τ leptons spin observables in the CMS experiment at the LHC

Journées de Rencontre des Jeunes Chercheurs 2018

Guillaume Bourgatte

Outline

- Tau reconstruction and identification
- Tau polarization and optimal variable in $Z \rightarrow \tau\tau$
- Analysis strategy
- Toward Higgs CP measurement

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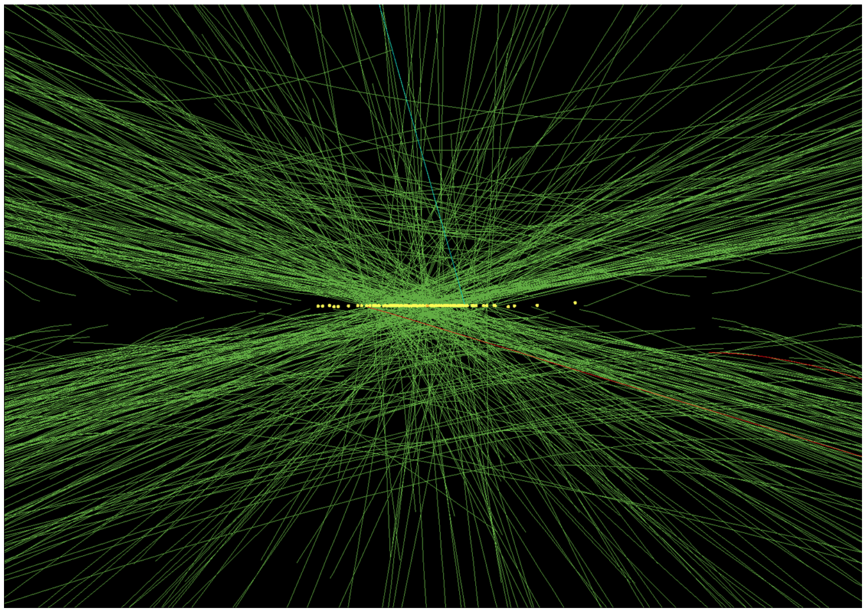
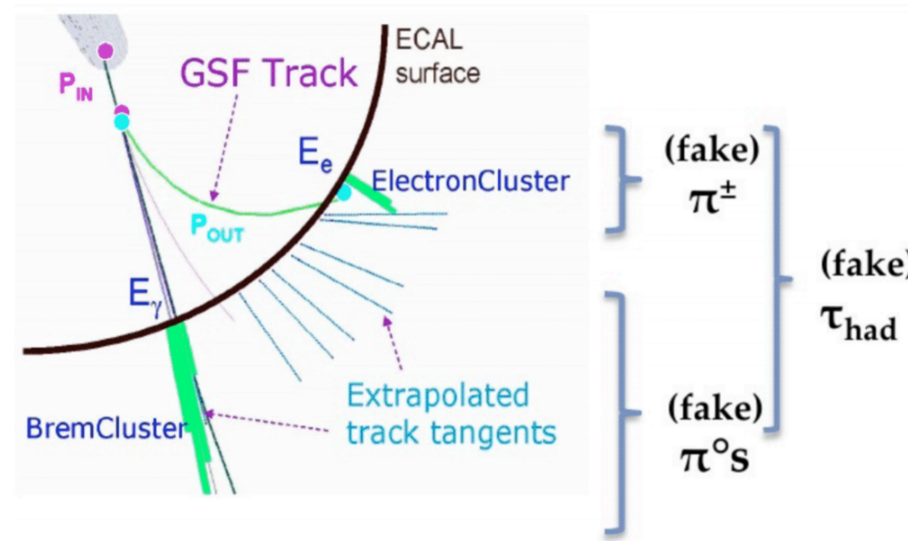
τ challenge

