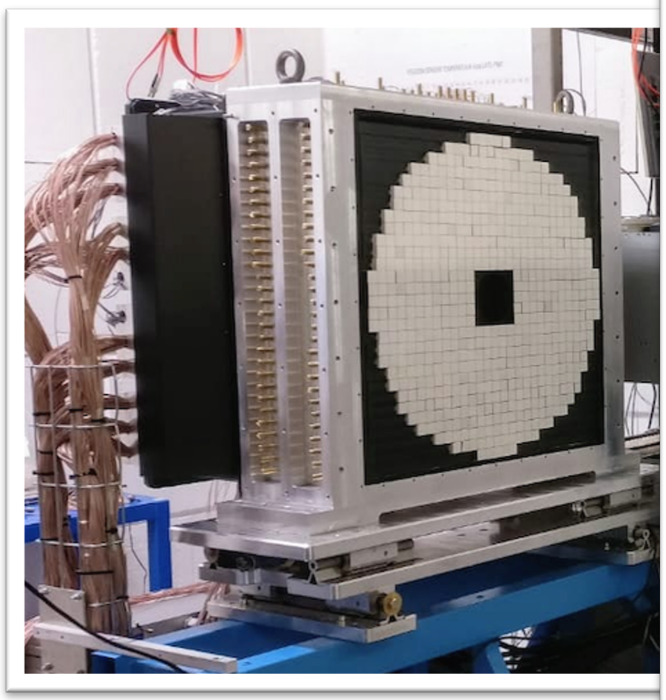
$$\Gamma_{A'} = \tfrac{1}{3}m_{A'}\varepsilon^2\alpha$$

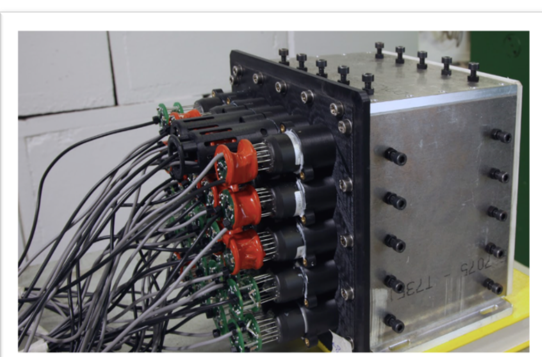
Detector

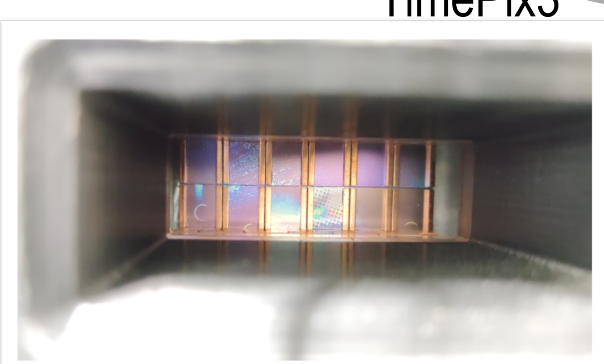
The detectors have been optimized for the invisible decays of a dark photon, in particular for rejecting the Standard Model backgrounds

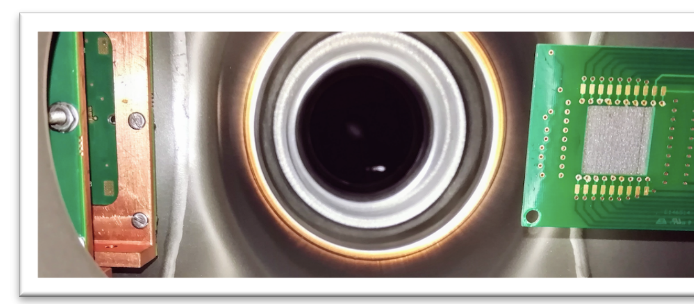


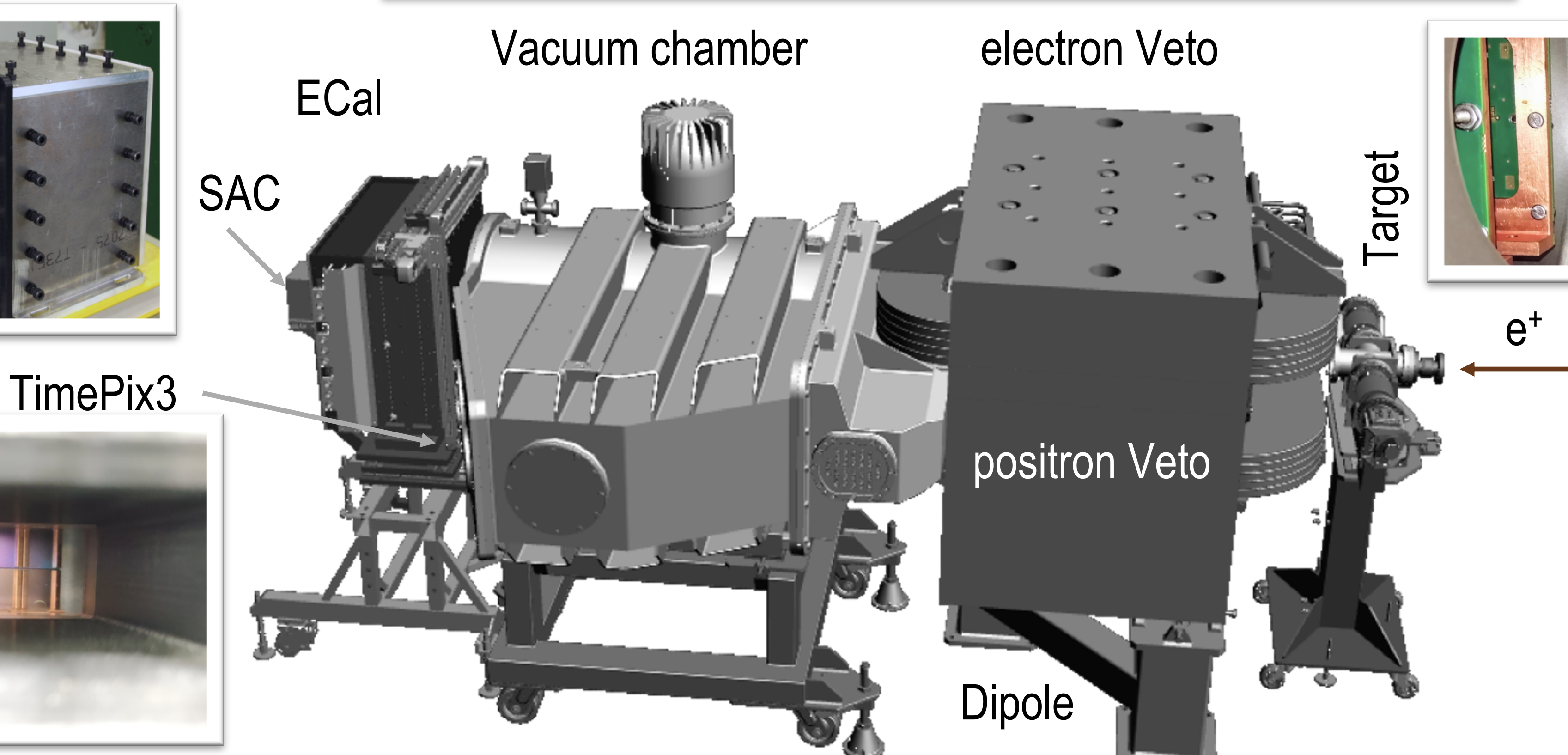
Detector










Vacuum chamber
electron Veto
ECal
SAC
Target
e+
TimePix3
positron Veto
Dipole

Signatures at PADME

Dark photon (A'):

$e^+e^- \rightarrow \gamma A'$

- Dark photon invisible decay, missing mass search (main channel)

$e^+e^- \rightarrow \gamma A' \rightarrow \gamma e^+e^-$

- Visible decay, only for short-lived A'
- Bump hunt possible by computing missing mass against recoil γ

$e^+e^- \rightarrow A' \rightarrow e^+e^-$

- Direct annihilation followed by visible decay
- Very narrow, need to know the mass in advance to exploit the resonance

ALP (A^0):

$e^+e^- \rightarrow \gamma A^0$

- Invisible decay, same A' signature

$e^+e^- \rightarrow \gamma A^0 \rightarrow \gamma\gamma\gamma$ (visible)

$e^+e^- \rightarrow \gamma A^0 \rightarrow \gamma e^+e^-$ (visible)

Dark Higgs (h')

$e^+e^- \rightarrow A'\,h' \rightarrow A'\,A'\,A' \rightarrow 3(e^+e^-)$

- Requires $m_{h'} \geq 2m_{A'}$

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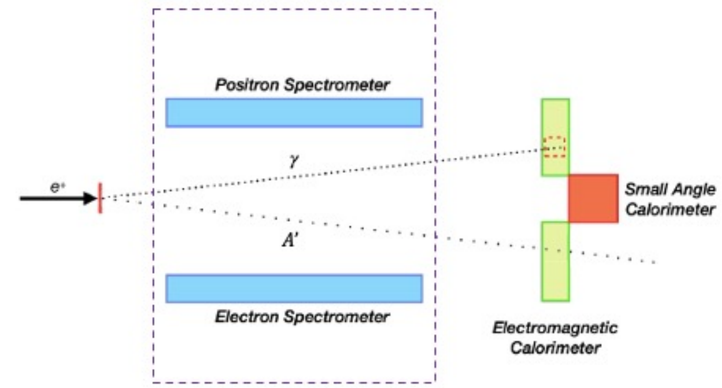
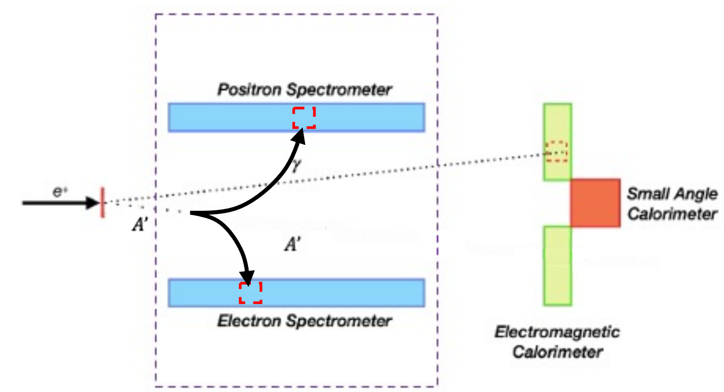
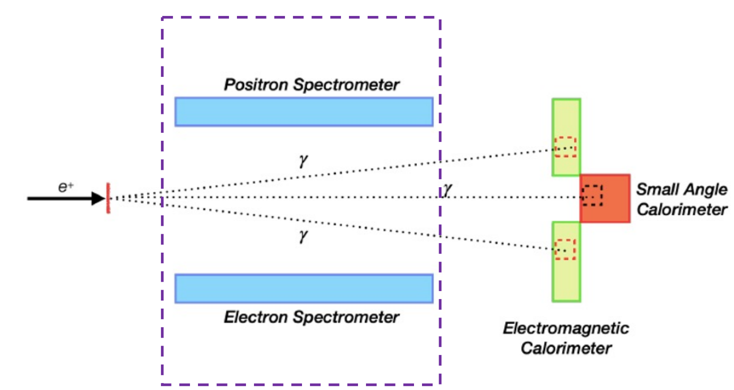






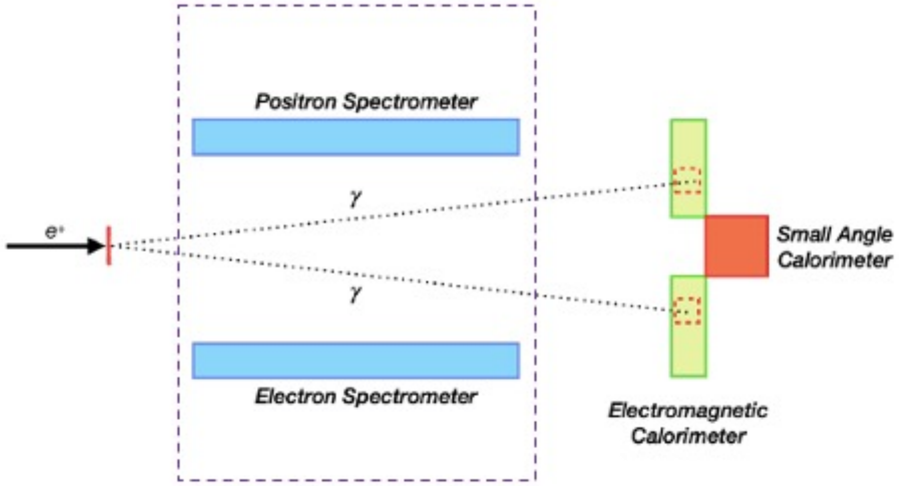
Signatures at PADME

Standard Model channels

(cross sections never measured around 20 MeV)

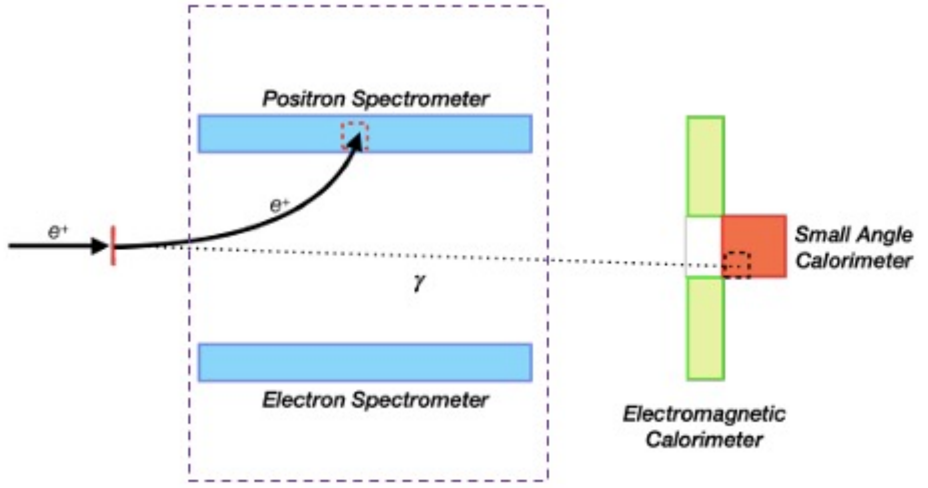
Pure photon final state: $e^+e^- \rightarrow \gamma\gamma[\gamma]$

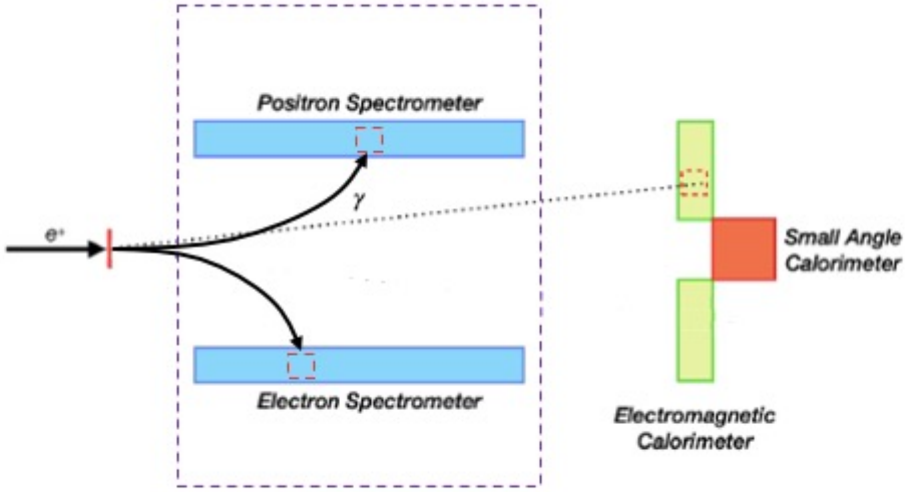
- Background to the main channel
- ~10^7 [10^4-10^5] candidates/year
- By-product of luminosity and A' invisible search
- Needed to compute absolute calorimeter energy scale
- 3γ need to be calculated and measured precisely



Mixed final state: $e^+e^- \rightarrow e^+e^-\gamma$; $e^\pm N \rightarrow e^\pm N\gamma$

- Bremsstrahlung, background to visible and invisible (lost e+) channels





Signatures at PADME

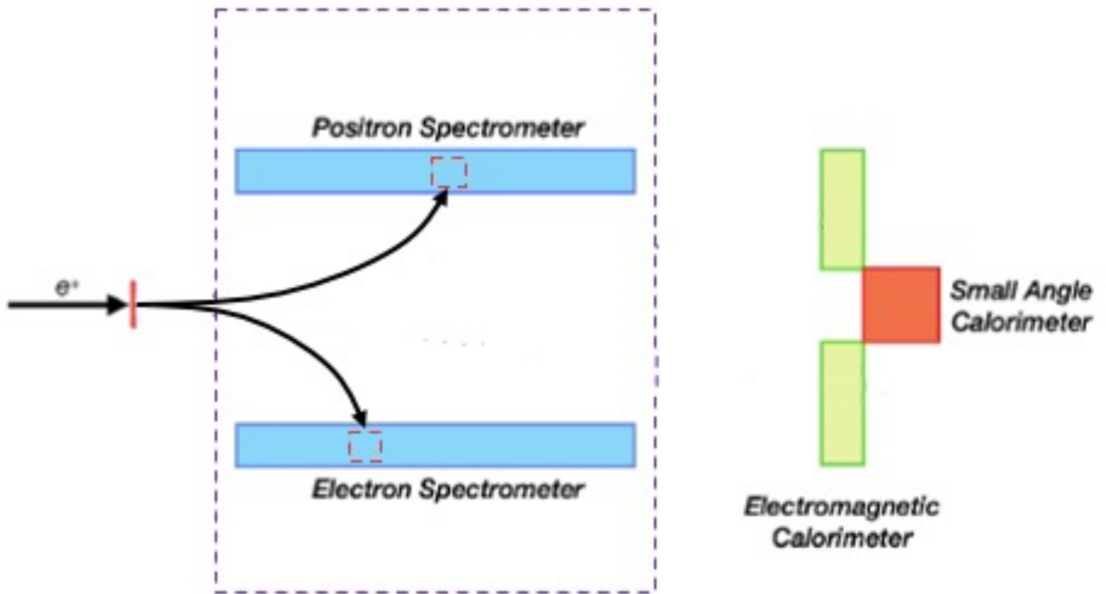
Standard Model channels

(cross sections never measured around 20 MeV)

Pure lepton final states:

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

- Can be used as luminosity reference to cross-check target and TimePix
- Huge statistics but may have problems with pile-up
- Background to visible channel

