# Forward-Backward Asymmetry and Pion Form Factor Contributions to $e^+ + e^- \to \pi^+ + \pi^- + \gamma$

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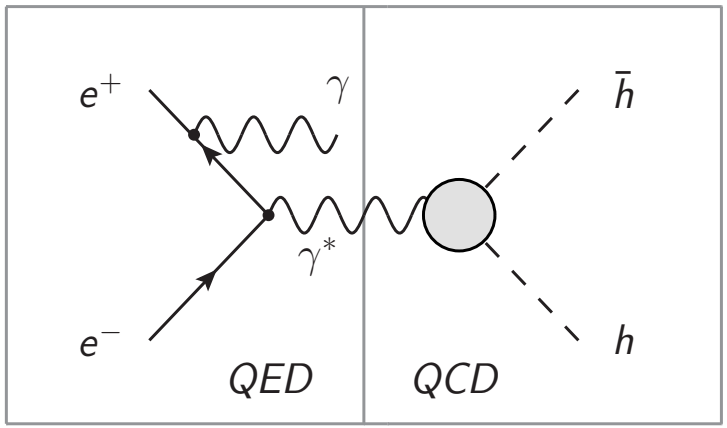
# Physical Process

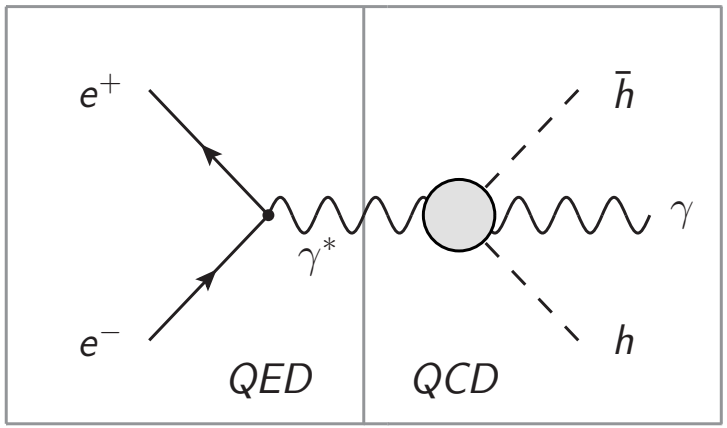
$$e^+ + e^- \longrightarrow \text{hadrons} + \gamma \qquad \text{via}$$

initial state radiation (ISR)




or

final state radiation (FSR)

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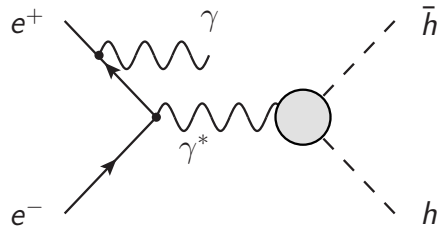
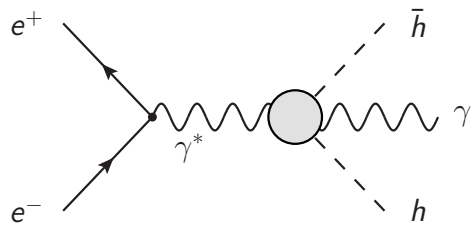
# A Few Keywords

Ingredients for a description of the given process

- (theoretical) models: ISR ← QED, FSR ← QCD
- for ISR and FSR: pion form factor
- for FSR, in addition: virtual Compton scattering

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# Cross Section

Cross section for $e^+e^- \to \pi^+\pi^-\gamma$

$$\mathrm{d}\sigma \propto |\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{ISR}}|^2 + |\mathcal{M}_{\mathrm{FSR}}|^2 + 2\mathrm{Re}[\mathcal{M}_{\mathrm{ISR}}\mathcal{M}^*_{\mathrm{FSR}}]$$

- different charge parity for pion pair in ISR or FSR channel
- third term in this equation causes charge asymmetry
- therefore[1]: forward-backward asymmetry (FBA) of $\pi^\pm$

[1] *Binner et. al.*, arXiv:hep-ph/9902399v1

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# Forward-Backward Asymmetry – Conjecture

$$\mathcal{A}_{\text{symmetry}} = \frac{N\left(\pi^{\pm}_{\text{bwd}}\right) - N\left(\pi^{\pm}_{\text{fwd}}\right)}{N\left(\pi^{\pm}_{\text{bwd}}\right) + N\left(\pi^{\pm}_{\text{fwd}}\right)} \propto \frac{\text{Re}\left[\mathcal{M}_{\text{ISR}}\mathcal{M}^{*}_{\text{FSR}}\right]}{\left|\mathcal{M}_{\text{ISR}}\right|^{2}}$$

- *"Given the dominance of initial state radiation [. . . ], the forward-backward asymmetry is roughly proportional to the ratio $\mathcal{M}_{FSR}/\mathcal{M}_{ISR}$."* [2]
- conjecture: asymmetry may be good quantity to determine contributions of final state radiation – and their impact on the cross section

