TauSpinner and its application to data analysis at the LHC

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TauSpinner – a playful tool to emulate tau spin effects

- Taus are short lived & decays are parity violating:

  => kinematics of decay products depend on the helicity of the parent tau lepton
  (visible pt, charged fraction, ...)

TauSpinner

- Simulates a desired spin effect (add/remove/revert) in *any* tau sample
  for which the production mechanism is known (W, charged Higgs, Z, H,..)
  @ analysis level
- Provides info on helicity states in Z->tautau decays (missing in HepMC record)
- Relies *exclusively* on information on tau 4-momenta (+daughters)
  and the boson 4-momenta
  -> suitable for embedded methods where Z->tautau background
  is emulated from Z->mumu sample.

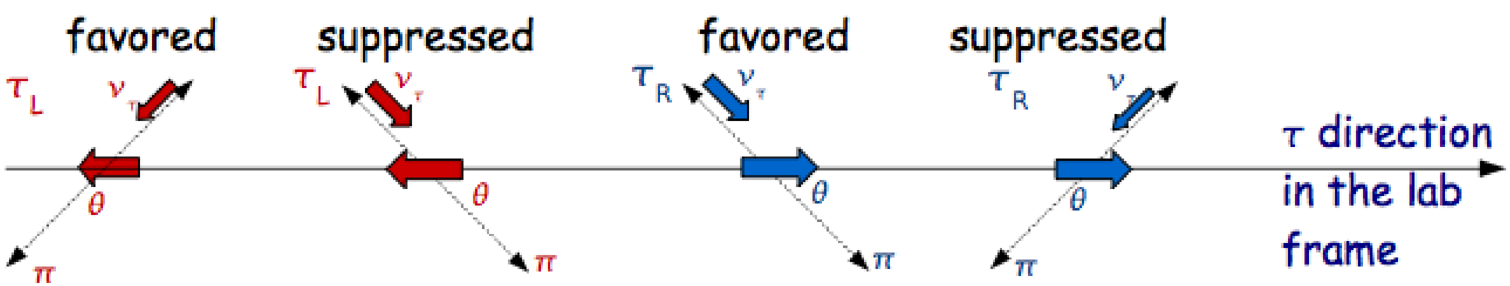
TauSpinner documented in:
EPJC 72 (2012) 4

Spin dependance of tau decays

- Encoded in spin factor: $1 - h_\mu s^\mu = 1 + \mathbf{h} \cdot \mathbf{s}$ *Tau rest frame*

