Experimental and synthetic measurements of polarized synchrotron emission from runaway electrons in Alcator C-Mod

RA Tinguely, RS Granetz, RT Mumgaard MIT PSFC

M Hoppe, O Embréus, T Fülöp Chalmers

S Scott PPPL

7th Meeting on Runaway Electron Modeling

15-18 January 2019

PSFC

CHALMERS

PPPL

Alcator C-Mod is a **high-field**, **compact** tokamak located at MIT

$R_0 = 68$ cm

$a = 22$ cm

$B_0 = 2\text{-}8$ T

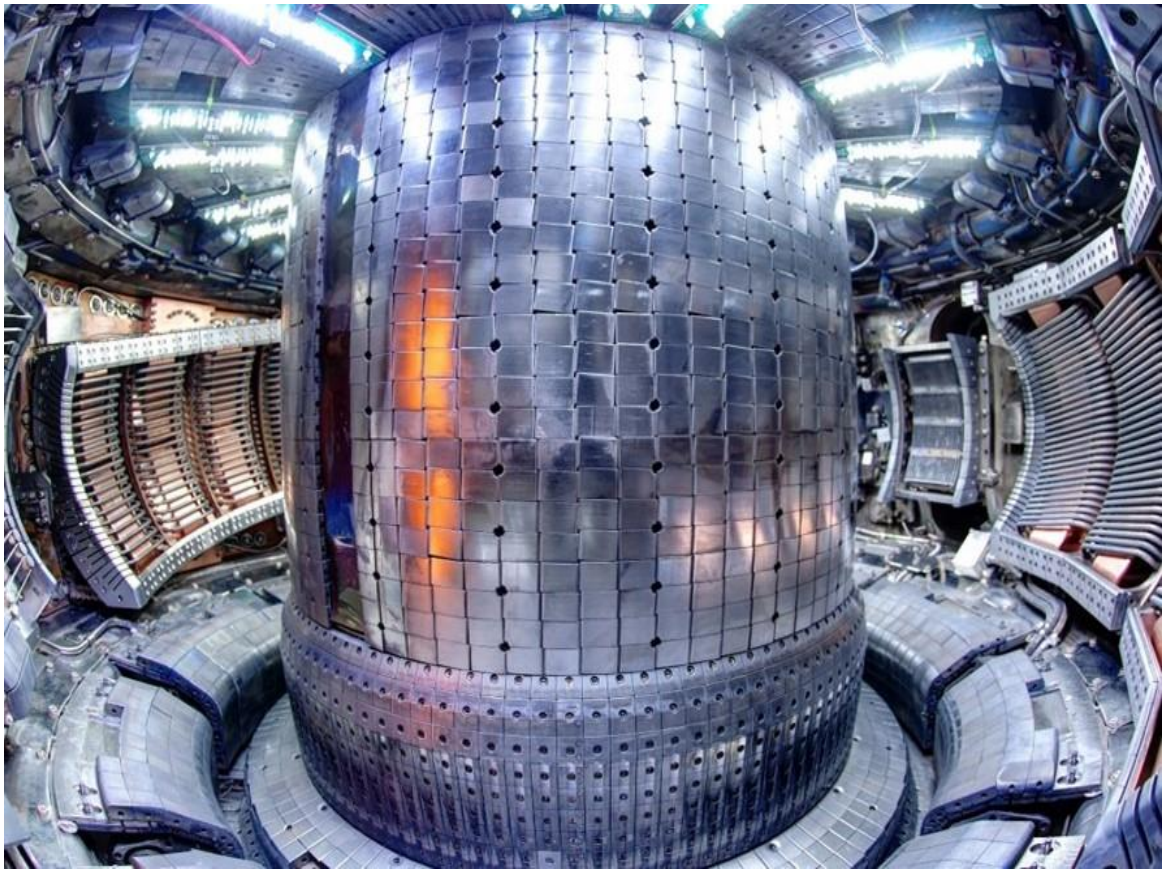
$I_P = 1\text{-}2$ MA

$n_e \sim 10^{20}$ m^{-3}

Mo walls

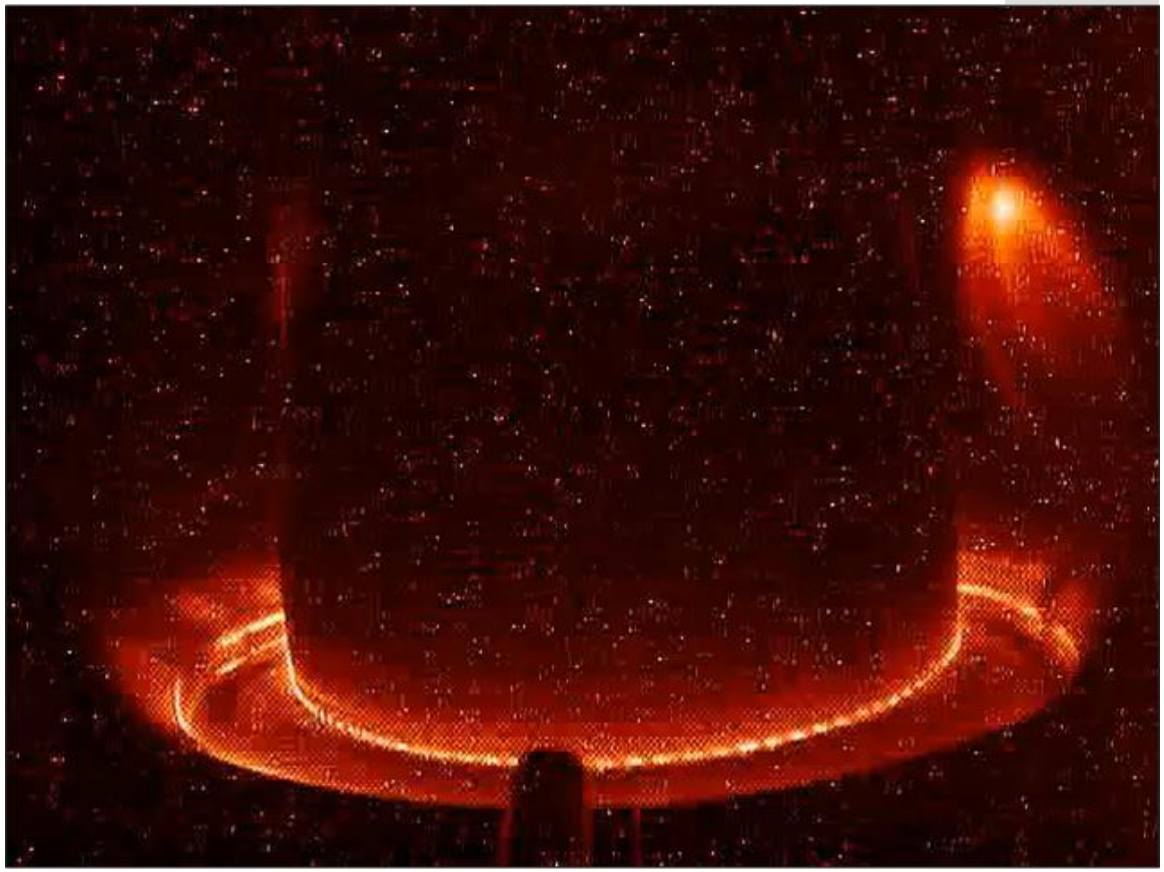
Diverted

RF heated



Runaway electron (RE) synchrotron emission is **visible** in Alcator C-Mod

Exp



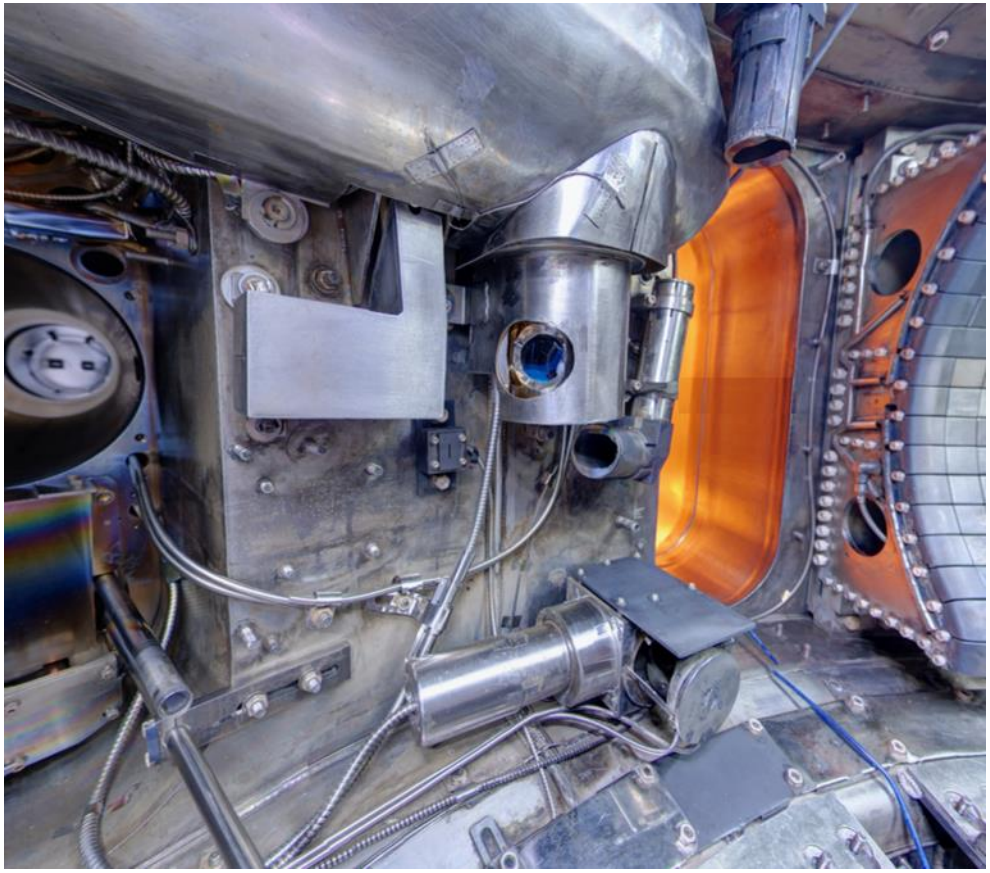
Outline

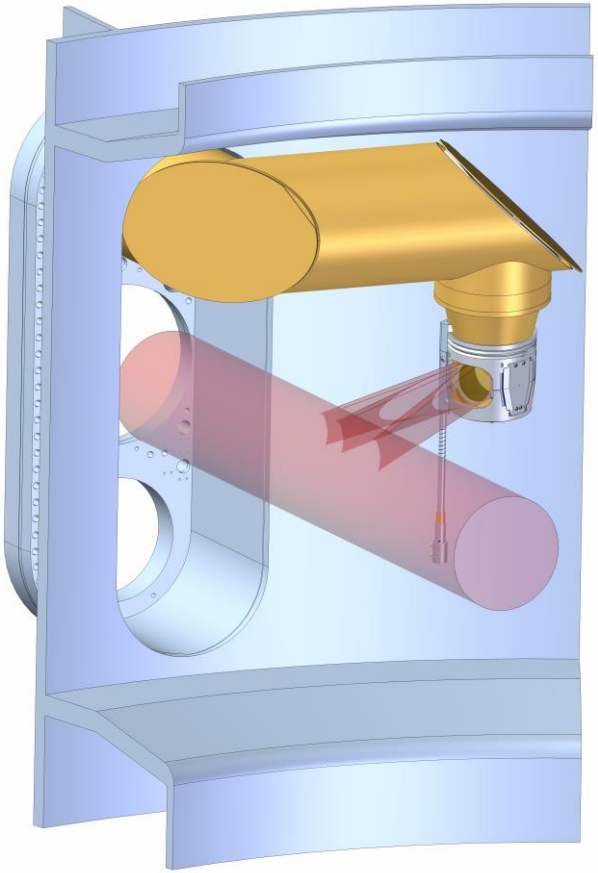
1. MSE diagnostic
2. Experimental data
3. Synthetic (SOFT) data
4. Comparing data
5. Future work

Outline

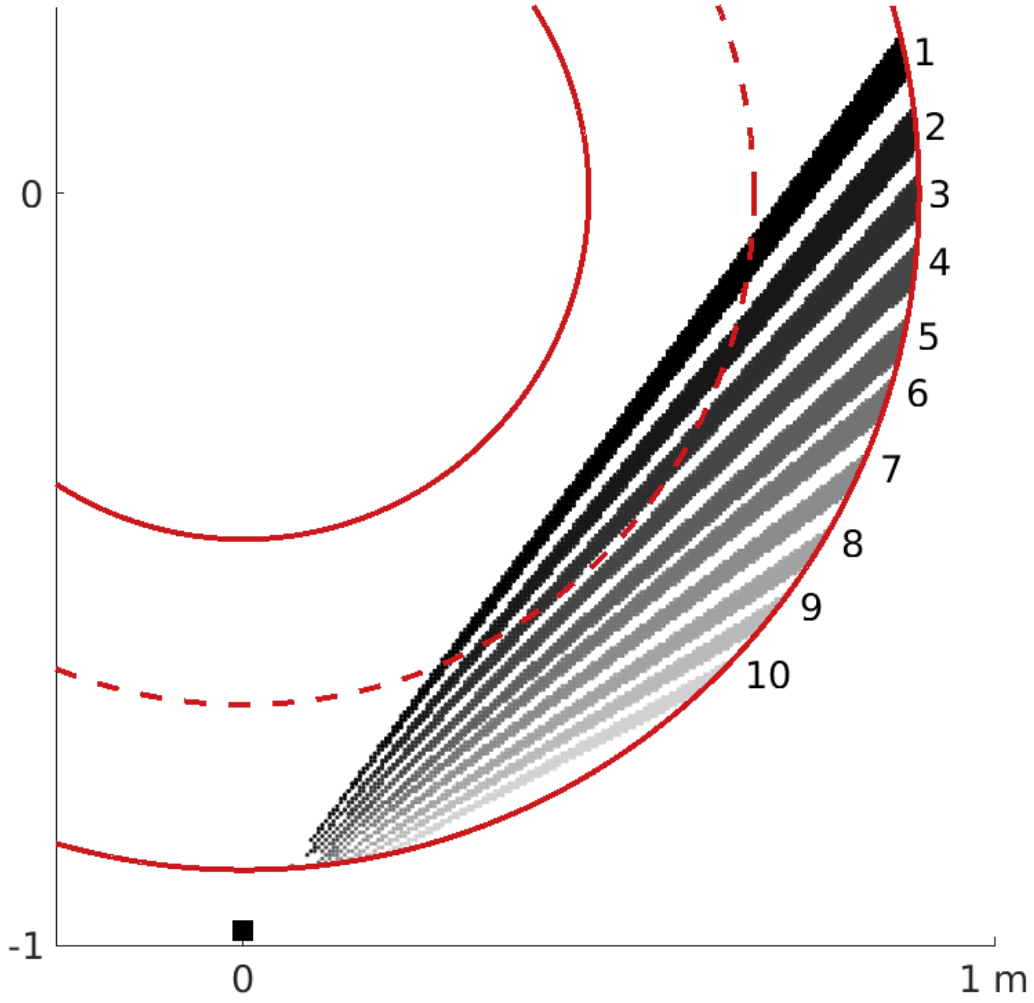
1. MSE diagnostic
2. Experimental data
3. Synthetic (SOFT) data
4. Comparing data
5. Future work

10-channel motional Stark effect (MSE) diagnostic views plasma **midplane**

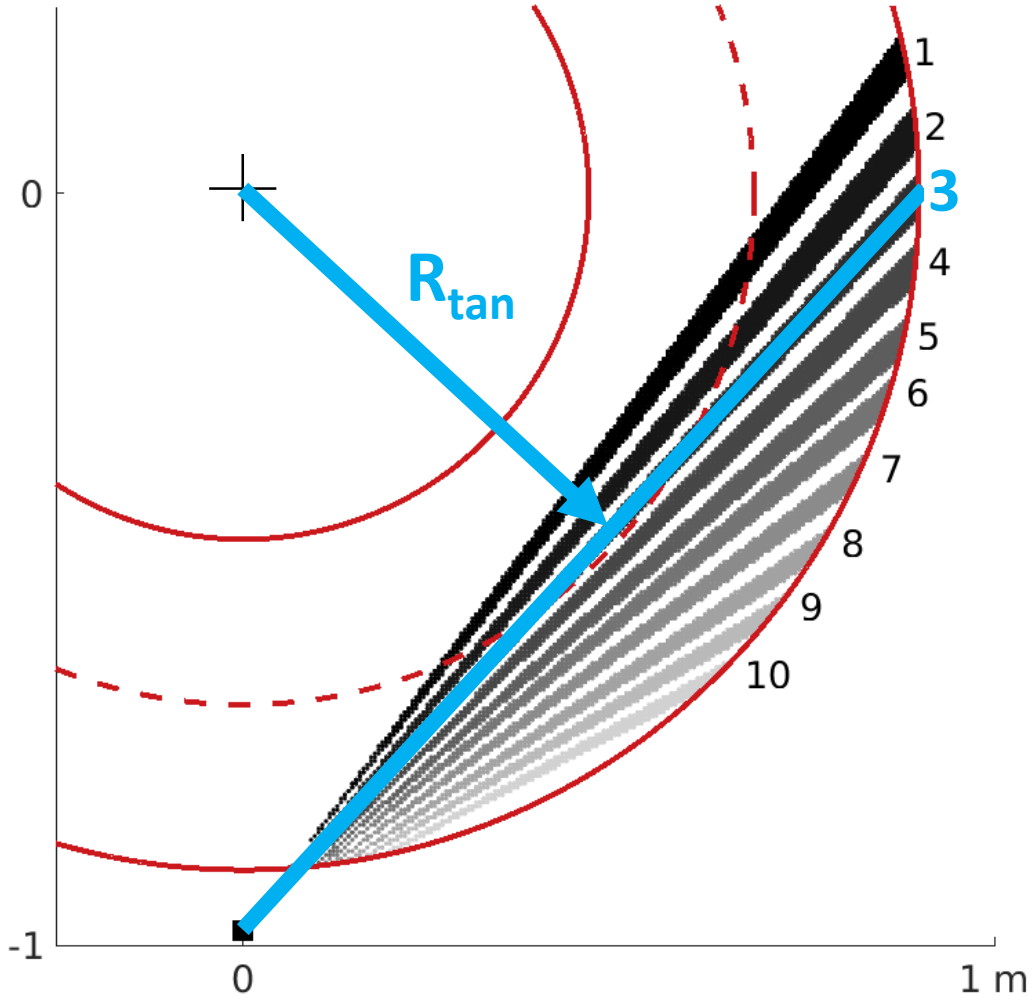




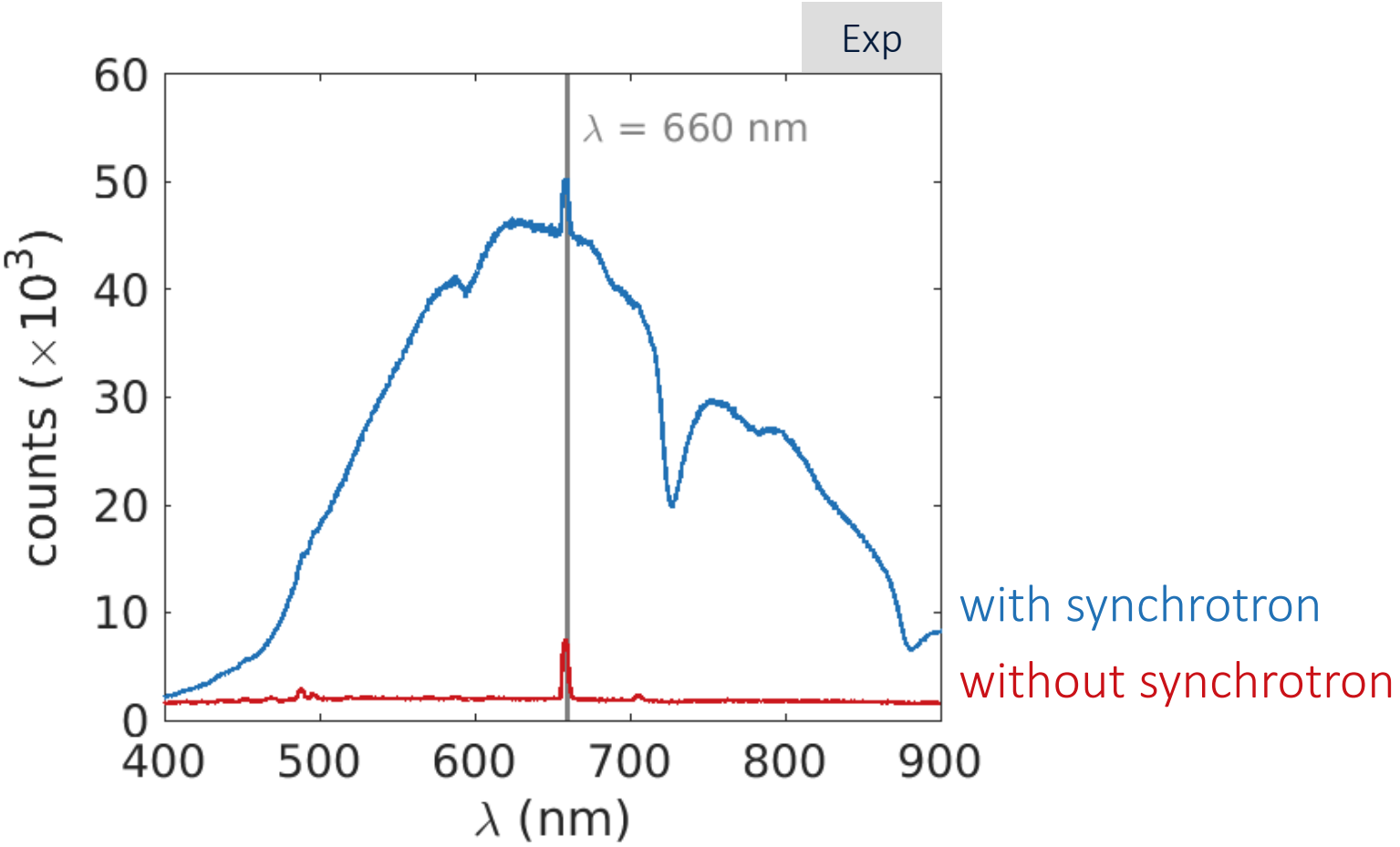
MSE system measures radial profile of **visible**, **linearly-polarized** light at λ = 660 nm



