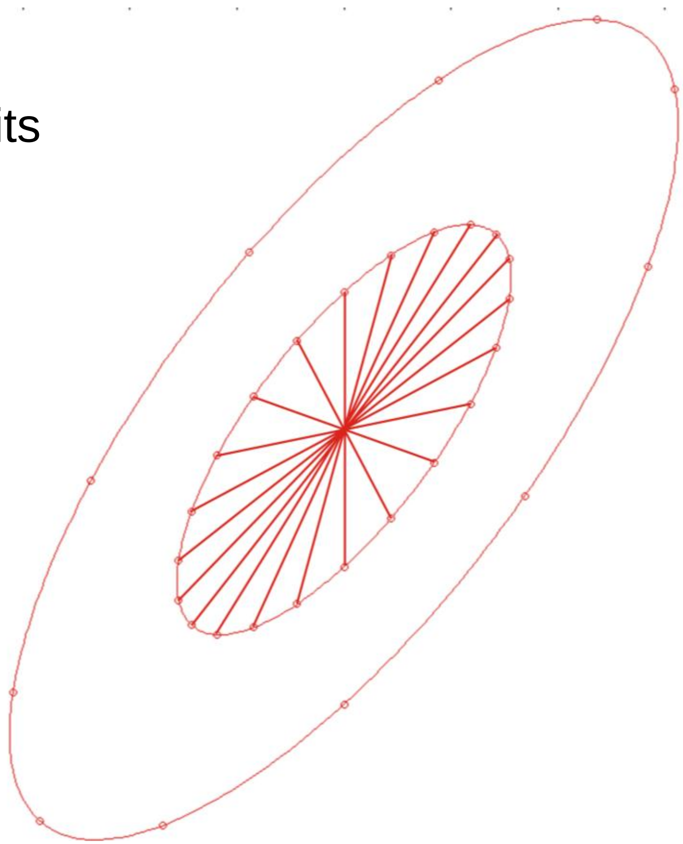
# Phase space painting for linear optics measurement

- **Pair of correctors used to 'paint' a phase space ellipse**
  - Ideally, correctors separated by drift
  - Linear combination of kicks produces difference orbits with desired *x, x'*
  - Orbits behave as macroparticles, an ensemble simulates a beam
  - Orbits uniformly distributed in normalised phase space to ensure good coverage
  - If desired, ellipse can be painted to match the design (MAD-X) phase space

# Phase space painting for linear optics measurement

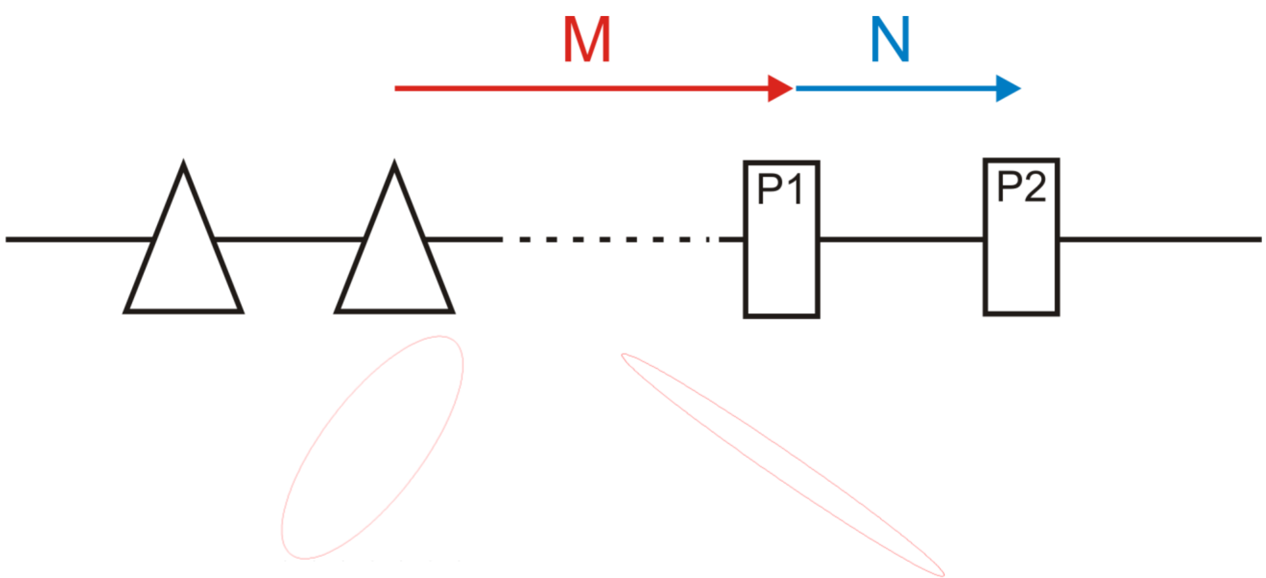
- **'Star' pattern painted to maximise signal to noise**
  - Difference orbits generated from two orbits separated by 180 deg. phase adv.
  - Beam drifts thus cancelled
  - Use an average over typically 5 difference orbits



- **Repeat measurement with multiple ellipses**
  - Increase the 'emittance' of the painted 'beam'
  - Use all data sets to fit a normalised ellipse, reducing sensitivity to drifts further

# Evolution of painted phase space ellipse

- **Aim to measure matrix *M***
  - Know phase space painted at downstream corrector
  - Want to observe how the phase space ellipse evolves at the BPM P1
  - This requires knowledge of position **and angle** at P1
  - Assume matrix *N* from MAD-X model, reconstruct using P1 & P2



