Tau signal on SPD

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Physical motivation

- Pair of taus carries information about polarisation state of initial partons
- Due to unique decay properties of tau lepton, it is possible to reconstruct polarisation state of tau through its decay products
- Possibility to access parton densities through polarisation state of taus

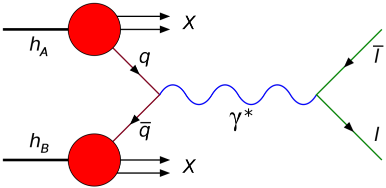

Figure: Representative diagram of the Drell-Yan process

Physical motivation

Initial hadronic tensor:

$$\begin{aligned} Q^{ij} &= tr\left[\not{p}_{\bar{u}}\gamma^i \frac{1 \pm \gamma_5}{2}\ \not{p}_u \gamma^j \frac{1 \pm \gamma_5}{2}\right] \\ &= 2 \cdot (p^i_{\bar{u}} p^j_u + p^i_u p^j_{\bar{u}} - g^{ij} p_{\bar{u}} p_u \mp i\varepsilon^{\alpha i \beta j} p_{\bar{u}\,\alpha} p_{u\,\beta}) \end{aligned}$$

Final leptonic tensor:

$$\begin{aligned} L_{ij} =& tr\big[(\not{p}_{\bar{\tau}} - m_\tau)\gamma_i(\not{p}_\tau + m_\tau)(1-\gamma_5)\ \not{p}_\nu(1+\gamma_5) \\ & \cdot (\not{p}_\tau + m_\tau)\gamma_j(\not{p}_{\bar{\tau}} - m_\tau)(1-\gamma_5)\ \not{p}_{\bar{\nu}}(1+\gamma_5)\big] \end{aligned}$$

Matrix element of the full process:

$$\begin{aligned} |M_{u\bar{u}\to\nu\bar{\nu}\pi^+\pi^-}|^2 =& \frac{factor}{2(p_u p_{\bar{u}})} \cdot \frac{1}{\left(2(p_\nu p_{\pi^-}) - m_\tau^2\right)^2 + \Gamma_\tau^2 m_\tau^2} \\ & \cdot \frac{1}{(2(p_{\bar{\nu}} p_{\pi^+}) - m_\tau^2)^2 + \Gamma_\tau^2 m_\tau^2} \cdot Q^{ij} L_{ij} \end{aligned}$$

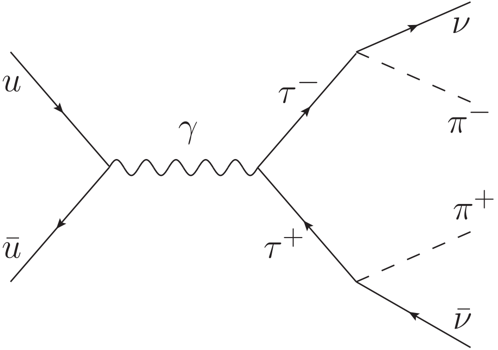

Figure: Drell-Yan process with the pair-production of tau leptons and their subsequent decay into single charged π-meson and neutrino.

Physical motivation

For initial polarization $\bar{q}_L q_R$:

$$\begin{aligned}
Q^{ij}L_{ij} = &- 2^8 \cdot m_\tau^2 \cdot (\\
&+ p_1p_2 \cdot p_3p_4 \cdot p_5p_6 - p_1p_2 \cdot p_3p_5 \cdot p_4p_6 - p_1p_2 \cdot p_3p_6 \cdot p_4p_5 \\
&- p_1p_3 \cdot p_2p_4 \cdot (p_5p_6 + m_\tau^2) + p_1p_3 \cdot p_2p_5 \cdot p_4p_6 - p_1p_3 \cdot p_2p_6 \cdot p_4p_5 \\
&- p_1p_4 \cdot p_2p_3 \cdot p_5p_6 + p_1p_4 \cdot p_2p_5 \cdot p_3p_6 + p_1p_4 \cdot p_2p_6 \cdot p_3p_5 \\
&+ p_1p_5 \cdot p_2p_3 \cdot p_4p_6 - p_1p_5 \cdot p_2p_4 \cdot p_3p_6 - p_1p_5 \cdot p_2p_6 \cdot (p_3p_4 + m_\tau^2) \\
&+ p_1p_6 \cdot p_2p_3 \cdot p_4p_5 + p_1p_6 \cdot p_2p_4 \cdot p_3p_5 - p_1p_6 \cdot p_2p_5 \cdot p_3p_4 \\
&)
\end{aligned} \tag{1}$$