A line-of-sight lies **tangent** to a circular orbit at its **tangency radius**, R_{tan}

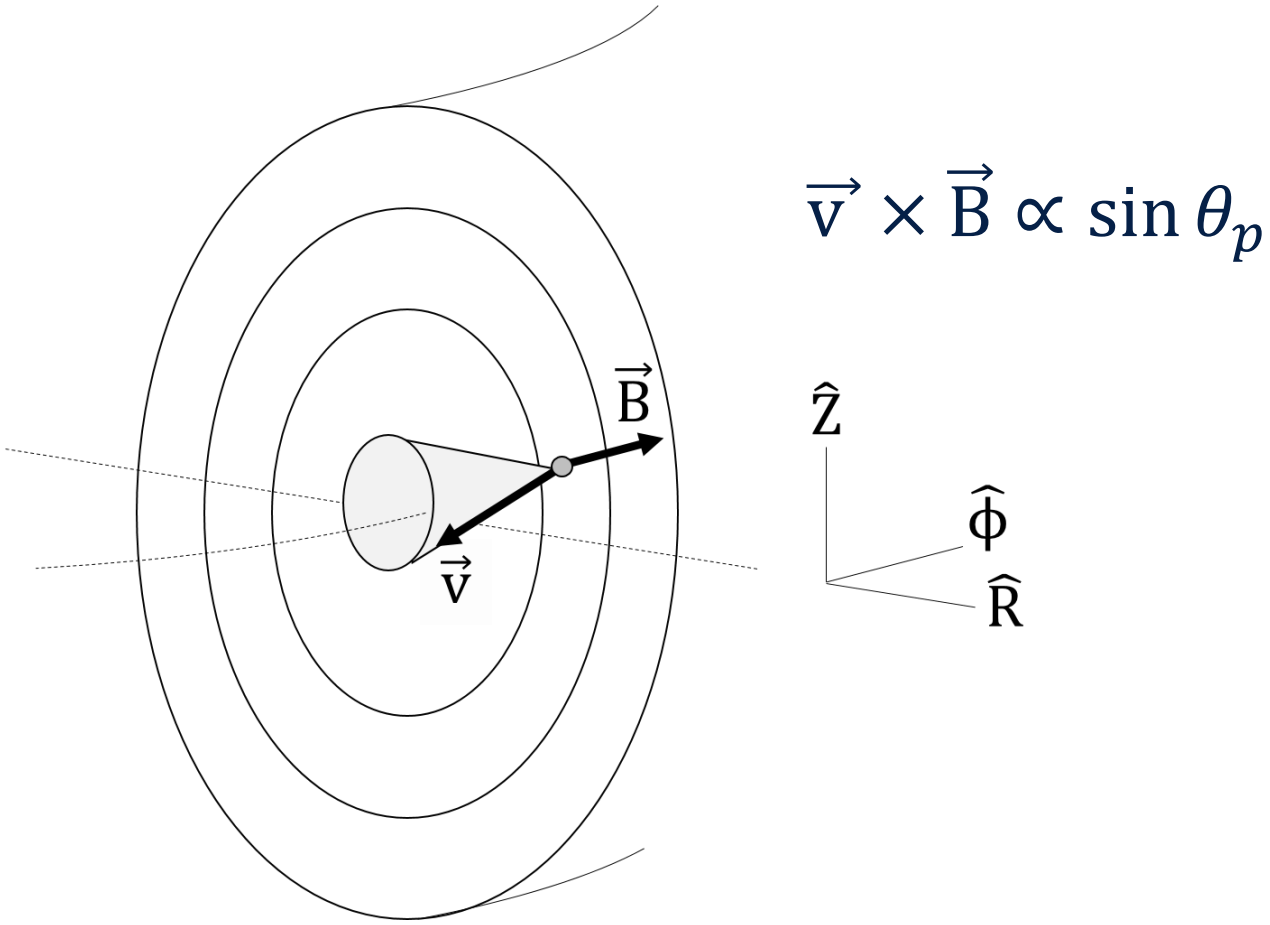


Synchrotron emission **dominates** measurement of visible light*



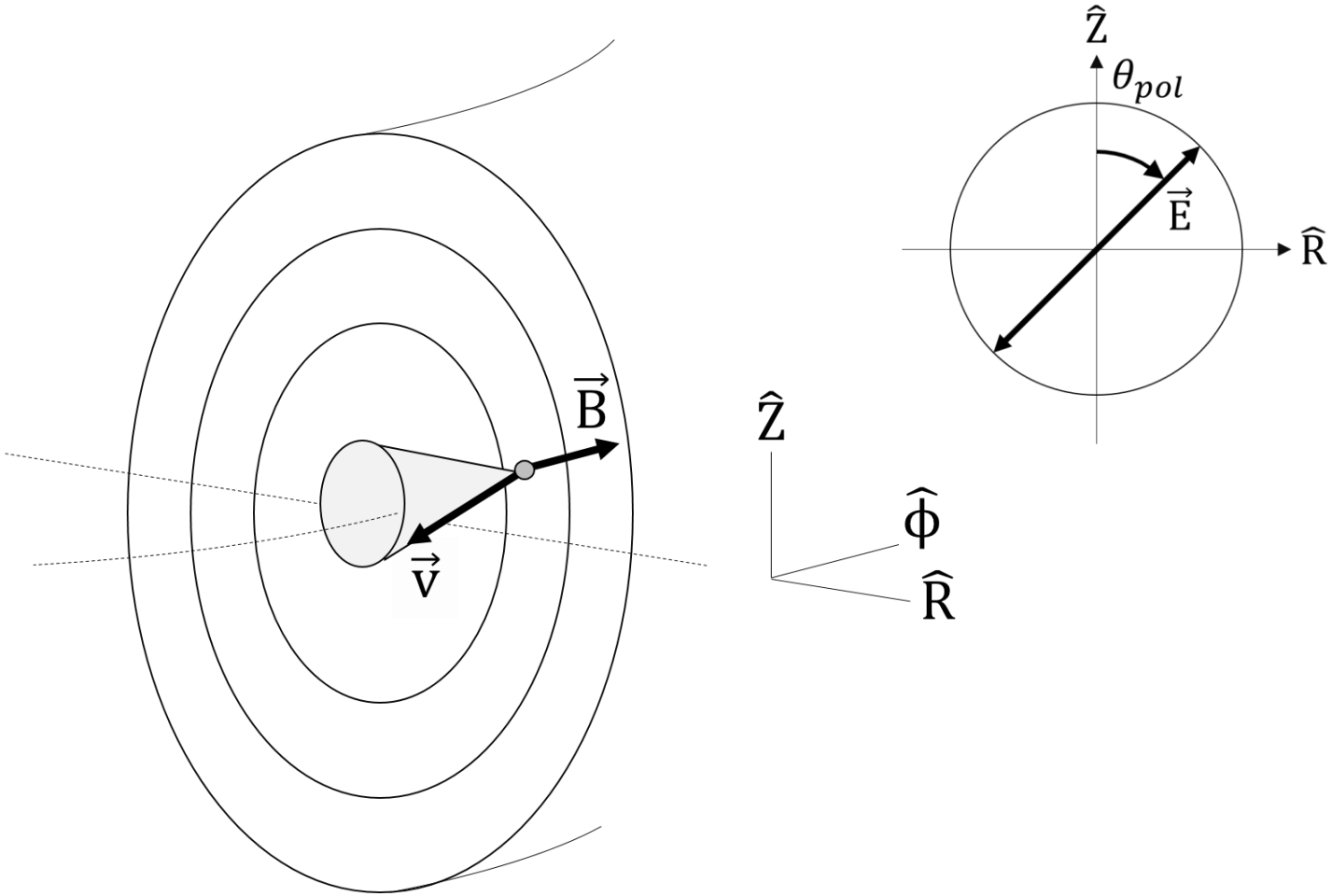
*Note: The diagnostic neutral beam is **off** during these discharges.

Synchrotron emission is **polarized** primarily in the direction of RE **acceleration**, $\vec{a} \sim \vec{v} \times \vec{B}$

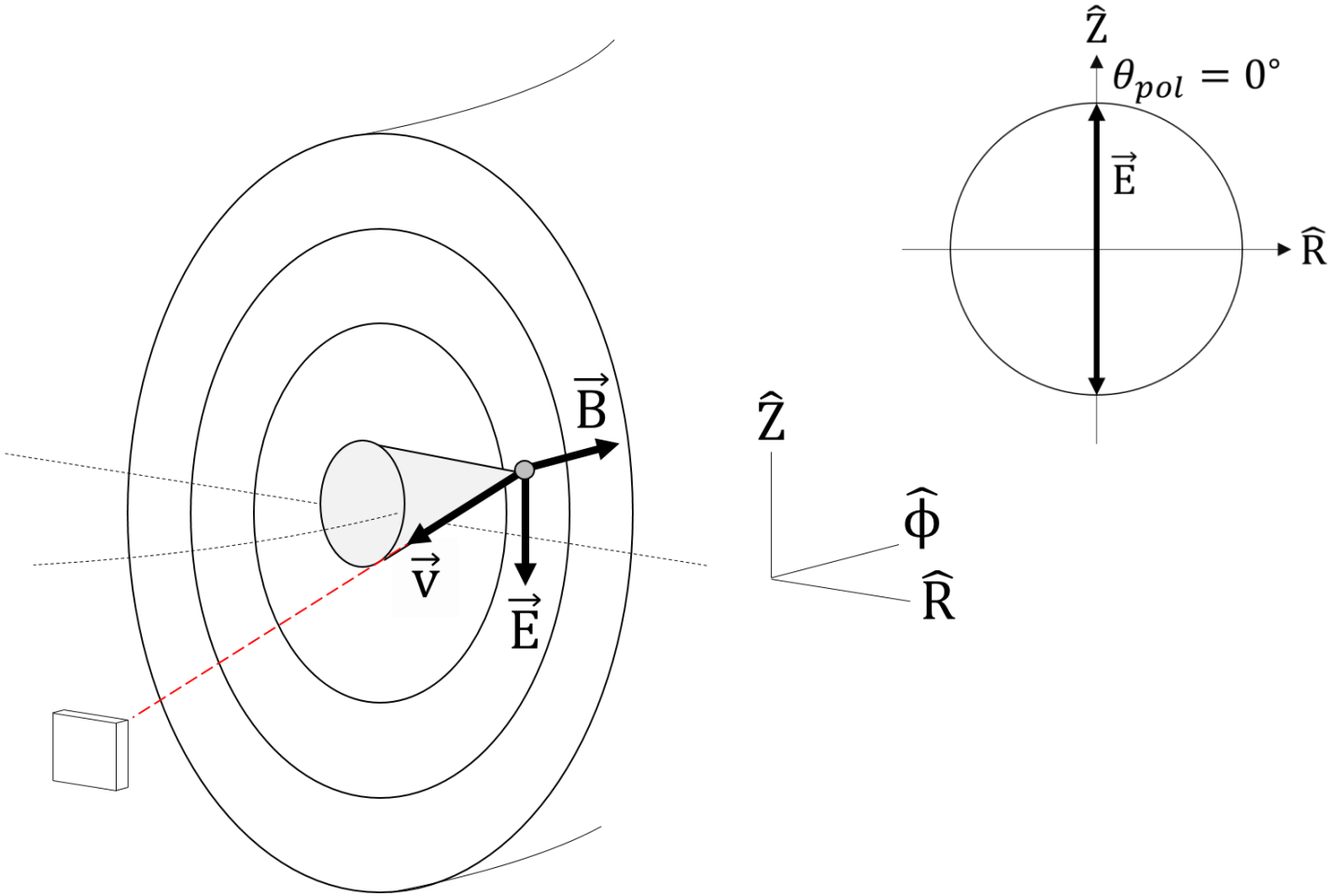


$$\vec{v} \times \vec{B} \propto \sin\theta_p$$

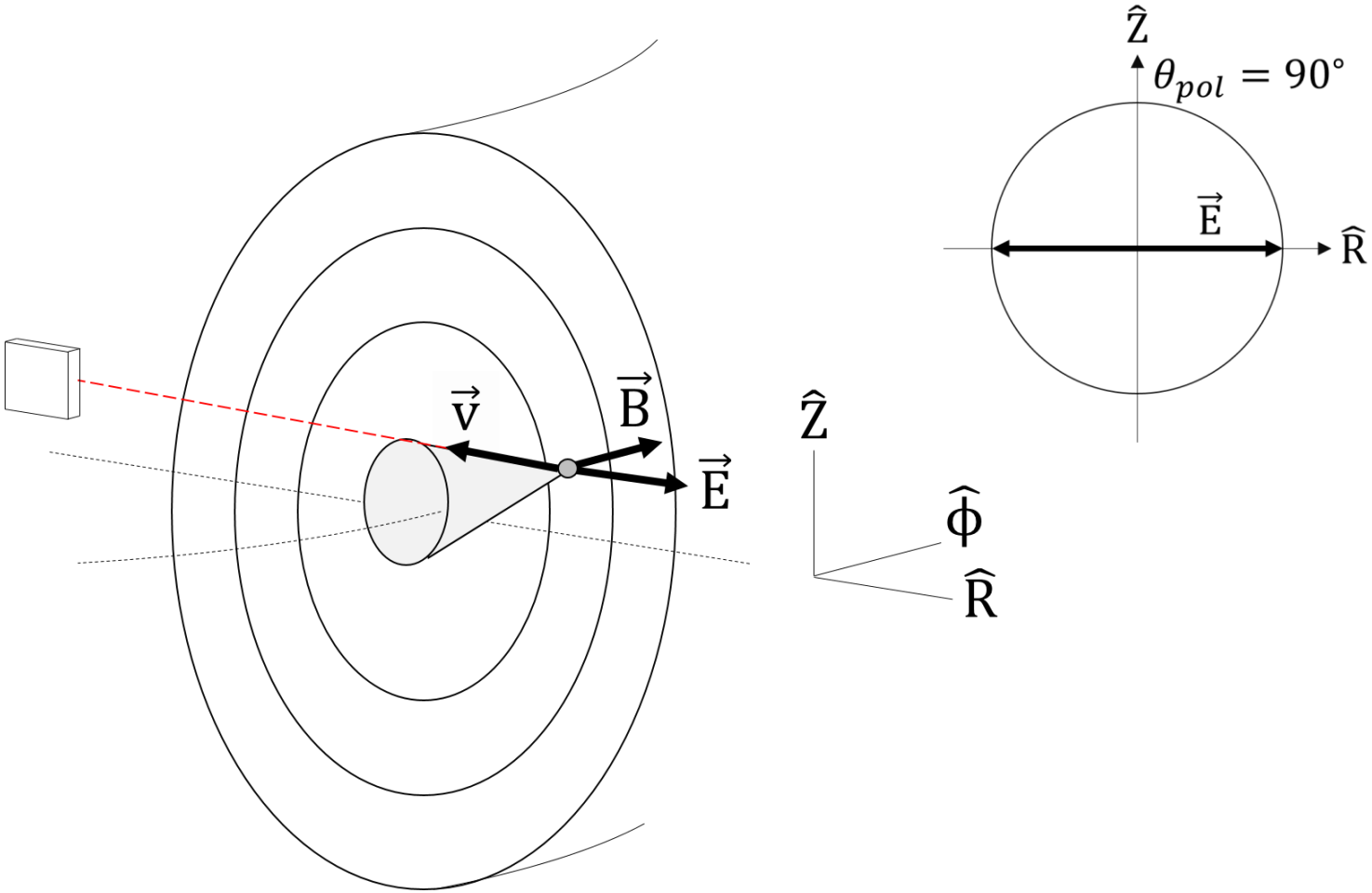
The polarization angle, θ_{pol}, is measured **clockwise** from the **vertical axis**



This **midplane** detector could see **vertically** polarized emission, $\theta_{pol} = 0°$



An **off-axis** detector could see **horizontally** polarized emission, $\theta_{pol} = 90°$



Stokes parameters encode all polarization information

$$\vec{E} = E_x\,\hat{x} + E_y\,\hat{y} \quad \begin{cases} I = E_x\,E_x^* + E_y\,E_y^* & \text{total intensity} \\ Q = E_x\,E_x^* - E_y\,E_y^* \\ U = 2\,\mathrm{Re}(E_x\,E_y^*) \\ V = -2\,\mathrm{Im}(E_x\,E_y^*) \end{cases}$$

Stokes parameters encode all polarization information

$$\vec{E} = E_x\,\hat{x} + E_y\,\hat{y}$$

$$\begin{cases} I = E_x\,E_x^* + E_y\,E_y^* & \text{total intensity} \\ Q = E_x\,E_x^* - E_y\,E_y^* \\ U = 2\,\mathrm{Re}(E_x\,E_y^*) \\ V = -2\,\mathrm{Im}(E_x\,E_y^*) \end{cases}$$

$$L = \sqrt{Q^2 + U^2}$$ intensity of linearly polarized light

$$f_{pol} = L/I$$ fraction of linearly polarized light

$$\tan(2\,\theta_{pol}) = U/Q$$ polarization angle

Stokes parameters encode all polarization information

$$\vec{E} = E_x\,\hat{x} + E_y\,\hat{y} \quad \begin{cases} I = E_x\,E_x^* + E_y\,E_y^* & \text{total intensity} \\ Q = E_x\,E_x^* - E_y\,E_y^* \\ U = 2\,\mathrm{Re}(E_x\,E_y^*) \\ V = -2\,\mathrm{Im}(E_x\,E_y^*) \end{cases}$$

$L = \sqrt{Q^2 + U^2}$ intensity of linearly polarized light

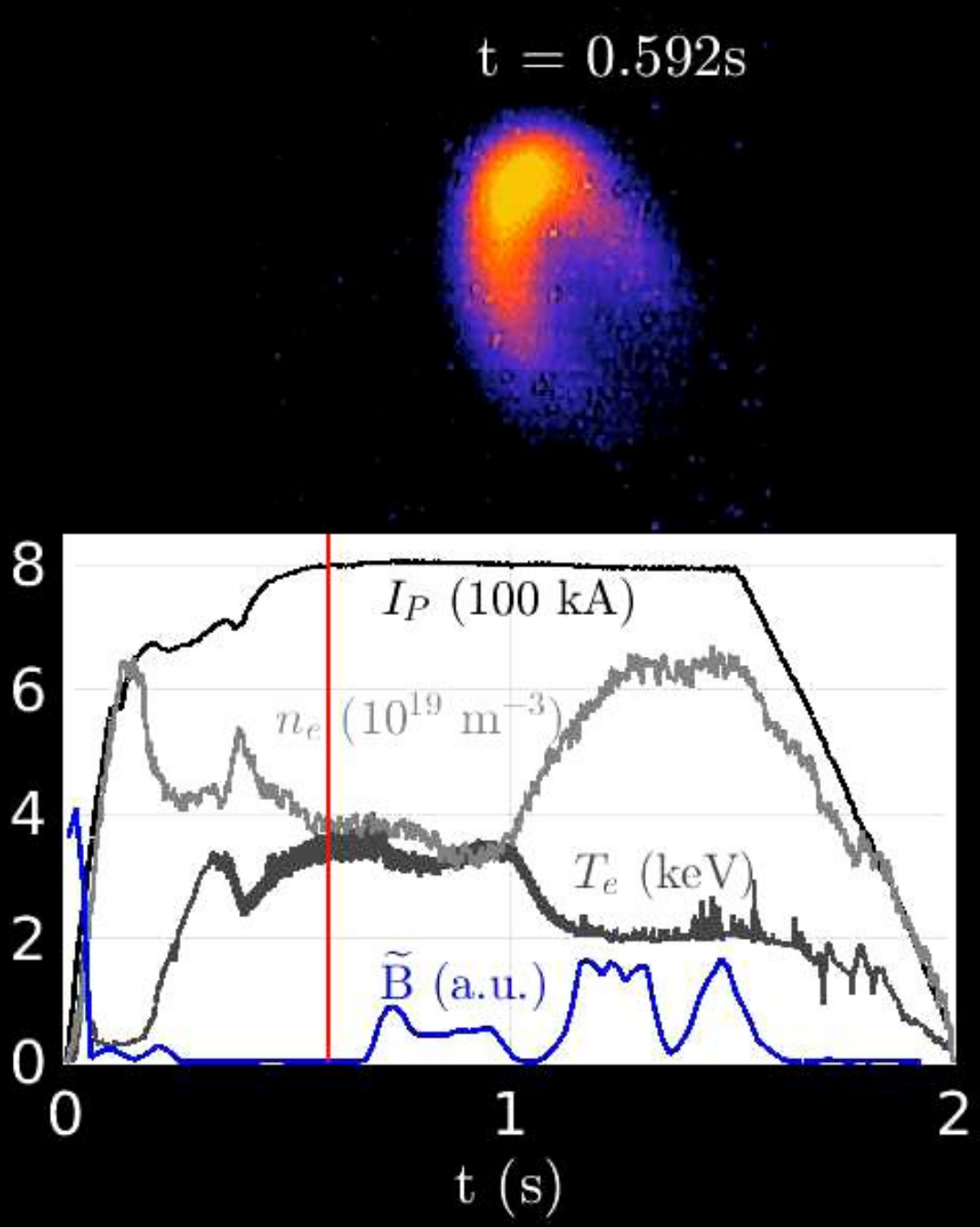
$\mathbf{f_{pol} = L/I}$ fraction of linearly polarized light