[2] *Binner et. al.*, arXiv:hep-ph/9902399v1

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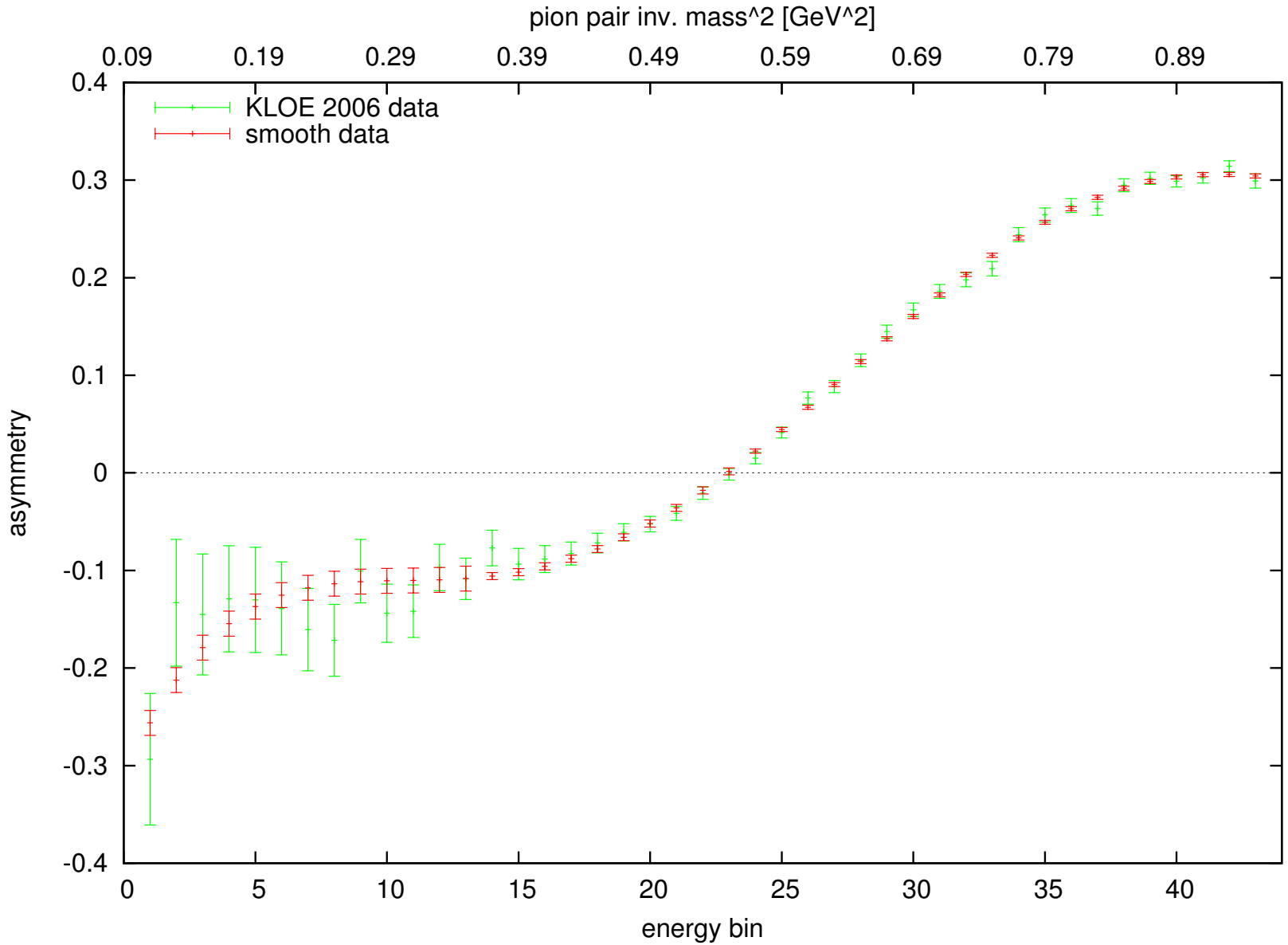
# FBA – Experimental Status

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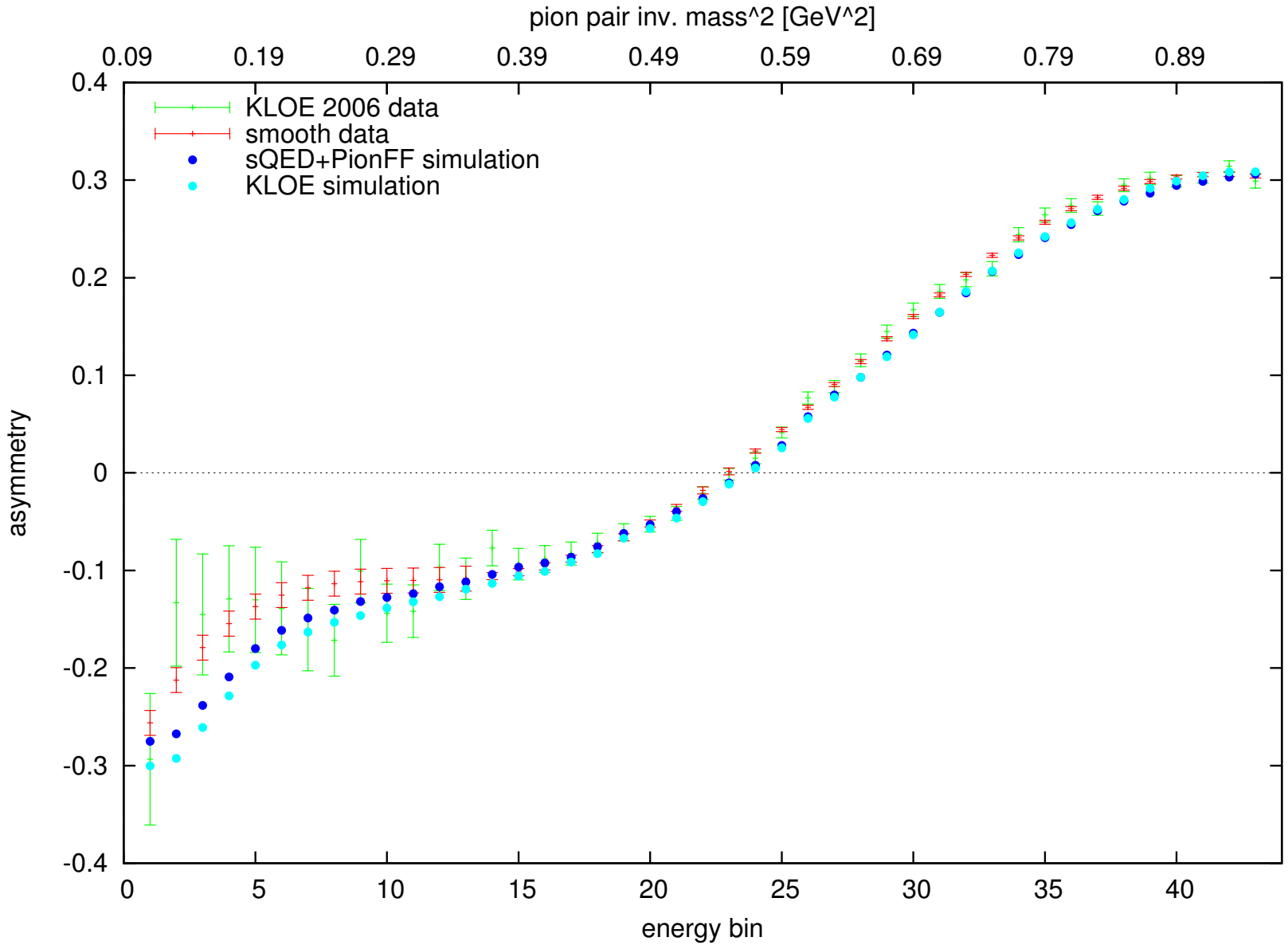
# FBA – Experimental Status

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# (Some) Technical Details

- Phokhara v6.1, modified for parallel computing
- FSR contributions are complex numbers (two d.o.f.)
- but in principle: six d.o.f.
- scale determined by KLOE model already included
- procedure:
  1. pick one energy bin and FSR amplitude $\longrightarrow$ configuration
  2. generate asymmetry and cross section
  3. compare with smooth data $\longrightarrow$ hit-list