# Reconstructing the transfer matrix with symplectic fit

- **Matlab non-linear fitting code. Solve for *M:***

$$\mathbf{x}_{BPM} - \mathrm{M}\mathbf{x}_K = 0$$

- **Where for the *N* difference orbits:**

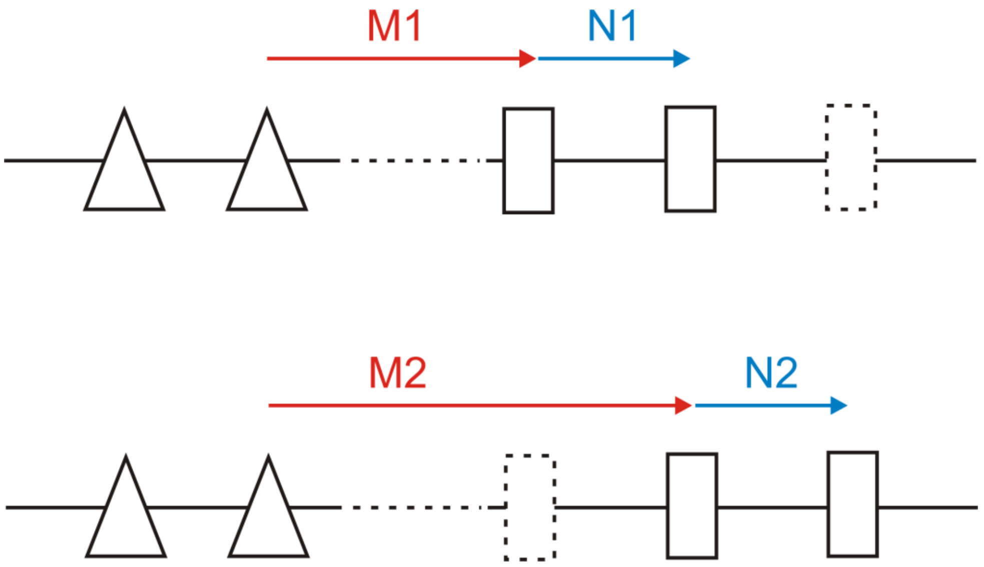
$$\mathbf{x} = \left(\vec{x_1}, \vec{x_2},\ \ldots\ \vec{x_N}\right)$$

- **And the symplectic constraint is applied:**

$$\mathrm{M}'\Omega\mathrm{M} - \Omega = 0$$

# Consistency of measured matrices

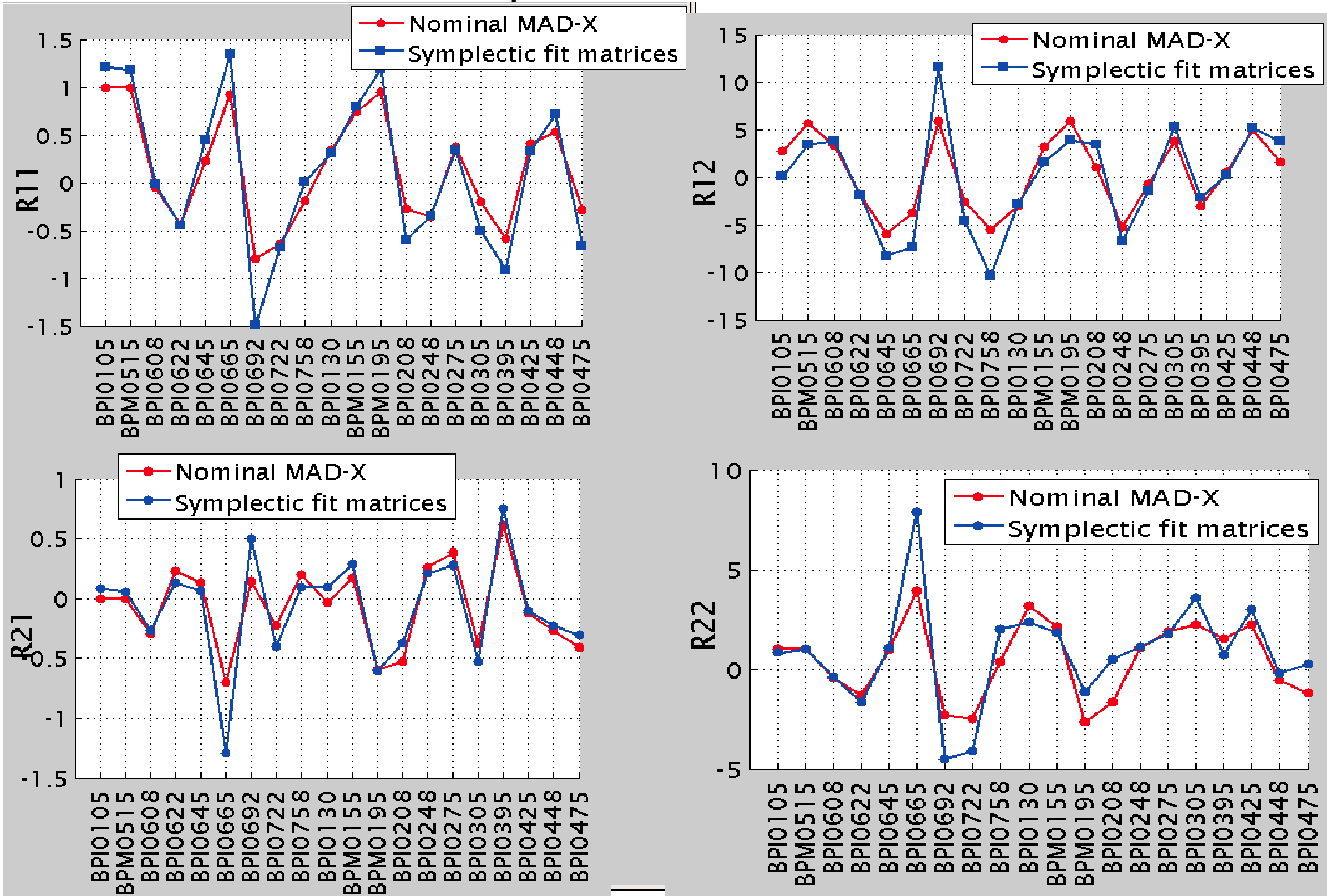
1. **Reconstruct $M_1$ by assuming $N_1$ from MAD-X**
2. **Move forward to next pair of BPMs**
3. **Reconstruct $M_2$ by assuming $N_2$**
4. **$M_2 = N_1 M_1$**
5. **If $M_1$ and $M_2$ are consistent with MAD-X, confident it was okay to assume $N_1$**
6. **Otherwise, have localised an optical error**
7. **Repeat for all BPMs**



