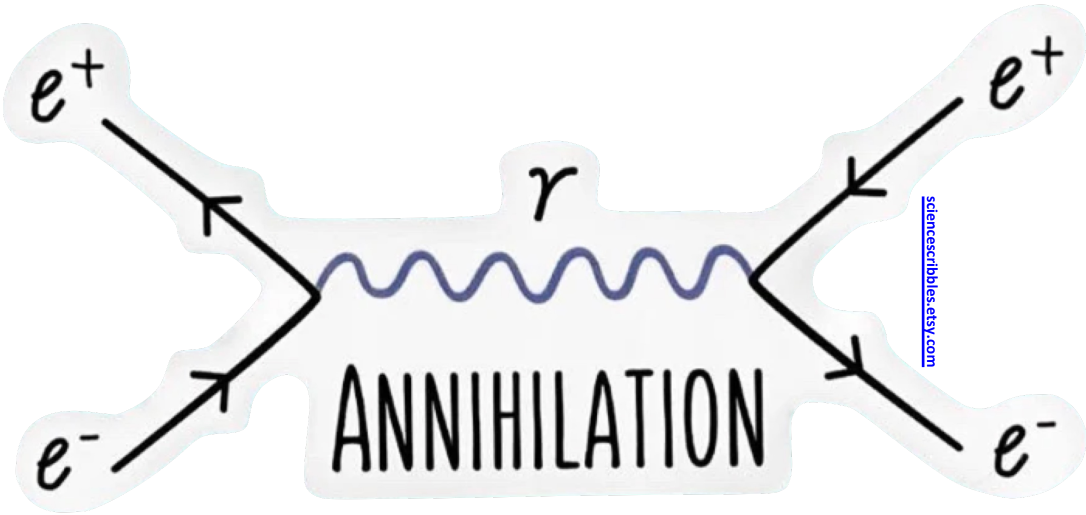
# Bhabha, dark matter and the comb

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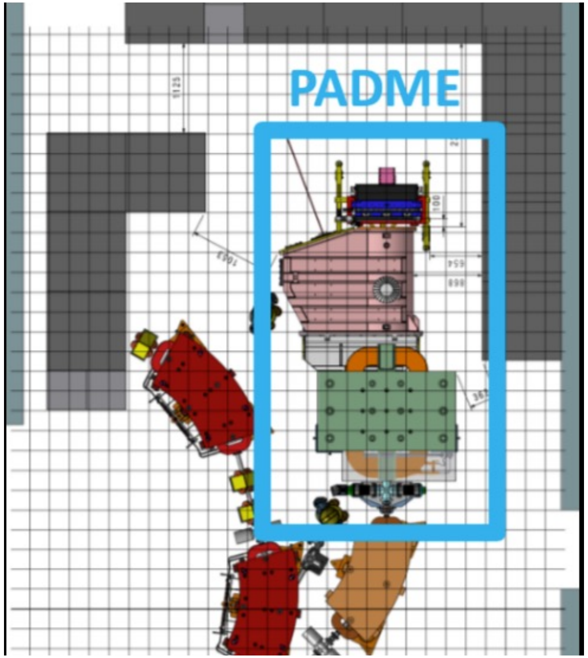
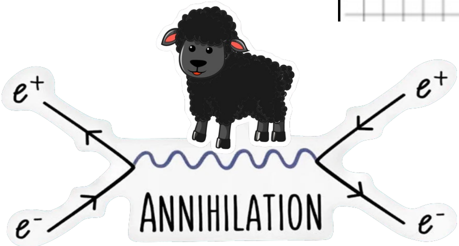
# Outline

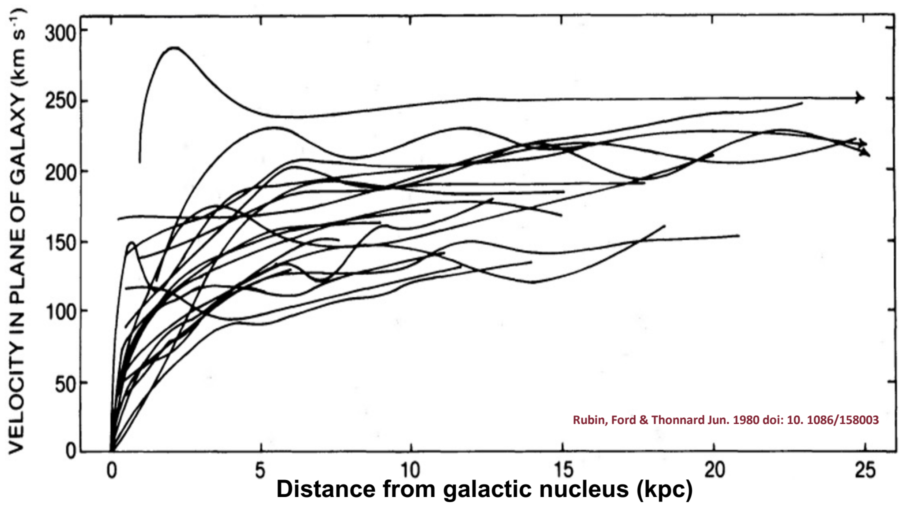
- What is dark matter?
- Dark sectors & the SM
- The PADME experiment
- The X17 anomaly
- X17 at PADME
- My analysis
- Results and implications



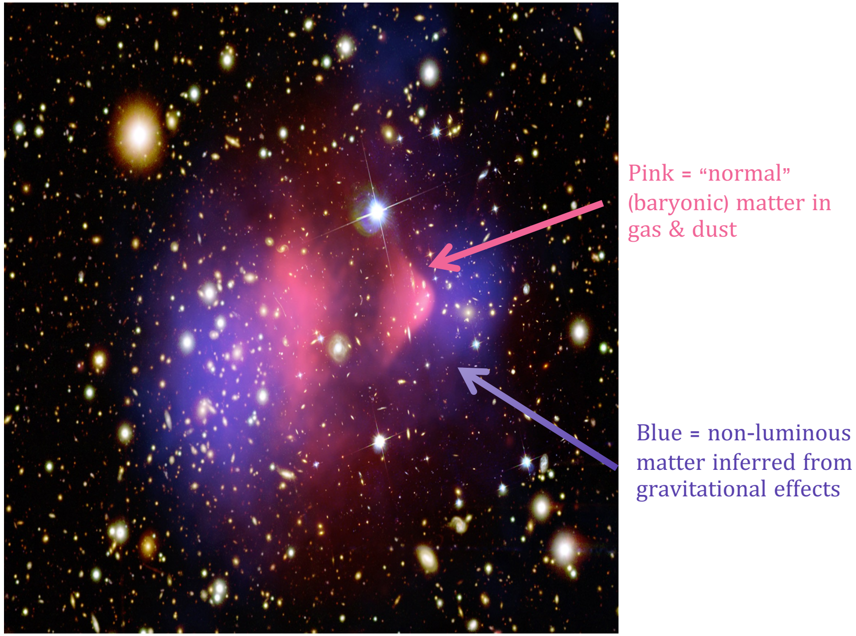




# The dark matter problem

- In 1930s studies of galaxy clusters Zwicky found **no clear mapping** between angular velocity and mass
- By the 1980s there was a large body of evidence showing the same effect



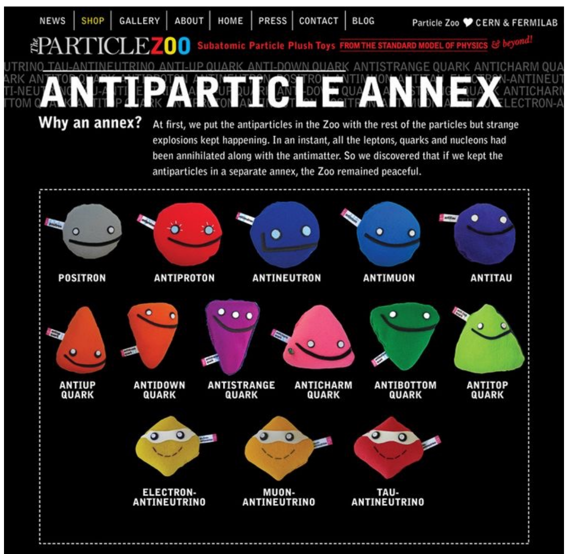

- Gravitational lensing shows that dark matter has a **low self-interaction cross section**




X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

# A particle physicist's reasoning

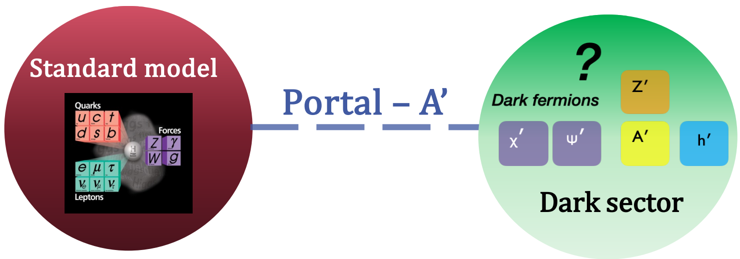
- The standard model works really well!
- Everything (that matters) is particles
- What if dark matter is particles too?

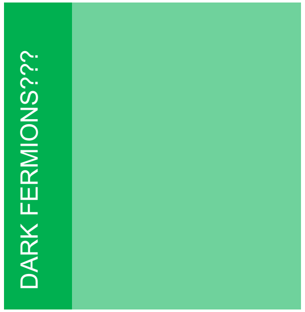



DARK FERMIONS???

# The dark sector

- Assume dark matter exists in secluded "dark sector"
- Interacts with standard model only through exchange of massive "portal particle"
- If the particle has spin 1, it's known as "**dark photon**" - "$A'/X/\cdots$"
- SM-$A'$ coupling $\epsilon \ll 1 \Rightarrow$ hidden

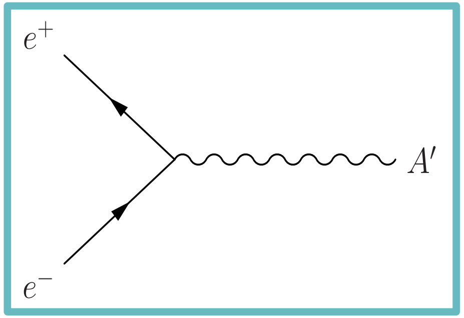


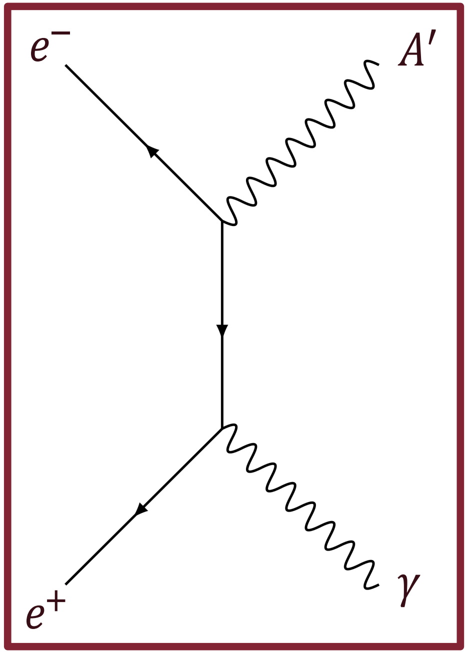




# PADME production mechanisms

**Production:** **Positron Annihilation**
**Centre of mass energy $\sqrt{s} \approx 20$ MeV**

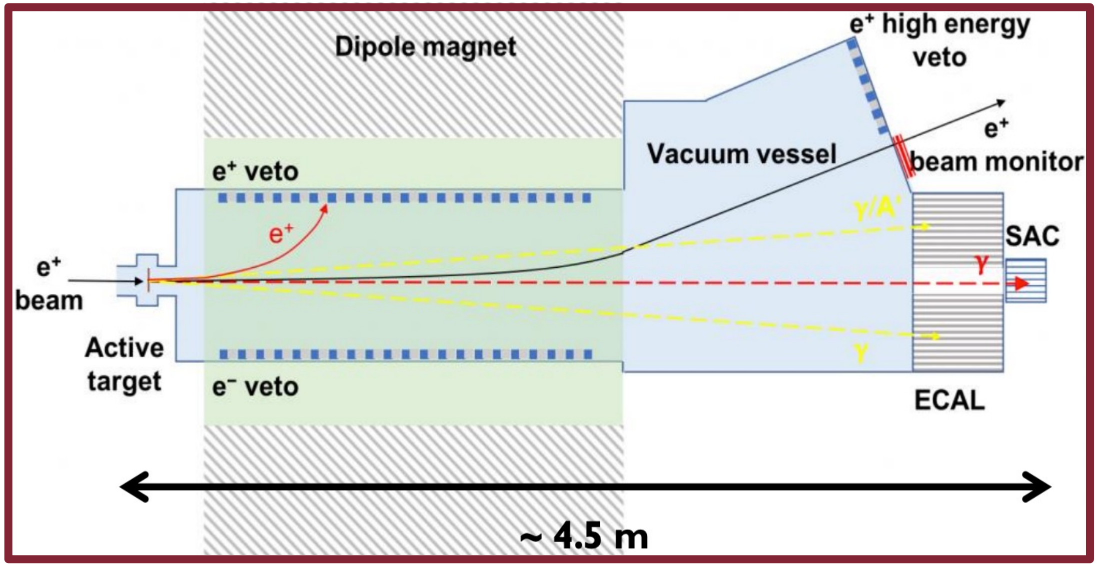
- Vector portal production at PADME:
  - **Resonant annihilation:**
    $e^+e^- \rightarrow A'$
    → Increased production when $\sqrt{s} \approx M_{A'}$
    → Only useful if you know $M_{A'}$
  - **Associated production:**
    $e^+e^- \rightarrow \gamma A'$
    → Nominal process in PADME Runs 1 & 2
    → Useful if you don't know $M_{A'}$