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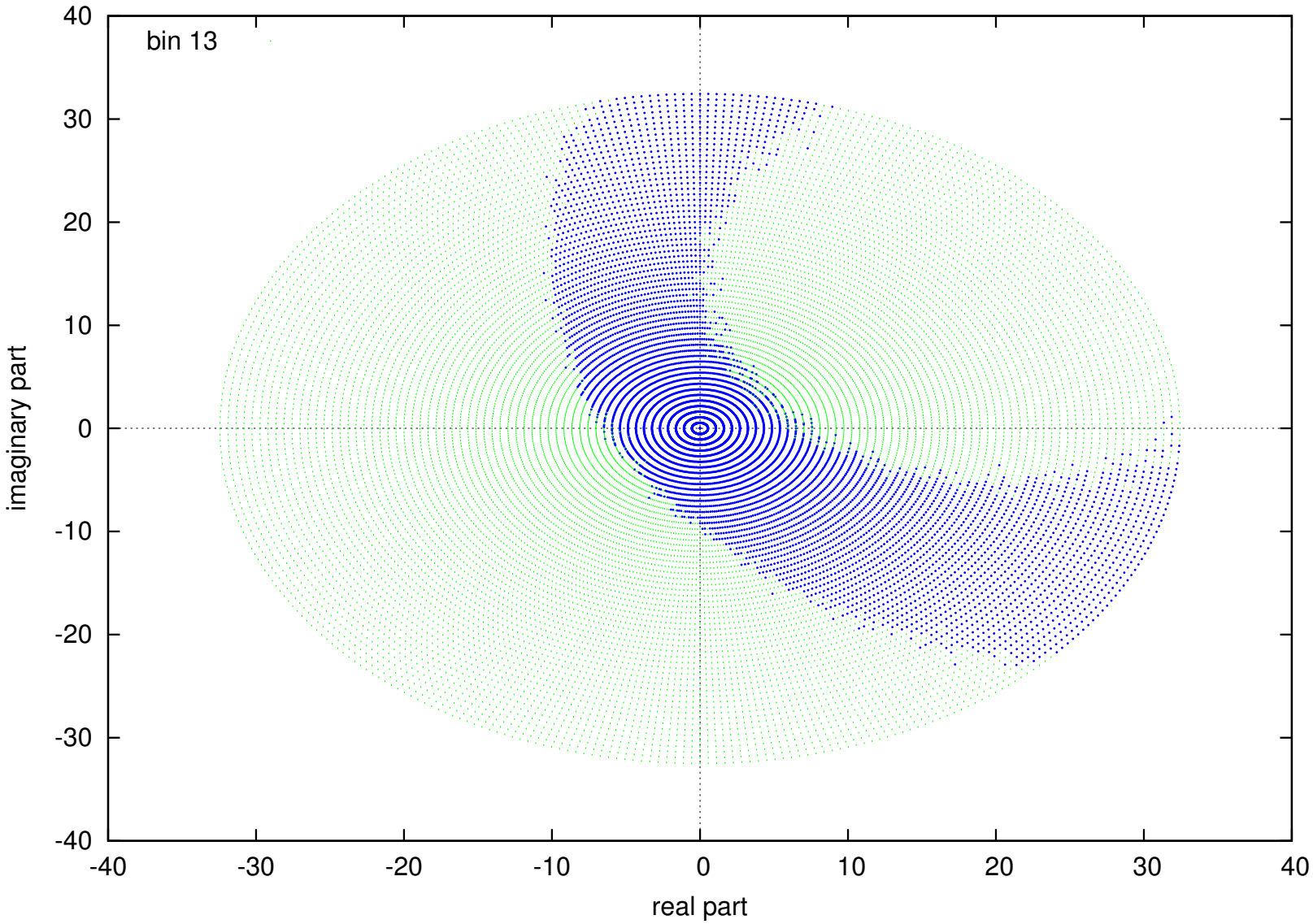
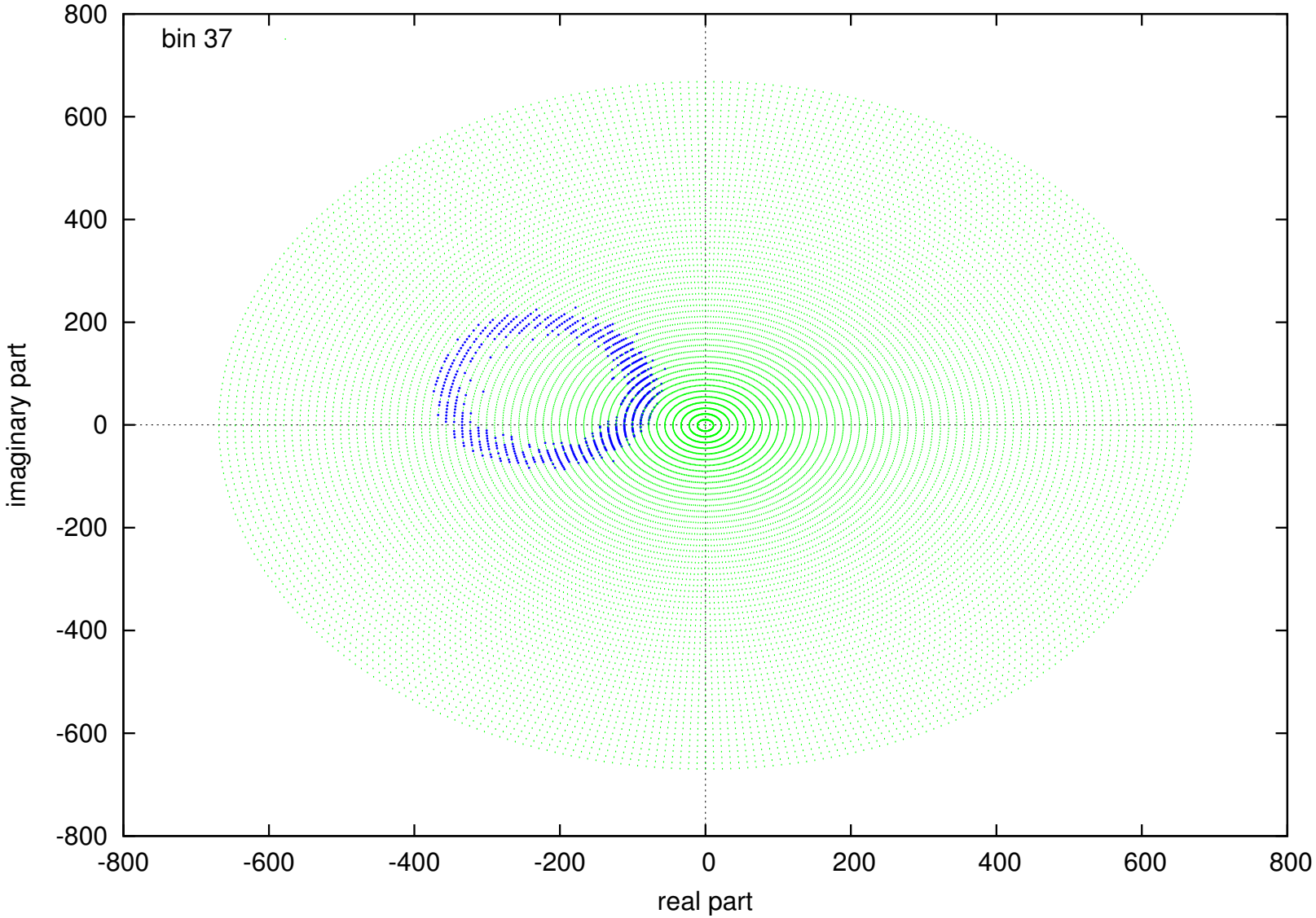
# FSR – Hit-List


bin 13
imaginary part
real part
40
30
20
10
0
-10
-20
-30
-40
-40
-30
-20
-10
0
10
20
30
40