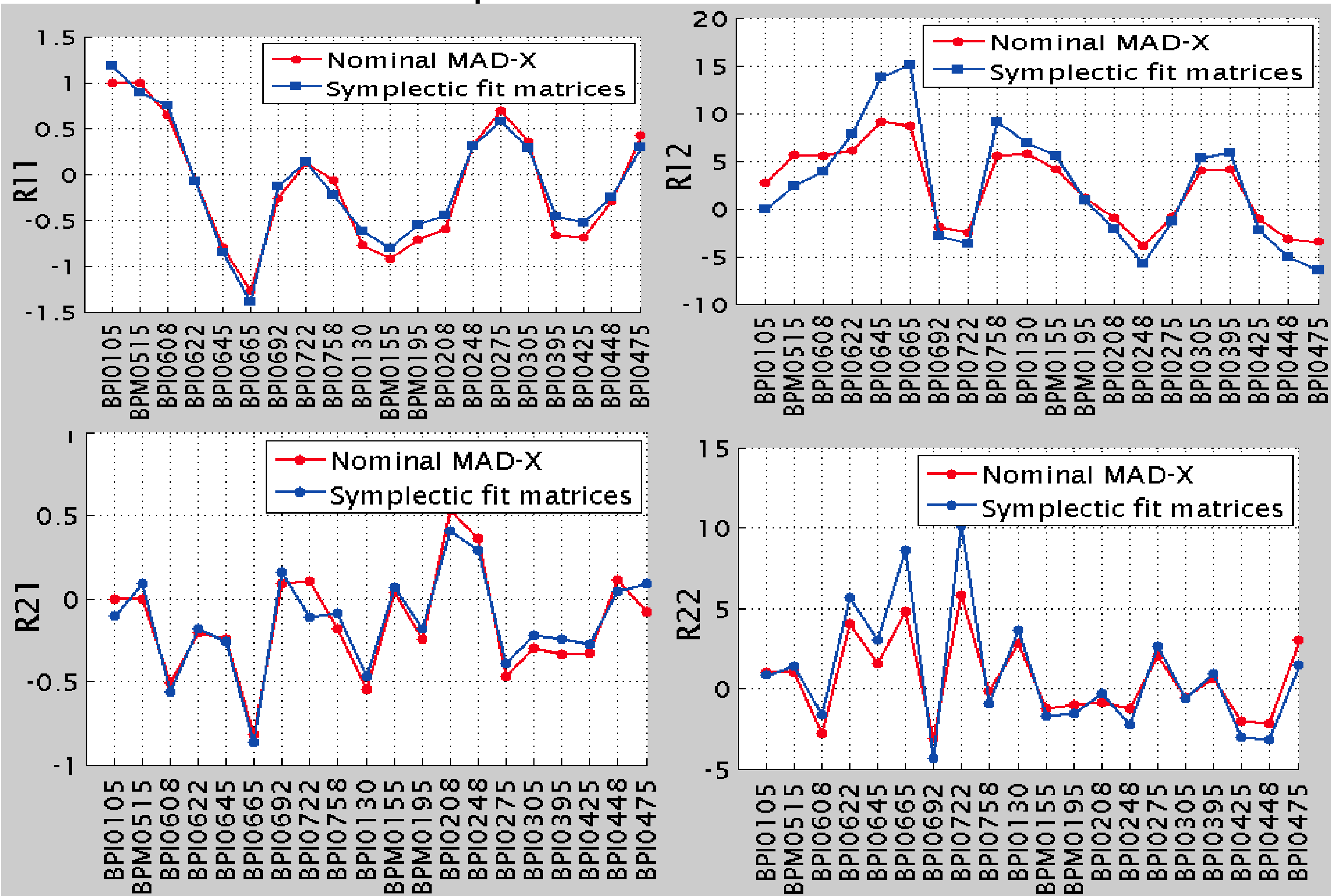
# Linear optics measurement in CT-TL1-CR

- **Machine conditions:**
  - 3 GHz, uncombined beam
  - Magnetic bypass of delay loop
  - Magnetic injection into combiner ring
  - Extracted after ½ turn
- **Correctors 0495 and 0505 at DL injection used (horizontal and vertical)**
- **Early data set – only single ellipse painted per plane**

