Electron Tracking Efficiency in Elastic Events in the MUonE Experiment

Liverpool Muon Group Meeting

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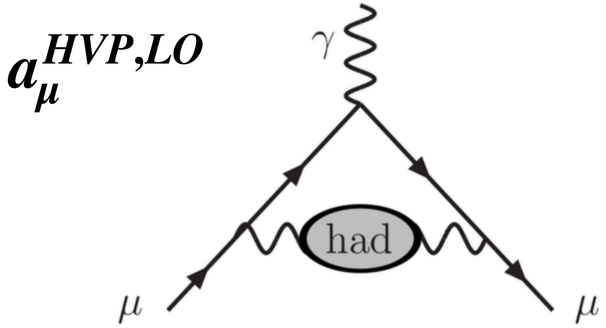
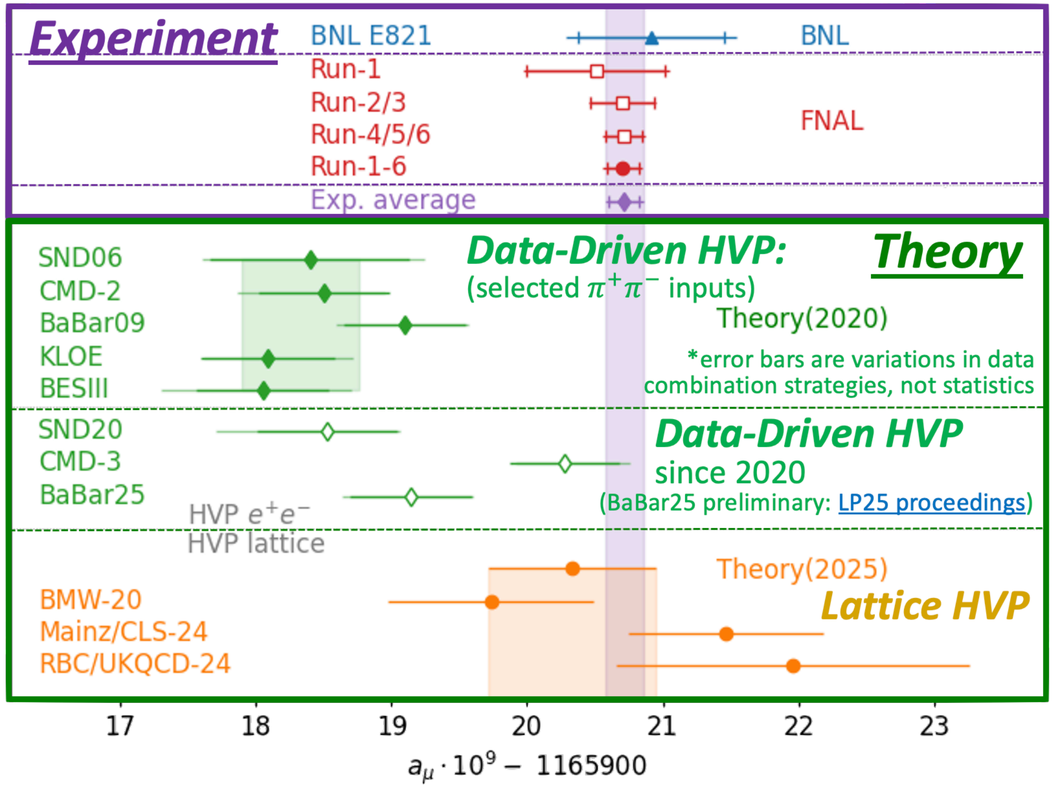
The Muon g-2 HVP Puzzle

- Currently ~5σ tensions between measured muon $a_\mu \equiv (g_\mu - 2)/2$ and its SM prediction, precision is limited by the **hadronic vacuum polarisation** contribution (HVP) → non-perturbative below ~ few GeV
- **Traditional data-driven dispersive approach to calculate a_μ^{HVP}** based on $\sigma(e^+e^- \to hadrons)$ data discrepant w.r.t. recent ***lattice* calculations of a_μ^{HVP}** and with directly measured **experimental world average a_μ^{Exp}** by FNAL/BNL
- Experiments at e^+e^- accelerators are improving their measurements of $\sigma(e^+e^- \to hadrons)$ using higher statistics and new methods, in order to shed light on the puzzle (e.g. KLOE HVP group in Liverpool!)
- ***A third independent approach to measuring HVP LO is crucial in order to understand where the issue lies***

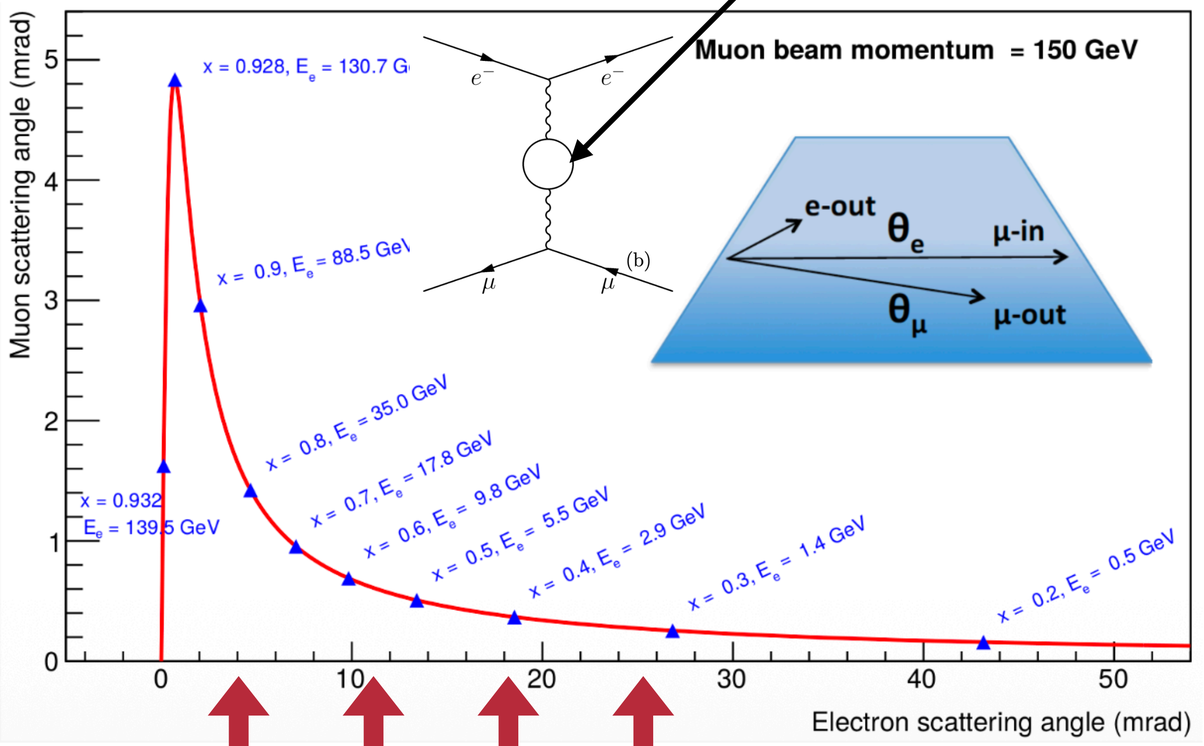




The MUonE Experiment

We measure this

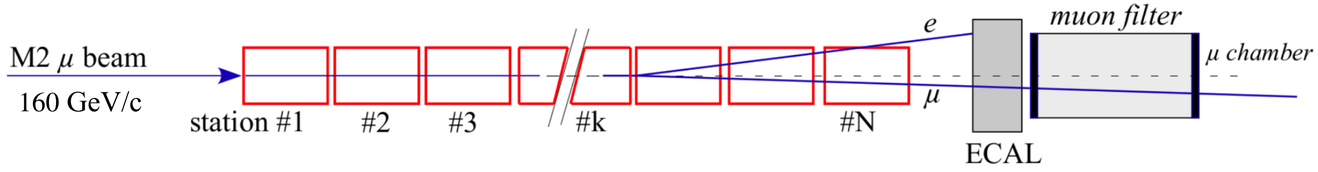
$$a_\mu^{HLO} = \frac{\alpha_0}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$



ELASTIC CURVE

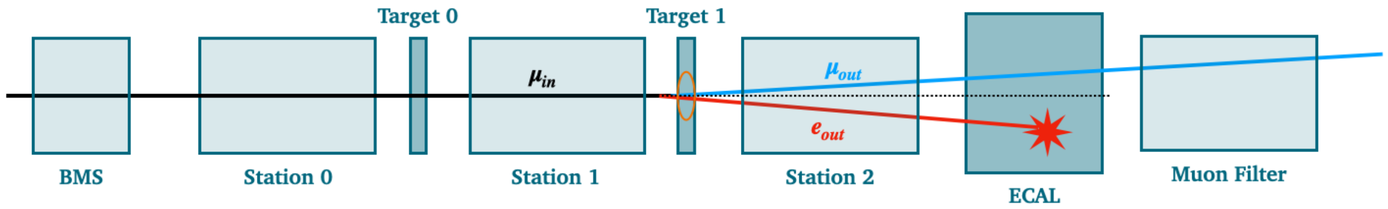
BMS

- a_μ^{HLO} can be extracted from hadronic running of α_{em}, measured from $\mu^+e^- \to \mu^+e^-$ elastic scattering
- **MUonE experiment proposed**: Scatter a beam of 160 GeV muons @40MHz on a target and measure the angles $(\boldsymbol{\theta_e}, \boldsymbol{\theta_\mu})$ of the outgoing muon and electron
- Aim for precision on $a_\mu^{HLO} \lesssim 0.5\%$ with 3 years of data taking at CERN M2 beam line after LS3
- To achieve statistics use 40 identical tracking stations on beam line, with ancillary BMS, ECAL, MF



Objective of This Study: Tracking Efficiency

- In 2025 MUonE ran for ~3 months with a downscaled version of the final apparatus: Only 3 tracking stations (2 targets) + BMS + ECAL (synchronised with tracker!) + Muon Filter → $\sim 5 \times 10^{11}$ signal events triggered!



