Reconstruction of τ using impact parameters

e.g. $e^+ e^- \rightarrow (H \rightarrow \tau\,\tau)\,(Z \rightarrow \mu\,\mu)$

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Some tau decay modes:

Simplest case

~11% $\tau^+ \rightarrow \pi^+ \nu$

Largest BR

~25% $\tau^+ \rightarrow \pi^+ \pi^0 \nu$

Leptonic

~35% $\tau^+ \rightarrow (e/\mu)^+ \nu \nu$

two missing neutrinos ← limited information, ignore for now

We would ideally like to fully reconstruct the momentum of tau and its decay products

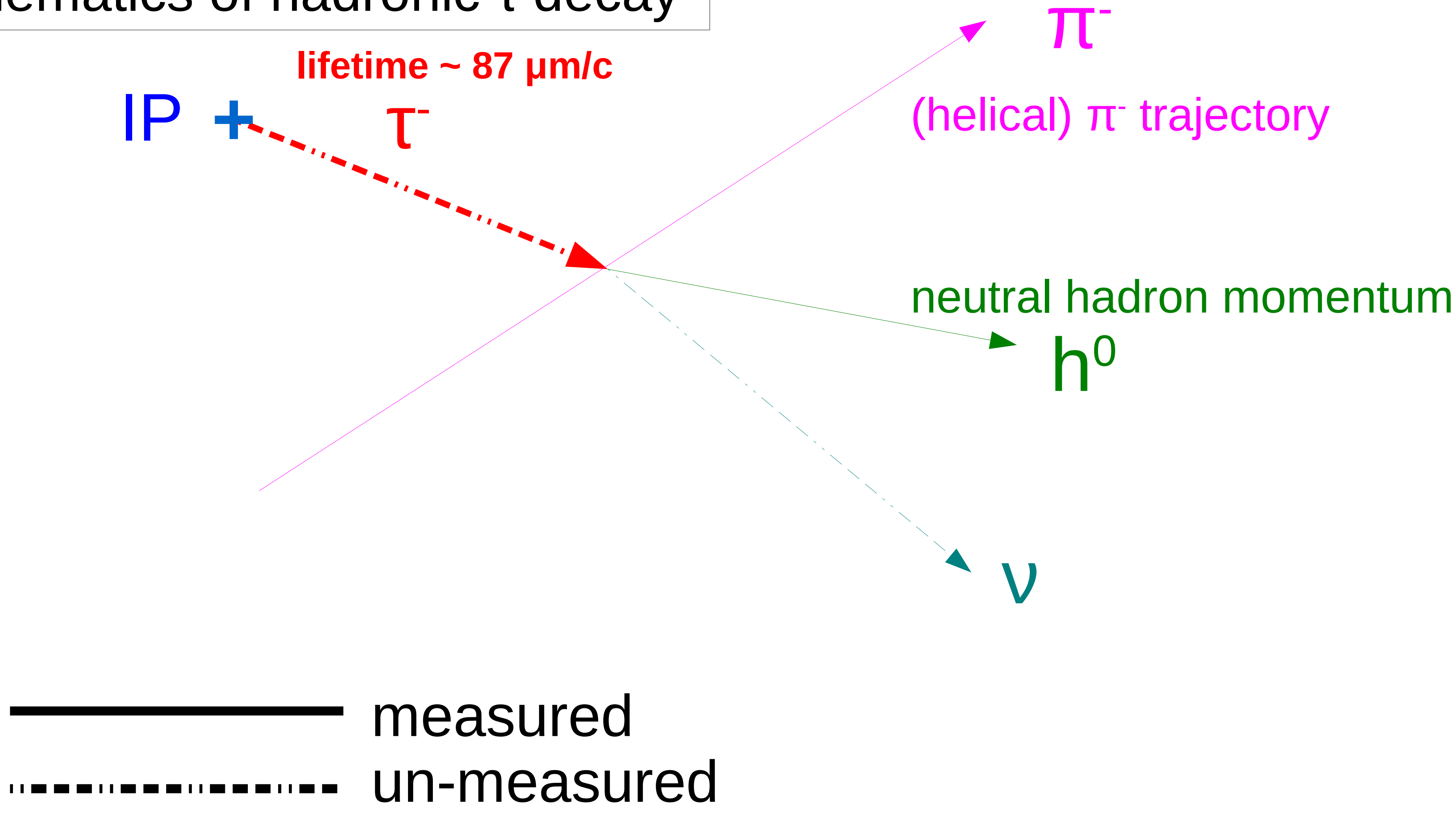
→ cleaner selection of e.g. $H \rightarrow \tau^+ \tau^-$ (better mass resolution)

→ use of τ spin correlations

However, τ always decays into at least one neutrino

→ lose information

kinematics of hadronic τ decay



To optimally use events with taus,
want to fully reconstruct the τ
how to reconstruct the invisible neutrino momentum?

traditional method

e.g. LEP, BELLE, …

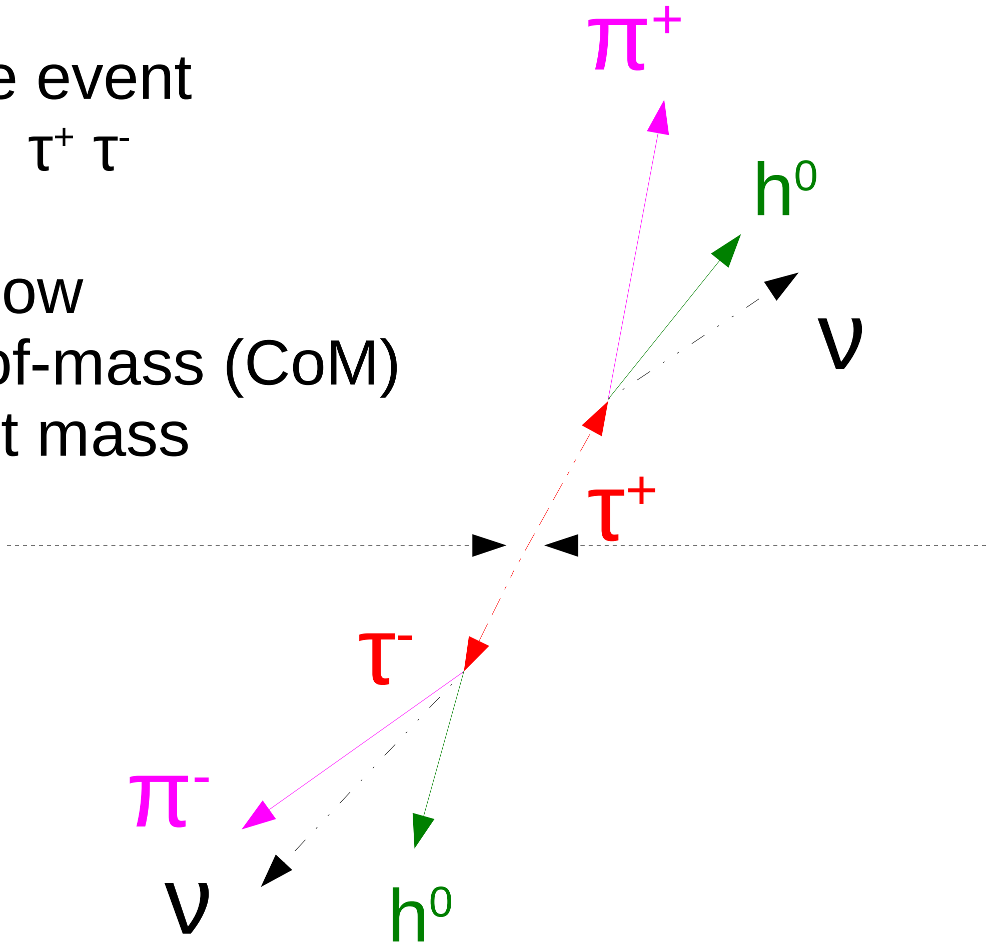
consider whole event

e.g. $e^+ e^- \rightarrow \tau^+ \tau^-$

assume we know

τ-τ centre-of-mass (CoM)

τ-τ invariant mass

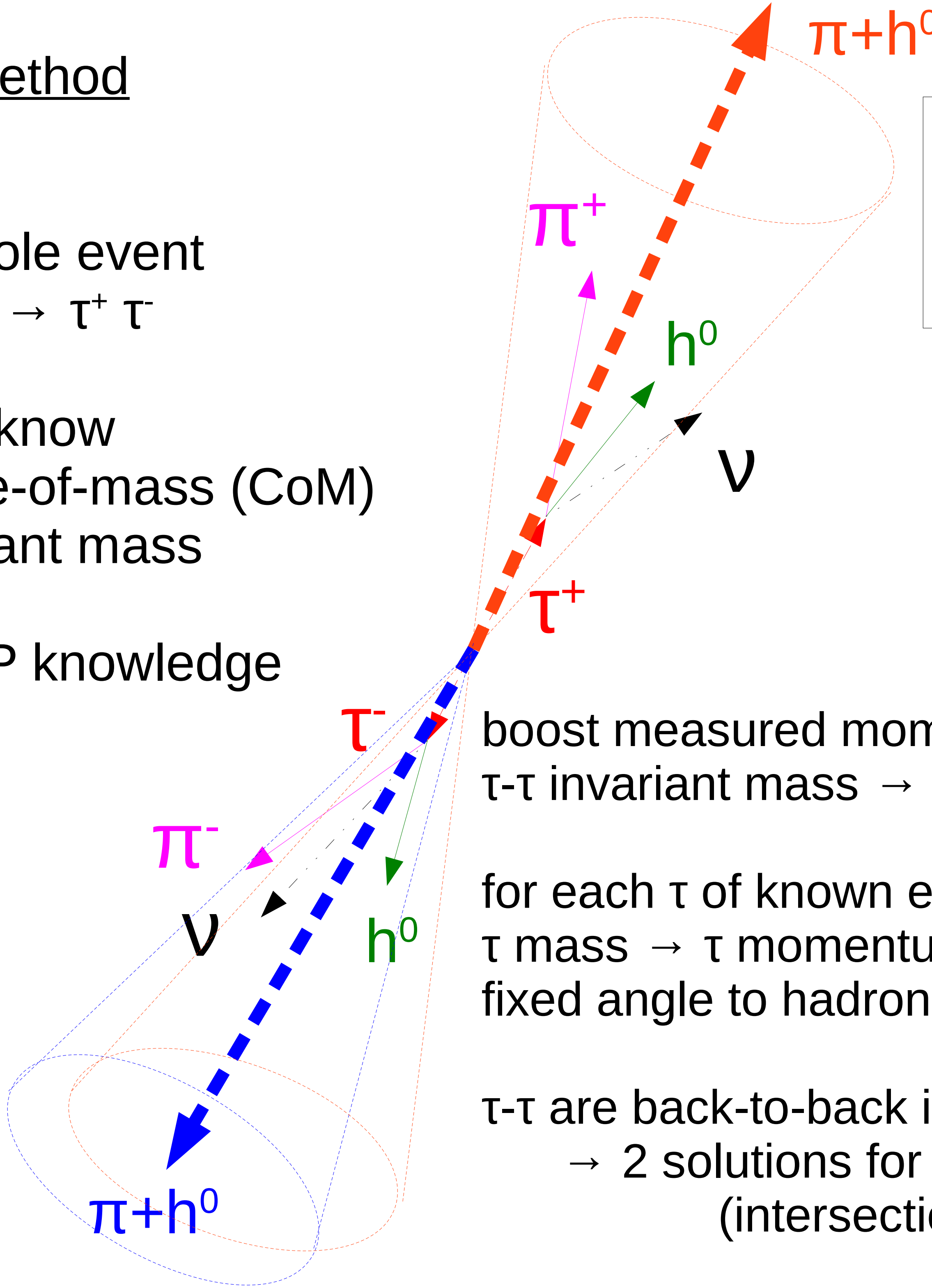


traditional method

consider whole event
e.g. $e^+ e^- \rightarrow \tau^+ \tau^-$

assume we know
τ-τ centre-of-mass (CoM)
τ-τ invariant mass

no precise IP knowledge



event in τ-τ CoM

cone angle depends on assumed τ energy

boost measured momenta into CoM
τ-τ invariant mass → τ energy

for each τ of known energy:
τ mass → τ momentum at fixed angle to hadronic momentum (cone)

τ-τ are back-to-back in CoM:
→ 2 solutions for τ momentum
(intersections of 2 cones)

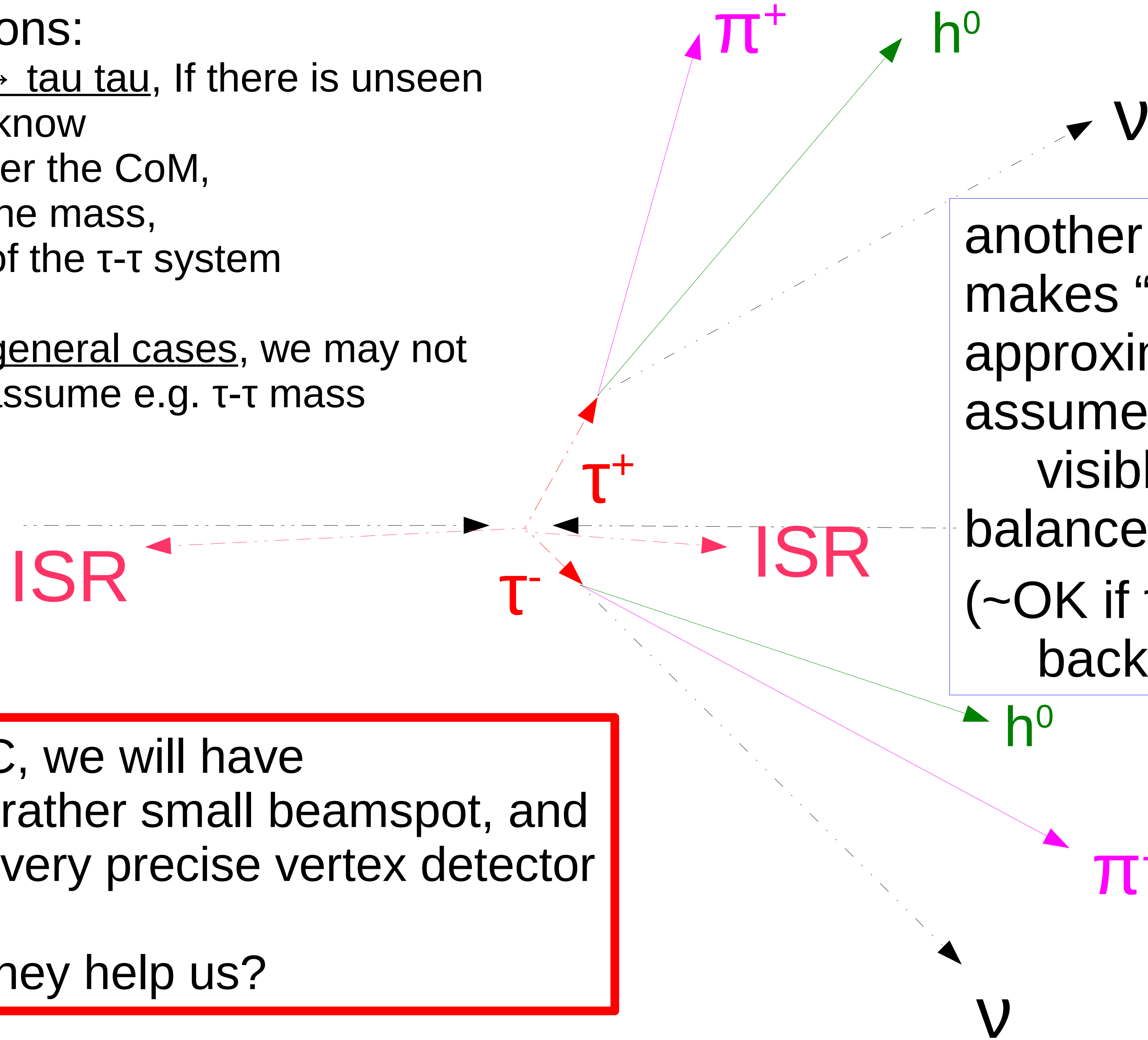
traditional method

Limitations:

in e+e- → tau tau, If there is unseen ISR, we know

neither the CoM,
nor the mass,
of the τ-τ system

in more general cases, we may not want to assume e.g. τ-τ mass

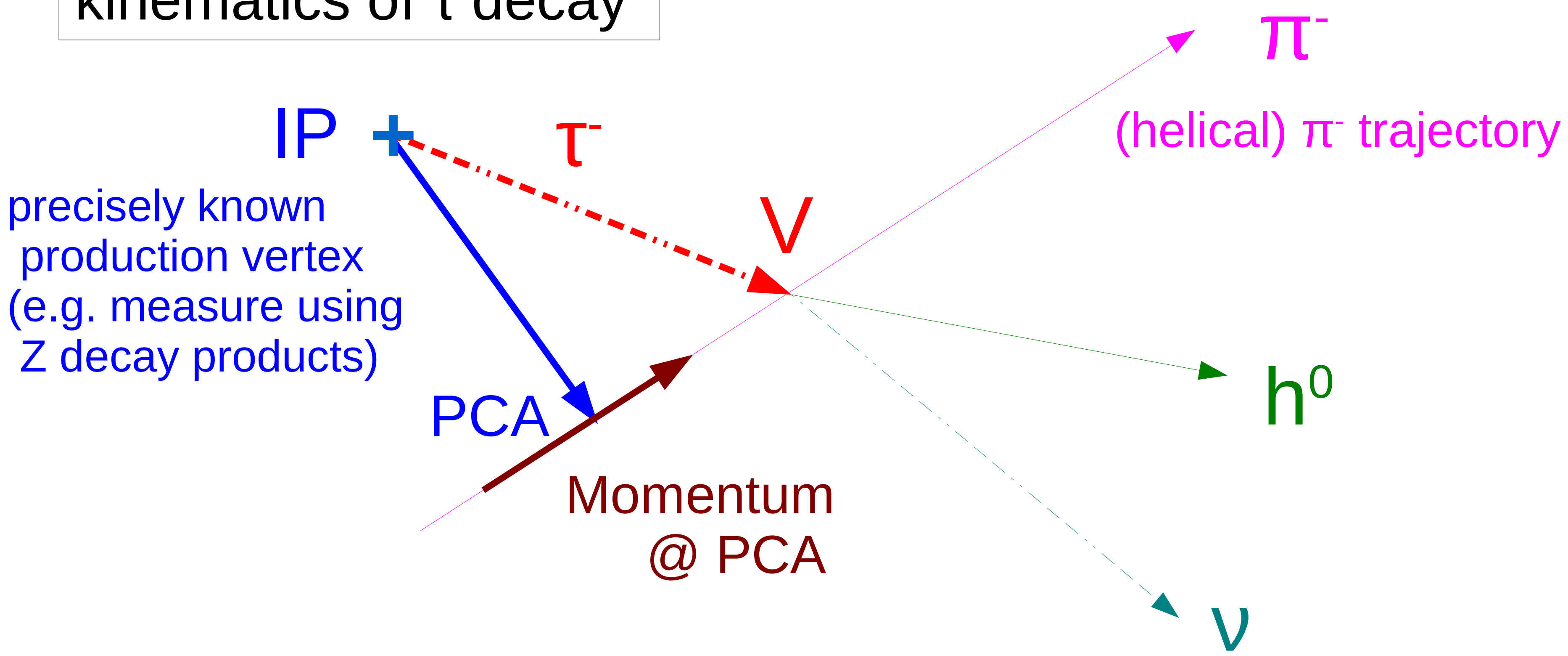


another method makes "colinear approximation":
assume ν || to visible tau jet;
balance event p_T
(~OK if τs not back-to-back)

at ILC, we will have
- a rather small beamspot, and
- a very precise vertex detector

can they help us?

kinematics of τ decay



assume that π/τ trajectory is approx linear between PCA/IP and V

OK since typical radius of curvature >> τ decay length

measured "track plane" defined by IP-PCA and Mom@PCA

(these two vectors are perpendicular for 3d PCA)

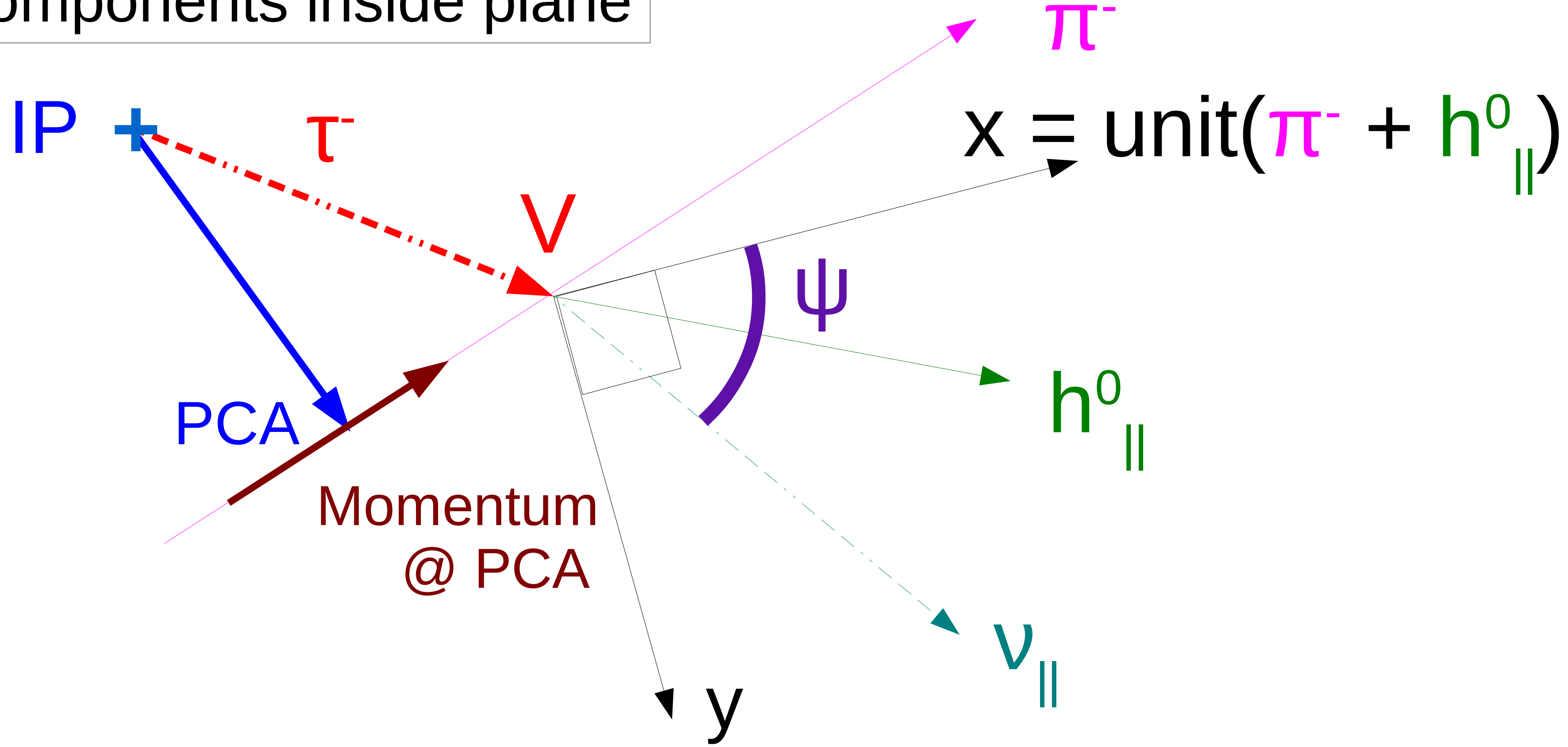
- τ momentum lies inside track plane (linear approx.)

→ (h^0 + ν) momentum lies in track plane

→ ν momentum out of plane = - h^0 momentum out of plane

$$\nu_{perp} = - h^0_{perp}$$

only components inside plane



then parameterise ν momentum inside plane:

- x is unit vector parallel to hadronic momentum inside plane
- y is unit vector in plane, perpendicular to x
- Q is magnitude of momentum in plane

$$\nu_{\parallel} = Q\,(\,x \cos\psi + y \sin\psi\,)$$

We can then write the neutrino momentum as

$\nu = Q (x \cos\psi + y \sin\psi) - h^0_{perp}$

two unknown parameters, Q and ψ

4-momentum of $\tau = \pi + h^0 + \nu$

invariant mass of τ is well-known, use to remove one param

→ for each choice of ψ can calculate Q (in general 2 solutions)

→ calculate full kinematics of τ for any assumed ψ including decay length, lifetime

(in πν decays, one Q solution gives a negative decay length, and can be rejected)

we have reduced ν momentum to one parameter ψ

HOW TO CHOOSE ψ ?

consider whole event

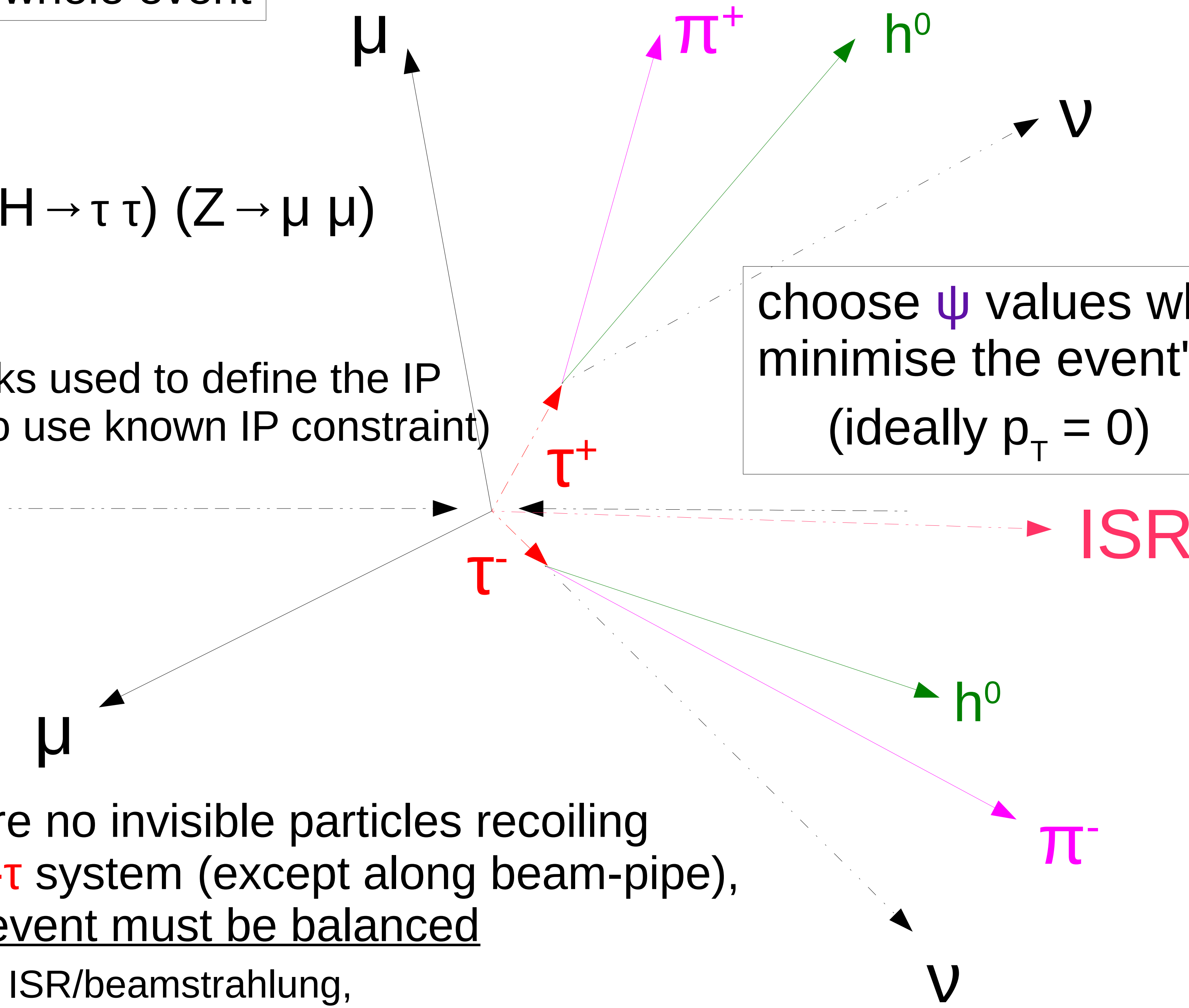
e.g.