# FSR – Hit-List

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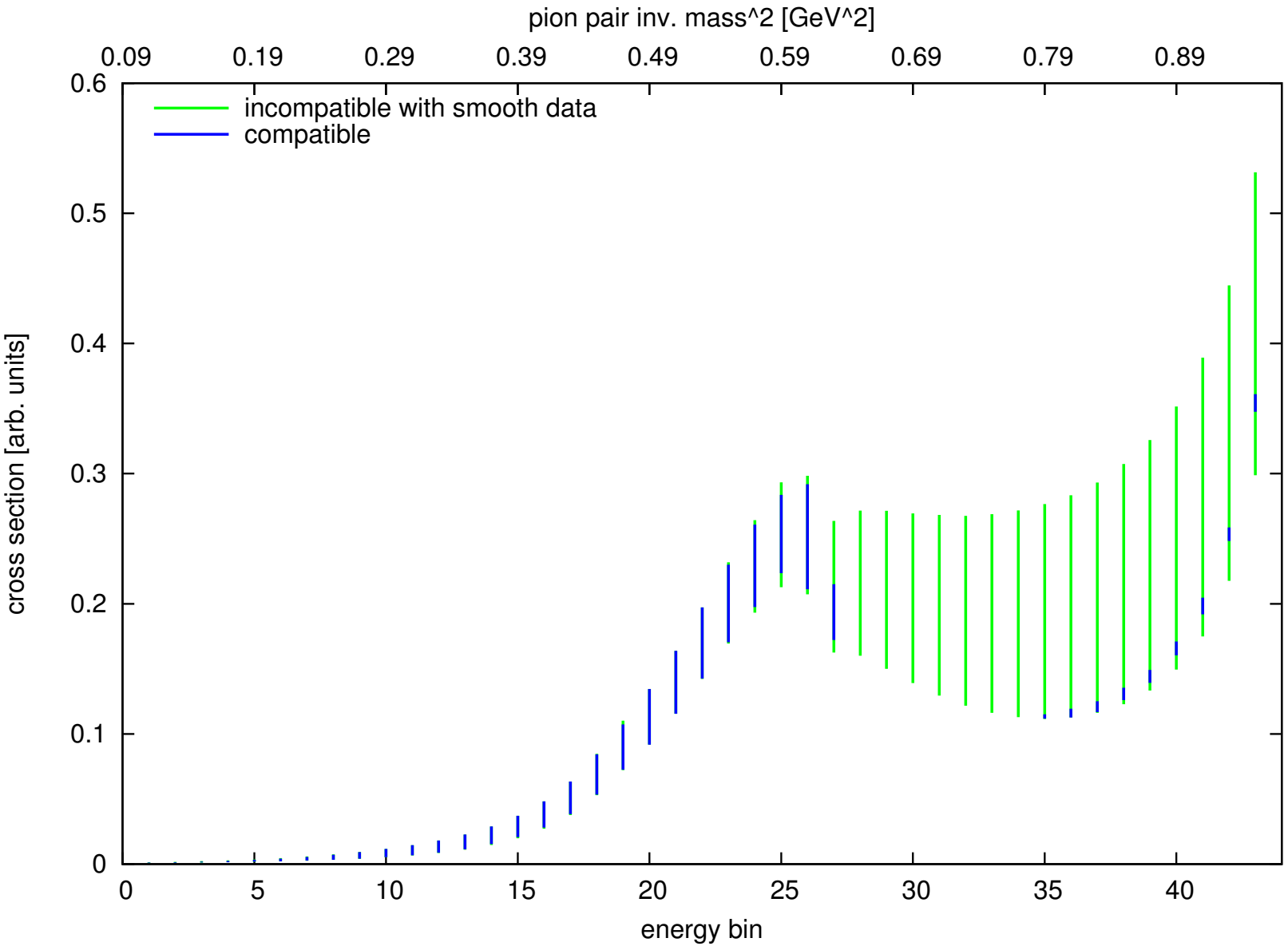
# FSR – Cross Section

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# Conclusion – FSR

- forward-backward asymmetry not very sensitive to final state radiation
- assumption $\mathcal{A} \propto \mathcal{M}_{\mathrm{FSR}}/\mathcal{M}_{\mathrm{ISR}}$ not unrestrictedly correct
- model independent estimation of FSR parameters by FBA not possible
- impact on the cross section not negligible

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# Pion Form Factor

Very important for the simulation: pion form factor at 1 $\mathrm{GeV}^2$

- plain complex number, i.e. modulus and phase resp. angle
- two approaches
  1. no restrictions, map out parameter space
  2. restrict modulus to $+\sqrt{3.2}$, all angles
- compare with smooth FBA data (as before)