- To achieve the targeted MUonE precision on a_μ^{HLO} it is necessary to keep the **tracking efficiency of outgoing tracks post-scattering under control with great accuracy** → this study represents a **first approach at determining such efficiency from 2025 data**

- Efficiency of reconstructing an "electron" is conditioned on the presence of a tag with a "muon" track (***tag and probe*** approach) as a function of electron angle

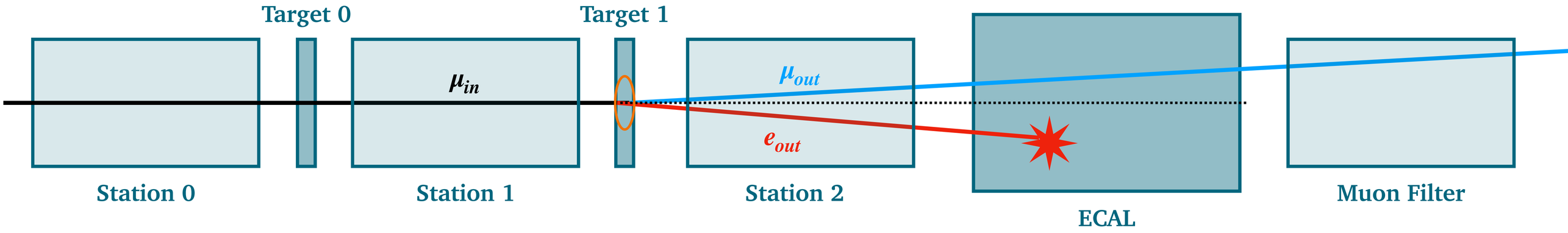
- This requires an adequate selection of elastic $\mu^+e^- \to \mu^+e^-$ events (signal) using only ***pre-vertexing*** information (we can't exploit info from both tracks in tag&probe approach)

- We can also start to judge the performance of the ECAL in tagging elastic events and its consistency with tracking information in 2025 data

$$\varepsilon(e_{prob}\,|\,\mu_{tag}) = \frac{N(\mu_{tag} \cap e_{prob})}{N(\mu_{tag})}$$

Data and Reconstruction

- Results shown correspond to 1 billion events from Run 32 data (2025) available on lxplus (CERN) & Liverpool clusters
- Focus on last station for now, closer to ECAL → `single_muon_interaction_1` trigger events used (trigger for signal elastic scattering in second target)
- Need a selection to tag elastic events while cutting background (mainly pair production $\mu^+N \rightarrow \mu^+Ne^+e^-$)

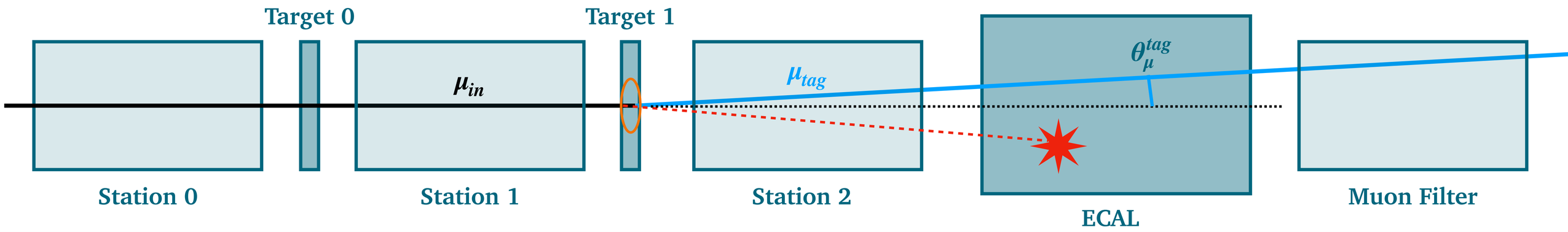


Elastic Event Selection: μ Tag

- Selection to **tag the presence of an elastic event using a muon track**
  - Exactly one track in Station 0
  - Exactly one track in Station 1 ("μ_{in}") with extrapolated position at Target 1 within 2 cm from center (***fiducial cut***)
  - Number of hits in Station 2 : $n_{hit}^{S2} \leq 15$
  - $1 \leq n_{trk}^{S2} \leq 2$ in Station 2, exactly one of which tagged as muon by Muon Filter (μ_{tag}), with measured angle θ_{μ}^{tag} wrt to μ_{in}
  - $0.2 \leq \theta_{\mu}^{tag} \leq 32$ mrad
  - ECAL cluster with energy ≥10 GeV $\longrightarrow$ $\lesssim$10 mrad electron angle

$$\sin\theta_{\mu} = \frac{p'_e \sin\theta_e}{p'_{\mu}} = \sin\theta_e \sqrt{\frac{E_e^2(\theta_e) - m_e^2}{[E_{\mu} + m_e - E_e(\theta_e)]^2 - m_{\mu}^2}} \qquad E_e = m_e \frac{1 + r^2 cos^2\theta_e}{1 - r^2 cos^2\theta_e}$$

  - **Elastic cut between muon angle and ECAL** $\Longrightarrow \theta_{\mu}^{tag} - \theta_{\mu}^{ECAL} \leq 0.1$ mrad, where $\theta_{\mu}^{ECAL} \equiv \theta_{\mu}^{LO}\left(\theta_e^{ECAL}\right) \equiv \theta_{\mu}^{LO}\left(\theta_e^{LO}\left(E_{ECAL}\right)\right)$



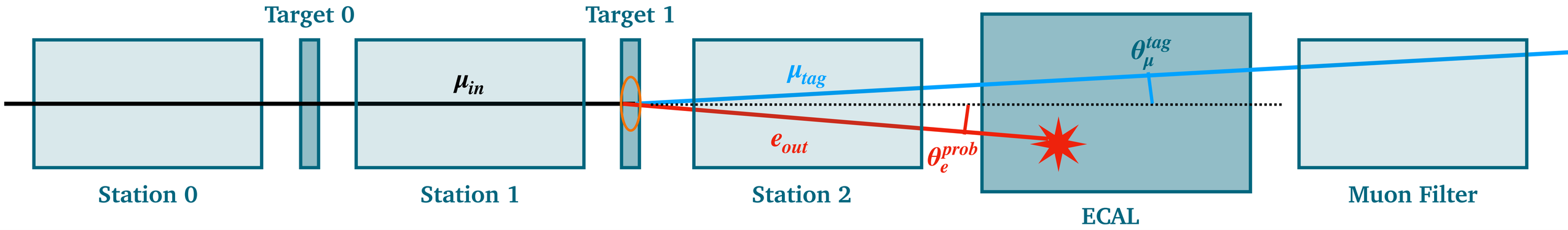
Elastic Event Selection: e^- Probe

- Conditions **in addition to μ tag** of previous slide for an electron to be ***probed***
  - Exactly one track in Station 2 ***not*** tagged by Muon Filter with measured angle θ_e^{prob} wrt to μ_{in} → "electron" candidate
  - Extrapolated position of "electron" track at ECAL within 0.7 cm of cluster centroid :

$$d_{e-clu}^{ecal} = \sqrt{\left(x_e^{ecal} - x_{clu}^{ecal}\right)^2 + \left(y_e^{ecal} - y_{clu}^{ecal}\right)^2} < 0.7 \ \text{cm}$$

  - Distance with respect to μ_{tag} at target : $d_{e-\mu}^{trgt} = \sqrt{(x_e^{trgt} - x_\mu^{trgt})^2 + (y_e^{trgt} - y_\mu^{trgt})^2} < 0.2$ cm (***IP cut***)
  - Modified acoplanarity with respect to μ_{in} and μ_{tag} : $\mathscr{A} < 0.4$
  - **Elastic cut between electron angle and ECAL** $\Longrightarrow |\theta_\mu^{tag} - \theta_\mu^{ele}| \leq 0.21$ mrad, where $\theta_\mu^{ele} \equiv \theta_\mu^{LO}(\theta_e^{prob})$

$$\sin\theta_\mu = \frac{p'_e \sin\theta_e}{p'_\mu} = \sin\theta_e \sqrt{\frac{E_e^2(\theta_e) - m_e^2}{[E_\mu + m_e - E_e(\theta_e)]^2 - m_\mu^2}}$$



Full Tag&Probe Selection Overview

- single_muon_interaction_1 trigger
- Cuts on number of tracks/hits in S0/1/2
- Fiducial cut on μ_{in} position at target
- $E_{ECAL} > 10$ GeV
- Elastic cut between μ_{tag} angle and ECAL energy

μ_{tag}

- Cut on extrapolated “electron” position at target
- Cut on distance at target between e and μ_{tag} (IP)
- Modified acoplanarity cut
- Elastic cut between “electron” measured angle and μ_{tag} measured angle

e_{prob}

$$N(\mu_{tag})$$

$$N(\mu_{tag} \cap e_{prob})$$

$$\varepsilon(e_{prob} \mid \mu_{tag}) = \frac{N(\mu_{tag} \cap e_{prob})}{N(\mu_{tag})}$$

Angles Before μ Elasticity Cut

- Distribution of expected $\theta_e^{ECAL} \equiv \theta_e^{LO}\left(E_{ECAL}\right)$ from ECAL energy and tagging muon angle θ_μ^{tag} ***before*** elastic cut on $\theta_\mu^{tag} - \theta_\mu^{ECAL}$
- Despite not having "requested any elasticity" for the outgoing muon ***we clearly see the elastic curve already!***
- When applying elastic cut on $\theta_\mu^{tag} - \theta_\mu^{ECAL}$ the result is selection of elastic band as expected