$\mathbf{\tan(2\,\theta_{pol}) = U/Q}$ polarization angle

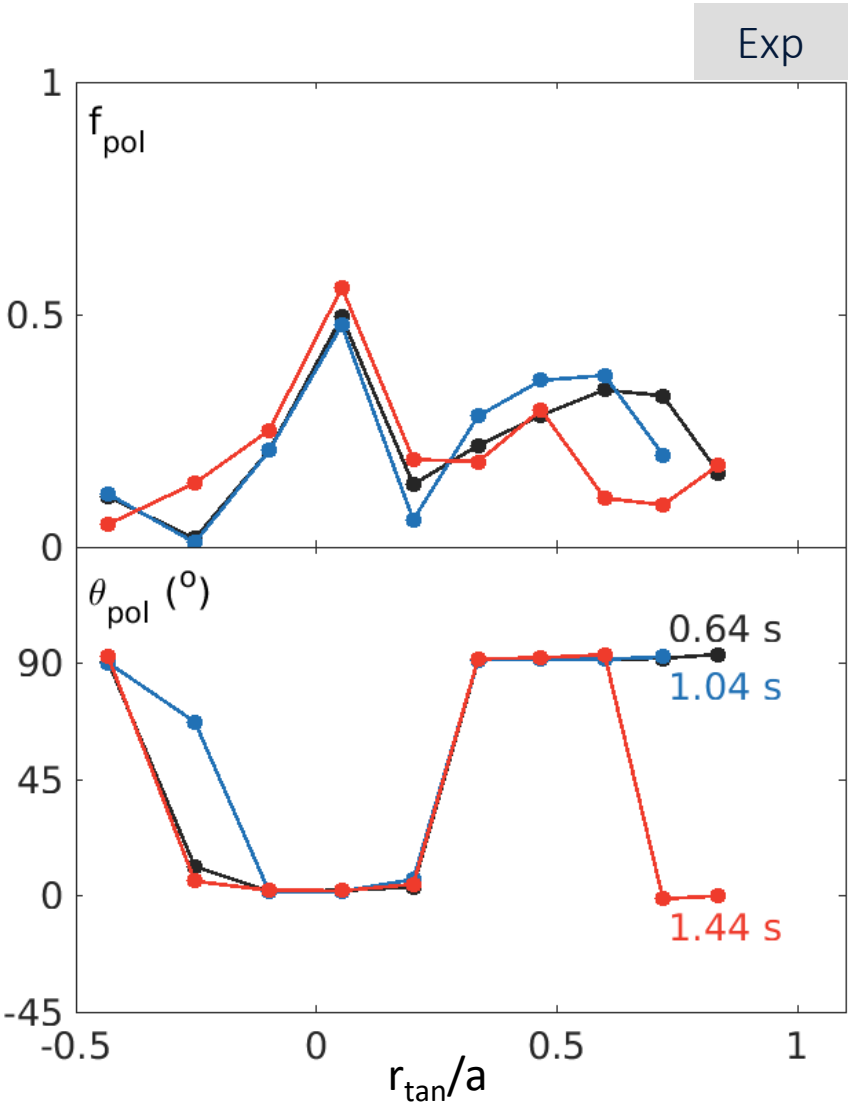
Outline

1. MSE diagnostic
2. Experimental data
3. Synthetic (SOFT) data
4. Comparing data
5. Future work

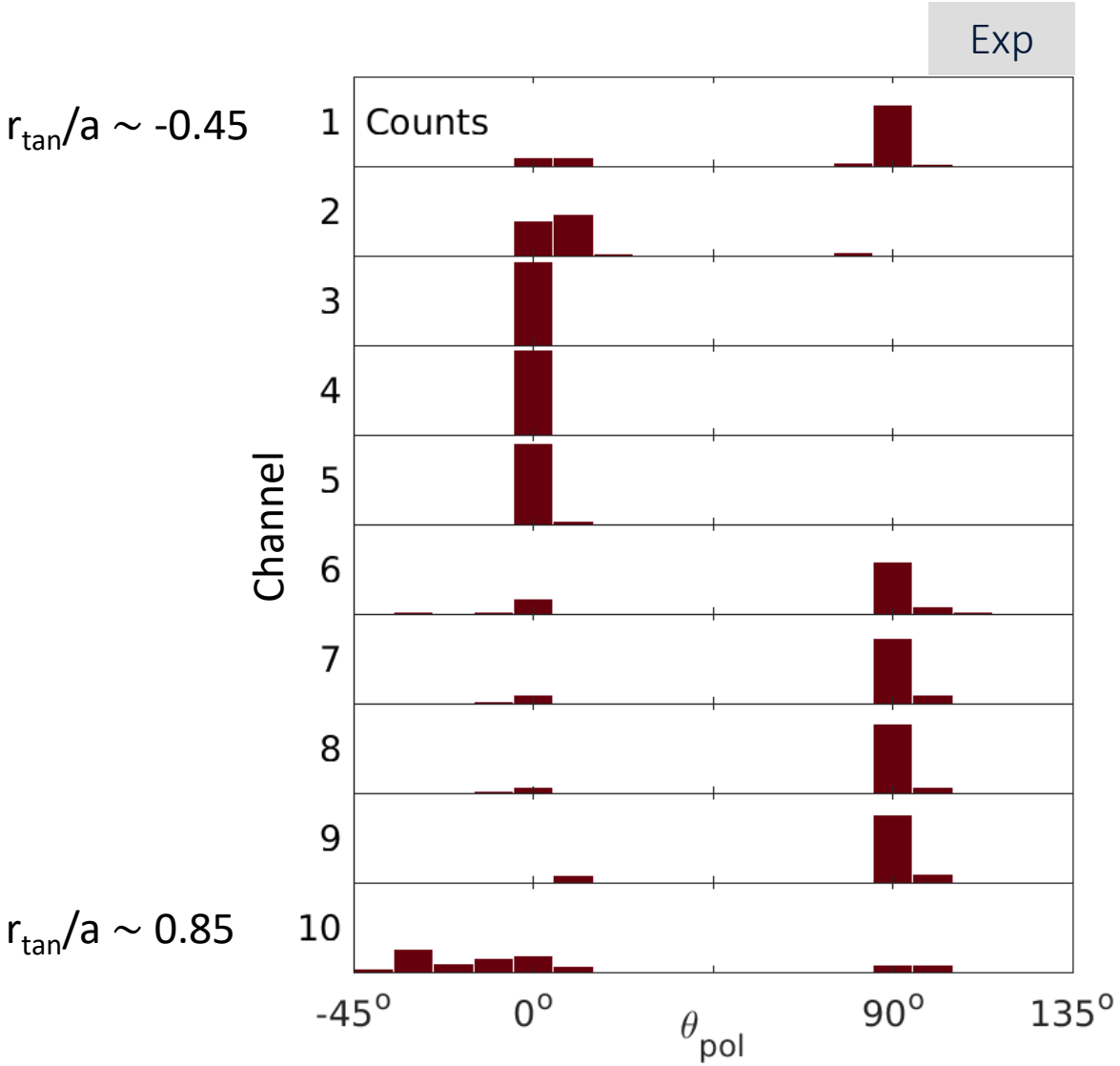
Exp



Experimental data show interesting **spatial/temporal features**



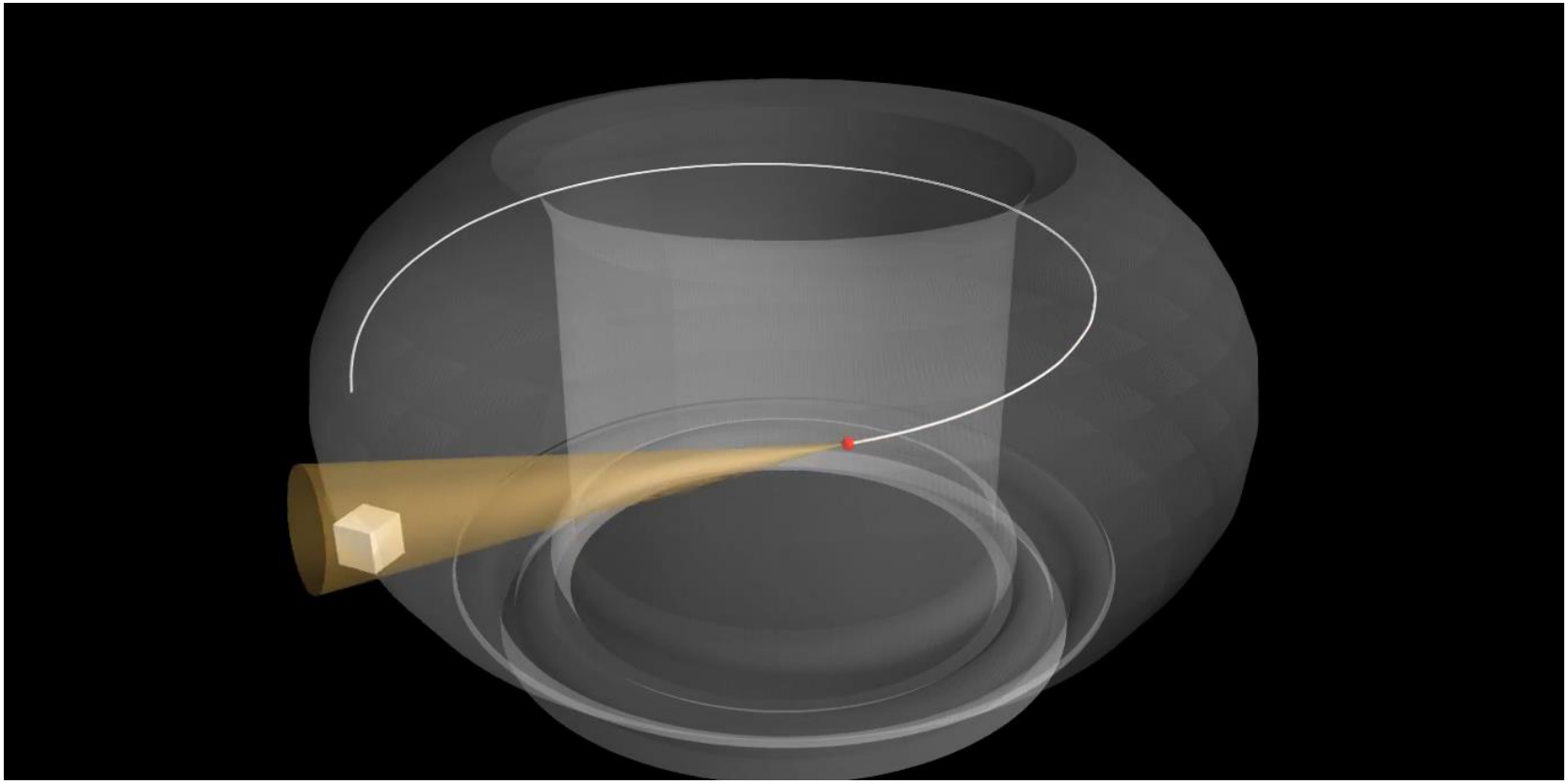
Data from 20+ plasma discharges indicate **strong dependence** on **geometry**



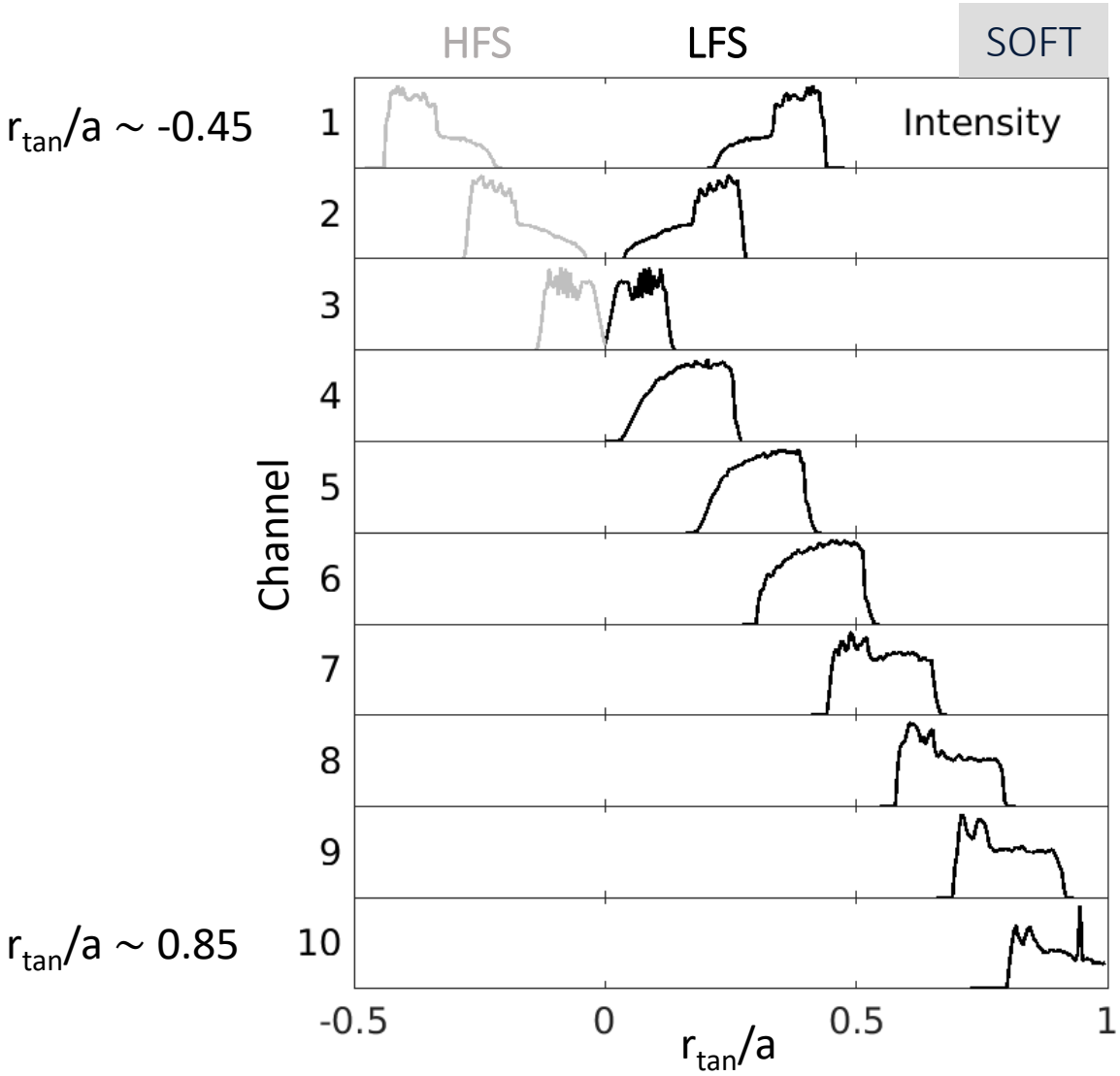
Outline

1. MSE diagnostic
2. Experimental data
3. **Synthetic (SOFT) data**
4. Comparing data
5. Future work

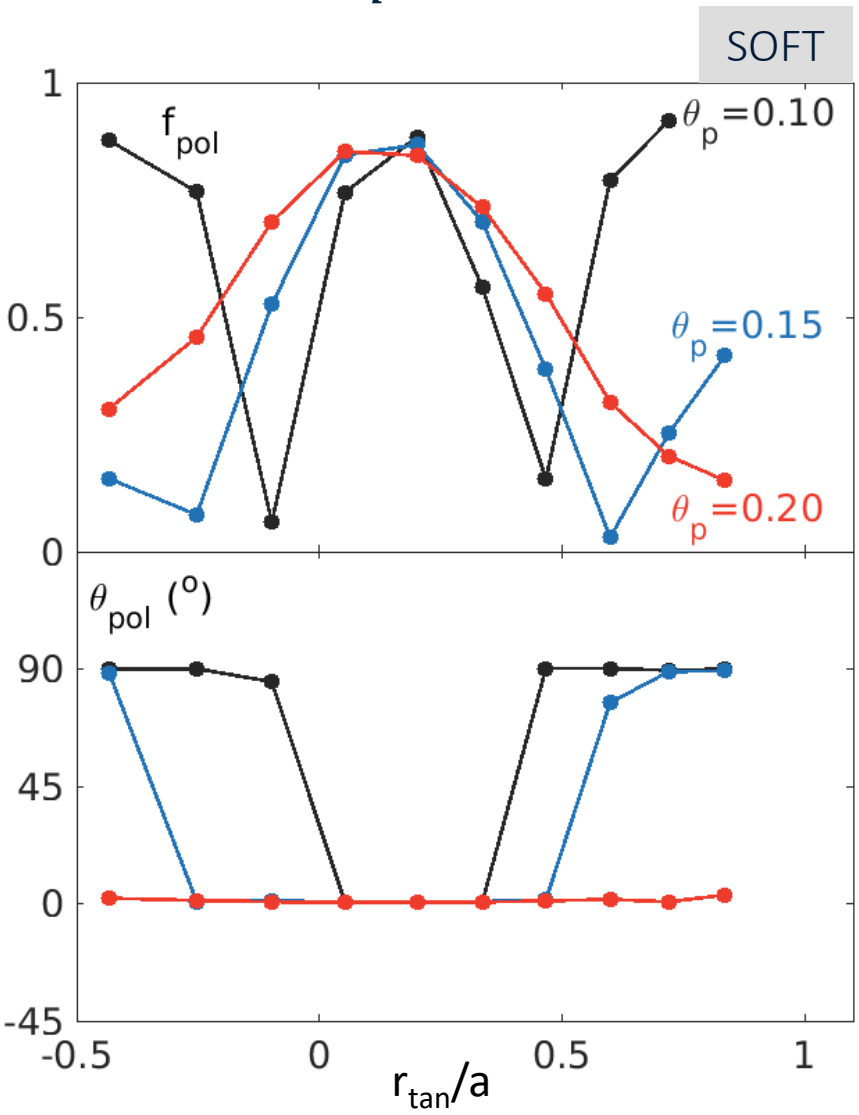
SOFT inputs: magnetic geometry, detector specifications, RE **phase space distribution**

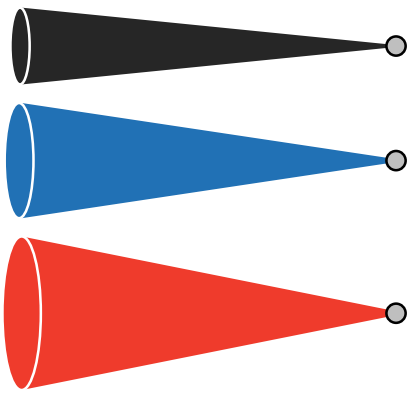


Modeled detectors indicate **localized measurements** of REs

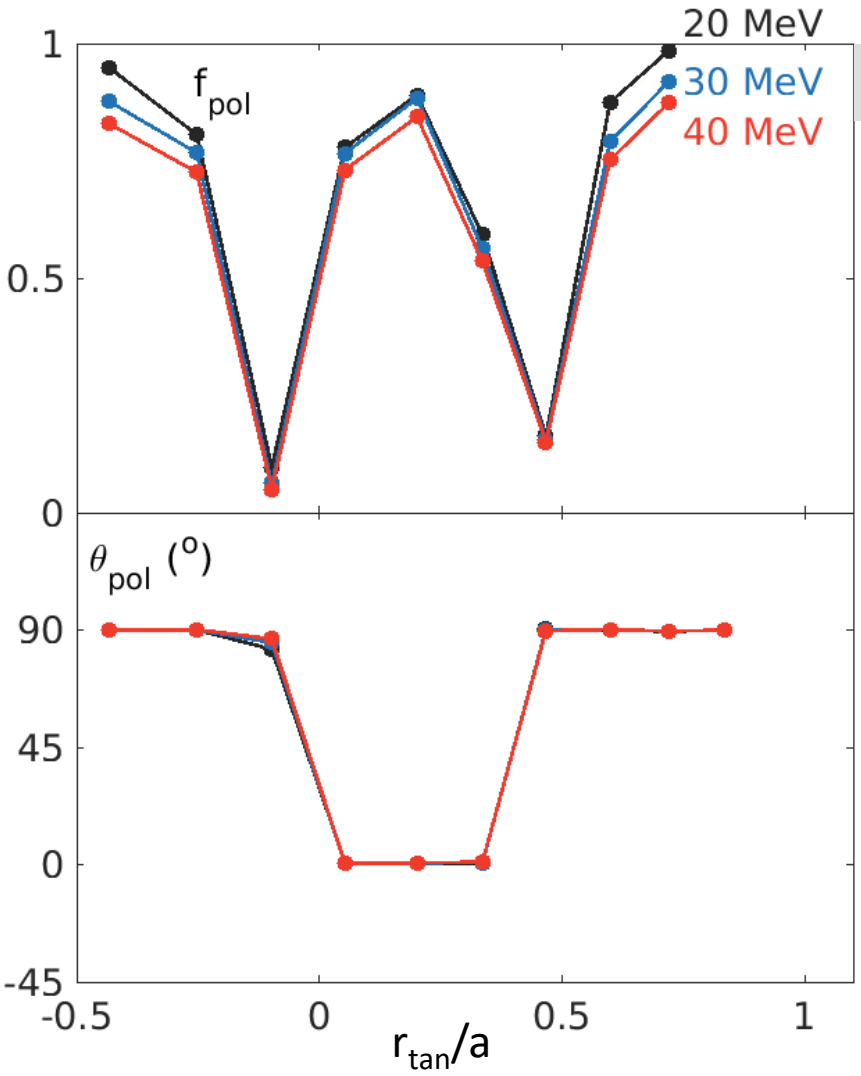


Synthetic data are **very sensitive** to RE **pitch angle**, θ_p

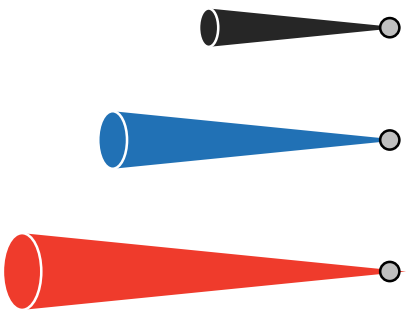




Synthetic data are **insensitive** to RE **energy** (and density)



