Quantum Tomography of e+e- → τ+τ- at a Higgs Factory

https://arxiv.org/abs/2604.04512
coming soon to EPJ C

May 2026

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Why ?

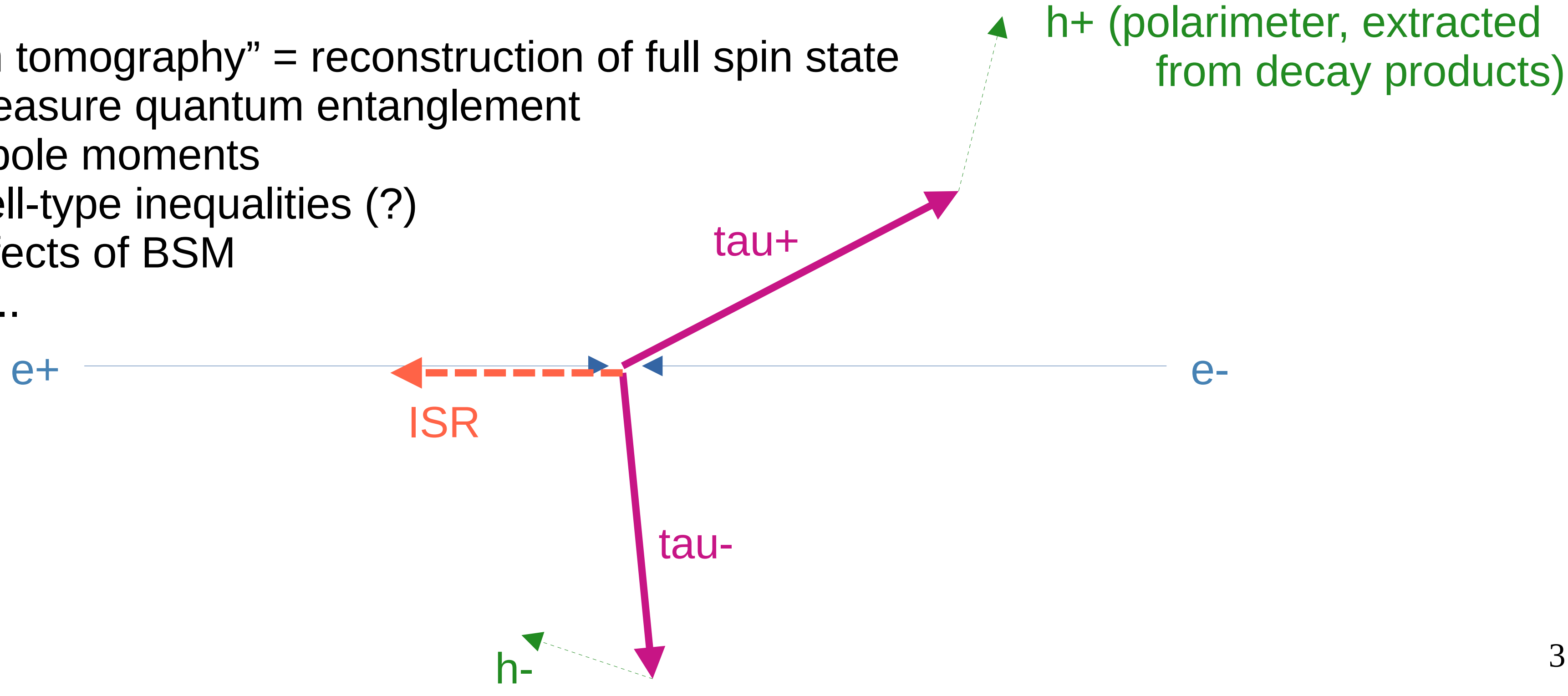
How ? to reconstruct events

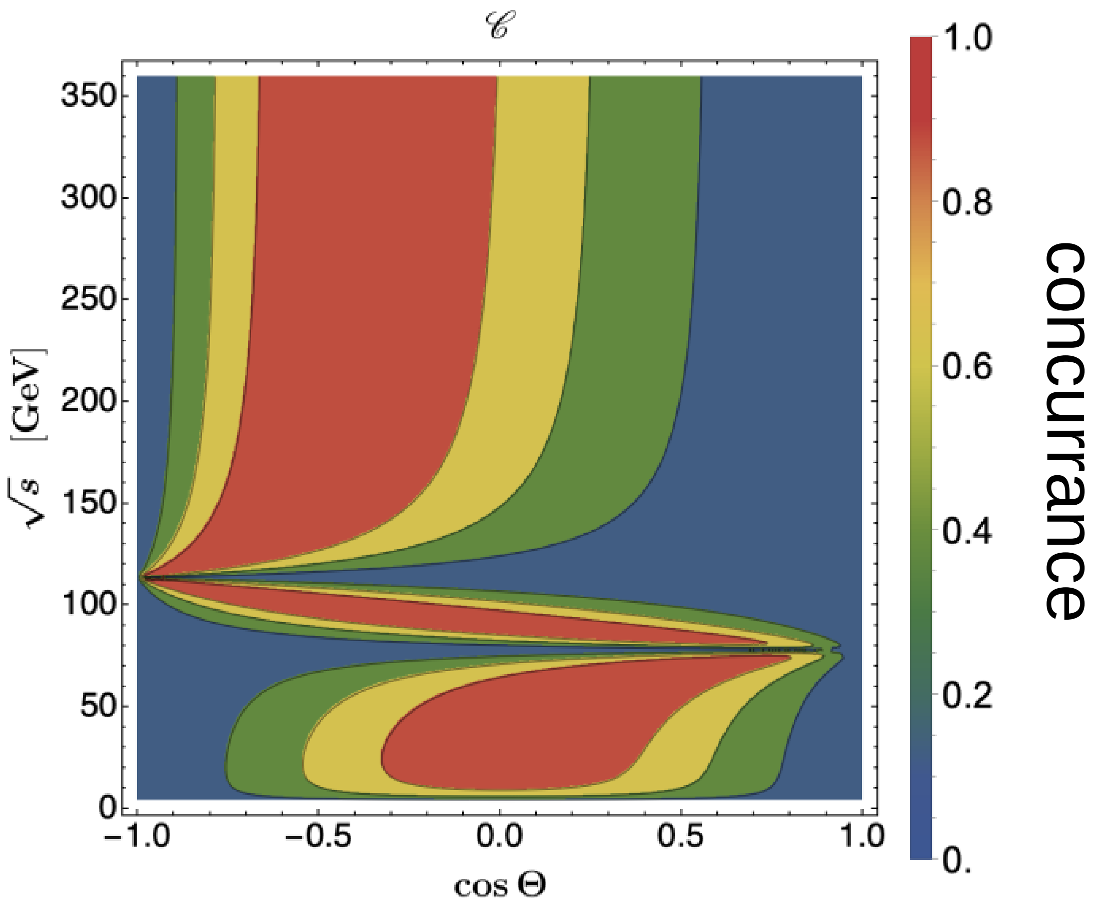
What ? detector resolution is needed

Why?