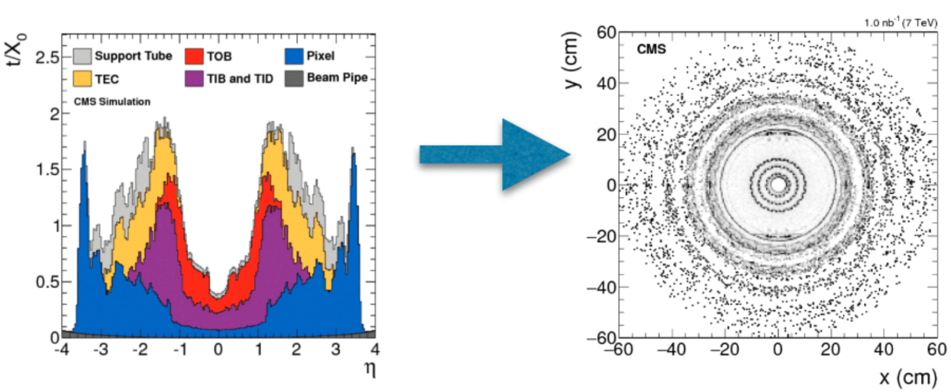
Pile-up



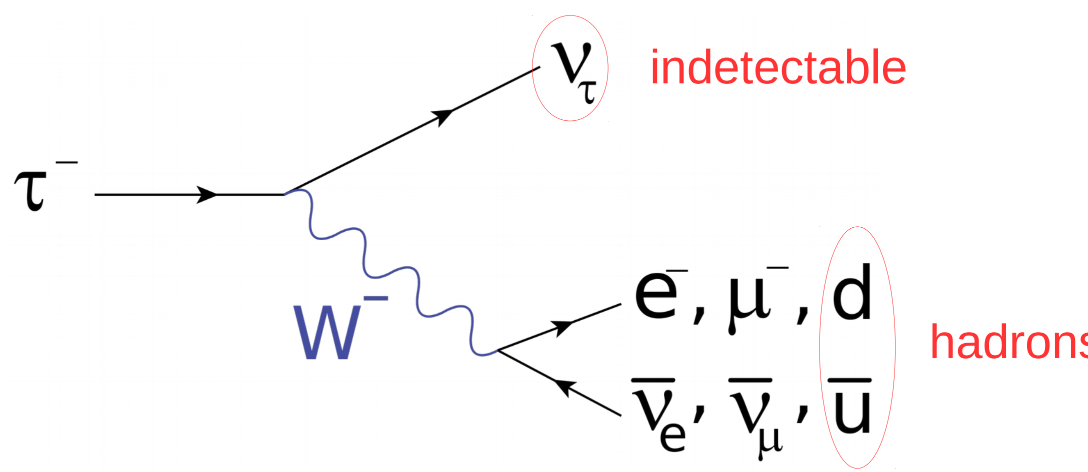
Fake τ from e⁻, μ⁻ and jets



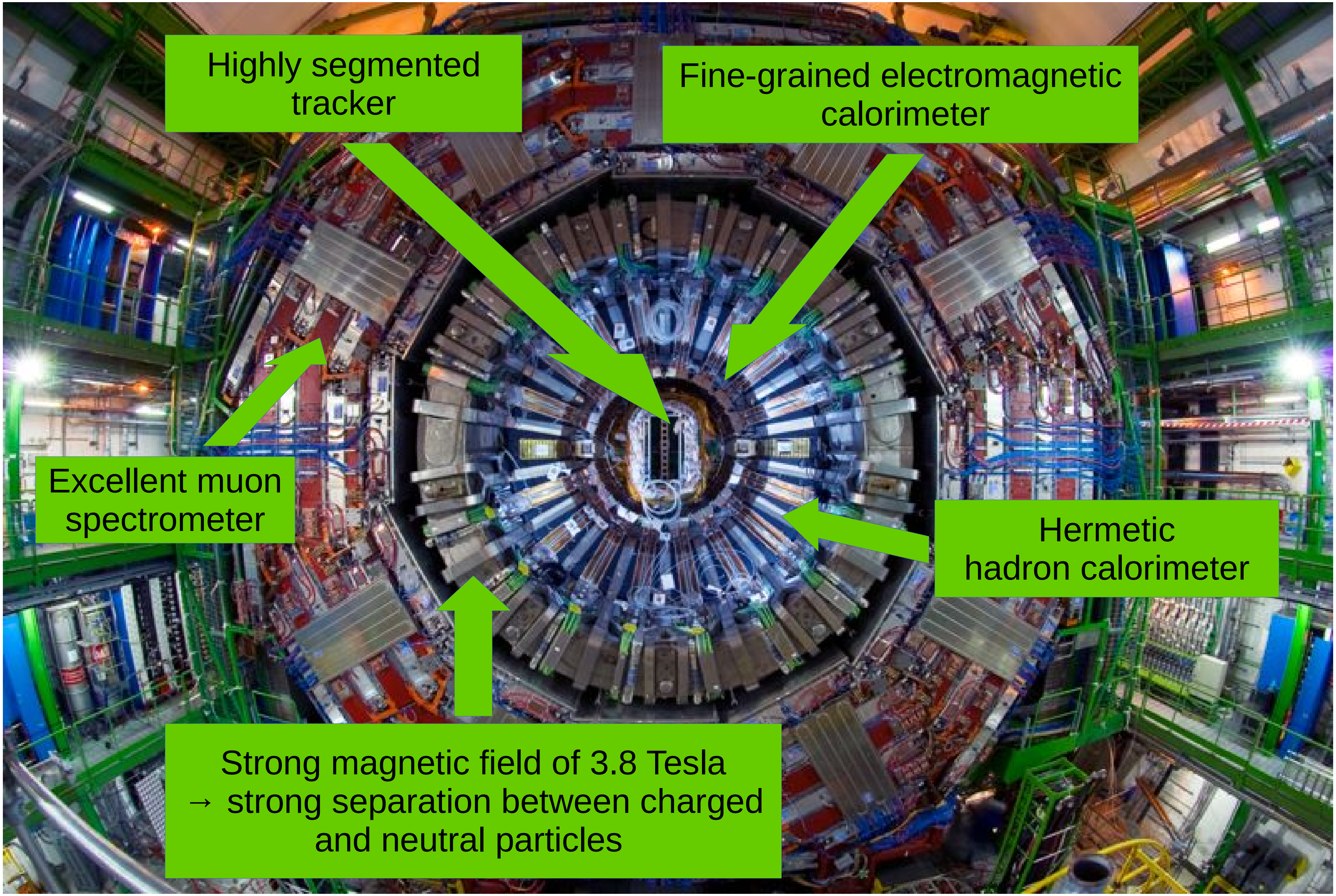
Heavy material



Neutrinos



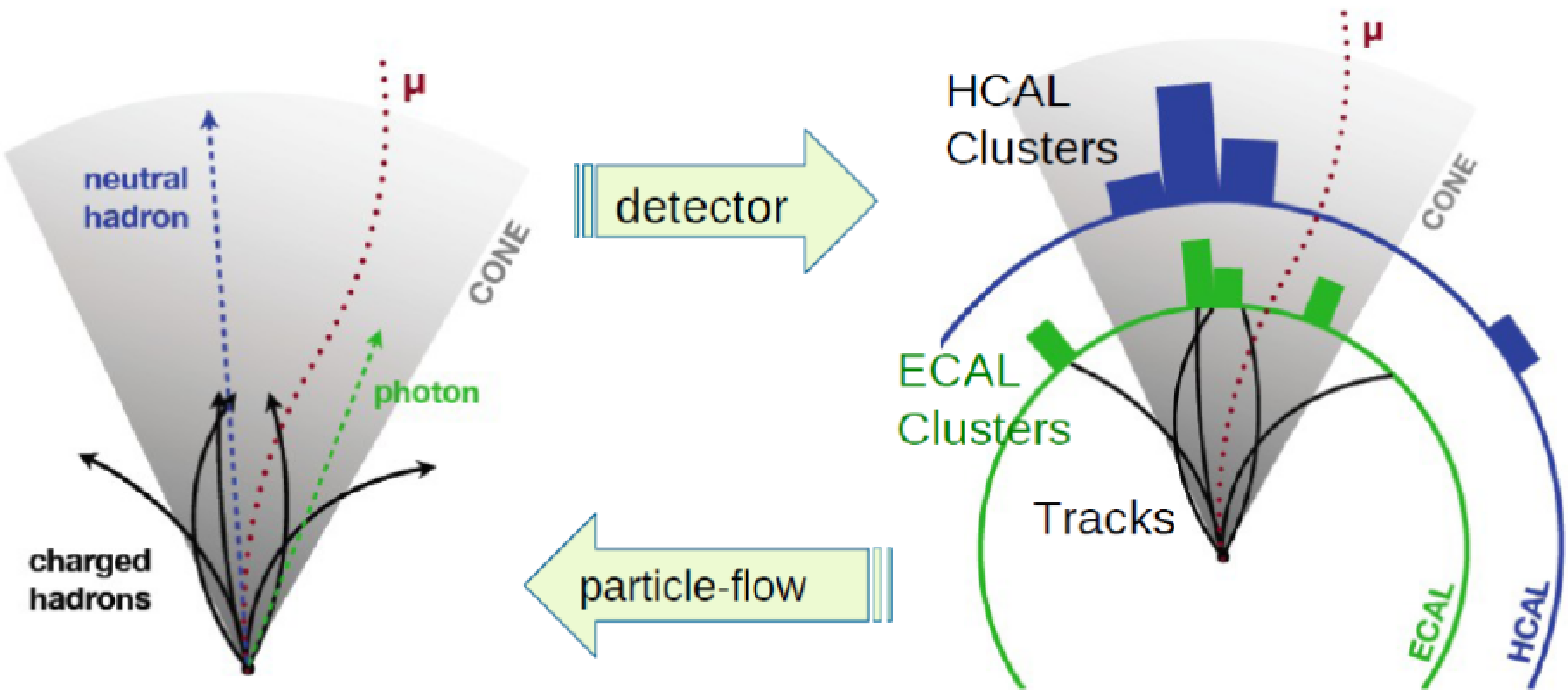
Compact Muon Solenoid



Particle Flow

Identify and reconstruct all particles detected through an optimal combination of the information from the entire detector

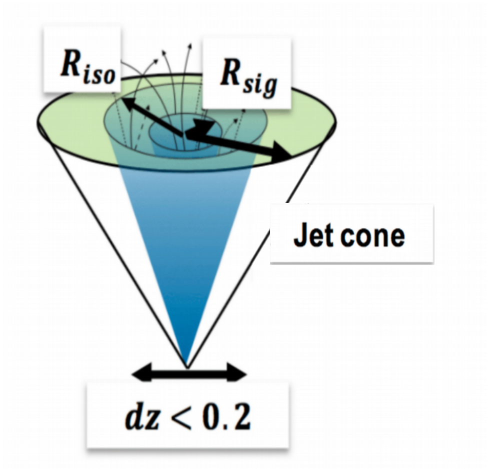
Then combine this particles to build higher-level physics objects like the missing transverse energy, taus, b-tagging...