- h is polarimetric vector
- $|\mathbf{s}| = P_\tau$ – tau polarization

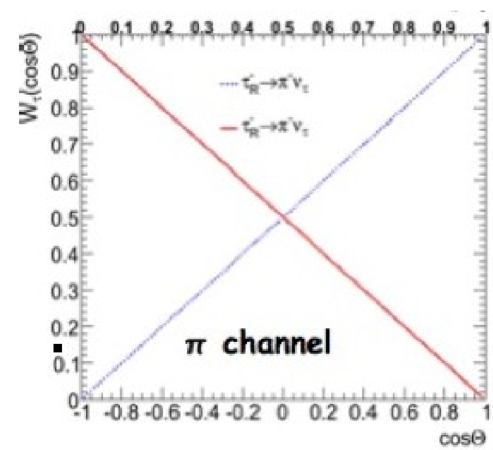
- Simplest case: $\tau \to \pi\nu$



- kinematics driven by left handed neutrino

=> h is a unit vector pointing in the direction of flight of the pion

Decay distribution $W \sim (1 - P_\tau \cos\theta)$



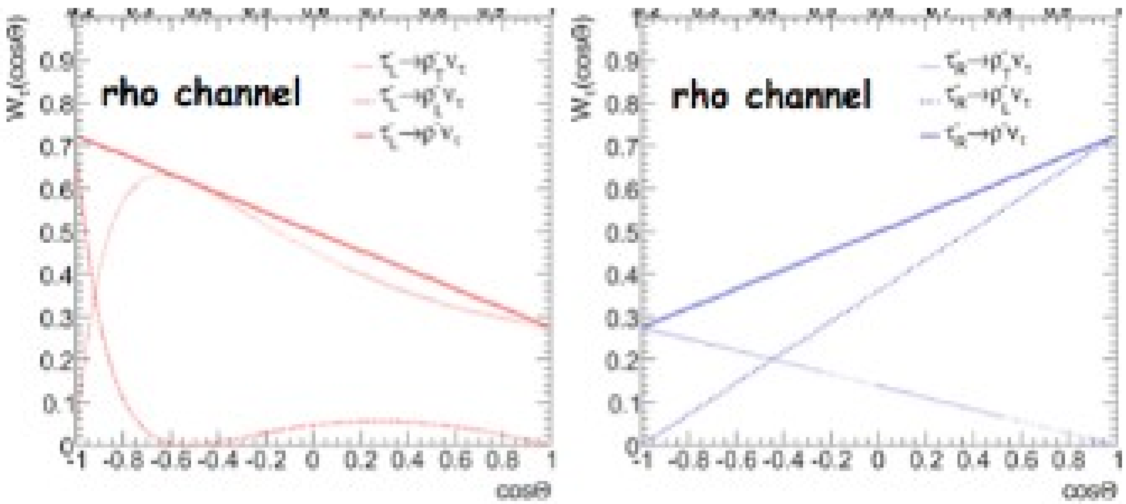
Multi-pion decays

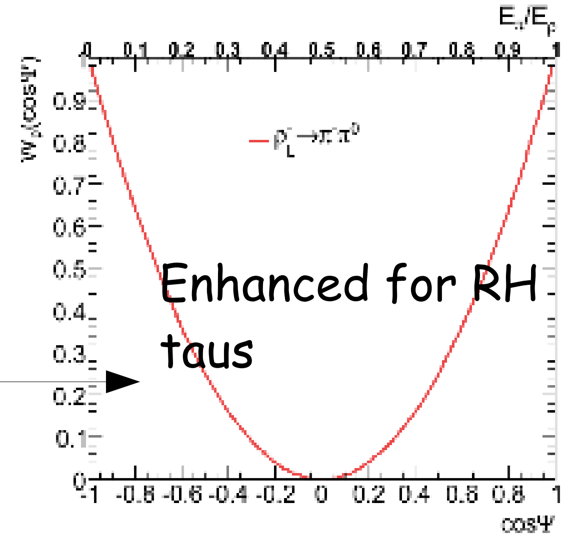
- Decays via rho

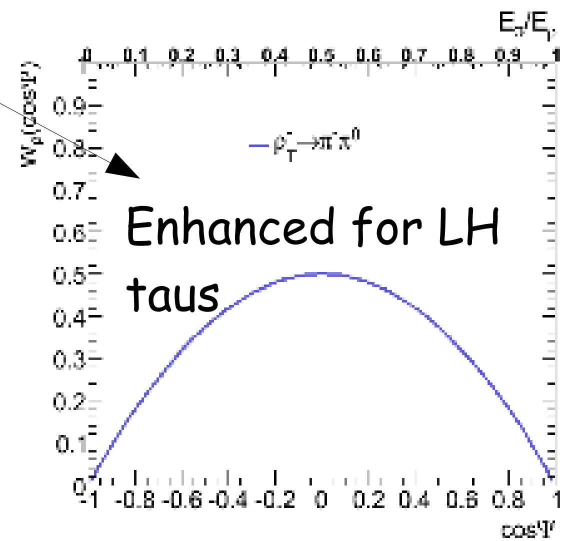
  W(cos θ) ~ 1-Pcos θ - transversely (T) polarized state
  W(cos θ) ~ 1+Pcos θ - longitudinally (L) polarized state

- Kinematics encoded by 2 angles: θ, ψ

$$\cos\psi = \frac{m_v}{\sqrt{m_v^2 - 4m_\pi^2}} \frac{E_{\pi^-} - E_{\pi^0}}{|\mathbf{p}_{\pi^-} + \mathbf{p}_{\pi^0}|},$$







- Multi-pion decays : h constructed using hadronic currents

Tau polarization depends on the parent boson

- P_τ constant for taus from W and $H^{\pm}$, H^0
- P_τ in Z->ττ decays originates from:

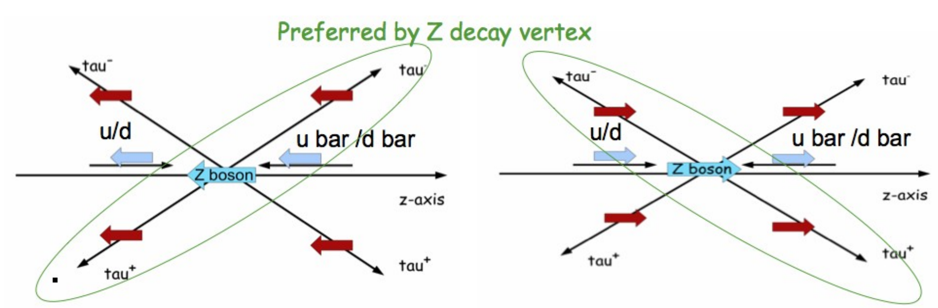
- PV in tau decays (av. polarization) & PV in Z production (depend on scat. angle θ)
- calculated using born level ME:

$$p_\tau^Z(s,\theta) = \frac{\frac{d\sigma}{d\cos\theta}(s,\cos\theta,P_\tau=1)}{\frac{d\sigma}{d\cos\theta}(s,\cos\theta,P_\tau=1)+\frac{d\sigma}{d\cos\theta}(s,\cos\theta,P_\tau,=-1)}$$

$$\frac{d\sigma}{d\cos\theta}(s,\cos\theta,P_\tau) = (1+\cos^2\theta)F_0(s) + 2\cos\theta F_1(s) - P_\tau[(1+\cos^2\theta)F_2(s) + 2\cos\theta F_3(s)],$$

Depends on:

- invariant mass due to interference with Photon
- incoming quark flavor – due to difference in coupling strength
- scattering angle θ (u/d & τ^- in Z frame)



Spin correlations (ττ final state)

- Encoded as: $1 + R_{ij}\, h^i\, h^j$

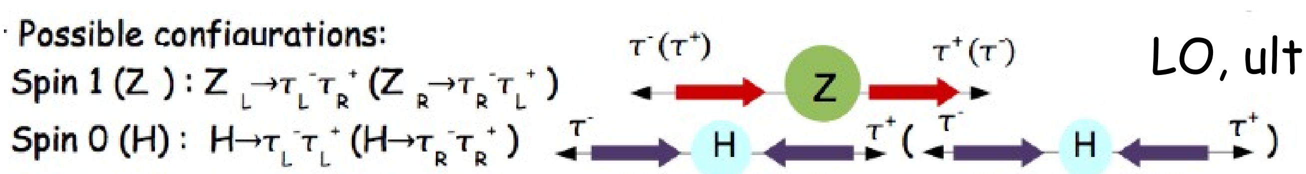
  - Matrix R describes spin correlations & spin states of individual taus
  - h^i and h^j are (t,x,y,z) components of polarimetric vectors

- Neglecting transverse spin degrees & in ultra relativistic limit:

$$1 + R_{ij}\, h^i\, h^j \sim 1 + h_{z+}\, h_{z-} + P_\tau h_{z+} + P_\tau\, h_{z-} \quad \text{for } Z\text{->}\tau\tau$$

$$1 + R_{ij}\, h^i\, h^j \sim 1 - h_{z+}\, h_{z-} \quad \text{for } H\text{->}\tau\tau$$

within this limit: $P_\tau = 2\, p_\tau^{\,Z} - 1$



LO, ultra relativistic limit

TauSpinner algorithm

1. Identify flavor of decaying boson

2. Calculate polarimetric vectors using taus (& daughters) 4-vectors

3. Randomly generate longitudinal tau polarization P_τ

4. Calculate spin weight

$W_T = 1 + P_\tau h_z$ - τν final state

$W_T = 1 + (P_\tau)^2 h_{z+} h_{z-} + P_\tau h_{z+} + P_\tau h_z$ – ττ final state

5. Attribute helicity states

X->ττ (τν) process can be generated by *any* τ production program or reconstructed from data

Origin	P_{τ_1}	P_{τ_2}	Probability
Neutral Higgs bosons: H	+1	−1	0.5
	−1	+1	0.5
Neutral vector boson: Z/γ^*	+1	+1	p_τ^Z
	−1	−1	$1-p_\tau^Z$
Charged Higgs: $H^\pm$	+1	–	1.0
Charged vector boson: $W^\pm$	−1	–	1.0

1. s of Z/γ - from Z boson 4-vector
2. cosΘ - from 1^{st} (2^{nd}) beam dir. & τ^+ (τ^-)
3. x_1 & x_2 by solving: $x_1 x_2 E_{CM}^2 = S$ and $(x_1-x_2) \cdot E_{CM} = P_z$ (Z boson)
4. Quark flavor: stochastically based on x-sect & PDFs
5. p_τ^Z - weighted average over initial state quark configuration

Only for pp collisions otherwise set to 0.5

Application of the spin weight

Spin weight should be applied @ analysis level:

- simulate spin effects: w_T
- remove spin effects: $1/w_T$
- revert spin effects in the single tau final state: $(2-w_T)/w_T$
- revert spin effect in di-tau sample: $w_T(Z)/w_T(H)$ (H->Z) and $w_T(H)/w_T(Z)$ (Z->H)