Final sate with two co-produced (entangled) fermions,
to whose spin orientation we are sensitive

“Quantum tomography” = reconstruction of full spin state
→ measure quantum entanglement
→ dipole moments
→ Bell-type inequalities (?)
→ effects of BSM
...



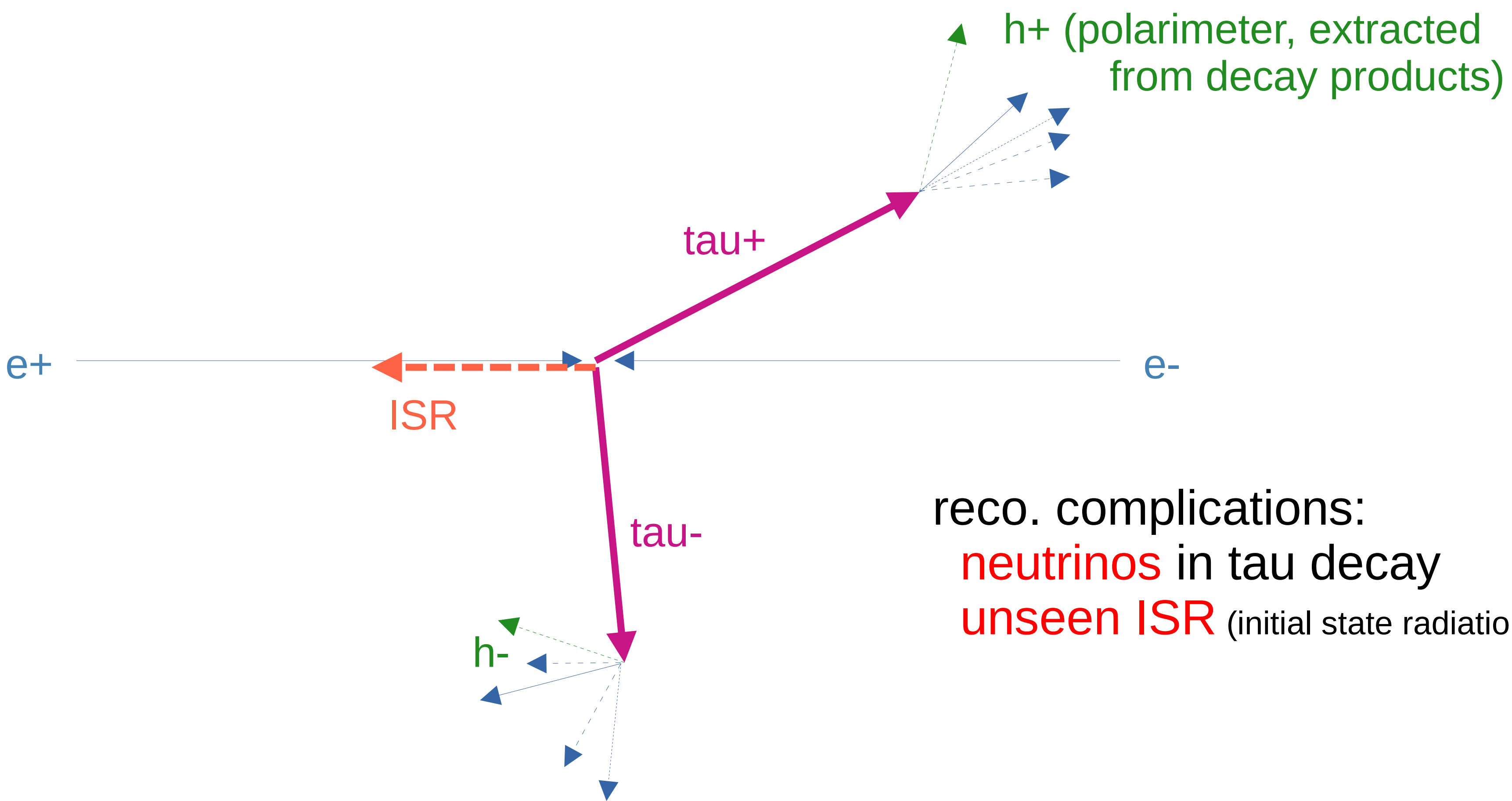


scattering angle

M. Fabbrichesi, L. Marzola

arXiv:2405.09201

How? Reconstructing the full event kinematics



reco. complications:
- neutrinos in tau decay
- unseen ISR (initial state radiation)

How? Reconstructing the full event kinematics

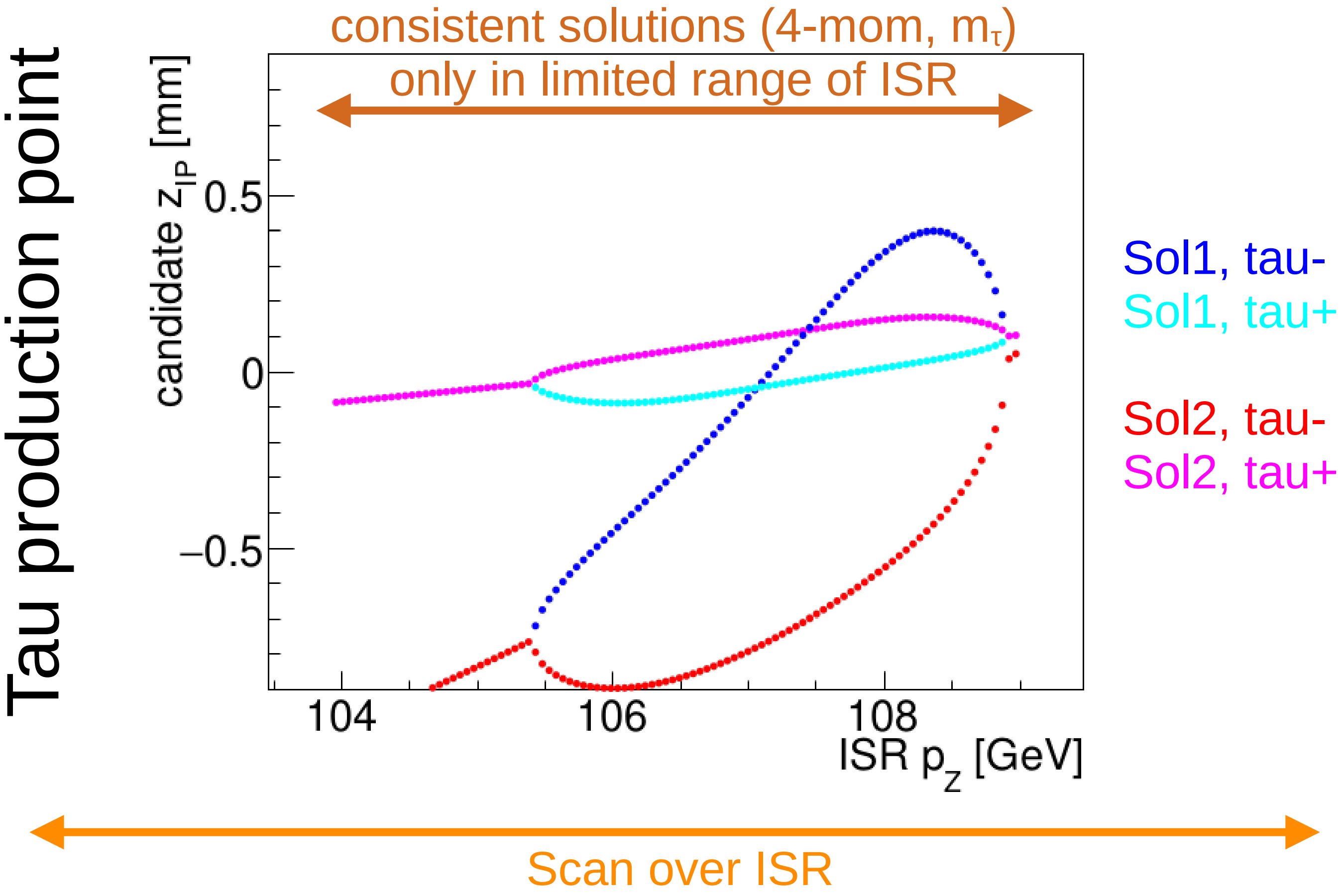
Measured parameters (visible tau jets) not enough to completely reconstruct kinematics