τ reconstruction

Anti-kT algorithm (R=0.4) for Pflow jet reconstruction to seed tau reconstruction

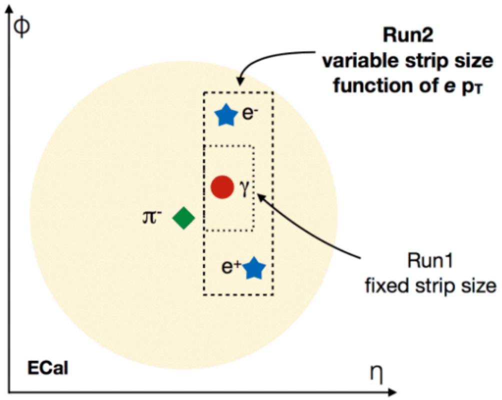
Charged hadrons



$R_{iso,}$ for isolation
R=0.5

R_{sig}, variable size, collect charged hadrons
p_T>0.5 GeV inside a cone of variable radius $R=3/p_T$

Neutral hadrons



$e^{\pm}$,ɣ with p_T>1 GeV clustered into “calorimeter strips”
Strips barycentre has to be inside R_{sig}

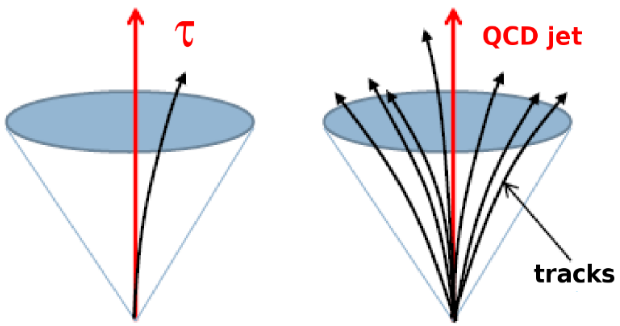
Jets, electrons, muons can fake taus

Fake τ: Electron, muon or QCD jets misidentified as hadronically decaying tau leptons by the tau reconstruction algorithm

The main challenge in tau reconstruction is to discriminate between τ_{had} and QCD jets

The experimental signatures of hadronically decaying taus:

- collimated jet
- low multiplicity (up to three charged hadrons and up to two π^0)
- decay products are isolated (require low detector activity around tau jet direction)



→ MVA Tau ID
Use isolation variables, τ reco and kinematic variables, variables sensitive to the impact parameter and secondary vertex sensitive variables

→ Obtain a results between 0 and 1 which is the probability of being a real τ

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- **Tau polarization and optimal variable in $Z \to \tau\tau$**
- Analysis strategy
- Toward Higgs CP measurement

CP symmetry

CP symmetry : Product of two symetries. C for charge which transforms a particle into its antiparticle and P for parity which inverses spatial coordinates

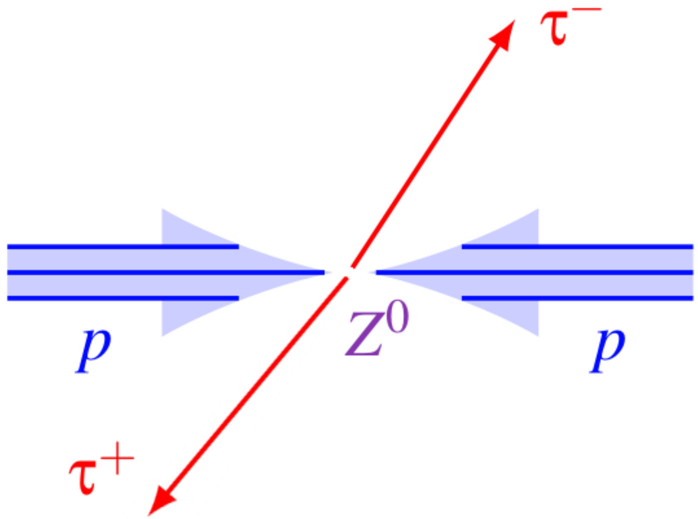
Helicity : projection of the spin onto the direction of momentum

$$h = \frac{\vec{\sigma} . \vec{p}}{|\vec{p}|} = \pm 1$$

Polarization : differencies between particles with h=+1 and h=-1 over the total number

$$P_\tau = \frac{N^- - N^+}{N^- + N^+} = \frac{N^- - N^+}{N^{total}}$$

The parity violation in the weak neutral current introduces the polarization asymmetry of τ leptons produced in Z → τ τ



τ polarization

Z^0 couples differently according to the helicity → Leptons polarization at the Z energy (Tree Level) :

$$\langle P_\tau \rangle \simeq -2 + 8 \sin^2 \theta_W$$

Observable bosons → $$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$ ← Gauge bosons

τ polarization provides:

- Measurement of the ratio of vector to axial-vector neutral couplings for τ leptons
- Measurement of effective weak mixing angle $\sin^2\theta_W$

τ decays

Mode	Decays channel	Branching ratio (%)
Leptonic	$\tau \rightarrow e\bar{\nu}_e\nu_\tau$	17.82
	$\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau$	17.39
Hadronic	$\tau \rightarrow \pi^{\pm}\nu_\tau$	10.82
	$\tau \rightarrow \rho^{\pm}\nu_\tau \rightarrow \pi^{\pm}\pi^0\nu_\tau$	25.49
	$\tau \rightarrow \rho^{\pm}\nu_\tau \rightarrow \pi^{\pm}2\pi^0\nu_\tau$	9.26
	$\tau \rightarrow \rho^{\pm}\nu_\tau \rightarrow \pi^{\pm}3\pi^0\nu_\tau$	1.04
	$\tau \rightarrow a_1\nu_\tau \rightarrow 3\pi^{\pm}\nu_\tau$	8.99
	$\tau \rightarrow a_1\nu_\tau \rightarrow 3\pi^{\pm}\pi^0\nu_\tau$	2.74

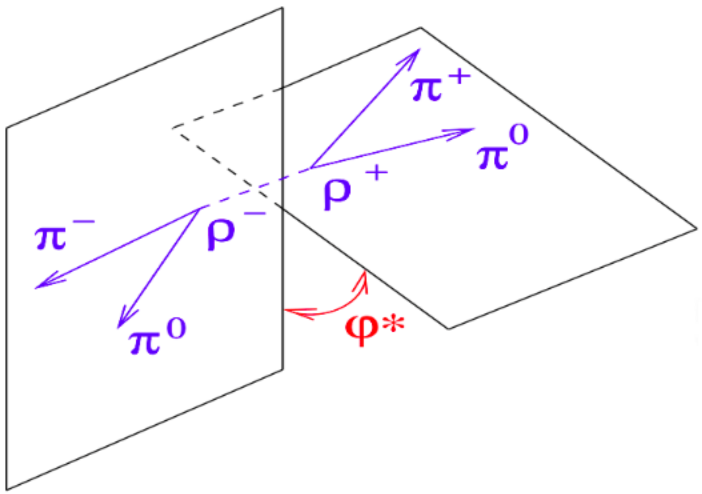
τ polarization in $Z \to \tau\tau$

Acollinearity angle: angle between the two charged pions from the two τ_{had} in Z rest frame

Only feasible for τ decaying in $\pi^{\pm}$ and hardly usable because difficult helicities separation

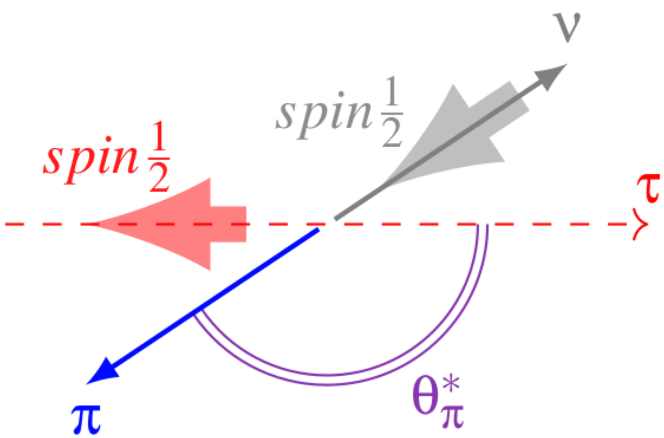
Acoplanarity angle: angle between plans formed by the τ decay products in $h^{+}h^{-}$ rest frame