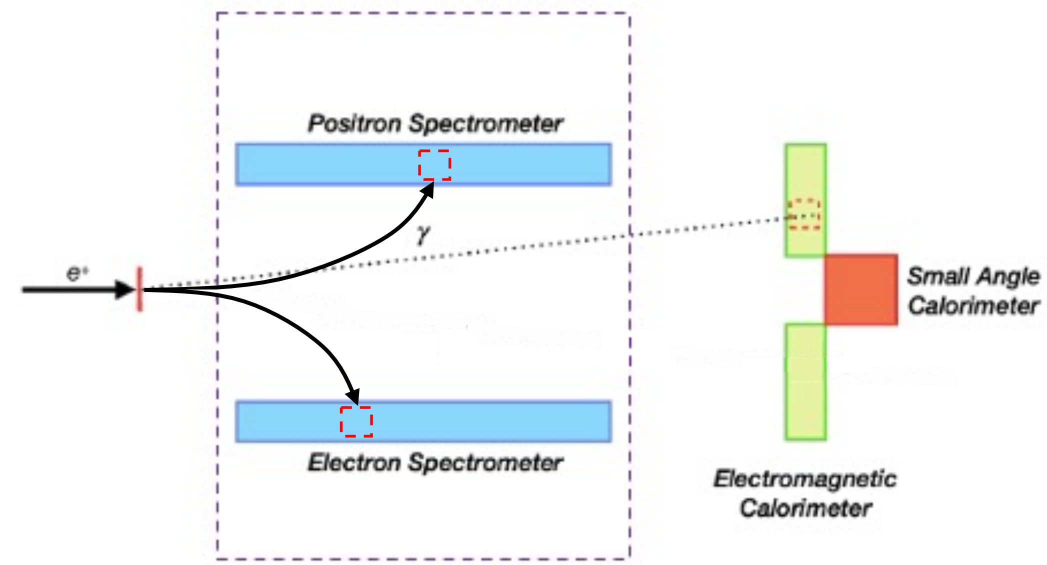


$e^+e^- \to 3(e^+e^-)$

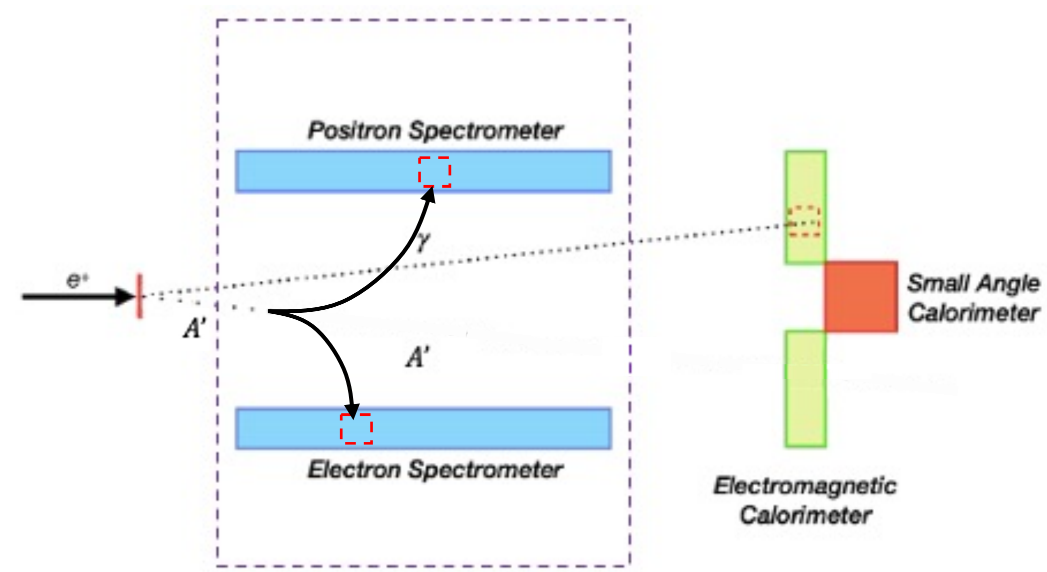
- Unknown SM cross section not trivial to compute (too many diagrams)
- May be measured or not due to acceptance issues (too low momentum)
- Background to dark Higgs

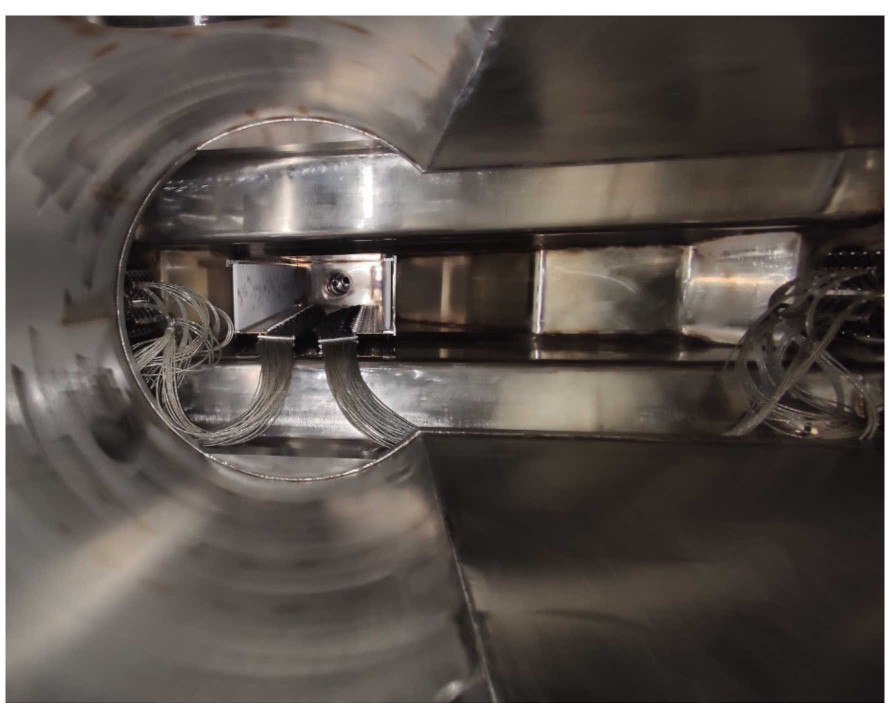
Charged tracks at PADME

[Radiative] Bhabha: $e^+e^- \to e^+e^- \, [\gamma]$



Visible dark photon decays: $e^+e^- \to [\gamma]A' \to [\gamma]e^+e^-$





- The electron and positron «spectrometers» are actually veto detectors: no vertexing capability
- In case of detached vertex the momentum determination from the hit position will be wrong

Integrated luminosity

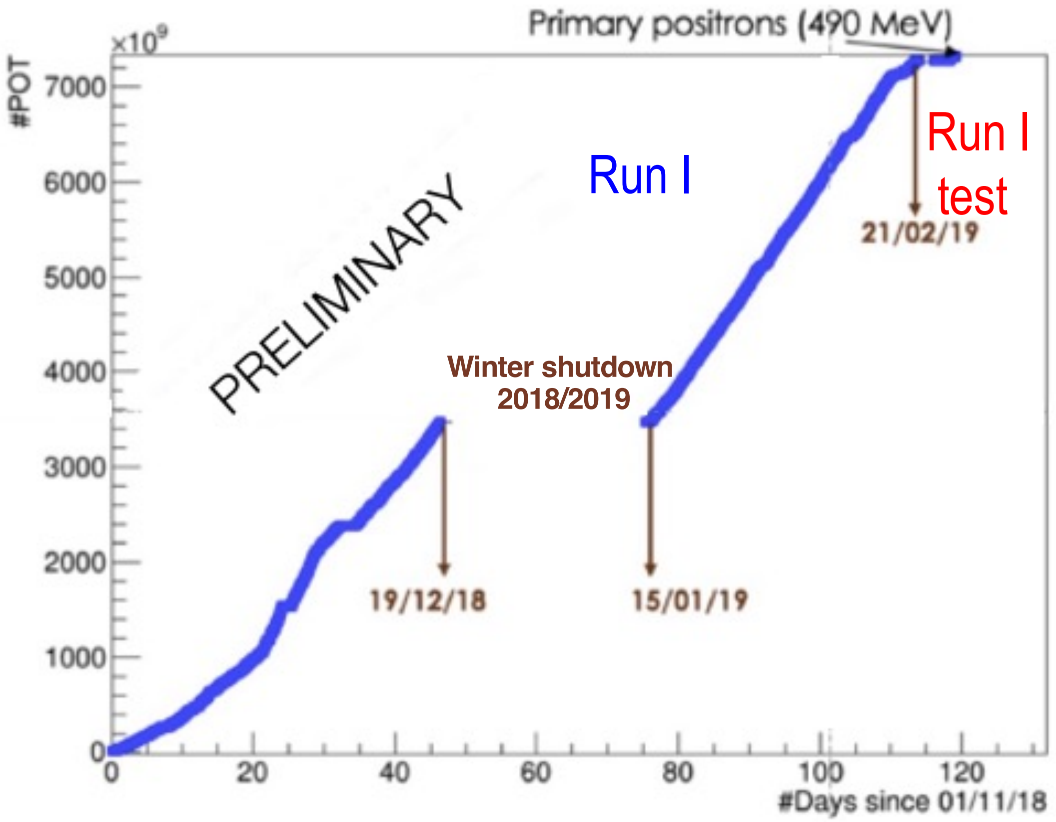
Run I with secondary e+, 530 MeV, produced on the beam-test facility degrader:
Nov. 2018-Feb. 2019. Short test at end of Run I (Mar. 2019) with 490 MeV primary beam.

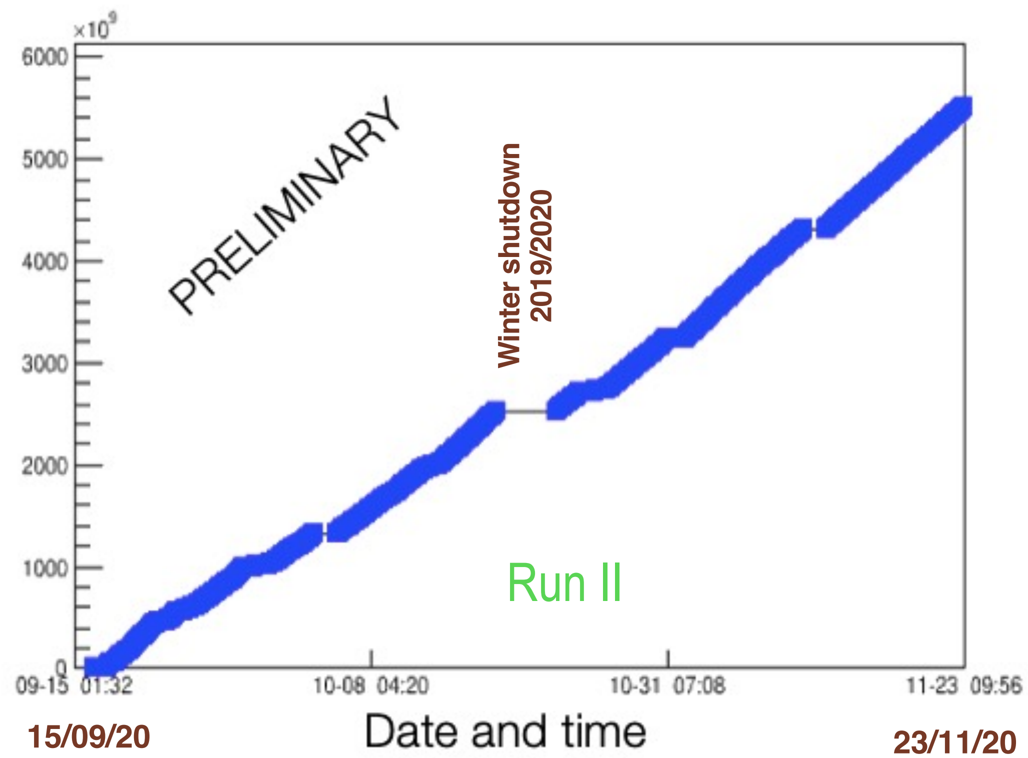
Primary e+ from LINAC, 430 MeV, from mid July to Dec. 2nd 2020

- Beam commissioning = $1.04 \cdot 10^{12}$ PoT
- Physics (calibration and test included) PoT = $6.28 \cdot 10^{12}$ (on-line estimation $6.64 \cdot 10^{12}$)

PADME physics **Run II**: 15/09/2020 → 26/11/2020:

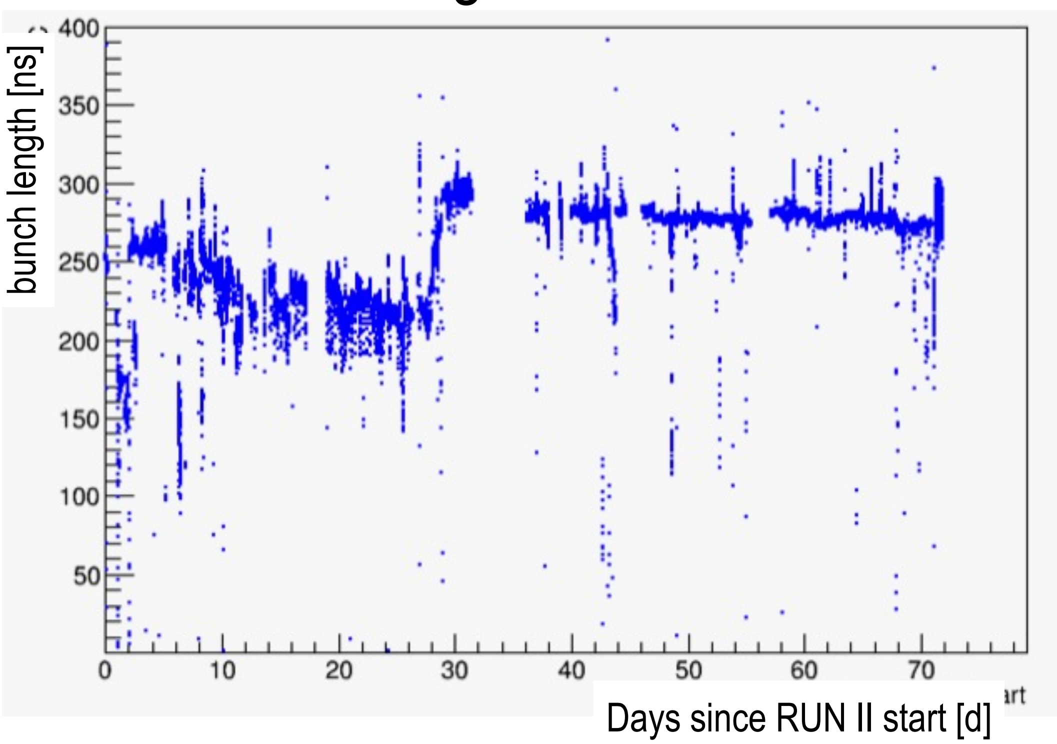
- PoT = $5.58 \cdot 10^{12}$ (to be refined with data quality) → $1.12 \cdot 10^{11}$ PoT/day