Can arrive at a **collection** of possible event solutions, by
- considering only semi-leptonic tau decays (1 neutrino per tau)
- imposing tau lepton mass
- 4-mom conservation
- scanning over unseen ISR momentum assume single (or multiple) ISR photon

Use various characteristics to **weight** each solution:
- track impact parameters thin beam, linear track approx
- tau lifetime
- expected ISR distribution
- length of luminous region

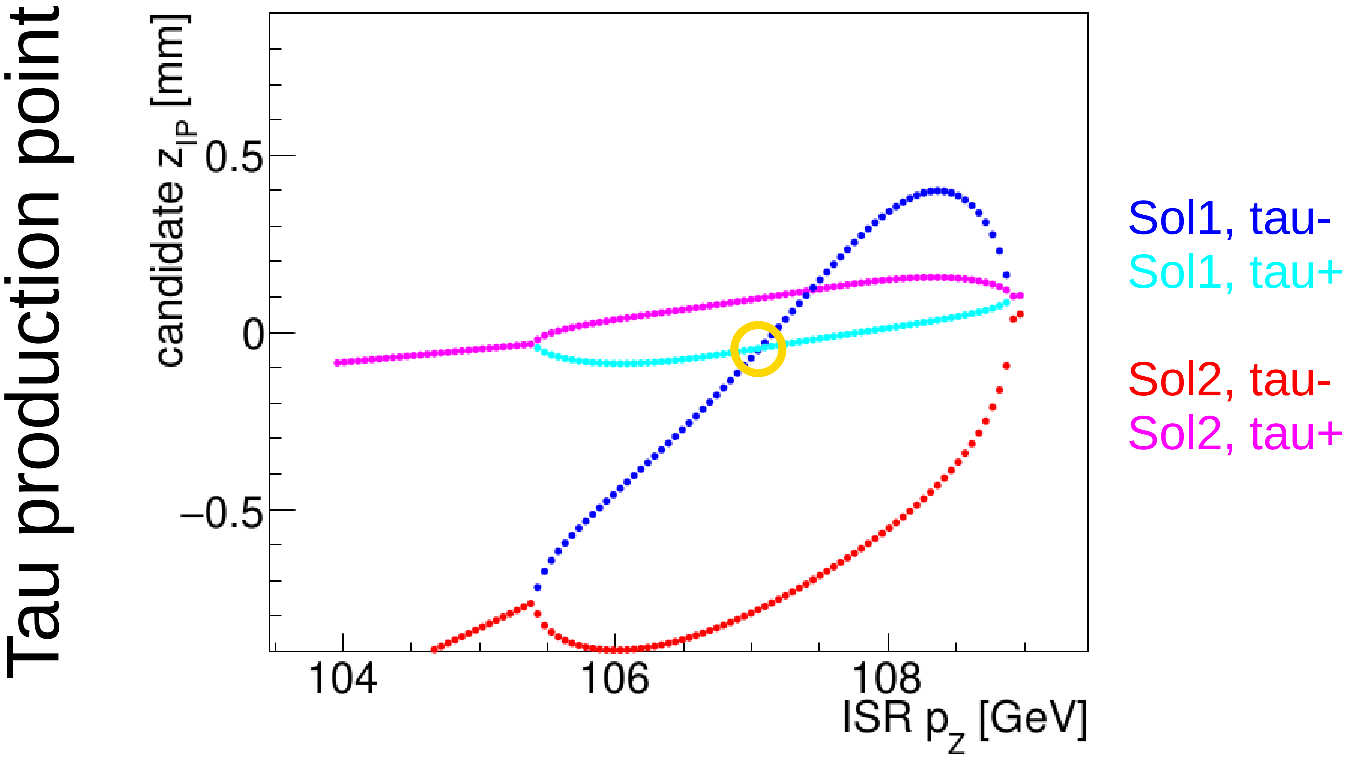
Keep up to 20 “good” solutions per event
(for each, have full event kinematics, including neutrinos & ISR; and a weight)

e.g. one event



consistent solutions (4-mom, m_τ)
only in limited range of ISR
Tau production point
candidate z_{IP} [mm]
0.5
0
−0.5
104
106
108
ISR p_Z [GeV]
Sol1, tau-
Sol1, tau+
Sol2, tau-
Sol2, tau+
Scan over ISR

e.g. one event

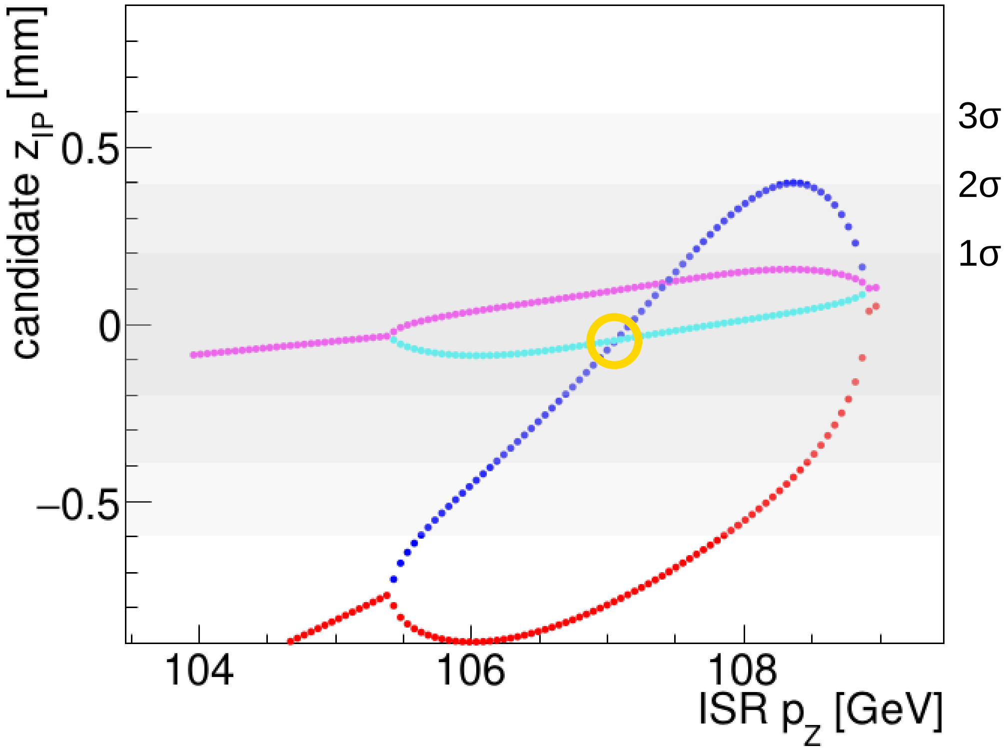


consistent **impact parameters** when (blue & cyan) or (red & magenta) lines cross