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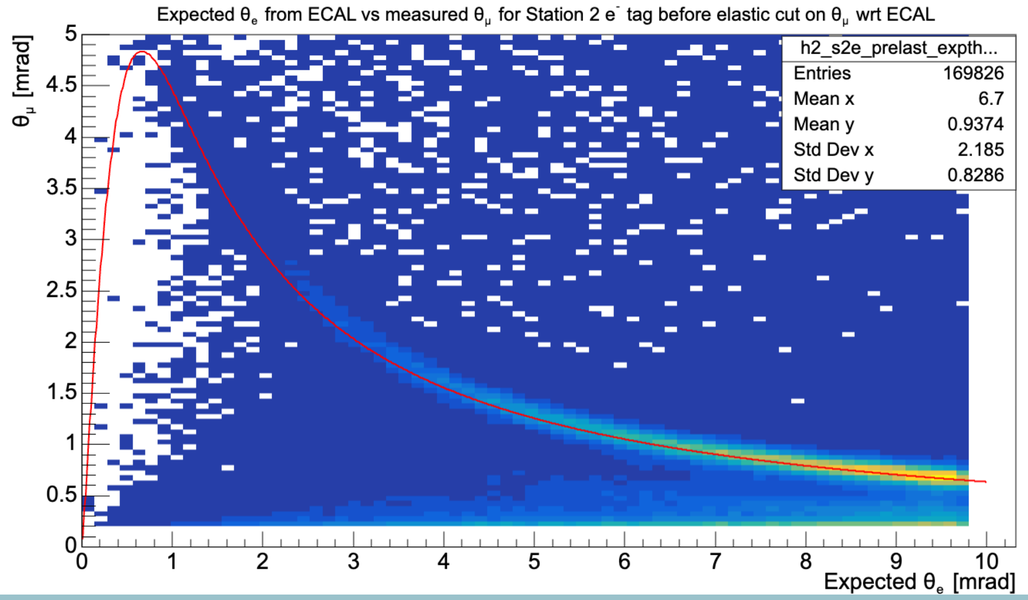
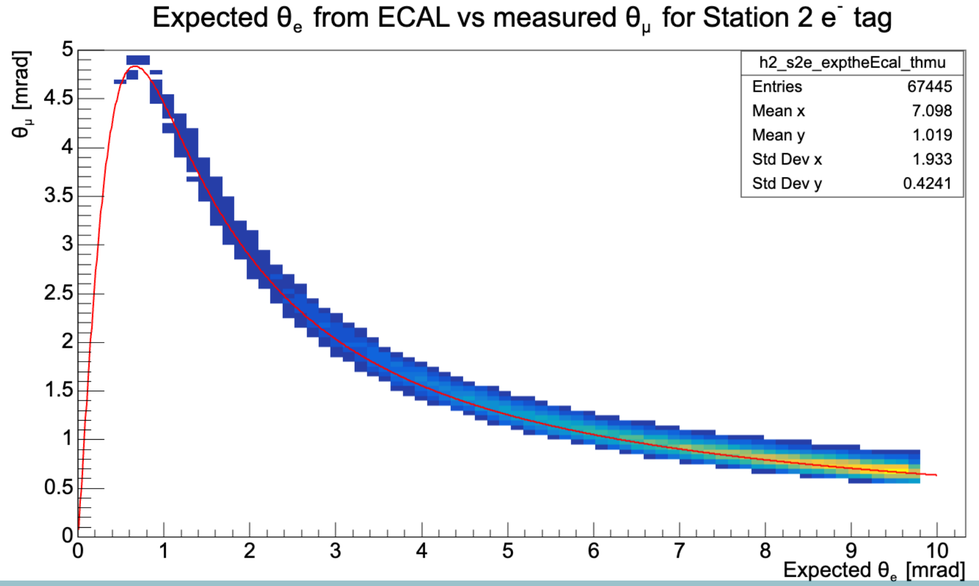


Elastic cut on tagging muon



θ_e^{ECAL}

“Electron”-Cluster Before e^- Elasticity Cut

- Distribution of extrapolated positions of “electron” track with respect to ECAL centroid ***before*** imposing any cuts on “electron” track (except not being tagged by MF)

- We have required elasticity between tag “muon” and ECAL energy, but this shouldn’t a priori imply consistency between the candidate “electron” and the ECAL cluster position → instead we observe that ***most of these “electrons” indeed match the cluster position***!

- single_muon_interaction_1 trigger
- Cuts on number of tracks/hits in S0/1/2
- Fiducial cut on μ_{in} position at target
- $E_{ECAL} > 10$ GeV
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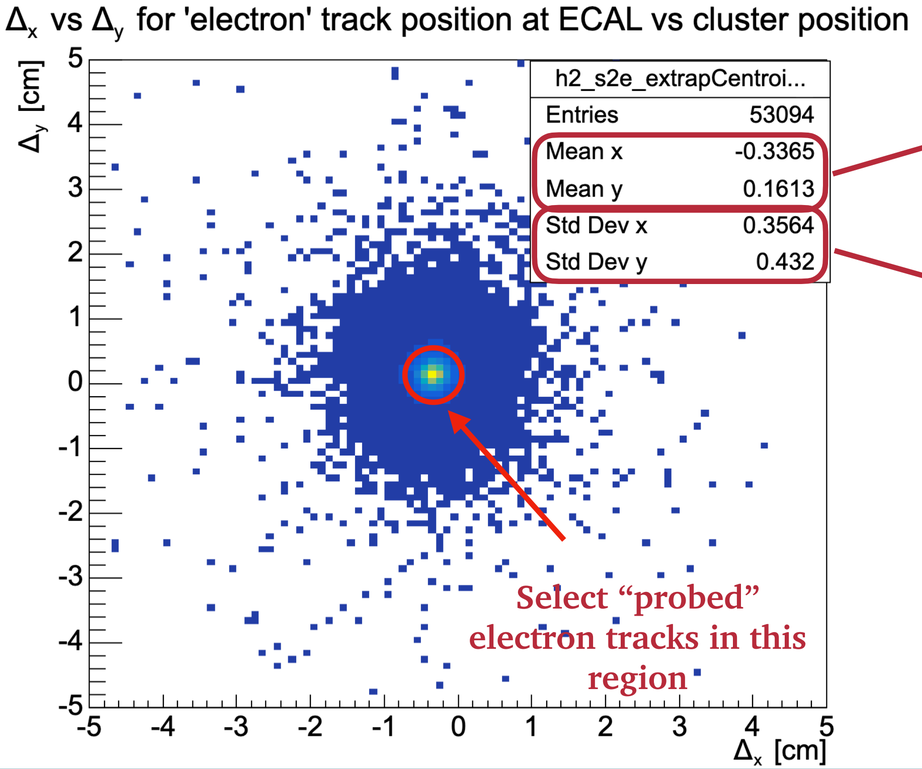


ECAL not aligned

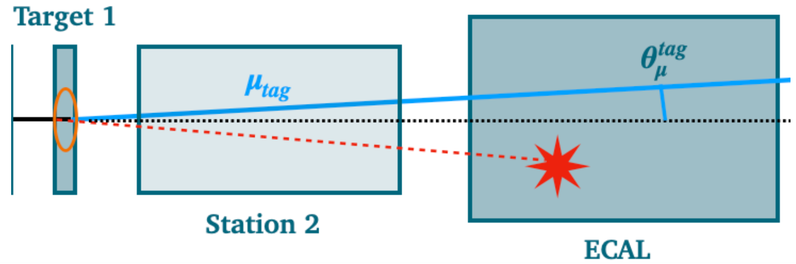
$\langle \Delta_x^{ele} \rangle \simeq -0.34$ cm

$\langle \Delta_y^{ele} \rangle \simeq 0.16$ cm

ECAL centroid resolution

$\oplus$

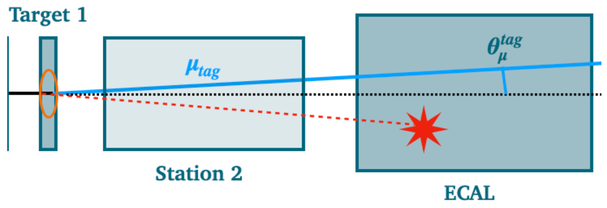
Extrapolated track position uncertainty

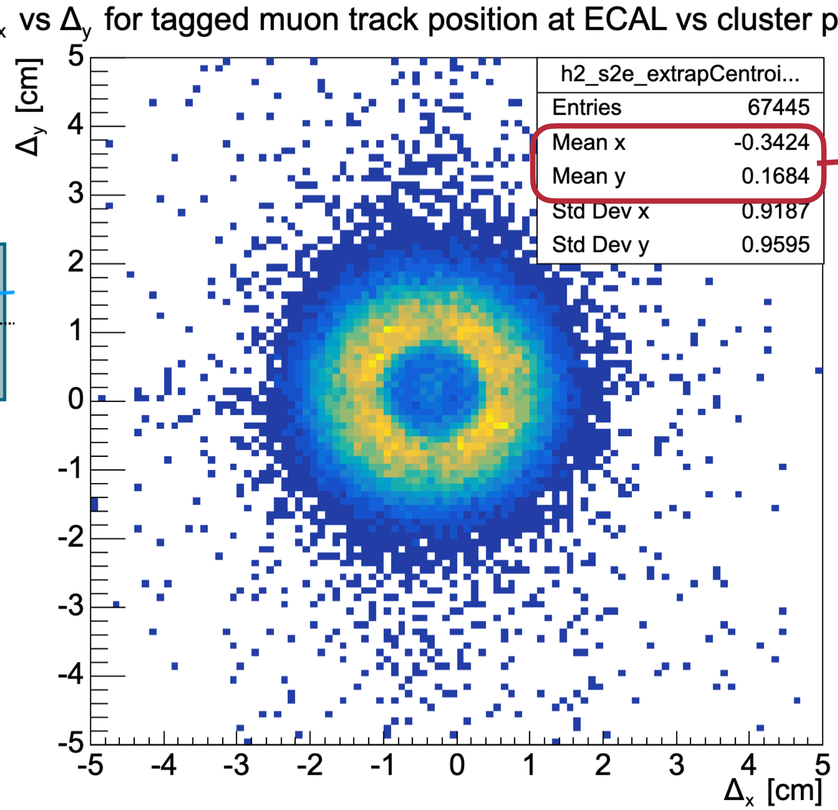


Muon-Cluster Before e^- Elasticity Cut

- Distribution of extrapolated positions of tag “muon” track with respect to ECAL centroid ***before*** imposing any cuts on “electron” track (except not being tagged by MF)

- Contrary to what happens with the “electron”, here the “muon” ***is clearly not responsible for the cluster position***, despite not having imposed any such constraint!





