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SEARCH FOR A DARK PHOTON WITH THE PADME EXPERIMENT

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on behalf of the PADME collaboration

INFN Lecce

UNIVERSITAS STUDIORUM LUPIENSIS

PADME

OUTLINE

- **The PADME concept**
  - Physics goal and experiment design
- **The detector and run**
  - The run experience; beam and detector commissioning
- **Status and prospects**
  - The potential of the PADME data so far
  - Prospects and plans

Dark matter

- *The most fascinating mystery and promise for new discoveries since the time of Fritz Zwicky a Vera Rubin observations*

    - beyond galaxy rotation velocities
        - *hot gas in galaxy clusters*
        - *gas, star and matter distributions in colliding galaxy clusters*
        - *CMB fluctuations*
        - *large structure formation*

    - *Non baryonic cold dark matter is an unknown accepted component (not the only one, see Dark Energy !) of current most successful Cosmological Models*

DARK MATTER

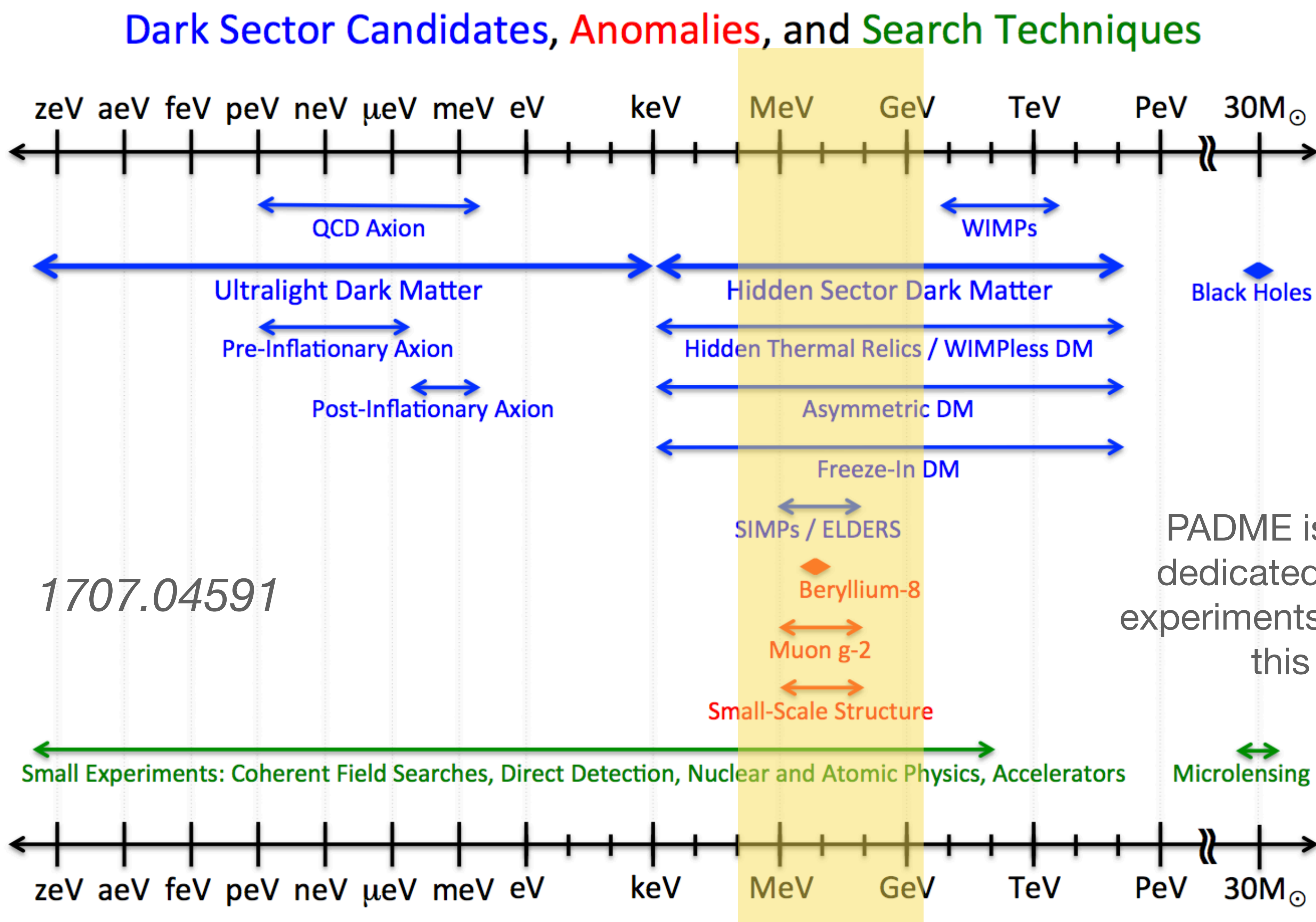
- *Candidates:*
  - *primordial black holes, axions, sterile neutrinos, weakly interacting massive particles (WIMPs)*
    - *relic density matched by electroweak scale and couplings*
    - *the most attractive solution, neutralino from R-parity conserving SUSY, challenged by searches at LHC, now constrained in corners of the phase space*

- *More exotic scenarios under intense theoretical and experimental scrutiny - 1707.04591*

  - ***hidden-sector dark matter**: from the electroweak down to the MeV scale for DM and/or mediators —> probed at accelerators, beyond the typical WIMP search strategies*
    - *compatible with relic abundance of thermal freeze-out of hidden sector*
  - *ultralight DM: sub-keV scale, QCD axions, very peculiar unconventional signatures*

DARK MATTER

- An interesting (anomalies) and “easily accessible” mass region



- *1707.04591*

PADME is one of the dedicated small scale experiments, investigating this region

The PADME concept

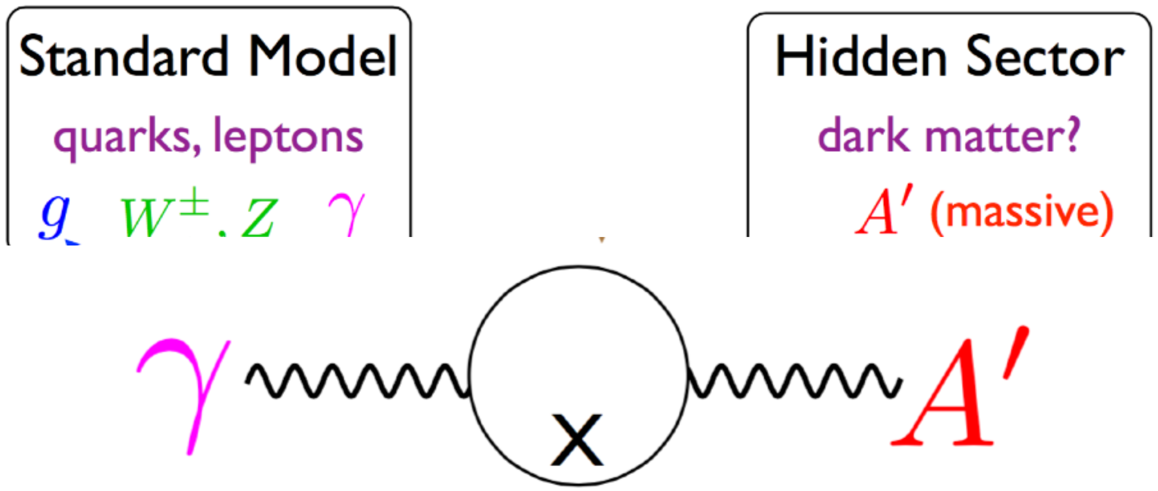
an experiment to search for the dark photon

M. Raggi and V. Kozhuharov, Adv. High Energy Phys.2014, 959802 (2014), 1403.3041

M. Raggi, V. Kozhuharov, and P. Valente, EPJ Web Conf.96, 01025 (2015), 1501.01867

THE PADME GOAL

Investigating the minimal vector portal scenario searching for the
dark photon A’



2 parameters ***A’ mass*** and **ε** giving the ***effective coupling*** to the SM fermions as $\varepsilon_f q_f$

$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

ε naturally arises from ***kinetic mixing***, in the presence of two U(1) gauge groups.

If this is the dominant mechanism, effective coupling of A’ to SM fermions is universal $\sim q_{fermion}$

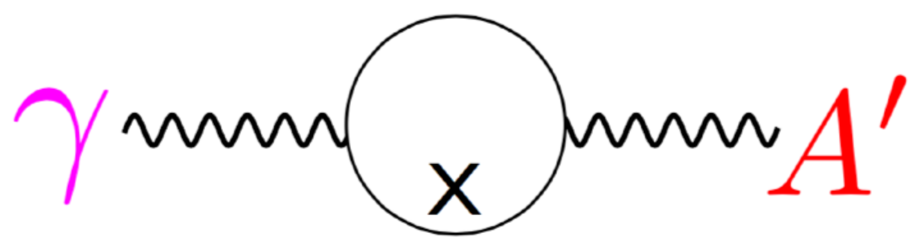
- Production mechanisms:
  - Meson decays, Bremsstrahlung, Annihilation
- Decays:
- A’→e+e-, μ+μ-, hadrons, “visible” decays depending on mass, if DM mass > $m_{A'}/2$
- A’ to invisible; BR(χχ) ~1 since BR(SM particles) ~ ε^2
  - From prompt decays to long lifetime

THE PADME GOAL

Investigating the minimal vector portal scenario searching for the
dark photon A'

Standard Model
quarks, leptons
g $W^{\pm}, Z$ γ

Hidden Sector
dark matter?
A' (massive)



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($e^+ e^-$)

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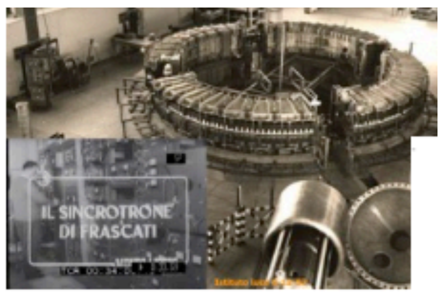
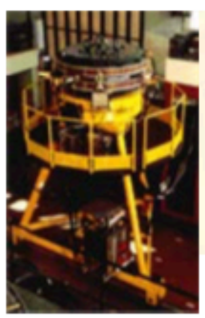
PADME@LNF

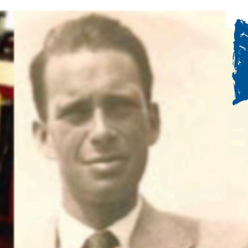
Laboratori **N**azionali di **F**rascati of INFN at the core of HEP at colliders

Electron Synchrotron (1959-1975) E=1 GeV



AdA 1960-1965 250 MeV





B. Touschek

ADONE (1968- 1993) 1.5 GeV 100 m

DAΦNE (1999) 510 MeV 100 m

colliders in the world

1961	AdA	Frascati	Italy
1964	VEPP2	Novosibirsk	URSS
1965	ACO	Orsay	France
1969	ADONE	Frascati	Italy
1971	CEA	Cambridge	USA
1972	SPEAR	Stanford	USA
1974	DORIS	Hamburg	Germany
1975	VEPP-2M	Novosibirsk	URSS
1977	VEPP-3	Novosibirsk	URSS
1978	VEPP-4	Novosibirsk	URSS
1978	PETRA	Hamburg	Germany
1979	CESR	Cornell	USA
1980	PEP	Stanford	USA
1981	SpS	CERN	Switzerland
1982	P-pbar	Fermilab	USA
1987	TEVATRON	Fermilab	USA
1989	SLC	Stanforrd	USA
1989	BEPC	Beijing	China
1989	LEP	CERN	Switzerland
1992	HERA	Hamburg	Germany
1994	VEPP-4M	Novosibirsk	Russia
1999	DAΦNE	Frascati	Italy
1999	KEKB	Tsukuba	Japan
2000	RHIC	Brookhaven	USA
2003	VEPP-2000	Novosibirsk	Russia
2008	BEPCII	Beijing	China
2009	LHC	CERN	Switzerland

The LINAC of the DAΦNE complex provides a positron beam for a fixed target experiment: PADME

THE DAΦNE COMPLEX

- The PADME positron beam: *two options*
  - ***secondary e+*** from e- accelerated by the LINAC up to 750 MeV, selected in energy and focused by the BTF transfer line
  - ***primary e+*** from the LINAC, from 220 MeV converted e-, can reach 550 MeV

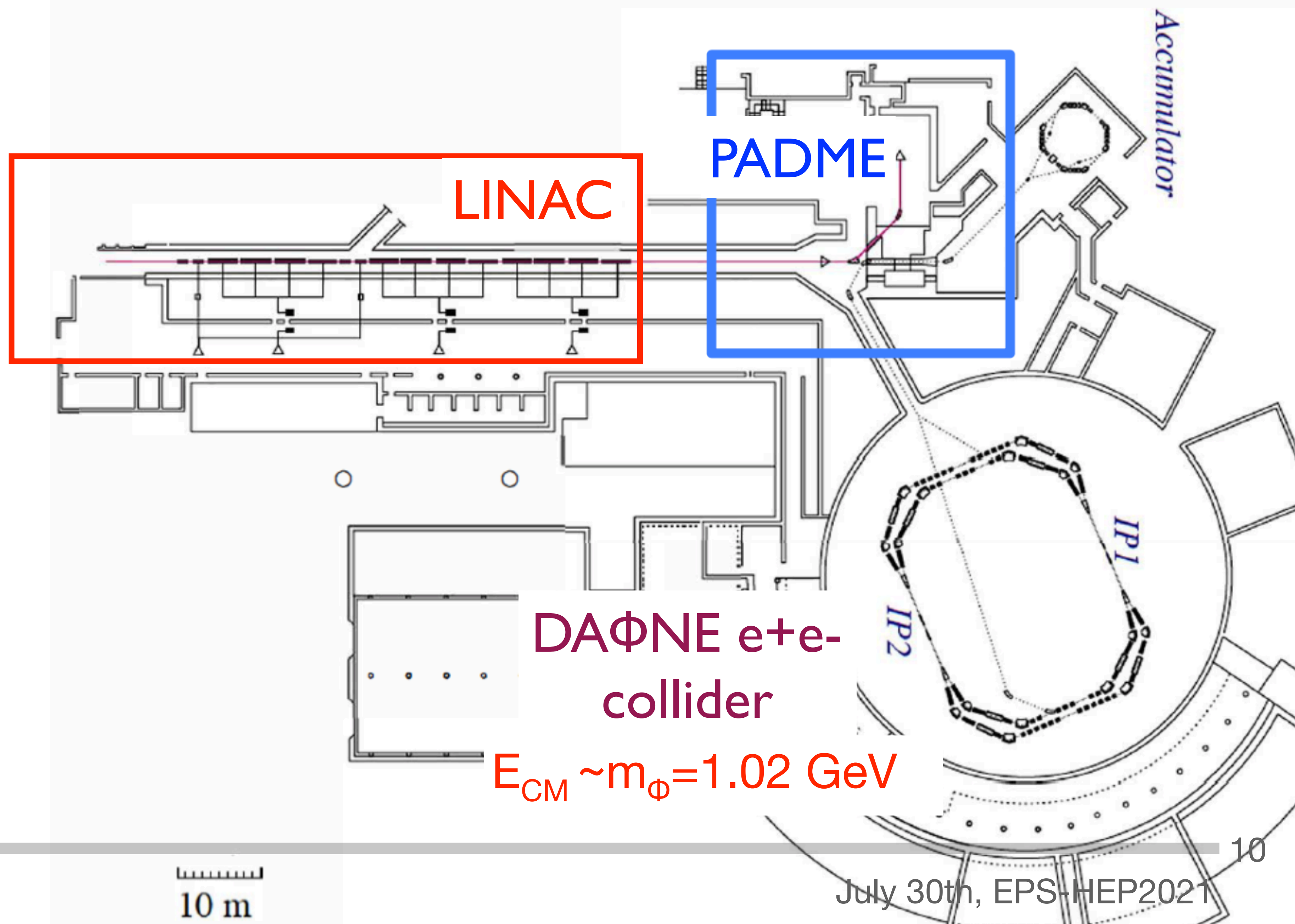
Positron beam features:

1% energy spread,

~1 mm spot size,

~1 mrad beam divergence

Pulsed beam,
repetition rate 50Hz,
current not allowed to
exceed 100e+/ns



THE PADME CONCEPT

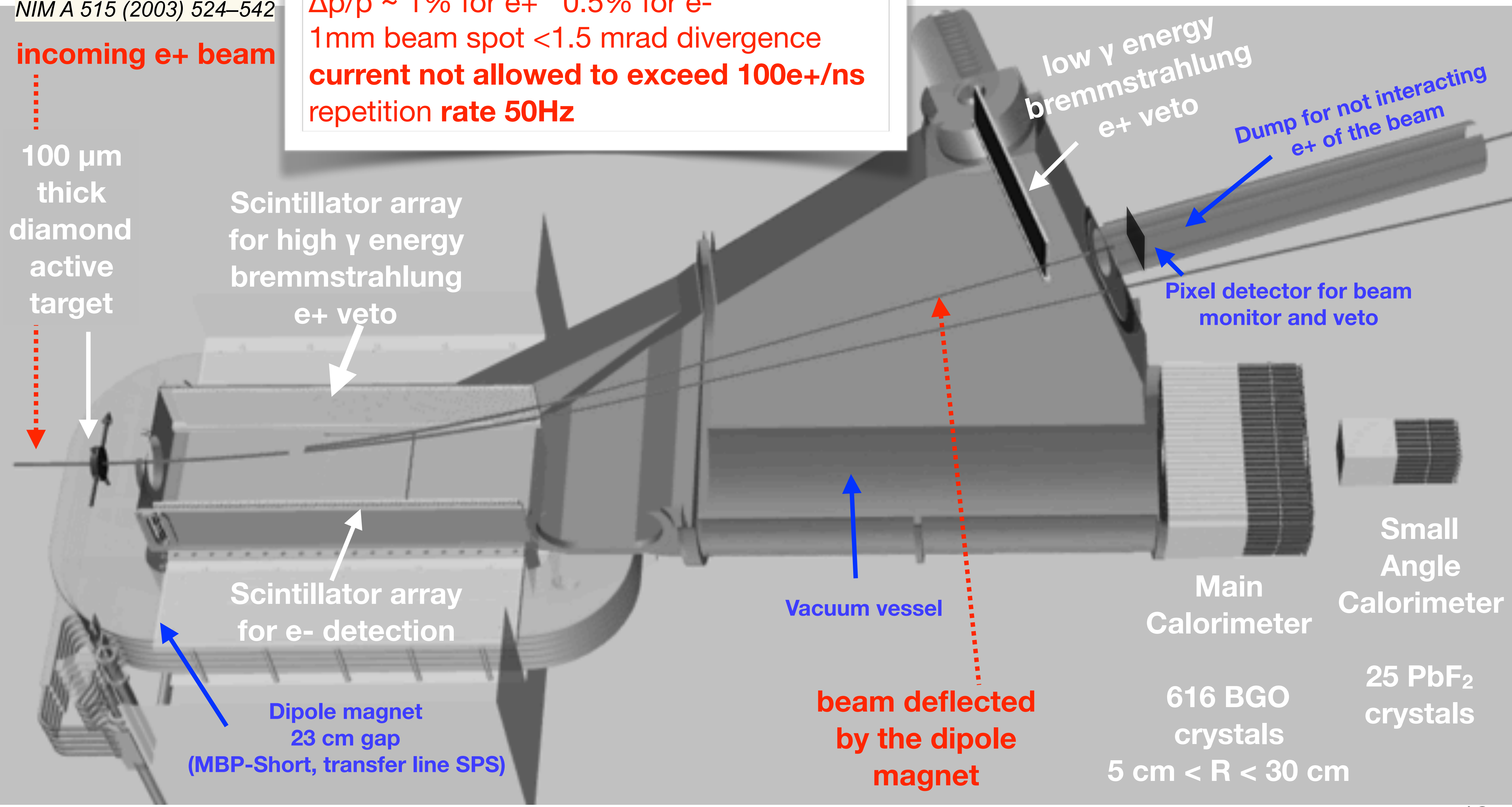
- Production from ***annihilation of an e+ beam*** (E<~550 MeV) ***on a thin target***
  - e+e- ➛ A'γ *(with A' to invisible)*
  - precision reconstruction of the SM γ and use of closed kinematics to statistically detect A' as ***missing mass***
    - signal does not depend on A' decays and dark sector parameters (α_D, M_χ)
    - the mass peak provides a clean signature which allows to measure both mass and coupling
    - small/simple detector
  - the challenge: backgrounds

PADME design sensitivity ε=~10^{-3}, $m_{A'}$ <23.7 MeV
- for ***E_{beam}=550 MeV***, ~10^{13} Positrons On Target: (2 years of data taking at 60% efficiency, ***bunch length >=160 ns and 20k e+/bunch*** @ 50 Hz)

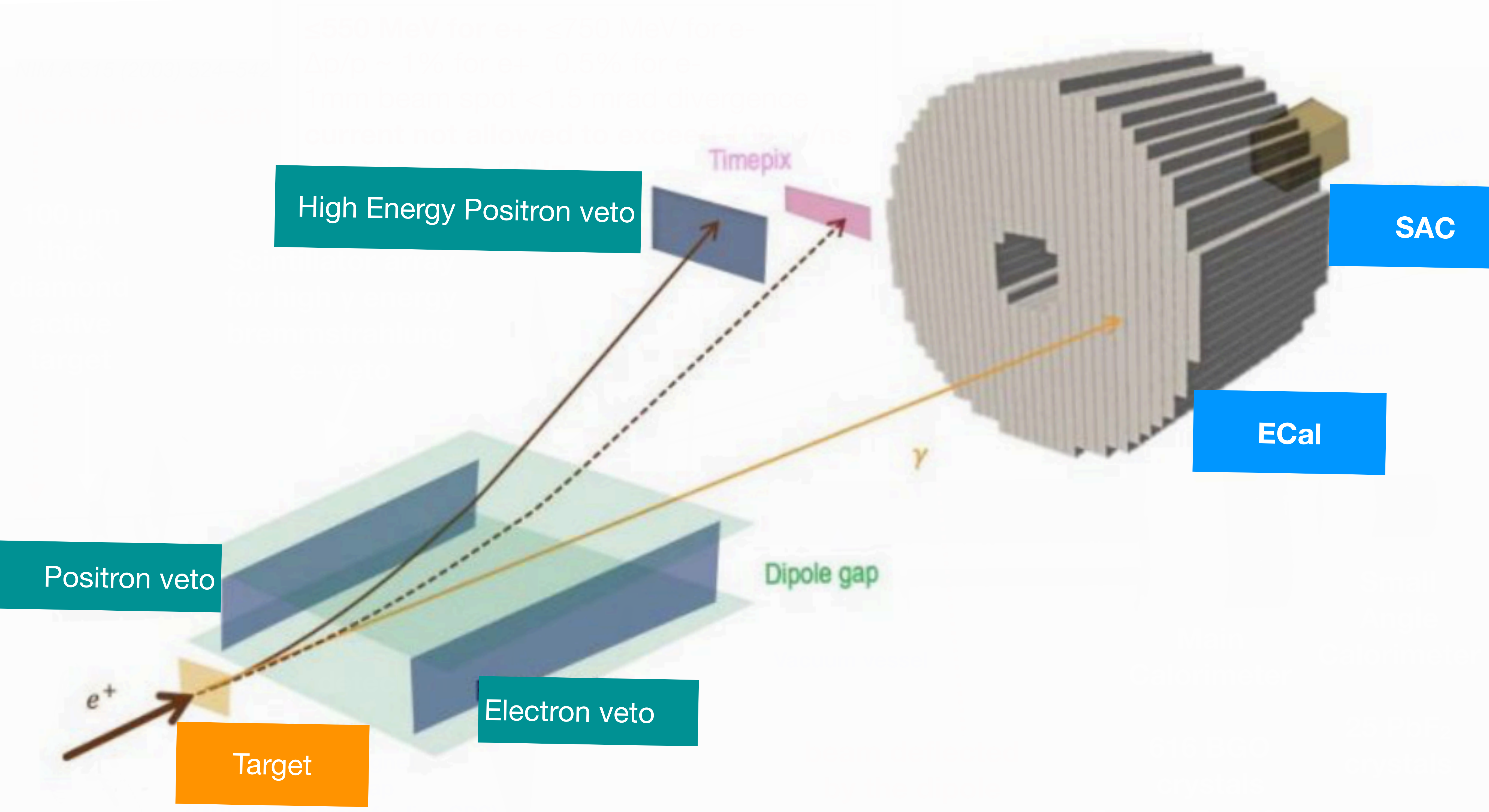
- Other physics opportunities can be explored (ALPs, etc …)

THE DETECTOR

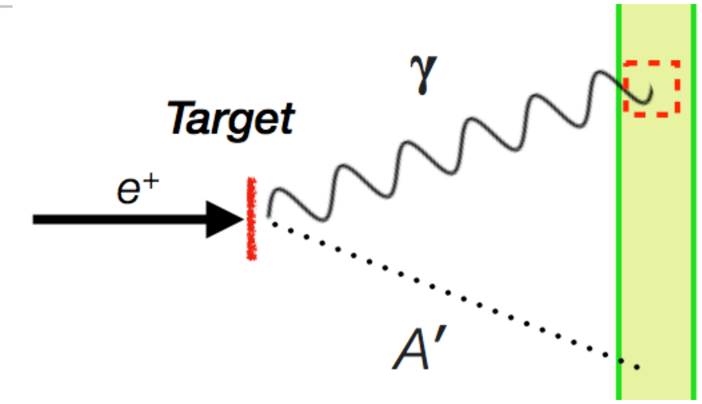
≤550 MeV for e+ ≤750 MeV for e-
Δp/p ~ 1% for e+ 0.5% for e-
1mm beam spot <1.5 mrad divergence
current not allowed to exceed 100e+/ns
repetition **rate 50Hz**



THE DETECTOR

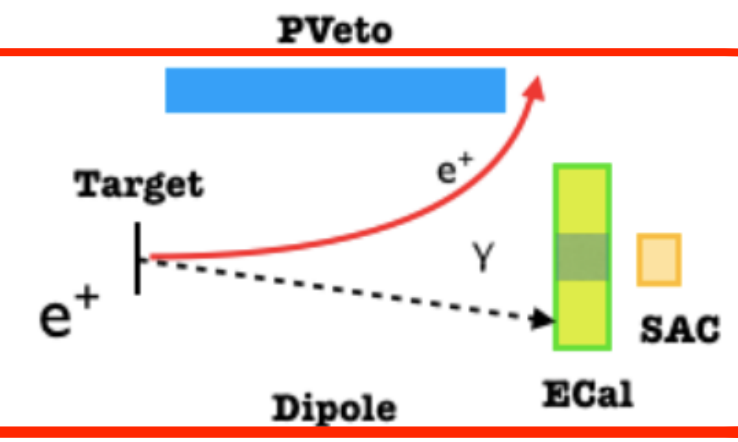


SCHEMATICALLY

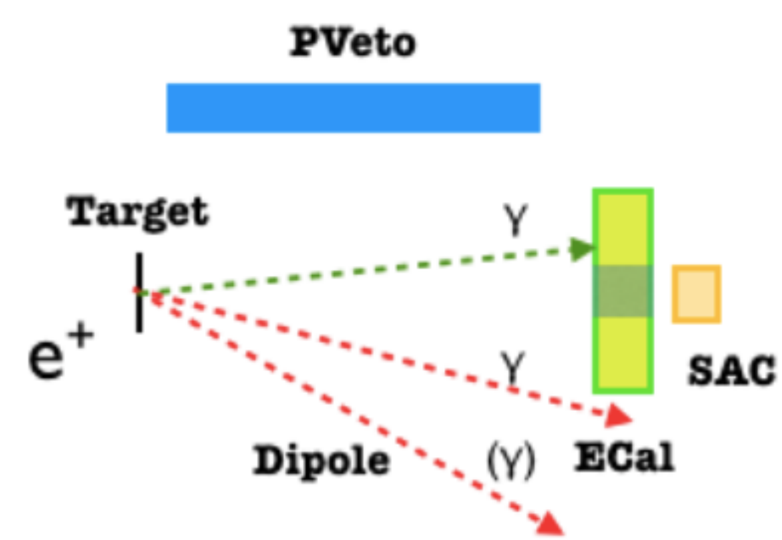


- **Signal signature**: one **γ** and no in time activity in the detectors

- **Standard Model backgrounds**:
  - Bremsstrahlung: e+ N -> e+ N **γ**
    - one isolated photon, but the in time low energy e+ can veto the event
    - 4 b / C-atom if $E_\gamma > 1$ MeV



  - Annihilation: e+e- -> γγ (γ)
    - 1.5 mb (0.15 mb for $E_\gamma > 1$ MeV) for e+ energy of 550 MeV
    - symmetric if two-body final state, more insidious the three body channel, if only one **γ** falls in the calo acceptance



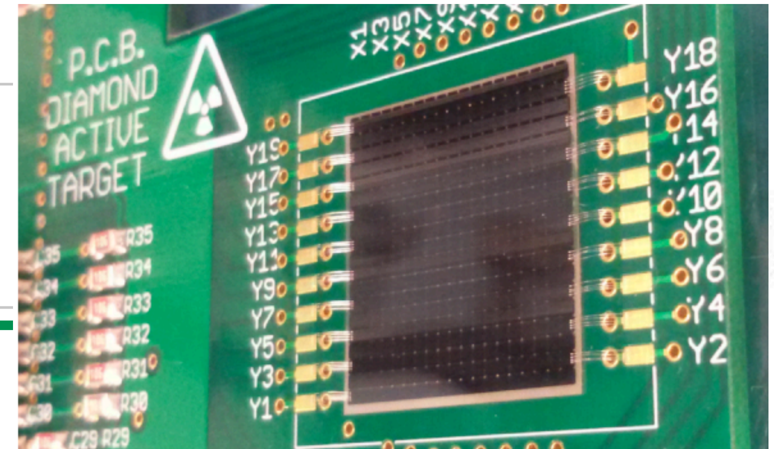
Timing, hermicity, control of non physics background are crucial