For initial polarization $\bar{u}_R u_L$:

$$\begin{aligned}
Q^{ij}L_{ij} = &- 2^8 \cdot m_\tau^2 \cdot (\\
&+ p_1p_2 \cdot p_3p_4 \cdot p_5p_6 - p_1p_2 \cdot p_3p_5 \cdot p_4p_6 - p_1p_2 \cdot p_3p_6 \cdot p_4p_5 \\
&- p_1p_3 \cdot p_2p_4 \cdot p_5p_6 + p_1p_3 \cdot p_2p_5 \cdot p_4p_6 + p_1p_3 \cdot p_2p_6 \cdot p_4p_5 \\
&- p_1p_4 \cdot p_2p_3 \cdot (p_5p_6 + m_\tau^2) - p_1p_4 \cdot p_2p_5 \cdot p_3p_6 + p_1p_4 \cdot p_2p_6 \cdot p_3p_5 \\
&+ p_1p_5 \cdot p_2p_3 \cdot p_4p_6 + p_1p_5 \cdot p_2p_4 \cdot p_3p_6 - p_1p_5 \cdot p_2p_6 \cdot p_3p_4 \\
&- p_1p_6 \cdot p_2p_3 \cdot p_4p_5 + p_1p_6 \cdot p_2p_4 \cdot p_3p_5 - p_1p_6 \cdot p_2p_5 \cdot (p_3p_4 + m_\tau^2) \\
&)
\end{aligned} \tag{2}$$

where: $p_1,\ p_2,\ p_3,\ p_4,\ p_5,\ p_6 \ = \ p_u,\ p_{\bar{u}},\ p_\nu,\ p_{\bar{\nu}},\ p_{\pi^+},\ p_{\pi^-}$

Physical motivation

Order	LO		
Order	cross-section, σ pb	MC error, $\Delta\sigma$ pb	scale variation
LO	100.01	0.1	+- 13.3%
NLO	113.81	0.1	+- 3.4%

Table: Cross-sections of the Drell-Yan tau pair production at energy $\sqrt{s} = 27$ GeV.

$\sqrt{s} = 27\text{GeV}(L = 1.2 \cdot 10^{32}\ \text{cm}^{-2}\text{s}^{-1})$

Lower cut on $M_{l^+l^-}$, GeV	3.56	4
$\sigma_{pp\to\tau^+\tau^-} \cdot Br_{\tau^-\to\pi^-\nu_\tau} \cdot Br_{\tau^+\to\pi^+\bar{\nu_\tau}}$, pb	1.22	0.88
Approximate number of events per 7000h	3100	2200

Table: Estimation of the number of events $pp \to \pi^-\nu_\tau\pi^+\bar{\nu_\tau}$ per year ($\sim$ 7000h) of data taking.

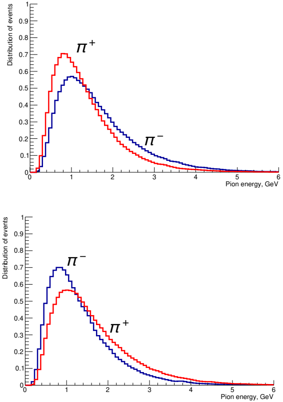

Figure: Energy spectra of pi-mesons produced in processes with different polarization of the initial partons

Significance estimation

Significance is estimated using the following formula:

$$2(\sqrt{S+B}-\sqrt{B})^{1}, \tag{3}$$

where S and B are signal and background events.

Estimation was conducted in the following environment:

- Signal: hard events + PS (Madgraph5 + Pythia8)
- Background: MB soft QCD (Pythia8)
- Detector response + reconstruction (Delphes)
- Tau reconstruction efficiency - 70%

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[1] S. Bityukov, N. Krasnikov, A. Nikitenko, and V. Smirnova, Proc. Sci., ACAT08 (2008) 118.

Significance estimation

Without any cuts the signal is totally dominated by background.
Basic solution is to introduce selection cuts, which will be more efficient at cutting the background, than signal.

Following simple selection cuts:

1. At least two reconstructed tau jets
2. Reconstructed tau jets $P_T > 2$ GeV
3. Reconstructed tau jets $\eta < 2.5$

Results in significance of the signal $\approx 1.2\sigma$

Significance estimation

Obtained significance level is too low to conduct phenomenology analyses.
Therefore simple selection cuts is not enough.