SOFT



SOFT has **powerful capability** to create **Green's (weight) functions**

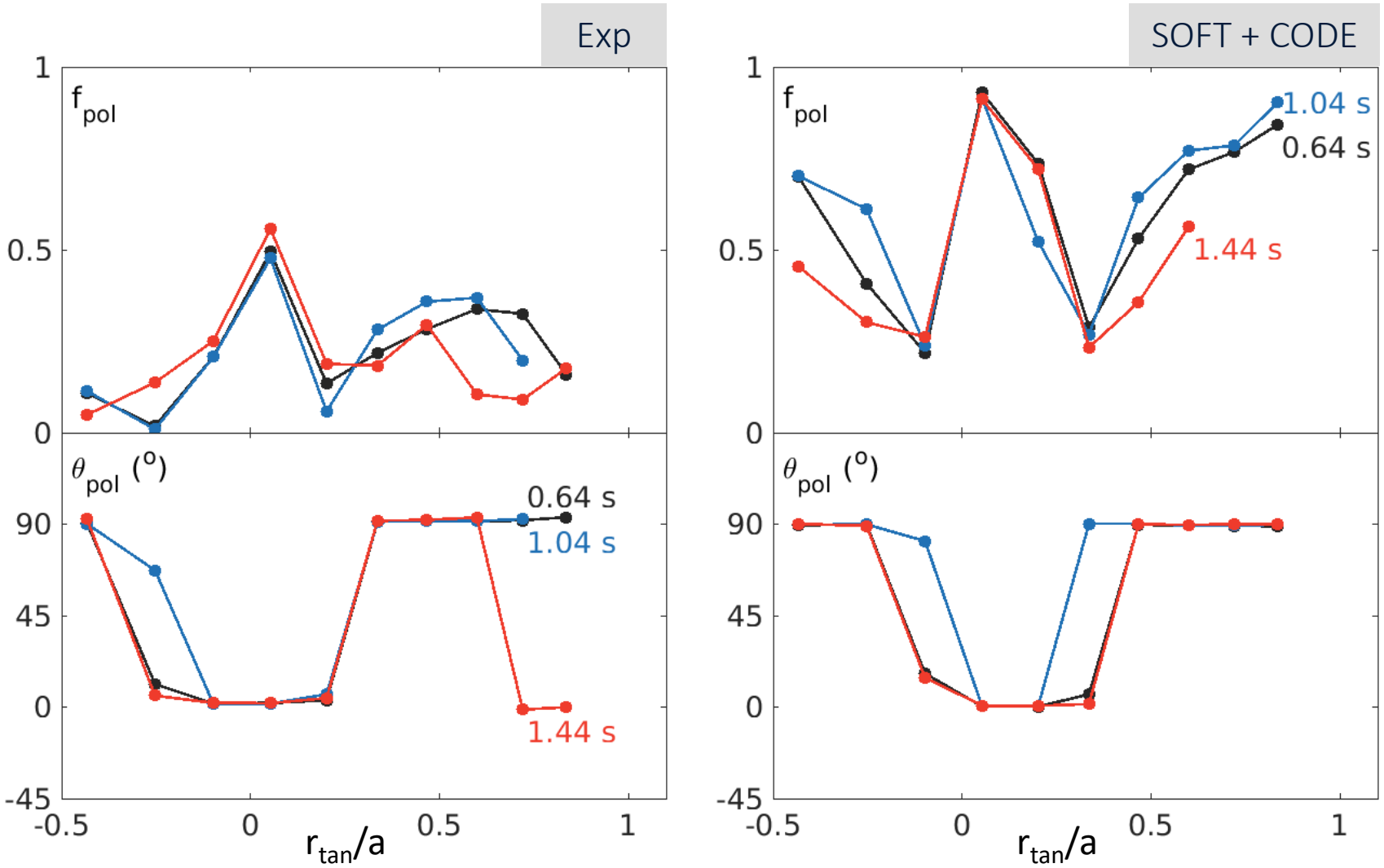
$$I = \int \mathrm{d}p\, \mathrm{d}\theta_p\, p^2 \sin\theta_p\; f\left(r, p, \theta_p\right) \hat{\mathrm{I}}(r, p, \theta_p)$$

$f_i\left(r_i, p, \theta_p\right)$ phase space distribution (**CODE***)
(stitched together over many radii, r_i)

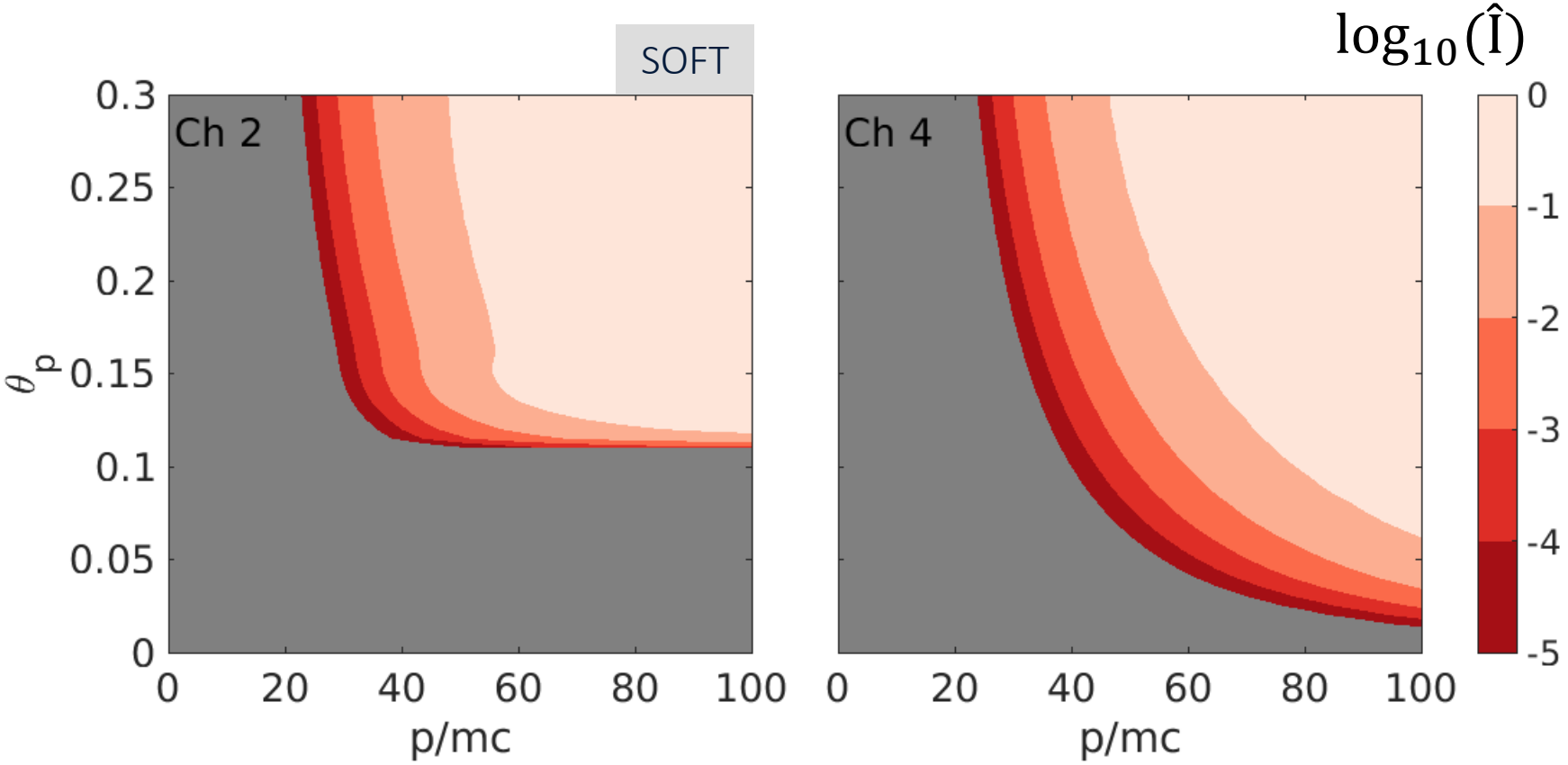
$\hat{\mathrm{I}}(r, p, \theta_p)$ Green's function (**SOFT****)

*Landreman CPC 2014
**Hoppe NF 2018

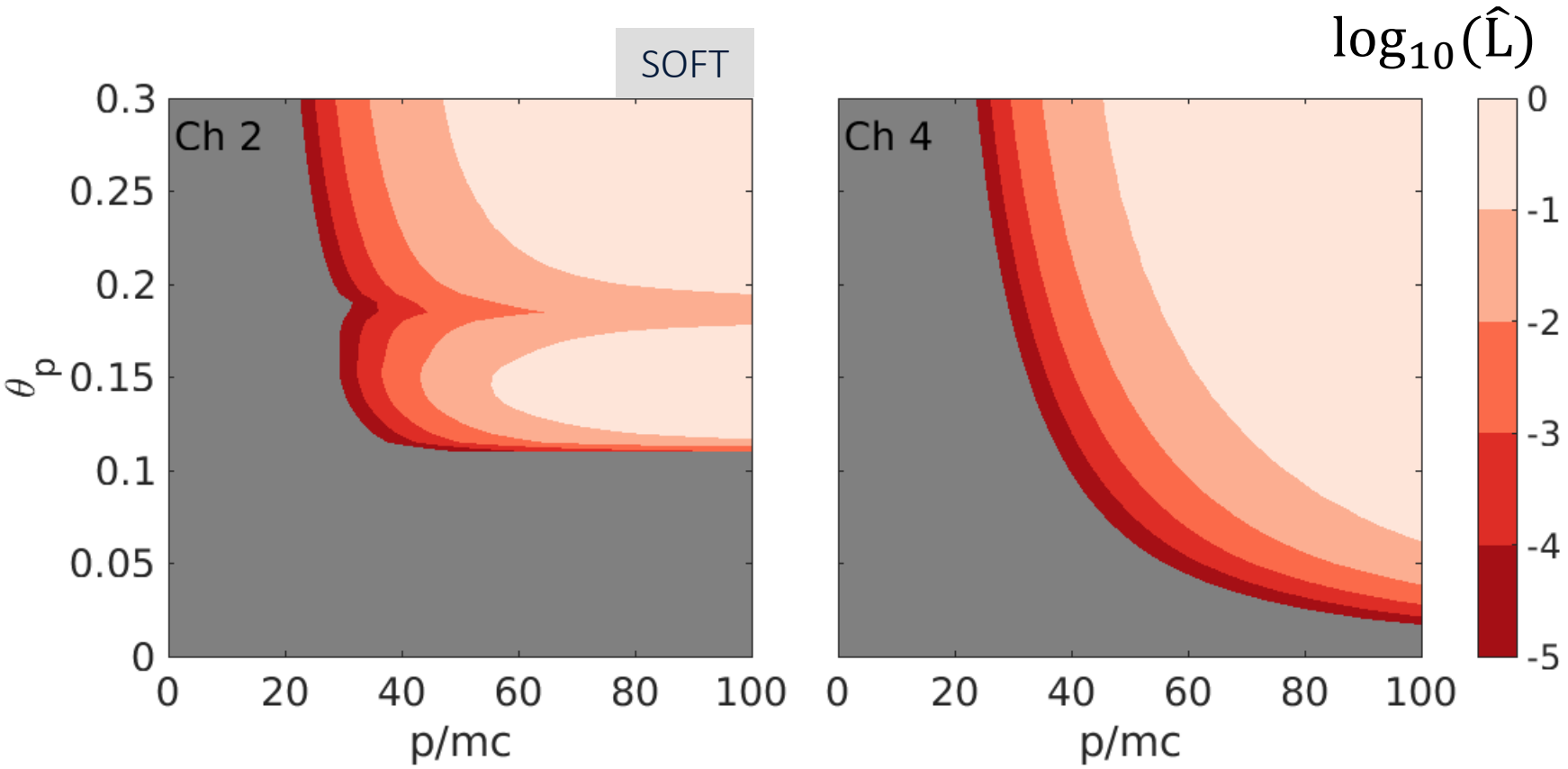
SOFT does **not** reproduce experiment using initial predictions from SOFT + CODE



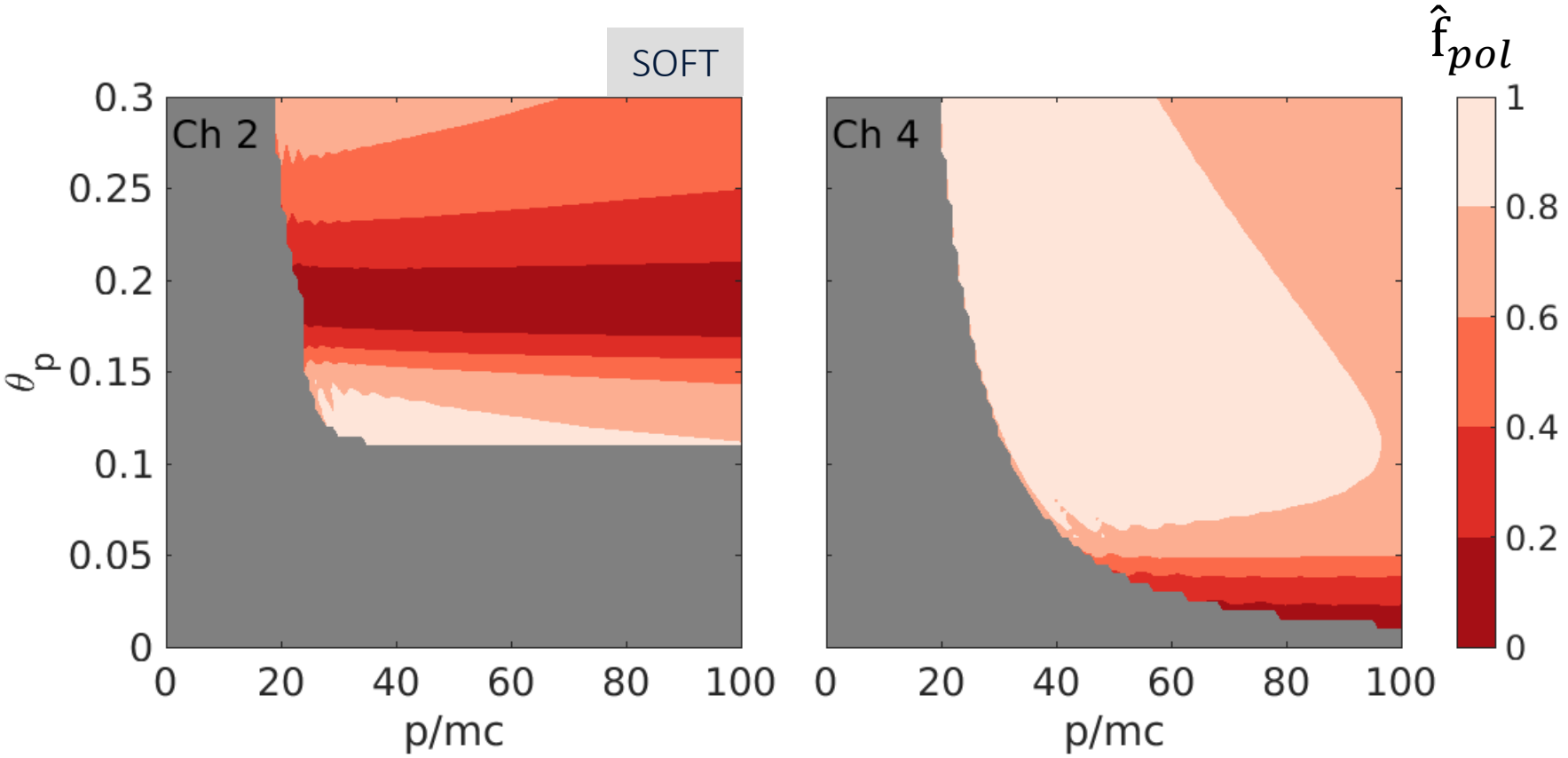
Green's function **intensity**, $\hat{I}$, indicates region of phase space probed



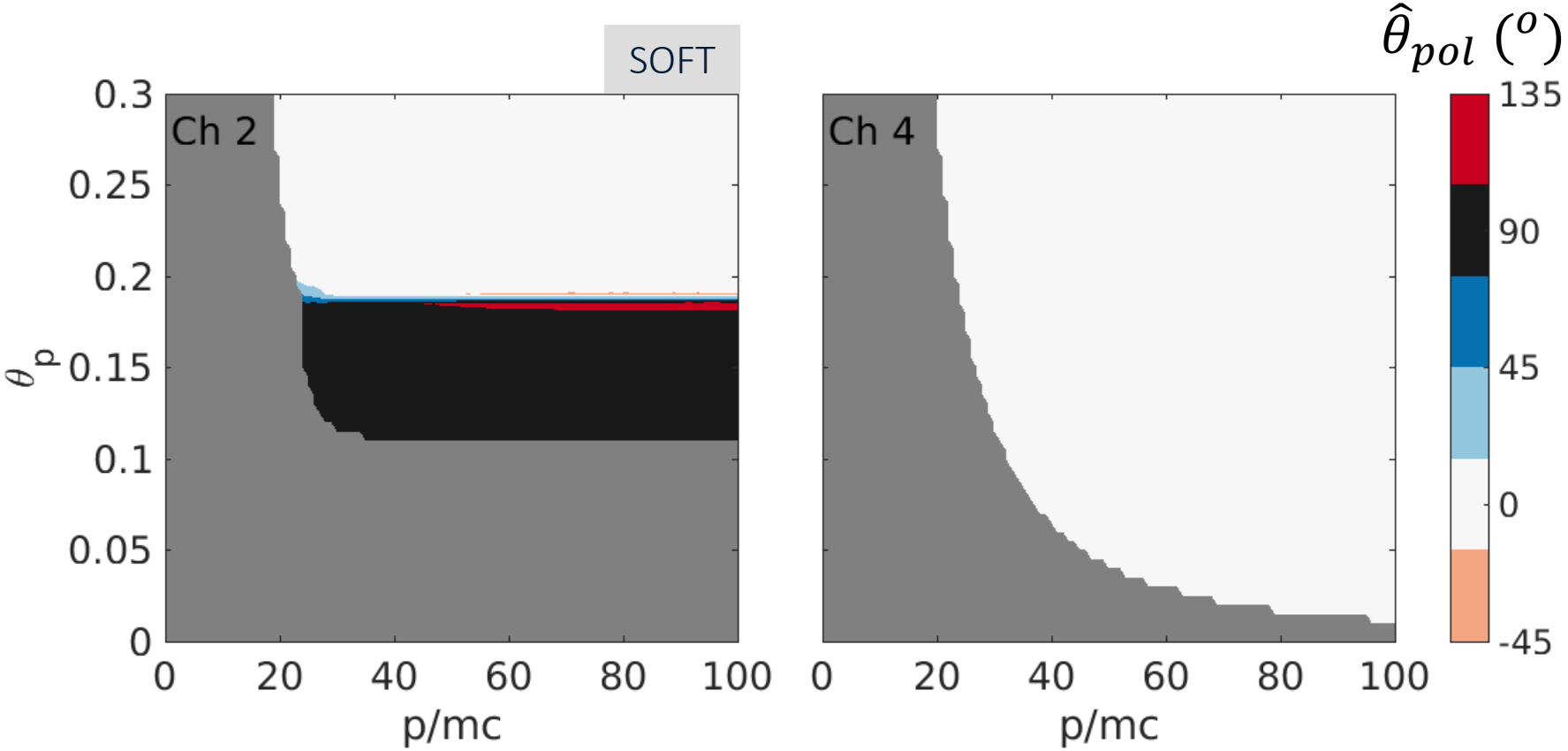
Intensity of linearly-polarized light, $\hat{\mathrm{L}}$, **"dips"** at certain pitch angles, θ_p