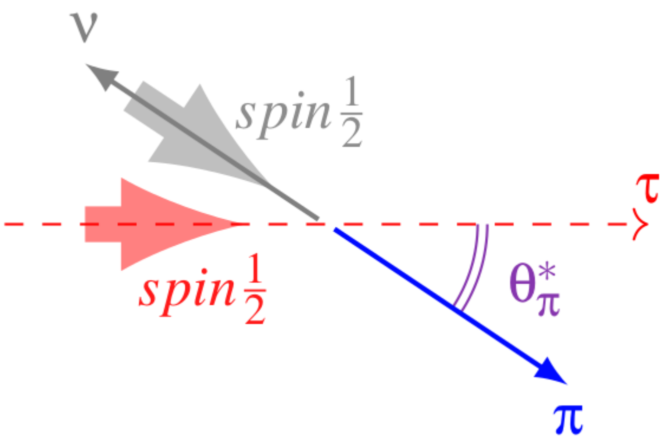
Not optimal because up to 16 plots have to be measured for example

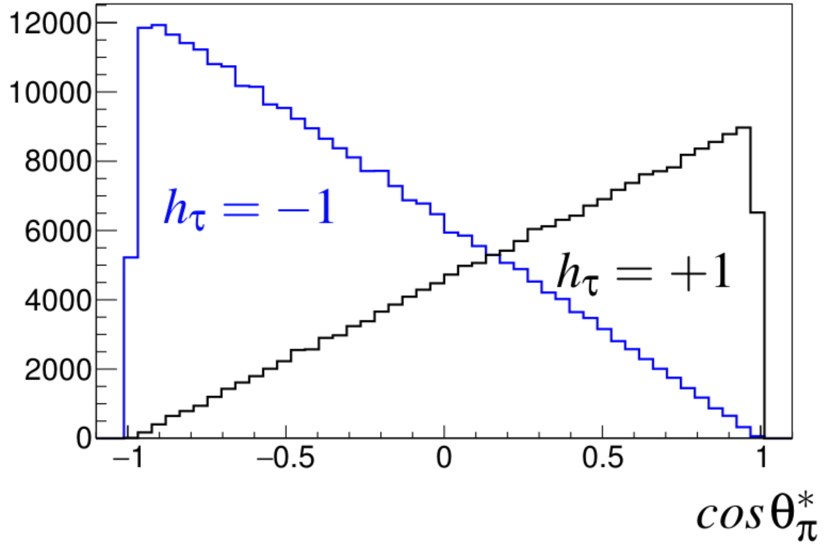


$\tau \to \pi \nu_\tau$ channel

$\pi^\pm$ spin = 0 → $\cos\theta^*_\pi$ gives the τ helicity

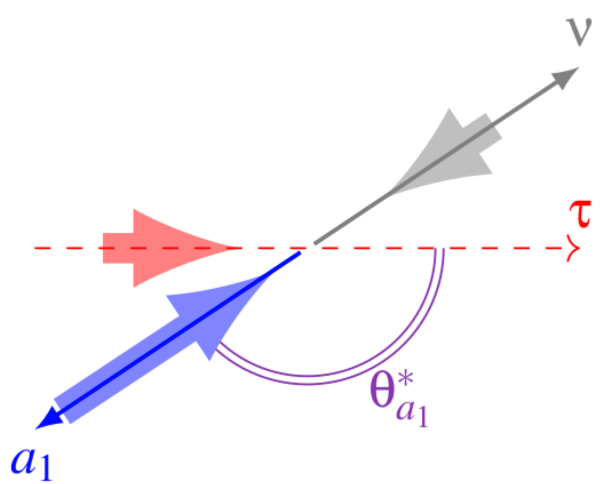


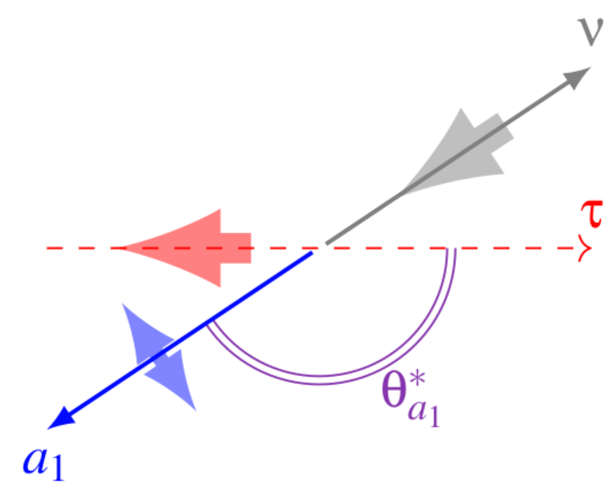




$\tau \rightarrow a_1 \nu_\tau$ channel

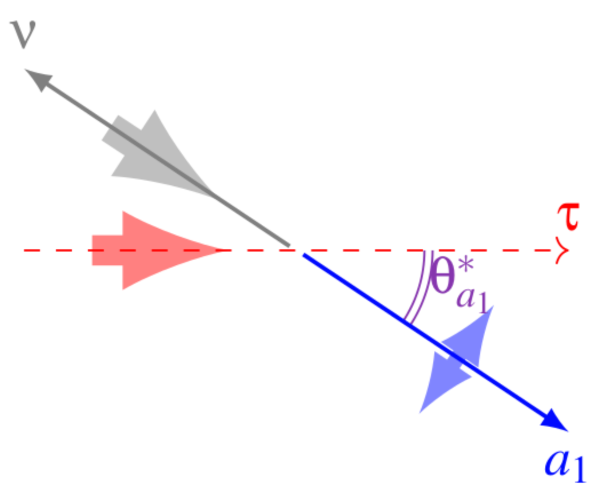
a_1 spin = 1 → $\theta^*_{a_1}$ doesn't give anymore the τ helicity because a_1 is polarized