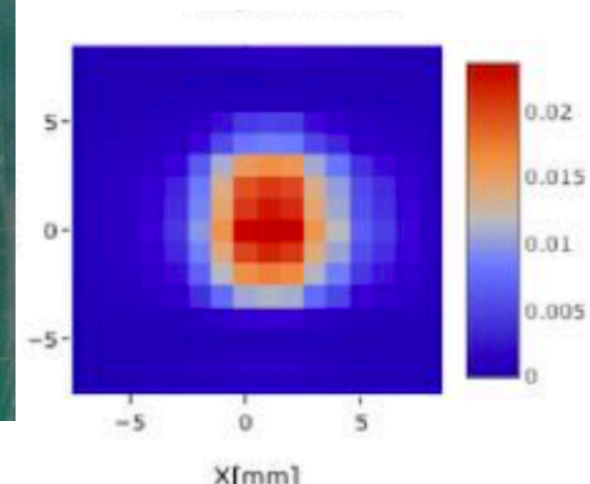
  - radiative Bhabha: 180 mb

THE DETECTOR AND THE RUN

the steps towards physics

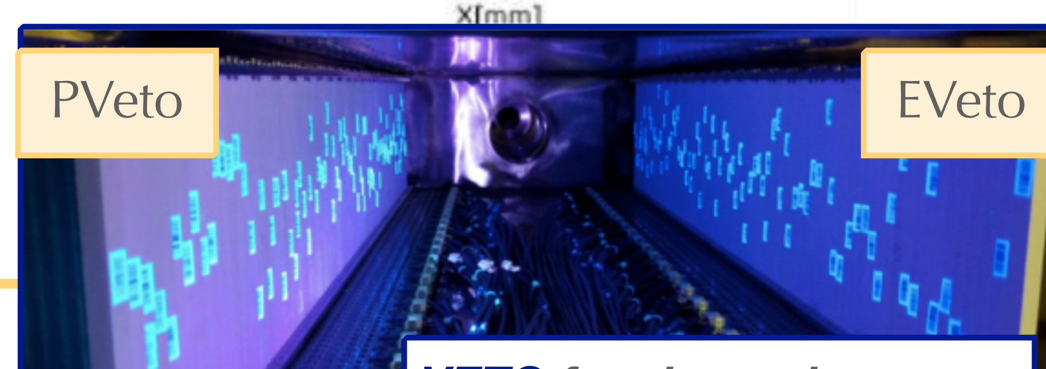
THE DETECTORS



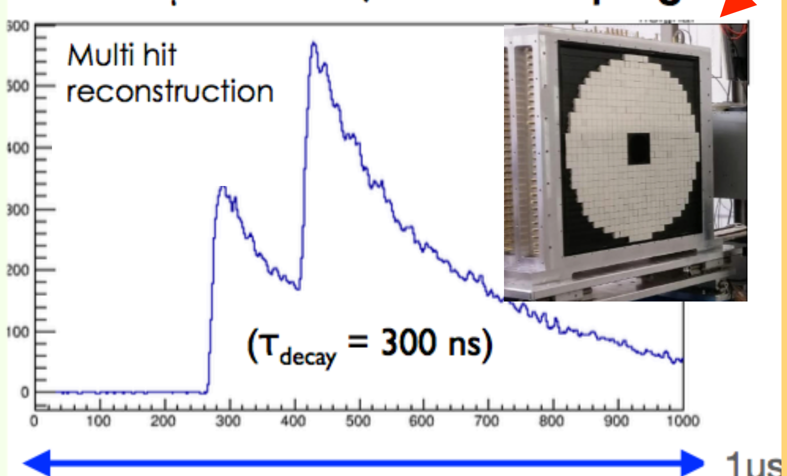


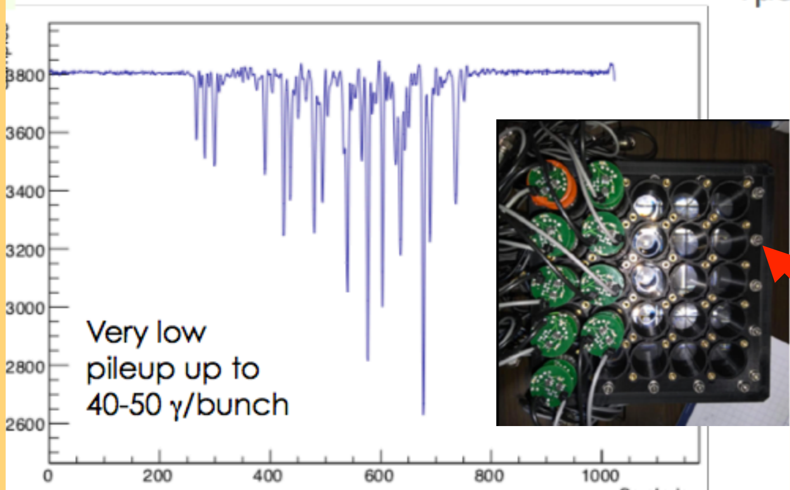
The active diamond target

- pCVD (Chemical Vapor Deposition)
  20 × 20 × 0.1 mm³; 16+16 graphitic strips (x and y), 1 mm pitch
  - measures # of e+/bunch, linear up to 15k e+/strip
  - beam profile and charge **centroid with 60 µm resolution**



Ecal 1 µs window, 1GHz sampling





SAC 250ns window, 2.5 GHz sampling

ECAL - High resolution EM Calorimeter

- 616 BGO crystals 21×21×230 mm³ PMT readout
- radius ~30 cm, 3.45 m distance form the target; central hole 105×105 mm² for SAC
- calibrated with cosmic rays trigger
- energy threshold = 0.5 MeV
- LY vs Temperature = -0.9%/°C

SAC – Small Angle Calorimeter

- 25 Cherenkov PbF2 crystals 30×30×140 mm³
- PMT readout
- angular coverage 0 ÷ 19 mrad
- **86 ps time resolution**

VETO for charged particles

- Plastic scintillator bars 10×10×200 mm³
- 3 arrays for a total of 208 channels, PVeto, EVeto, HEPVeto
- **< 700 ps time resolution**
- efficiency for mip > 99.5%

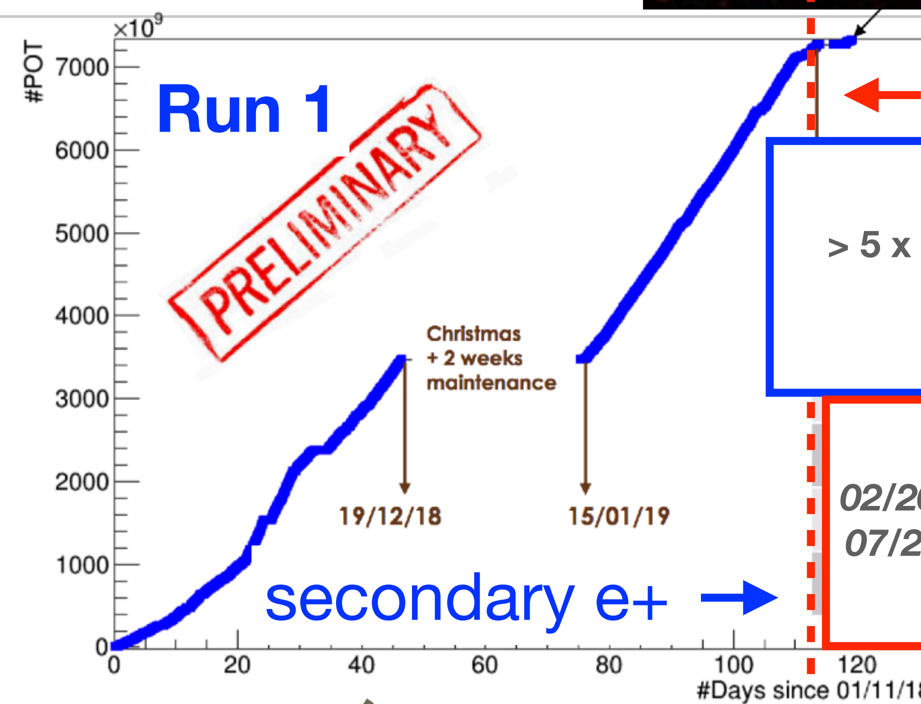
more in backup

THE PADME RUNS

RUN 1 09/2018-02/2019

Calibration runs 07/2019
Mods in the beam transfer line
Commissioning runs 07/2020

RUN 2 09/2020-12/2020



primary e+

RUN 1
> 5 x 10^{12} POT with secondary beam
09/2018-02/2019
E = 540 MeV

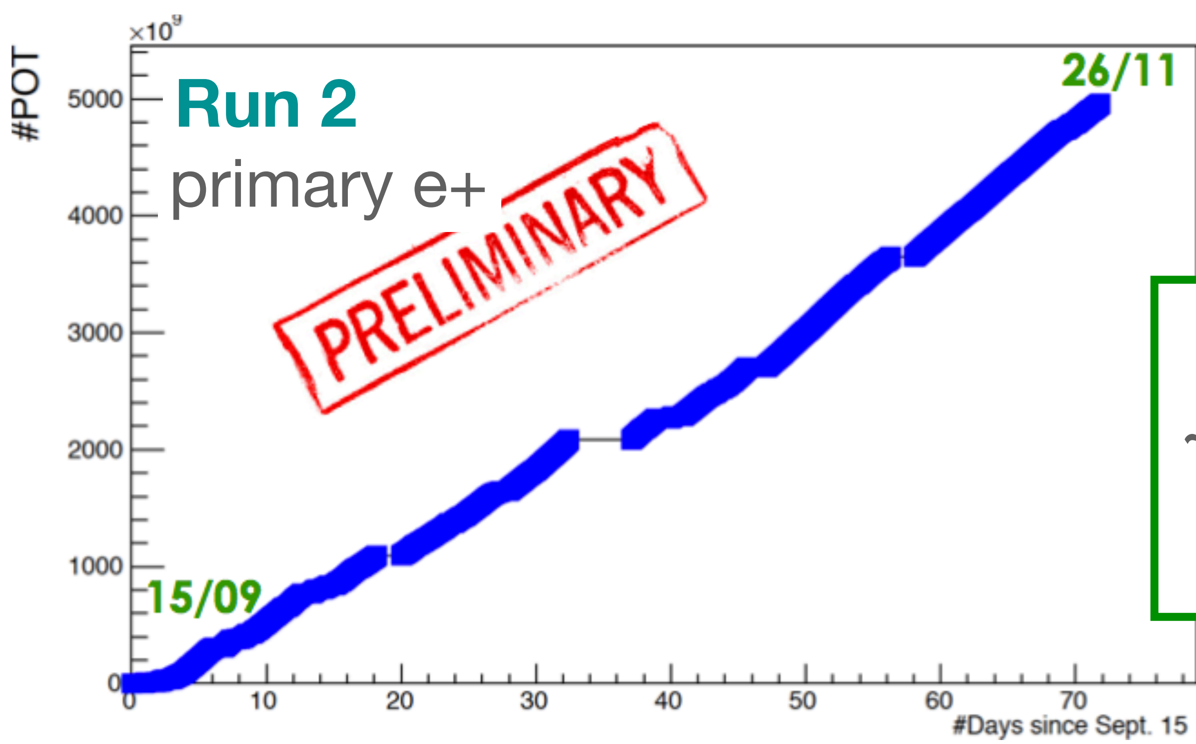
Calibration runs
02/2019 ~10^{10} POT, with primary e^+ beam
07/2019 ~10^{10} POT with primary e^+ beam
E = 490 MeV