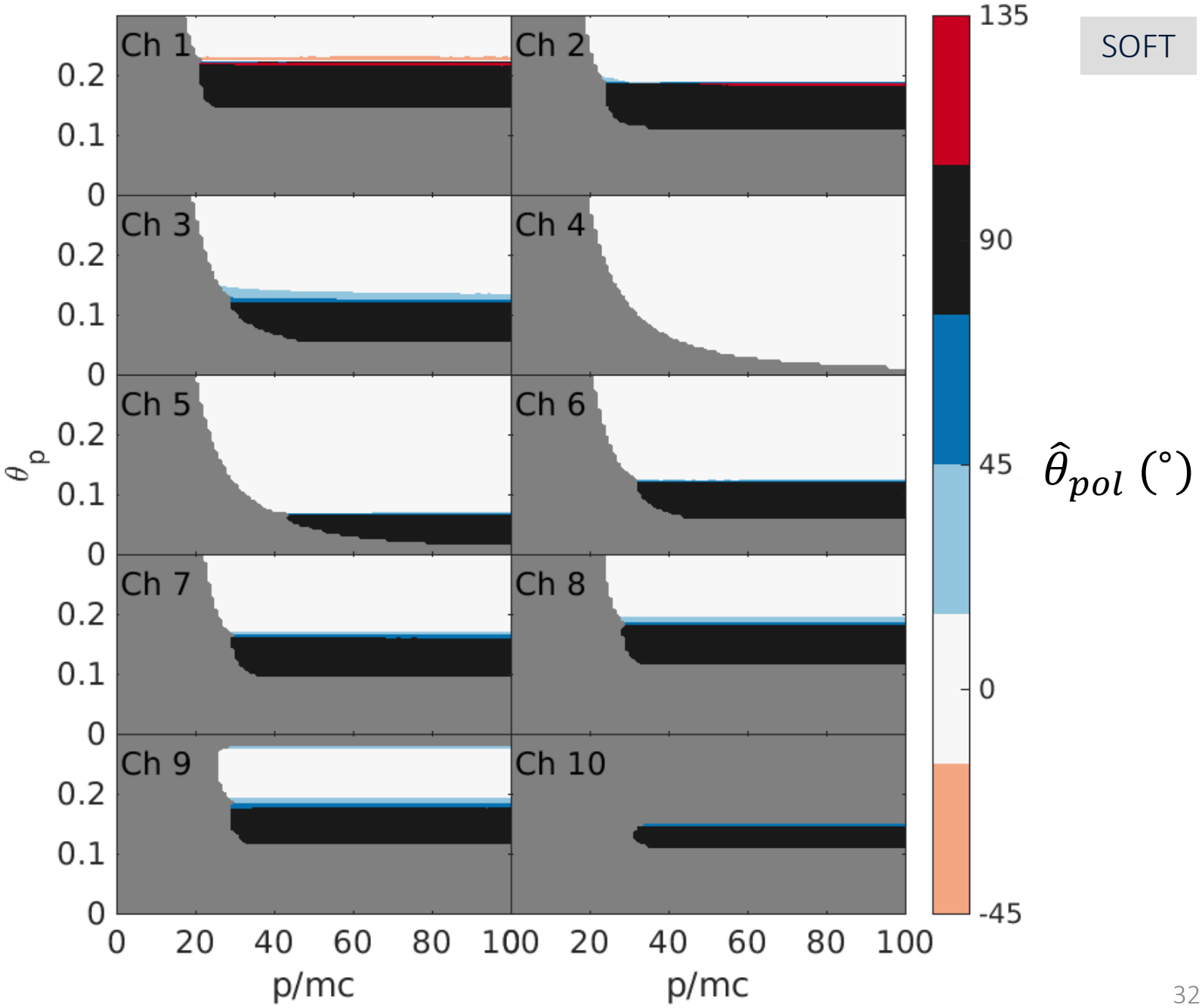


Minimum of fraction of linearly polarized light, $\hat{f}_{pol}$, **divides** phase space



90 degree shift in polarization angle, $\hat{\theta}_{pol}$, also **bifurcates** phase space

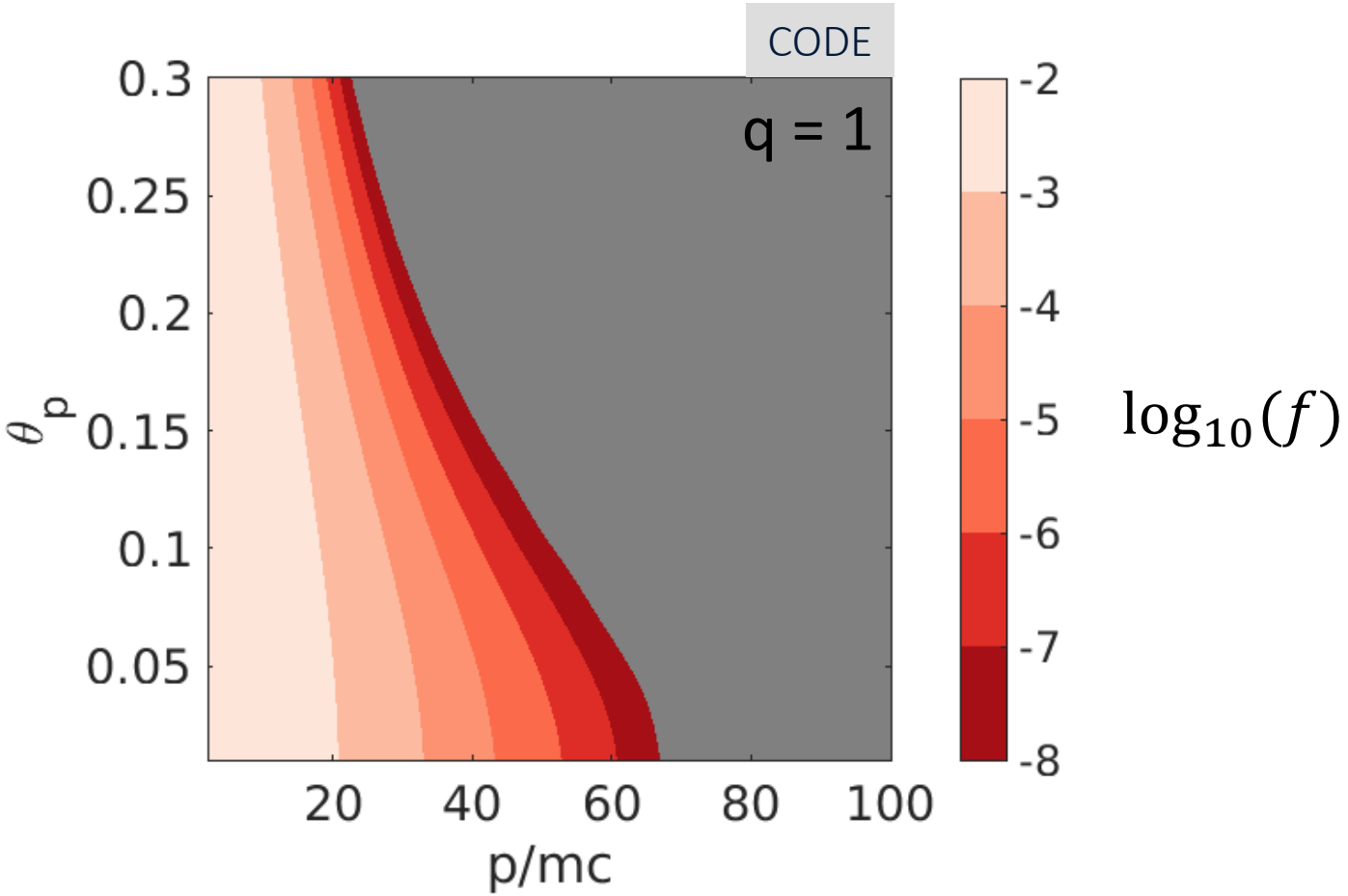



SOFT
Ch 1
Ch 2
Ch 3
Ch 4
Ch 5
Ch 6
Ch 7
Ch 8
Ch 9
Ch 10
θ_p
0
0.1
0.2
0
20
40
60
80
100
p/mc
135
90
45
0
-45
$\hat{\theta}_{pol}$ (°)

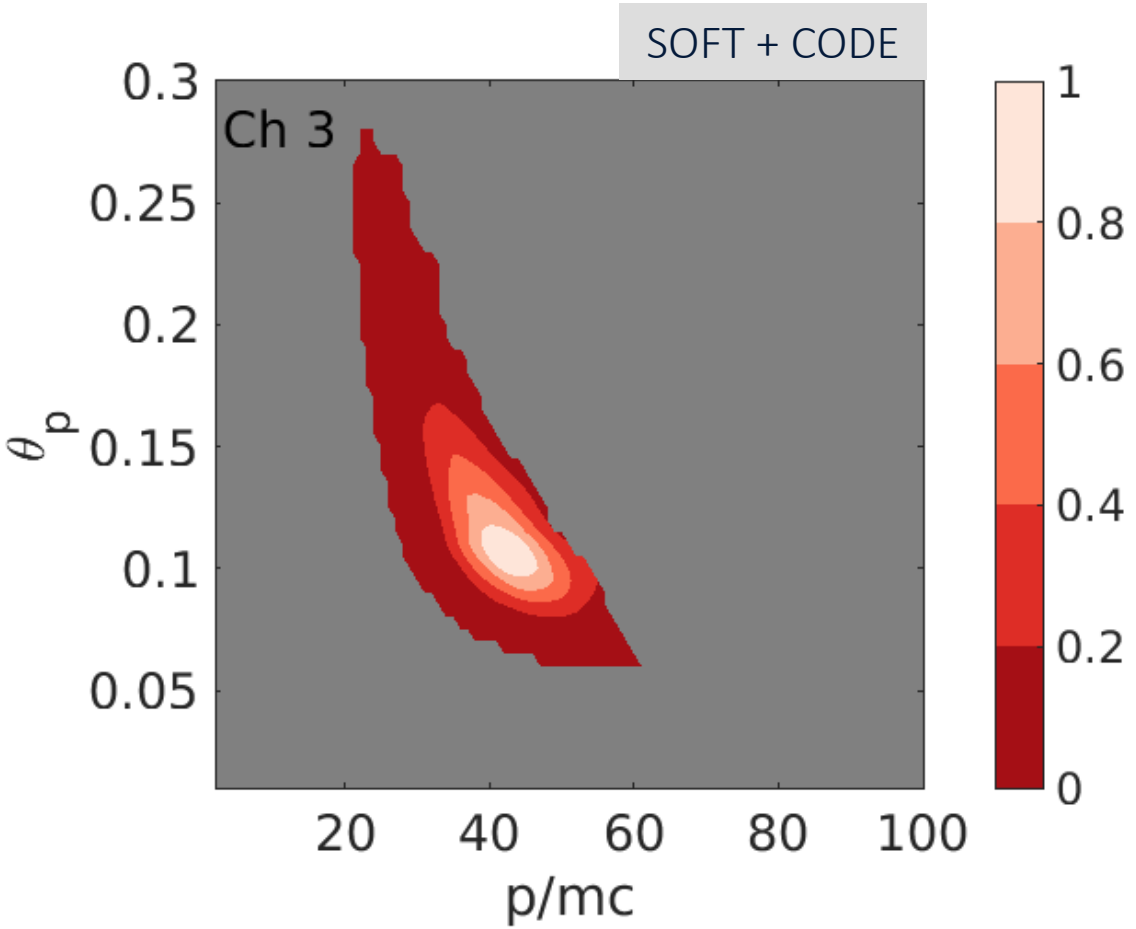
Outline

1. MSE diagnostic
2. Experimental data
3. Synthetic (SOFT) data
4. Comparing data
5. Future work

We evolve the **momentum space** distribution function at several radii with **CODE**

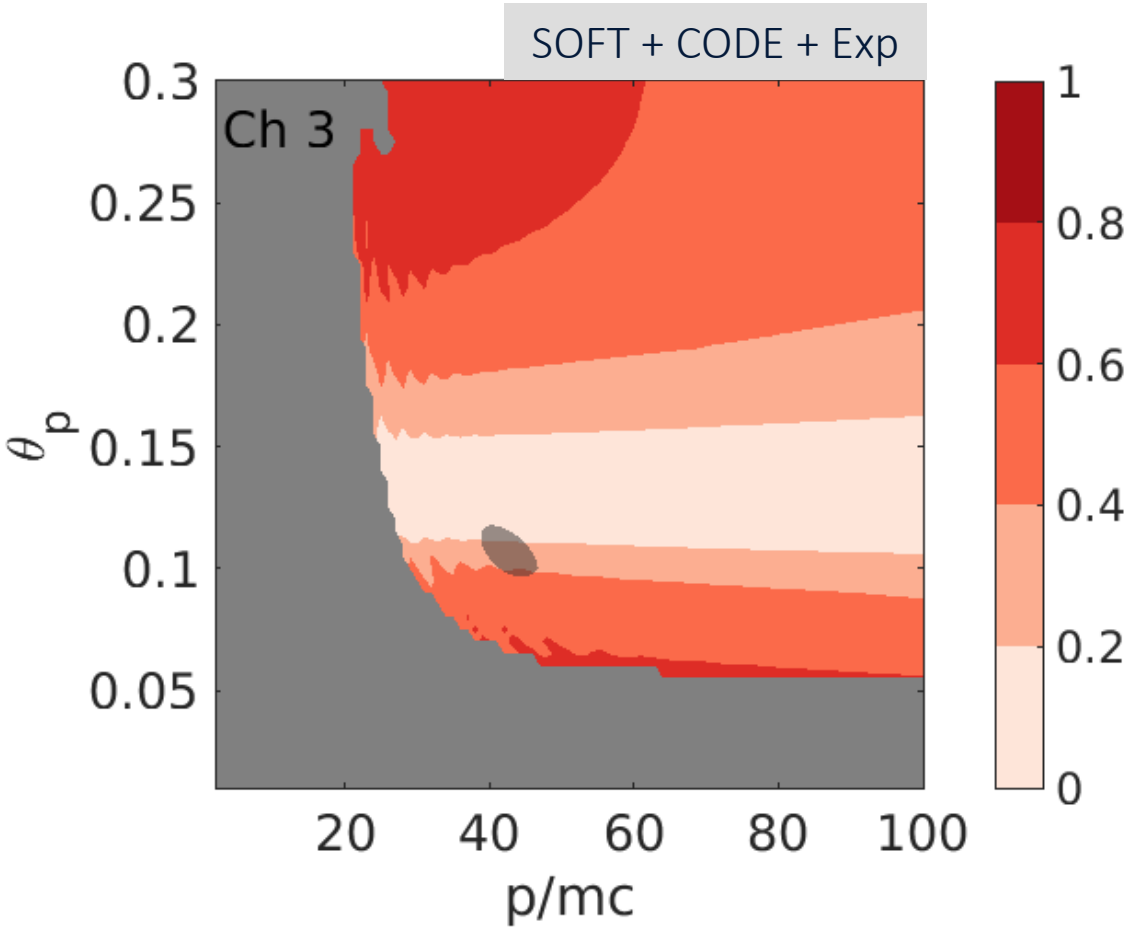


Convolution of f with $\hat{I}$ shows region of **peak** synchrotron emission **detected**



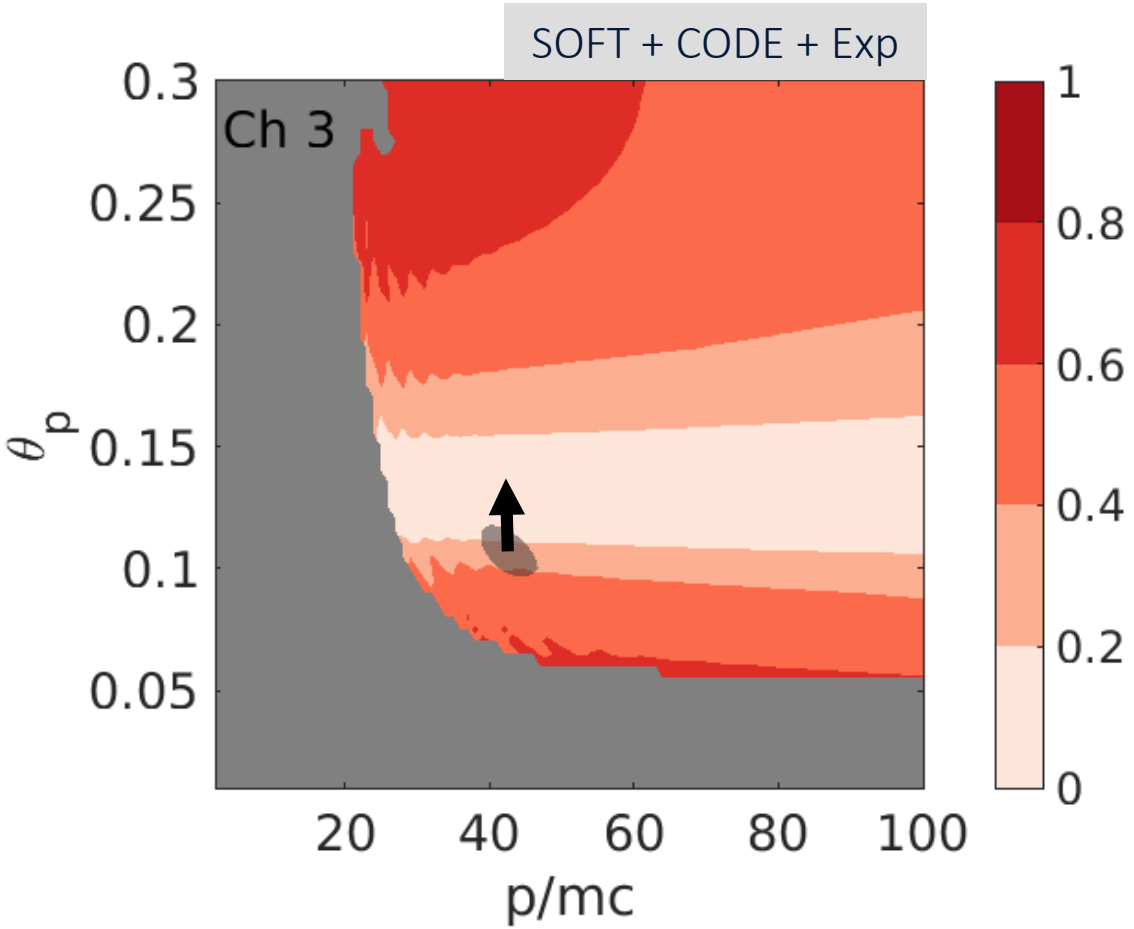
$$\mathrm{norm}(\hat{I} \times f \times J)$$

We can **infer** how the **pitch angle** distribution must **change** to match experiment



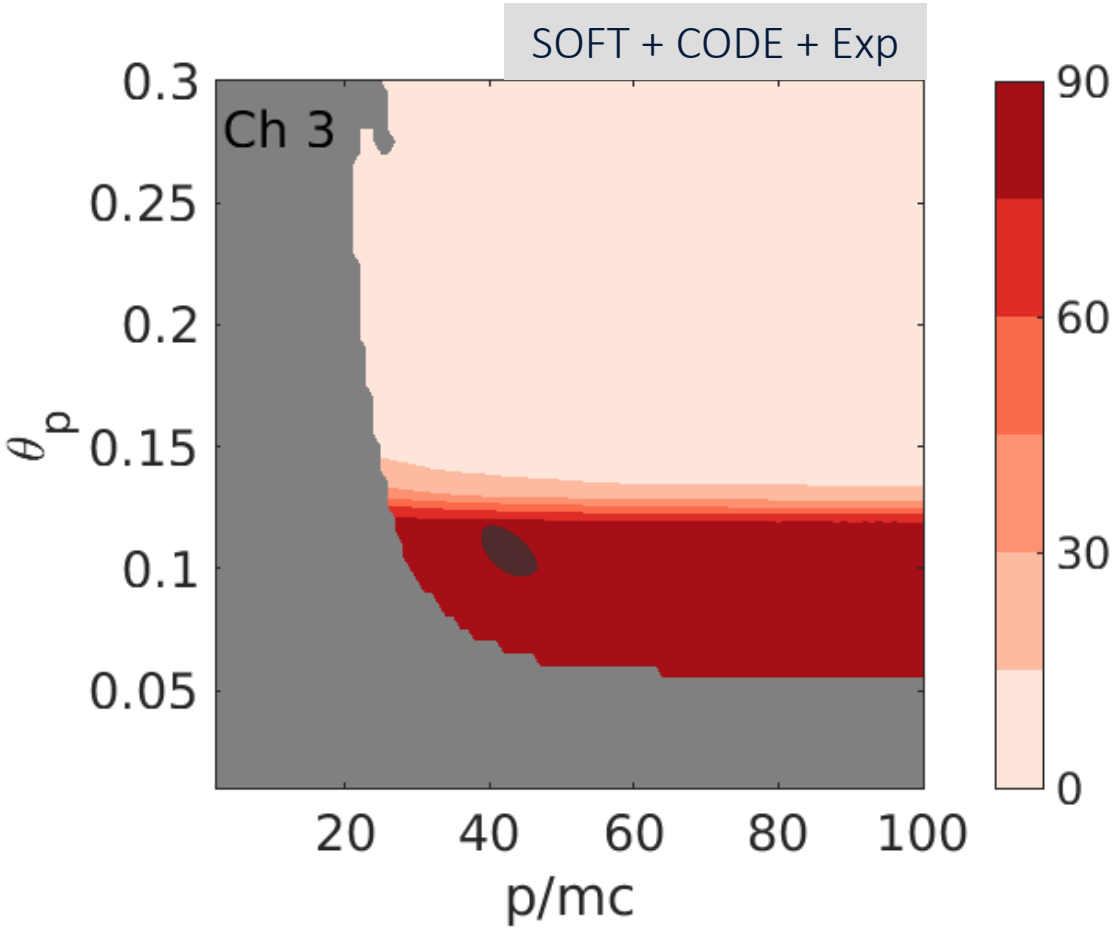
$$|\hat{f}_{pol,SOFT} - f_{pol,Exp}|$$

We can **infer** how the **pitch angle** distribution must **change** to match experiment