# Horizontal linear optics measurement in CT-TL1-CR



# Vertical linear optics measurement in CT-TL1-CR

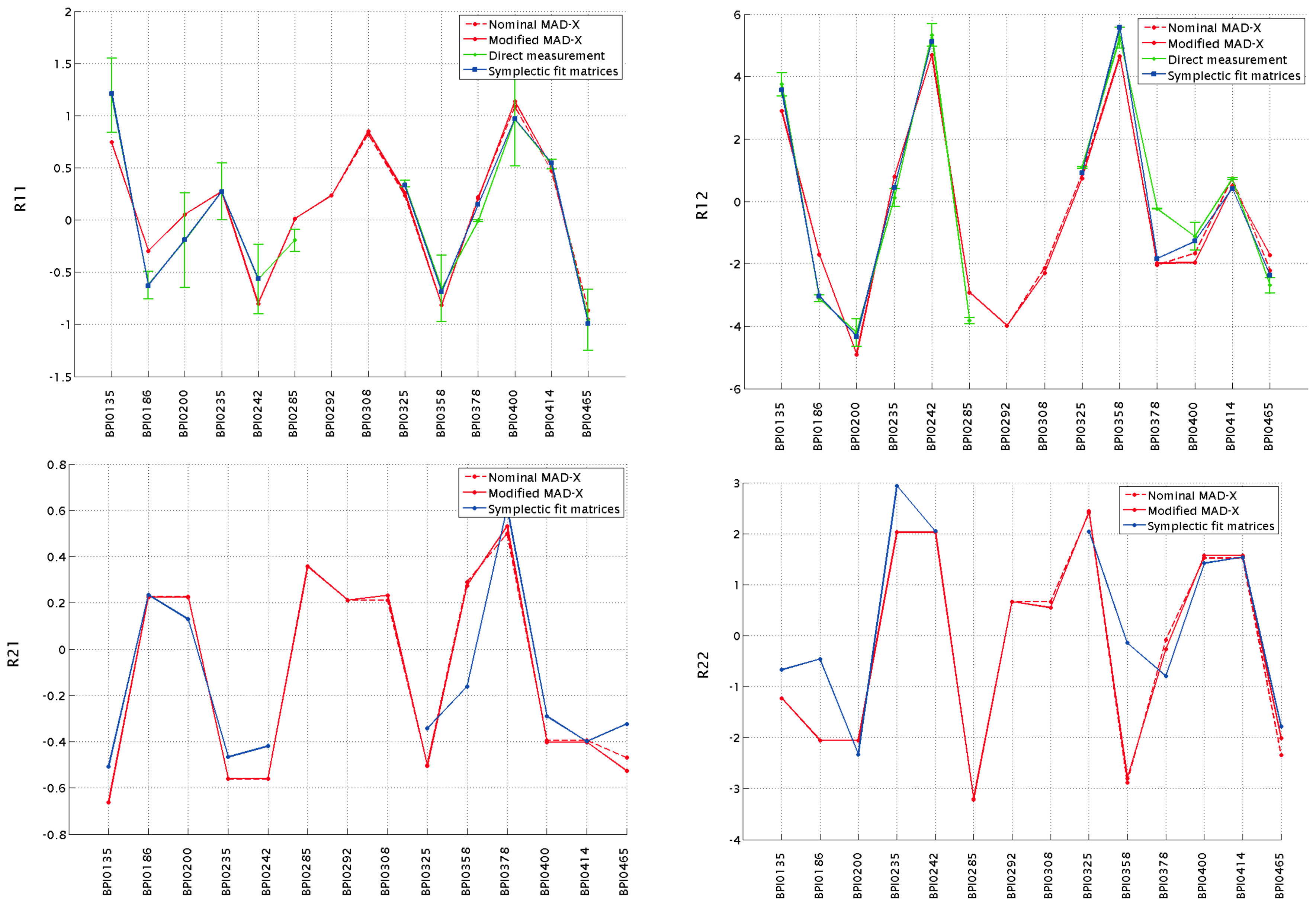


# Linear optics measurement in delay loop

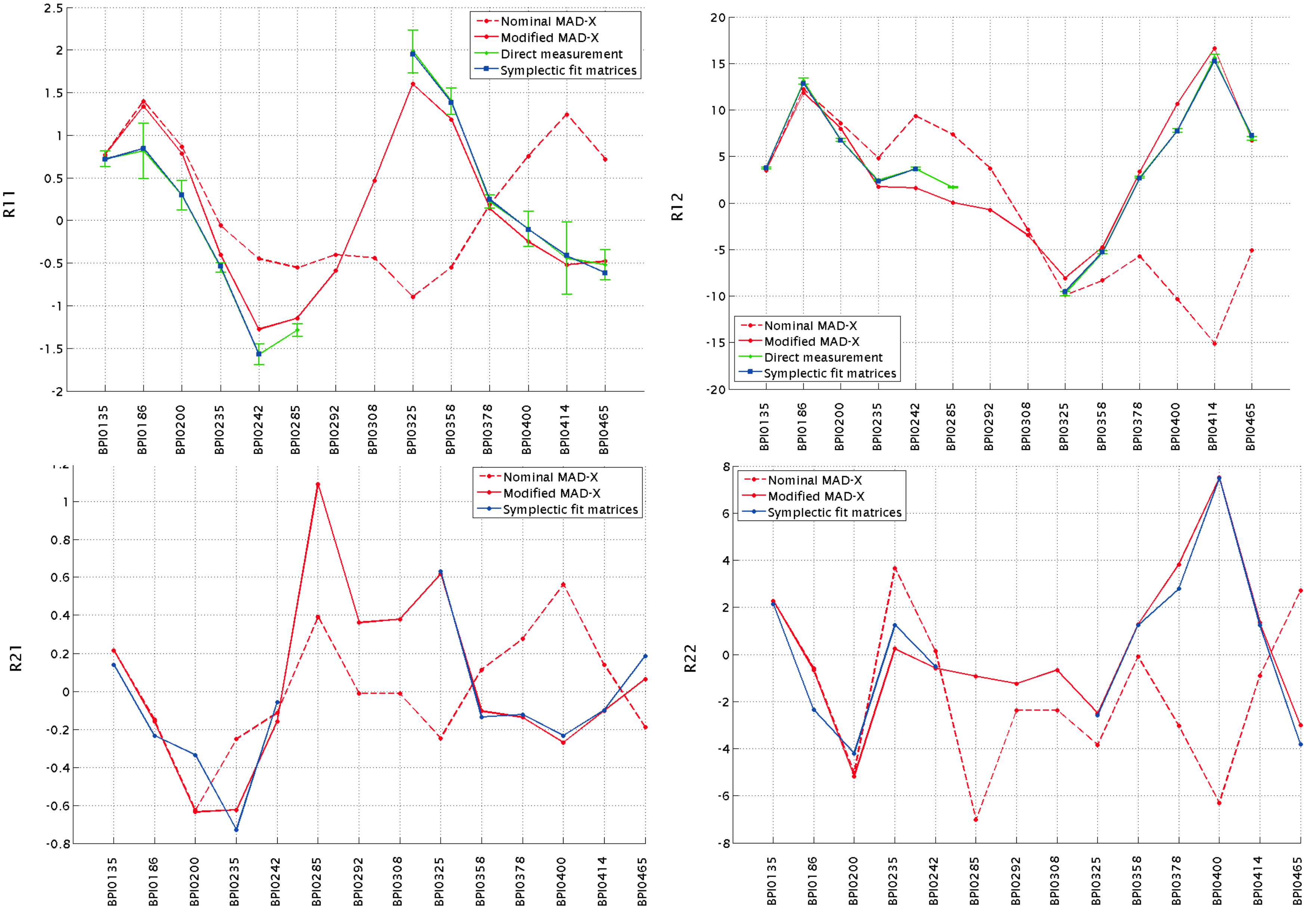
- **Machine conditions:**
  - 3 GHz beam
  - Magnetic injection into delay loop
- **Correctors 0495 and 0505 at DL injection used (horizontal and vertical)**
- **Five ellipses painted per plane and matched to nominal MAD-X**

- **Discrepancy in vertical optics found**
  - Included Biscar wiggler model in MAD-X
  - Used Matlab optimisation code to run analysis with various MAD-X parameters
  - Good agreement between model and data by optimising dipole field integrals
  - Optimum FINTs 0.708 and 0.503 for the two dipole families (other & EPA resp.)