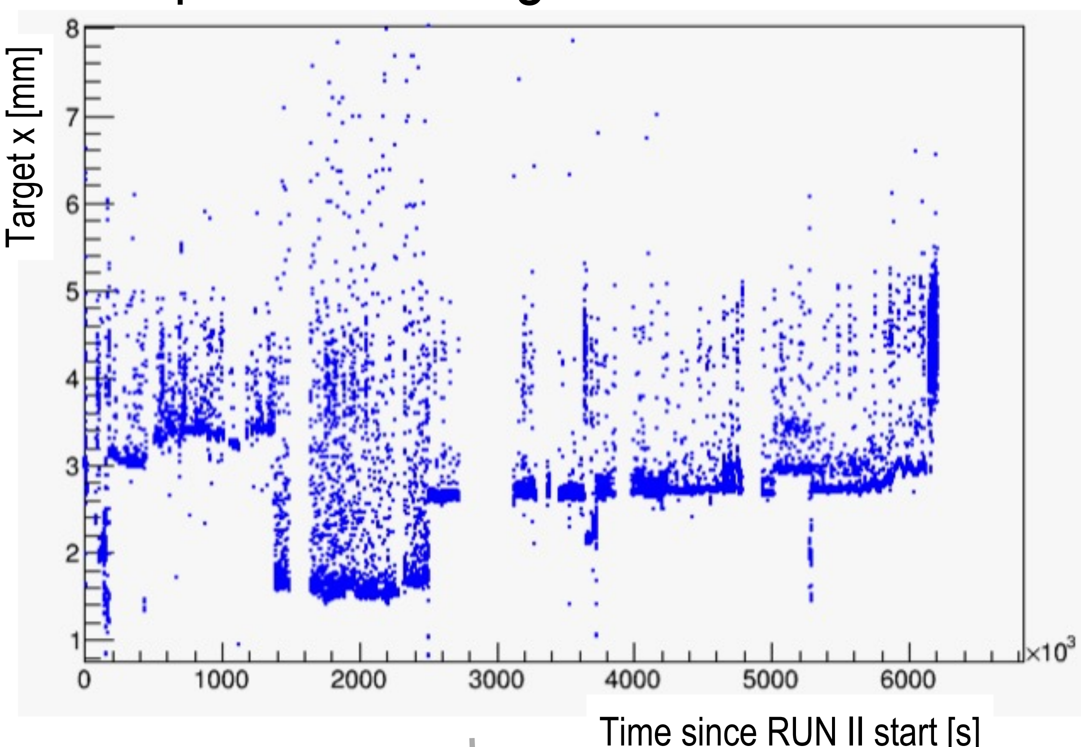


Positron beam 2020 data taking

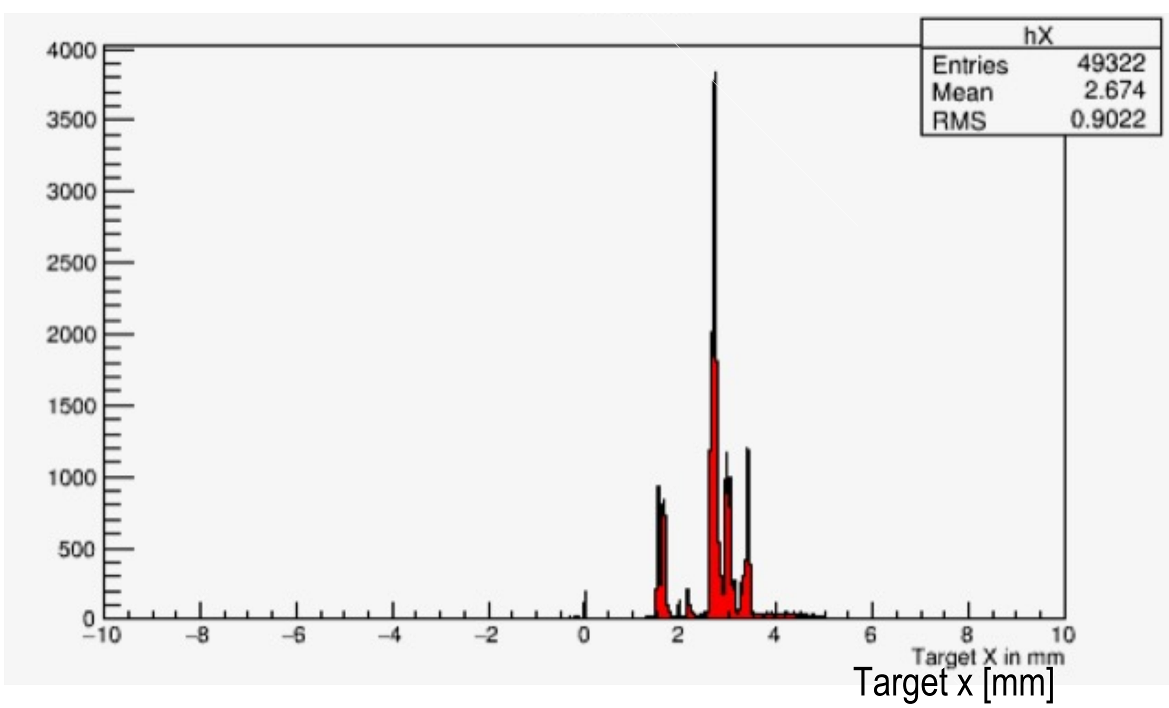
Bunch length vs Run number



x-position at target vs Run number



x-position at target

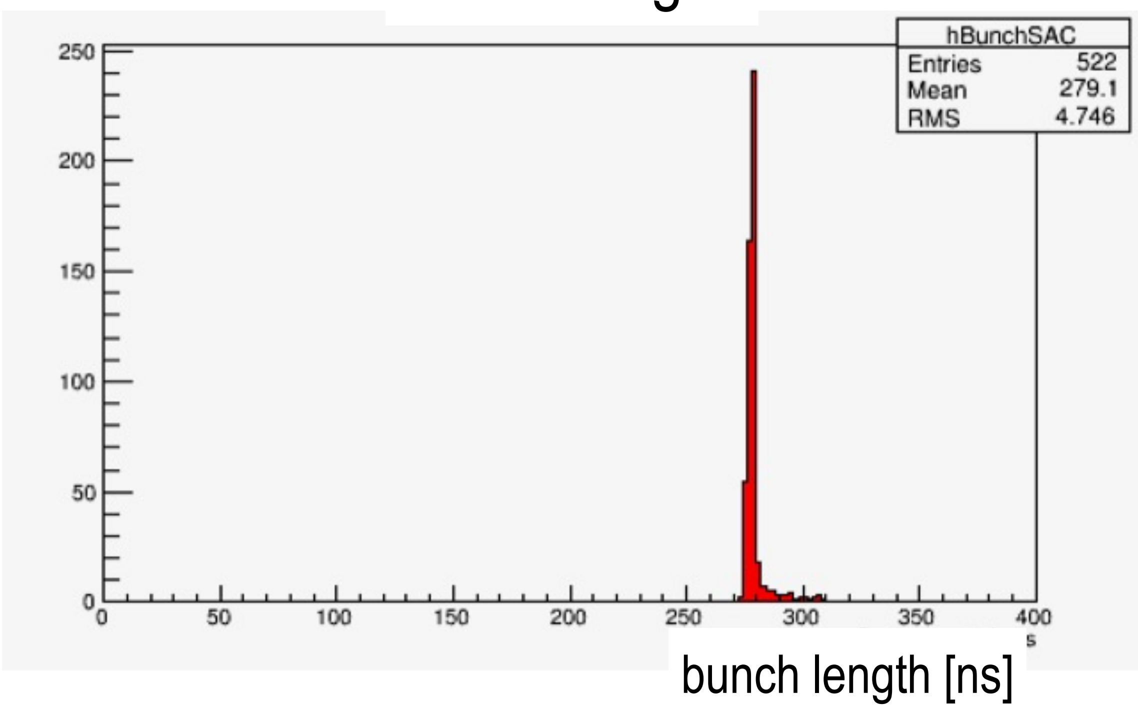


Variations due to optimization of hit point on target

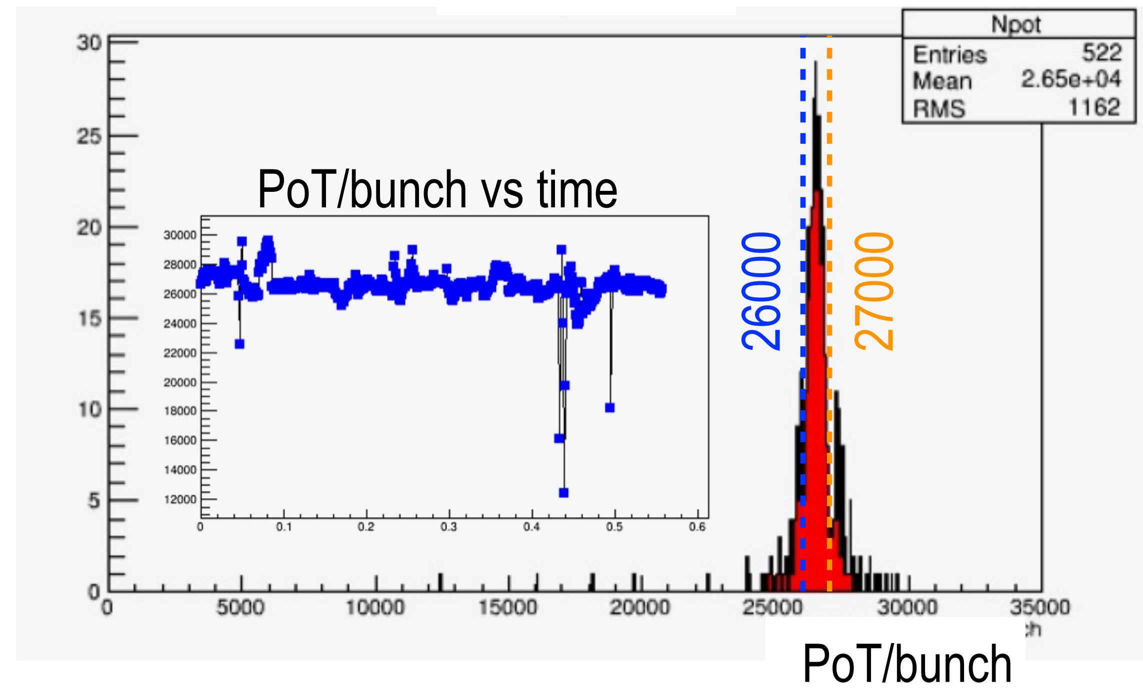
Stability: (100±16) μm

Positron beam, single run

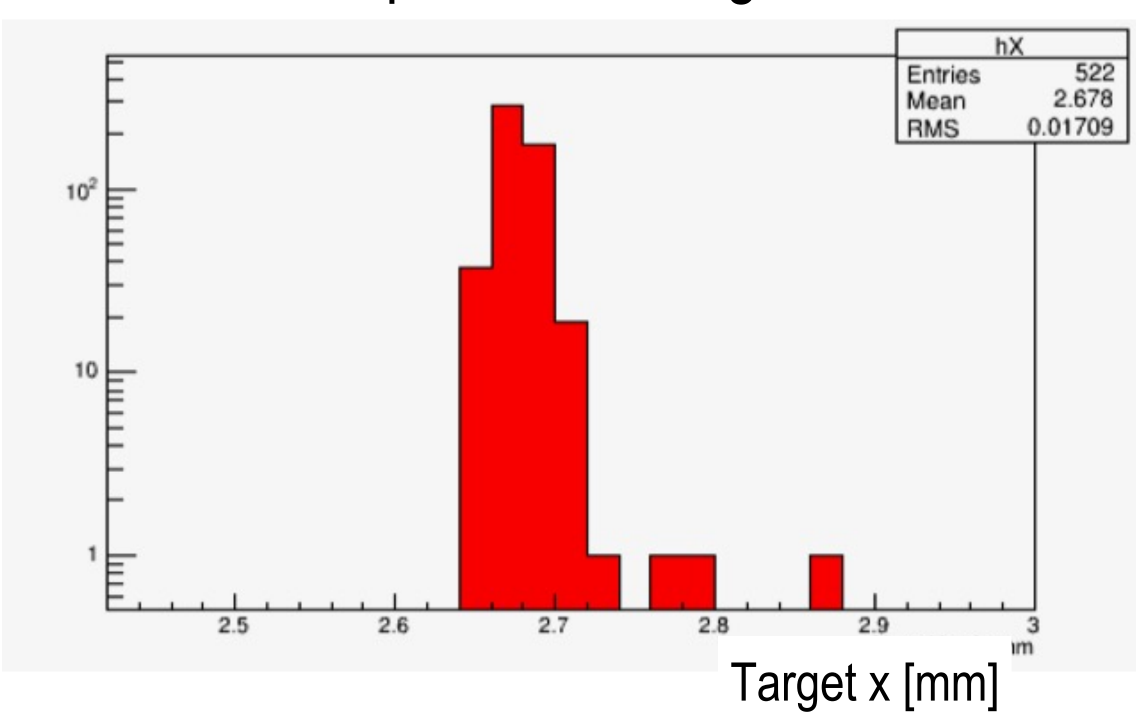
Bunch length



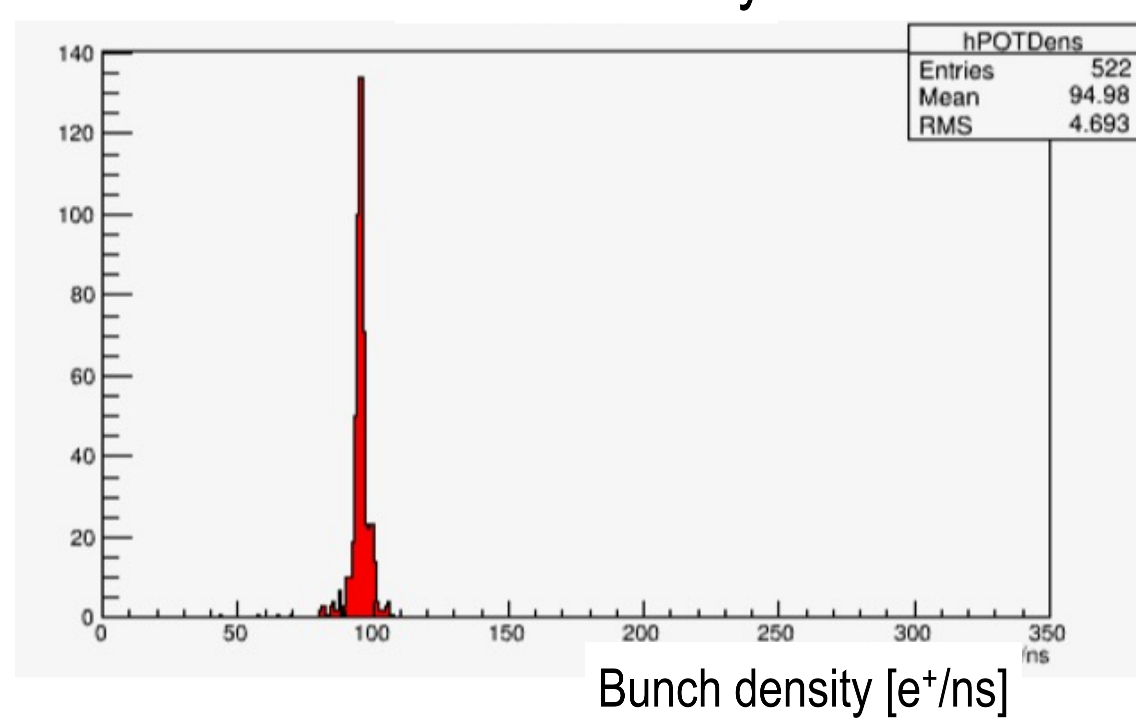
PoT/bunch



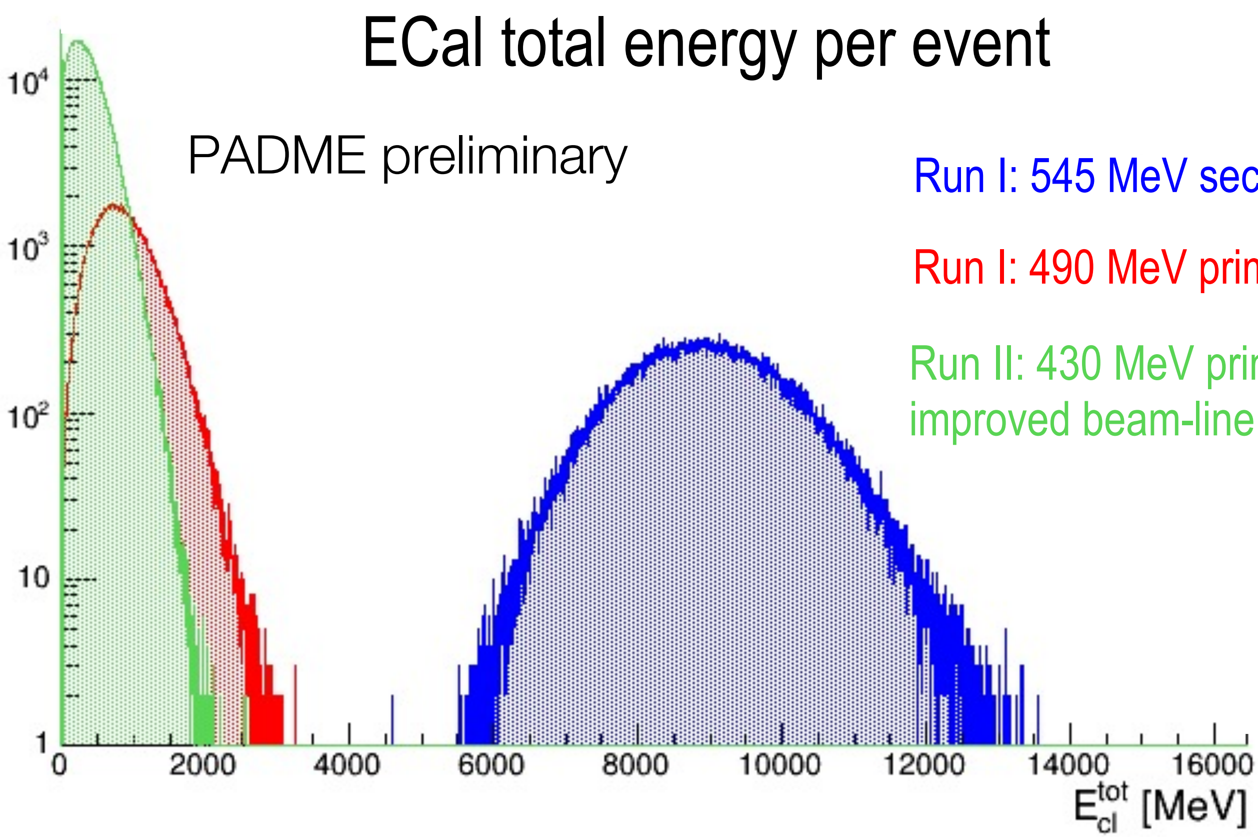
x-position at target



Bunch density



Beam background



Background index:

Run I: 545 MeV secondary, 25k e+, 250 ns — $0.36\ MeV/e^+$

Run I: 490 MeV primary, 25k e+, 250 ns — $0.03\ MeV/e^+$

Run II: 430 MeV primary, 28k e+, 280 ns improved beam-line — $0.013\ MeV/e^+$

Run 1 secondary beam

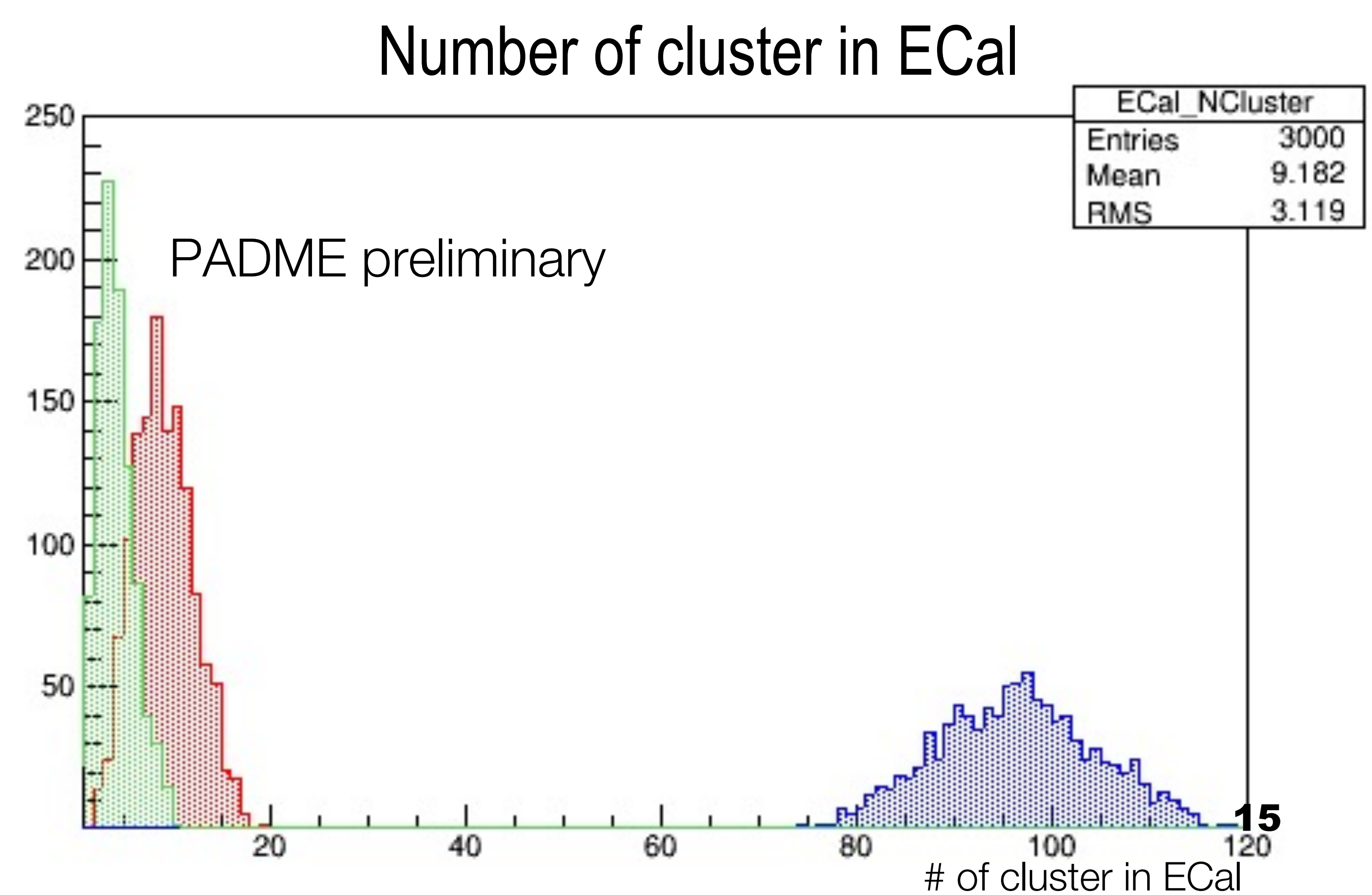
- High beam-related background

Run1 primary beam

- Reduced background, but simulations indicate that the thin Be window at the separation between linac and experiment vacuum is an important source of beam energy spread (converted in transverse offset by dispersion in dipoles)