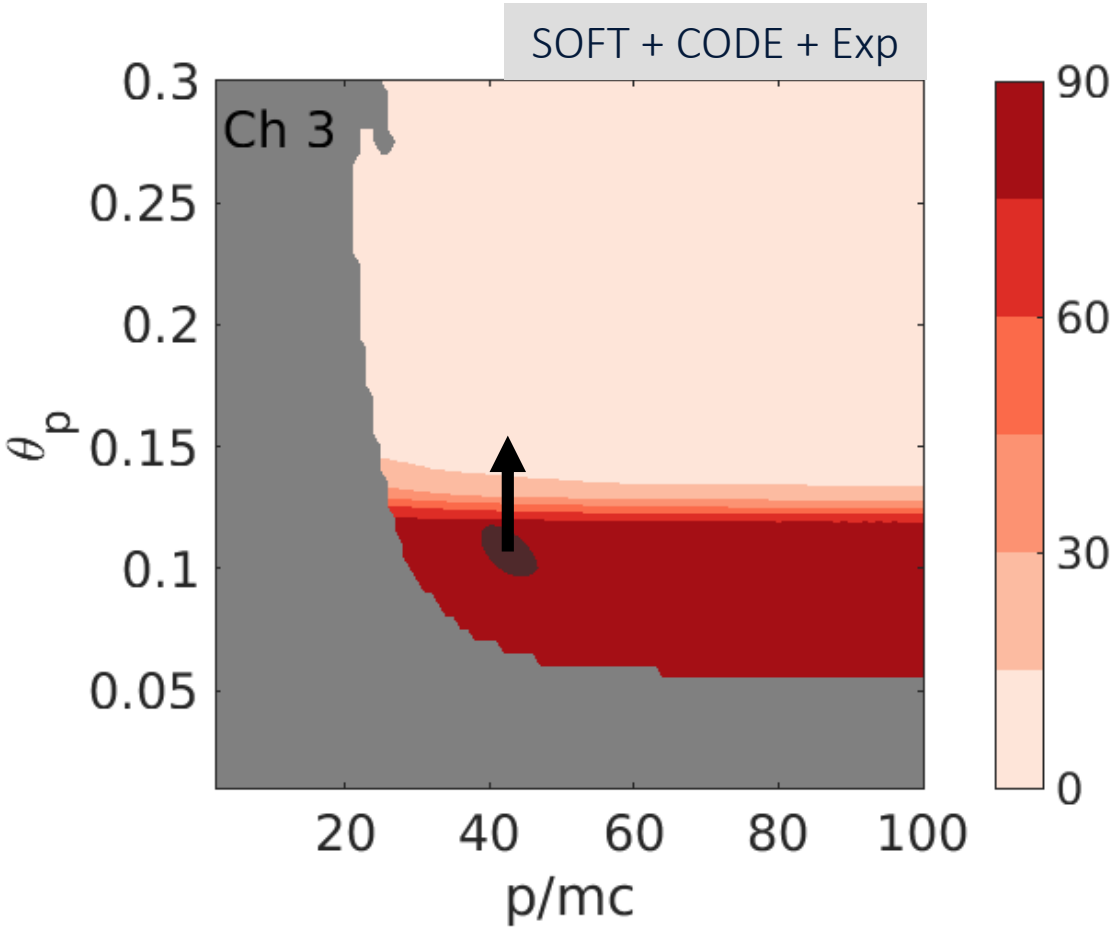
$$|\hat{f}_{pol,SOFT} - f_{pol,Exp}|$$

Data point to pitch angle distribution with **higher** pitch angles → increased scattering?



$$|\hat{\theta}_{pol,SOFT} - \theta_{pol,Exp}|$$

Data point to pitch angle distribution with **higher** pitch angles → increased scattering?

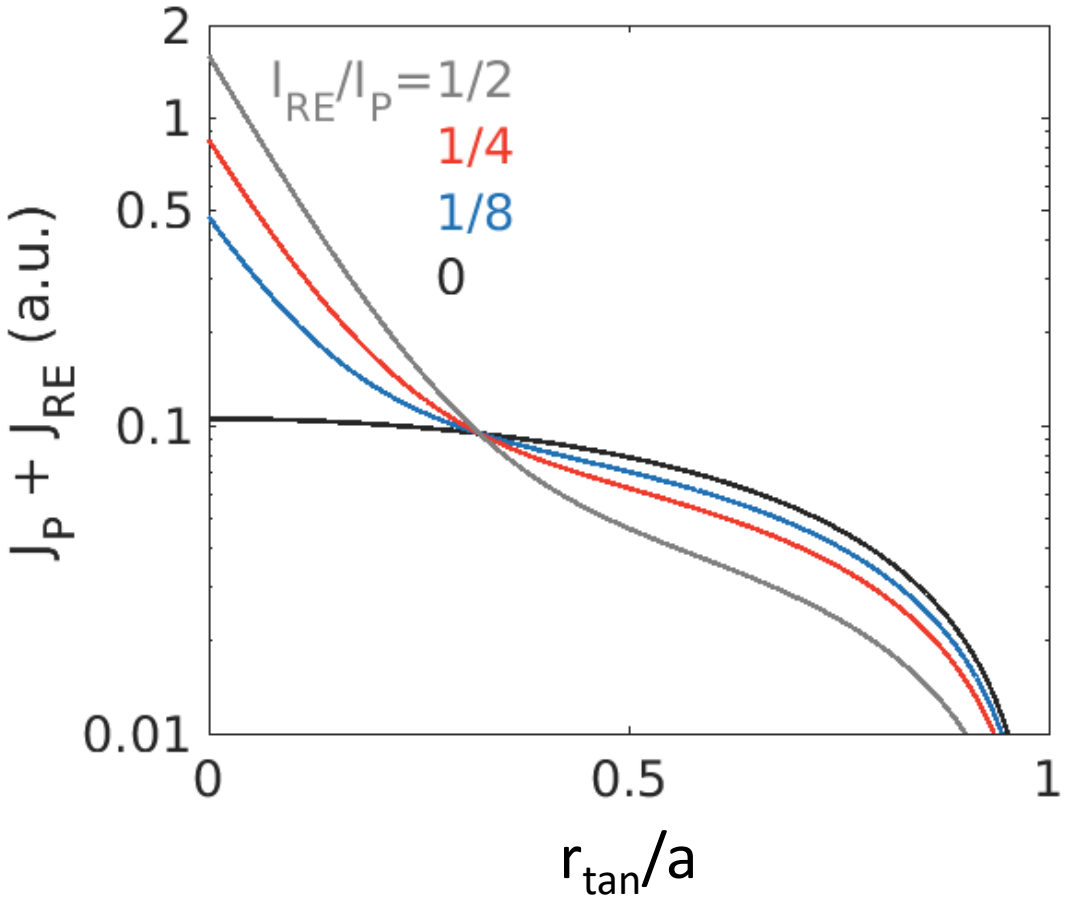


$$|\hat{\theta}_{pol,SOFT} - \theta_{pol,Exp}|$$

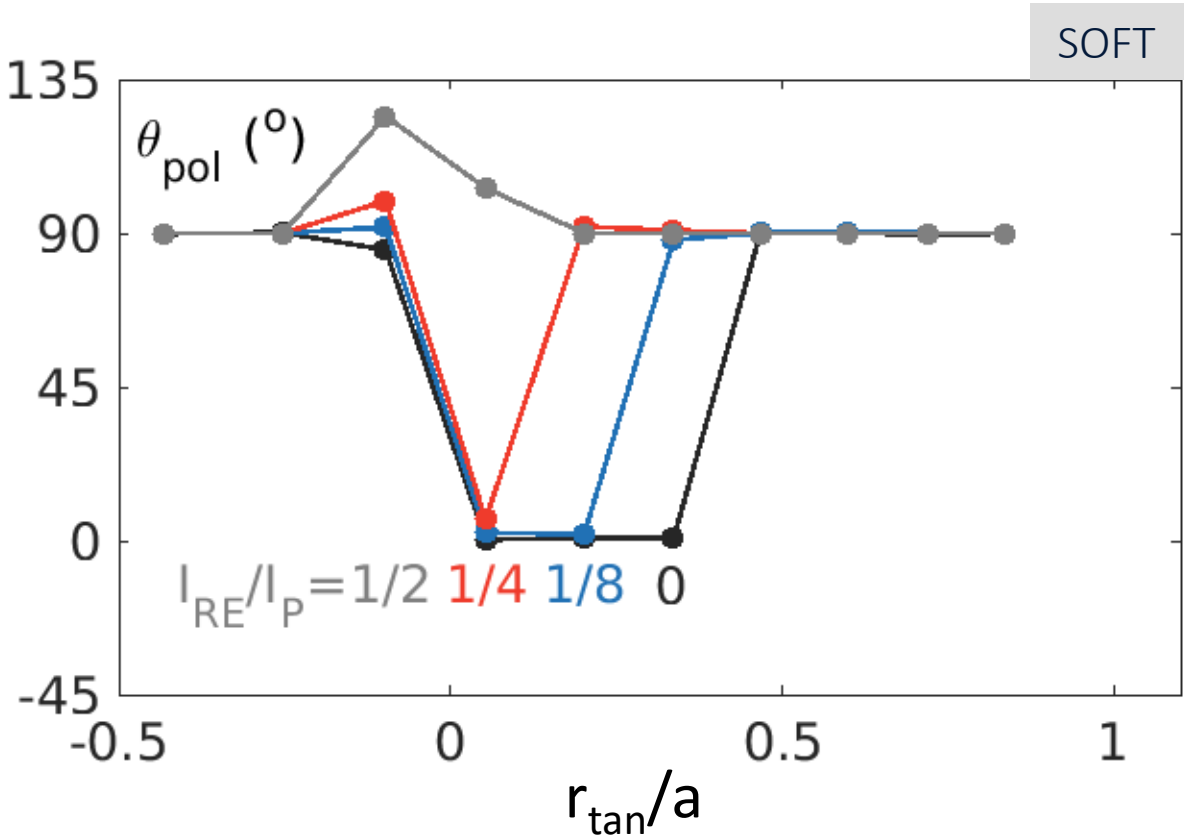
Outline

1. MSE diagnostic
2. Experimental data
3. Synthetic (SOFT) data
4. Comparing data
5. Future work

Polarized synchrotron emission could give insight into the **RE current profile**, $J_{RE}(r)$



Synthetic data are **sensitive** to the **local magnetic field** (and current density)

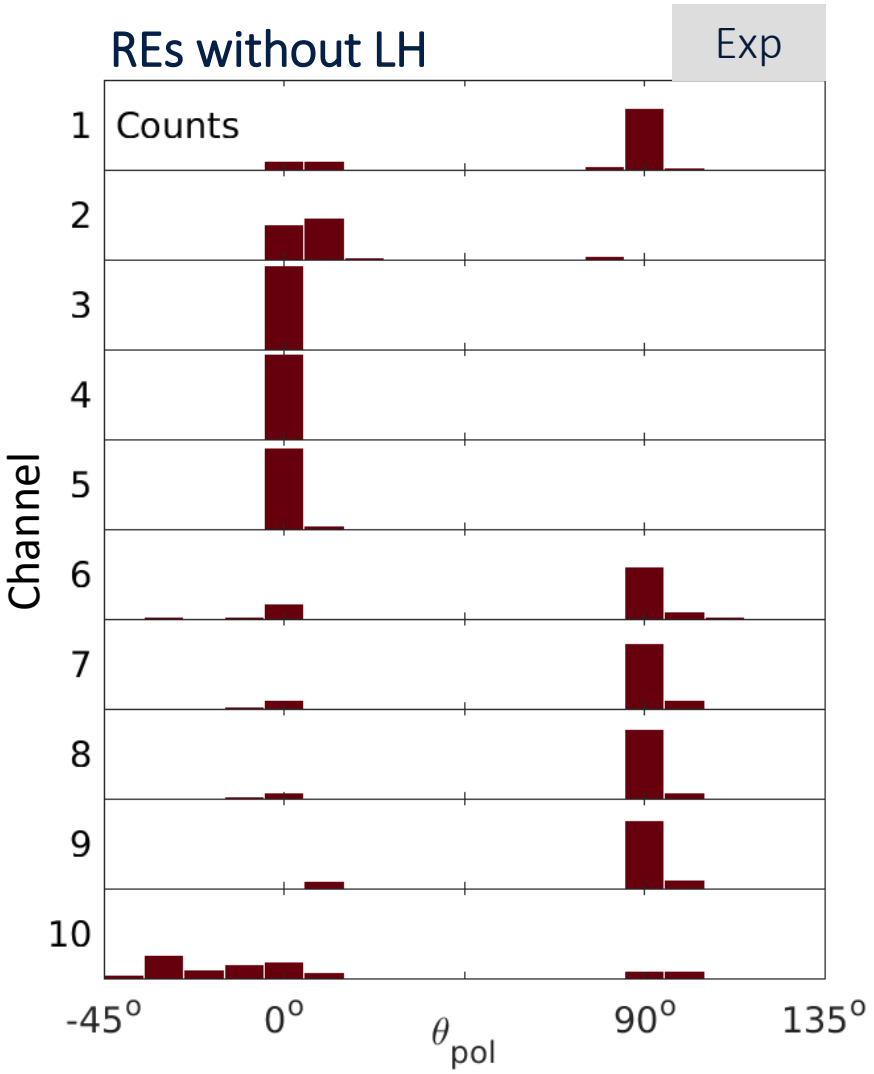


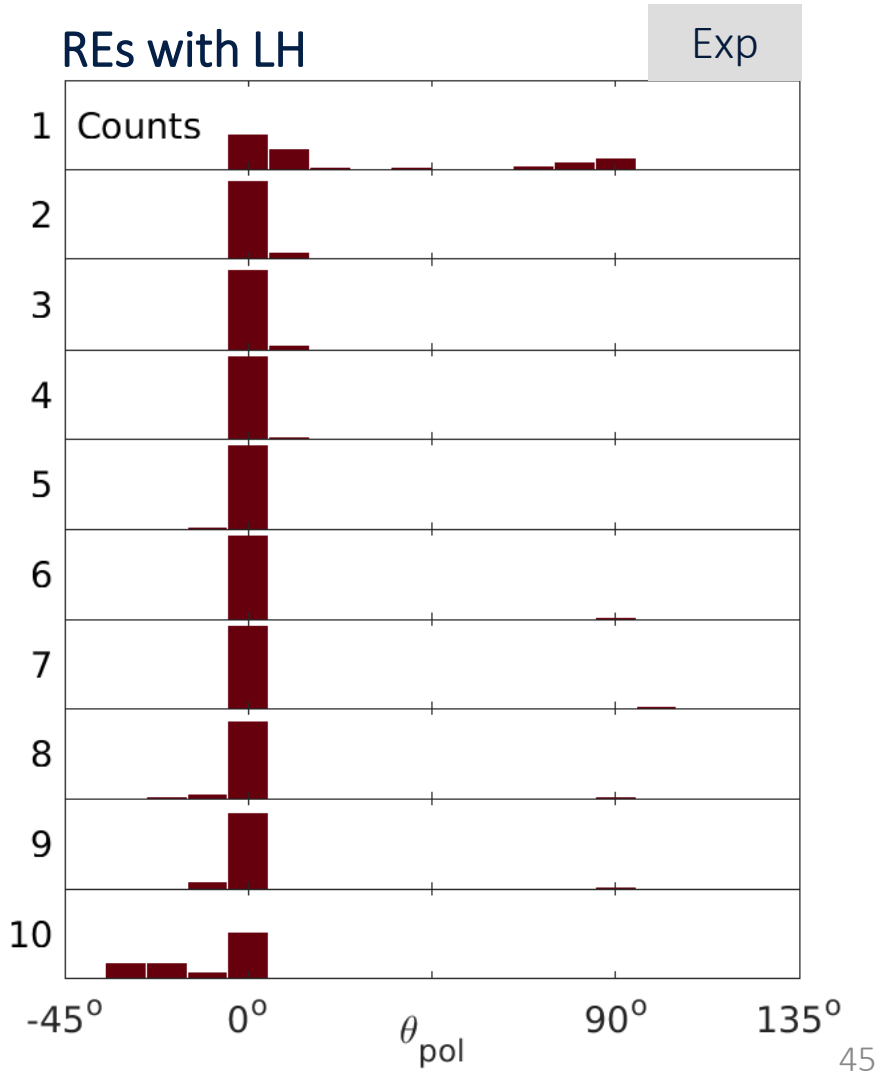
Summary

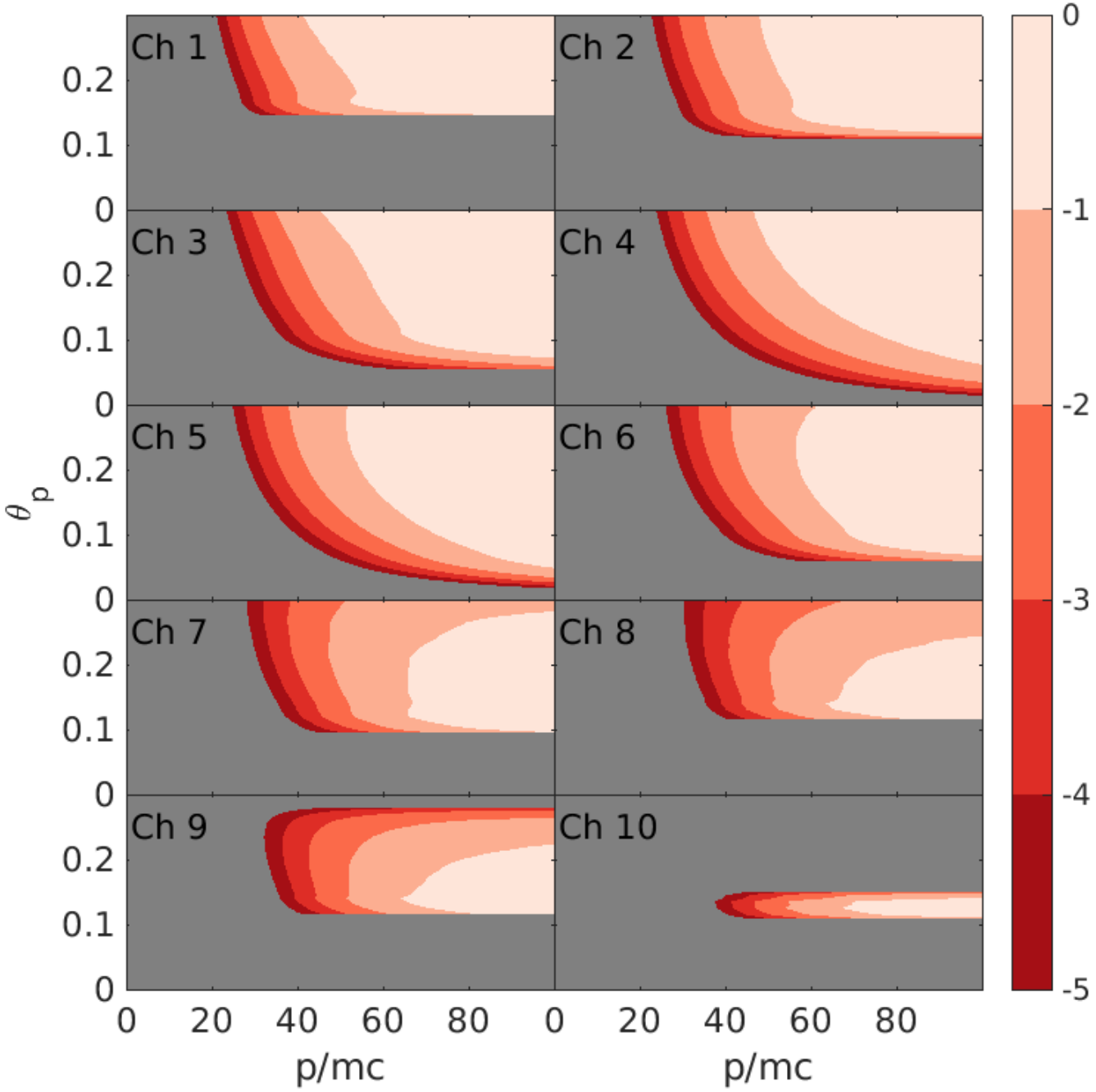
1. MSE diagnostic can be used for measurements of visible, polarized synchrotron emission from runaway electrons
2. Experimental data show spatiotemporal evolution of linearly-polarized light intensity, fraction, and angle
3. Synthetic (SOFT) data provide weight functions of (and divide up) phase space for parameters of interest
4. Comparing data allows inference of the pitch angle distribution consistent with experimental results
5. Future work could investigate the runaway current profile using polarization measurements

Bonus

Lower Hybrid (LH) seeds REs and changes B_{pol} profile, leading to distinct measurements