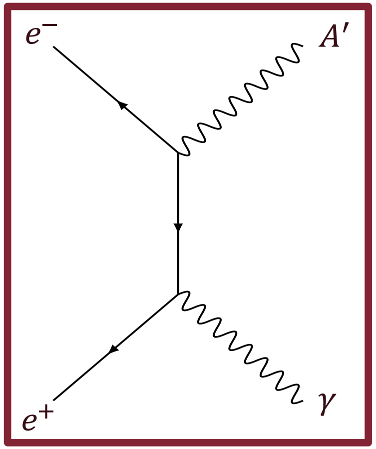


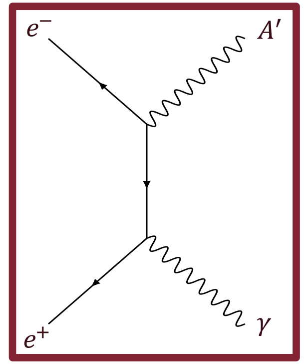
# PADME setup: Runs 1 and 2

- 100 $\mu$m Active diamond **Target** luminosity monitor
- **Nominal A' signal**: 1 $\gamma$ in BGO Electromagnetic Calorimeter (ECal) & nothing elsewhere

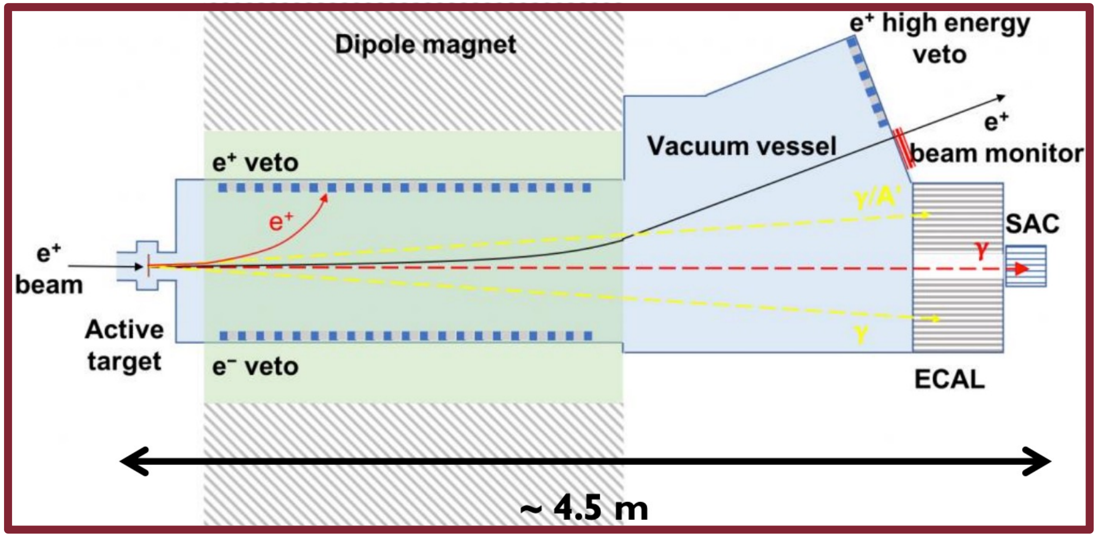


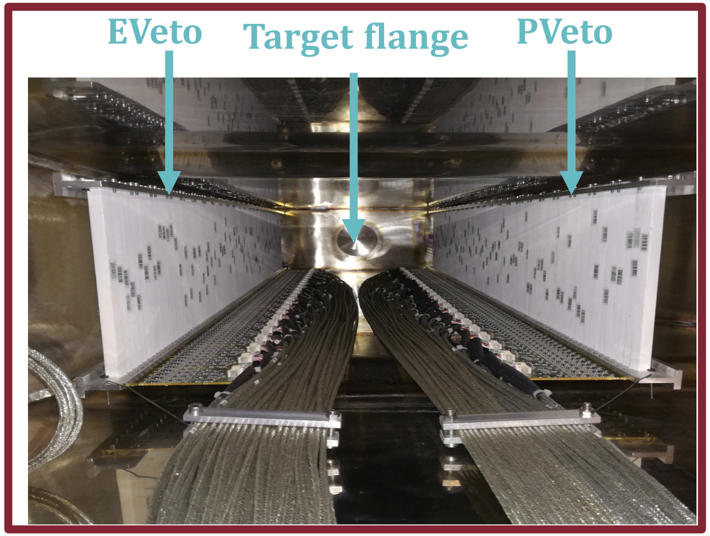



# PADME setup: Runs 1 and 2



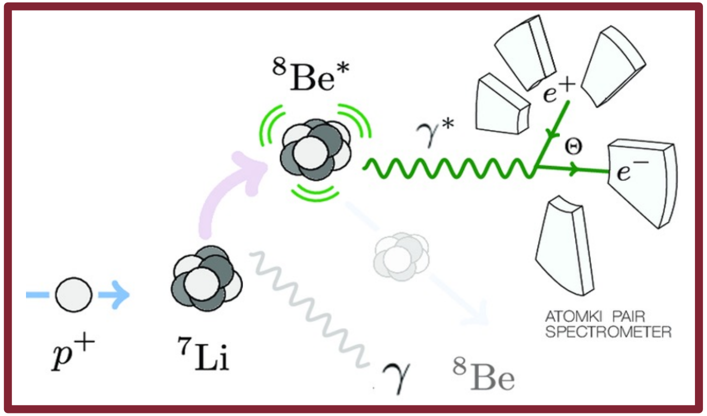

- Main background **Bremsstrahlung** avoided by:
  - Plastic scintillator bars as **charged particle vetoes**, in combination with SAC
  - **Symmetrical bars**, numbered 0-96 from target to ECal



# The ATOMKI anomaly: 2016 - 2022

- Collaboration at ATOMKI institute in Hungary studying IPC decays of excited $^8$Be (2016)/$^4$He (2020)/ $^{12}$C (2022) nuclei
- Found anomaly compatible with new particle of 17 MeV mass

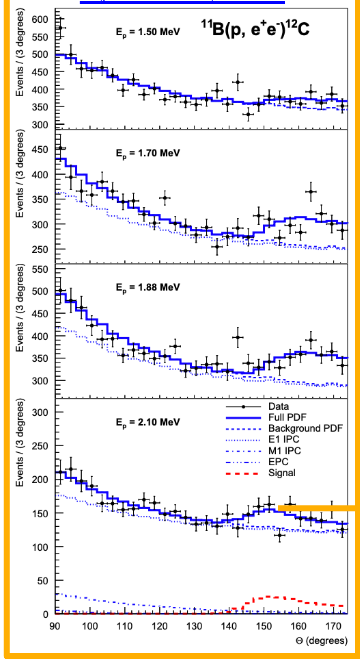


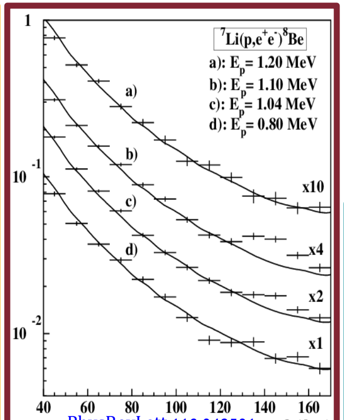

$m_X c^2 = 17.01 \pm 0.16(\text{tot})$ MeV

$m_X c^2 = 17.03 \pm 0.11(\text{stat}) \pm 0.20(\text{syst})$ MeV

$m_X c^2 = 16.98 \pm 0.16(\text{stat}) \pm 0.20(\text{syst})$ MeV

Phys. Rev. C 106, L061601

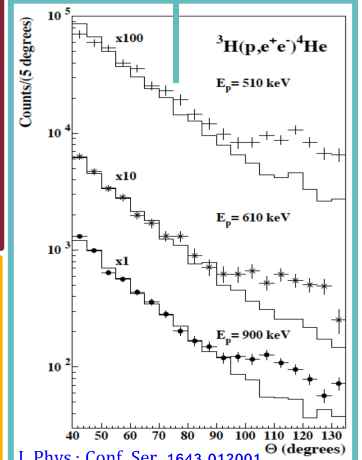



PhysRevLett.116.042501

| E$_p$ (MeV) | B$_x$ $\times10^{-6}$ | Mass (MeV/c$^2$) | Confidence |
|---|---|---|---|
| 1.50 | 1.1(6) | 16.81(15) | 3σ |
| 1.70 | 3.3(7) | 16.93(8) | 7σ |
| 1.88 | 3.9(7) | 17.13(10) | 8σ |
| 2.10 | 4.9(21) | 17.06(10) | 3σ |
| Averages | 3.6(3) | 17.03(11) | |
| Previous [14] | 5.8 | 16.70(30) | |
| Previous [28] | 5.1 | 16.94(12) | |
| Predicted [30] | 3.0 | | |

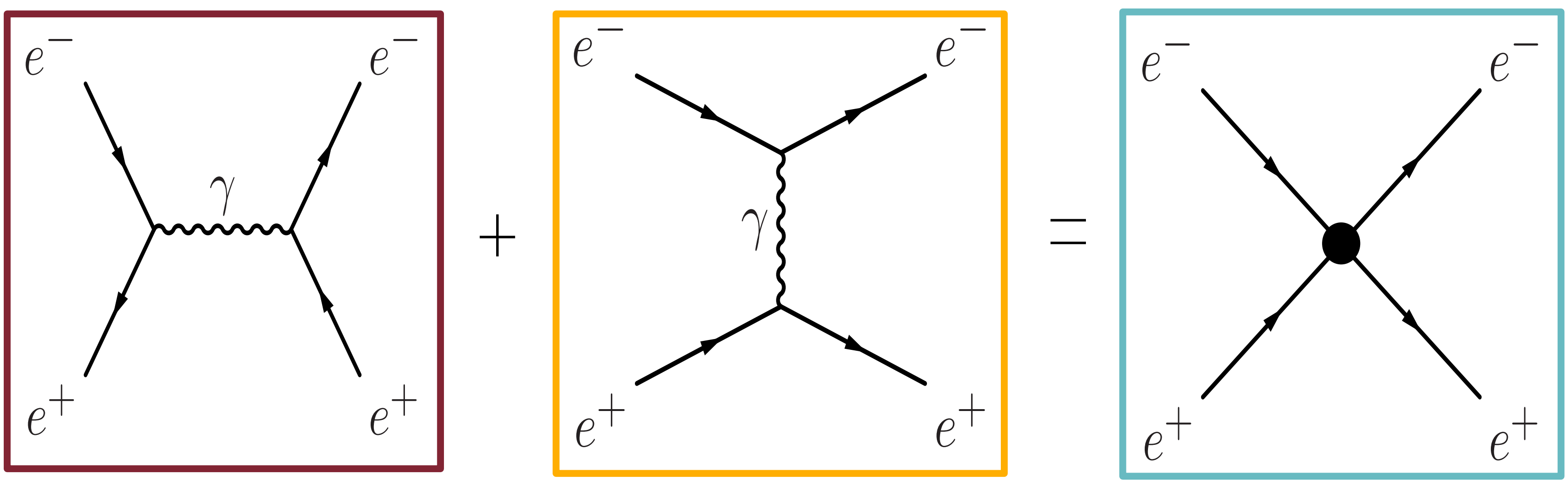
| E$_p$ (keV) | IPCC $\times10^{-4}$ | B$_x$ $\times10^{-6}$ | Mass (MeV/c$^2$) | Confidence |
|---|---|---|---|---|
| 510 | 2.5(3) | 6.2(7) | 17.01(12) | 7.3σ |
| 610 | 1.0(7) | 4.1(6) | 16.88(16) | 6.6σ |
| 900 | 1.1(11) | 6.5(20) | 16.68(30) | 8.9σ |
| Averages | | 5.1(13) | 16.94(12) | |
| $^8$Be values | | 6 | 16.70(35) | |




J. Phys.: Conf. Ser. 1643 012001

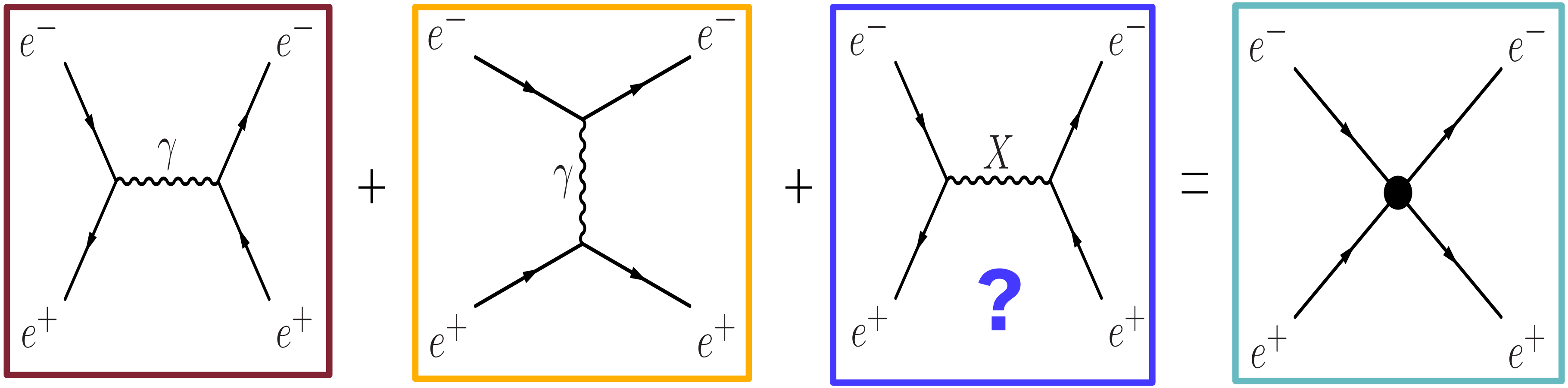
# X17 signal: Bhabha scattering

- If a new neutral boson X exists and decays to $e^+e^-$, must be producible in $e^+e^- \rightarrow X$
- In SM, $e^+e^- \rightarrow e^+e^-$ is known as Bhabha scattering
- Two SM channels: **S-channel** and **T-channel**