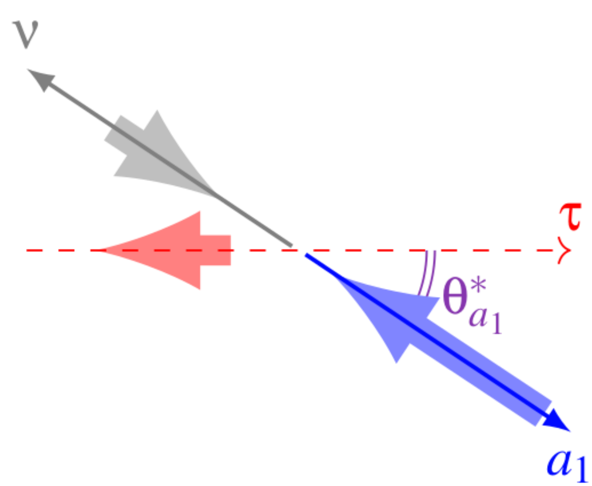




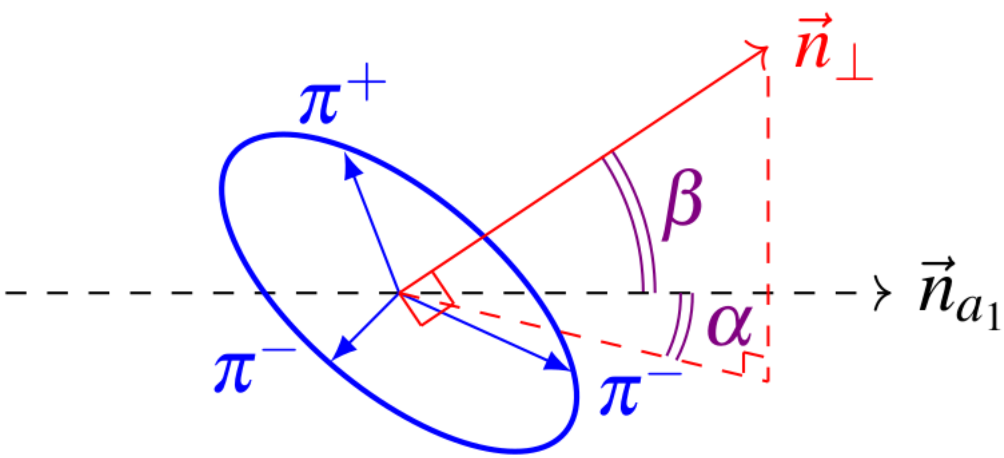
Righ handed

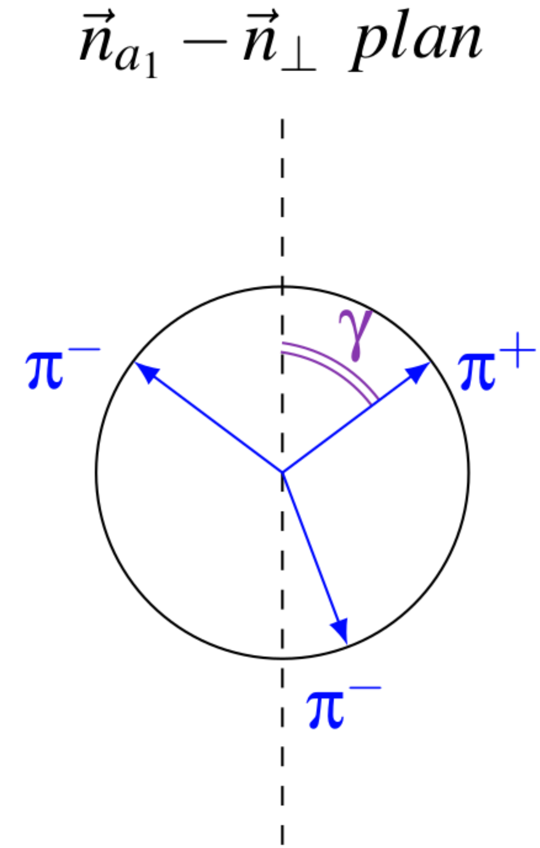
Left handed





α, β and γ angles





α: azimutal angle between $\vec{n}_\perp$ in the a_1 rest frame and $\vec{n}_{a1}$
$\alpha \in [\, 0,\, 2\pi \,]$

β: polar angle between $\vec{n}_\perp$ in the a_1 rest frame and $\vec{n}_{a1}$
$\beta \in [\, 0,\, \pi \,]$

γ: rotation of the $3\pi^\pm$ plan around $\vec{n}_\perp$
$\gamma \in [\, 0,\, 2\pi \,]$

Optimal variable

Decay distributions depend linearly of the polarization : $W(\vec{\xi}) = f(\vec{\xi}) + P_\tau g(\vec{\xi})$

With $\vec{\xi}$ the vector of all spin sensitive kinematic variables

Let $\omega = \dfrac{g(\vec{\xi})}{f(\vec{\xi})} = \dfrac{|M_+(\vec{\xi})|^2 - |M_-(\vec{\xi})|^2}{|M_+(\vec{\xi})|^2 + |M_-(\vec{\xi})|^2} \Rightarrow W(\vec{\xi}) = f(\vec{\xi})[1 + P_\tau \omega]$

With $M_\pm$ the matrix element of the decay with helicity ± 1

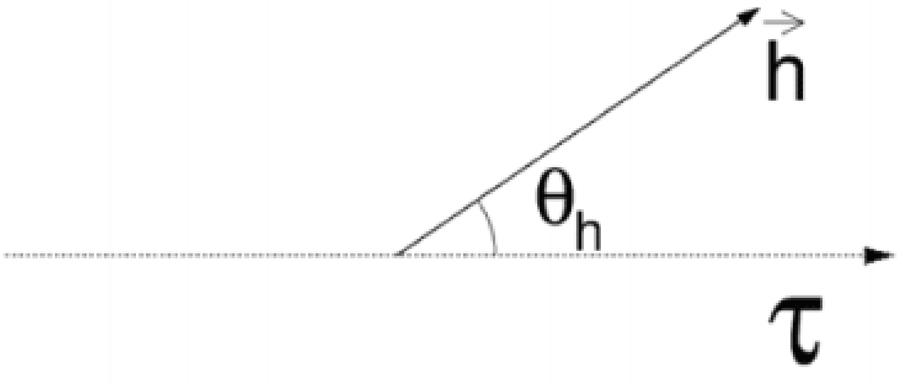
For N measurements and P_τ let as free parameter, the maximum likelihood is:

$$L = (\vec{\xi}, P_\tau) = \prod_{i=1}^{N} \{f(\vec{\xi}) + P_\tau g(\vec{\xi})\} = \prod_{i=1}^{N} \{f(\vec{\xi})[1 + P_\tau \omega_i]\}$$

$$\frac{\partial \log(L(\vec{\xi}_i, P_\tau))}{\partial P_\tau} = \sum_{i=1}^{N} \frac{\partial \log(1 + P_\tau \omega_i)}{\partial P_\tau} + 0 = \sum_{i=1}^{N} \frac{\omega_i}{1 + P_\tau \omega_i} = N \langle \frac{\omega}{1 + P_\tau \omega} \rangle = 0$$

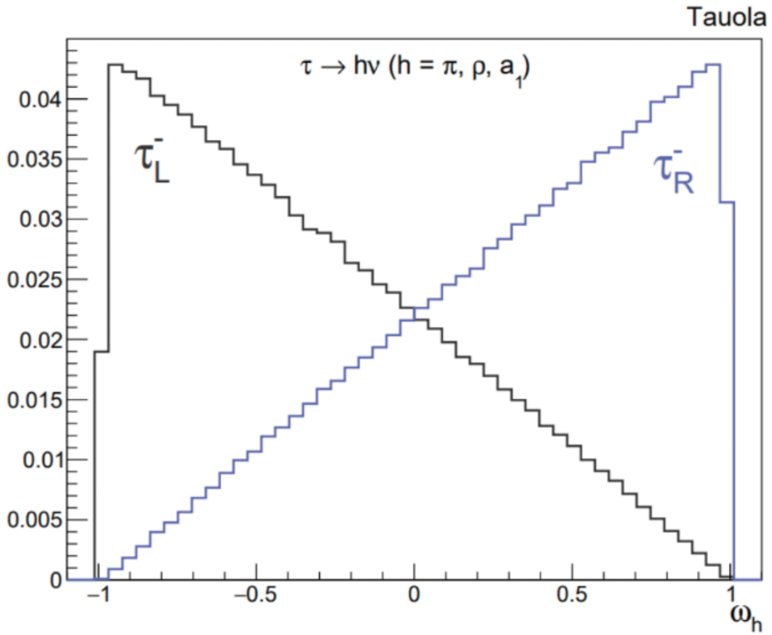
Optimal variable

Polarimetric vector: Unit vector which is in the most probable direction of the τ spin calculated in the τ rest frame



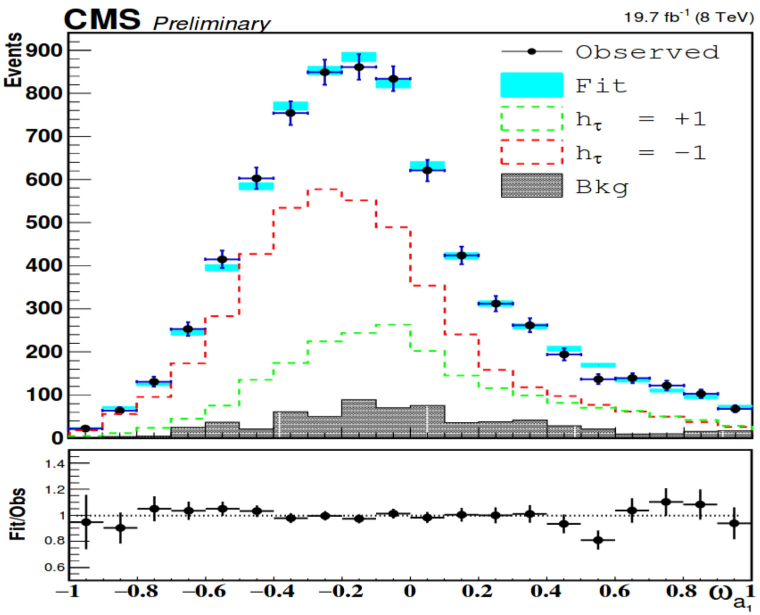
If all decay products are reconstructed
→f = ½ and g = ½ cos θ_h