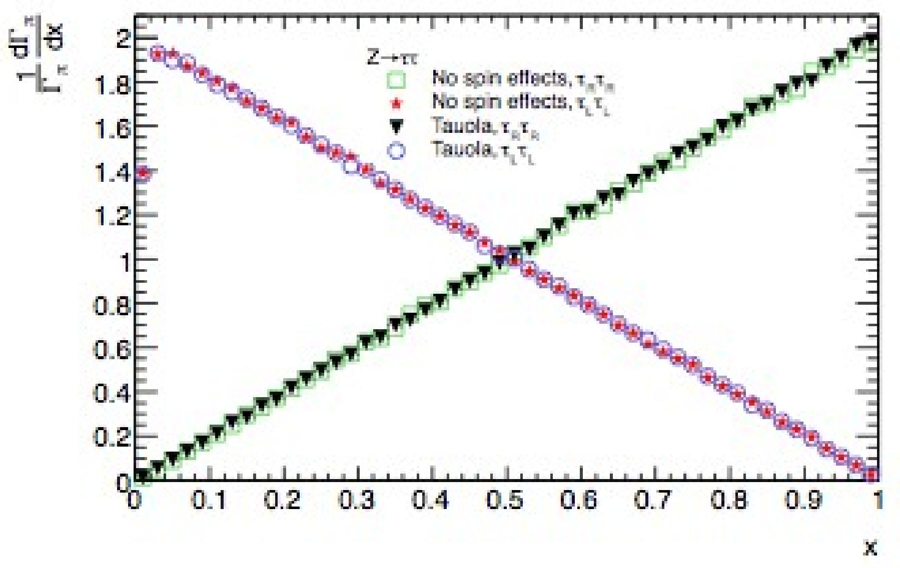
Limitations

- Transverse spin degrees are neglected
- x_1 & x_2 resolved within collinear approximation:
  ISR quarks & gluons p_T's are neglected
- Photons from FSR are omitted from Z boson decay vertex (practically no impact)
- Spin effects are treated @ LO
- 5 pion decays and multi prong decays via kaons are not implemented (weak spin effects)

Tau decay mode	Branching fraction %
$e^-\bar{\nu}_e\nu_\tau$	17.85
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.36
$\pi^-\nu$	10.91
$\pi^-\pi^0\nu$	25.51
$\pi^-\pi^0\pi^0\nu$, $\pi^-\pi^+\pi^-\nu$	9.29, 9.03 (incl. ω)
$K^-\nu$	0.70
$K^-\pi^0\nu$, $\pi^-K^0\nu$	0.43, 0.84
$\pi^-\pi^+\pi^-\pi^0\nu$	4.54 (incl. ω)
$\pi^-\pi^0\pi^0\pi^0\nu$	1.04
Other	2.5

Attributing helicity states

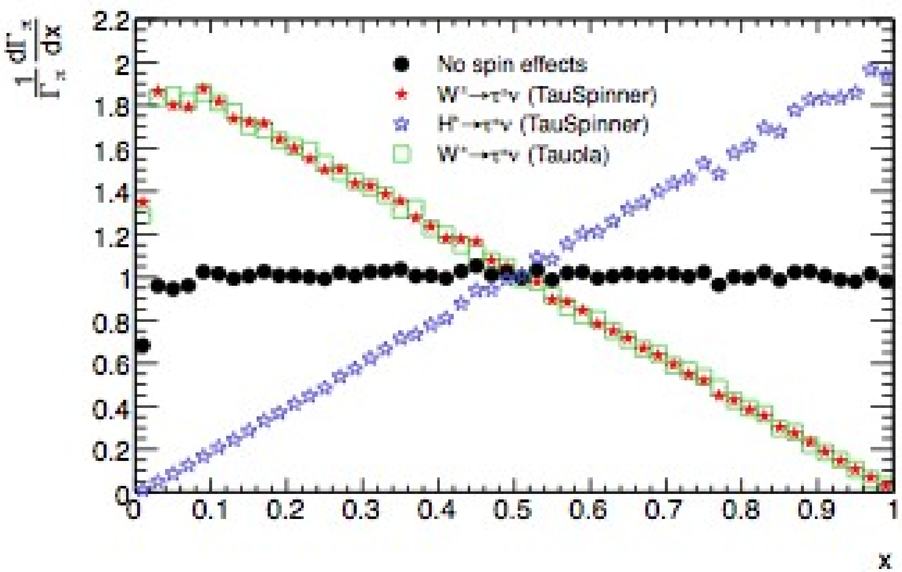
TauSpinner attributes helicity states stochastically by comparing a random number with probability of the right handed configuration to occur: $p_\tau^Z \, w_T \,(p_\tau^Z = 1) / w_T$



Info on helicity states:

- not available in ATLAS MC data (not stored in HepMC)
- crucial for tau polarization studies (measurement relies on fitting data with a combination LH and RH templates)

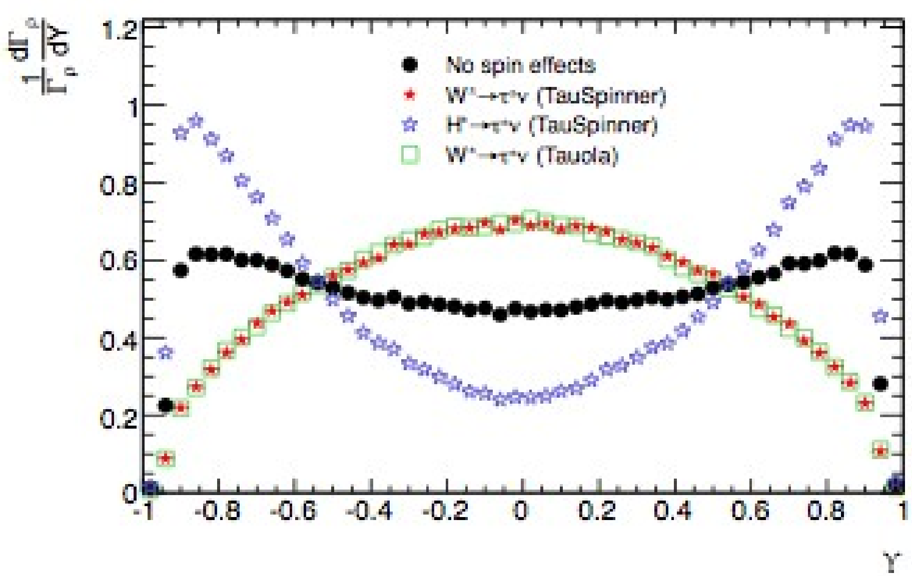
TauSpinner vs Tauola - τν final state



In "no spin effects" sample taus are decayed by Tauola

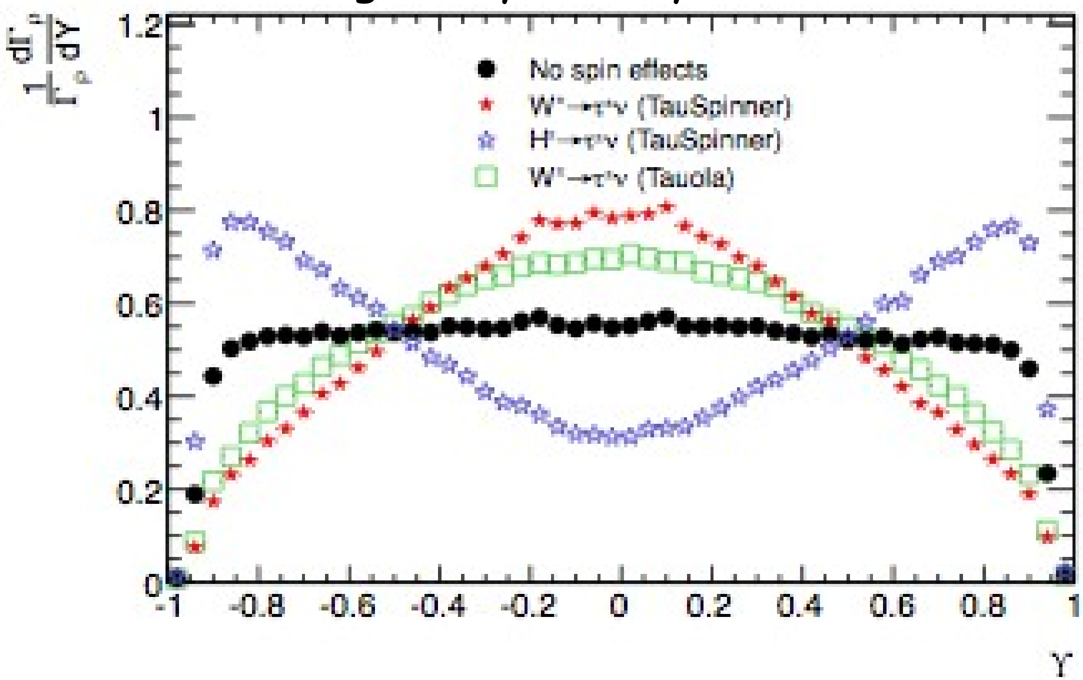
Fraction of tau momentum taken by Pion in $\tau \to \pi\nu$ decay