$e^+ e^- \rightarrow (H \rightarrow \tau\, \tau)\ (Z \rightarrow \mu\, \mu)$

muon tracks used to define the IP
(could also use known IP constraint)

choose ψ values which minimise the event's p_T

(ideally $p_T = 0$)



If there are no invisible particles recoiling against τ-τ system (except along beam-pipe),

<u>p_T of event must be balanced</u>

because of ISR/beamstrahlung,
don't make requirements on p_Z

Test the method

$e^+ e^- \rightarrow H \mu^+ \mu^-$ events generated @ 250 GeV Whizard with CIRCE1 ISR/BS

$H \rightarrow \tau\tau$; τ decayed by TAUOLA: either both $\pi^+\nu$ or both $\pi^+\pi^0\nu$ ($\rho\nu$)

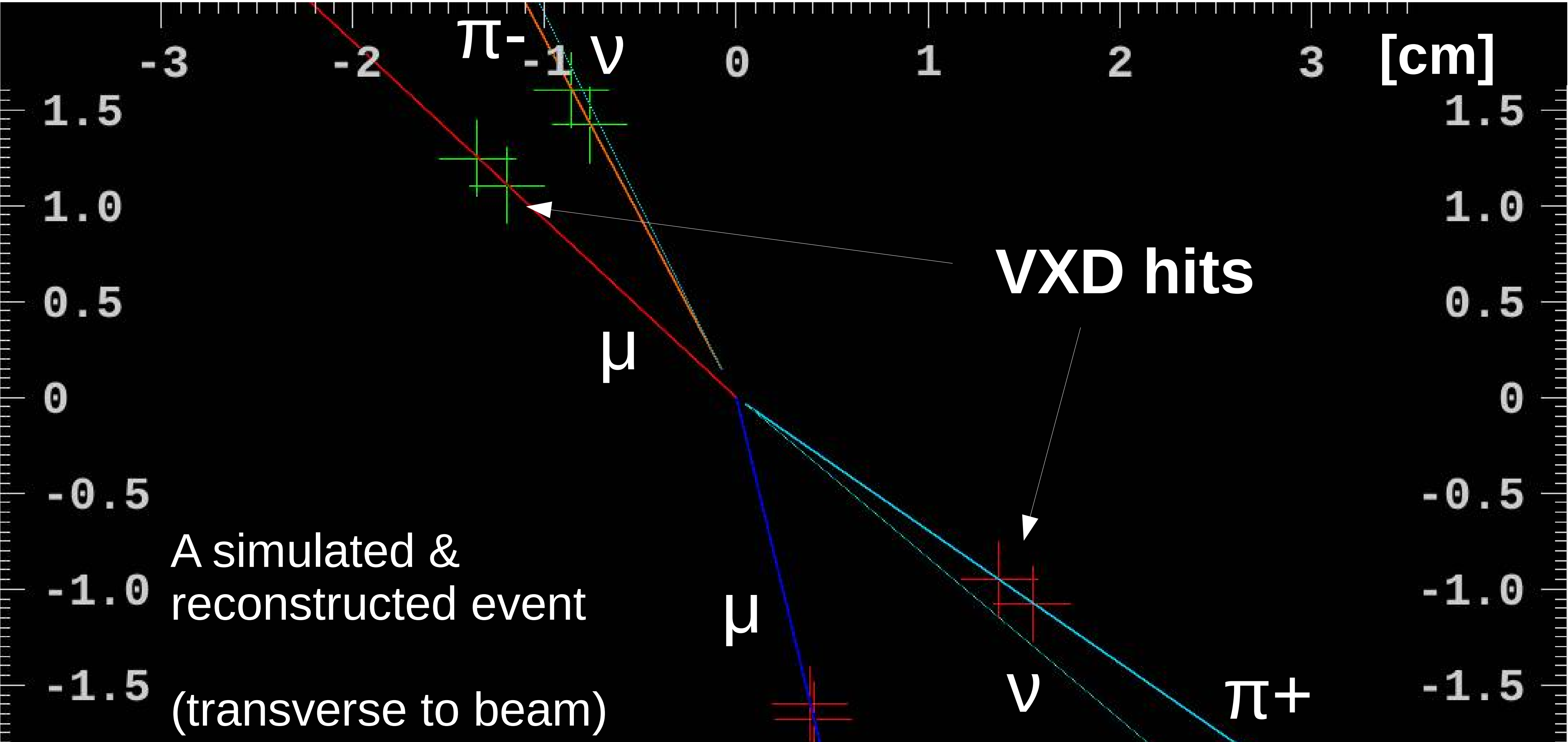
Full ILD simulation, DBD version ILD_v05_o1

Usual ILD reconstruction + GARLIC, no underlying event overlay

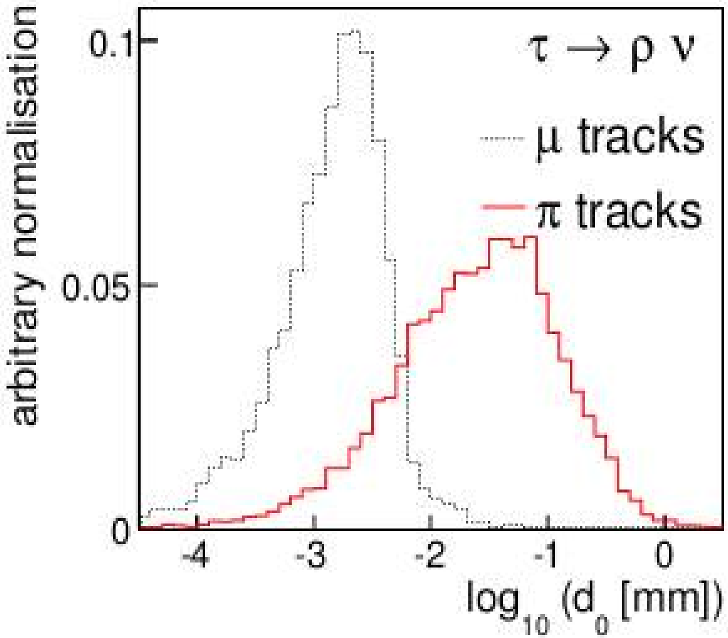
Cheat matching of GARLIC/Pandora clusters to π^0, and of π^0 & π^+ to τ

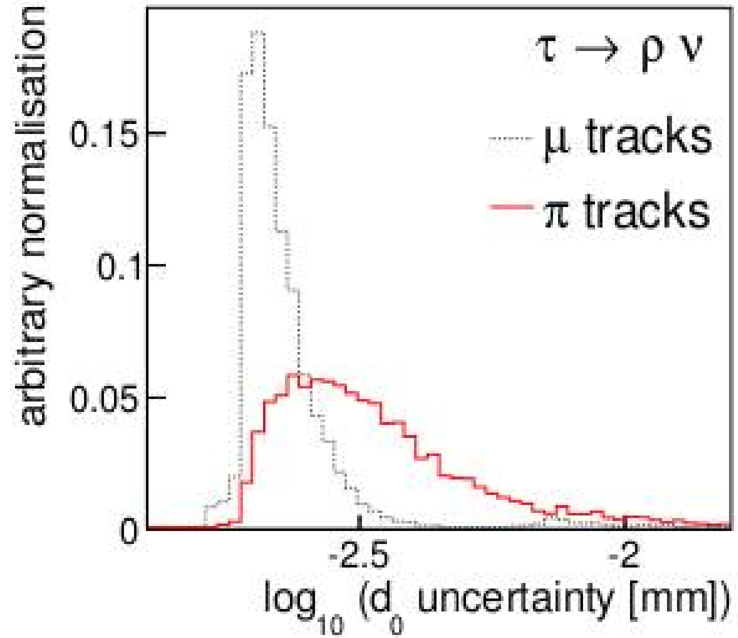
apply π^0 mass constraint to two photon system

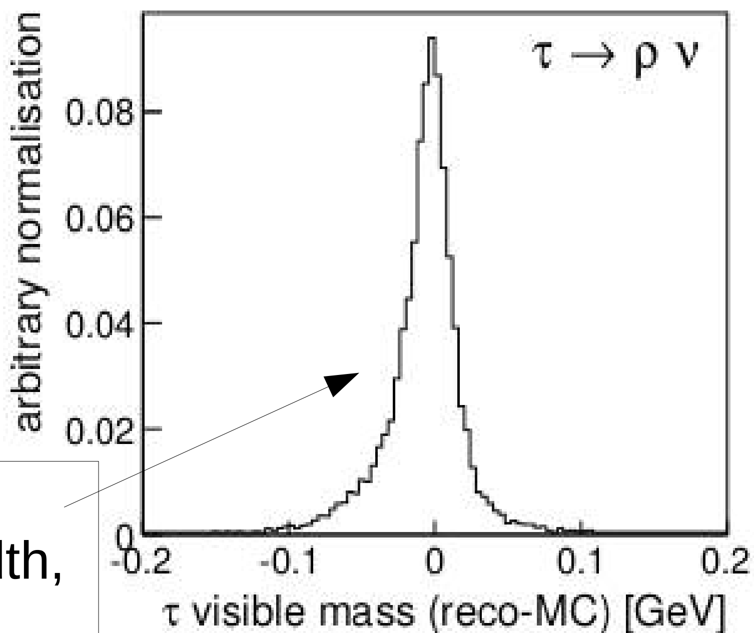
Use $\mu^+ \mu^-$ tracks to reconstruct IP: ~3μm precision



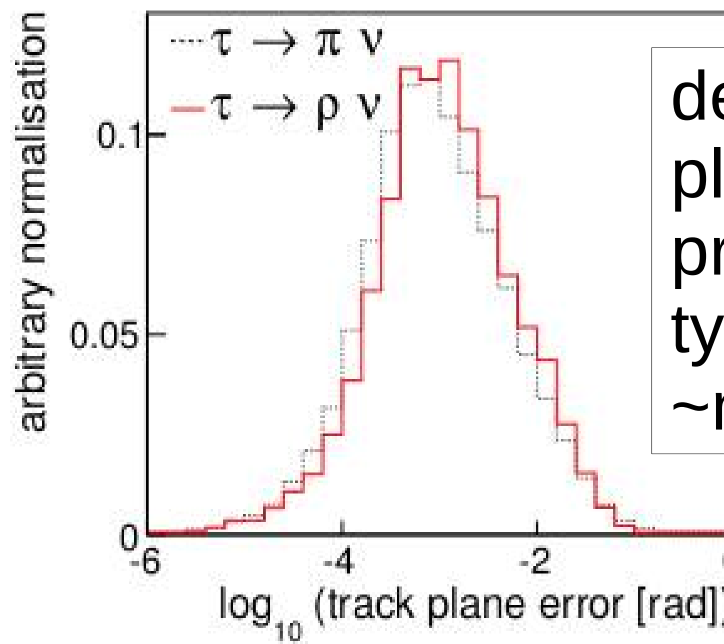
Track, π^0, ρ reconstruction





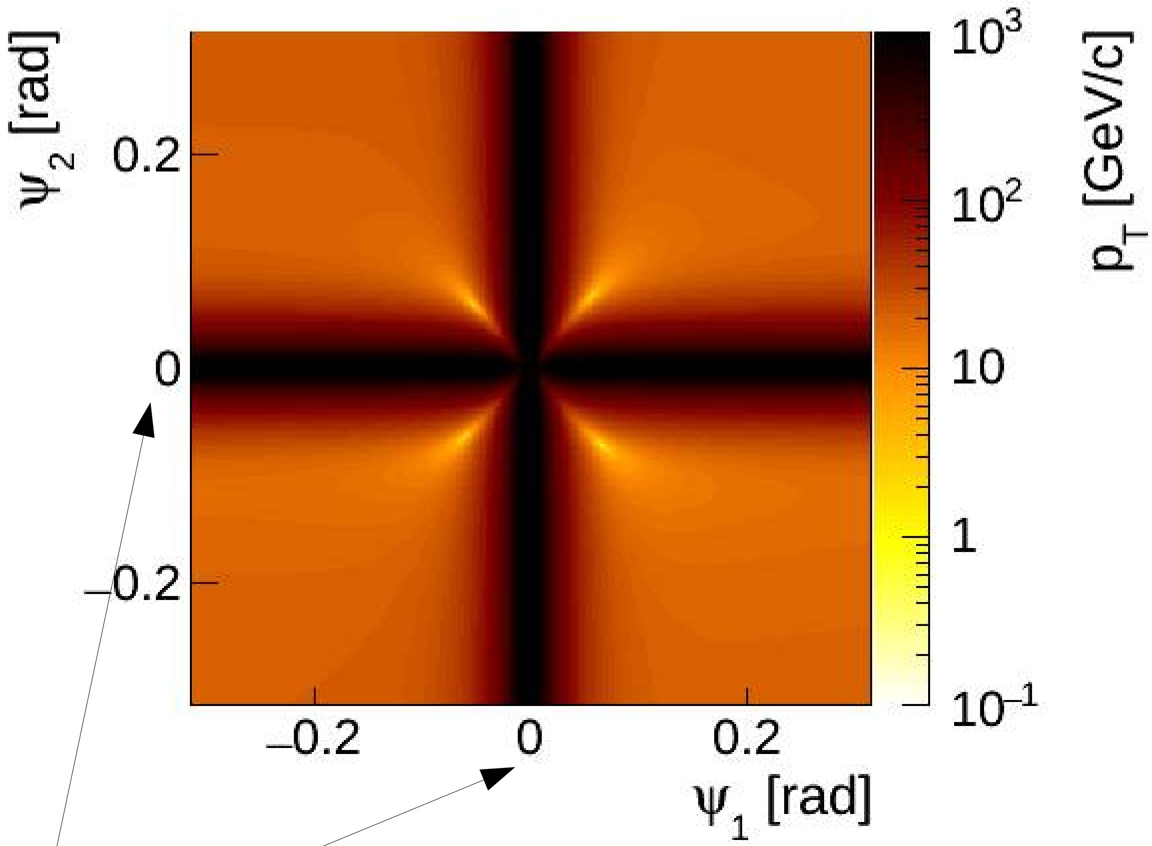


smaller than natural ρ width, small bias



decay plane precision typically ~mrad

How does event p_T depend on neutrino angle ψ chosen for two taus?



neutrino colinear
with hadrons in
track plane

one event @ 250 GeV
$e^+e^- \rightarrow (H \rightarrow \tau\tau)\ (Z \rightarrow \mu\mu)$

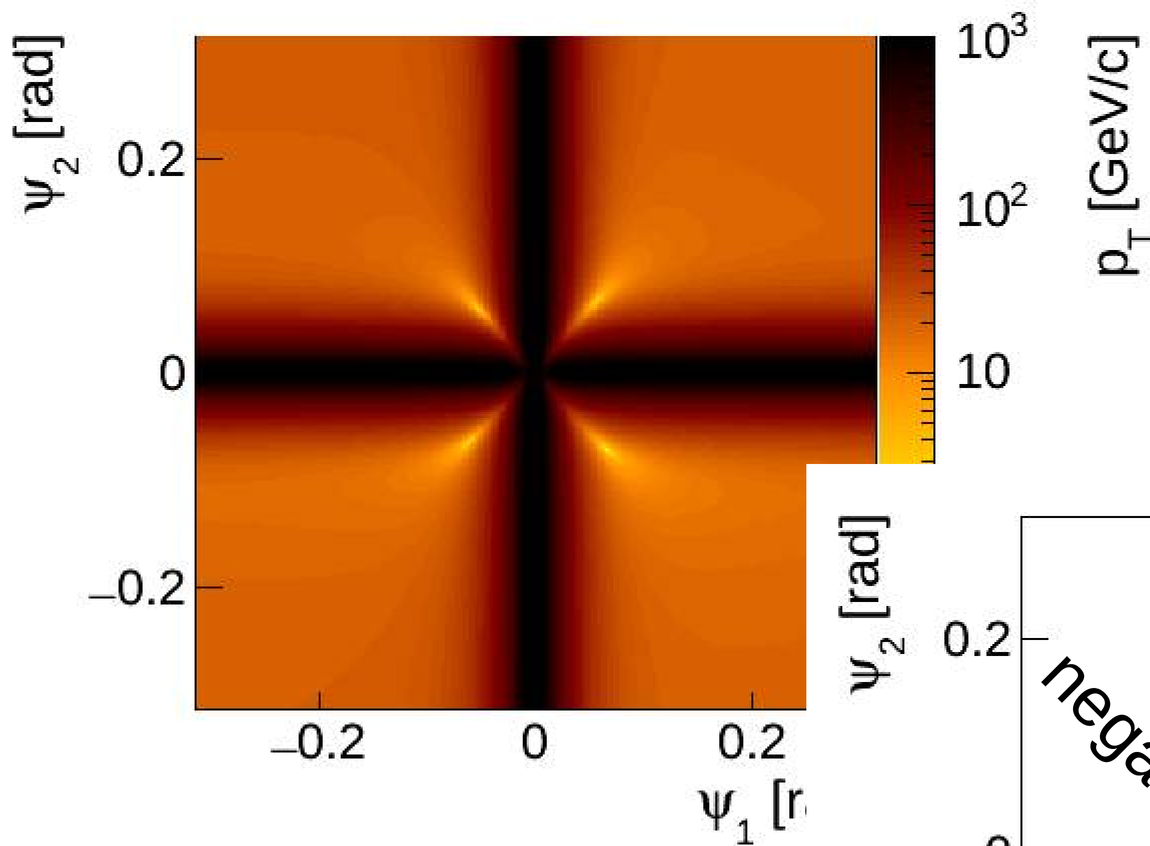
both $\tau \rightarrow \pi\ \nu$

simulated and reconstructed in ILD

Four possible solutions with small p_T
easy to find minima using e.g. MINUIT

how to choose which one?

How does event p_T depend on neutrino angle ψ chosen for two taus?

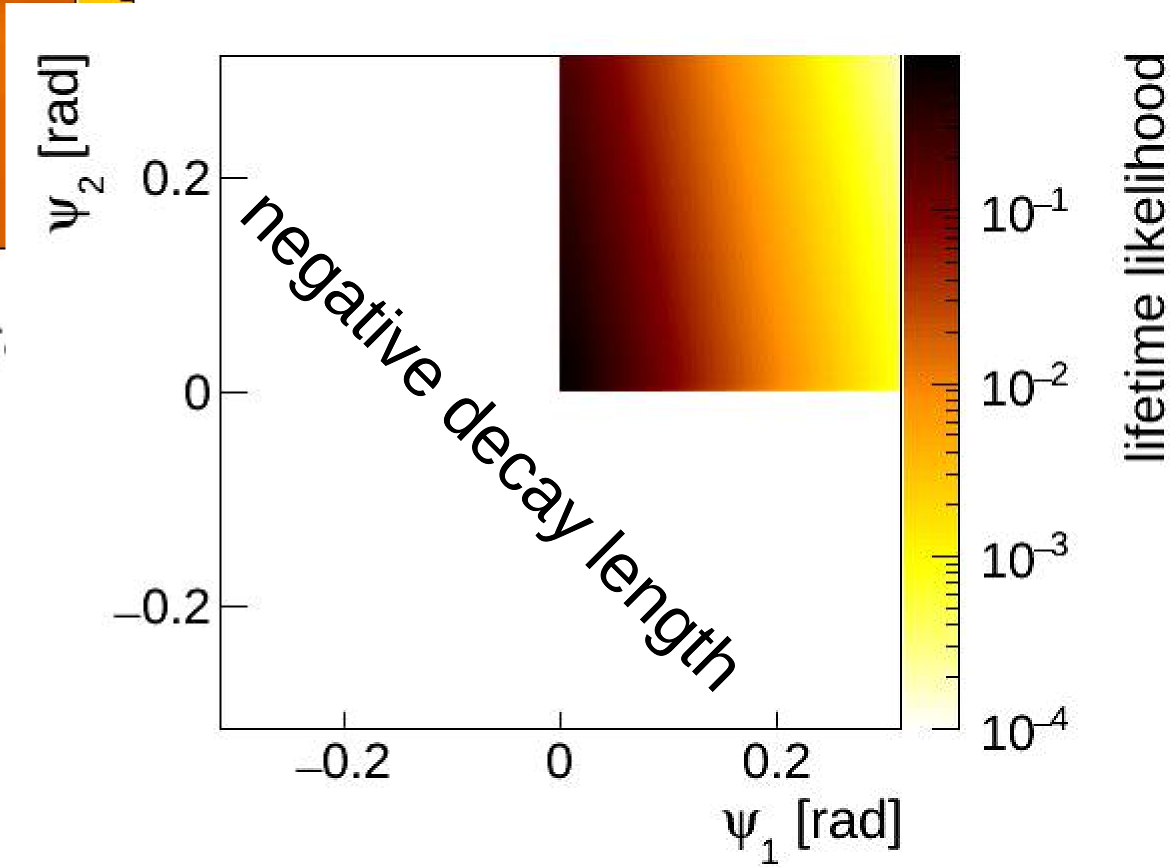


lifetime likelihood

exp{ - candidate lifetime / mean tau lifetime } for +ve candidate decay length,

0 for -ve decay length

look at tau's reconstructed decay length / lifetime for each solution



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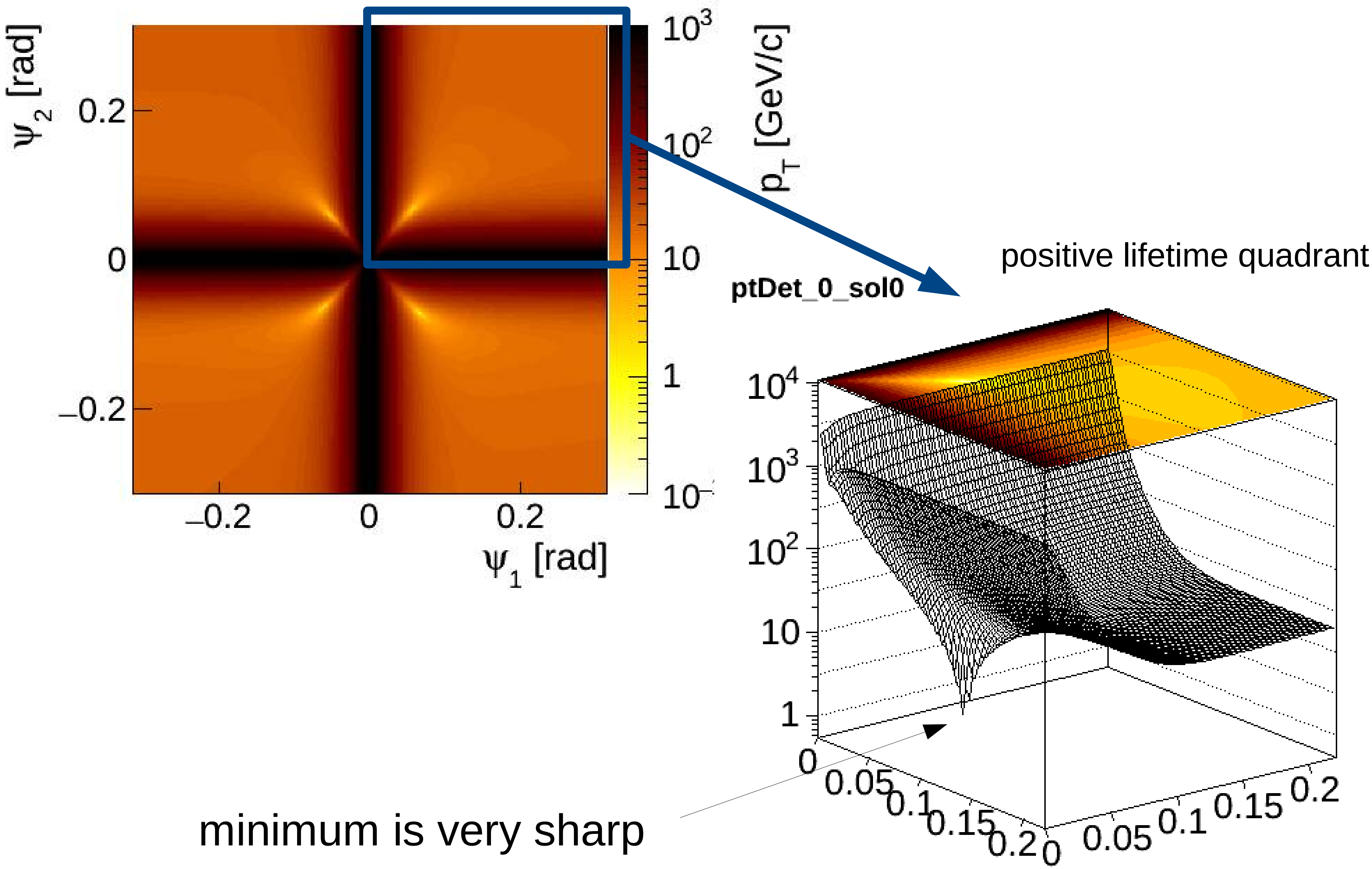
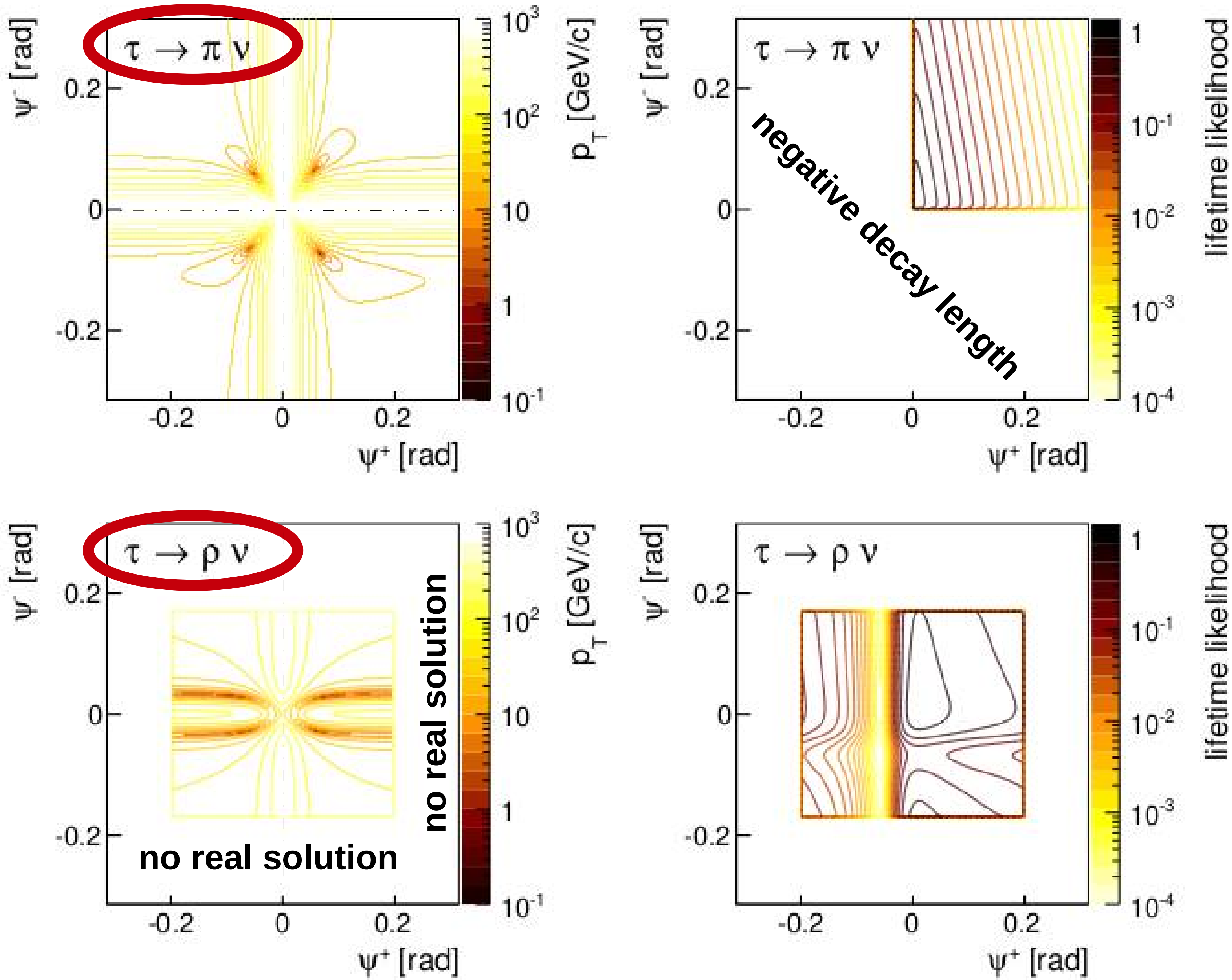
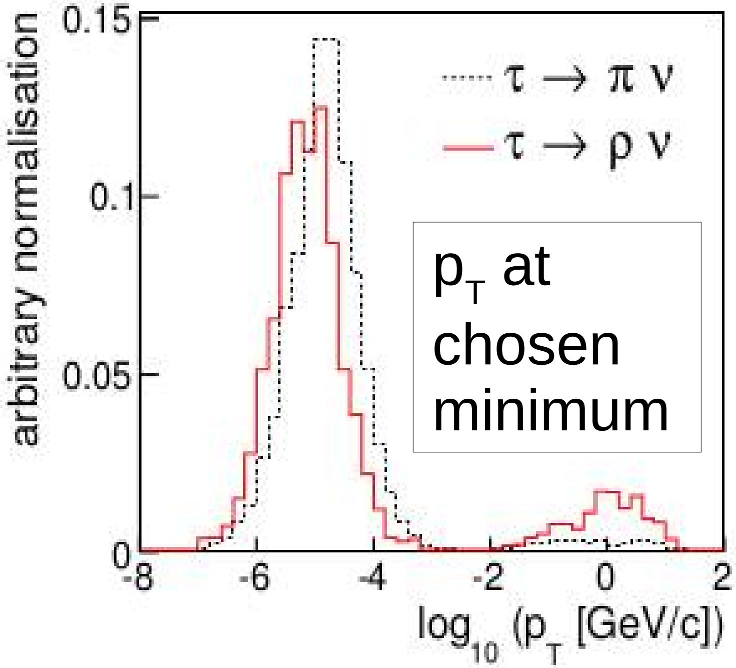