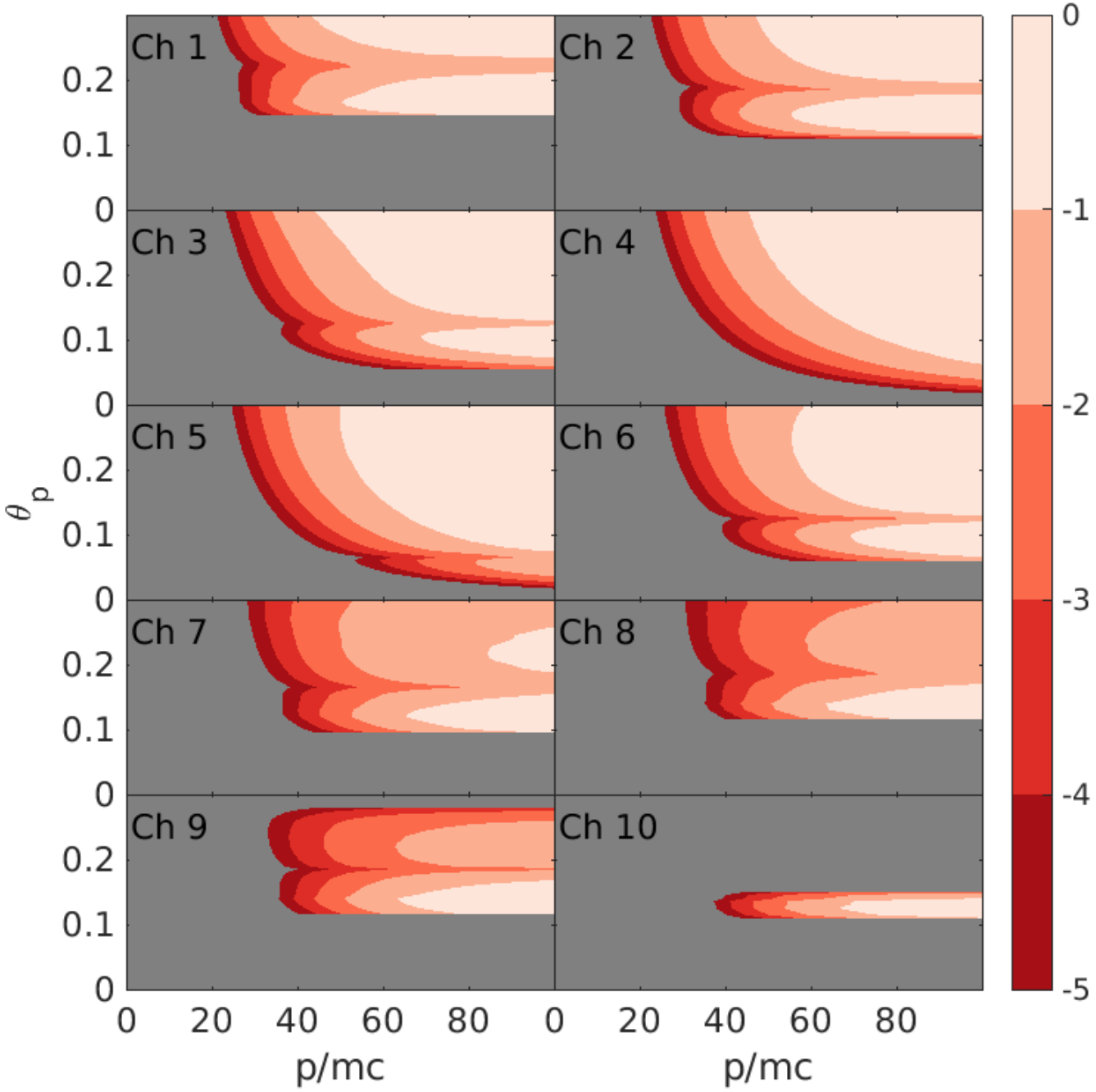






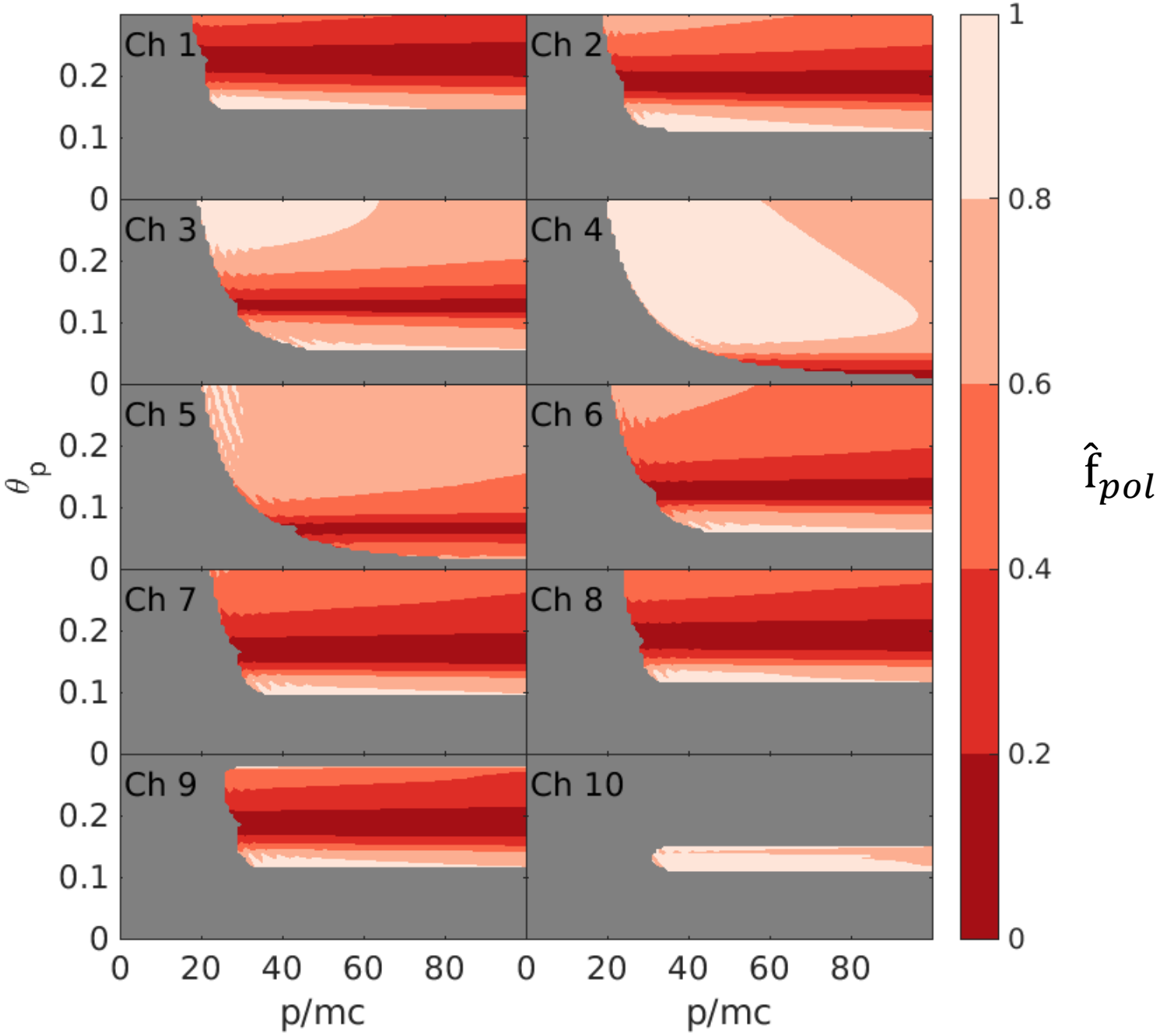
SOFT

$\log_{10}(\hat{I})$

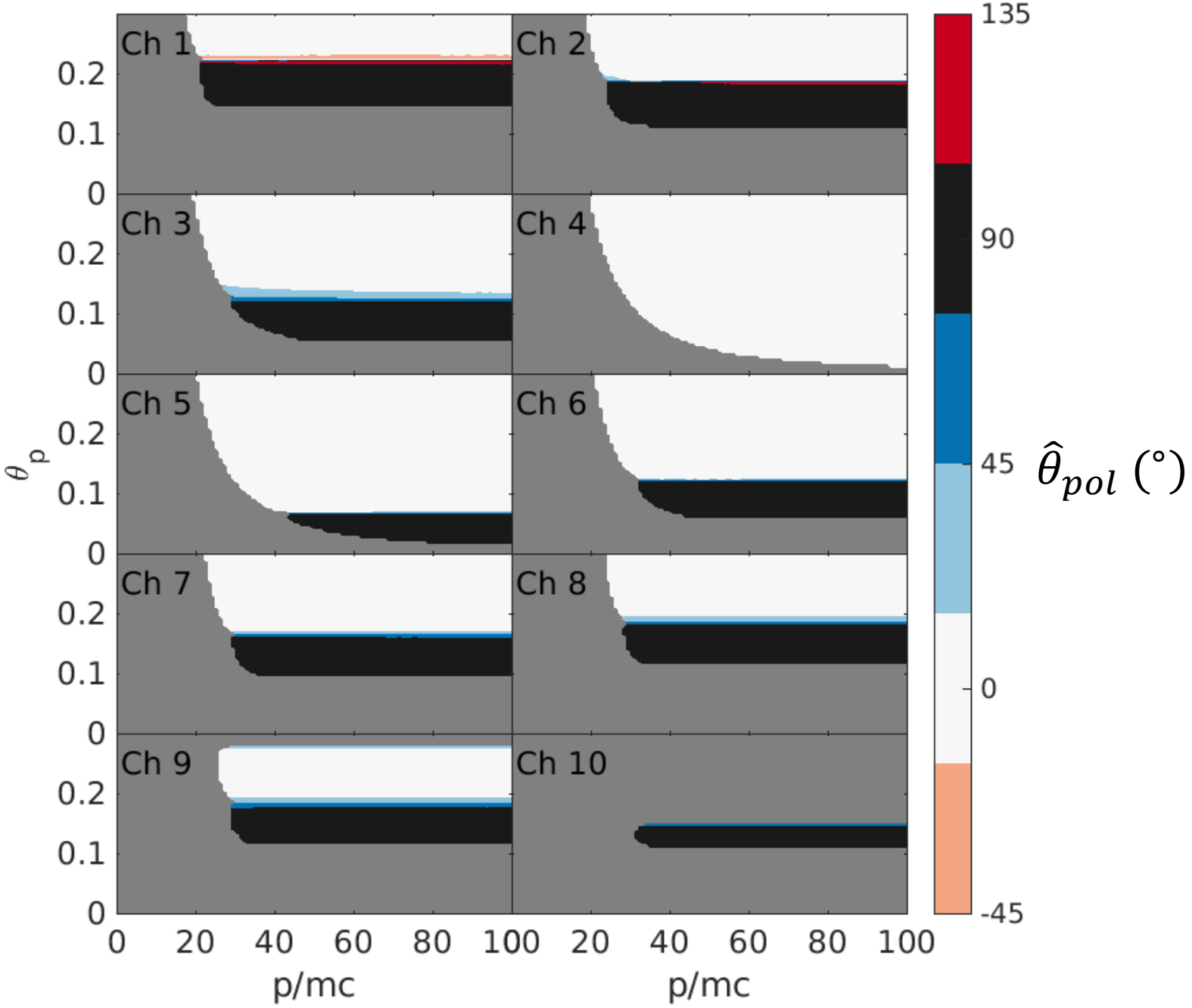


SOFT

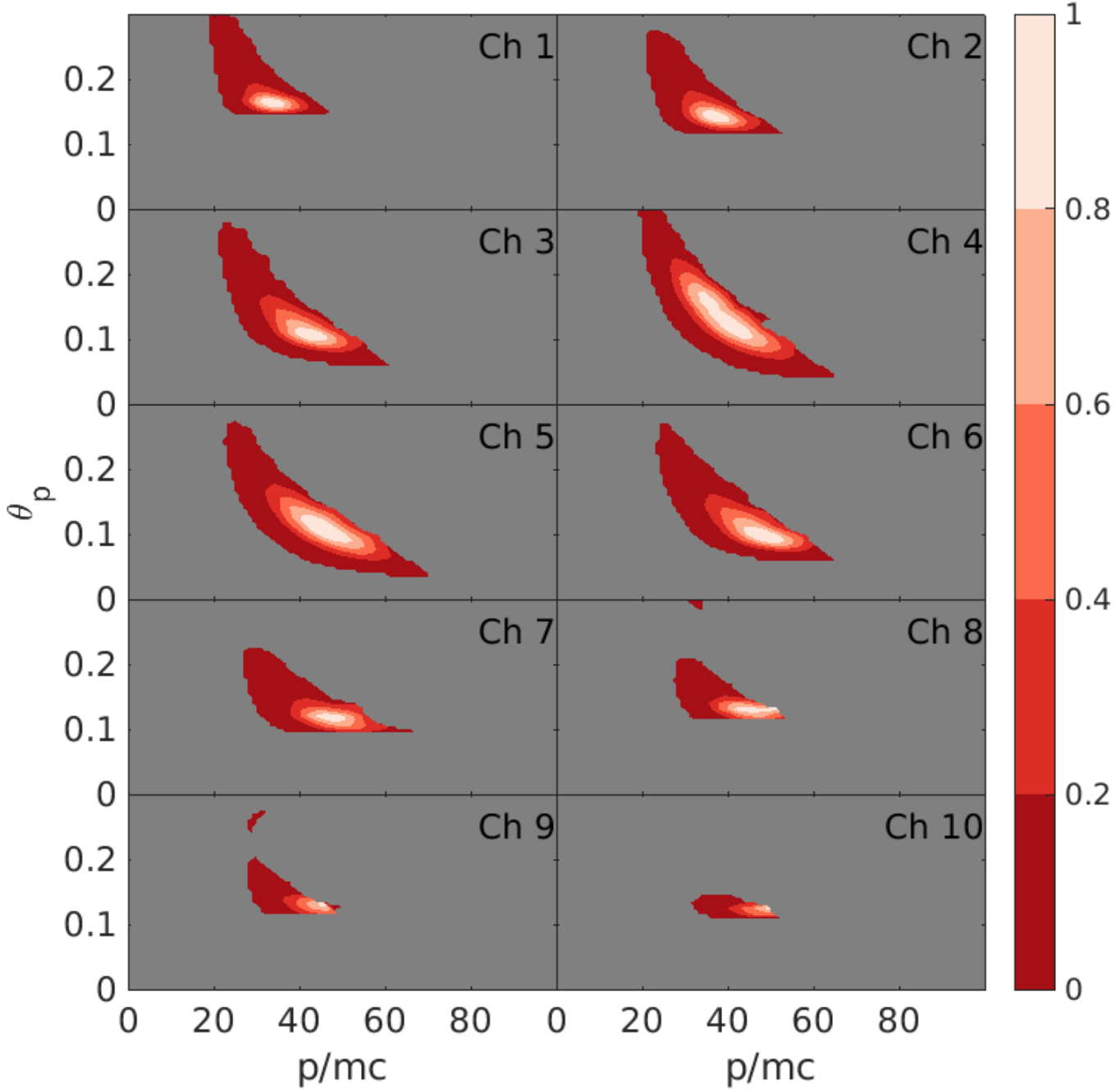
$\log_{10}(\hat{L})$


Ch 1
Ch 2
Ch 3
Ch 4
Ch 5
Ch 6
Ch 7
Ch 8
Ch 9
Ch 10
θ_p
0
0.1
0.2
0
20
40
60
80
p/mc
1
0.8
0.6
0.4
0.2
0
$\hat{f}_{pol}$

SOFT

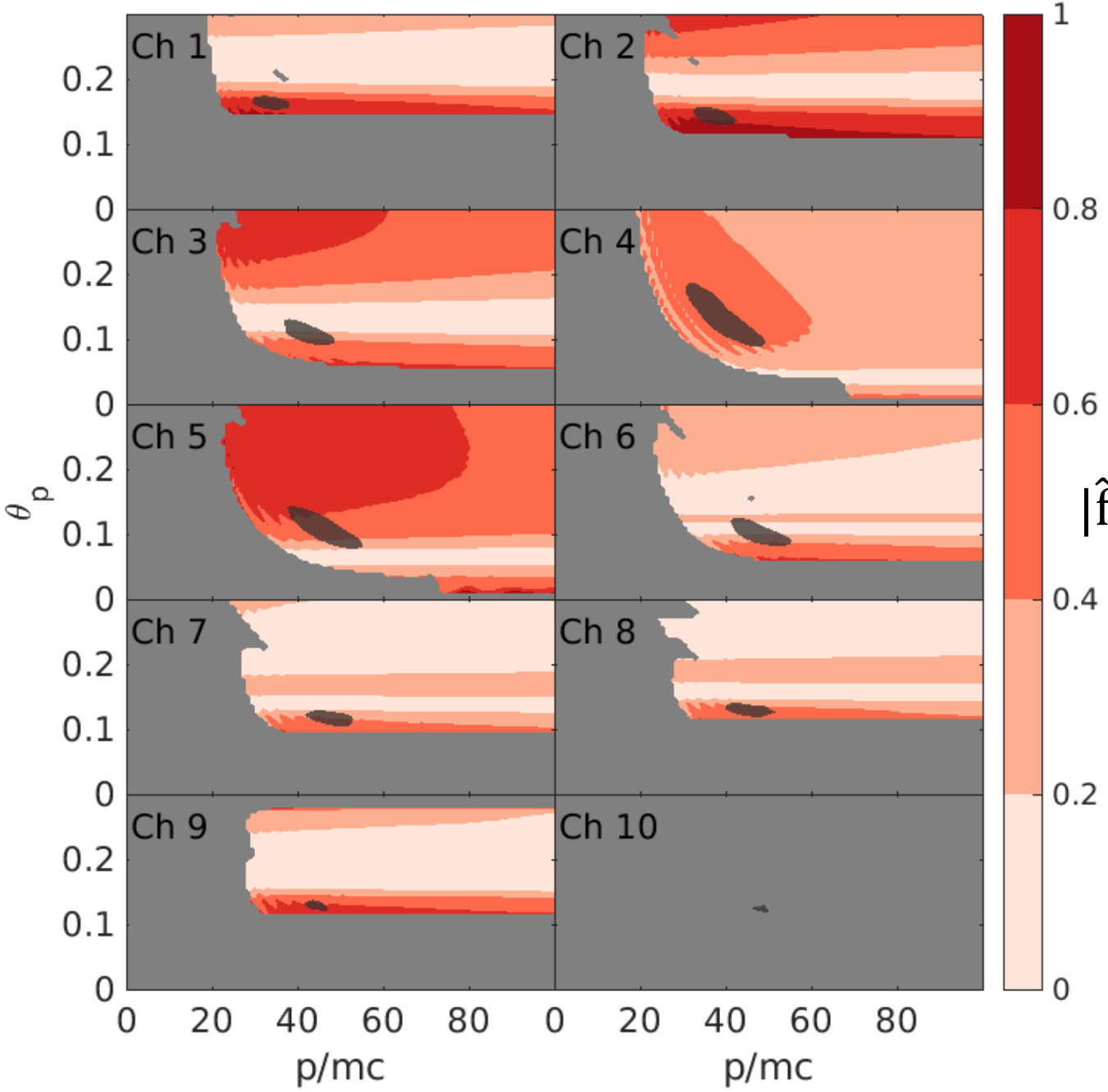

Ch 1
Ch 2
Ch 3
Ch 4
Ch 5
Ch 6
Ch 7
Ch 8
Ch 9
Ch 10
θ_p
0
0.1
0.2
0
20
40
60
80
100
p/mc
135
90
45
0
-45
$\hat{\theta}_{pol}$ (°)