# X17 production

- Production cross section is non-negligible only around $\sqrt{s} = M_X$
  - Kinematic profile for $e^+ e^- \to X \to e^+ e^-$ identical to that of S-channel Bhabha scattering
- Expect increased N($e^+ e^- \to e^+ e^-$)

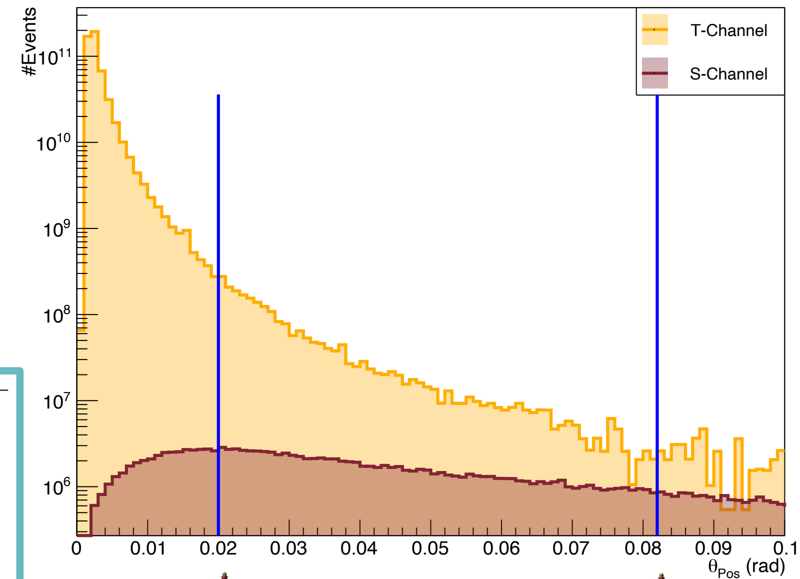


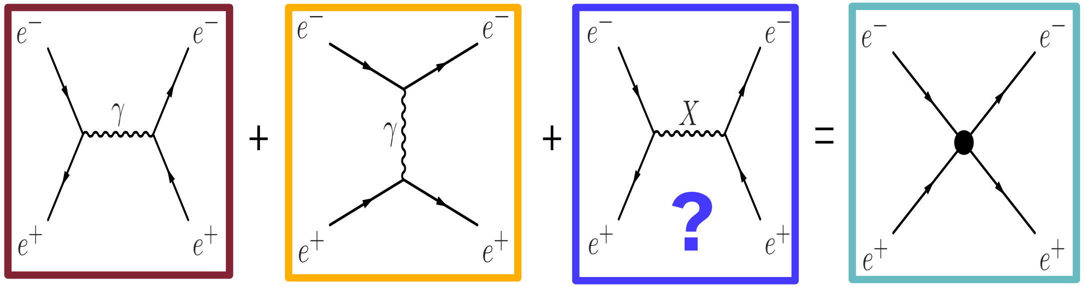
# Bhabha scattering: Inclusive of Dark Sectors

- Cross section should be big enough to observe at PADME
  - ~ 1000 X17 producible per $10^{10}$ PoT (24 hours in Run 3)
- Fixed target ⇒ strong cut on T-Channel Bhabha
  - (Doing this measurement at a collider would be really hard!!!)
- Thus a thesis was born!

$$\mathcal{N}_{X_{17}}^{\text{Vect.}} \simeq 1.8 \cdot 10^{-7} \times \left(\frac{g_{ve}}{2 \cdot 10^{-4}}\right)^2 \left(\frac{1\ \text{MeV}}{\sigma_E}\right)$$

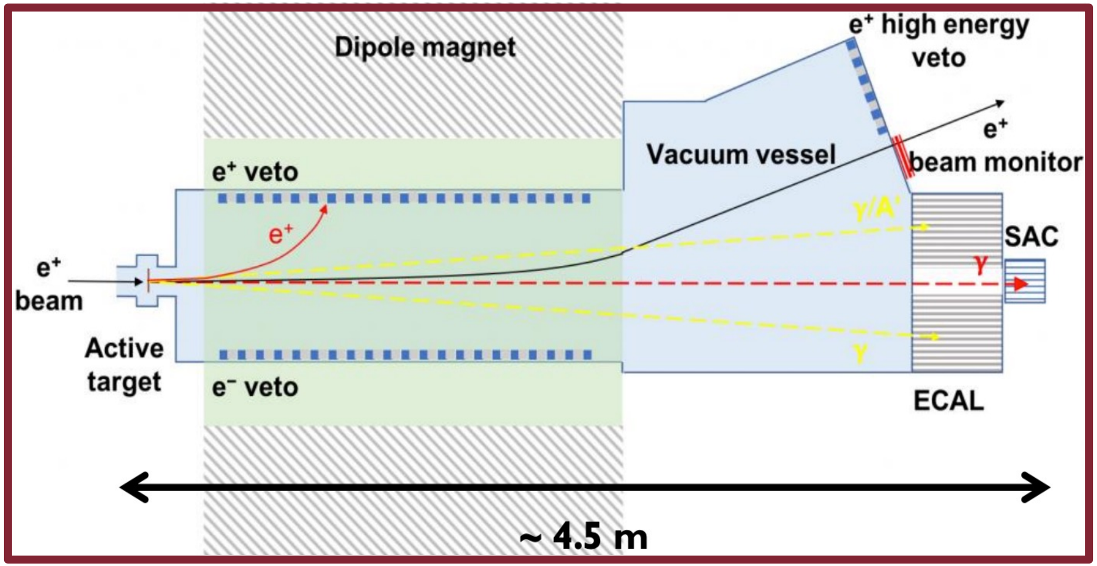
L. Darmé et al Phys.Rev.D 106 (2022) 11, 115036 10.1103/PhysRevD.106.115036



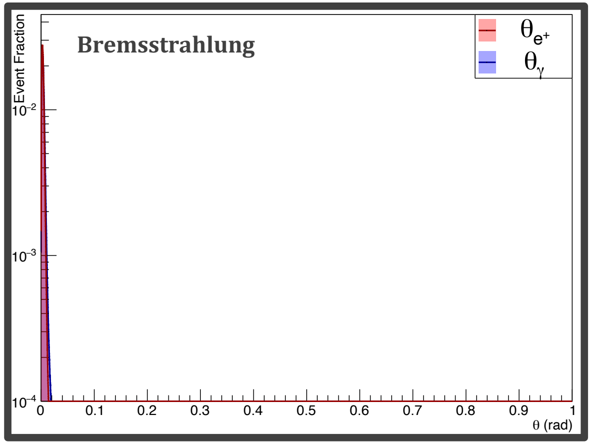

# Bhabha at PADME

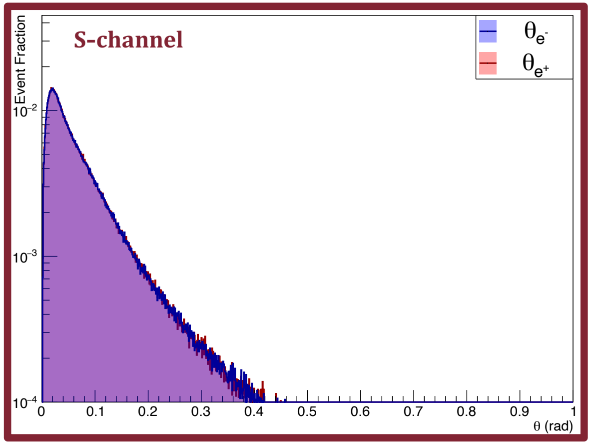
- Charged particle final states -> use charged particle detectors == vetoes

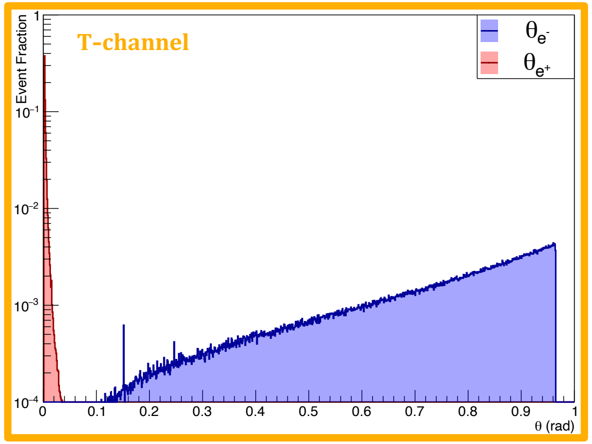


# Bhabha at PADME

- Charged particle final states -> use charged particle detectors
- Vetoes designed to detect Bremsstrahlung positrons
- Bhabha kinematics ≠ Bremsstrahlung kinematics

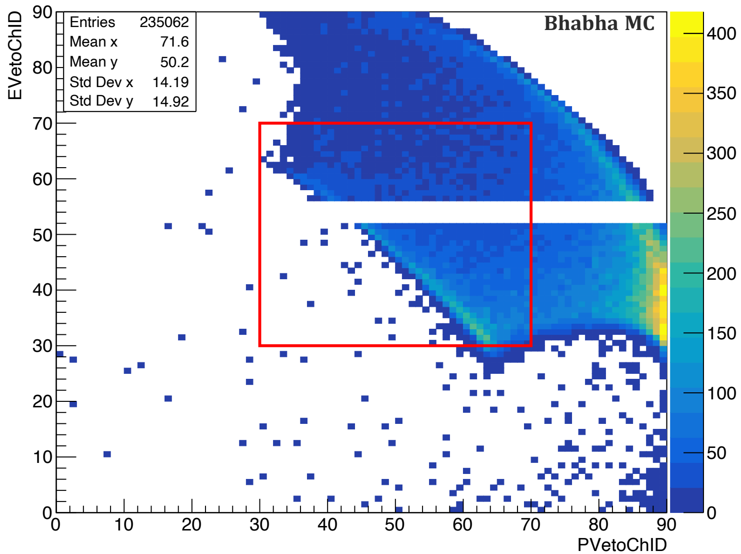


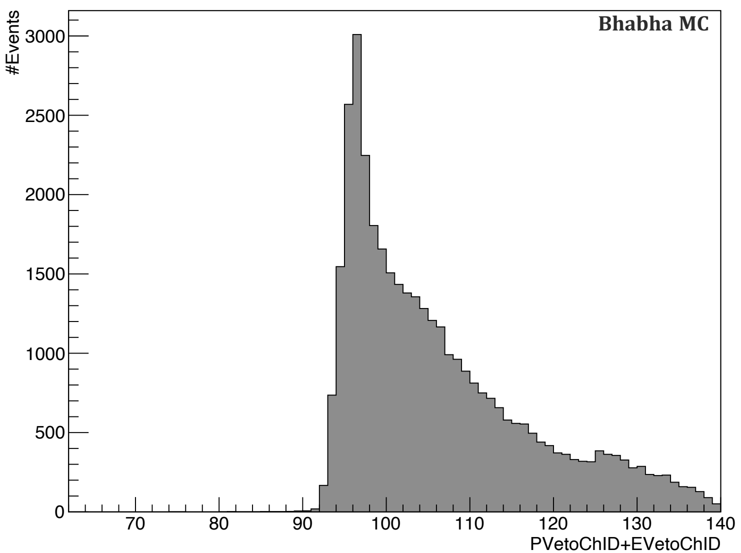



# Bhabha topology

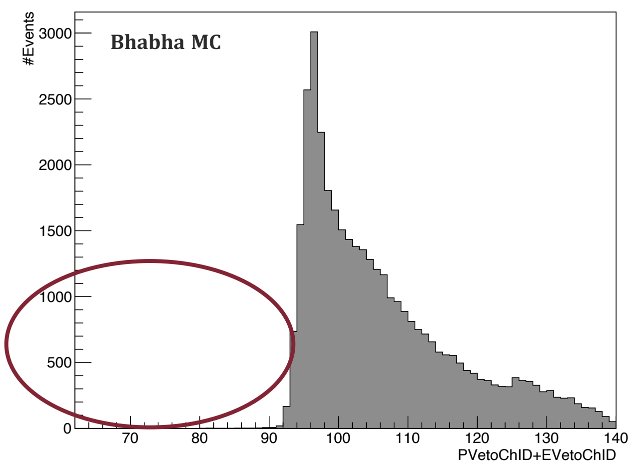
- Bhabha kinematics ≠ Bremsstrahlung kinematics
- Looking at Bhabha topology, select based on ChID sum