$$\omega = \cos \theta_h$$



Vladimir Cherepanov's paper

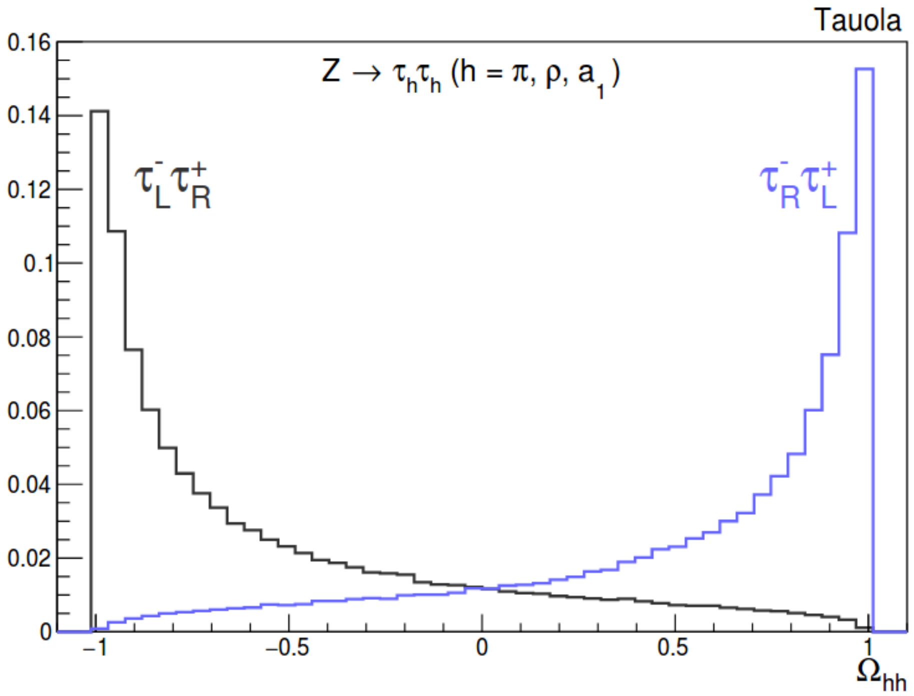
Fit with the relative fraction of the two helicities as a free parameter



Variable validated with 8 TeV data
Plot from Vladimir Cherepanov 2016

Optimal variable

The optimal variable for the τ pair is defined as: $\Omega = \frac{\omega_1 + \omega_2}{1 + \omega_1 \omega_2}$



Vladimir Cherepanov's paper

≈100% anti-correlation of τ leptons spins → allows a very good separation
so good news for analysis

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- Toward Higgs CP measurement

$\tau_h\tau_h$ channel

Trigger : Two taus isolated using charged tracks and photons (or only charged tracks), Pt>35 GeV, $|\eta| < 2.1$
+ Matching with DeltaR < 0.5

Id and Kinematic:
τ_1 and τ_2 :
- pt > 36 GeV && $|\eta| < 2.1$
- Vertex: $|dz| < 0.2$
- Against Muon Loose && against Electron Very Loose
- τ charge = ±1

Pair creation

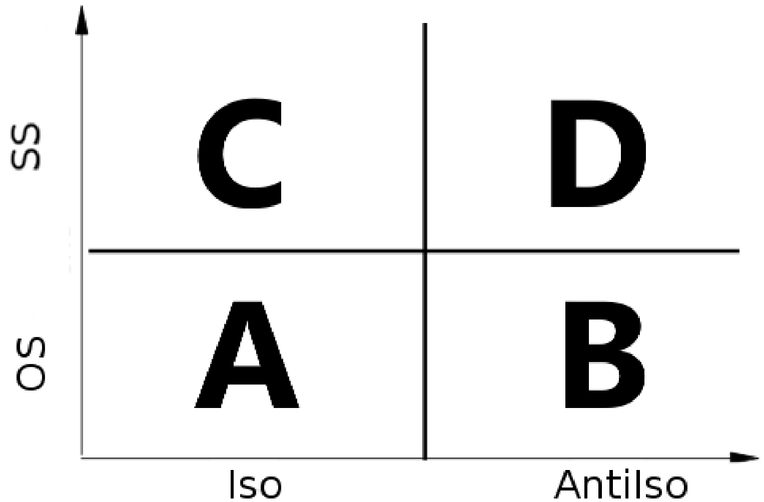
DeltaR(τ_h, τ_h) > 0.5

Selection of the most isolated pair for each event

Tau Isolation : Tight
Third Lepton Veto
Opposite Sign Pairs

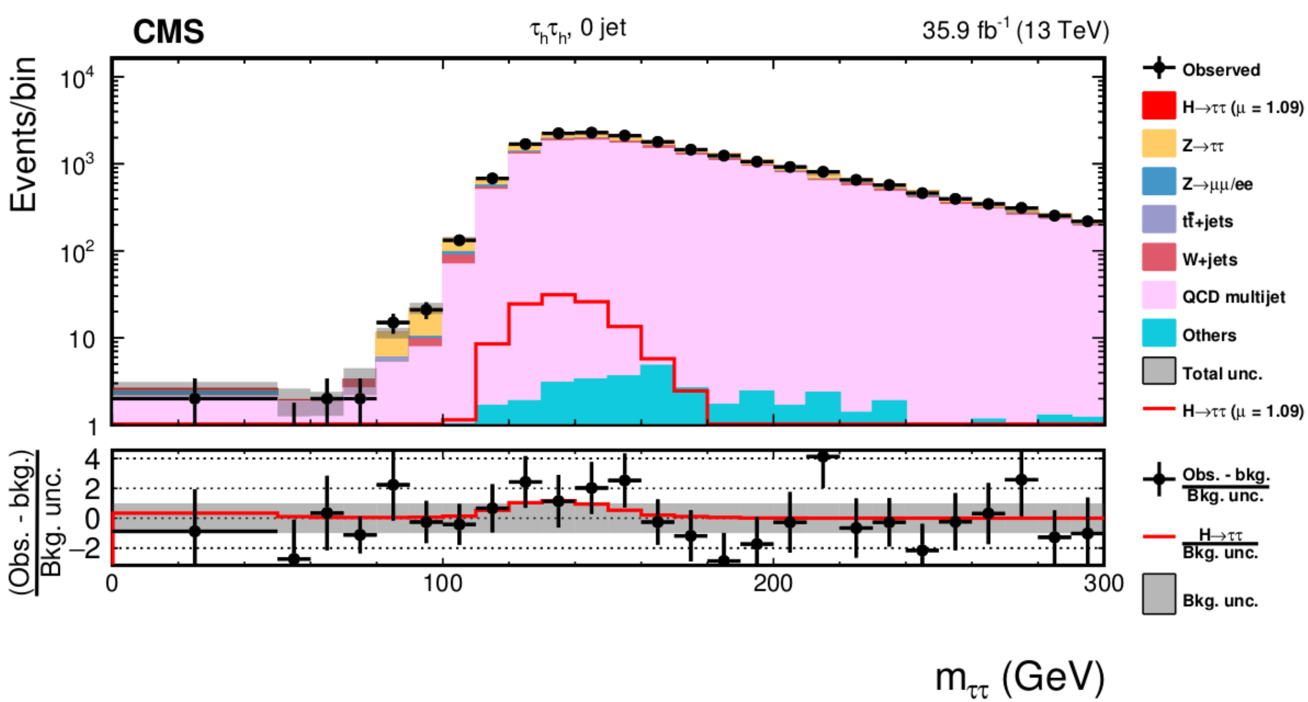
MC used
DY+Jets
W+Jets
tt
WW→2l2ν
WZ
ZZ→2l2ν
ZZ→2l2q
ZZ→4l