25000 POT/bunch
beam energy: 545 MeV
bunch length: 250 ns

25000 POT/bunch
beam energy: 490 MeV
bunch length: 250 ns

28000 POT/bunch
beam energy: 430 MeV
bunch length: 280 ns

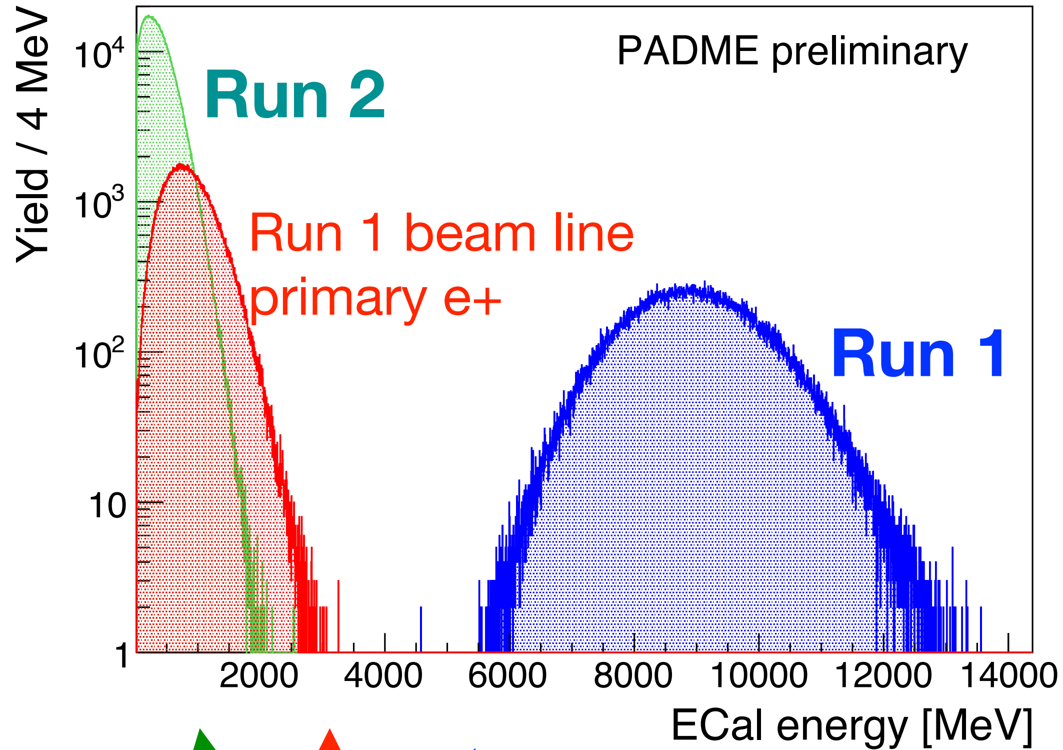
Covid-19
transfer line improvements



RUN 2

~ 5 x 10^{12} POT primary e+ beam
09/2020-12/2020
E = 430 MeV

BEAM COMMISSIONING



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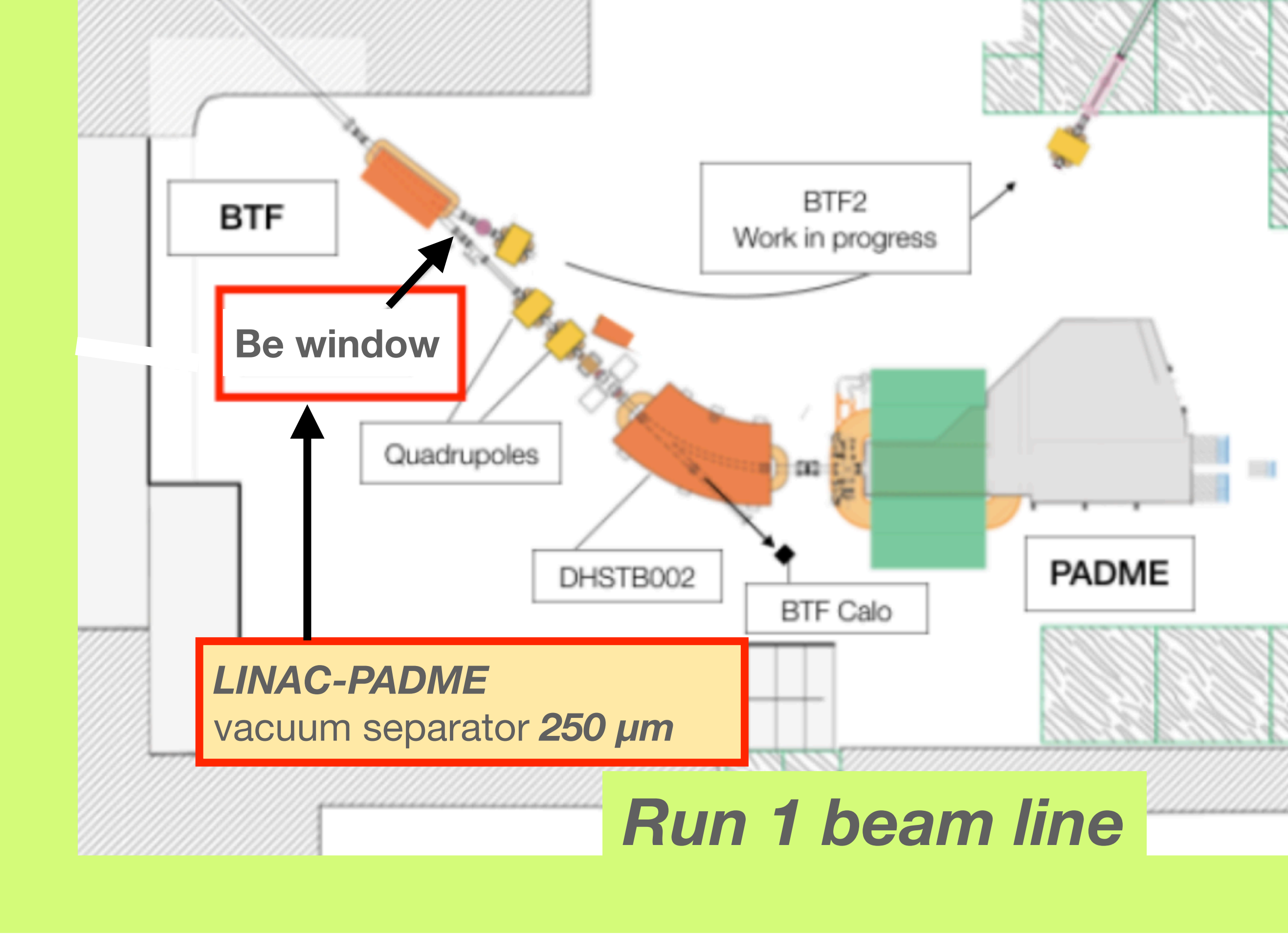
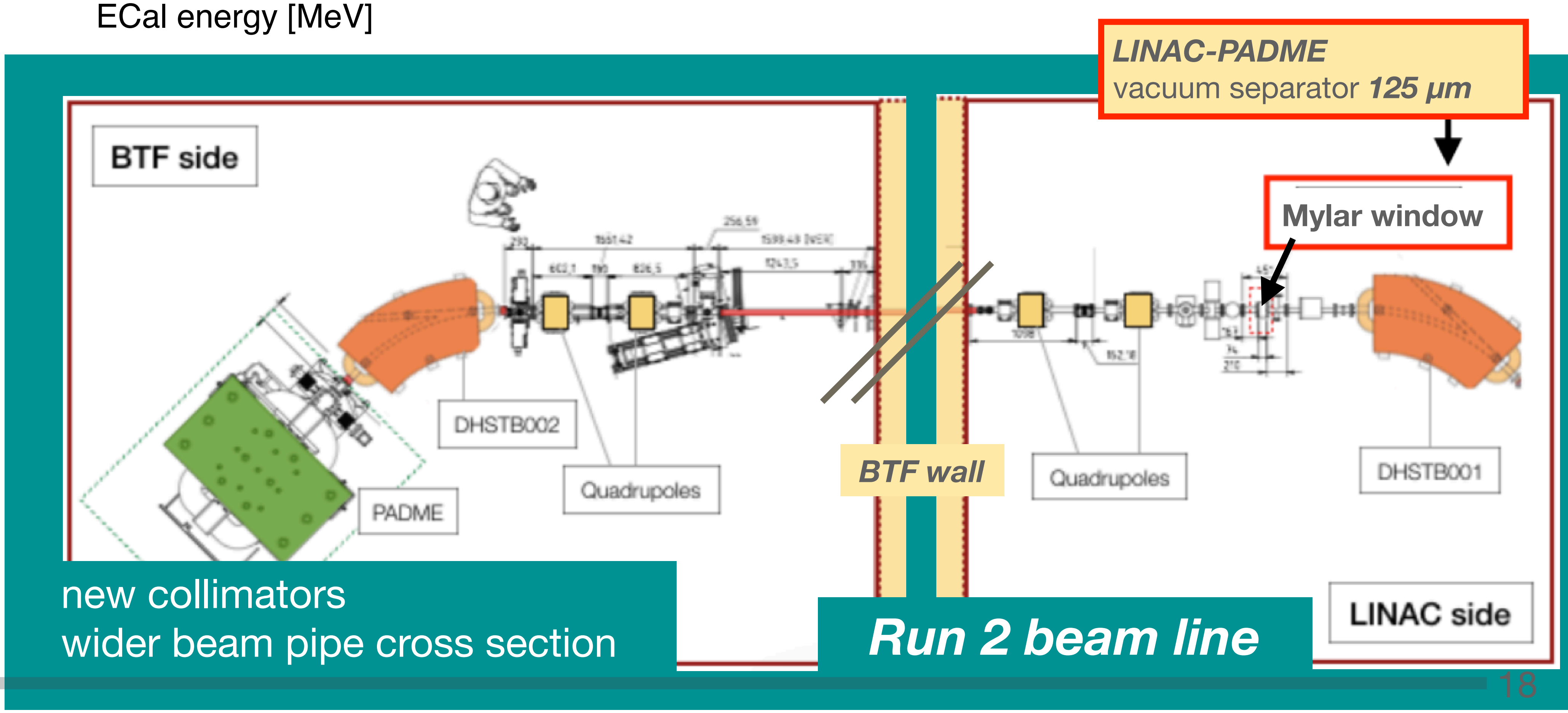




STATUS AND PROSPECTS

Studying the SM candles to assess the potential

POSITRON BREMSSTRAHLUNG

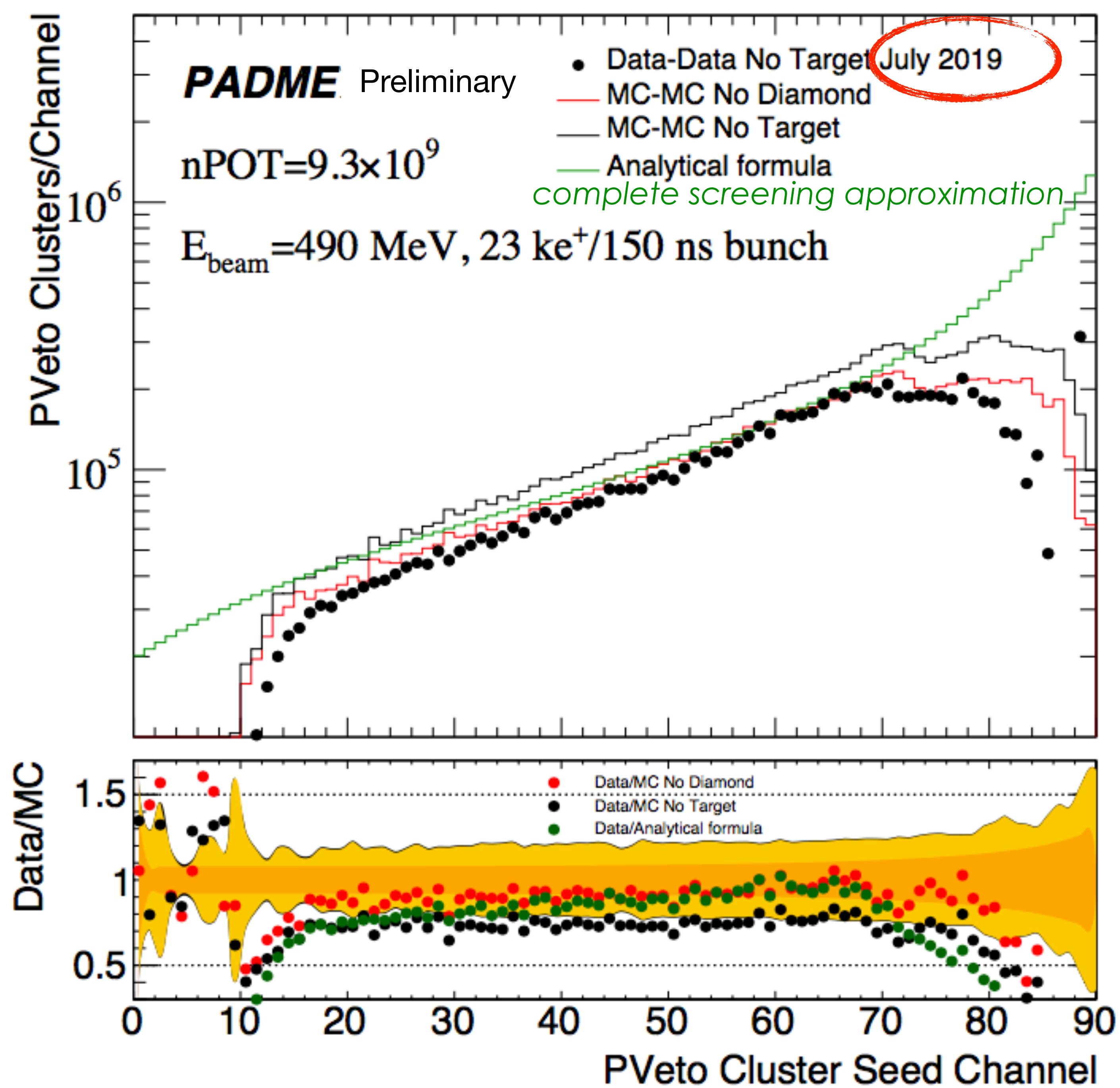
Cluster distribution in ***PVeto*** *after beam background subtraction*

- *dominated by Bremsstrahlung e+, measures the Bremsstrahlung rate*

- *beam background from a run recorded after moving the PADME target out of the beam line*

Main systematic uncertainties:

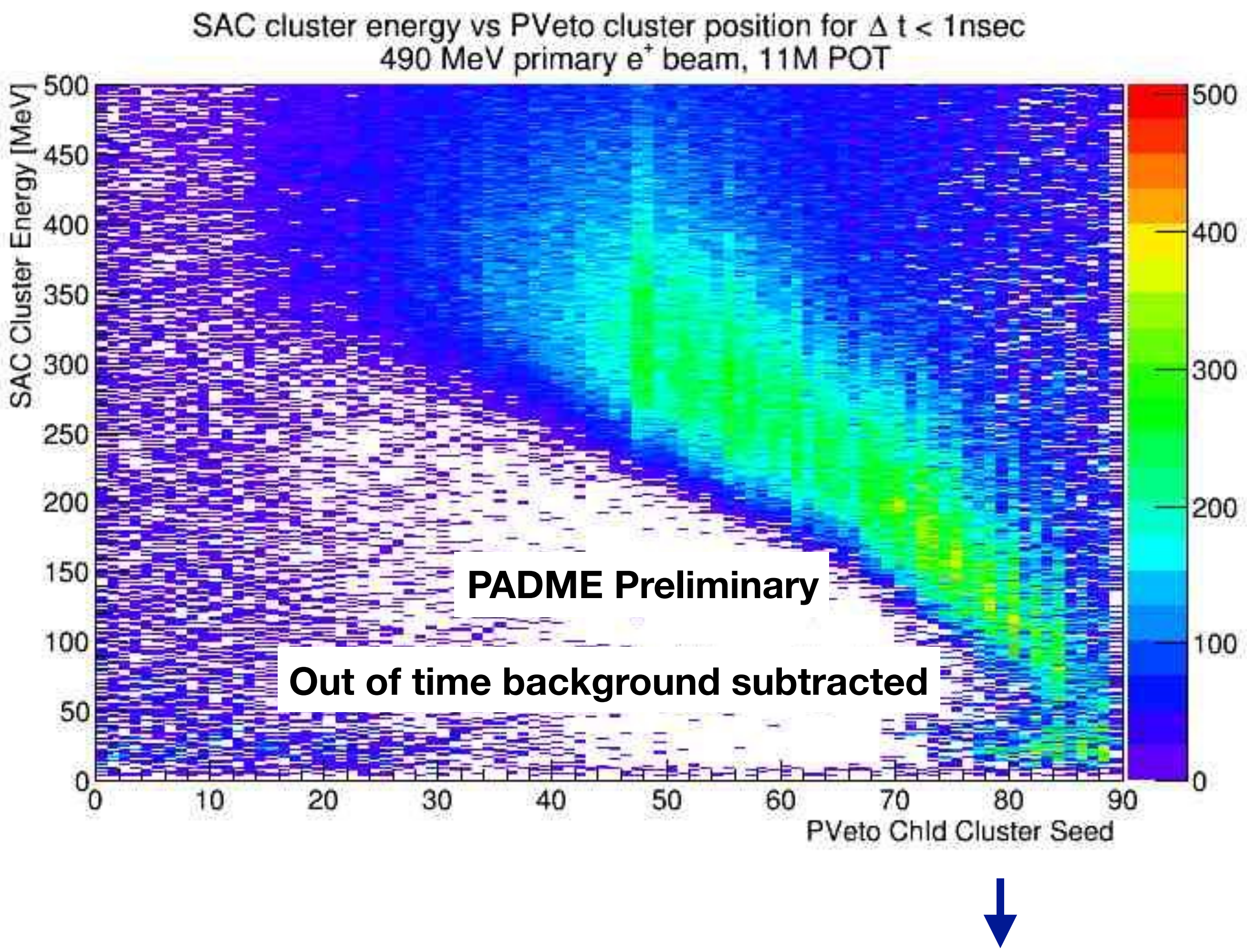
- *background subtraction template and normalization (10-20%), positron momentum scale (4%), absolute and relative calibration of the NPOT measurement (5%+5%), modeling of Bremsstrahlung in simulation (~3-5%)*