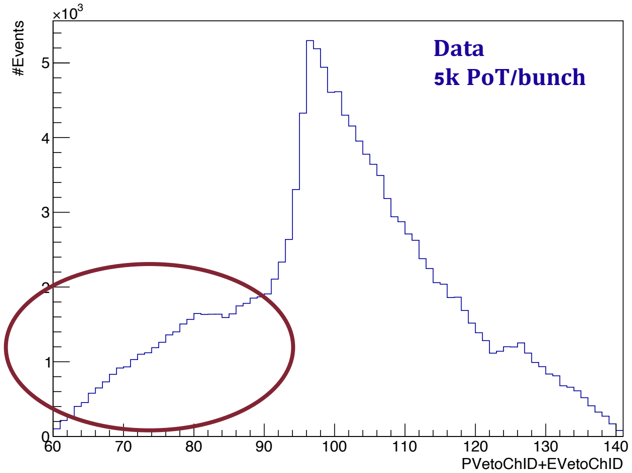


# Bhabha signal

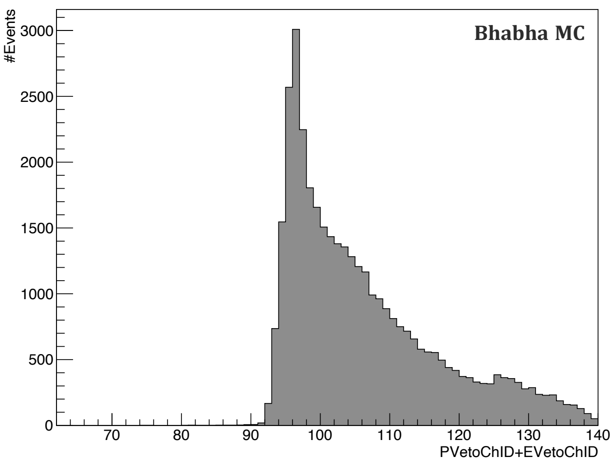
- Select events with cluster in each Veto within 5 ns
- Events with **ChaSum** $= (PVetoChID + EVetoChID) < 90$ are combinatorial background

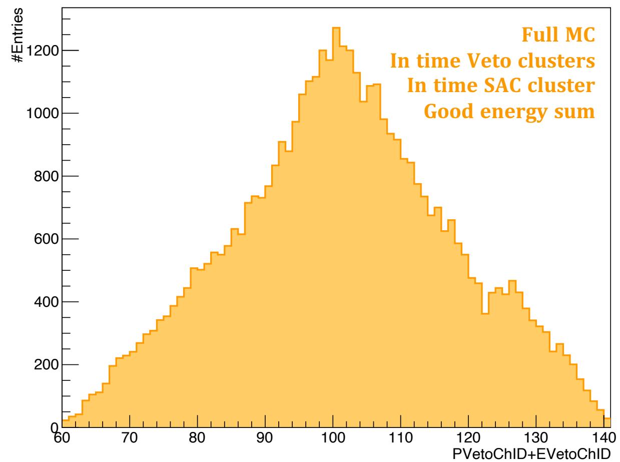


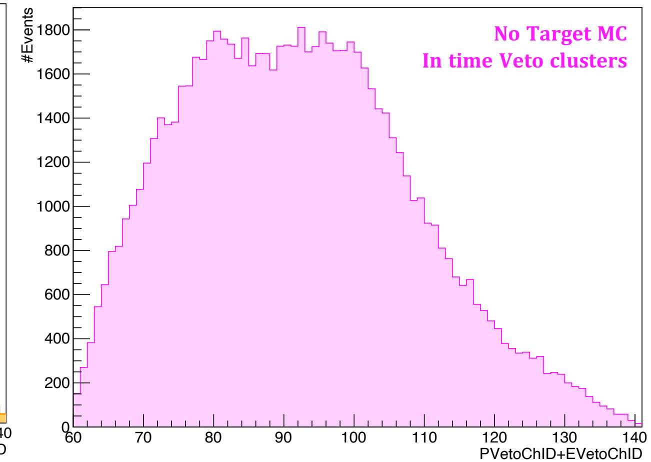



# Backgrounds to Bhabha

- Backgrounds:
  - **Bremsstrahlung**: $e^+$ from Bremsstrahlung with un-related in-time cluster in EVeto
    - → Search SAC for cluster **in time** with PVeto cluster
  - **Beam background**: particles not from Target which enter Vetoes
    - → Subtract **no-Target** data set



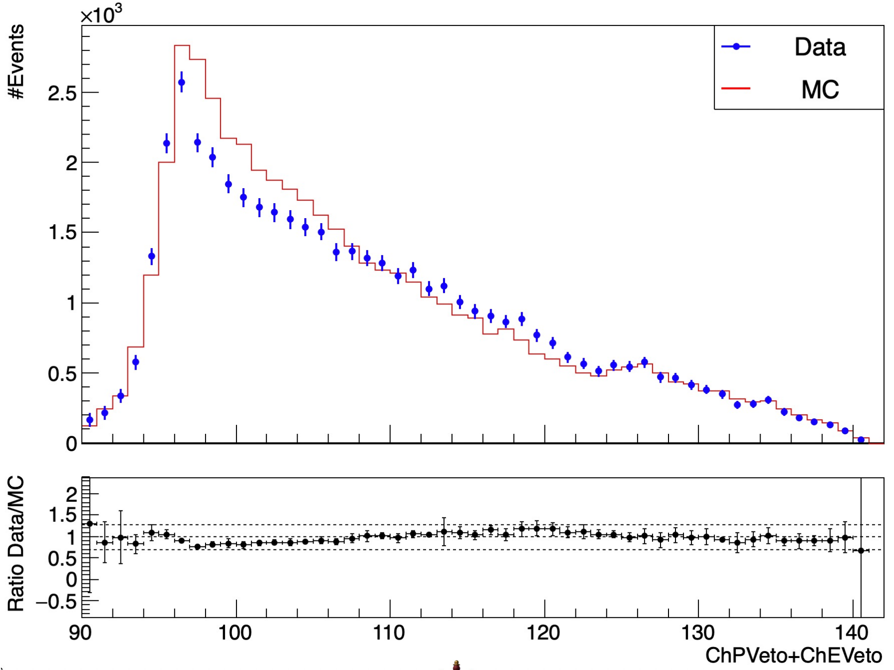



# Data-MC comparison

- Acceptance is calculated from MC
  - NSignals/NPoT
- Integrating ChaSum≥ 90:
  - **NSignals Data** = 46,148
  - **NSignals MC** = 48,240
- Cross section given by:

$$\sigma = \frac{NObs}{NPoT}\frac{1}{Acc}\frac{A_C}{N_A Z_C \rho d}\times 10^{36}\text{ pb}$$




- $NPoT = 1.03188\times10^{10}$
- $Acc = 0.0013$
- $A_C = 12$
- $N_A = 6.022\times10^{23}$
- $Z_C = 6$
- $\rho = 3.2 g/cm^3$
- $d = 0.0097\ cm$

**Data**

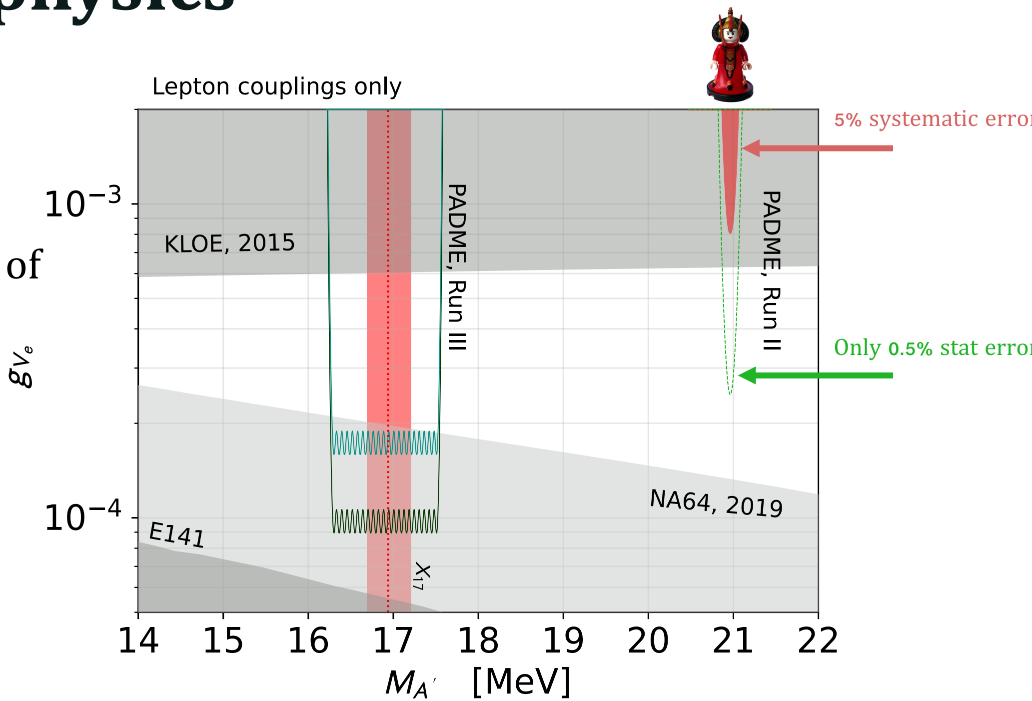
$$\sigma(e^+e^- \to e^+e^-) = (3.90 \pm 0.030_{stat} \pm 0.39_{sys}) \times 10^{11}\text{ pb}$$

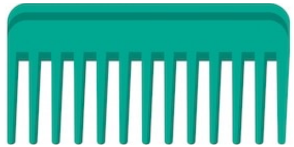
**Geant4**

$$\sigma(e^+e^- \to e^+e^-)_{G4} = (4.078 \pm 0.0288_{stat}) \times 10^{11}\text{ pb}$$

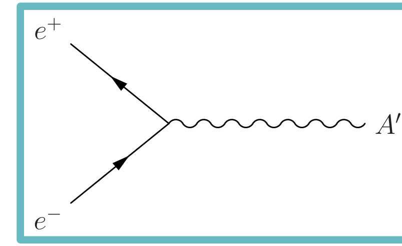
# Interpretation for new physics

- No excess ⇒ 90% exclusion limit
- To be competitive, total error on measurement needs to be O(1%)
- The difficulty of measuring NPoT & lack of invariant mass reconstruction led to modified setup for Run 3

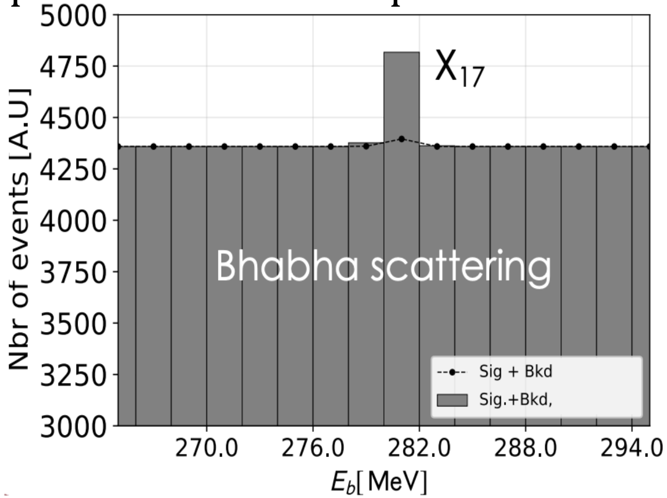


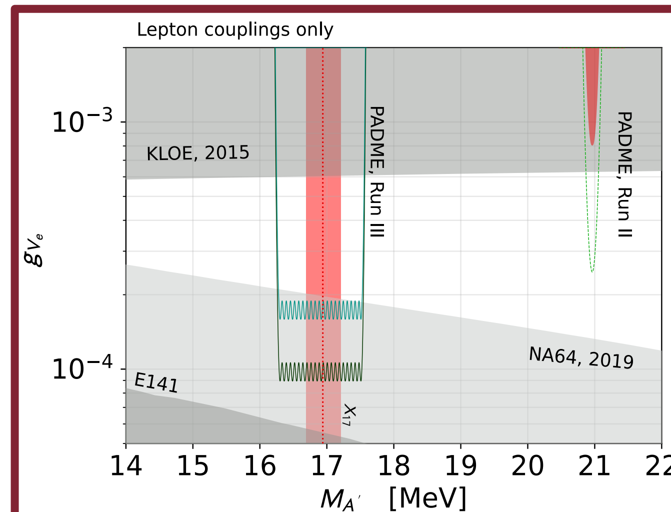



# PADME Run 3: the comb (energy scan)




- Production cross section increases very sharply at resonance - $\sqrt{s} \approx$ 17 MeV available only at Frascati!
- Scan $E_{beam} = 260\text{–}300$ MeV in steps of ~0.7 MeV
- Need only ~$10^{10}$ POT per point
- Signal should emerge on top of Bhabha BG in multiple bins around one point of the scan



# Conclusions

- PADME was designed to search for dark sectors, but has proved capable of performing SM measurements as well
- Bhabha cross section was successfully measured in agreement with the SM ✔
- Run 2 setup not optimised for X17 ❌
- ∴ Improved setup for Run 3, based partly on this work ✔

Thank you for listening…

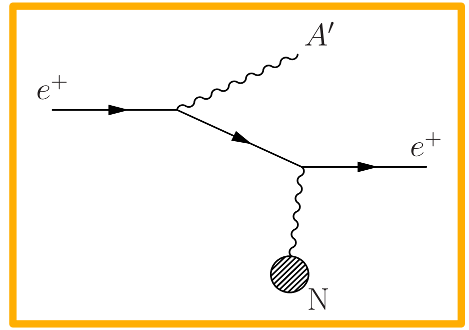
Let's turn on the dark!