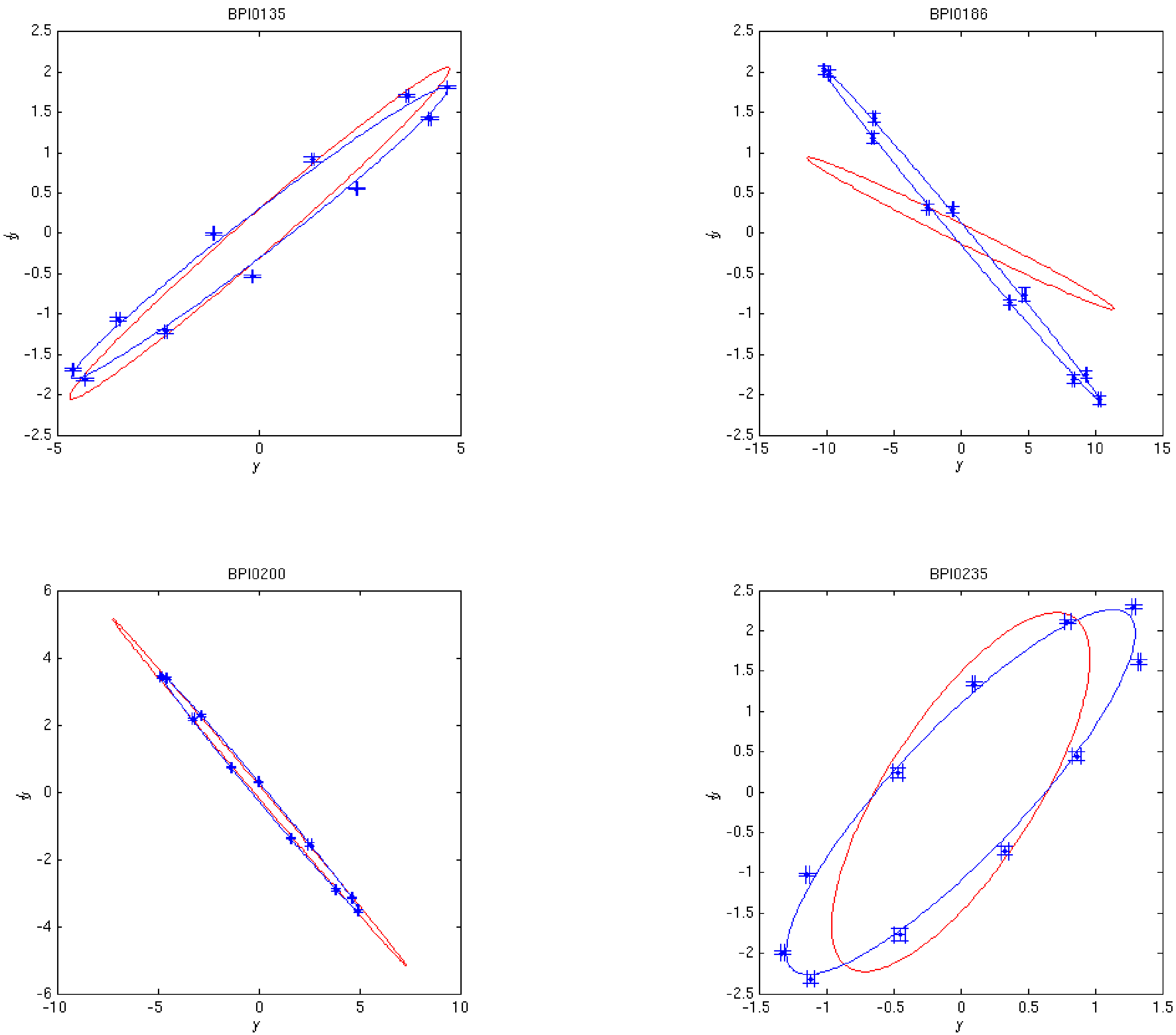
# Horizontal linear optics measurement in delay loop



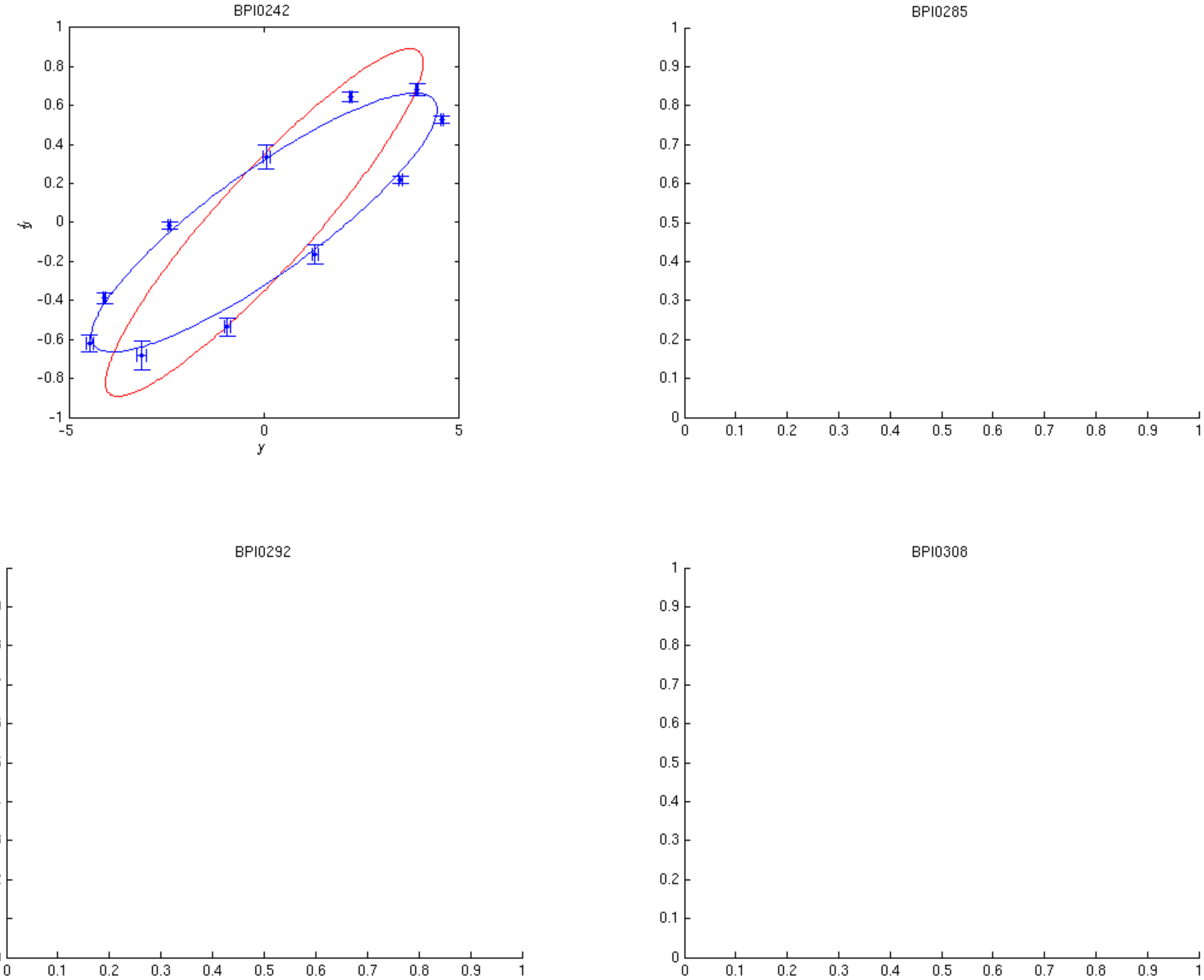
# Vertical linear optics measurement in delay loop