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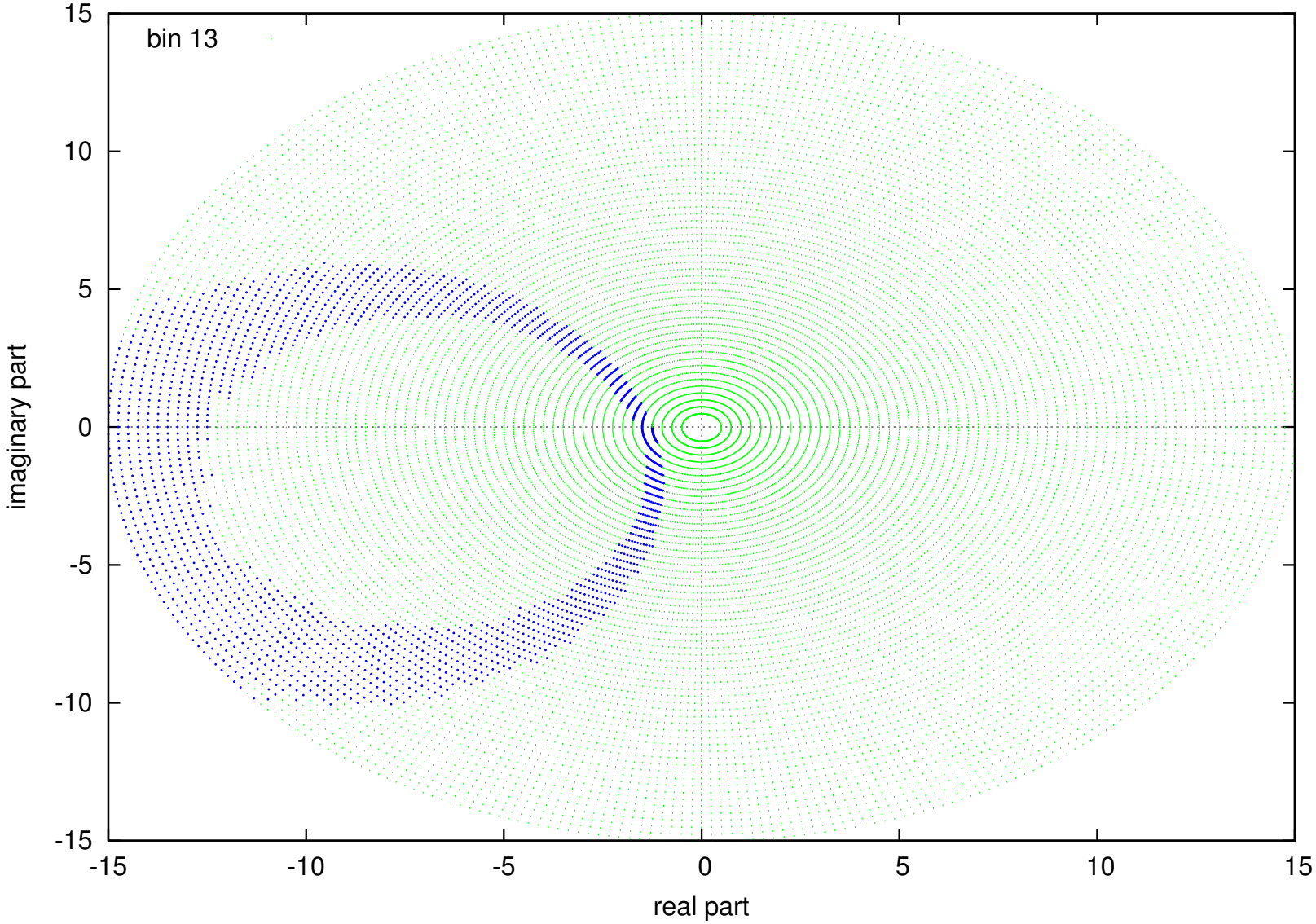
# PionFF 1 – Hit-List

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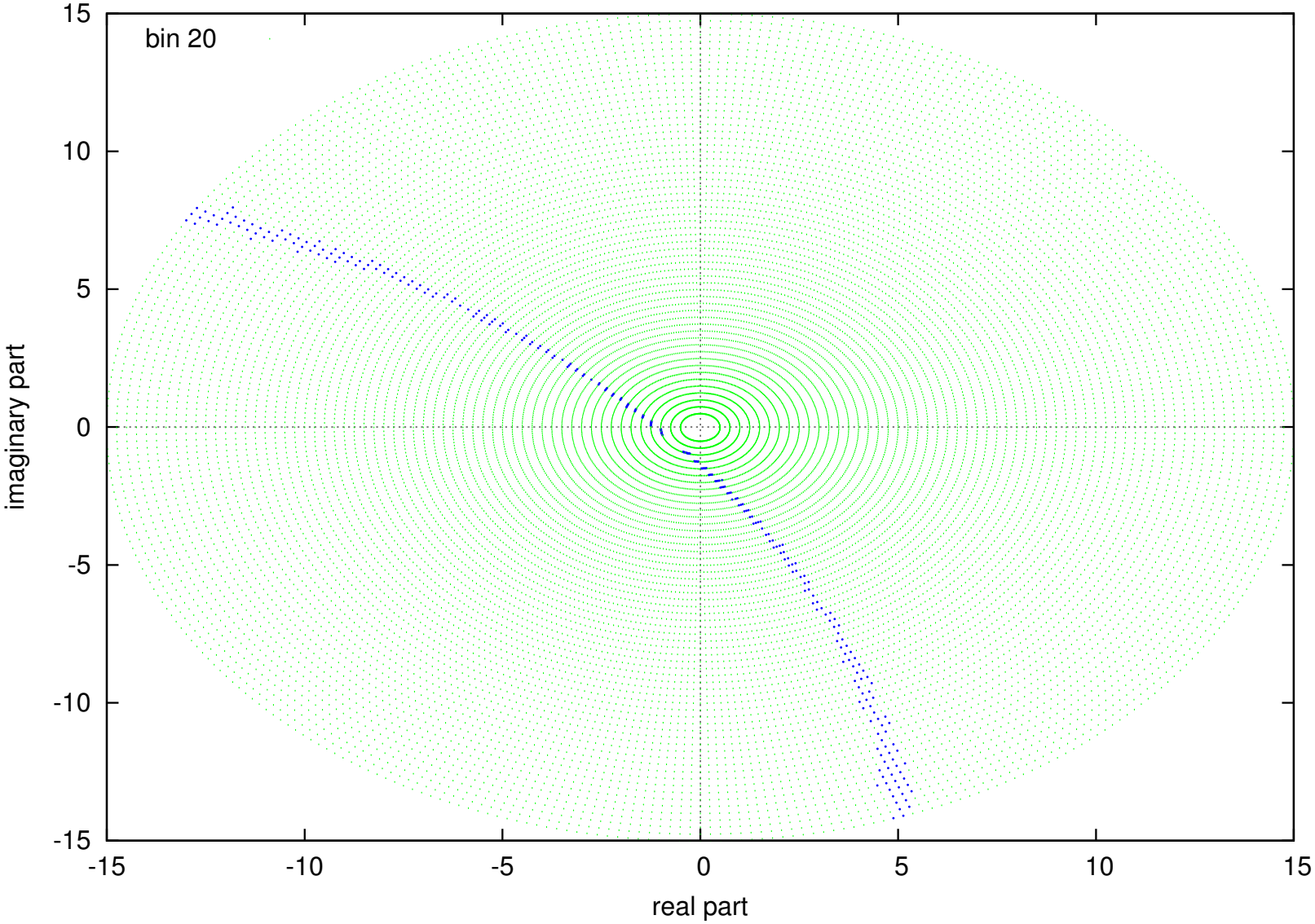
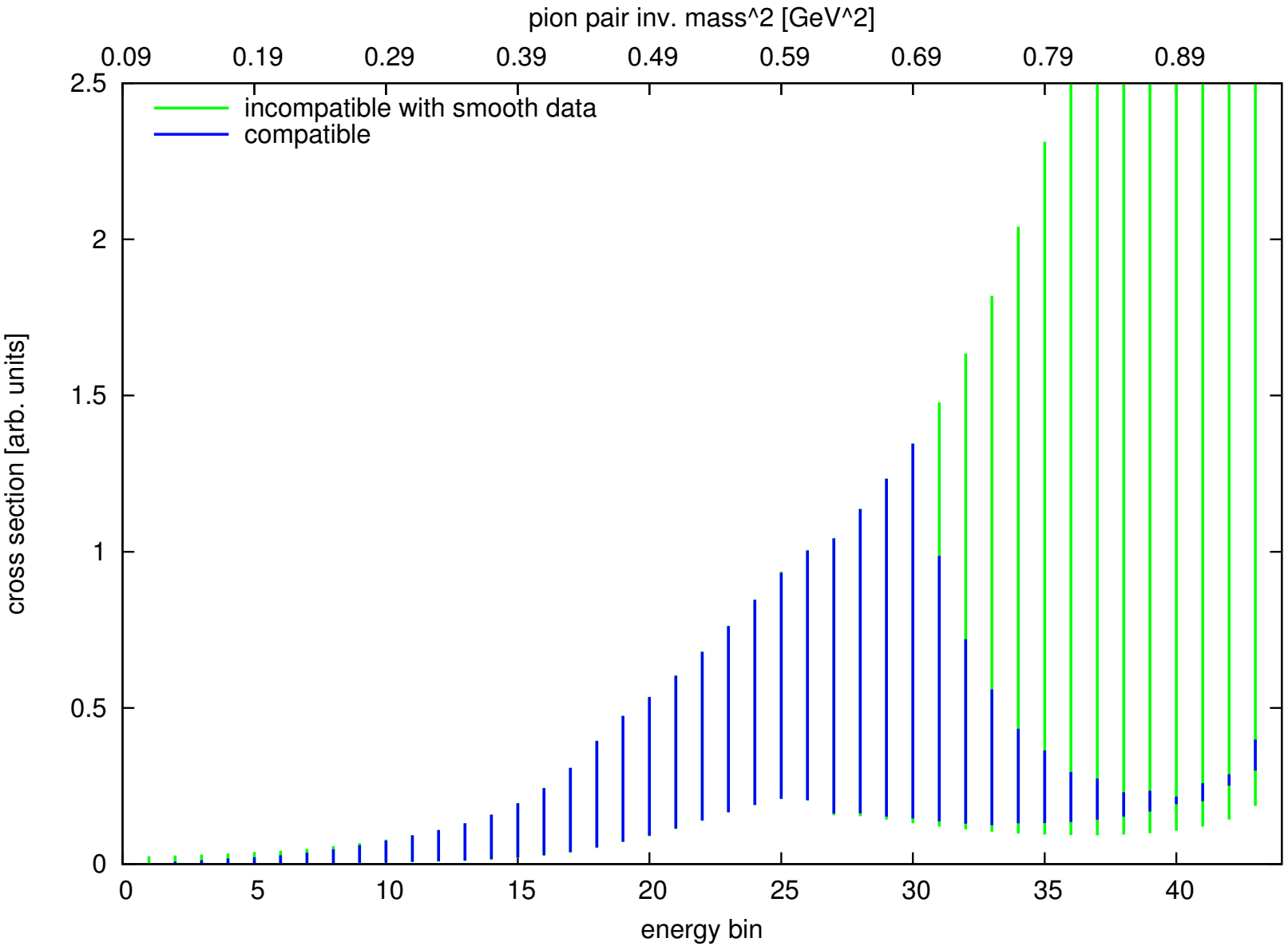
# PionFF 1 – Hit-List