SOFT



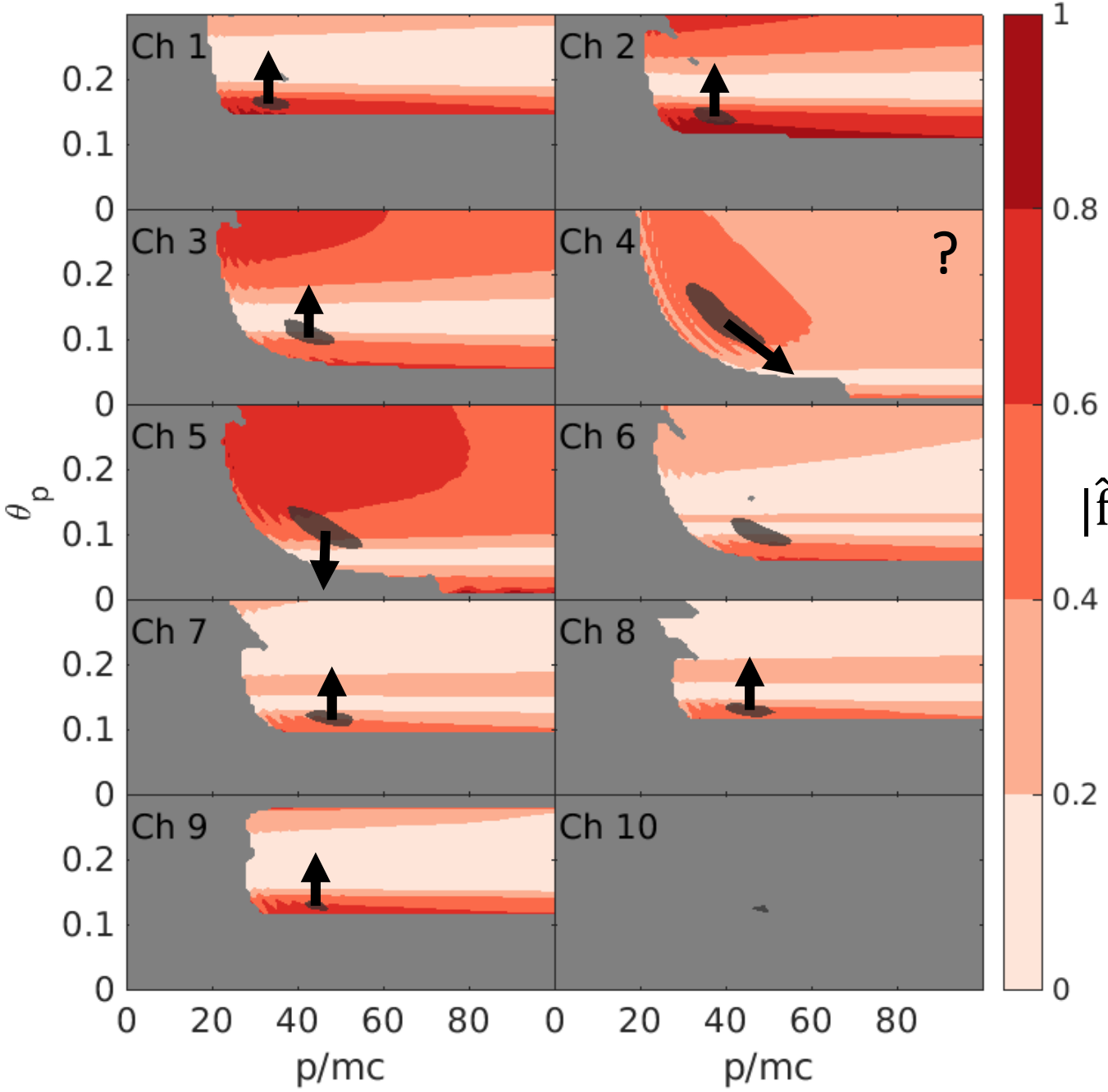
SOFT + CODE

$$\mathrm{norm}(\hat{I} \times f \times J)$$



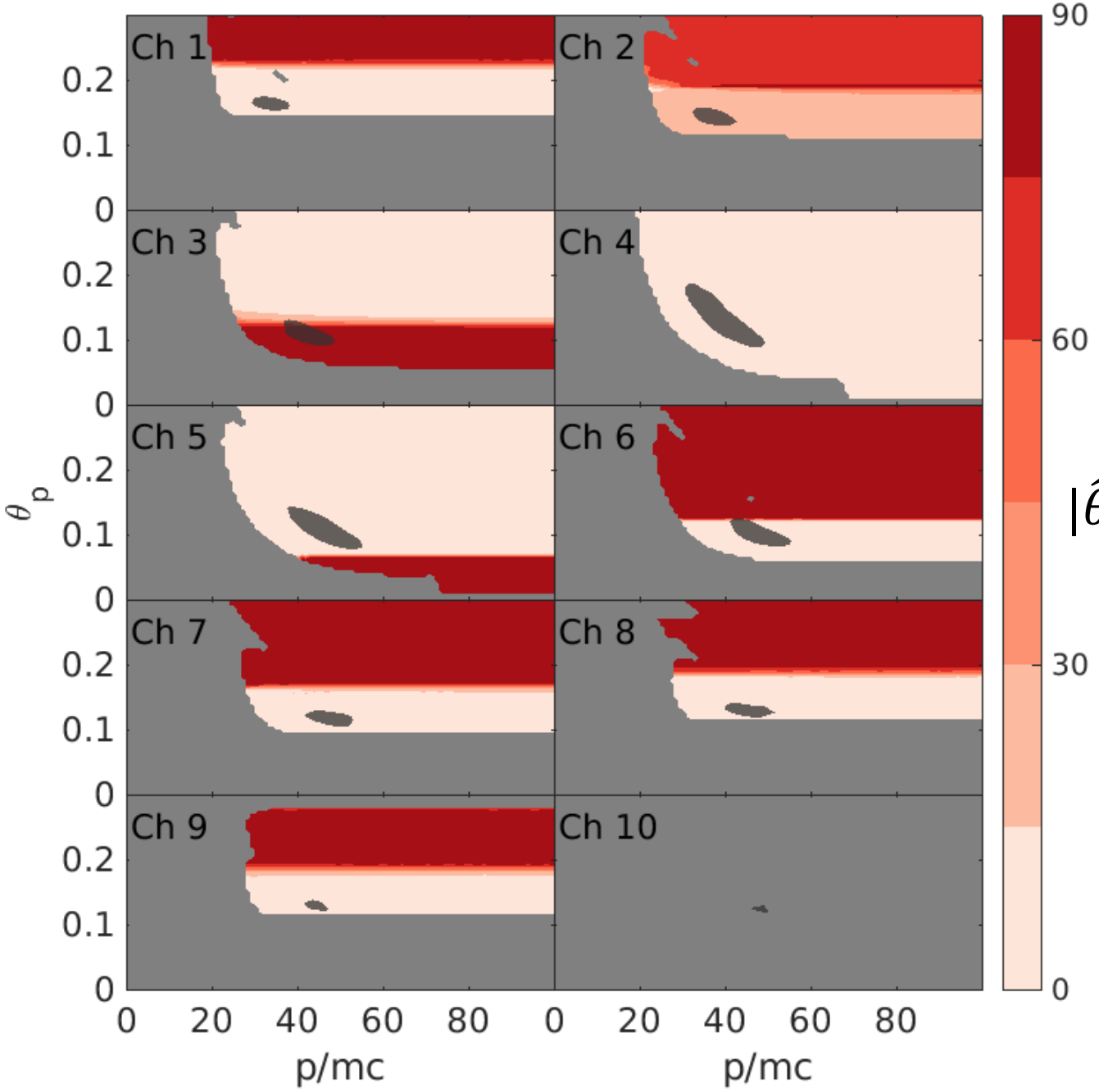
SOFT + CODE + Exp

$$|\hat{f}_{pol,SOFT} - f_{pol,Exp}|$$



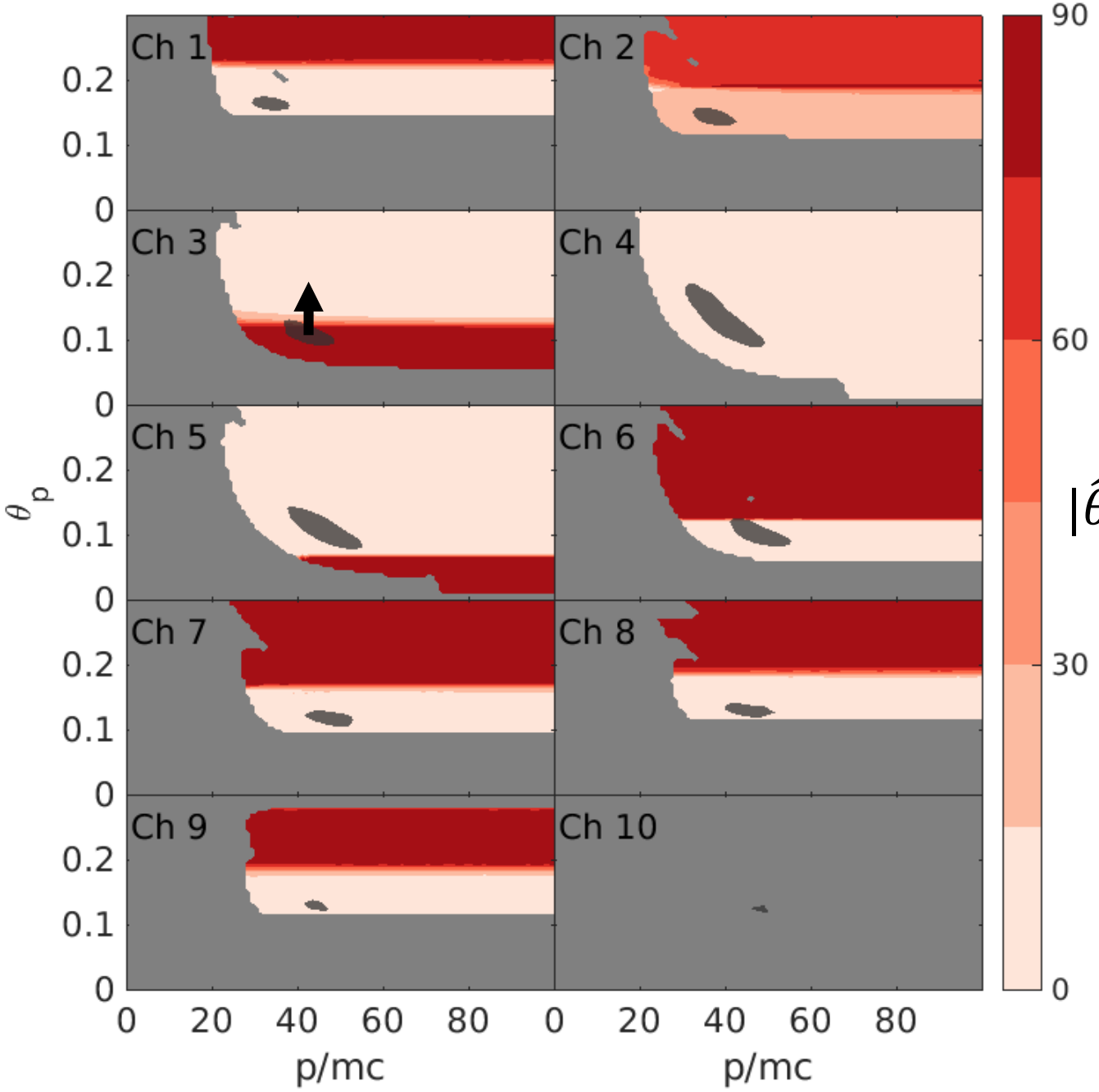
SOFT + CODE + Exp

$$|\hat{f}_{pol,SOFT} - f_{pol,Exp}|$$



SOFT + CODE + Exp

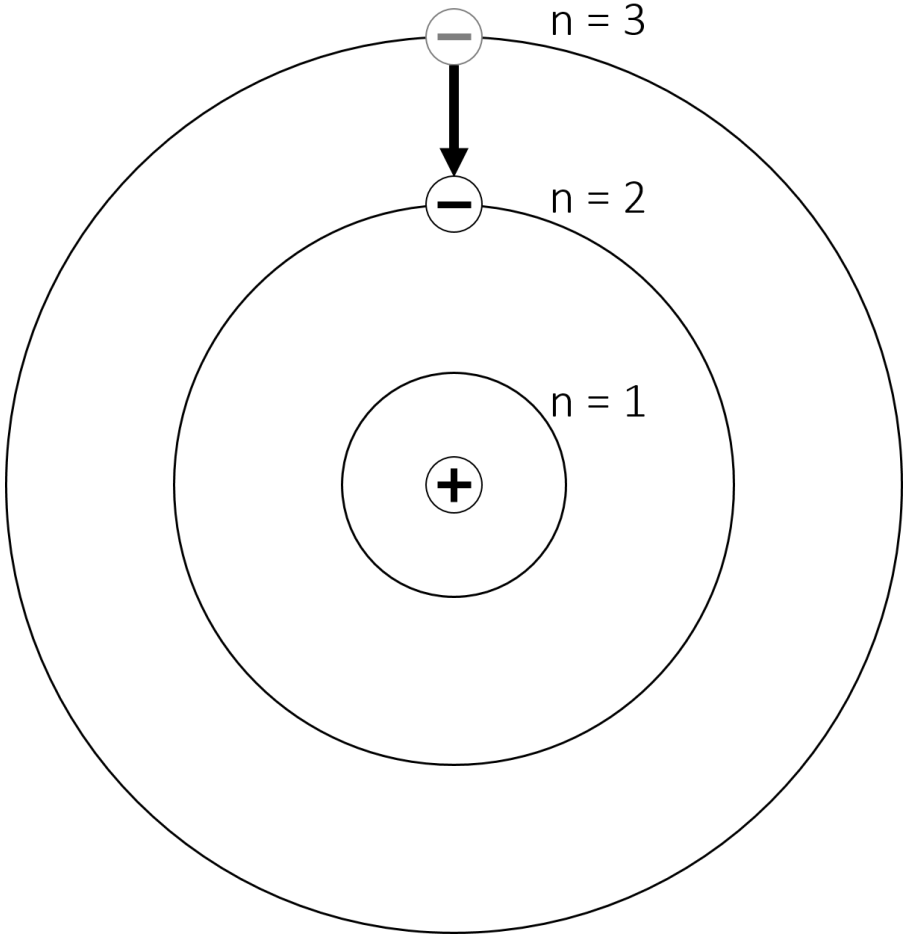
$$|\hat{\theta}_{pol,SOFT} - \theta_{pol,Exp}|$$



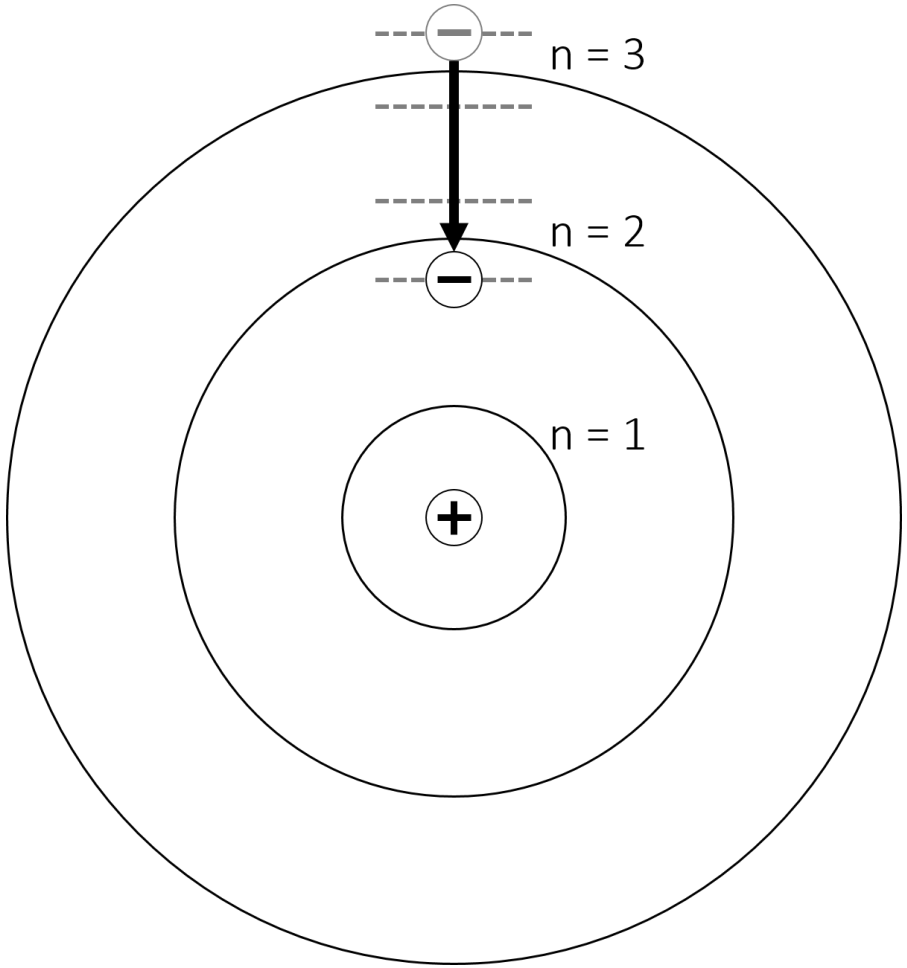
SOFT + CODE + Exp

$$|\hat{\theta}_{pol,SOFT} - \theta_{pol,Exp}|$$

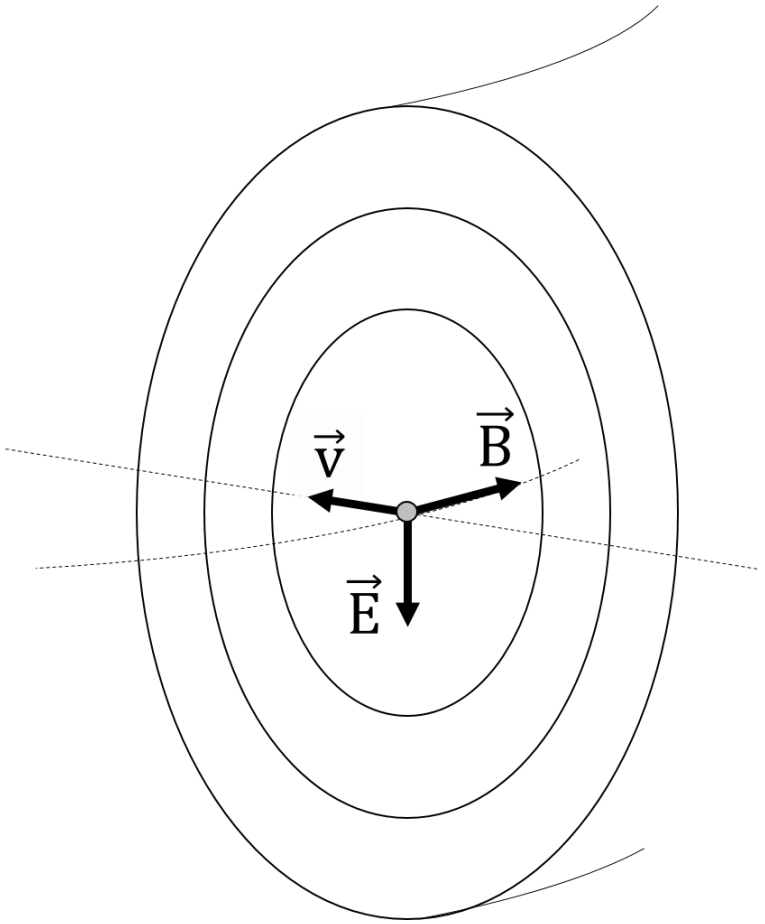
MSE system measures H-α line radiation from a **diagnostic neutral beam**



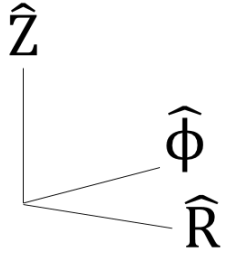
Stark effect splits energy levels, changing photon **frequency** and **polarization**



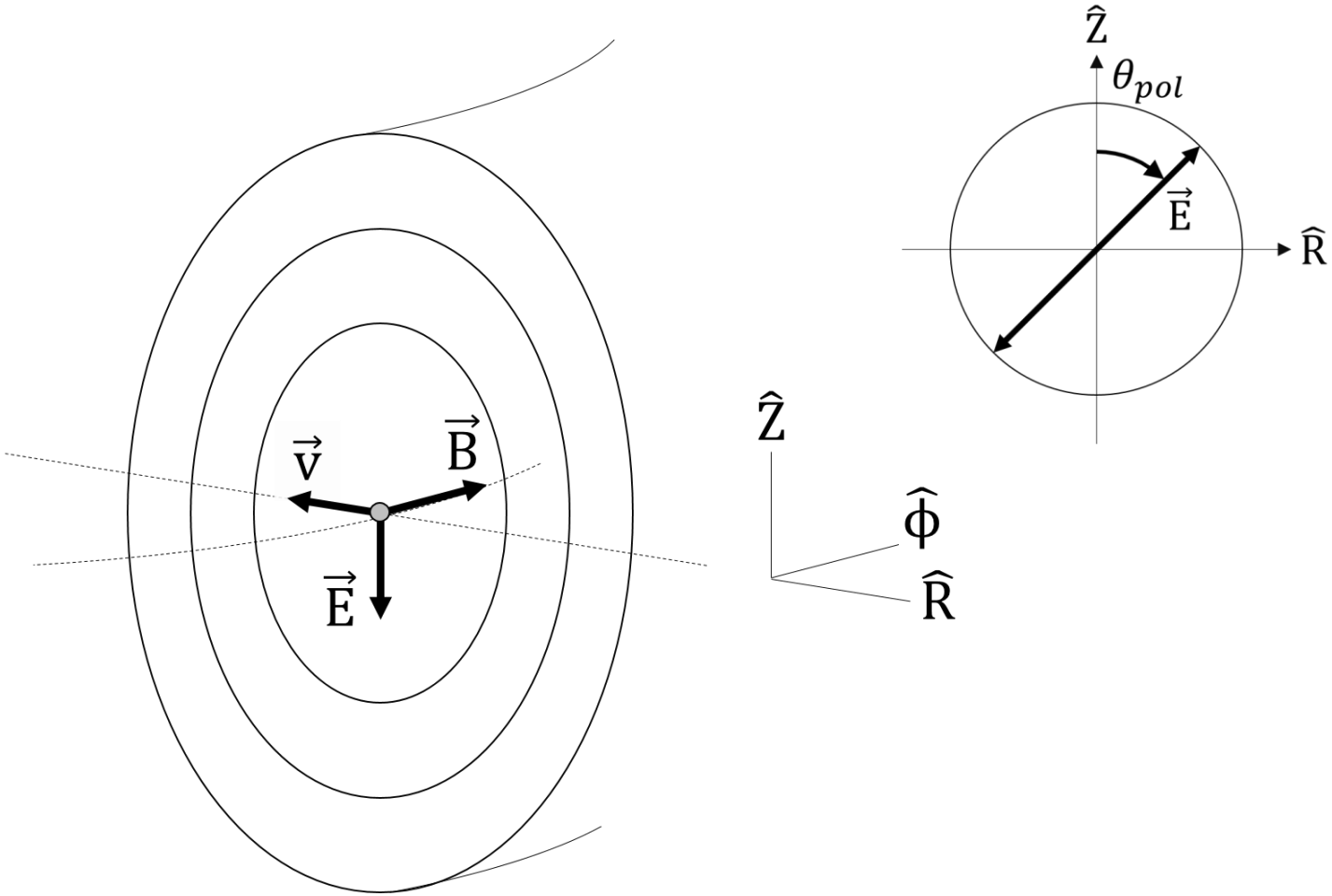
Motional Stark effect occurs due to particle motion through the background **magnetic field**



$$\vec{E} = \vec{v} \times \vec{B}$$



The polarization angle, θ_{pol}, is measured **clockwise** from the **vertical axis**



The **polarization angle**, θ_{pol}, is used to determine the **local magnetic field**