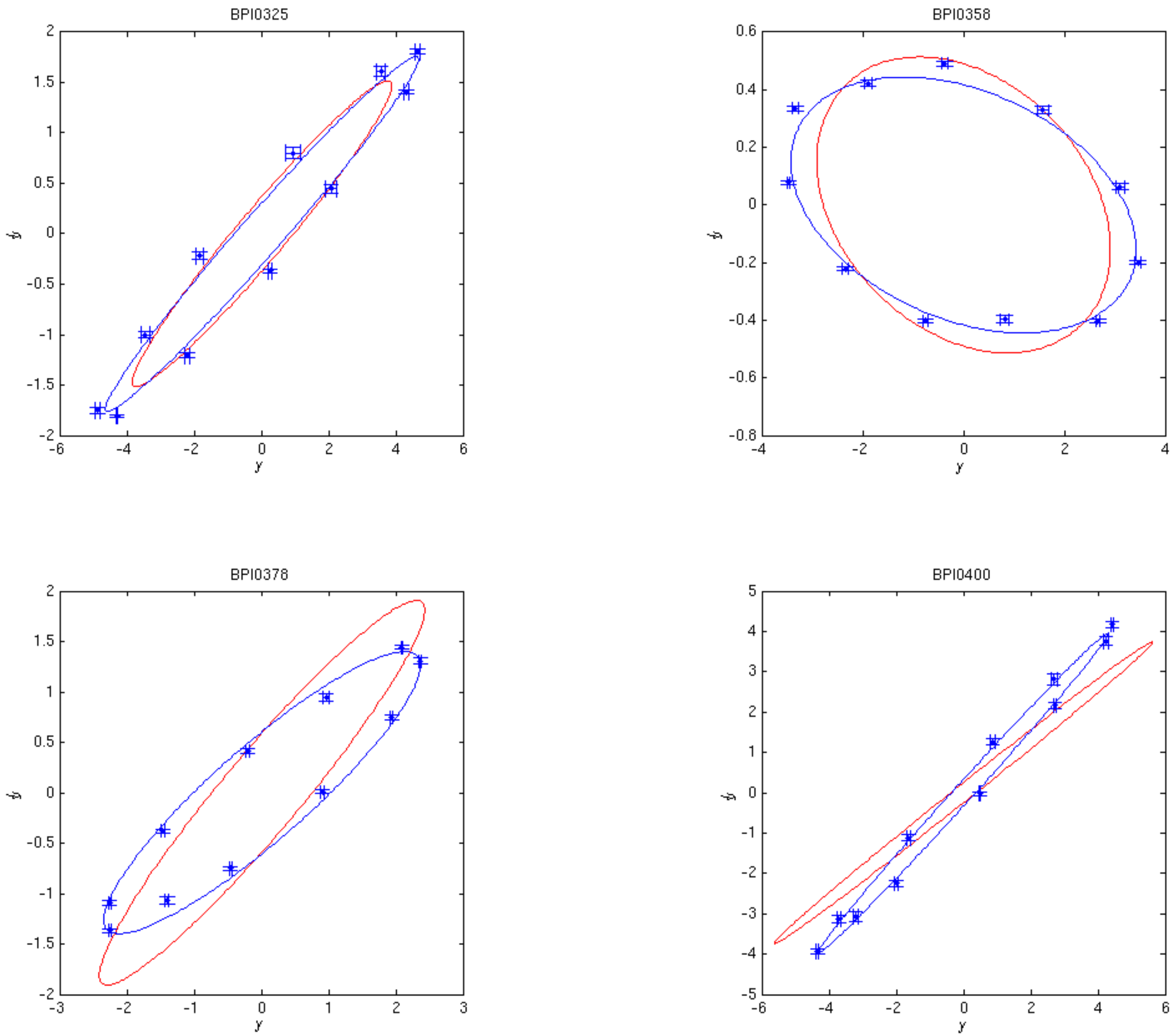
# Alternative view – delay loop vertical measurements 1



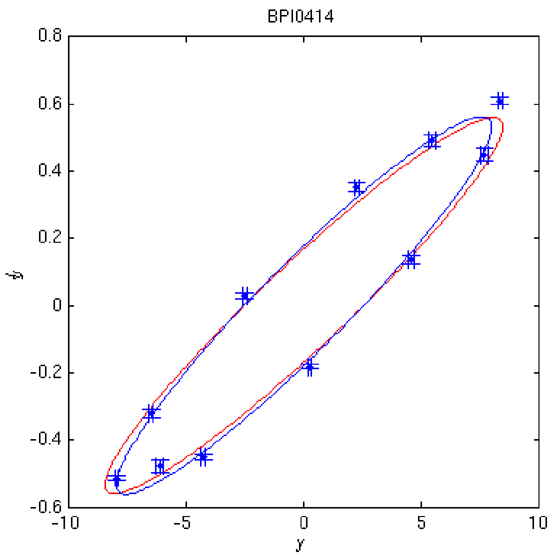
# Alternative view – delay loop vertical measurements 2