"Charged asymmetry"
Relative fraction of
Charge and neutral pion p_T
in the $\tau \to \rho\nu \to \pi^{\pm}\pi^{0}\nu$ decay



TauSpinner applied to taus decayed by Pythia

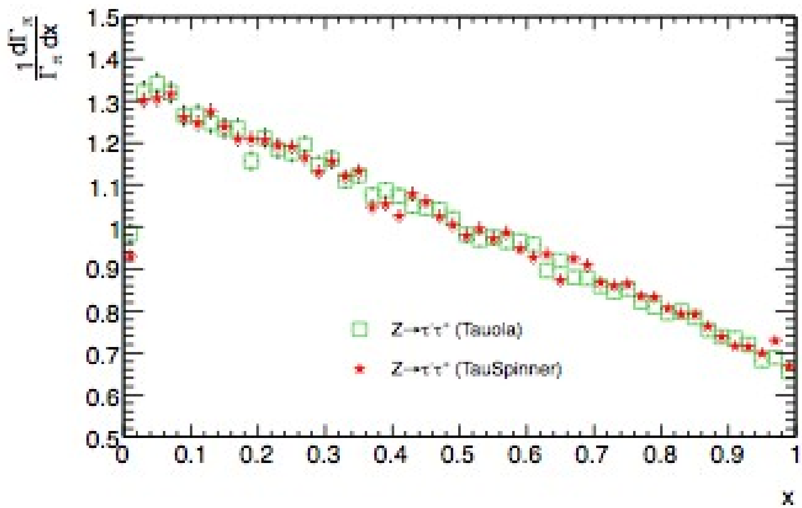
"Charged asymmetry"



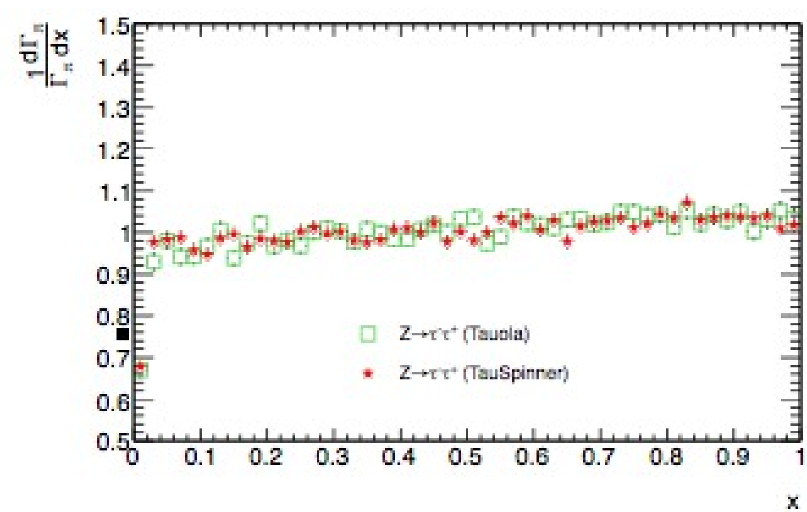
In "no spin effects" sample taus are decayed by Pythia

No conservation of angular momentum in tau->ρν decays in Pythia
=> large systematics

TauSpinner vs Tauola - Z->ττ events

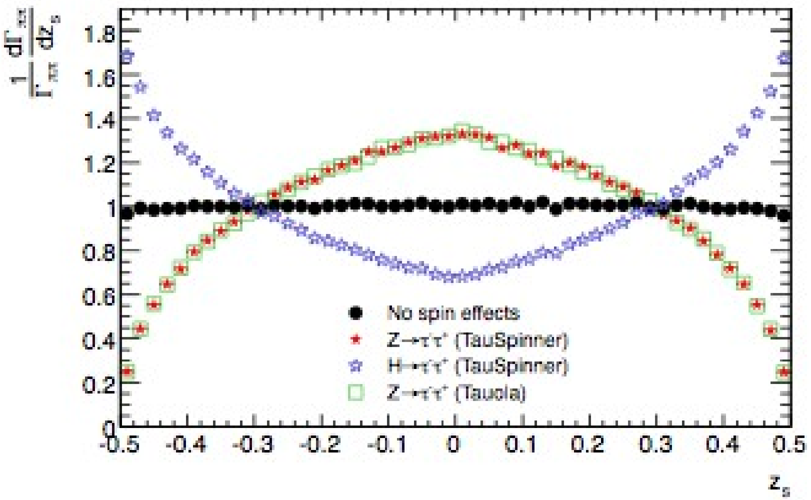


Z boson emitted in the forward direction



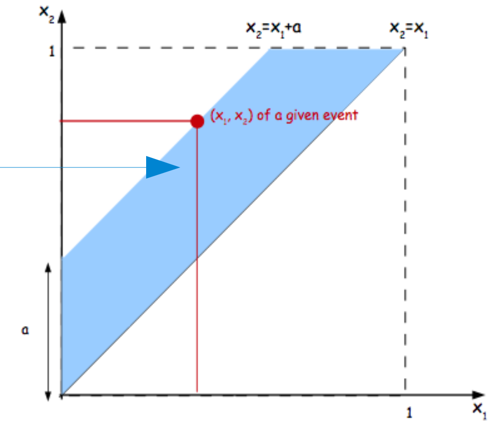
Z boson emitted in the backward direction