→ two τs produced at same point

e.g. one event

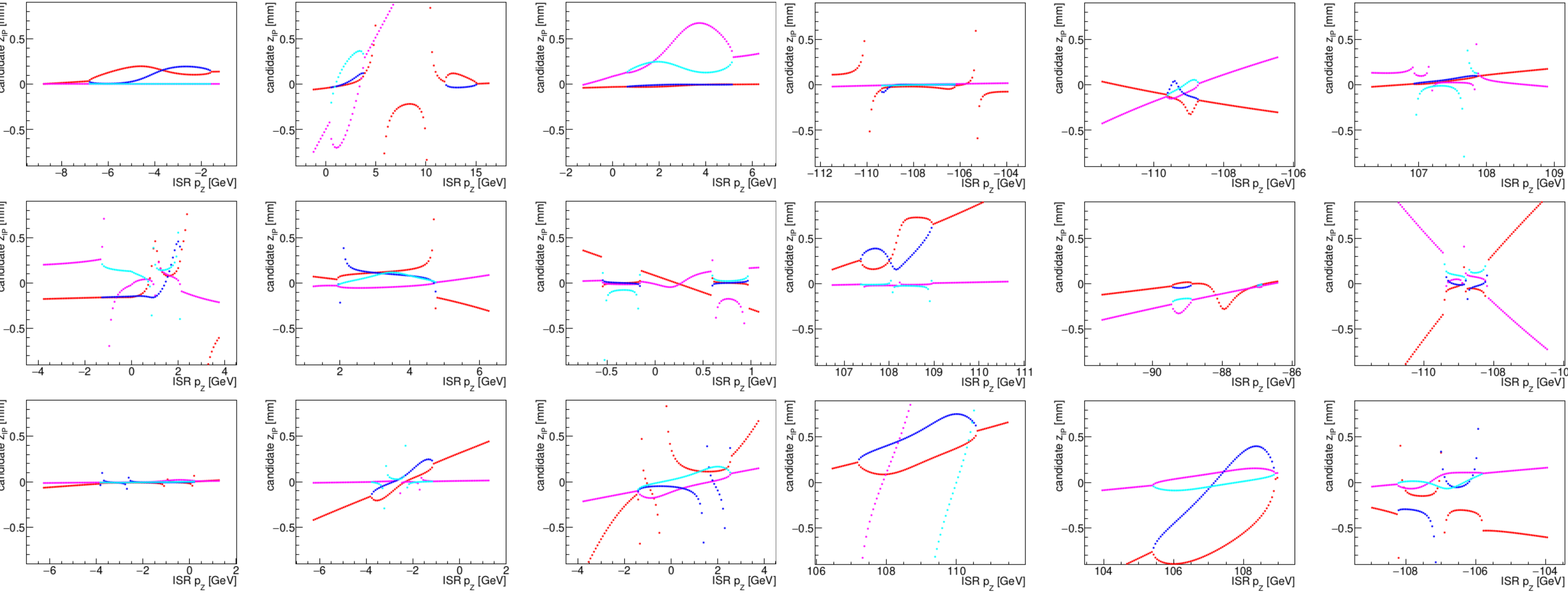
Tau production point



Solutions should be consistent with beamspot
σ_Z ~ 200 μm (ILC)

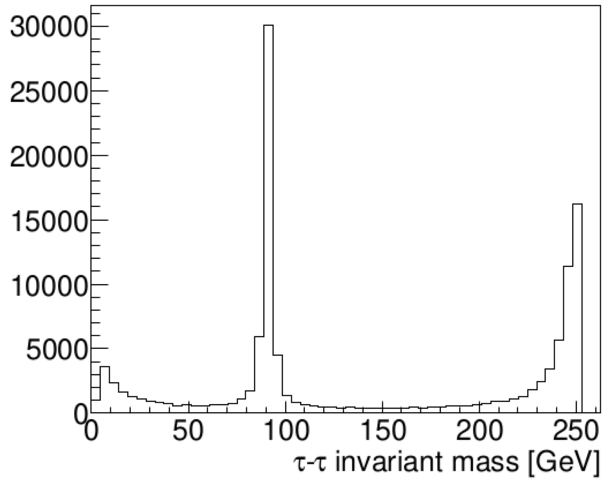
more events...