Much improved situation in Run 2

BREMSSTRAHLUNG: PVETO VS SAC

SAC Cluster and **PVeto** Cluster in ΔT < 1 ns

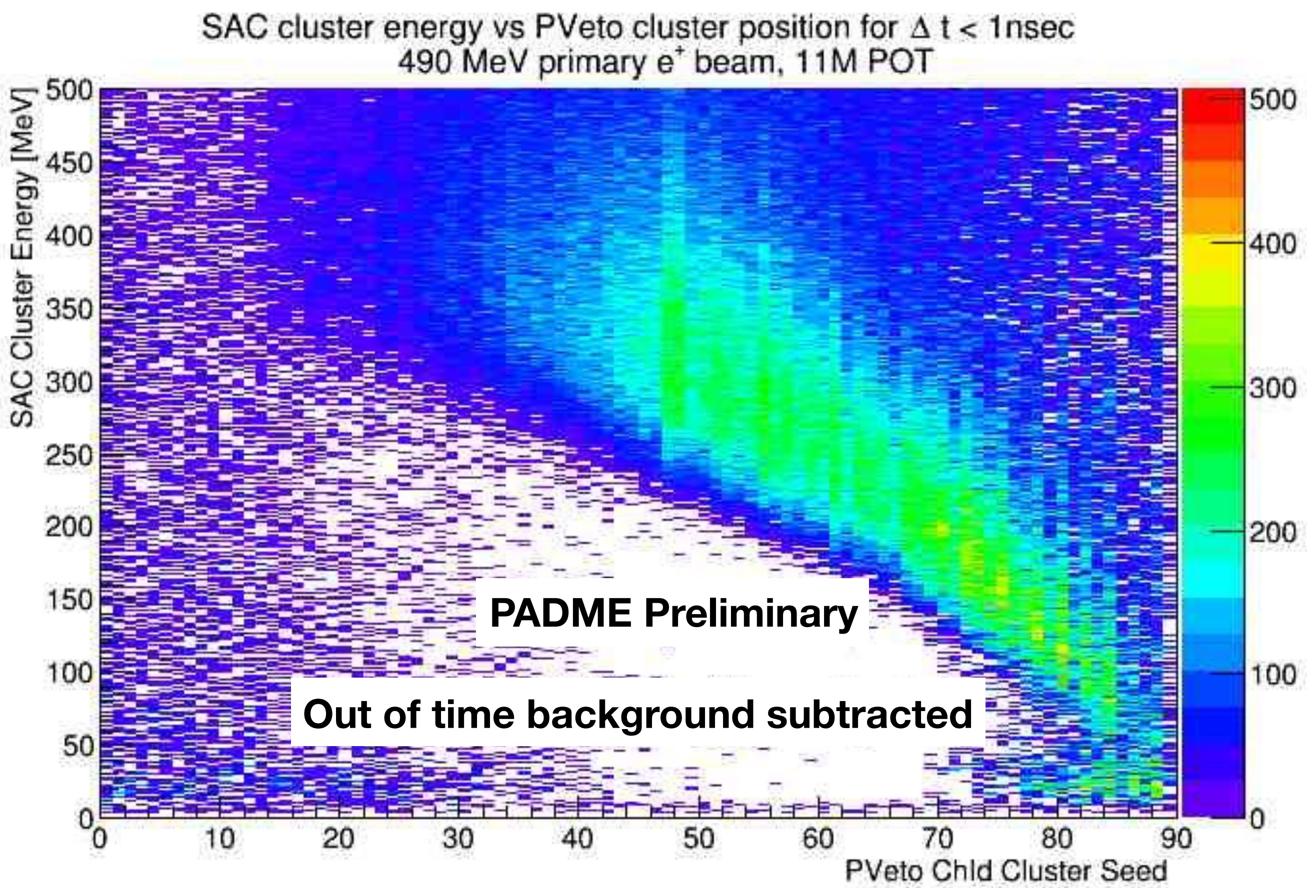


can be calibrated in positron momentum

Photon energy +
slowed down positron energy
~ beam energy

BREMSSTRAHLUNG: PVETO VS SAC

SAC Cluster and ***PVeto*** Cluster in ΔT < 1 ns



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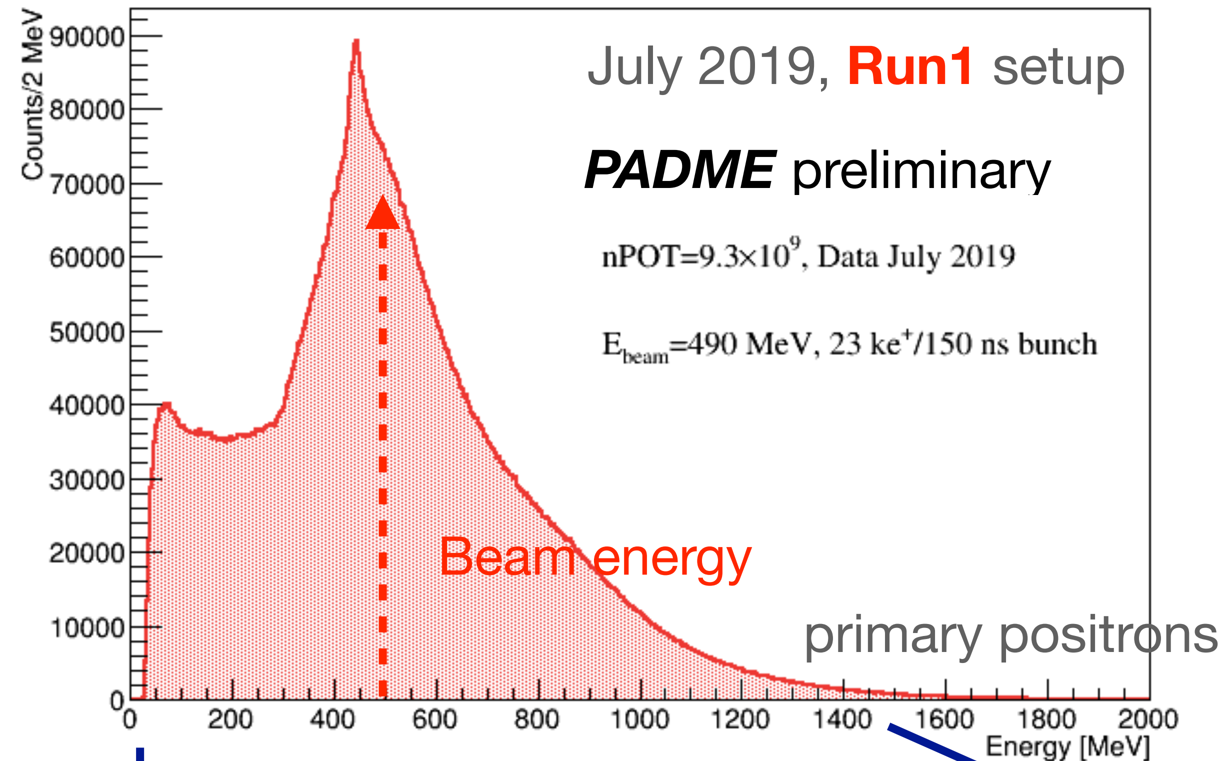
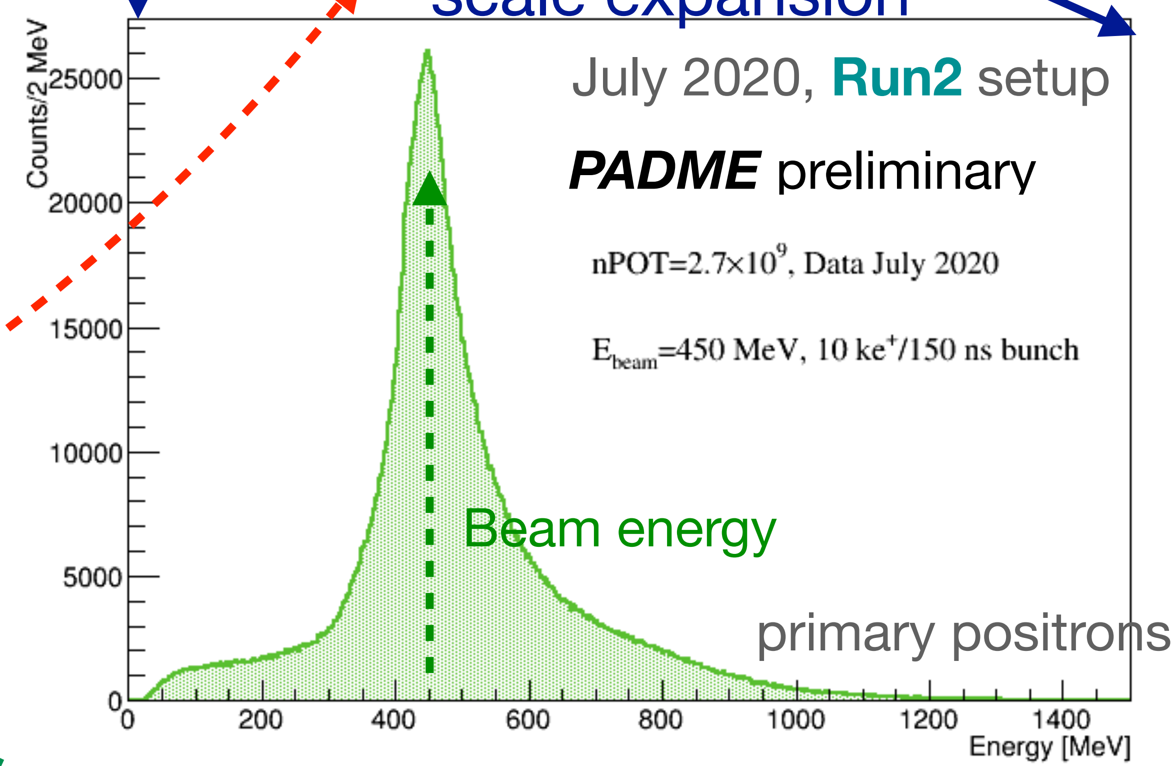
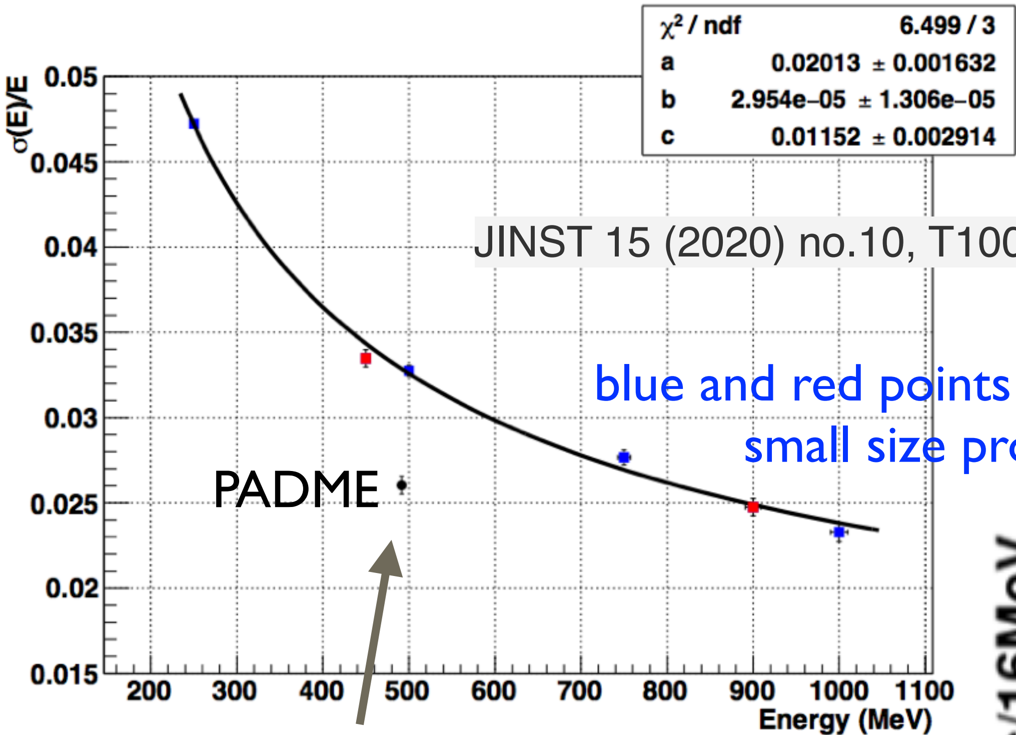