Run2 primary beam, new mylar window moved upstream

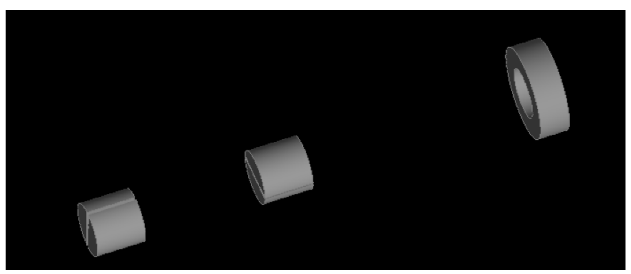
- Much reduced background, easy to identify SM processes

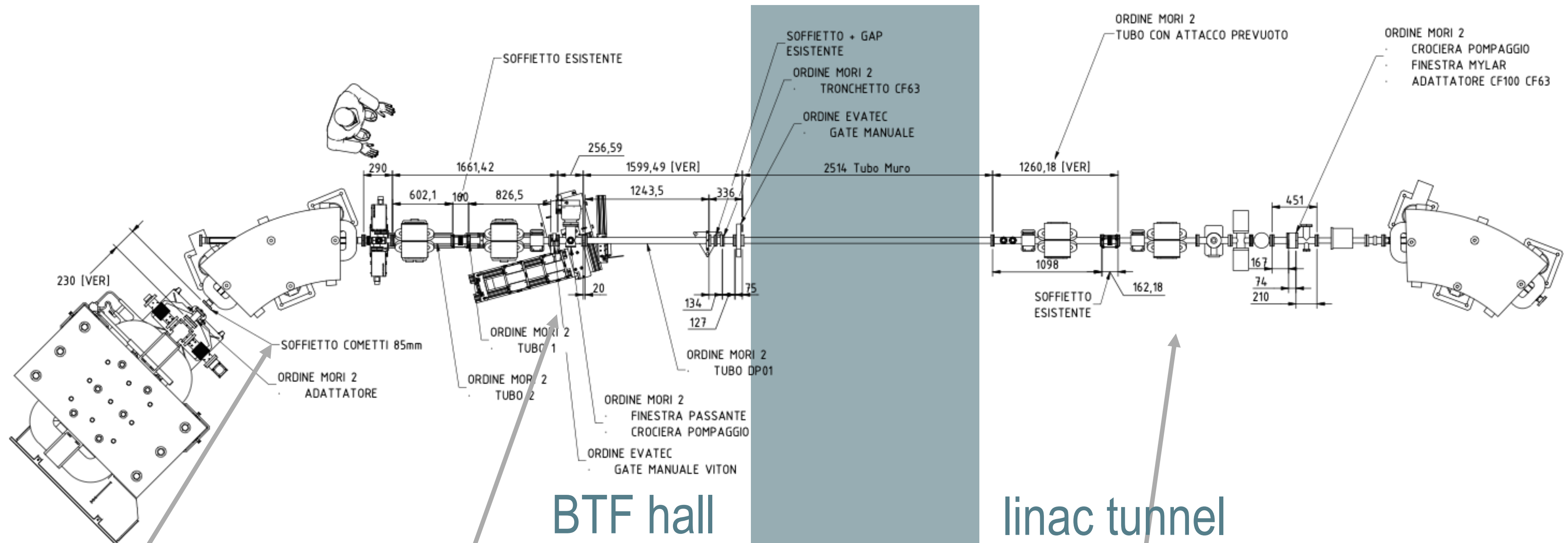


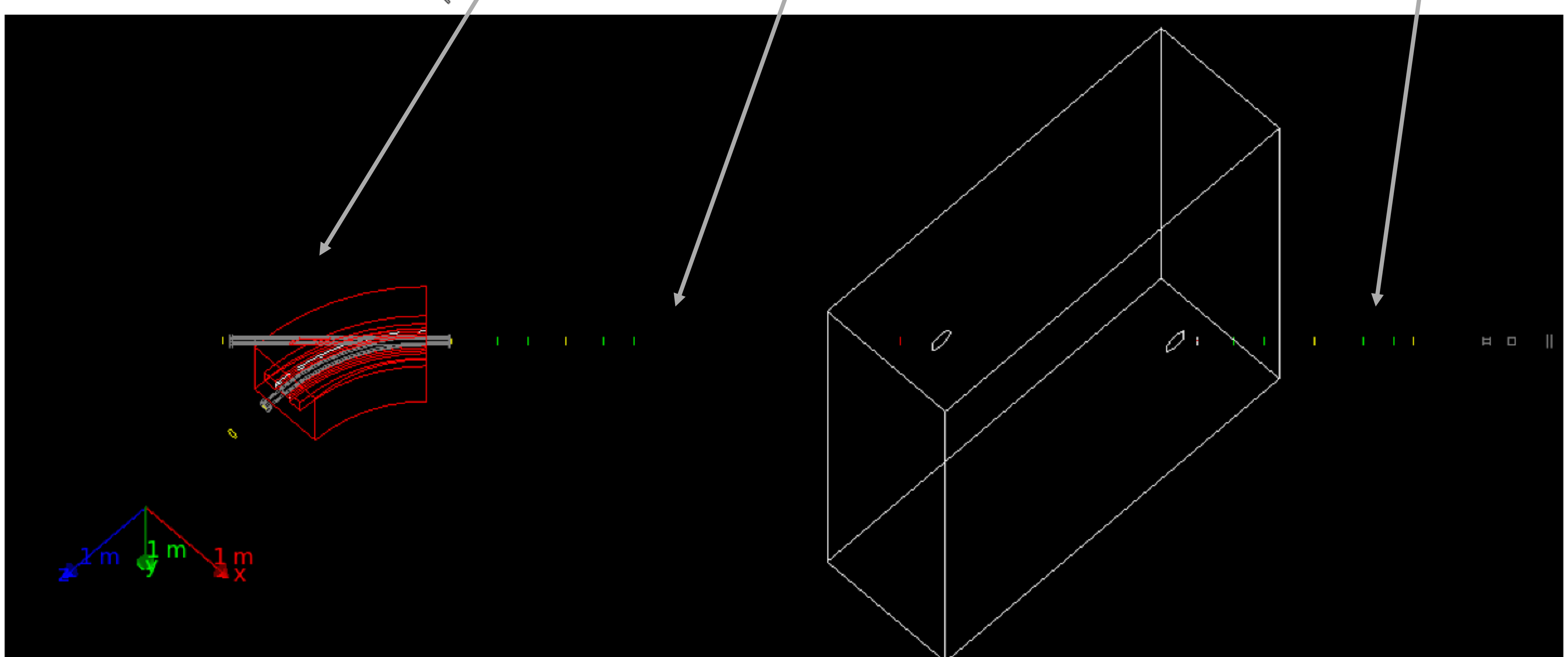
Beamline simulation

Detailed MC of the final 15 m of the beam-line allowing realistic simulations of beam-related background

Example of simulated beamline components





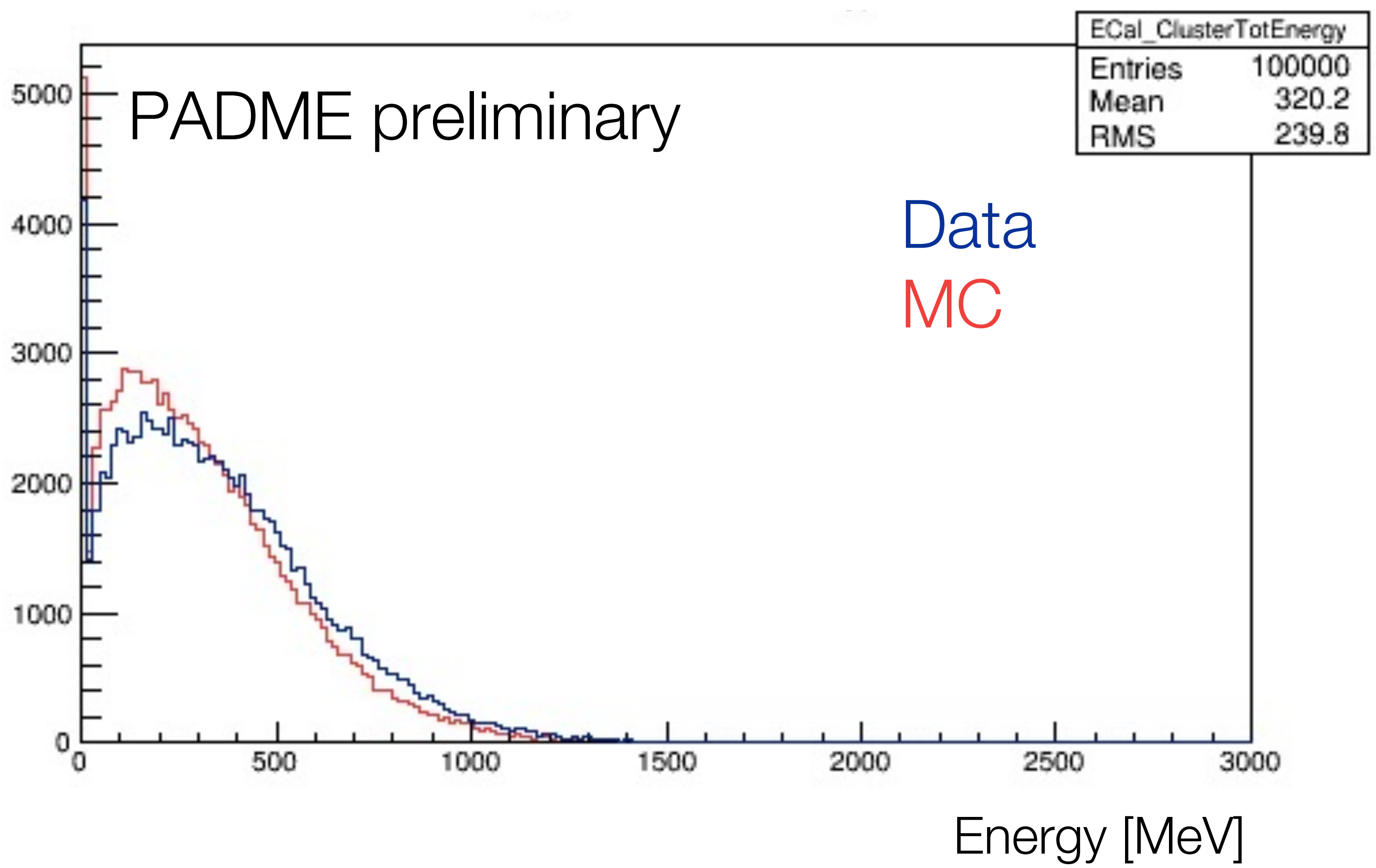


Beamline simulation vs real world

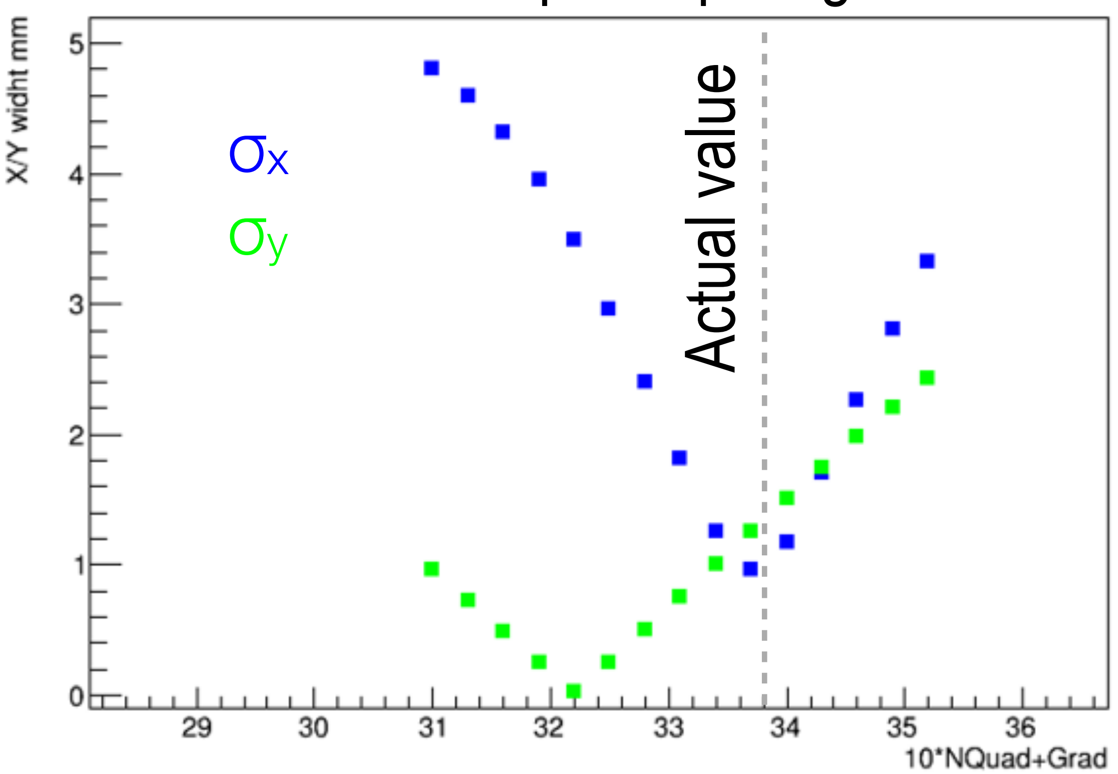
New implementations:

- Mylar/Be window thickness
- Quadrupoles and dipoles currents
- Collimators aperturee
- Initial beam parameters

Simulated energy deposit in ECal



Beam width vs quadrupole gradient



Optimization of the gradient for one of the quadrupoles of the beam-line (Q3):

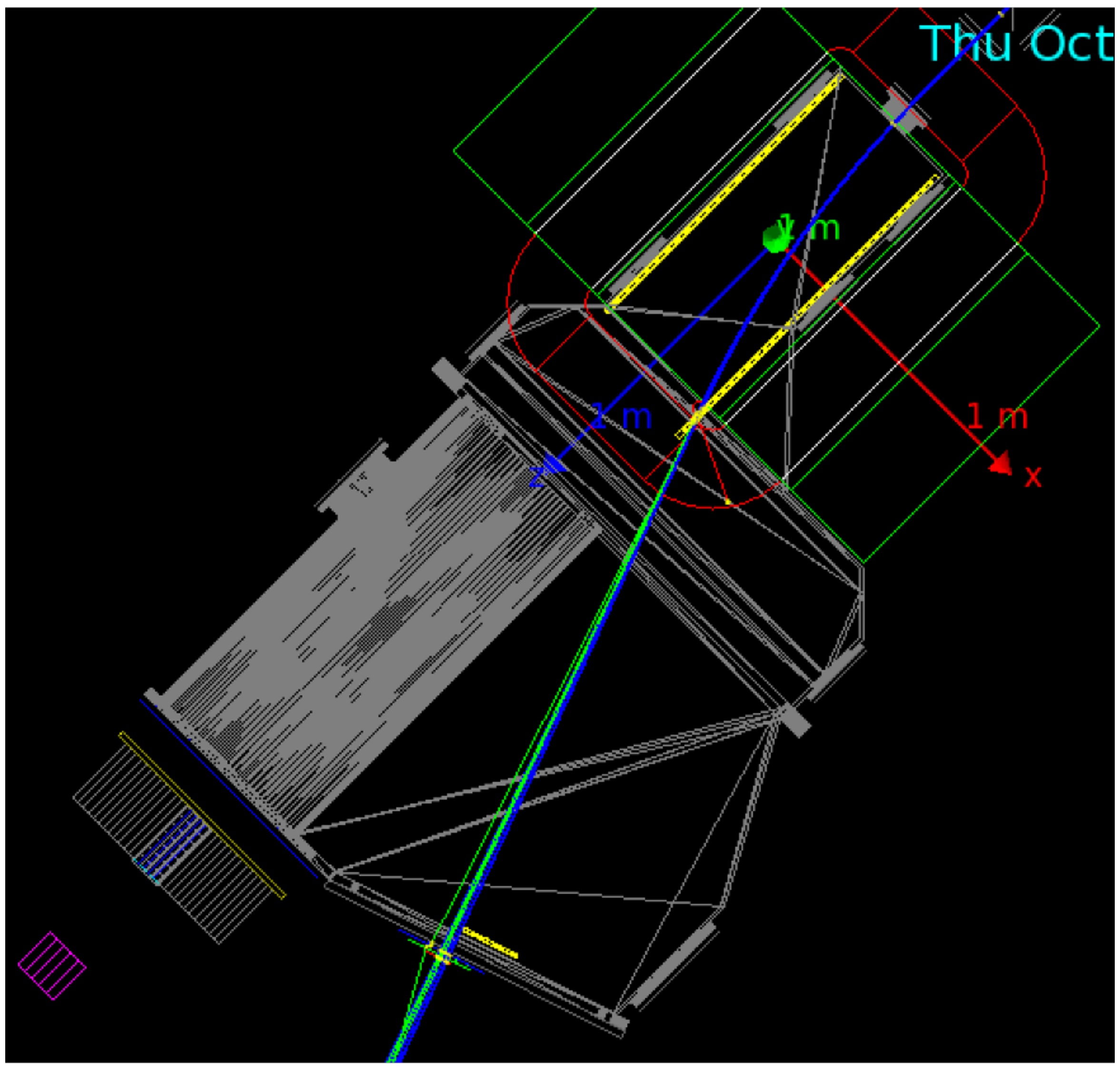
- best from simulation = 3.7 ± 0.2
- value in use at 07/2020 = 3.83