Compare with electron case:

$$\langle \Delta_x^{ele} \rangle \simeq -0.337 \text{ cm}$$
$$\langle \Delta_y^{ele} \rangle \simeq 0.161 \text{ cm}$$

Should be fitted for accurate comparison

Cut on Distance at Target

- I also apply a cut on distance at the target between outgoing tracks (tagged muon and probed electron) at 0.2 cm as done in current standard elastic event selection

- It looks like in this case it is too loose given the cuts previously applied → will tighten the cut

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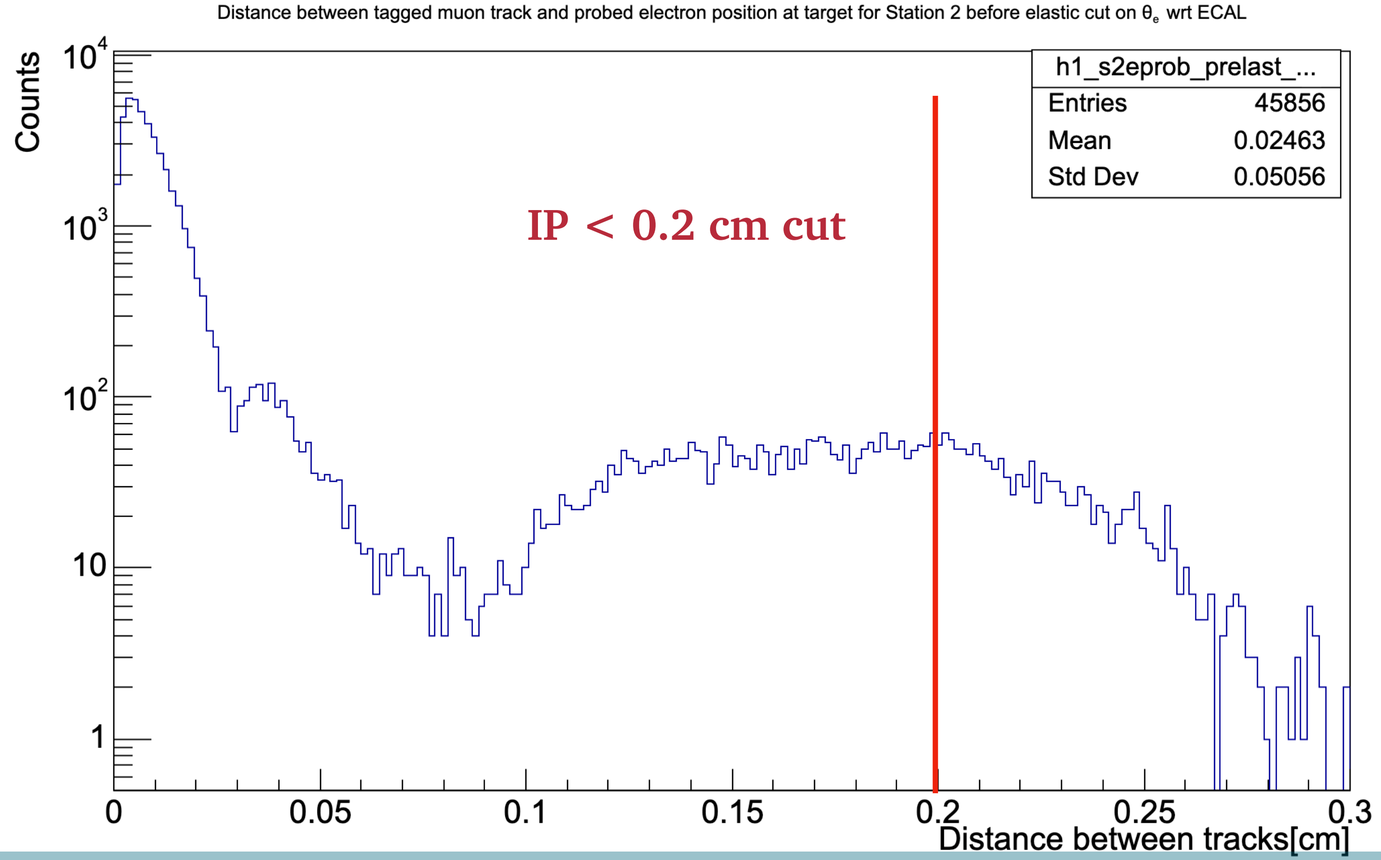

Cut on Modified Acoplanarity

- I apply a cut on the modified acoplanarity between the three elastic event tracks μ_{in} , μ_{tag}, e_{prob}
- Modified acoplanarity is defined as the angle between the planes μ_{in}-μ_{tag} and μ_{in}-e_{prob} → ideally $\mathscr{A} = 0$ for a perfect 3 body event without scattering or radiative corrections
- I apply the "standard selection" cut at $\mathscr{A} < 0.4$ ⟶ it too seems loose given previous cuts

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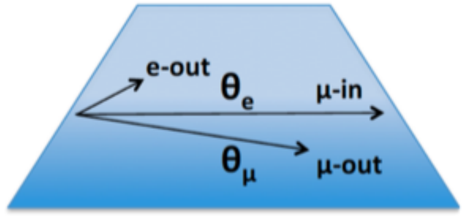
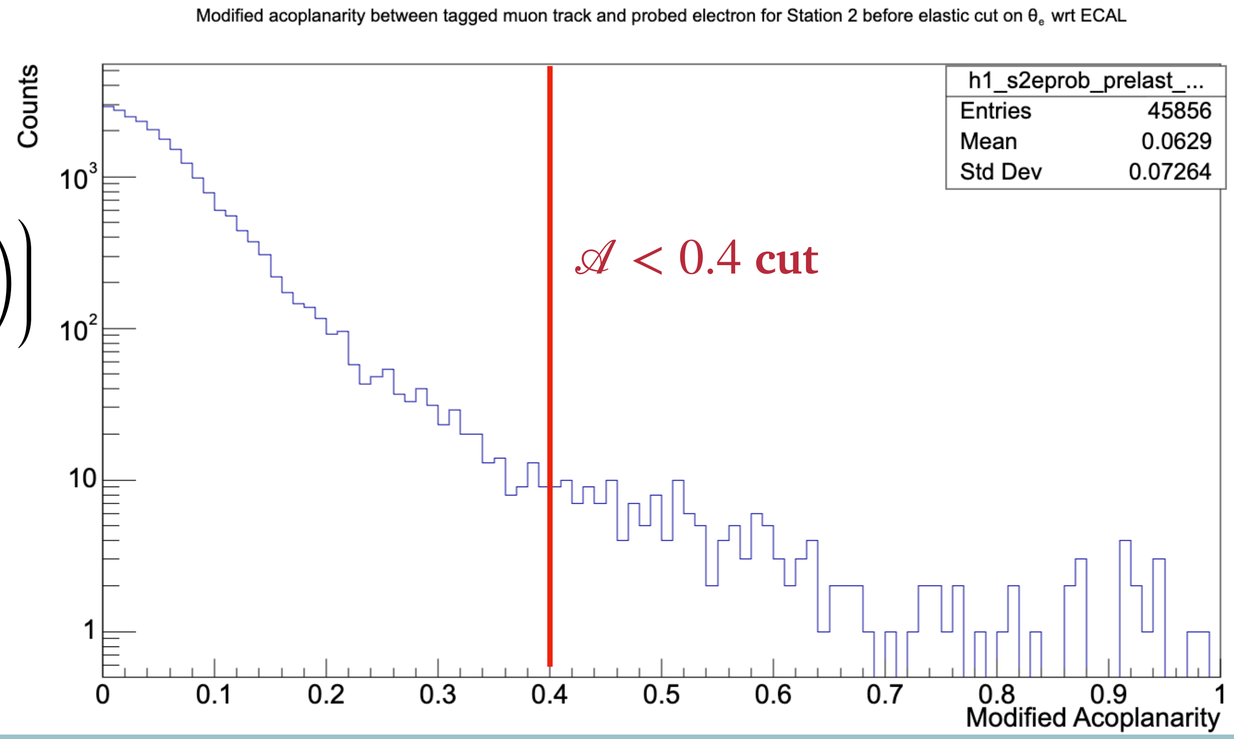
$$\mathscr{A} \equiv \pm\left(\pi - \left(\frac{(\vec{p}_{in}\times\vec{p}_{tag})\cdot(\vec{p}_{in}\times\vec{p}_{ele})}{|\vec{p}_{in}\times\vec{p}_{tag}||\vec{p}_{in}\times\vec{p}_{ele}|}\right)\right)$$





Angles Before e^- Elasticity Cut

- Distribution of measured "probed" electron angle θ_e^{prob} and tag muon angle θ_μ^{tag} ***before*** elastic cut on $\theta_e^{prob} - \theta_e^{ECAL}$

- Despite not having yet "requested any elasticity" for the "electron" angle ***we clearly observe the expected elastic behaviour!***

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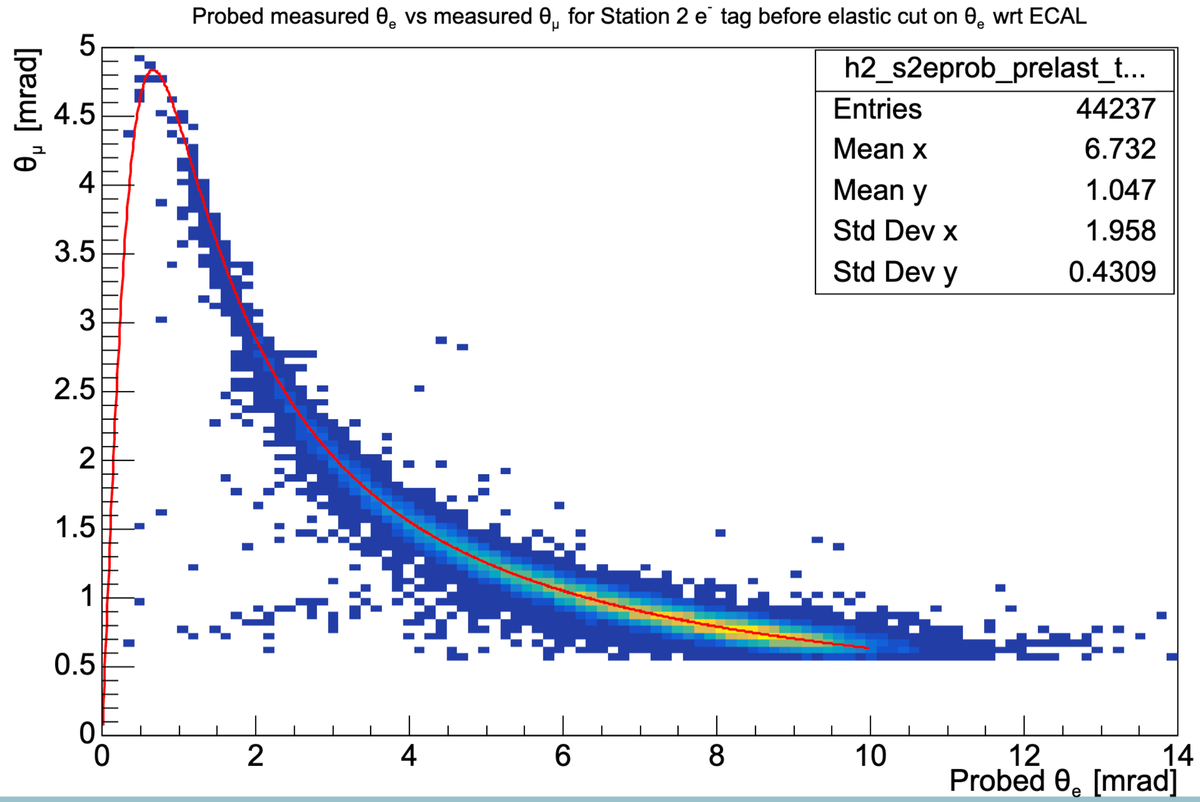