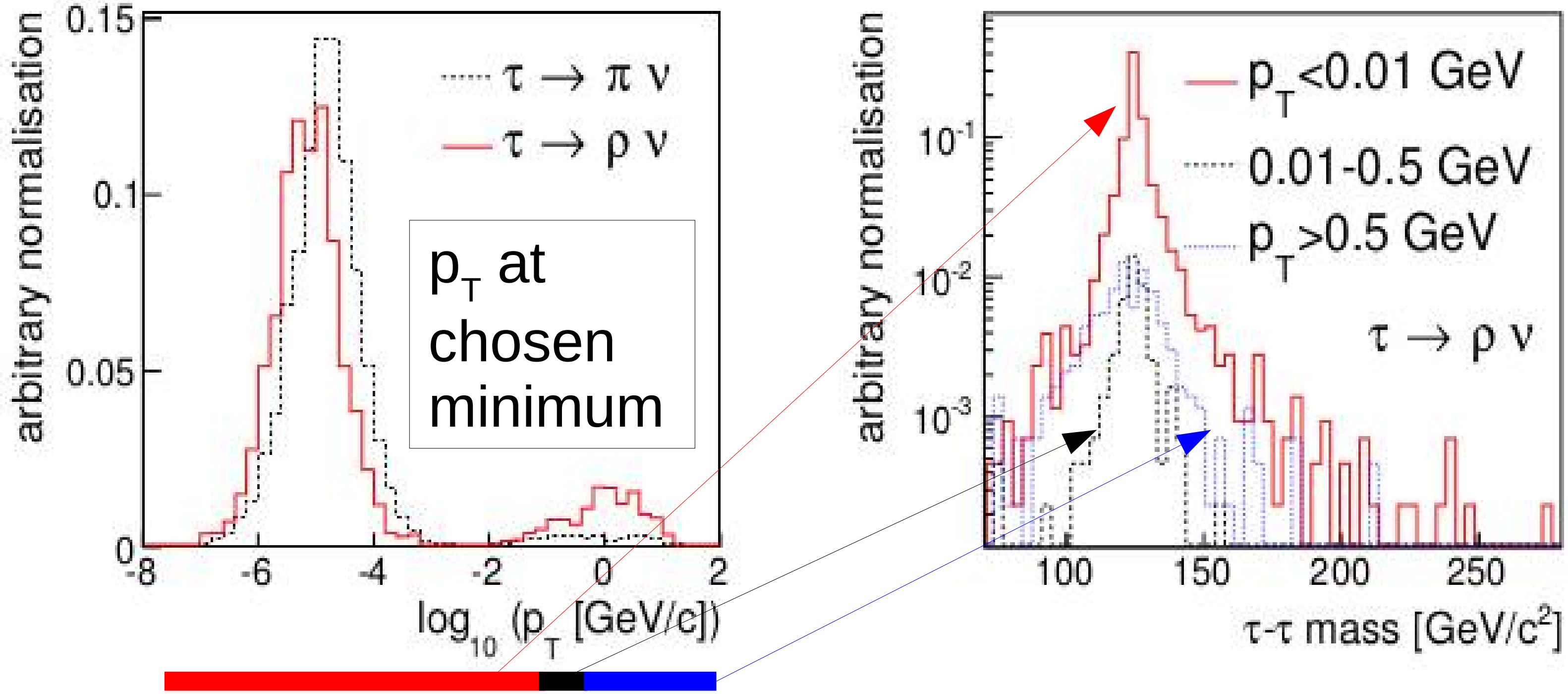
Find p_T minimum in each quadrant:

choose smallest p_T minimum with positive decay length

How well does it work?



How well does it work?
Check the invariant mass of ττ system: should be 125 GeV



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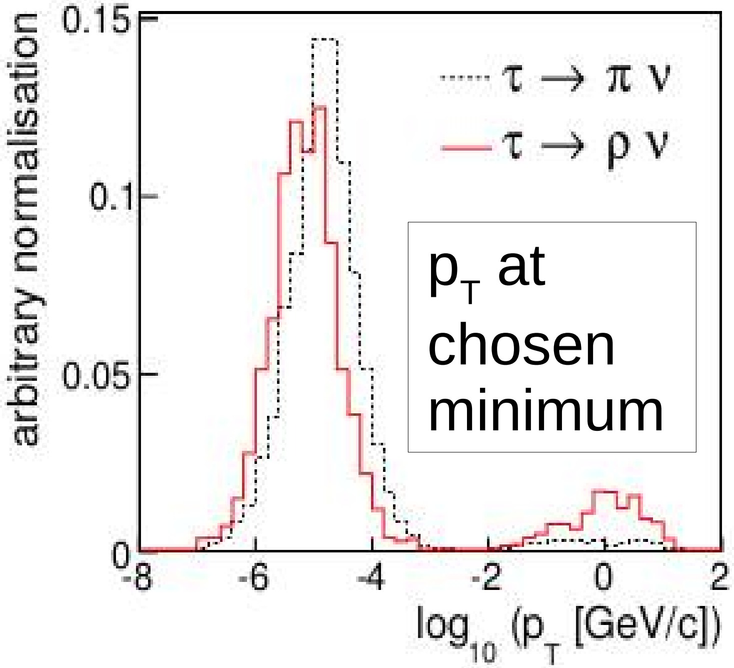
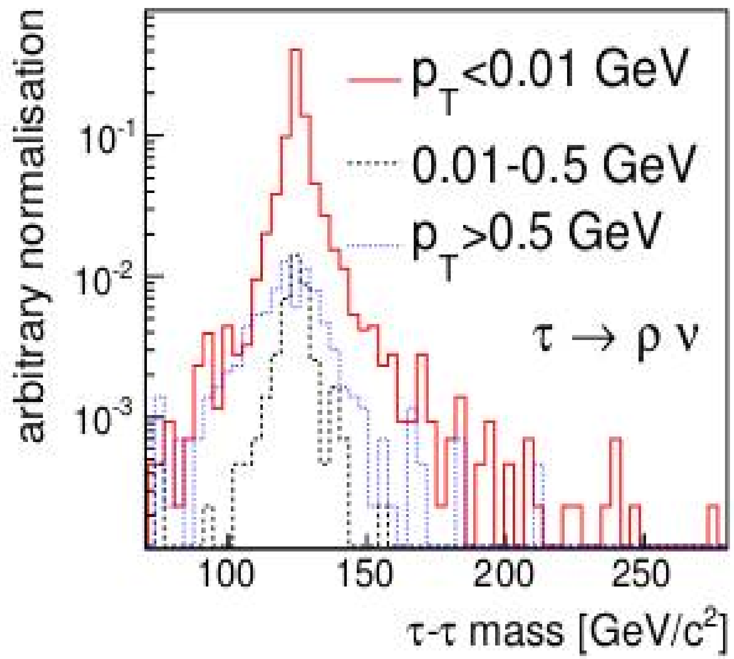
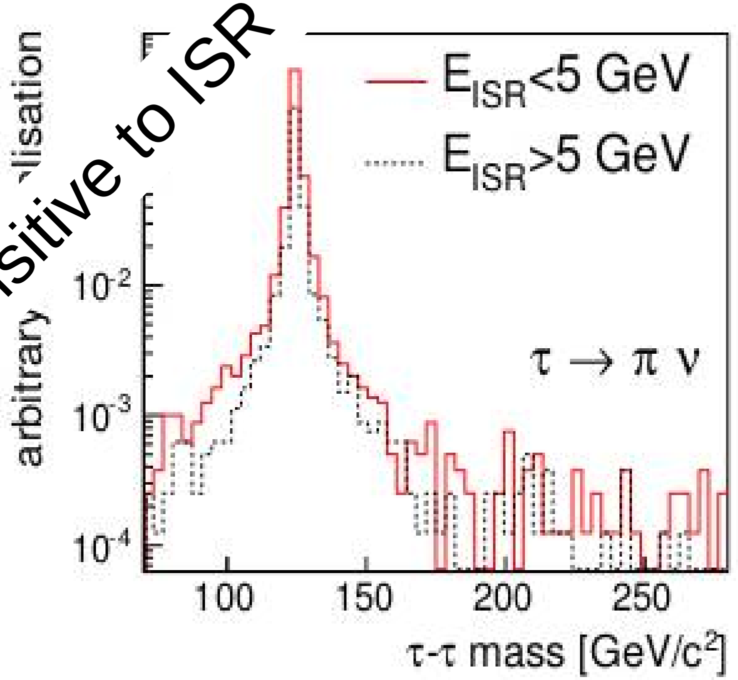
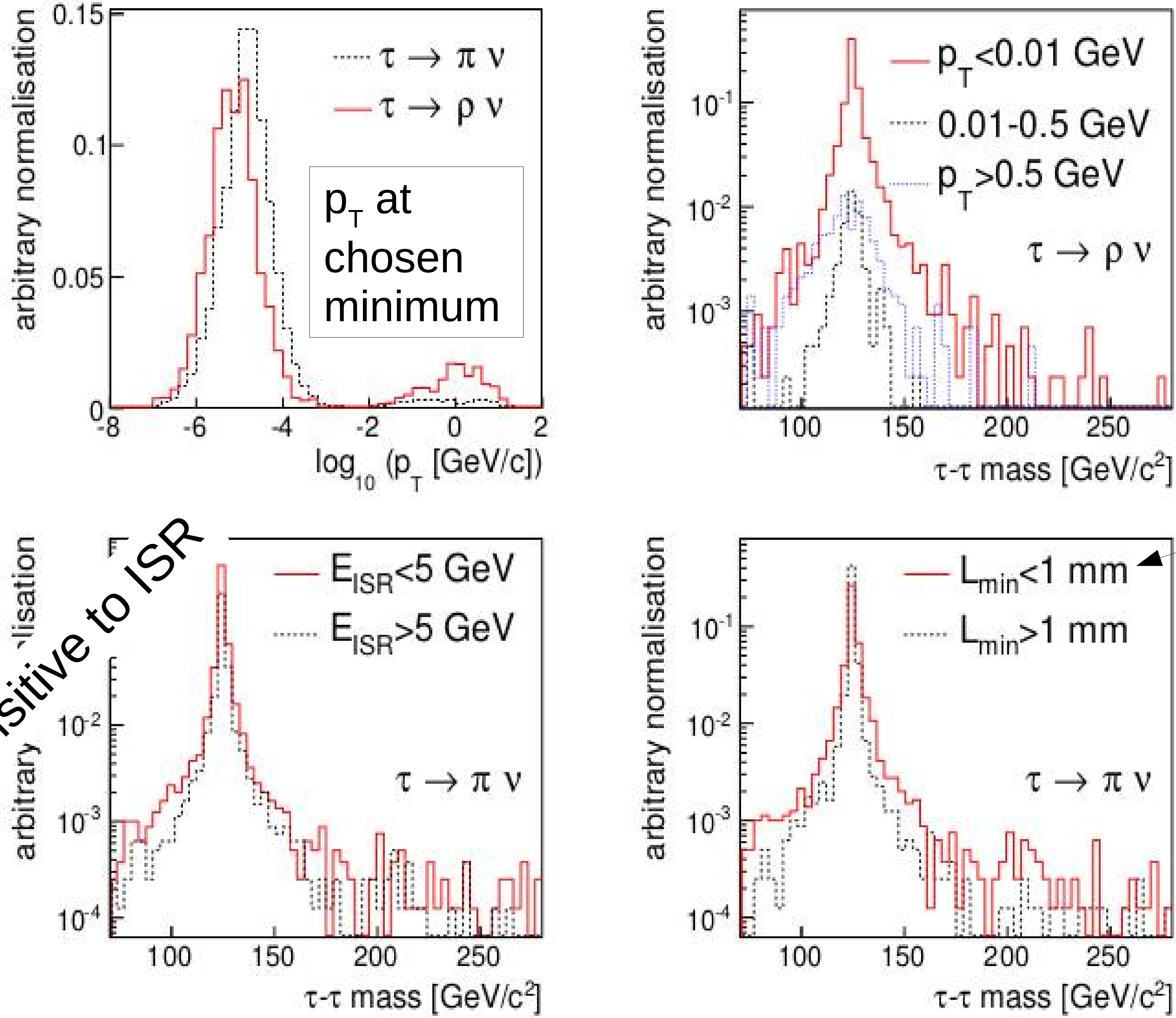






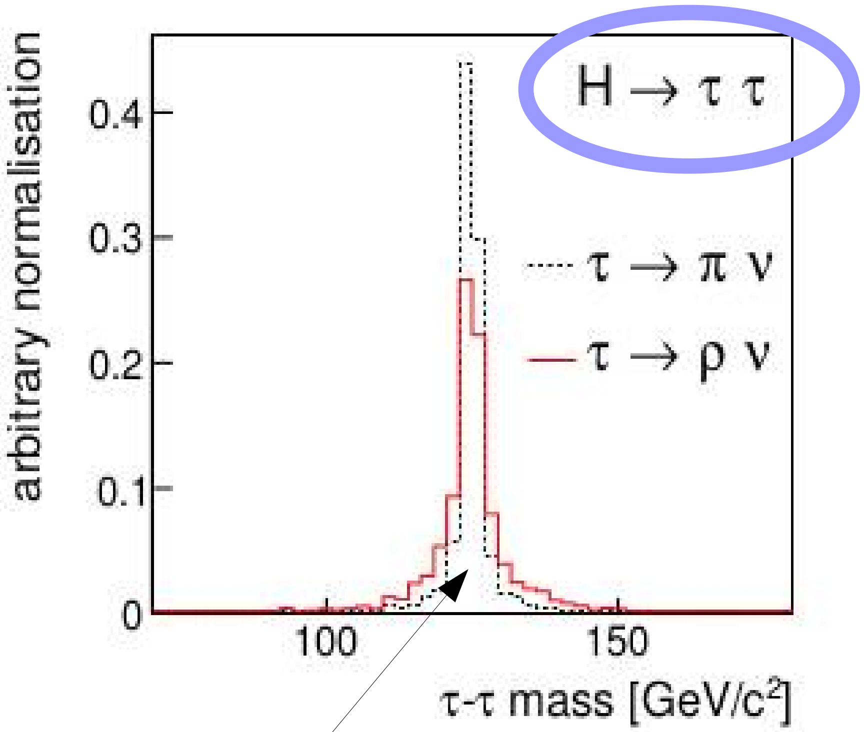
insensitive to ISR

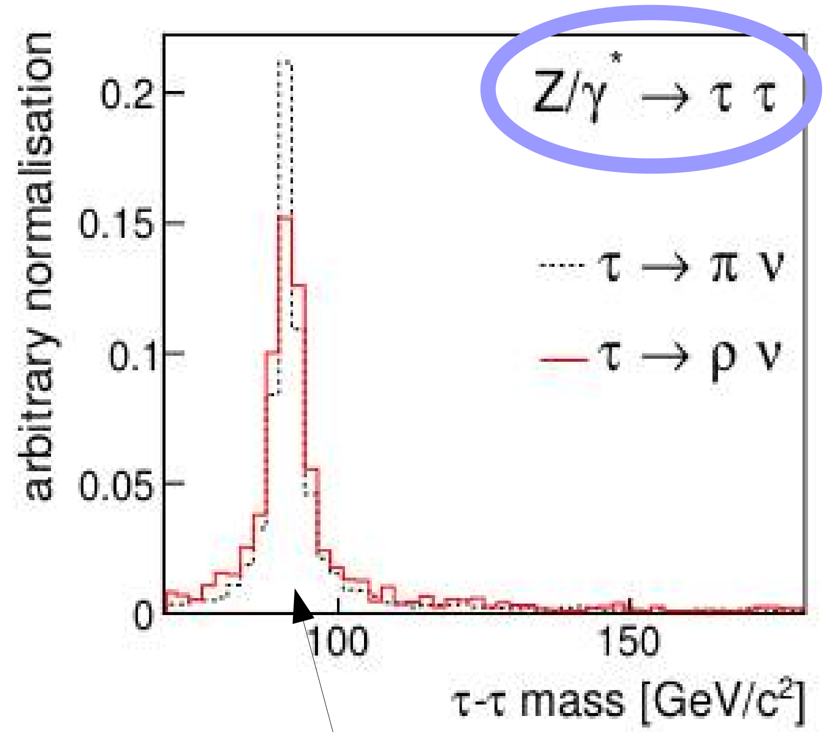
How well does it work?
Check the invariant mass of ττ system: should be 125 GeV



insensitive to ISR

“unlucky” short-lived taus are somewhat less-well measured



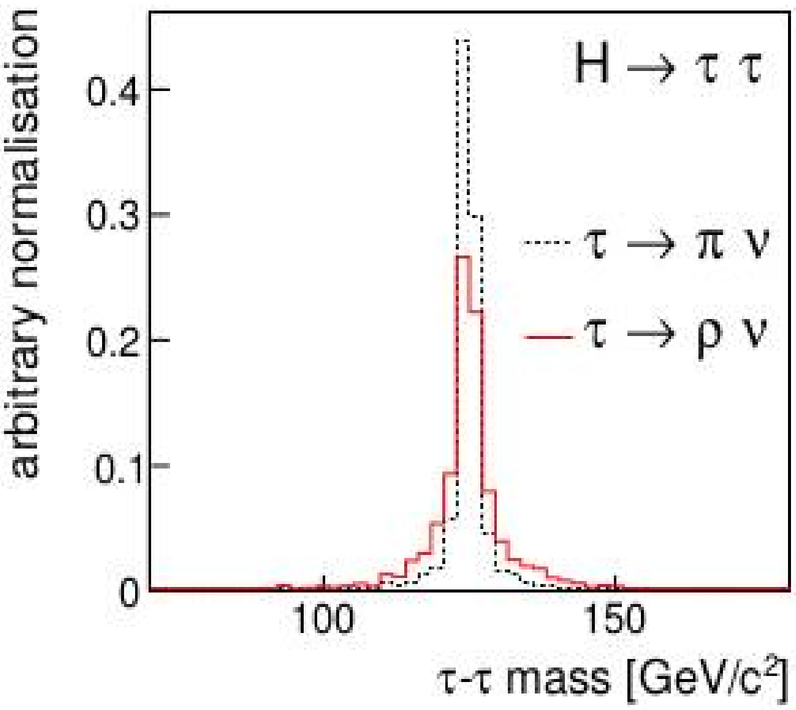


width of central peak
~ 0.6 GeV for $\pi^+\nu$
~ 1.1 GeV for $\pi^+\pi^0\nu$

within (125 ± 10) GeV:
~ 95% of $\pi^+\nu$
~ 89% of $\pi^+\pi^0\nu$

easily distinguished from Z

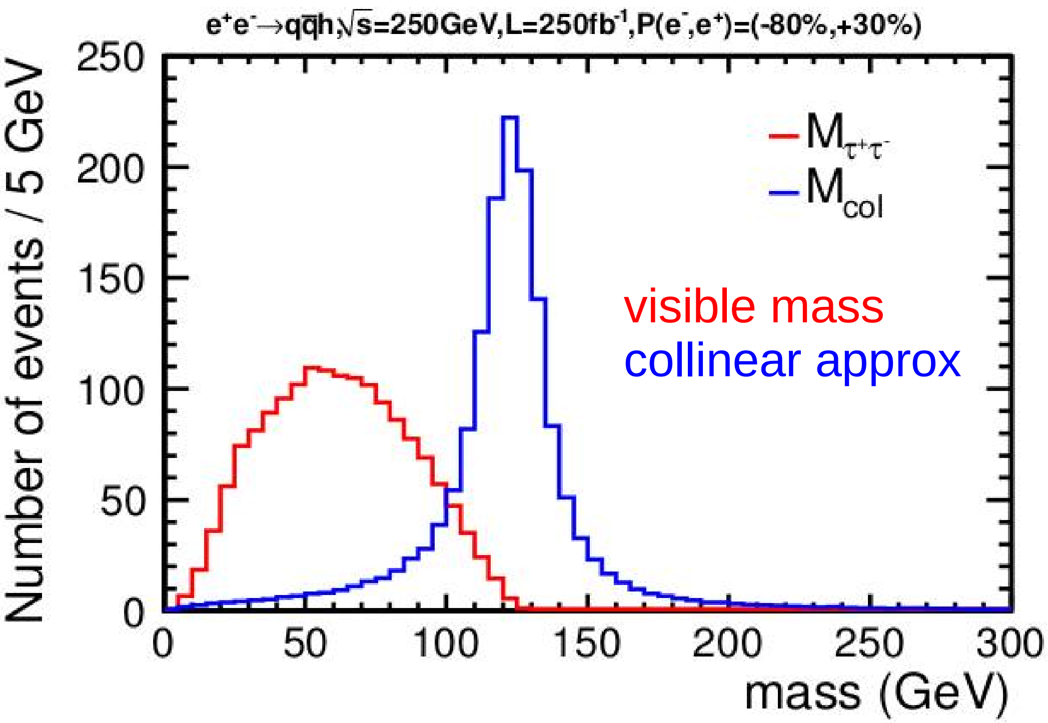
Compare to methods not using impact parameter



n.b. full ILD reco, μμH,
pure tau decay modes,
cheated γ,π,τ association

e.g. Kawada et al [arXiv:1509.01885v1]

Colinear approximation:
- assume neutrinos collinear with visible decay products
- require p_T balance in event



n.b. full ILD reco, qqH,
all tau decay modes,
no cheating of association

Summary

reconstruction method for hadronic tau decays works well @ ILC

requires good IP reconstruction and impact parameter resolution
of order 10 microns (interesting to exactly how good it needs to be)

insensitive boost along beam axis
→ ISR, beamstrahlung OK → HZ @ high energy OK
→ in principle, also applicable to hadron collider experiments
if impact parameter resolution sufficiently good
if IP can be measured

Reconstructs τ-τ mass to a precision of ~ 1 GeV

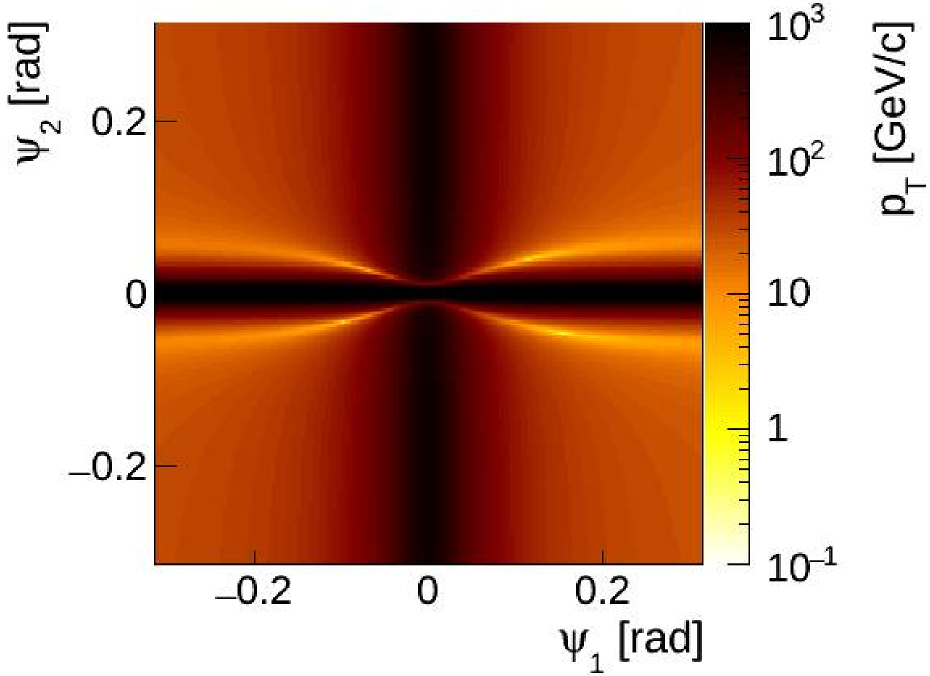
Paper submitted to NIM-A (arXiv:1507.01700)