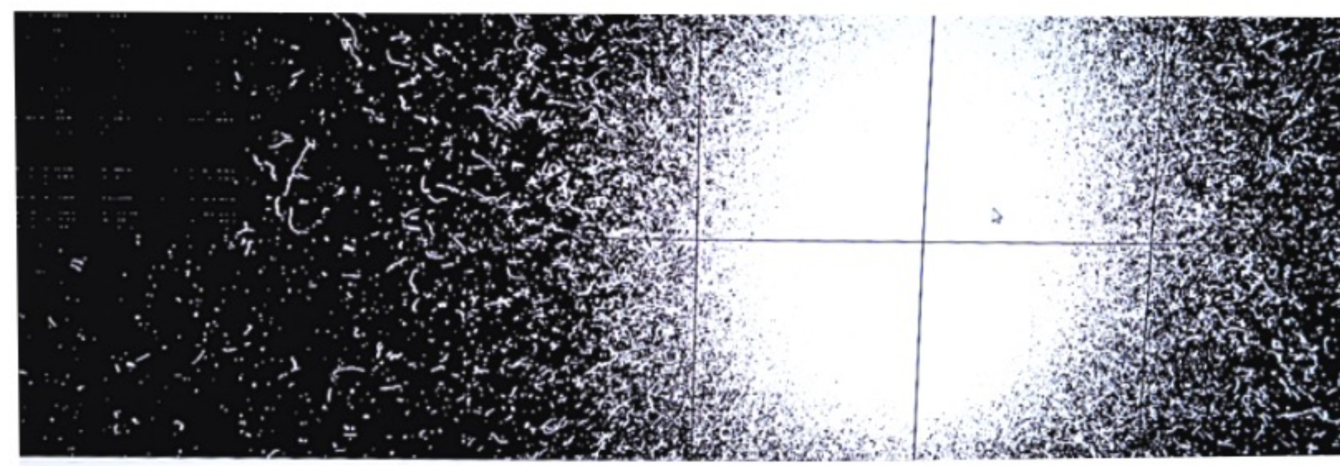
Independent beam energy estimation

Using:

- the beamline and PADME MC (including the PADME magnetic field map)
- a measurement of the beam position at the target and at the TimePix3

we estimated the beam energy independently from the beam-line setting





E_{BTF}(beam) = 431.6 MeV

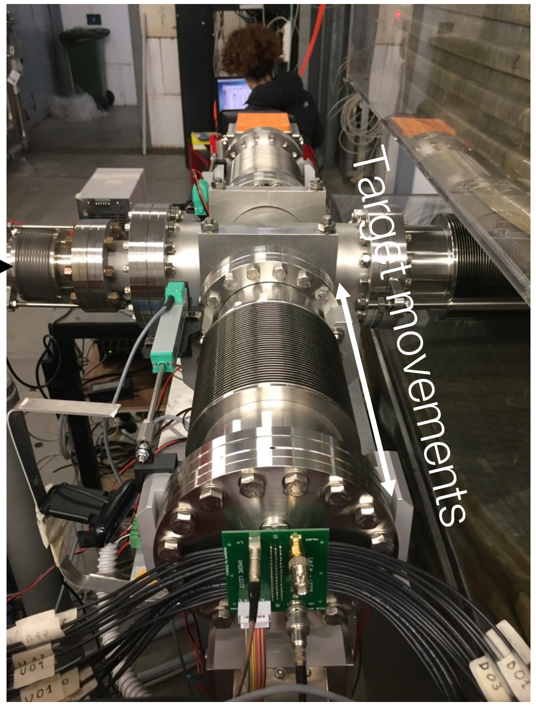
E_{PADME}(beam) = 433.0 MeV

0.33% difference

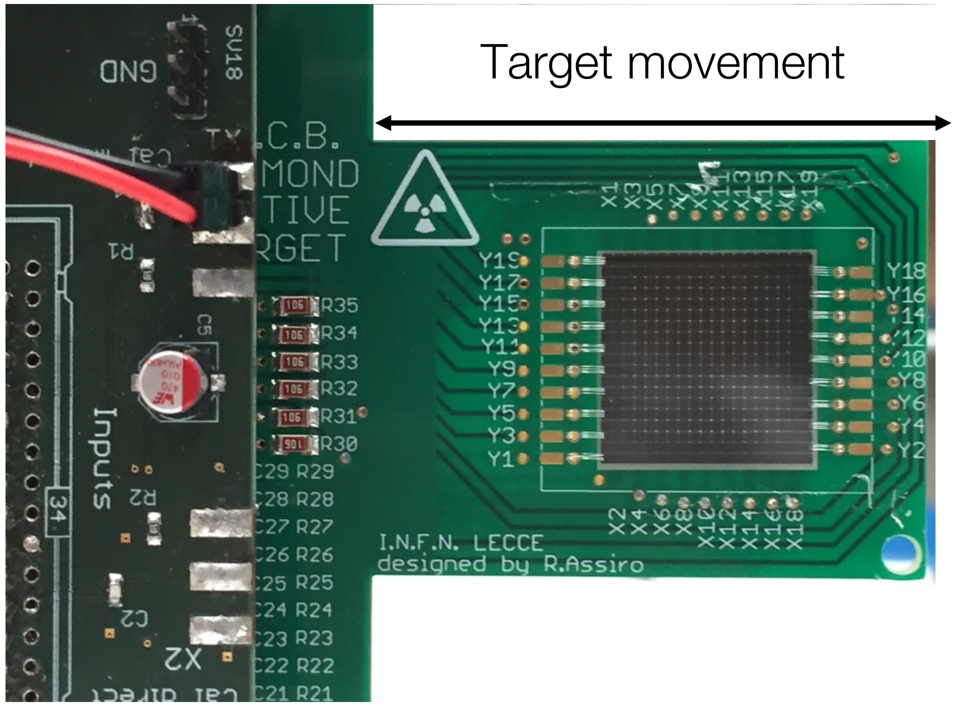
Active target

- Large size thin diamond: 1 cm × 1 cm × 100 μm (CCD=17um)
- Laser made 16X+16Y graphitic strips: CSN5 DIAPIX spin-off
- Y strips wire bonding Aluminum on Graphite: INFN Perugia
- X strips conductive epoxy
- Remotely controlled In&Out from beam in vacuum
- Stable operation in vacuum since first installation in Sept 2018:
  - no HV discharge, no $I_{leakage}$ drifts, no change in response
- Good response uniformity in position
- After calibration, used for BTF beam commissioning and beam on-line monitoring
- Provides Positron On Target (POT) and XY beam profiles on a bunch-by-bunch basis

e^+



In&Out in vacuum

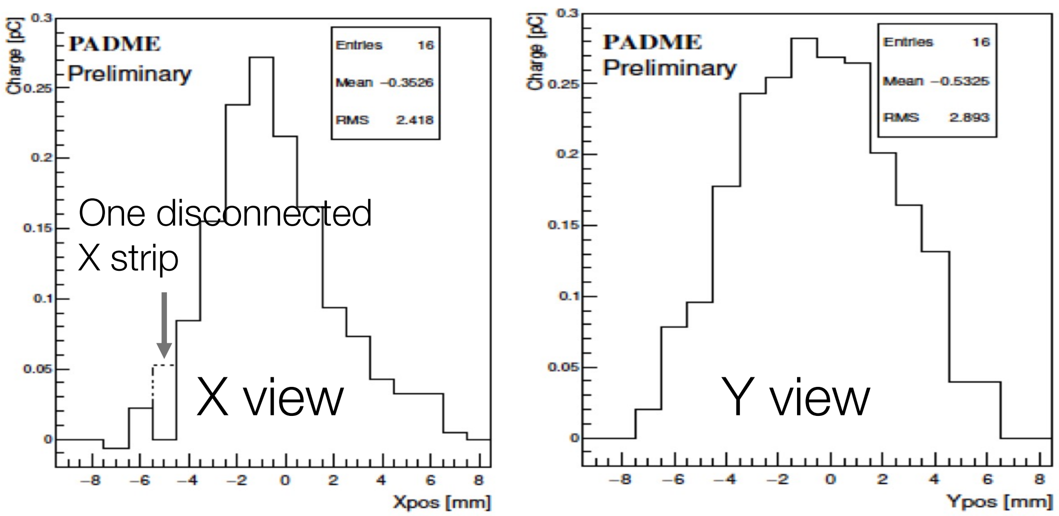


Beam measurements with the active target

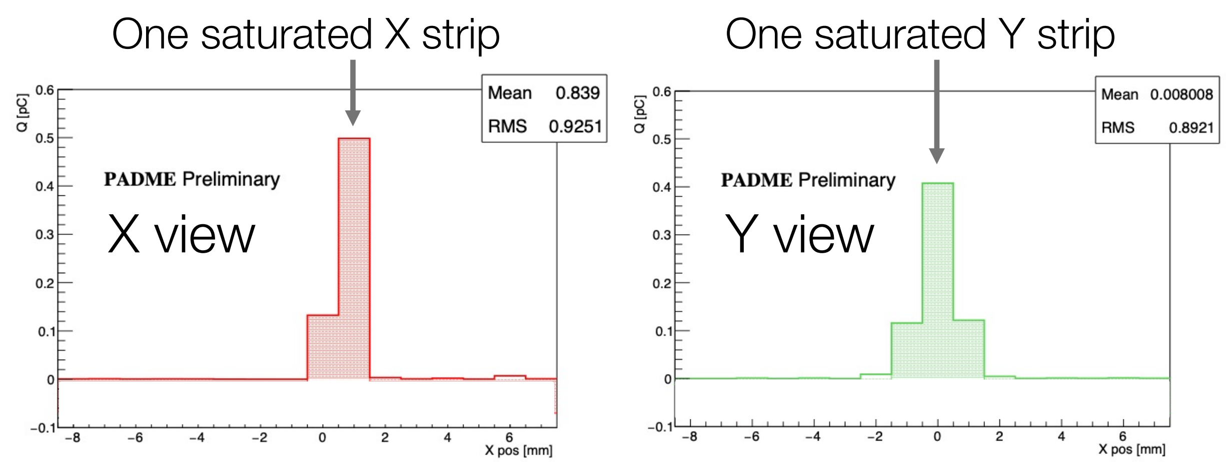
RUN I in 2019 not focused beam: all FE channels in linear regime

RUN II in 2020 focused beam: FE channel of hottest strip saturated

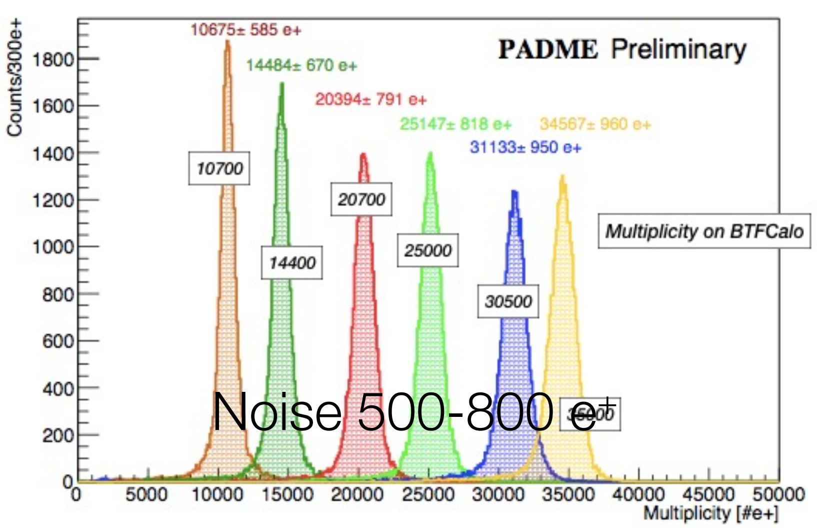
NPoT=20ke+

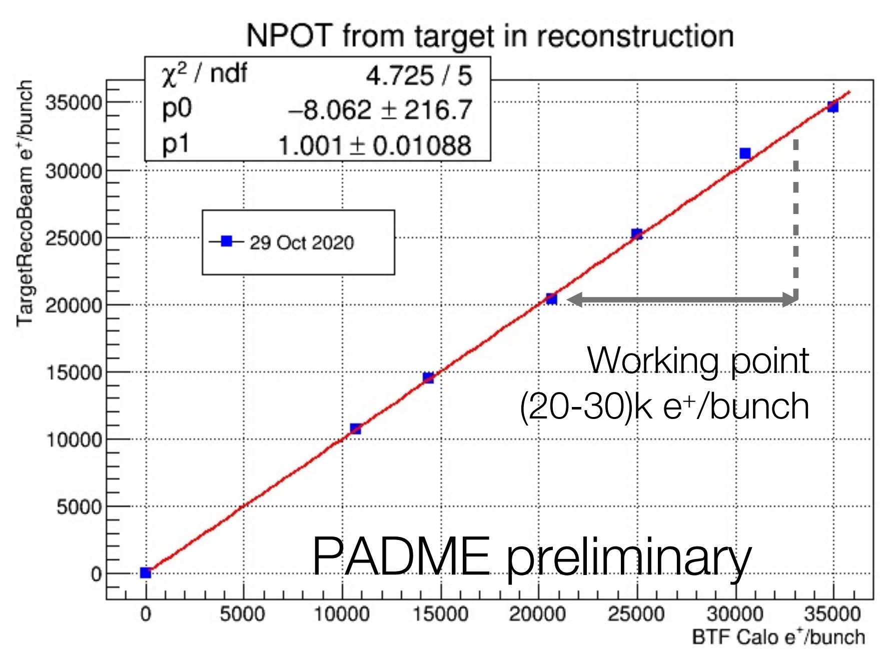


NPoT=10ke+



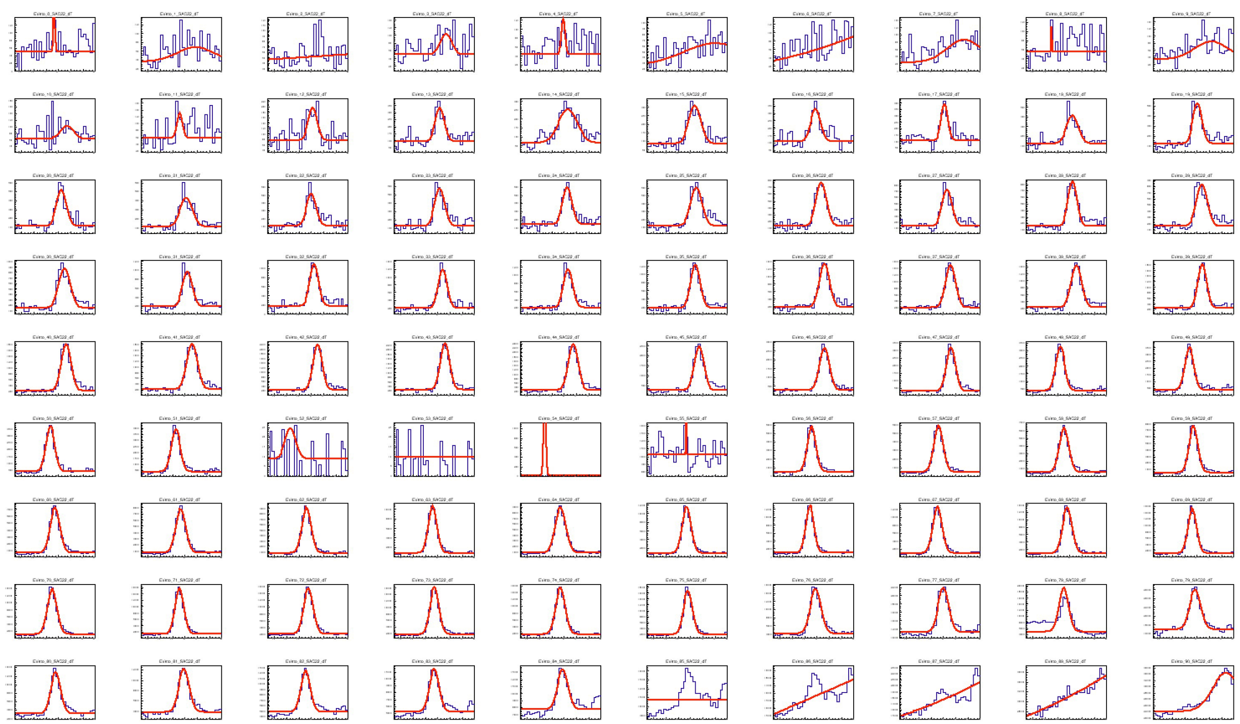
Beam profiles corrected from PoT





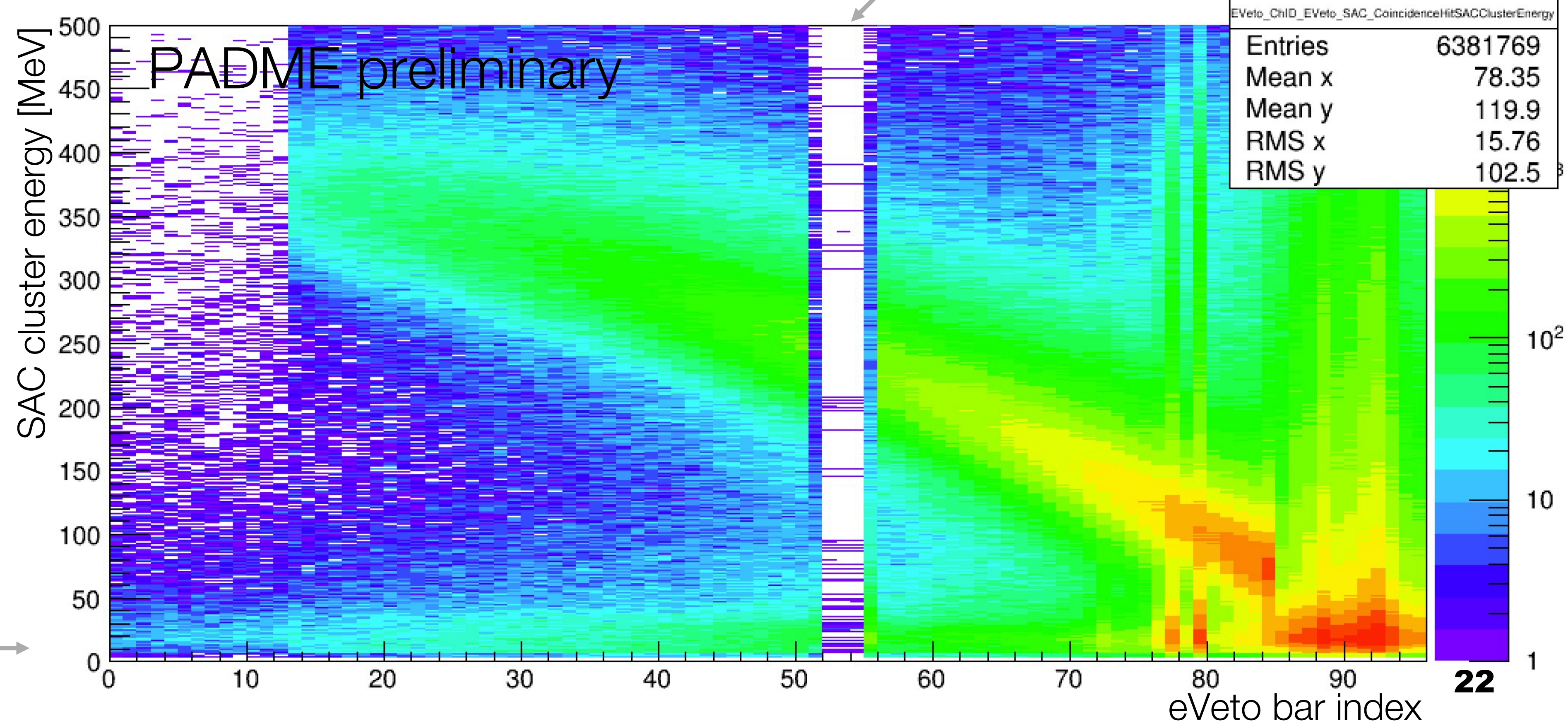
Detector designed for 5000 e+ reached 35000 e+/pulse