# PionFF 1 – Cross Section

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# Pion Form Factor – Approach Two

- value of pion form factor fixed by models
- already implemented

  GS: $F_\pi = 1.770 \exp\left\{\mathrm{i} \times 155^\circ \frac{\pi}{180^\circ}\right\}$

  KS: $F_\pi = 1.785 \exp\left\{\mathrm{i} \times 160^\circ \frac{\pi}{180^\circ}\right\}$
- now: check modulus between 1.775 and 1.800, all angles
- no final state radiation
- $\longrightarrow$ extract phase of pion form factor in a model independent way using only asymmetry data

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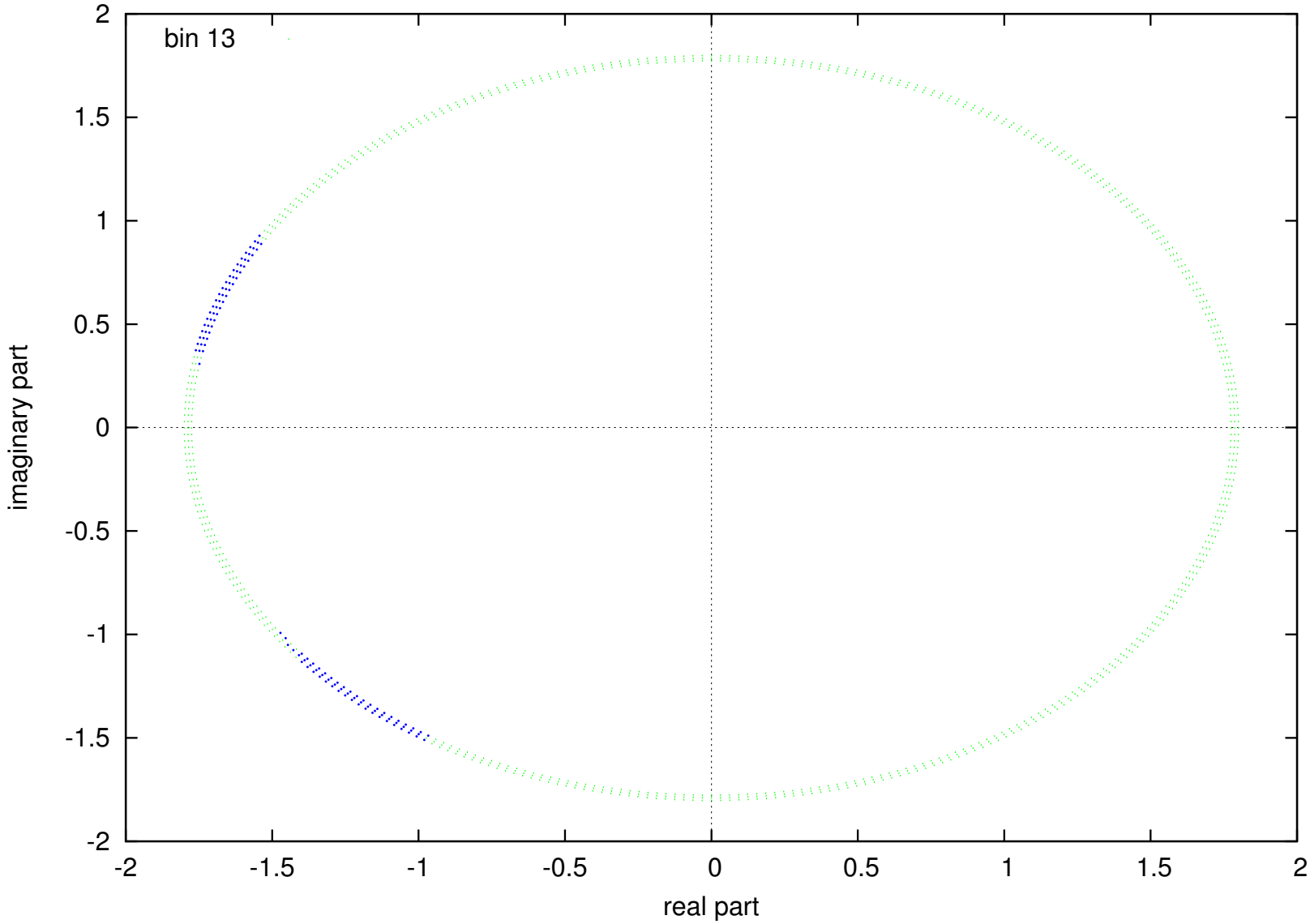
# PionFF 2 – Hit-List