scale expansion



CHALLENGING ECAL RECONSTRUCTION



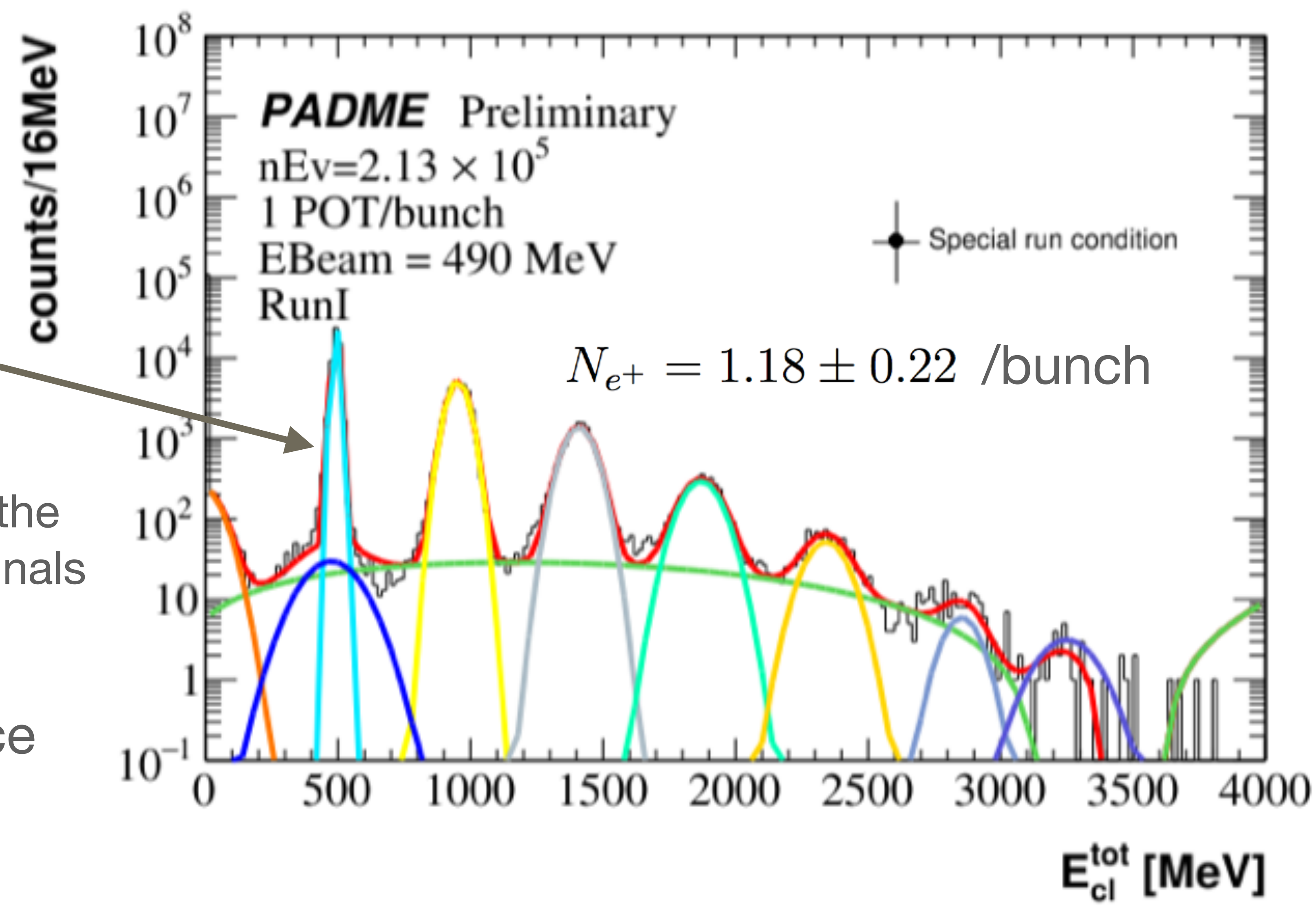
JINST 15 (2020) no.10, T10003

blue and red points from previous small size prototype

Energy resolution

$2.62 \pm 0.05\,(\text{stat})\%$ @ 490 MeV in PADME

- ECal energy resolution in PADME from ***a single positron calibration run***



$N_{e^+} = 1.18 \pm 0.22$ /bunch

Multihit reconstruction

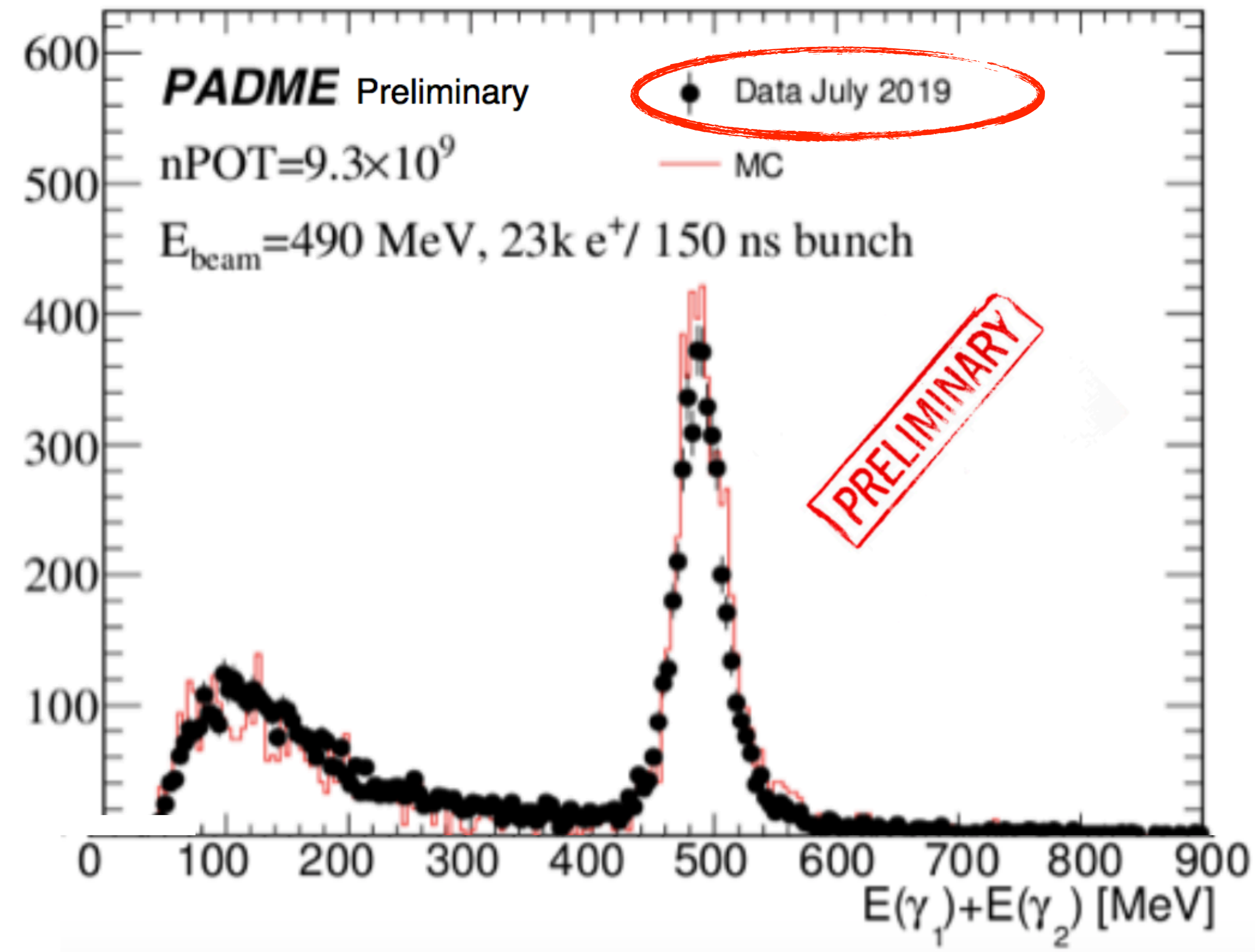
- successful Poissonian fit to the number of reconstructed signals

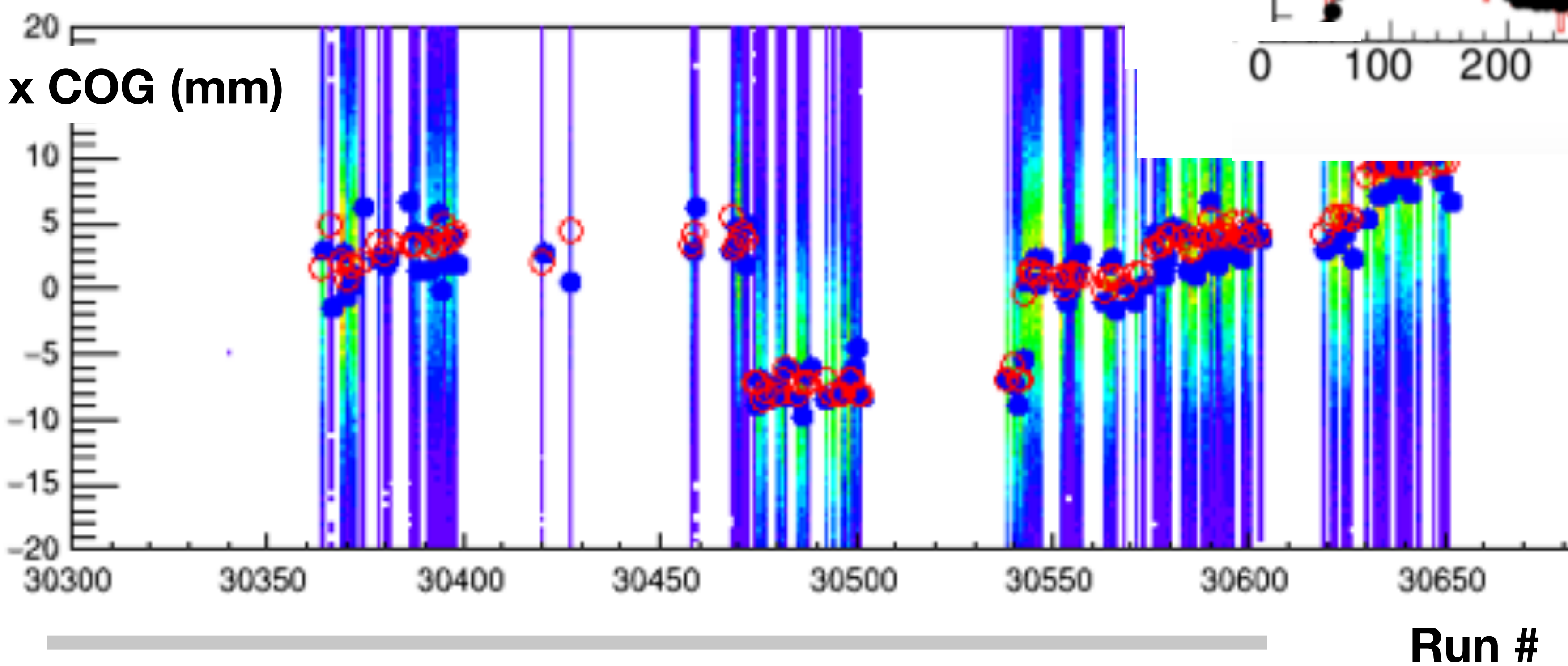
Time resolution from difference in time of a selection of 2**γ** events ***1 ns***

SM ANNIHILATION

- e+e- annihilation signal easily emerging with primary e+ beam
  - $\Delta T < 10$ ns, $\Delta\phi < 25^0$
  - γγ center of gravity < 1 cm

- provides a powerful run-dependent monitor of the luminous point corroborating detector surveys





Toward a cross section measurement with cleaner Run II sample:
- differential in ϕ
- data driven estimate of γ efficiency

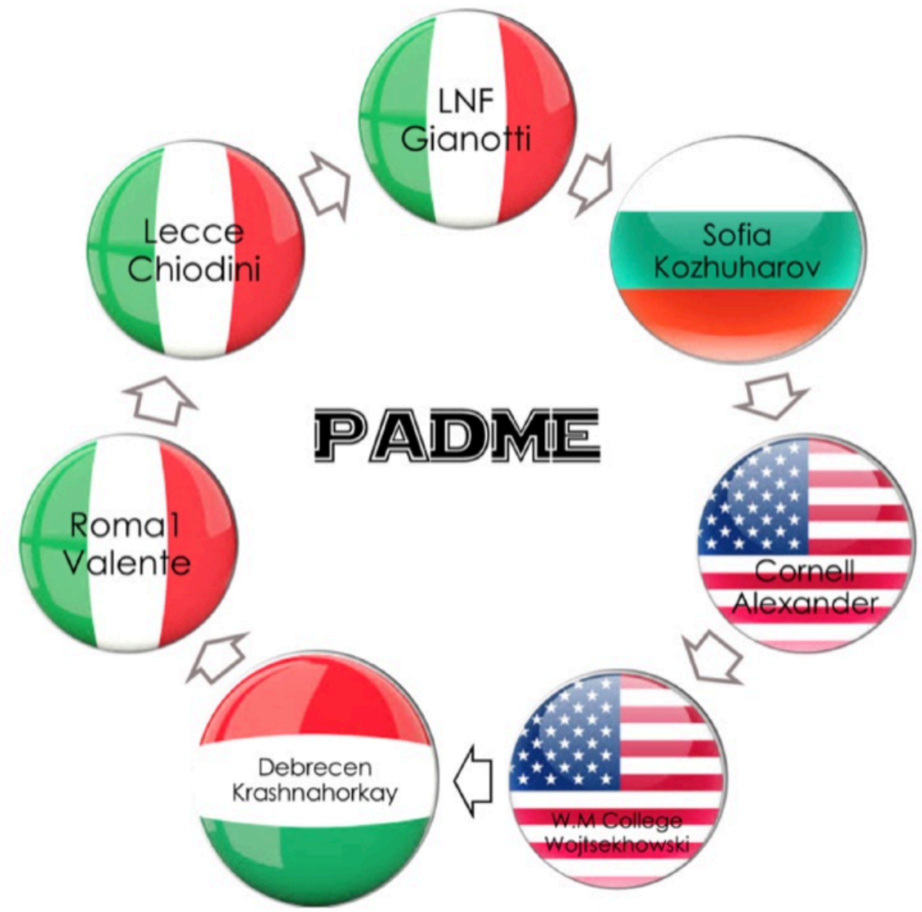
CONCLUSIONS

- PADME is a small experiment (4m from target to beam dump) and a small collaboration ~50 physicists

- Detector performance as required
- Physics background under control
- Challenging beam induced background
  - Simulation effort addressing the new beam line

- Data understanding approaching the level necessary for the dark photon target search
  - sensitivity not expected to exceed competitors, but first bench-test for a unique technique:
    - fixed target, annihilation, pulsed high intensity beam, ~slow high resolution calorimetry

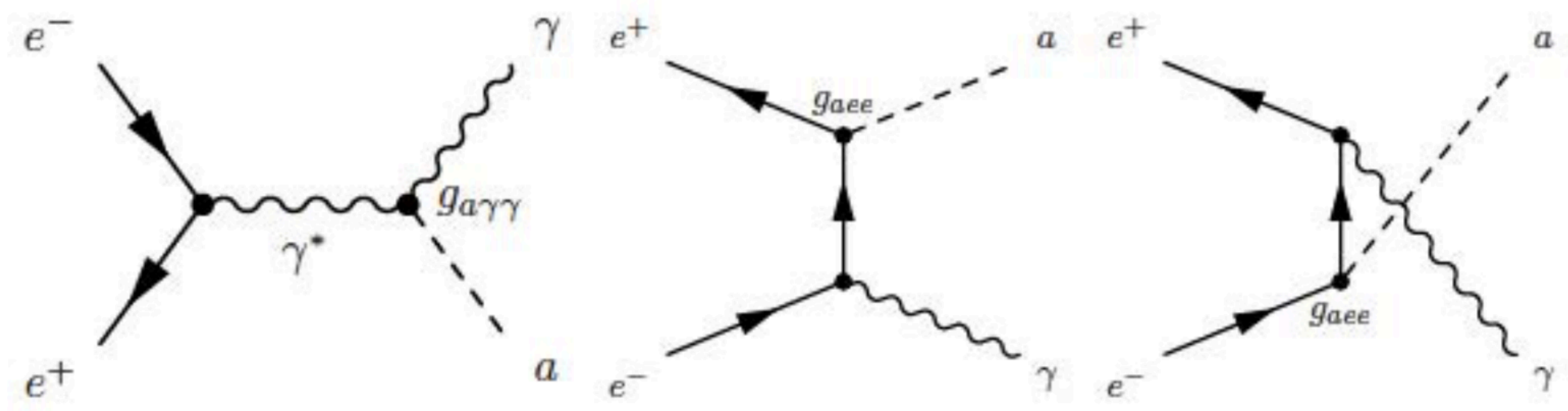
- Other opportunities @ PADME in backup



BACKUP

AXION LIKE PARTICLES

- Various production mechanisms in e+e– annihilations.
- Search for Axion-like signals can be performed in PADME for a mass range similar to that explored with the dark-photon search
- Ongoing studies to evaluate the reach in coupling strength



Feynman diagrams for $e^+e^- \rightarrow \gamma$ + Alp

X17 ^{8}BE ANOMALY

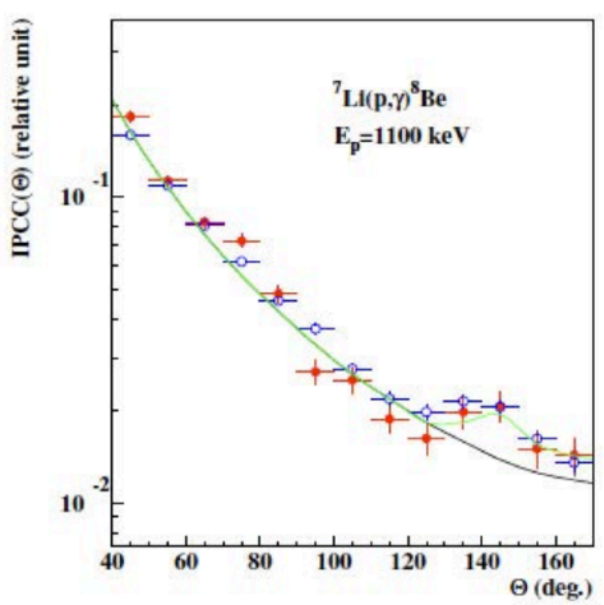
- Atomic transitions in light nuclei ^{8}Be and ^{4}He hints to a signal anomaly
- New observation in ^{3}H(p, e+e−)^{4}He of a peak in the e+e− angular correlations at 115○ with 7.2σ significance [arXiv:1910.10459v1, 23/10/19]
  - compatible with m_X=16.84 ± 0.16(stat) ± 0.20(syst) MeV and Γ_X= 3.9 × 10^{-5} eV
    - PRL 116, 052501 (2016)

☐ Nardi et Al, "Resonant production of dark photons in positron beam dump experiments" ArXiv1802.04756
Phys. Rev. D **97** (2018) 095004

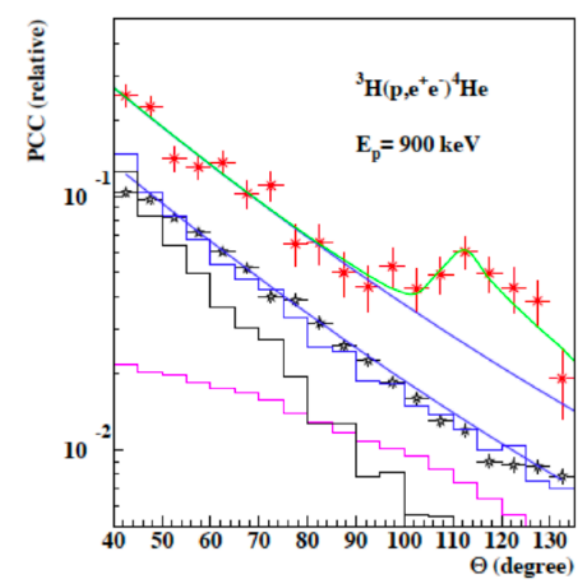
☐ Using a beam of e^{+} 282.7 MeV might lead to observation of the resonant production