Bremsstrahlung in eVeto



Using a special run with inverted magnetic field it is possible to find the eVeto channels time constant with respect to the SAC central channel, to align them in time with the rest of the detector.

non-working channels (52-55)

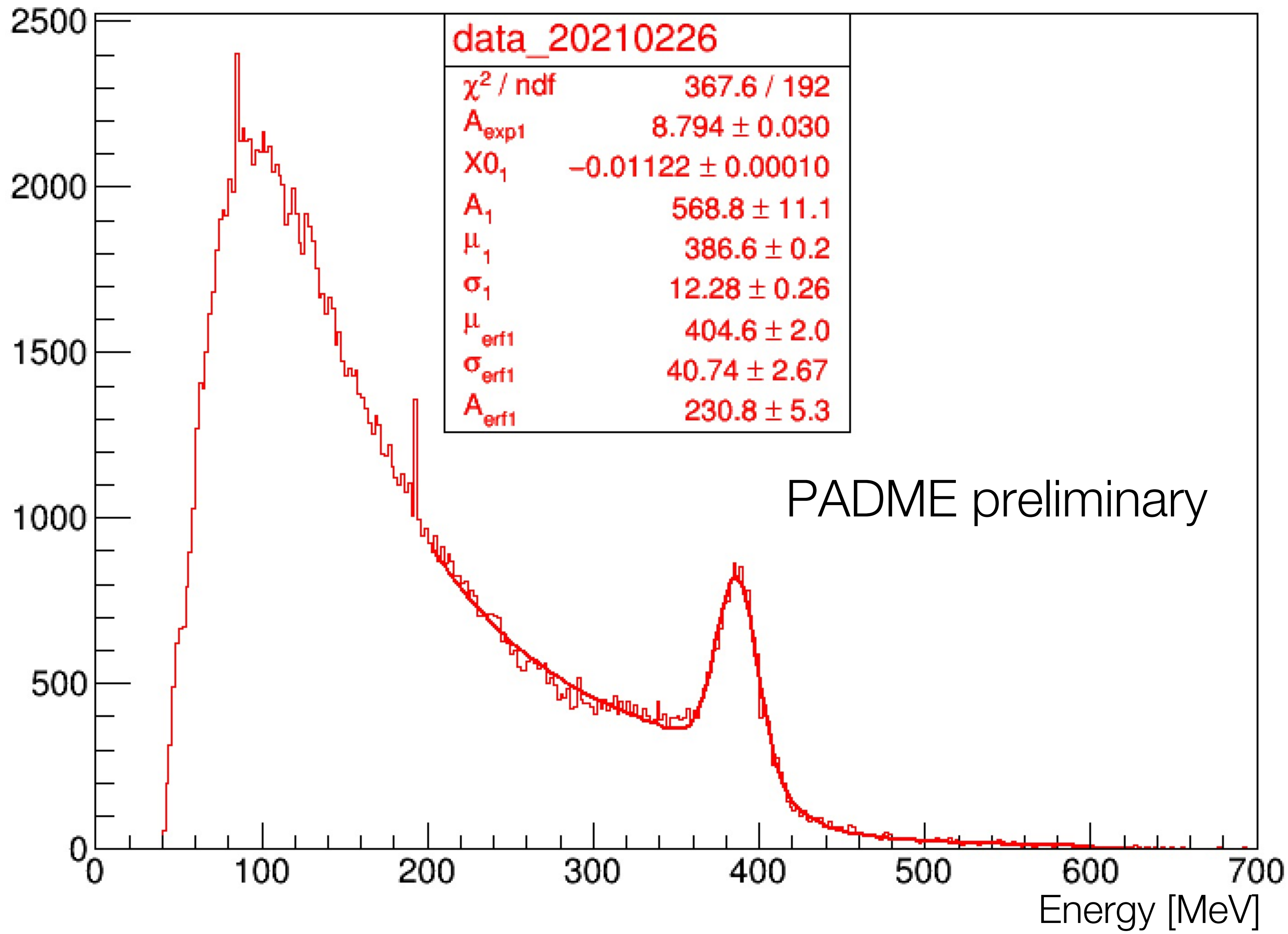


Time constants allow to see Bremsstrahlung in eVeto.

γγ events in ECal, single run

Statistic is such to allow to see the $\gamma\gamma$ peak in single runs.
Fitting the spectrum we can get the peak value and the energy resolution.

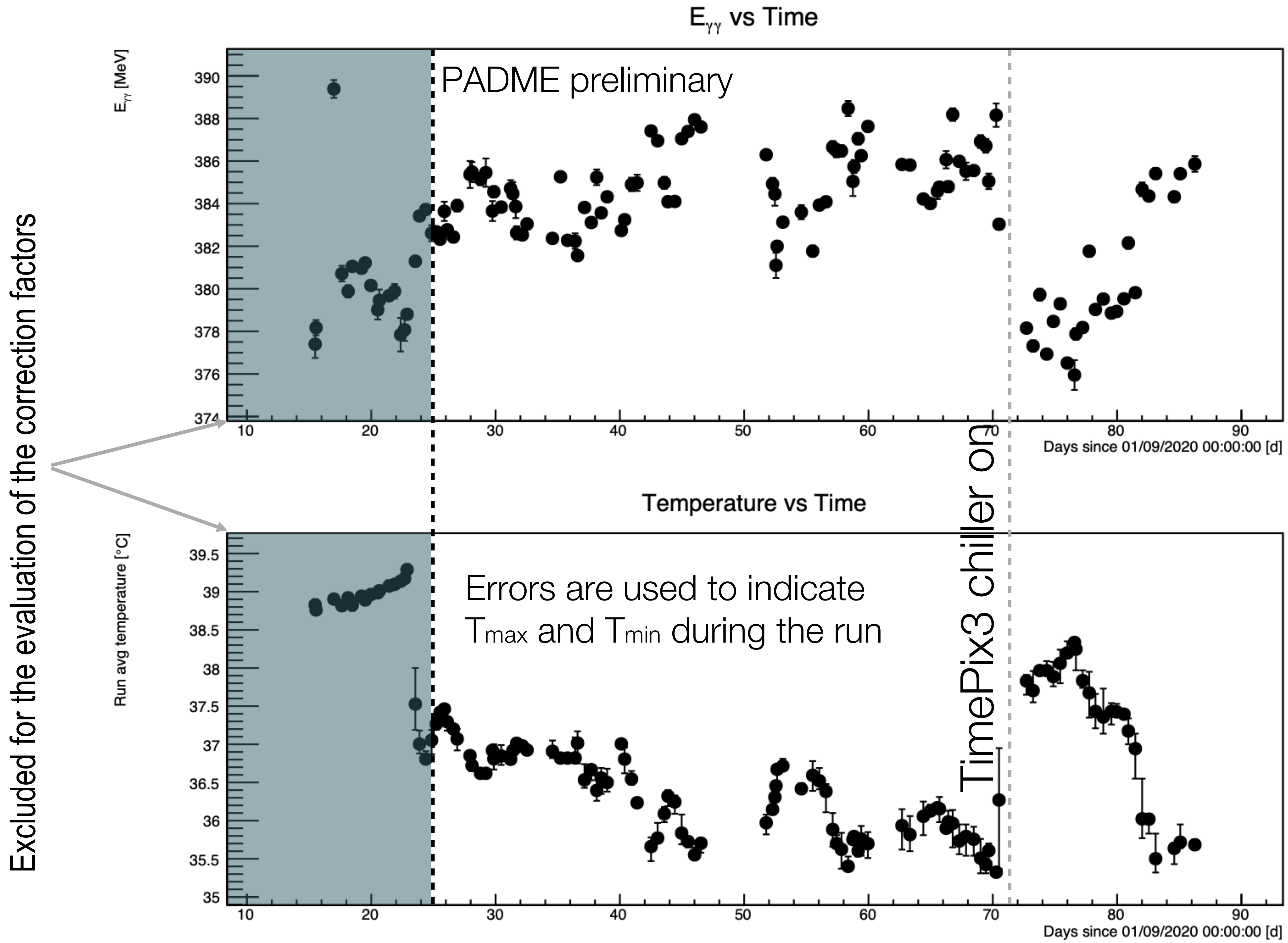
```
// modelling the exponential background (0->1) + gaussian signal (2->4) + (complementary) erf background (5->7)
string func = "TMath::Exp([0]+[1]*x)+[2]*TMath::Exp(-0.5*((x-[3])/[4])**2)+(TMath::Erf(([5]-x)/[6])/2.+0.5)*[7]";
```



Spectrum before corrections
5 ns time coincidence required.

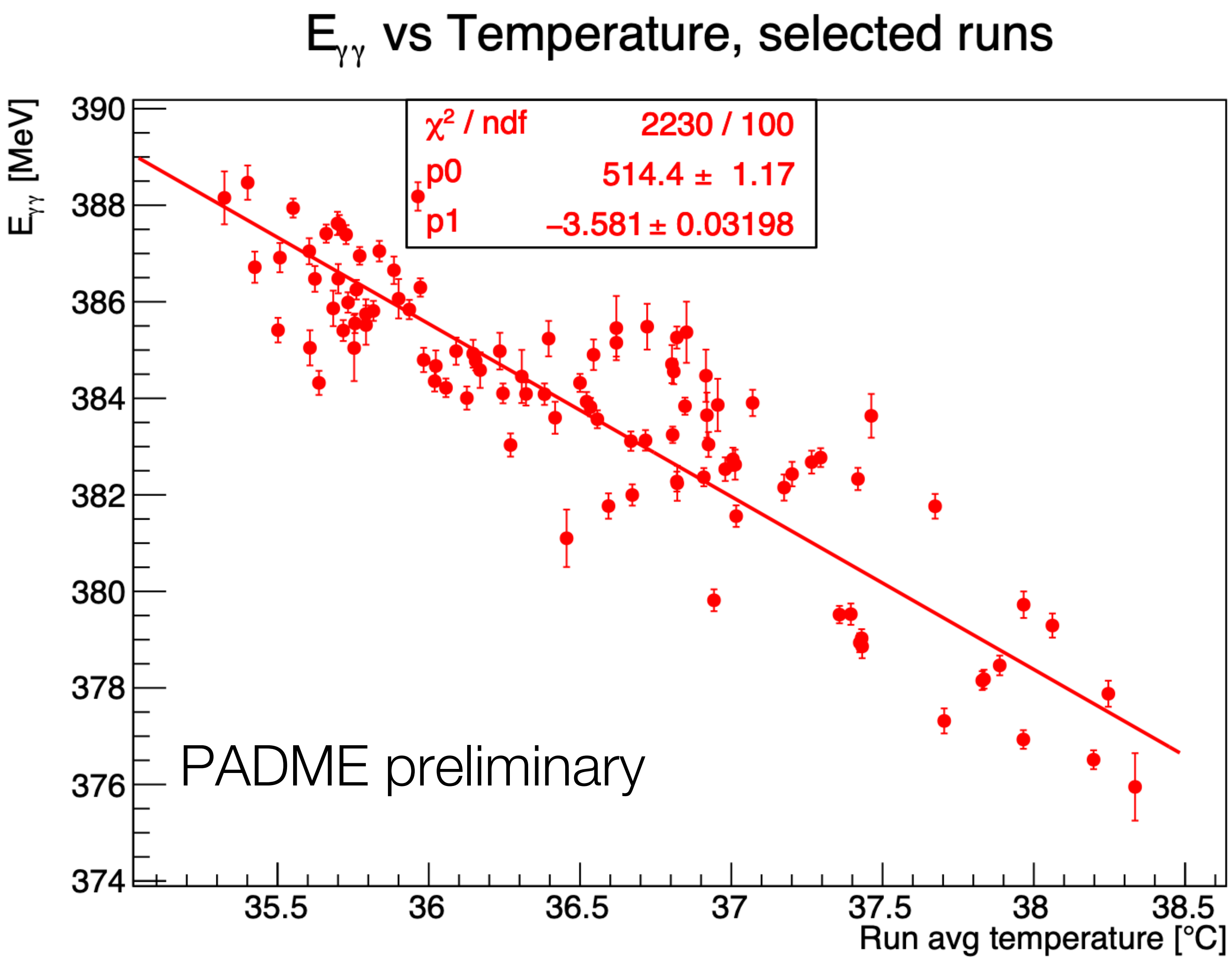
$E_{\gamma\gamma}$ and temperature vs time before corrections

Runs and fit quality selection applied.



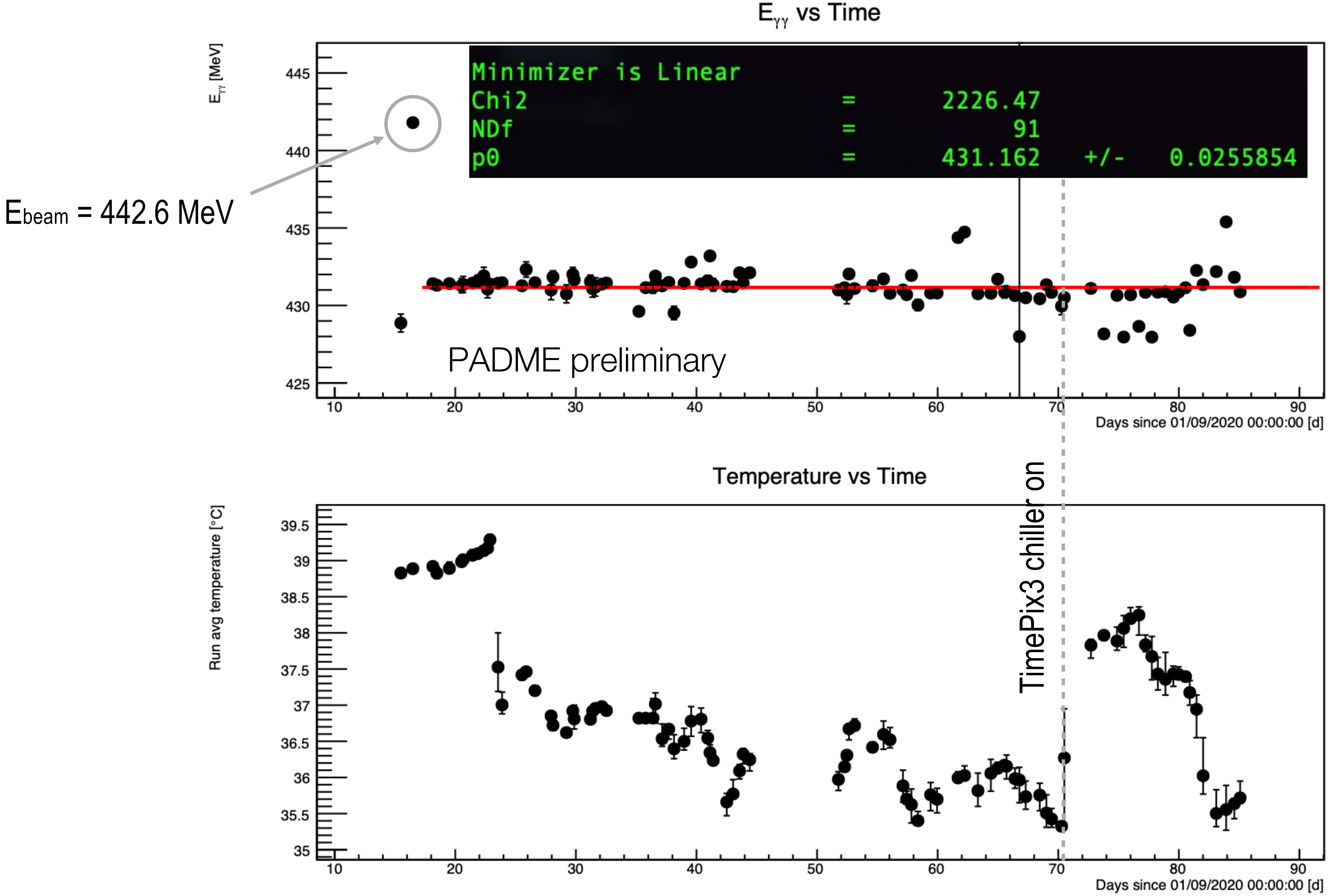
$E_{\gamma\gamma}$ vs temperature correction

Runs and fit quality selection applied plus first 25 days of September excluded: cleaner dataset only to evaluate the correction factors.