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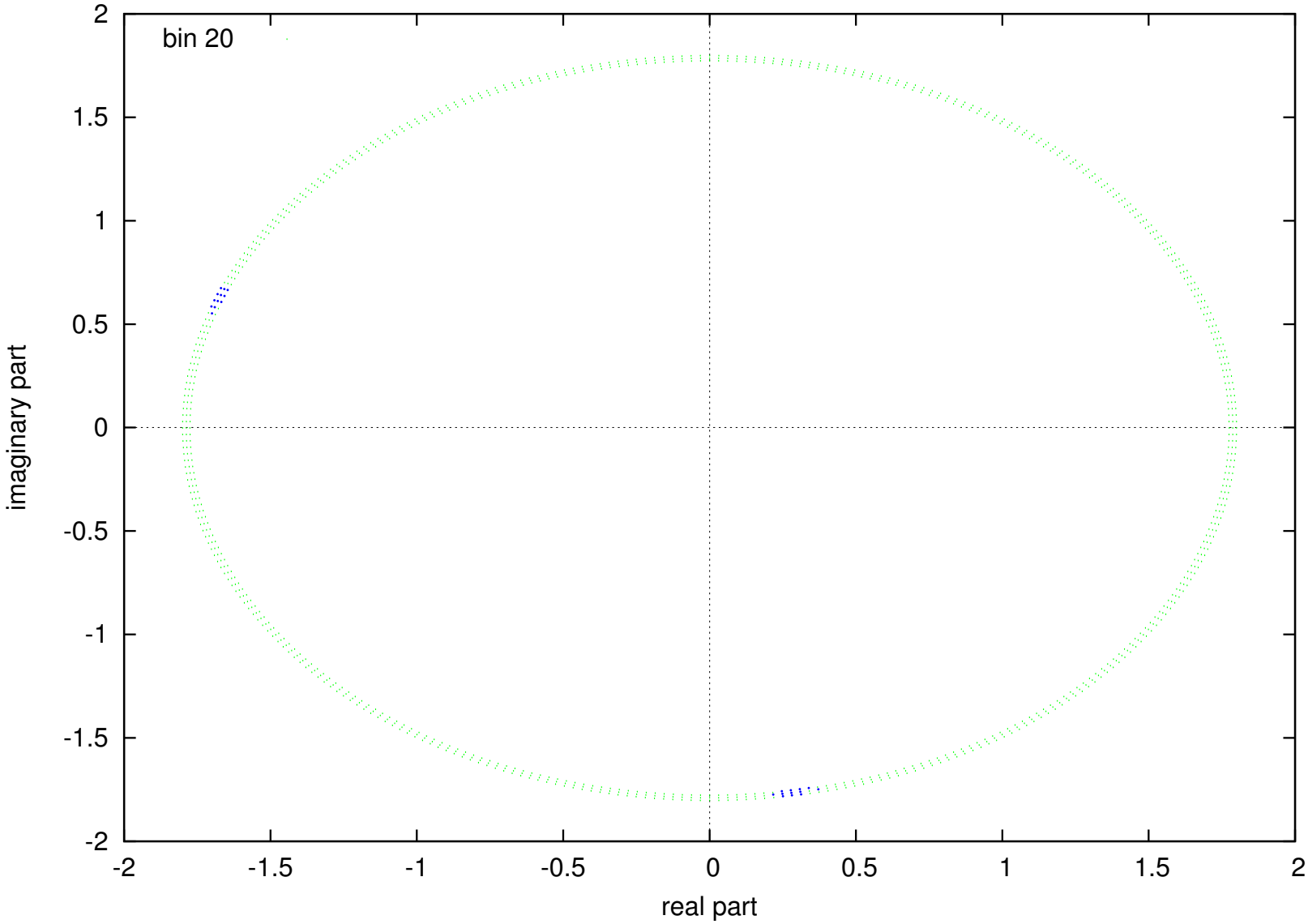
# PionFF 2 – Hit-List