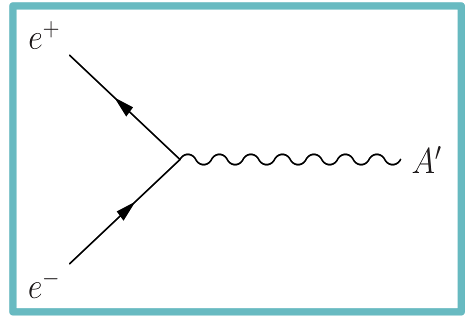
# PADME production mechanisms

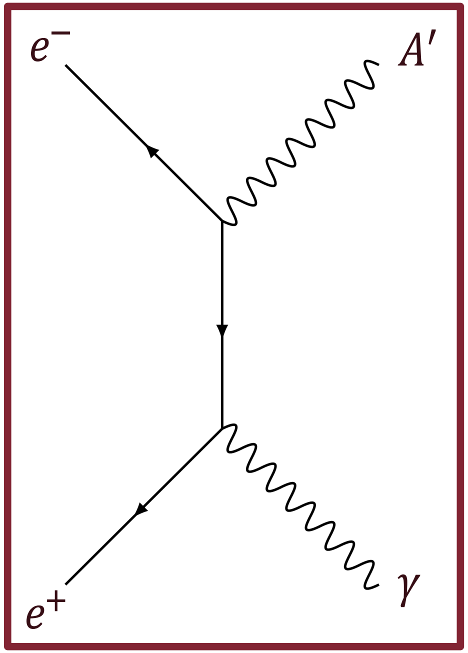
**Production:** **Positron Annihilation**

$\sqrt{s} \approx$ **20 MeV**

- Vector portal production at PADME:
  - ***A′*-strahlung**
  - **Resonant annihilation: $e^+e^- \to A'$**
  - **Associated production: $e^+e^- \to \gamma A'$**

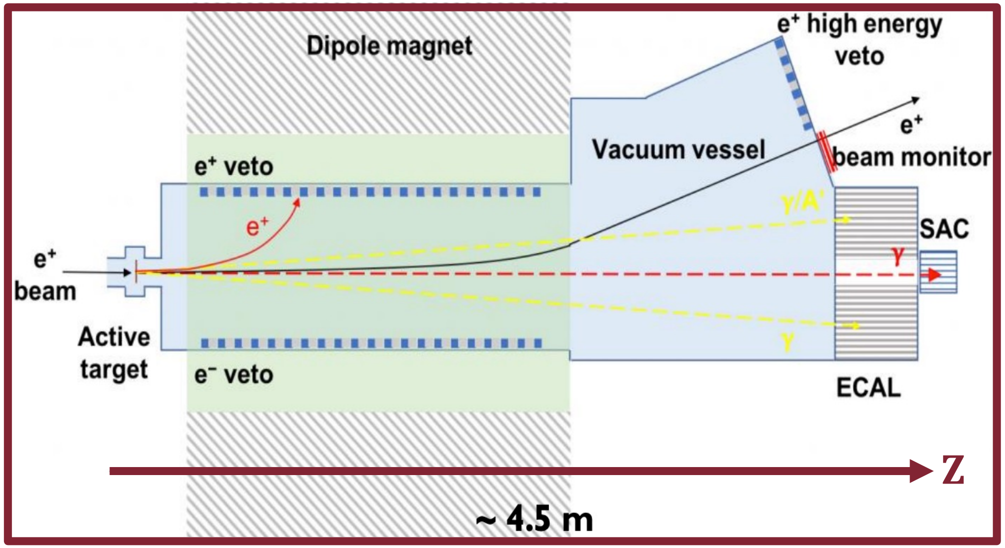


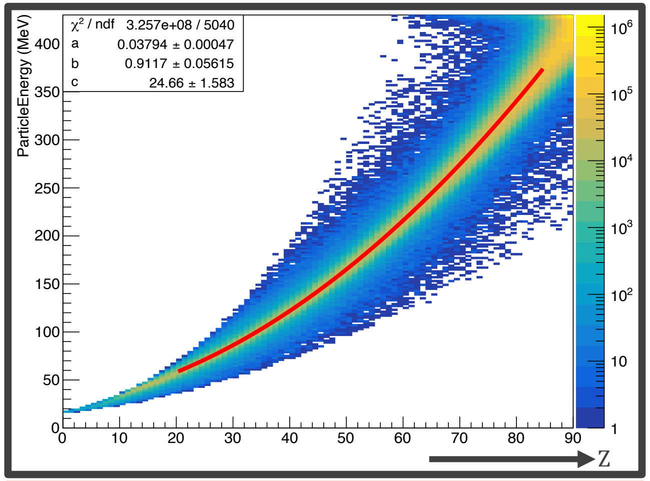



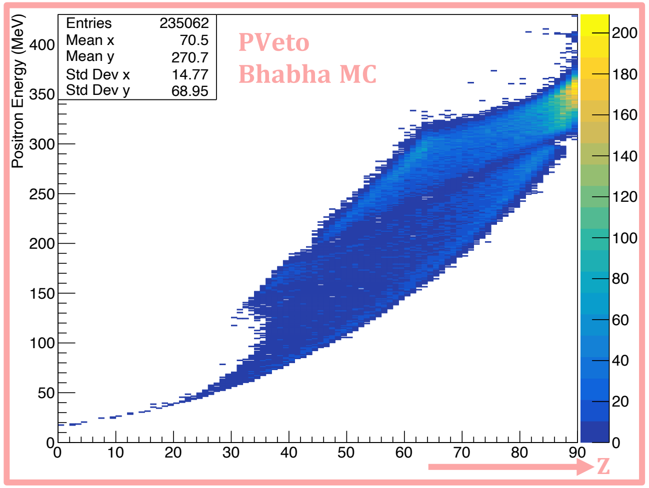



# Bhabha analysis

- Bhabha kinematics ≠ Bremsstrahlung kinematics
- ∴ no 1-1 relation between ChannelID and Bhabha particle energy & no way to select $E_{e^+} + E_{e^-} = E_{beam}$



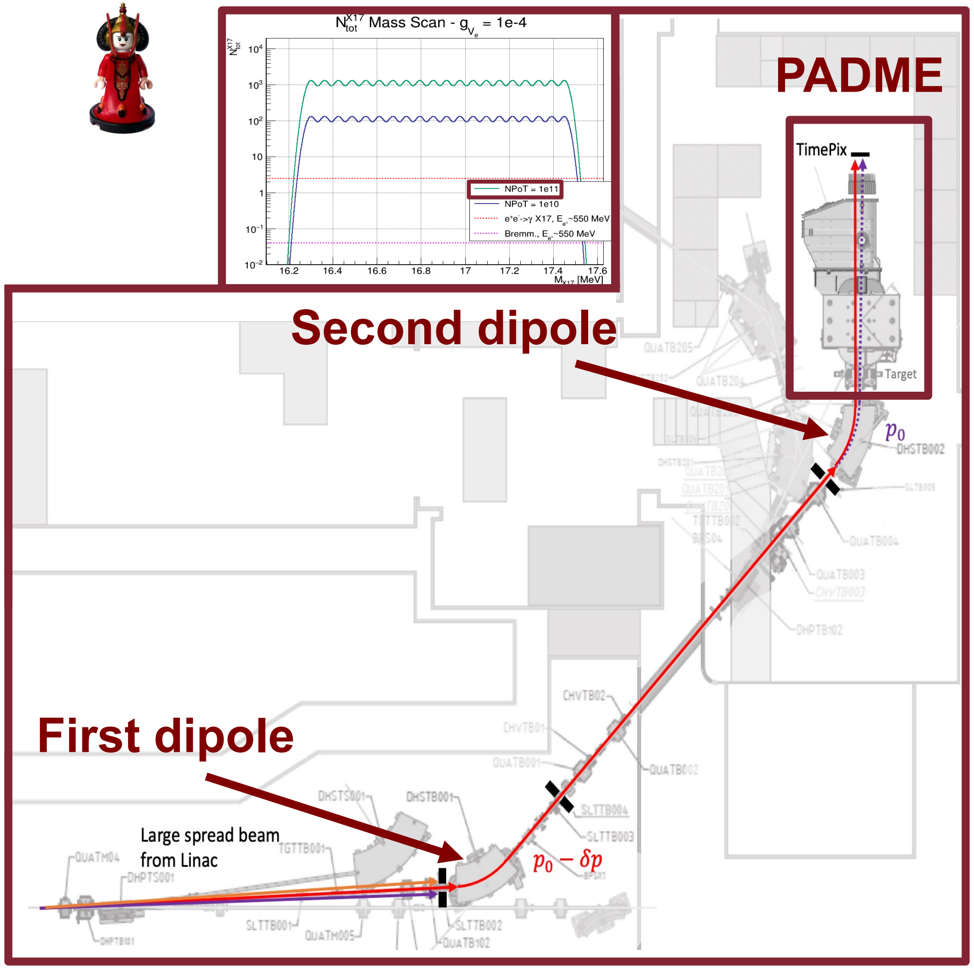



# Energy scan

- First dipole and collimators select energy
  - $dp \propto$ collimator aperture
- Correct the trajectory using second dipole to put the beam back on axis at PADME
- Closed collimators:

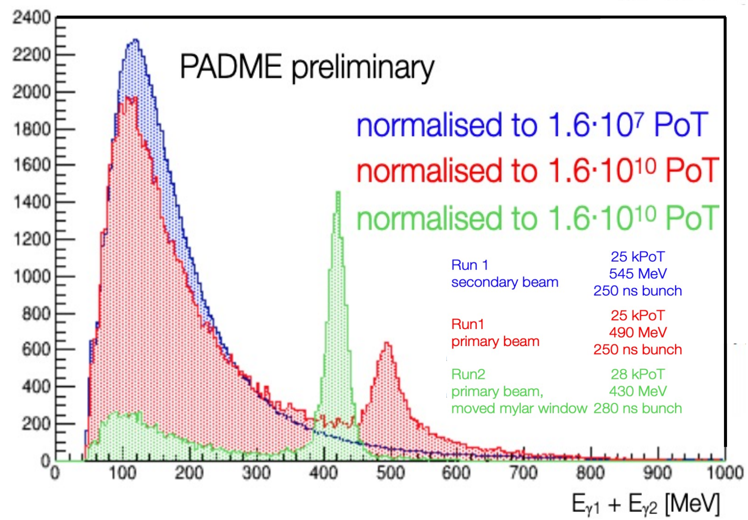
  -> low energy spread -> excellent invariant mass resolution

  -> low beam multiplicity -> low pileup -> excellent event separation



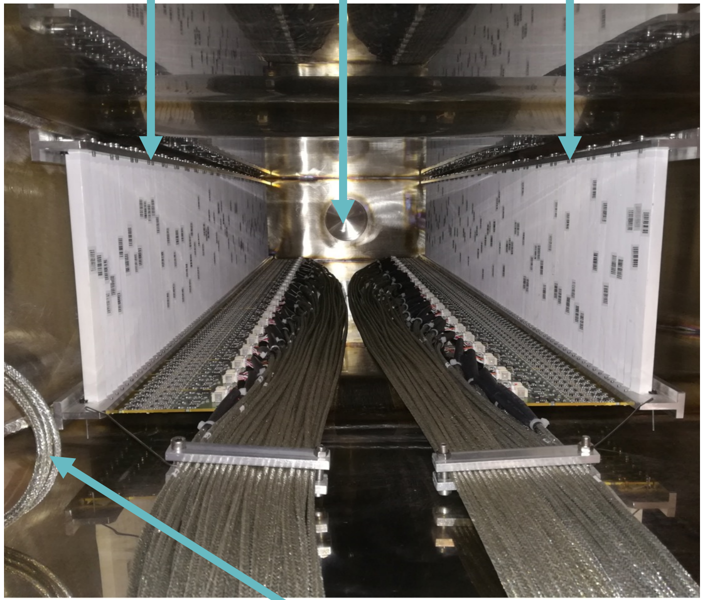
# Data Taking: Runs 1 and 2

- Two runs in three configurations between Sept. 2018 and Dec 2020
- Acquired luminosity > $10^{13}$ PoT
- Detailed MC simulation of beamline (JHEP 09 (2022), 233)
  → **Run 1a** → **Run 1b** → **Run 2:** beam improvements reduced pileup in detectors



# The Vetoes

- **Two sets** of 10×10×178 mm plastic scintillating bars:
  - In **Run 2:** 90 PVeto bars and 96 EVeto bars
  - **Between** Run 1 and Run 2, preamp boards of 4 central EVeto channels stopped working so were disconnected
- Detectors are inside vacuum chamber, inside 3.6 kGauss **B-field**
- Channels are numbered 0-89(95):
  - **channel 0** closest to Target
  - **channel 89(95)** closest to ECal
- Energy of Bremsstrahlung $e^+$ **increases** quadratically with channel number