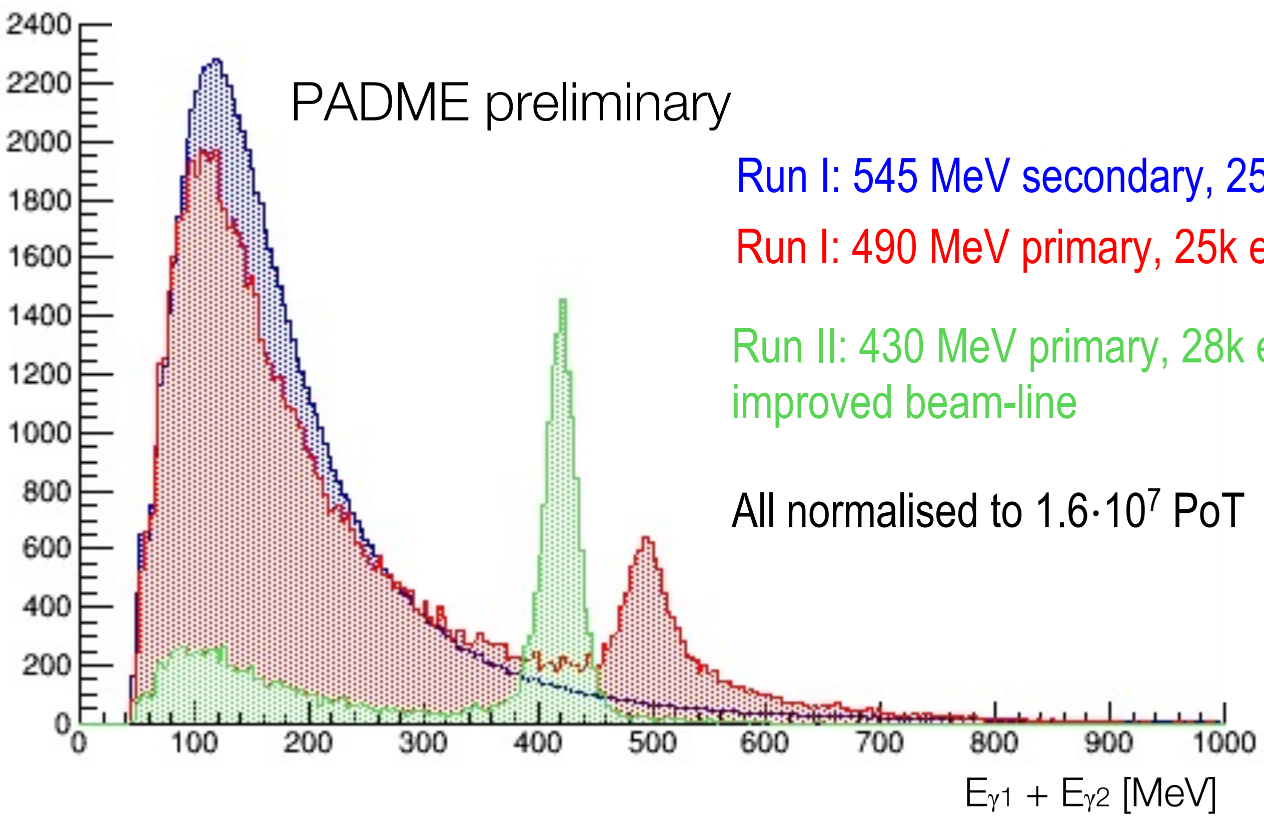


$E_{\gamma\gamma}$ and temperature vs time after corrections

Runs and fit quality selection applied. $E_{\gamma\gamma}$ is at the right value and the RMS is very small (using a run based energy correction).



γγ event in ECal comparison



$\gamma\gamma$ selection

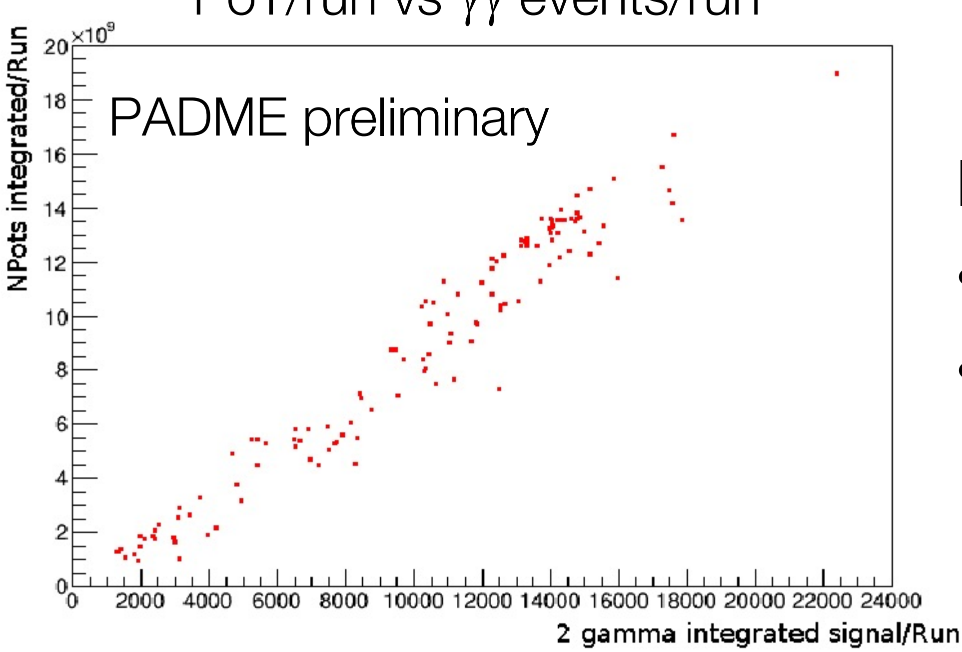
$$\Delta t < 10 \text{ ns}$$

$$x_{CoG} = \left| \frac{x_{\gamma_1} \times E_{\gamma_1} + x_{\gamma_2} \times E_{\gamma_1}}{E_{\gamma_1} + E_{\gamma_2}} \right| < 5.\text{ cm}$$

$$y_{CoG} = \left| \frac{y_{\gamma_1} \times E_{\gamma_1} + y_{\gamma_2} \times E_{\gamma_1}}{E_{\gamma_1} + E_{\gamma_2}} \right| < 5.\text{ cm}$$

$$R_{\gamma_1}\ ,\ R_{\gamma_2} \in \text{ FR}$$

PoT/run vs γγ events/run



In Run II we have operated in a intensity/background regime such that:

- Background in ECal is low
- Target is linear

$\gamma\gamma$ event selection and yield extraction

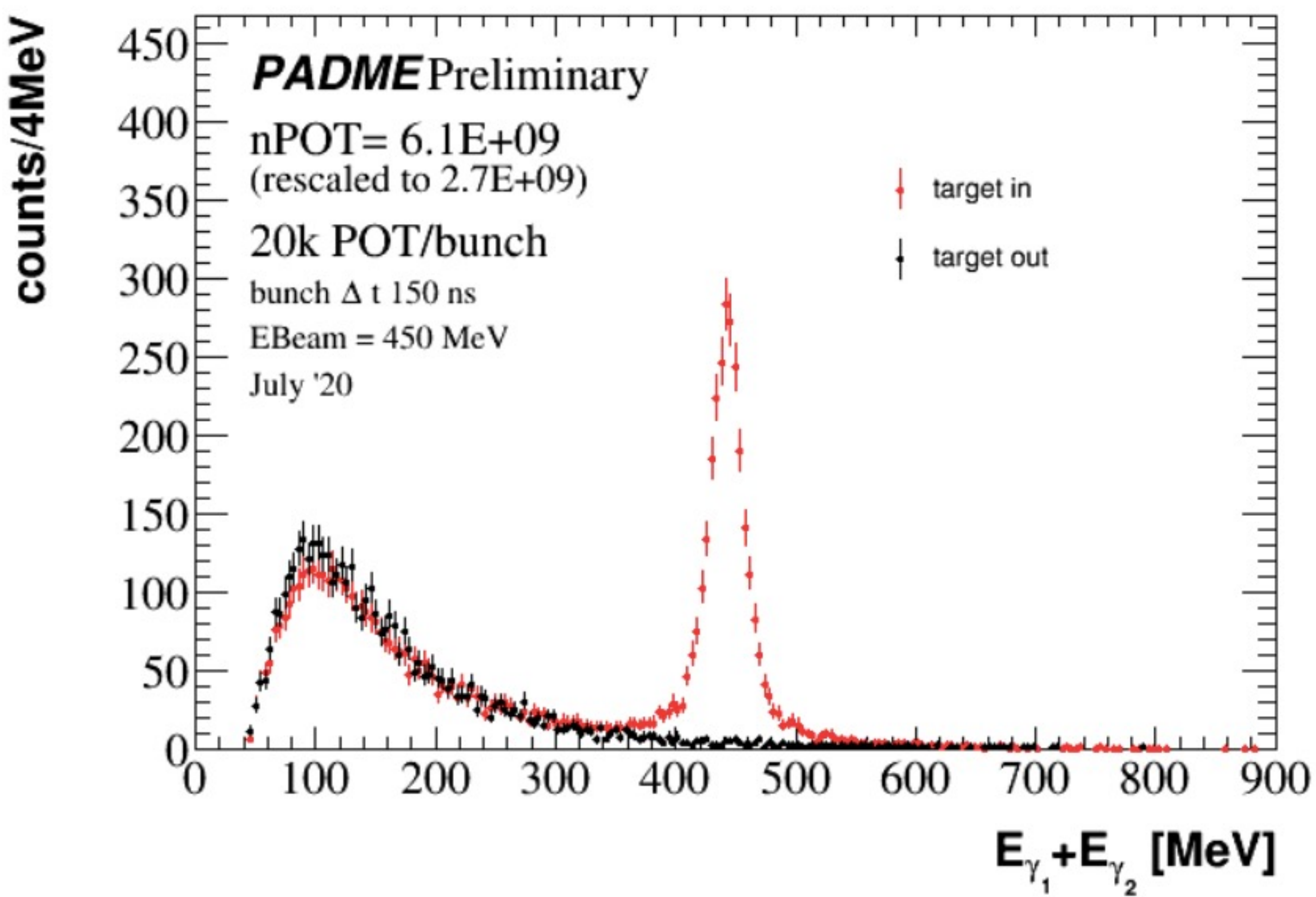
- Coincidence time: $|t_{\gamma1} - t_{\gamma2}| < 10$ ns
- $R_{\gamma1} \in$ FR ($R_{\gamma2} \in$ FR)

FR = Fiducial Region

- $|x_{CoG}| < 5$ cm & $|y_{CoG}| < 5$ cm

The number of $\gamma\gamma$ is obtained after background subtraction.

Background is estimated using a special run with the target out of beam.



$e^+ e^- \to \gamma\gamma$ cross section measurement strategy

Efficiency determination

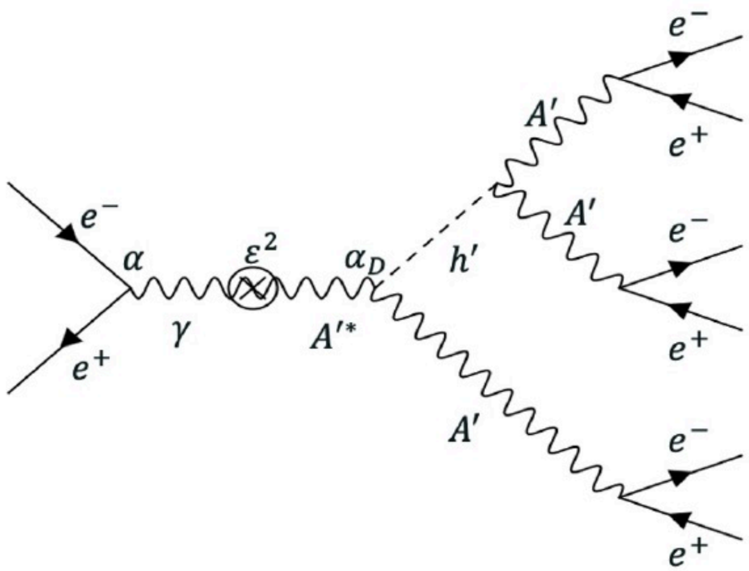
- Two photon events in data can be used to assess the single photon reconstruction efficiency in PADME: an annihilation-like photon allows to probe the efficiency on the opposite hemisphere
- $\varepsilon(\varphi_i, R_i)$ efficiency map measured on data and validated on a clean simulation sample (CalcHEP)

Correcting the yield

- By applying scale factors $\varepsilon(\text{data}|\varphi_i, R_i)/\varepsilon(\text{MC}|\varphi_i, R_i)$ to the simulation
  - Needs a good simulation
- By scaling the yield in data for single photon efficiency and event acceptance
- The two methods are validated on simulation and give consistent results

- Goal is a 5-10% precision measurement

Dark Higgs in 6 leptons final states



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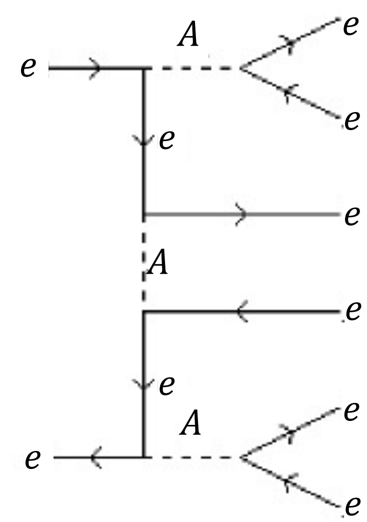
$$\sigma_{e^+e^-\to Vh'} \approx 20\text{ fb} \times \left(\frac{\alpha'}{\alpha}\right)\left(\frac{\kappa^2}{10^{-4}}\right)\frac{(10\text{ GeV})^2}{s},$$



$$\sigma_{e^+e^-\to 3(e^+e^-)} \approx \frac{\alpha^2}{6\pi^2}\sigma_{(\gamma\gamma\to e^+e^-e^+e^-)}\left(\log\frac{s}{m_e^2}\right)^4$$

$$\sigma_{e^+e^-\to 3(e^+e^-)} \approx \frac{\alpha^6}{\pi^3 m_e^2}\left(\log\frac{s}{m_e^2}\right)^4$$

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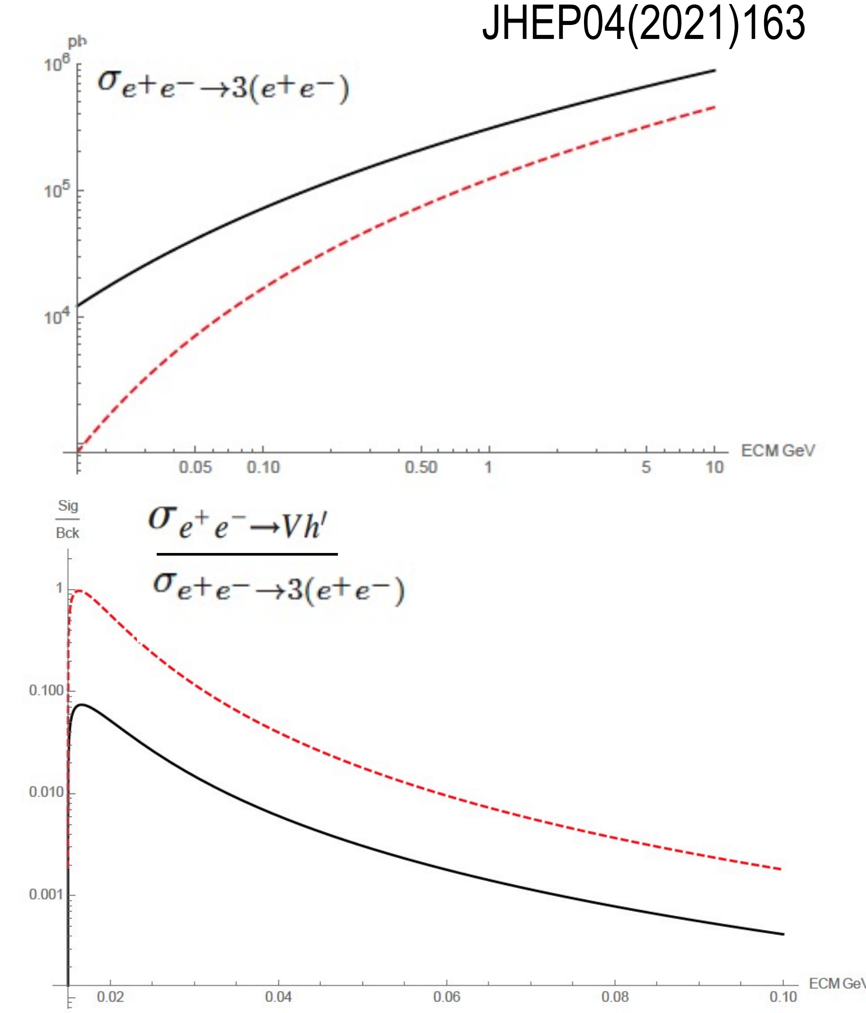


- At low energy LL-EPA fails due to accidental cancellation
- A new complete Log formula has been developed for PADME
- SM BG reduced by factor of ~10 at E_{CM} ~ 20MeV
- Dark sector cross section close to SM one is an unique opportunity
  - h' cross section ~1000 pb (ε^2=1E-6 , α_D=0.1) **150 events/10^{13} POT**
  - SM 6 leptons ~1500 pb **200 events/10^{13} POT**

Future perspectives

A few proposals to increase the PADME (or a similar experiment) potential:

- **Modify the LINAC** in order to get [even] longer pulses
  - Implies some hardware modification on LINAC RF, but limited by modulator and gun pulser to <5 μs
  - At the price of a **lower energy**: could impact X17 searches (need to go above 300 MeV)
  - **Allows using PADME in its current location**
- Use the **positron main ring of the DAFNE collider** as pulse stretcher of the LINAC
  - Using the **synchrotron loss** to drive the $n + \frac{1}{3}$ resonance: $\frac{\Delta E}{E}$ fixes the **spill length**
  - Requires **new** electrostatic (ES) and magnetic (M) **septa** (close to one of the two rings' crossings)
  - An extraction line towards the experiment has to be realized (in the collider hall)
  - Also a **direct injection** line into the main ring is required
- Use the **damping ring** (DR) as pulse stretcher of the LINAC
  - Similar scheme as for extraction from the main ring, with additional pros and cons
    - **Shorter spill** due to length=1/3 L_{MR} and smaller acceptance when trying to get large β at ES
    - Extraction (M) **septa** (2°+34°) **already existing**
    - **Much simpler** (and cheaper to run) wrt main ring; beam from LINAC already comes with large $\frac{\Delta E}{E}$
    - DR inside a small building; need to find a **location for the experiment.** This drives the **repetition rate** due to the configuration of pulsed magnets of the transfer-lines.