Discrepancy Before e^- Elasticity Cut

- Discrepancy between measured θ_μ^{tag} and muon angle expected at LO from the measured angle of the "electron" track $\theta_\mu^{ele} \equiv \theta_\mu^{LO}(\theta_e^{prob})$

- Despite not having yet applied elastic cut on the electron, the ***central peak indicates we are already selecting elastic events!***

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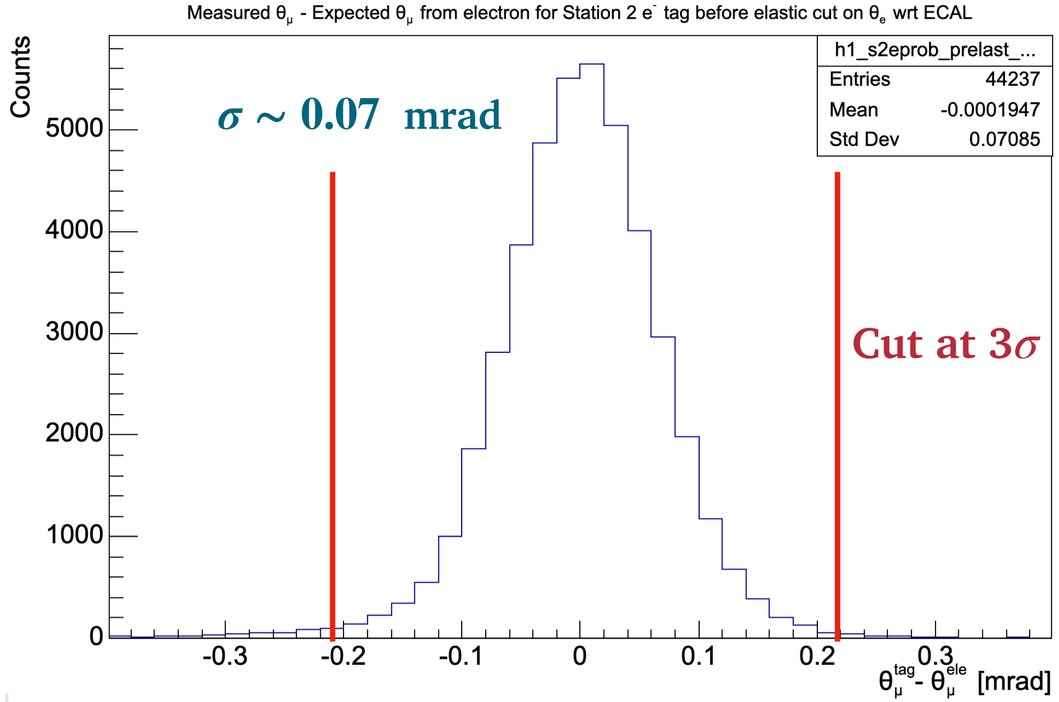
$\theta_\mu^{tag} - \theta_\mu^{ele}$



Efficiencies on Probed Electron Track

- Final efficiency of probing the electron **with** and **without** applying final elasticity cut on electron angle given the presence of a tagging muon

- Efficiencies must be expressed as a function of the ***expected*** electron angle → needs to be defined even when there is no probed track!

$$\varepsilon(e_{prob}\,|\,\mu_{tag}) = \frac{N(\mu_{tag} \cap e_{prob})}{N(\mu_{tag})}$$

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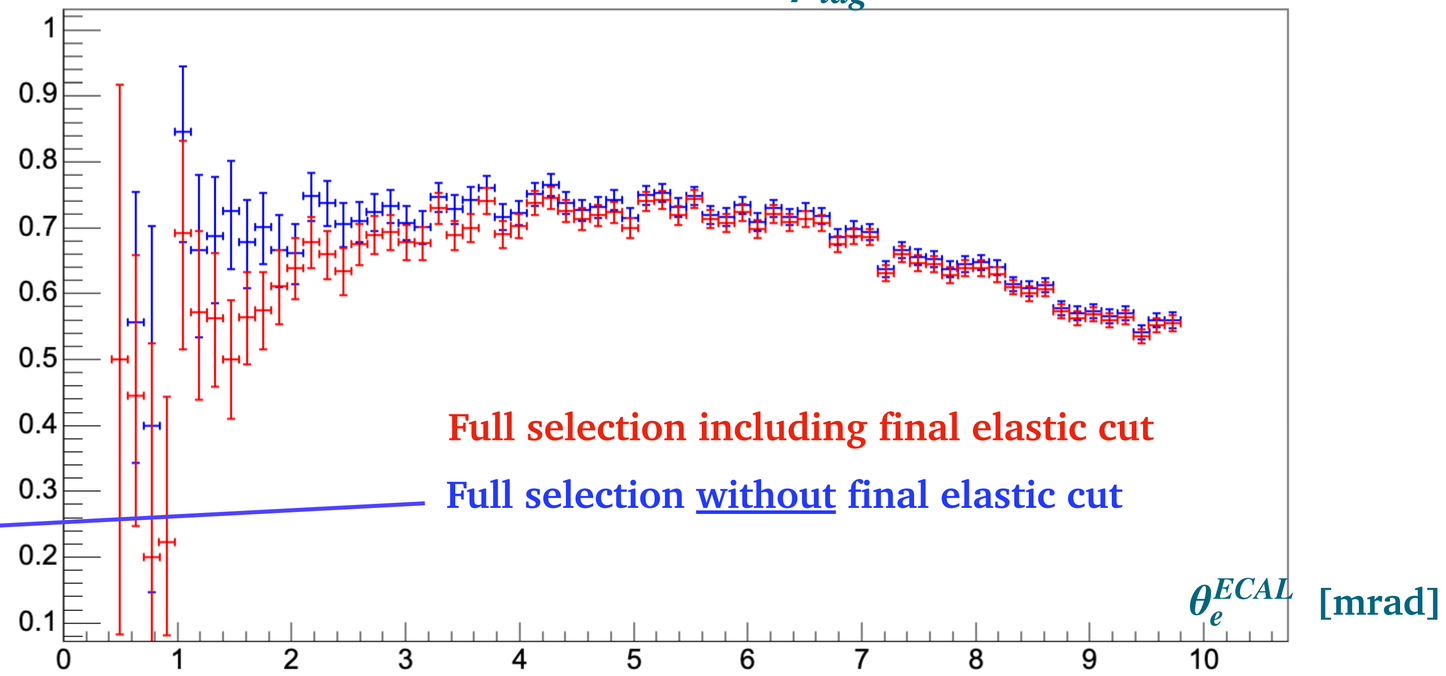
$N(\mu_{tag})$

$N(\mu_{tag} \cap e_{prob})$



Conclusions and Outlook

- I have tested a set of cuts to select for elastic events using only pre-vertexing info, using the ECAL for PID and elasticity constraints → $\sim 4 \times 10^{-5}$ efficiency for full tag&probe conditions on data from trigger `single_muon_interaction_1`

- ECAL shows promising consistency in helping to identify elastic events **even when only *one* track is observed** (crucial for efficiency studies)

- With the tag&probe approach proposed efficiency as a function of electron angle can be estimated

- ⚠CAVEAT⚠: efficiency also contains the efficiency on signal events of the **selection cuts applied to define a "probed" electron**

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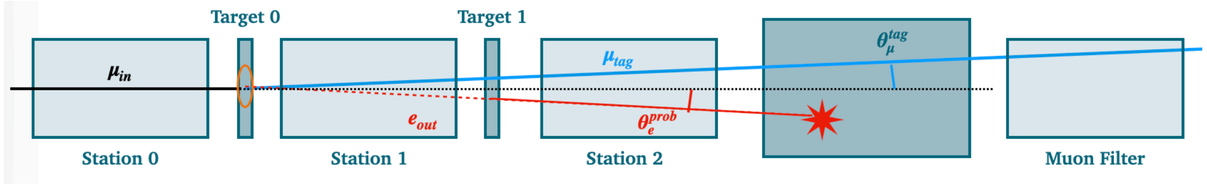
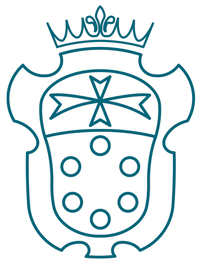
Conclusions and Outlook

- Next steps:
  - Increase statistics to better resolve low θ_e region
  - Explore region below $E_{ECAL} = 10$ GeV, manually building cluster centroid if needed
  - Use MC simulation of signal and background to evaluate the efficiency and purity of the selection cuts → could apply ***less*** cuts to not bias efficiency as much
  - Adapt selection cuts applied based on observed distributions (e.g. IP , modified acoplanarity, …)
  - **Measure efficiency in Station 1:**



    - Use tracks in Station 2 to tag the presence of an electron in Station 1
    - Less dependent on ECAL performance → can rely solely on tracker
    - Linking μ_{in} is S0 with $\mu_{out} + e_{out}$ in S2 and the μ_{out} tracks in S1 and S2 requires new dedicated reconstruction software (currently supported features)

Thank you!