TauSpinner vs Tauola - spin correlations in ττ final state



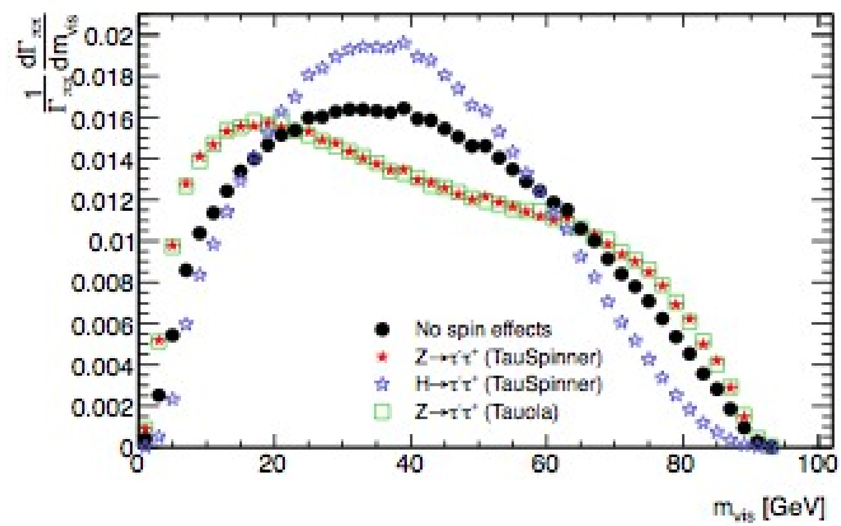
z_s: signed surface

both taus decay τ->πν

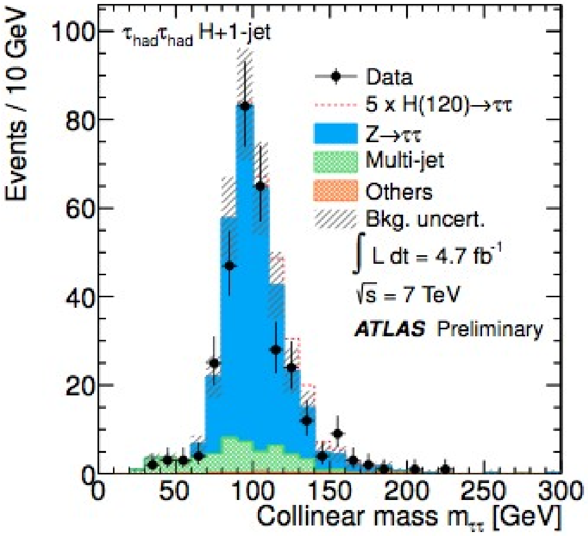


Invariant mass of two charged pions

both taus decay τ->πν



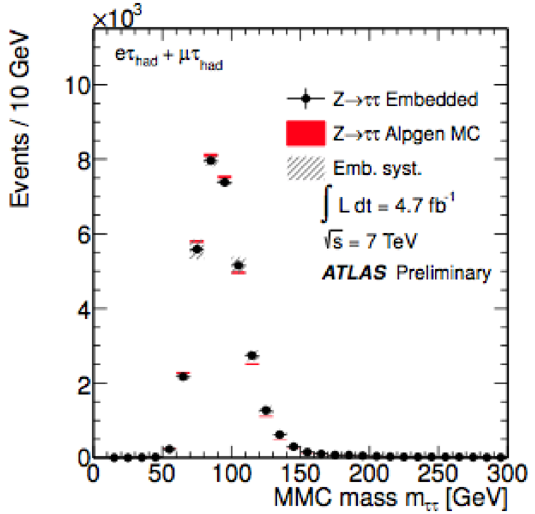
Application to embedded methods



"Tau embedding" algorithm:

-Start from Z->μμ sample extracted from data
- remove muon tracks & calo deposits
- simulated Z->ττ decays with tau 4- momentum same as the removed muon 4-momentum (after mass correction)
- merge & re-reconstruct objects & met