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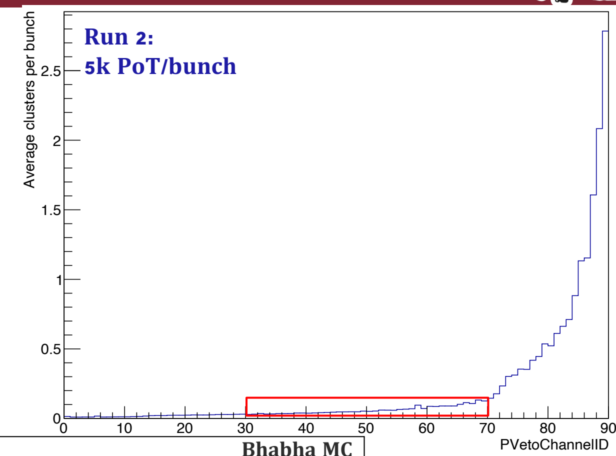
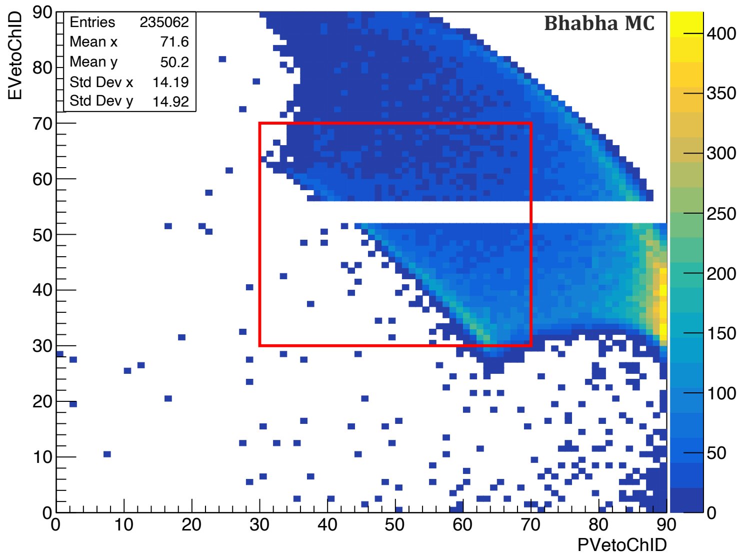
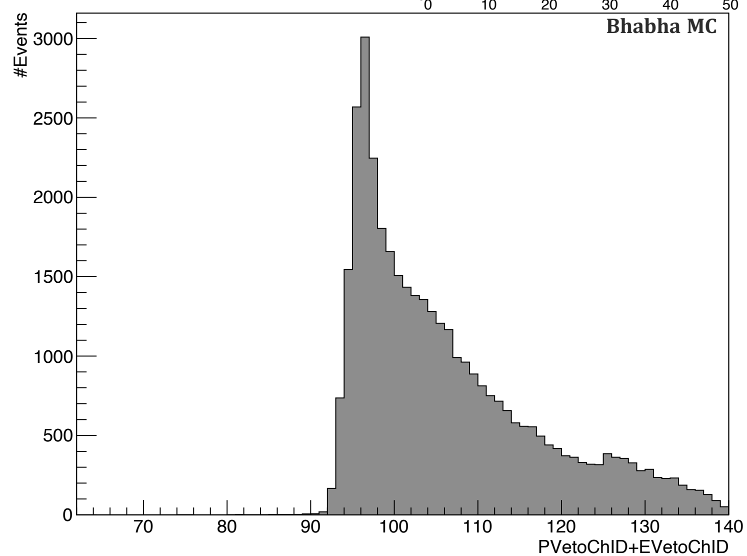
- ∴ no 1-1 relation between ChannelID and Bhabha particle energy & no way to select $E_{e^+} + E_{e^-} = E_{beam}$
- Looking at Bhabha topology, select based on ChID sum

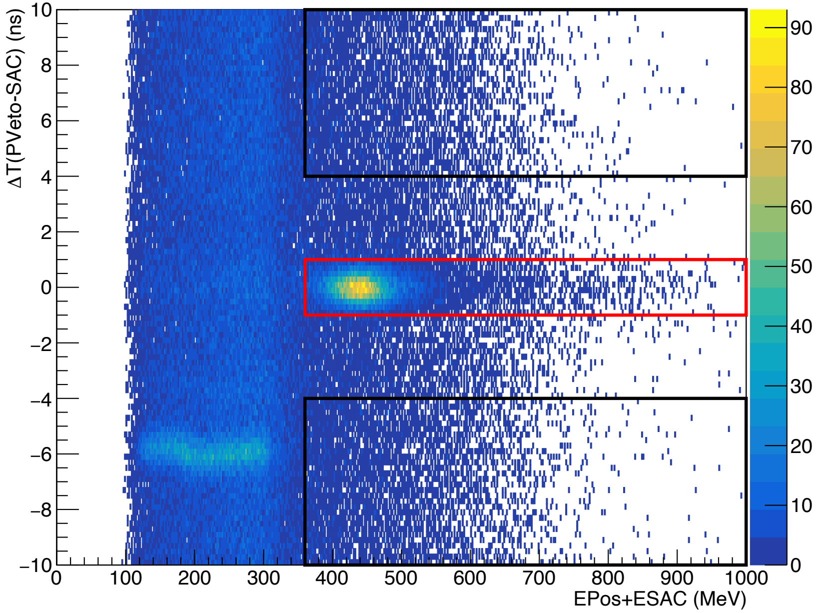


# Bremsstrahlung background

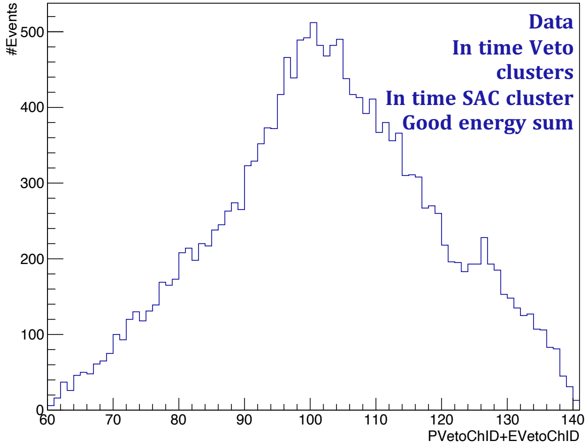
- **Bremsstrahlung** contains **beam background**
  - Subtract **time side-bands**

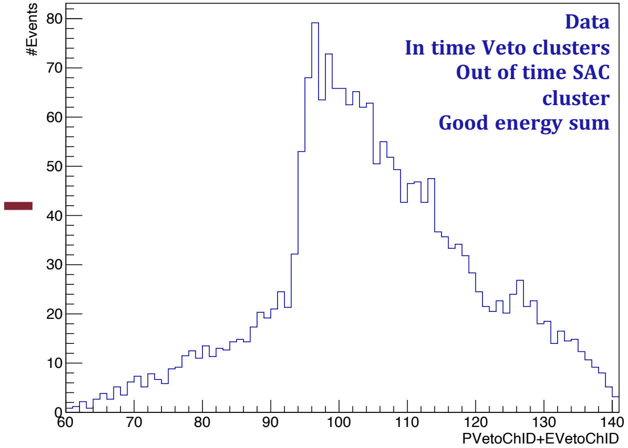


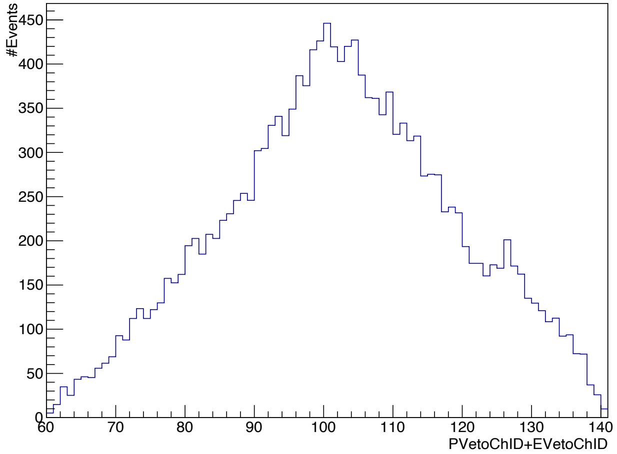
# "Pure Bremsstrahlung" background

- Take time side-bands, divide by 6 and subtract from in-time distribution:

All PVeto+EVeto+SAC – Side-Bands = "Pure Bremsstrahlung"

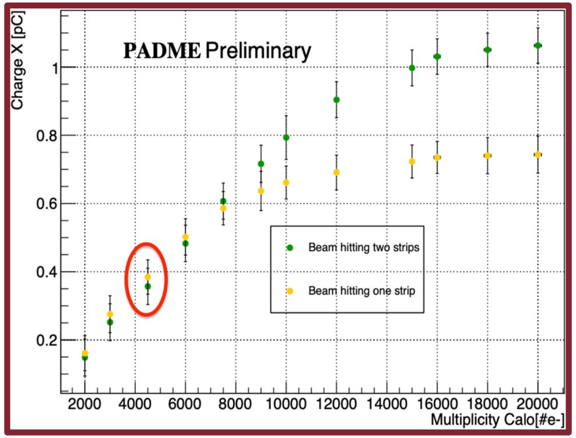


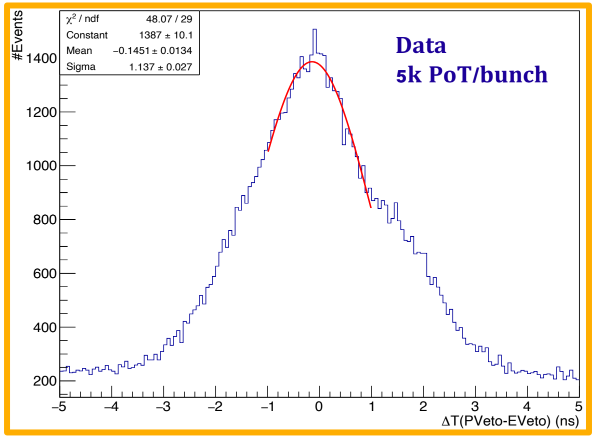



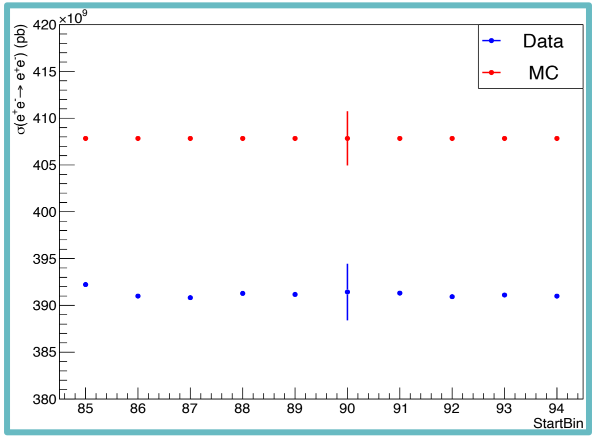
# Systematic errors

- Error on **NPoT** ~ 10%
- Error from $\Delta T(PVeto - EVeto)$ ~ 2%
- Target density ~ 2%
- Target thickness ~ 1%
- Error from **integration window** ~ 0.5%
- Beam energy < 0.5%
- **Ratio Bhabha/Bremsstrahlung** eliminates Target uncertainties




| | Data | MC | Ratio |
|---|---|---|---|
| Bhabha | 46,148 ± 354 | 48,240 ± 340 | 0.957 ± 0.010 |
| Bremsstrahlung | 60,376 ± 161 | 65,789 ± 153 | 0.918 ± 0.0033 |
| Ratio | 0.764 ± 0.0062 | 0.733 ± 0.0054 | 1.04 ± 0.011 |



# New physics model

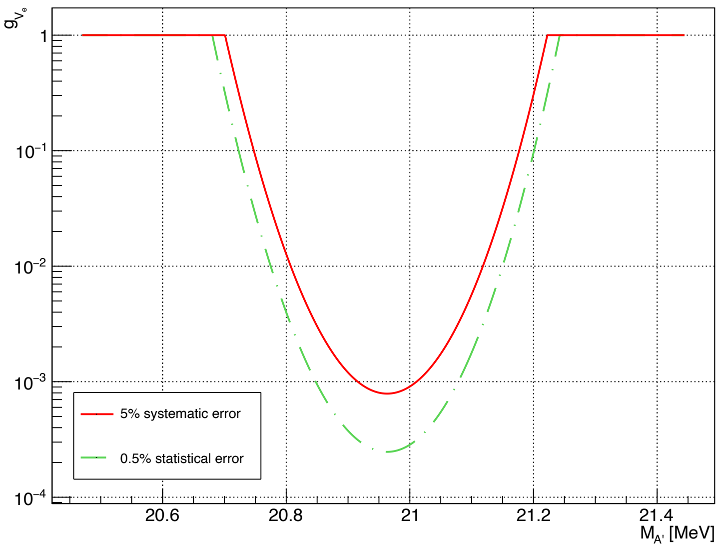
- No excess ⇒ exclusion limit
- Production rate (assuming width of resonance is negligible compared to $\sigma_E$):

$$\mathcal{N}_{A'} = N_{PoT} \frac{g_{Ve}^2}{2m_e} \frac{N_A d\rho Z}{A} f(E_{res}, E_+)$$

$$f(E_{res}, E_+) = \frac{1}{\sqrt{2\pi}\sigma_E} \exp\left\{ -\frac{(E_{res} - E_+)^2}{2\sigma_E^2} \right\}$$

- Assuming 10% error → 5% error (cf $\gamma\gamma$ PhysRevD.107.012008), max no. $A'$ accepted to agree with SM, at 90% CL:

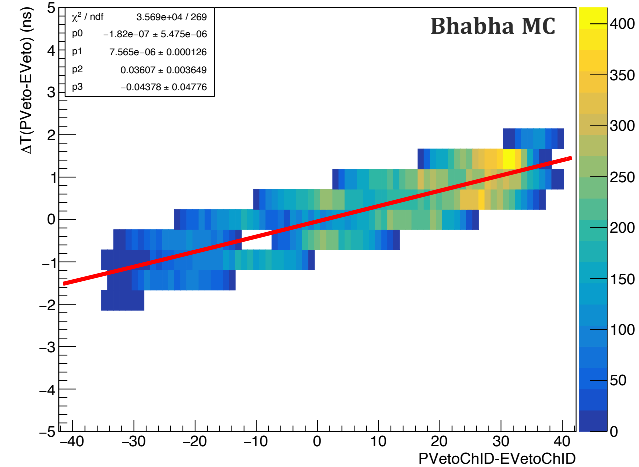
$$\mathcal{N}_{A'}^{Acc} \leq 1.35 \times 0.05 \times \mathcal{N}_{ee}^{Acc}$$