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Backup

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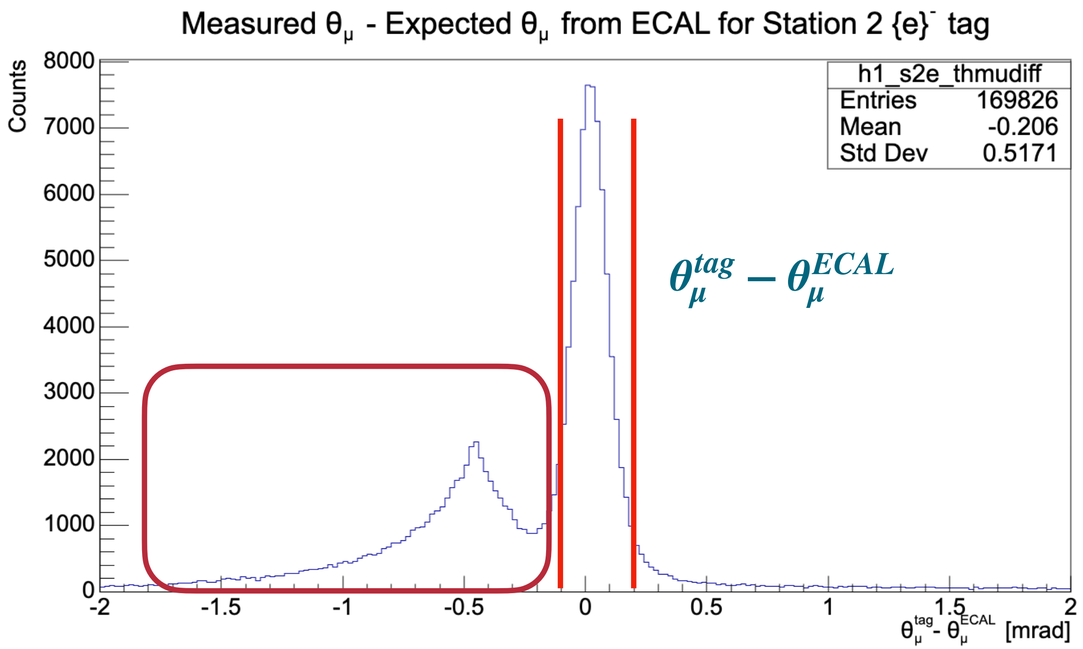
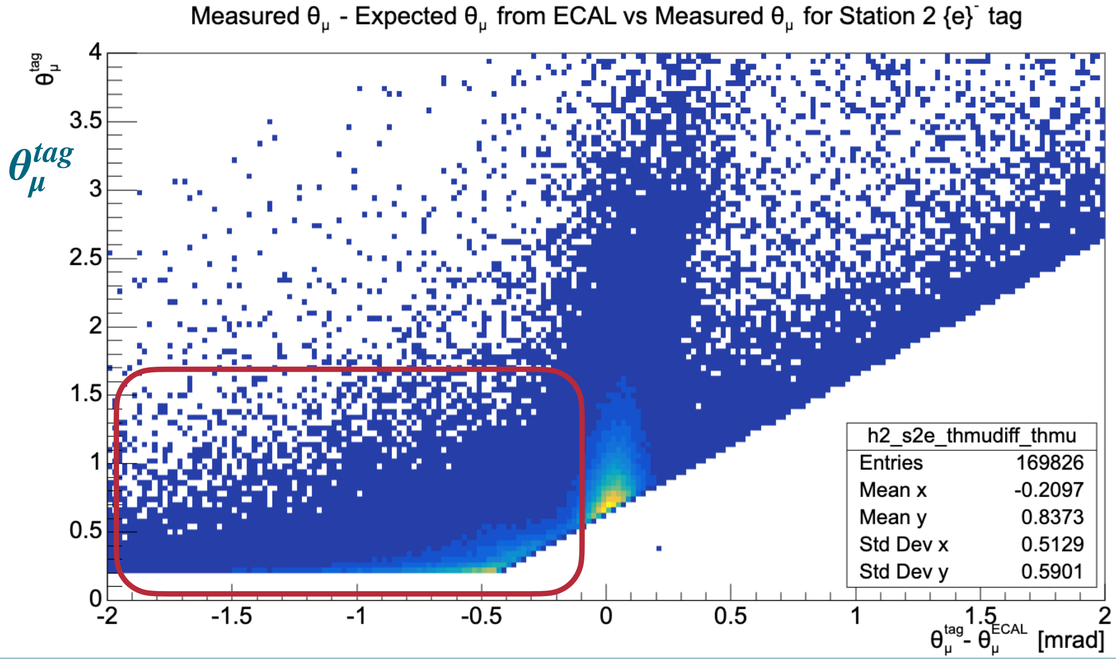
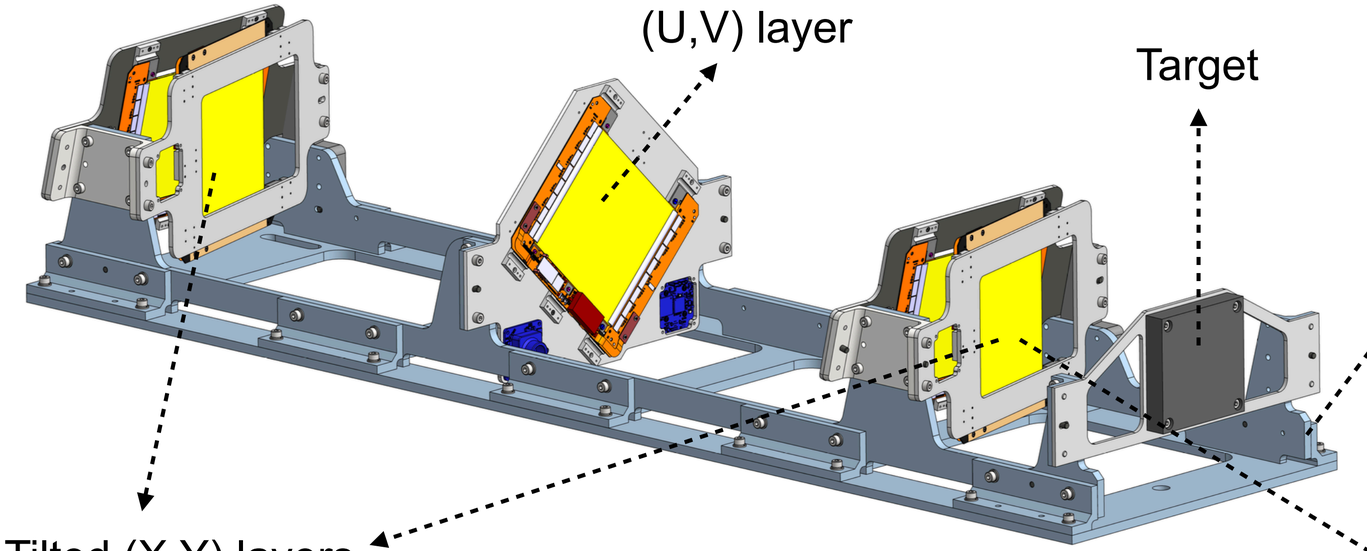
θ_μ^{tag} Discrepancy w.r.t. Elastic Prediction

- Discrepancy between θ_μ^{tag} and muon angle $\theta_\mu^{ECAL} \equiv \theta_\mu^{LO}\left(\theta_e^{LO}\left(E_{ECAL}\right)\right)$ expected from ECAL cluster energy ***before*** applying elastic cut on their difference
- Despite not having yet requested any elasticity for the muon (only number of tracks/hits and ECAL cluster), the ***central peak proves we are already seeing elastic events!***
- There is a left tail ($\theta_\mu^{tag} < \theta_\mu^{ECAL}$) and a peak around -0.5 mrad, mainly due to low θ_μ^{tag} events





Tracking Modules and Stations

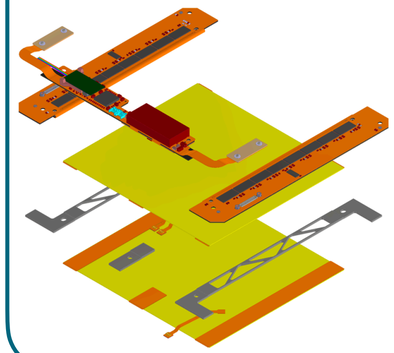


INVAR (Fe-Ni alloy) with CTE ~ 1.2 ppm/K

Relative positions must be controlled **at level of 10 µm!**

- Tilting the X and Y layers by 233 mrad improves hit resolution by a factor ~2
- (U,V) layer to solve reconstruction ambiguities

2S Modules (CMS Phase2 Upgrade)

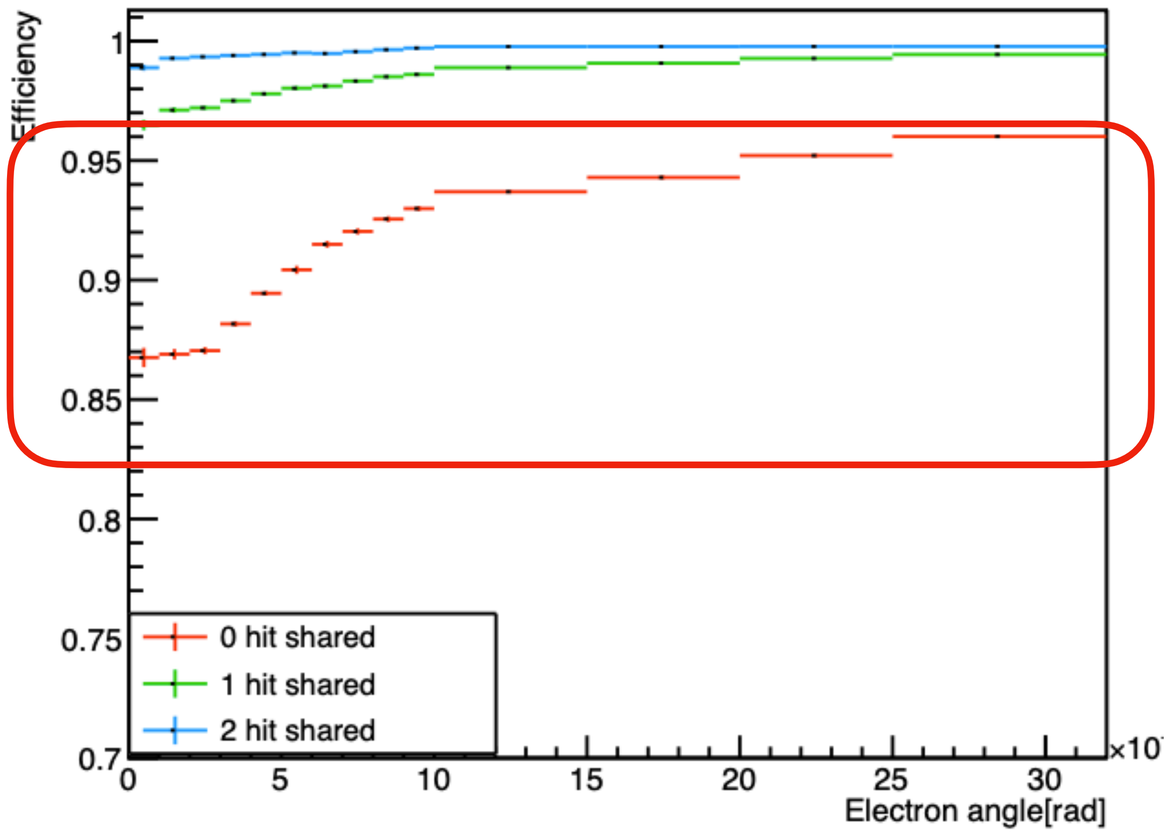


- ~90 cm^2 active area
- 2 strip sensors 1.8 mm apart
- 320 µm thickness
- 40 MHz binary readout
- 90 µm strip pitch (~26 µm hit resolution)