high mass ⟷ Z return



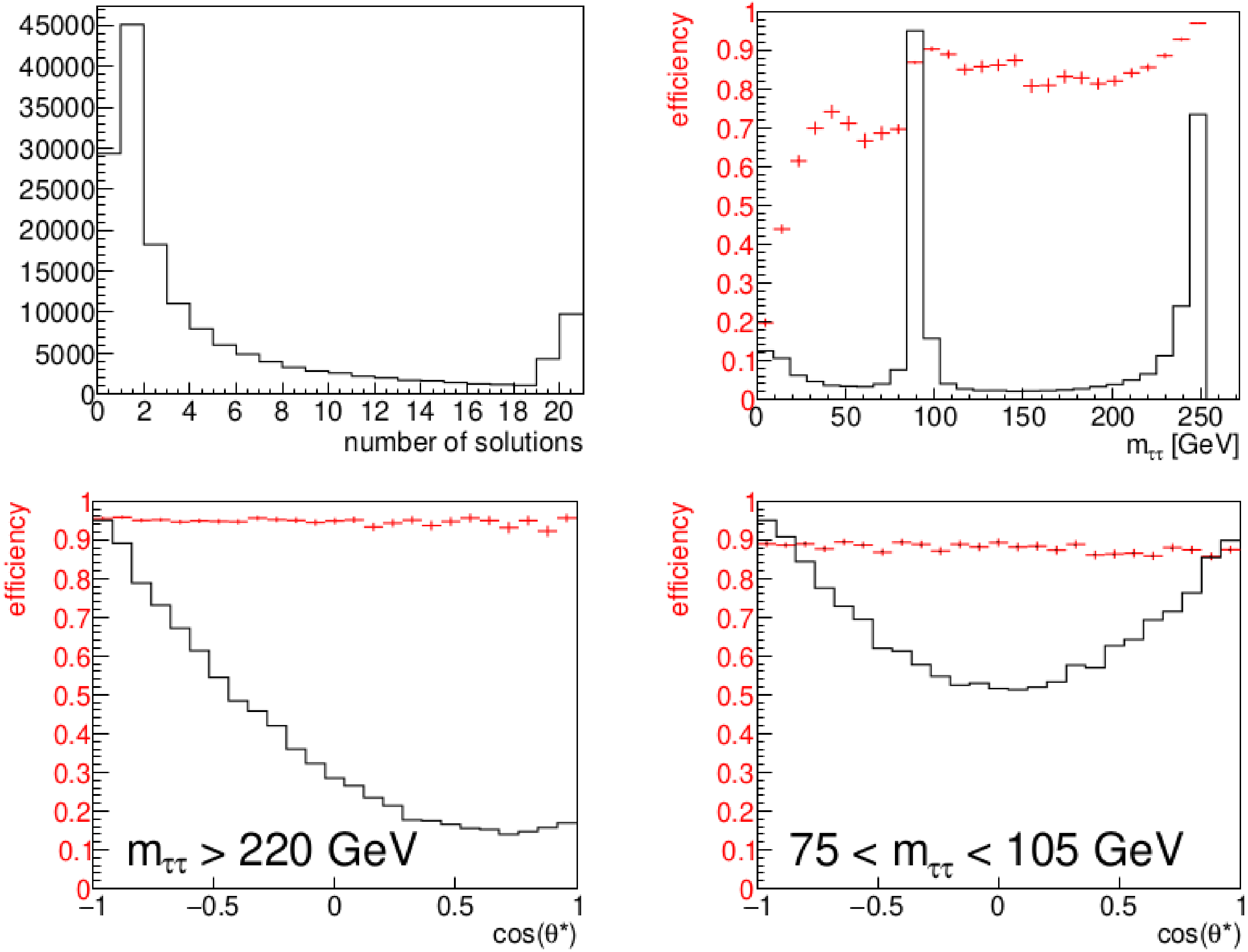
I could not work out how to analytically calculate the crossing points…search “by hand”

ILC 250, beamstrahlung + ISR
WHIZARD+TAUOLA common generated sample



Consider events in which both taus decay to
neutrino + { 1 pion (10.8%), 2 pions (25.5%), or 3 pions (9.3+9.3%) }
→ know how to extract optimal polarimeter for these modes

First, use true momenta of photons and charged pions
cheat association of photons to pi0



Efficiency to find
at least one solution

Multiple solutions
per event

Reconstruction of polarimeters

from momenta of decay products *in tau rest frame*,
calculate polarimeters **h** → estimators of spin orientation

$$\mathbf{h}(\tau^{\pm} \to \pi^{\pm}\nu) \propto \mathbf{p}_{\pi^{\pm}}$$
$$\mathbf{h}(\tau^{\pm} \to \pi^{\pm}\pi^{0}\nu) \propto m_{\tau}(E_{\pi^{\pm}} - E_{\pi^{0}})(\mathbf{p}_{\pi^{\pm}} - \mathbf{p}_{\pi^{0}}) - \frac{1}{2}(p_{\pi^{\pm}} - p_{\pi^{0}})^{2}\mathbf{p}_{\nu},$$

More complicated for 3-pion decays, use code of
V. Cherepanov and C. Veelken, Comput. Phys. Commun. 299, 109153 (2024), arXiv:2311.10490

Need full reconstruction of tau kinematics to use these optimal forms
→ neutrino momentum is provided by our method

In principle these polarimeters have same(*) analysing power
(*) in my understanding, 3-pi cases a little less because of ambiguities from identical final state particles

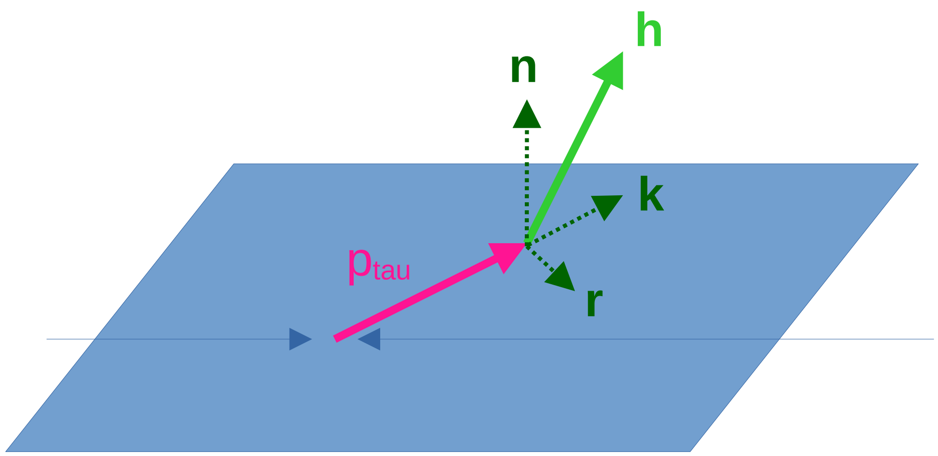
Decompose the polarimeter vector **h** into 3 components

- k: along the tau- momentum direction

- n: normal to the plane containing the taus and beams

- r: in the plane, normal to k

“helicity basis”