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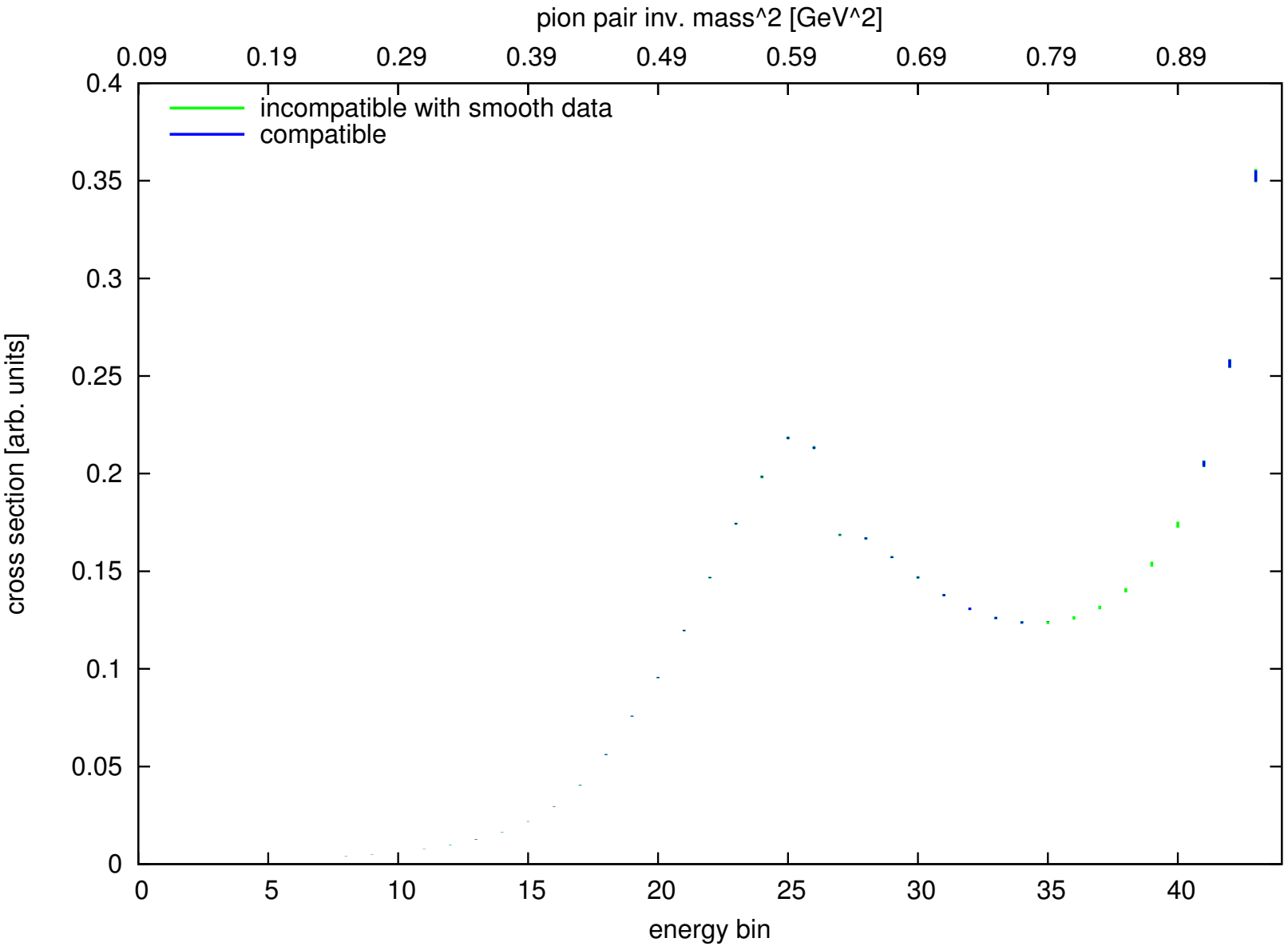
# PionFF 2 – Cross Section

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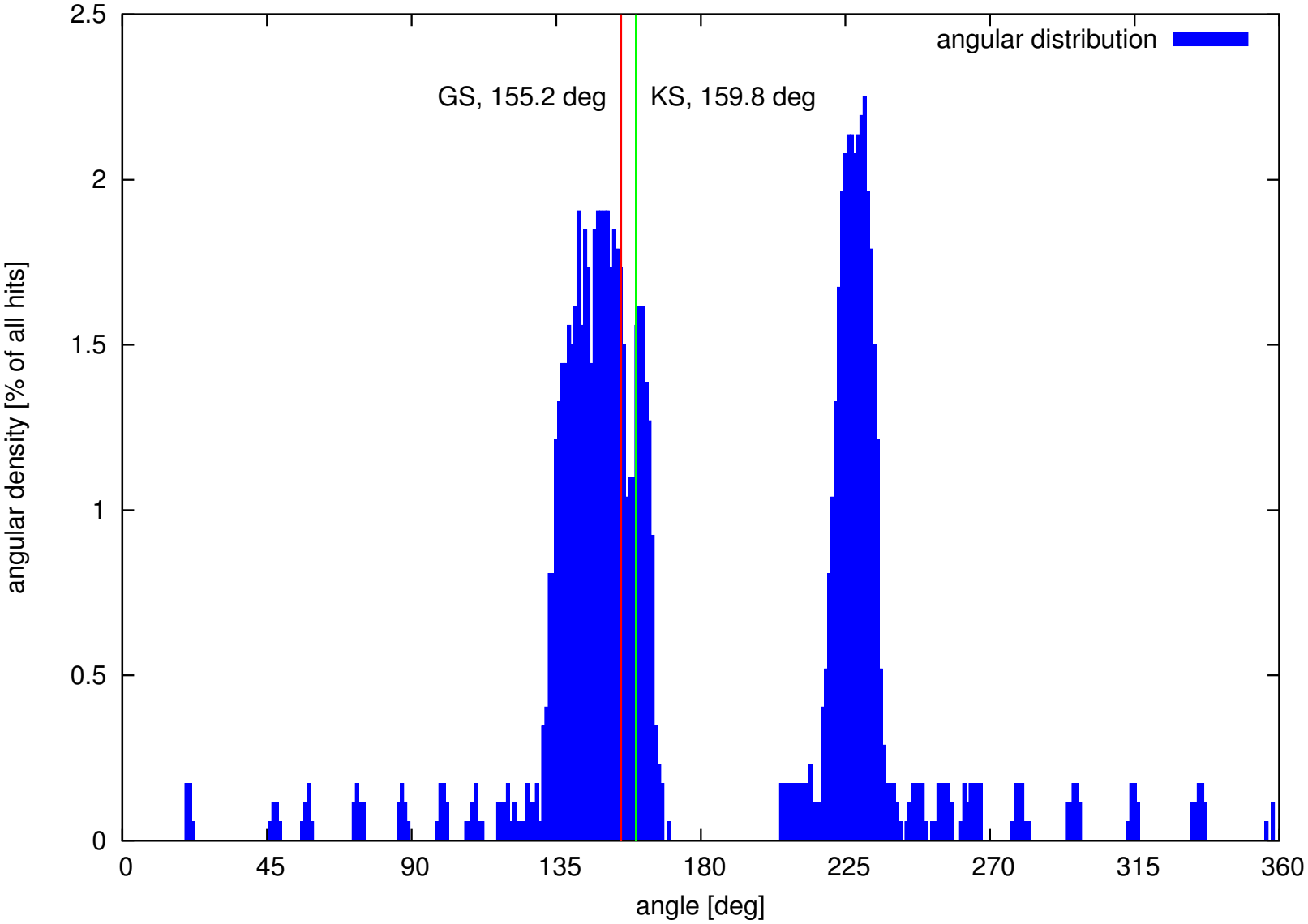
# PionFF 2 – Phase

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# Conclusion – PionFF

- variation has big impact on cross section
- asymmetry not suitable for restricting parameters
- model independent extraction of phase only for fixed modulus possible

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# Summarization & Outlook

- asymmetry not sufficient to determine either final state radiation or pion form factor contributions
- cross section data has to be taken into account
- model independent "measurement" of pion form factor phase for given modulus possible
- use theoretical models to impose restrictions on final state radiation and pion form factor (e.g. $\chi$ET)

Thank you for listening.