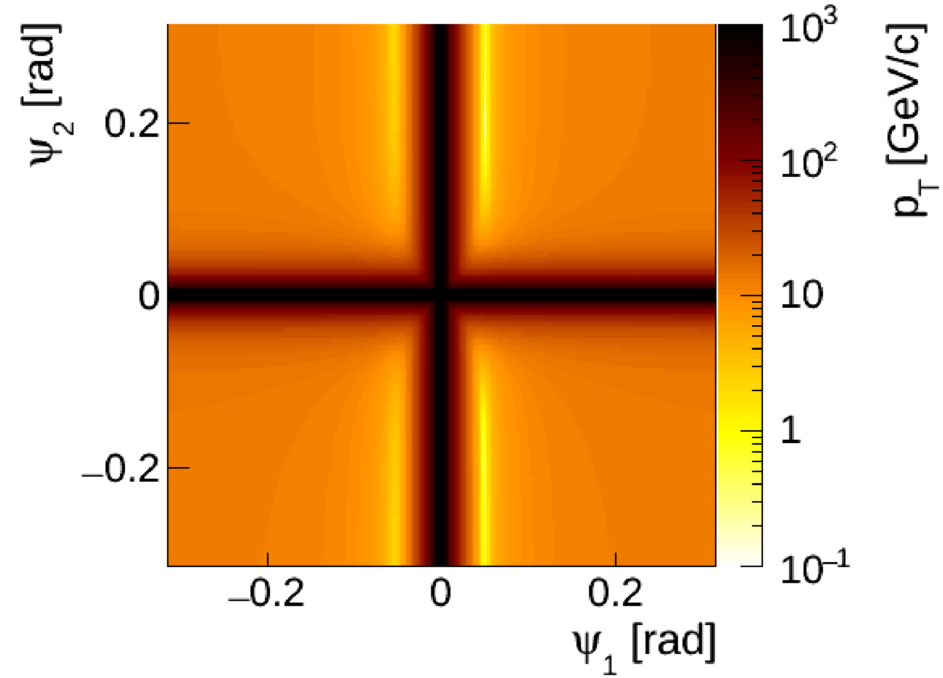
Now working on removing cheating (associating tracks, clusters to taus)
then use tau spin correlations to measure Higgs CP

electron, hadronic Z decays: p_T less well measured

BACKUP

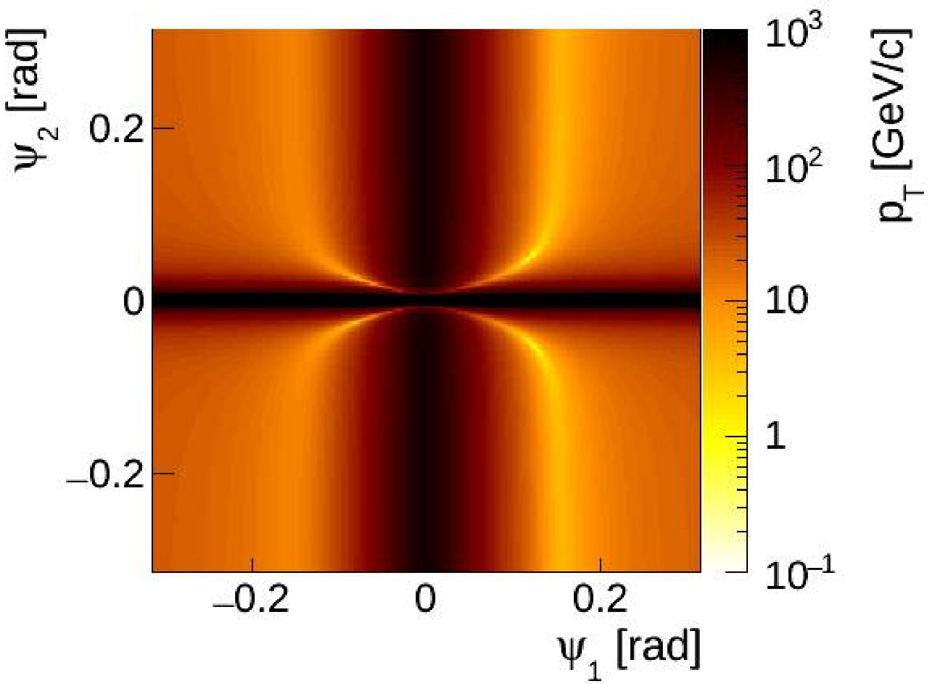
and old slides

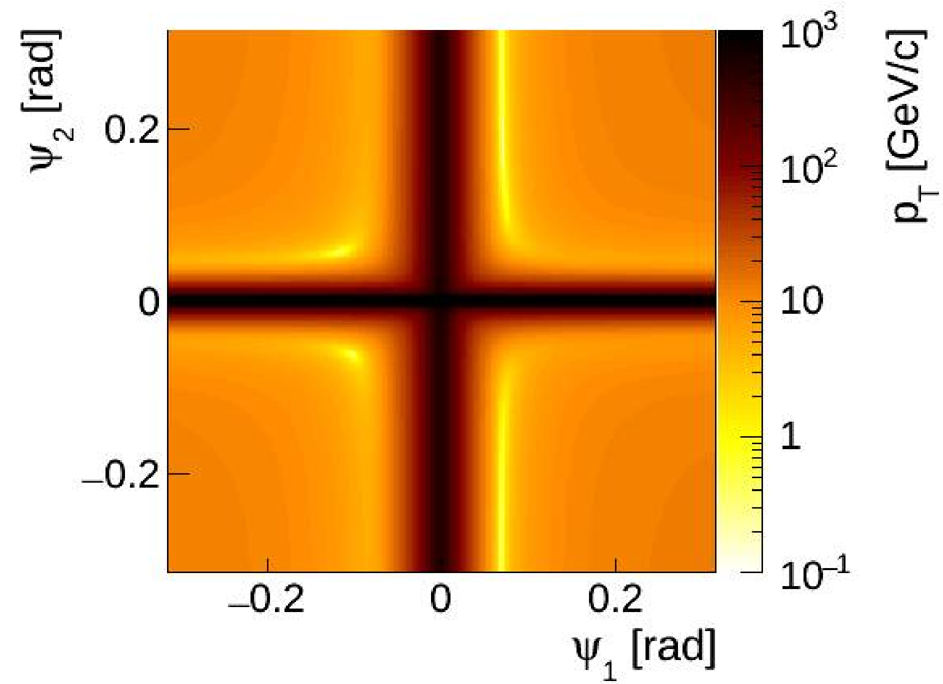


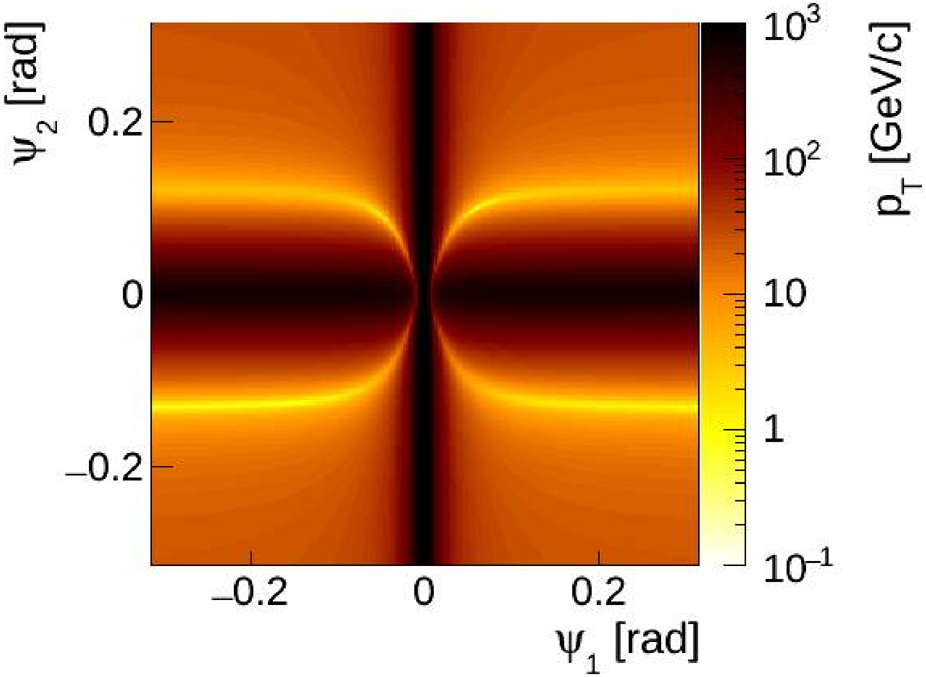


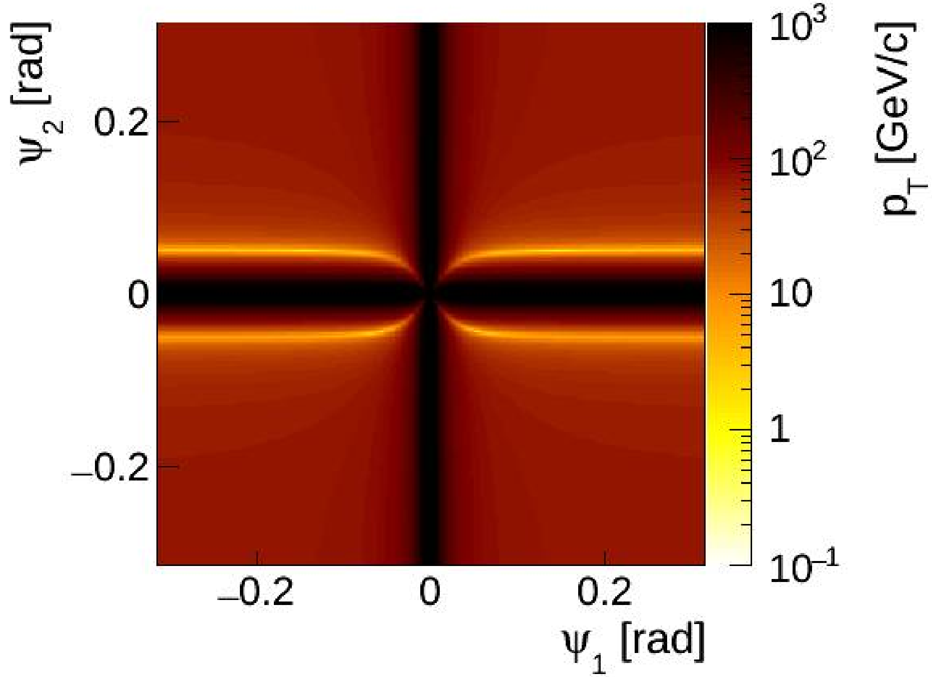
a few more events

both $\tau \rightarrow \pi \nu$



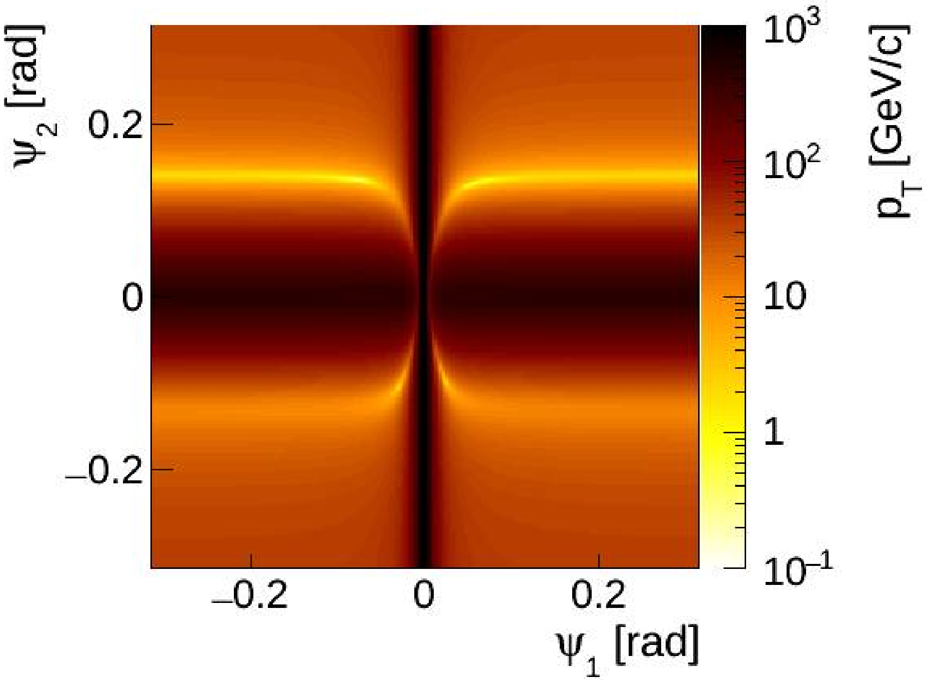


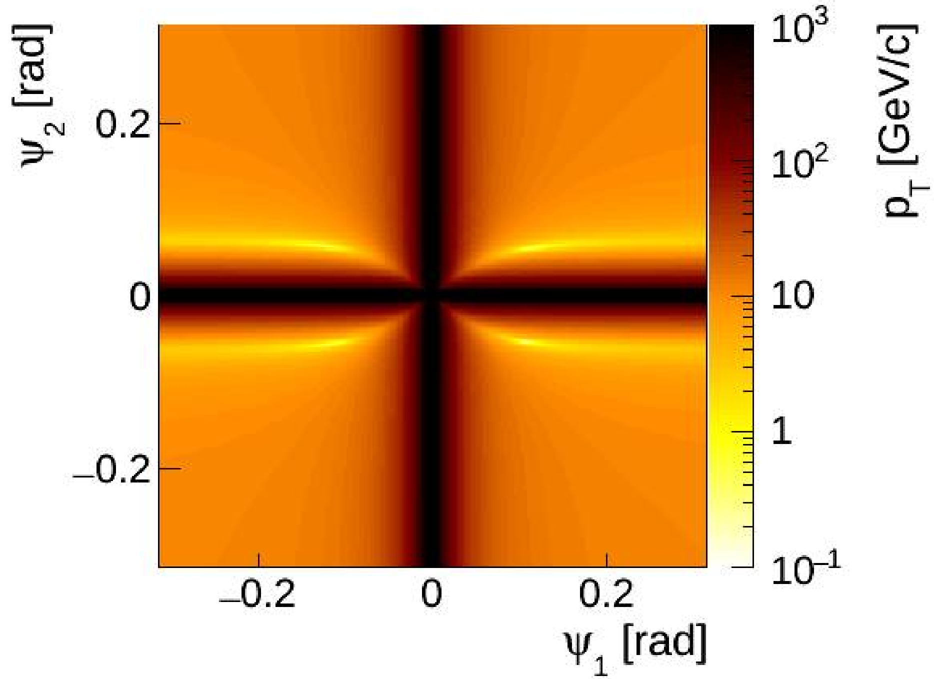




a few more events

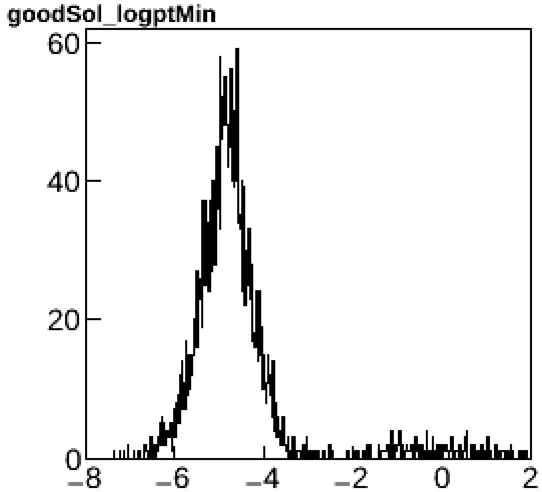
both $\tau \rightarrow \pi \nu$



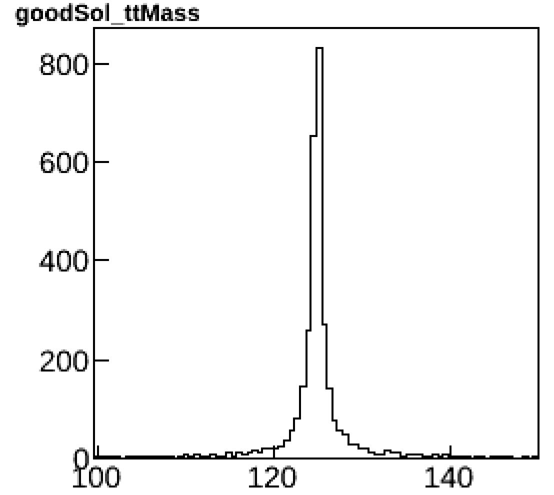


Full reconstruction

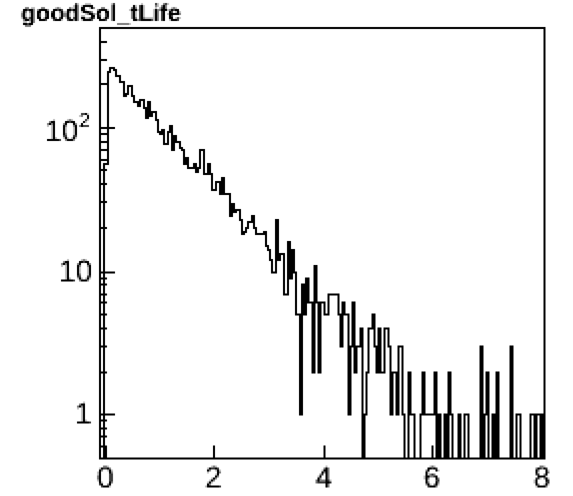
both τ → π ν



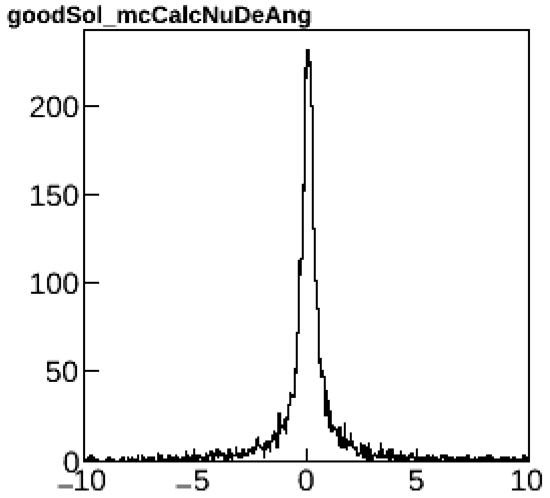
log10(pT) at best solution [GeV]



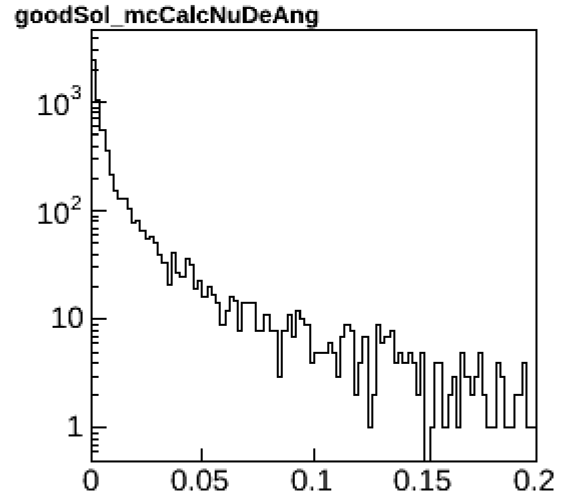
tau-tau mass [GeV]



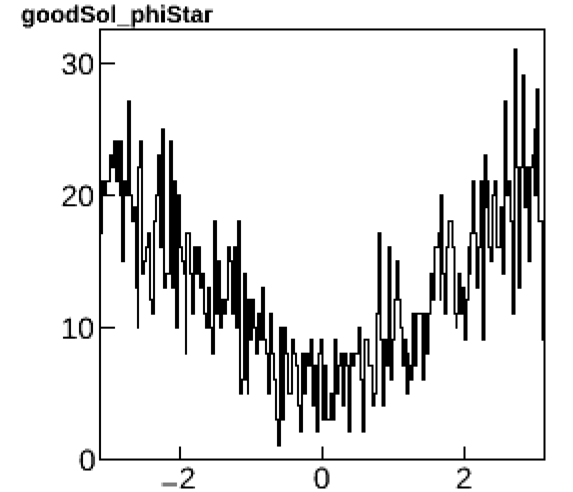
reconstructed lifetime/ 87 um/c



difference between true and reco neutrino energy [GeV]



angle between true and reco neutrino [rad]



angle used to measure Higgs CP

both $\tau \rightarrow \pi\,\nu$

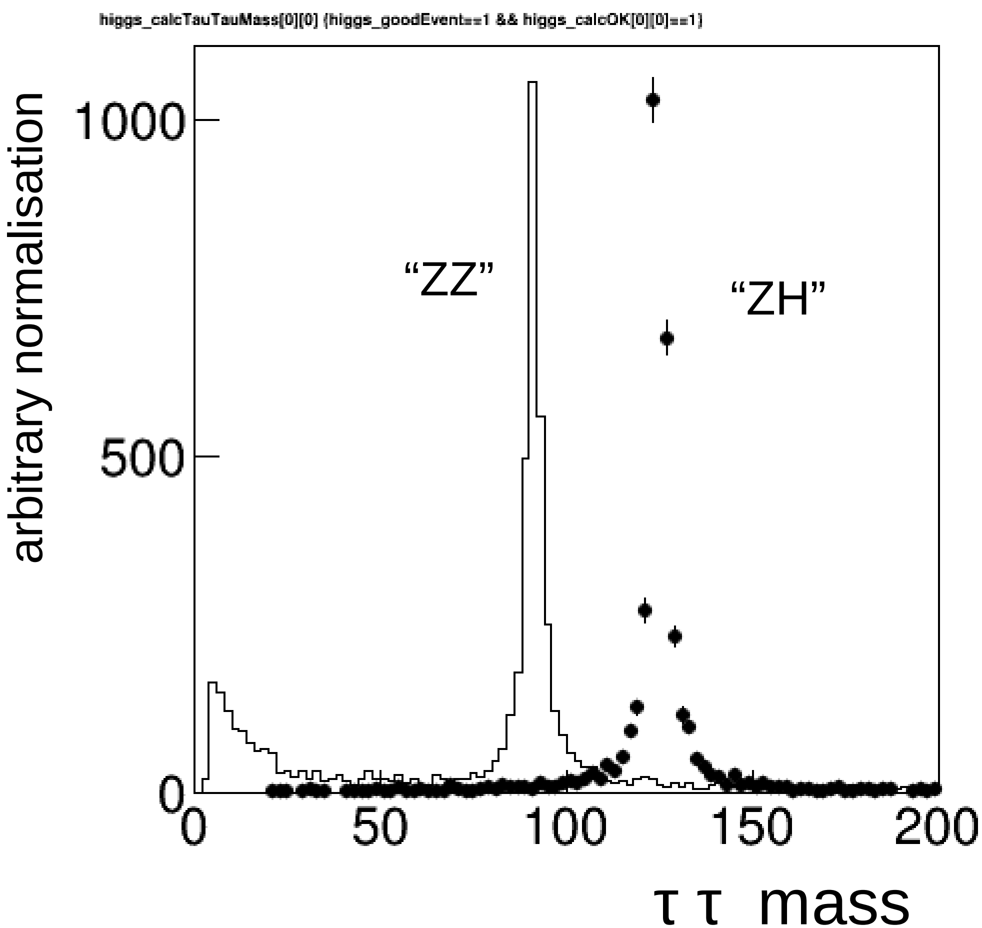
compare

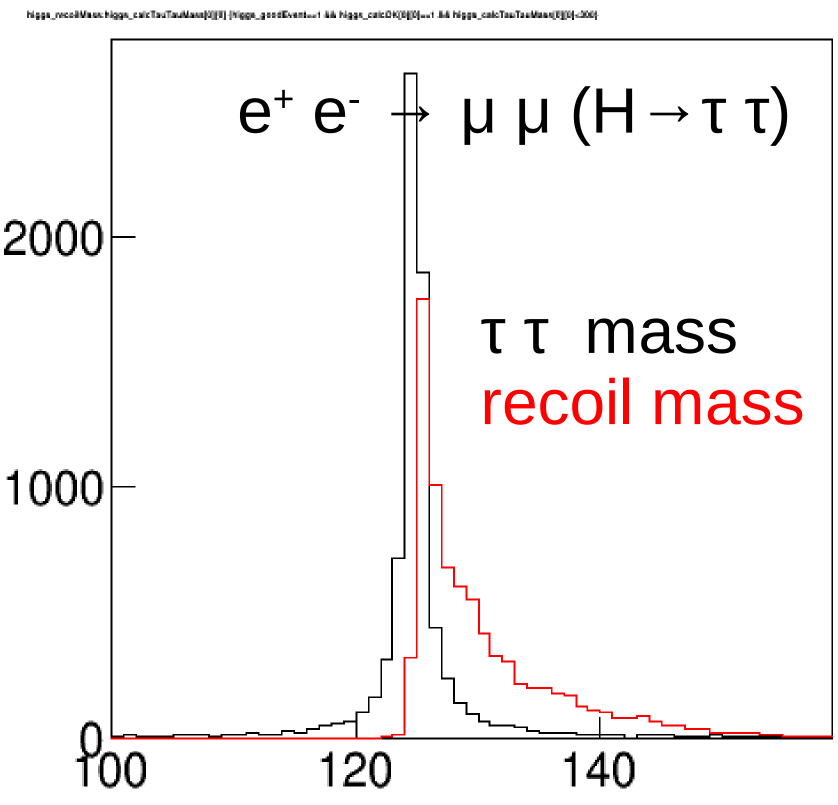
$e^+ e^- \rightarrow \mu\,\mu\,(H \rightarrow \tau\,\tau)$

to its major irreducible background

$e^+ e^- \rightarrow \mu\,\mu\,\tau\,\tau$

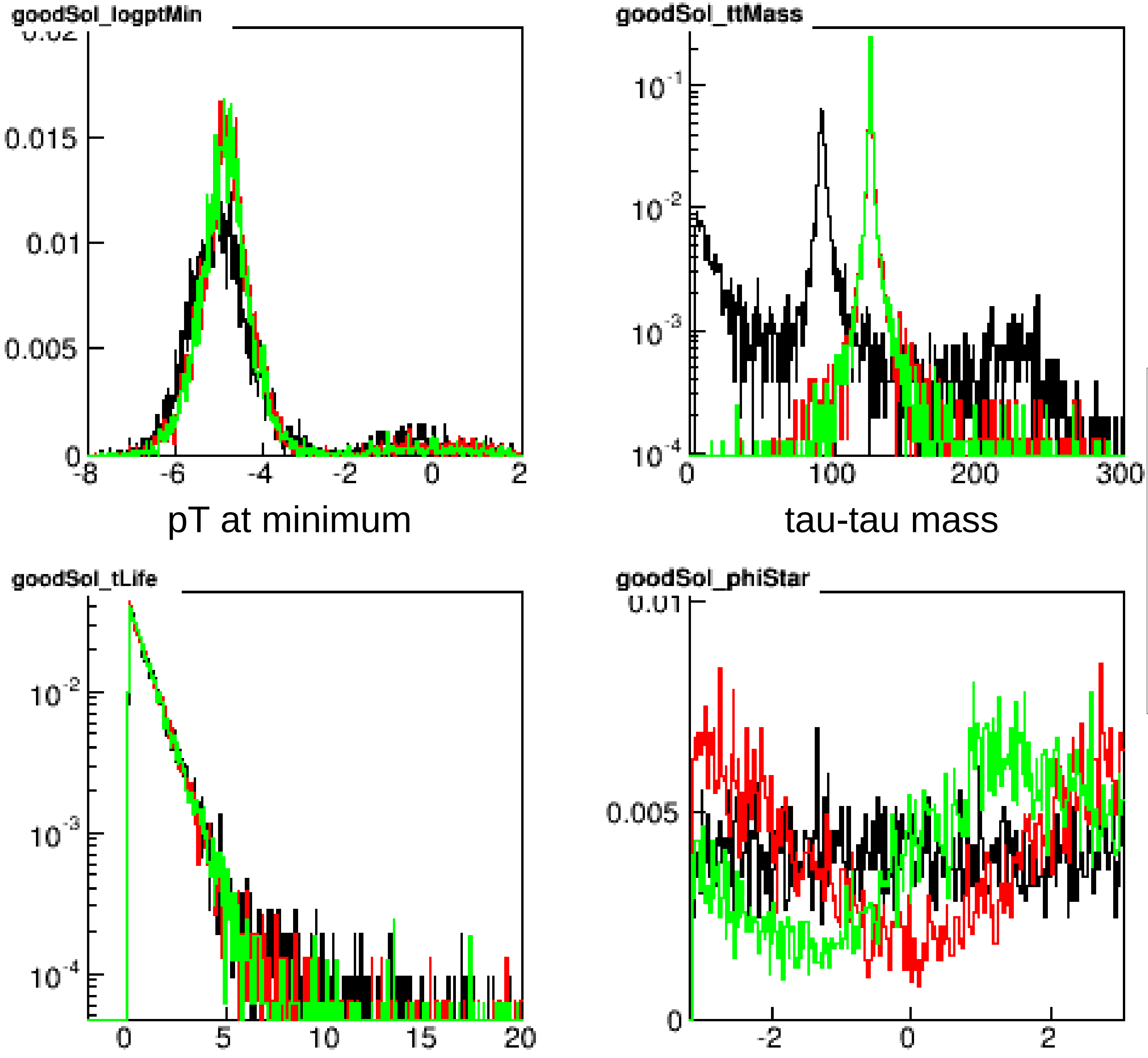
(without H contribution: Z, gamma*)





arbitrary normalisation

both $\tau \rightarrow \pi \nu$



CP^{+} Higgs

H = cos (π/4) CP^{+} + sin (π/4) CP^{-}

non-Higgs μμττ

Summary

method to fully reconstruct hadronic tau decays
- needs:
  - good vertex detector
  - precise knowledge of IP
  - no extra neutrinos in event
- no assumption on:
  - tau-tau mass
  - tau-tau centre-of-mass
  - ISR/beamstrahlung