- many uncertainties (narrow resonance, electron velocities, etc) but potentially an interesting opportunity that PADME cannot elude

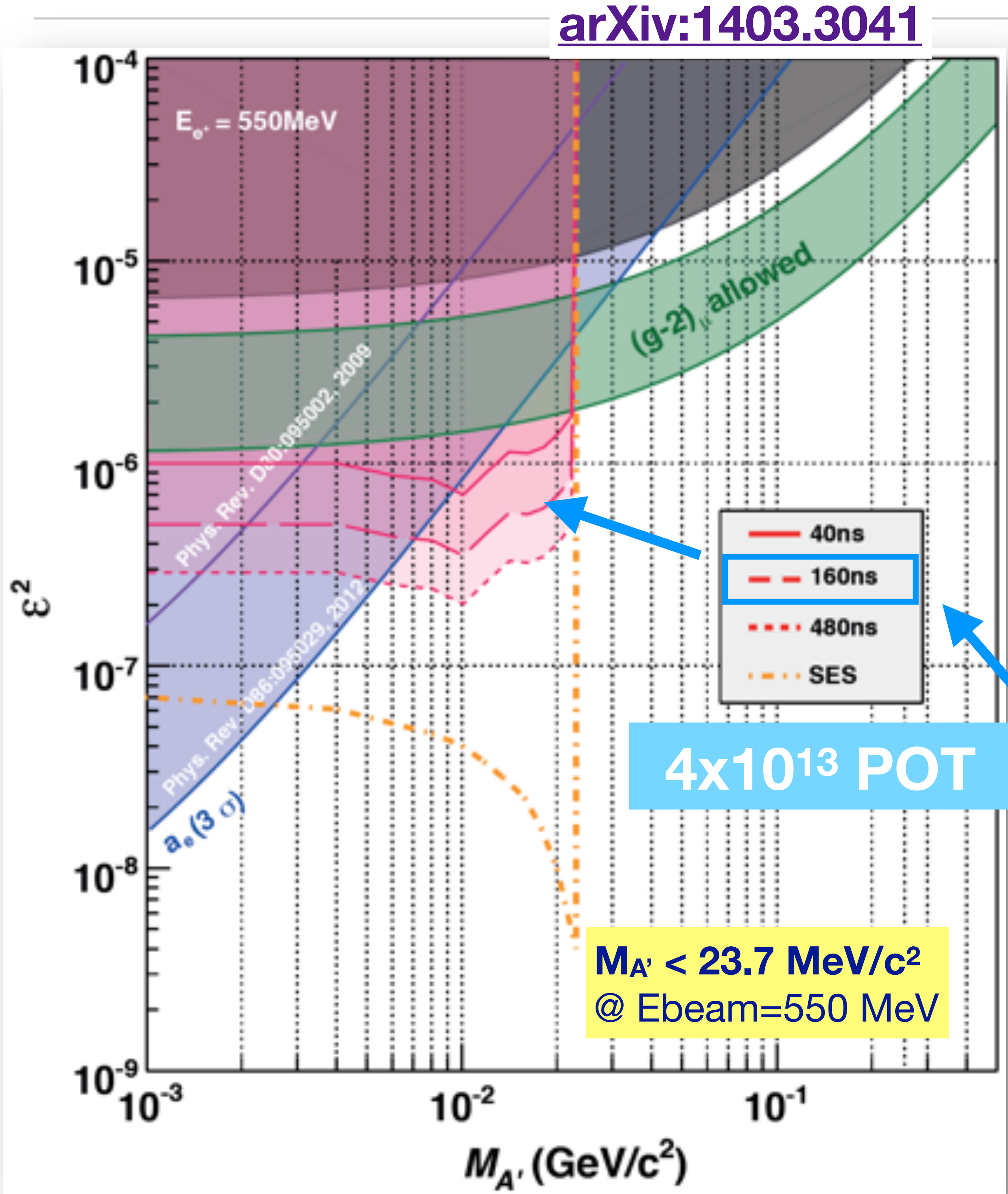
^{8}Be anomaly (18MeV to GS)



^{4}He anomaly (21MeV to GS)



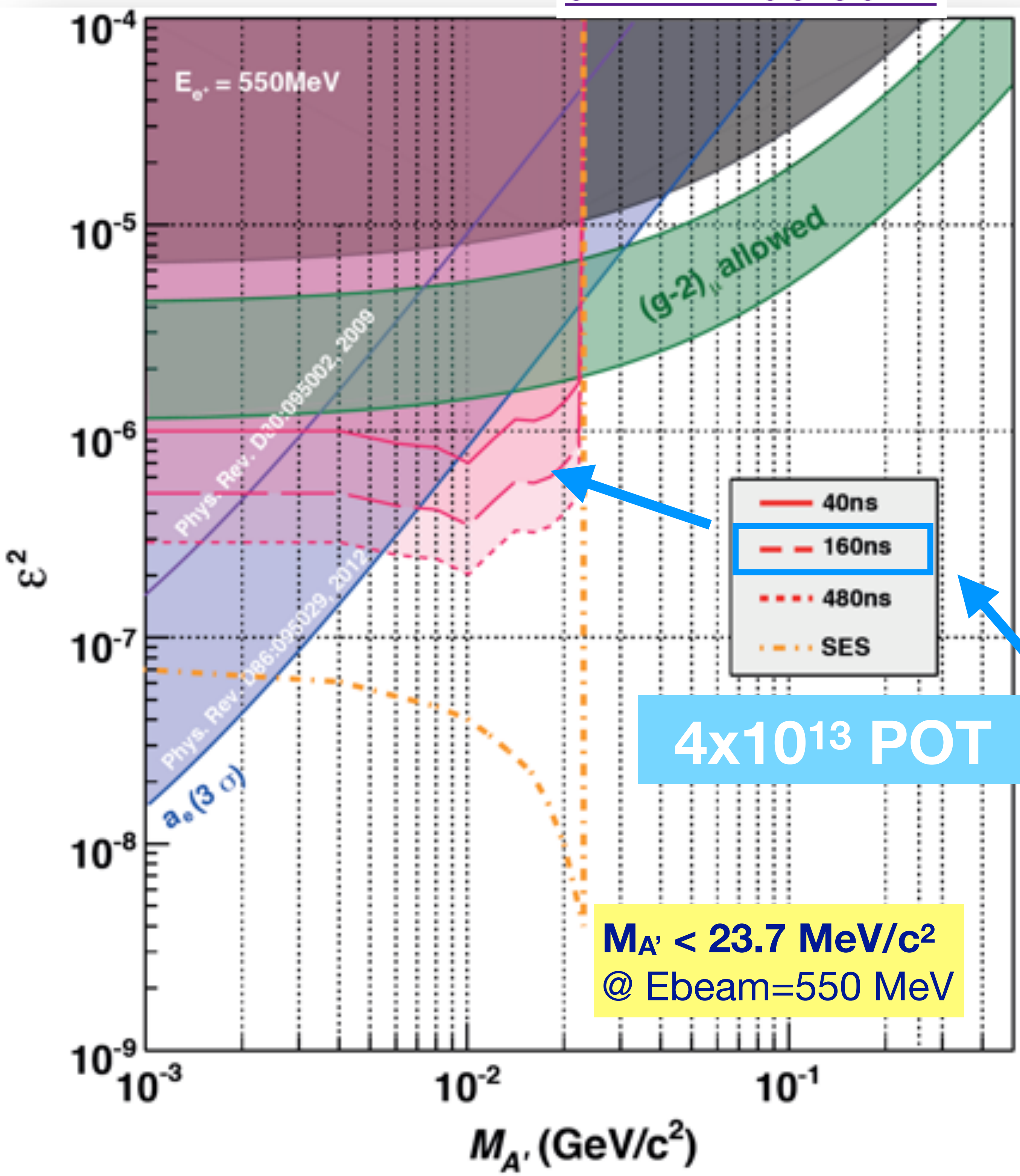
PADME REACH FROM DESIGN



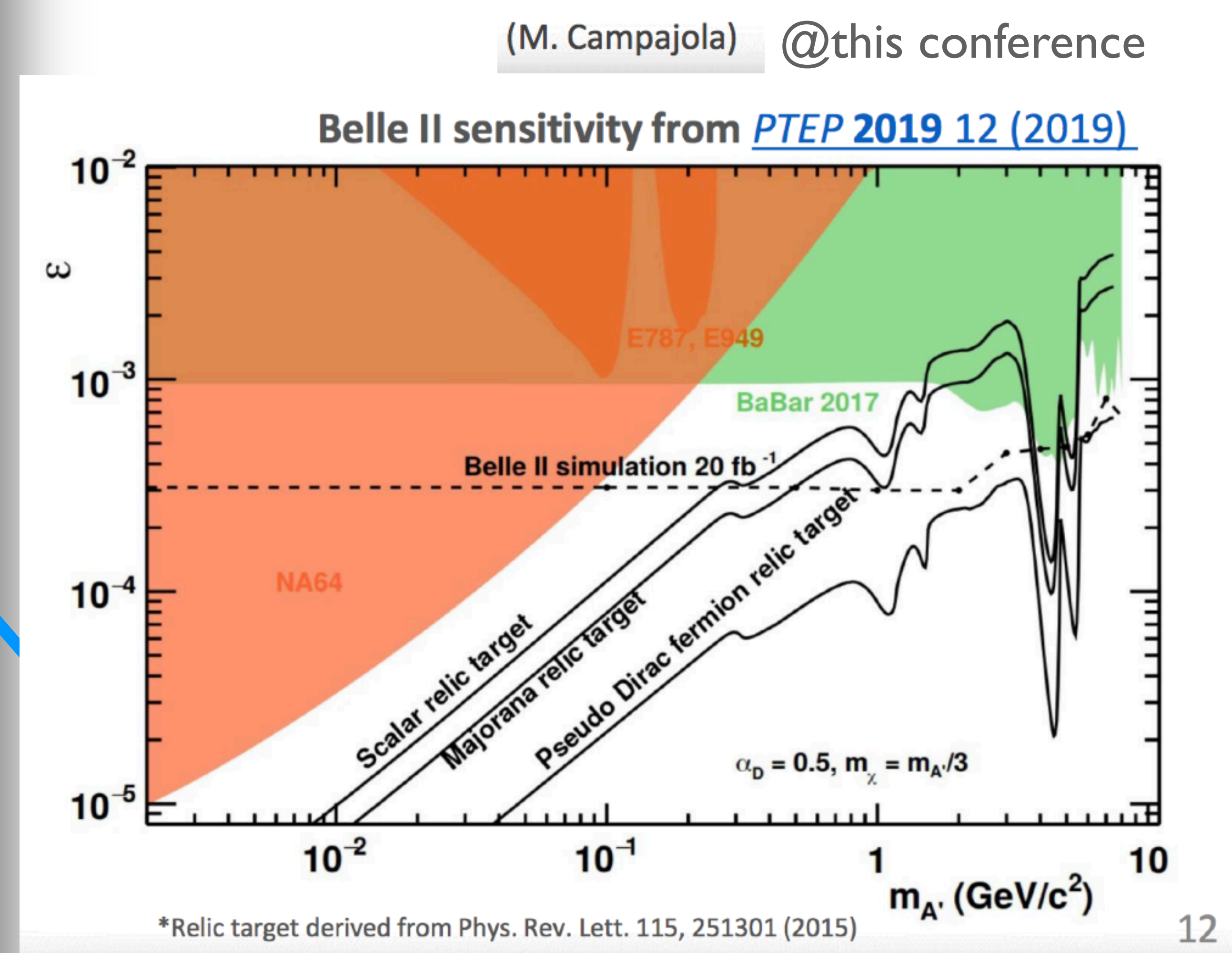
- in the absence of indications of signal events in data
- expected limits on ε^2 as a function of $m_{A'}$
  - from $N(A'\gamma)=\sigma(N_{BkG})$
- 2 years of data taking at 60% efficiency with bunch length of 160 ns
  - **3.6×10^{13} POT** = 20000 e+/bunch × 2 × 3×10^7s x 0.6 x 49 Hz
- Possible extension of the mass range (< 32 MeV) increasing beam energy < 1 GeV