Background Estimation



$$QCD^{OS/SS}\,Factor = \frac{DATA_C - OtherBkg_C}{DATA_D - OtherBkg_D}$$

$$QCD_A = QCD^{OS/SS}\,Factor * \left(DATA_B - OtherBkg_B\right)$$



CMS paper

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- **Toward Higgs CP measurement**

τ to study Higgs CP properties

- Best channel for observing Higgs boson fermionic decays
- Can be use for lepton non-universality searches
- And for Lepton Flavor Violation searches

CP violation in the tau Yukawa coupling

$$L_Y = g_\tau \left(\cos\alpha_\tau \bar{\tau}\tau + \sin\alpha_\tau \bar{\tau}\gamma_5\tau \right)$$

α_τ=0 in the SM

Studying transverse correlation in Z boson decays allows us to study the transverse correlation of the Higgs

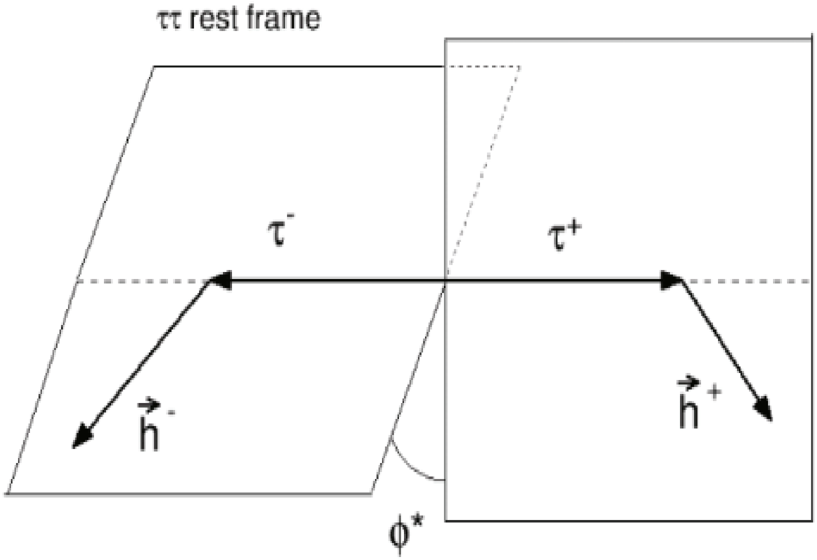
$$C_{TT} = -C_{TN} = \frac{F_2(s)\sin^2\theta}{1 + P_Z Pf\, 2\cos\theta / (1 + \cos^2\theta)}$$

$$C_{TN} = \frac{A_{TN}\sin^2\theta / (1 + \cos^2\theta)}{1 + P_Z Pf\, 2\cos\theta / (1 + \cos^2\theta)}$$

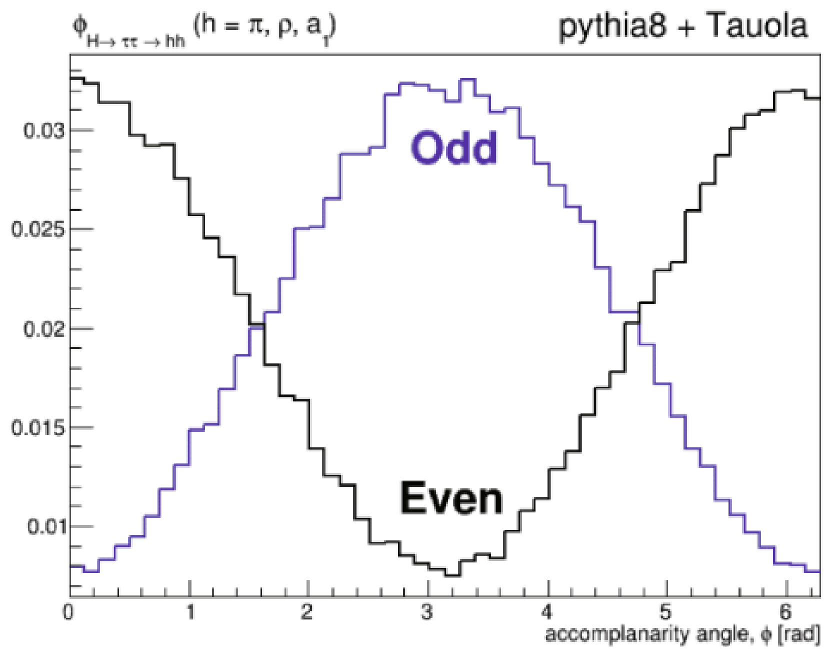
$Z \rightarrow \tau\tau$ analysis useful because it’s the main background of $H \rightarrow \tau\tau$

We can extract the Higgs parity from the correlations between the τ decay products in the plane transverse to the $\tau^+\tau^-$ axes

Transverse spin correlation

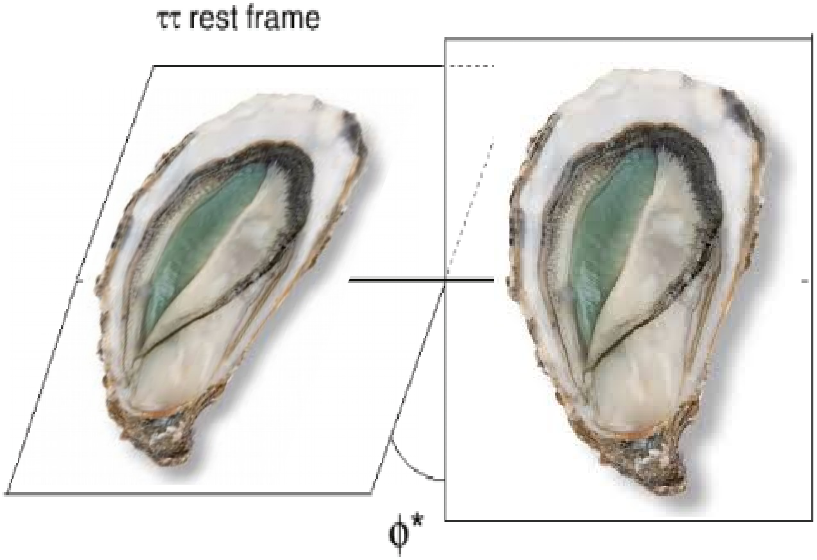


Acoplanarity angle can be build using direction of taus in Higgs rest frame and polarimetric vectors



Tau lepton workshop 2018

Transverse spin correlation



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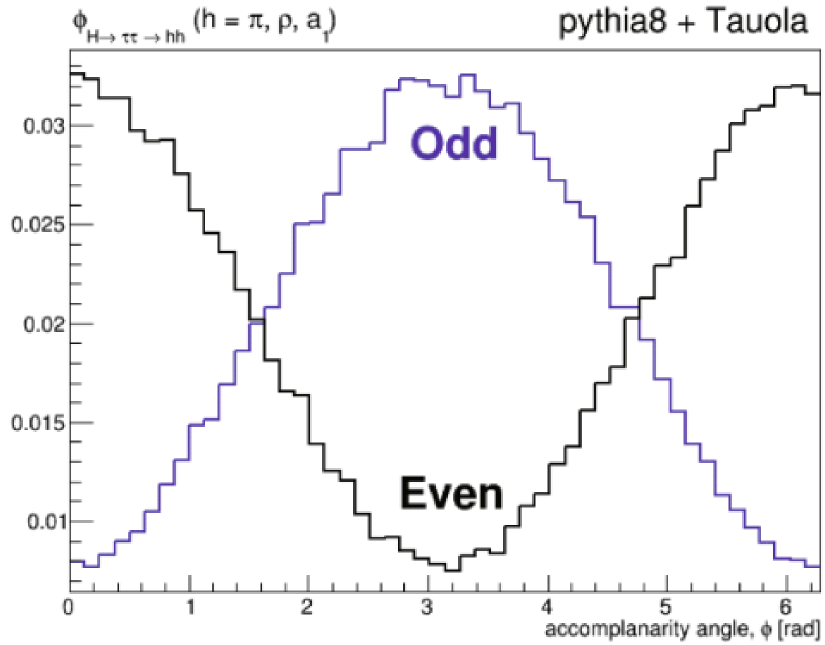