Demonstrated in tau+ → pi+ nu
- now working on tau+ → pi+ pi0 nu

Then proceed to full CP analysis

backup slides

Motivation:

the Higgs decays to

ZZ , WW , $\tau^+\tau^-$, converted photons

are particularly interesting, because spin state of W, Z, τ, photon are reflected in the distribution of its decay products

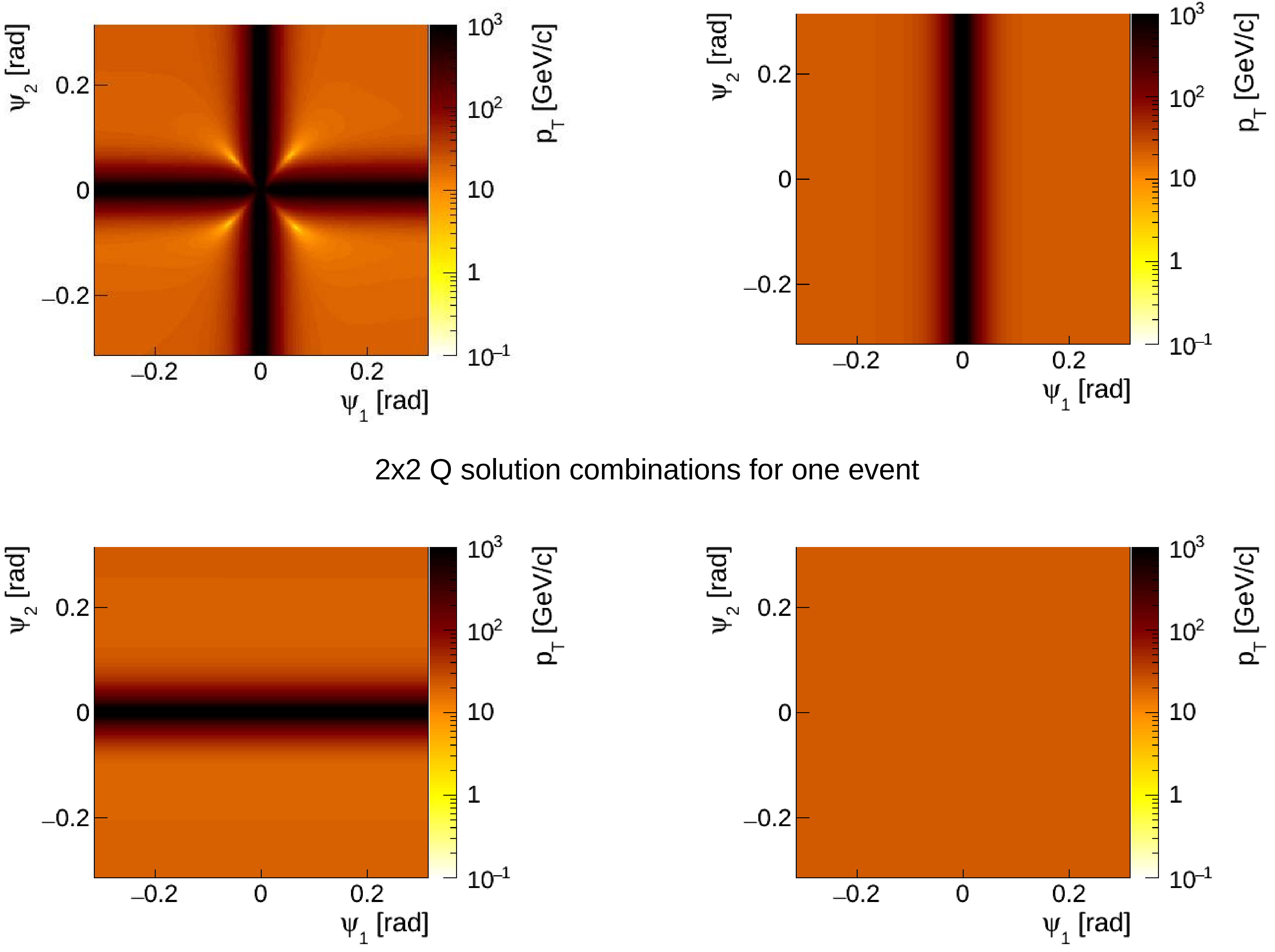
This allows measurement of *e.g.* Higgs CP properties

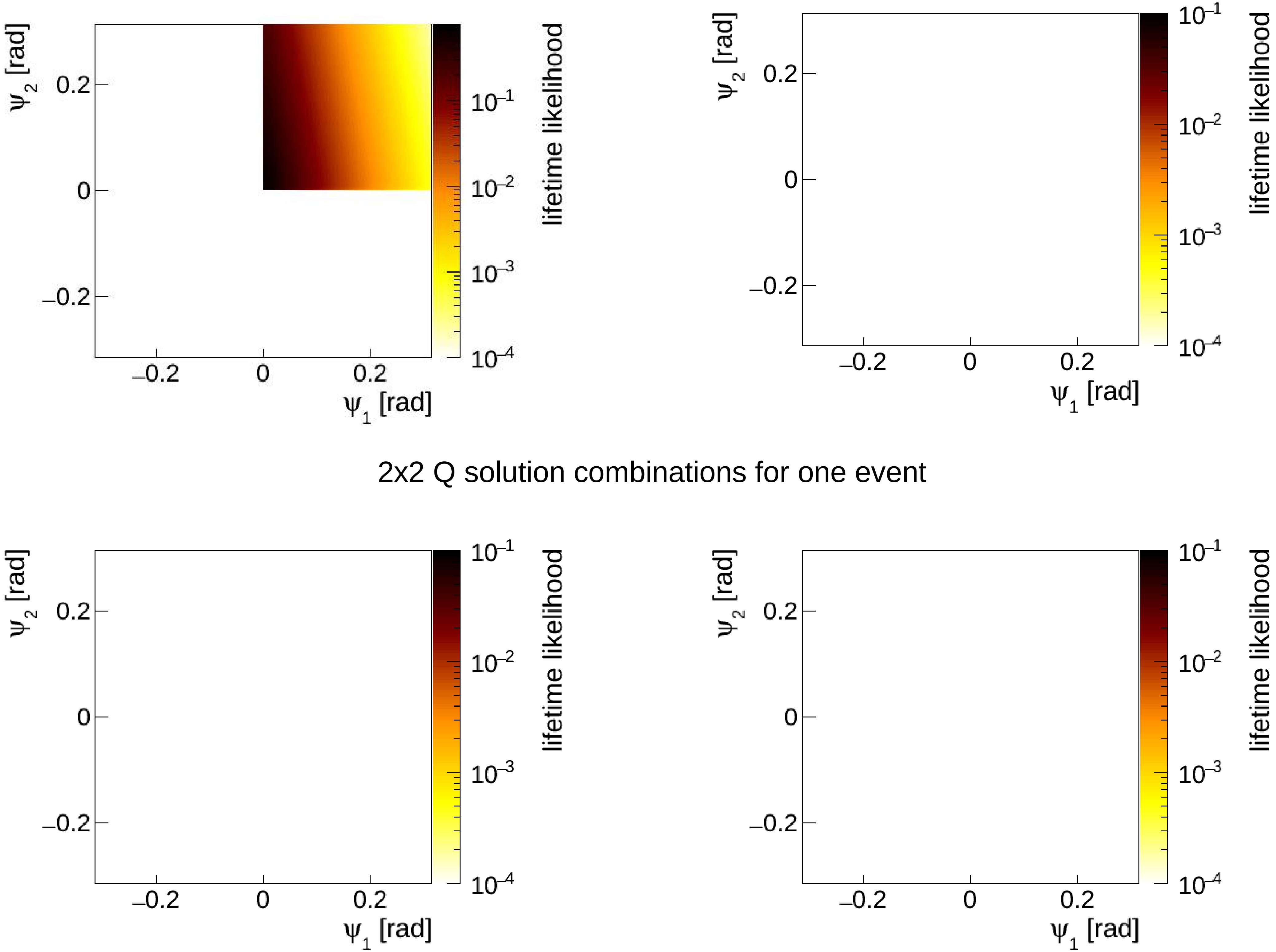
$H = \cos\varphi\,(CP+) + \sin\varphi\,(CP-)$

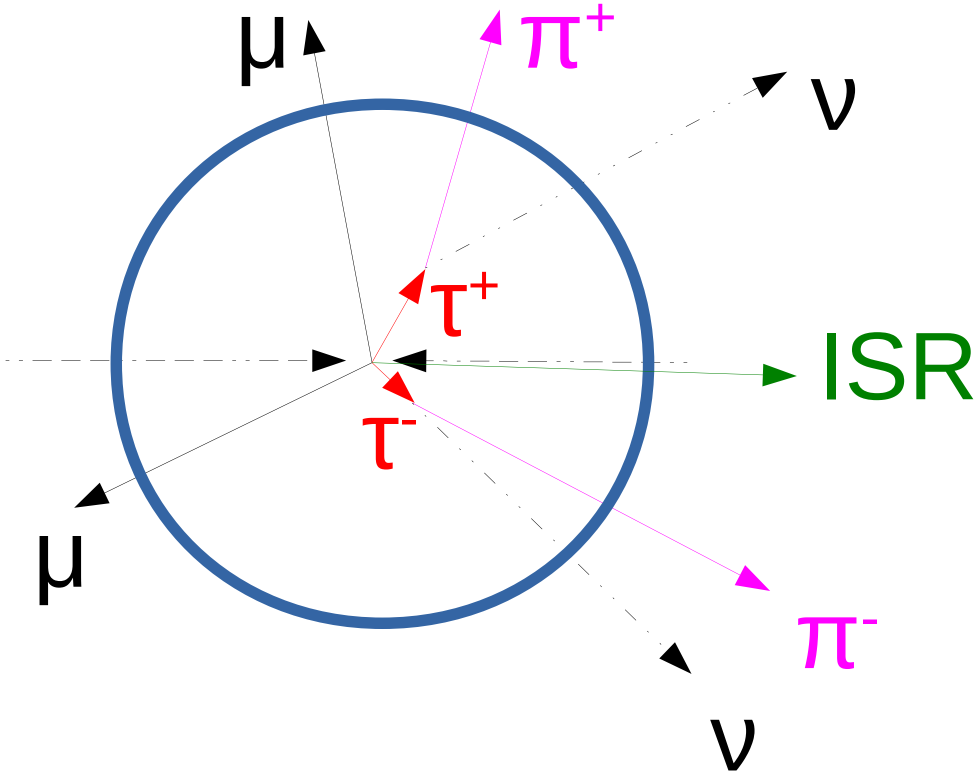
$H \rightarrow \tau^+\tau^-$ ~ 6% for m_H = 125 GeV

~2 times larger than ZZ

fermionic


2x2 Q solution combinations for one event
ψ2 [rad]
ψ1 [rad]
pT [GeV/c]
0.2
0
–0.2
10^3
10^2
10
1
10^–1


2x2 Q solution combinations for one event
ψ1 [rad]
ψ2 [rad]
lifetime likelihood
–0.2
0
0.2
10–1
10–2
10–3
10–4



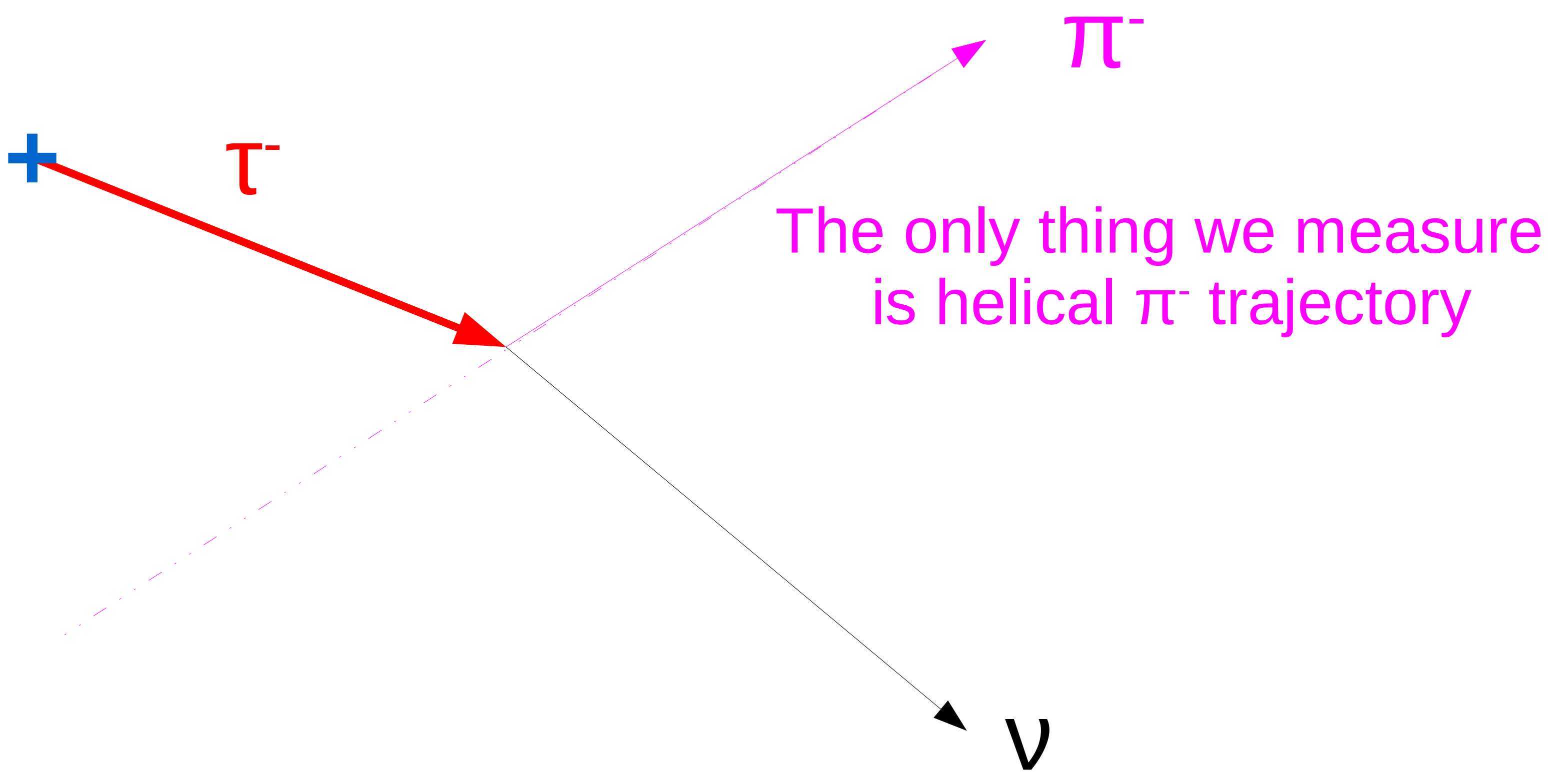
Unmeasured quantities

2 x neutrino 3-momenta
lost ISR photons

Kinematic constraints

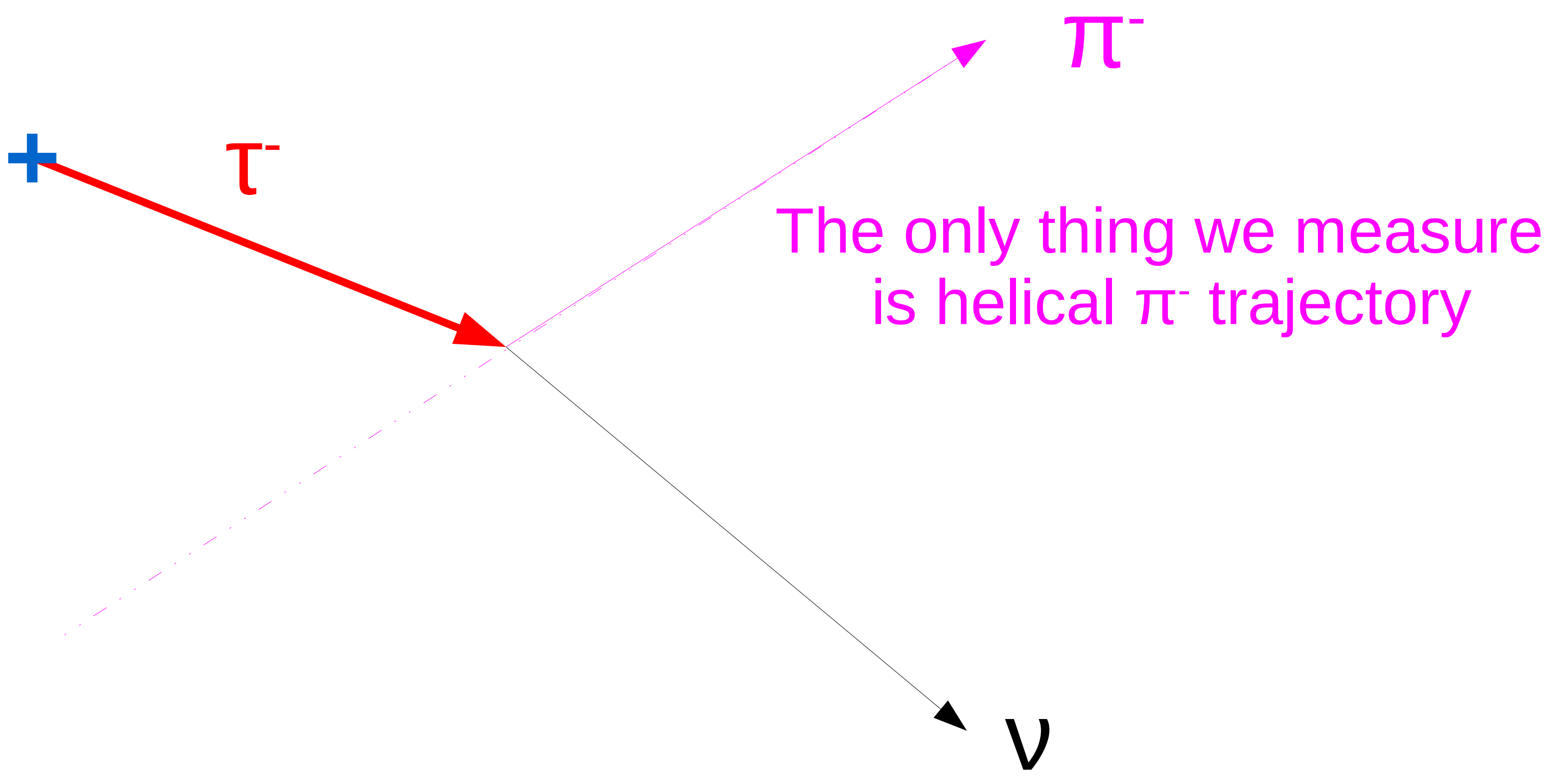
overall 4-momentum conservation
2 x tau decay kinematics ← more details next

τ τ mass (if we assume H->τ τ)
μ-μ mass not useful: resolution much better than Z width



We know that:

- endpoint of τ lies on pi- trajectory



We know that:

- endpoint of τ lies on pi- trajectory

→ neutrino momentum lies in plane
defined by τ- and pi- momenta

Let's test these ideas:

private production of

- $e^+e^- \rightarrow Z\,H \rightarrow \mu\mu\,\tau^+\tau^-$ events

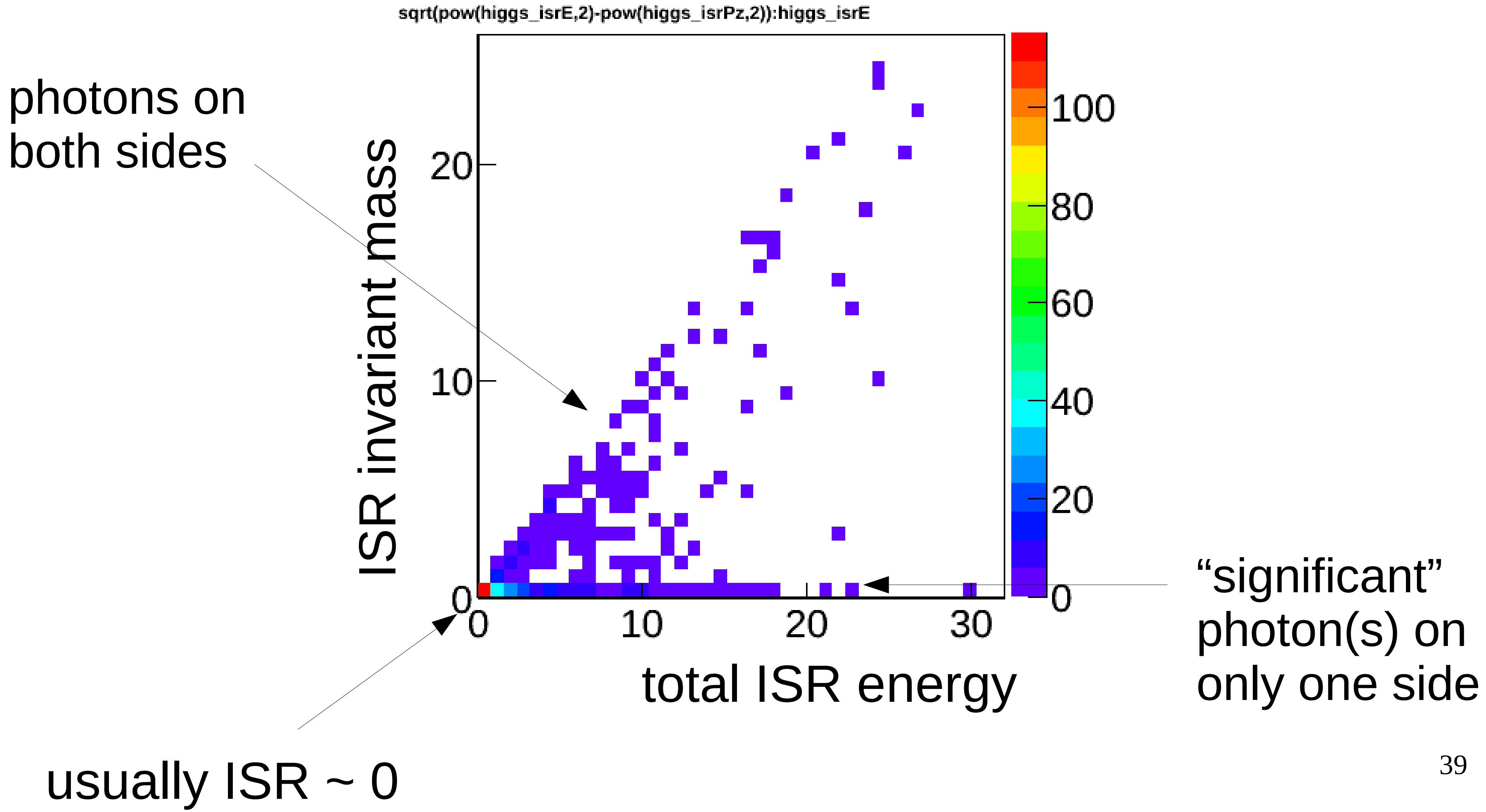
  e+e- → Z H → mu mu τ+ τ- events

- Whizard 2.2.2,
  - with ISR, beamstrahlung (also samples without)
  - 250 GeV centre-of-mass
  - eL pR beam polarisation
- τ decay to pi-neutrino only
  - Tauola 1.1.4,
    - with correct spin correlations
- simulated in ILD detector (Mokka)
  - ILD_o1_v06 detector model
- ilcsoft v01-17-04 reconstruction
  - use tracks from MarlinTrkTracks collection
  - PID by MC cheating (for now)