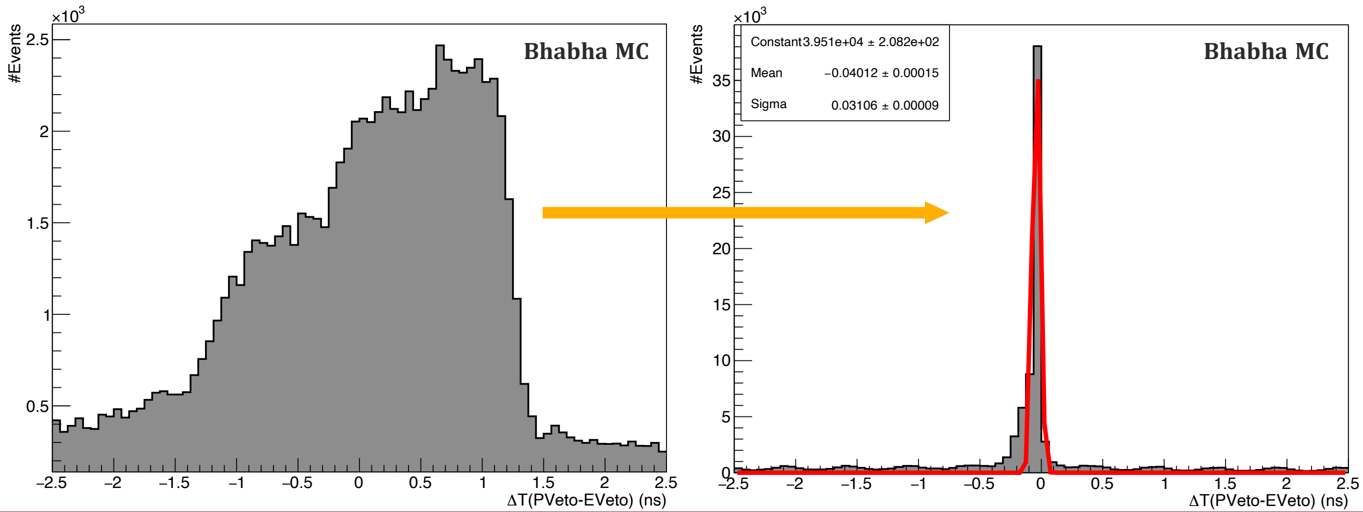



- $\mathcal{N}_{A'}$ = No. $A'$ produced
- $g_{Ve}$ = $A'$-$e$ coupling
- $d, \rho, Z, A$ = Target parameters
- $E_{res} = M_{A'}^2/2m_e$ = resonant energy
- $E_+$ = positron beam energy
- $\sigma_E$ = beam energy spread
- $\mathcal{N}_{A'}^{Acc}$ = No. $A'$ accepted
- $\mathcal{N}_{ee}^{Acc}$ = No. SM $ee$ accepted

# Bhabha time of flight correction

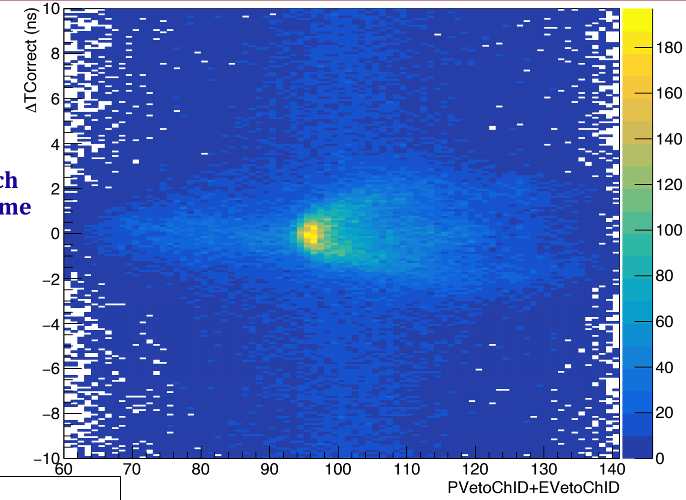
- $\Delta T(PVeto - EVeto) = f(\Delta Ch(PVeto - EVeto))$

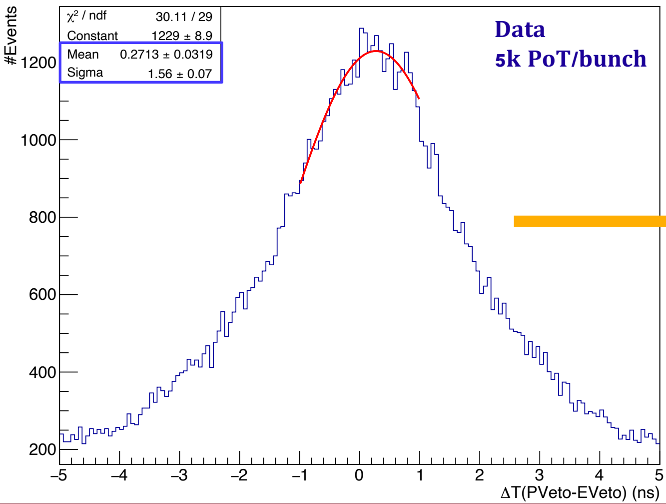


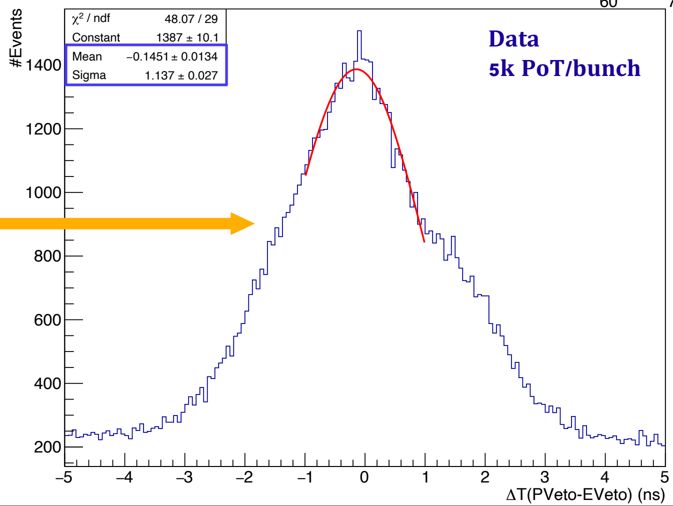



# Bhabha time of flight correction

**Data**
**5k PoT/bunch**
**Corrected time**



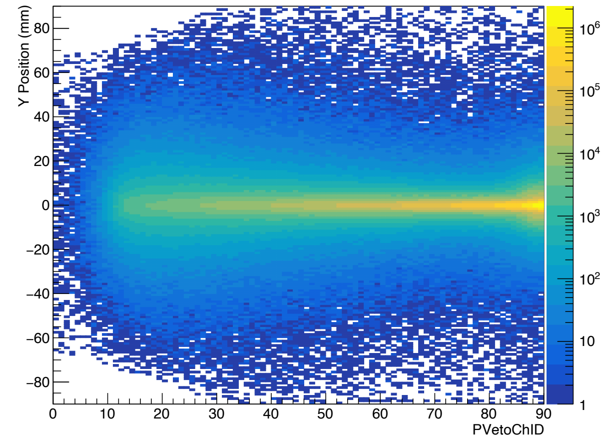



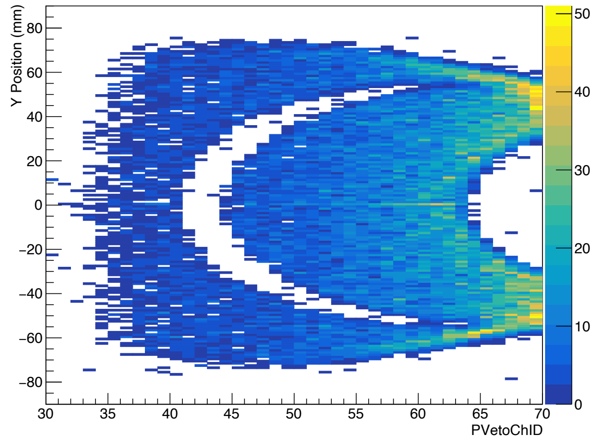
# Bhabha time resolution

- Data-MC difference comes from:
  - 0.5 ns Veto time resolution
  - 2.7 ns decay time of re-emission light in waveguide in Veto bars
  - $\leq$ 0.95 ns propagation time from top of bar to SiPM readout at bottom

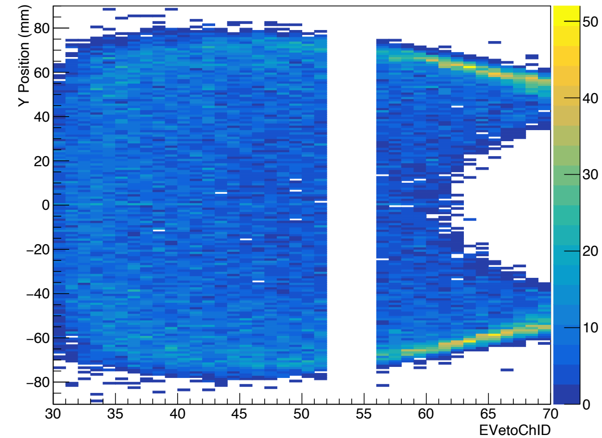
Bremsstrahlung MC




Bhabha MC

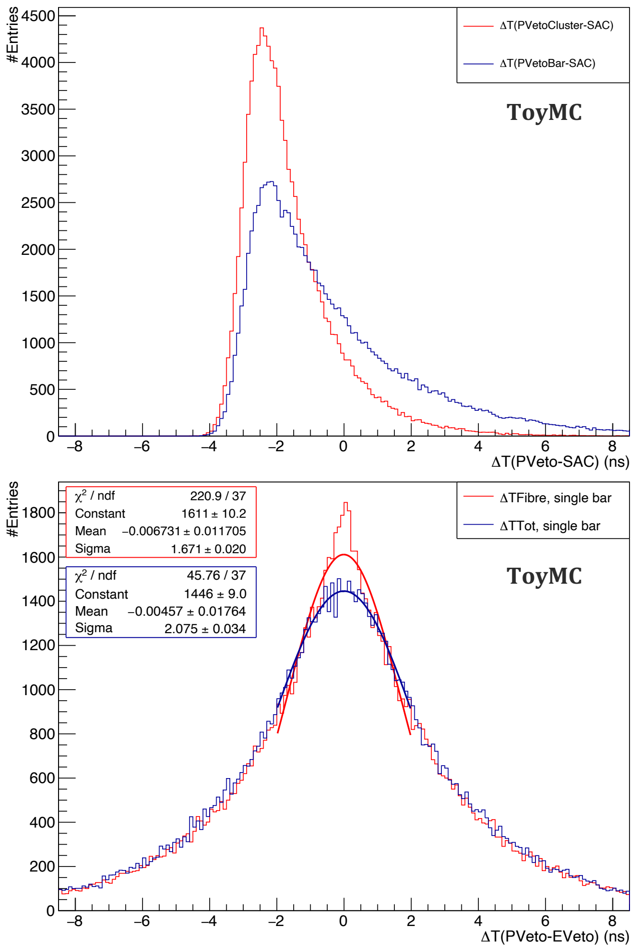



Bhabha MC



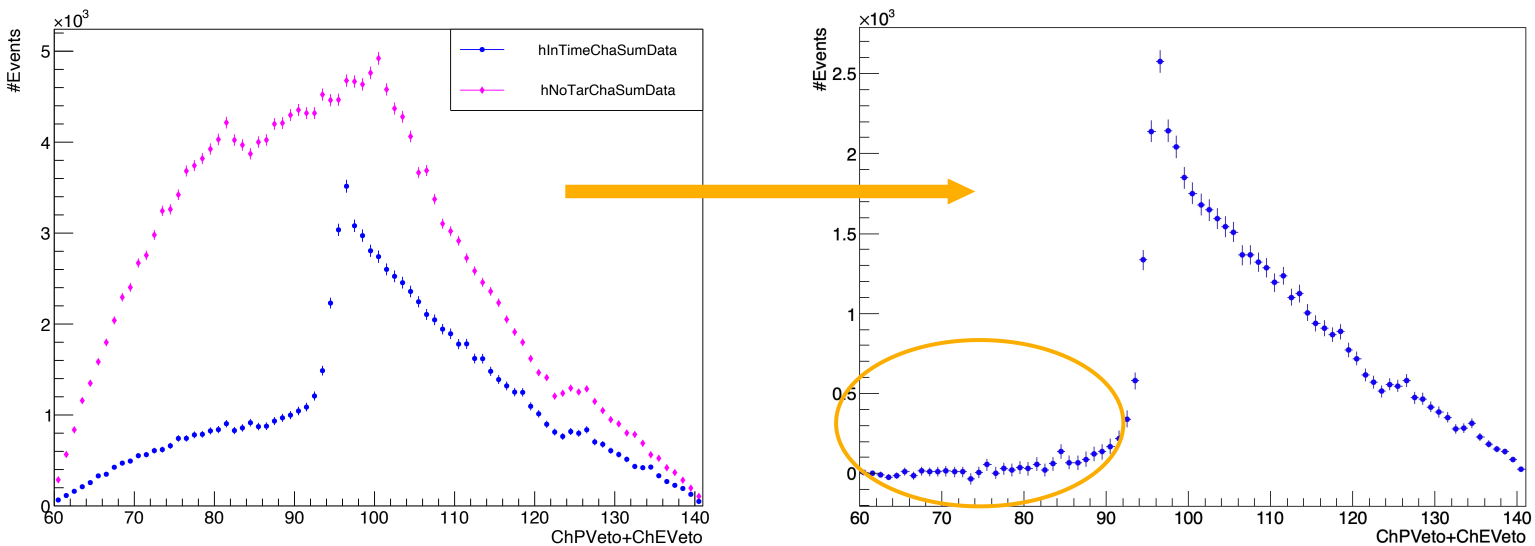
# Bhabha time resolution

- Brem-Bhabha difference comes from:
  - Two Vetoes, not one Veto + fast SAC
  - Larger angle Bhabha particles ⇒ fewer hits per cluster ⇒ average of emission times more variable
- Simulating SAC resolution as Gaus(0,0.15) ns, Veto electronic resolution as Gaus(0,0.4), Veto propagation time as U(1,-1) ns and emission time exp(−1/2.7) ns
- Assuming two bar PVeto Cluster