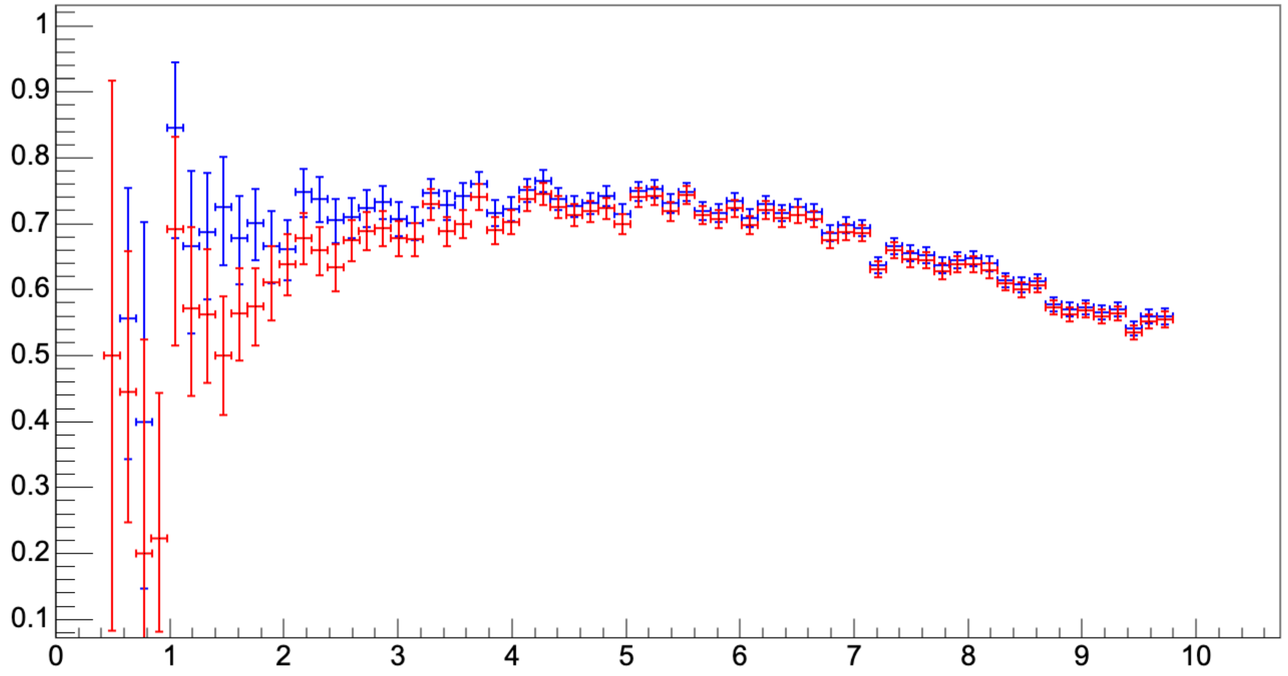
TDR CMS Tracker Phase2 Upgrade

Eugenia's Results on MC

From Eugenia's PhD Thesis



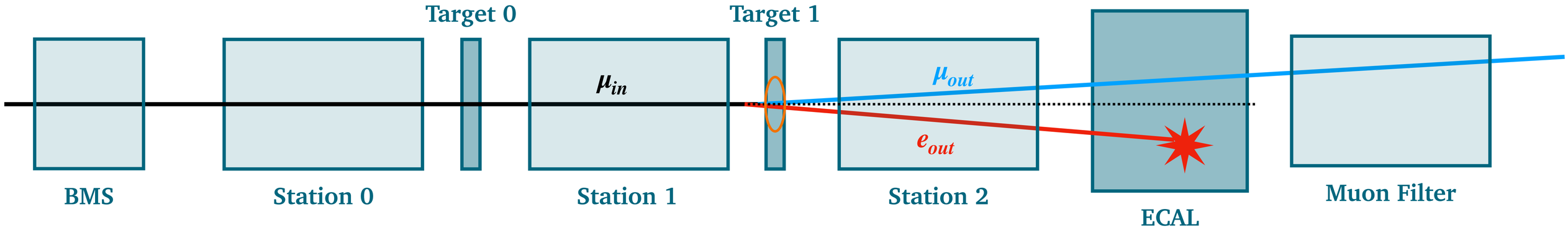
$$\varepsilon(e_{prob}\,|\,\mu_{tag}) = \frac{N(\mu_{tag} \cap e_{prob})}{N(\mu_{tag})}$$



θ_e^{ECAL} [mrad]

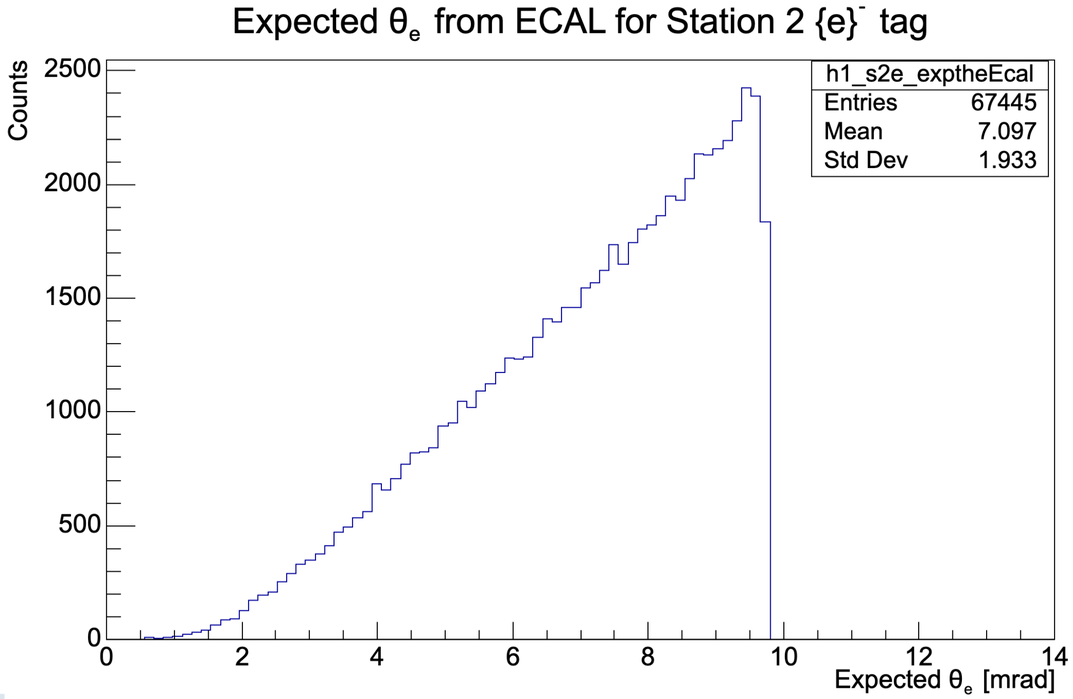
Figure 3.3: Single particle reconstruction efficiency for muon (left) and electron (right) as a function of the lepton scattering angle. The behavior with the three different configurations for the maximum allowed number of shared hits is shown (0,1,2).

Eugenia's Results on MC

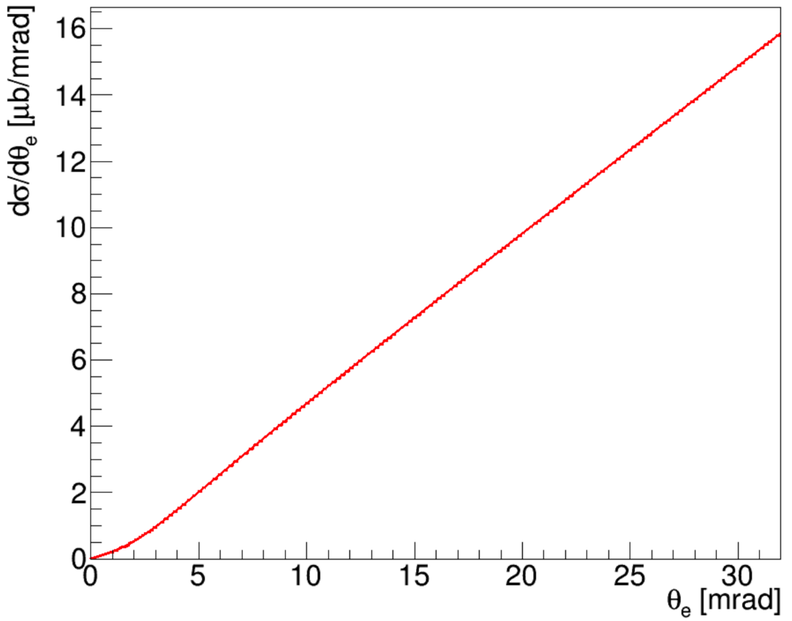


Electron Expectation After μ Elasticity Cut

- 1D distribution of expected θ_e^{ECAL} ***after*** elastic cut on $\theta_\mu^{tag} - \theta_\mu^{ECAL}$
- It look as expected, but this is by definition because of our cuts for signal events
- However background events passing the cuts would distort the shape, so purity shouldn't be horrible (expected also from Katie Ferraby's studies)