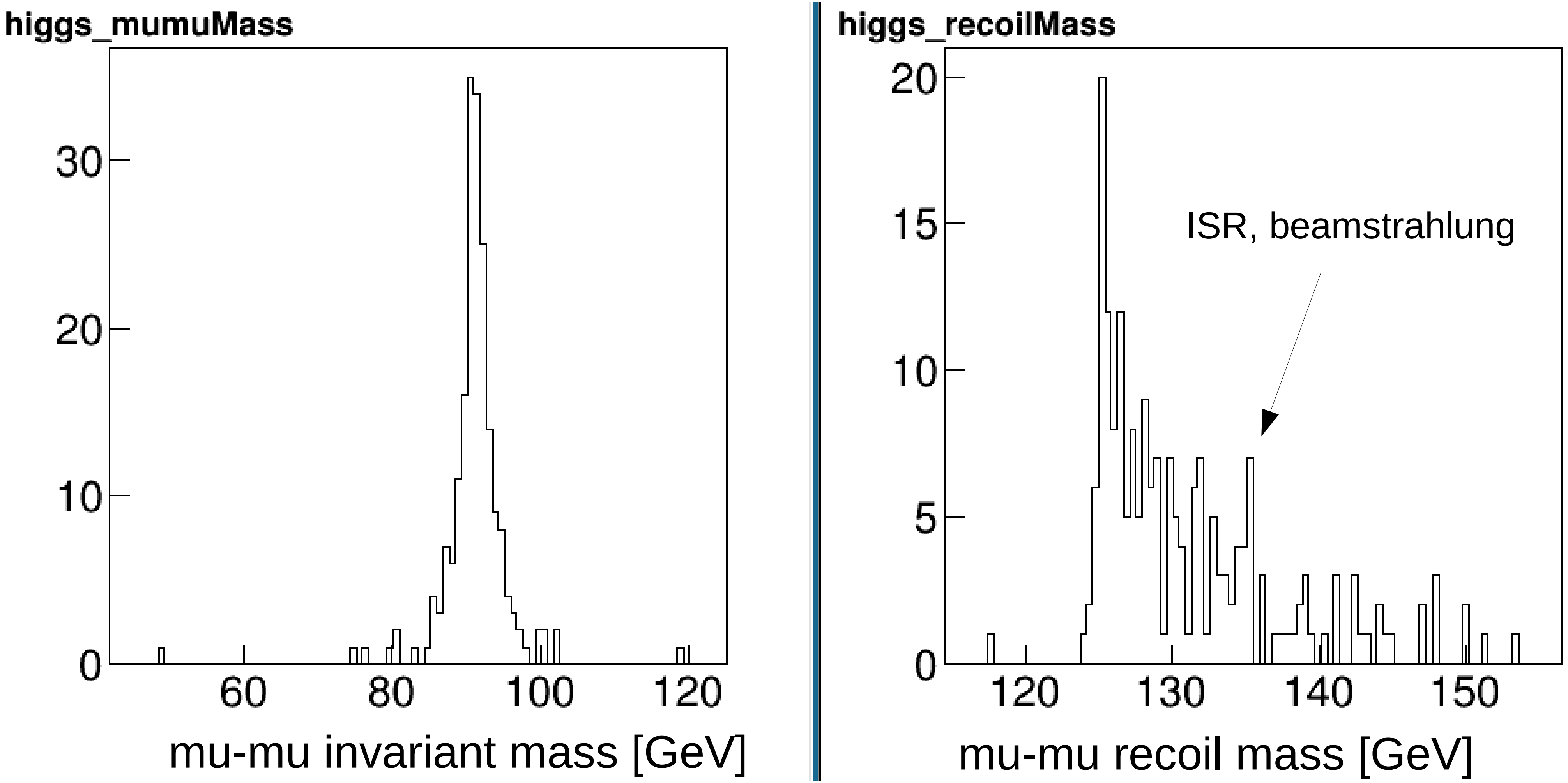
ISR properties

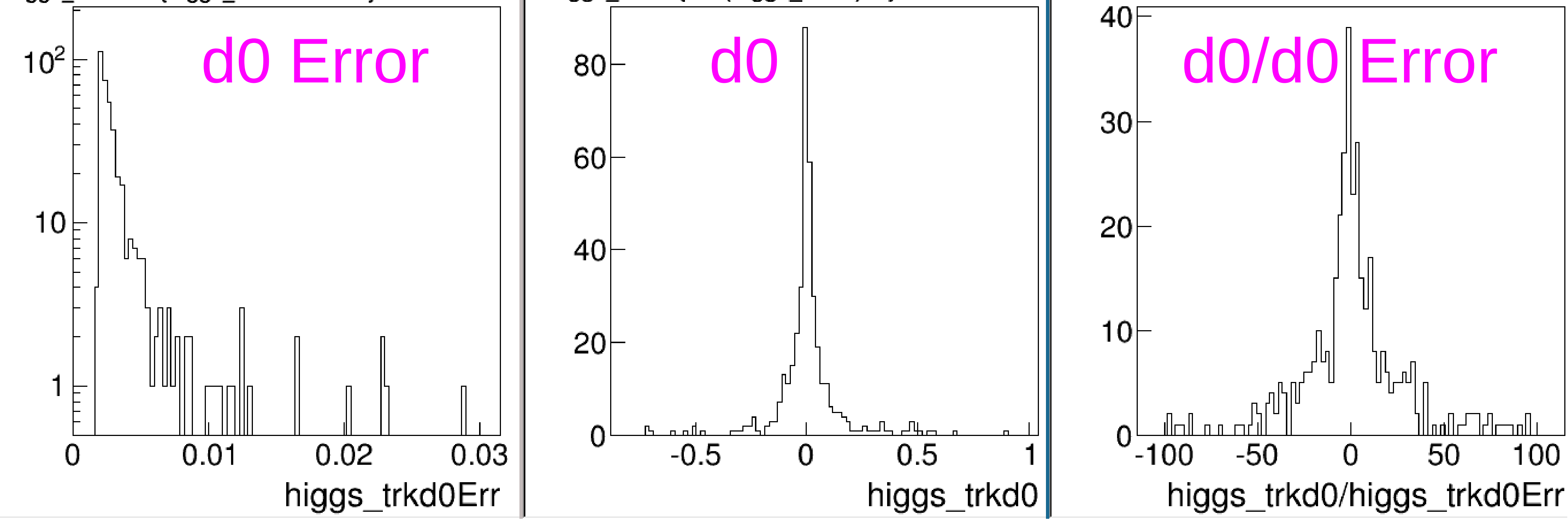
actually ISR + beamstrahlung

- total Energy
- invariant mass of sum of all ISR/BS photons ← zero if only on one side e.g. single ISR photon

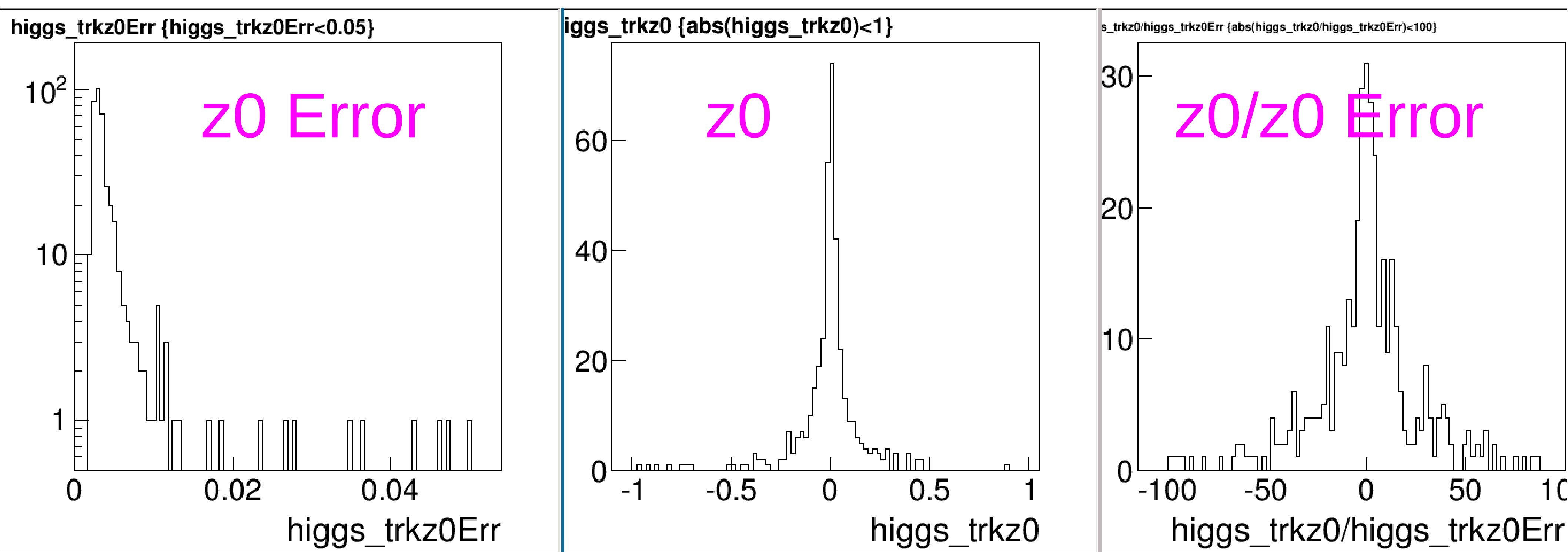


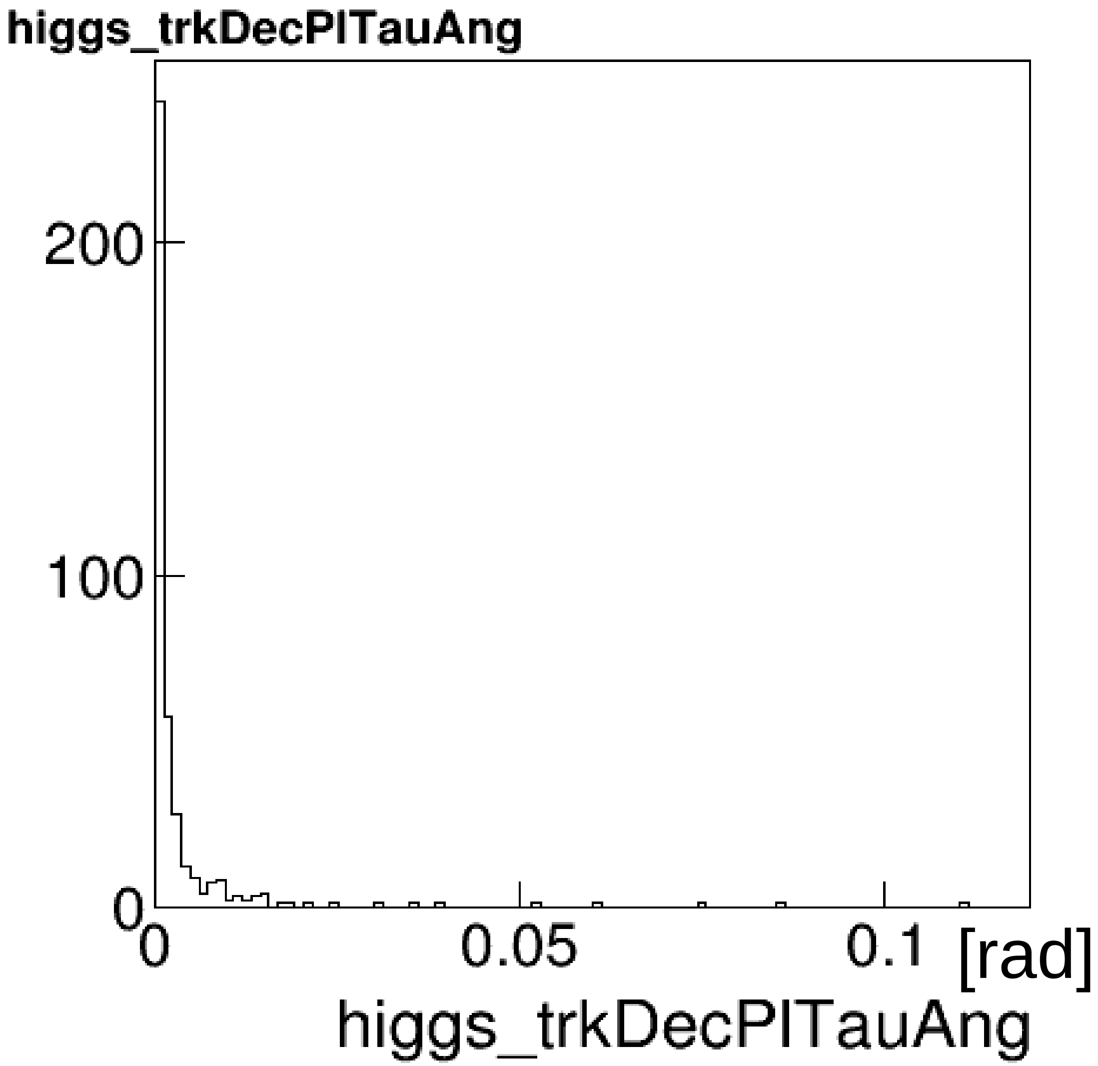
the reconstructed muon tracks





Charged pion track parameters [in mm]





Cross-check

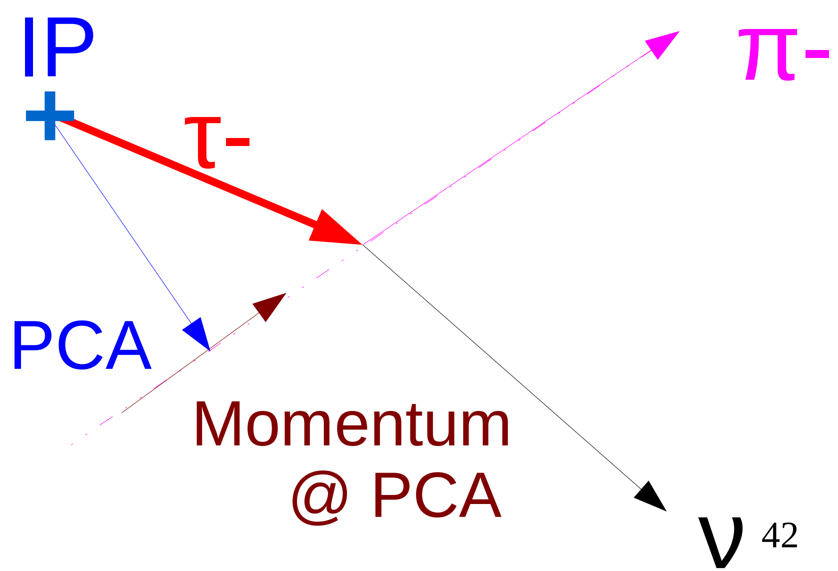
Angle between

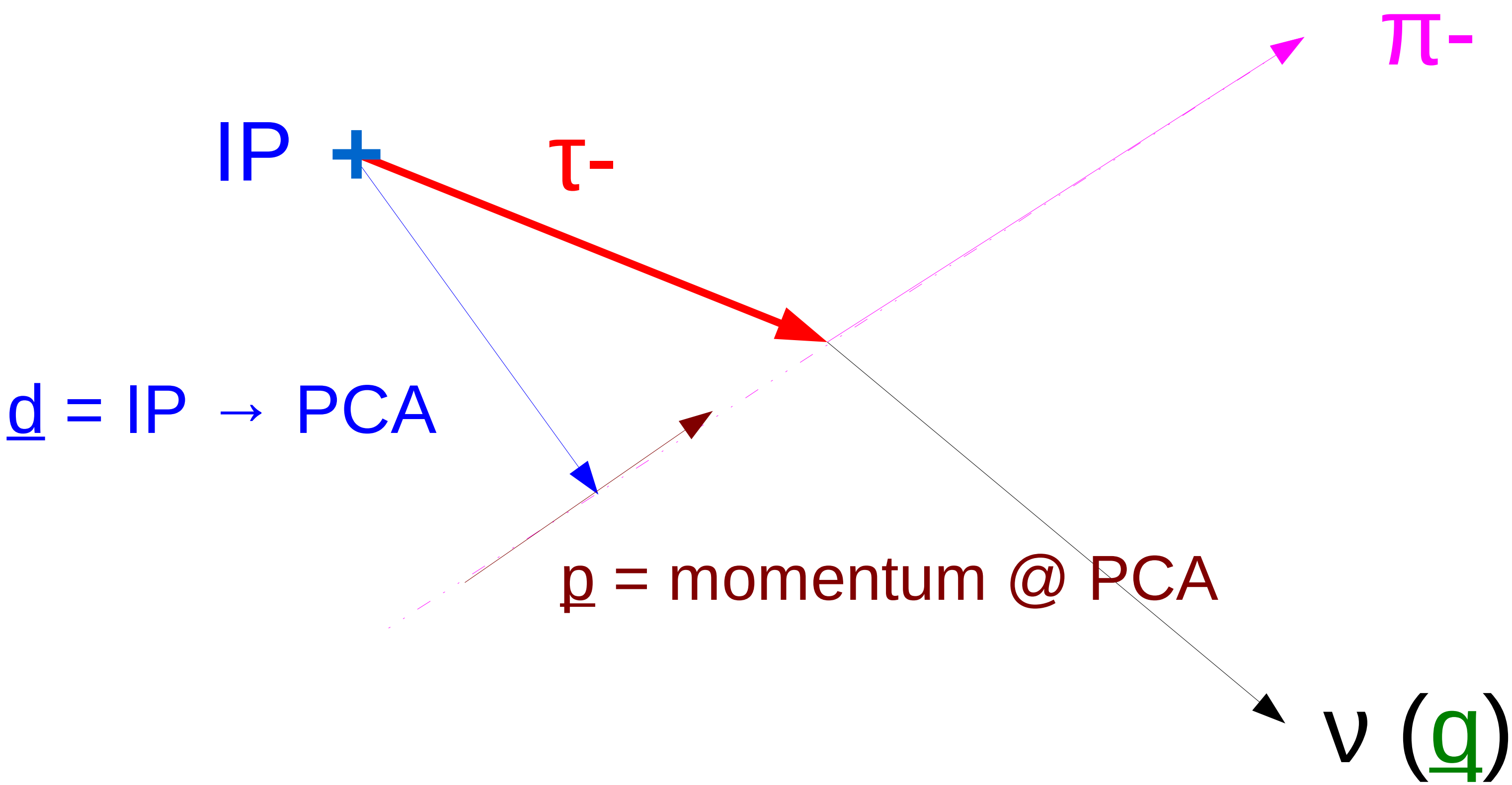
MC τ momentum

and

reconstructed plane of pion track

(should ideally be 0)





d and p are perpendicular in x-y, but not in 3d

define d' = p x (d x p) ← inside p-d plane, perpendicular to p

neutrino momentum q lies in plane of d and p

so we can write: q = |q| (cosψ p* + sinψ d'*)

where x* is a unit vector: x / |x|

We know that the invariant mass of (p + q) is m_{tau}

so we can calculate the neutrino energy |q| for each value of ψ

For a given event, we can then see how the
total event **pT** (muons, pions, neutrinos)
should be ~0, even with lost ISR
depends on the
angles **ψ1, ψ2** (for the 2 taus)

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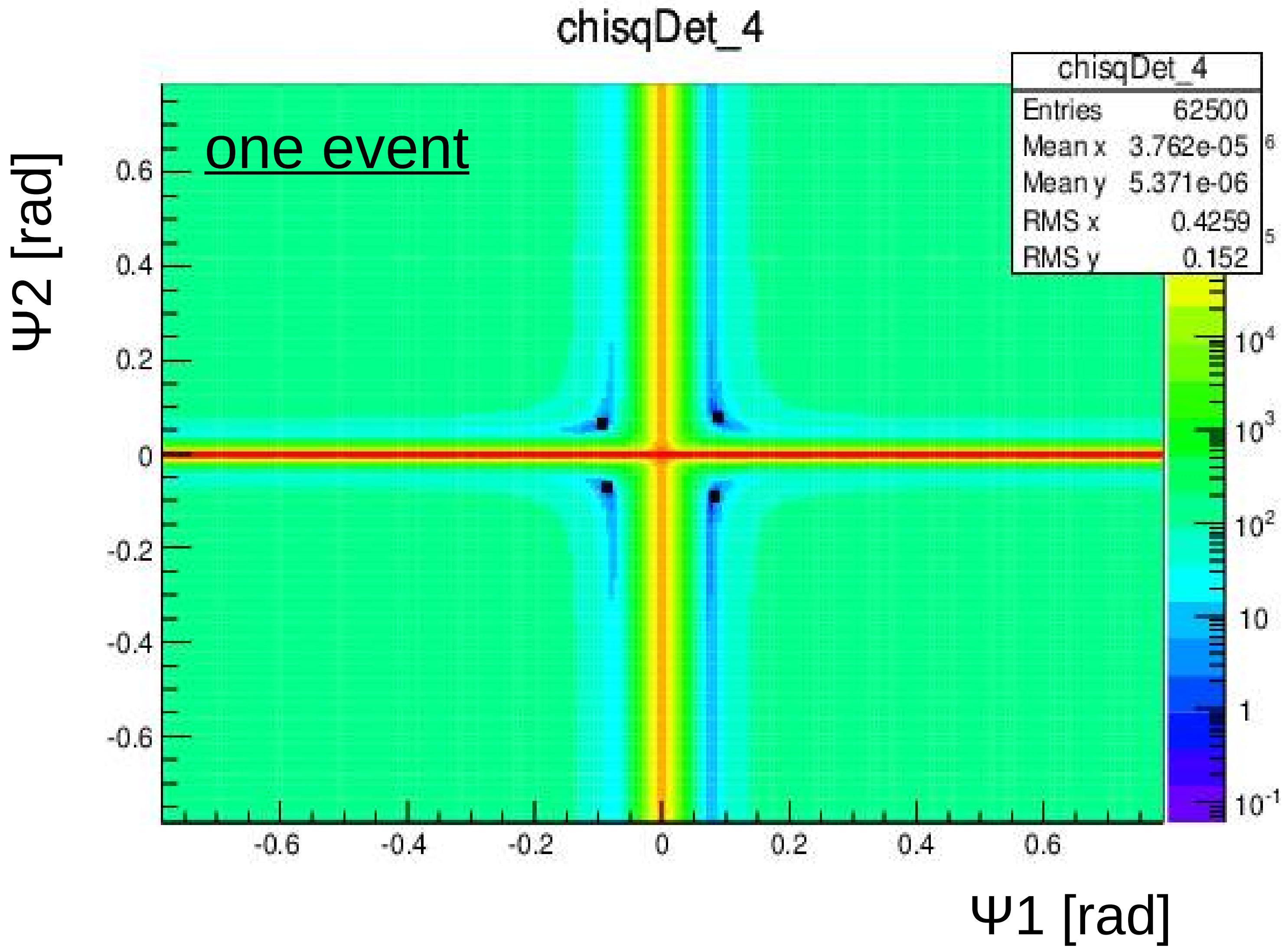


pT**2

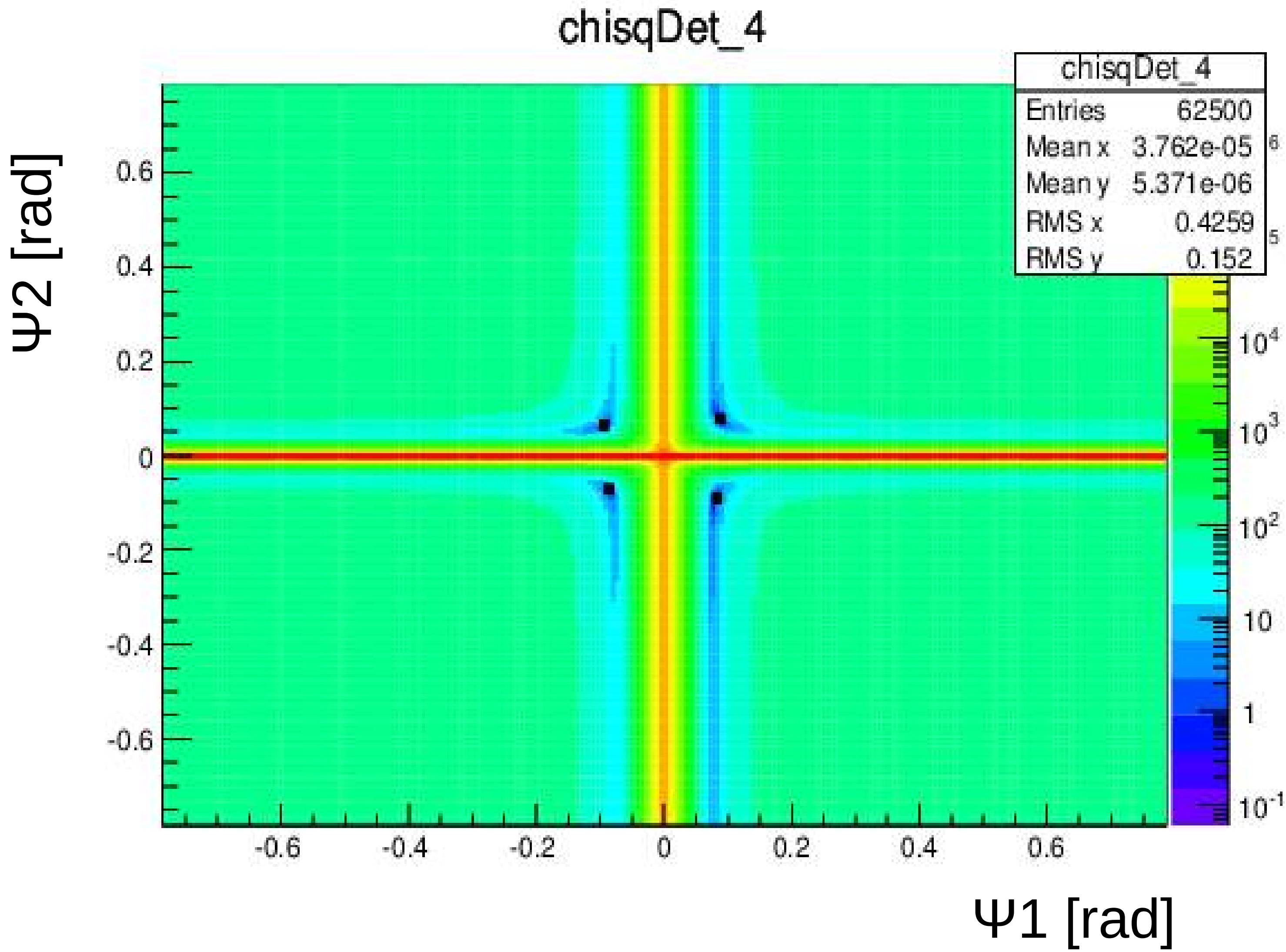
$(100GeV)^2$

$(1GeV)^2$

Ψ = 0 corresponds to neutrino colinear with pion
needs large energy to make tau mass
gives very large pt imbalance

$\underline{q} = |q| (\cos\psi\ \underline{p}^* + \sin\psi\ \underline{d}^*)$

We can see local minima in each of the 4 quadrants
Is the nu momentum on the d = +ve or -ve side of the pion momentum