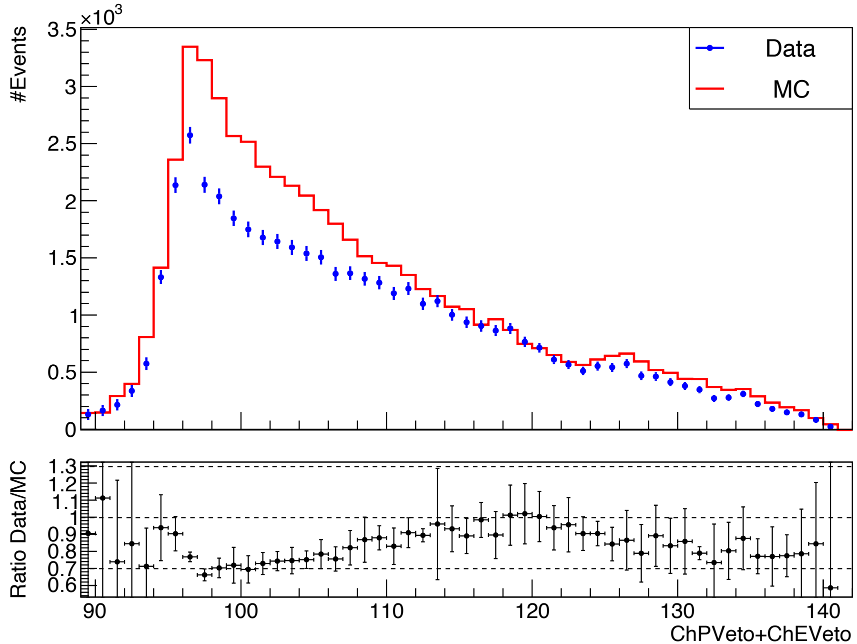
# Background subtraction

- **Full Target data** - **Bremsstrahlung** - **no-Target distribution**
  - Bremsstrahlung is auto-scaled
  - **No-Target distribution** scaled to integral of first 10 bins (ChaSum = [60,70]) in full Target data
    → If done successfully, final distribution will have ChaSum = [70,90] at 0 as well



# Data-MC comparison

- Acceptance is calculated from MC
  - NSignals/NPoT
- Integrating ChaSum≥ 90:
  - **NSignals Data** = 46,148
  - **NSignals MC** = 56,934
  - Ratio = 0.81
- Same deficit found in Bremsstrahlung
  - Points to similar experimental error in both measurements



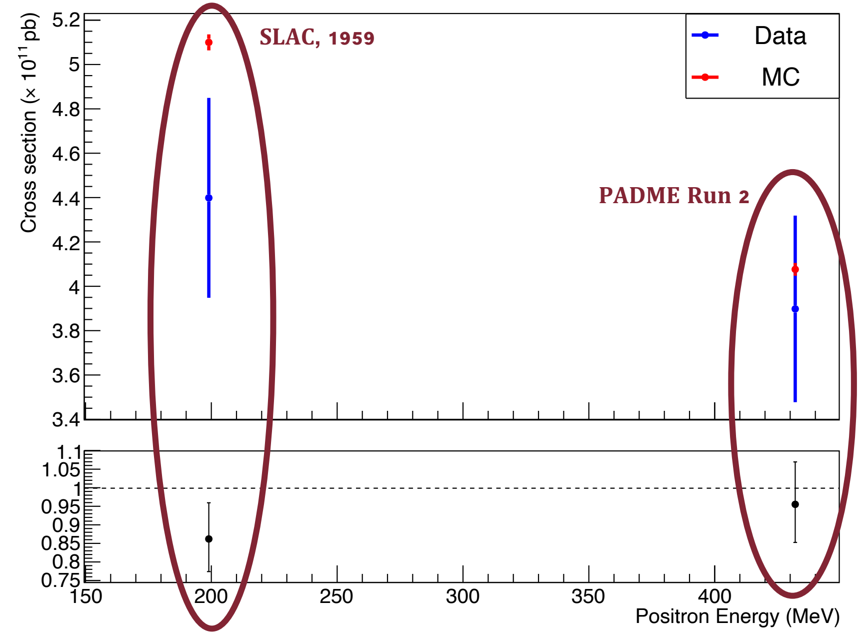

| | Data | MC | Ratio |
|---|---|---|---|
| Bhabha | 46,148 ± 354 | 56,934 ± 402 | 0.811 ± 0.0082 |
| Bremsstrahlung | 60,376 ± 161 | 77,644 ± 181 | 0.778 ± 0.0028 |
| Ratio | 0.764 ± 0.0062 | 0.733 ± 0.0054 | 1.04 ± 0.011 |

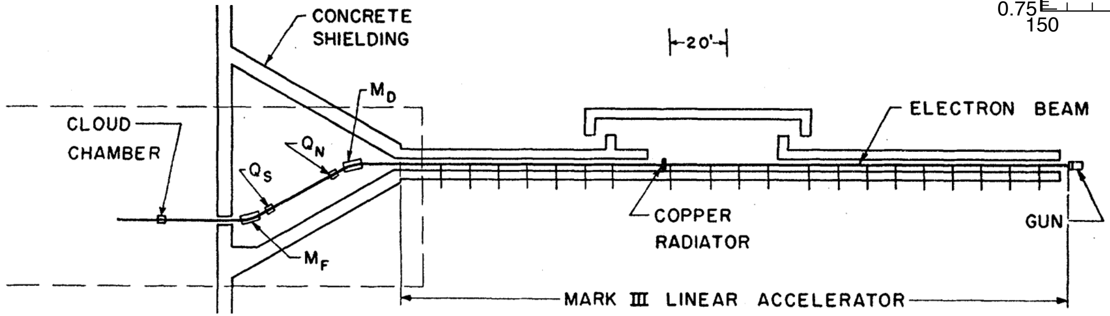
# Target uncertainties

- At 28k (for which Target is optimised), NPoT error is ~5% (cf $\gamma\gamma$ PhysRevD.107.012008)
- Target thickness 97 $\mu$m average, with 1 $\mu$m roughness
- Graphitised strips 5-10 $\mu$m thick per side ⇒ 10-20 $\mu$m total
- Graphitised strips reduce Target density from 3.515 g/cm$^3$ to 3.2 g/cm$^3$

# Cross section history

- In 1959, group at SLAC measure the Bhabha cross-section at beam energy 200 MeV, to test the Dirac nature of $e^+/e^-$
- Found $\sigma(e^+e^- \to e^+e^-) = (4.40 \pm 0.45)\times 10^{11}$ pb, 13% deficit compared to theory
- "This difference cannot be interpreted until radiative corrections to the theory have been evaluated."



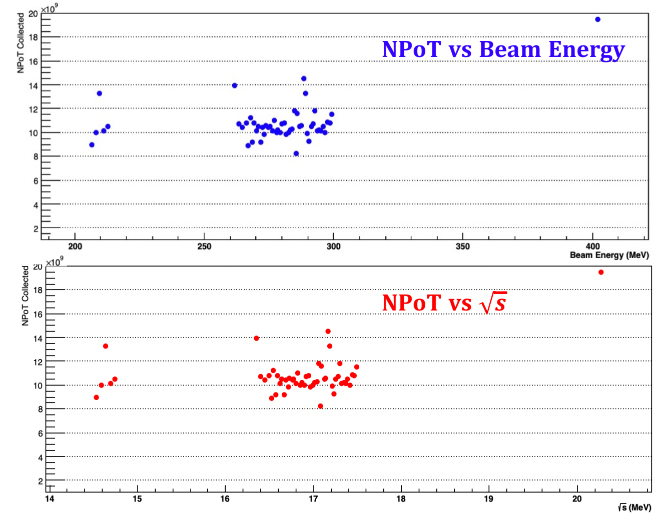
# LEP measurements

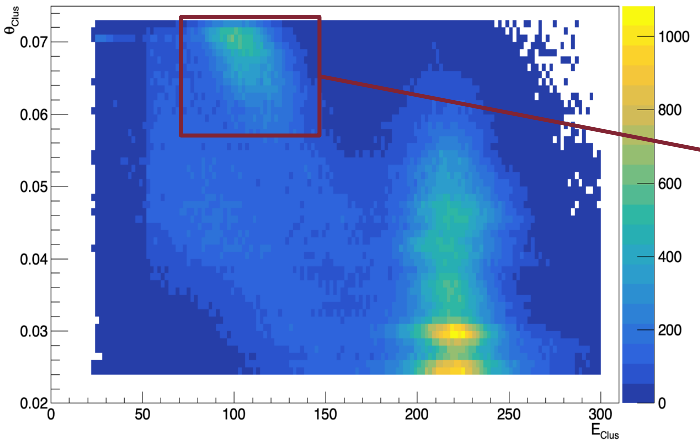
- Searching for internal structure of electron
- Table refers to L3 at LEP
- Luminosity measurement was small angle Bhabha ⇒ table implies: assuming no new physics at small angles, wide angle scattering also agrees with SM

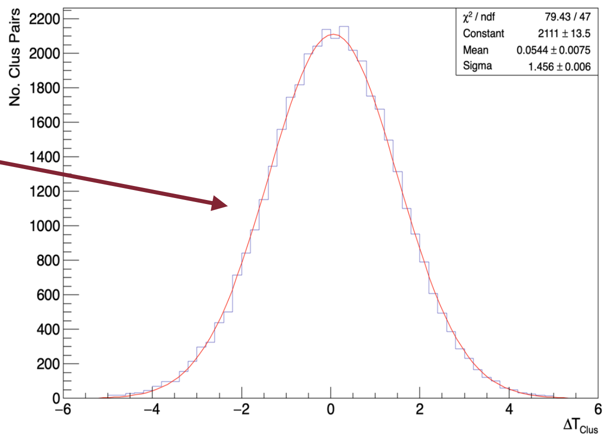
| $\sqrt{s'}$ [GeV] | $\langle\sqrt{s'}\rangle$ [GeV] | $N_{ee}$ | $\sigma_{ee} \pm$ (stat.) $\pm$ (syst.) [pb] | $\sigma_{ee}^{Born}$ [pb] |
|---|---|---|---|---|
| < 60 | 52.0 | 152 | 449.4 ± 35.1 ± 20.2 | 423.7 |
| 60 – 68 | 64.5 | 153 | 258.3 ± 23.5 ± 12.5 | 285.1 |
| 68 – 76 | 72.5 | 335 | 231.5 ± 13.2 ± 7.4 | 238.2 |
| 76 – 82 | 79.2 | 594 | 235.5 ± 9.3 ± 5.5 | 223.9 |
| 82 – 85 | 83.7 | 575 | 224.0 ± 10.6 ± 5.9 | 246.0 |
| 85 – 87 | 86.1 | 622 | 300.0 ± 12.6 ± 8.1 | 297.6 |
| 87 – 92 | 88.3 | 169 | 483.9 ± 37.1 ± 13.2 | 471.5 |
| 92 – 105 | 96.9 | 36 | 117.6 ± 16.9 ± 8.3 | 101.4 |
| 105 – 130 | 118.4 | 68 | 76.1 ± 7.8 ± 3.7 | 63.5 |
| 130 – 160 | 148.2 | 70 | 34.0 ± 5.0 ± 2.3 | 41.3 |
| 160 – 175 | 167.1 | 82 | 33.5 ± 3.6 ± 2.1 | 32.5 |

# Data collected

- Collected $\sim 10^{10}$ PoT per point at:
  - 47 points around X17 resonance
  - 5 points below resonance
  - 1 point above resonance
- Using kinematic relation between $E_\gamma$ and $\theta_\gamma$
  -> very good signal-background separation



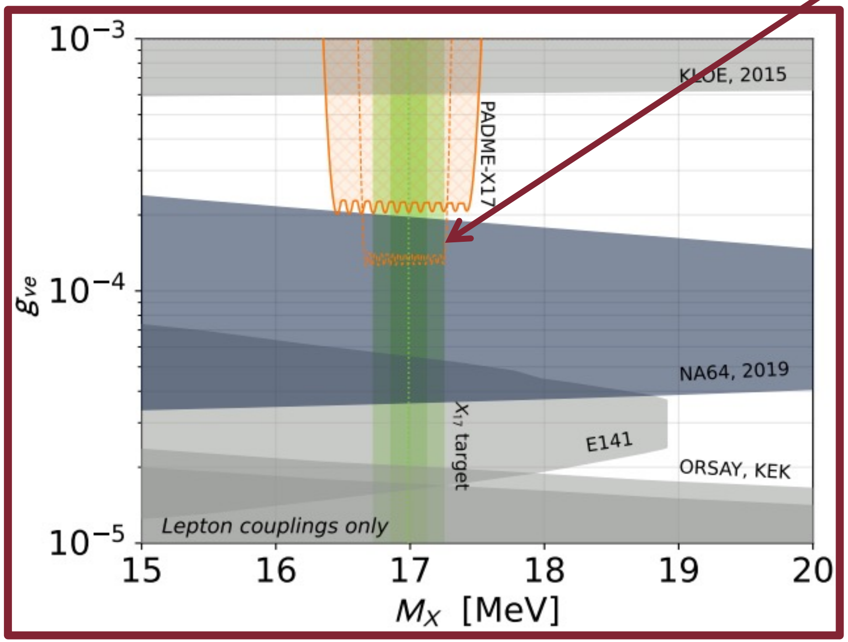



# Expected limits

PADME limit aim

[Phys.Rev.D 106 (2022) 11, 115036](https://doi.org/10.1103/PhysRevD.106.115036)

**Vector X17**




**Pseudo scalar X17**