More exotic options:

- **Crystal channeling** is an interesting alternative to the ES septum (non-local extraction)
- "RF knock-out" as used in proton machines (e.g. using a kicker)

Future perspectives

Accelerator	Beam-line	Upgrades	Time scale	Pulse length	Maximum energy†	Positrons on target/year#	
LINAC	BTF-1	*none*	Now	300 ns	490 MeV e+	$3 \cdot 10^4 \times 49 \times 10^7 = \mathbf{1.5 \cdot 10^{13}}$	Present configuration
		De-tuned SLED's	2 years	3 μs	300 MeV e+	$3 \cdot 10^5 \times 49 \times 10^7 = \mathbf{1.5 \cdot 10^{14}}$	
		LLRF modulation	2 years	800 ns	420 MeV e+	$8 \cdot 10^4 \times 49 \times 10^7 = \mathbf{4 \cdot 10^{13}}$	

Accelerator	Beam-line	Upgrades	Time scale	Pulse length	Maximum energy†	Positrons on target/year#
LINAC + main ring*	POSEYDON	ES septum [or crystal] + M septum + extraction line + direct injection	3 years	0.45 ms	510 MeV e+	$4.5 \cdot 10^7 \times 49 \times 10^7 = \mathbf{2 \cdot 10^{16}}$
				2 ms	300 MeV e+	$2 \cdot 10^8 \times 49 \times 10^7 = \mathbf{10^{17}}$

* Wigglers off

†Energy range with a circulating positron beam: probably 250-520 MeV

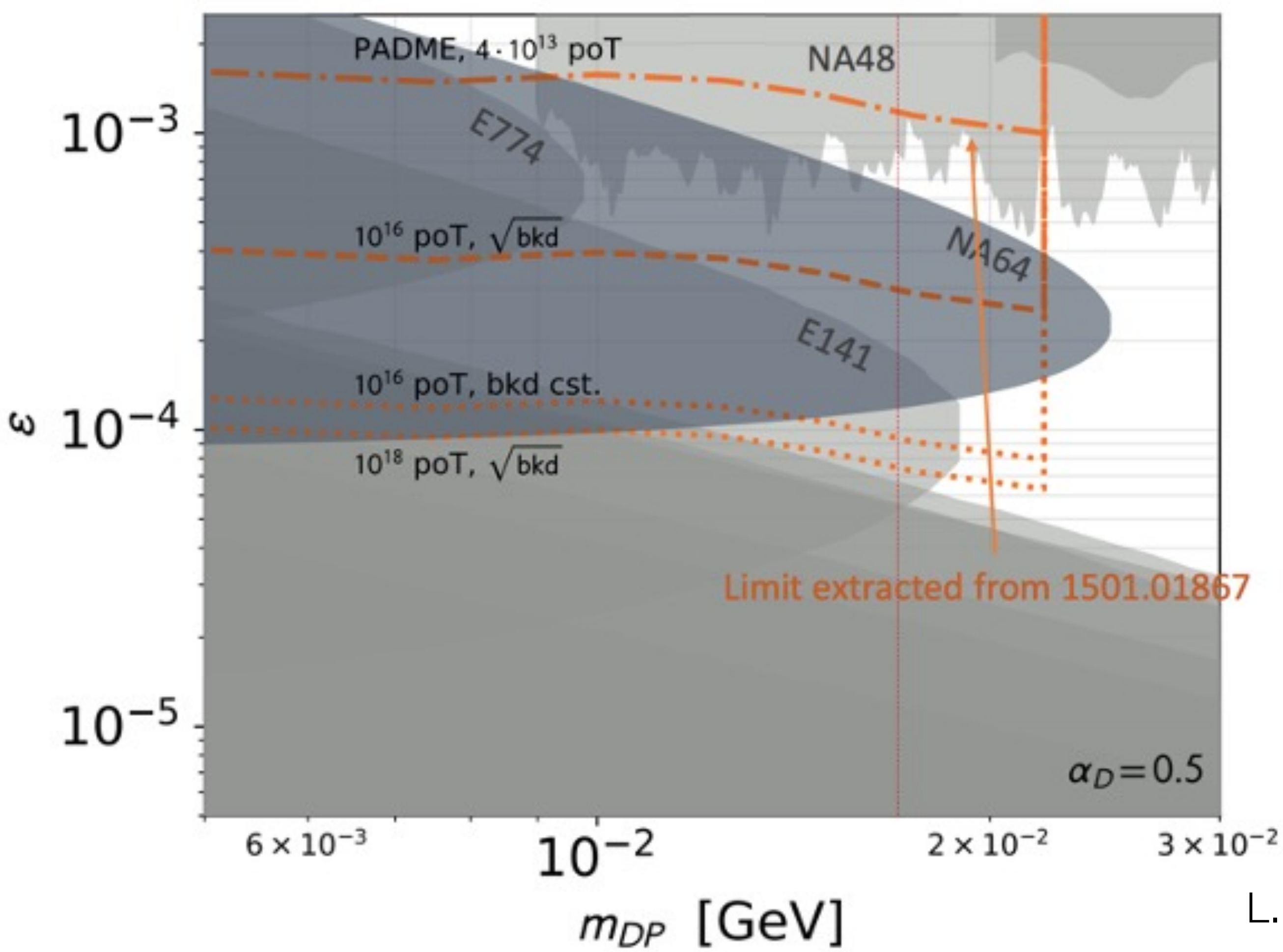
Accelerator	Beam-line	Upgrades	Time scale	Pulse length	Maximum energy†	Positrons on target/year#	
LINAC + accumulator	*tbd*	Extraction line [+ crystal] [+ Pulsed dipoles]	3 years	60 (120) μs	510 MeV e+	$6 \cdot 10^6 \times 49 \times 10^7 = \mathbf{3\ (6) \cdot 10^{15}}$	At 2 Hz: $\mathbf{1\ (2) \cdot 10^{14}}$
				0.3 (0.6) ms	300 MeV e+	$3 \cdot 10^7 \times 49 \times 10^7 = \mathbf{1.5\ (3) \cdot 10^{16}}$	At 2 Hz: $\mathbf{0.6\ (1.2) \cdot 10^{15}}$

\# Assuming **10^2 particles/ns.**
Divide by 10^3 to get «single particle» or **1 particle/10 ns**
Divide by 10^2 to get «low-density» or **1 particle/1 ns**

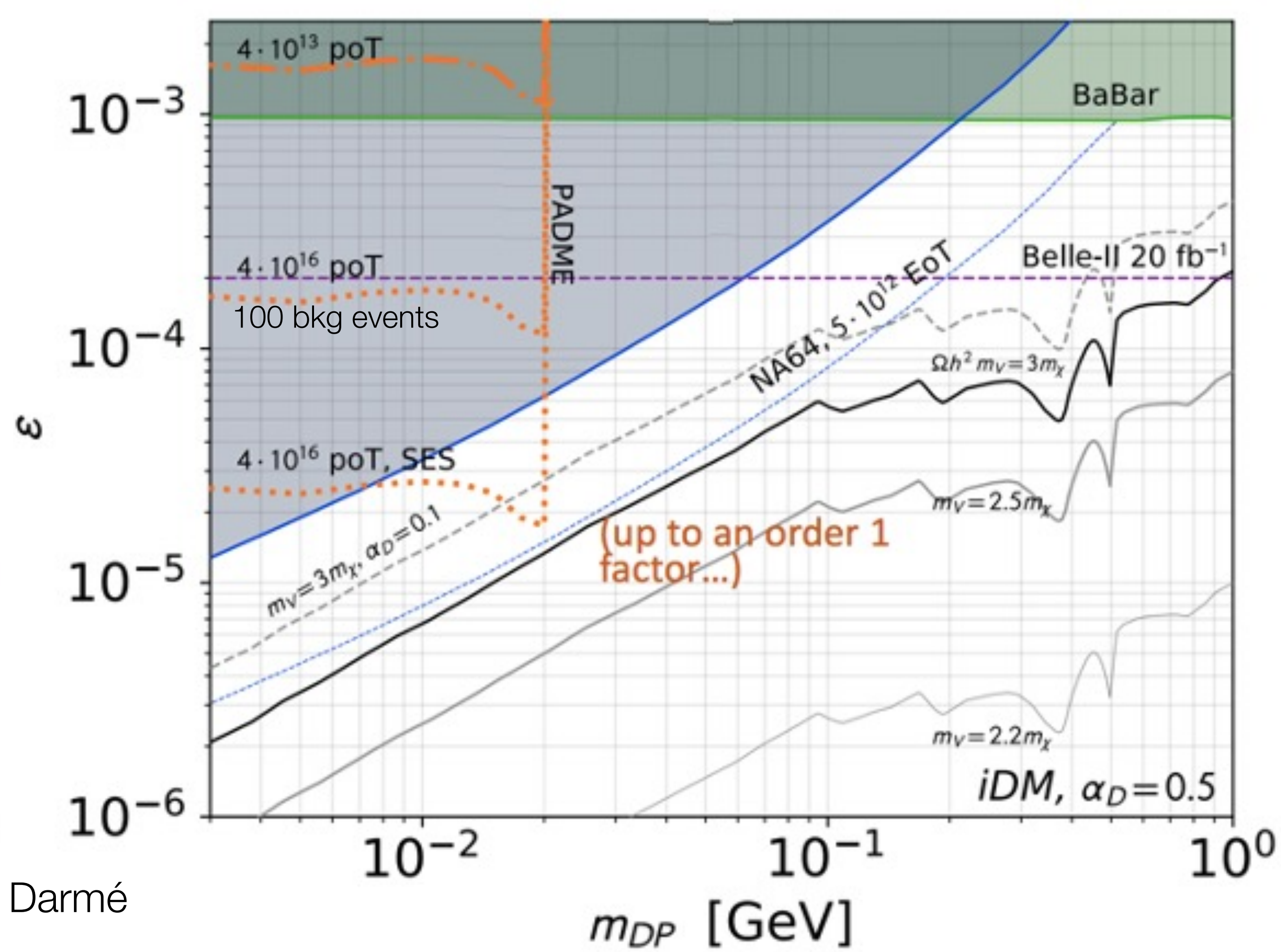
Summary (100e+/ns current PADME intensity):

- LINAC+ BTF : ~1.5 10^{13} POT/Y
- LINAC+DAΦNE ring : ~ 2.0 10^{16} POT/Y
- LINAC+Accumulator : ~ 1.0 10^{15} POT/Y (limited by injection/extraction rep. rate)

Sensitivity scaling: dark photon



L. Darmé

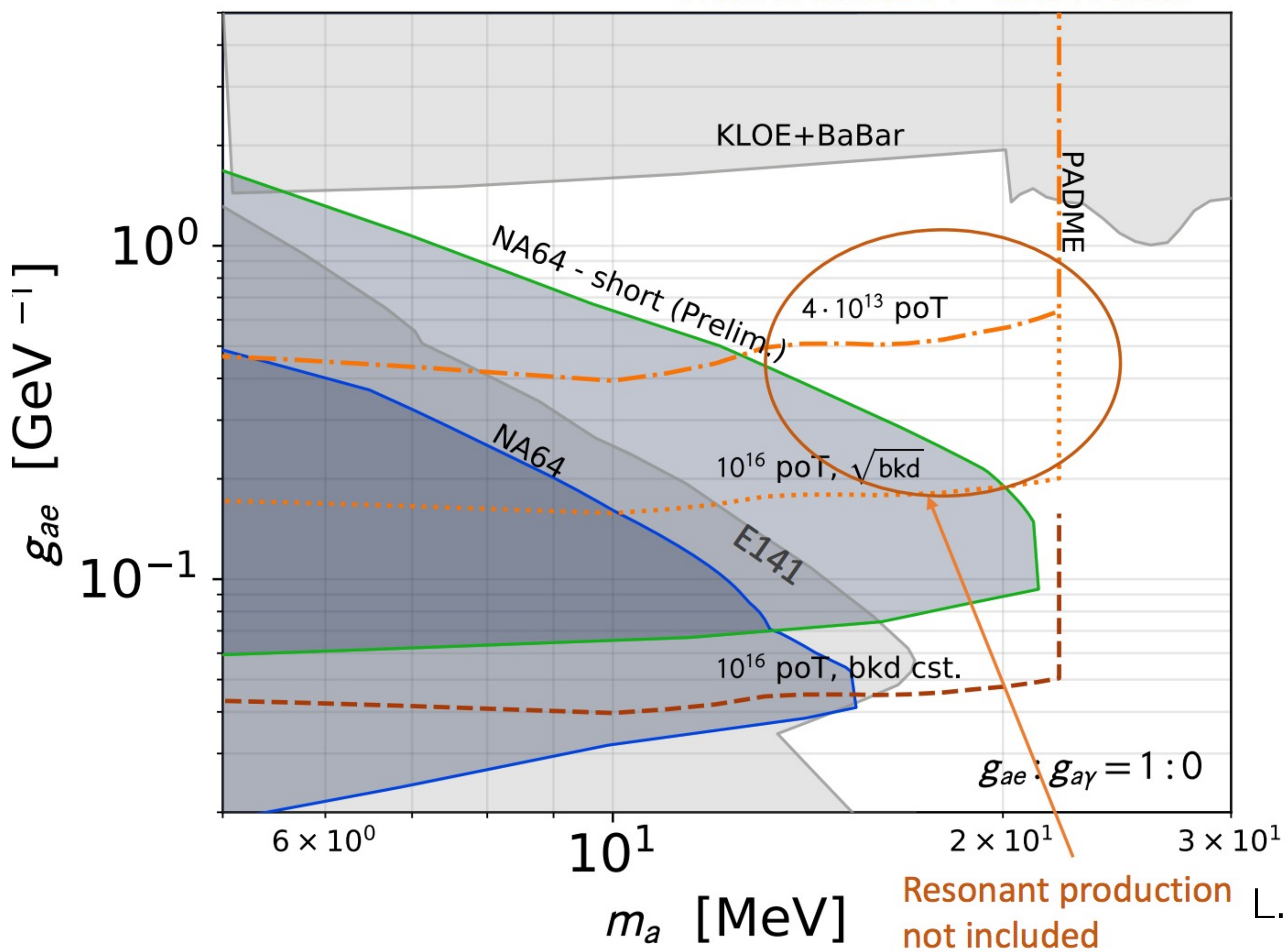


$e^+e^- \to \gamma A' \to \gamma e^+e^-$

$e^+e^- \to \gamma A' \to \gamma\chi\chi$

Sensitivity scaling: ALPs

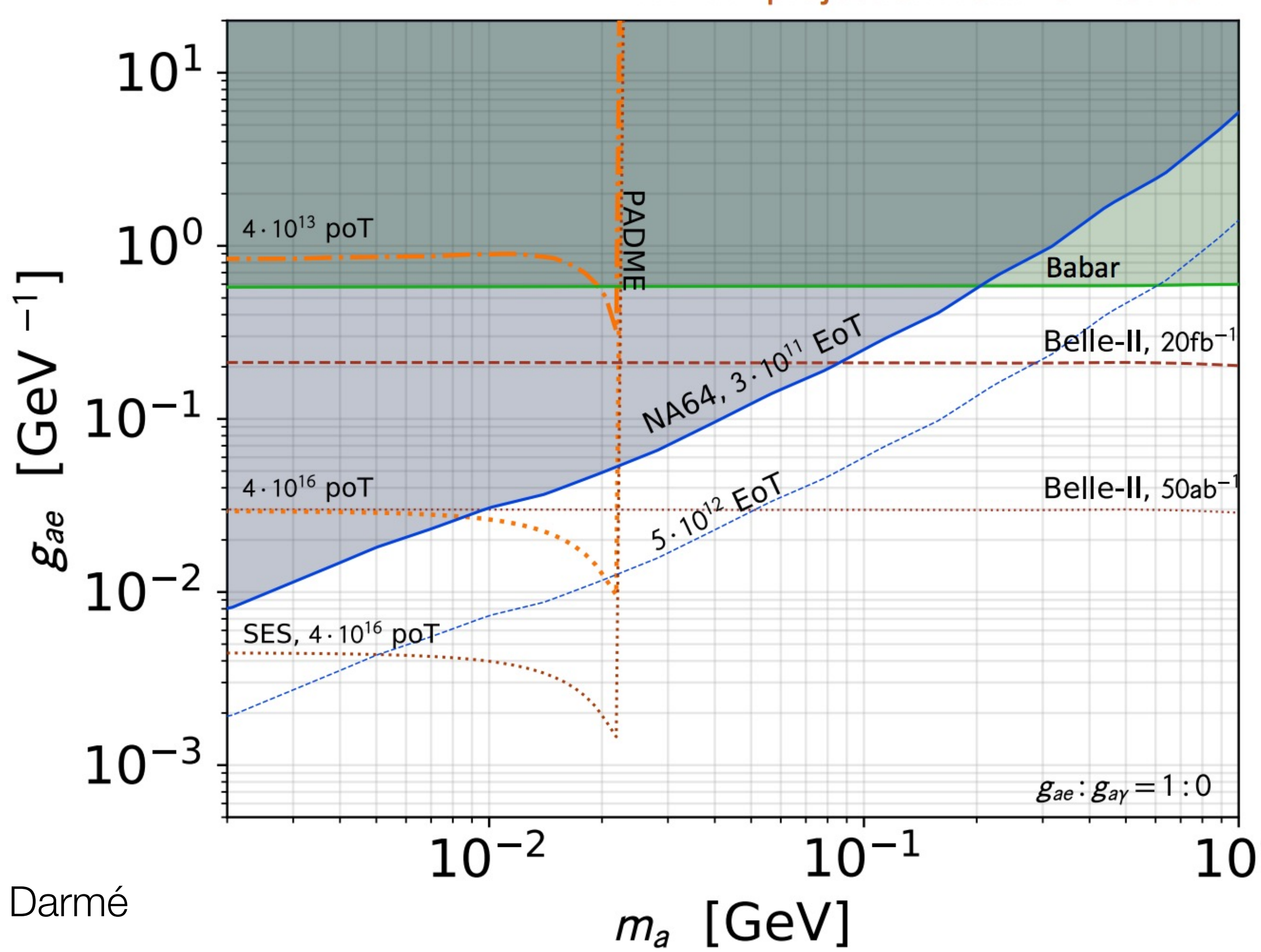
From 1710.03764 + NA64 recast



Resonant production not included

L. Darmé

PADME projection from 2012.07894



$$e^+e^- \to \gamma a \to \gamma e^+e^-$$

$$e^+e^- \to \gamma a \to \gamma\chi\chi$$

Conclusions

- PADME Run II data taking conditions (with primary beam) are clearly better than the Run I conditions
- A **reliable** Monte Carlo beamline simulation is available
- PADME collected $5.58 \cdot 10^{12}$ PoT, about one half of the planned statistics, during the pandemics
- After the Run II stop in December and the carrying out of some tests the collaboration started an intense **detector study** and **analysis** campaign.
- Run II data analysis is ongoing: $e^+e^- \rightarrow \gamma\gamma$ (interesting by itself and a step towards the invisible dark photon result)
- Studies on how to **significantly increase the luminosity** and improve the background/pile-up by further **diluting** the LINAC beam pulses are promising