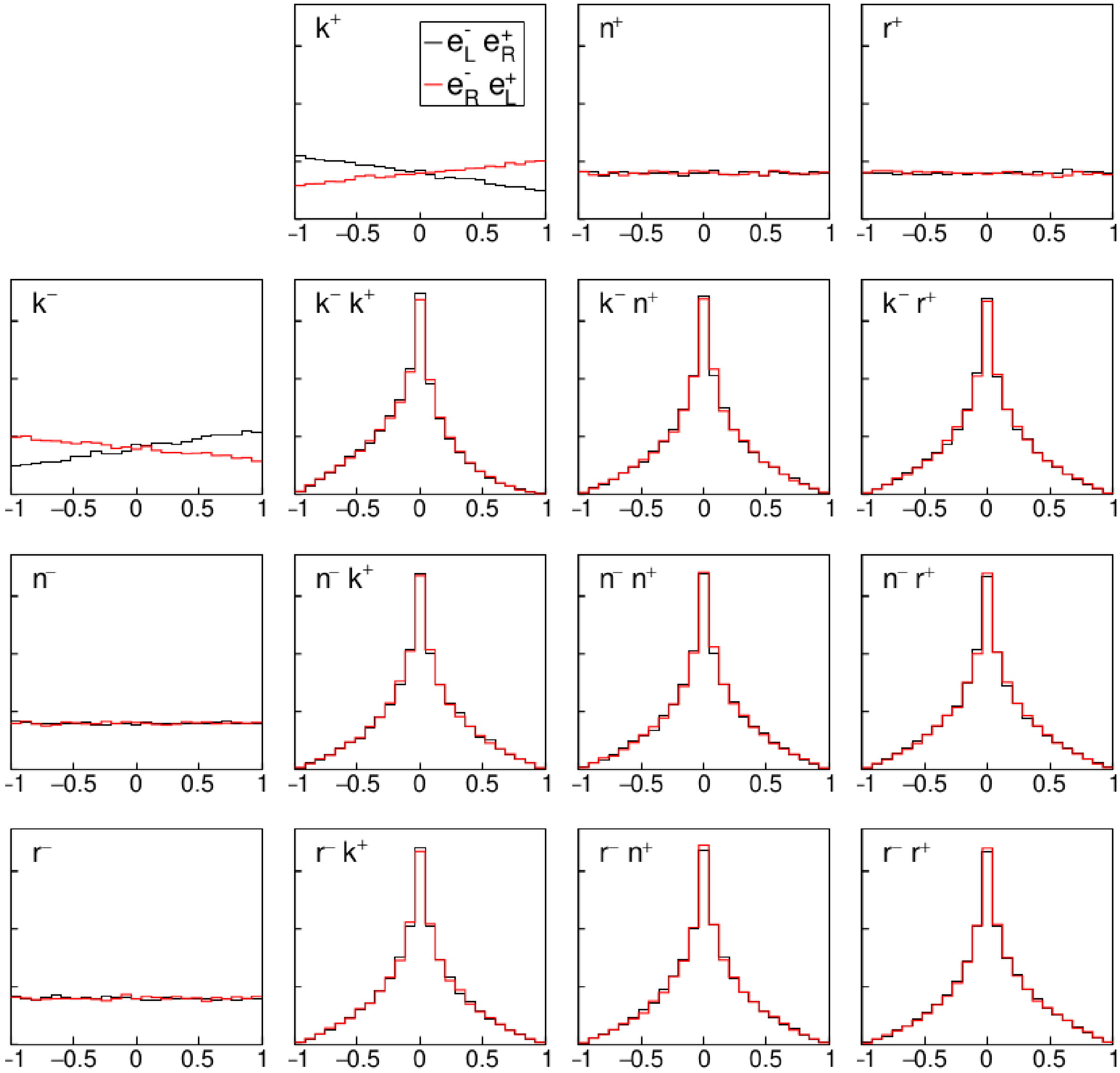


Individual components k,n,r,
"helicity basis"

and their products across $\tau^+ \tau^-$

Spin Density Matrix

all the info we need for
full quantum tomography



Event reconstruction is not perfect, even with a perfect detector: degraded by wrong solutions

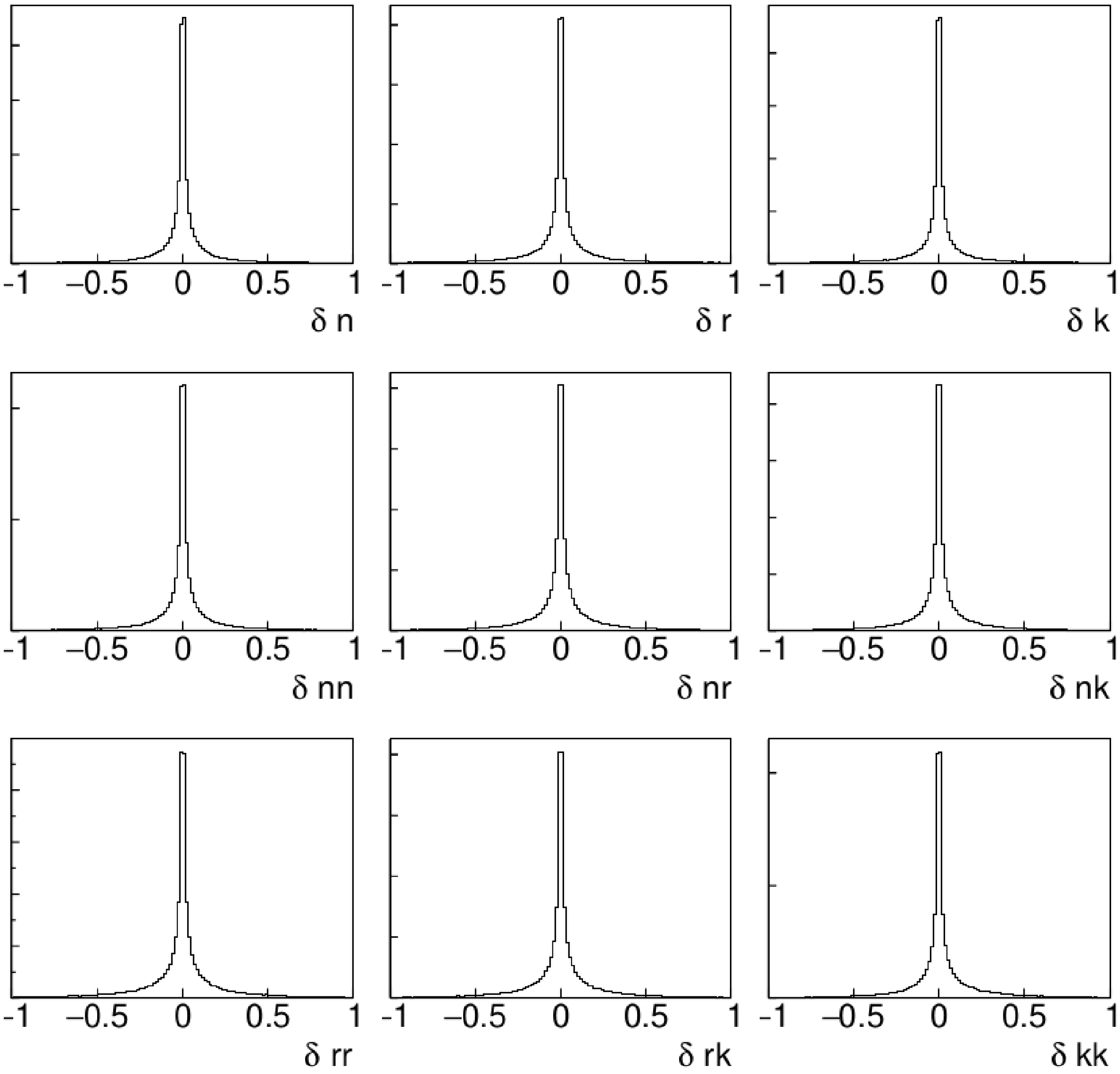
How precisely can we reconstruct these spin density matrix elements?

Compare MC truth values with those calculated using our method (with perfect detector)

Typical precision is << 0.1

→ significantly smaller than interesting range [-1,1]

→ good enough to measure distribution of spin density elements (?)