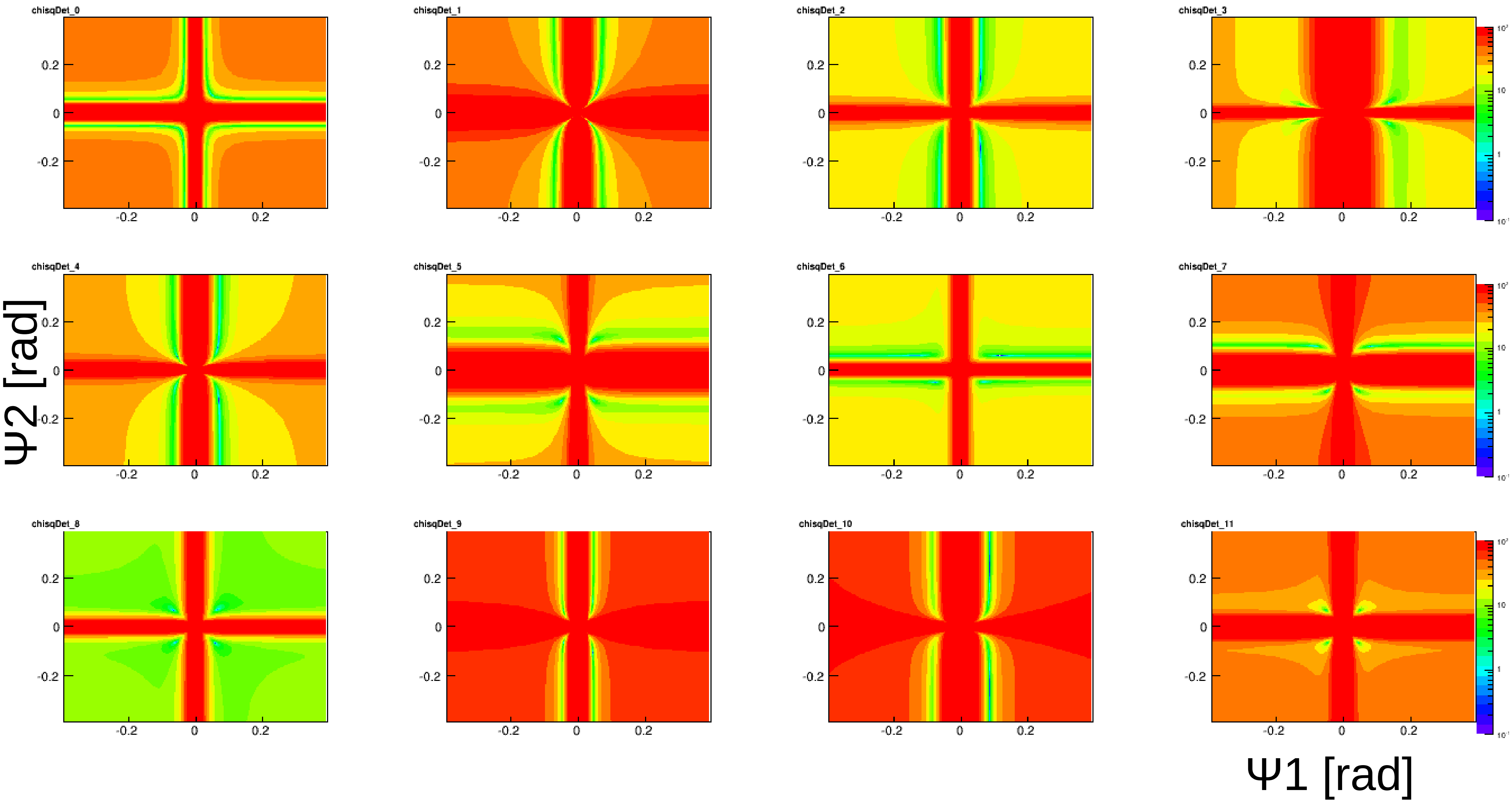


pT**2

$(100\text{GeV})^2$

$(1\text{GeV})^2$

A few more events:



color = pT (0.1 1 10 100) GeV

by requiring pt-balance in the event [sum px = sum py = 0]

it is possible (but somewhat messy) to calculate the angles Ψ

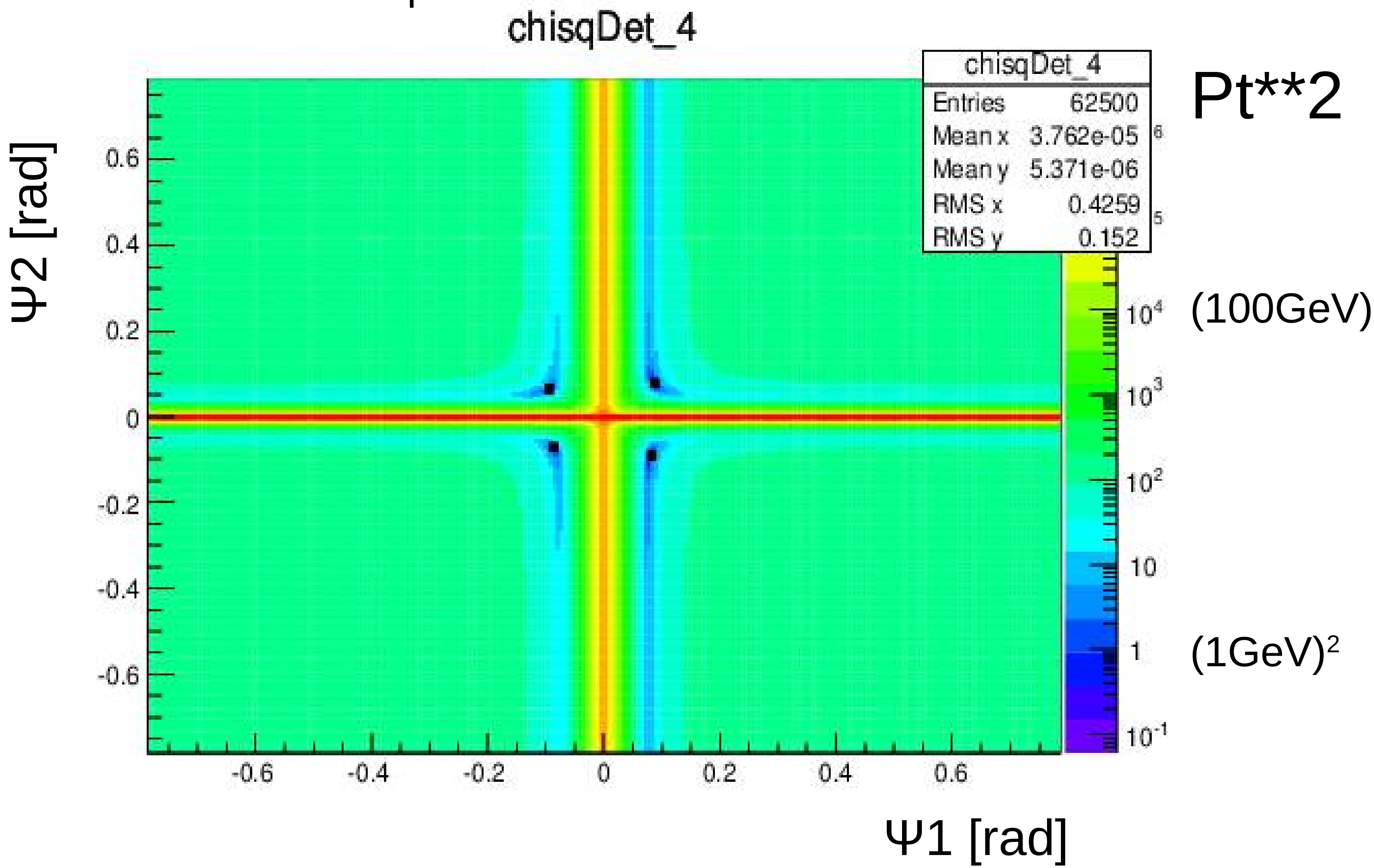
due to finite resolution of measured quantities,

a real solution is not always possible

More robust approach is to do a

standard minimisation [i.e. not a constrained fit]

to minimise the event pT



Minuit minimisation separately in each quadrant (no constraints needed)

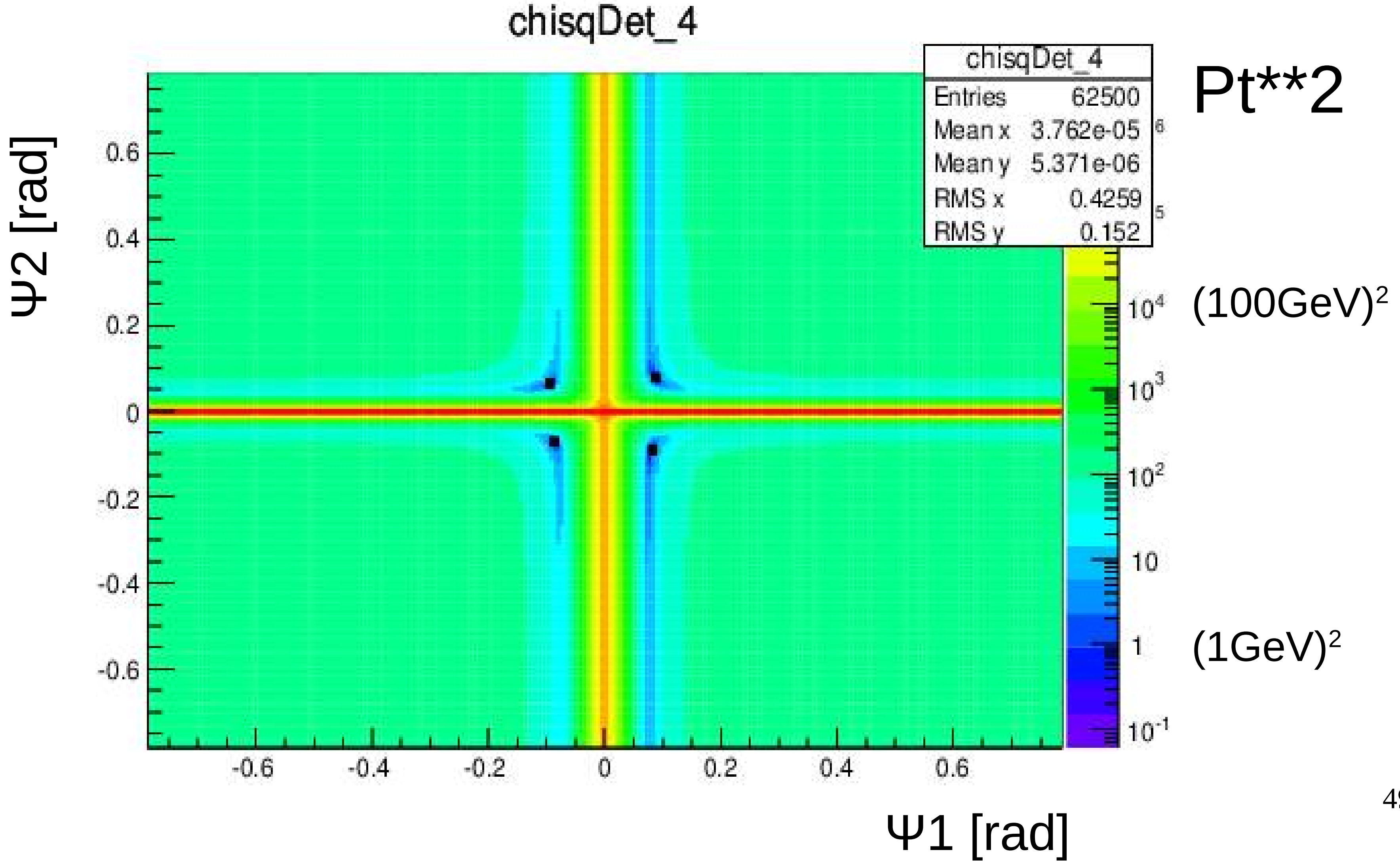
→ Four solutions

How to choose which one is the best?

Value at minimum ← pt as small as possible

Comparison of |pz| and missing energy ← same, if 1 ISR photon

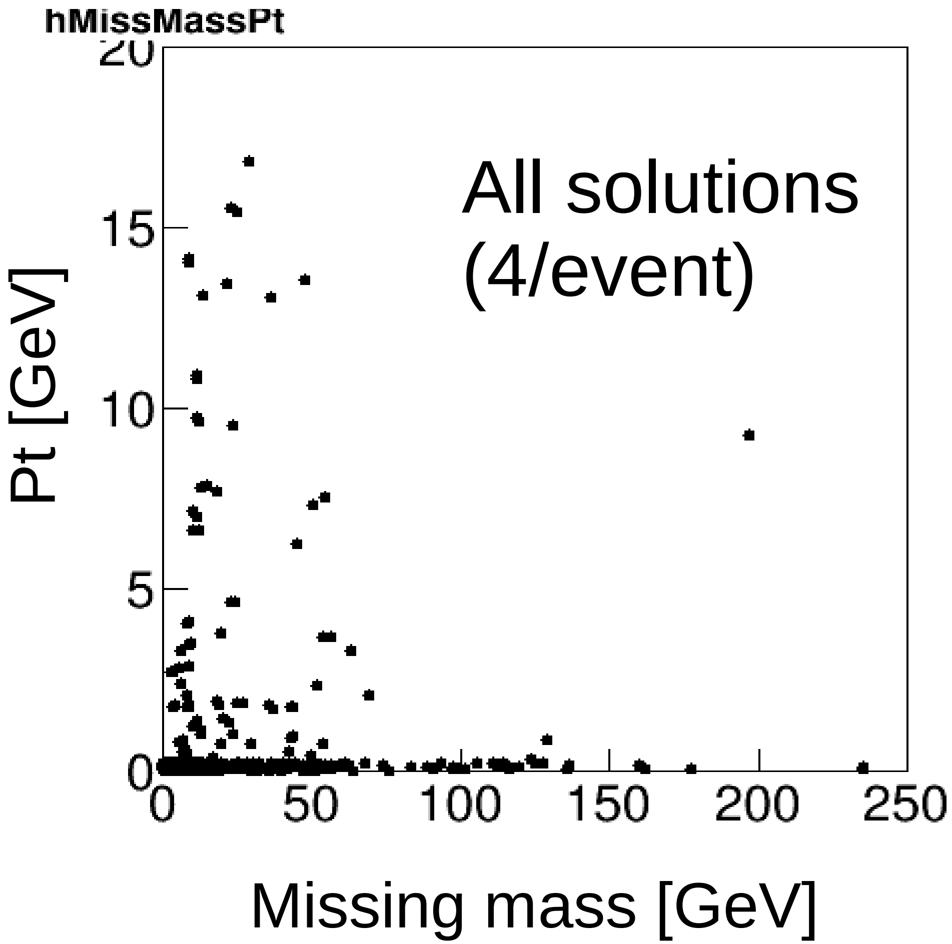
invariant mass of 2 taus (if we assume presence of Higgs)

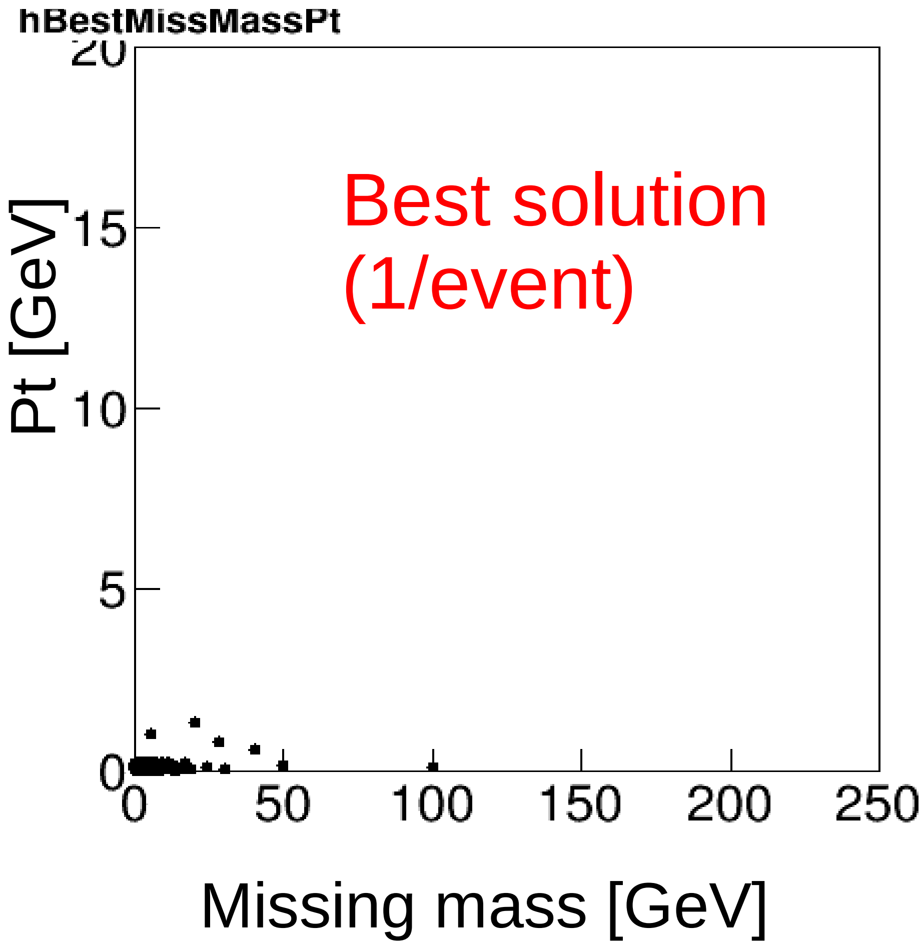


For now, define “best” solution as one with smallest value of

pT + missing mass

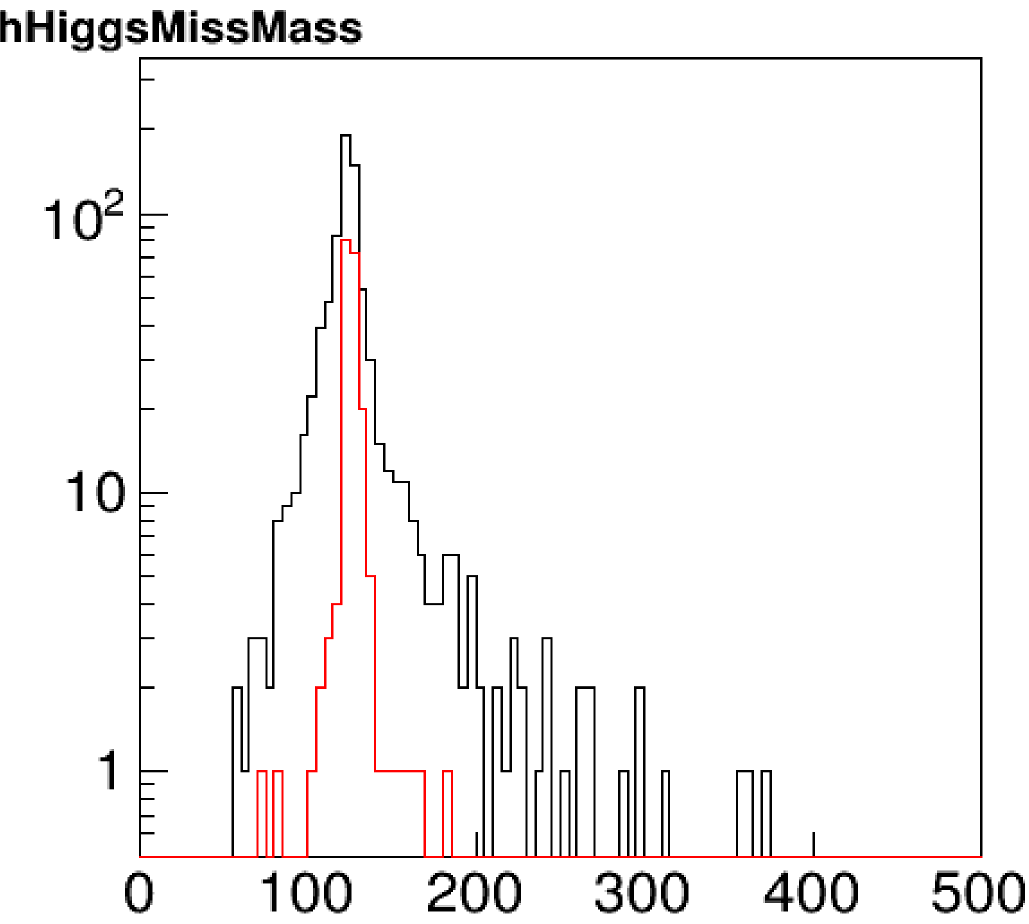
If we have zero or one ISR photon, missing mass = 0



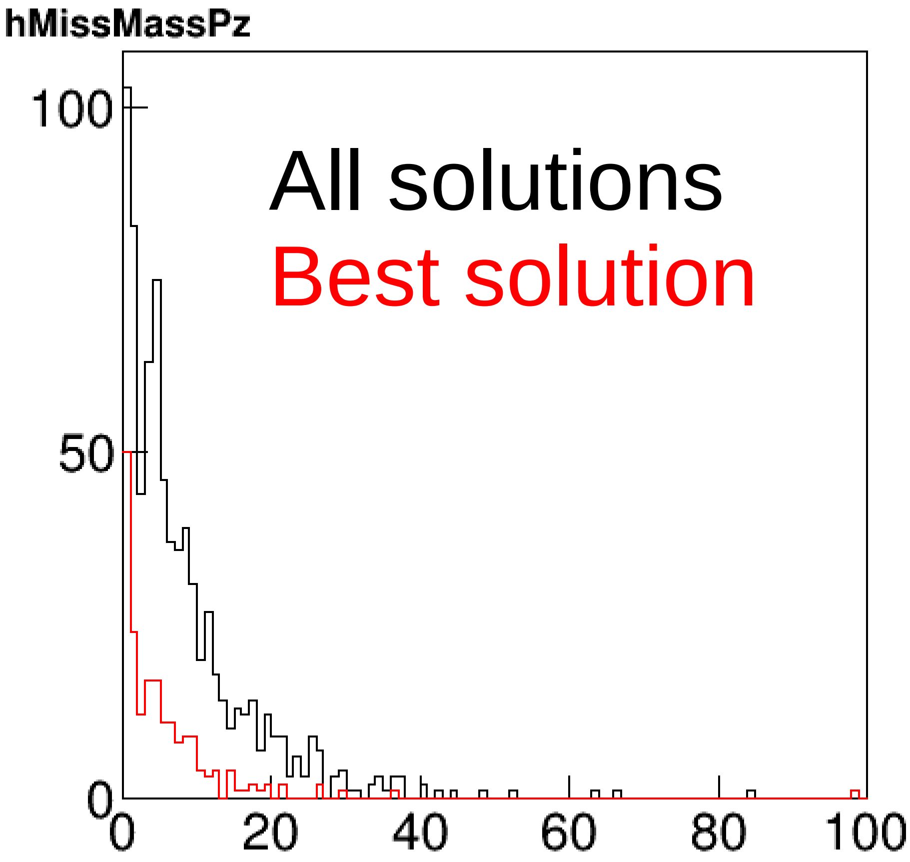


Check: Invariant mass of two τs, total pz (*e.g.* of ISR)

n.b. we have not used these in any part of the analysis



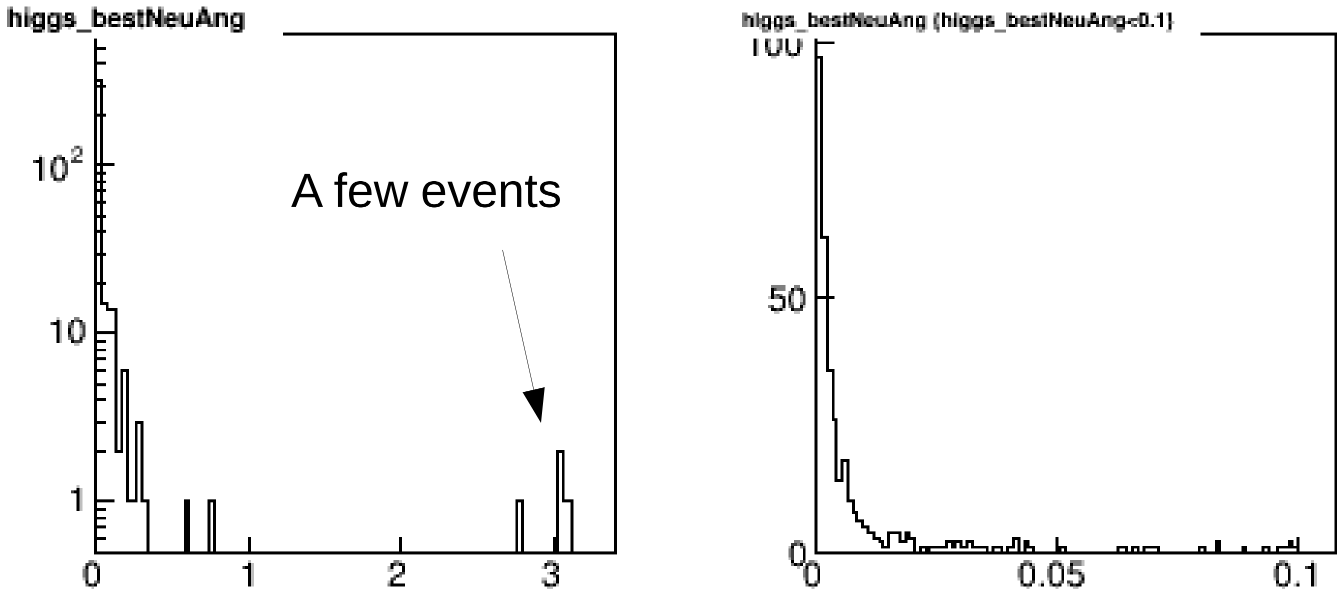
τ-τ mass [GeV]



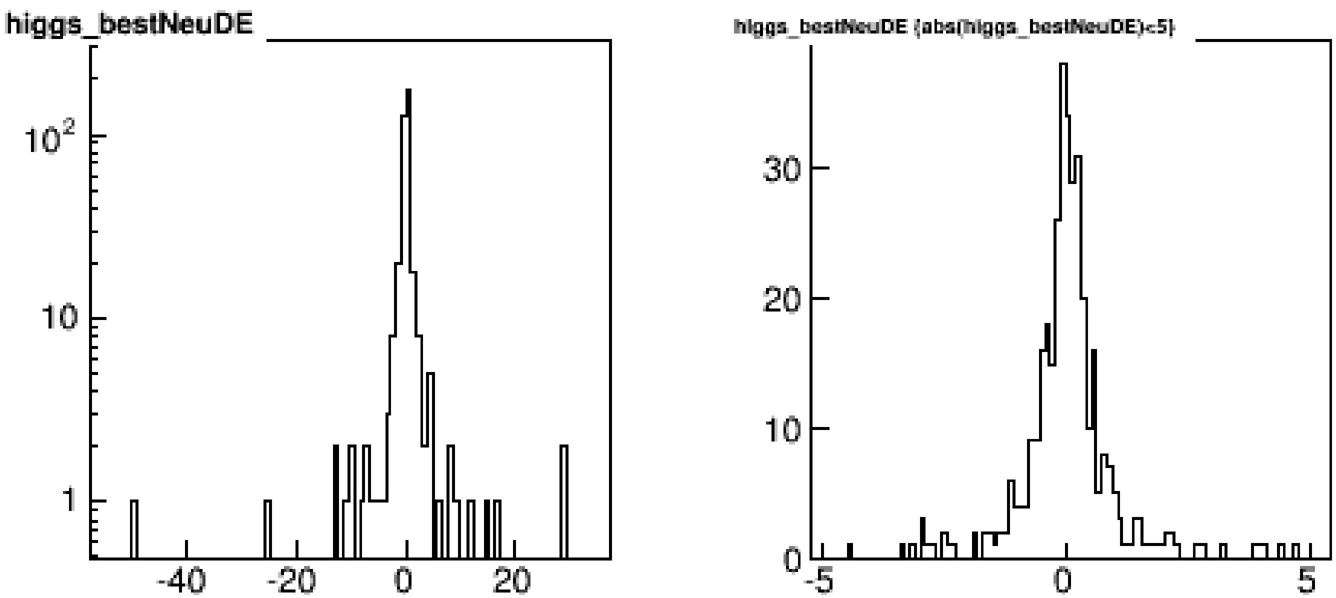
|pz| [GeV]

Compare fitted and true neutrino energies and directions

Only best solution



Angle between MC and fitted neutrinos [rad]



MC – fitted neutrino energy [GeV]