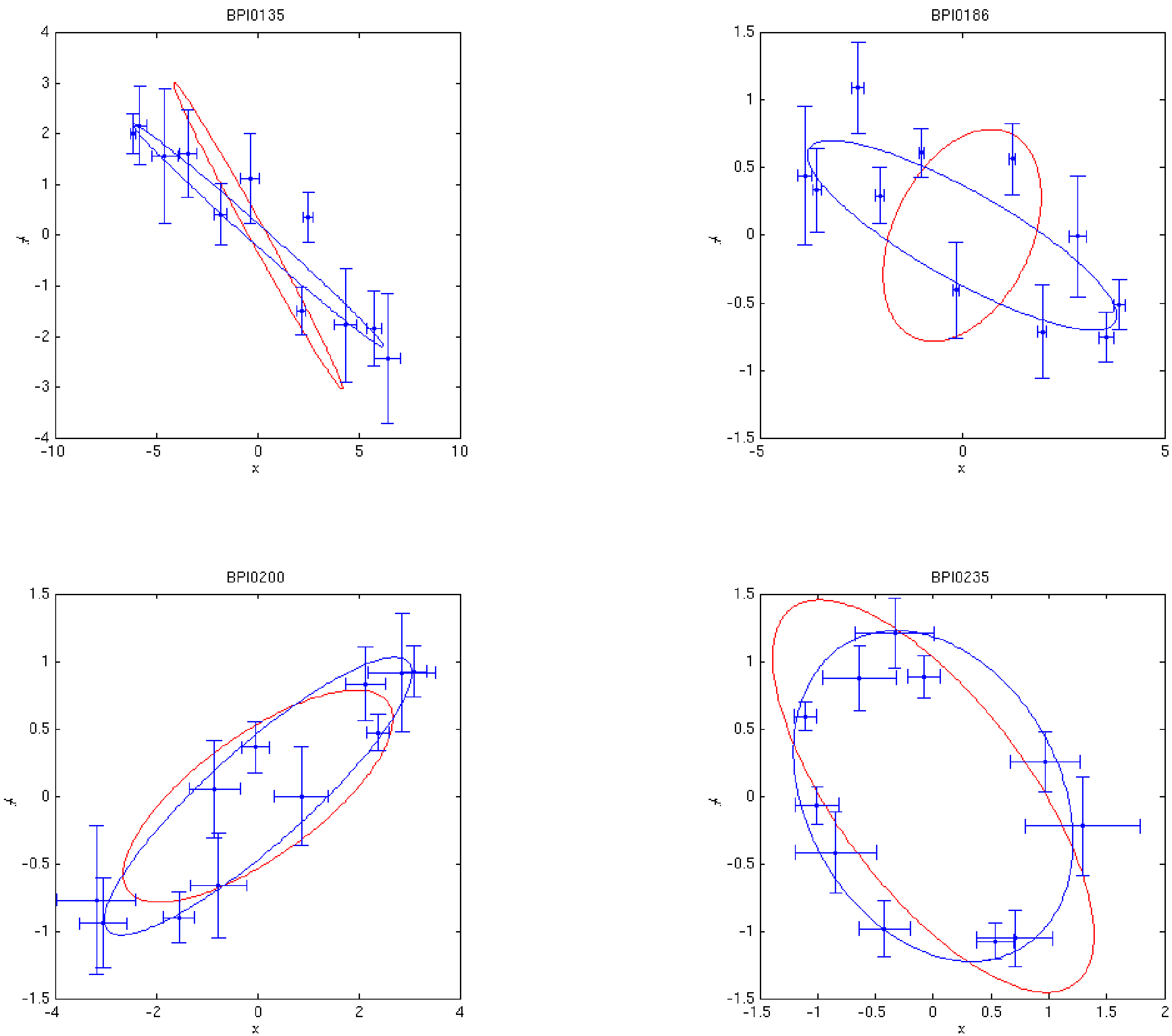
# Alternative view – delay loop vertical measurements 3