ATLAS-CONF-2012-014



Spin effects in the embedded samples:

- correlations are included
- average tau polarization is zero (no info on Initial state quarks)

Effects investigated in ATLAS using TauSpinner

- no plots are public
- for ATLAS folks:

https://indico.cern.ch/contributionDisplay.py?contribId=2&confId=158211

Application to measurement of P_T in W->τν events

- Observable: charged asymmetry
  - energy sharing of the charged and neutral pions in the tau decay

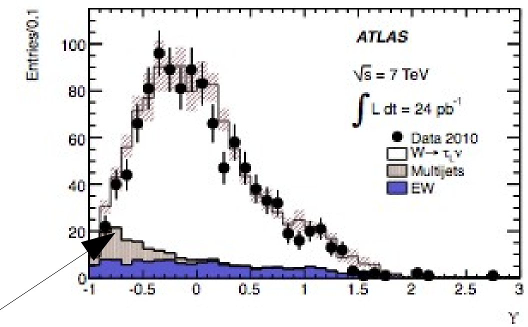
- P_T extracted using fit of the observed distribution in data to a linear combination of the MC templates

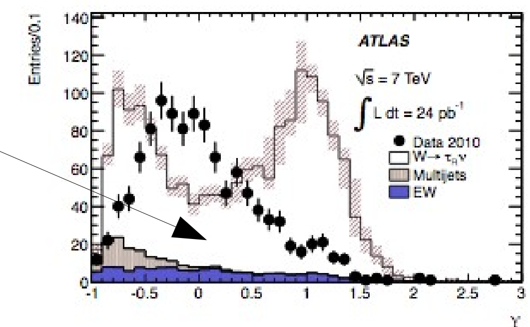
- Result: P_T = =-1.06 +/- 0.04 (stat) + 0.05 - 0.07

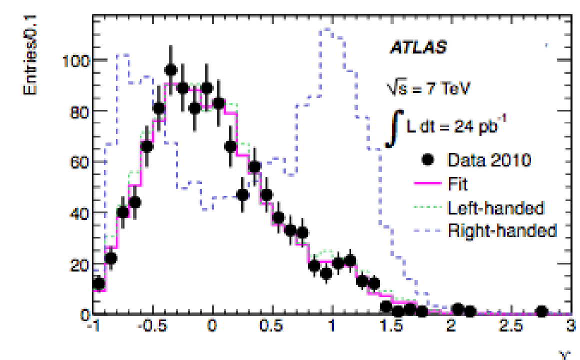
  $P_T \in$ [-1, -0.91] with 95% probability

- Dominant systematics: energy scale and MC model

RH template constructed by re-weighting half of original LH events using TauSpinner







arXiv:1204.6720v1

First measurement of tau polarization @ hadronic collider

Very first direct test of tau helicity structure @ $Q^2=m_W^2$

Systematics uncertainties

Disclaimer:
- I have been asked to discuss theoretical uncertainties
- But...I am an experimentalist and I know very little about this topic
- Since I am not the right person to do it
  I will state a few obvious facts and leave the discussion to the audience;)

- Very good agreement between TauSpinner and Tauola at first glance reassures that no additional systematics in emulation of spin effects have been introduced in TauSpinner
  - Note that x_1 & x_2 are resolved using collinear approximation => performance of TauSpinner should be checked carefully in a Z sample with high p_T jets

- Both Tauola & TauSpinner treat spin effects @ LO: comparison with NLO matrix element calculations should be performed

Summary

- TauSpinner is the first tool which allow one to simulate/remove/revert a given spin effect in any tau sample (data or MC) provided the origin of taus is known (so far: Z, $W^{\pm}$, h, A, H, $H^{\pm}$)

- Limitations:

  - longitudinal spin degrees (possible extension to transverse degrees)
  - In Z-> ττ kinematics resolved using collinear approximation (systematics in presence of high p_T jets to be checked)

- Applications:

  - Z->ττ bkg estimation using embedded techniques
  - Polarization measurements (preparation of templates, helicity attribution)
  - Simulation of spin effects if missing/incomplete in production

Documentation & code

- Documentation:
  - "TauSpinner program for studies on spin effect in τ production at the LHC." EPJC 72 (2012) 4

- Code:
  - Generic (input in HepMC format):
    http://wasm.web.cern.ch/wasm/Welcome.html
    http://hibiscus.if.uj.edu.pl/~przedzinski/tau-reweight

  - ATLAS (input in D3PD format) :
    https://svnweb.cern.ch/trac/atlasusr/browser/czyczula/TauSpinner