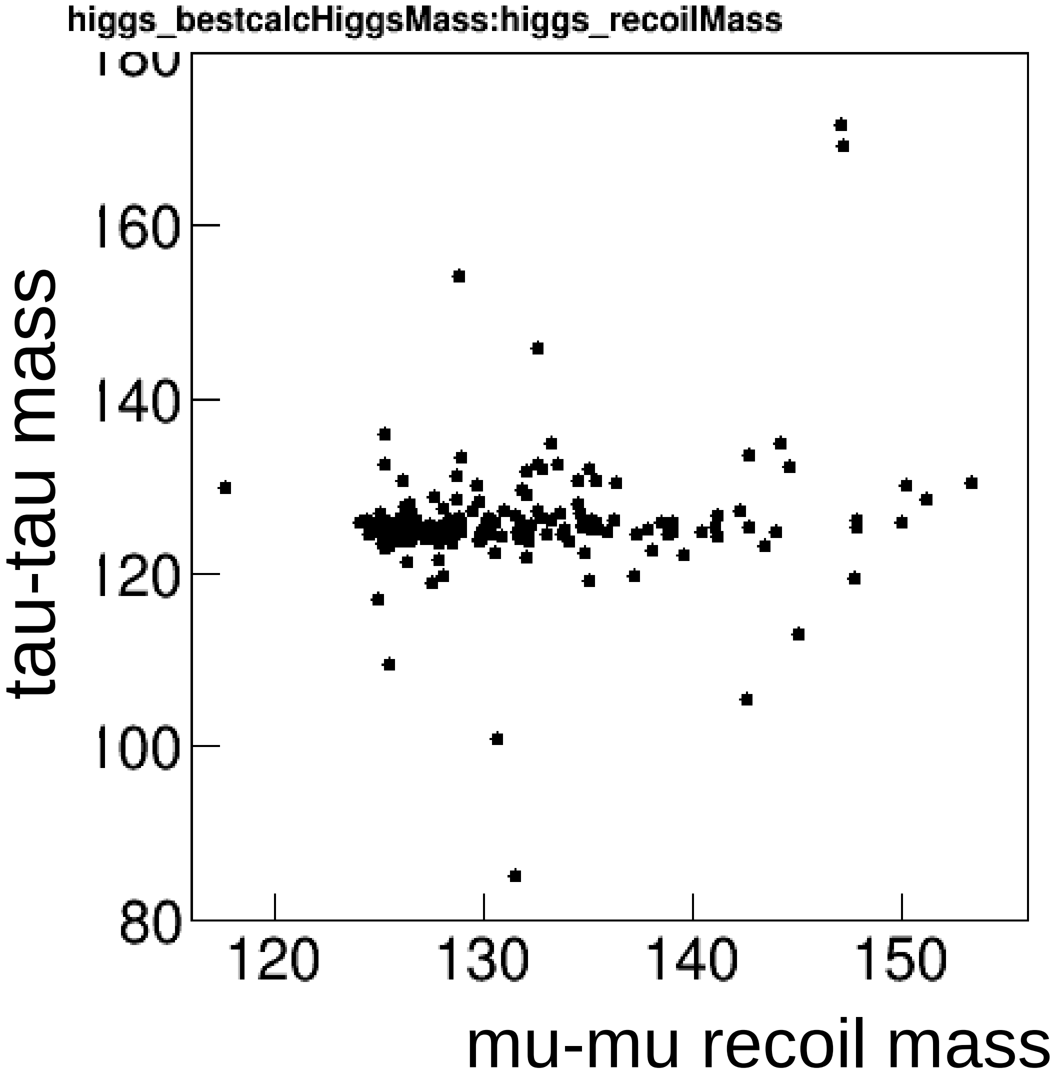
Precision typically

< ~ 10 mrad

< ~ GeV

recoil mass (from muons) vs. reconstructed τ-τ mass

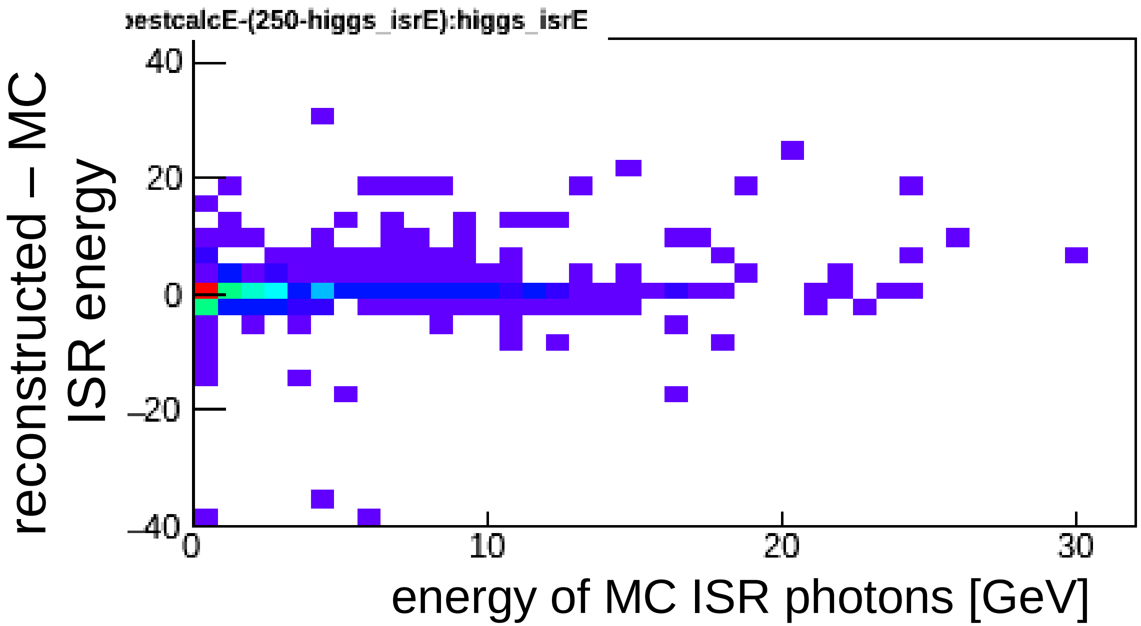
Only best solution

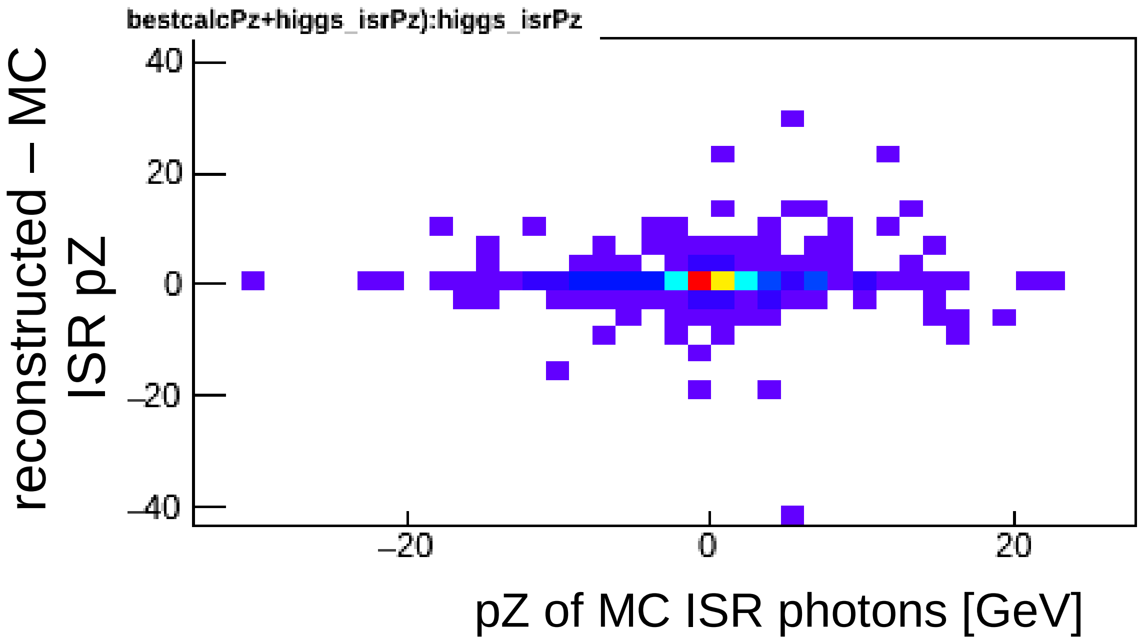


As expected, this method of mass reco not affected by ISR

unlike recoil mass

How well is ISR/BS energy and pZ reconstructed?





Summary

It's interesting to try to fully reconstruct τs:
- significant BR of Higgs
- they can act as "polarimeters"
  - → reconstruct their spin state by looking at their decay products

The ILC machine and detectors have great potential for tau reco:
- tiny beam spot
- high precision vertex detector

In hadronic tau decays of (τ τ + "X") processes
- we can calculate the tau neutrino momenta with good precision
  - if we can measure pT of "X"
    - If this is not possible, other approaches may be possible
      - → make different assumptions about event

Kinematic fitting should give some improvements in precision
- take account of uncertainties in measured quantities
  - tools are ~in hand

Things to do next:

- apply kinematic fit on the identified (best) solutions
    may improve the resolution

- apply to tau → rho nu decay mode
    I think (almost) same method can be used

    Multi-prong decays should be easier
        Identify vertex → tau momentum direction
    Leptonic decays need more constraints
        maybe if only one tau decays leptonically,
            something can still be done with some extra assumptions

- apply to Higgs CP measurement

First approach:

Constrained kinematic fitting

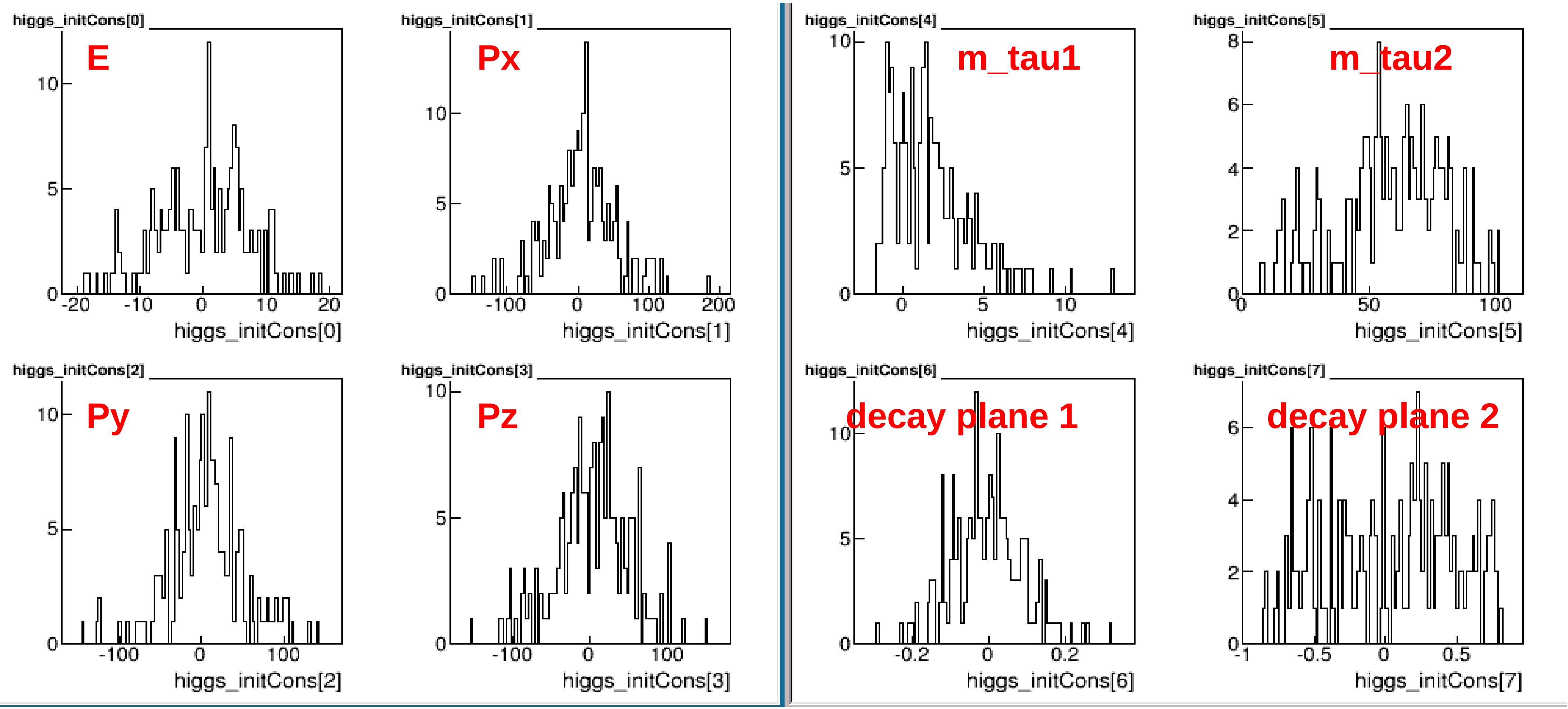
Using MarlinKinFit package
extended to use LCIO tracks (with full covariance matrix)
a lot of patient help from Jenny & Benno List

neutrino momenta: unknown parameters
muon & charged pion tracks: measured parameters
(ISR treatment also possible, using expected ISR distribution)

Overall 4-momentum constraint
Tau mass constraints
Tau decay plane constraints

Adjust measured and un-measured paramteters to satisfy constraints,
while minimising the “chisq” (deviations from measured values)

Choice of starting position for neutrino momentum
turns out to be rather important
here use randomly smeared direction around charged pion track

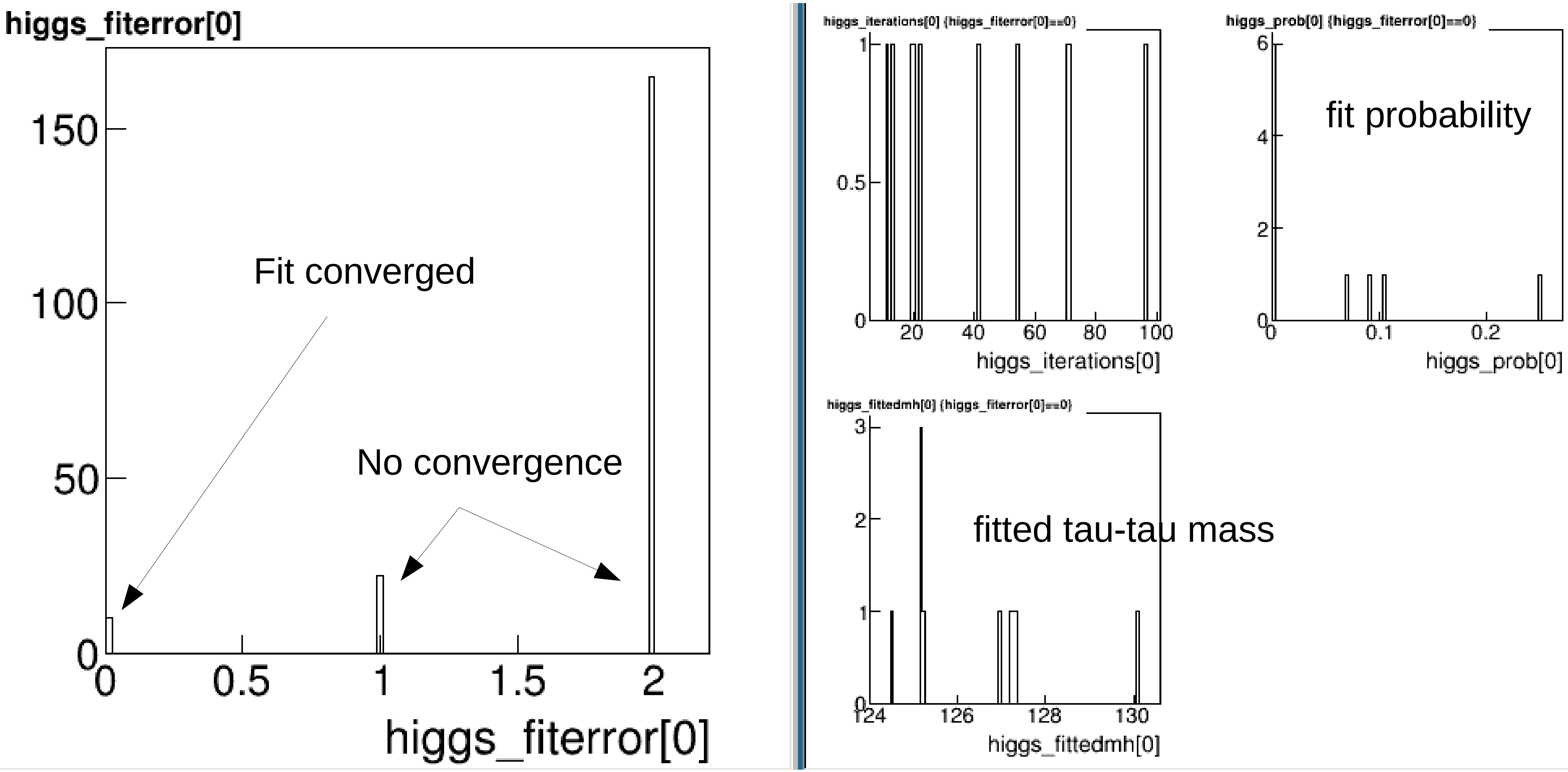


Value of constraints before fitting

far from being satisfied

Units are
GeV for momenta/masses
cos(angle) for decay plane

Fit results

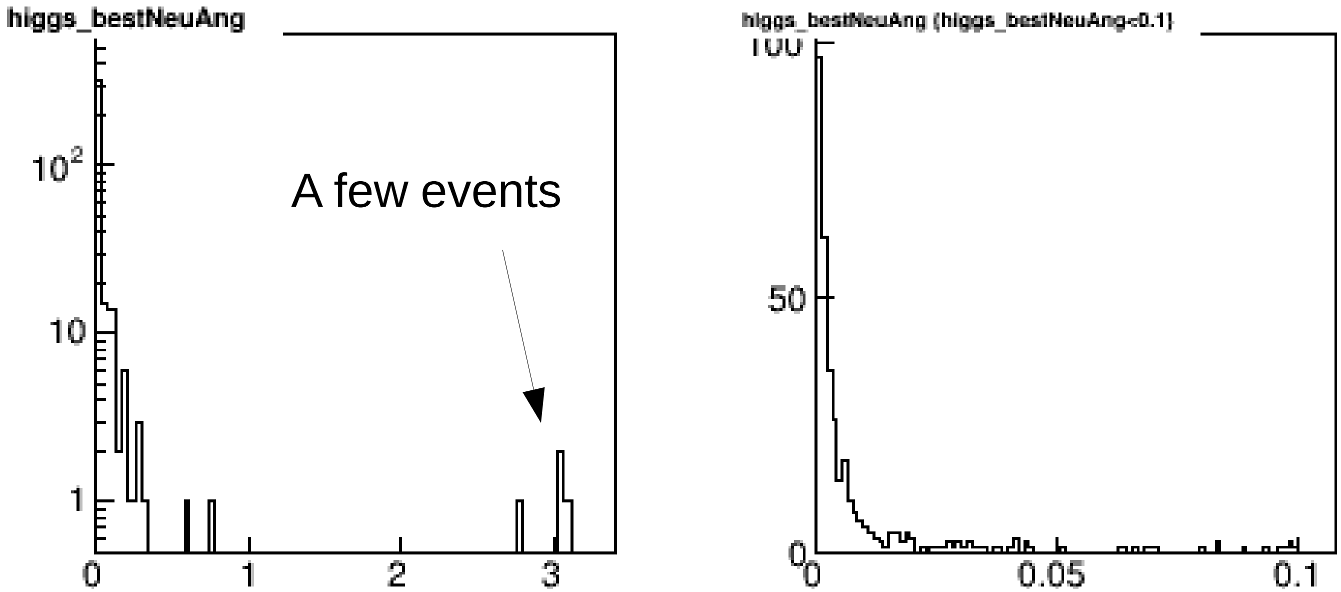


Only very small fraction of fits converge
Those that do look somewhat OK, but not great...

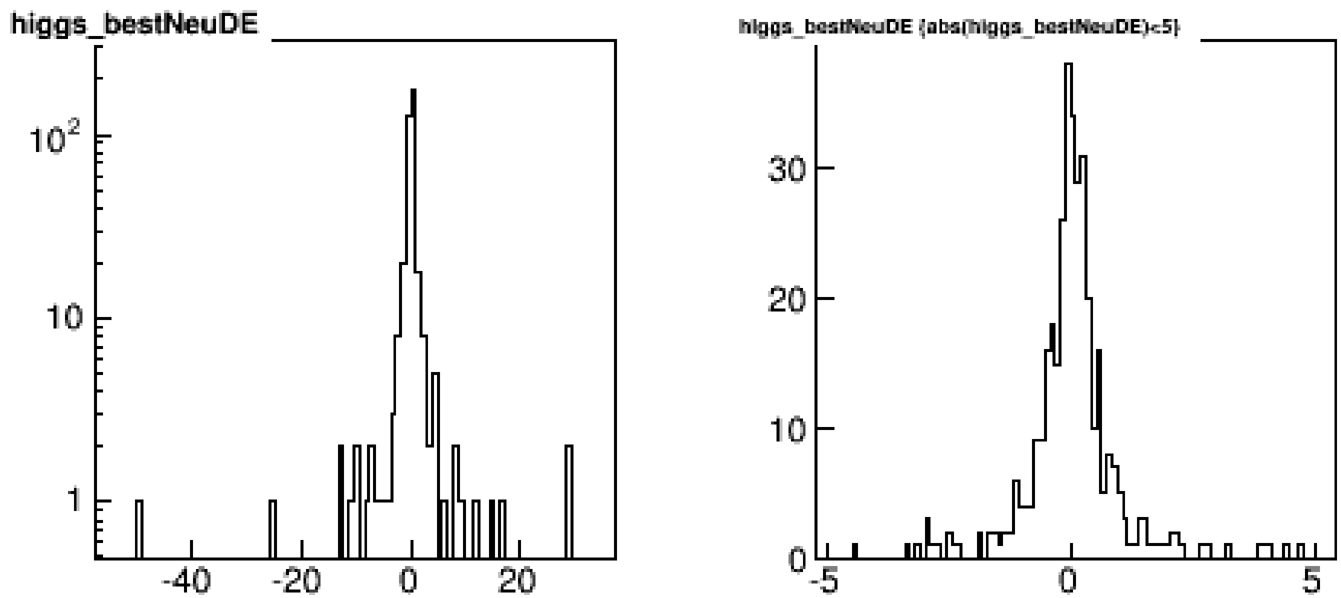
If initial guess for neutrino momenta are smeared around MC value,
it works <u>much</u> better ← need better initial estimates

Compare fitted and true neutrino energies and directions

Only best solution



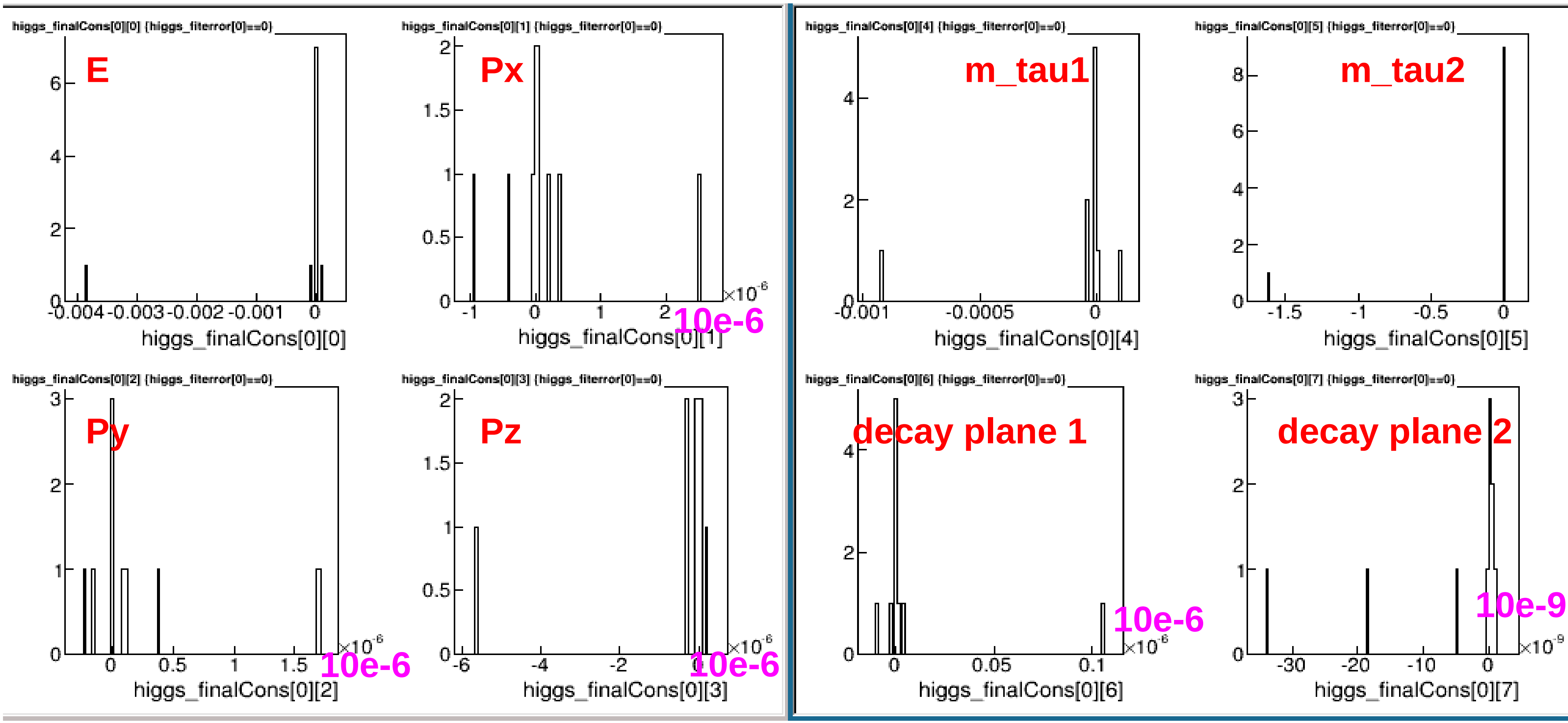
Angle between MC and fitted neutrinos [rad]



MC – fitted neutrino energy [GeV]

Precision typically
< ~ 10 mrad
< ~ GeV

Value of constraints after converged fitting



Constraints well satisfied:
Fitter itself is working ~OK

Units are
GeV for momenta/masses
cos(angle) for decay plane

It seems essential to have a good initial estimate of unknown quantities (neutrino momenta) before applying a constrained kinematic fit

Second approach:

Try to calculate the unknown quantities

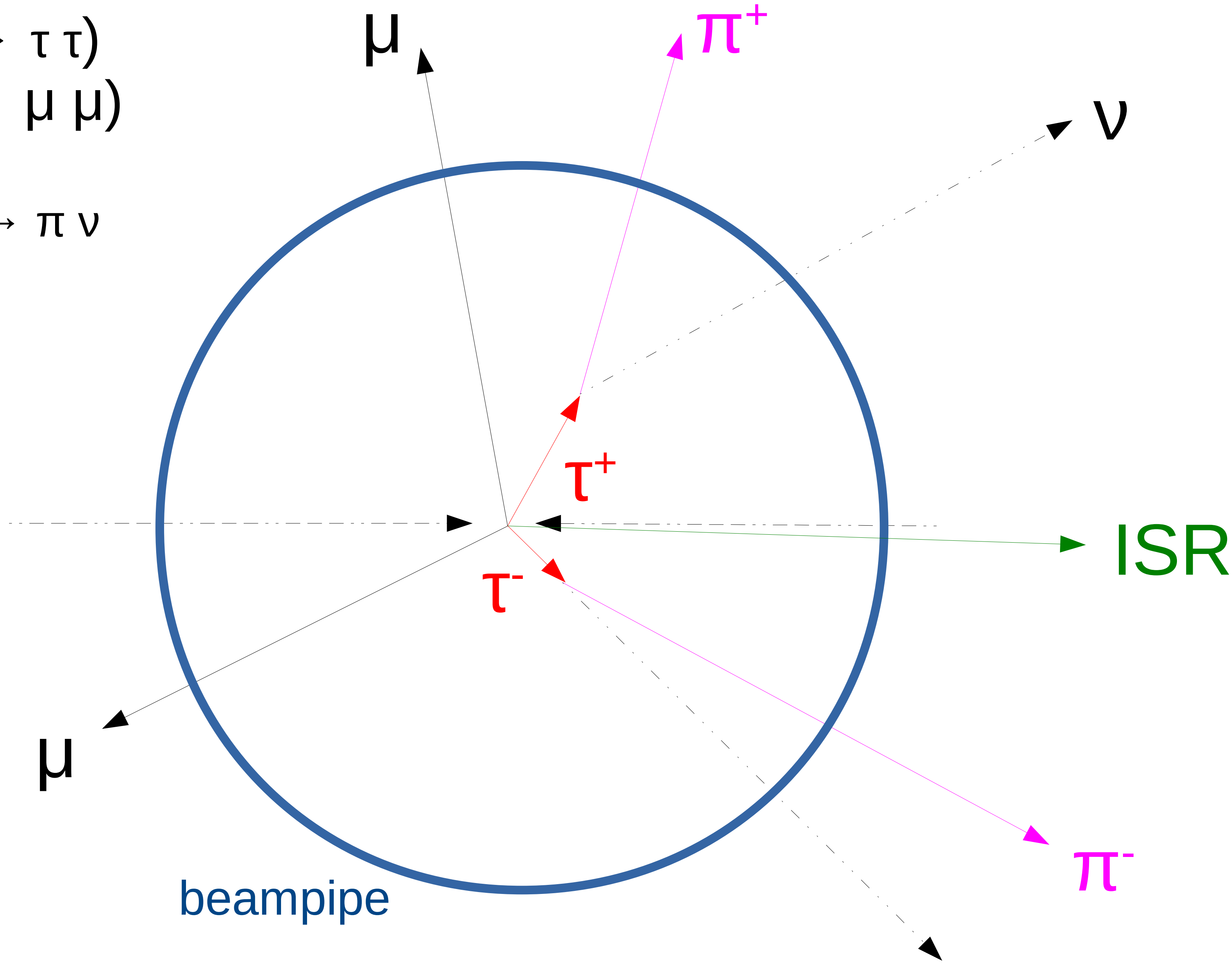
Ignore uncertainties on measured quantities

$e^+ e^- \to$

$(H \to \tau \tau)$

$(Z \to \mu \mu)$

both $\tau \to \pi \nu$



For 60 GeV τ, γ*c*t ~ 3 mm

ILD impact parameter resolution ~5 μm