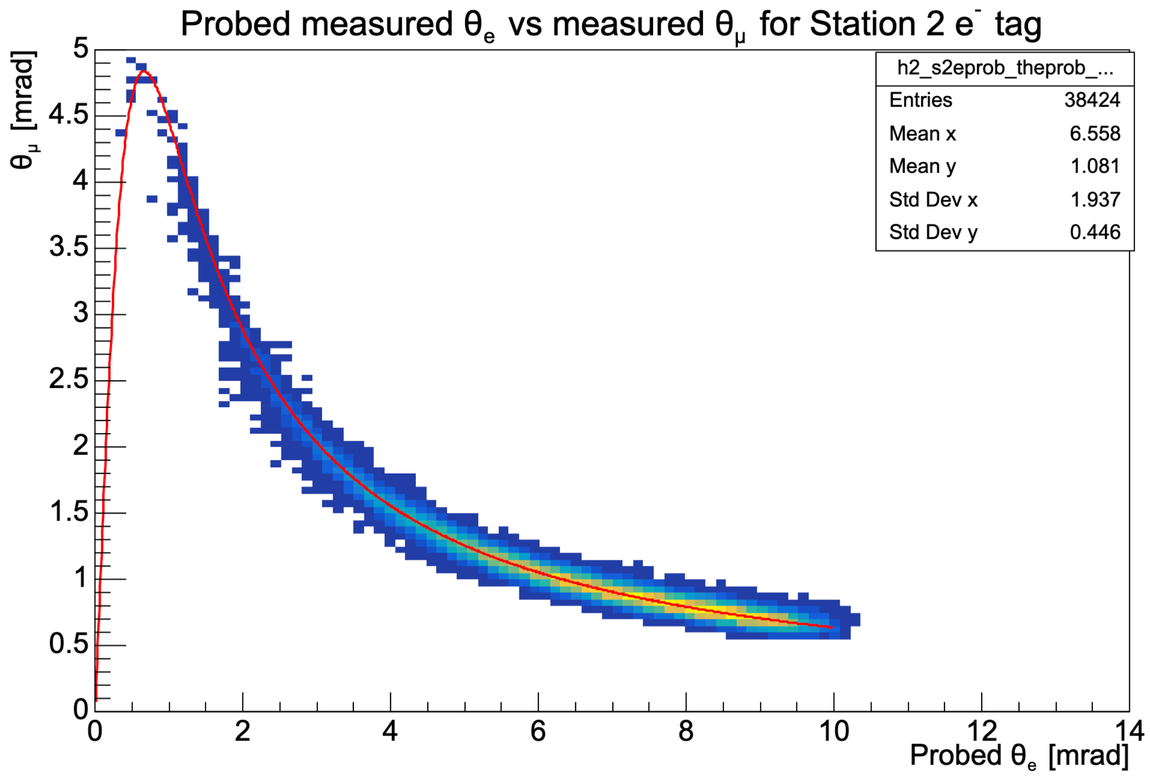
Expected LO behaviour

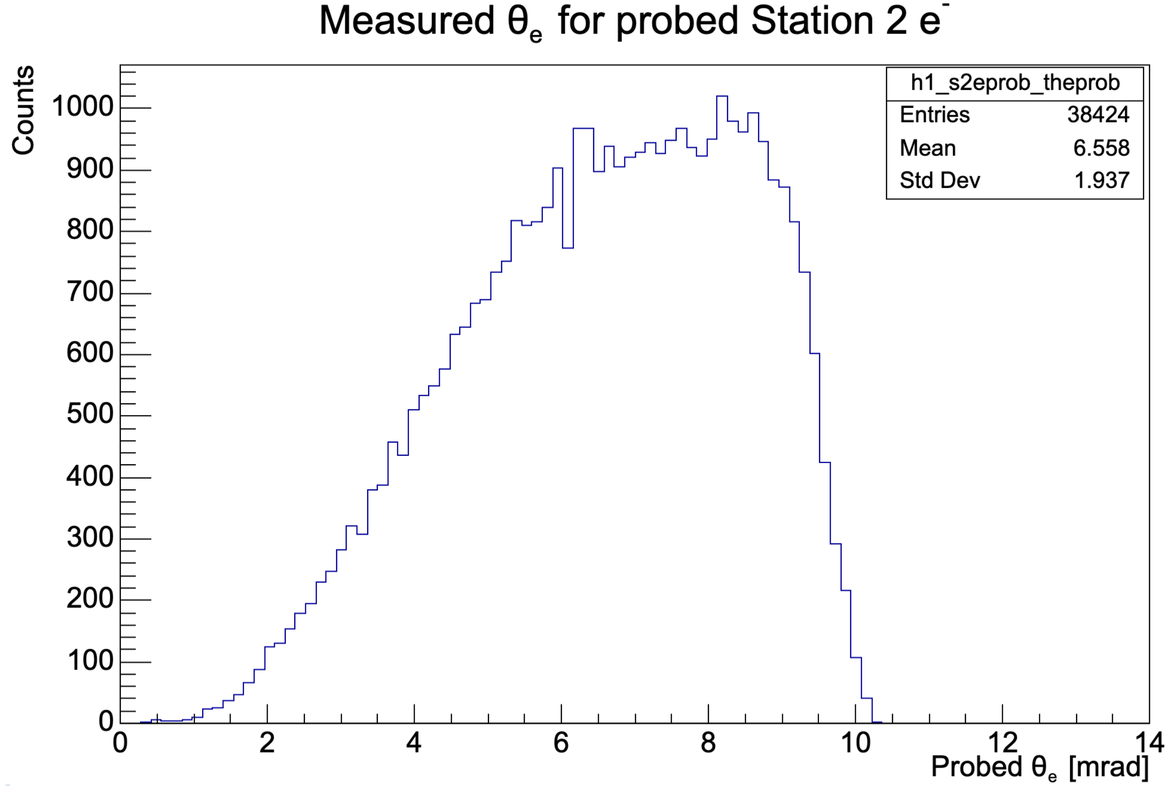


Angles After e^- Elasticity Cut

- Distribution of measured probed electron angle θ_e^{prob} and tag muon angle θ_μ^{tag} ***after*** elastic cut on $\theta_e^{prob} - \theta_e^{ECAL}$

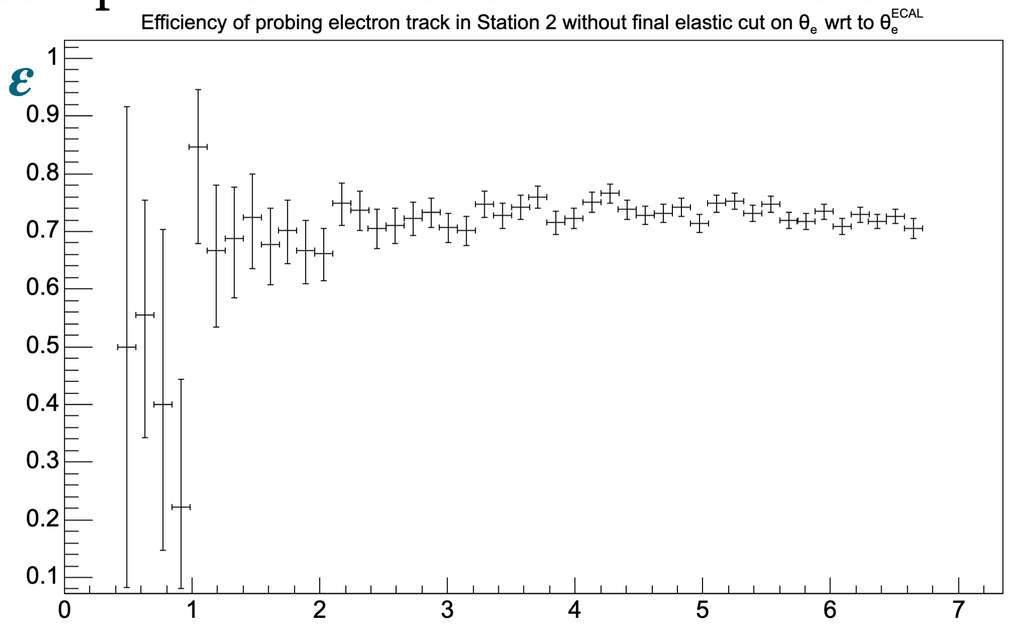
- Elastic behaviour has been clearly imposed by our cuts, irregular distribution of θ_e^{prob} observed



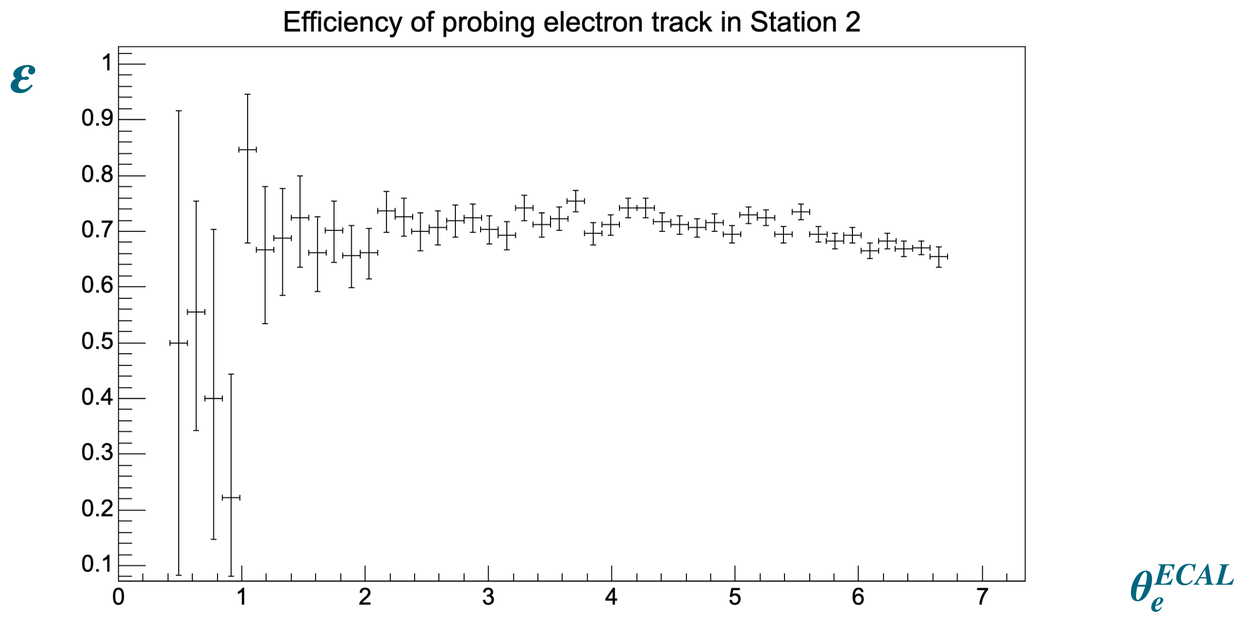


Efficiencies with $E_{ECAL} < 20$ GeV

- Efficiency of probing the electron ***without imposing elasticity*** wrt ECAL (only cut on ECAL centroid position and IP with tagging muon) given the presence of a tagging muon compatible with elastic ECAL cluster



- Efficiency of probing the electron ***after imposing elasticity*** wrt ECAL given the presence of a tagging muon compatible with elastic ECAL cluster



- Efficiencies must be expressed as a function of the ***expected*** electron angle → needs to be defined even when there is no probed track!

Electron Discrepancy w.r.t. Elastic Prediction

- Discrepancy between θ_e^{prob} and electron angle $\theta_e^{ECAL} \equiv \theta_e^{LO}\left(E_{ECAL}\right)$ expected from ECAL cluster energy ***before*** elastic cut on electron angle

- Despite not having yet requested any elasticity for the electron, the ***central peak proves we are already selecting elastic events!***

- The cut can be improved by selecting on the difference between θ_μ^{tag} and muon angle expected from measured electron angle $\theta_\mu^{ele} \equiv \theta_\mu^{LO}(\theta_e^{prob}) \longrightarrow$ ***better resolution*** because it only relies on tracker

$\theta_e^{prob} - \theta_e^{ECAL}$