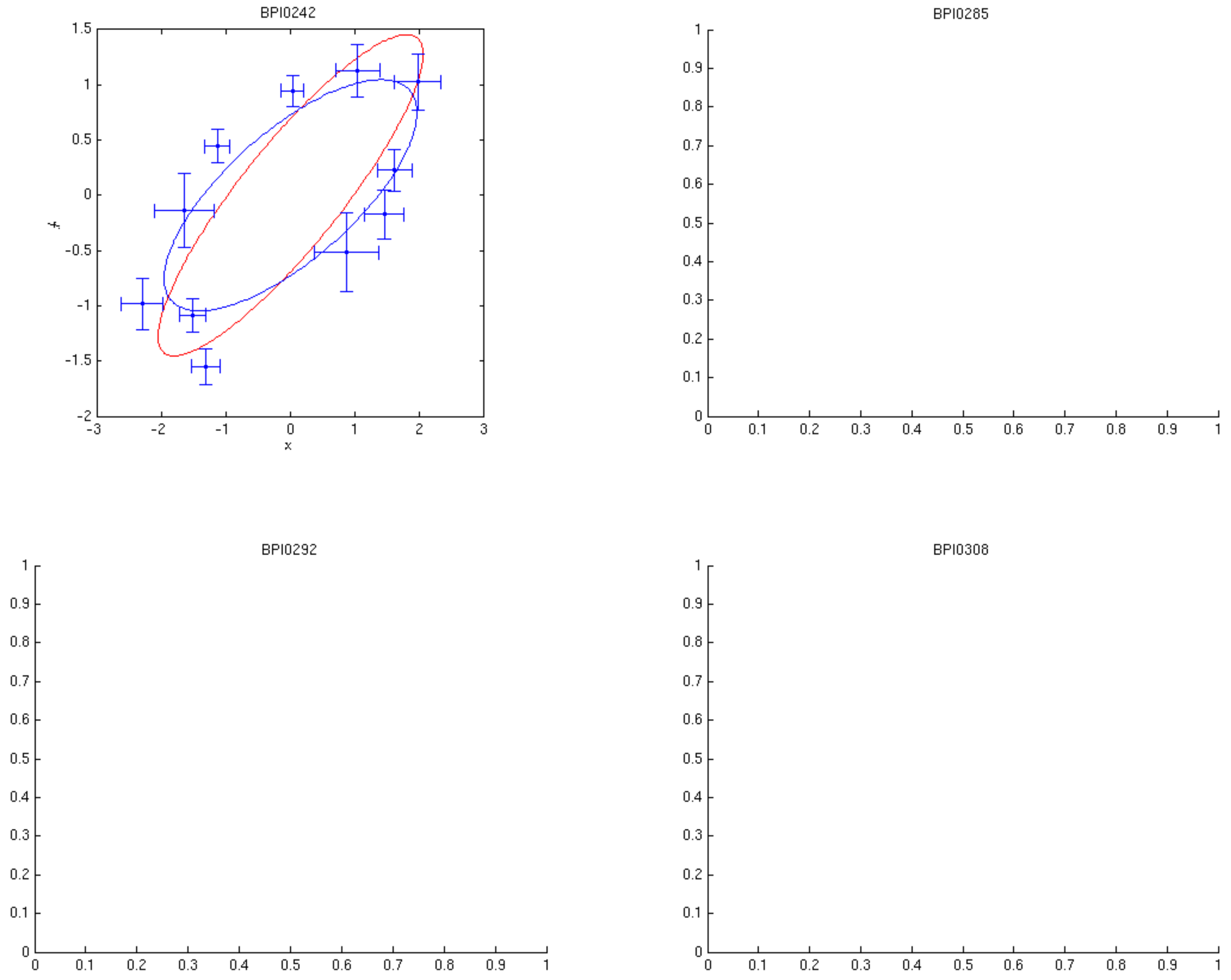
# Alternative view – delay loop vertical measurements 4



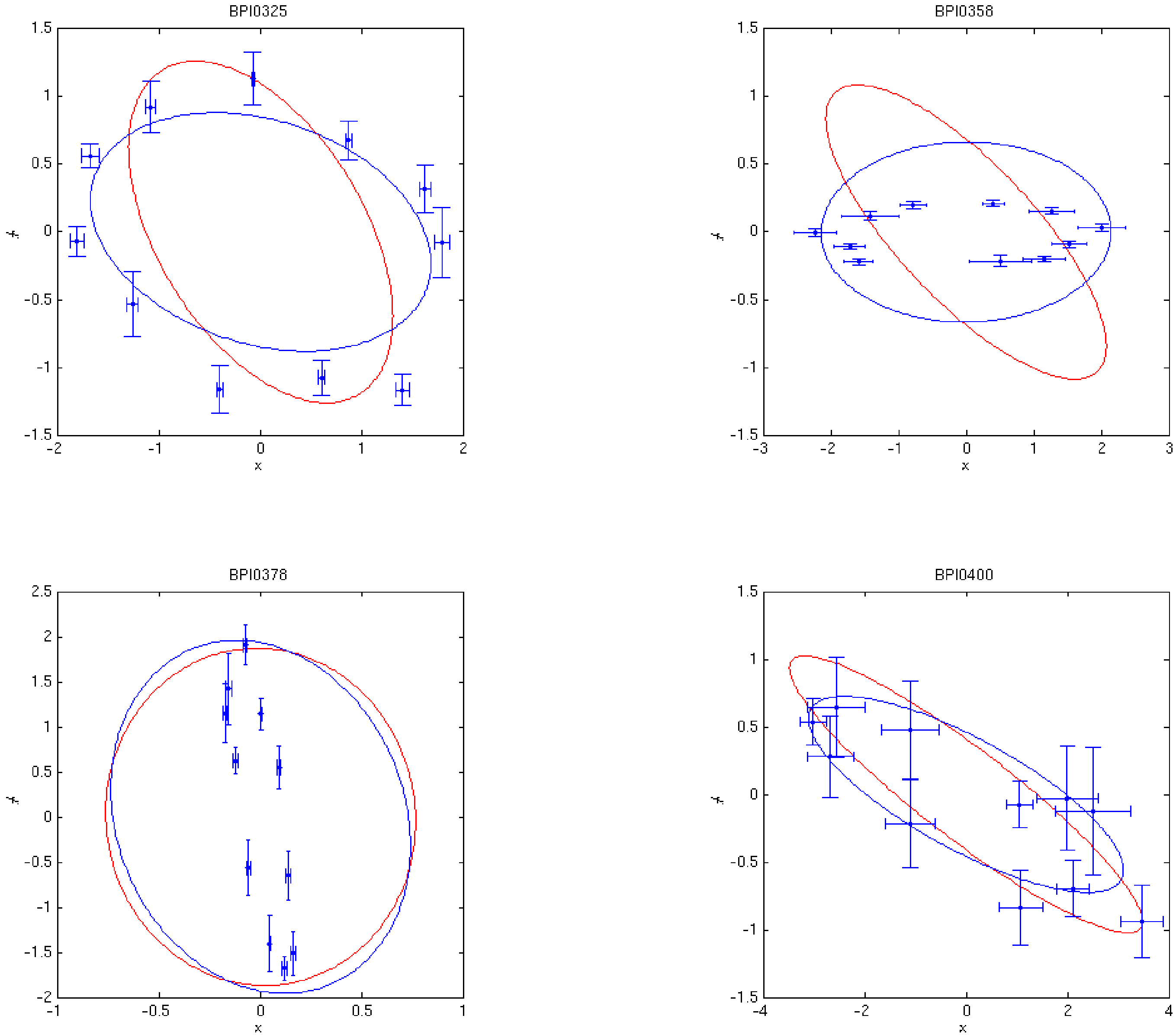
# Alternative view – delay loop horizontal measurements 1



# Alternative view – delay loop horizontal measurements 21



# Alternative view – delay loop horizontal measurements 3



# Alternative view – delay loop horizontal measurements 4