Tau lepton workshop 2018

Conclusion

- A competitive precision to LEP can be achieved using spin variables to measure θ_W at LHC
- My thesis aims the transverse correlation measurements in the Z boson which will be used for the Higgs
- Since it's discovery, the Higgs seems to be the standard Higgs → Need to looking for a CP violation in the τ Yukawa coupling
- Useful tool useable for other analysis/experiments

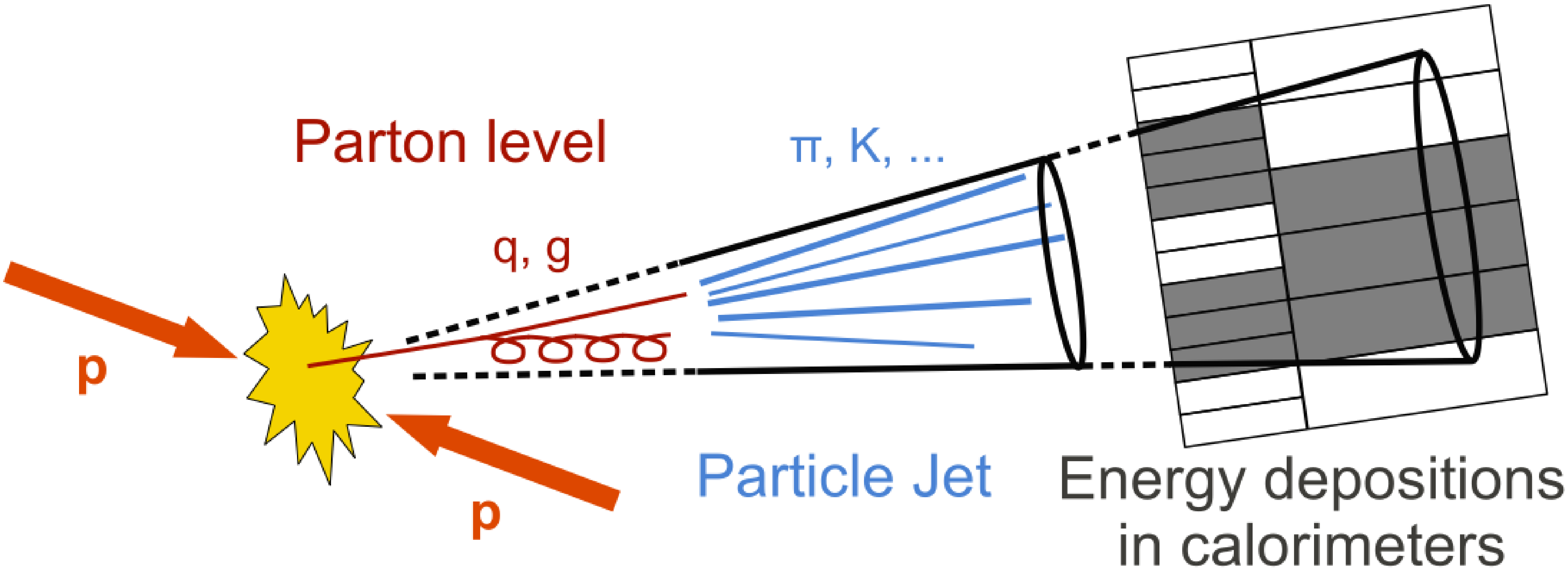
Thanks for your attention

Backup

Jets

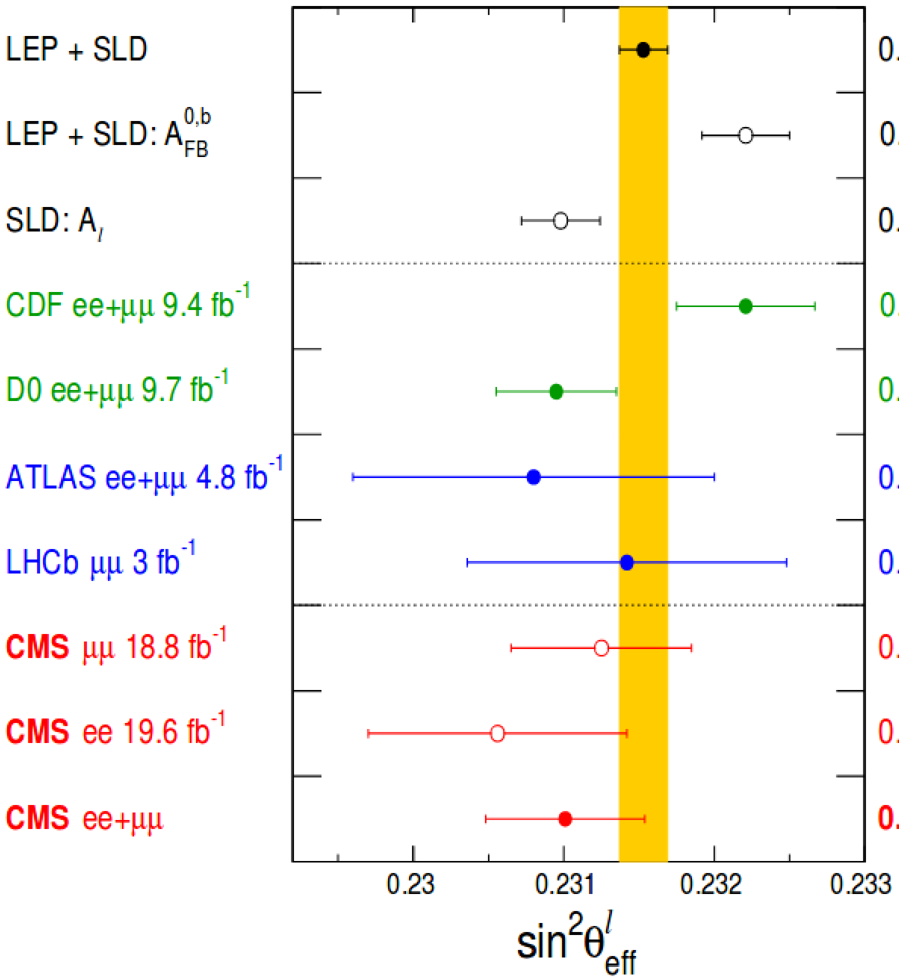
A collimated bunch of hadrons flying roughly in the same direction

Pure QCD effect



The classification of particles into jets is best done using a clustering algorithm

Past measurements



Vladimir's thesis: 8 TeV, 19.6 fb^{-1}

$Z^0 \rightarrow \tau^+\tau^- \rightarrow \mu\nu\nu, a_1\nu$

$$\langle P\tau \rangle = -0.1261 \pm 0.073(stat)^{+0.018}_{-0.019}(syst)$$

$$\sin^2\theta_{eff} = 0.2336 \pm 0.0096$$

SM:

$$C_{TT} = +0.99$$
$$C_{TN} = -0.01$$

From ALEPH:

$$C_{TT} = 1.06 \pm 0.13(stat) \pm 0.05(syst)$$
$$C_{TN} = 0.08 \pm 0.13(stat) \pm 0.04(syst)$$

Sensitivity

Decays channel	Theoretical sensitivity
$\tau \rightarrow e\bar{\nu}_e\nu_\tau$	0.27
$\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau$	0.27
$\tau \rightarrow \pi^\pm\nu_\tau$	0.58
$\tau \rightarrow \rho^\pm\nu_\tau$	0.58
$\tau \rightarrow a_1\nu_\tau$	0.58

Sensitivity reaches the value of 0.73 for any combination of hadronic decays of τ^+ and τ^-