Following approaches can help to improve signal to background ratio:

- Pre-selection cuts

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Following approaches can help to improve signal to background ratio:

- Pre-selection cuts
- The use of more sophisticated variables, which follows from understanding of the inner structure of ME for hard process (2d distributions, spin correlations, etc)
- The use of more sophisticated models, which allow for solution of non-linear classification problems (Gradient Boosted Decision Trees, Deep Neural Networks)

Delphes

Delphes is a C++ framework, performing a fast multipurpose detector response simulation[2].

- Fast
- Particle and event structure based on ROOT
- Convenient interface for Pythia, LHE, HepMC
- Many inbuild detector cards
- Analyses can be performed via ROOT

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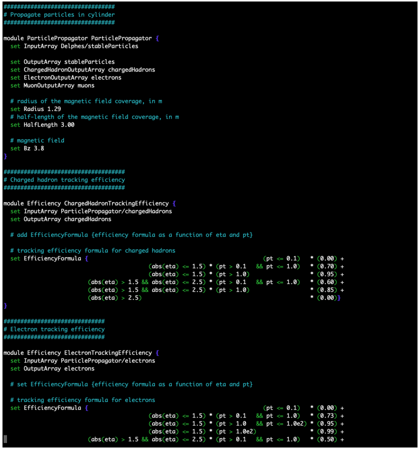
[2] The DELPHES 3 collaboration., de Favereau, J., Delaere, C. et al. DELPHES 3: a modular framework for fast simulation of a generic collider experiment. J. High Energ. Phys. 2014, 57 (2014).

Delphes

- Properly configured detector card is required
- Given such card exists and properly calibrated, Delphes provides extreme convenience for any kind of phenomenology studies
- One of the current focuses of our working group - is to create and validate such card for NICA SPD detector



```
#################################
# Propagate particles in cylinder
#################################

module ParticlePropagator ParticlePropagator {
  set InputArray Delphes/stableParticles

  set OutputArray stableParticles
  set ChargedHadronOutputArray chargedHadrons
  set ElectronOutputArray electrons
  set MuonOutputArray muons

  # radius of the magnetic field coverage, in m
  set Radius 1.29
  # half-length of the magnetic field coverage, in m
  set HalfLength 3.00

  # magnetic field
  set Bz 3.8
}

####################################
# Charged hadron tracking efficiency
####################################

module Efficiency ChargedHadronTrackingEfficiency {
  set InputArray ParticlePropagator/chargedHadrons
  set OutputArray chargedHadrons

  # add EfficiencyFormula {efficiency formula as a function of eta and pt}

  # tracking efficiency formula for charged hadrons
  set EfficiencyFormula {                                                    (pt <= 0.1)   * (0.00) +
                                           (abs(eta) <= 1.5) * (pt > 0.1   && pt <= 1.0)   * (0.70) +
                                           (abs(eta) <= 1.5) * (pt > 1.0)                  * (0.95) +
                         (abs(eta) > 1.5 && abs(eta) <= 2.5) * (pt > 0.1   && pt <= 1.0)   * (0.60) +
                         (abs(eta) > 1.5 && abs(eta) <= 2.5) * (pt > 1.0)                  * (0.85) +
                         (abs(eta) > 2.5)                                                  * (0.00)}
}

##############################
# Electron tracking efficiency
##############################

module Efficiency ElectronTrackingEfficiency {
  set InputArray ParticlePropagator/electrons
  set OutputArray electrons

  # set EfficiencyFormula {efficiency formula as a function of eta and pt}

  # tracking efficiency formula for electrons
  set EfficiencyFormula {                                                    (pt <= 0.1)   * (0.00) +
                                           (abs(eta) <= 1.5) * (pt > 0.1   && pt <= 1.0)   * (0.73) +
                                           (abs(eta) <= 1.5) * (pt > 1.0   && pt <= 1.0e2) * (0.95) +
                                           (abs(eta) <= 1.5) * (pt > 1.0e2)                * (0.99) +
                         (abs(eta) > 1.5 && abs(eta) <= 2.5) * (pt > 0.1   && pt <= 1.0)   * (0.50) +
```

Figure: Delphes detector card example

Summary

- Significance estimation for pair tau production signal at NICA SPD is presented. At the current stage of the project simple selection cuts were utilized. Obtained significance level is not enough for phenomenology applications, but it can be further improved by adopting more sophisticated approaches: spin-related composite variables and modern classification algorithms
- Delphes - a tool for fast detector response simulation and event reconstruction was briefly discussed

Acknowledgements

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