PADME REACH FROM DESIGN

arXiv:1403.3041

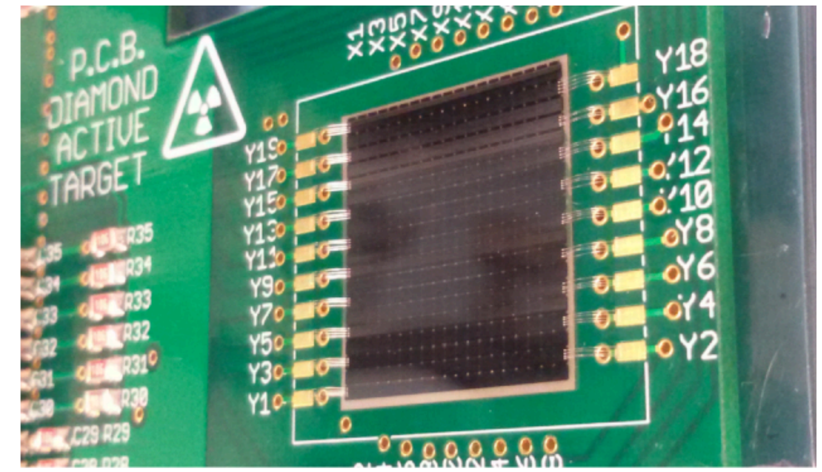


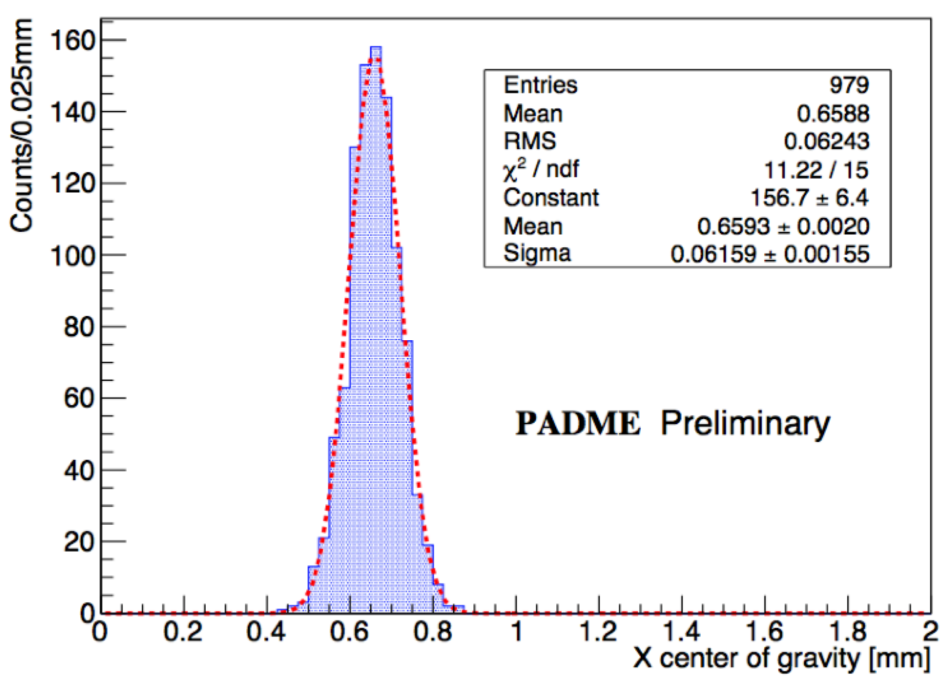
(M. Campajola) @this conference

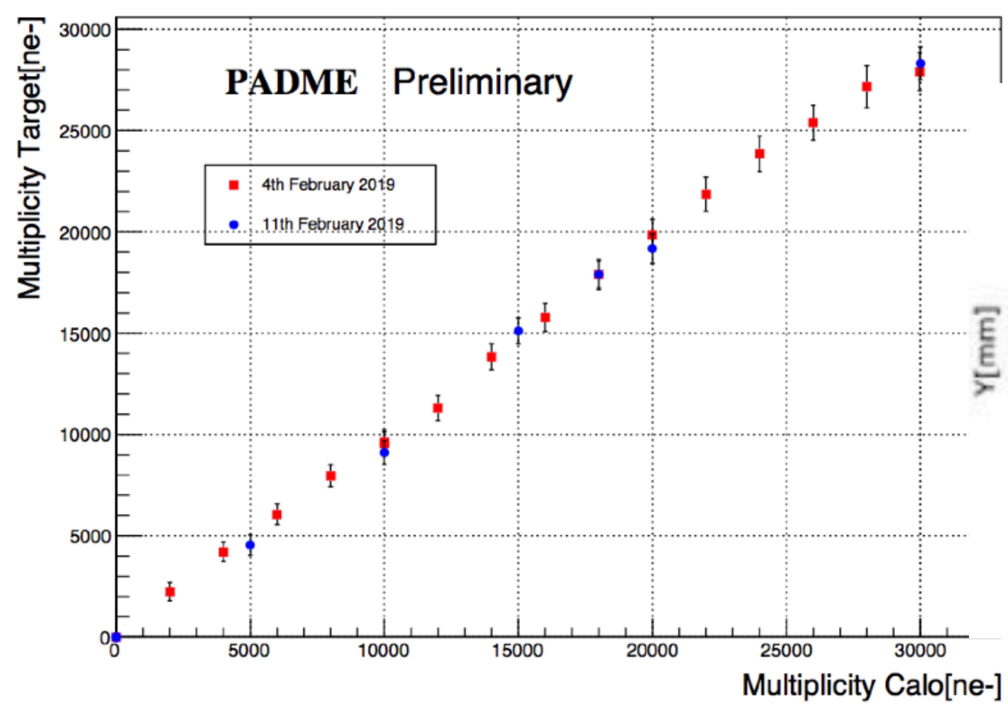


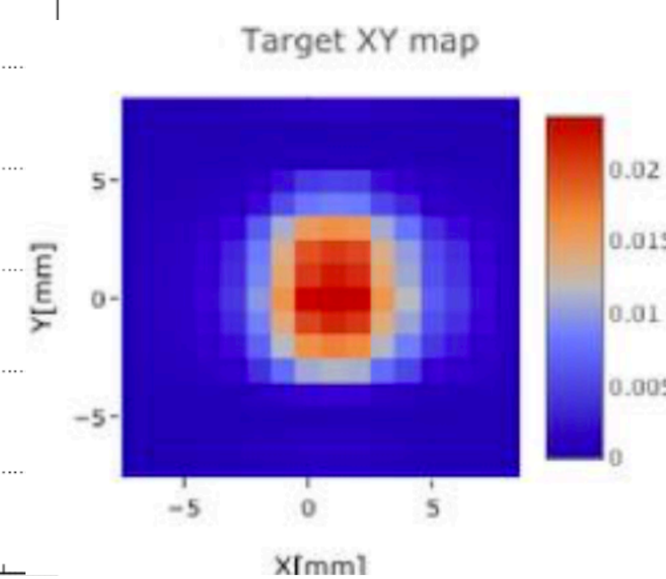
The Target

- ***The active diamond target***
- CVD (Chemical Vapor Deposition) 20 × 20 × 0.1 mm³ polycrystalline diamond; 16+16 graphitic strips (x and y), 1 mm pitch
  - measures the number of e+/bunch,
    good linearity with current FEE up to 15k e+/strip
  - measures/monitors beam profile and charge centroid in two views with 60 μm resolution << required precision









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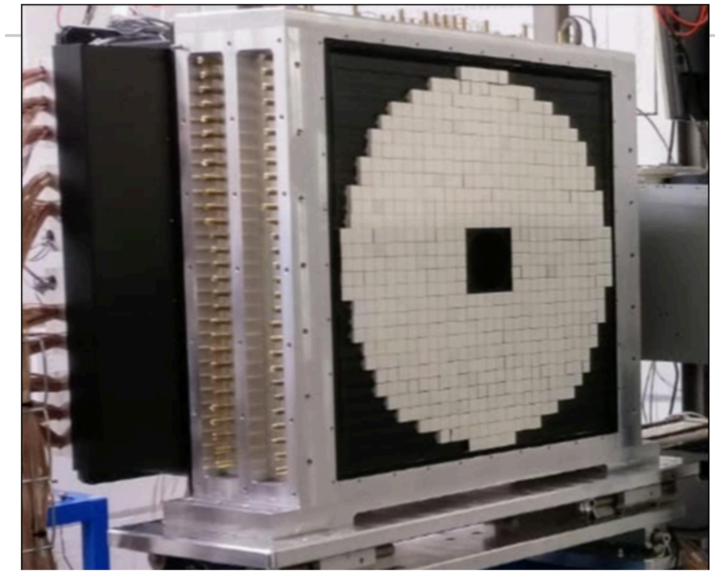
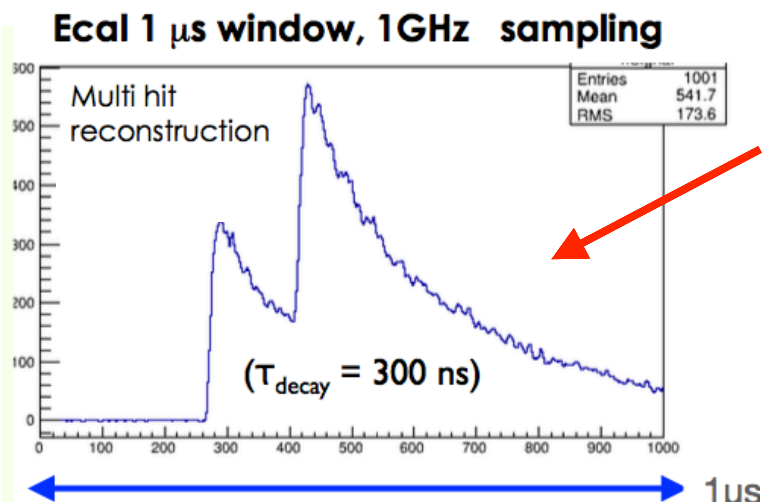
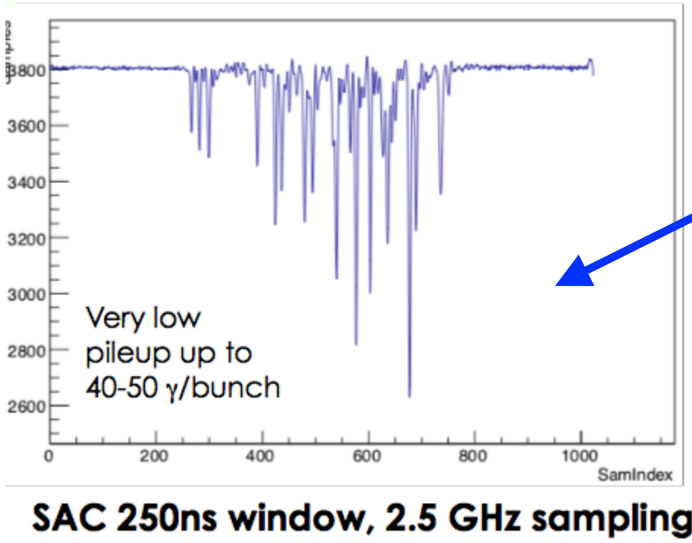
NIM A 958, 1 April 2020, 162354

THE CALORIMETERS







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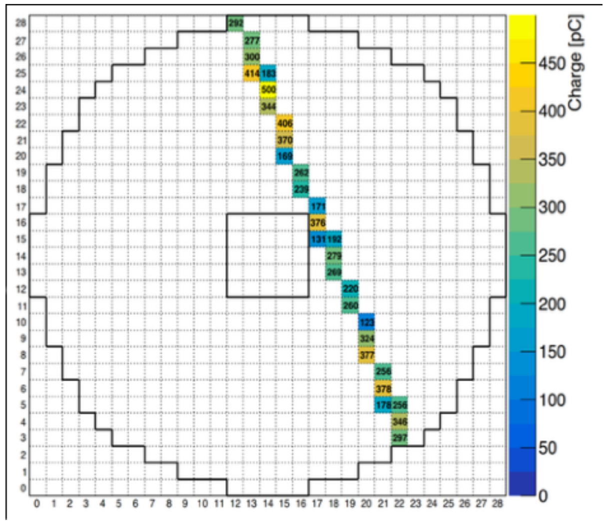
***ECAL* - High resolution Electromagnetic Calorimeter**

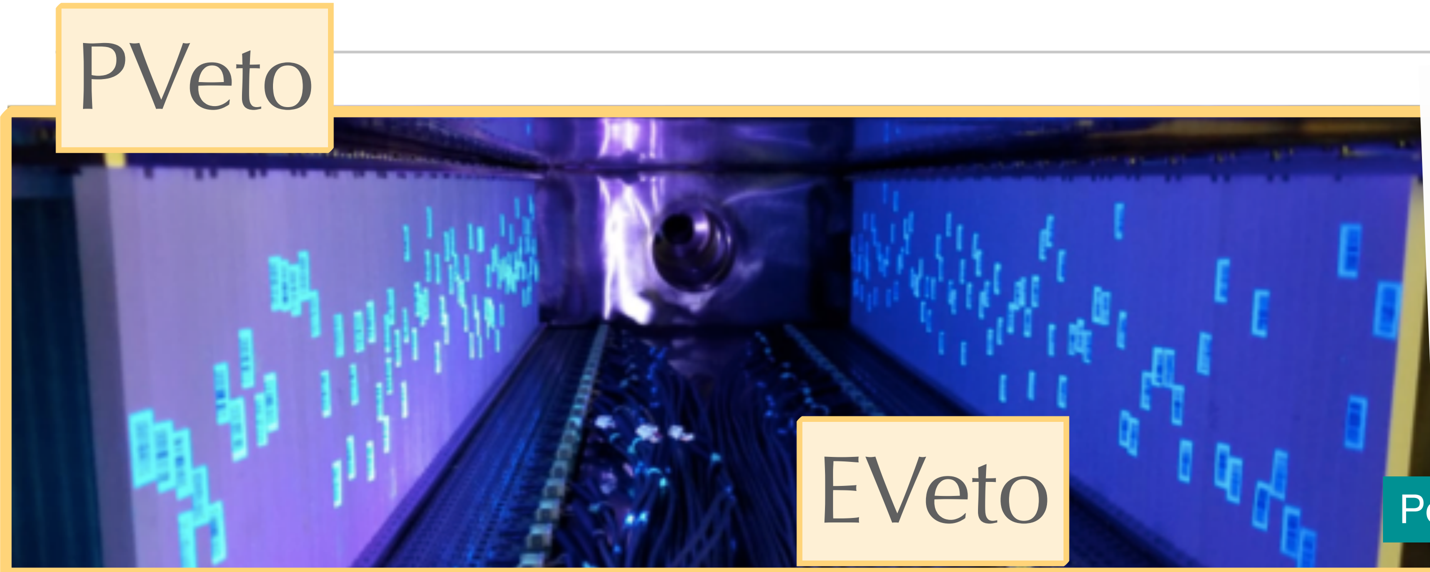
- 616 scintillating BGO crystals 21×21×230 mm³ PMT readout
- radius ~30 cm, 3.45 m distance form the the target
- central hole 105×105 mm² for SAC
- angular coverage 15 ÷ 84 mrad
- calibrated with cosmic rays during data taking
- energy threshold = 0.5 MeV
- LY vs Temperature = -0.9%/°C

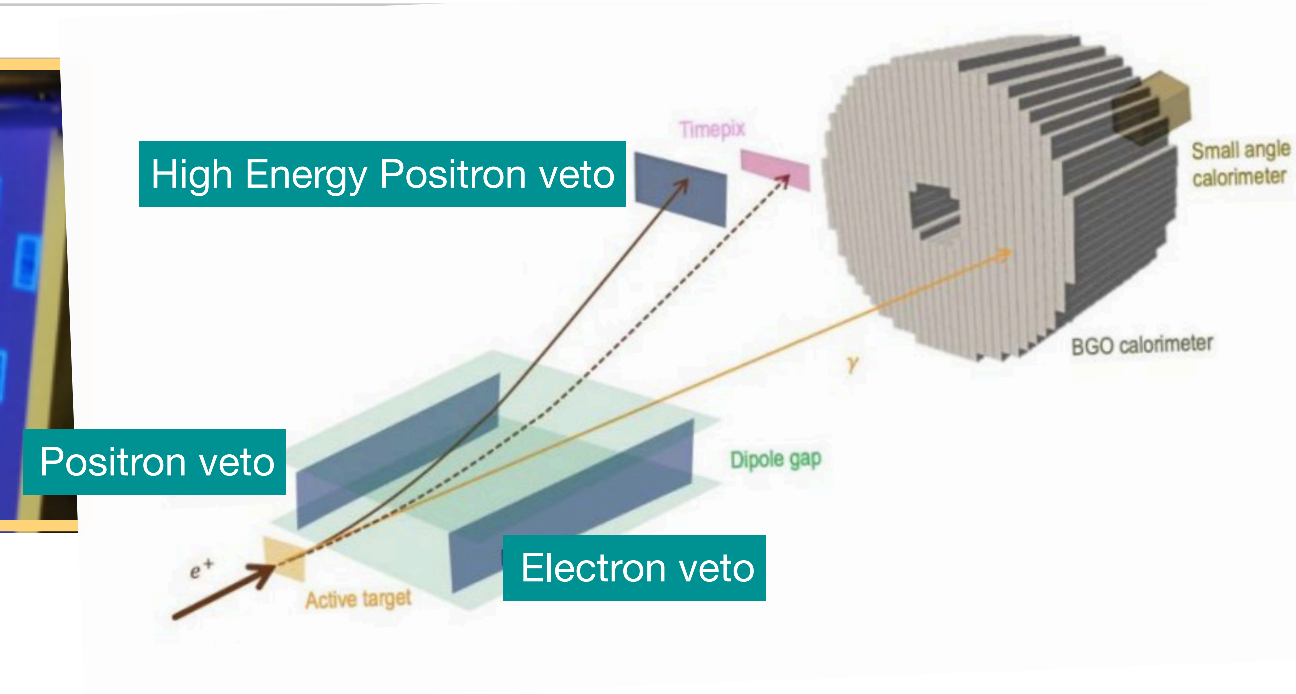


***SAC* – Small Angle Calorimeter**

- 25 Cherenkov PbF2 crystals 30×30×140 mm³
- PMT readout
- 50 cm behind ECAL
- angular coverage 0 ÷ 19 mrad
- 86 ps time resolution

VETOS AND DAQ





- Plastic scintillator bars 10×10×200 mm^3
- 3 arrays for a total of 208 channels

DAQ/Offline

VME digitizers CAEN V1742

- 1-5 Gs/s sampling speed
- 12bit ADC signal range
- ~1000 channels

Data throughput: ~ 900 KB/bunch