What? detector resolution is needed

Use SGV model of ILD

fast simulation giving track covariance matrix

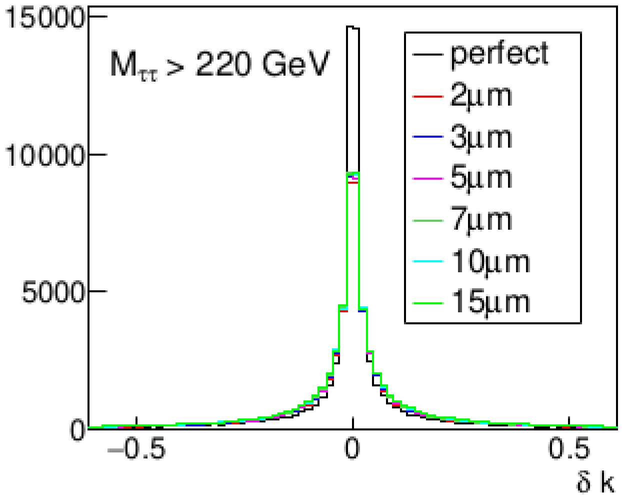
Impact parameter measurement used for weighting soluions

→ vertex detector point resolution

2 → 3 (default) → 15 microns

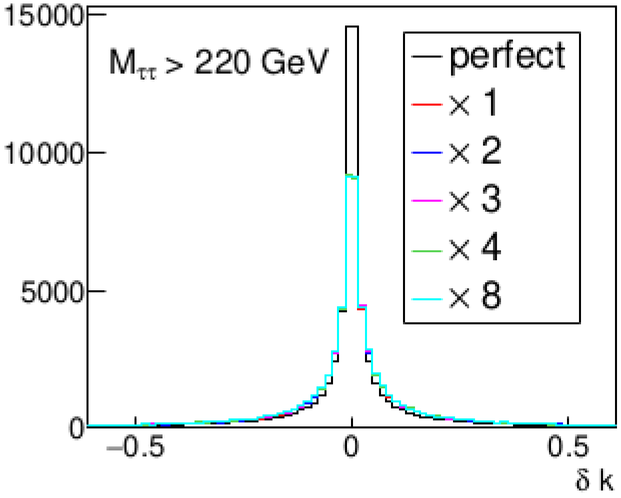
→ scale vertex detector material budget (x1 → x8)

Vertex detector point resolution



k (reco) – k (true)

Vertex detector material



k (reco) – k (true)

Very little effect

What? detector resolution is needed

Use SGV model of ILD

fast simulation giving track covariance matrix

Dominant rho decay mode → requires reconstruction of $\pi^0 \to \gamma\gamma$

→ smear photon energy

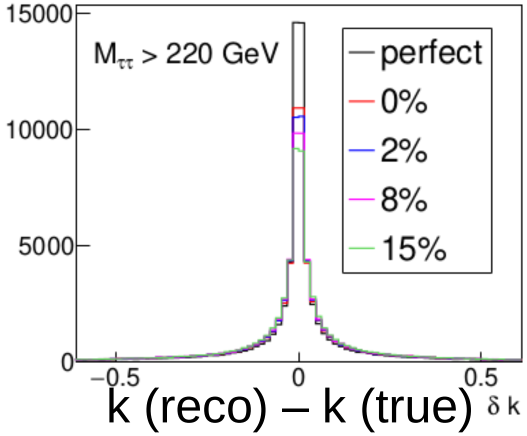
$\sigma_E/E = 0$ (perfect)

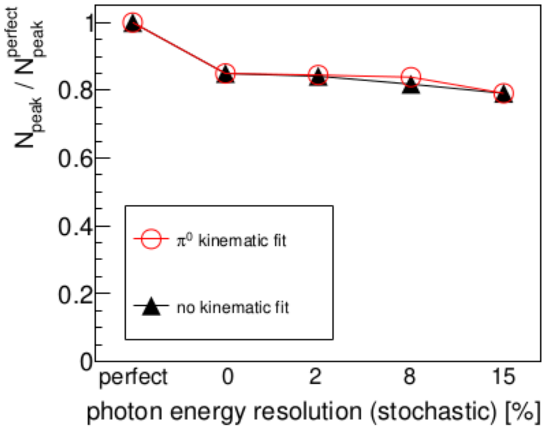
stochastic term (2, 8, 15)% ⊕ constant term 1%

→ smear photon direction

(0, 0.2, 0.5, 1, 5) mrad

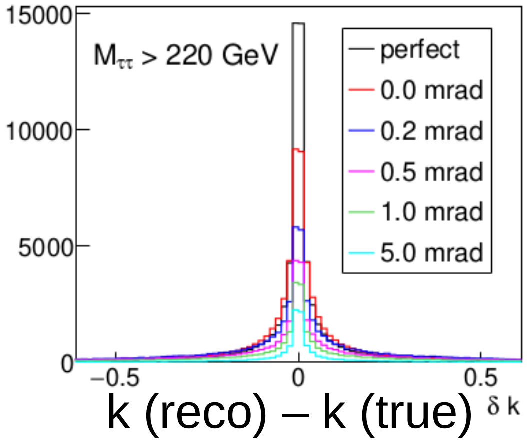
photon energy
stochastic term

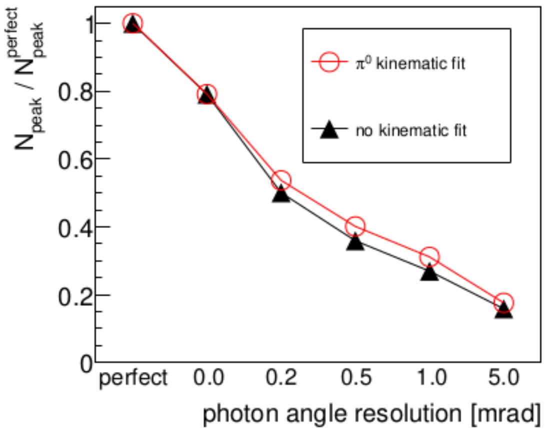




Energy:
Small effect

photon angle
precision





Angle:
Large effect
even @ 0.2 mrad

Kinematic fit of π^0:
limited impovement

Summary

Quantum tomography of e+ e- → τ+ τ-

Full reconstruction: under-constrained → several solutions per event

Resulting precision on spin density matrix elements looks good enough

Vertex detector precision looks non-critical

ECAL position resolution [<<1 mrad] more important than energy resolution

Further work:

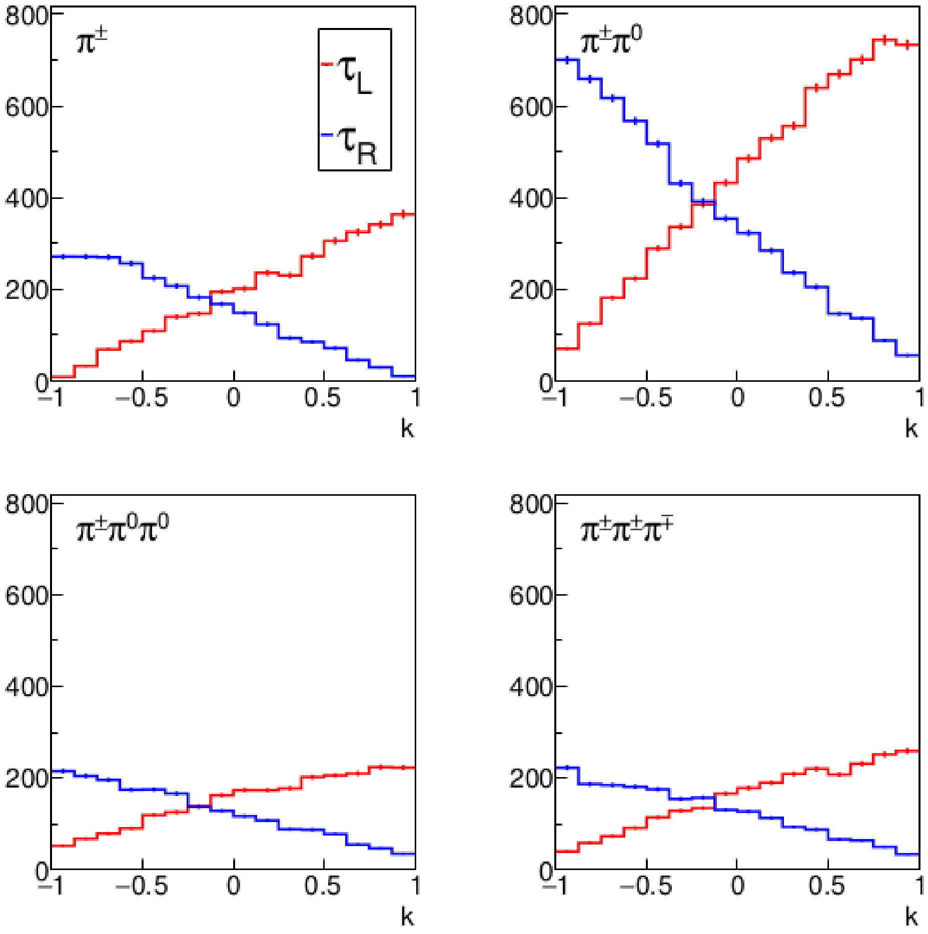
Extract entanglement observables from spin matrix

Similar analysis for e+ e- → Z H, H → τ+ τ- (underway)

Z-pole

backup

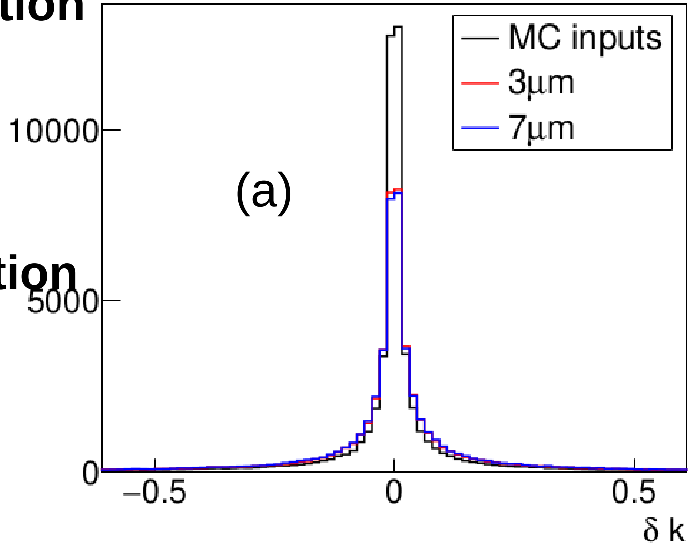
component k, used to measure the longitudinal tau polarisation

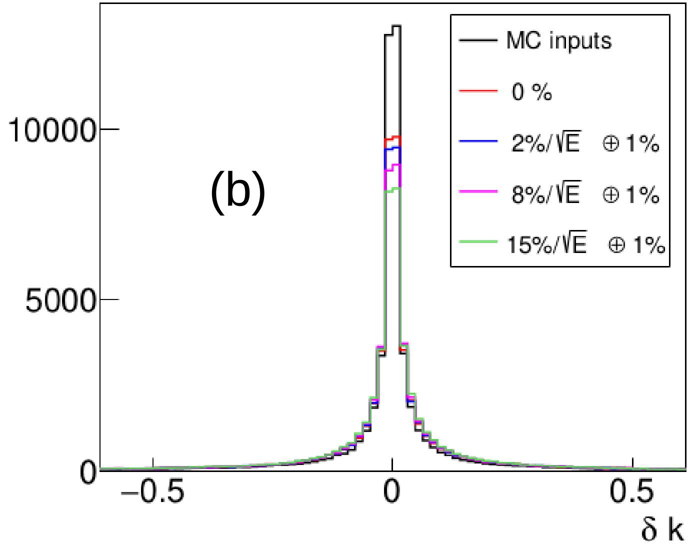


(multiple solutions per event)

a) vertex detector resolution

→ almost no effect



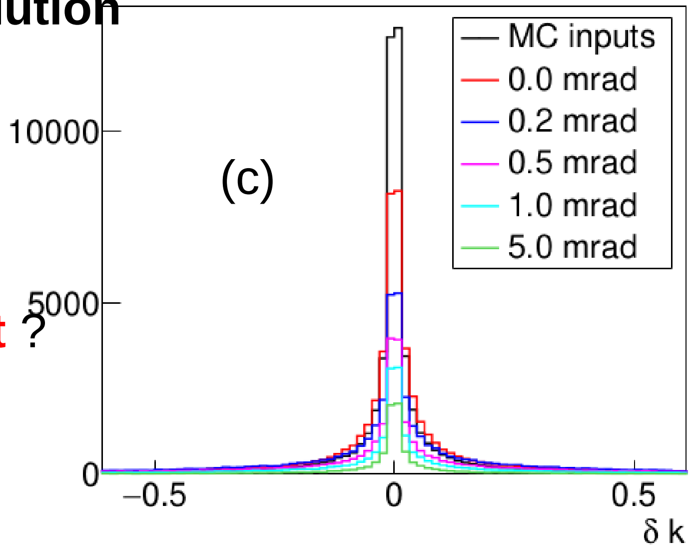


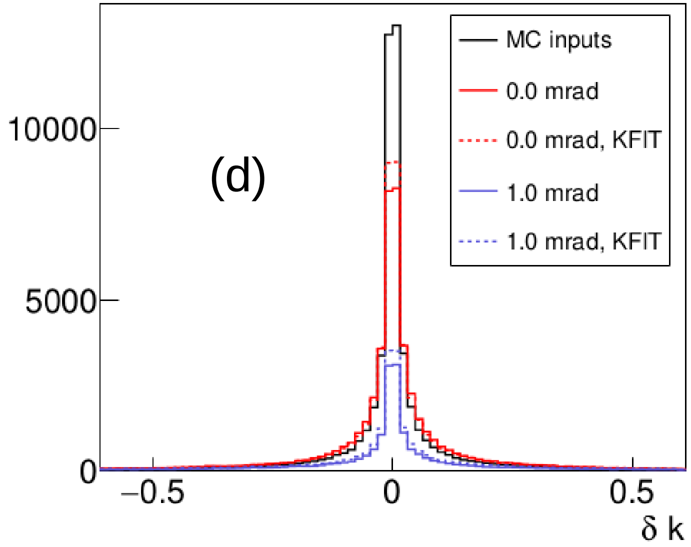
b) photon energy resolution

→ small effect

c) photon direction resolution

→ large effect





d) Can we recover using a **constrained kinematic fit** ?

→ a little

Now doing similar analysis for ZH, H → tau tau

e.g. for CP measurement

conclusions look similar: photon angular resolution < 0.5 mrad